LHC Days
(Split)
03/10/2022

The SM Higgs Boson

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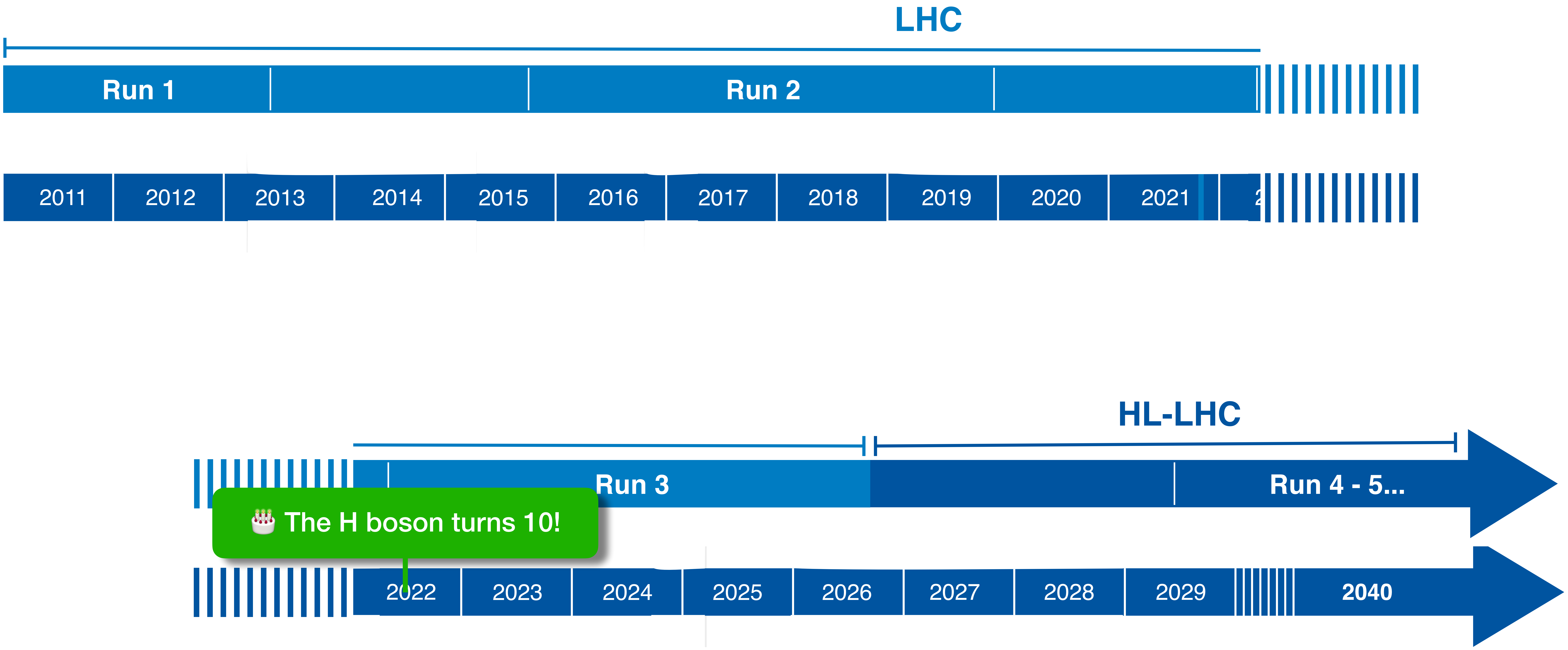
(University of Hamburg)
On behalf of the CMS Collaboration

FSP CMS
Erforschung von
Universum und Materie

Overview the Higgs boson at LHC



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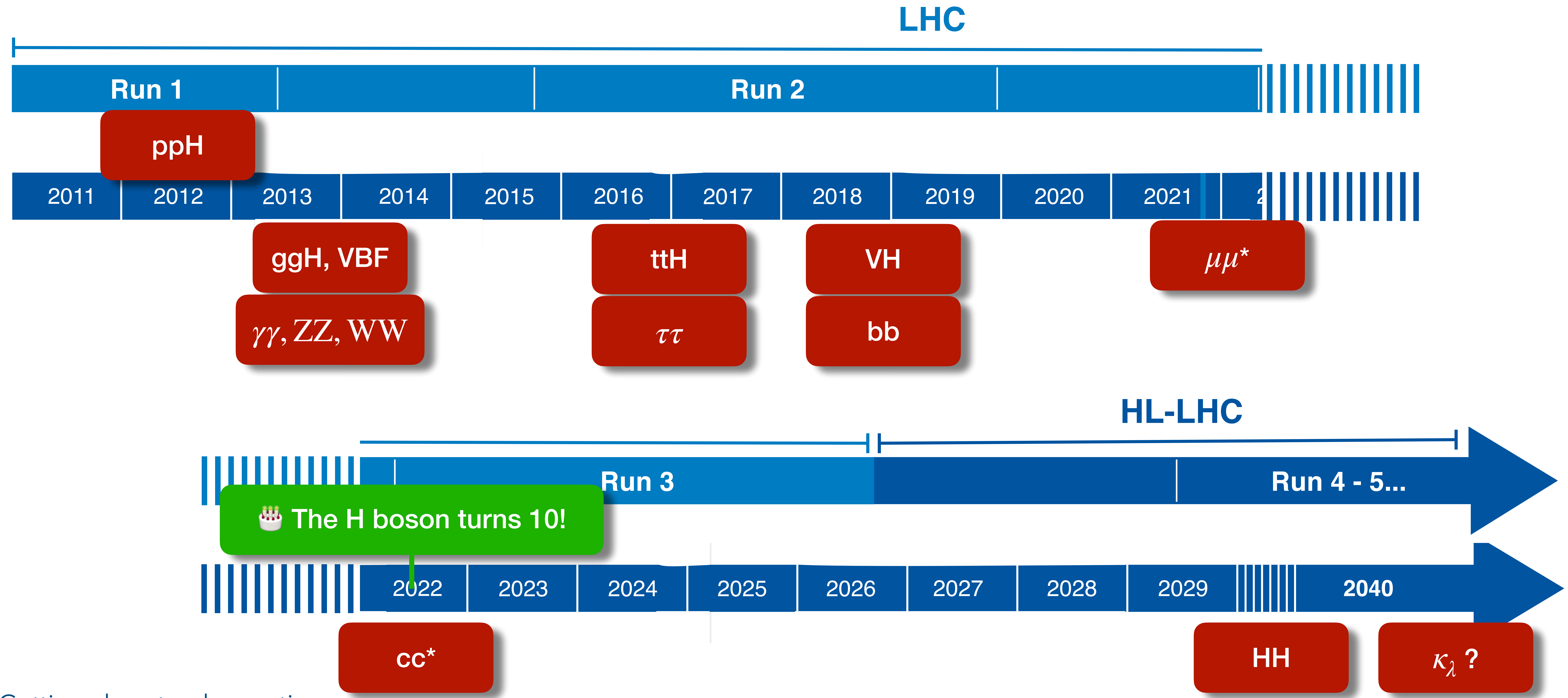
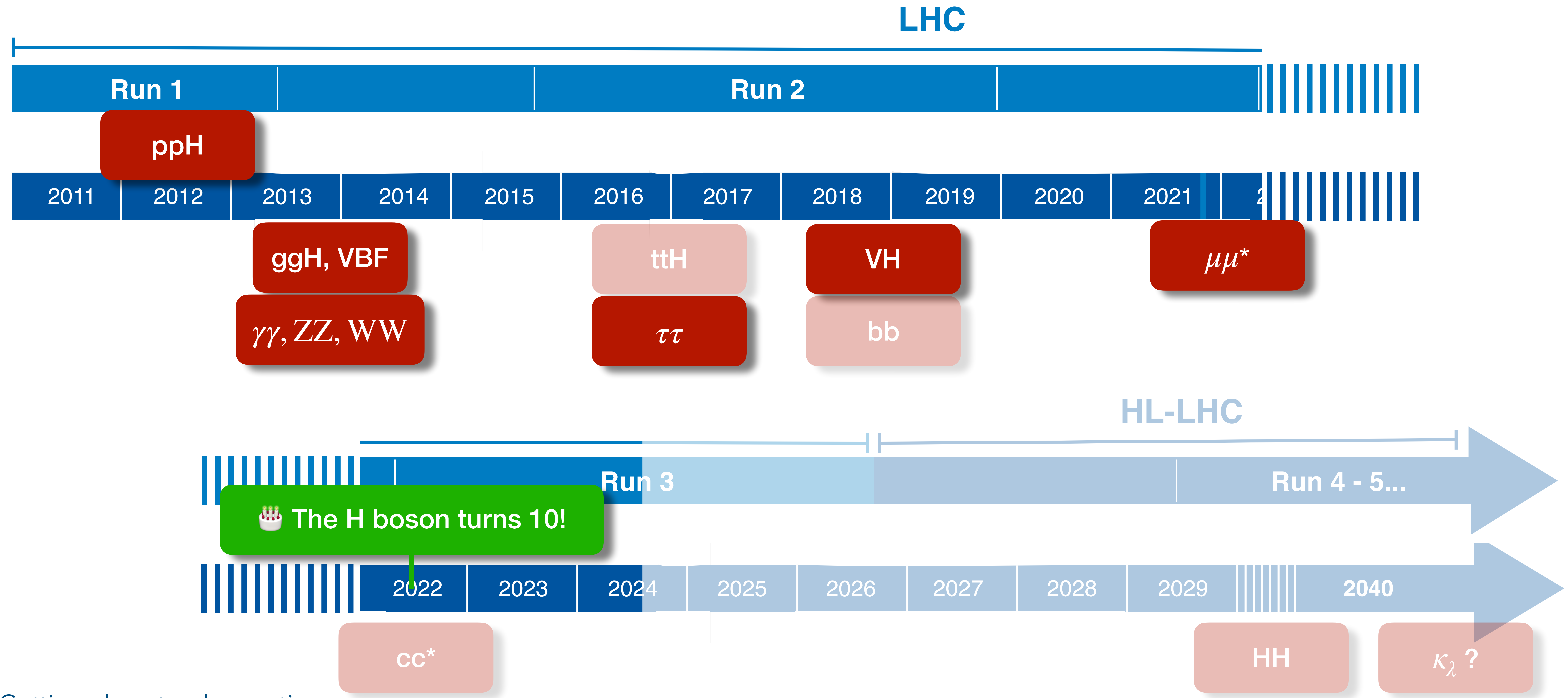


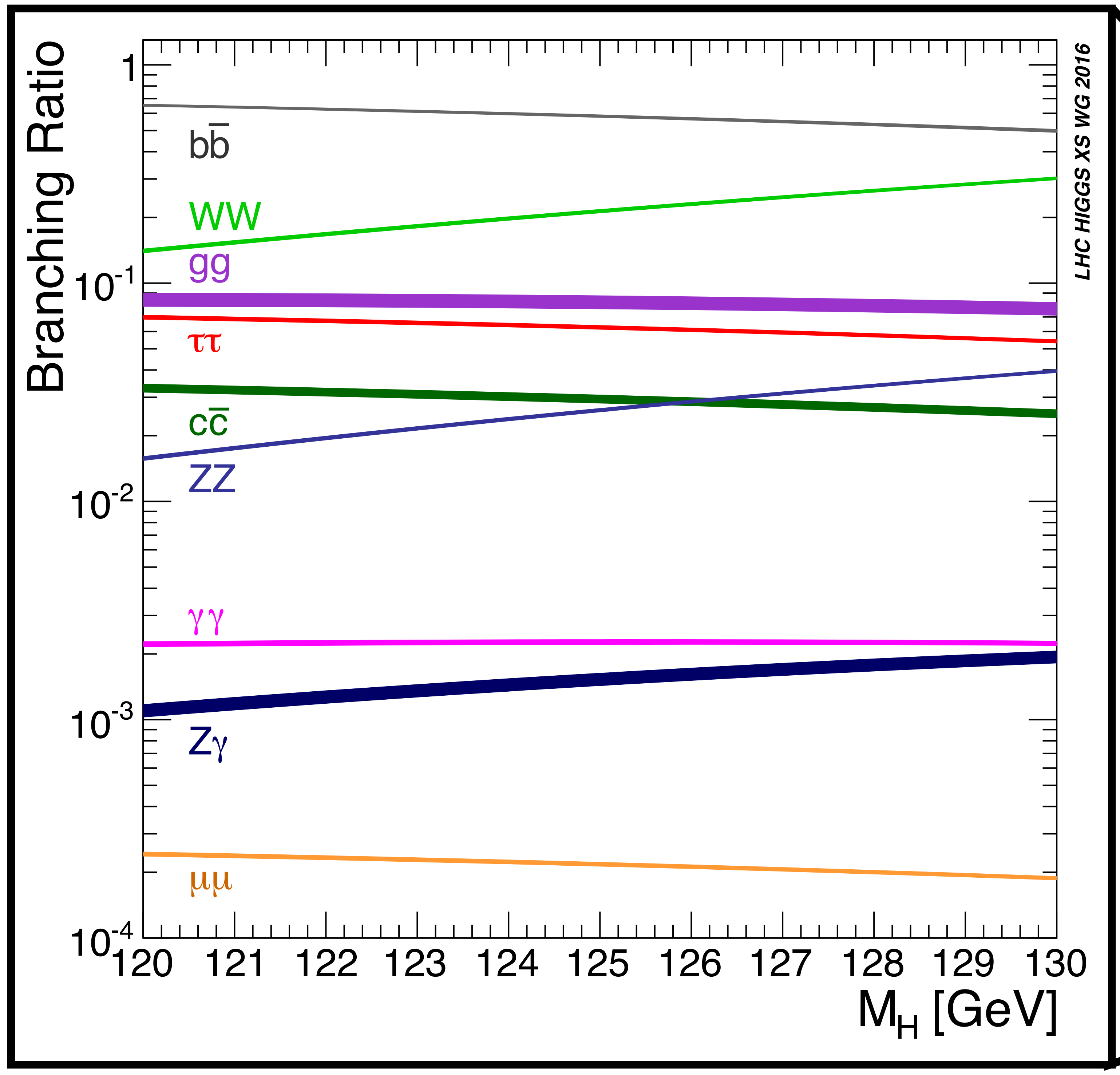
* Getting close to observation

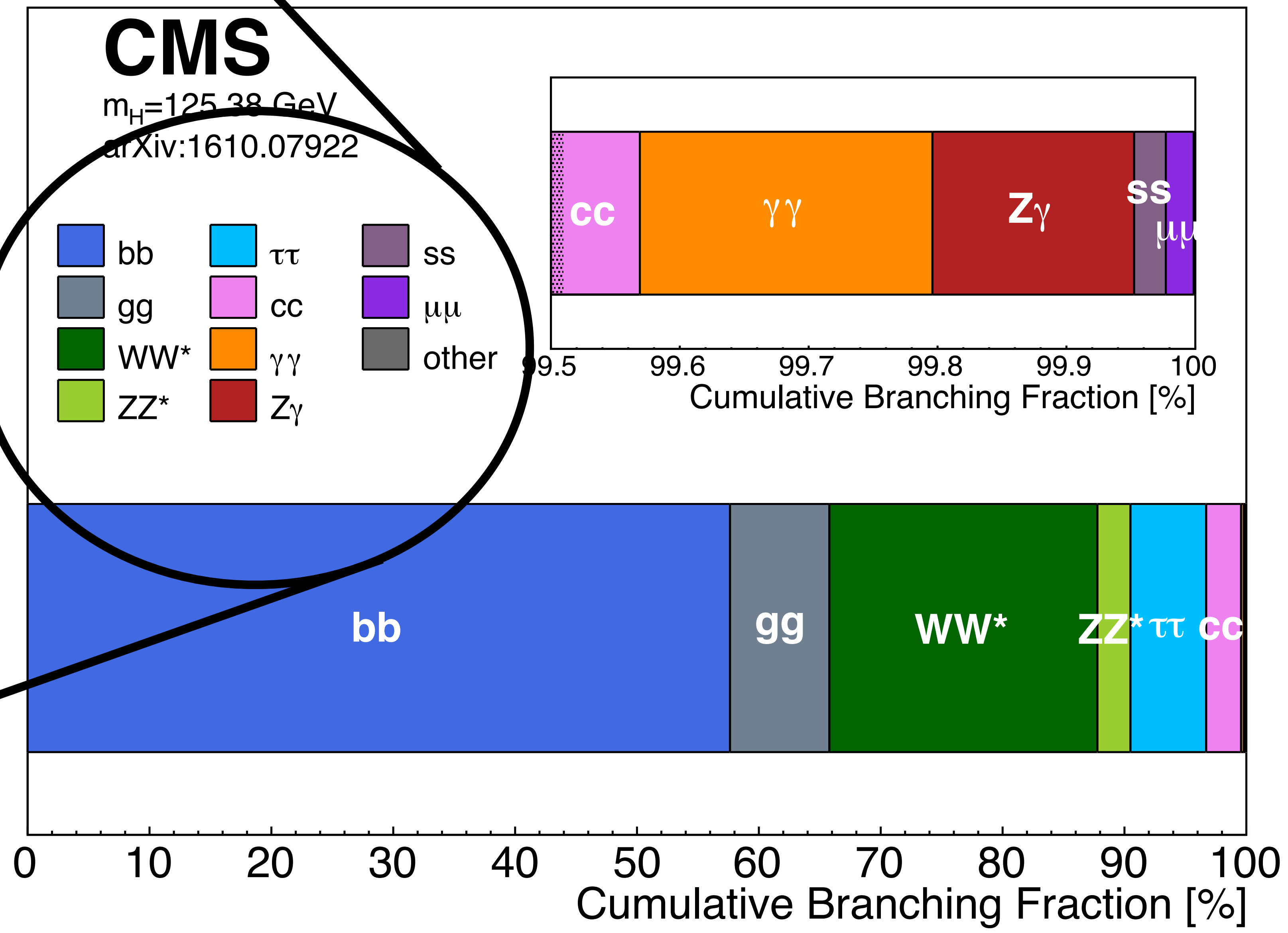
What we are going to cover today



* Getting close to observation

Anatomy of a boson



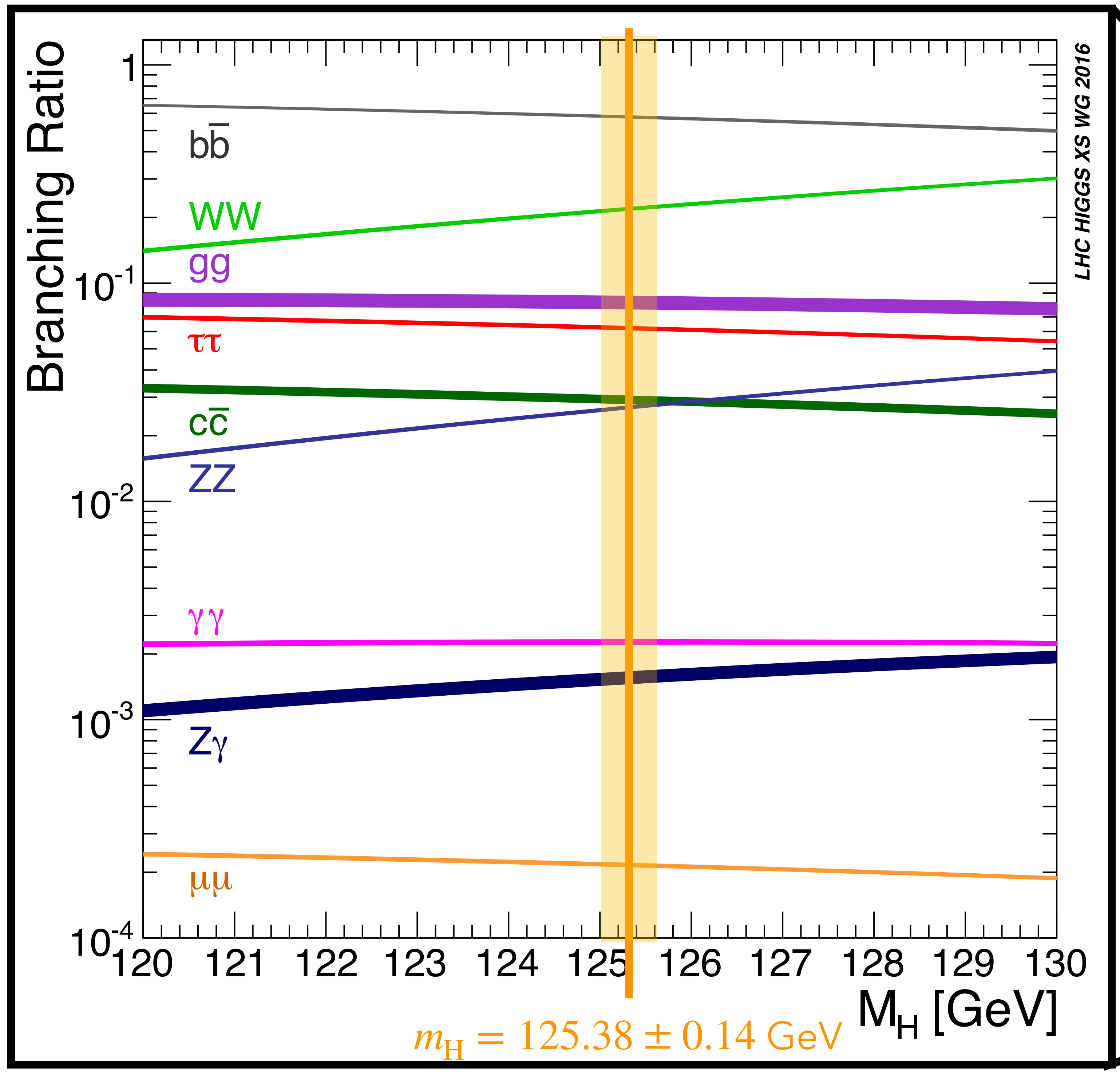


Production **cross sections** and **branching ratios** of the **H boson depend on** its **mass**

Two main questions at the start of the LHC:

- Can we observe the H boson?
- What is its mass?

Find mH to understand the



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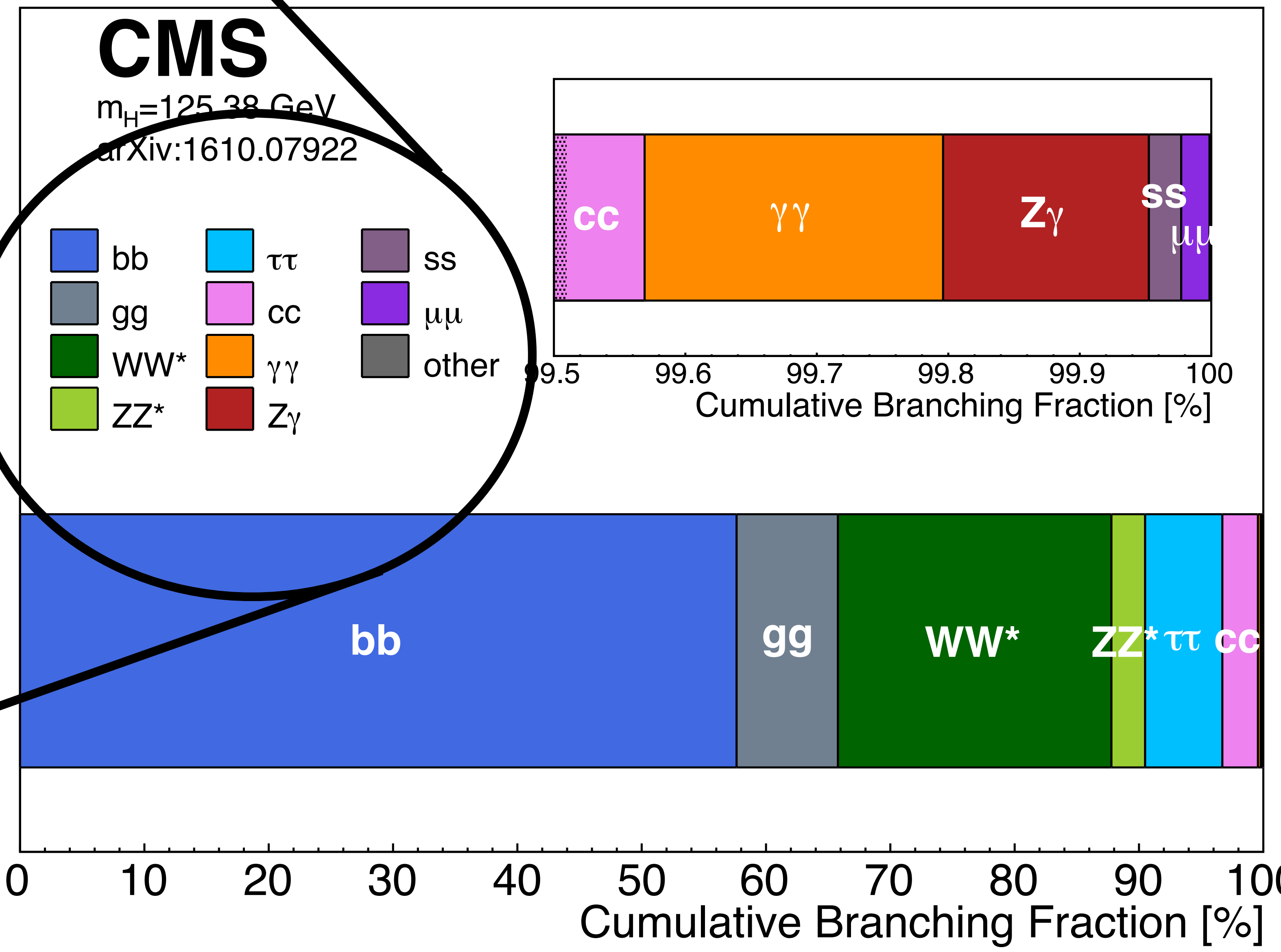

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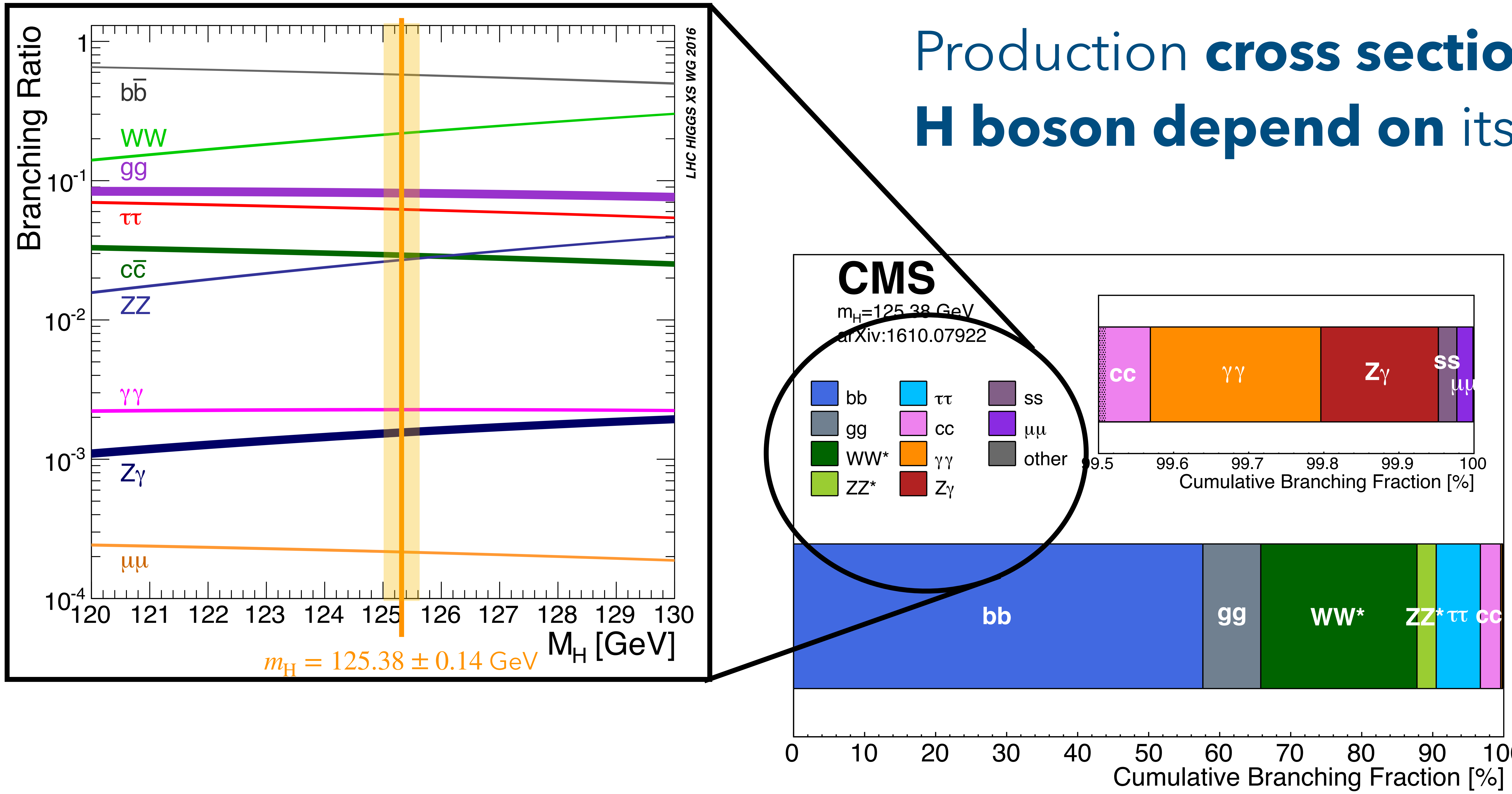

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- Can we observe the H boson?
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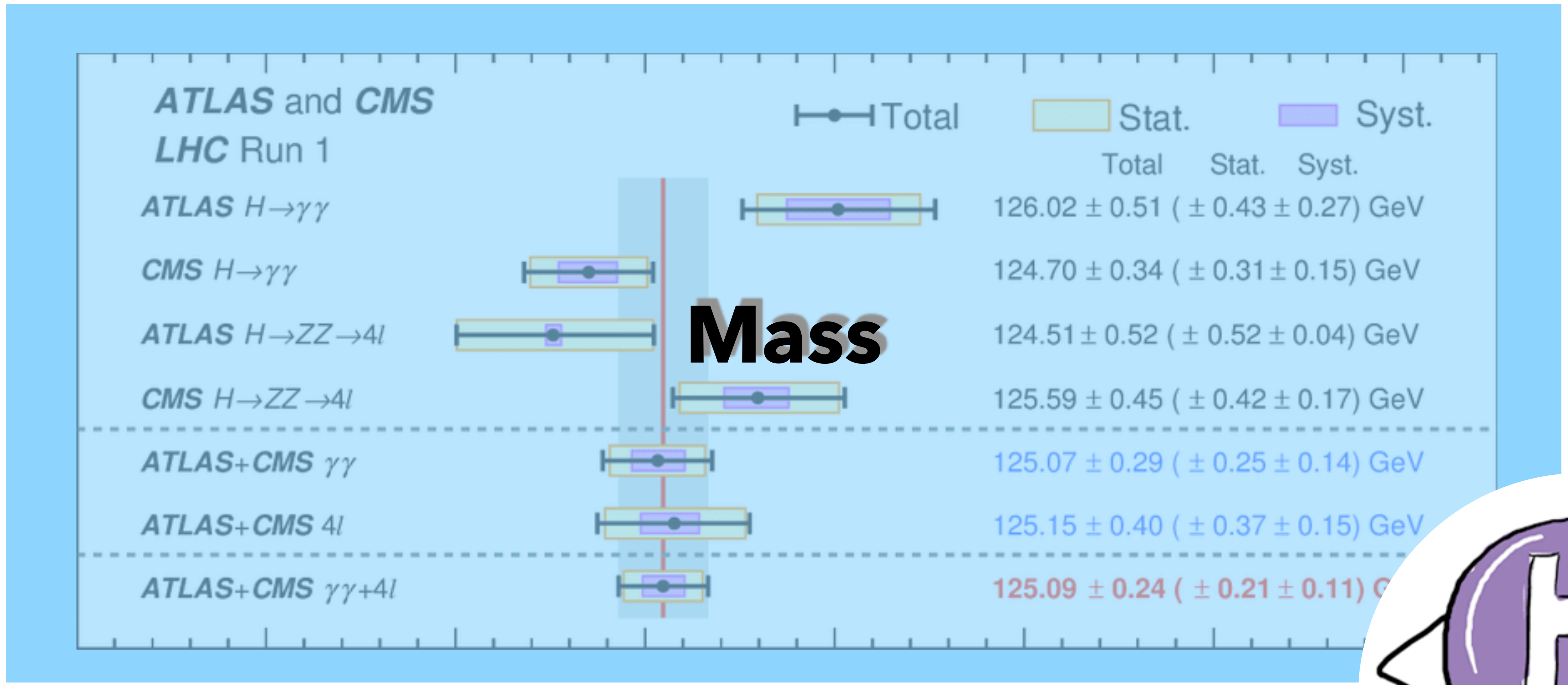
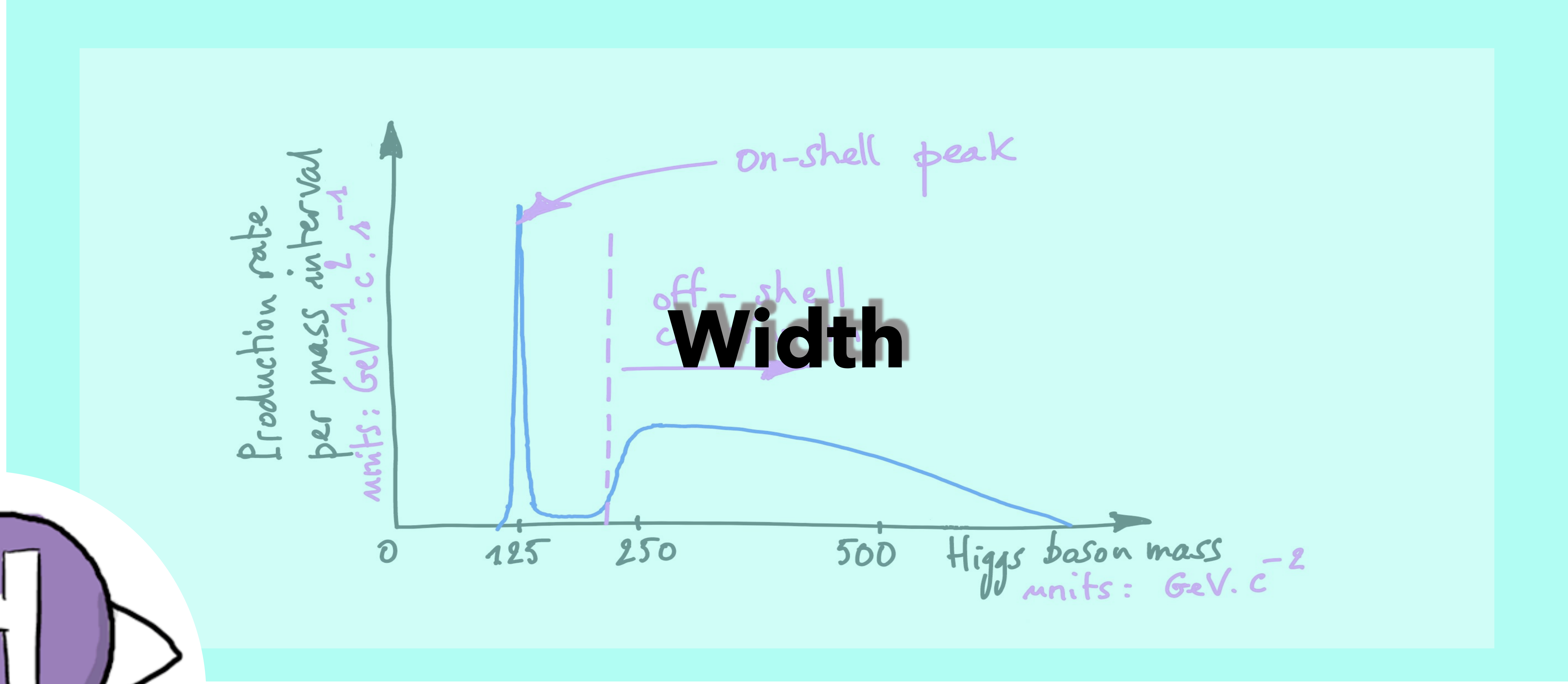
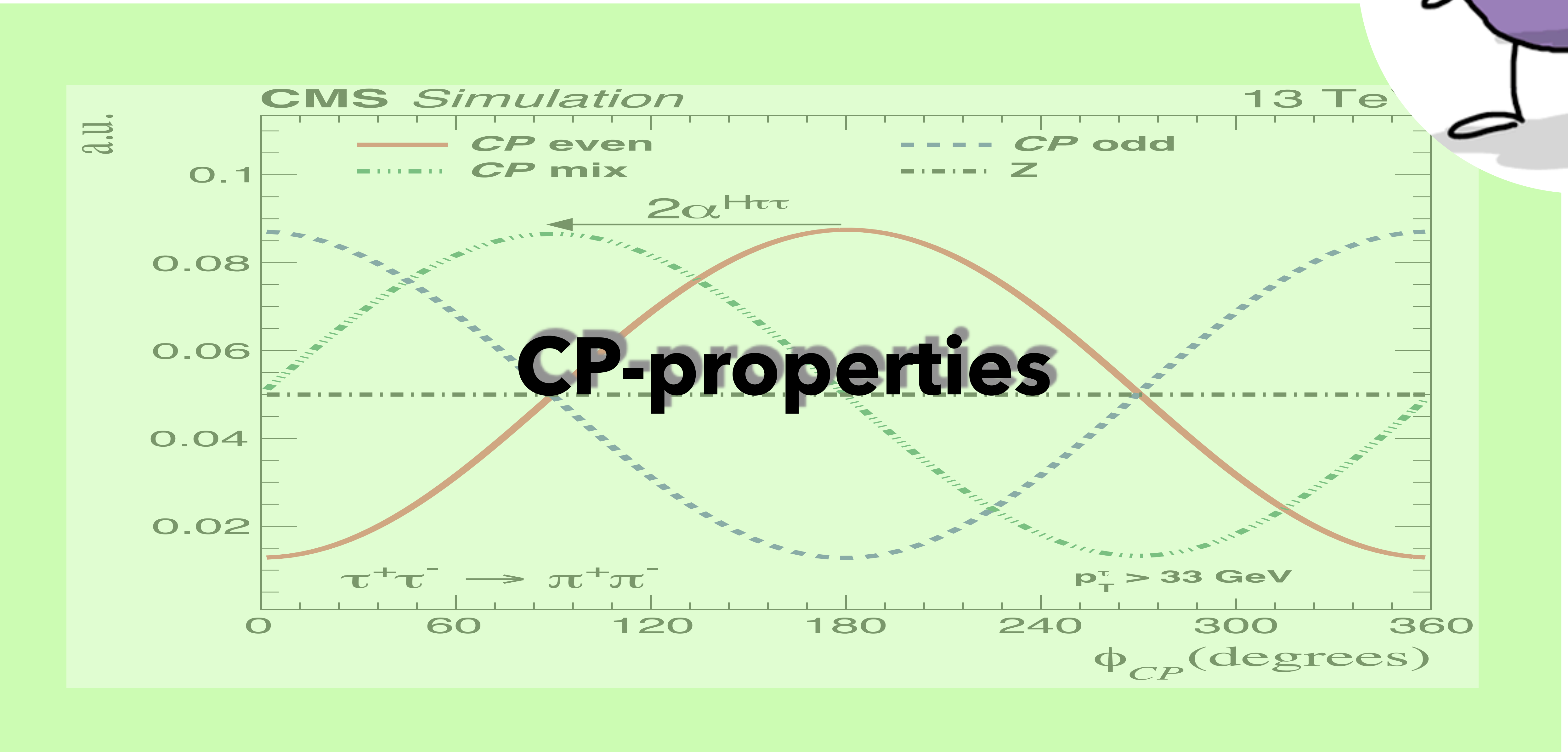
The H boson has a too short lifetime ($\tau_H \sim 2 \times 10^{-22} s \Rightarrow \Gamma_H = 4.1$ MeV) to be detected directly at the LHC

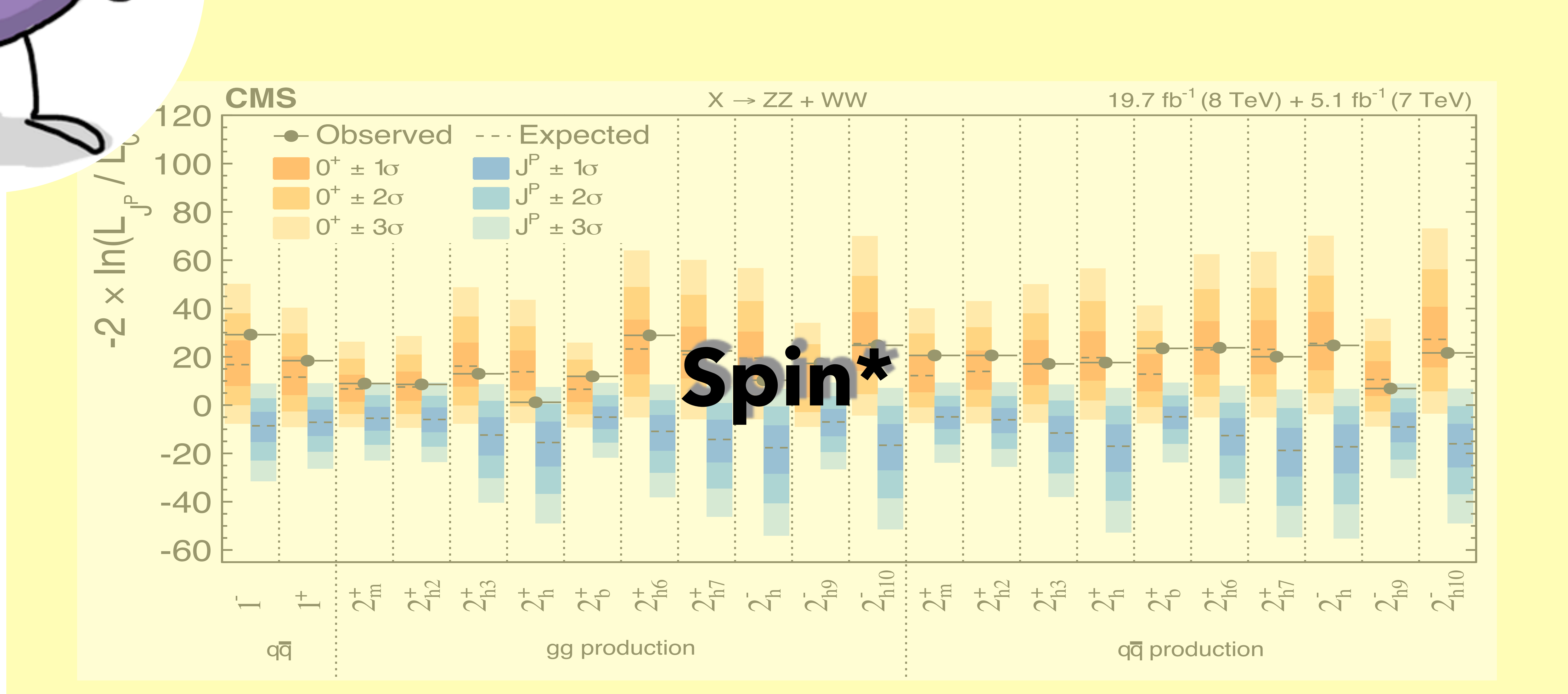
$\Rightarrow$ **exploit its decay products to reconstruct the final states and characterise it**

Global profile of the Higgs boson



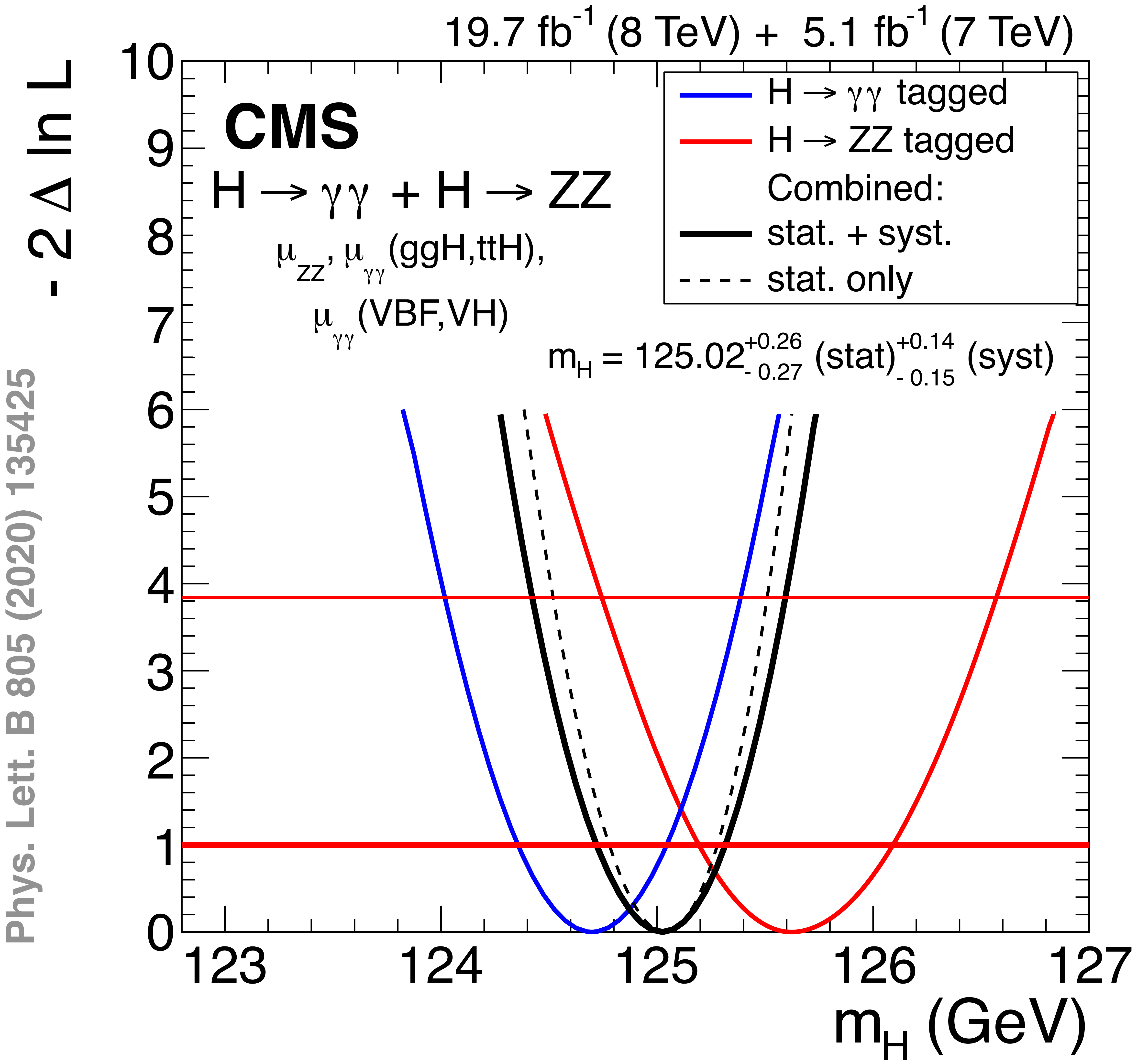






* not covered in this talk

Higgs boson mass



m_{H} is a free parameter in the SM

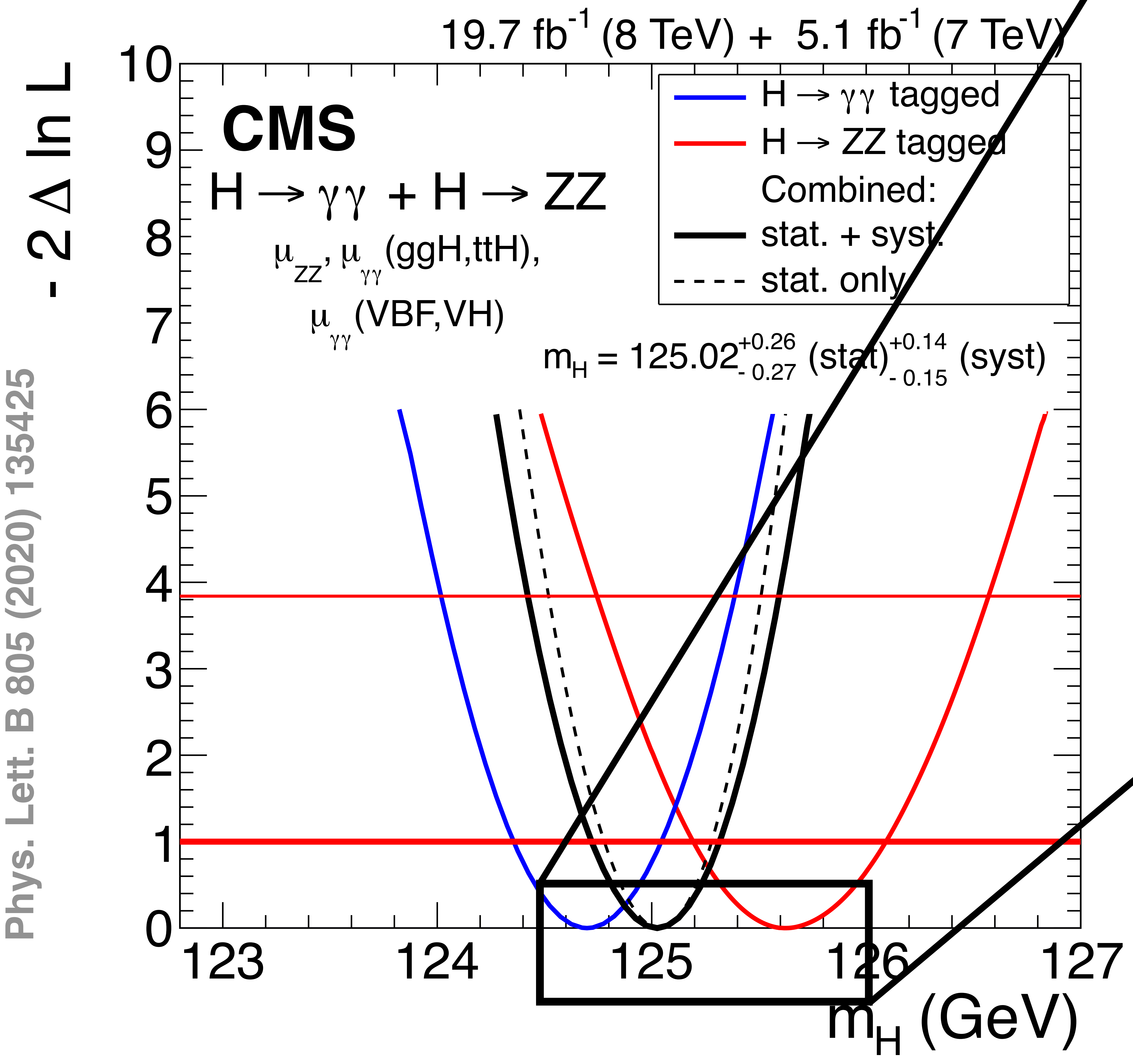
→ its determination is left to experimentalists

- Fixes production xsec and BRs
- Allows to probe the minimum of the H potential, fundamental to understand BEH mechanism

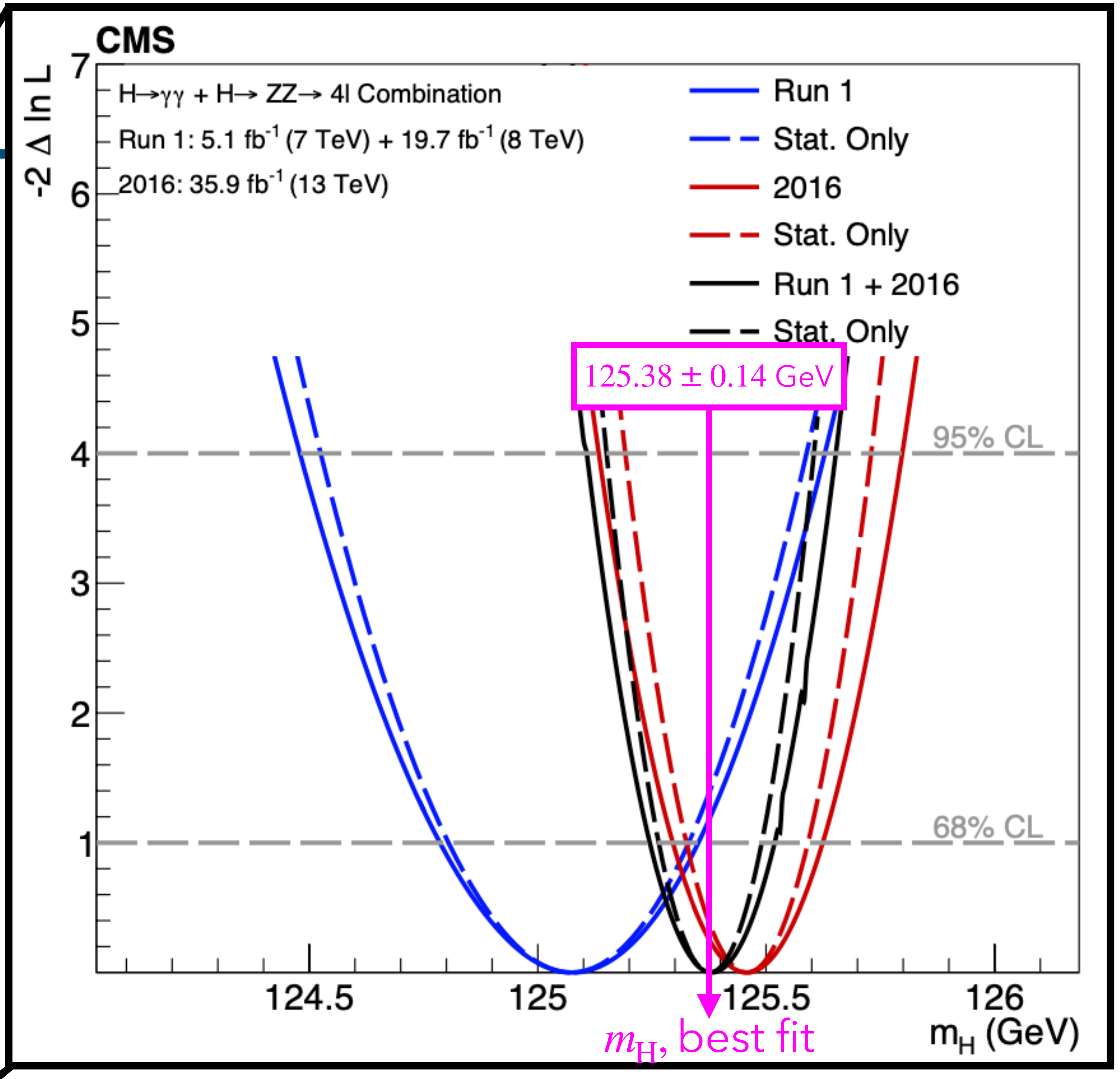
First precision measurement performed in the Higgs sector (sub-% uncertainty)

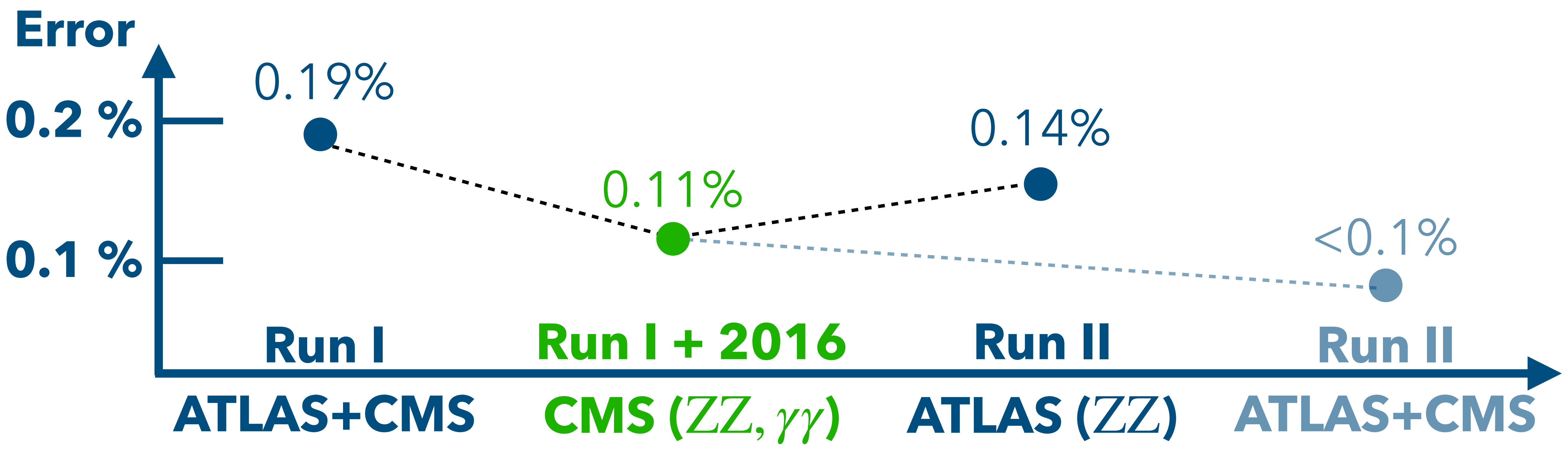
High precision achieved thanks to $\mathrm{H} \rightarrow \gamma\gamma$ **and** $\mathrm{H} \rightarrow \mathrm{ZZ}$

Higgs boson mass



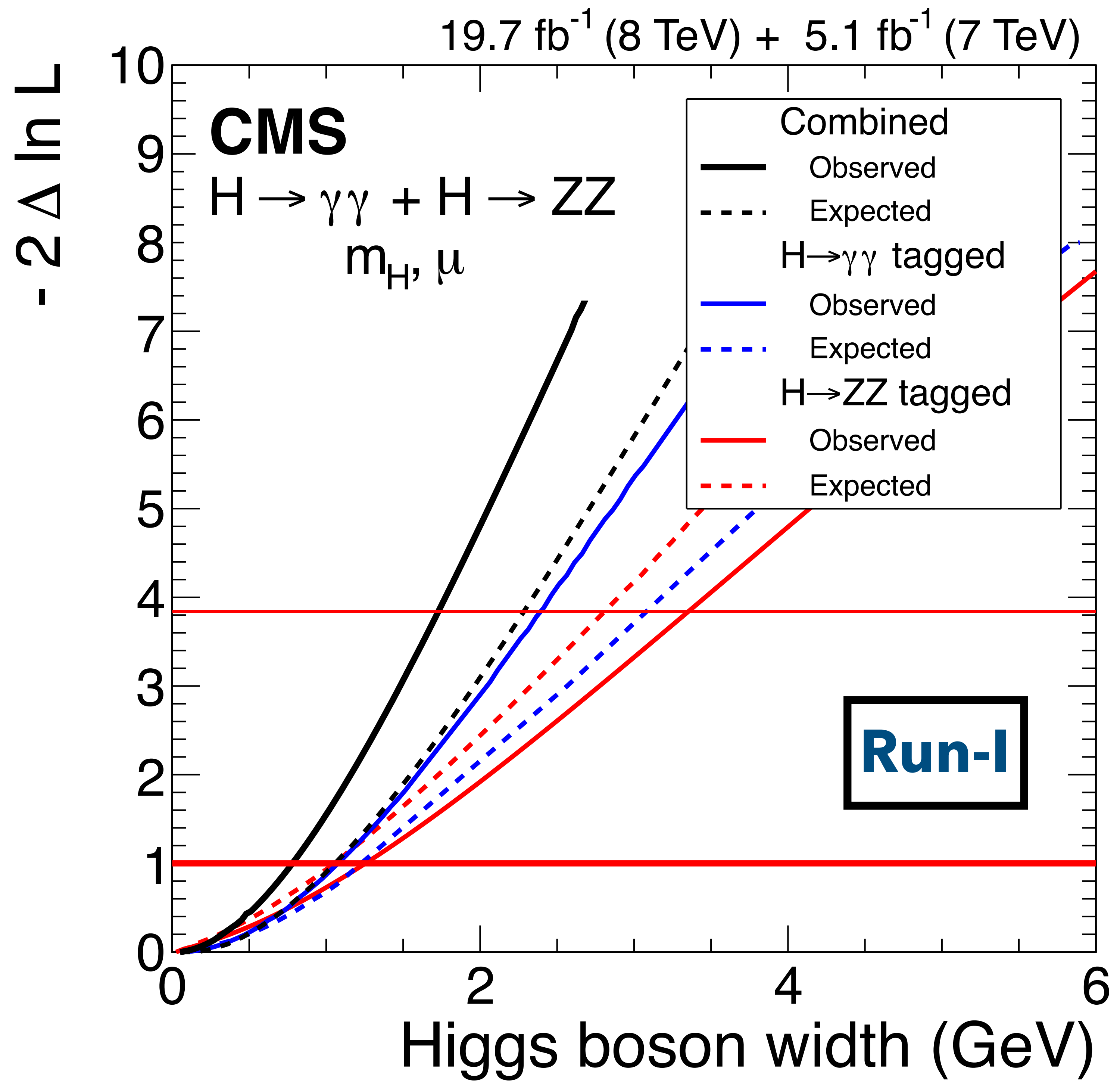
Phys. Lett. B 805 (2020) 135425

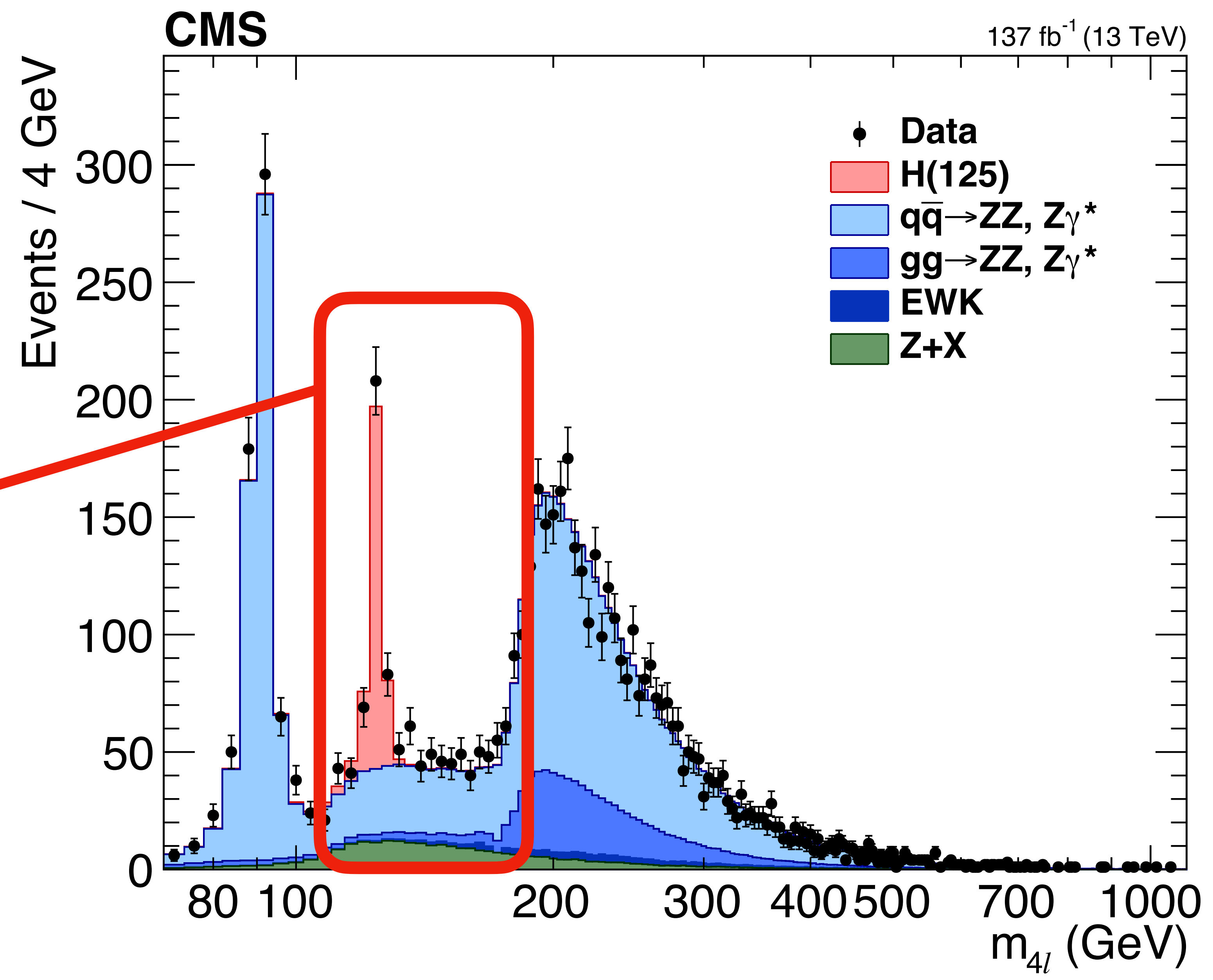




Higgs boson width

$\sigma^{\text{on-shell}}: \dfrac{g_{prod}^2 g_{dec}^2}{m_H^2 \Gamma_H^2} dq_H^2 \propto \mu_{prod}$





m_H **unconstrained**

On-shell and 2016 dataset: only upper limit on Γ_H

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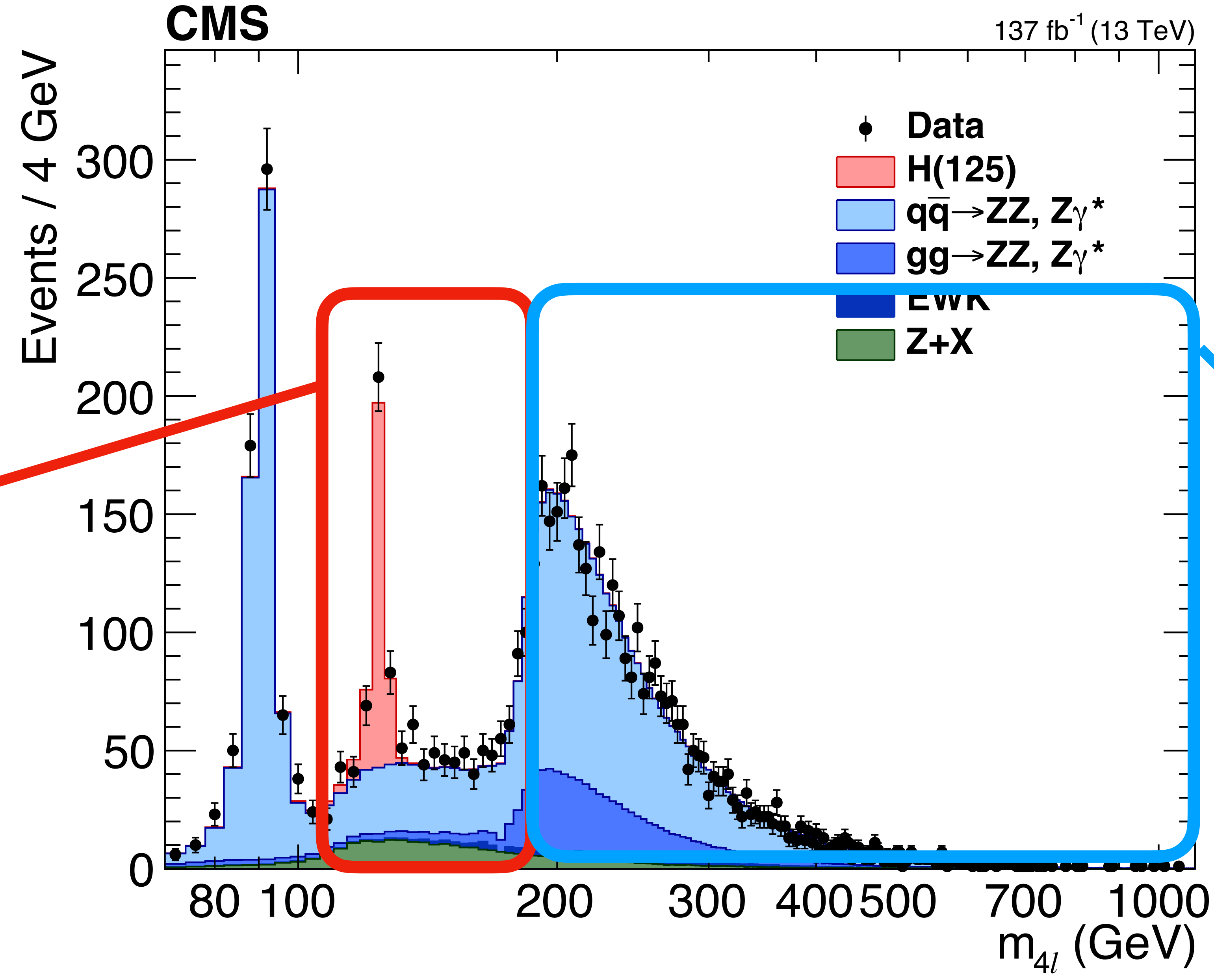

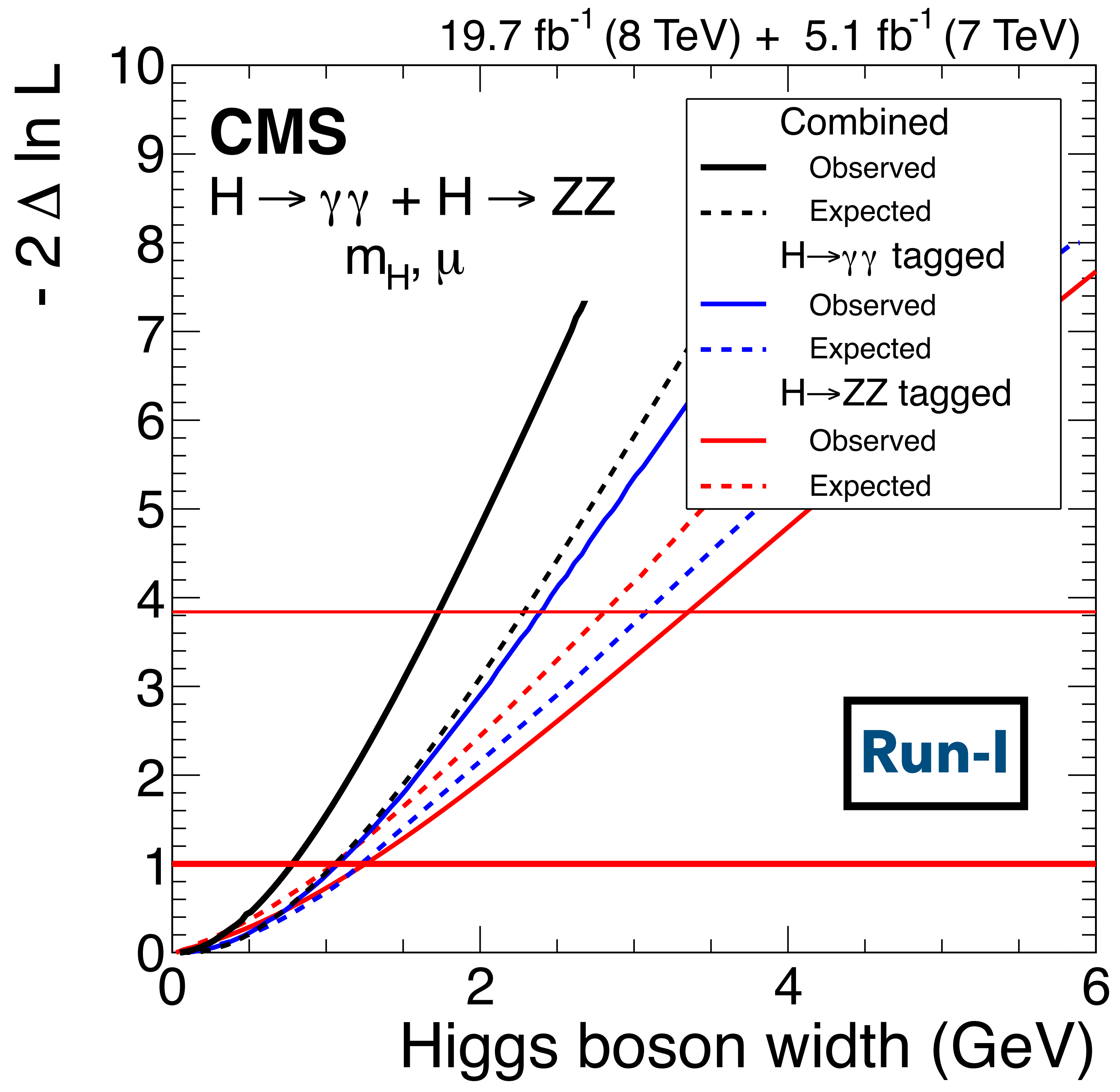

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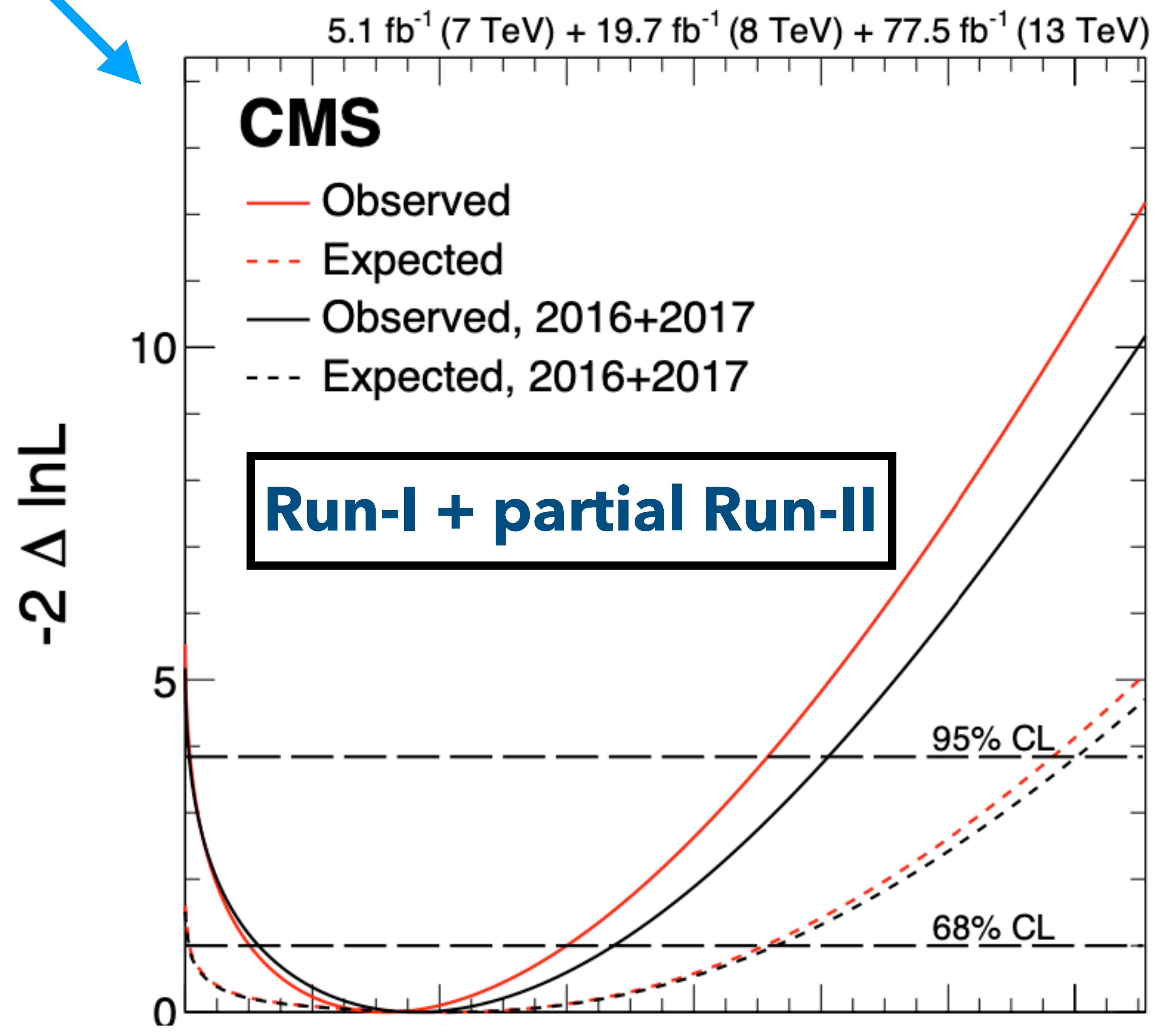

Assuming SM-like couplings

m_H unconstrained

On/off-shell events + RunI dataset:

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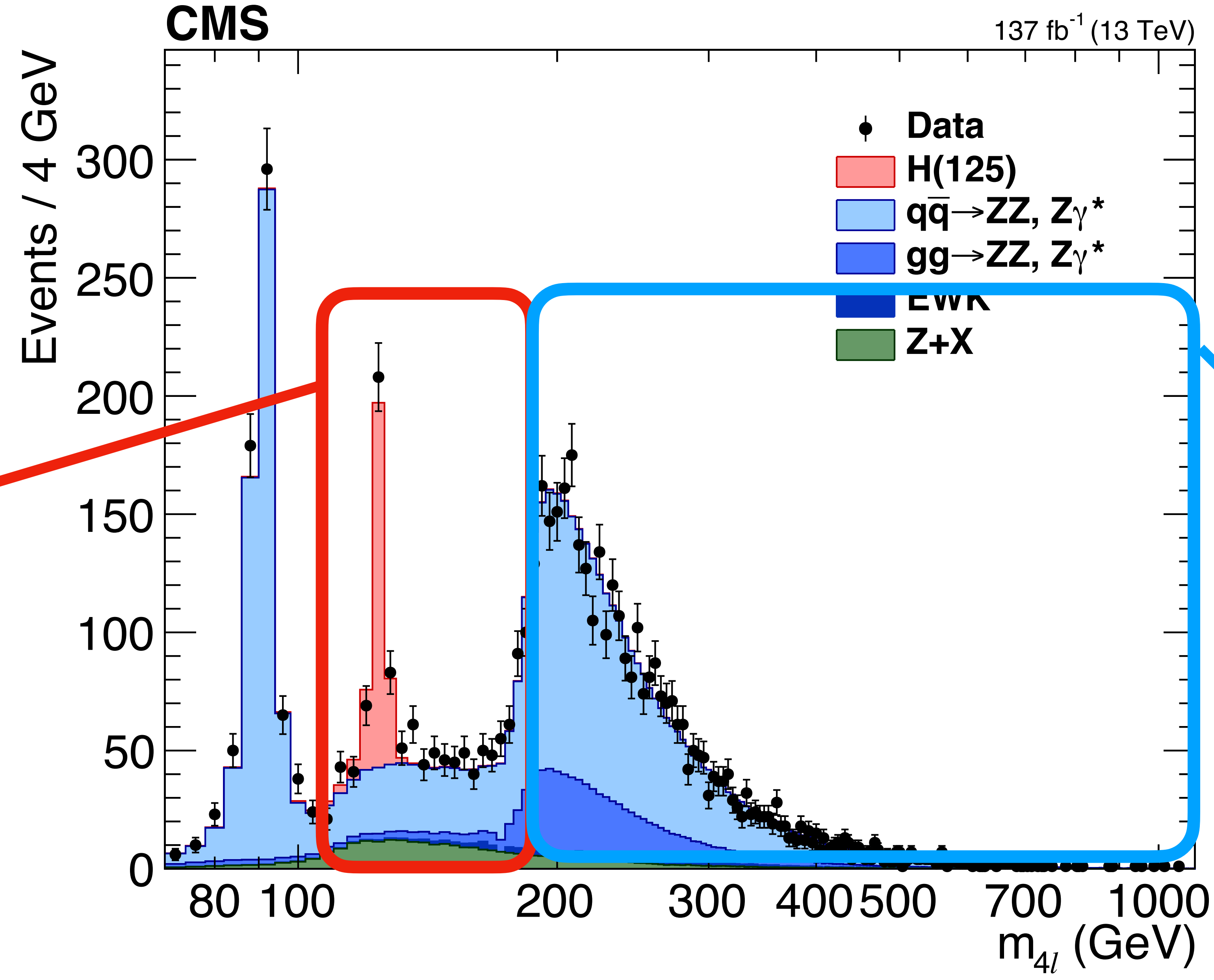

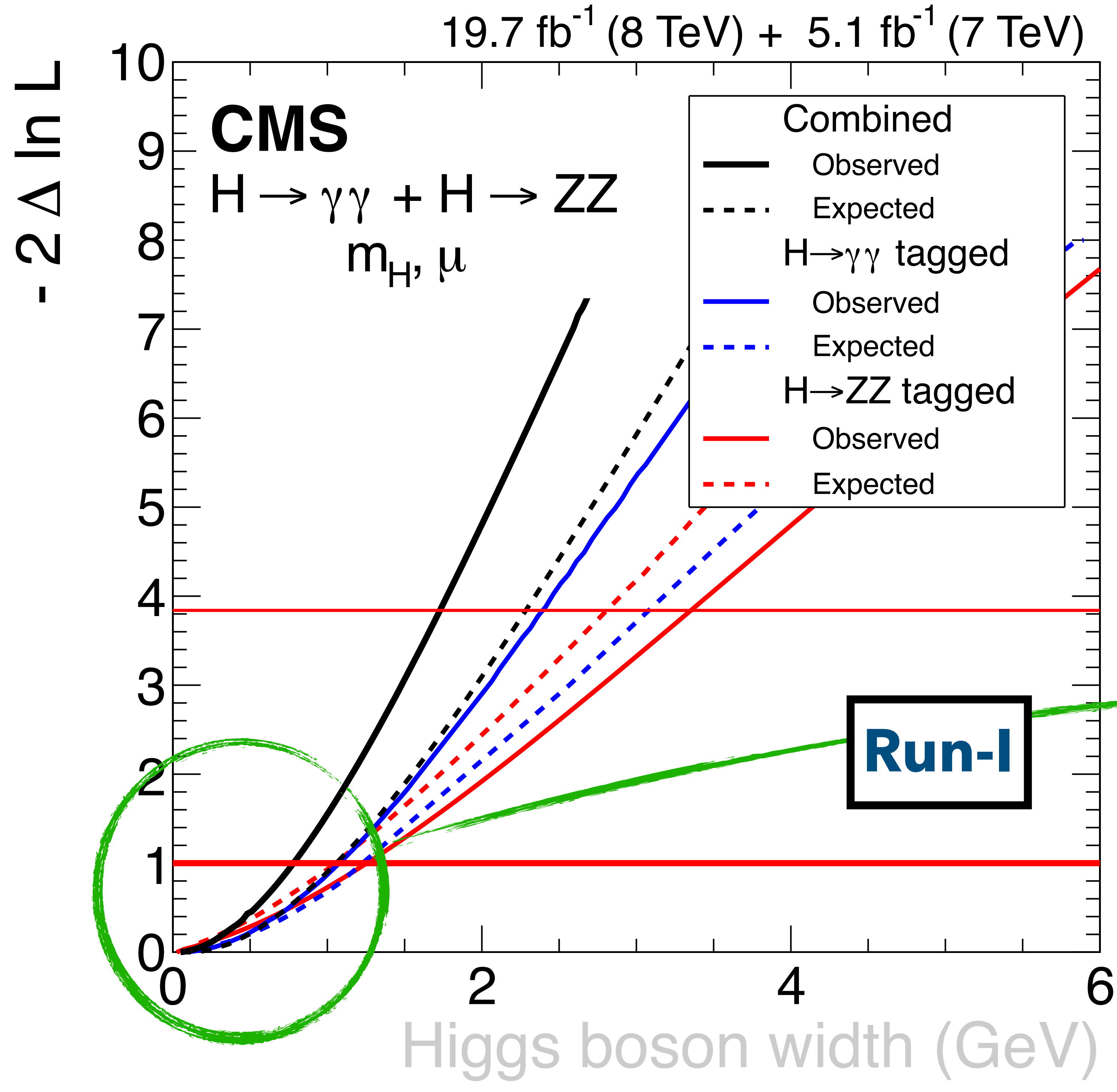

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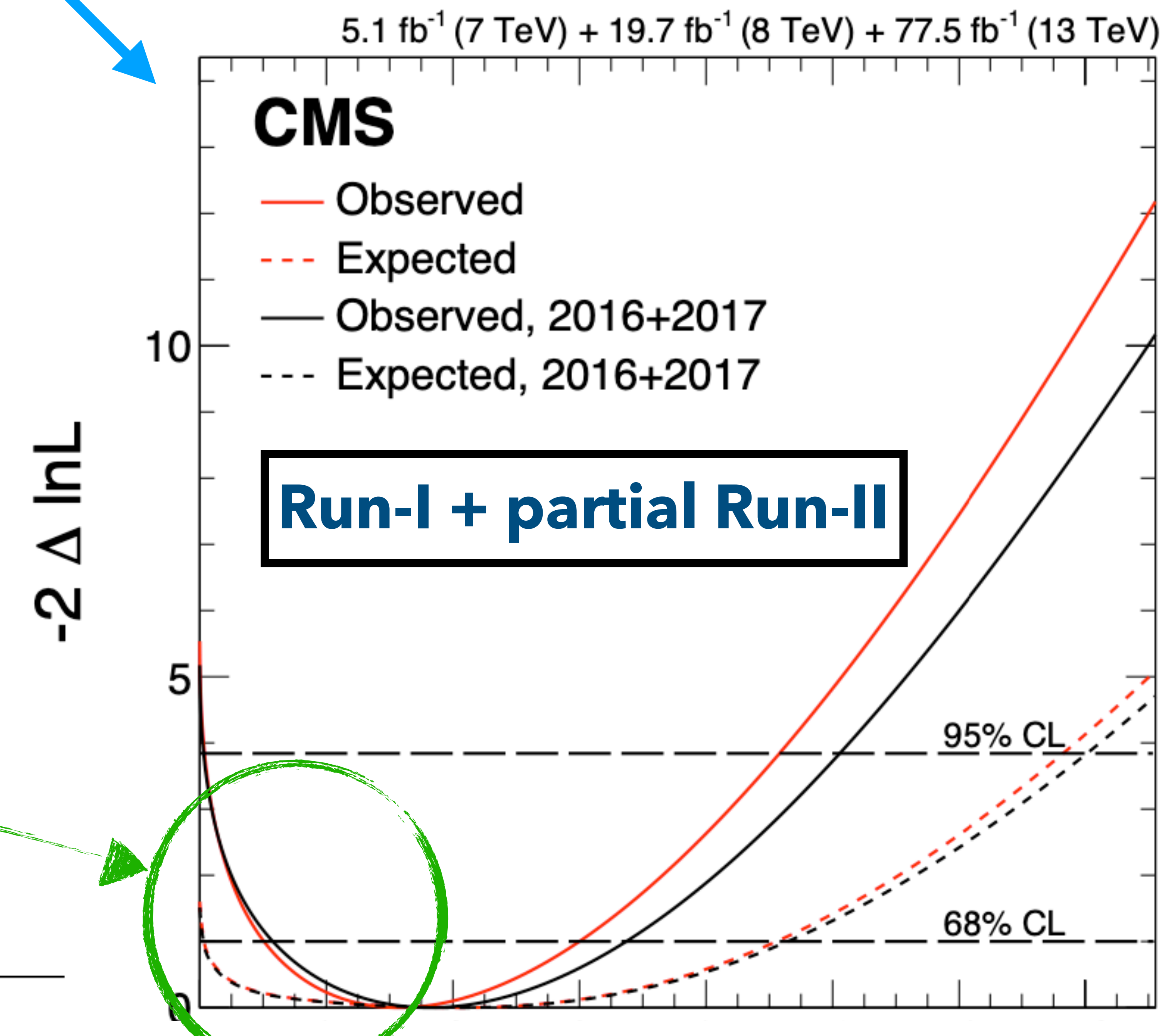


Assuming SM-like couplings

m_H unconstrained

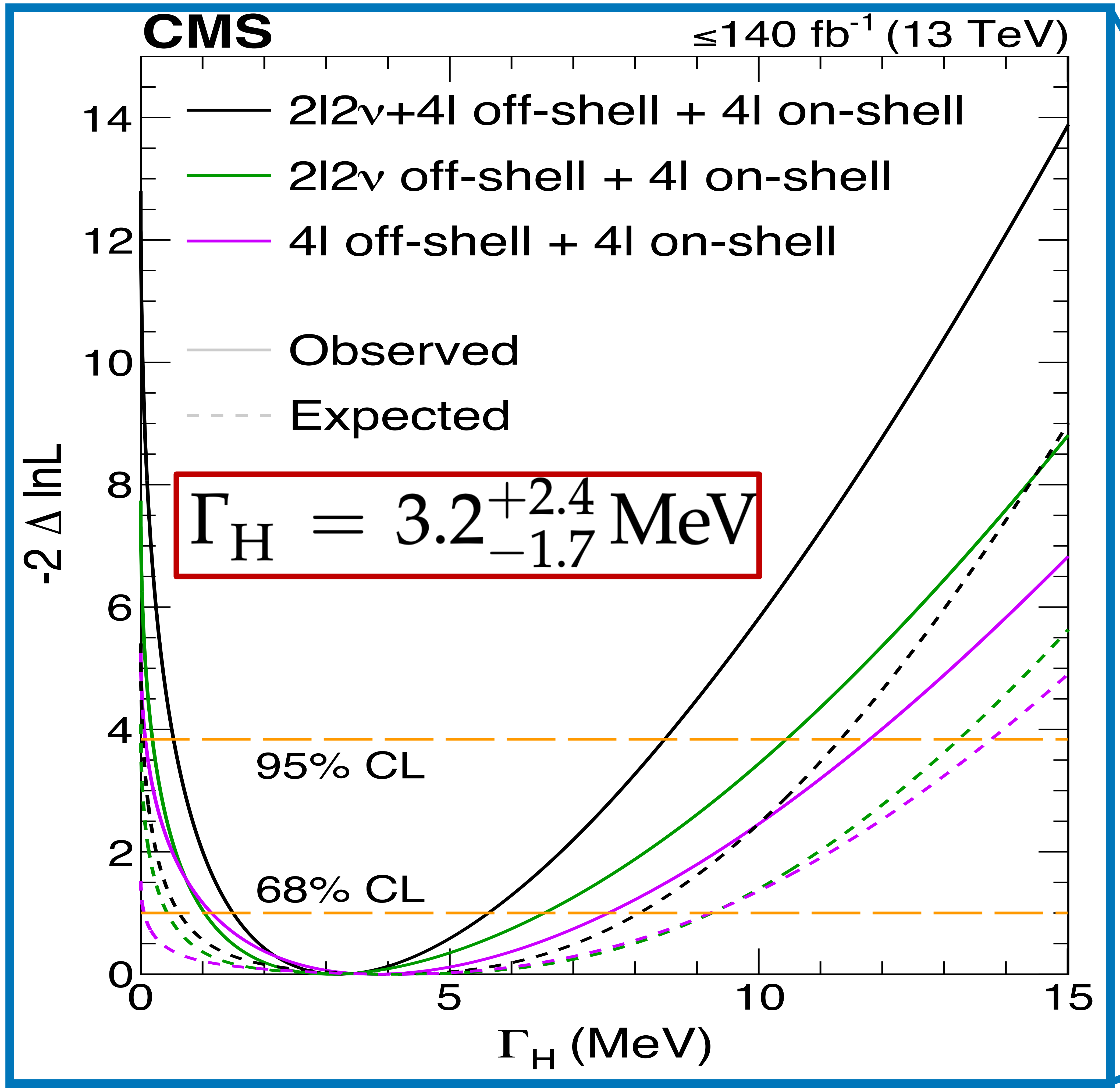
Run-I + partial Run-II

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

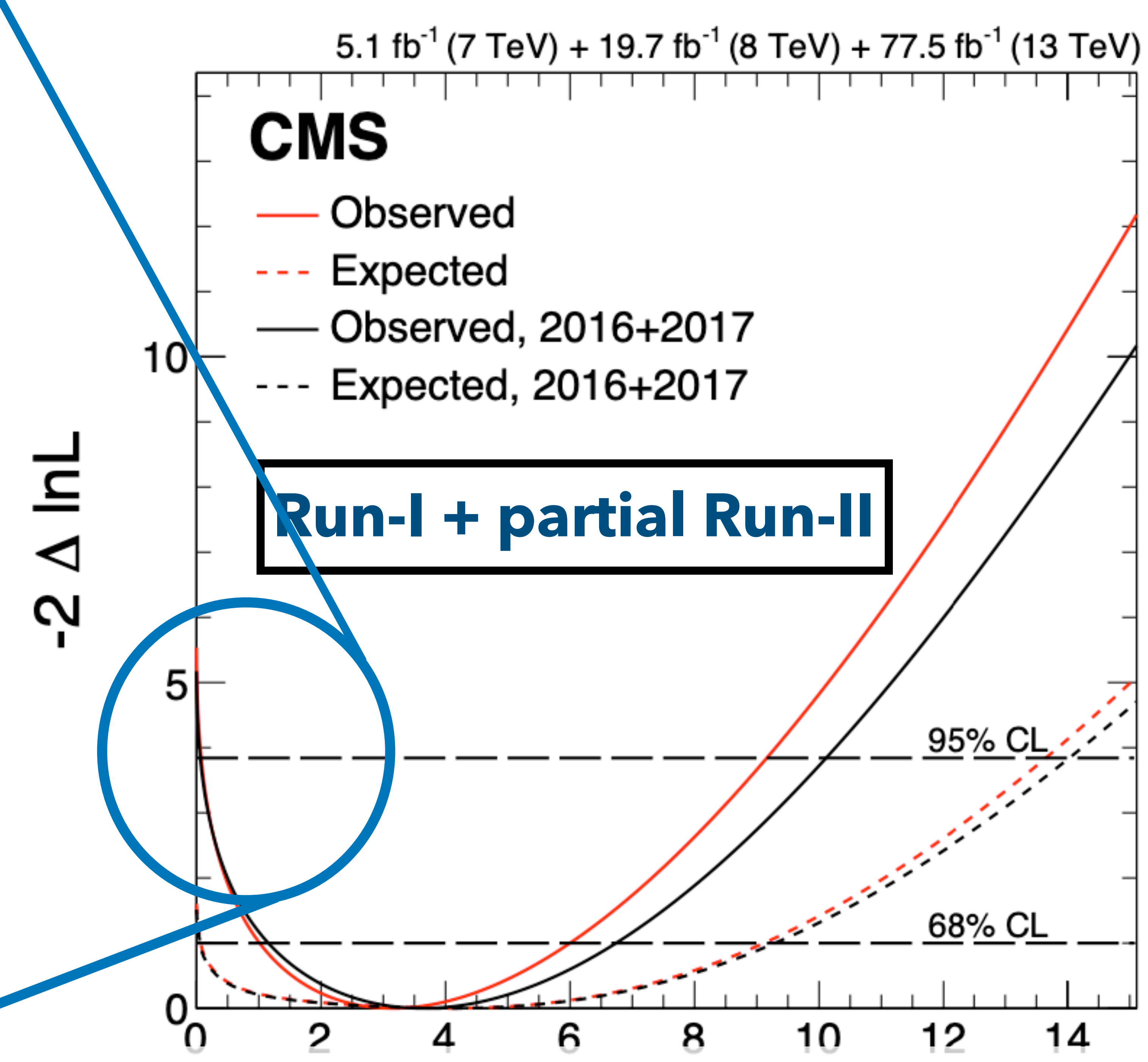
On-shell and 2016 dataset: only upper limit on Γ_H

On/off-shell events + RunI dataset: Γ_H measurement

Higgs boson width



arxiv:2202.06923



Full Run-II : Evidence for off-shell Higgs boson production @3.6σ!

Higgs boson CP properties: $H\tau\tau$

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau}).$$

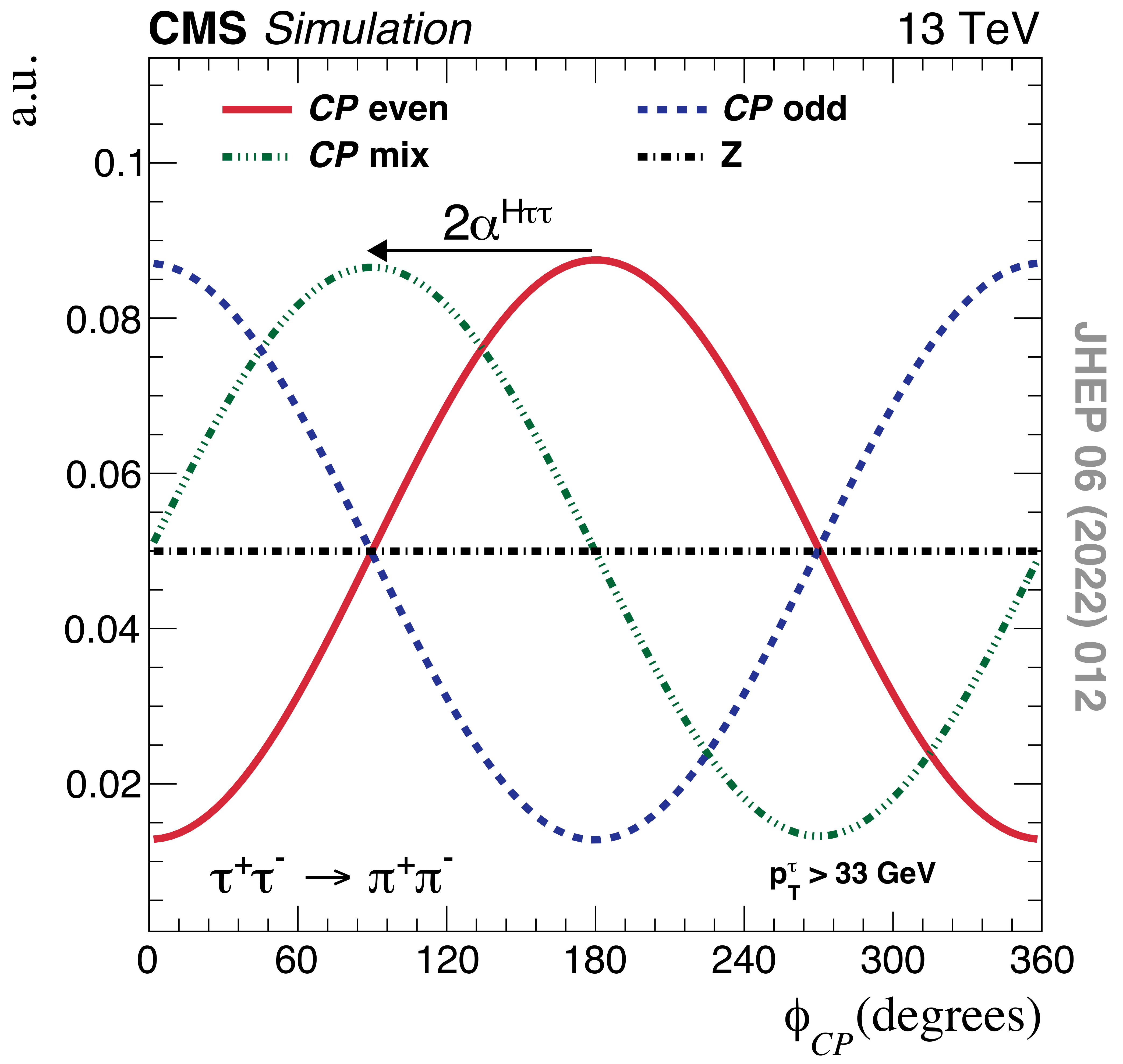
Effective Lagrangian for Yukawa coupling to tau leptons parameterized by **CP-even** and **CP-odd** components

$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}H(\kappa_\tau\bar{\tau}\tau + \tilde{\kappa}_\tau\bar{\tau}i\gamma_5\tau)$$

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

Table 1: Possible *CP* scenarios

Scenario	α
Purely *CP*-even	0° or 180°
Purely *CP*-odd	90°
Mixed	$\neq 0°, \neq 90°, \neq 180°$



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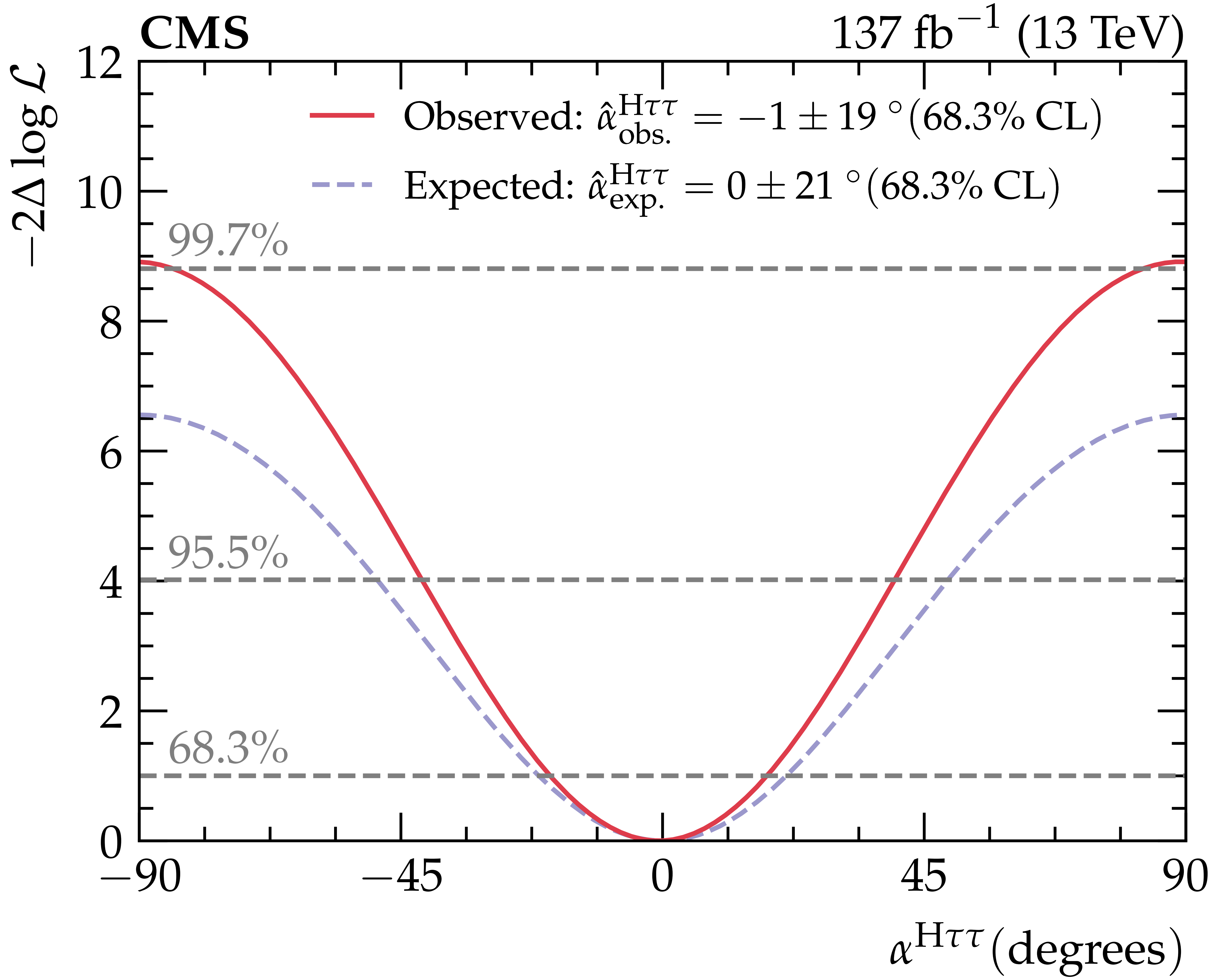

JHEP 06 (2022) 012

$\alpha^{H\tau\tau} = -1 \pm 19°$ (21° exp)

Pure CP-odd coupling excluded at 3σ

Higgs boson CP properties: ttH

Effective Lagrangian for Yukawa coupling to top quarks parameterized by **CP-even** and **CP-odd** components

$$A(Hff) = \frac{m_f}{v}\bar{\psi}_f(\kappa_t + i\tilde{\kappa}_t\gamma_5)\psi_f$$

$$f_{CP}^{Htt} = \frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2} \qquad |\, f_{CP}^{Htt} \,| = (\sin\alpha)^2$$

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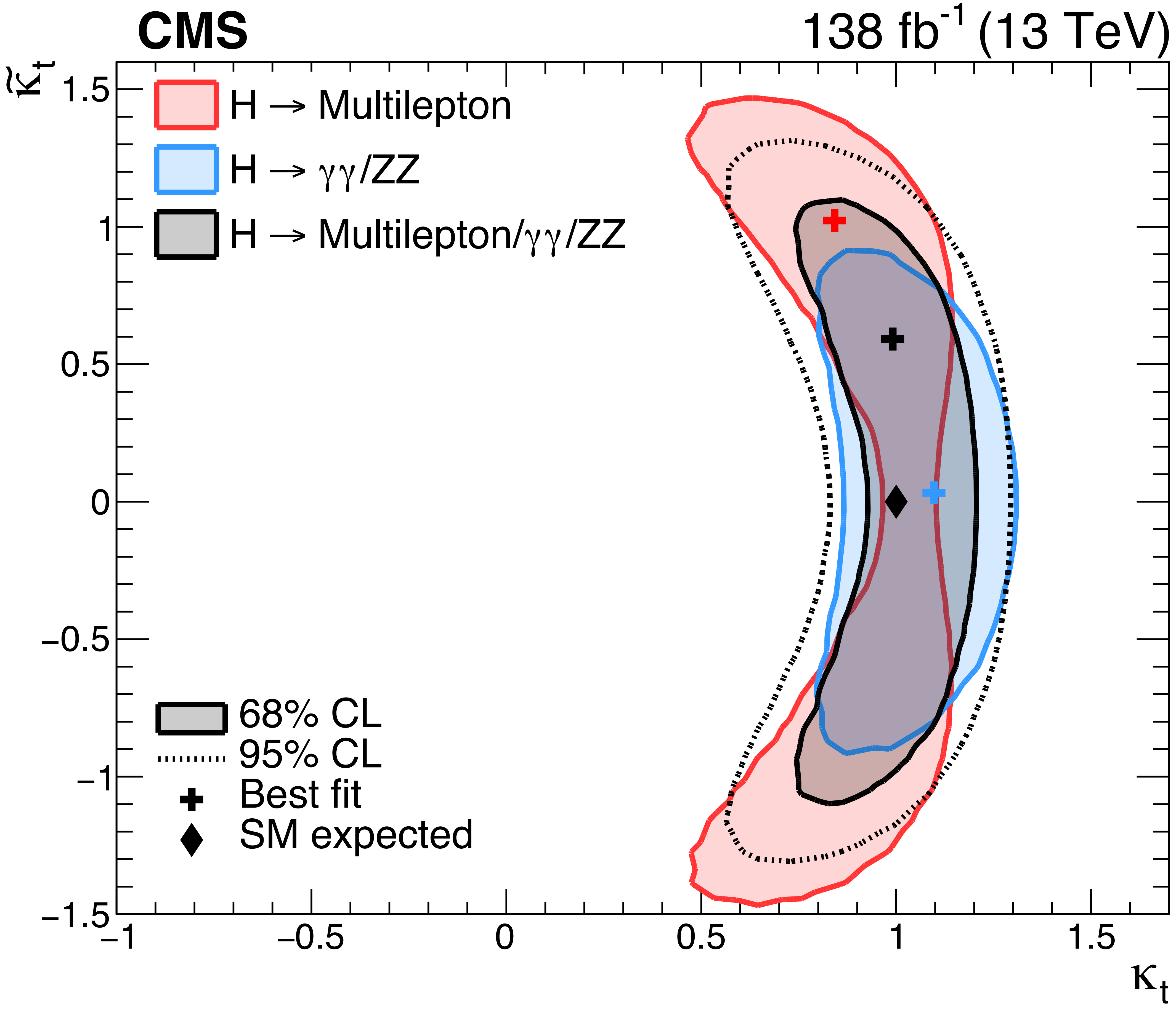


arXiv:2208.02686

$|\, f_{CP}^{Htt} \,| = 0.28\ (< 0.55$ at $1\sigma)$

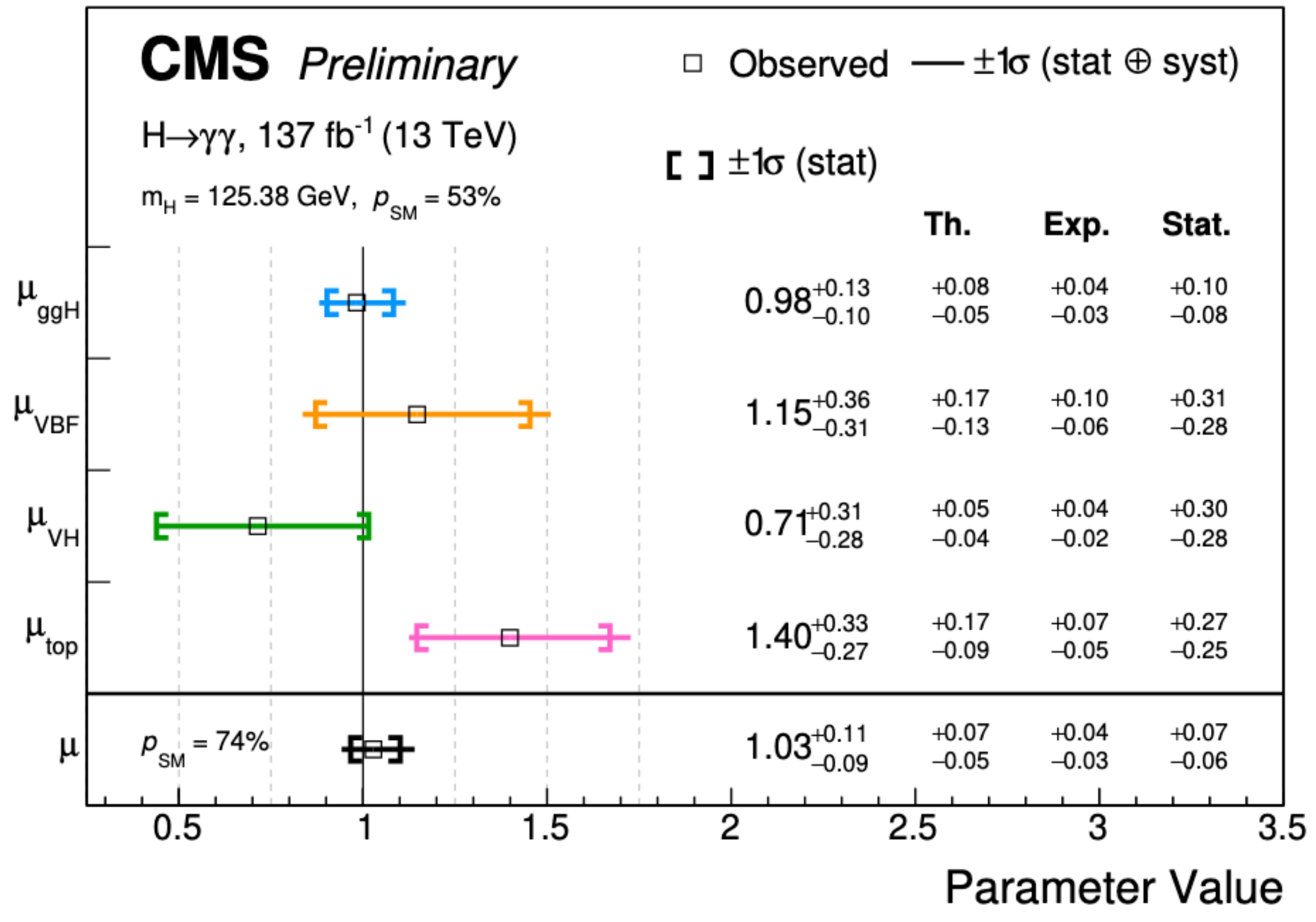
Pure CP-odd coupling excluded at 3.7σ

Characterise production and decay

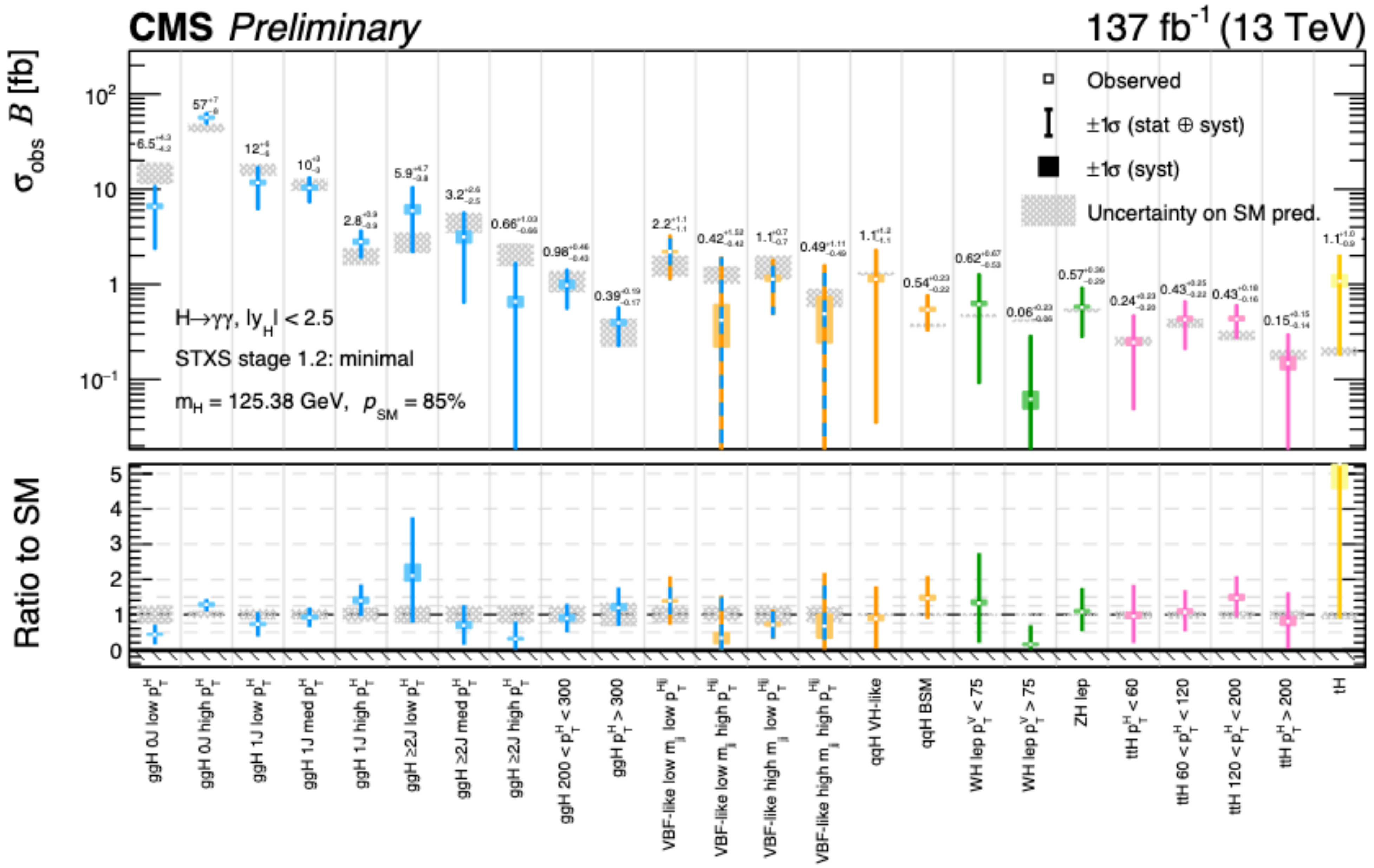
Model independent results

Statistically limited

Inclusive xsec
Signal strenghts



Simplified Template Cross Sections



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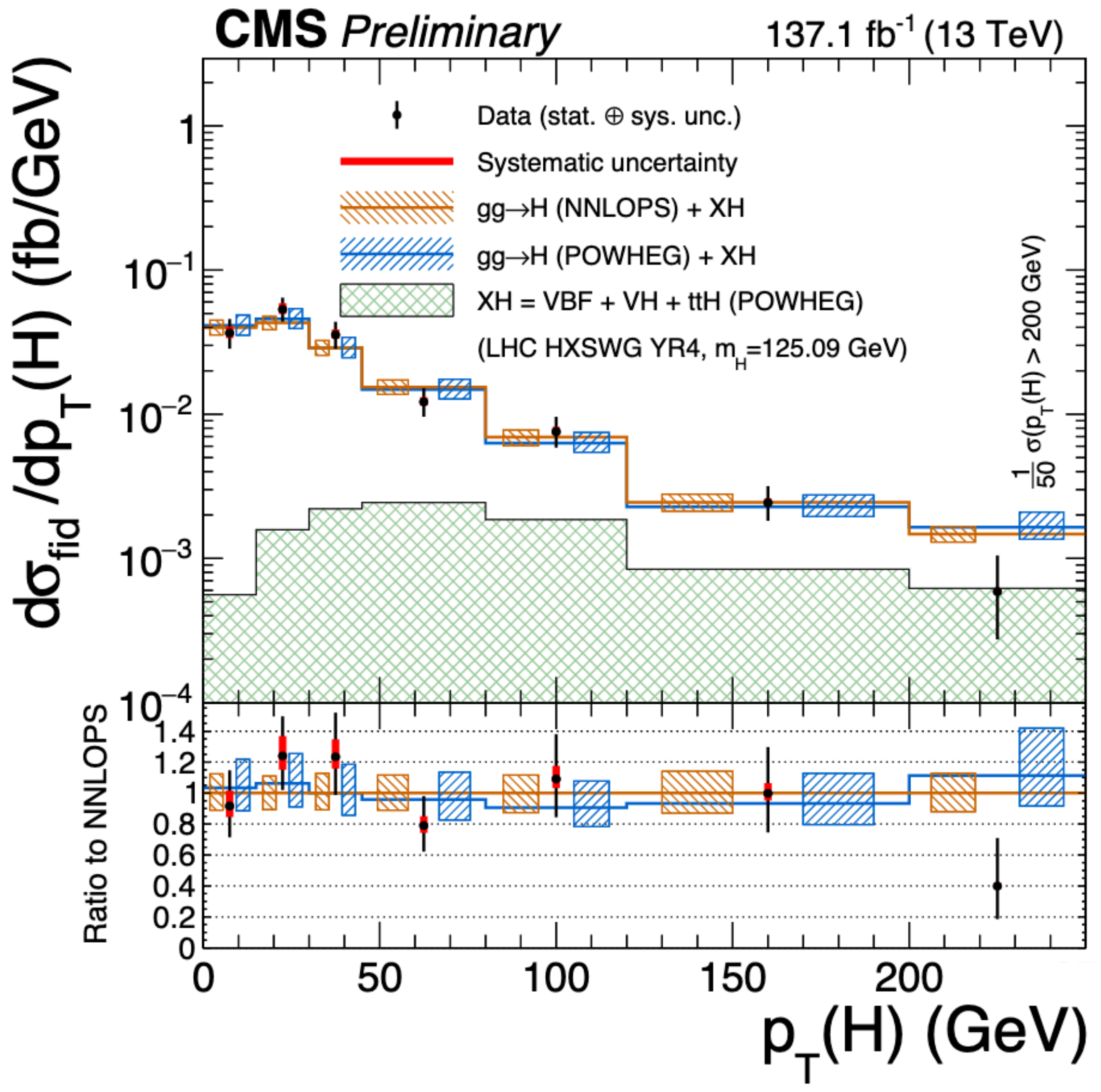


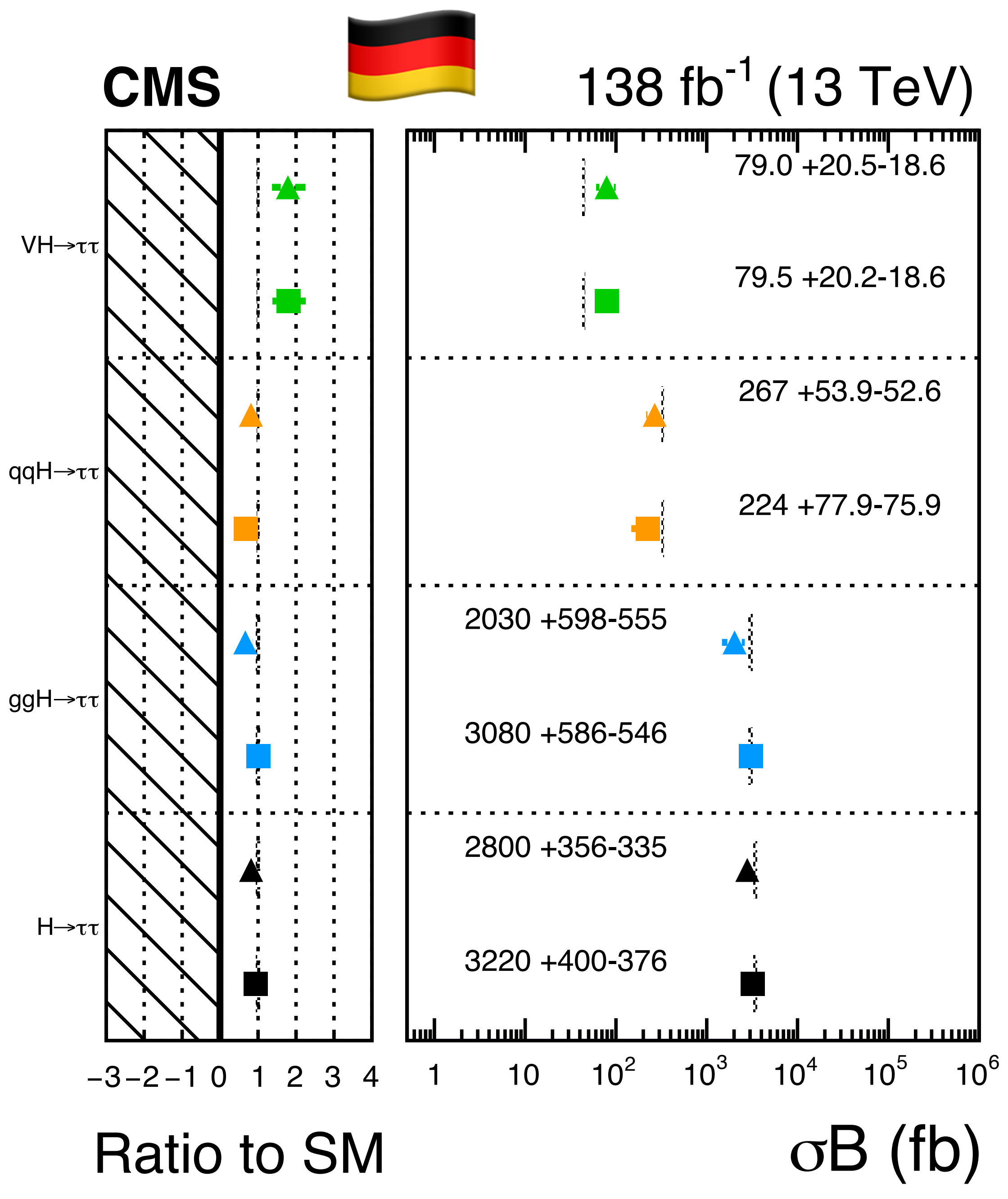
Signal strength modifiers

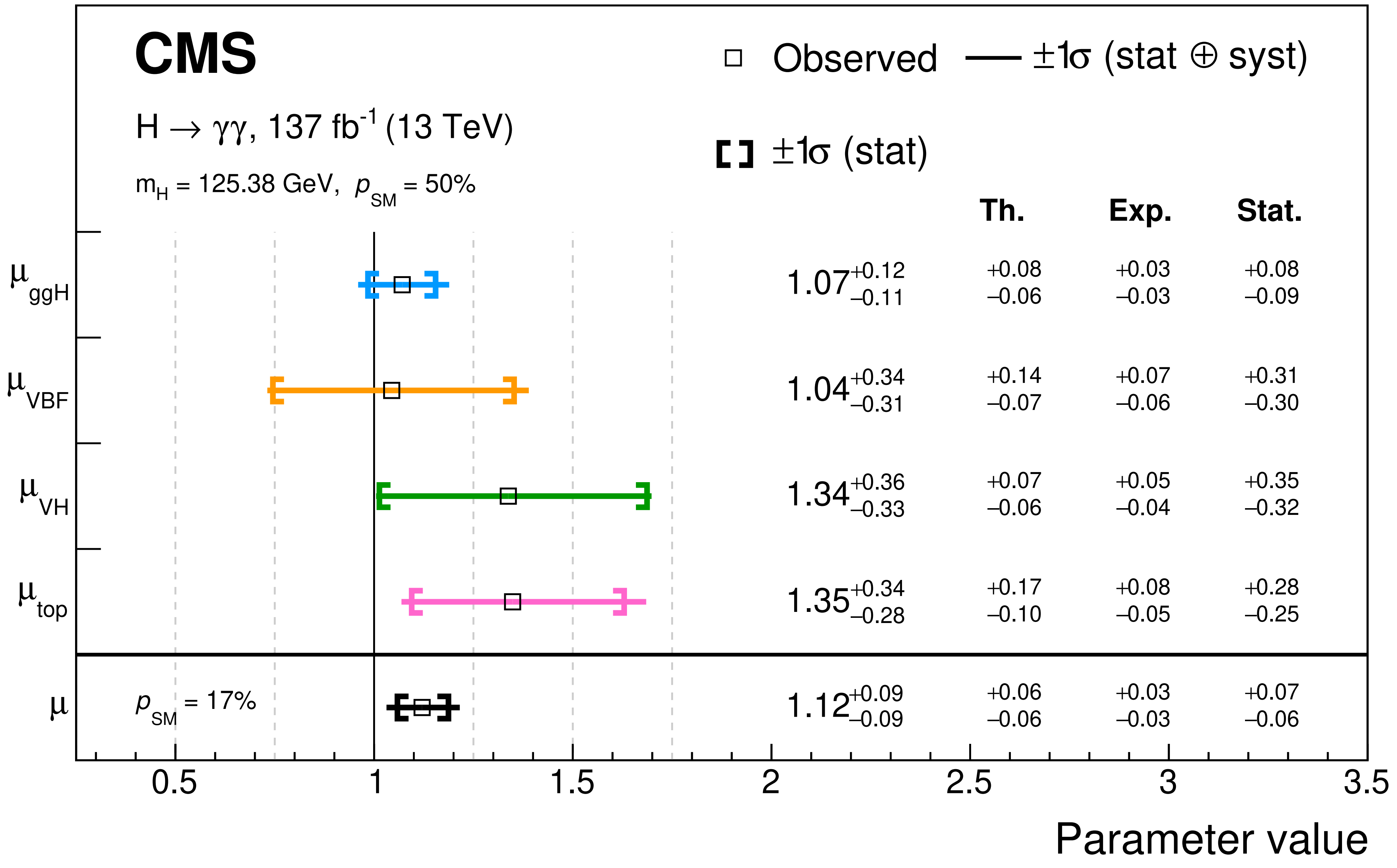
HZZ: Eur. Phys. J. C 81 (2021) 488
Hgg: JHEP 07 (2021) 27
Htt: Phys. Rev. Lett. 128, 081805

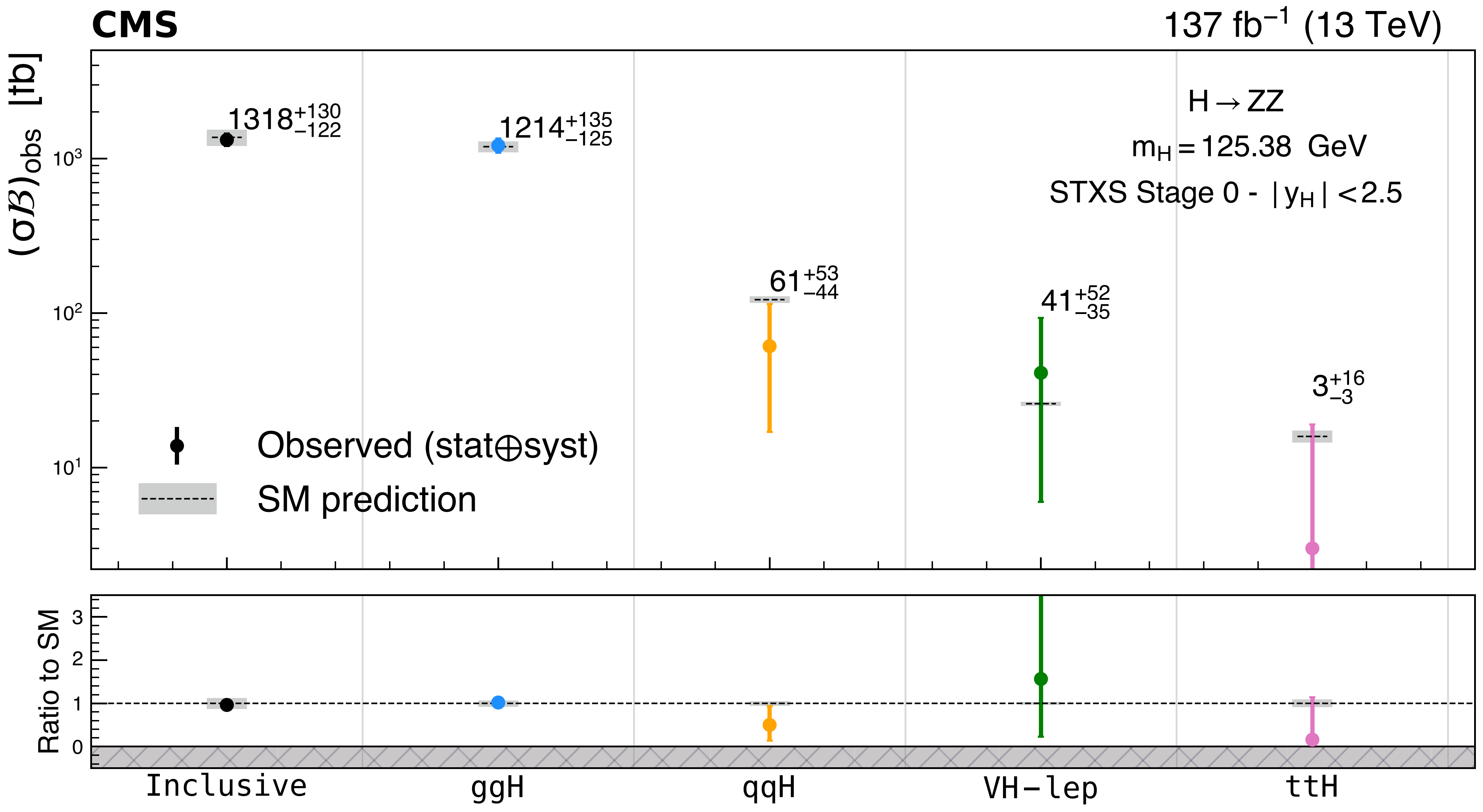
Inclusive characterisation of **ggF**, **VBF**, **VH**, and **ttH** **production** modes

Run-II dataset exploited **in all final states**: *precision physics realm*

⇒ **Competitive** contribution of **statistic** and **systematic uncertainties**







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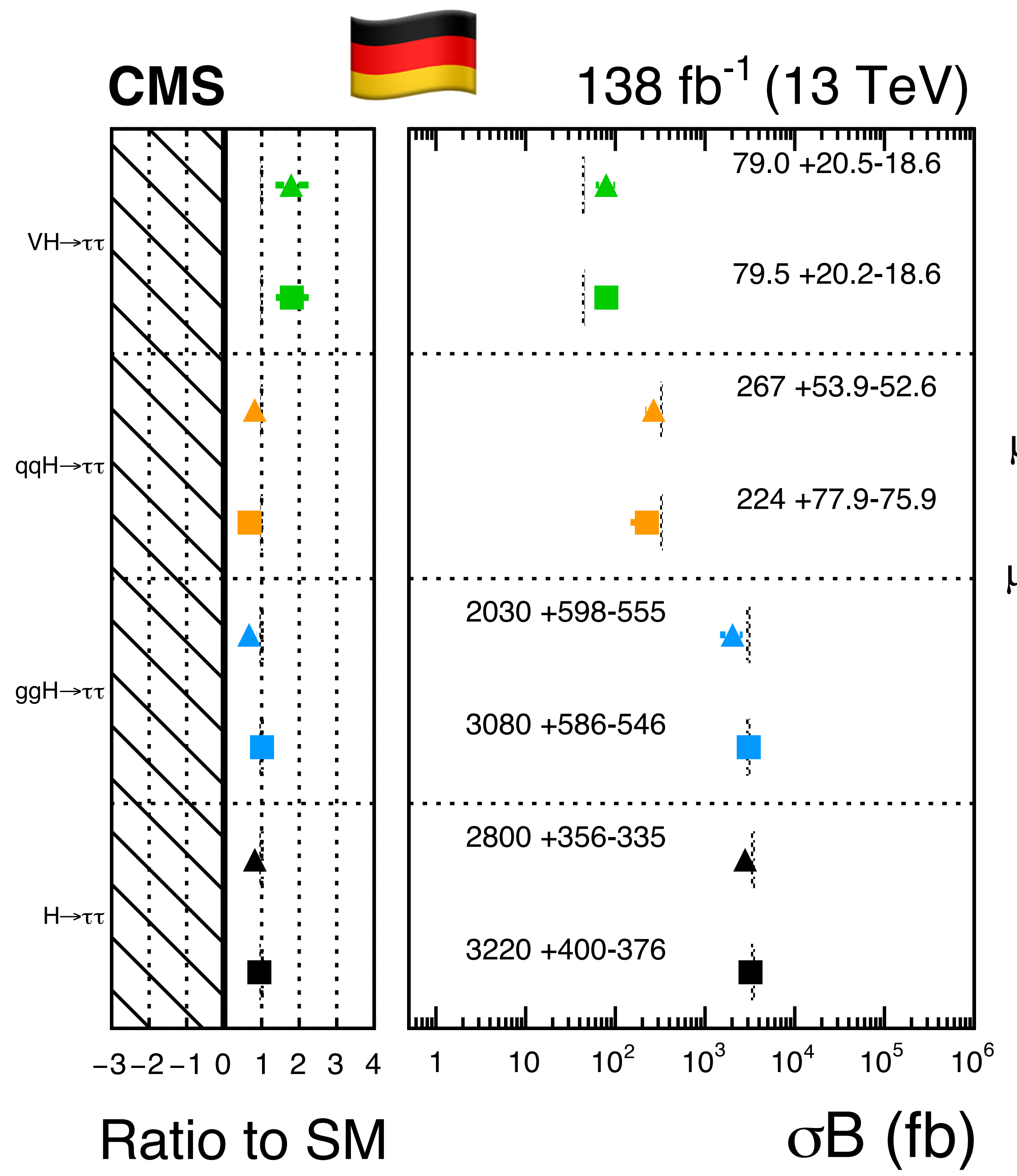

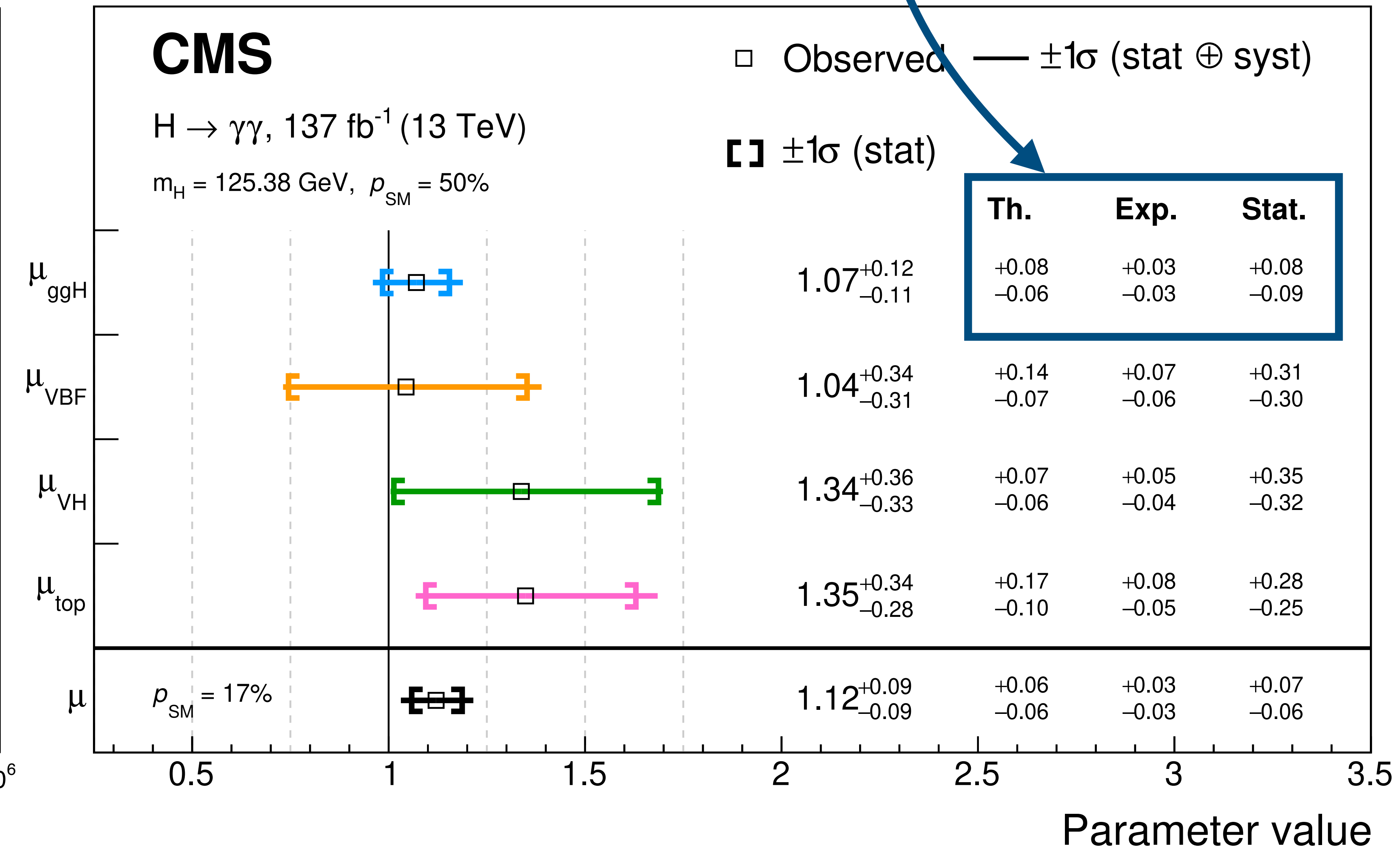

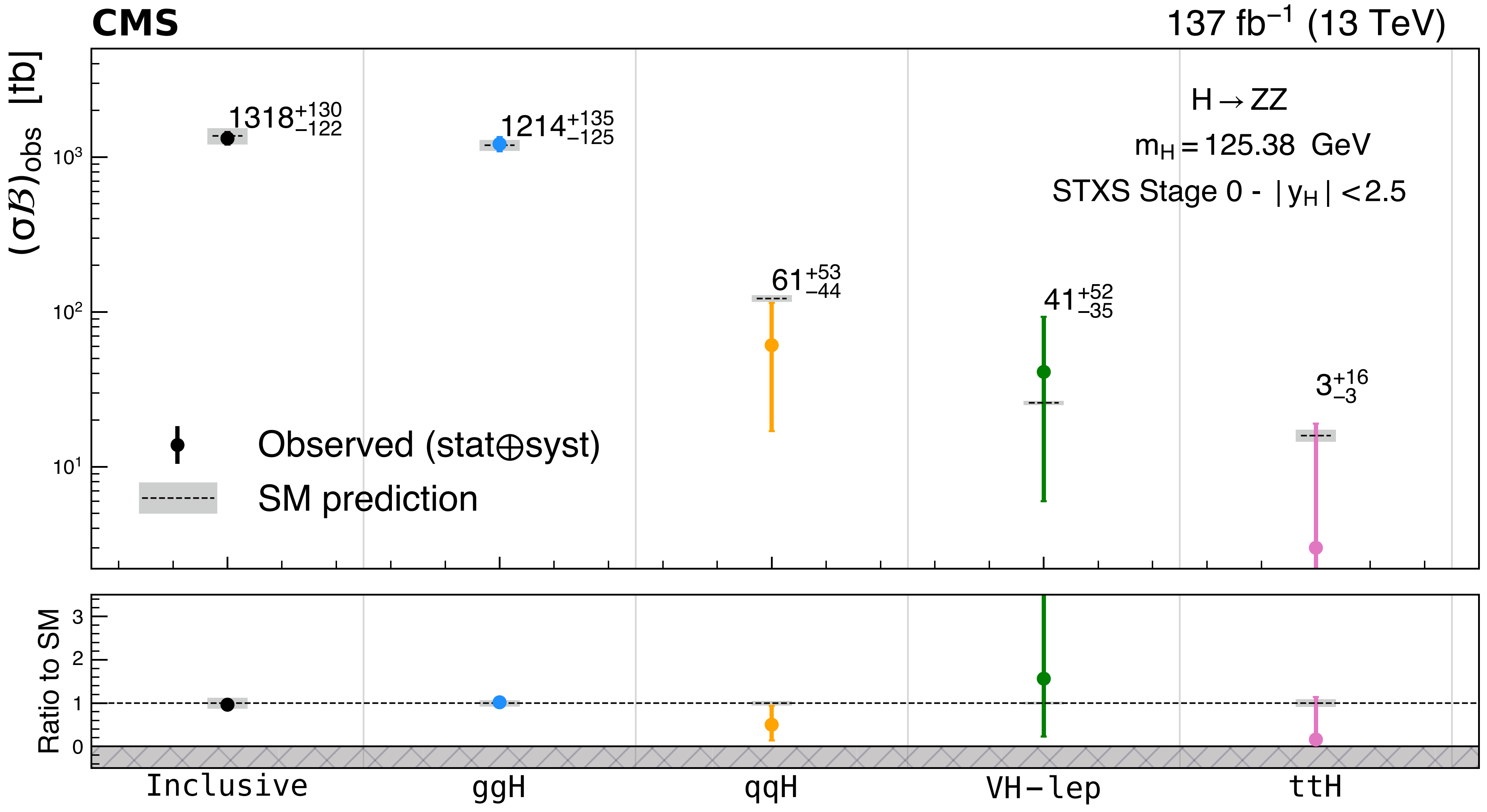

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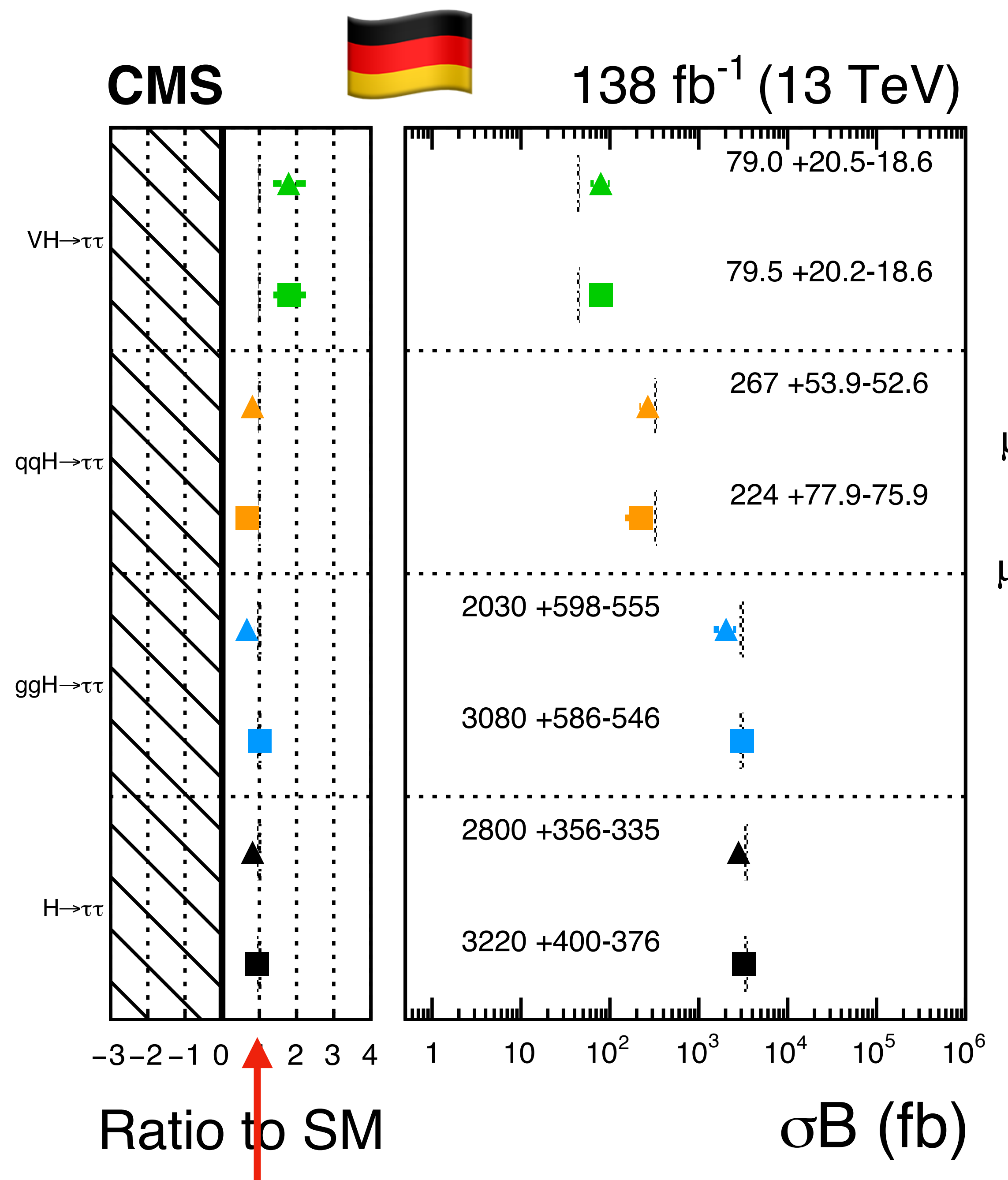
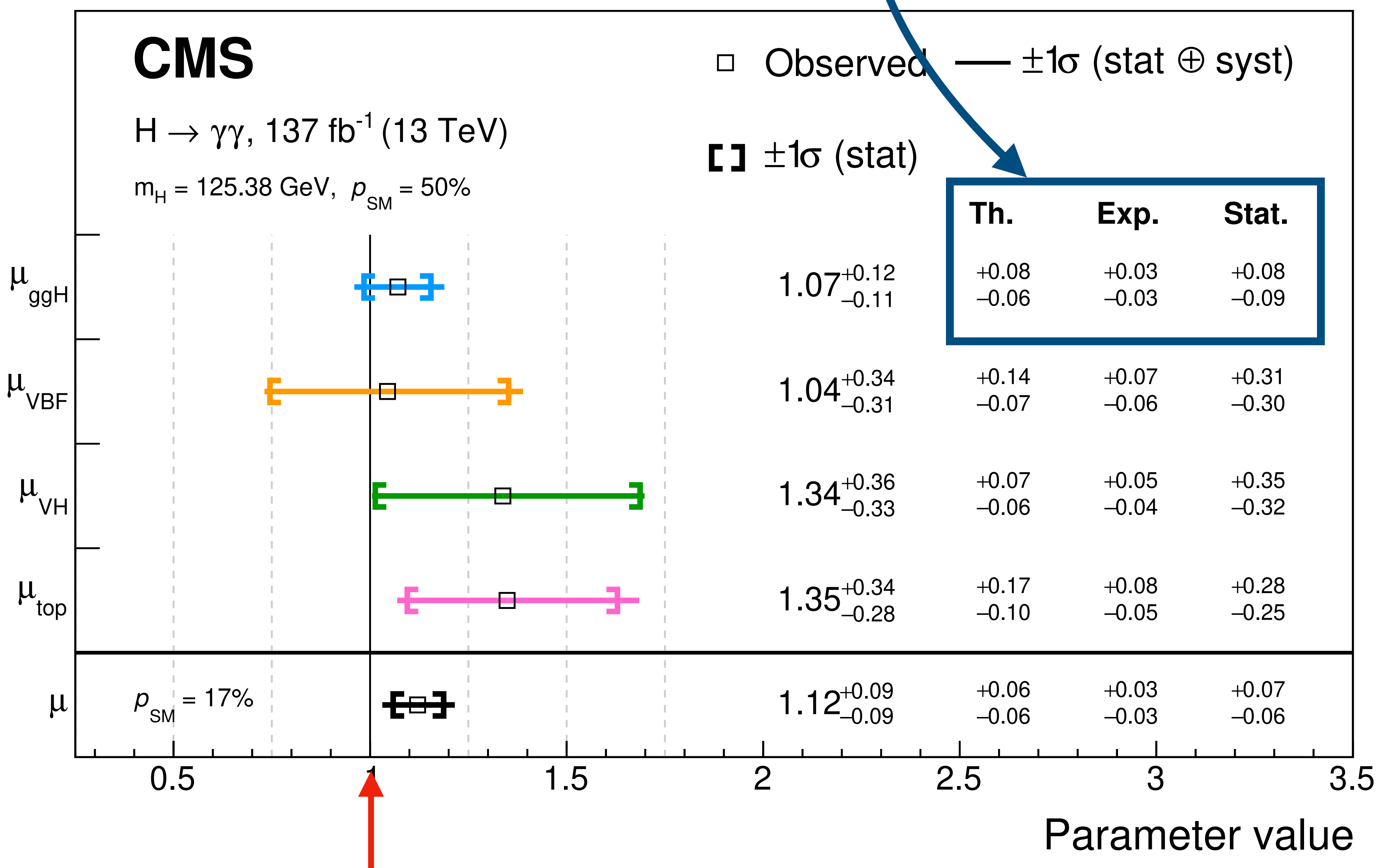
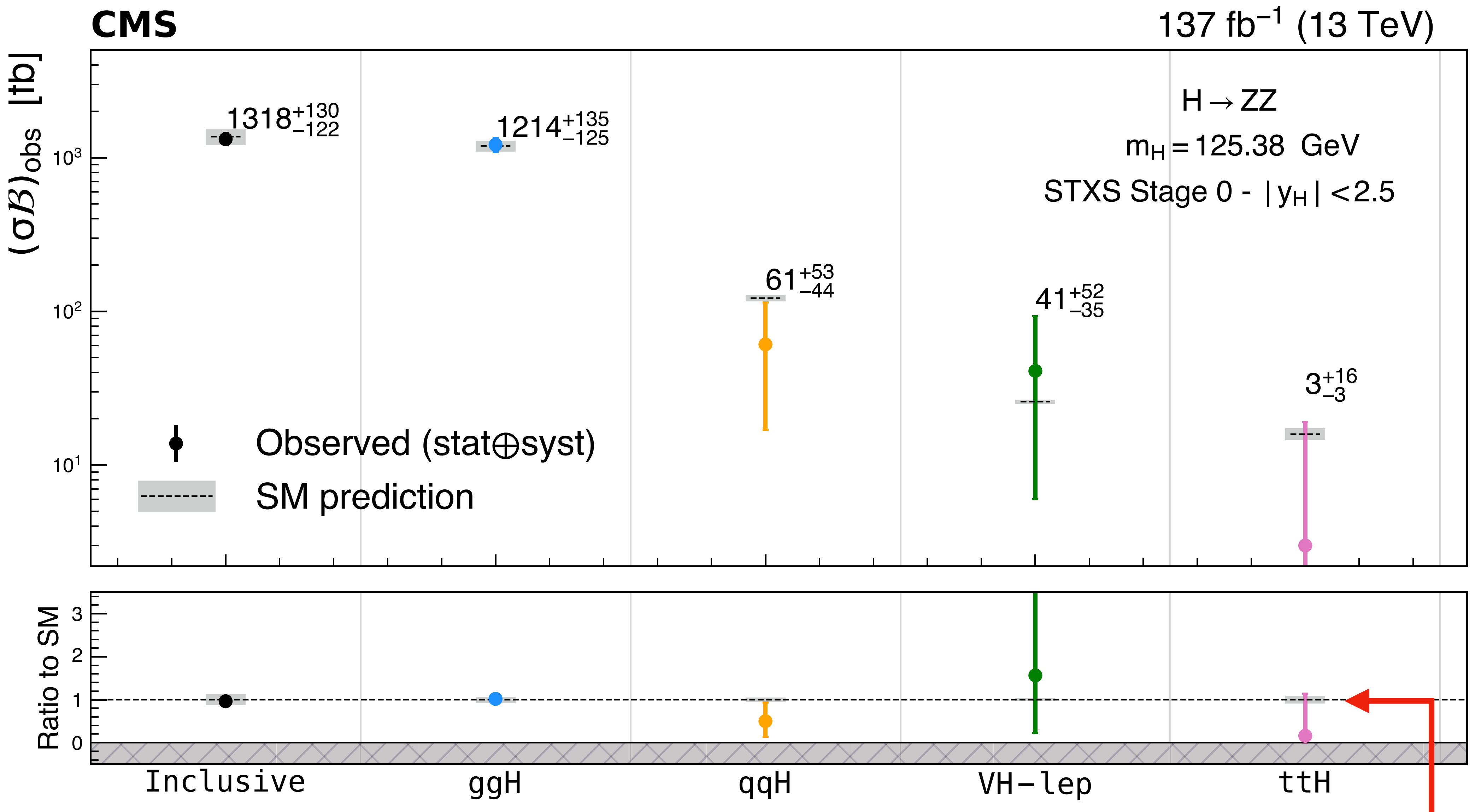




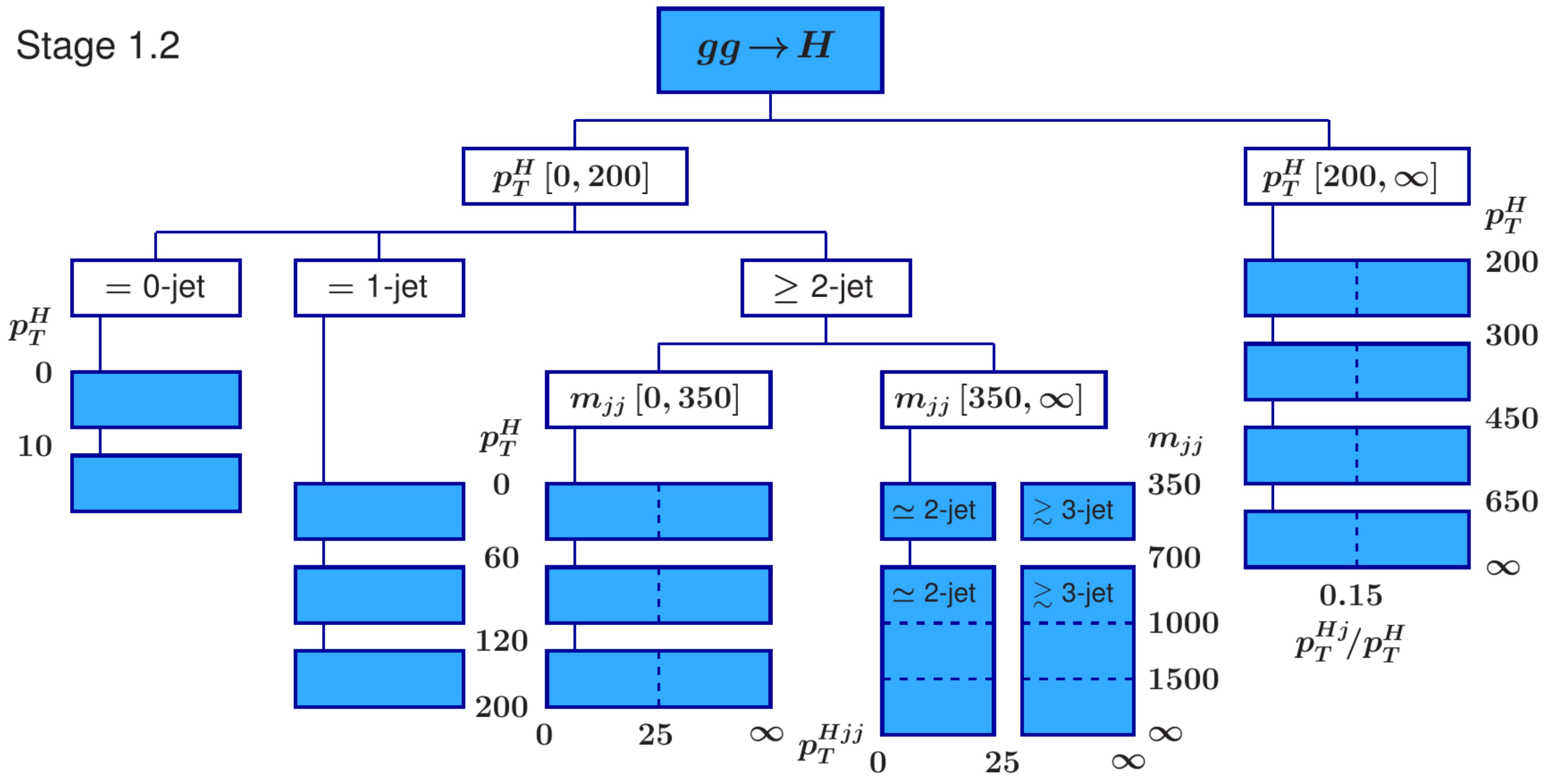


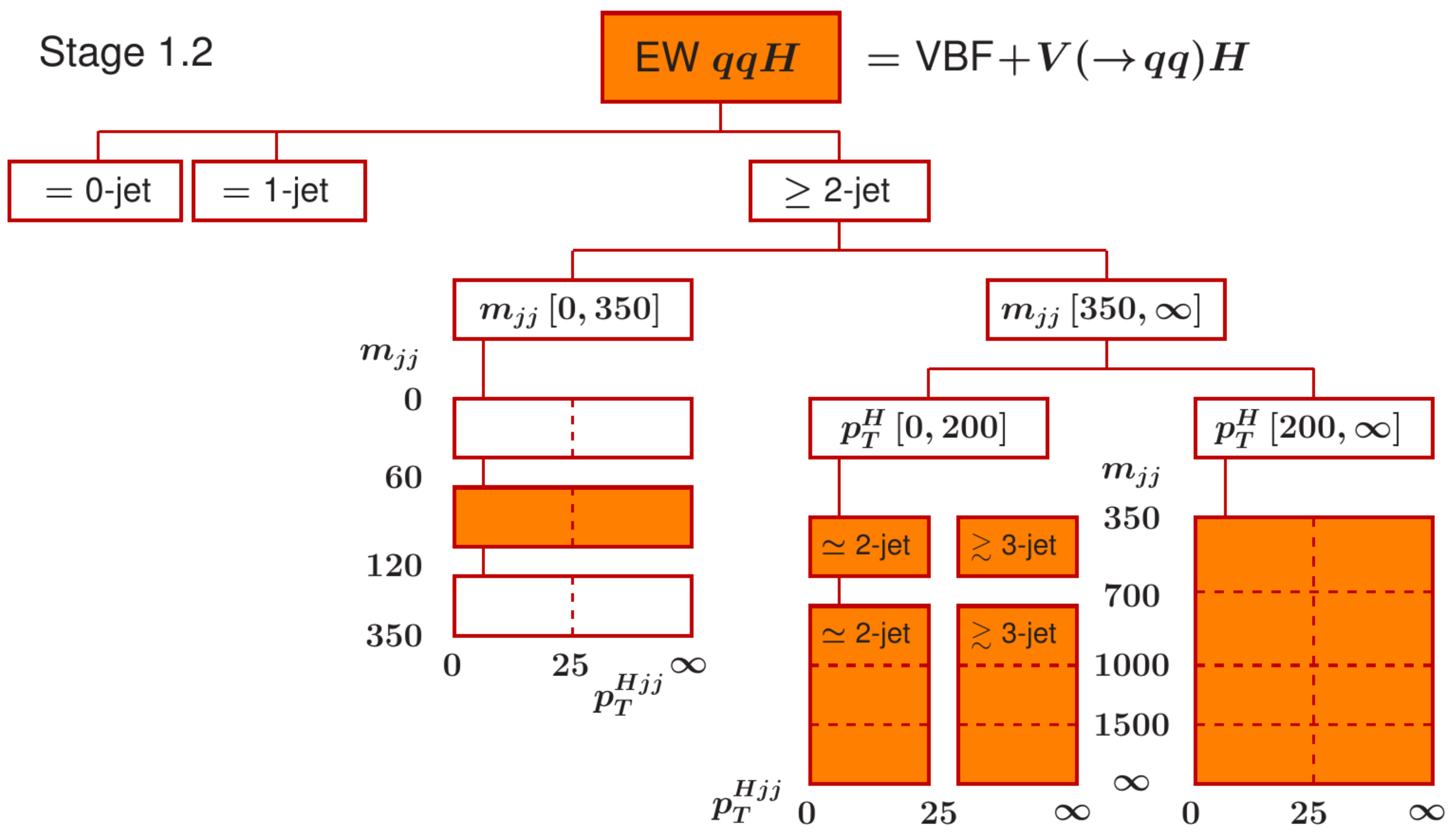
Good agreement with SM predictions across different channels!

Simplified Template Cross Sections

The primary goal of STXS framework is to minimise the measurement dependence on theory predictions without losing sensitivity

Coverage of the entire phase space and **specific regions** designed **to detect BSM effects**





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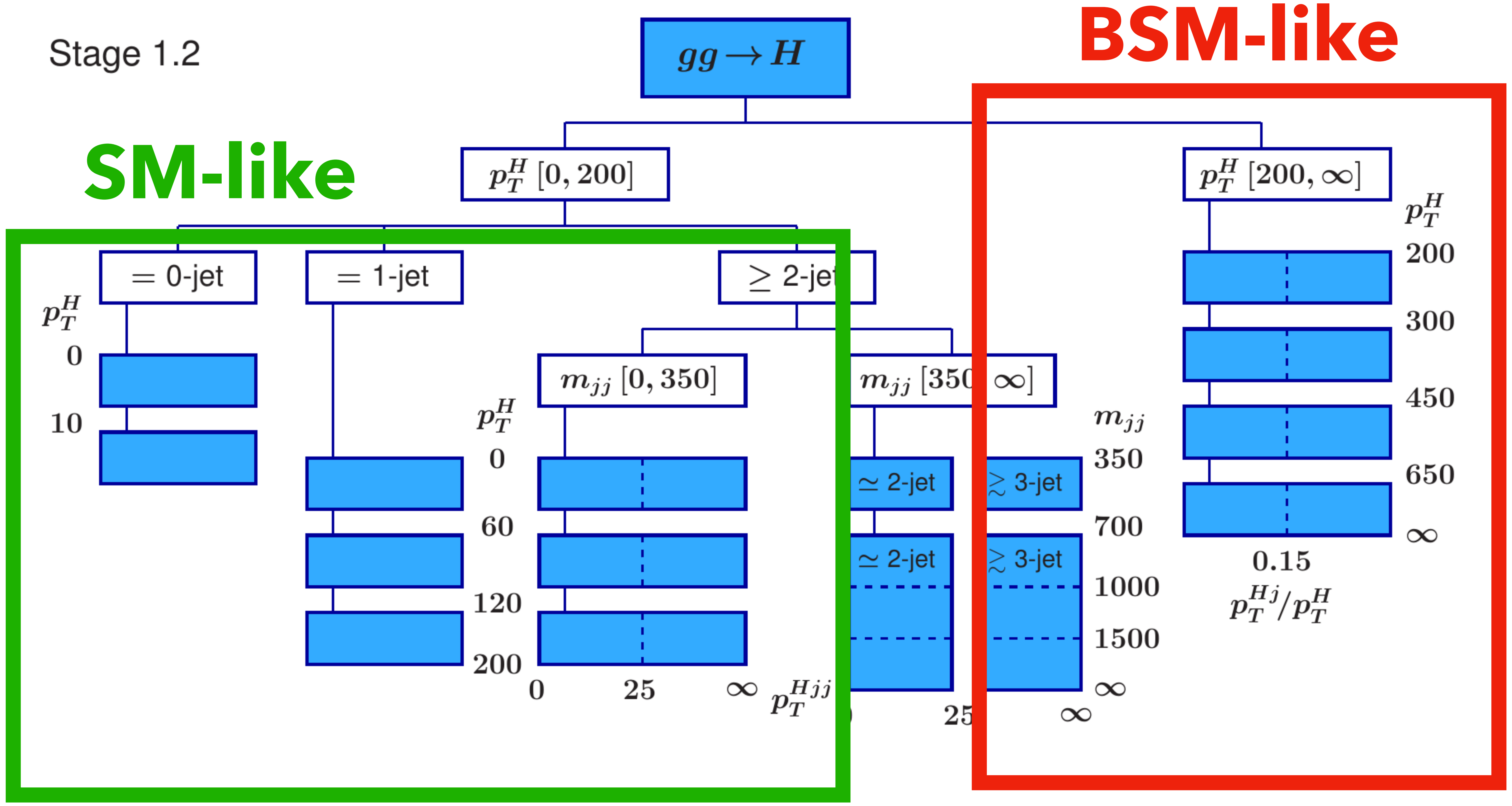
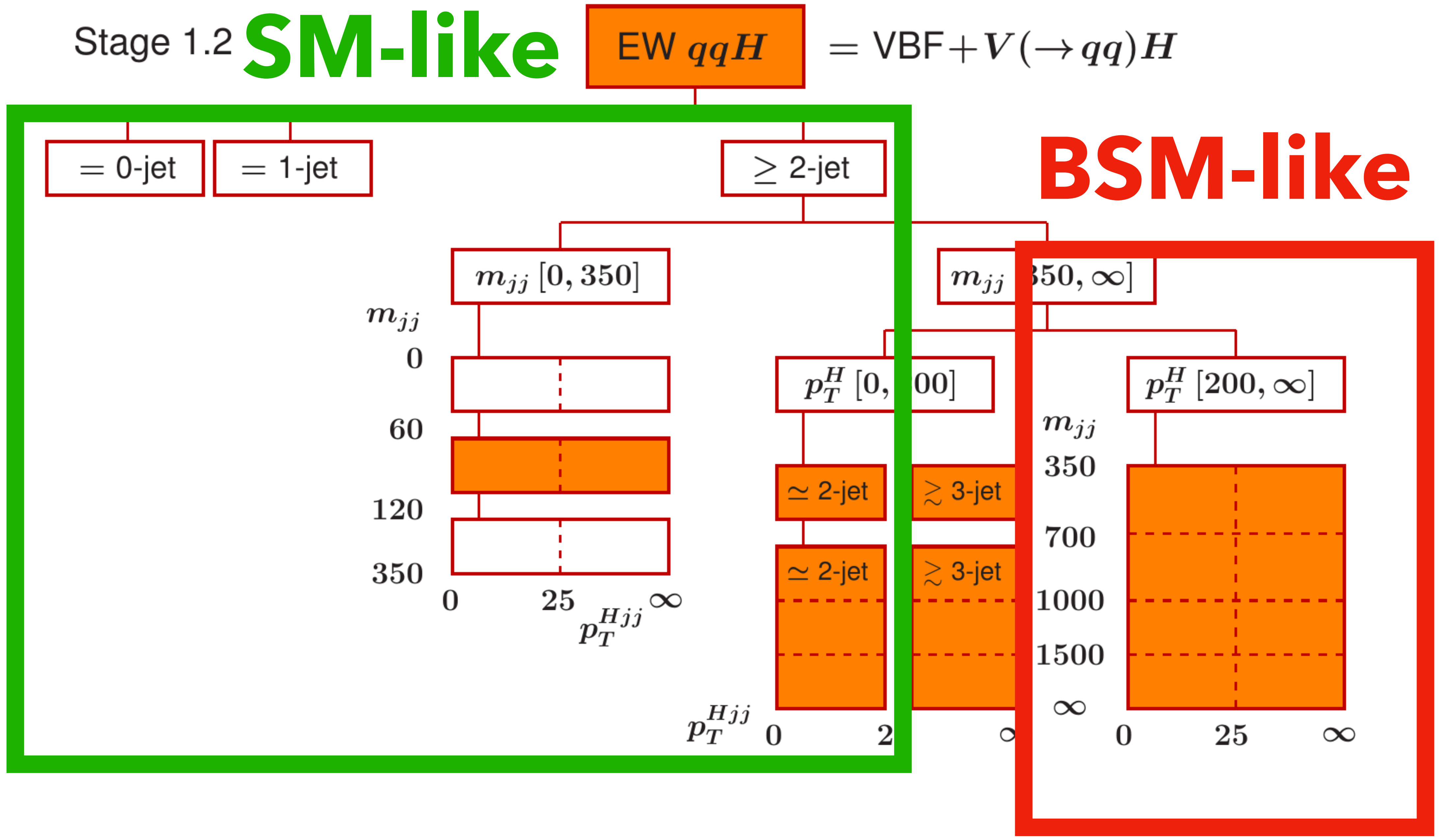
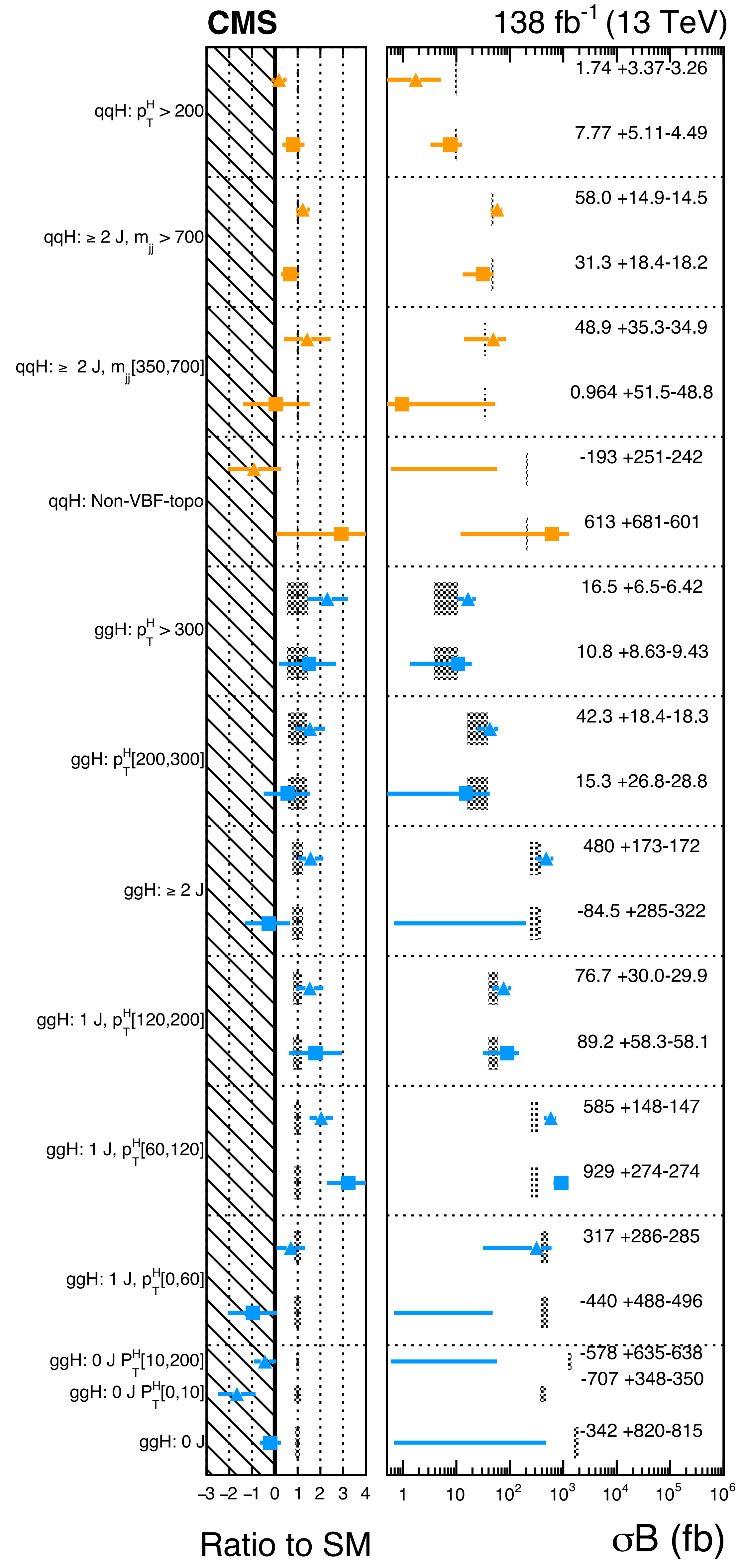


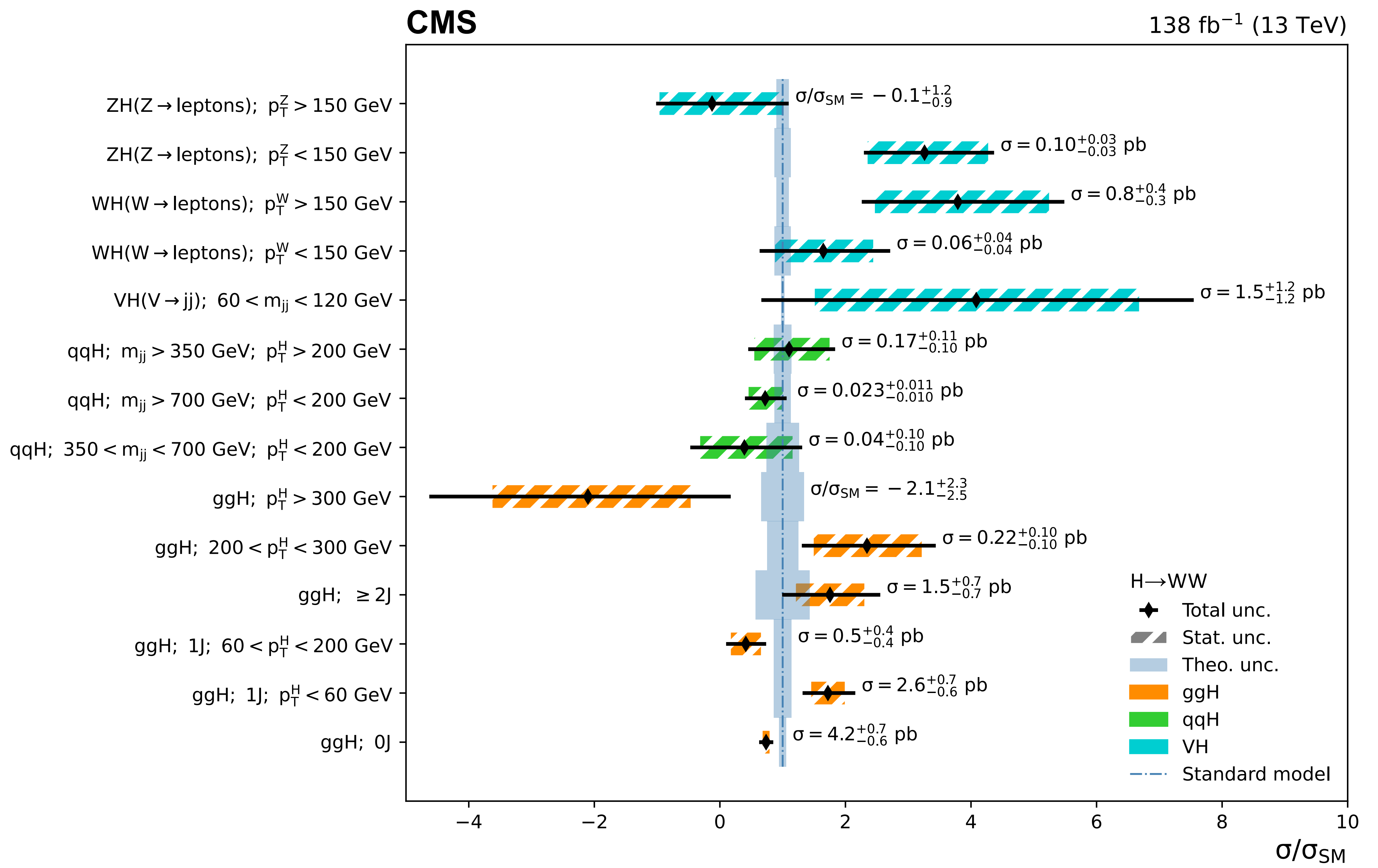


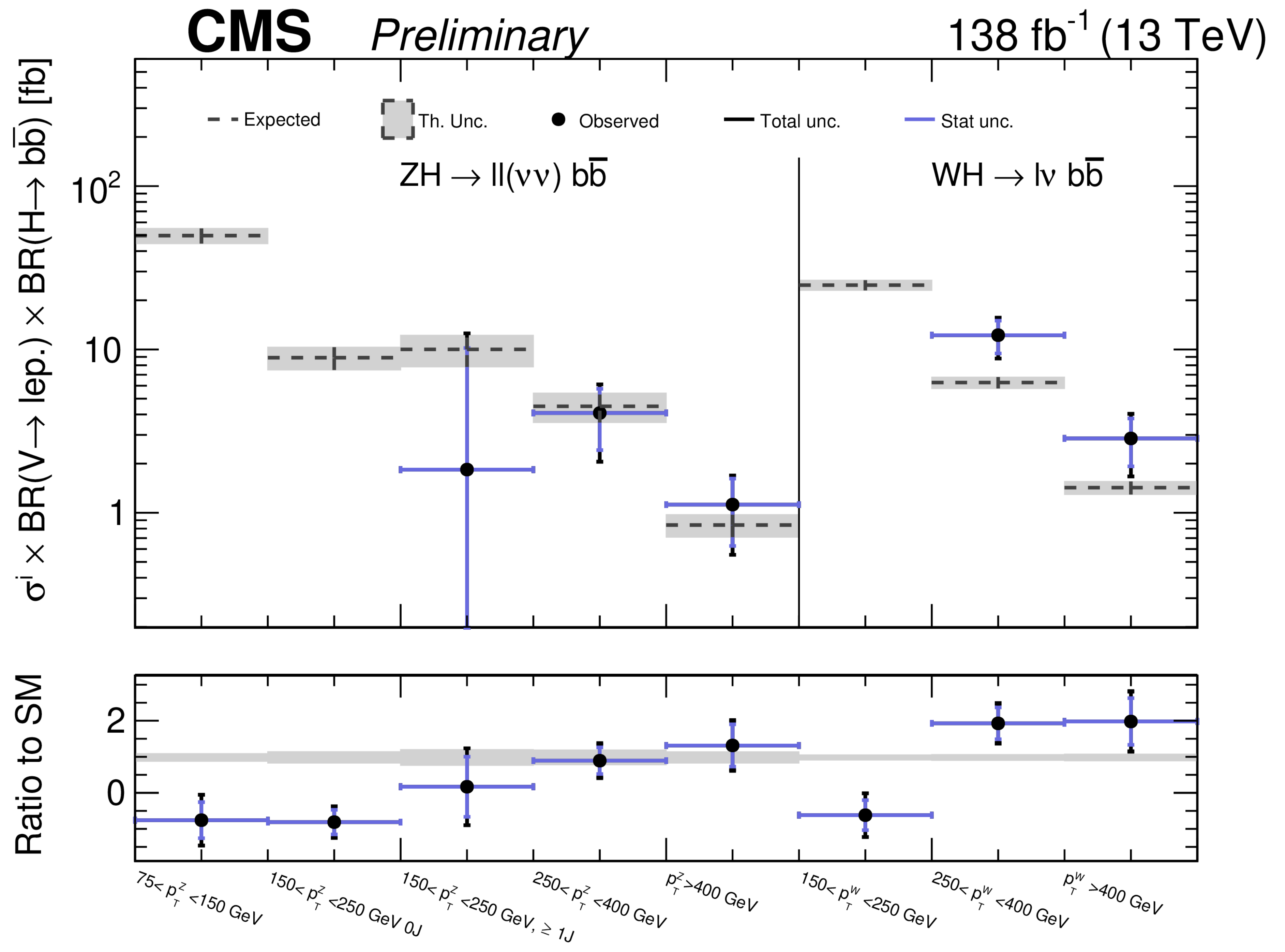
Going granular: STXS

Highly granular characterisation of **ggF**, **VBF**, **VH**, and **ttH** **production** modes

Run-II dataset exploited **in all final states**: **access to** various phase space regions (e.g. **high pT ggH**, **tH in** $H\gamma\gamma$), but many **results** are **still stat.-dominated**







HWW: arXiv:2206.09466

Htt: arXiv:2204.12957

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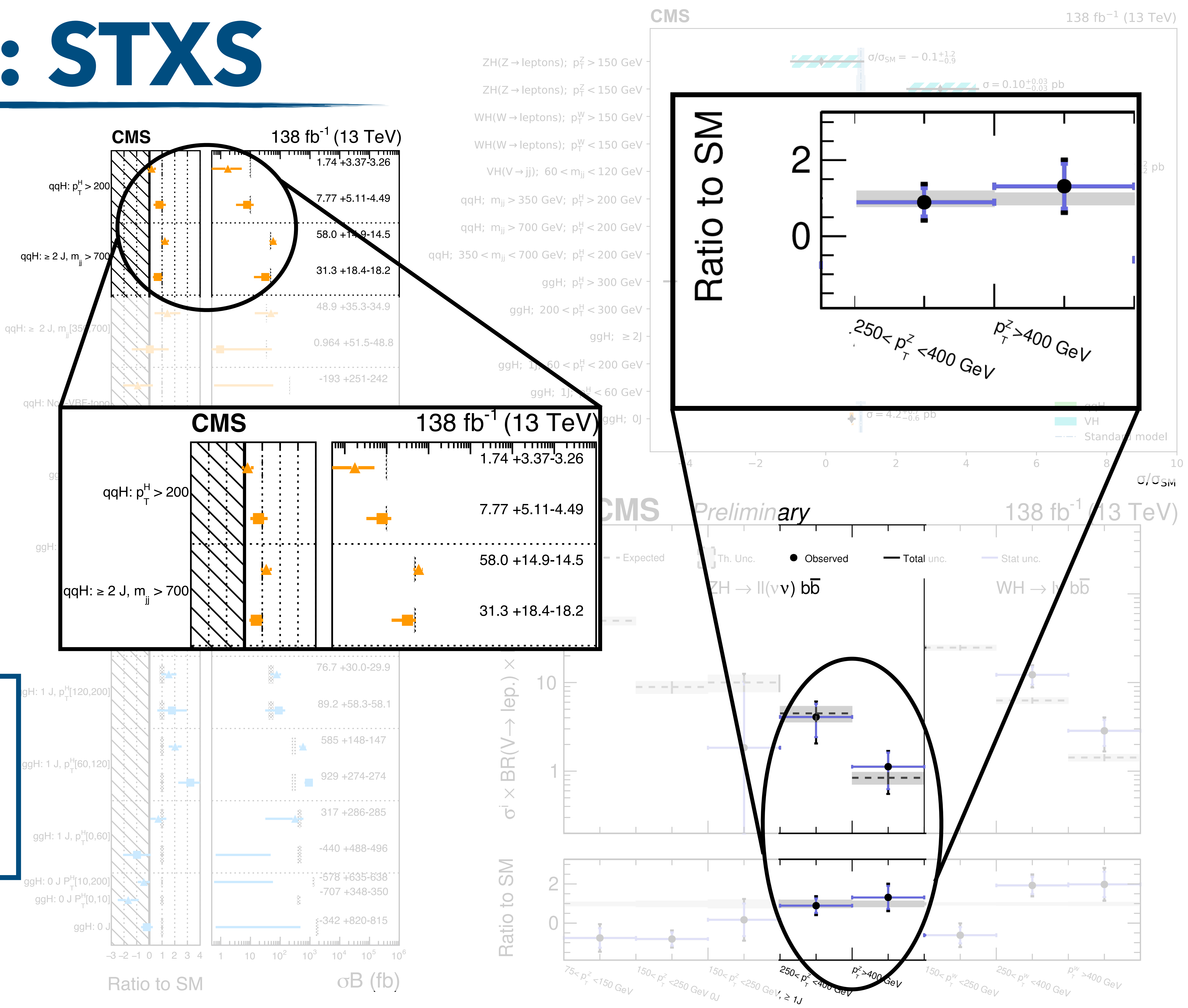
Precious measurements to test SM predictions (**theory uncertainties**) **and probe possible BSM effects:**
qqH high pT and VH high pTV regions



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Fiducial Cross Sections

Htt: arXiv:2204.12957
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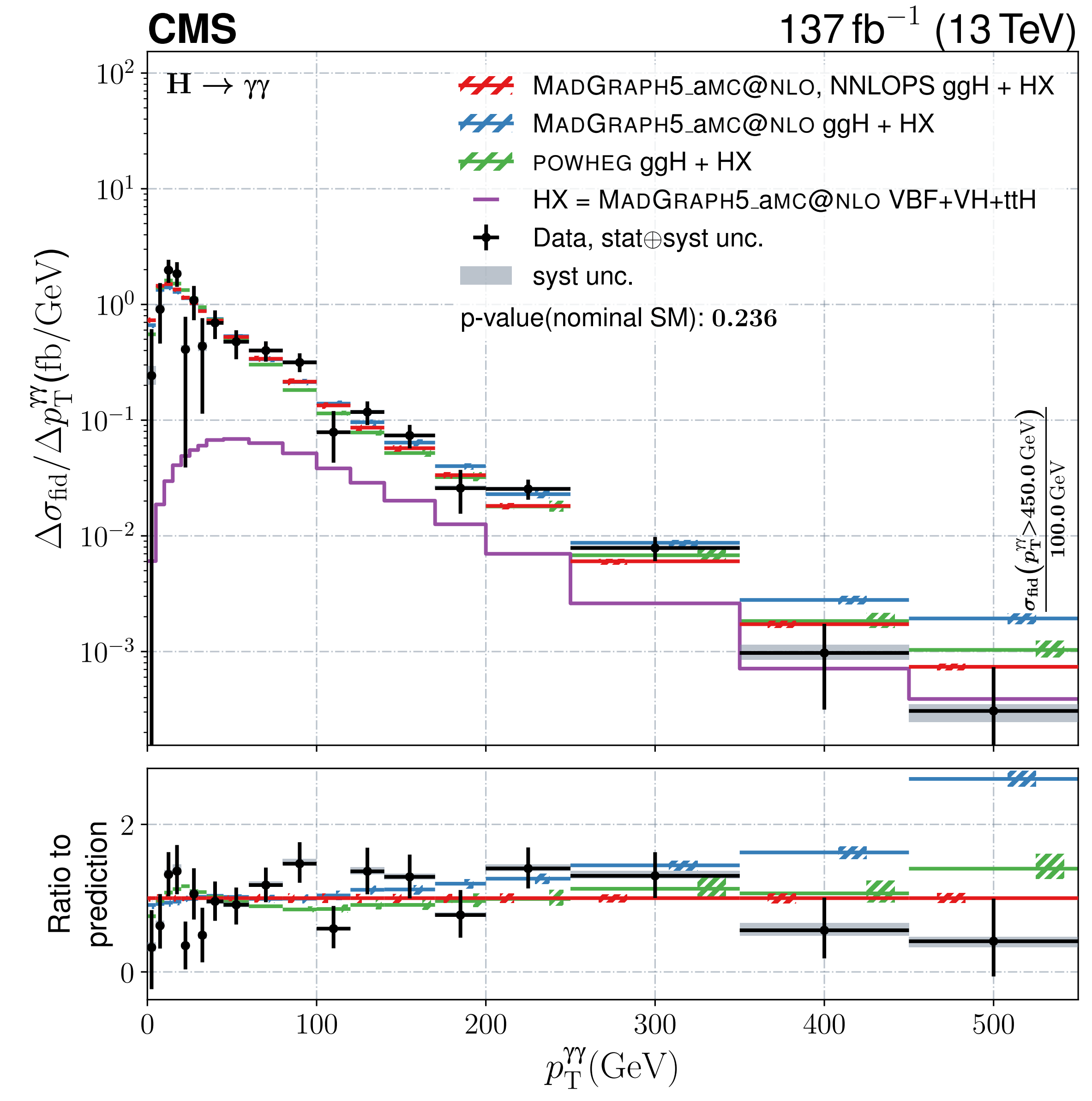
Hgg: arXiv:2208.12279
HWW: JHEP 03 (2021) 003

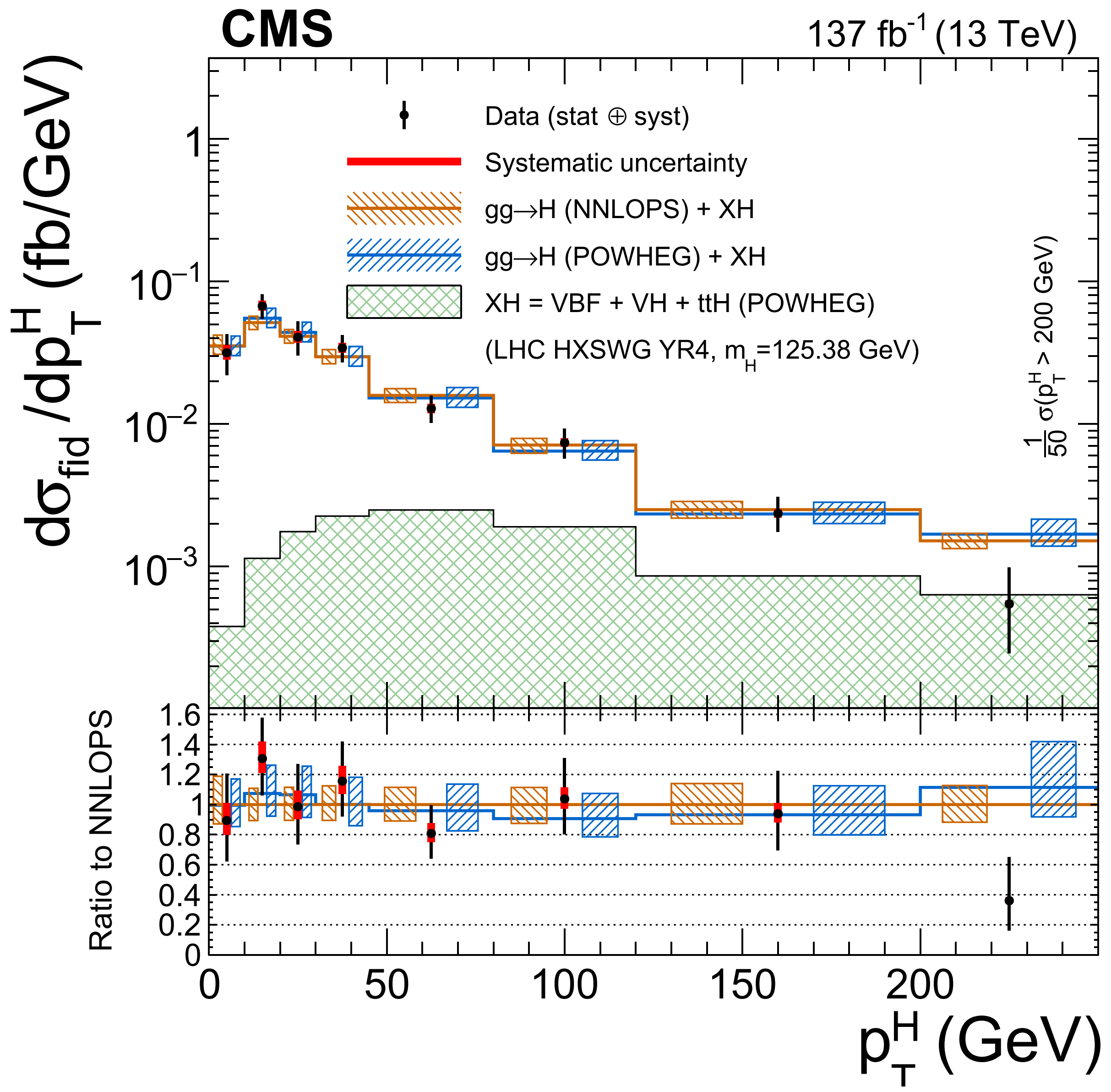
Unfold detector effects to measure cross sections in a fiducial phase space that matches analysis acceptance

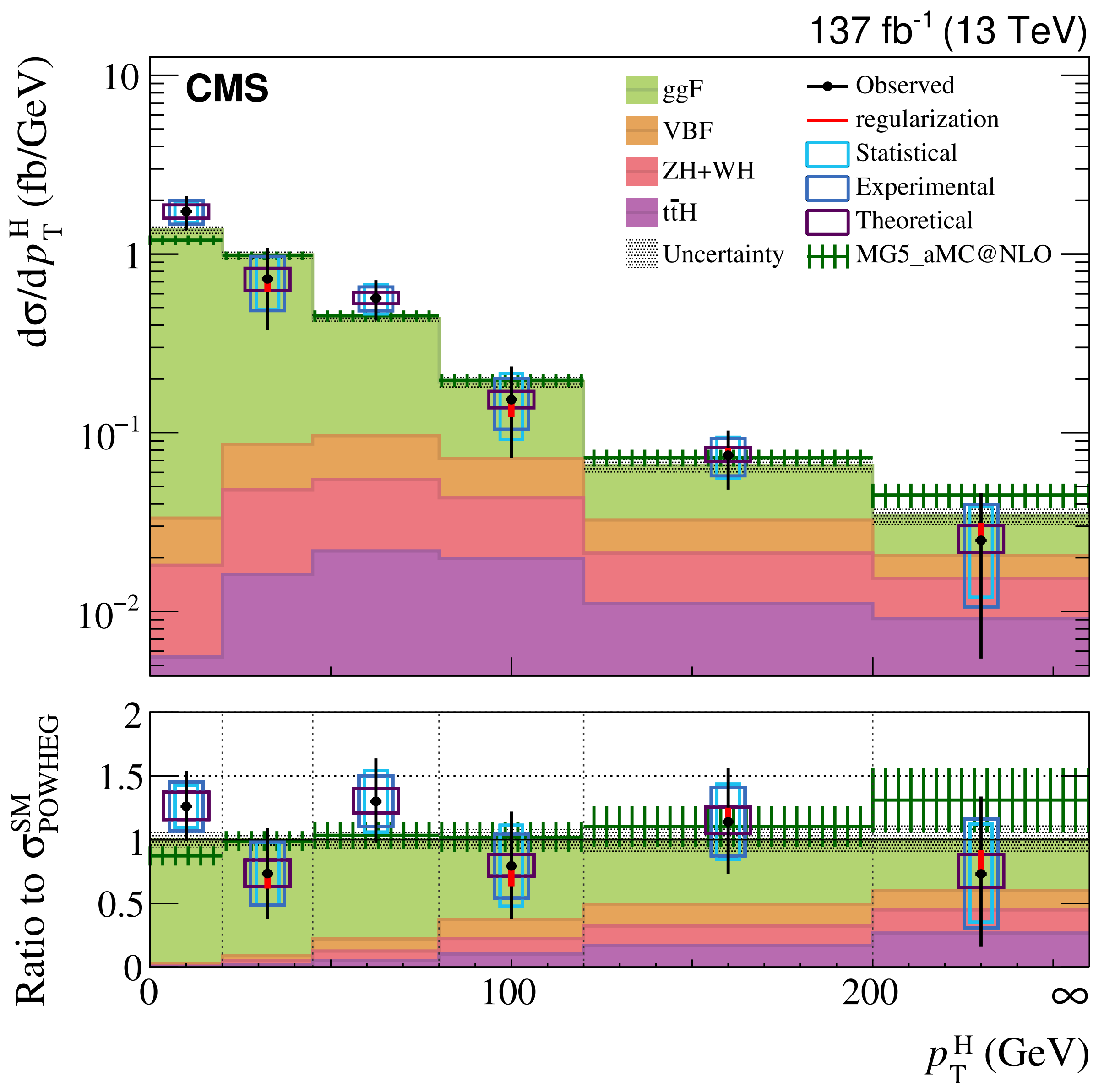
Sensitivity limited by the **statistics** available
→ **fundamental** measurements **in** the **next years**

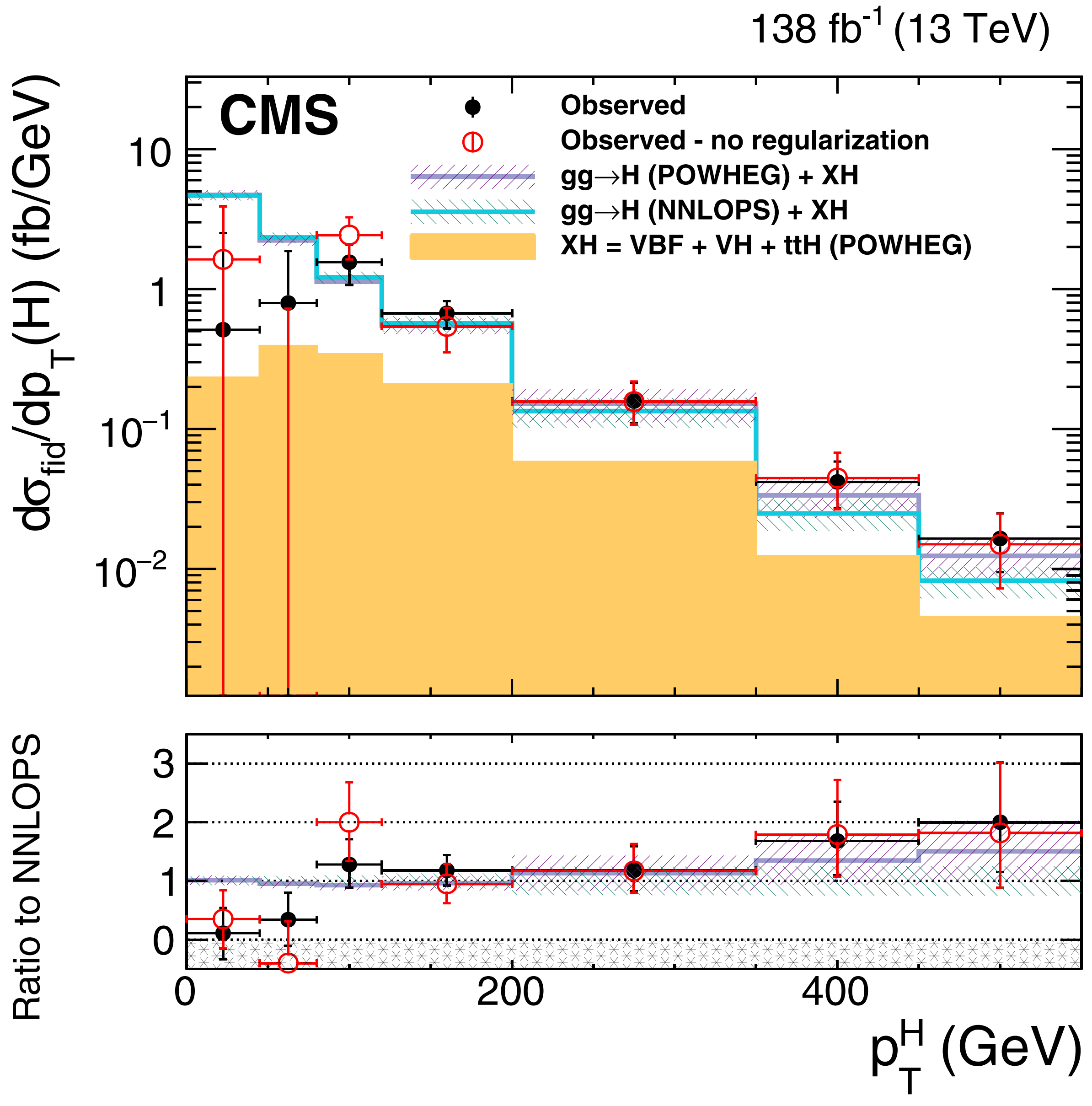
Direct assessment of theoretical predictions

<u>**High sensitivity to BSM/EFT effects**</u> (e.g. w/ <u>**pT(H)**</u>)









Fiducial Cross Sections

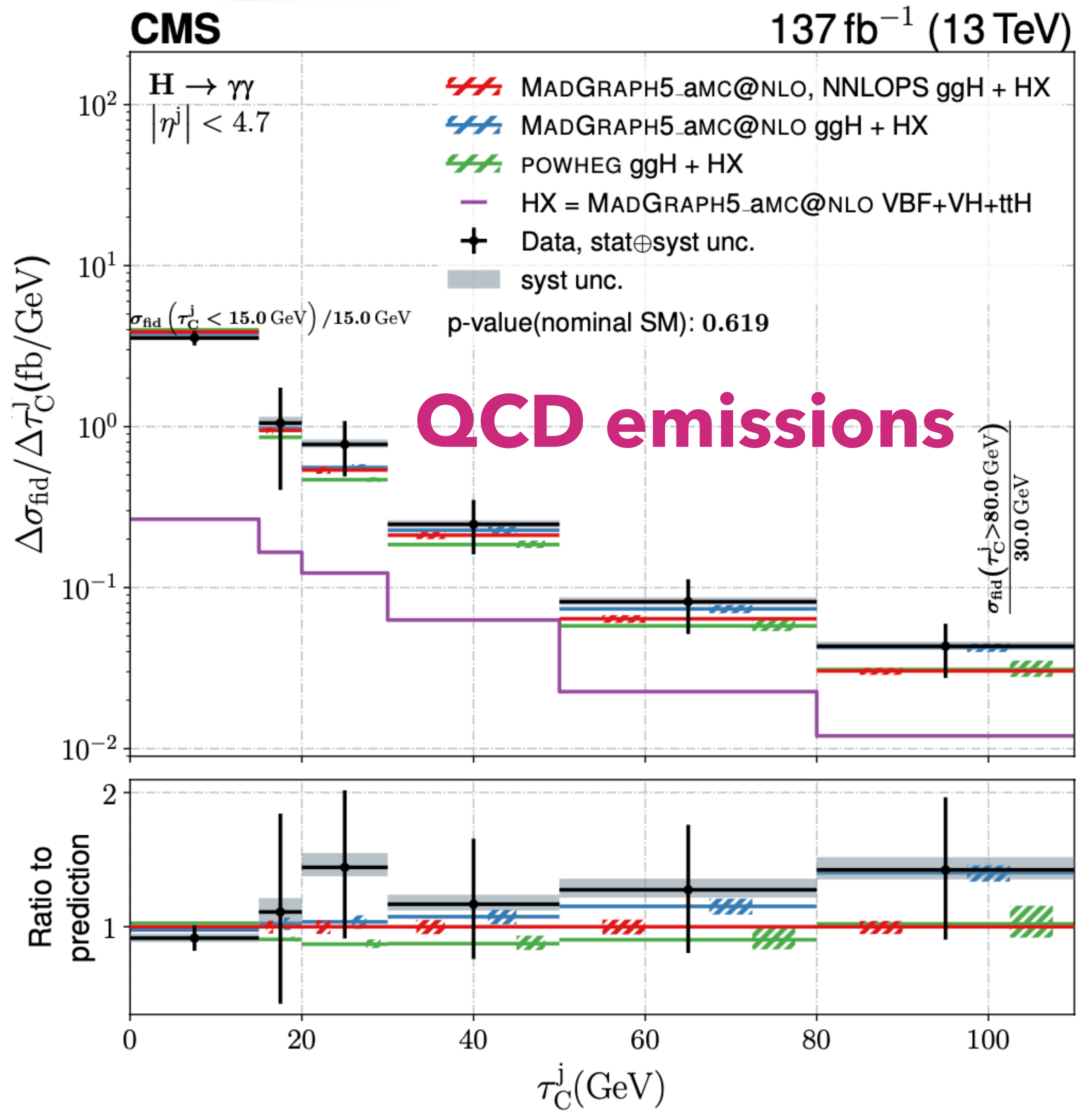
Htt: arXiv:2204.12957
HZZ: Eur. Phys. J. C 81 (2021) 488
Hgg: arXiv:2208.12279
HWW: JHEP 03 (2021) 003

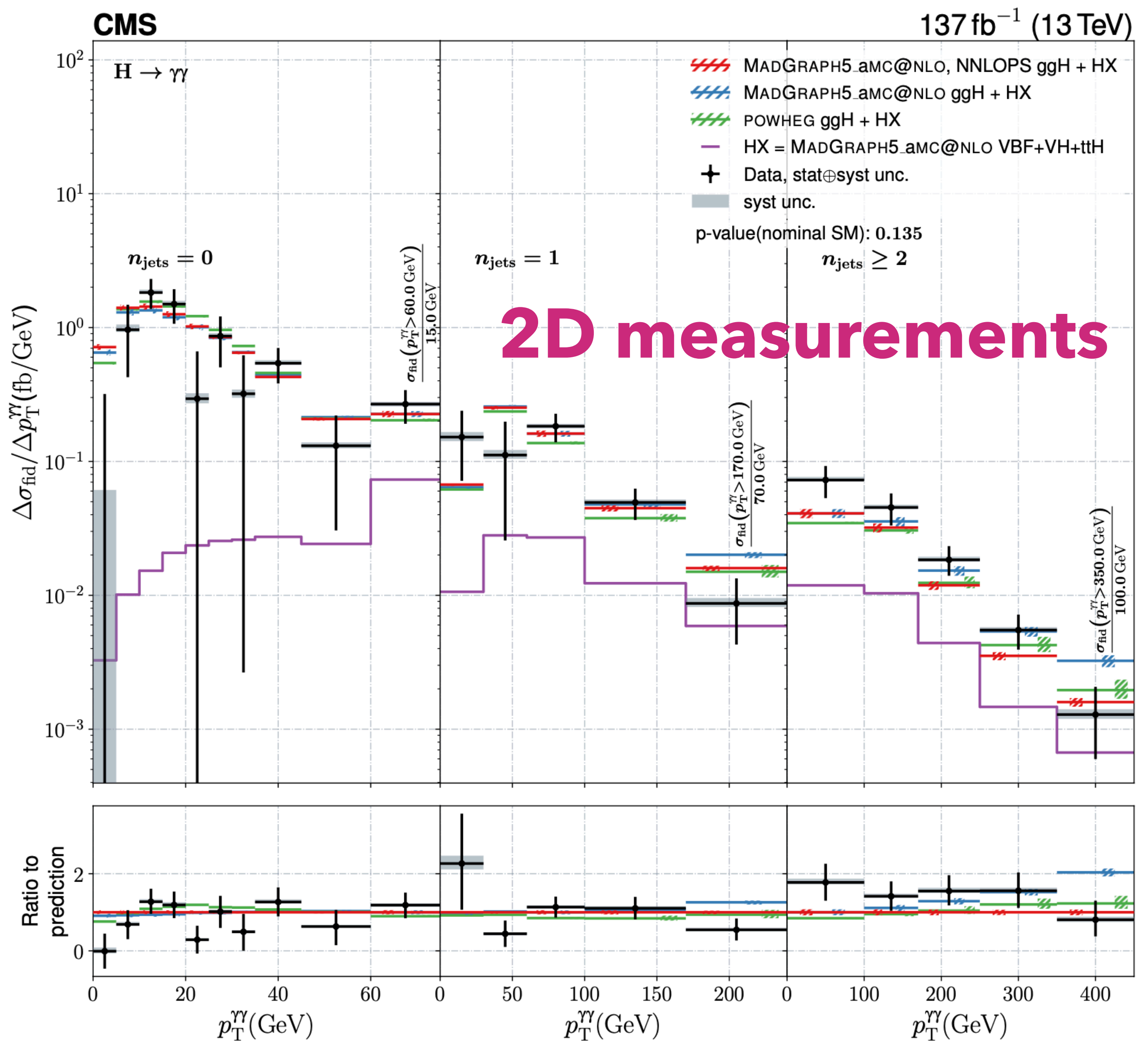
Unfold detector effects to measure cross sections in a fiducial phase space that matches analysis acceptance

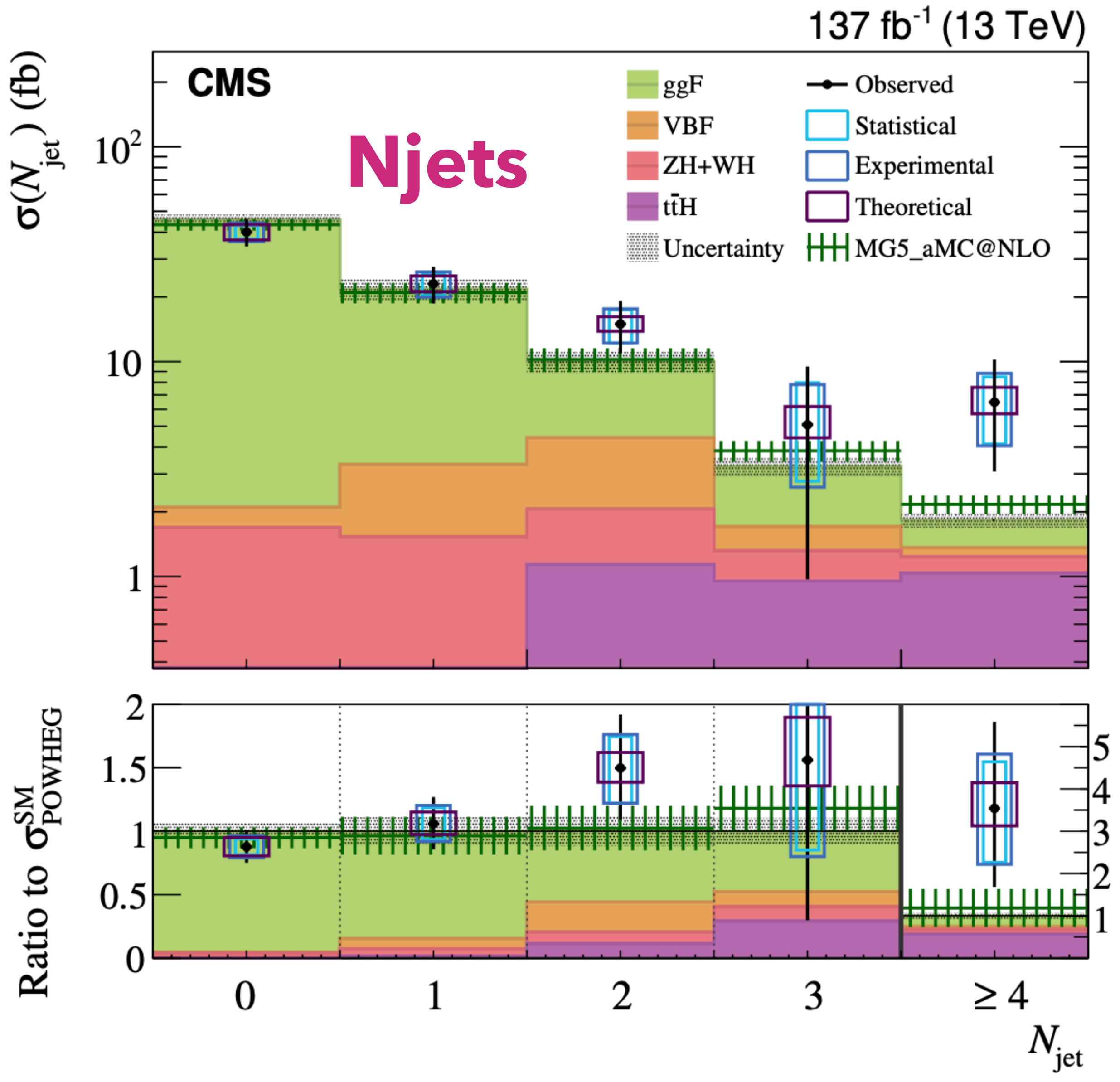
Sensitivity limited by the **statistics** available
→ **fundamental** measurements **in** the **next years**

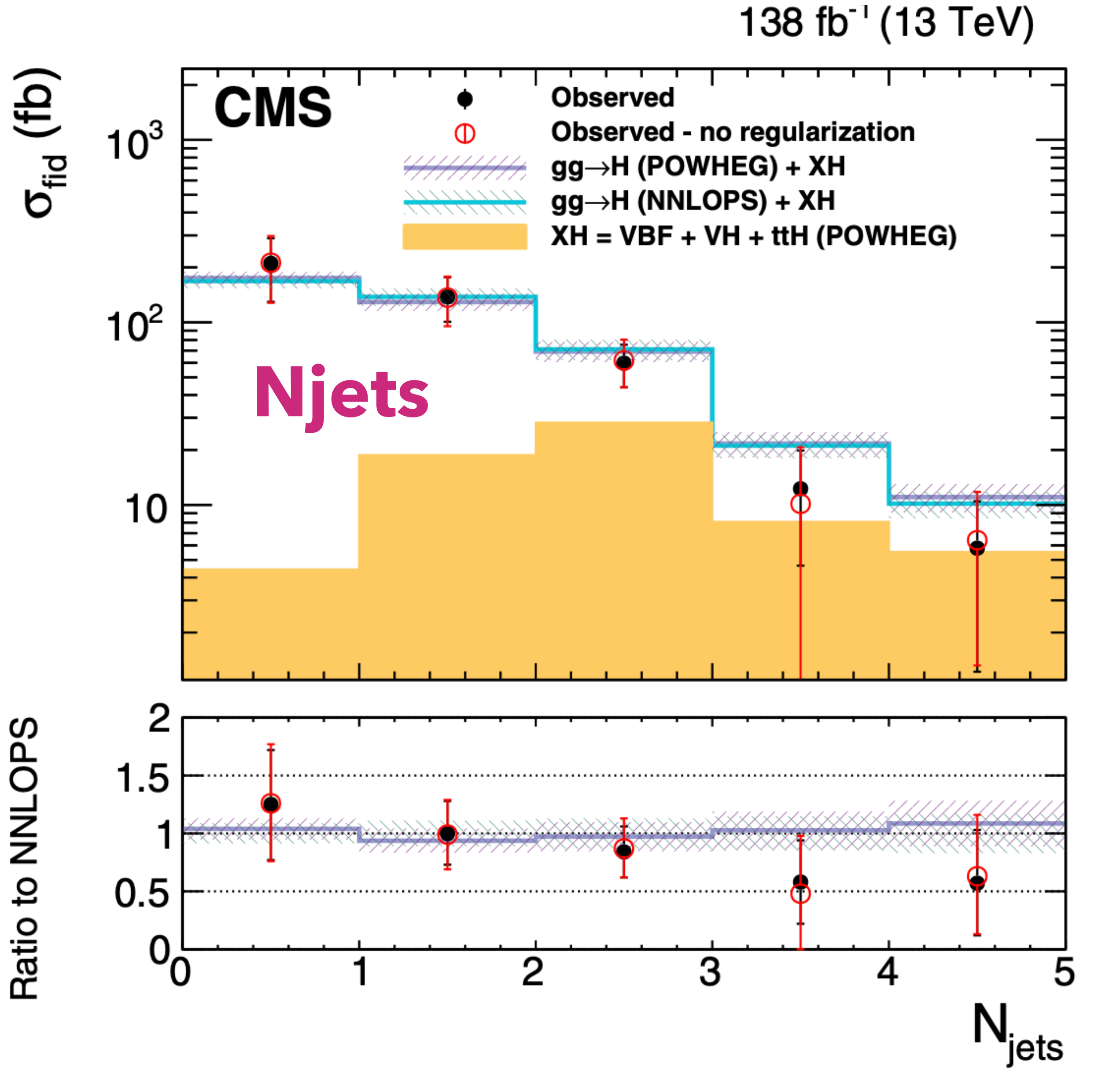
Direct assessment of theoretical predictions

High sensitivity to BSM/EFT effects (e.g. w/ **pT(H)**)









Large set of **observables** measured in
several decay channels
→ **comprehensive characterisation**
of Higgs' production and decay

How to probe H couplings?

The κ**-framework facilitates** the **characterisation** of **Higgs couplings in terms of** a series of **coupling modifiers*** κ_i

$$(\sigma \cdot \mathrm{BR})(i \rightarrow \mathrm{H} \rightarrow f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2}$$

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Coupling modifiers κ_i for production, decay, and total width, defined as the ratio w.r.t. the SM prediction (i.e. $\kappa_i = 1 = \mathrm{SM}$)

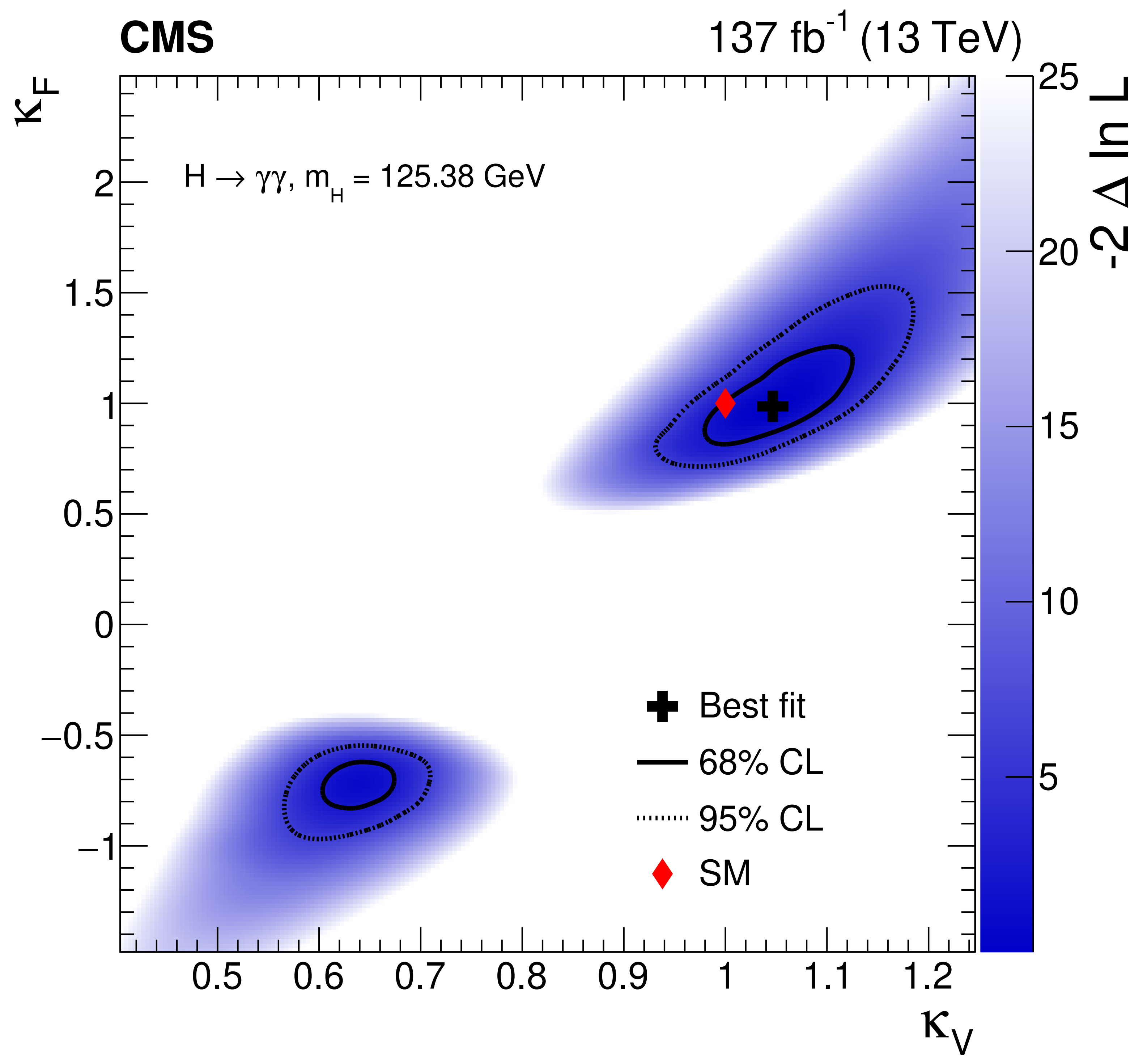
"LO" Couplings: κ_V, κ_f

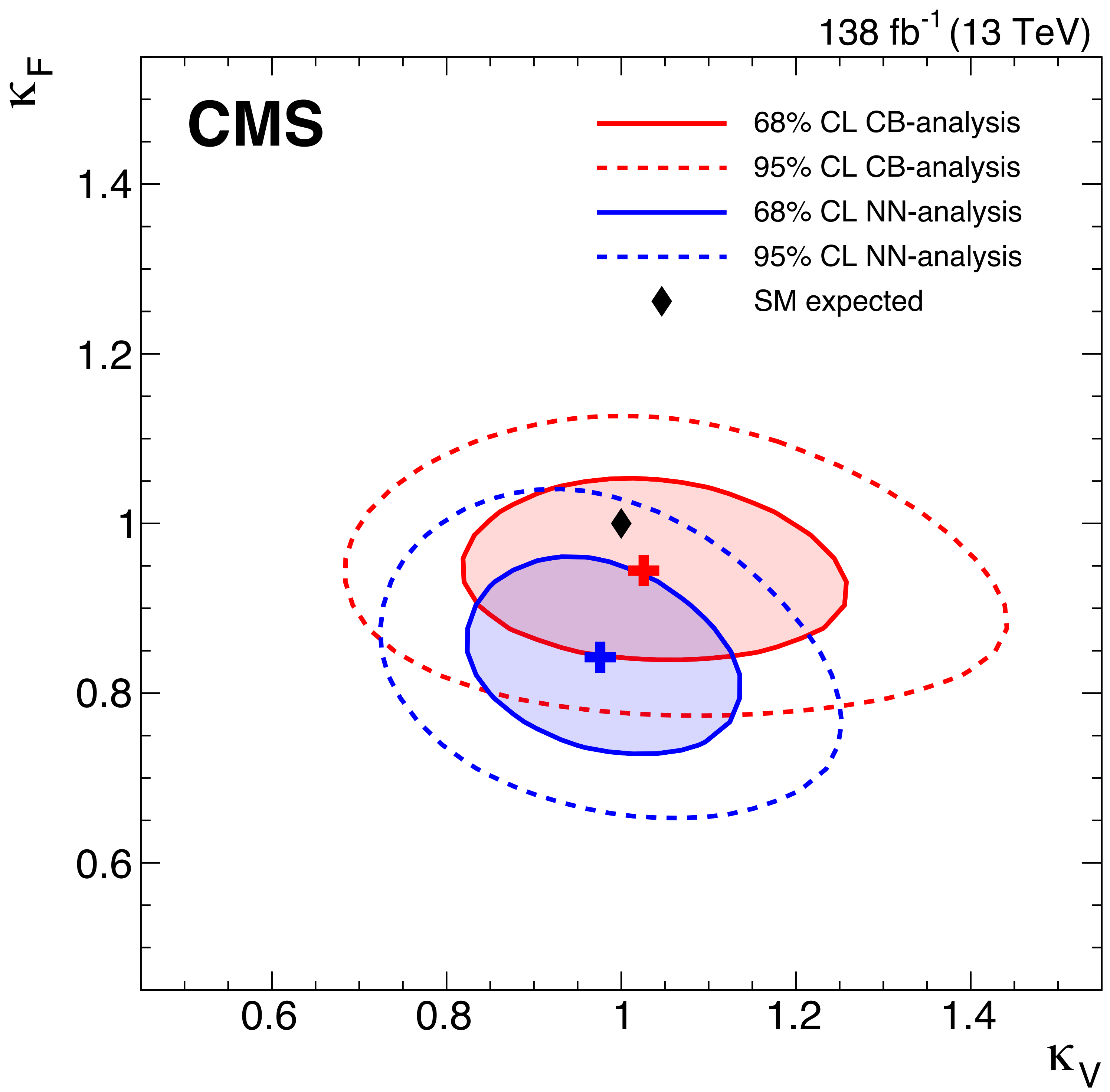
Htt: arXiv:2204.12957
Hgg: JHEP 07 (2021) 27

κ_V, κ_f : **bosonic- and fermionic-like coupling modifiers** measured **from pT(H) spectrum** (re-)interpretation

Measured in Run-I and gave hints of the existence of these couplings, nailed down with Run-II dataset

Substantial improvement in precision with respect to Discovery : now **agreement with** the **SM at** level of **10%**

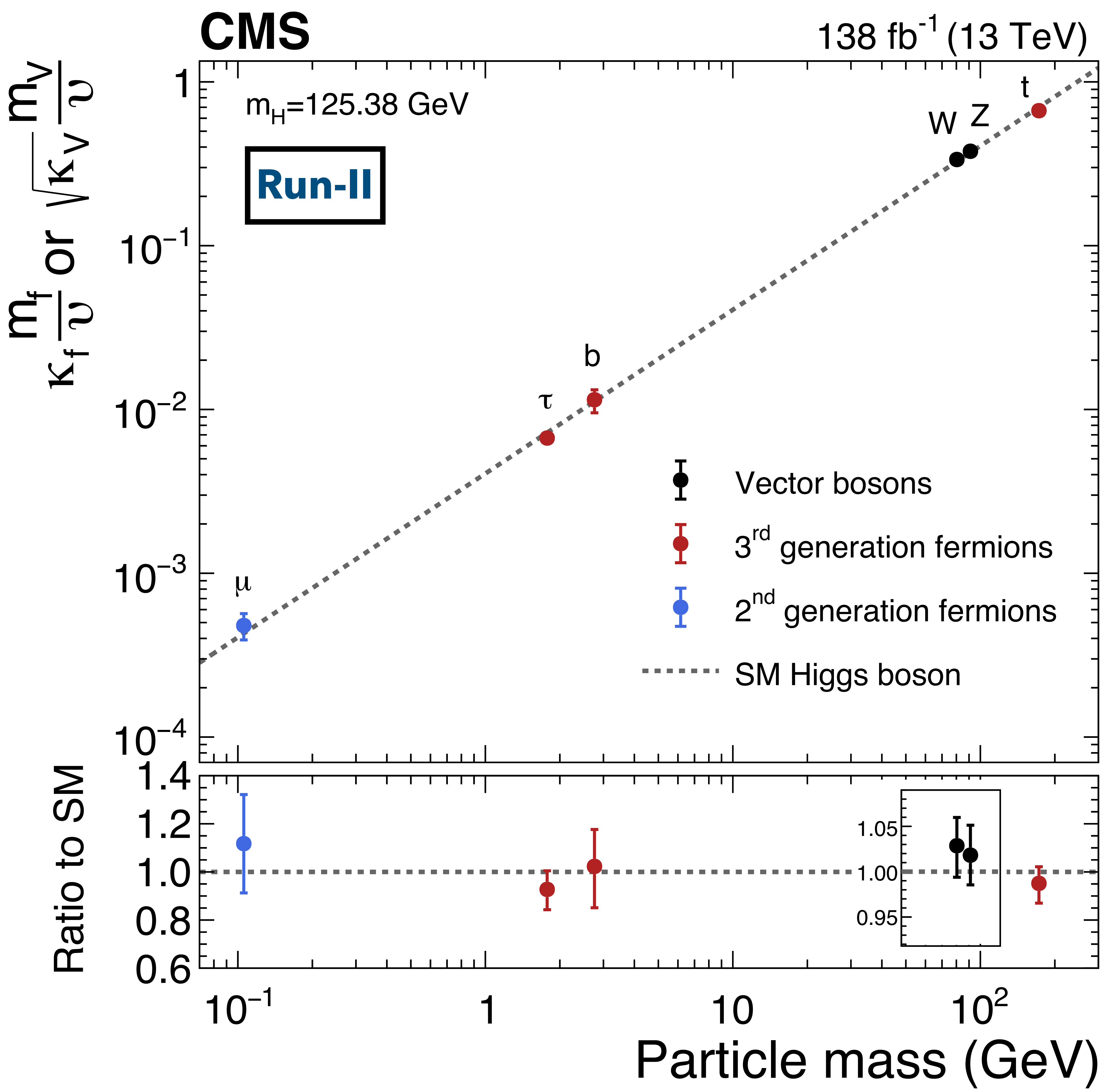




"NLO" Couplings: scaling with mass

We entered the ***realm of precision physics***, with **similar sys and stat** component of the **uncertainties**

New points are accessible: started to probe the couplings with 2nd generation fermions

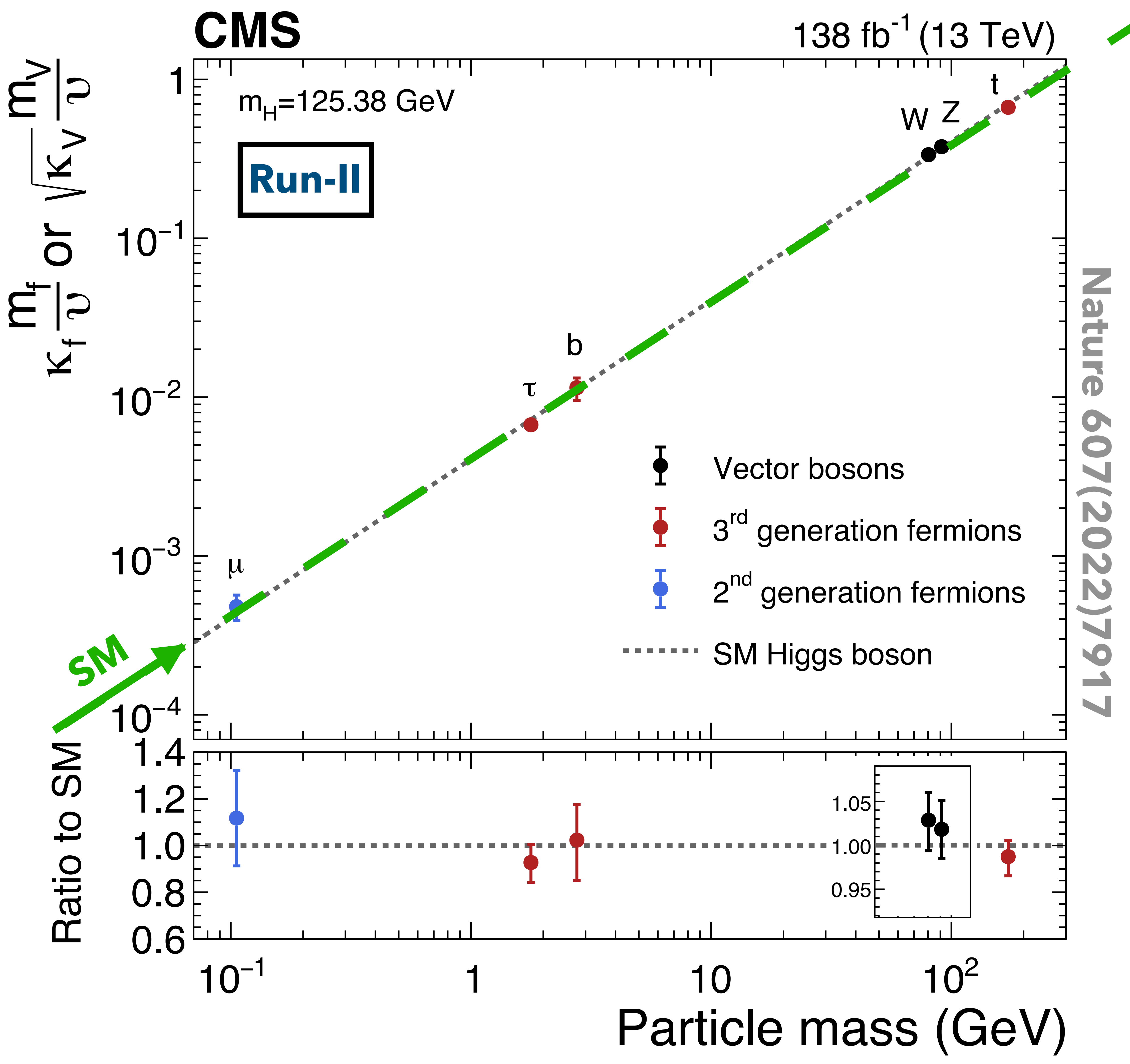


Nature 607(2022)7917

The SM prediction, not a fit!

We entered the ***realm of precision physics***, with **similar sys and stat** component of the **uncertainties**

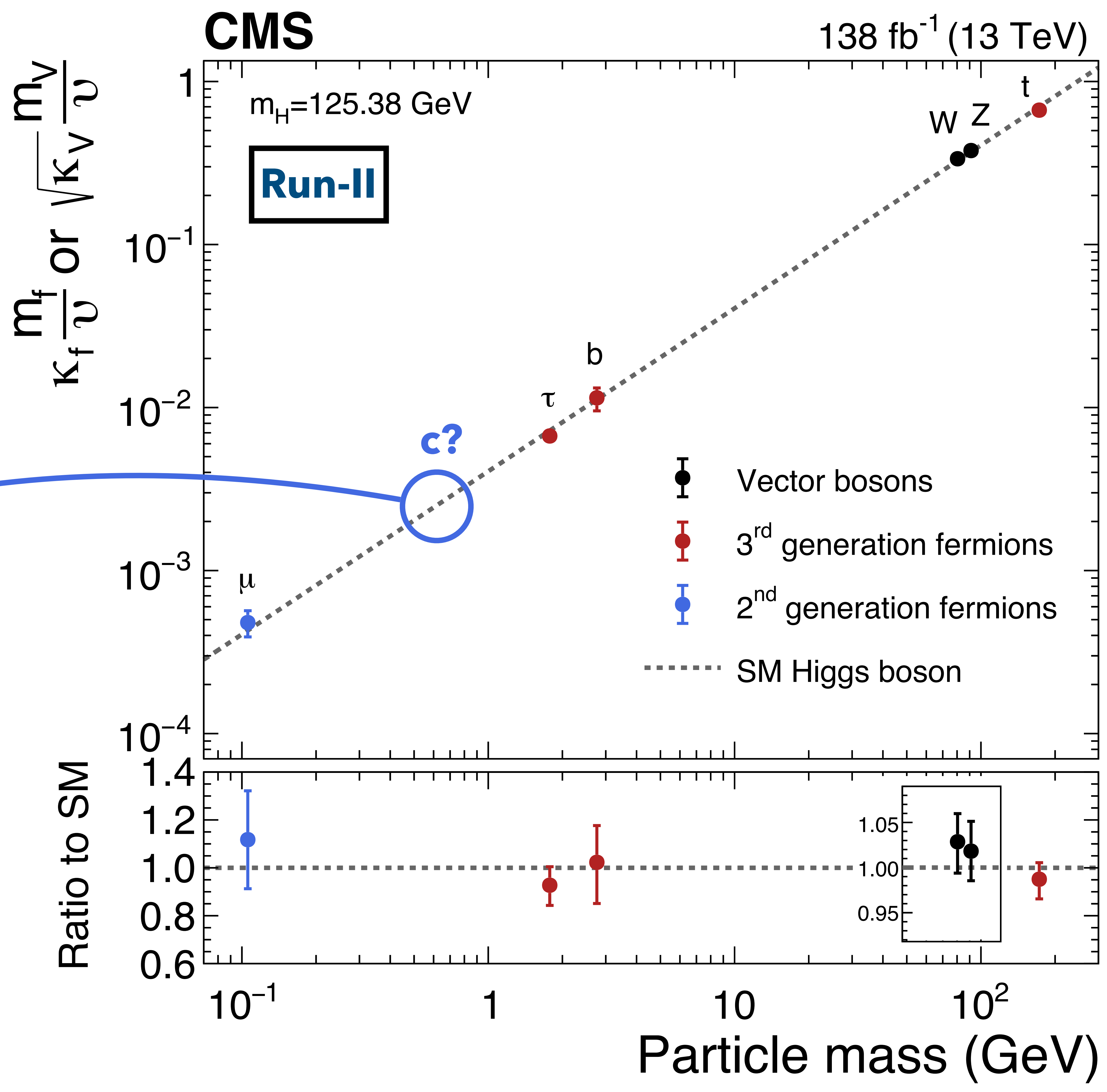
New points are accessible: started to probe the couplings with 2nd generation fermions



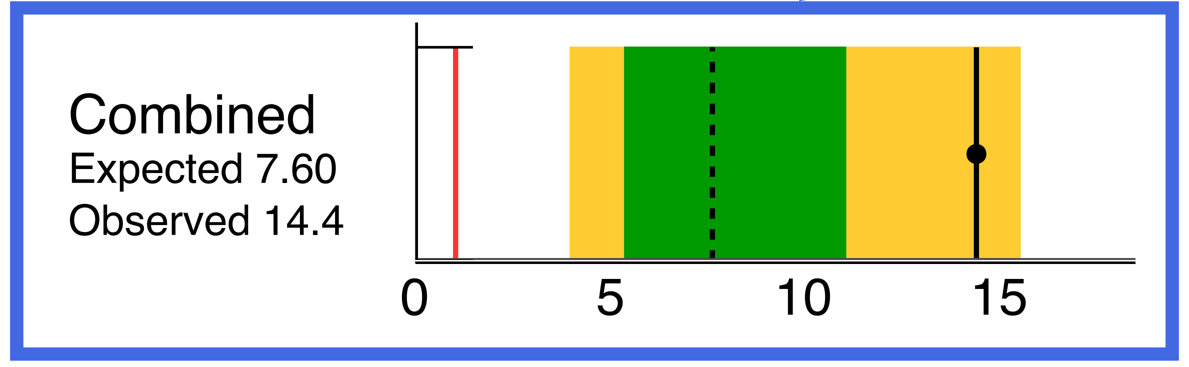
What about missing points?

We entered the ***realm of precision physics***, with **similar sys and stat** component of the **uncertainties**

New points are accessible: started to probe the couplings with 2nd generation fermions



Nature 607(2022)7917

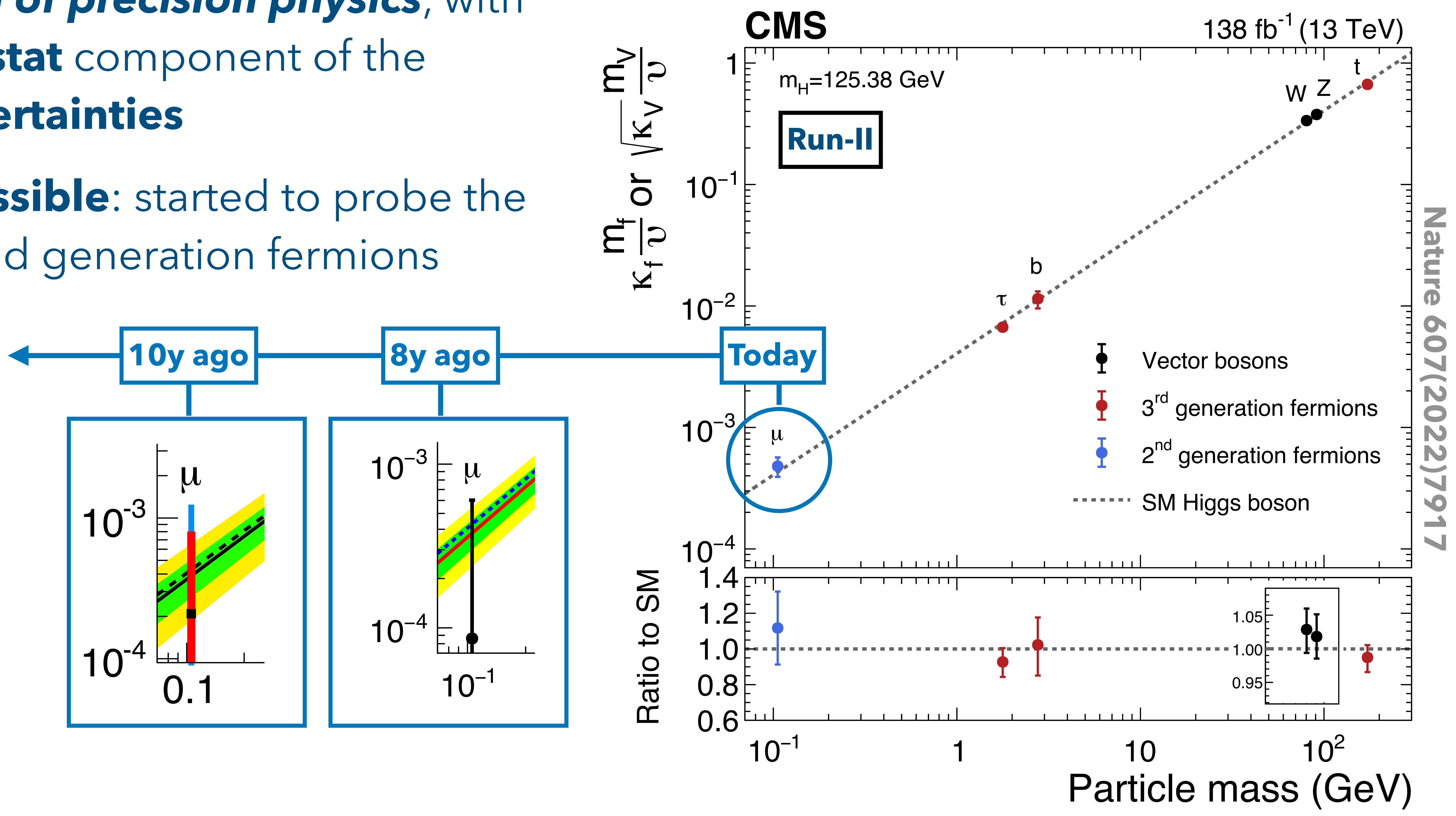


More in J. Malcles' talk

Shrinking error bars

We entered the ***realm of precision physics***, with **similar sys and stat** component of the **uncertainties**

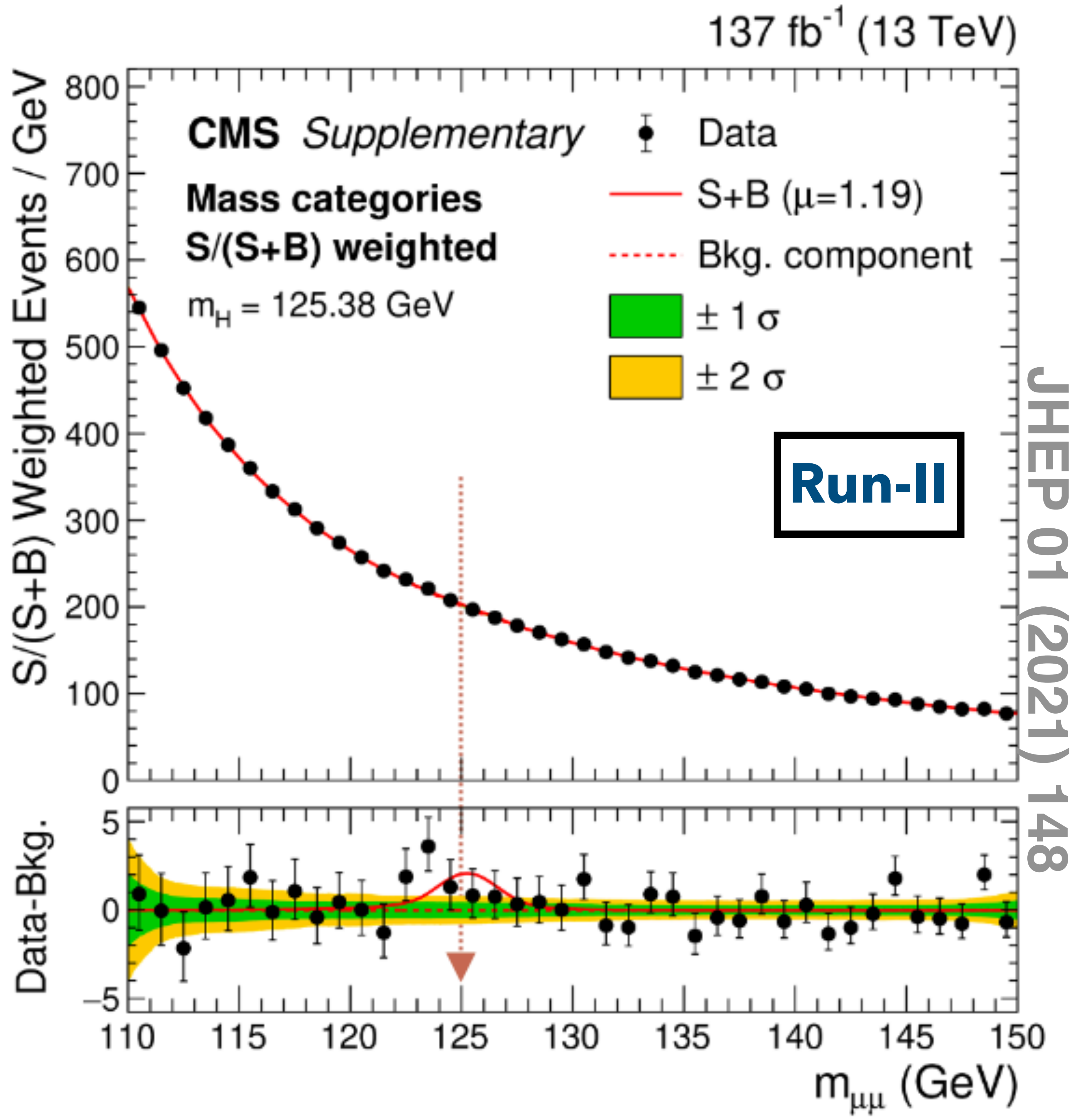
New points are accessible: started to probe the couplings with 2nd generation fermions



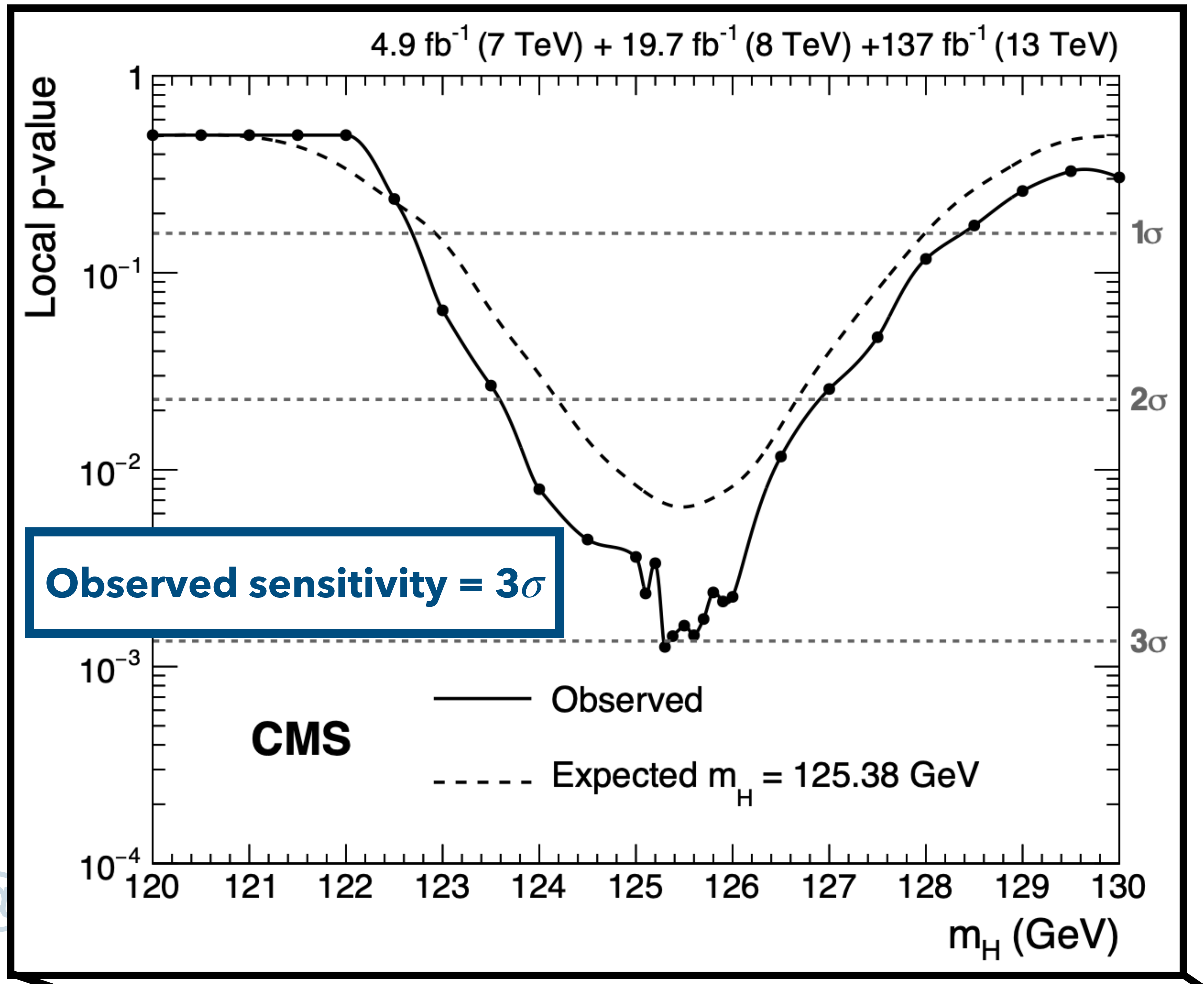
The power of Run-II : $H\mu\mu$

Tiny BR of 2.18×10^{-4} @ $m_{\mathrm{H}} = 125$ GeV

Most experimentally sensitive probe of the Higgs boson **couplings to second-generation fermions**



The power of Run-II : $H\mu\mu$



Tiny BR of 2.18×10^{-4} @

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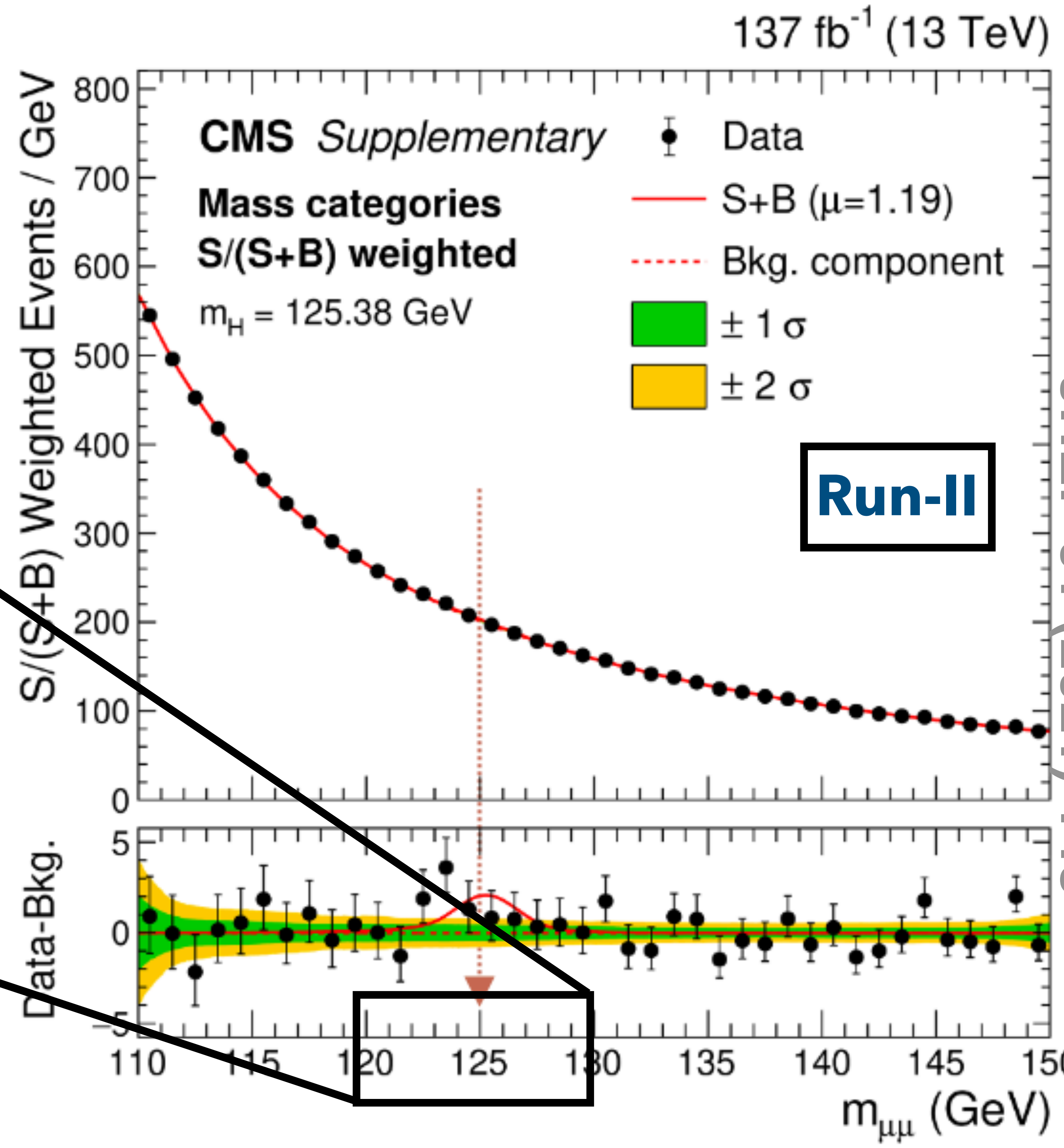


JHEP 01 (2021) 148

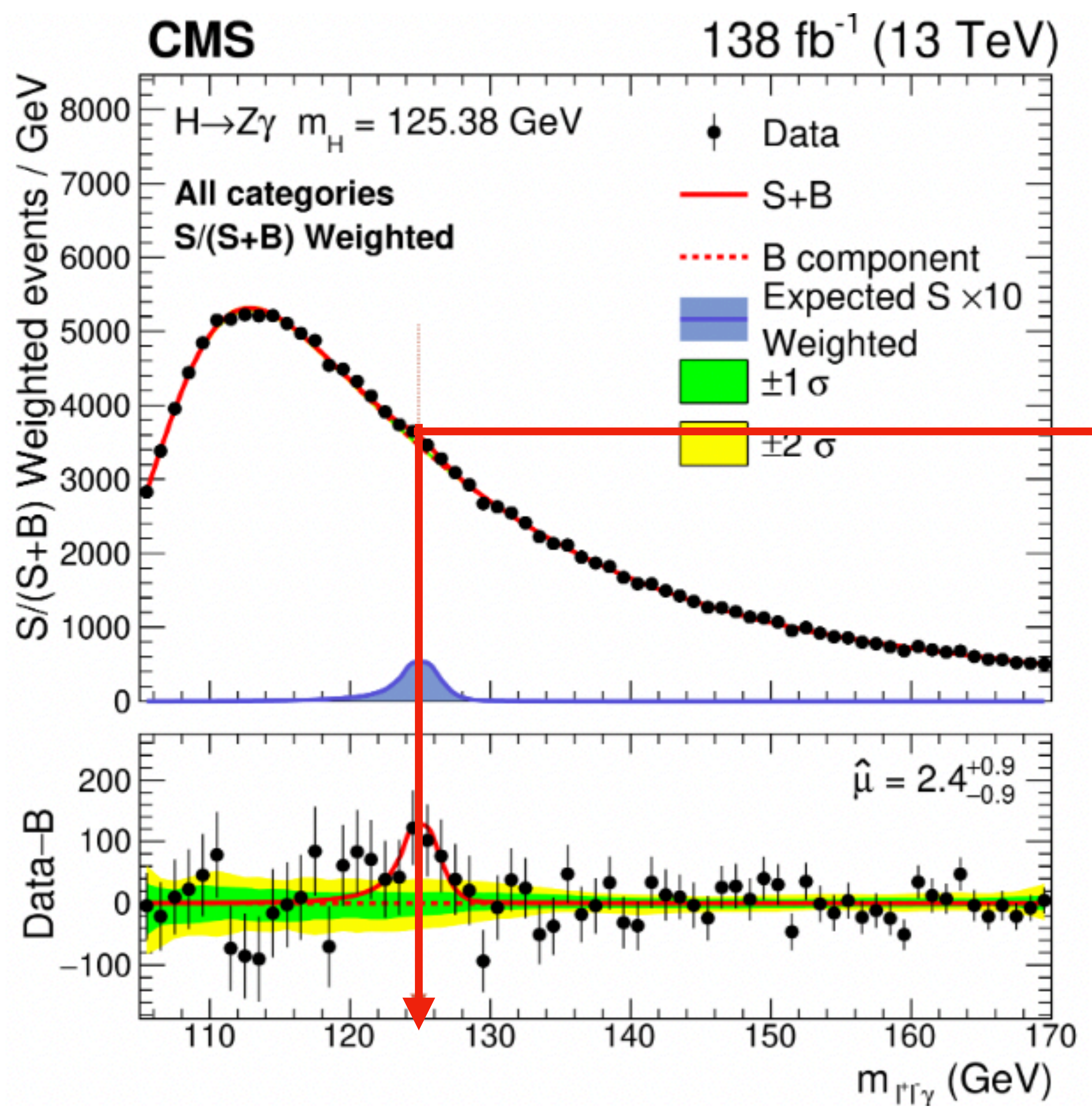
First observation of $H \to \mu\mu$ only possible **with full Run-II statistics**

The power of Run-II : HZγ

Possible **portal to BSM** physics from the $\mathrm{BR}(\mathrm{H} \to \mathrm{Z}\gamma)/\mathrm{BR}(\mathrm{H} \to \gamma\gamma)$ measurement

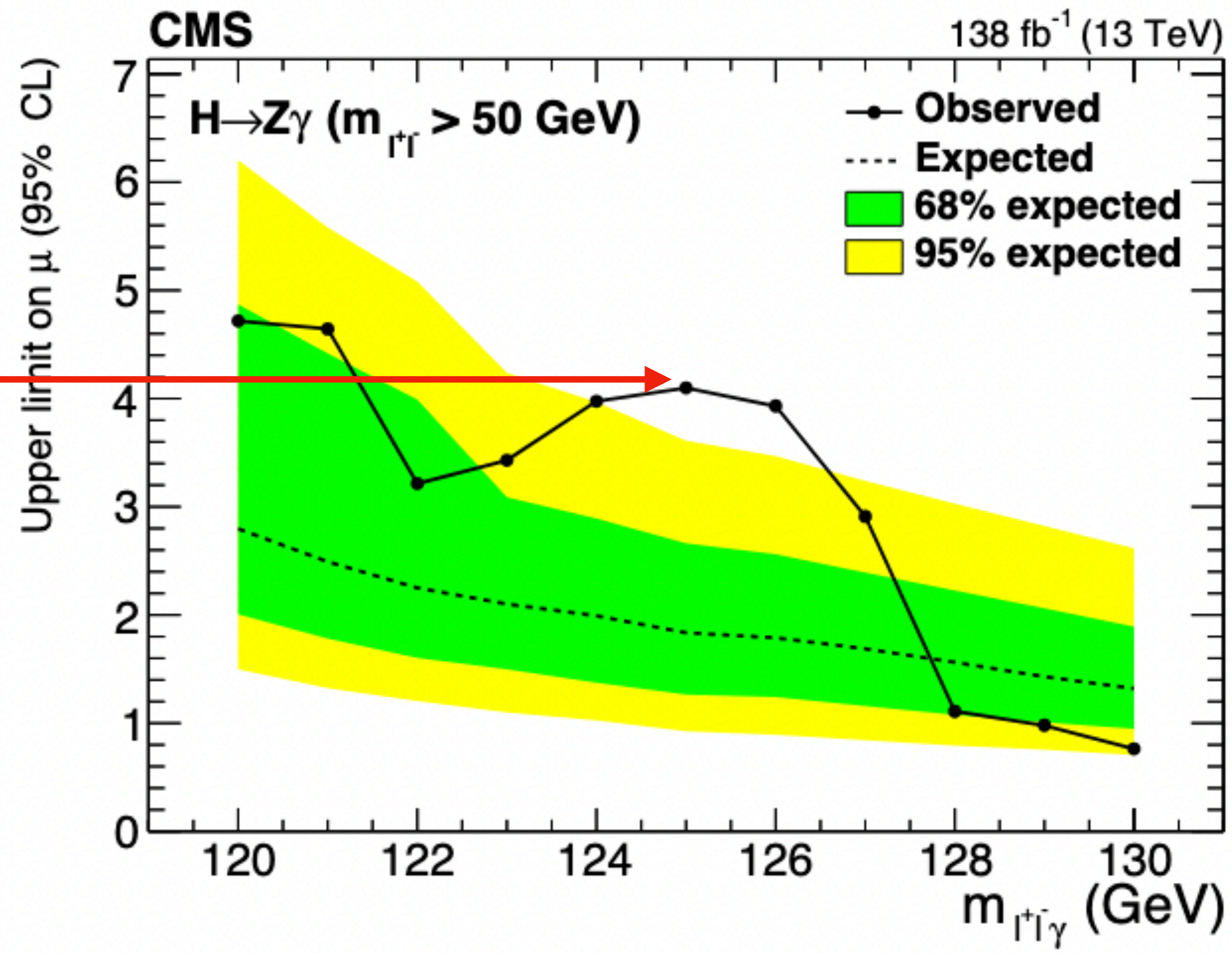
Good channel to test SM predictions and **identify** possible **new physics** arising **from loop corrections**

arXiv:2204.12945



2.7σ excess

at 125 GeV



Conclusion

2012: The LHC sees something

- ***Observation of a scalar particle*** (q=0, J^{PC} = 0++) **compatible with the SM Higgs boson**
- **Run-I** measurements, yet largely dominated by stat, **confirmed** the **agreement with** the **SM** predictions

2022: The LHC sees (way) better

- **All** the **production modes** (except for tH) have been **observed** with > 5SDs
- **Many** decay **channels entered** the realm of **precision physics and** we started probing new couplings
- **Combining all** the **channels**, excellent **agreement with SM** predictions **at 10%** level
- Overall, ***fourfold* improvement *in precision*** with respect to the discovery

(see J. Malcle's talk)

2040: The LHC sees at High-Luminosity

- Observation of **couplings to 2nd generation fermions** and stress tests of the SM
- Observation of **HH production and** stringent **constraints on** the trilinear **self-coupling**

Conclusion

"It is widely understood that the standard model is but a low energy approximation of a more comprehensive theory. CMS is entering into the era of precision Higgs physics that may shed light on the physics beyond the standard model."

BACKUP SLIDES

Global profile of the Higgs boson

HZZ

- **Matrix element discriminants** to separate signal from bkg
- Maximum likelihood fit in 2D/3D to extract the results
- Main qq/ggZZ backgrounds: MC, Z+jets bkg: Data driven

Hgg

- **Boosted Decision Trees (BDT)** to separate signal from background
- Maximum likelihood fit on mgg to extract the results
- Envelope method to estimate exponentially falling background

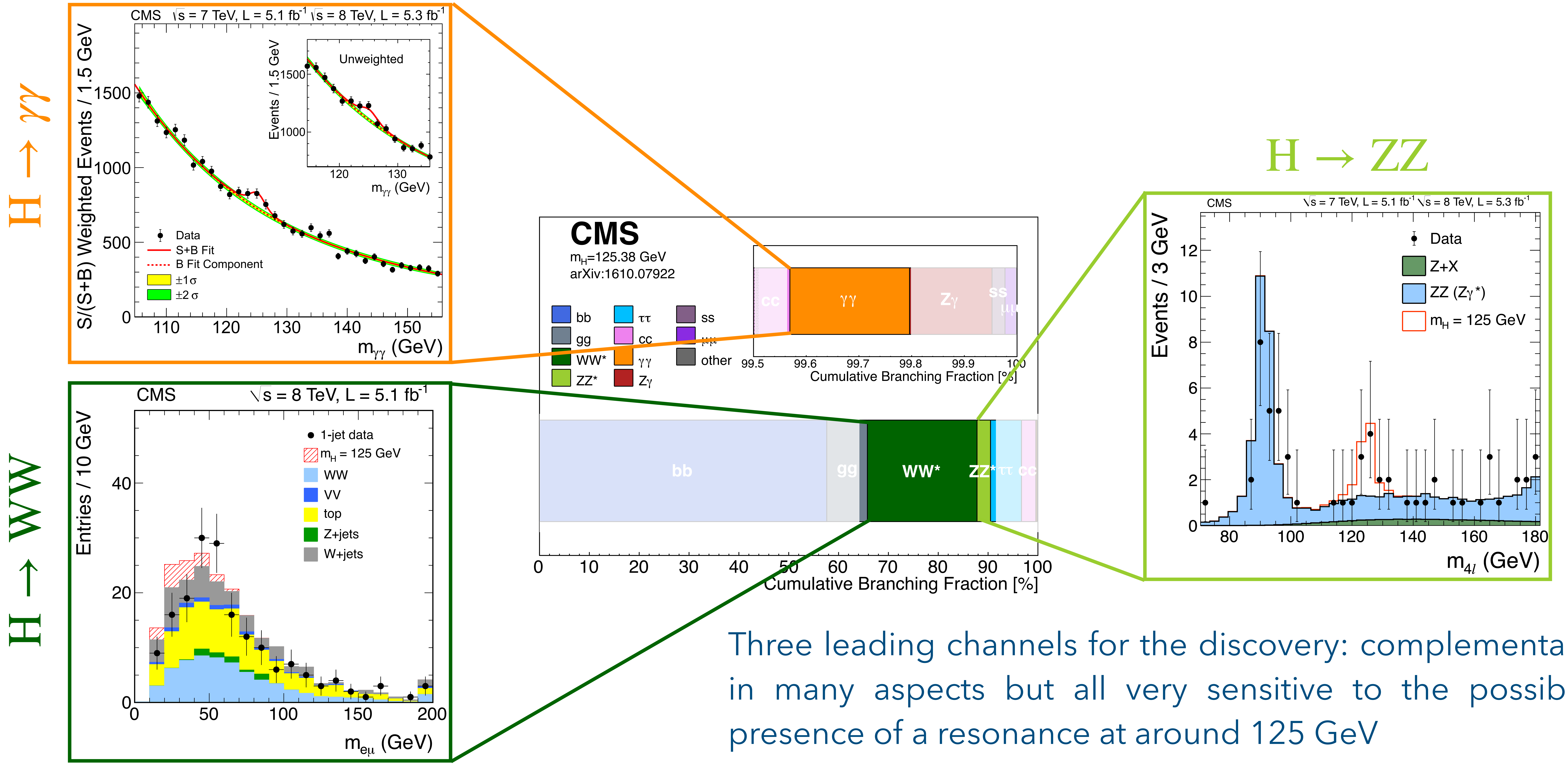
HWW

- **Combination of reconstructed observables and MVA techniques (BDT/DNN)** to separate signal from background
- Maximum likelihood fit on different observables according to the analysis category
- Complex background modelling: MC, data driven estimates, rates from dedicated CRs

Htt/ttH

- **Combination of reconstructed observables and MVA techniques (BDT/DNN)** to separate signal from background and categorise events
- Maximum likelihood fit on MVA score to extract results of the analysis
- MC and data driven estimates (e.g. fake rates method)

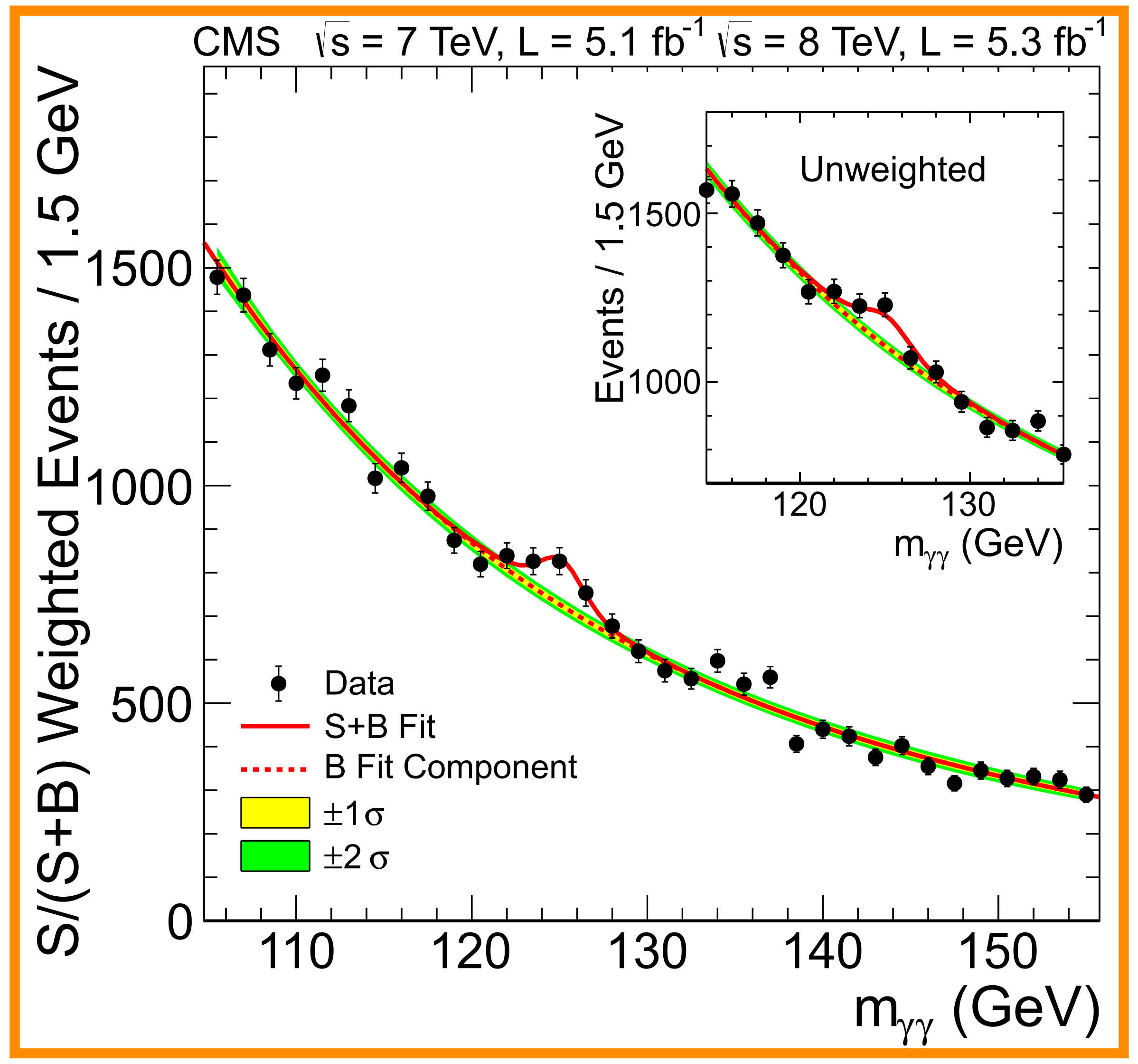
The discovery channels



Three leading channels for the discovery: complementary in many aspects but all very sensitive to the possible presence of a resonance at around 125 GeV

H → $\gamma\gamma$

H → $\gamma\gamma$



H → WW

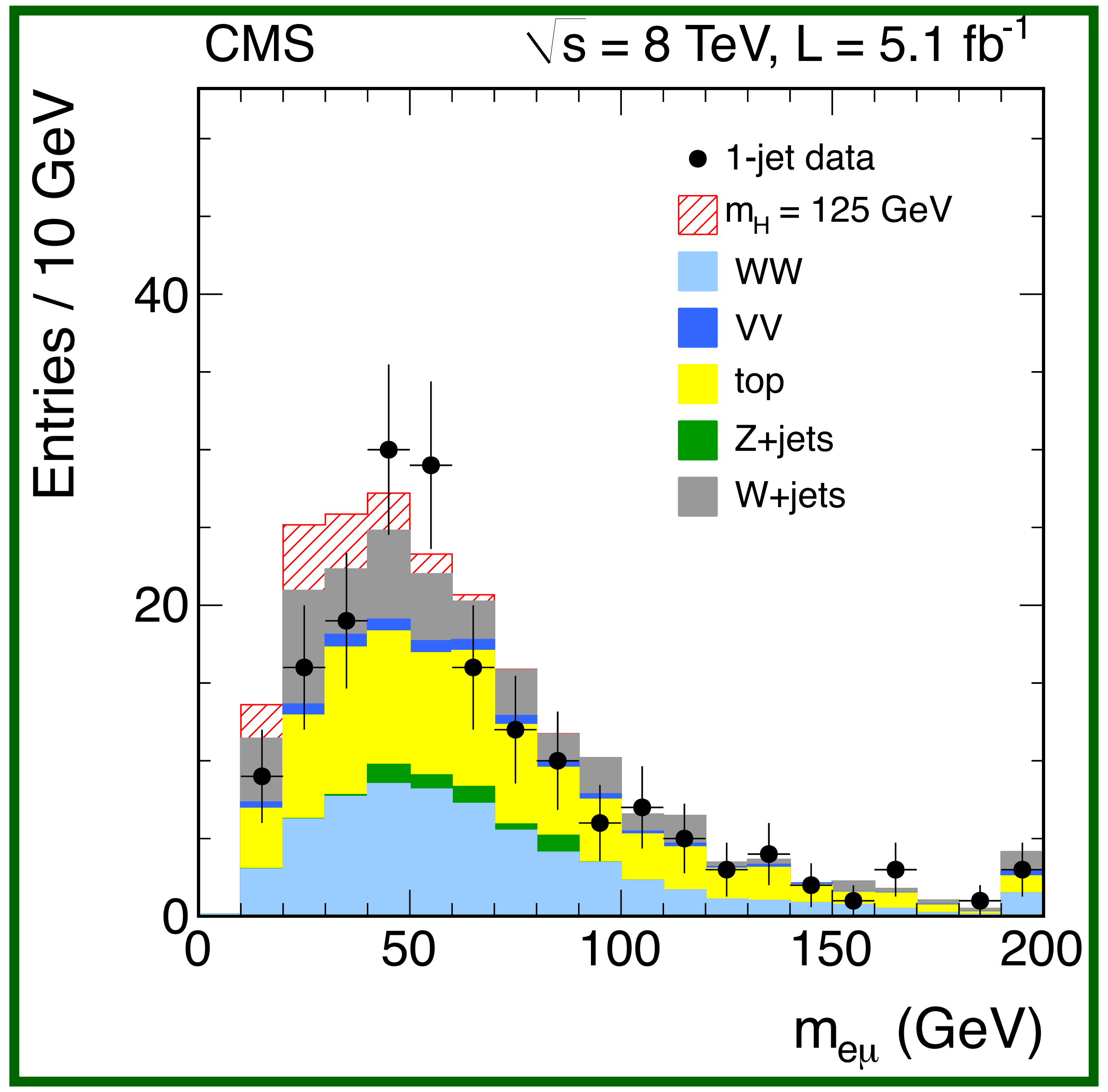
- Small signal yield due to the small BR (0.2%)
- Large background, dominated by $\gamma\gamma$ non-resonant production
- Need to suppress by O(1000) the large $\pi^0 \rightarrow \gamma\gamma$ background
- Excellent resolution: optimal for measurement of the H boson mass

H → ZZ

$H \to WW$

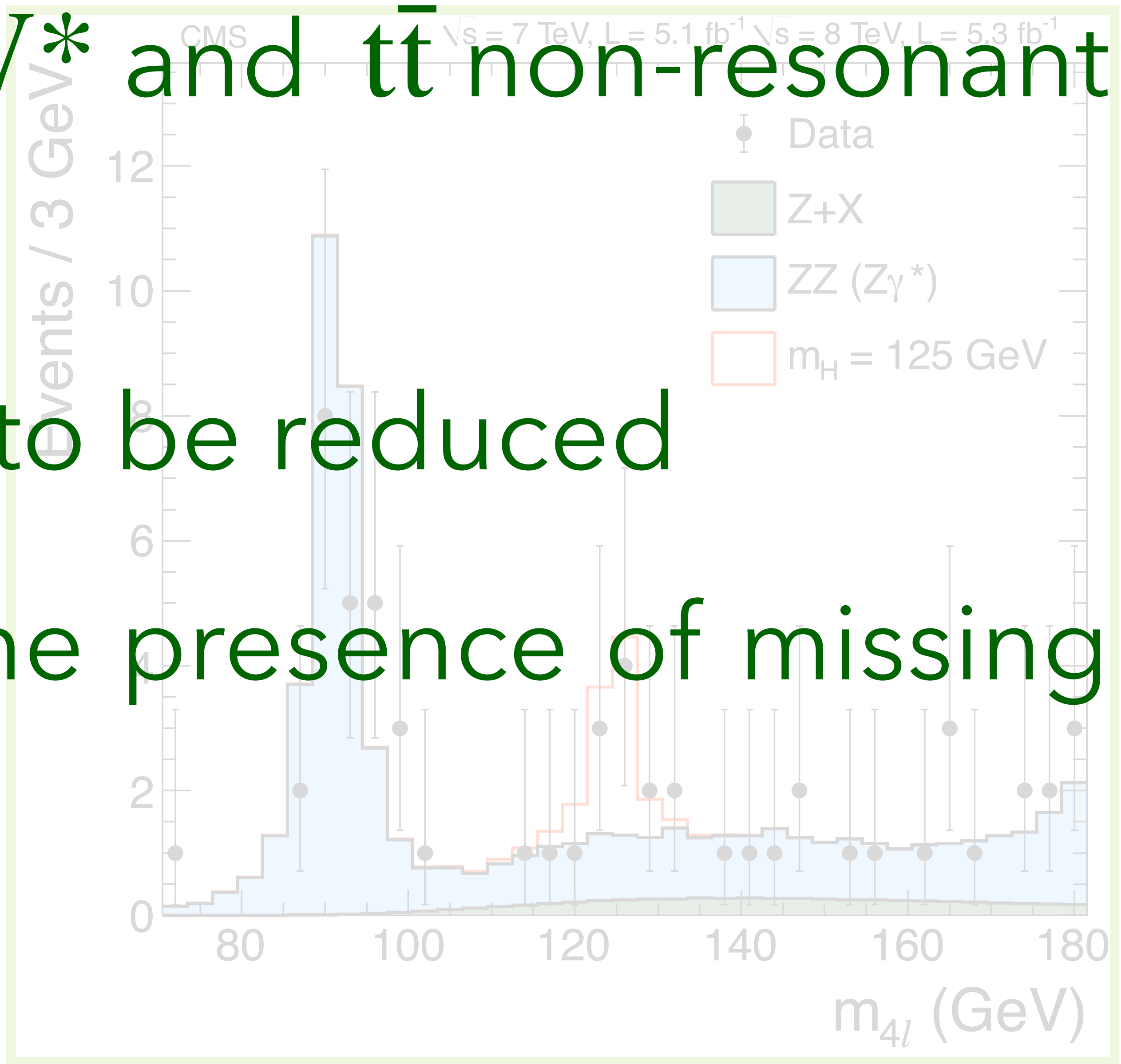
$H \to \gamma\gamma$

$H \to WW$



- Large signal yield due to the large BR (~20%)
- Large backgrounds from WW^* and $t\bar{t}$ non-resonant production
- $W + j$ background challenging to be reduced
- Suboptimal resolution due to the presence of missing energy in the final state

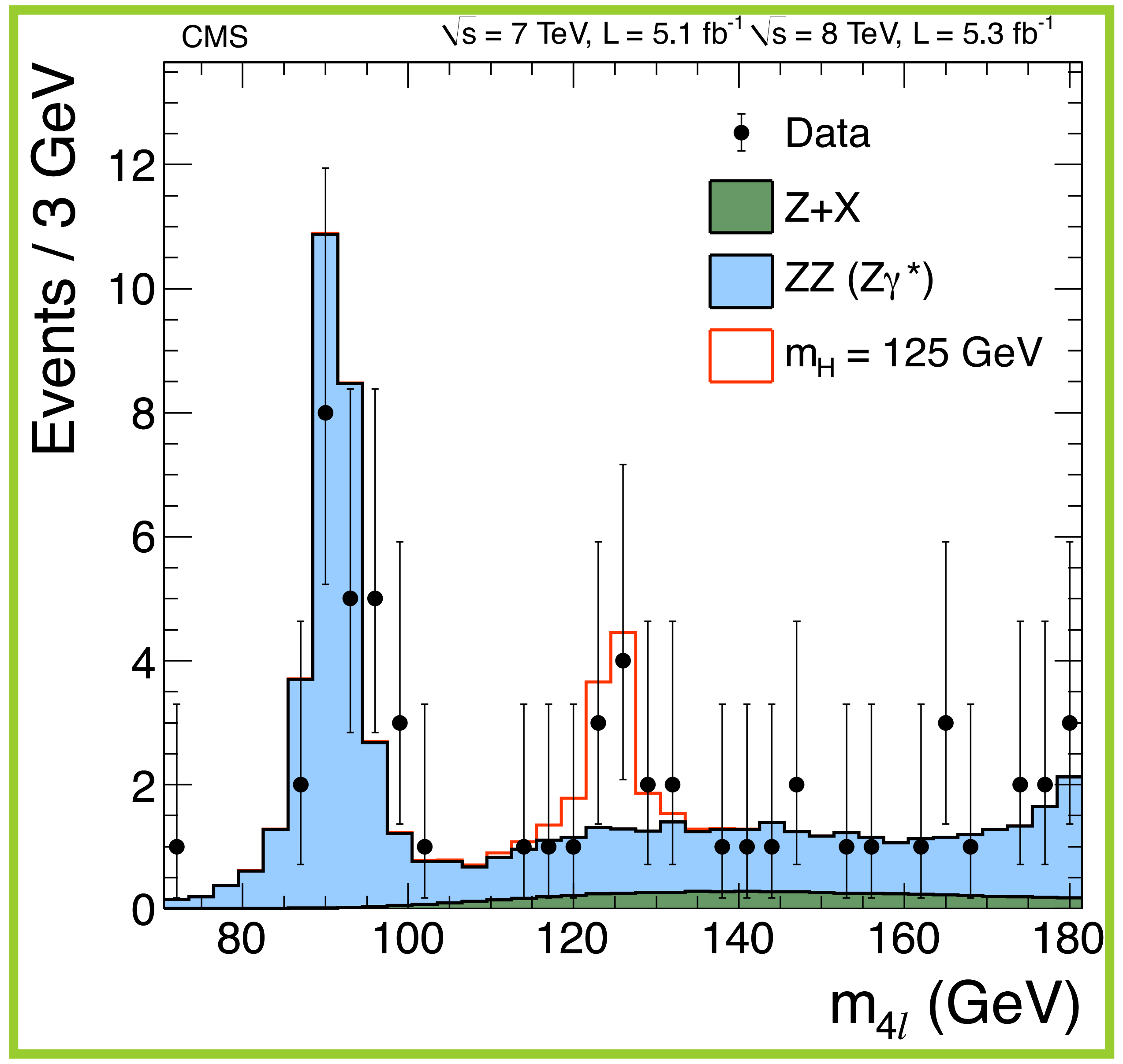
$H \to ZZ$



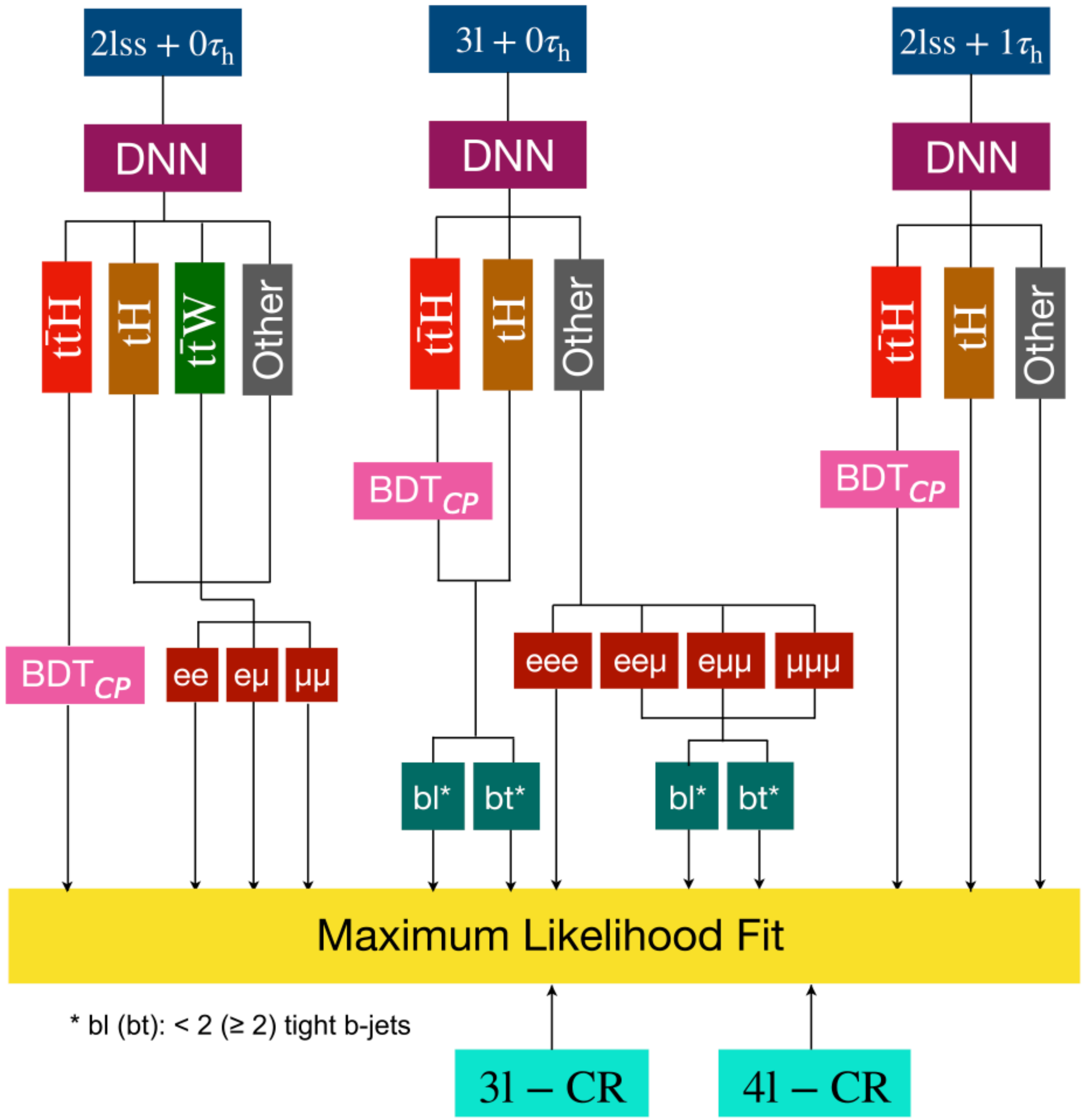
H → ZZ

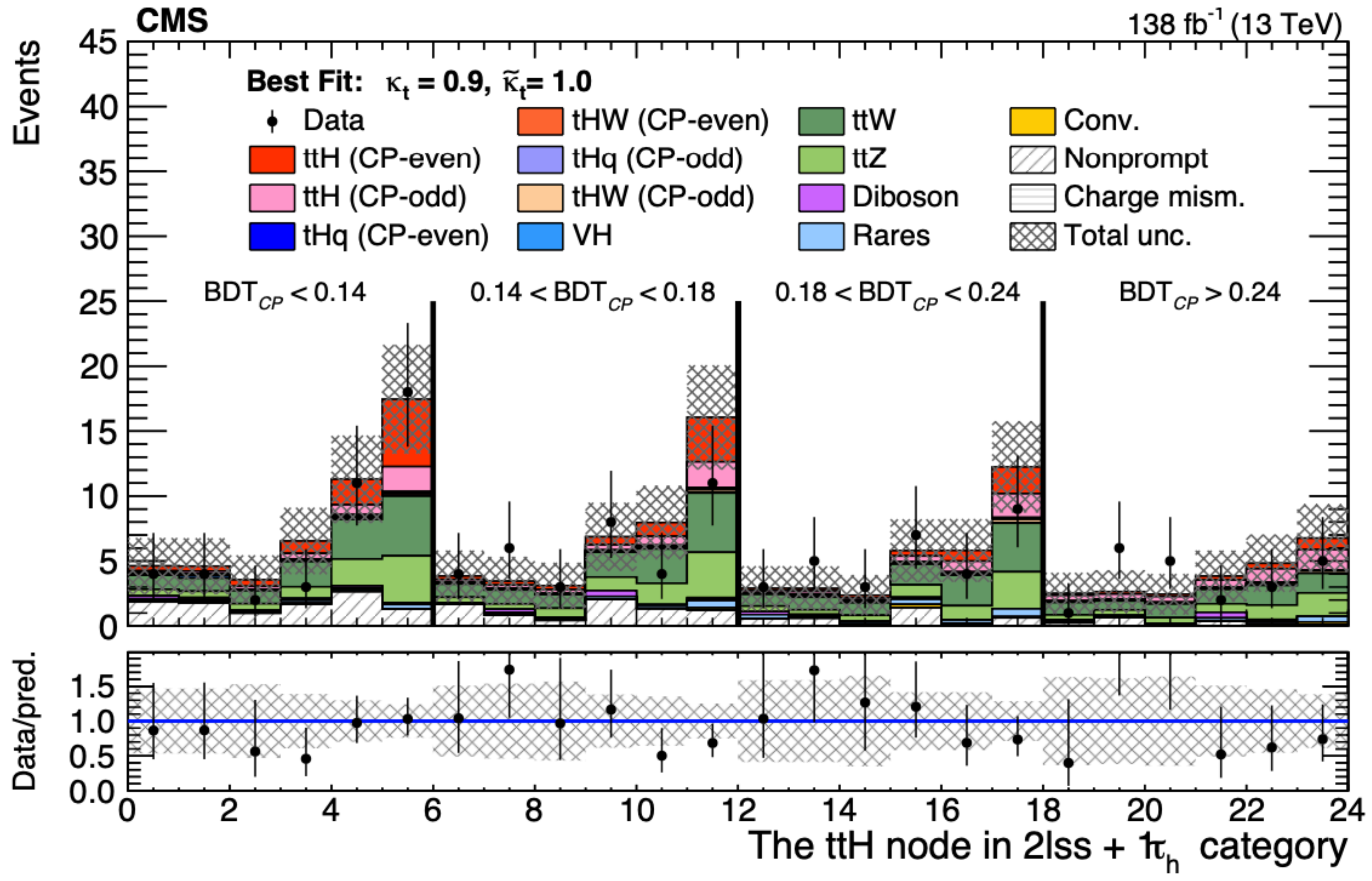
- Small signal yield due to the tiny BR (~2%)
- The irreducible background from non-resonant ZZ production has a small yield under the peak
- Z + j reducible background: challenging to model but tiny yield
- Excellent S/B ratio and mass resolution & completely resolved final state

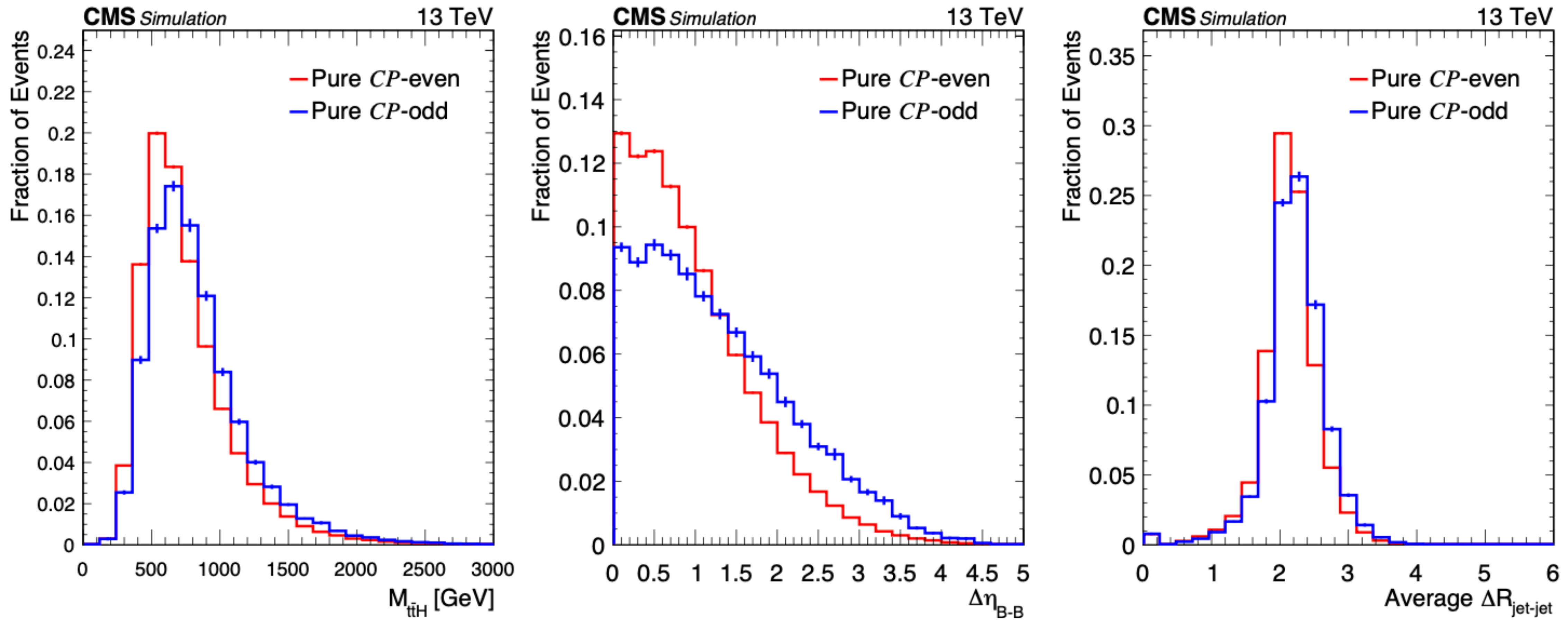
H → ZZ



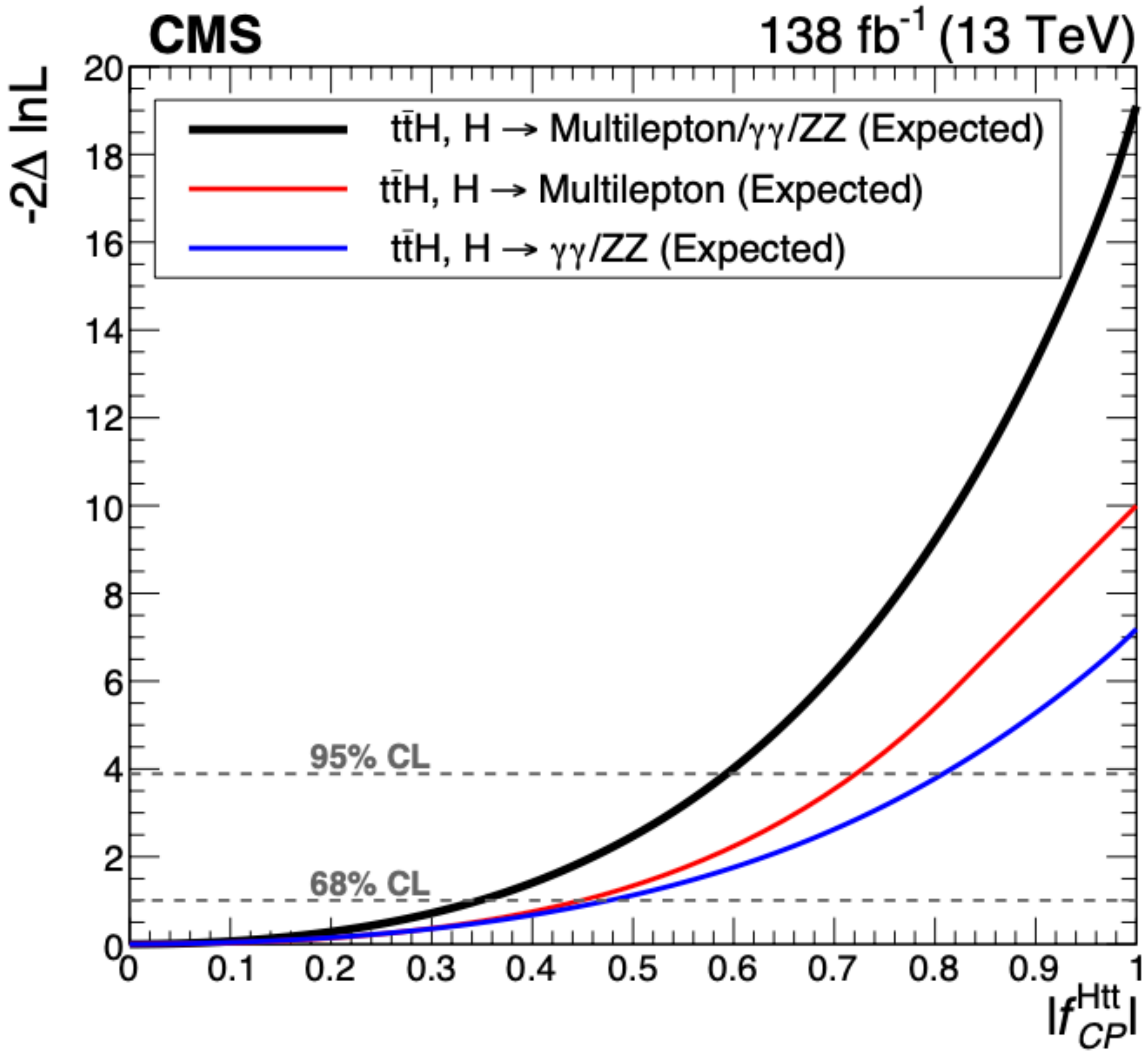
Higgs boson CP properties: ttH

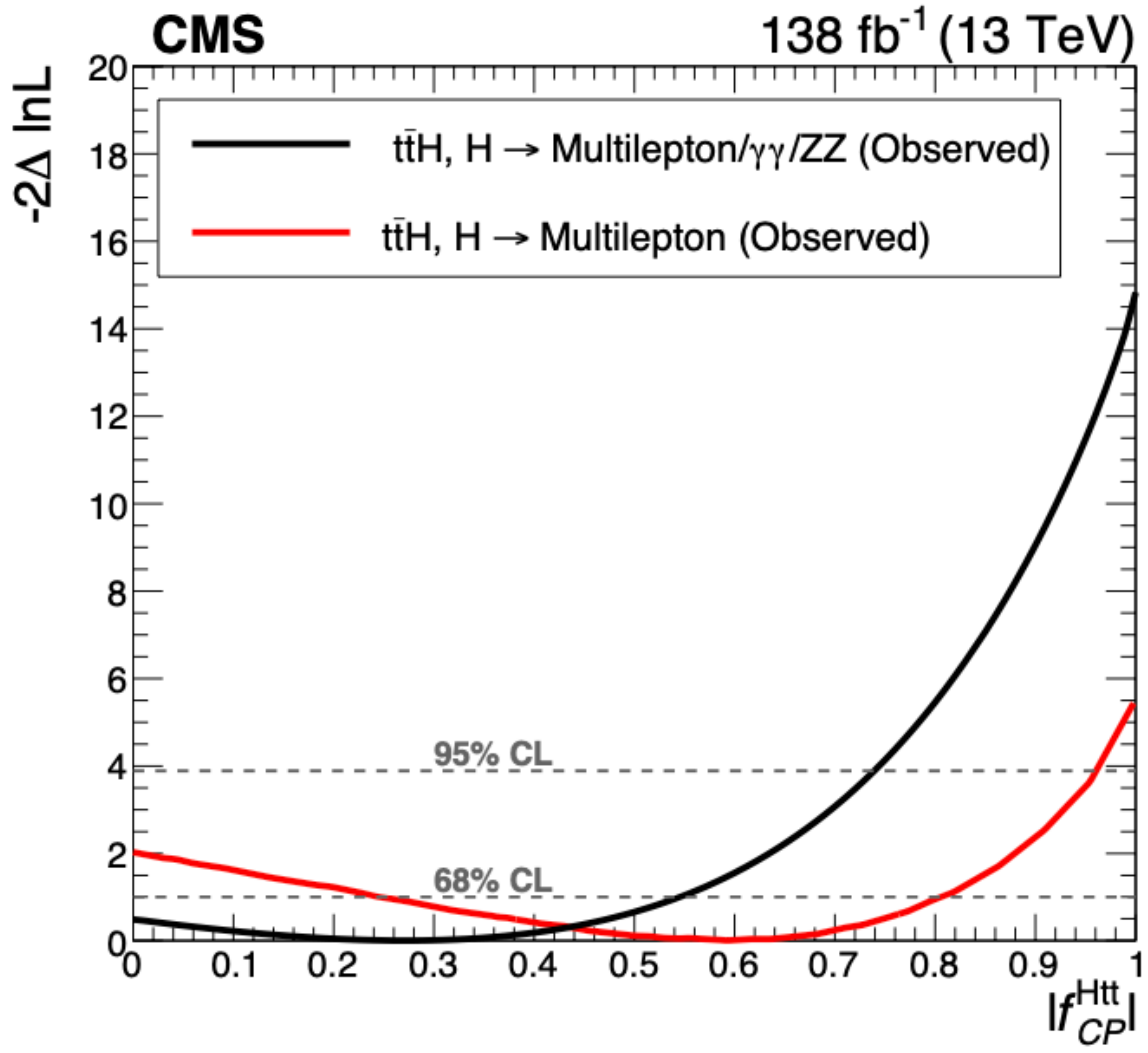






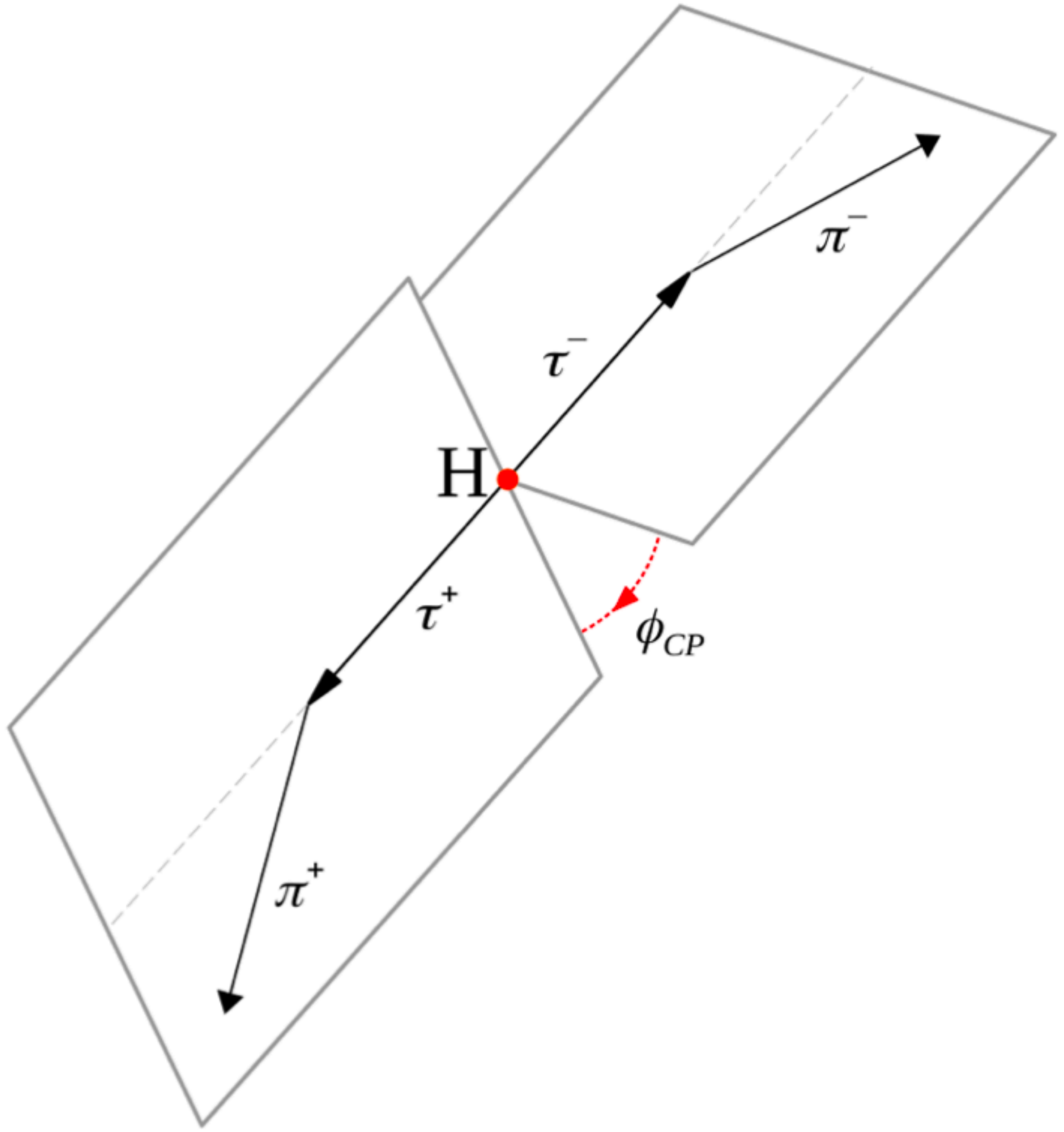
Higgs boson CP properties: ttH

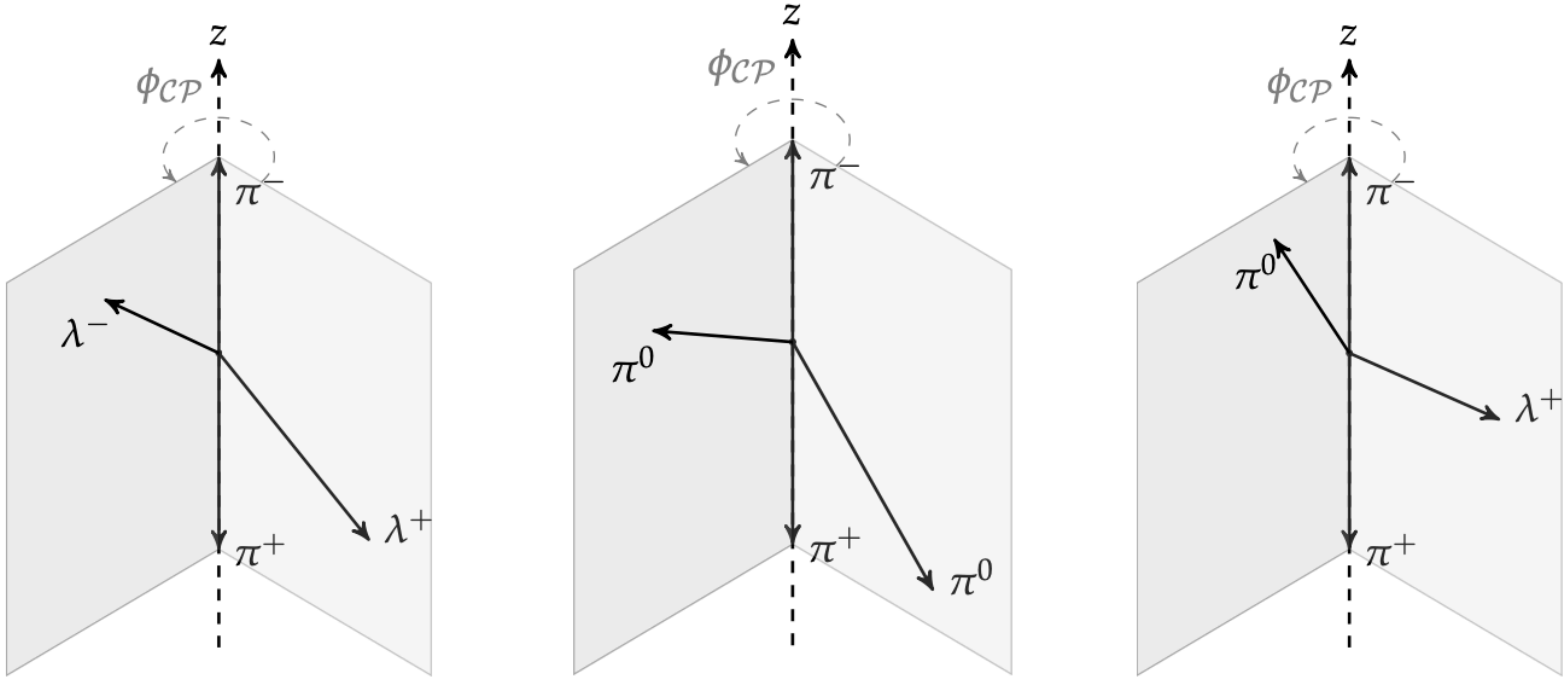




Higgs boson CP properties: $\mathrm{H}\tau\tau$

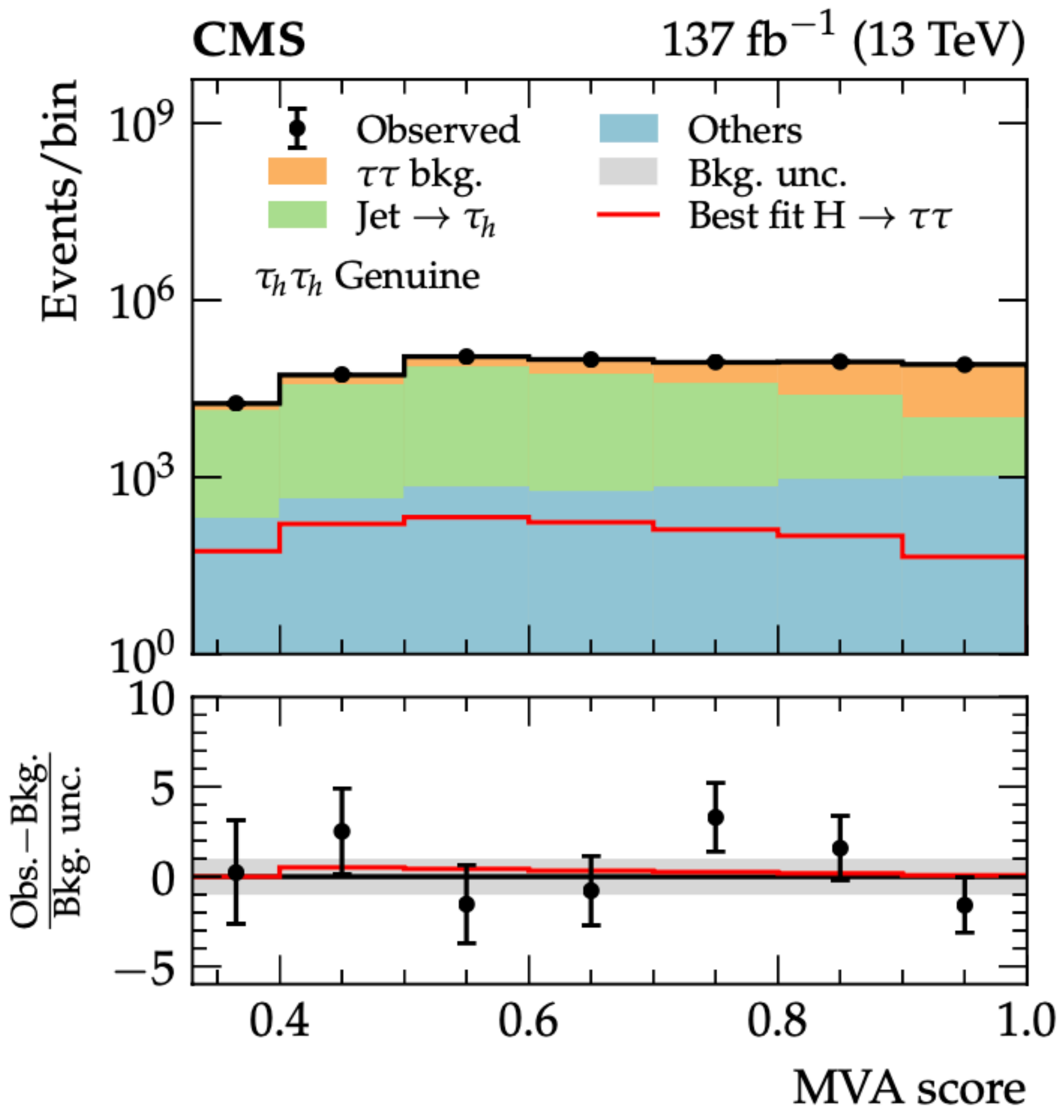
$$\frac{d\Gamma}{d\phi_{CP}}(\mathrm{H} \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{\mathrm{H}\tau\tau}).$$

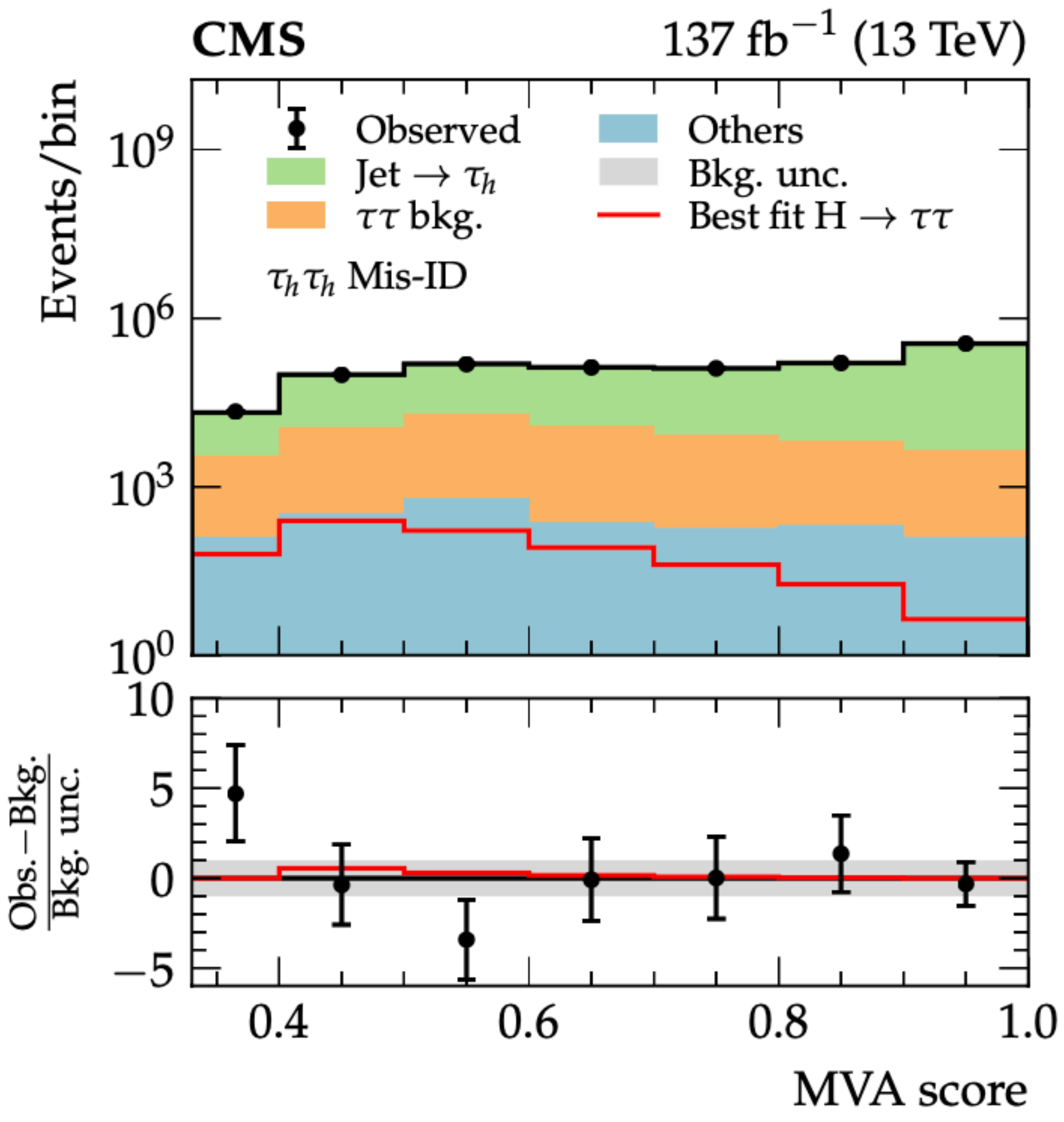




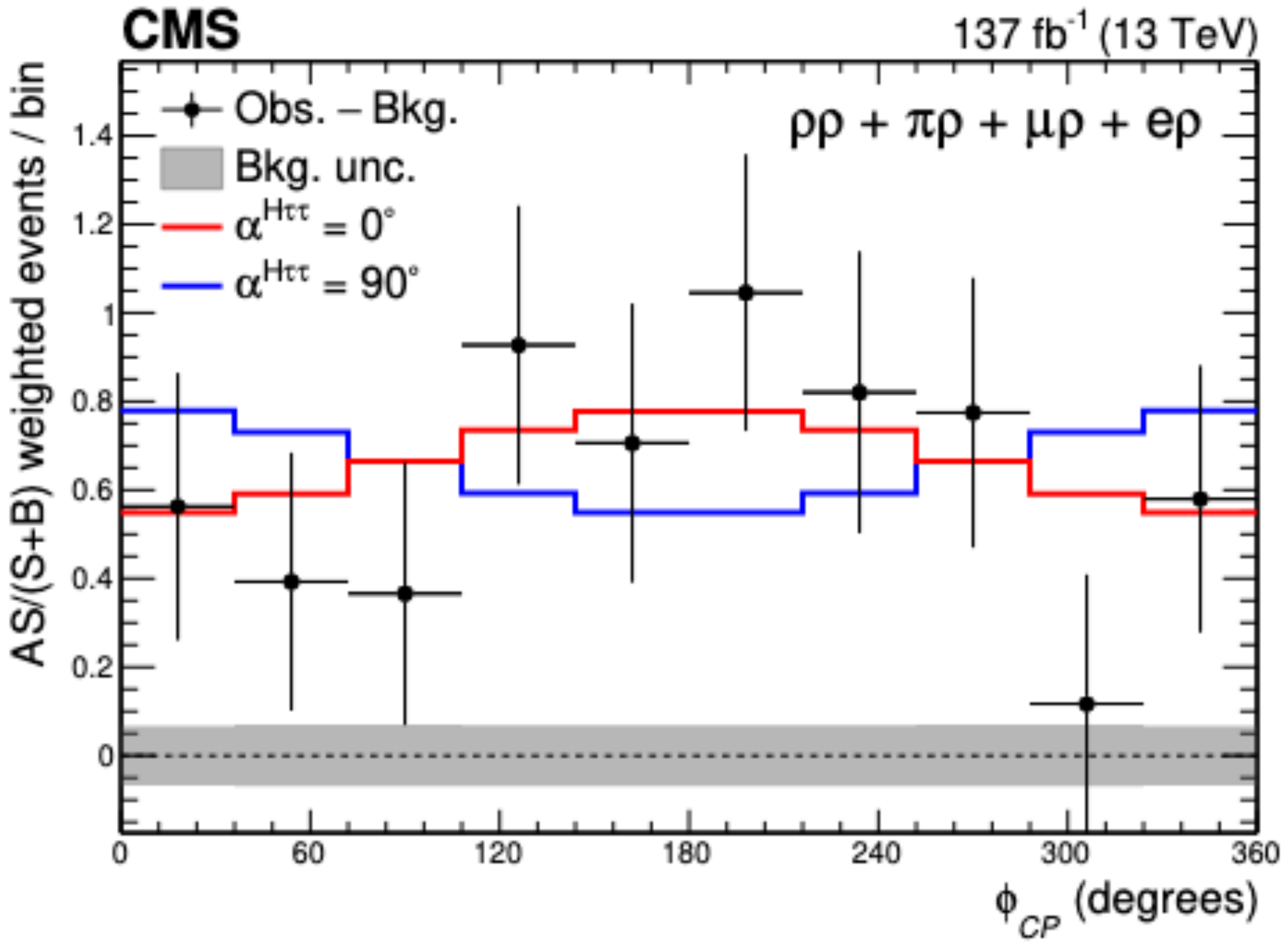
Higgs boson CP properties: $H\tau\tau$

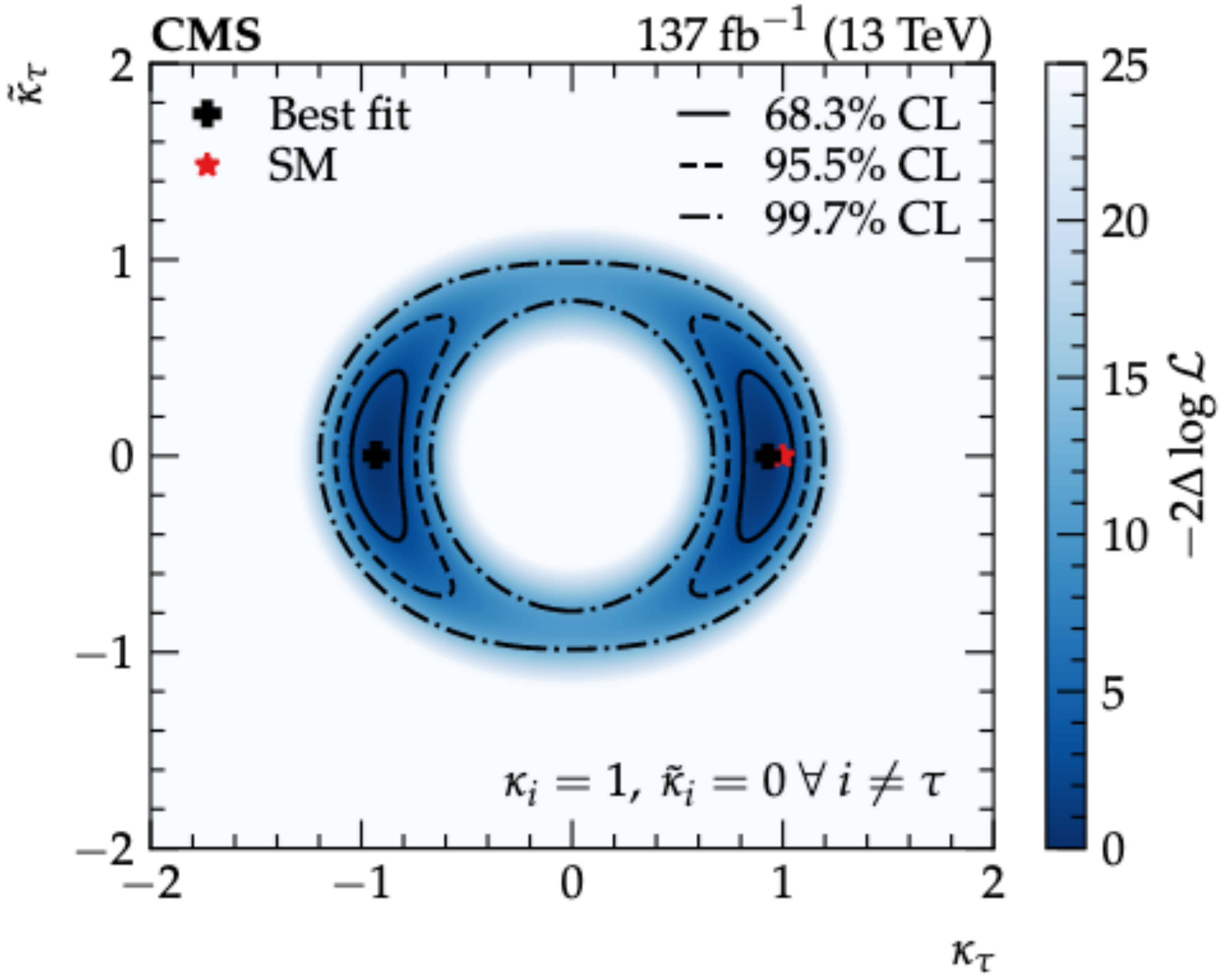
Observable	$\tau_\ell\tau_h$	$\tau_h\tau_h$
p_T of leading τ_h	✓	✓
p_T of trailing τ_h	—	✓
p_T of τ_ℓ	✓	—
p_T of visible di-τ	✓	✓
p_T of di-τ_h + p_T^{miss}	—	✓
p_T of $\tau_\ell\tau_h$ + p_T^{miss}	✓	—
Visible di-τ mass	✓	✓
Di-τ mass (using SVFIT)	✓	✓
Leading jet p_T	✓	✓
Trailing jet p_T	✓	
Jet multiplicity	✓	✓
Dijet invariant mass	✓	✓
Dijet p_T	✓	
Dijet $\lvert\Delta\eta\rvert$	✓	
p_T^{miss}	✓	✓

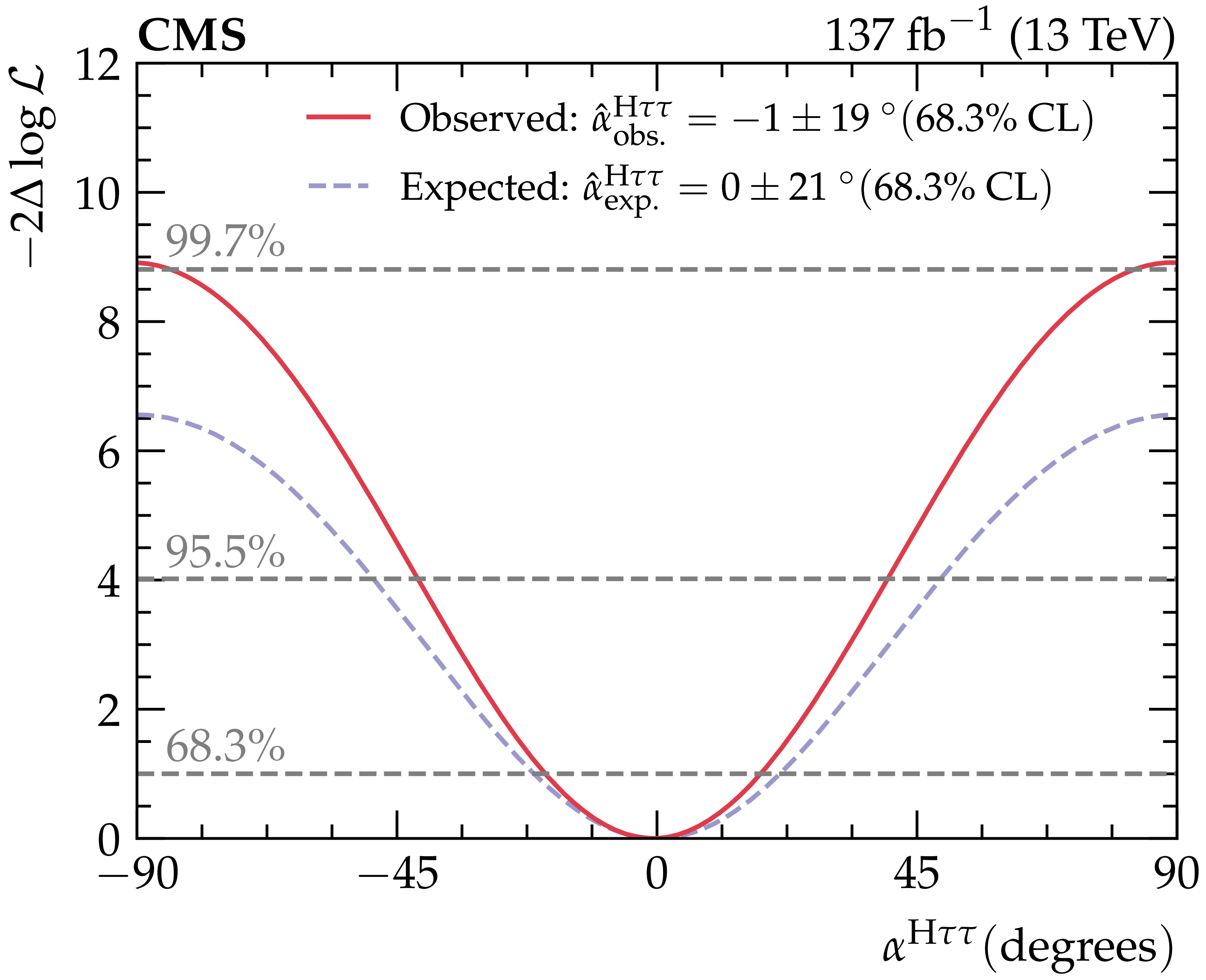




Higgs boson CP properties: $H\tau\tau$

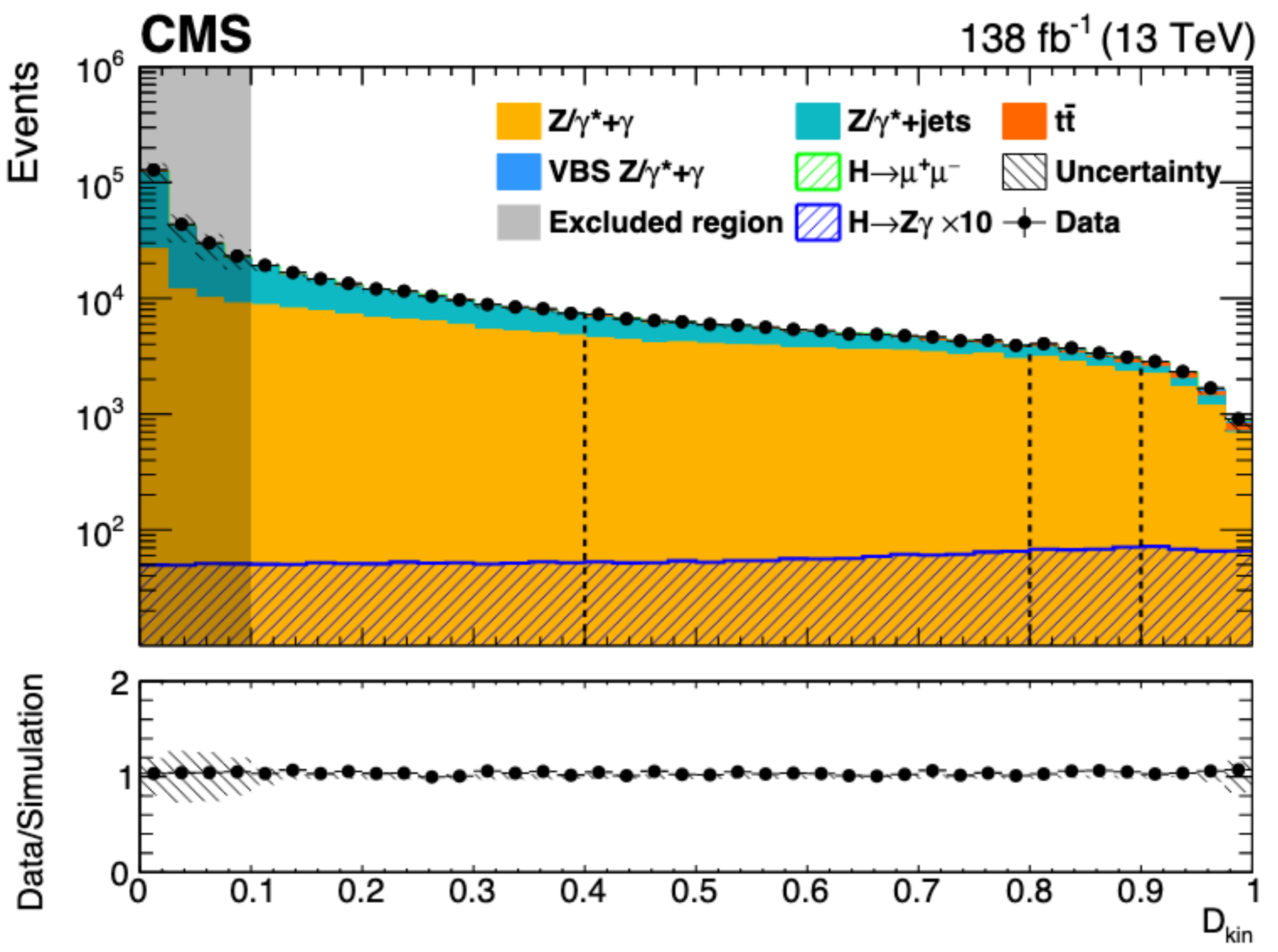


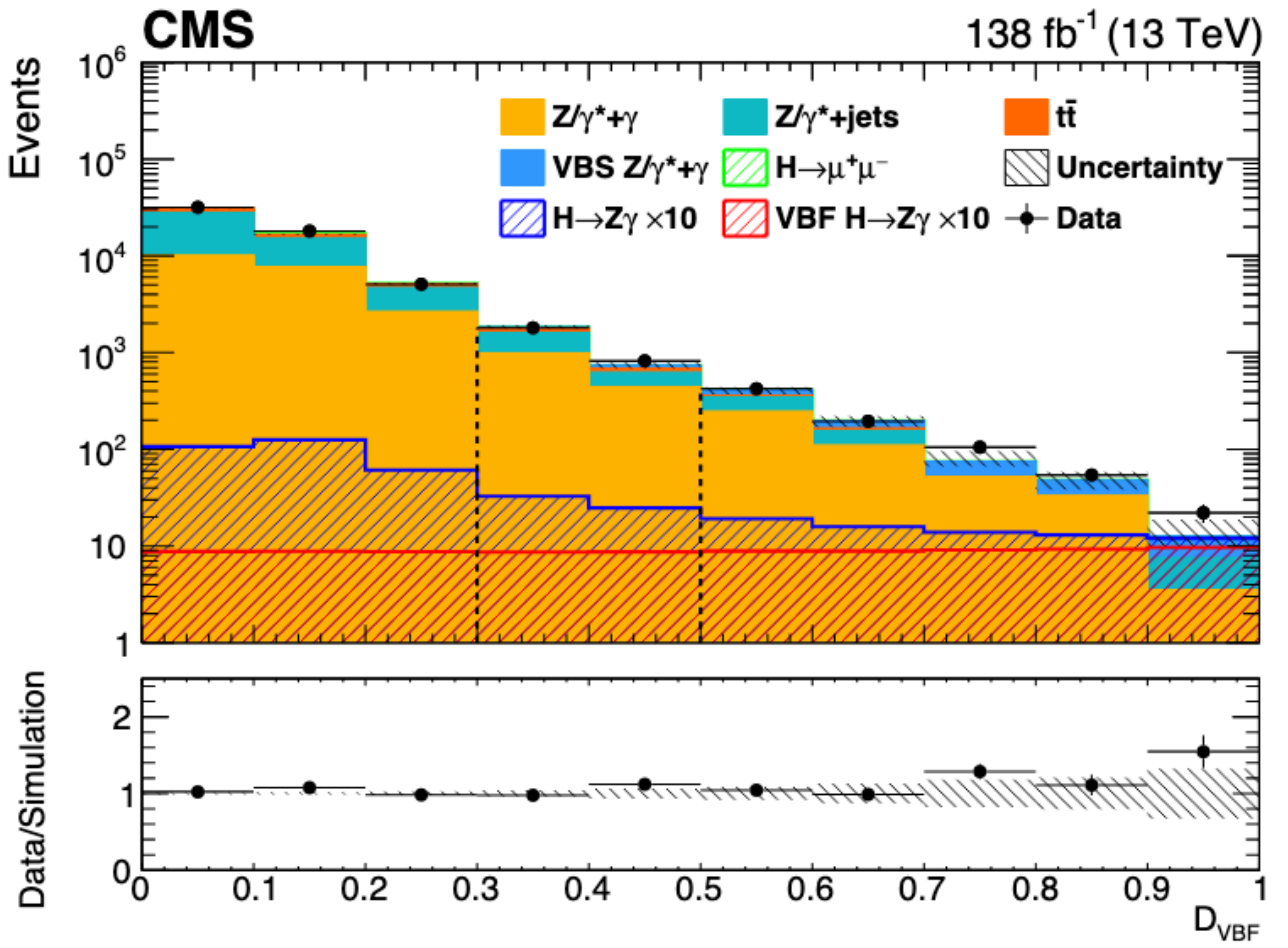




The power of Run-II : $HZ\gamma$

Sources	Uncertainty (%)	Year-to-year correlation
	Normalization	
Theoretical		
– $\mathcal{B}(H \to Z\gamma)$	5.7	Yes
– ggH cross section (μ_F, μ_R)	3.9	Yes
– ggH cross section (α_S)	2.6	Yes
– ggH cross section (PDF)	1.9	Yes
– VBF cross section (μ_F, μ_R)	0.4	Yes
– VBF cross section (α_S)	0.5	Yes
– VBF cross section (PDF)	2.1	Yes
– WH cross section (μ_F, μ_R)	$^{+0.6}_{-0.7}$	Yes
– WH cross section (PDF)	1.7	Yes
– ZH cross section (μ_F, μ_R)	$^{+3.8}_{-3.1}$	Yes
– ZH cross section (PDF)	1.3	Yes
– WH/ZH cross section (α_S)	0.9	Yes
– $t\bar{t}H$ cross section (μ_F, μ_R)	$^{+5.8}_{-9.2}$	Yes
– $t\bar{t}H$ cross section (α_S)	2.0	Yes
– $t\bar{t}H$ cross section (PDF)	3.0	Yes
Underlying event and parton shower	3.7–4.4	Partial
Integrated luminosity	1.2–2.5	Partial
L1 trigger	0.1–0.4	No
Trigger		
– Electron channel	0.9–1.9	No
– Muon channel	0.1–0.4	No
Photon identification and isolation	0.2–5.0	Yes
Lepton identification and isolation		
– Electron channel	0.5–0.7	Yes
– Muon channel	0.3–0.4	Yes
Pileup	0.4–1.0	Yes
Kinematic BDT	2.5–3.7	Yes
VBF BDT	5.9–14.0	Yes
	Shape parameters	
Photon energy and momentum		
– Signal mean	0.1–0.4	Yes
– Signal resolution	3.1–5.9	Yes
Lepton energy and momentum		
– Signal mean	0.007	Yes
– Signal resolution	0.007–0.010	Yes





The power of Run-II : HZγ

Sources	Uncertainty (%)	Year-to-year correlation
	Normalization	
Theoretical		
– $\mathcal{B}(H \to Z\gamma)$	5.7	Yes
– ggH cross section (μ_F, μ_R)	3.9	Yes
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– ggH cross section (PDF)	1.9	Yes
– VBF cross section (μ_F, μ_R)	0.4	Yes
– VBF cross section (α_S)	0.5	Yes
– VBF cross section (PDF)	2.1	Yes
– WH cross section (μ_F, μ_R)	$^{+0.6}_{-0.7}$	Yes
– WH cross section (PDF)	1.7	Yes
– ZH cross section (μ_F, μ_R)	$^{+3.8}_{-3.1}$	Yes
– ZH cross section (PDF)	1.3	Yes
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Trigger		
– Electron channel	0.9–1.9	No
– Muon channel	0.1–0.4	No
Photon identification and isolation	0.2–5.0	Yes
Lepton identification and isolation		
– Electron channel	0.5–0.7	Yes
– Muon channel	0.3–0.4	Yes
Pileup	0.4–1.0	Yes
Kinematic BDT	2.5–3.7	Yes
VBF BDT	5.9–14.0	Yes
	Shape parameters	
Photon energy and momentum		
– Signal mean	0.1–0.4	Yes
– Signal resolution	3.1–5.9	Yes
Lepton energy and momentum		
– Signal mean	0.007	Yes
– Signal resolution	0.007–0.010	Yes