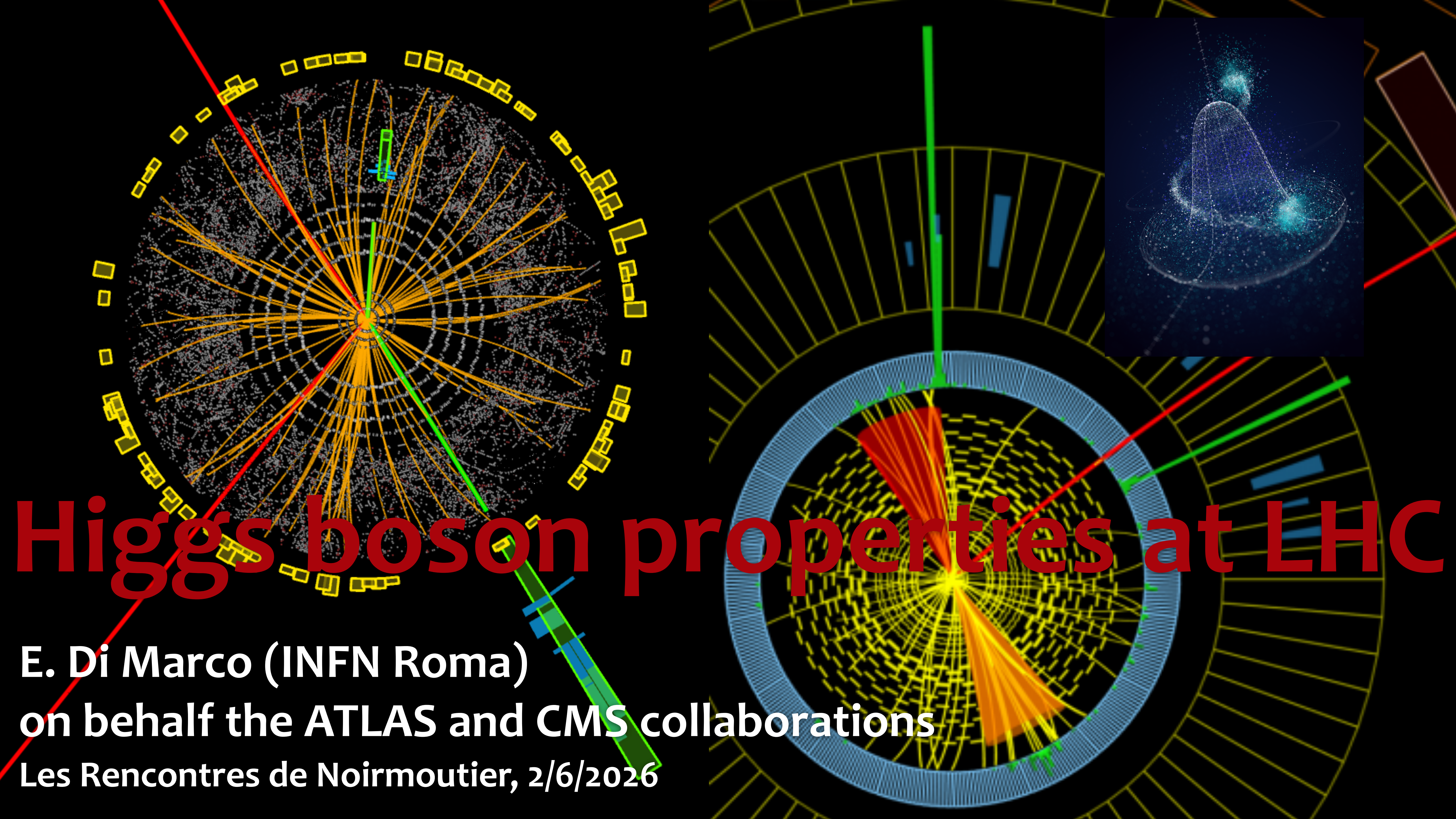




Higgs boson properties at LHC

E. Di Marco (INFN Roma)
on behalf the ATLAS and CMS collaborations
Les Rencontres de Noirmoutier, 2/6/2026

The Higgs in the Standard Model

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Electroweak (3 pars.) and QCD sector (1 pars.)

$$+ |D_{\mu}\Phi|^2$$

Gauge interactions (0 pars.)

$$- V(\Phi)$$

Higgs potential (2 pars.)

$$+ \psi_i y_{ij} \psi_j \Phi$$

Yukawa interactions (fermion masses => proton, neutron masses), CKM matrix and CP violation (13 pars.: $6 \times m_q + 3 \times m_{\ell} + 4 \times \theta_{CKM}$)

Out of 19 free parameters in the Standard Model Lagrangian, 15 are in the scalar sector

Higgs mass, Higgs self-couplings,
fermion masses, CKM parameters

1/2 of the SM Lagrangian is about Higgs!

The Higgs potential

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

Expanding around **potential minimum (SM)**:

$$V(H) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$

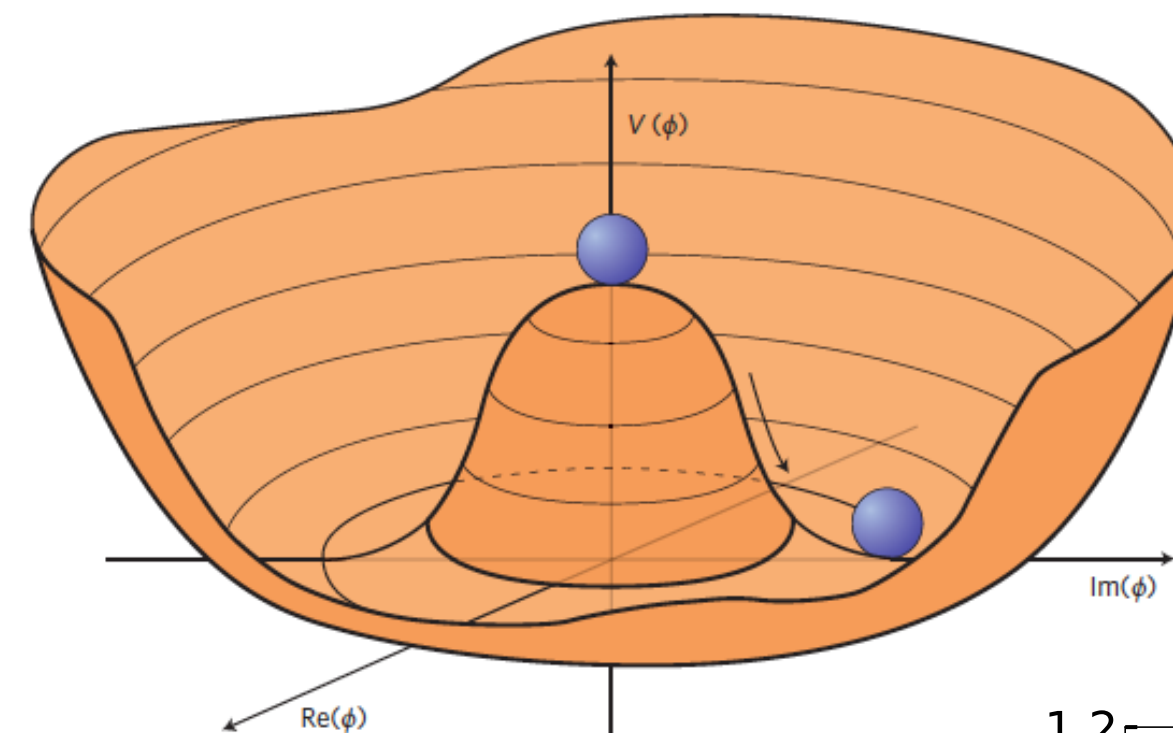
- **3 parameters:** v , m_H , λ $v = \left(\frac{1}{\sqrt{2} G_F} \right)^{1/2}$: vacuum exp. value

- Relationships between them are fixed in the SM:

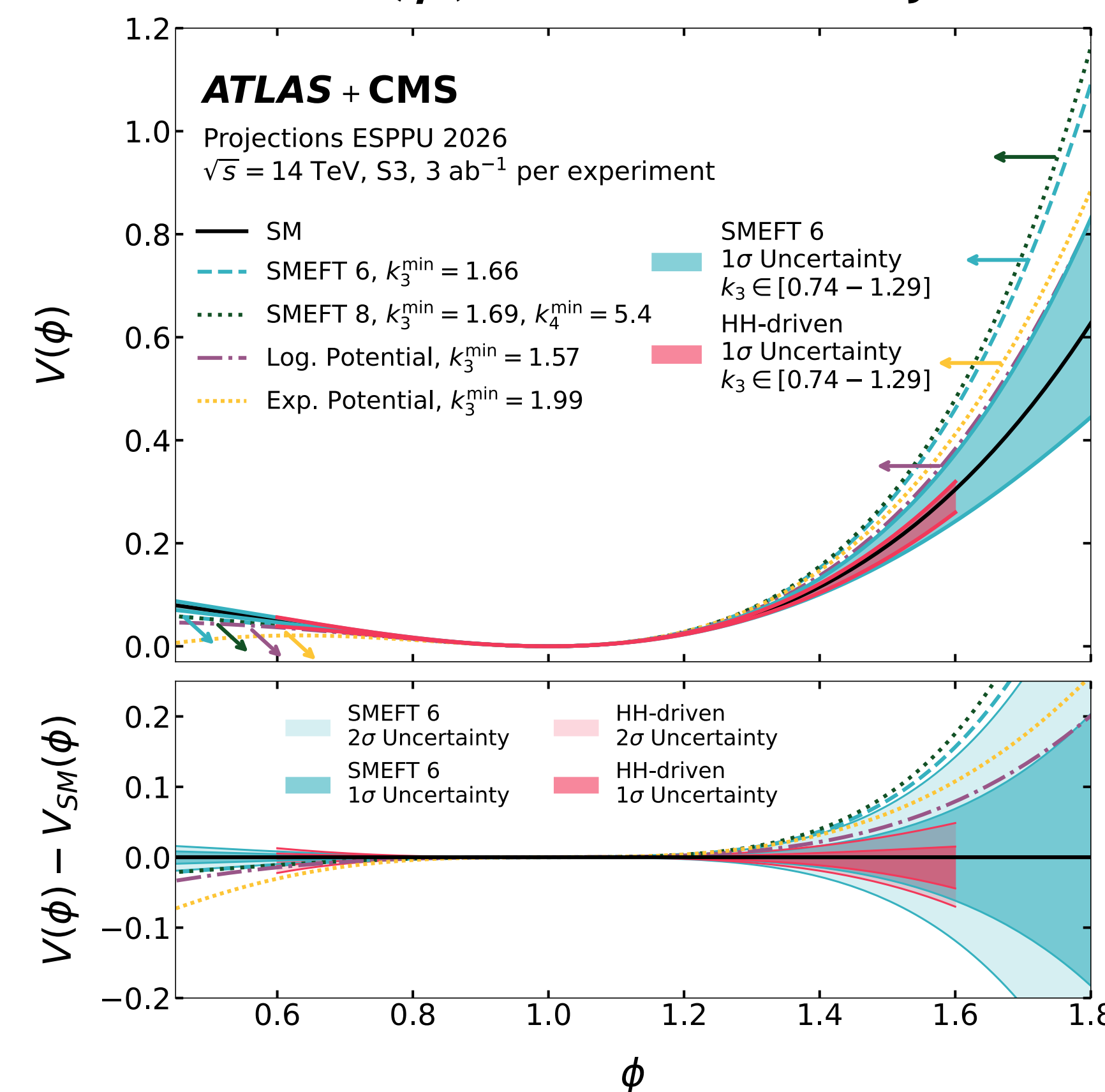
$$\lambda = \frac{m_H^2}{2v^2}$$

- Characterizing the Higgs potential means measuring the **H boson mass** (μ) and the strength of **its self coupling** (λ)

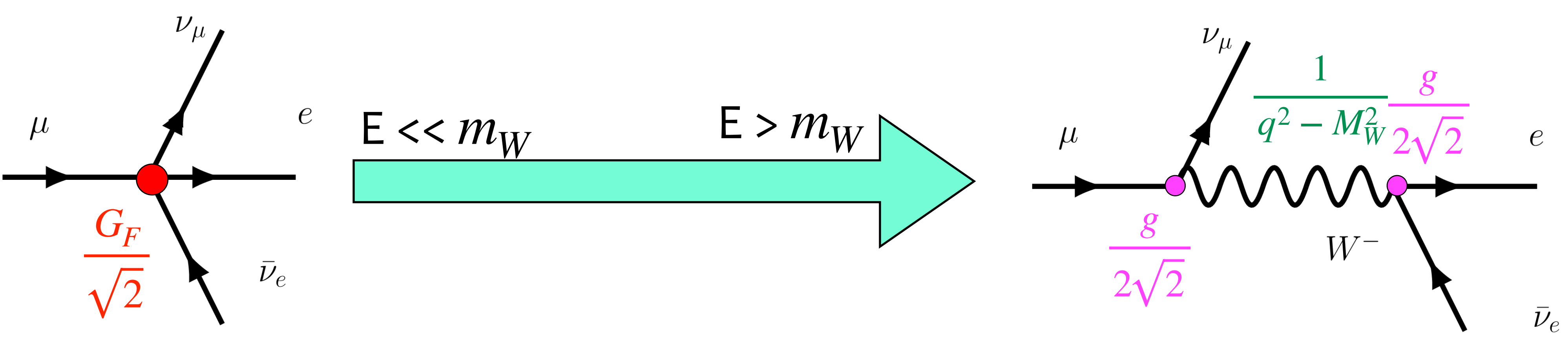
Test of the SM!



$V(\phi)$ in SM and beyond



Low energy measurements (muon decay lifetime) determine the **vacuum expectation value v** of the SM

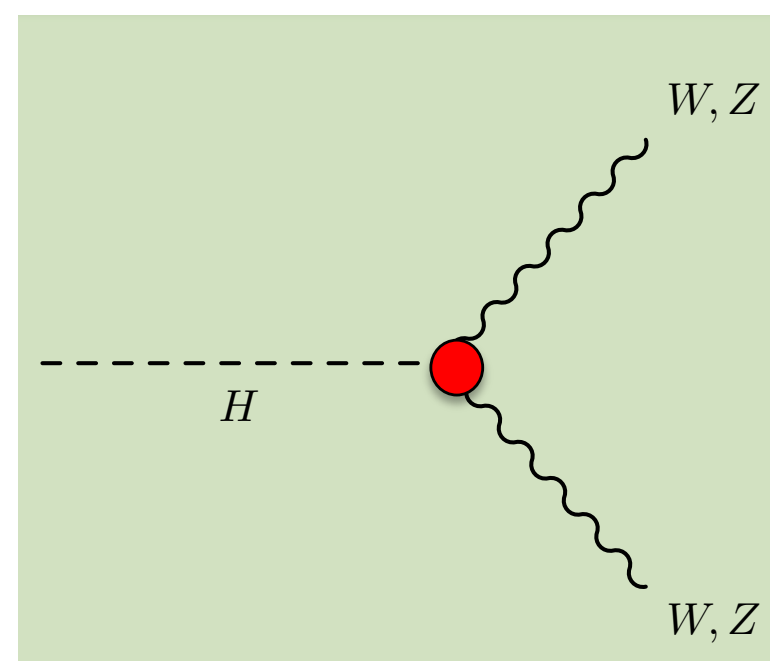


$$\frac{G_F}{\sqrt{2}} = \left[\frac{g}{2\sqrt{2}} \right]^2 \frac{1}{M_W^2} = \frac{g^2}{8M_W^2} = \frac{g^2}{8(gv/2)^2} = \frac{1}{2v^2}$$

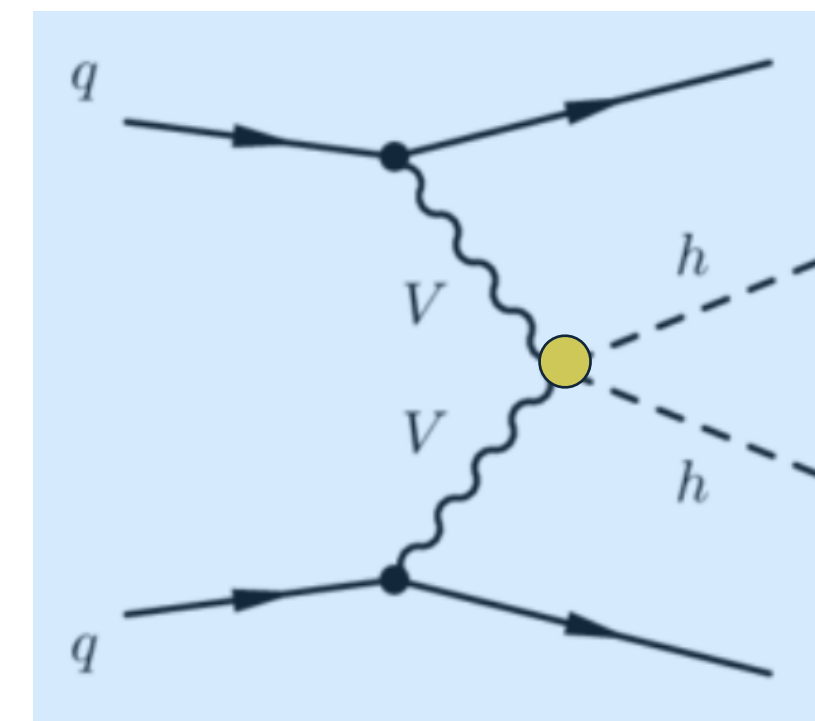
$$\frac{1}{\tau_\mu} = \Gamma_\mu \propto \frac{m_\mu^5}{v^4} \quad \longrightarrow \quad m_H \text{ remains the only free parameter of the SM !}$$

$|D_\mu \Phi|^2$: minimal gauge invariant couplings

The SM determines the relationships between masses and gauge couplings:



$$g_{HVV} \propto \frac{M_V^2}{v}$$



$$g_{HHVV} \propto \frac{M_V^2}{v^2}$$

Crucial test of the SM paradigm:

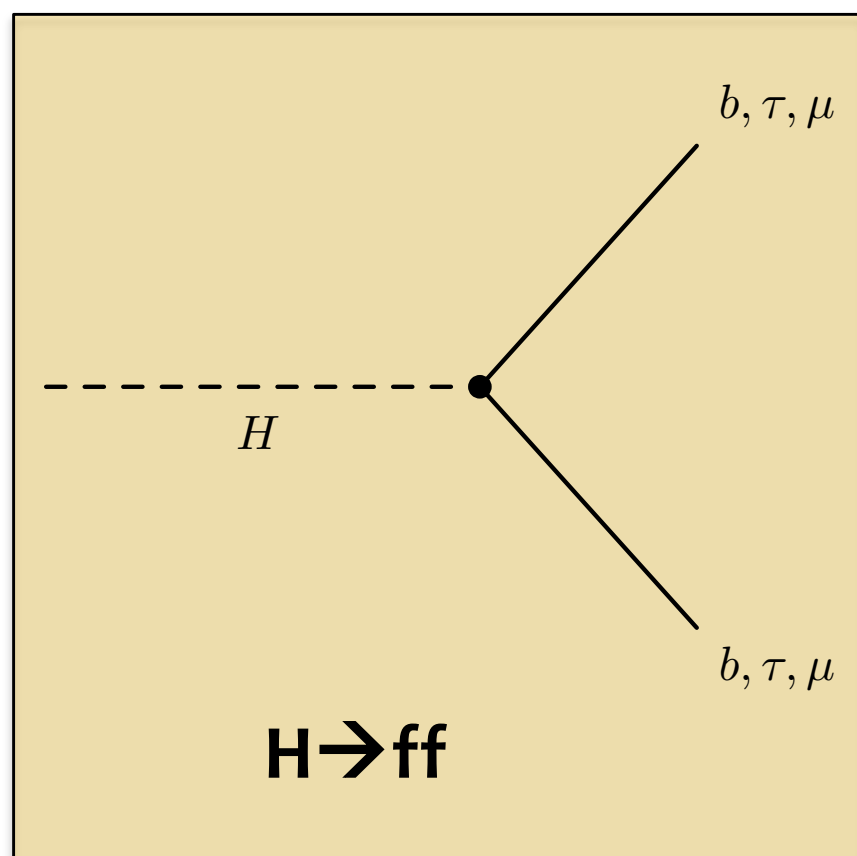
Consistency of these predictions at a quantum level **with a scalar field ϕ** :

- loop effects in W and Z propagators
- Unitarity preservation in $VV \rightarrow VV$ scattering

=> direct measurement of the Higgs couplings to W and Z

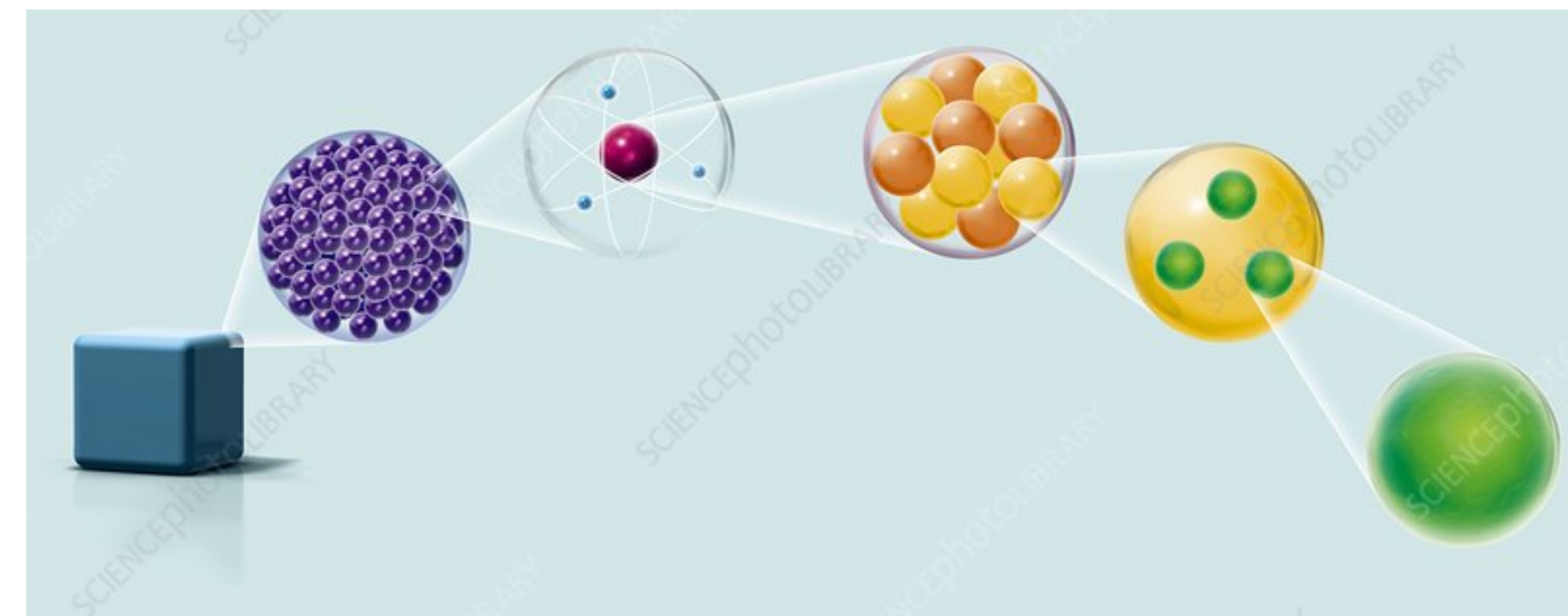
$$L_{Yuk} = y_{ij} \bar{\psi}_L^i \psi_R^j \phi$$

, with $\phi \rightarrow H + \nu$



Yukawa
Higgs couplings

$$y_{i,j} \propto \frac{m_f}{v} \delta_{ij}$$



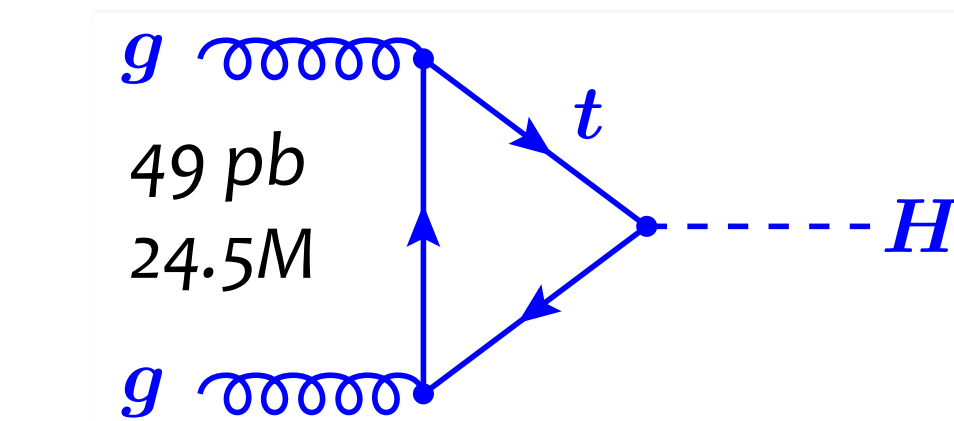
Fermion masses
(i.e. masses of matter particles)

The **Yukawa part** of the SM Lagrangian determines the mass of the quarks and leptons

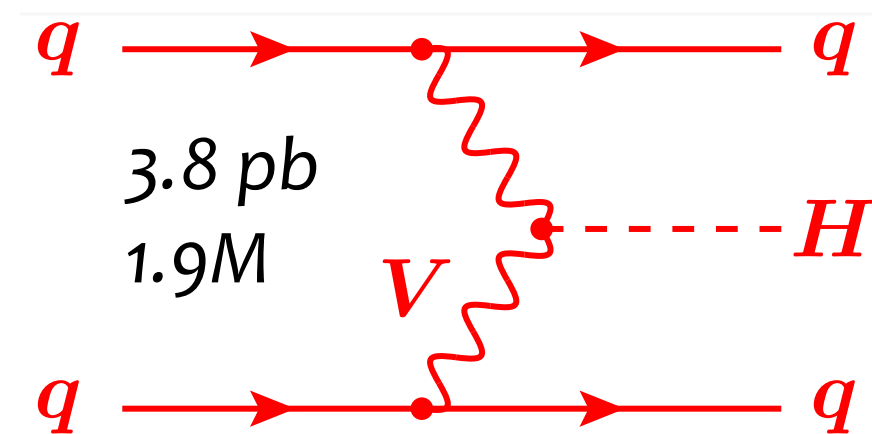
The SM though, **doesn't explain**:

- Why the **hierarchy of the fermion masses**
- Why the **hierarchy of the Yukawa couplings**
- The rotation between the mass and flavour states (**CKM matrix**)

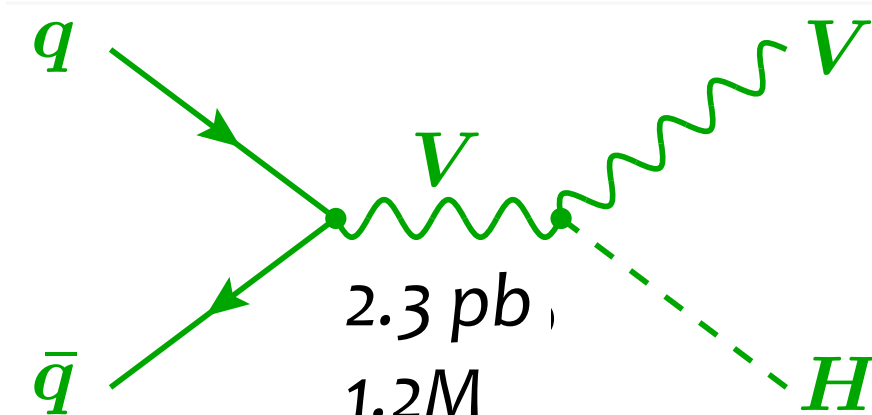
Higgs production at the LHC



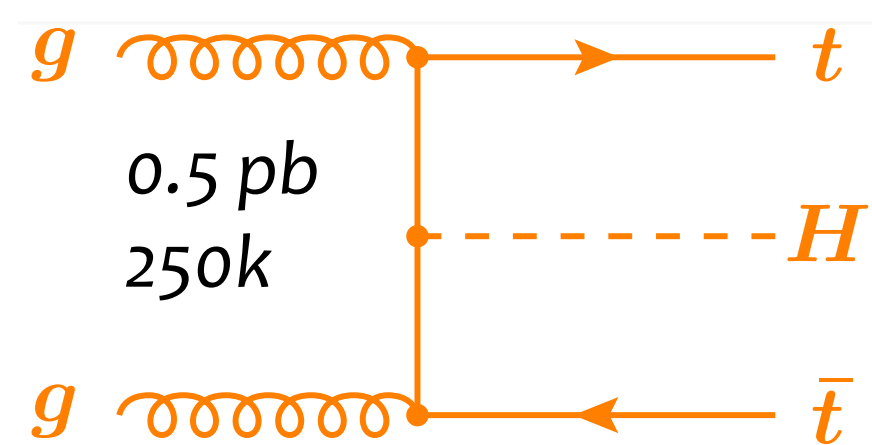
gluon fusion
ggH



vector boson
fusion (**VBF**)



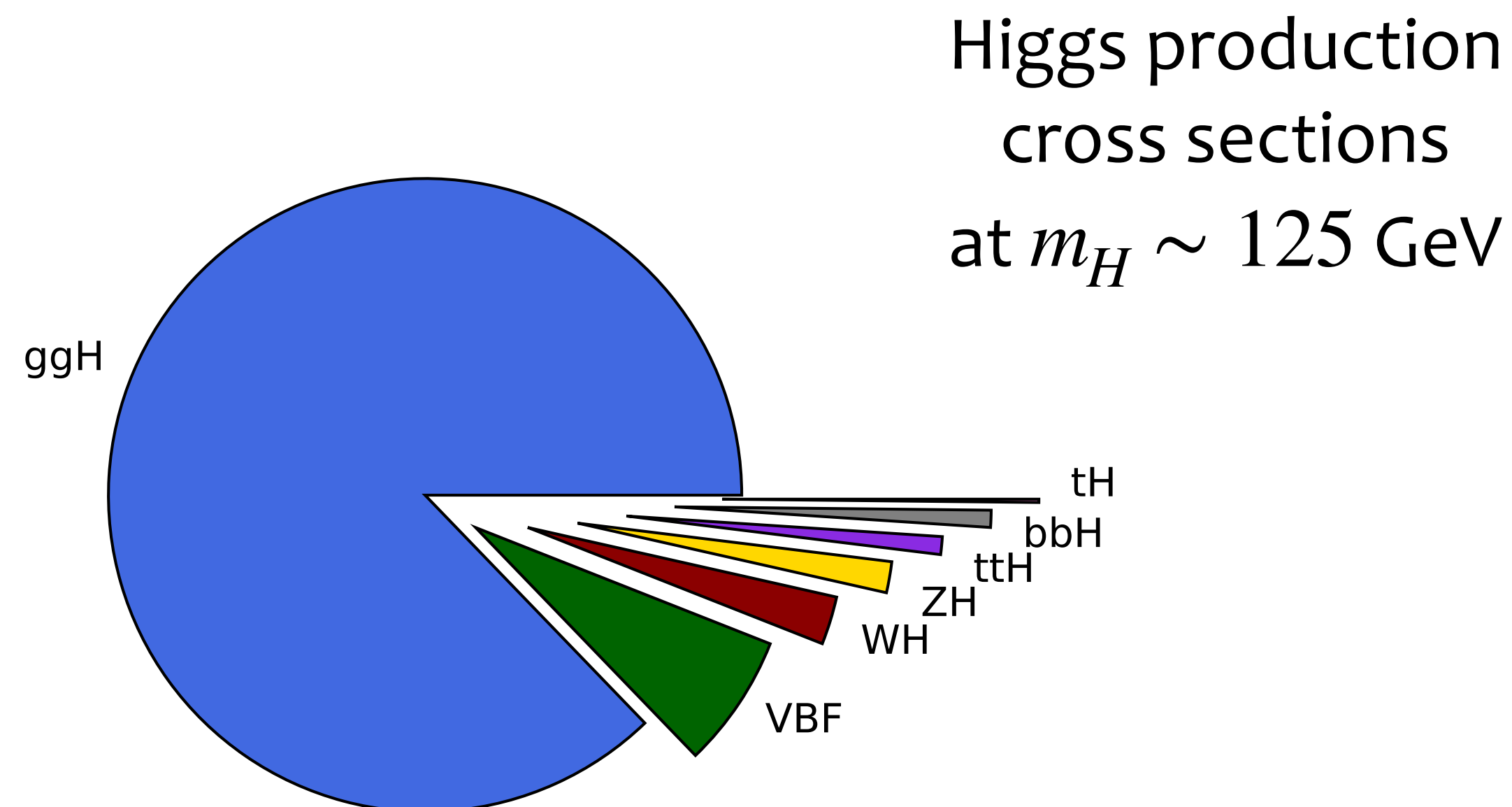
W,Z associated
production
WH/ZH



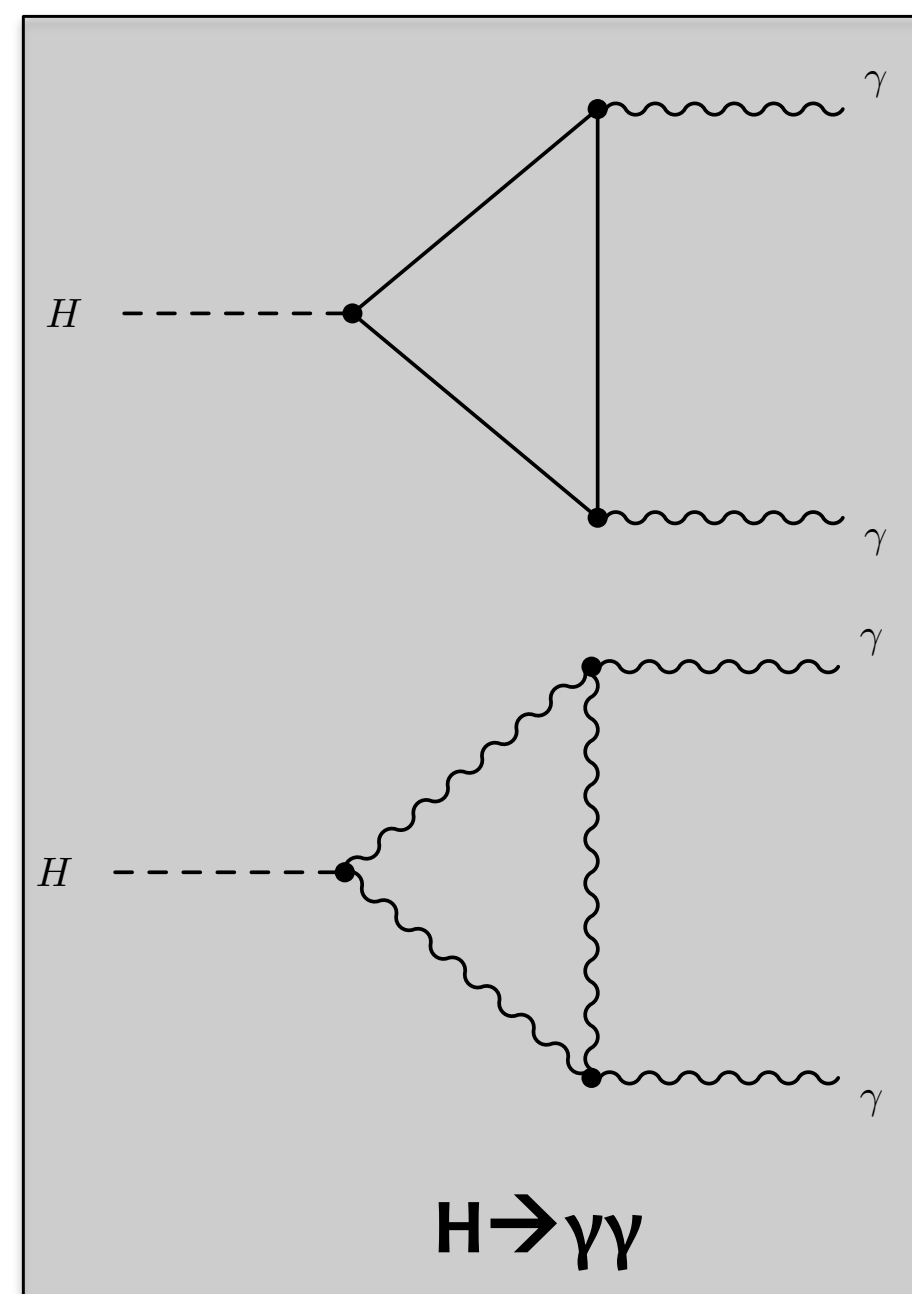
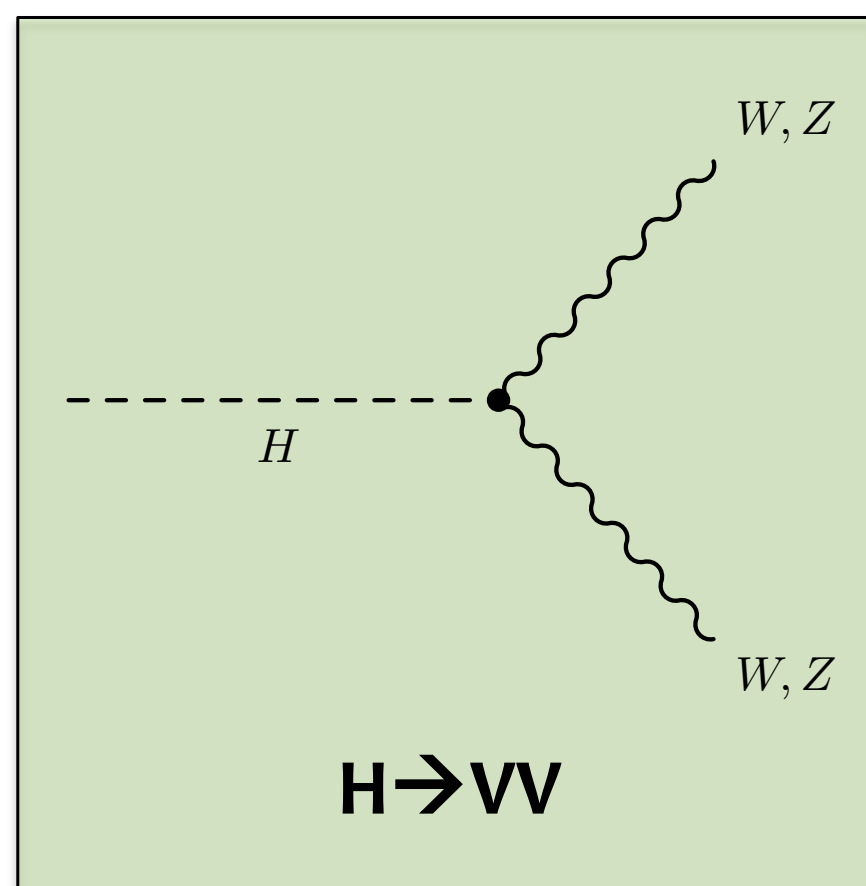
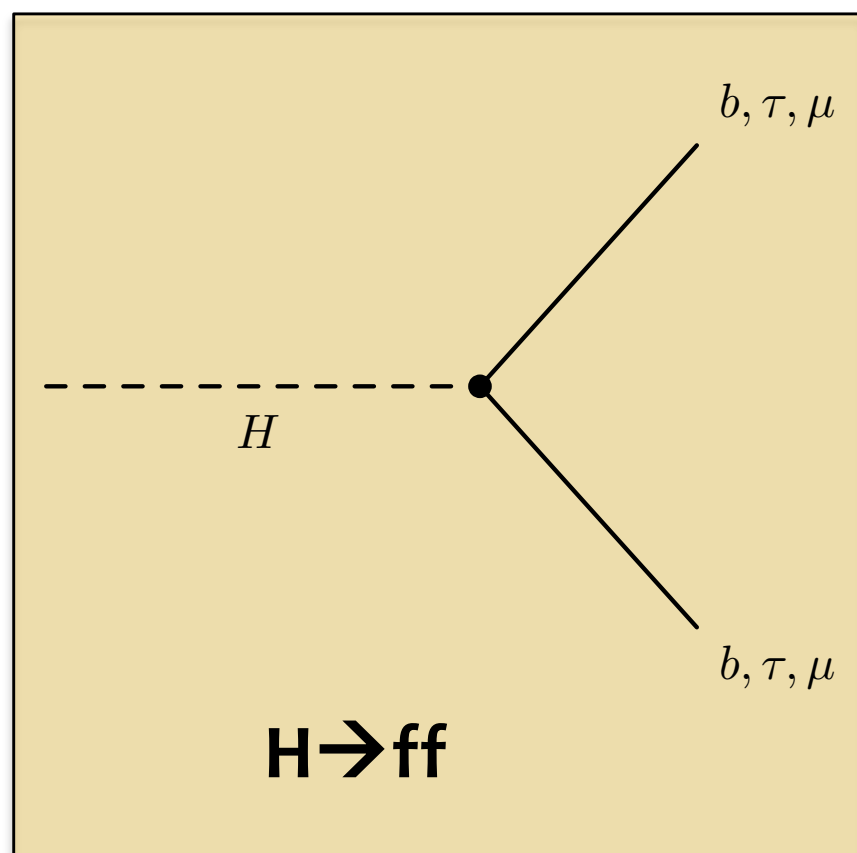
$t\bar{t}H$ associated
production

σ [pb]
Higgs produced during
Run2 + Run3

- About **28 million Higgs bosons** produced by LHC during Run2 + Run3
- For $m_H \sim 125$ GeV a wide range of production and decay modes accessible
- Establishing each production mode and studying its properties

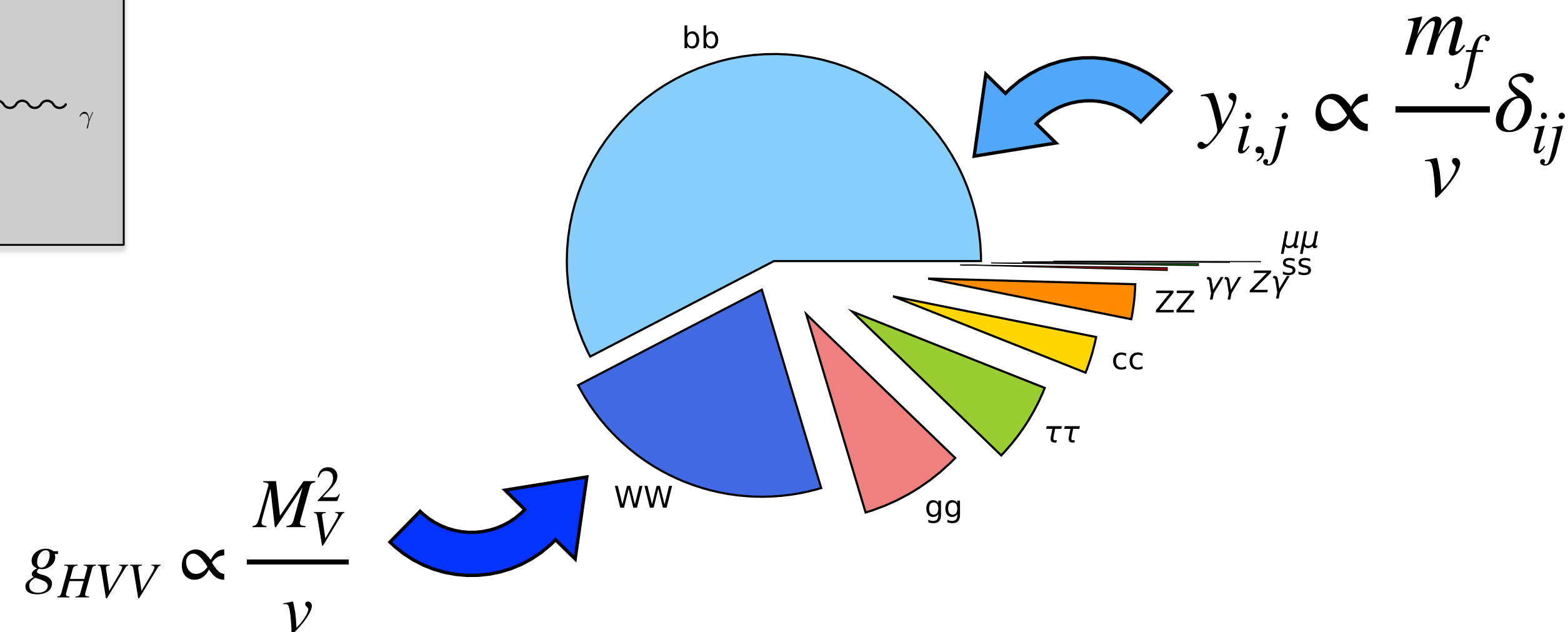


Higgs decays



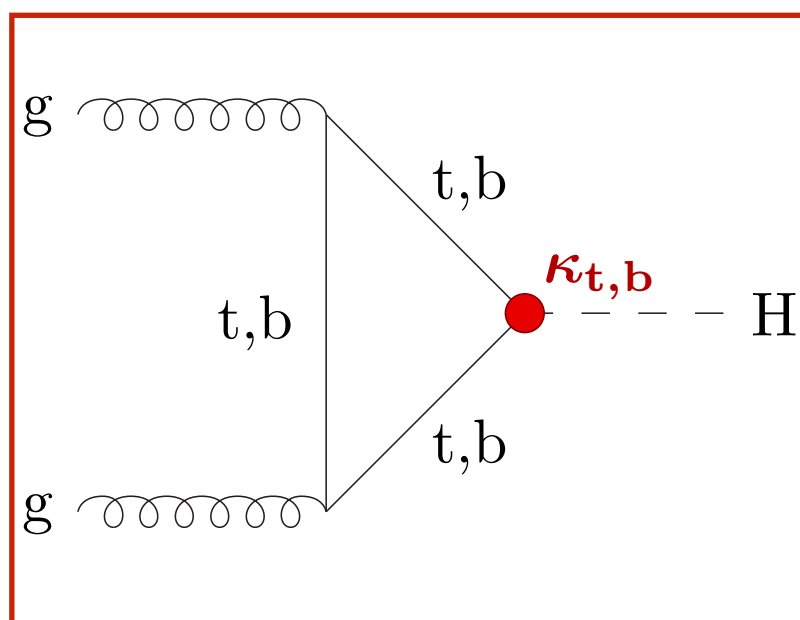
Decay channel	Branching fraction (%)	
bb	57.63	± 0.70
WW	22.00	± 0.33
gg	8.15	± 0.42
$\tau\tau$	6.21	± 0.09
cc	2.86	± 0.09
ZZ	2.71	± 0.04
$\gamma\gamma$	0.227	± 0.005
$Z\gamma$	0.157	± 0.009
ss	0.025	± 0.001
$\mu\mu$	0.0216	± 0.0004

$H \rightarrow b\bar{b}$ dominant,
but very challenging
at a hadron collider!

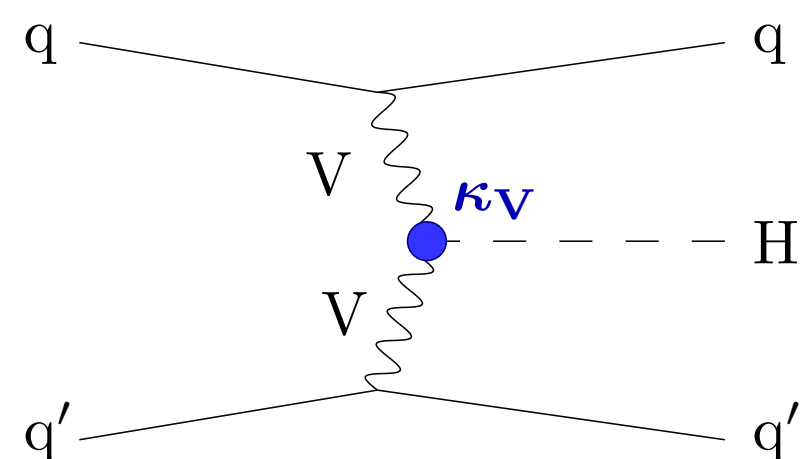


Higgs couplings in production and decay

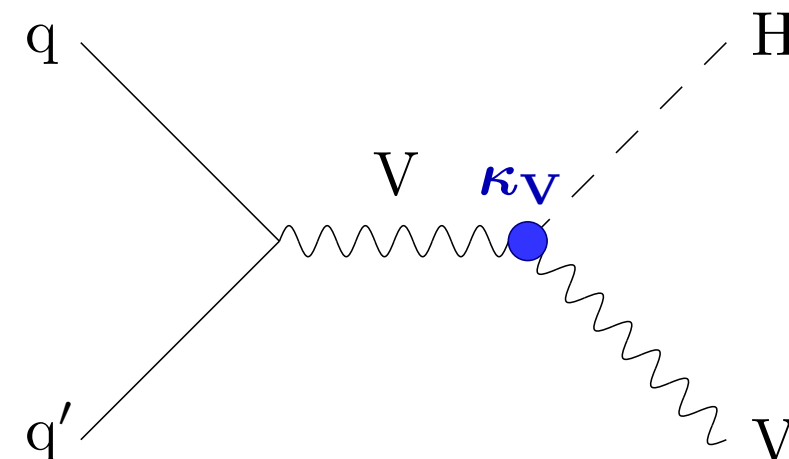
ggH



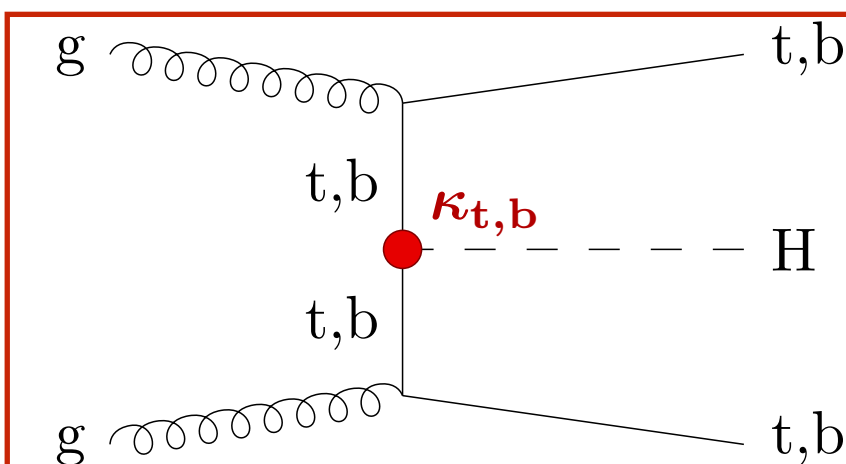
VBF



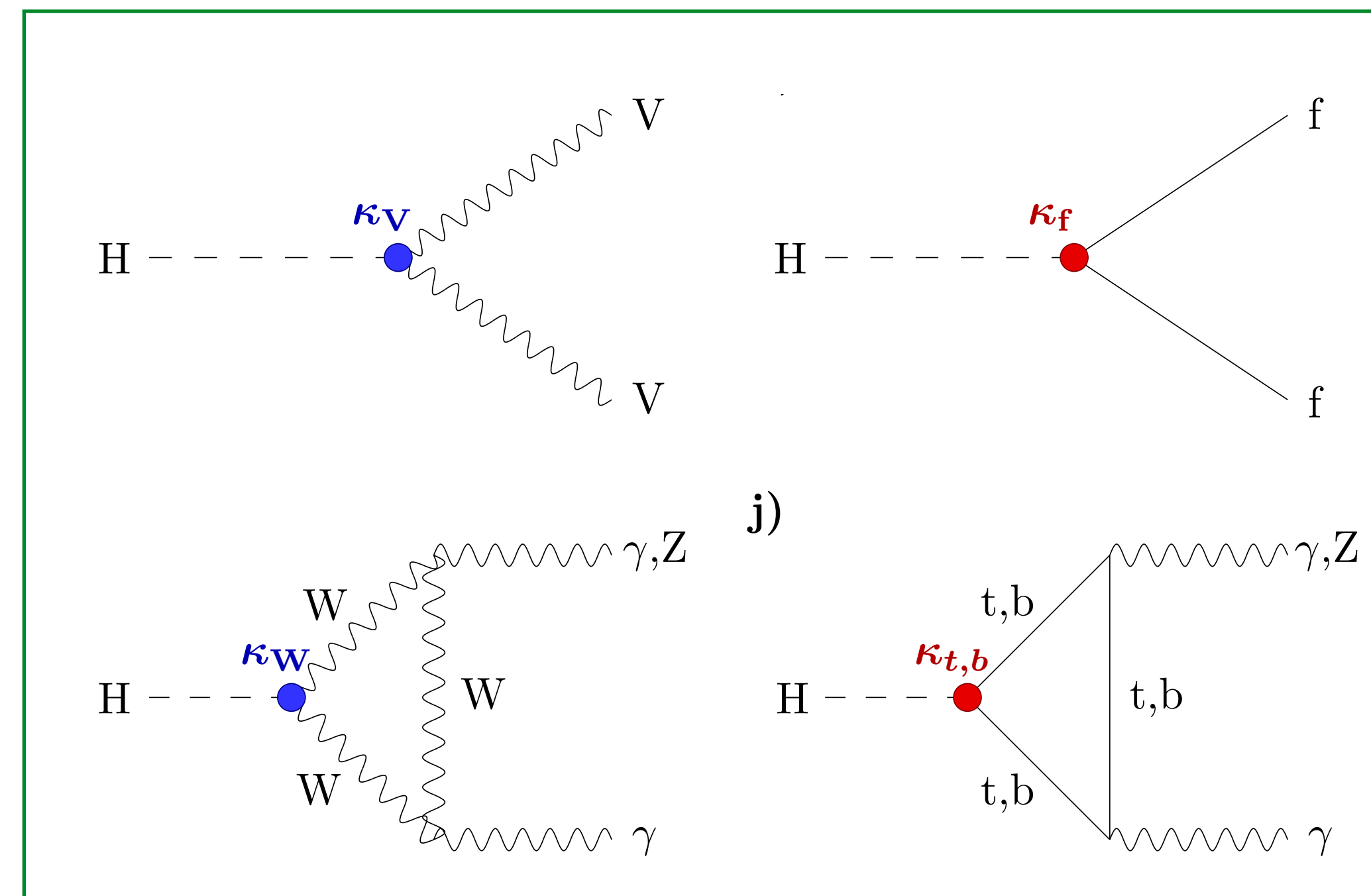
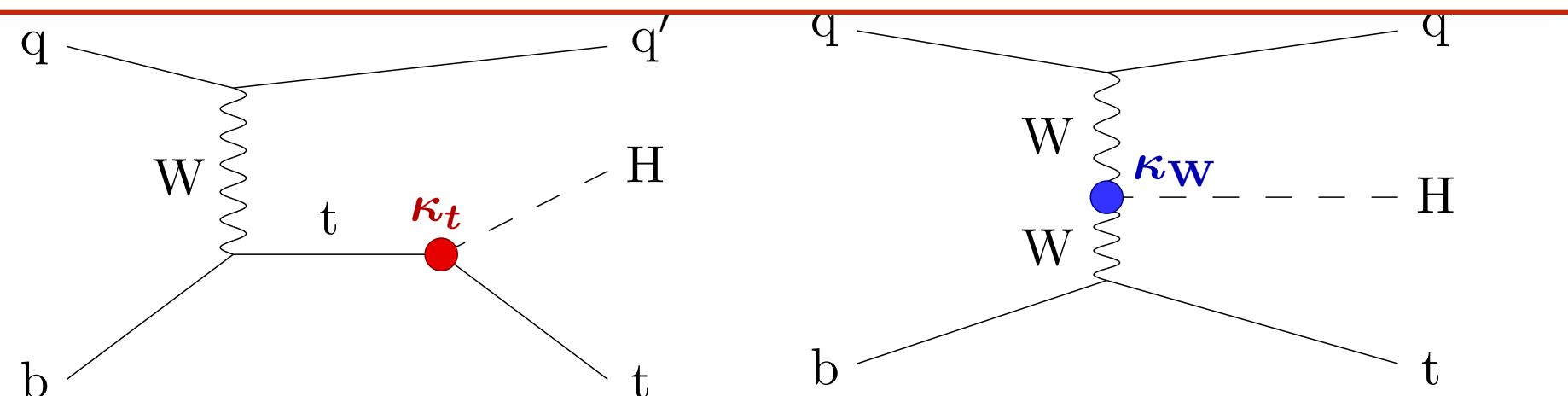
WH/ZH



ttH



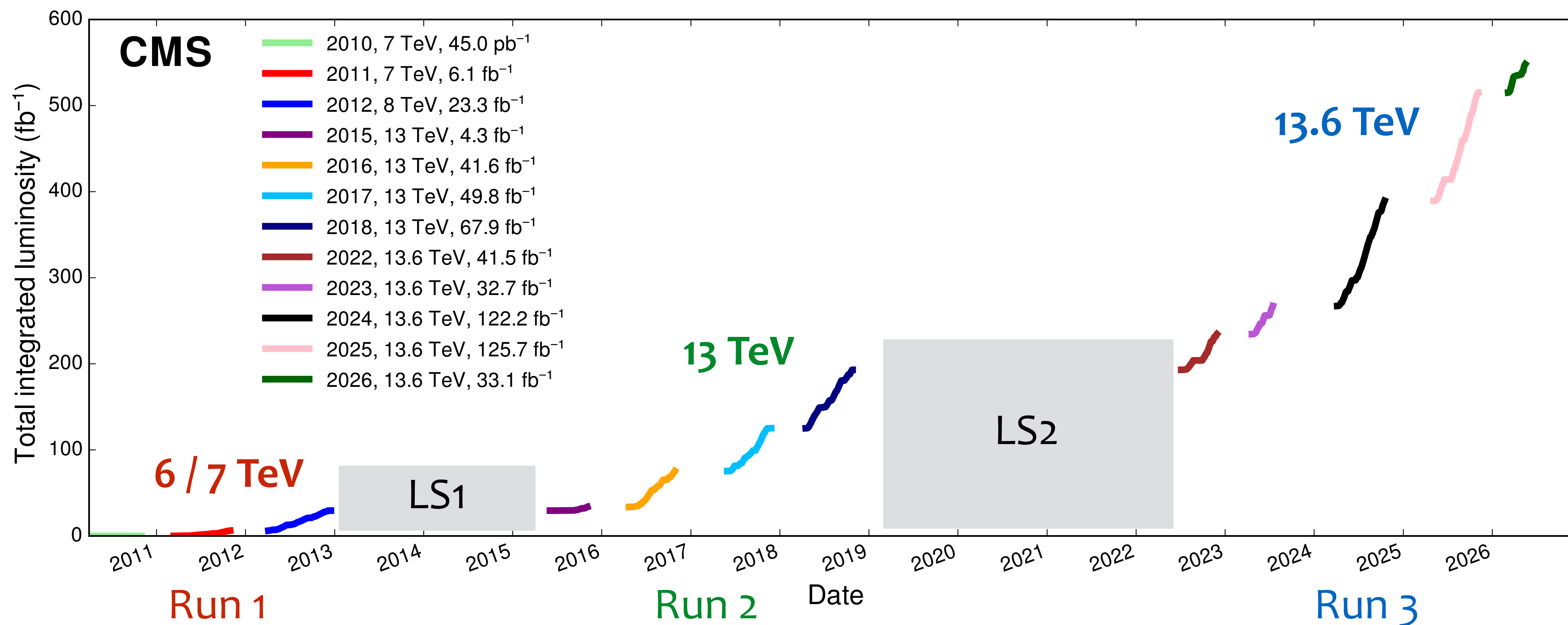
tHq



Each Higgs coupling appears in several production and decay modes

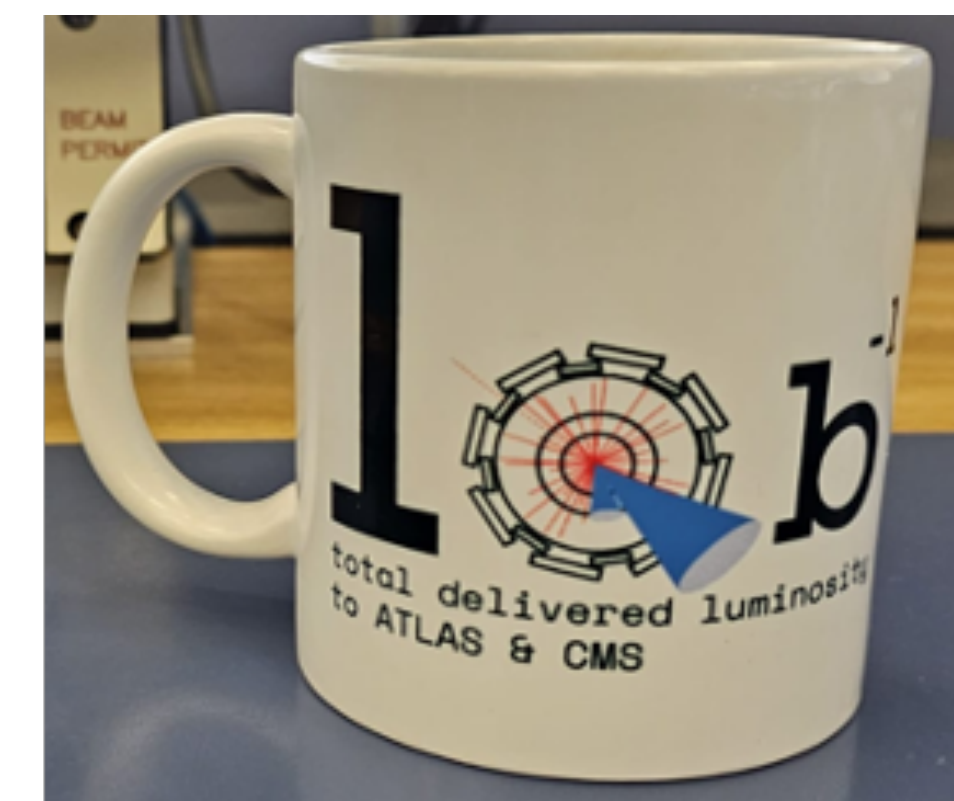
$\kappa_i = \frac{g_i}{g_i^{SM}}$: checking all $\kappa_i = 1$ allows over-constraint test of the SM Higgs

LHC from Run 1 to Run 3



$\approx 540 \text{ fb}^{-1}$

$\times 2$ (ATLAS+CMS)



Integrated luminosity $> 500 \text{ fb}^{-1}$ by now, means ~ 30 millions of Higgs bosons recorded by CMS (and the same quantity by ATLAS)

- **Run3** is $\sim$ **Run2** $\Rightarrow$ expect nice results from LHC phase1 dataset

Entering the attobarn era!

Higgs bosons in CMS



CMS Experiment at the LHC, CERN

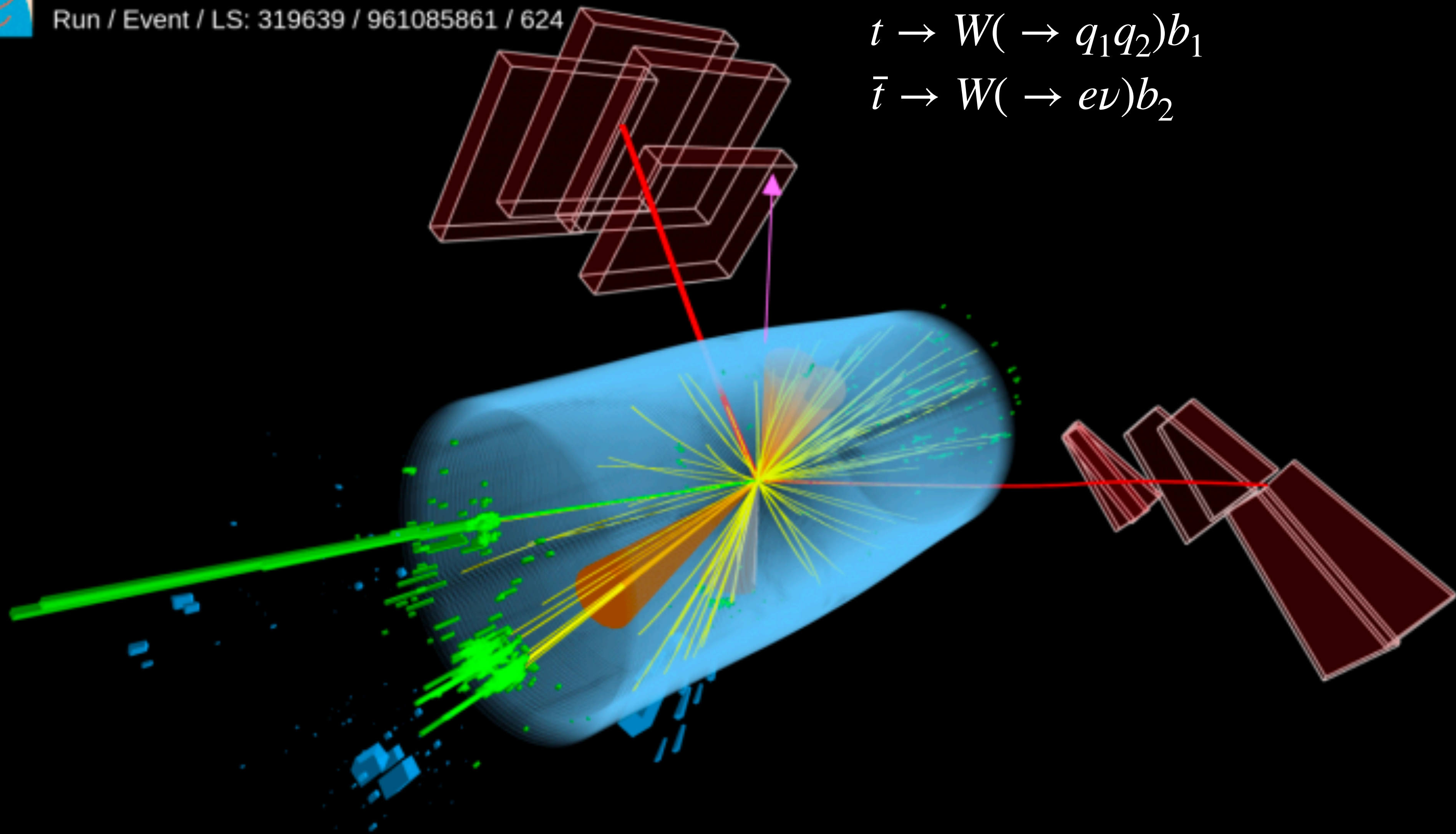
Data recorded: 2018-Jul-14 22:42:55.530432 GMT

Run / Event / LS: 319639 / 961085861 / 624

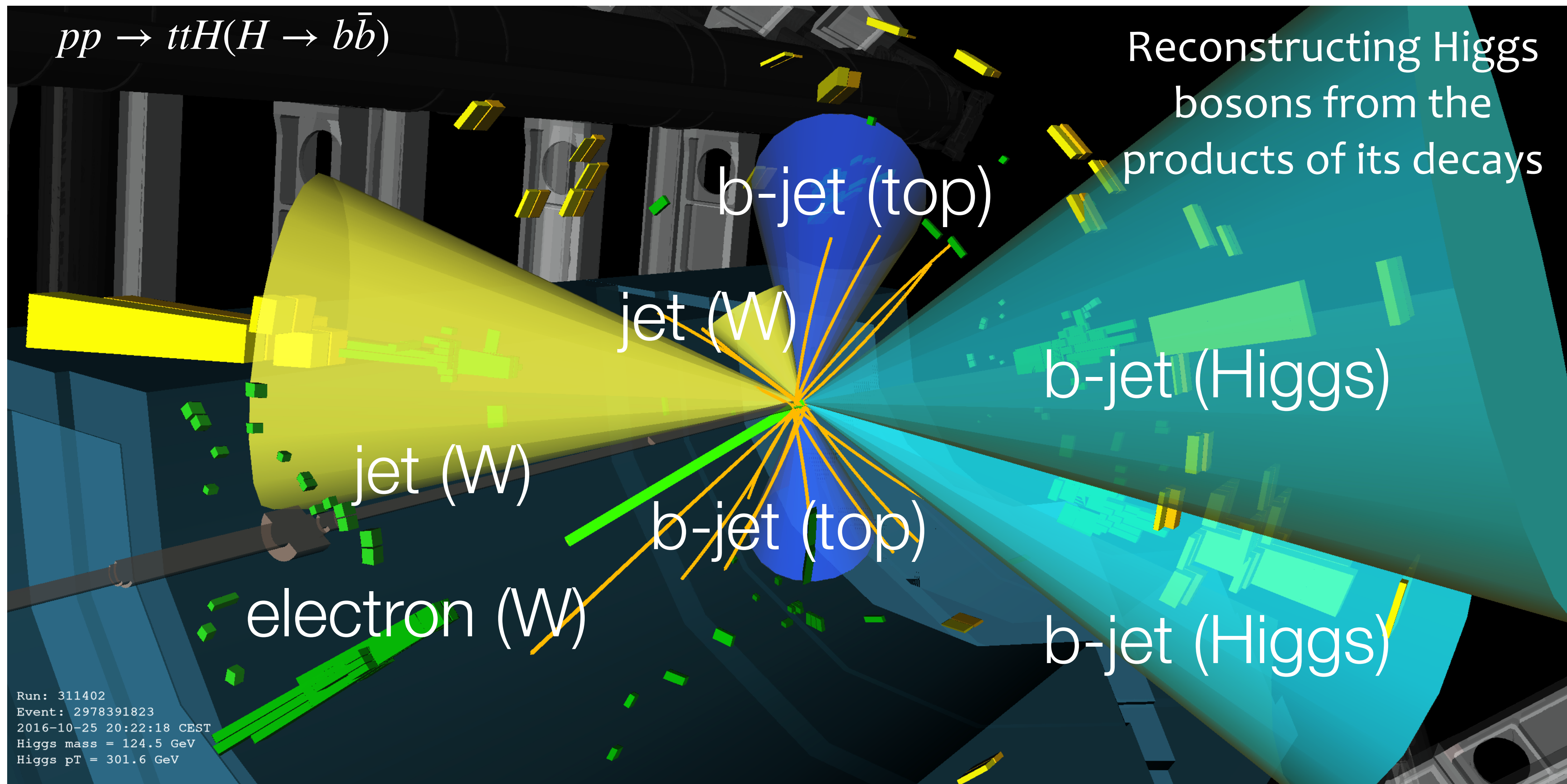
$pp \rightarrow t\bar{t}H(\rightarrow \mu\mu)$ candidate

$t \rightarrow W(\rightarrow q_1q_2)b_1$

$\bar{t} \rightarrow W(\rightarrow e\nu)b_2$



Zoom inside a Higgs event in ATLAS



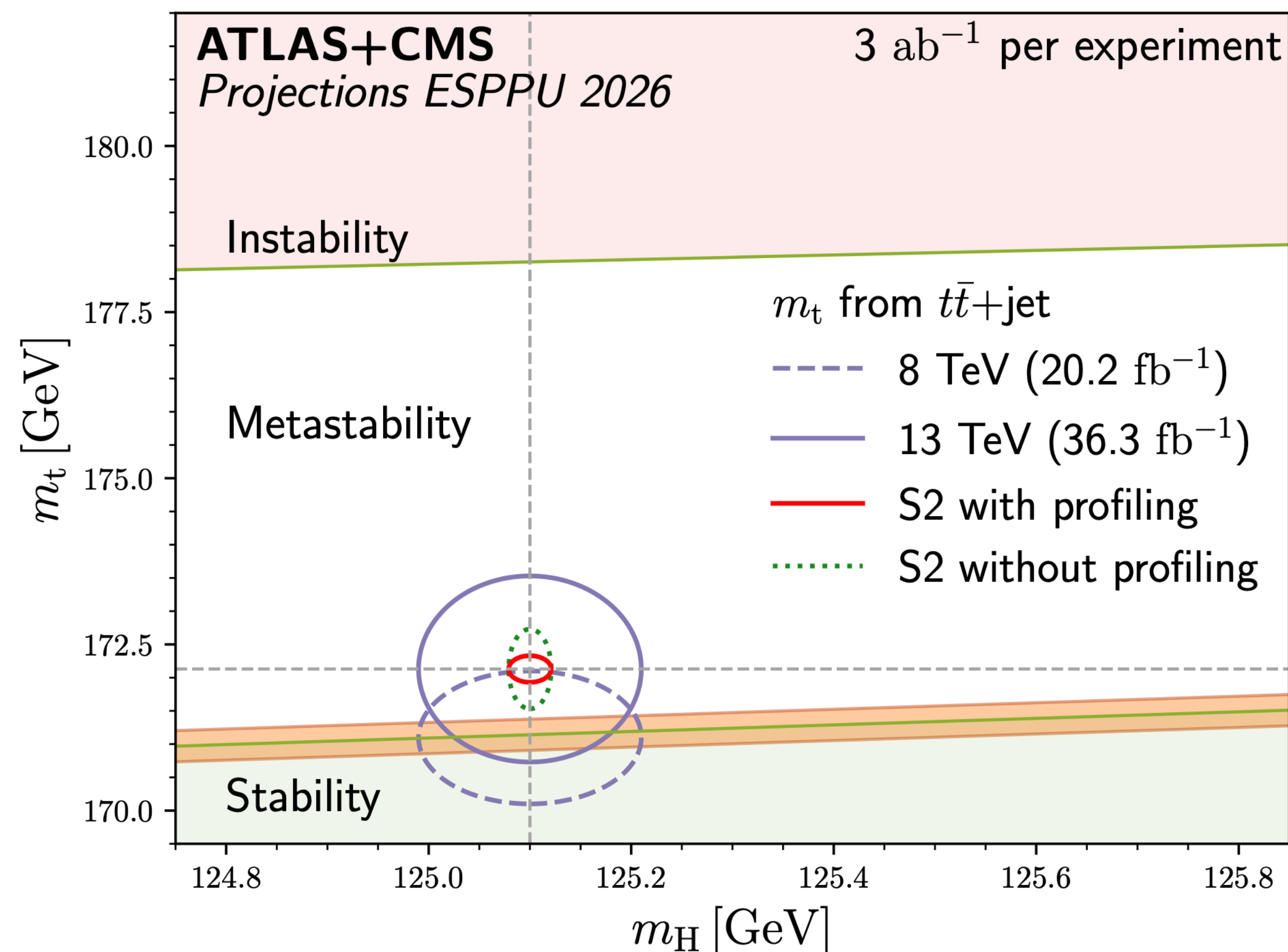
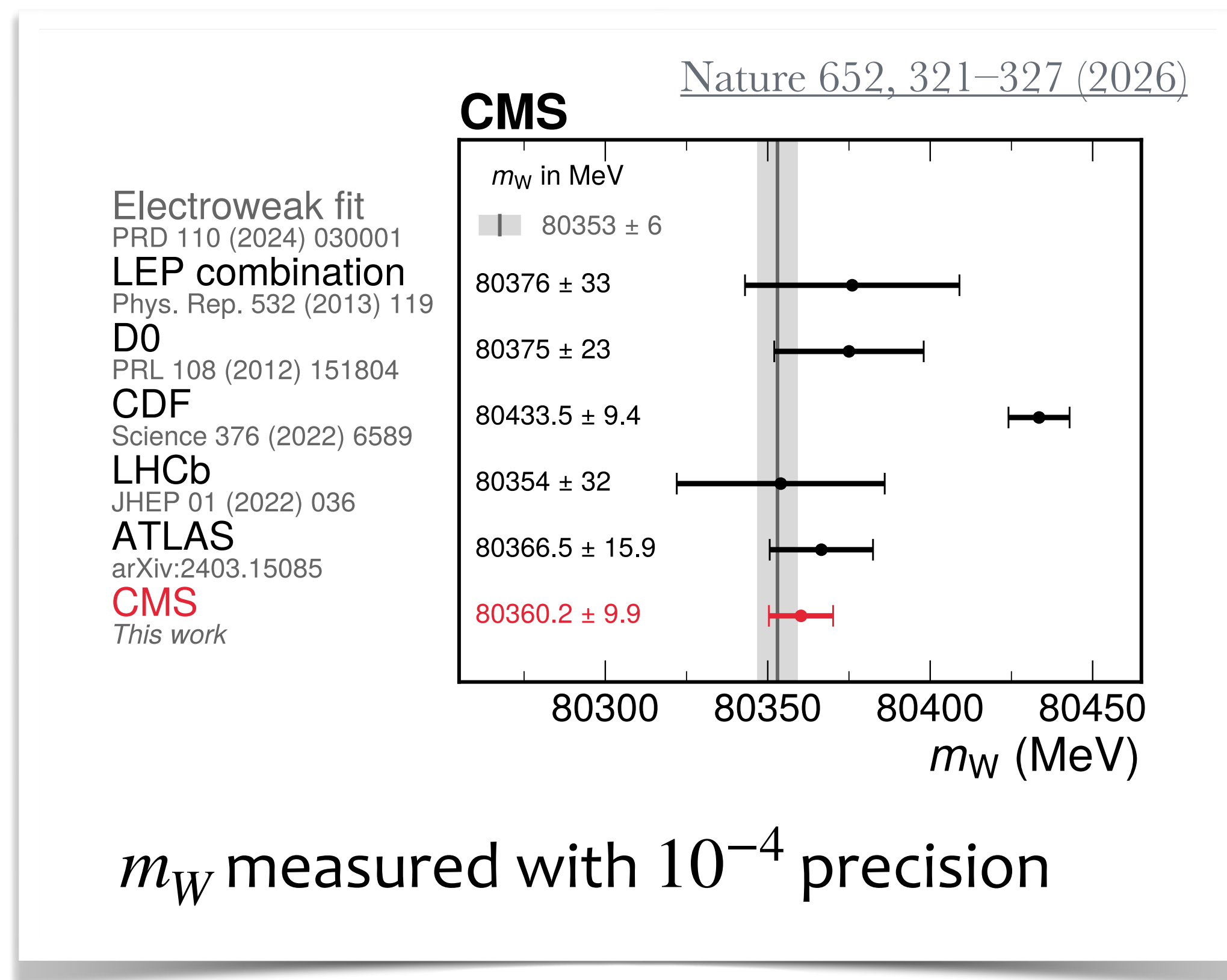
Why do we need the m_H measurement?

It's a parameter not predicted by the SM. Measuring it, allows predicting:

- all the other Higgs properties (cross sections, couplings)
- EWK observables (m_W , m_t , $\sin \theta_W$)

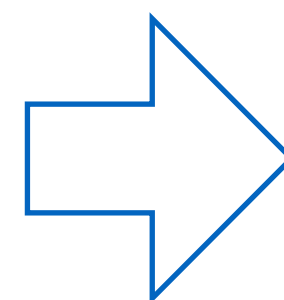
ATL-PHYS-PUB-2025-018

CMS-HIG-25-002

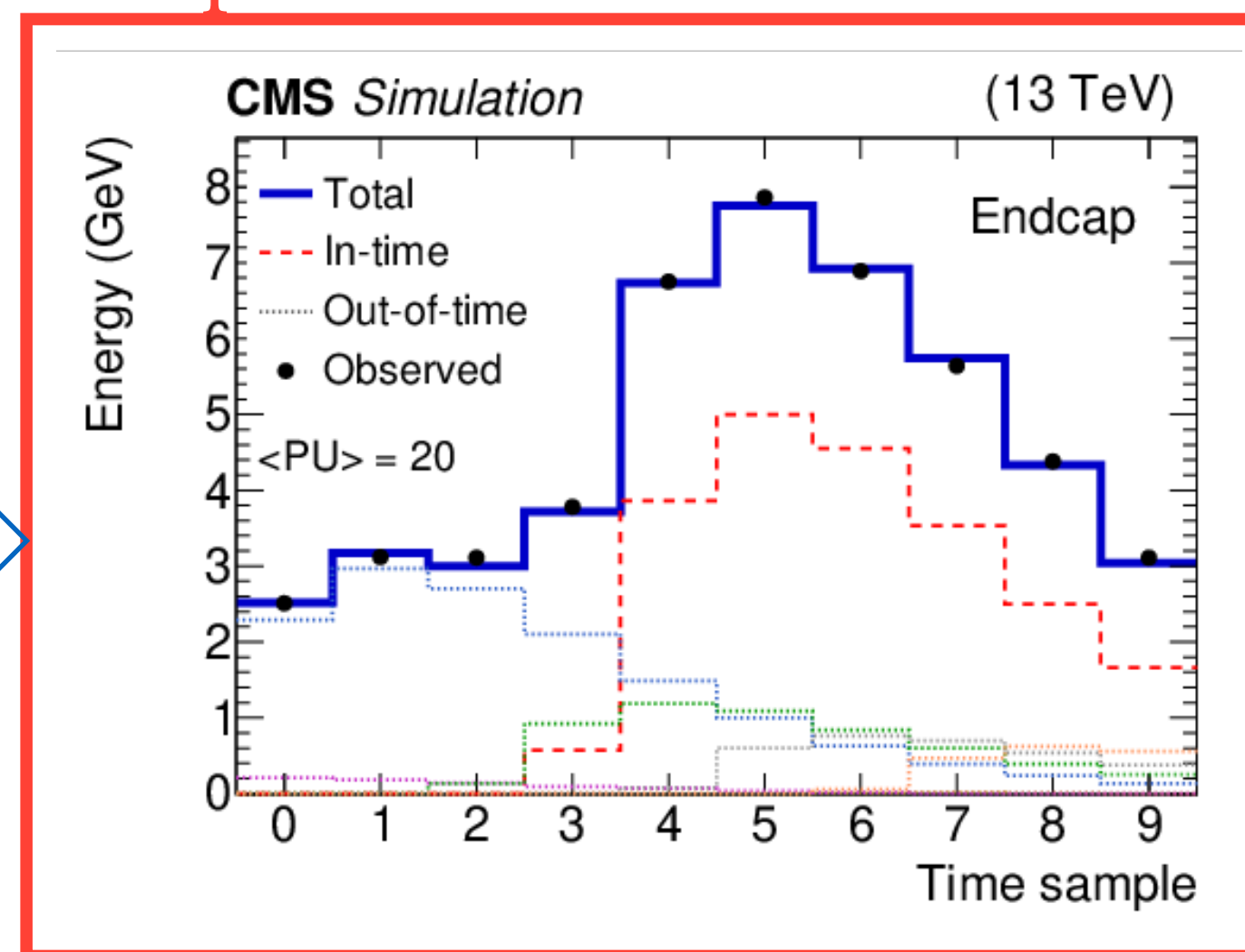


A precise m_H measurement, together with m_W and m_t is connected to the universe stability

Need an excellent ECAL



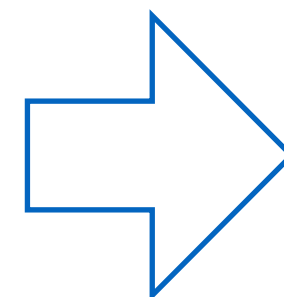
Amplitude fit



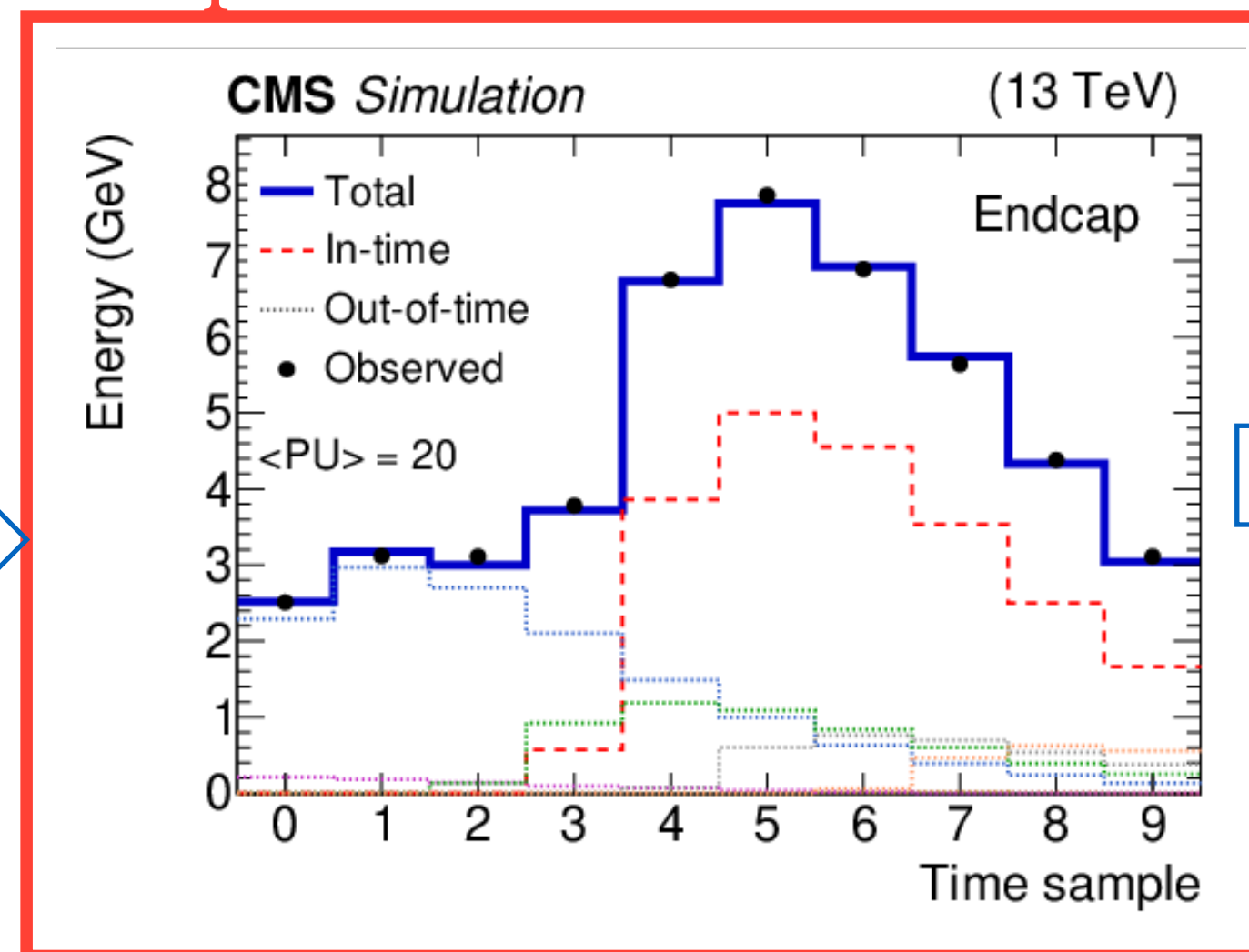
Single channel energy

How to measure the Higgs mass ($H \rightarrow \gamma\gamma$)

Need an excellent ECAL

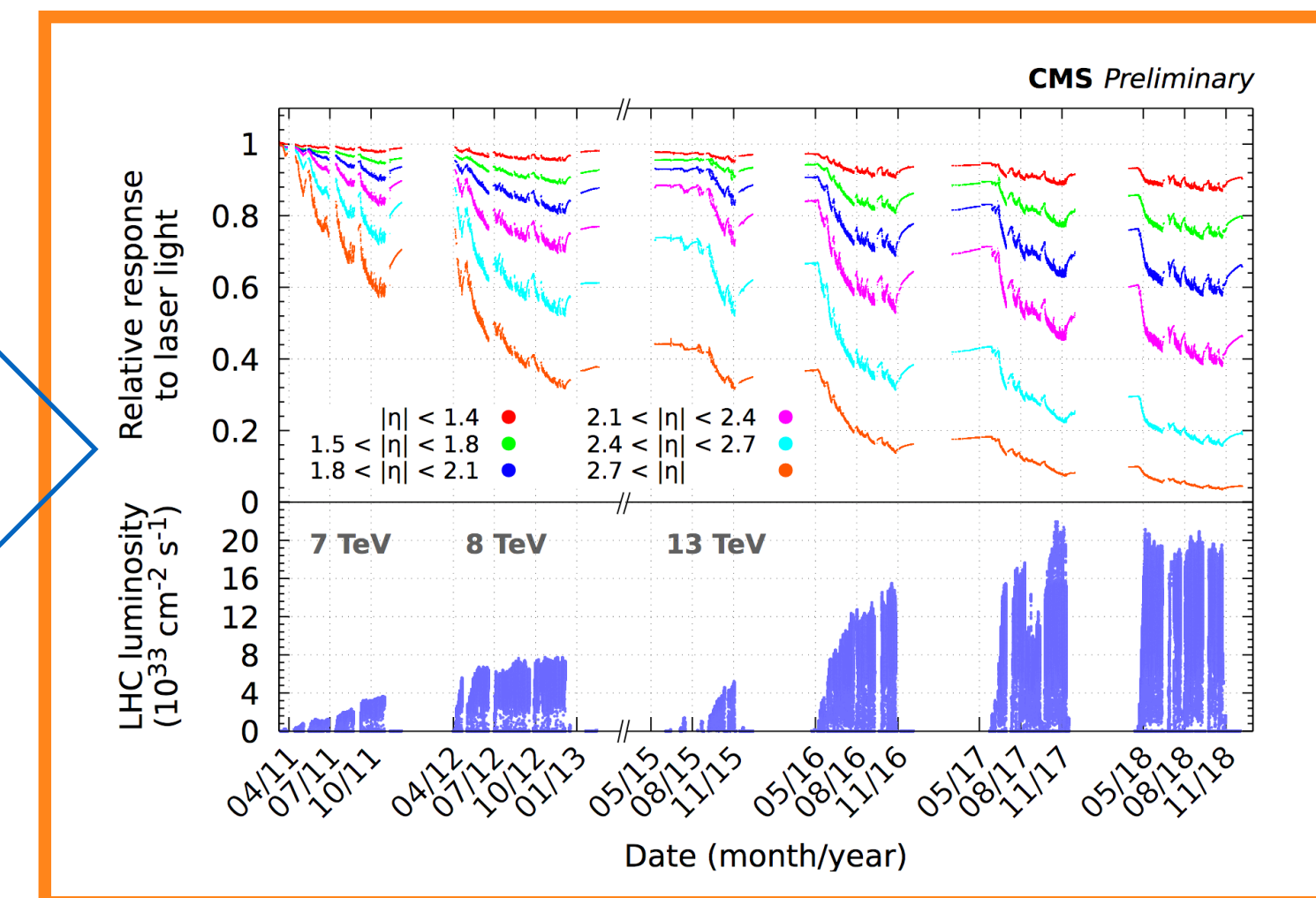


Amplitude fit



Single channel energy

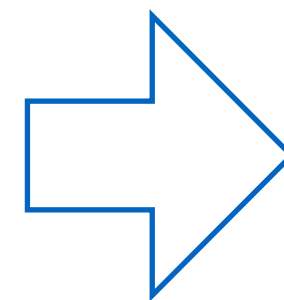
Laser correction



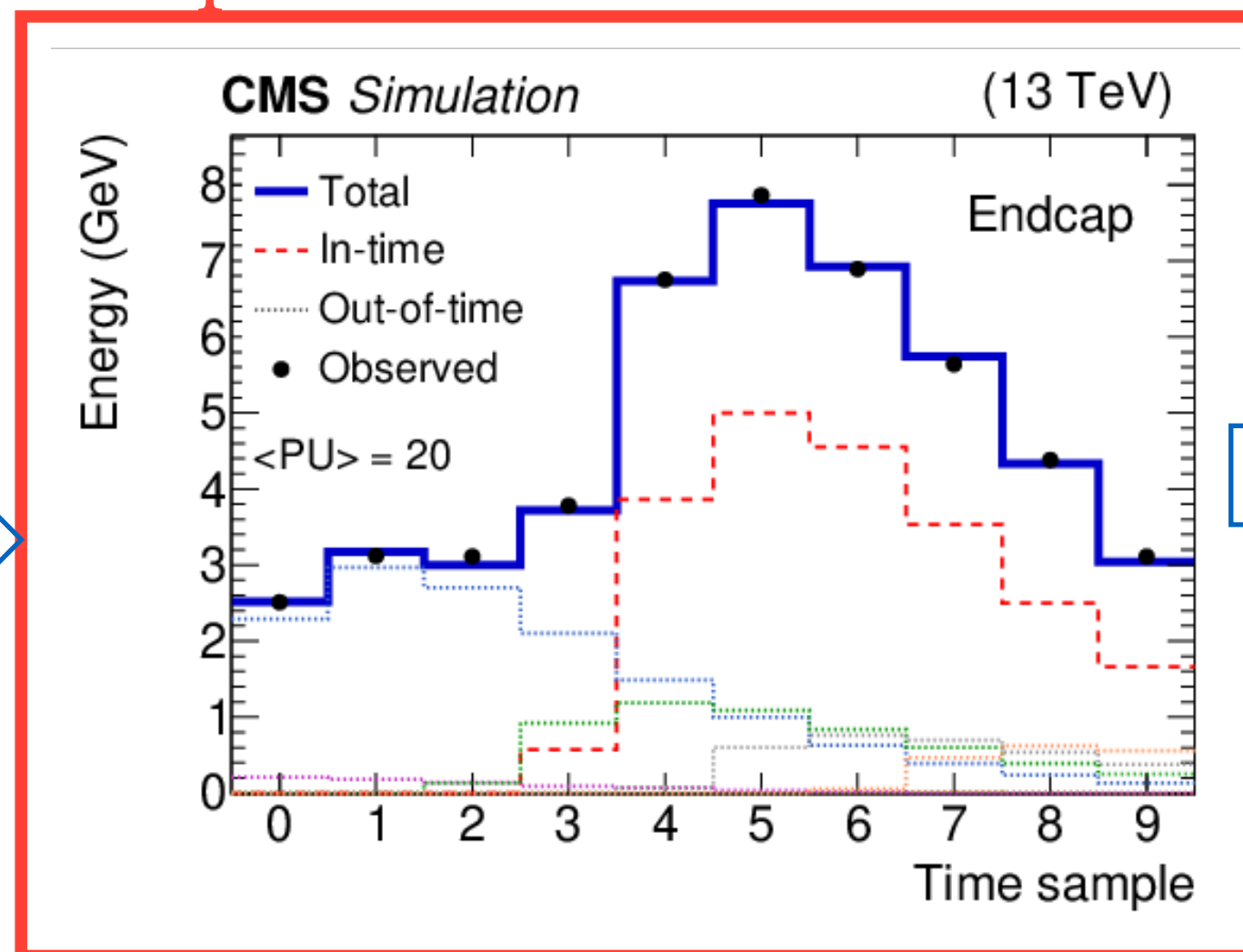
Detector response vs time

How to measure the Higgs mass ($H \rightarrow \gamma\gamma$)

Need an excellent ECAL

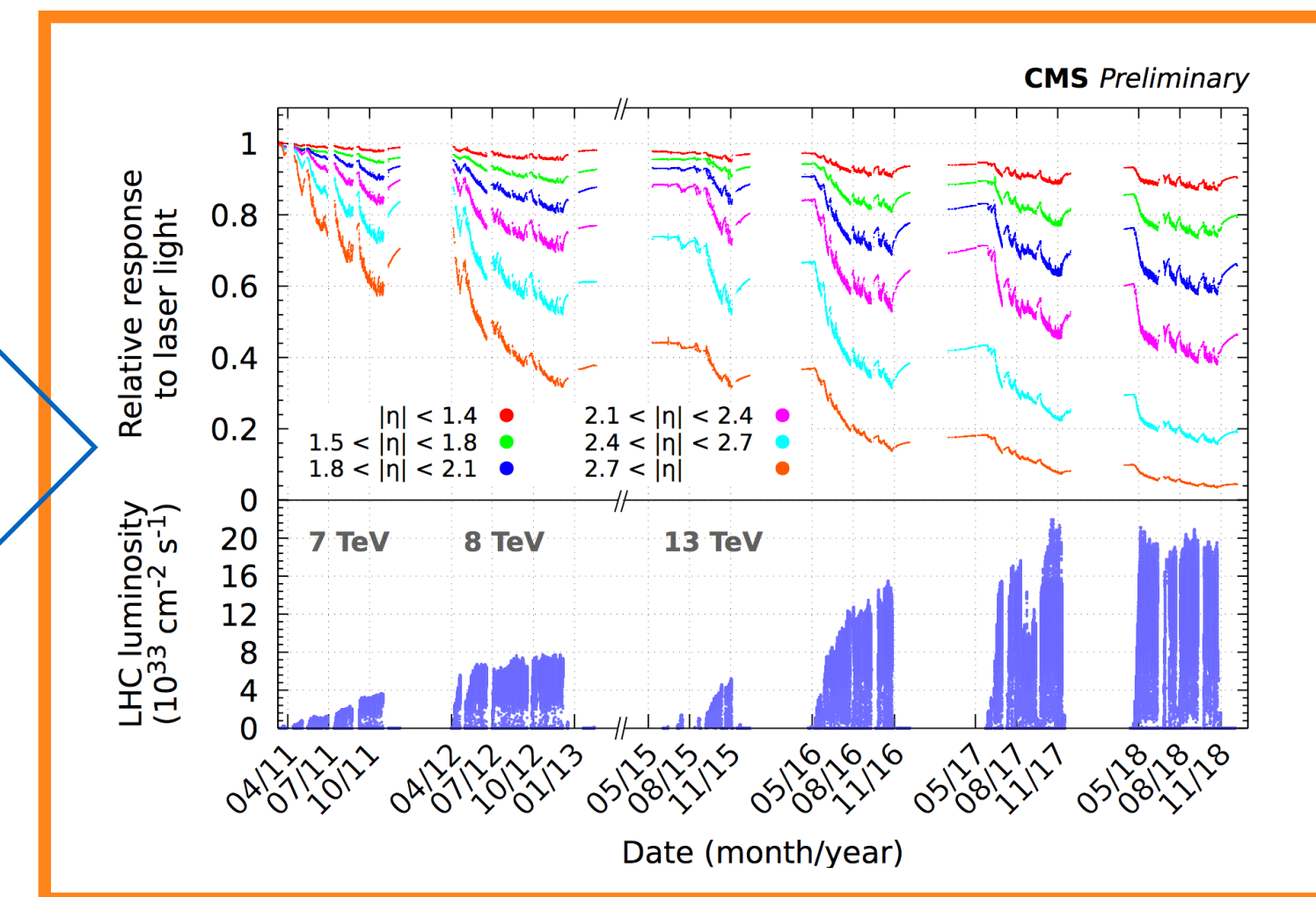


Amplitude fit



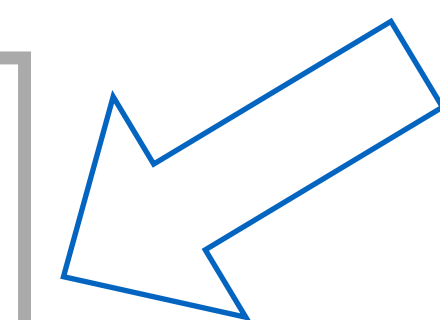
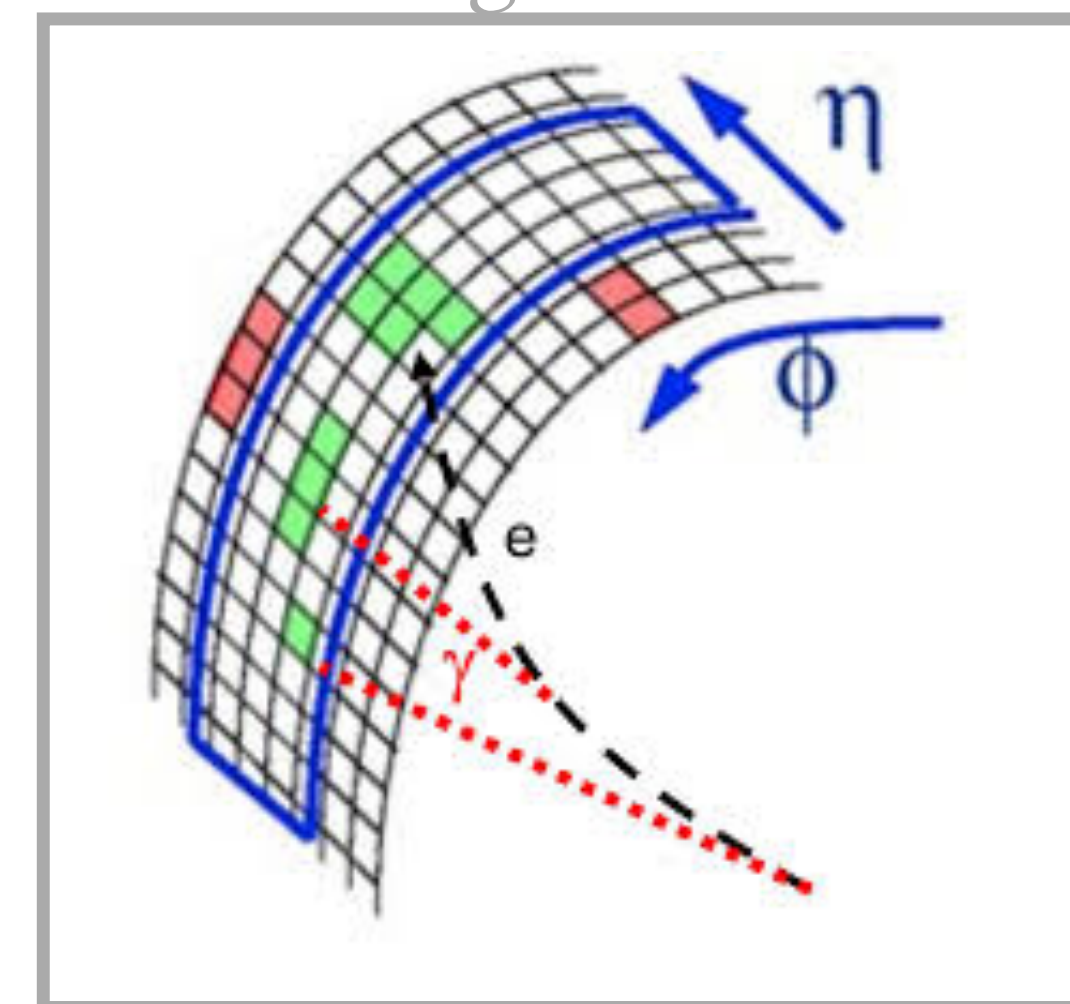
Single channel energy

Laser correction



Detector response vs time

Clustering



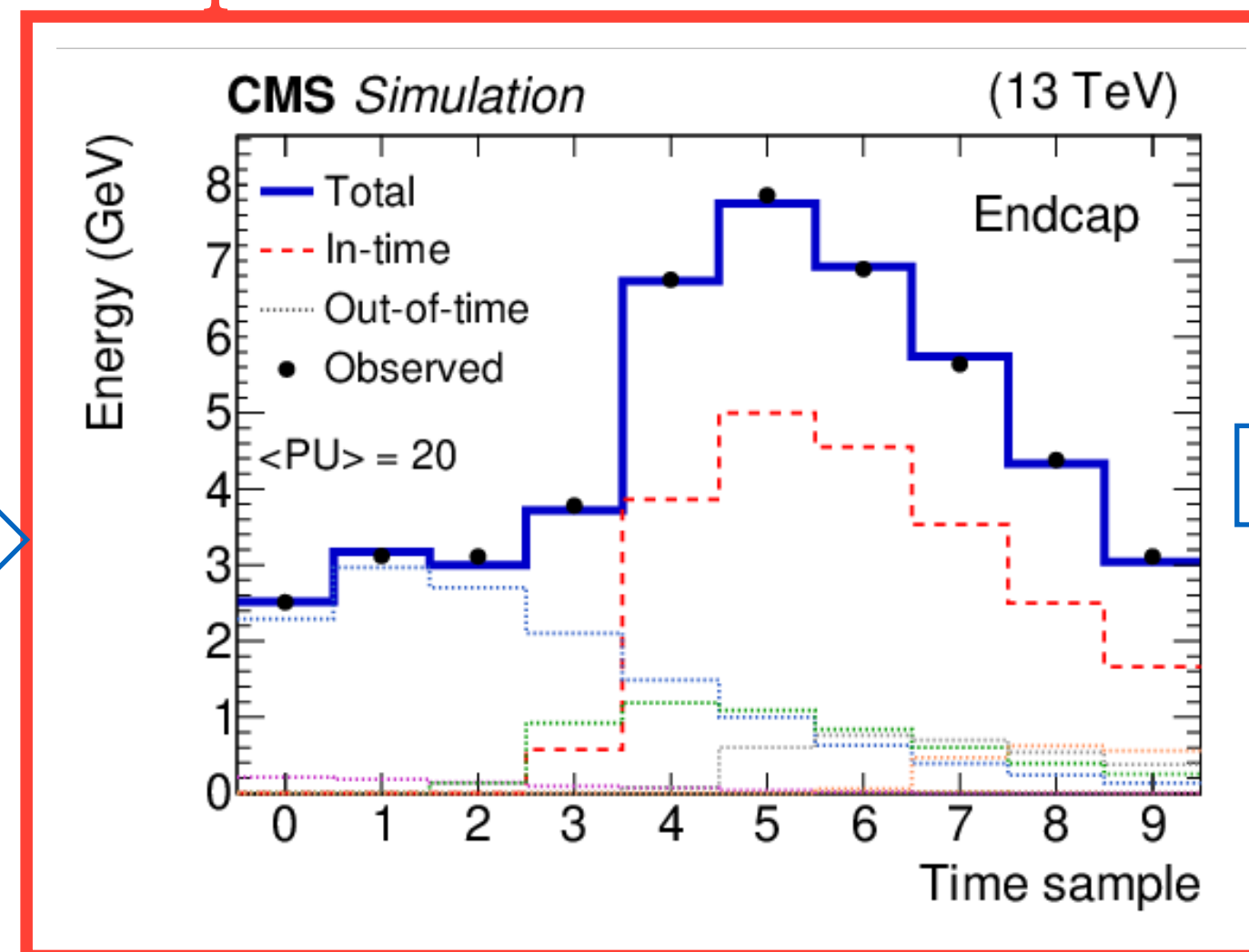
Electromagnetic
shower

How to measure the Higgs mass ($H \rightarrow \gamma\gamma$)

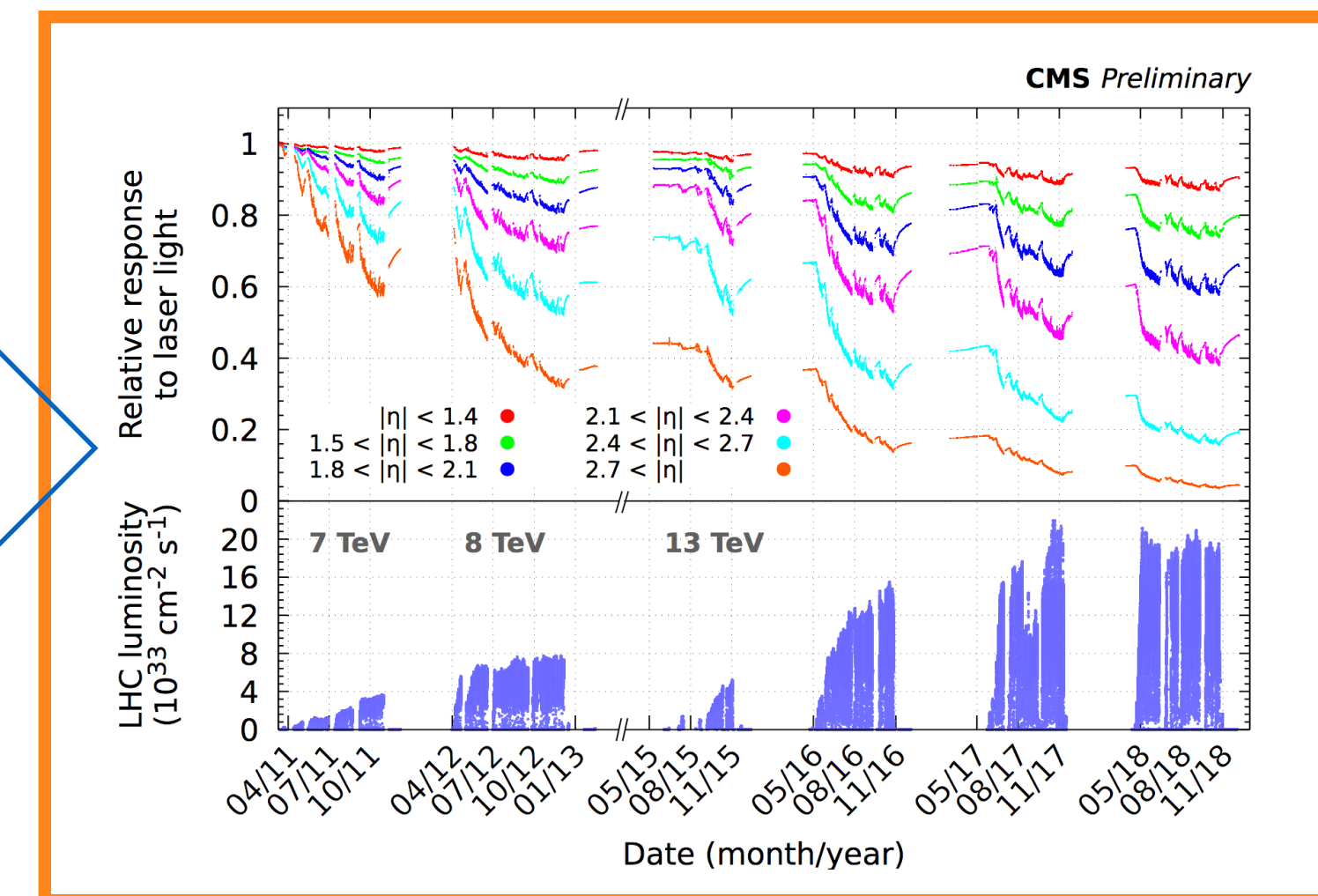
Need an excellent ECAL



Amplitude fit



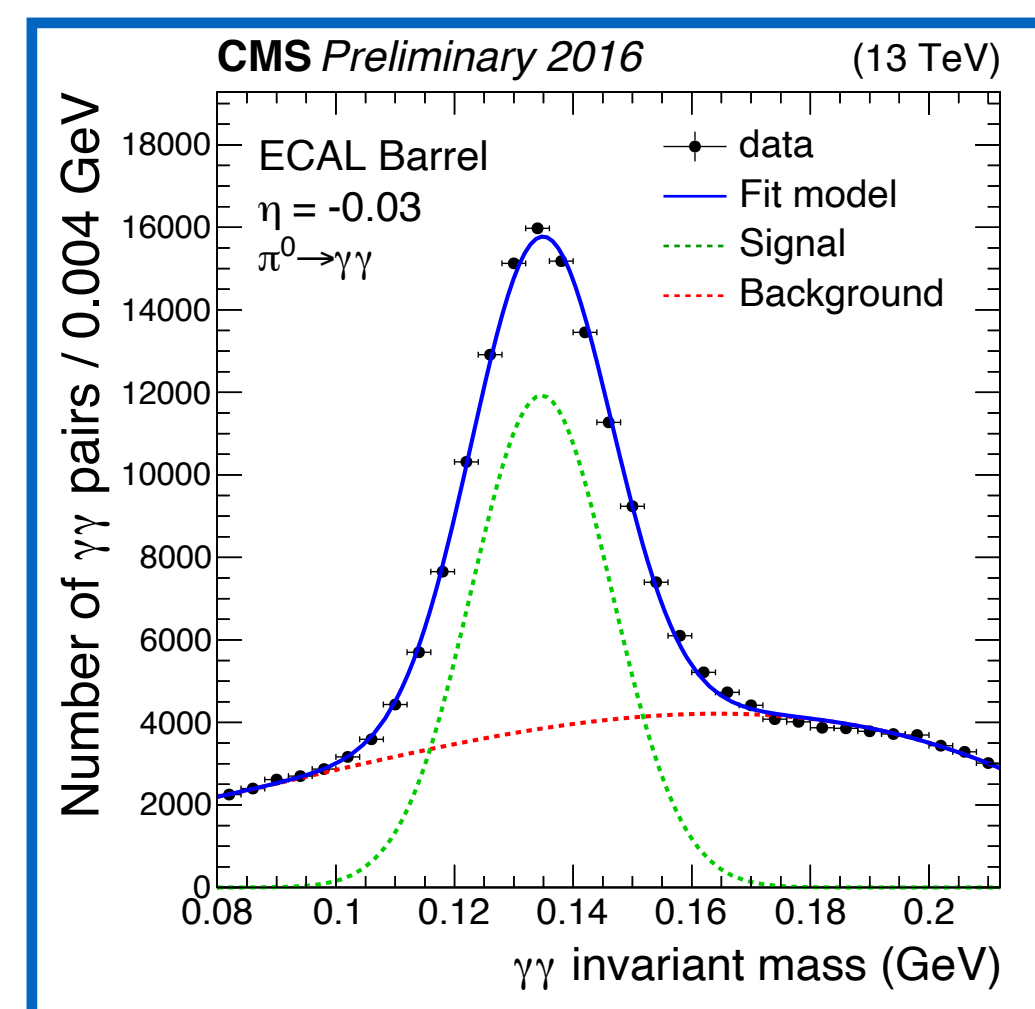
Laser correction



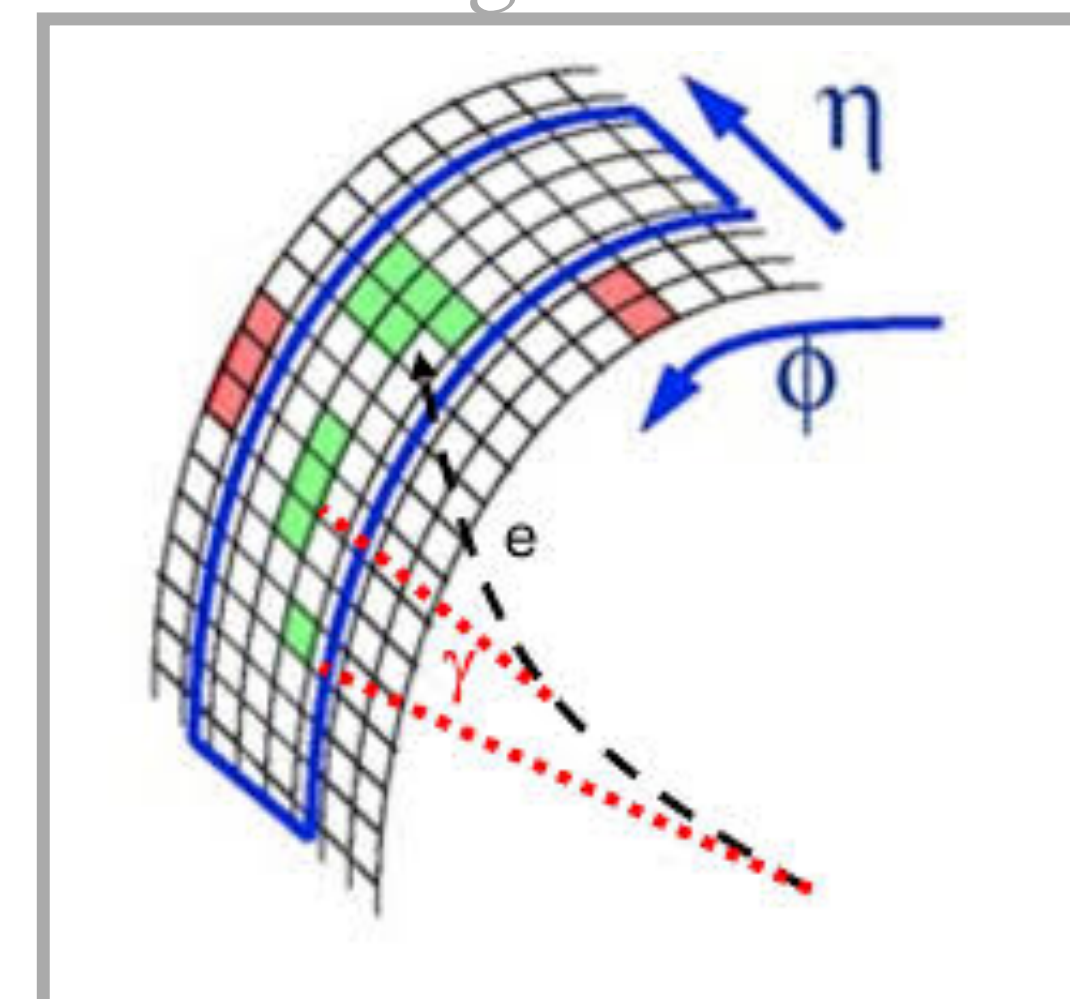
Single channel energy

Detector response vs time

Calibrations



Clustering



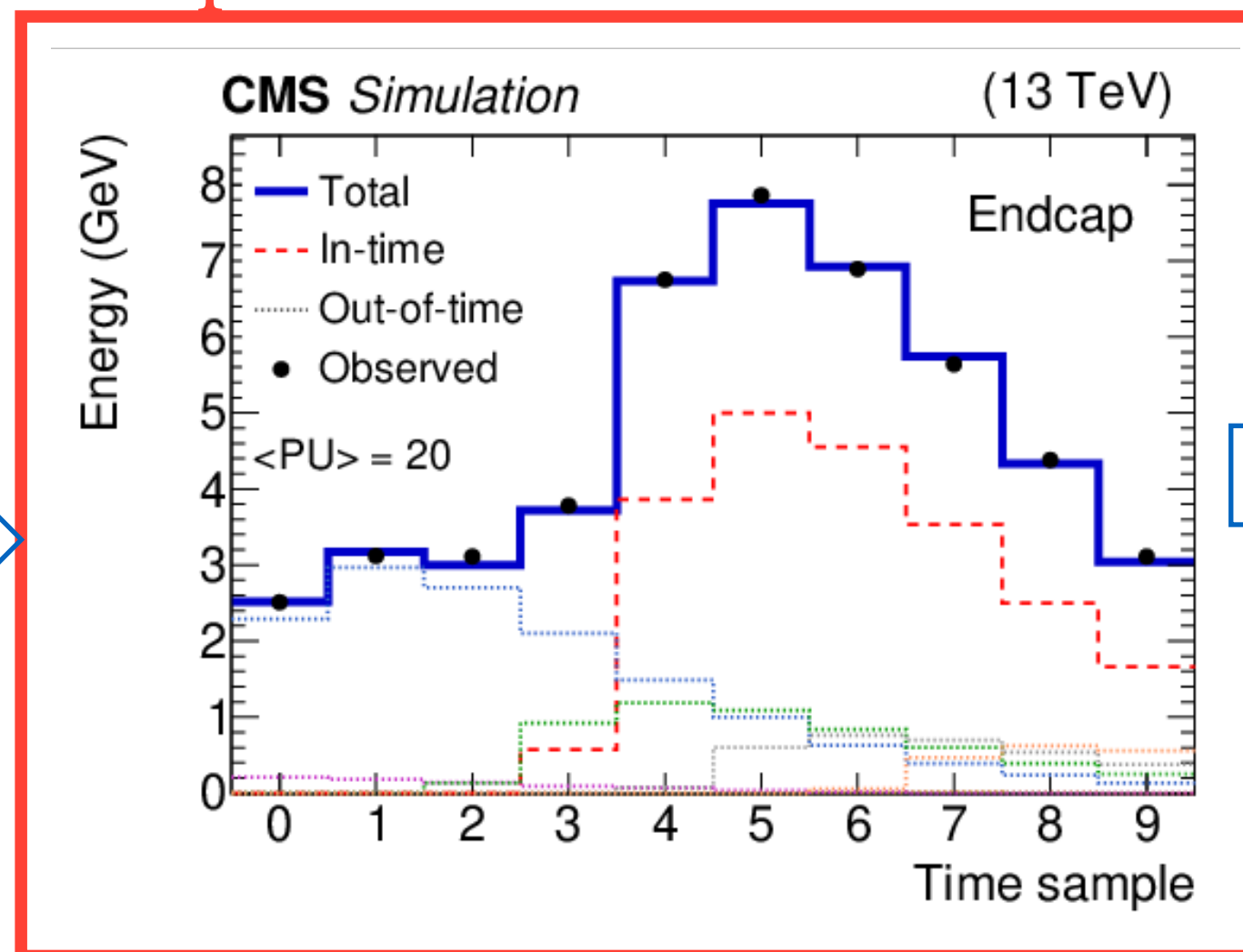
Electromagnetic
shower

How to measure the Higgs mass ($H \rightarrow \gamma\gamma$)

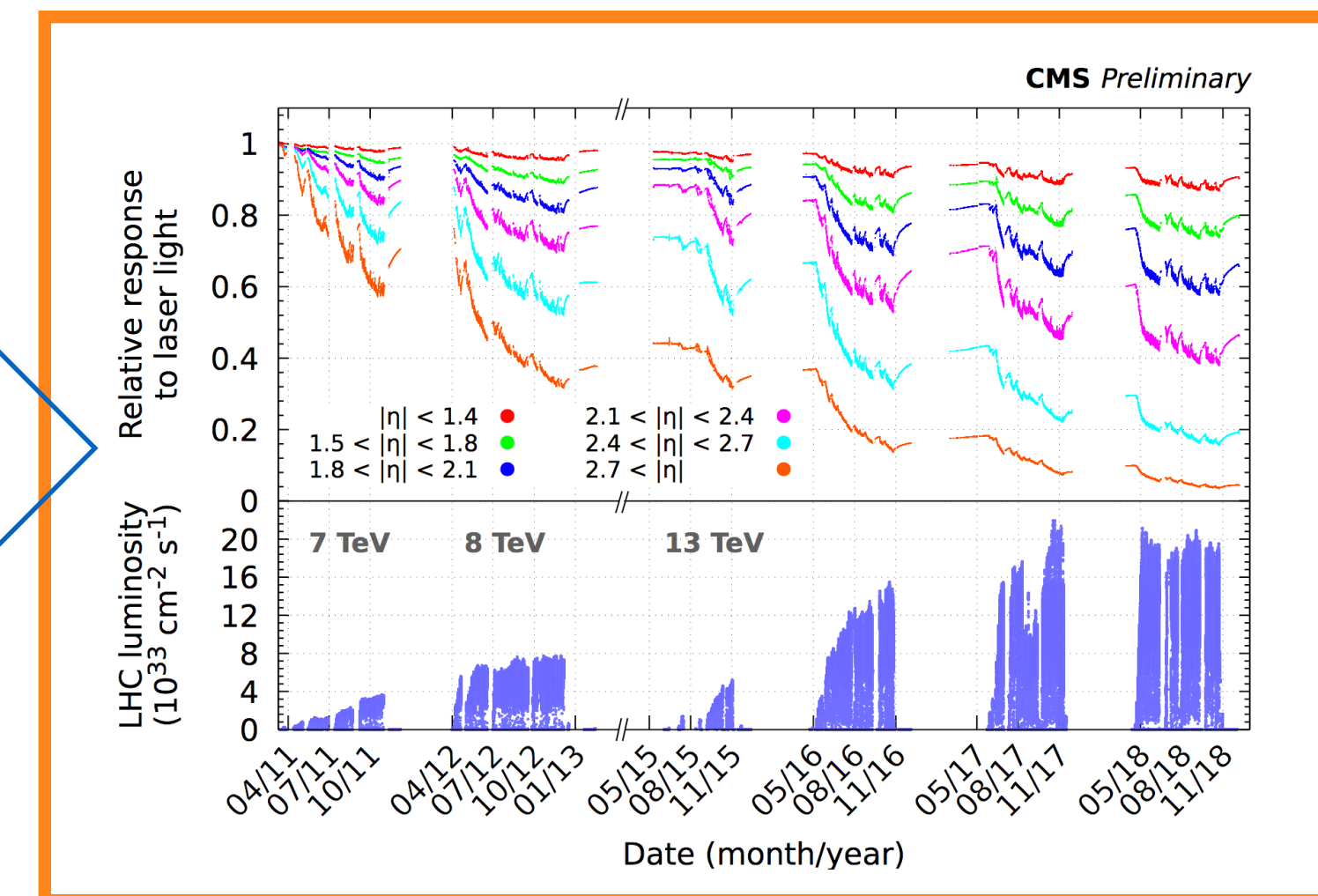
Need an excellent ECAL



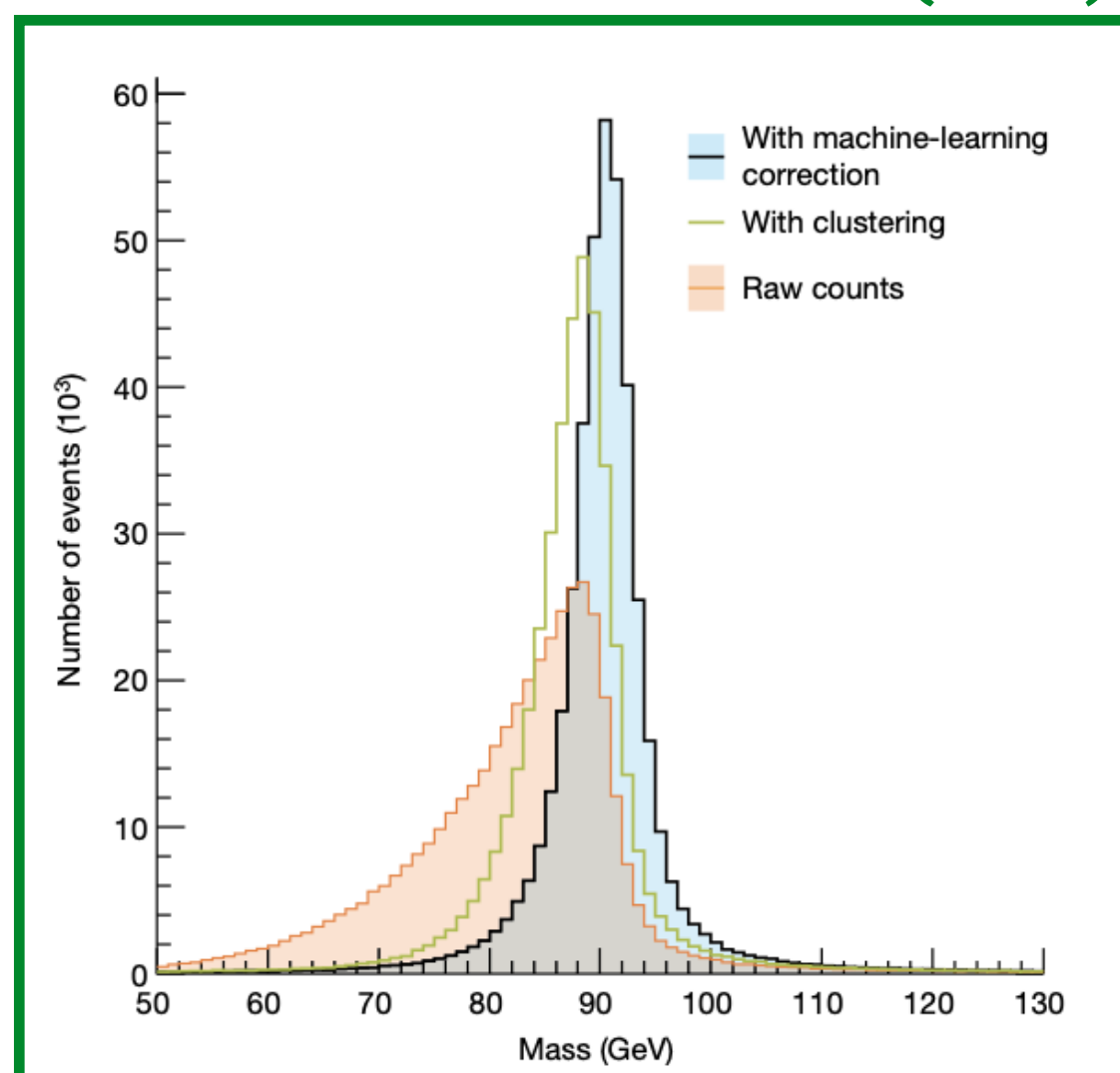
Amplitude fit



Laser correction

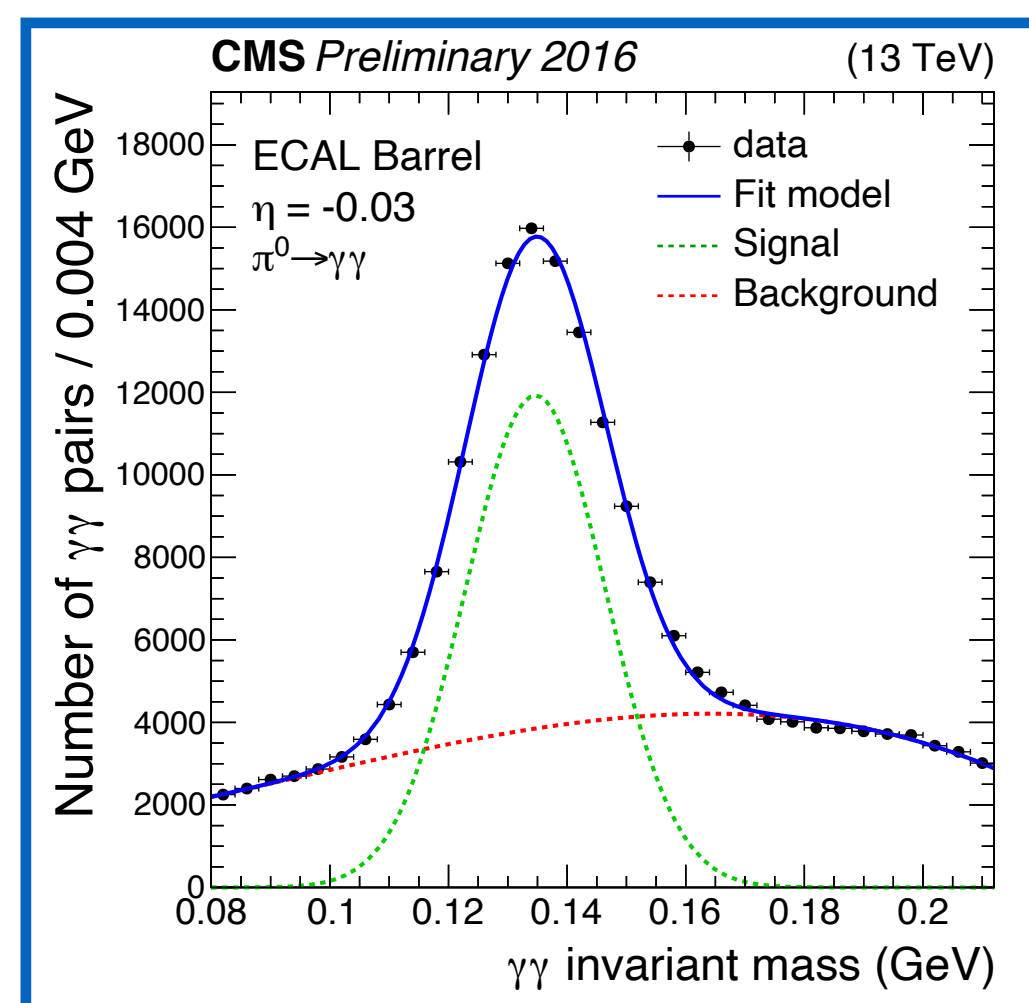


Cluster corrections (ML)



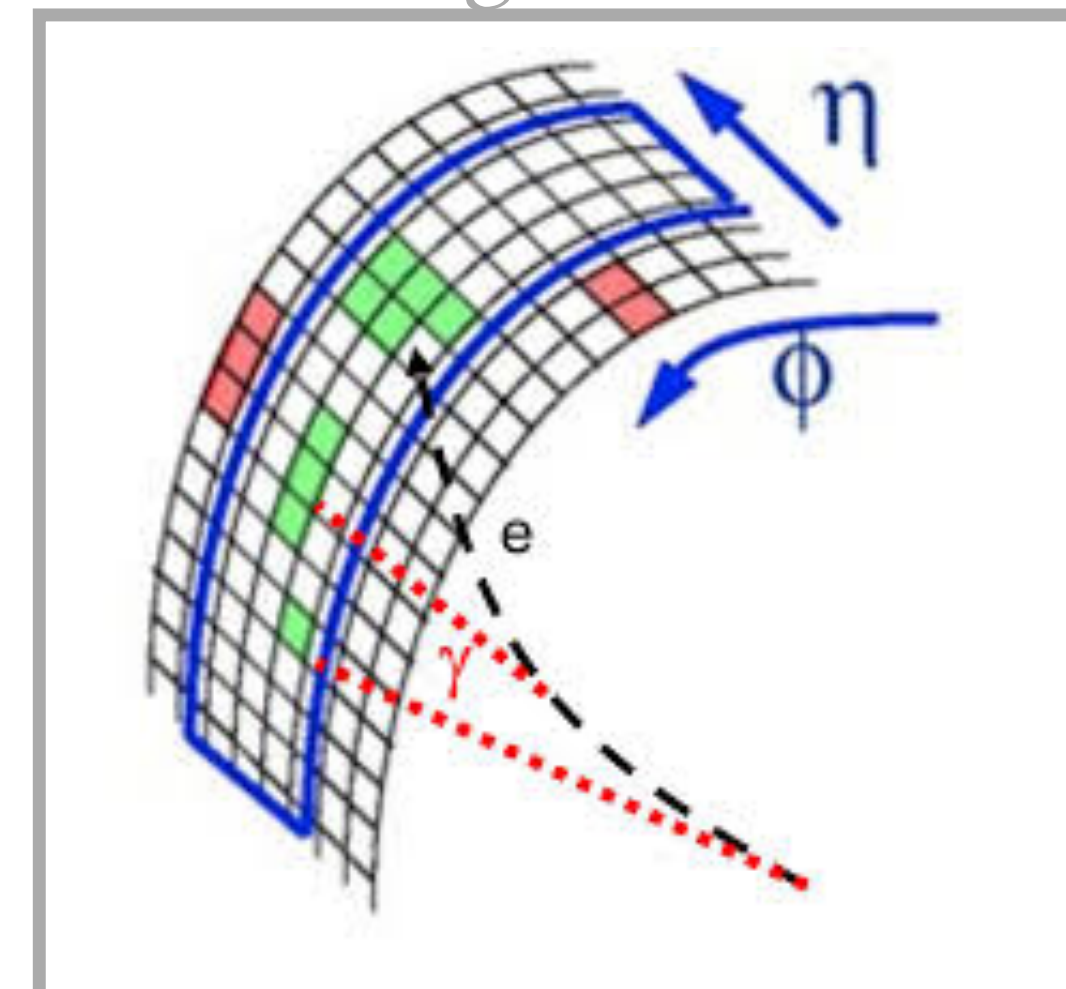
Single channel energy

Calibrations



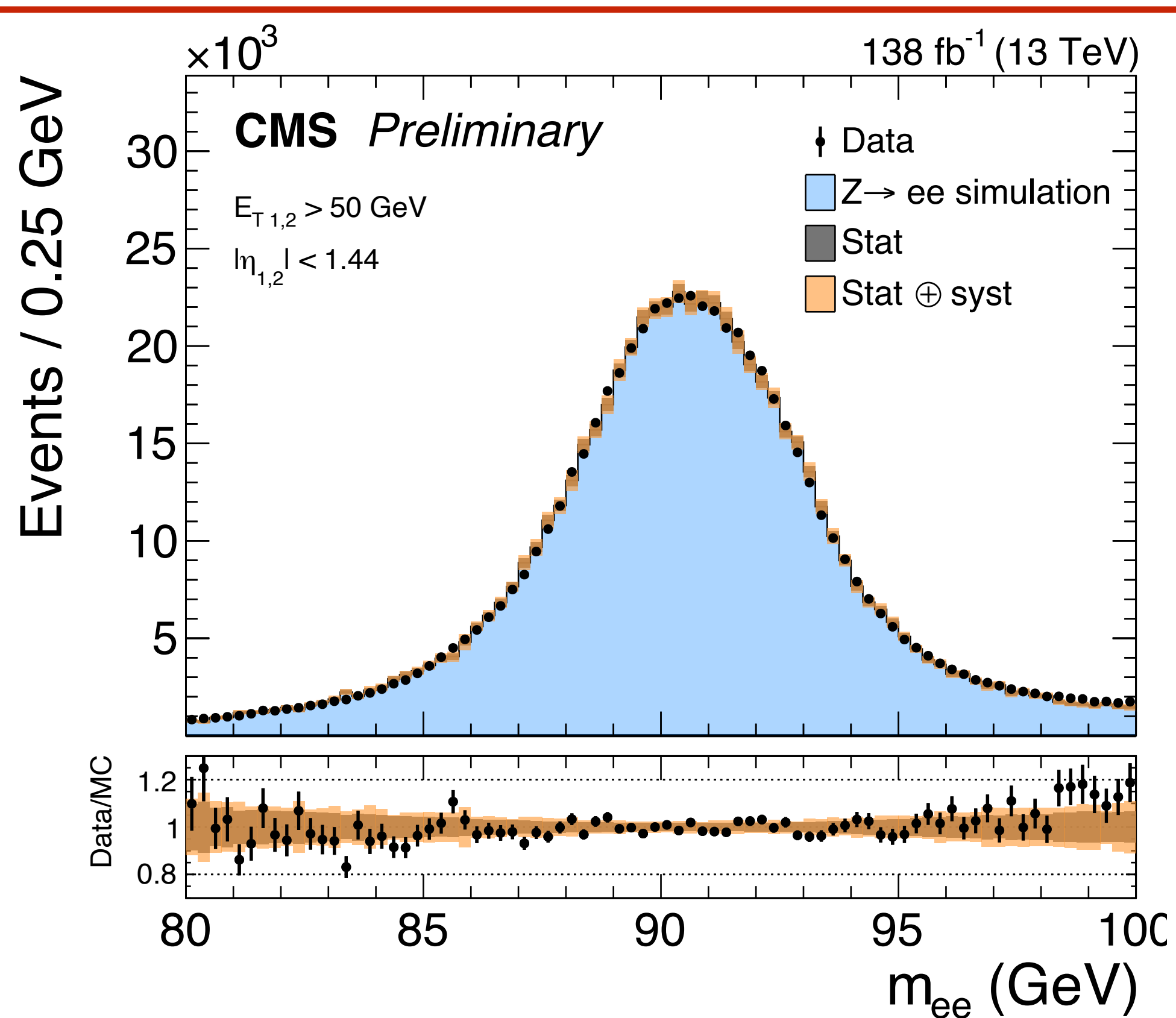
Detector response vs time

Clustering

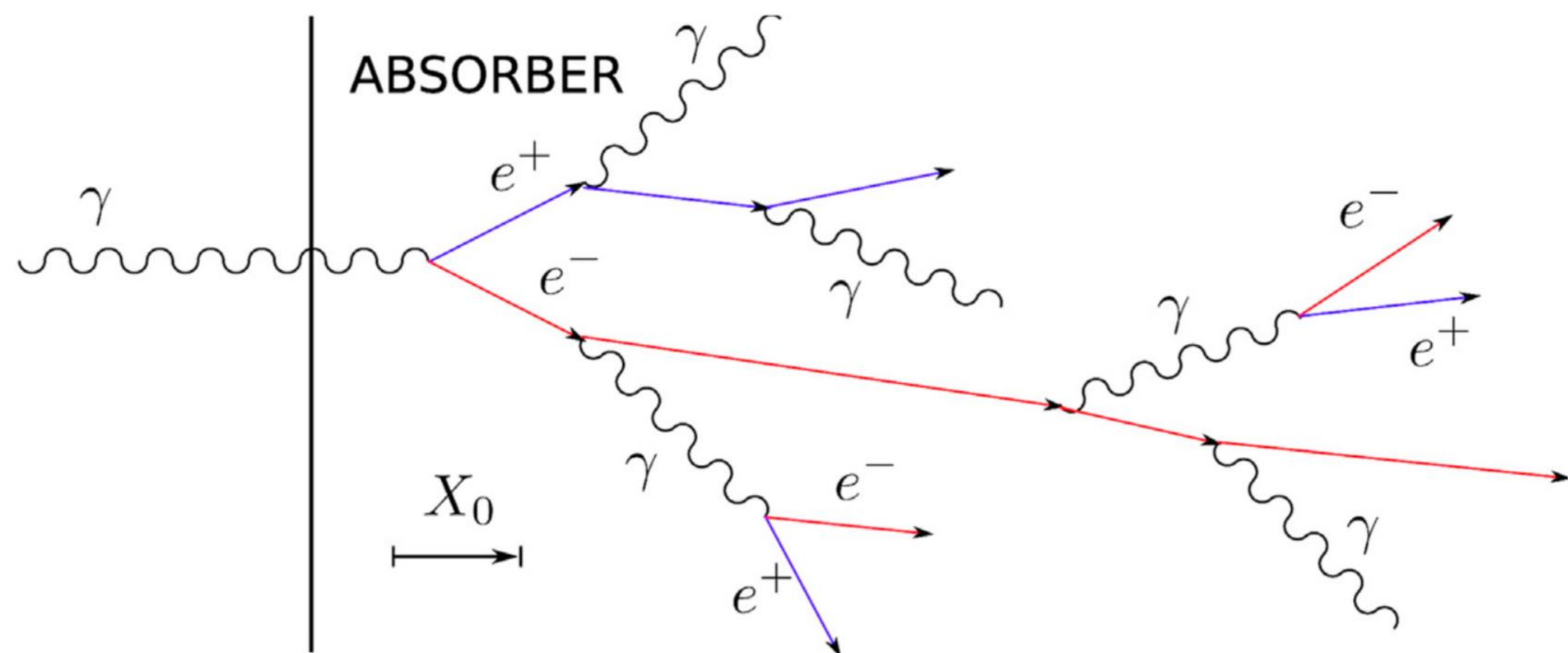


Electromagnetic
shower

$Z \rightarrow e^+e^-$ is a clean & copious source of e.m. clusters at LHC, **very similar to photons**.
Used to do granular data/simulation corrections (vs $\eta, p_T, \dots$)



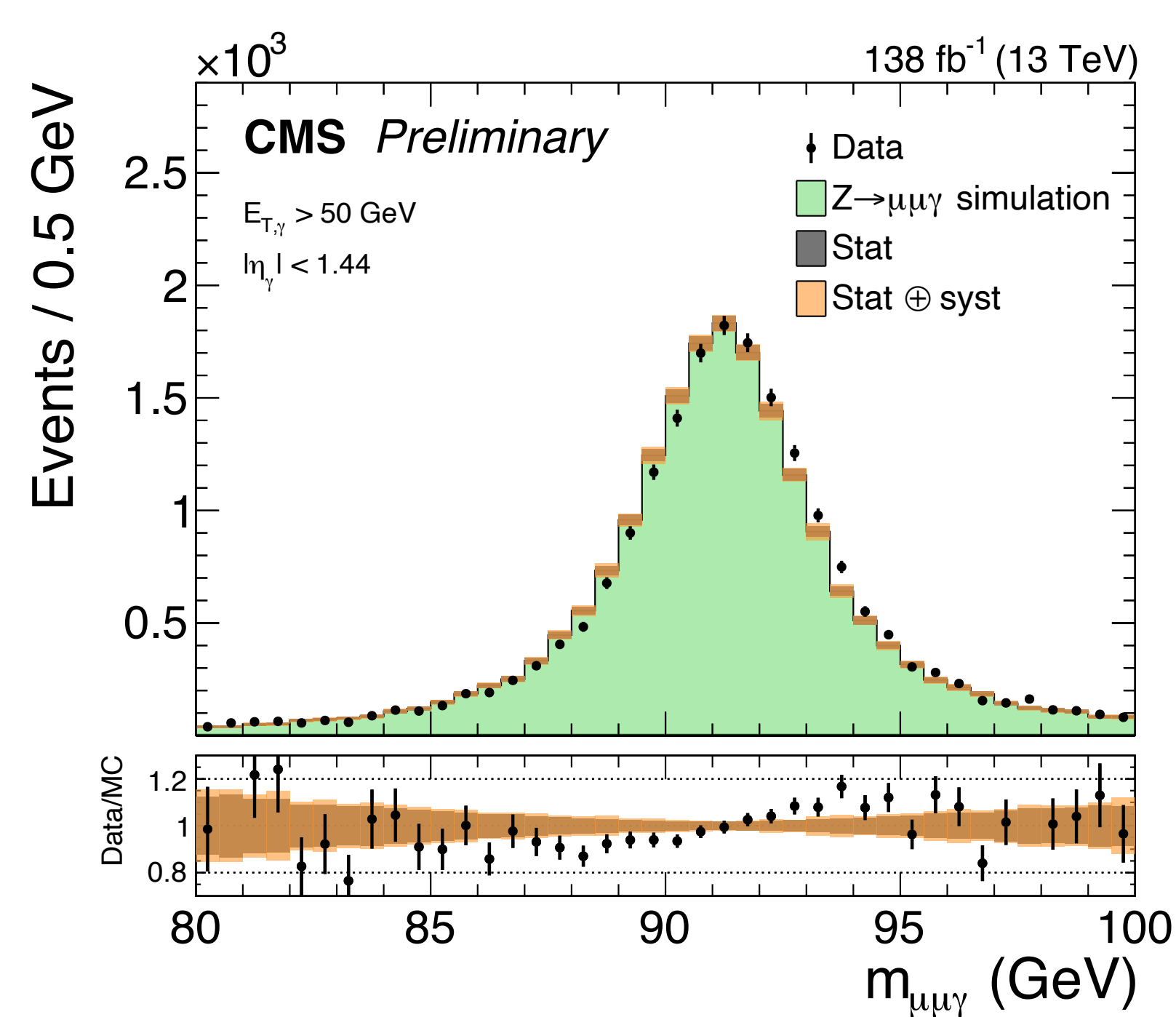
Perfect data/MC closure after
 $Z \rightarrow ee$ corrections



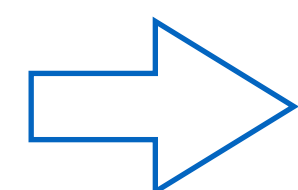
BUT: **electrons** / **photons**:

- first hard interaction is a **brem** / **conversion**
- Interaction length is $1 X_0$ / $1.3 X_0$

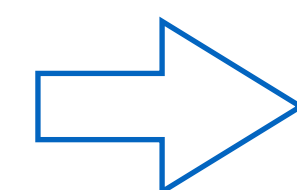
Once applied on real photons in $Z \rightarrow \mu\mu\gamma$ events (γ from muon FSR), a **residual small energy shift is observed** $\Rightarrow$ **derive e/ γ residual corrections**



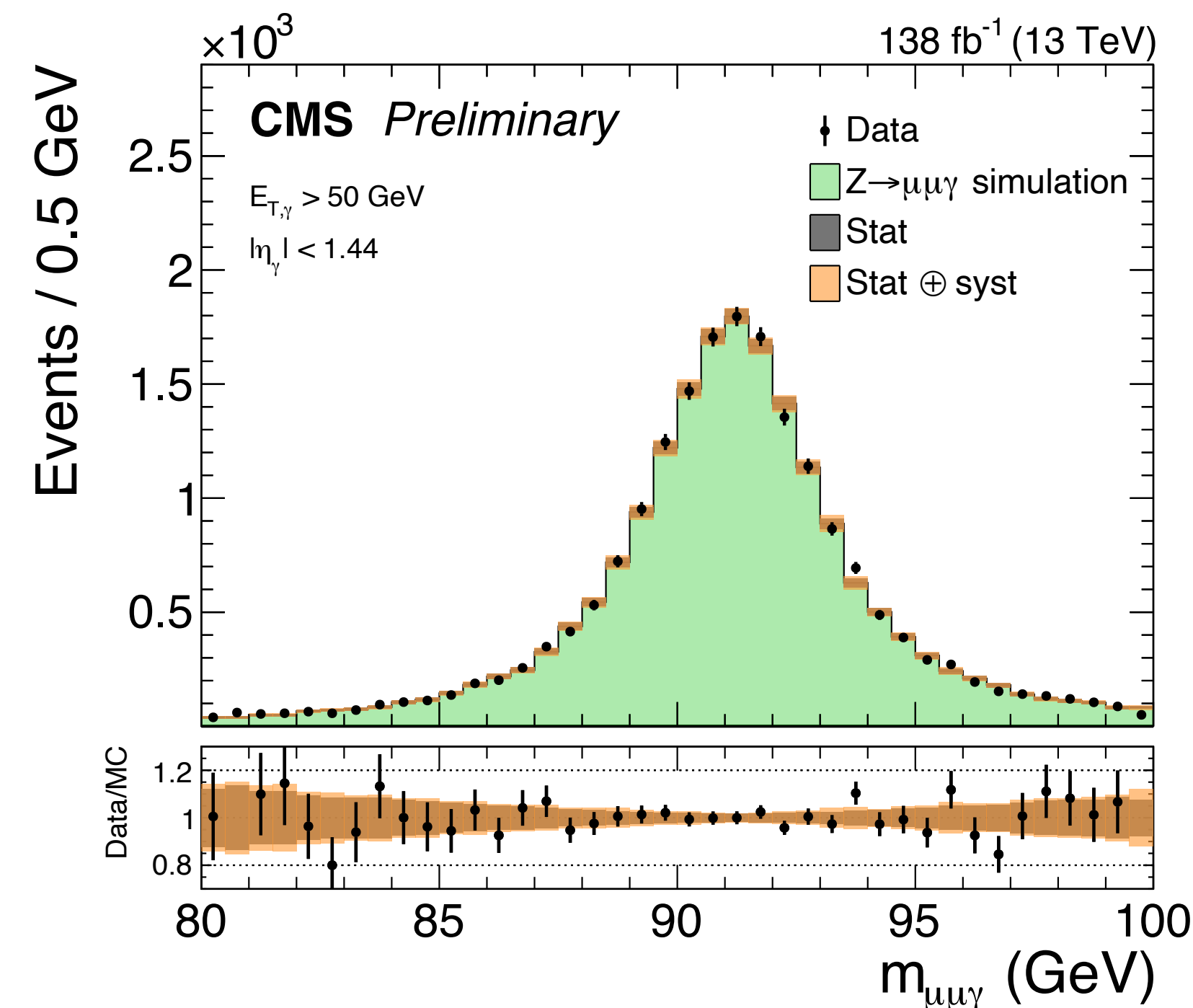
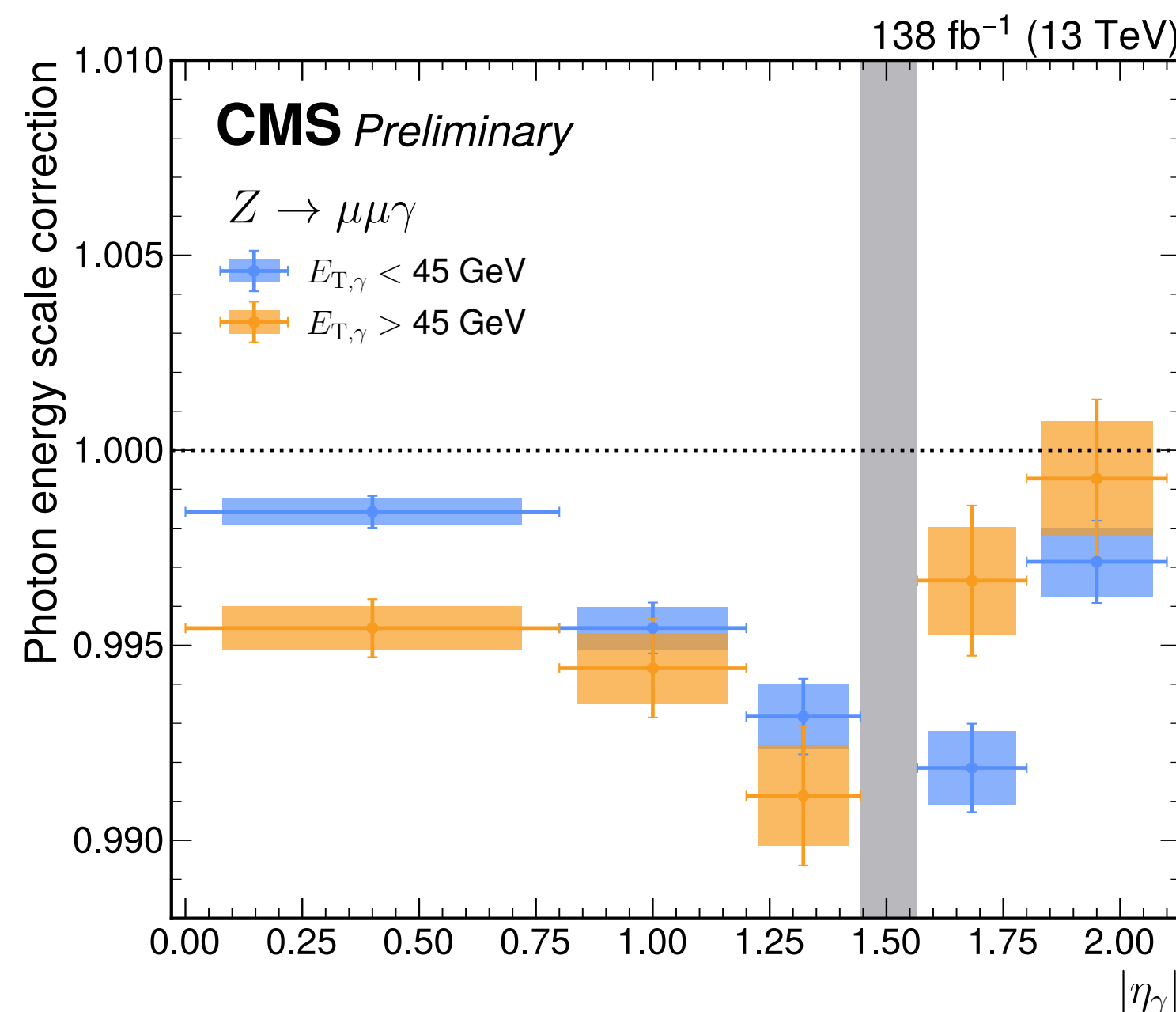
After $Z \rightarrow ee$



$Z \rightarrow \mu\mu\gamma$ corrections



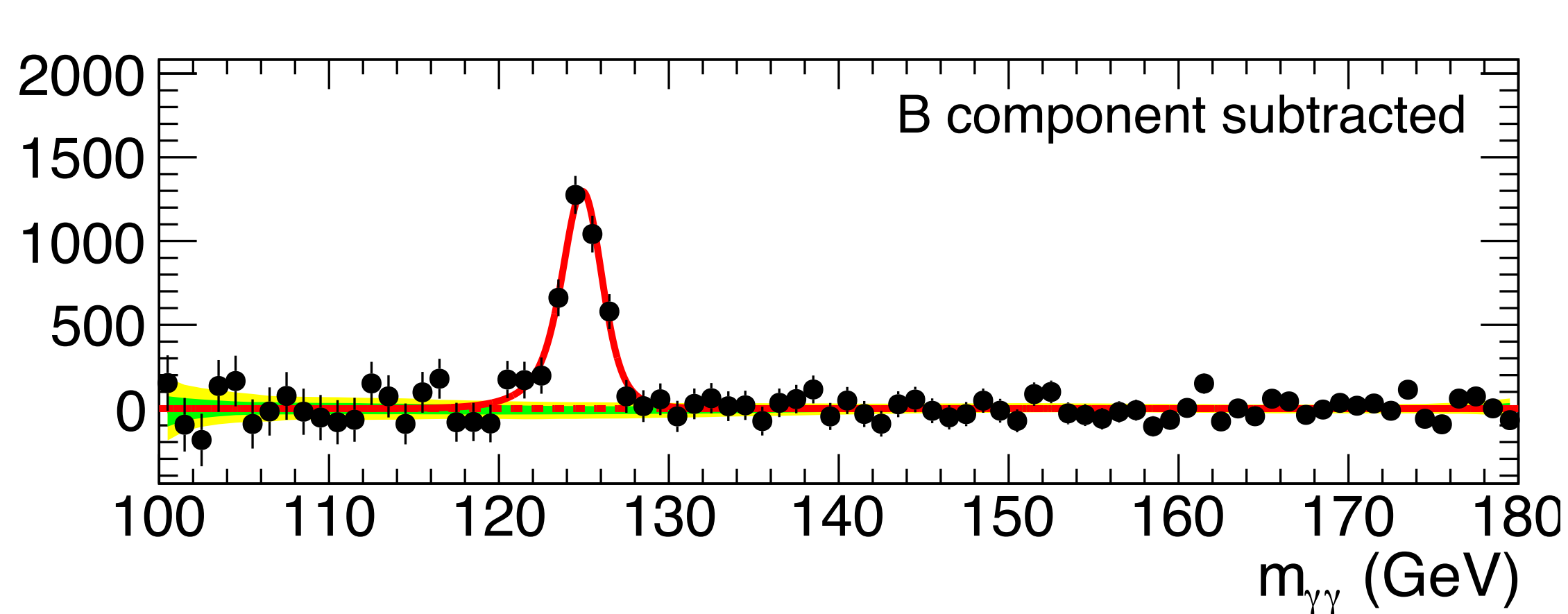
After $Z \rightarrow \mu\mu\gamma$



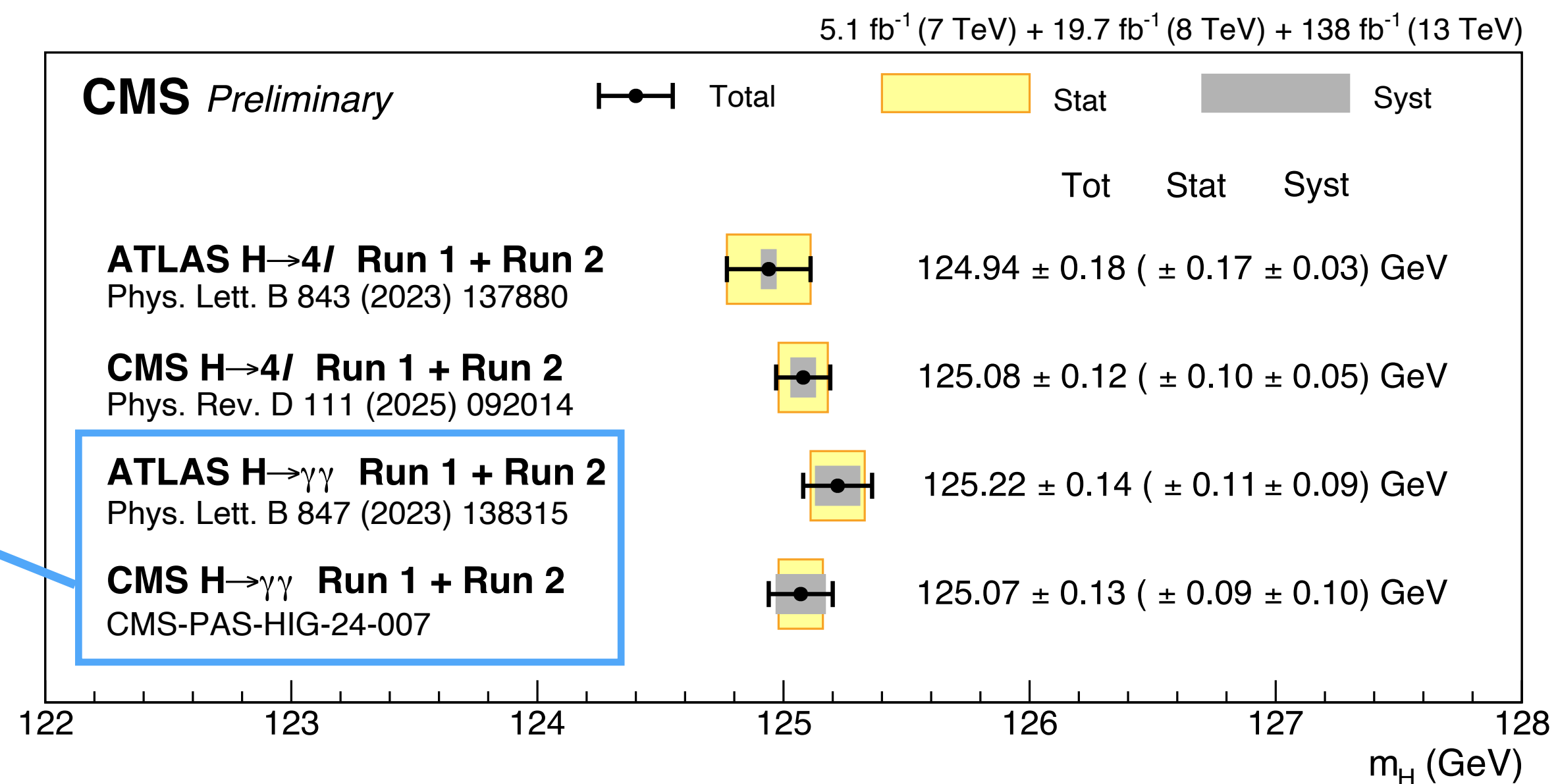
Corrections within **0.5% $\rightarrow$ 0.8% in barrel**

Limited by: the $Z \rightarrow \mu\mu\gamma$ sample and muon scale systematics





Source	Contribution (MeV)
Photon energy scale	
Statistical uncertainty of muon sample	75
Residual non-linearity	64
Muon momentum	38
Electromagnetic shower	23
Photon energy resolution	7
Interference between ggH signal and background	27
Other sources	13
Statistical uncertainty	100
Total uncertainty	150



Measurement precision: $\delta m_H / m_H \sim 10^{-3}$
from both ATLAS and CMS

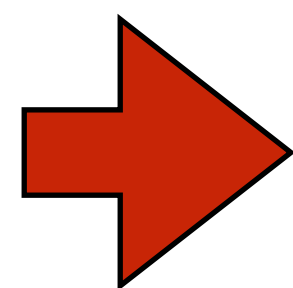


Main systematics from **muon scale**
($Z \rightarrow \mu\mu\gamma$) and **ECAL scale** ($Z \rightarrow ee$)

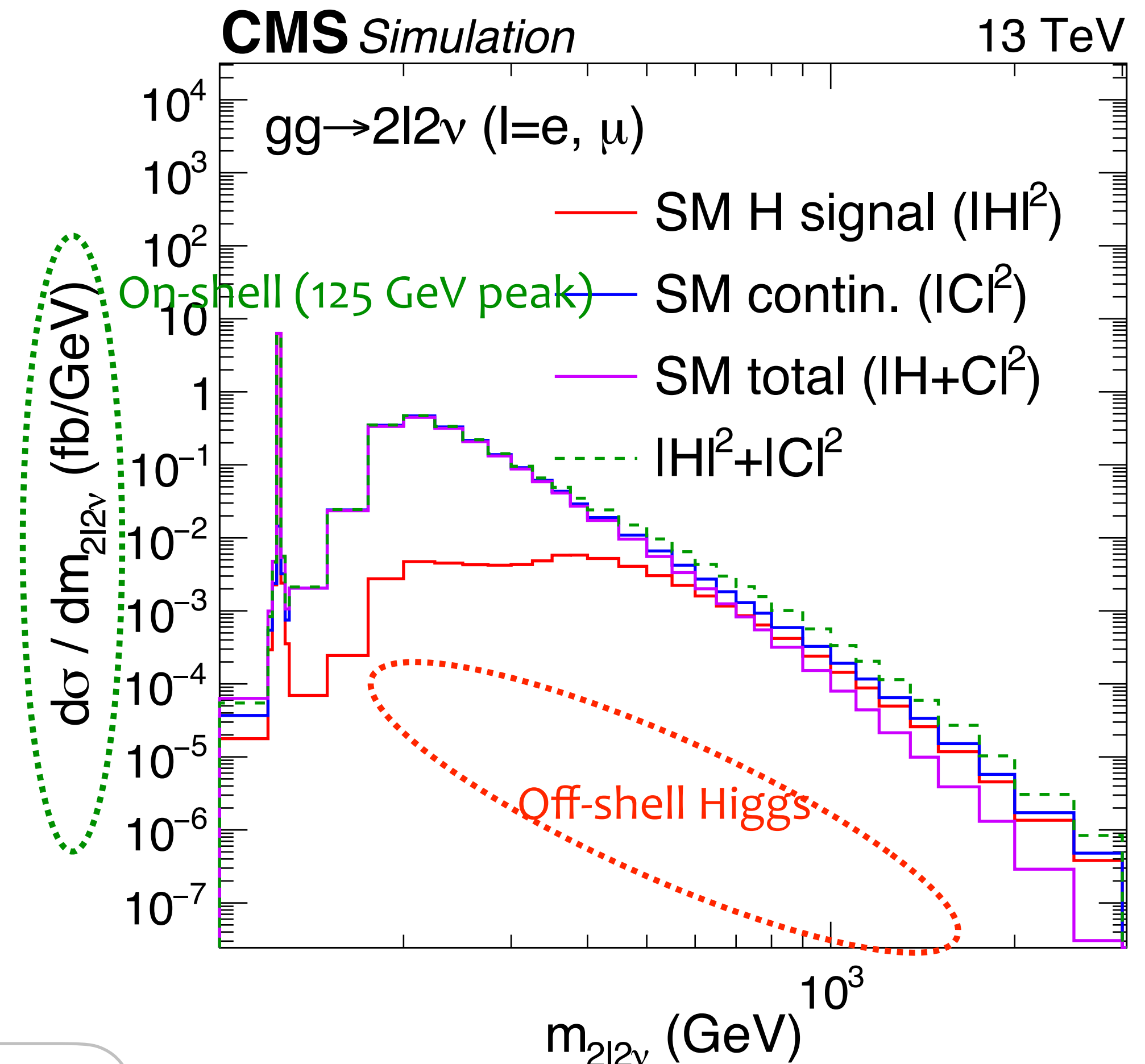
Higgs boson total width

- Another way to look for invisible decays: measure the **total Higgs width** Γ_H
- $\Gamma_H^{SM} = 4.1 \text{ MeV}$ ($\Leftrightarrow$ lifetime $\tau_H \sim 1.6 \times 10^{-22} \text{ s}$) too small to be measured directly:
 - $\Gamma_H < 1.1 \text{ GeV}$ from on-shell Higgs, limited by detector resolution
- Textbook use of Heisenberg uncertainty principle:
 - finite particle lifetime $\Rightarrow$ off-shell production must exist
 - Higgs width can be extracted from the **ratio of on-shell and off-shell yields**

$$\sigma \propto \frac{1}{(m^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$$



$$\frac{\sigma_{pp \rightarrow H \rightarrow 4\ell}^{\text{off-shell}}}{\sigma_{pp \rightarrow H \rightarrow 4\ell}^{\text{on-shell}}} \propto \Gamma_H$$



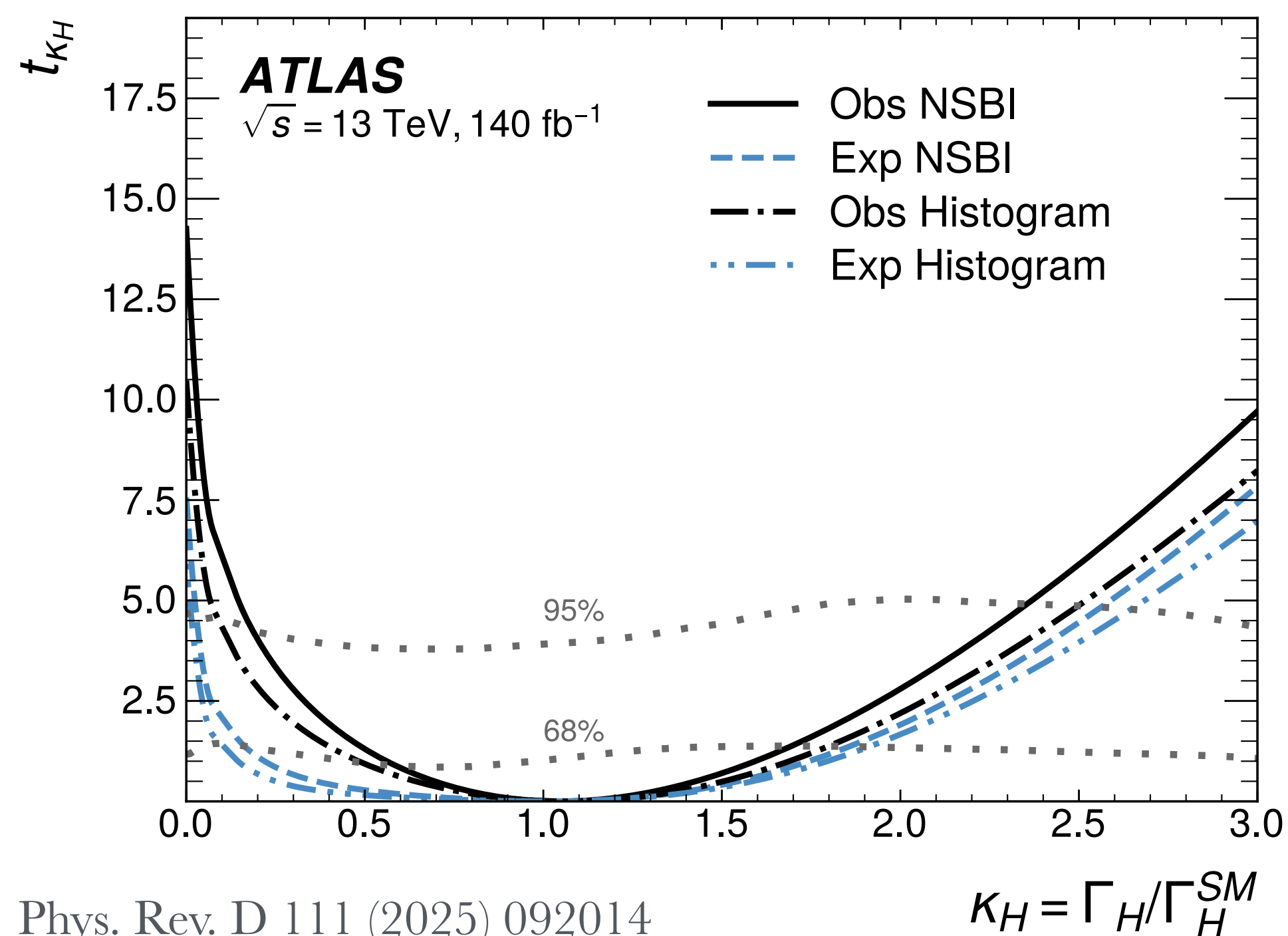
- Strong evidence of Higgs off-shell production in both CMS and ATLAS:

- 3.7σ in ATLAS HZZ, 3.6σ in CMS HZZ, 3.4σ in CMS HWW

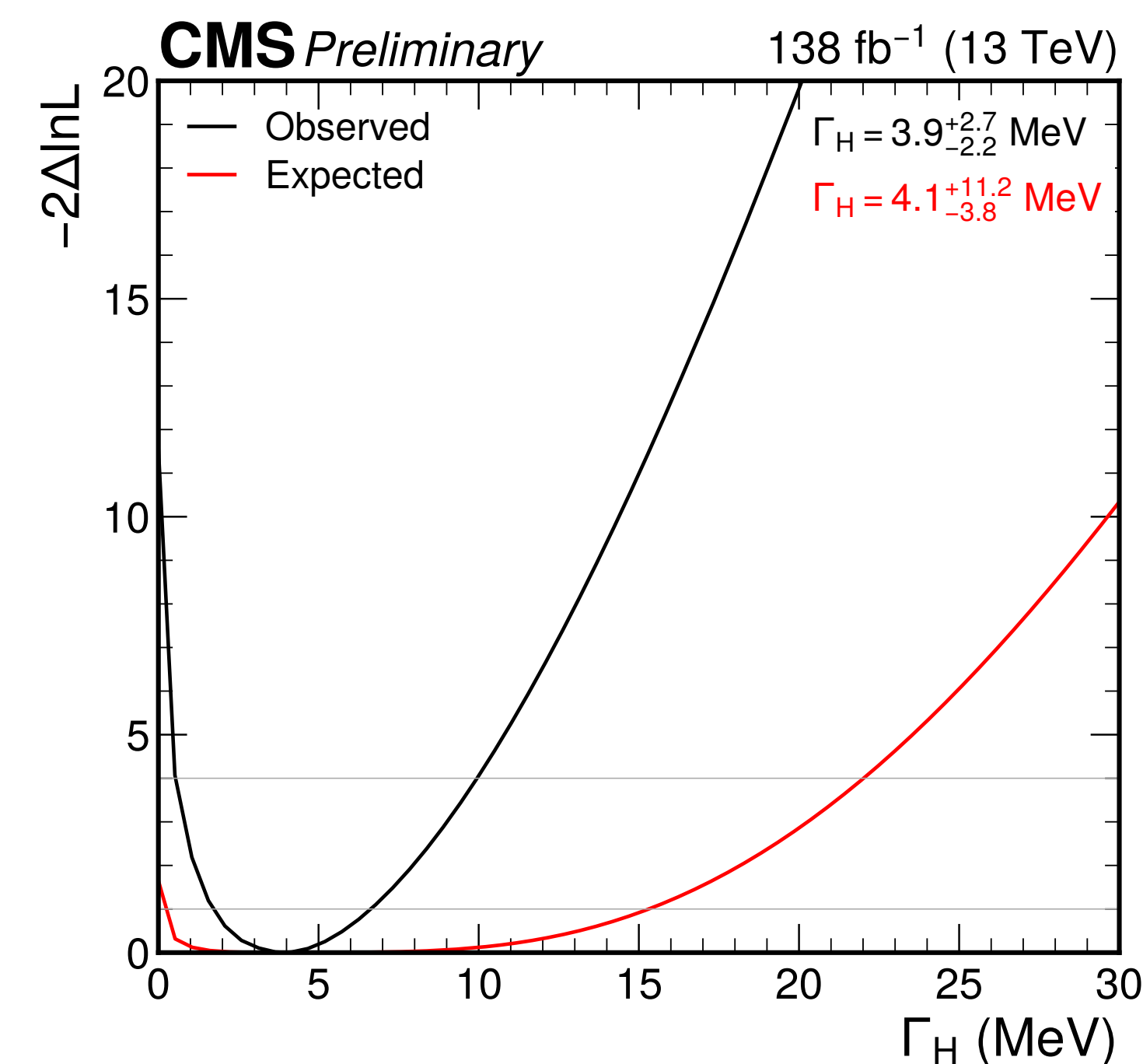
arXiv:2601.05168

$$H \rightarrow ZZ(4\ell + 2\ell 2\nu) \quad \Gamma_H = 4.3^{+2.7}_{-1.9} \text{ MeV}$$

$$H \rightarrow WW^* \quad \Gamma_H = 3.9^{+2.7}_{-2.2} \text{ MeV}$$



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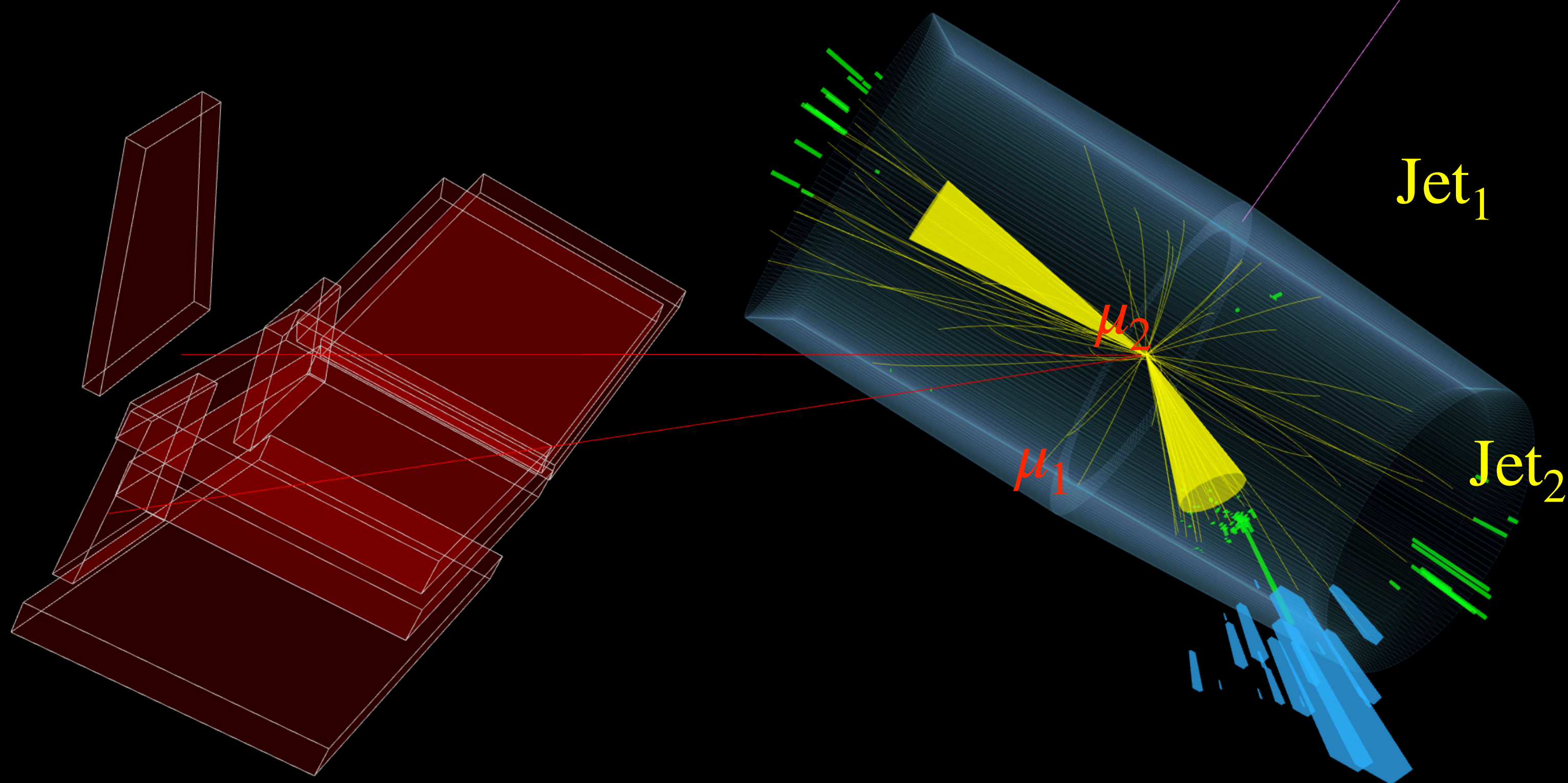
Neural Simulation Based Inference (ATLAS) multidim fit (CMS) help in presence of interference
Measurements down to 50% precision !

$H \rightarrow ZZ \rightarrow 2\mu 2\nu_\mu$ candidate

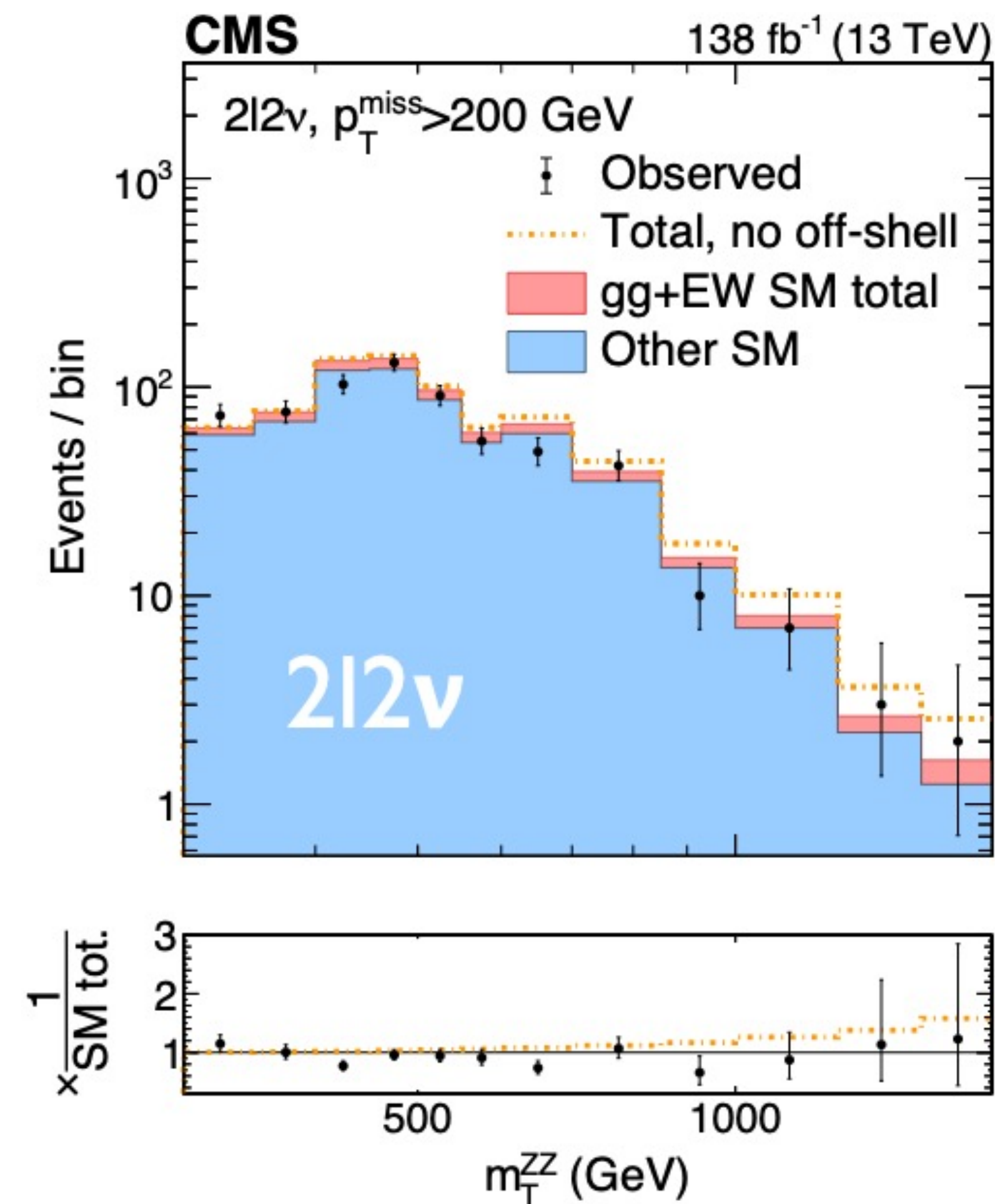


CMS Experiment at the LHC, CERN
Data recorded: 2018-May-14 14:38:36.044544 GMT
Run / Event / LS: 316240 / 1062964357 / 755

$p_T^{\text{miss}}(\nu_1 + \nu_2)$

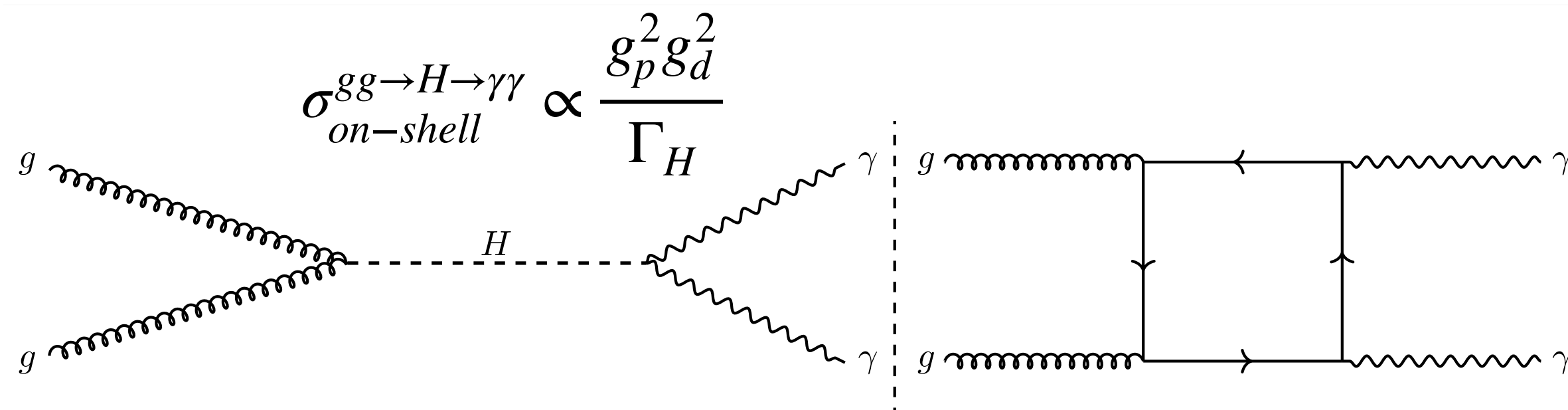


$pp \rightarrow H \rightarrow ZZ(\rightarrow 2\mu 2\nu) + 2 \text{ jets, VBF candidate}$



Higgs width measurement (on-shell)

$pp \rightarrow (H) \rightarrow \gamma\gamma$: **the interference** between resonant and non-resonant di-photon production interferes and distorts the Breit-Wigner depending on Γ_H



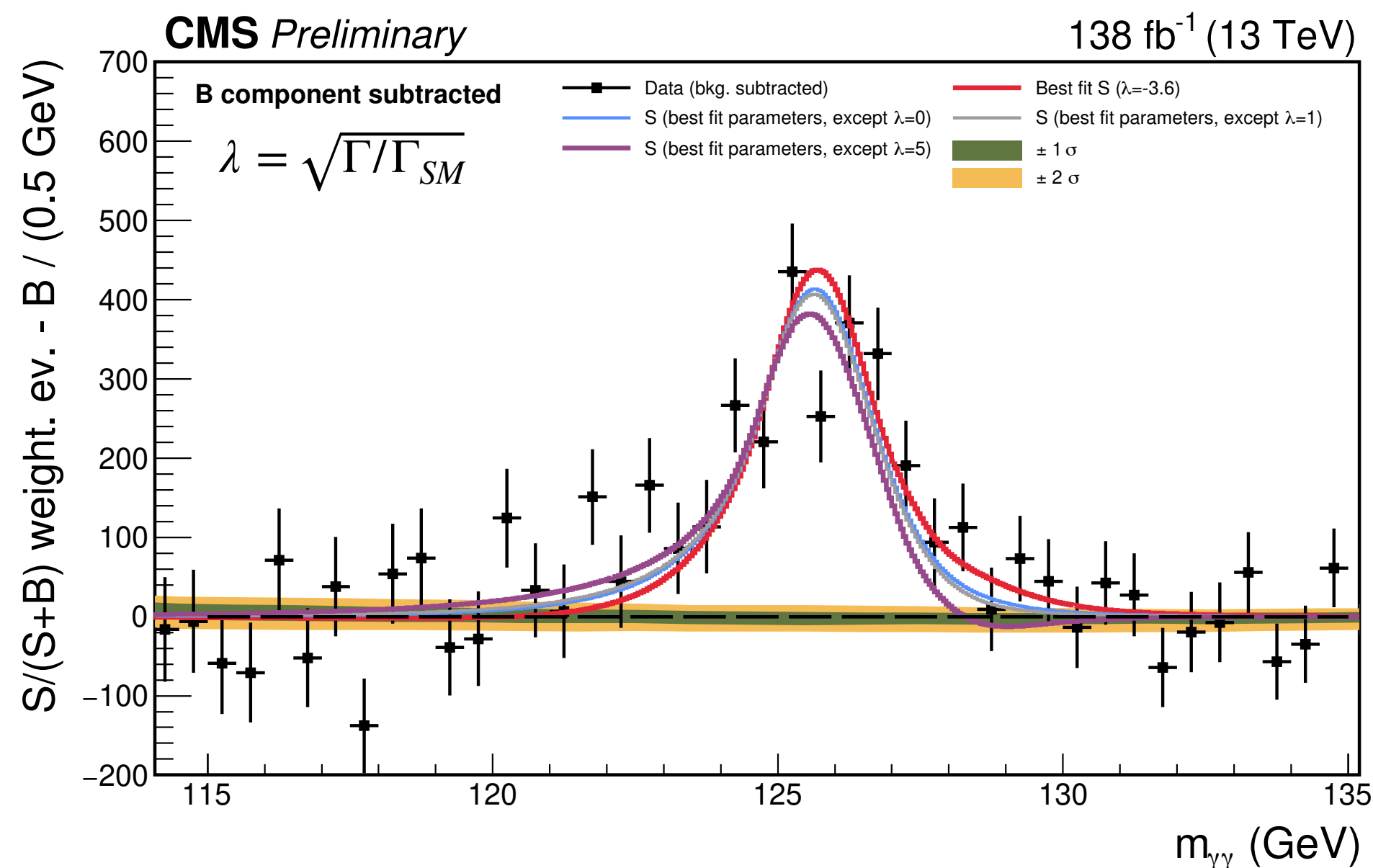
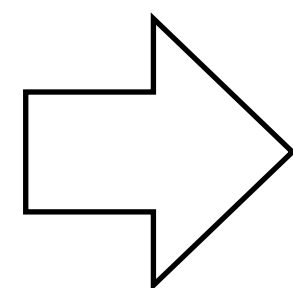
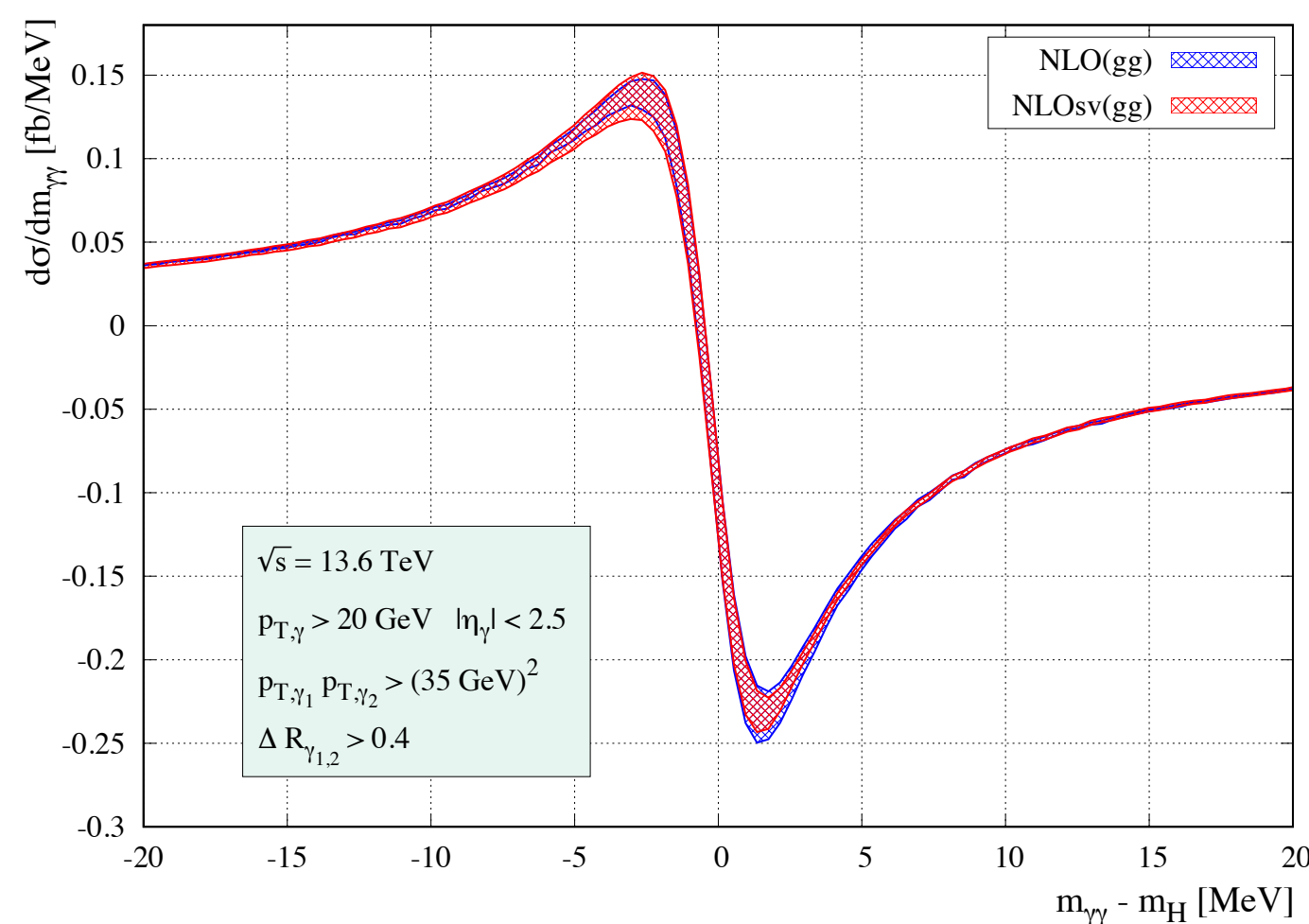
Signal: $gg \rightarrow H \rightarrow \gamma\gamma$

Background: $gg \rightarrow \gamma\gamma$

$$\mu_F = \frac{\sigma_{measured}}{\sigma_{SM}} = \frac{c_{g\gamma}^2 / \Gamma}{c_{g\gamma,SM}^2 / \Gamma_{SM}} = c_{g\gamma}^2 \frac{\Gamma_{SM}}{\Gamma}$$

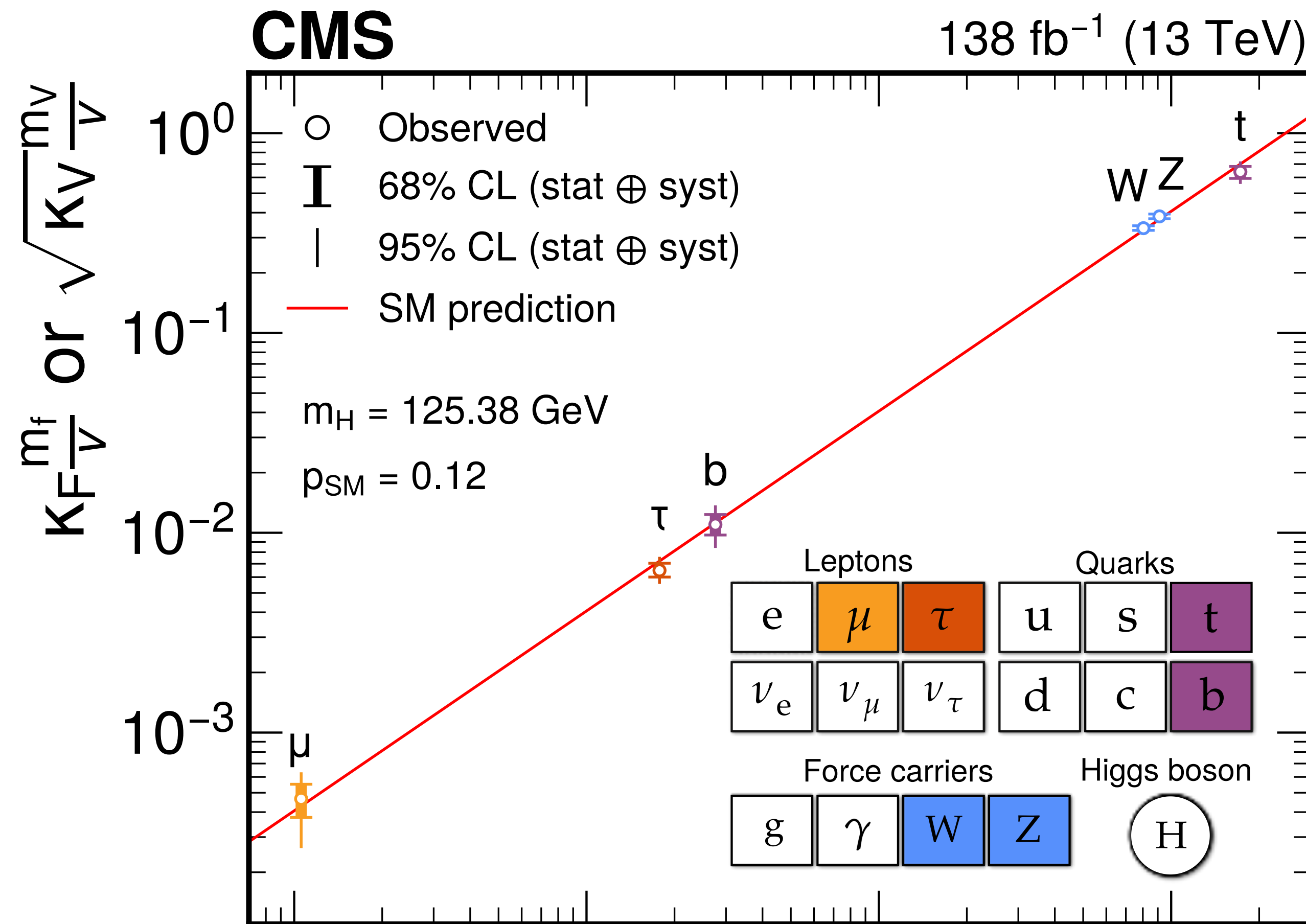
NEW

Interference effect on $m_{\gamma\gamma}$



Limit $\Gamma_H < 9.4 \text{ MeV}$
@95% CL:
 x10 less sensitive
 than off-shell, but
**fewer theory
 assumptions**

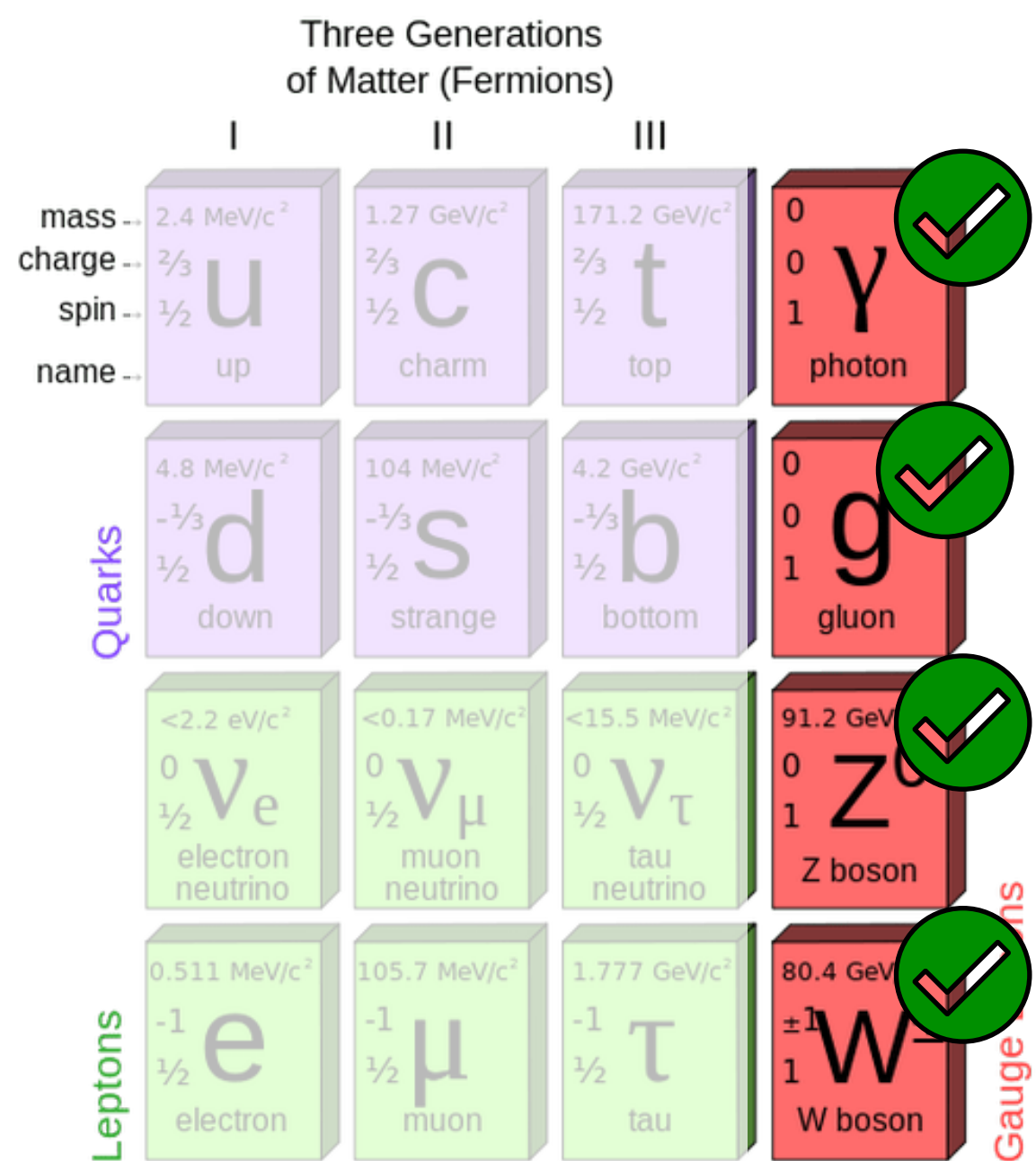
Higgs boson couplings with SM particles



Higgs with gauge bosons

- Couplings to vector bosons in $H \rightarrow ZZ$, $H \rightarrow WW$ and indirectly in $H \rightarrow \gamma\gamma$ well established since Run-1
 - gluon-fusion production (loop process) precisely determined: $\sim 5\%$ uncertainty
 - VBF production observed at $> 5 \sigma$ (ATLAS+CMS)

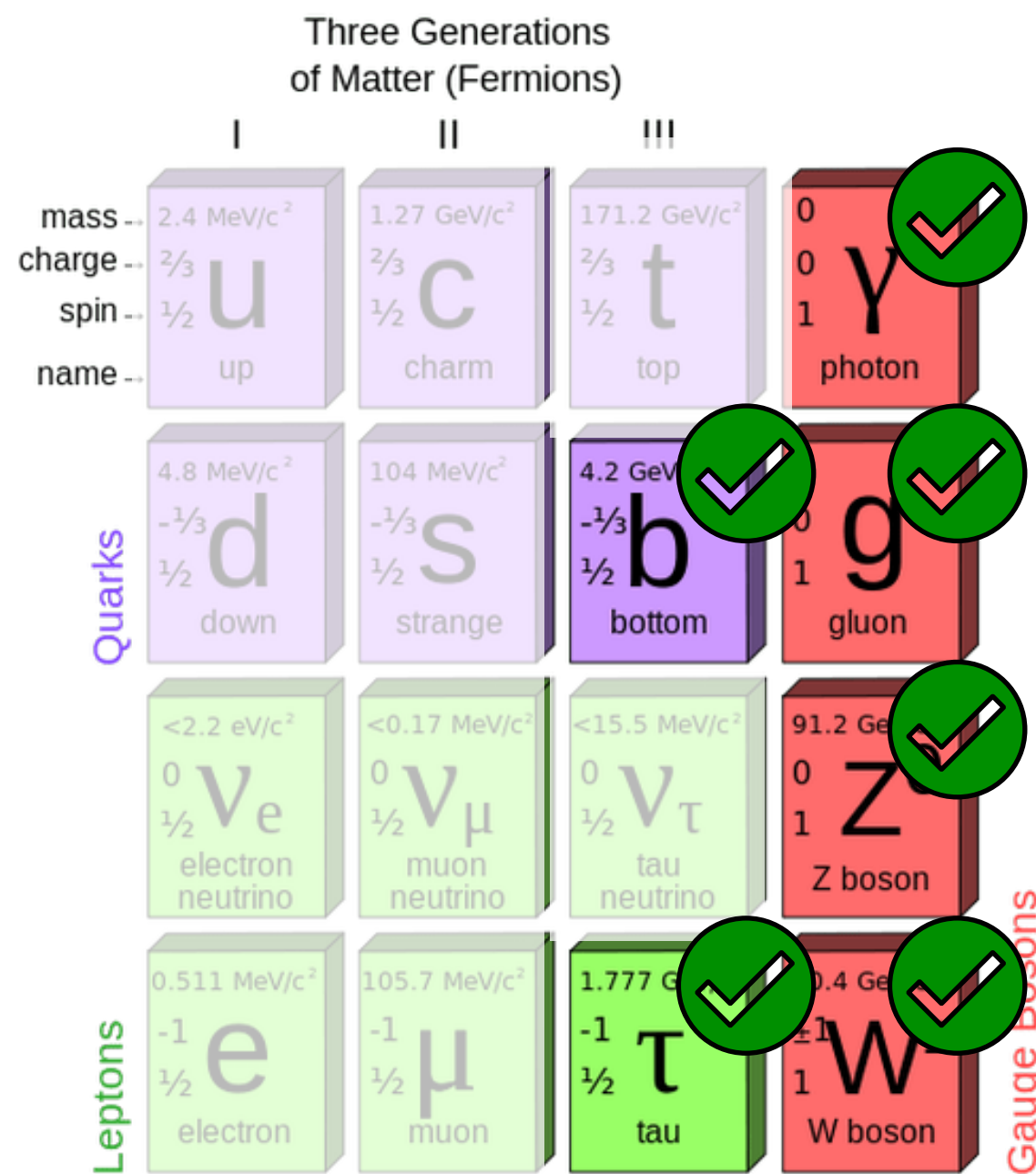
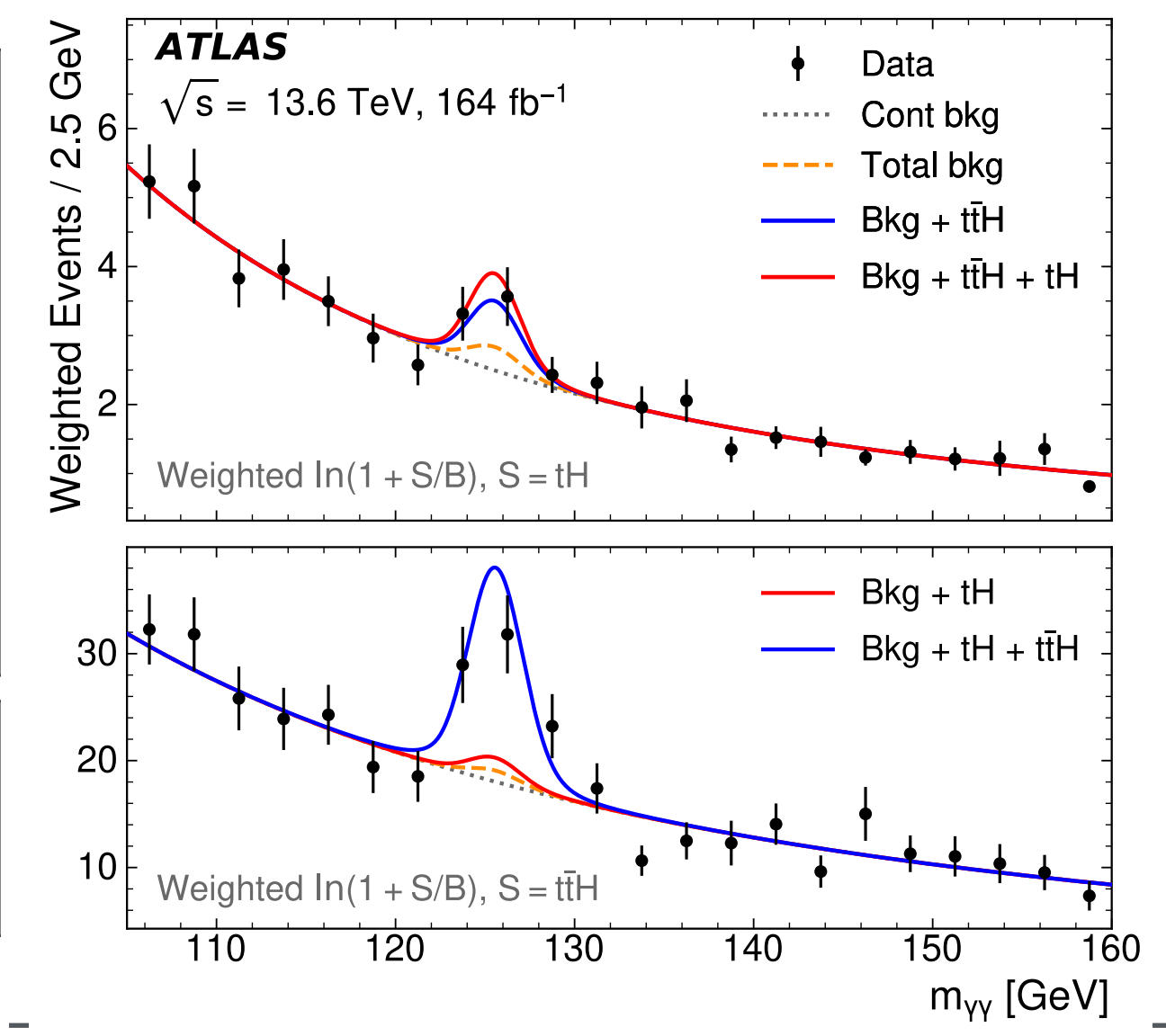
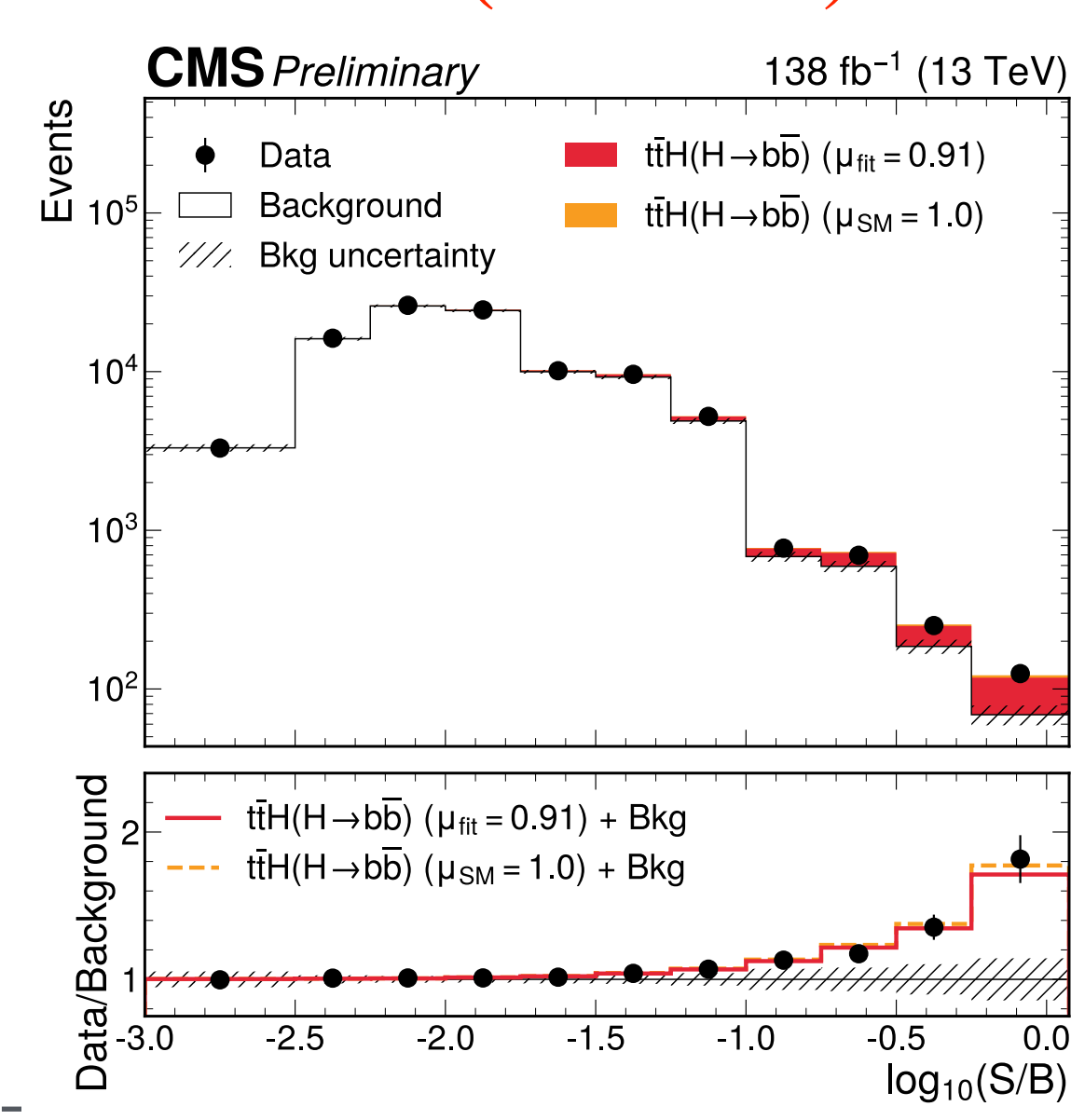
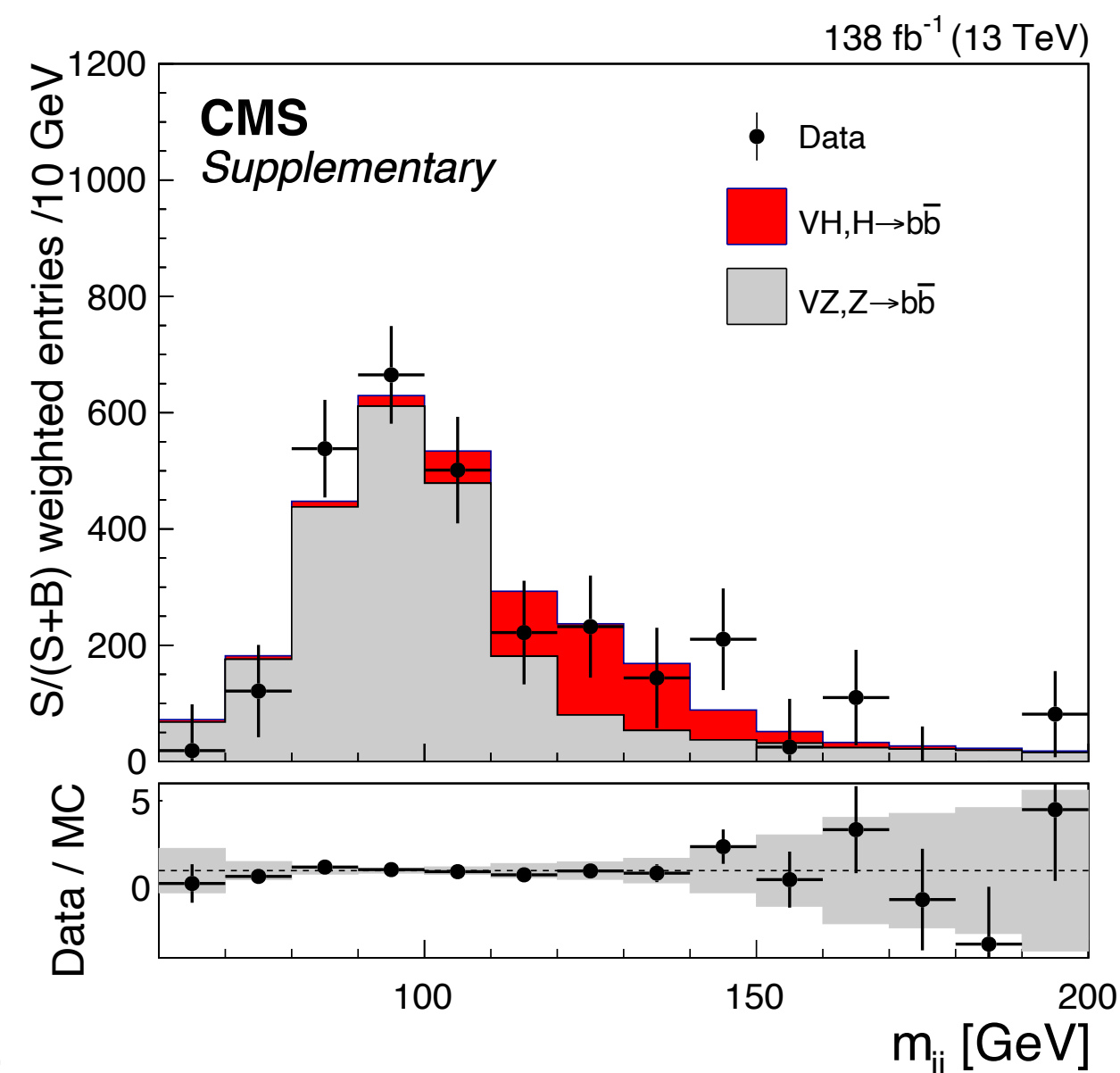
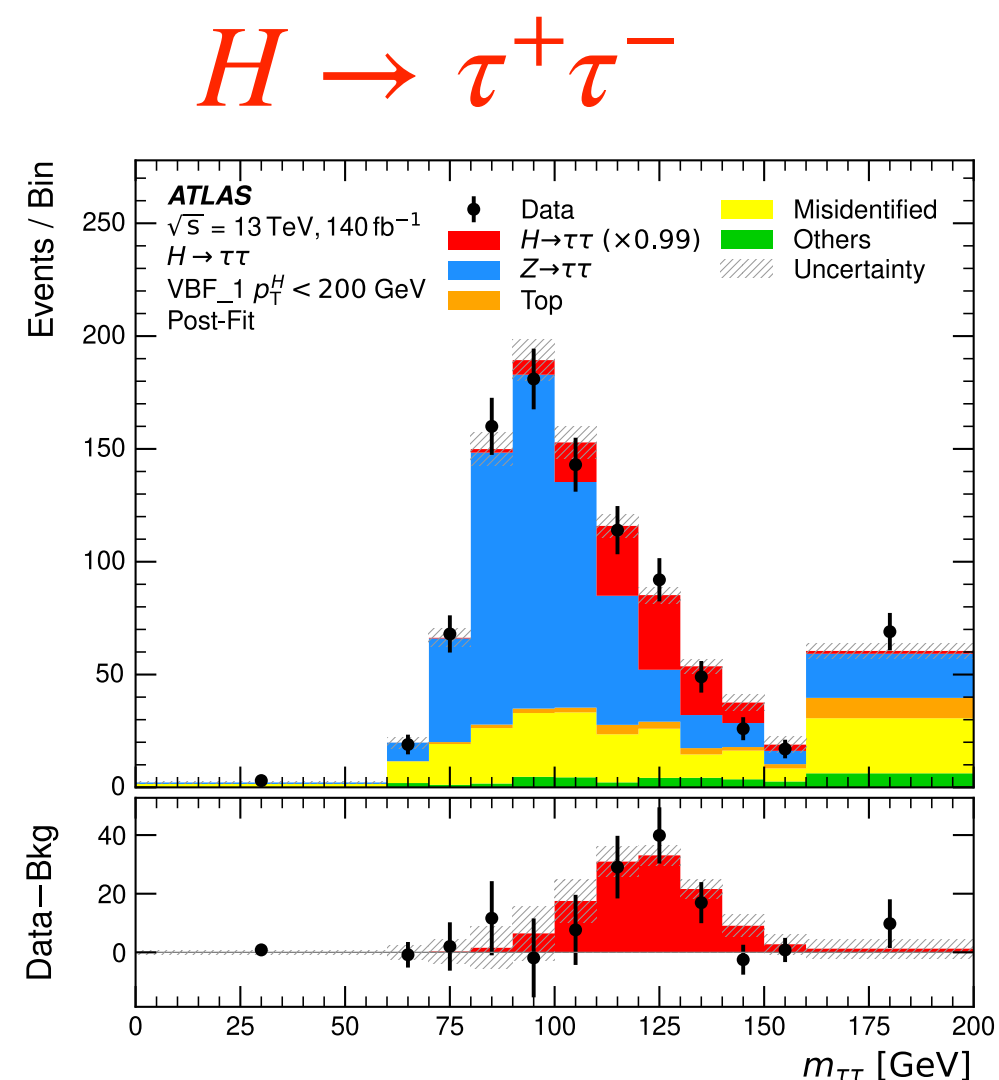
State of the art

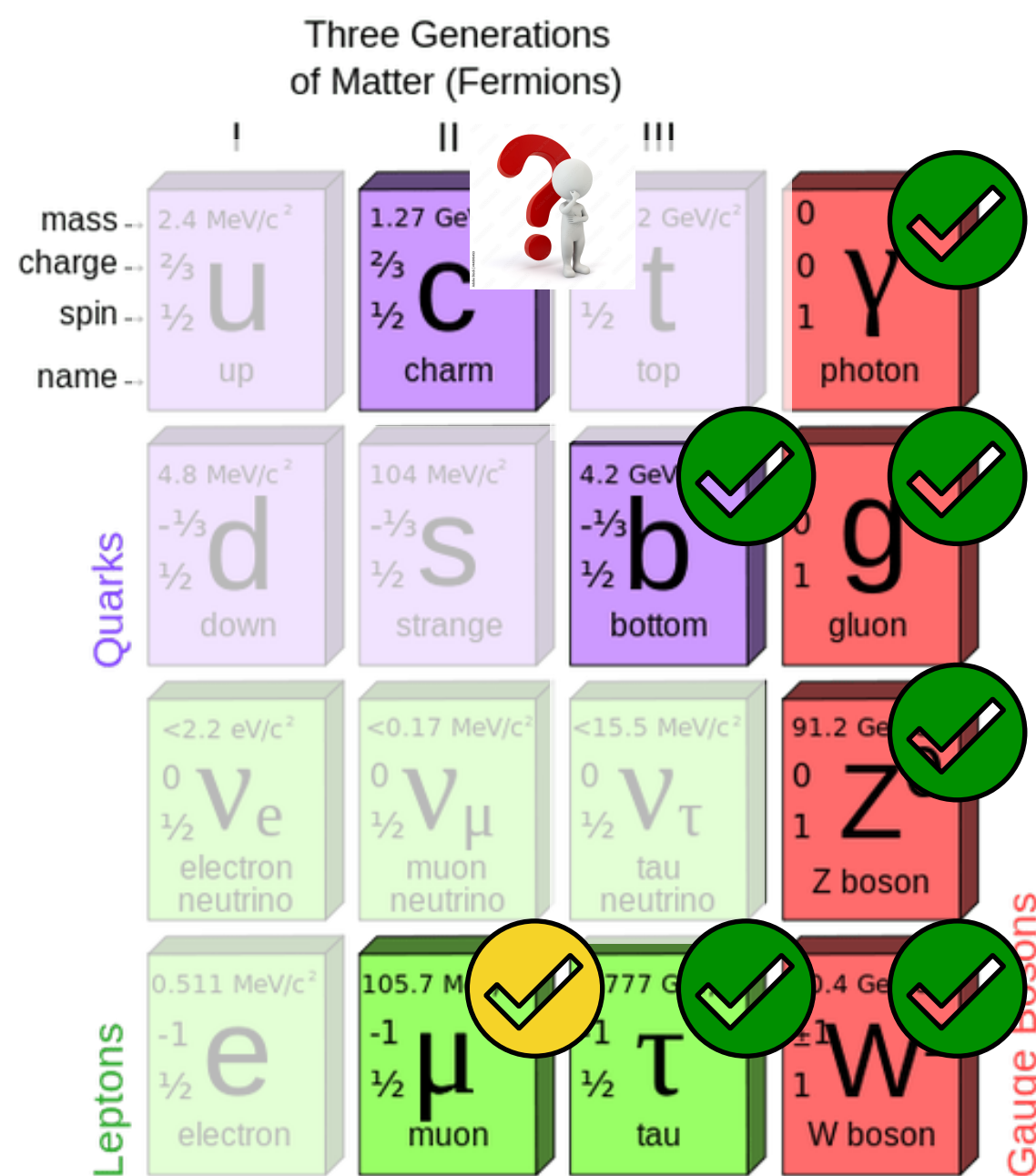


Higgs and 3rd generation fermions

- Couplings to 3rd generation fermions:
 - $H \rightarrow \tau\tau$: observed at $> 5\sigma$
 - $H \rightarrow b\bar{b}$: observed in the associated VH(bb) production at $> 5\sigma$
- Top quark Yukawa coupling $y_t \sim 1$:
 - can be inferred indirectly from loops in ggH production and $H \rightarrow \gamma\gamma$ decay
 - observed directly in ttH associated production in combination of different channels, and also in a single channel mode ($H \rightarrow \gamma\gamma$)

State of the art


$$H \rightarrow b\bar{b}$$
 $t\bar{t}H(H \rightarrow b\bar{b})$ $t\bar{t}H, H \rightarrow \gamma\gamma$ 



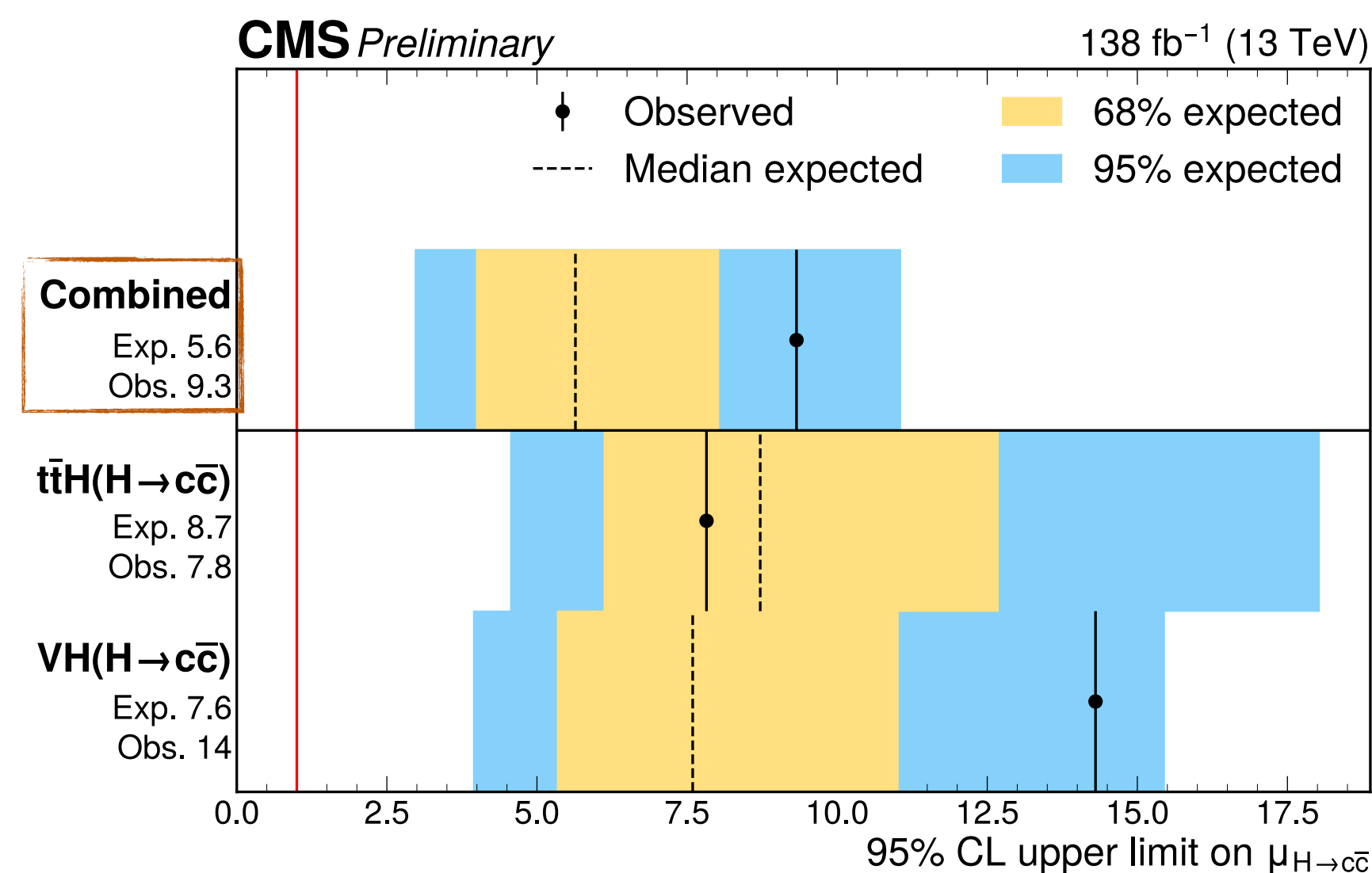
- Couplings to 2nd generation (small BRs: $y_f \propto m_f$):
 - Evidence of $H \rightarrow \mu\mu$ at 3.0σ for both CMS and ATLAS
 - challenging $H \rightarrow c\bar{c}$

$$VH(H \rightarrow c\bar{c})$$

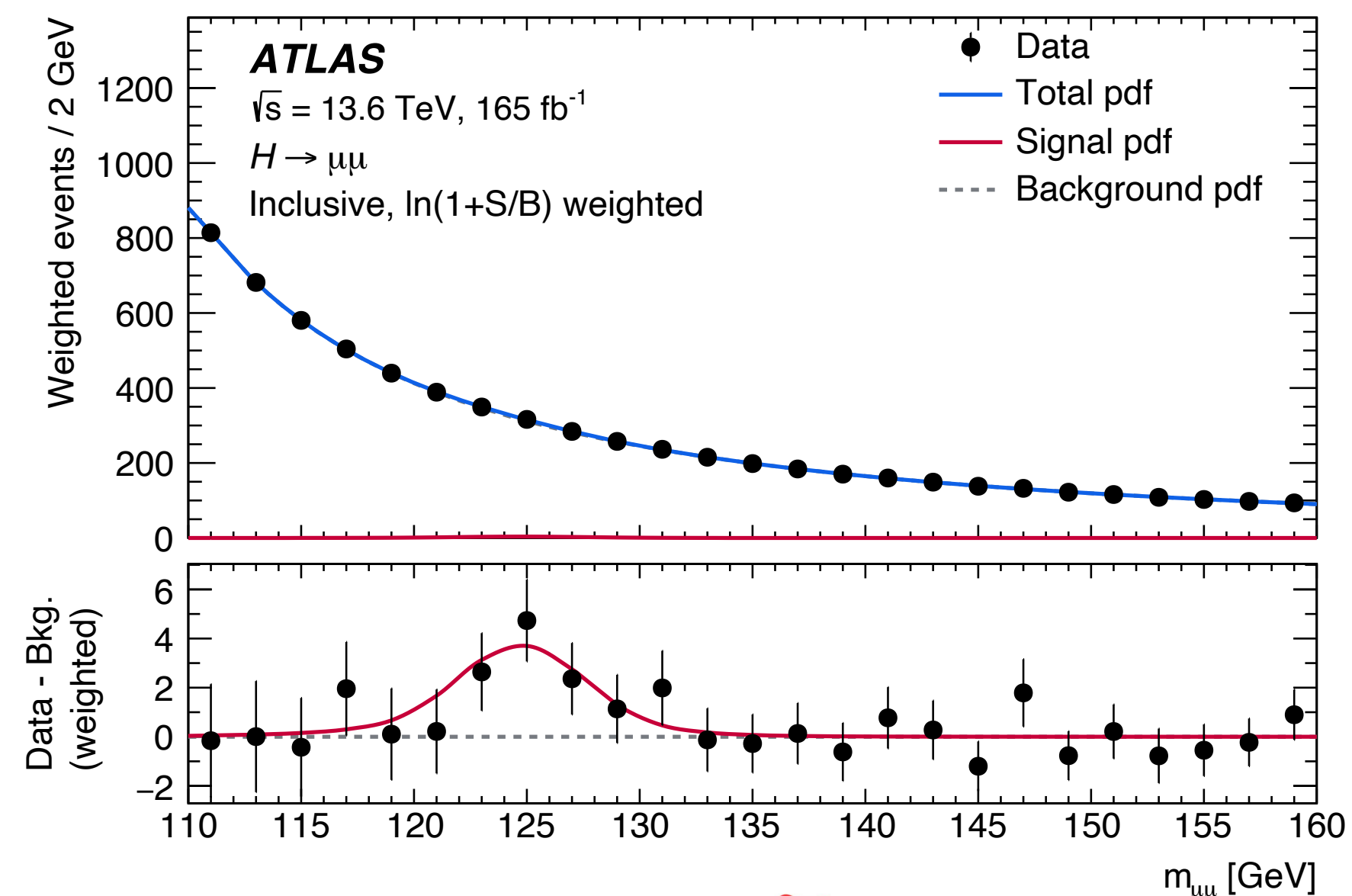
$$t\bar{t}H(H \rightarrow c\bar{c})$$

$$H \rightarrow \mu^+\mu^-$$

More on these recent results later on



Will need much more data to observe $H \rightarrow c\bar{c}$

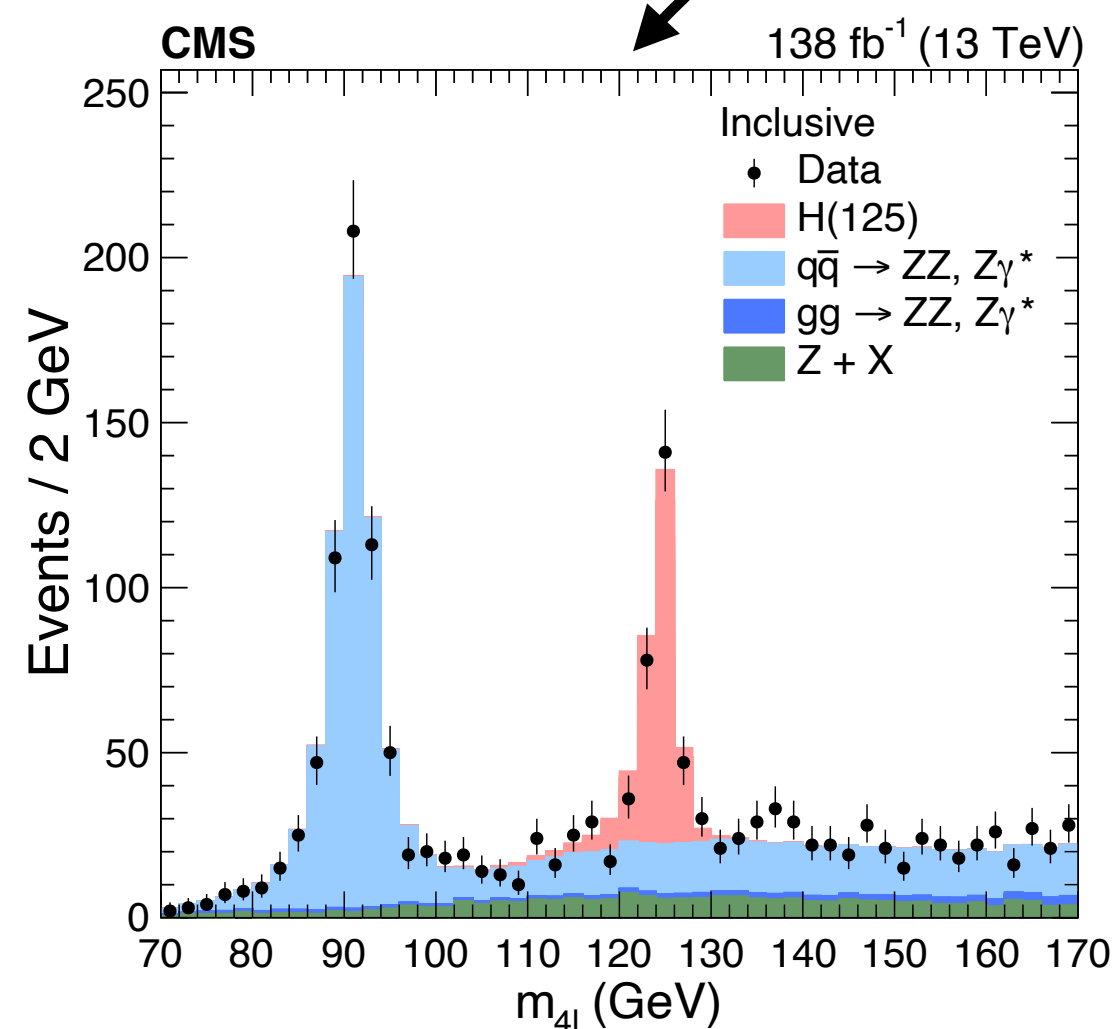


The experimental likelihood is constructed in each channel “ r ” to extract the Higgs signal rate (s_r^{if}) on top of (usually) a much larger background b_r

- Simultaneously in many production modes “ i ” and several decays “ f ”

$$L_r(\vec{x}; \vec{\alpha}, \vec{\theta}) = \text{Pois} \left(n; \sum_{if} s_r^{if}(\vec{\alpha}, \vec{\theta}) + b_r(\vec{\theta}) \right) \cdot \prod_d p(\vec{x}_d; \vec{\alpha}, \vec{\theta}).$$

Data:
observed counts



The experimental likelihood is constructed in each channel “ r ” to extract the Higgs signal rate (s_r^{if}) on top of (usually) a much larger background b_r

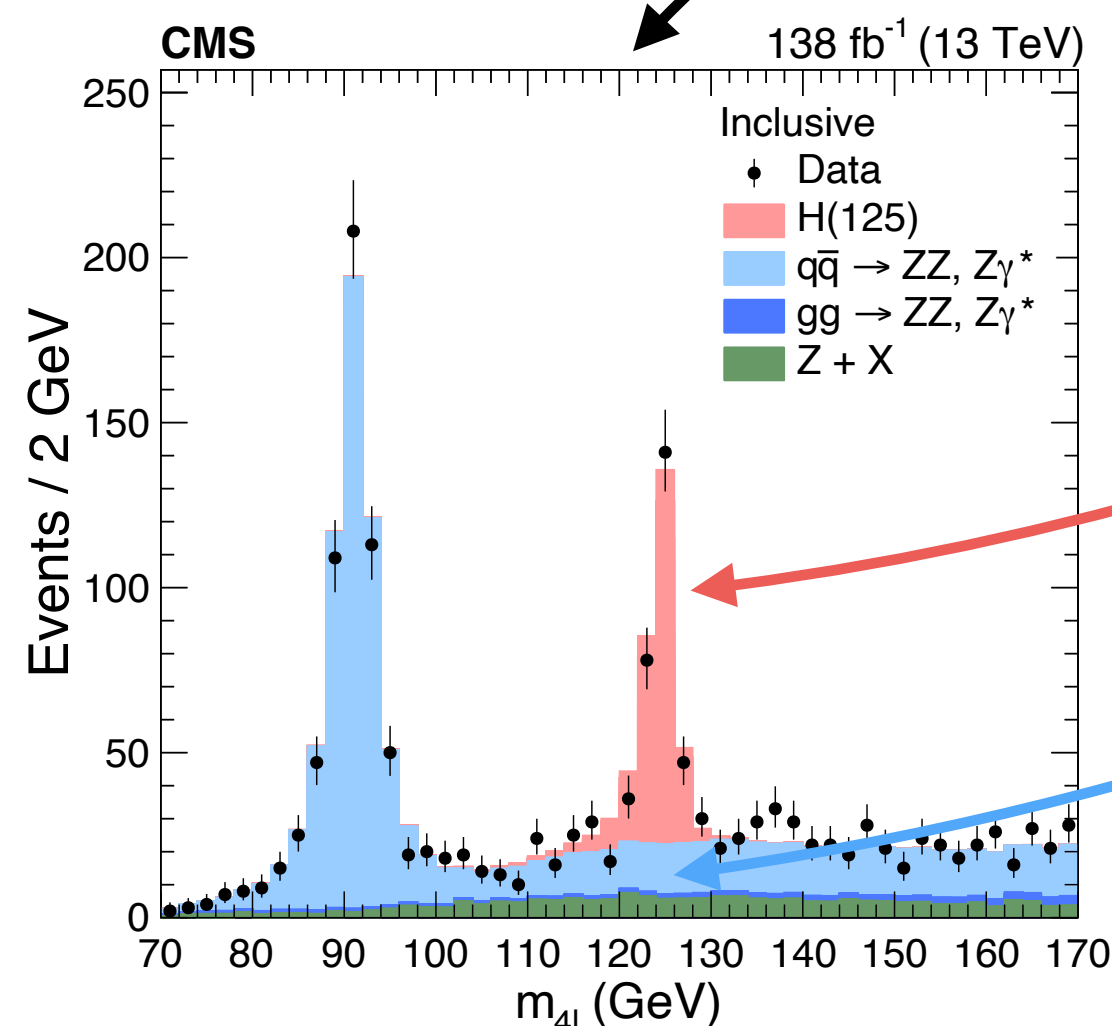
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Data:
observed counts

Inference:
Signal yield

Inference:
Background(s) yield



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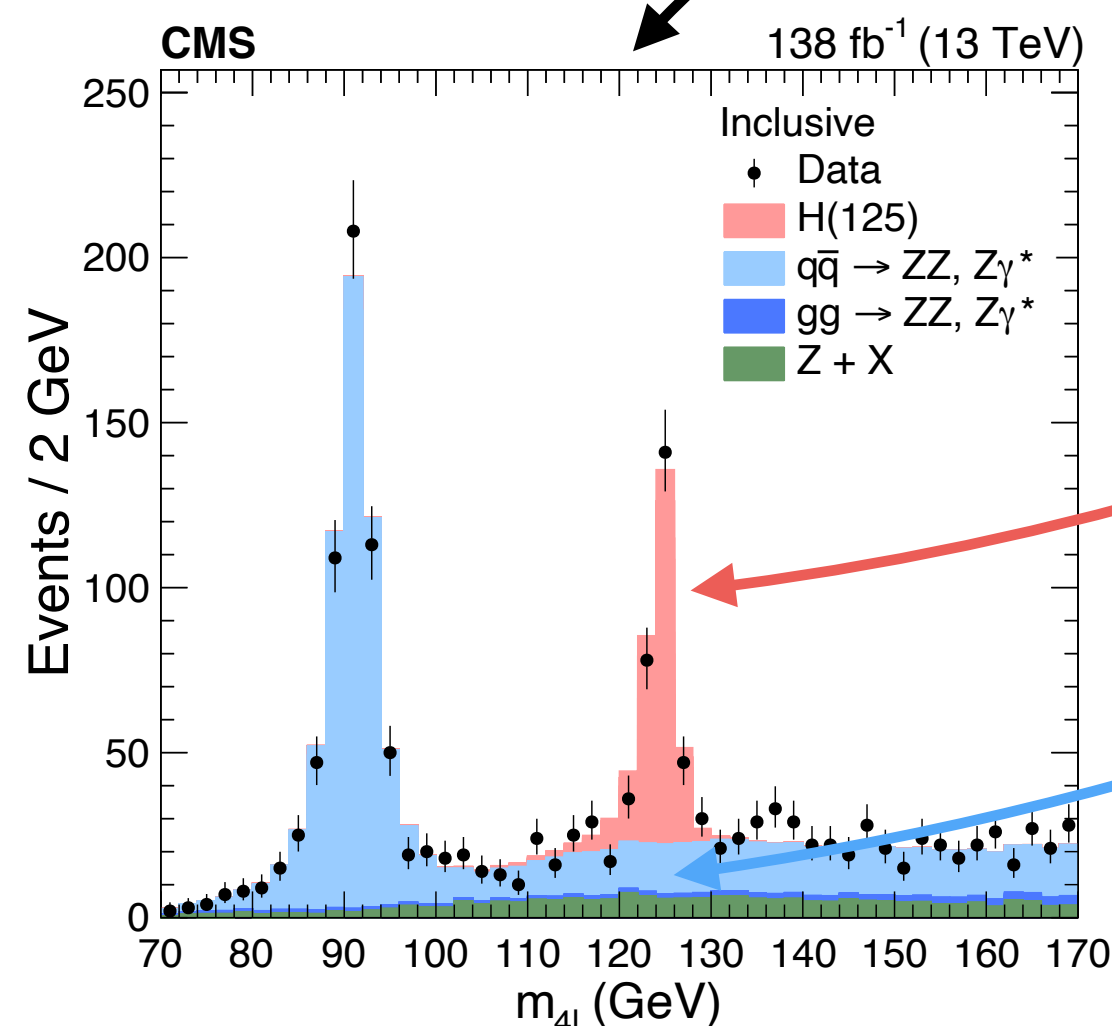
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Data:
observed counts

Inference:
Signal yield

Inference:
Background(s) yield

Nuisance parameters:
encode the model of all
experimental and
theoretical **systematic**
uncertainties



The experimental likelihood is constructed in each channel “ r ” to extract the Higgs signal rate (s_r^{if}) on top of (usually) a much larger background b_r

- Simultaneously in many production modes “ i ” and several decays “ f ”

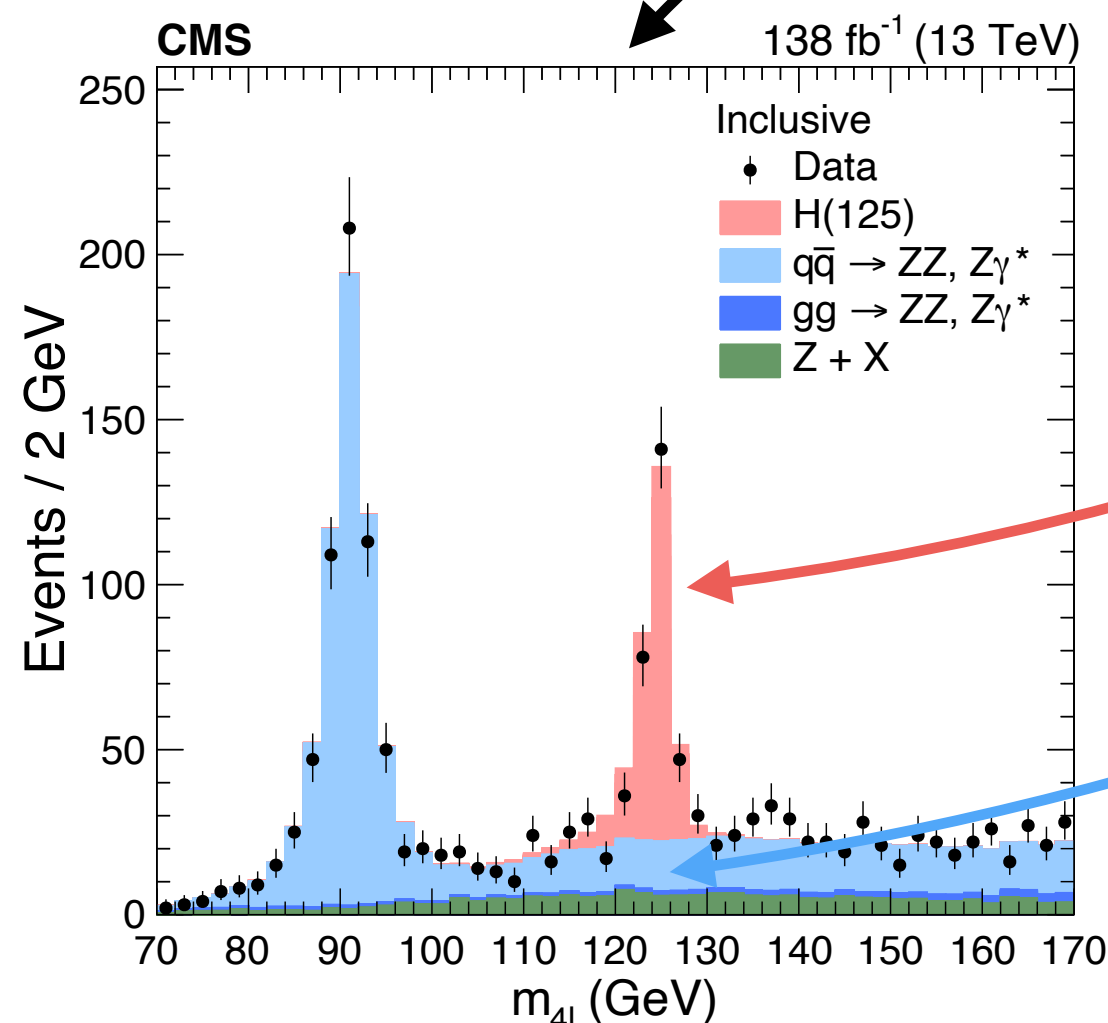
$$L_r(\vec{x}; \vec{\alpha}, \vec{\theta}) = \text{Pois} \left(n; \sum_{if} s_r^{if}(\vec{\alpha}, \vec{\theta}) + b_r(\vec{\theta}) \right) \cdot \prod_d p(\vec{x}_d; \vec{\alpha}, \vec{\theta}).$$

Data:
observed counts

Inference:
Signal yield

Inference:
Background(s) yield

Nuisance parameters:
encode the model of all
experimental and
theoretical **systematic**
uncertainties



$$s_r^{if} = \mu^i \cdot \mu^f \cdot [\sigma^i \times BR^f]_{SM} \cdot \epsilon^{if} \cdot \mathcal{L}_{int}$$

“**Signal strengths**” approach: rates relative to SM:

$$\mu_i = \frac{\sigma^i}{\sigma_{SM}^i} \quad \text{and} \quad \mu_f = \frac{BR^f}{BR_{SM}^f}$$

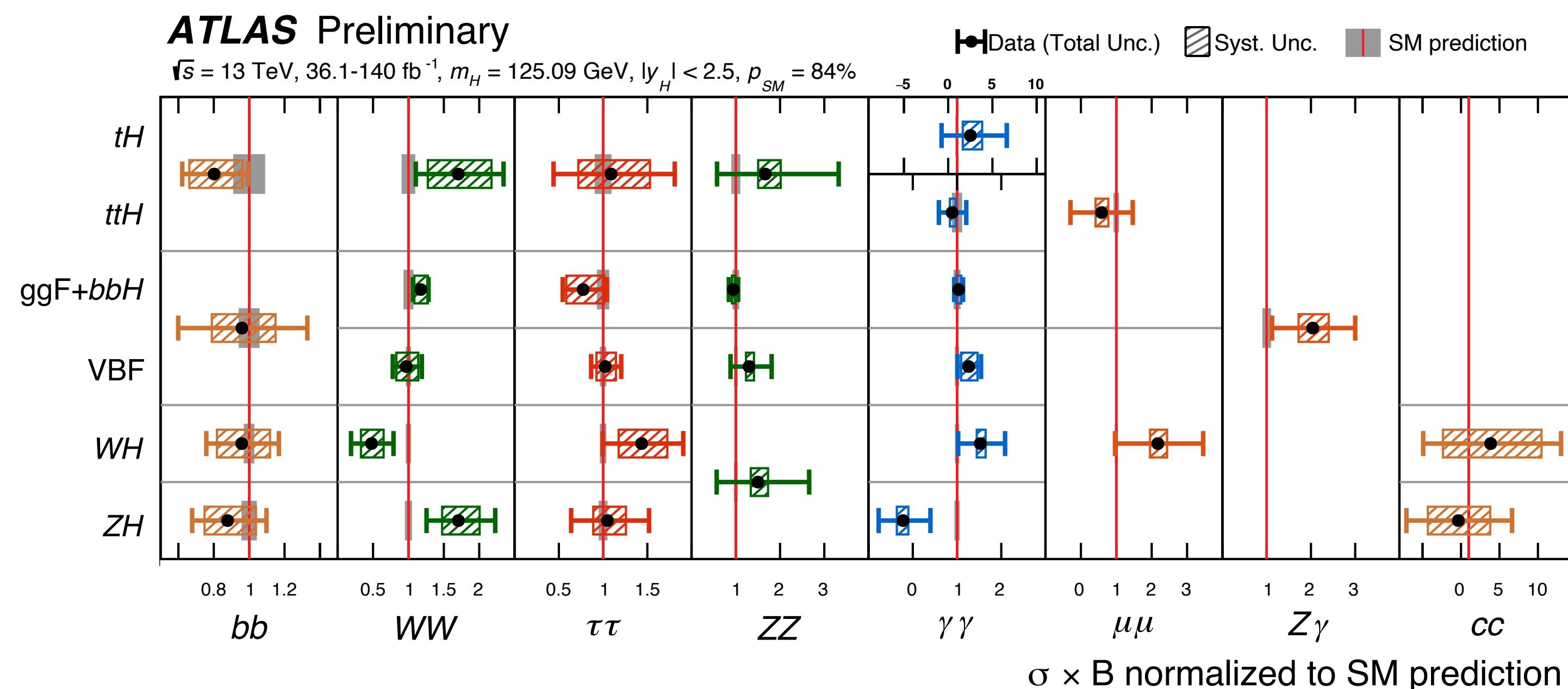
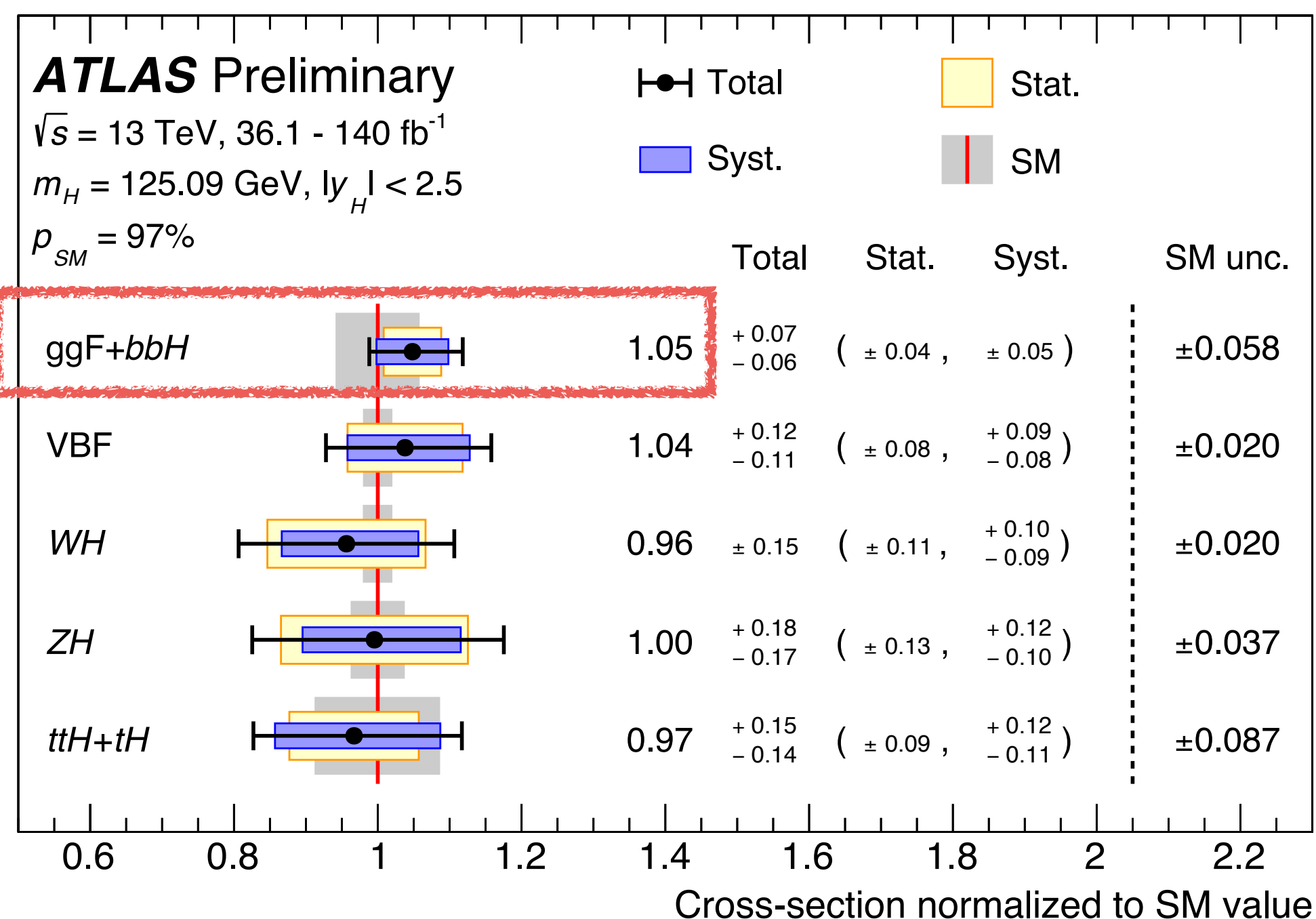
Precision era for Higgs physics:

State of the art

$$\mu = 1.023 \pm 0.056 = 1.023 \pm 0.028 \text{ (stat.)}^{+0.026}_{-0.25} \text{ (exp.)}^{+0.039}_{-0.036} \text{ (sig. theo.)} \pm 0.012 \text{ (bkg. theo.)}$$

New combination of inclusive / per-production / per Higgs decay σ 's

ATLAS-CONF-2025-006



largest production / decays:

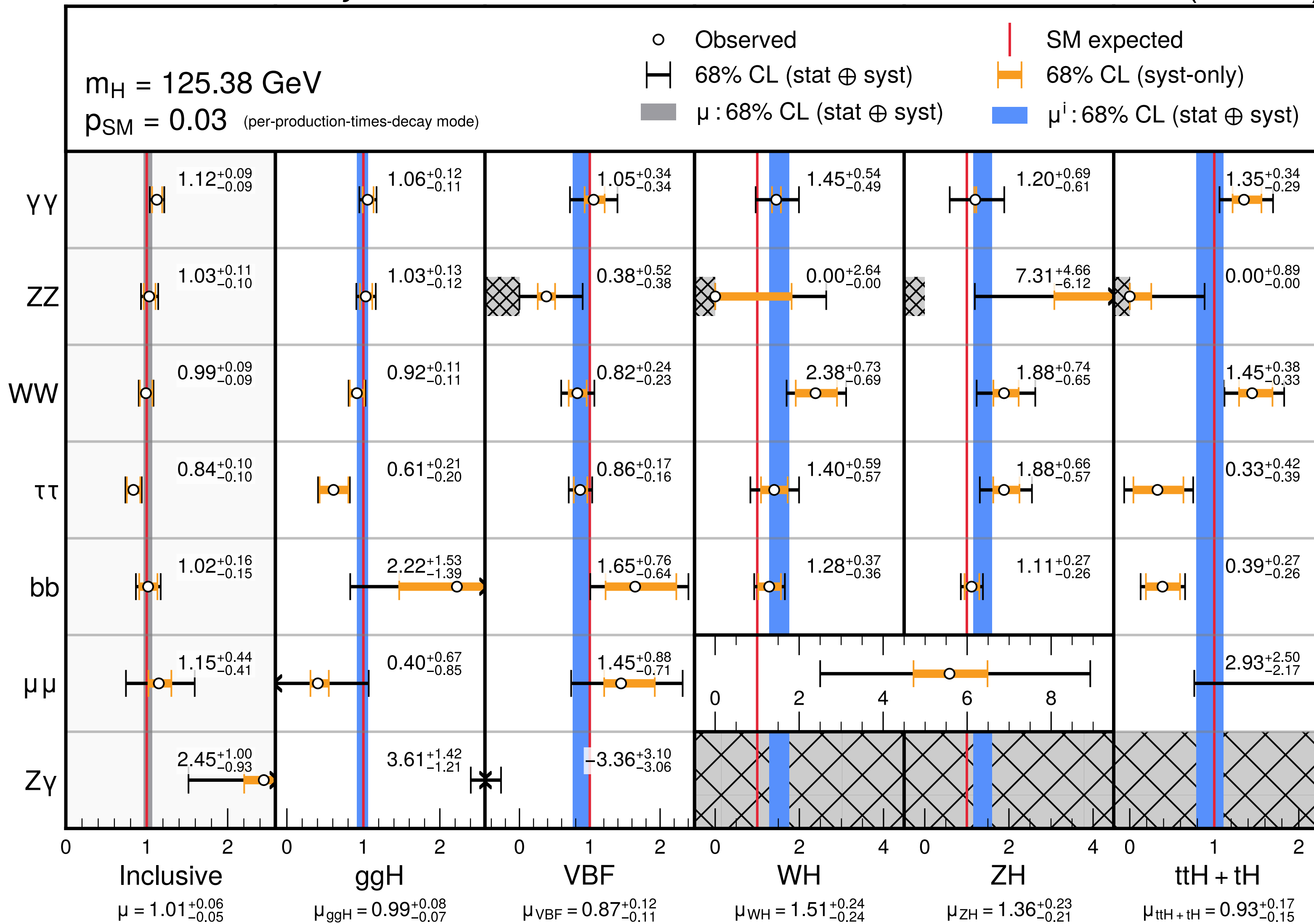
$\sigma_{stat} \sim \sigma_{syst} : \sim 5\% \text{ precision}$

Split by production & decay

Results per production per decay

CMS Preliminary

138 fb⁻¹ (13 TeV)



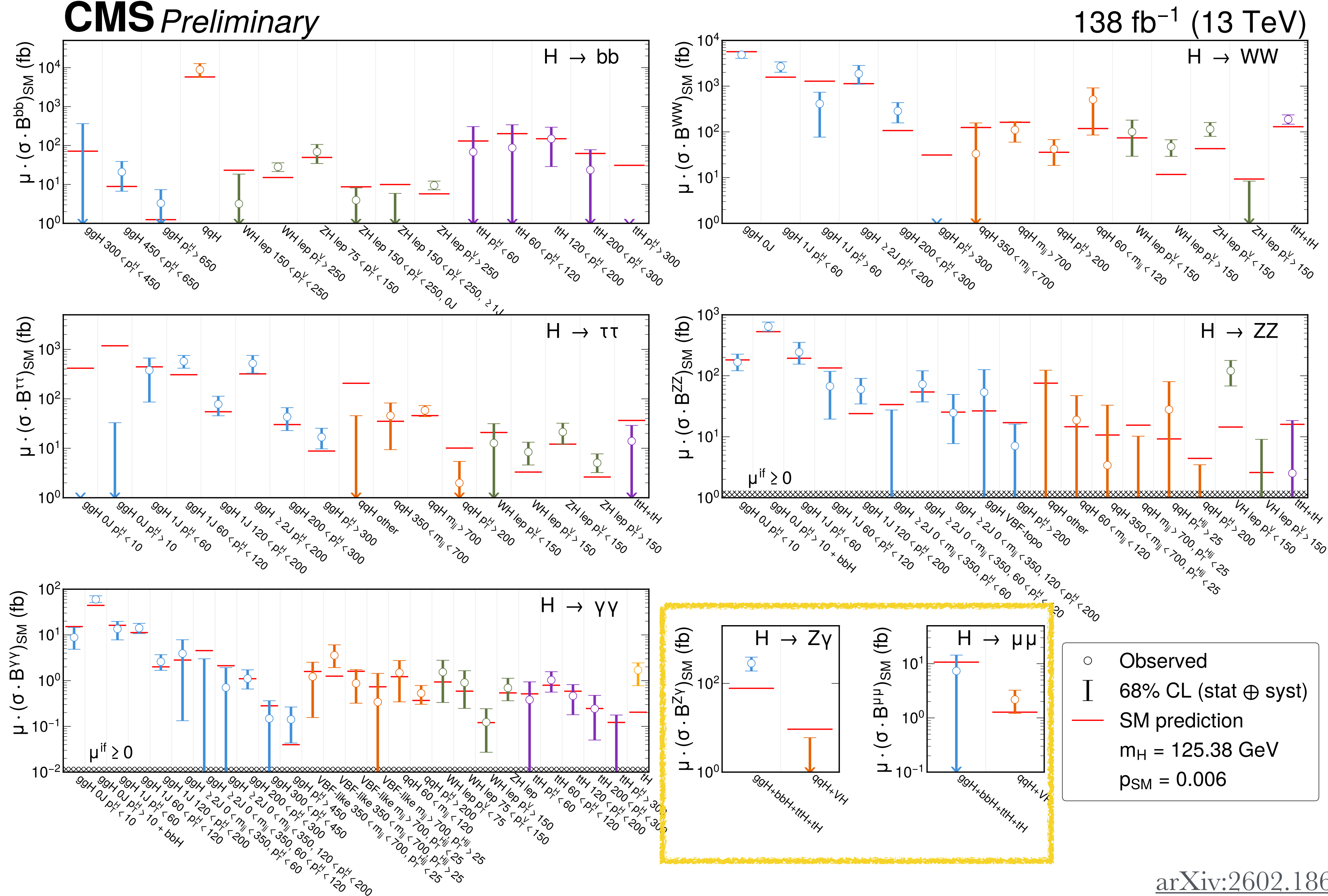
Relaxed theory assumptions:
 μ_i and μ_f separate for each
 production mode and for each
 decay mode

[arXiv:2602.18611](https://arxiv.org/abs/2602.18611)

State of the art

The most differential $\sigma \times \mathcal{B}$ fit

CMS Preliminary



Measured $97 \sigma^i \times BR^f$:

$$\mu^{if} = \frac{[\sigma^i \times BR^f]_{\text{obs}}}{[\sigma^i \times BR^f]_{\text{SM}}}$$

Higgs cross sections
measured **over 4**
orders of magnitude

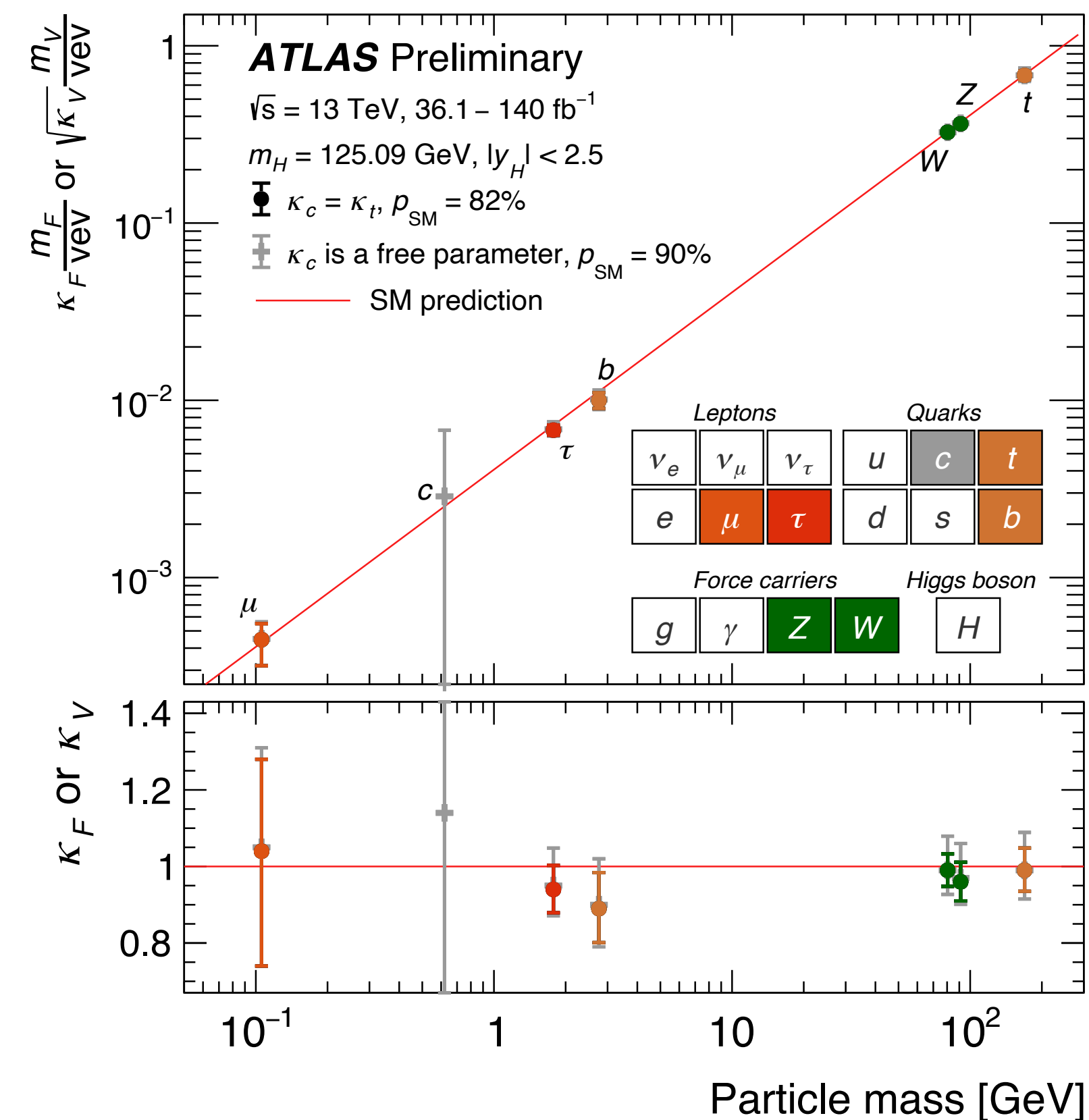
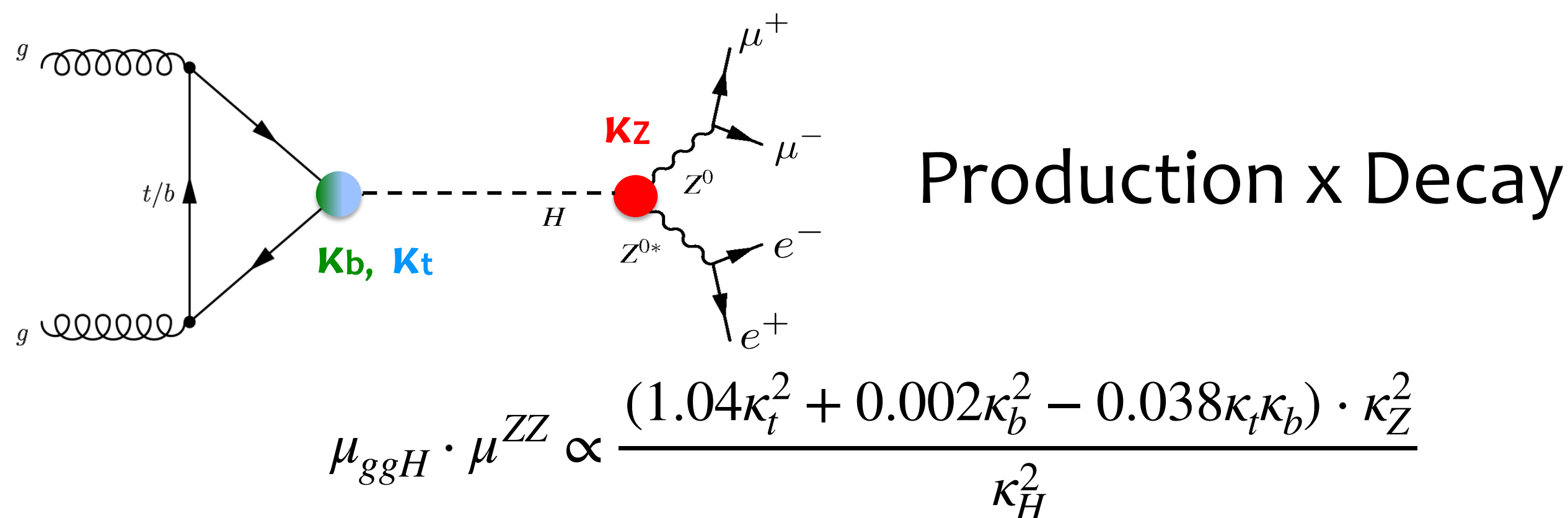
Evidence for **rare**
decays: $H \rightarrow \mu\mu$,
 $H \rightarrow Z\gamma$

State of the art

arXiv:2602.18611

The likelihood can be explicitly written in terms of “coupling modifiers”: **κ -framework**

$$\mu_i = \frac{\sigma^i}{\sigma_{SM}^i} \quad \text{and} \quad \mu_f = \frac{BR^f}{BR_{SM}^f} \quad \mu \rightarrow \mu(\kappa): \mu^{if}(\kappa) = \sigma^i(\kappa) BR^f(\kappa) = \frac{\sigma^i(\kappa) \Gamma^f(\kappa)}{\Gamma_H(\kappa)}$$



State of the art

In the SM, Higgs couplings to particles are **proportional to particle masses** => test the SM

- Couplings to **W/Z at 5-10%**
- Couplings to **3rd generation to 10-20%**
- Couplings to **2nd generation 50%**

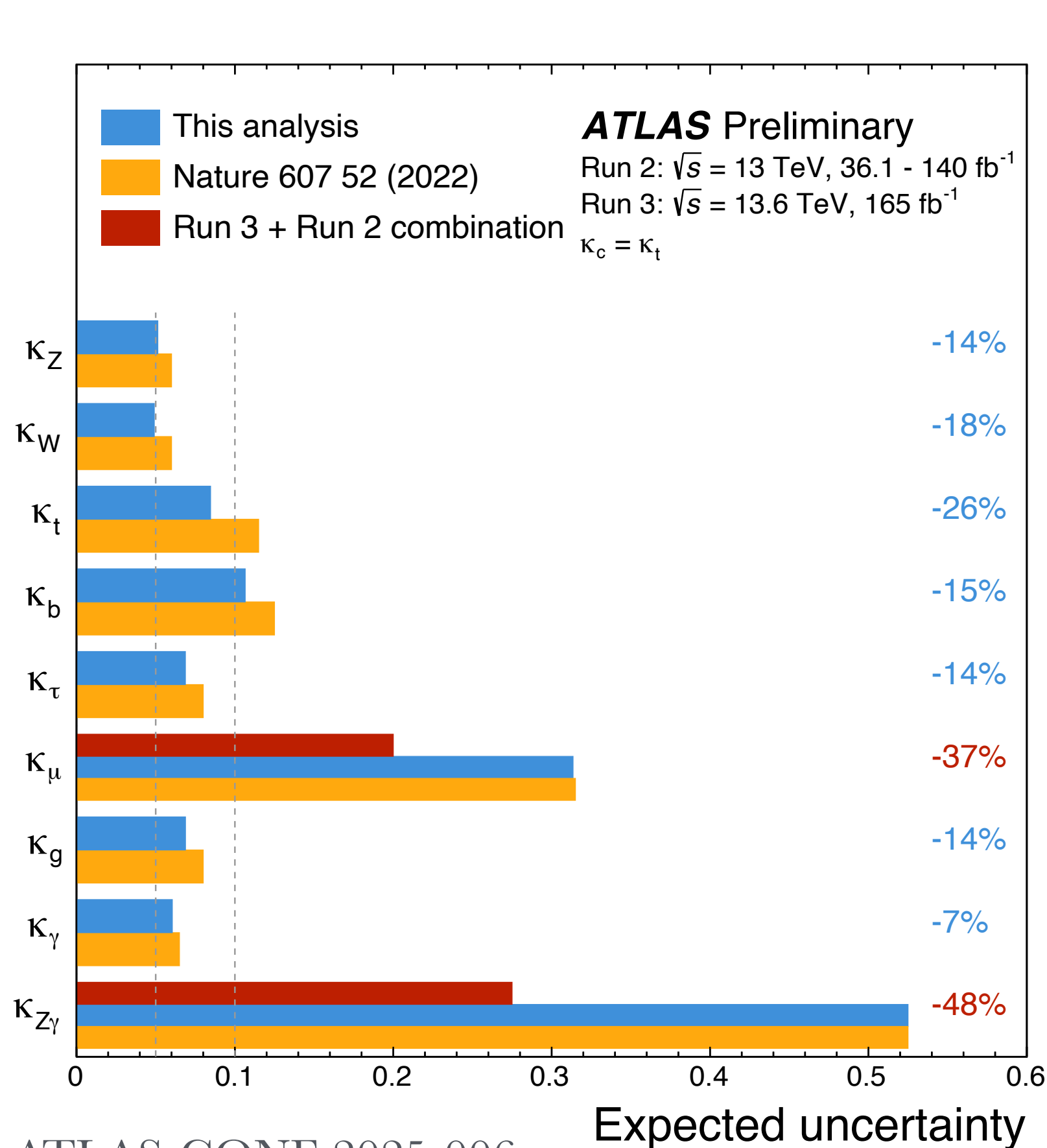
ATLAS-CONF-2025-006

Why improving precision on K ?

In the SM, all $\kappa_i = 1$. In BSM, $\kappa = 1 + \Delta\kappa$

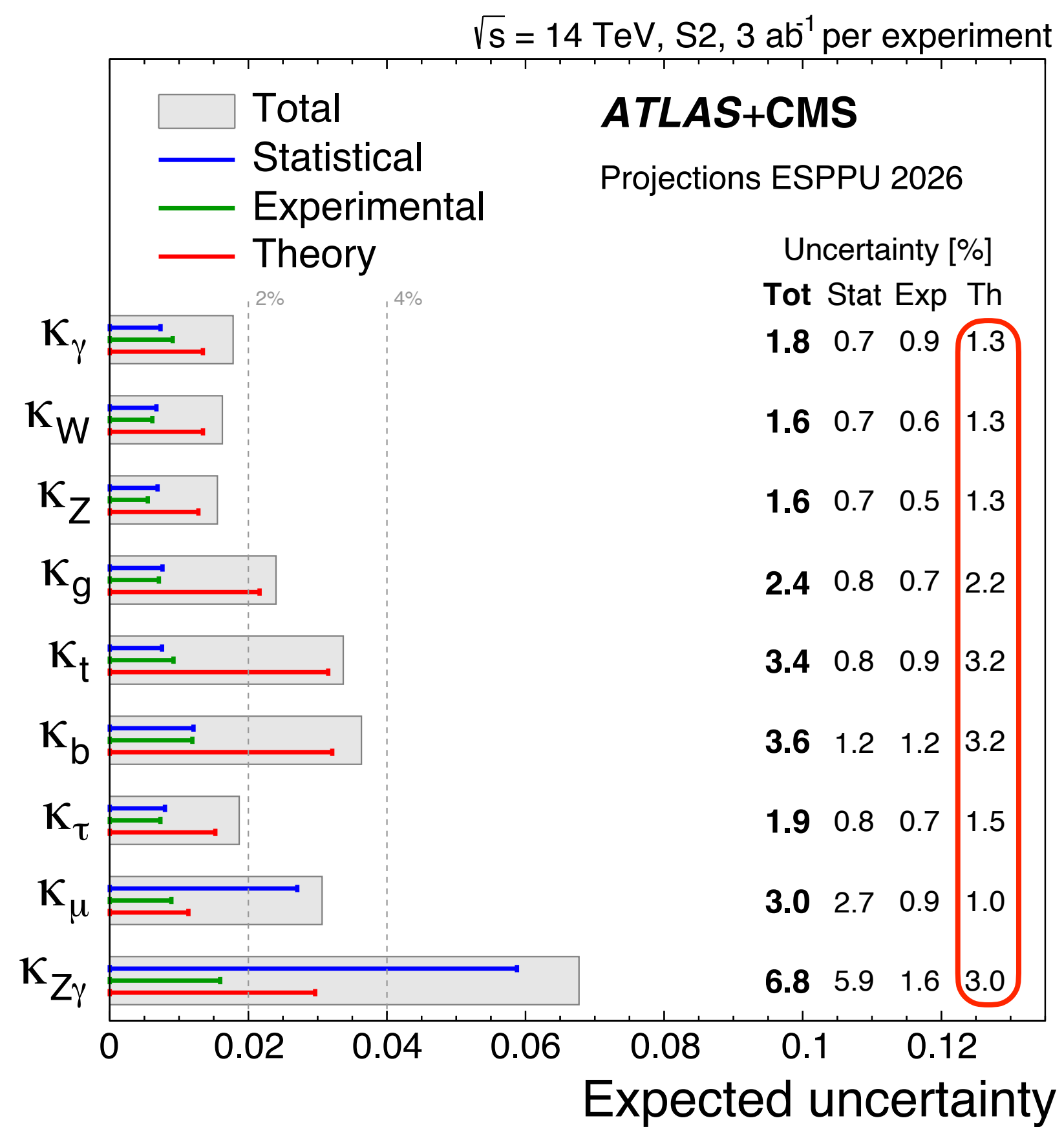
ATL-PHYS-PUB-2025-018
CMS-HIG-25-002

$\Delta\kappa \propto v^2/\Lambda_{\text{BSM}}^2$, so precision on $\Delta\kappa \Leftrightarrow$ reach in new physics scale, Λ_{BSM} , to the TeV range



ATLAS-CONF-2025-006

ATLAS-only: Lumi $\sim 300 \text{ fb}^{-1}$

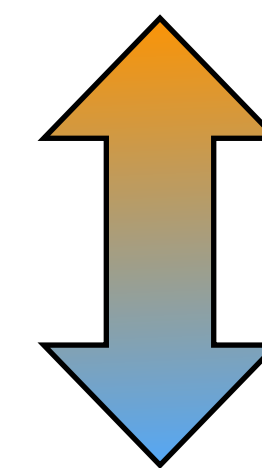


ATLAS+CMS,

HL-LHC projections 3000 fb^{-1}

$$\Delta\kappa/\kappa \sim O(v^2/\Lambda_{\text{BSM}}^2)$$

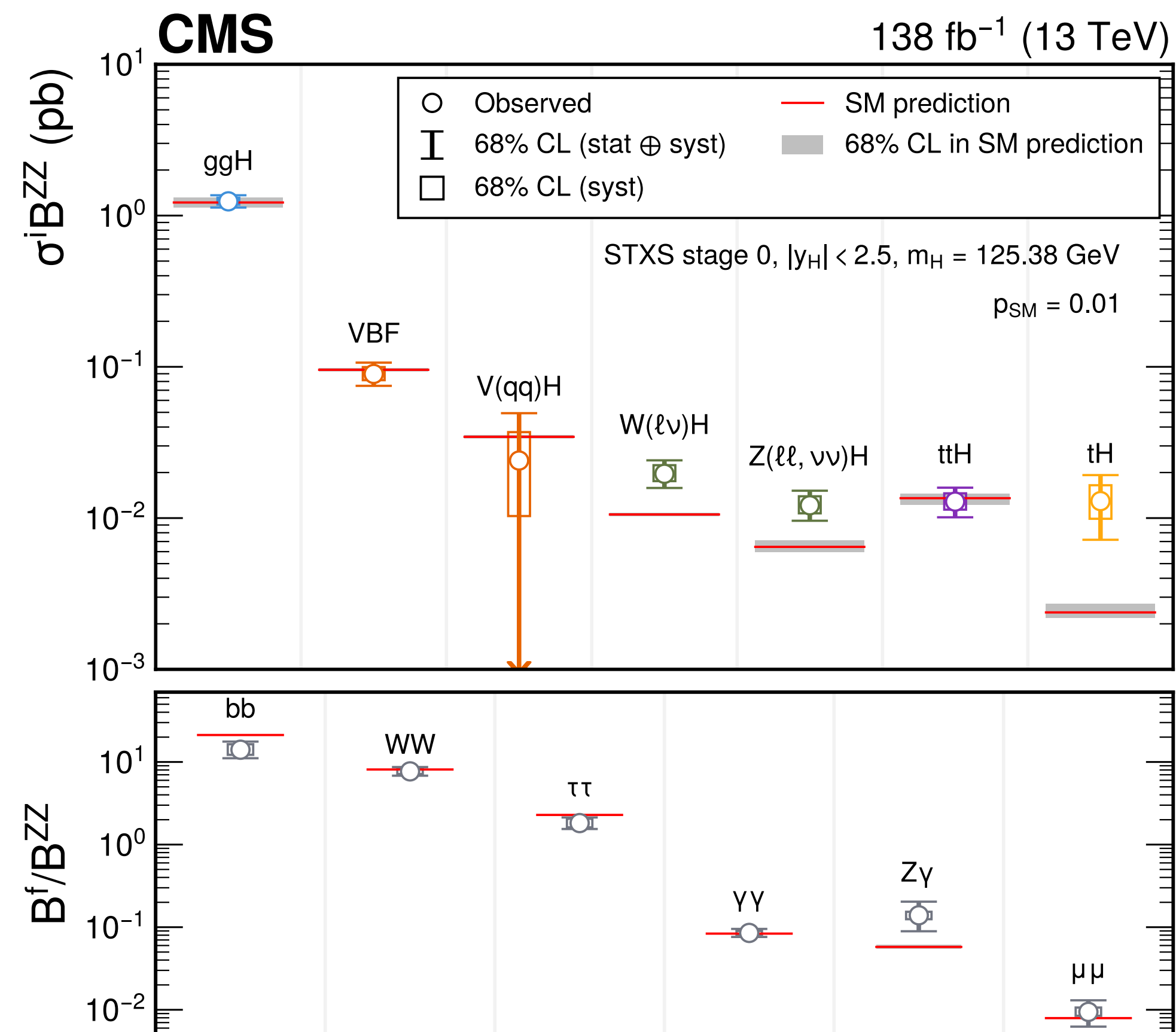
New physics at **1 TeV** =>
deviations $\Delta\kappa/\kappa \sim 6\%$



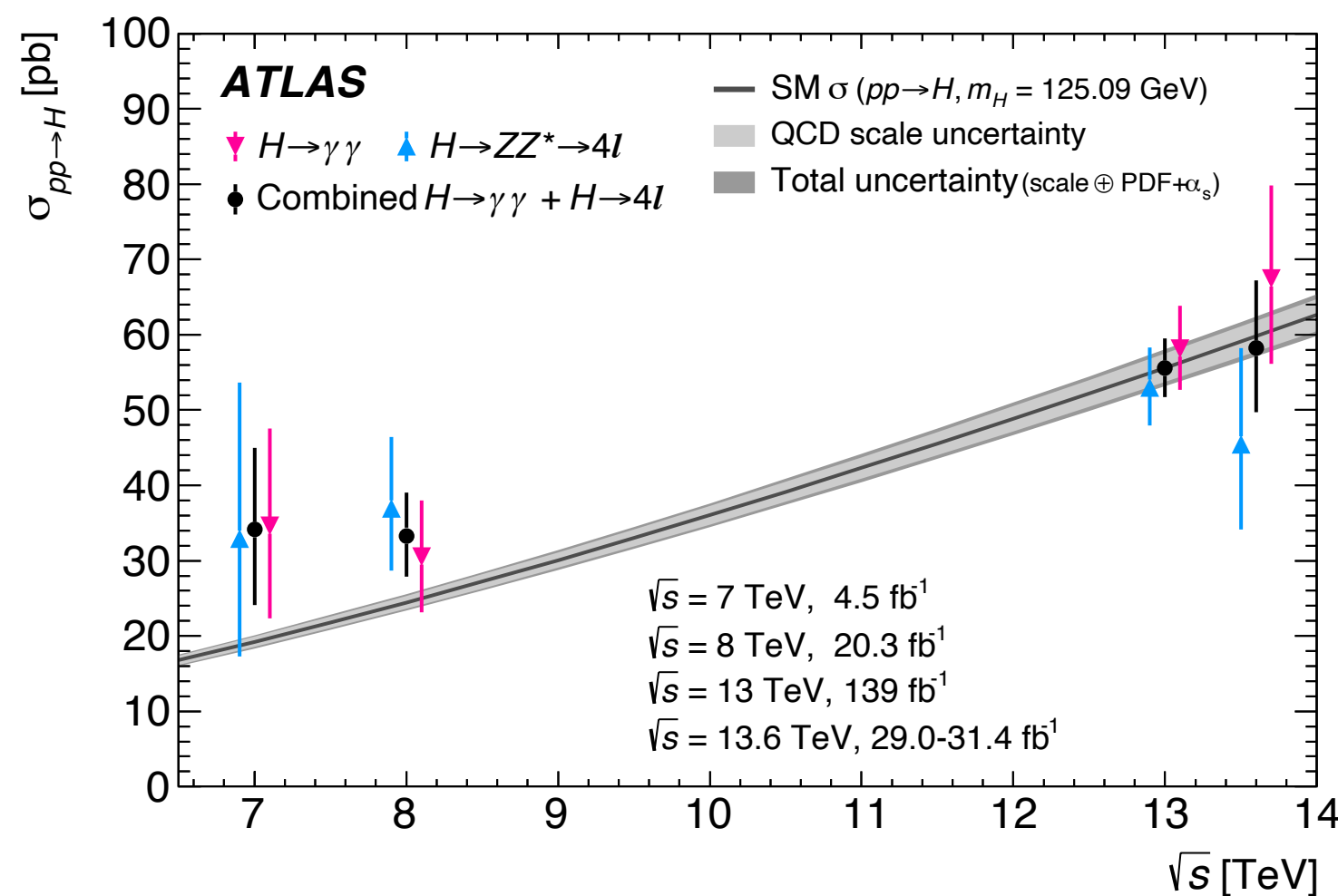
Theory uncertainties should
improve together with
experimental precision

State of the art

Higgs boson production cross sections

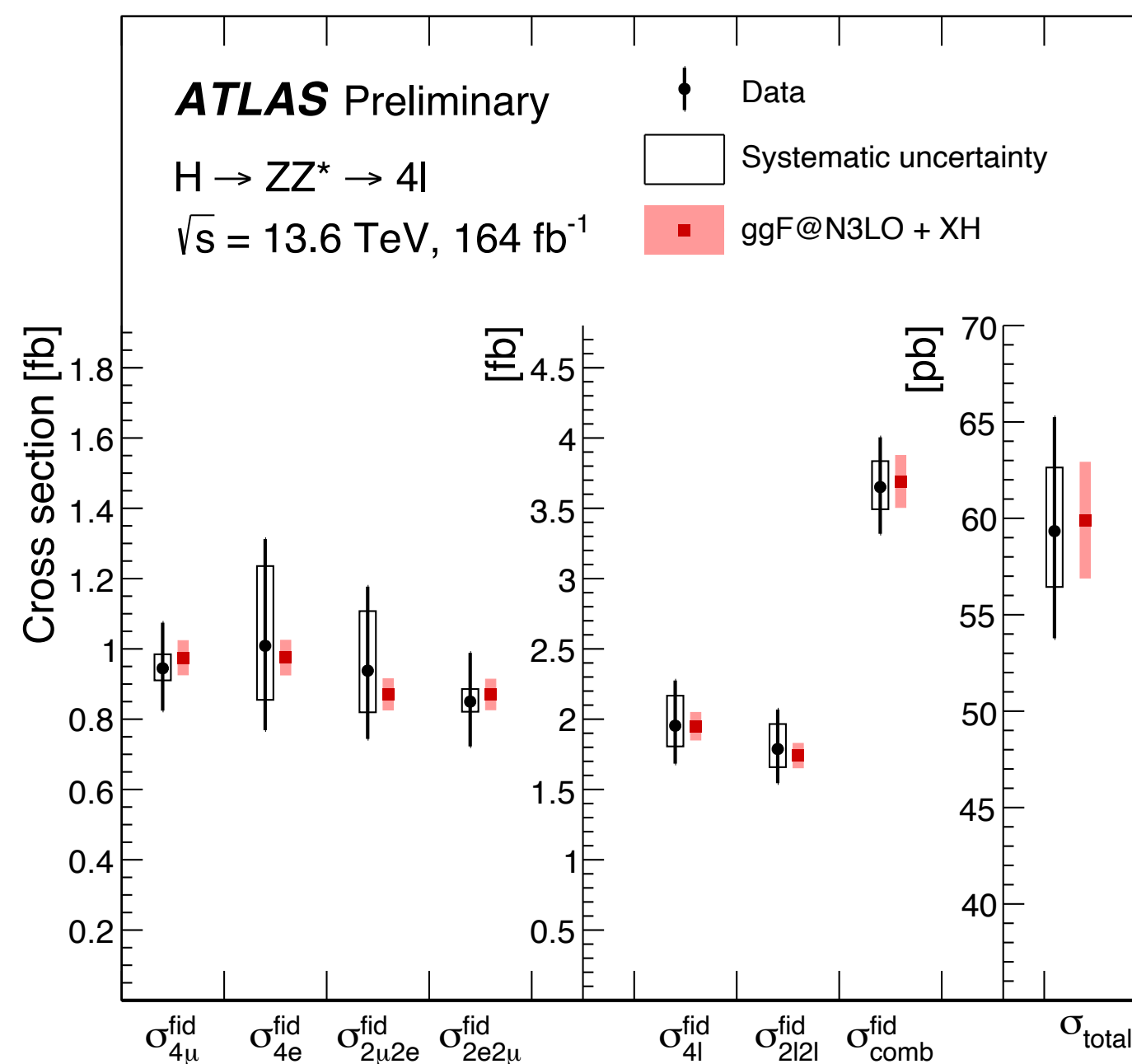


Total Higgs cross section



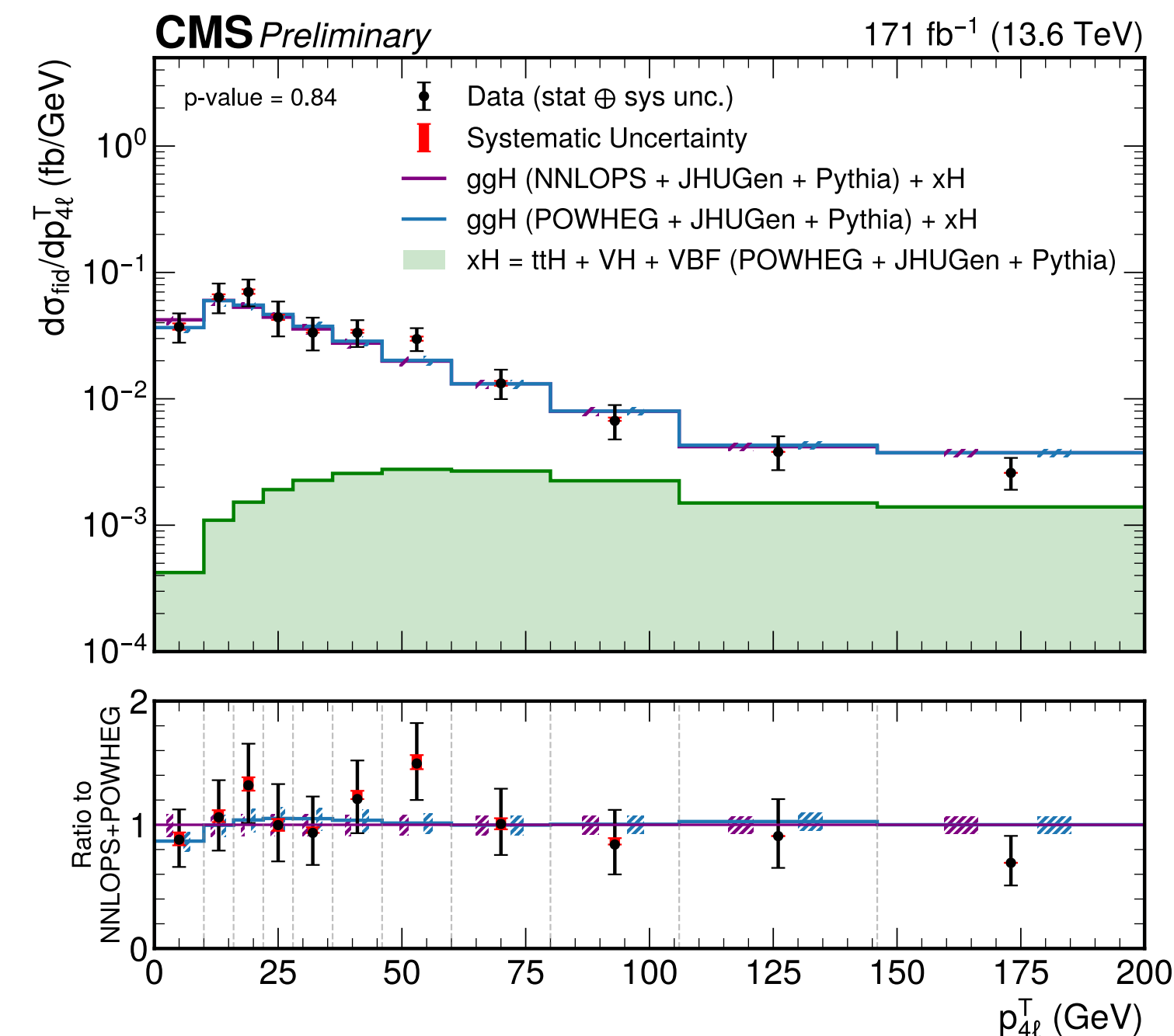
[Eur. Phys. J. C 84 \(2024\) 78](#)

Fiducial cross sections



[arXiv:2605.19016](#)

Differential cross sections



[CMS-PAS-HIG-25-015](#)

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$
 $\sqrt{s}$ from 7 to 13.6 TeV

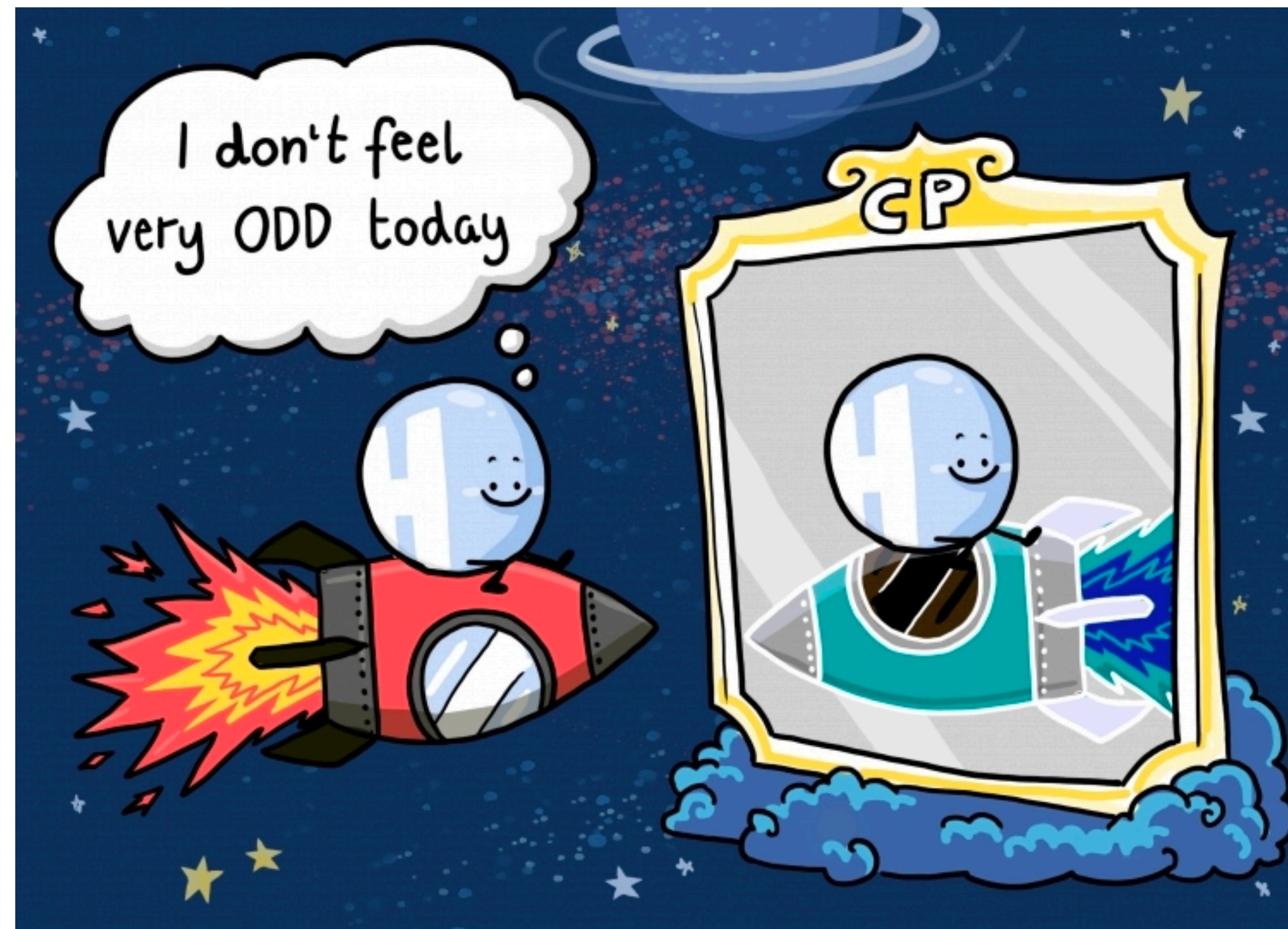
Kinematics **at particle level** defined in phase spaces to match the detector level selection

Look for new physics effects in the tails with reduced model assumptions

Increasing granularity in phase space

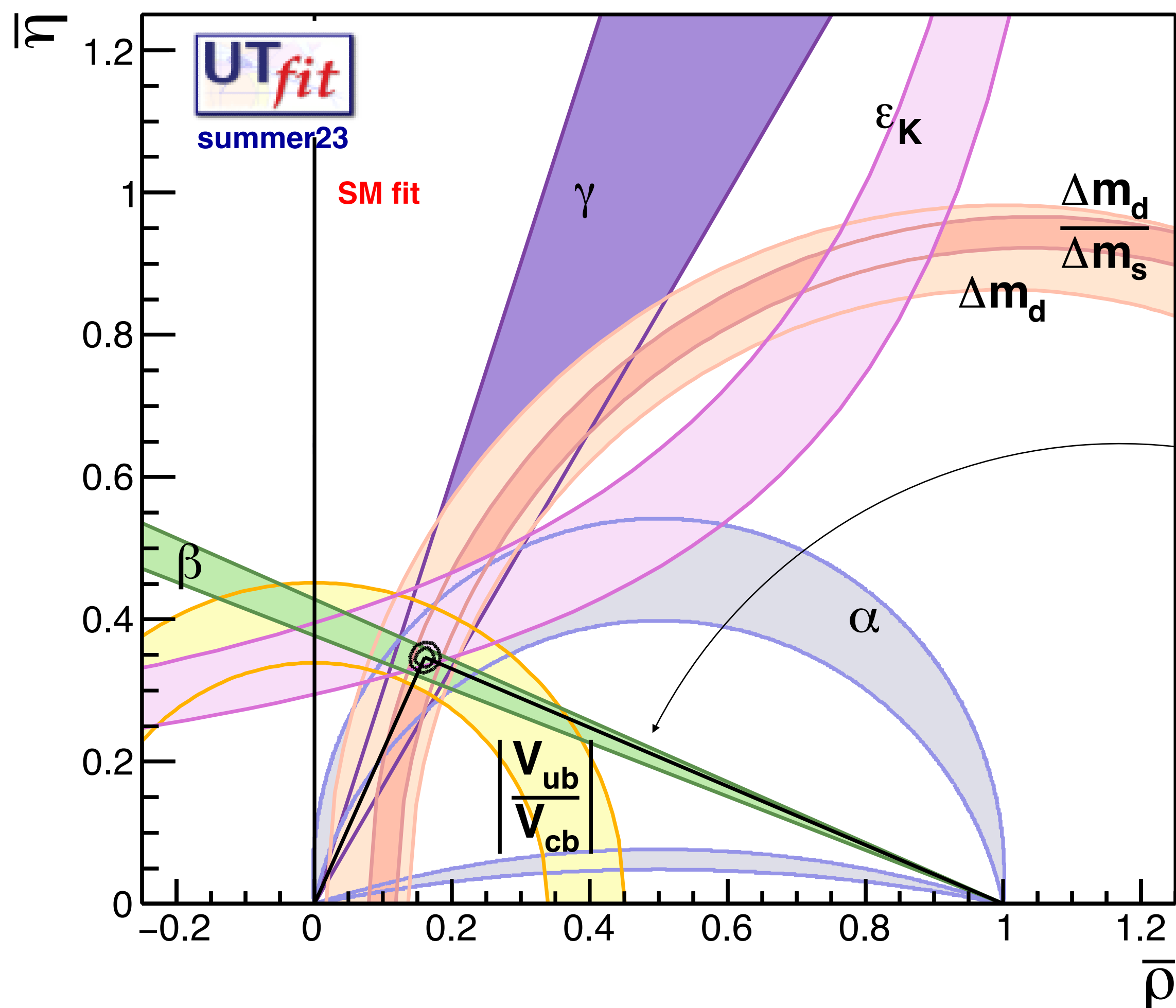
All in good agreement with SM expectations: precise and model independent

Higgs boson Charge-Parity properties

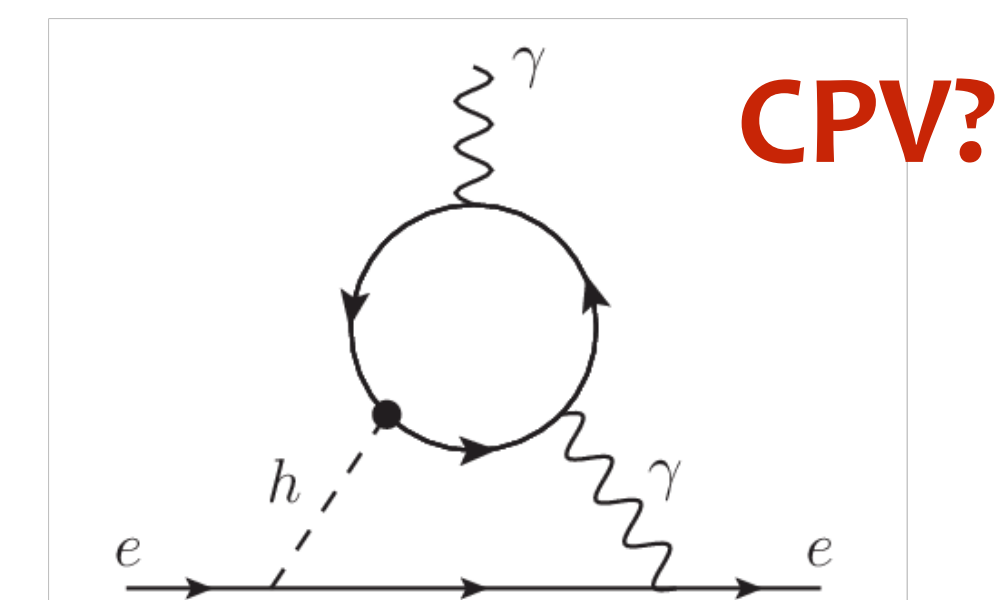


Why matter $\gg$ anti-matter in the universe, i.e. $n_B \gg n_{\bar{B}}$ [baryon-asymmetry]?

The only known source of CP-violation (CPV) is the CKM matrix in the quark sector

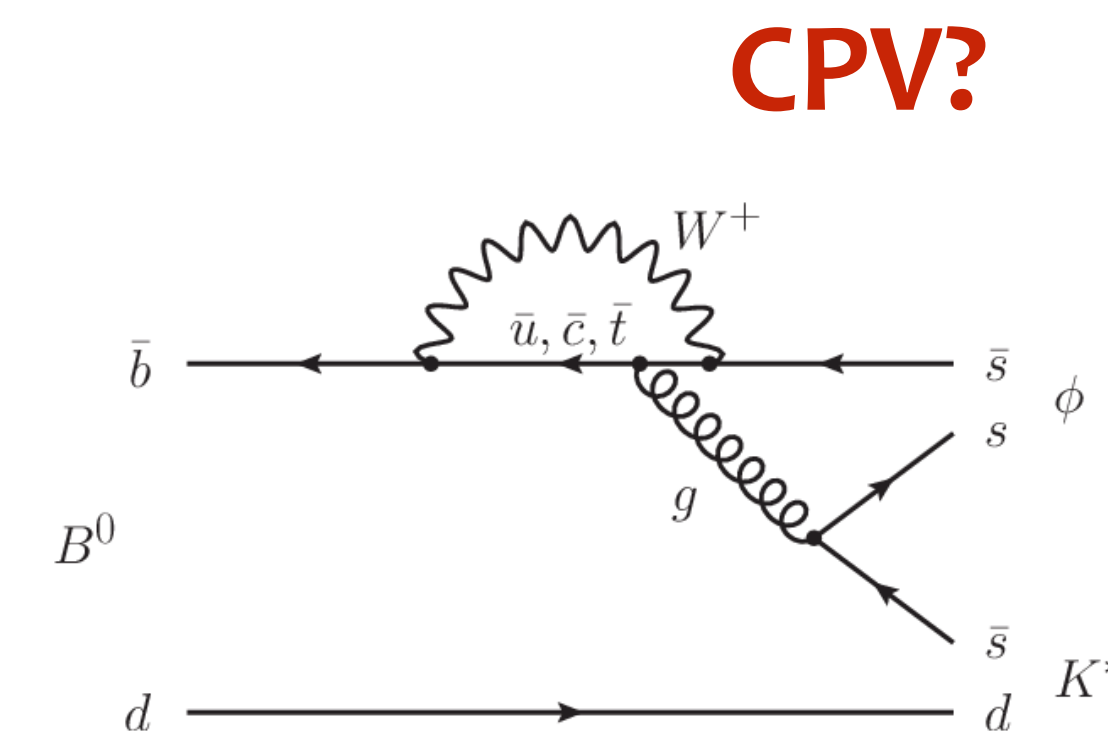


Low-energy experiments:
Electric Dipole Moment of electron

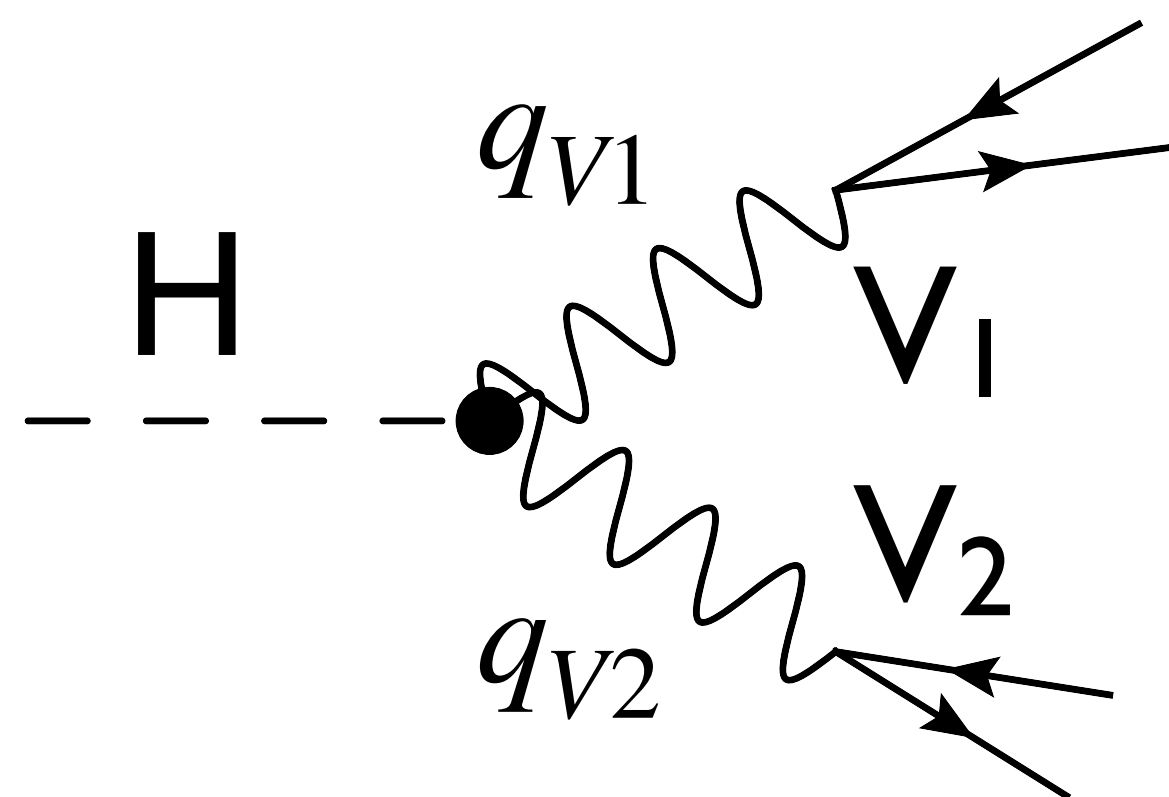


Heavy-Quark decays:
B-meson decays, e.g.
 $b \rightarrow c, s$ transitions

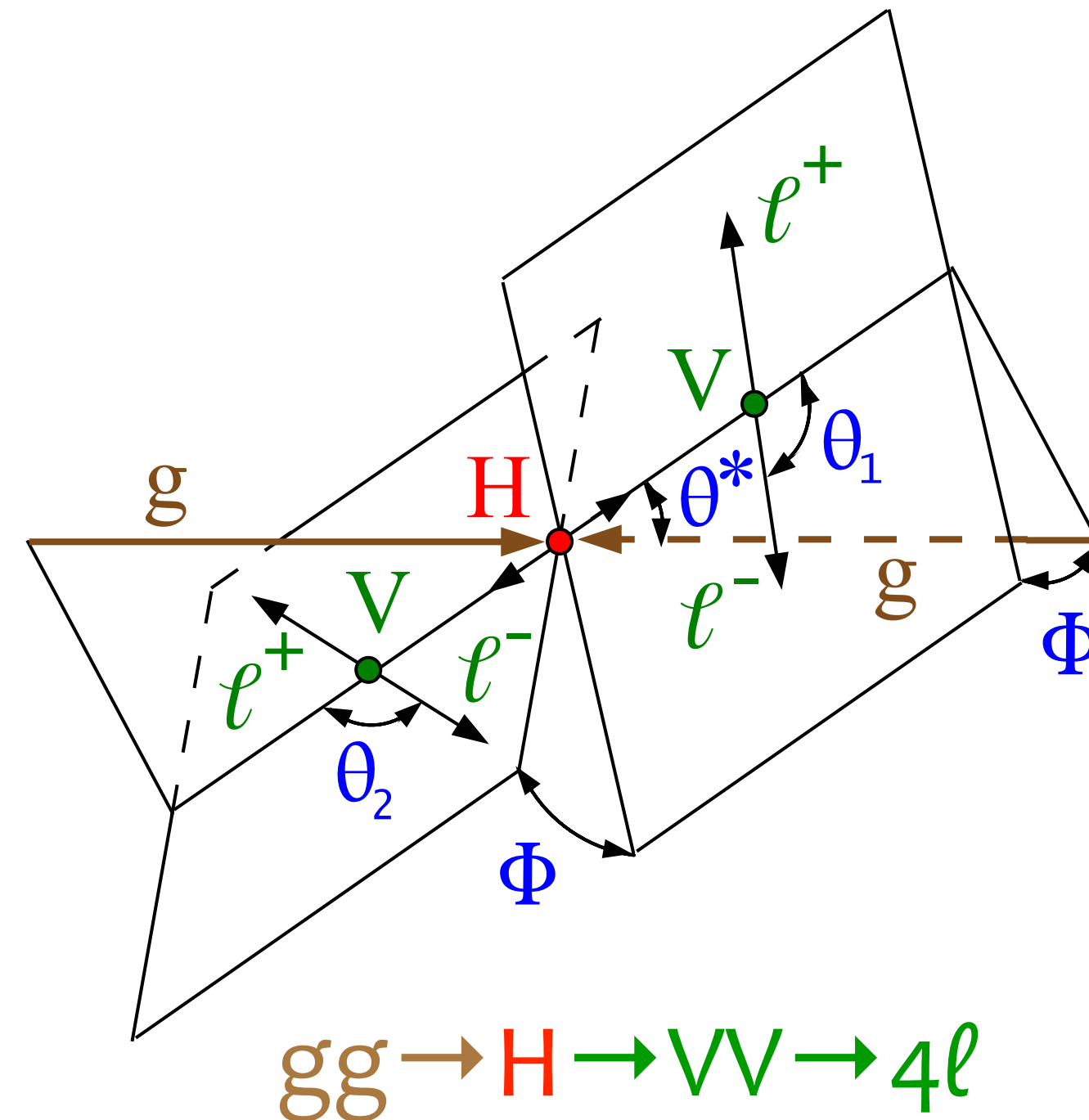
- e^+e^- : Cleo, BaBar, Belle
- pp: CDF/Do, LHCb



CP structure of H - $V_i V_i$ interactions can be constrained well from $H \rightarrow ZZ^* \rightarrow 4\ell$ completely reconstructed final state kinematics



$$V_i = W, Z, \gamma, g$$



Two bases used for the results:

- CMS: a_i (Higgs basis)
- ATLAS: c_{Hi} (Warsaw basis)

Can be related with a “Rosetta” rotation

$$A(HV_1V_2) = \frac{1}{v} \left[\boxed{a_1^{VV}} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV} (q_{V1} + q_{V2})^2}{(\Lambda_Q^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \boxed{\frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}} + \boxed{\frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}},$$

a₁: SM Dim-6 BSM operators at a scale $\Lambda \gg \Lambda_{EWK}$ a₂: CP even BSM a₃: CP odd BSM

If Higgs is an admixture of CP-even ($A_{\text{CP even}}$) and CP-odd ($A_{\text{CP odd}}$) states, build two dedicated discriminants:

$$|A|^2 = |A_{\text{CP even}}|^2 + 2\text{Re}\left(A_{\text{CP even}} A_{\text{CP odd}}^*\right) + |A_{\text{CP odd}}|^2$$

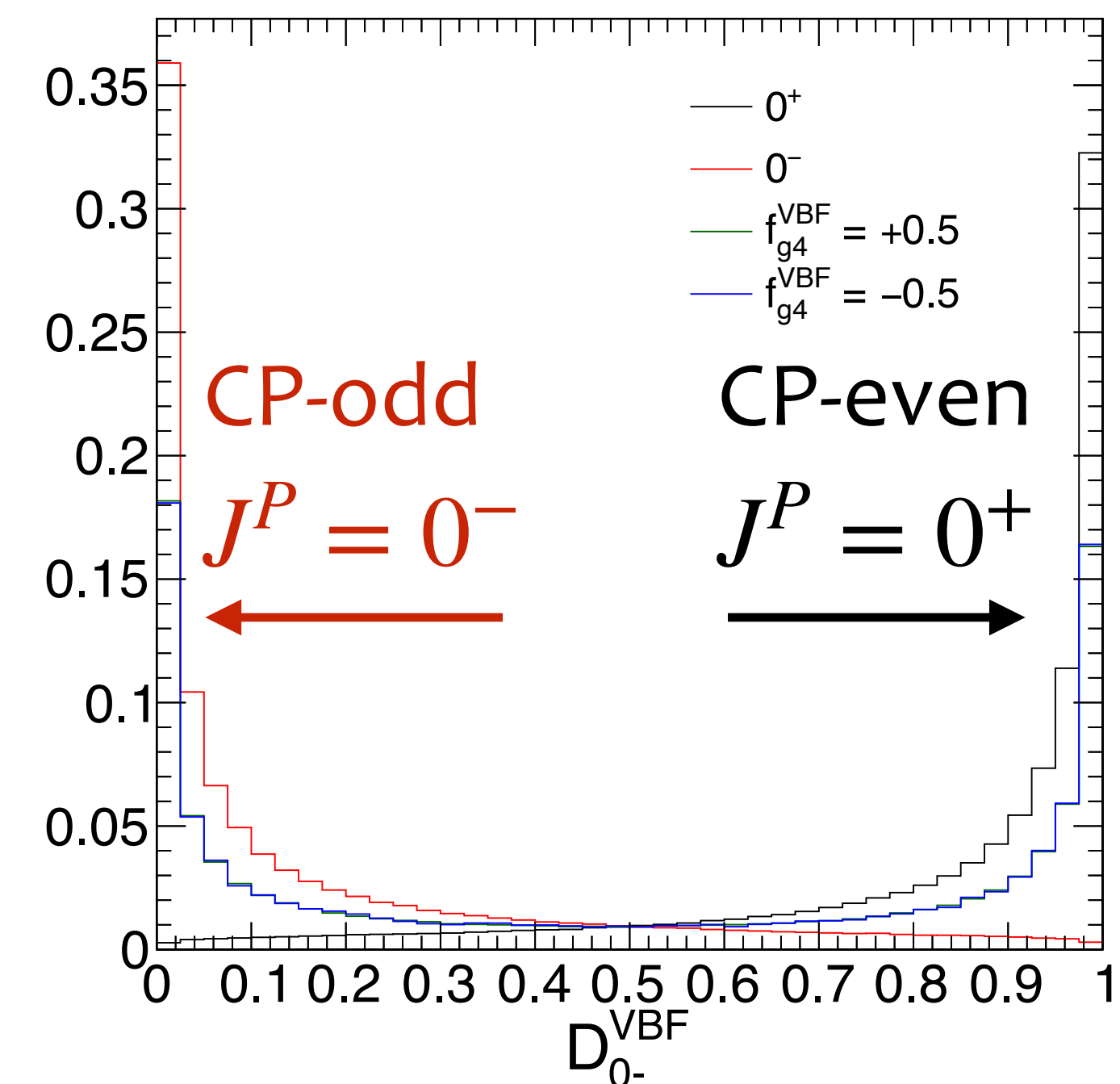
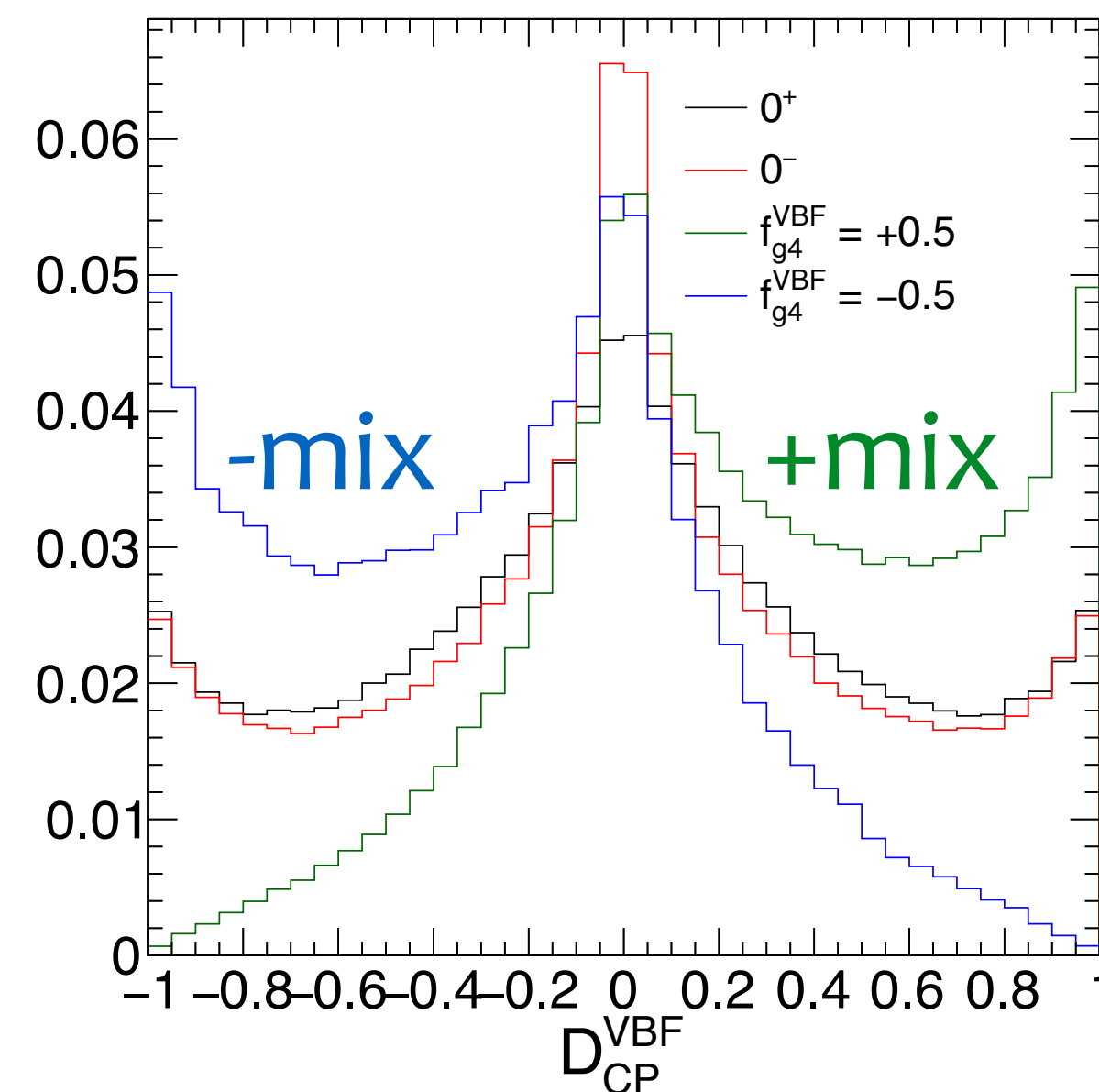
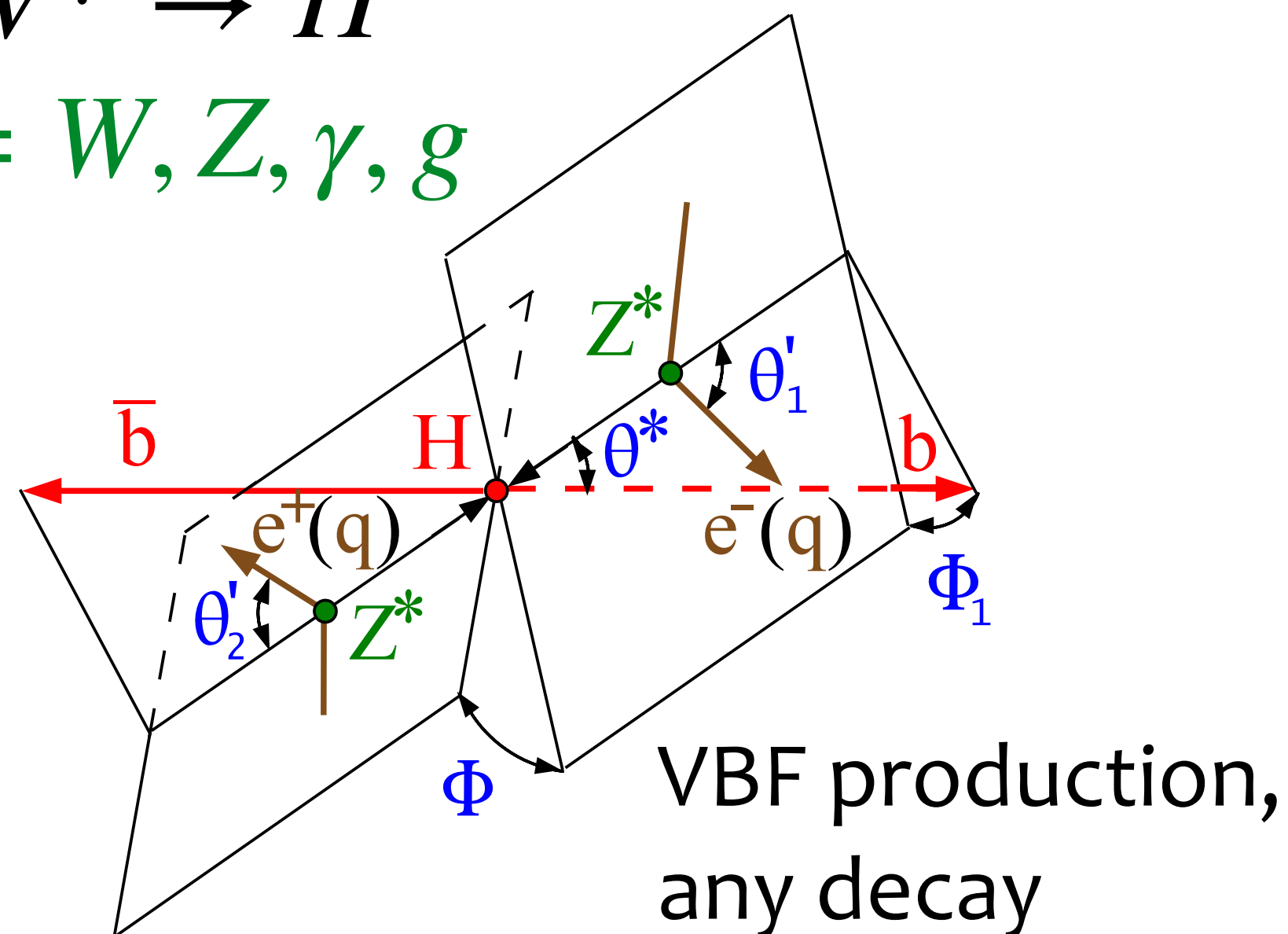
SM term,
discriminate vs backgrounds

Doesn't change rates,
only kinematics
CP-sensitive observable
(Induces a shape asymmetry)

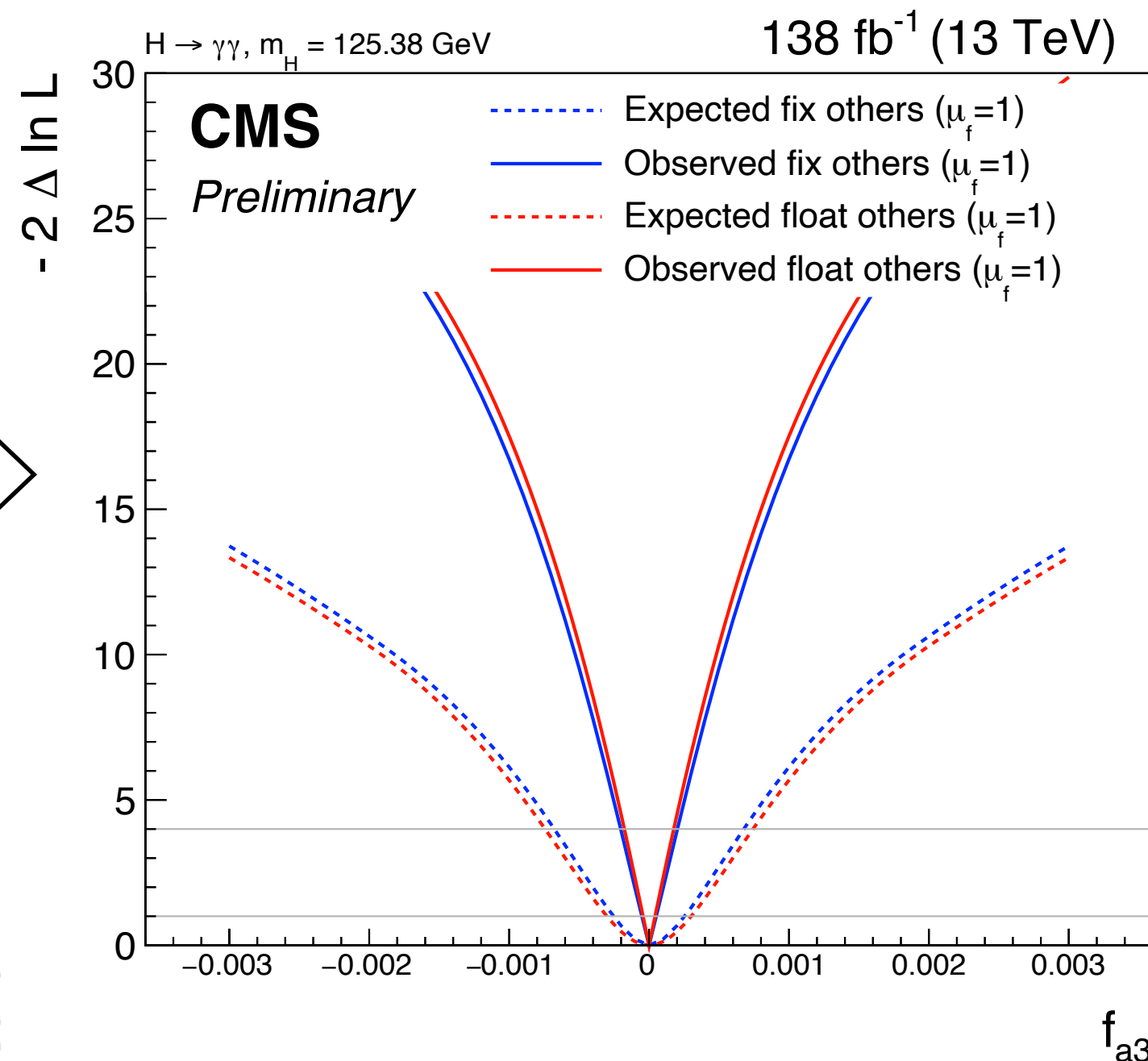
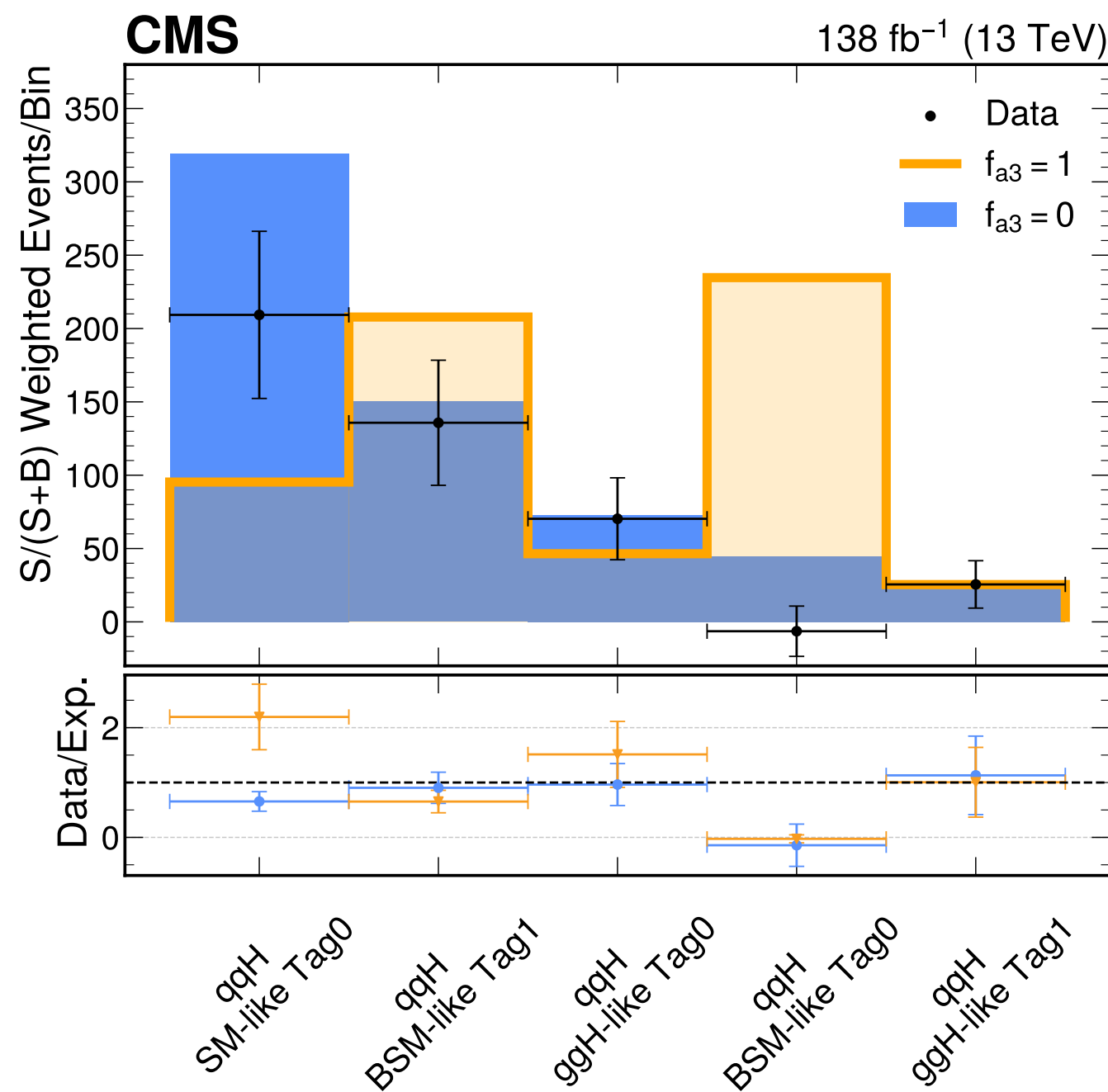
BSM term,
discriminate vs SM

$$V^* V^* \rightarrow H$$

$$V = W, Z, \gamma, g$$



CPV in HVV (CMS $H \rightarrow \gamma\gamma$)



Fraction of CP-odd

HVV amplitude $\lesssim 10^{-4}$

Parameter

Observed [$\times 10^{-4}$]
 $H \rightarrow \gamma\gamma$ (68% CL)

Expected [$\times 10^{-4}$]
 $H \rightarrow \gamma\gamma$ (68% CL)

f_{a3}

$0.00^{+0.39}_{-0.39}$

[+2.1, -2.1]

f_{a2}

$-0.81^{+0.65}_{-2.0}$

[-2.3, +3.1]

$f_{\Lambda 1}$

$-0.014^{+0.032}_{-0.14}$

[-0.12, +0.35]

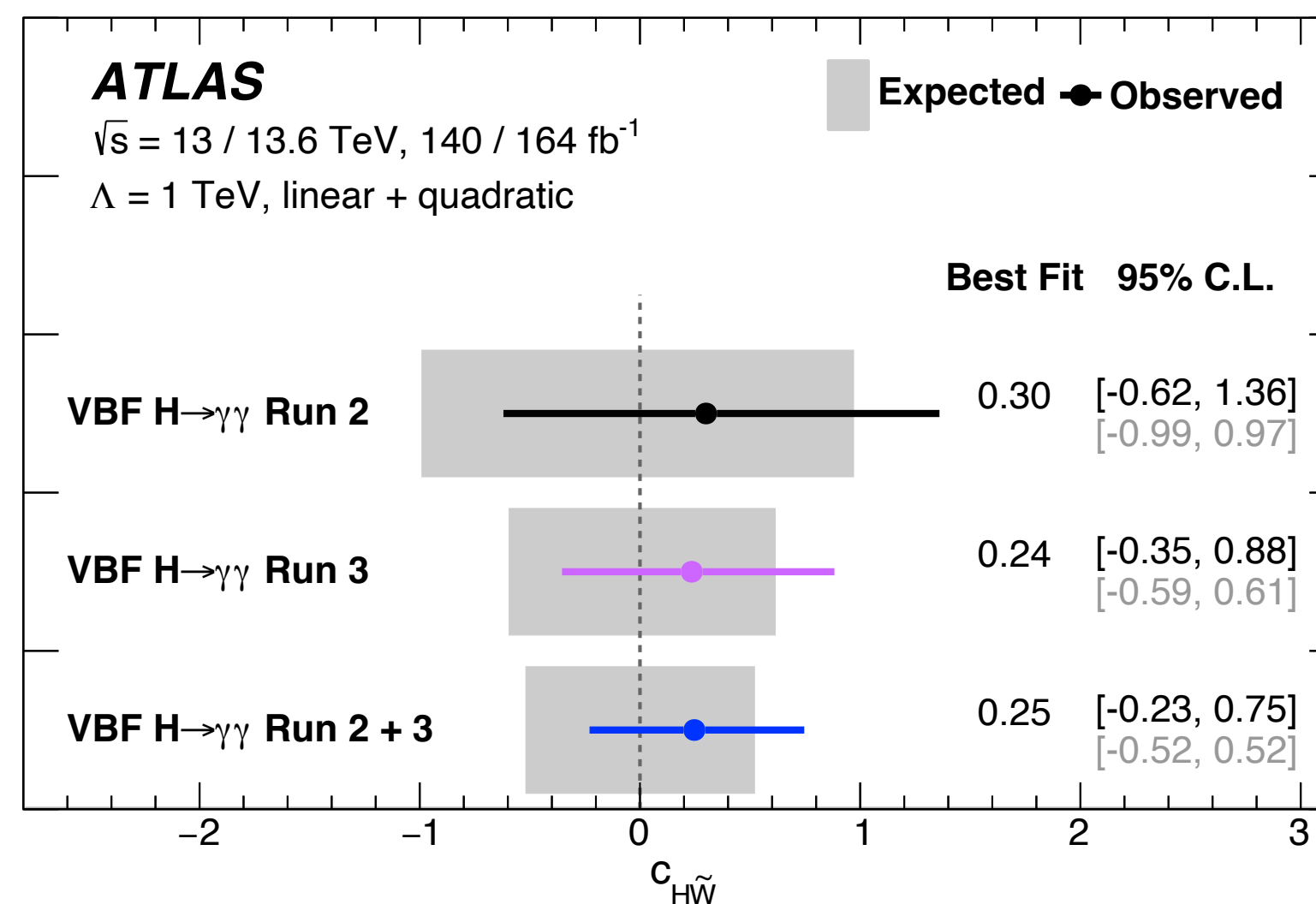
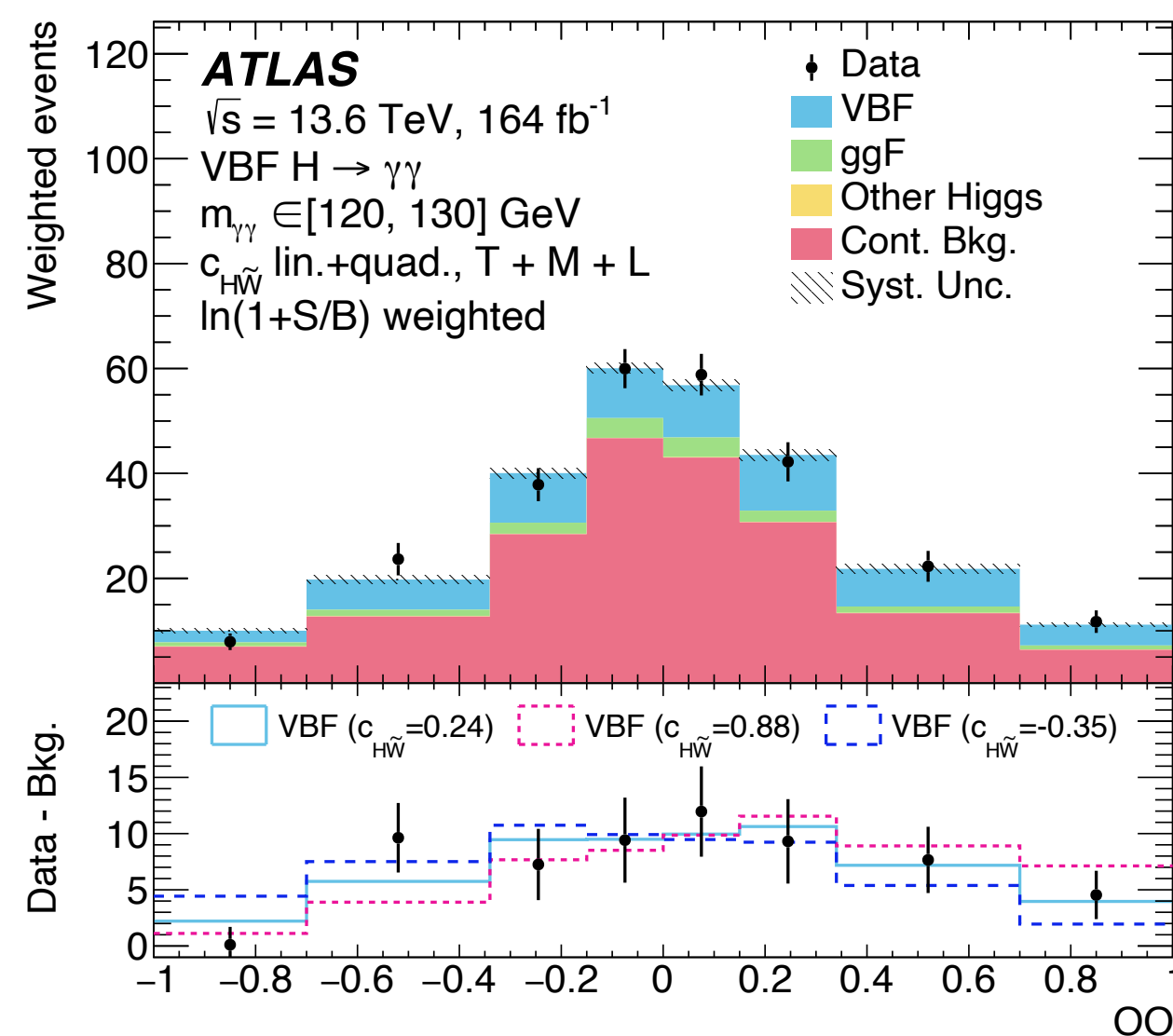
$f_{\Lambda 1}^{Z\gamma}$

$0.83^{+1.5}_{-0.92}$

[-3.3, +3.7]

arXiv:2605.14245v1

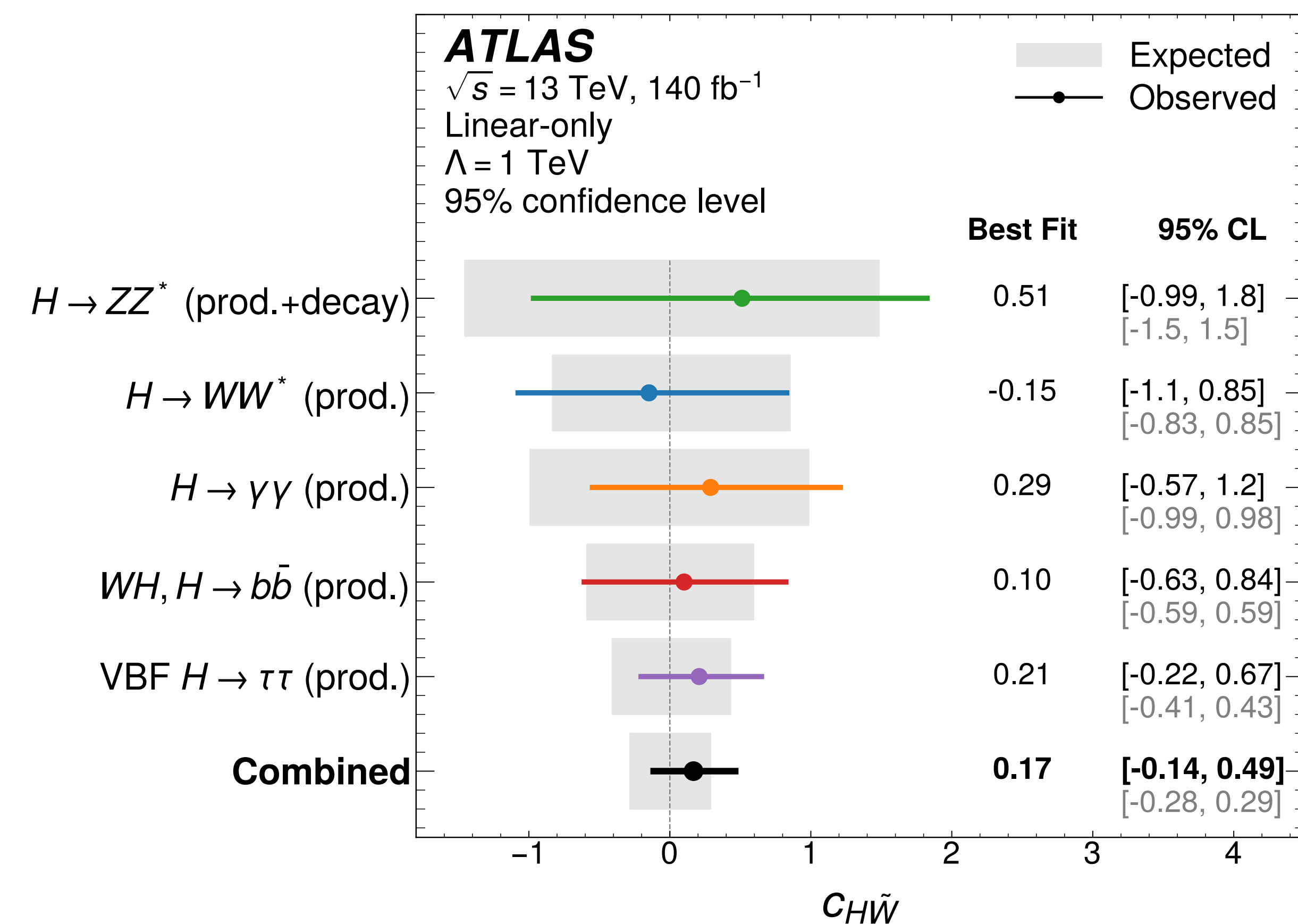
NEW



EFT interpretation:
Constraints on the CP-odd
operator $c_{H\tilde{W}}$

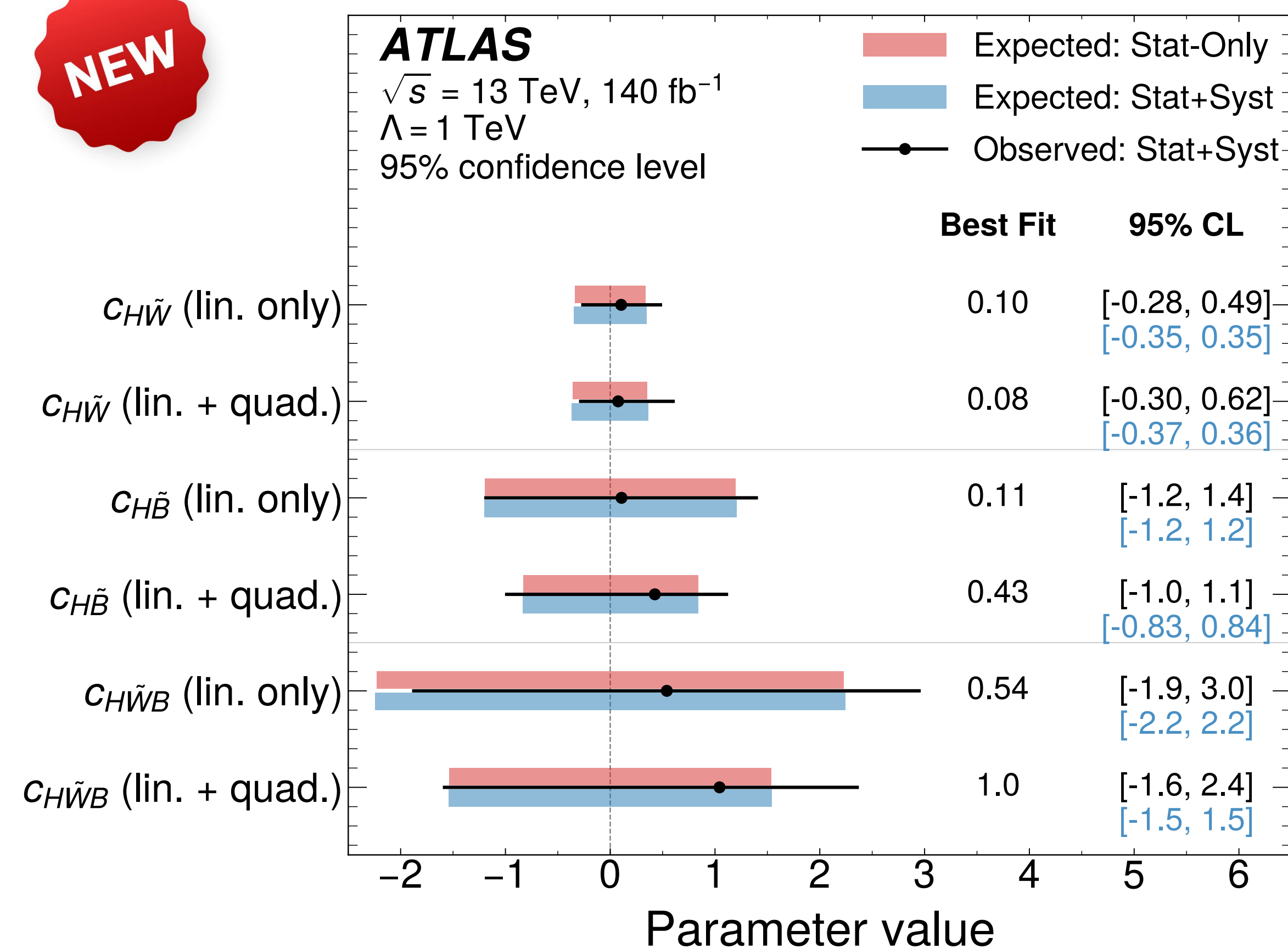
arXiv:2603.20087v1

Combination of CP properties of the HHV vertex from ATLAS, in the context of the SMEFT Constraints for several Wilson coefficients



NEW

First simultaneous fit constraining the coefficients of three CP-violating operators

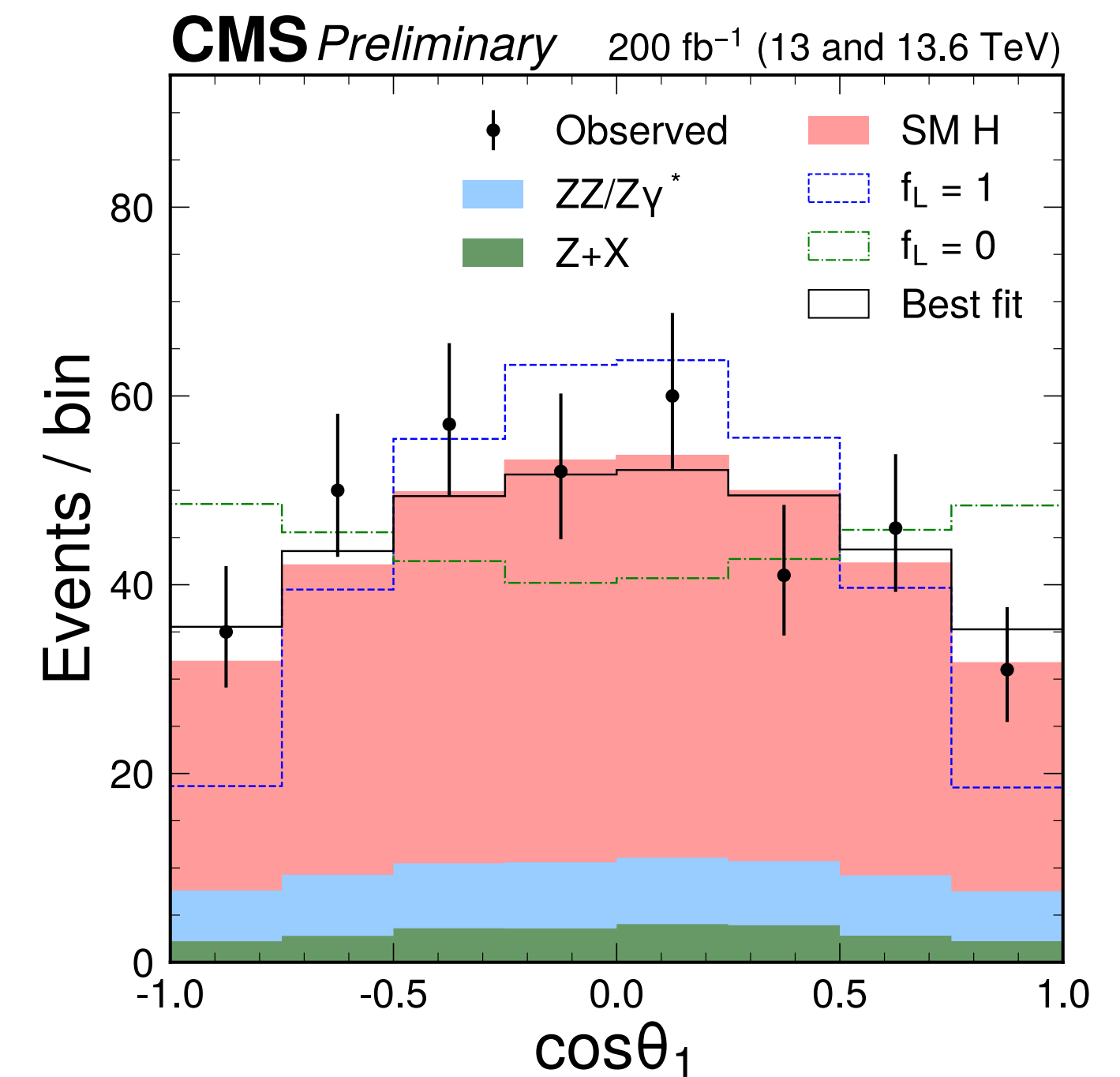


arXiv:2603.20117

Decay of a scalar Higgs to vector gauge bosons sensitive to its polarisation:

- $H \rightarrow ZZ^* \rightarrow 4\ell$ produces a superposition of $|++\rangle, |00\rangle, |--\rangle$ polarisations
- measurement of the Higgs spin density matrix ρ

$$\rho = \int \frac{dm_1 dm_2 \mathcal{P}(m_1, m_2)}{|A_{++}|^2 + |A_{00}|^2 + |A_{--}|^2} \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{++}A_{++}^* & 0 & A_{++}A_{00}^* & 0 & A_{++}A_{--}^* & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{00}A_{++}^* & 0 & A_{00}A_{00}^* & 0 & A_{00}A_{--}^* & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{--}A_{++}^* & 0 & A_{--}A_{00}^* & 0 & A_{--}A_{--}^* & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$



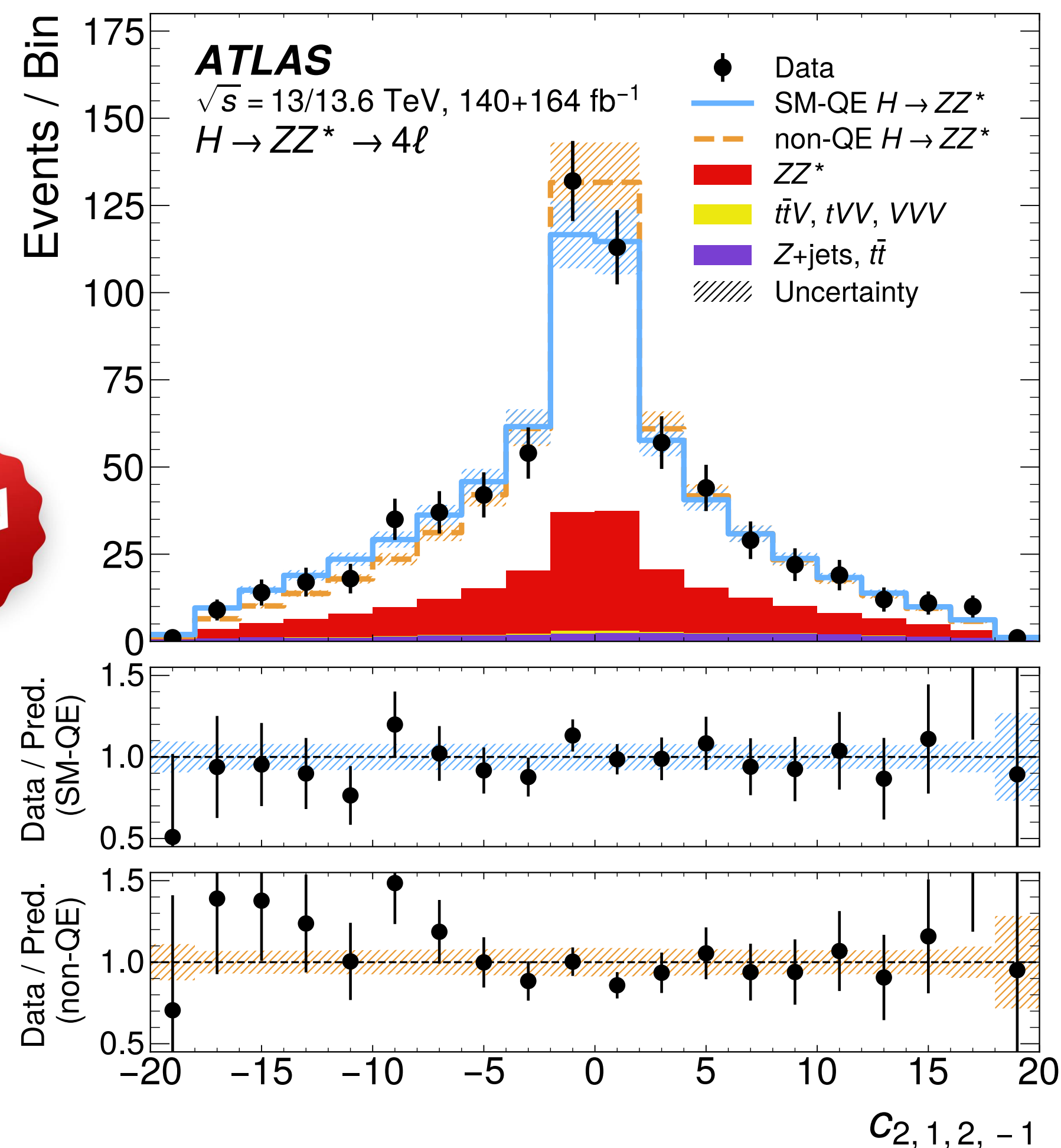
Can be used to measure the fractions of longitudinal (f_L) and the two transverse ($f_\perp, f_\parallel$) polarisations

Assuming no CPV, **rejecting the longitudinal polarisation $|00\rangle \Rightarrow$ quantum entangled state**

* first test of entanglement in massive vector bosons

Higgs polarisation results

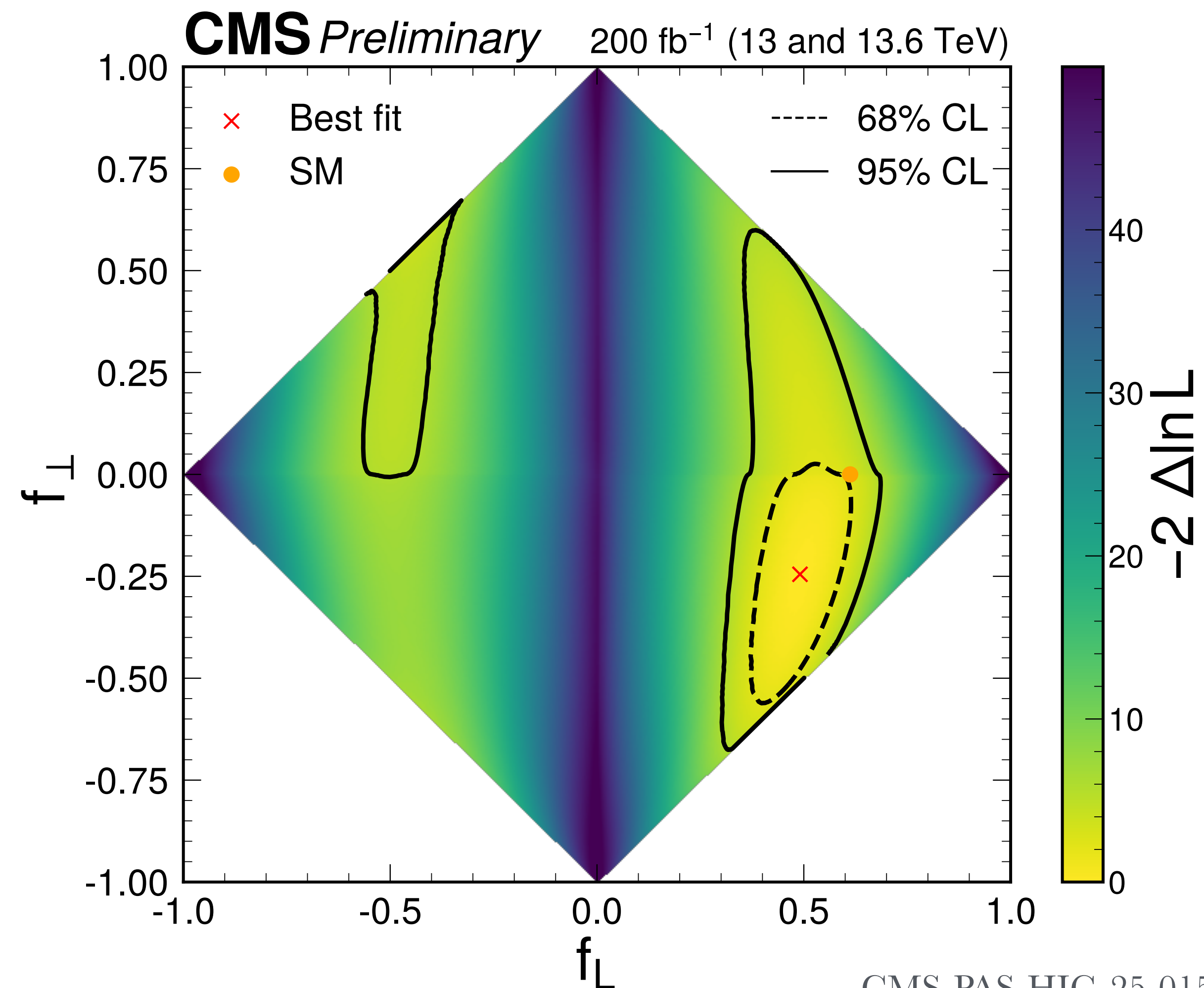
NEW



arXiv:2603.26463

$C_{2,1,2,-1}$ (equivalent to $A_{00}A_{++}^*$) extracted from the mean of the distribution.

Entanglement is proven at 4.7σ



CMS-PAS-HIG-25-015

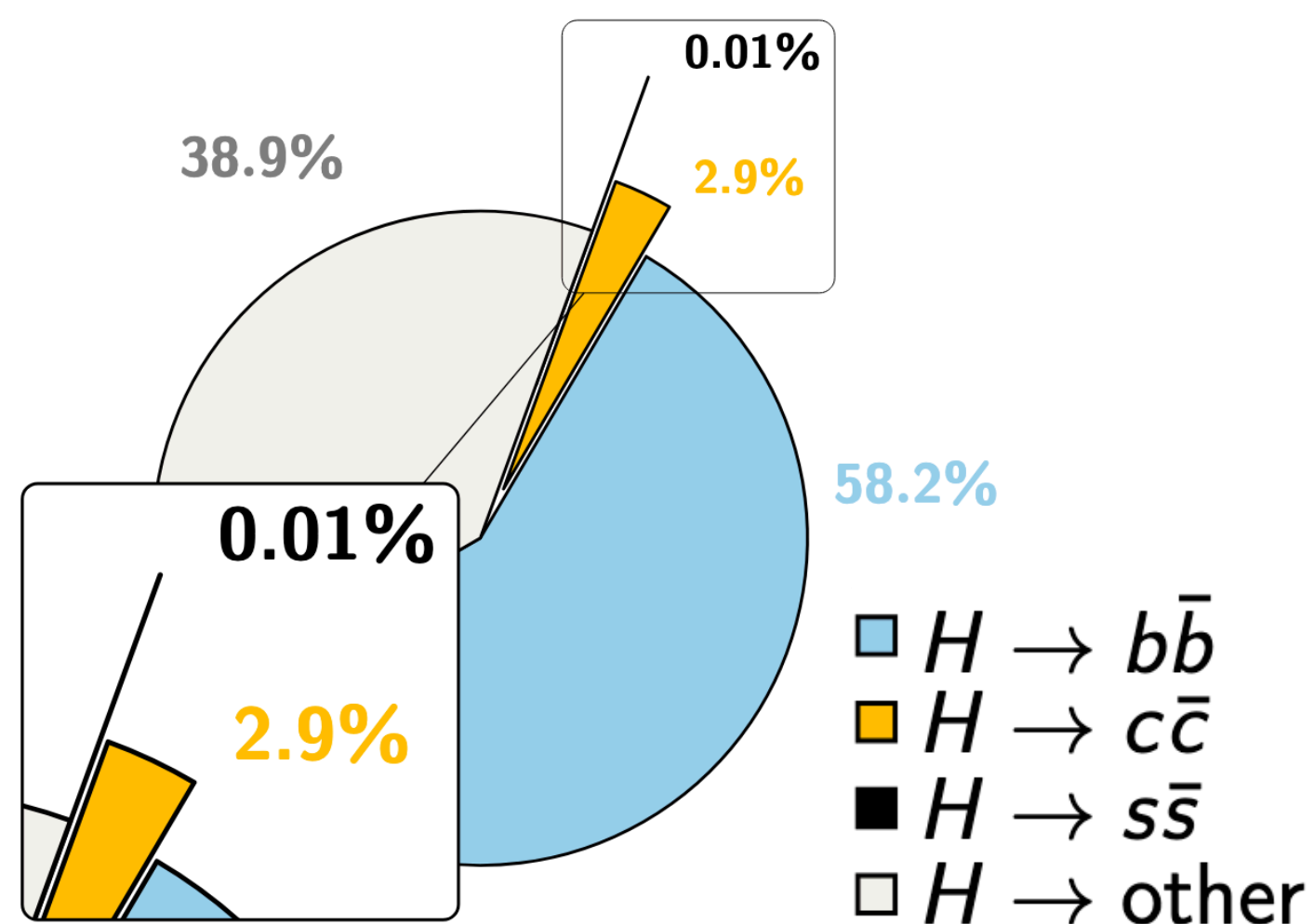
Extreme points $f_L = 0$ and $f_L = 1$ excluded at

> 6σ proves ZZ^* is an entangled state

Coupling to 3rd generation fermions established at $\sim 10\%$ precision

Evidence of couplings to muons

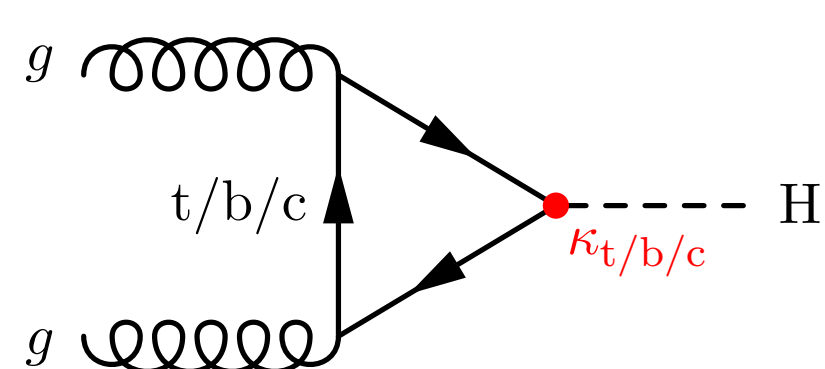
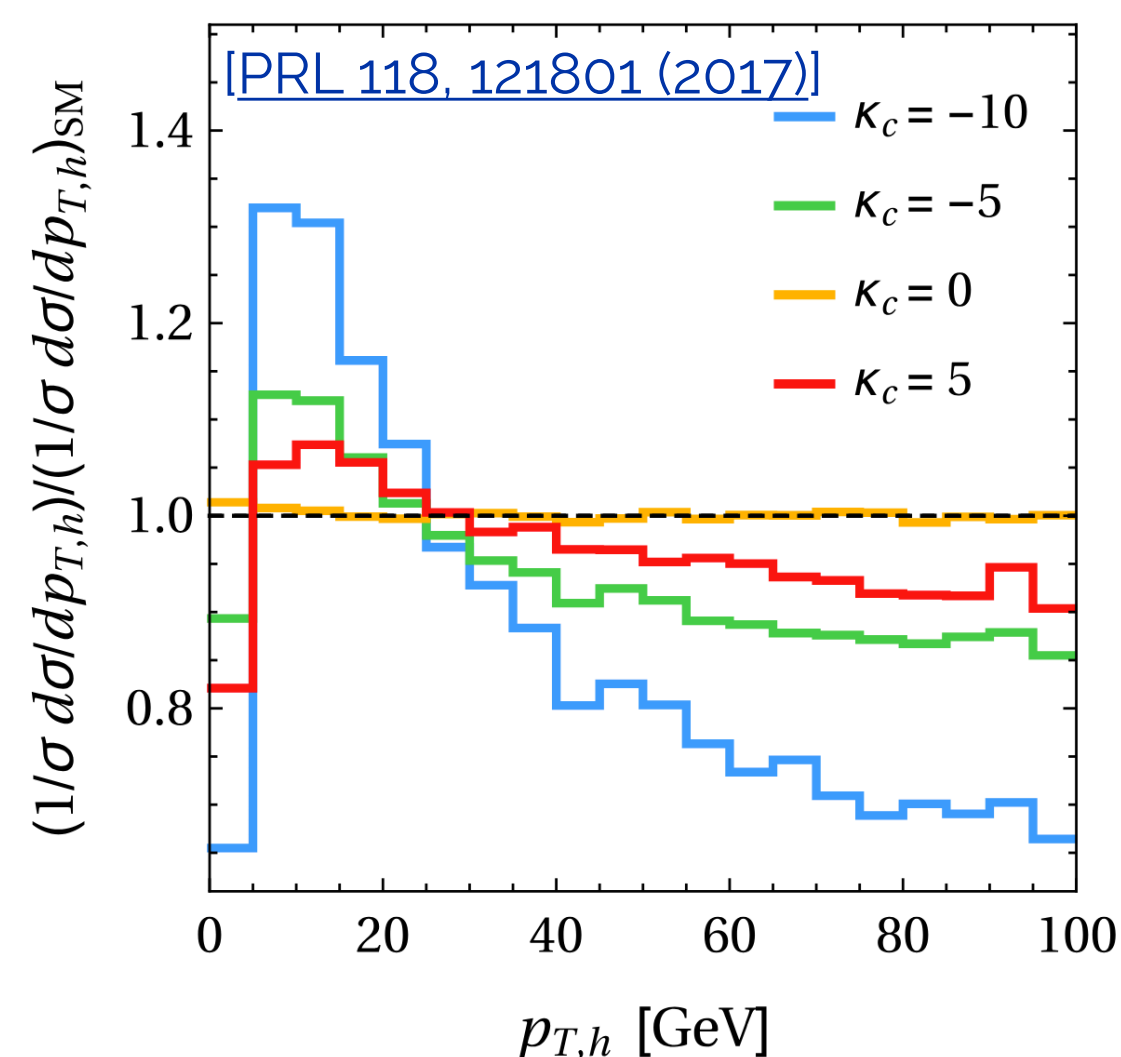
Next step is couplings to **charm quarks**: very challenging!



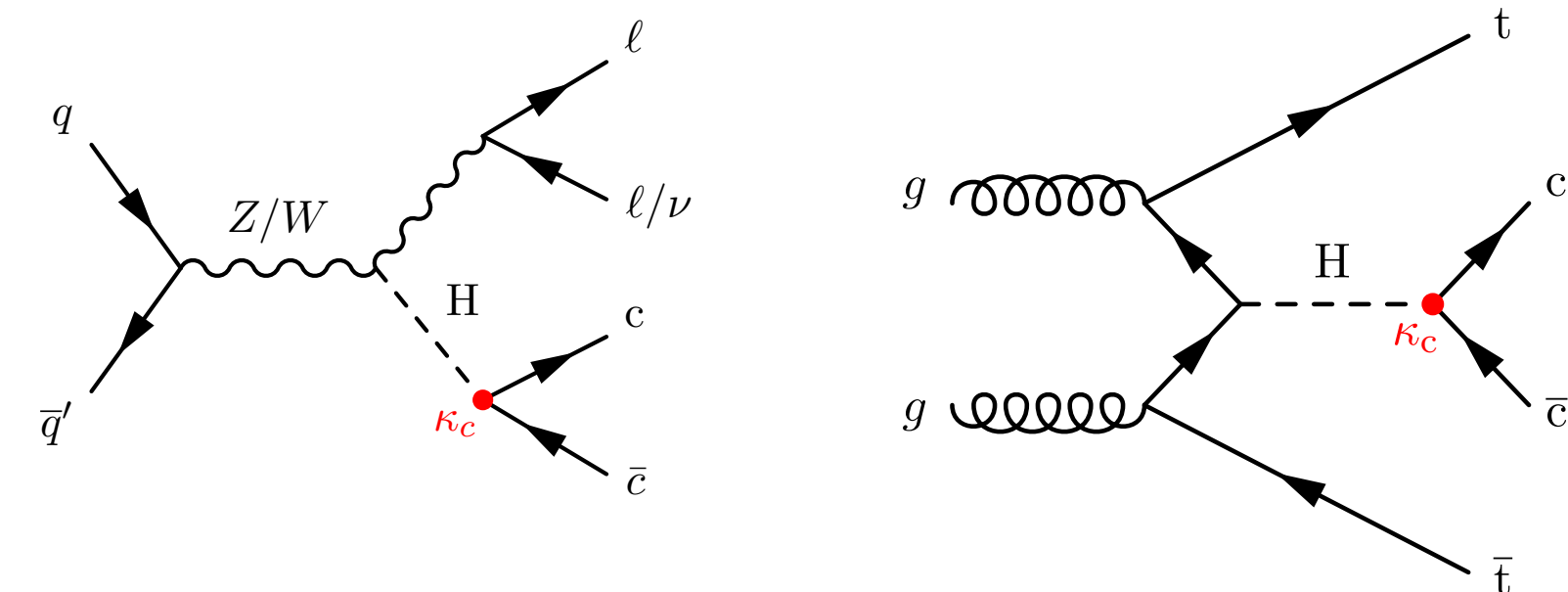
SM $m_H = 125$ GeV $H \rightarrow q\bar{q}$ branching fractions,

$H \rightarrow u\bar{u}/d\bar{d}$ too small to show!

Indirect κ_c from Higgs p_T



Direct searches with $H \rightarrow c\bar{c}$ decays

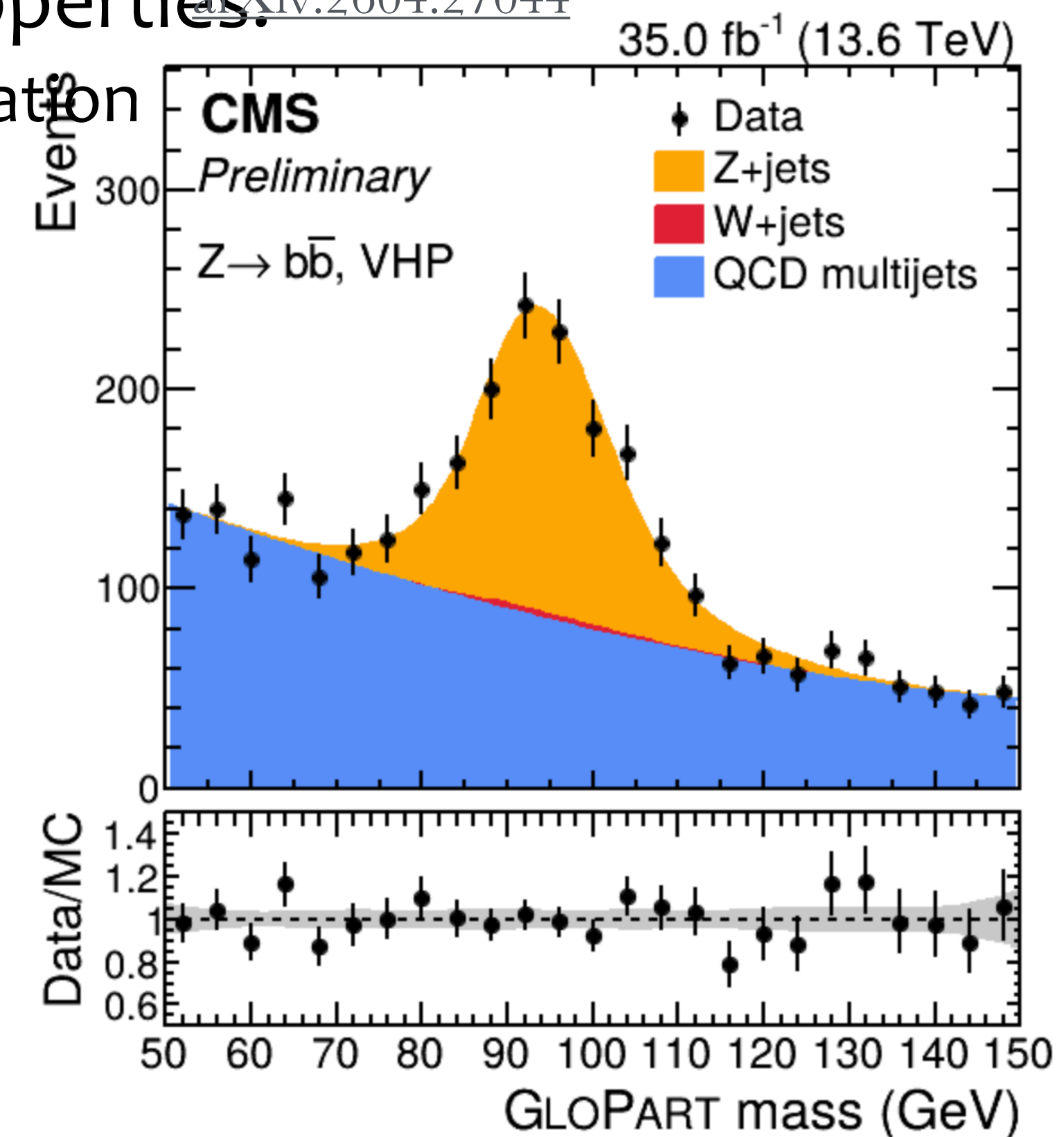
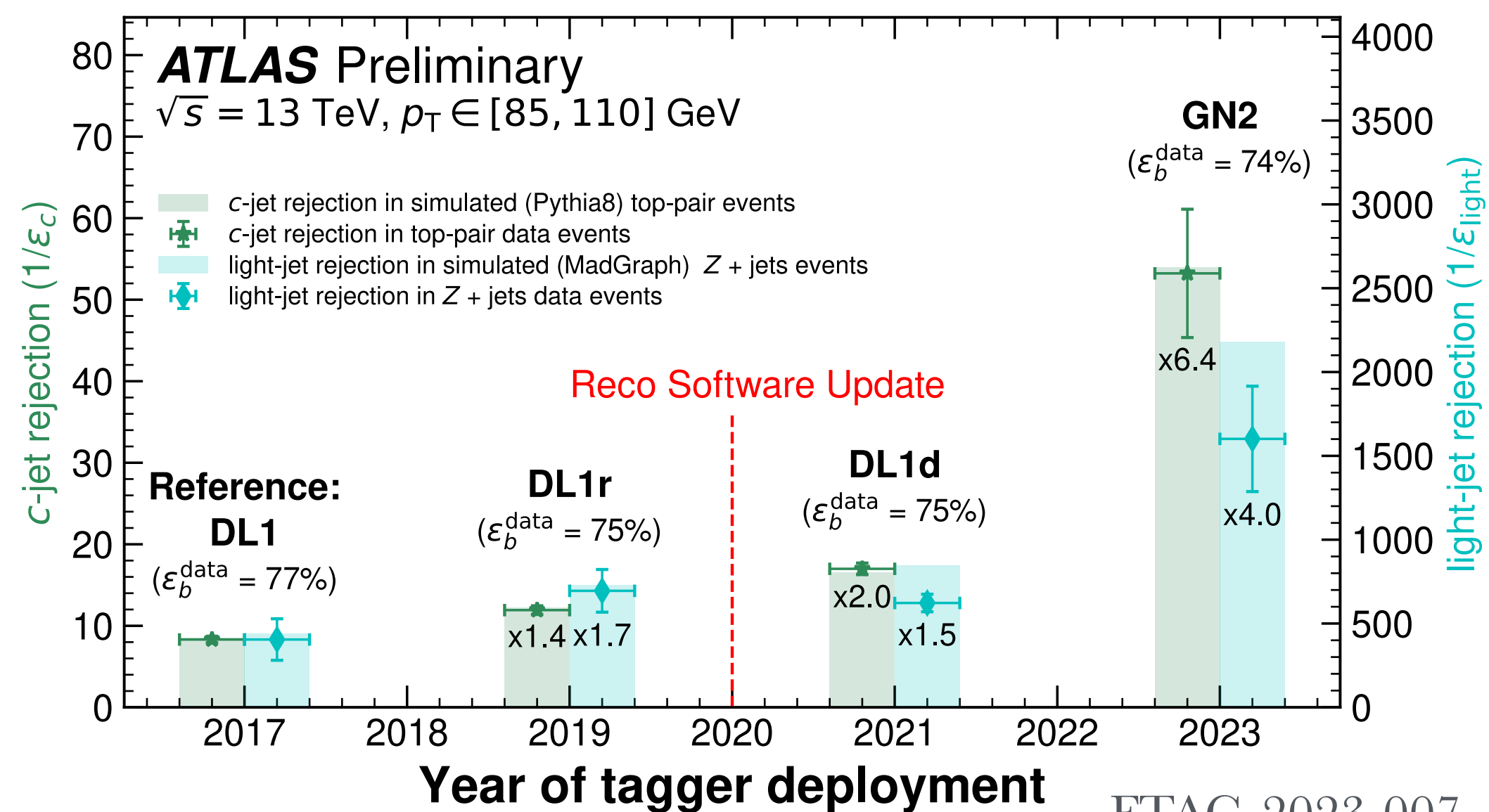
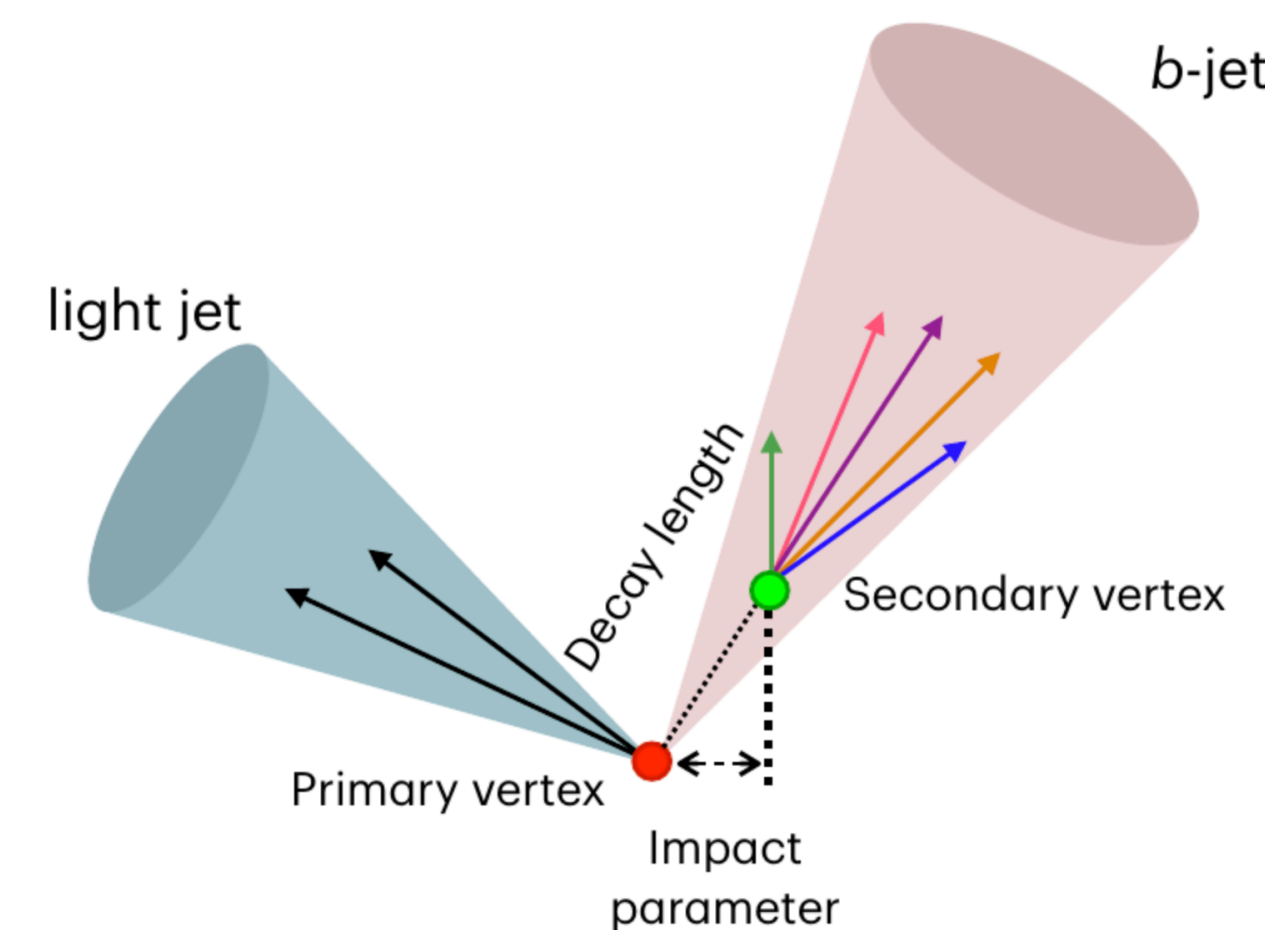


WH, ZH or ttH productions to suppress the huge QCD multi-jet background

The flavor tagging challenge



- At LHC, challenging hadronic decays: $H \rightarrow b\bar{b}$ and $H \rightarrow c\bar{c}$:
- trigger, large backgrounds, poor energy resolution
- Vibrant developments for jet flavor tagging using b/c-hadron properties: [arXiv:2604.27044](https://arxiv.org/abs/2604.27044)
- long lifetime, decay multiplicity, jet composition, heavy-quark fragmentation

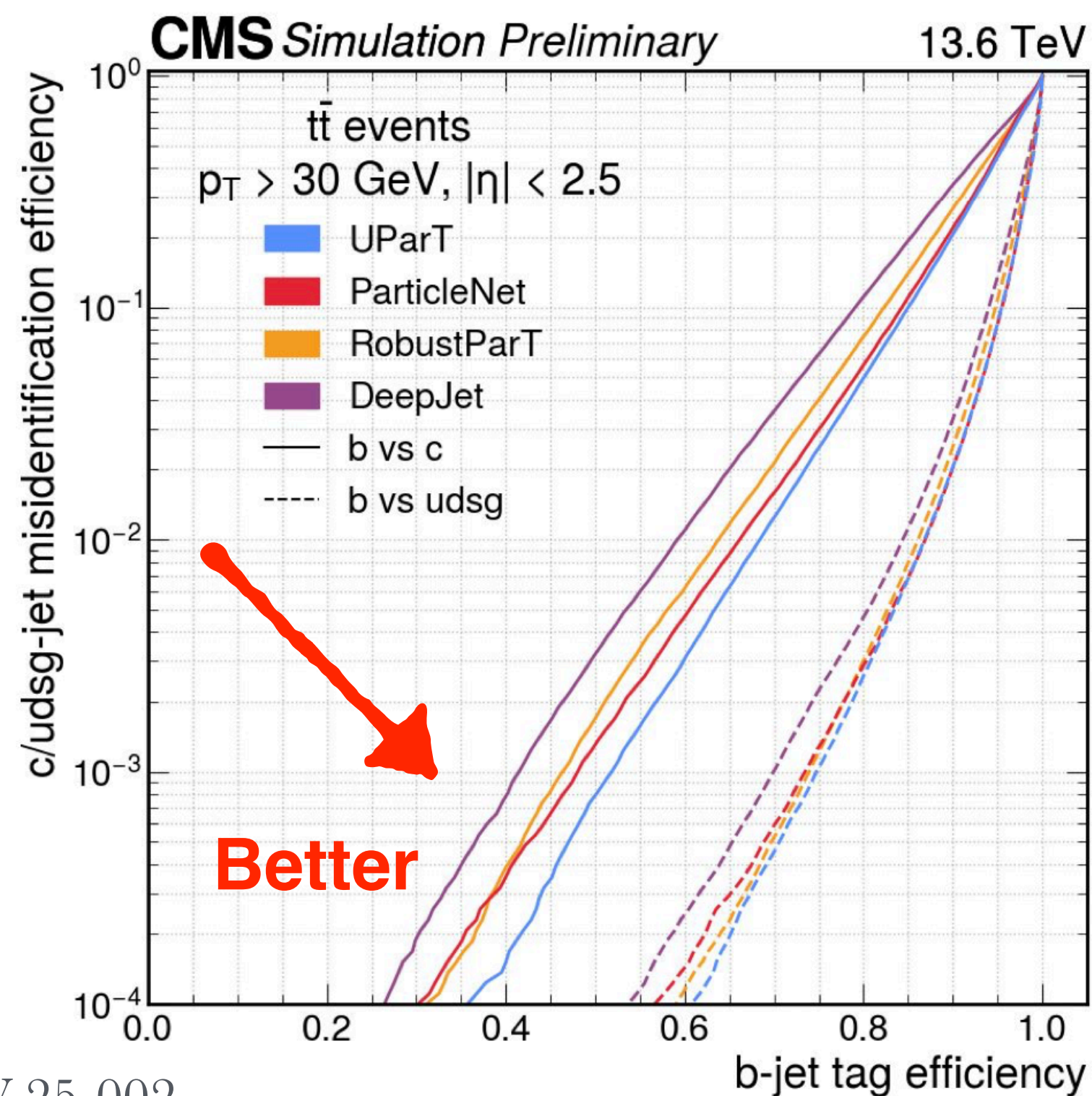


Advanced algorithms (eg. GNN):
x 4 (x6) better rejection for light-jets (c-jets) than before

$Z \rightarrow b\bar{b}$ mass in-situ
calibration

Double challenge for $H \rightarrow cc$

1. Separate heavy flavour (c-jets) from light flavour (u,d,s,g)-jets
2. Separate 2 kinds of heavy flavour jets: c-jets from b-jets



CMS-PAS-BTV-25-002

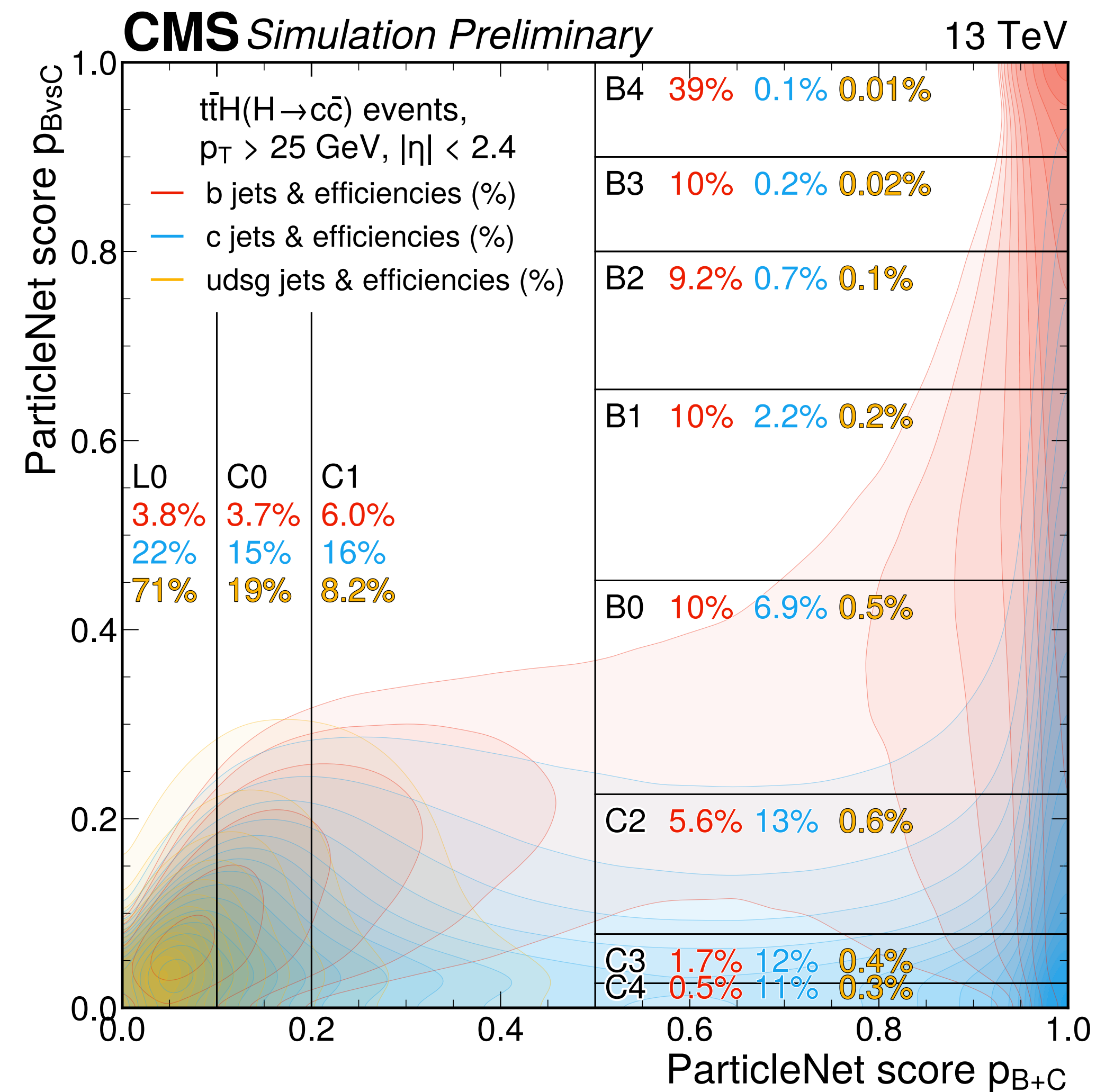
Use the detector max granularity + and advanced algorithms (Graph Neural Networks):

better than before $\Leftrightarrow$ 4 times more data

x2

c-like

b-like

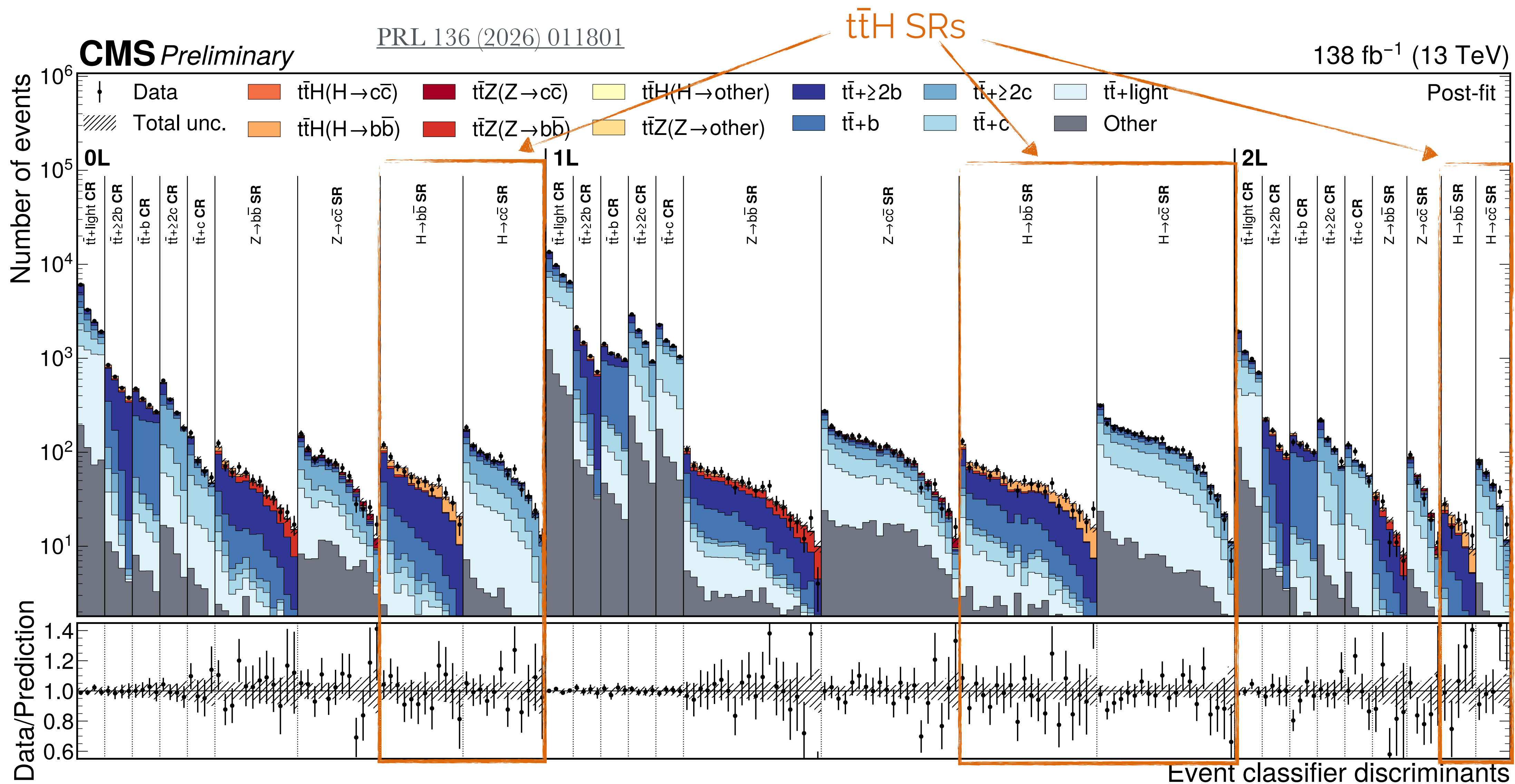


PRL 136 (2026) 011801

u,d,s,c-like

b,c-like

The name of the complexity: $t\bar{t}H(cc/bb)$

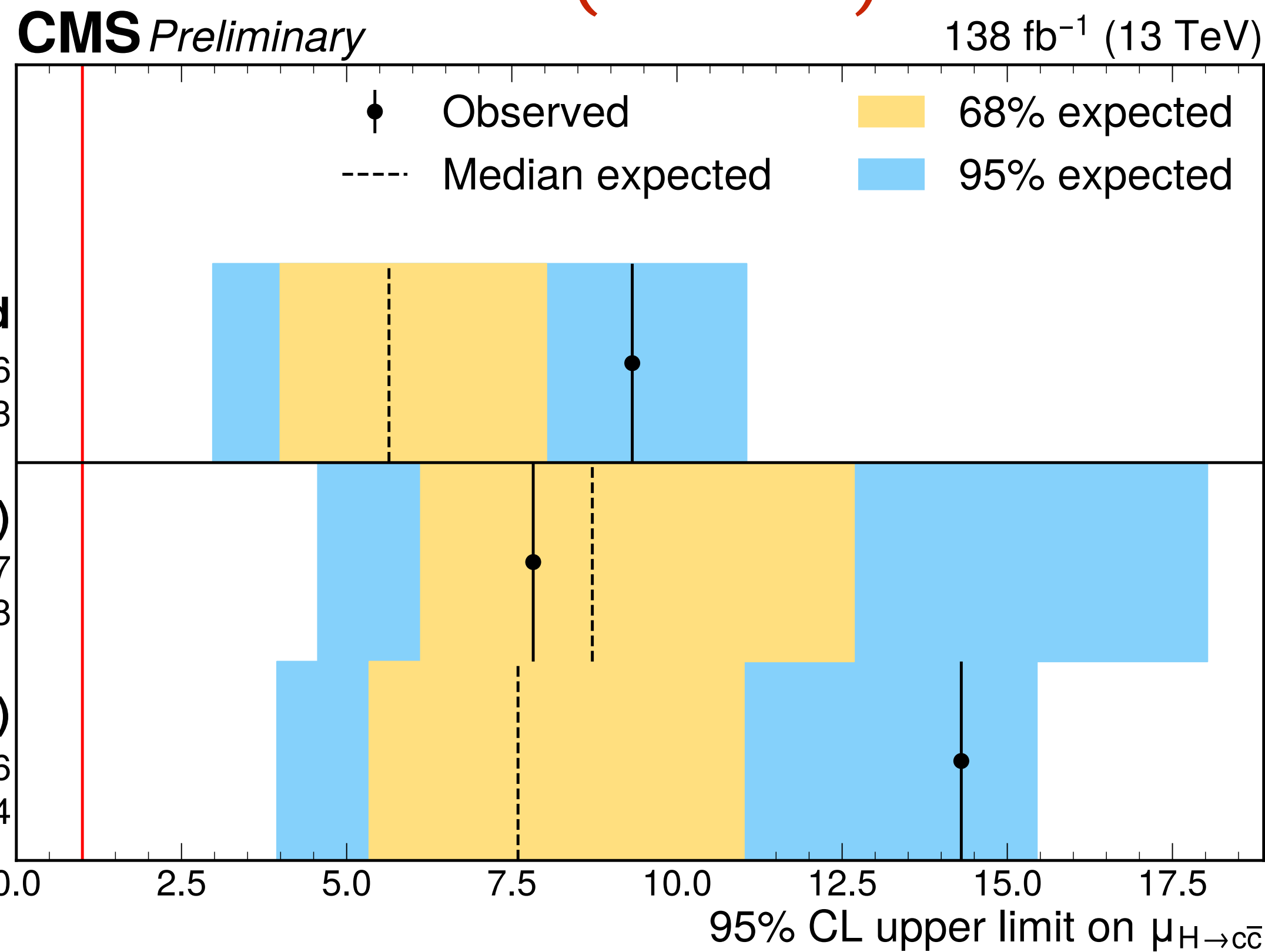


Measure simultaneously $t\bar{t}H(H \rightarrow b\bar{b})$ and $t\bar{t}H(H \rightarrow c\bar{c})$, and SM candles $t\bar{t}Z(b\bar{b}/c\bar{c})$

Limits on 2nd generation Higgs-Yukawa

$ttH(H \rightarrow c\bar{c})$

$VBF(H \rightarrow c\bar{c})$

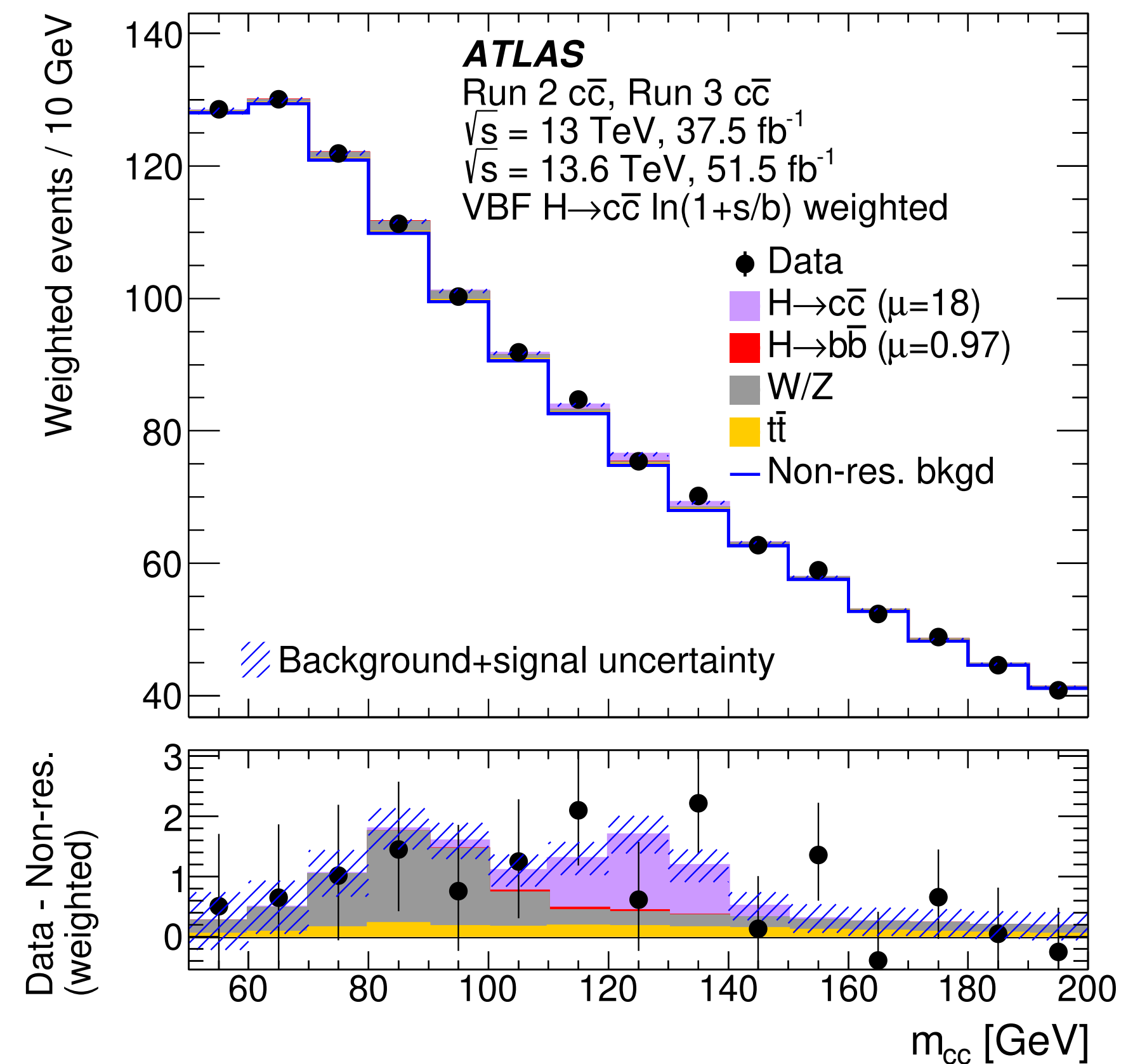


PRL 136 (2026) 011801

Observed limits on $\mu_{ttH(H \rightarrow c\bar{c})}$: ≈ 7.8 wrt. SM
 in Run2 done 18-years equivalent of progress in 3 years

We also measure the $ttH(bb)$ process:

$$\mu_{ttH(H \rightarrow b\bar{b})} = 0.91 + 0.26 / -0.22 \quad (4.4\sigma)$$



arXiv:2511.21911

Observed limits on
 $\mu_{VBF(H \rightarrow c\bar{c})}$: ≈ 41 wrt. SM

Rare decays: $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$

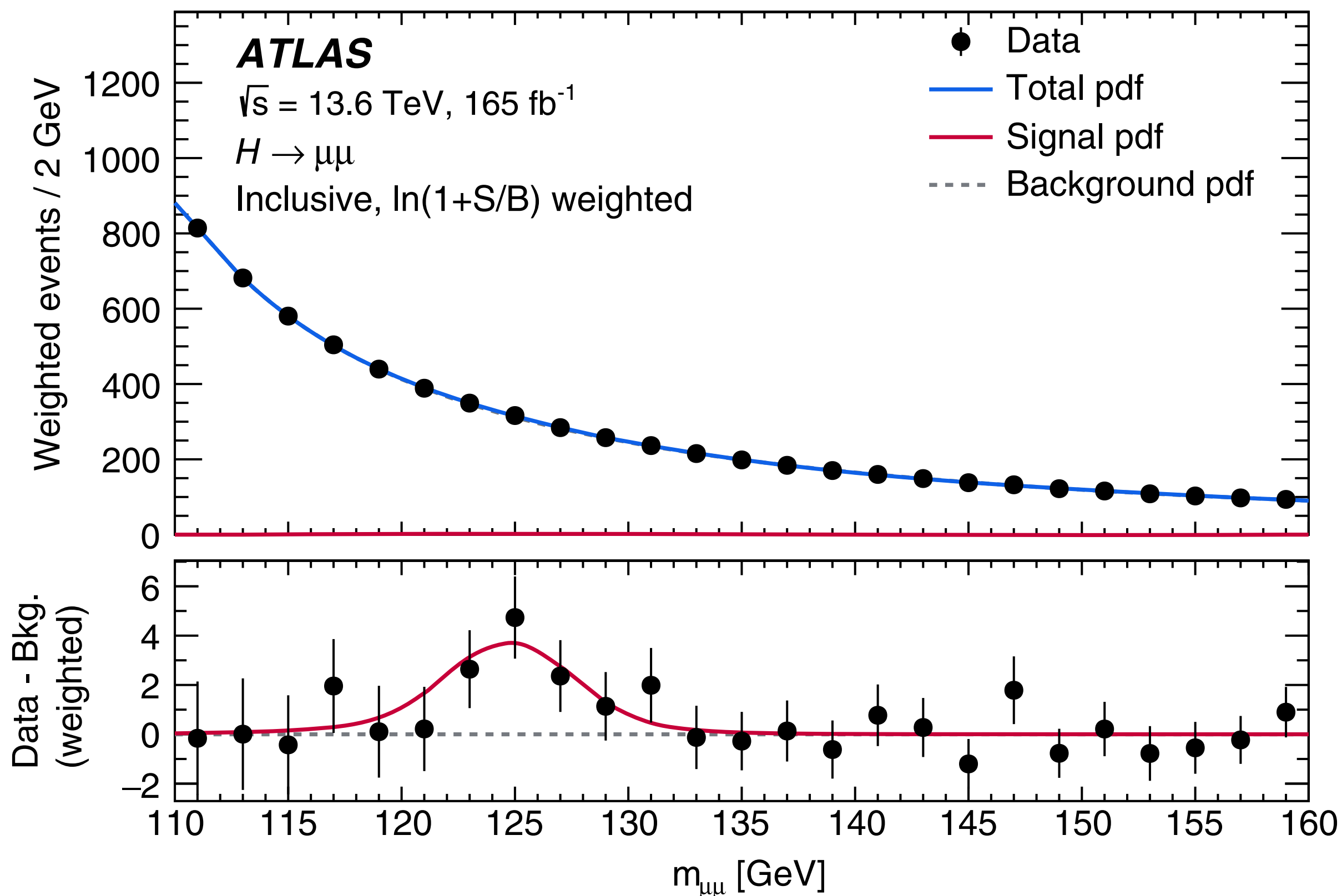
$H \rightarrow \mu\mu$ ($\mathcal{B} = 0.022\%$): direct probe of the Higgs Yukawa couplings to 2nd generation fermions

$H \rightarrow Z\gamma$ ($\mathcal{B} = 0.13\%$): Loop-induced => sensitive to BSM effects

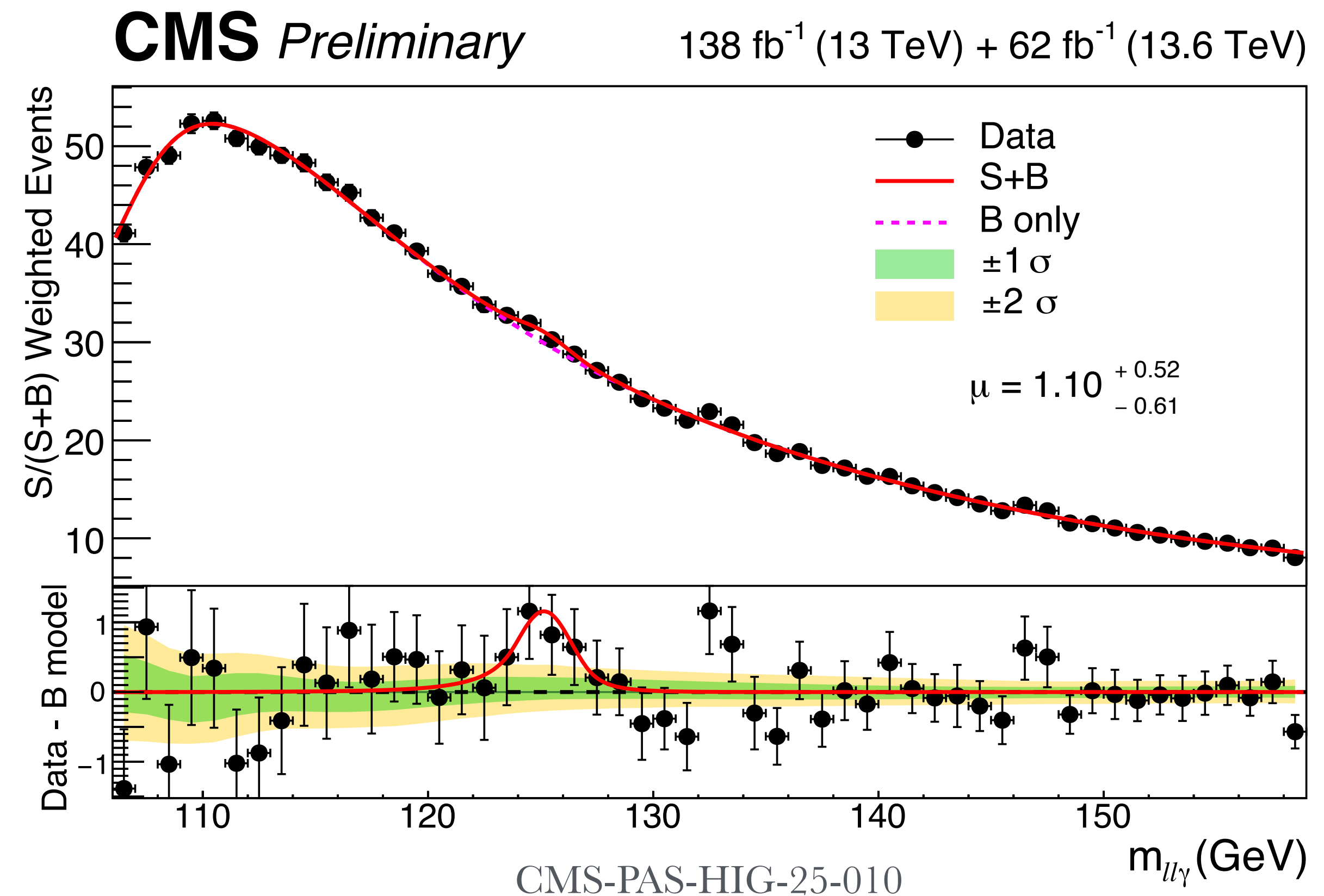


$H \rightarrow \mu\mu$

$H \rightarrow Z\gamma$



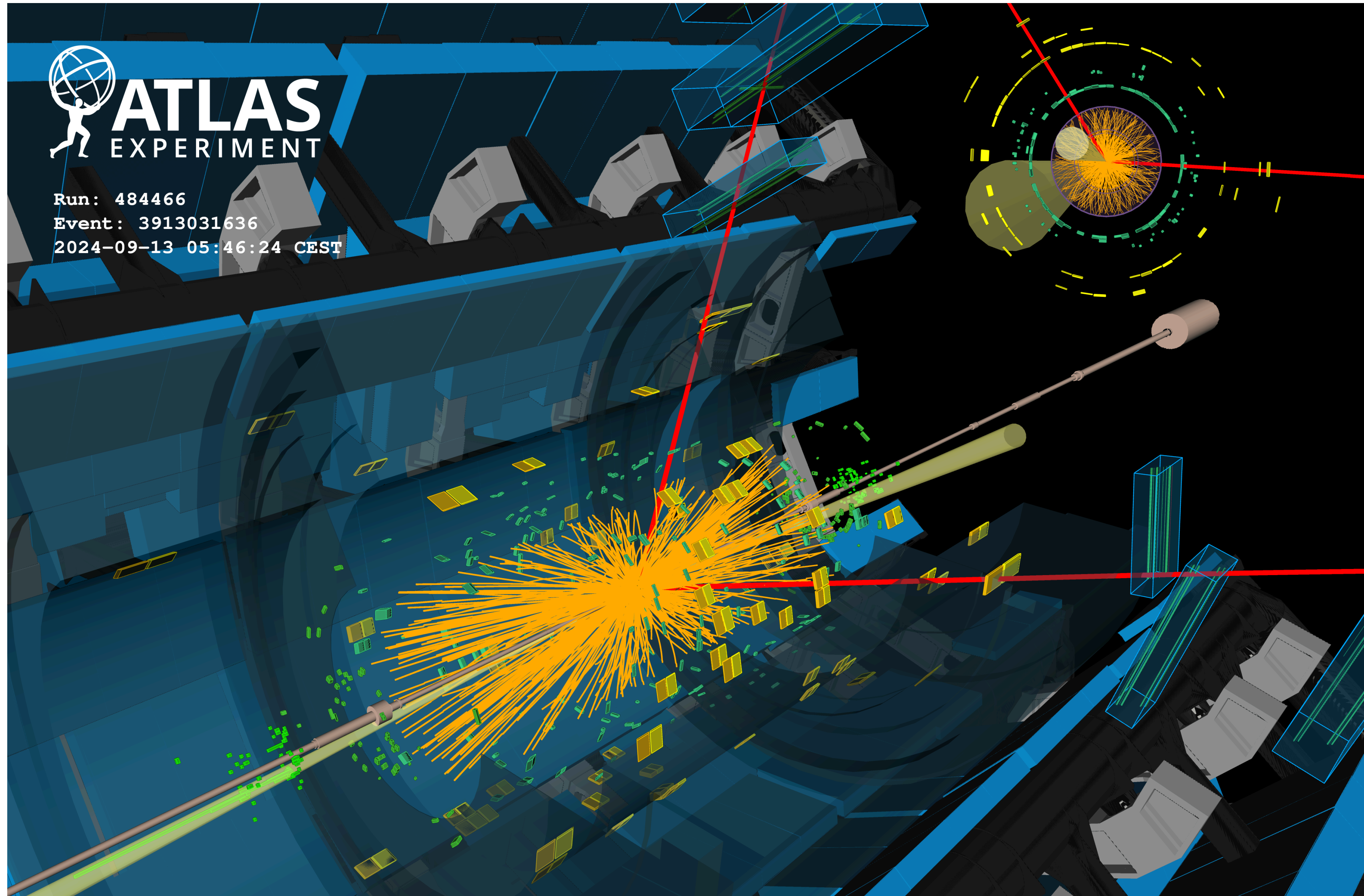
Phys. Rev. Lett. 135 (2025) 231802



Evidence ($\sim 3\sigma$) with Run2 ATLAS+CMS

Now chasing single experiment measurements

Evidence ($\sim 3\sigma$) from both ATLAS and CMS



- The **LHC Run2** provided data for a lot of results characterizing the Higgs boson
 - mass measured with 0.1% precision, and width measured for the first time with 50% precision
 - the production cross section are now measured differentially in many decay bins, in all production modes
 - fiducial cross sections and coupling modifiers measured at 5-10% level, allowing interesting EFT interpretations

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- **The LHC has just ended pp Run3 (and the phase-1)** with after having collected $\sim 500 \text{ fb}^{-1}$ per experiment, i.e. $\sim 1 \text{ ab}^{-1}$ total
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- After the end of Run3:
 - Expect 20x more data by the end of HL-LHC
 - Expect improvements from analysis techniques to boost new physics search in the Higgs sector

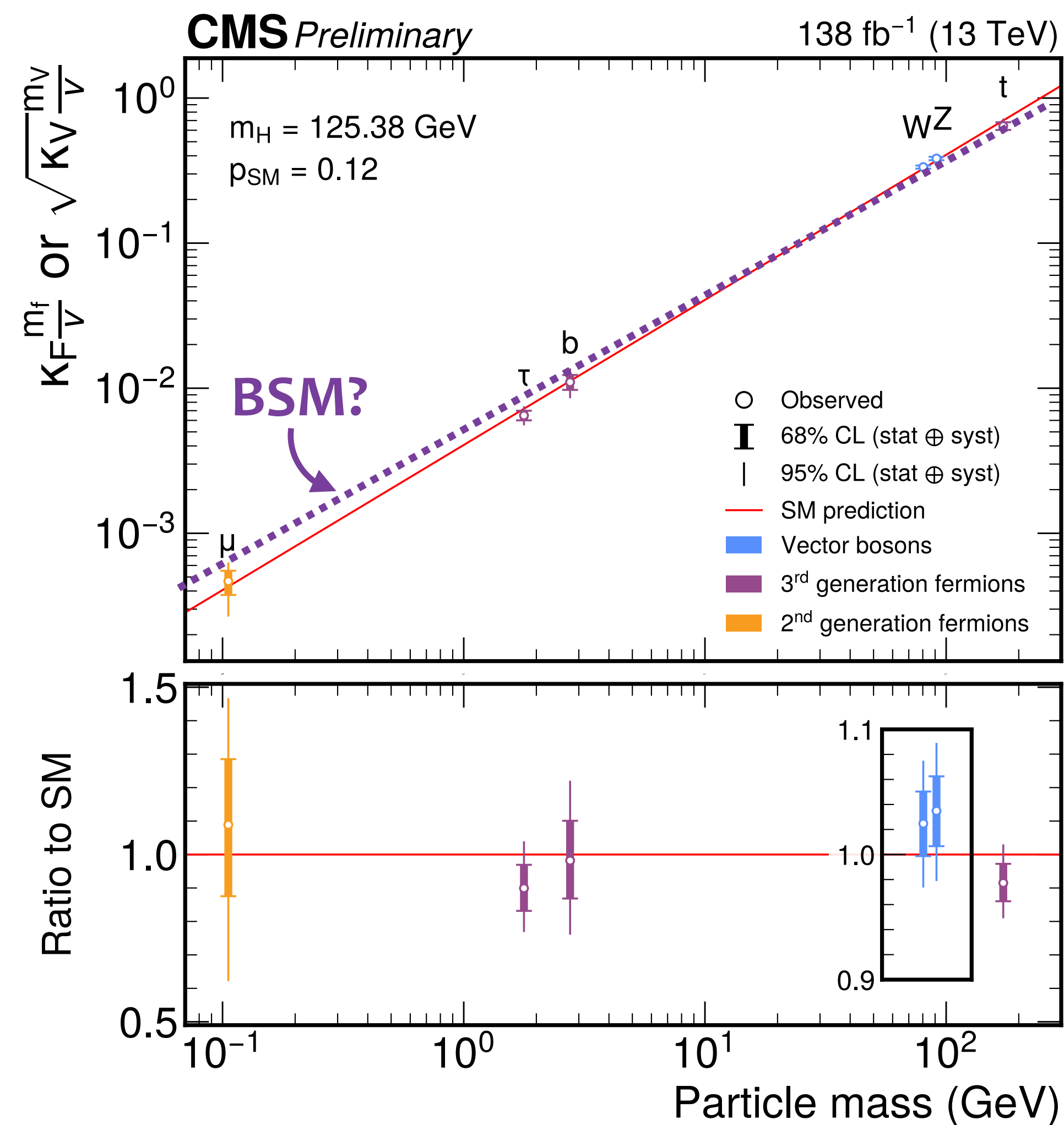
Backup

Higgs as BSM discovery tool

The SM can be the tip of the iceberg.

Higgs discovered 13 years ago was the last SM piece, still many questions:

- Is the 125 GeV particle the **SM H boson**?

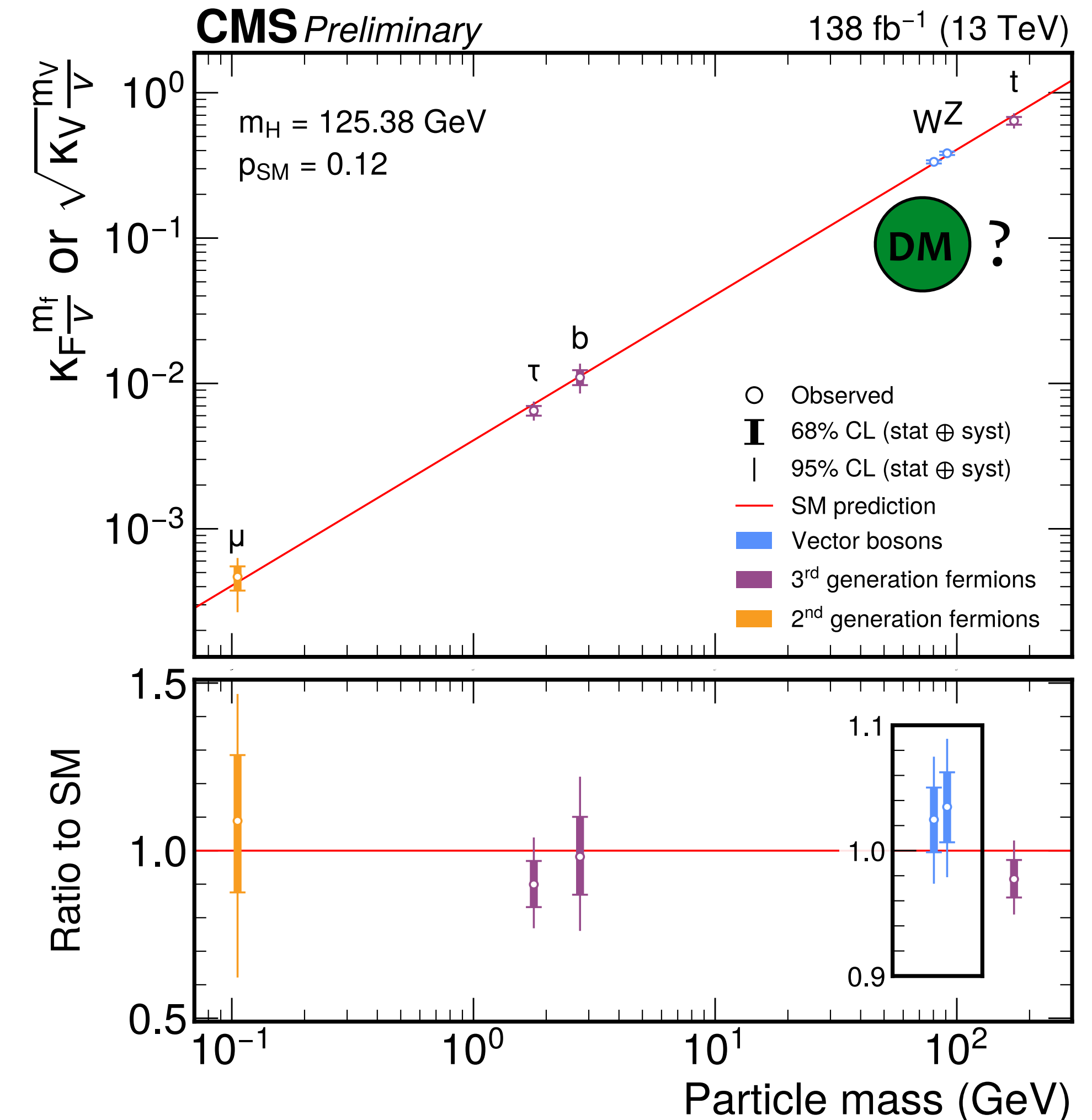
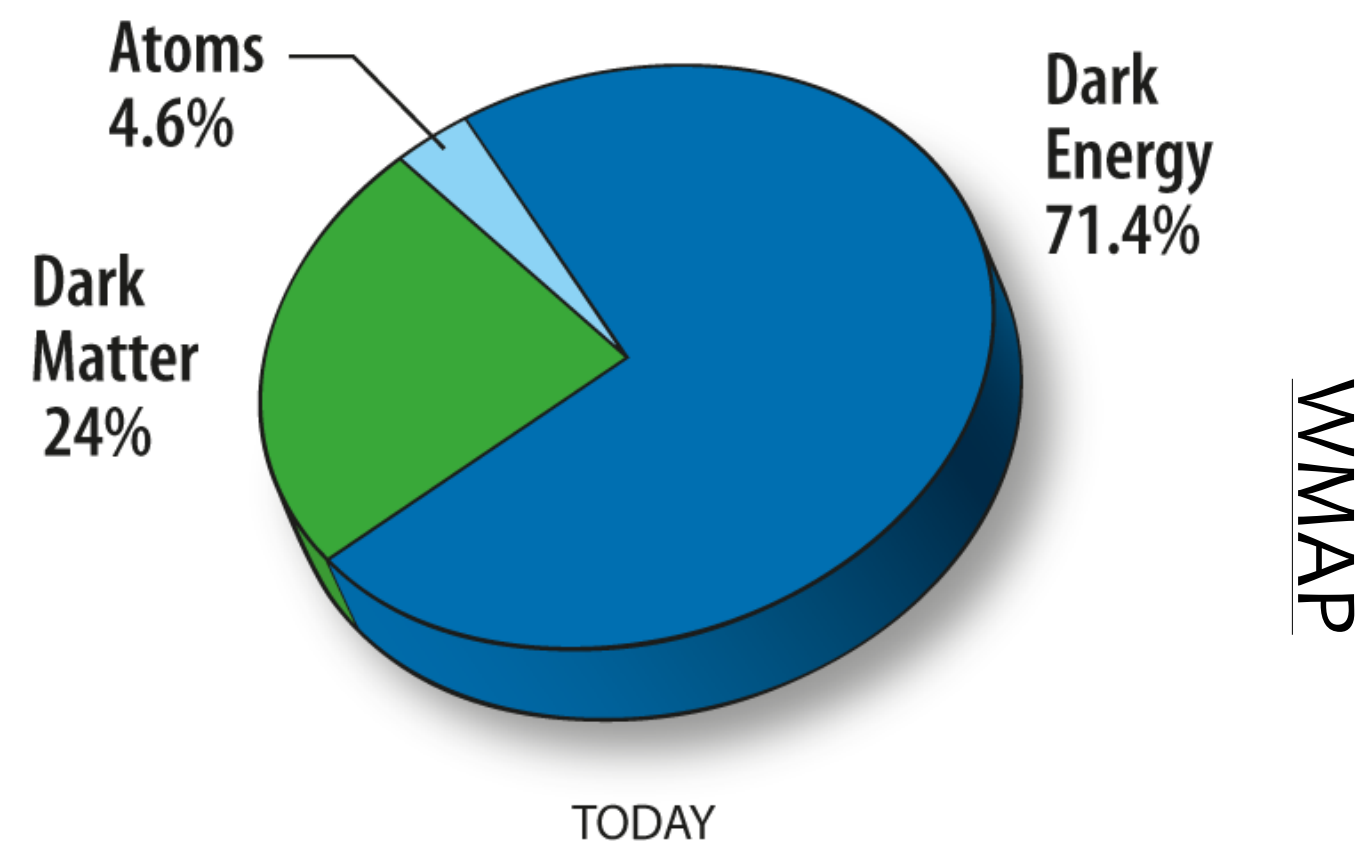


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- What makes **~70%** of the Universe energy?
- Of the remaining **~30%** (i.e. matter) **~85%** is still unknown: Dark Matter (DM)?
 - If DM are massive particles, do they **couple to the Higgs**?

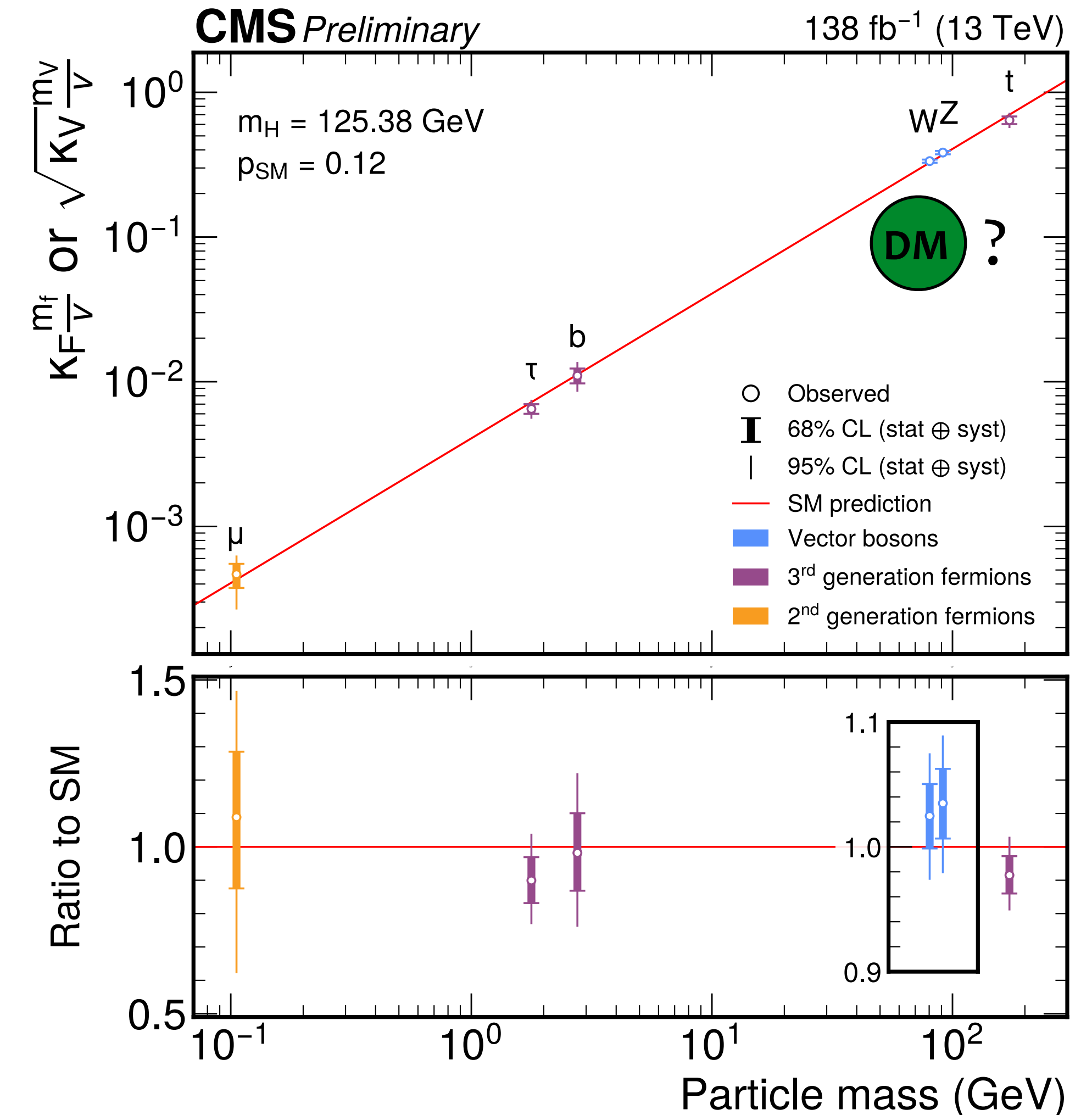
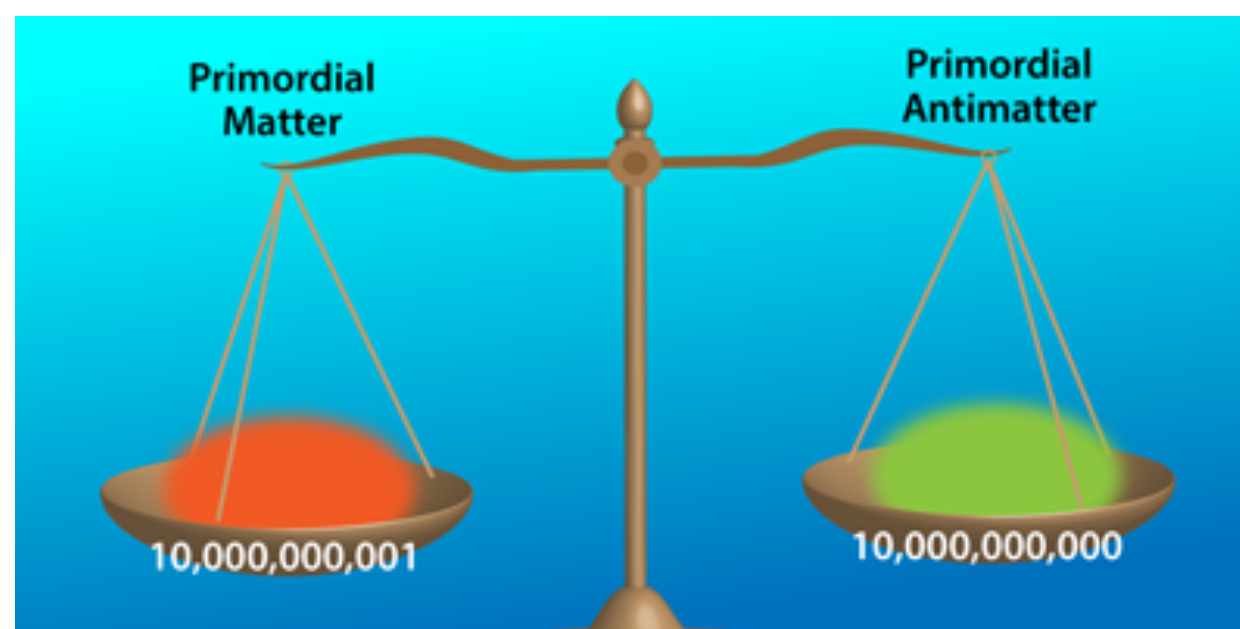


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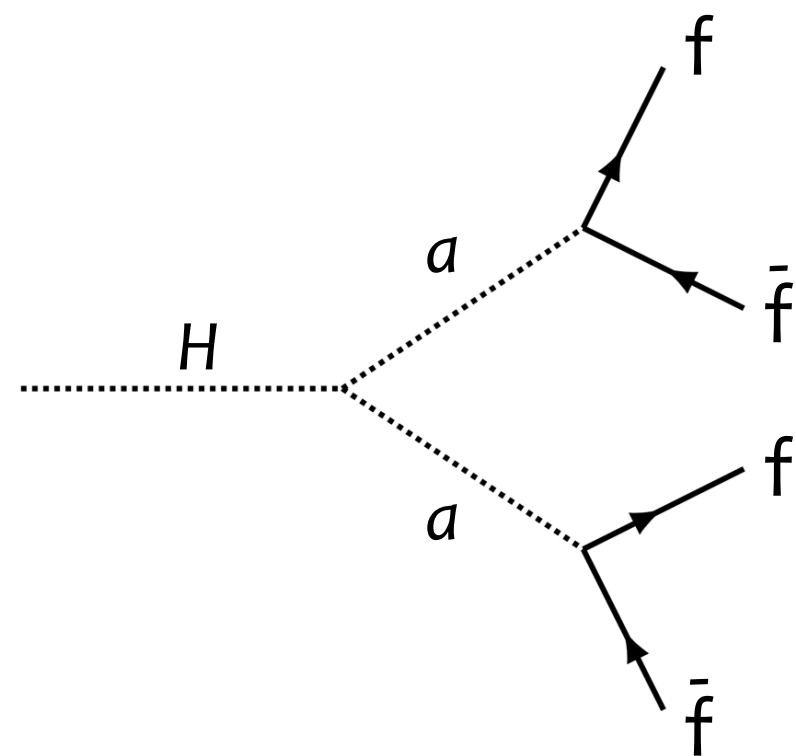
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- Why there is **more matter than antimatter** in the universe?



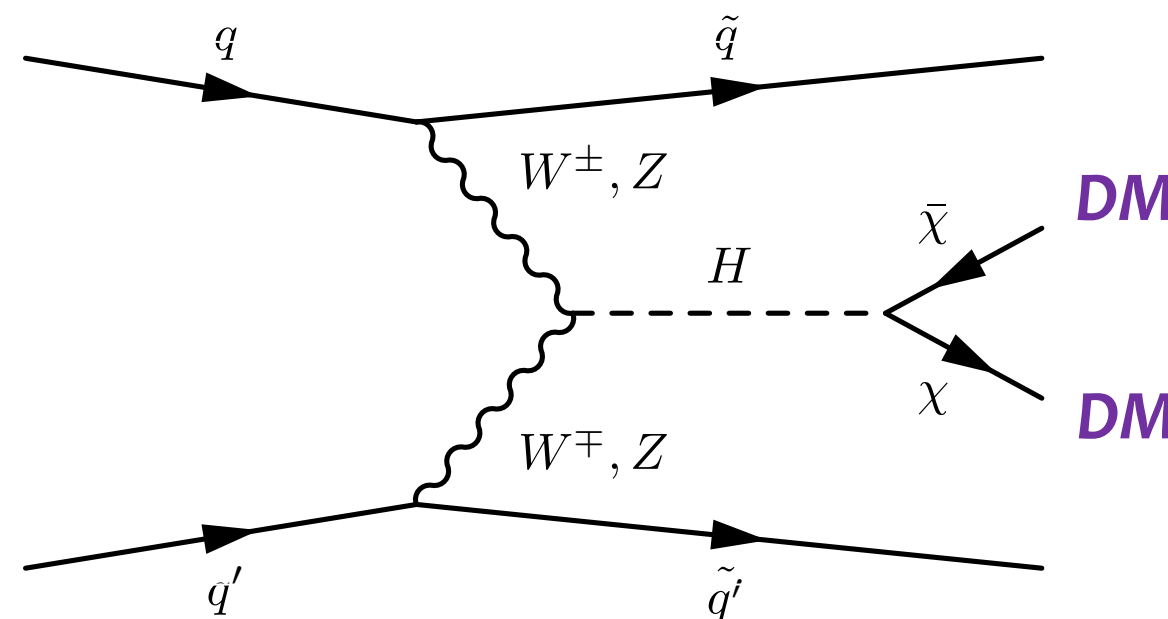
Higgs as direct BSM probe

Current measurements of Higgs couplings still allow decay modes to BSM particles:

- **Undetected decay modes** (eg. 2HDM+s, nMSSM,...)
- **Invisible particles** (eg. Dark Matter)



$H \rightarrow 2$ light (pseudo-)scalars



$H \rightarrow 2$ DM particles

CMS Preliminary

138 fb⁻¹ (13 TeV)

