Higgs Physics at the LHC

Margarete Mühlleitner, KIT

Symposium
Collider Higgs Physics
Paul Scherrer Institute

Higgs Physics at the LHC

Neus **Neuß-Grevenbroicher Zeitung**

07.07.2012 , 00:00 Uhr · 3 Minuten Lesezeit

Neusser jagt "Gottesteilchen"

Neuss · Weltweit geraten tausende Wissenschaftler in Euphorie: Das Higgs-Teilchen als fehlende Klammer zur Erklärung des Aufbaus der Welt scheint entdeckt. Der Neusser Physiker Michael Spira gehört zum globalen Forschernetz.

Von Ludger Baten

Michael Spira ist so alt wie die Suche nach dem Higgs-Teilchen: 48 Jahre. Seit Mittwoch gehen Wissenschaftler weltweit davon aus, dass sie mit ihrem Sensationsfund am Cern in Genf die fehlende Klammer zur Erklärung des Aufbaus der Welt entdeckt haben.

Zehntausende Physiker beteiligen sich weltweit an der Suche nach dem Higgs-Teilchen; 6000 allein am Cern. In Genf steht der Teilchenbeschleuniger, der mit 27 Kilometer Länge das größte Experiment der Menschheit ist. Die dort gewonnenen Ergebnisse werden von einem Heer von Theoretikern durchgerechnet, die wiederum den Experimenteuren neue Berechnungen für ihre Arbeit an die Hand geben. Einer dieser Theoretiker ist Michael Spira.

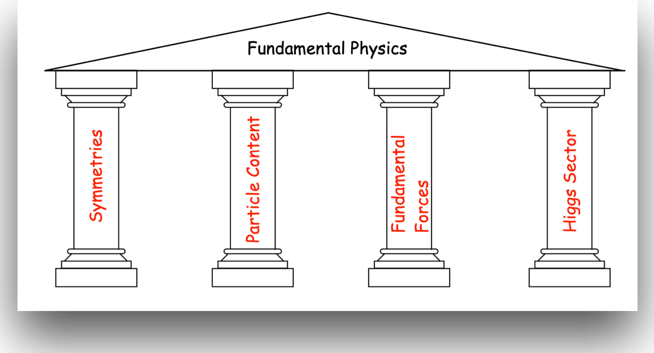
Michael selbst war Deutscher Hochschulmeister und kann sich mit seinen Bestzeiten über 1500 Meter (3:52 Minuten) und 5000 Meter (14:39 Minuten) heute noch sehen lassen. Spira studierte Physik in Aachen und kam über seinen Doktor-Vater zur Higgs-Forschung: "Der hat mich 1989 auf das Thema angesetzt." Es folgten Stationen bei Desy und der Universität Hamburg, am Cern in Genf, wieder Hamburg, ehe er sich schließlich vor zwölf Jahren am PSI wiederfand, wo er Teil des weltweiten Higgs-Erfolges wurde.

"Der heutige Tag ist einer der ganz großen in unserem Forschungsgebiet", sagt Dr. Michael Spira (48), der aus Neuss stammt, Quirinus-Abiturient ist und seit 23 Jahren in der Higgs-Physik forscht: "Fakt ist, dass wir etwas Neues entdeckt haben. Wir wissen aber nicht mit Sicherheit, was wir entdeckt haben." Wahrscheinlich handelt es sich um das Higgs-Teilchen, auch "Gottesteilchen" genannt, vielleicht aber auch um ein verwandtes Teilchen.

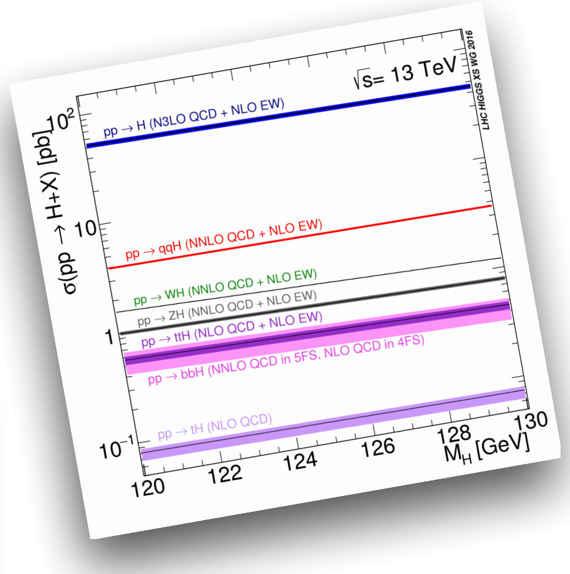
"Wir haben eine beratende Funktion", sagt Michael Spira, der seit dem Jahr 2000 in Diensten des schweizerischen Paul-Scherrer-Institutes (PSI) steht. 60 Mitarbeiter des öffentlichen Forschungsinstitutes sind seit Anfang 2010 in eine vom Cern gebildete Projektgruppe eingebunden, um die theoretischen Vorhersagen für die experimentellen Analysen bereitzustellen. In dem globalen Forschernetzwerk leitet Michael Spira zwei Arbeitsgruppen.

Outline

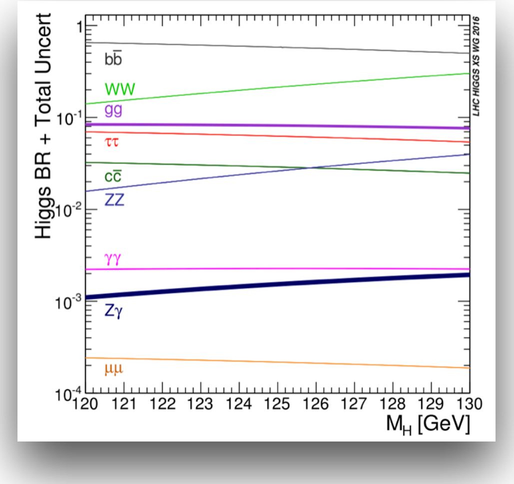
❑ Introduction

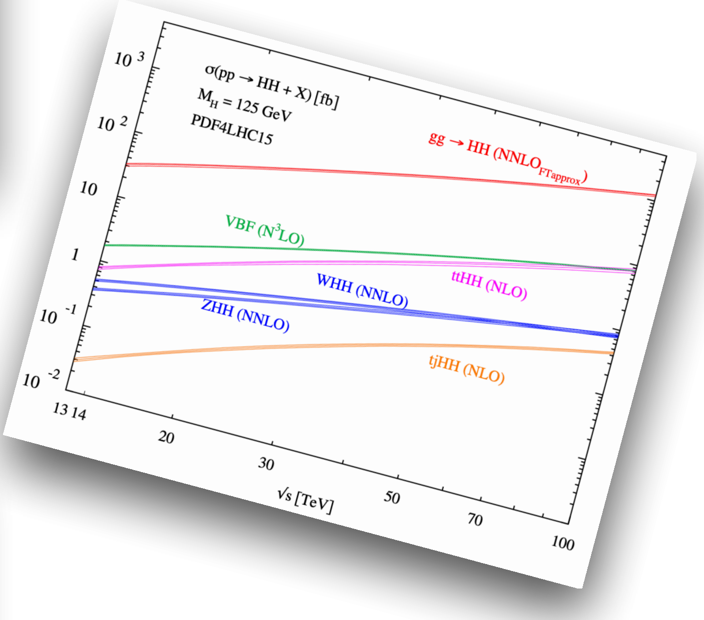


❑ Higgs Boson Production

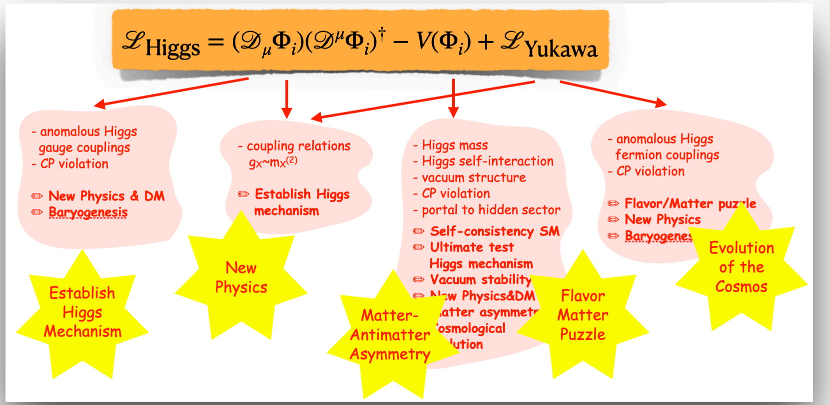


❑ Higgs Boson Decays





❑ Measuring Electroweak Symmetry Breaking



❑ Conclusions

Introduction

Oct. 1983 – Sept. 1989	Study of Physics at RWTH Aachen
September 1989	Physics Diploma, RWTH Aachen Diploma Thesis supervised by Prof. P.M. Zerwas Title: "Quarks und Leptonen: Konsequenzen einer Substruktur im TeV–Bereich"
October 1992	Ph.D., RWTH Aachen Ph.D. Thesis supervised by Prof. P.M. Zerwas Title: "QCD–Strahlungskorrekturen zu Higgsboson–Zerfall und –Produktion in e^+e^-– und pp–Beschleunigern" Graduation: Ph.D. with 'summa cum laude', Borchers Award of RWTH Aachen

Rompimiento de la Simetría Electrodébil y la Física del Higgs: Conceptos Básicos

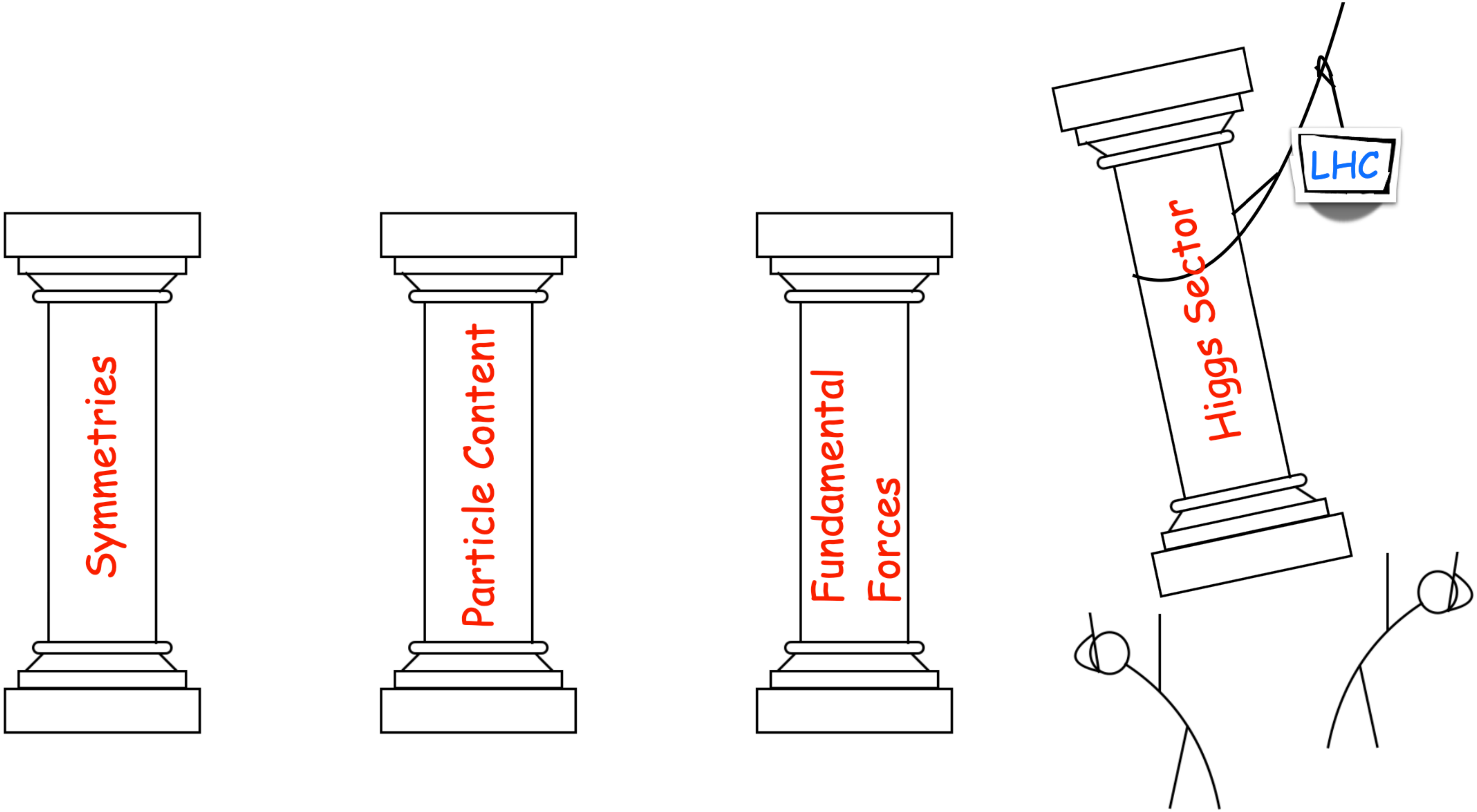
M. Gomez-Bock[1], **M. Mondragón**[2], **M. Mühlleitner**[3,4],
R. Noriega-Papaqui[1], **I. Pedraza**[1], **M. Spira**[3], **P.M. Zerwas**[5]
[1] Inst. de Física "LRT", Benemérita Univ. Autón. de Puebla, 72570 Puebla, Pue, México
[2] Inst. de Física, Univ. Nac. Auton. de México, 01000 México D.F., México
[3] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[4] Laboratoire d'Annecy-Le-Vieux de Physique Théorique, LAPTH, Annecy-Le-Vieux, France
[5] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Resumen. Presentamos una introducción a los conceptos básicos del rompimiento de la simetría electrodébil y la física del Higgs dentro del Modelo Estándar y sus extensiones supersimétricas. Se presenta también una breve perspectiva general de mecanismos alternativos del rompimiento de la simetría. Además de las bases teóricas, se discute el estado actual de la física experimental del Higgs y sus implicaciones para futuros experimentos en el LHC y en colisionadores lineales e^+e^-.

1. Introducción

1. Revelar el mecanismo físico responsable del rompimiento de las simetrías electrodébiles, es uno de los problemas principales en la Física de Partículas. Si las partículas fundamentales -leptones, quarks y bosones de norma (gauge)- siguen interactuando débilmente a altas energías, potencialmente cercanas a la escala de Planck, el sector en el cual la simetría electrodébil es rota debe contener uno o más bosones escalares fundamentales de Higgs con masas ligeras del

The Standard Model is Structurally Complete



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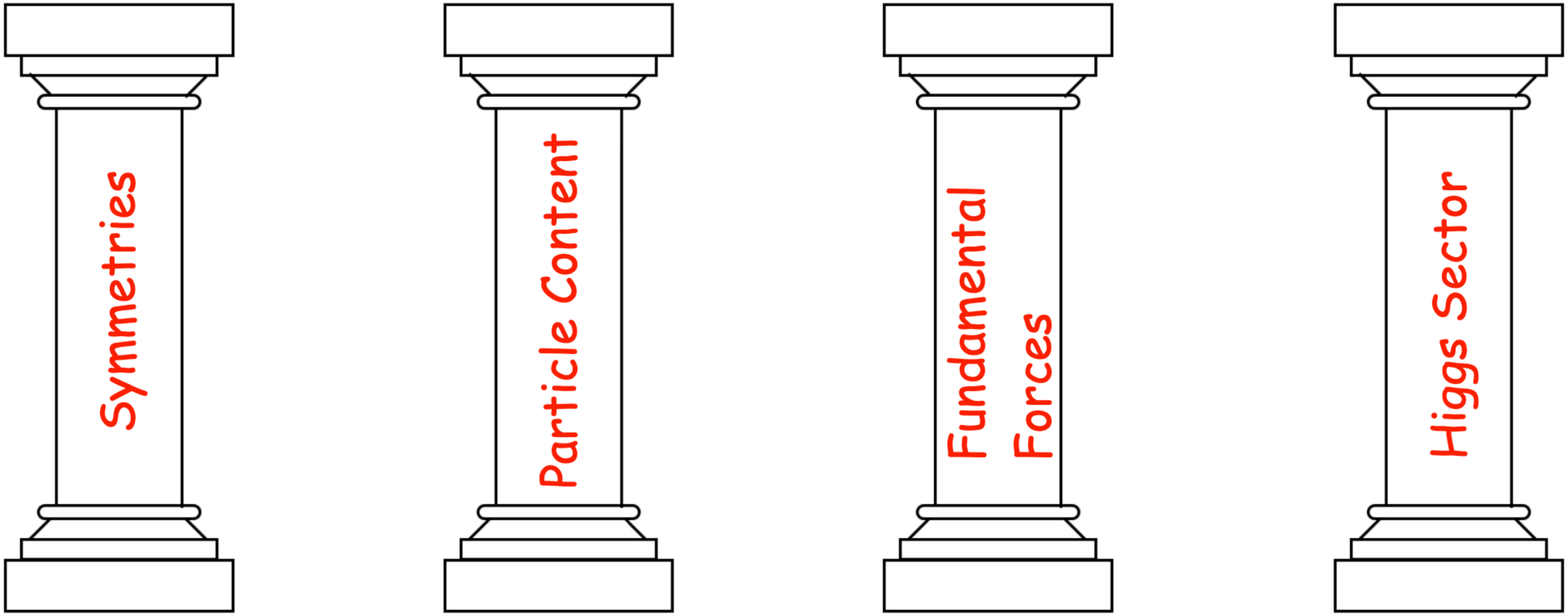


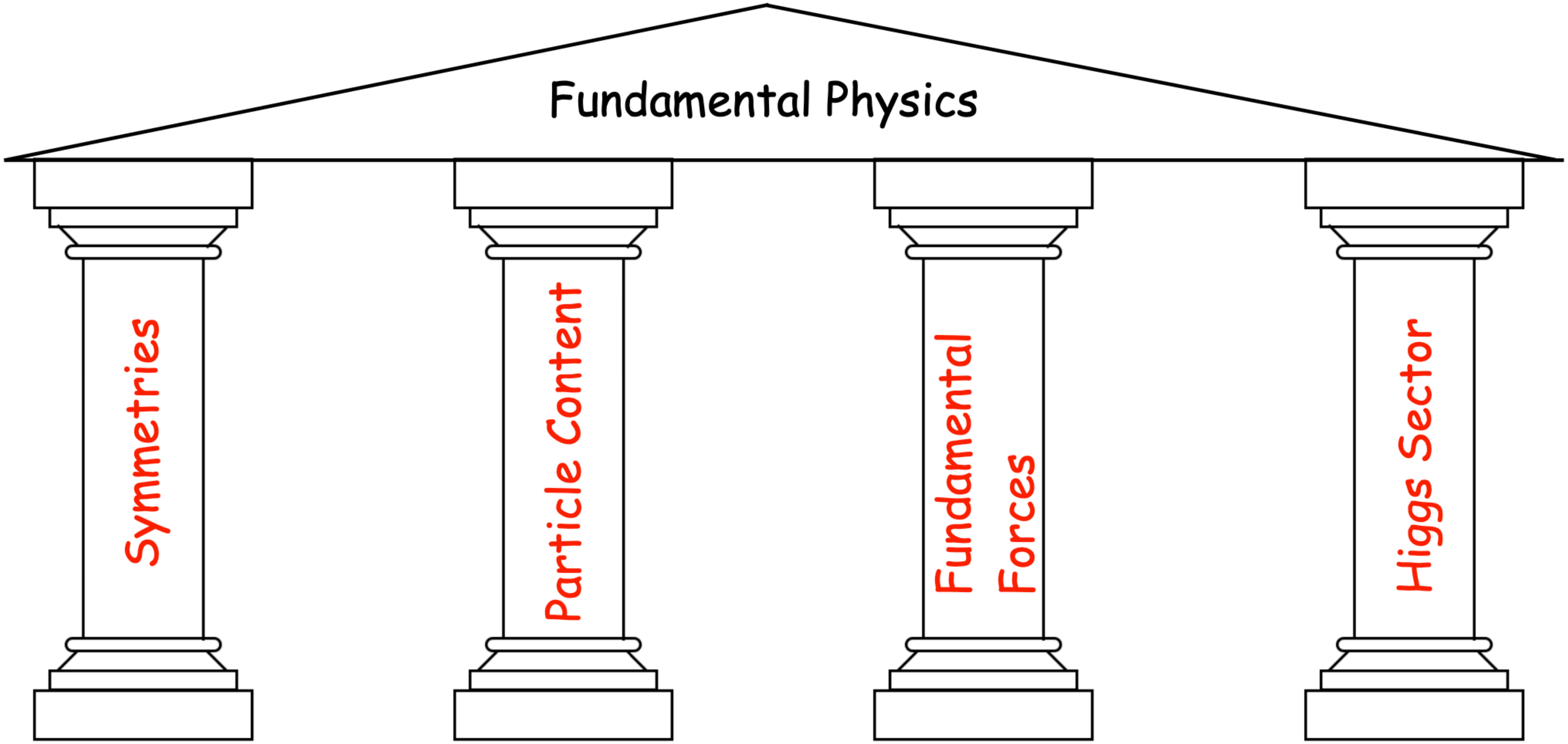
Symmetries

Particle Content

Fundamental Forces

Higgs Sector

The Standard Model is Structurally Complete



Fundamental Physics

Symmetries

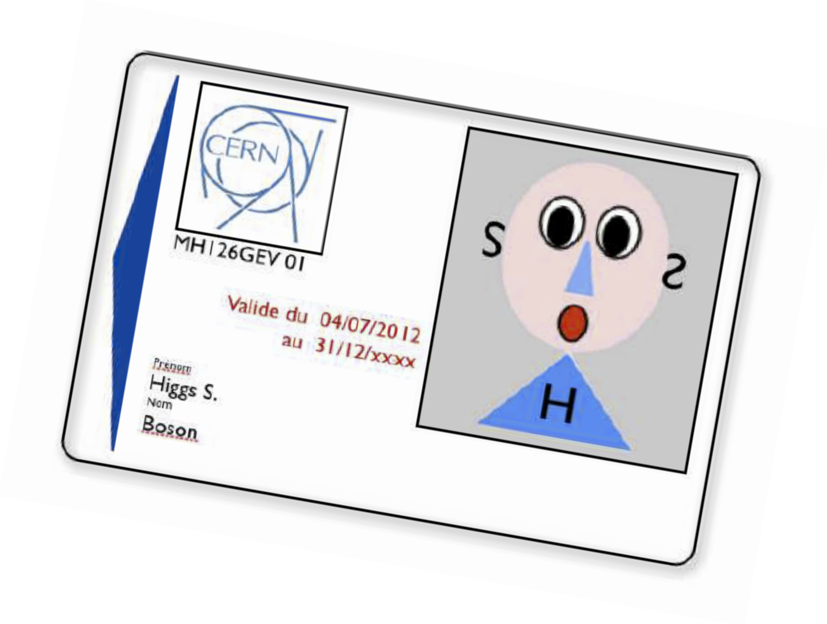
Particle Content

Fundamental Forces

Higgs Sector

Establishing the Higgs Mechanism

M.Spira, 2012: „Wahrscheinlich handelt es sich
um das Higgs-Teilchen."
„Probably it is the Higgs particle."



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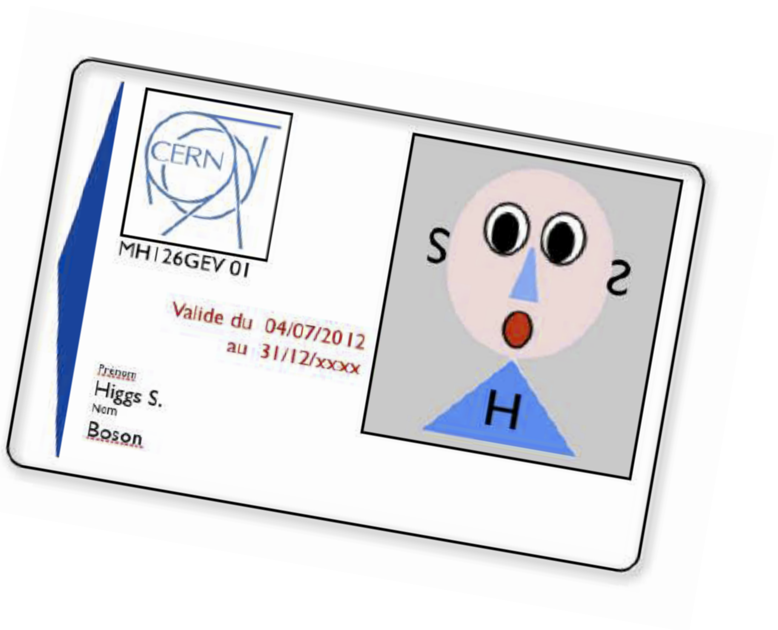


4th July 2012

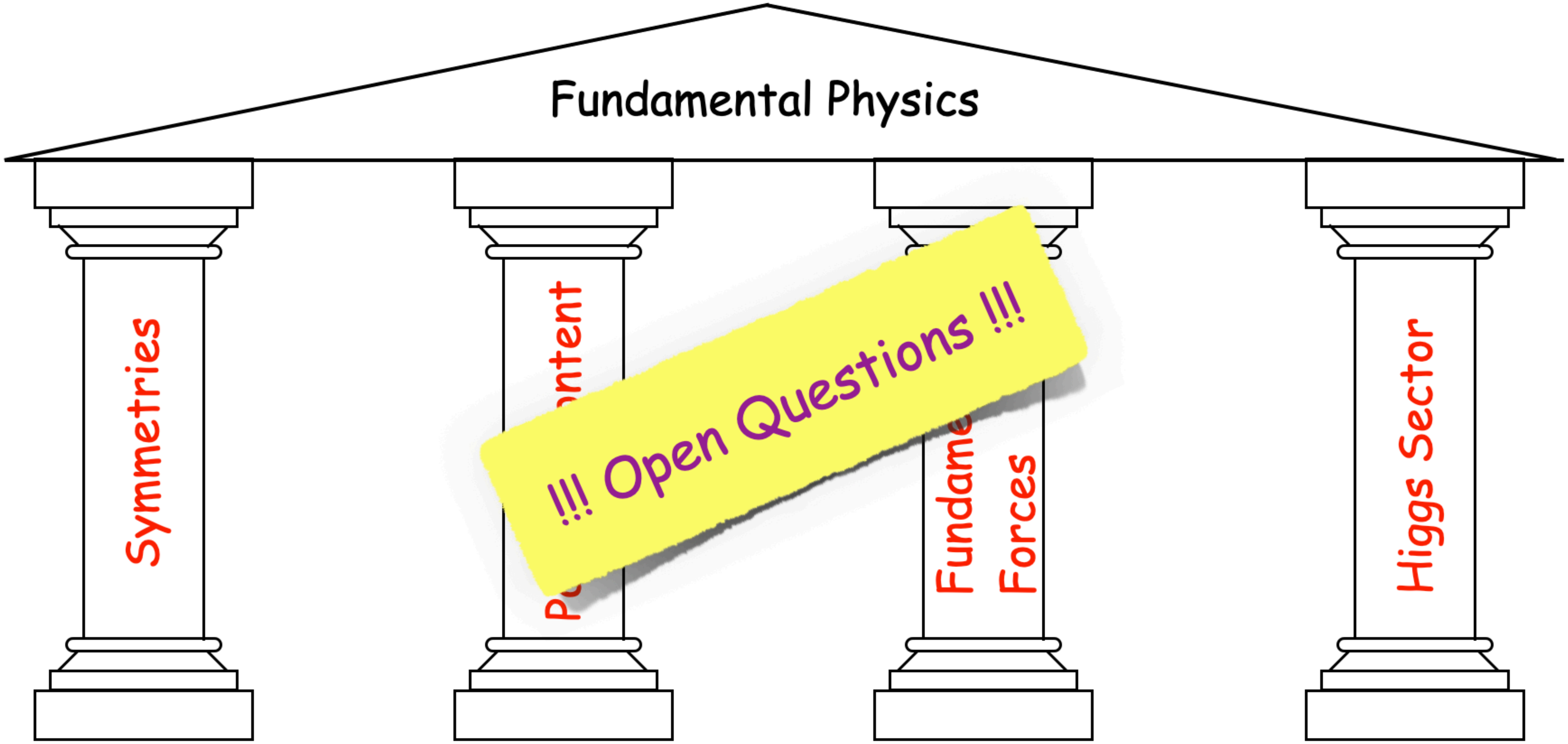
Discovery of new particle announced by CERN!!

But how can we be sure that it is a Higgs? We must

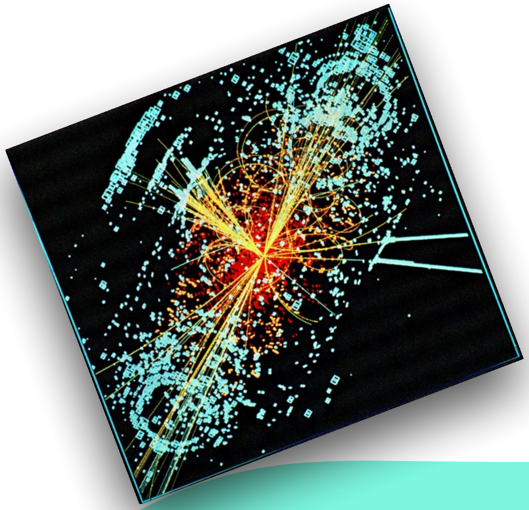
- ○ Measure its couplings to the other SM particles
- ○ We must determine its spin and CP quantum numbers
- ○ We must measure the Higgs potential, I.e. its self-couplings

My Diary

The Standard Model is Structurally Complete - But

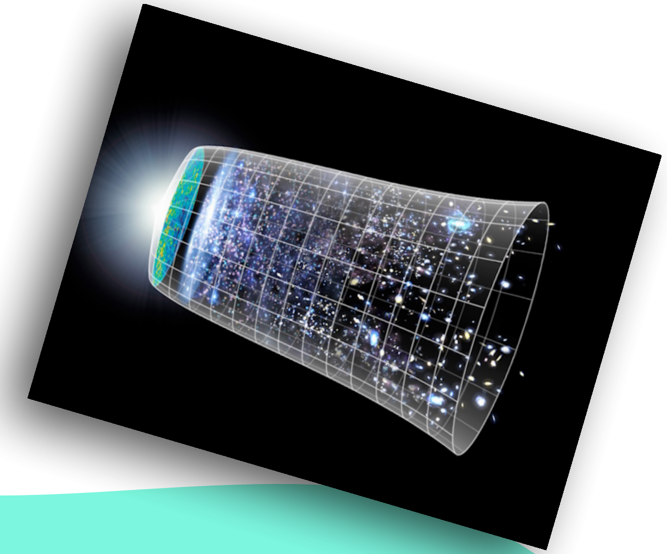


Open Questions



Particle physics

- origin of electroweak symmetry breaking
- hierarchy problem
- nature of the Higgs boson
- fermion mass and flavor puzzle
- origin of neutrino masses



Cosmology

- nature of Dark Matter
- matter-antimatter asymmetry
- dark energy
- inflation
- how to incorporate gravity

Decipherment of fundamental laws of nature:
judicious combination of
theoretical methods/interpretation
and experimental input/scrutiny

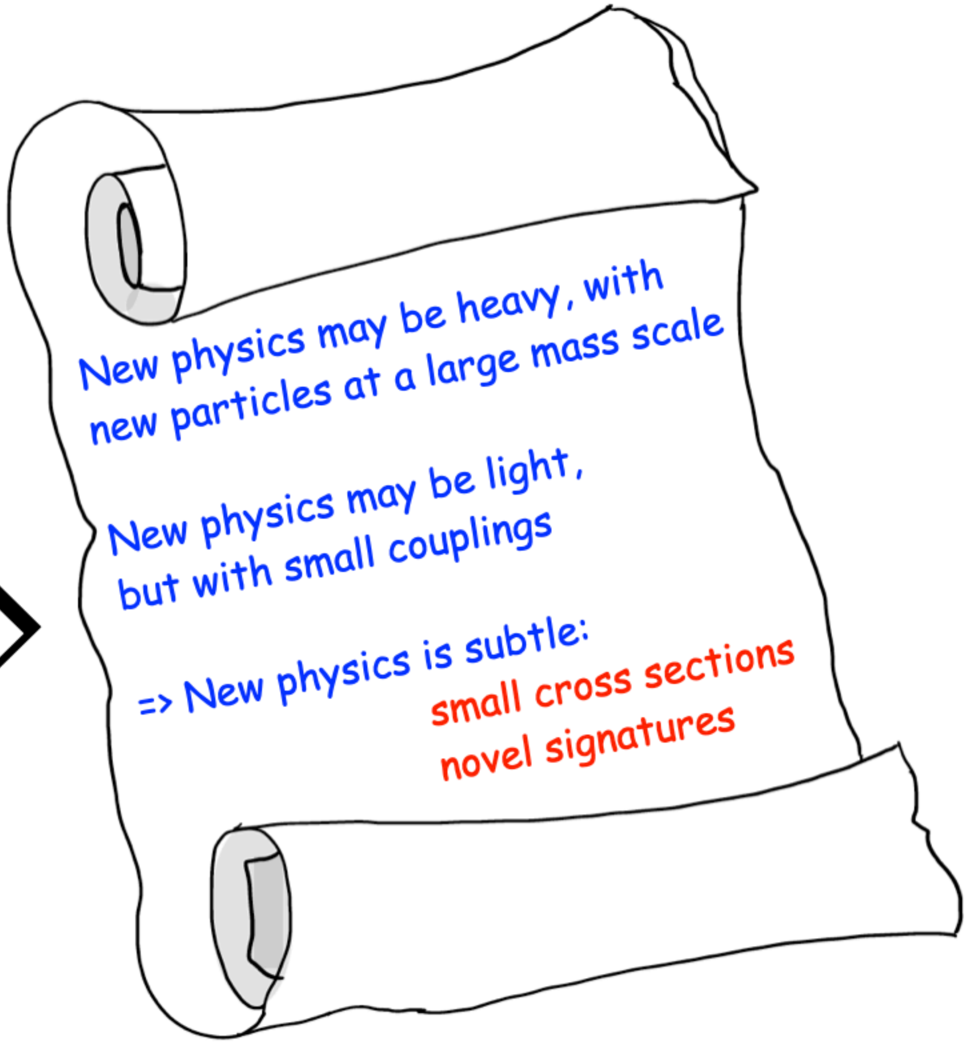
New physics is required, but there is no clear indication at which energy scale

The Challenge

Discovered Higgs Boson
behaves very SM-like

Consistency Test
of the SM
at the quantum level

No direct discovery of
New Physics so far

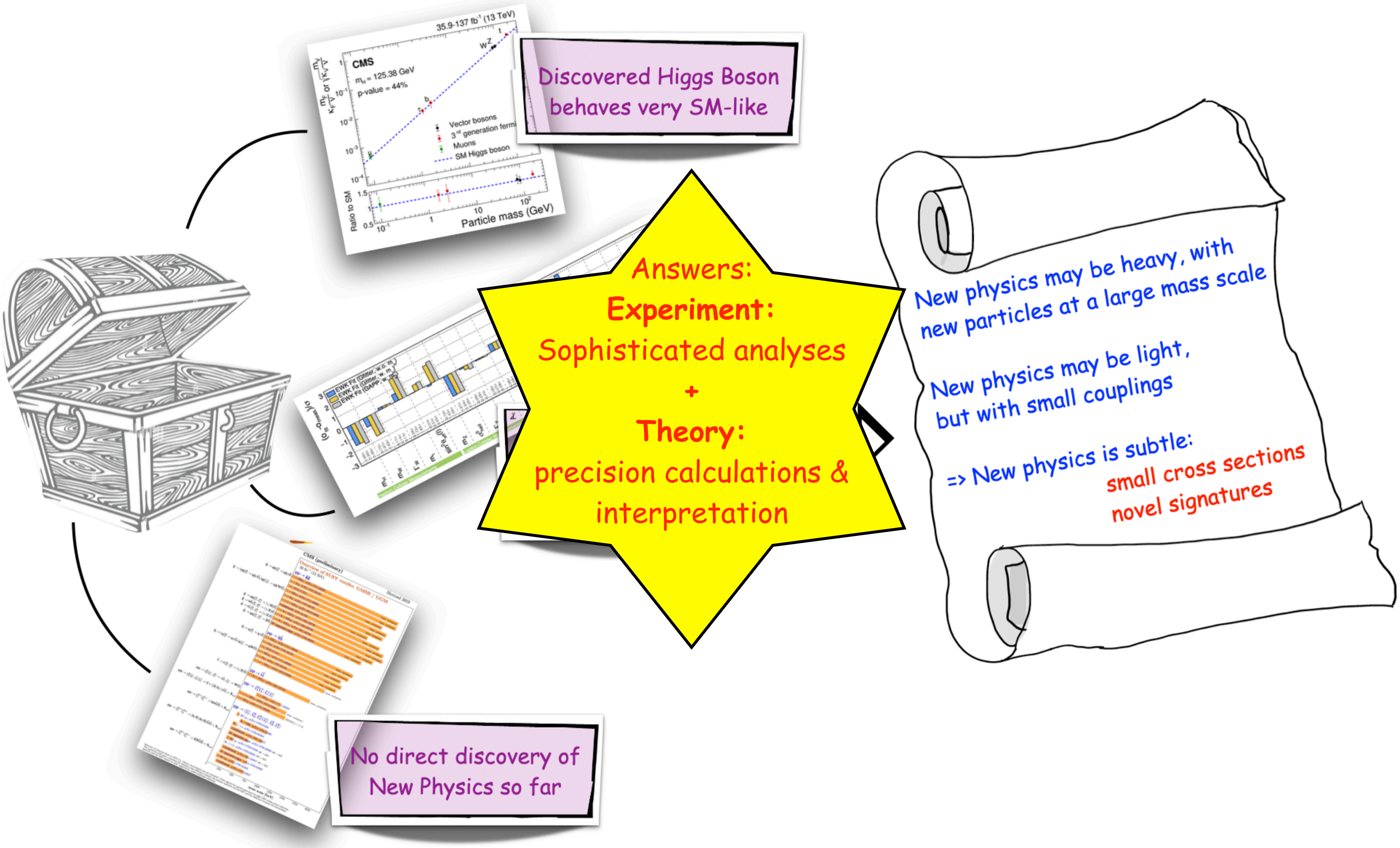


New physics may be heavy, with
new particles at a large mass scale

New physics may be light,
but with small couplings

=> New physics is subtle:
small cross sections
novel signatures

The Challenge



Discovered Higgs Boson behaves very SM-like

No direct discovery of New Physics so far

Answers:

Experiment:

Sophisticated analyses

\+

Theory:

precision calculations & interpretation

New physics may be heavy, with new particles at a large mass scale

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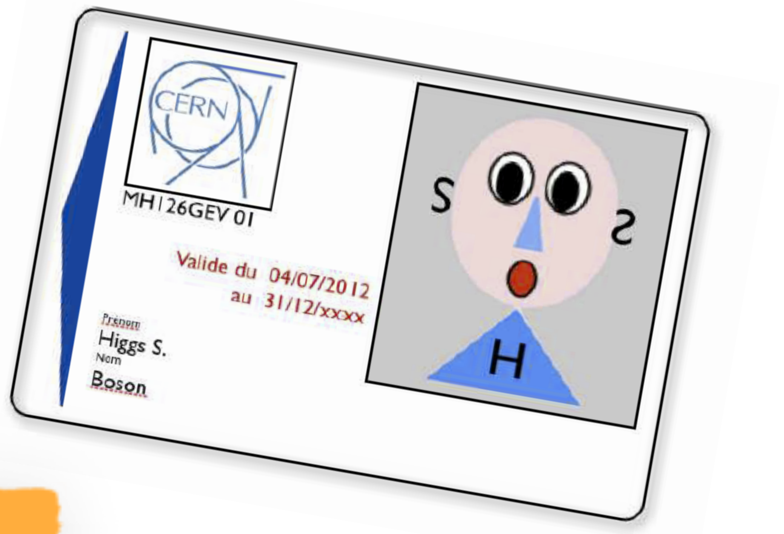
novel signatures

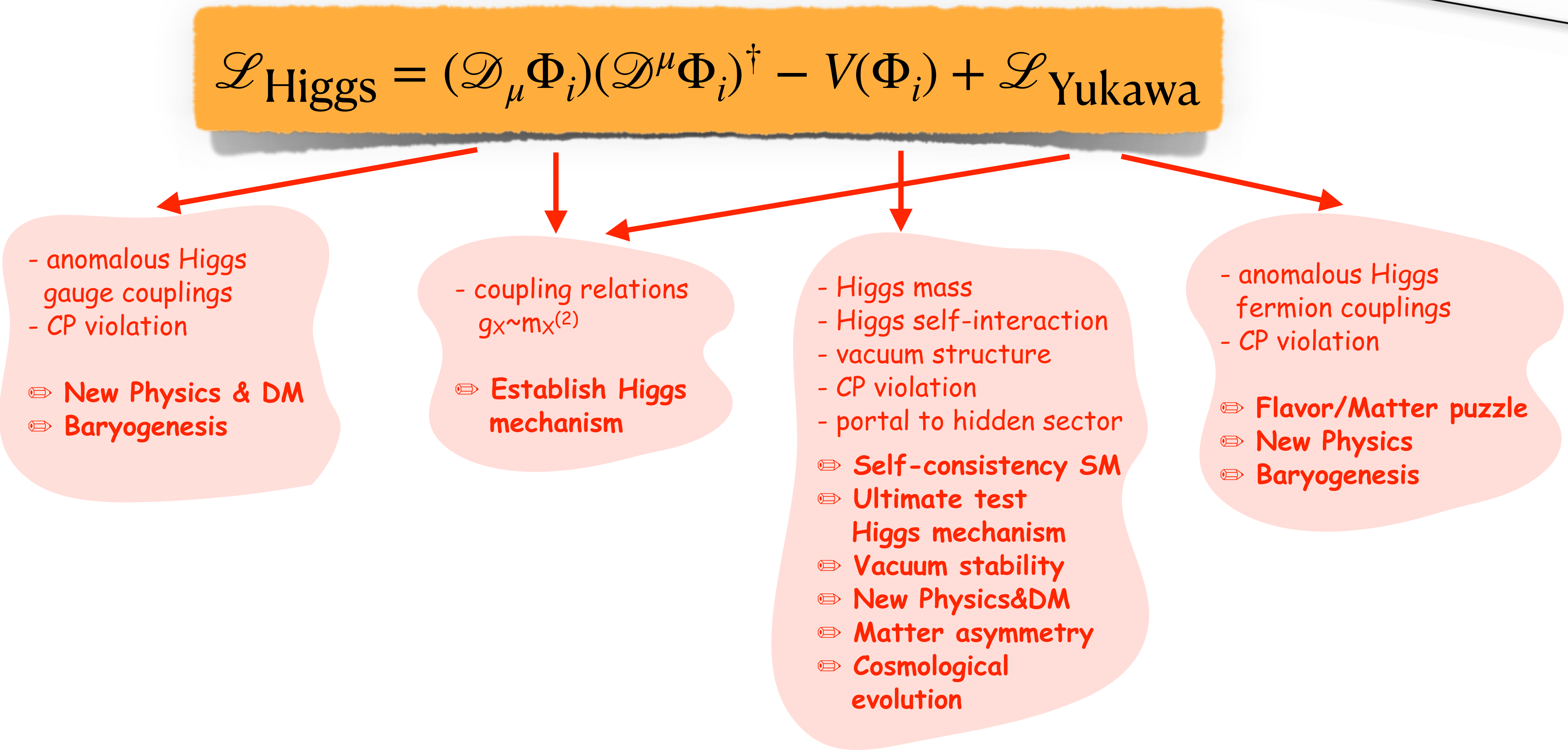
Role of the Higgs Boson



- We have the SM-like Higgs boson

  What can we learn from Higgs physics?

- Corner new physics with the Higgs:



$$\mathscr{L}_{\text{Higgs}} = (\mathscr{D}_\mu \Phi_i)(\mathscr{D}^\mu \Phi_i)^\dagger - V(\Phi_i) + \mathscr{L}_{\text{Yukawa}}$$

- anomalous Higgs gauge couplings
- CP violation

✏ **New Physics & DM**
✏ **Baryogenesis**

- coupling relations $g_X \sim m_X^{(2)}$

✏ **Establish Higgs mechanism**

- Higgs mass
- Higgs self-interaction
- vacuum structure
- CP violation
- portal to hidden sector

✏ **Self-consistency SM**
✏ **Ultimate test Higgs mechanism**
✏ **Vacuum stability**
✏ **New Physics&DM**
✏ **Matter asymmetry**
✏ **Cosmological evolution**

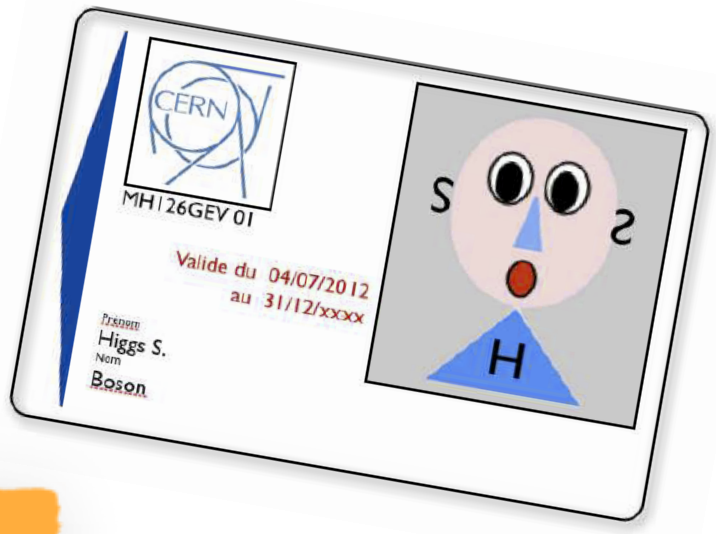
- anomalous Higgs fermion couplings
- CP violation

✏ **Flavor/Matter puzzle**
✏ **New Physics**
✏ **Baryogenesis**

Role of the Higgs Boson

- We have the SM-like Higgs boson

  What can we learn from Higgs physics?



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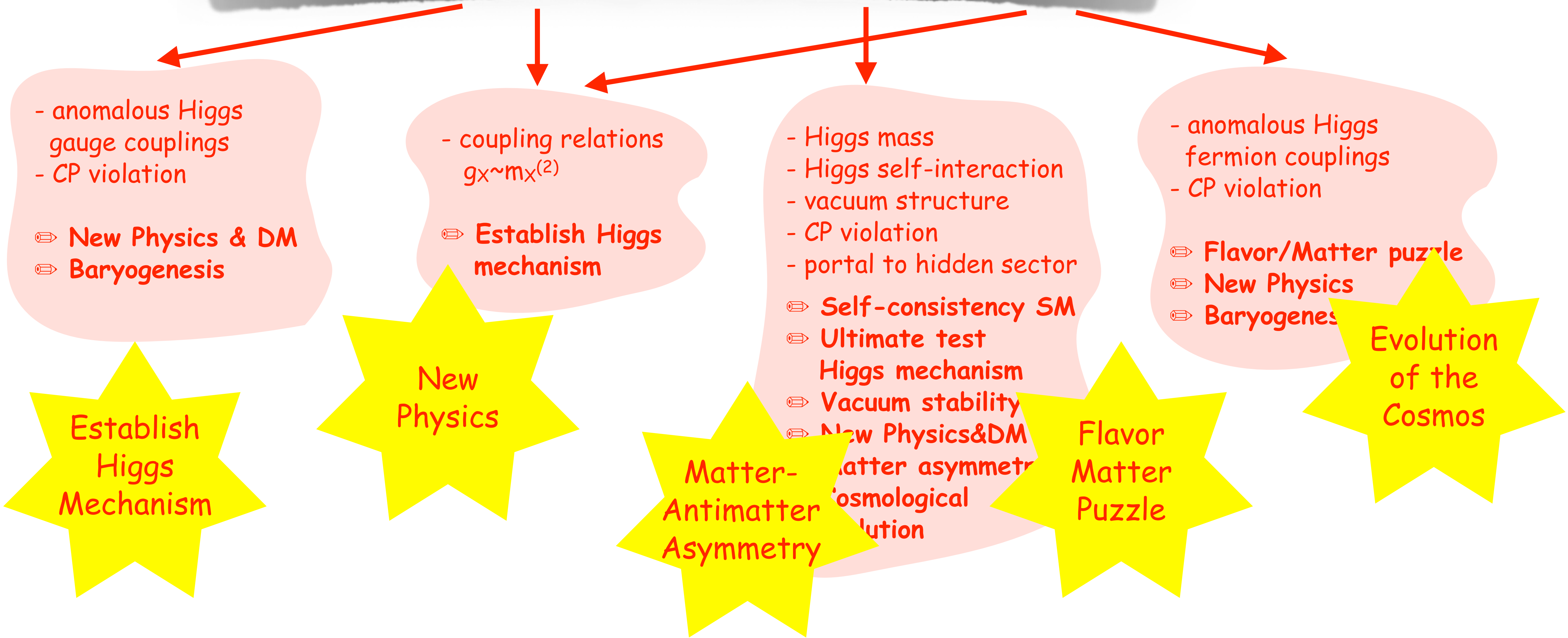

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Matter-Antimatter Asymmetry

Flavor Matter Puzzle

- anomalous Higgs fermion couplings
- CP violation

✏ **Flavor/Matter puzzle**
✏ **New Physics**
✏ **Baryogenes**

Evolution of the Cosmos

BSM Higgs Physics - Extended Higgs Sectors

Nov. 1992 – Oct. 1994 Postdoctoral position at DESY, Hamburg

Physics Letters B 318 (1993) 347–353
North-Holland

PHYSICS LETTERS B

SUSY Higgs production at proton colliders

M. Spira[a], A. Djouadi[b,1], D. Graudenz[c,2] and P.M. Zerwas[a]

Corrections to SUSY Higgs Production: The Role of Squark Loops

S. Dawson[1], A. Djouadi[2] and M. Spira[3]

epartment of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

[2] *Institut für Theoretische Physik, Universität Karlsruhe, D–76128 Karlsruhe, Germany*

neva 23, Switzerland

8)

A NOTE ON DOUBLY-CHARGED HIGGS PAIR PRODUCTION AT HADRON COLLIDERS*

MARGARETE MÜHLLEITNER AND MICHAEL SPIRA

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

May 2003

Vast New Physics Landscape

Extended Higgs Sectors

Why extended Higgs sectors?

* fermion/gauge sectors not minimal - why should the Higgs sector be minimal?

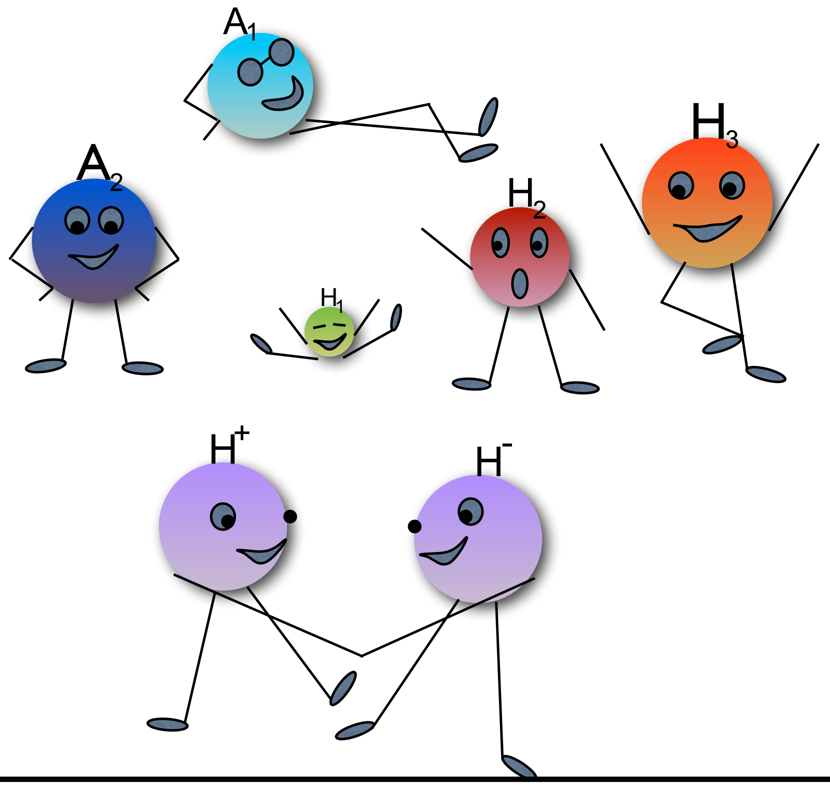
* extended Higgs sectors:
  alleviate metastability, DM candidate, additional sources of CP-violation ← baryogenesis

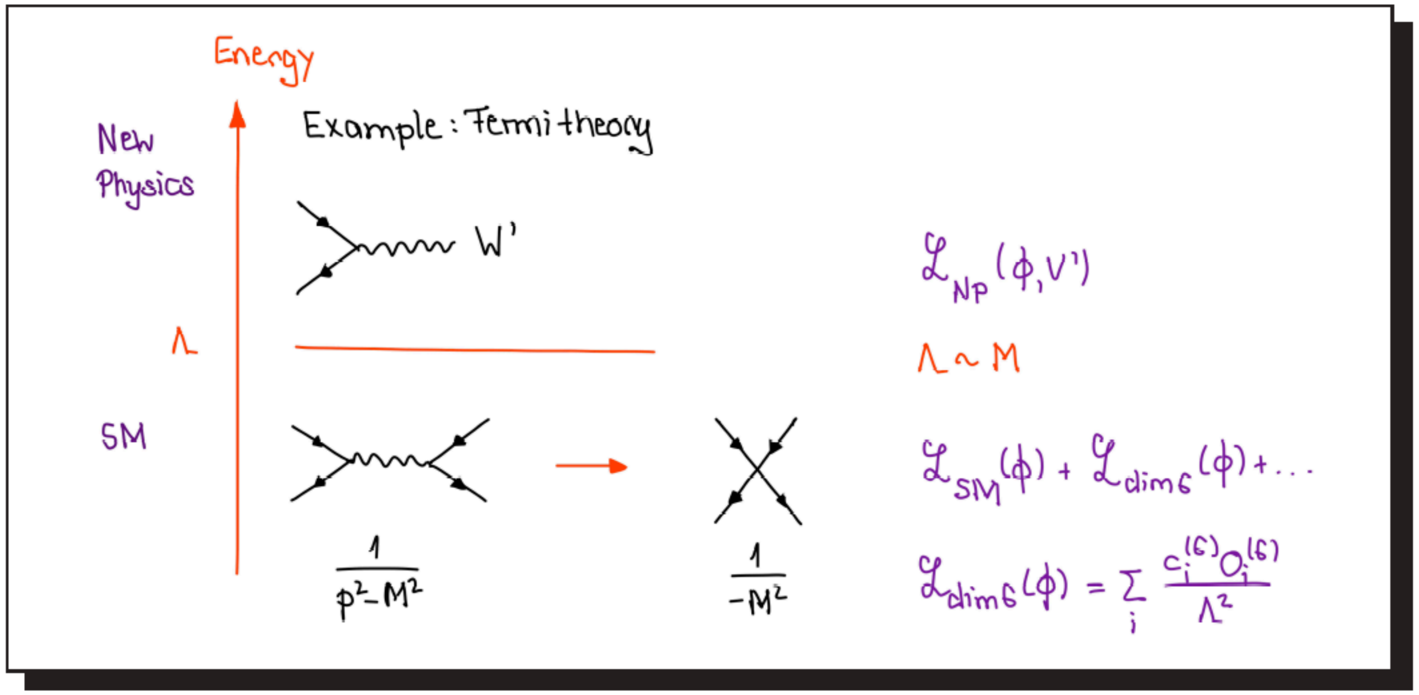
* many new physics models require extended Higgs models ← supersymmetry!

How systemize approach not to miss any new physics sign?

* effective theory (rather model-independent, new physics effects at high energy scales)

* specific well-motivated UV-complete models





Specific UV-Complete New Physics Models

Investigations of specific UV-complete models:

* Indisponible: complement EFT approach

* EFT approach cannot capture new physics effects due to new light particles

Guidelines for model selection

* simplicity

* compatibility with relevant experimental
and theoretical constraints

* solve (some of the) flaws of the SM

* testable in experiment

Validity of the models: they have comply with

* experimental constraints

* theoretical constraints

Supersymmetry

✦ Motivation:

∗ maximal possible symmetry compatible with Poincaré group (space-time symmetry)

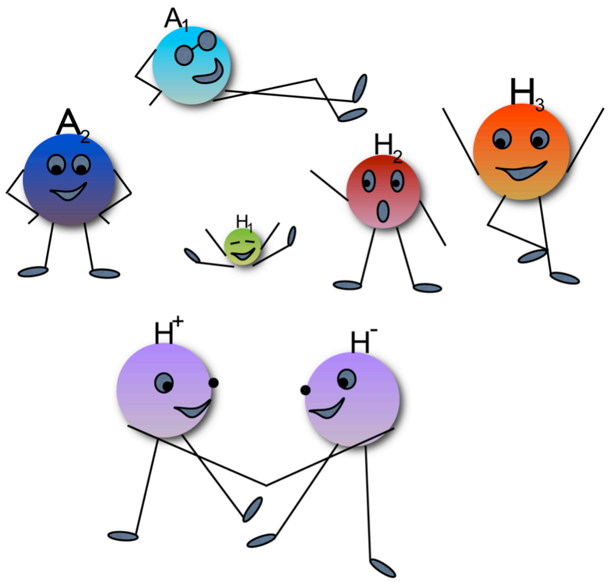
∗ solves some of the open problems of the SM, e.g.:

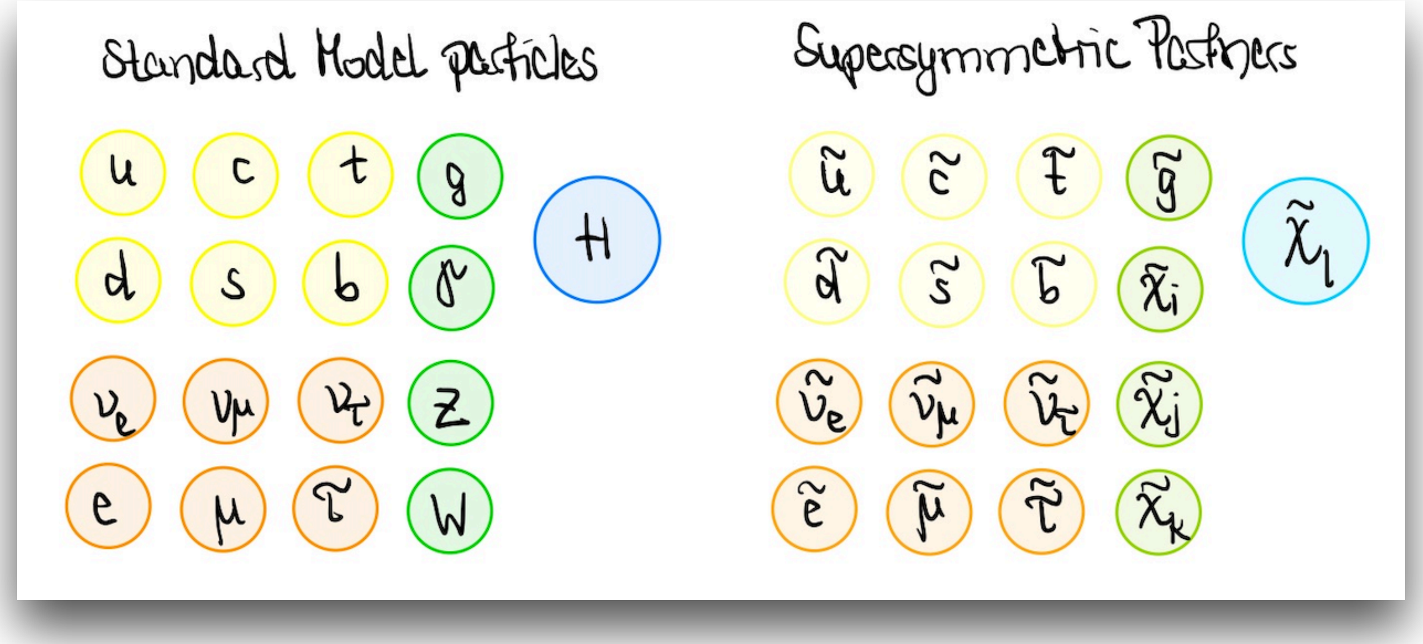
- candidate for Dark Matter
- possibly inclusion of gravity
- unification of fundamental forces

✦ Implications:

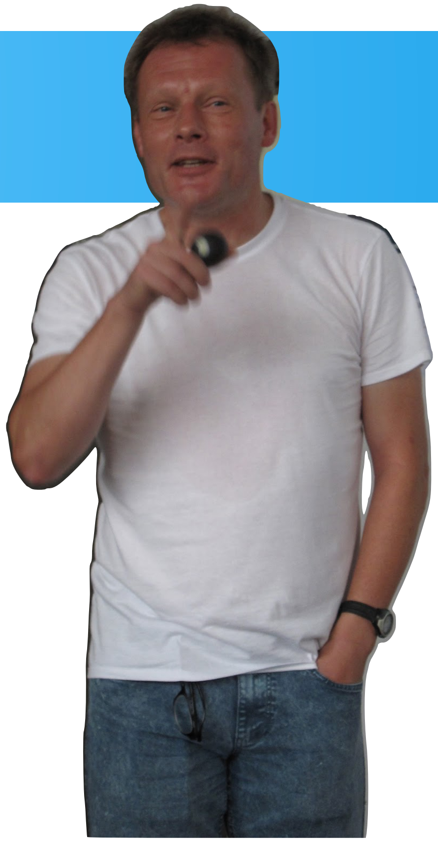
∗ enlarged particle spectrum: each SM particle has supersymmetric partner particle

∗ enlarged Higgs sector





Exploring Supersymmetry



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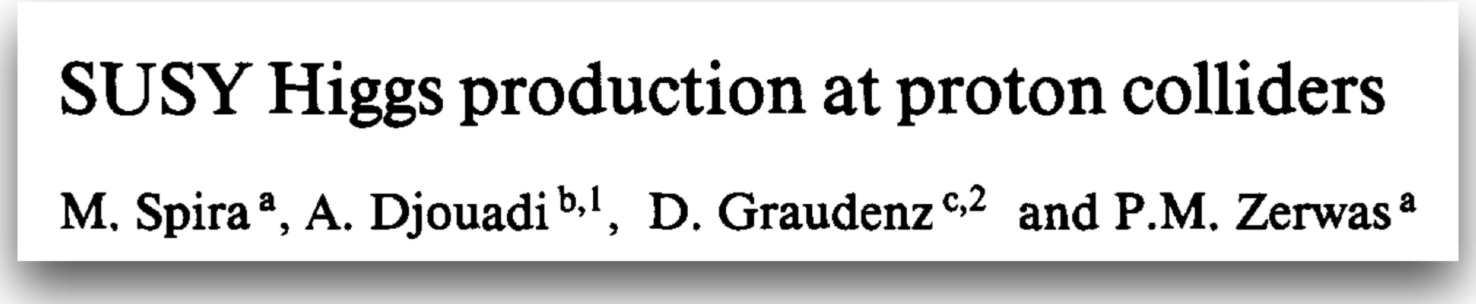

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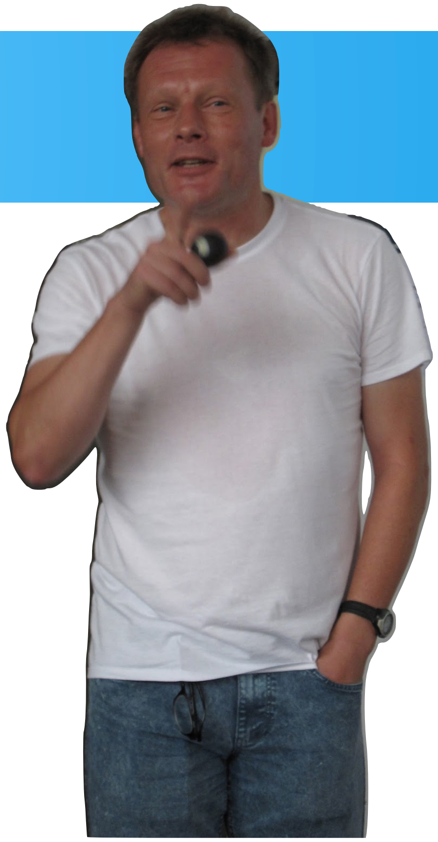

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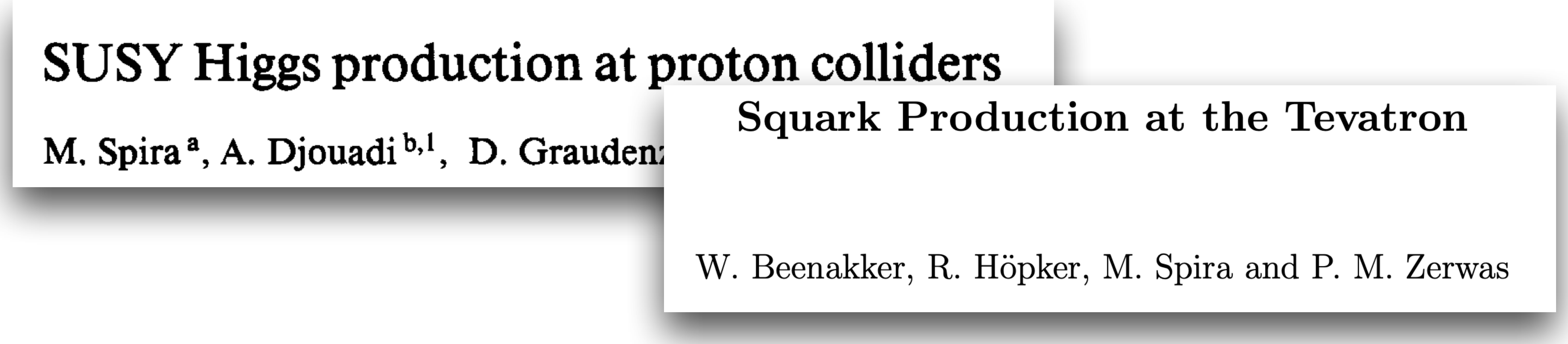

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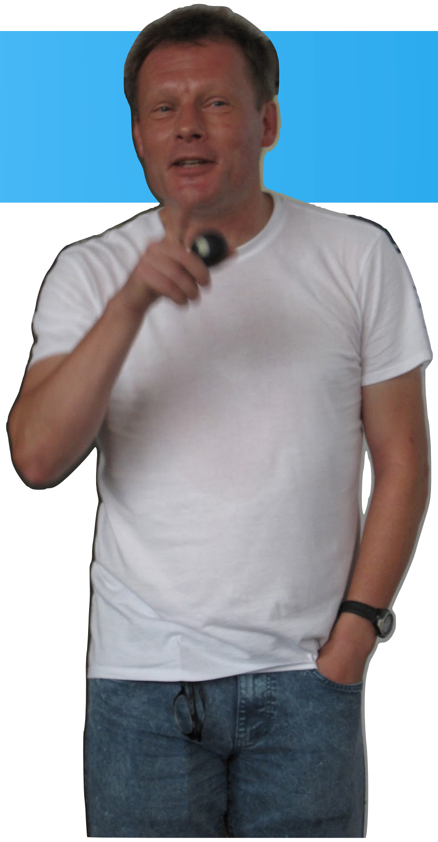
Squark Production at the Tevatron

W. Beenakker, R. Höpker, M. Spira and P. M. Zerwas



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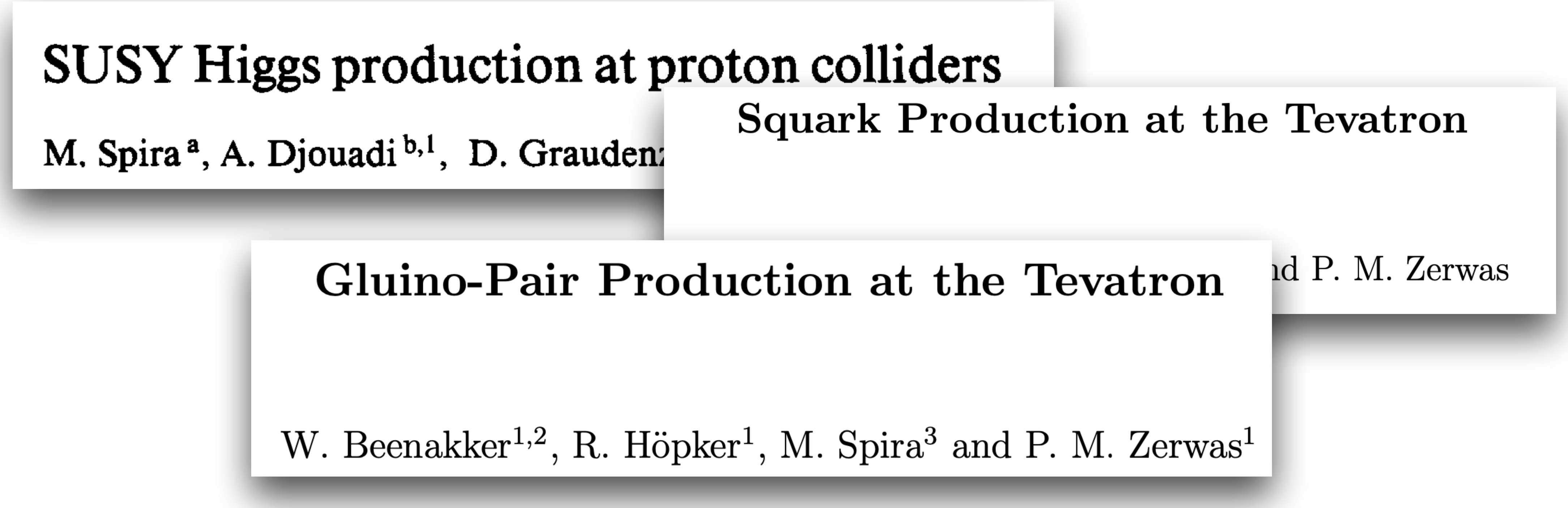

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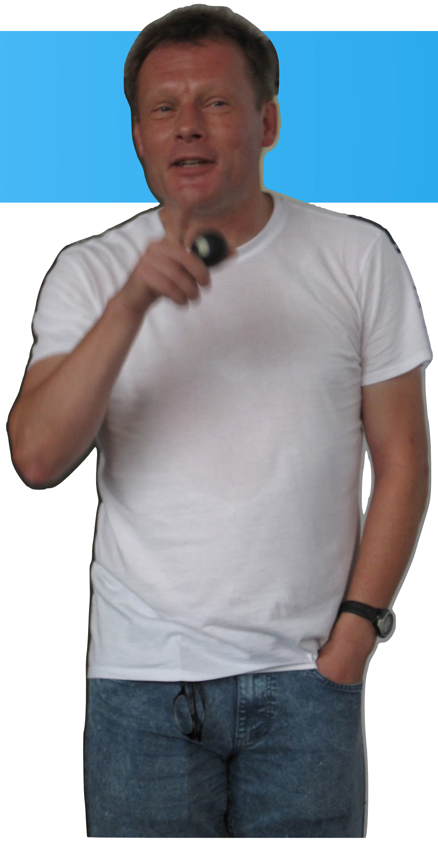
nd P. M. Zerwas

Gluino-Pair Production at the Tevatron

W. Beenakker[1,2], R. Höpker[1], M. Spira[3] and P. M. Zerwas[1]



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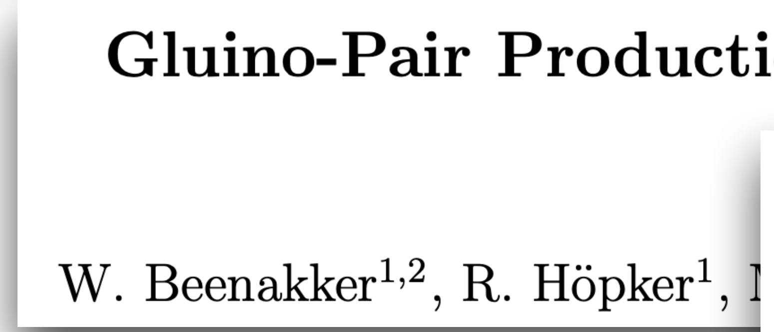

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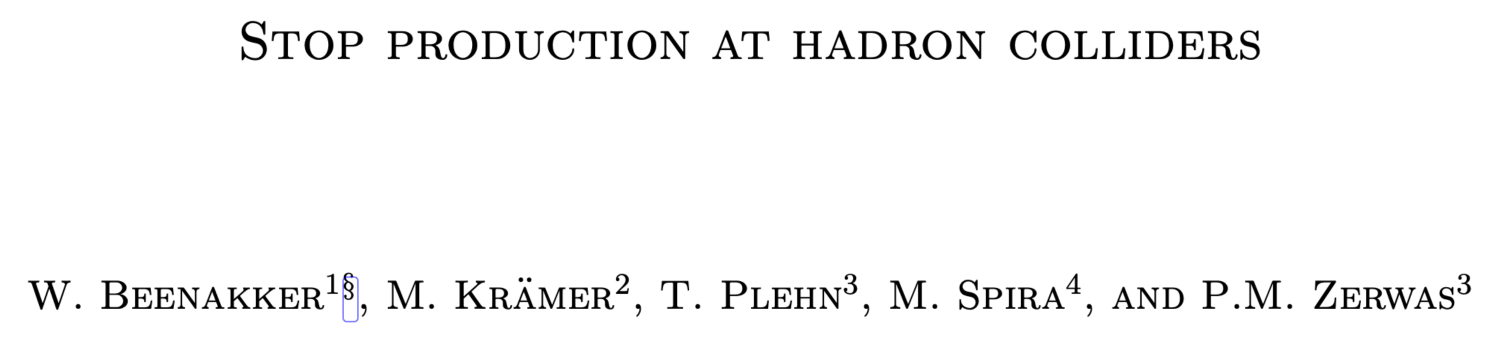
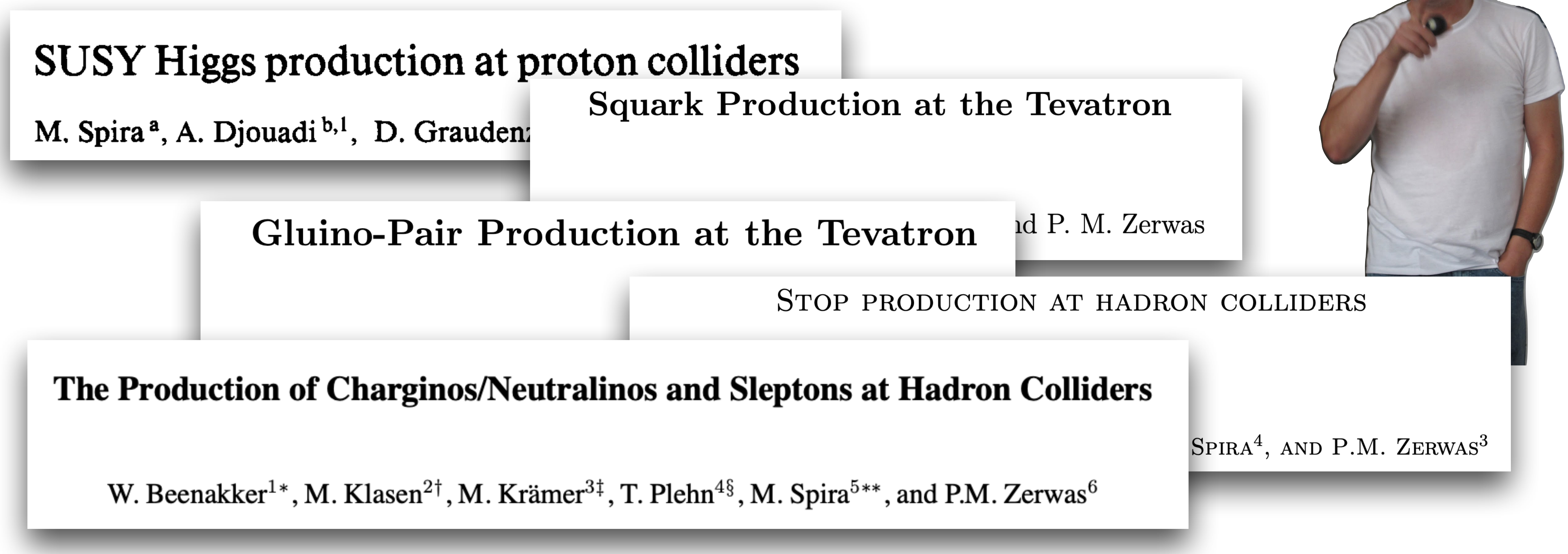


STOP PRODUCTION AT HADRON COLLIDERS

W. BEENAKKER[1§], M. KRÄMER[2], T. PLEHN[3], M. SPIRA[4], AND P.M. ZERWAS[3]

Exploring Supersymmetry



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STOP PRODUCTION AT HADRON COLLIDERS

SPIRA^4, AND P.M. ZERWAS^3

The Production of Charginos/Neutralinos and Sleptons at Hadron Colliders

W. Beenakker^{1*}, M. Klasen^{2†}, M. Krämer^{3‡}, T. Plehn^{4§}, M. Spira^{5**}, and P.M. Zerwas^6

Exploring Supersymmetry

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di[2] and M. Spira[3]

SUSY–QCD Corrections to Higgs Boson Production at Hadron Colliders

A. DJOUADI[1] AND M. SPIRA[2*]

Exploring Supersymmetry

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SUSY–QCD Corrections to Higgs Boson Production at H

A. DJOUADI[1] A

SUSY Les Houches Accord: Interfacing SUSY Spectrum Calculators, Decay Packages, and Event Generators

P. Skands[1], B.C. Allanach[2], H. Baer[3], C. Balázs[3,4], G. Bélanger[2], F. Boudjema[2], A. Djouadi[5,6], R. Godbole[7], J. Guasch[8], S. Heinemeyer[6,9], W. Kilian[10], J-L. Kneur[5], S. Kraml[6], F. Moortgat[11], S. Moretti[12], M. Mühlleitner[8], W. Porod[13], A. Pukhov[14], P. Richardson[6,15], S. Schumann[16], P. Slavich[17], M. Spira[8], G. Weiglein[15]

Exploring Supersymmetry

SUSY Higgs production at proton colliders

M. Spira [a], A. Djouadi [b,1], D. Grauden

Squark Production at the Tevatron

d P. M. Zerwas

Gluino-Pair Production at the Tevatron

STOP PRODUCTION AT HADRON COLLIDERS

SPIRA[4], AND P.M. ZERWAS[3]

The Production of Charginos/Neutralinos and Sleptons at Hadron Colliders

W. Beenakker[1*], M. K

QCD Corrections to SUSY Higgs Production: The Role of Squark Loops

di[2] and M. Spira[3]

SUSY–QCD Corrections to Higgs Boson

Production at H

SUSY Les Houches Accord: Interfacing SUSY Spectrum Calculators, Decay Packages, and Event Generators

Boudjema[2], A. Djouadi[5,6], Kneur[5], S. Kraml[6], ov[14], P. Richardson[6,15], lein[15]

Supersymmetry Parameter Analysis: SPA Convention and Project

J.A. Aguilar-Saavedra[1], A. Ali[2], B.C. Allanach[3], R. Arnowitt[4], H.A. Baer[5], J.A. Bagger[6], C. Balazs[7 a], V. Barger[8], M. Barnett[9], A. Bartl[10], M. Battaglia[9], P. Bechtle[11], G. Bélanger[12], A. Belyaev[13], E.L. Berger[7], G. Blair[14], E. Boos[15], M. Carena[16], S.Y. Choi[17], F. Deppisch[2], A. De Roeck[18], K. Desch[19], M.A. Diaz[20]

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Decays of Supersymmetric Particles: the program SUSY-HIT (SUspect-SdecaY-Hdecay-InTerface)

A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

Exploring Supersymmetry

SUSY Higgs production at proton colliders

M. Spira[a], A. Djouadi[b,1], D. Graudenz

Squark Production n

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Gluino-Pair Prod

ODUCTION AT HADRON COLLIDERS

SPIRA[4], AND P.M. ZERWAS[3]

Higgs Properties and Supersymmetry

Constraints and Sensitivity from the LHC to an e^+e^- Collider

A. Arbey[1,2], M. Battaglia[2,3], A. Djouadi[4,5], F. Mahmoudi[1,2], M. Mühlleitner[6] and M. Spira[7]

The P and Sleptons at Hadron Colliders

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QCD Corrections to SUSY Higgs Production: The Role of Squark Loops

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Exploring Supersymmetry

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Higgs Properties and Supersymmetry

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A. Arbey[1,2], M. Battaglia[2,3], A. Djouadi

QCD Corrections

HADRON COLLIDERS

HIGGS RADIATION OFF QUARKS
IN SUPERSYMMETRIC THEORIES AT e^+e^- COLLIDERS

S. DITTMAIER[1], M. KRÄMER[2*], Y. LIAO[3,4],
M. SPIRA[5†] AND P.M. ZERWAS[4]

SUSY-QCD Corrections to Higgs Boson
Production at H

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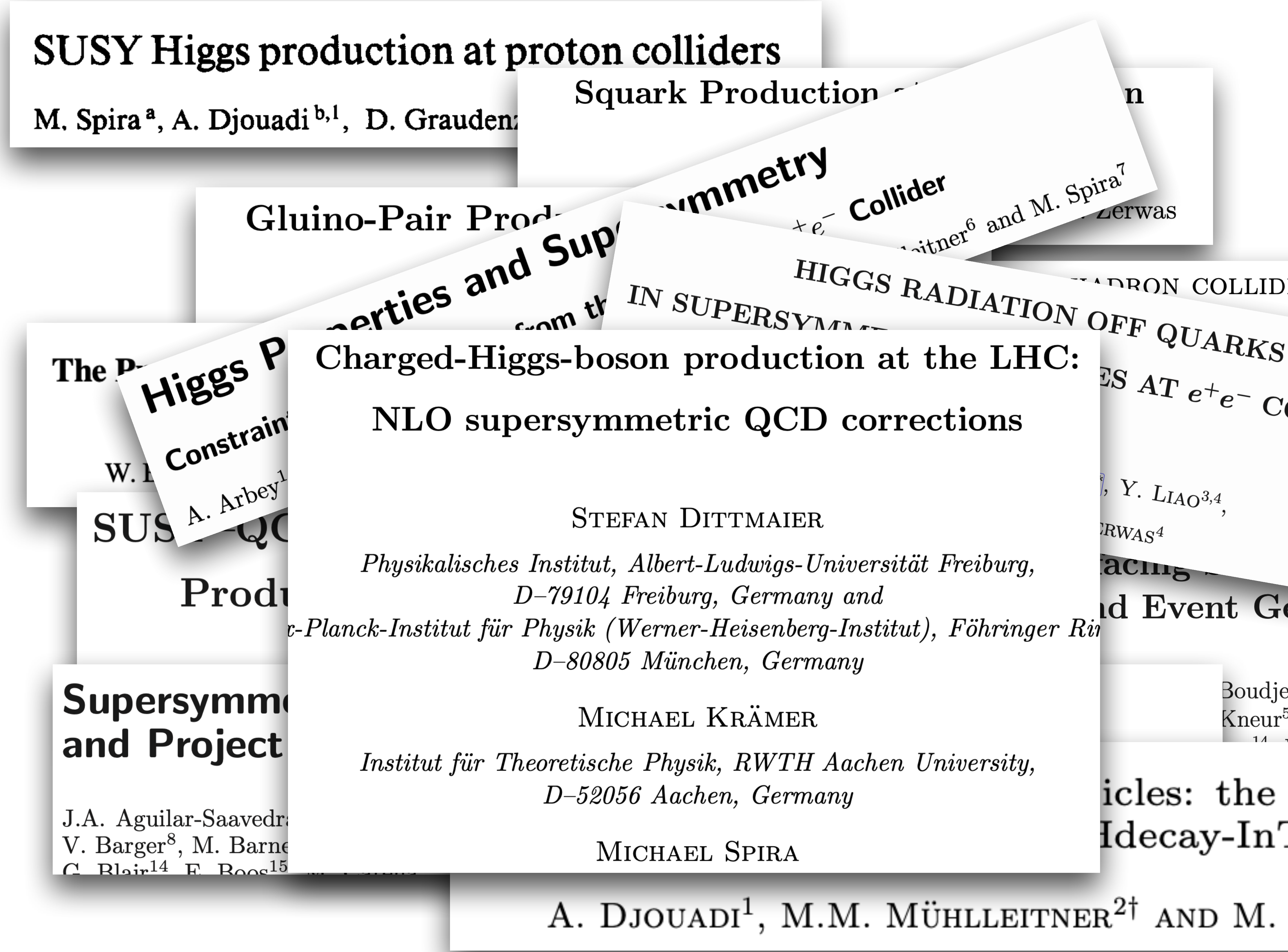
A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

Exploring Supersymmetry



SUSY Higgs production at proton colliders

M. Spira[a], A. Djouadi[b,1], D. Graudenz

Squark Production … n

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HIGGS RADIATION OFF QUARKS

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Charged-Higgs-boson production at the LHC:

NLO supersymmetric QCD corrections

Stefan Dittmaier

Physikalisches Institut, Albert-Ludwigs-Universität Freiburg,
D–79104 Freiburg, Germany and
…-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ri…
D–80805 München, Germany

Michael Krämer

Institut für Theoretische Physik, RWTH Aachen University,
D–52056 Aachen, Germany

Michael Spira

Supersymm…
and Project…

J.A. Aguilar-Saavedr…
V. Barger[8], M. Barne…
G. Blair[14], E. Boos[15]

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…icles: the program
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A. Djouadi[1], M.M. Mühlleitner[2†] and M. Spira[3]

Exploring Supersymmetry

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HIGGS RADIATION OFF QUARKS

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D–80805 Mün…

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Supersymm…
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J.A. Aguilar-S…
V. Barger[8], M. …
G. Blair[14], E. F…

Neutral MSSM Higgs-Boson Production With Heavy Quarks:
NLO Supersymmetric QCD Corrections

S. Dittmaier[1], P. Häfliger[2,3], M. Krämer[4], M. Spira[3] and M. Walser[3,5]

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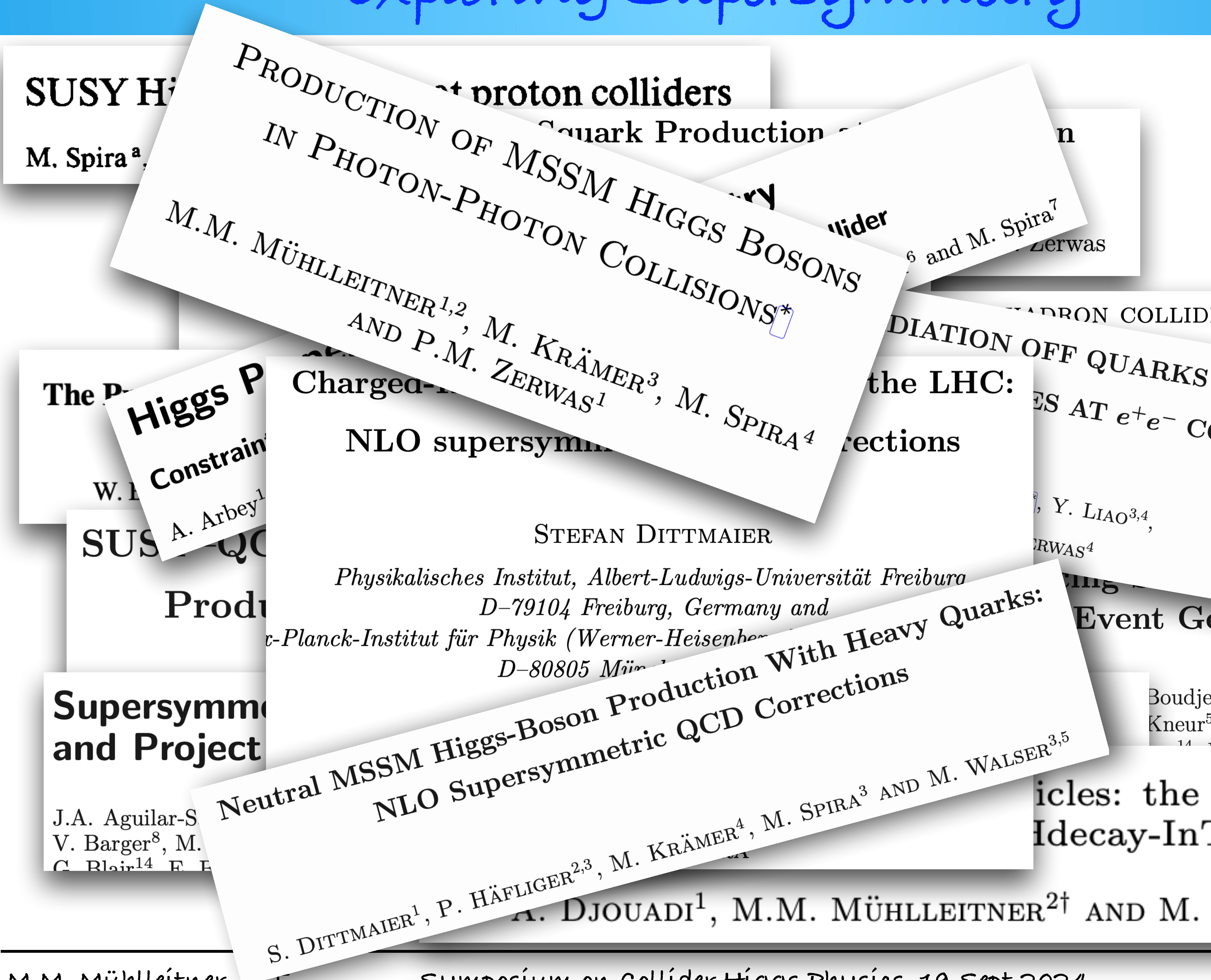
A. Djouadi[1], M.M. Mühlleitner[2†] and M. Spira[3]

Exploring Supersymmetry



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M. Spira[a],

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PRODUCTION OF MSSM HIGGS BOSONS IN PHOTON-PHOTON COLLISIONS*

M.M. MÜHLLEITNER[1,2], M. KRÄMER[3], M. SPIRA[4] AND P.M. ZERWAS[1]

…HADRON COLLIDERS

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Charged-H… …the LHC:

NLO supersymm… …rections

STEFAN DITTMAIER

Physikalisches Institut, Albert-Ludwigs-Universität Freiburg
D–79104 Freiburg, Germany and
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A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

Exploring Supersymmetry

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M.M. MÜHLLEITNER[1,2], M. KRÄMER[3], M. SPIRA[4] AND P.M. ZERWAS[1]

Gluino Polarization at the LHC

M. Krämer[1], E. Popenda[1], M. Spira[2], and P. M. Zerwas[3,1]

6 and M. Zerwas

ADRON COLLIDERS

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Physikalisches Institut, Albert-Ludwigs-Universität Freiburg
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-Planck-Institut für Physik (Werner-Heisenber
D–80805 Mün

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Event Generators

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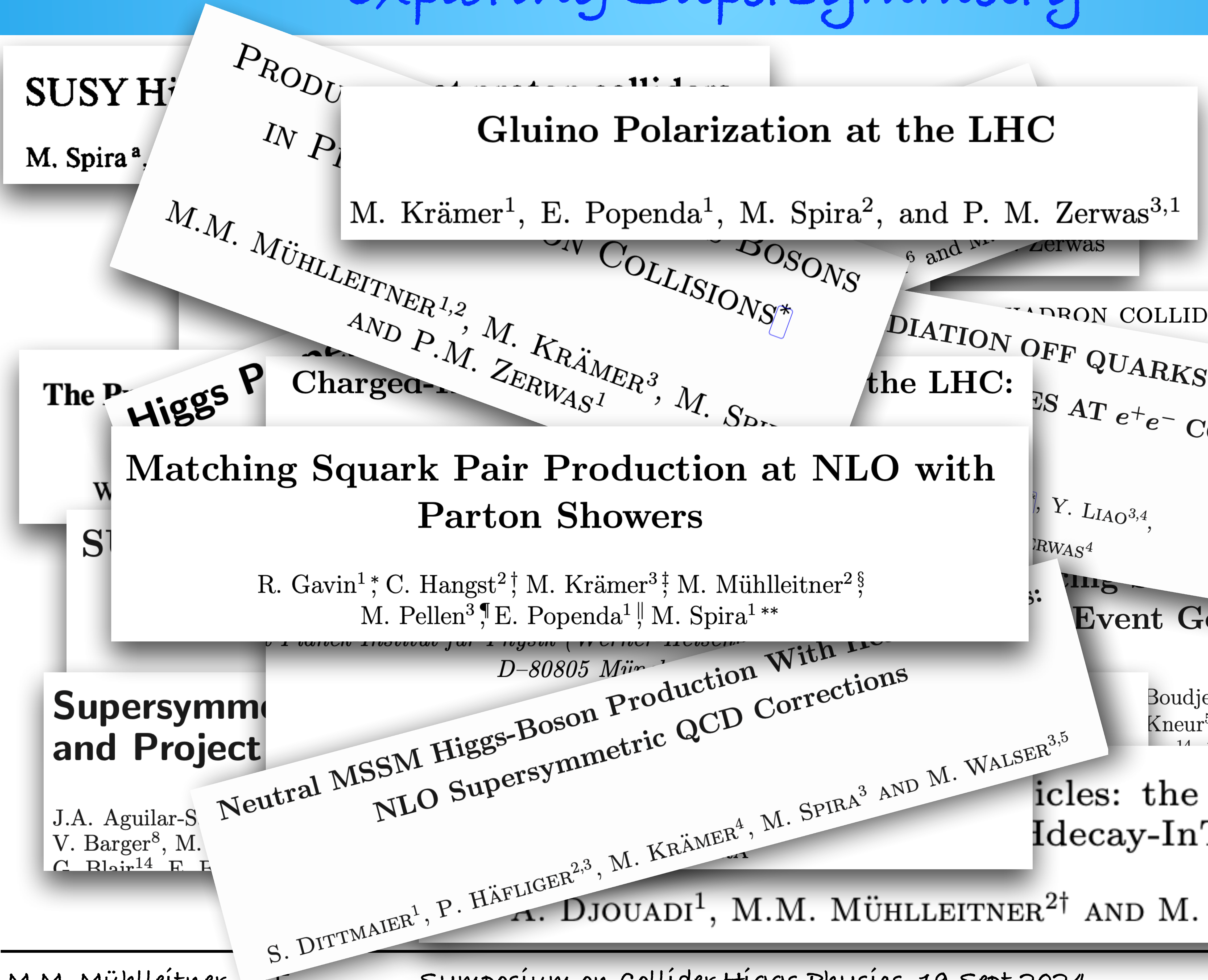

SUSY Hi

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RWAS[4]

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the LHC:

Matching Squark Pair Production at NLO with Parton Showers

R. Gavin[1]*, C. Hangst[2]†, M. Krämer[3]‡, M. Mühlleitner[2]§, M. Pellen[3]¶, E. Popenda[1]‖, M. Spira[1]**

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J.A. Aguilar-S
V. Barger[8], M.
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Neutral MSSM Higgs-Boson Production With He
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Kneur[5], S. Kraml[6],

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A. DJOUADI[1], M.M. MÜHLLEITNER[2]† AND M. SPIRA[3]

Exploring Supersymmetry

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M.M. MÜHLLEITNER[1,2], M. KRÄMER

AND P.M. ZERWAS[1]

Gluino Polarization at the LHC

M. Krämer[1], E. Pope... Spira[2], and P. M. Zerwas[3,1]

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Squark Production and Decay matched with Parton Showers at NLO

R. Gavin[1,*] C. Hangst[2,†] M. Krämer[3,‡] M. Mühlleitner[2,§] M. Pellen[3,¶] E. Popenda[1,‖] M. Spira[1 **]

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Matching Squark Pair Production at Parton Showers

R. Gavin[1,*] C. Hangst[2,†] M. Krämer[3,‡] M. Mühlleitner[2,§]
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J.A. Aguilar-S
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Neutral MSSM Higgs-Boson Production With He NLO Supersymmetric QCD Corrections

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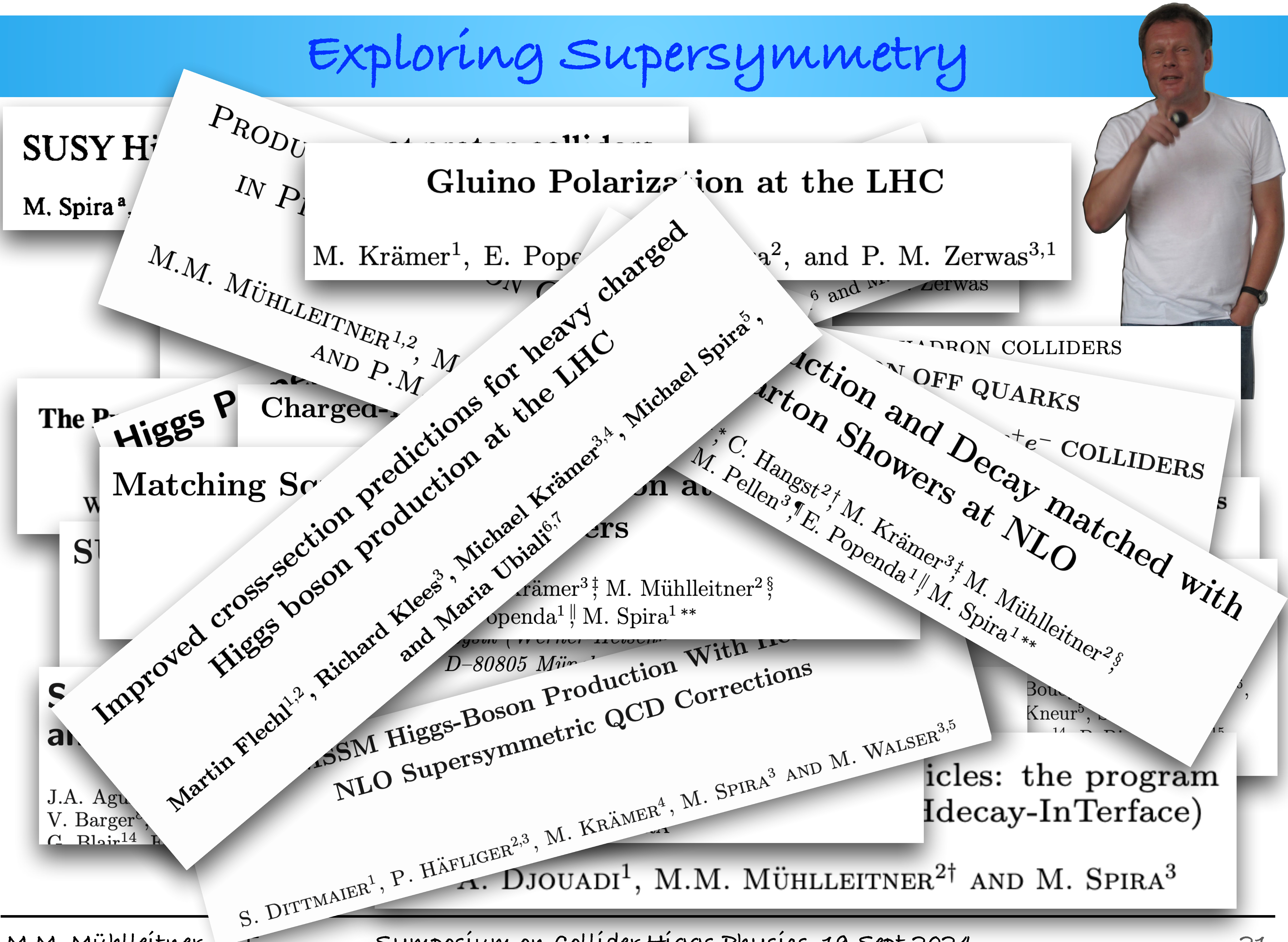
A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

Exploring Supersymmetry



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Gluino Polariza ion at the LHC

M. Krämer[1], E. Pope a[2], and P. M. Zerwas[3,1]

6 and M. Zerwas

Improved cross-section predictions for heavy charged Higgs boson production at the LHC

Martin Flechl[1,2], Richard Klees[3], Michael Krämer[3,4], Michael Spira[5], and Maria Ubiali[6,7]

uction and Decay matched with rton Showers at NLO

*C. Hangst[2]†, M. Krämer[3]‡, M. Mühlleitner[2]§, M. Pellen[3]¶, E. Popenda[1]‖, M. Spira[1]**

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G. Blair[14]

MSSM Higgs-Boson Production With He NLO Supersymmetric QCD Corrections

S. DITTMAIER[1], P. HÄFLIGER[2,3], M. KRÄMER[4], M. SPIRA[3] AND M. WALSER[3,5]

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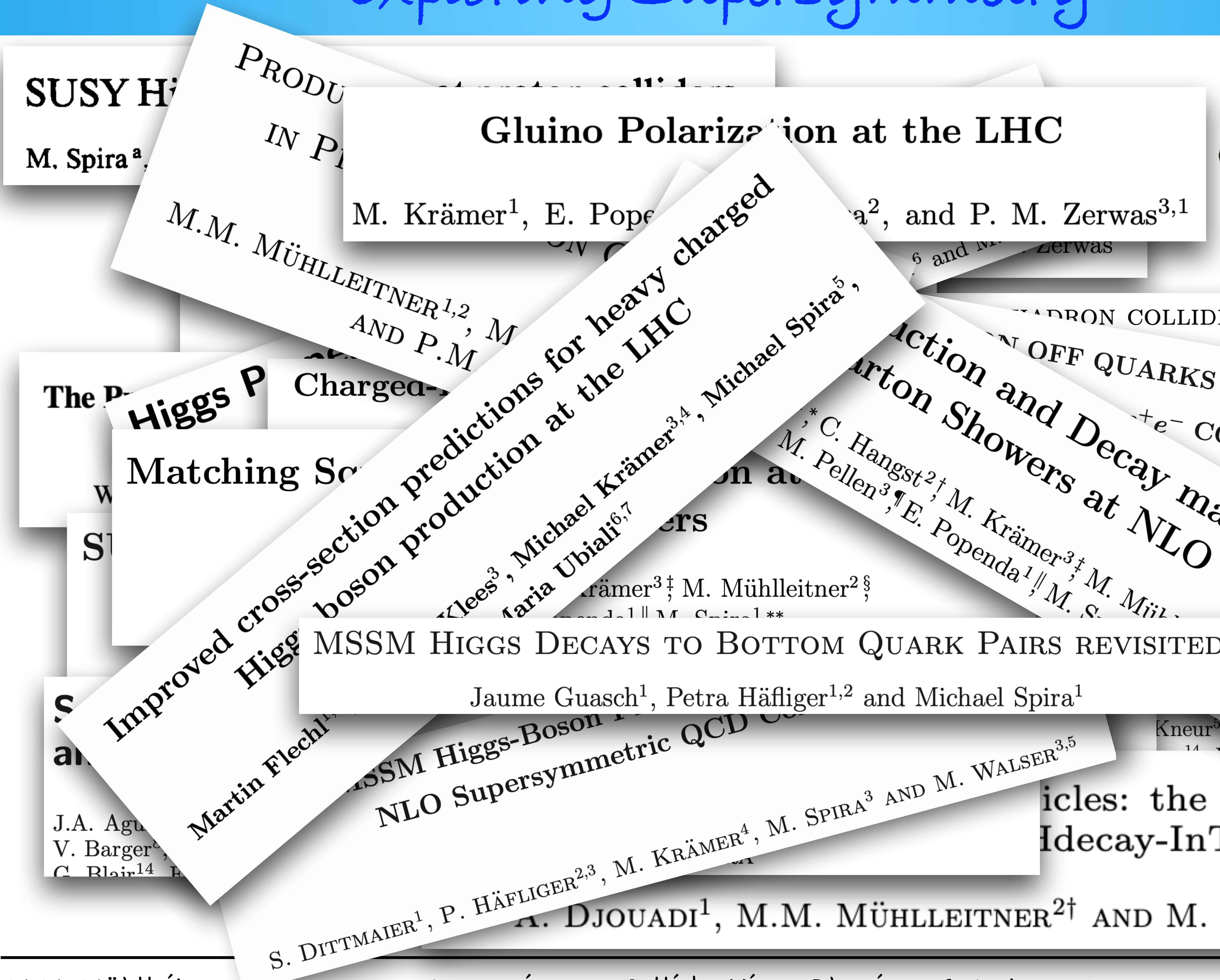

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Gluino Polariza ion at the LHC

M. Krämer1, E. Pope a2, and P. M. Zerwas3,1

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Improved cross-section predictions for heavy charged Higgs boson production at the LHC

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M. Pellen3,¶ E. Popenda1,‖ M. S

HADRON COLLIDERS

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MSSM HIGGS DECAYS TO BOTTOM QUARK PAIRS REVISITED*

Jaume Guasch1, Petra Häfliger1,2 and Michael Spira1

SSM Higgs-Boson P

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S. DITTMAIER1, P. HÄFLIGER2,3, M. KRÄMER4, M. SPIRA3 AND M. WALSER3,5

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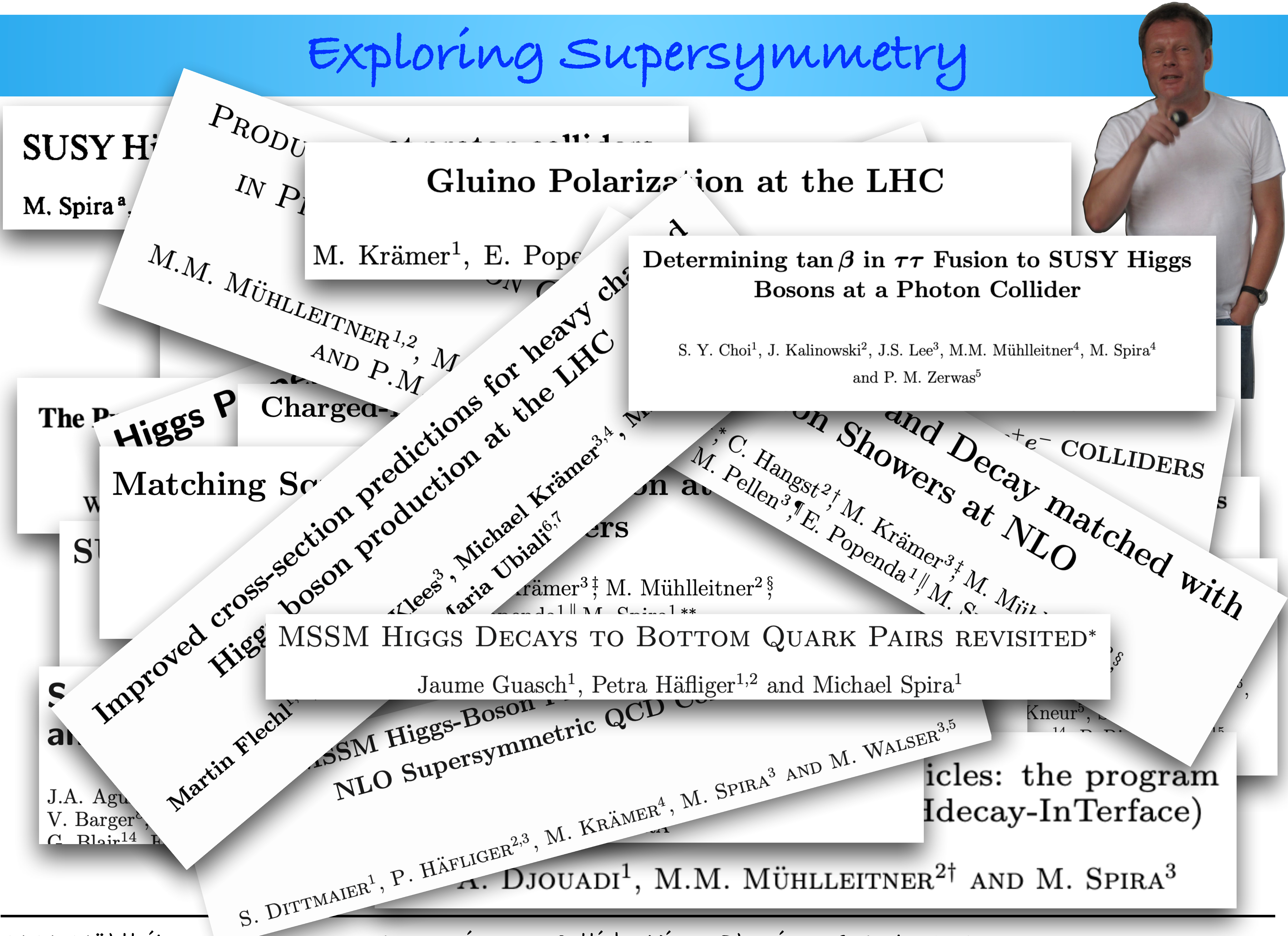
A. DJOUADI1, M.M. MÜHLLEITNER2† AND M. SPIRA3

Exploring Supersymmetry



SUSY Hi

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Gluino Polarization at the LHC

M. Krämer1, E. Pope

Determining tan β in $\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

S. Y. Choi1, J. Kalinowski2, J.S. Lee3, M.M. Mühlleitner4, M. Spira4
and P. M. Zerwas5

The P

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… Maria Ubiali6,7

… on Showers at NLO

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… C. Hangst2,† M. Krämer3,‡ M. Müh…

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MSSM HIGGS DECAYS TO BOTTOM QUARK PAIRS REVISITED*

Jaume Guasch1, Petra Häfliger1,2 and Michael Spira1

MSSM Higgs-Boson P…

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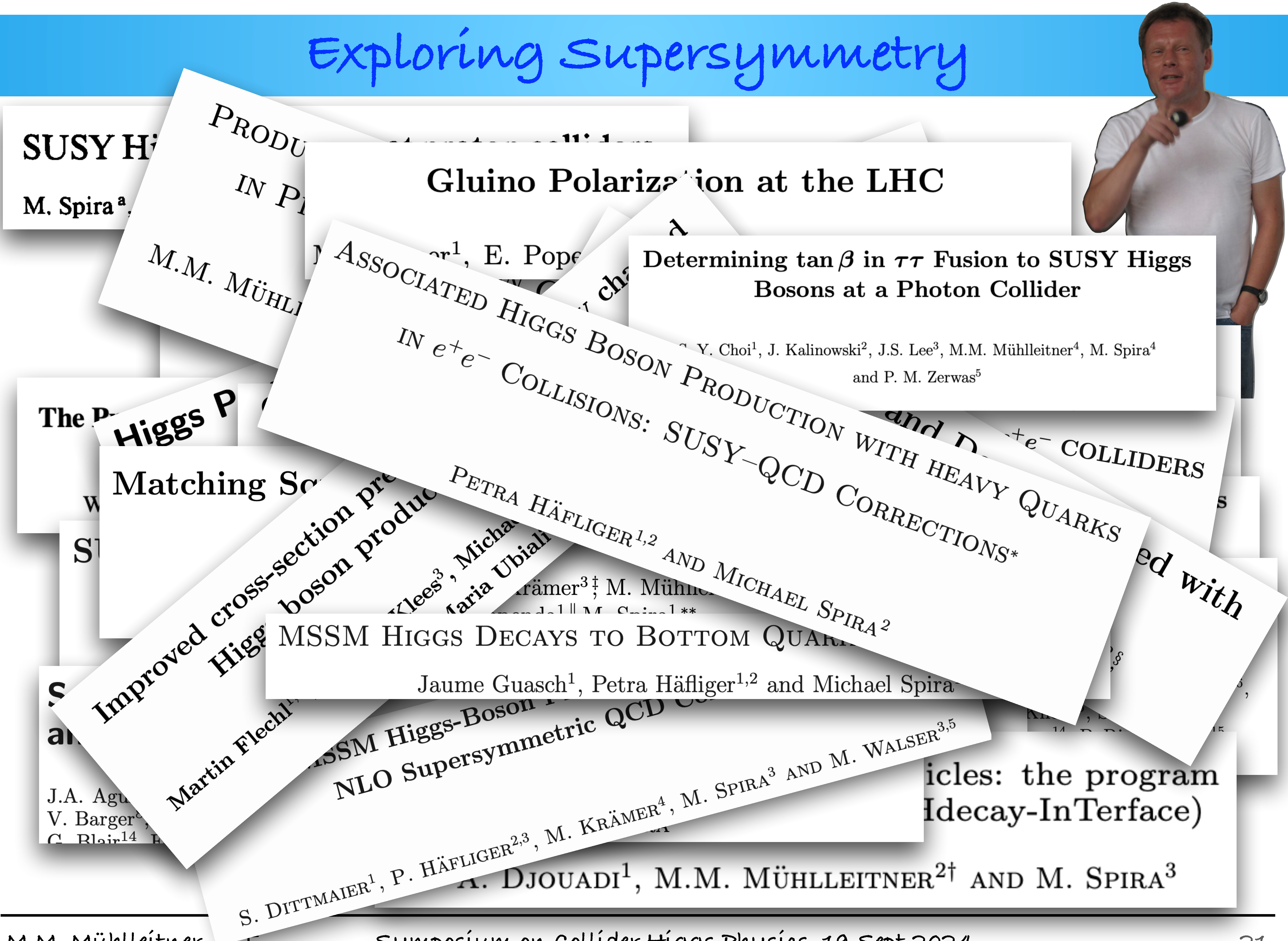
S. DITTMAIER1, P. HÄFLIGER2,3, M. KRÄMER4, M. SPIRA3 AND M. WALSER3,5

…icles: the program …decay-InTerface)

A. DJOUADI1, M.M. MÜHLLEITNER2† AND M. SPIRA3

J.A. Agu…
V. Barger8,
G. Blair14

Exploring Supersymmetry



SUSY Hi

M. Spira ^{a},

PRODU at proton colliders

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Gluino Polarization at the LHC

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Determining tan β in $\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

Y. Choi[1], J. Kalinowski[2], J.S. Lee[3], M.M. Mühlleitner[4], M. Spira[4]
and P. M. Zerwas[5]

ASSOCIATED HIGGS BOSON PRODUCTION WITH HEAVY QUARKS IN e^+e^- COLLISIONS: SUSY–QCD CORRECTIONS*

PETRA HÄFLIGER[1,2] AND MICHAEL SPIRA[2]

e^+e^- COLLIDERS

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Martin Flechl[1],

Klees[3], Micha

Maria Ubiali

Krämer[3]‡ M. Mühl

M. Spira[1] **

MSSM HIGGS DECAYS TO BOTTOM QUAR

Jaume Guasch[1], Petra Häfliger[1,2] and Michael Spira

SSM Higgs-Boson P

NLO Supersymmetric QCD Co

S. DITTMAIER[1], P. HÄFLIGER[2,3], M. KRÄMER[4], M. SPIRA[3] AND M. WALSER[3,5]

icles: the program

Hdecay-InTerface)

A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

J.A. Agu

V. Barger

G. Blair[14]

Exploring Supersymmetry

SUSY Hi

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Gluino Polariza ion at the LHC

er1, E. Pope

Determining tan β in $\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

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and P. M. Zerwas[5]

ASSOCIATED HIGGS BOSON PRODUCTION WITH HEAV

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PSEUDOSCALAR MSSM HIGGS PRODUCTION AT NLO SUSY–QCD

Emanuele Bagnaschi[1], Lukas Fritz[2,3], Stefan Liebler[4‡], Margarete Mühlleitner[4], Thanh Tien Dat Nguyen[4] and Michael Spira[2]

Jaume Guasch[1], Petra Häfliger[1,2] and Michael Spira

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Martin Flechl[1]

SSM Higgs-Boson

NLO Supersymmetric QCD Co

S. DITTMAIER[1], P. HÄFLIGER[2,3], M. KRÄMER[4], M. SPIRA[3] AND M. WALSER[3,5]

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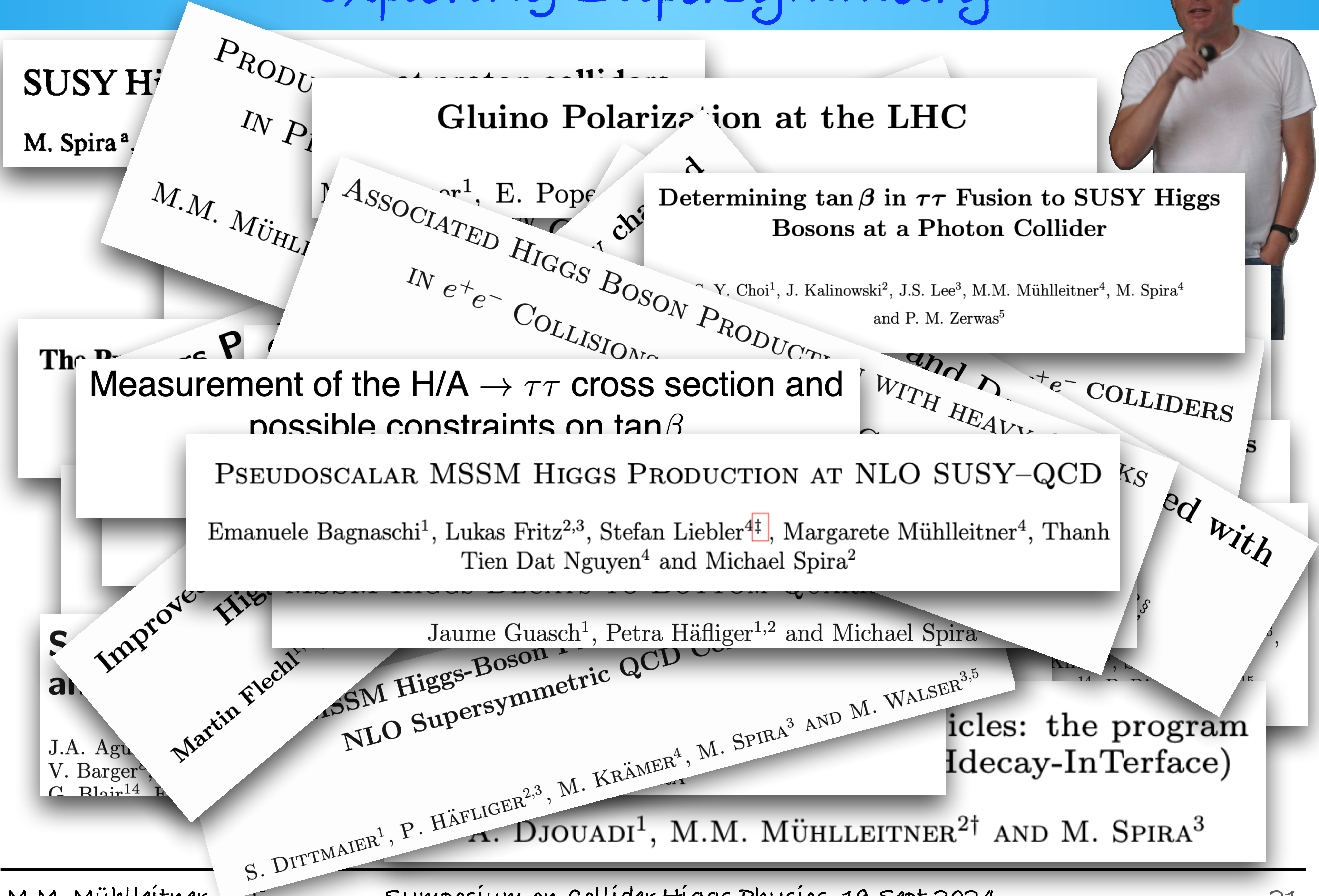
A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

J.A. Agu

V. Barger

Exploring Supersymmetry



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PRODU at proton colliders

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Gluino Polarization at the LHC

M er1, E. Pope

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Determining tan β in $\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

Y. Choi[1], J. Kalinowski[2], J.S. Lee[3], M.M. Mühlleitner[4], M. Spira[4] and P. M. Zerwas[5]

ASSOCIATED HIGGS BOSON PRODUCTION WITH HEAVY

IN e^+e^- COLLISIONS

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e^+e^- COLLIDERS

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Measurement of the H/A $\rightarrow \tau\tau$ cross section and possible constraints on tanβ

PSEUDOSCALAR MSSM HIGGS PRODUCTION AT NLO SUSY–QCD

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Exploring Supersymmetry

SUSY Hi

M. Spira [a],

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Gluino Polarization at the LHC

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Measurement of the H/A → section and
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Martin Flechl[1],

MSSM Higgs-Boson P
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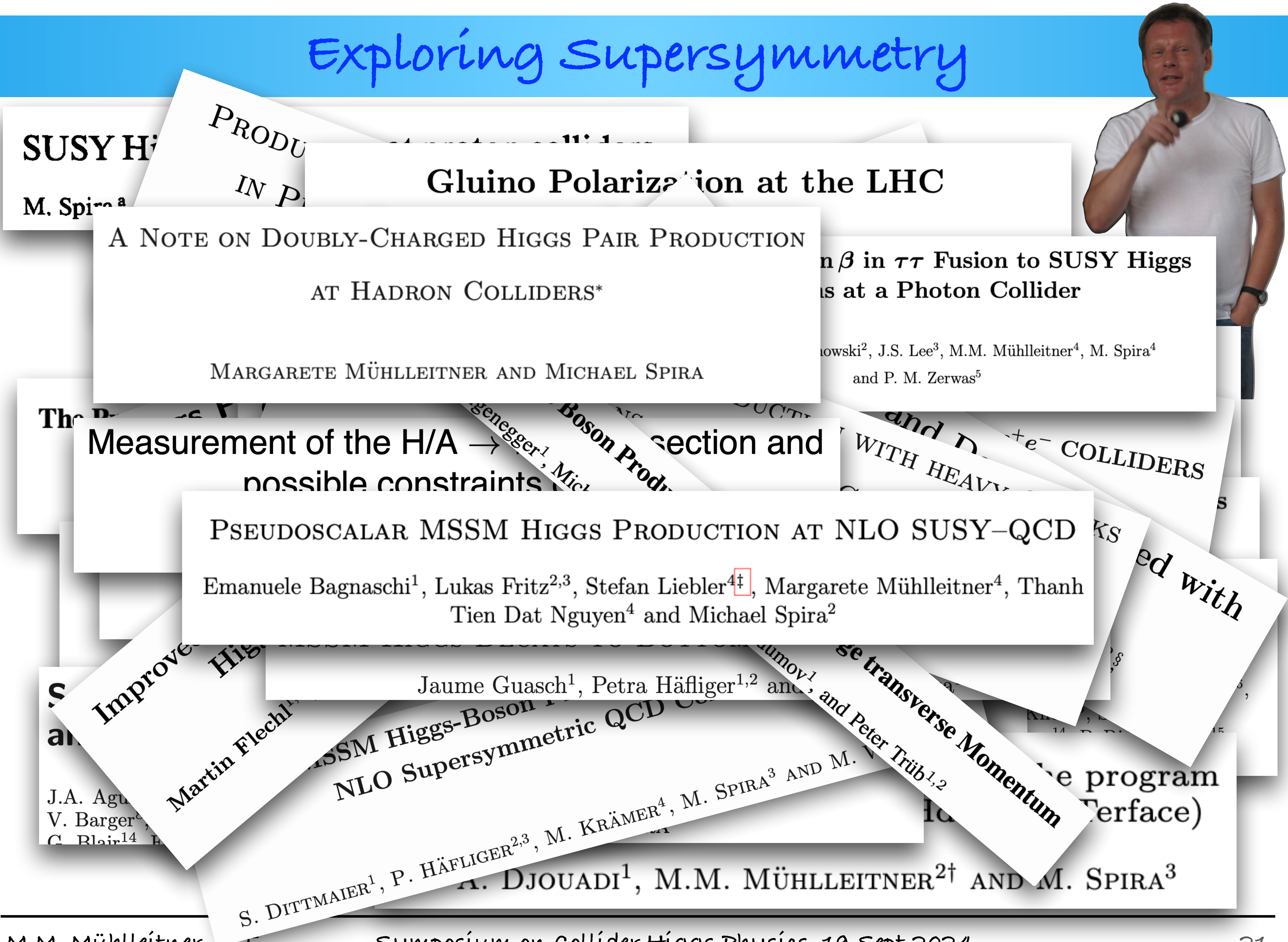
Exploring Supersymmetry



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Gluino Polariza ion at the LHC

A NOTE ON DOUBLY-CHARGED HIGGS PAIR PRODUCTION AT HADRON COLLIDERS*

MARGARETE MÜHLLEITNER AND MICHAEL SPIRA

n β in $\tau\tau$ Fusion to SUSY Higgs
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owski[2], J.S. Lee[3], M.M. Mühlleitner[4], M. Spira[4]
and P. M. Zerwas[5]

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Measurement of the H/A → section and
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PSEUDOSCALAR MSSM HIGGS PRODUCTION AT NLO SUSY–QCD

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Martin Flechl

SSM Higgs-Boson
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Exploring Supersymmetry

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PSEUDOSCALAR MSSM HIGGS PRODUCTION AT NLO SUSY–QCD

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MARGARETE MÜHLLEITNER[1,2] AND MICHAEL SPIRA[3]

SSM Higgs-
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S. DITTMAIER[1], P. HÄFLIGER[2,3], M. KRÄMER[4], M. SPIRA[3] AND M.

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A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

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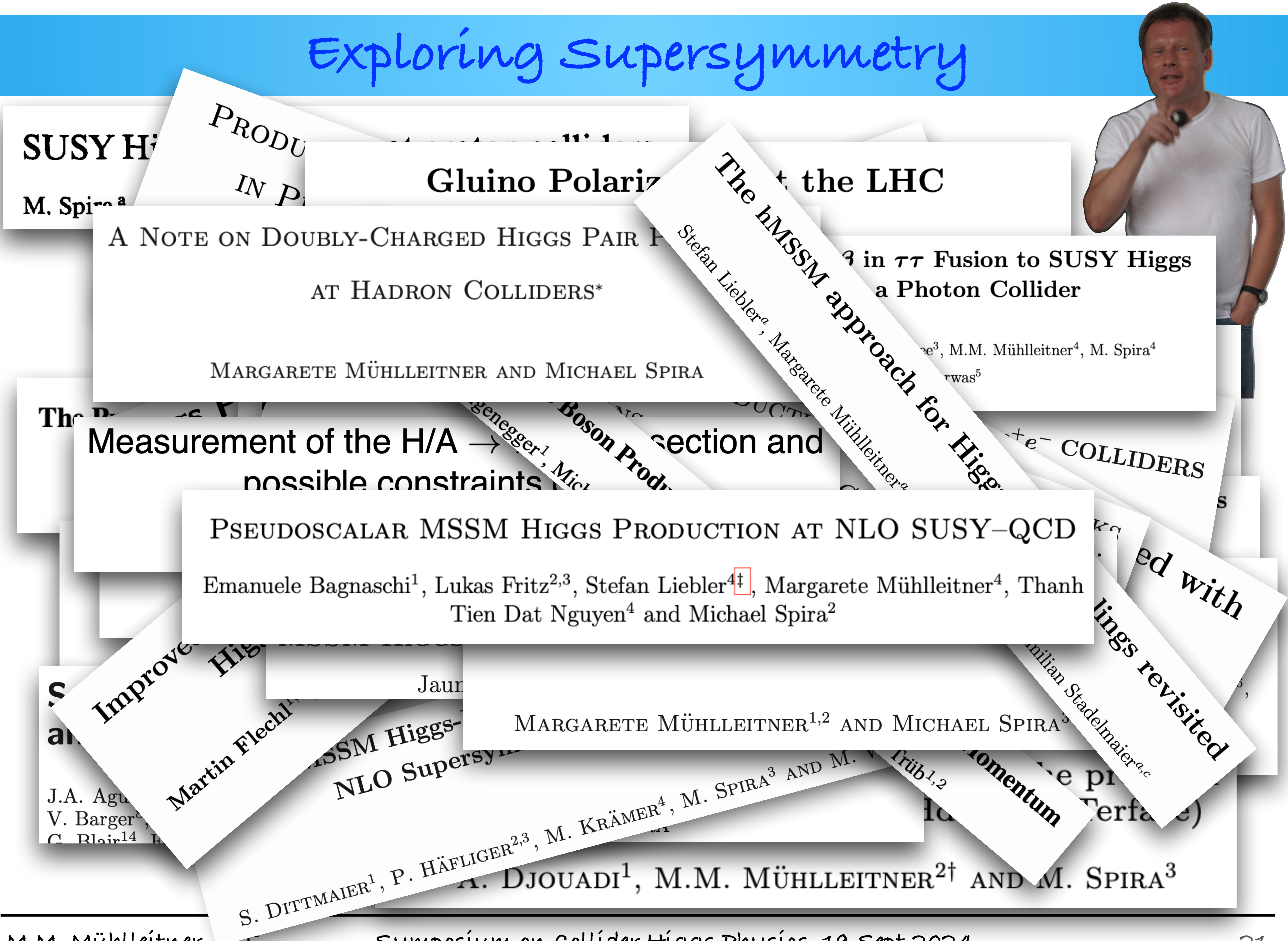
V. Barger
G. Blair[14]

Exploring Supersymmetry



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A NOTE ON DOUBLY-CHARGED HIGGS PAIR P

AT HADRON COLLIDERS*

MARGARETE MÜHLLEITNER AND MICHAEL SPIRA

The hMSSM approach for Higgs

Stefan Liebler[a], Margarete Mühlleitner[a]

in $\tau\tau$ Fusion to SUSY Higgs

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PSEUDOSCALAR MSSM HIGGS PRODUCTION AT NLO SUSY–QCD

Emanuele Bagnaschi[1], Lukas Fritz[2,3], Stefan Liebler[4‡], Margarete Mühlleitner[4], Thanh Tien Dat Nguyen[4] and Michael Spira[2]

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A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

Exploring Supersymmetry

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PSEUDOSCALAR MSSM HIGGS PRODUCTION AT NLO SUSY–QCD

Emanuele Bagnaschi[1], Lukas Fritz[2,3], Stefan Liebler[4‡], Margarete Mühlleitner[4], Thanh Tien Dat Nguyen[4] and Michael Spira[2]

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A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

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C. Blair[14]

Exploring Supersymmetry

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The hMSSM approach for Higg

Stefan Liebler[a], Margarete Mühlleitner[a]

β in $\tau\tau$ Fusion to SUSY Higgs

Photon Collider

M.M. Mühlleitner[4], M. Spira[4]

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Benchmark scenarios for low tan β in the MSSM

Sven Heinemeyer[3,c], Ma Carn[5,g],

Ema

Gabriel Lee[4]

Jérémie Qu

UO

MIT

e^+e^- COLLIDERS

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PSEUDOSCALAR MSSM HIGGS PRODUCTION AT NLO SUSY–QCD

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A. DJOUADI[1], M.M. MÜHLLEITNER[2†] AND M. SPIRA[3]

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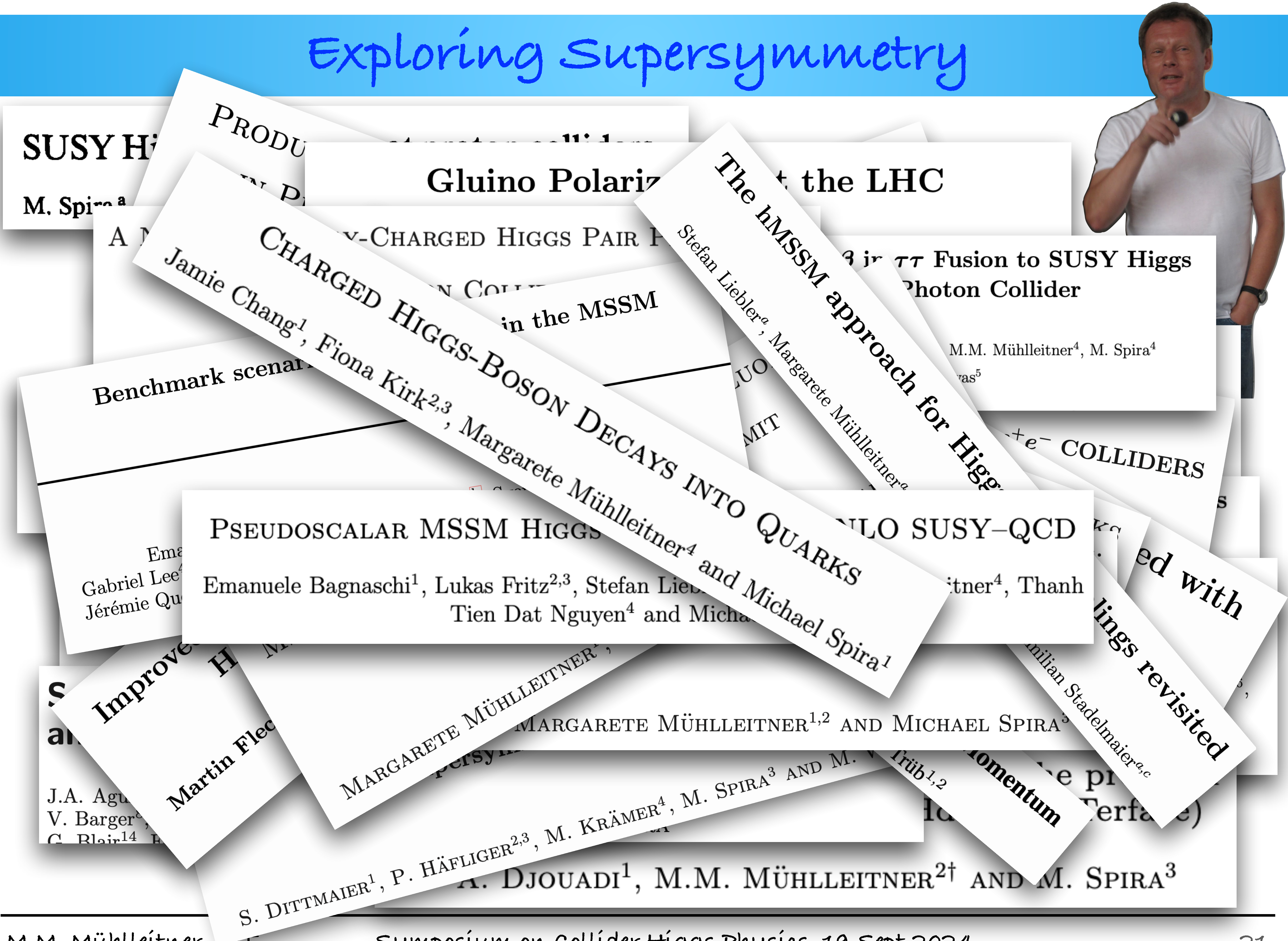

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Benchmark scenar

CHARGED HIGGS-BOSON DECAYS INTO QUARKS

Jamie Chang[1], Fiona Kirk[2,3], Margarete Mühlleitner[4] and Michael Spira[1]

The hMSSM approach for Higgs

Stefan Liebler[a], Margarete Mühlleitner[a]

β in $\gamma\gamma$ Fusion to SUSY Higgs
Photon Collider

M.M. Mühlleitner[4], M. Spira[4]
vas[5]

UO
MIT

$^+e^-$ COLLIDERS

PSEUDOSCALAR MSSM HIGGS NLO SUSY–QCD

Emanuele Bagnaschi[1], Lukas Fritz[2,3], Stefan Lieb itner[4], Thanh
Tien Dat Nguyen[4] and Micha

Ema
Gabriel Lee[4]
Jérémie Qu

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MARGARETE MÜHLLEITNER[1,2] AND MICHAEL SPIRA[3]

S. DITTMAIER[1], P. HÄFLIGER[2,3], M. KRÄMER[4], M. SPIRA[3] AND M.

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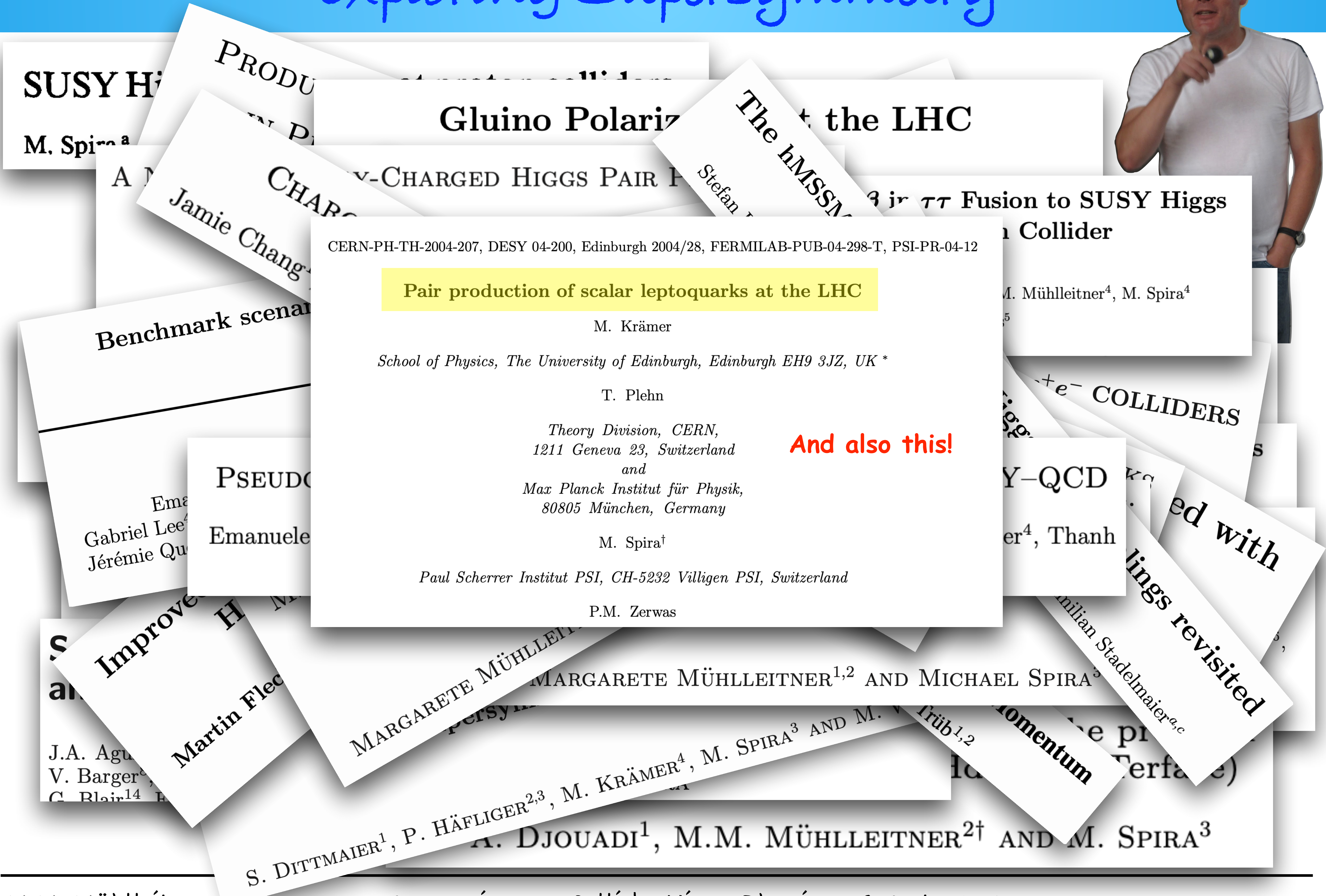
Exploring Supersymmetry



CERN-PH-TH-2004-207, DESY 04-200, Edinburgh 2004/28, FERMILAB-PUB-04-298-T, PSI-PR-04-12

Pair production of scalar leptoquarks at the LHC

M. Krämer

School of Physics, The University of Edinburgh, Edinburgh EH9 3JZ, UK *

T. Plehn

Theory Division, CERN,
1211 Geneva 23, Switzerland
and
Max Planck Institut für Physik,
80805 München, Germany

M. Spira†

Paul Scherrer Institut PSI, CH-5232 Villigen PSI, Switzerland

P.M. Zerwas

And also this!

Higgs Physics at the LHC - Higgs Production

Nov. 1994 – Dec. 1995 Postdoctoral position at Hamburg University

pr 1995

HIGGS BOSON PRODUCTION AT THE LHC

M.

1997

QCD Effects in Higgs Physics

Michael Spira

Geneva 23, Switzerland

Higgs Boson Production and Decay at Hadron Colliders

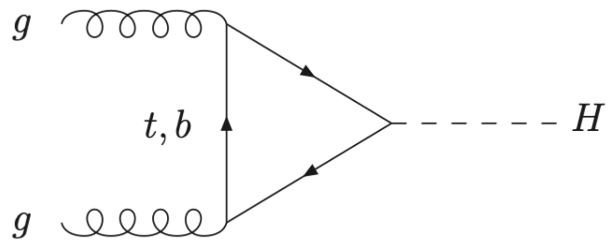
Michael Spira

Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland

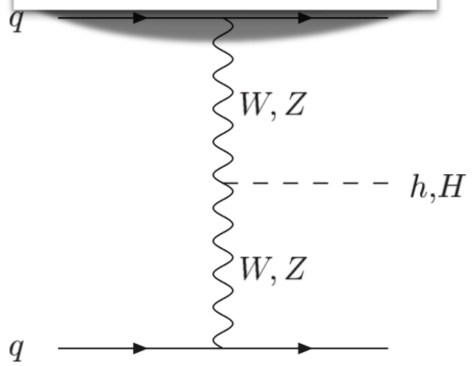
March 15, 2021

Production Processes at the LHC

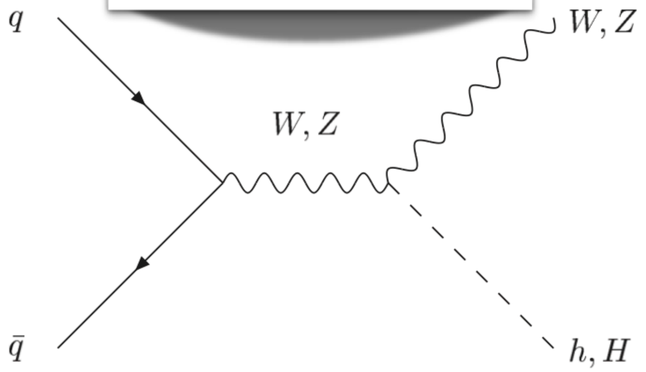
Gluon Fusion



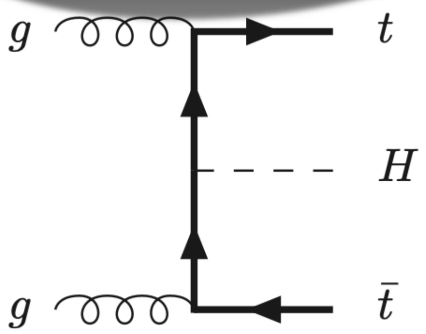
W Boson Fusion

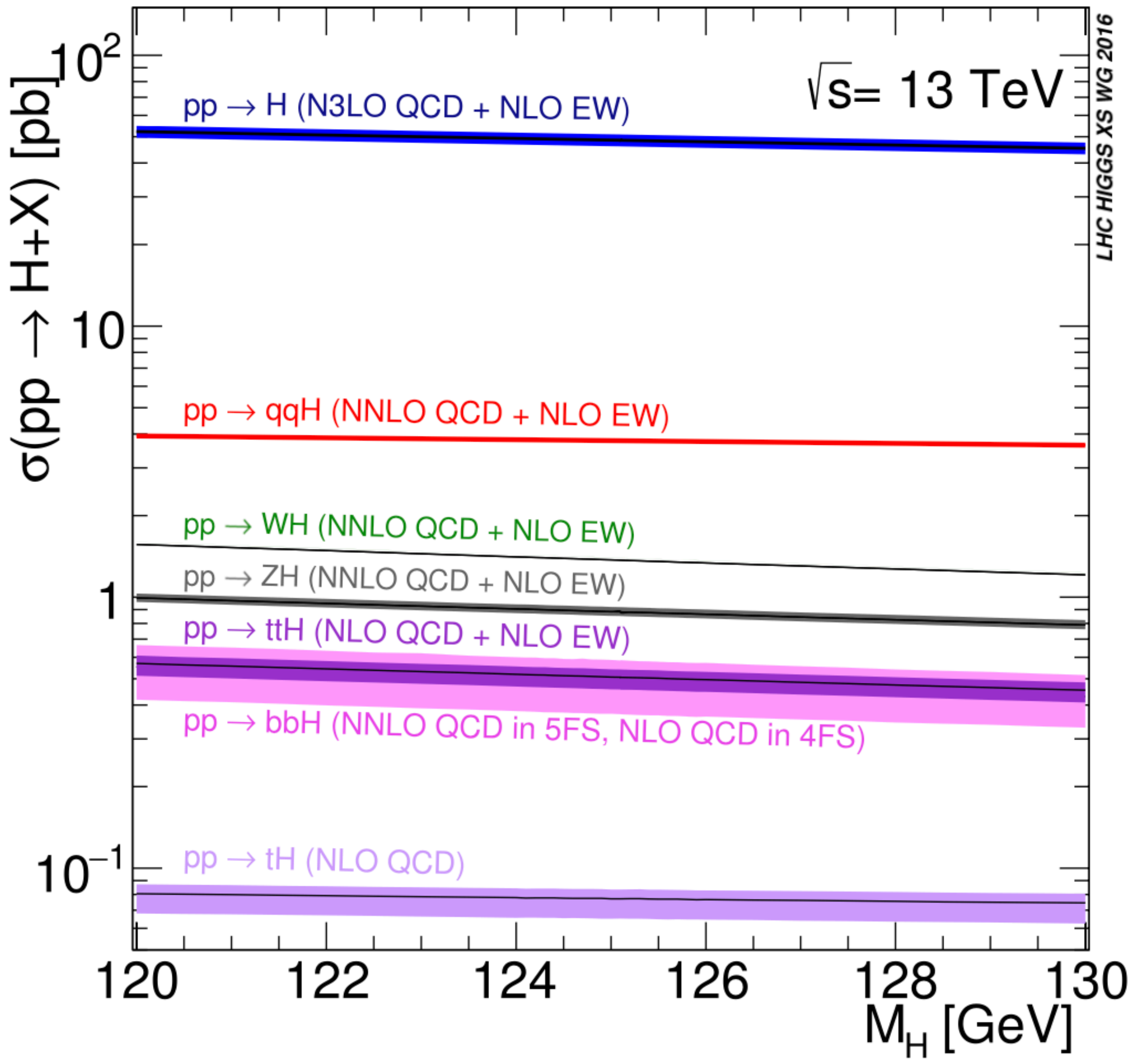


Higgs-strahlung

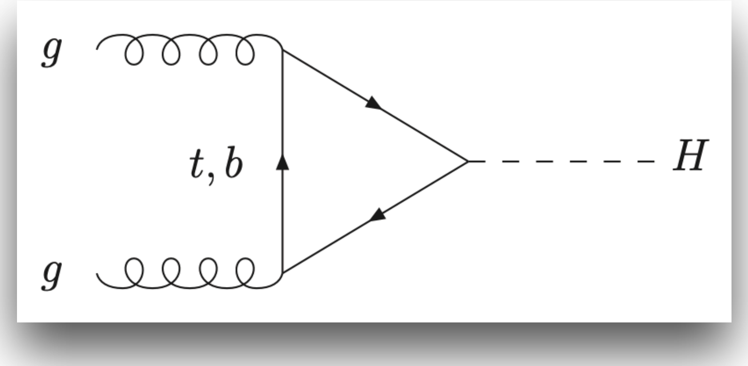


Bremsstrahlung





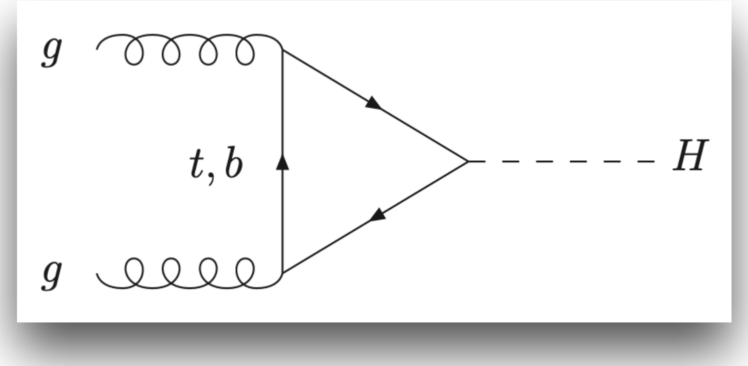
Gluon Fusion $gg \to H$



- ✏ Leading-order (LO) result already loop mediated [Georgi,Glashow,Machacek,Nanopoulos,'78]

Sensitivity to new physics in the loop

Gluon Fusion $gg \to H$



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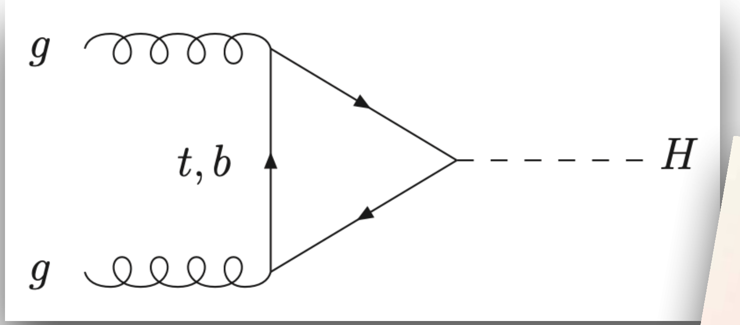

- Leading-order (LO) result ... gi,Glashow,Machacek,Nanopoulos,'78]
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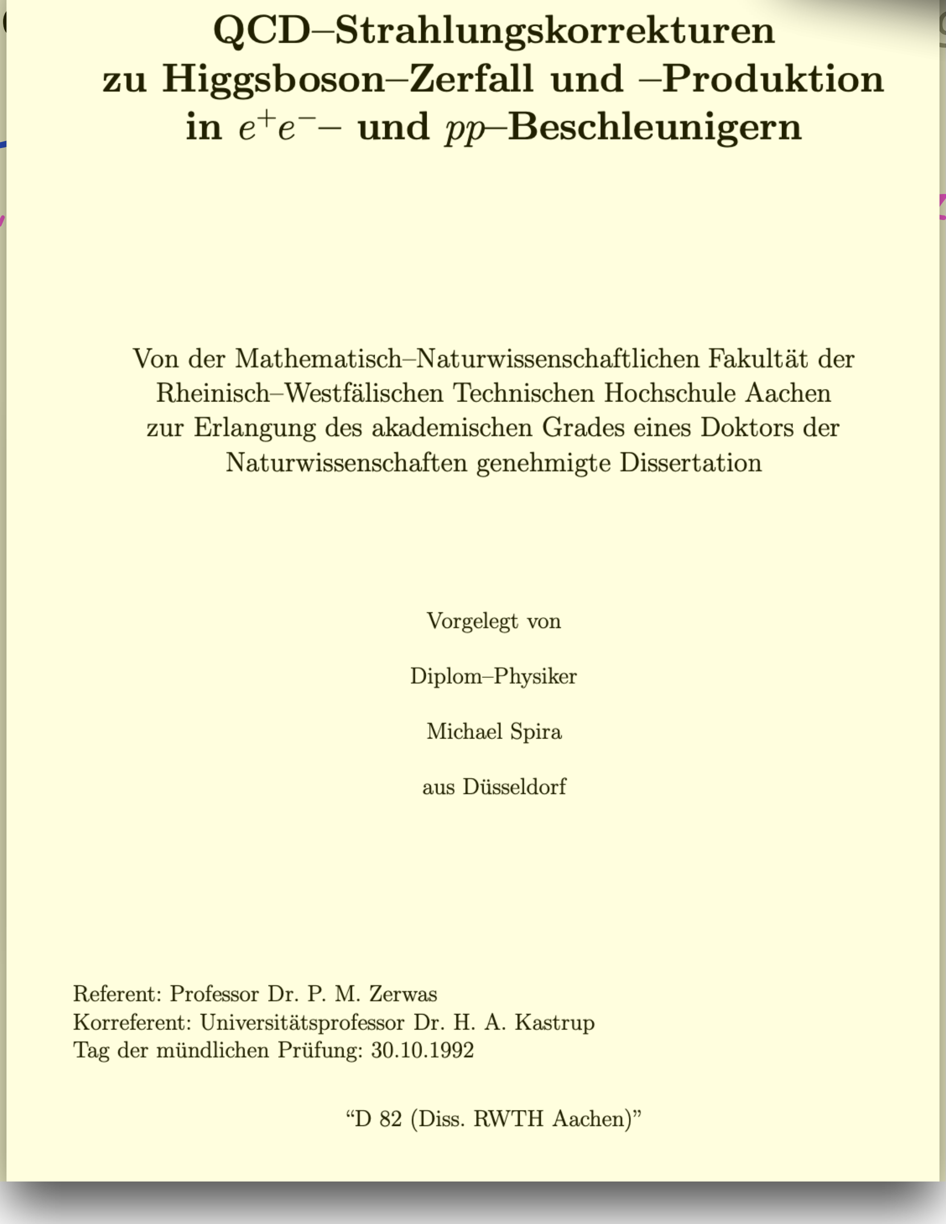


QCD–Strahlungskorrekturen
zu Higgsboson–Zerfall und –Produktion
in e^+e^-– und pp–Beschleunigern

Von der Mathematisch–Naturwissenschaftlichen Fakultät der
Rheinisch–Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades eines Doktors der
Naturwissenschaften genehmigte Dissertation

Vorgelegt von

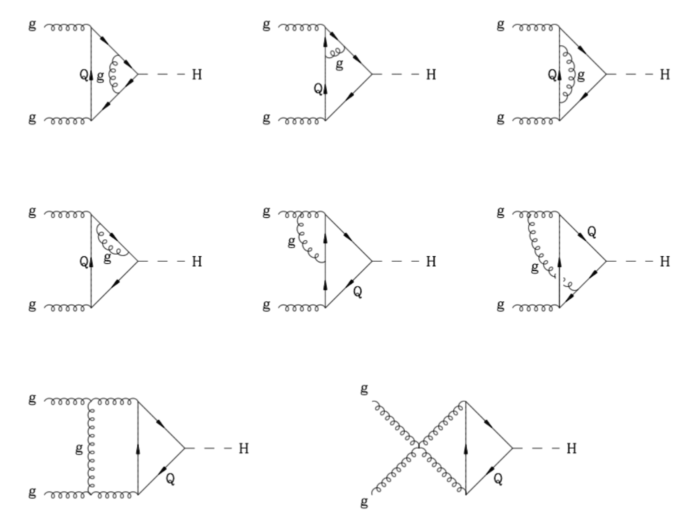
Diplom–Physiker

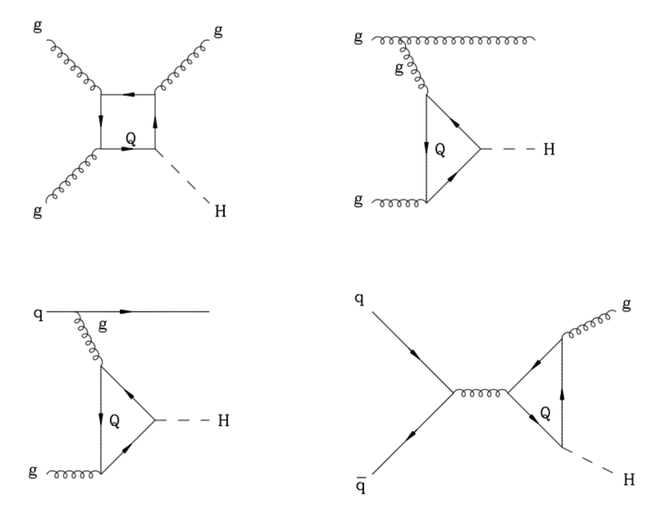
Michael Spira

aus Düsseldorf

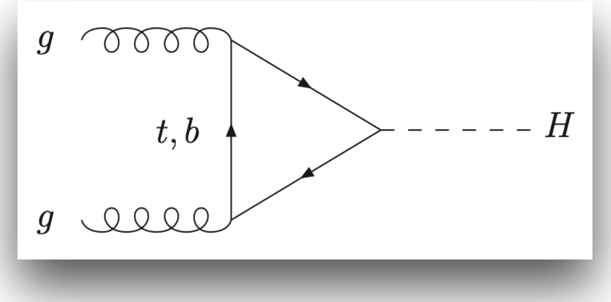
Referent: Professor Dr. P. M. Zerwas
Korreferent: Universitätsprofessor Dr. H. A. Kastrup
Tag der mündlichen Prüfung: 30.10.1992

"D 82 (Diss. RWTH Aachen)"



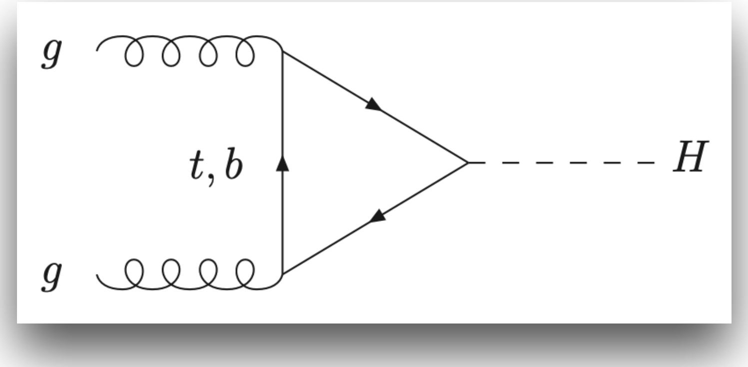


Gluon Fusion $gg \to H$



- Leading-order (LO) result already loop mediated [Georgi,Glashow,Machacek,Nanopoulos,'78]
- Next-to-leading-order (NLO) QCD corrections: ~100% [Djouadi,Spira,Zerwas,'91] [Graudenz,Spira,Zerwas,'93][Spira,Djouadi,Graudenz,Zerwas,'95] [Dawson,Kauffmann,'93]
- Next-to-next-to-leading order (NNLO) for $m_t \gg M_\phi \Rightarrow$ further increase by 20-30% (top mass effects small in the SM) [Harlander,Kilgore] [Anastasiou,Melnikov] [Ravindran,Smith,van Neerven] [Marzani,Ball,DelDuca,Forte,Vicini] [Harlander,Ozeren] [Pak,Rogal,Steinhauser] [Czakon,Harlander,Klappert,Niggetied]
- $\mathrm{N^3LO}$ for $m_t \gg M_\phi \Rightarrow$ scale stabilization, scale dep. $\Delta \lesssim 5\,\%$ [Moch,Vogt] [Ravindran] [deFlorian,Mazzitelli,Moch,Vogt] [Ball,Bonvini,Forte,Marzani,Ridolfi] [Anastasiou,Duhr,Dulat,Furlan,Gehrmann,Herzog,Mistlberger]
- $\mathrm{N^3LL}$ soft gluon resummation: $\lesssim 1\,\%$ [Catani,deFlorian,Grazzini,Nason] [Ravindran] [Ahrens,Becher,Neubert,Yang] [Ball,Bonvini,Forte,Marzani,Ridolfi] [Bonvini,Marzani] [Schmidt,Spira,'15]
- NNLO w/ exact top mass dependence: +0.62% (purely gluonic channel), w/ partonic channels: −0.32% (−0.16%) @ $\sqrt{s} = 13\ (8)$ TeV [Czakon.Harlander,Klappert,Niggetiedt,21]

Gluon Fusion $gg \to H$



- implementation of $gg \to \phi$ in POWHEG w/ mass effects @ NLO (QCD also valid for 2HDM & other Higgs extension)

[Bagnaschi,Degrassi,Slavich,Vivini]

- Electroweak corrections: $\sim 5\,\%$

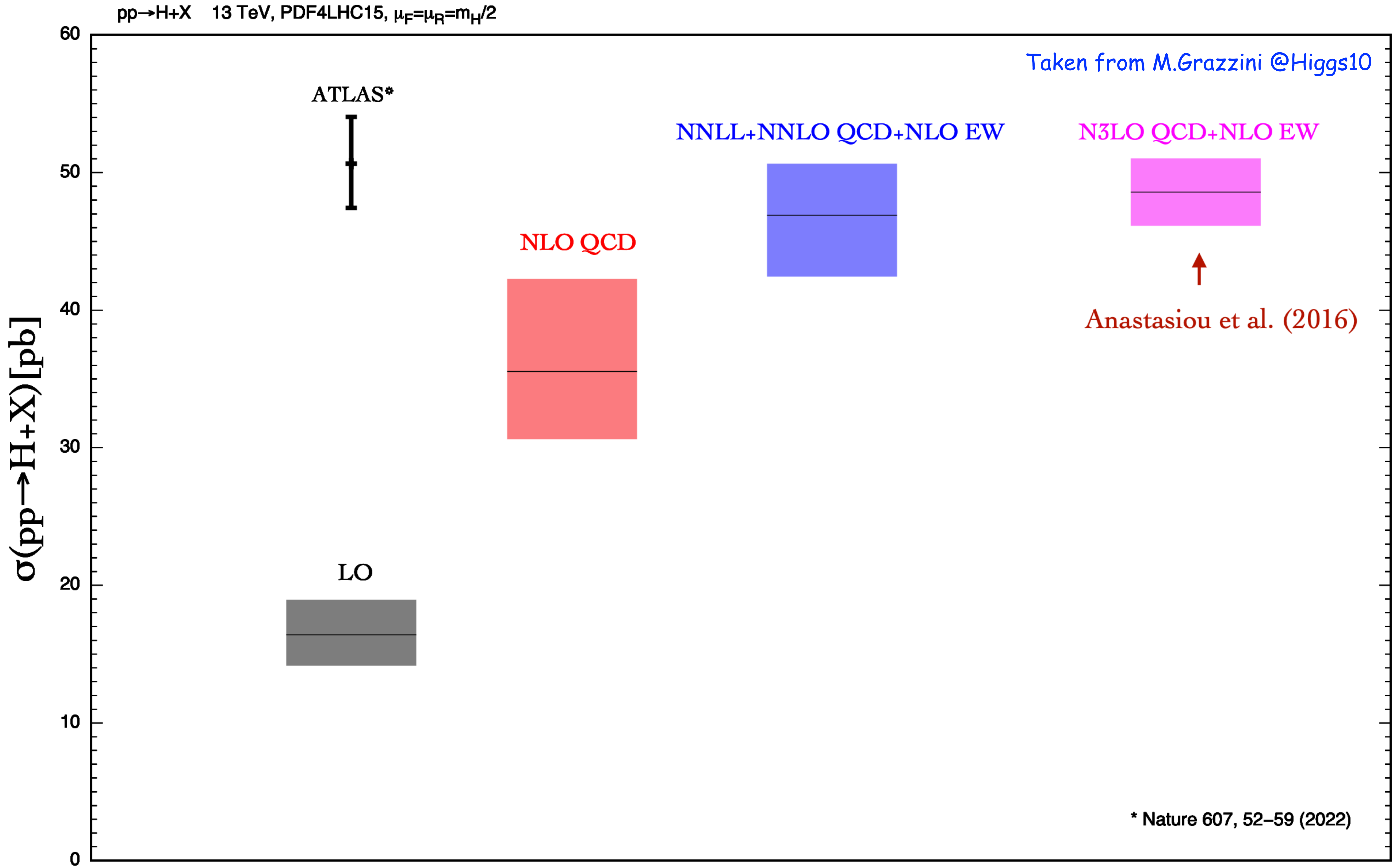
[Aglietti,Bonciani,Degrassi,Vicini] [Degrassi,Maltoni]
[Actis,Passarino,Sturm,Uccirati]

- $\sigma(gg \to H) = (54.72^{+4.3\%}_{-6.5\%}(\text{TH}) \pm 3.2\,\%\,(\text{PDF}, \alpha_s))$ pb @ $\sqrt{s} = 14$ TeV

[deFlorian eal;LHC Higgs WG,'16]

- Uncertainties: — PDF+α_s — renormalization/factorization scale
  — top/bottom masses: $\sim \pm 0.8\,\%$ (scale/scheme dependence)

Importance of Higher-Order Corrections

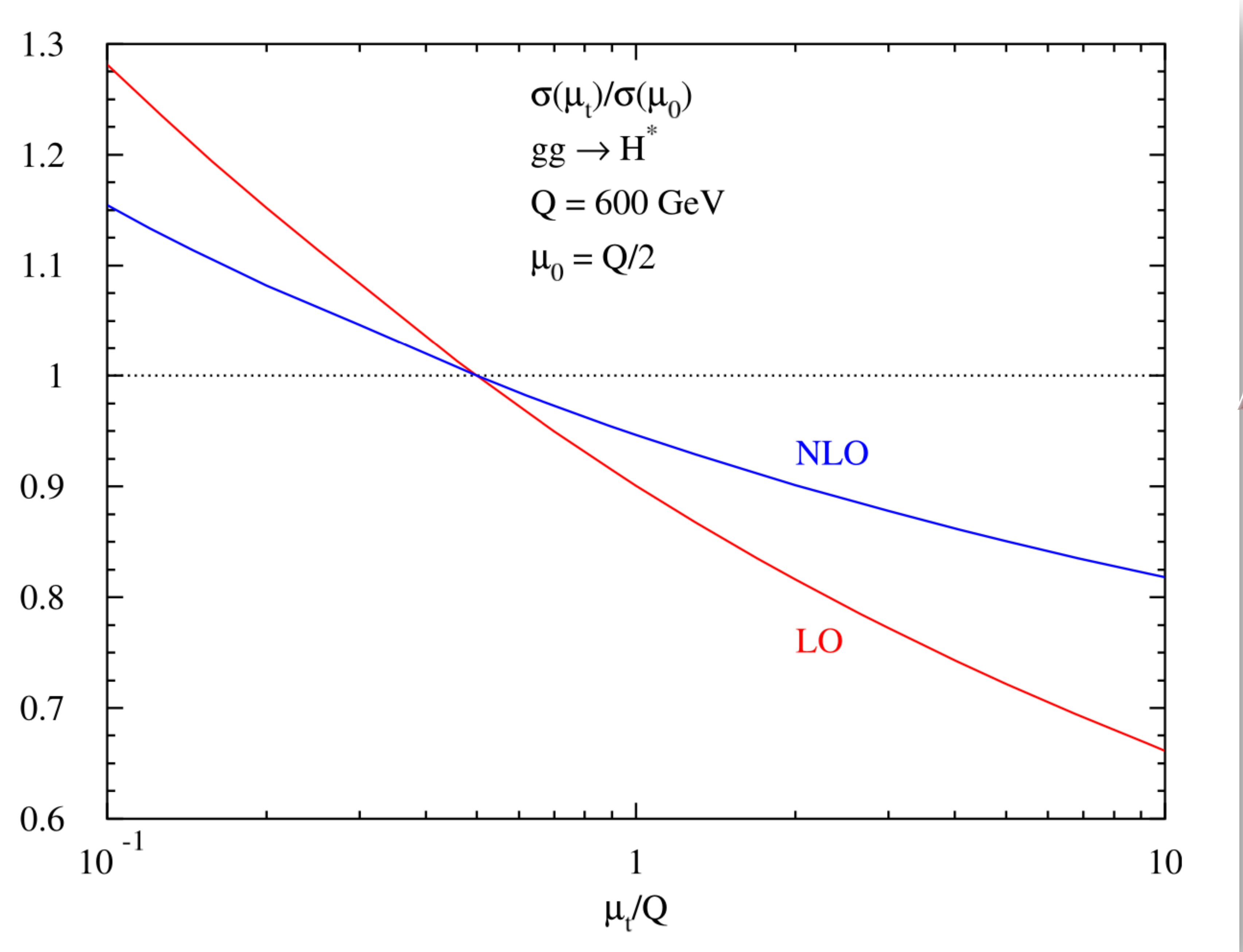


Taken from M.Grazzini @Higgs10

* Nature 607, 52–59 (2022)

Uncertainties - Top Mass Scale Uncertainty

[Jones,Spira]

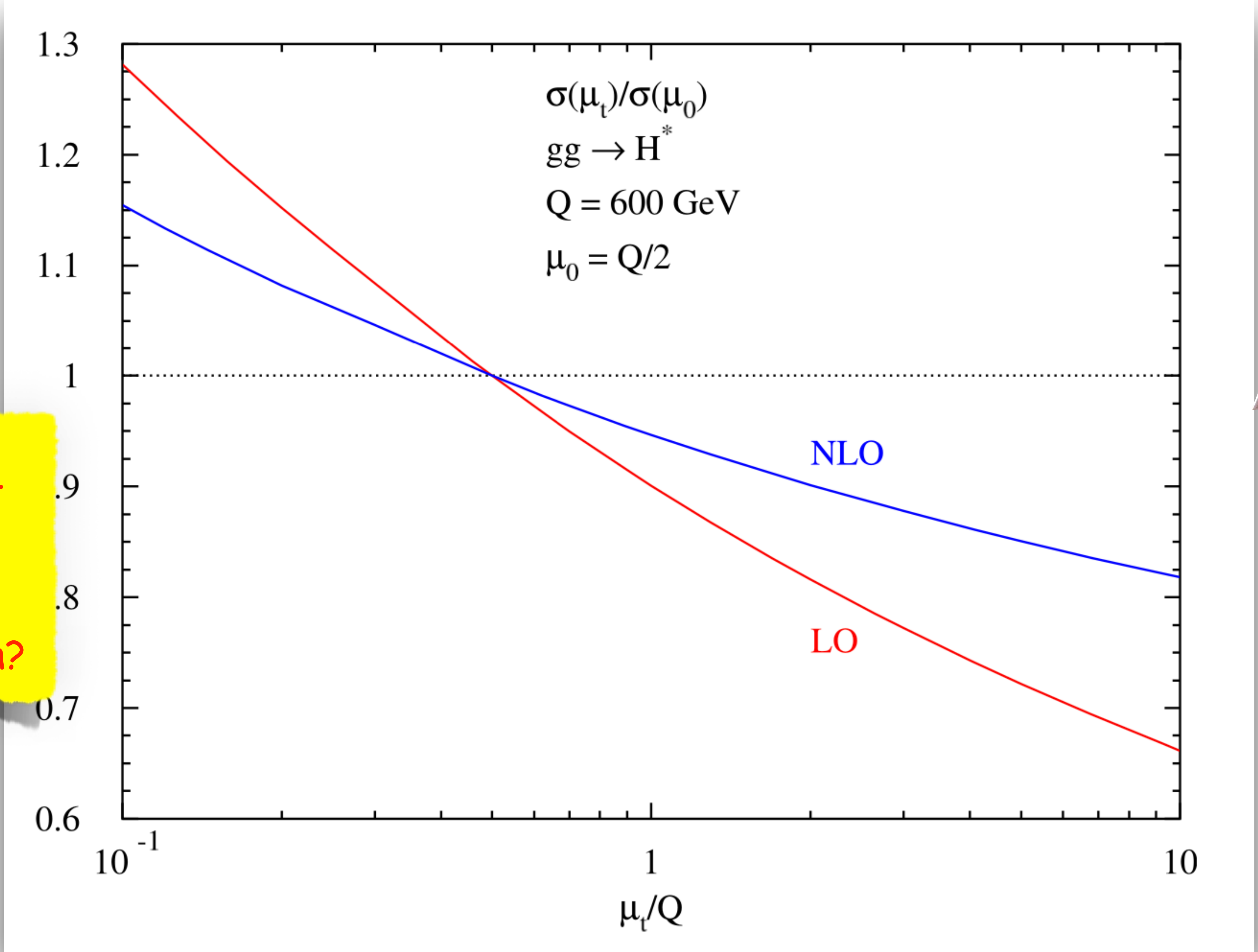


$\sigma(gg \to H)_{LO} = 18.43^{+0.8\%}_{-1.1\%}$ pb

$\sigma(gg \to H)^{QCD}_{NLO} = 42.17^{+0.4\%}_{-0.5\%}$ pb

Uncertainties - Top Mass Scale Uncertainty

[Jones,Spira]



What about BSM Higgs production and precision?

$\sigma(gg \to H)_{LO} = 18.43^{+0.8\%}_{-1.1\%}$ pb

$\sigma(gg \to H)^{QCD}_{NLO} = 42.17^{+0.4\%}_{-0.5\%}$ pb

Example: MSSM Higgs Sector

- ✏ MSSM Higgs sector:
  supersymmetry & anomaly free theory => 2 complex Higgs doublets

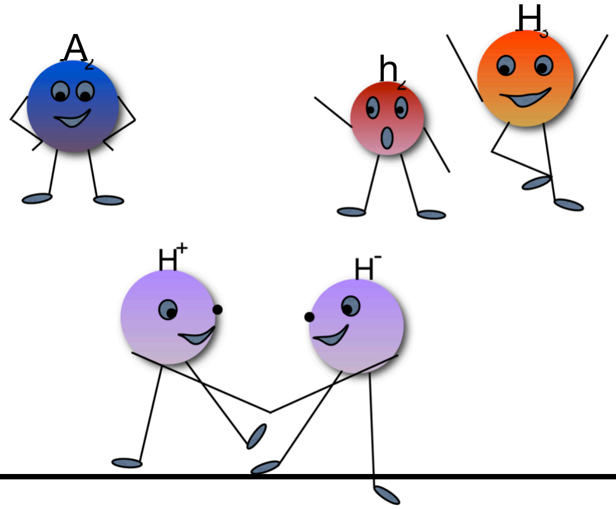
$$\xrightarrow{\text{EWSB}} \boxed{\text{neutral, CP-even } h, H \qquad \text{neutral, CP-odd } A \qquad \text{charged } H^+, H^-}$$

- ✏ Confrontation w/ experiment: one Higgs boson must behave SM-like

- ✏ Higgs boson mass:
  - SM: fundamental parameter, not predicted by the theory
  - Supersymmetry: calculable from input parameters; upper bound on SM-like Higgs mass $m_h \leq m_Z \rightsquigarrow$ quantum corrections to SM-like Δm_h^2 are important!

- ✏ Why precision?:
  - Test parameter relations in beyond-SM theories

indirect constraints
on viable BSM
parameter space



MSSM Higgs Production in Gluon Fusion

✏ Dominant LHC production processes $gg \to h/H/A$:

* NLO QCD corrections to top/bottom loops w/ full mass dependence: increase by ~100%

[Spira,Djouadi,Graudenz,Zerwas,'95]

* NLO QCD corrections to squark loops in limit of heavy squarks [Dawson,Djouadi,Spira,'96]
* SUSY-QCD corrections for heavy SUSY mass

[Harlander,Steinhauser,'03,'04;Harlander,Hofmann,'06]

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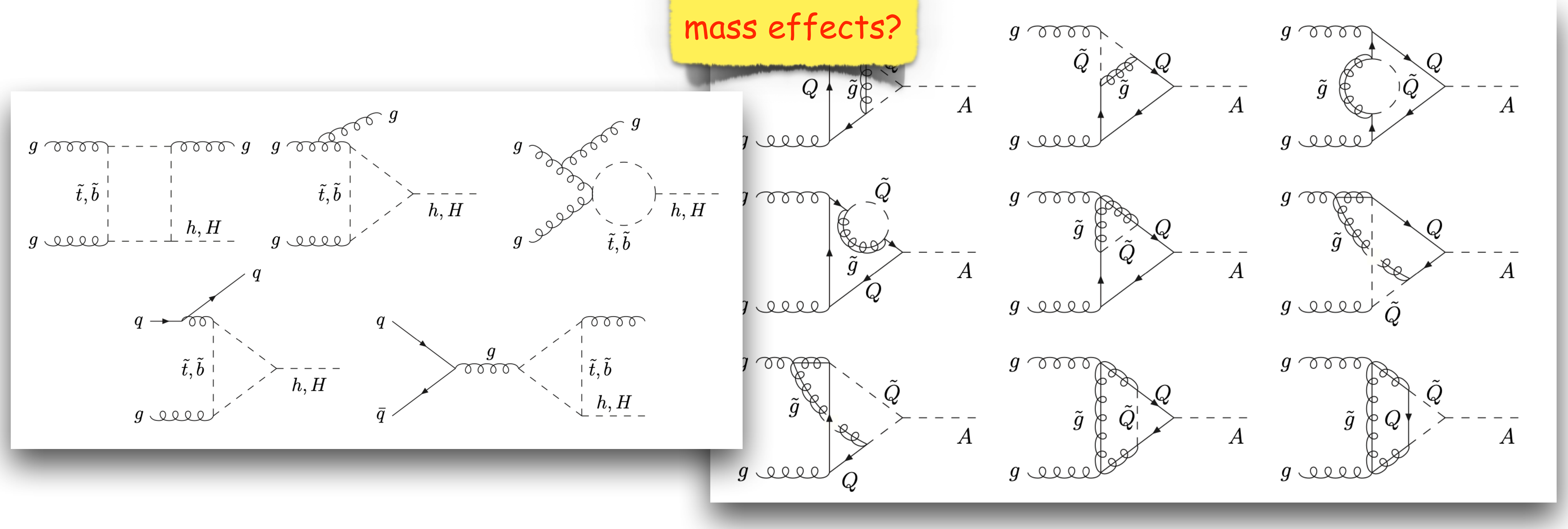
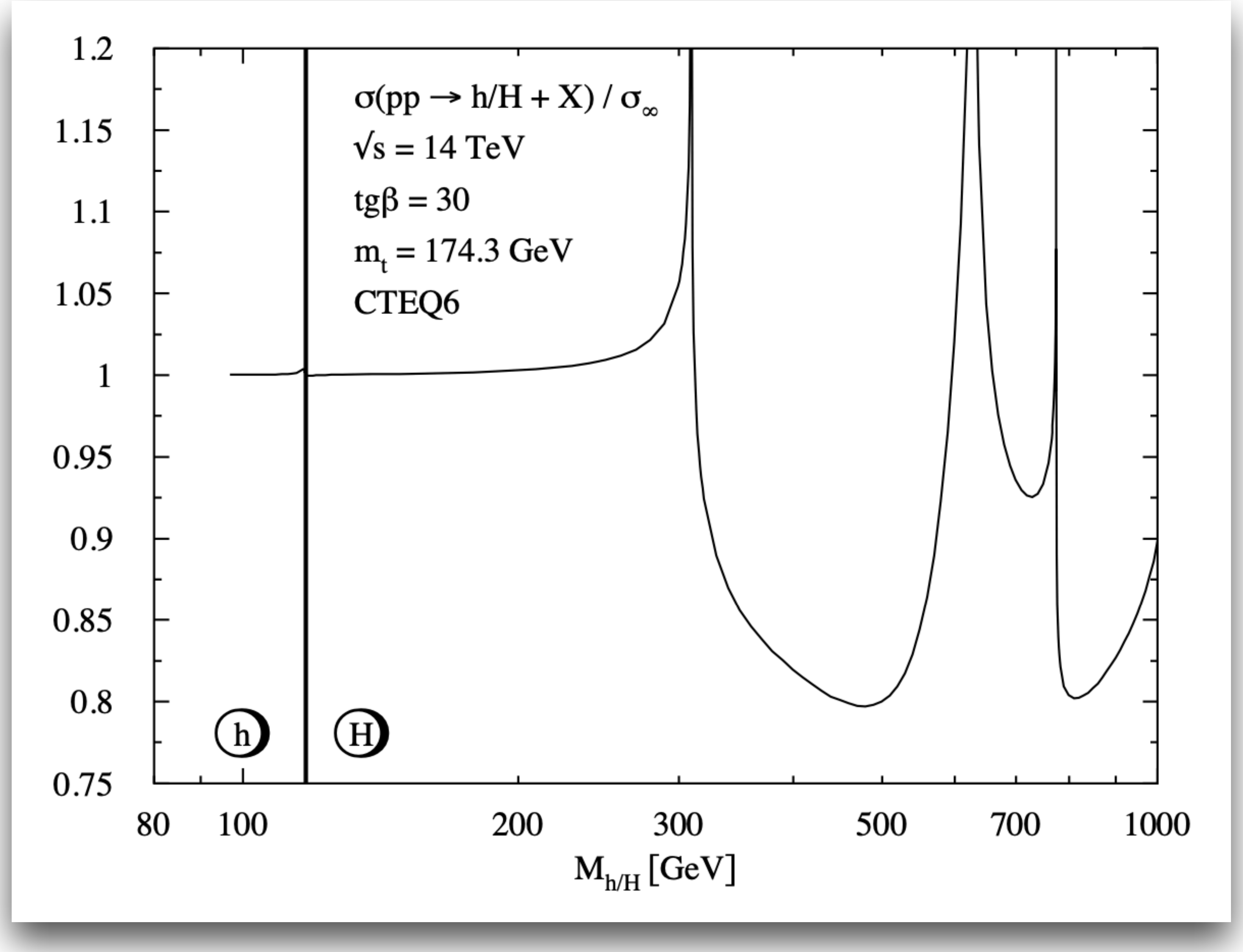


Finite SUSY mass effects?

Scalar MSSM Higgs Production in Gluon Fusion

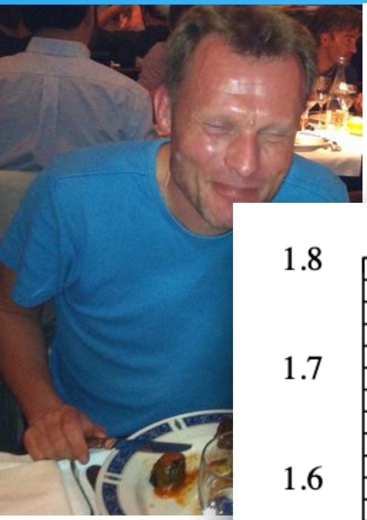
[MM,Spira,'06]



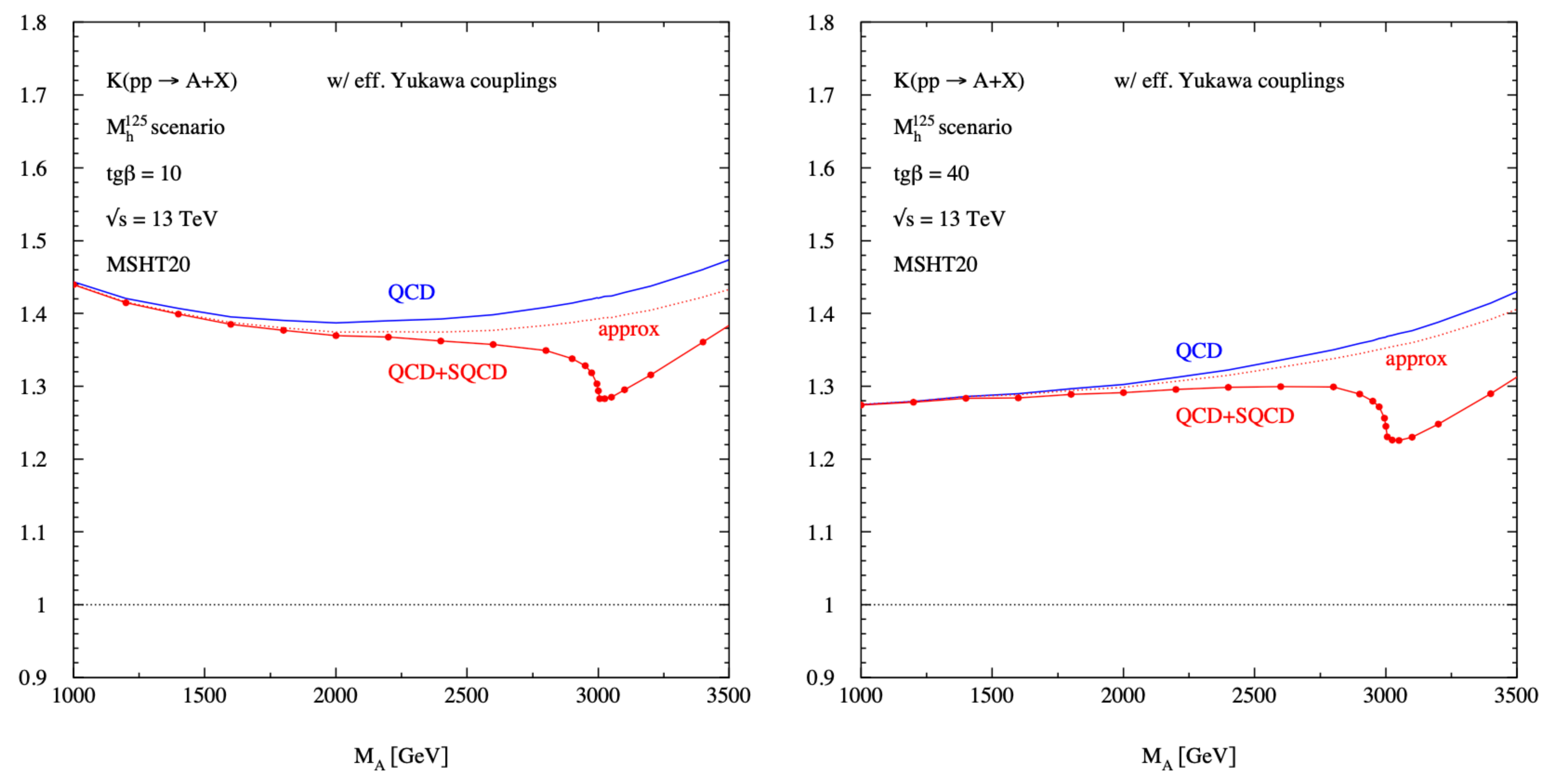
Squark mass effects of K-factor can be up to 20%
(spikes: squark pair thresholds)

See also:
[MM,Rzehak,Spira,'08]

Pseudoscalar MSSM Higgs Production in Gluon Fusion



[Bagnaschi,Fritz,Liebler,MM,Nguyen,Spira,'22]

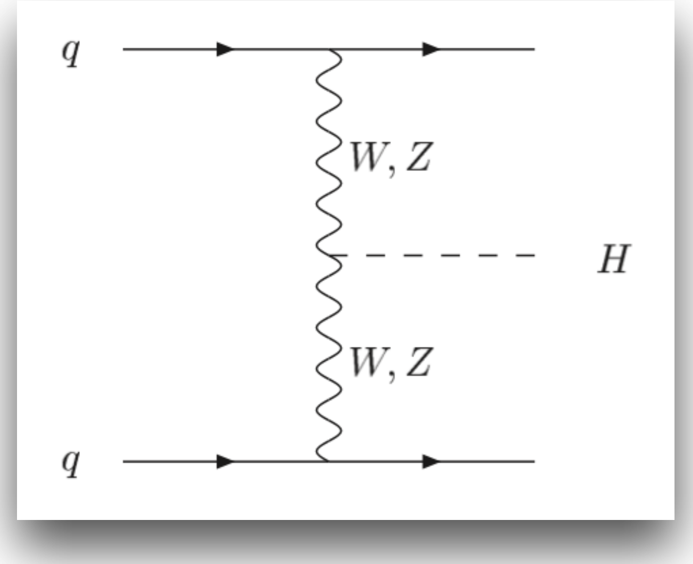


Bulk of corrections can be absorbed in effective Yukawa couplings

SUSY remainder of moderate size (barring virtual squark thresholds)

WW/ZZ Fusion

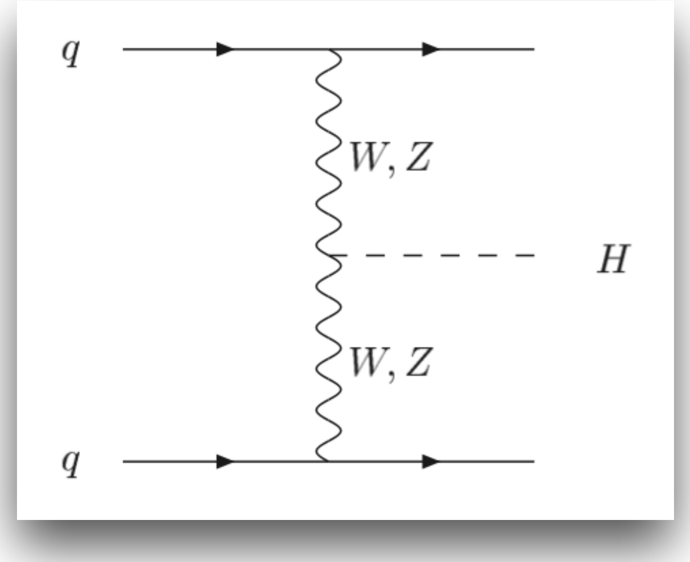
✏ $pp \rightarrow W^*W^*/Z^*Z^* \rightarrow H$:



tagging jets helpful for S/B separation

WW/ZZ Fusion

✏ $pp \to W^*W^*/Z^*Z^* \to H$:



[Cahn,Dawson]
[Hikasa]
[Altarelli,Mele,Pitolli]

✏ QCD corrections ← DIS: ~10%

[Han,Valencia] [Willenbrock]
[Figy,Oleari,Zeppenfeld] [Berger,Campbell]

(approx) 2-loop: $\lessapprox 1\,\%$

[Bolzano,Maltoni,Moch,Zaro]
[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

(approx) 3-loop: $\lessapprox 0.3\,\%$

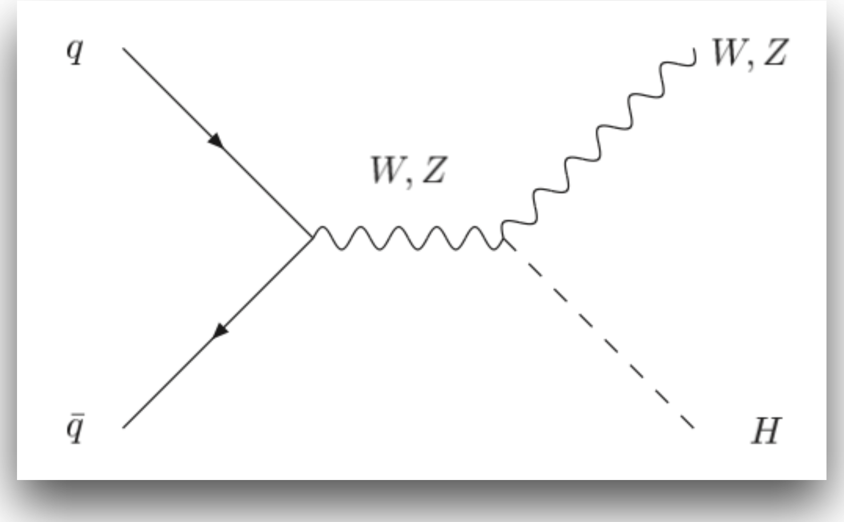
[Dreyer,Karlberg]

✏ electroweak corrections: ~10%

[Ciccolini,Denner,Dittmaier]

Higgs-strahlung

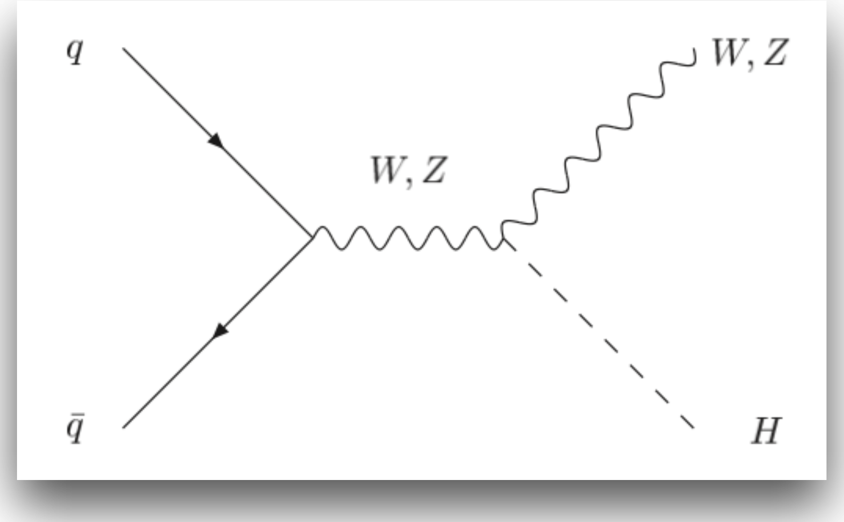
✏ $pp \rightarrow W^*/Z^* \rightarrow W/Z + H:$



Tag associated W/Z: important process for Hbb/Hcc coupling measurement

Higgs-strahlung

✏ $pp \to W^*/Z^* \to W/Z + H$:



[Glashow,Nanopoulos,Yildiz]
[Kunszt,Trocsanyi,Stirling]

✏ QCD corrections ← DY: ~30% [Han,Willenbrock]

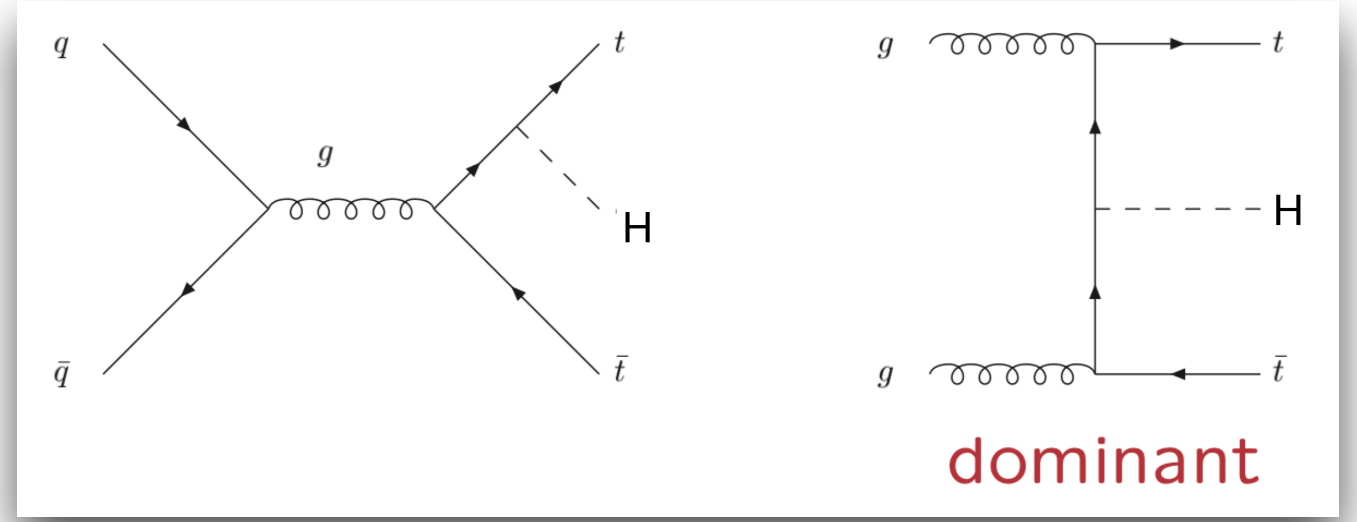
2-loop: $\lesssim 5\,\%$ [Brein,Djouadi,Harlander]

✏ electroweak corrections: ~-10% [Ciccolini,Dittmaier,Krämer]

✏ W/Z+H: fully exclusive @ NNLO QCD [Ferrera,Grazzini,Tramontano]

Bremsstrahlung

- $pp \to t\bar{t} + H$:



$t\bar{t}H \to t\bar{t}b\bar{b}$
important at LHC
→ top Yukawa coupling

- QCD corrections (SM): ~20% [Beenakker,Dittmaier,Krämer,Plümper,Spira,Zerwas,'02]
  (threshold suppressed: $\sigma_{LO} \sim \beta^4$) [Dawson,Orr,Reina,Wackeroth]
  [Broggio,Ferroglia,Pecjak,Signer,Yang]

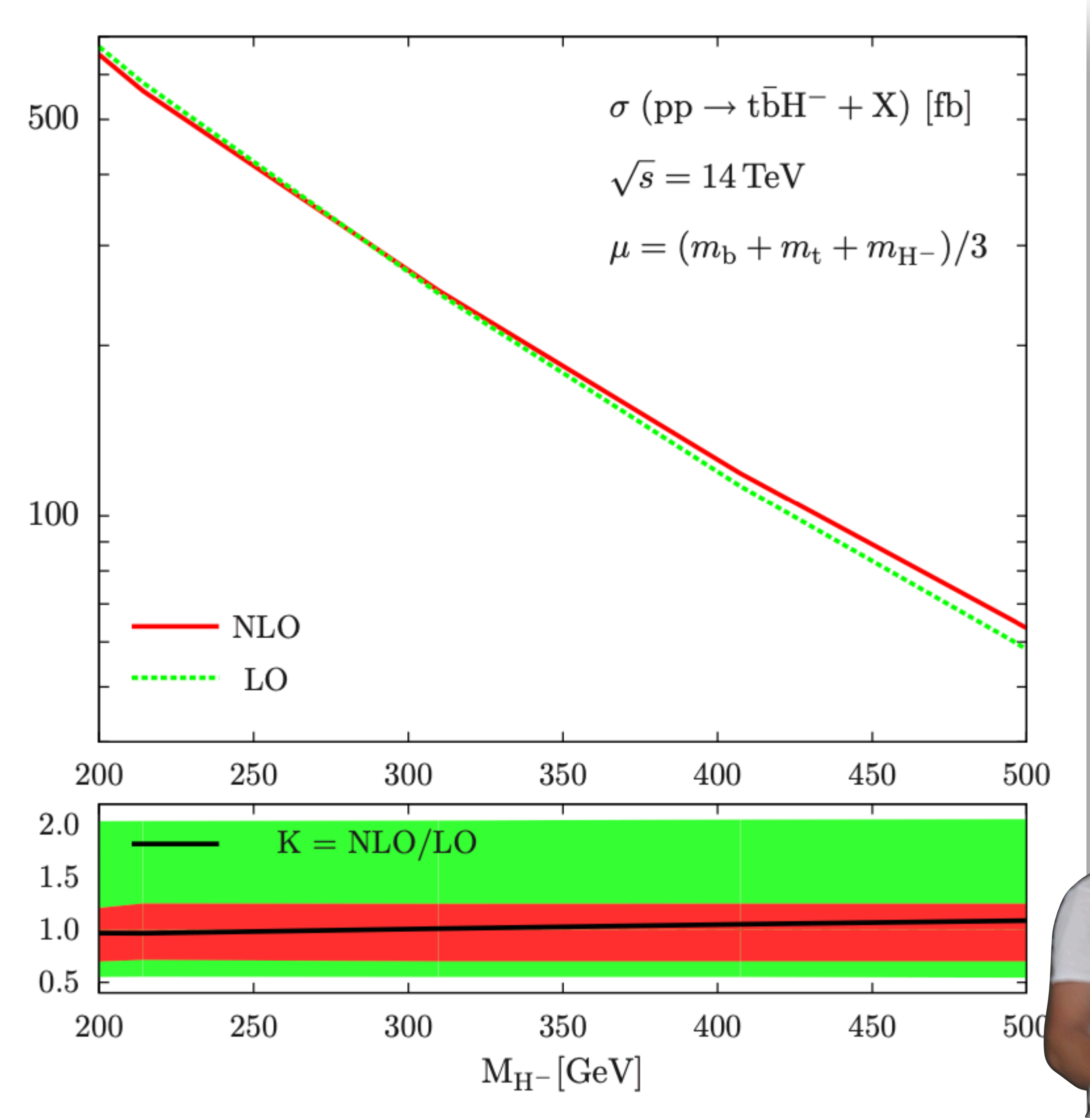
- link to Parton showers: aMC@NLO, PowHel [Frederix eal] [Garzelli,Kardos,Papadopoulos,Trocsanyi]

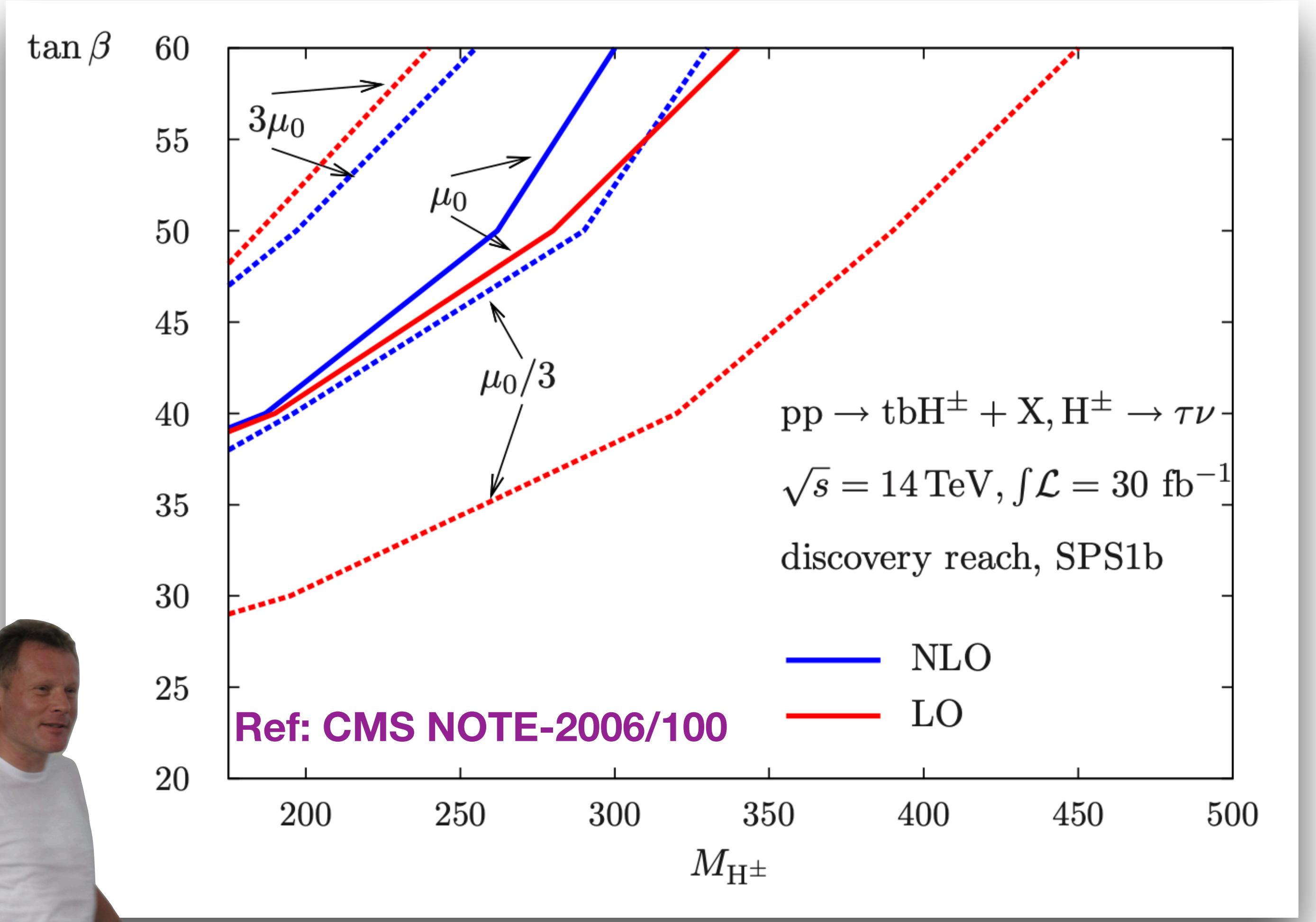
- important work on backgrounds $t\bar{t}b\bar{b}$, $t\bar{t}jj$, etc. [Bredenstein,Denner,Dittmaier,Pozzorini]
  [Bevilacqua,Czakon,Papadopoulos,Pittau,Worek] [Cascioli,Maierhofer,Pozzorini]

Charged Higgs Production through Bremsstrahlung

✏ Dominant production process for heavy charged Higgs bosons: $q\bar{q}, gg \to tbH^{\pm}$:
NLO SUSY-QCD corrections [Dittmaier,Krämer,Spira,Walser,'09]

See also for anterior works: [Zhu,'01;Gao eal,'02;Plehn,'02;Berger eal,'03;Kidonakis,'05;Peng eal,'06]

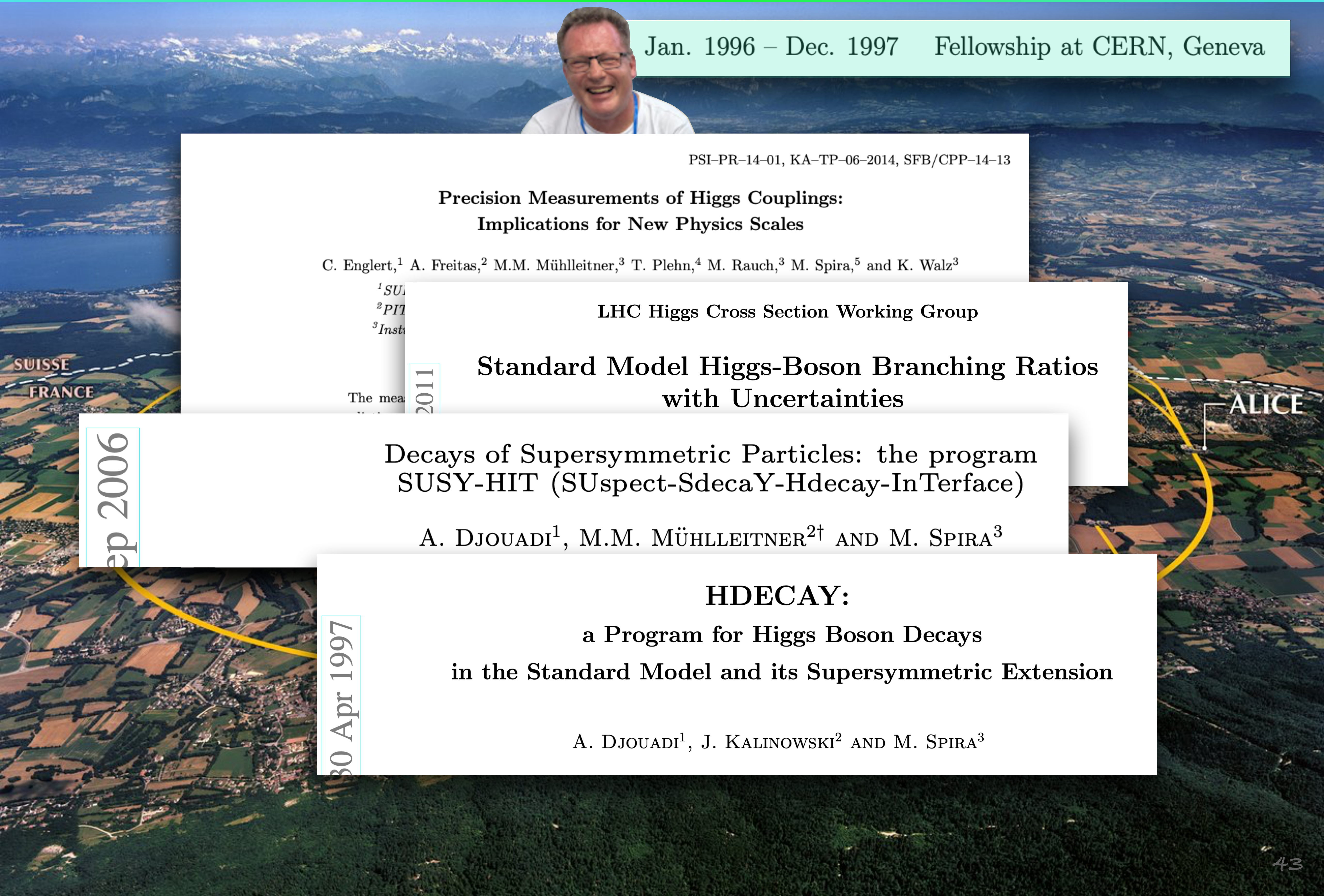




Reduced ren./fac. scale dependence ⇝ stabilized theory prediction

NLO predictions crucial to fully exploit LHC potential for Higgs MSSM searches

Higgs Couplings



Jan. 1996 – Dec. 1997 Fellowship at CERN, Geneva

PSI–PR–14–01, KA–TP–06–2014, SFB/CPP–14–13

Precision Measurements of Higgs Couplings:
Implications for New Physics Scales

C. Englert,[1] A. Freitas,[2] M.M. Mühlleitner,[3] T. Plehn,[4] M. Rauch,[3] M. Spira,[5] and K. Walz[3]

[1]*SU*
[2]*PIT*
[3]*Insti*

The mea

LHC Higgs Cross Section Working Group

Standard Model Higgs-Boson Branching Ratios with Uncertainties

2011

ep 2006

Decays of Supersymmetric Particles: the program SUSY-HIT (SUspect-SdecaY-Hdecay-InTerface)

A. Djouadi[1], M.M. Mühlleitner[2†] and M. Spira[3]

30 Apr 1997

HDECAY:

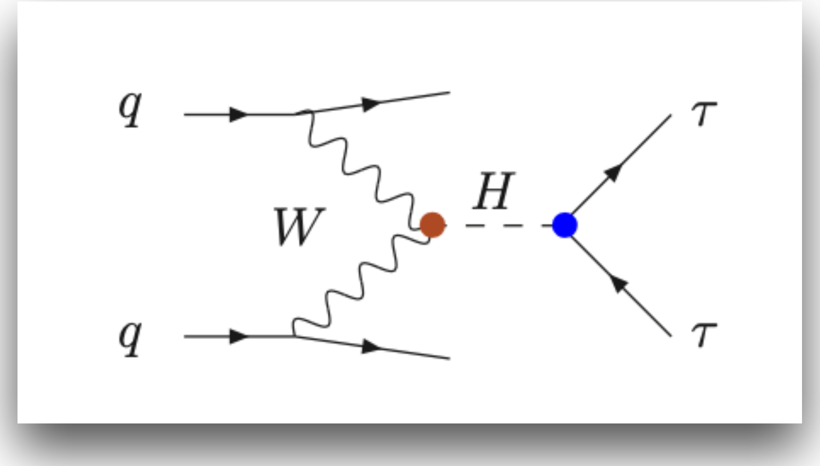
a Program for Higgs Boson Decays
in the Standard Model and its Supersymmetric Extension

A. Djouadi[1], J. Kalinowski[2] and M. Spira[3]

Higgs Coupling Measurements

- **Higgs mechanism:** Higgs couplings to SM particles ~ to masses of the particles

- **Experimental test:** various production and decay channels ~> extract couplings



~ Γ_{WW} x BR(H->ττ) ~ Γ_{WW} x Γ(H->ττ)/Γ_{tot}

at LHC: not all final states are accessible
small SM Γ_{tot} non measurable

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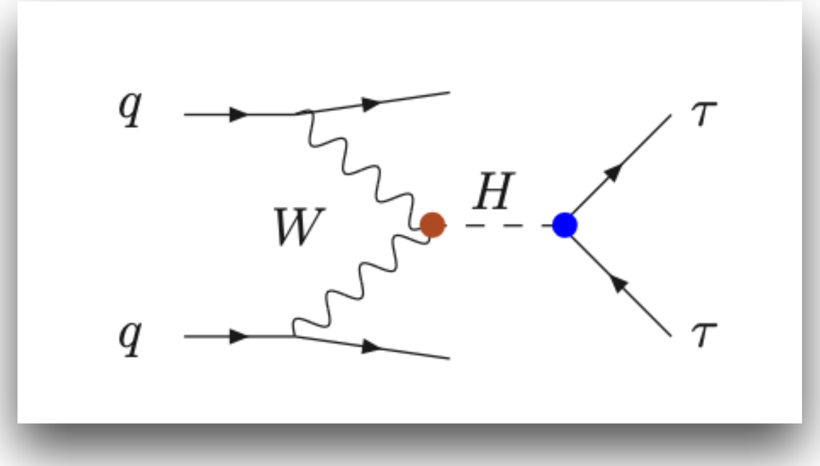


~ Γ_{WW} x BR(H->ττ) ~ Γ_{WW} x Γ(H->ττ)/Γ_{tot}

at LHC: not all final states are accessible
small SM Γ_{tot} non measurable

We must measure its couplings to the other SM particles

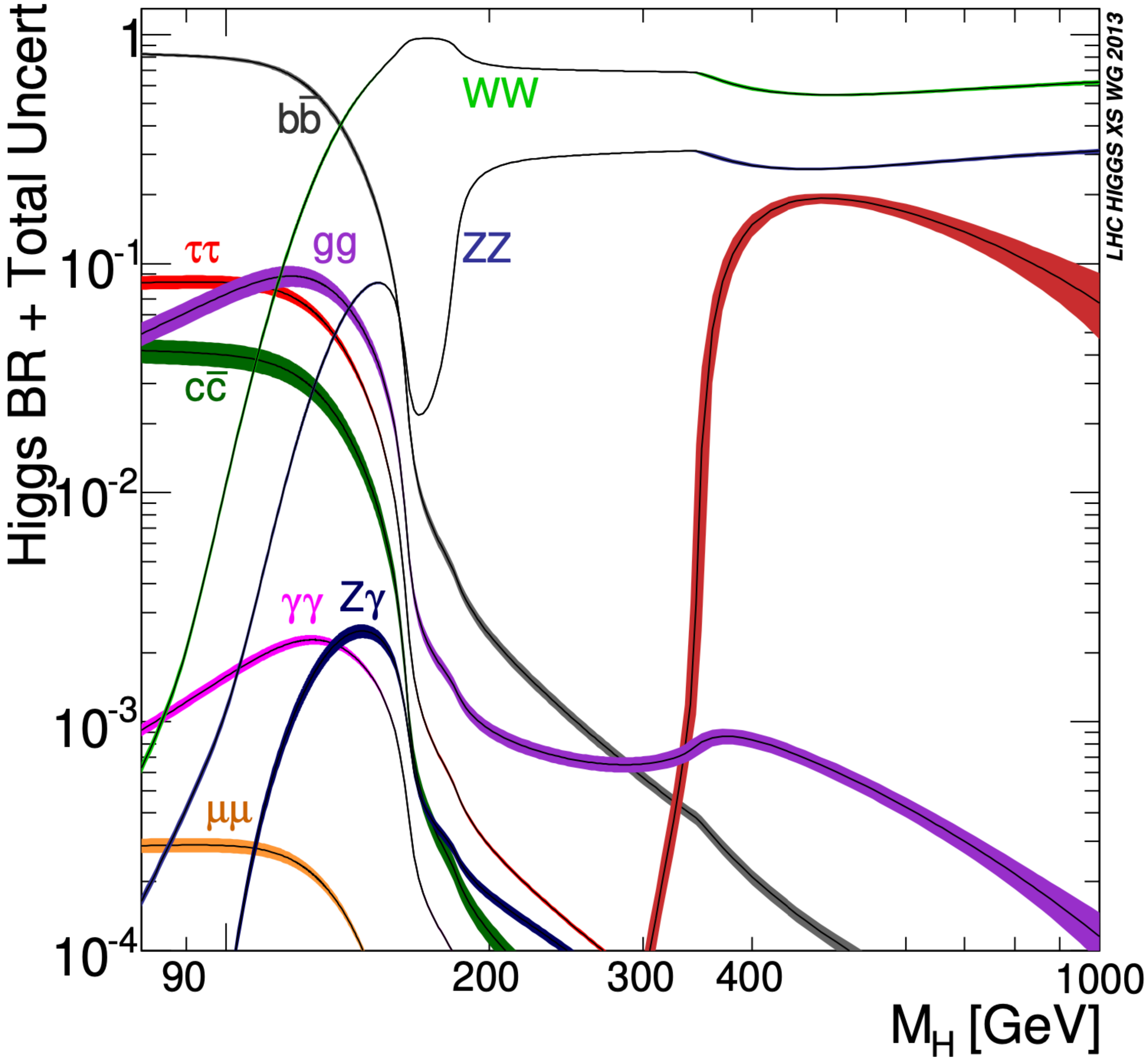
- Experimental provide best fit values on mu-values (signal strength parameters):

$$\mu = \frac{\sigma_{\text{prod}} \times BR(H \to XX)}{(\sigma_{\text{prod}} \times BR(H \to XX))_{\text{SM}}}$$

For extraction of coupling values, a Lagrangian parametrizing possible new physics couplings needs to be defined ~> kappa framework, SMEFT/HEFT approach

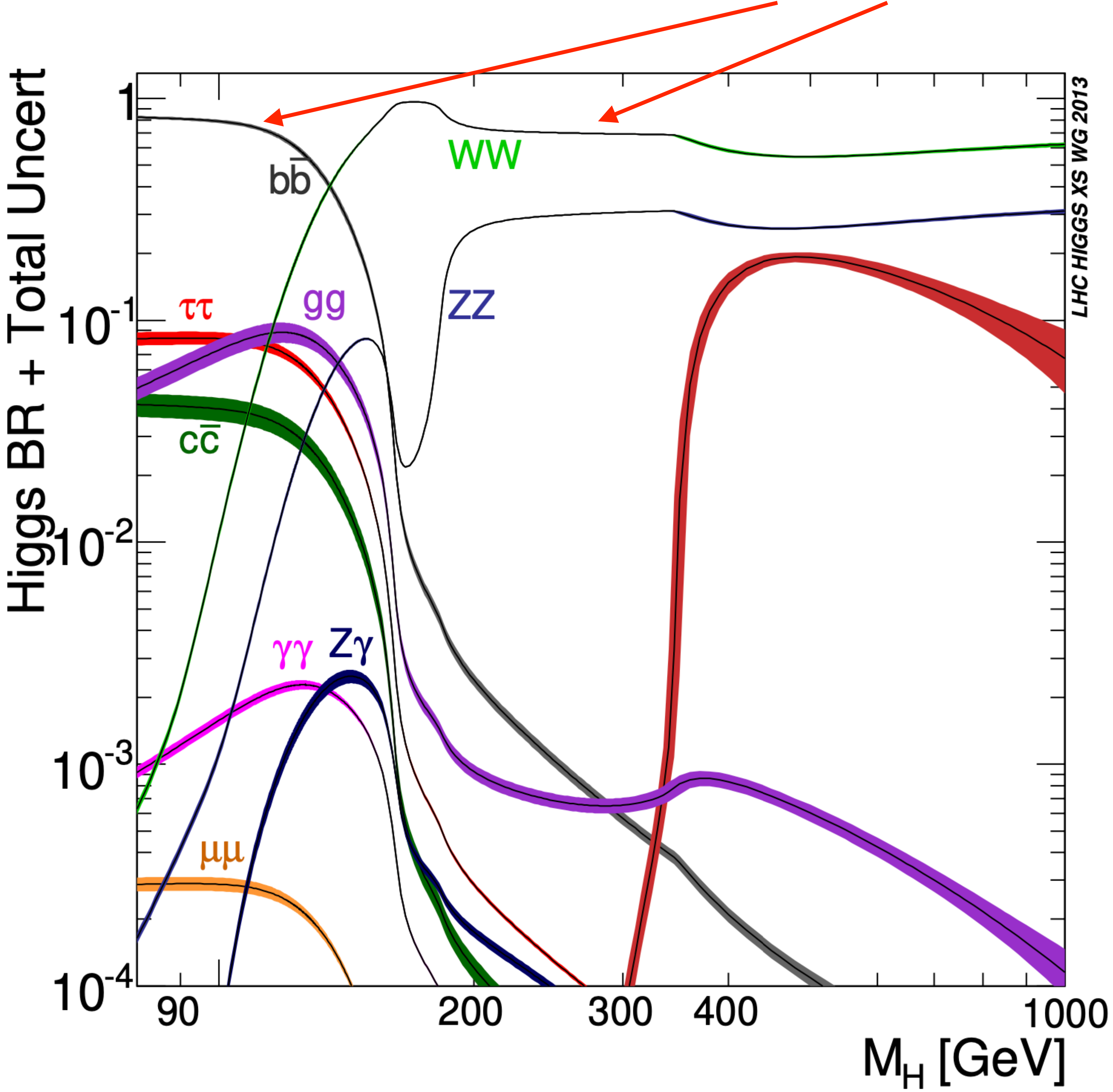
Higgs Boson Decays

- **Higgs mechanism:** Higgs couplings to SM particles ~ to masses of the particles



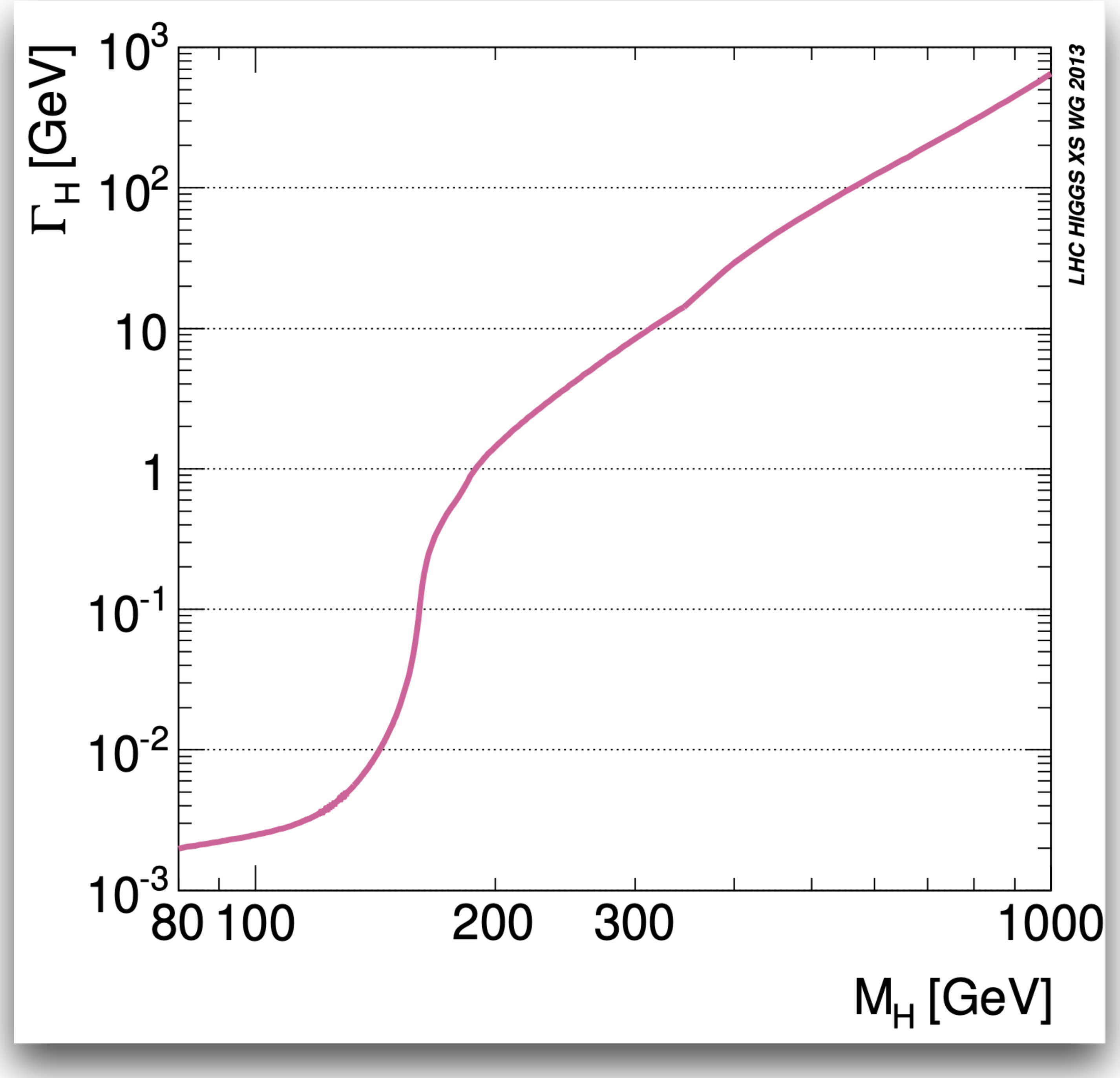
Higgs Boson Decays

- **Higgs mechanism:** Higgs couplings to SM particles ~ to masses of the particles



Higgs Total Width

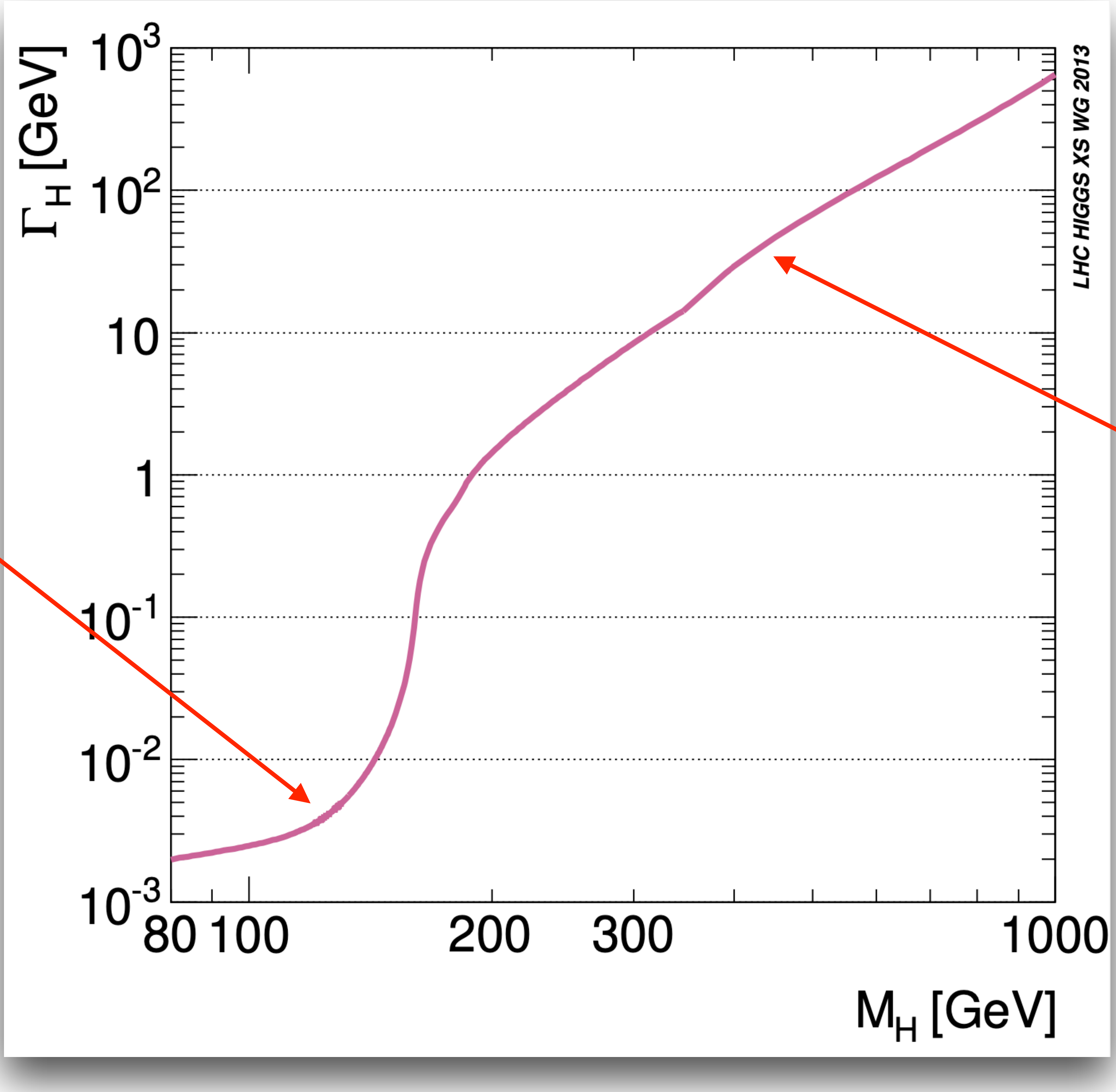
- Higgs mechanism: Higgs couplings to SM particles ~ to masses of the particles



Higgs Total Width

- **Higgs mechanism:** Higgs couplings to SM particles ~ to masses of the particles

$M_H = 125.09$ GeV
$\Gamma_H = 4.4$ MeV



$\Gamma(H \to VV) \sim M_H^3$

Decays: Precision & Uncertainties

Partial Width	**QCD**	**Electroweak**	**Total**	**On-shell Higgs**
$H \to b\bar{b}/c\bar{c}$	~0.2%	~0.5%	~0.5%	N^{4}LO/NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		~0.5%	~0.5%	NLO
$H \to gg$	~3%	~1%	~3%	N^{3}LO approx/NLO
$H \to \gamma\gamma$	<1%	<1%	~1%	NLO/NLO
$H \to Z\gamma$	<1%	~5%	~5%	(N)LO/NLO
$H \to WW/ZZ \to 4f$	~0.5%	~0.5%	~0.5%	(N)NLO

✏ QCD: variation $\mu_R = [1/2, 2]\mu_0$
electroweak: missing higher-order corrs. estimated from known structure @NLO

✏ parametric uncertainties: $m_t = 172{,}5 \pm 1$GeV , $\alpha_s(M_Z) = 0.118 \pm 0.0015$,
$m_b(m_b) = 4.18 \pm 0.03$ GeV , $m_c(3$ GeV$) = 0.986 \pm 0.025$ GeV ,
different uncertainties added quadratically for each channel

Decays: Precision & Uncertainties

Partial Width	QCD	Electroweak	Total	On-shell Higgs
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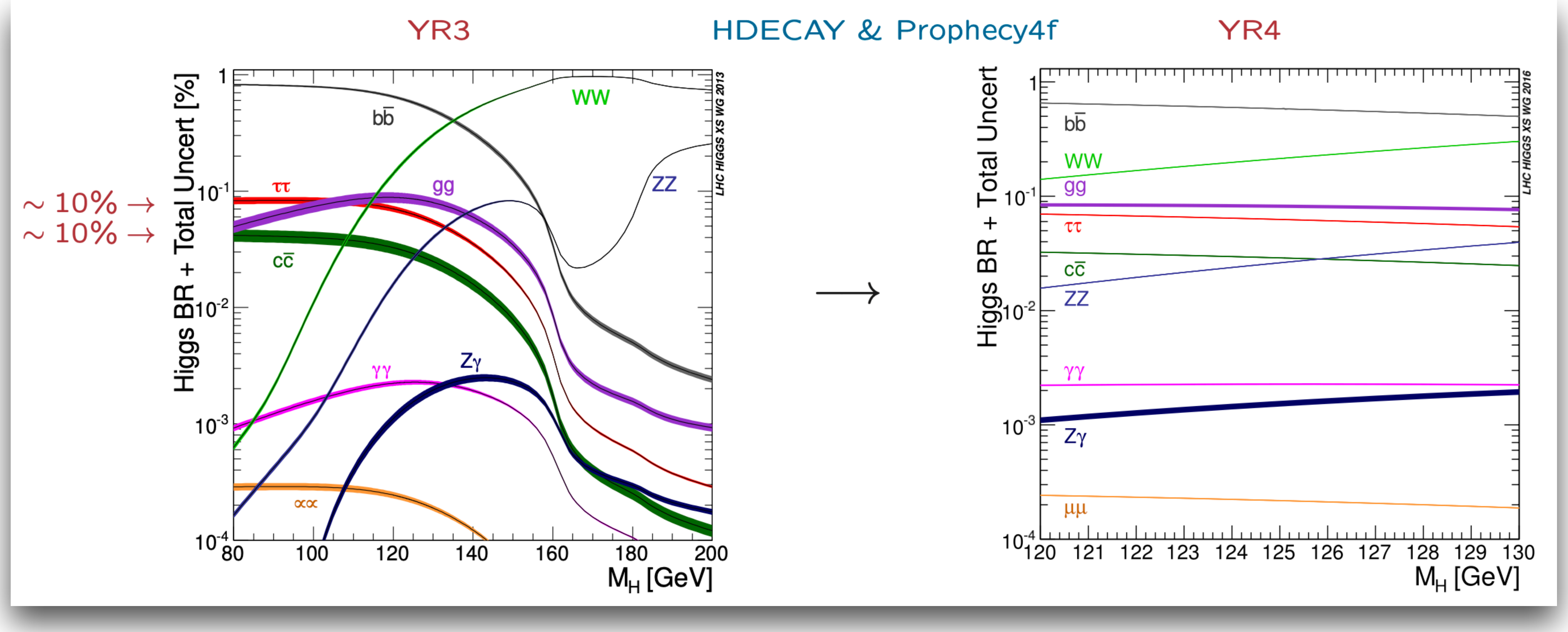
$H \to Z\gamma$	<1%	~5%	~5%	(N)LO/NLO
$H \to WW/ZZ \to 4f$	~0.5%	~0.5%	~0.5%	(N)NLO

✏ total uncertainties: parametric and theoretical uncertainties added linearly

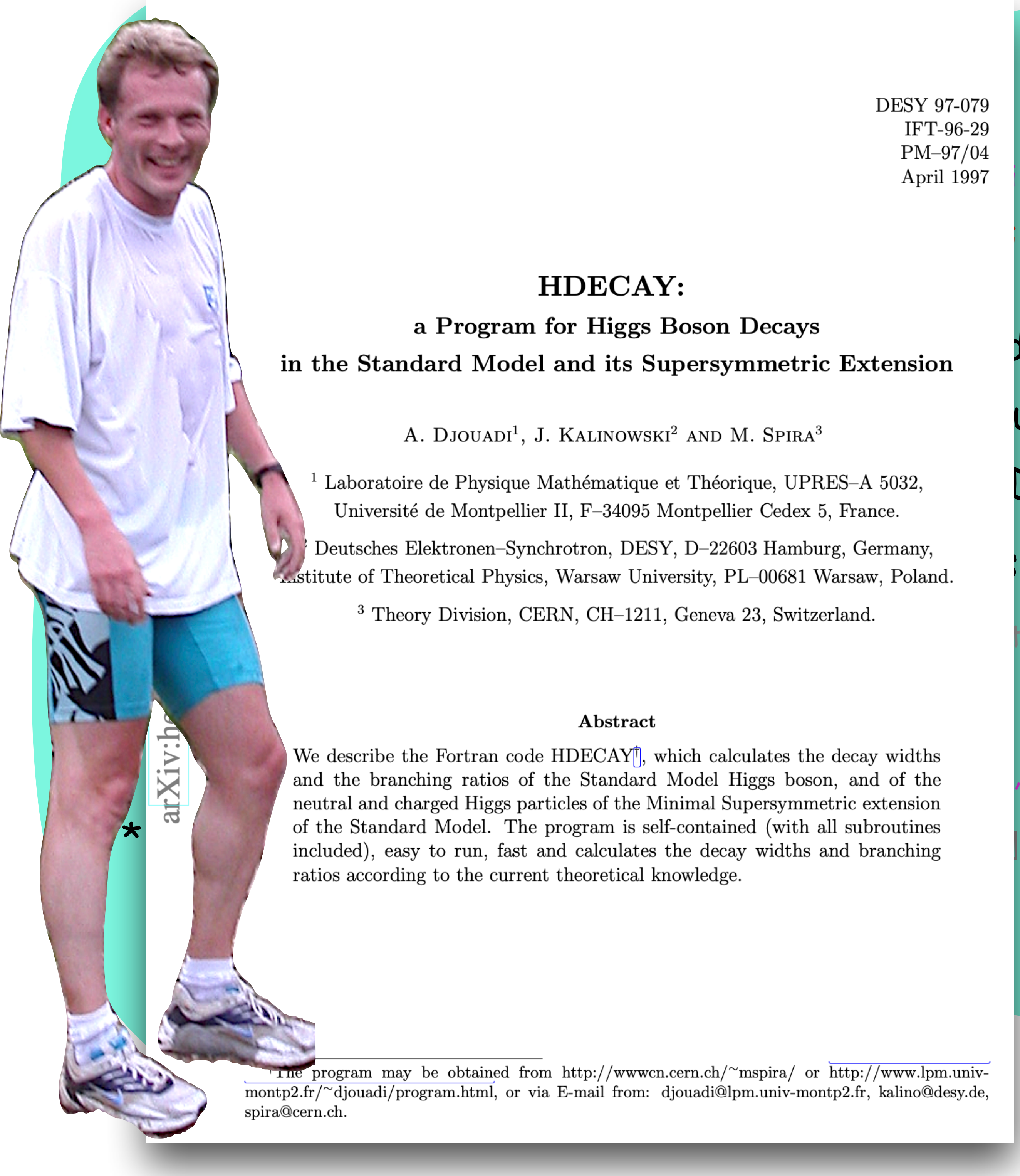
[Denner,Heinemeyer,Puljak,Rebuzzi,Spira,'11]

Improved Uncertainties



- refinements: input parameters
- full NLO electroweak corrections to $H \to f\bar{f}$
- NLO quark-mass effects in $H \to gg$

The Code HDECAY



DESY 97-079
IFT-96-29
PM–97/04
April 1997

HDECAY:
a Program for Higgs Boson Decays in the Standard Model and its Supersymmetric Extension

A. Djouadi[1], J. Kalinowski[2] and M. Spira[3]

[1] Laboratoire de Physique Mathématique et Théorique, UPRES–A 5032, Université de Montpellier II, F–34095 Montpellier Cedex 5, France.
Deutsches Elektronen–Synchrotron, DESY, D–22603 Hamburg, Germany,
nstitute of Theoretical Physics, Warsaw University, PL–00681 Warsaw, Poland.
[3] Theory Division, CERN, CH–1211, Geneva 23, Switzerland.

Abstract

We describe the Fortran code HDECAY[†], which calculates the decay widths and the branching ratios of the Standard Model Higgs boson, and of the neutral and charged Higgs particles of the Minimal Supersymmetric extension of the Standard Model. The program is self-contained (with all subroutines included), easy to run, fast and calculates the decay widths and branching ratios according to the current theoretical knowledge.

The program may be obtained from http://wwwcn.cern.ch/~mspira/ or http://www.lpm.univ-montp2.fr/~djouadi/program.html, or via E-mail from: djouadi@lpm.univ-montp2.fr, kalino@desy.de, spira@cern.ch.

HDECAY: Twenty$_{++}$ Years After

Abdelhak Djouadi[a], Jan Kalinowski*[b,c], Margarete Mühlleitner[d], and Michael Spira[e]

[a] Laboratoire de Physique Théorique, CNRS – UMR 8627, Université Paris-Sud XI, F-91405 Orsay Cedex, France
[b] Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL-02-093 Warsaw, Poland
[c] CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland
[d] Institute for Theoretical Physics, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany
[e] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

Abstract

The program `HDECAY` determines the partial decay widths and branching ratios of the Higgs bosons within the Standard Model with three and four generations of fermions, including the case when the Higgs couplings are rescaled, a general two–Higgs doublet model where the Higgs sector is extended and incorporates five physical states and its most studied incar tion, the minimal supersymmetric Standard Model (MSSM). The progr addresses all decay channels including the dominant higher-order effects s as radiative corrections and multi-body channels. Since the first launc the program, more than twenty years ago, important aspects and new ing dients have been incorporated. In this update of the program descripti some of the developments are summarized while others are discussed in detail.

Keywords: Higgs boson; decay widths; decay branching ratio Model; two-Higgs doublets; supersymmetric extensions;

Preprint CERN-TH-2017-262
LPT-Orsay-18-04
KA-TP-03-2018
PSI-PR-18-02

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*Corresponding author. *E-mail address: Jan.Kalinowski@fuw.edu.pl*

Preprint submitted to Computer Physics Communications Jan

The Code HDECAY

- HDECAY [Djouadi,Kalinowski,Spira,´97;,Djouadi,Kalinowski,MM,Spira,´18]:

  SM, MSSM, 2HDM decay widths and branching ratios

  * state-of-the-art HO QCD corrections in qq decays; full NLO mass effects & NNLO in heavy-top-limit to gluonic decays; full NLO mass effects in photonic decays; SUSY-QCD to decays into squarks; resummed SUSY-QCD & SUSY-EW corrections through $\Delta_{b,}, \Delta_s, \Delta_\tau$ effects, also in H^+ decays; off-shell effects in decays into heavy quarks & WW/ZZ; SM: approximated EW to H->W*W*/Z*Z*->4f (within 1% of [Bredenstein,Denner,Dittmaier,Weber] ,[Boselli eal]), full EW to gluonic decay through grid [Actis,Passarino,Sturm,Uccirati];
  * for details on 2HDM decays, see [Harlander,MM,Rathsman,Spira,Stal'13]
  * Link to FeynHiggsFast [Heinemeyer,Hollik,Weiglein]

SUSY HDECAY variants

- SUSY-HIT [Djouadi,MM,Spira]

  Links to HDECAY to SuSpect [Djouadi,Kneur,Moultaka,Ughetto,Zerwas] and SDECAY [MM,Djouadi,Mambrini] =>

  to also calculate MSSM SUSY particle decays

- NMSSMCALC [Baglio,Gröber,MM,Nhung,Rzehak,Spira,Streicher,Walz,'13]

  [Baglio,Borschensky,Dao,Gabelmann,Gröber,Krause,Le,MM,Rzehak,Spira,Streicher,Walz,'24]

  CP-conserving and CP-violation NMSSM

  * Calculator of the NMSSM Higgs boson masses (now up to $\mathcal{O}((\alpha_t + \alpha_\lambda + \alpha_\kappa)^2 + \alpha_t\alpha_s)$,

  including also high-scale scenario; loop-corrected Higgs self-couplings up to $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$)

  * NMSSM Higgs boson decays including the state-of-the-art higher-order corrections

Non-SUSY HDECAY Variants

Extensions of HDECAY to BSM Higgs sectors - QCD corrections can be transferred:

- sHDECAY [Costa,MM,Sampaio,Santos,'15]: real and complex singlet extension of the SM (RxSM, CxSM), both in dark matter and broken phase
- C2HDM_HDECAY [Fontes,MM,Romao,Santos,Silva,Wittbrodt] complex 2-Higgs-Doublet Model
- 2HDECAY [Krause,MM,Spira,1810.00768] EW corrections to 2HDM decays including state-of-the-art QCD corrections in different (gauge-independent) renormalization schemes [Krause,Lorenz,MM,Santos,Ziesche,1605.04853] including those of [Altenkamp,Dittmaier,Rzehak,1704.02645;Denner,Dittmaier,Lang,1808.03466]

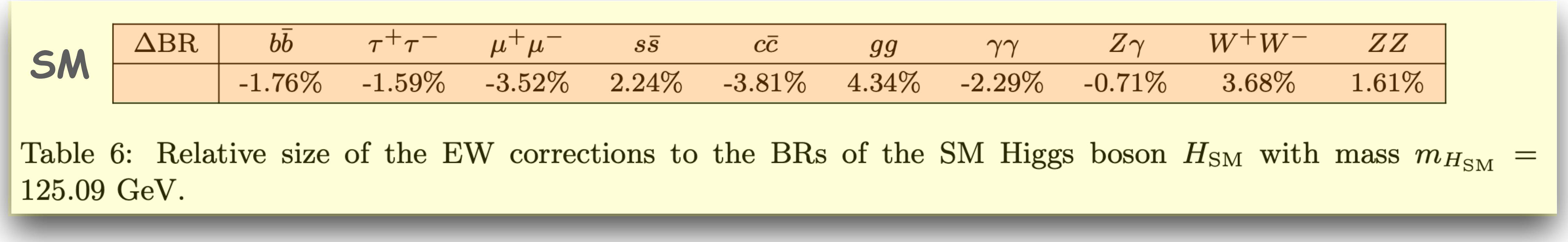
- N2HDECAY [MM,Sampaio,Santos,Wittbrodt], N2HDM decays (doublet+singlet extension), in different phases (broken, dark singlet, dark doublet, dark singlet+doublet) [Engeln,MM,Wittbrodt]
- ewN2HDECAY [MM,Krause] EW corrections to 2HDM decays including state-of-the-art QCD corrections in different (gauge-independent) renormalization schemes [Krause,Lopez-Val,MM,Santos,1708.01578]
- eHDECAY [Contino,Ghezzi,Grojean,MM,Spira] EFT in linear and non-linear realization, composite Higgs (MCHM4, MCHM5), inclusion of QCD corrections, EW corrections to SM part only
- anyHDECAY [Wittbrodt] modern C++ interface to the HDECAY variants for scalar extensions

Impact of EW HO Corrections to the 2HDM BR's

- **Fortran code 2HDECAY:** [Krause,MM,Spira,'18]

  partial decay widths and branching ratios at one-loop EW and including the state-of-the-art HO QCD corrections; includes tree-level off-shell decays and QCD corrections to the loop-induced decays; offers choice among renormalization schemes w/ automatic parameter conversion

[Krause,MM,'19]



SM

ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Table 6: Relative size of the EW corrections to the BRs of the SM Higgs boson $H_{\rm SM}$ with mass $m_{H_{\rm SM}} =$ 125.09 GeV.

- **Based on Fortran code HDECAY:** [Djouadi,Kalinowski,Spira,'97; Djouadi,Kalinowski,MM,Spira,'18]

  computation of LO decay widths, off-shell decays and loop-induced 2HDM decays including state-of-the-art QCD corrections

Impact of EW HO Corrections to the 2HDM BR's

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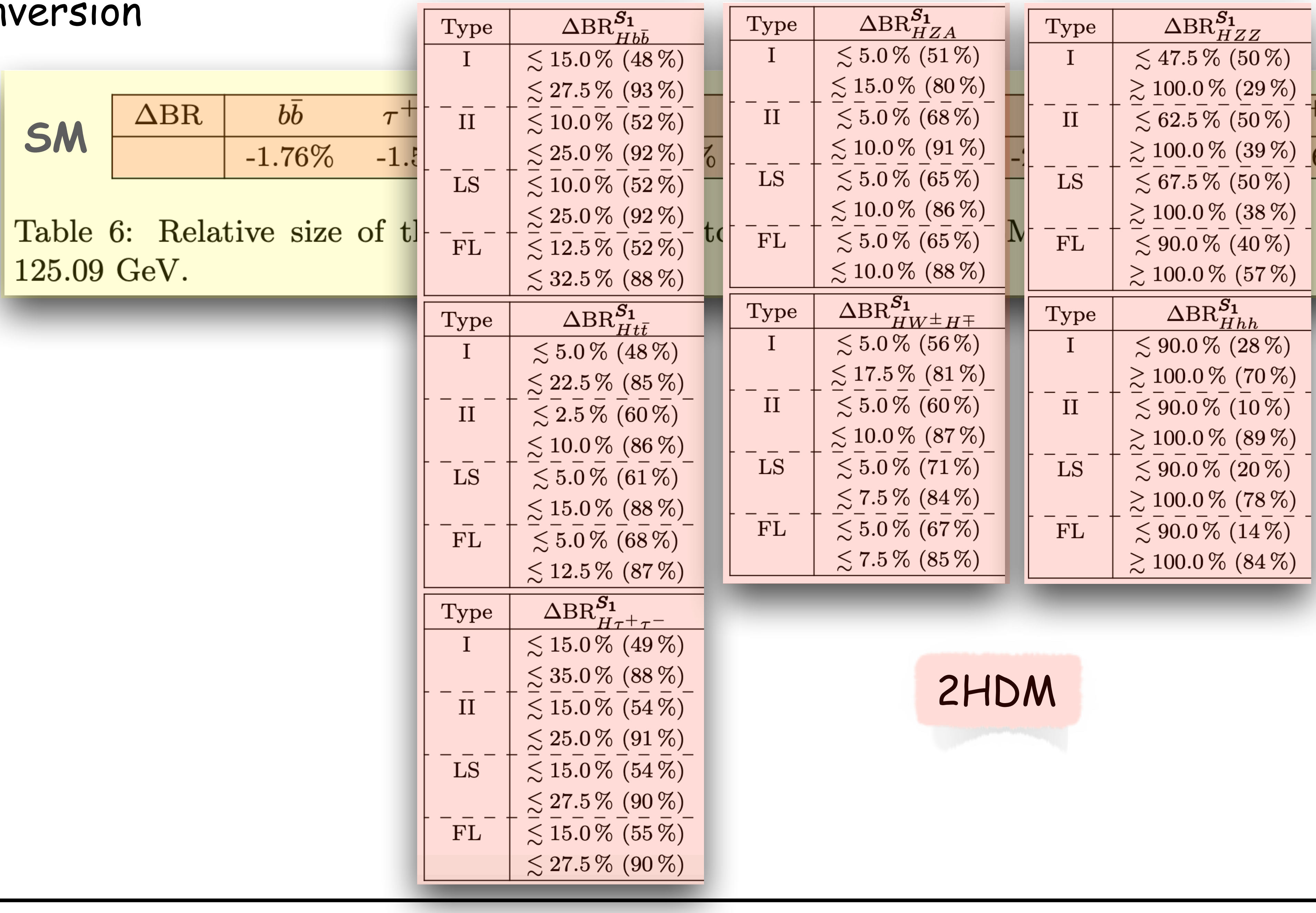
partial decay widths and branching ratios at one-loop EW and including the state-of-the-art HO QCD corrections; includes tree-level off-shell decays and QCD corrections to the loop-induced decays; offers choice among renormalization schemes w/ automatic parameter conversion

[Krause,MM,'19]



SM

ΔBR	$b\bar{b}$	τ^+	$^+W^-$	ZZ
	-1.76%	-1.5	68%	1.61%

Table 6: Relative size of tl tc M with mass $m_{H_{\rm SM}}$ = 125.09 GeV.

Type	$\Delta\mathrm{BR}^{S_1}_{Hb\bar{b}}$
I	$\lesssim$ 15.0 % (48 %)
	$\lesssim$ 27.5 % (93 %)
II	$\lesssim$ 10.0 % (52 %)
	$\lesssim$ 25.0 % (92 %)
LS	$\lesssim$ 10.0 % (52 %)
	$\lesssim$ 25.0 % (92 %)
FL	$\lesssim$ 12.5 % (52 %)
	$\lesssim$ 32.5 % (88 %)

Type	$\Delta\mathrm{BR}^{S_1}_{Ht\bar{t}}$
I	$\lesssim$ 5.0 % (48 %)
	$\lesssim$ 22.5 % (85 %)
II	$\lesssim$ 2.5 % (60 %)
	$\lesssim$ 10.0 % (86 %)
LS	$\lesssim$ 5.0 % (61 %)
	$\lesssim$ 15.0 % (88 %)
FL	$\lesssim$ 5.0 % (68 %)
	$\lesssim$ 12.5 % (87 %)

Type	$\Delta\mathrm{BR}^{S_1}_{H\tau^+\tau^-}$
I	$\lesssim$ 15.0 % (49 %)
	$\lesssim$ 35.0 % (88 %)
II	$\lesssim$ 15.0 % (54 %)
	$\lesssim$ 25.0 % (91 %)
LS	$\lesssim$ 15.0 % (54 %)
	$\lesssim$ 27.5 % (90 %)
FL	$\lesssim$ 15.0 % (55 %)
	$\lesssim$ 27.5 % (90 %)

Type	$\Delta\mathrm{BR}^{S_1}_{HZA}$
I	$\lesssim$ 5.0 % (51 %)
	$\lesssim$ 15.0 % (80 %)
II	$\lesssim$ 5.0 % (68 %)
	$\lesssim$ 10.0 % (91 %)
LS	$\lesssim$ 5.0 % (65 %)
	$\lesssim$ 10.0 % (86 %)
FL	$\lesssim$ 5.0 % (65 %)
	$\lesssim$ 10.0 % (88 %)

Type	$\Delta\mathrm{BR}^{S_1}_{HW^\pm H^\mp}$
I	$\lesssim$ 5.0 % (56 %)
	$\lesssim$ 17.5 % (81 %)
II	$\lesssim$ 5.0 % (60 %)
	$\lesssim$ 10.0 % (87 %)
LS	$\lesssim$ 5.0 % (71 %)
	$\lesssim$ 7.5 % (84 %)
FL	$\lesssim$ 5.0 % (67 %)
	$\lesssim$ 7.5 % (85 %)

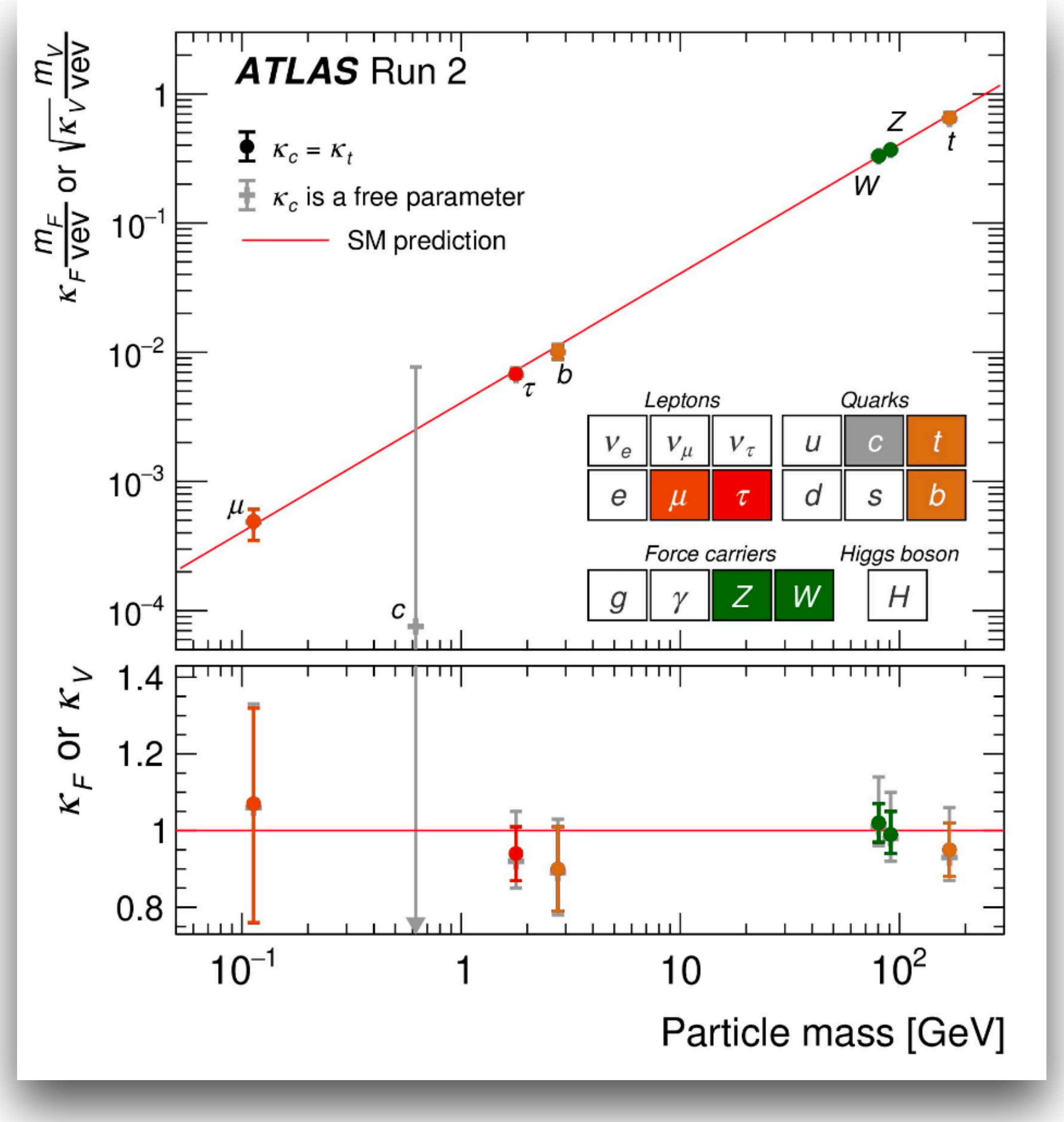
Type	$\Delta\mathrm{BR}^{S_1}_{HZZ}$
I	$\lesssim$ 47.5 % (50 %)
	$\gtrsim$ 100.0 % (29 %)
II	$\lesssim$ 62.5 % (50 %)
	$\gtrsim$ 100.0 % (39 %)
LS	$\lesssim$ 67.5 % (50 %)
	$\gtrsim$ 100.0 % (38 %)
FL	$\lesssim$ 90.0 % (40 %)
	$\gtrsim$ 100.0 % (57 %)

Type	$\Delta\mathrm{BR}^{S_1}_{Hhh}$
I	$\lesssim$ 90.0 % (28 %)
	$\gtrsim$ 100.0 % (70 %)
II	$\lesssim$ 90.0 % (10 %)
	$\gtrsim$ 100.0 % (89 %)
LS	$\lesssim$ 90.0 % (20 %)
	$\gtrsim$ 100.0 % (78 %)
FL	$\lesssim$ 90.0 % (14 %)
	$\gtrsim$ 100.0 % (84 %)

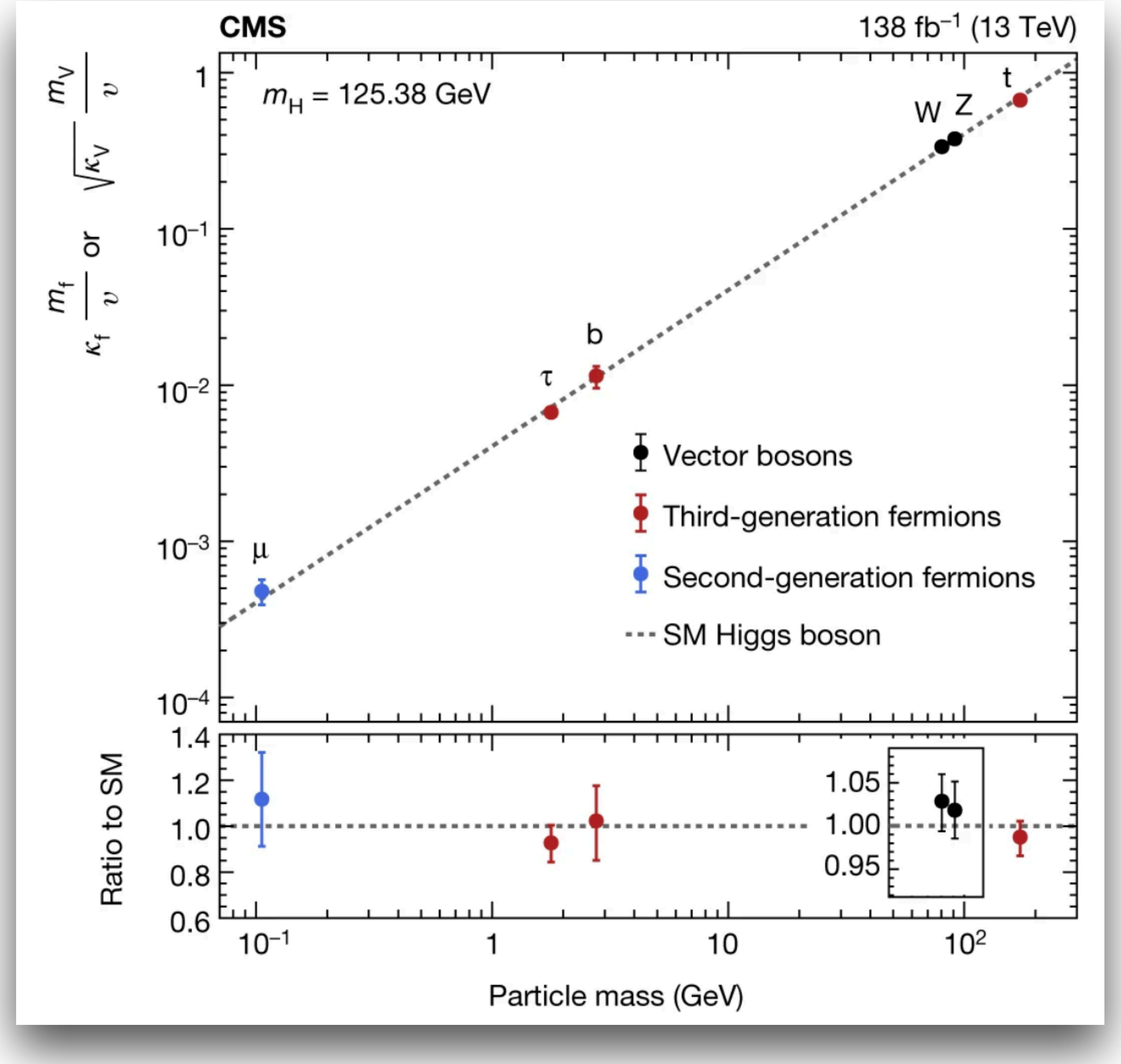
2HDM

Experimental Results: Couplings

[ATLAS, Nature 607 (2022) 52]



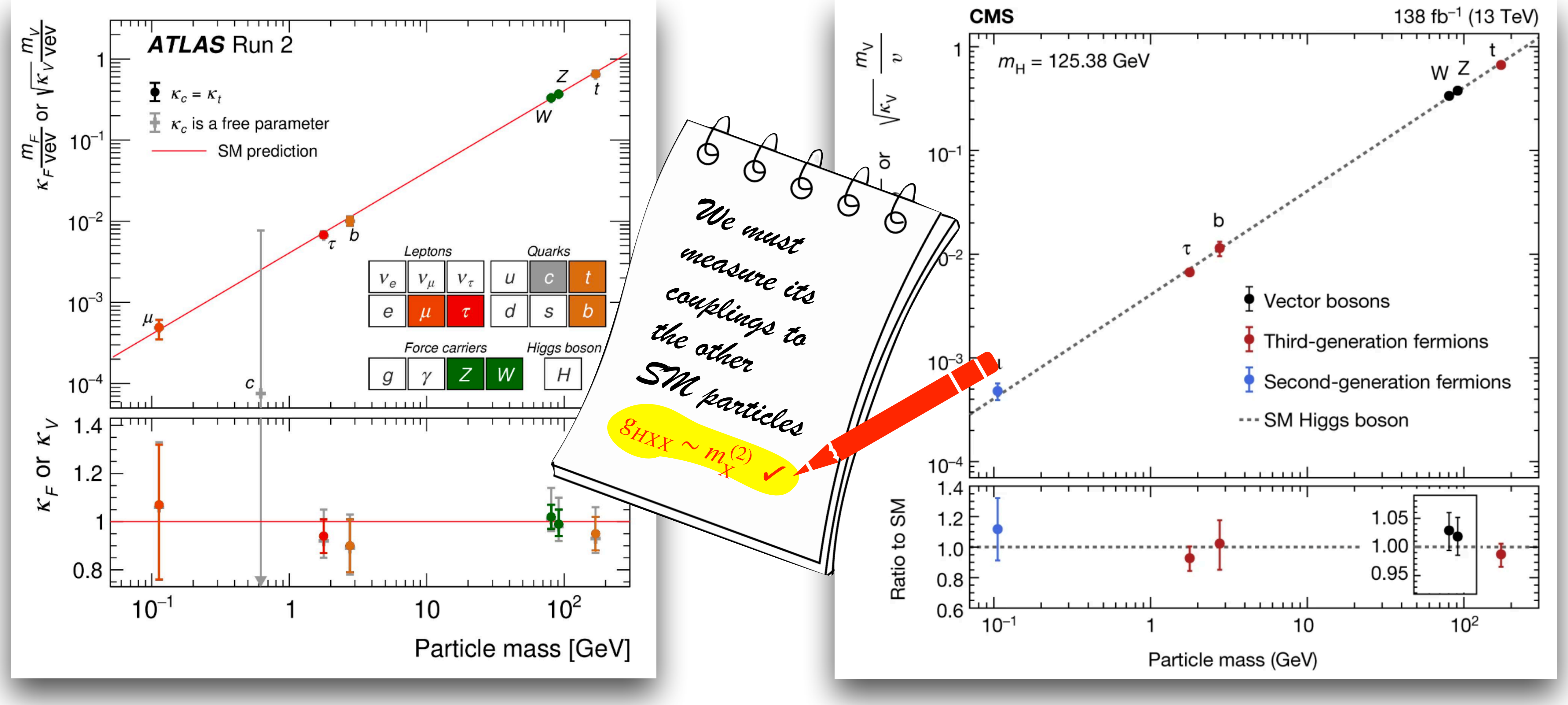
[CMS, Nature 607 (2022) 60]



Experimental Results: Couplings

[ATLAS, Nature 607 (2022) 52]

[CMS, Nature 607 (2022) 60]



We must measure its couplings to the other SM particles

$g_{HXX} \sim m_X^{(2)}$ ✓

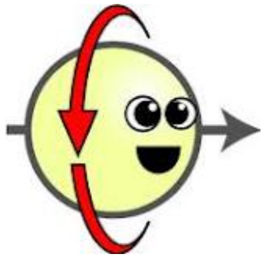
Higgs Spin and CP Quantum Numbers

❖ Quantum numbers of the Higgs boson: J^{PC}

J spin

P parity

C charge conjugation



✻ γγ→H or H→γγ ~> J ≠ 1

❖ CP properties:

✻ SM Higgs $J^{CP} = 0^{++}$; beyond the SM (BSM)

- more than one spin-0 particle possible
- CP-even, CP-odd, CP-violating Higgs states

✻ Study of CP properties ~> insights in beyond-SM (BSM) physics

✻ existing and future colliders:
establish CP properties, determine amount of CP-mixing

Determination of Higgs Quantum Numbers

- **Spin and CP quantum numbers: threshold effects and angular correlations in**

- angular correlations in production: Hjj in vector boson fusion,

  Plehn,Rainwater,Zeppenfeld;
  Hankele,Klämke,Zeppenfeld

  gluon gluon fusion

  Odagiri; Klamke,Zeppenfeld;
  Campanario eal;
  Del Duca eal; Andersen eal

- Higgs decays into W and Z pairs

  Dell'Aquila,Nelson; Barger eal; Kramer,Kühn,Stong,Zerwas;
  Skjold,Osland; Choi,Kalinowski,Liao,Zerwas
  Miller,MMM,Zerwas;Bluj; Dova eal;
  Buszello,Fleck,Marquard,van der Bij;
  Gao eal:Englert eal: Sancti eal

  observables sensitive to CP-violation

  Chang eal; Skjold,Osland; Choi eal; Niezurawski,Zarnecki,Krawczyk;
  Godbole,Kraml;Rindani,Singh Godbole,Miller,MMM; De Rujula eal

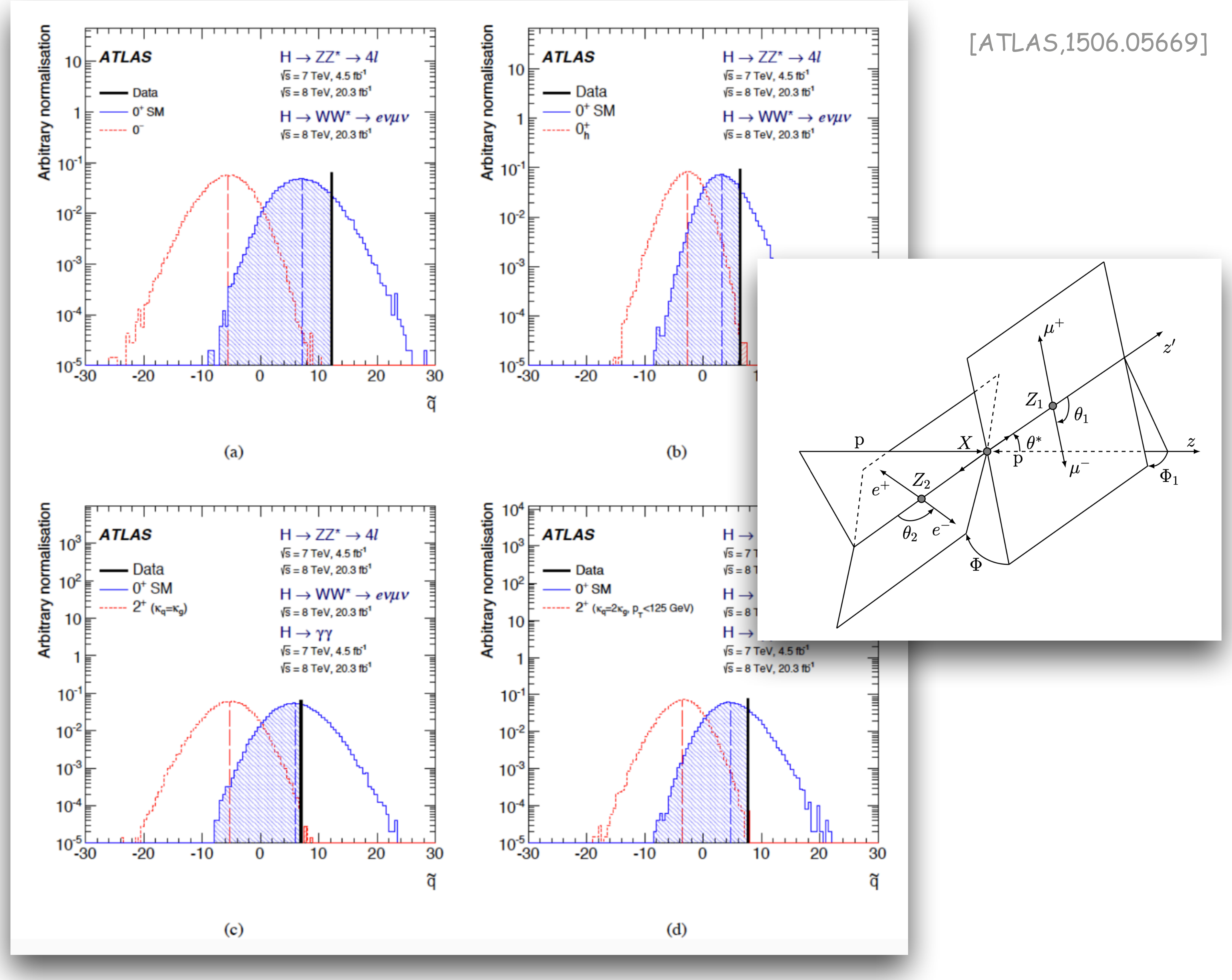
- $\gamma\gamma$ collisions

  Grzadkowski,Gunion; Asakawa,Choi,Hagiwara;
  Godbole,Rindani,Singh; Godbole,Kraml,Rindani,Singh

- Higgs-radiation & VBF at e^+e^- colliders, also Higgs-ZZ coupling

  Godbole,Roy; Hagiwara,Stong; Gounaris,Renard; Rao,Rindani
  Miller,Choi,Eberle,MMM,Zerwas; Skjold,Osland; Hagiwara eal;
  Han,Jiang; Biswal, Godbole, Singh; Biswal, Choudhury, Godbole eal

Experiment: Hypothesis Test



[ATLAS,1506.05669]

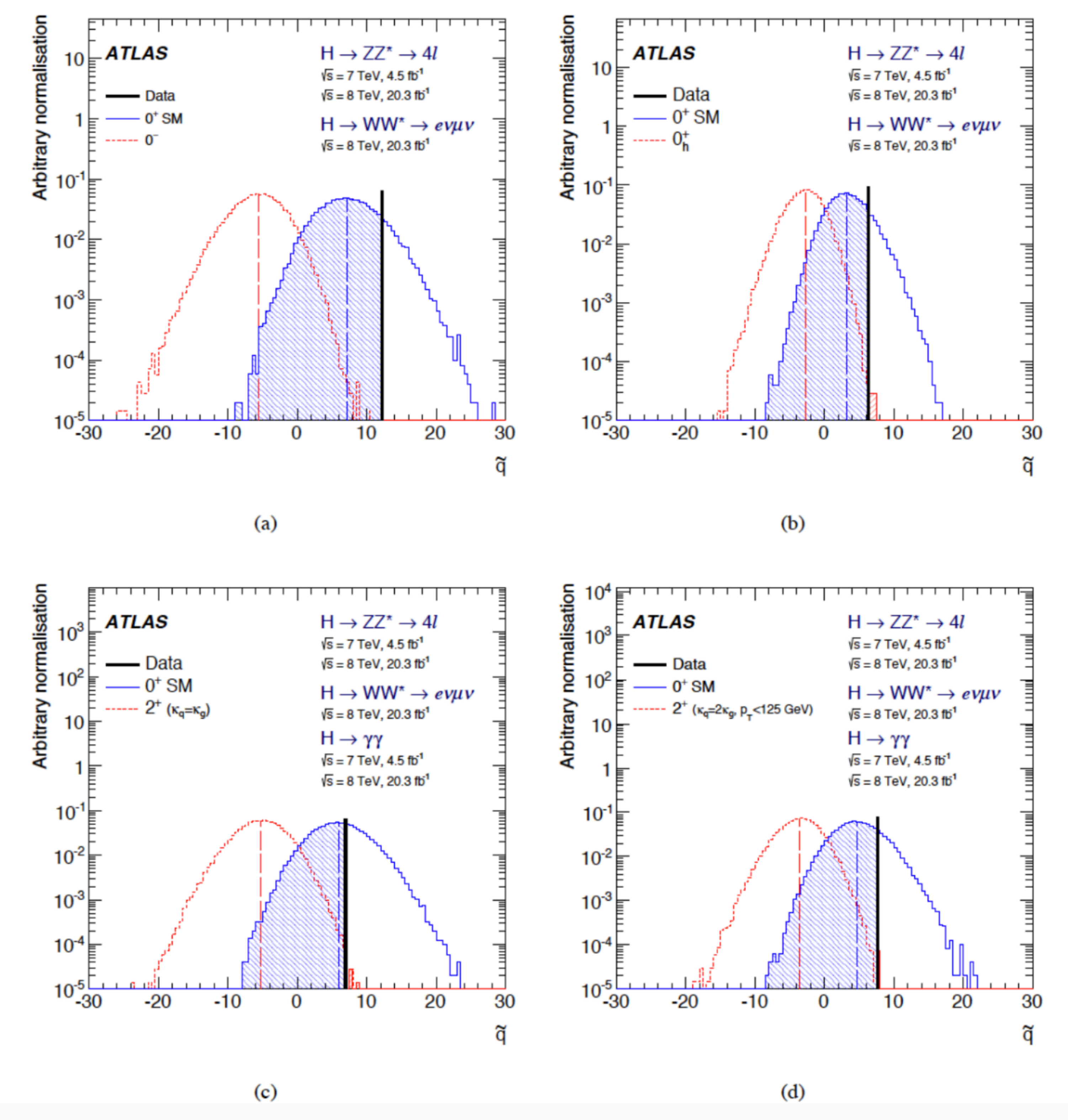
Experiment: Hypothesis Test

- distributions of the test statistic to distinguish between two spin-parity hypotheses

- observed values: vertical solid lines

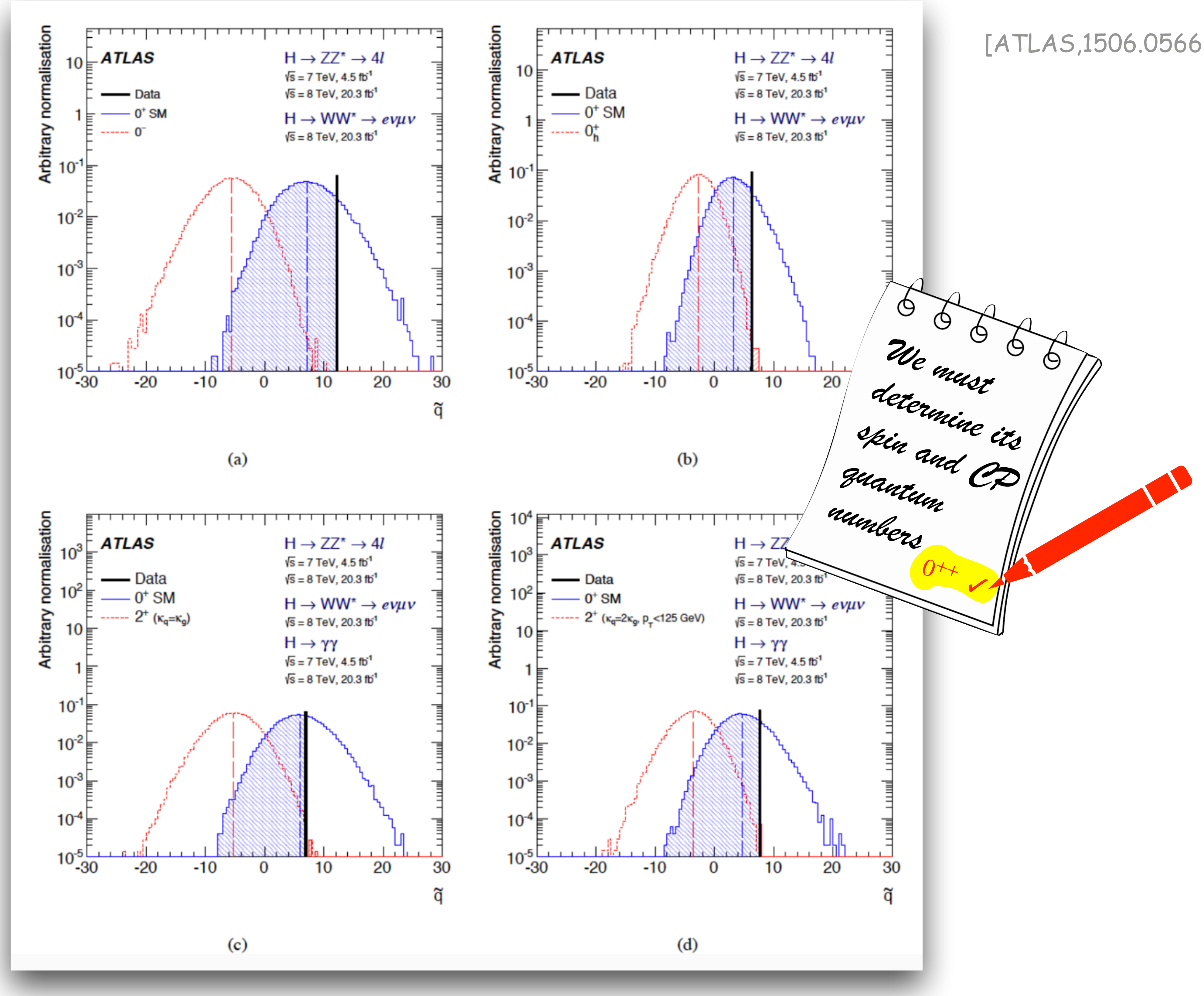
- expected medians: dashed lines

- shaded areas: integrals of the exp. distributions used to compute the p-values for hypothesis rejection



[ATLAS,1506.05669]

Experiment: Hypothesis Test

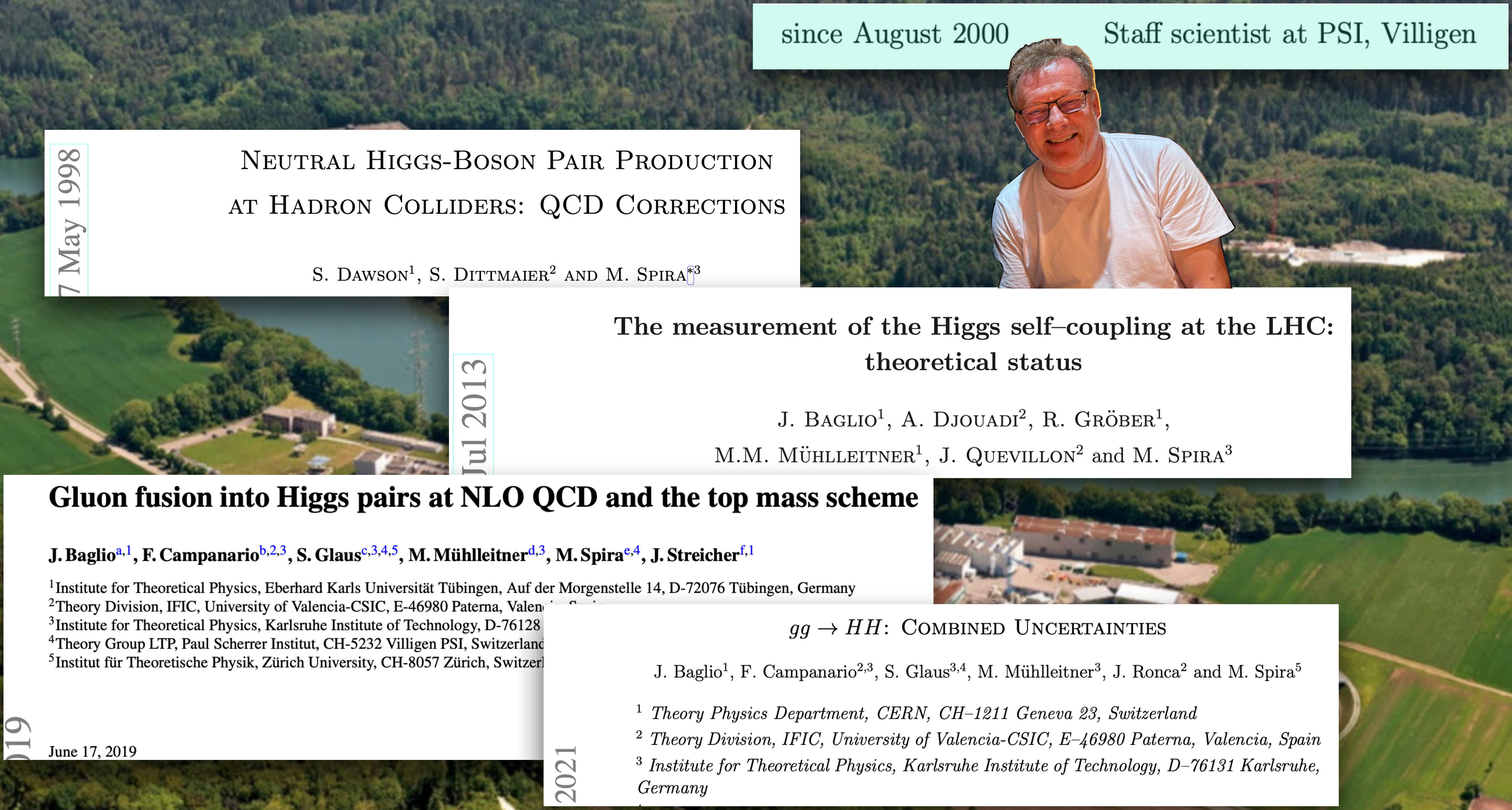


[ATLAS,1506.05669]

We must determine its spin and CP quantum numbers

0^{++} ✓

Measuring EWSB



since August 2000 Staff scientist at PSI, Villigen

7 May 1998

NEUTRAL HIGGS-BOSON PAIR PRODUCTION AT HADRON COLLIDERS: QCD CORRECTIONS

S. DAWSON[1], S. DITTMAIER[2] AND M. SPIRA[*3]

Jul 2013

The measurement of the Higgs self–coupling at the LHC: theoretical status

J. BAGLIO[1], A. DJOUADI[2], R. GRÖBER[1],
M.M. MÜHLLEITNER[1], J. QUEVILLON[2] and M. SPIRA[3]

Gluon fusion into Higgs pairs at NLO QCD and the top mass scheme

J. Baglio[a,1], F. Campanario[b,2,3], S. Glaus[c,3,4,5], M. Mühlleitner[d,3], M. Spira[e,4], J. Streicher[f,1]

[1]Institute for Theoretical Physics, Eberhard Karls Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
[2]Theory Division, IFIC, University of Valencia-CSIC, E-46980 Paterna, Valen
[3]Institute for Theoretical Physics, Karlsruhe Institute of Technology, D-76128
[4]Theory Group LTP, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[5]Institut für Theoretische Physik, Zürich University, CH-8057 Zürich, Switzer

June 17, 2019

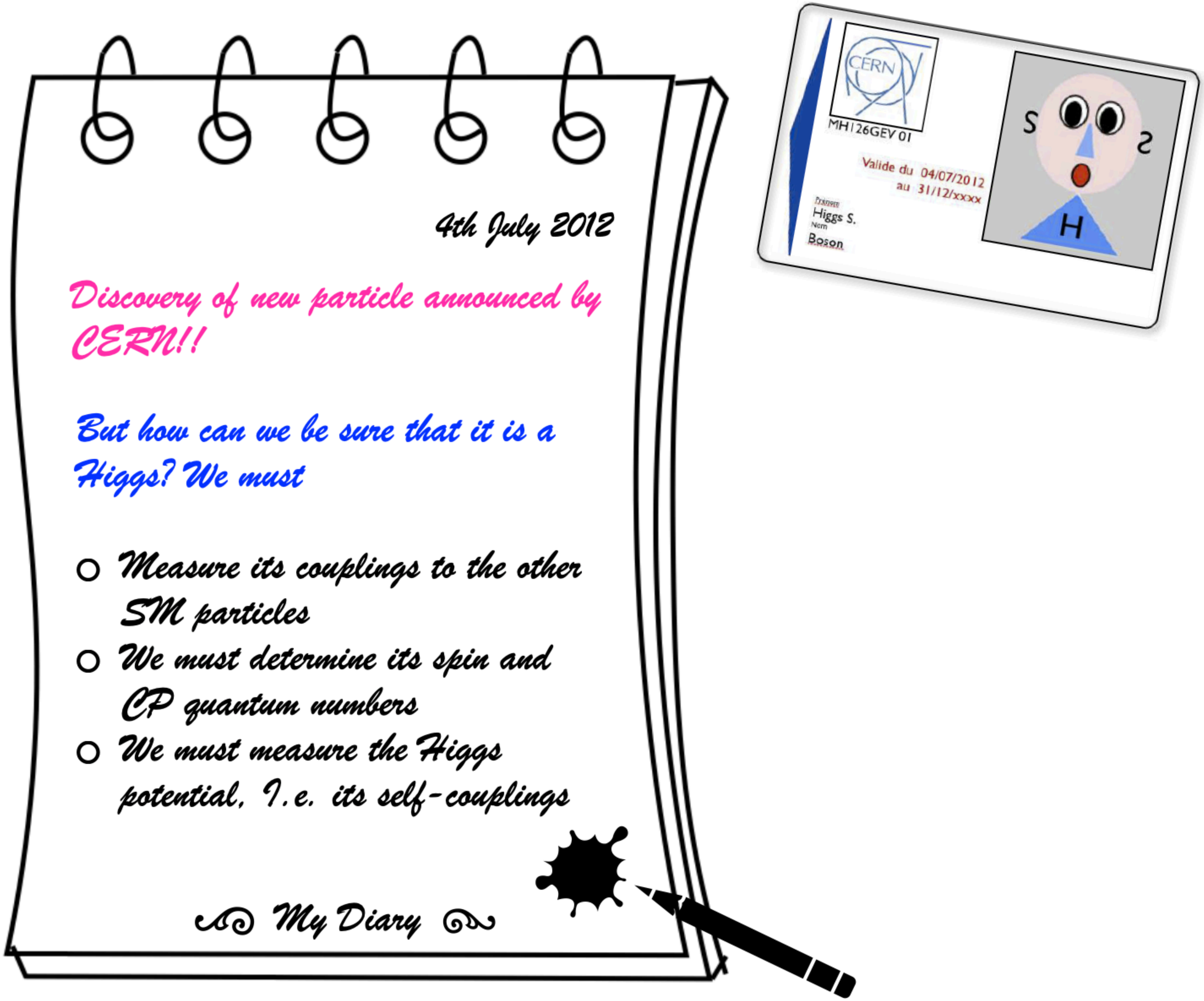
2021

$gg \to HH$: COMBINED UNCERTAINTIES

J. Baglio[1], F. Campanario[2,3], S. Glaus[3,4], M. Mühlleitner[3], J. Ronca[2] and M. Spira[5]

[1] *Theory Physics Department, CERN, CH–1211 Geneva 23, Switzerland*
[2] *Theory Division, IFIC, University of Valencia-CSIC, E–46980 Paterna, Valencia, Spain*
[3] *Institute for Theoretical Physics, Karlsruhe Institute of Technology, D–76131 Karlsruhe, Germany*

Establishing the Higgs Mechanism



4th July 2012

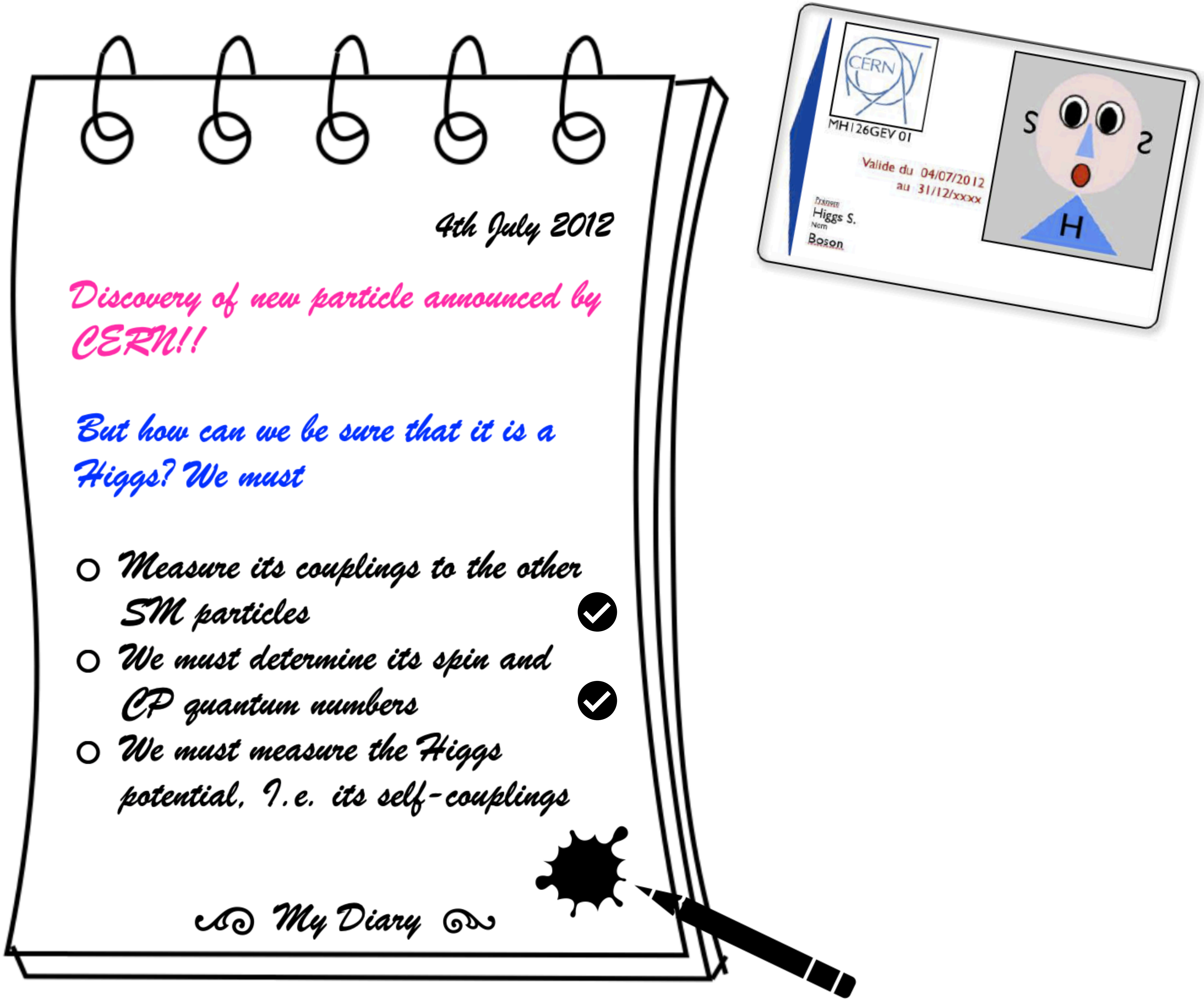
Discovery of new particle announced by CERN!!

But how can we be sure that it is a Higgs? We must

- Measure its couplings to the other SM particles
- We must determine its spin and CP quantum numbers
- We must measure the Higgs potential, I.e. its self-couplings

My Diary

Establishing the Higgs Mechanism



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○ Measure its couplings to the other SM particles ✓
○ We must determine its spin and CP quantum numbers ✓
○ We must measure the Higgs potential, I.e. its self-couplings

My Diary

Trilinear Higgs Self-Coupling

We must measure the Higgs potential, i.e. self-couplings

- SM Higgs potential: in physical gauge

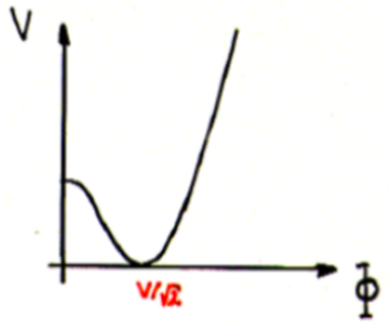
$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higg self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$

quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3 M_H^2 / M_Z^4$

(units $\lambda_0 = 33.8 GeV / \lambda_0^2$)



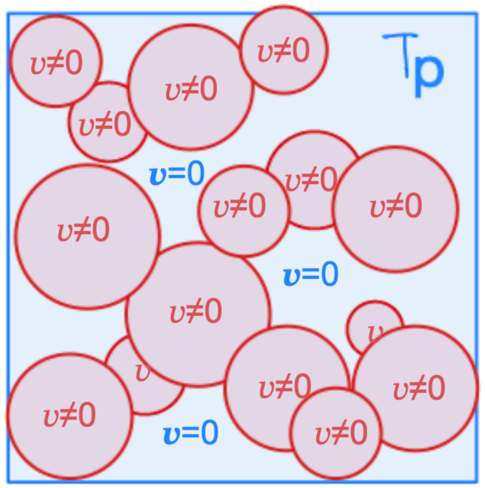
Measurement of the scalar boson self-couplings

and

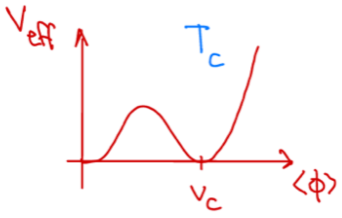
Reconstruction of the EWSB potential

} Experimental verification Of the scalar sector of the EWSB mechanism

- Importance of the trilinear Higgs self-coupling:
  - determines shape of the Higgs potential
  - sensitive to beyond-Standard-Model physics
  - important input for Higgs pair production
  - important input for Higgs-to-Higgs decays
  - important input for electroweak phase transitions*

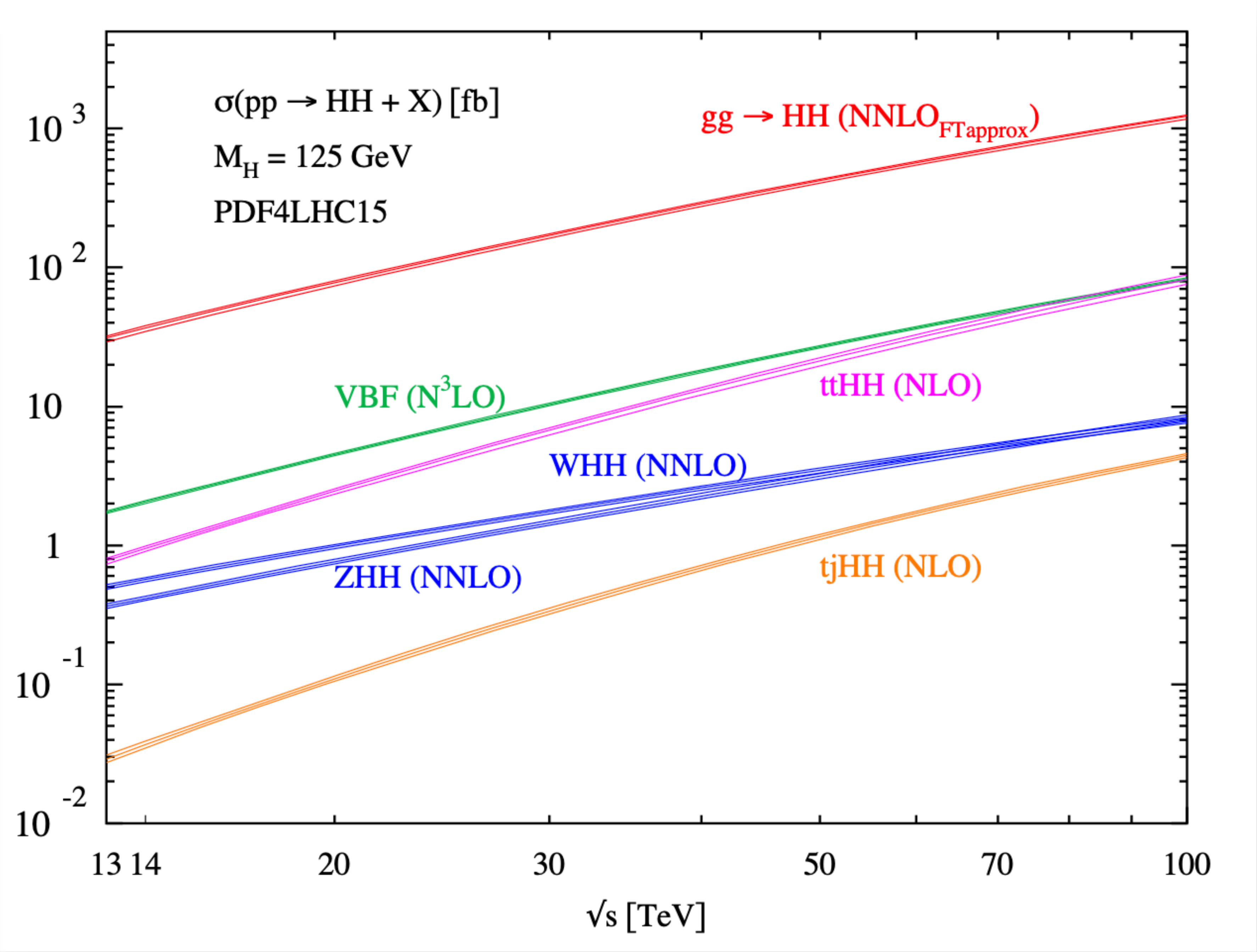


*matter-asymmetry through electroweak baryogenesis



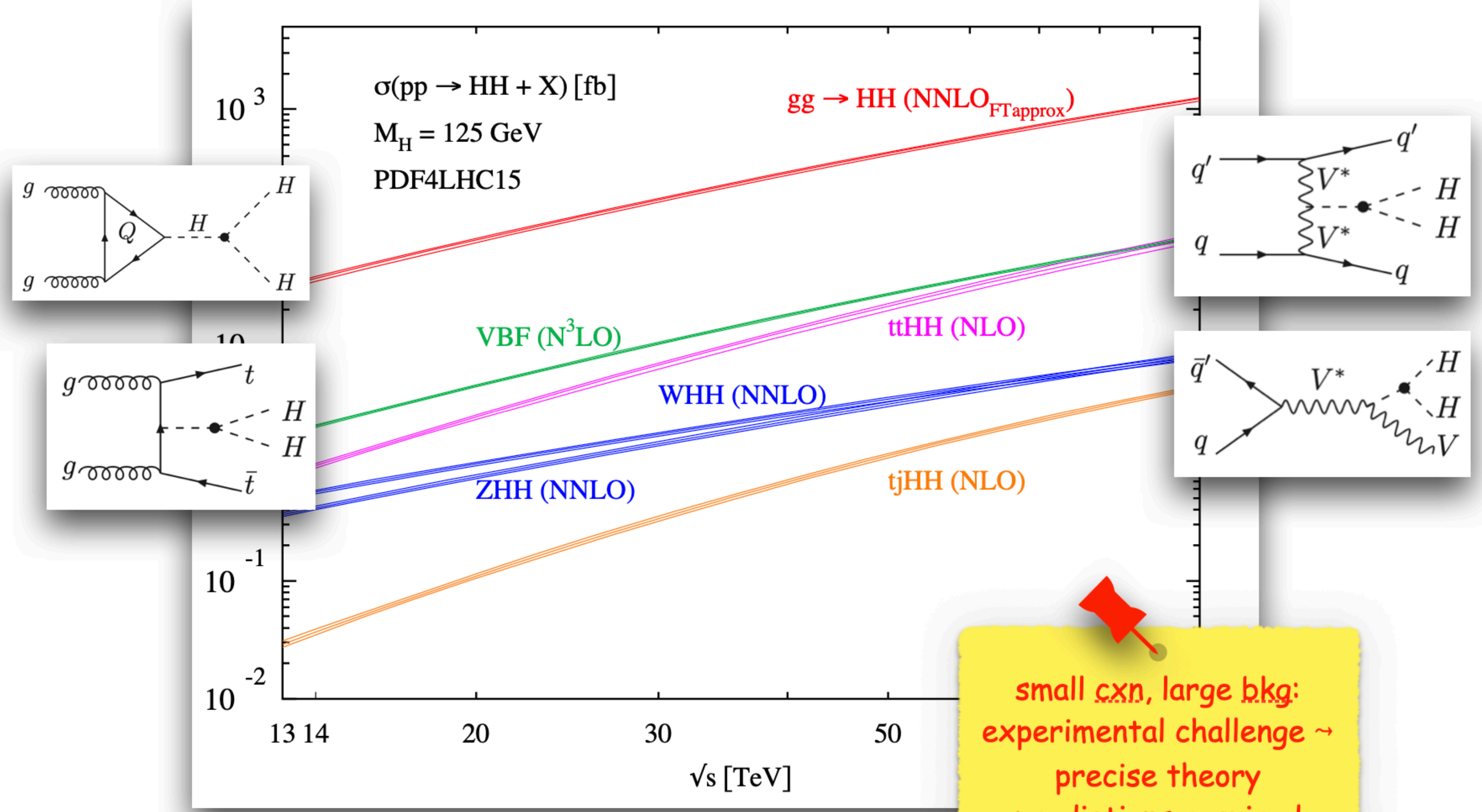
Measurement of λ_{HHH} - Higgs Pair Production

[HH, White paper]



Measurement of λ_{HHH} - Higgs Pair Production

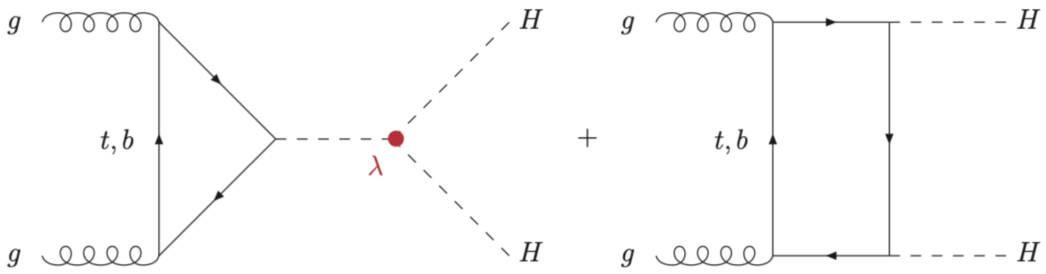
[HH, White paper]



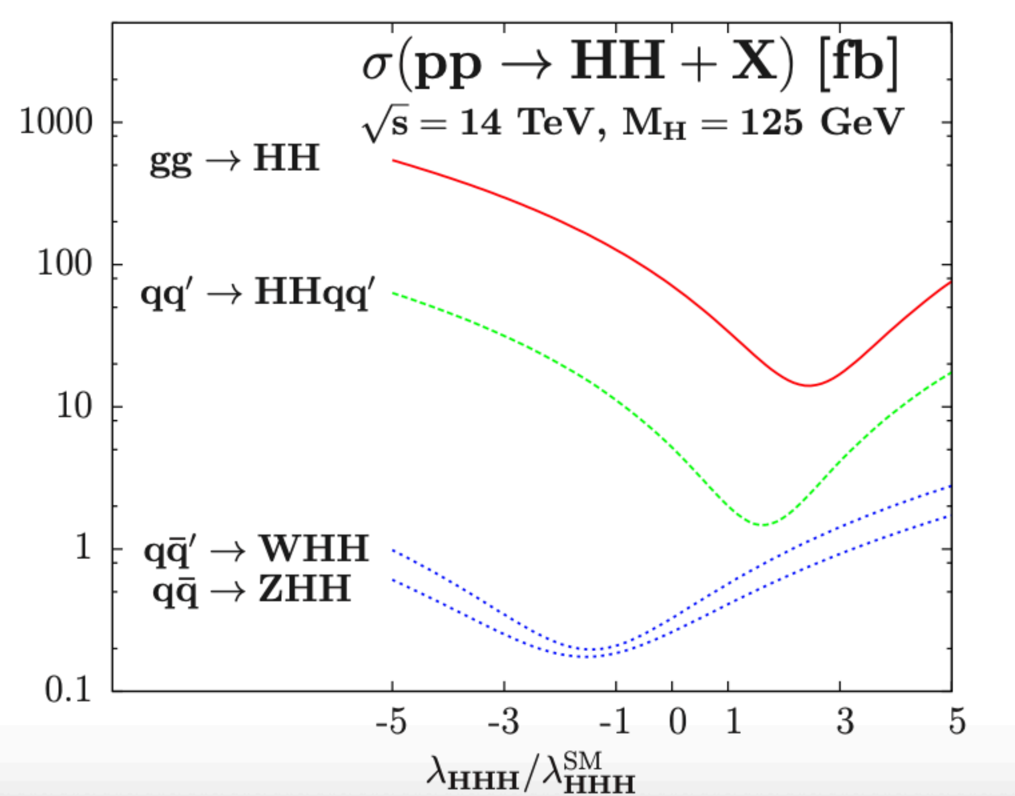
small cxn, large bkg:
experimental challenge ⇝
precise theory
predictions required

Higgs Pair Production Through Gluon Fusion

- Loop mediated at leading order - SM: third generation dominant



- Threshold region sensitive to λ; large M_{HH}: sensitive to c_{tt}/c_{bb} [e.g. boosted Higgs pairs]

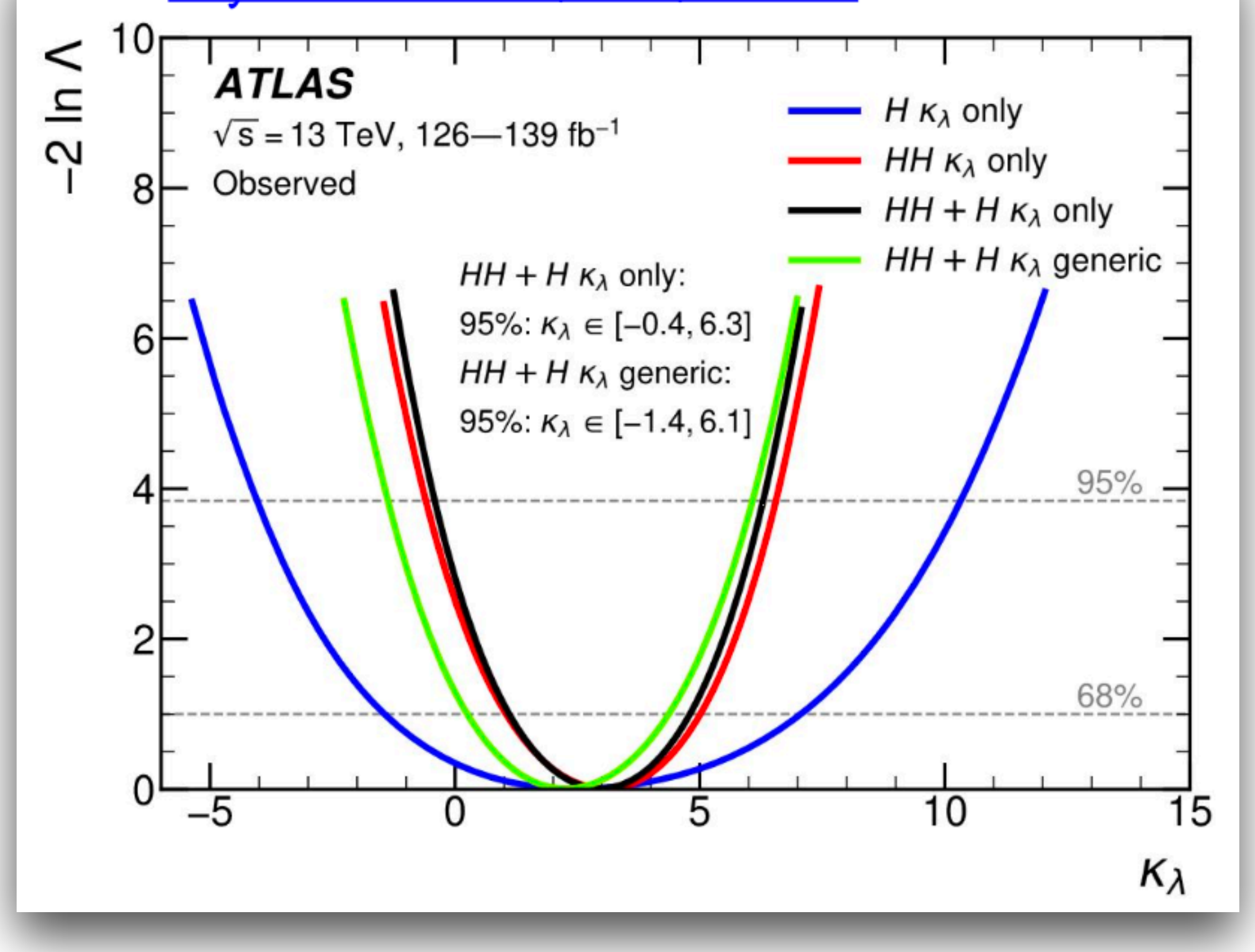


[Baglio,Djouadi,Gröber,MM,Quévillon,Spira]

$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

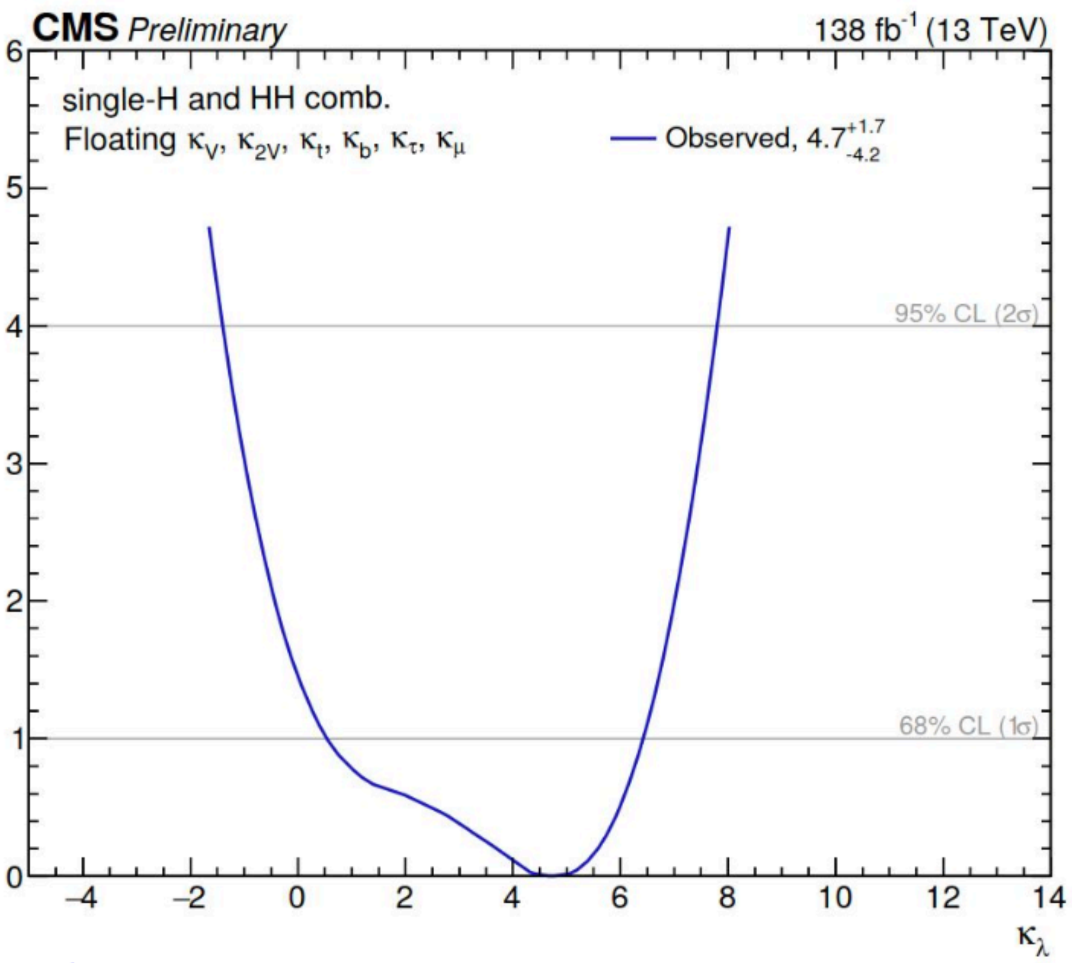
Experimental Results - Limits on λ_{HHH}

Phys. Lett. B 843 (2023) 137745



ATLAS: $-1.4 < \kappa_\lambda < 6.1$ at 95 % CL

CMS-HIG-23-006



CMS: $-1.2 < \kappa_\lambda < 7.5$ at 95 % CL

Higher-Order QCD Corrections

- 2-loop QCD corrections: $\lesssim$ 70% [HTL, $\mu=M_{HH}/2$] [Dawson,Dittmaier,Spira,'98]
- 2-loop QCD corrections: $\sigma = \sigma_0 + \sigma_1/m_t^2 + \ldots + \sigma_4/m_t^8$

  [refinement: full LO at differential level] [Grigo,Hoff,Melnikov,Steinhauser,'13]
- NNLO QCD corrections: ~ 20% [HTL] [de Florian,Mazzitelli,'13; Grigo,Melnikov,Steinhauser,'14]
- Mass effects @ NLO in real corrections: ~ - 10%

  [Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Torrielli,Vryonidou,Zaro,'14]
- NLO: inclusion of full top-mass effects @ NLO

  [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke,'16]
- NLO: matching to parton showers [Heinrich,Jones,Kerner,Luisoni,Vryonidou,'17;Jones,Kuttimalai,'17]
- NNLO Monte Carlo: inclusion of full top-mass effects @ NLO [partly at NNLO] (FT_{approx})

  [Grazzini,Heinrich,Jones,Kallweit,Kerner,Lindert,Mazzitelli,'18]
- NLO: inclusion of full top-mass effects @ NLO & top mass scheme

  [Baglio,Campanario,Glaus,MM,Spira,Streicher,'18,'20]
- $gg \to HH$ combined uncertainties [Baglio,Campanario,Glaus,MM,Ronca,Spira,'21]
- N^3LO QCD corrections: ~ 5% [HTL] [Chen,Li,Shao,Wang,'19]

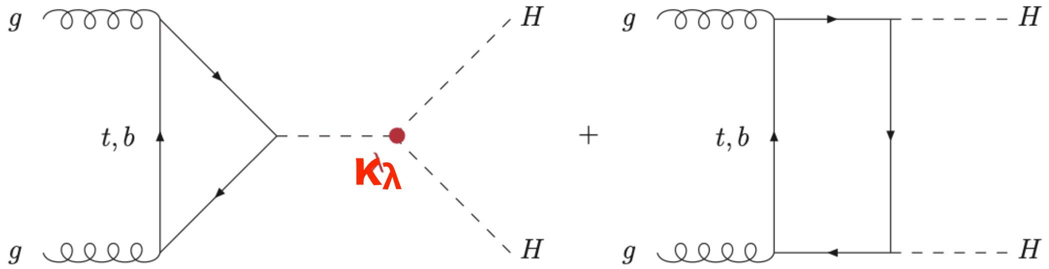
Higher-Order QCD Corrections

- New expansion/extrapolation methods:
  (i) $1/m_t^2$ expansion + conformal mapping + Padé approximants [Gröber,Maier,Rauh,'17]
  (ii) p_T^2 expansion [Bonciani,Degassi,Giardino,Gröber,'18]
- NLO: small mass expansion [$Q^2 \gg m_t^2$] [Davies,Mishima,Steinhauser,Wellmann,'18]
- Combination of full NLO and small mass expansion
  [Davies,Heinrich,Jones,Kerner,Mishima,Steinhauser,Wellmann,'19]

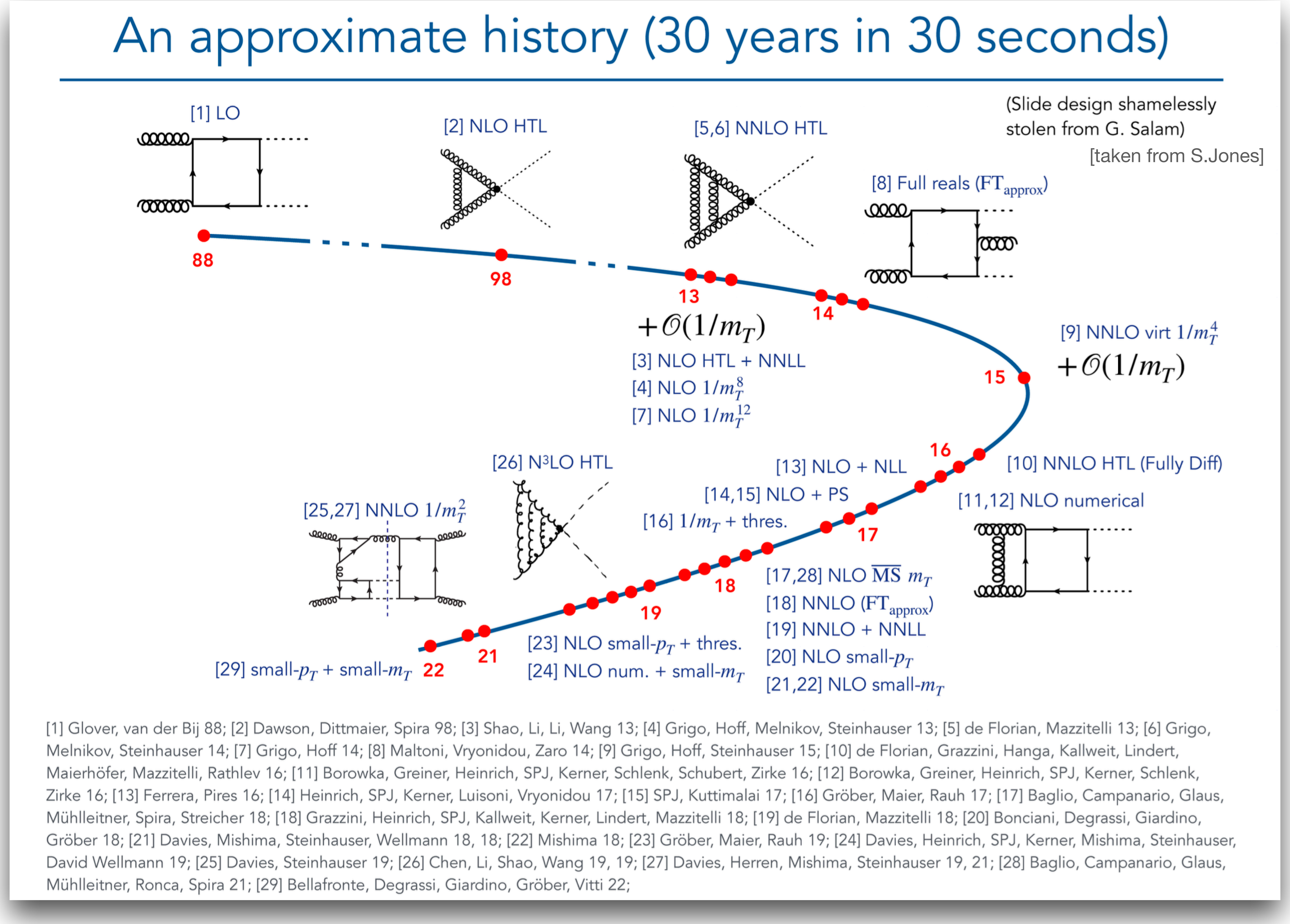
Complete list, see e.g. twiki of LHC Higgs Working Subgroup HH and recent reviews

-> recommendations for cross sections to be used given for
- different c.m. energies
- different coupling modifiers κ_λ

-> uncertainties on di-Higgs cross sections



HH Higher-Order QCD History



An approximate history (30 years in 30 seconds)

(Slide design shamelessly stolen from G. Salam)

[taken from S.Jones]

[1] LO

[2] NLO HTL

[5,6] NNLO HTL

[8] Full reals ($\mathrm{FT}_{\mathrm{approx}}$)

$+\mathcal{O}(1/m_T)$

[3] NLO HTL + NNLL

[4] NLO $1/m_T^8$

[7] NLO $1/m_T^{12}$

[9] NNLO virt $1/m_T^4$

$+\mathcal{O}(1/m_T)$

[10] NNLO HTL (Fully Diff)

[11,12] NLO numerical

[13] NLO + NLL

[14,15] NLO + PS

[16] $1/m_T$ + thres.

[26] $\mathrm{N^3LO}$ HTL

[25,27] NNLO $1/m_T^2$

[17,28] NLO $\overline{\mathrm{MS}}$ m_T

[18] NNLO ($\mathrm{FT}_{\mathrm{approx}}$)

[19] NNLO + NNLL

[20] NLO small-p_T

[21,22] NLO small-m_T

[23] NLO small-p_T + thres.

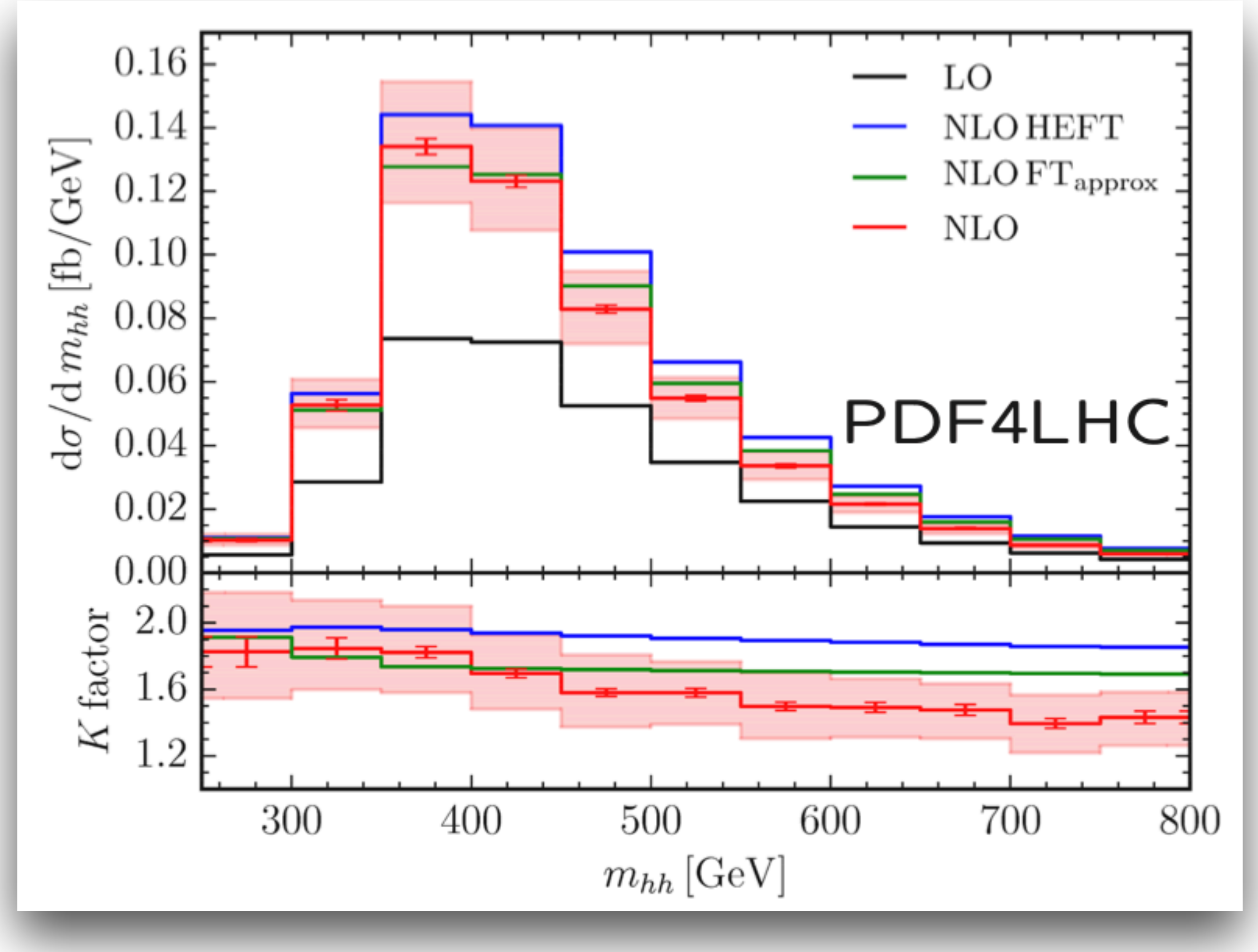
[24] NLO num. + small-m_T

[29] small-p_T + small-m_T

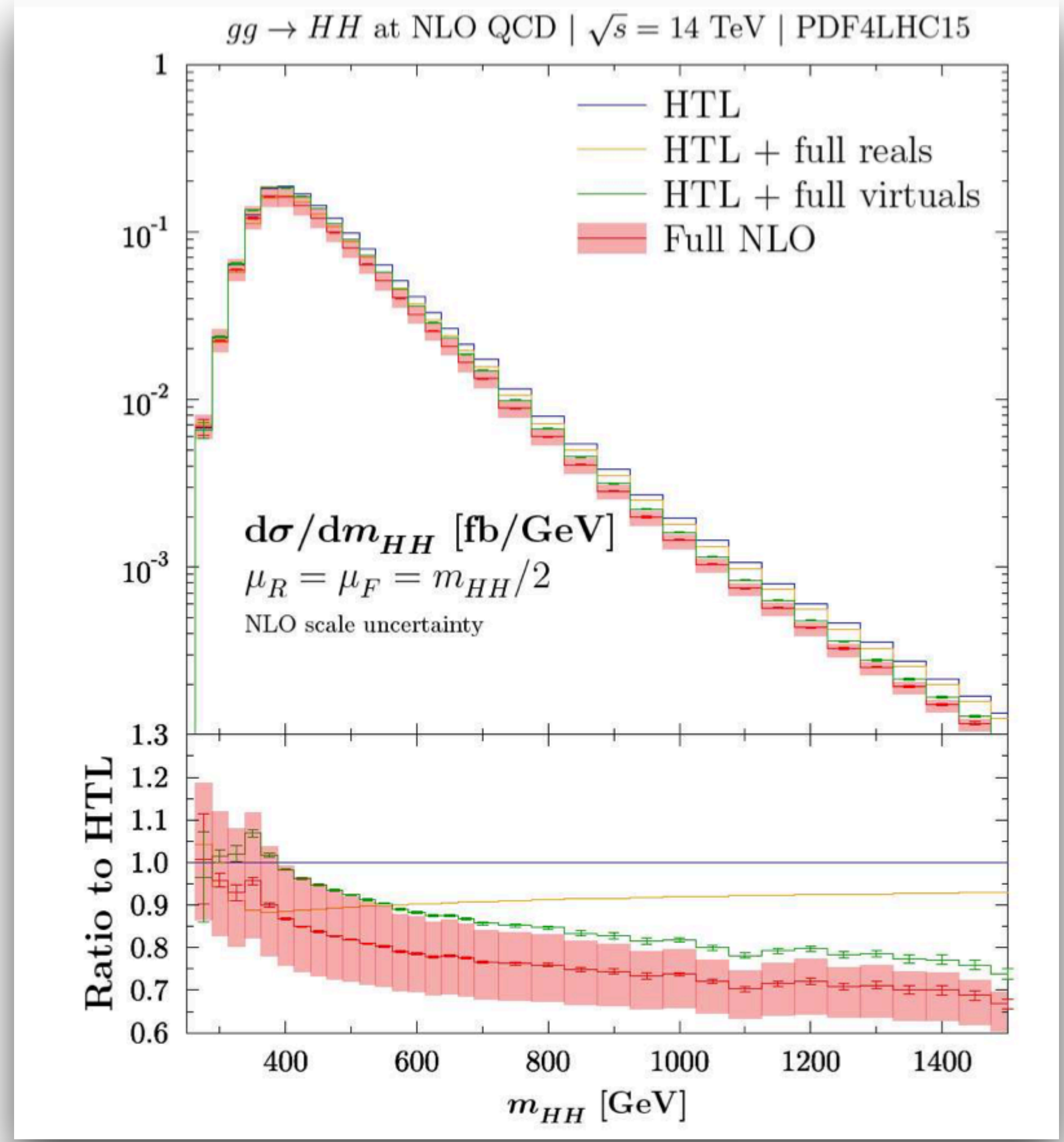
[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

NLO QCD Corrections W/ Full Top Mass Dependence

[Borowka,Greiner,Heinrich,Jones,Kerner,
Schlenk,Schubert,Zirke,'16]



[Baglio,Campanario,Glaus,MM,Ronca,Spira,Streicher,'18,'20]



$\sigma_{NLO} =$	$32.91(10)^{+13.8\%}_{-12.8\%}\ fb$	$32.81(7)^{+13.5\%}_{-12.5\%}\ fb$
$\sigma^{HTL}_{NLO} =$	$38.75^{+18\%}_{-15\%}\ fb$	$38.66^{+18\%}_{-15\%}\ fb$
$m_t =$	173 GeV	172.5 GeV

⇒ -15% mass effects on top of LO

Uncertainties at NLO

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'21]

- Renormalization and factorization scale uncertainties at NLO:

$$\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: &\quad \sigma_{tot} = 27.73(7)^{+13.8\%}_{-12.8\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: &\quad \sigma_{tot} = 32.81(7)^{+13.5\%}_{-12.5\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: &\quad \sigma_{tot} = 127.0(2)^{+11.7\%}_{-10.7\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: &\quad \sigma_{tot} = 1140(2)^{+10.7\%}_{-10.0\%} \text{ fb}
\end{aligned}$$

- m_t scale/scheme uncertainties at NLO:

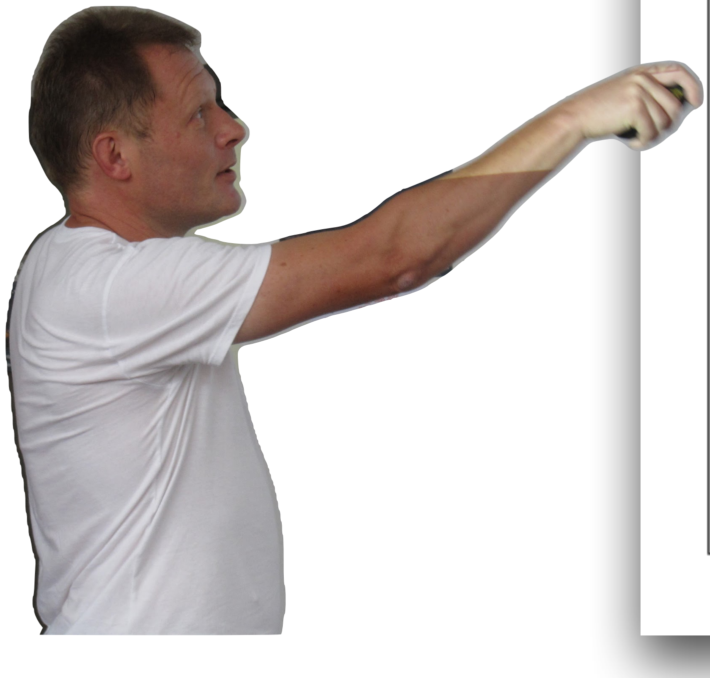
$$\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: &\quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: &\quad \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: &\quad \sigma_{tot} = 127.8(2)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: &\quad \sigma_{tot} = 1140(2)^{+3\%}_{-18\%} \text{ fb}
\end{aligned}$$

- Linear sum of uncertainties ~>

Final Uncertainties at $\mathrm{FT_{approx}}$

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'21]

- Final combined renormalization/factorization scale and m_t scale/scheme uncertainties at $\mathrm{NNLO_{FTapprox}}$*:



$$
\begin{aligned}
\sqrt{s} = 13\ \text{TeV}: &\quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb} \\
\sqrt{s} = 14\ \text{TeV}: &\quad \sigma_{tot} = 36.69^{+6\%}_{-23\%}\ \text{fb} \\
\sqrt{s} = 27\ \text{TeV}: &\quad \sigma_{tot} = 139.9^{+5\%}_{-22\%}\ \text{fb} \\
\sqrt{s} = 100\ \text{TeV}: &\quad \sigma_{tot} = 1224^{+4\%}_{-21\%}\ \text{fb}
\end{aligned}
$$

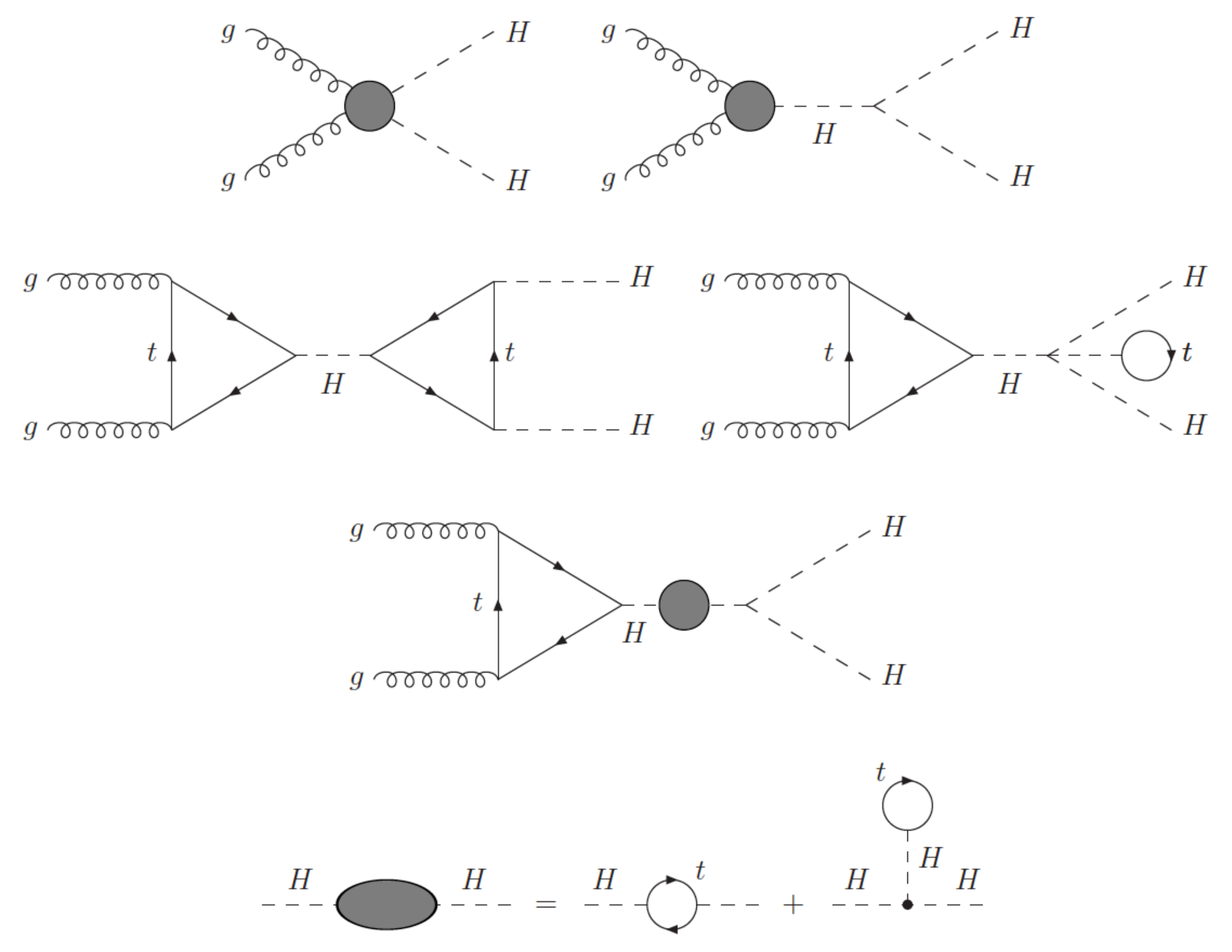
*$\mathrm{FT_{approx}}$: full NNLO QCD in the heavy-top-limit with full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO QCD

Electroweak Corrections to SM Higgs Pair Production

- EW corrections due to self-couplings [Borowka,Duhr,Maltoni,Pagani,Shivaji,Zhao,'18]
- Top-Yukawa-induced corrections to Higgs pair production [MM,Schlenk,Spira,` 22]
- Higgs boson contribution to the leading 2-loop Yukawa corrections to gg->HH [Davies,Mishima,Schönwald,Steinhauser,Zhang,´ 22]
- NLO EW corrections to gg->HH and gg->gH in the large m_t limit [Davies,Schönwald,Steinhauser,Zhang,'23]
- Complete NLO EW corrections [Bi,Huang,Huang,Ma,Yu,'23]
- Yukawa-enhanced & Higgs self-coupling-type EW corrections [Heinrich,Jones,Kerner,Stone,Vestner,'24]

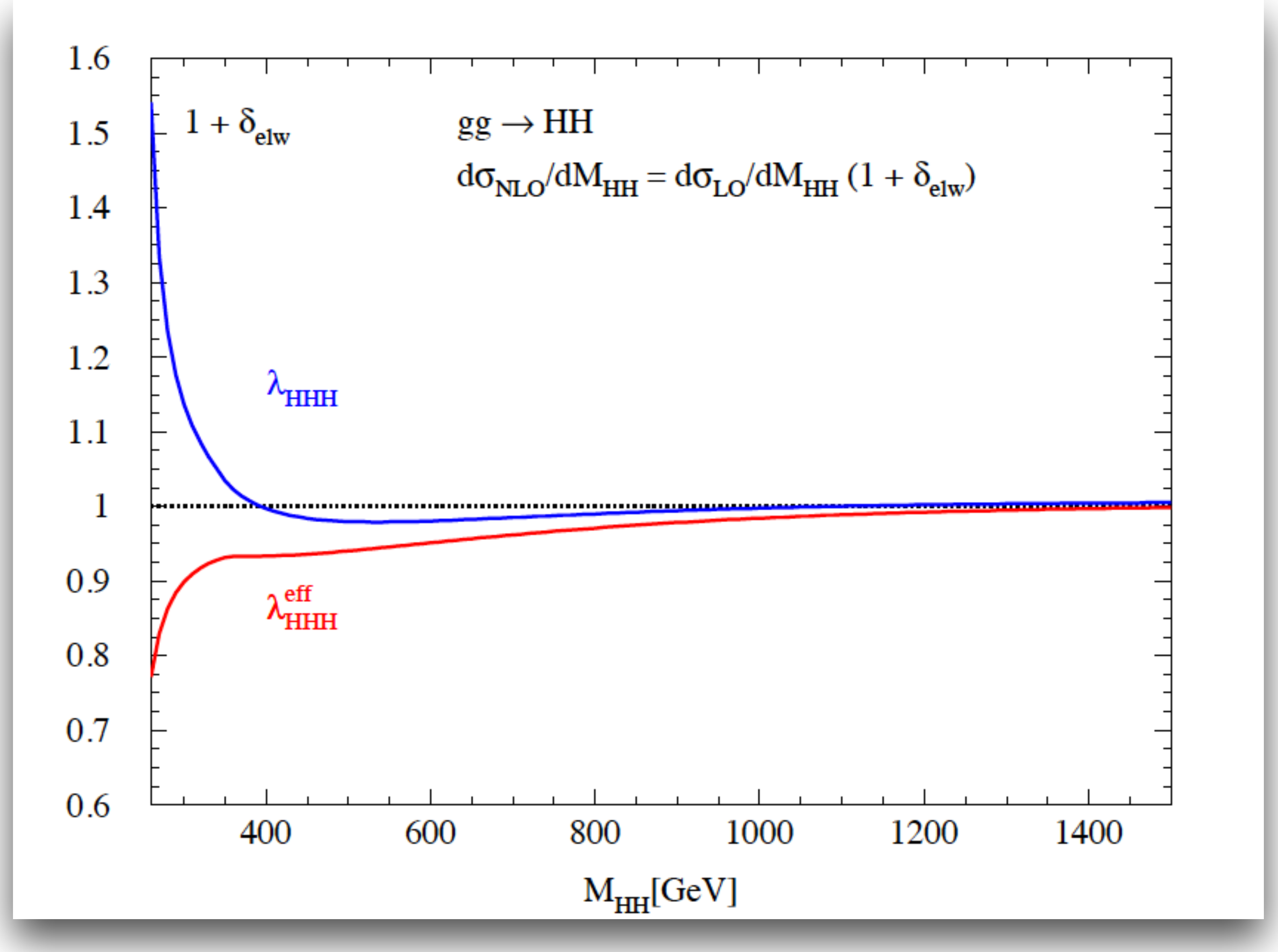
Top Yukawa Induced Corrections to Higgs Pair Production

- Part of the electroweak corrections to Higgs pair production [MM,Schlenk,Spira,'22]
- Full top-mass dependence in the triple Higgs vertex and self-energy corrections
  HTL in radiative corrections to the effective ggH and ggHH vertices (b-loops neglected)



Relative Top Quark Induced EW Correction to Differential HH Prod

[MM,Schlenk,Spira,'22]

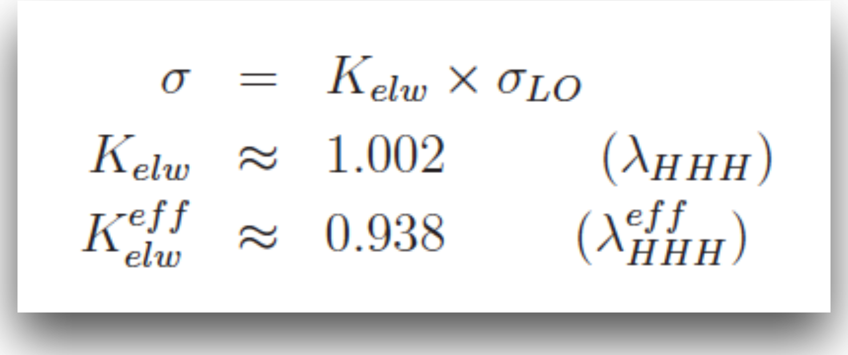


- Large enhancement near threshold because of vanishing LO matrix element
- Suppression is lifted by mismatch of EW corrections to triangle and box diagrams

Effect of Top Yukawa Induced Corrections on total CXN

[MM,Schlenk,Spira,'22]

✦ Effect of top-Yukawa-induced EW correction on total integrated hadronic cross section:



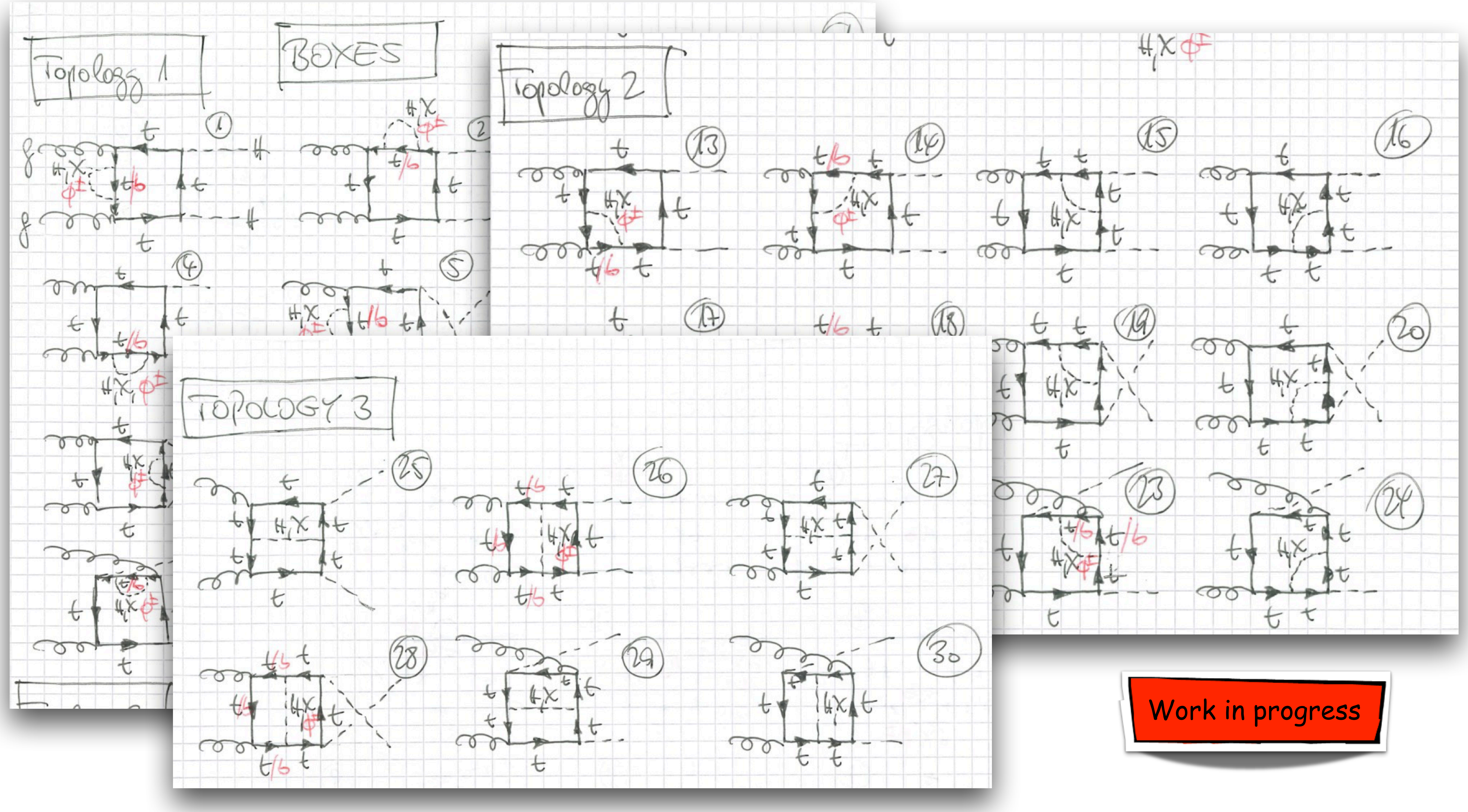
$$\begin{aligned} \sigma &= K_{elw} \times \sigma_{LO} \\ K_{elw} &\approx 1.002 \qquad (\lambda_{HHH}) \\ K_{elw}^{eff} &\approx 0.938 \qquad (\lambda_{HHH}^{eff}) \end{aligned}$$

- Corrections induce an effect of about 0.2%
- Bulk of corrections cannot be absorbed in the effective trilinear Higgs coupling (leads to an artificial increase of the relative EW corrections)
- ~> Inclusion of complete EW corrections is mandatory

Top-Yukawa Induced EW Corrections - Mass Effects

[Bhattacharya,Campanario,Carlotti,Chang,Mazzitelli,MM,Ronca,Spira]

- With top- and bottom-quark mass dependence, gaugeless limit



Work in progress

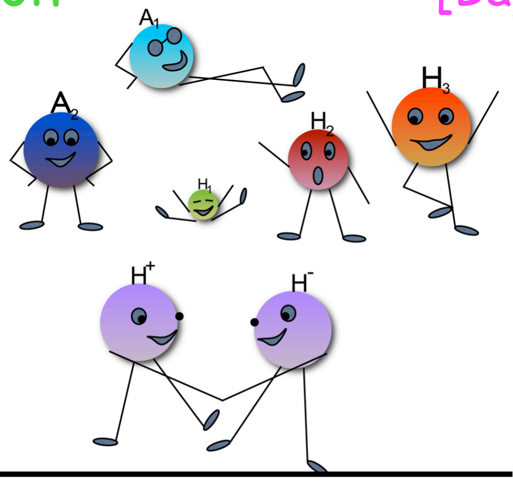
BSM Higgs Pair Production

✏ NLO QCD corrections in the heavy-top limit:

- MSSM Higgs pair production [LO:Plehn,Spira,Zerwas,'96][NLO:Dawson,Dittmaier,Spira,'98]
  - ⇝ HPAIR
- Other extended Higgs sectors:
  - Composite Higgs [Gröber,MM,'10][Gillioz,Gröber,Grojean,MM,Salvioni,'12][Gröber,MM,Spira,'16]
  - NMSSM [Nhung,MM,Streicher,Walz,'13]
  - EFT [Gröber,MM,Spira,Streicher,'16]
  - CP-violating 2HDM [Gröber,MM,Spira,'17]
  - 2HDM, Next-to-2HDM (N2HDM) [Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'22]
  - Composite 2HDM [DeCurtis,DelleRose,Egle,MM,Moretti,Sakurai,'23]

✏ NLO QCD corrections w/ full top-mass dependence:

- 2HDM hH and AA Higgs pair production [Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]

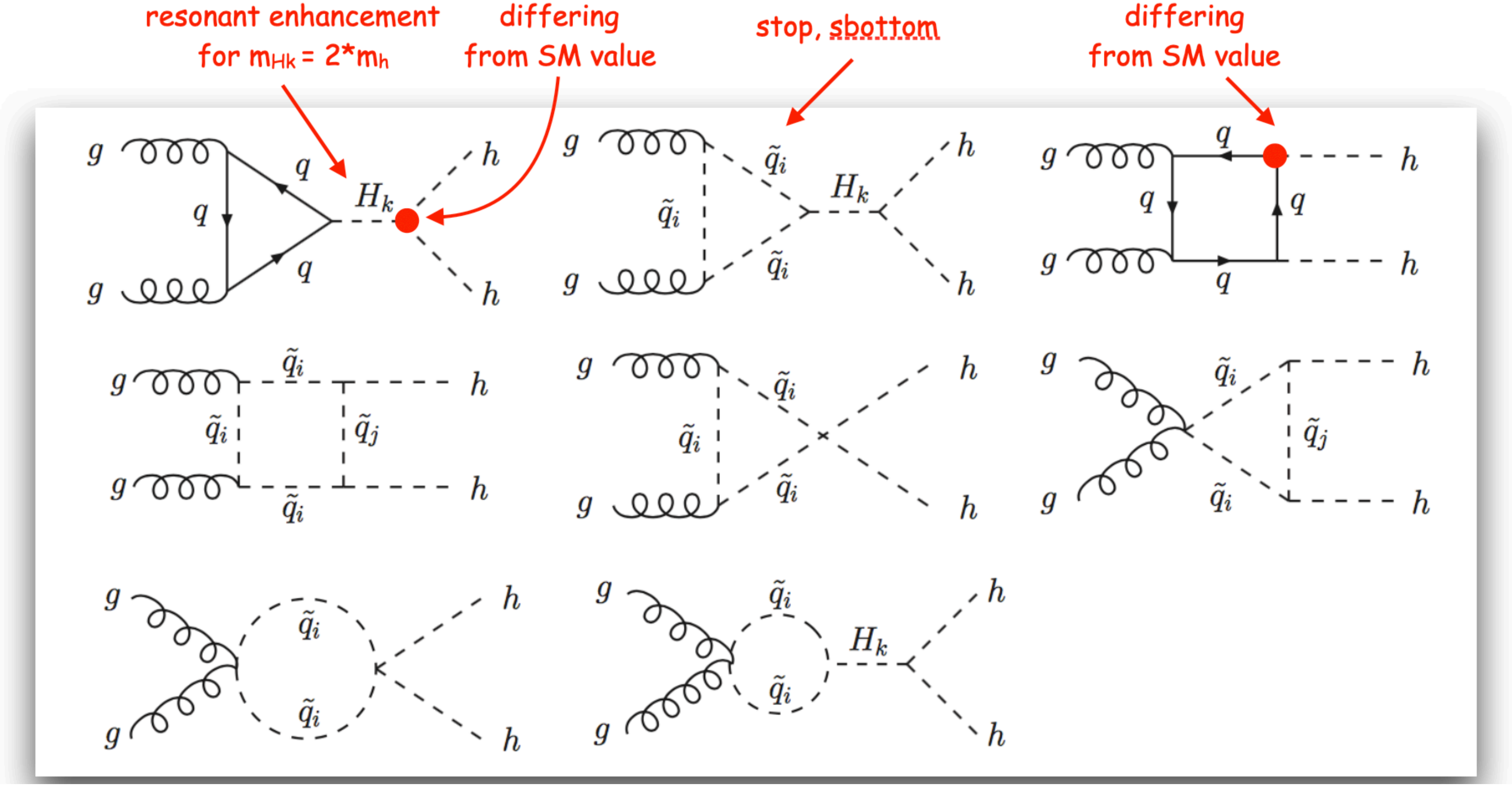


New Physics Effects in Higgs Pair Production

- Cross section: - different trilinear couplings - different Yukawa couplings - novel particles in the loops - resonant enhancement - novel couplings

- Example NMSSM:

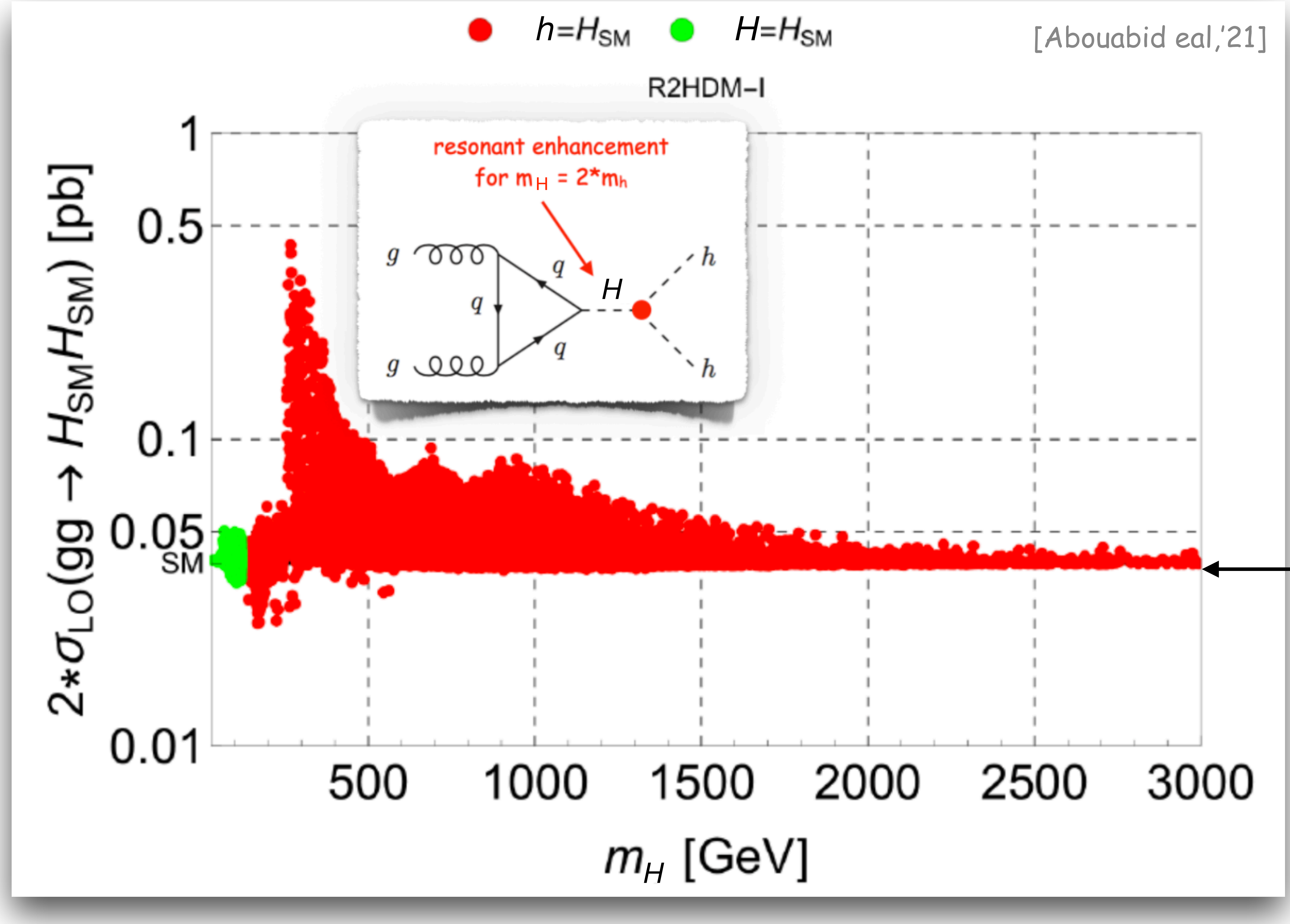
[taken from Dao,MM,Streicher,Walz,´13]



Example 2-Higgs-Doublet Model (2HDM)

✏ 2HDM Higgs sector: 2 Higgs doublets $\xrightarrow{\text{EWSB}}$

neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-



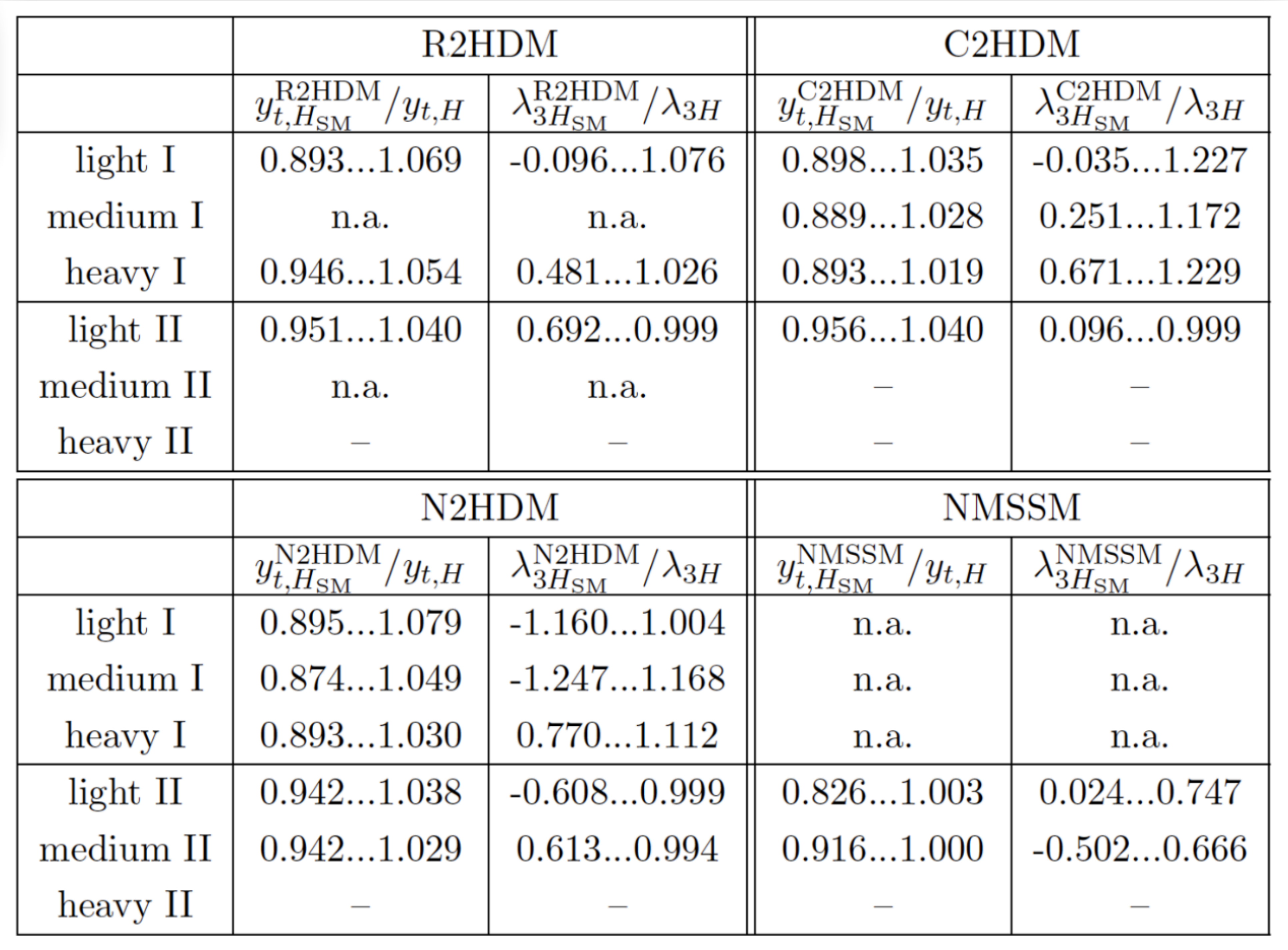
● ● Parameter scan points compatible w/ all relevant theoretical & experimental constraints

SM HH cxn value (LO)

Allowed Ranges of Trilinear Higgs Couplings

[Abouabid eal,'21]

Large values of $\lambda_{3H_{SM}}$ required for SFOEWPT!



	R2HDM		C2HDM	
	$y^{\mathrm{R2HDM}}_{t,H_{\mathrm{SM}}}/y_{t,H}$	$\lambda^{\mathrm{R2HDM}}_{3H_{\mathrm{SM}}}/\lambda_{3H}$	$y^{\mathrm{C2HDM}}_{t,H_{\mathrm{SM}}}/y_{t,H}$	$\lambda^{\mathrm{C2HDM}}_{3H_{\mathrm{SM}}}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

	N2HDM		NMSSM	
	$y^{\mathrm{N2HDM}}_{t,H_{\mathrm{SM}}}/y_{t,H}$	$\lambda^{\mathrm{N2HDM}}_{3H_{\mathrm{SM}}}/\lambda_{3H}$	$y^{\mathrm{NMSSM}}_{t,H_{\mathrm{SM}}}/y_{t,H}$	$\lambda^{\mathrm{NMSSM}}_{3H_{\mathrm{SM}}}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

Electroweak Baryogenesis

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

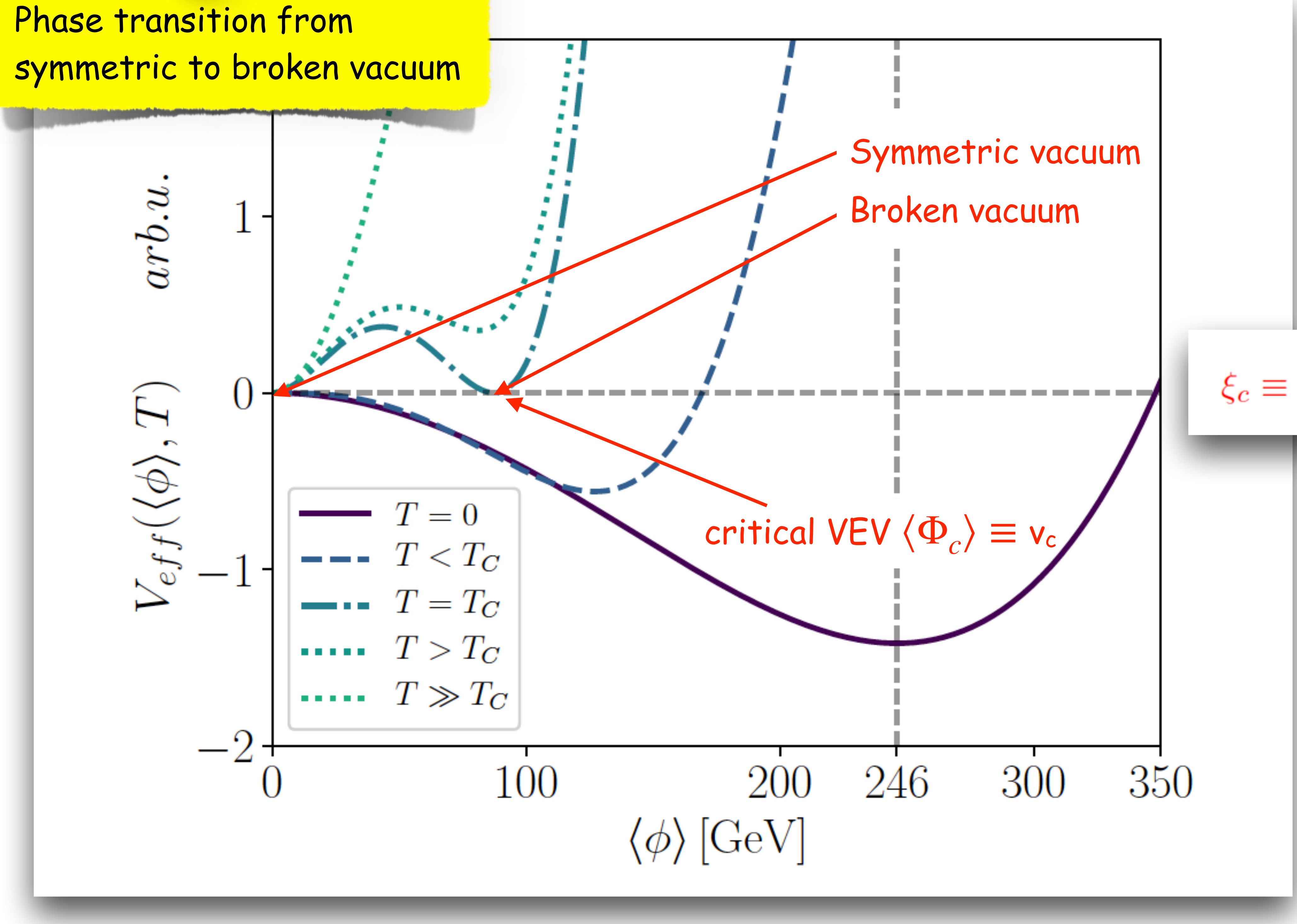
- **Sakharov Conditions:** [Sakharov '67]
  - (i) B number violaton (sphaleron processes)
  - (ii) C and CP violation
  - (iii) Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

Strong First-Order Electroweak Phase Transition (SFOEWPT)

[From Ph. Basler, PhD Thesis]

Phase transition from symmetric to broken vacuum



Symmetric vacuum

Broken vacuum

critical VEV $\langle\Phi_c\rangle \equiv v_c$

$$\xi_c \equiv \frac{\langle\Phi_c\rangle}{T_c} \geq 1$$

Electroweak Baryogenesis

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- **Sakharov Conditions:** [Sakharov '67]
  - (i) B number violaton (sphaleron processes)
  - (ii) C and CP violation
  - (iii) Departure from thermal equilibrium

- SM: smooth cross-over
- not enough CP violation
- large trilinear Higgs coupling required

=> physics beyond the SM needed

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]

Strong-First-Order Phase Transitions (SFOPT) and Gravitational Waves

LIGO Laser Interferometer Gravitational-Wave Observato
Supported by the National Science Founda
Operated by Caltech and MIT

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Image credit: The SXS (Simulating eXtreme Spacetimes) Project

Gravitational Waves Detected 100 Years After Einstein's Prediction

News Release • February 11, 2016

SFOEWPT
(for EWBG)

can source ↓

Gravitational Waves
(GW)

sensitive to ↑

Pulsar timing arrays, LISA
(space bound interferometer)

Strong-First-Order Phase Transitions (SFOPT) and Gravitational Waves


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can source

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Pulsar timing arrays, LISA
(space bound interferometer)

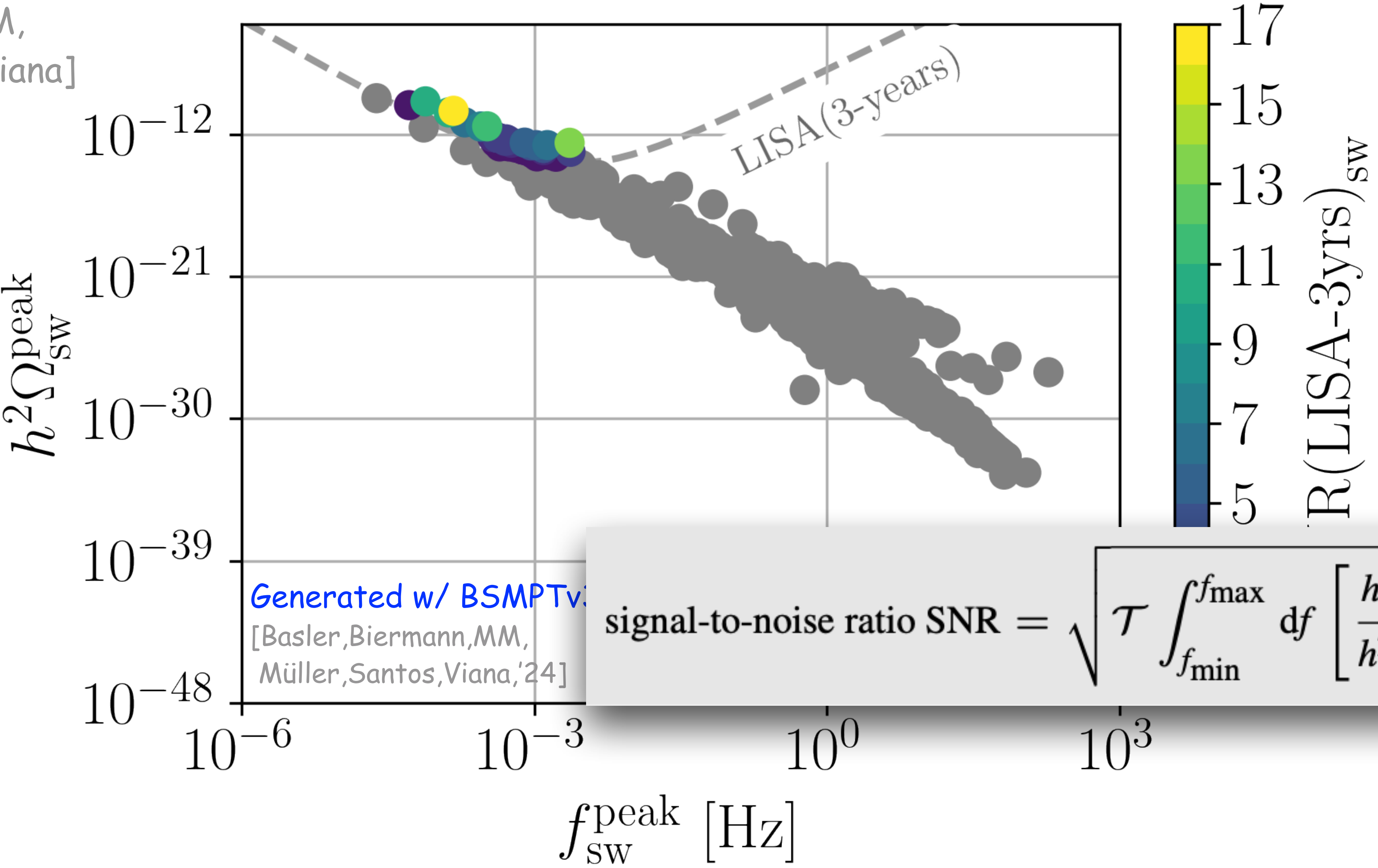
Directly probe echo of
Cosmological FOPT

Discovery of Physics
Beyond the SM

GW from (S)FOEWPT in „CP in the Dark"*

[Basler,Biermann,
Borschensky,MM,
Müller,Santos,Viana]

*[Azevedo,Ferreira,
MM,Patel,Santos,
Wittbrodt]



Generated w/ BSMPTv3
[Basler,Biermann,MM,
Müller,Santos,Viana,'24]

$$\text{signal-to-noise ratio SNR} = \sqrt{\mathcal{T}\int_{f_{\rm min}}^{f_{\rm max}} \mathrm{d}f \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm Sens}(f)}\right]^2}$$

- ∃ points w/ SNR(LISA-3yrs)>10, compatible w/ all relevant theor. and exp. constraints
- all points lead to EW minimum at T=0 (no vacuum trapping)
- all of the LISA-sensitive points (colored points) have SFOEWPT: ξ_c>1

GW from (S)FOEWPT in „CP in the Dark"*

[Basler,Biermann,
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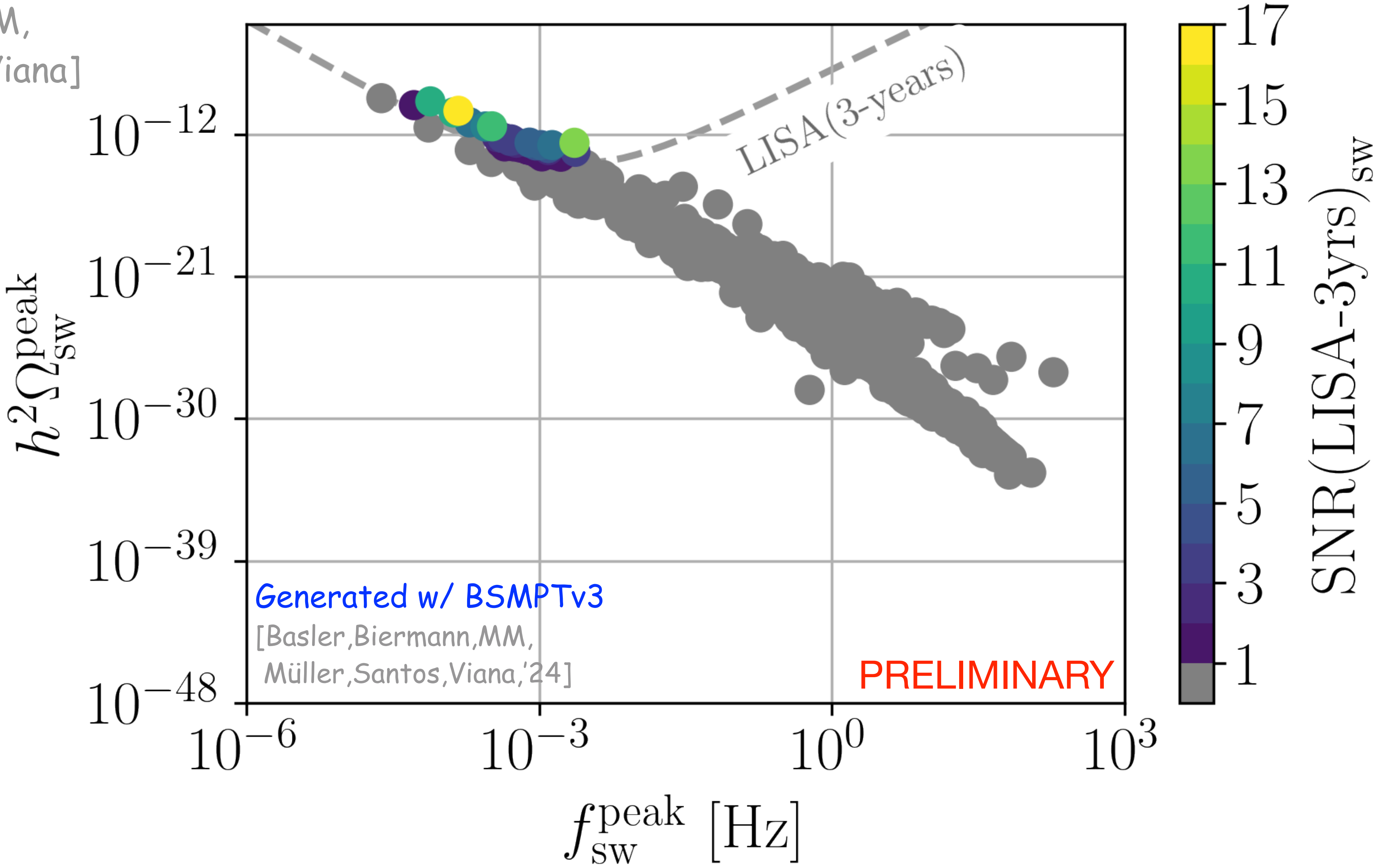

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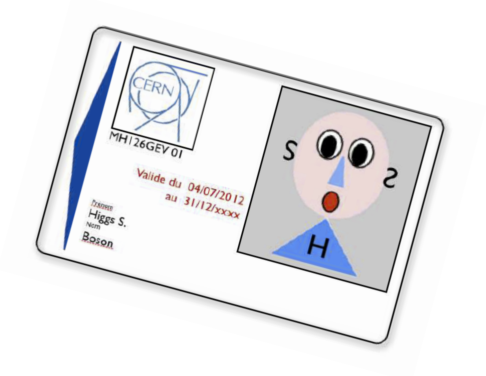
Conclusions



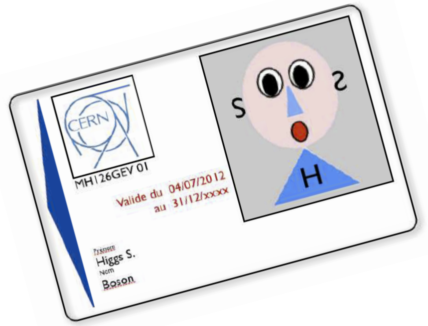
✏ LHC Higgs discovery
- milestone for particle physics
- triggered precise investigation of Higgs properties ⇐ requires precise theory predictions

✏ Discovered Higgs boson behaves very SM-like; open questions require BSM physics
new physics is subtle! ⇐ requires precise theory predictions

✏ Trilinear Higgs self-coupling still leaves room for BSM physics
its measurement is an experimental challenge ⇐ requires precise theory predictions

Nature makes it exciting for us
The journey only started
Exciting times ahead!

Conclusions



- ✏ LHC Higgs discovery
  - milestone for pa
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- ✏ Discovered Higgs SM physics

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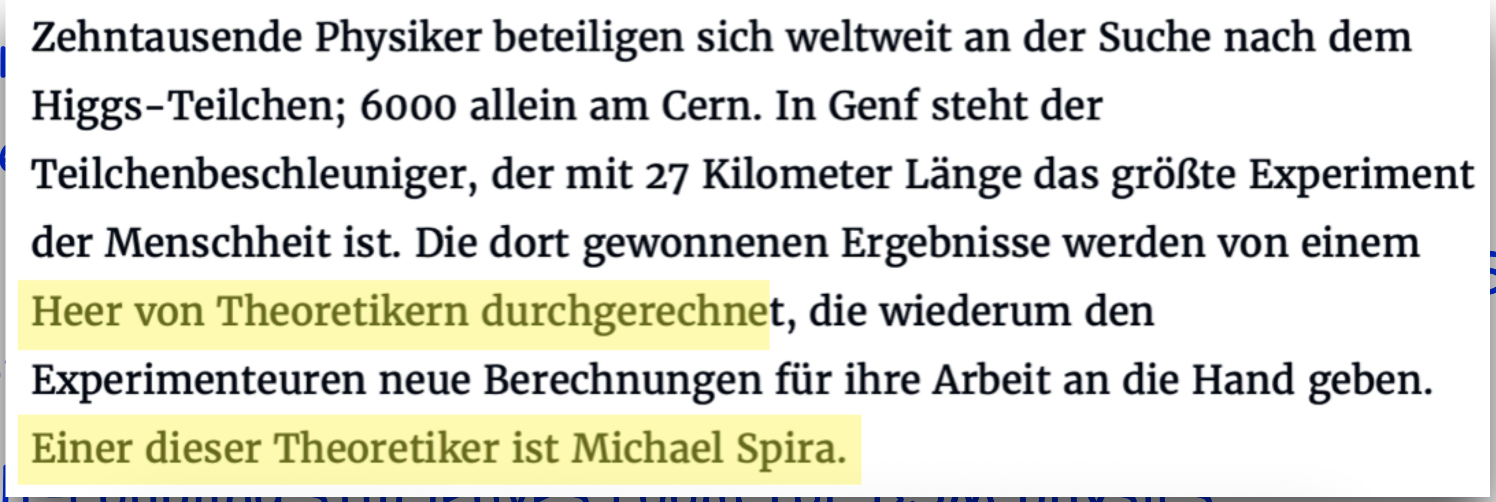


Zehntausende Physiker beteiligen sich weltweit an der Suche nach dem Higgs-Teilchen; 6000 allein am Cern. In Genf steht der Teilchenbeschleuniger, der mit 27 Kilometer Länge das größte Experiment der Menschheit ist. Die dort gewonnenen Ergebnisse werden von einem Heer von Theoretikern durchgerechnet, die wiederum den Experimenteuren neue Berechnungen für ihre Arbeit an die Hand geben. Einer dieser Theoretiker ist Michael Spira.

Happy Birthday, to you two,

Michael and Higgs boson!

Thank you for your attention!

The Higgs Mass

✦Present Accuracy: [ATLAS,CMS]

M_H = 125.11 ± 0.09 (stat) ± 0.06 (syst) GeV = 125.11 ± 0.11 GeV

Measured in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ decay channels

✦Why precision?

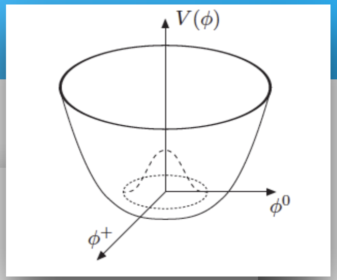
∗ Self-consistency test of SM at quantum level
(e.g.: Higgs loop corrections to W boson mass)

∗ M_H ↔ stability of the electroweak vacuum [Degrassi eal;Bednyakov eal]

∗ Higgs mass uncertainty feeds back in uncertainty on Higgs observables

∗ Test parameter relations in beyond-SM theories

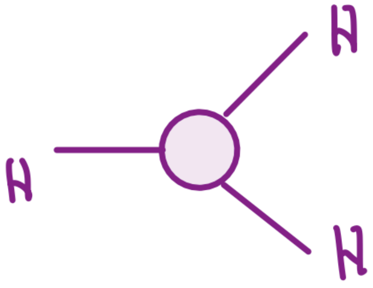
Stability of the Electroweak Vacuum



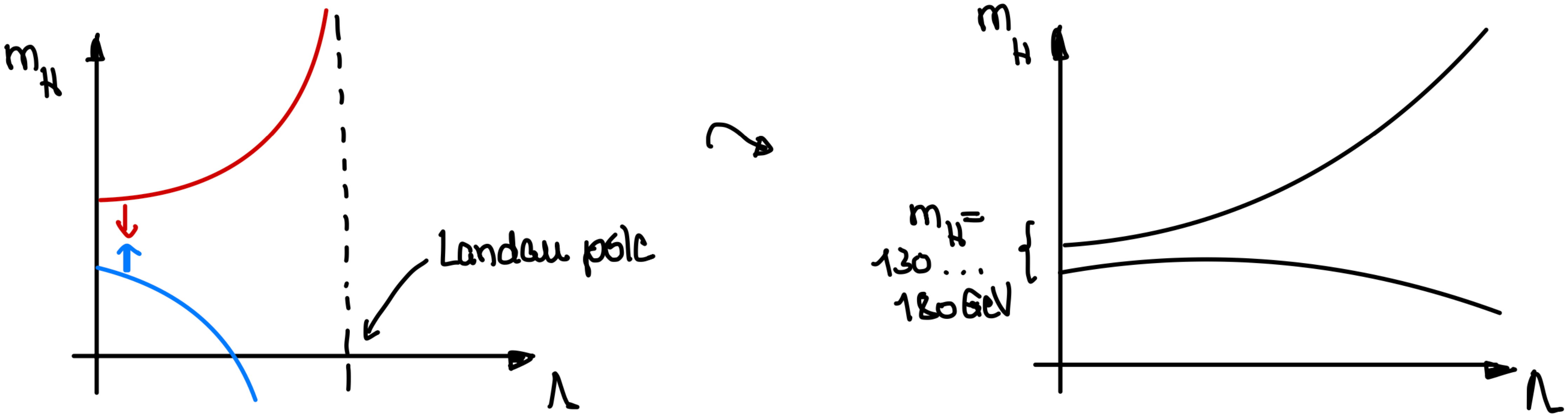
$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{1}{3!} \lambda_{HHH} H^3 + \frac{1}{4!} \lambda_{HHHH} H^4$$

$$\lambda_{HHH} = 3 \frac{M_H^2}{v}$$

quantum corrections to self-coupling from all SM particles

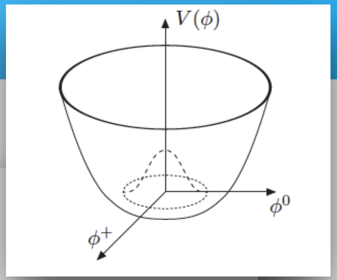


top : negative contribution ; all others positive



if SM valid until Planck scale

Stability of the Electroweak Vacuum



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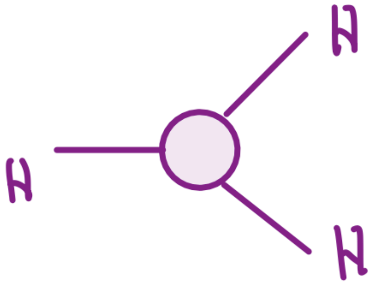
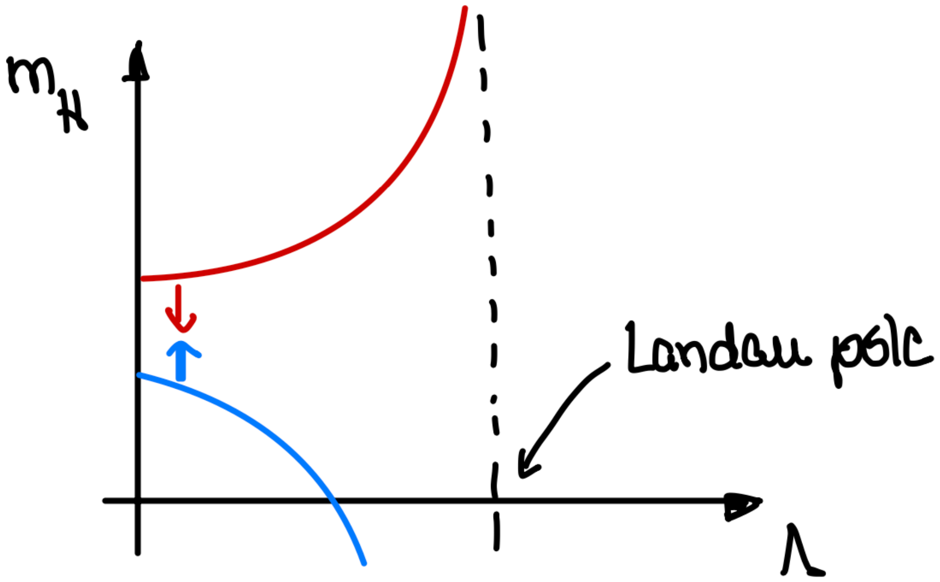
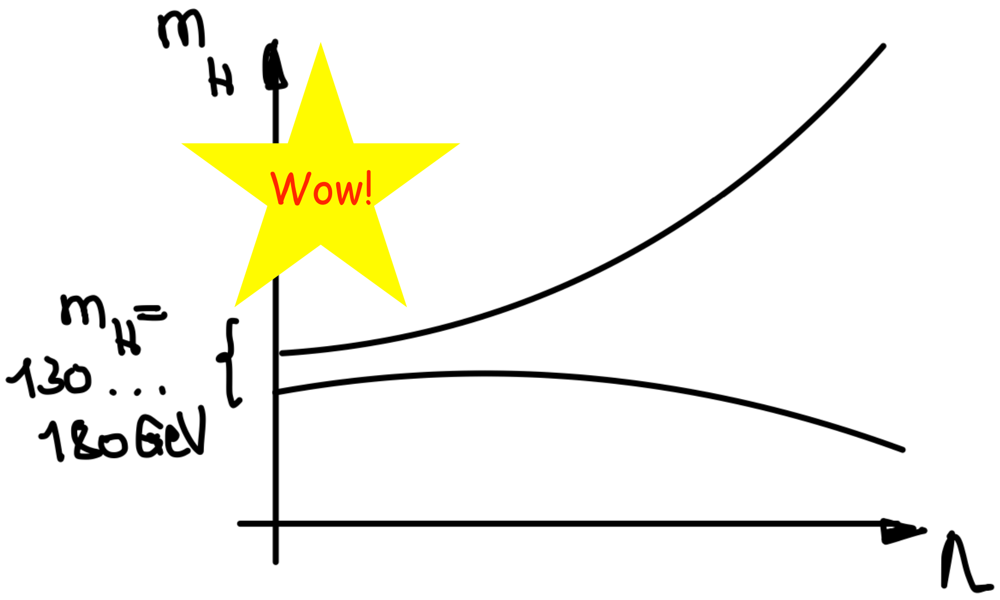
quantum corrections to self-coupling from all SM particles

top : negative contribution ; all others positive



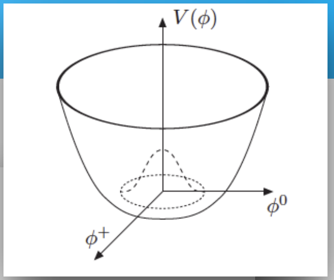


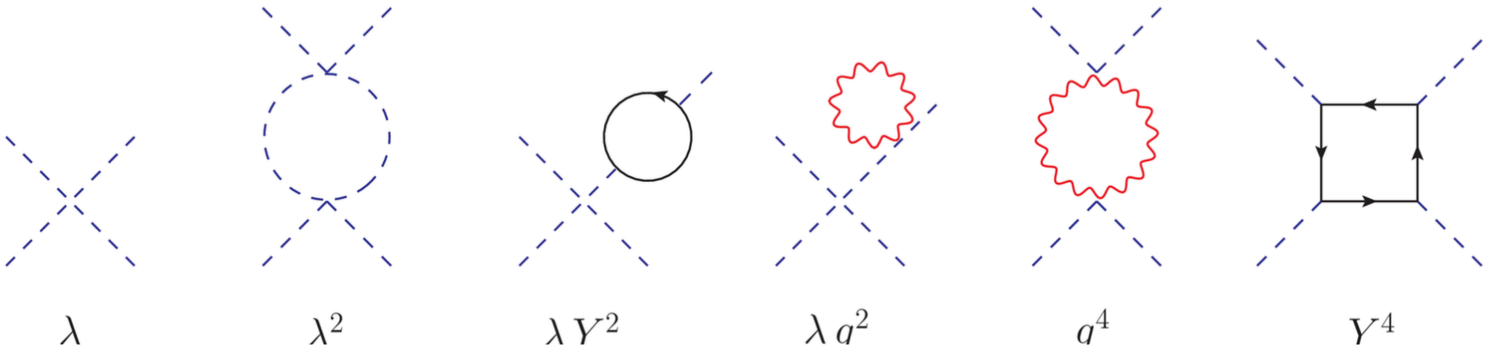
↷



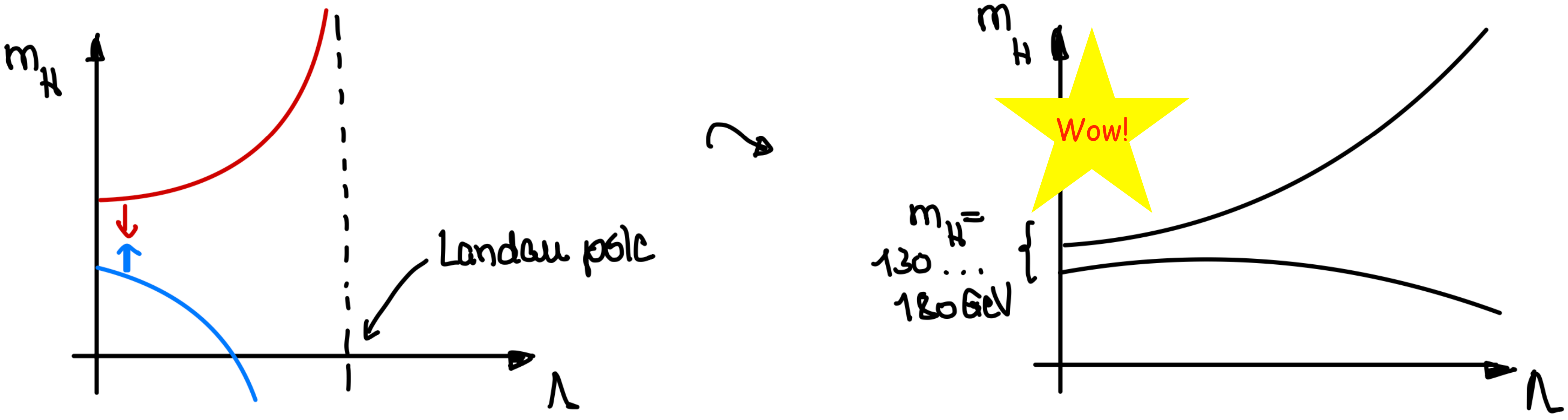
if SM valid until Planck scale

Stability of the Electroweak Vacuum





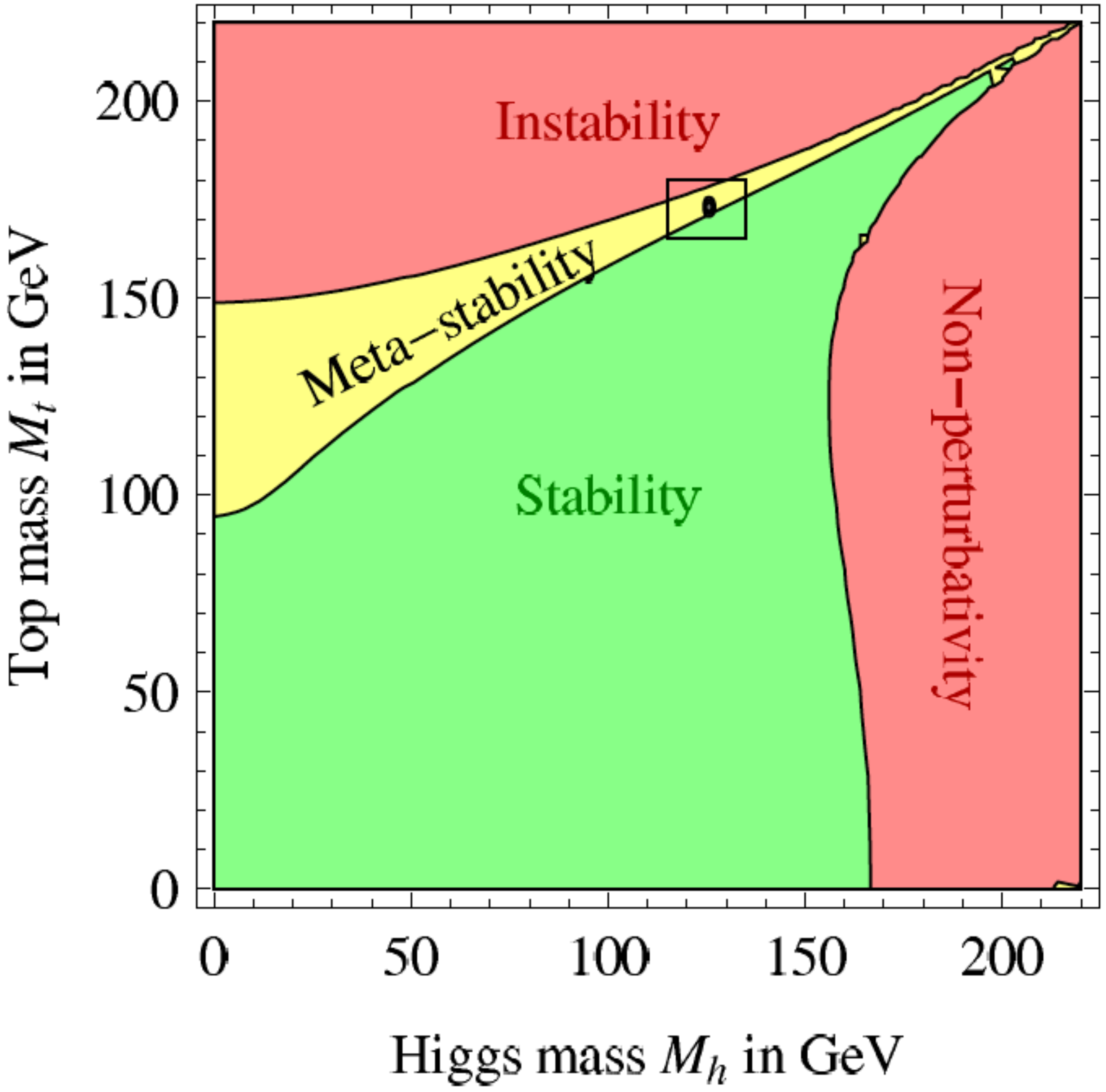
$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_cY_t - 9g^2 - 3g'^2\right) - 2N_cY_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2g'^2 + \ldots\right]$$



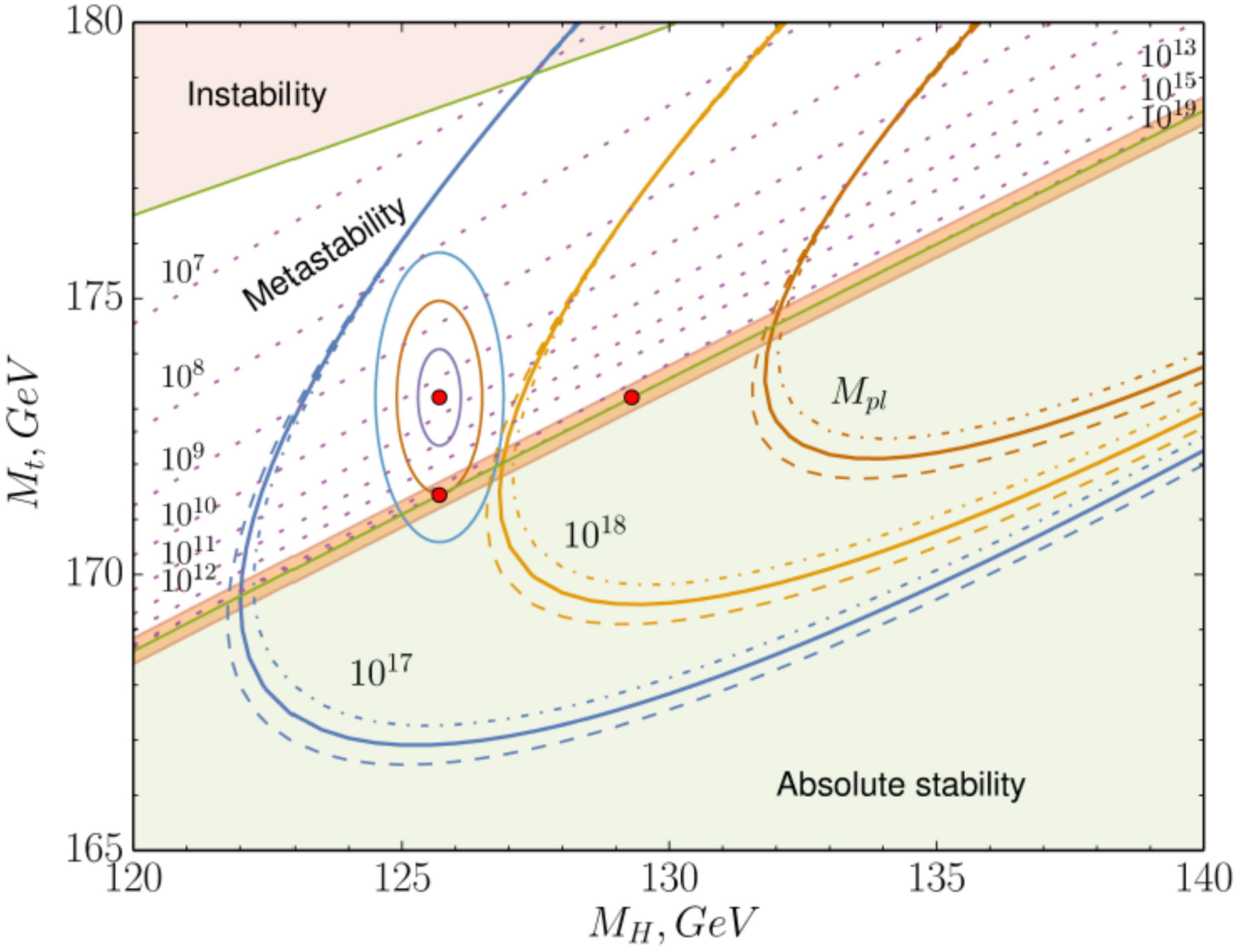
if SM valid until Planck scale

Stability of the Electroweak Vacuum

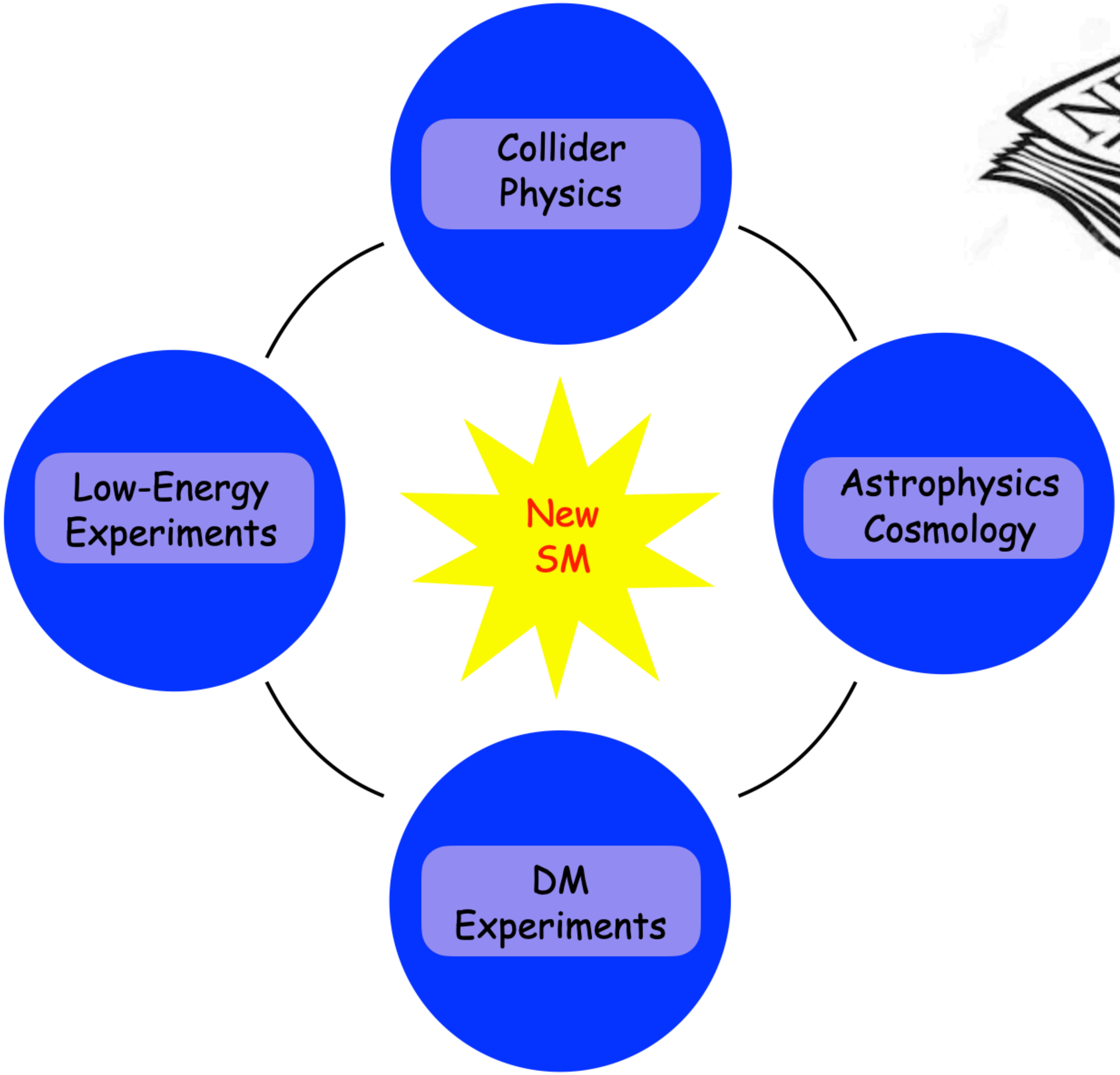
[Degrassi,Di Vita,Elias-Miro,Espinosa,'12]



[Bednyakov,Kniehl,Pikelner,Veretin,'15]

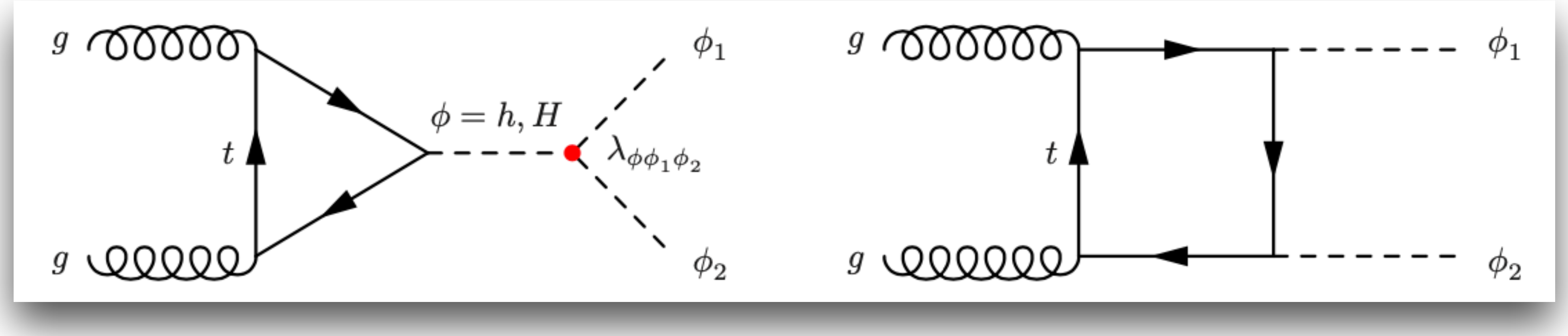


Corner New Physics - Multi-Pronged Approach



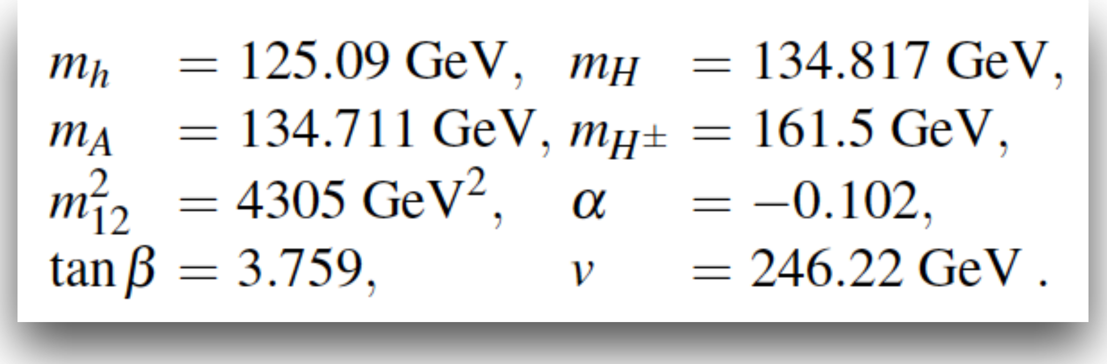
Gluon Fusion into $\phi_1\phi_2$ with $\phi_1\phi_2 = hH, AA$

- Contributing diagrams at leading order:



- 2HDM type 1 benchmark point (compatible w/ theor. & exp. constraints):

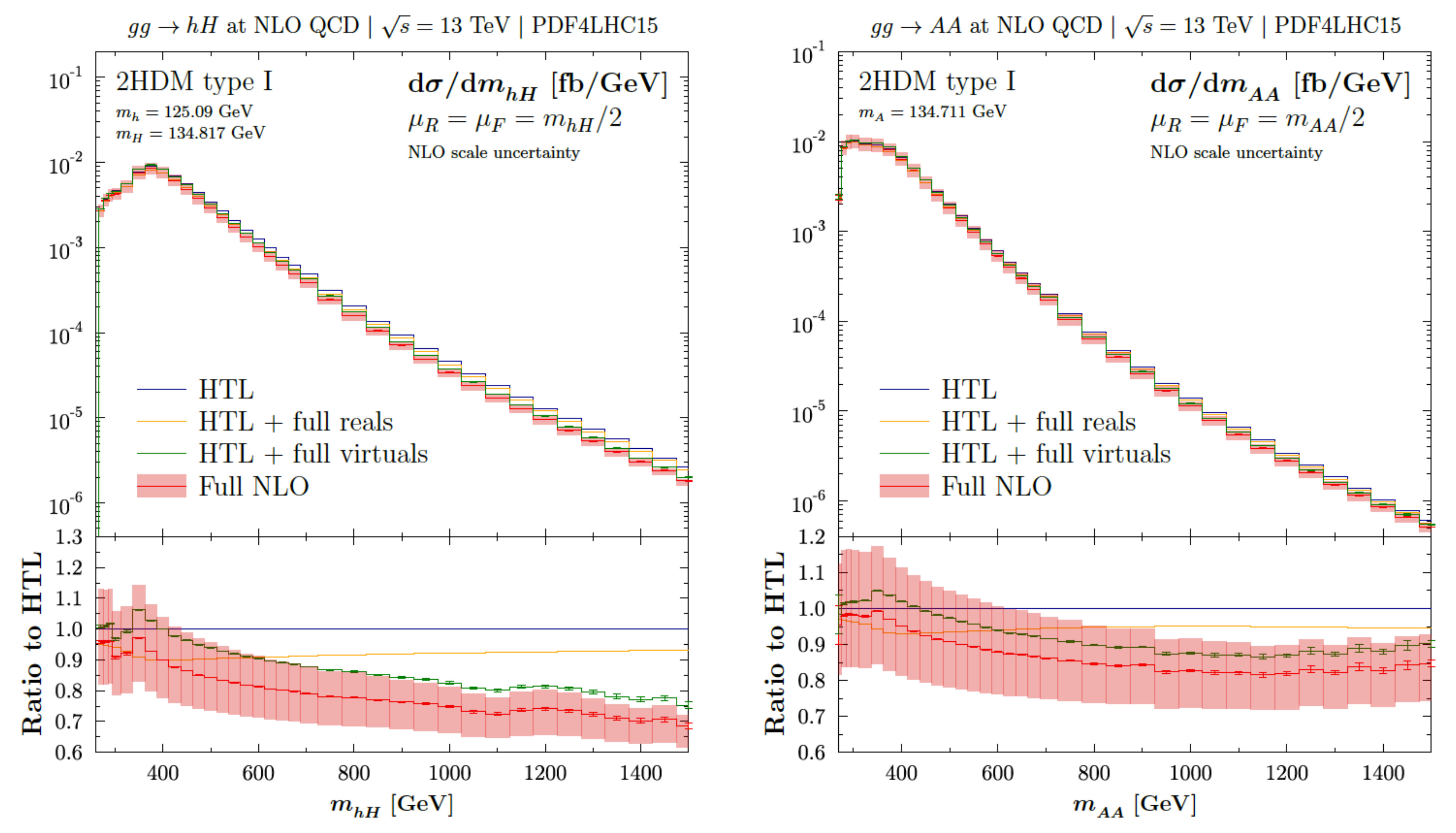
[taken from Abouabid et al.,'22]



$$\begin{aligned} m_h &= 125.09\text{ GeV}, & m_H &= 134.817\text{ GeV}, \\ m_A &= 134.711\text{ GeV}, & m_{H^\pm} &= 161.5\text{ GeV}, \\ m_{12}^2 &= 4305\text{ GeV}^2, & \alpha &= -0.102, \\ \tan\beta &= 3.759, & v &= 246.22\text{ GeV}\ . \end{aligned}$$

NLO Top Mass Effects in Invariant Mass Distributions

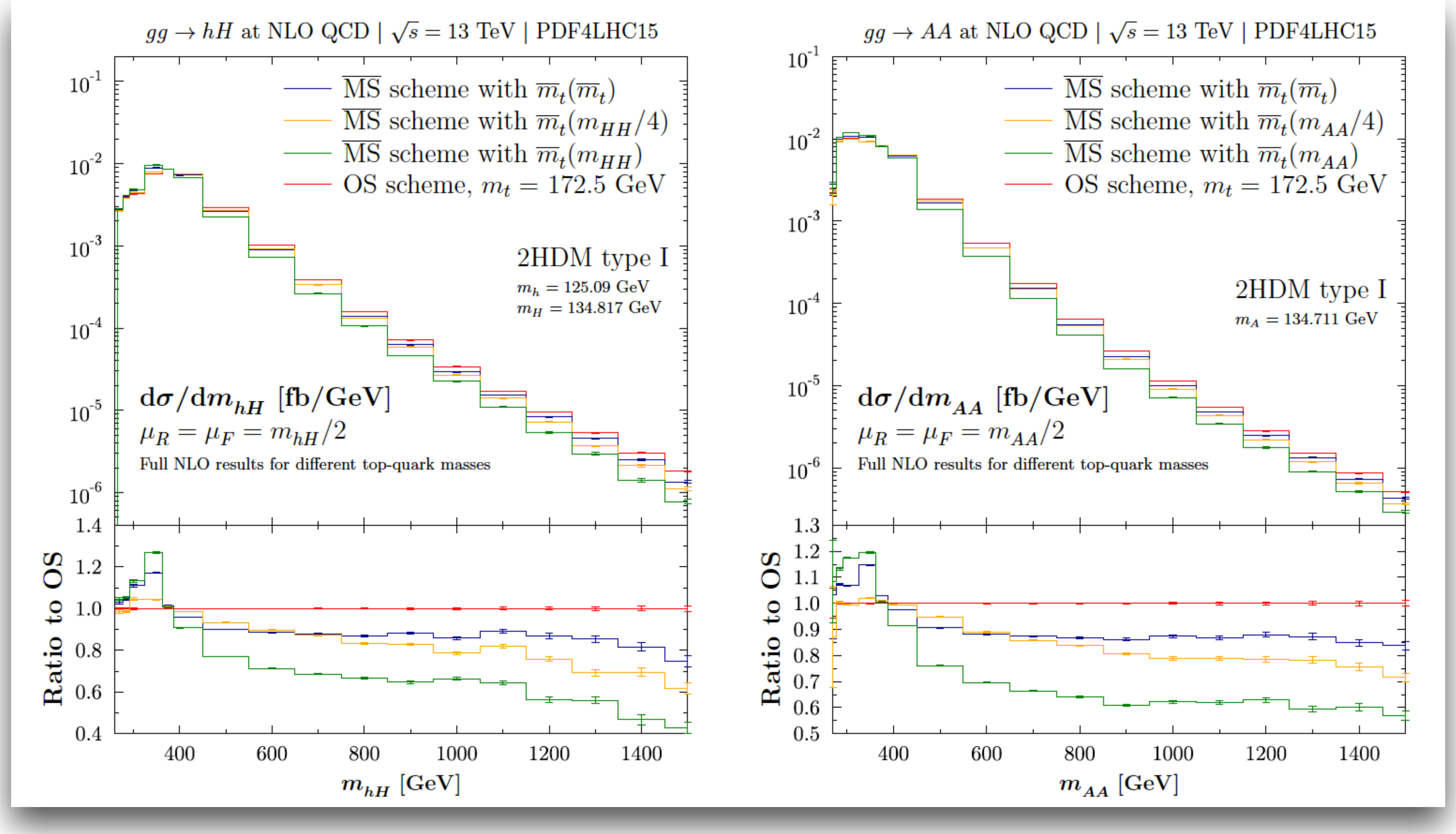
[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]



- Mass effects in distributions: -30% (-15%) at Q~1.5 TeV for hH (AA)
- increases w/ c.m. energy (results provided for 14, 27, 100 TeV)
- Mass effects on total cxn: -12% (-5%) at 13 TeV (increases w/ c.m. energy)

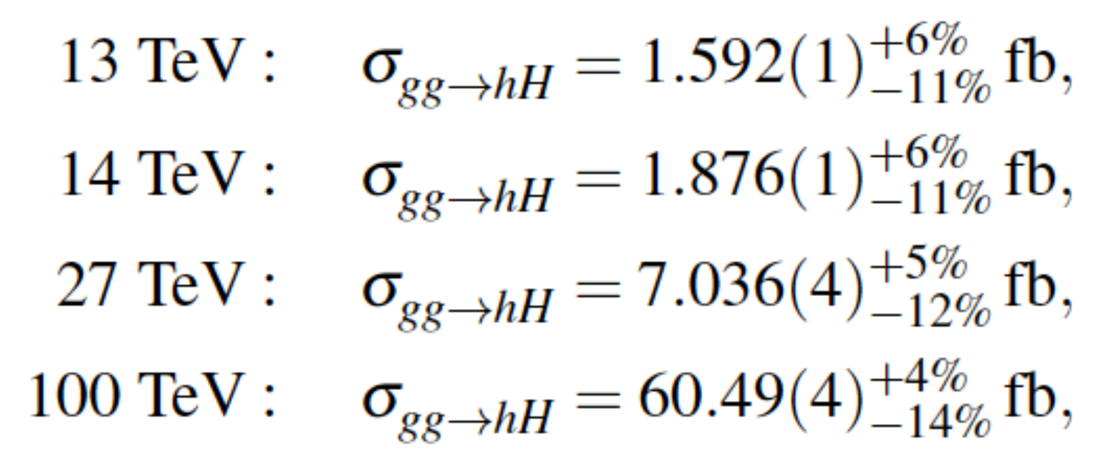
Top Quark Scale and Scheme Uncertainties

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]

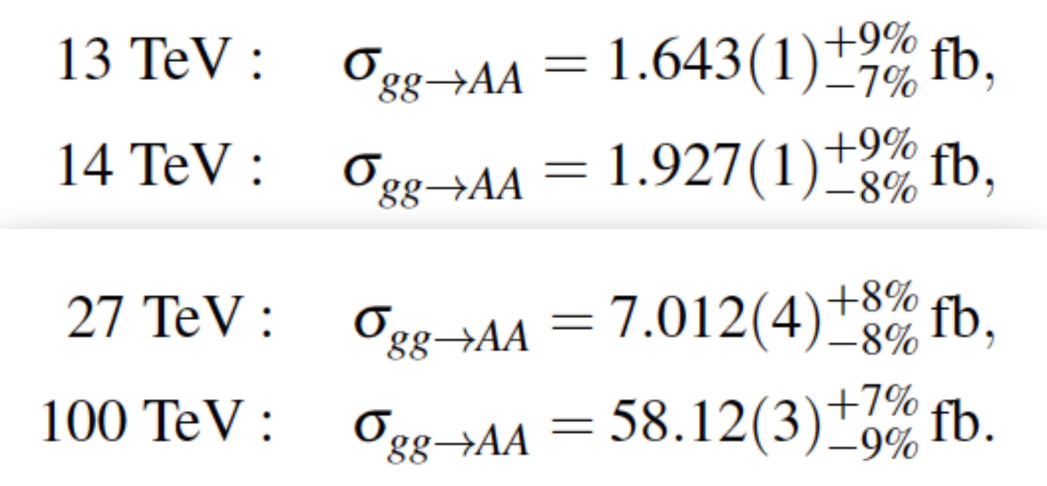


Top Quark Scale and Scheme Uncertainties in Total Cross Section

[Baglio,Campanario,Glaus,MM,Ronca,Spira,'23]



$$\begin{aligned}
13\ \text{TeV}: &\quad \sigma_{gg\to hH} = 1.592(1)^{+6\%}_{-11\%}\ \text{fb},\\
14\ \text{TeV}: &\quad \sigma_{gg\to hH} = 1.876(1)^{+6\%}_{-11\%}\ \text{fb},\\
27\ \text{TeV}: &\quad \sigma_{gg\to hH} = 7.036(4)^{+5\%}_{-12\%}\ \text{fb},\\
100\ \text{TeV}: &\quad \sigma_{gg\to hH} = 60.49(4)^{+4\%}_{-14\%}\ \text{fb},
\end{aligned}$$



$$\begin{aligned}
13\ \text{TeV}: &\quad \sigma_{gg\to AA} = 1.643(1)^{+9\%}_{-7\%}\ \text{fb},\\
14\ \text{TeV}: &\quad \sigma_{gg\to AA} = 1.927(1)^{+9\%}_{-8\%}\ \text{fb},\\
27\ \text{TeV}: &\quad \sigma_{gg\to AA} = 7.012(4)^{+8\%}_{-8\%}\ \text{fb},\\
100\ \text{TeV}: &\quad \sigma_{gg\to AA} = 58.12(3)^{+7\%}_{-9\%}\ \text{fb}.
\end{aligned}$$

SM Effective Theory (SMEFT)

◆ SMEFT approach:

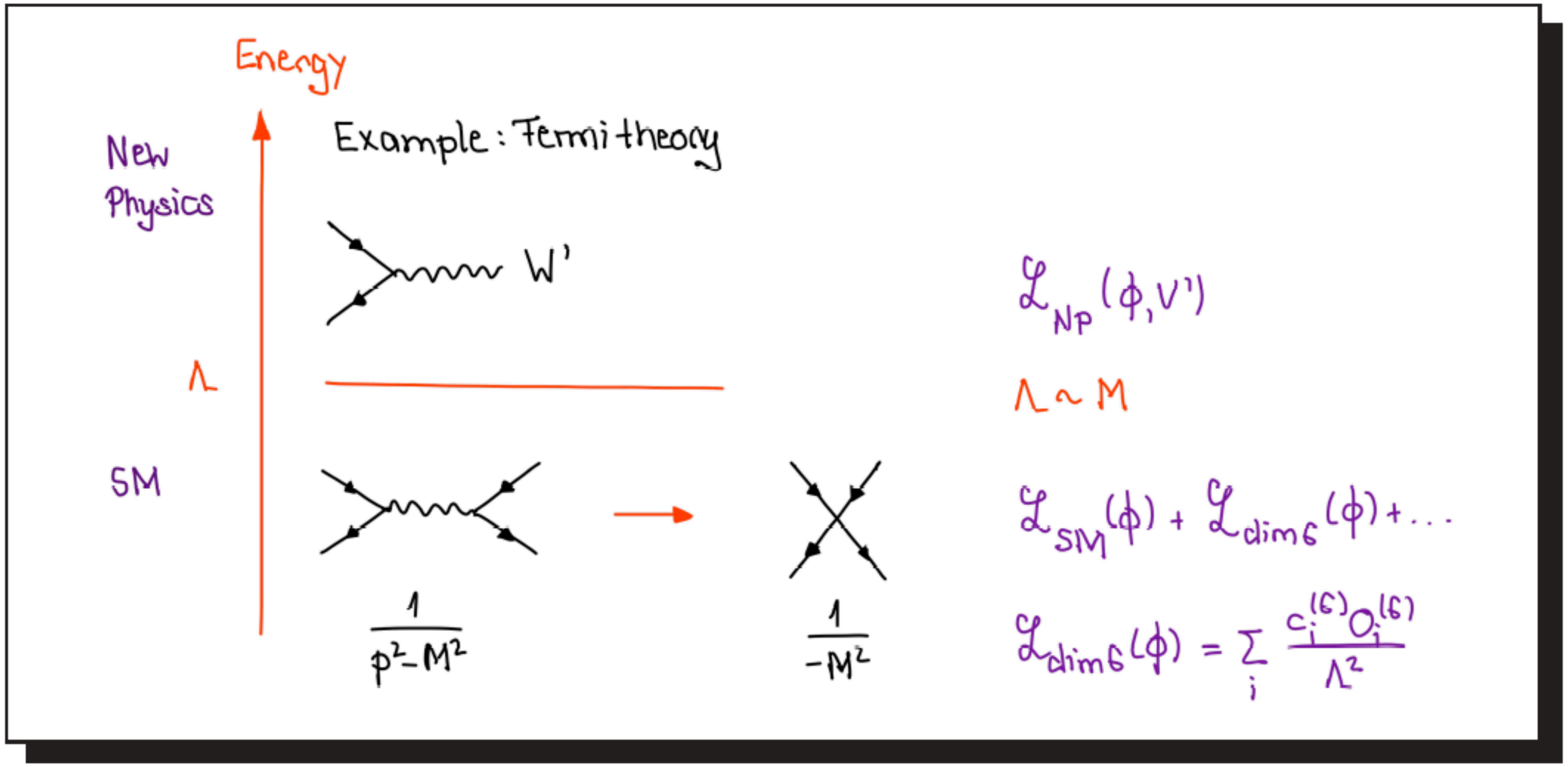
[Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal;
Hagiwara,Ishihara,Szalapski;Zeppenfeld;Giudice eal]

✻ SM field content and SM gauge symmetries, no New Physics at E < Λ

✻ SM deviations: higher-dimensional operators built from SM fields

✻ Operators = low-energy remnants of heavy new physics integrated out at Λ =>

✻ Operators suppressed by scale Λ



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- ✻ Operators = low-energy remnants of heavy new physics integrated out at Λ =>
- ✻ Operators suppressed by scale Λ

◆ New interactions of SM particles: Higgs part of a doublet field (EWSB linearly realized) ~> leading new physics (NP) effects described by D=6 operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Electroweak Chiral Lagrangian (EWChL)

◆ SMEFT approach:

[Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal;
Hagiwara,Ishihara,Szalapski;Zeppenfeld;Giudice eal]

✻ EWSB linearly realized: Higgs boson part of a weak doublet

✻ Additional expansion in $g_* v/\Lambda \ll 1$ (g_* typical coupling of the NP sector)

◆ EW Chiral Lagrangian (EWChL):

[Contino eal; Azatov eal; Alonso eal;
Brivio eal; Elias-Miró eal; Buchada eal]

✻ EWSB non-linearly realized: Higgs treated as singlet

✻ Chiral expansion

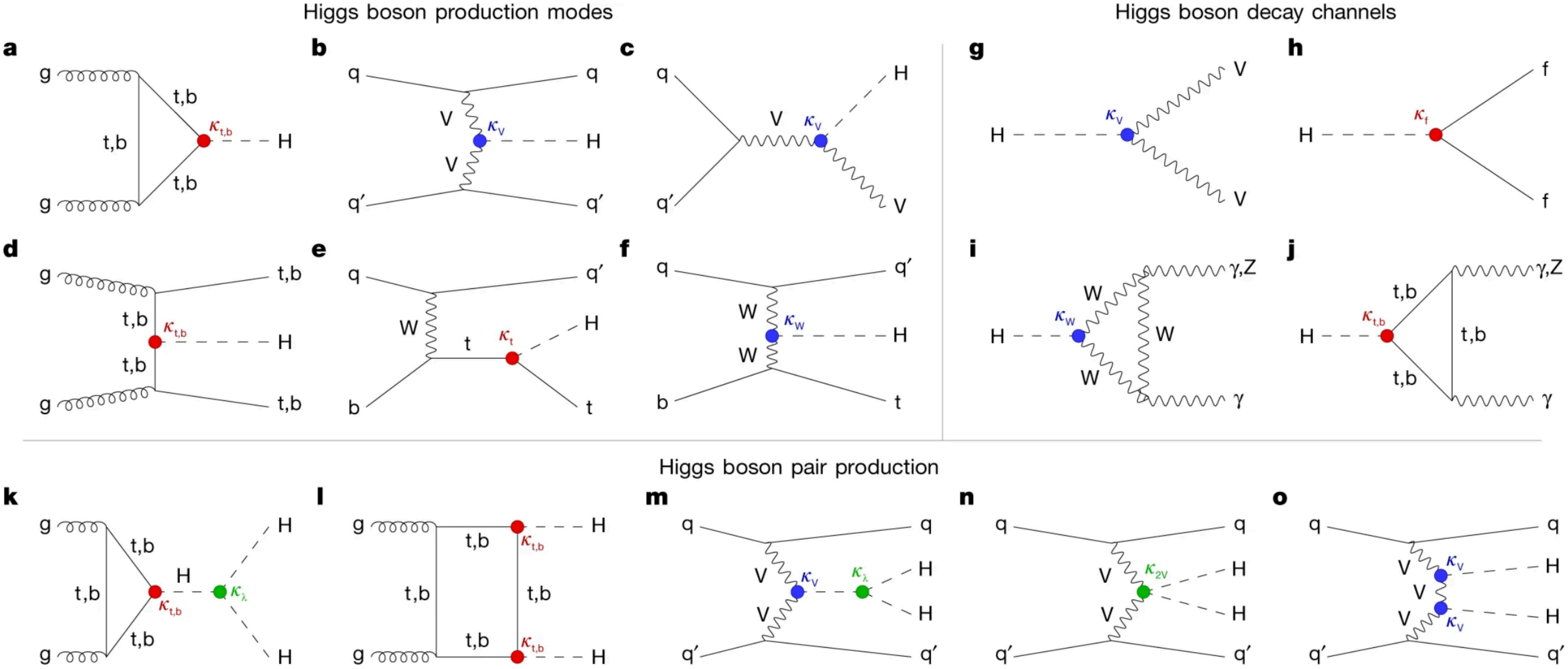
The Kappa Framework

❖ Kappa Framework: Simplest approach

$$\mathcal{L} = \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V \frac{h}{v} + \mathcal{O}(h^2)] - m_{\psi_i} \bar{\psi}_i \psi_i [1 + \kappa_F \frac{h}{v} + \mathcal{O}(h^2)] + \ldots$$

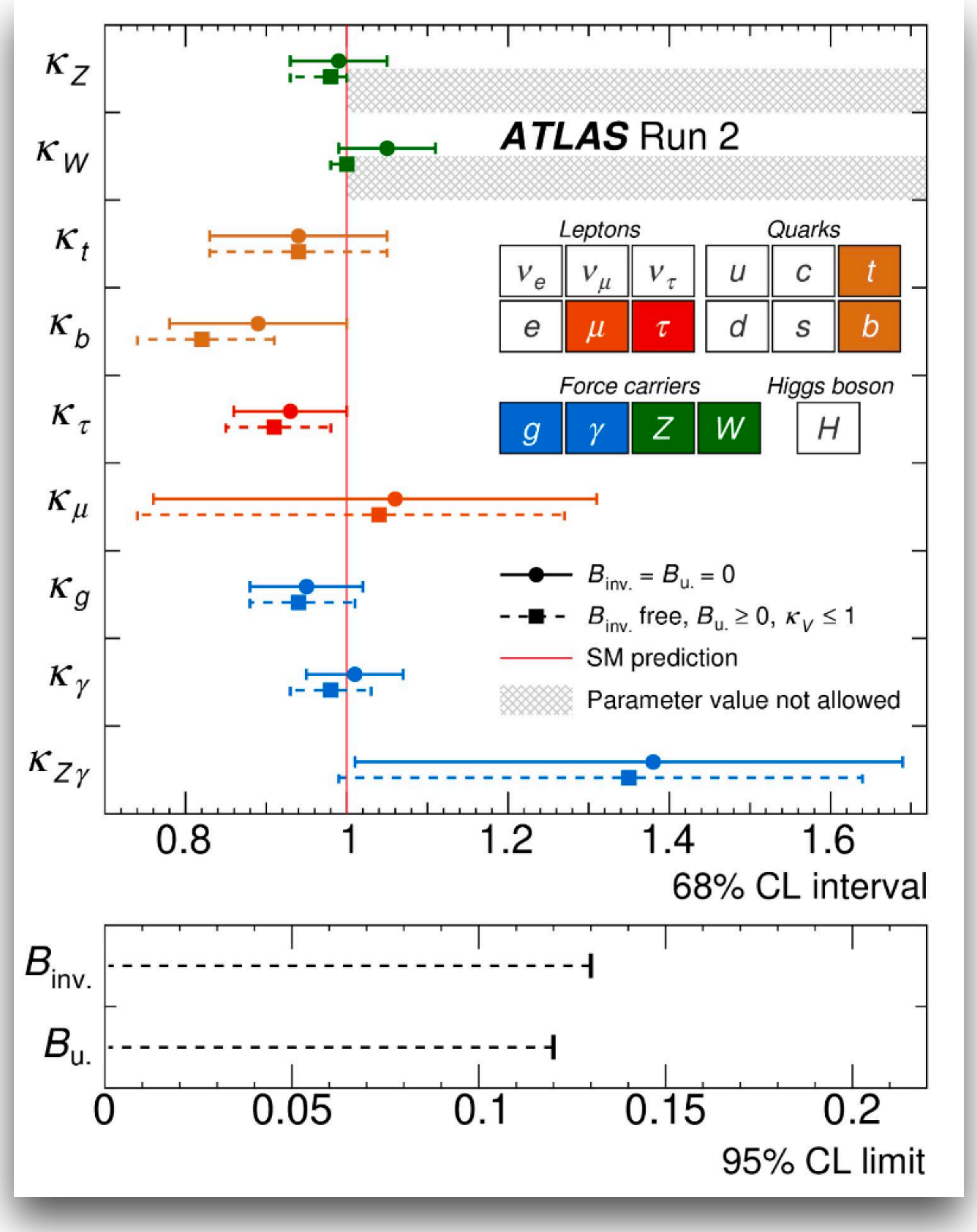
- ✏ $\kappa_W = \kappa_Z \equiv \kappa_V$ justified by assumed custodial symmetry
- ✏ assumes that there are no flavor-changing neutral couplings (FCNCs)
- ✏ loop induced couplings ($H\gamma\gamma$, $HZ\gamma$, Hgg) parametrized in terms of fundamental couplings
- ✏ assumes that there are no invisible or undetected Higgs decays beyond the SM
- ✏ with more data, higher precisions take individual κ_F for the different fermions
- ✏ distributions are also sensitive to the Lorentz structure of the couplings, which is taken to be SM-like in the kappa framework
- ✏ For Γ_{tot} model assumptions have to be made (e.g. Γ_{tot} dominated by partial widths into WW,ZZ,bb,$\tau\tau$,gg,$\gamma\gamma$)

Combined Results

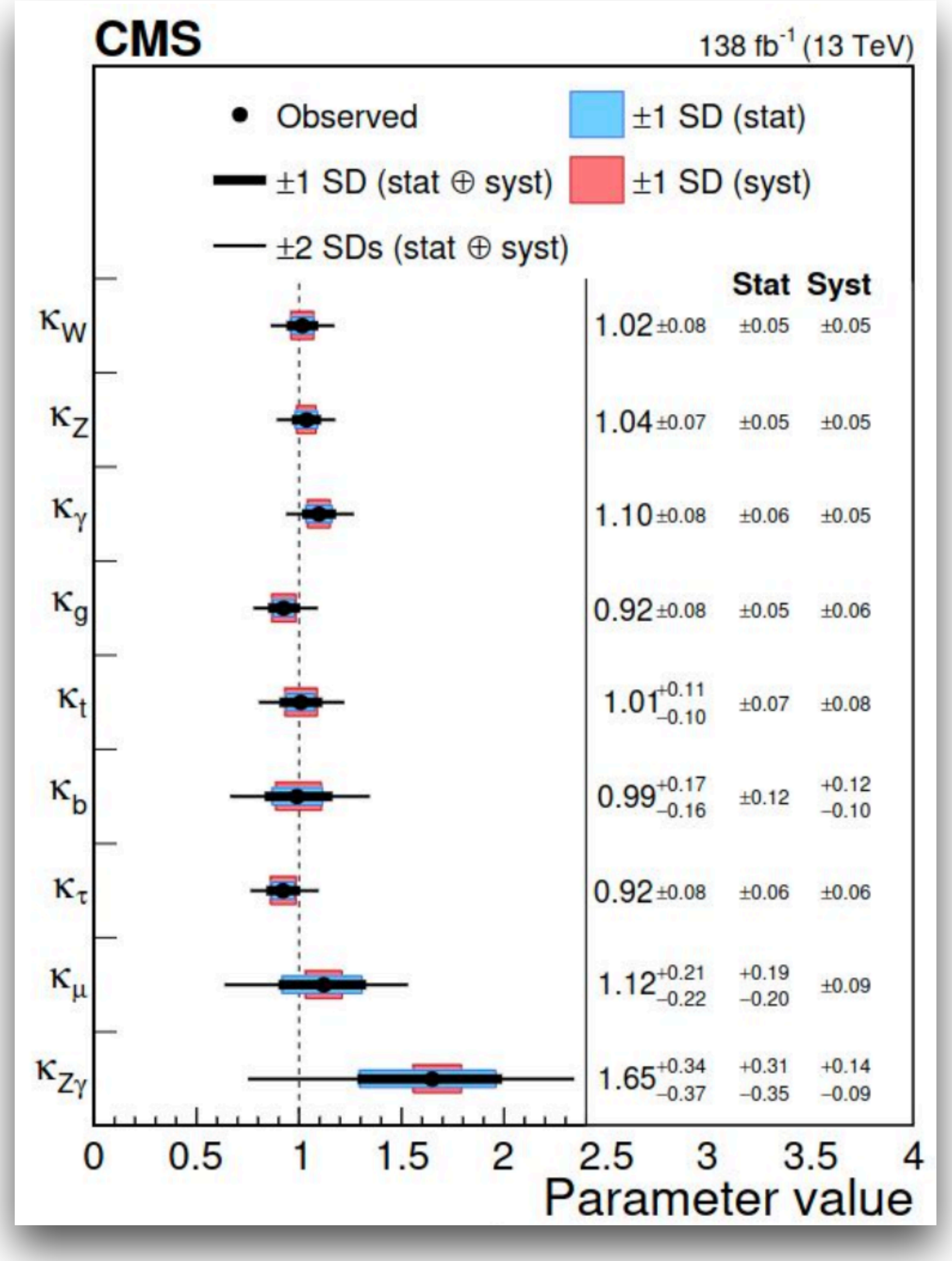


Combined Results

[ATLAS,Nature607(2022)52]



[CMS,Nature607(2022)60]



Experimental Results - Rare Decays: $H \to \bar{c}c$

✏ $H \to \bar{c}c$: relies on VH associate production to trigger interesting events and suppress bkgs

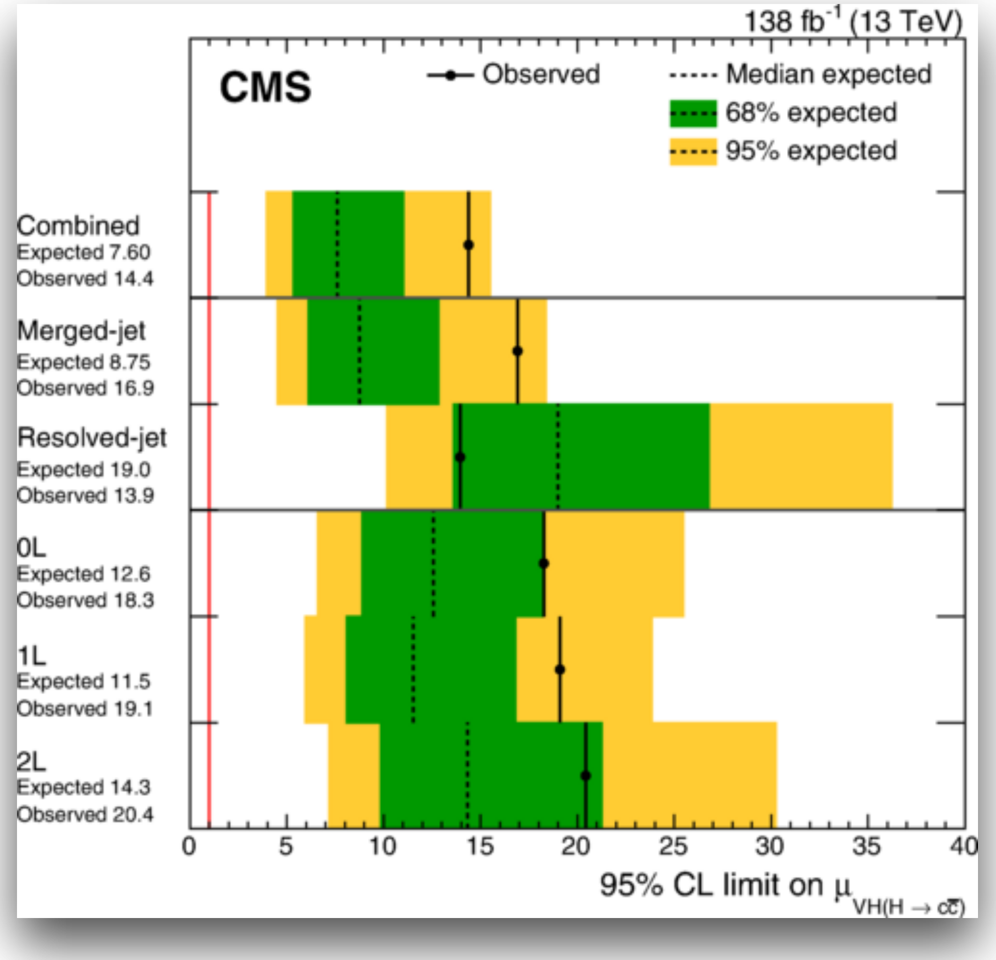
- ➢ CMS: $\sigma(VH) \times \mathrm{BR}(H \to \bar{c}c) < 14\,(7.6^{+3.4}_{-2.3})$ SM at 95% CL,

  $1.1 < |\kappa_c| < 5.5$(expected: $|\kappa_c| < 3.4$) at 95% CL

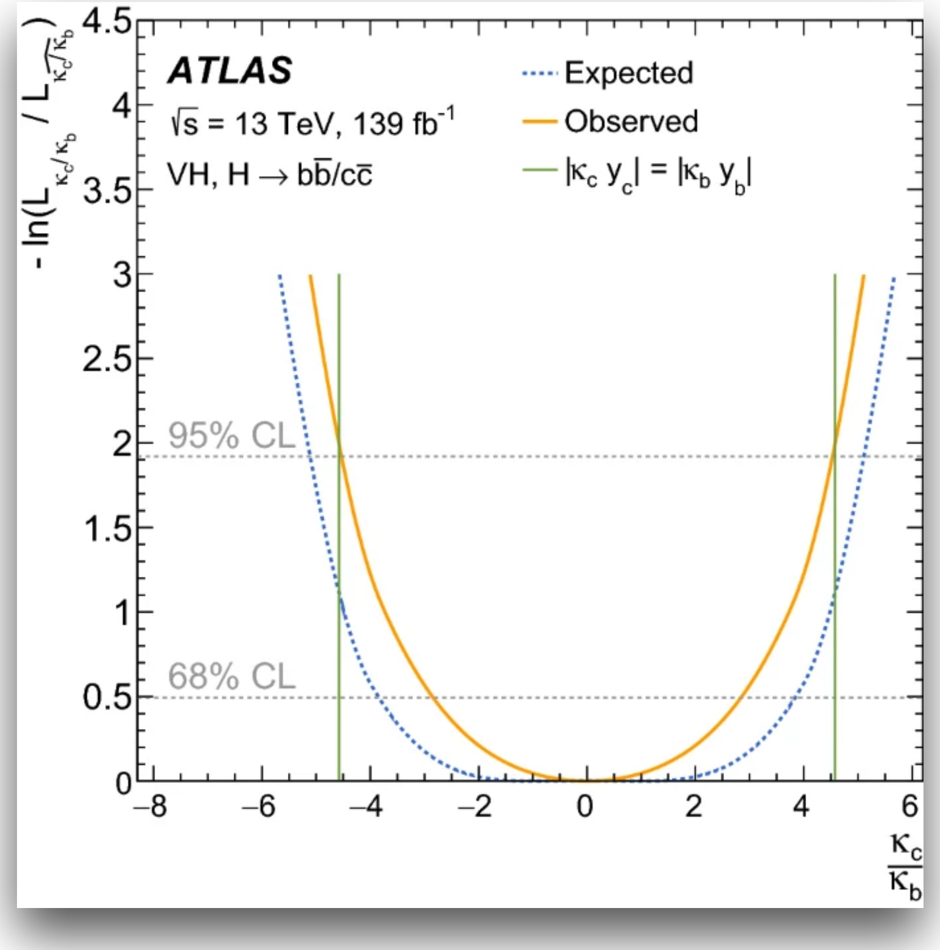
- ➢ ATLAS: $\mu(VH \to \bar{c}c) = -9 \pm 10(\text{stat}) \pm 12(\text{syst})$

  $|\kappa_c| < 8.5\,(12.4)$ at 95% CL

[Phys.Rev.Lett.131.061801]



[Eur.Phys.J.C82(2022)717]



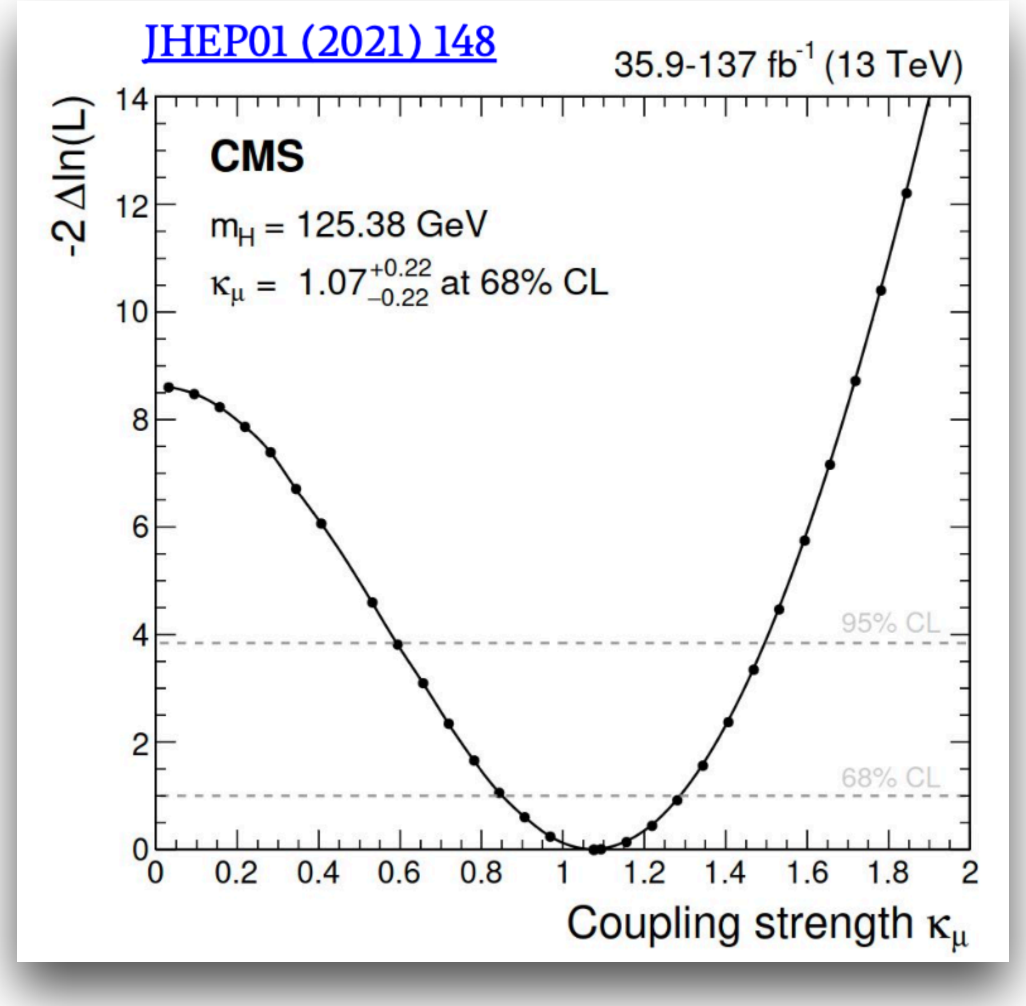
Experimental Results - Rare Decays: $H \to \mu^+\mu^-$

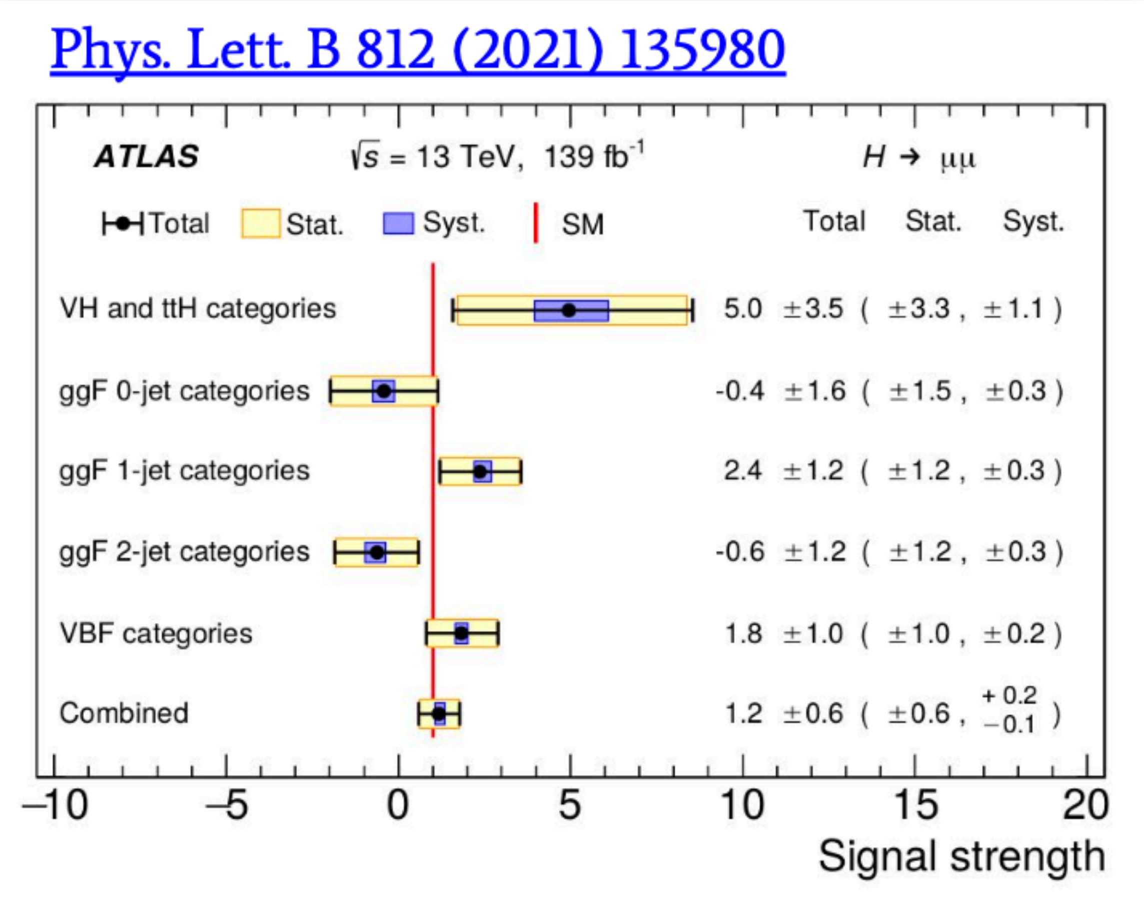
✏ $H \to \mu^+\mu^-$: low branching fraction: include ggF, VBF, WH, ZH, ttH production modes

- CMS: First evidence of $H \to \mu^+\mu^-$ process ($3.0\,\sigma$ significance)

  $\kappa_\mu = 1.07 \pm 0.22$ at 68% CL

- ATLAS: $\mu = 1.2 \pm 0.6$, dominated by statistical uncertainty





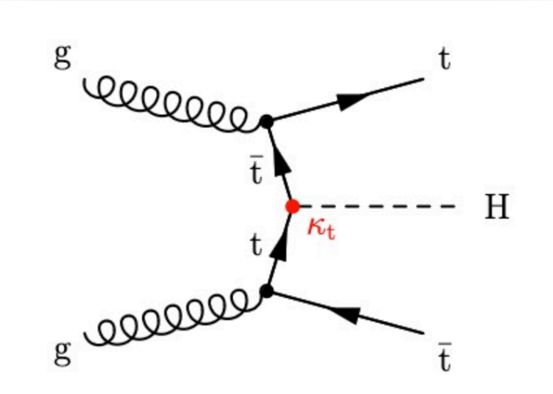
Experimental Results: Targeting $t\bar{t}H \to b\bar{b}$

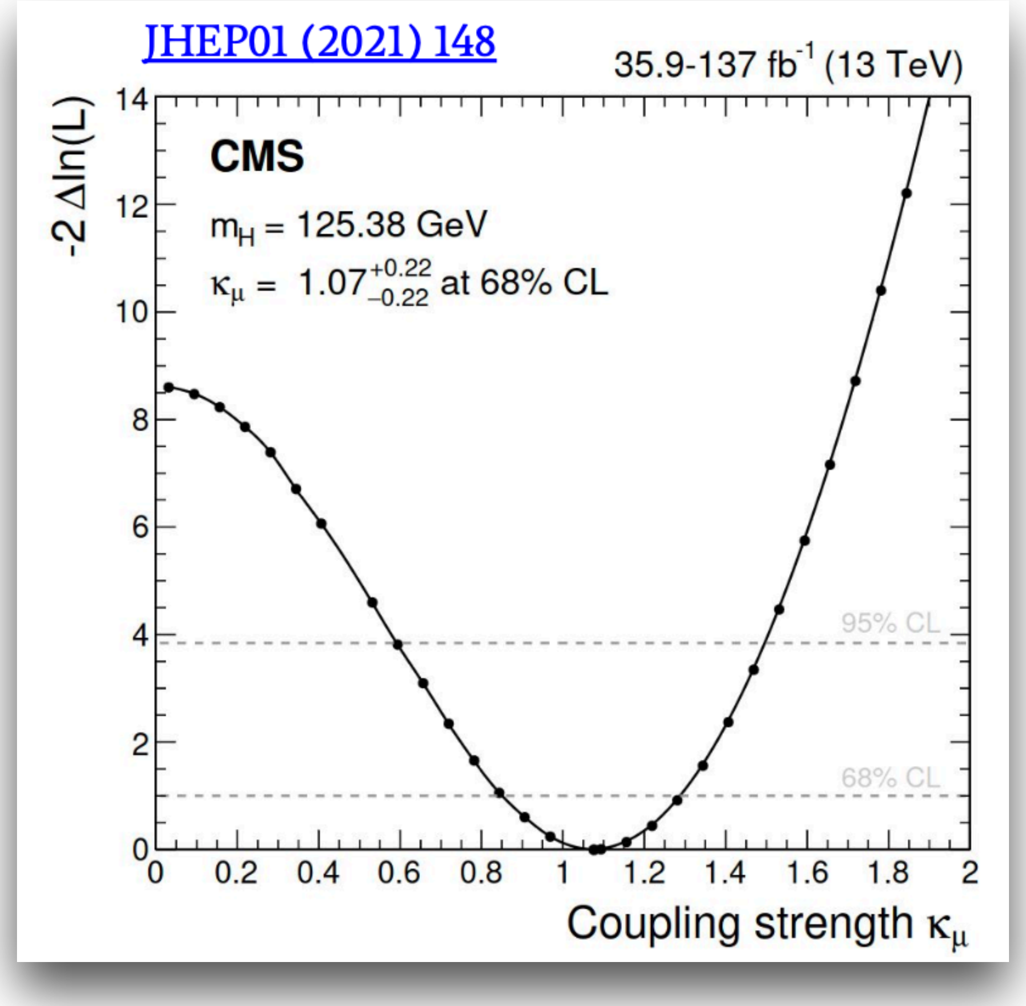
✏ $t\bar{t}H \to b\bar{b}$: allows to measure both κ_t and κ_b

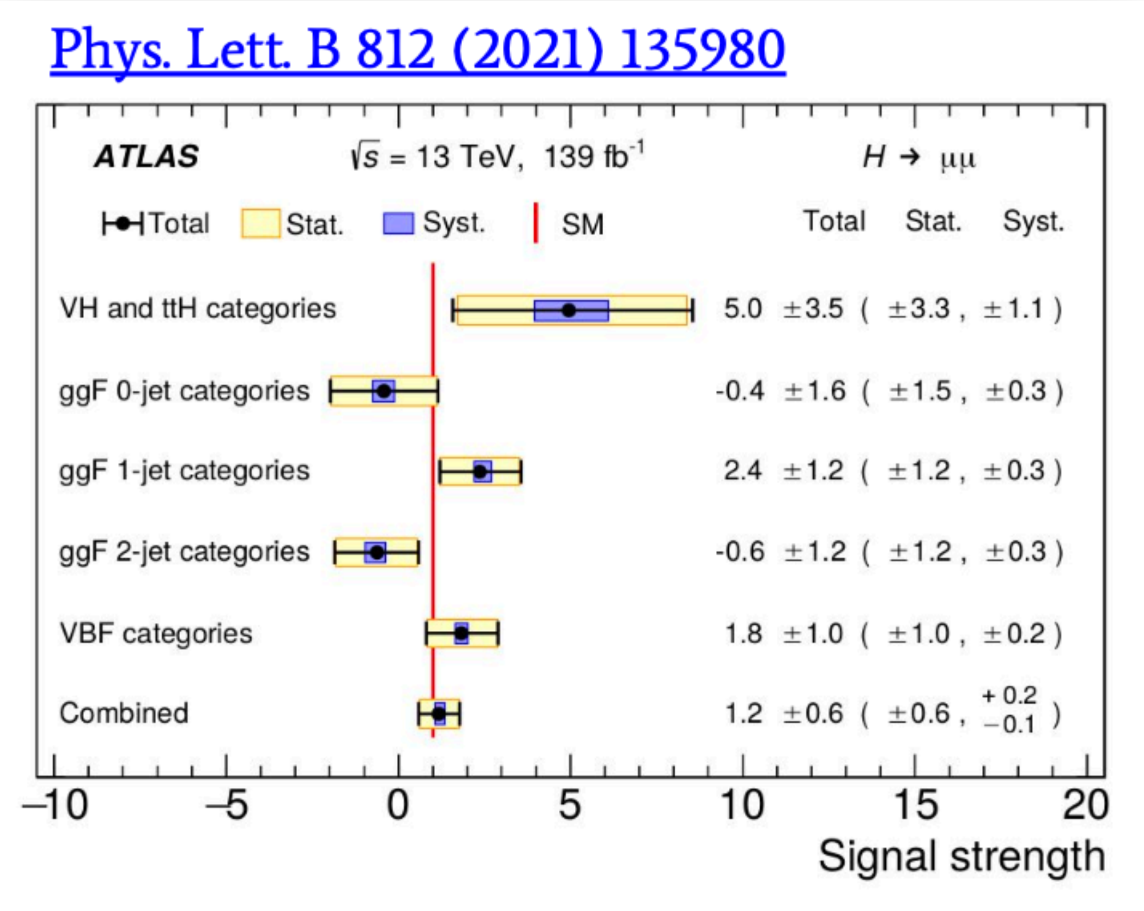
- ➢ CMS: First evidence of $H \to \mu^+\mu^-$ process ($3.0\,\sigma$ significance)

  $\kappa_\mu = 1.07 \pm 0.22$ at 68% CL

- ➢ ATLAS: $\mu = 1.2 \pm 0.6$, dominated by statistical uncertainty



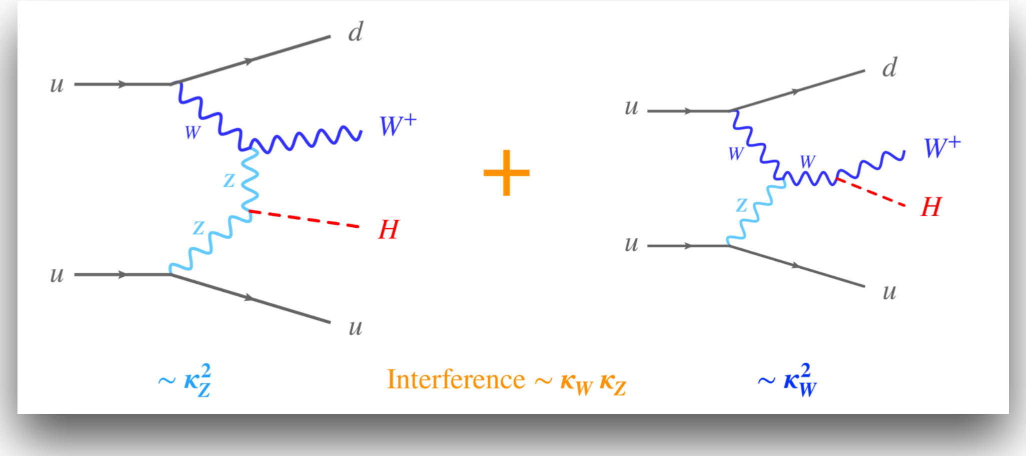

JHEP01 (2021) 148


Phys. Lett. B 812 (2021) 135980

Experimental Results: VBF $WH \to b\bar{b}$

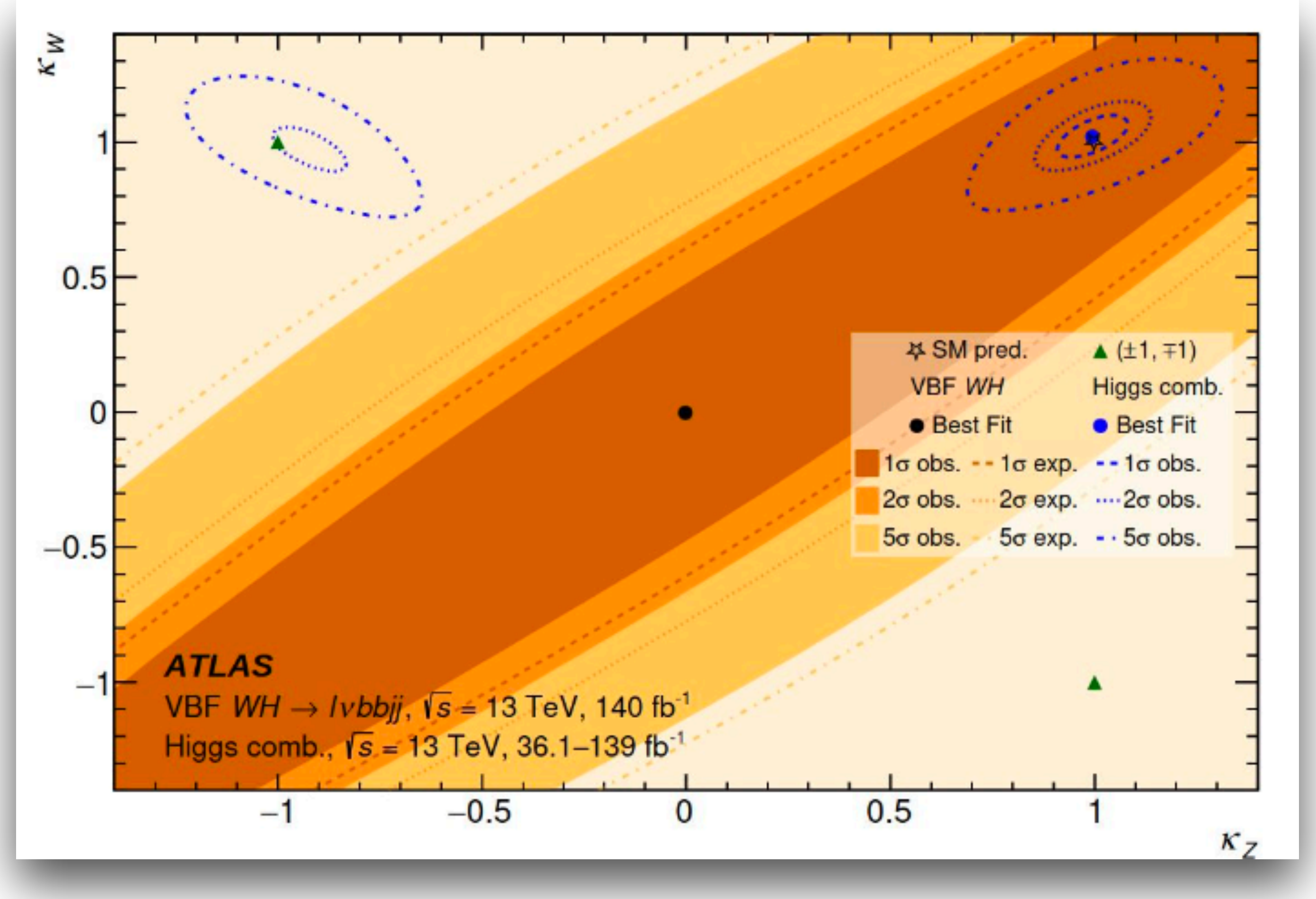
✏ Check relative sign between κ_W & κ_Z in VBF $WH \to b\bar{b}$
($H \to WW/ZZ$ only checks square of κ_W/κ_Z)

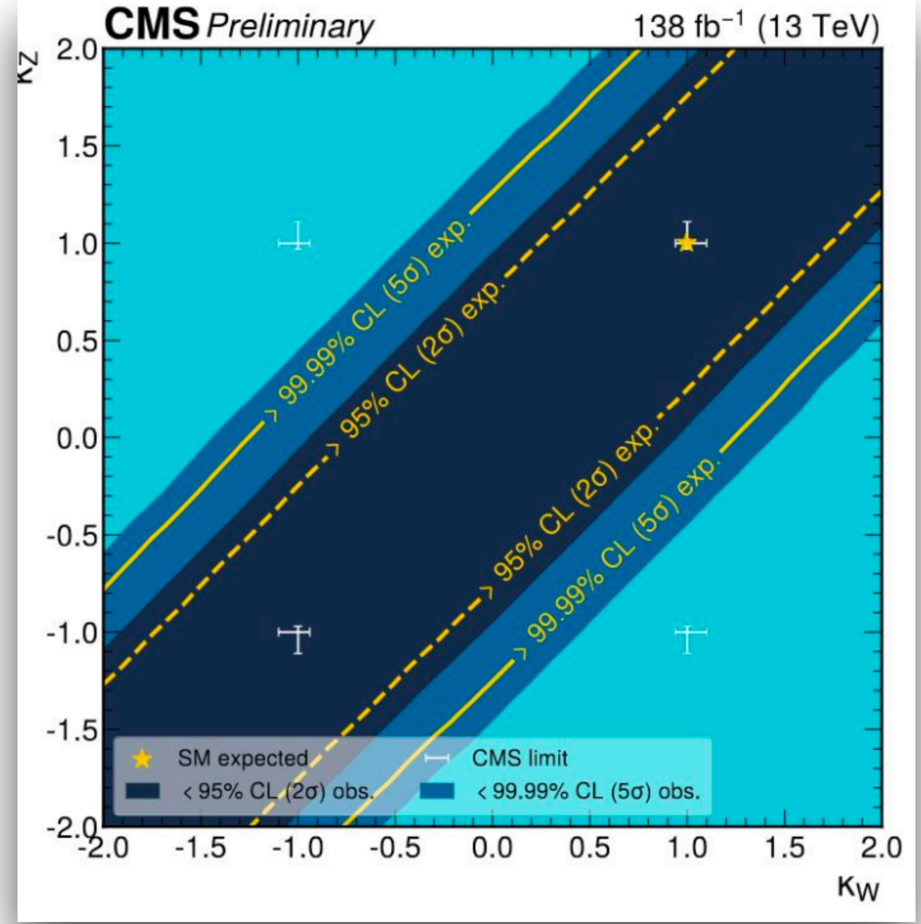
- ➢ SM: $\lambda_{WZ} \equiv \kappa_W/\kappa_Z = 1$, negative λ_{WZ} would enhance VBF WH production
- ➢ ATLAS/CMS:, exclude negative λ_{WZ} at more than 5σ



[ATLAS,arXiv:2402.00426]

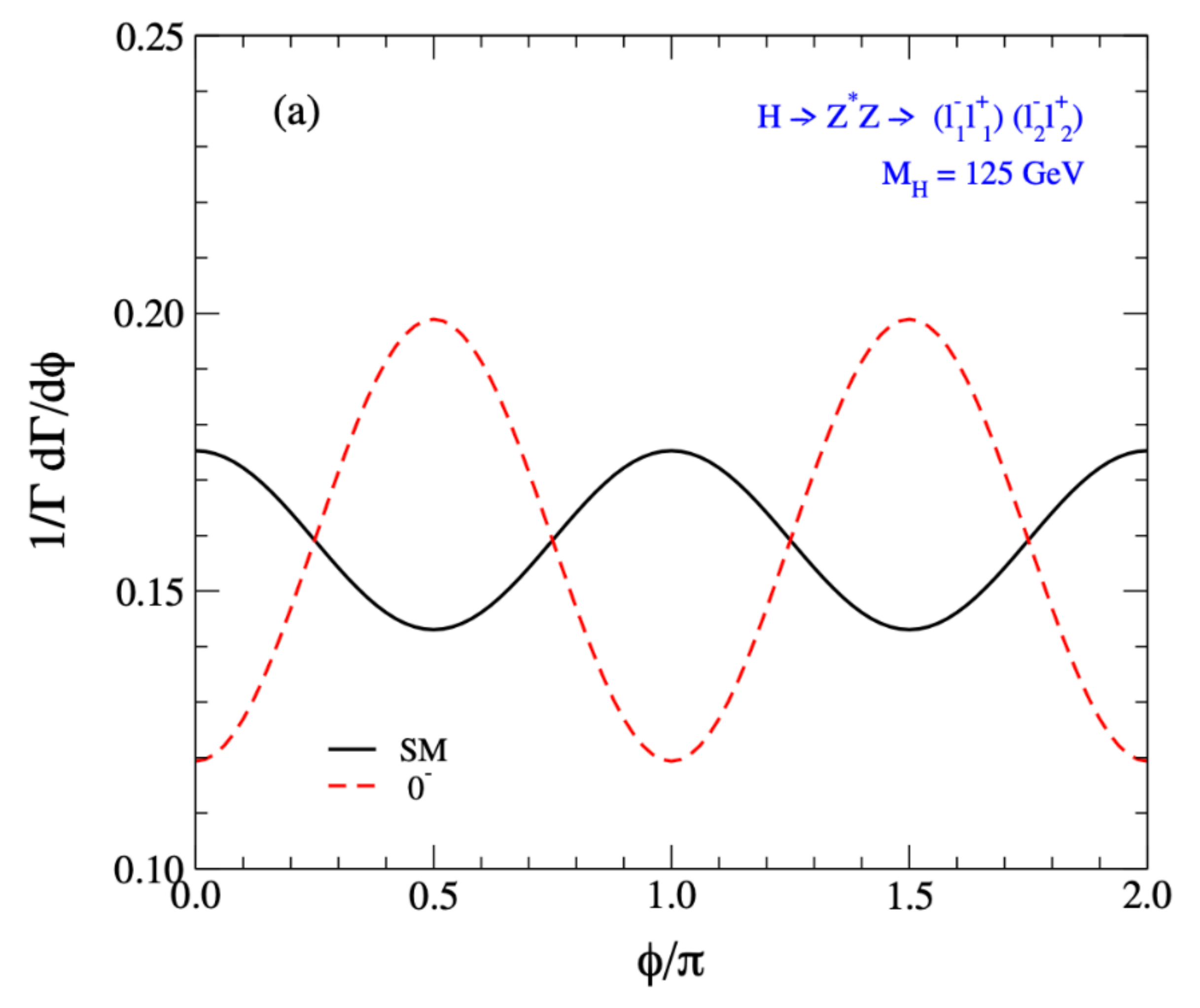
[CMS-HIG-23-007]





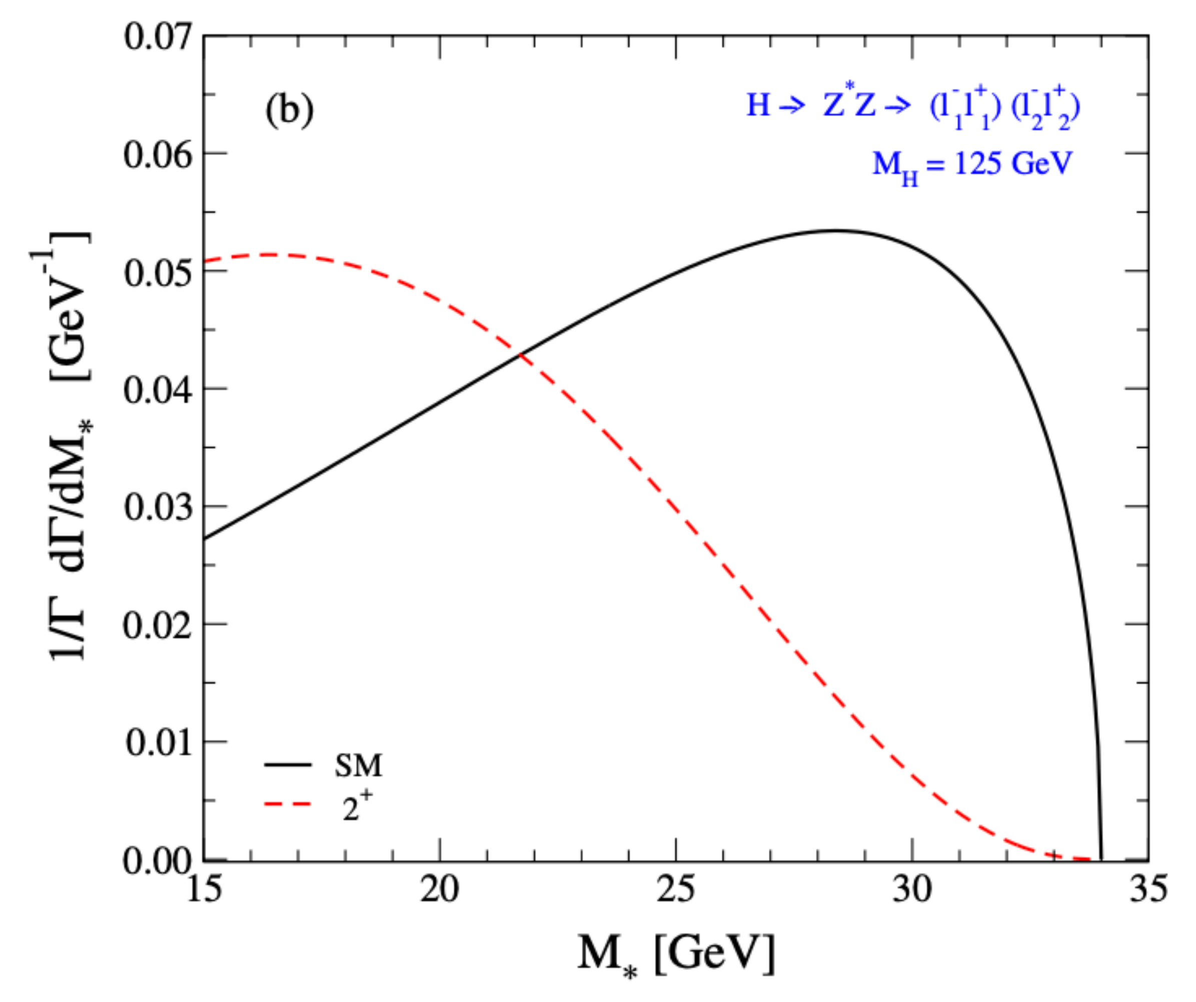
Extraction of Higgs Quantum Numbers

CP-even or CP-odd



[Adapted from Choi,Miller,MM,Zerwas,´03]

Spin 0 or Spin 2

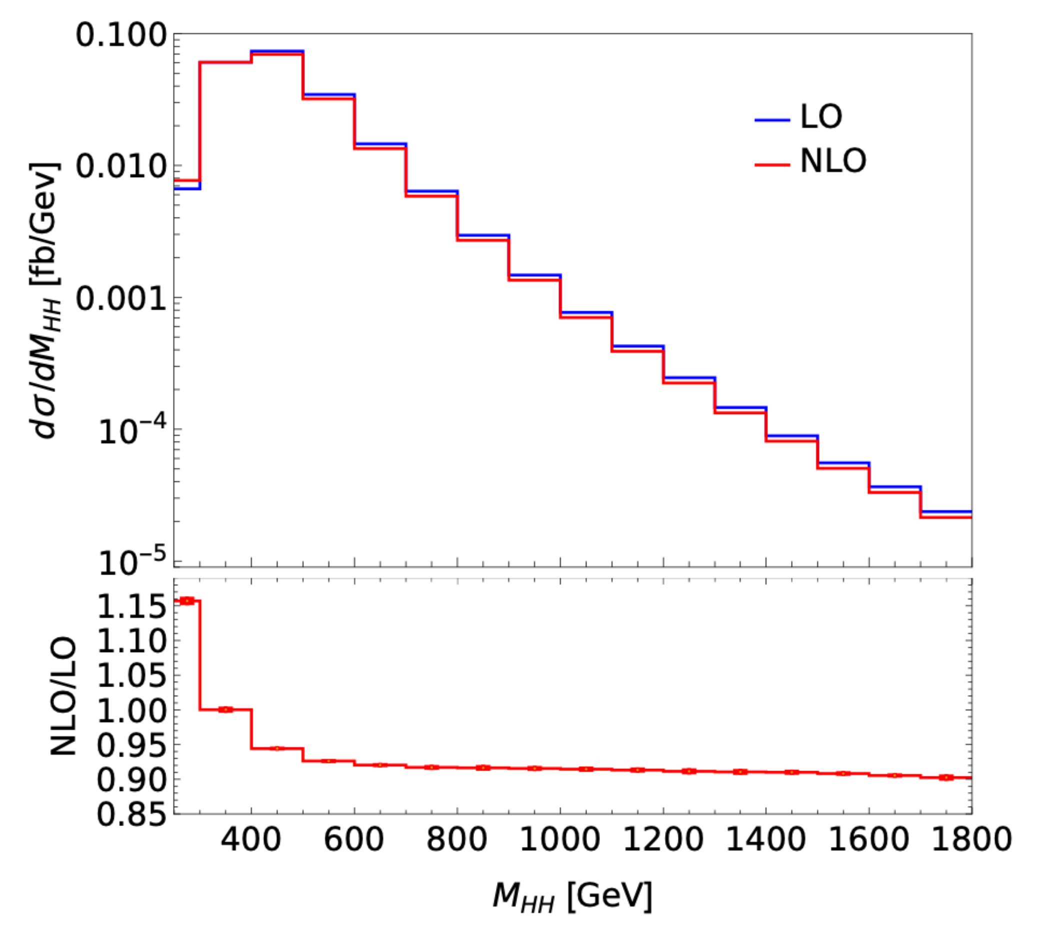


[Adapted from Choi,Miller,MM,Zerwas,´03]

Electroweak Corrections to SM Higgs Pair Production

- Complete NLO EW corrections

[Bi,Huang,Huang,Ma,Yu,'23]



Impact of EW corrections on total cxn: -4%

Impact on differential distributions can be +15%...-10%

Significantly reduced theoretical uncertainty

The Model „CP in the Dark“

- Next-to-Minimal 2-Higgs Doublet Model: [Azevedo,Ferreira,MM,Patel,Santos,Wittbrodt,'18]

$$
\begin{aligned}
V^{(0)} = \; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + \text{ h.c.}\right) \\
& + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2] \\
& + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 \,.
\end{aligned}
$$

- with one discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$

  one SM-like Higgs plus dark sector: h_1,h_2,h_3,$H^\pm$

- trilinear coupling A is complex: dark sector with explicit CP violation <- not constrained by electric dipole moment

Vacuum Structure of „CP in the Dark“

- General vacuum structure at T≠0:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + \omega_1 + i\Psi_1 \end{pmatrix}, \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_2 + \omega_{\text{CB}} + i\eta_2 \\ \zeta_2 + \omega_2 + i(\Psi_2 + \omega_{\text{CP}}) \end{pmatrix}, \Phi_S = \zeta_S + \omega_S$$

electroweak VEVs: ω_1,ω_2 , CP-violating VEV: ω_{CP}

charge-breaking VEV: ω_{CB} (unphysical; found to be zero for all of our scan points)

Z_2-symmetry breaking VEV: ω_S

- General vacuum structure at T=0:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + v_1 + i\Psi_1 \end{pmatrix}, \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_2 + i\eta_2 \\ \zeta_2 + i\Psi_2 \end{pmatrix}, \Phi_S = \zeta_S$$

$$\langle\Phi_1\rangle|_{T=0} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \langle\Phi_2\rangle|_{T=0} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \langle\Phi_S\rangle|_{T=0} = 0$$

$\omega_1|_{T=0\text{ GeV}}$ = v1 ≡ v = 246.22 GeV

Experimental Constraints on Extended Higgs Sectors

✏ Electroweak rho parameter very close to 1: $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \approx 1$ (in SM automatically fulfilled)

- * model with n scalar multiplets ϕ_i with weak isospin I_i, weak hypercharge Y_i and VEVs v_i of the neutral components: rho parameter at tree level

$$\rho_i = \frac{\sum_{i=1}^n [I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i}{\sum_{i=1}^n \frac{1}{2}Y_i^2 v_i}$$

- * SU(2) singlets with $Y=0$ and SU(2) doublets with $Y=\pm 1$ satisfy

$$I(I+1) = \frac{3}{4}Y^2$$

and hence $\rho = 1$

✏ Flavor-changing neutral currents (FCNCs): very stringent constraints from experiment

solution for multi-Higgs models: apply symmetries such that all right-handed fermions of a given electric charge couple to exactly one Higgs doublet (cf. e.g.(N)2HDM type I…IV); minimal flavor violation (flavor violation only arises from CKM matrix)

Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

* Electroweak precision tests (EWPTs): Peskin-Takeuchi resp. S,T,U parameters parametrize potential NP contributions to EW radiative corrections; S,T,U are zero for SM ref. point; assumptions:

- EW gauge group is SU(2)$_L$xU(1)$_Y$ ~> no additional gauge bosons beyond $Z, W^\pm, \gamma$, e.g. no Z´
- New physics couplings from light fermions are suppressed ~> only oblique corrections (= vacuum polarization), no box and vertex corrections need to be considered
- NP energy scale is large compared to the EW scale ~> expansion in q^2/M^2, M = NP scale

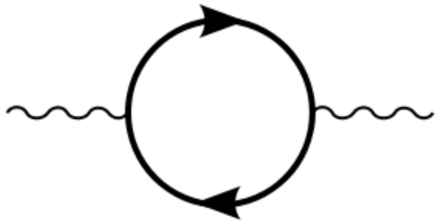
=> parametrization in terms of four vacuum polarization functions: self-energies of the $Z, W^\pm, \gamma$ and mixing between Z and γ induced by loop diagrams

$$\Pi_{\gamma\gamma}(q^2) = q^2\Pi'_{\gamma\gamma}(0)+\dots$$

$$\Pi_{Z\gamma}(q^2) = q^2\Pi'_{Z\gamma}(0)+\dots$$

$$\Pi_{ZZ}(q^2) = \Pi_{ZZ}(0) + q^2\Pi'_{ZZ}(0)+\dots$$

$$\Pi_{WW}(q^2) = \Pi_{WW}(0) + q^2\Pi'_{WW}(0)+\dots$$



$$\alpha S = 4s_w^2c_w^2\left[\Pi'_{ZZ}(0) - \frac{c_w^2 - s_w^2}{s_w c_w}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$

$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha U = 4s_w^2\left[\Pi'_{WW}(0) - c_w^2\Pi'_{ZZ}(0) - 2s_wc_w\Pi'_{Z\gamma}(0) - s_w^2\Pi'_{\gamma\gamma}(0)\right]$$

Experimental Constraints on Extended Higgs Sectors

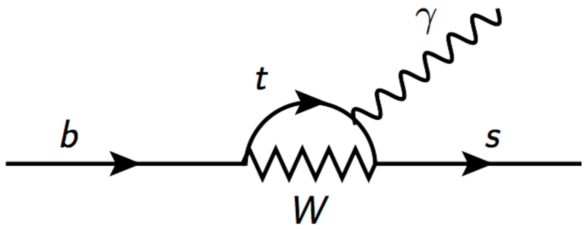
✏ Further constraints:

- Electroweak precision tests S,T,U parameters
  - S parameter: measures difference between left-handed & right-handed fermions w/ weak isospin ~> tightly constrains number of new fourth-generation chiral fermions
  - T parameter: measures isospin violation (<- sensitive to loop corrections to Z and W vacuum polarization)
  - S and T parameter: affected by varying the Higgs boson mass
    Before discovery: mass of Higgs boson constrained by EWPTs to lie within close to LEP lower bound (114 GeV) and 200 GeV.
  - U parameter: not very useful in practice, parametrizes dim-8 effects

- Flavour constraints: NP effects to flavor observables from loop corrections
  - Example: $B \to X_s \gamma$ receives NP contributions from $H^\pm$ exchange;
    sets lower bound of about 800 GeV on $m_{H^\pm}$ in the 2HDM type II

[Deschamps eal,'09;Mahmoudi,Stal,'09;Hermann eal,'12;Misiak eal,'15; Misiak,Steinhauser,'17;Misiak,Rehman,Steinhauser,'20]

SM diagram:



Experimental Constraints on Extended Higgs Sectors

✏ Further constraints:

* Higgs data:
- one of the Higgs bosons has to have a mass of 125 GeV and behave very SM-like, i.e. comply with LHC Higgs data
- remaining Higgs bosons have to comply with LHC exclusion limits from searches for additional Higgs bosons

* Direct searches for new particles predicted by the model:
- model has to respect exclusion limits on these particles (e.g. lower bounds on stop or gluino masses in supersymmetric models)

* Low-energy observables like the anomalous magnetic moment

* Electric Dipole Moment (EDM) constraints: stringent constraints on CP violation in CP-violating models

* Dark Matter (DM) observables (relic density, direct and indirect detection limits): constrains models w/ DM candidate

Theory Constraints on Extended Higgs Sectors

✏ Theory constraints: (will be discussed in detail below)

* Higgs potential bounded from below

* EW vacuum with v=246 GeV is the global minimum

* Perturbative unitarity

Parameter Scans of the Models

Parameter scans w/ constraints:
Reduction of the parameter space
to the still allowed parameter space
~> sharpens predictions of the models

✏ Parameter scans performed with ScannerS: [Coimbra,Sampaio,Santos;MM,Sampaio,Santos,Wittbrodt]

ScannerS: Tool for performing scans in models with extended Higgs sectors checking for the theoretical and experimental constraints

- link to HiggsTools to check for Higgs constraints [Bahl,Biekötter,Bechtle,Heinemeyer,Li,Paasch,Weiglein,Wittbrodt]
- link to MicrOMEGAs to check for Dark Matter constraints [Bélanger,Boudjema,Pukhov eal]