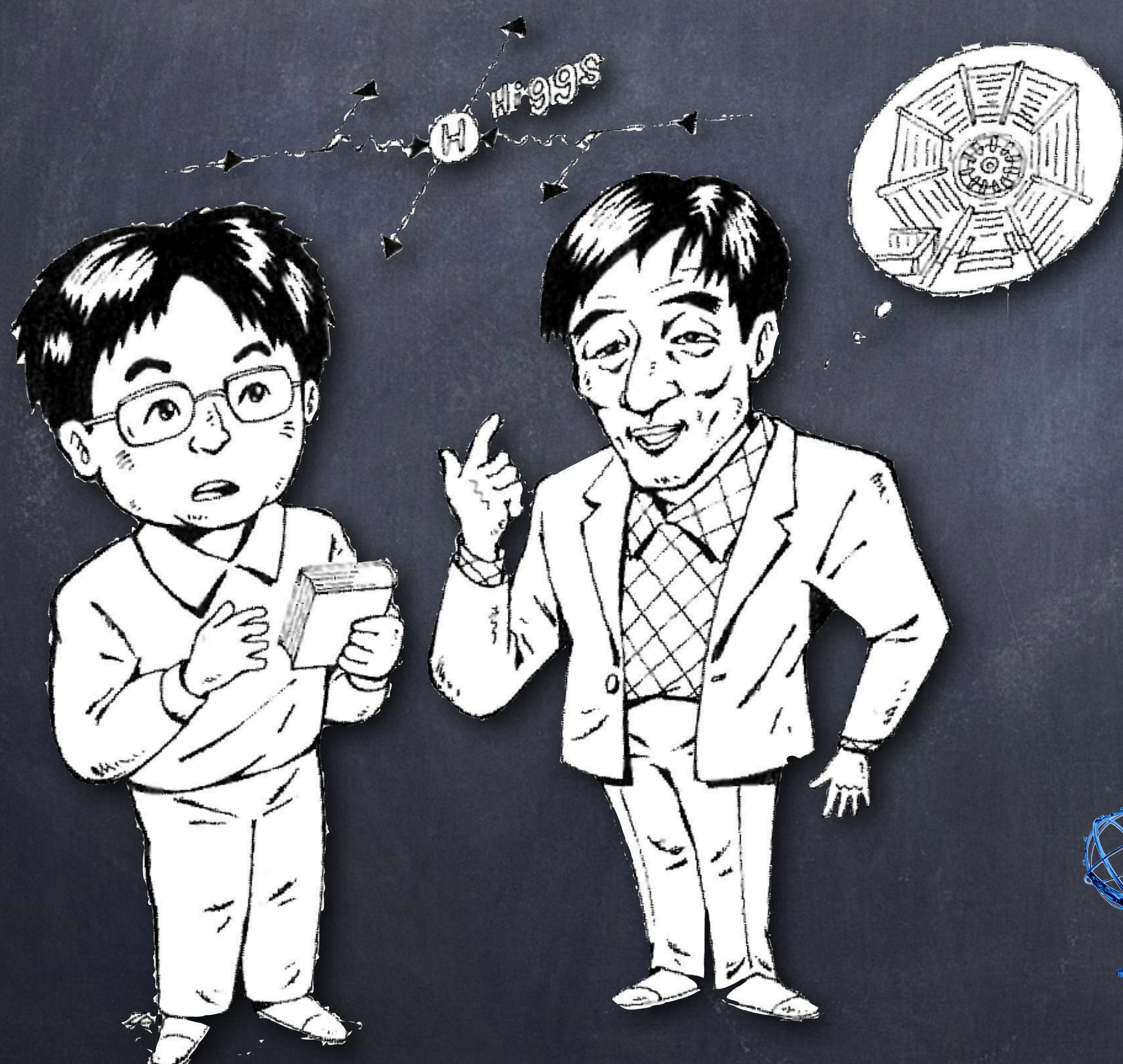
# *Experimental Aspects and Perspectives on Higgs Physics at LHC*



KAGAKU, Vol.79 No.5, May 2009

Reisaburo Tanaka (IJCLab, Orsay)

on occasion of Michael Spira’s 60th Birthday

September 19, 2014, PSI Switzerland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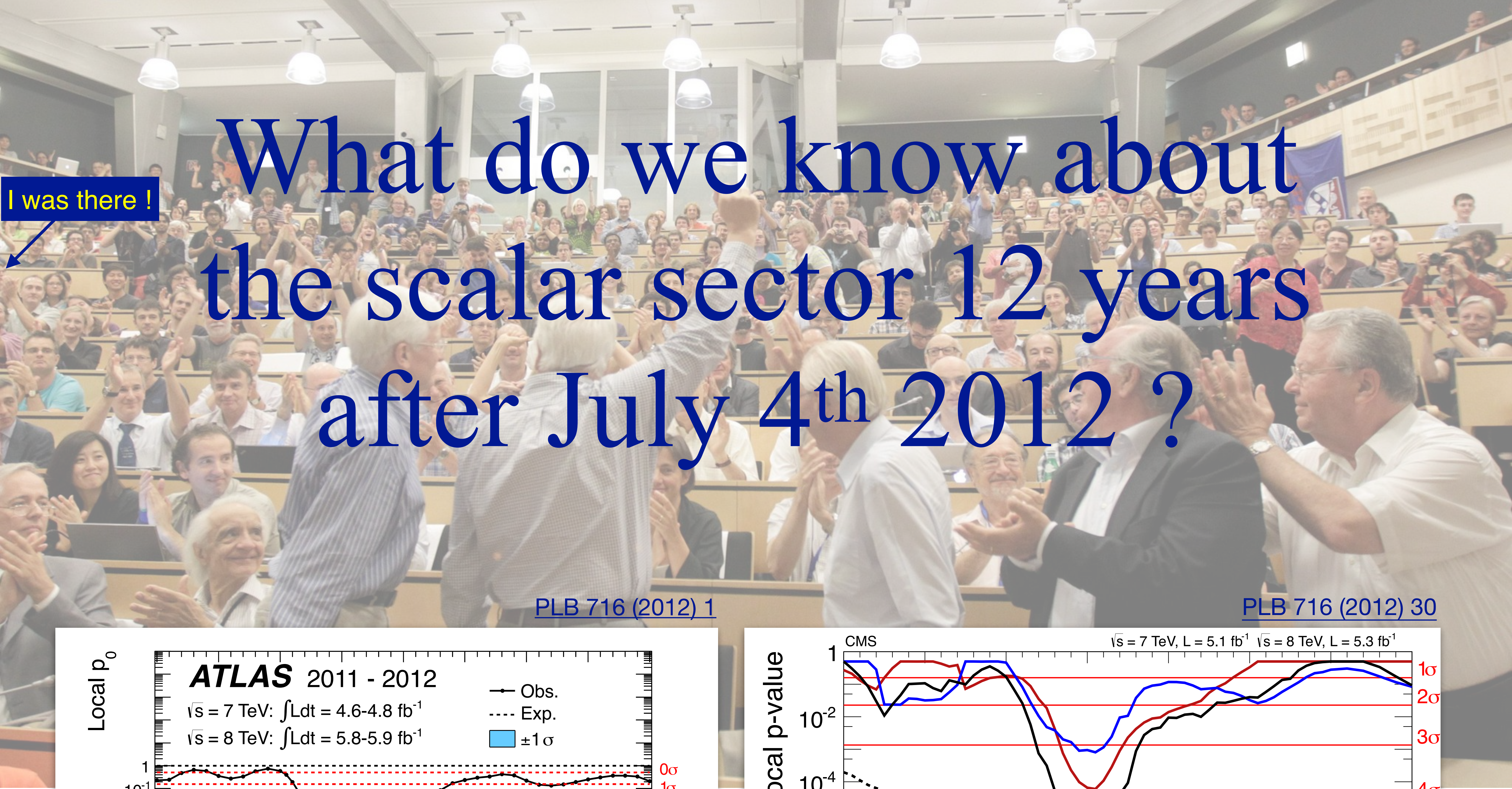
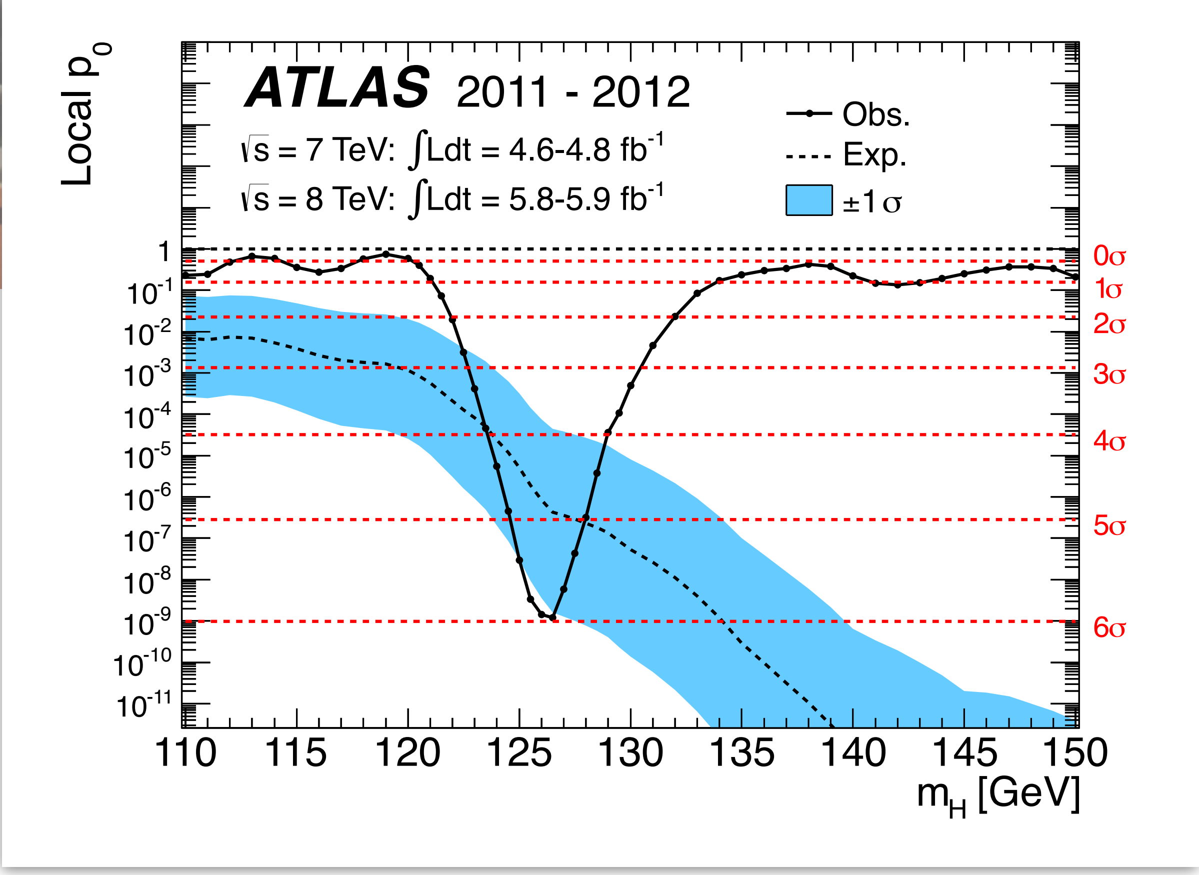
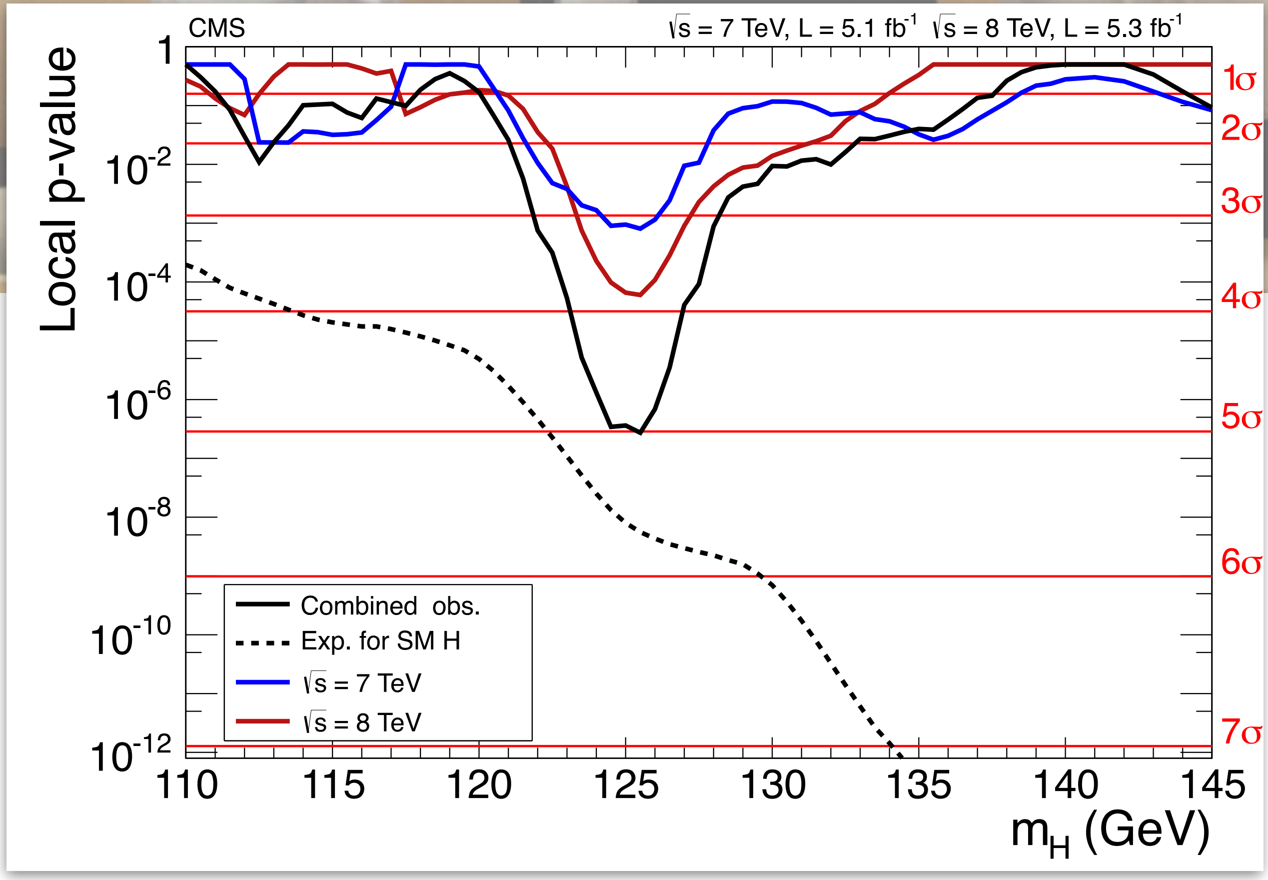
# What do we know about the scalar sector 12 years after July 4th 2012 ?



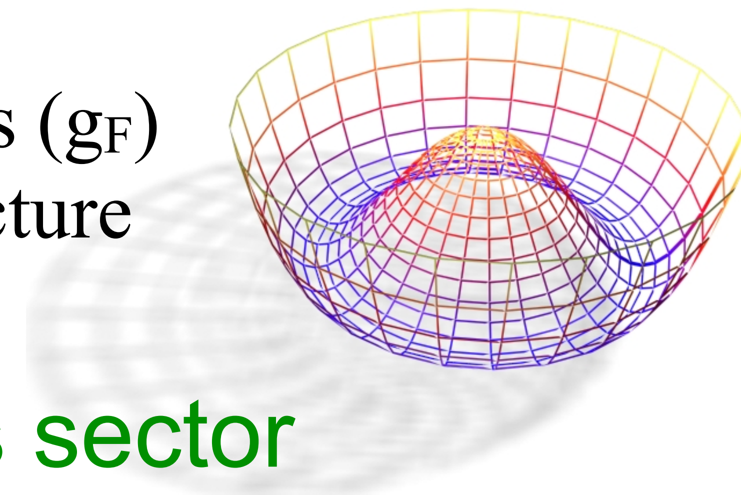

PLB 716 (2012) 1




PLB 716 (2012) 30



# Higgs Boson Property Measurements




1. Higgs boson mass ($M_H$) & decay width ($\Gamma_H$)
2. Higgs couplings to gauge bosons ($g_V$) and fermions ($g_F$)
3. Higgs boson quantum numbers $J^{PC}$ and tensor structure
4. Higgs potential - Higgs self-coupling ($\lambda$)

## The Standard Model Lagrangian - Higgs sector

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons

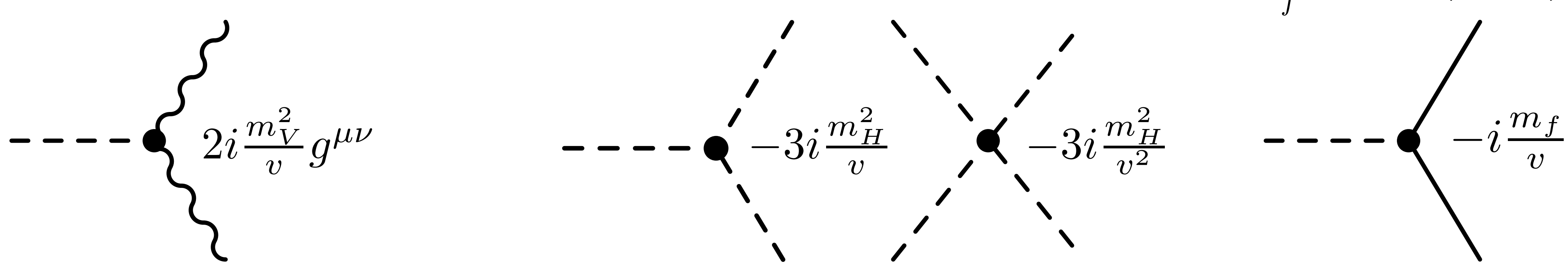
Higgs self-couplings

Couplings to fermions

$$\left[m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2$$

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



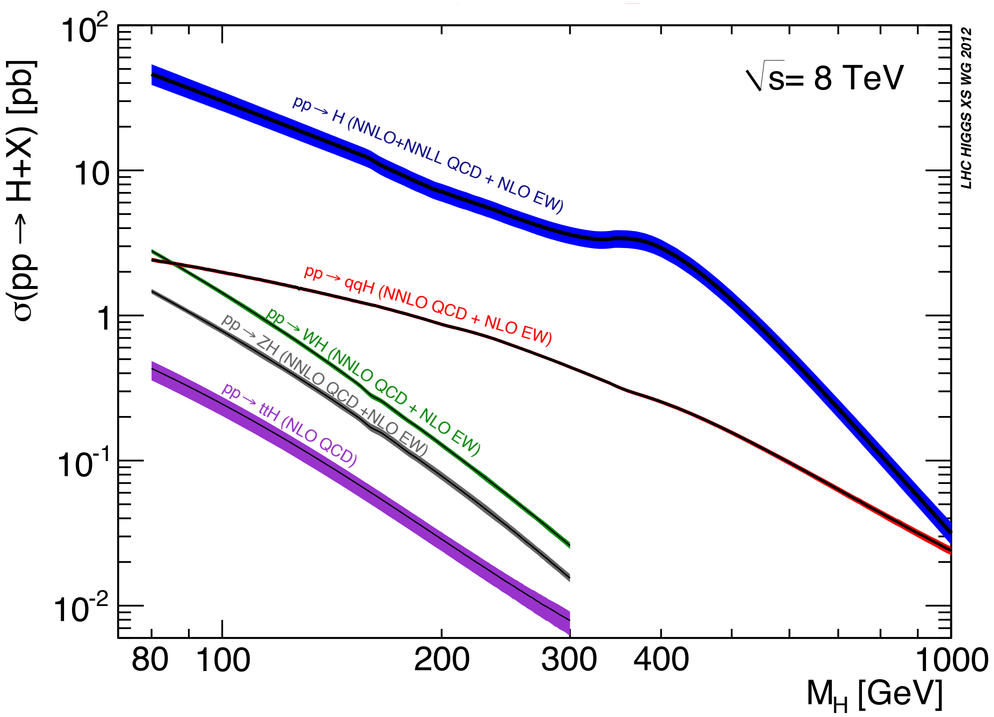

$$m_H = \sqrt{2}\mu = \sqrt{\lambda}v \;\; (v = \text{vacuum expectation value})$$

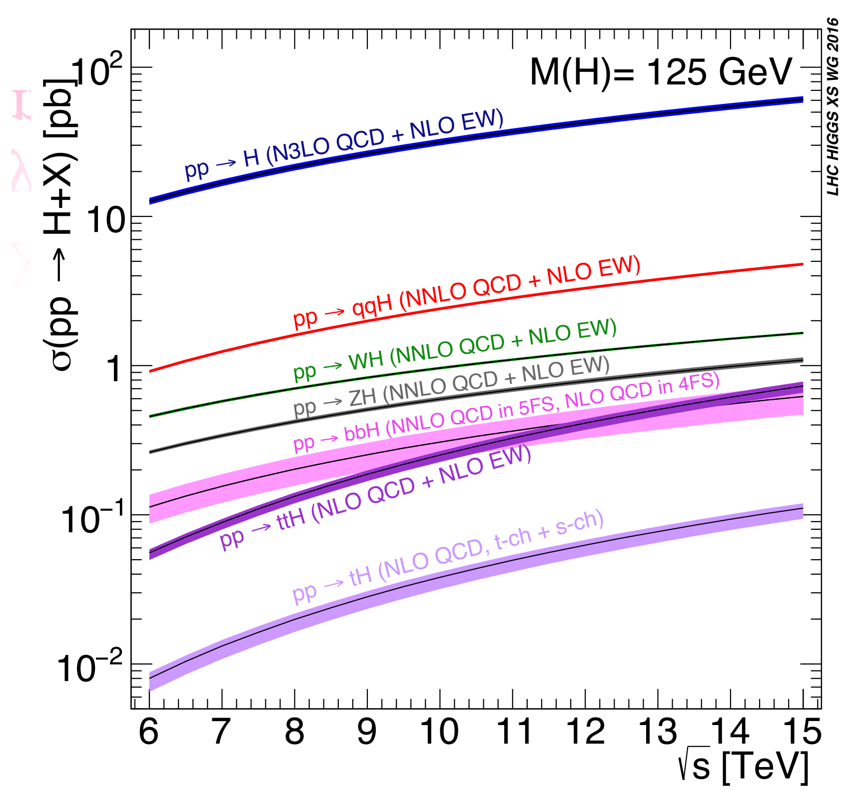
The ultimate goal of particle physics of today is to fix the Standard Model (SM) Lagrangian and find the physics beyond the Standard Model (BSM).

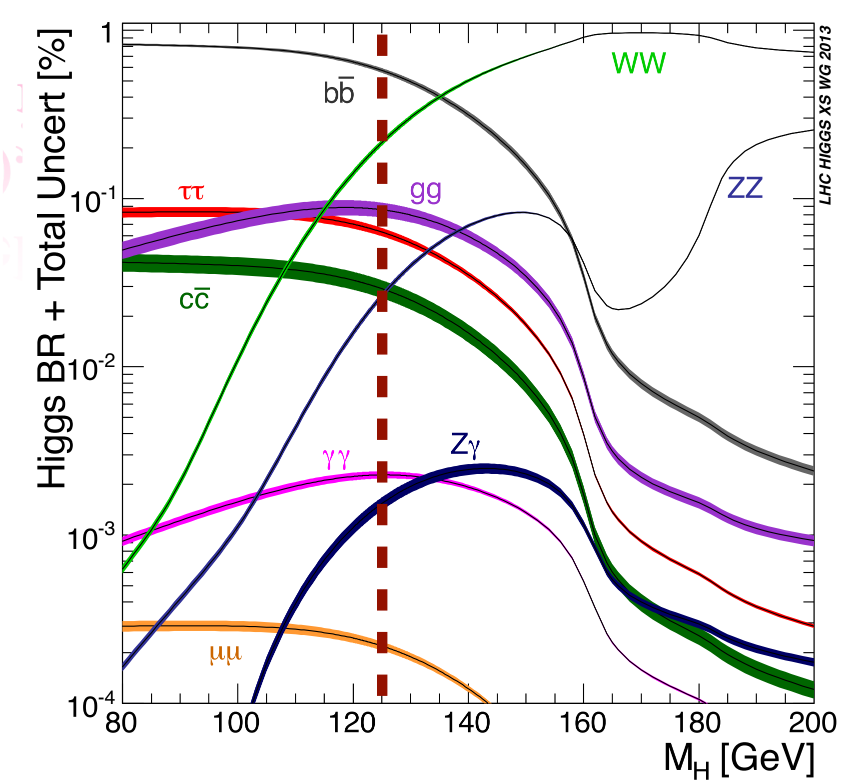
# Higgs boson production XS & decay BR

- State-of-the-art Higgs XS and BR predictions … major contribution from Michael Spira
  - Common SM input parameters coordinated for calculation for different processes
  - Mostly NNLO QCD + NLO EW production cross section
    - N3LO for ggF (ATLAS and CMS adopted promptly), Michael's pioneering work on NLO
  - $M_H$=125GeV was lucky to have many different decay channels
    - We would have had only WW/ZZ and other rare decay subgroups in ATLAS&CMS if $M_H$ = 200 GeV.

- ATLAS and CMS had common XS&BR numbers since Day-0 well before Higgs boson discovery
- ~240k Higgs boson @ Discovery (L=5-6 $fb^{-1}$ at each $\sqrt{s}$=7/8 TeV), 9M in RUN-2 (L=160 $fb^{-1}$ at $\sqrt{s}$=13 TeV), will produce 17M in RUN-3 (L=290 $fb^{-1}$) and 190M in HL-LHC (L=3 $ab^{-1}$).




https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

# gg→H gluon-gluon fusion Cross Section

New in CERN Report 4

JHEP05 (2016) 058

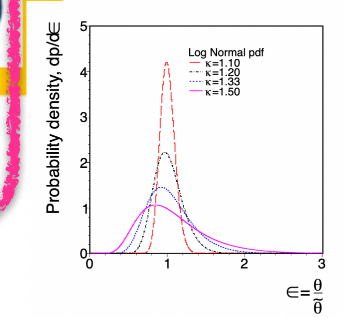
- First complete N3LO calculation at hadron collider !

| $\delta(\text{scale})$ | $\delta(\text{trunc})$ | $\delta(\text{PDF-TH})$ | $\delta(\text{EW})$ | $\delta(t,b,c)$ | $\delta(1/m_t)$ |
|---|---|---|---|---|---|
| $^{+0.10}_{-1.15}$ pb | $\pm 0.18$ pb | $\pm 0.56$ pb | $\pm 0.49$ pb | $\pm 0.40$ pb | $\pm 0.49$ pb |
| $^{+0.21\%}_{-2.37\%}$ | $\pm 0.37\%$ | $\pm 1.16\%$ | $\pm 1\%$ | $\pm 0.83\%$ | $\pm 1\%$ |
| missing higher-orders | uncertainty from the soft expansion | missing N3LO PDFs | EW corrections | uncertainty from heavy-quark mass dependence | uncertainty in the $1/m_t$ included corrections |

$\sqrt{s}$=13TeV, $M_H$=125GeV: cross section went up by +10%

$$\sigma = 48.58\,\text{pb}\,^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\;(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\;(\text{PDF}+\alpha_s)$$

- NNLO+NNLL: σ = 44.14 pb +7.6 -8.1% (QCD scale) ± 3.1% (PDF+$\alpha_s$)




- Debates on TH QCD scale uncertainty treatment
  - **TH: use Flat uncertainty: [−6.7, +4.6]% @100% CL**
  - **EXP: use Gaussian uncertainty: max{neg,pos}/√3 = ±3.9% @67% CL**

$$\rho(\theta) = \frac{1}{\sqrt{2\pi}\ln(\kappa)} \exp\left(-\frac{(\ln(\theta/\tilde{\theta}))^2}{2(\ln\kappa)^2}\right)\frac{1}{\theta}$$

$\theta$=σ for κ=1

- LHC Higgs Combination Working Group (LHC-HCG)

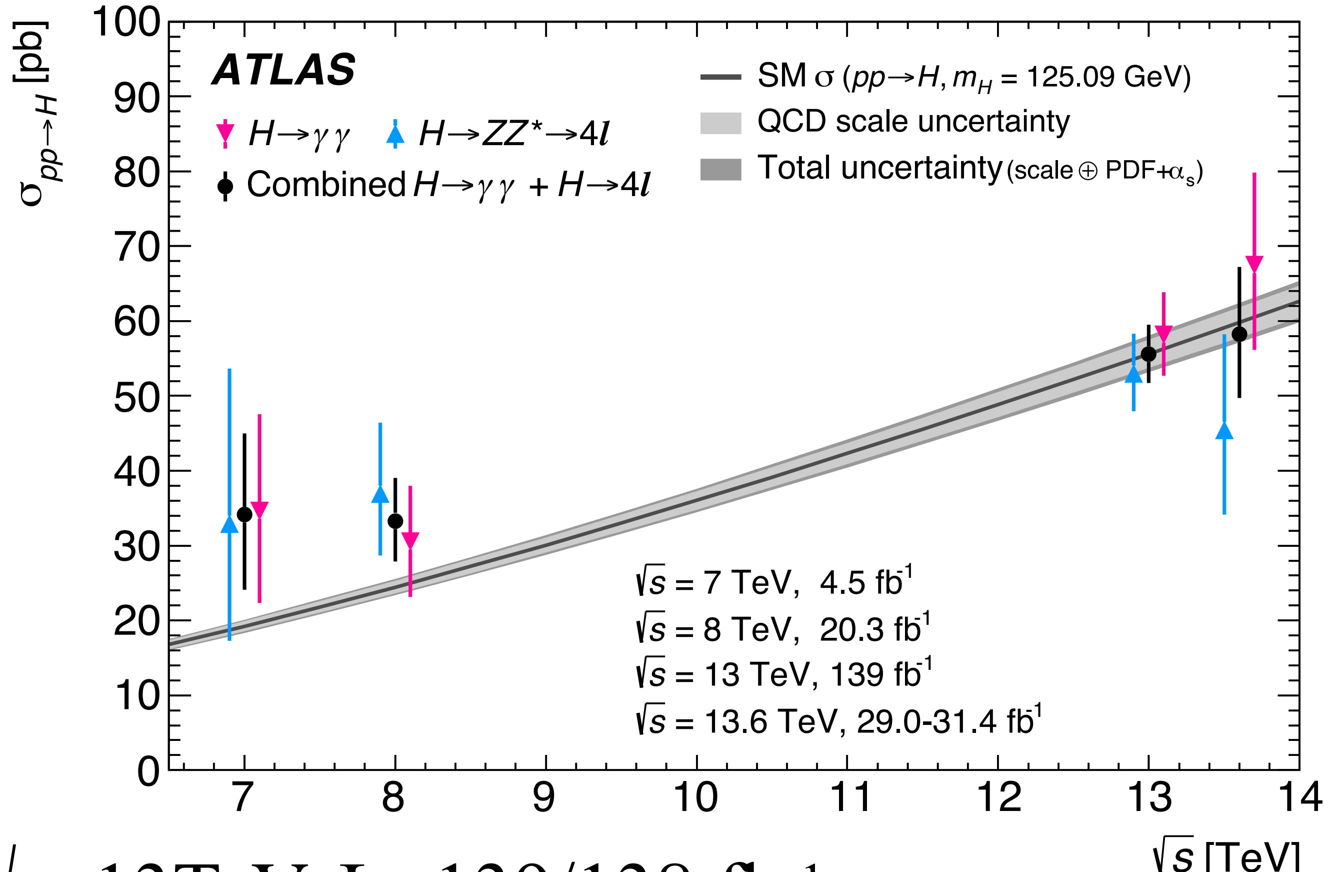
"Procedure for the LHC Higgs boson search combination in Summer 2011", ATL-PHYS-PUB-2011-11 CMS NOTE-2011/005

  - Sub-divide all nuisance parameters until they become independent each other.

# Higgs Boson Production Cross Section at LHC

- I thought theory community went too far but EXP and TH uncertainties are competing after RUN-2 !!
- Very important to have the competitive numbers.
- Example: ATLAS H→γγ+4ℓ, RUN-2 √s=13TeV, 139 $fb^{-1}$

$$\sigma_{\rm obs}/\sigma_{\rm TH} = 1.00 \pm 5.8\%\,(\text{stat.}) \pm 4.1\%\,(\text{syst.}) \pm 4.5\%\,(\text{theory})$$




Eur. Phys. J. C 84 (2024) 78

M. Spira et al. have to calculate ggF at N4LO in QCD !

- Full RUN-2 √s=13TeV, L=139/138 $fb^{-1}$

Nature 607 (2022) 52–59

Nature 607 (2022) 60–68

$$\text{ATLAS}\quad \mu = 1.05 \pm 0.06 = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.syst.}) \pm 0.04(\text{sig.th.}) \pm 0.02(\text{bkg.th.})$$

$$\text{CMS}\quad \mu = 1.002 \pm 0.057 = 1.002 \pm 0.029(\text{stat.}) \pm 0.033(\text{exp.syst.}) \pm 0.036(\text{sig.th.})$$

# Higgs boson decay width and branching ratio

## Uncertainties in Branching Ratio (LHC-HCG)

1. Start with Higgs boson decay width

$$\Gamma_H = \Gamma^{HDECAY} - \Gamma^{HDECAY}_{WW} - \Gamma^{HDECAY}_{ZZ} + \Gamma^{Prophecy4f}_{4f}$$

2. Categorize PU($\alpha_s$, $m_b$, $m_c$, $m_t$) and THU

   Separate treatment of PU($\Delta\alpha_s$, $\Delta m_q$) and THU

3. Convert to BR (correlations are taken into)

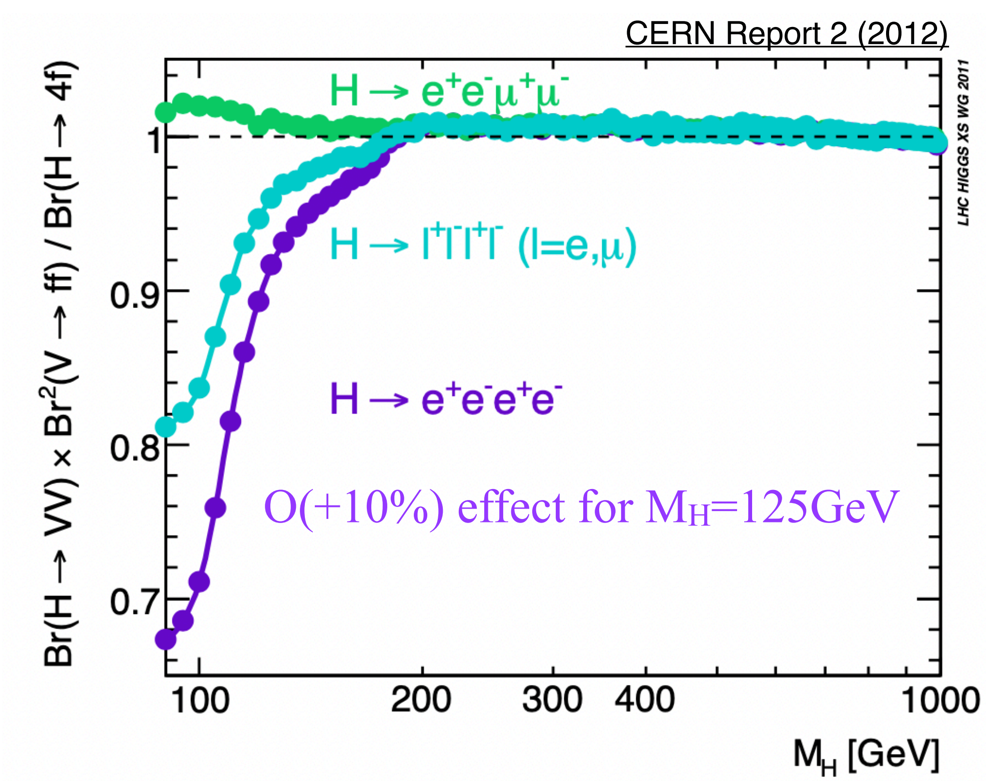
$$BR(H \to VV) = \frac{\Gamma_{VV}}{\Gamma_{tot}} = \frac{\Gamma_{VV}}{\Gamma_{f\bar{f}} + \Gamma_{gg} + \Gamma_{VV}}$$

$$\Gamma_{f\bar{f}} : \Gamma_{VV} \simeq 3:1 \text{ (dominated by } \Gamma_{b\bar{b}})$$

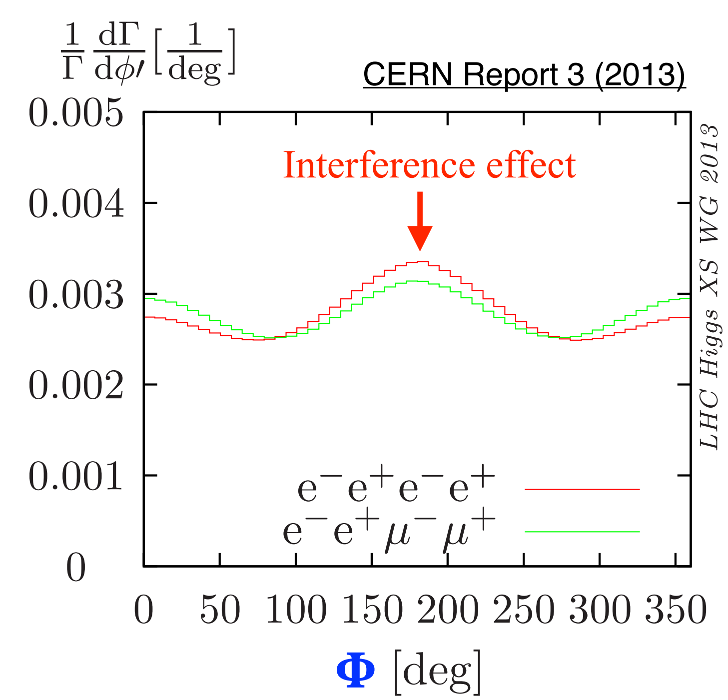
| $M_H$=126GeV | Decay width uncertainty | | | | |
|---|---|---|---|---|---|
| **Decay** | $\Delta\alpha_s$ | $\Delta m_b$ | $\Delta m_c$ | $\Delta m_t$ | THU |
| H→bb | ∓2.3% | ±3.3% | ±0.0% | ±0.0% | ±2.0% |
| H→cc | ∓7.1% | -0.1% | ±6.2% | ±0.1% | ±2.0% |
| H→ττ | ±0.0% | ±0.0% | ±0.0% | ±0.1% | ±2.0% |
| H→μμ | ±0.0% | ±0.0% | ±0.1% | ±0.1% | ±2.0% |
| H→gg | ±4.2% | -0.1% | ±0.0% | ∓0.2% | ±3.0% |
| H→γγ | ±0.0% | ±0.0% | ±0.0% | ±0.1% | ±1.0% |
| H→Zγ | ±0.0% | ±0.0% | ±0.1% | ±0.1% | ±5.0% |
| H→WW | ±0.0% | ±0.0% | ±0.0% | ±0.0% | ±0.5% |
| H→ZZ | ±0.0% | ±0.0% | ±0.0% | ±0.0% | ±0.5% |

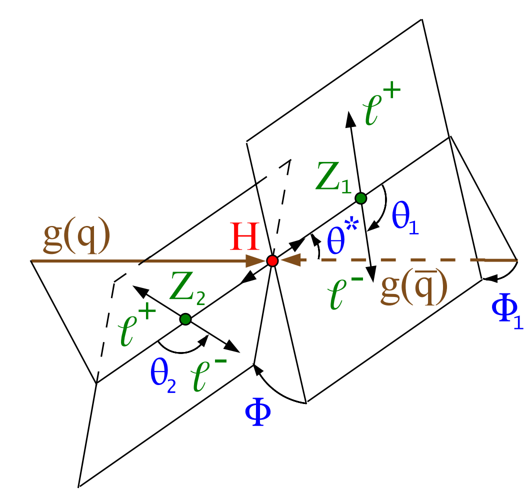
**Precise H→4f BR estimation and Monte Carlo at NLO EW**

Interference effect in $H \to ZZ^* \to e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$




Precise H→4f Monte Carlo (Prophecy4f) at NLO EW




$(M_{4\ell}, M_{Z_1}, M_{Z_2})$,

$\vec{\Omega} = (\theta^*, \cos\theta_1, \cos\theta_2, \Phi_1, \Phi)$

# LHC Higgs Cross Section Working Group

Run 1 | Run 2 | Run 3

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 20

Aug. TH&ATLAS&CMS proposal for joint forum for Higgs XS

Nov. 23-24 Torino WS @ LHC 1st pp collision

Jan. Creation LHCHXSWG

Apr. Inauguration WS in Freiburg

YR1 YR2 YR3

July 4th Higgs boson Discovery

YR4

Nov. LHC Higgs XS WG ➪ LHC Higgs WG


**WG1: Higgs XS&BR**
**WG2: Higgs Properties**
**WG3: BSM Higgs**

Annual meetings at Freiburg, Bari, BNL, LAL and CERN

Important interaction with:
- PDF4LHC, MCNet
- LHC Higgs Combination WG
- LHC EW/Top Physics WG
- LHC Effective Field Theory WG

LHC Higgs XS WG CERN Reports

**Handbook of LHC Higgs Cross Sections**:
1. Inclusive Observables (CERN-2011-002, 151 pp.)
2. Differential Distributions (CERN-2012-002, 275 pp.)
3. Higgs Properties (CERN-2013-004, 392 pp.)
4. Deciphering the nature of the Higgs sector (CERN-2017-002-M, 869 pp.)

← July 4th 2012 Higgs boson Discovery

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

# M. Spira's most cited papers via iNSPIRE as of 024.09.19

Bibles

151 results | cite all — Citation Summary — Most Cited

**Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector** #1
LHC Higgs Cross Section Working Group • D. de Florian (ICAS, UNSAM, Buenos Aires) et al. (Oct 25, 2016)
Published in: CERN Yellow Reports: Monographs, 2/2017 • e-Print: 1610.07922 [hep-ph]
pdf DOI cite claim reference search 2,297 citations

**HDECAY: A Program for Higgs boson decays in the standard model and its supersymmetric extension** #2
A. Djouadi (Montpellier U.), J. Kalinowski (DESY and Warsaw U.), M. Spira (CERN) (Apr, 1997)
Published in: *Comput.Phys.Commun.* 108 (1998) 56-74 • e-Print: hep-ph/9704448 [hep-ph]
pdf DOI cite claim reference search 2,072 citations

**Handbook of LHC Higgs Cross Sections: 3. Higgs Properties** #3
LHC Higgs Cross Section Working Group • S Heinemeyer (Cantabria Inst. of Phys.)(ed.) et al. (Jul 4, 2013)
Published in: CERN Yellow Reports: Monographs • e-Print: 1307.1347 [hep-ph]
pdf DOI cite claim reference search 1,835 citations

**Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables** #4
LHC Higgs Cross Section Working Group • S. Dittmaier et al. (Jan, 2011)
Published in: CERN Yellow Reports: Monographs • e-Print: 1101.0593 [hep-ph]
pdf DOI cite claim reference search 1,758 citations

**CMS technical design report, volume II: Physics performance** #5
CMS Collaboration • G.L. Bayatian (Yerevan Phys. Inst.) et al. (2007)
Published in: *J.Phys.G* 34 (2007) 6, 995-1579
pdf links DOI cite claim reference search 1,689 citations

**Higgs boson production at the LHC** #6
M. Spira (Hamburg U.), A. Djouadi (Montreal U. and DESY), D. Graudenz (CERN), P.M. Zerwas (DESY) (Feb, 1995)
Published in: *Nucl.Phys.B* 453 (1995) 17-82 • e-Print: hep-ph/9504378 [hep-ph]
pdf DOI cite claim reference search 1,613 citations

# Higgs boson mass

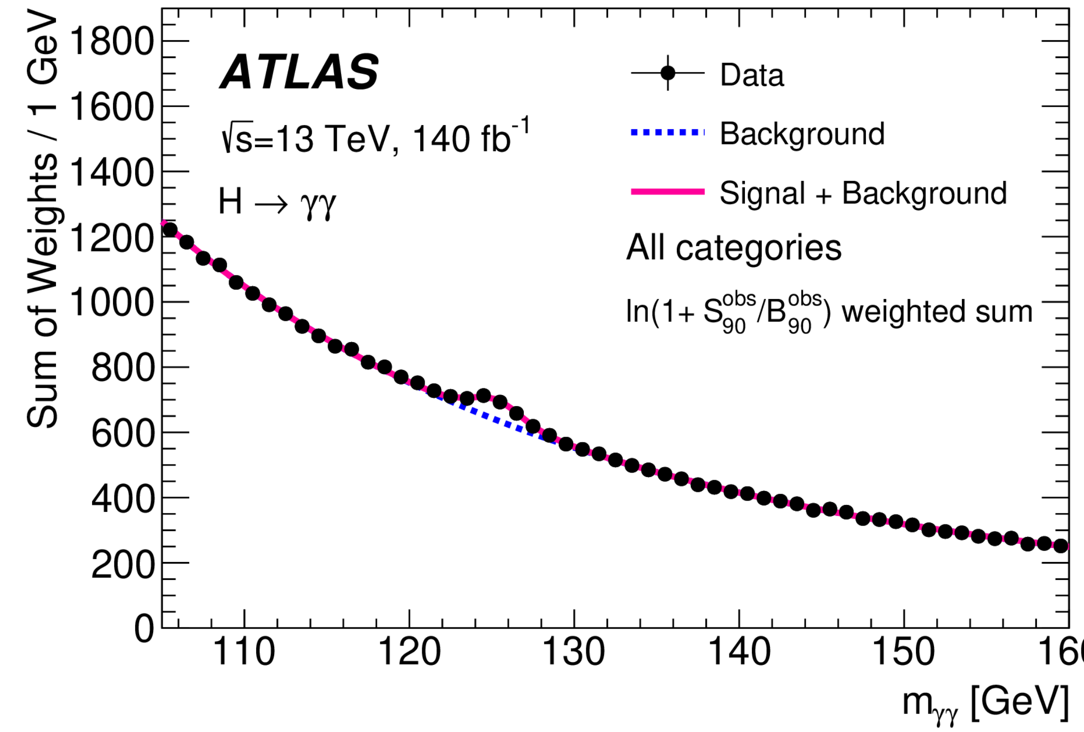
RUN-2

- ATLAS $4\ell + \gamma\gamma$

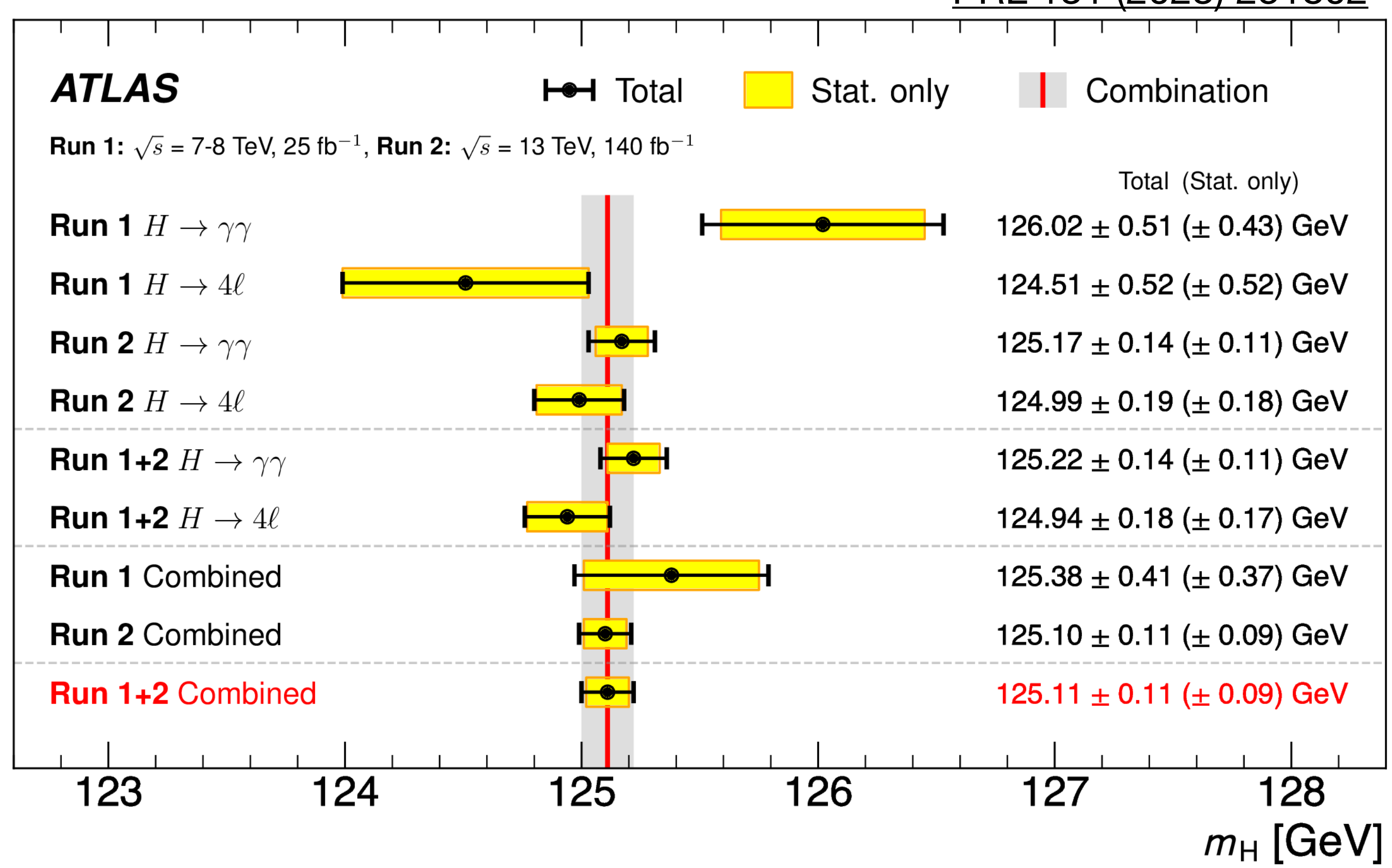
$M_H = 125.11 \pm 0.09\ (\mathrm{stat}) \pm 0.06\ (\mathrm{syst})\ \mathrm{GeV}$

Improved photon calibration, systematic uncertainty on $H \rightarrow \gamma\gamma$ mass resolution reduced by a factor of 4.

PLB 847 (2023) 138315




PRL 131 (2023) 251802



# Higgs boson mass

RUN-2

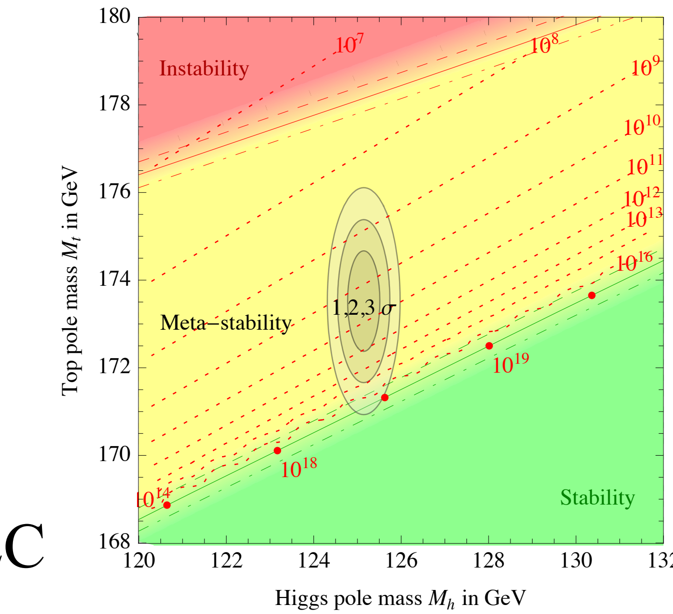
- CMS 4ℓ

Most precise single measurement in $H \rightarrow 4\,\ell$

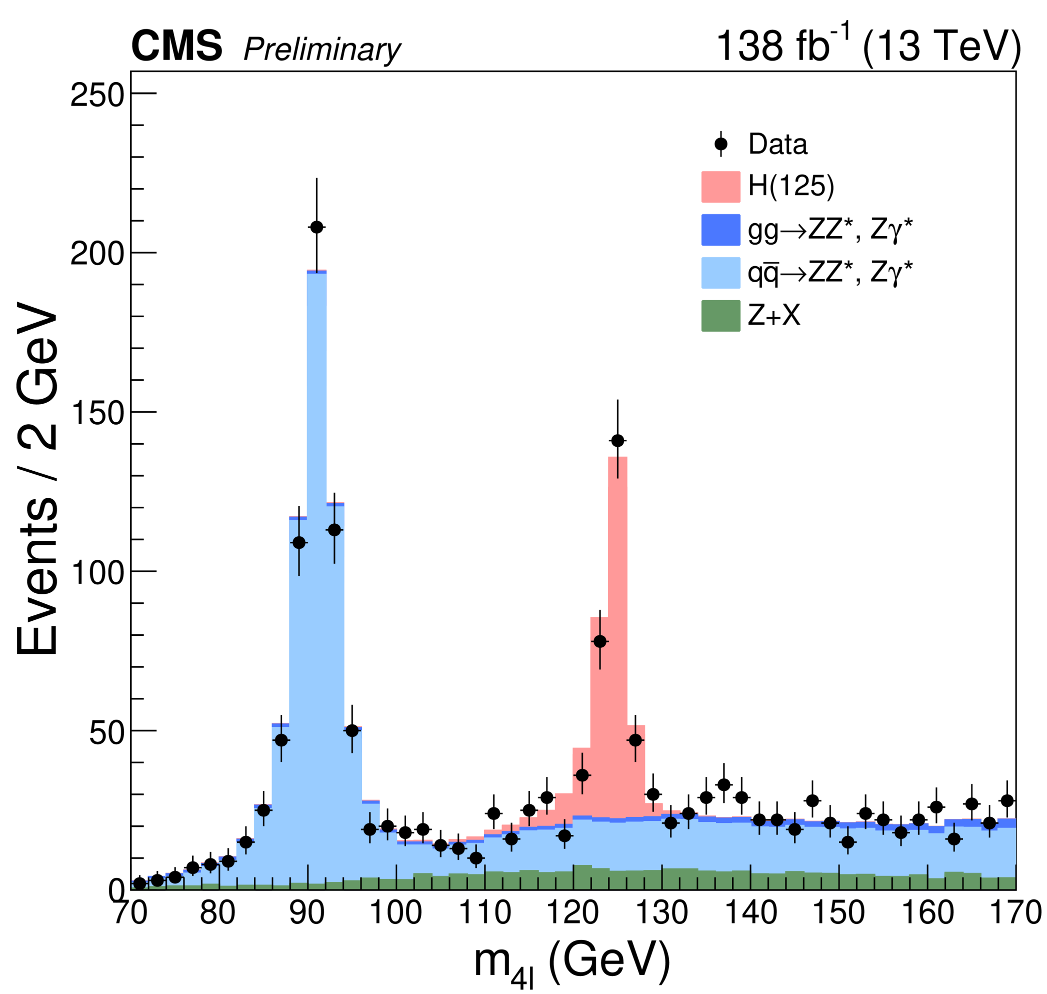
$M_H = 125.08 \pm 0.10\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})\ \mathrm{GeV}$

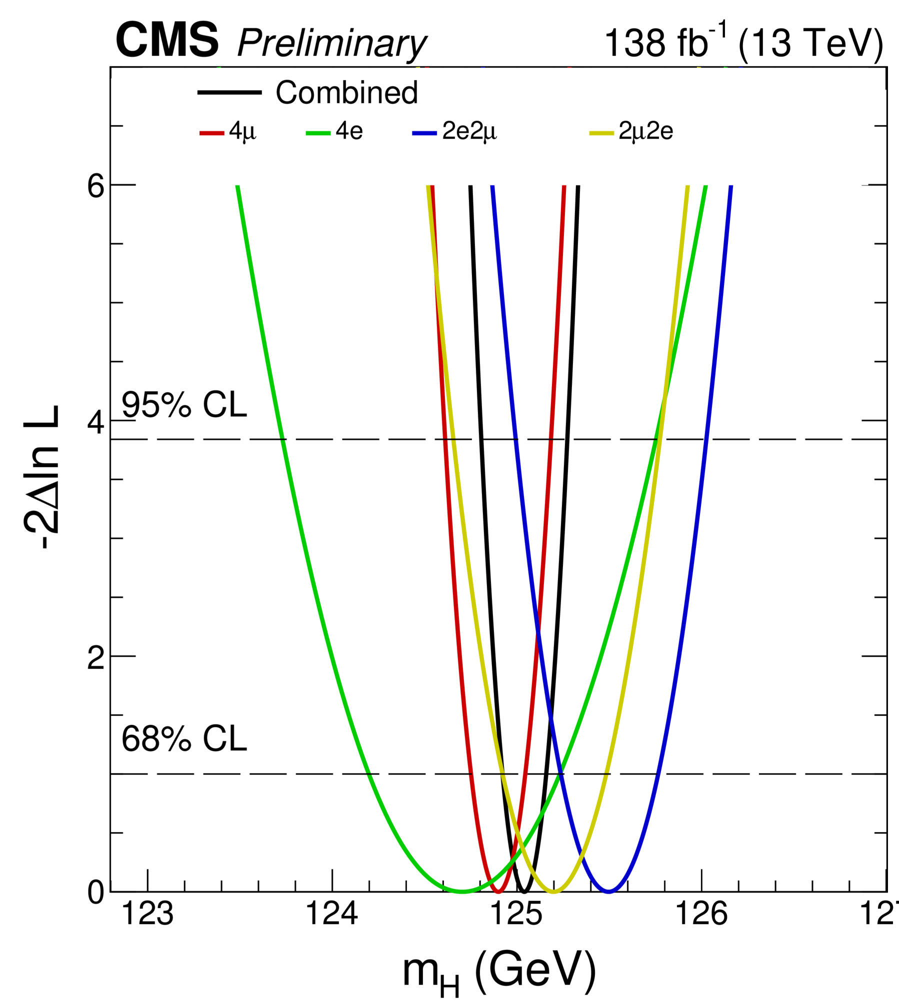
- Will be dominated by CMS H→4μ channel thanks to 4T solenoid
- Further improvement $M_H$ important ? Coupling dσ/dBr, H→ee @ILC

D. Buttazzo et al., JHEP 12 (2013) 089




CMS-PAS-HIG-21-019



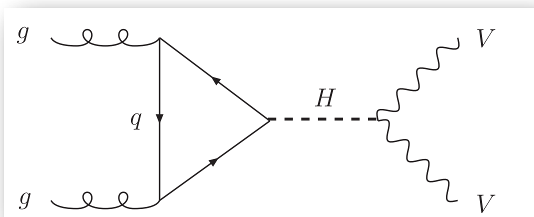



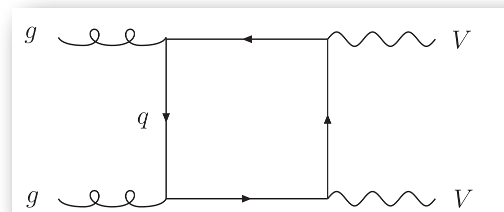
# Off-shell Higgs Boson Production and Interference

- Kauer-Passarino-Caola-Melnikov Effect
- Total gg→H→VV* receives an O(10%) off-shell correction
  - On-shell signal cross section is proportional to $1/\Gamma_H$
  - Off-shell signal cross section is independent of $\Gamma_H$
  - $\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$ gives the information on $\Gamma_H$ !
- Negative signal-background interference effect

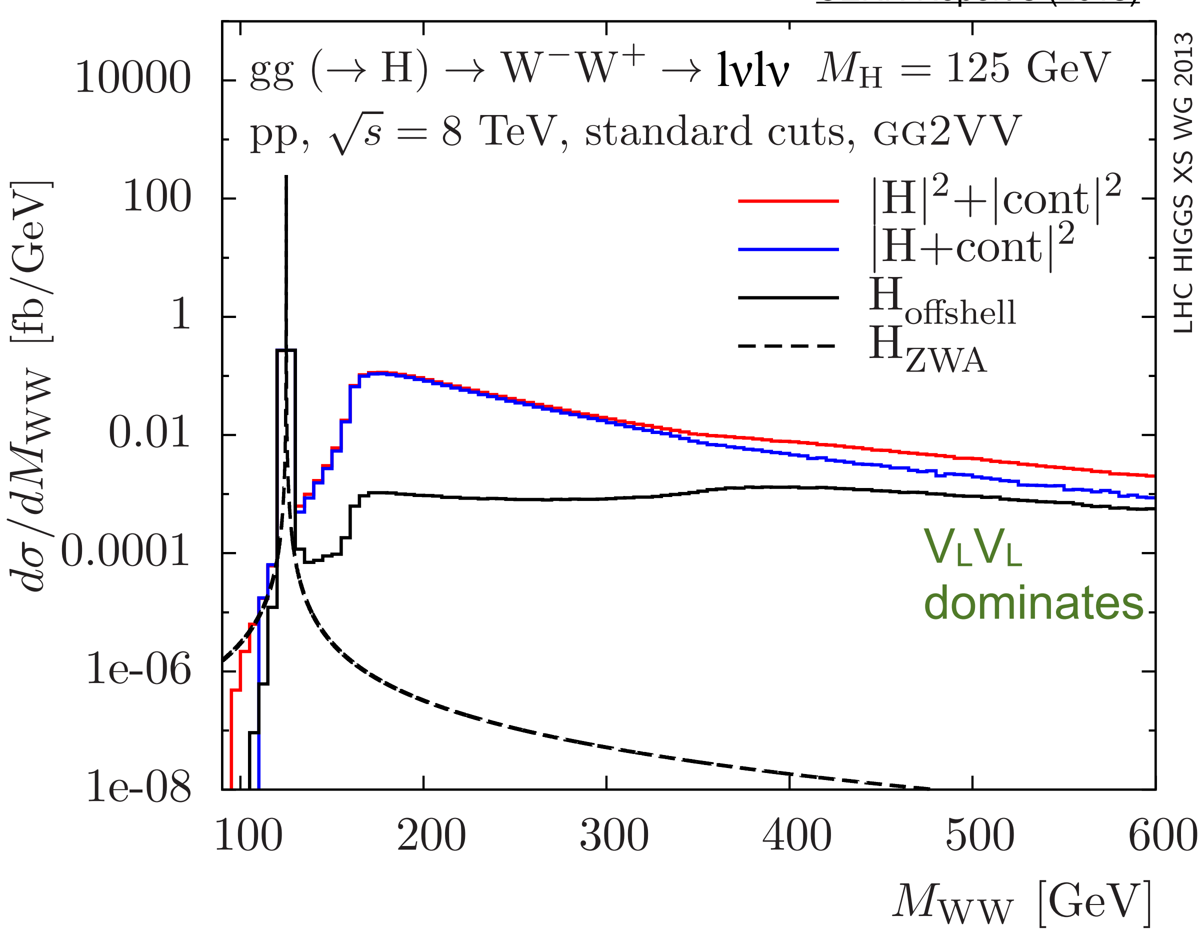
$$\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{Hgg}\, g^2_{HVV}}{m_H \Gamma_H}$$

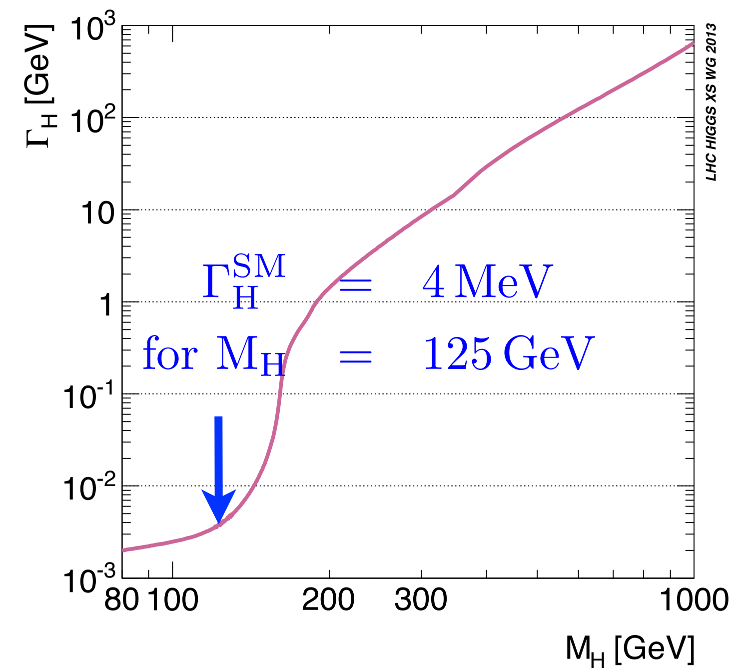
$$\sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{Hgg}\, g^2_{HVV}}{m^2_{VV}}$$




CERN Report 3 (2013)



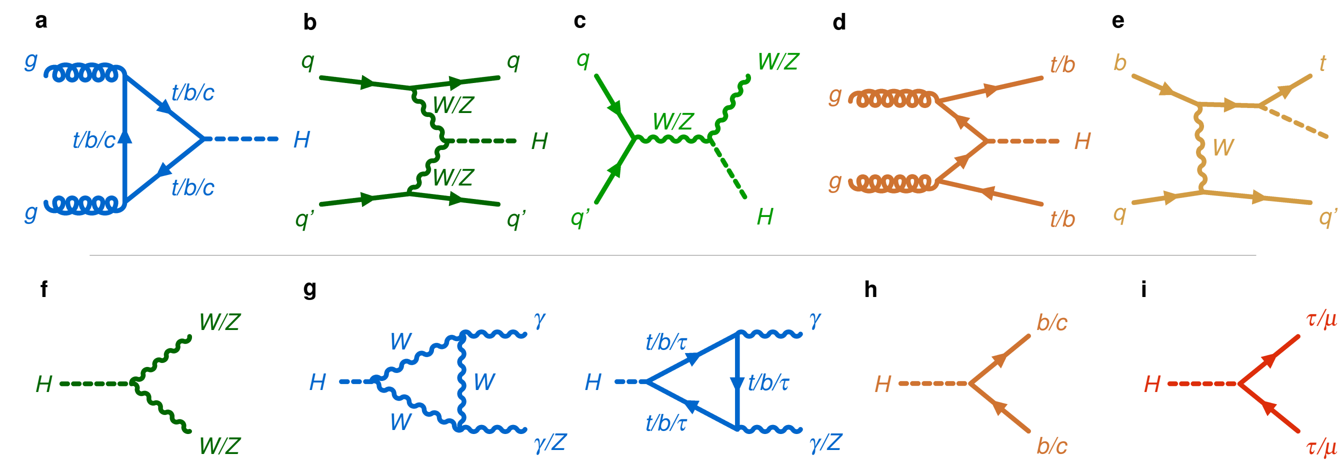

- 125GeV Higgs boson discovery by theorist ! Breit-Wigner has long-tail.
- Off-shell Sensitive to new physics
  ➪ EFT interpretation
- Large theoretical uncertainties in kinematical distributions due to QCD, PDF and EW corrections of O(20-30%) at high-mass.

# Higgs boson production and decay at LHC

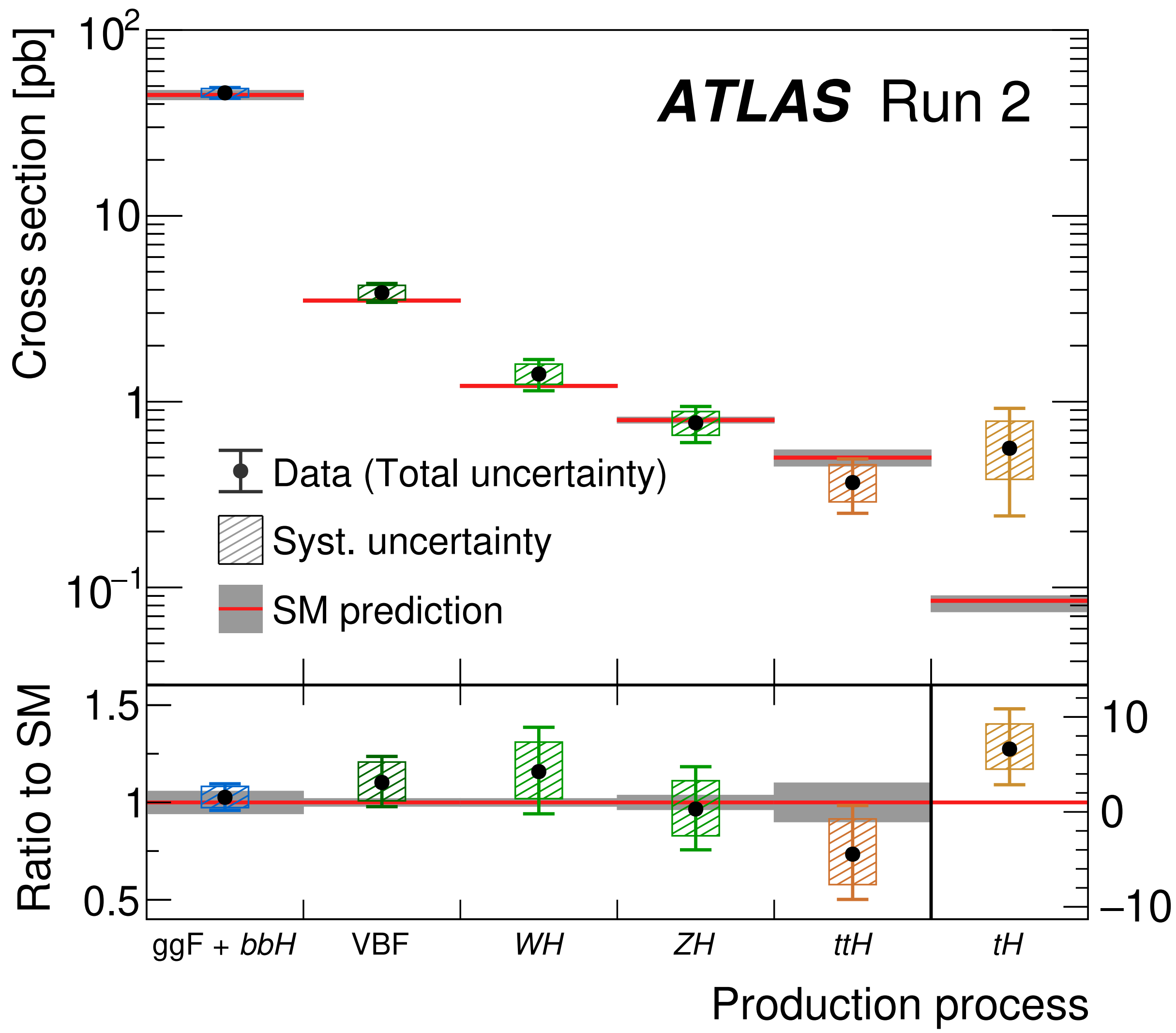
RUN-2

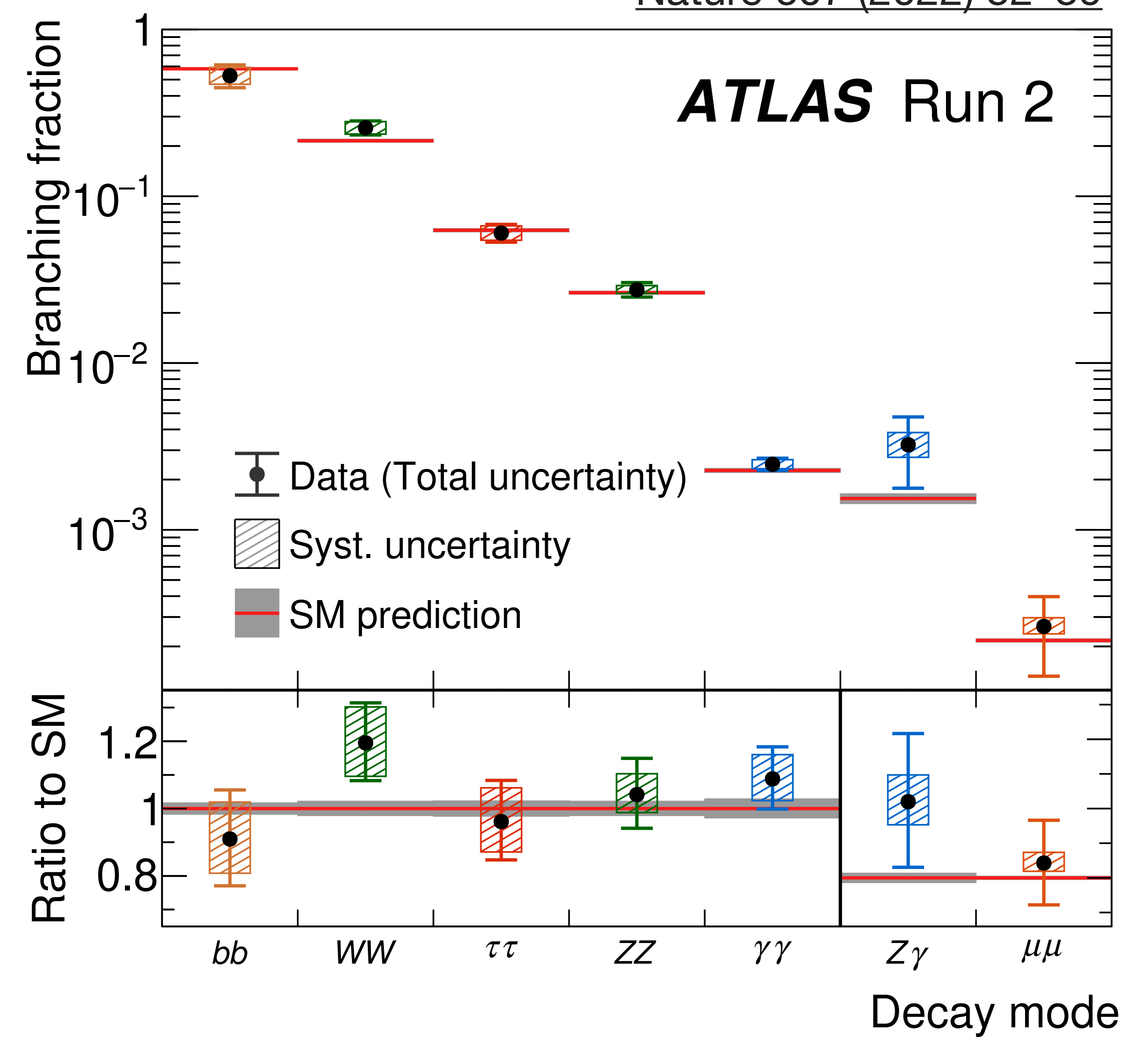
Production

Decay




Nature 607 (2022) 52–59

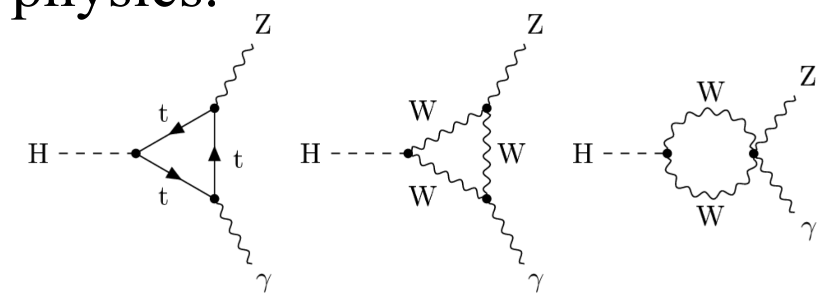


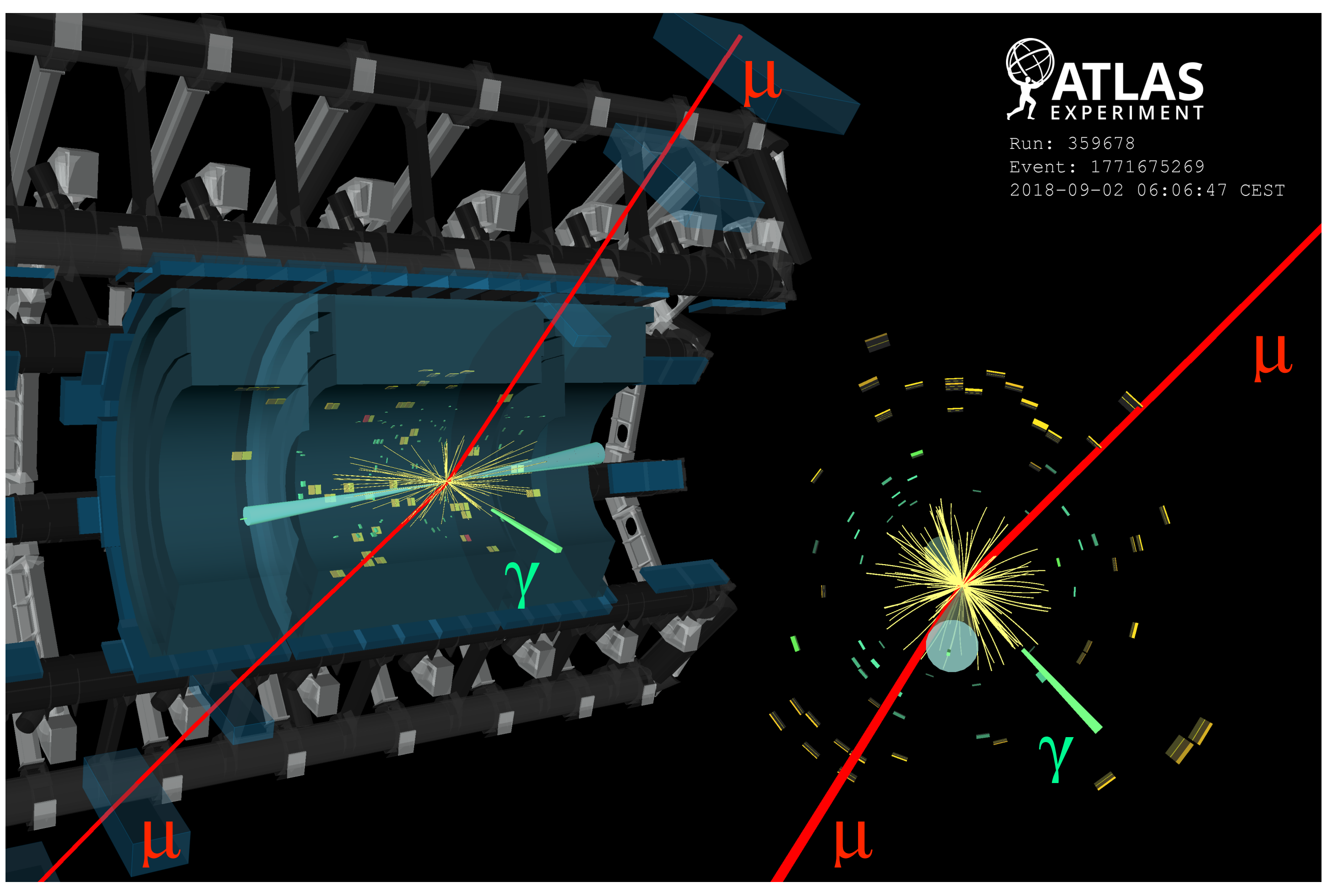
# Evidence for H→Zγ decay

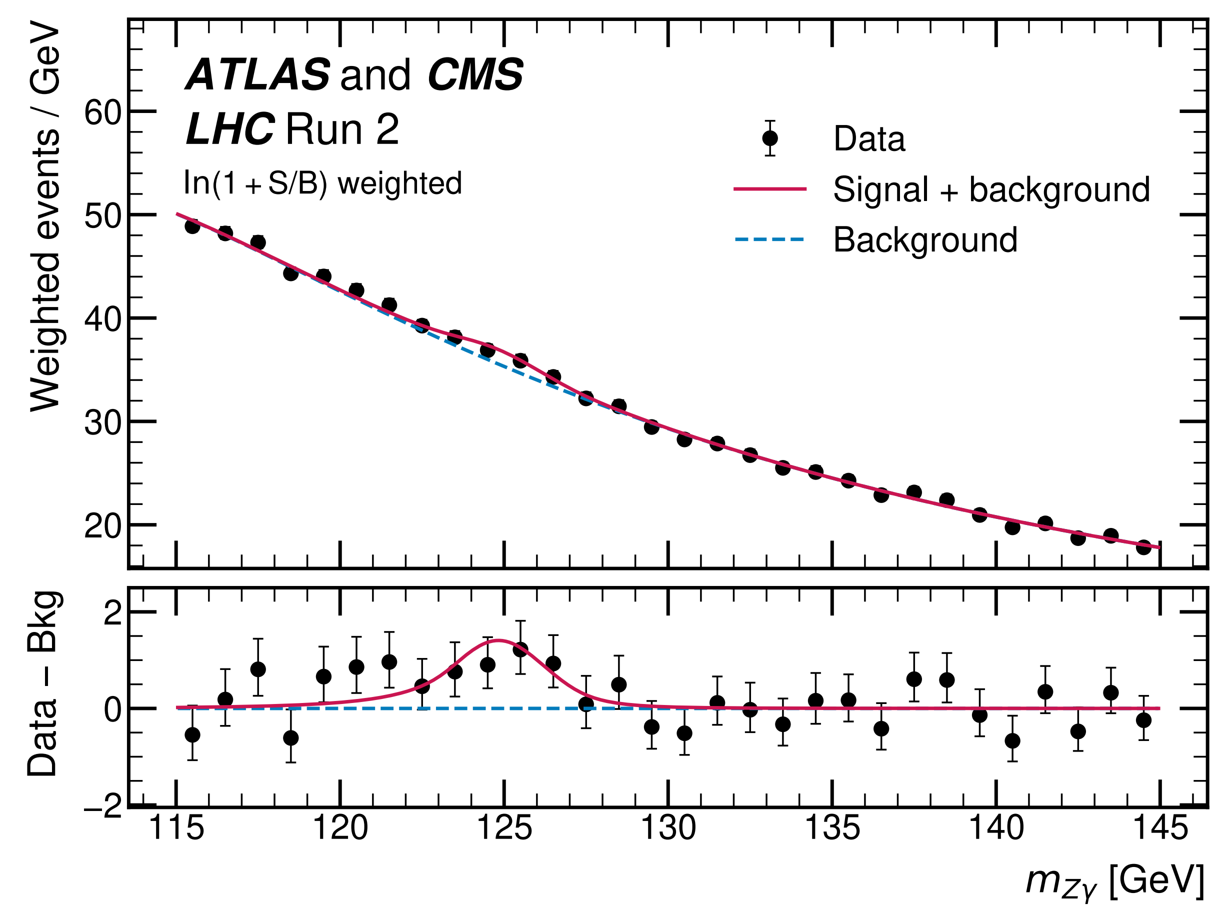
RUN-2

- Statistics limited by very important channel to search for BMS physics.
- The measured H→Zγ branching fraction is (3.4±1.1)x10$^{-3}$.
- SM BR(H→Zγ)=(1.54±0.09)x10$^{-3}$
  - 5.7% uncertainty in THU
- The largest systematic uncertainties are TH BR(H→Zγ) and background modeling.
- BR subgroup needs to wake up !




Phys. Rev. Lett. 132 (2024) 021803



# Note on Coupling versus Mass relation by M. Spira in 2013

- Discussions on quark mass (M. Spira)

  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SMInputParameter

  Memorandum by M. Spira (2013)

$$\begin{cases} y_F = \kappa_F \frac{m_f}{v} \\ y_V = \sqrt{\kappa_V}\frac{m_V}{v} \end{cases}$$

1. One can define quark mass for Yukawa coupling,

$$\bar{g}_Q(M_H), \bar{g}_Q(M_Q), g_Q^{\text{pole}}$$

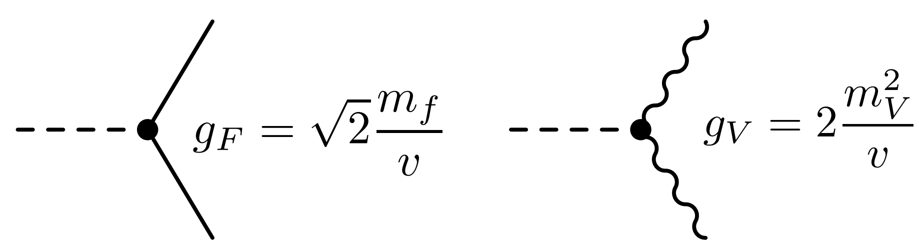
2. Though above are theoretically equivalent, running mass evaluated at Higgs mass scale is better to avoid the offset due to non-universal corrections in quarks and leptons,

$$\Gamma(H \to Q\bar{Q}) = \bar{g}_Q^2(M_H)\frac{3M_H}{16\pi}\left\{1 + \frac{17}{3}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\}$$

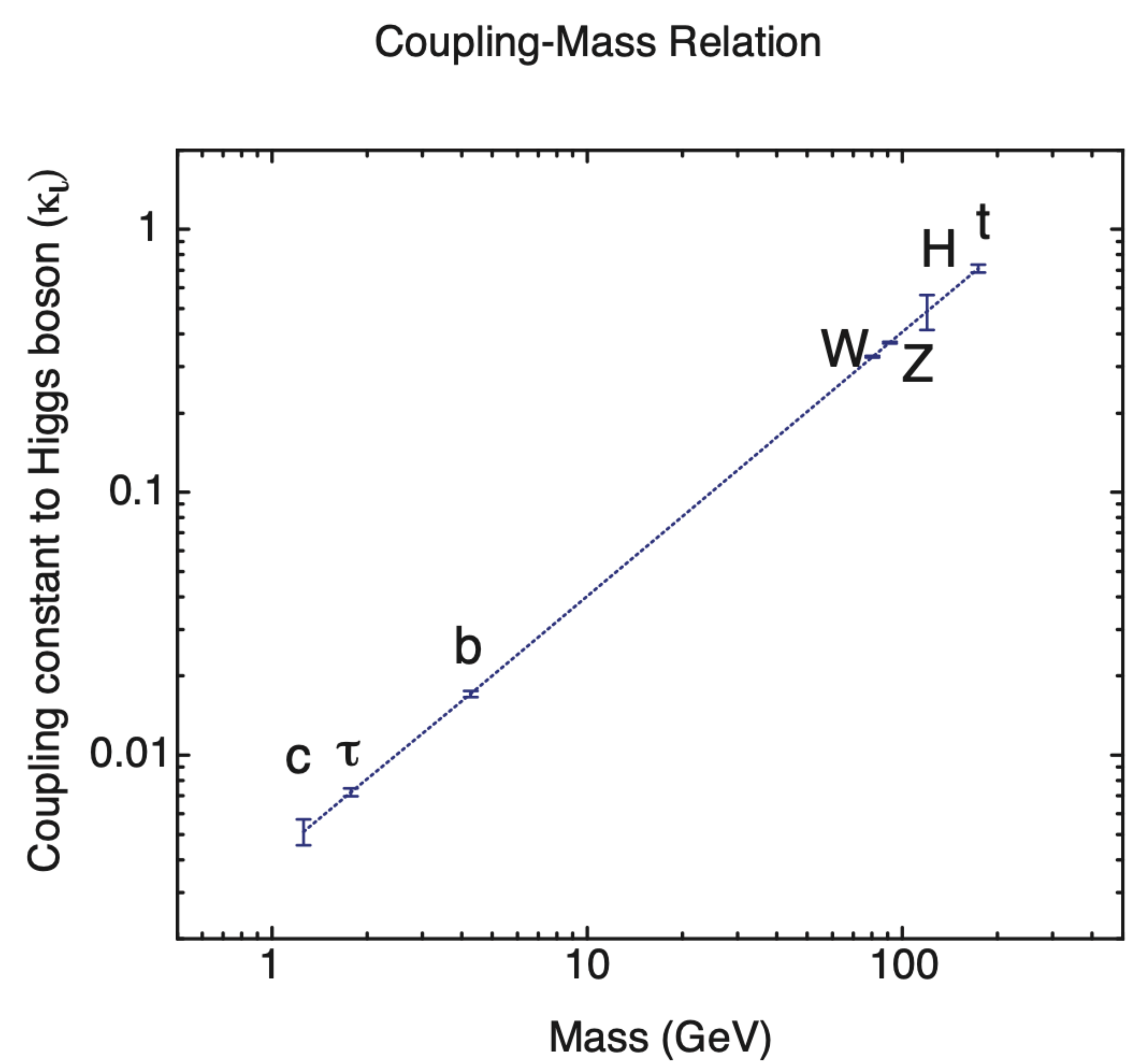
$$m_b(m_b) = 4.16\,\text{GeV}, m_b(M_H) = 2.76\,\text{GeV}$$

3. Use pole mass for top quark (172.5 GeV).

4. Use PDG values for leptons and W/Z boson masses. The universal QED corrections for leptons are small.



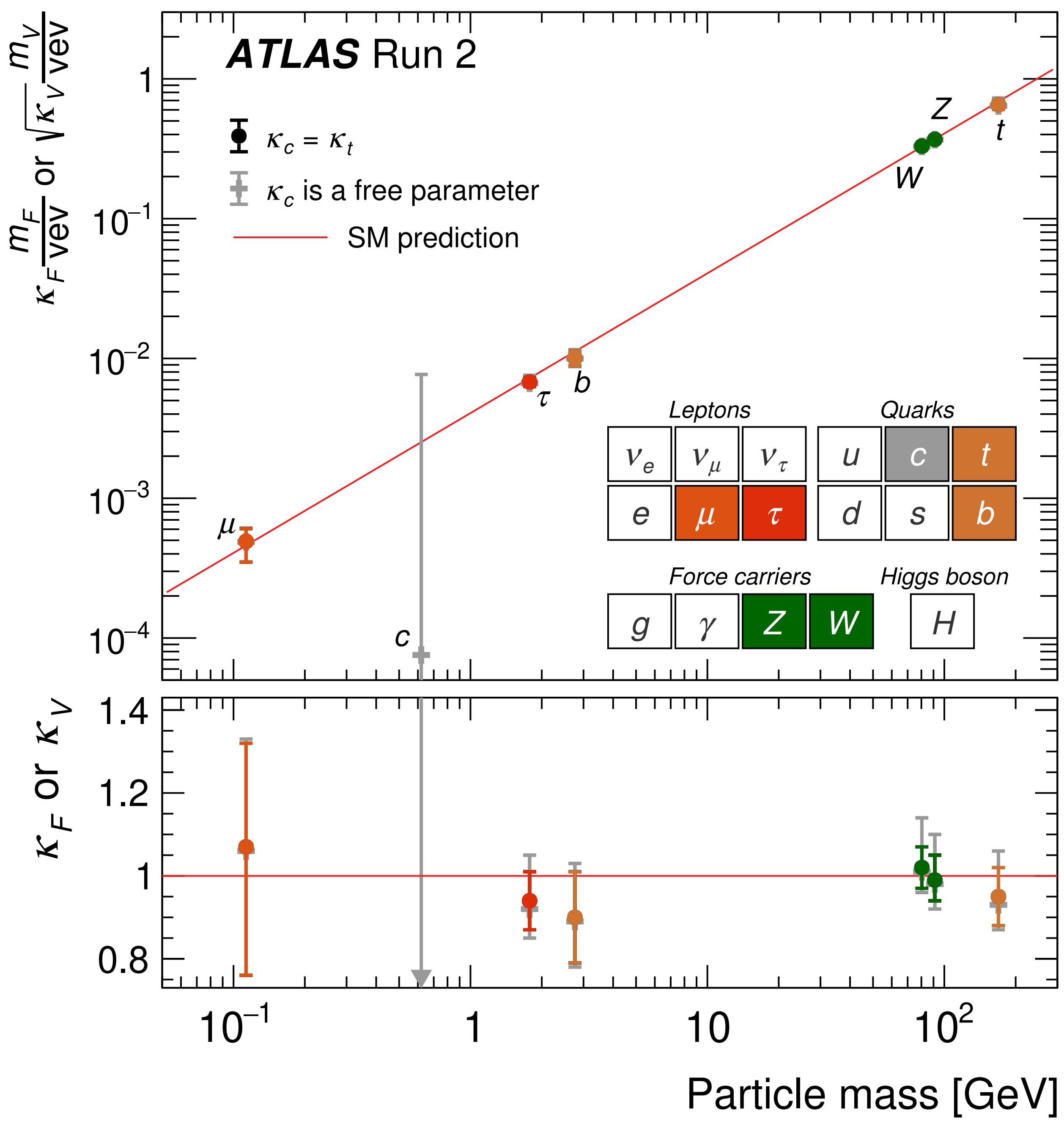

GLC project: Linear Collider for TeV Physics, KEK-REPORT-2003-7

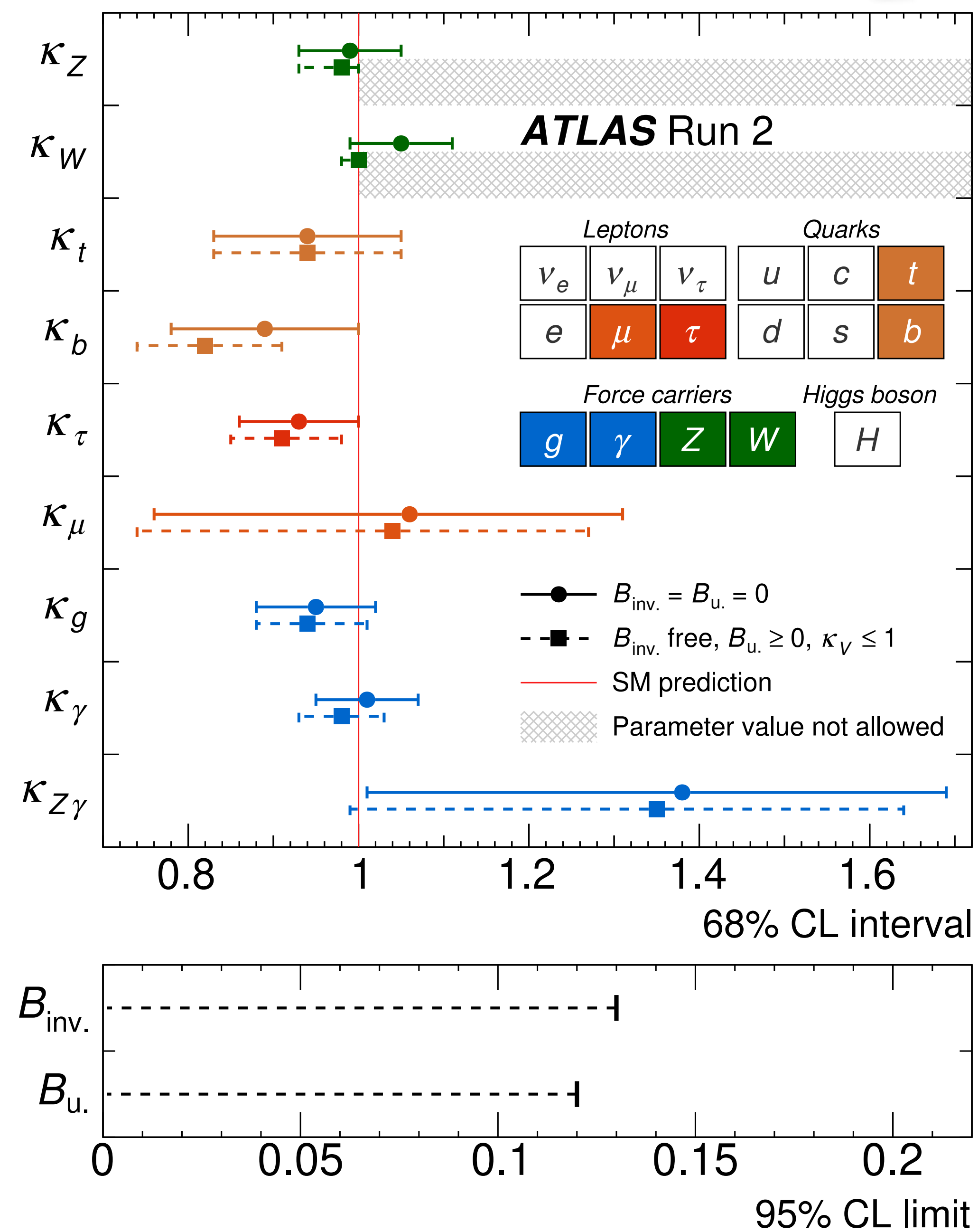



- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W/Z gauge bosons and fermions and unitarity conservation below 1 TeV.
- Non-linear relation would indicate the Higgs sector is not single doublet.

# Higgs boson couplings to bosons and fermions

RUN-2



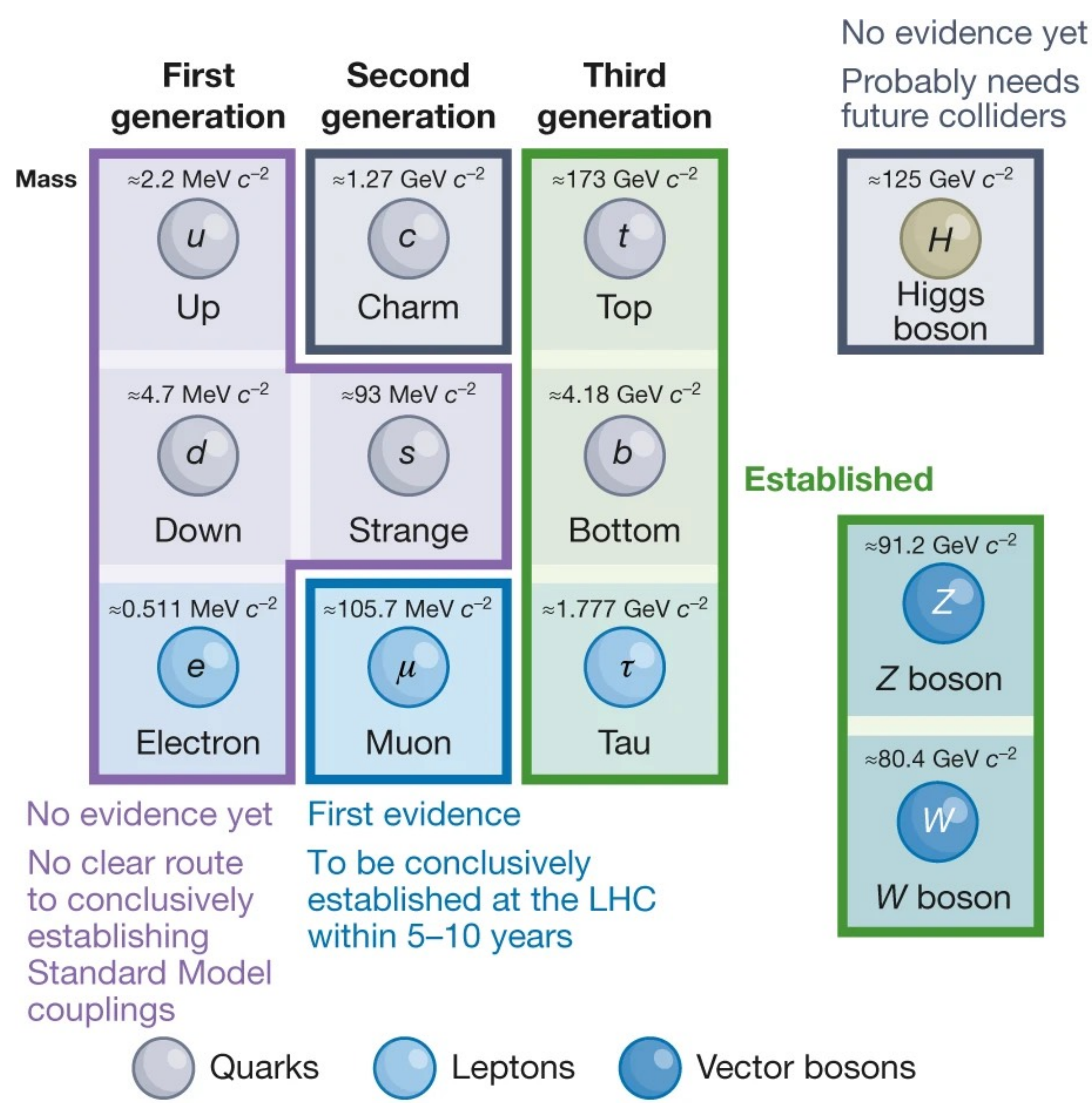




Nature 607 (2022) 52–59

# Higgs boson couplings to bosons and fermions

- Current major interest
  - 2nd generation in H→cc via VH(H→cc) etc., and $H\to\mu^+\mu^-$
- First generation $H\to e^+e^-$ (BR~$10^{-9}$) impossible at LHC … large bkg. $Z\gamma\to10^{-4}$
- $e^+e^-\to$H resonance scan at ILC? $M_H$ is important as $\Gamma_H$=4.1MeV while Ecm spread 40-50 MeV.
- European strategy update
  - HL-LHC, ILC, FCC-ee for Higgs self-coupling measurement

G. Salam et al., Nature 607 (2022) 41

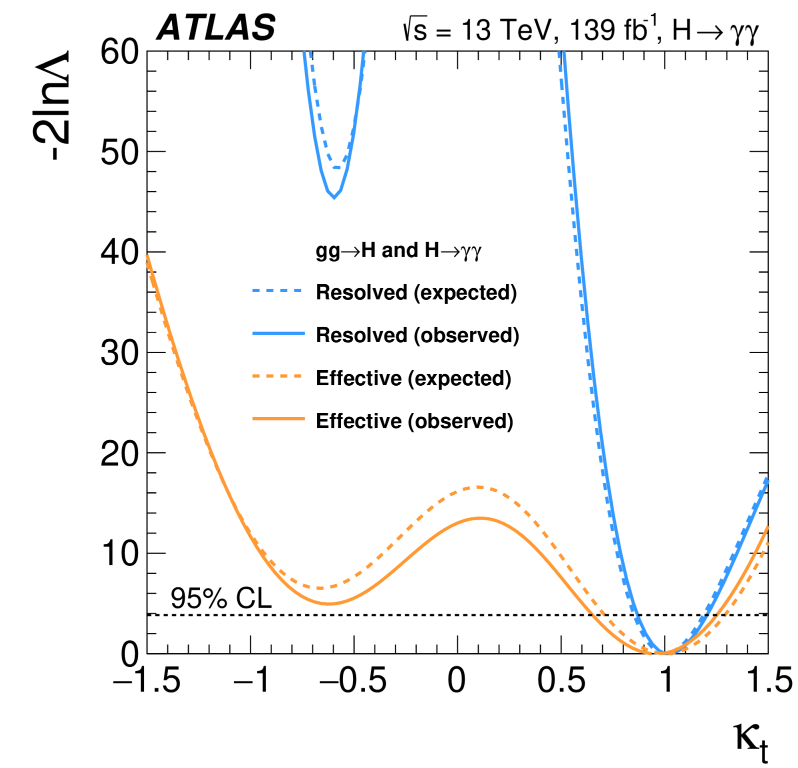


# Higgs boson couplings to fermions $\kappa_F < 0$?

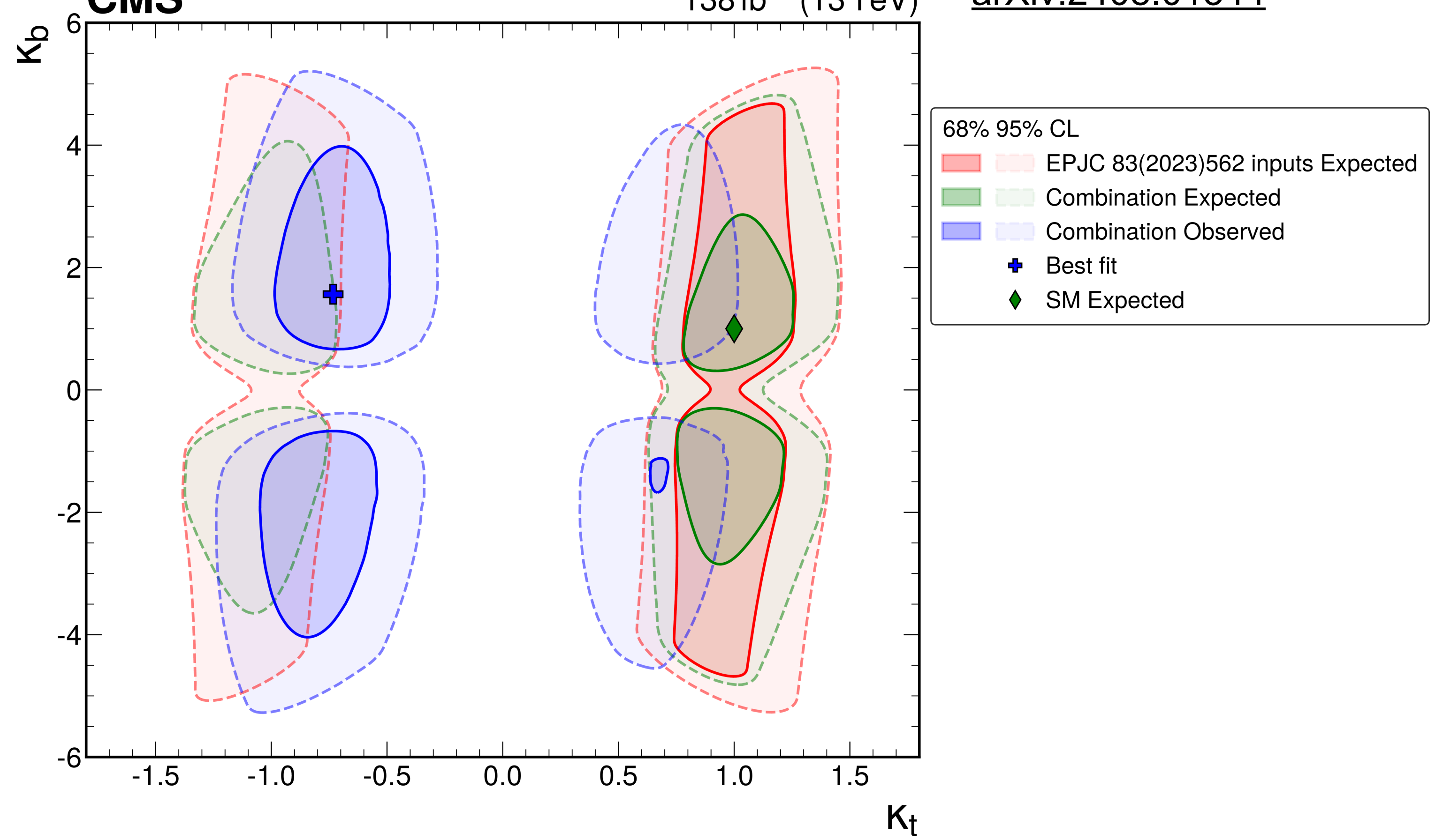
RUN-2

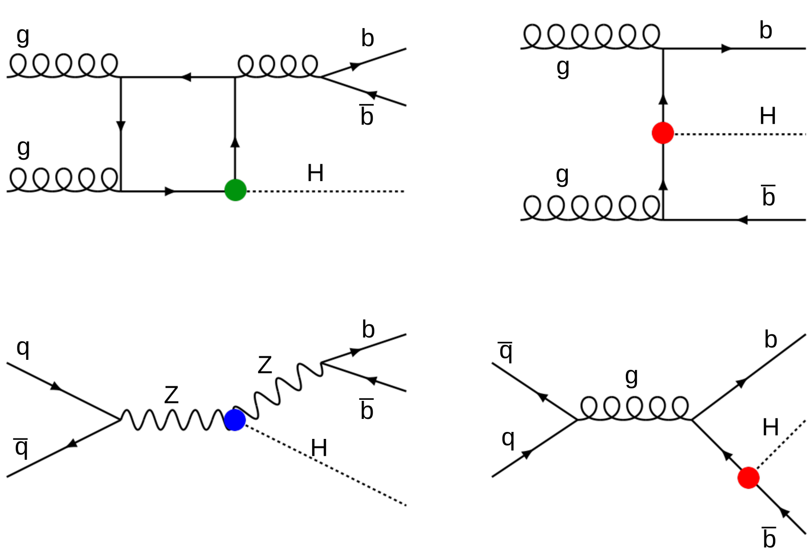
- $\kappa_V$ sign is conventional (only relative sings between $\kappa_V$ and different $\kappa_F$ is physical, overall sign is unphysical as one can flip sign via h→-h ), hence we take $\kappa_V$ as convention.
- $\kappa_F$ positive is preferred if constrained from EWPD as negative $\kappa_F$ would imply deviation from $\kappa_V$,
- Relative sign between $\kappa_{up}$ up and $\kappa_{borrom}$ matters in BSM like 2HDM.
- When the $H\to\gamma\gamma$ (W,t,b) and $gg\to H$ (t,b) loops are resolved, negative values of $\kappa_t$ are excluded with a significance of 6.7σ (2.2σ with tH and gg→ZH only)
- Recent CMS bbH(H→ττ, WW) … slight preference $\kappa_t < 0$

JHEP 07 (2023) 088




arXiv:2408.01344

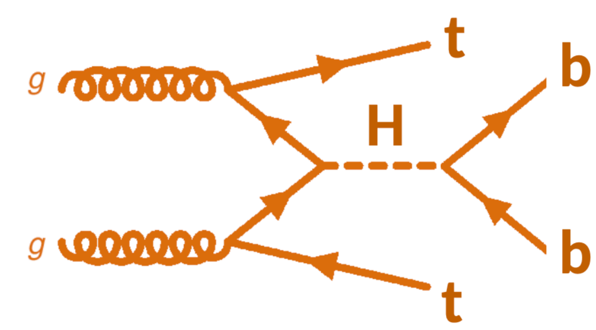


# ttH(H→bb)

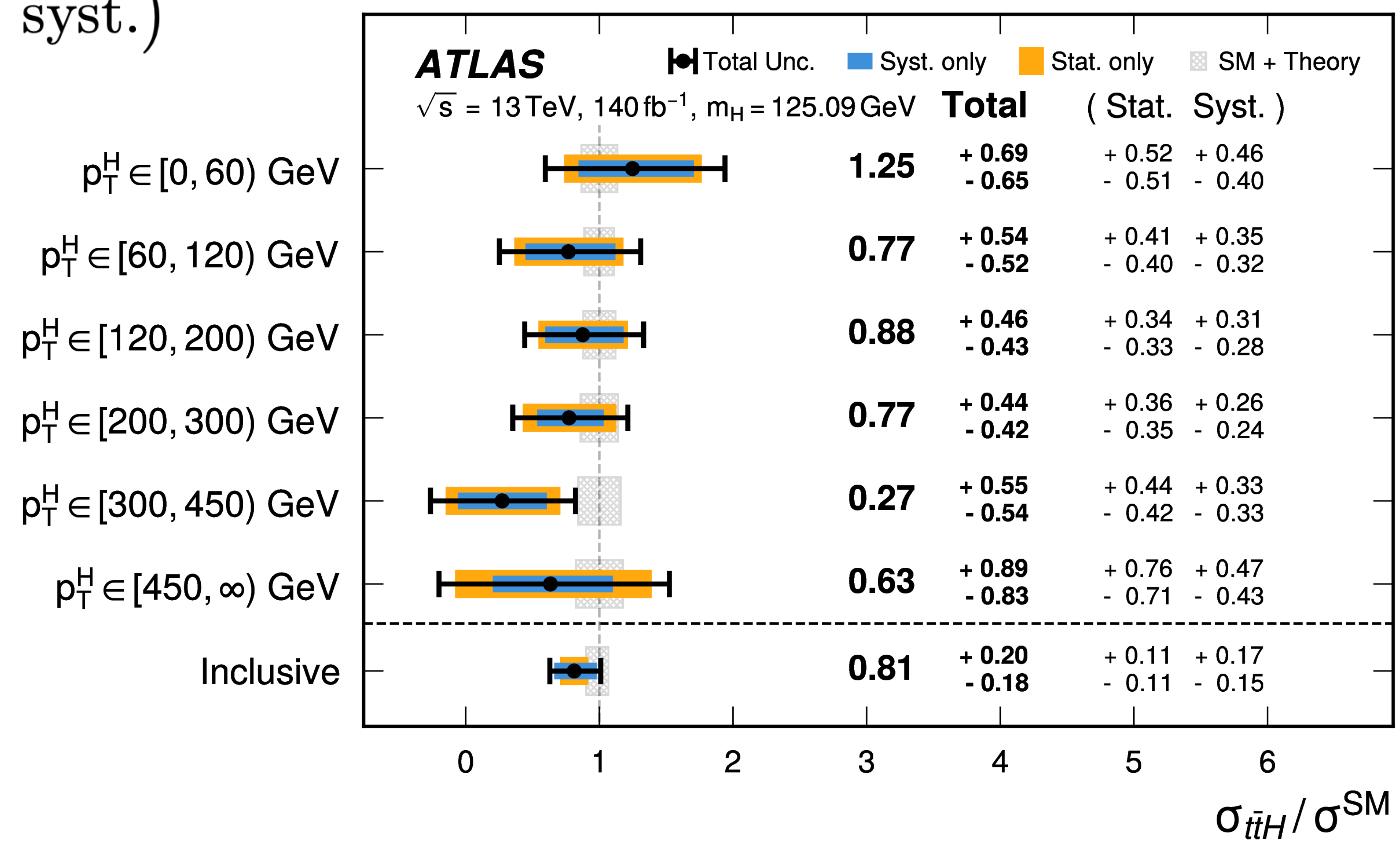
RUN-2

- Complex final state ttH→ttbb→WbWbbb (via 1 or 2 e/μ)
- Used to have ttH→ttγγ as most sensitive (but small Br(H→γγ))
- ATLAS
  - Improved b-tagging (DL1r)
  - Improved modelling of major backgrounds ttbb, etc.
  - Overall uncertainty improved by factor 1.8, 4.6σ observed.




arXiv:2407.10904

$$\mu = 0.81^{+0.22}_{-0.19}\ \left(^{+0.20}_{-0.16}\ \text{syst.}\right)$$

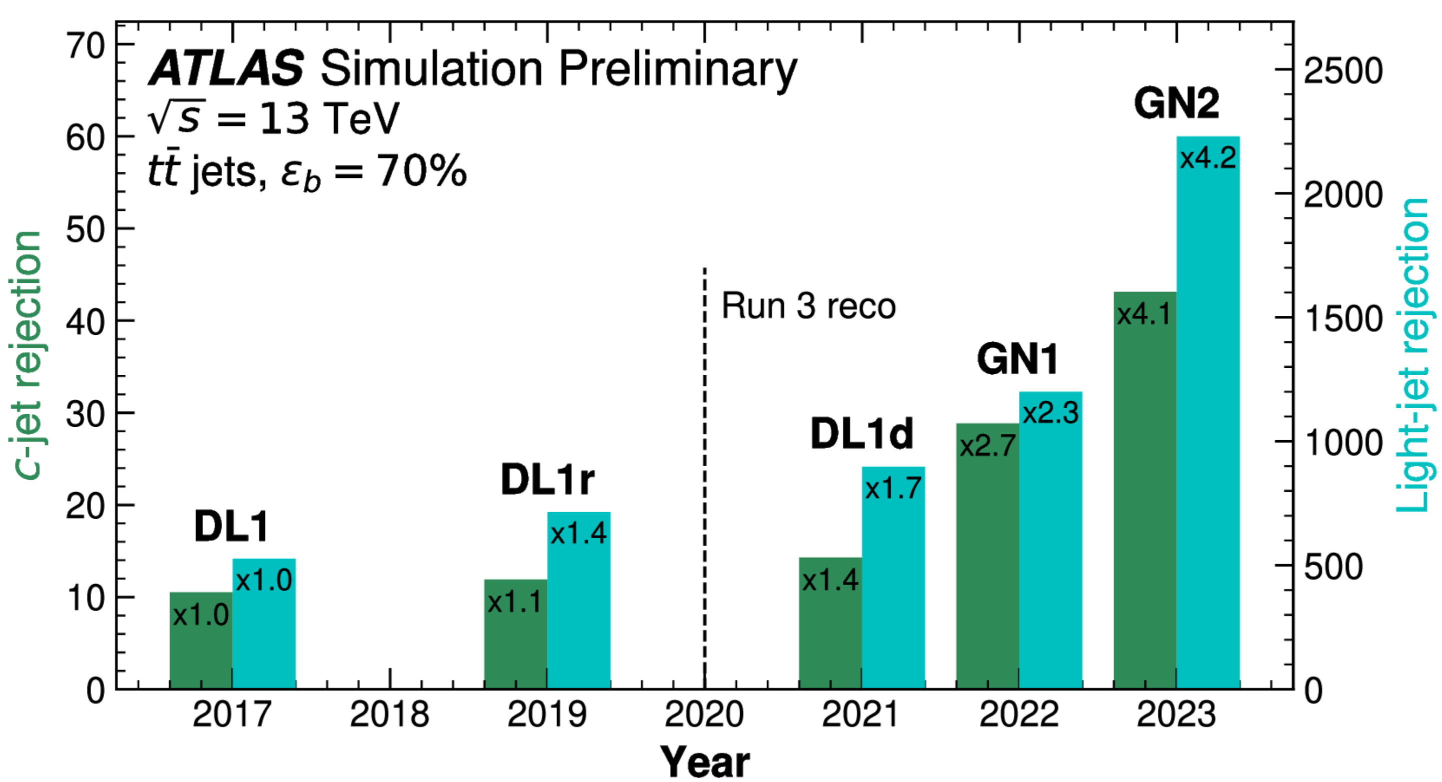


# Progress in experimental analysis techniques

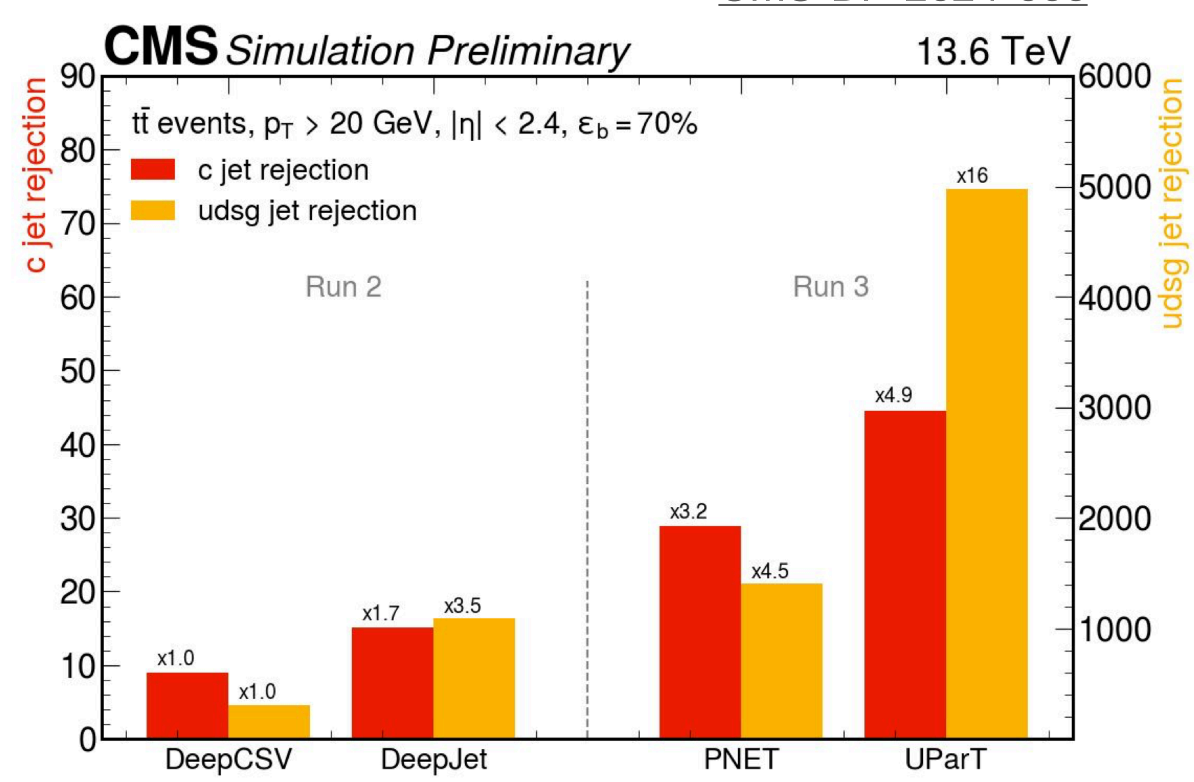
- Rapid progress in techniques:
  - ATLAS: BDT => feed-forward DNN => Graph NN,Transformers networks …
  - CMS: DeepCSV => DeepJet => ParticNet => UParT (Particle Transformer) …

- Factor 3 improvement in c-jet&light-jet rejection wrt RUN-2 !!!
  - Will impact largely in coming data analyses in RUN3 and HL-LHC
  - ttH(H→bb), HH(H→bbbb, bbγγ, bbττ), etc.

Eur. Phys. J. C 83 (2023) 681 FTAG-2023-01




CMS-DP-2024-066



# Effective Field Theory

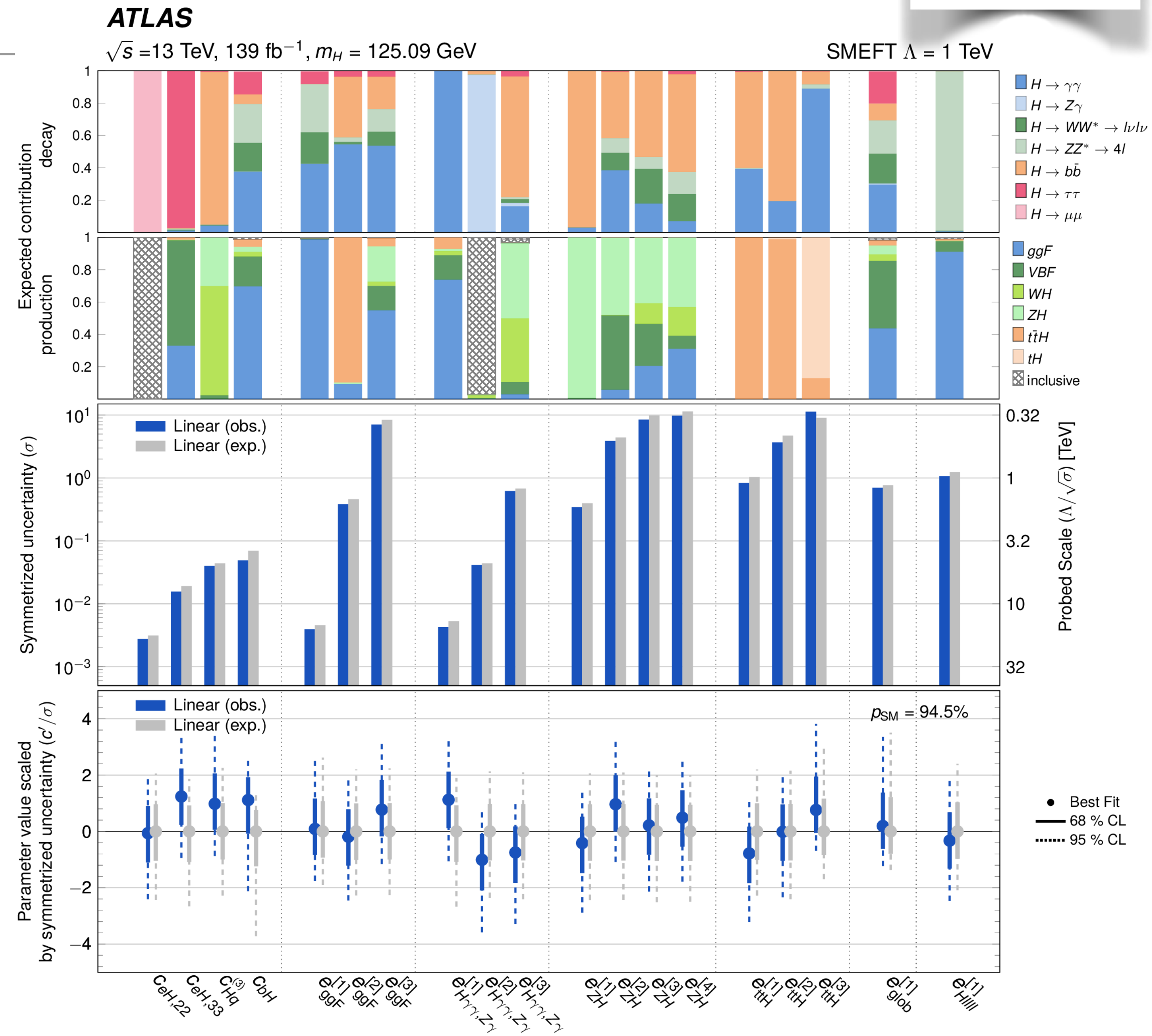
RUN-2

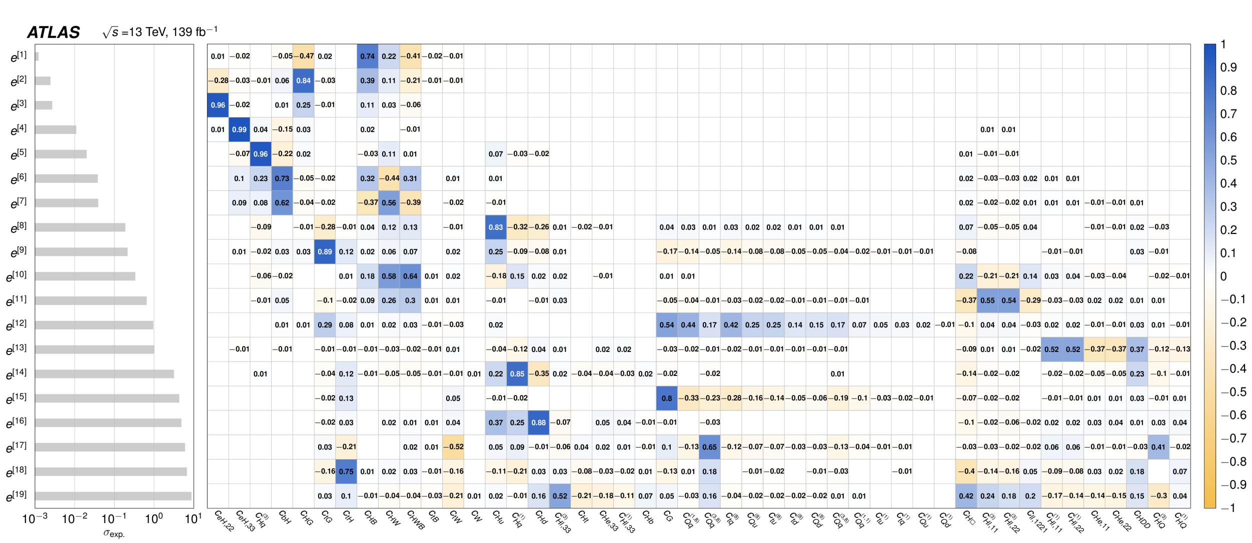
arXiv:2402.05742

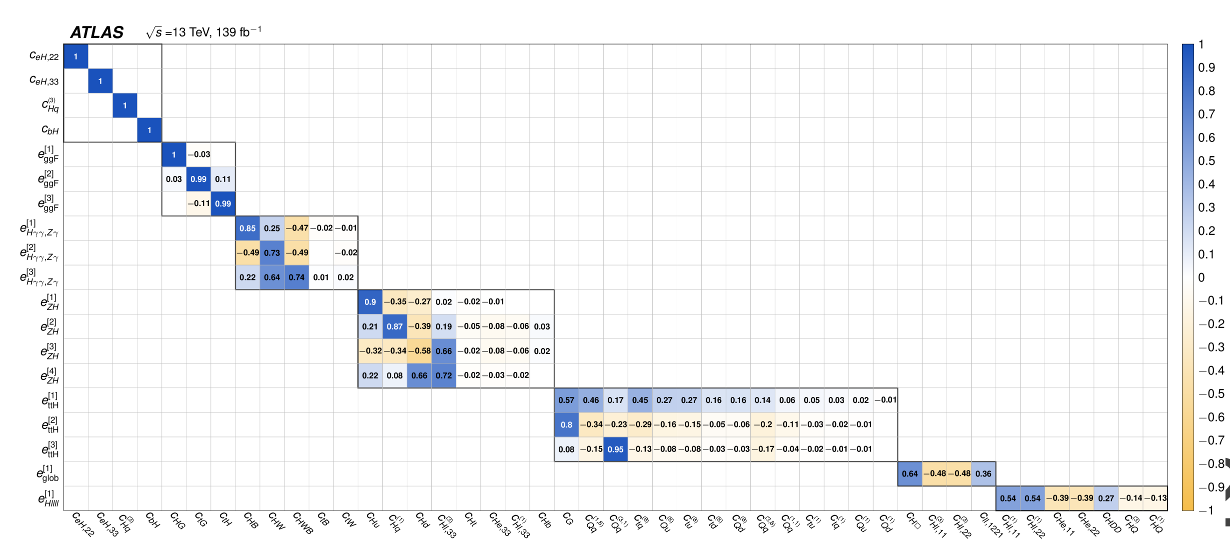
- Principal difficulty is to find the minimal set of Wilson coefficients

- ATLAS analysis - rotate Eigenvector to minimize correlation

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM}^{(4)} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i$$

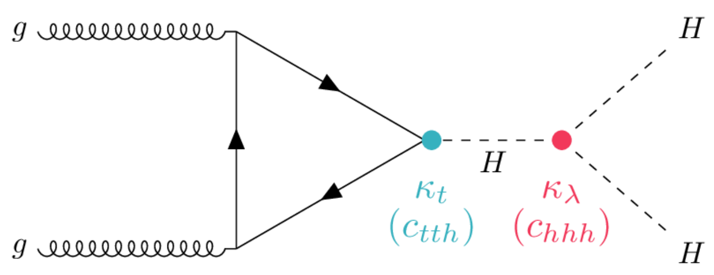


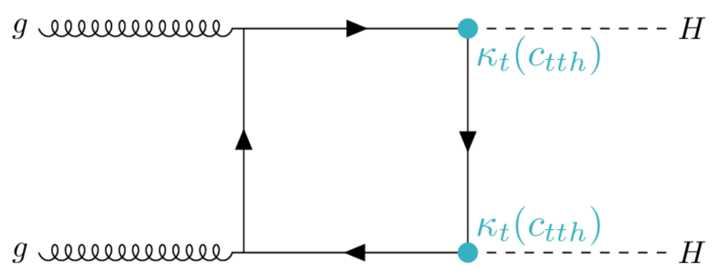



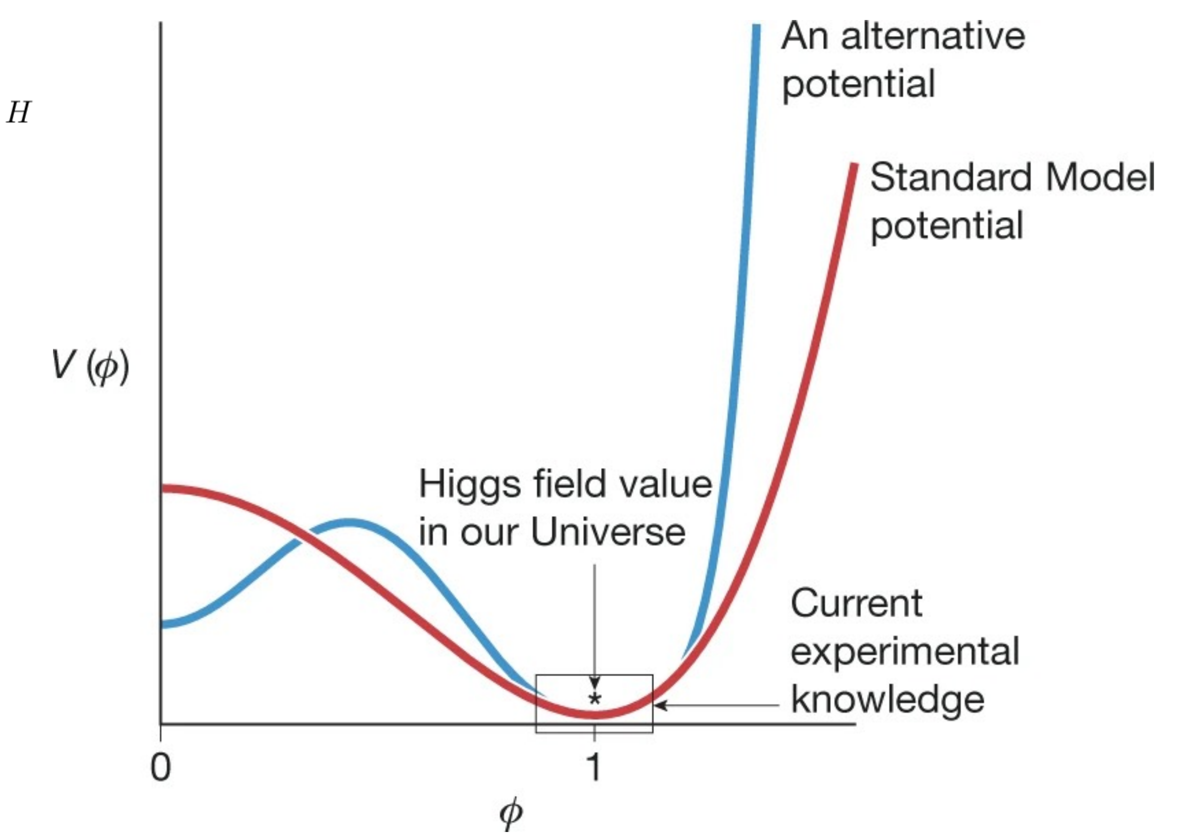
# Higgs boson self-interactions

- pp → HH: cross section 1000 times smaller than pp → H



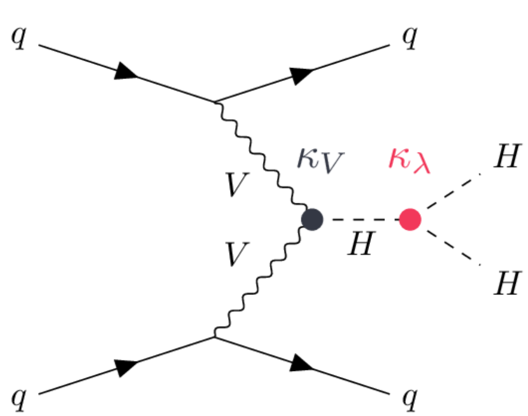



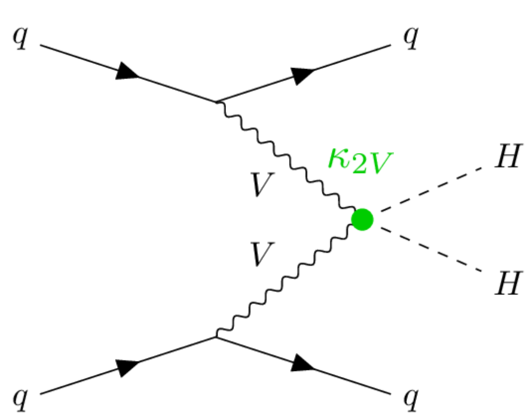

G. Salam et al., Nature 607 (2022) 41




- Access to the triple Higgs boson coupling $\kappa_\lambda$
  - Probe the shape of the Higgs potential

- Access to other interactions, e.g. VVHH $\kappa_{2V}$



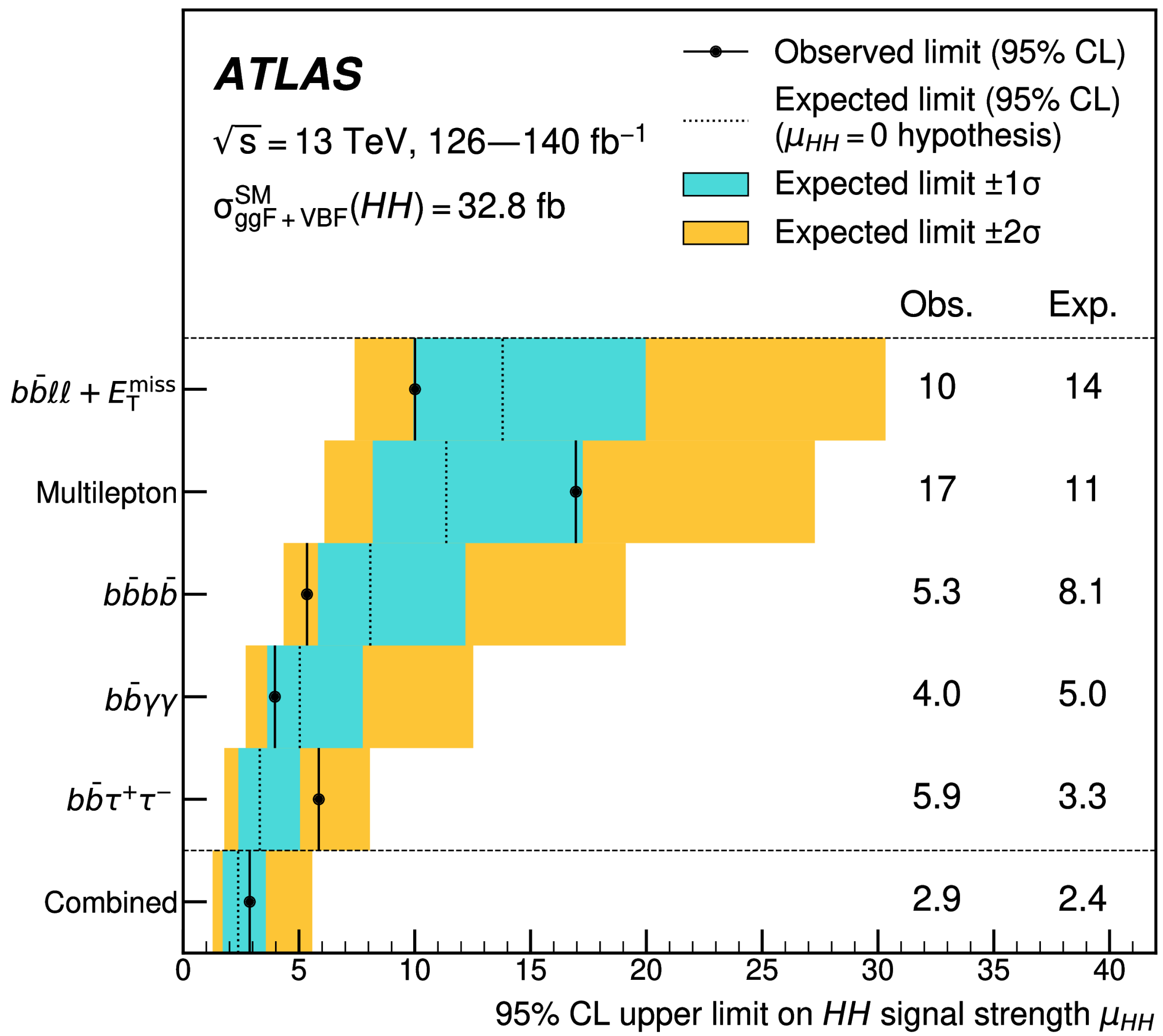



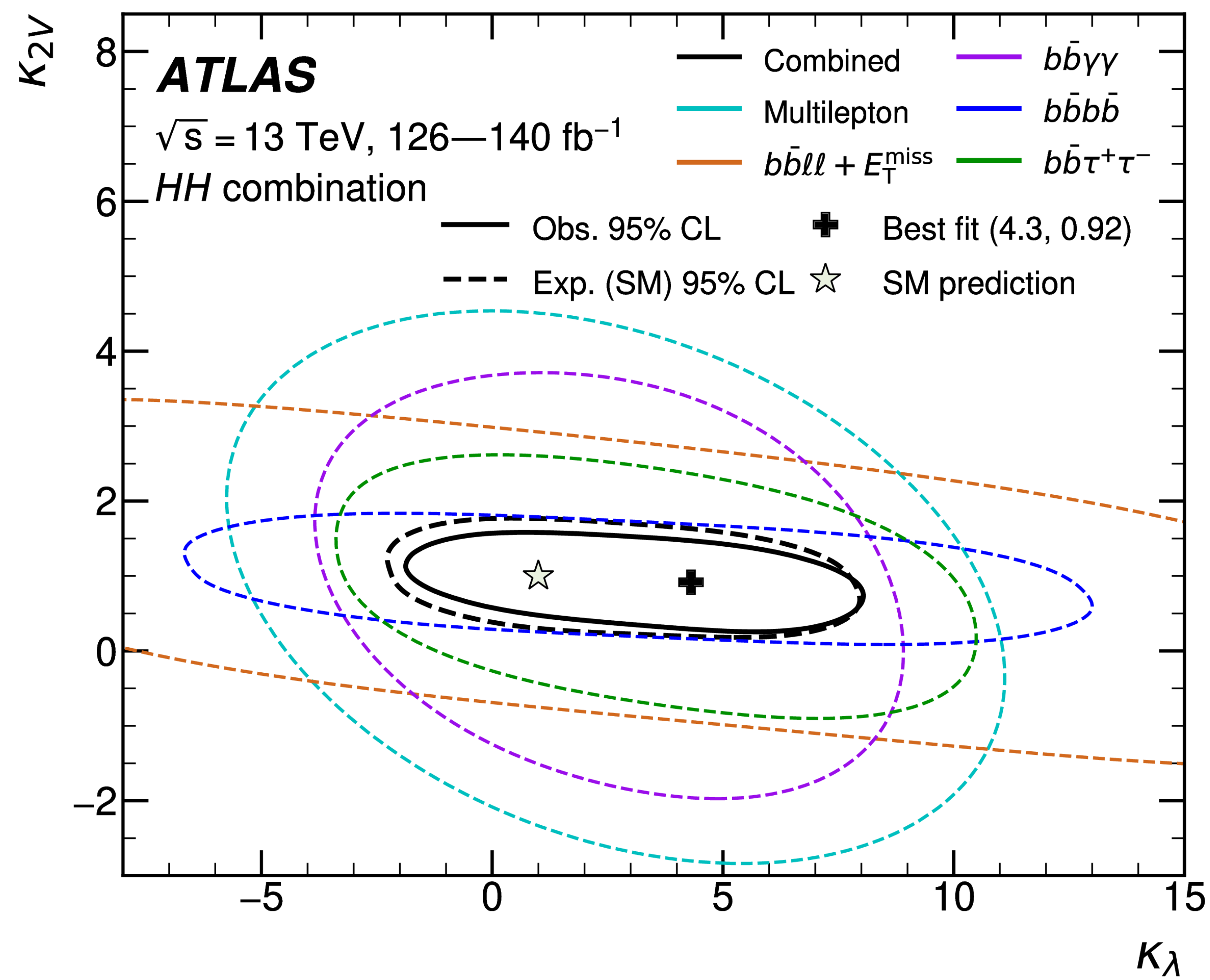
# Higgs boson self-interactions

RUN-2

- Combine HH → bbττ + bbγγ + bbbb + multi leptons + bbll+MET
- Signal strength: $\mu = 0.5^{+1.2}_{-1.0}\ (^{+0.7}_{-0.6}\ \text{syst.})$
- $-1.2 < \kappa_\lambda < 7.2$ @ 95% CL … dominated by ggF HH → bbγγ + bbττ
- $0.6 < \kappa_{2V} < 1.5$ @ 95% CL … dominated by VBF HH → bbbb

Phys. Rev. Lett. 133 (2024) 101801



HL-LHC

# Projections for HL-LHC

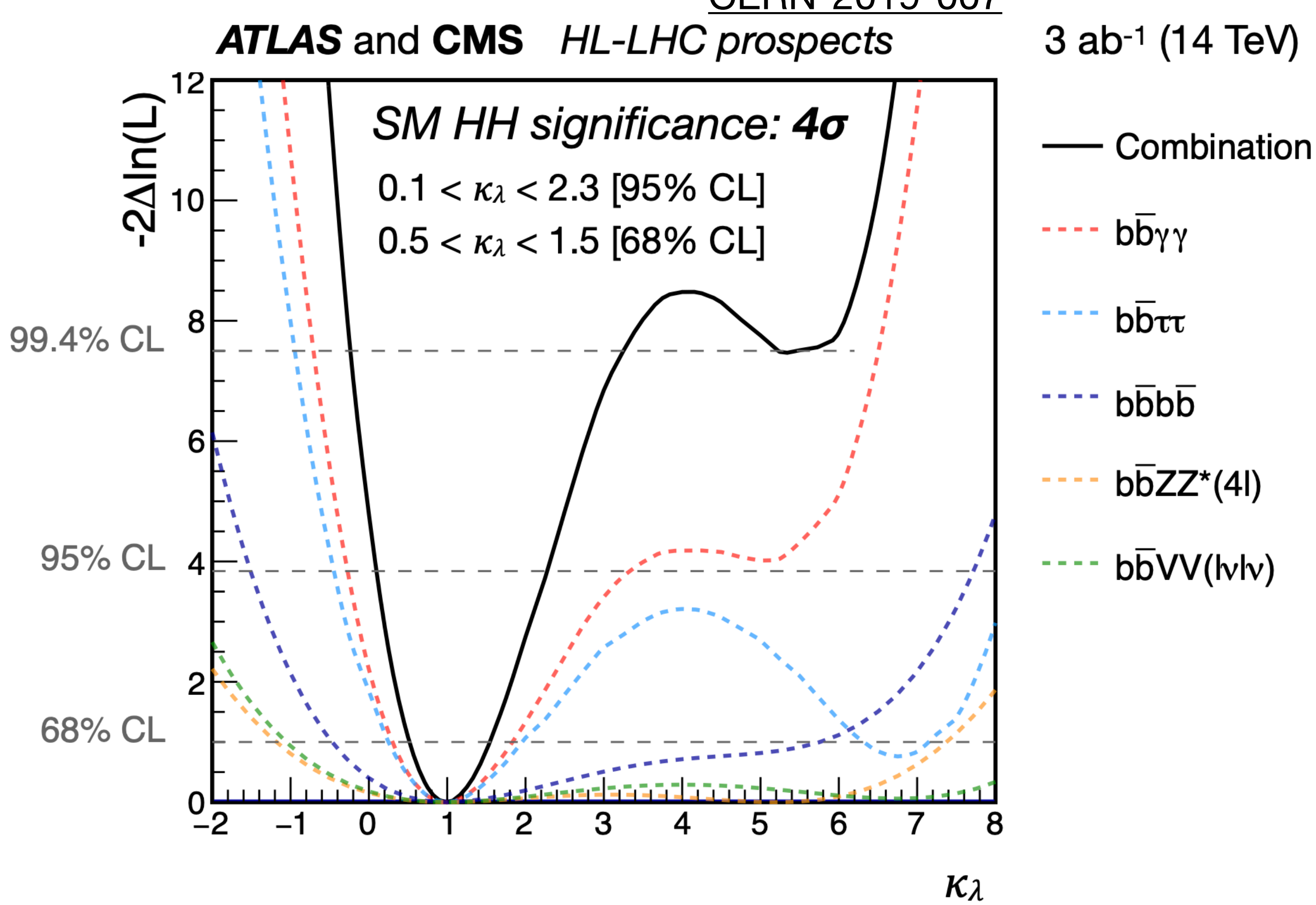
- European Strategy (2018)

Combination of 5 HH channels,
based on partial Run2 results
50% precision in self coupling
4σ for SM HH (ATLAS + CMS)

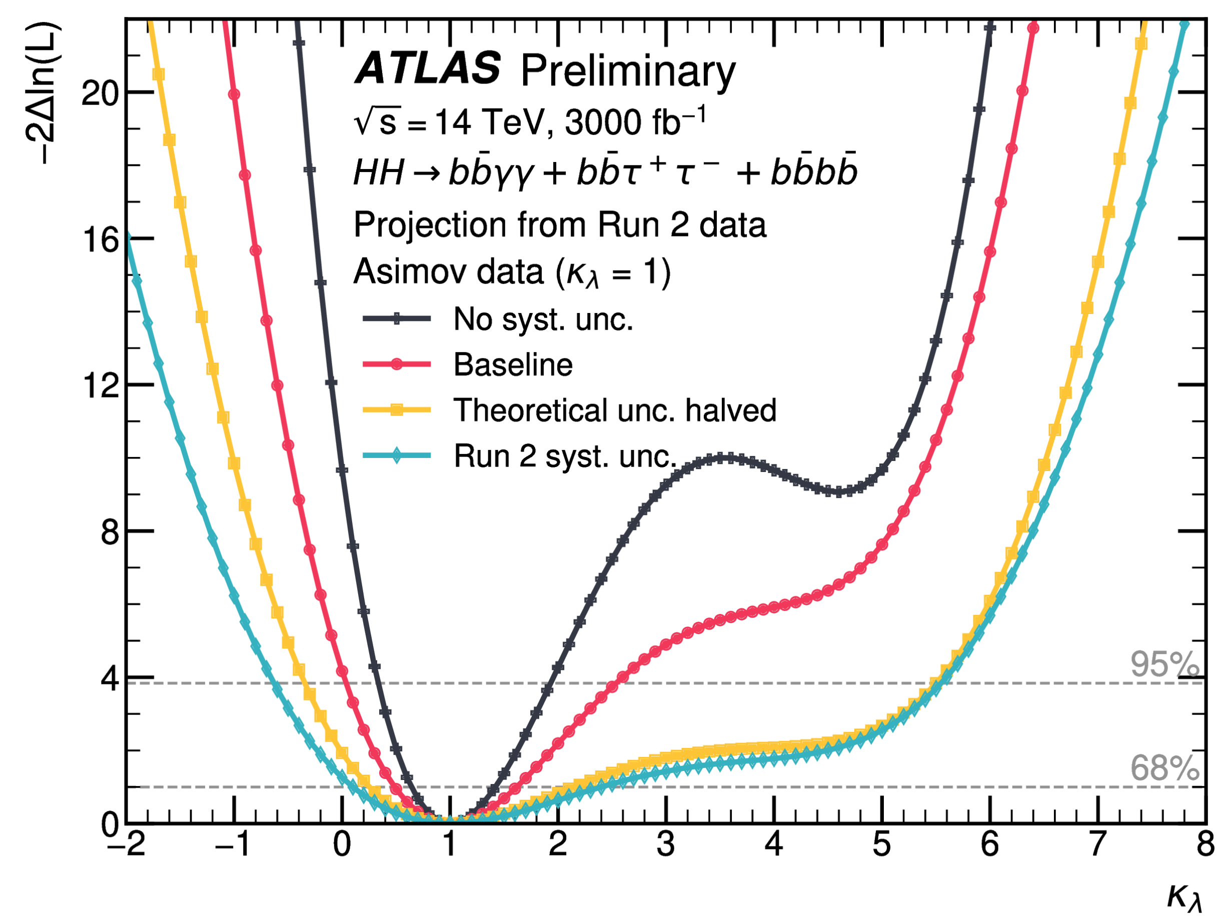
- Snowmass+ (2022)

ATLAS Updated bbbb, bbγγ, and bbττ,
CMS updated bbγγ, γγWW, γγττ, ttHH
Likely 5σ from back of the envelope
estimations

CERN-2019-007




ATL-PHYS-PUB-2022-053




Update for European Strategy is very^3 important !!!

# *Tools for Higgs Analysis*

**ggF**
- ihixs (N3LO QCD+NLO EW)
- HIGLU (NNLO QCD+NLO EW)
- FeHiPro (NNLO QCD+NLO EW)
- HNNLO, HRes (NNLO+NNLL QCD)
- RGHiggs (NNLO+NNNLL QCD)
- SusHi, aMCSusHi (N3LO/NLO QCD)
- ggHiggs (N3LO QCD)
- TROLL (N3LL' QCD)

**VBF**
- VV2H (NLO QCD)
- VBFNLO (NLO QCD)
- HAWK (NLO QCD+EW)
- VBF@NNLO (NNLO QCD)
- HJets (NLO QCD)
- proVBFH (NNLO QCD)

**WH/ZH**
- V2HV (NLO QCD)
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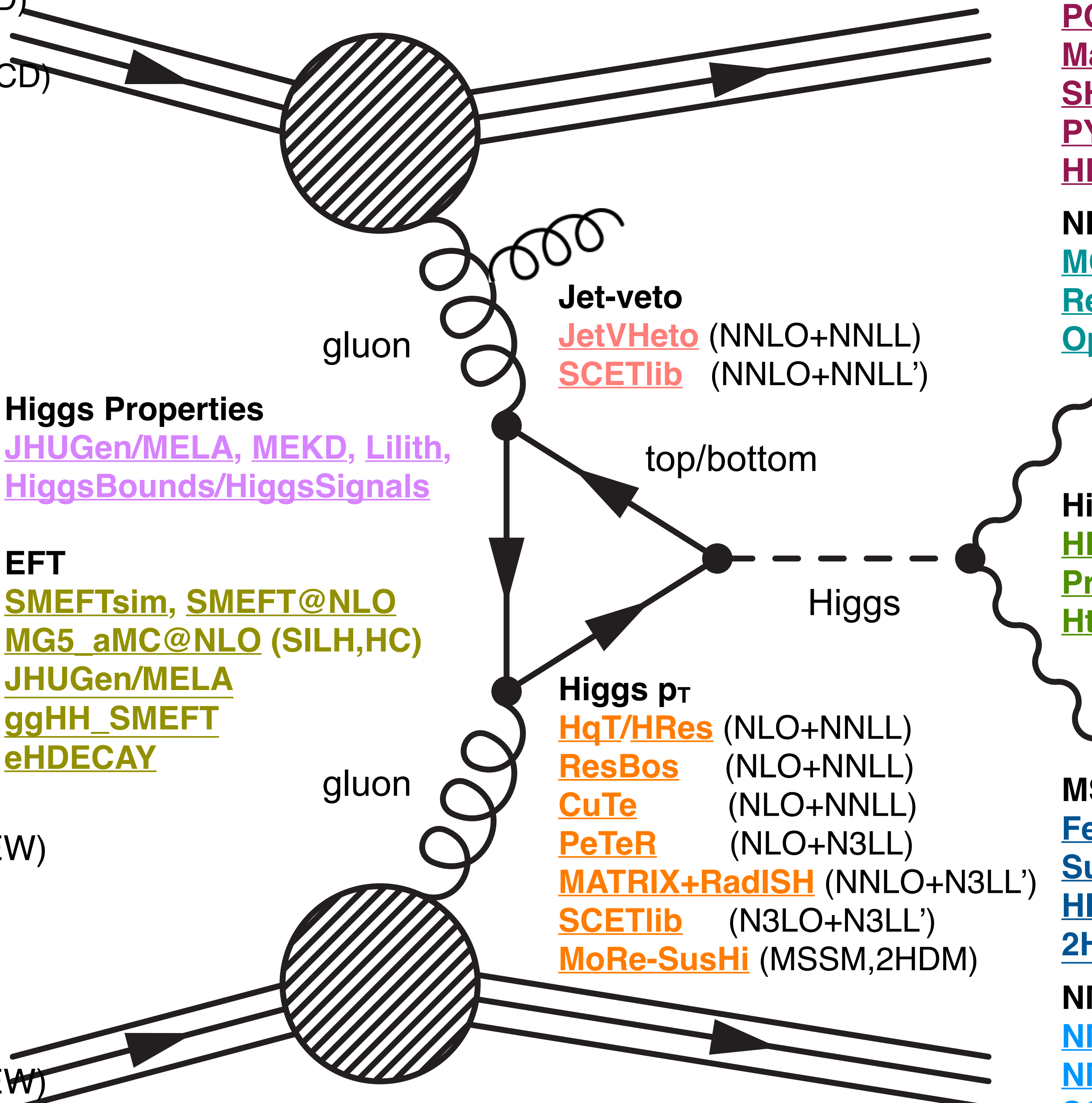
- VH@NNLO (NNLO)

**ttH**
- HQQ (LO QCD)
- POWHEL (NLO QCD)
- MG5_aMC@NLO (NLO QCD+EW)

**bbH**
- bbh@NNLO (NNLO QCD)
- bbhFONLL (NLO+NNLL QCD)
- bbX (NLO+NNLL QCD)
- MG5_aMC@NLO (NLO QCD+EW)

**HH**
- HPAIR (NLO QCD)
- ggHH (NLO QCD)
- proVBFHH (NNLO QCD)




**Jet-veto**
- JetVHeto (NNLO+NNLL)
- SCETlib (NNLO+NNLL')

**Higgs Properties**
JHUGen/MELA, MEKD, Lilith, HiggsBounds/HiggsSignals

**EFT**
- SMEFTsim, SMEFT@NLO
- MG5_aMC@NLO (SILH,HC)
- JHUGen/MELA
- ggHH_SMEFT
- eHDECAY

**Higgs $p_T$**
- HqT/HRes (NLO+NNLL)
- ResBos (NLO+NNLL)
- CuTe (NLO+NNLL)
- PeTeR (NLO+N3LL)
- MATRIX+RadISH (NNLO+N3LL')
- SCETlib (N3LO+N3LL')
- MoRe-SusHi (MSSM,2HDM)

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METAPDF, LHAPDF, HOPPET, APFEL

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**NNLO+PS MC**
- NNLOPS (MiNLO'+reweighting)
- MiNNLO
- GenEvA

**NLO+PS MC (Multi-purpose)**
- POWHEG-BOX
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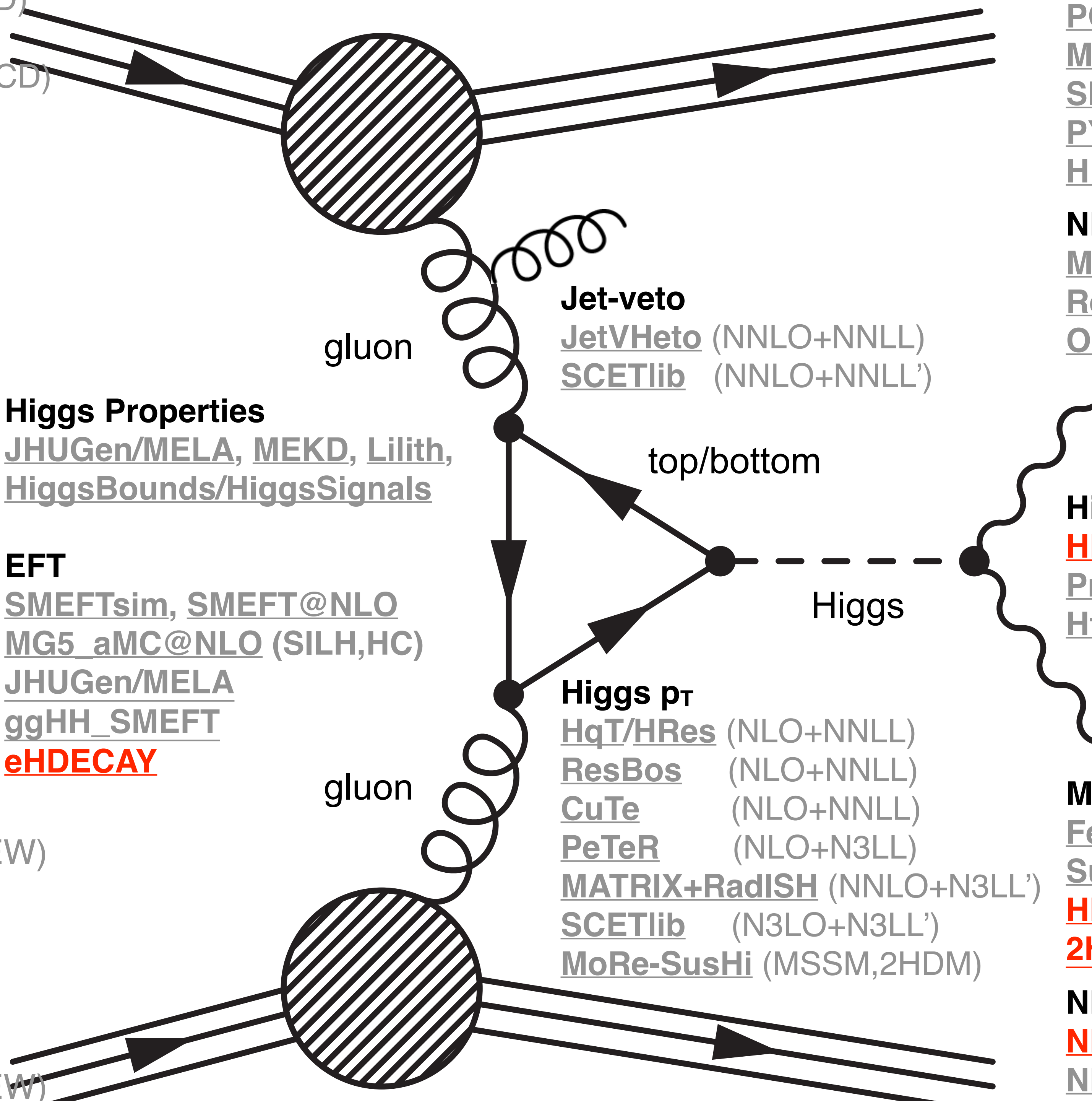


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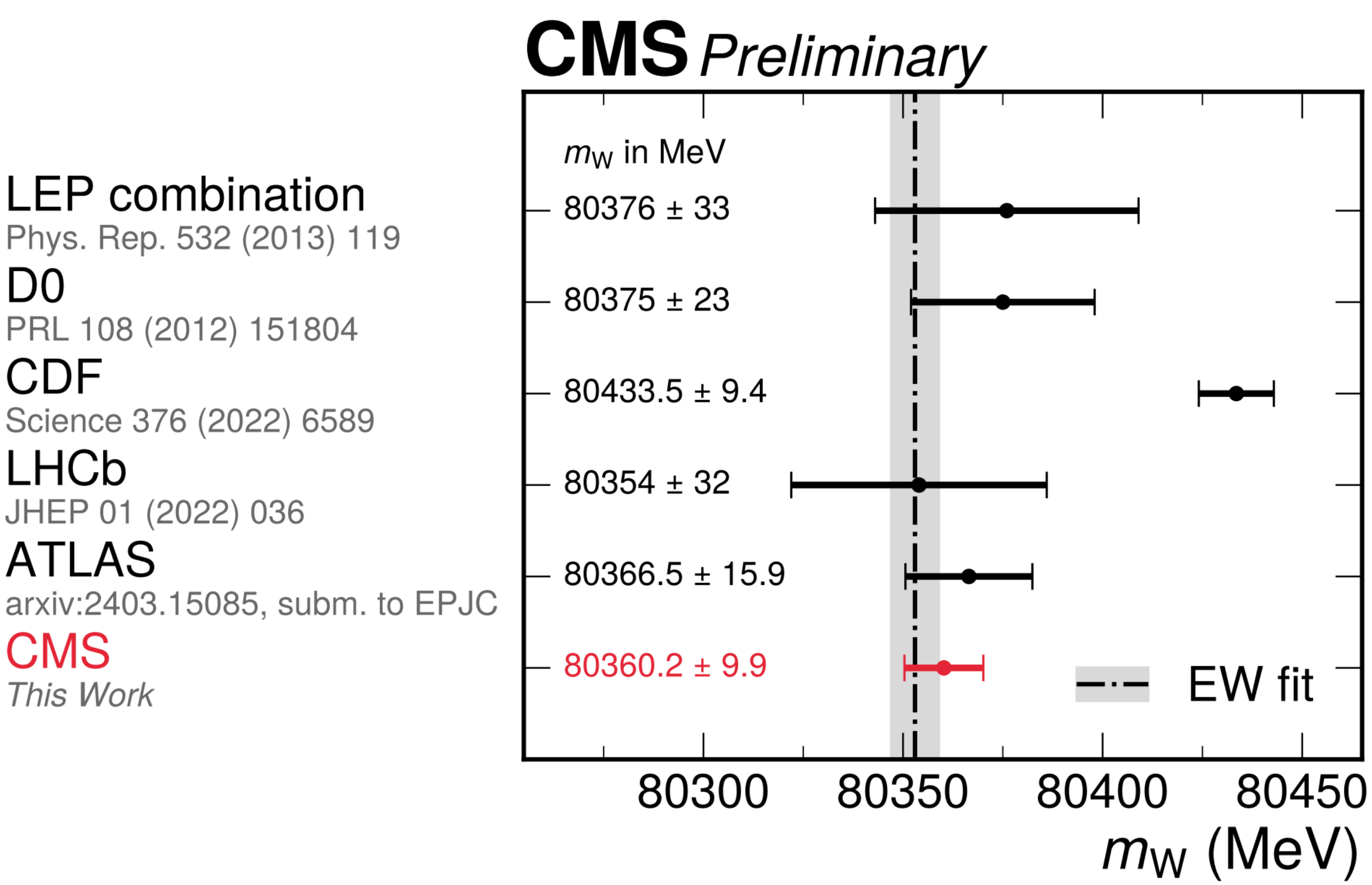
# Summary and Perspectives

- LHC is reaching unforeseen level of precision measurements in many areas !
  - LHC is the precision machine !
  - Thanks to hermetic detector design with no hole, better understanding and modeling the backgrounds, higher-order theory calculations, etc.
  - No anomalies at LHC !!! (Nostalgia for excitements at LEP, Tevatron …)
- Projection updates for future HL-LHC (3 ab$^{-1}$) and fair comparison with ILC, FCC-ee, etc. are now very important.

CMS-PAS-SMP-23-002



# At the Occasion of Michael Spira's 60th Birthday

*Last but not least, happy 60th birthday Michael !!!*
*You have been the core of Higgs physics at LHC, very close to experimentalists.*
*Hope you will achieve another important works before/after your retirement !*

Higgs Hunting in Paris/Orsay, Sept. 13, 2022
(sorry for deformation in photo)