Searching for Higgs+charm production in the $\gamma\gamma$+c final state at CMS

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PSI LTP Seminar

11-20-23

Outline

Introduction:

- Motivation.
- State of the art.
- New approaches.

Ingredients:

- Monte Carlo simulation.
- $H \rightarrow \gamma\gamma$ method.
- Framework development.
- Charm tagging.

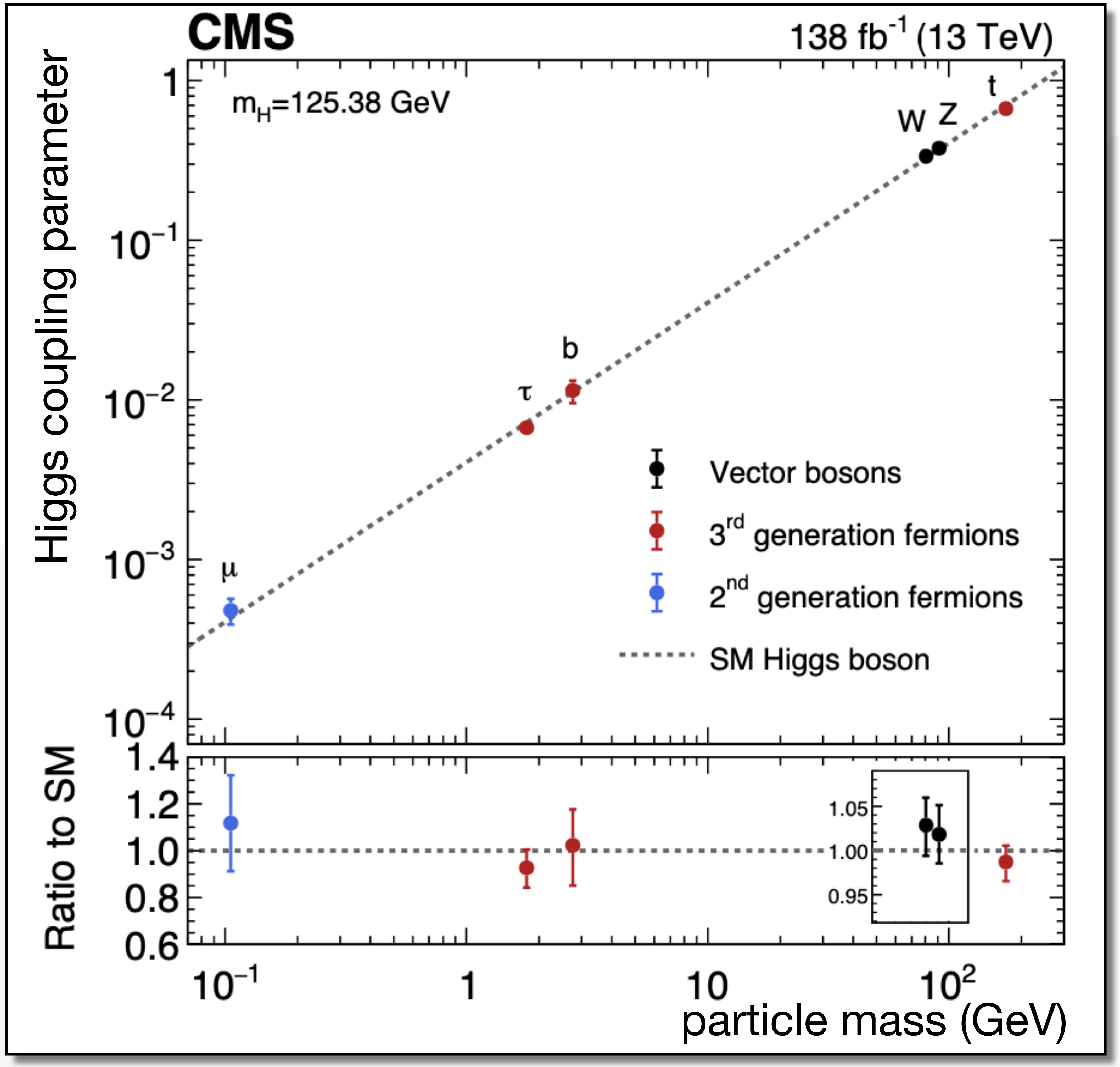
H+c analysis status:

- Analysis strategy.
- Preliminary results.

Motivation

The Higgs boson:

- Last addition to the Standard Model:
    - Theorised in ’64, discovered in 2012 🏅 at the LHC.
- It has a unique role in the SM:
    - **Important benchmark of the theory**.
    - Responsible for the mechanism that gives masses to elementary particles.
- Precise measurements of the Higgs couplings is of crucial importance:
    - The SM is amazing, but it’s an incomplete theory.
    - The Higgs sector could be a **bridge to** understanding **new physics.**

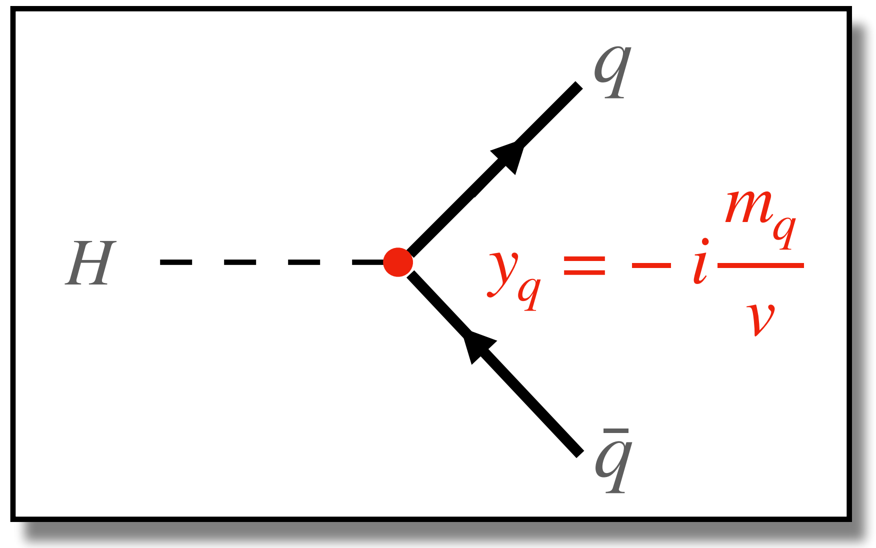


Nature 607, 60–68 (2022)

Motivation

Higgs couplings:

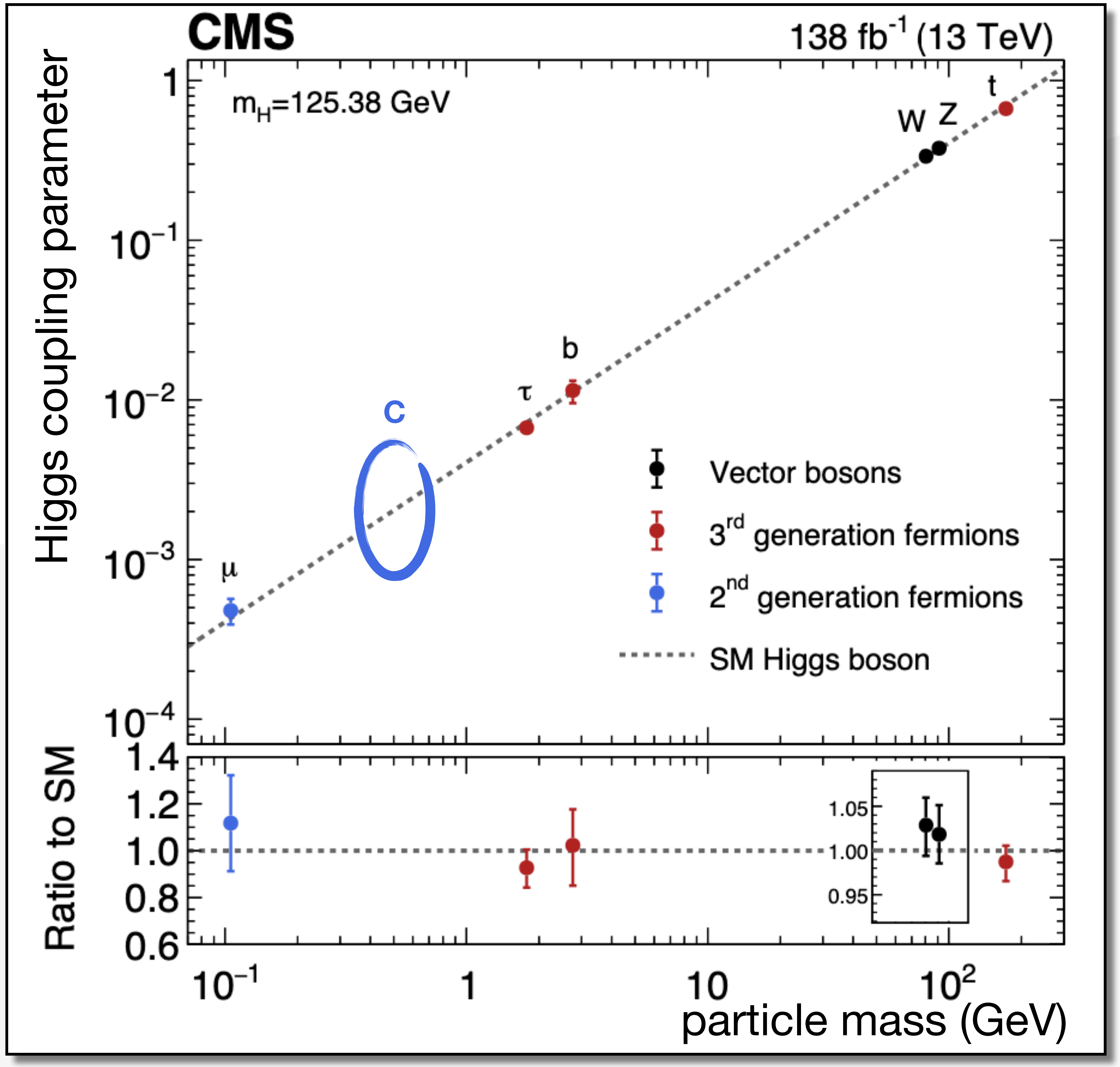
- Couplings to other particles are precisely predicted and **proportional to the particle masses**:



  - BR $H \rightarrow b\bar{b} \sim 58\,\%$
  - BR $H \rightarrow c\bar{c} \sim 3\,\%$

- **3rd generation** couplings already measured, 1 to 3 orders of magnitude bigger than 2nd generation couplings.

- **2nd generation** fermion couplings are one of the primary goals of CMS physics program:
  - $H \rightarrow \mu\mu$: 3σ evidence (JHEP 01 (2021) 148)
  - What about **charm**?



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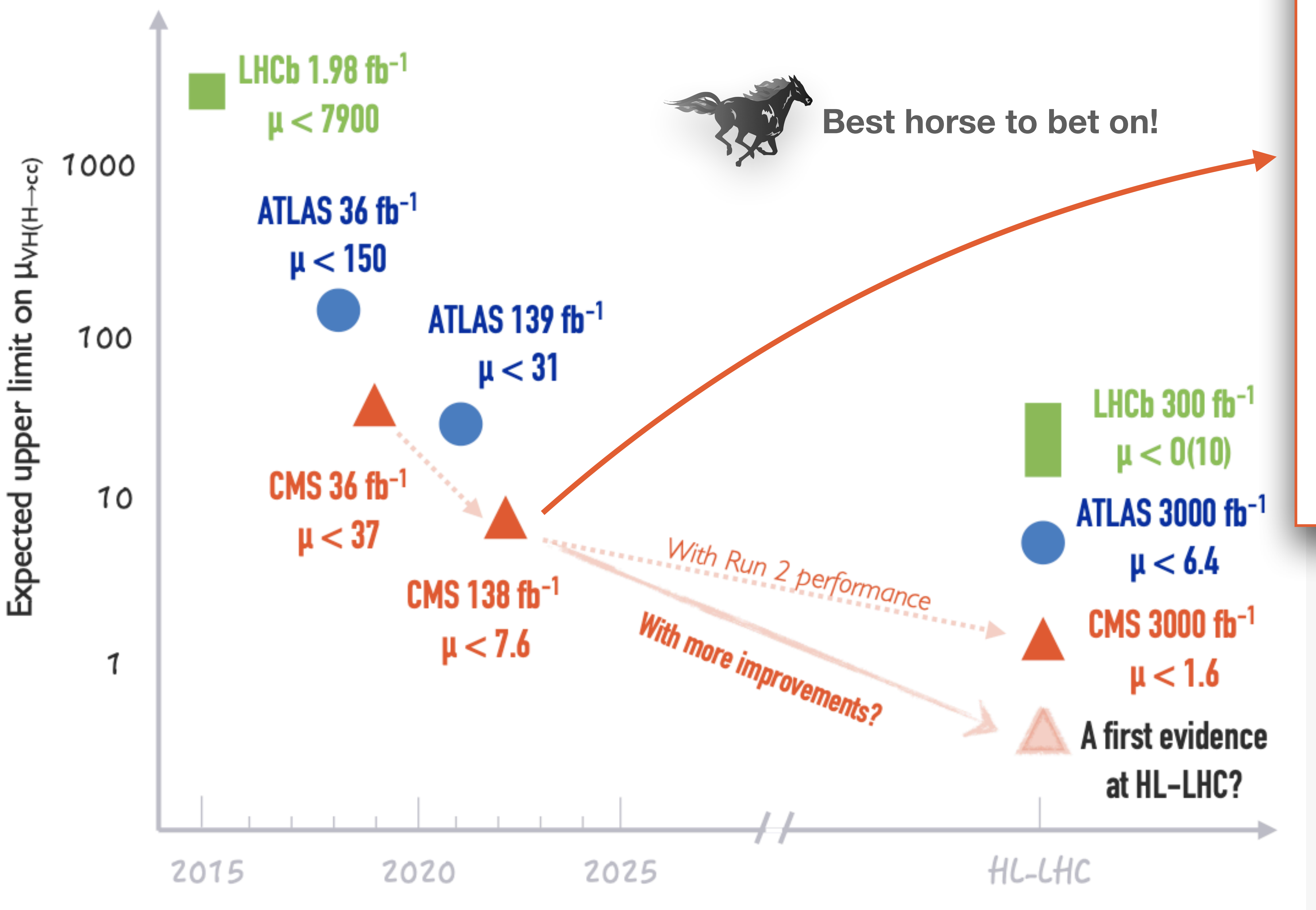
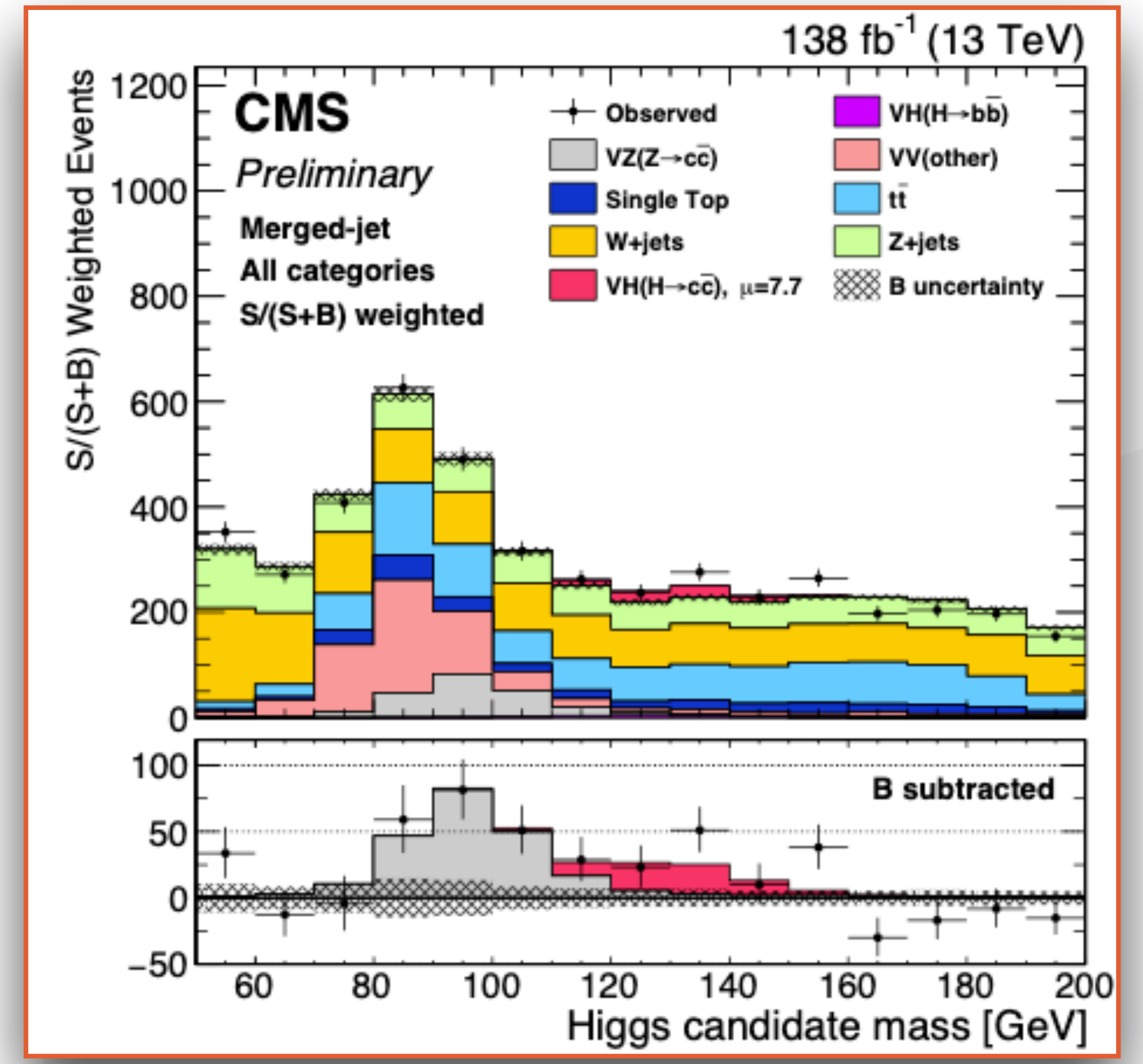
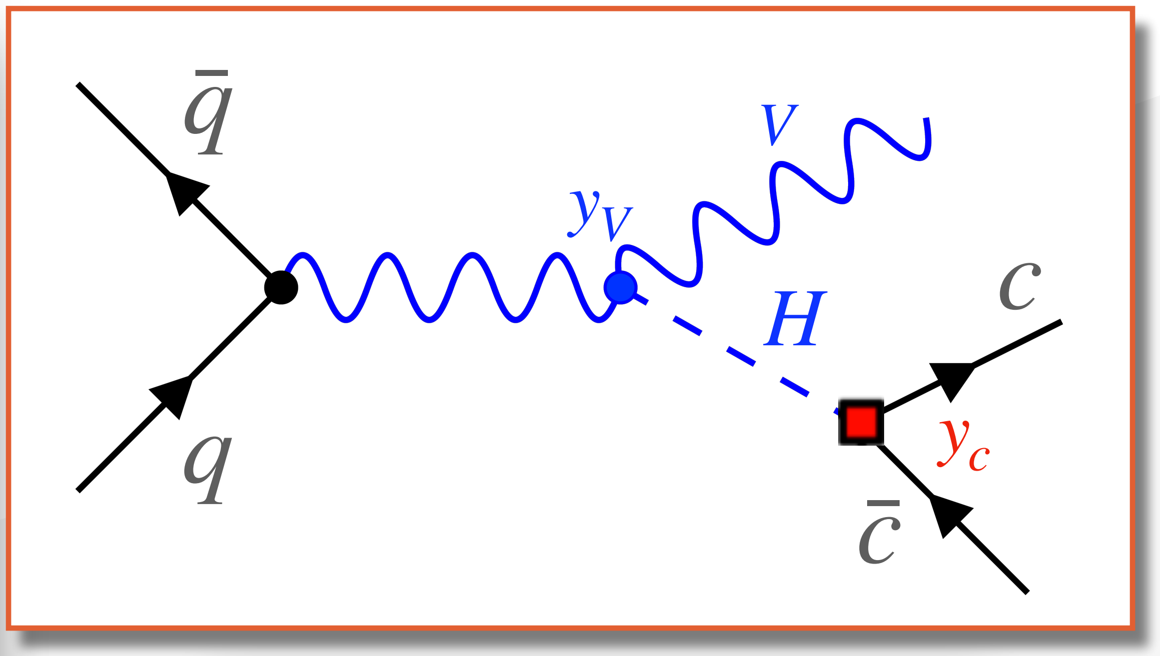
State of the art: Previous results

- **Direct search** for $VH(H \to c\bar{c})$ PRL 131 (2023) 061801: recent improvements, most stringent limit on $H \to c\bar{c}$.

Upper limit $\mu_{VH(H\to c\bar{c})} < 14\ (7.6)$ observed (expected) ⇐







$$k_c = y_c / y_c^{SM}$$

$$\mu = \sigma / \sigma_{SM}$$

- **Other approaches**: Exclusive rare decays, $p_T(H)$ differential measurements …

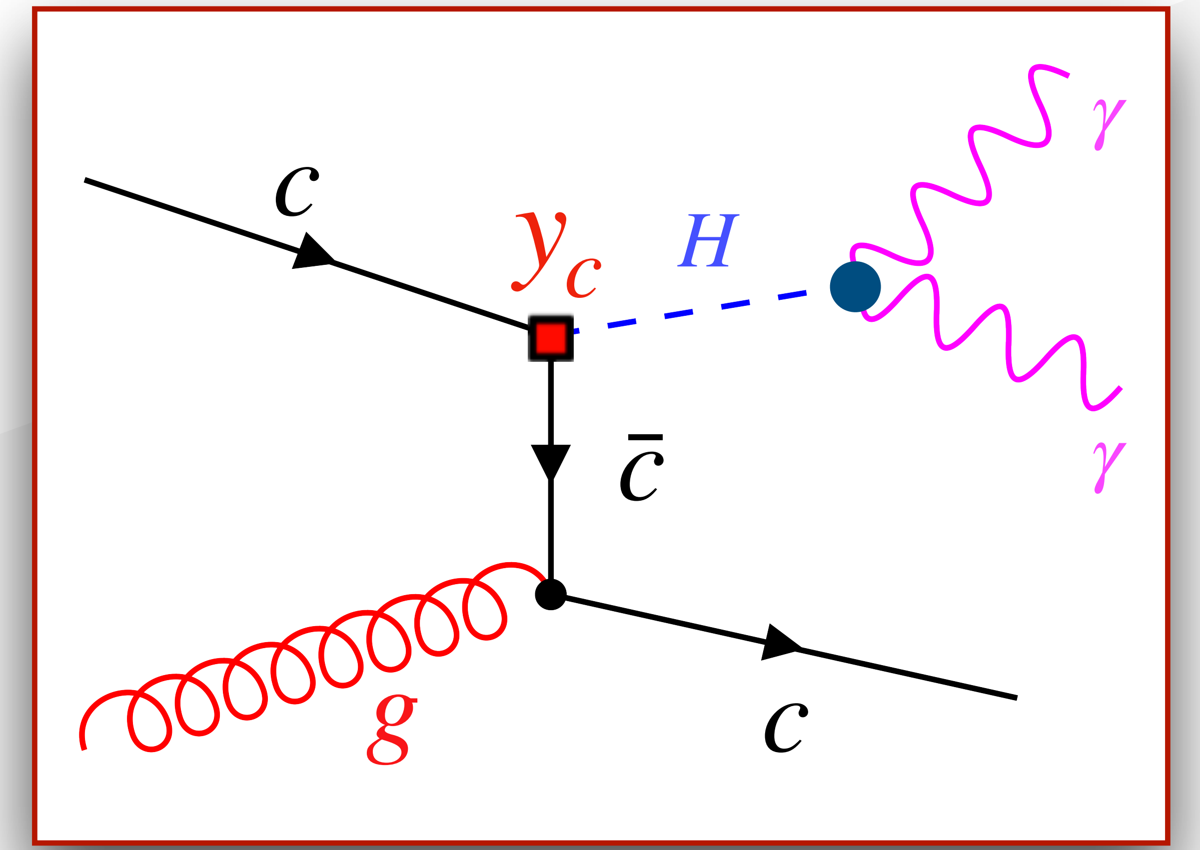
H. Qu

New approaches

H+c associated production:

But it's a group effort!

- Proposed by theorists (Isidori et al. 2015).
- Advantages of this channel:
  - Leading contribution requires only 1 charm to be tagged.
  - **Coupling with charm in production** ⇒ clean Higgs decays $(H \rightarrow \gamma\gamma)$.
  - Uncovered phase space, **complementary to existing** $H \rightarrow c\bar{c}$ **searches**.
- But also a few challenges:
  - Small cross section (~ 0.2 fb for $cH(H \rightarrow \gamma\gamma)$ vs 6.6 fb for $VH(H \rightarrow c\bar{c})$).
  - Non trivial signal MC simulation.
  - Challenging soft c-tagging.



No experimental results yet!

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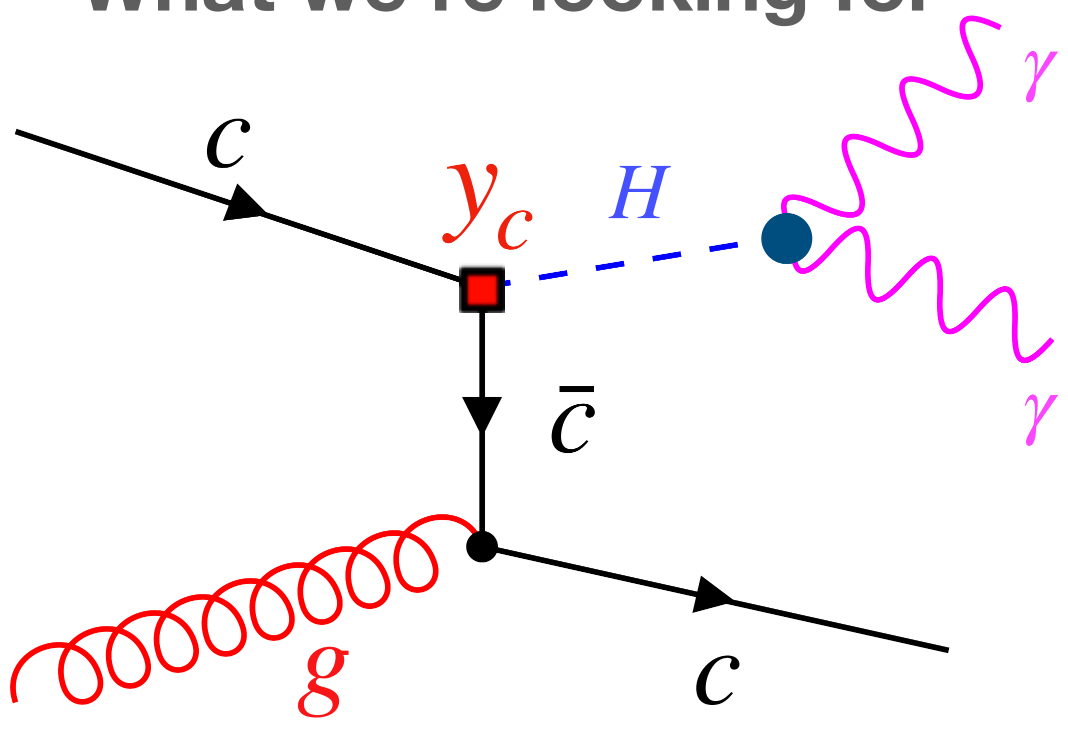
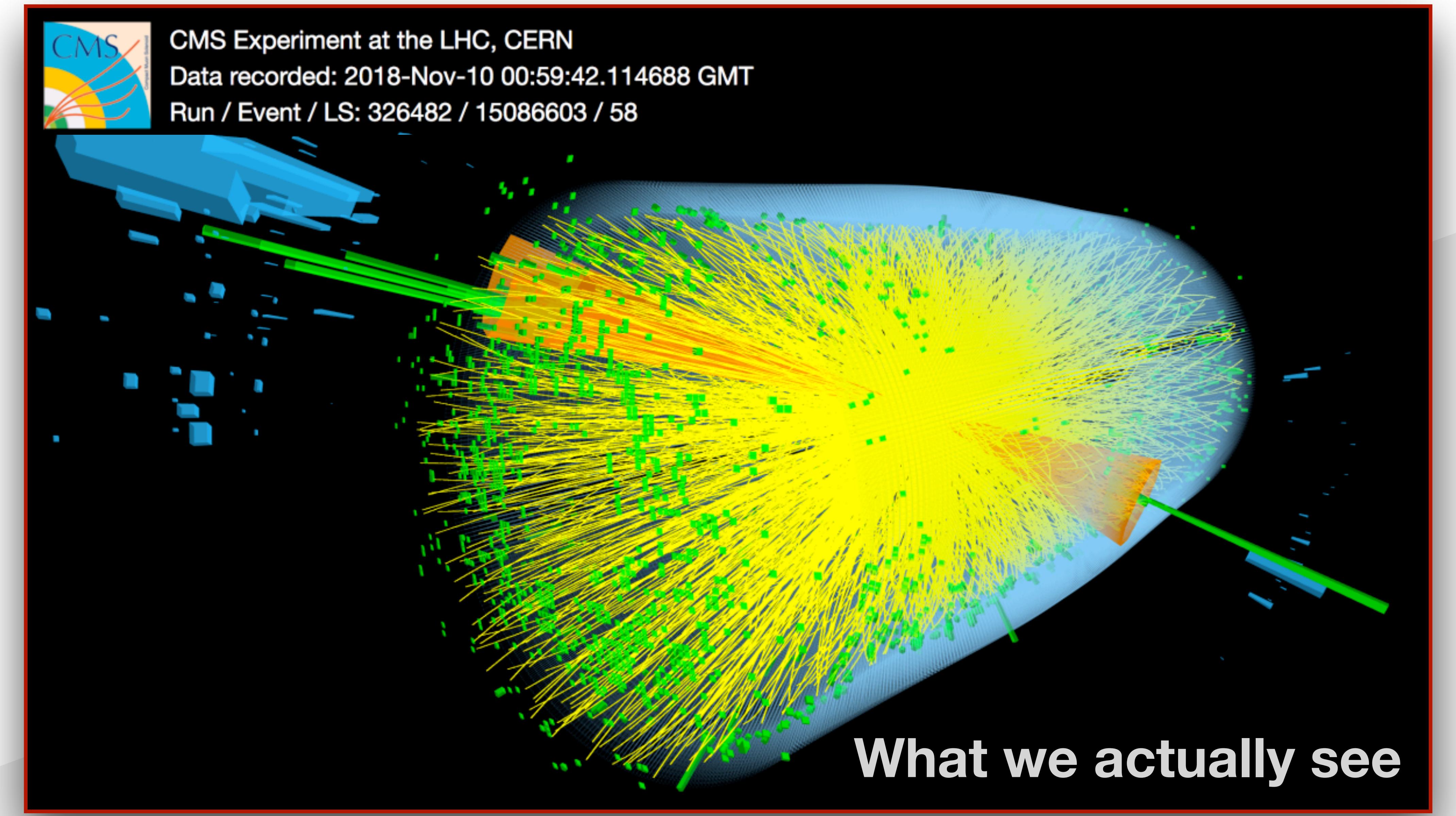
MC simulation

Why we need them?

What we're looking for





What we actually see

Quantum Chromo Dynamics

HEP experimental physicists

MC simulation

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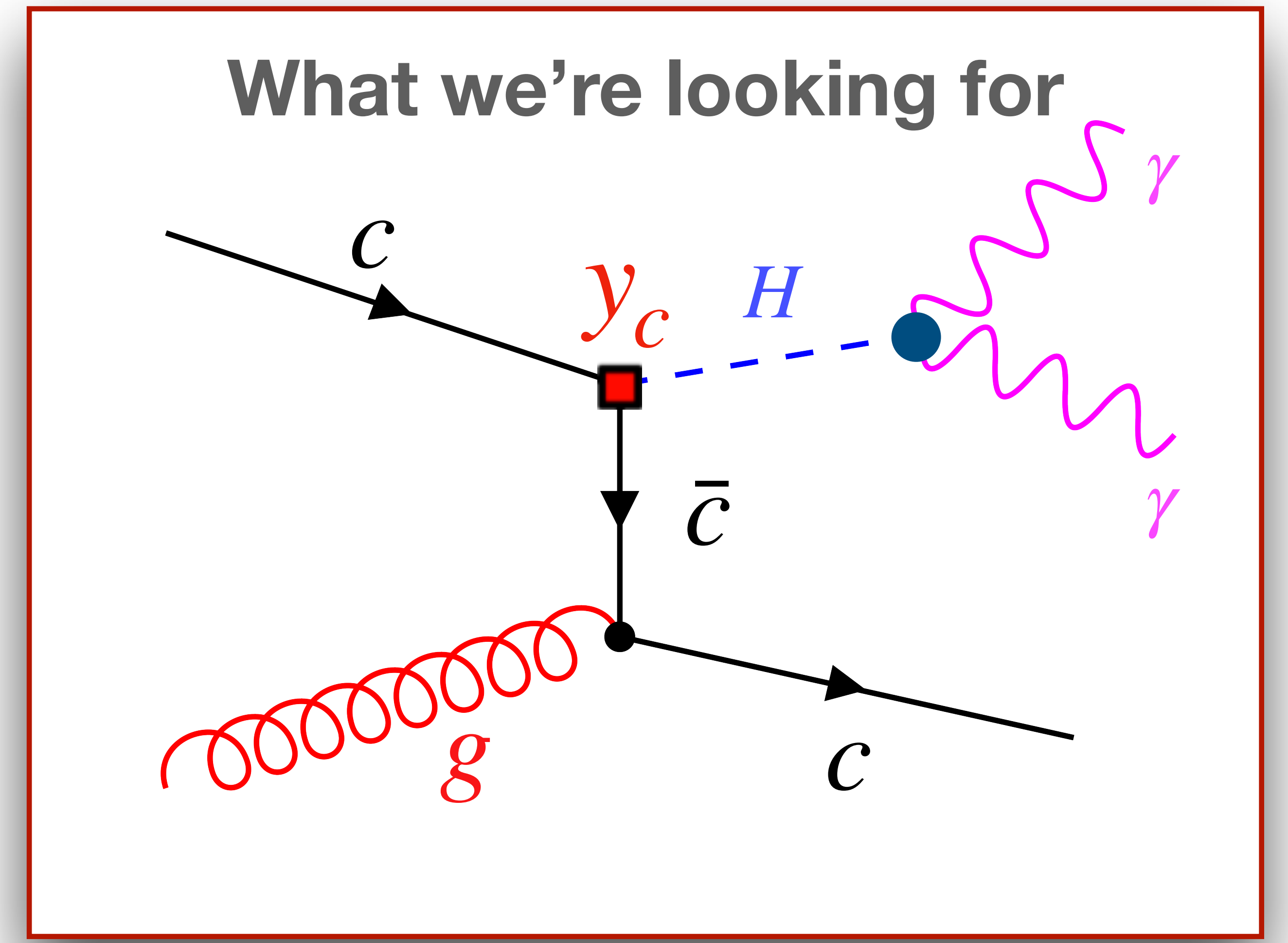
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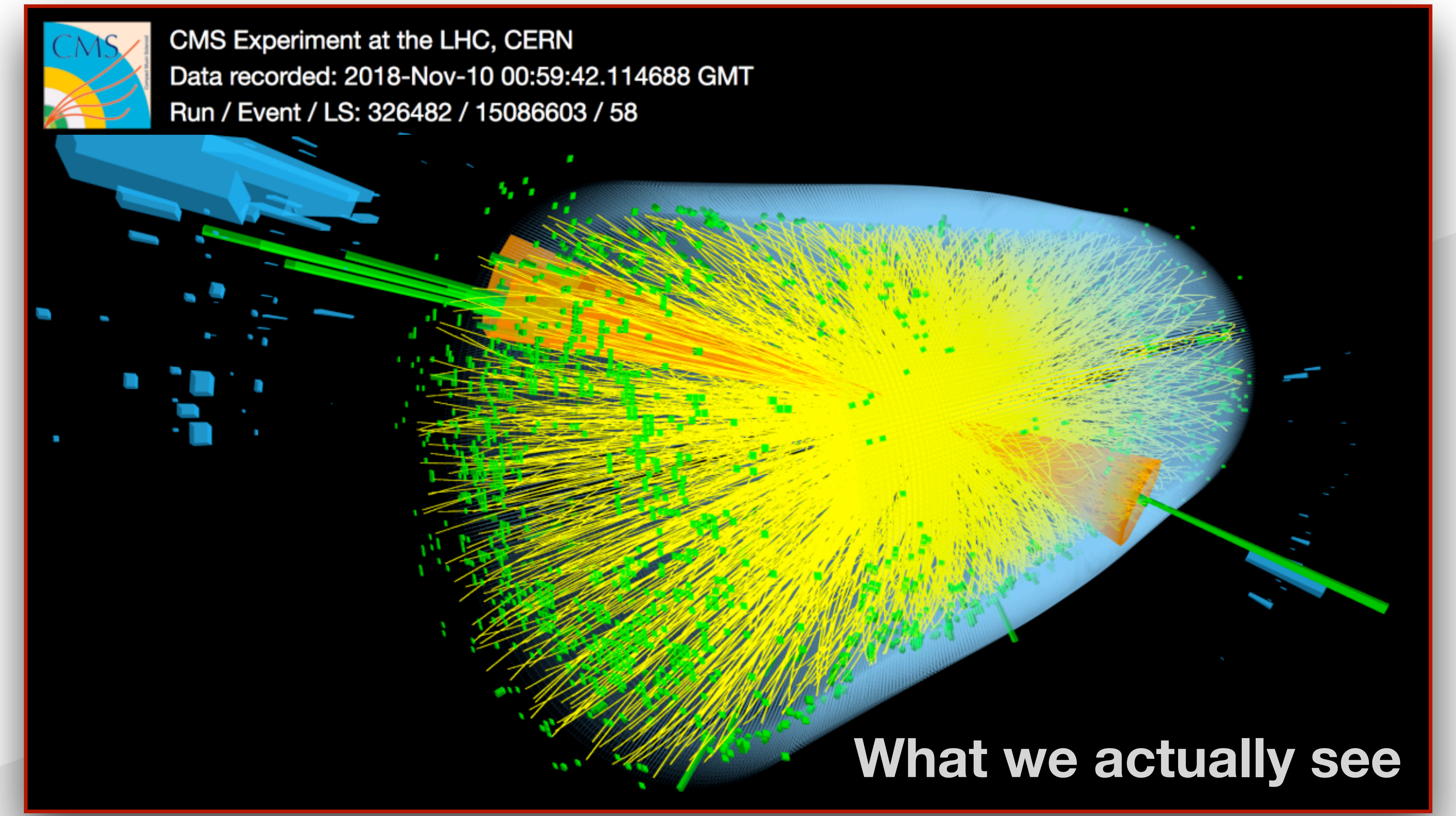


What we actually see


Quantum Chromo Dynamics

HEP experimental physicists

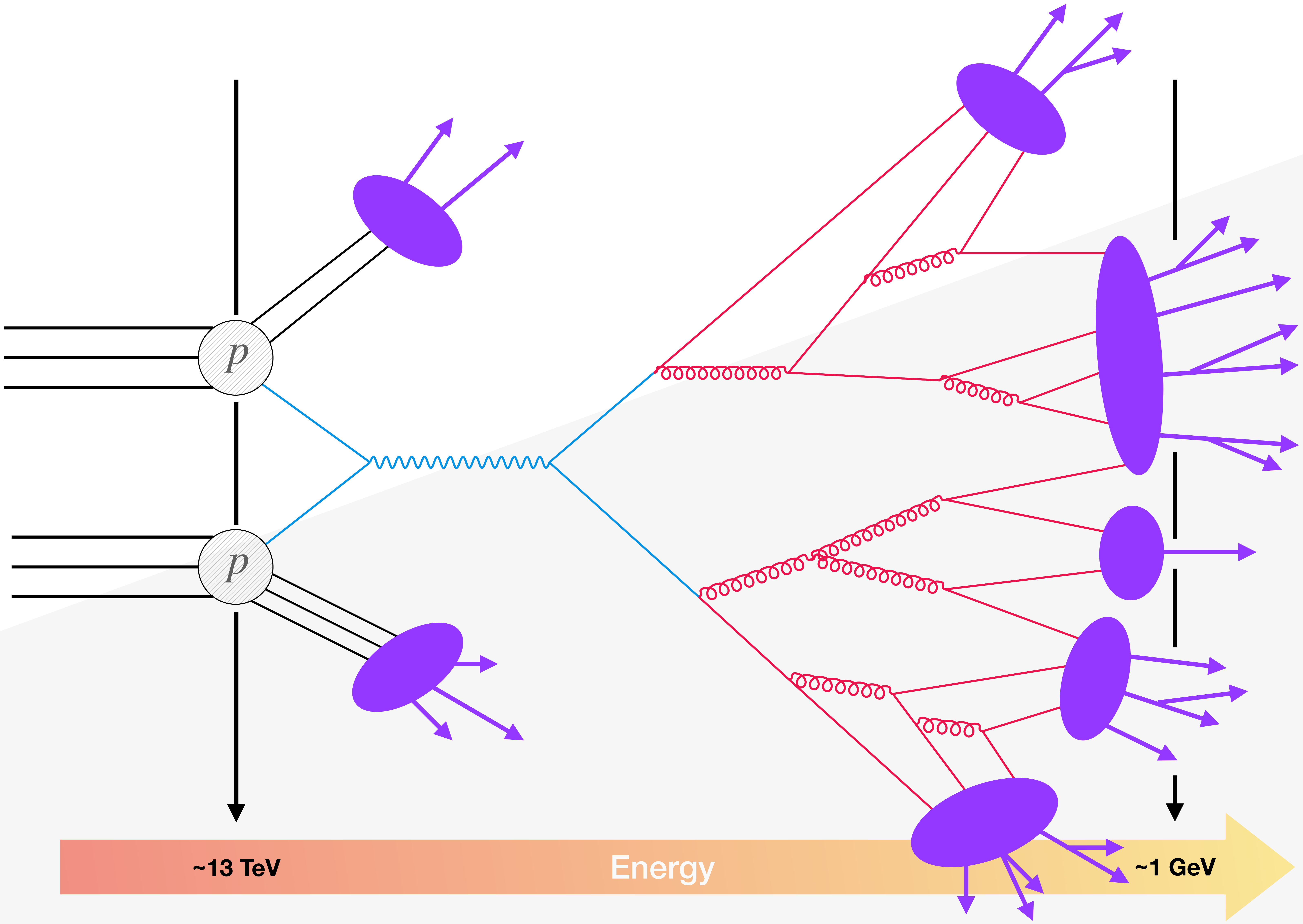
How?

- Theoretical knowledge of fundamental interactions.
- Random number generators give us **events,** extracted **from probability distributions.**

MC simulation

Event generation:

- PDFs.
- ME calculation, high Q^2, perturbative calculation.
- Gluon radiation and splitting (PS) .
- Hadronisation and decay, Q^2~1 GeV (PS).



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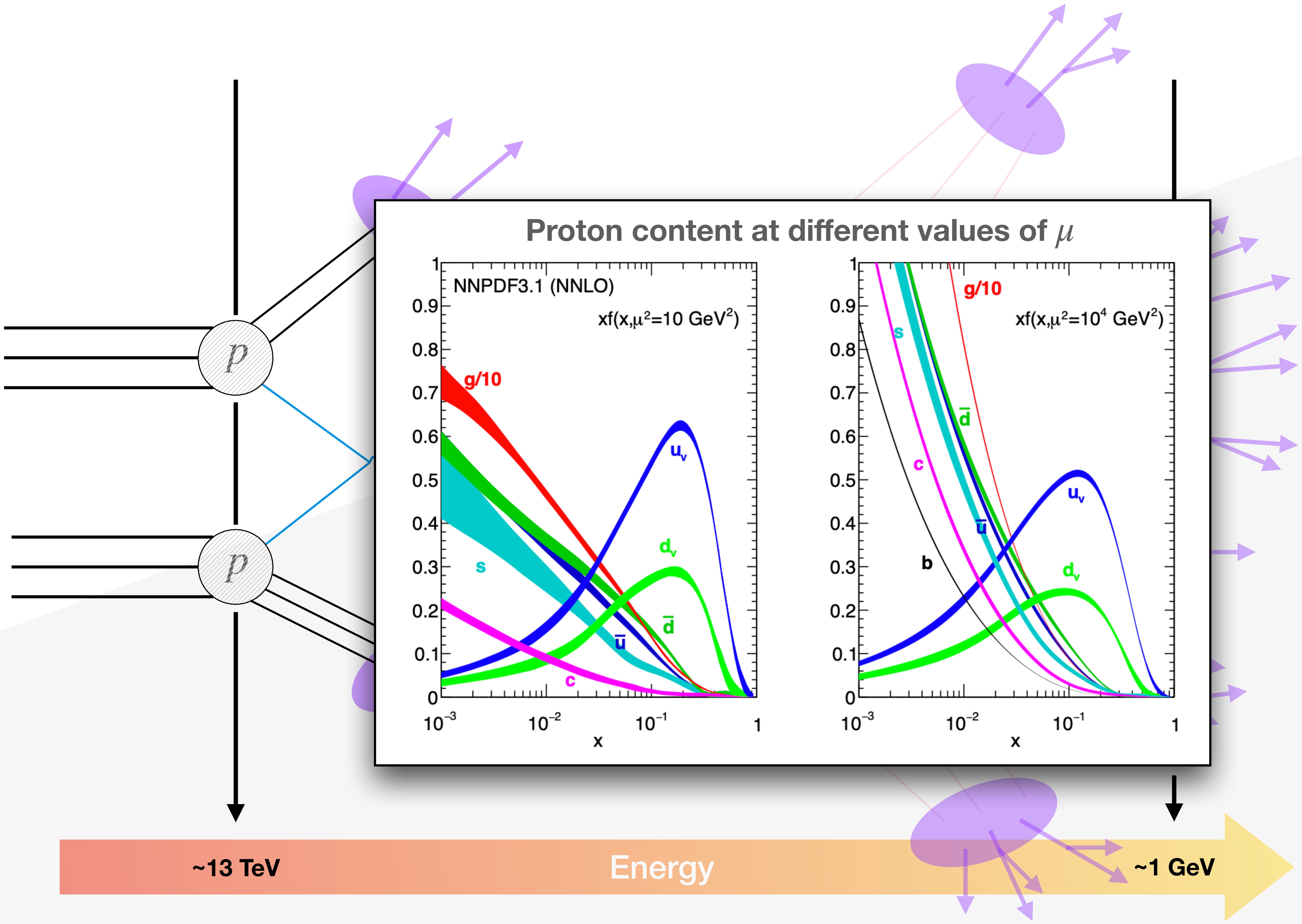
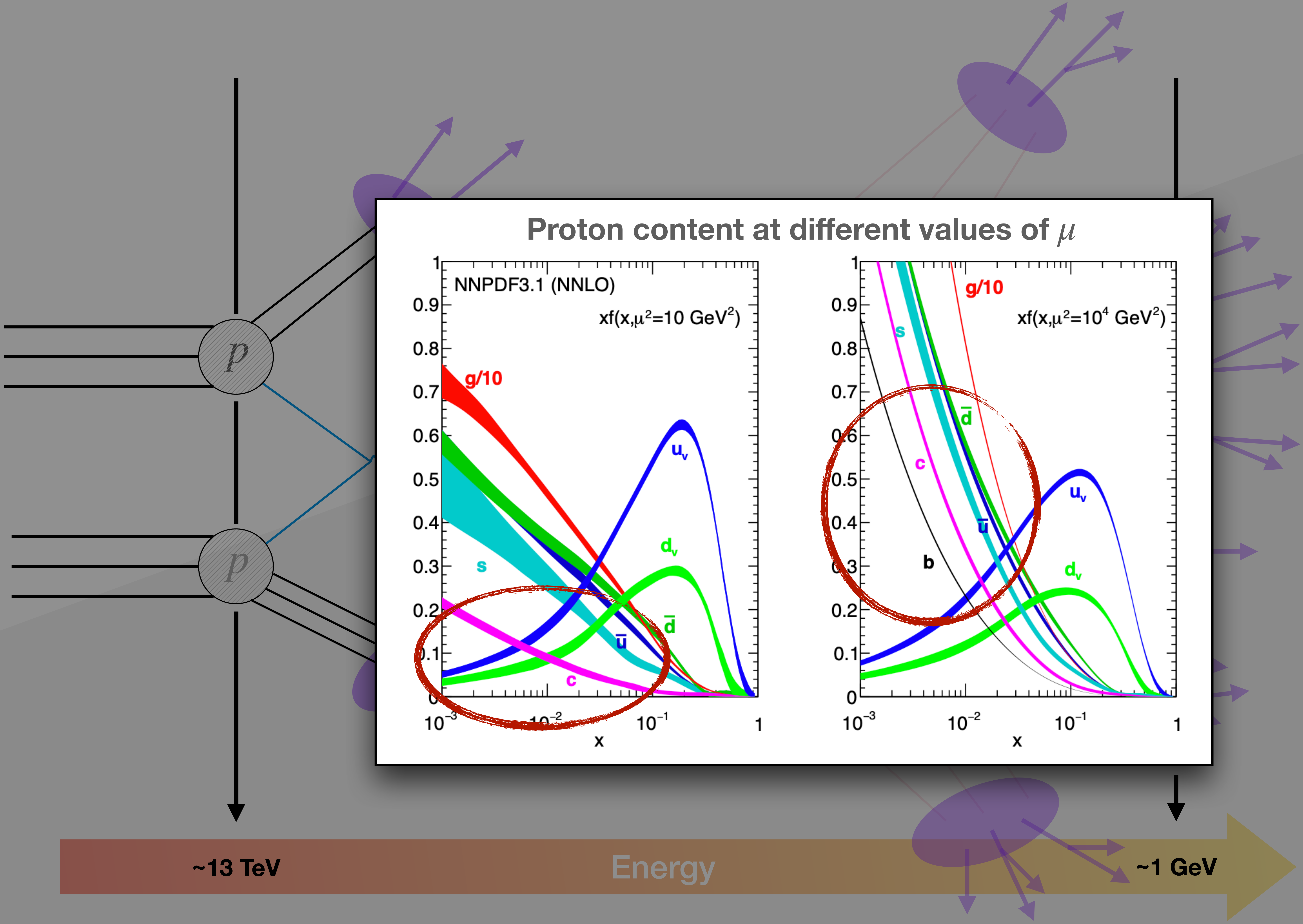


Proton content at different values of μ

MC simulation

Event generation:

- PDFs.
- For **different energy scales** of the process, a **different number of flavours** is relevant.
- Probability to find a Parton of type i inside the proton with a fraction of momentum x_i.



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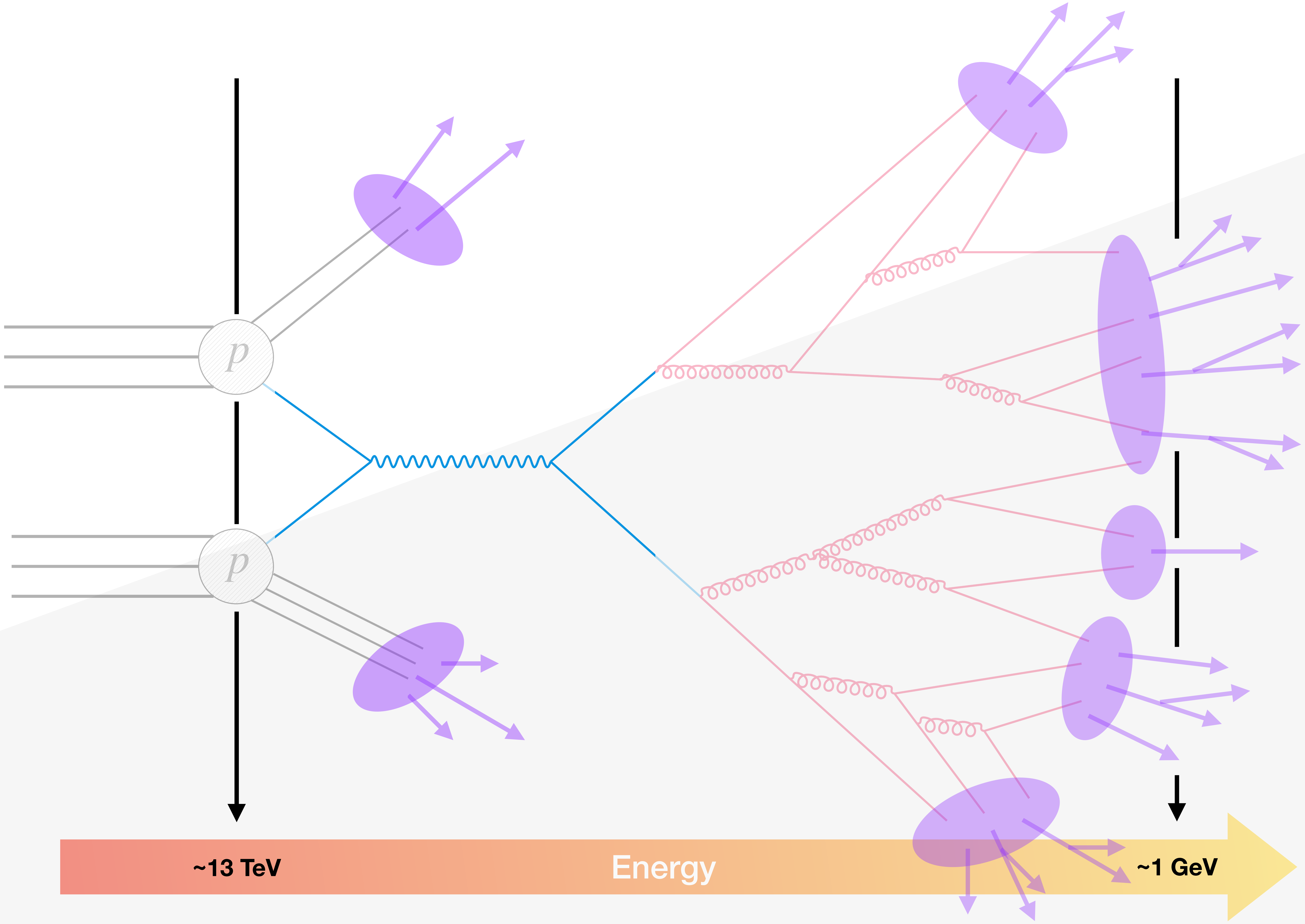


MC simulation

ME calculation: Hadronic cross section

The hadronic cross section producing a final state X:

$$\sigma_{pp\to X} = \sum_{a,b} \int dx_a \cdot dx_b \cdot f_a(x_a, \mu_F^2) \cdot f_b(x_b, \mu_F^2) \cdot \hat{\sigma}_{ab\to X}(x_a p_a, x_b p_b, \mu_F^2, \mu_R^2)$$

- Separation between short- and long-distance effect delimited by a factorization scale μ_F (Factorisation theorem).
- **Parton density functions** f_i for flavour type i with a momentum fraction x_i.
- $\hat{\sigma}_{ab\to X}$ is the **partonic cross section** of the process $ab \to X$ and is computed at fixed order in perturbation theory, introducing a dependence on the renormalization scale μ_R.

MC simulation

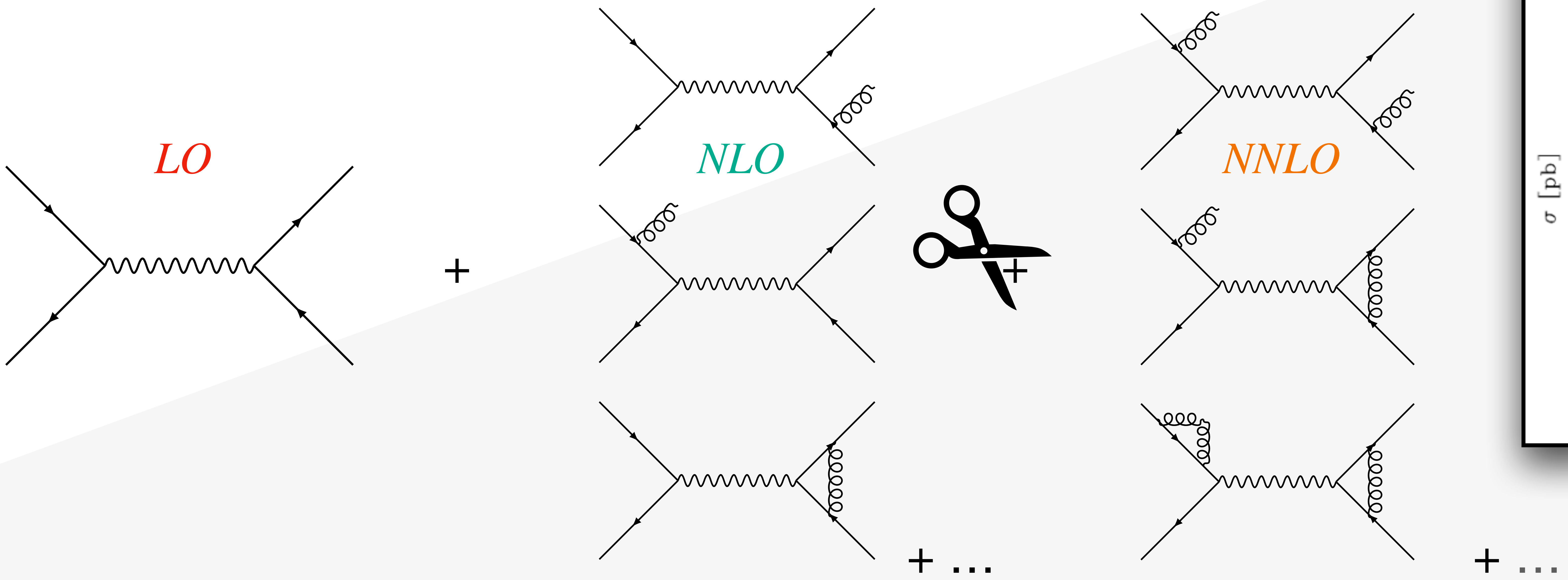
ME fixed order calculations:

Partonic cross section computed as **series expansion** in the strong coupling α_s:

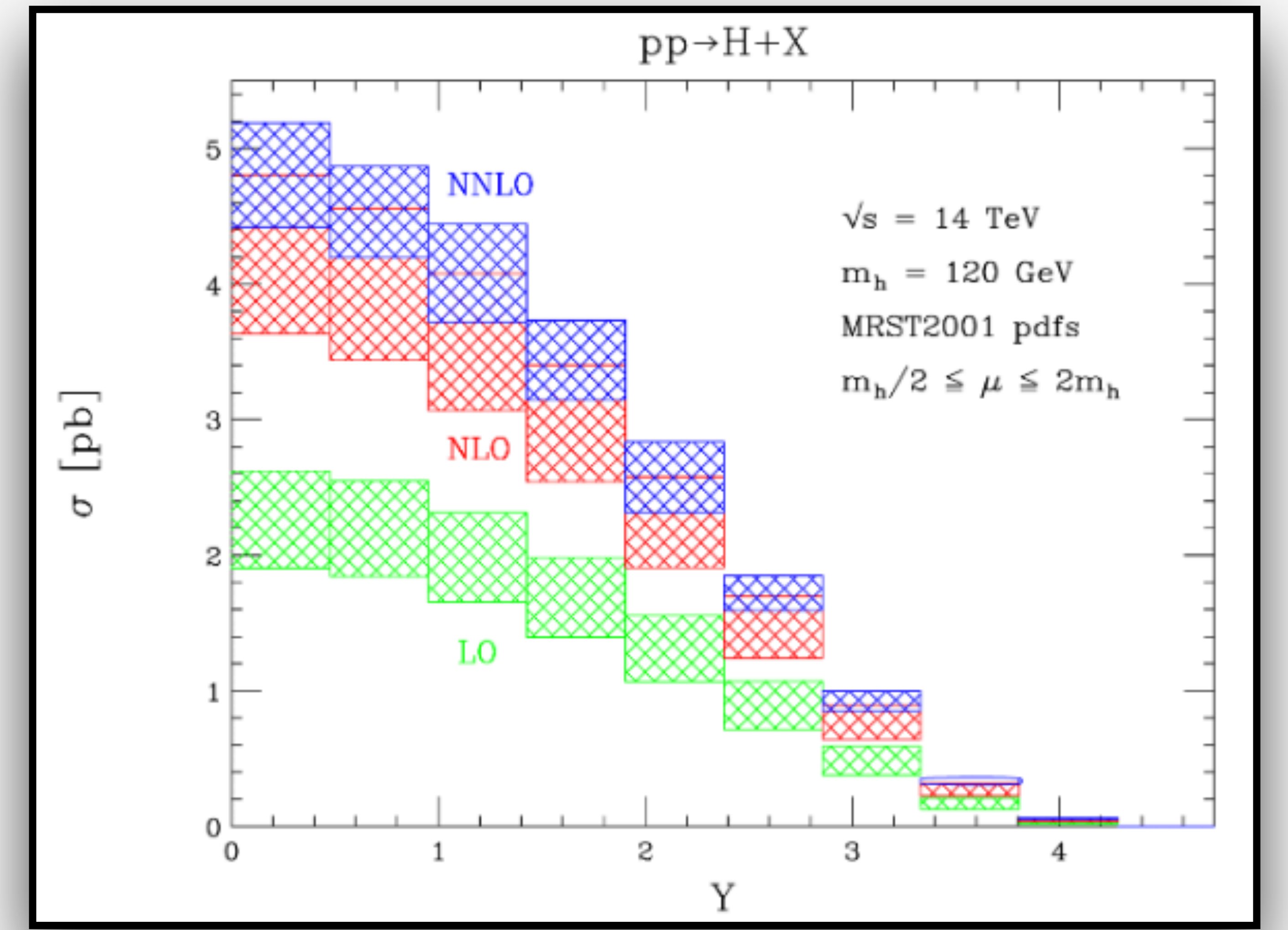
$$\hat{\sigma}_{ab\to X} = \alpha_s^n(\sigma_0 + \alpha_s\cdot\sigma_1 + \alpha_s^2\cdot\sigma_2 + O(\alpha^3))$$

$$LO + NLO + NNLO + \ldots$$

ME generators compute partonic cross section at Fixed Order (FO):



Fixed order cross section



Anastasiou, Melnikov, Petriello, '05

MC simulation

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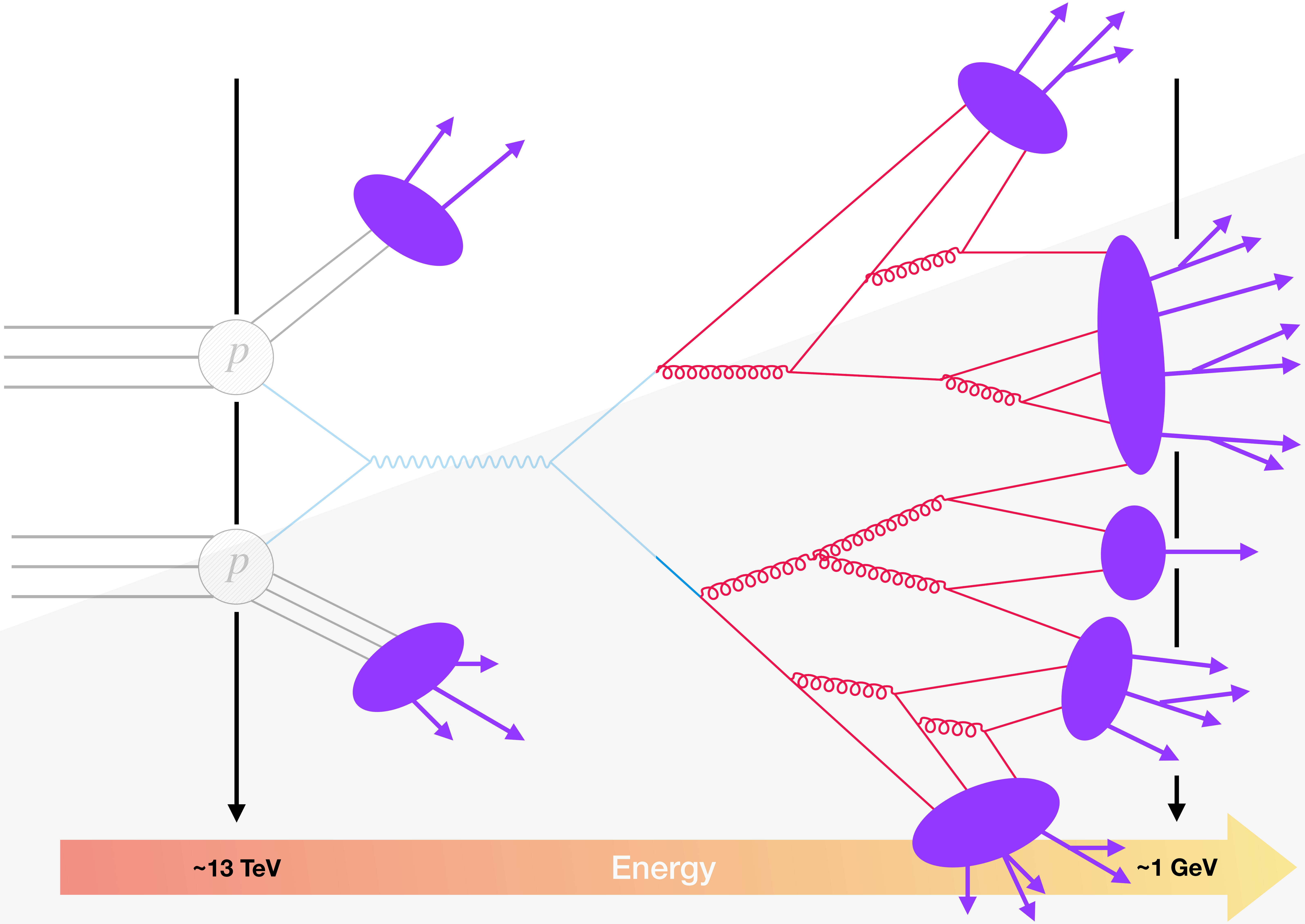


MC simulation

Parton Shower:

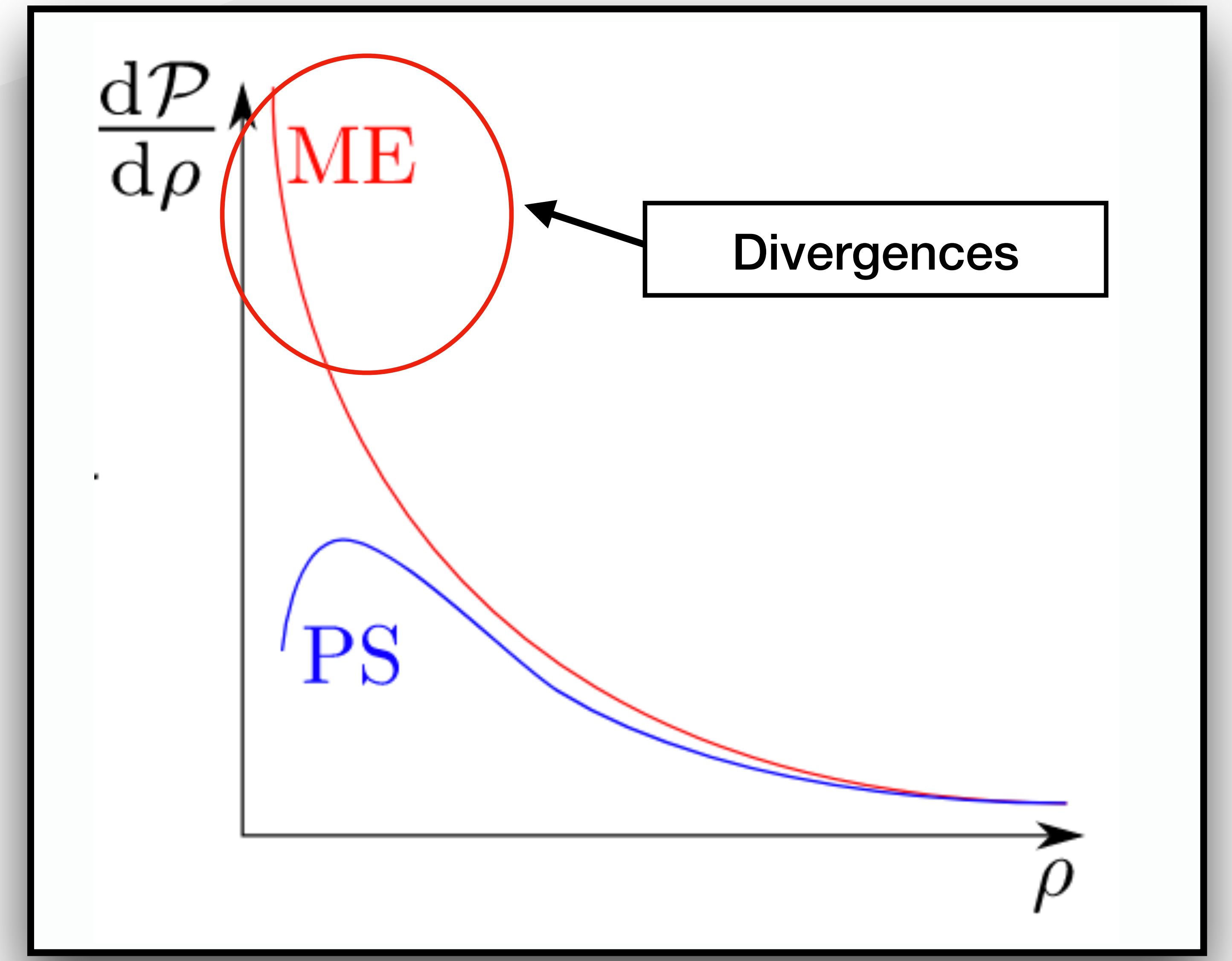
Partonic cross section computed at Fixed Order:

$$\hat{\sigma}_{ab\to X} = \alpha_s^n(\sigma_0 + \alpha_s \cdot \sigma_1)$$

$$LO + NLO$$

The rest (additional radiation and showering) is taken care by the PS:

- Account for the rest of higher order contributions.
- It uses approximations to reach high multiplicities.
- Valid in the soft and collinear phase space.
- Always finite.



Borrowed from L. Gellersen

MC simulation

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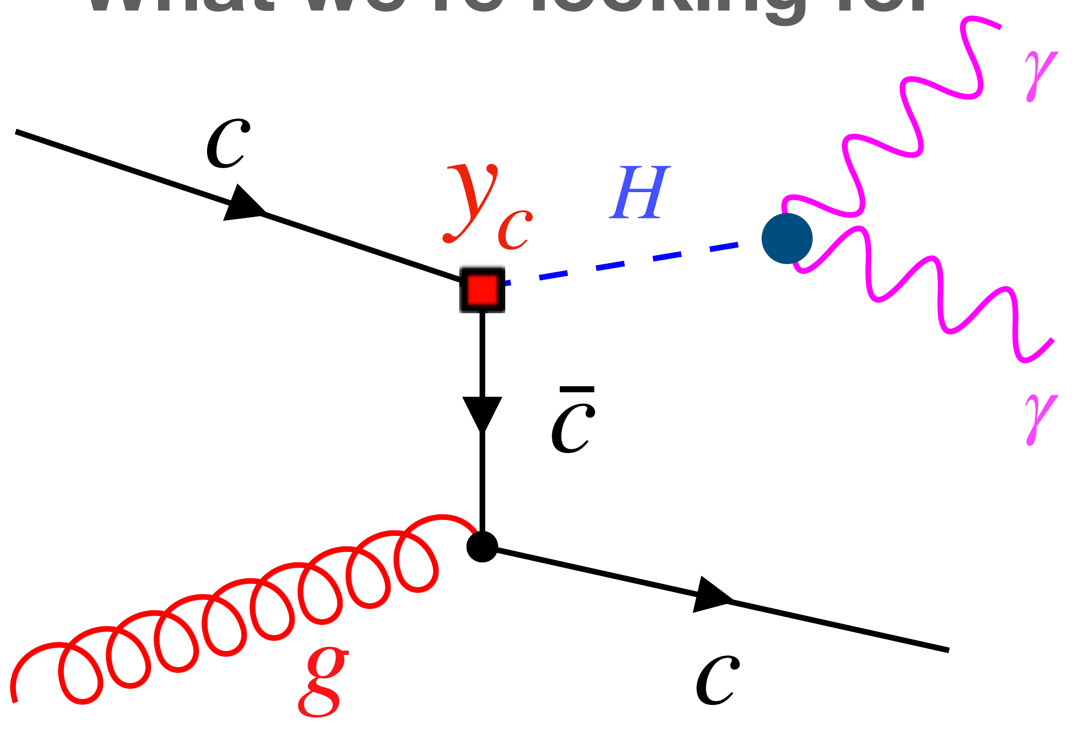
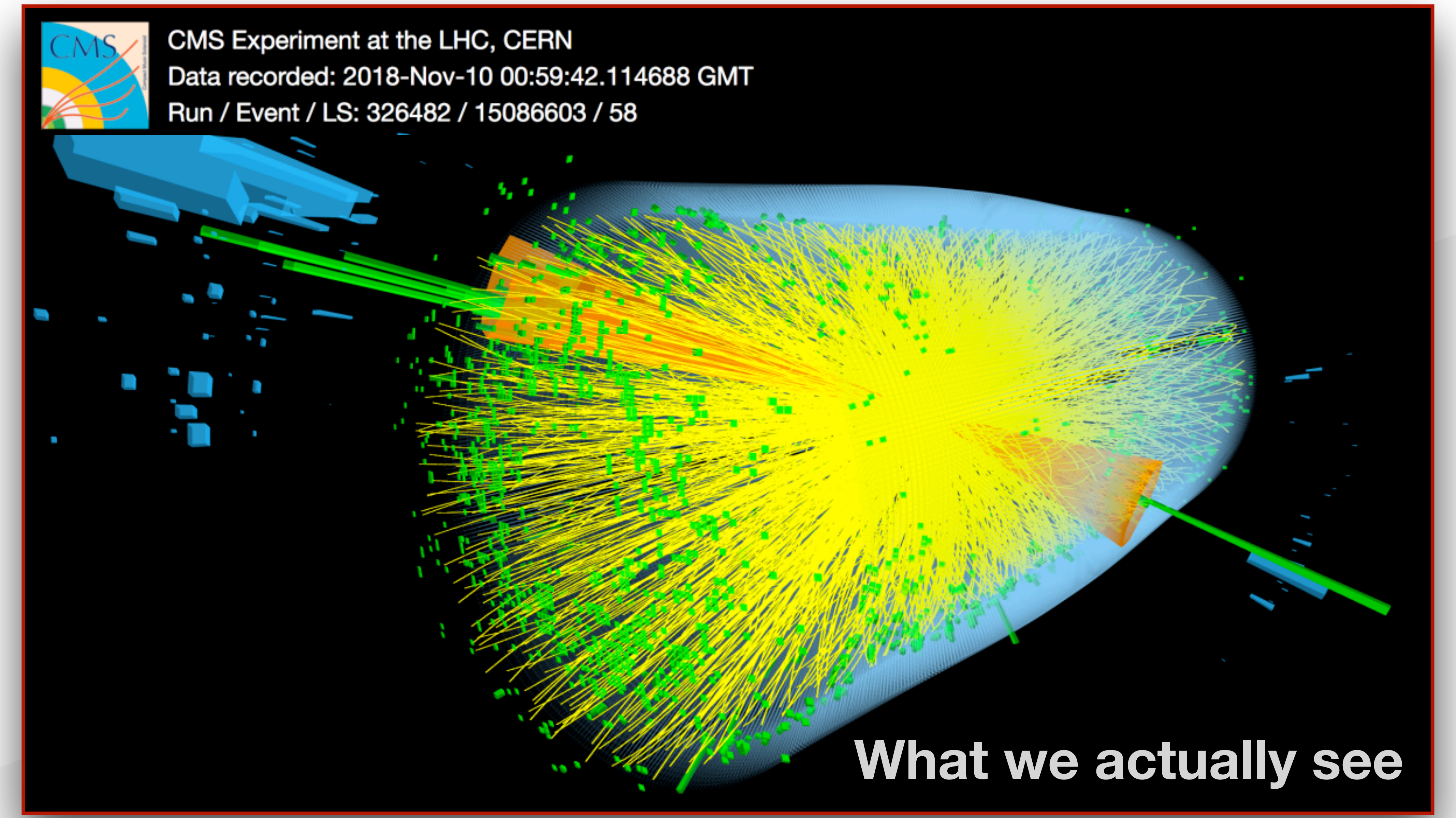




What we actually see

Still HEP experimental physicists

- Still challenging but possible!

MC simulation

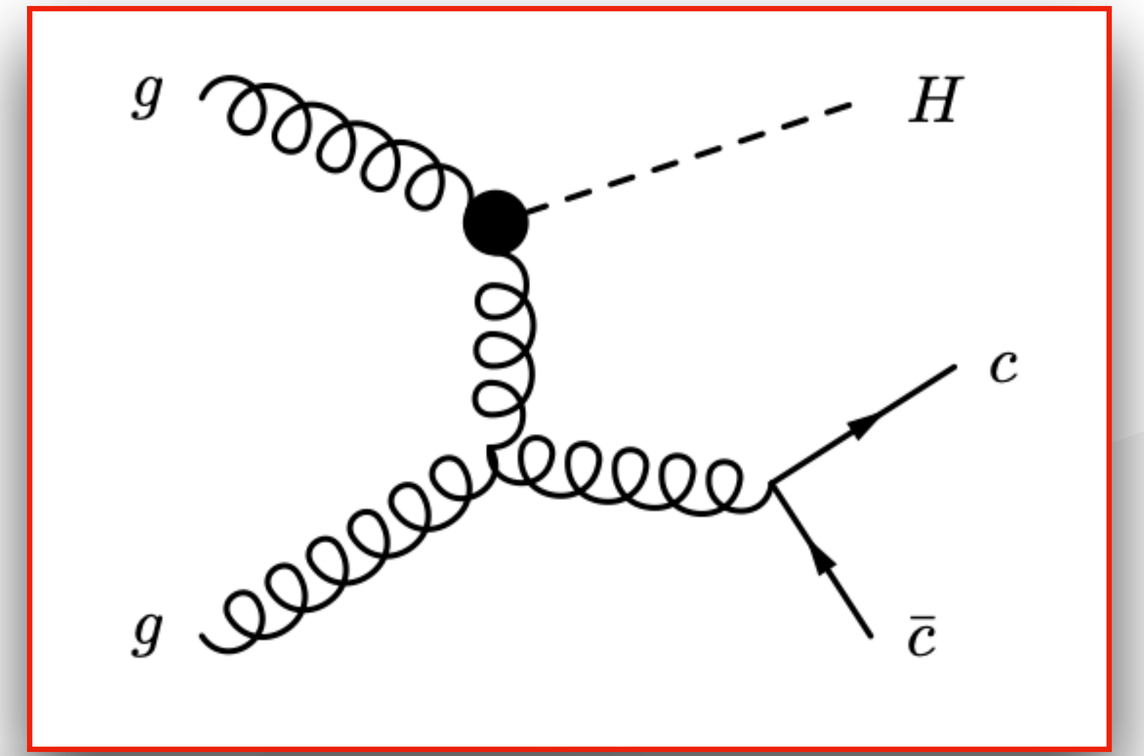
H+c production:

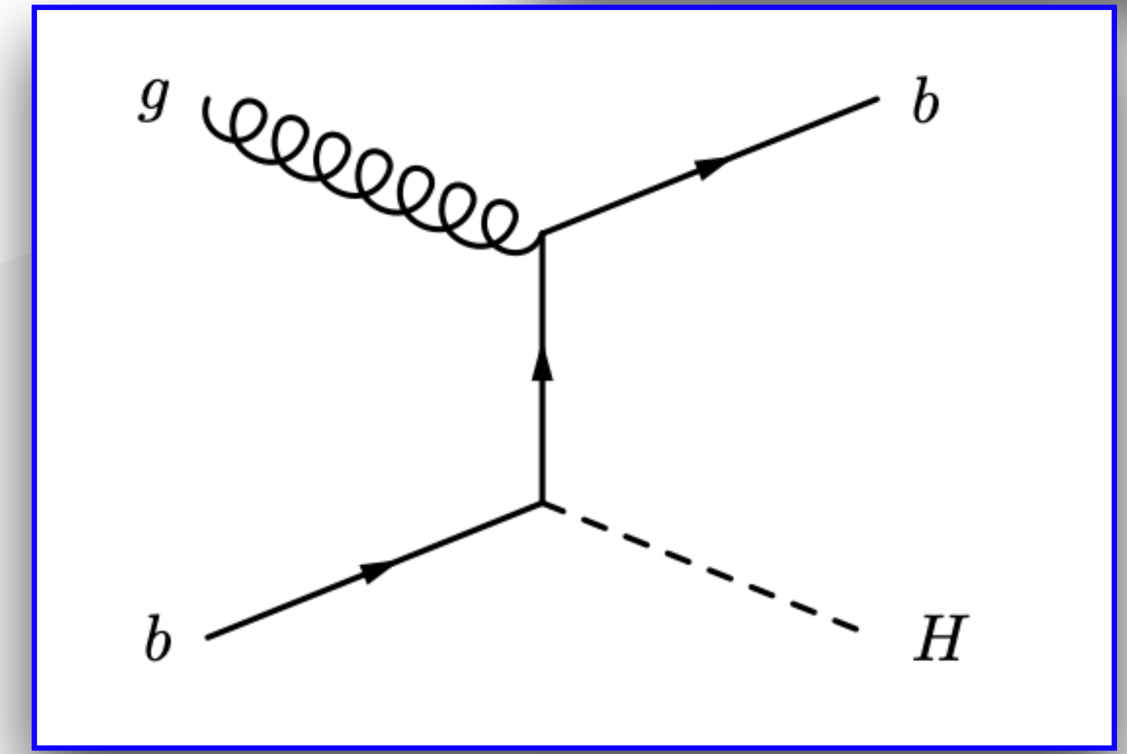
- Includes several contributions that do not depend on y_c :
  - $H+g$ (fakes and $g \to c\bar{c}$)
  - $H+b(b \to c)$
  - $H+c$ not induced by y_c.

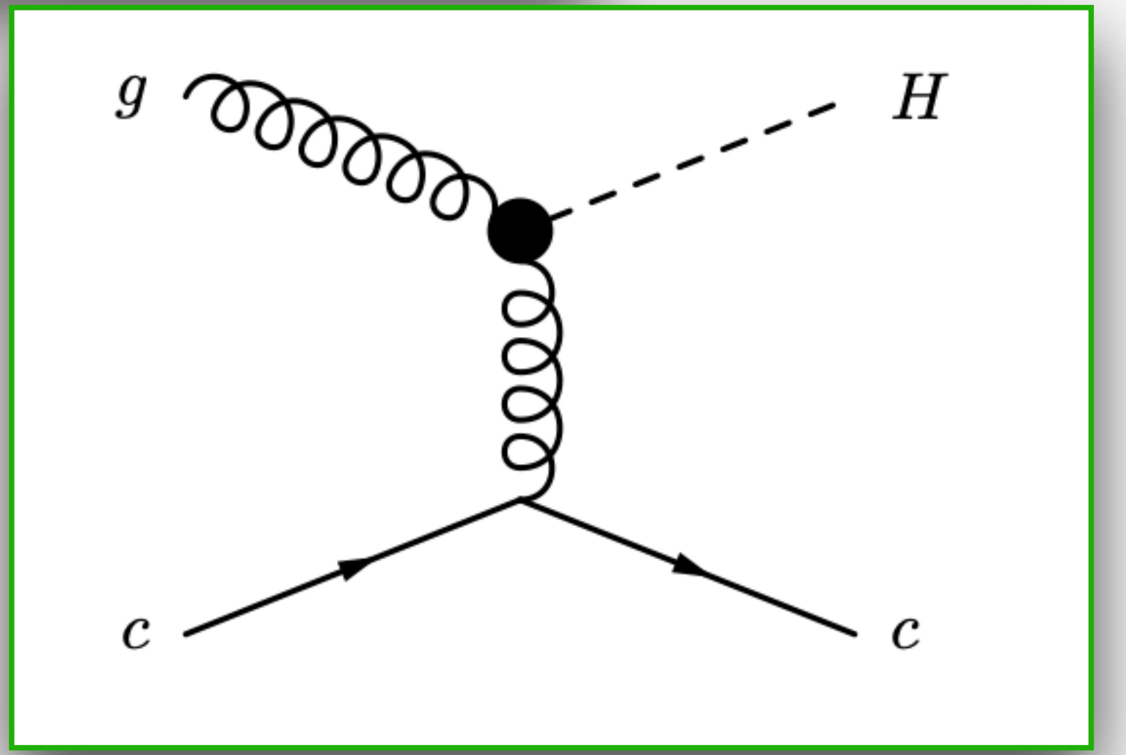
  ⇒ **most of the $H+c$ cross section is not sensitive to y_c.**

- Modelling uncertainties on reducible and irreducible ‘Higgs backgrounds’ can limit sensitivity to y_c in $H+c$ channel .

- **Open questions:** How to simulate y_c induced H+c?
  - All these non-y_c contributions are already included in $H+jets$ MCs used by experiments (except for $H+b$ component that depends on y_b).
  - Many studies on $H+b$ simulation but none on $H+c$.







Higgs+charm simulation

H+c signal:

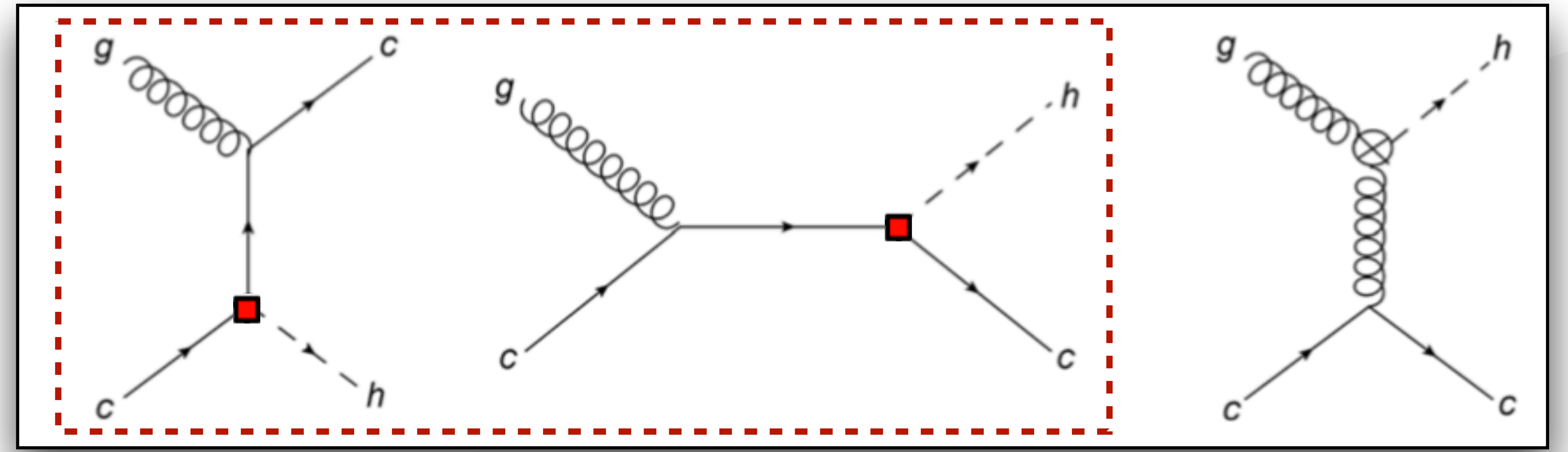
- Focusing on the signal simulation for $H + c$ MC (not available in CMS up to now).

$$\sigma(hc) = A + B \cdot y_c + C \cdot y_c^2$$

	σ [fb]
A	254.5
B	-3.5
C	34.5

[$y_c = y_c^{sm}$]

[GEN charm $p_T > 20$ GeV]

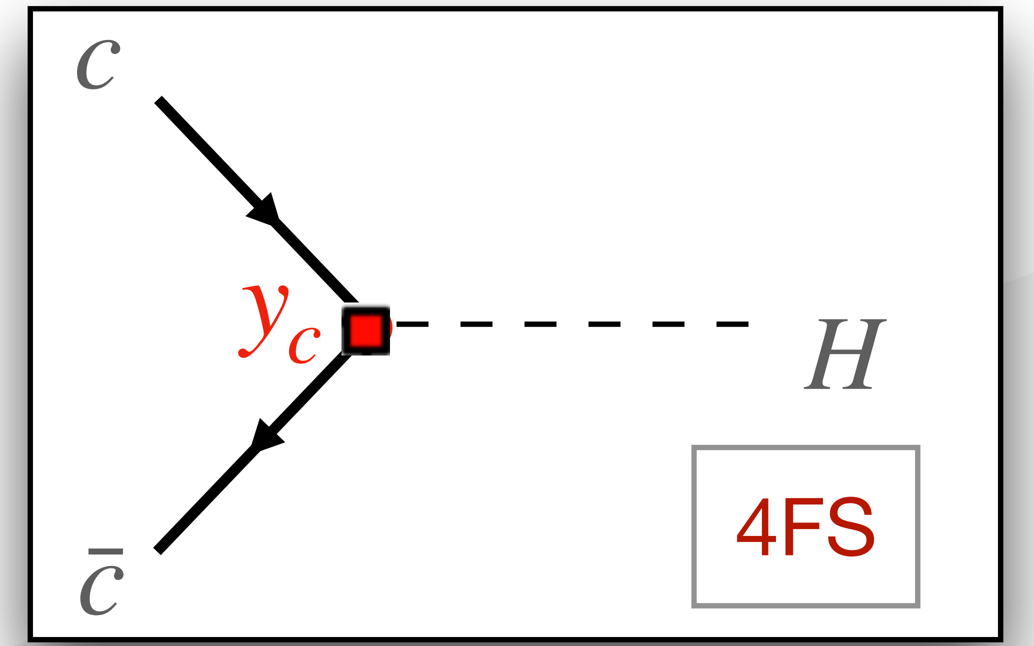


- $\sigma(hc)$ does not scale trivially with y_c, some tests were run with effective ggH coupling at LO.
- Biggest contribution from the term that does not probe y_c, but small y_c proportional interference term (~10 times smaller than the y_c^2 dependent term), for sensitivity $O(10 \cdot SM)$ contribution of ~1%.
- As first approximation one can generate signal probing y_c^2 and bgs/interference in separate MC, avoid overlap with $H + jets$ MCs.

Higgs+charm simulation

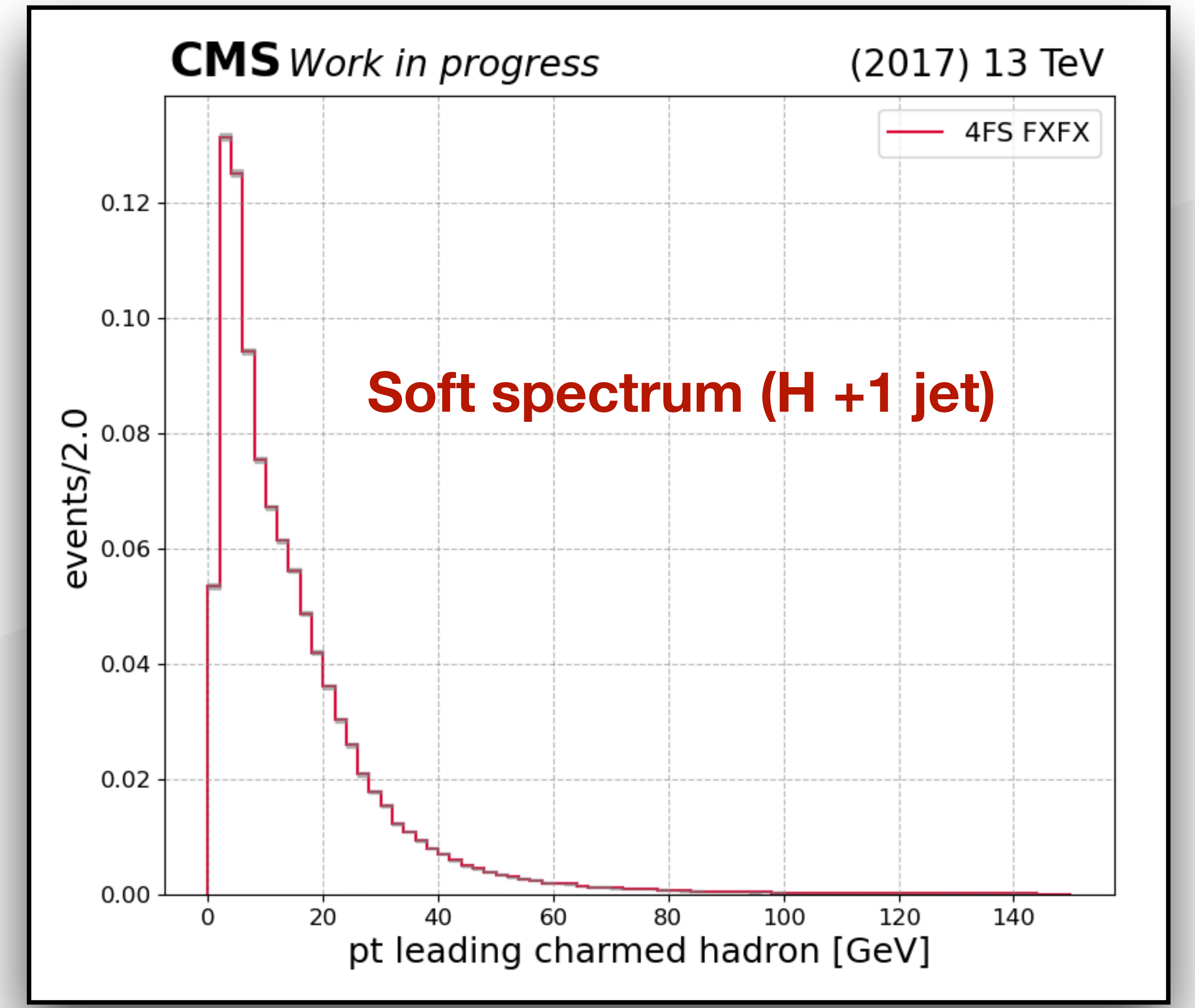
Focus on the y_c^2 term:

- Simulated with MadGraph_aMC@NLO ([QCD] NLO) + Pythia8 Parton Shower.
- Simulated using `loop_sm` model to have y_c in the $\overline{MS}$ renormalisation scheme and include running of $y_c \rightarrow \overline{y}_c(\mu_R)$ and $m_c \rightarrow \overline{m}_c(\mu_R)$.
- Simulated using 4 Flavour Scheme (4FS), to have charm quarks in the initial state.



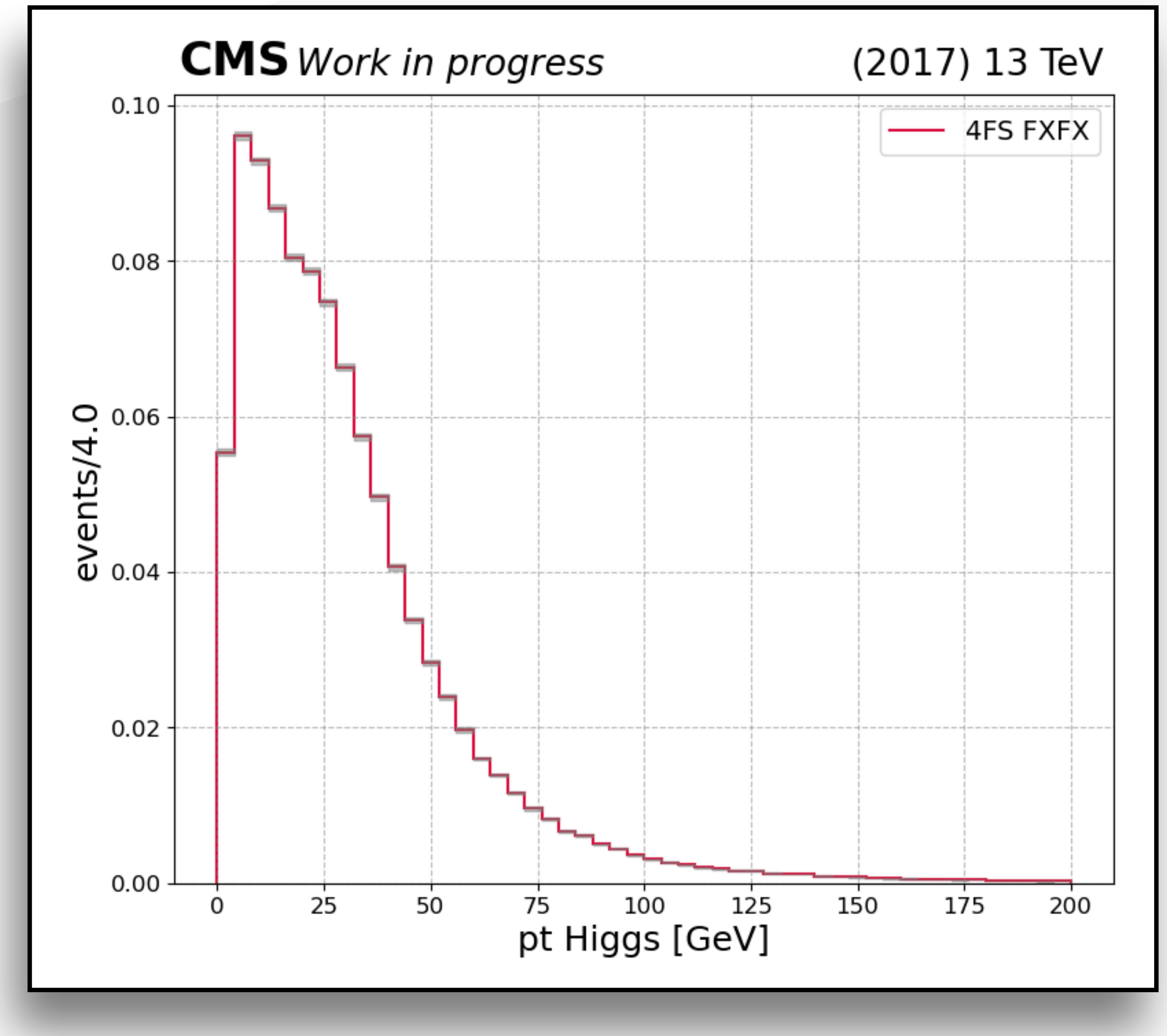
$m_C = 0$

Pt lead charmed hadron



Soft spectrum (H +1 jet)

Pt Higgs

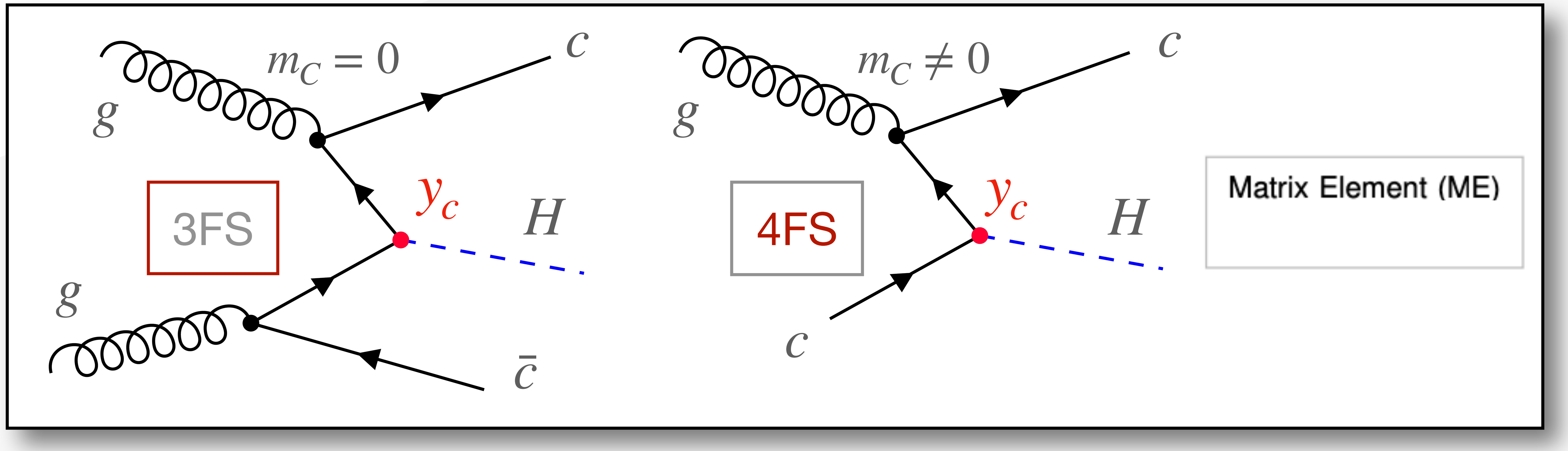


Higgs+charm simulation

Theoretical uncertainty studies:

- H+c MC ME calculation can be done in either 3FS or 4FS, i.e. considering the c massive or massless.
- In principle equivalent → In practice to assess the additional theory uncertainty we **compare samples produced using both methods:**
  ⇒ FS uncertainty $O(30\%)$ of the yields in analysis categories.
- Uncertainty due to Scales and PDFs are smaller than FS uncertainty.
- We also studied the impact of the choice of simulation input parameters on the two FS:
  ⇒ decide the best choice of theory scales (μ_R, μ_F, and R_{sh}).

LO diagrams



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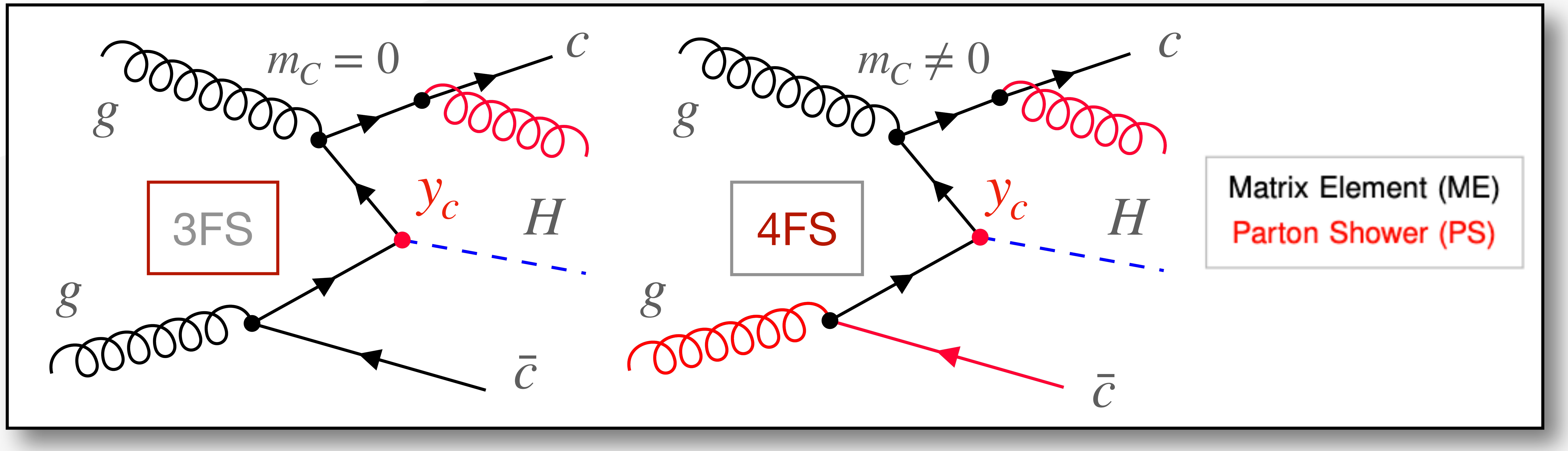
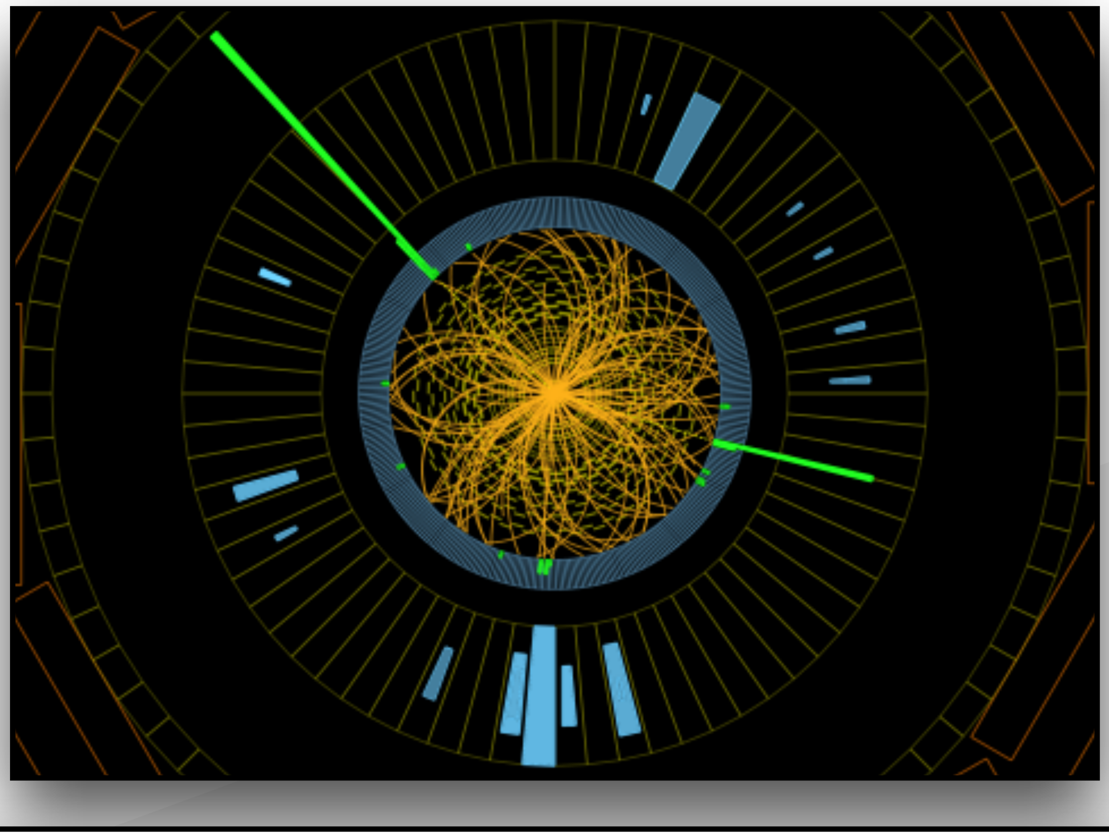
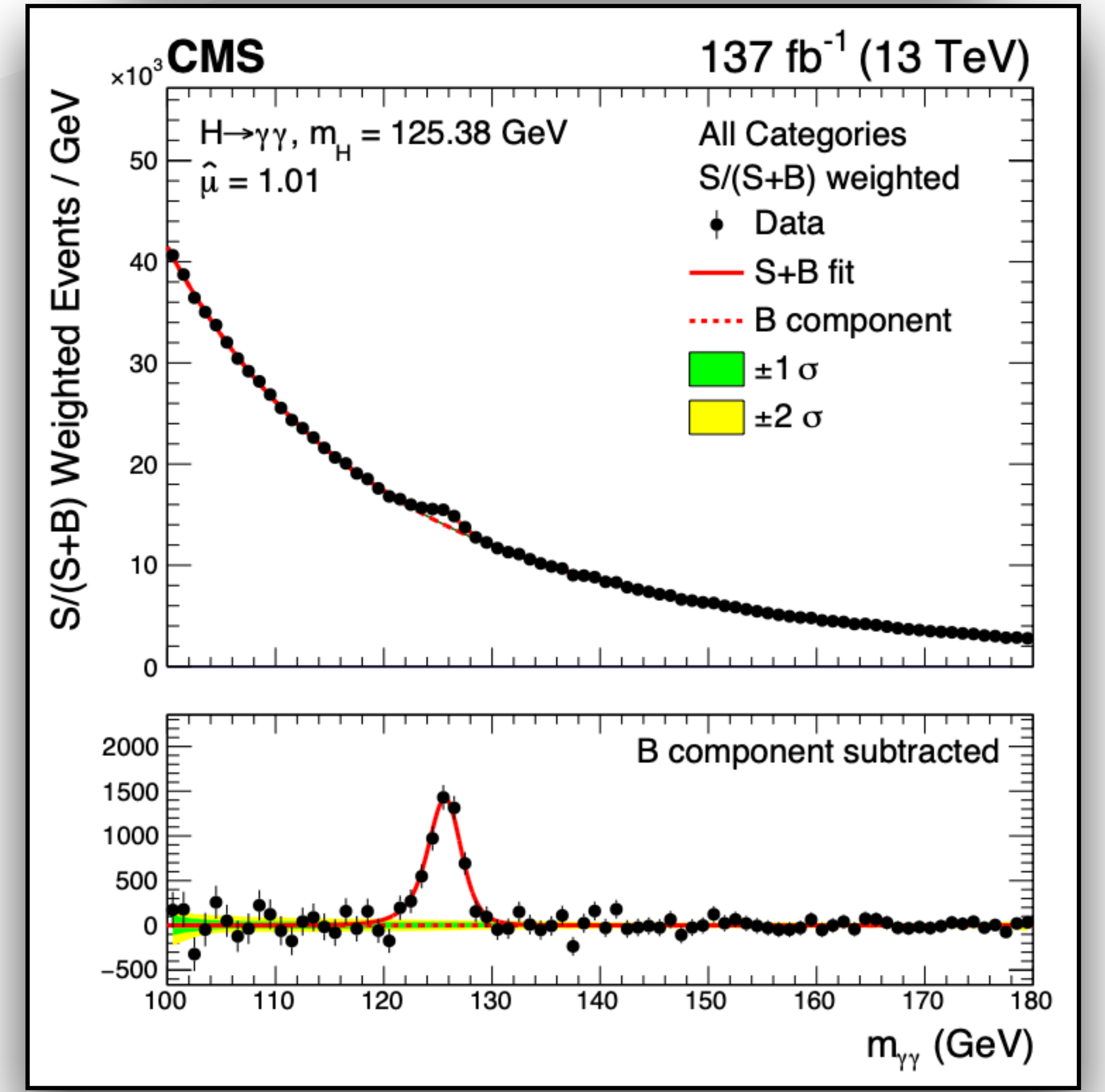


Higgs to $\gamma\gamma$ analysis strategy

Diphoton decay channel:



- Golden channel (since 2012) with a very clear signature: two isolated photons.
- All the possible diphoton candidates are constructed and the one with highest p_T is selected.
- **Fit to the diphoton** candidate **mass spectrum**.
- The signal shows as a **peak over a continuously falling background** from non resonant $\gamma\gamma$ and $\gamma + jets$ events.
- To do an accurate measurement the photon reconstruction systematics have to be kept under control.
- In our H+c we use the full Run 2 dataset (2016, 2017, 2018) of 137 fb^{-1} and we plan to include in the future also Run 3 data.

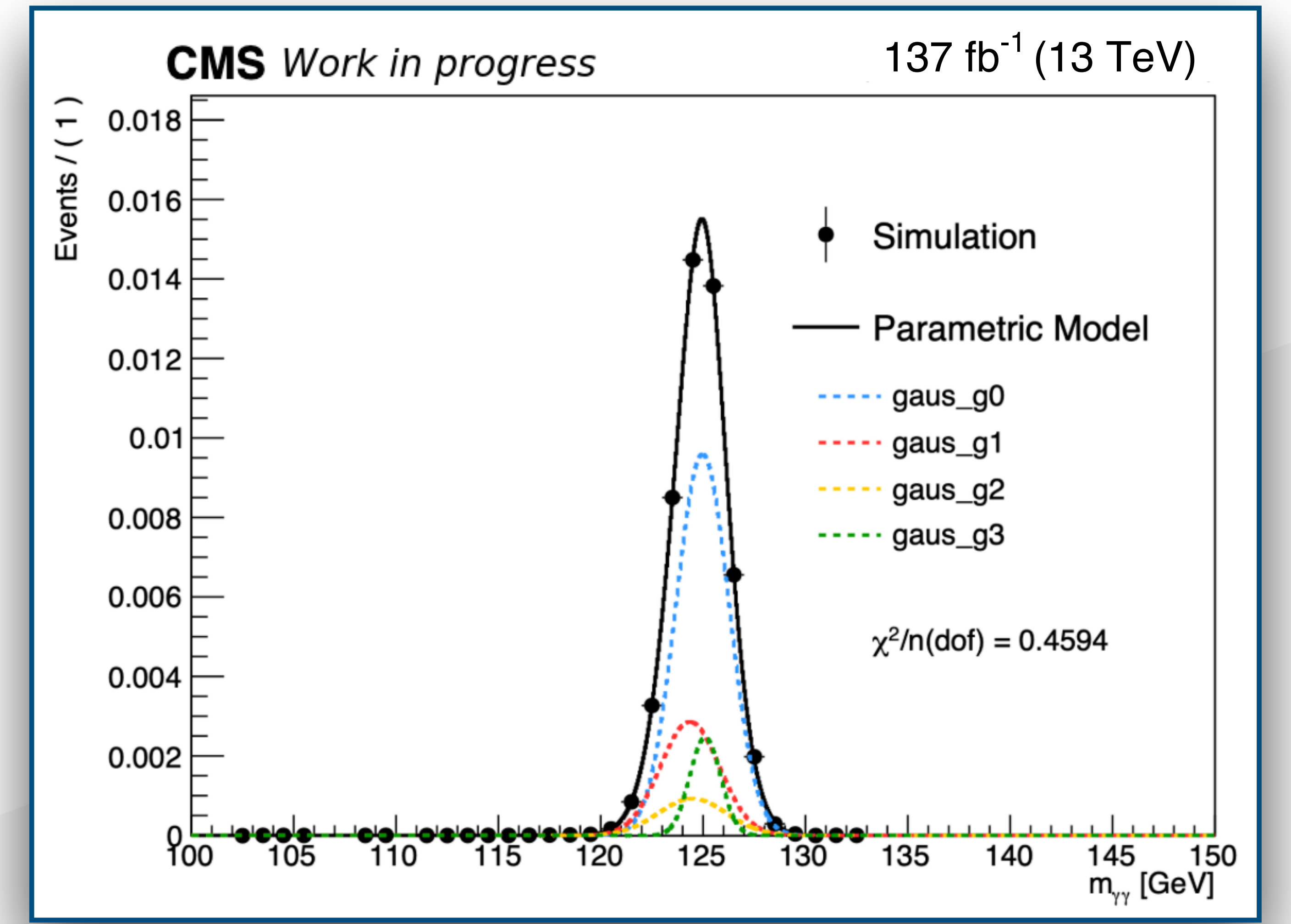


10.1007/JHEP07(2021)027

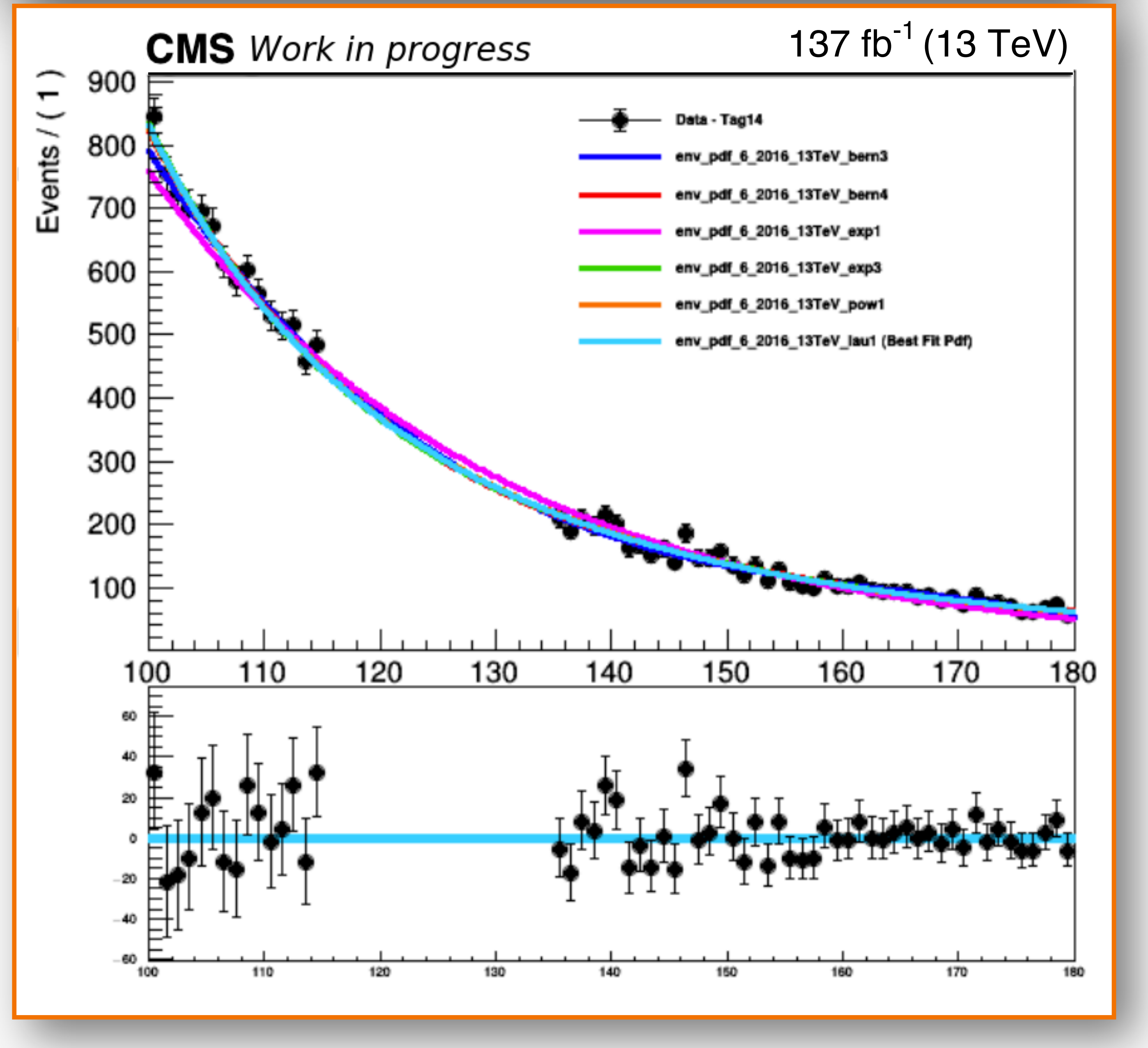
Higgs to $\gamma\gamma$ analysis strategy

Statistical analysis:

- Signal modelling:
  - Higgs processes ($H + c$, ggH, VBF, ttH, VH) are modelled by **fitting** a sum of gaussian to the **MC distribution**.



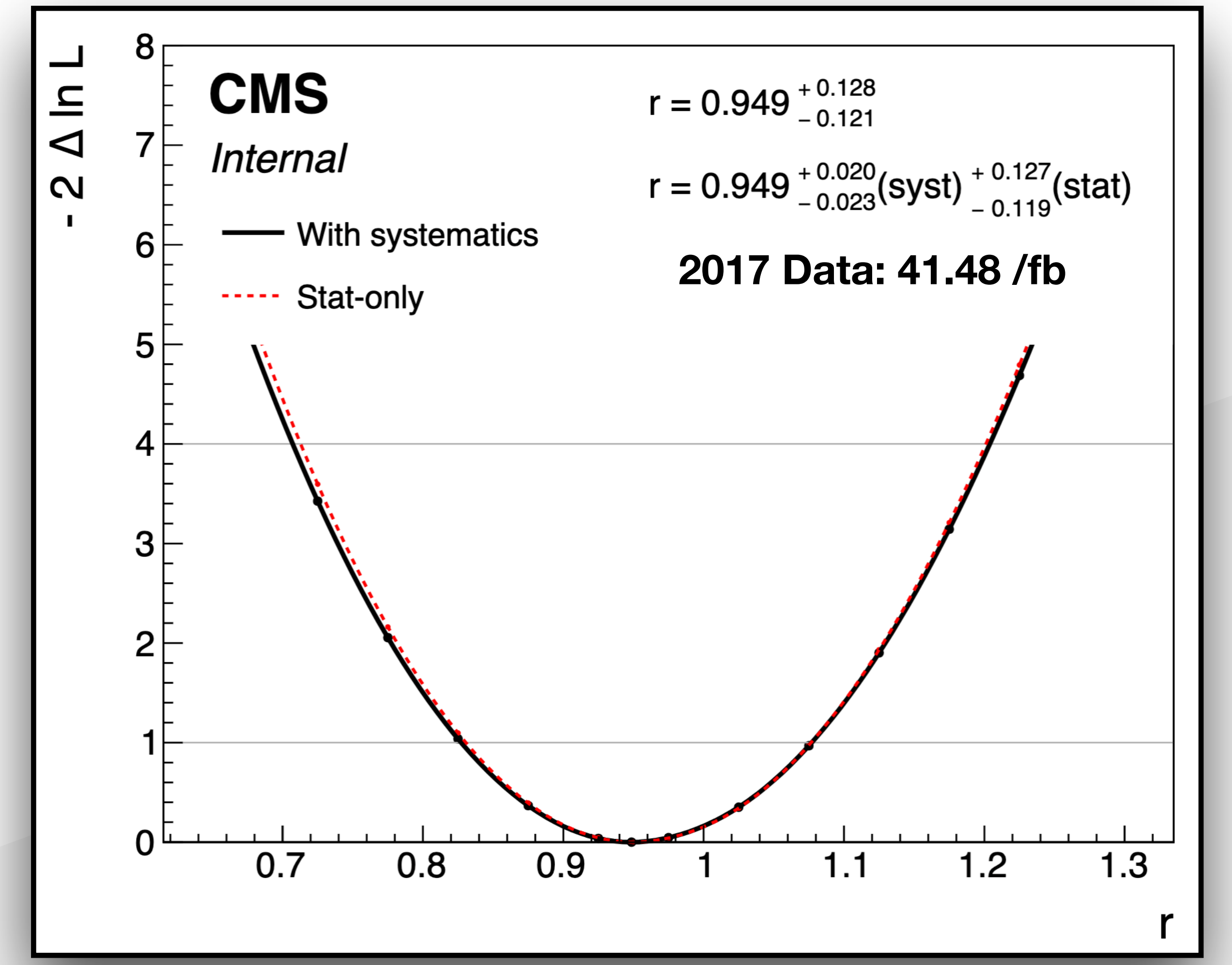
- Background modelling:
  - non-Higgs background is modelled in a **data driven way**, fitting the data sideband to extract the continuum $\gamma\gamma$ functional form.
  - Multiple families of functions are considered, the best one is used in the fit.
  - An uncertainty coming from the choice of the one family over the others is calculated *via* the **discrete profiling** or “envelope” **method**.

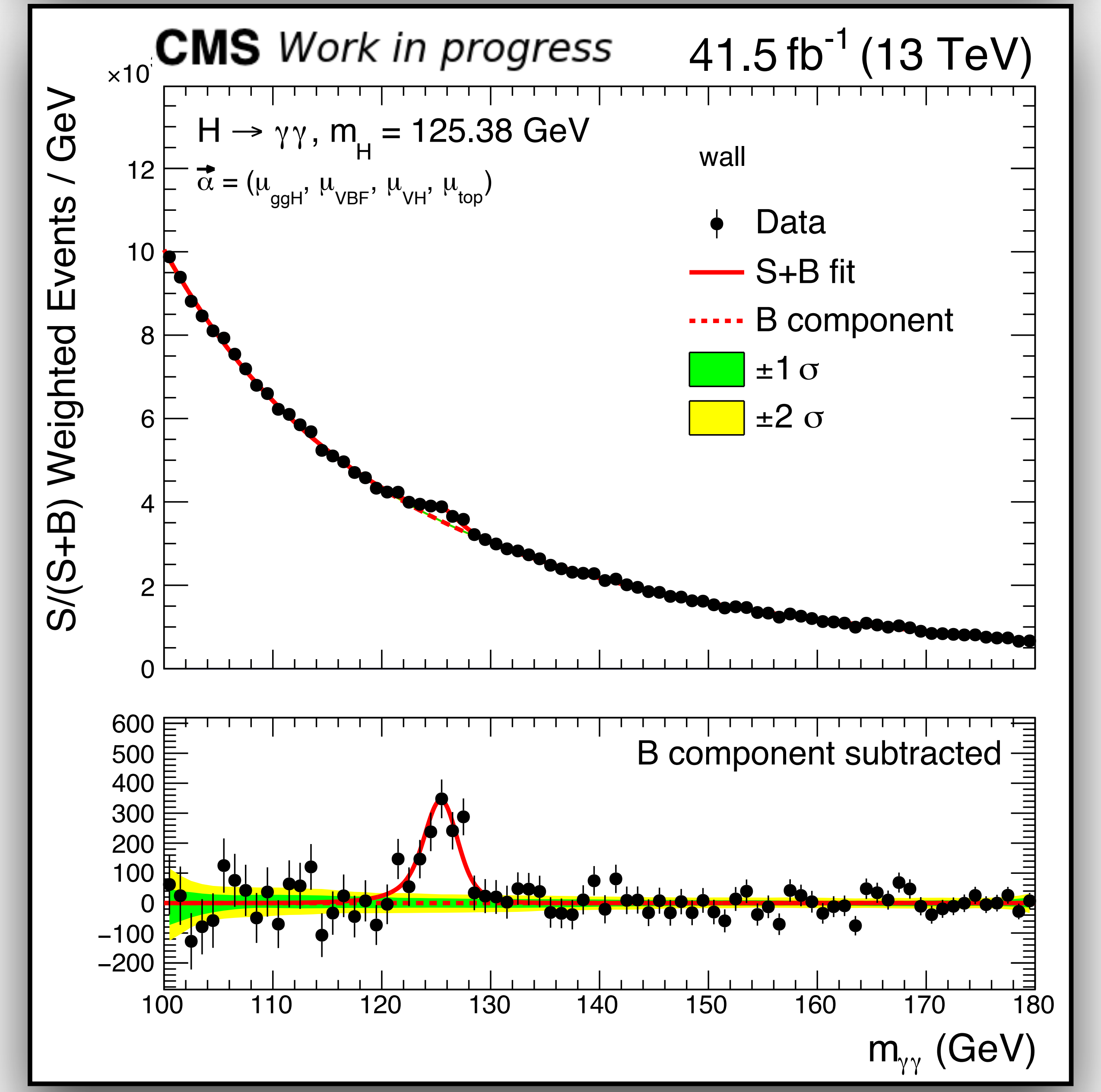


Framework development

HiggsDNA (Diphoton NanoAOD):

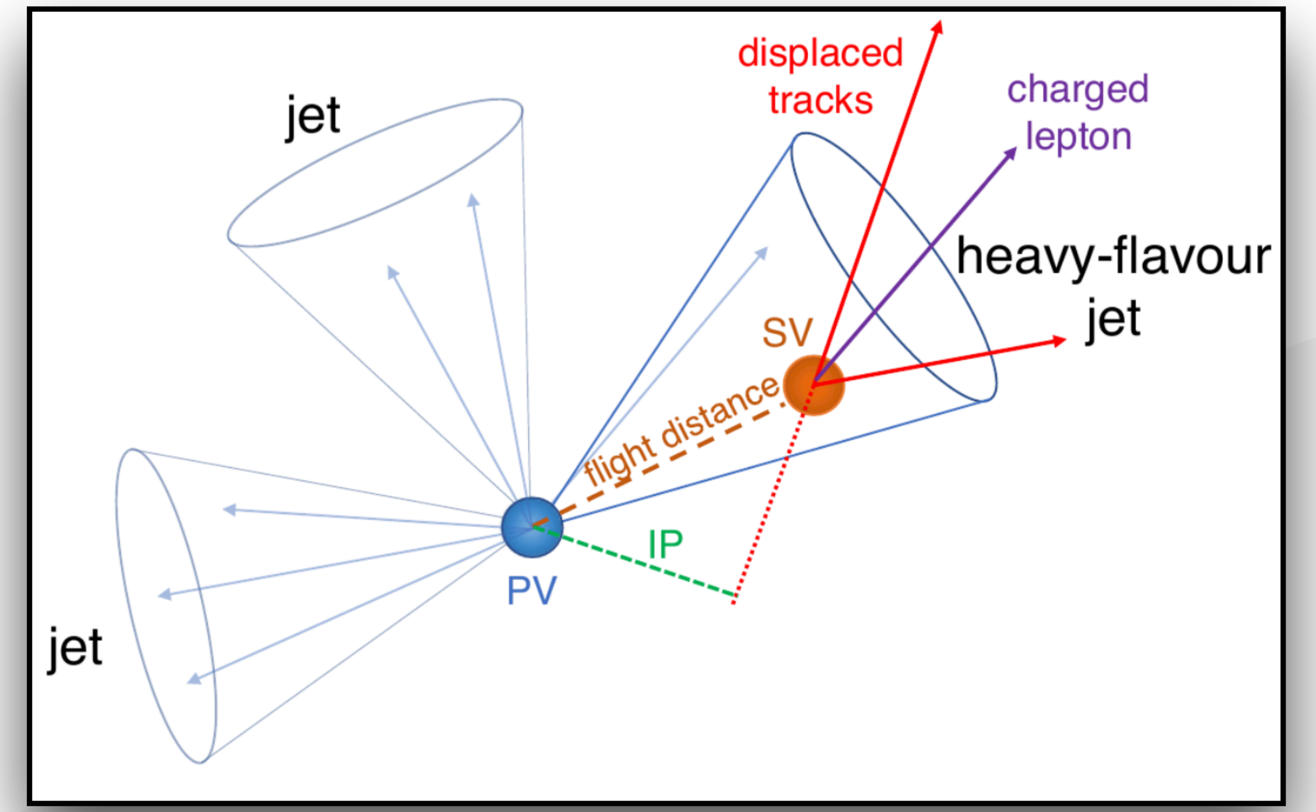
- The CMS $H \rightarrow \gamma\gamma$ group decided to switch to a **new** (Python based) **common framework for Run 3 analysis**.
- Run on flat NTuples (NanoAOD) that are centrally produced.
  $\Rightarrow$ faster running time, columnar analysis.
- Under active development, I joined the group of the core developers to work on the common ingredients.
- I was able to produce the **first complete analysis-like results** reproducing a simplified version of the Run 2 cross section measurement:
  - Event selection.
  - Systematics variations (a few).
  - Statistical fit.



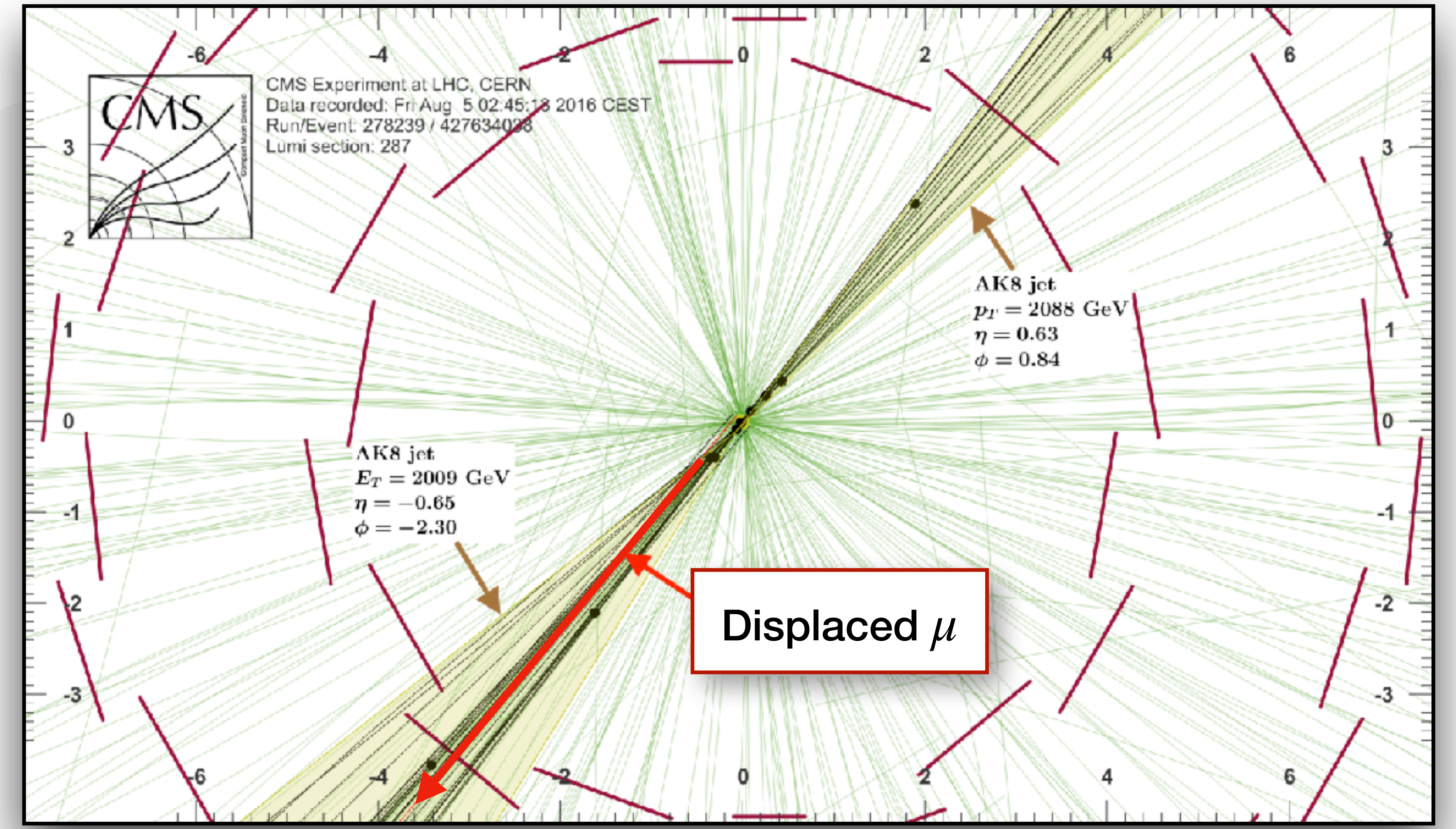


Charm tagging

Heavy flavour hadrons:



- **Have long lifetimes** (for HEP standards!) ~ ps:
  - They travel in the detector ~ mm before decaying.
- The Jets coming from HF quarks **often contain soft non-isolated leptons**.
- CMS is equipped with an excellent Inner Tracker system, the Pixel Detector:
  - 4 Barrel layers (built at PSI) and 6 Forward disks.
  - Excellent 3D spatial resolution ~ 50 μm.
  - Very high granularity ~ 124 M channels.



Displaced μ

Charm tagging

Heavy flavour hadrons:

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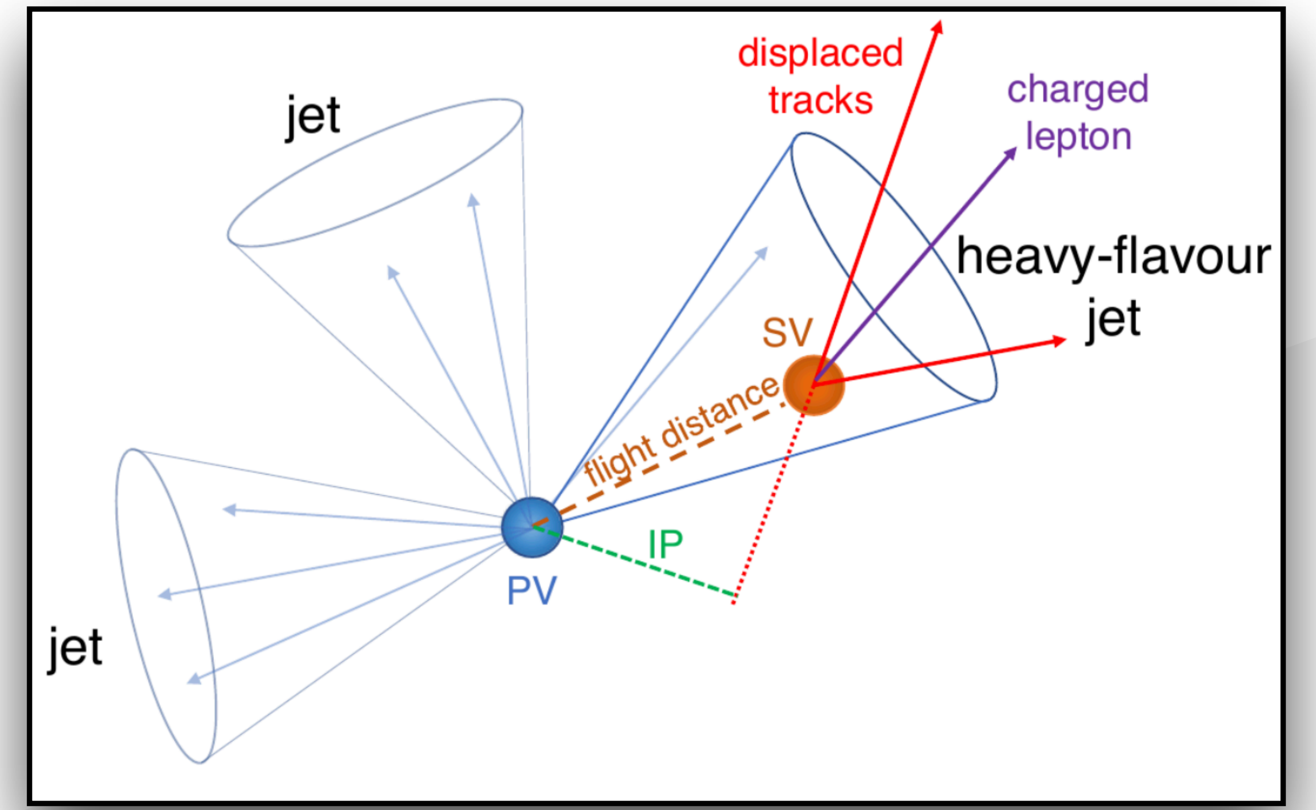
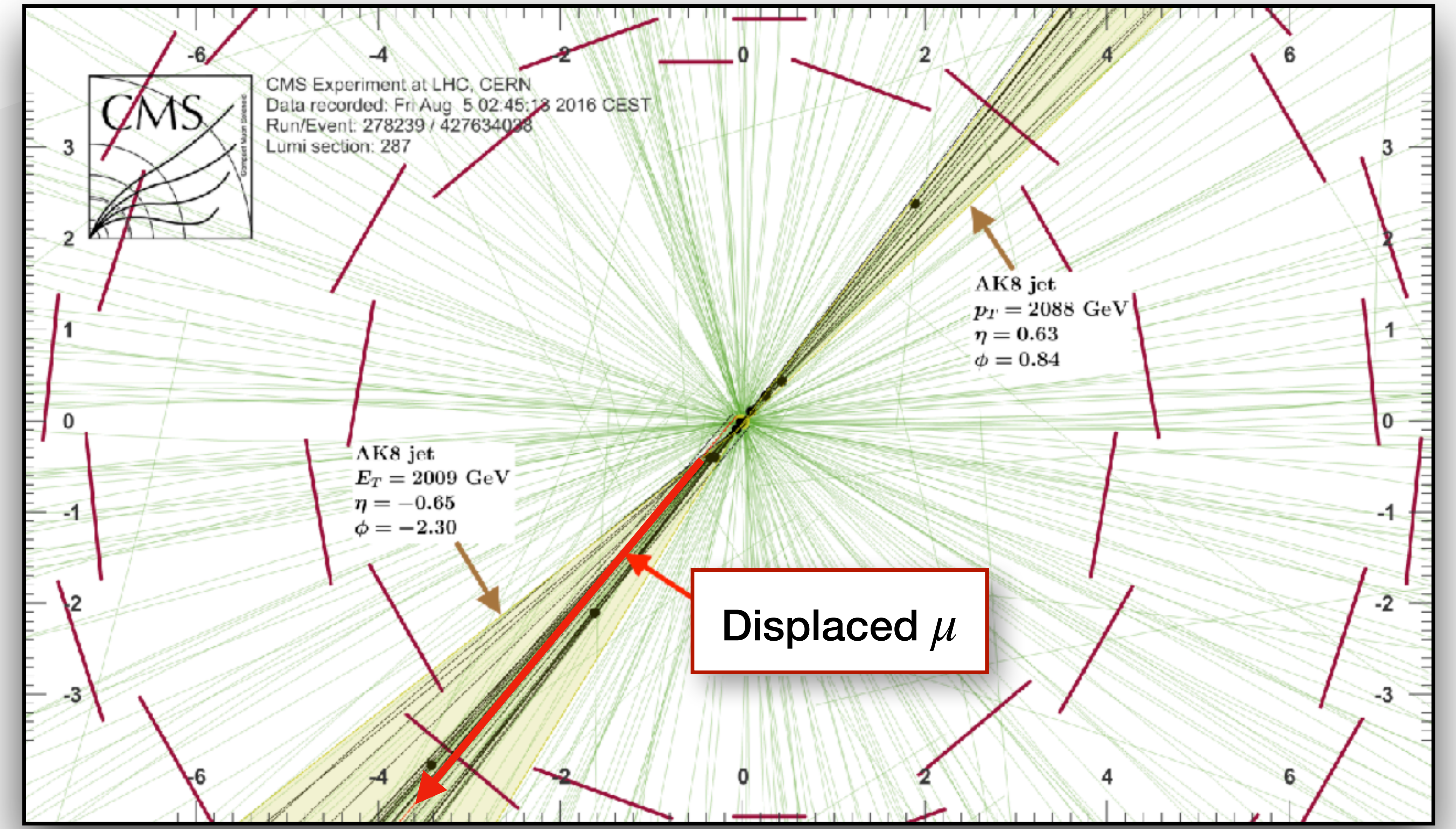
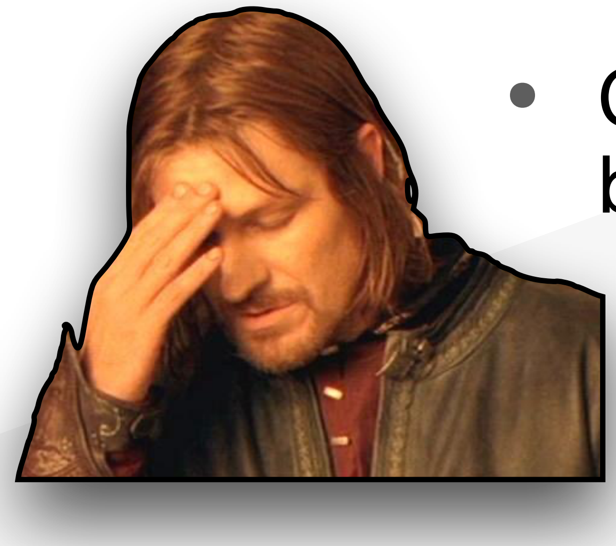
    - 4 Barrel layers (built at PSI) and 6 Forward disks.
    - Excellent 3D spatial resolution ~ 50 μm.
    - Very high granularity ~ 124 M channels.
- Nonetheless one does not simply do Charm tagging:
    - Charmed hadrons have **intermediate properties** between bottom and light Jets.
        - B mesons decay can include D mesons.



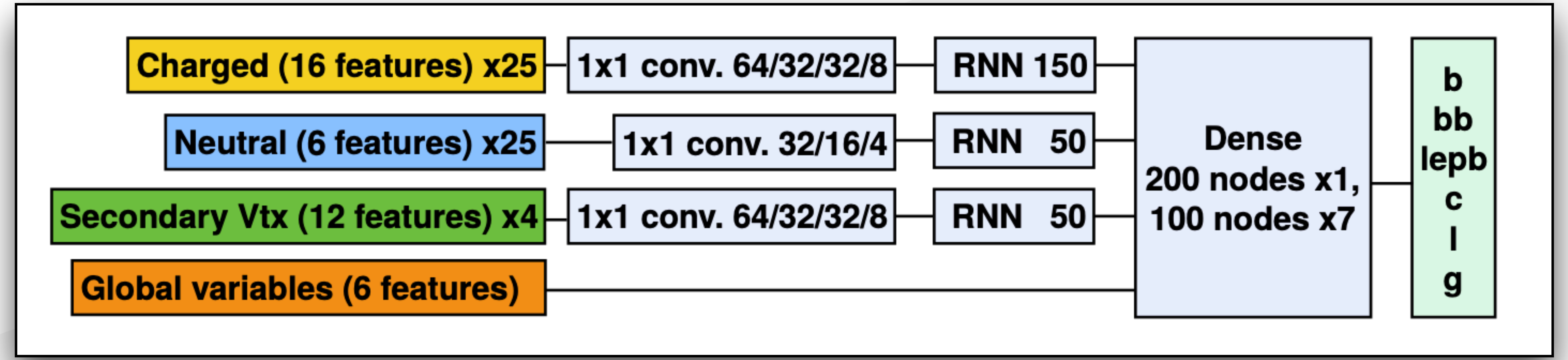

CMS Experiment at LHC, CERN
Data recorded: Fri Aug 5 02:45:18 2016 CEST
Run/Event: 278239 / 427634038
Lumi section: 287



Charm tagging

DeepJet algorithm:

- A complex Neural Network (NN) based discriminator is used to identify charmed jets in CMS.
- It exploits more than 600 input variables:
  - ⇒ global variables,
  - ⇒ charged candidate features,
  - ⇒ neutral candidate features,
  - ⇒ SV features.
- At Medium WP (2017): c-tag efficiency → 60%, b/light-mistag rate → 26%.



Charged (16 features) x25 — 1x1 conv. 64/32/32/8 — RNN 150

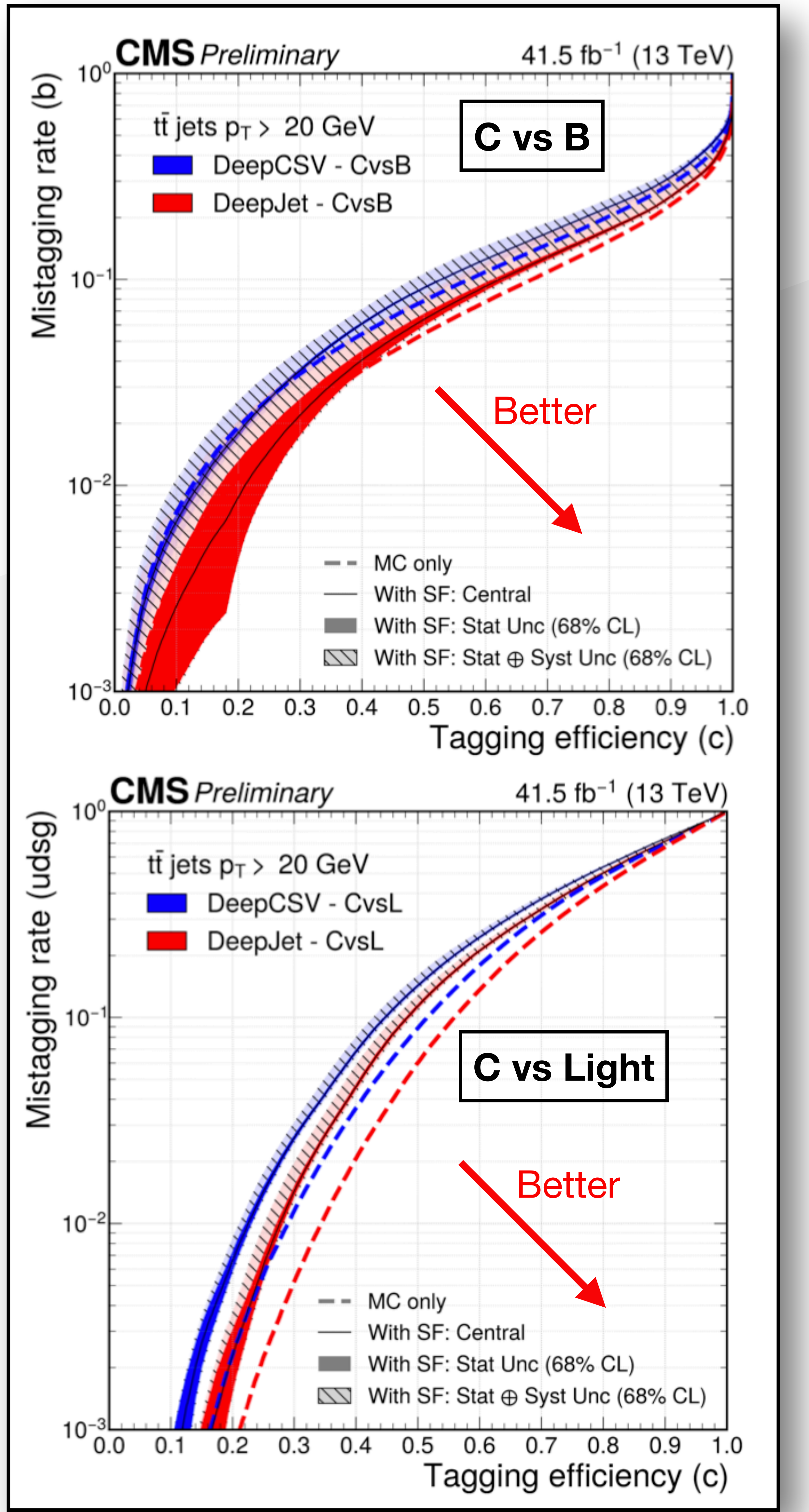
Neutral (6 features) x25 — 1x1 conv. 32/16/4 — RNN 50

Secondary Vtx (12 features) x4 — 1x1 conv. 64/32/32/8 — RNN 50

Global variables (6 features)

Dense 200 nodes x1, 100 nodes x7

b
bb
lepb
c
l
g



Outline

Introduction:

- Motivation.
- State of the art.
- New approaches.

Ingredients:

- Monte Carlo simulation.
- $H \to \gamma\gamma$ method.
- Framework development.
- Charm tagging.

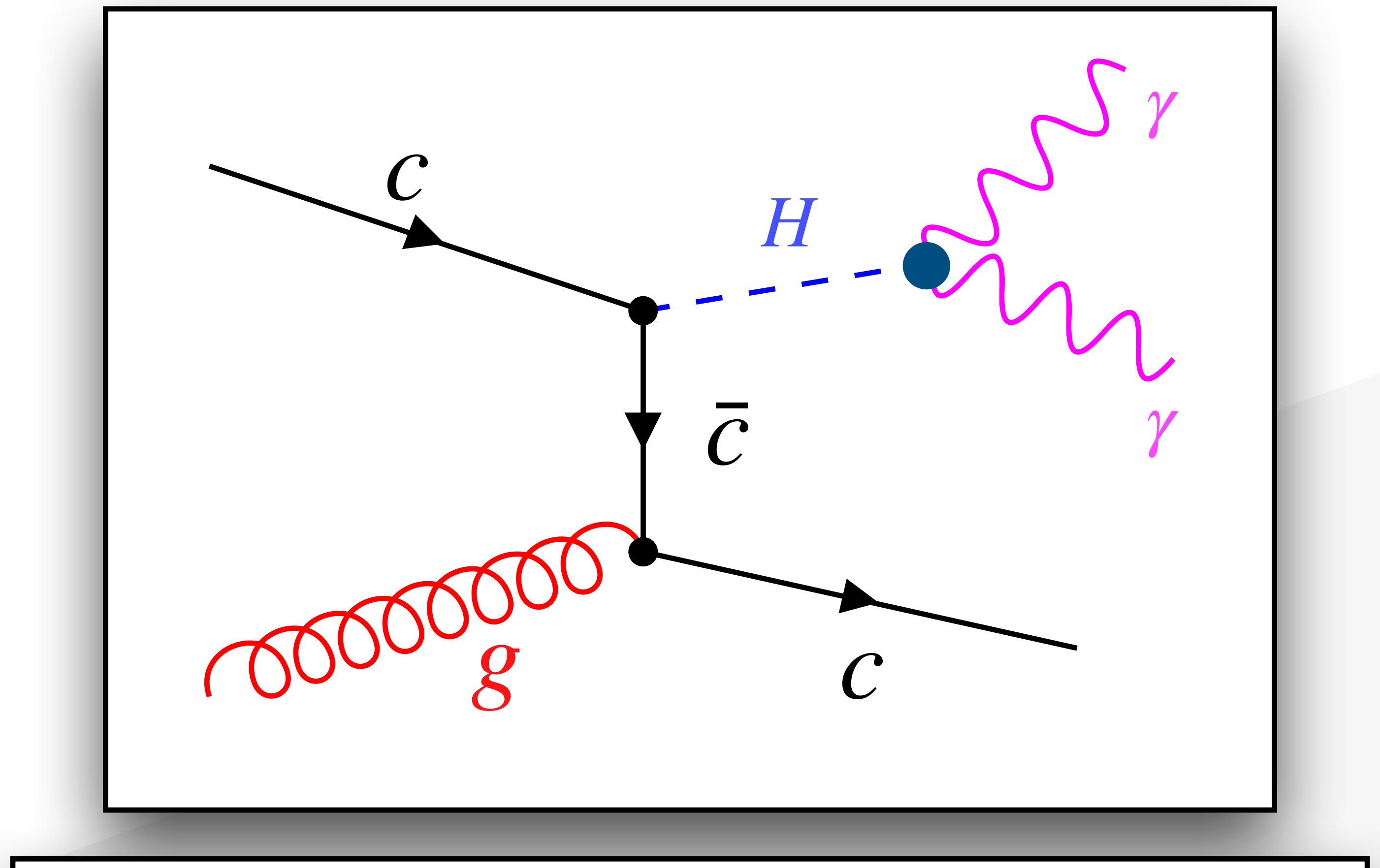
H+c analysis status:

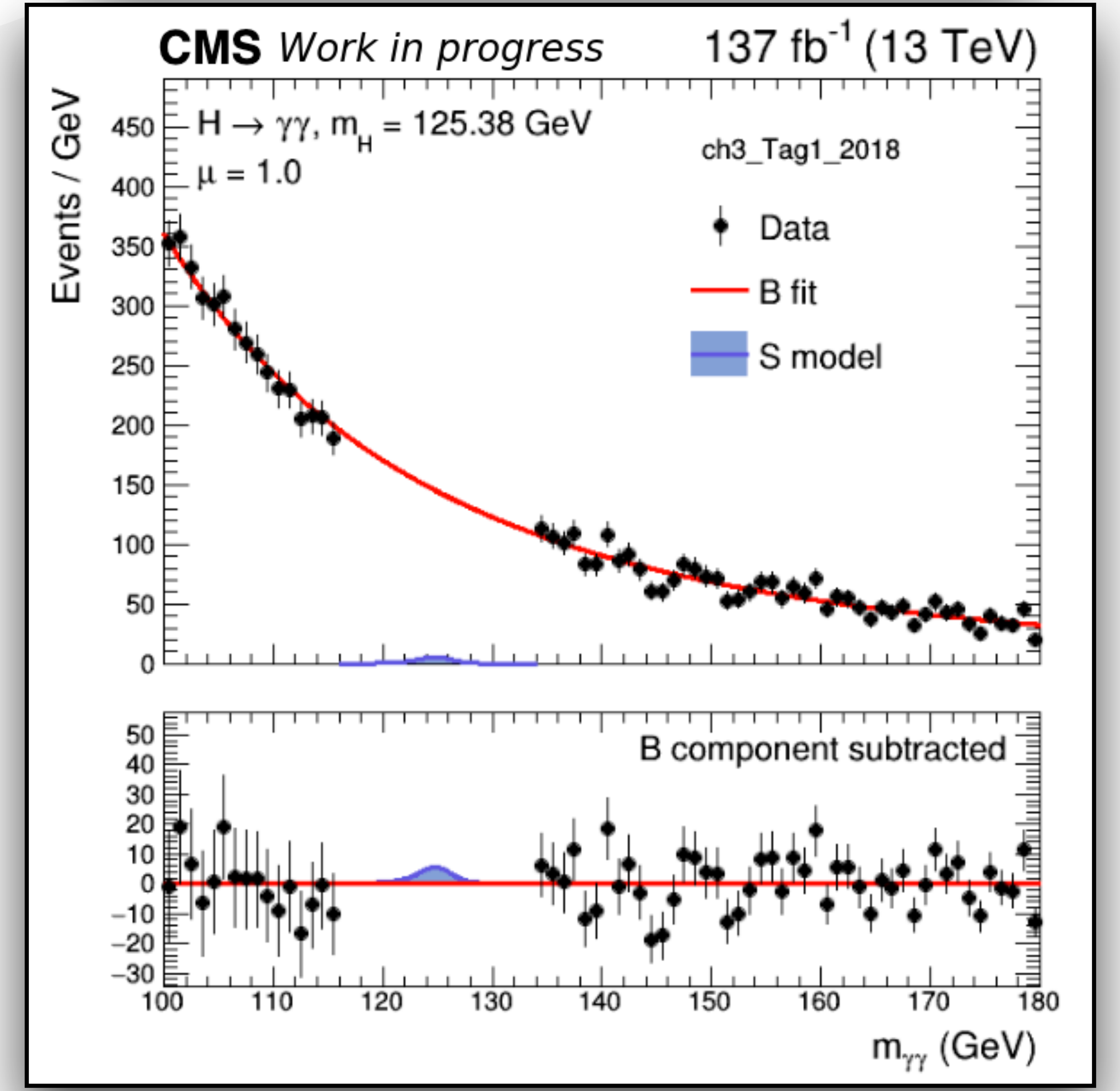
- Analysis strategy.
- Preliminary results.

H+c analysis status:

Analysis strategy:

- We select events with:
  - A good diphoton candidate.
  - At least one c-jet (DeepJet tagger score CvsL > 0.25).
- Main backgrounds:
  - Irreducible “standard” Higgs production through gluon fusion (ggH).
  - Continuous diphoton background (CB) from $\gamma\gamma$ and $\gamma + jets$ events (as in the plain $H \to \gamma\gamma$ analysis).





H+c analysis status:

2D Categories:

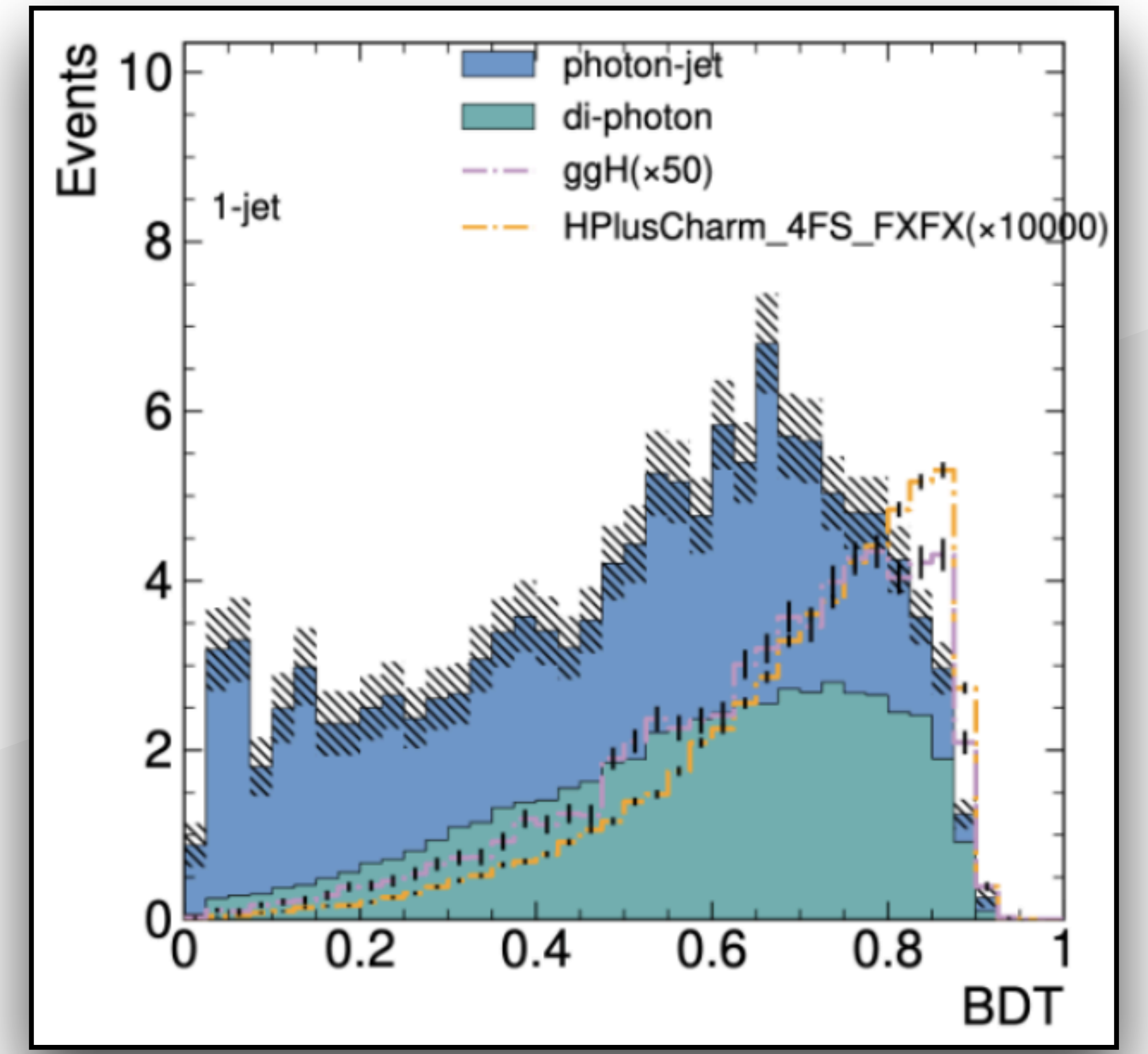
- We separate events in 9 categories according to:
  - A Boosted Decision Tree (BDT) trained to distinguish $H + c$ events from ggH.
  - A BDT trained to distinguish $H + c$ events from the continuous $\gamma\gamma$ background.

BDT training:

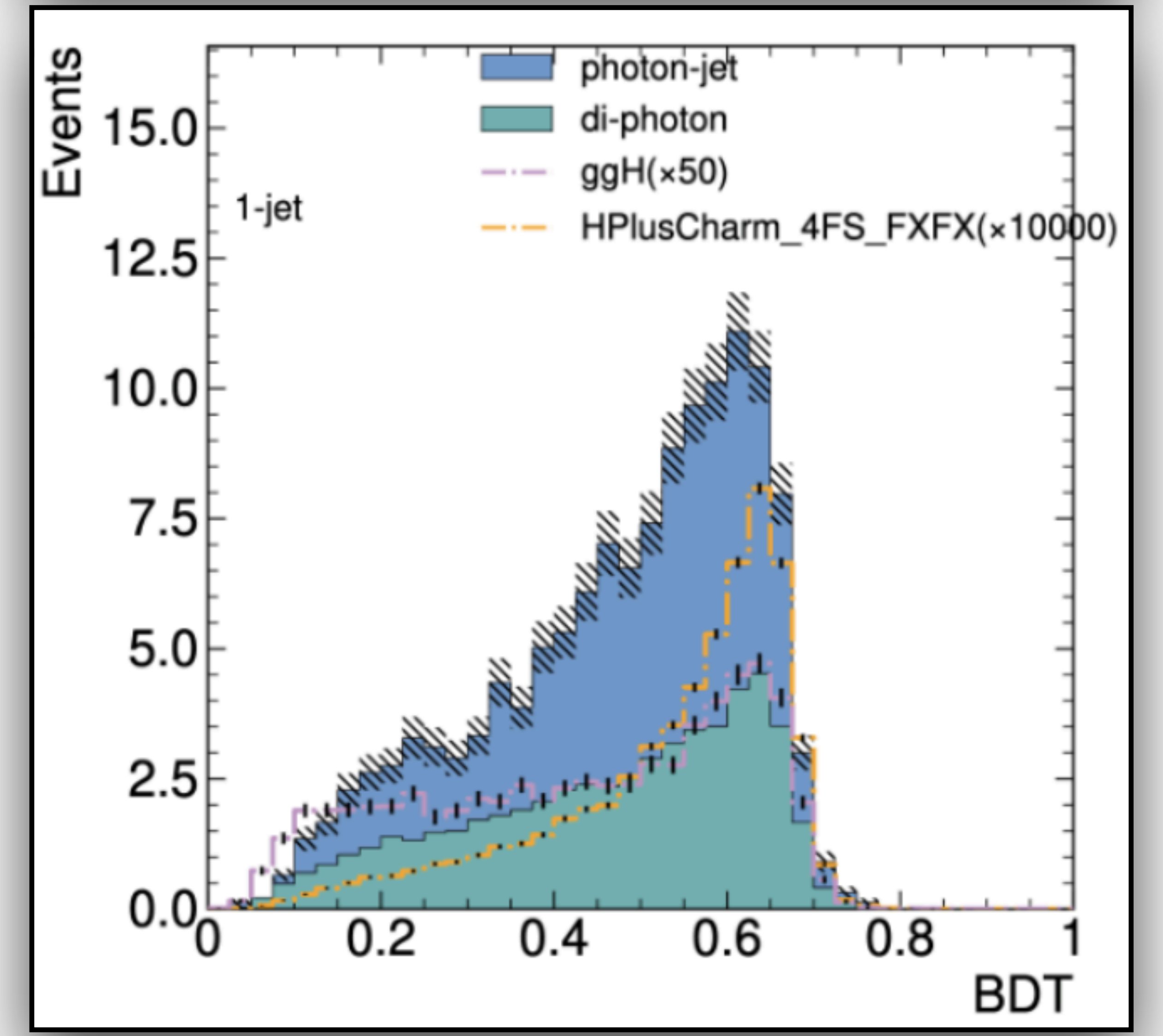
- Separation is achieved exploiting the kinematics of the Photons and Jets in the event.
- To address the irreducible ggH background we avoid using c-tagging information in the BDT training:

  $\Rightarrow$ use low BDT score regions to constrain ggH directly from data.

cH vs CB BDT score



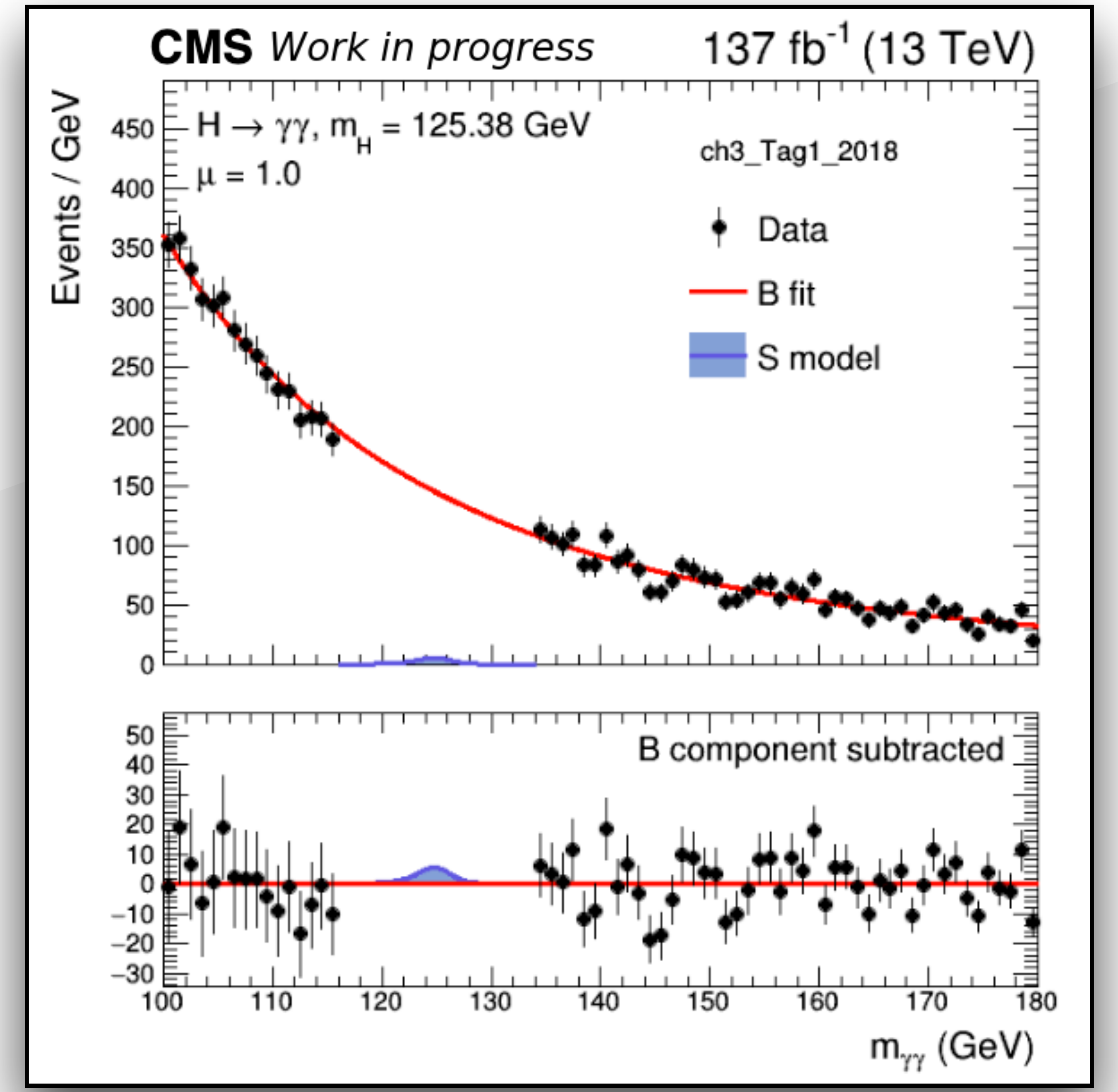
cH vs ggH BDT score



H+c analysis status:

Preliminary results:

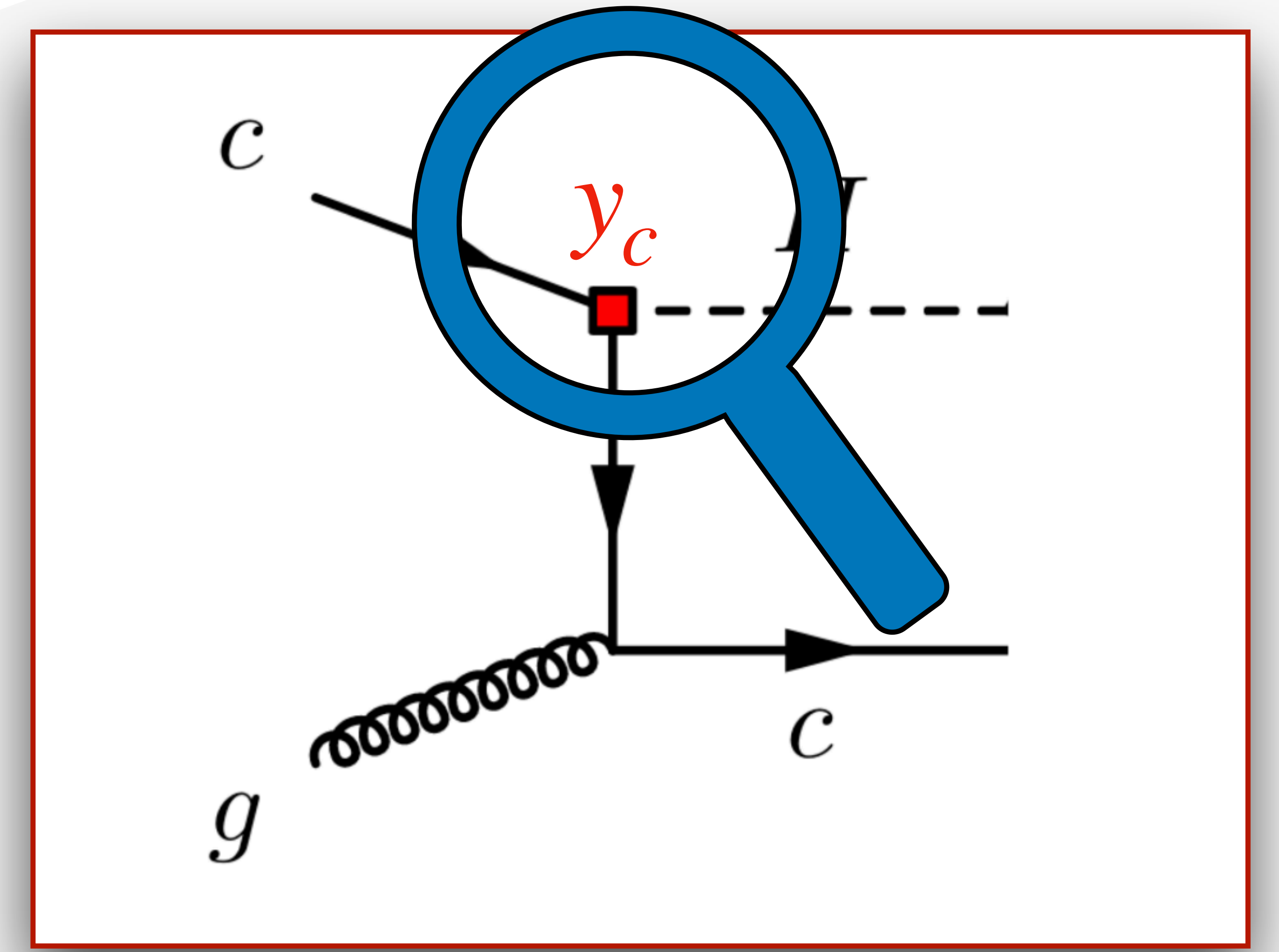
- The Run 2 analysis is still blinded, we’ll be going to CMS internal review soon.
- The expected limit on k_c is of $O(20)$.
- We’re planning of improve the analysis strategy, moving to new, more performing taggers and including Run 3 data.



Conclusions

Summary:

- The strategy of the CMS $H + c$ associated production analysis has been presented.
- The analysis presents some challenges (MC simulation, charm-tagging…)
- Nonetheless it is a very interesting channel to explore, given the complementarity of this approach with other existing searches.
- The Run 2 analysis is still blinded, results coming soon.



Conclusions

Summary:

- The strategy of the CMS $H + c$ associated production analysis has been presented.
- The analysis presents some challenges (MC simulation, charm-tagging…)
- Nonetheless it is a very interesting channel to explore, given the complementarity of this approach with other existing searches.
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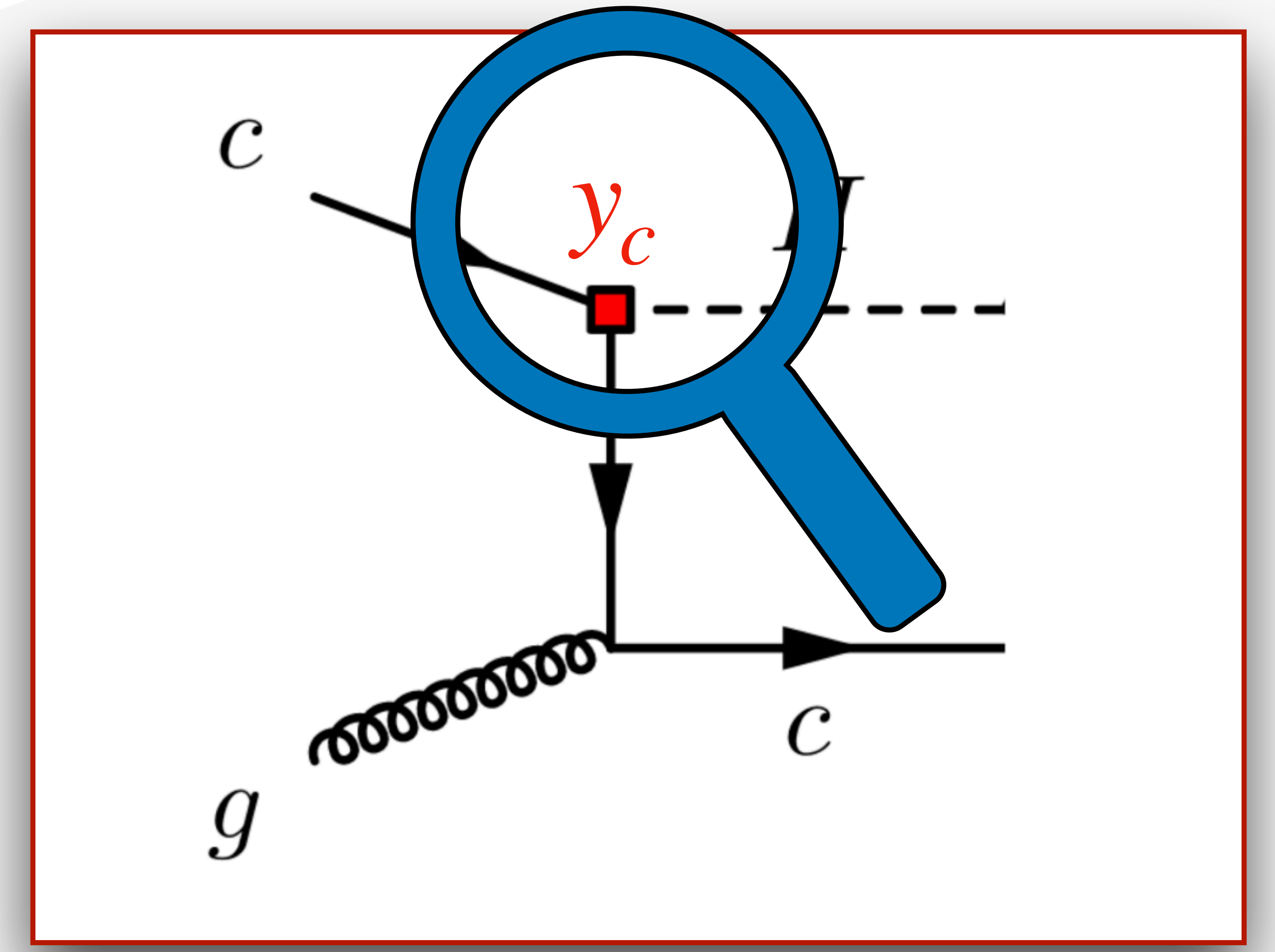
- **Stay tuned!**

Thank you!



Back up

Status: Common tools

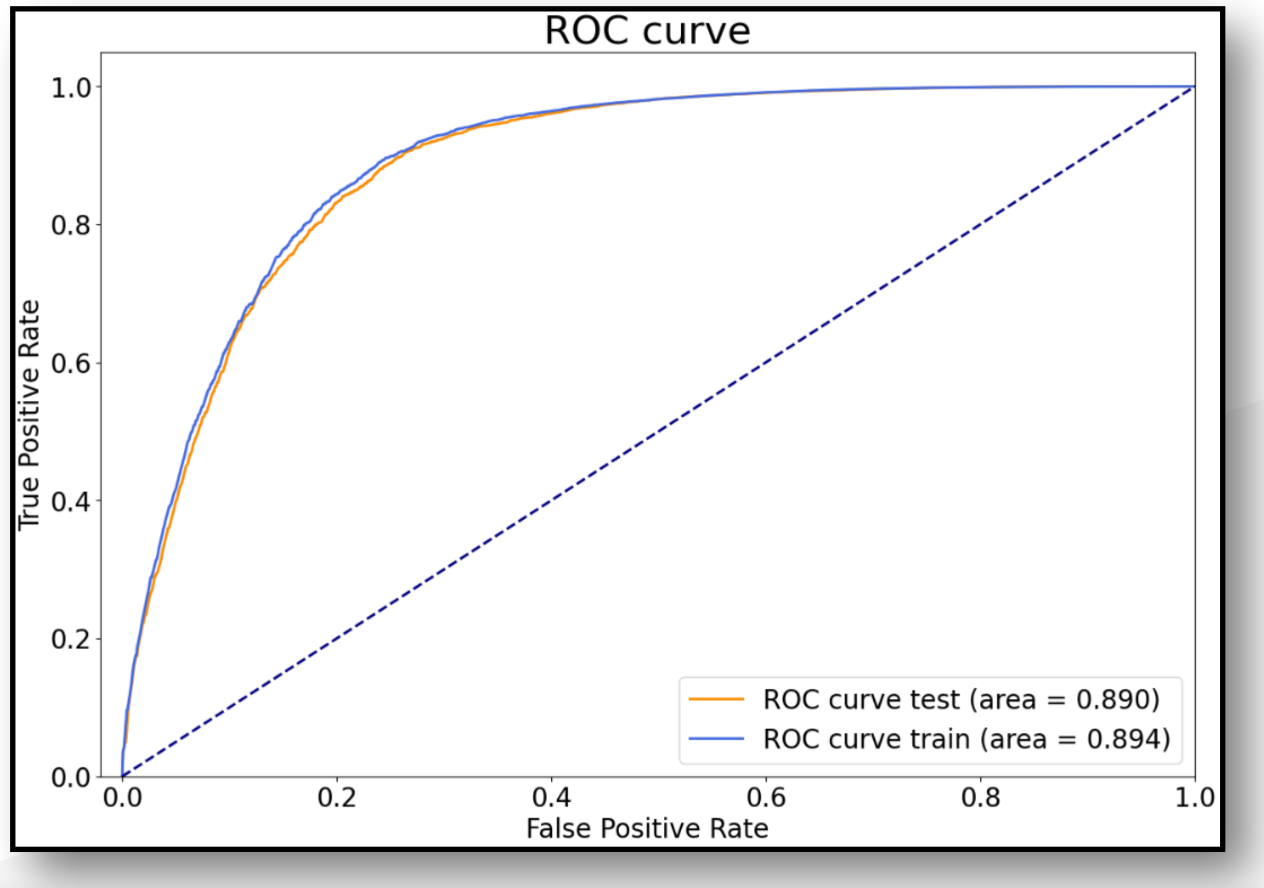
HiggsDNA:

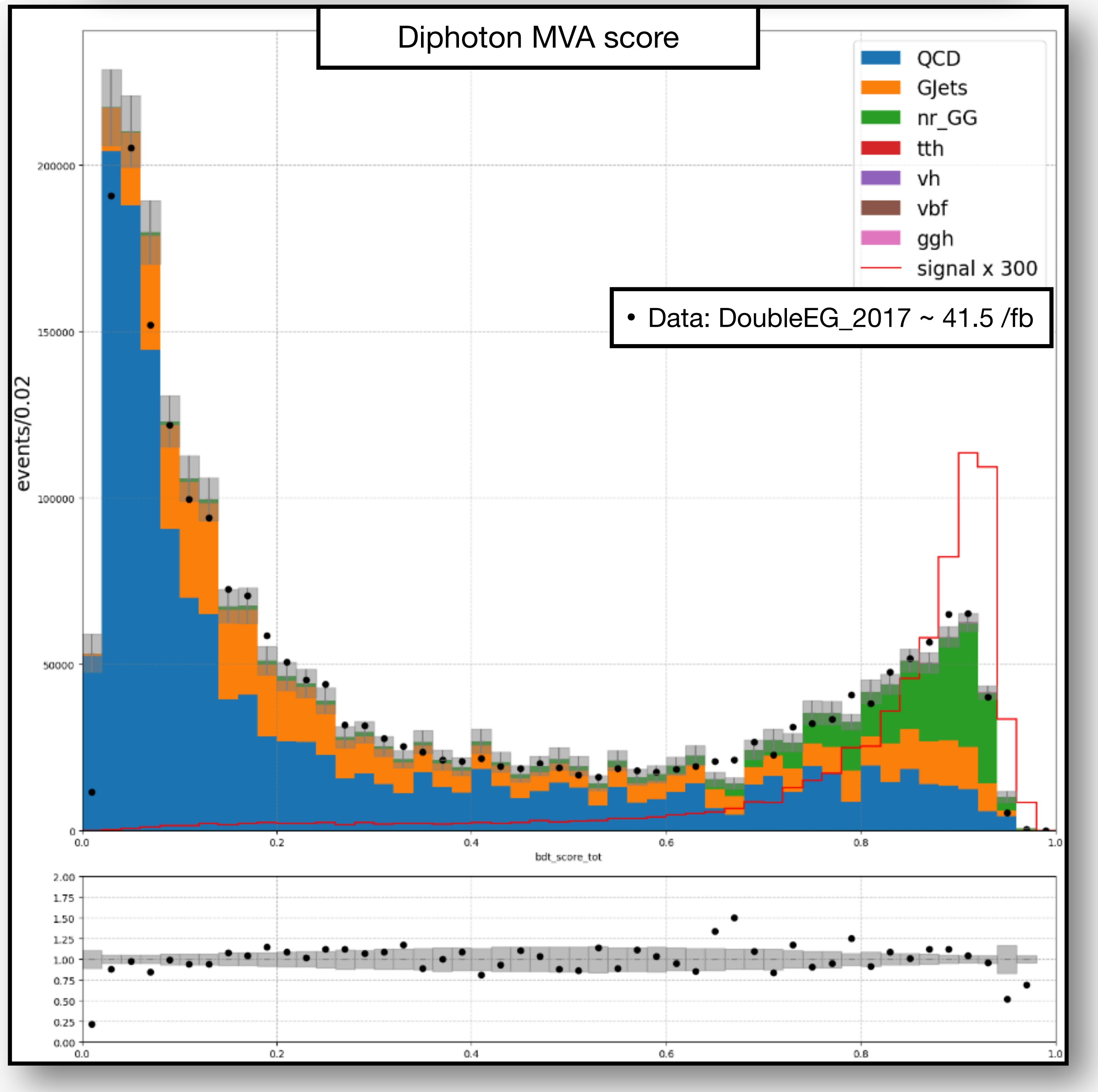
- The framework is **ready to perform an analysis** with Run 3 data.
  - Individual corrections/systematics may still need to be implemented, but the machinery is already in place alongside the main corrections.
  - Development of analysis specific tools is going on.

Diphoton ID BDT:

- Used to discriminate signal and fake γ background.
- In particular I'm focusing on the retraining of the BDT for Run 3:
  - Performed test on 2017 Data starting from nAOD.
  - Results are good but further comparisons with the old framework are needed:

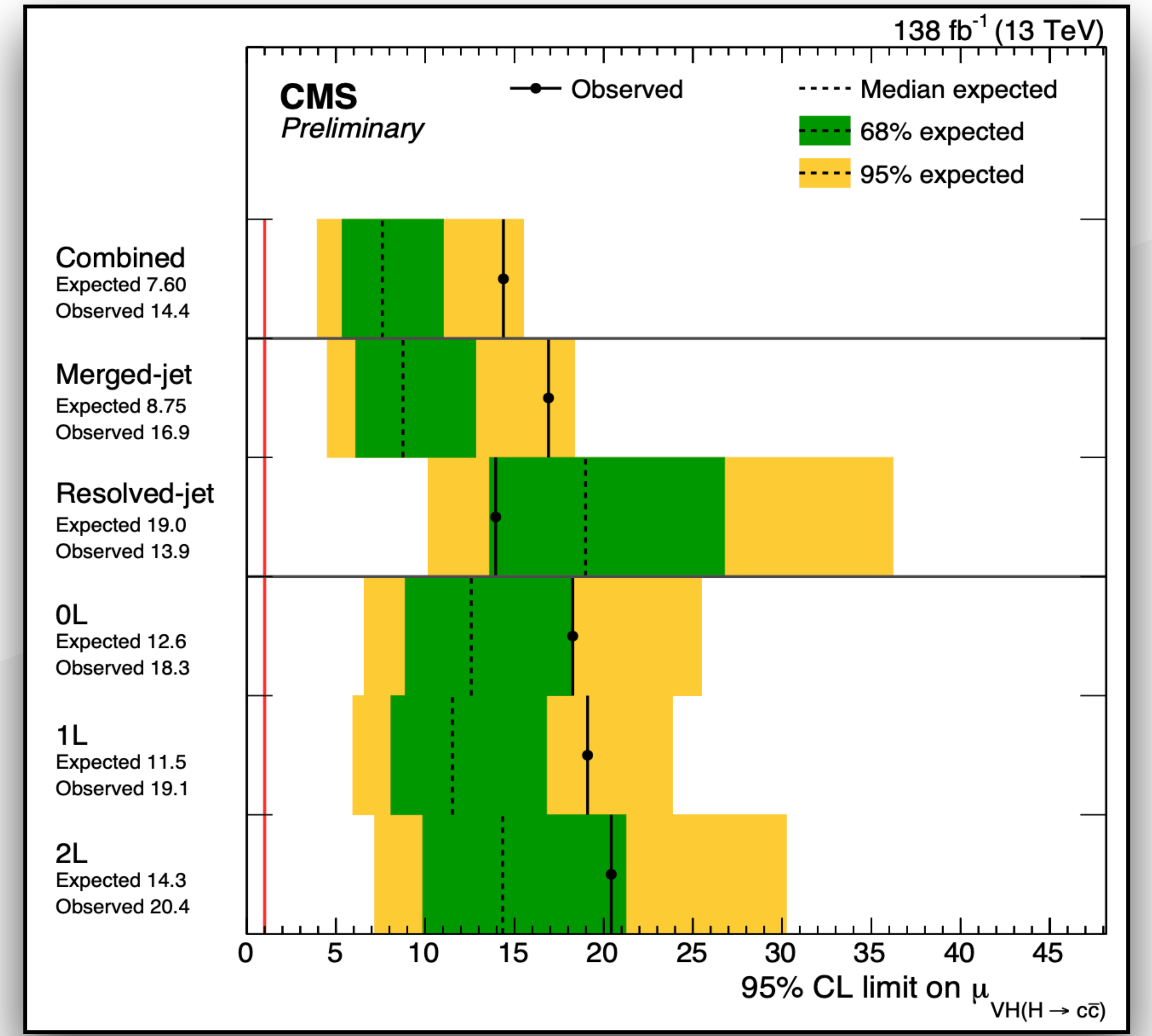
    $\Rightarrow$ **Performances of new framework training are better than with the Run 2 one.**





Previous results

- Direct search for $VH(H \rightarrow c\bar{c})$ arXiv:2205.05550: recent improvements, most stringent limit on $H \rightarrow c\bar{c}$.
  - Upper limit $\mu_{VH(H\rightarrow c\bar{c})} < 14\ (7.6)$ observed (expected).
  - $1.1 < |k_c^{[*]}| < 5.5\ (|k_c| < 3.4)$ observed (expected) at 95% C.L.
    [ATLAS : $|k_c| < 8.5(12.4)$ obs (exp) at 95% C.L.]
  - First observation of $Z \rightarrow c\bar{c}$ at a hadron collider (5.7σ)
- Boosted $ggH(H \rightarrow c\bar{c})$ HIG-21-012:
  - $\mu < 38\ (45)$ observed (expected) at 95% C.L.
- Exclusive $H \rightarrow J/\Psi + \gamma$ decays, clean signature, $J/\Psi \rightarrow \mu\mu$ but very rare process:
  - $BR/BR_{SM} < 220\ (170)$ observed (expected) at 95% C.L.
    [ATLAS : proj. for $3\ ab^{-1}$ $\mu < \mu_{SM}$ at 95% C.L.]
- H differential measurements, variation of $p_T(H)$ as a function of k_c:
  - $-4.9 < k_c < 4.8\ (-6.1 < k_c < 6.0)$ observed (expected) at 95% C.L.



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[*] $k_c = y_c/y_c^{SM}$

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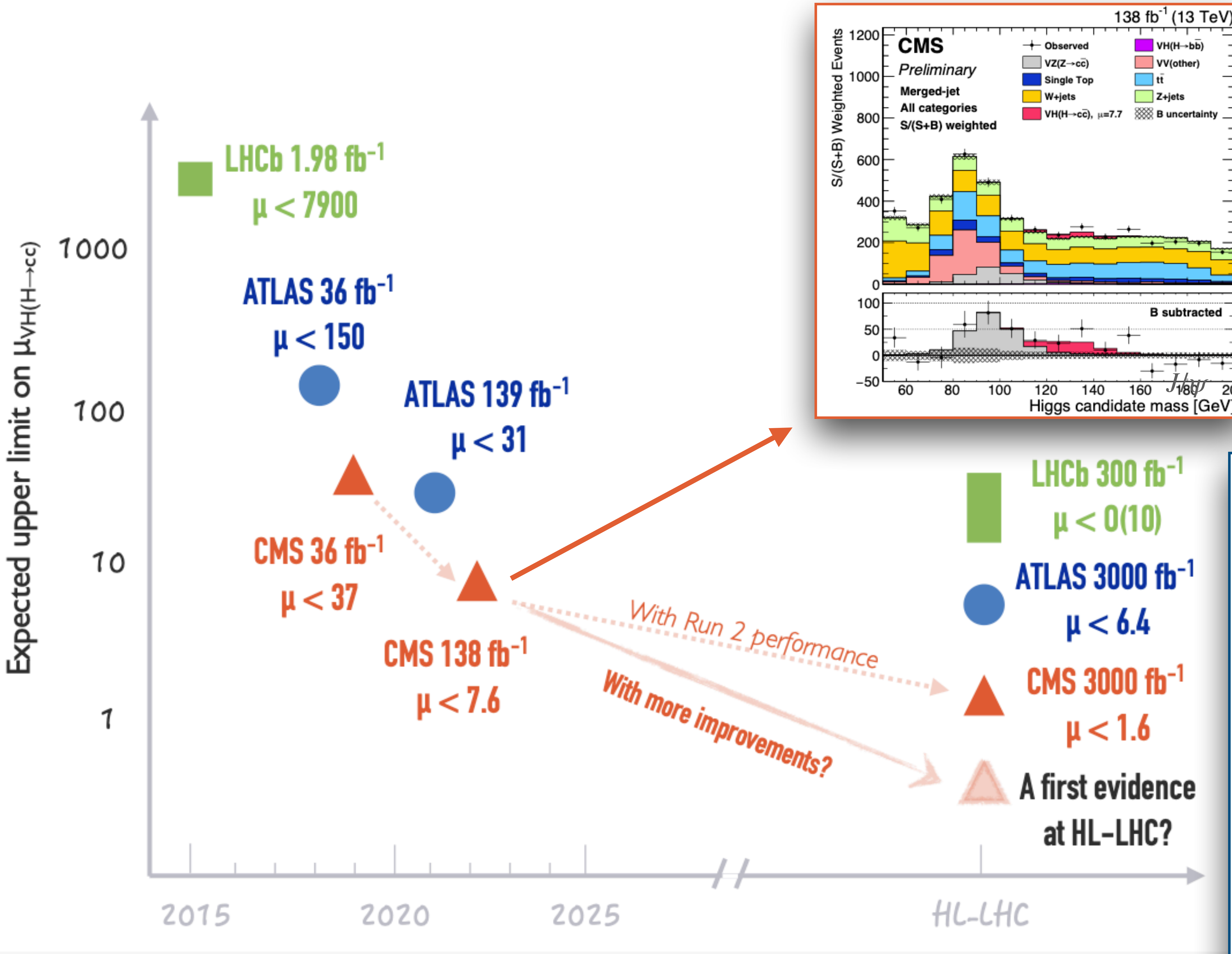
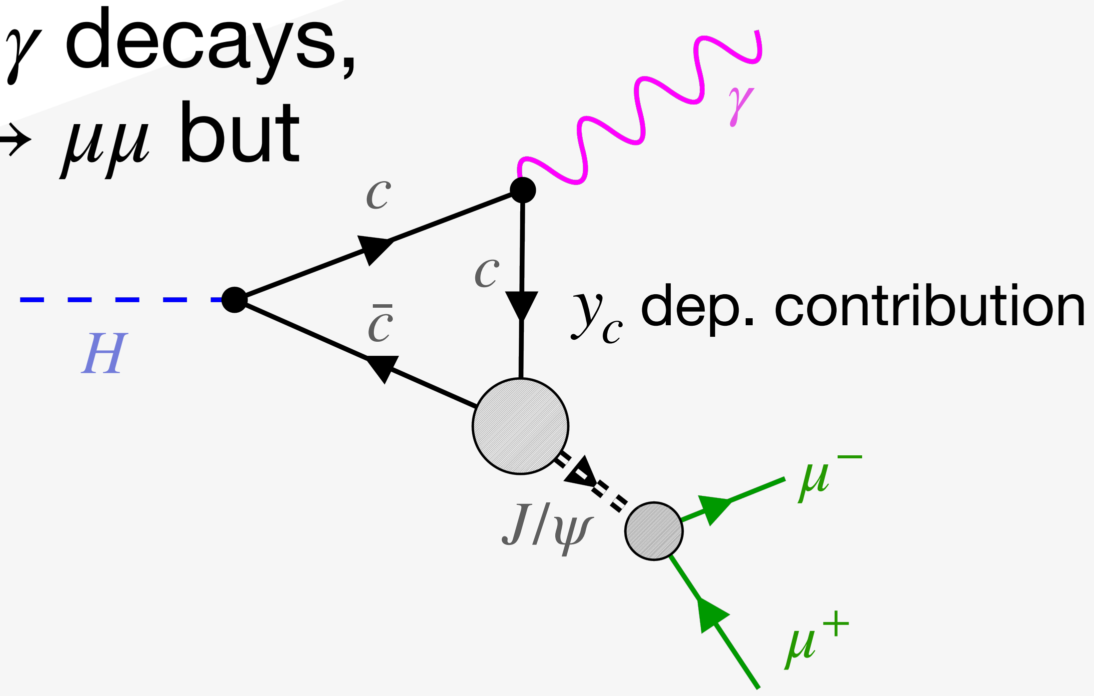
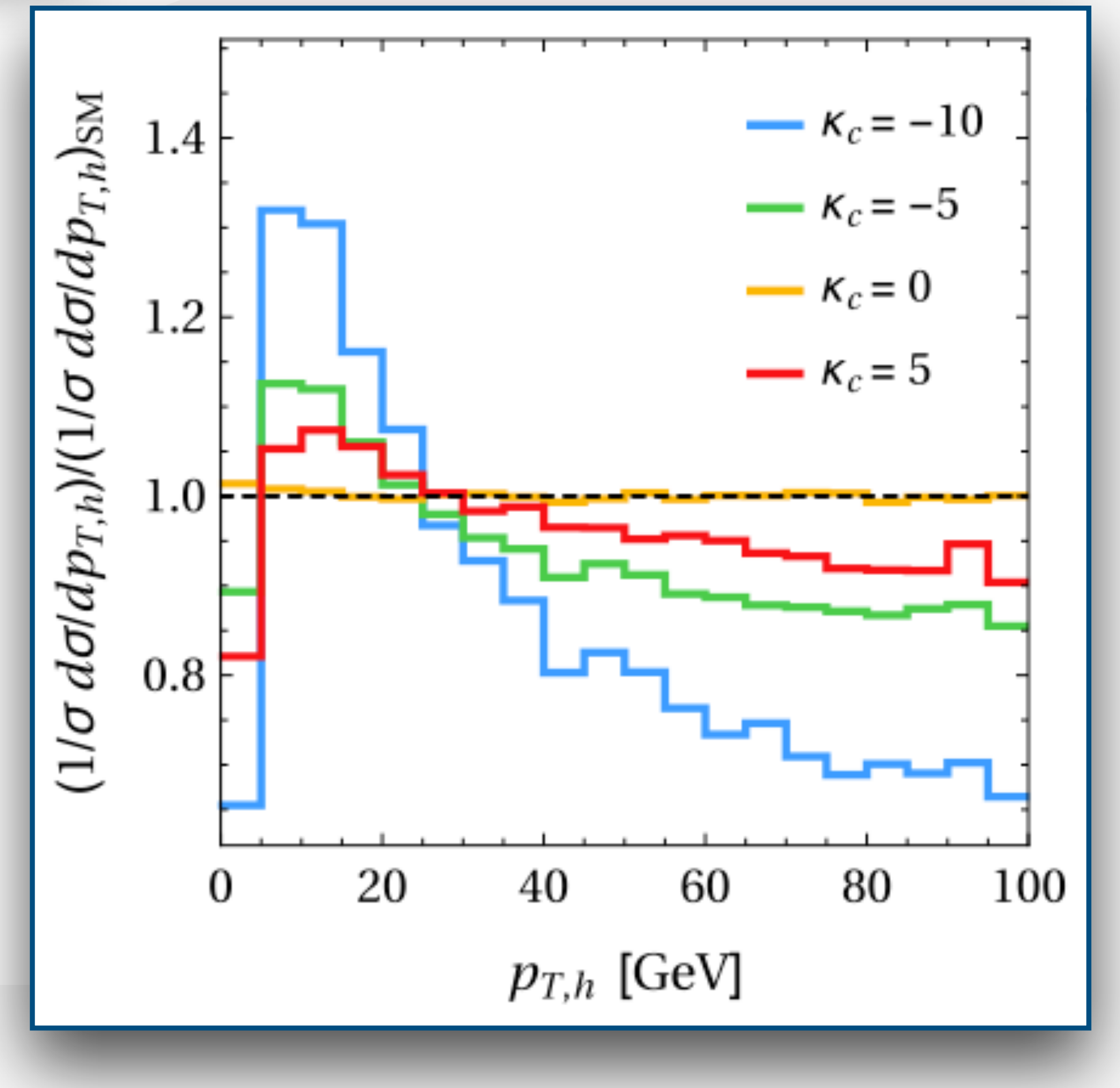


⇒ Upper limit $\mu_{VH(H\to c\bar{c})} < 14\ (7.6)$ observed (expected).

- **Exclusive** $H \to J/\Psi + \gamma$ decays, clean signature, $J/\Psi \to \mu\mu$ but very rare process:





- H differential measurements, variation of $p_T(H)$ as a function of k_c[*].

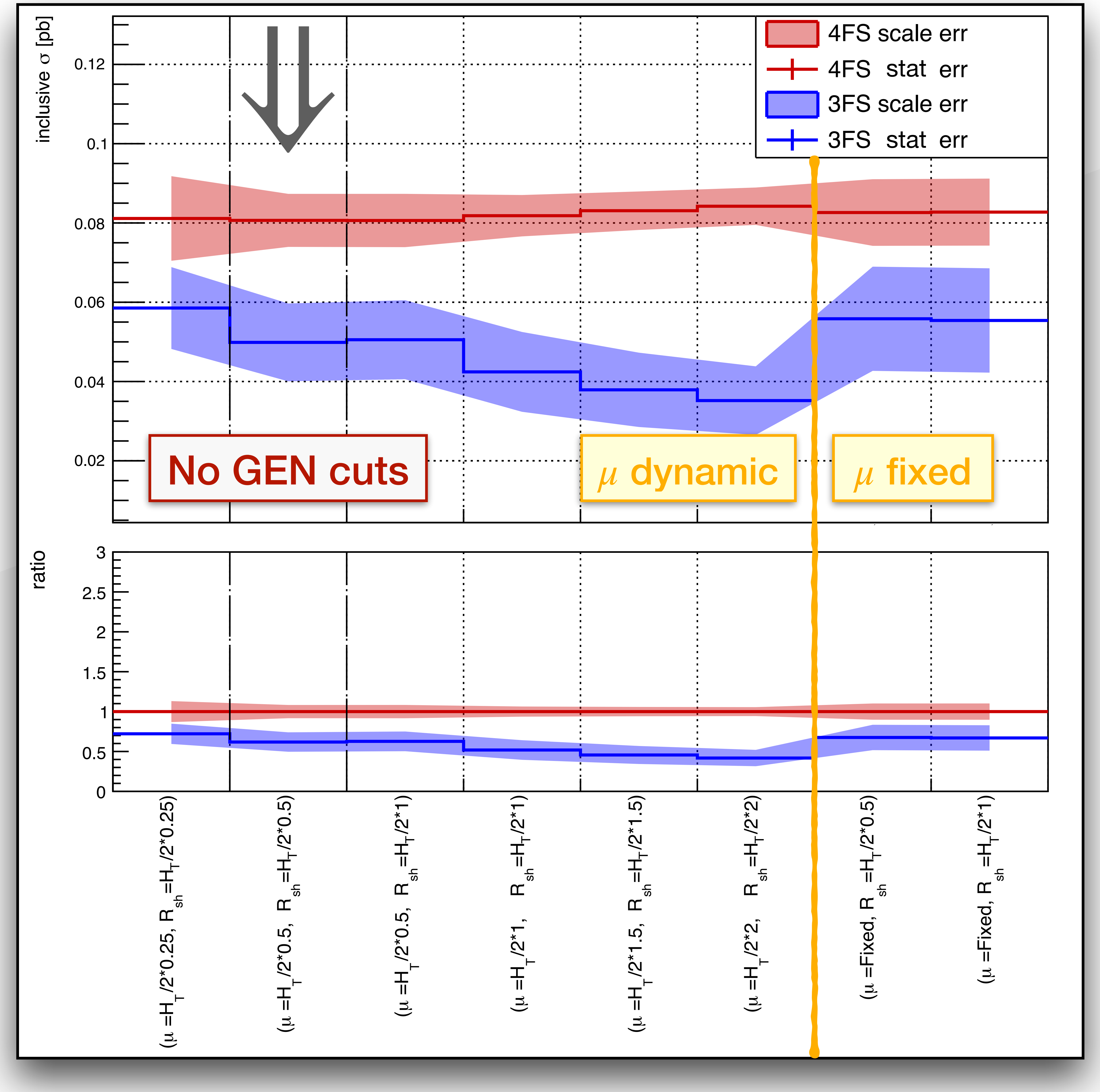
[*] $k_c = y_c / y_c^{SM}$

Phys. Rev. Lett. 118, 121801

GEN-level results

$H + c$ cross section for different scale choices:

- Large differences between 3FS and 4FS on the inclusive cross sections (up to ~2x).
- To minimise uncertainty on nominal sample (4FS-FXFX) we studied the dependence of the X-section on MG scale parameters (μ_R, μ_F, R_{SH}).
- Uncertainties: μ_R/μ_F scale ~ 15%, PDF ~ 5-10%.



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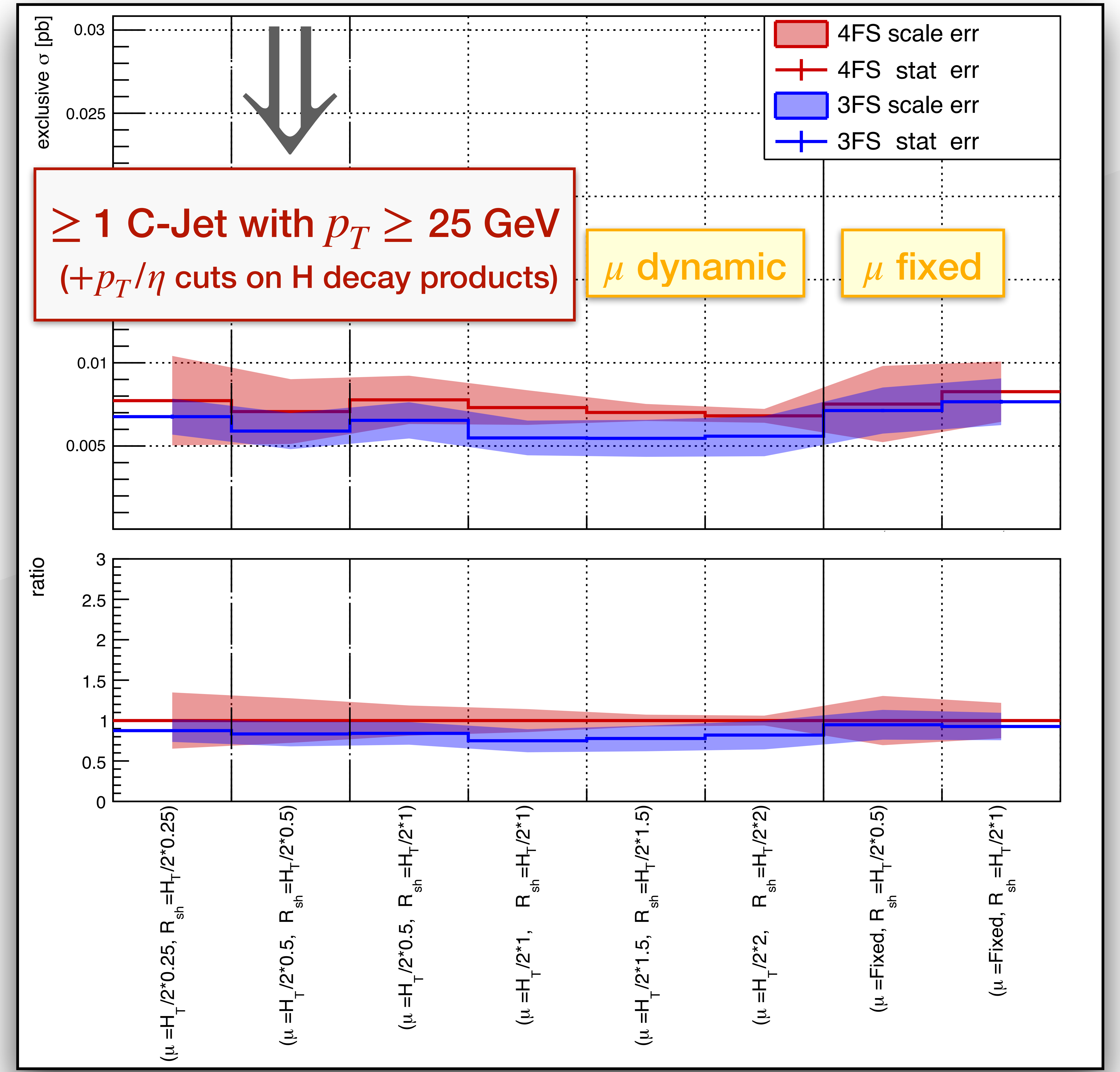
- Uncertainties: μ_R/μ_F scale ~ 15%, PDF ~ 5-10%.
- **Smaller (10-20%) differences for analysis-like phase space** (>=1 gen-c-jet w/ $p_T > 25$ GeV).



$\geq$ 1 C-Jet with $p_T \geq 25$ GeV

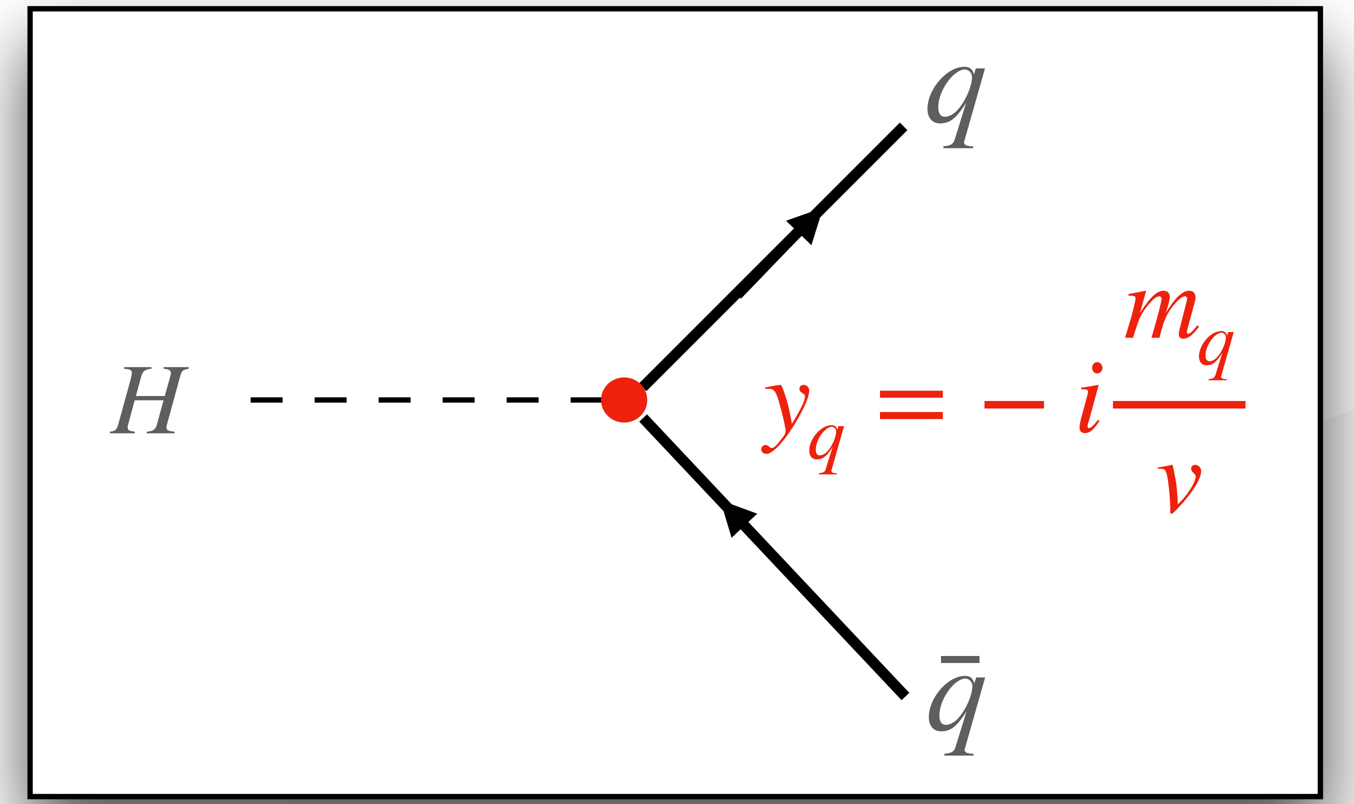
($+p_T/\eta$ cuts on H decay products)

μ dynamic

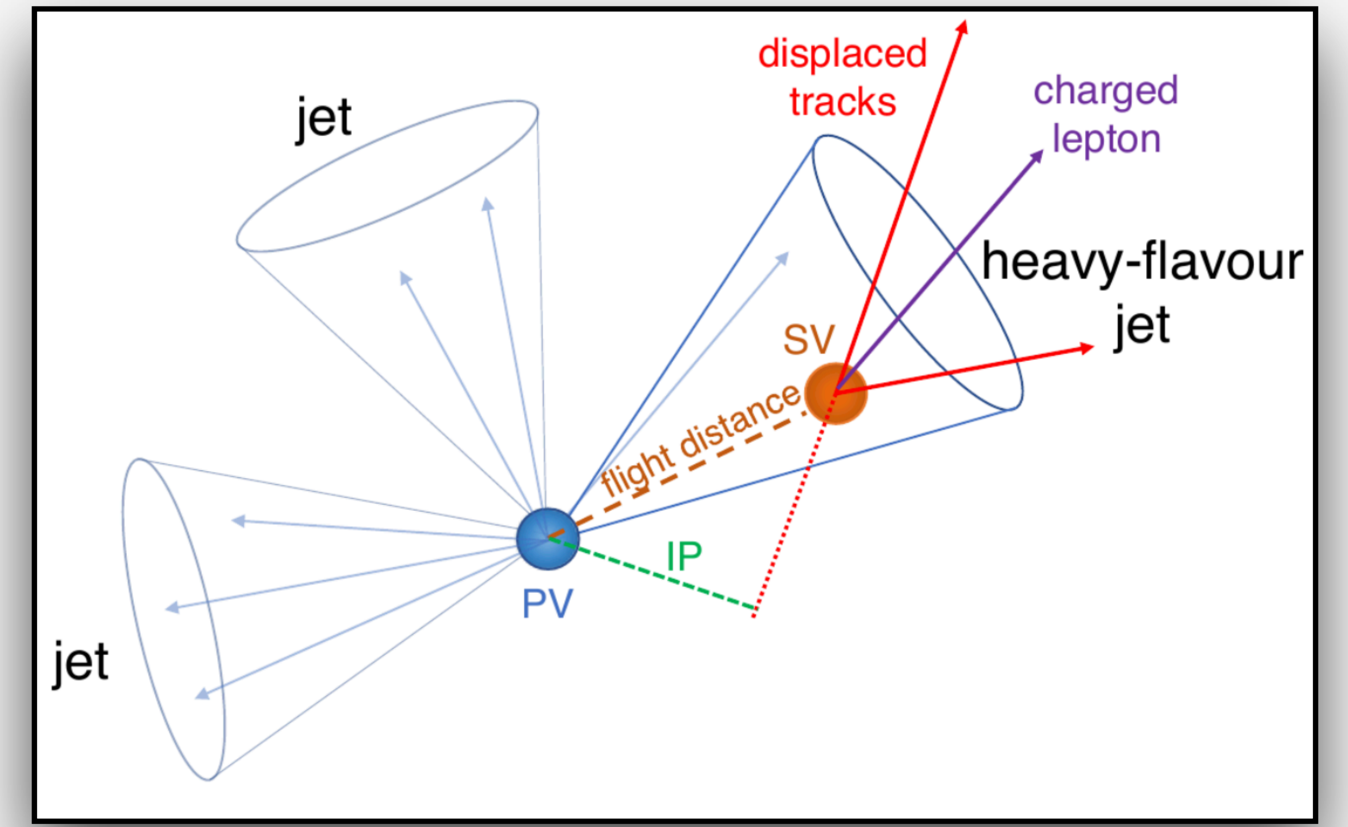
μ fixed

Challenges

- Decay width of Higgs boson to quarks $\Gamma_{H\to q\bar{q}} = 3\frac{m_q^2 \cdot m_H^2}{8\pi v^2}$
  - BR $H \to b\bar{b} \sim 58\,\%$
  - BR $H \to c\bar{c} \sim 3\,\%$



- Discriminate c-flavoured jets from background (b and light jets):
  - D-mesons lifetime ~ 1/2 of B-mesons, less SV displacement.
  - Discrimination wrt light jets more challenging than for b-jets.
  - B-mesons often have decay chains via D-mesons, which can fake c jets.



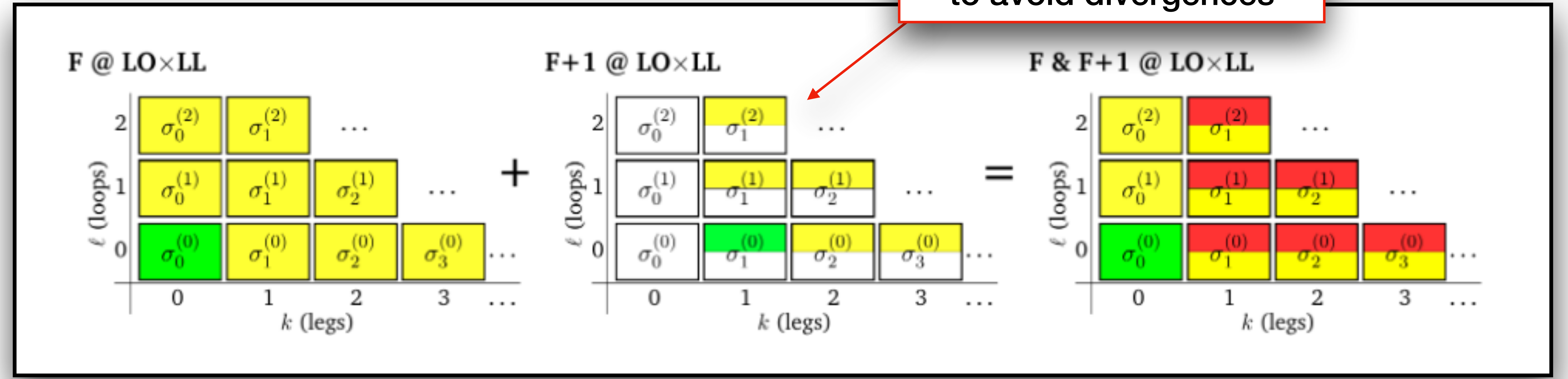
Matching and Merging:

Merging (FXFX):

A separate tree-level calculation is performed for each parton multiplicity of interest. Soft and collinear divergences of the hard matrix elements are regulated by resolution cuts.

- Generate the process $[X]_{ME}$ + PS
- Generate the process $[X + 1\ jet]_{ME}$ + PS
- Generate the process $[X + 2\ jet]_{ME}$ + PS […]

Double counting !

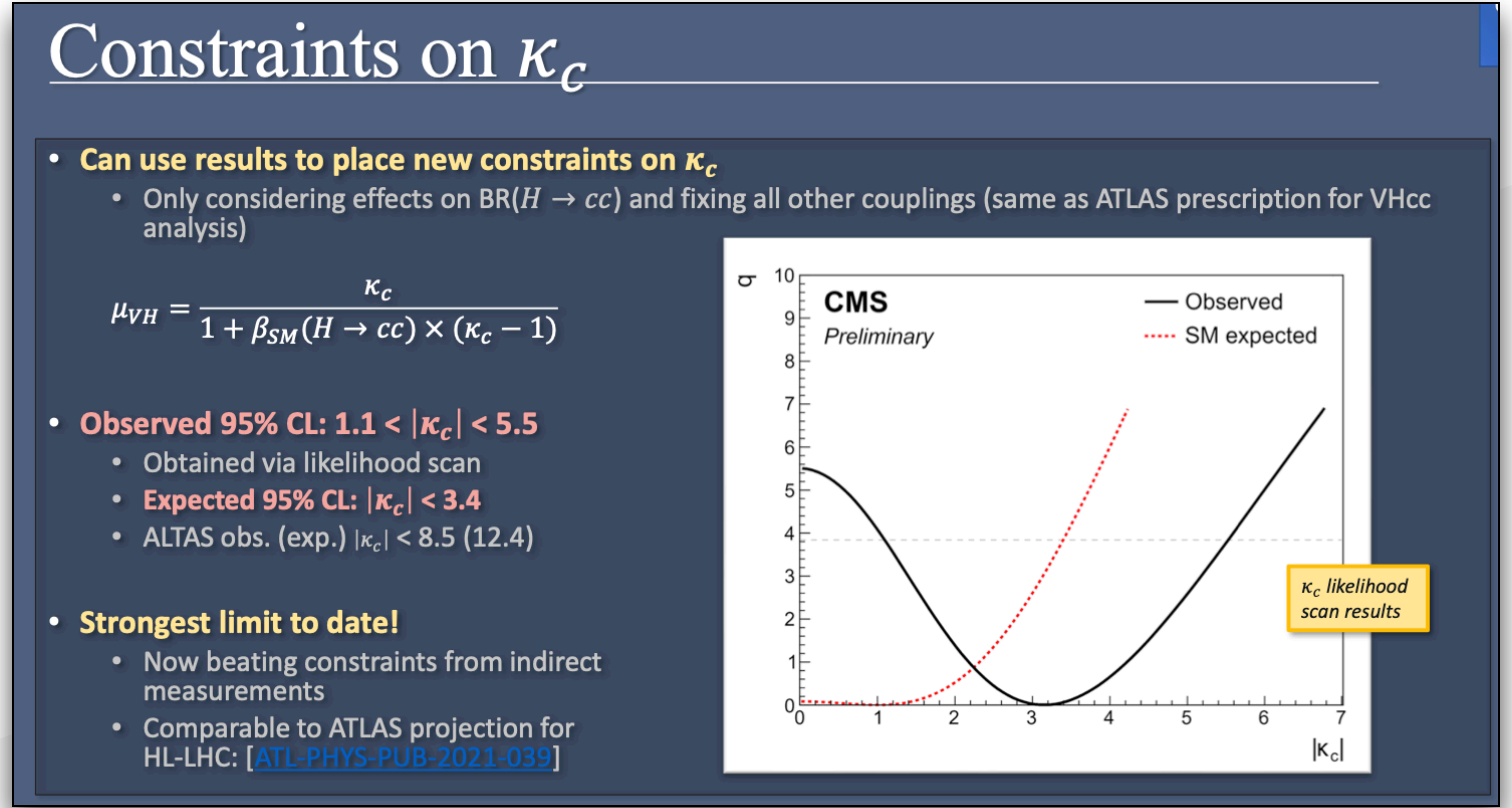


Cuts on the ME emission to avoid divergences

Borrowed from L. Gellersen

Making exclusive by reweighting with no-emission probabilities, i.e. how would PS have produced this configuration, and using normal shower in “soft region” below q_{merg}.

VH(Hcc): from Bjorn Burkle



Constraints on κ_c

- **Can use results to place new constraints on κ_c**
  - Only considering effects on BR($H \to cc$) and fixing all other couplings (same as ATLAS prescription for VHcc analysis)

$$\mu_{VH} = \frac{\kappa_c}{1 + \beta_{SM}(H \to cc) \times (\kappa_c - 1)}$$

- **Observed 95% CL: 1.1 < $|\kappa_c|$ < 5.5**
  - Obtained via likelihood scan
  - **Expected 95% CL: $|\kappa_c|$ < 3.4**
  - ALTAS obs. (exp.) $|\kappa_c|$ < 8.5 (12.4)
- **Strongest limit to date!**
  - Now beating constraints from indirect measurements
  - Comparable to ATLAS projection for HL-LHC: [ATL-PHYS-PUB-2021-039]

κ_c likelihood scan results

FS

- While 4FS results lack logarithmic terms beyond the first few, 5FS results lack power-suppressed terms (mb/Q)n. Which of the two classes of terms is more important depends on the observable studied, that determines the dominant kinematic regime.
- If logarithms are large, the 5FS should be superior to the 4FS; if they are not, and thus power-suppressed terms might be important, then 4FS approaches should be preferred.
- One expects that, for processes and in regions of the phase space where both resummation and mass effects are not dominant, the two approaches should give similar results.

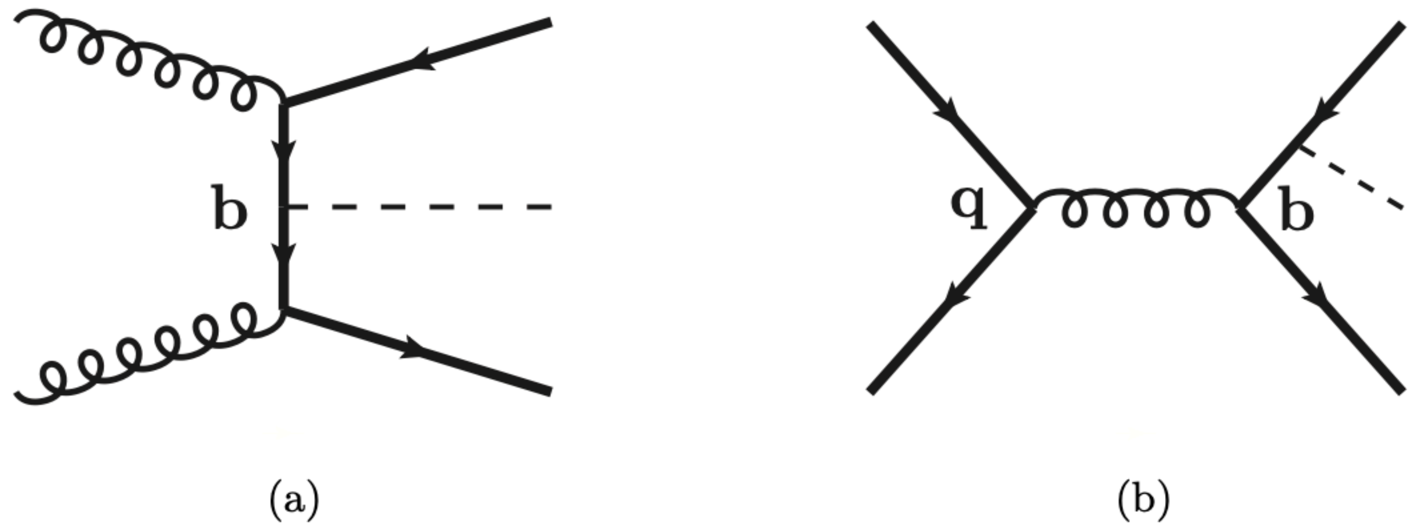


Figure 1: Sample of LO Feynman diagrams for $b\bar{b}H$ production in the four-flavour scheme, for the two relevant classes of partonic subprocesses: (a) $gg \to b\bar{b}H$; (b) $q\bar{q} \to b\bar{b}H$.

from: arXiv:1409.5301v2

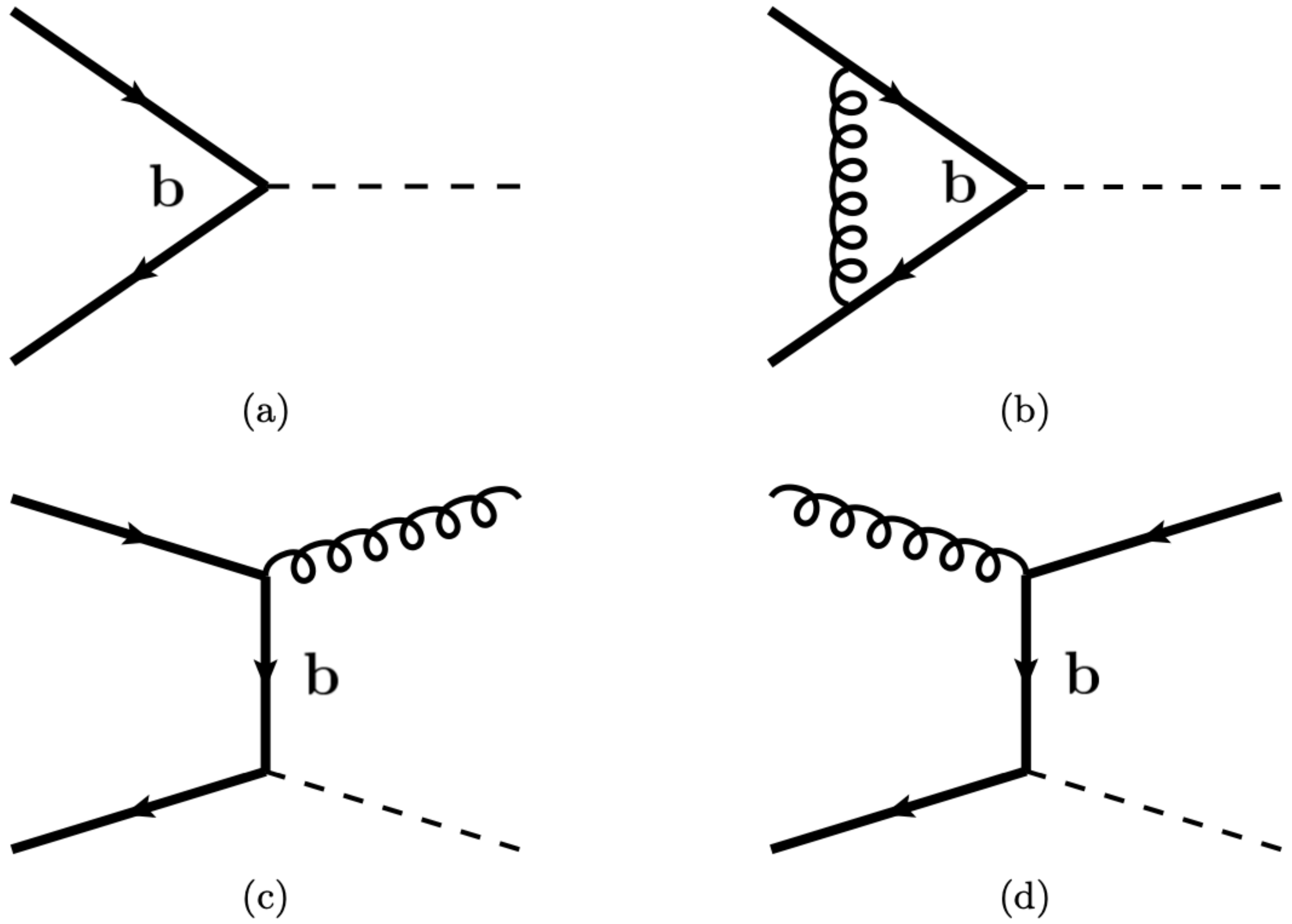


Figure 4: A sample of Feynman diagrams for $b\bar{b}H$ production in the five-flavour scheme: (a) LO; (b) one-loop; (c-d) real emission.