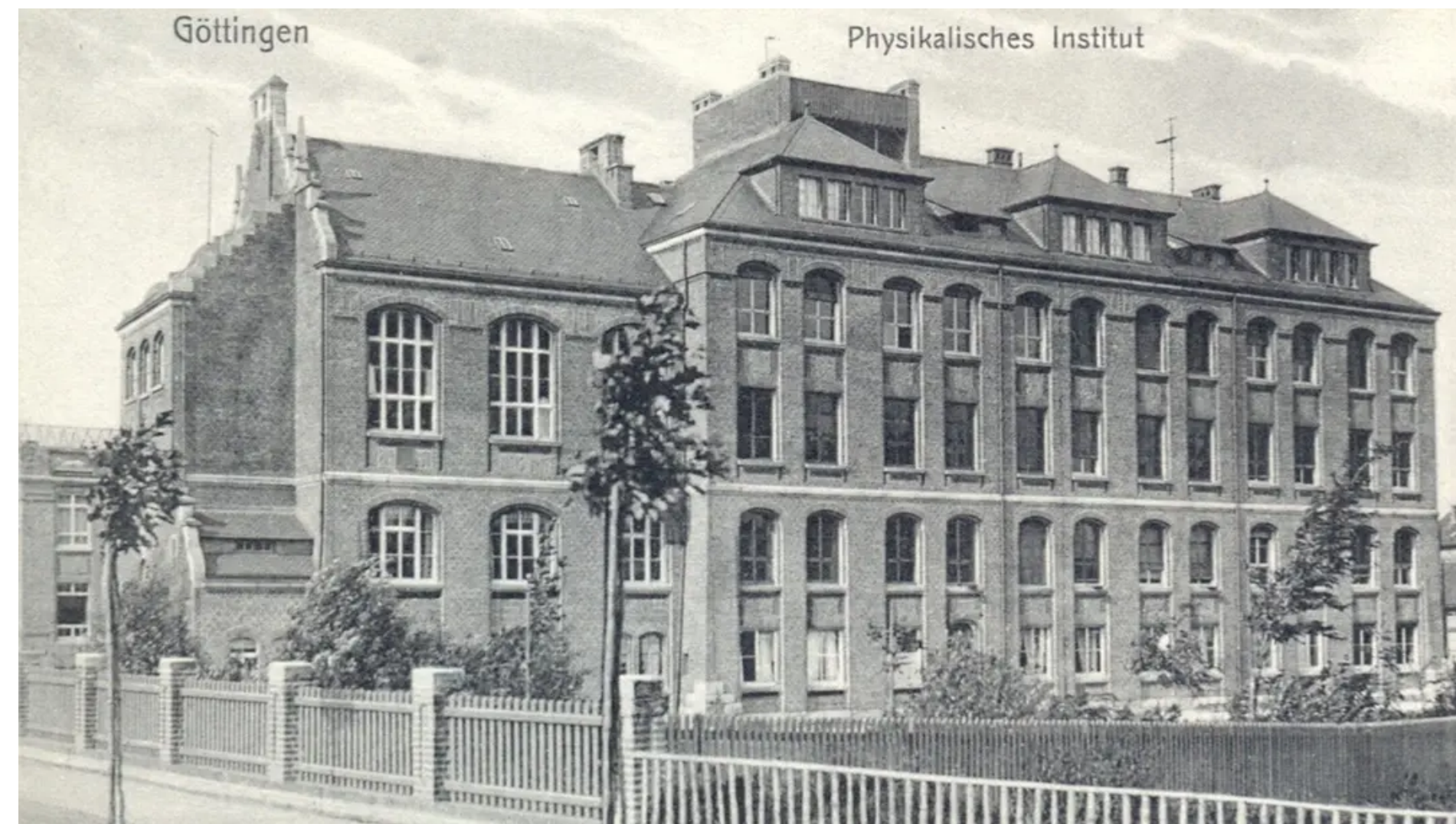


The Higgs boson revealed:

What current experiments teach us about this unique quantum state



2nd DPG Fall Meeting

Symposium: Quantum Physics at the High-Energy Frontier – The Higgs Boson in the Standard Model and Beyond

Georg-August-Universität Göttingen

10. 9. 2025

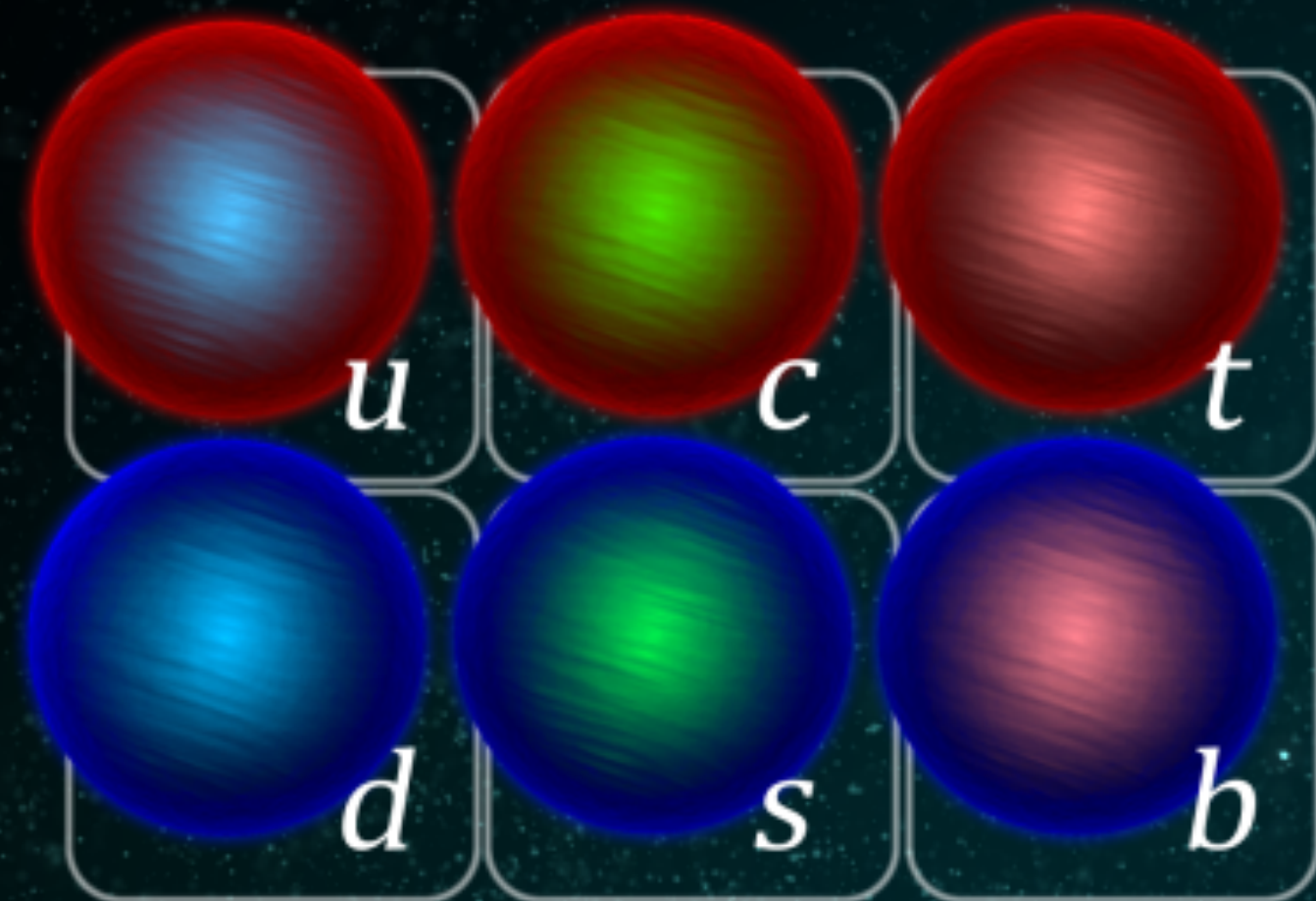
With funding from the:



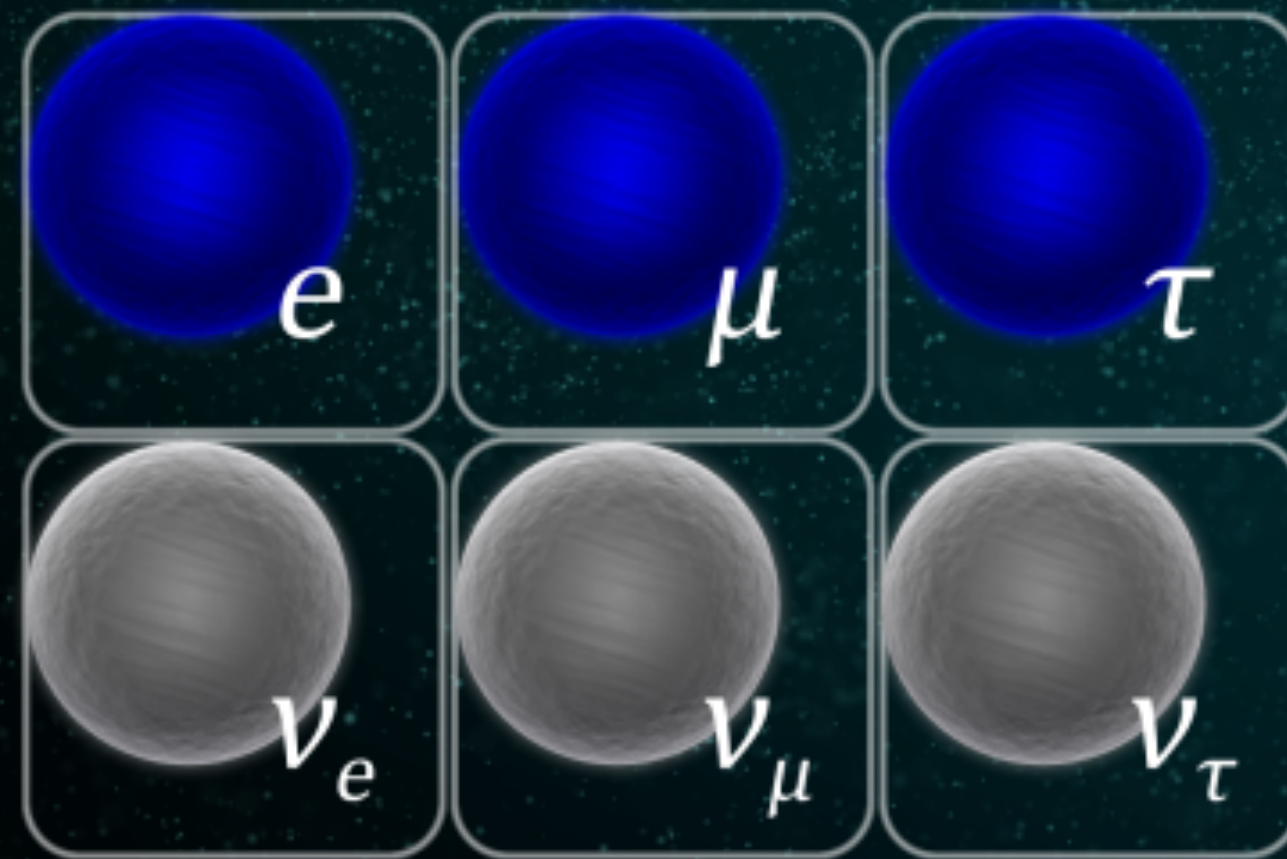
Karsten Köneke
II. Physikalisches Institut
Georg-August-Universität Göttingen
karsten.koenেকে@cern.ch



Recap: Problem of Mass

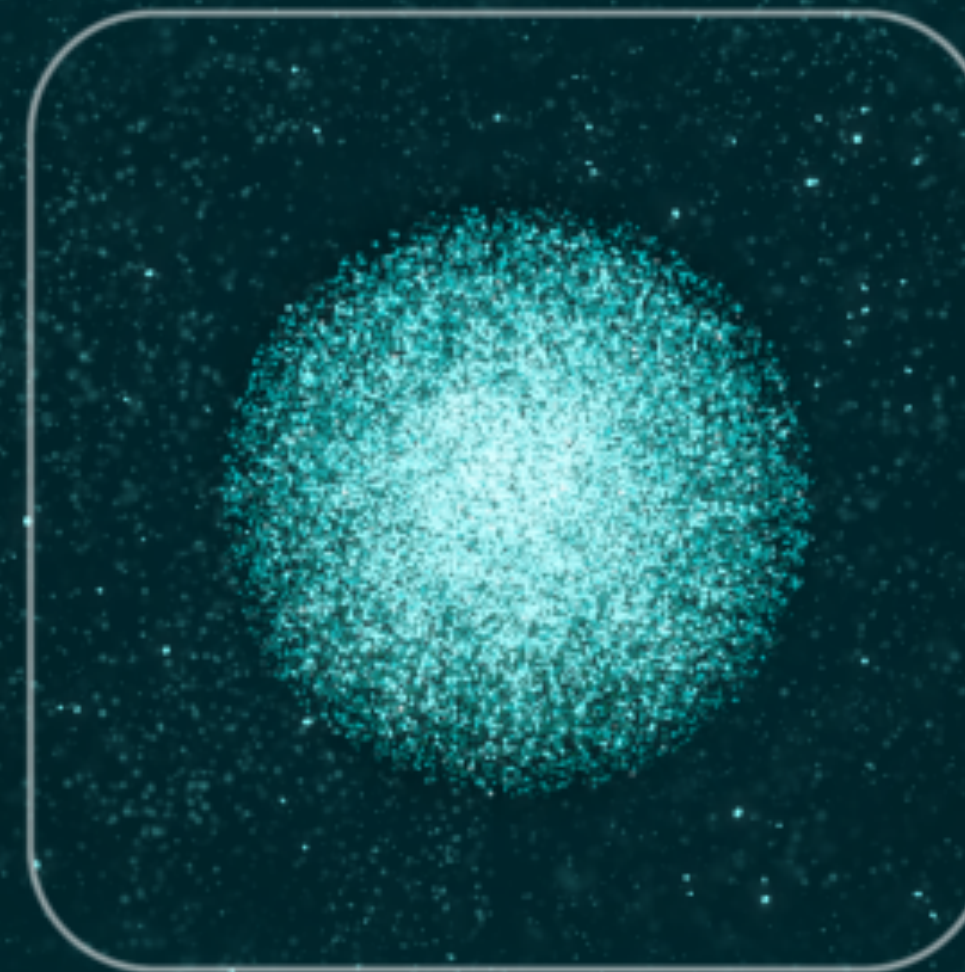


Quarks



Leptons

- Theoretical description $\Rightarrow$ **massless particles!**
- New field (Higgs field) postulated, permeates vacuum



Higgs boson



Forces

- Masses generated via *interaction of particles with Higgs field*



Consequences



- Higgs boson with mass:

$$m_H = \sqrt{2\lambda}v$$

not predicted!



Consequences



- Higgs boson with mass:

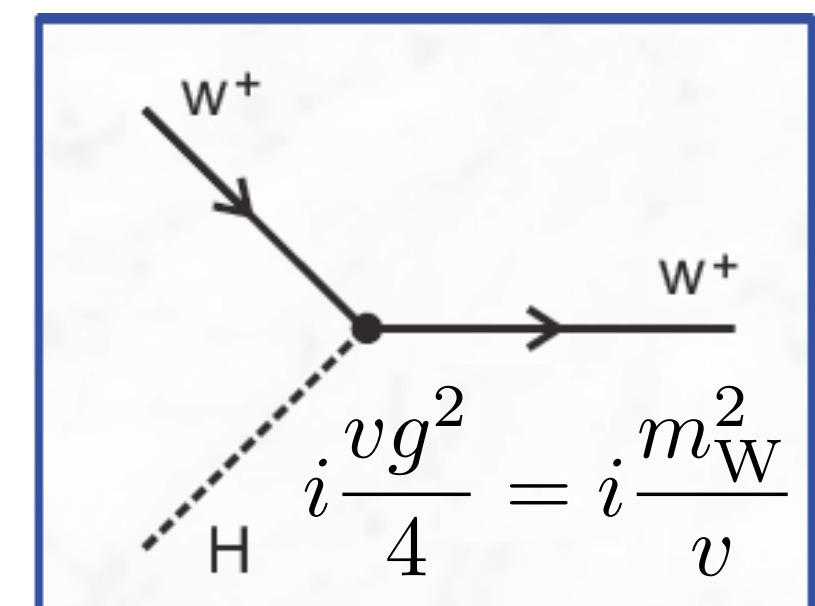
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- W boson mass and interaction:

$$m_W = \frac{vg}{2}$$

direct connection





Consequences



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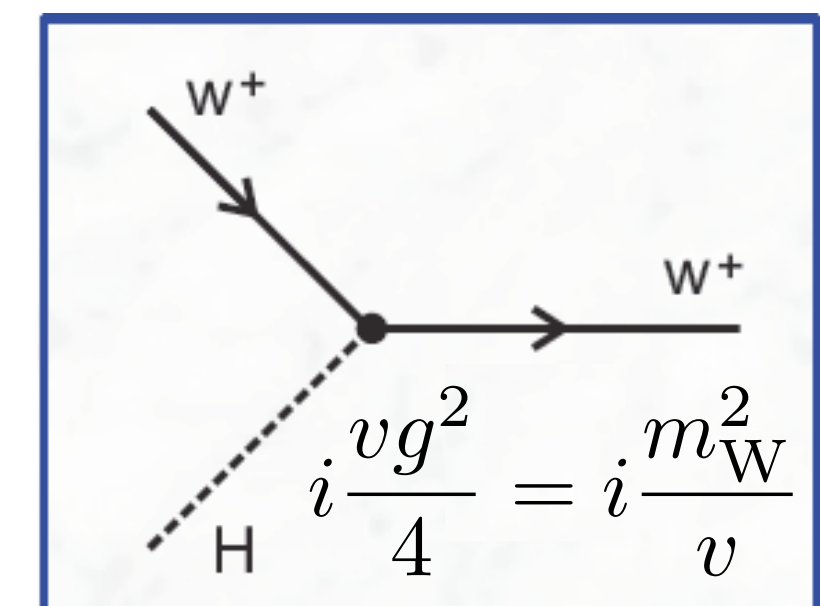
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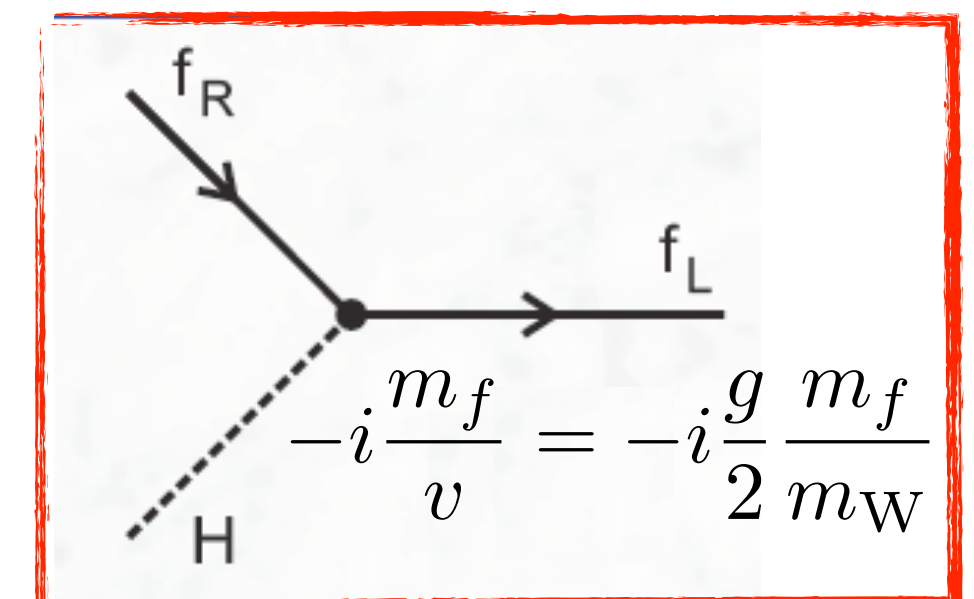
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- Fermion masses and Yukawa interactions:

$$m_f = \frac{y_f v}{\sqrt{2}}$$

direct connection





Consequences



- Higgs boson with mass:

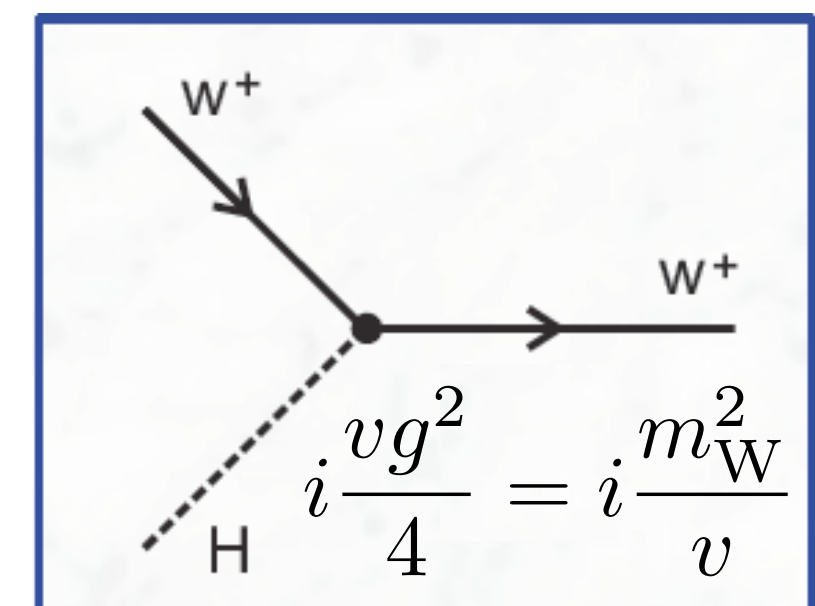
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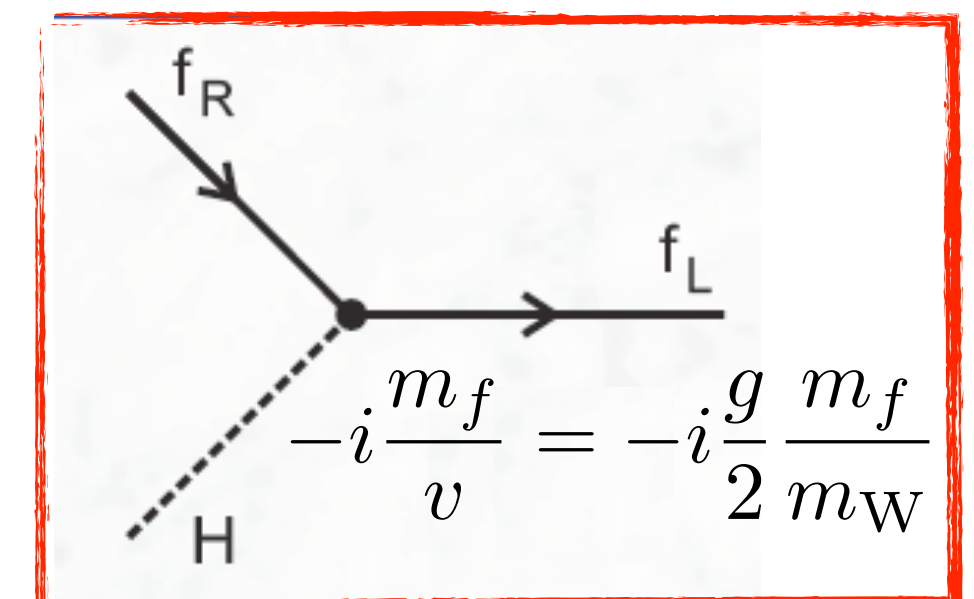
direct connection



- Fermion masses and Yukawa interactions:

$$m_f = \frac{y_f v}{\sqrt{2}}$$

direct connection



- Higgs potential:

HH production

$$\text{In SM: } \lambda = \frac{1}{2} m_H^2 / v^2$$

$$-\mu^2 \phi^2 - \lambda \phi^4$$

H potential as in SM?



The beating heart of the Standard Model



- Higgs boson: not just another particle!

$$\mathcal{L}_{\text{Higgs}} = T - V$$

Higgs field

$$\mathcal{L}_{\text{Higgs}} = (D_{\mu}\phi)^2 - \mu^2\phi^2 - \lambda\phi^4$$

'Covariant' derivative

Kinetic term:
• Masses of W and Z

-Higgs potential
Higgs mass Higgs self-interaction



The beating heart of the Standard Model



- Higgs boson: not just another particle!

$$\mathcal{L}_{\text{Higgs}} = T - V + \mathcal{L}_{\text{Yukawa}}$$

$$\mathcal{L}_{\text{Higgs}} = (D_{\mu}\phi)^2 - \mu^2\phi^2 - \lambda\phi^4 + y_f\phi\psi^2$$

Higgs field (points to ϕ)

'Covariant' derivative (points to D_{μ})

Kinetic term:
• Masses of W and Z

-Higgs potential
Higgs mass Higgs self-interaction

Fermion (points to ψ)

Yukawa term:
• Fermion masses



The beating heart of the Standard Model



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Higgs field

Fermion

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'Covariant'
derivative

Kinetic term:

- Masses of W and Z

- CP violation?

- Dark Matter?

-Higgs potential

Higgs mass

Higgs self-
interaction

- Naturalness?
- Hierarchy problem

- Vacuum stability?
- Baryogenesis?

Yukawa term:

- Fermion masses

- Flavor structure

- CP violation?

- Dark Matter?



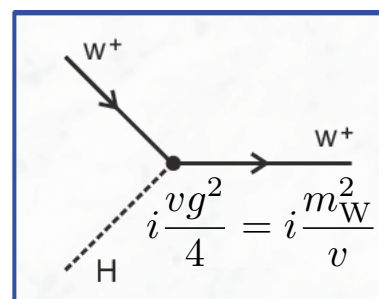
Mass $\sim$ Coupling Strength



$$\mathcal{L}_{\text{Higgs}} = \boxed{(D_\mu \phi)^2} - \mu^2 \phi^2 - \lambda \phi^4 + \boxed{y_f \phi \psi^2}$$

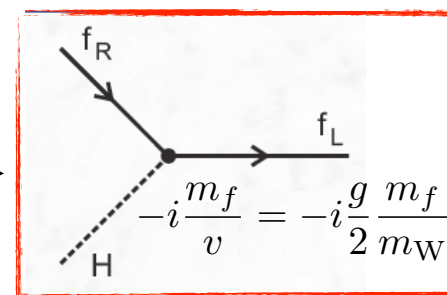
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direct connection

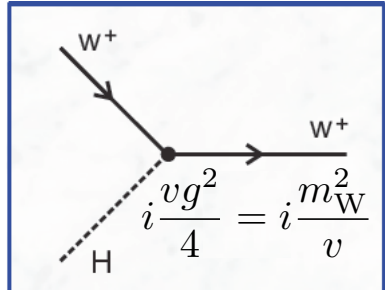


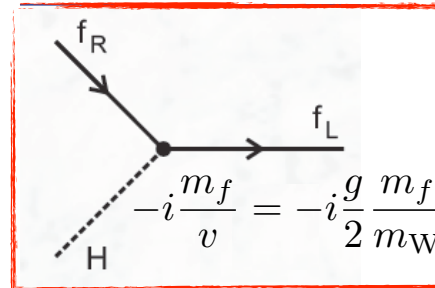


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$m_W = \frac{vg}{2}$ $\longleftrightarrow$ direct connection 

$m_f = \frac{y_f v}{\sqrt{2}}$ $\longleftrightarrow$ direct connection 

- New **Quantum** concept of *mass*!
 - After classical Newton and Einstein



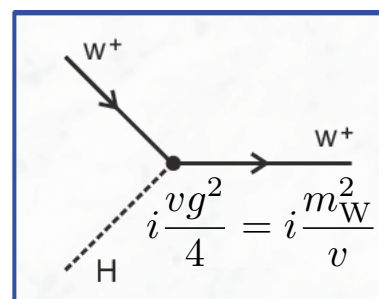
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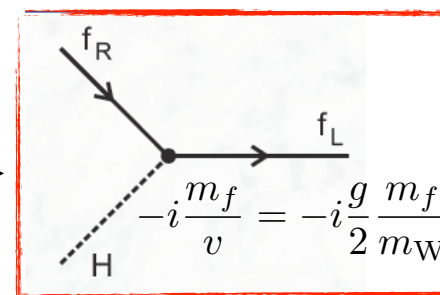
$$m_W = \frac{vg}{2}$$

direct connection

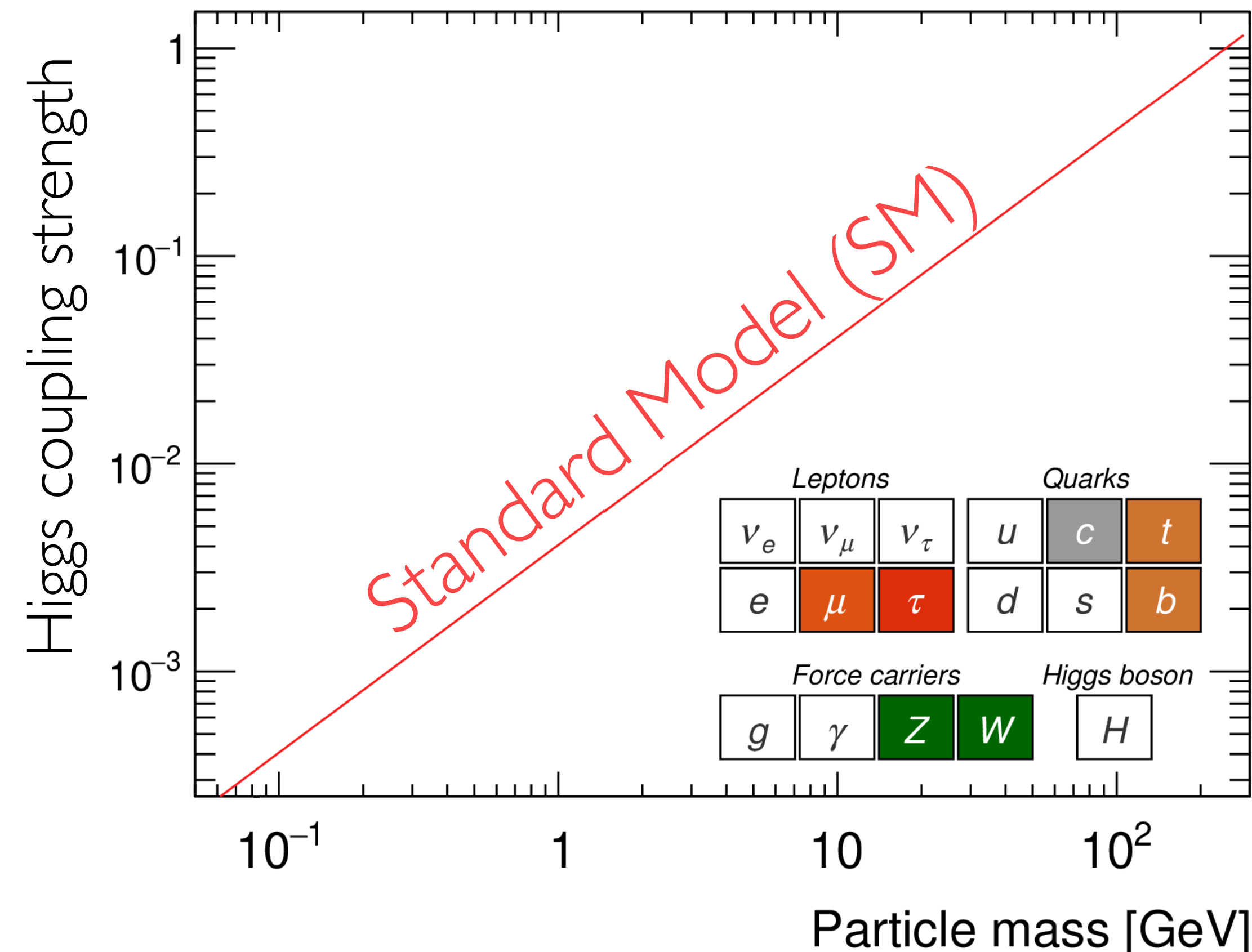


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direct connection



- New **Quantum** concept of *mass*!
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Assumption:

- Higgs boson couples only to SM particles, i.e. no “beyond SM” (BSM) physics
- effective couplings to photons and gluons, and Higgs-boson width resolved using SM assumptions



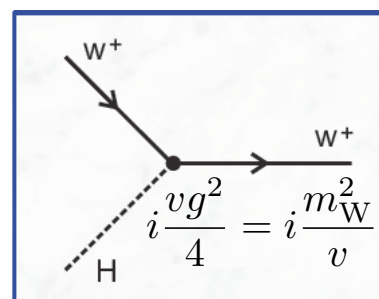
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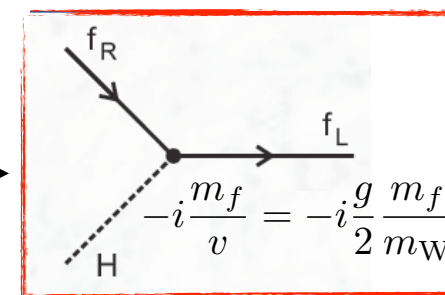
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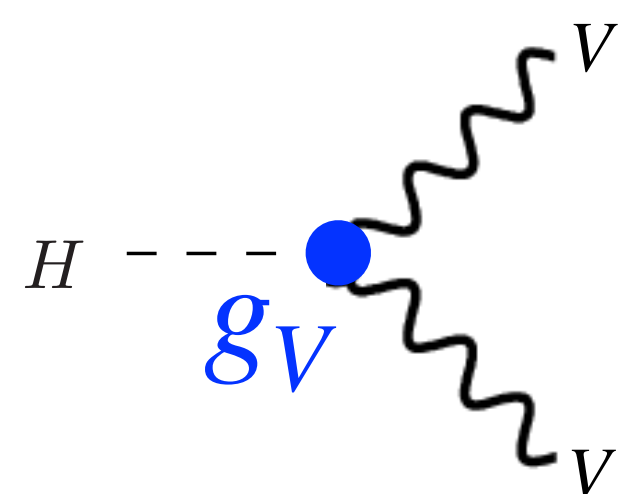
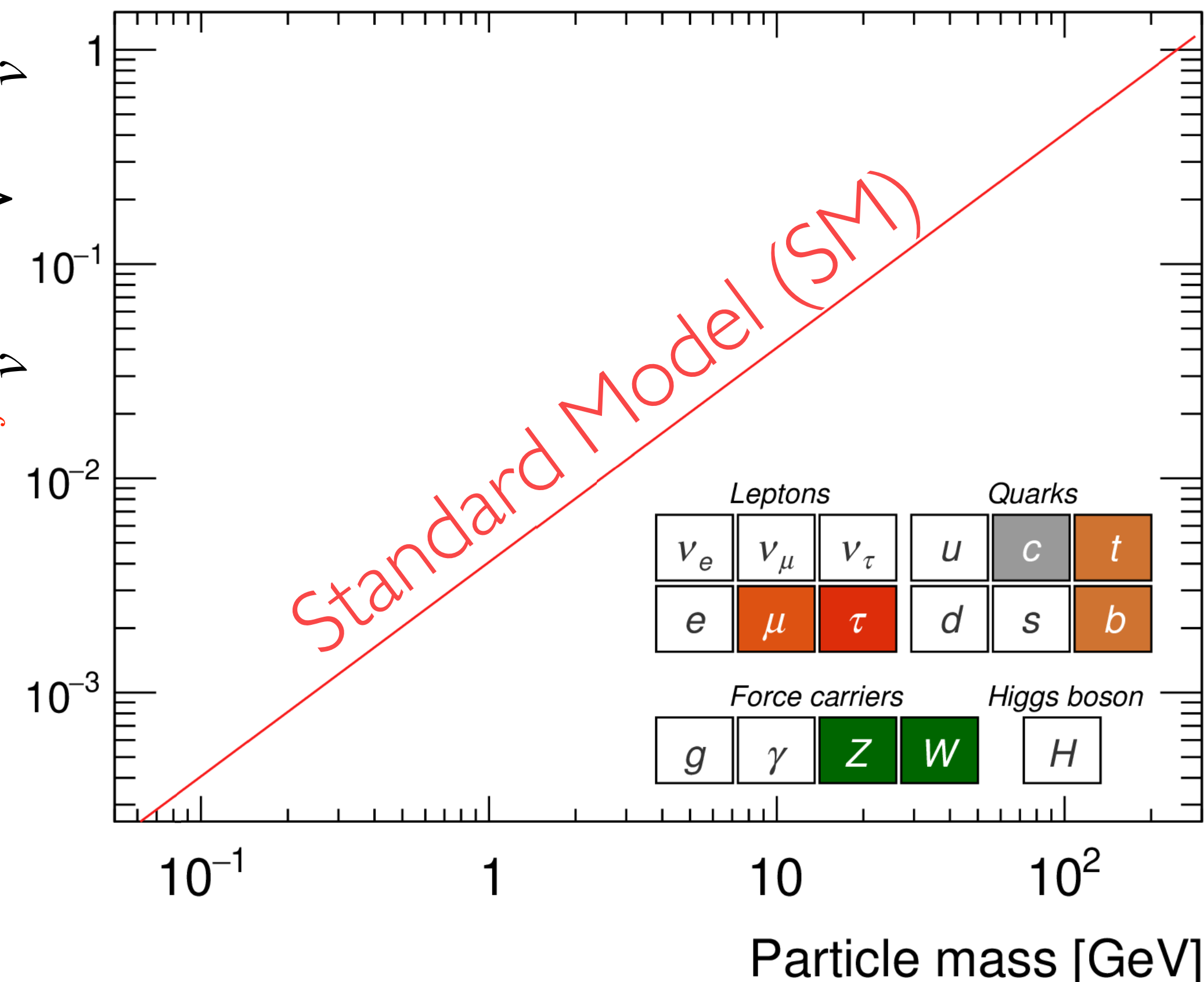
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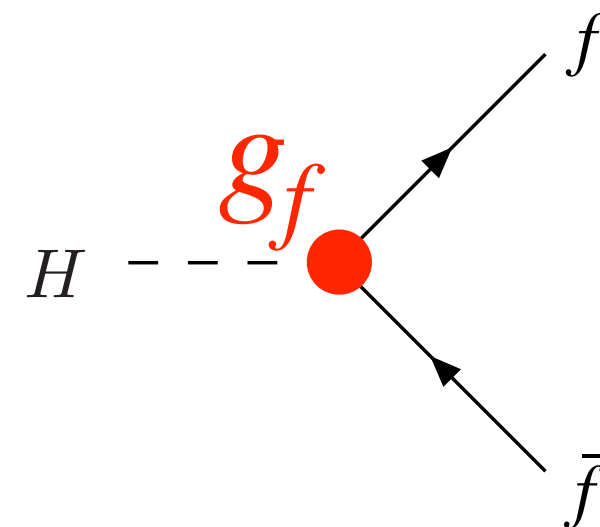


$$\frac{m_V}{\sqrt{\kappa_V}} \text{ or } \frac{m_f}{\kappa_f}$$

- New **Quantum** concept of *mass*!
- After classical Newton and Einstein



$$\kappa_V = g_V / g_{V, \text{SM}}$$



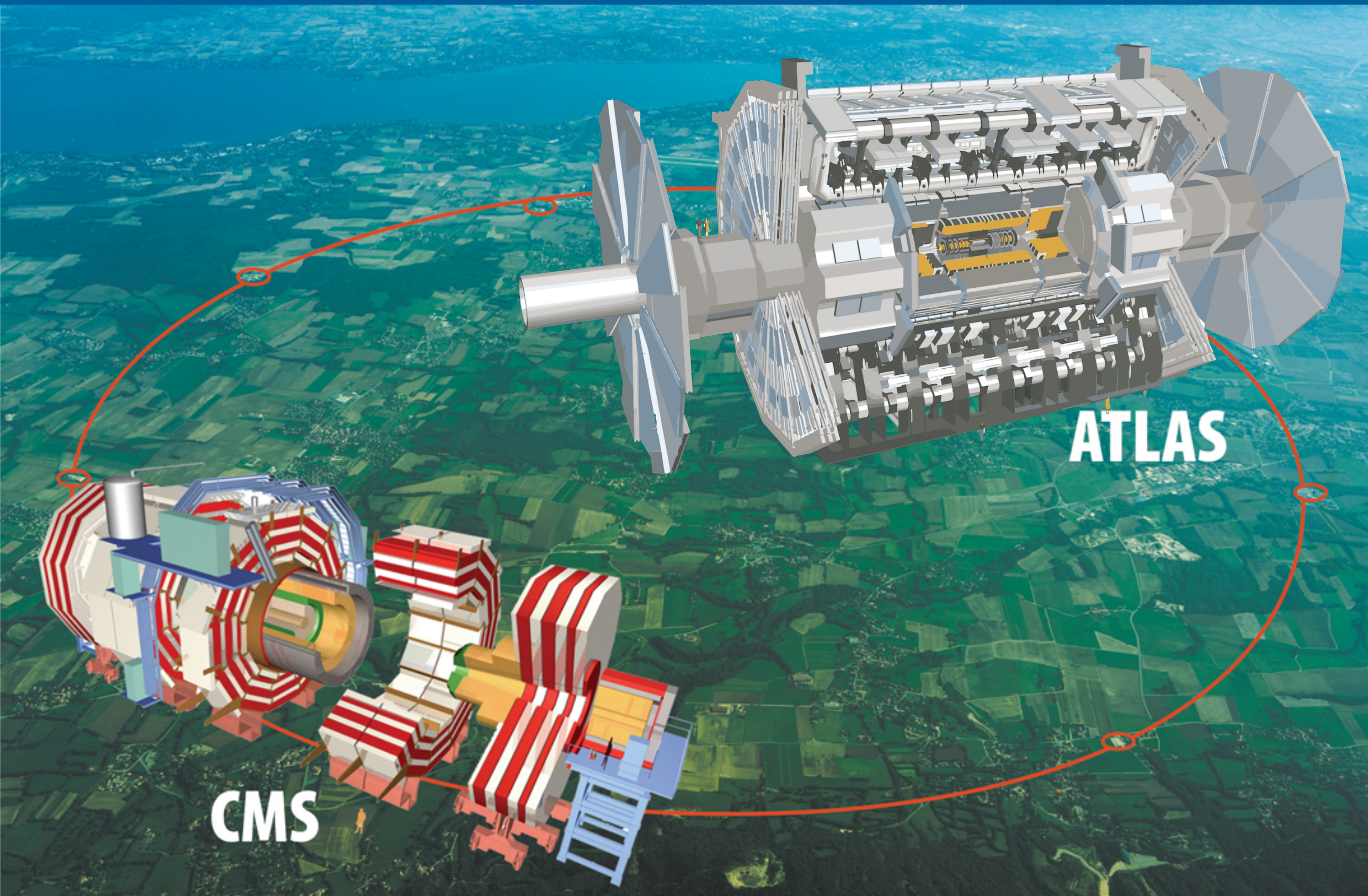
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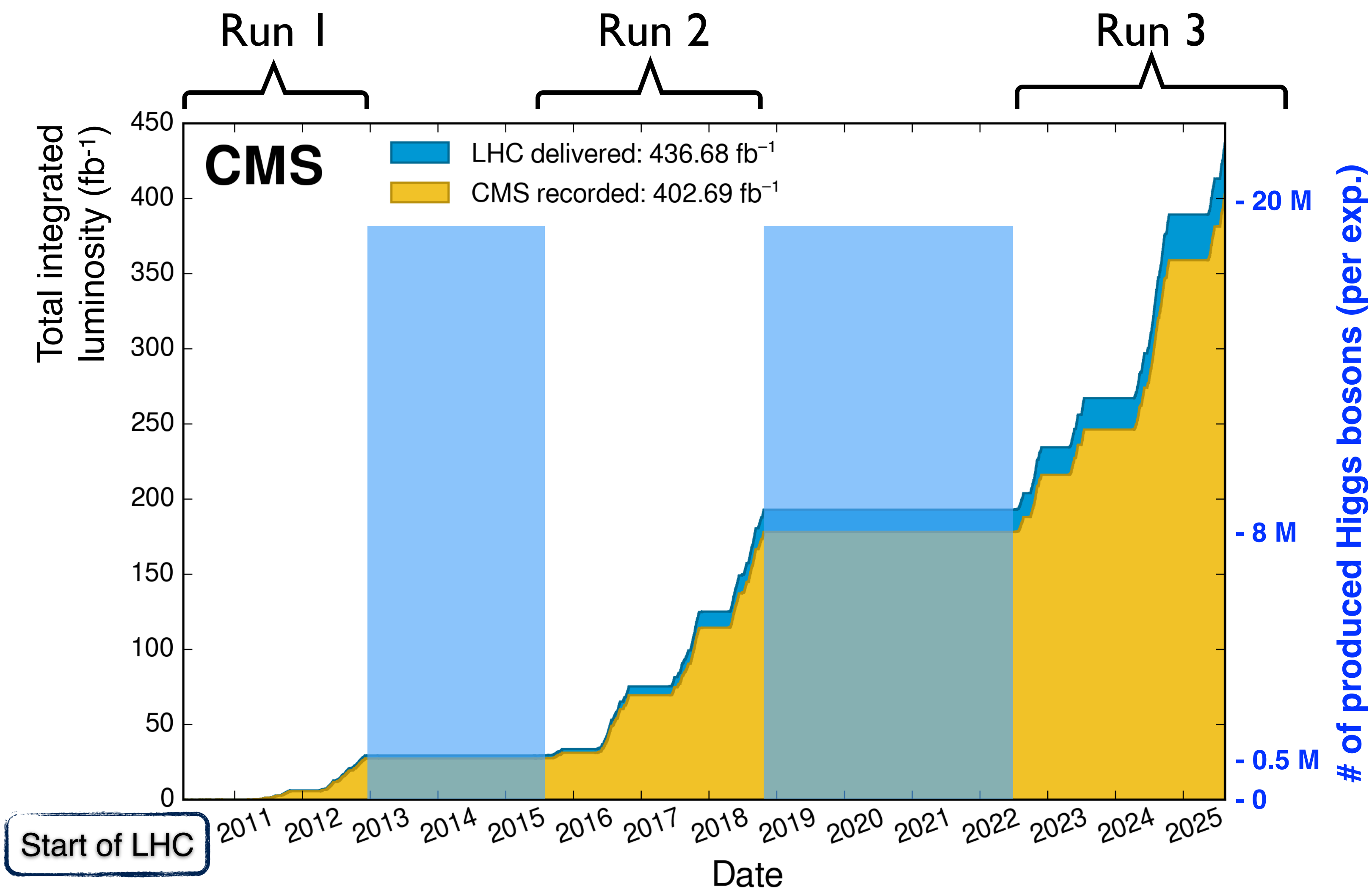
The LHC with ATLAS & CMS



Nearly 3 billion
pp-collisions
per Second



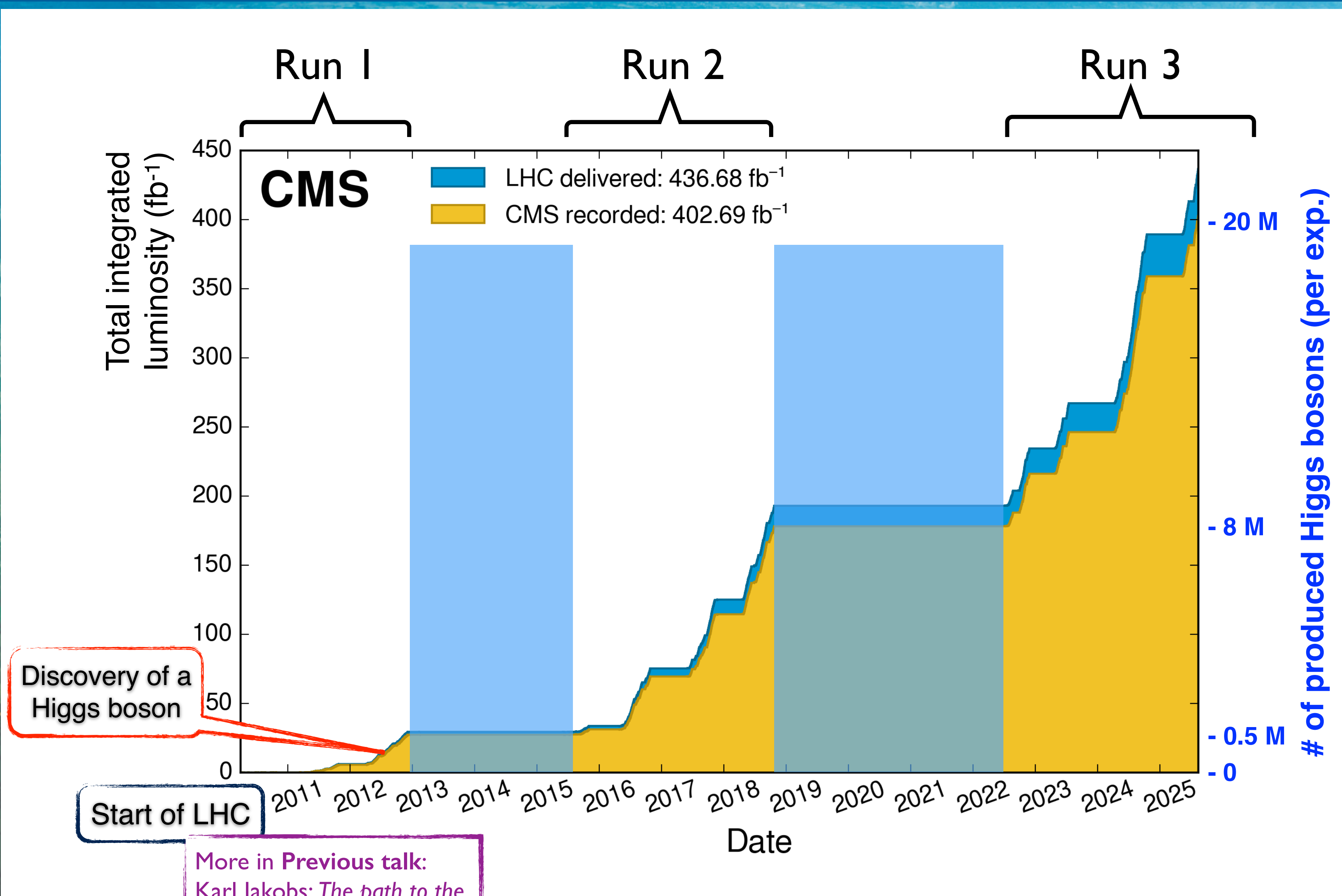
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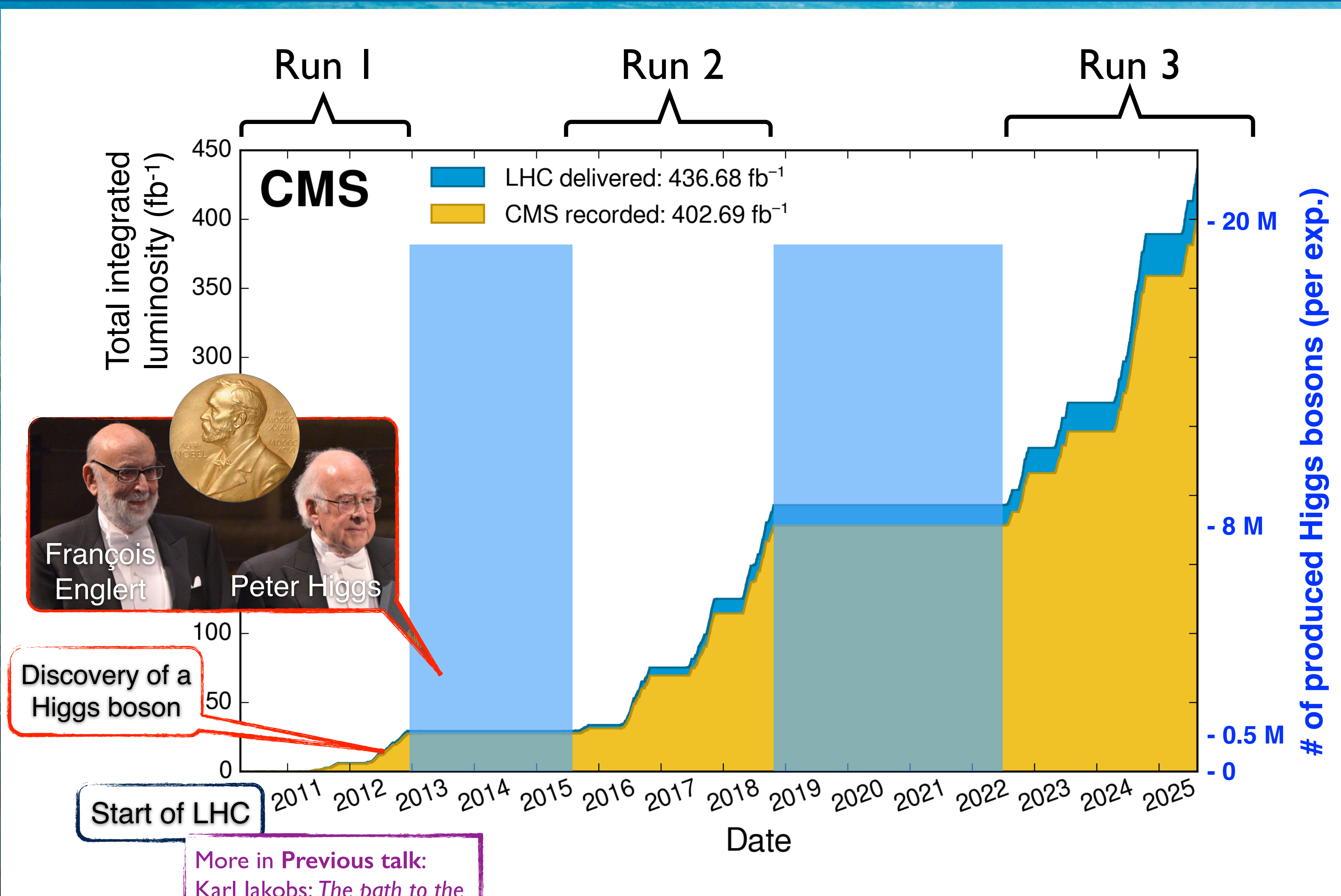
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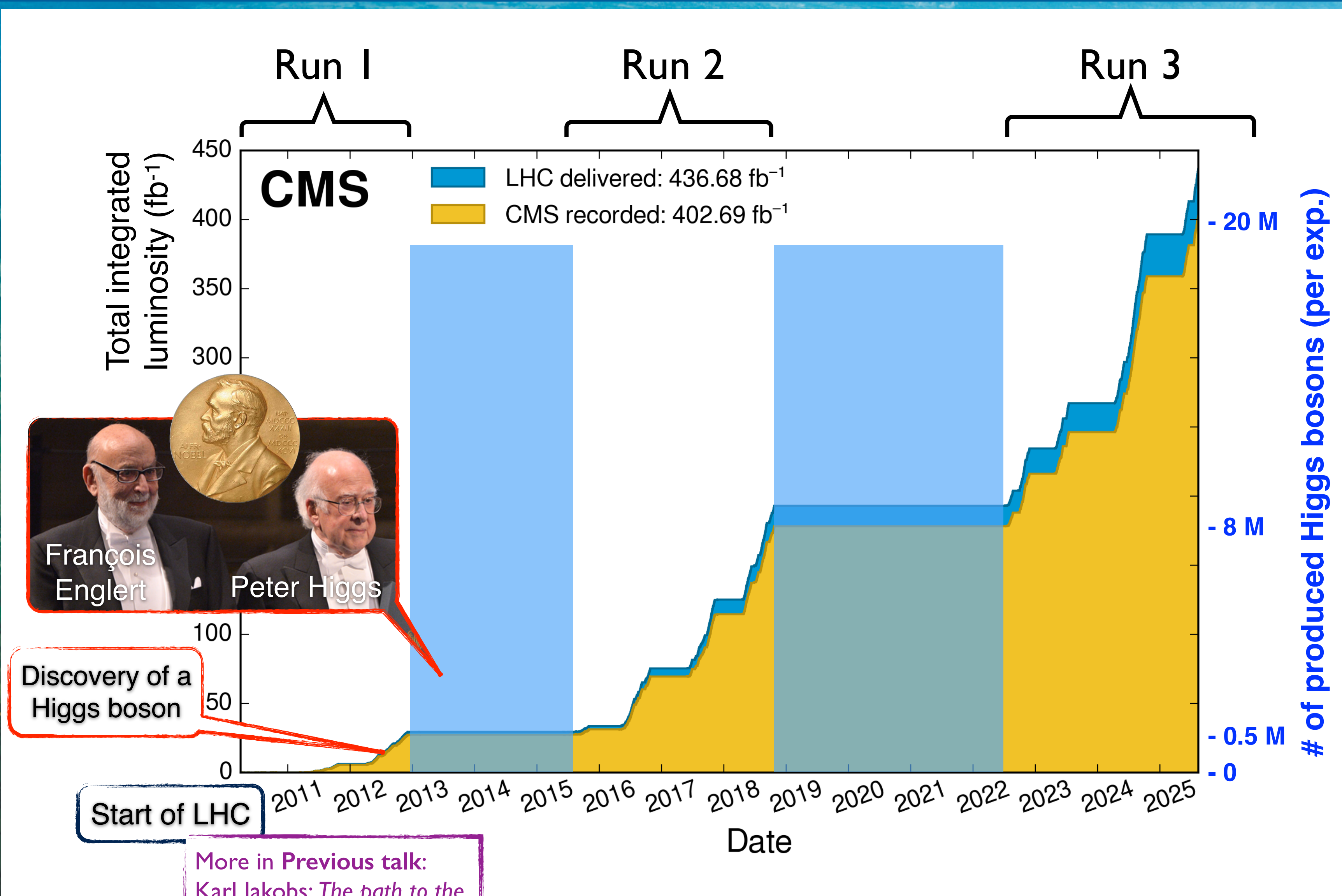
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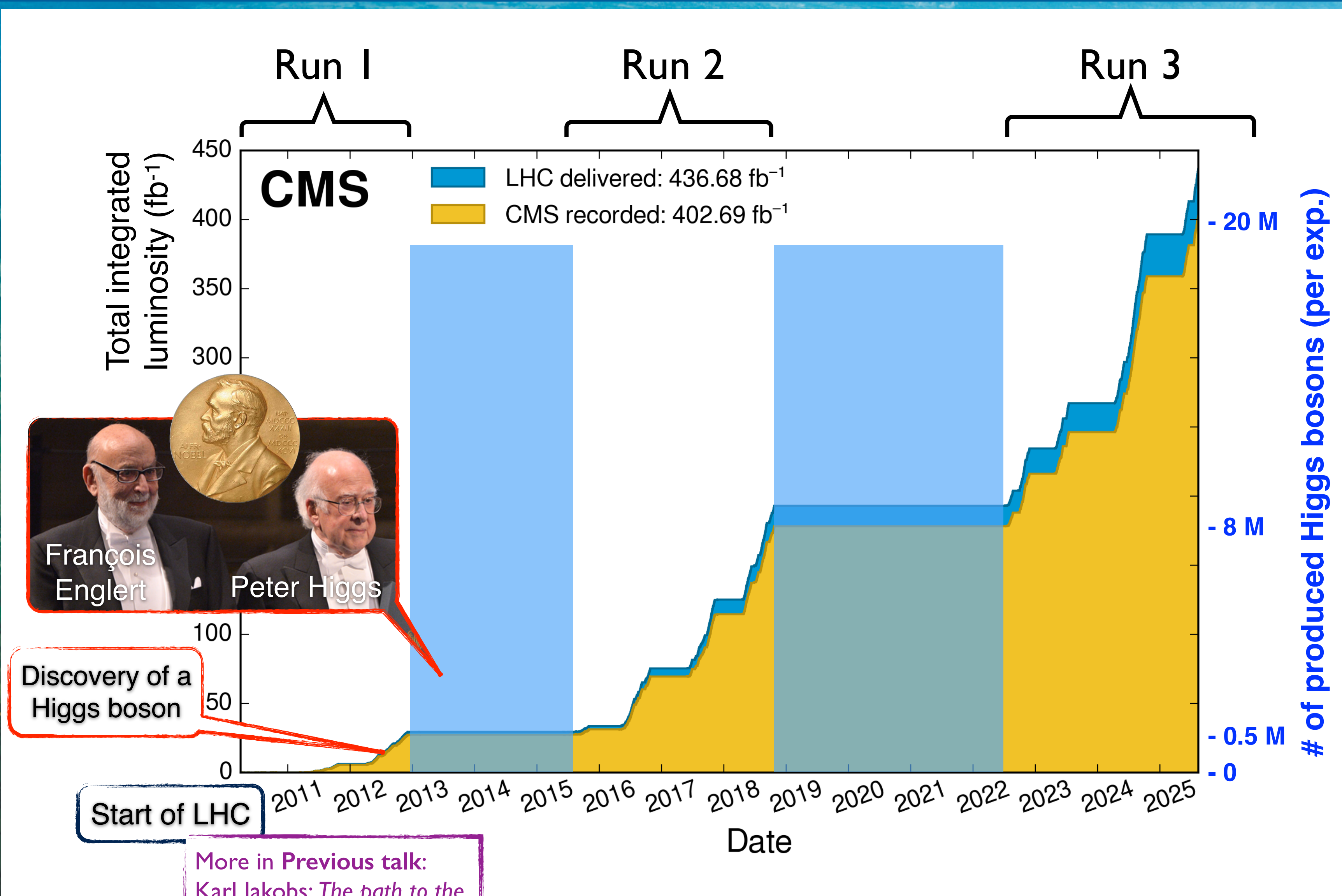


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~20 000 000
Higgs bosons
produced!
(per experiment)



The LHC with ATLAS & CMS



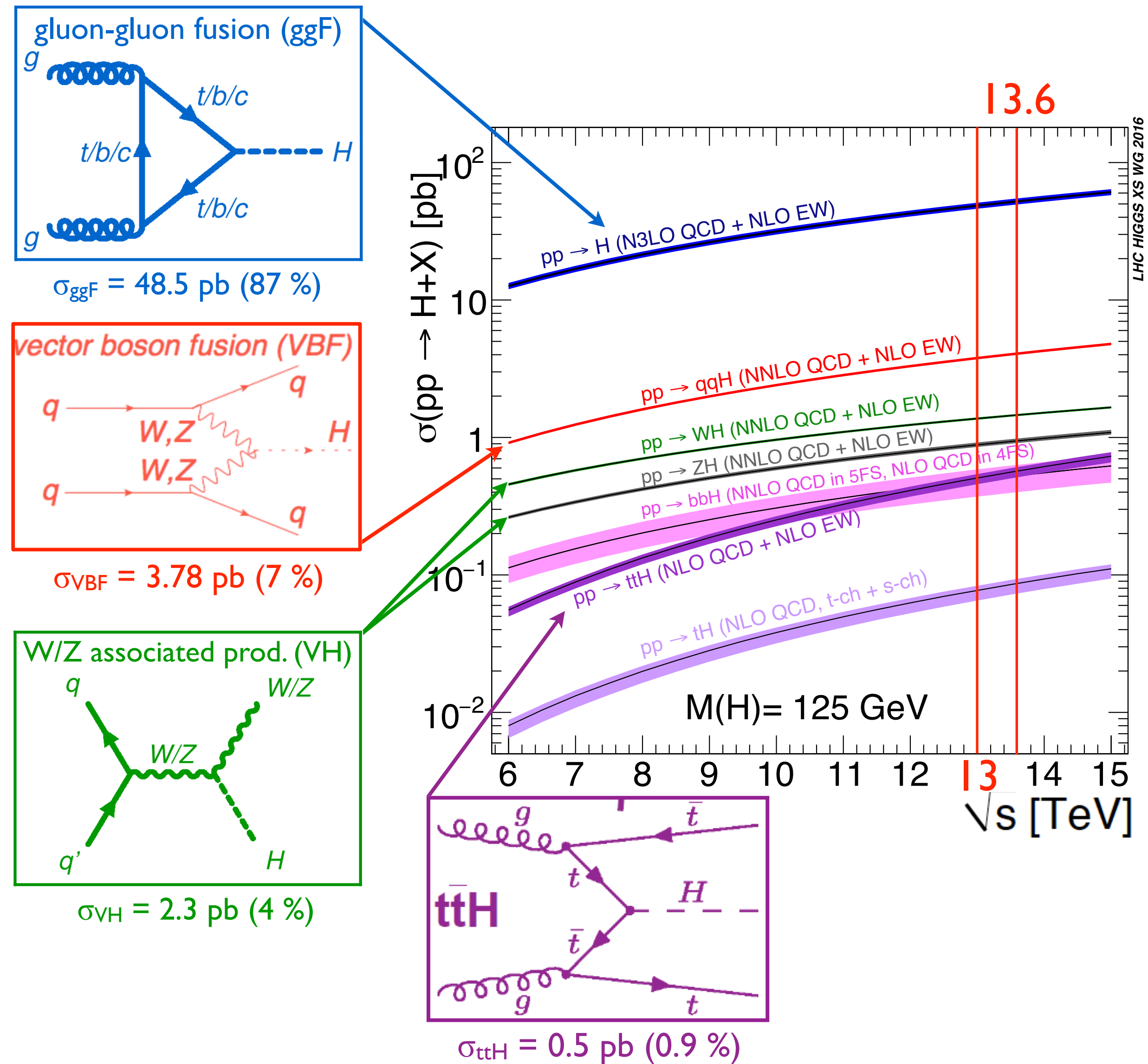
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A Higgs boson
is produced in
1 of 10^9
collisions!

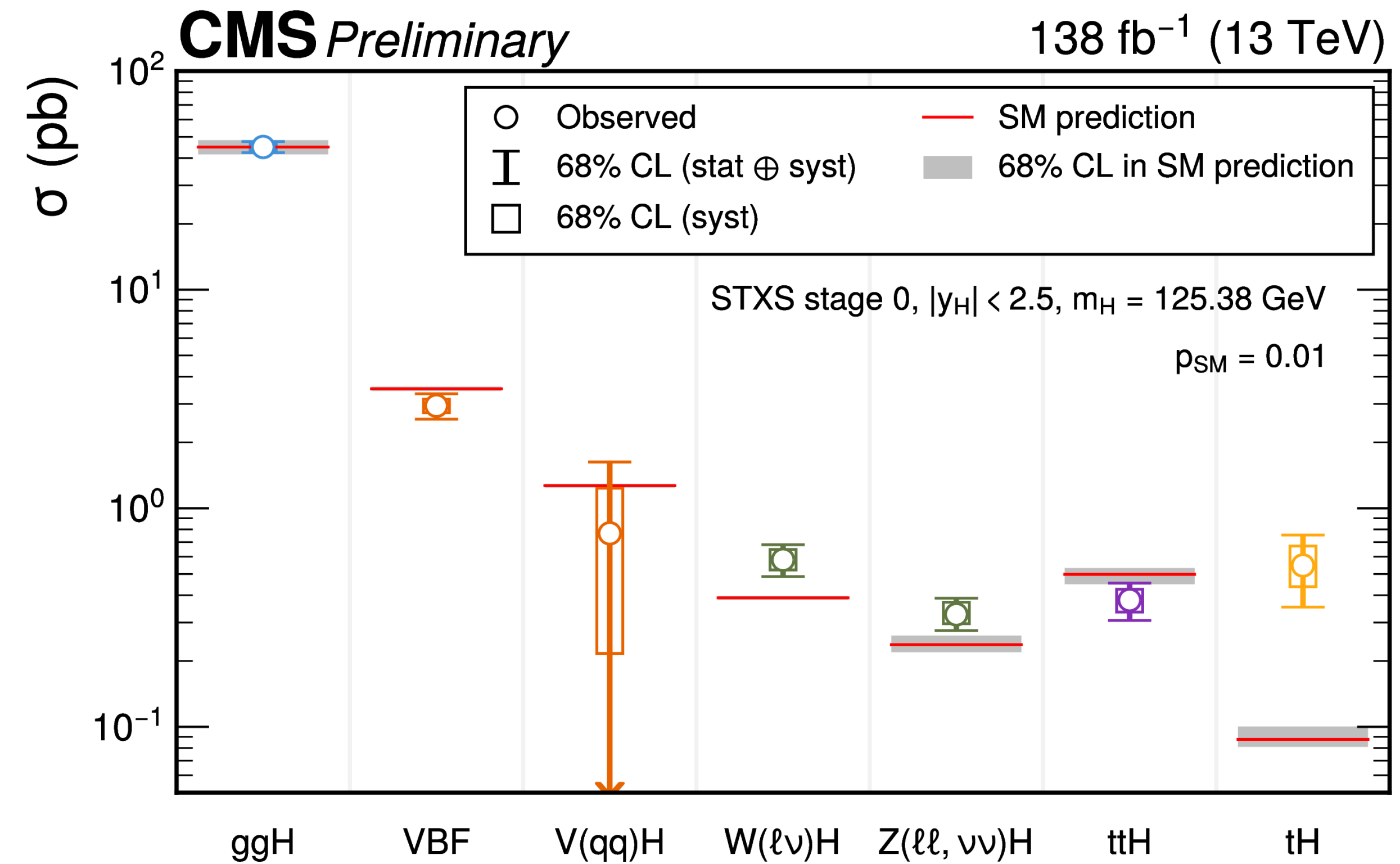
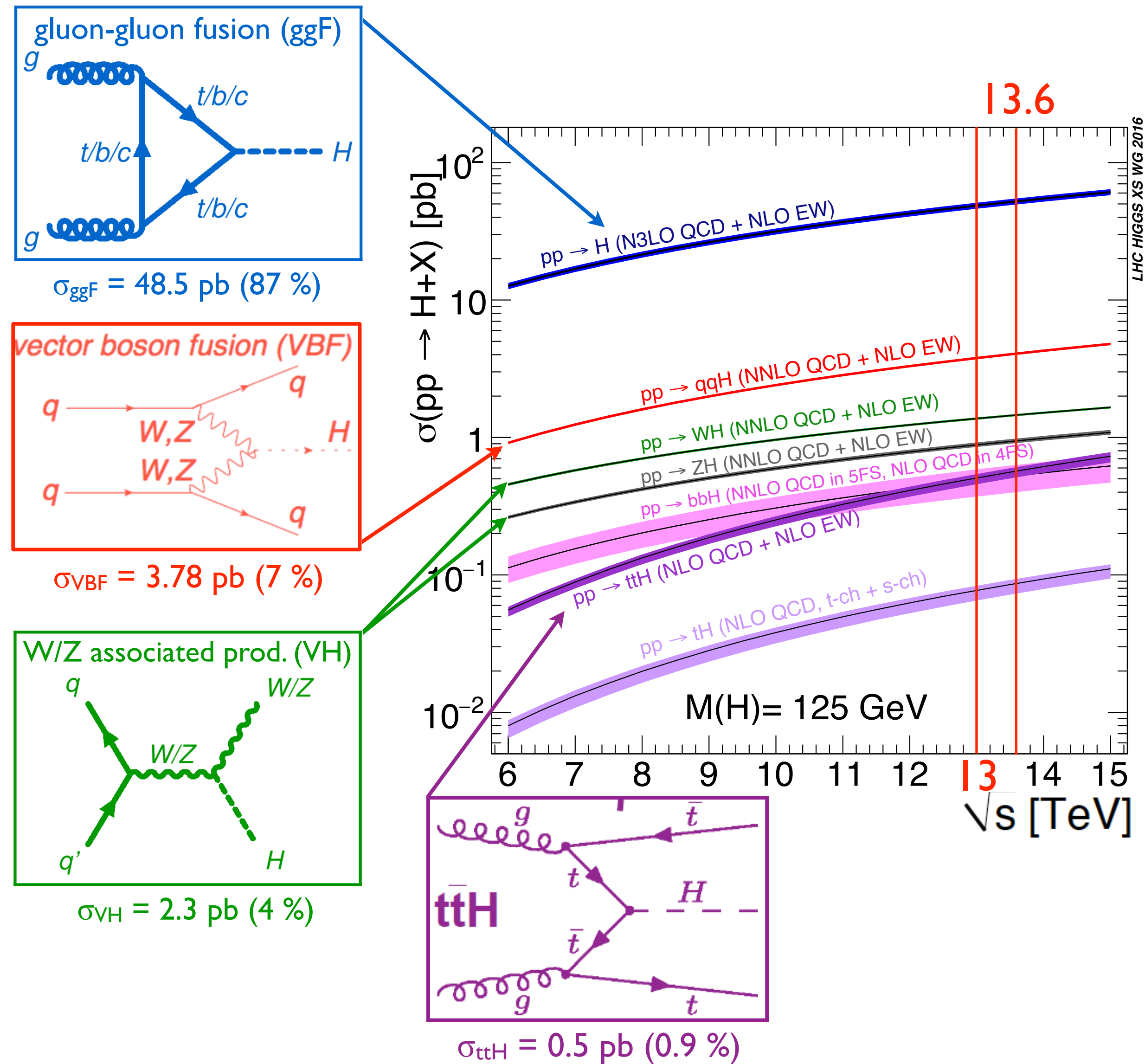


Higgs Boson Production at the LHC





Higgs Boson Production at the LHC

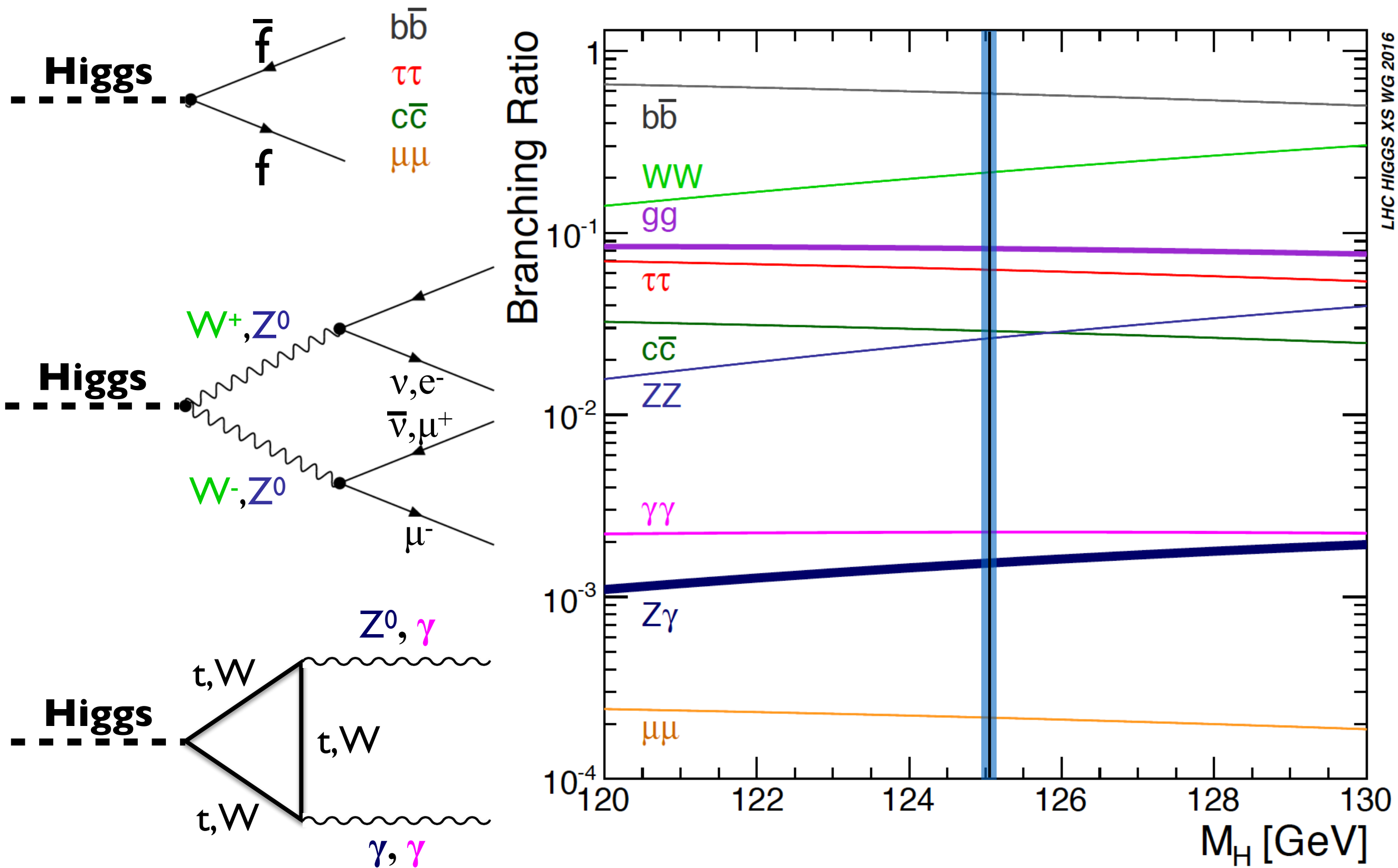


CMS-PAS-HIG-21-018

Apr
2025

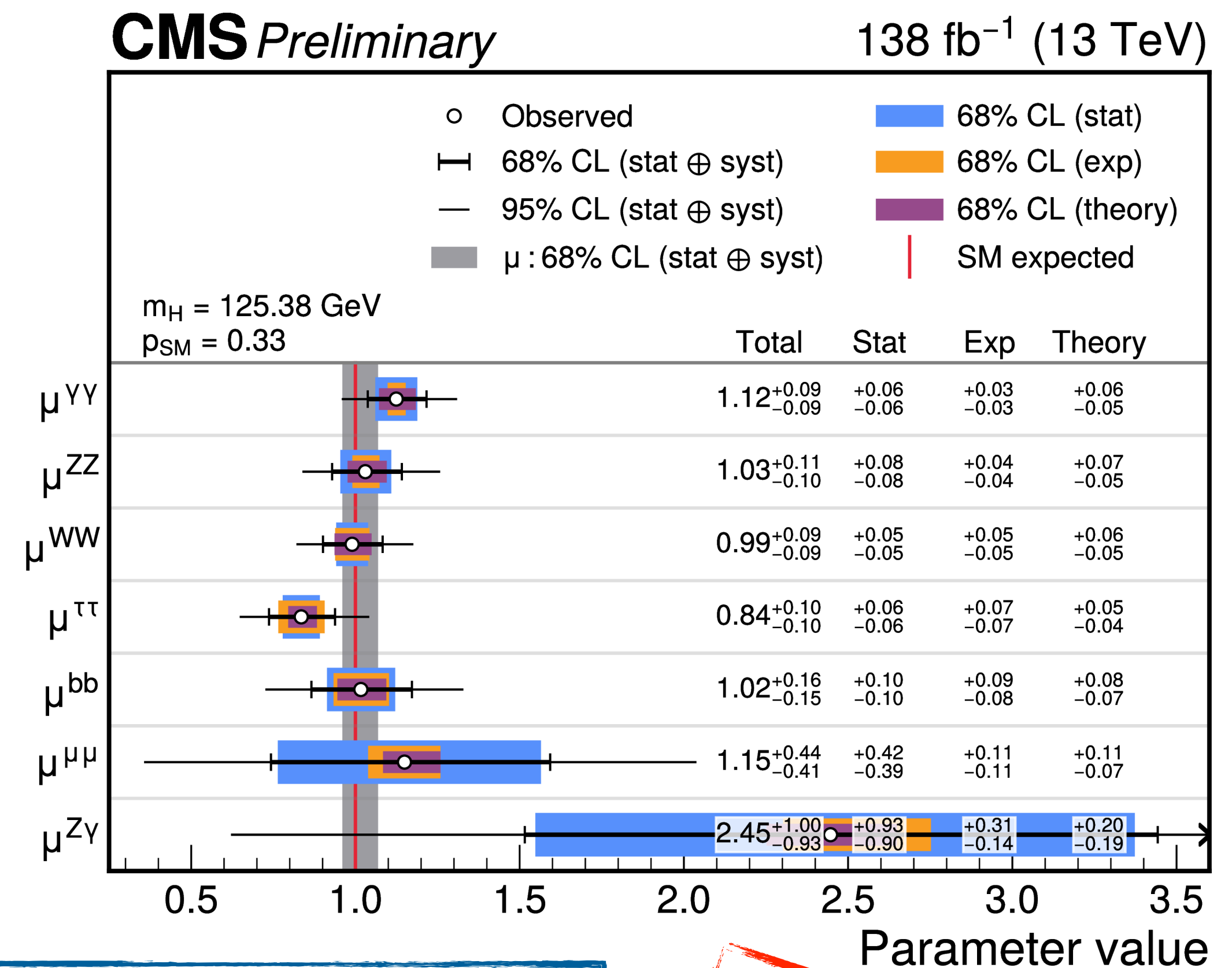
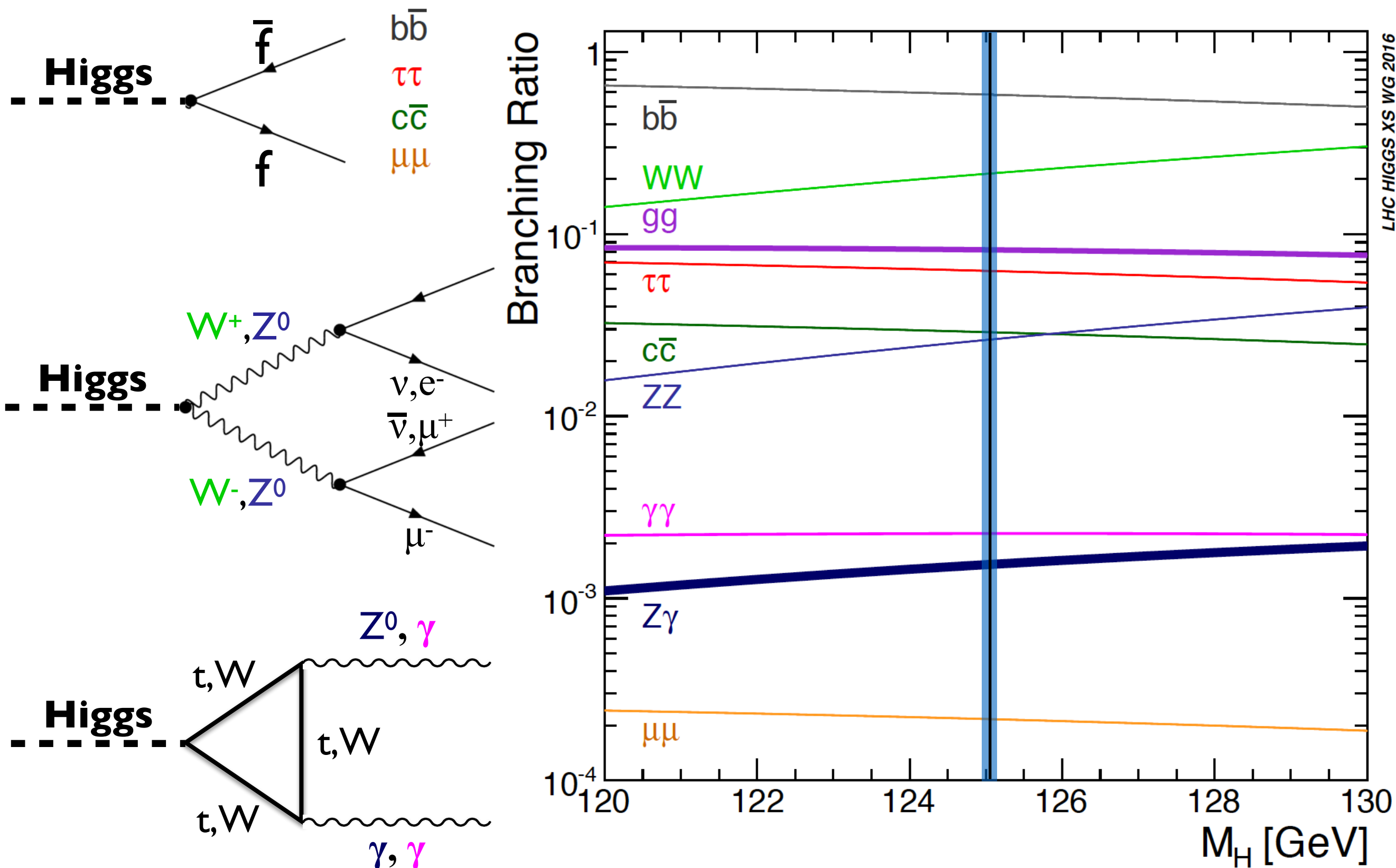


Higgs Boson Decays





Higgs Boson Decays



Signal strength:

$$\mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{SM}} = \frac{\text{observed rate}}{\text{expected rate}}$$

Apr
2025

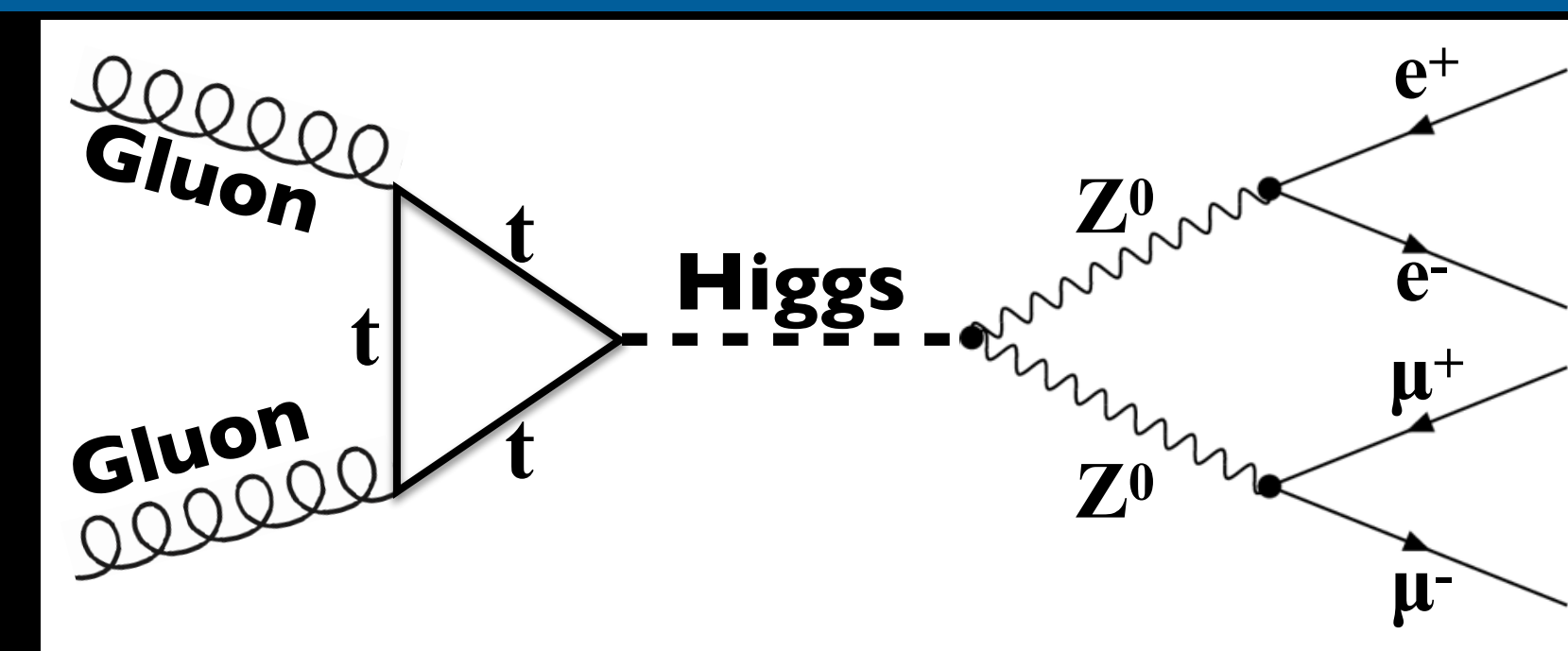
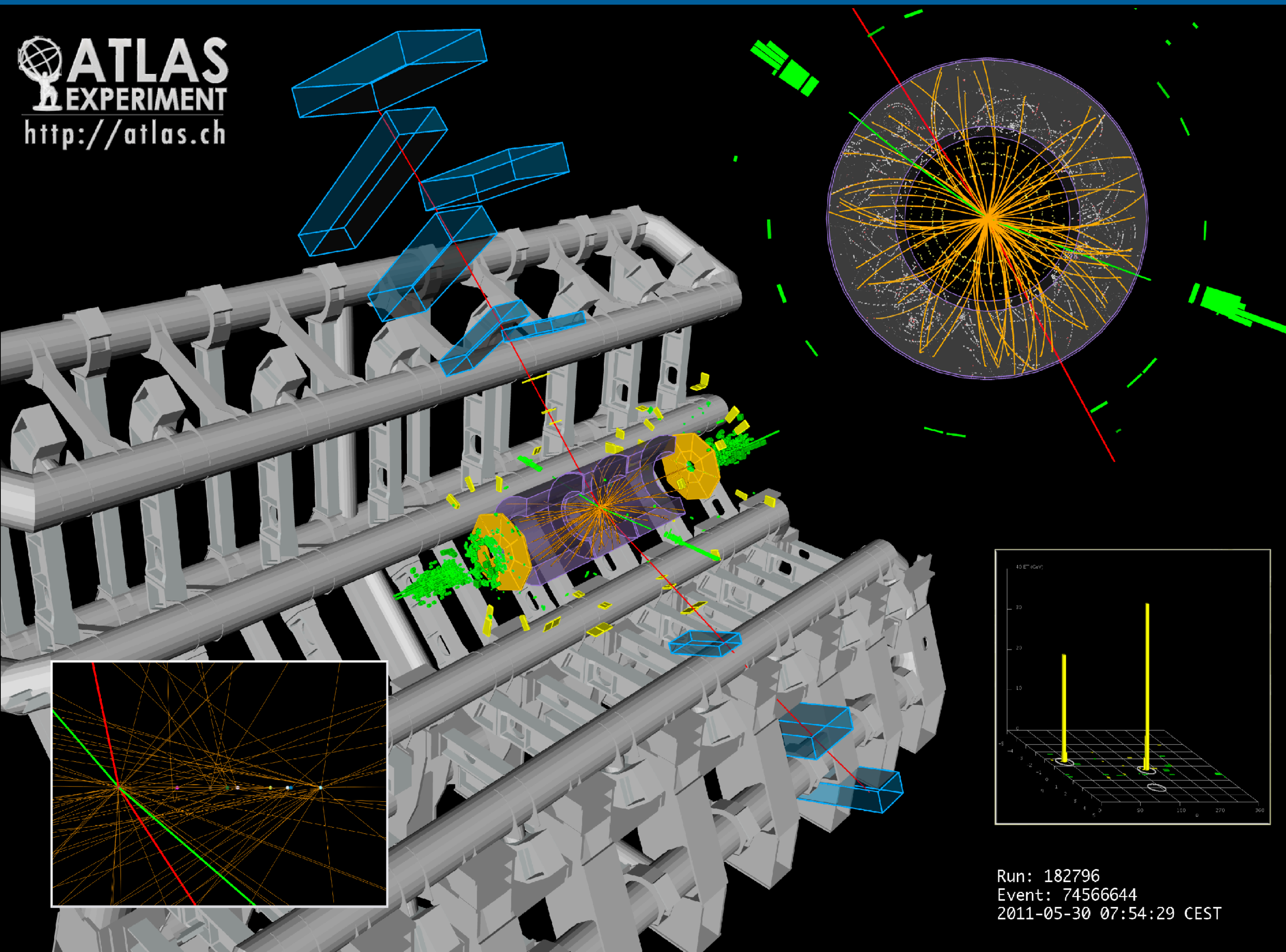


CMS-PAS-HIG-21-018



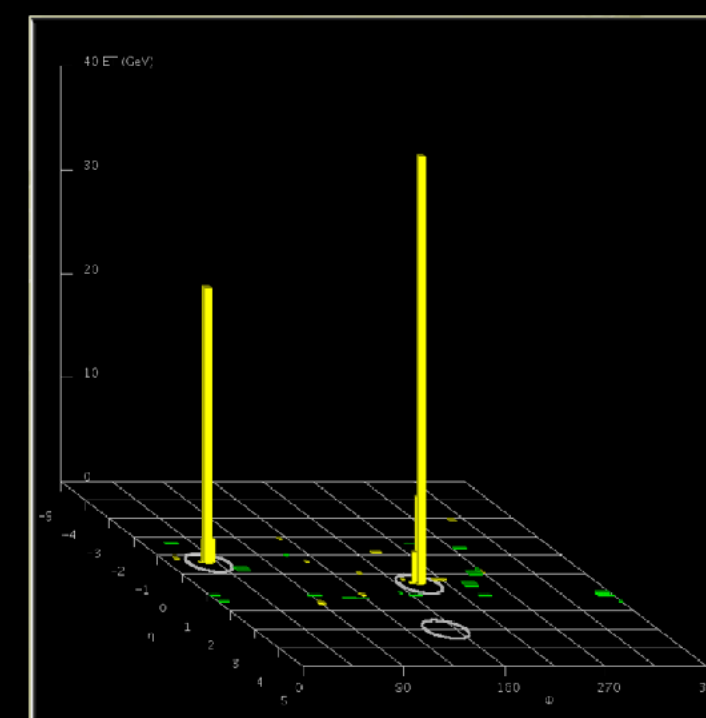
How do we “see” the Higgs boson? GA

ATLAS
EXPERIMENT
<http://atlas.ch>



“Clean” Signatures: leptons or photons, e.g.,

$$H \rightarrow ZZ^* \rightarrow 4\ell$$

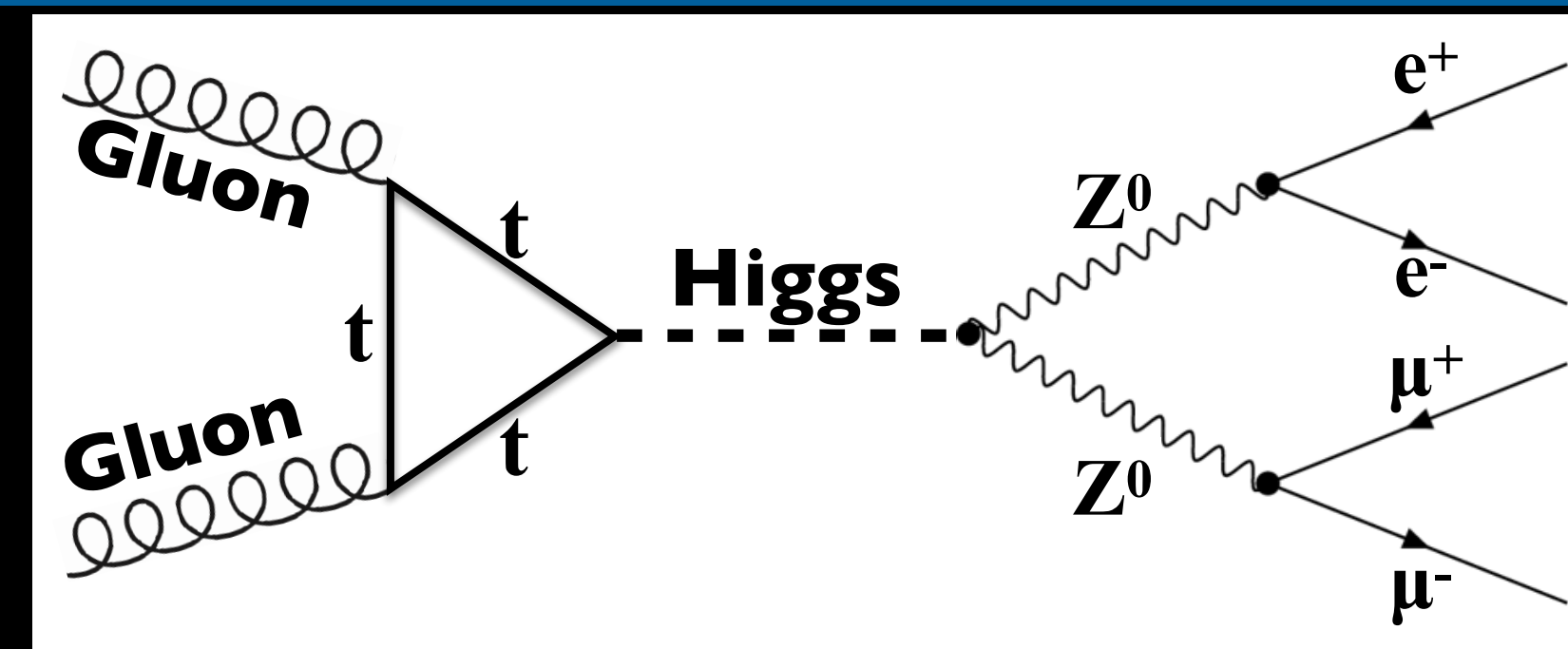
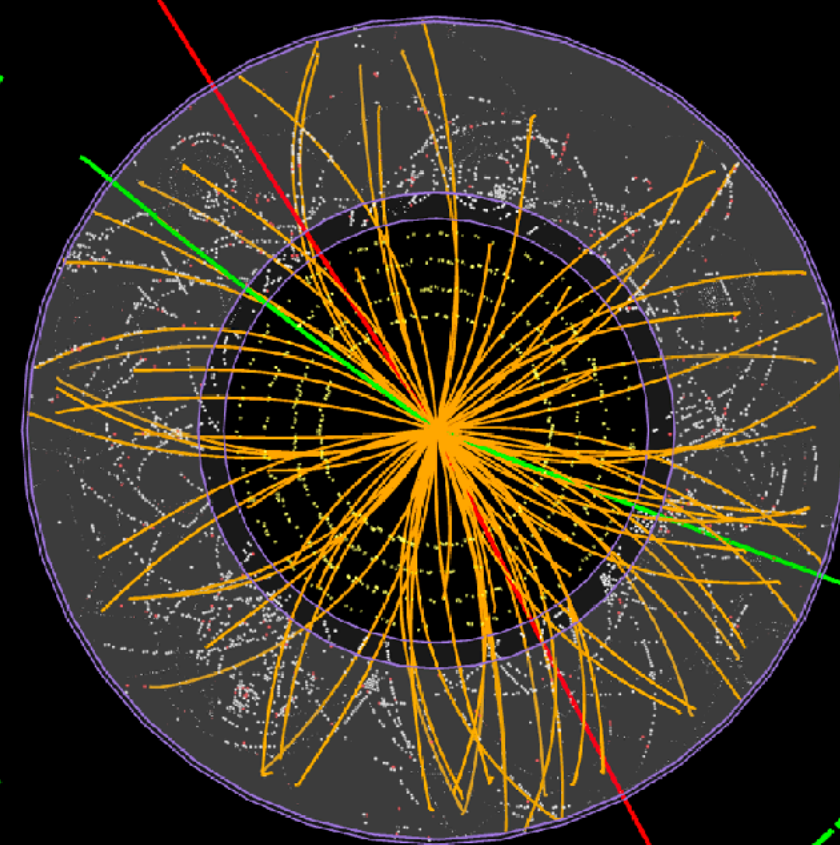
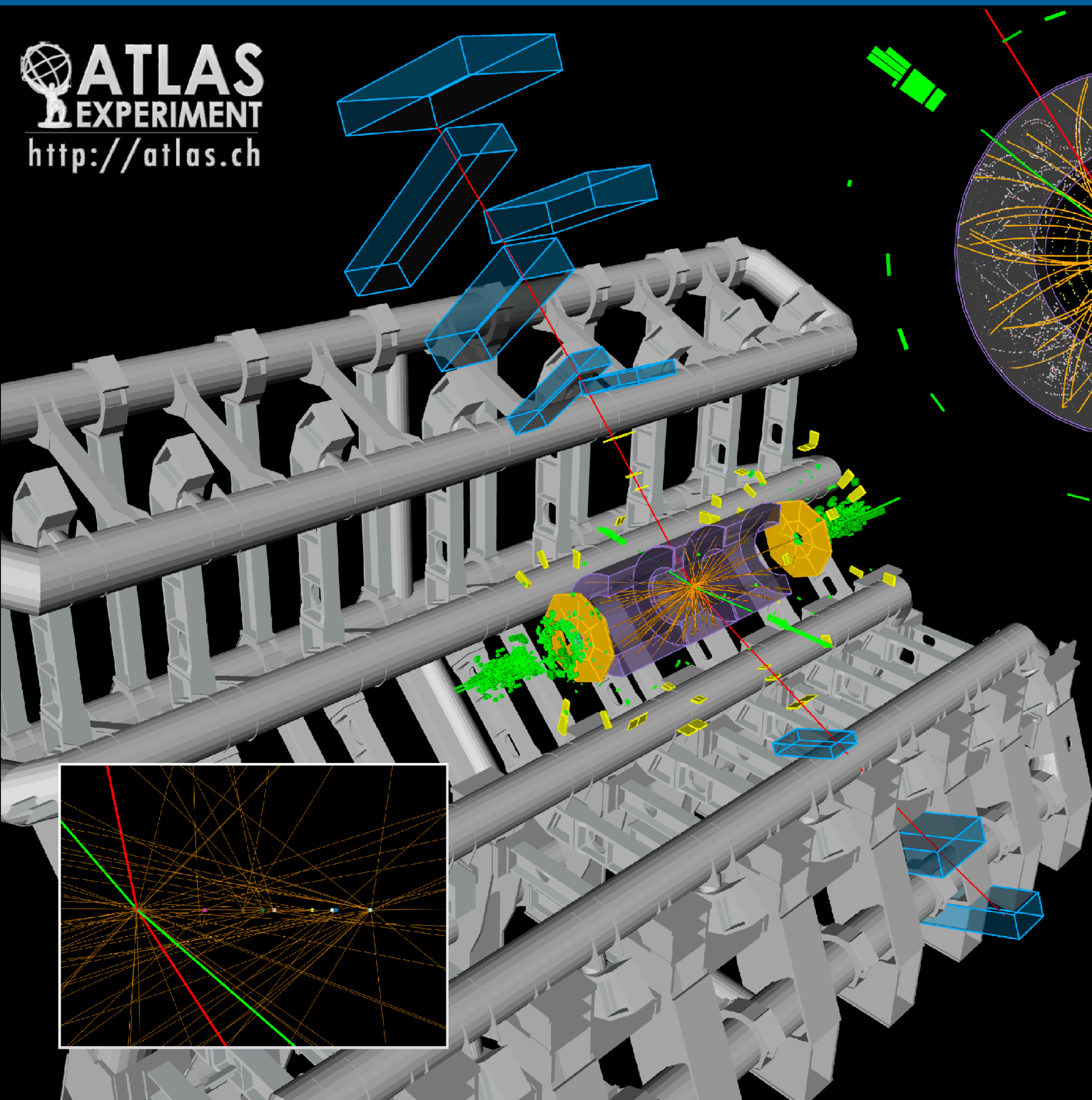


Run: 182796
Event: 7456644
2011-05-30 07:54:29 CEST



How do we “see” the Higgs boson? GA

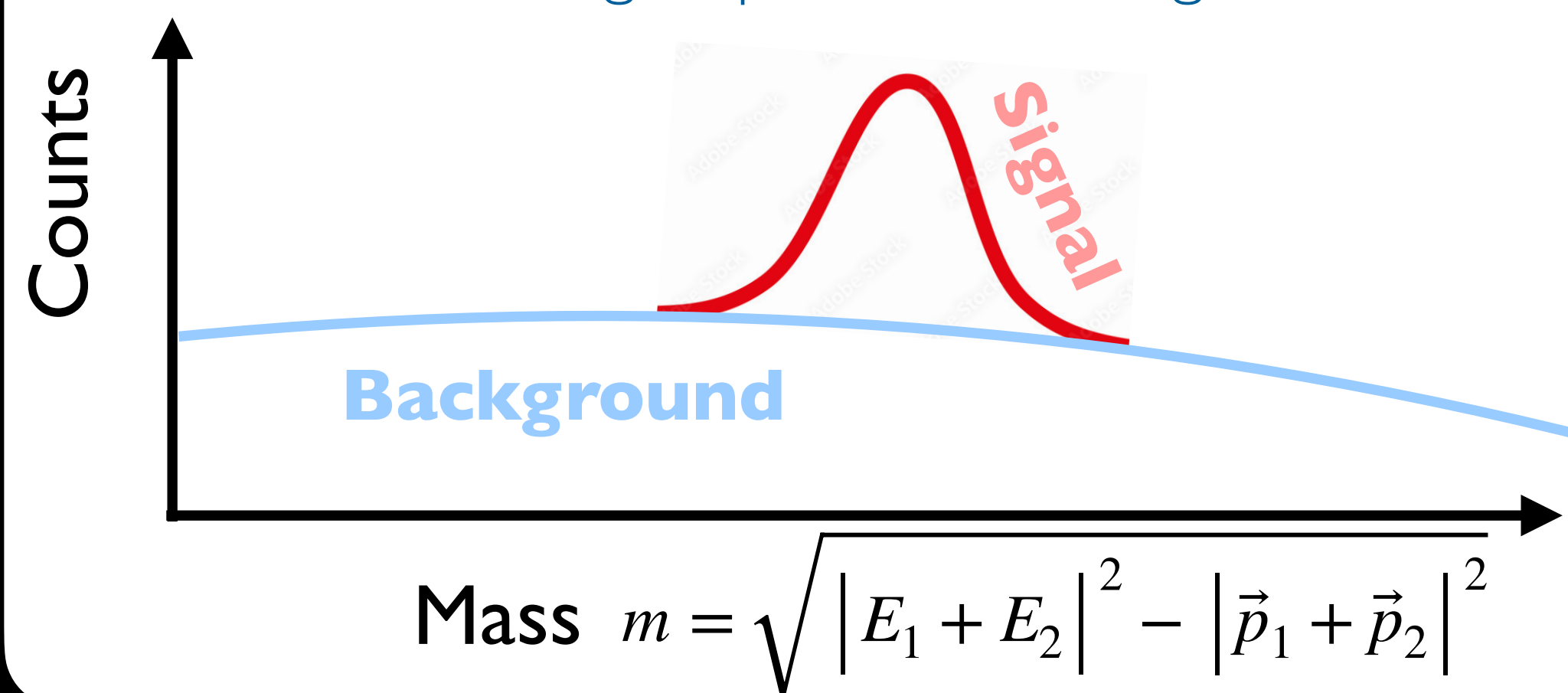
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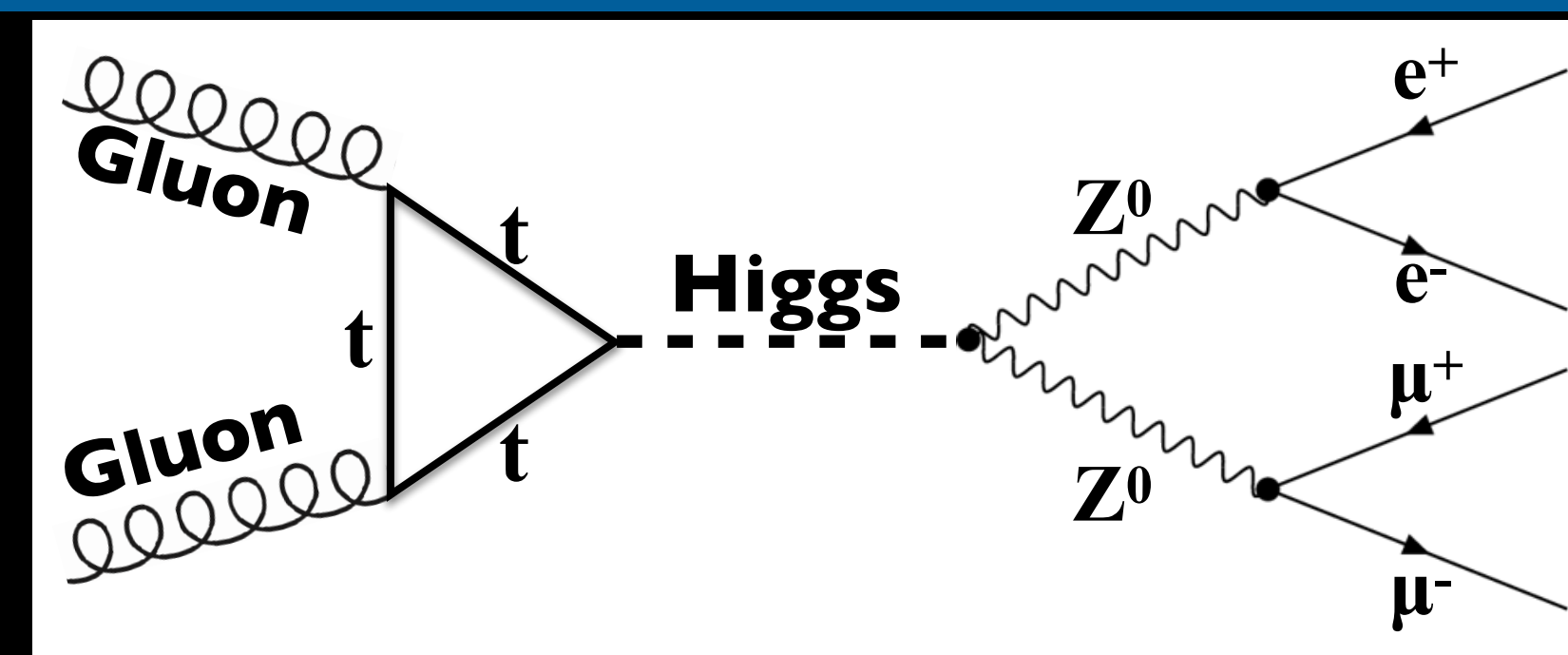
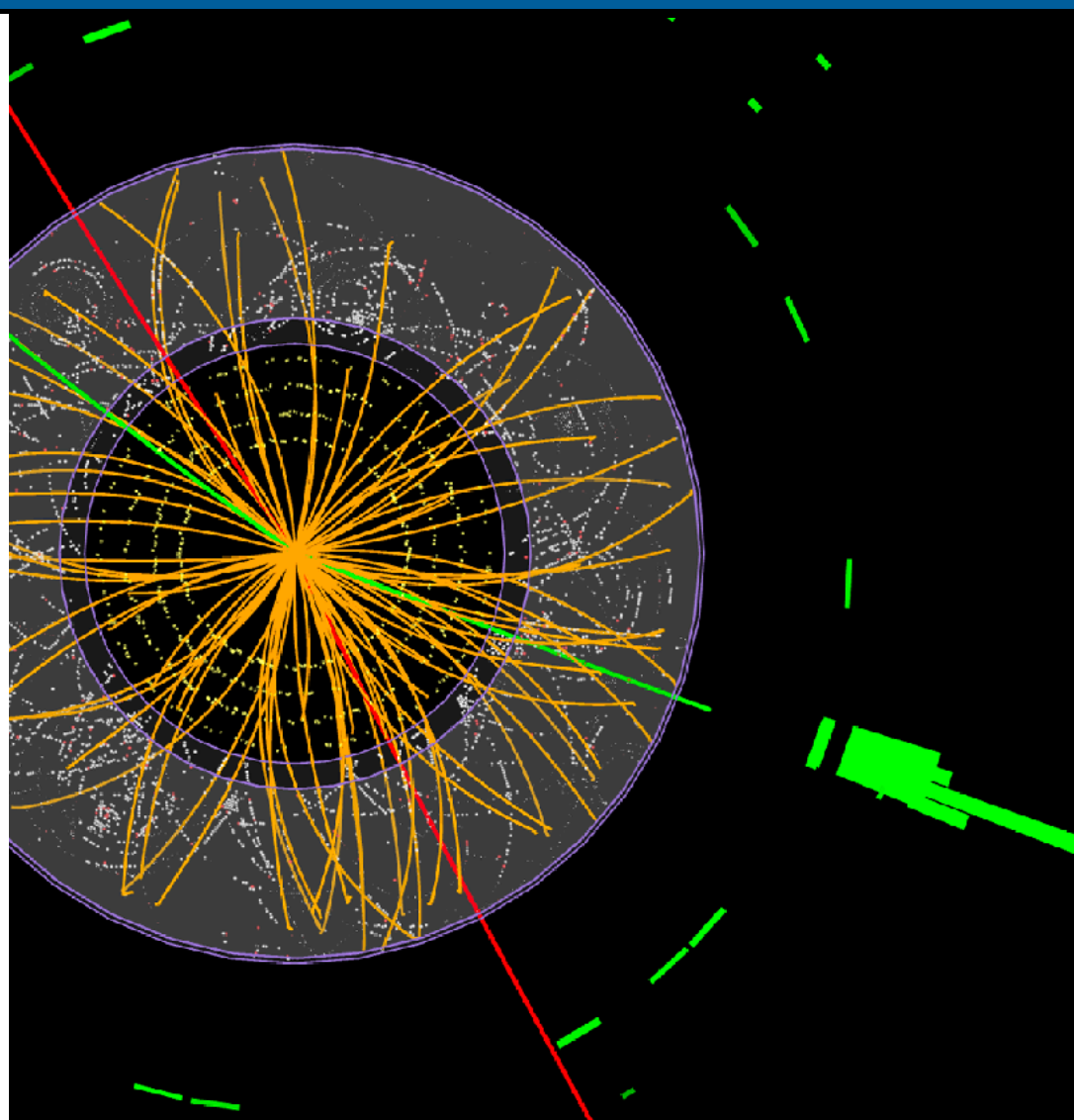
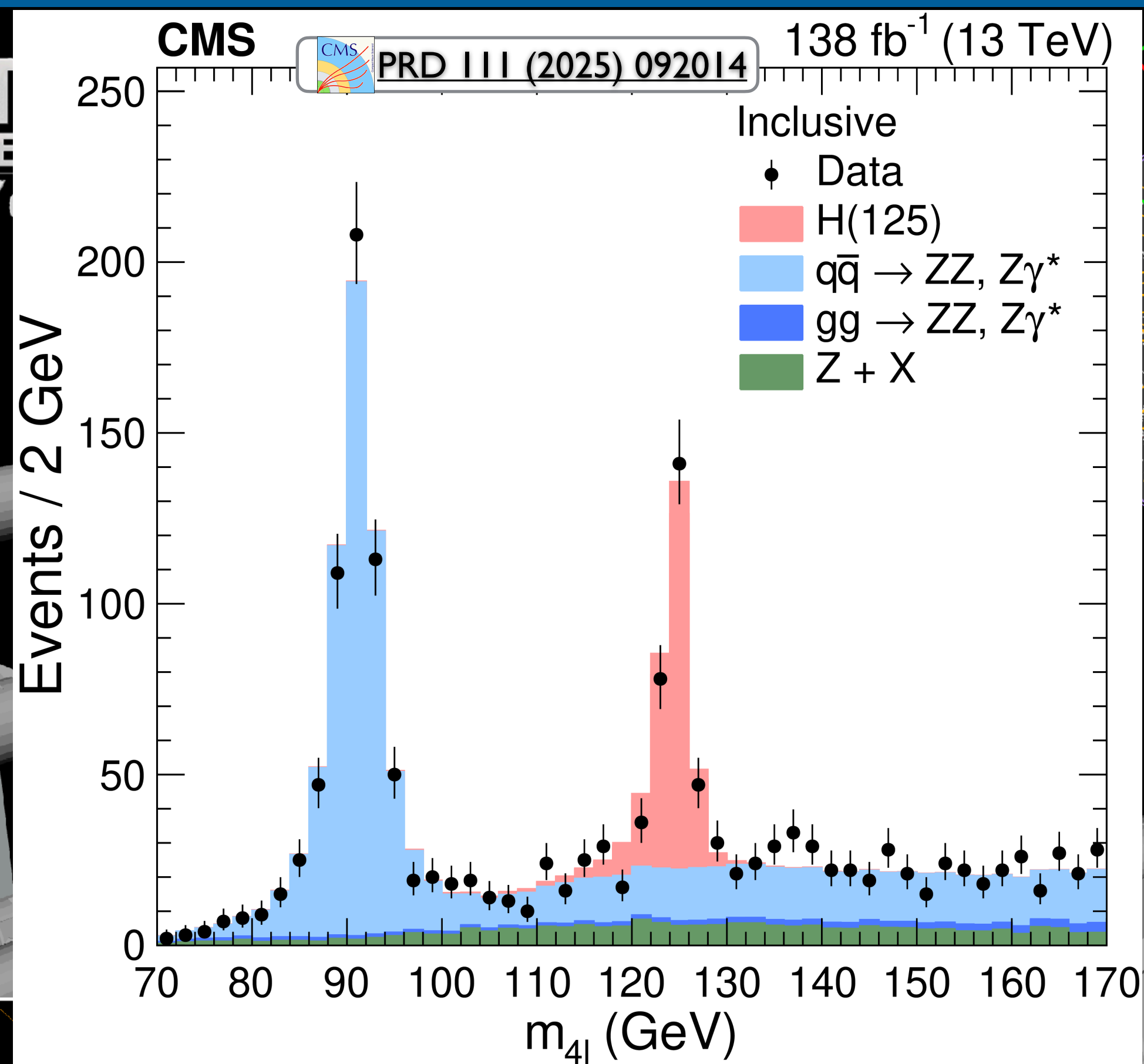
$$H \rightarrow ZZ^* \rightarrow 4\ell$$

- Calculate invariant mass from decay products
- Fill selected events into histogram
- Search for a signal peak over background:





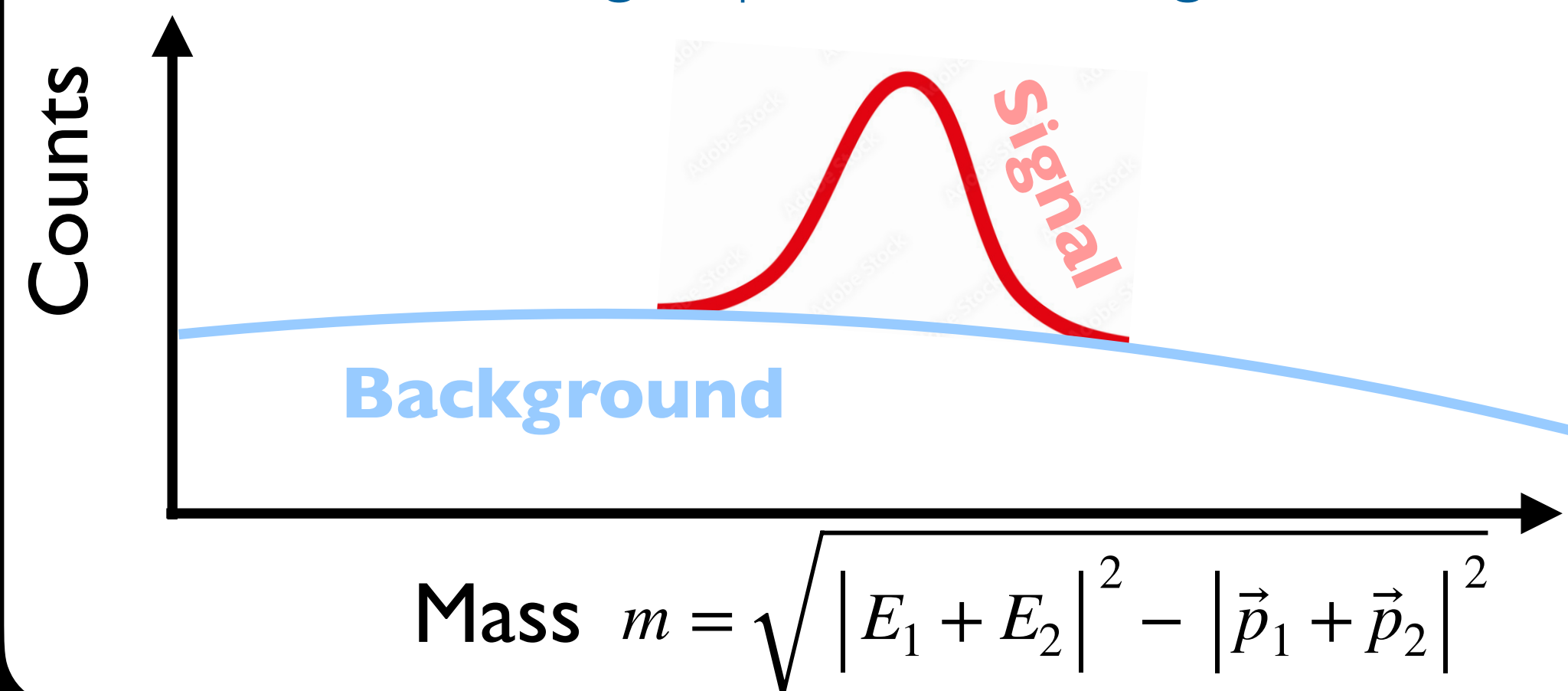
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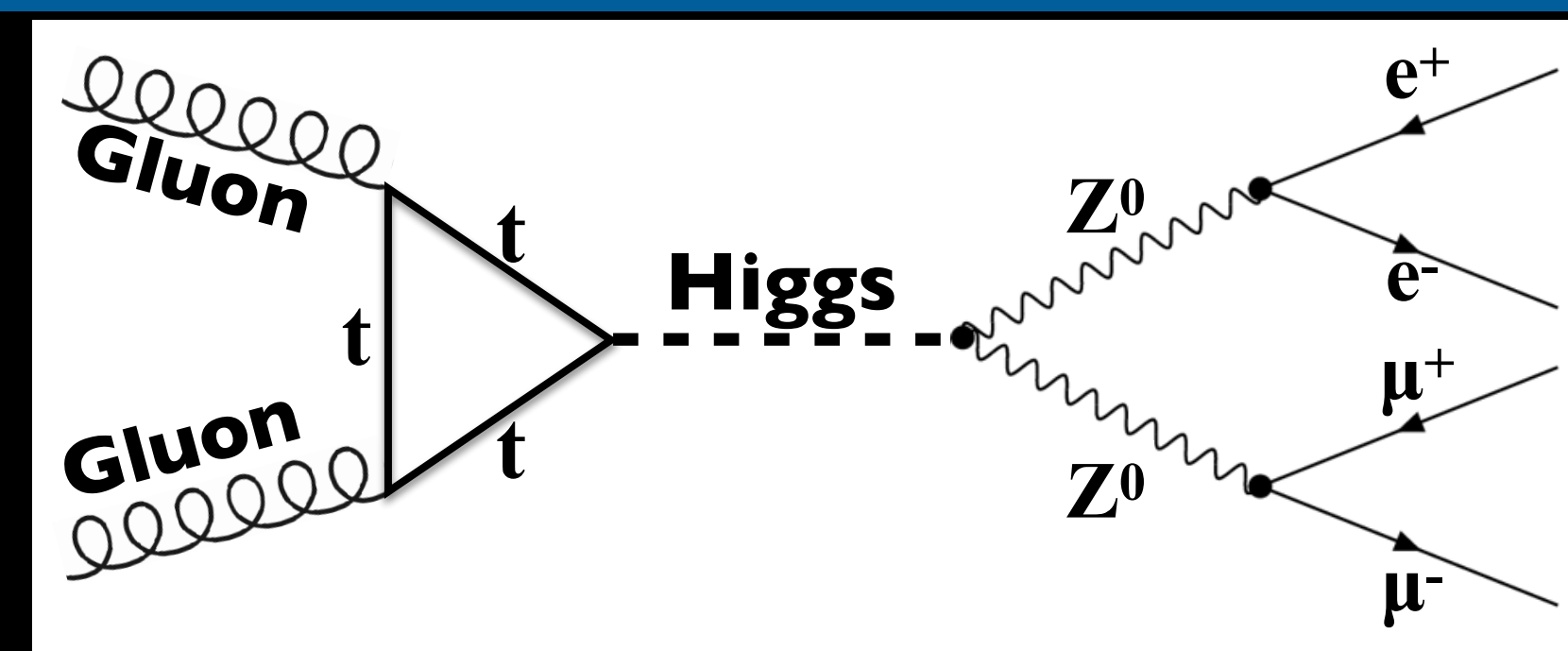
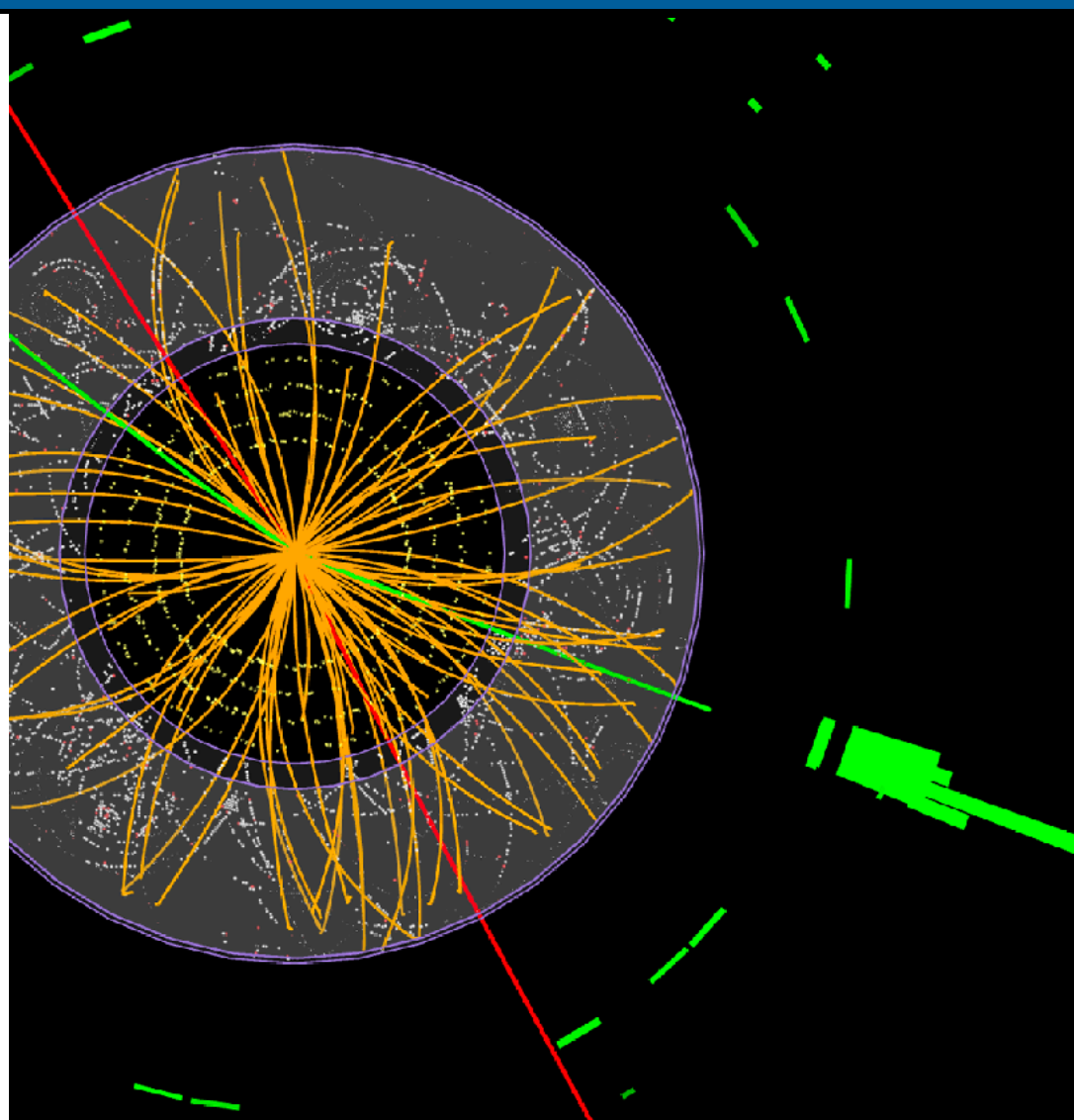
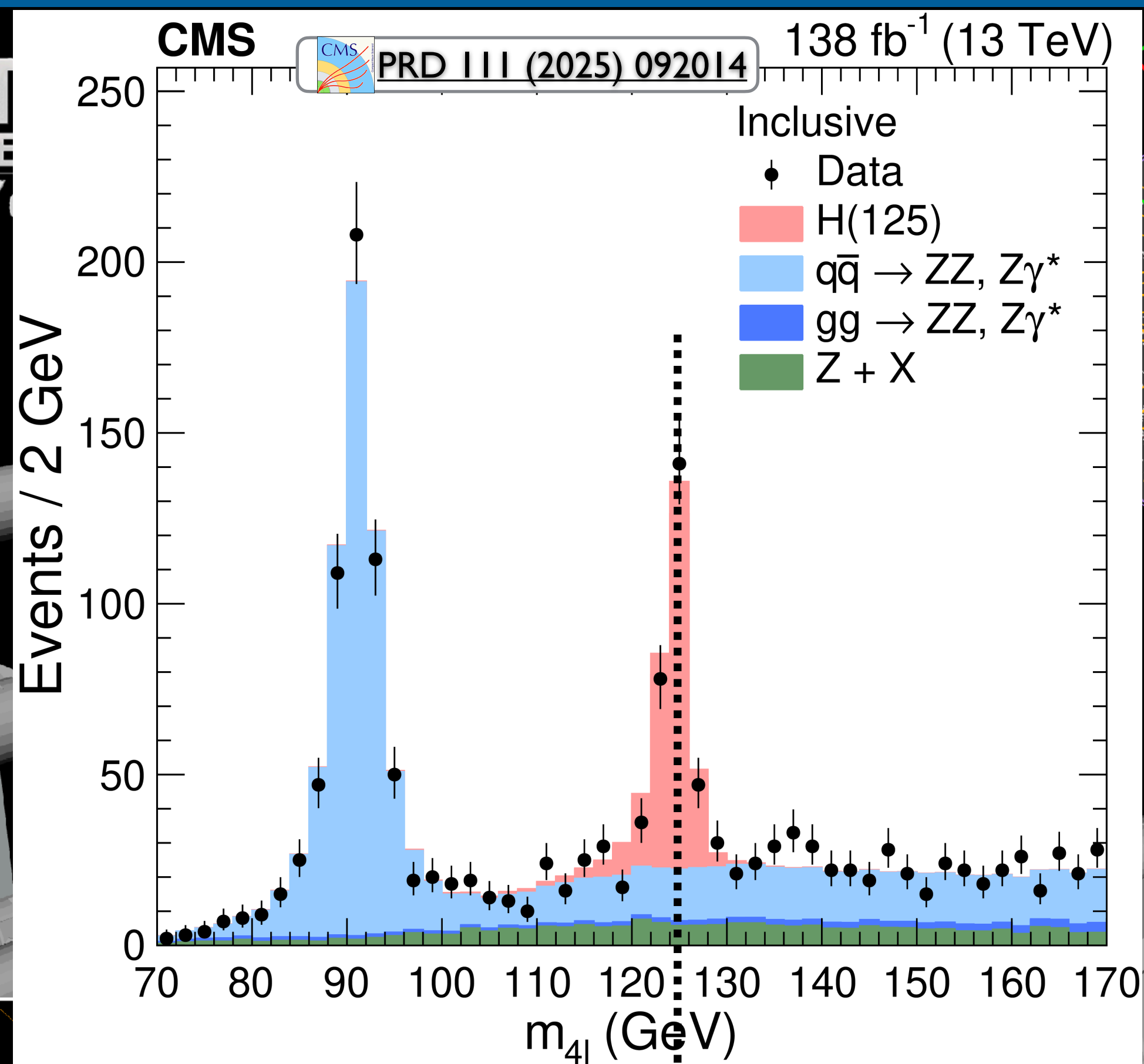
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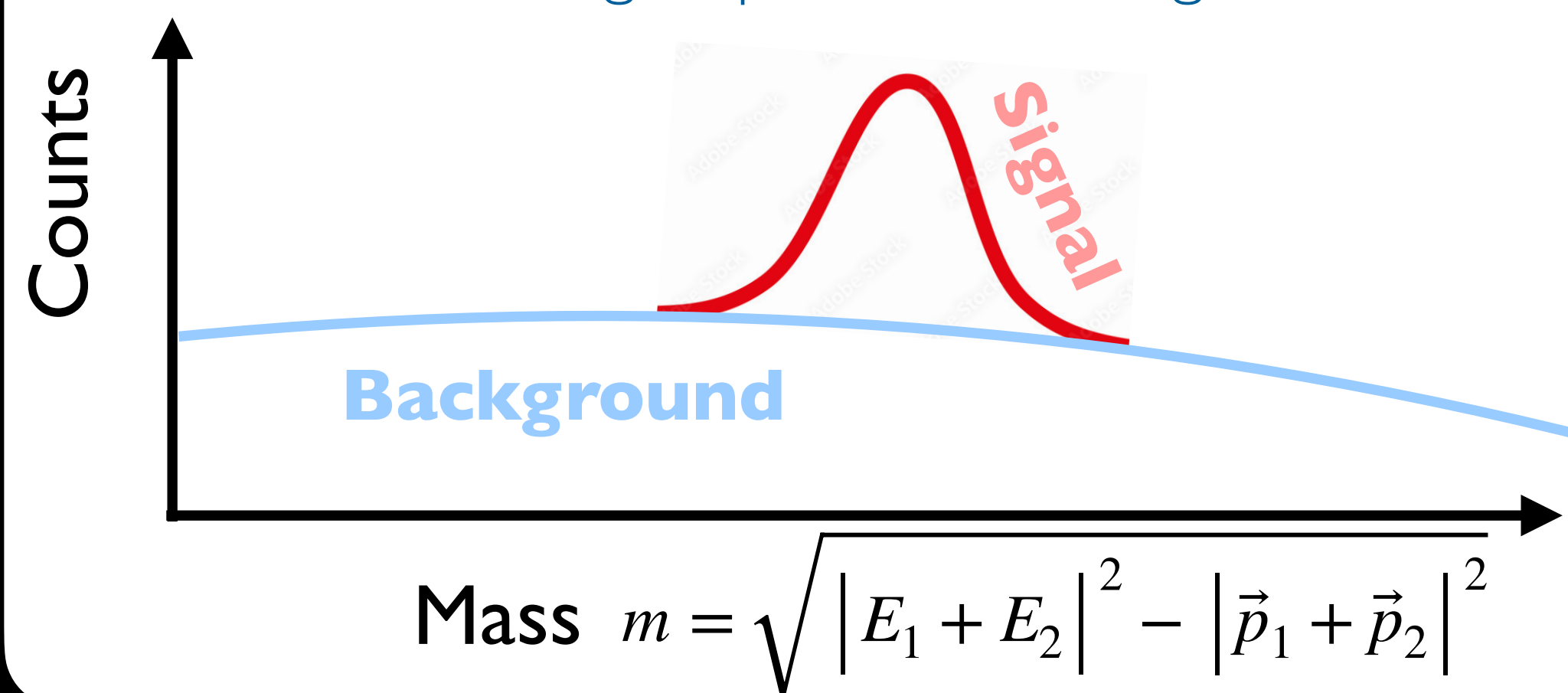
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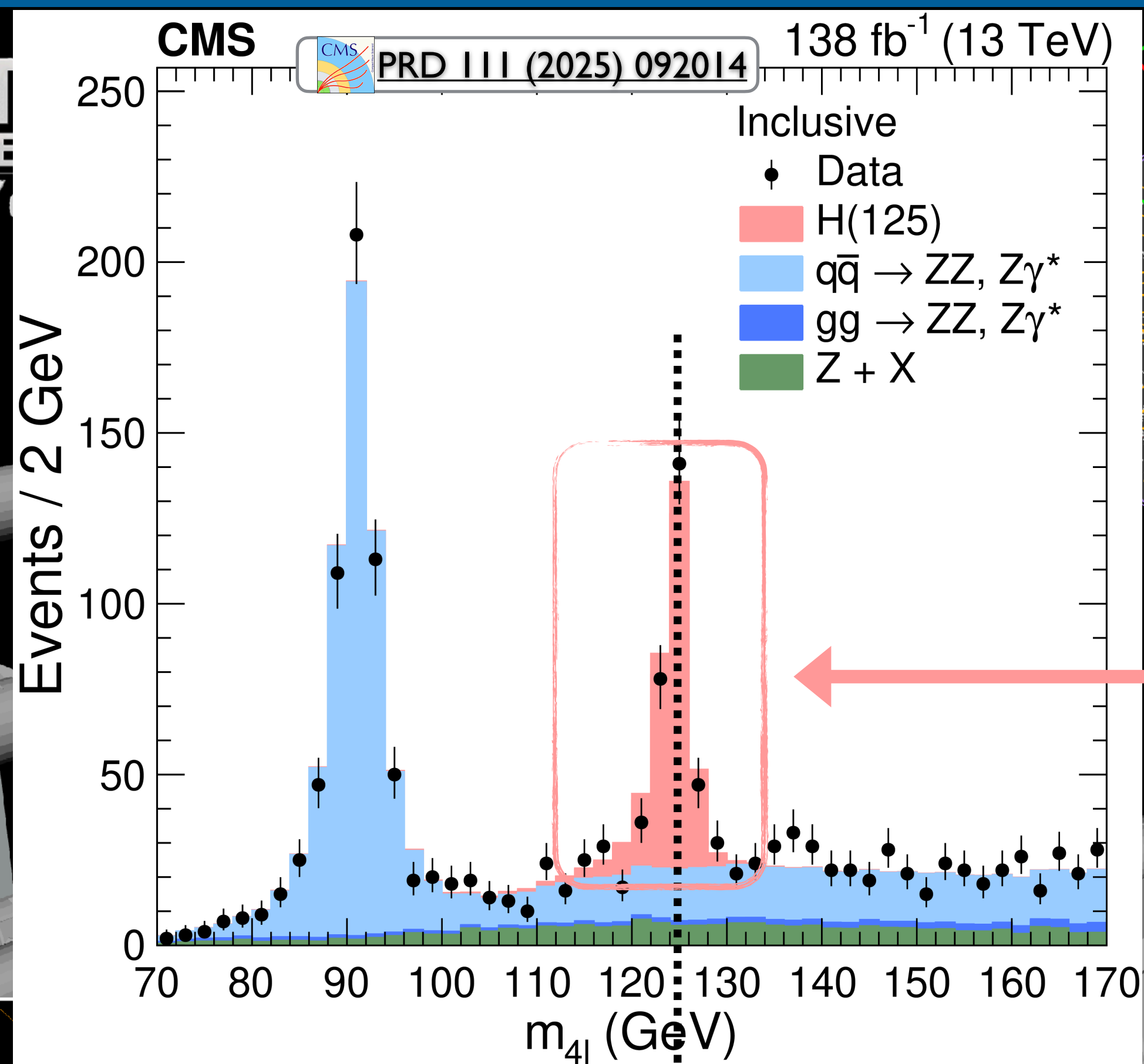
$m_H = \sqrt{2\lambda}v$ not predicted!

$m_H = 125.04 \pm 0.11(\text{stat}) \pm 0.05(\text{syst}) \text{ GeV}$

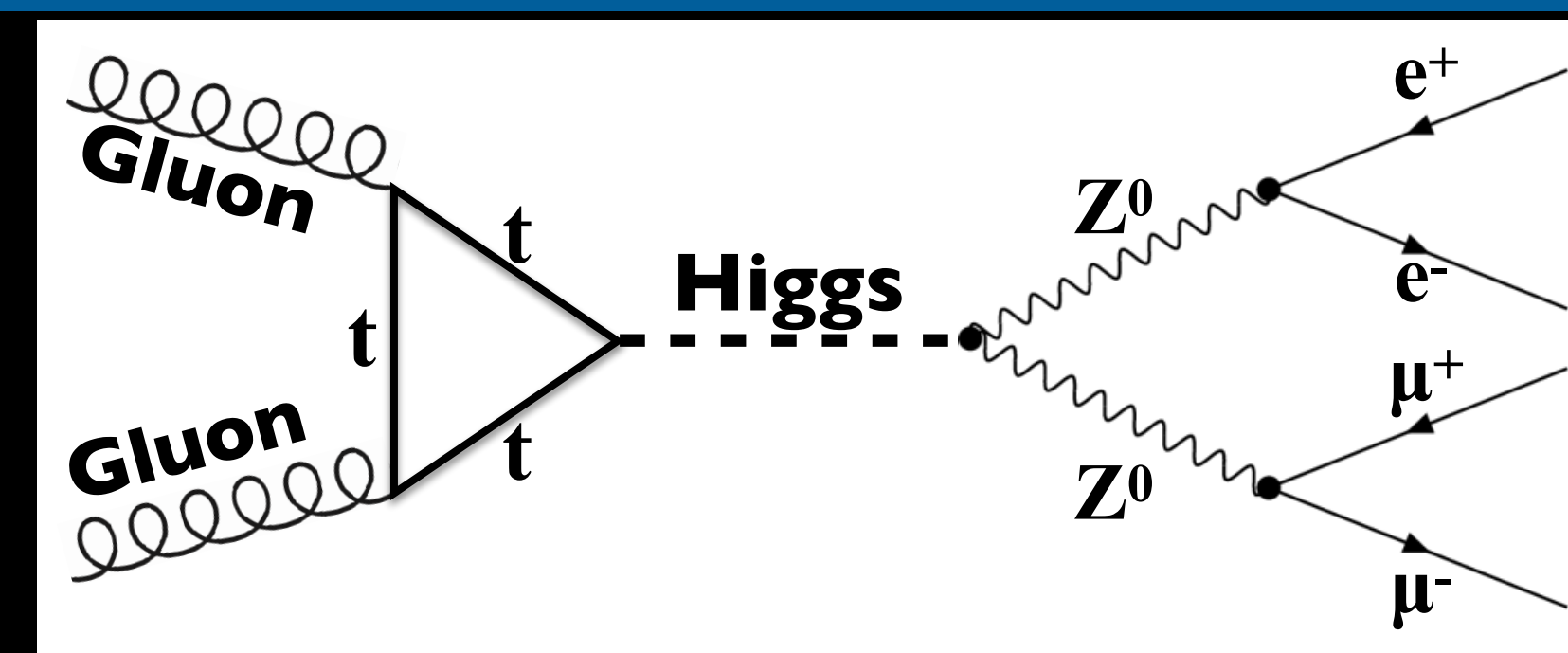
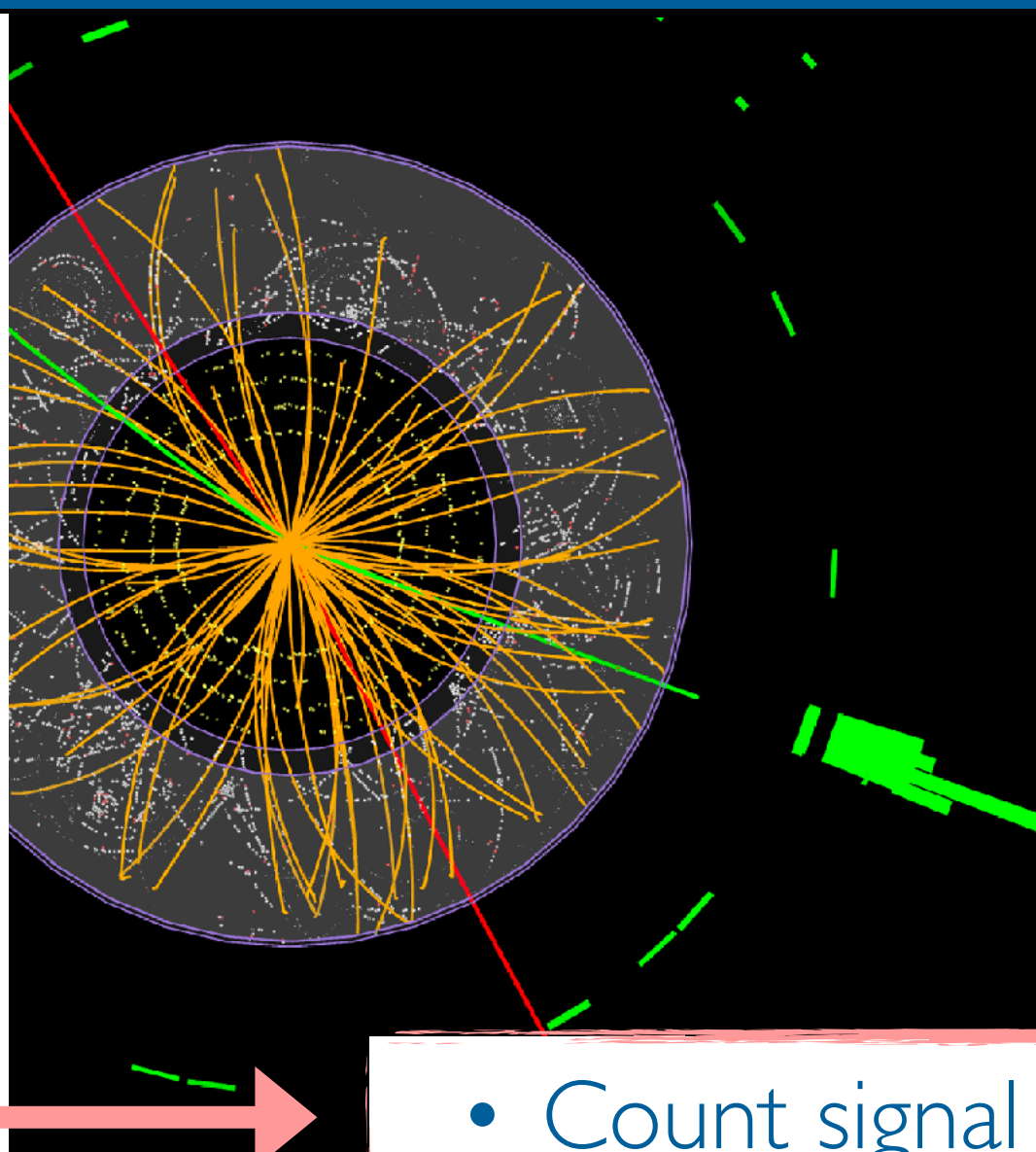
⇒ Now, everything else is calculable



How do we “see” the Higgs boson? GA



$m_H = \sqrt{2\lambda}v$ not predicted!
 $m_H = 125.04 \pm 0.11(\text{stat}) \pm 0.05(\text{syst})$ GeV
⇒ Now, everything else is calculable



“Clean” Signatures: leptons or photons, e.g.,

$$H \rightarrow ZZ^* \rightarrow 4\ell$$

- Count signal events:

$$N_{\text{sig}} = N_{\text{data}} - N_{\text{bkg}}$$

- With signal efficiency ϵ : $N_{\text{total signal}} = N_{\text{sig}}/\epsilon$

- and “size” of dataset:

$$\text{time integrated luminosity: } L_{\text{int}} = \int \mathcal{L} dt$$

- ➔ Cross section $\times$ branching ratio:

$$N_{\text{sig}}/(\epsilon \times L_{\text{int}}) = \sigma(pp \rightarrow H) \times \mathcal{B}(H \rightarrow ZZ^* \rightarrow 4\ell)$$

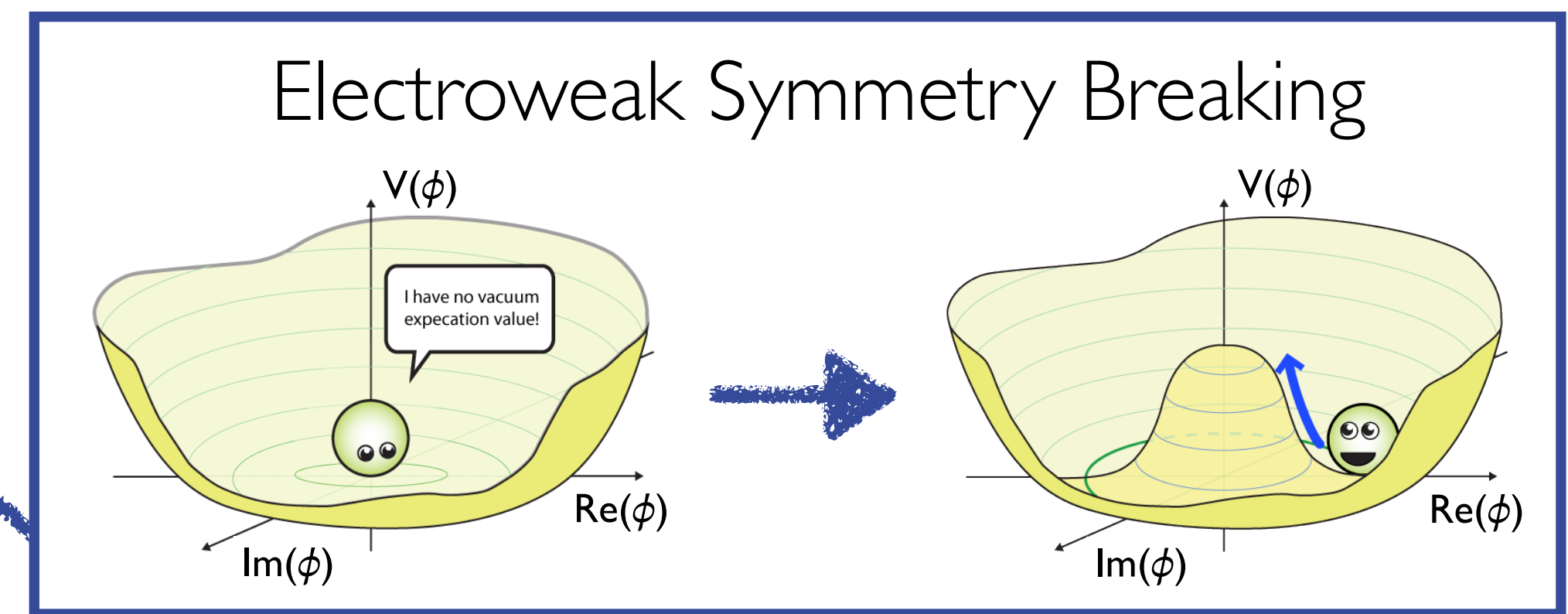
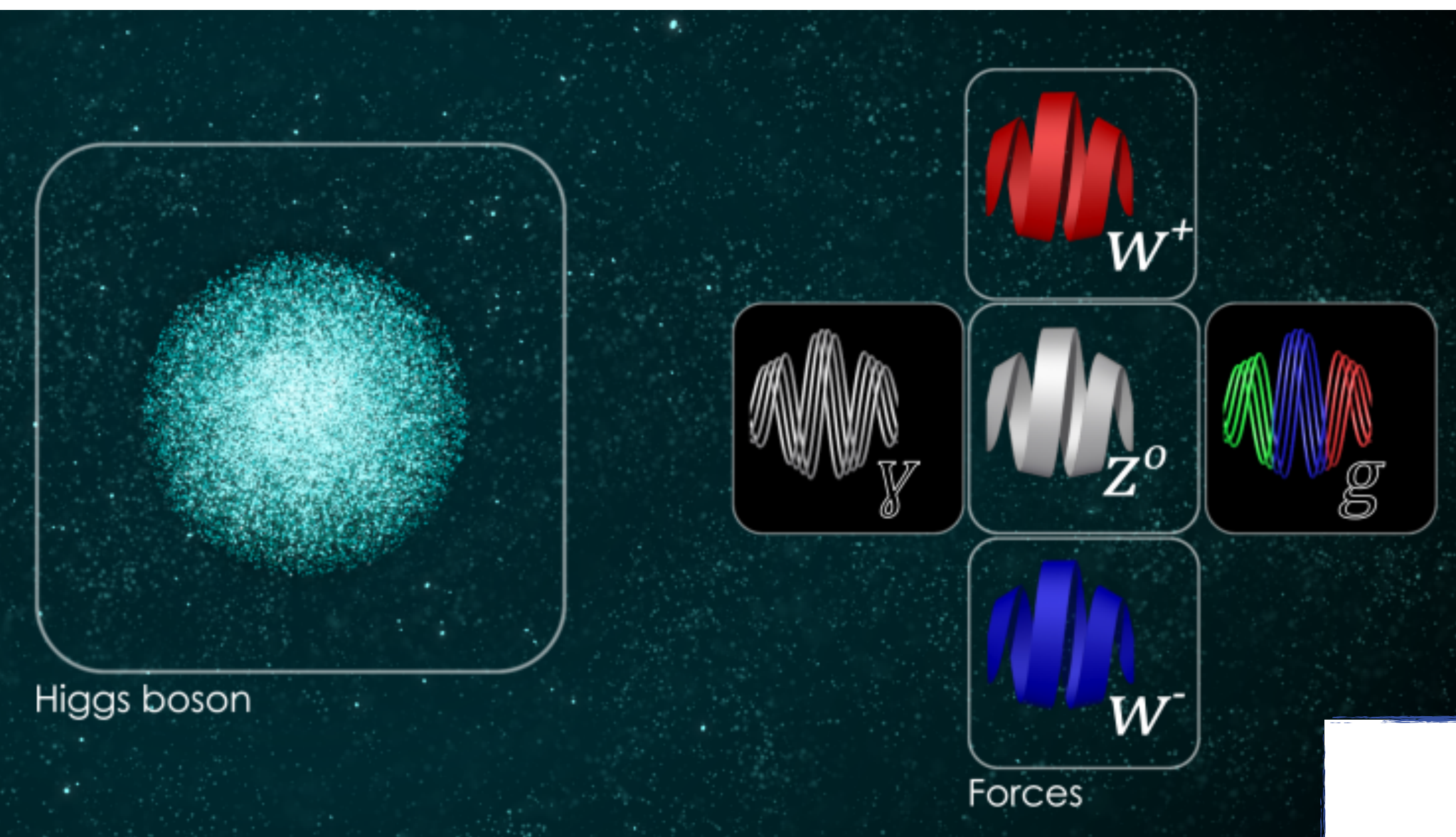
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I. Higgs Couplings to Bosons

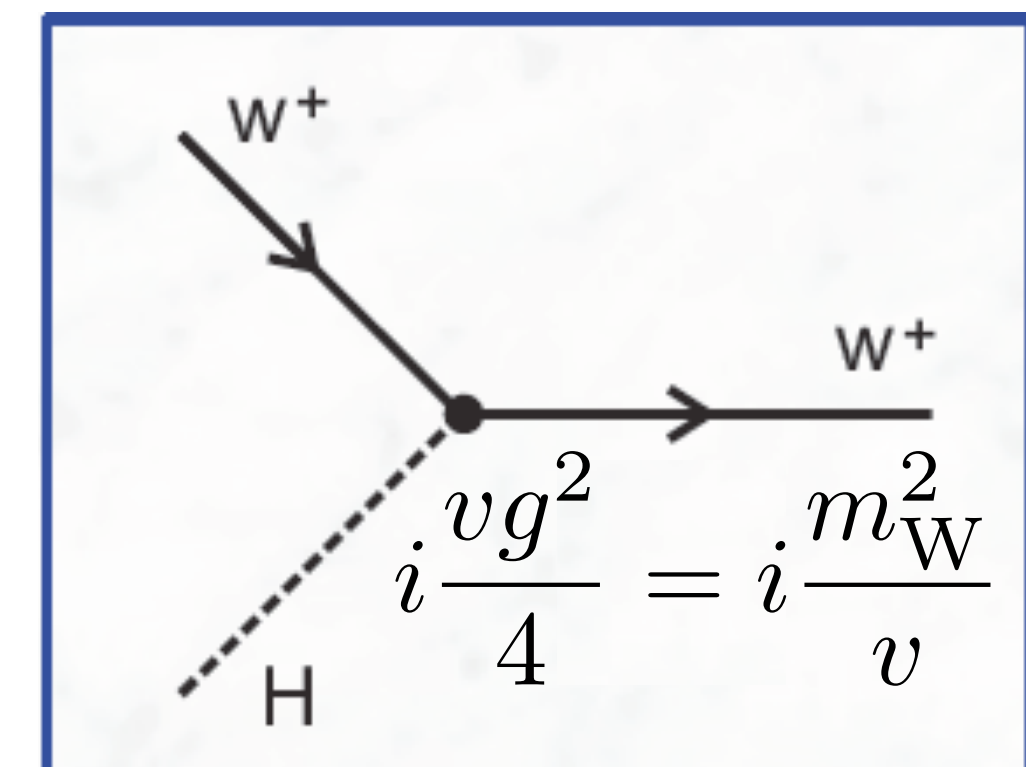


$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^2 - \mu^2 \phi^2 - \lambda \phi^4 + y_f \phi \psi^2$$



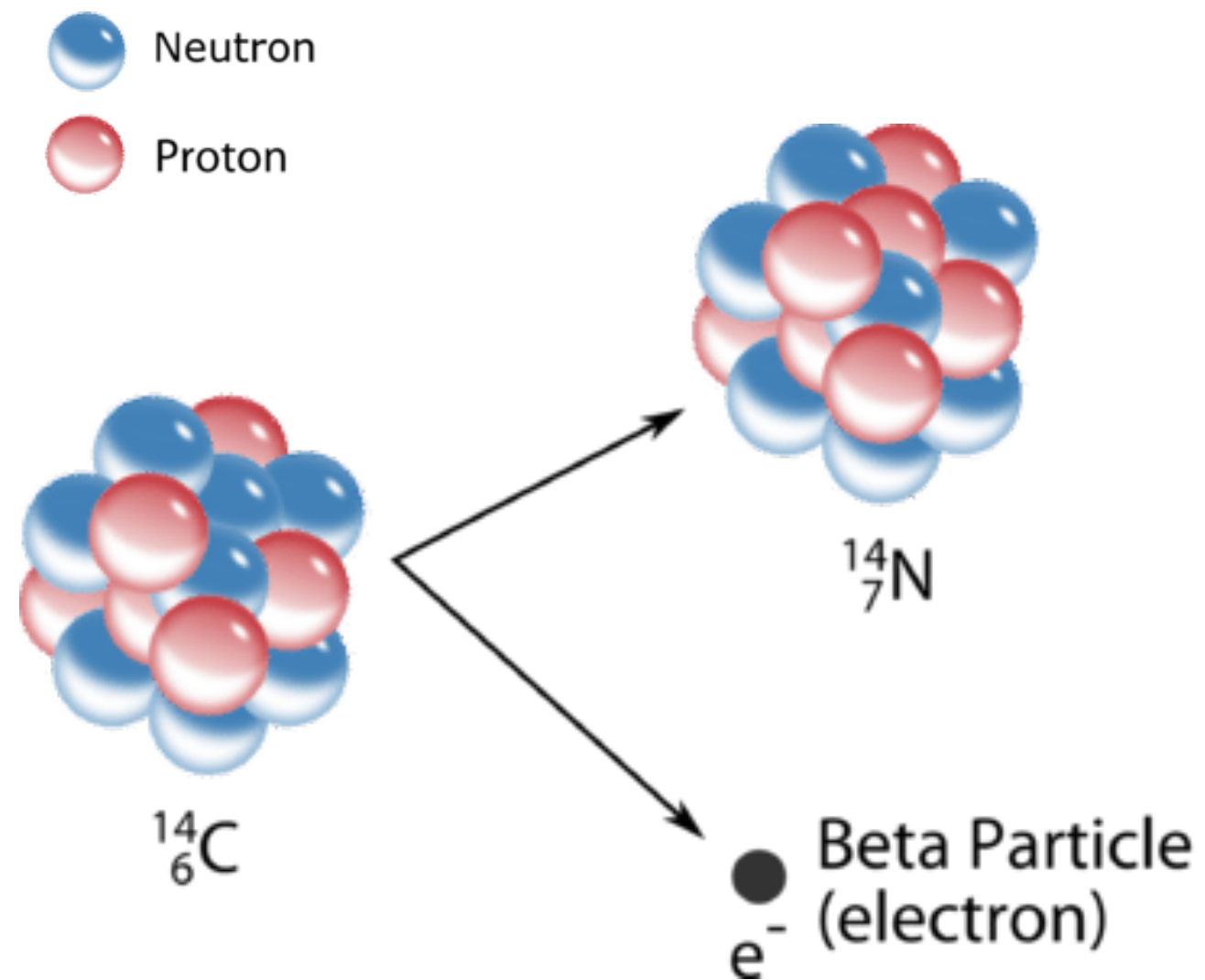
$$m_W = \frac{vg}{2}$$

direct connection

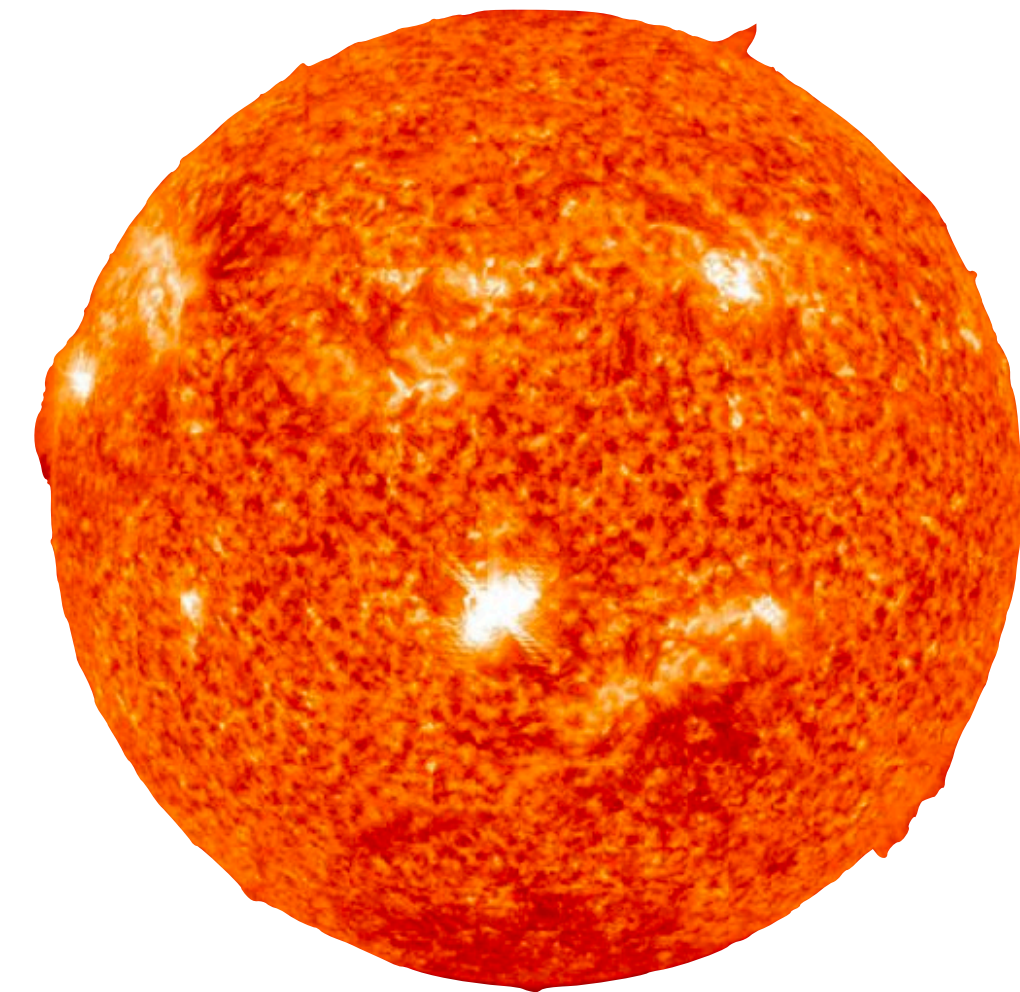
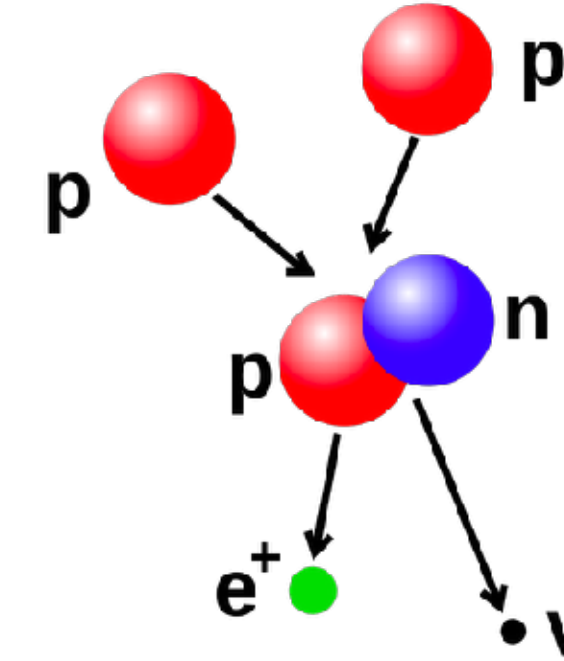




I. Higgs Couplings to Bosons



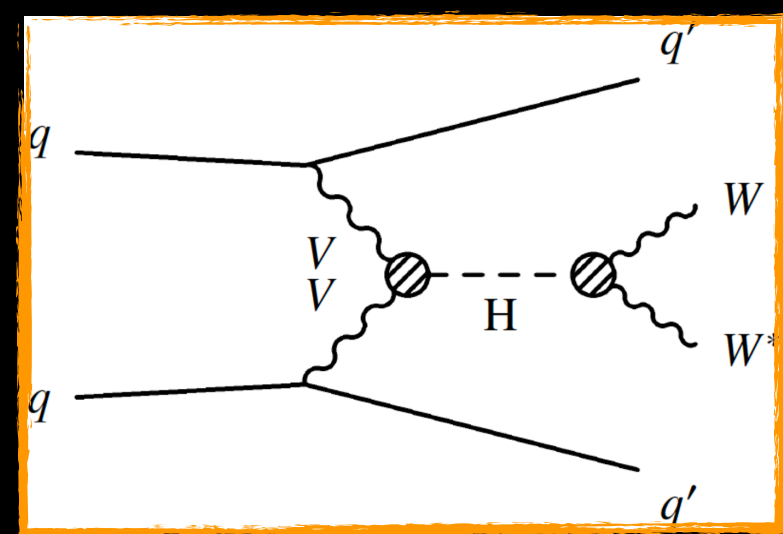
$$\text{rate} \propto \frac{1}{m_W^4}$$



**W-boson mass (m_W) sets
rate of radioactive β -decay
and burning of the sun**



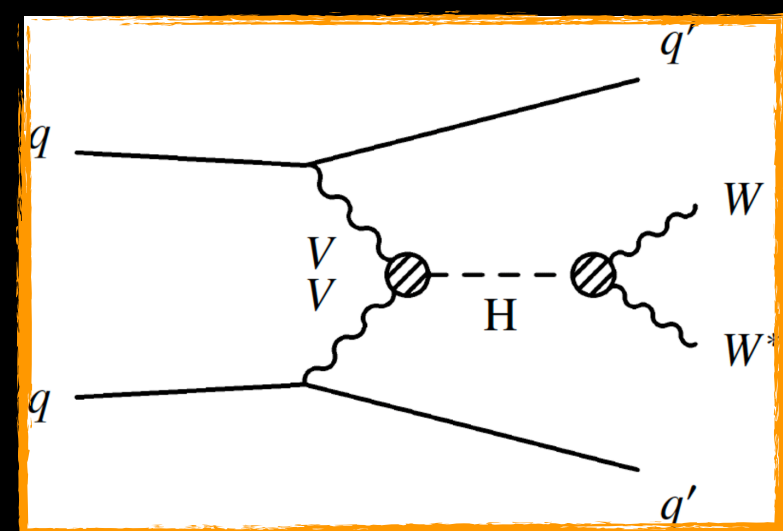
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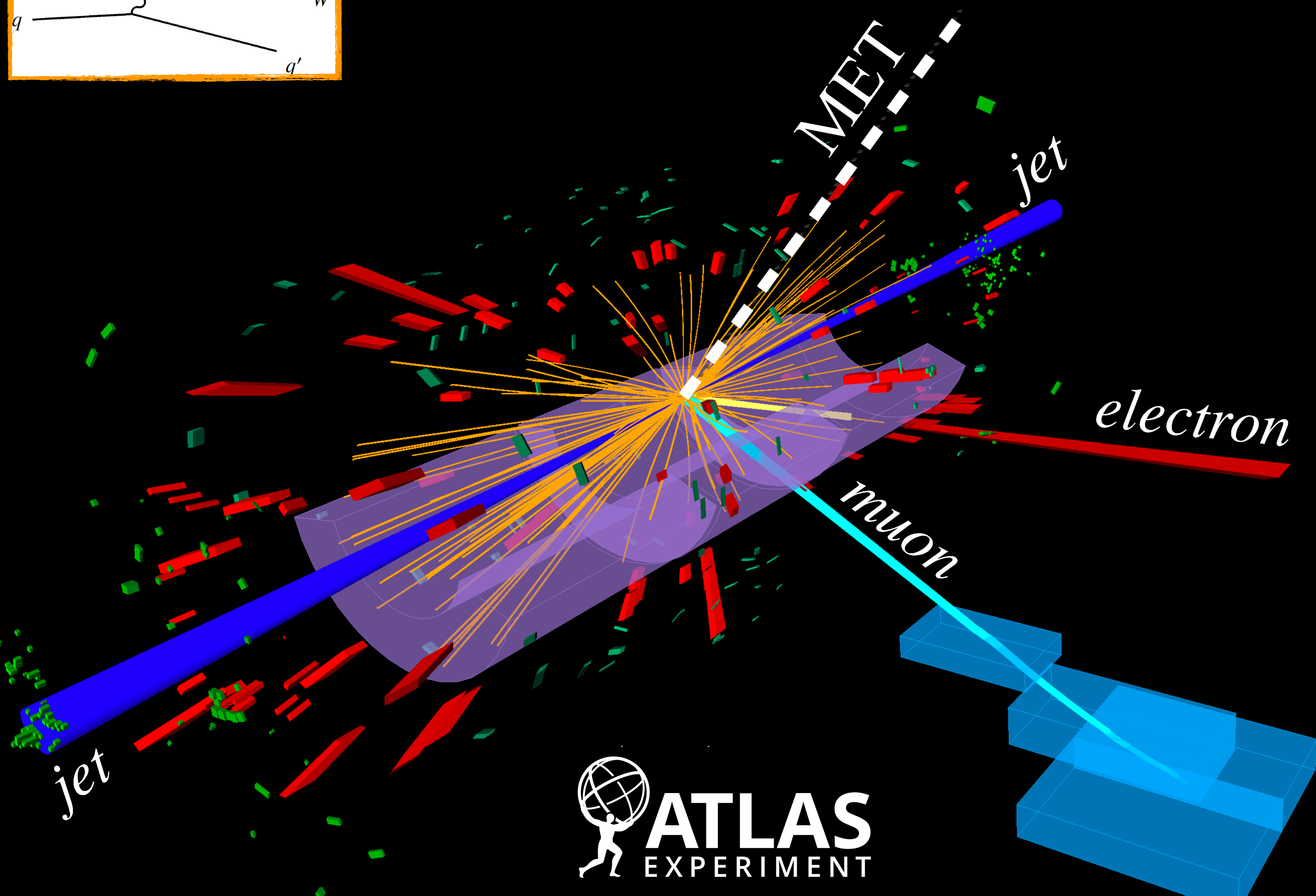
$$\text{VBF } H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$$



I. Higgs Couplings to Bosons

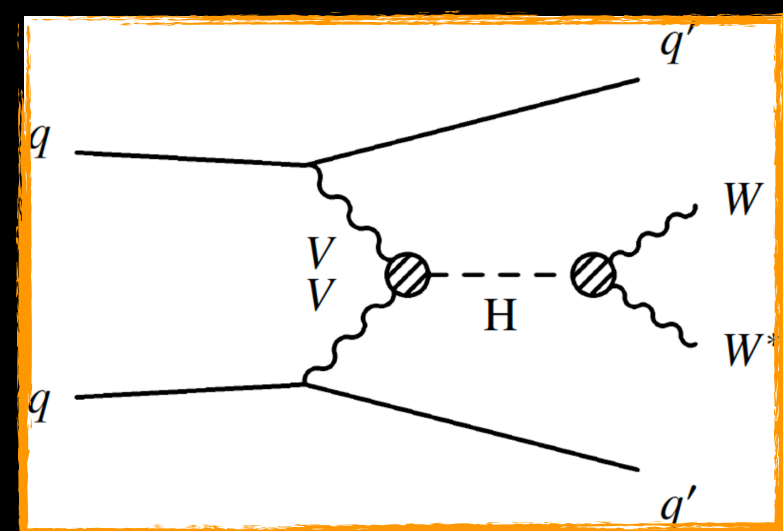


$$\text{VBF } H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$$





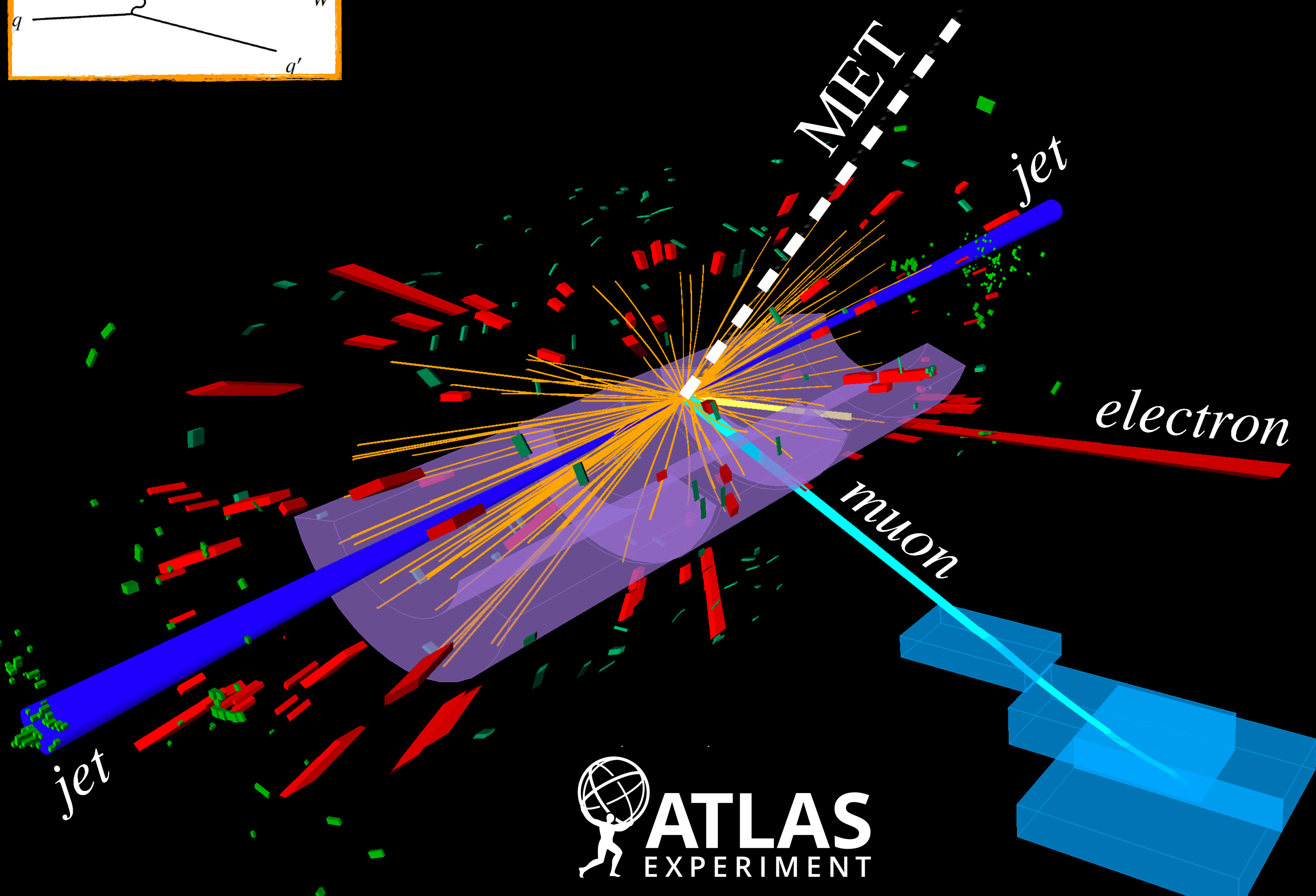
I. Higgs Couplings to Bosons



VBF $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

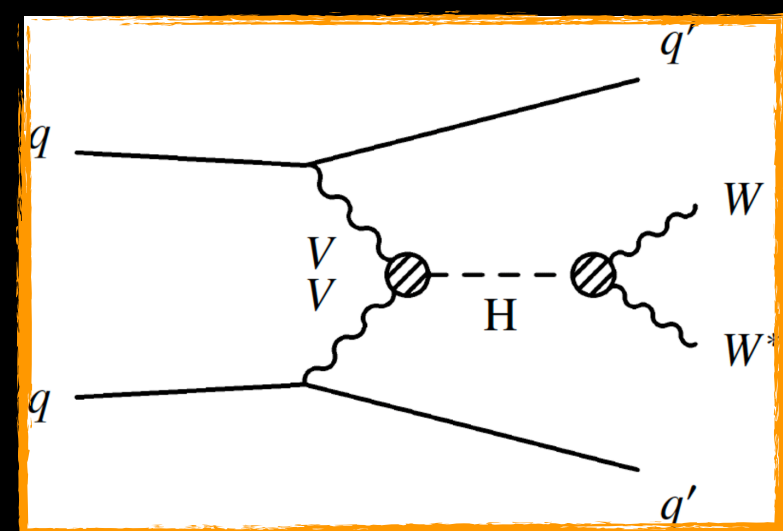
$$\mathcal{B}_{\text{SM}}(H \rightarrow WW^*) \approx 22\%$$

$$- \mathcal{B}_{\text{SM}}(H \rightarrow WW^* \rightarrow \ell\nu\ell\nu) \approx 1\%$$





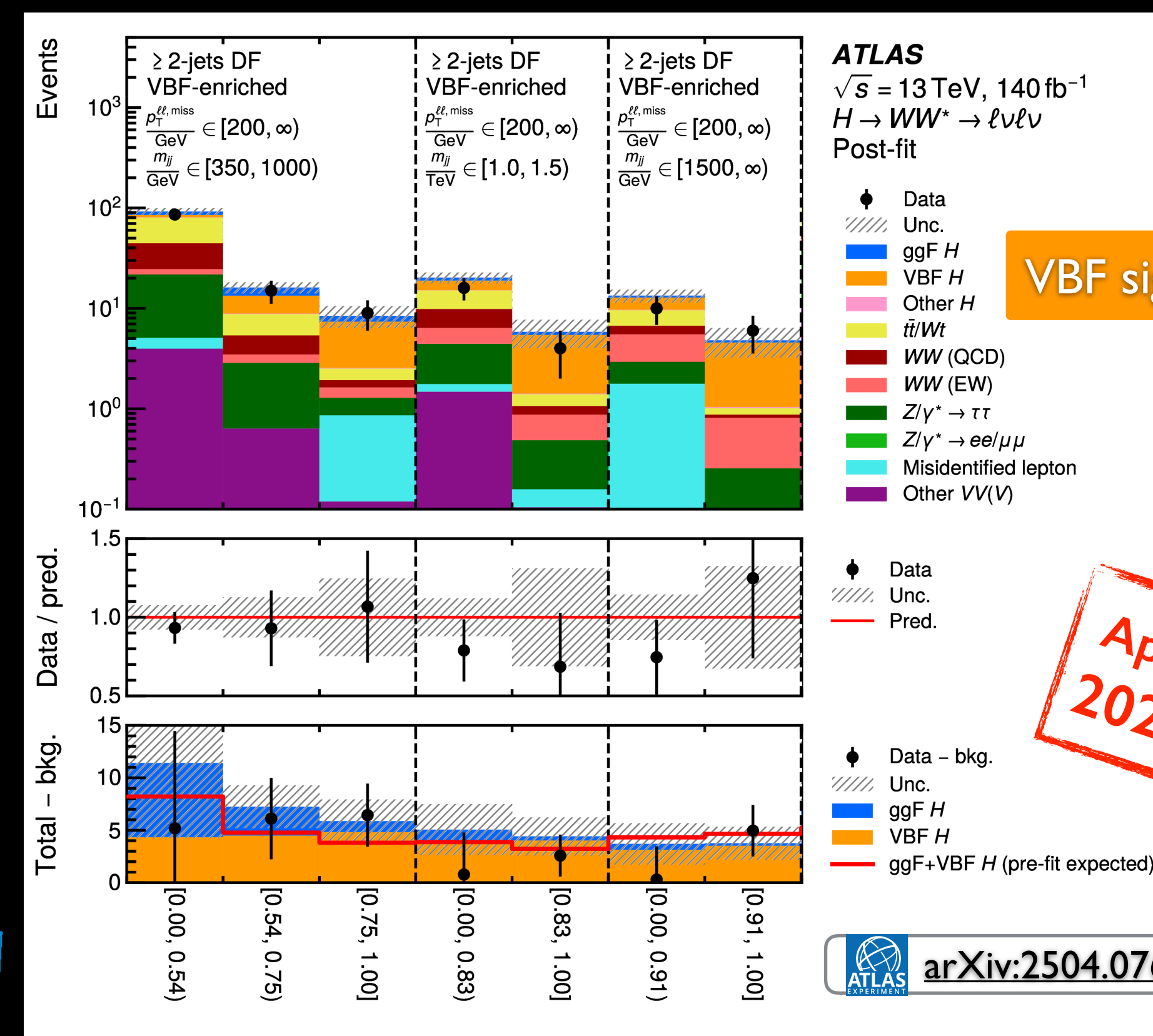
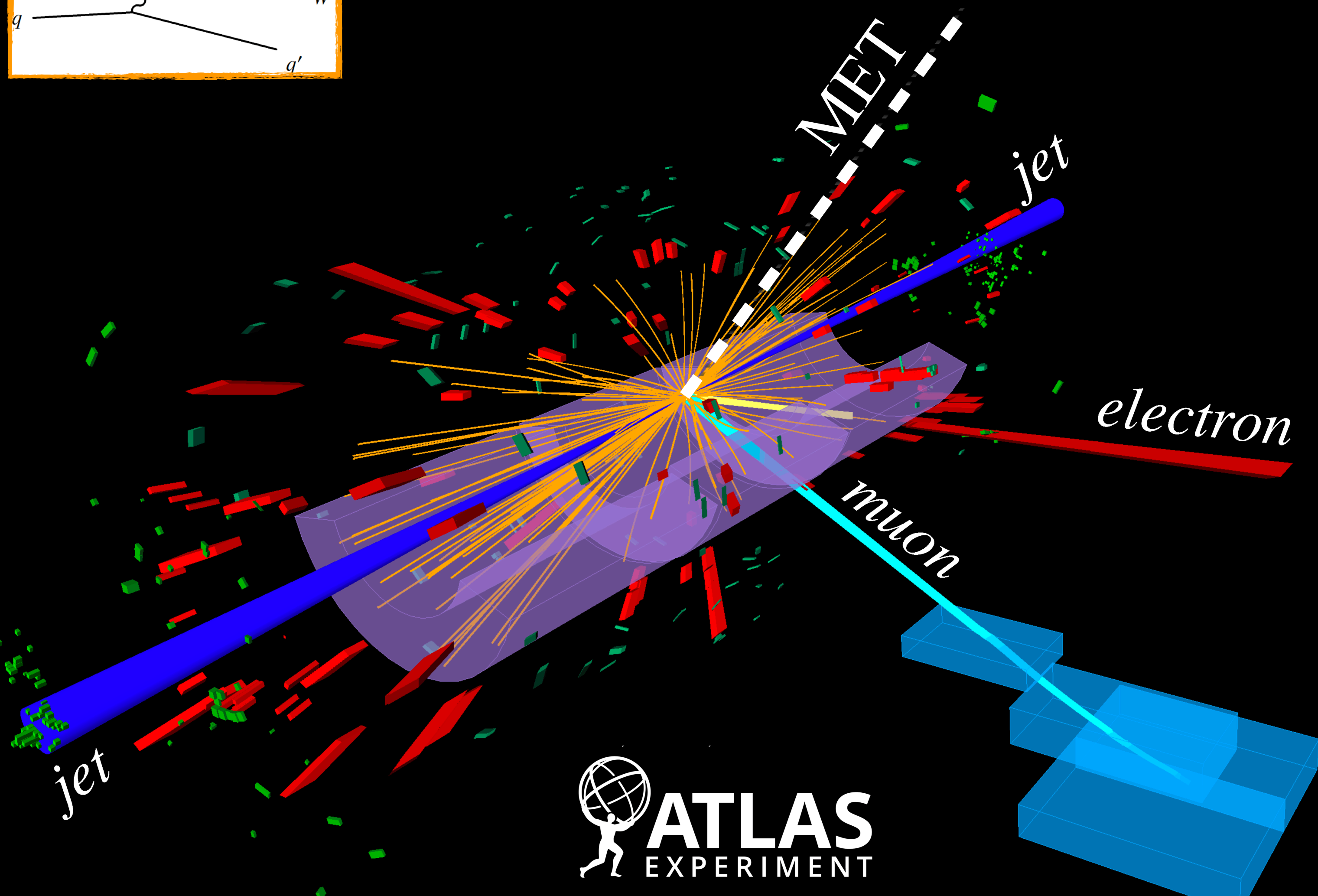
I. Higgs Couplings to Bosons



$$\text{VBF } H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$$

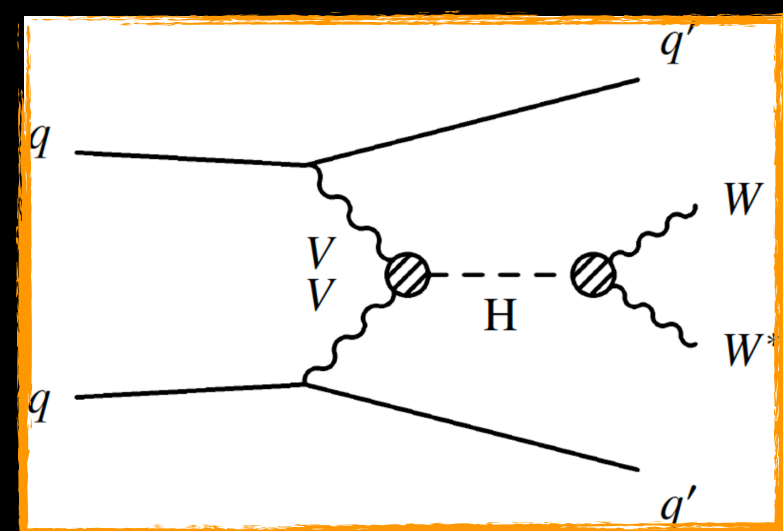
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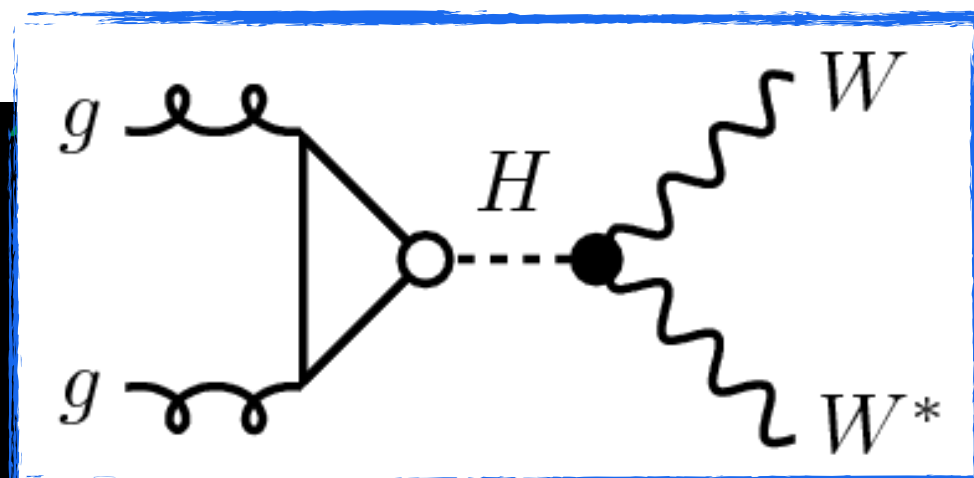
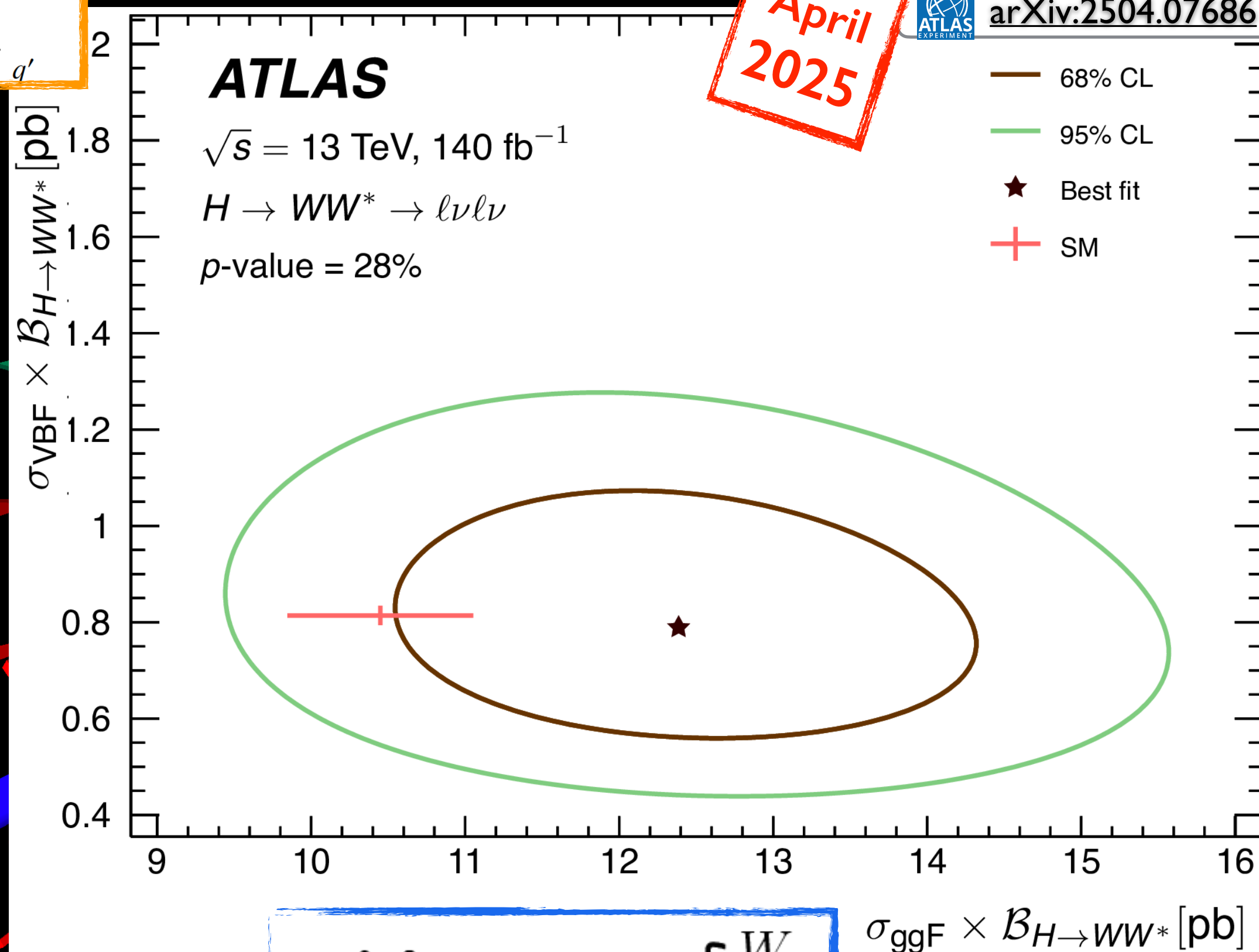




I. Higgs Couplings to Bosons

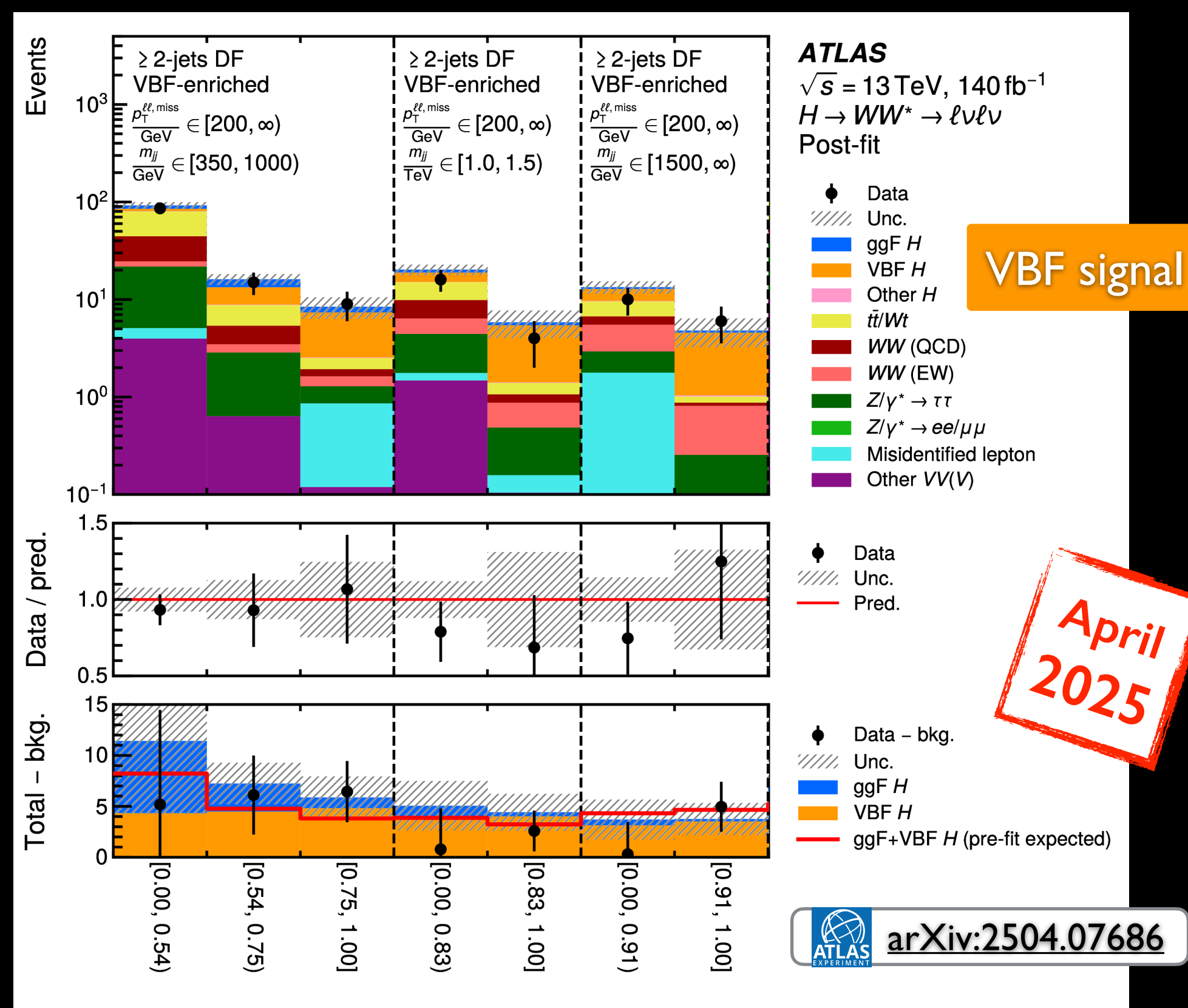


$$\text{VBF } H \rightarrow WW^* \rightarrow \ell\ell\ell\ell$$



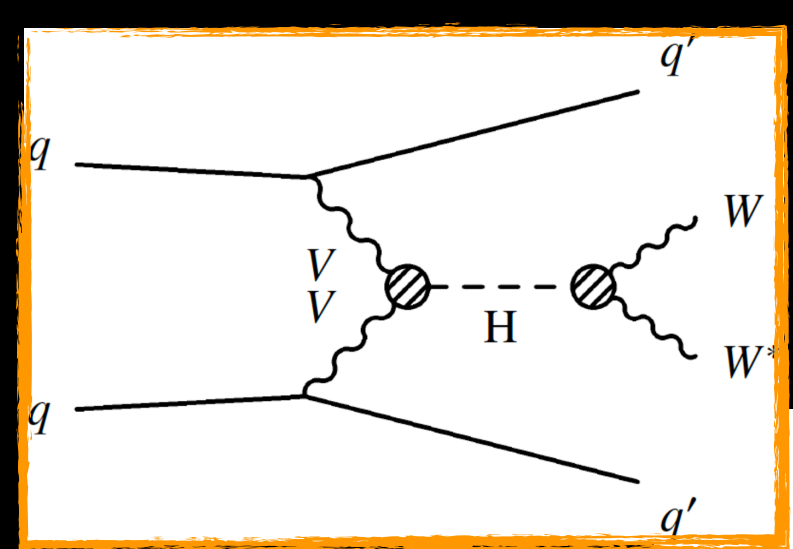
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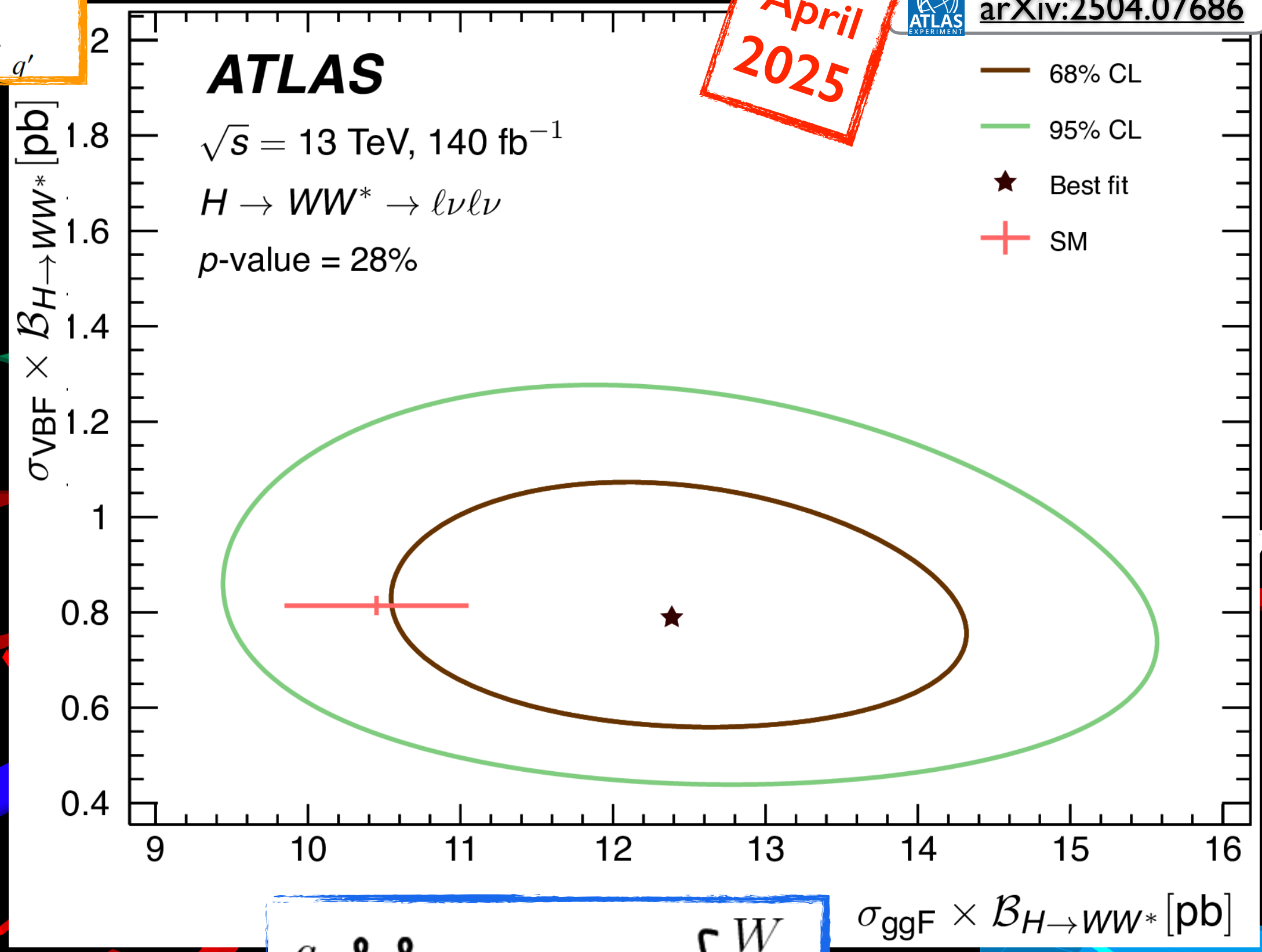




I. Higgs Couplings to Bosons

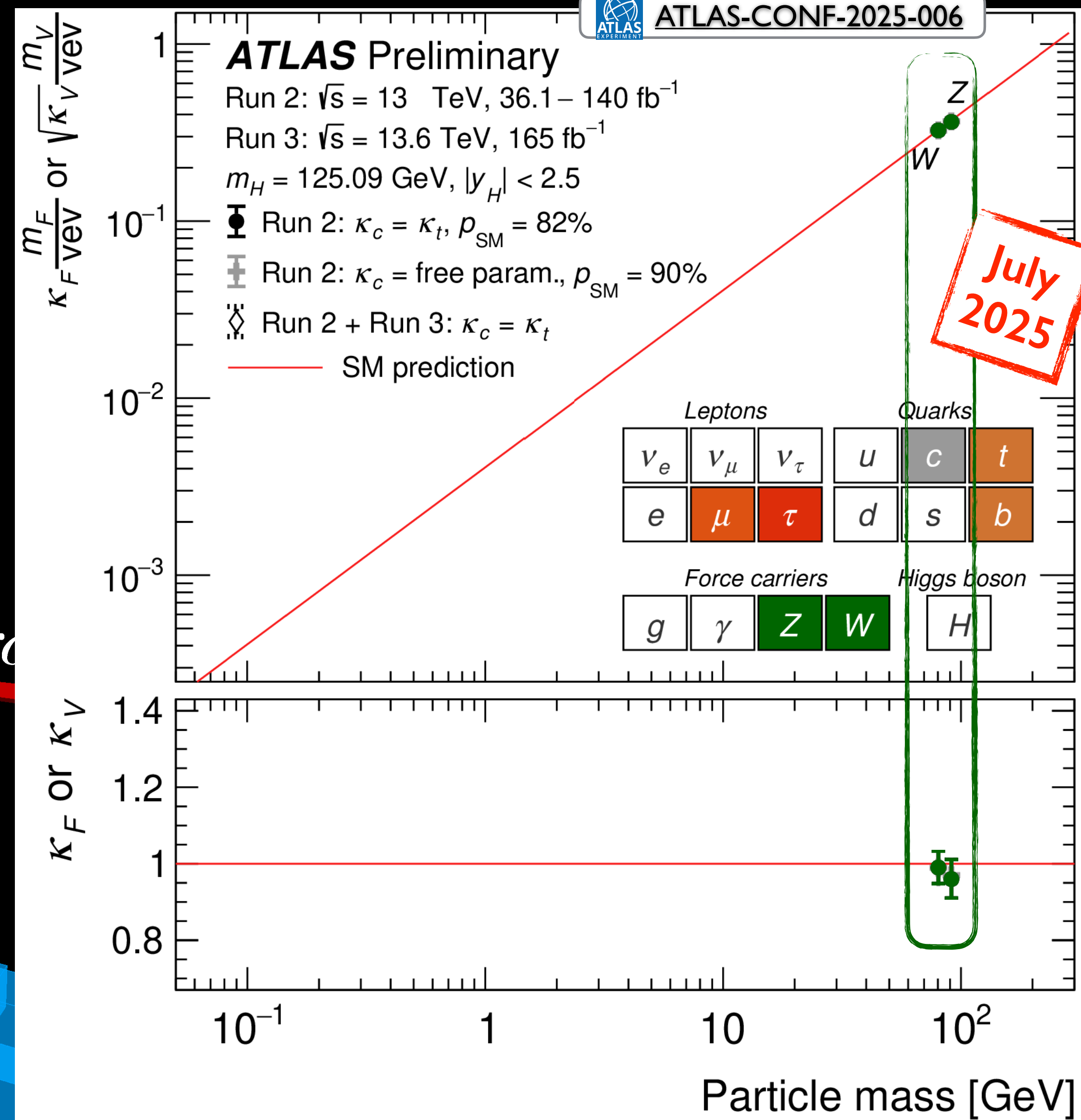
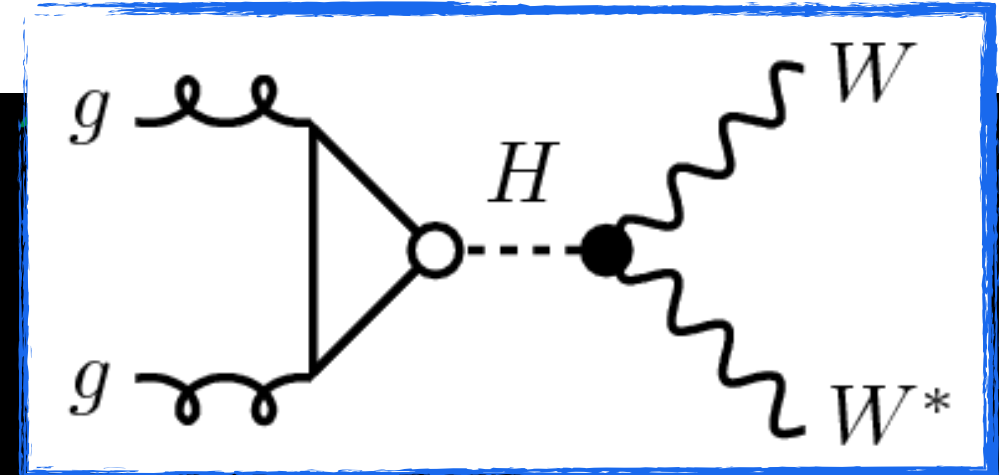


$$\text{VBF } H \rightarrow WW^* \rightarrow \ell\ell\ell\ell$$



April 2025

arXiv:2504.07686



July 2025

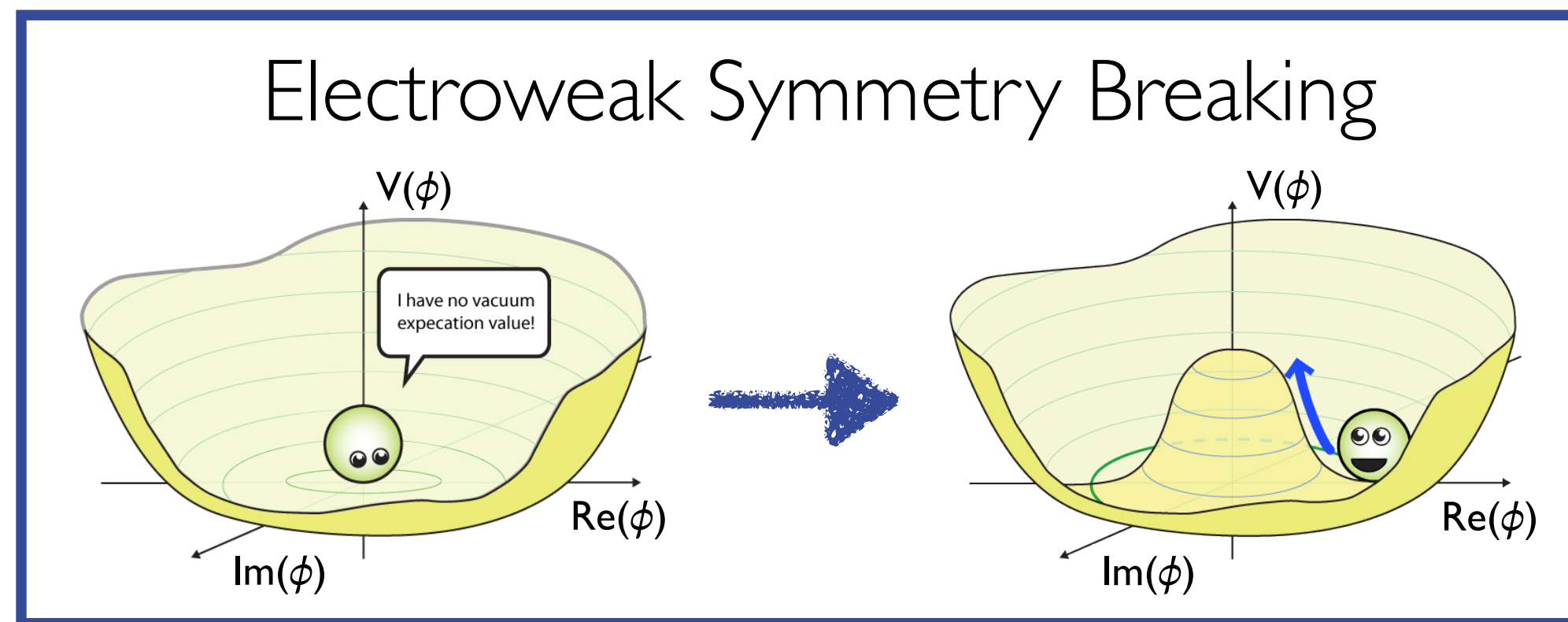
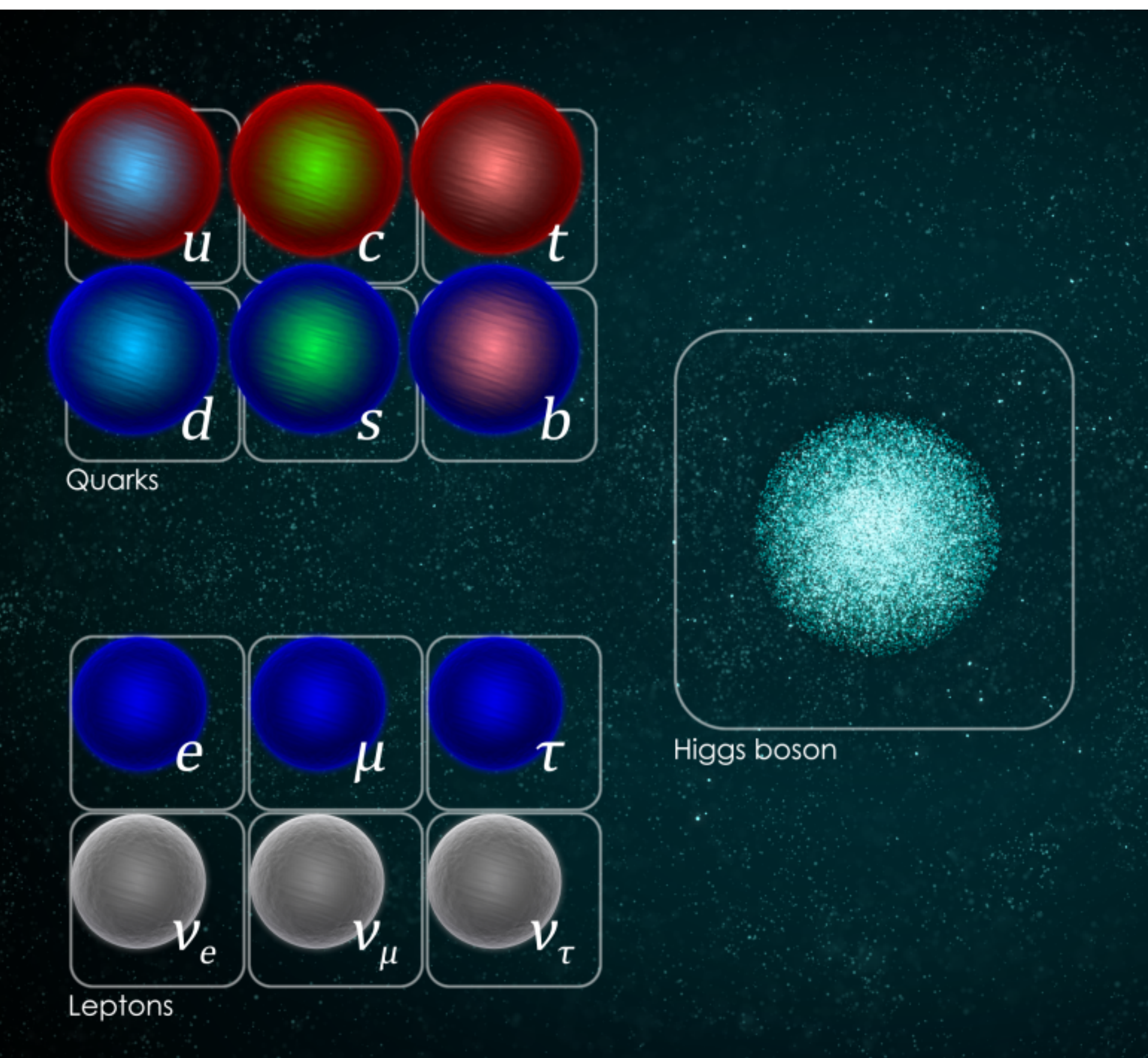
jet



2. Higgs Couplings to Fermions



$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^2 - \mu^2 \phi^2 - \lambda \phi^4 + \boxed{y_f \phi \psi^2}$$



$$\boxed{m_f = \frac{y_f v}{\sqrt{2}}}$$

direct connection

$$-i \frac{m_f}{v} = -i \frac{g}{2} \frac{m_f}{m_W}$$

Fundamentally independent from mass generation for gauge bosons!



2. Higgs Couplings to Fermions



Electron mass (m_e) sets size of atoms & energy levels of chemical reactions



2. Higgs Couplings to Fermions



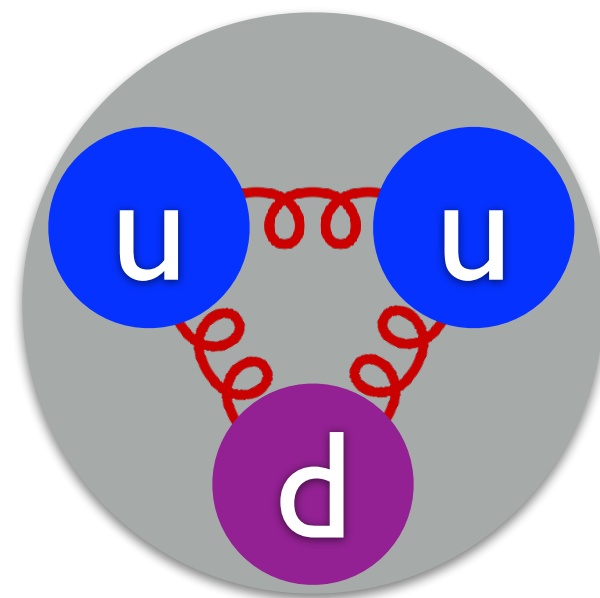
$$\text{atomic radius} \propto \frac{1}{m_e}$$

Electron mass (m_e) sets size of atoms & energy levels of chemical reactions

Up quarks (mass ~ 2.2 MeV) *lighter than* down quarks (mass ~ 4.7 MeV)

Proton:

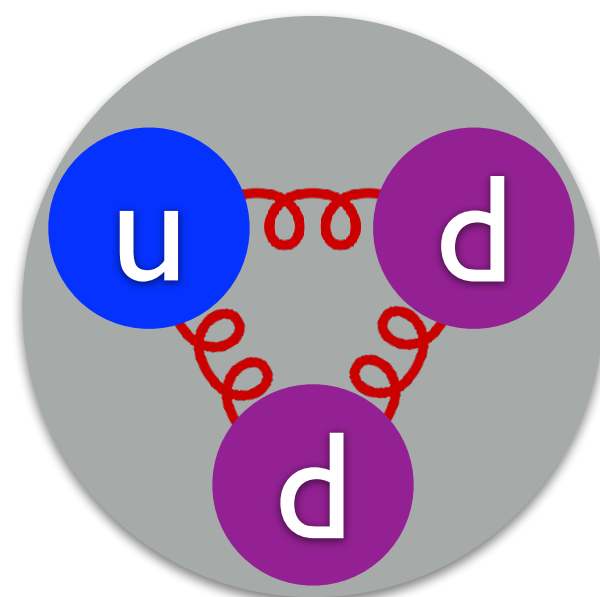
(up|**up**|down)



Mass: $2.2 + 2.2 + 4.7$ MeV + EM+strong force = **938.3 MeV**

Neutron:

(up|**down**|down)

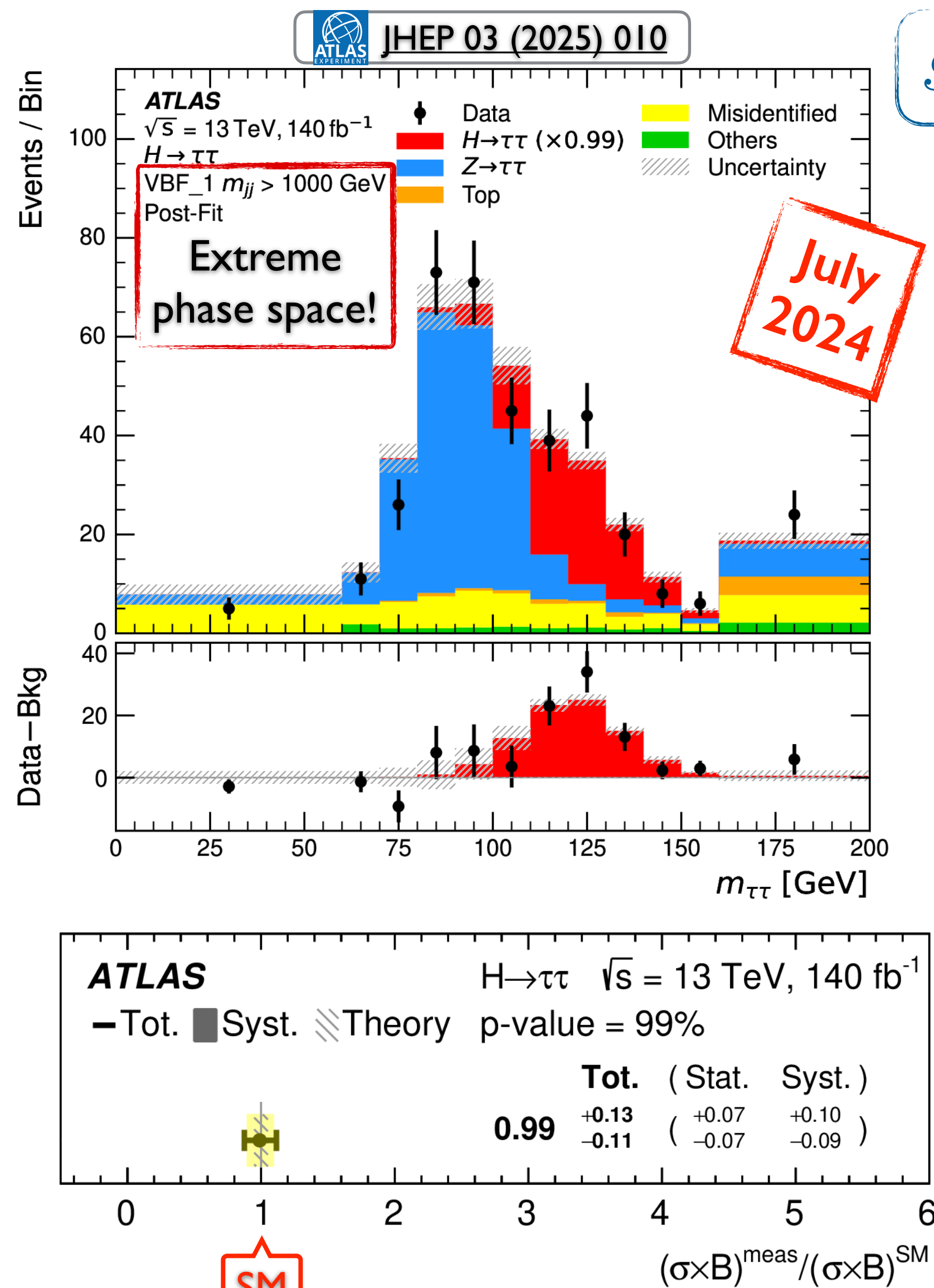


Mass: $2.2 + 4.7 + 4.7$ MeV + EM+strong force = **939.6 MeV**

Proton lighter than Neutron
 $\Rightarrow$ Protons are stable
 $\Rightarrow$ Hydrogen atom

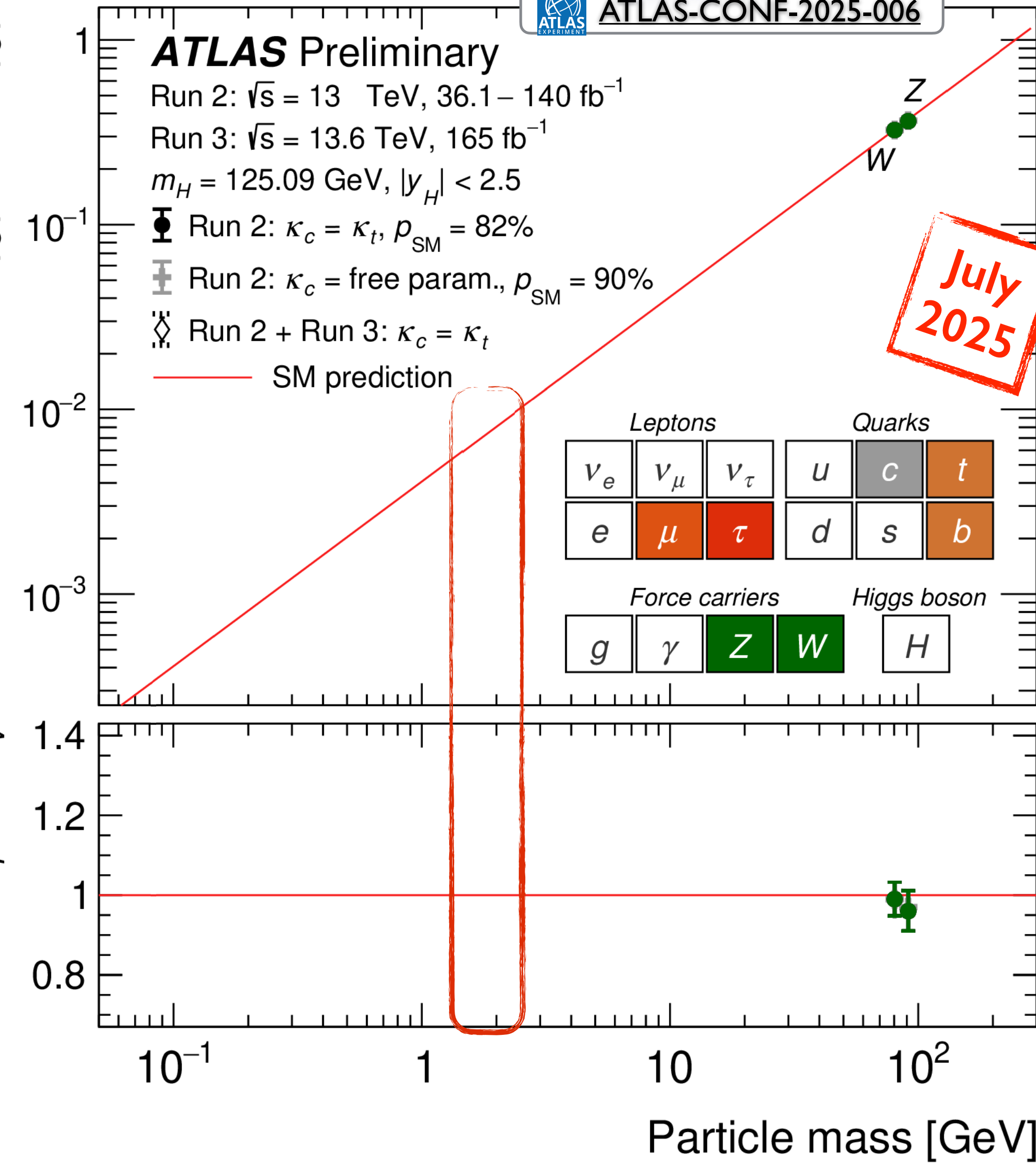


$$H \rightarrow \tau\tau$$



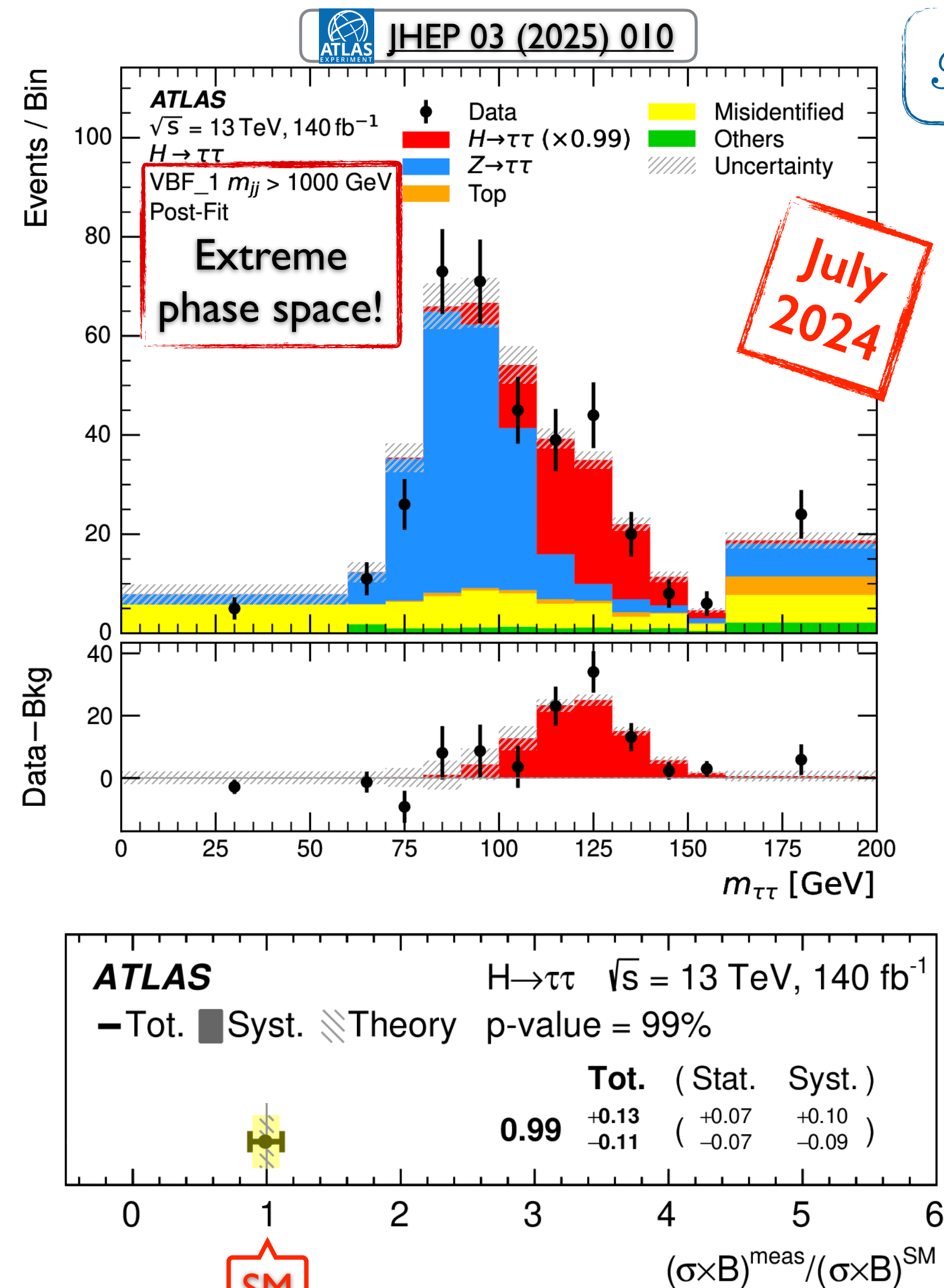
$$\mathcal{B}_{\text{SM}}(H \rightarrow \tau\tau) = 6.3 \%$$

$$\frac{m_V}{\kappa_F \text{ vev}} \text{ or } \sqrt{\kappa_V} \text{ vev}$$



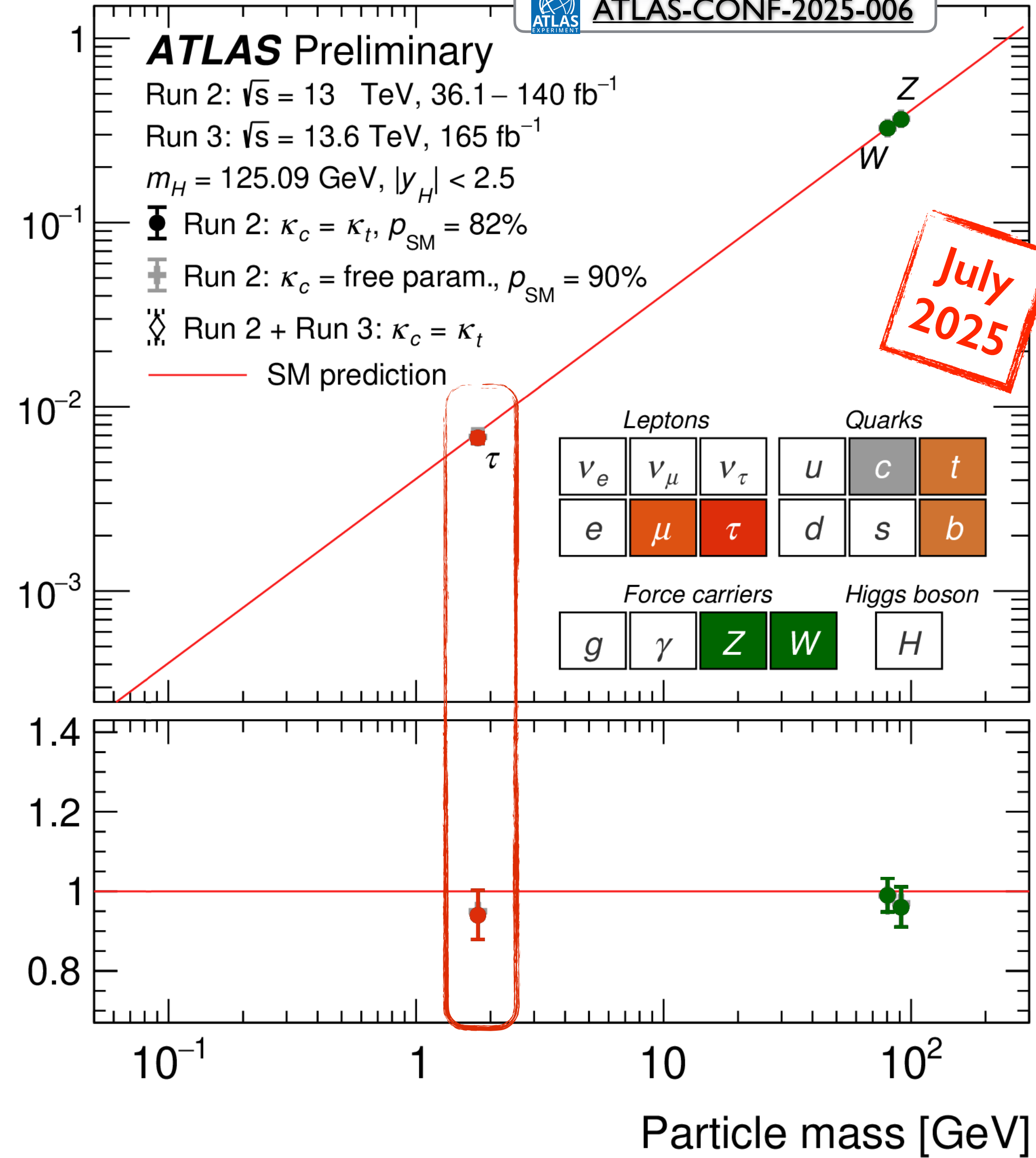


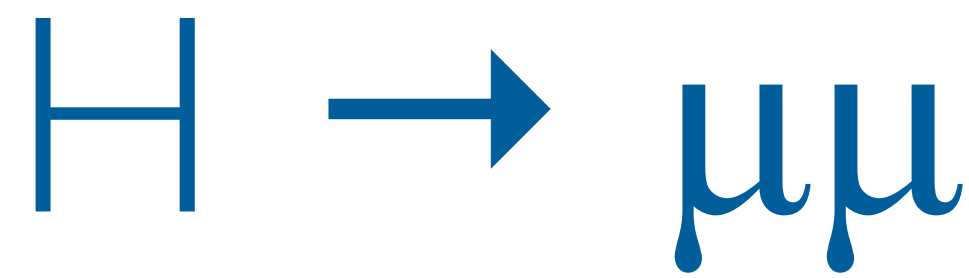
$$H \rightarrow \tau\tau$$



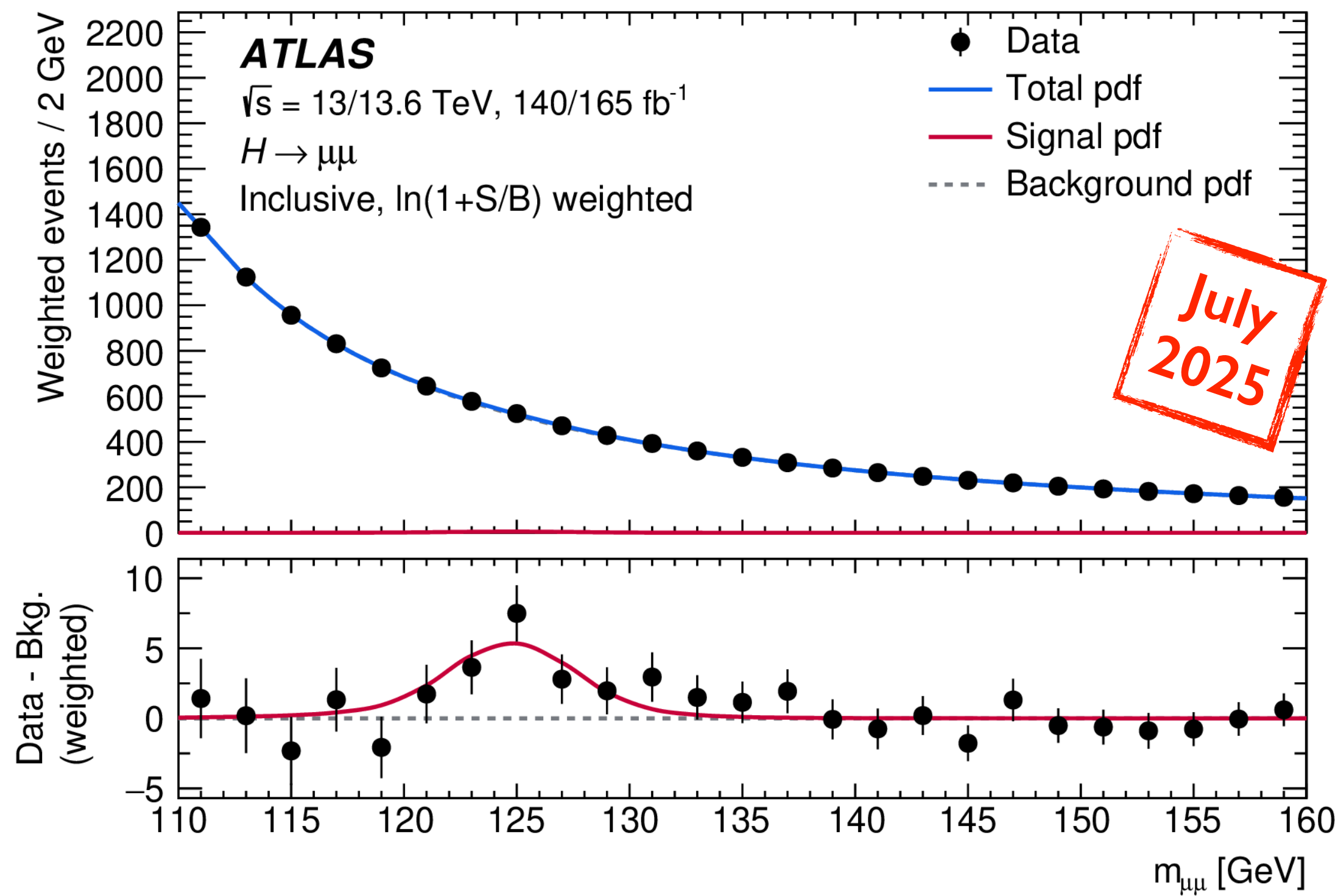
$$\mathcal{B}_{\text{SM}}(H \rightarrow \tau\tau) = 6.3 \%$$

$$\frac{m_V}{\kappa_F \text{ vev}} \text{ or } \sqrt{\kappa_V} \text{ vev}$$





$$\mathcal{B}_{\text{SM}}(H \rightarrow \mu\mu) = 2.18 \times 10^{-4}$$



arXiv:2507.03595

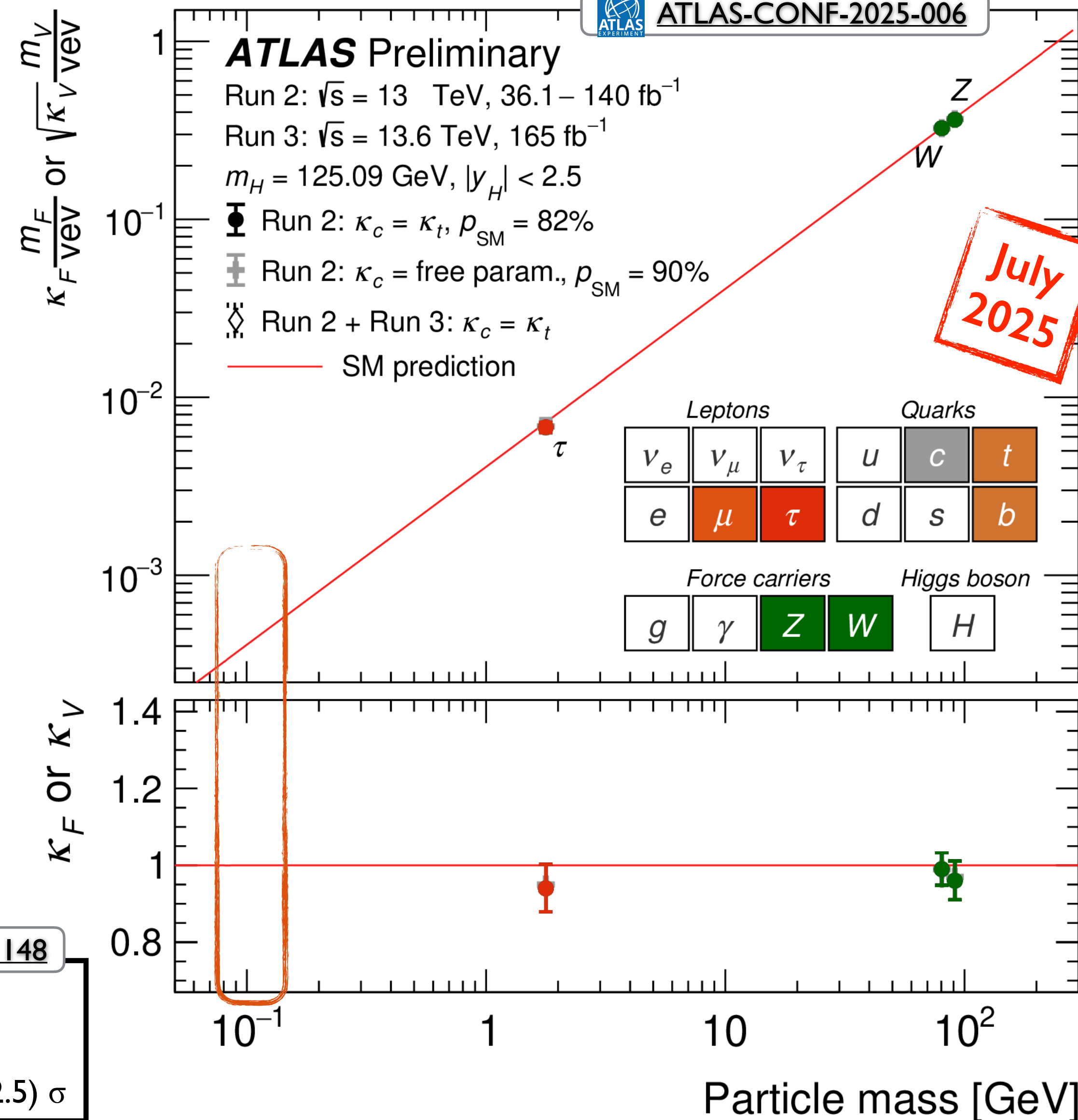
Results:

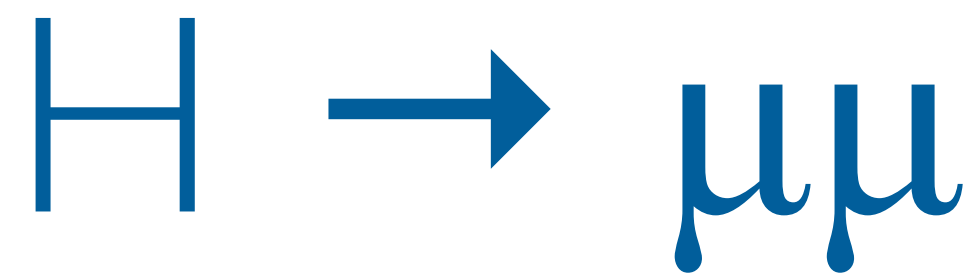
- Signal strength $\mu = 1.4 \pm 0.4$
- Observed (expected) significance: **3.4 (2.5) σ**

JHEP 01 (2021) 148

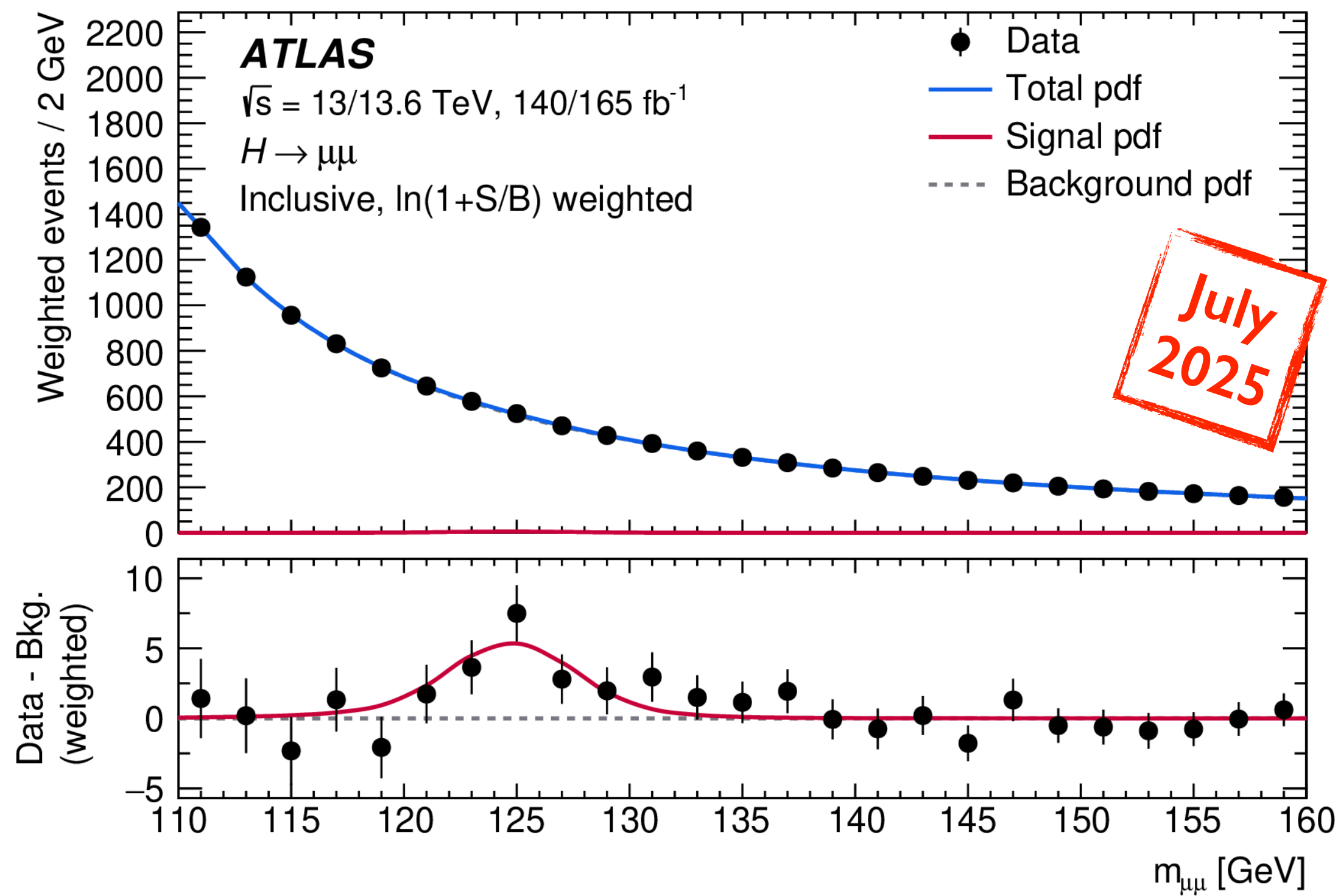
CMS Run-2 result:

- Signal strength $\mu = 1.19^{+0.44}_{-0.42}$
- Obs. (exp.) significance: **3.0 (2.5) σ**





$$\mathcal{B}_{\text{SM}}(H \rightarrow \mu\mu) = 2.18 \times 10^{-4}$$



arXiv:2507.03595

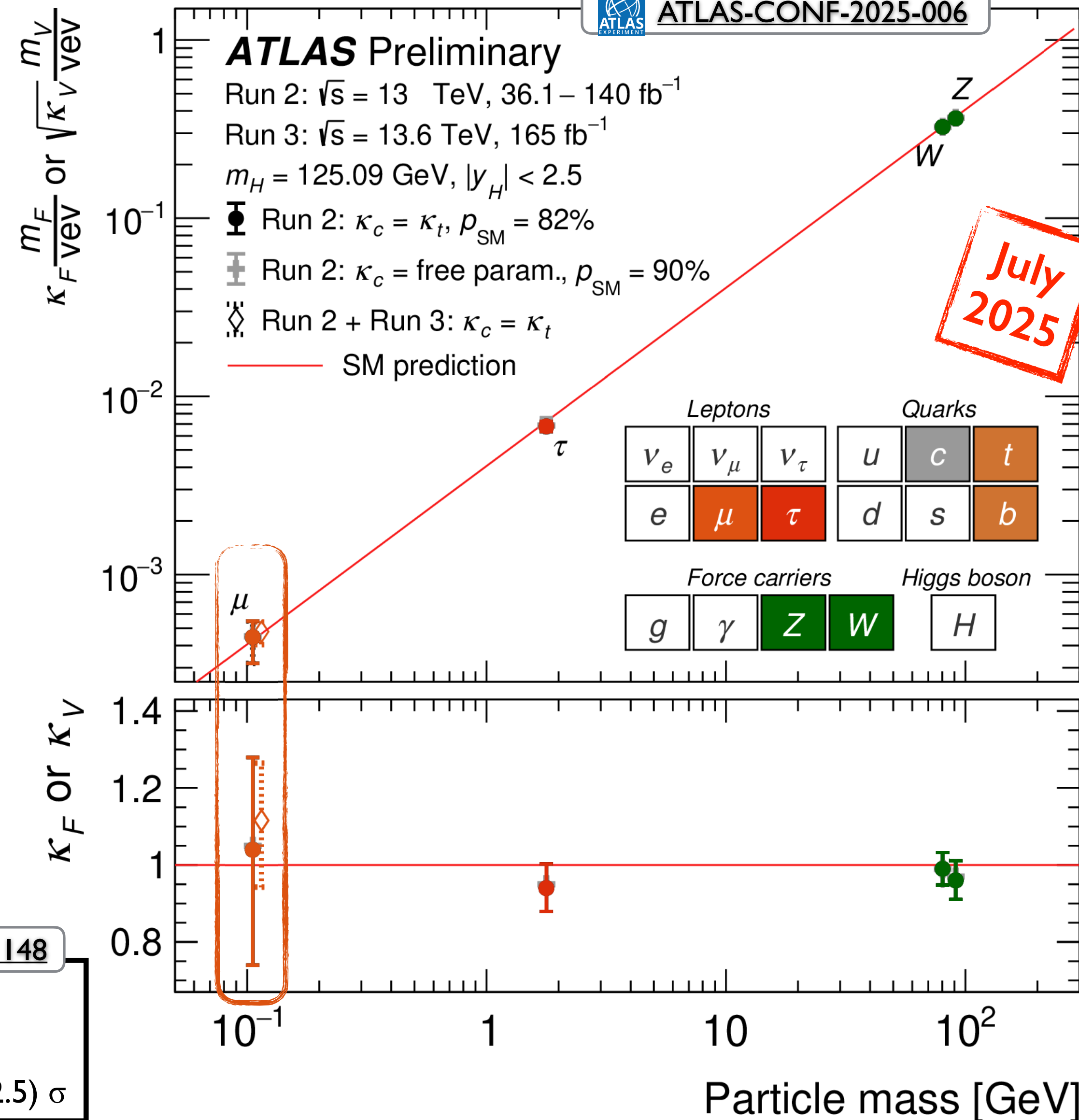
Results:

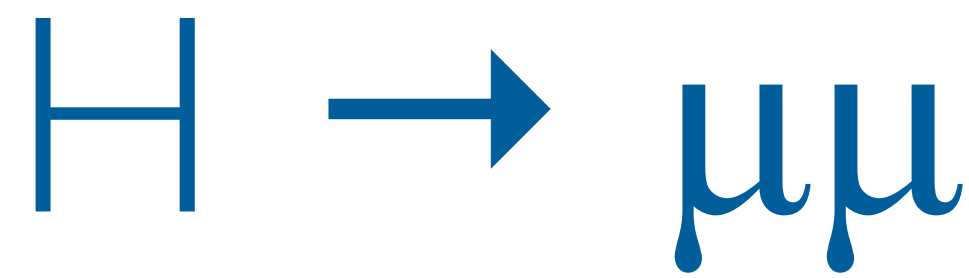
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JHEP 01 (2021) 148

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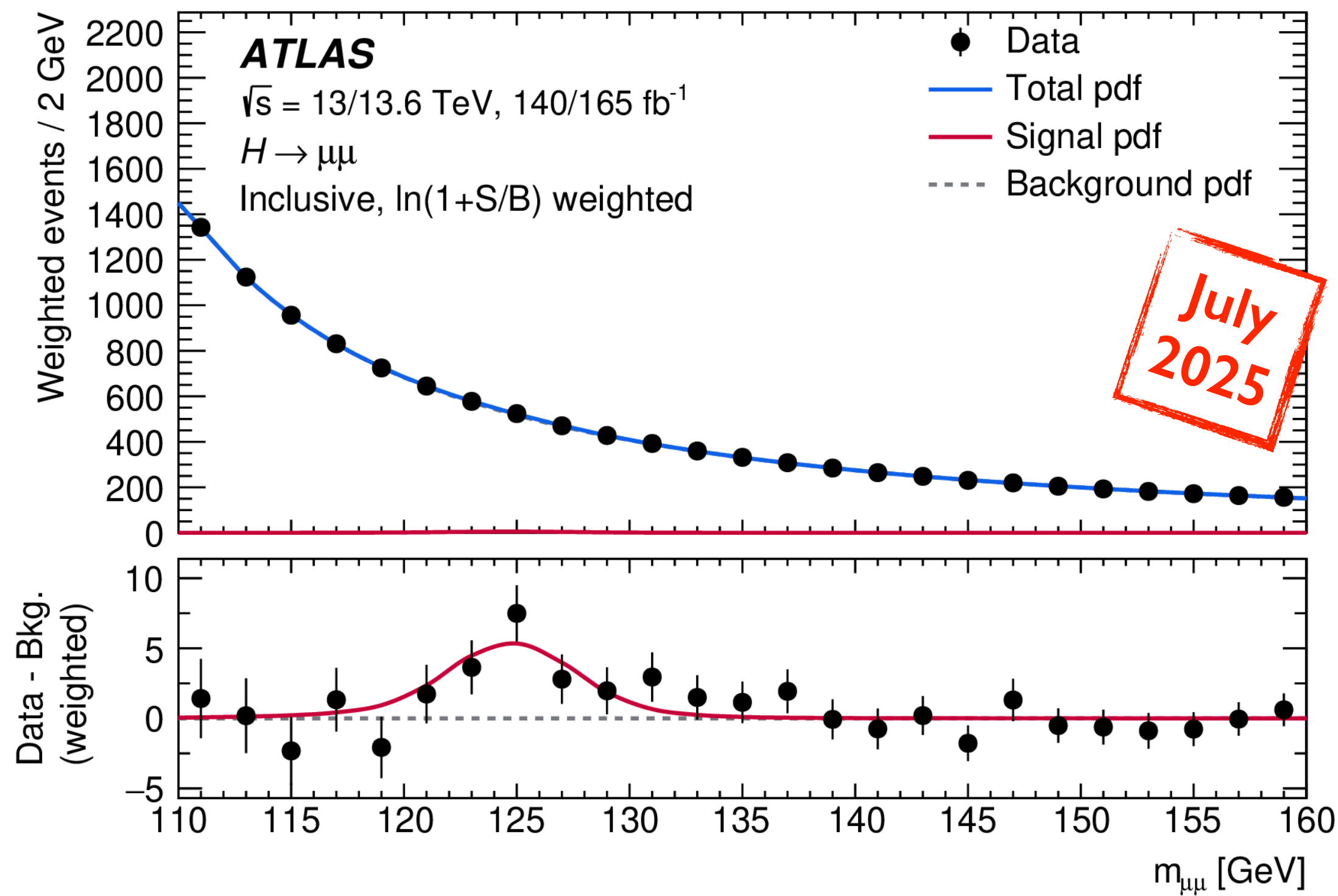
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$m_\mu \approx 0.1 \text{ GeV}$

$$\mathcal{B}_{\text{SM}}(H \rightarrow \mu\mu) = 2.18 \times 10^{-4}$$



Results:

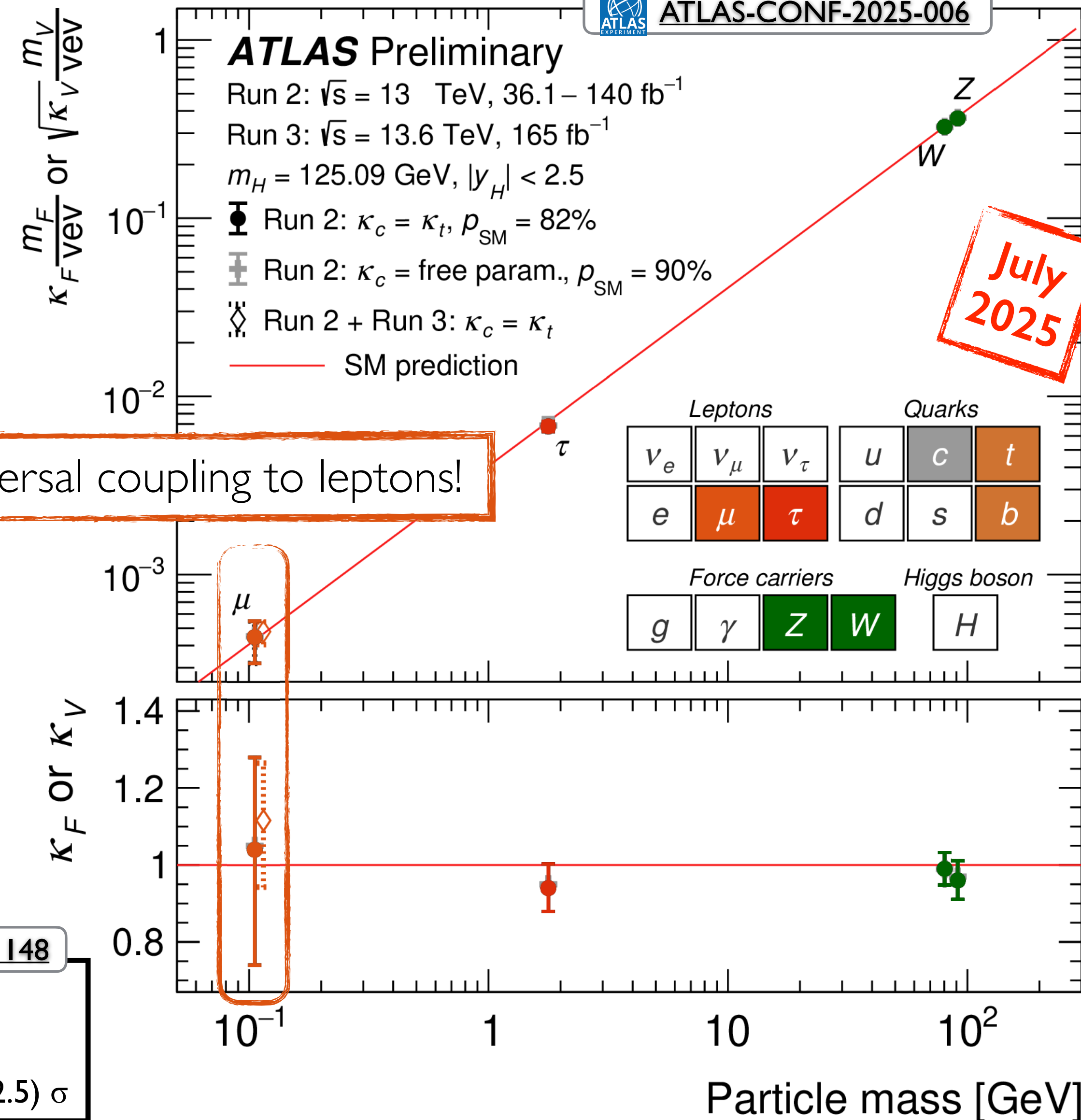
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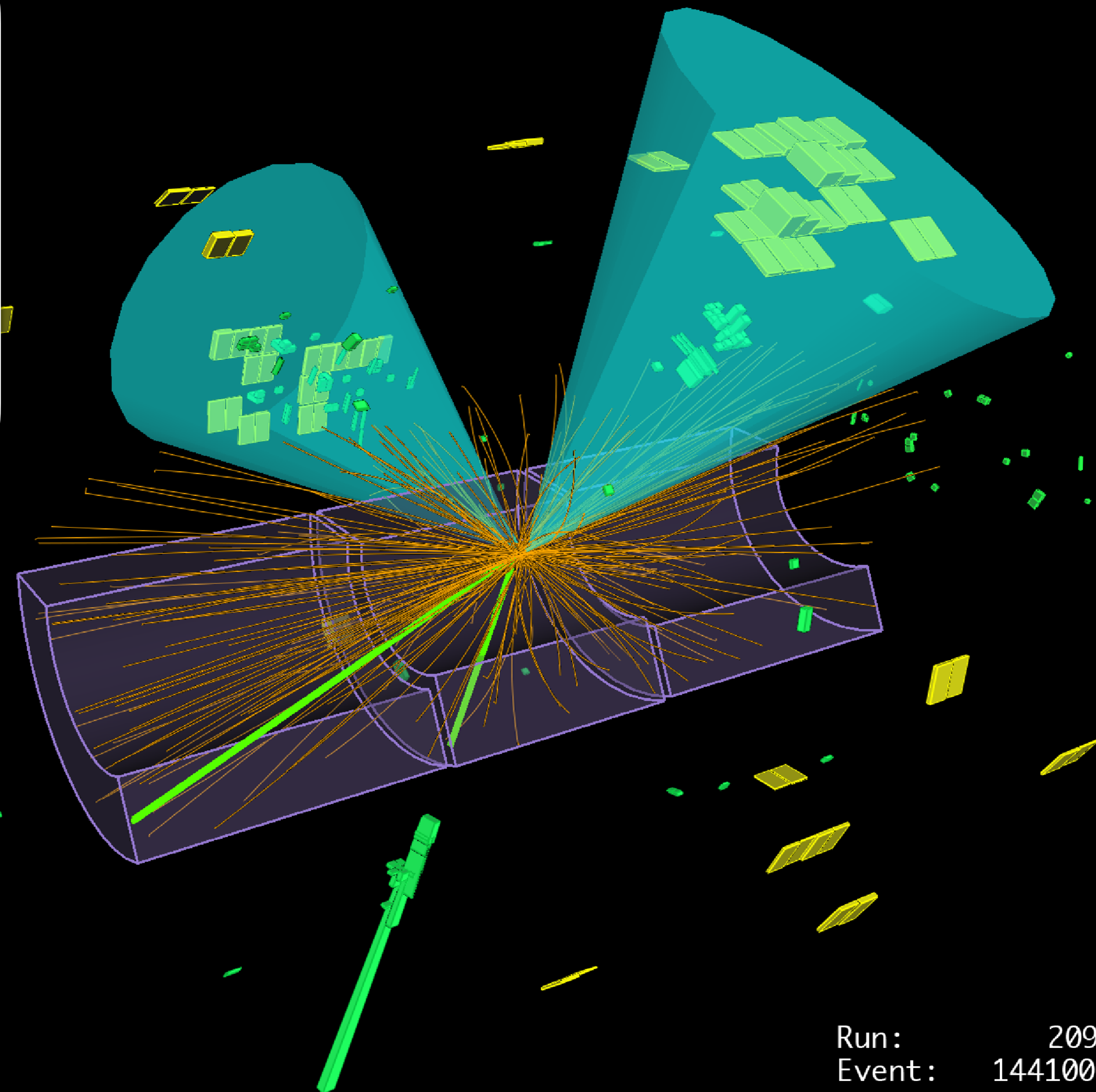
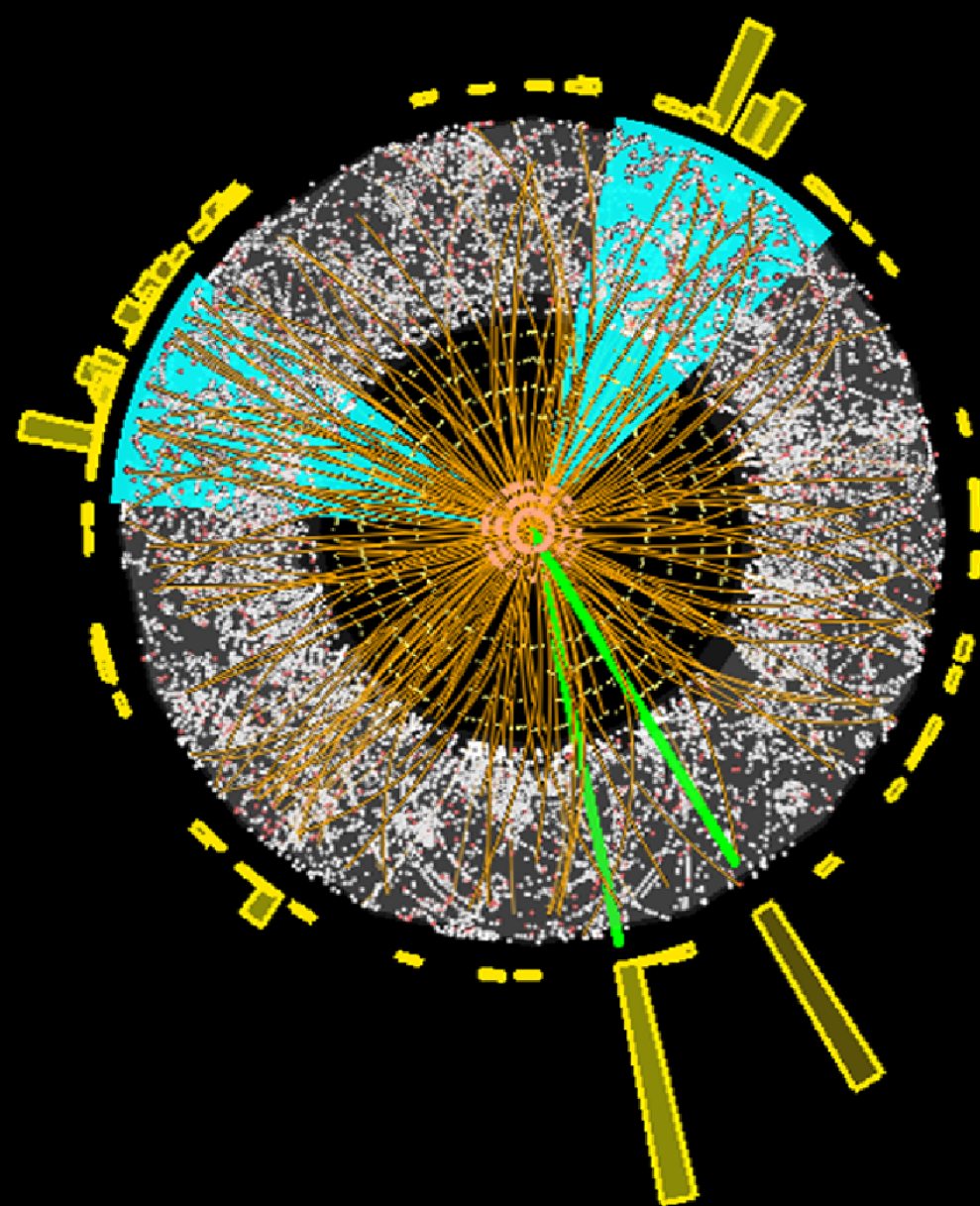
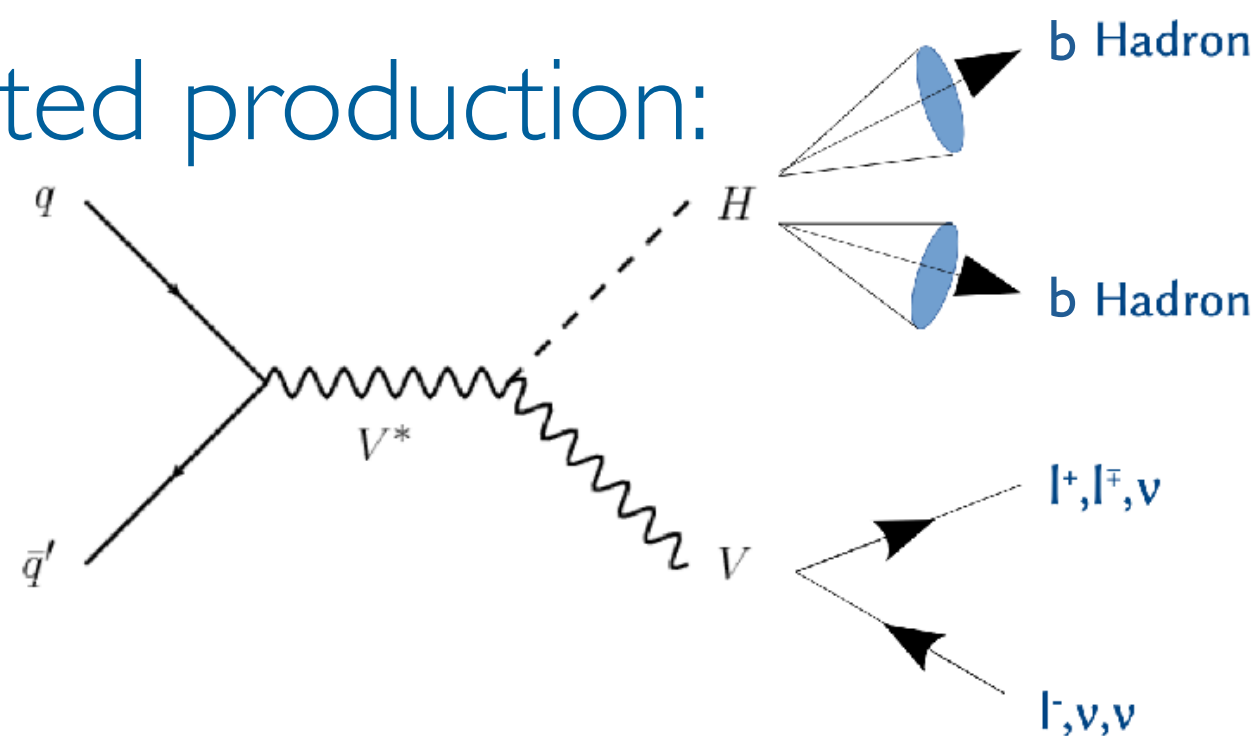




$$H \rightarrow b\bar{b}$$



- $\mathcal{B}_{\text{SM}}(H \rightarrow b\bar{b}) = 58\%$
- VH (V=W or Z) associated production:
 - 0 lepton ($Z \rightarrow \nu\nu$)
 - 1 lepton ($W \rightarrow \ell\nu$)
 - 2 lepton ($Z \rightarrow \ell\ell$)

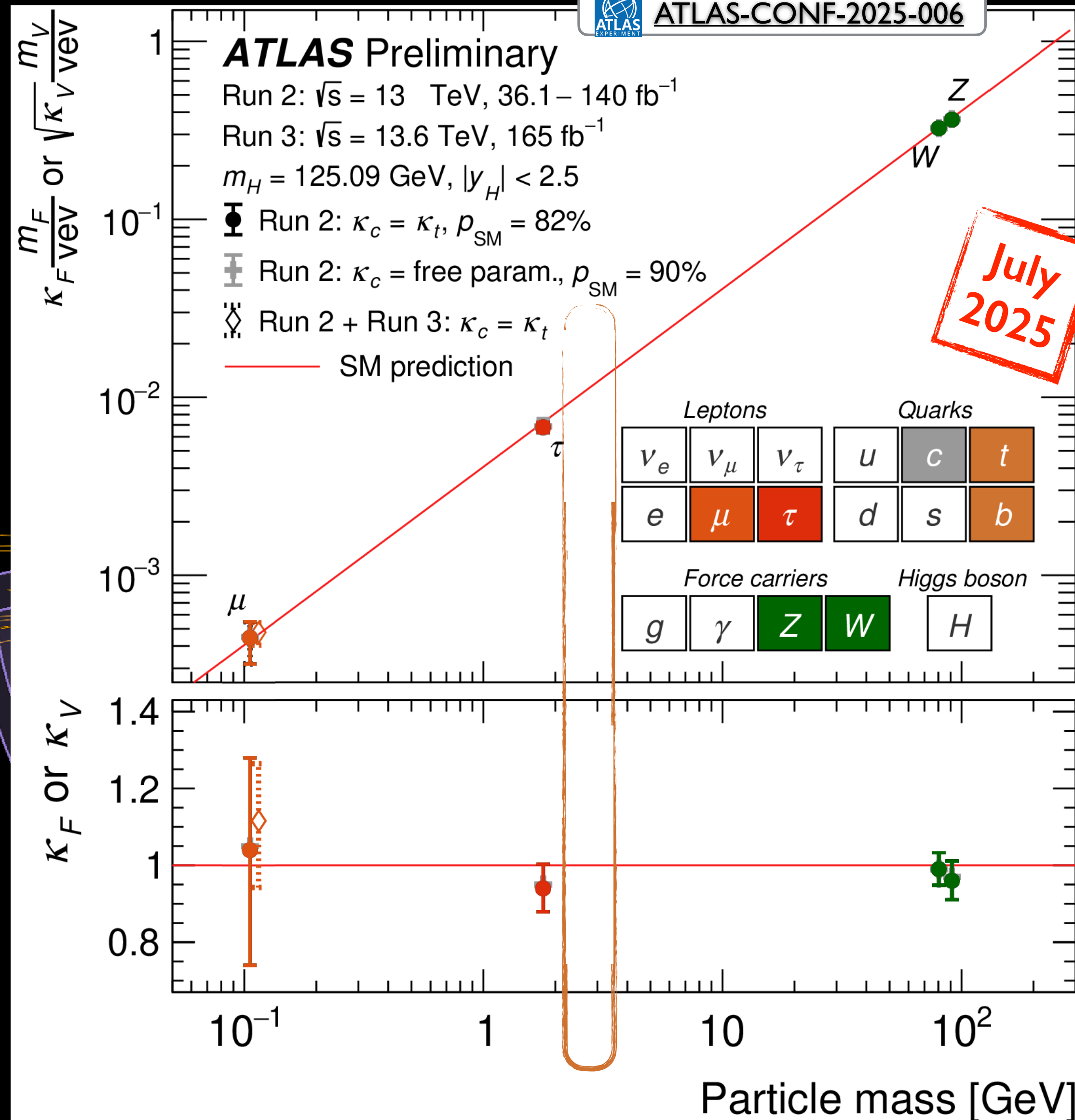
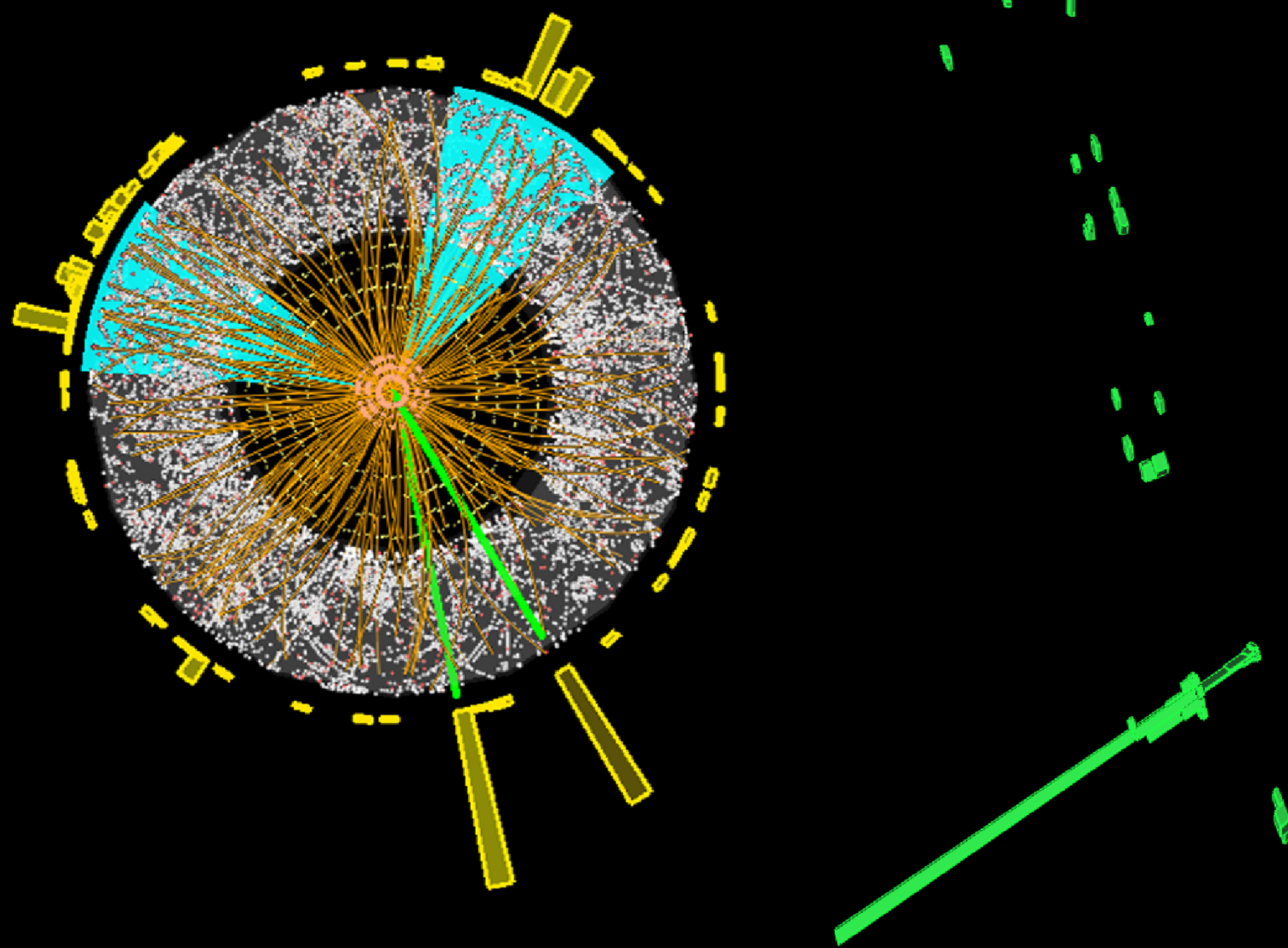
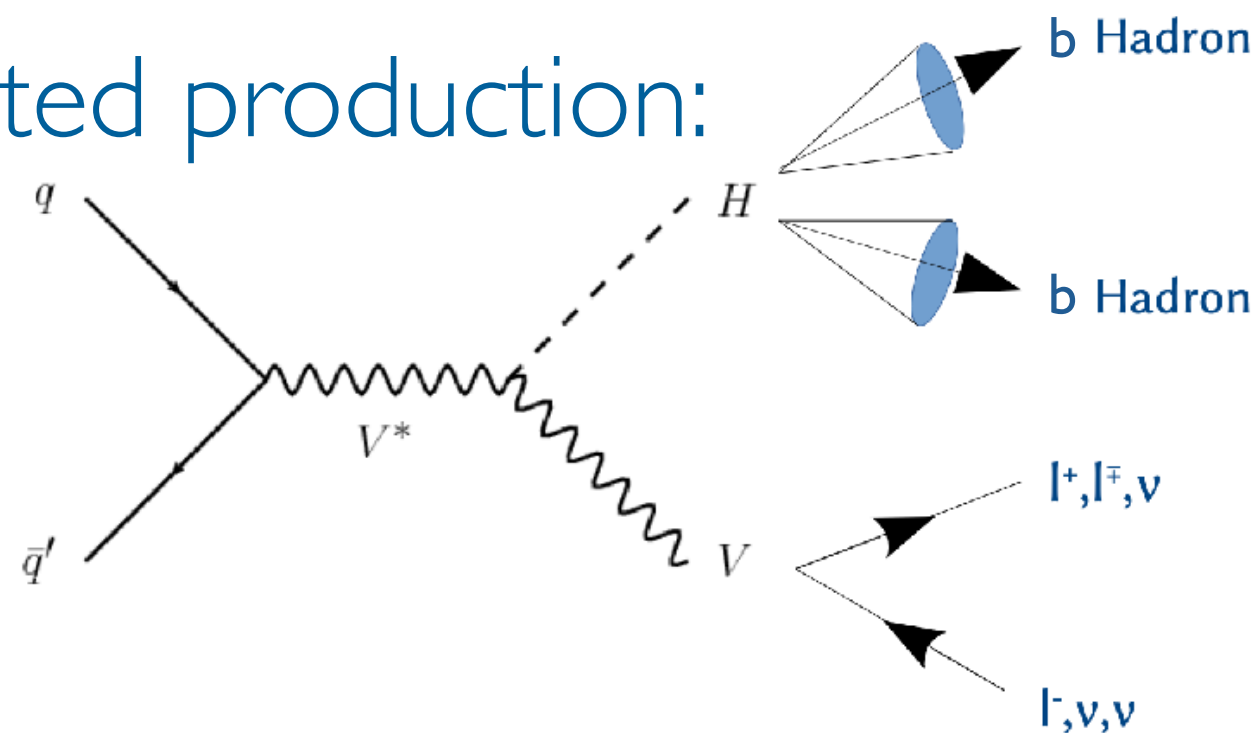




$$H \rightarrow b\bar{b}$$

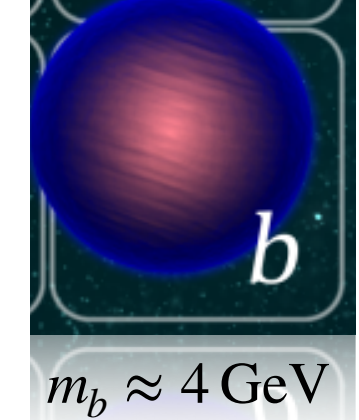


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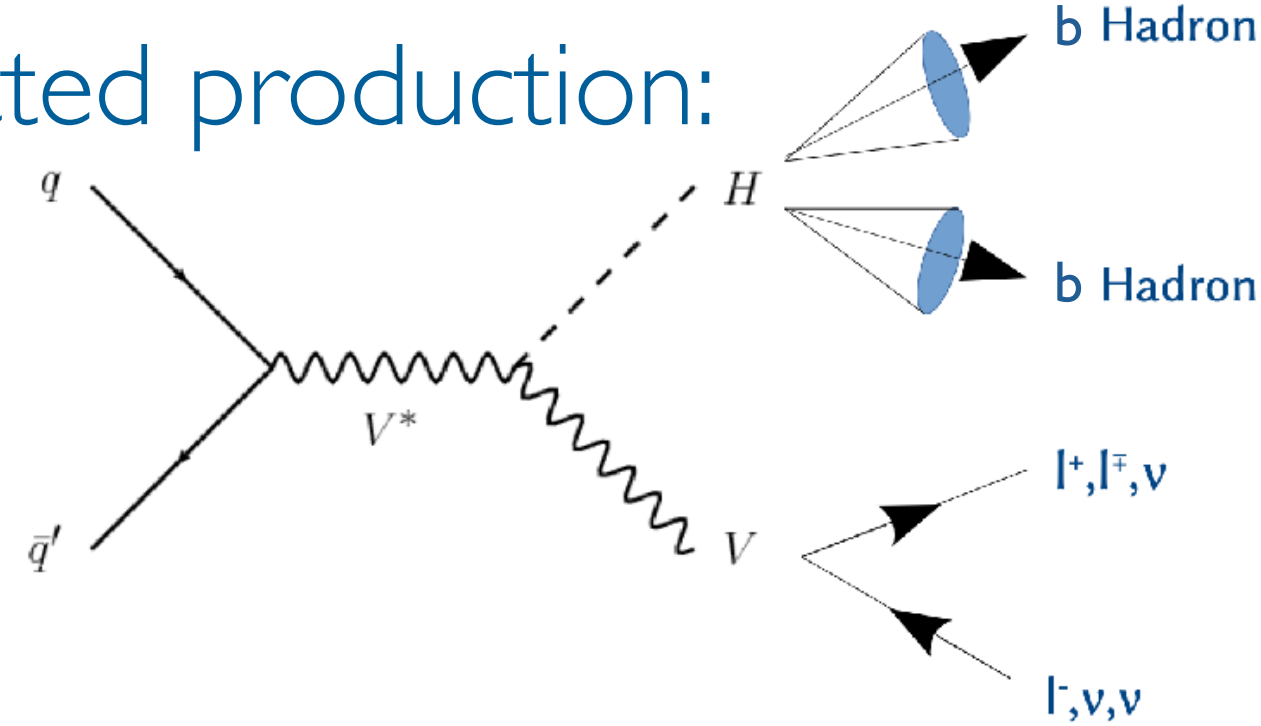




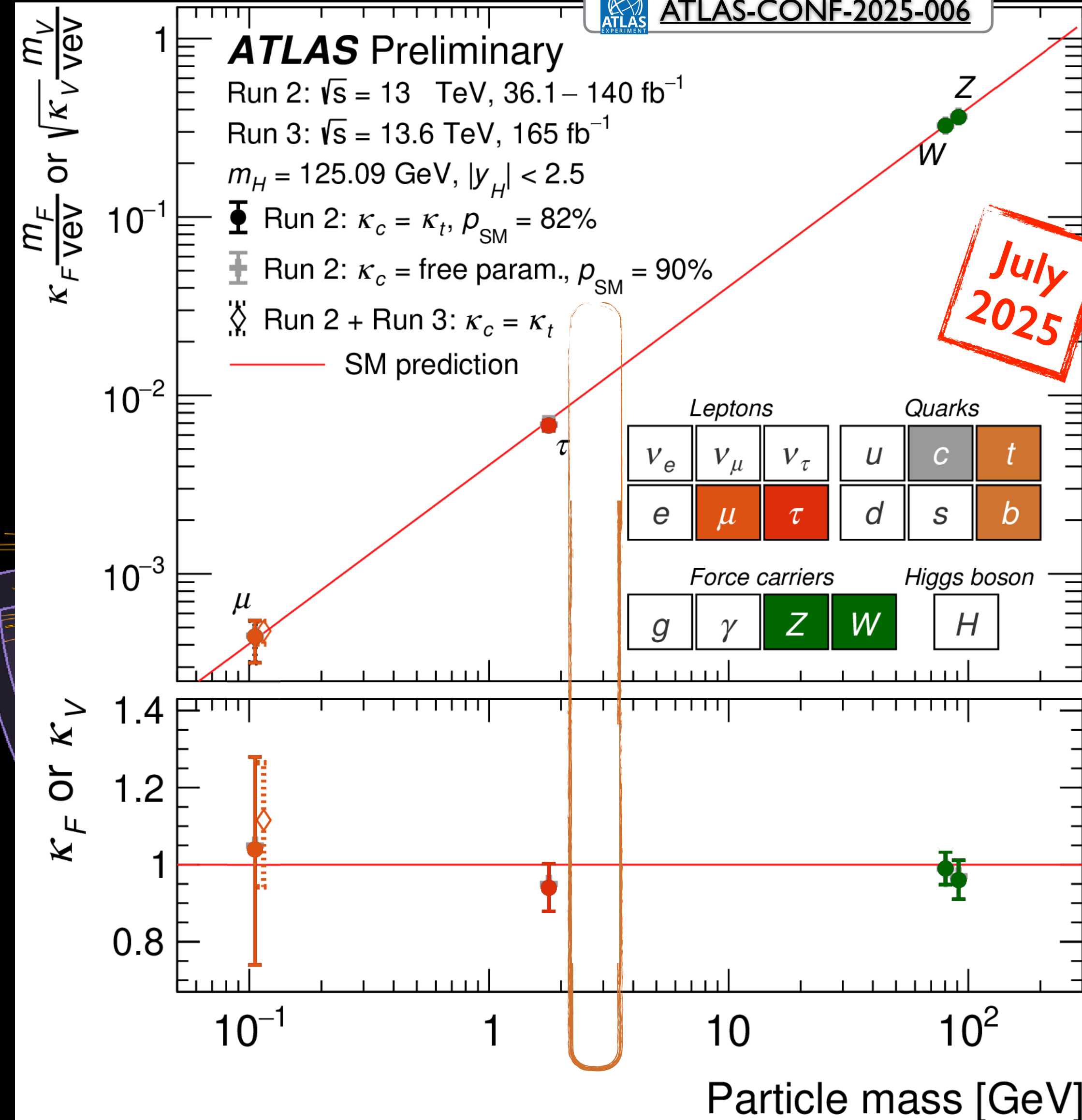
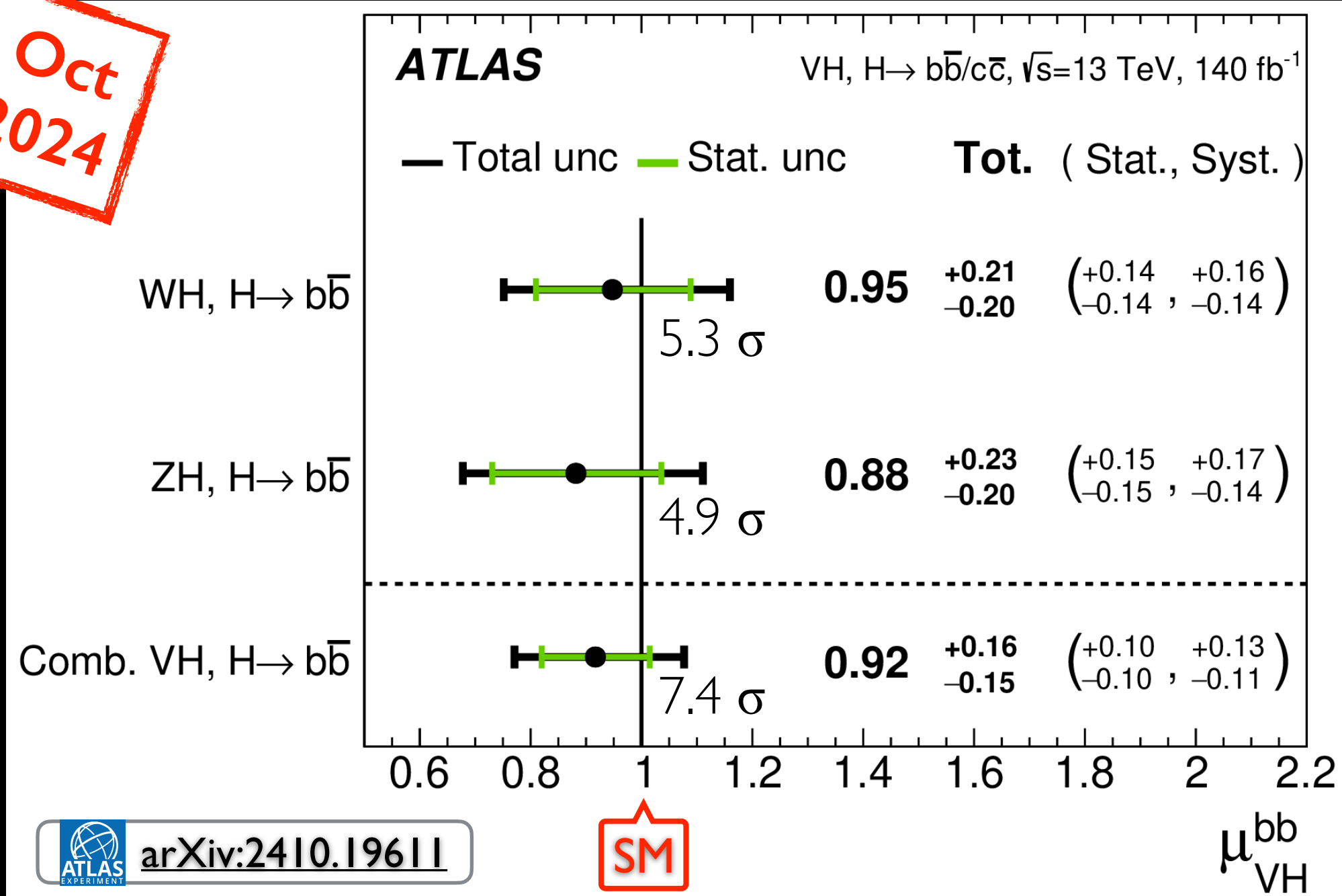
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Oct 2024

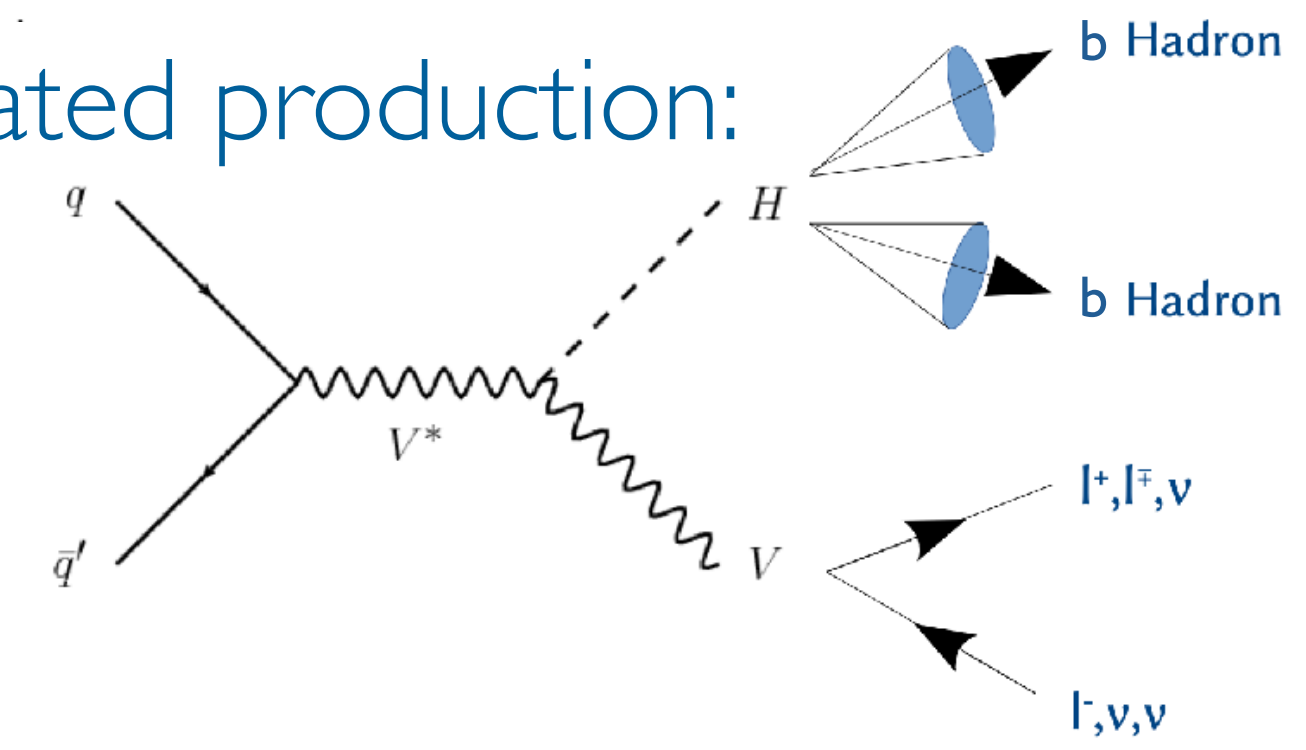




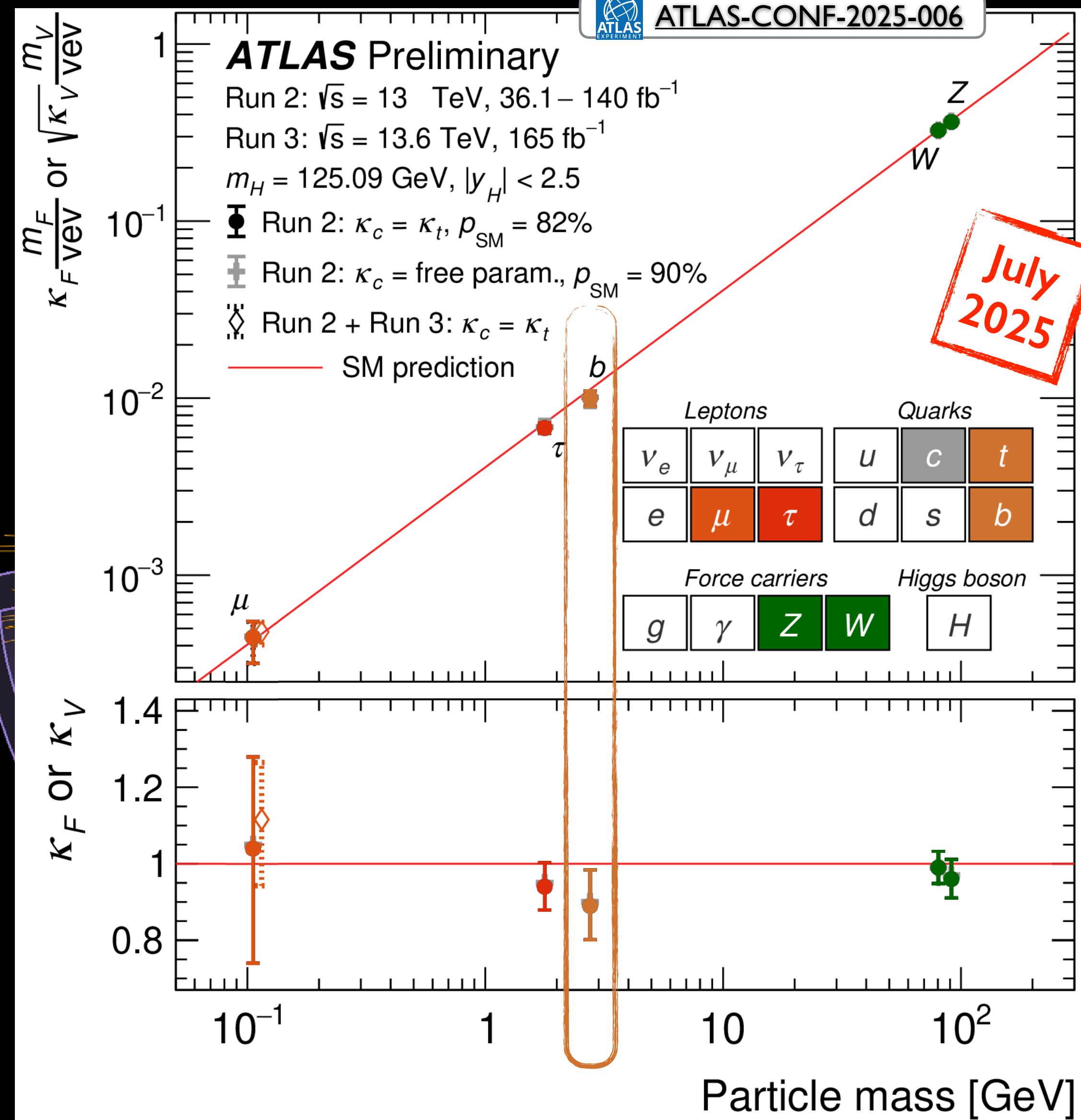
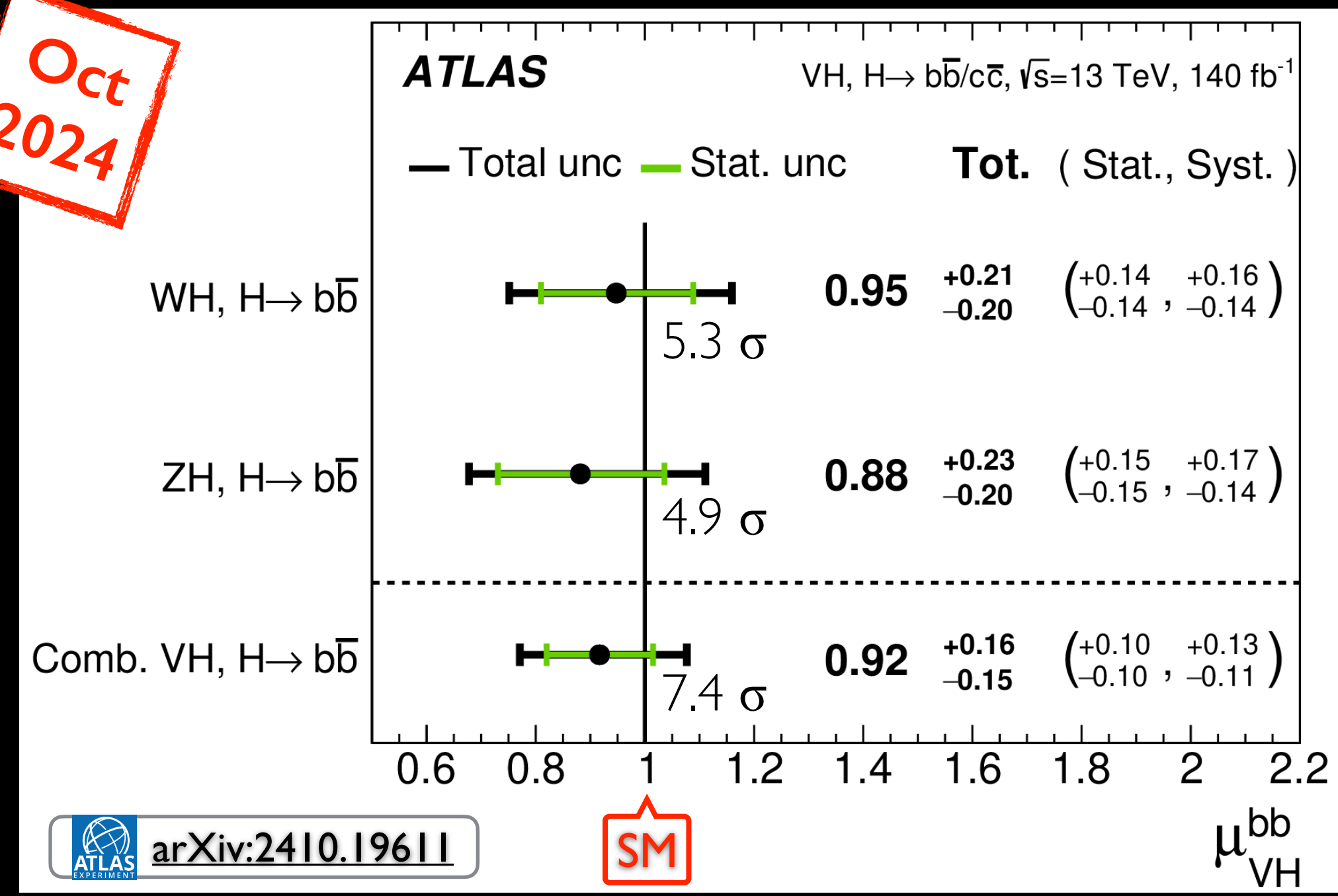
$$H \rightarrow b\bar{b}$$

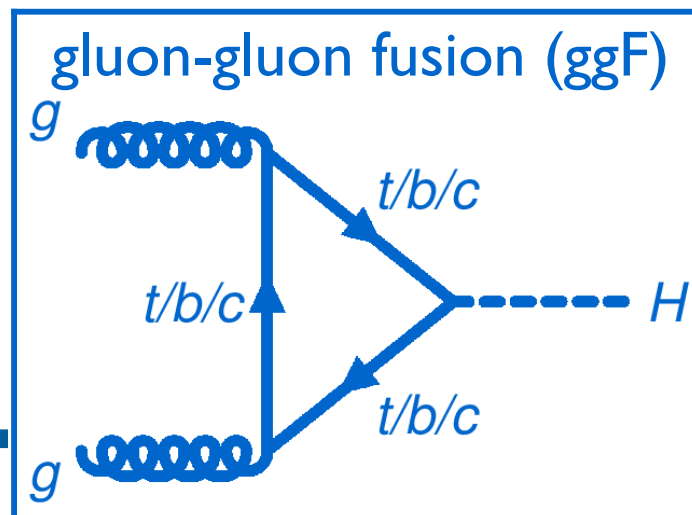


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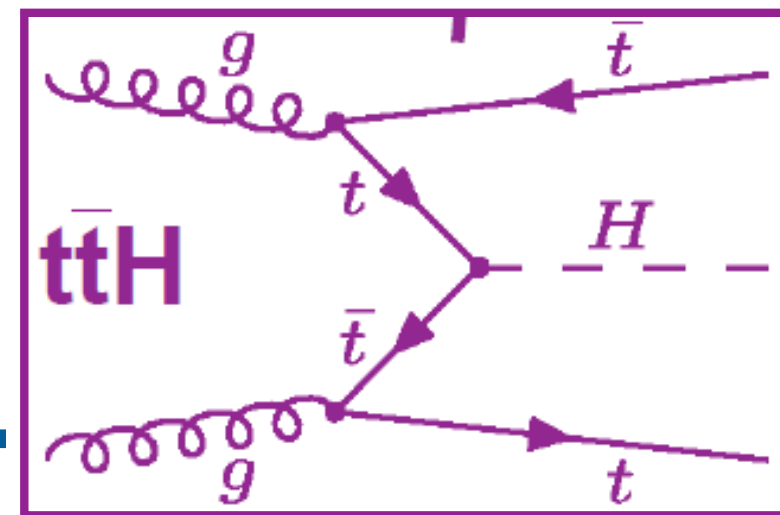


Oct 2024



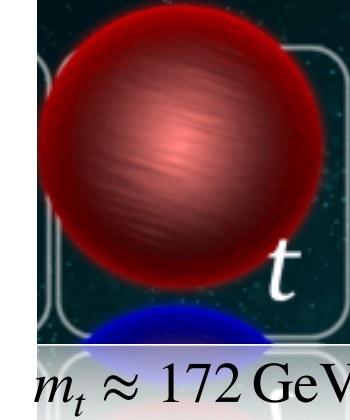


$$\sigma_{\text{ggF}} = 48.5 \text{ pb (87 \%)}$$



$$\sigma_{t\bar{t}H} = 0.5 \text{ pb (0.9 \%)}$$

$$t\bar{t}H, H \rightarrow b\bar{b}$$



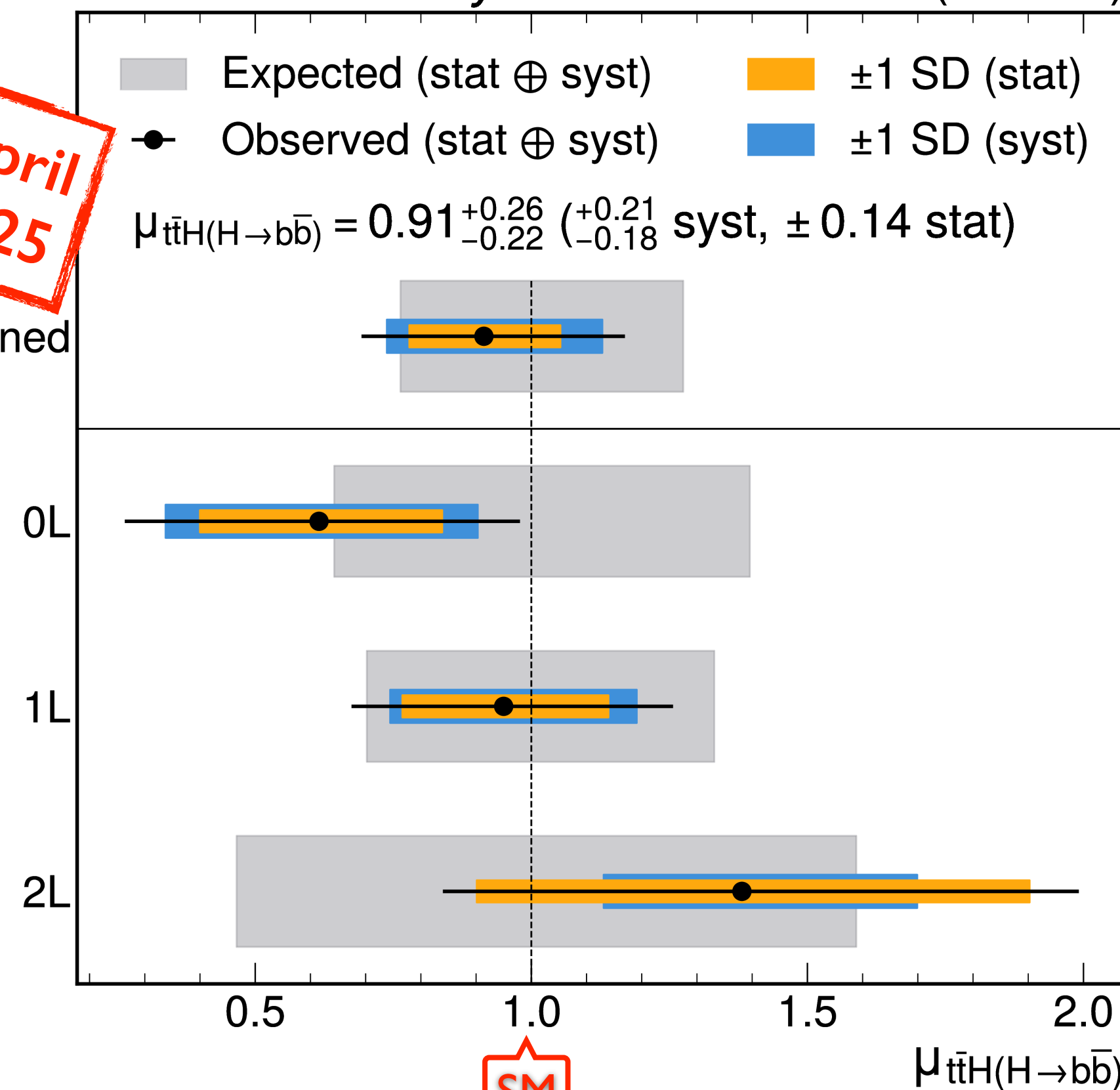
• Tree-level **top-Yukawa** measurement

- Very difficult to predict and model dominant $t\bar{t}b\bar{b}$ background

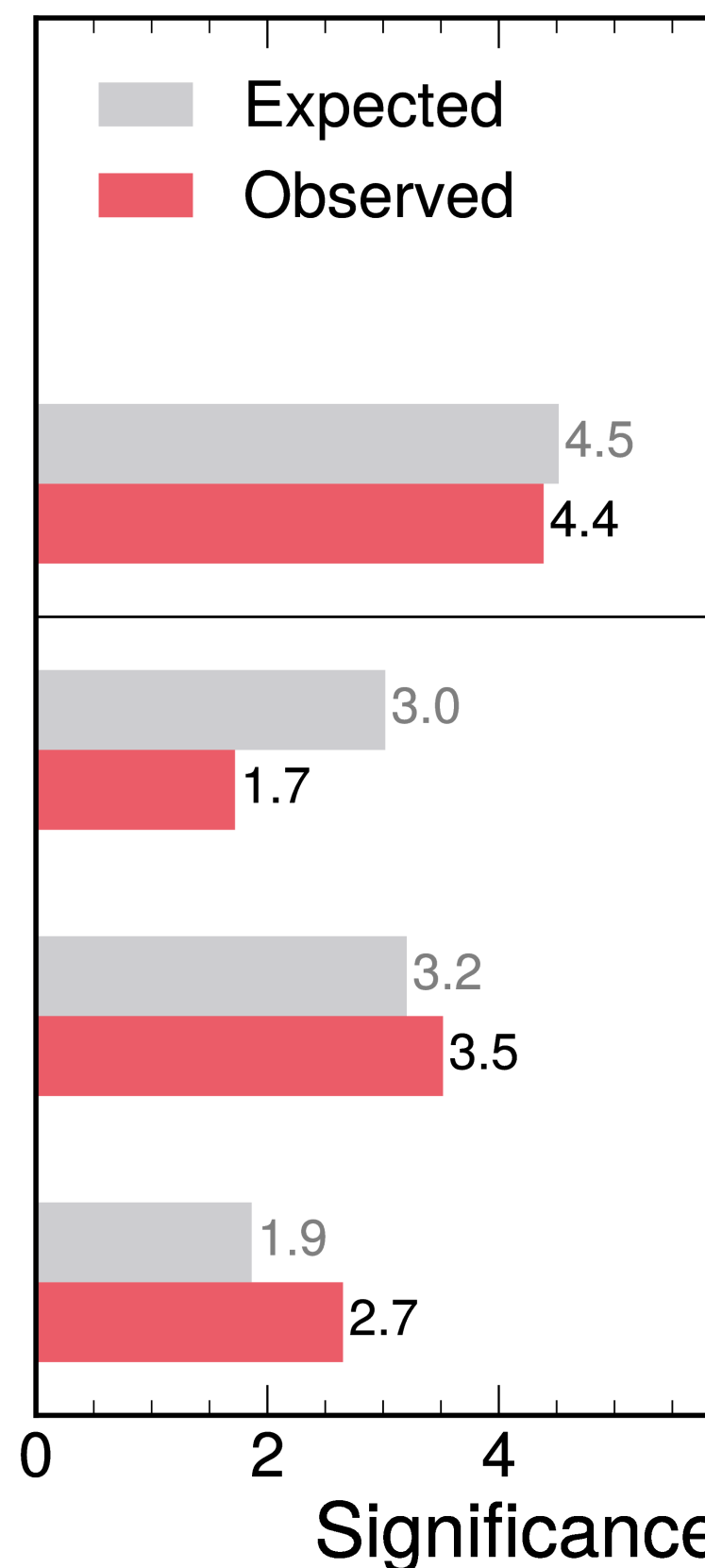
CMS Preliminary 138 fb⁻¹ (13 TeV)

April 2025

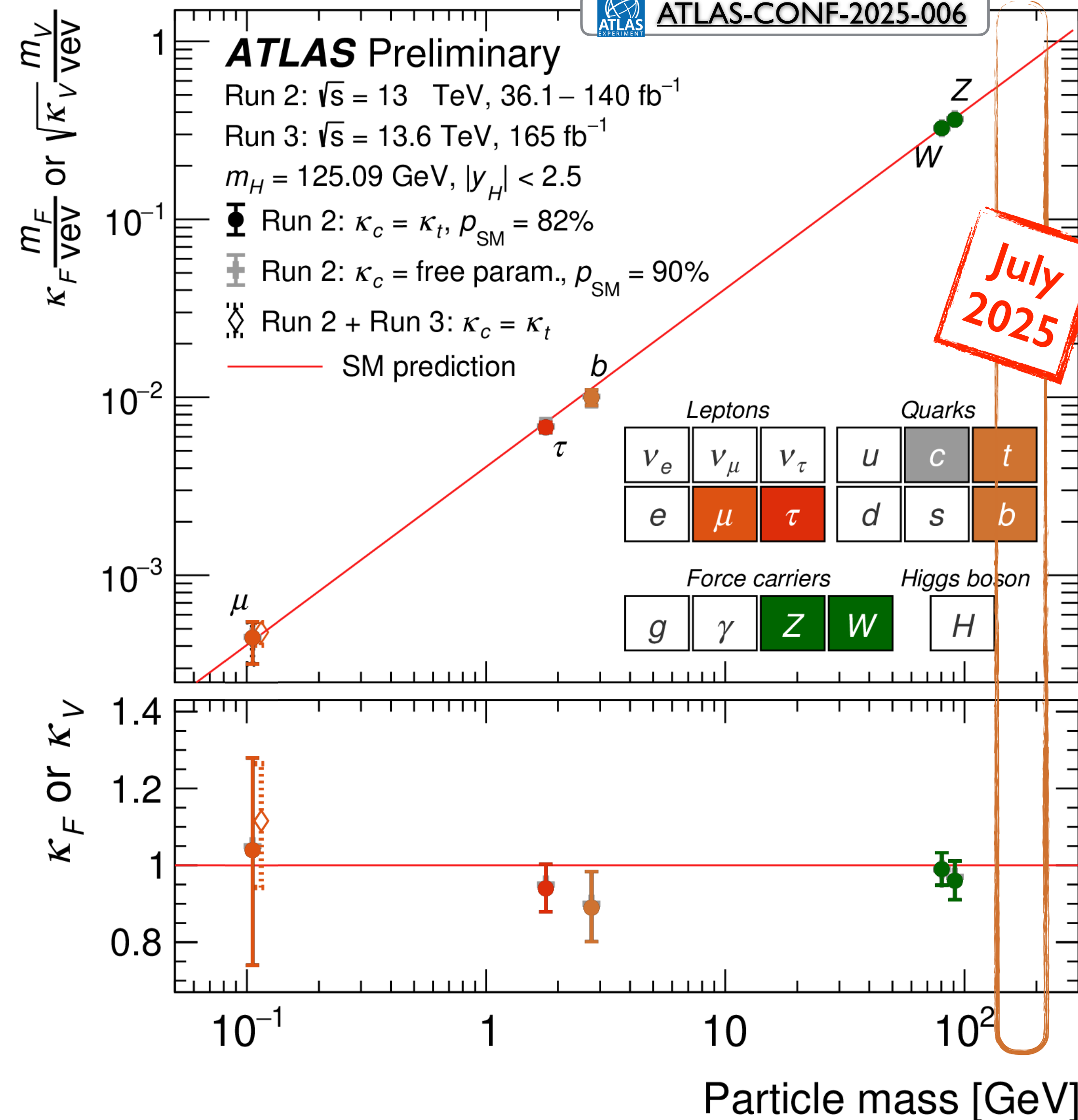
Combined

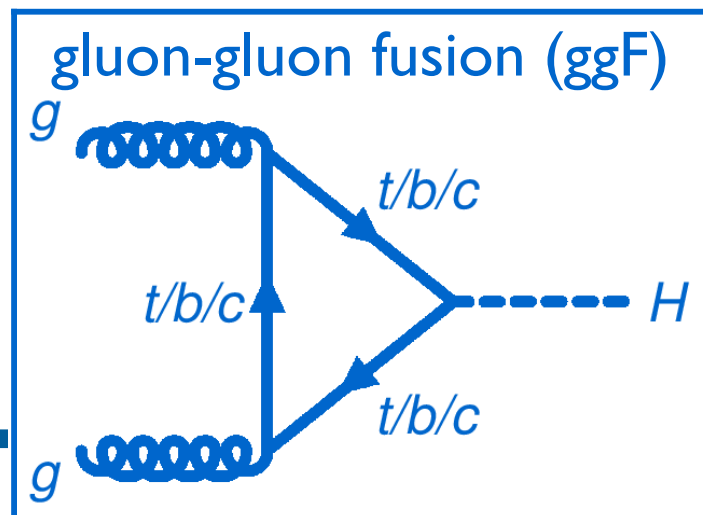


SM

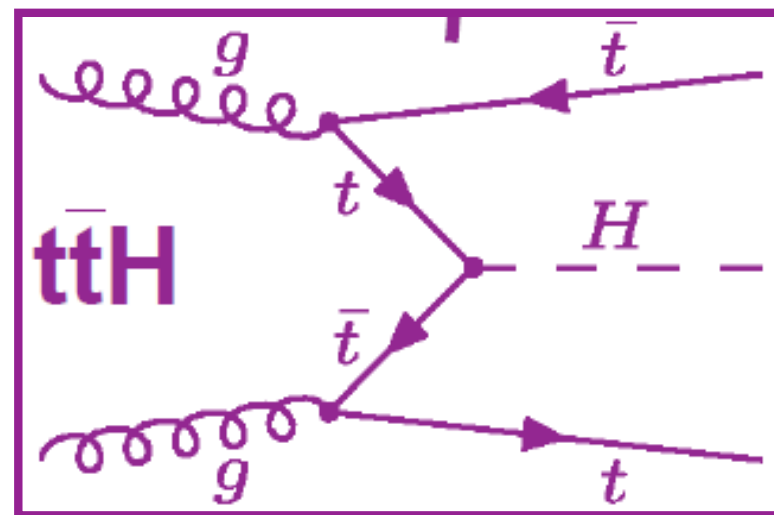


$$\frac{m_V}{\kappa_F \text{ vev}} \text{ or } \sqrt{\kappa_V} \text{ vev}$$



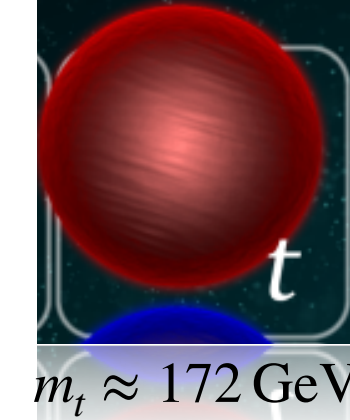


$\sigma_{\text{ggF}} = 48.5 \text{ pb (87 \%)}$



$\sigma_{\text{ttH}} = 0.5 \text{ pb (0.9 \%)}$

$$t\bar{t}H, H \rightarrow b\bar{b}$$



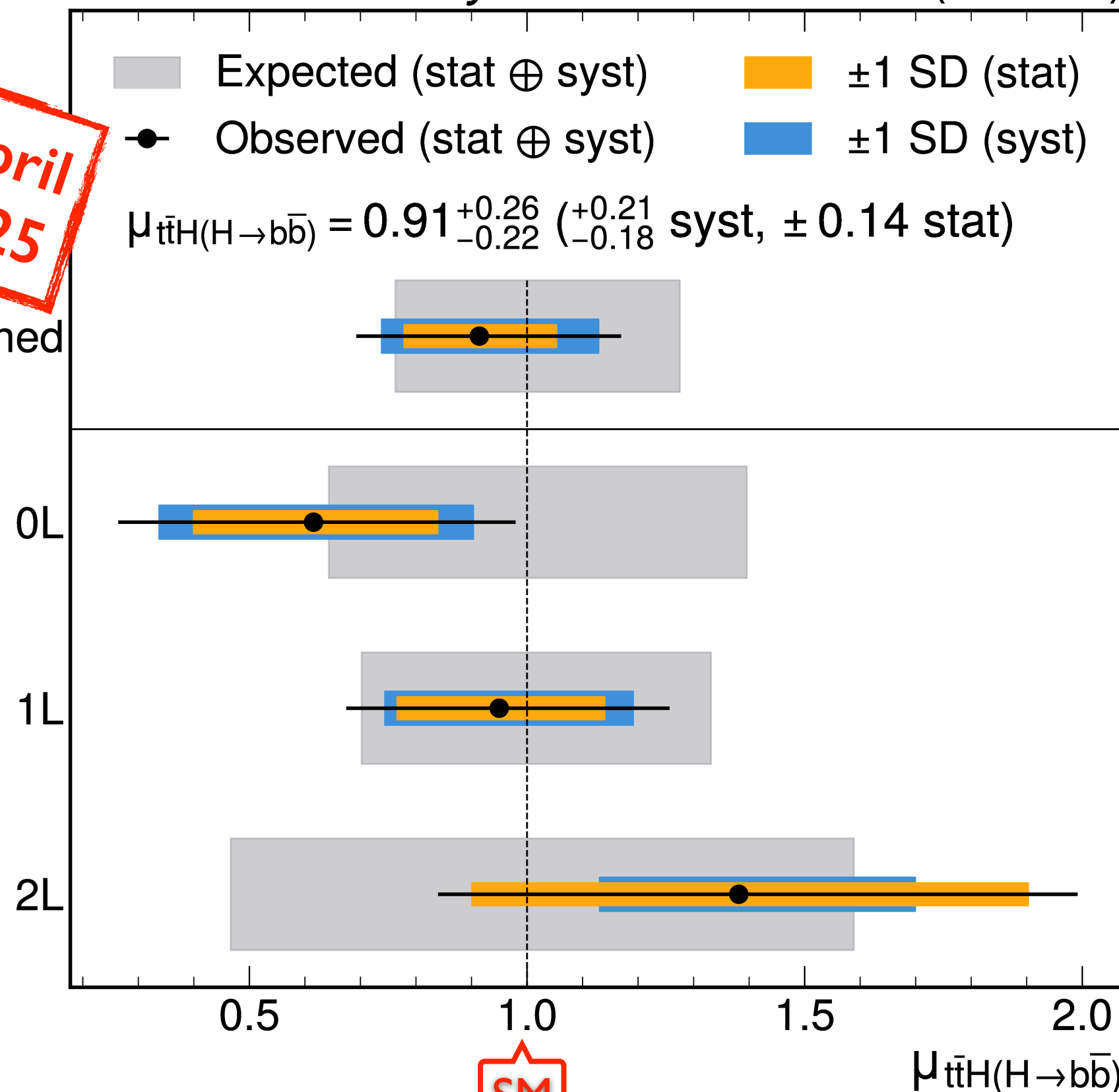
- **Tree-level top-Yukawa** measurement

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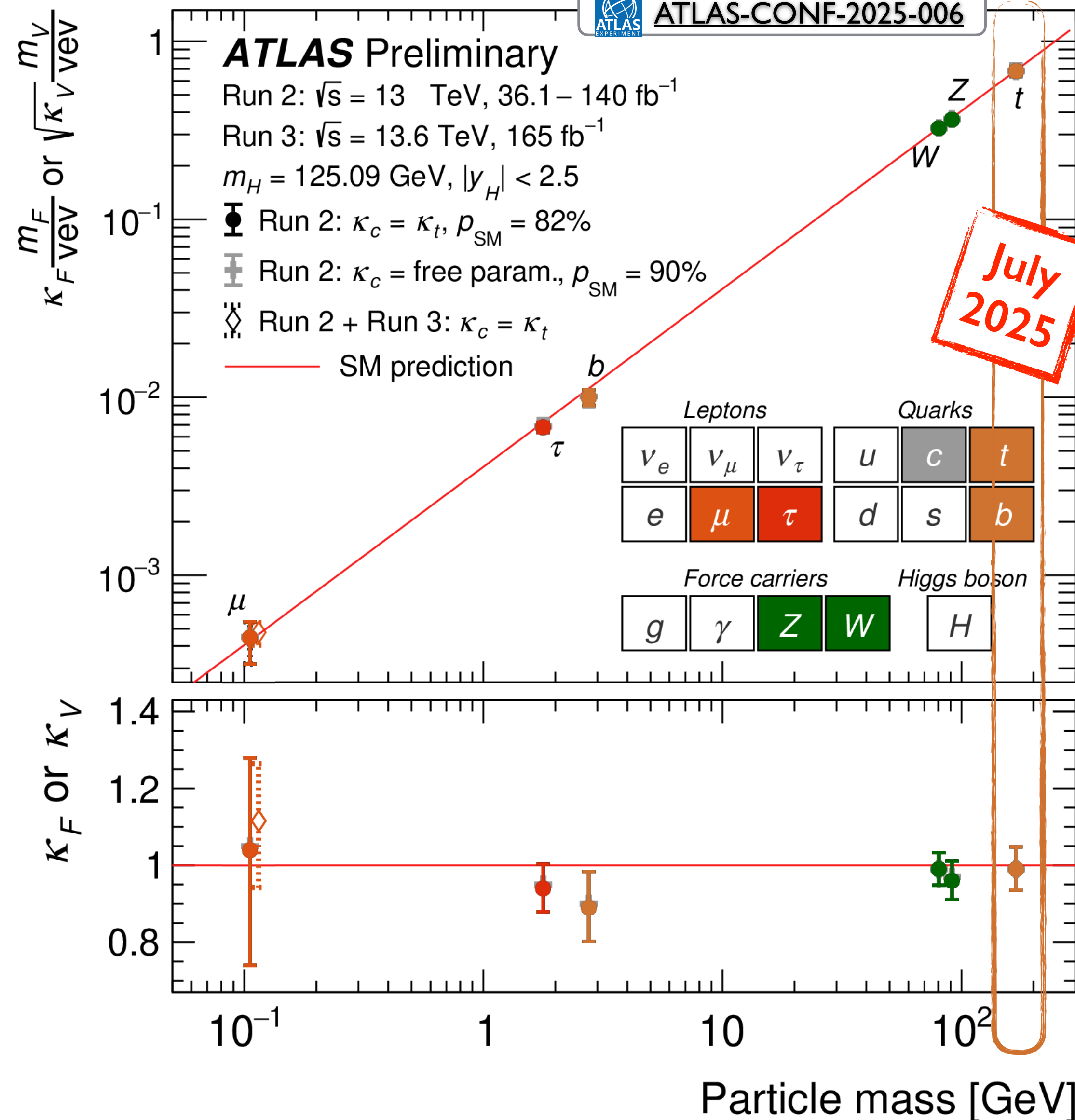
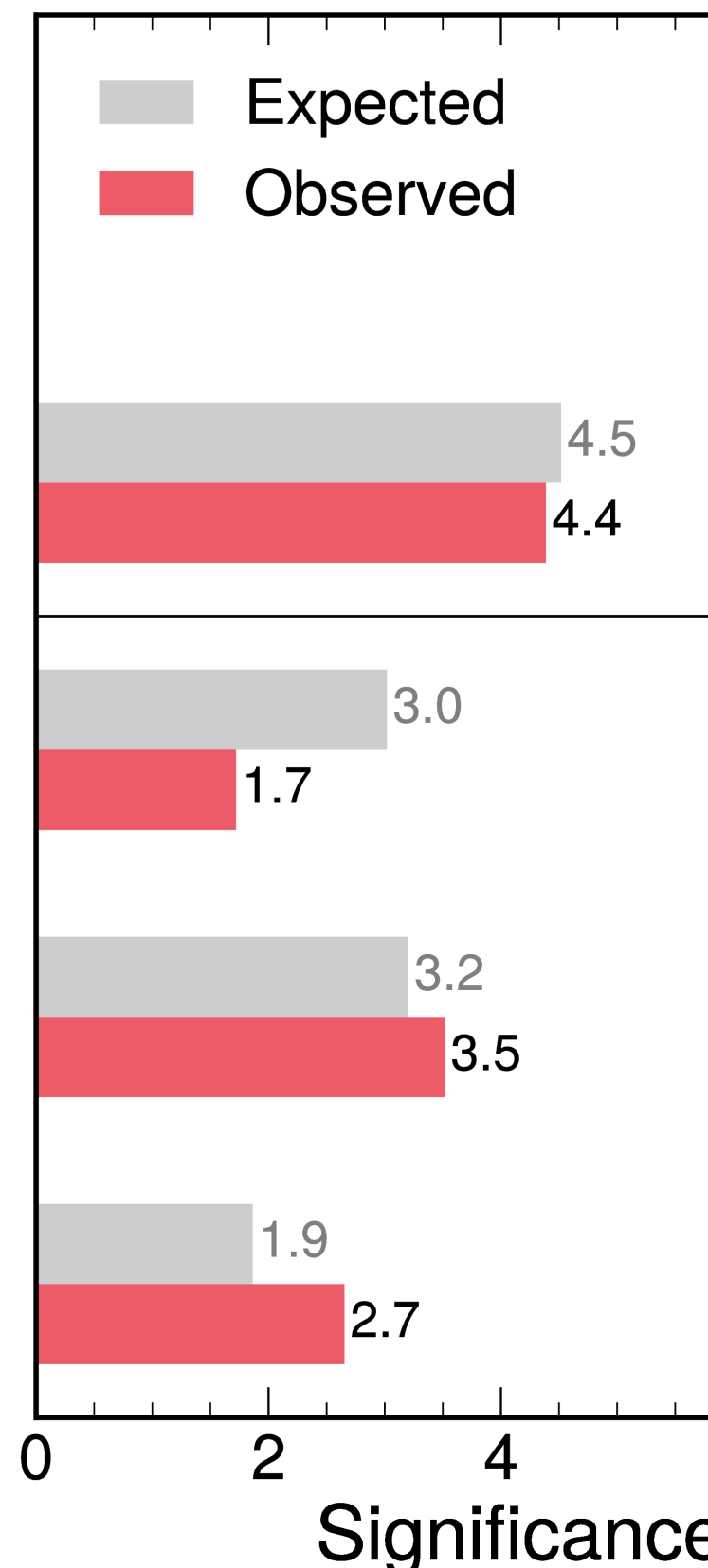
CMS Preliminary 138 fb⁻¹ (13 TeV)

April 2025

Combined

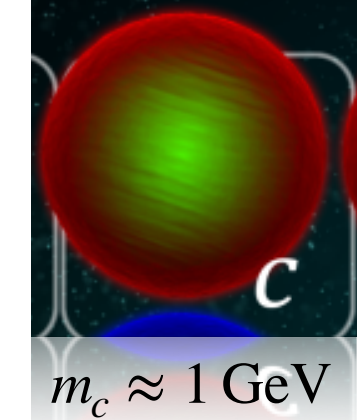


SM

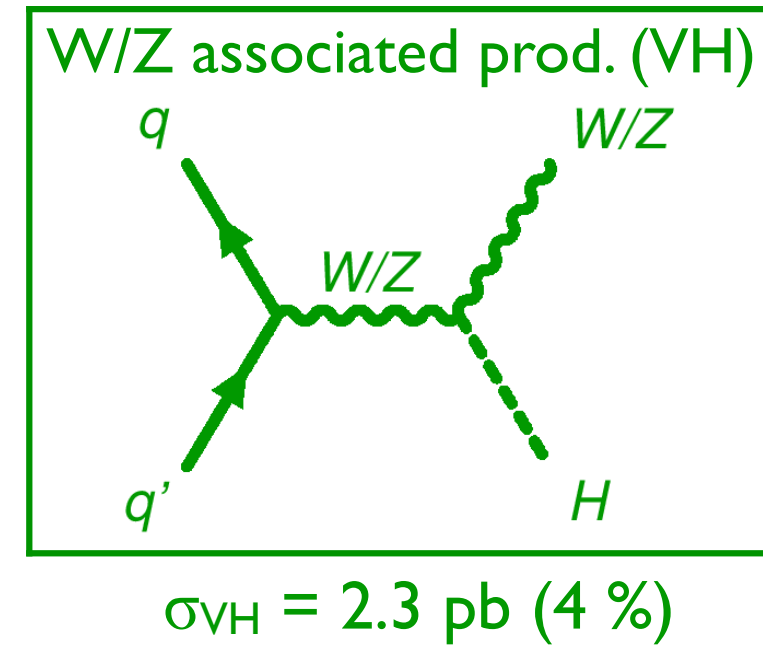




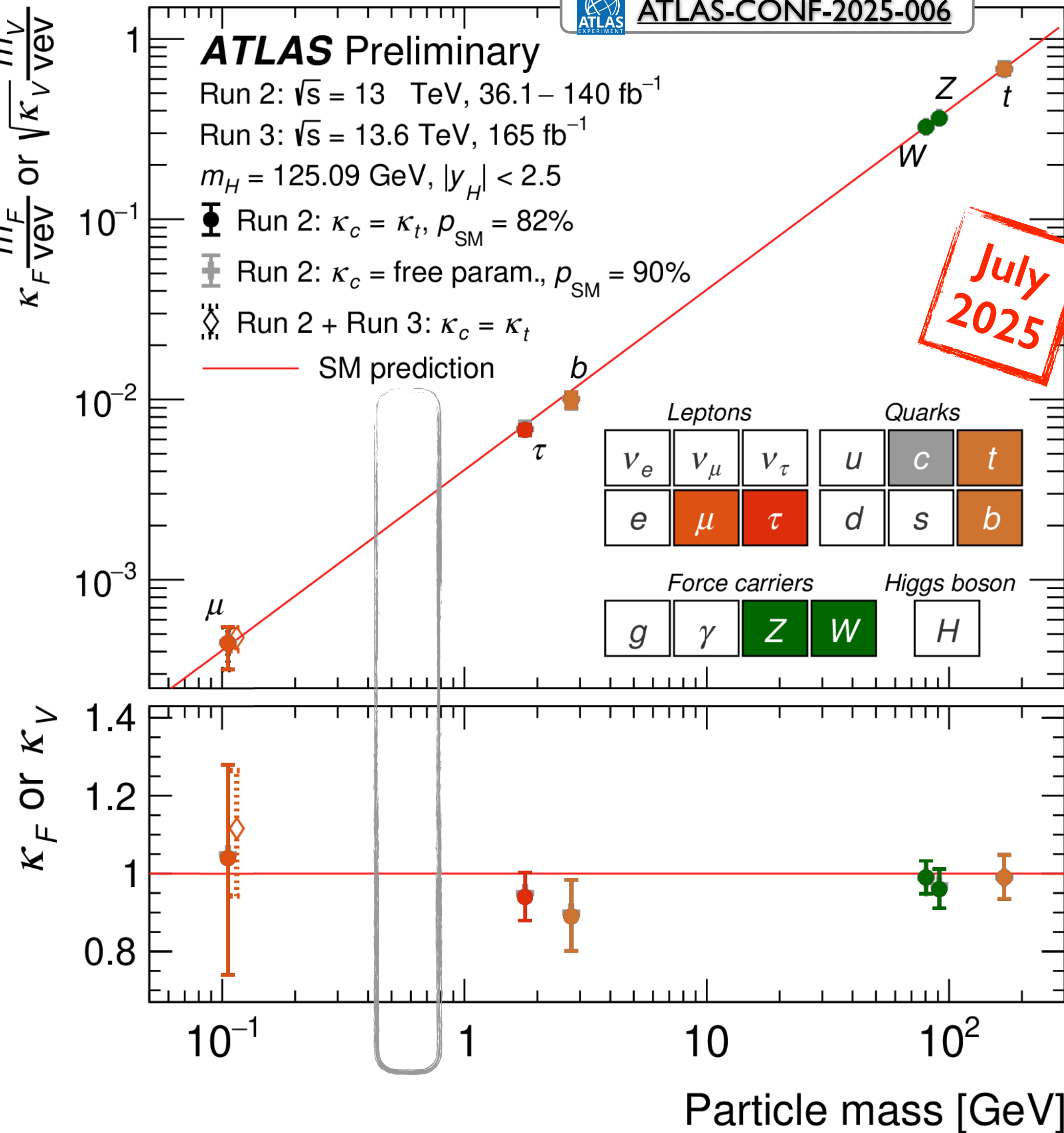
$$H \rightarrow c\bar{c}$$



$$\mathcal{B}_{\text{SM}}(H \rightarrow c\bar{c}) = 2.9\%$$

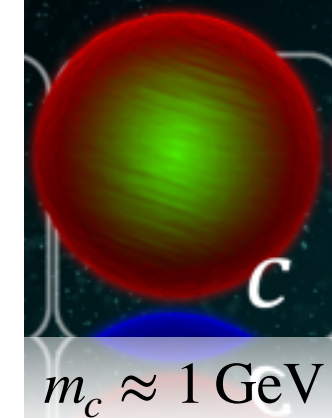


$$\frac{m_F}{\kappa_F \text{ vev}} \text{ or } \frac{m_V}{\sqrt{\kappa_V} \text{ vev}}$$



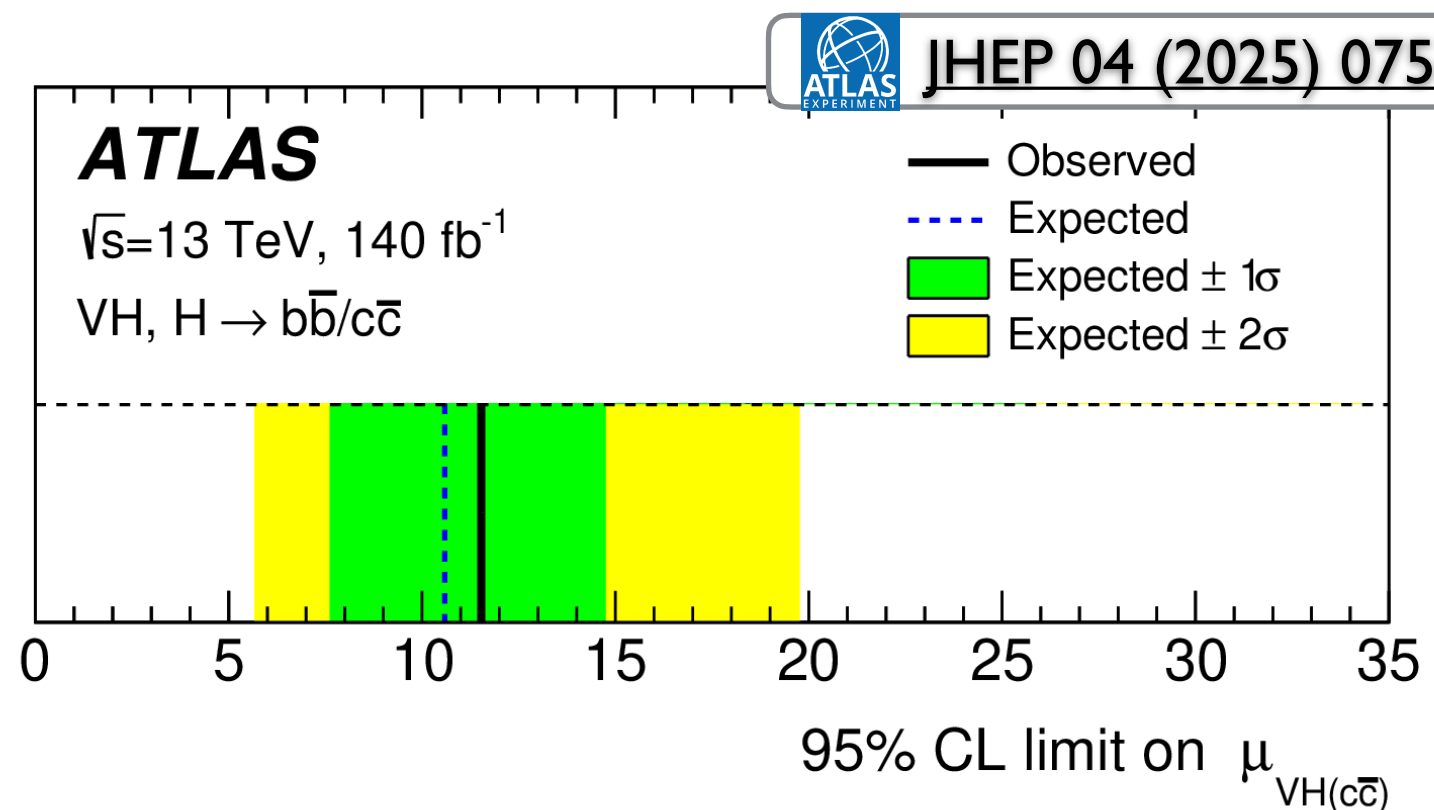


$$H \rightarrow c\bar{c}$$

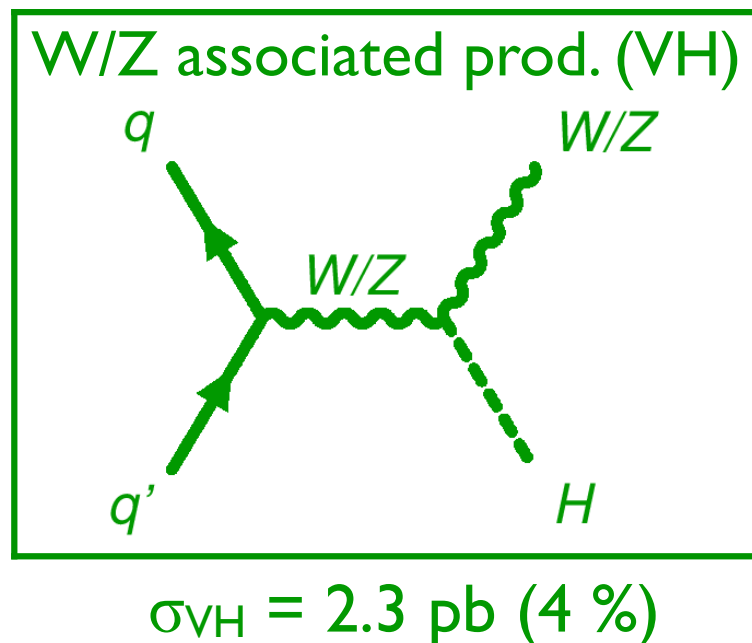
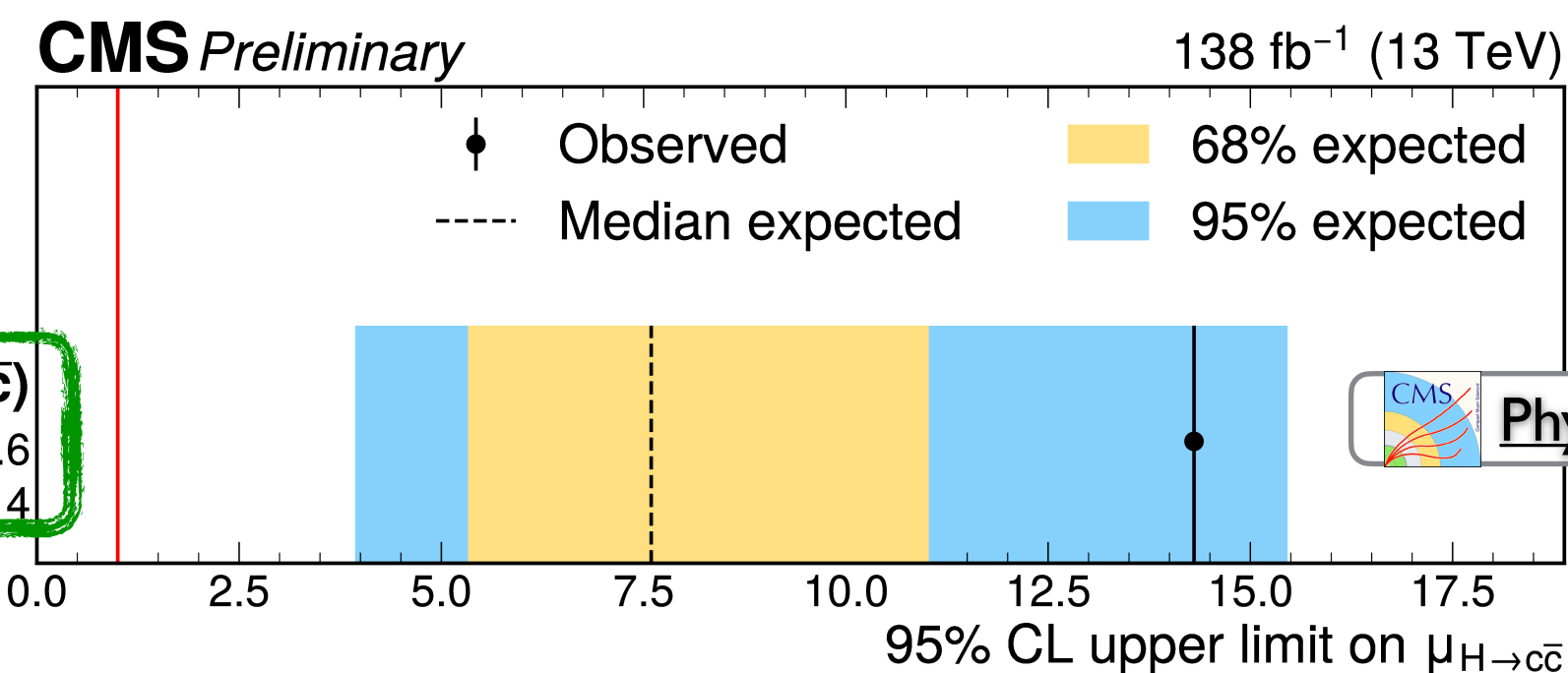


$$\mathcal{B}_{\text{SM}}(H \rightarrow c\bar{c}) = 2.9\%$$

Combination
Exp. = 11 × SM
Obs. = 12 × SM

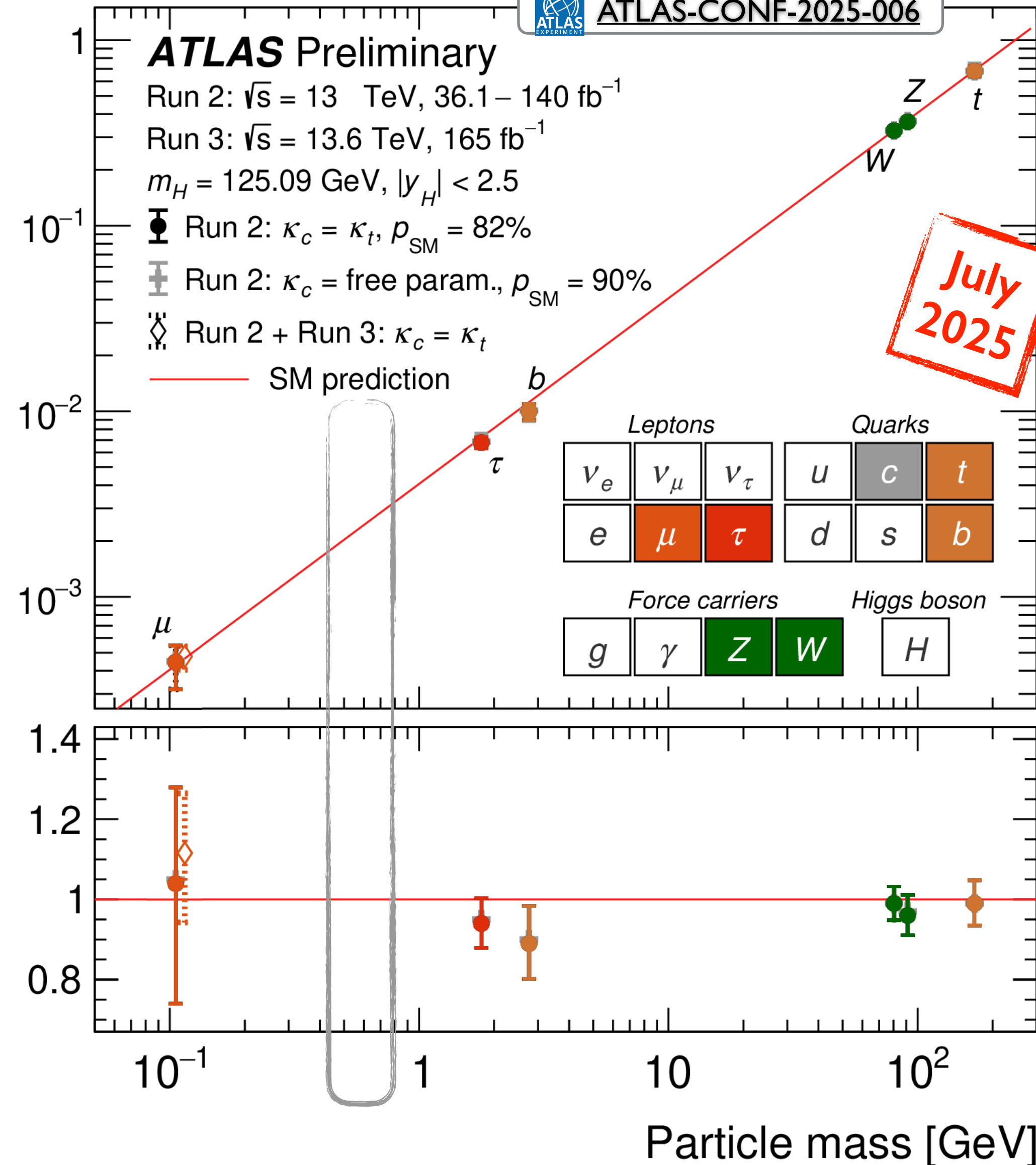


VH($H \rightarrow c\bar{c}$)
Exp. 7.6
Obs. 14



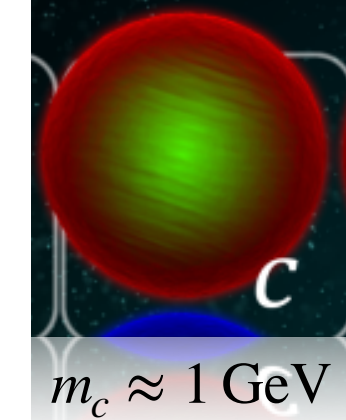
Phys. Rev. Lett. 131 (2023) 061801

$$\frac{m_V}{\kappa_F \text{ Vev}} \text{ or } \sqrt{\kappa_V} \text{ Vev}$$

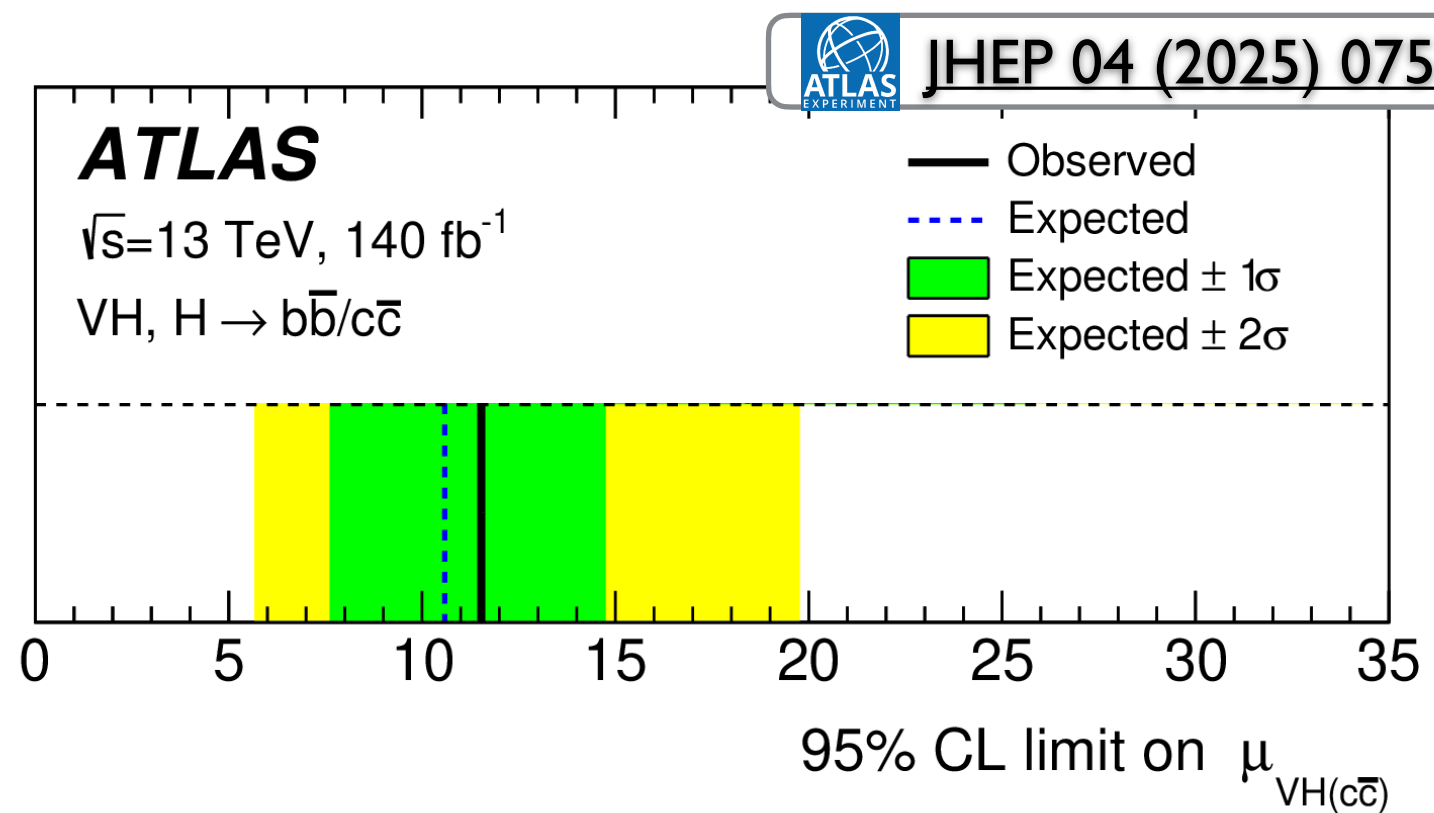




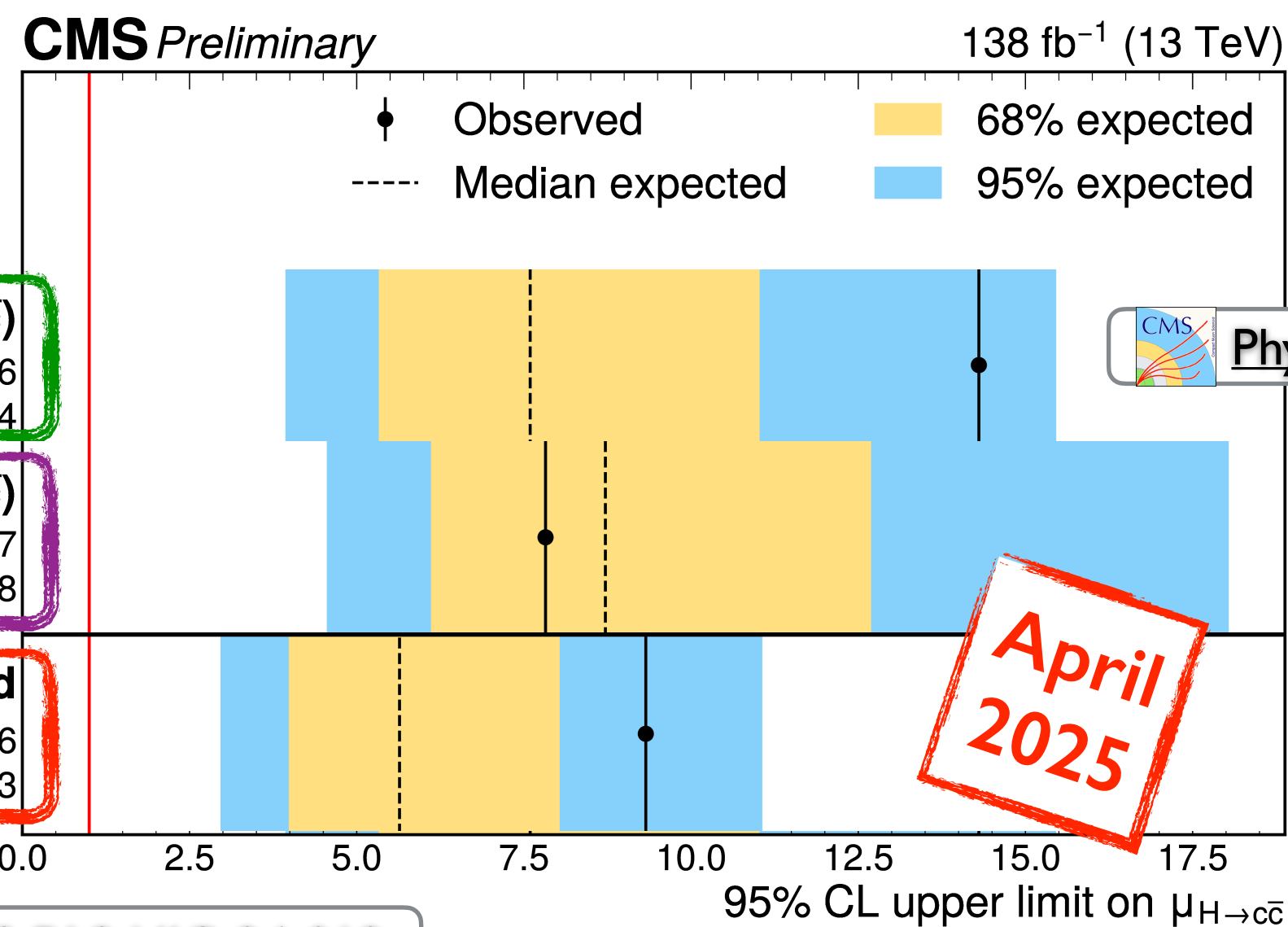
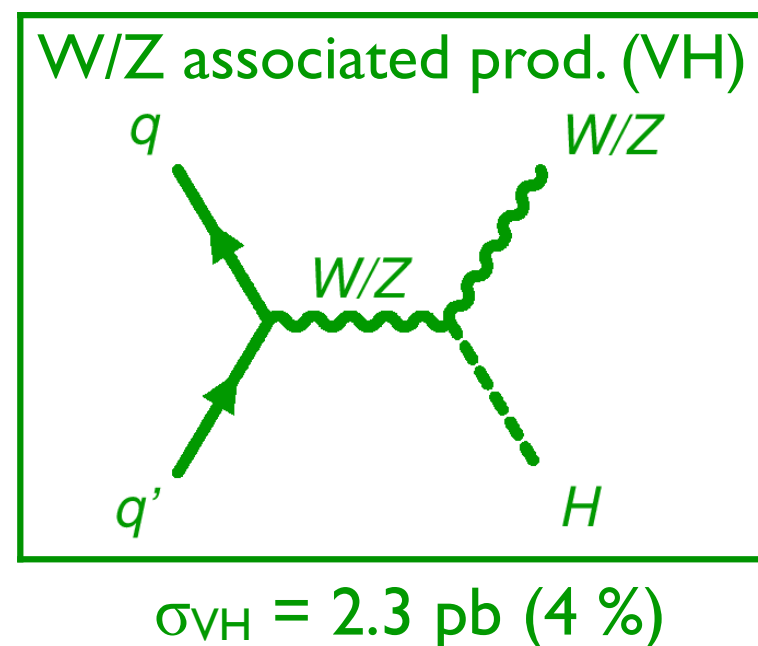
$$H \rightarrow c\bar{c}$$



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Combination
Exp. = 11 × SM
Obs. = 12 × SM



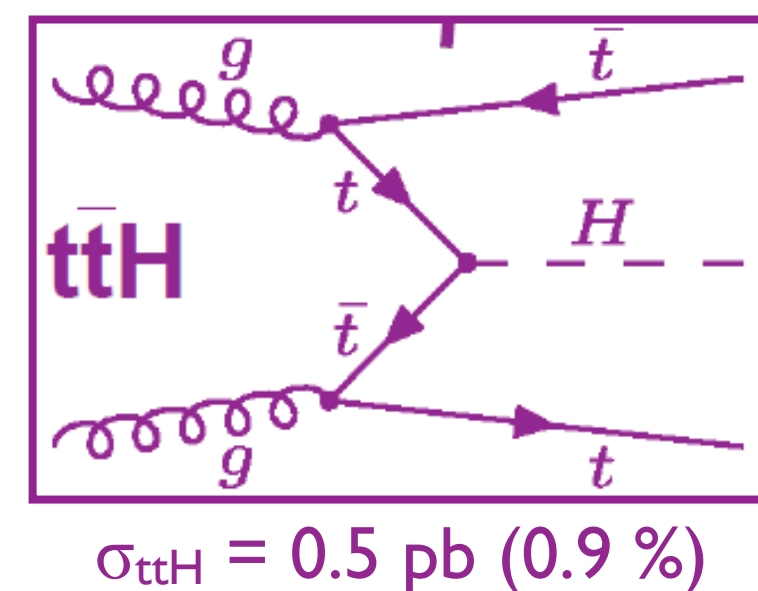
VH($H \rightarrow c\bar{c}$)
Exp. 7.6
Obs. 14

$t\bar{t}H(H \rightarrow c\bar{c})$
Exp. 8.7
Obs. 7.8

Combined
Exp. 5.6
Obs. 9.3

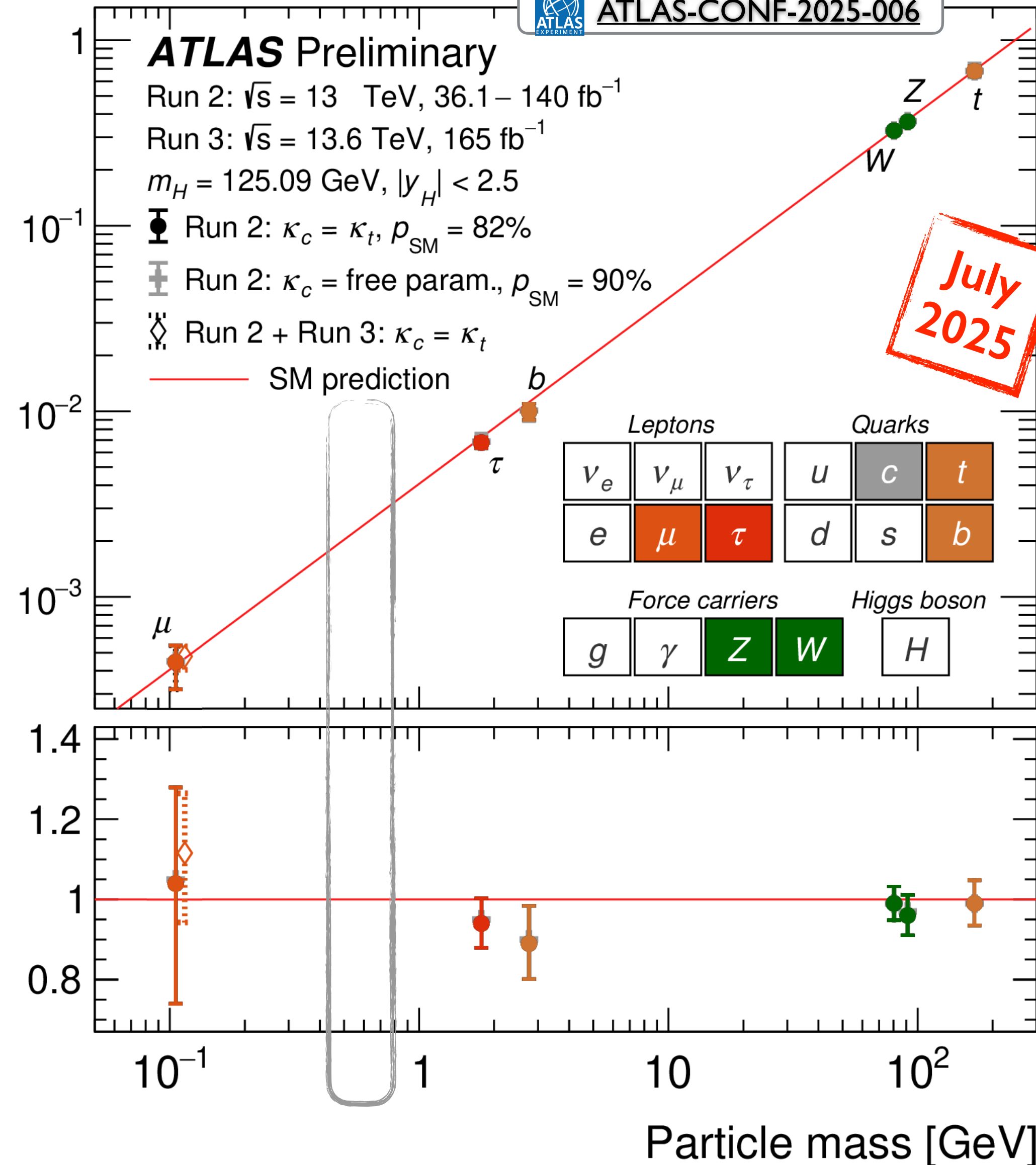
April 2025

Phys. Rev. Lett. 131 (2023) 061801



$$\frac{m_V}{\kappa_F \text{ Vev}} \text{ or } \sqrt{\kappa_V} \text{ Vev}$$

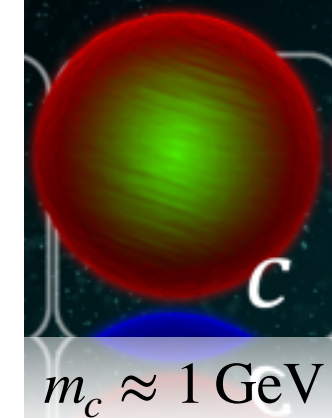
$$\kappa_F \text{ or } \kappa_V$$



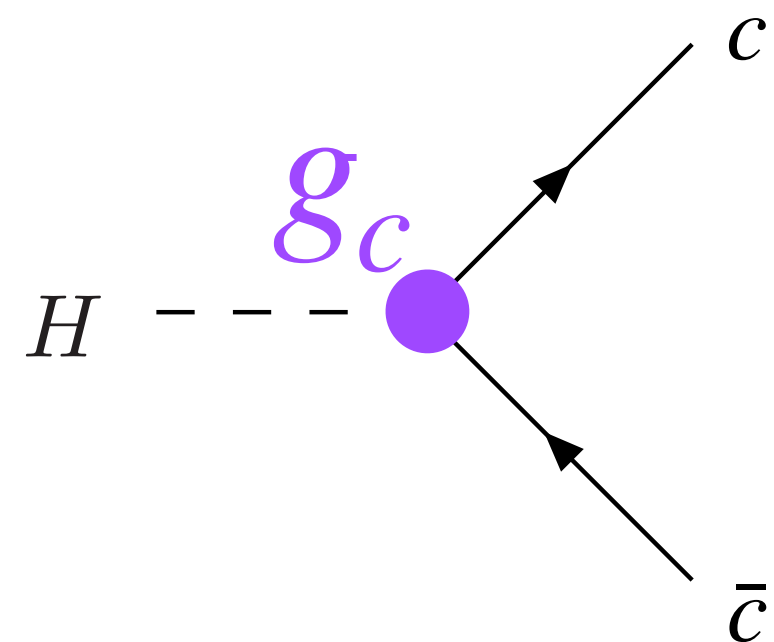
CMS-PAS-HIG-24-018



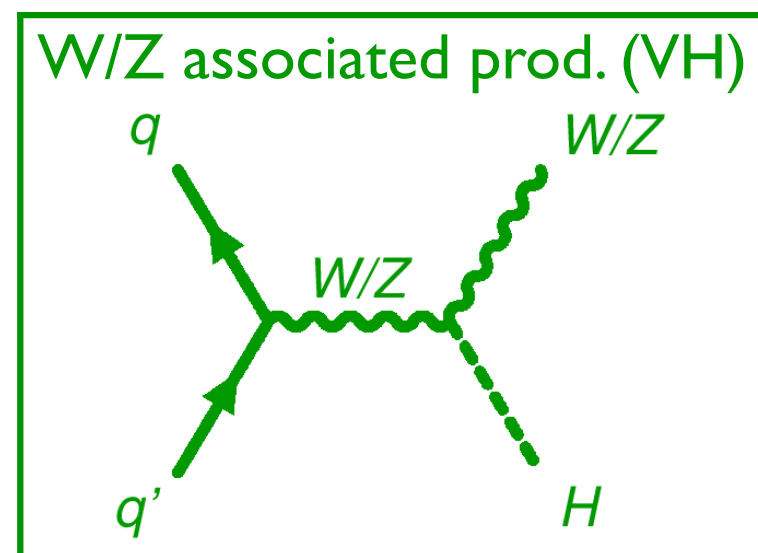
$$H \rightarrow c\bar{c}$$



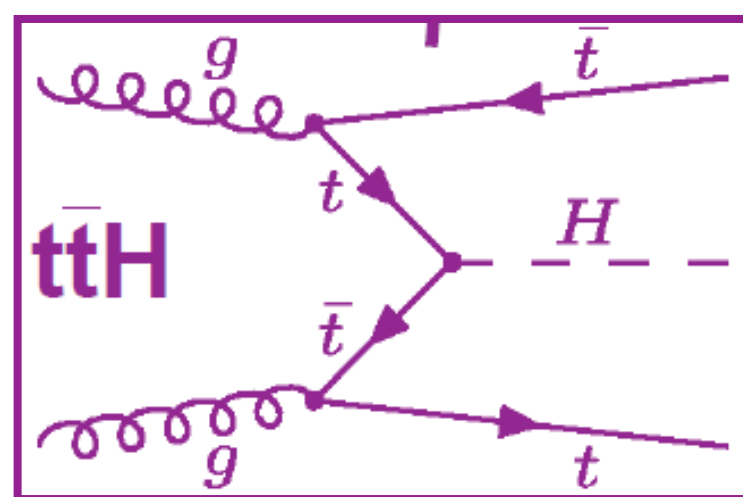
$$\mathcal{B}_{\text{SM}}(H \rightarrow c\bar{c}) = 2.9\%$$



$$\kappa_c = g_c / g_{c,\text{SM}}$$



$$\sigma_{\text{VH}} = 2.3 \text{ pb (4\%)}$$



$$\sigma_{\text{ttH}} = 0.5 \text{ pb (0.9\%)}$$

Observed (expected) limits on Higgs-charm coupling modifier at 95 % C.L.:

$$|\kappa_c| < 4.2 \text{ (4.1)}$$

$$1.1 < |\kappa_c| < 5.5 \text{ (} |\kappa_c| < 3.4 \text{)}$$

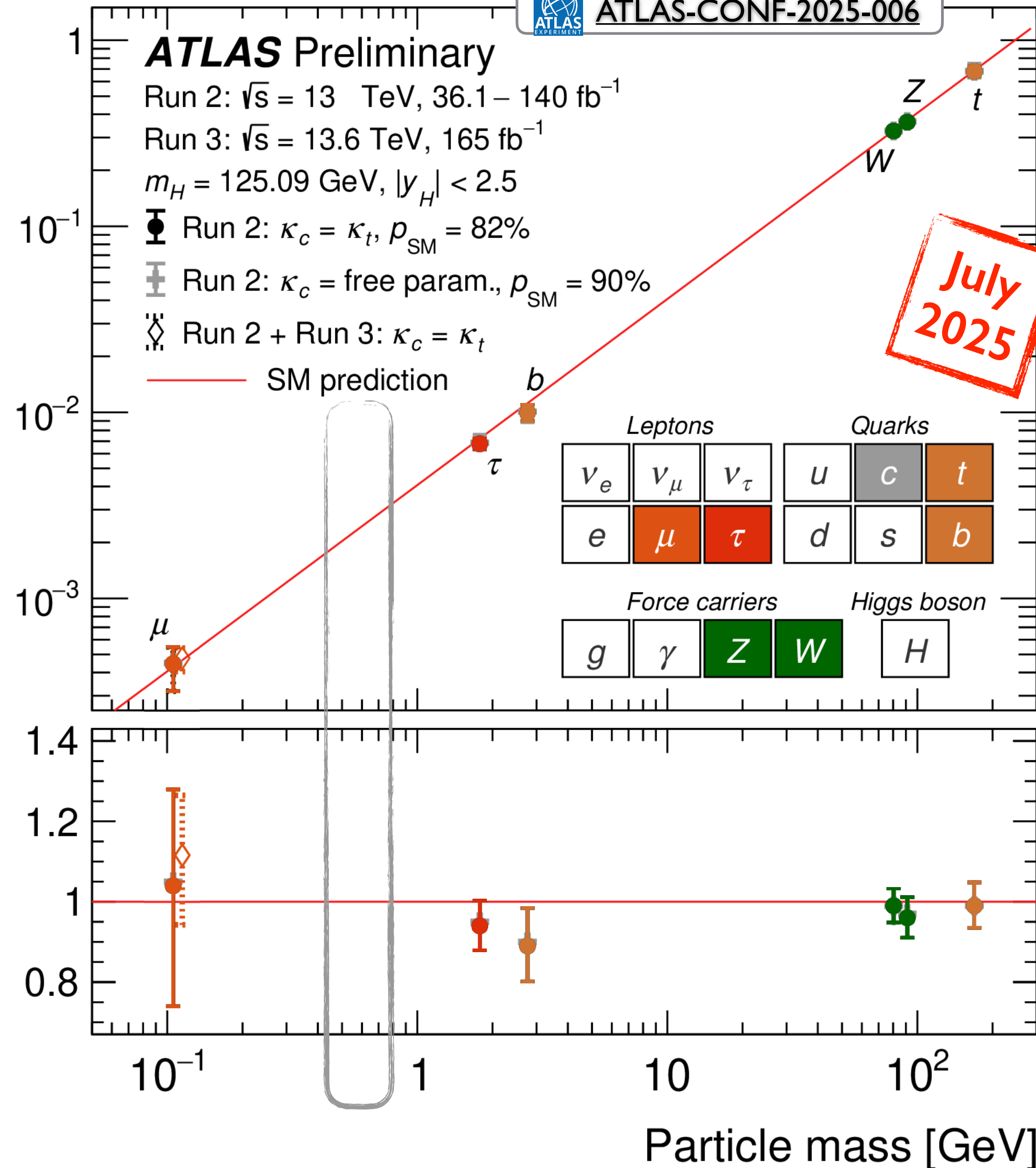
$$|\kappa_c| < 3.5 \text{ (2.7)}$$

JHEP 04 (2025) 075

Phys. Rev. Lett. 131 (2023) 061801

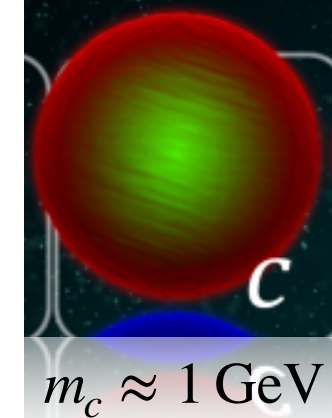
CMS-PAS-HIG-24-018

$$\frac{m_F}{\kappa_F \text{ vev}} \text{ or } \sqrt{\kappa_V} \frac{m_V}{\text{vev}}$$

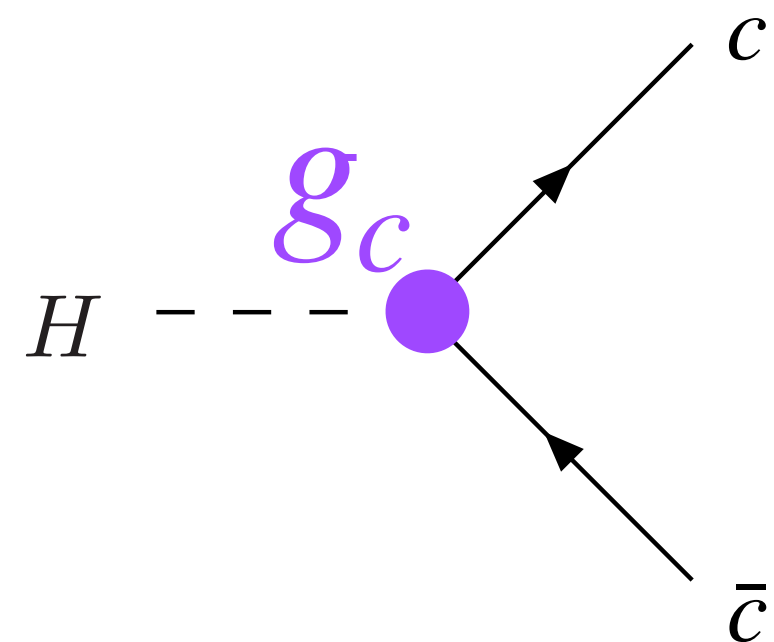




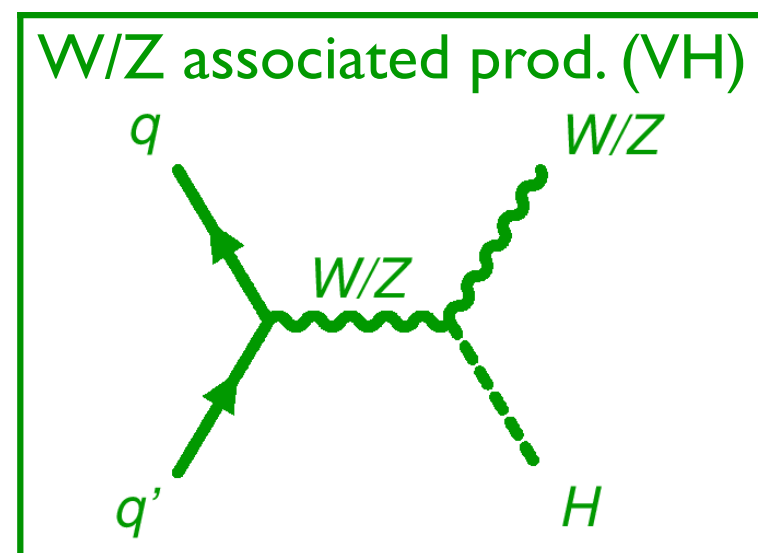
$$H \rightarrow c\bar{c}$$



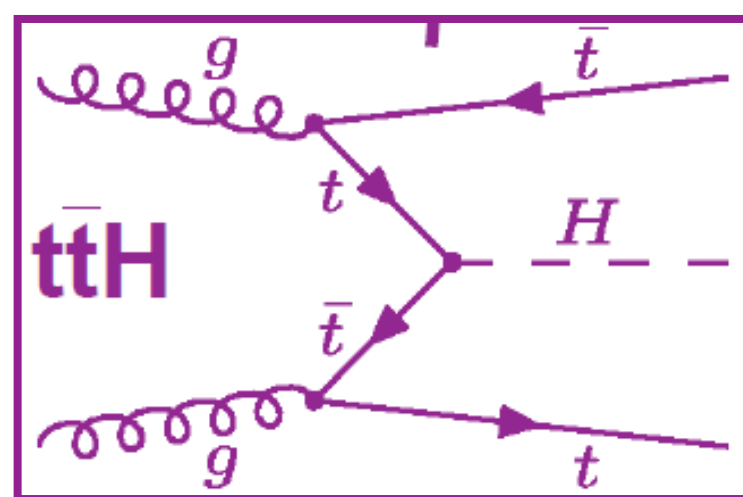
$$\mathcal{B}_{\text{SM}}(H \rightarrow c\bar{c}) = 2.9\%$$



$$\kappa_c = g_c / g_{c,\text{SM}}$$



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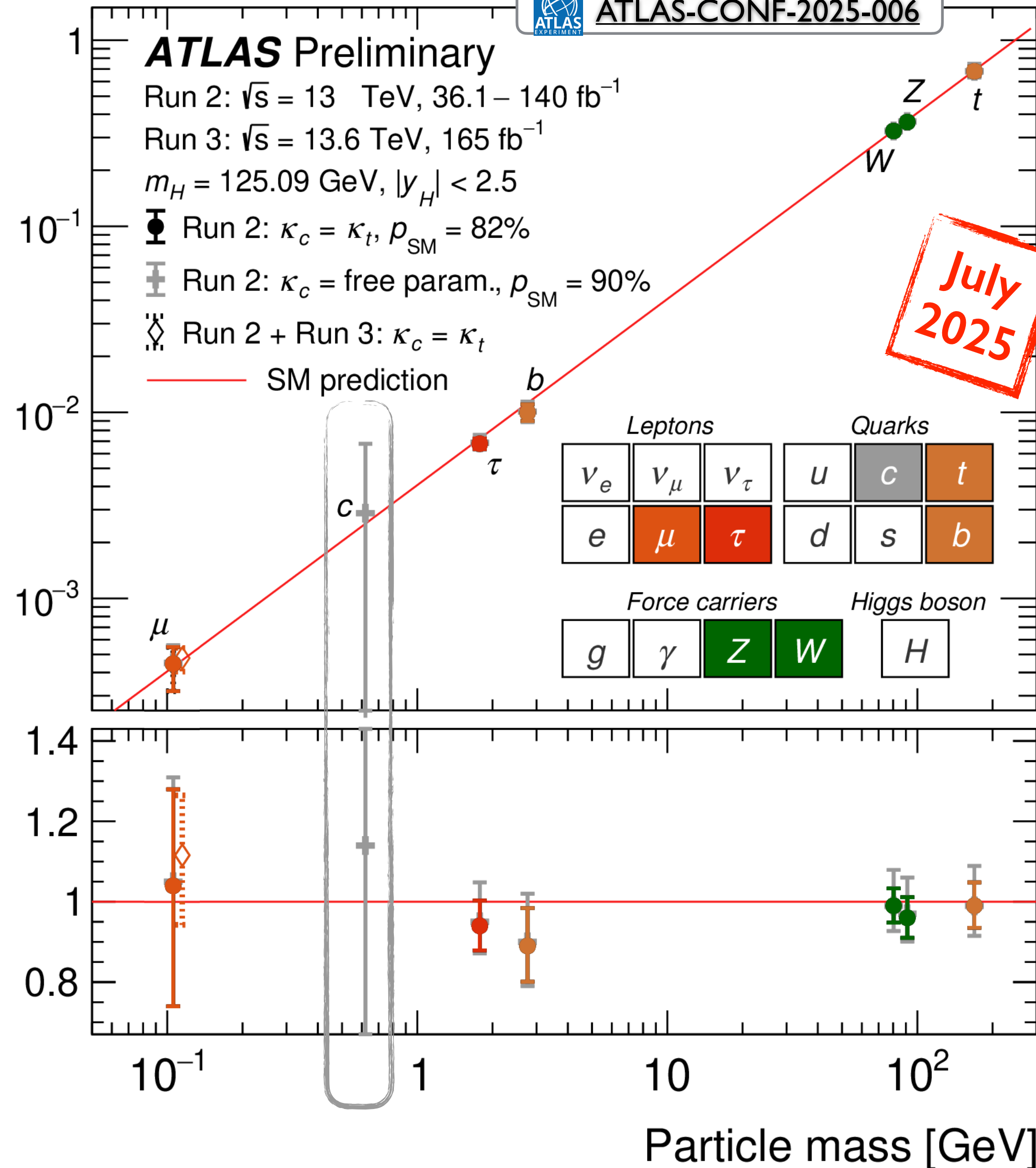
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ATLAS JHEP 04 (2025) 075

CMS Phys. Rev. Lett. 131 (2023) 061801

CMS CMS-PAS-HIG-24-018

$$\frac{m_F}{\kappa_F \text{ vev}} \text{ or } \sqrt{\kappa_V} \frac{m_V}{\text{vev}}$$

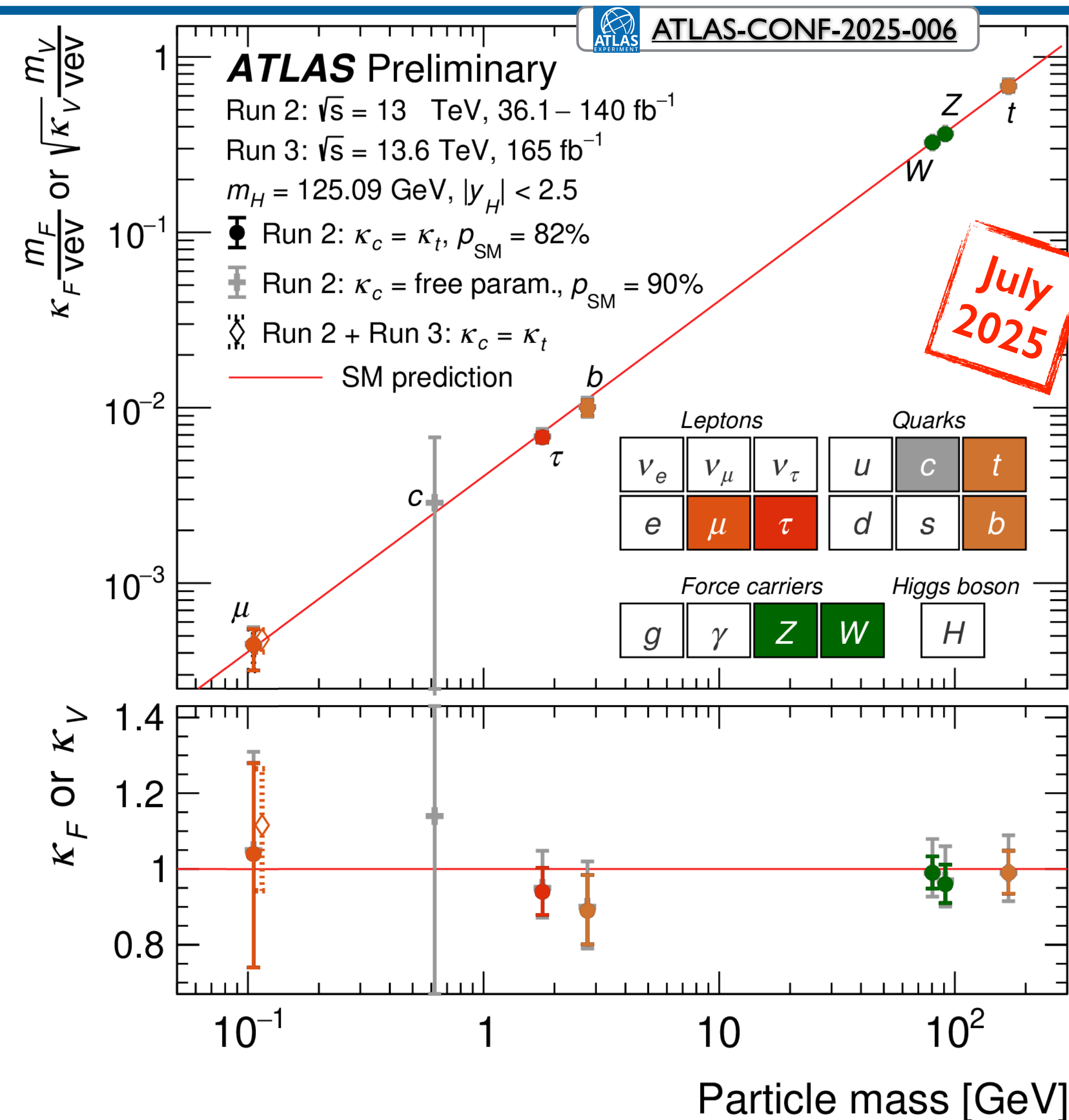




Mass $\sim$ Coupling Strength



- New Quantum concept of *mass*...
 $\Rightarrow$ Seems to work!





3. Higgs Potential



$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^2 \boxed{-\mu^2 \phi^2 - \lambda \phi^4} + y_f \phi \psi^2$$

HH production

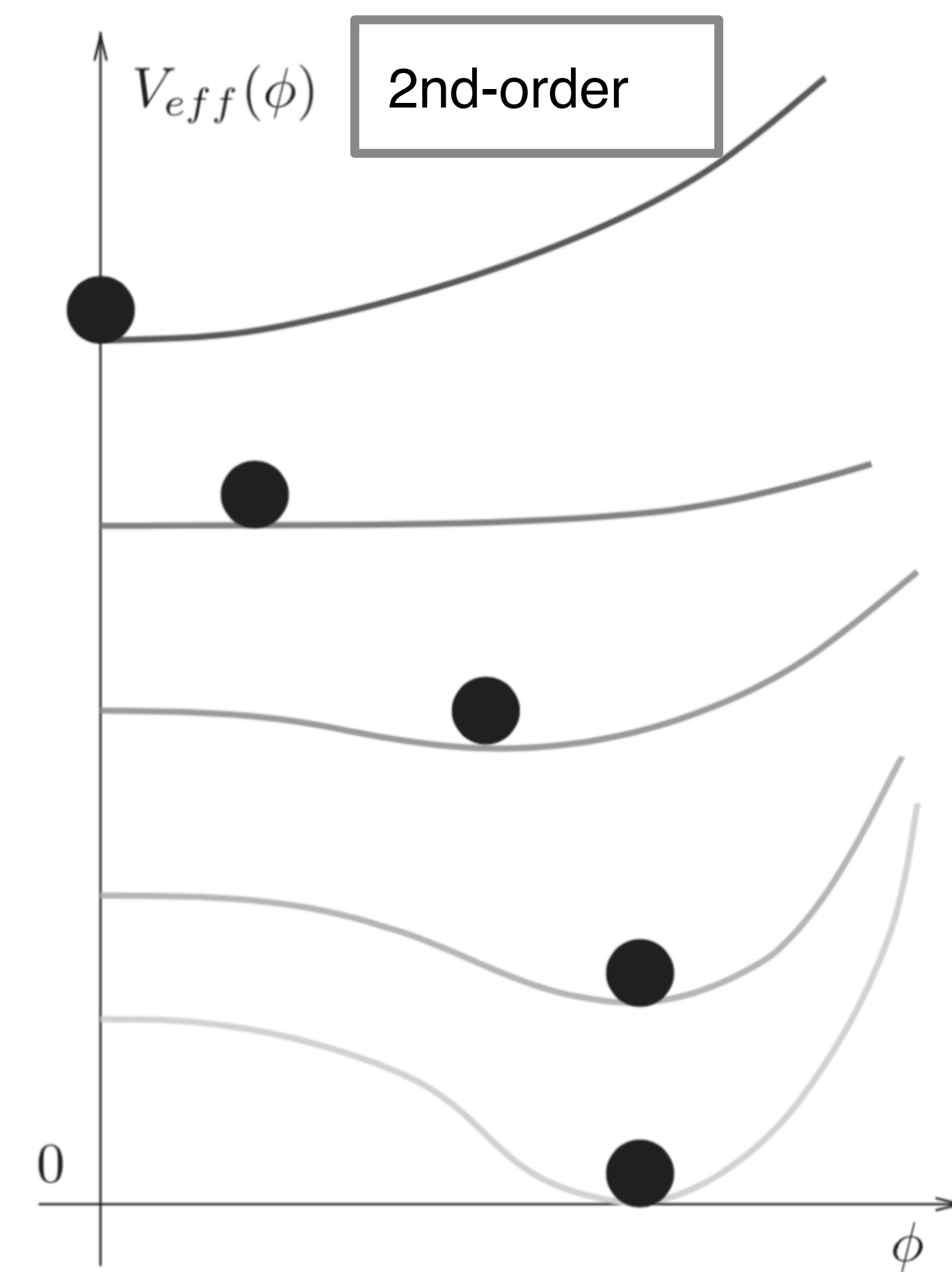
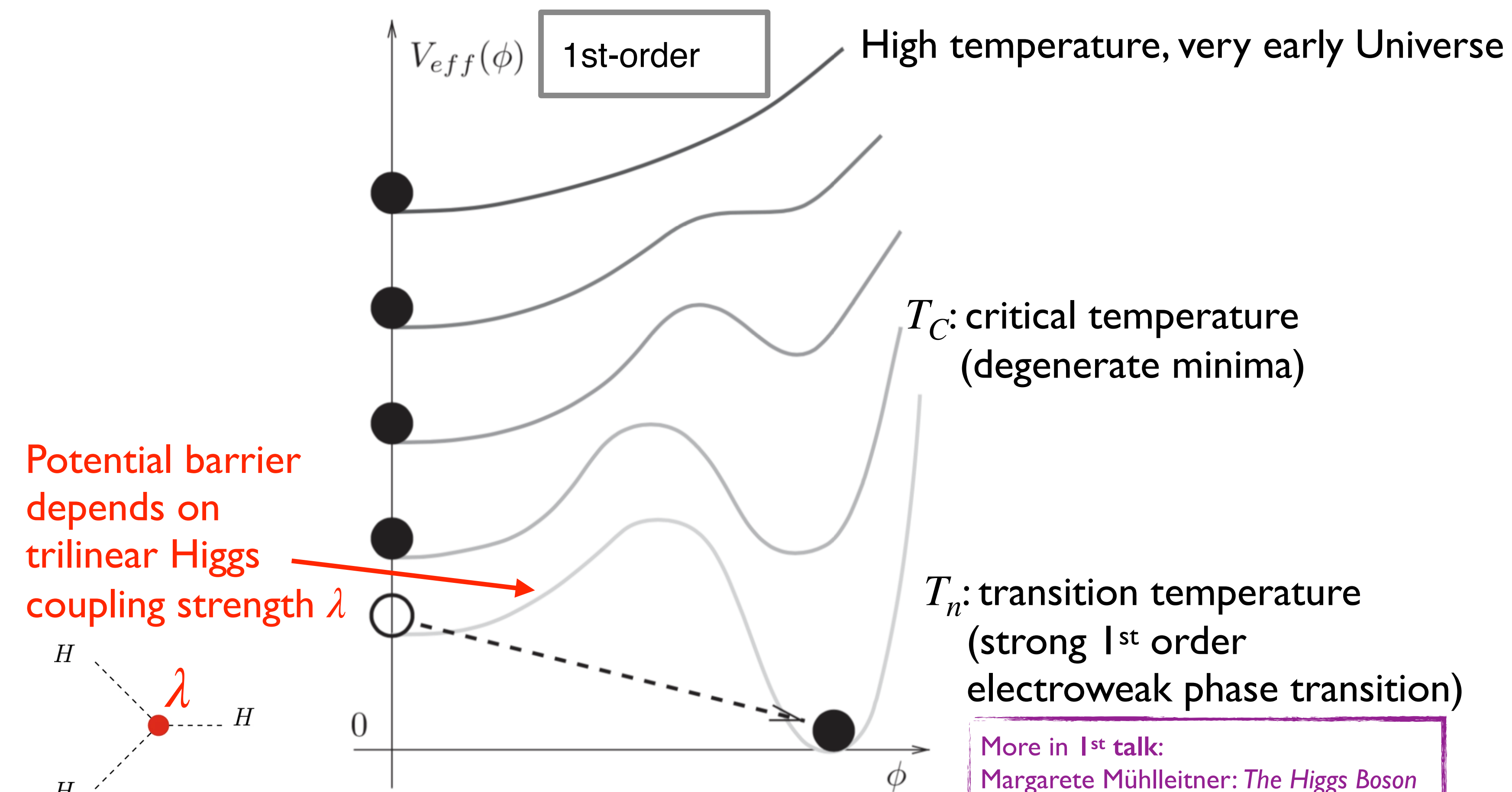
In SM: $\lambda = \frac{1}{2} m_H^2 / v^2$

$\boxed{-\mu^2 \phi^2 - \lambda \phi^4}$
H potential as in SM?



Early Universe: Electroweak Phase Transition GA

Baryogenesis: creation of *matter-antimatter asymmetry in the Universe*
requires 1st order electroweak phase transition



More in 1st talk:
Margarete Mühlleitner: *The Higgs Boson*
– Key to our Understanding of the Universe



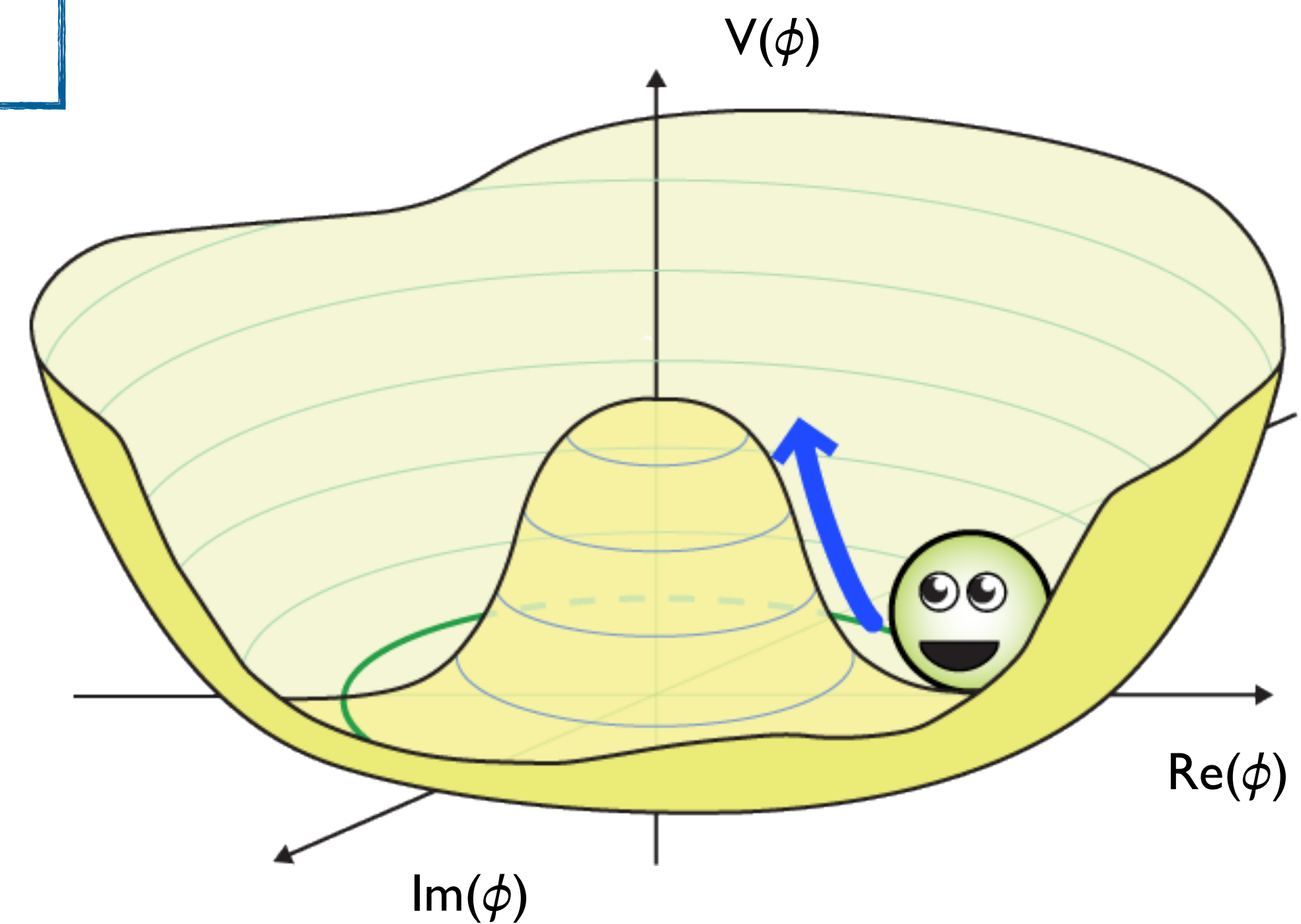
HH Production



- Map out Higgs potential

$$\mathcal{L} \ni -\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

H self interactions





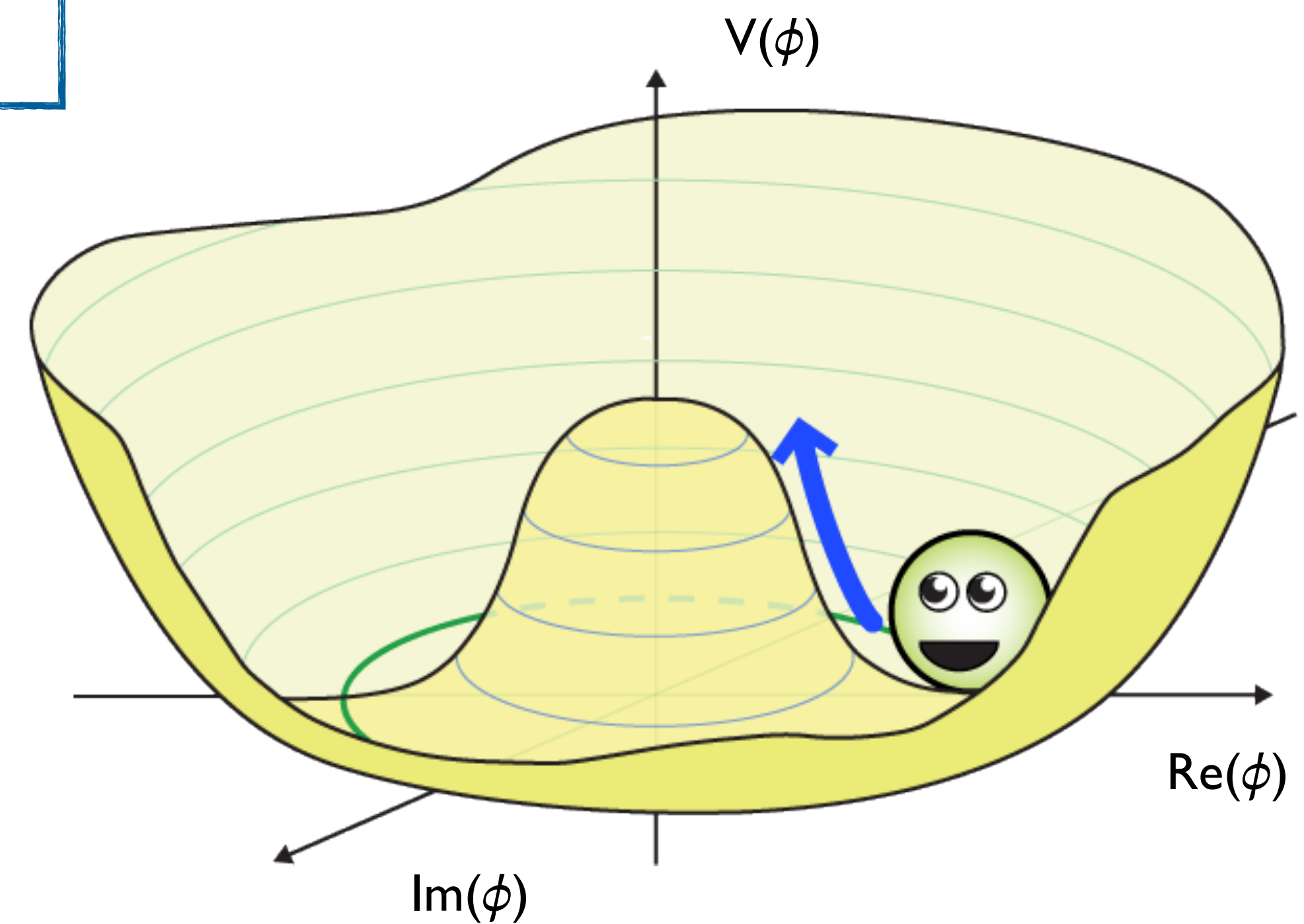
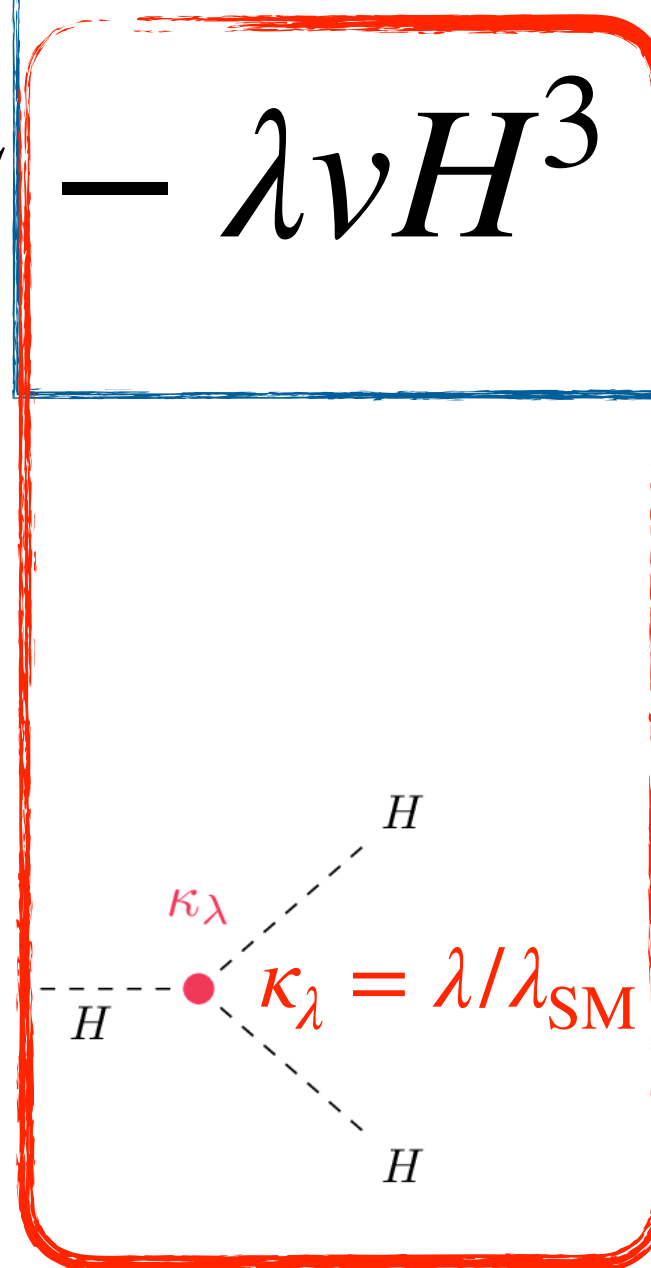
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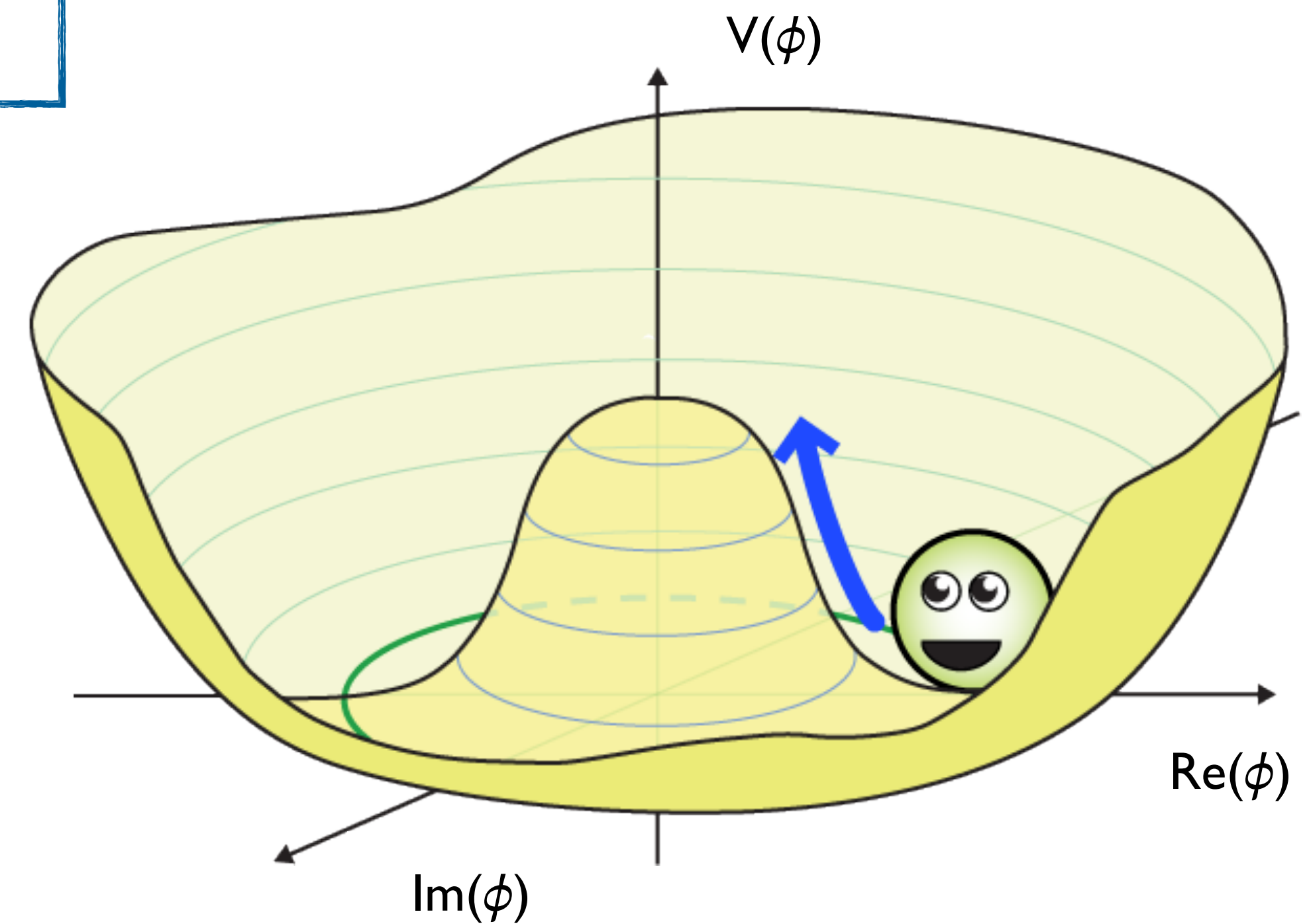
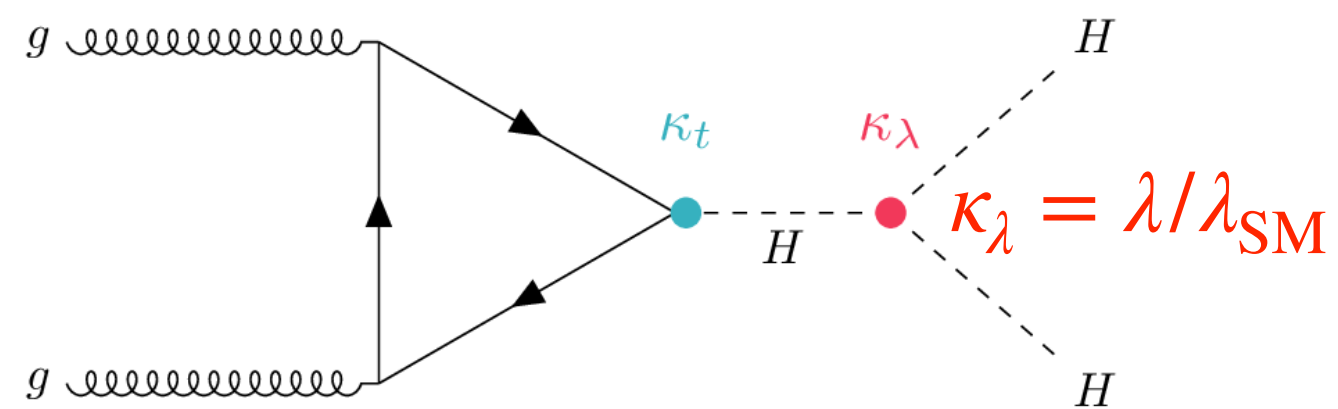
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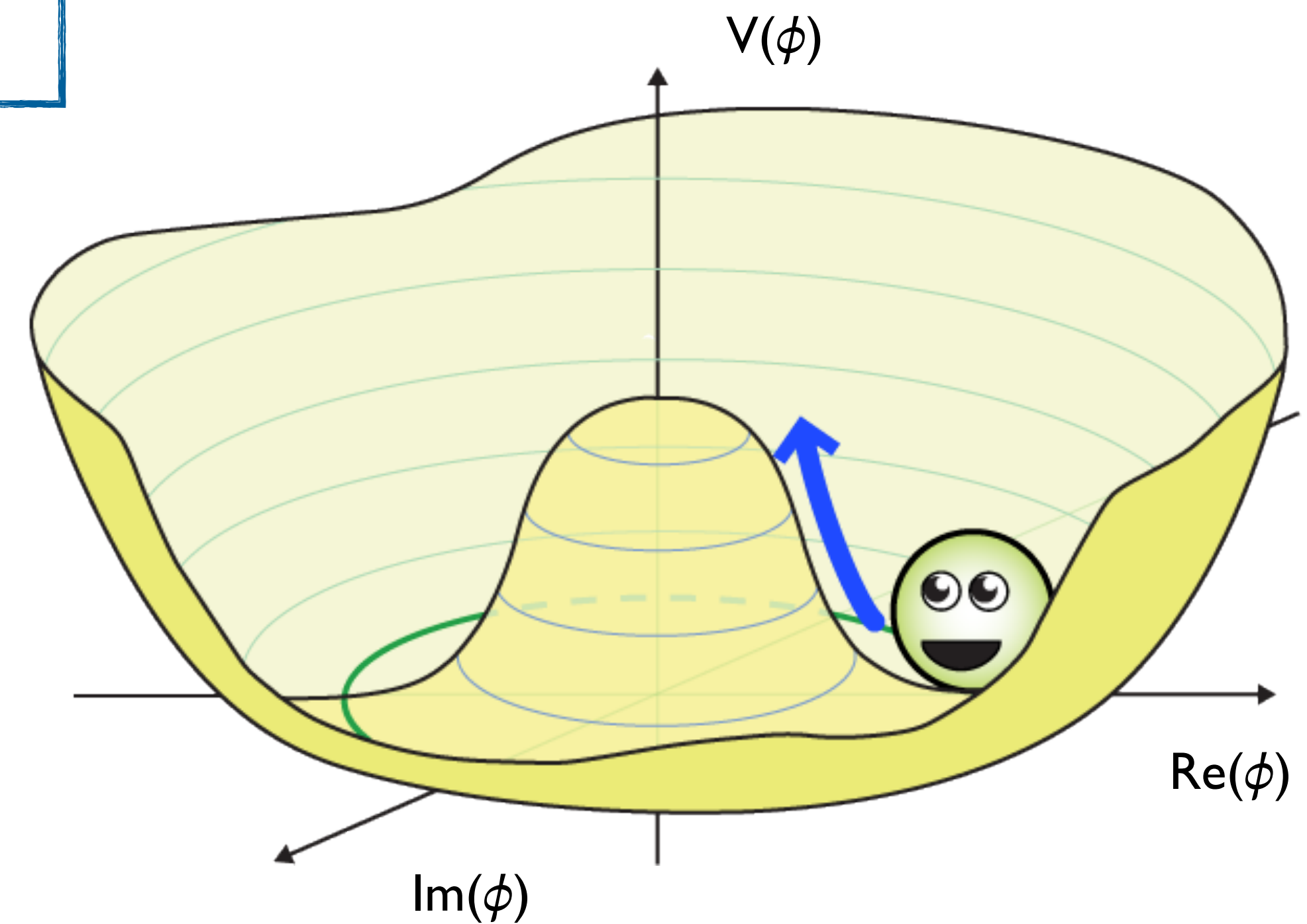
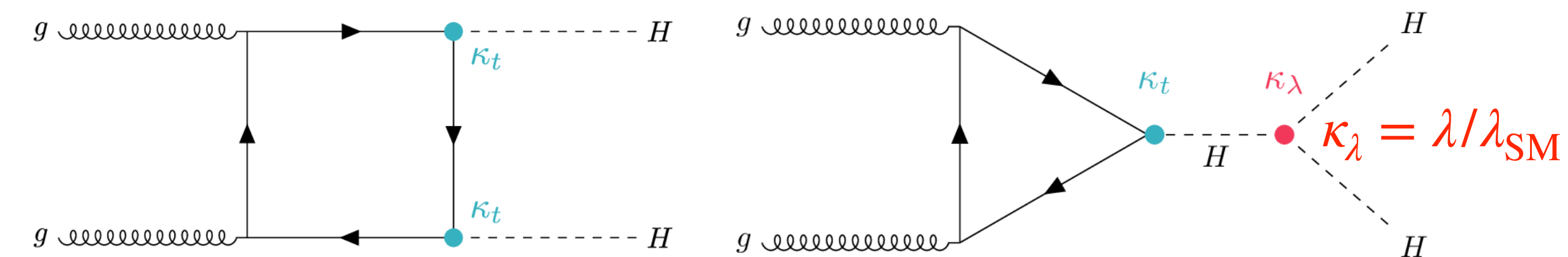
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H self interactions





HH Production

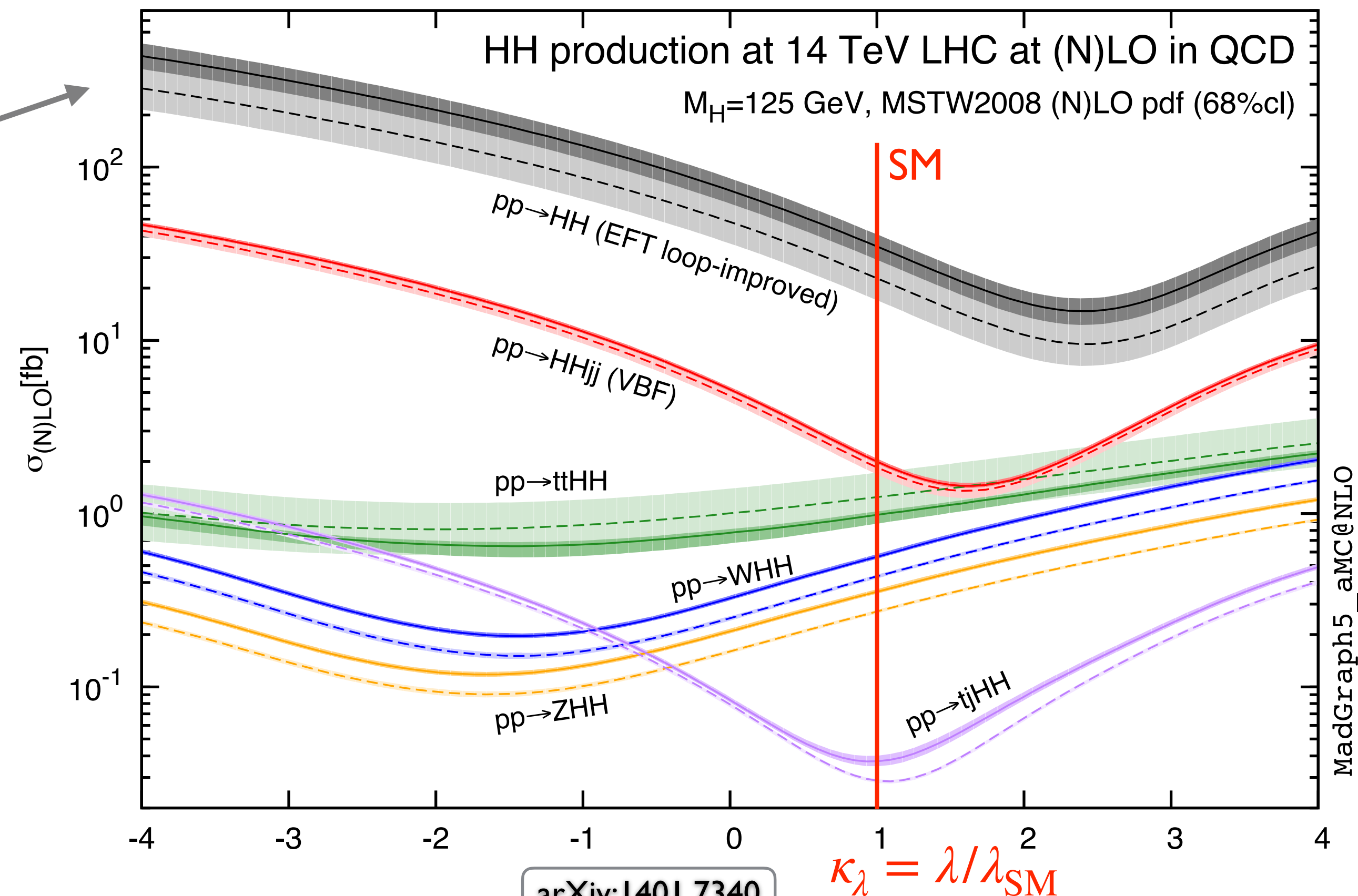
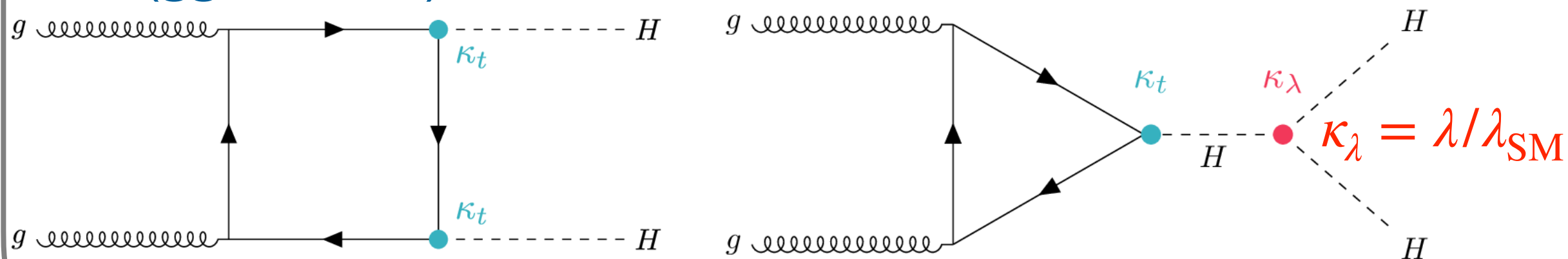


- Map out Higgs potential

$$\mathcal{L} \ni -\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

H self interactions

$$\sigma(gg \rightarrow HH) = 31.05 \text{ fb}$$



arXiv:1401.7340

$$\kappa_\lambda = \lambda/\lambda_{\text{SM}}$$



Di-Higgs Decays



$$H \rightarrow xx$$

$$H \rightarrow yy$$

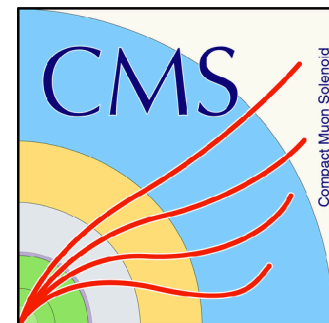
	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.10%	0.029%	0.013%	0.0005%

“Large” BR & clean signatures:

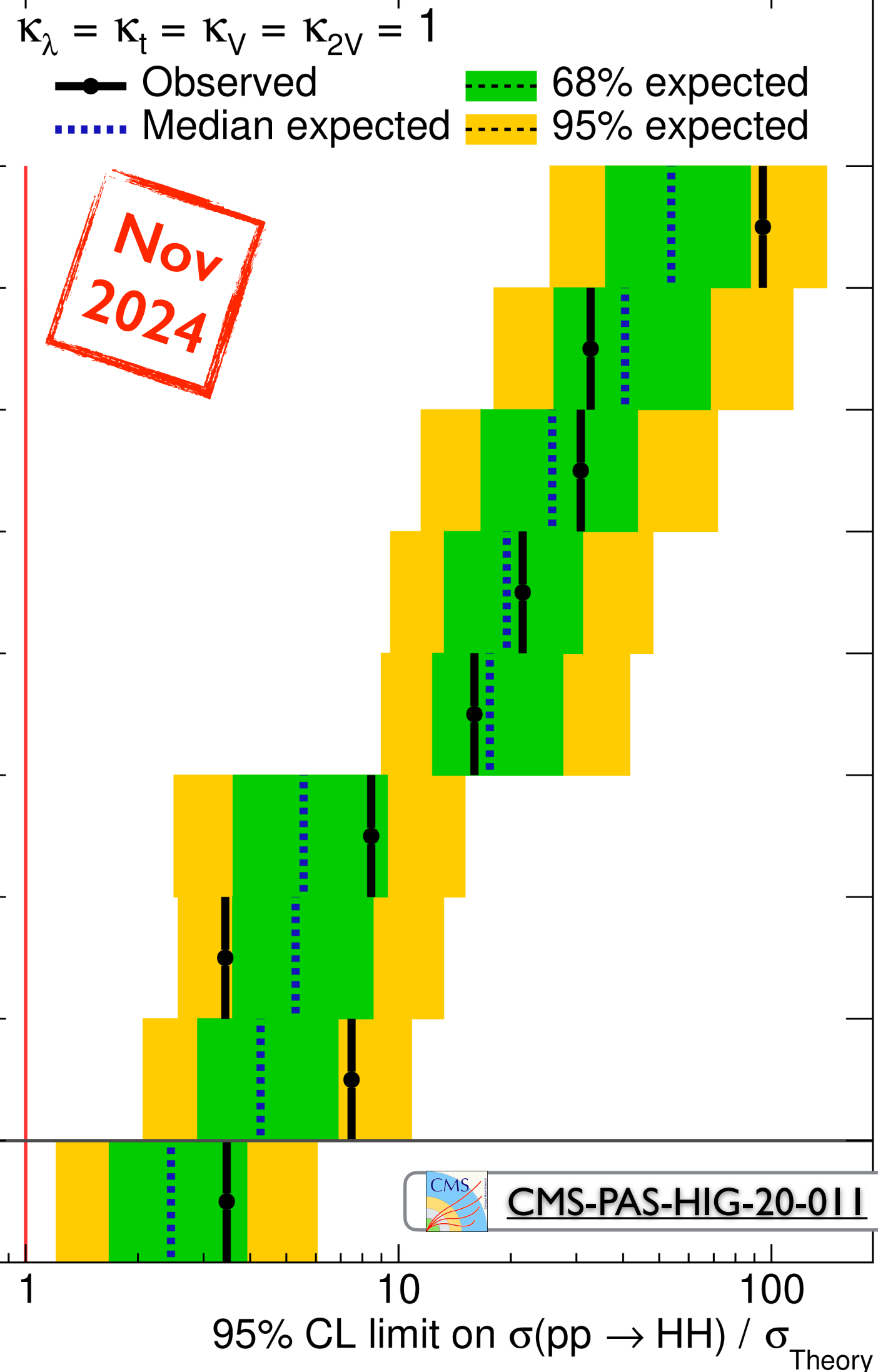
- $\text{BR}_{\text{SM}}(\mathbf{HH} \rightarrow \mathbf{bbbb}) = 33\%$
- $\text{BR}_{\text{SM}}(\mathbf{HH} \rightarrow \mathbf{bb}\tau\tau) = 7.3\%$
- $\text{BR}_{\text{SM}}(\mathbf{HH} \rightarrow \mathbf{bb}\gamma\gamma) = 0.26\%$



Di-Higgs Results

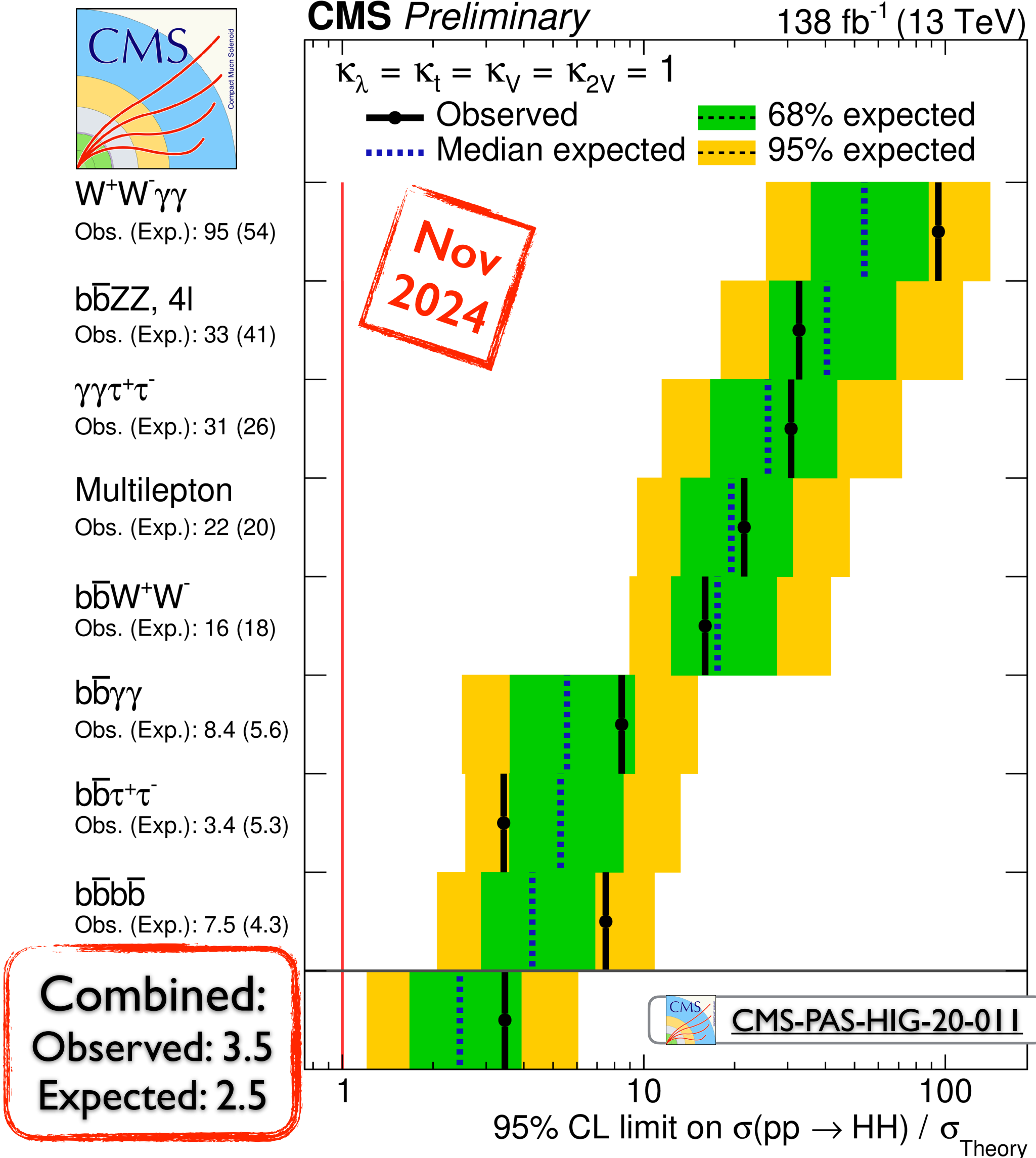


CMS Preliminary 138 fb⁻¹ (13 TeV)





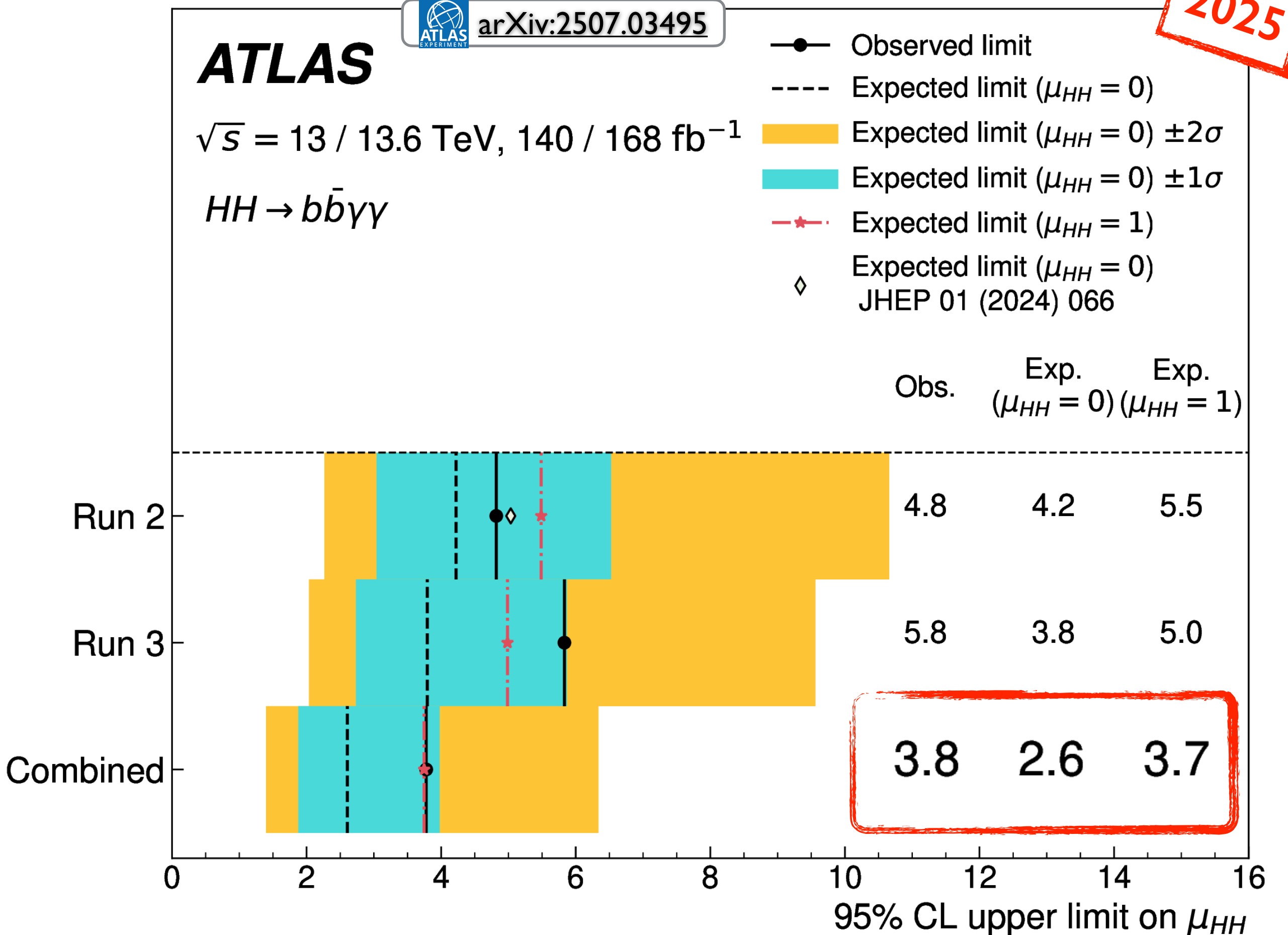
Di-Higgs Results



Run 2 and 3 (2022-2024) $HH \rightarrow b\bar{b}\gamma\gamma$:

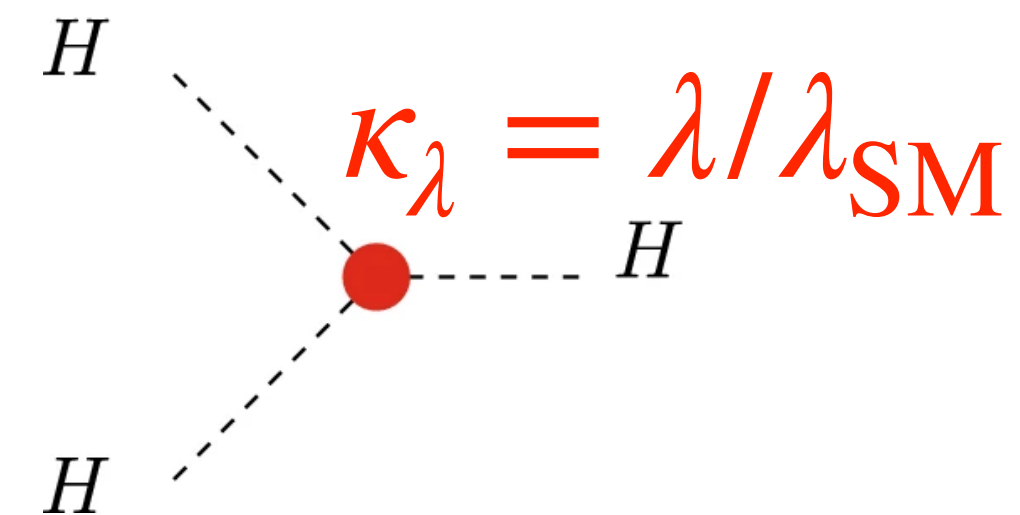
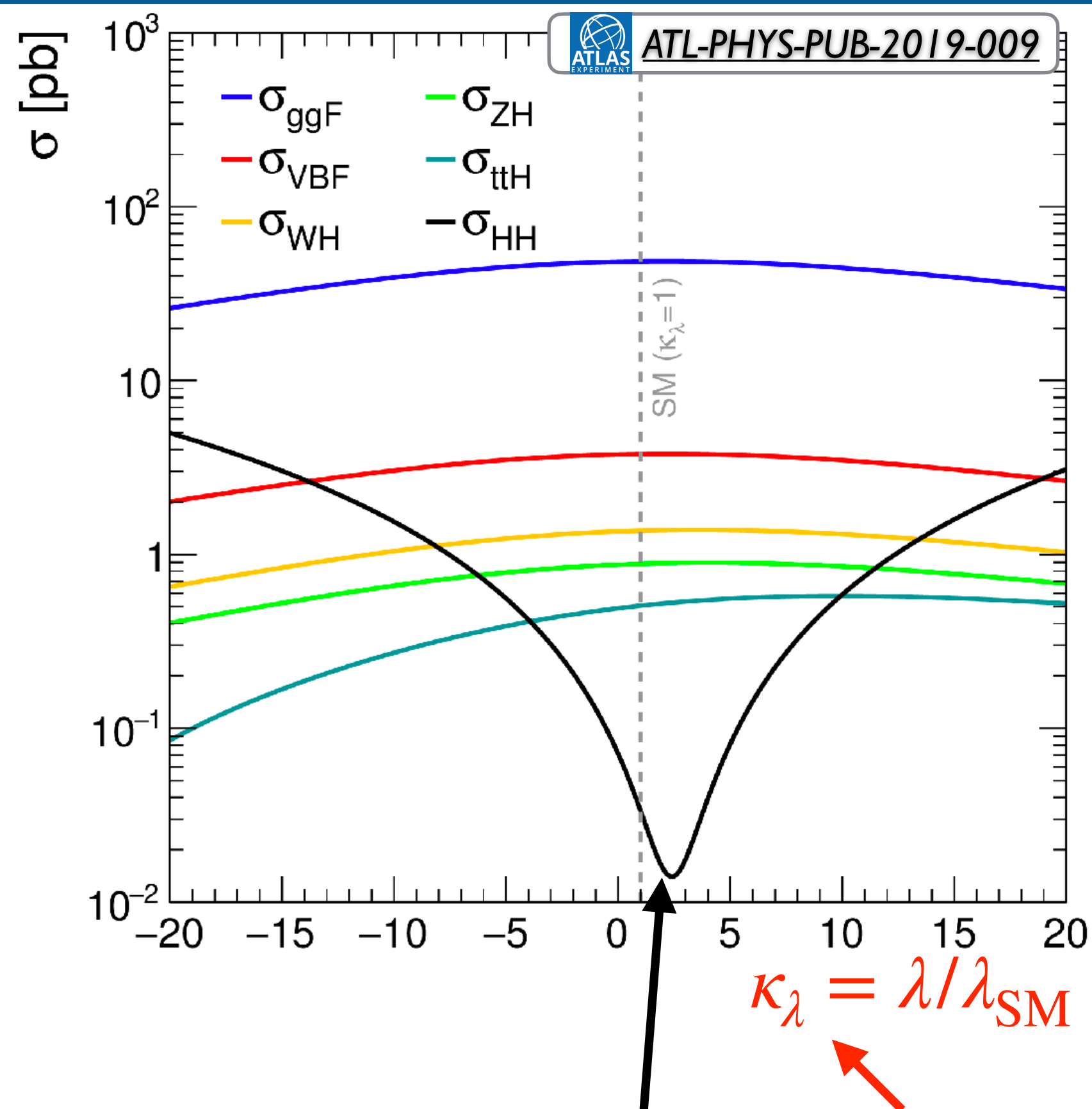
$$\mu_{HH}^{\text{obs.}} = 0.9^{+1.4}_{-1.1} \quad (\mu_{HH}^{\text{exp.}} = 1.0^{+1.3}_{-1.0})$$

July 2025





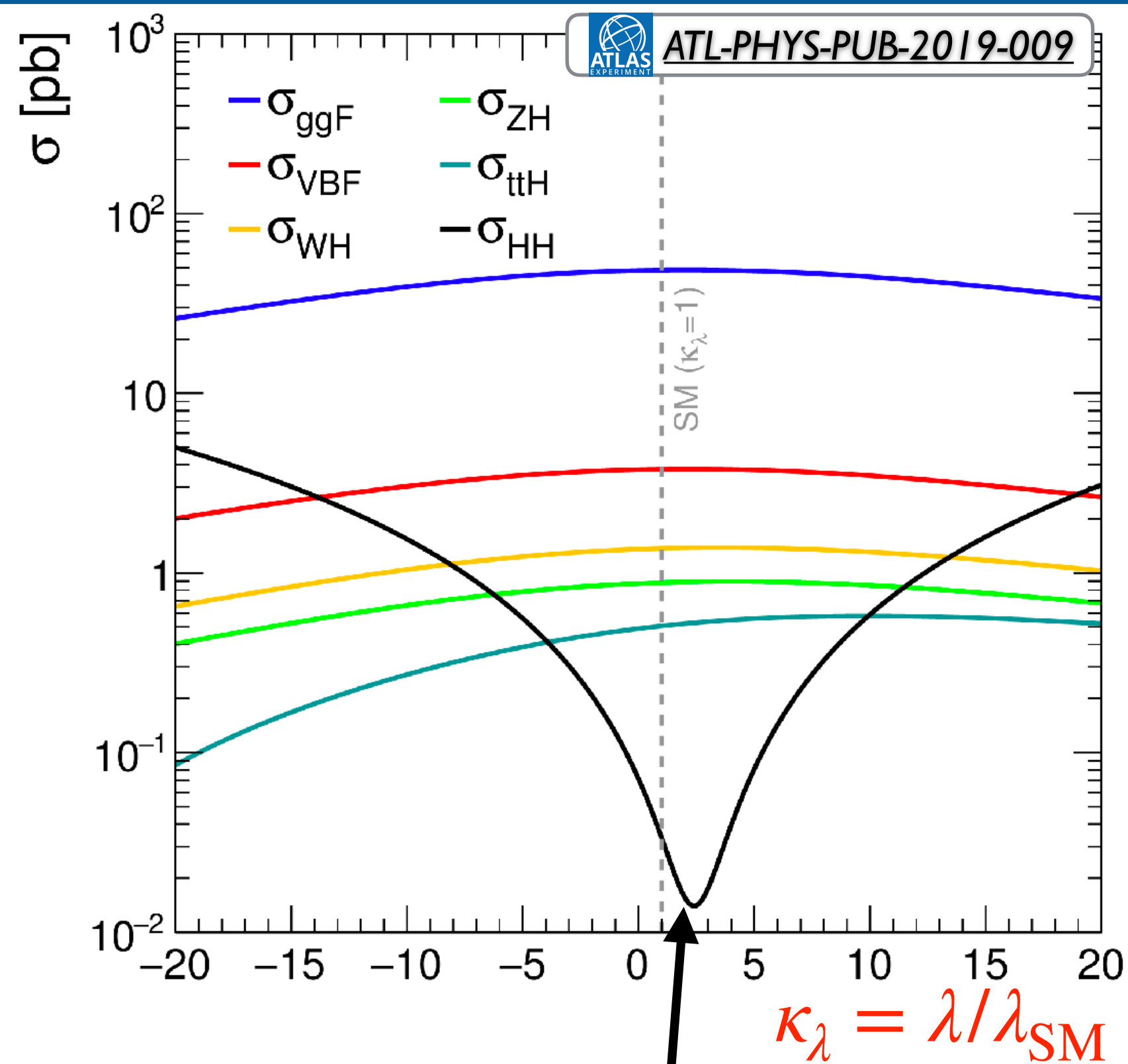
Extracting Trilinear Higgs Coupling λ



Strong sensitivity of $\sigma(HH)$ on κ_λ

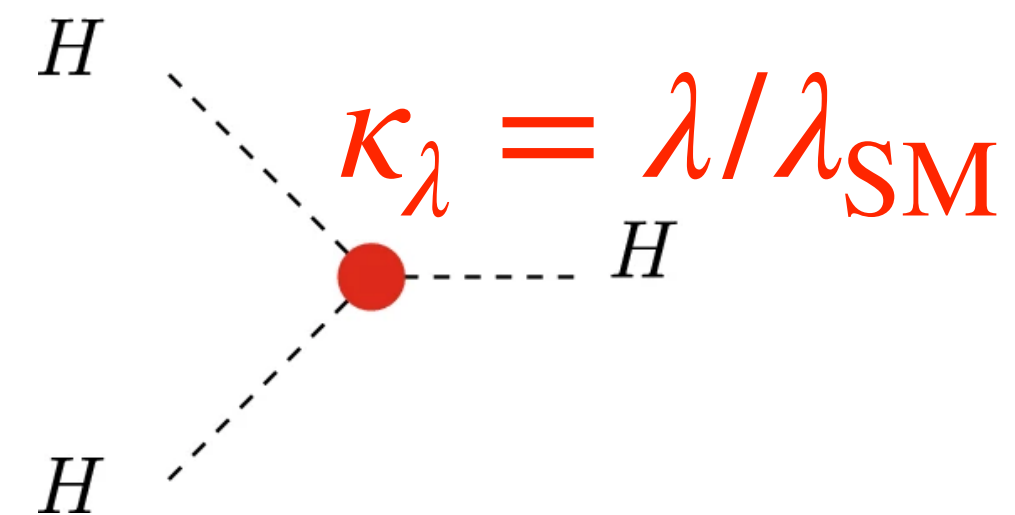
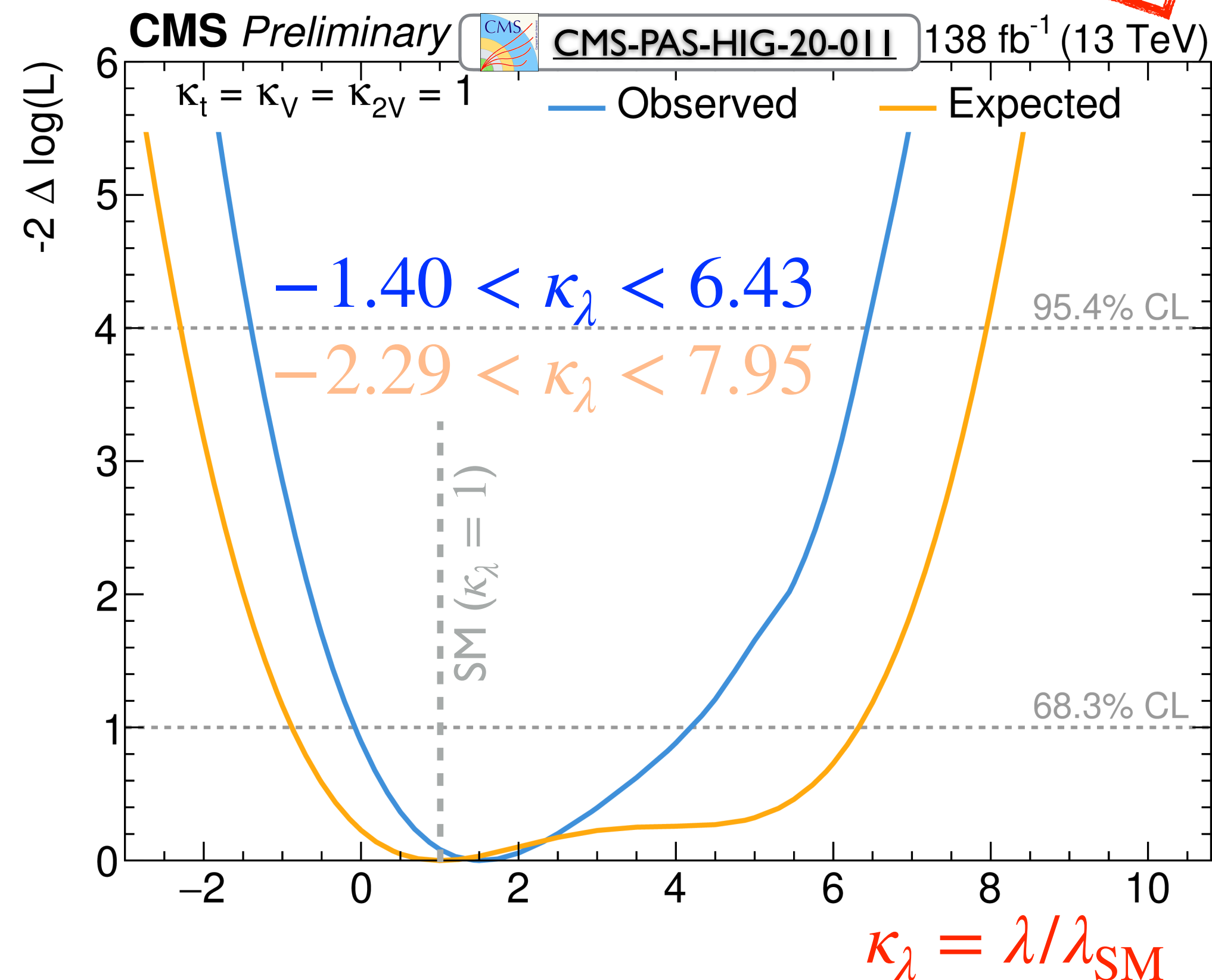


Extracting Trilinear Higgs Coupling λ



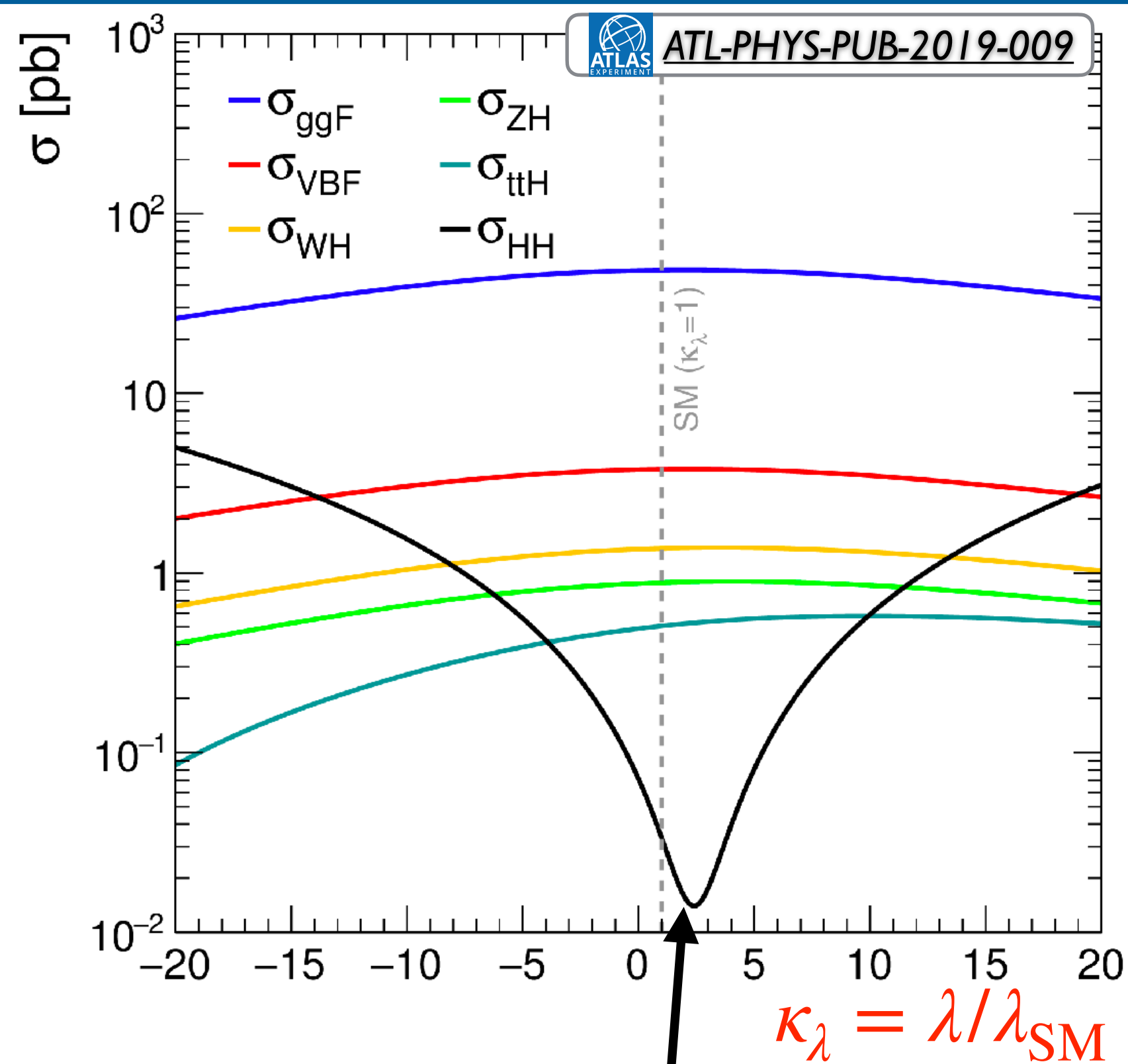
Strong sensitivity of $\sigma(HH)$ on κ_λ

All-channel combination:

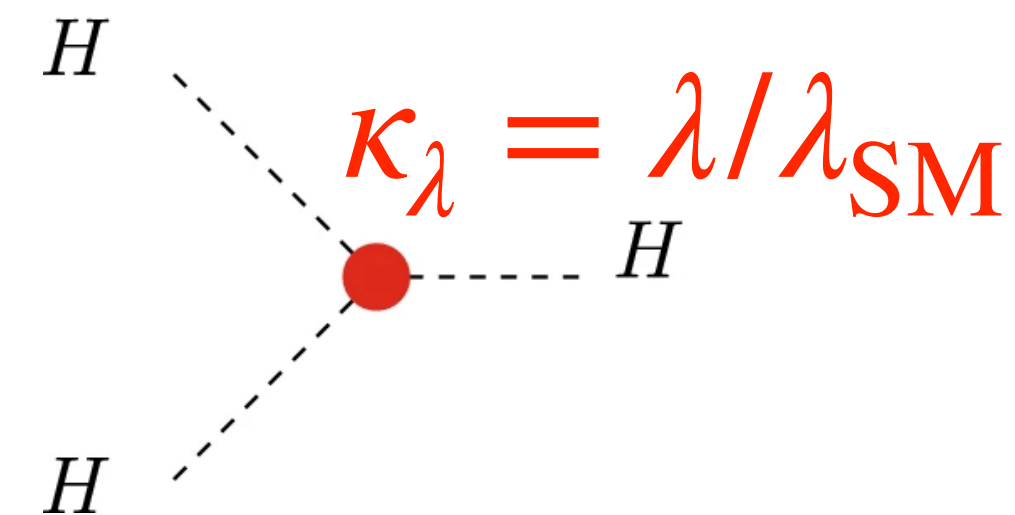
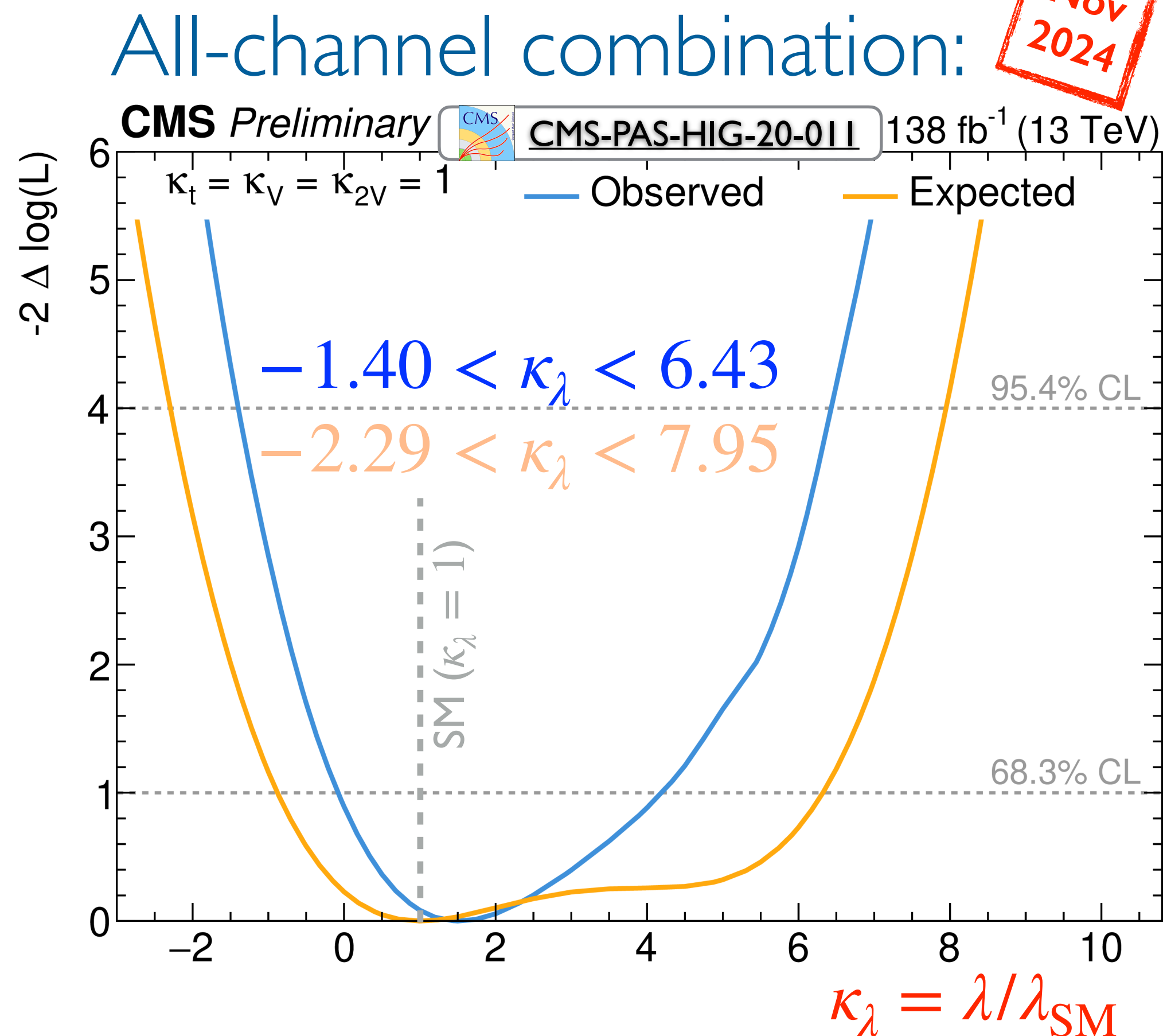




Extracting Trilinear Higgs Coupling λ



Strong sensitivity of $\sigma(HH)$ on κ_λ



ATLAS arXiv:2507.03495 **July 2025**

Run 2+3

$HH \rightarrow b\bar{b}\gamma\gamma$:

$-1.7 < \kappa_\lambda^{\text{obs.}} < 6.6$

$(-1.8 < \kappa_\lambda^{\text{exp.}} < 6.9)$



4. Search for *New Physics*



$$\mathcal{L}_{\text{Nature}} = \mathcal{L}_{\text{SM}} + \boxed{\mathcal{L}_{???}}$$



Effective Field Theory Interpretations GA

Extend SM with new physics operators:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$

(assumes no new particles below $\Lambda = 1 \text{ TeV}$)



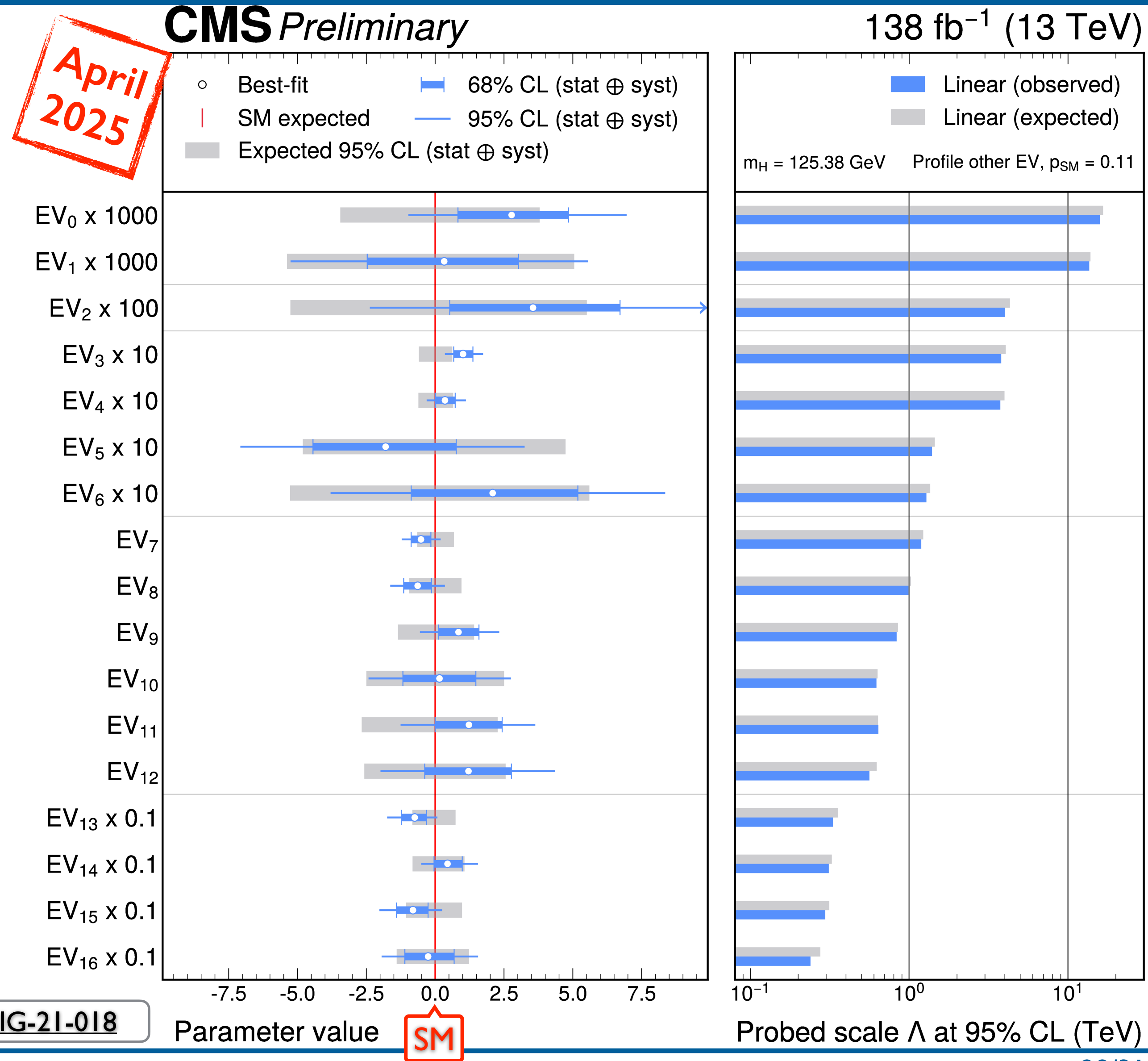
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- Use combined measurement of many differential cross-section results
- 17 EFT parameters fitted simultaneously!
 - Eigenvector rotation (to remove insensitive directions)



CMS-PAS-HIG-21-018



Effective Field Theory Interpretations

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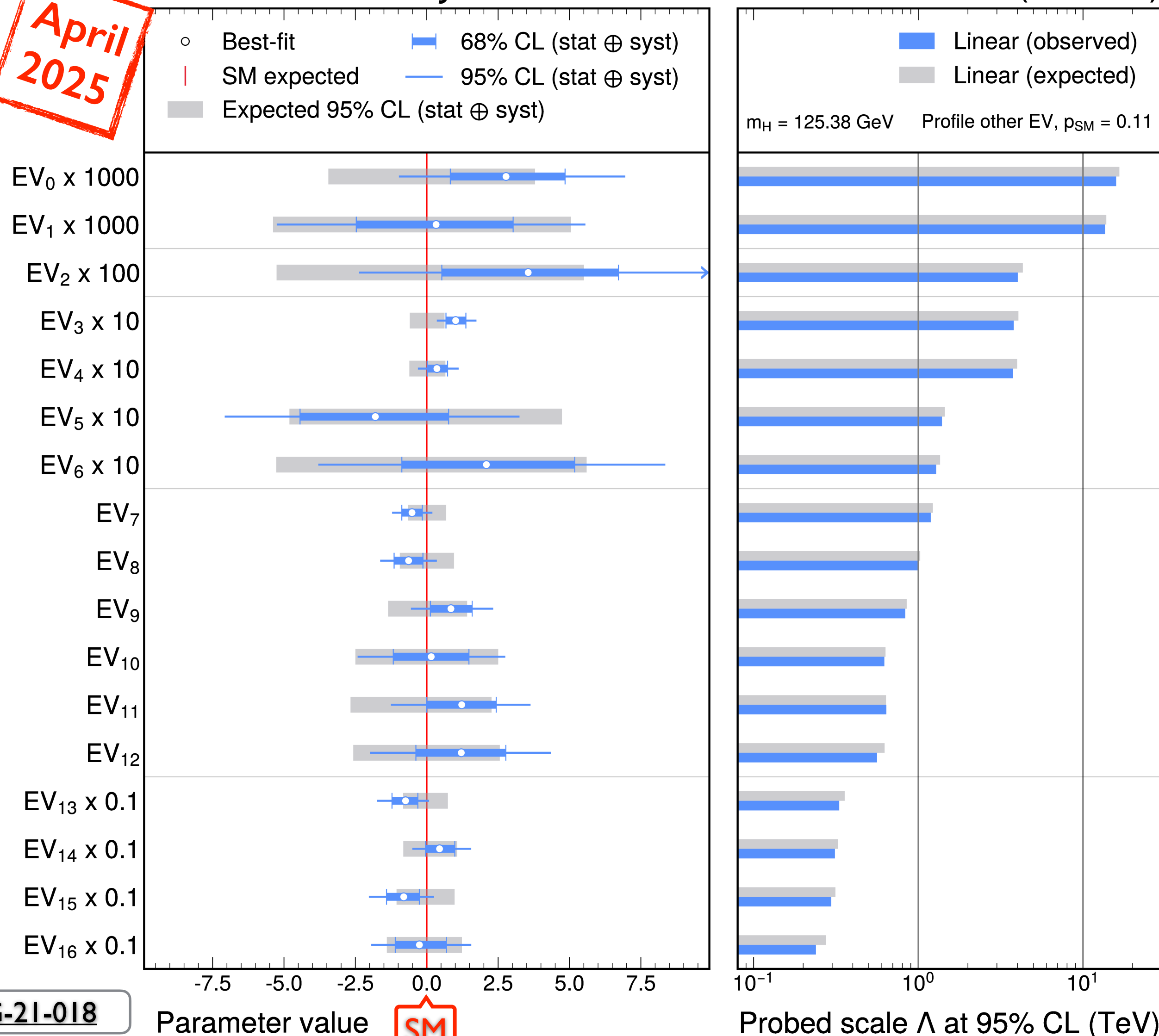
- Use combined measurement of many differential cross-section results
- 17 EFT parameters fitted simultaneously!
 - Eigenvector rotation (to remove insensitive directions)

Opens the window to global combined analyses!

April 2025

CMS Preliminary

138 fb⁻¹ (13 TeV)



CMS-PAS-HIG-21-018

Parameter value

SM

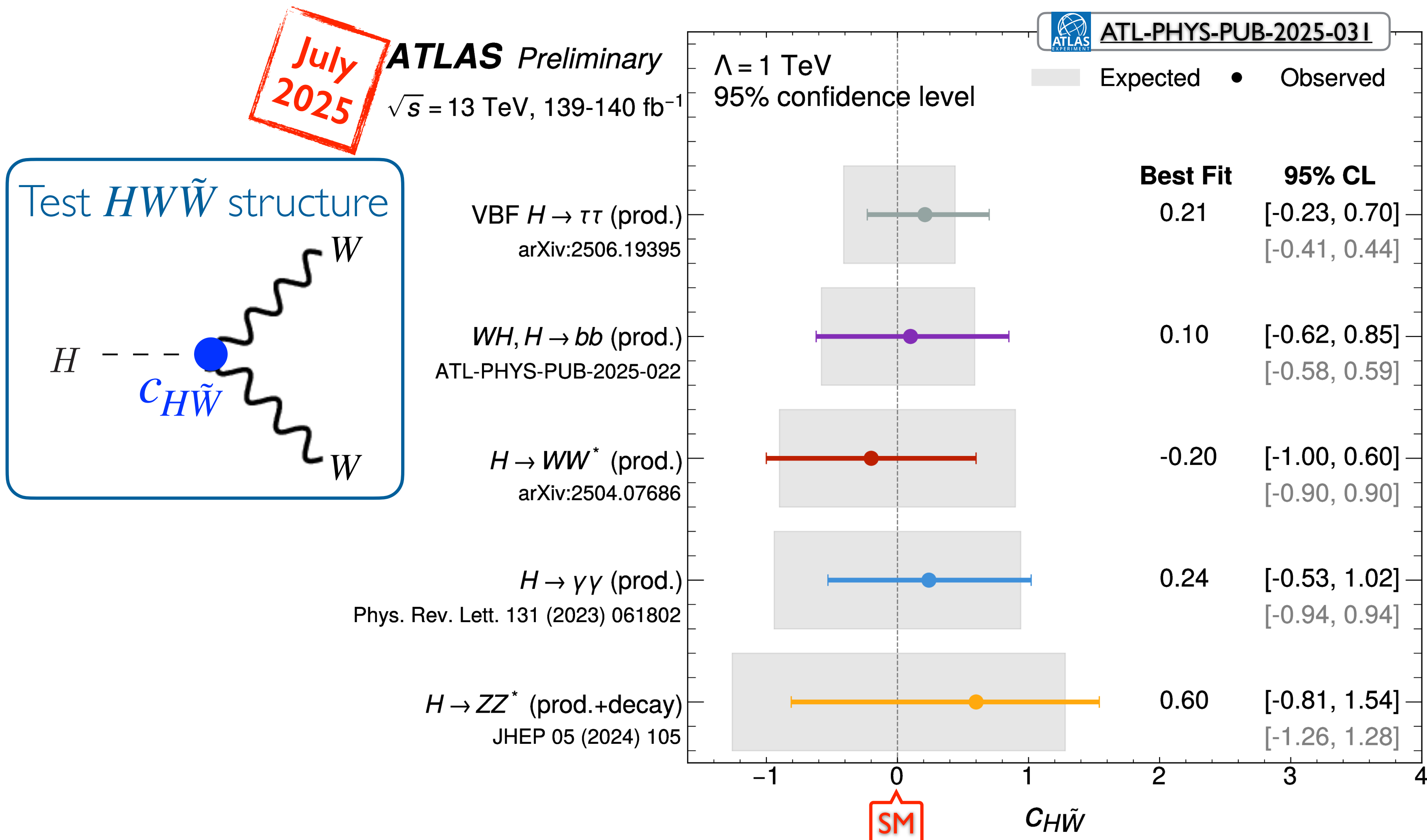
Probed scale Λ at 95% CL (TeV)



Higgs couplings different?



- SM: Higgs interactions CP-even → test for CP-odd contributions





Higgs couplings different?



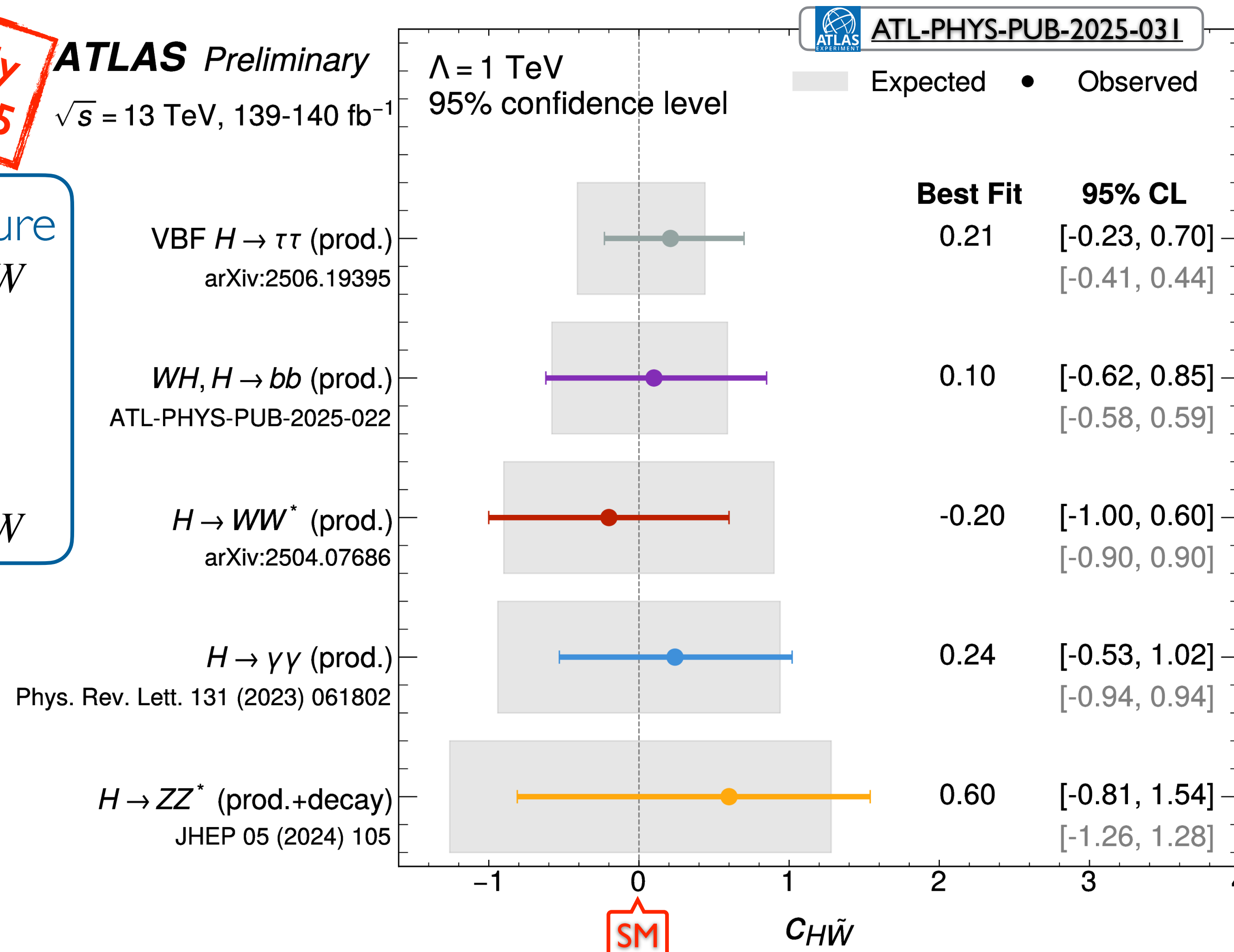
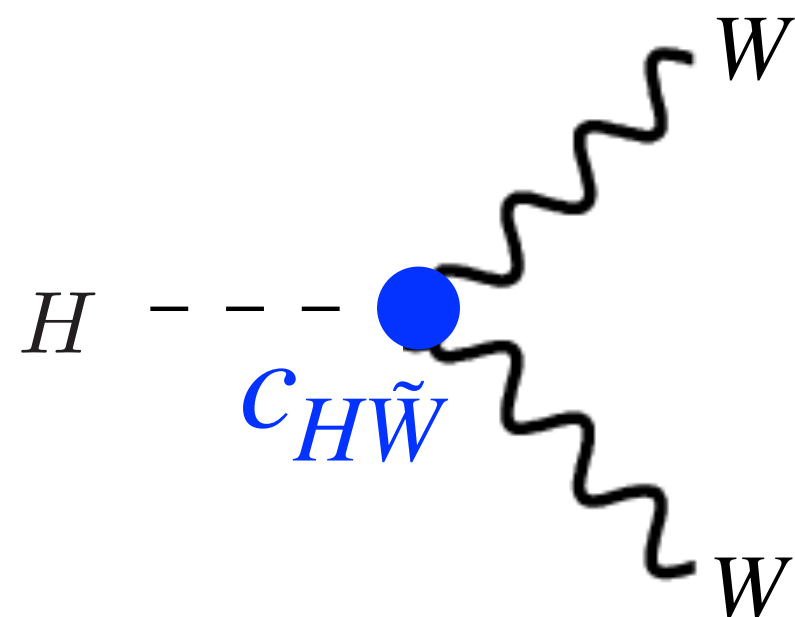
- SM: Higgs interactions CP-even → test for CP-odd contributions

July 2025

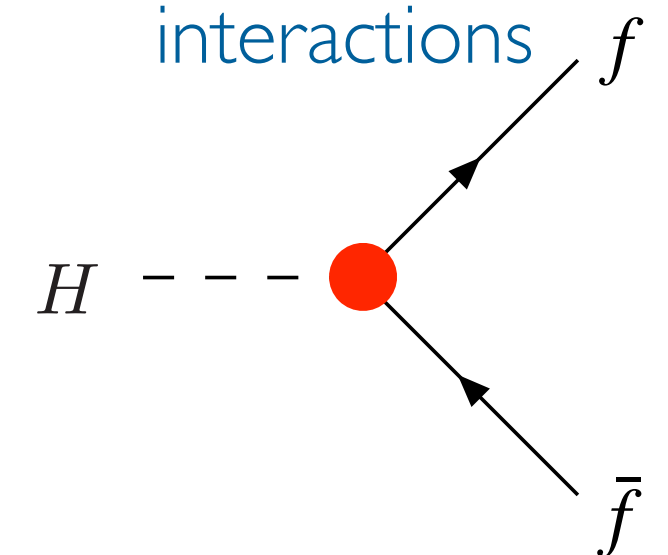
ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}, 139\text{-}140 \text{ fb}^{-1}$

Test $HW\tilde{W}$ structure



No CP-odd contribution
observed in Higgs-fermion
interactions

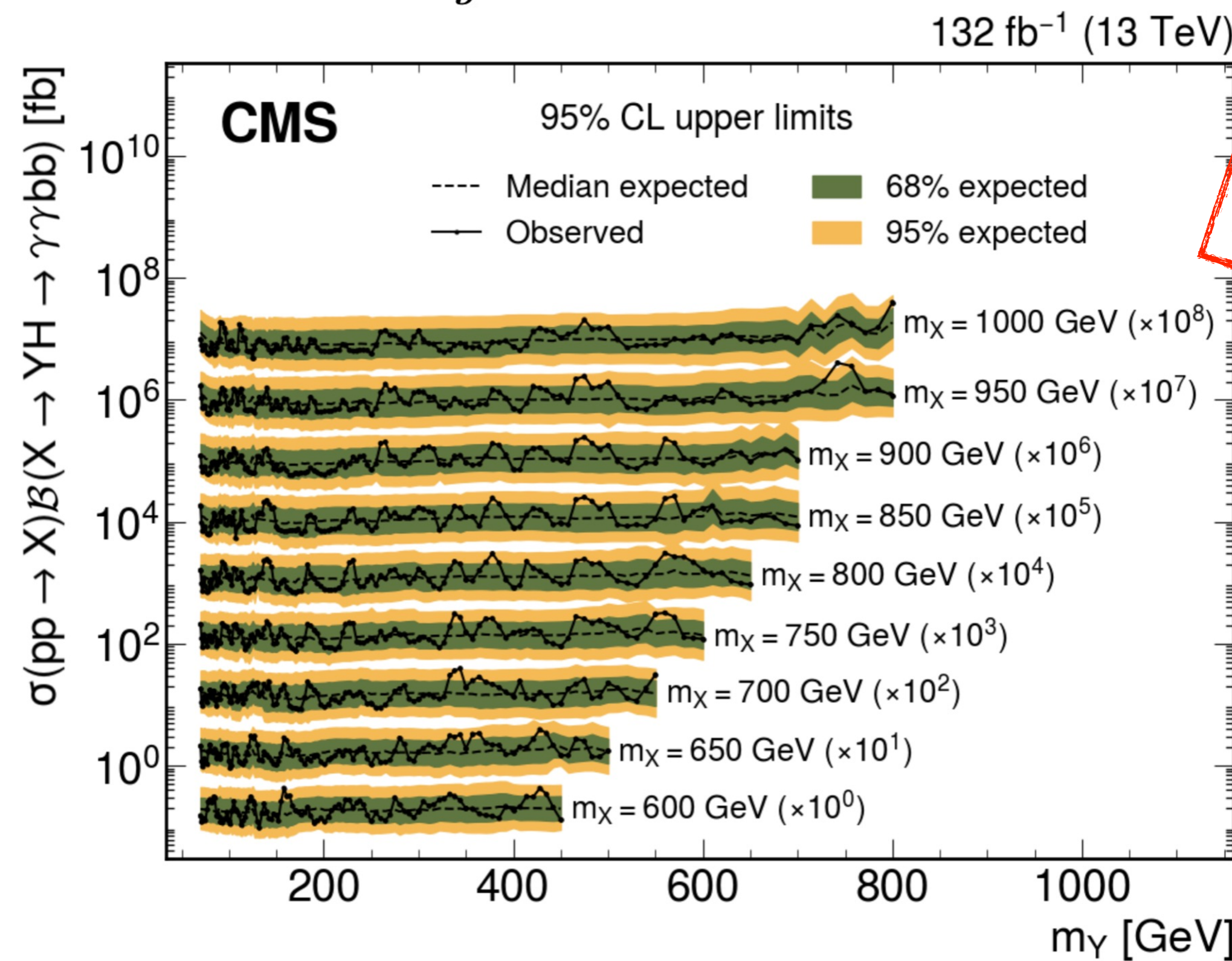
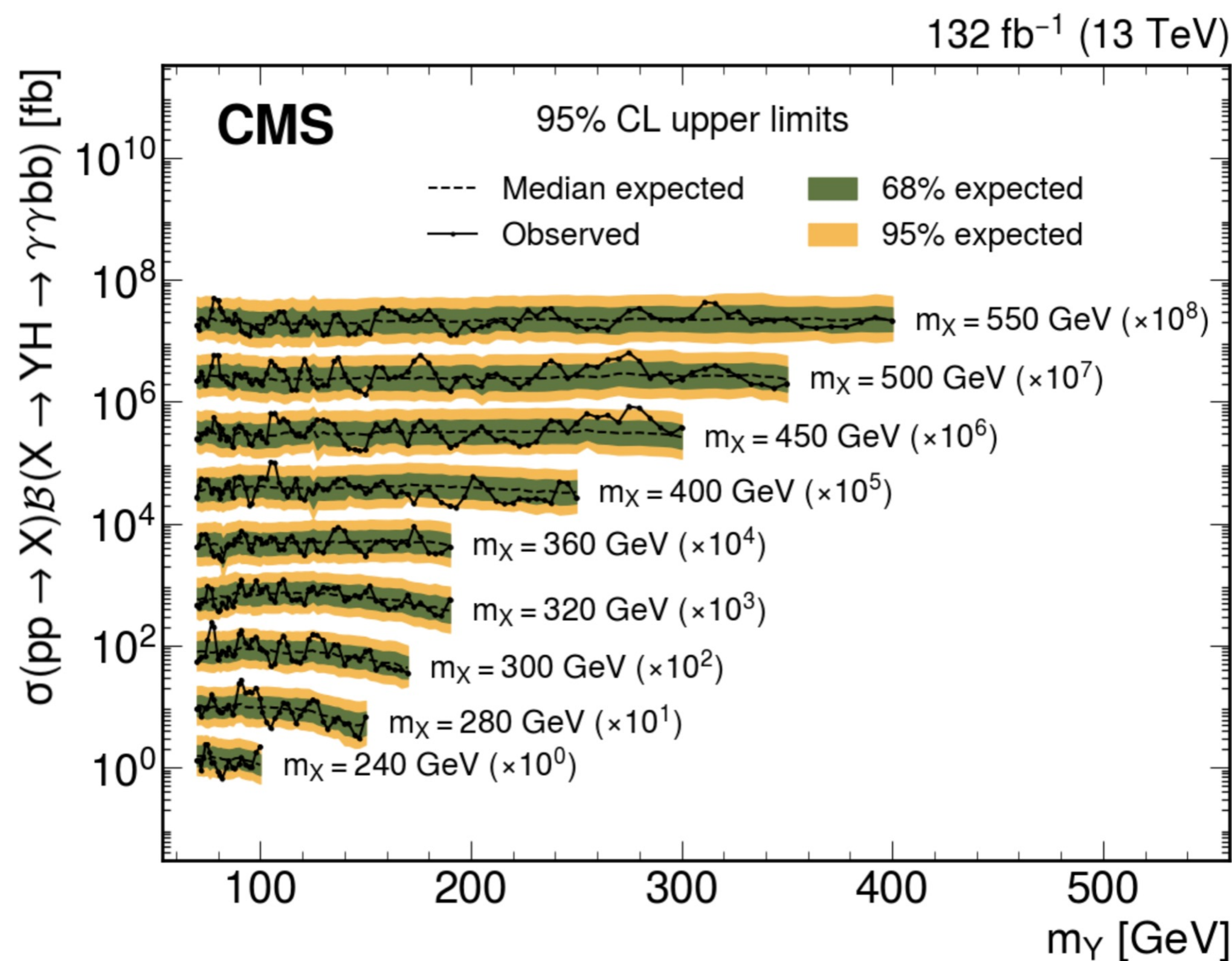
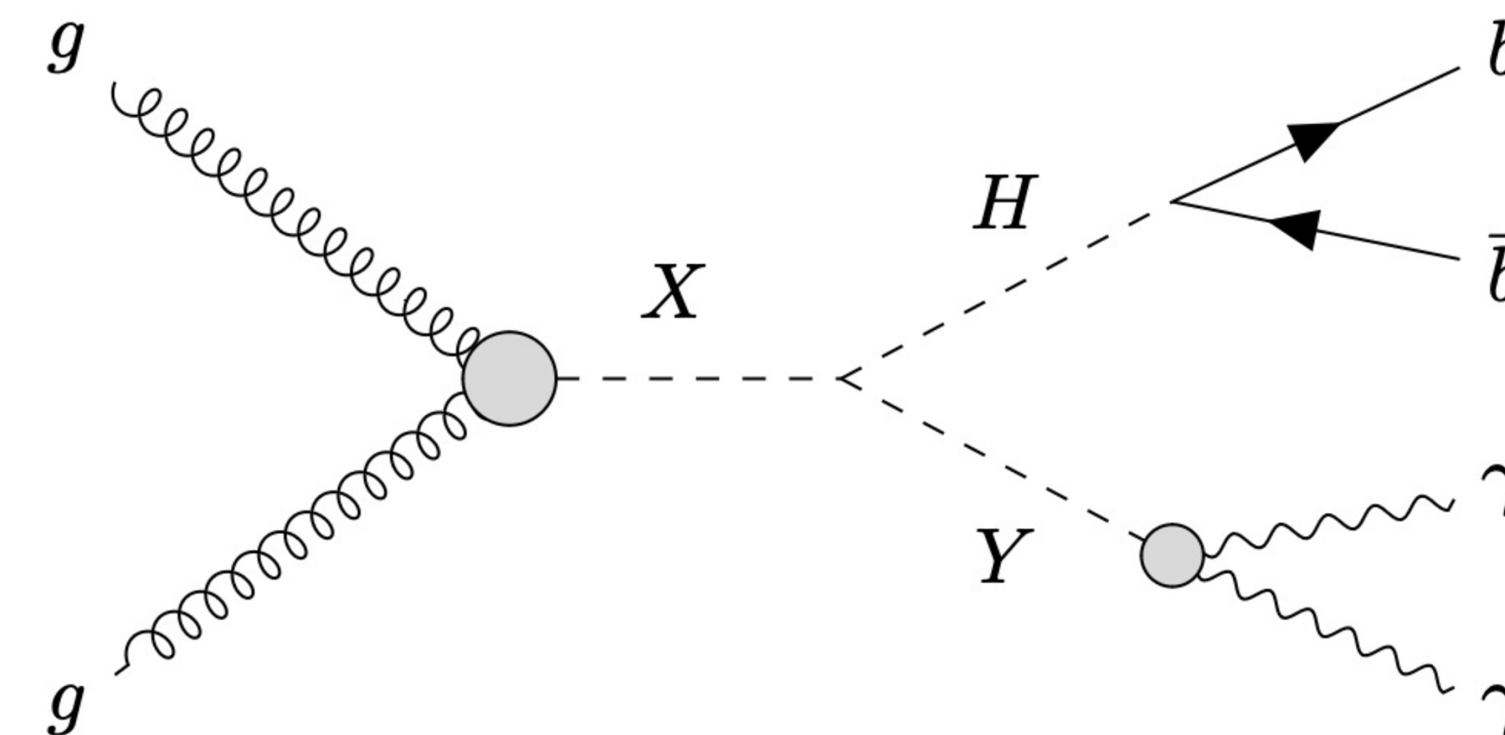




Additional Scalar/Higgs Bosons?



- Search: heavy scalar resonance X decaying to light scalar resonance Y and H_{125} boson
- Largest excess in $\sigma_{13\text{ TeV}}(pp \rightarrow X) \mathcal{B}(X \rightarrow YH \rightarrow \gamma\gamma b\bar{b})$ at $(m_X, m_Y) = (300, 77) \text{ GeV}$: 0.65σ (3.33σ) global (local)



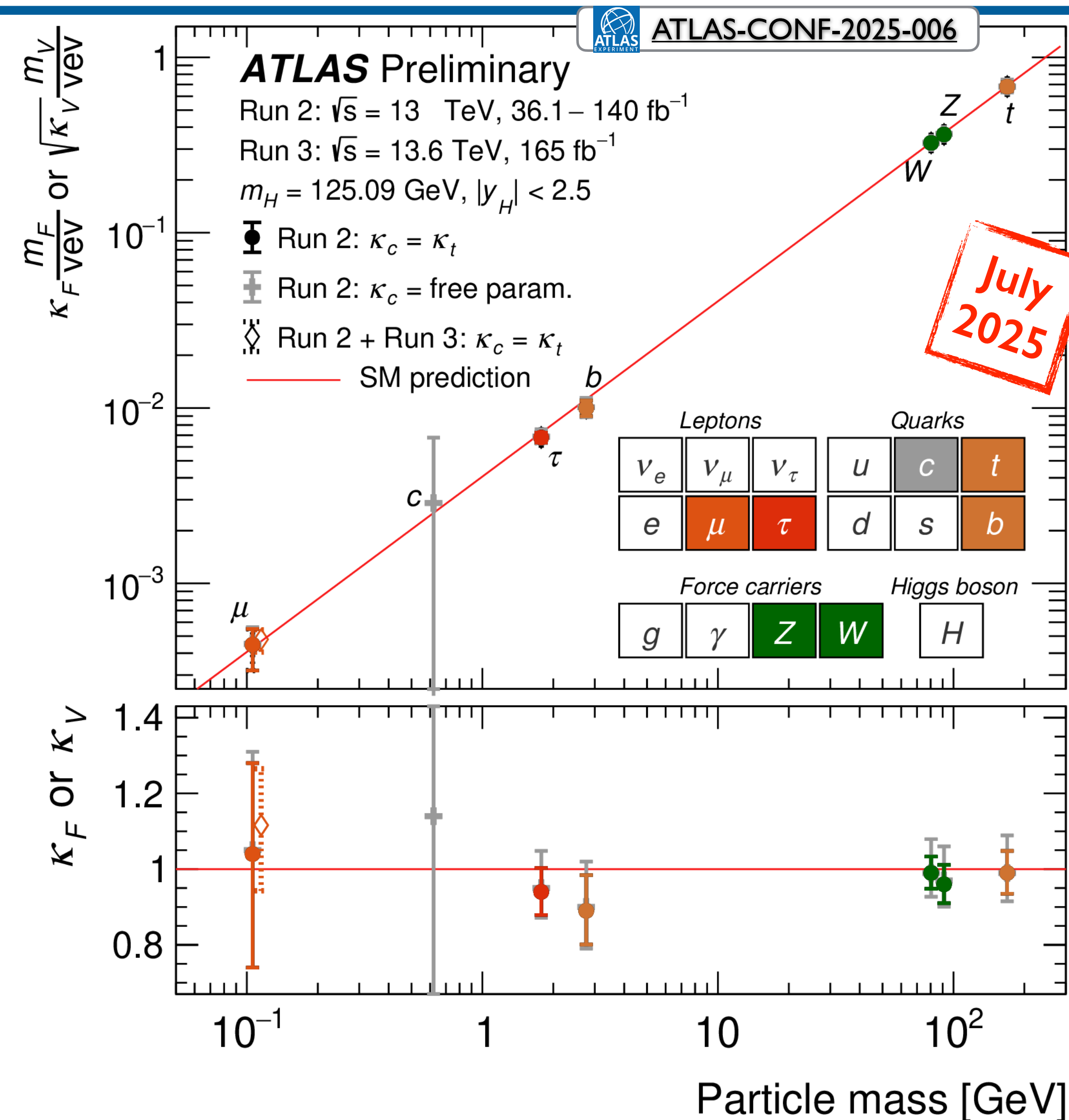
Aug
2025



Concluding Remarks



Mass $\sim$ Coupling Strength
 $\Rightarrow$ New **Quantum** concept of *mass* seems to work!





Concluding Remarks



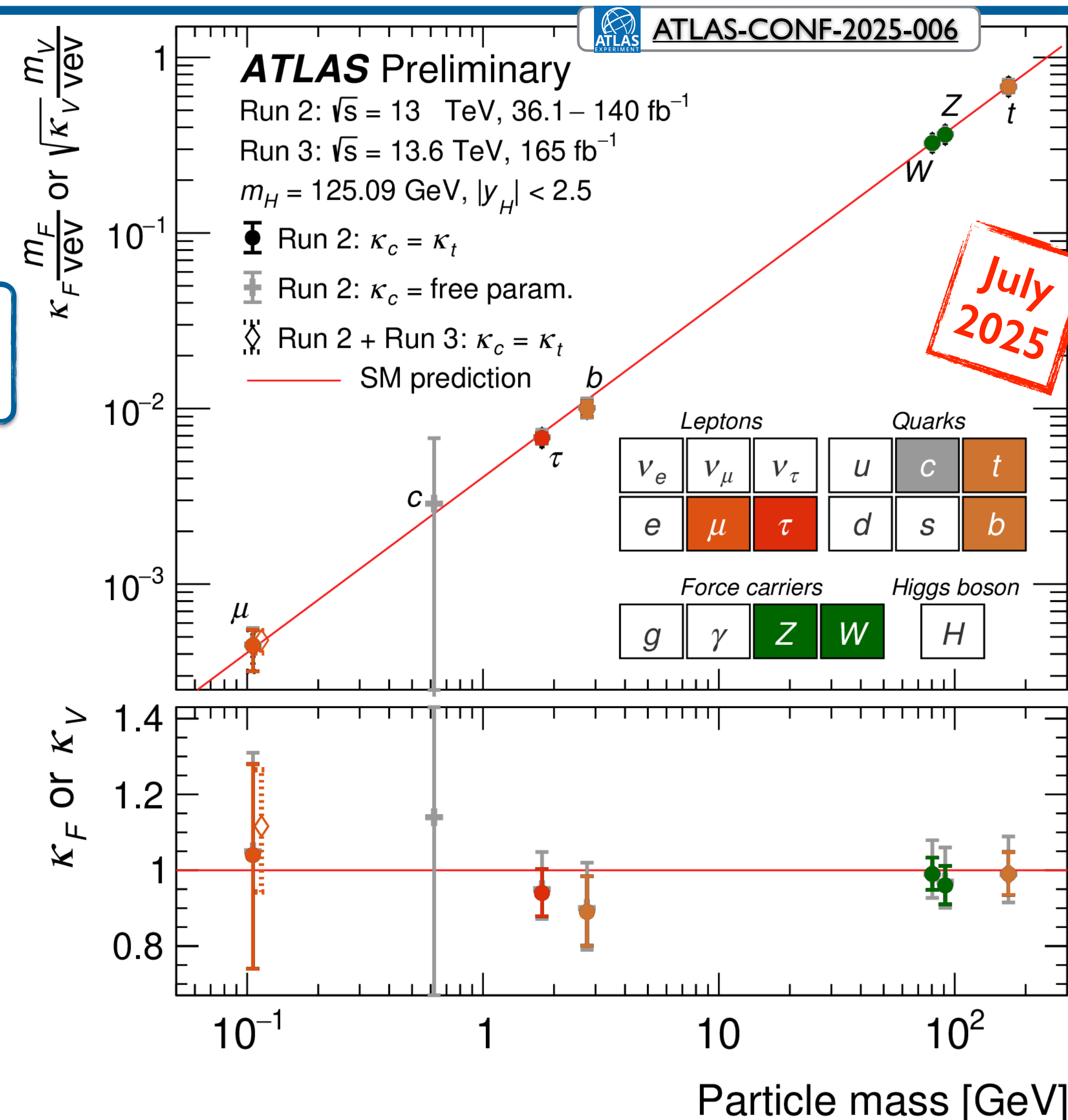
Mass $\sim$ Coupling Strength

$\Rightarrow$ New **Quantum** concept of *mass* seems to work!

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^2 - \mu^2 \phi^2 - \lambda \phi^4 + y_f \phi \psi^2$$

The heart of the Standard Model is beating strong

- Plethora of results improve our understanding of nature
- Better statistical precision and **ingenuity of people!**





Concluding Remarks



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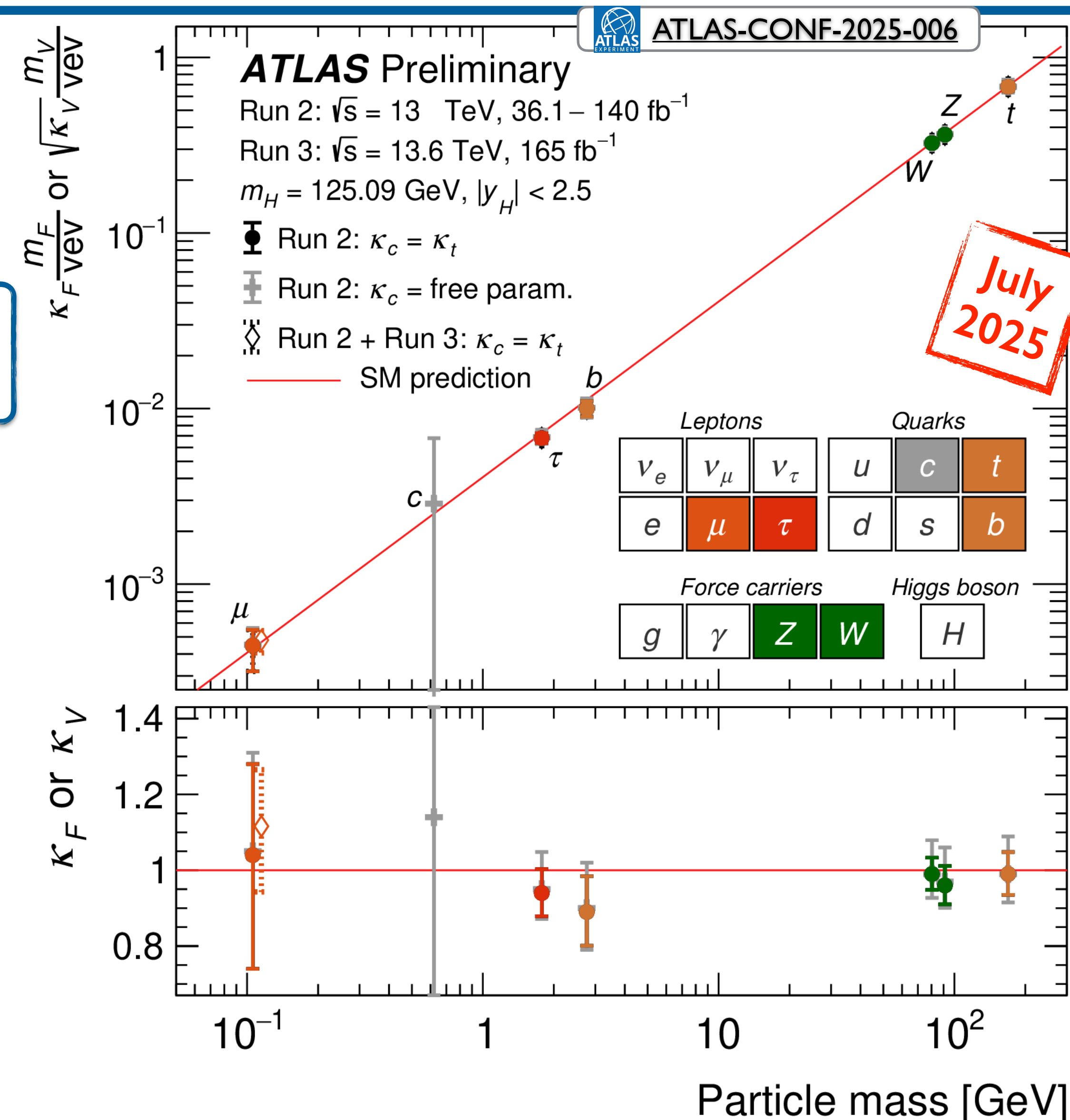
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Future can be even brighter

- Much better precision...
- Higgs potential...





Concluding Remarks



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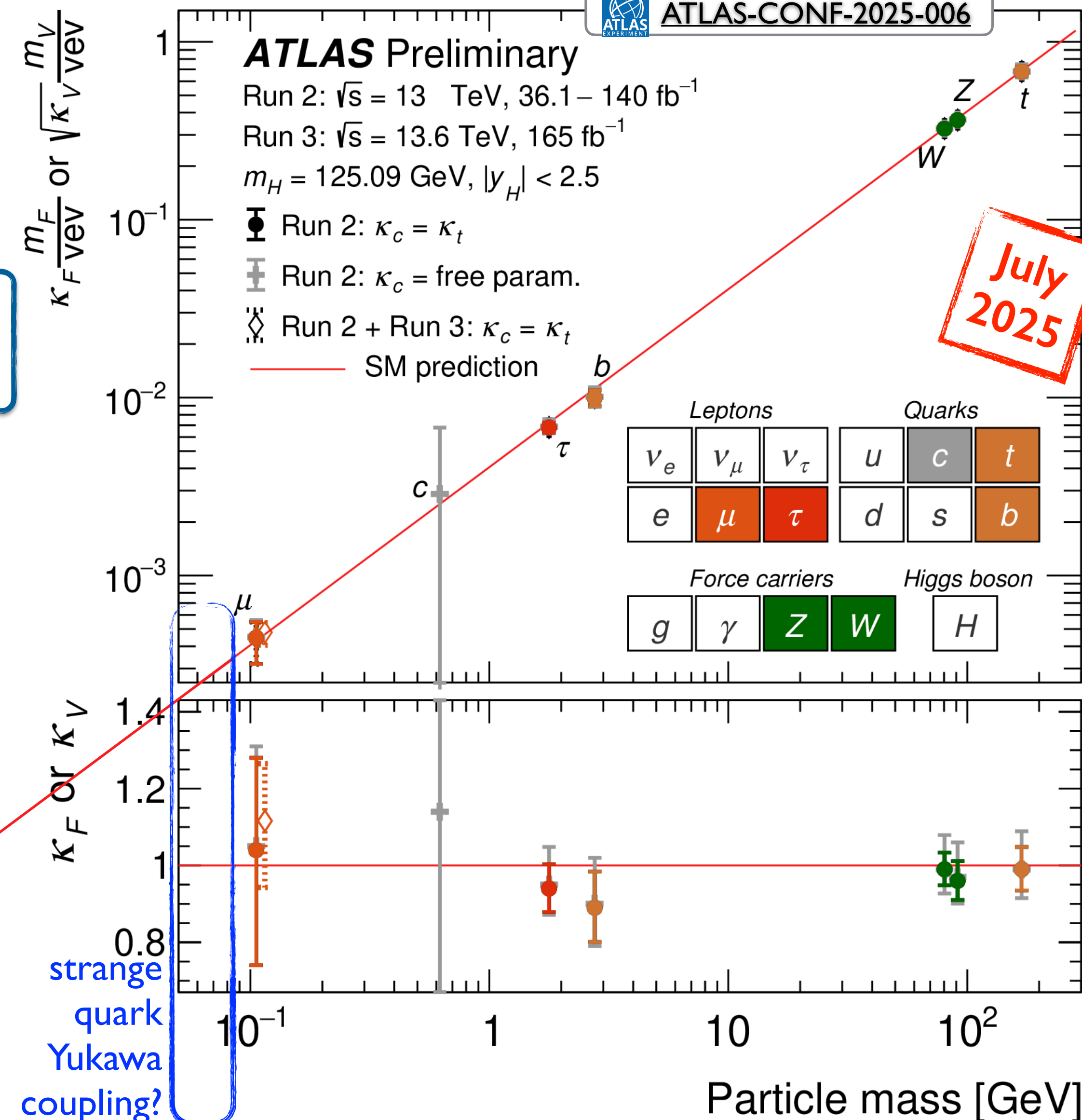
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- Much better precision...
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electron
Yukawa
coupling???





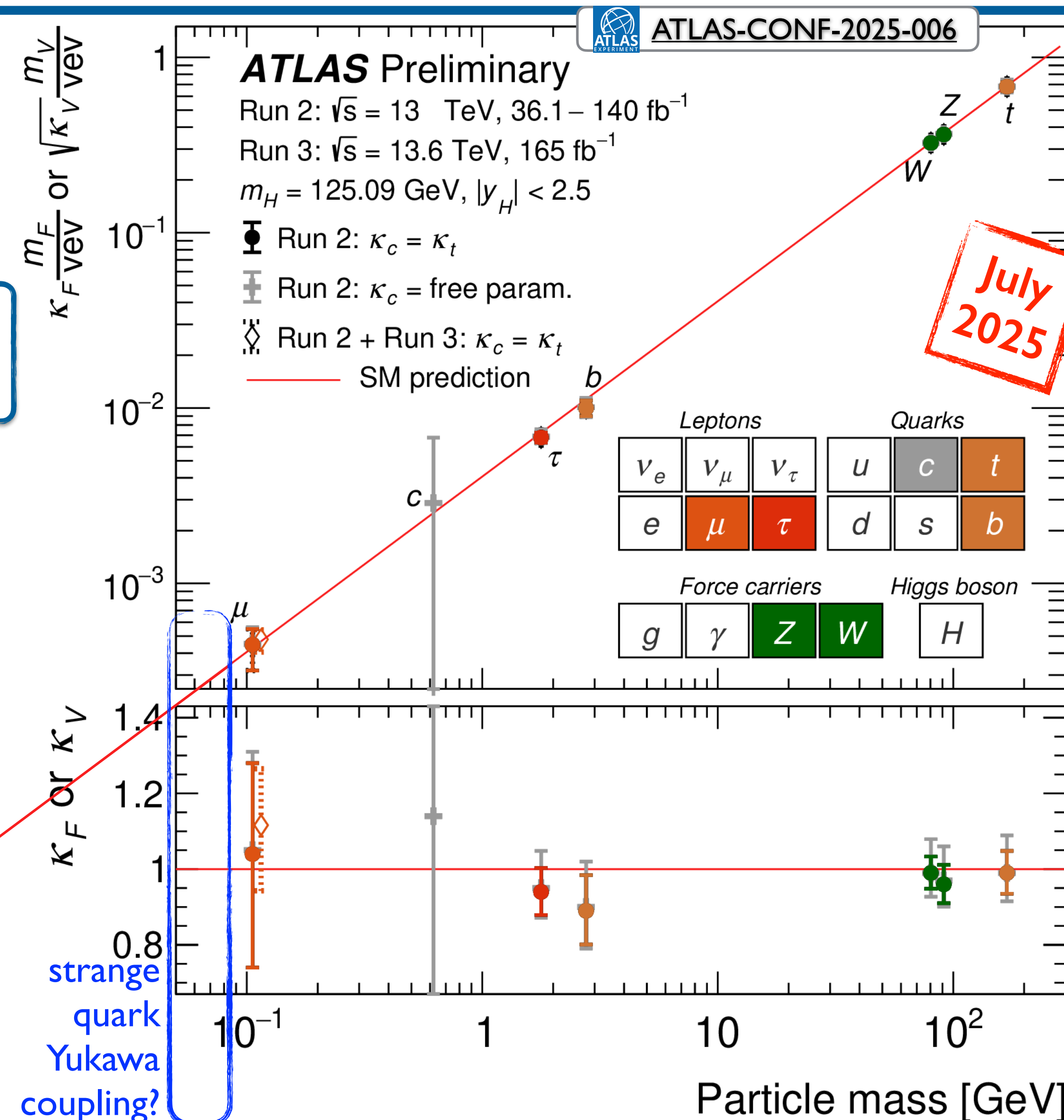
⇒ New **Quantum** concept of *mass* seems to work!

The heart of the Standard Model is beating strong

- # Future can be even brighter

- More in Next talk:**
Markus Klute: *A Quantum Leap Forward: Unlocking the Higgs Boson at Future Colliders*

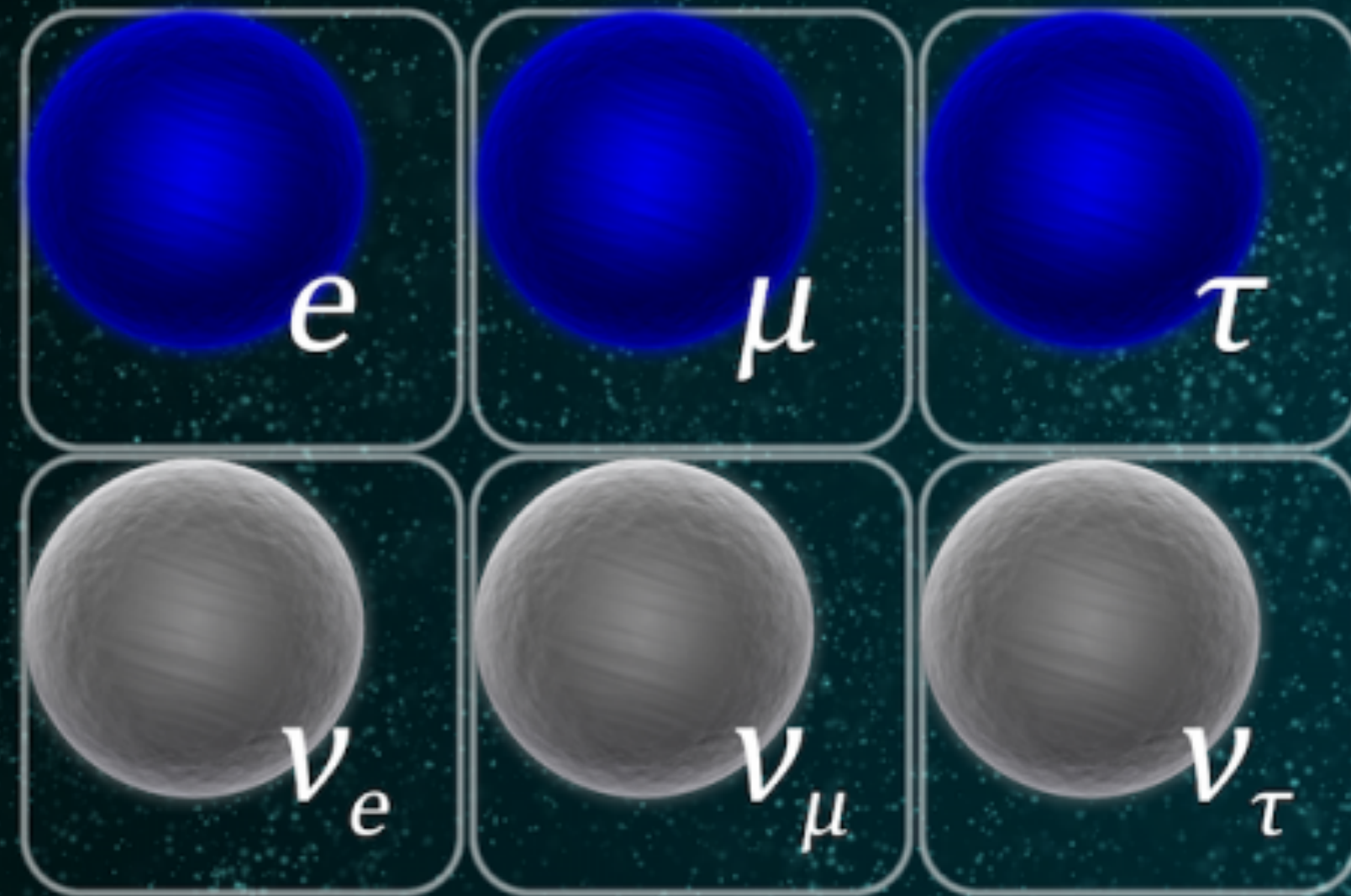
electron
Yukawa
coupling???



Matter

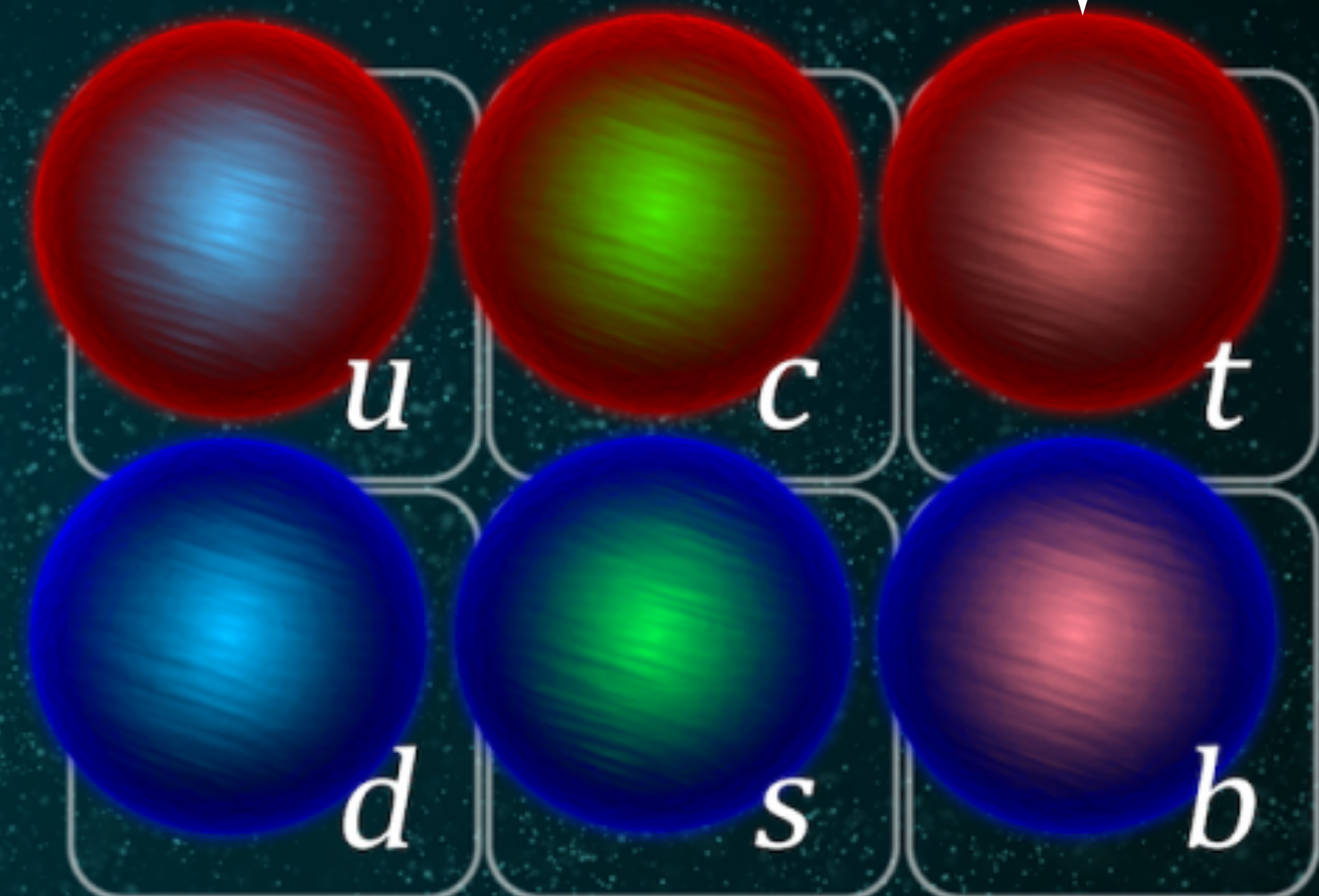
$$m_e \approx 0,5 \text{ MeV}$$

$$m_\mu \approx 106 \text{ MeV}$$



Leptons

$$m_{\text{top}} \approx 173\,000 \text{ MeV} \\ = 173 \text{ GeV } (\approx m_{\text{Tungsten}})$$



Quarks



Forces



Electromagnetism

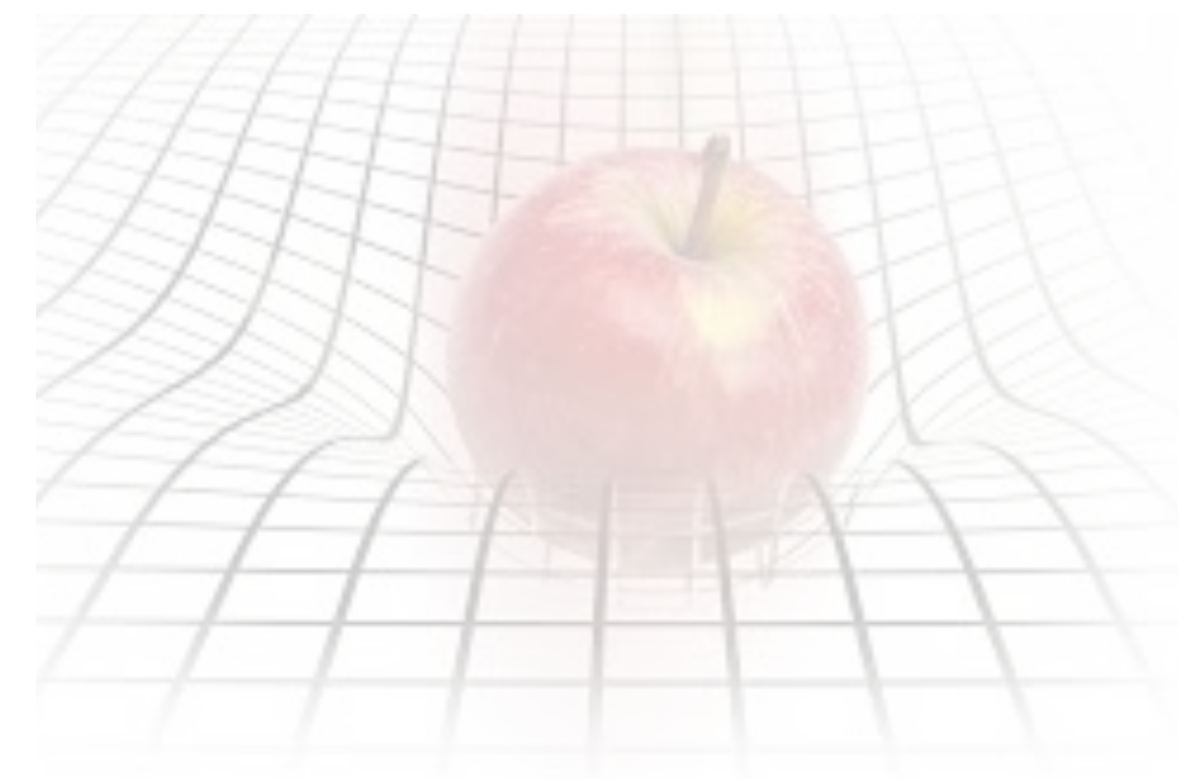
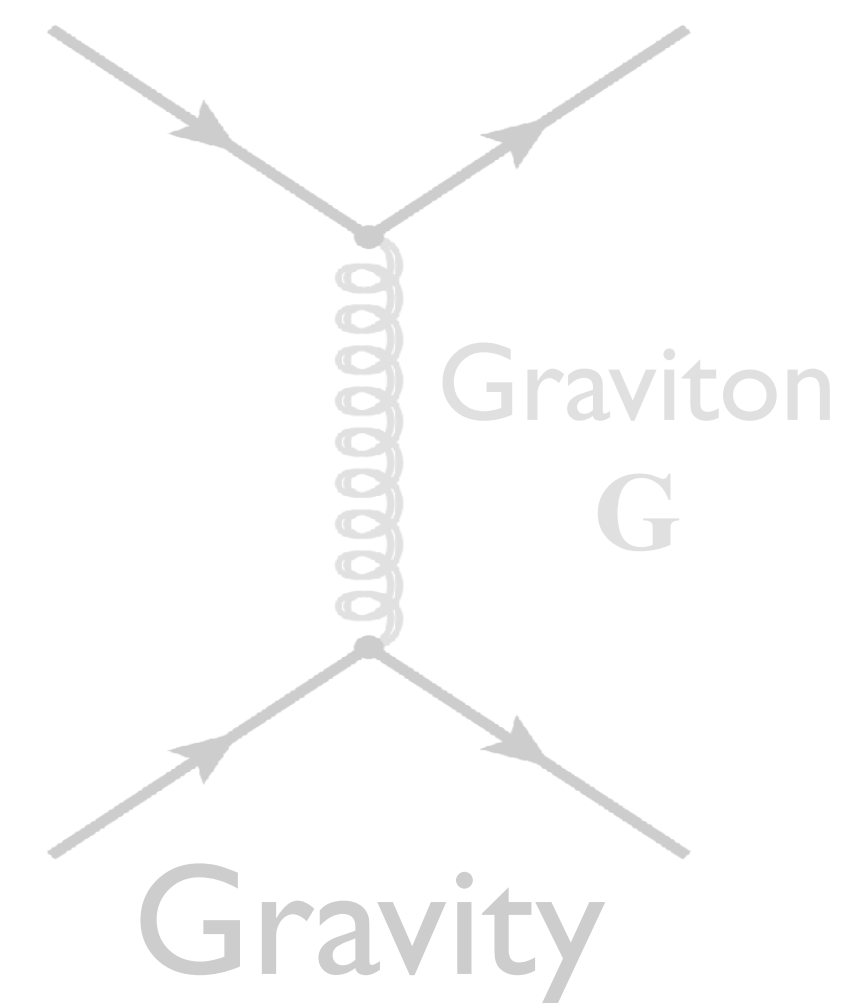
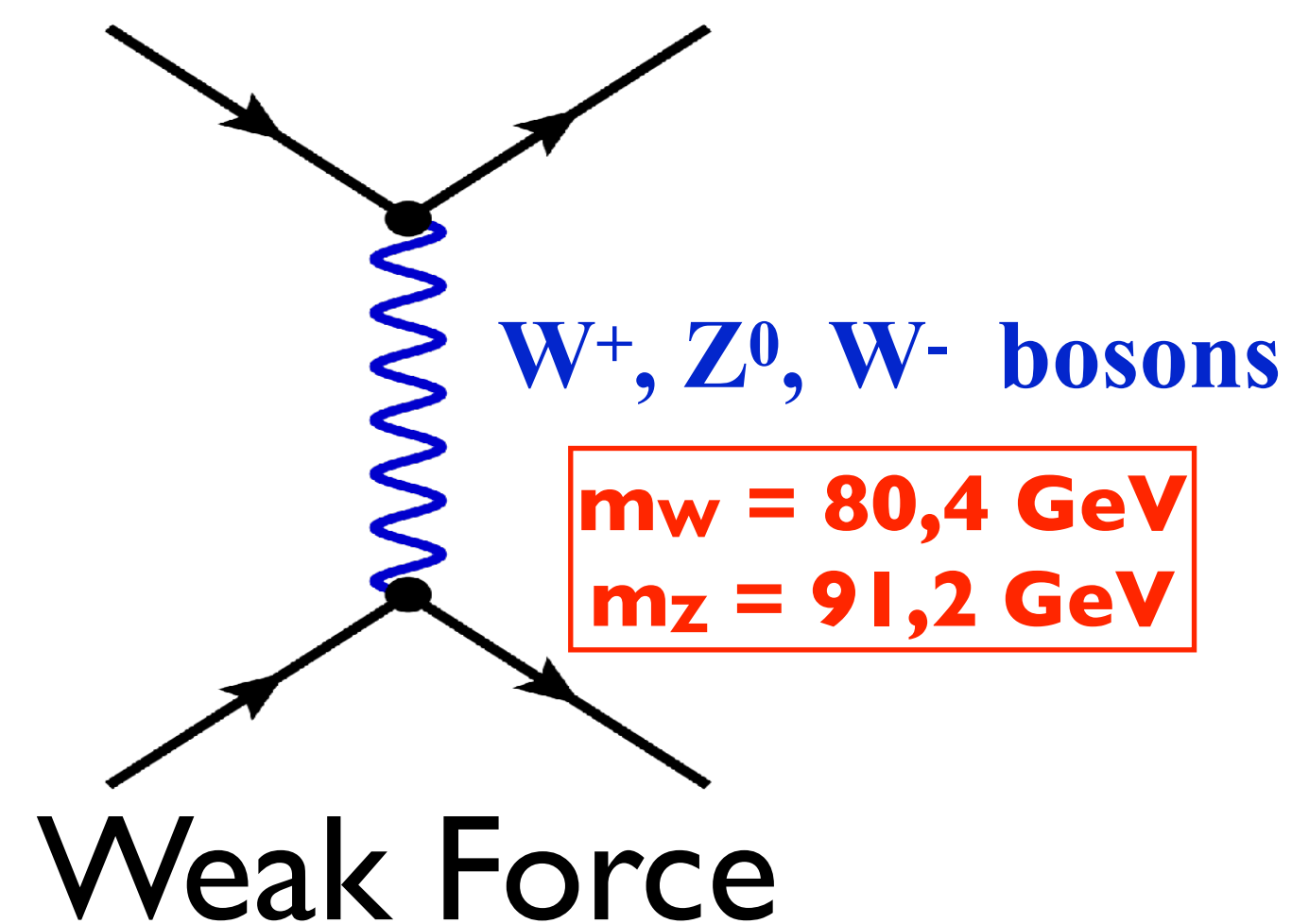
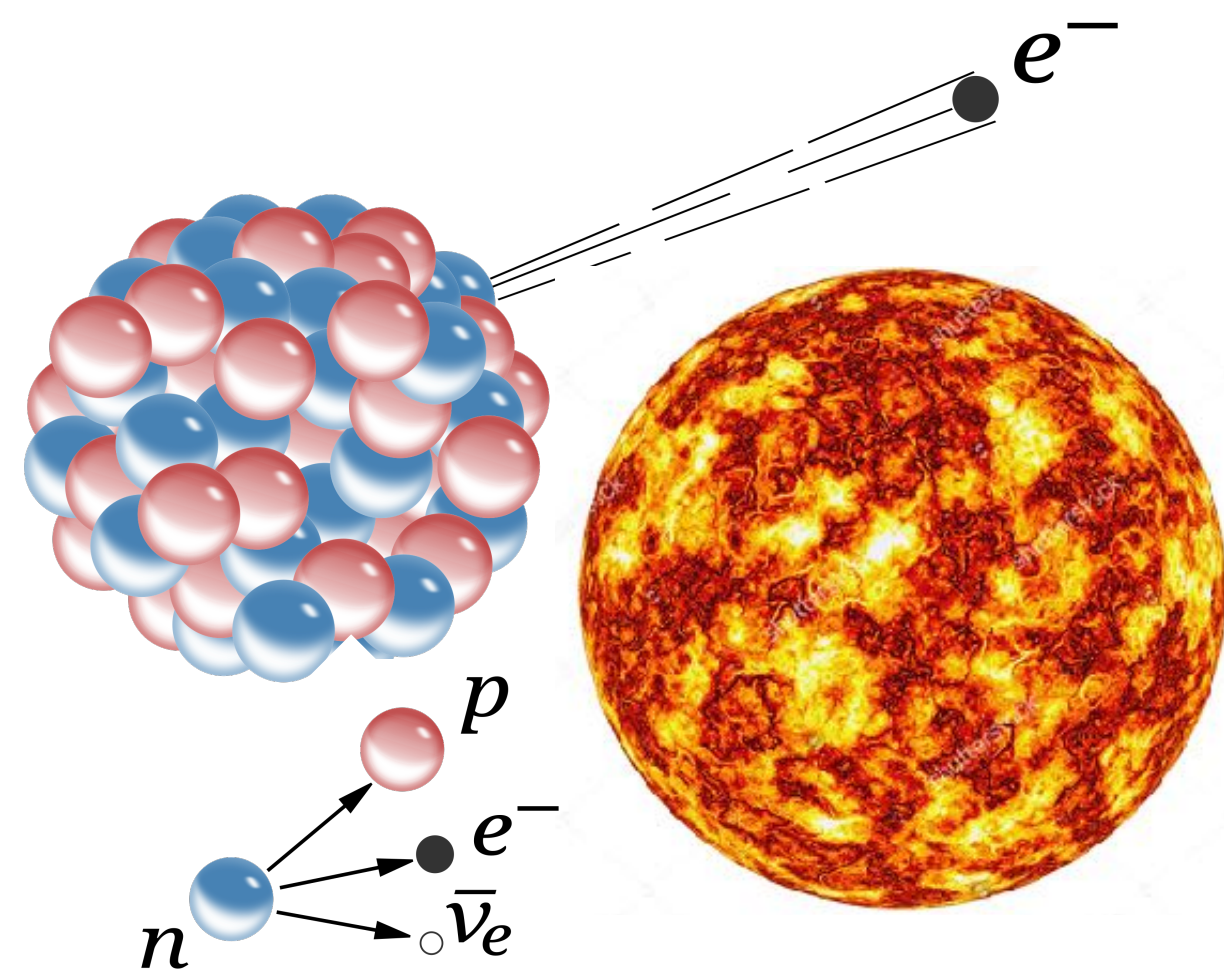
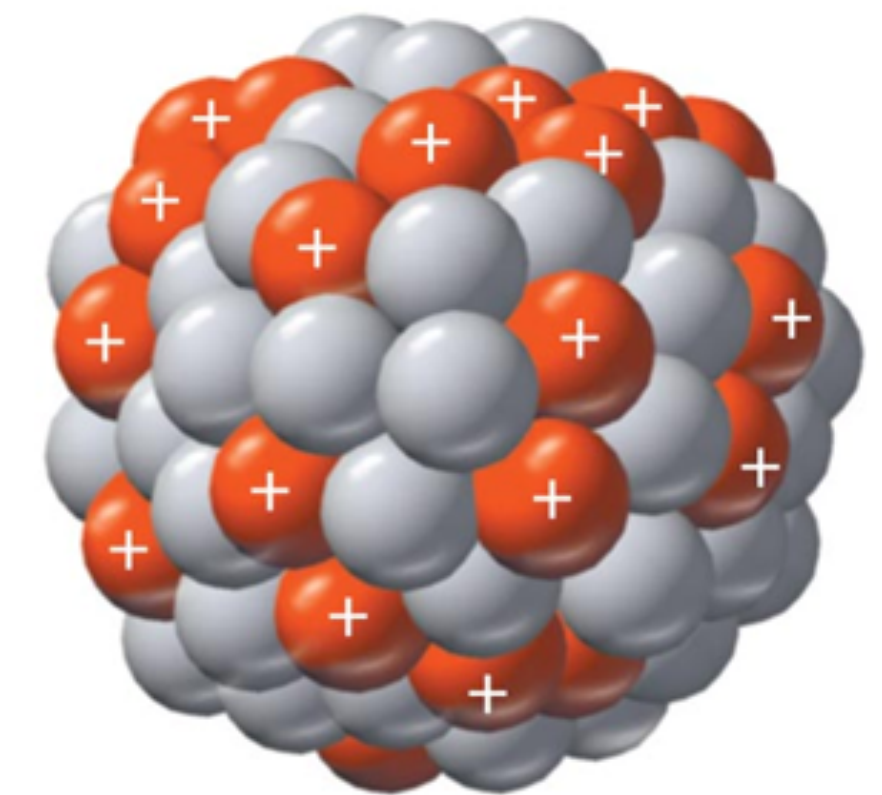
Matter particle,
e.g. electron

Photon γ Force carrier

Time

Strong Force

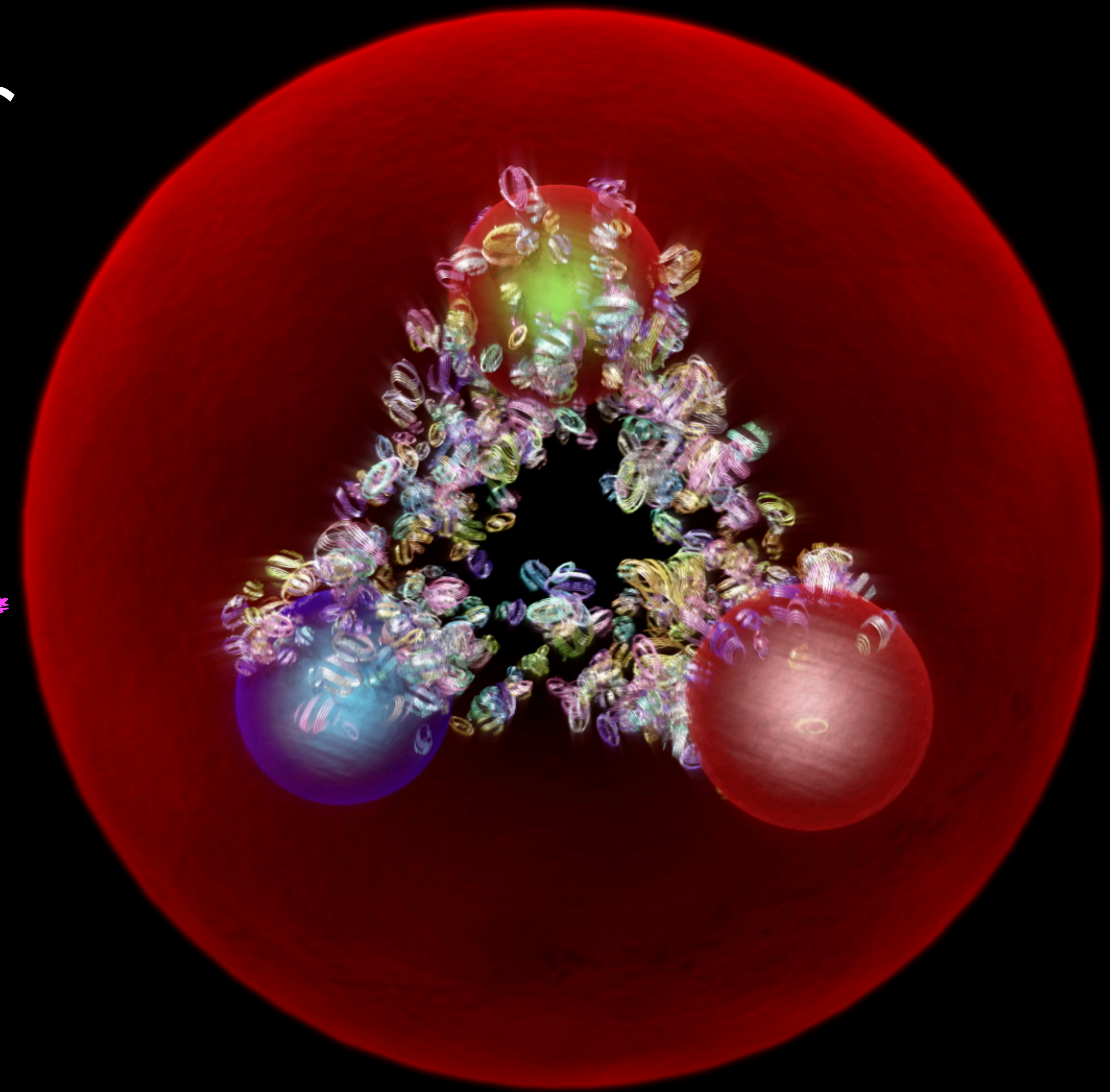
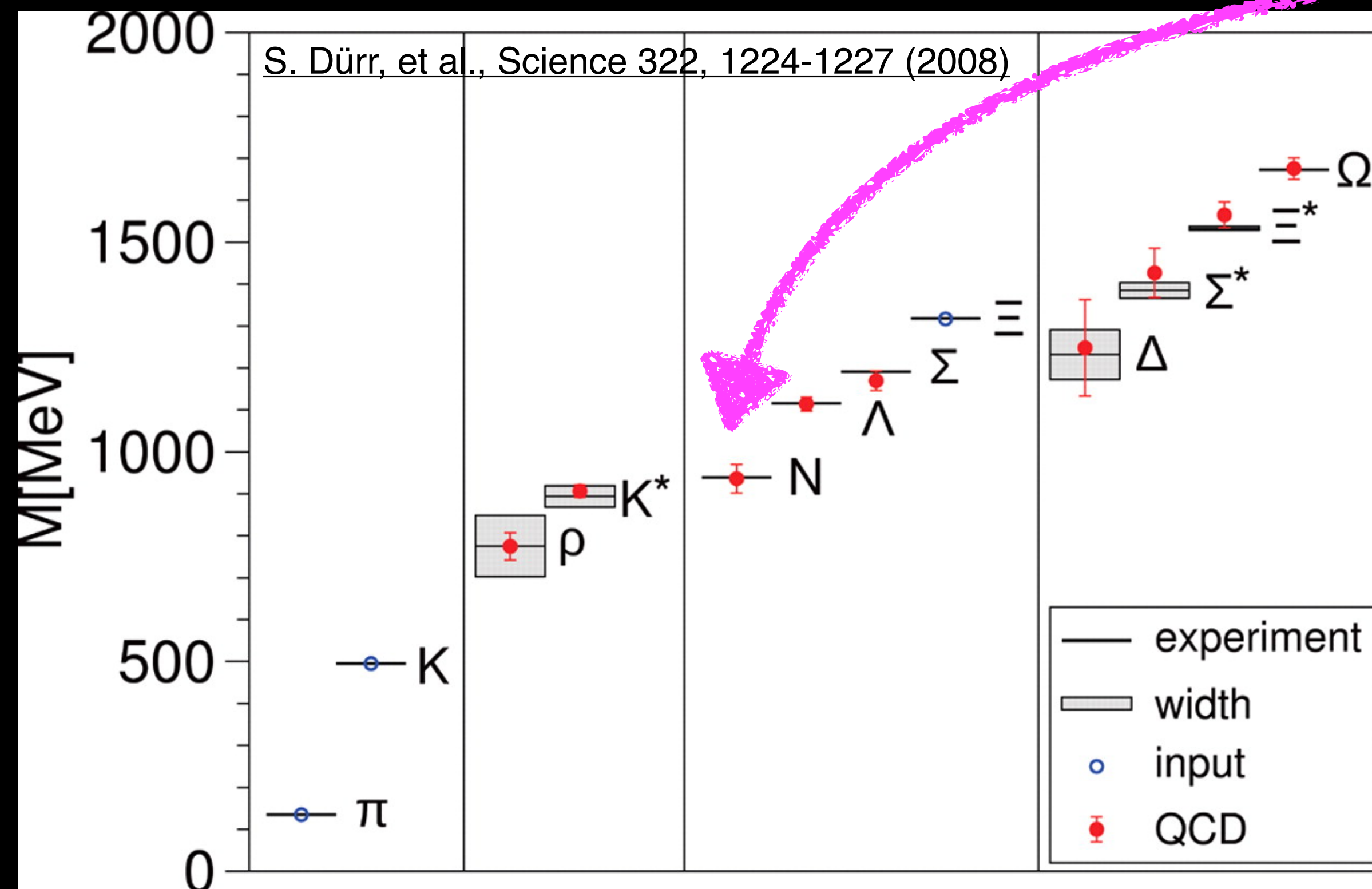
Gluons g



Mass in “normal” Matter

- **Mass in Atoms:**
> 99.9% in nucleus
- **Mass in nucleus:**
~95% due to **binding energy** of the *Strong Force*

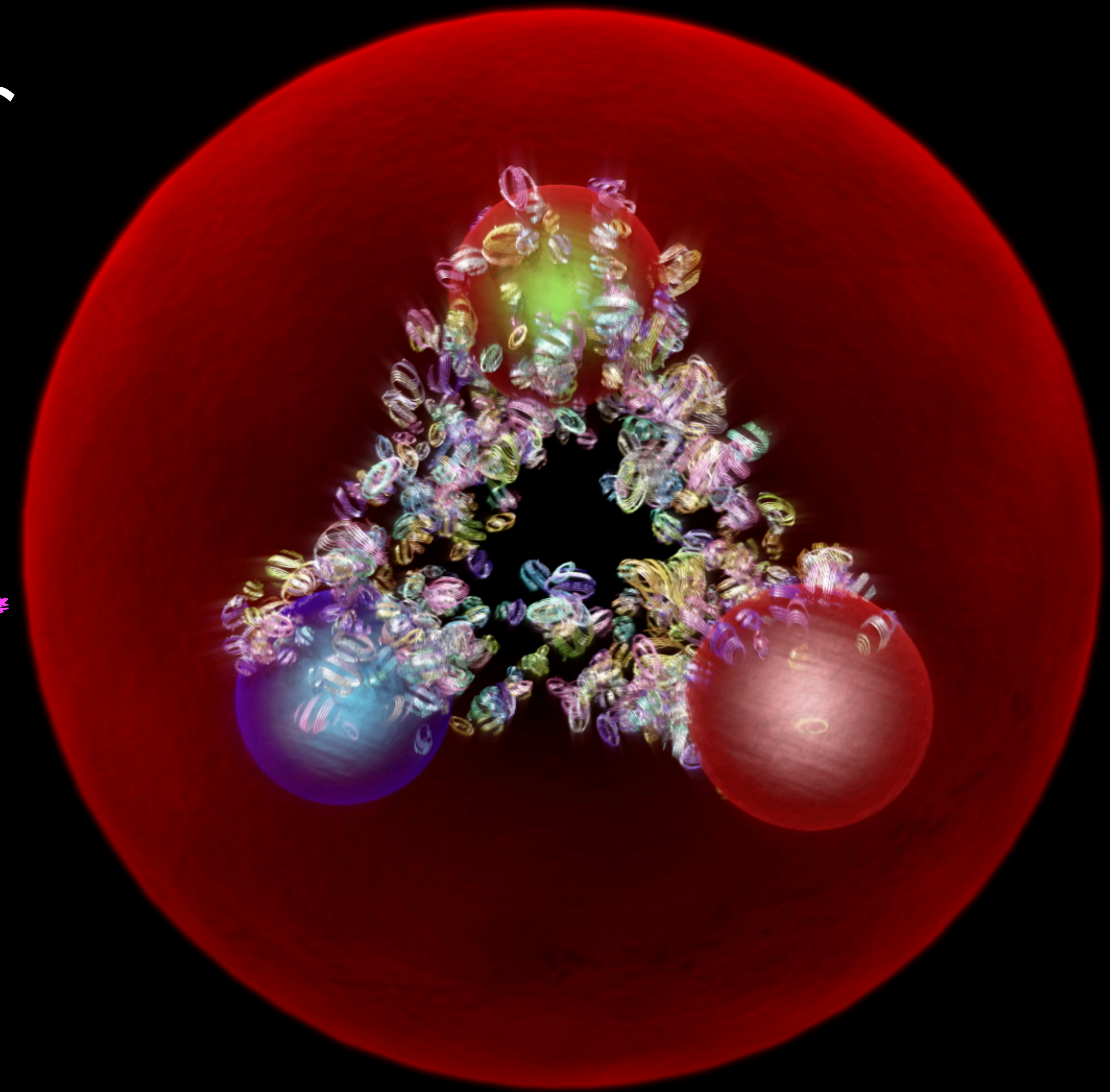
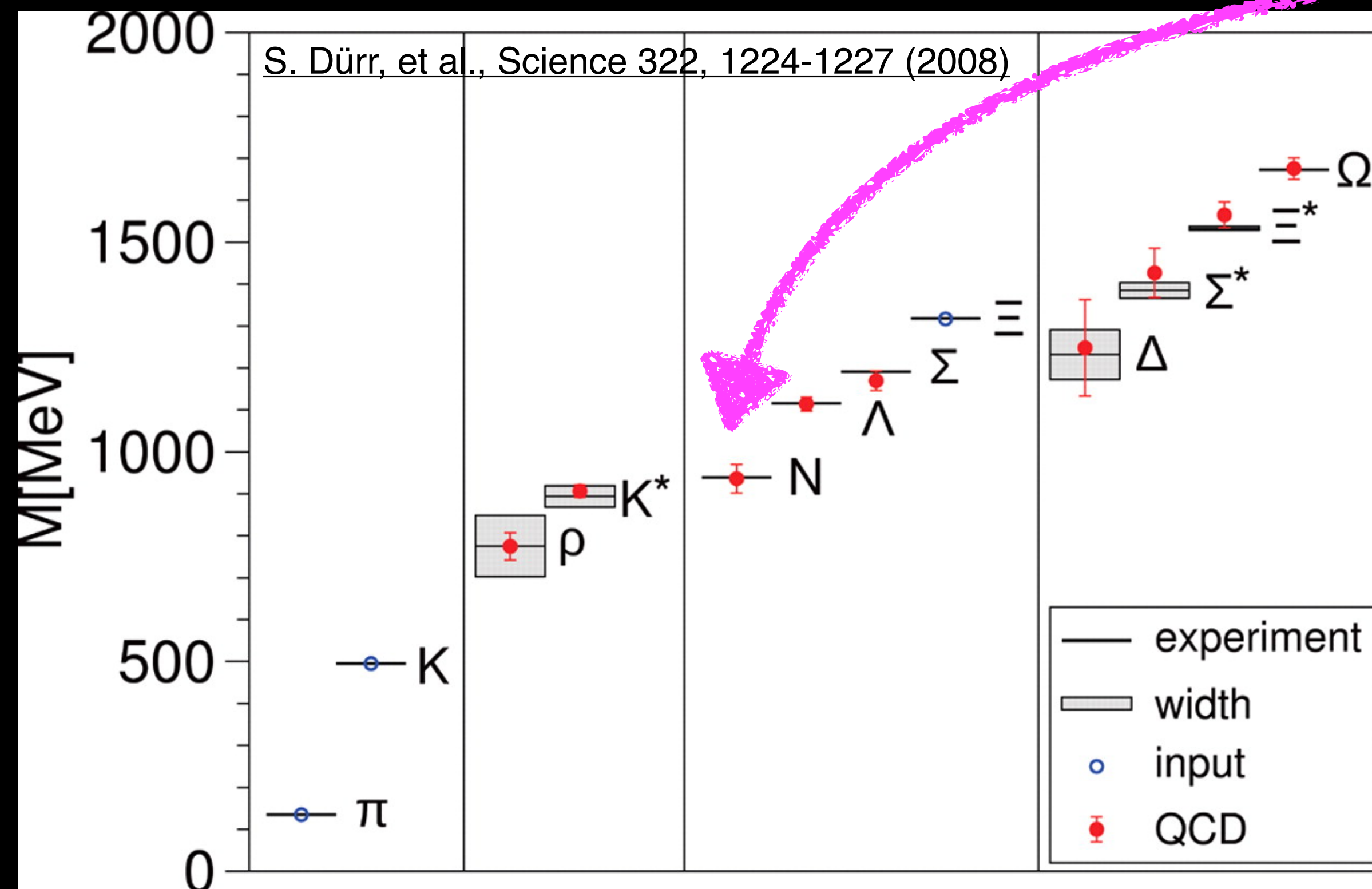
Proton mass:
 $938.3 \text{ MeV} \approx 1 \text{ GeV}$



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Brout-Englert-Higgs Mechanism



- **Solution to problem of masses of elementary particles:** (developed in 1960s by Brout, Englert, Higgs, et al.)
 - Introduce scalar field $\phi(x)$ with potential:

$$V(\phi) = \mu^2 \phi^2 + \lambda \phi^4$$

Higgs
field



Brout-Englert-Higgs Mechanism



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$$V(\phi) = \mu^2 \phi^2 + \lambda \phi^4$$

Diagram illustrating the potential $V(\phi)$ components:

- The term $\mu^2 \phi^2$ is associated with "numbers" (via a curved arrow).
- The term $\lambda \phi^4$ is associated with "Higgs field" (via a curved arrow).



Brout-Englert-Higgs Mechanism



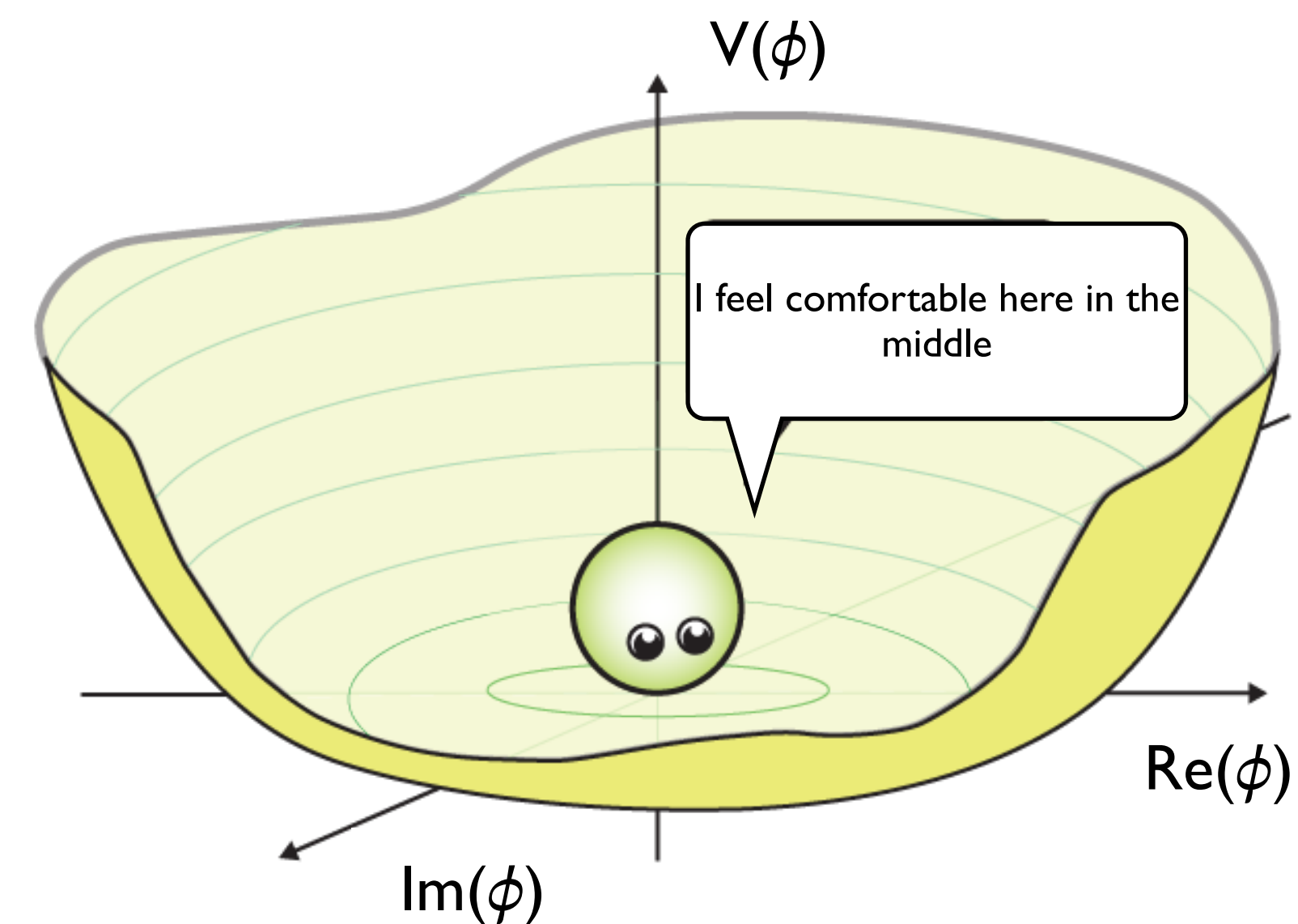
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- Introduce scalar field $\phi(x)$ with potential:

$$V(\phi) = \mu^2 \phi^2 + \lambda \phi^4$$

Diagram illustrating the potential $V(\phi)$ for the Higgs field. The equation shows the potential as a function of the scalar field ϕ . The terms μ^2 and λ are labeled as "numbers". The term ϕ is labeled as "Higgs field".

For $\lambda > 0$, $\mu^2 > 0$:





Brout-Englert-Higgs Mechanism



- **Solution to problem of masses of elementary particles:** (developed in 1960s by Brout, Englert, Higgs, et al.)

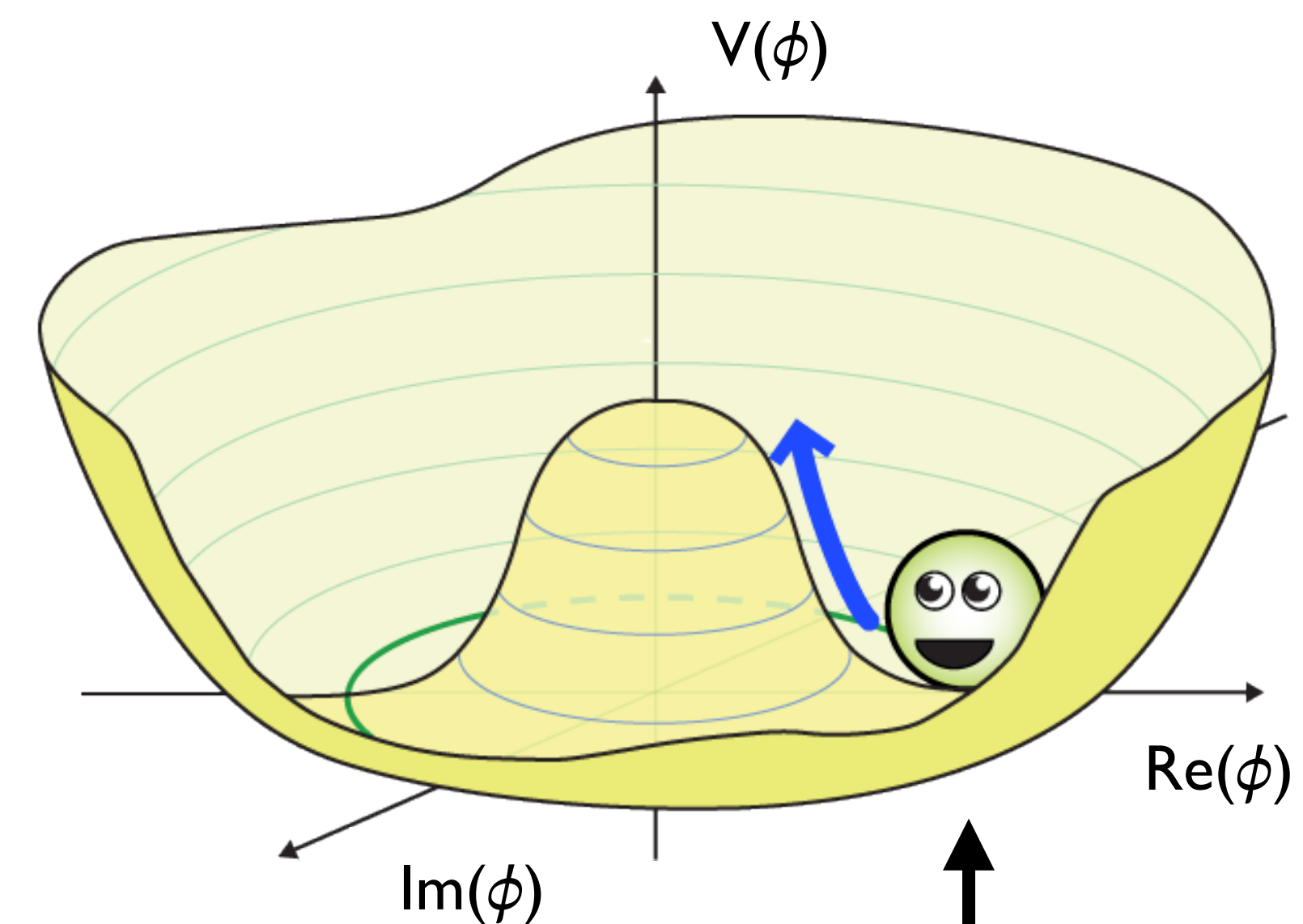
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$$V(\phi) = \mu^2 \phi^2 + \lambda \phi^4$$

Diagram illustrating the potential $V(\phi)$ for the Higgs field. The term $\mu^2 \phi^2$ is labeled "numbers" and the term $\lambda \phi^4$ is labeled "Higgs field".

For $\lambda > 0$, $\mu^2 < 0$:

Spontaneous symmetry breaking



Minimum at $\langle \phi \rangle = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$, $v \approx 246 \text{ GeV}$



Brout-Englert-Higgs Mechanism



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Diagram showing the potential equation with annotations: "numbers" points to the coefficients μ^2 and λ , and "Higgs field" points to the ϕ terms.

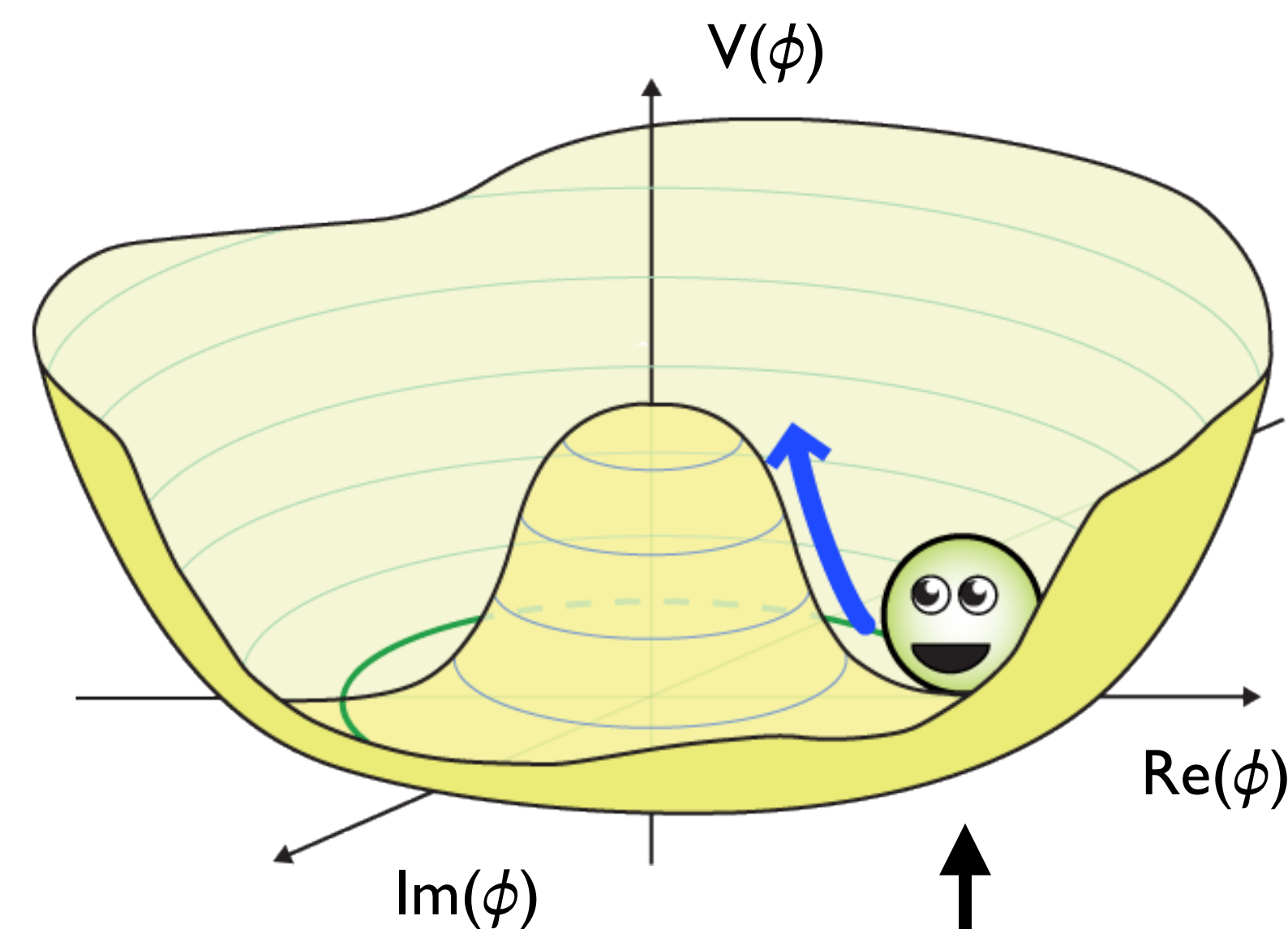
Electroweak Symmetry Breaking

Expand $\phi(x)$ around new ground state (vacuum):

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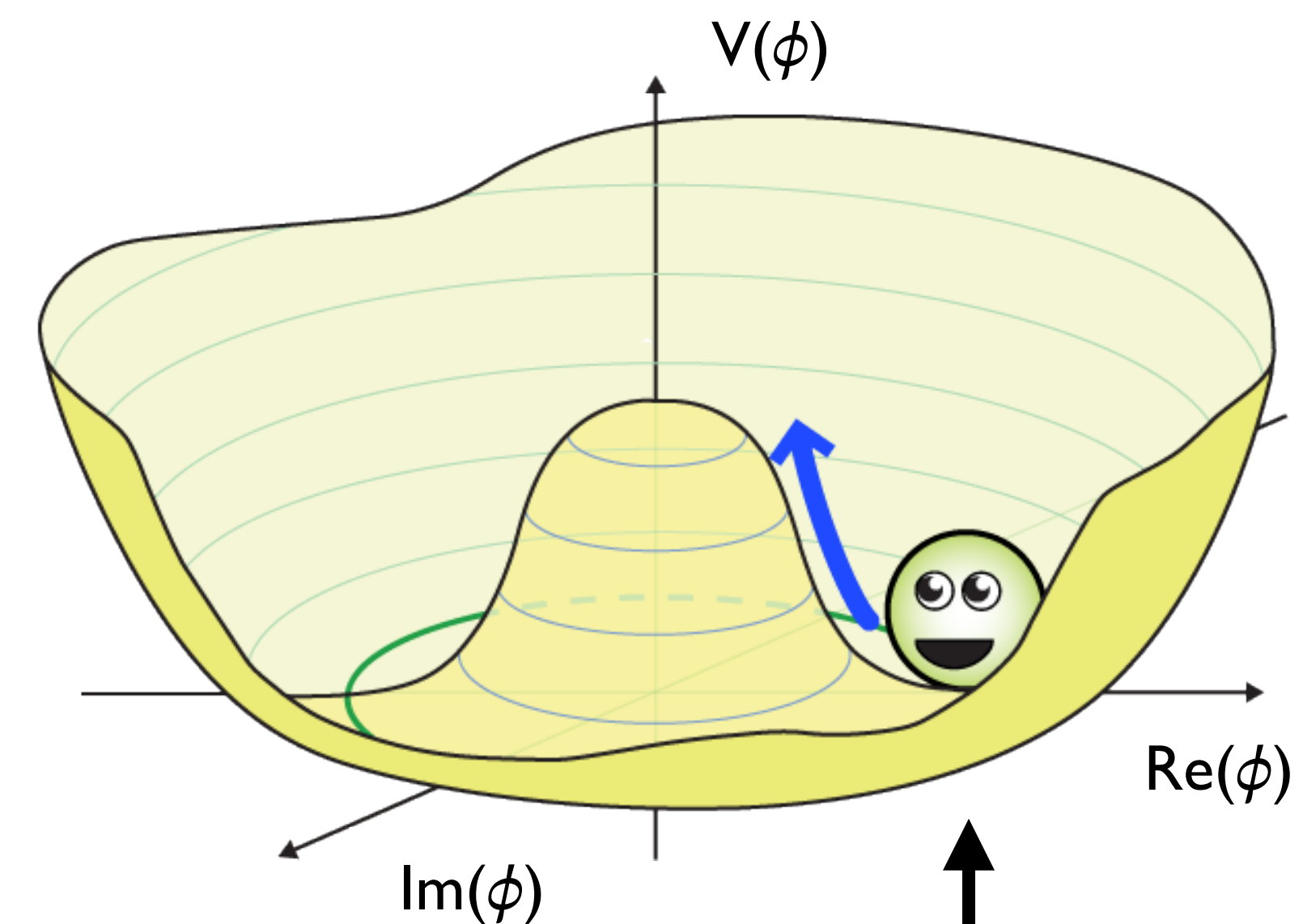
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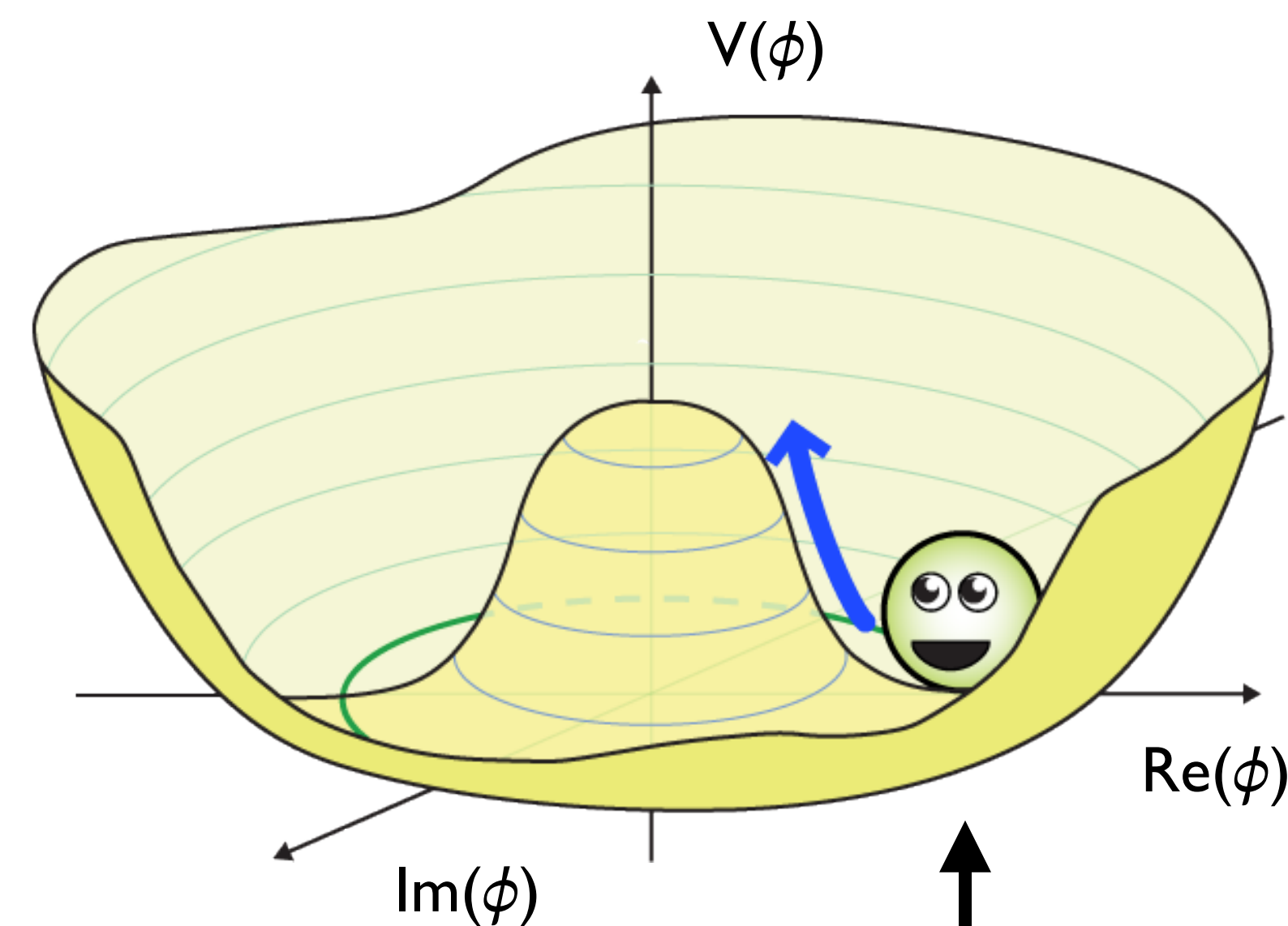
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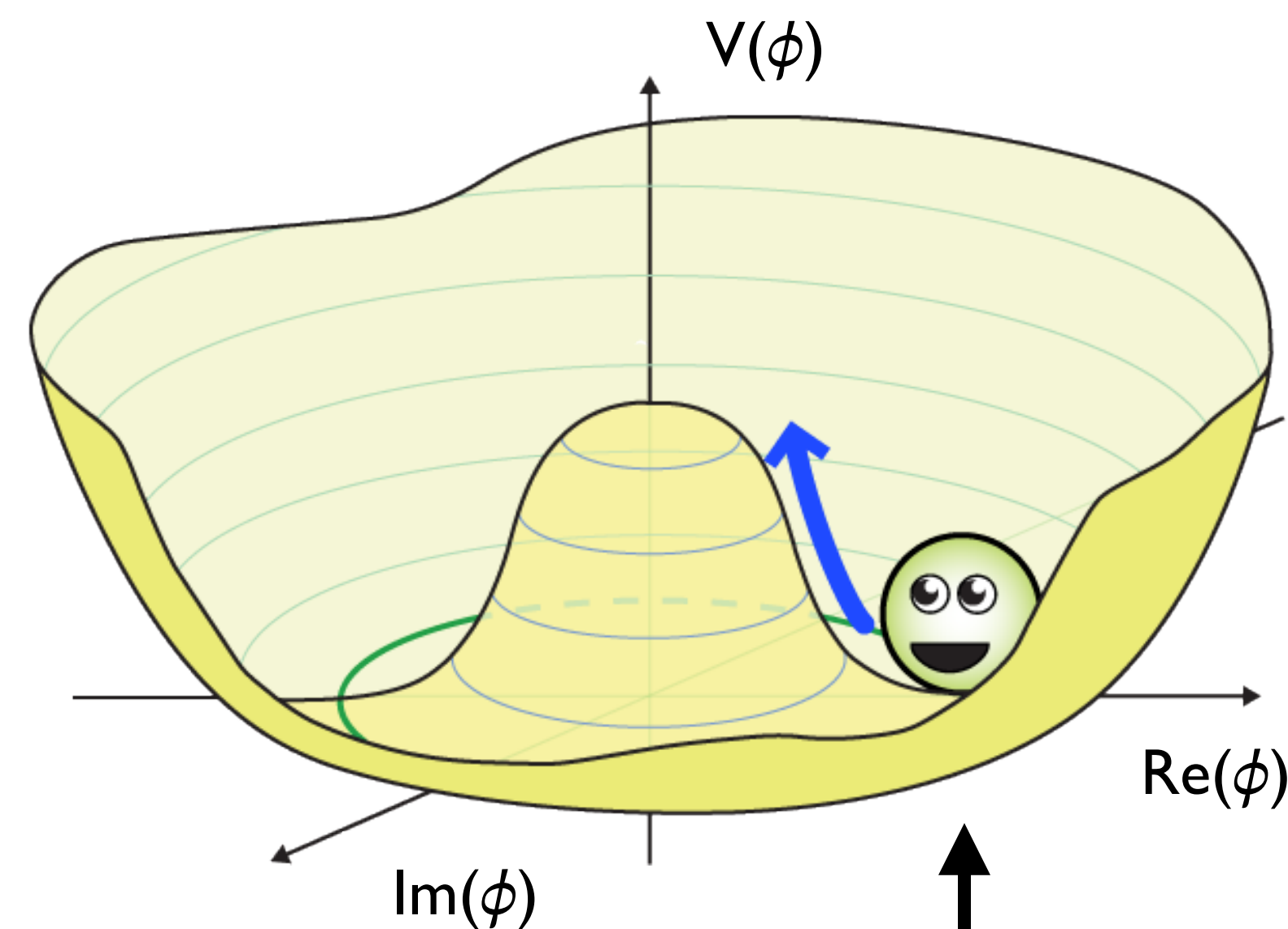


$$m_H = \sqrt{2\lambda}v$$

not predicted!

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Mass of Elementary Particles?



- The problem of gauge boson masses:

- Principle of local gauge invariance:

$$\psi \rightarrow e^{i\alpha(x)} \psi$$

Arbitrary phase

Matter field/particle

- Gauge fields ($\sim$ force carriers), transform as:

(W) gauge boson

$$W \rightarrow W + \frac{1}{g} \frac{d}{dx} \alpha$$

Coupling (interaction) strength

- Problem:

$$\frac{1}{2} m_W^2 W^2 = \frac{1}{2} m_W^2 \left(W + \frac{1}{g} \frac{d}{dx} \alpha \right)^2 \neq \frac{1}{2} m_W^2 W^2$$

(W) Boson mass term



Electroweak Symmetry Breaking: W Boson Mass



$$\mathcal{L}_{\text{Higgs}} = T - V$$



$$\mathcal{L}_{\text{Higgs}} = T - V \quad \in \quad \frac{g^2}{4} \phi^2 W^2$$



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Higgs field

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Electroweak Symmetry Breaking: W Boson Mass



Interaction/coupling
strength (number)

Higgs
field

W boson
field

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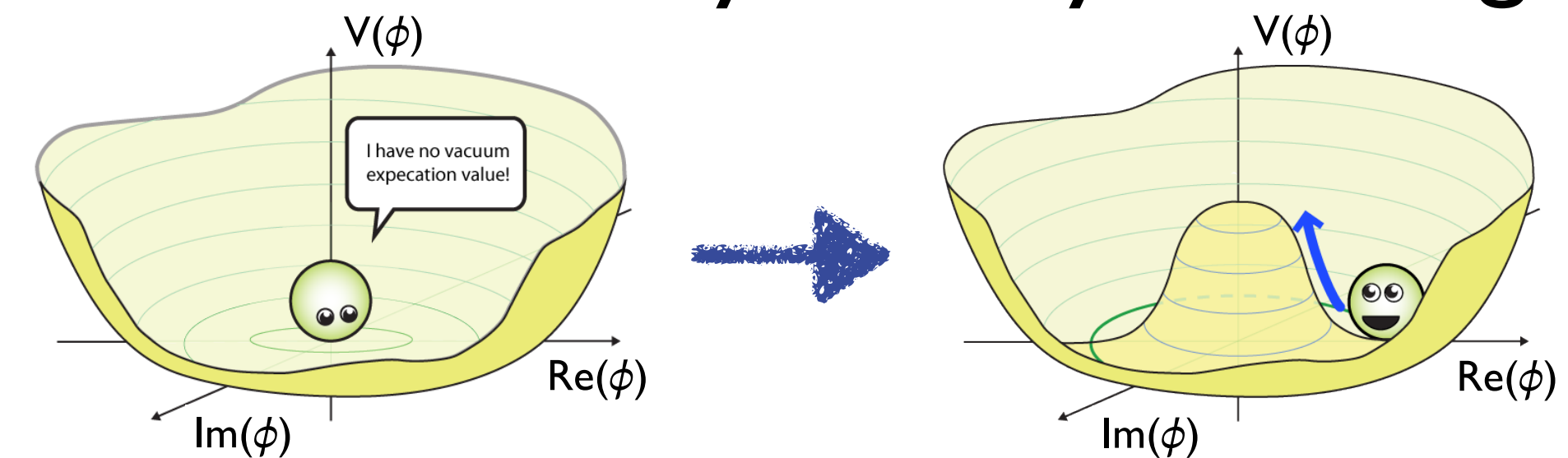
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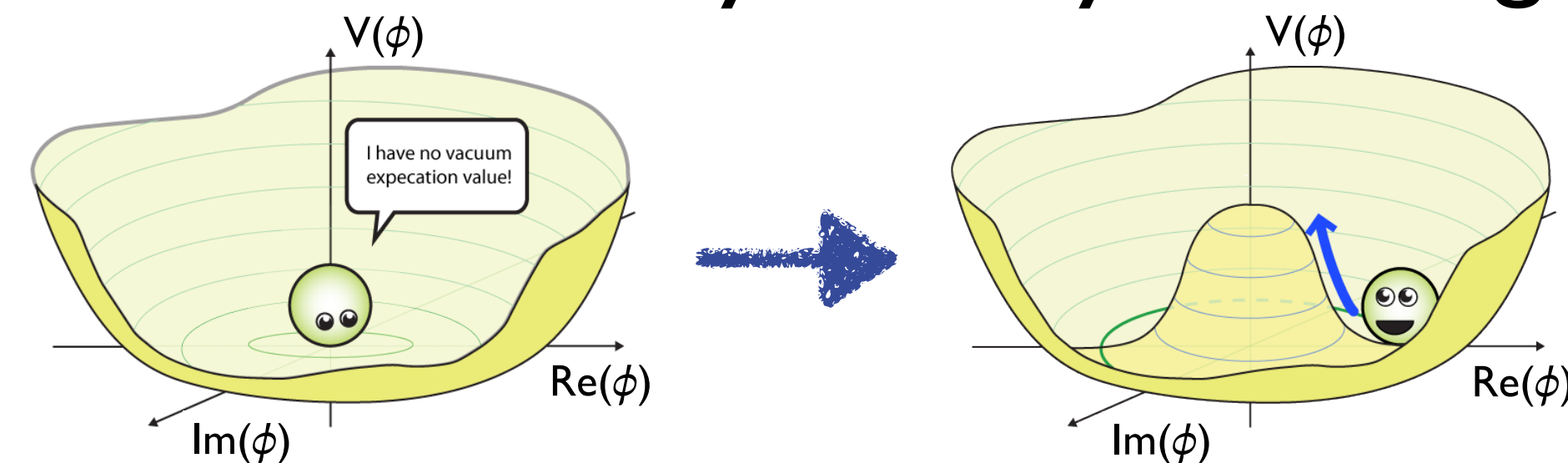
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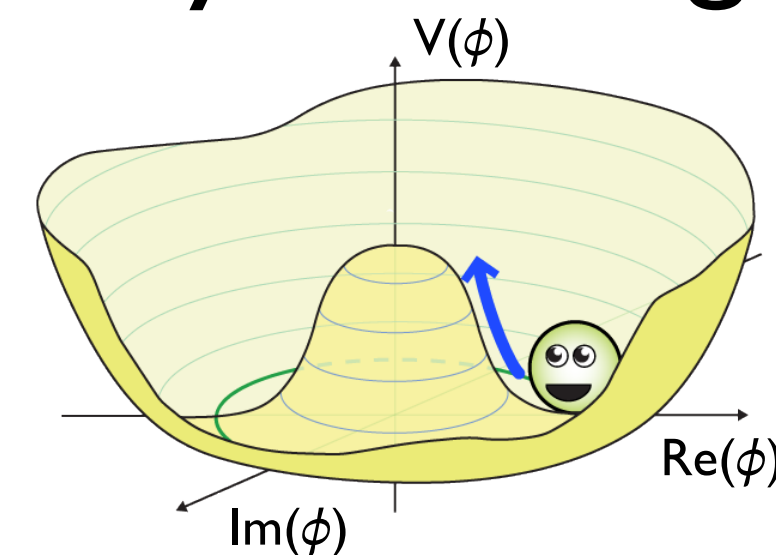
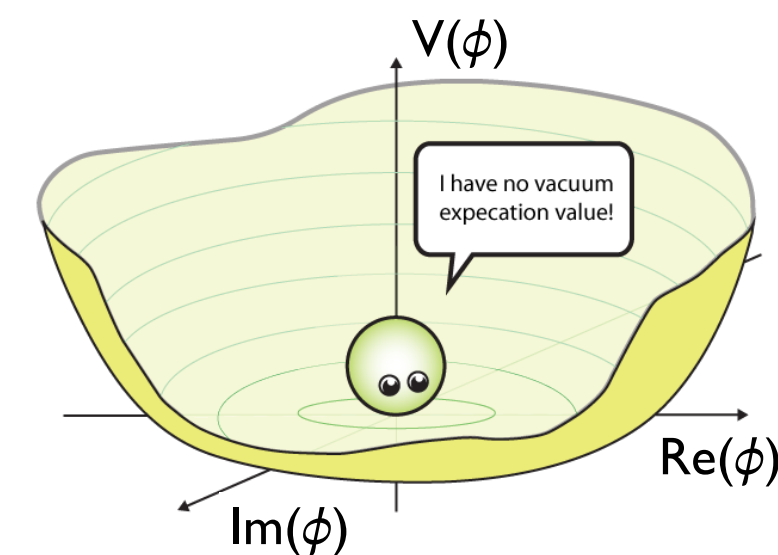
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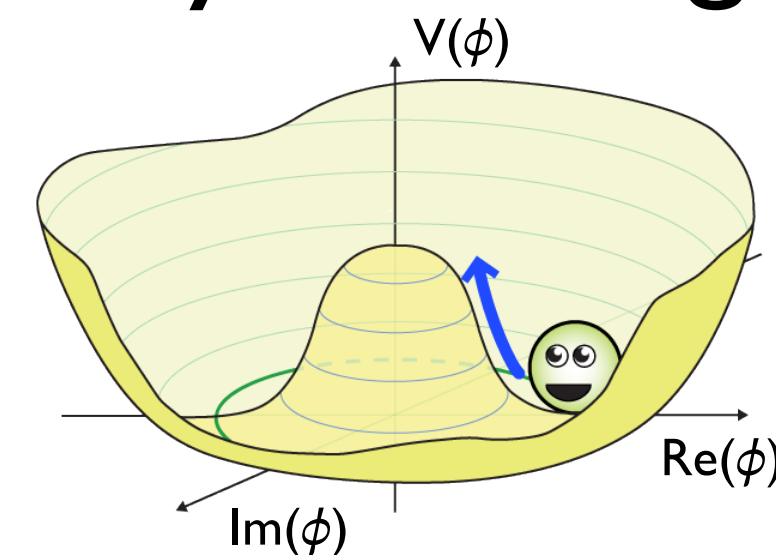
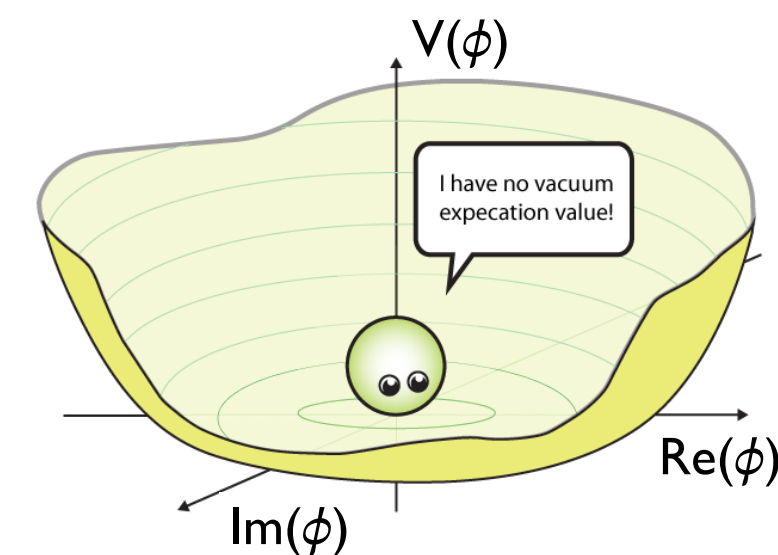
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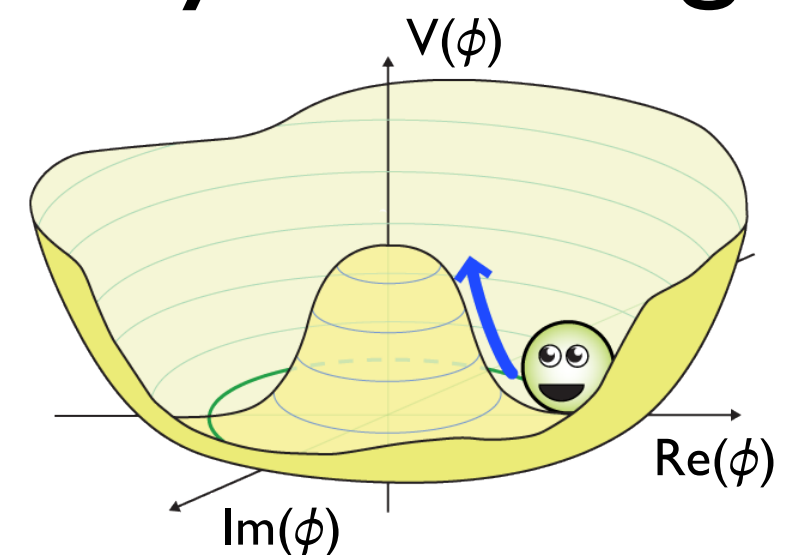
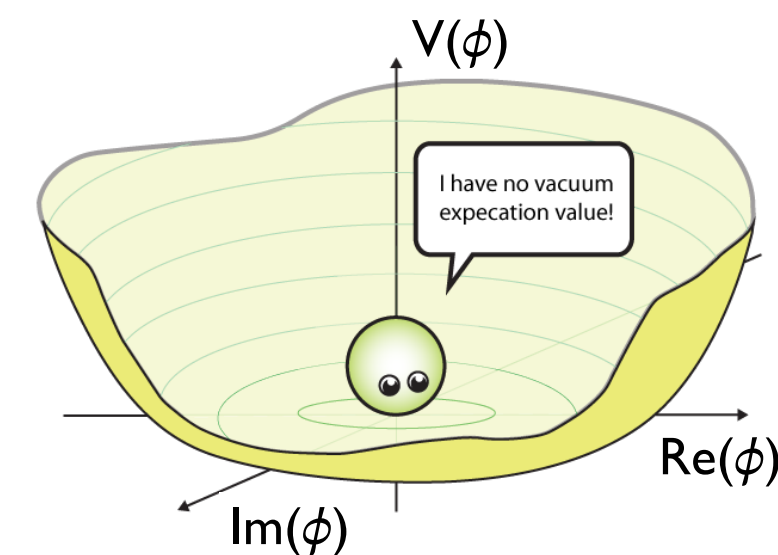
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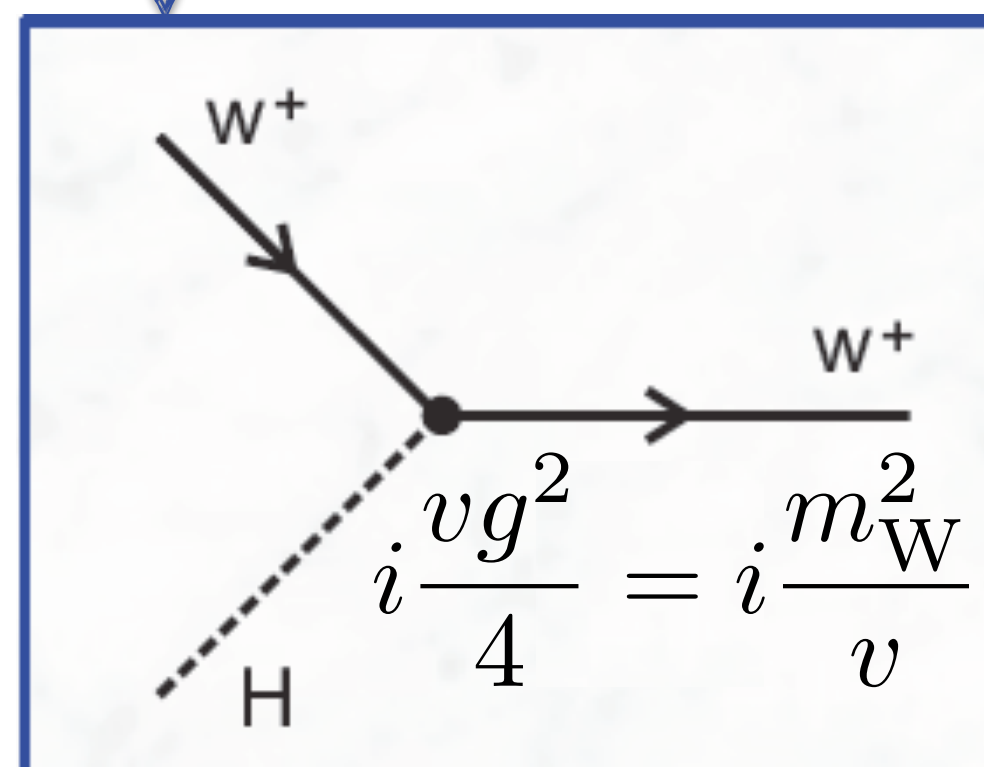


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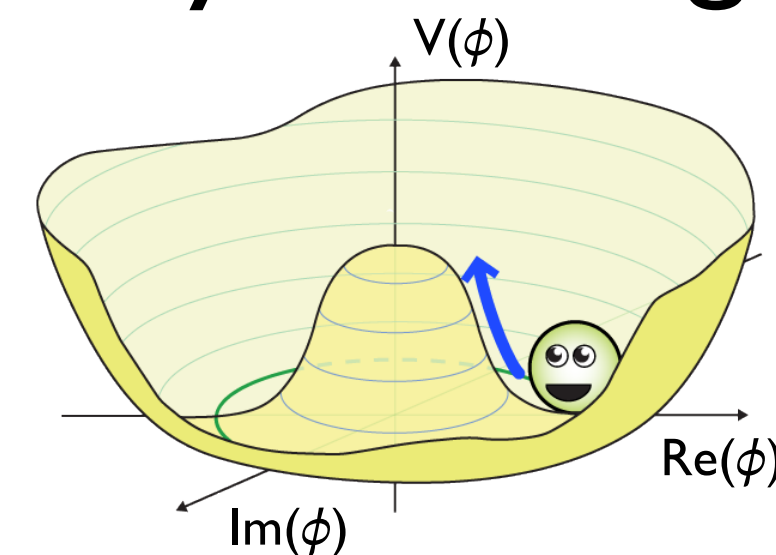
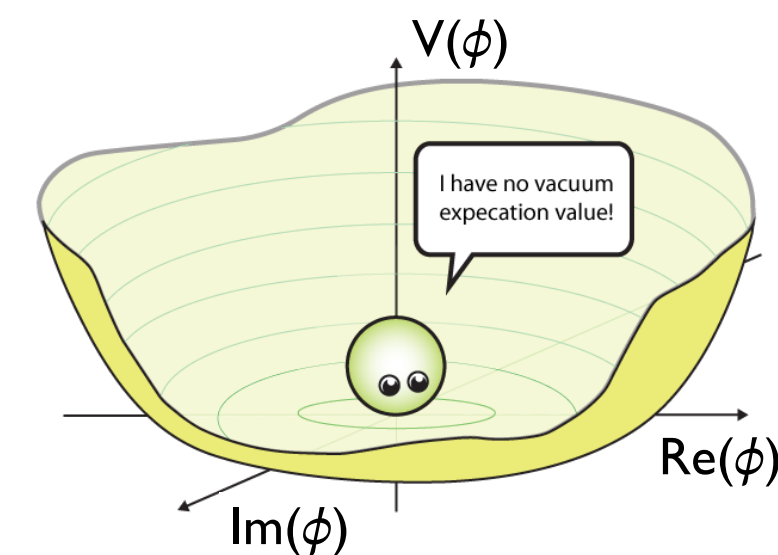
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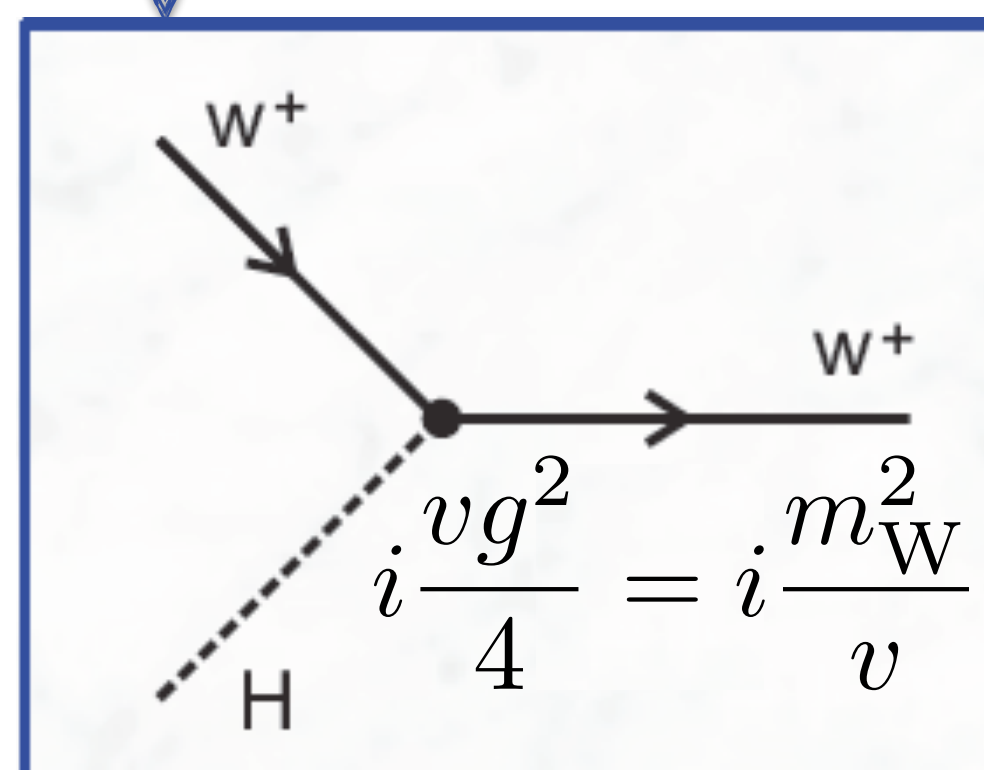
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direct connection





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Fermion

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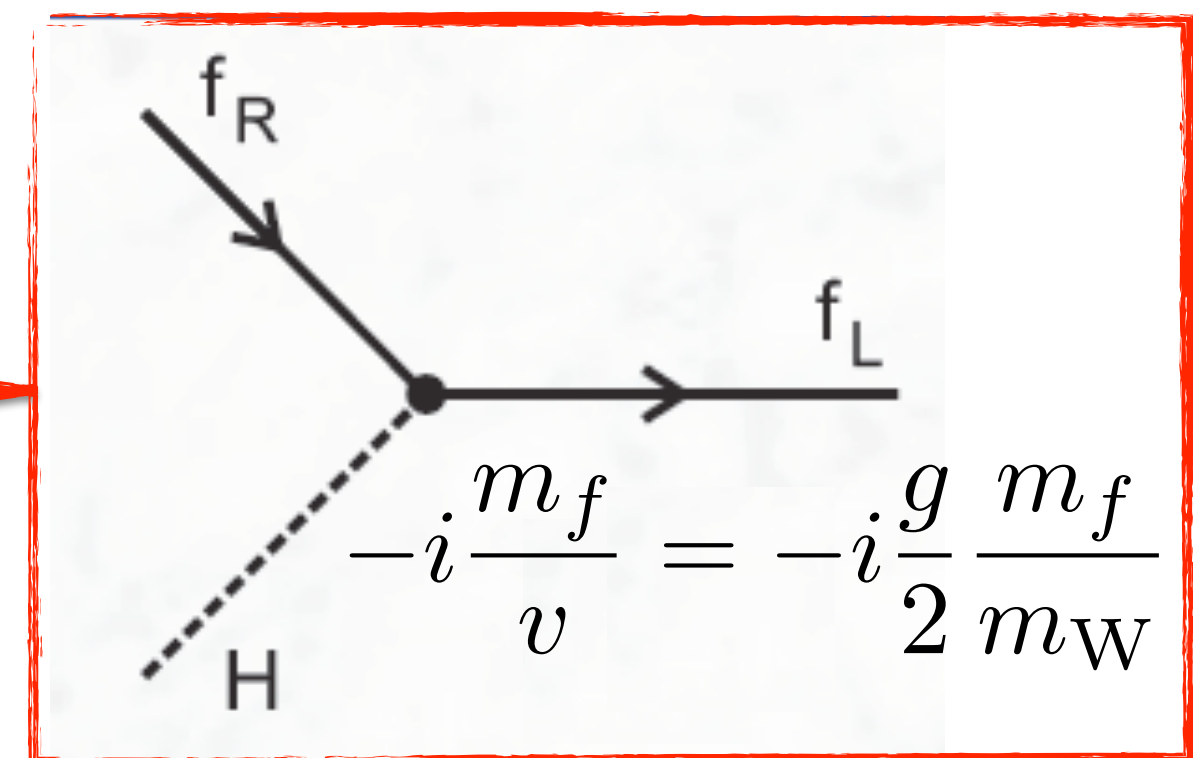
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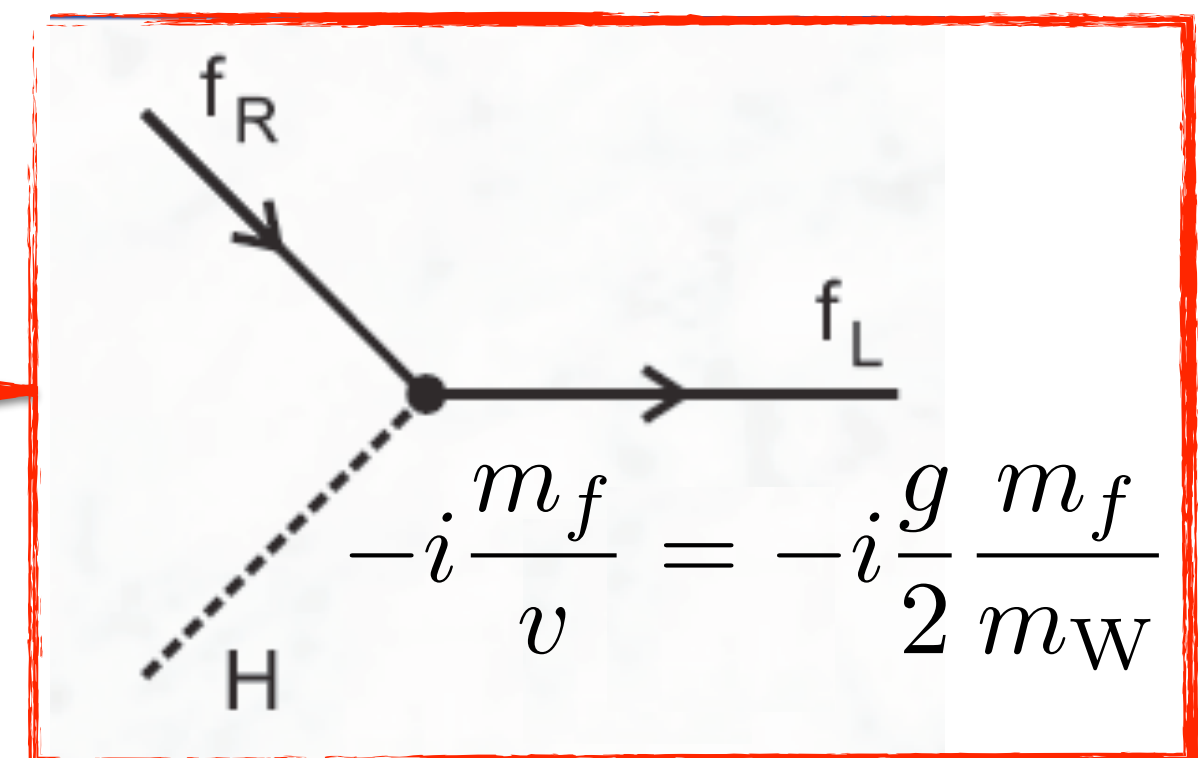
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Fundamentally independent from mass generation for gauge bosons!



Lagrangian after electroweak Symmetry Breaking GA

- Higgs-boson Lagrangian:

$$\mathcal{L}_H \ni \frac{g^2}{4} \phi^2 W^2 - \mu^2 \phi^2 - \lambda \phi^4$$



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W boson
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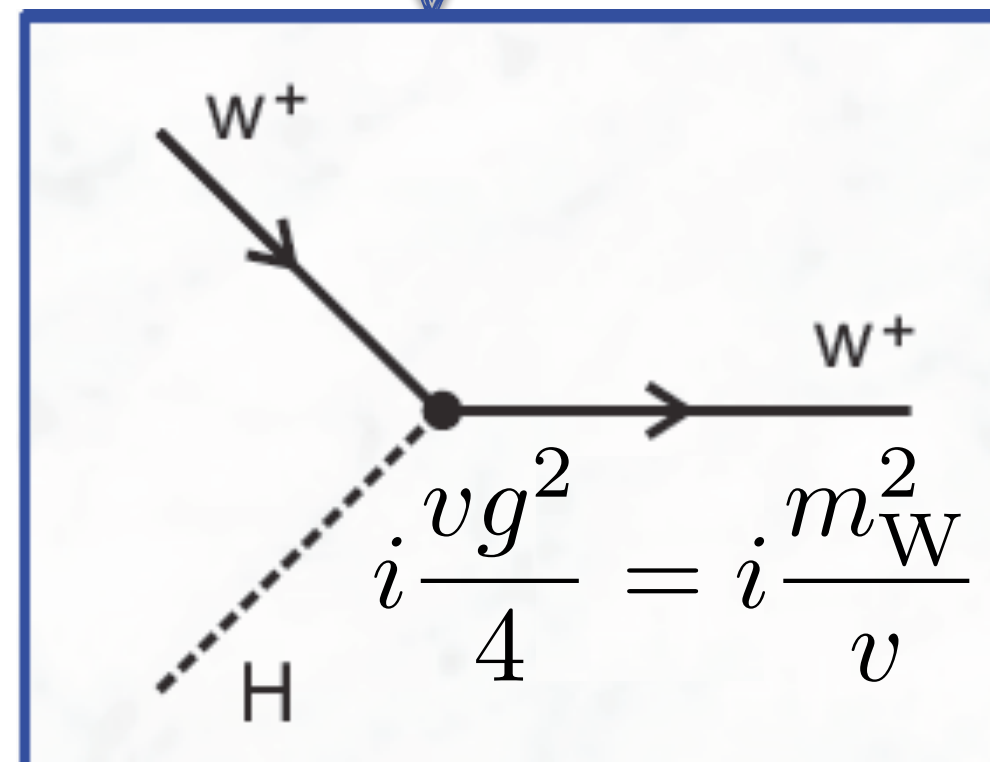
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$m_W = \frac{vg}{2}$

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not predicted!

H self interactions



How sure are we?



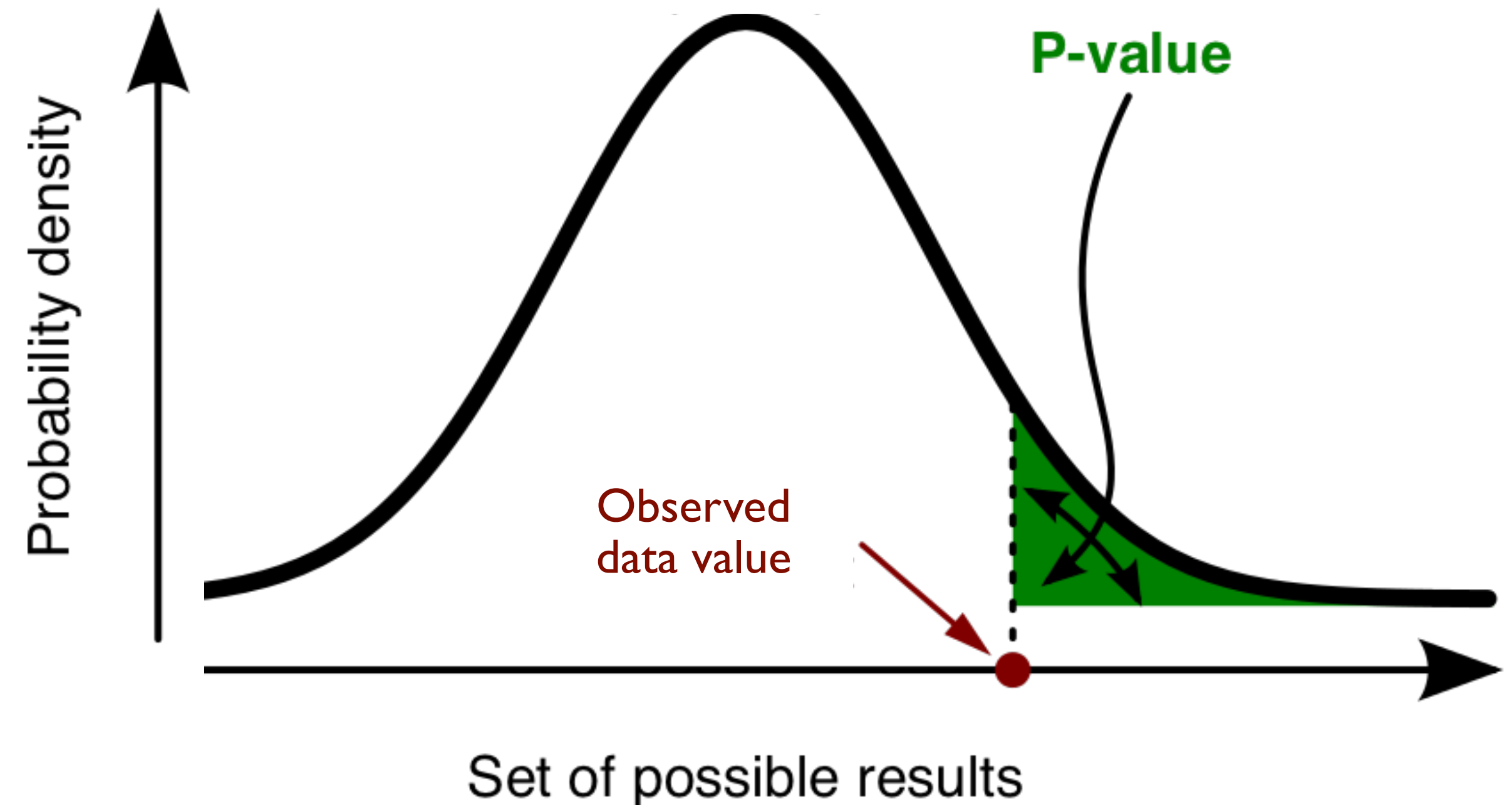
- Calculate the “p-value”:

1. Build probability density distribution f for background-only hypothesis $H_0: f(x|H_0)$
2. Probability to obtain result x_{obs} or less likely, given $f(x|H_0)$:

$$p = \int_{x_{\text{obs}}}^{\infty} f(x|H_0) dx$$

- Map p-value to Gaussian standard deviations N_σ :

$$p = \int_{N_\sigma}^{\infty} \frac{e^{-y^2/2}}{\sqrt{2\pi}} dy$$





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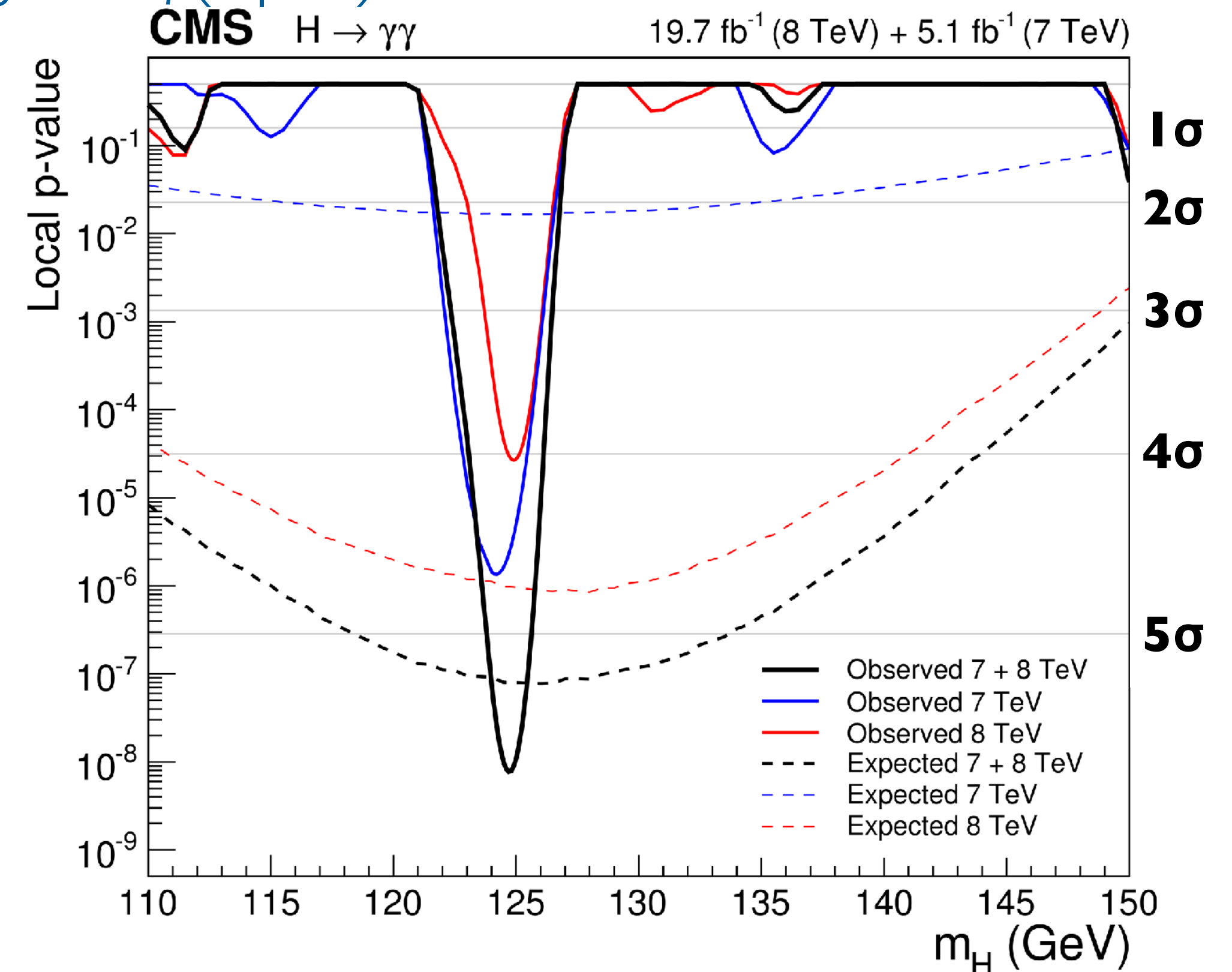
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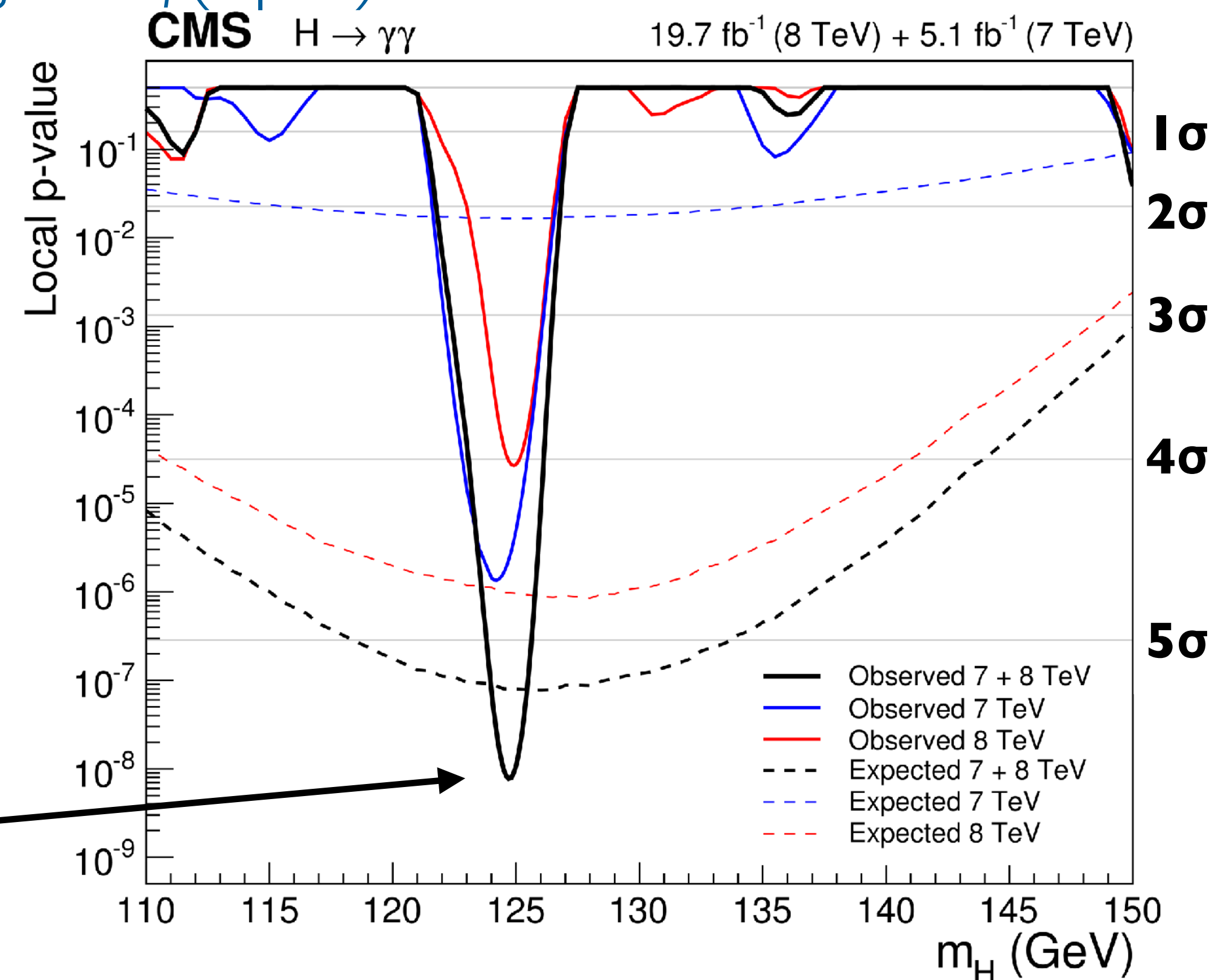
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- Significance: **5.7 σ**





Look elsewhere effect: Local vs. Global significance



- Significance:
 - How likely does the background fluctuate to the observed (or more extreme) value $\Rightarrow$ ***p-value***
 - Transform p-value into (local) significance assuming Gaussian probability distribution $\Rightarrow Z \sigma$
 - $3 \leq Z < 4$: “evidence”; $4 \leq Z < 5$: “strong evidence”; $Z \geq 5$: “observation”
 - Depends on background
- When there is another unknown signal parameter, e.g., unknown mass m_X of a resonance: what to do?
 - How to claim “*observation*” for any value of m_X within a search range?
 - Much larger chance to find an excess in a narrow mass window if we scan this narrow window over a very wide mass range $\Rightarrow$ “***look elsewhere effect***”
 - Correct p-value by scaling it by the “*number of places we have looked*”, or a “***trials factor***”
 - ***Trials factor*** could, e.g., be simply $\frac{\text{wide mass search range}}{\text{mass resolution}}$
 - Often called “*Bonferroni-type* correction”

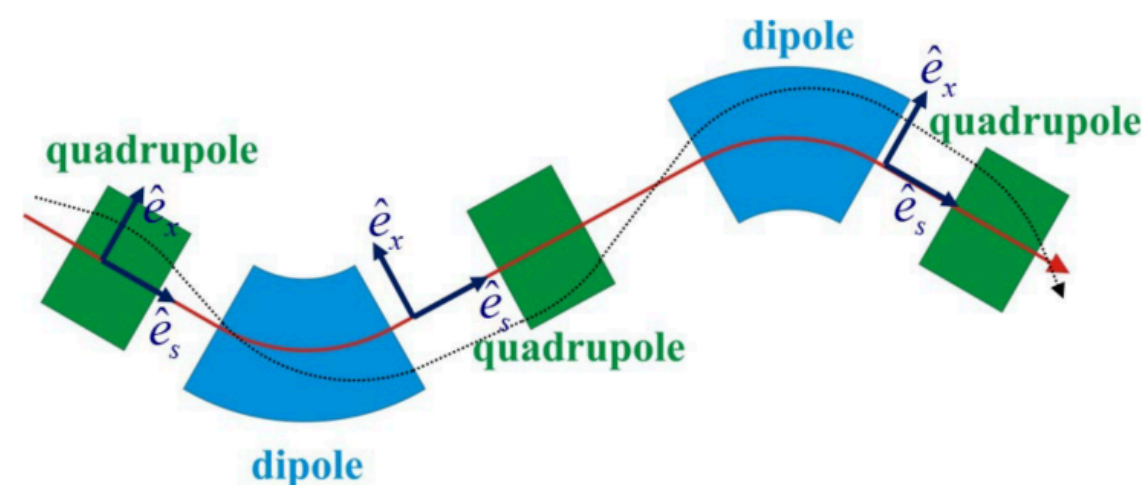


Beam acceleration and control



Use of Electromagnetic fields $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$

Steering



The magnetic field is more efficient

$$F_c = \gamma_r m_0 \frac{v^2}{\rho} = q(E_{\perp} + vB_{\perp})$$

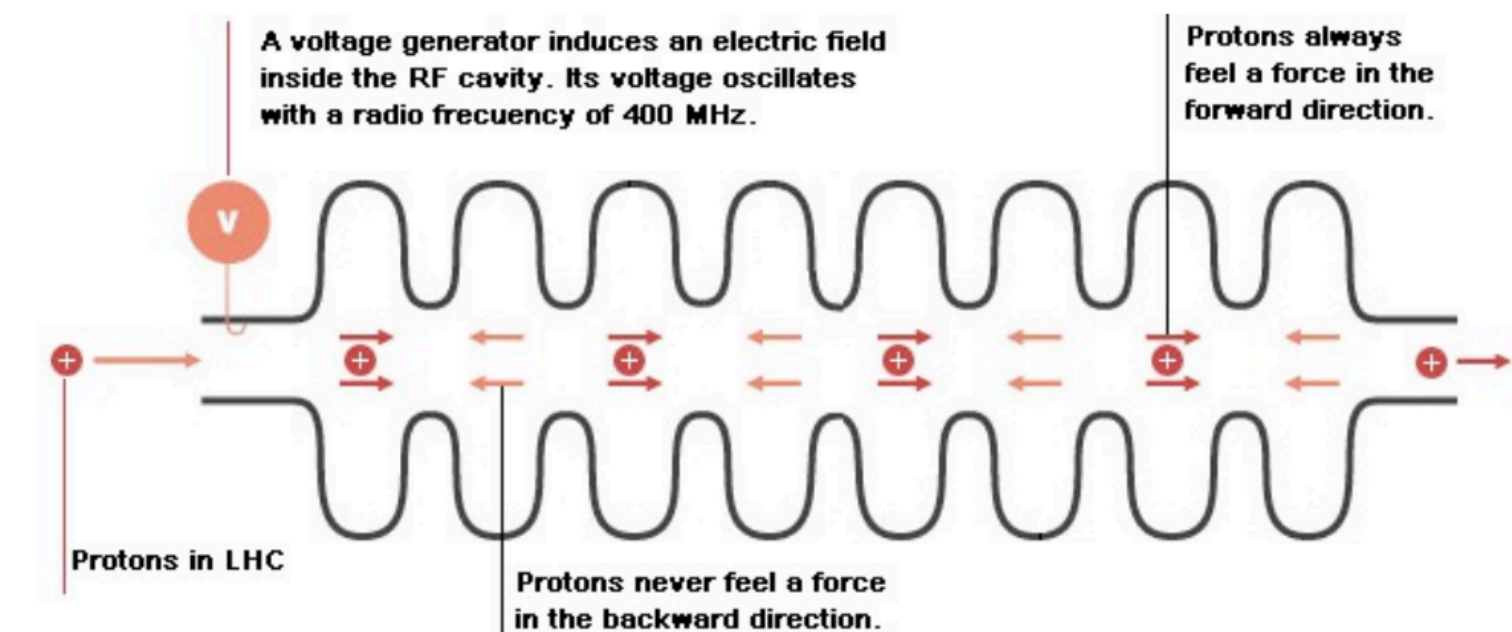
$$= \frac{pv}{q} = \rho(E_{\perp} + vB_{\perp})$$

For ultra relativistic particles ($v \approx c$) and $\rho E_{\perp} \equiv c\rho B_{\perp}$, the required:

electric rigidity ($E_{\perp}\rho$) is: 300MV -> “impossible”

magnetic rigidity ($B_{\perp}\rho$) is: 1Tm -> “easy”

Acceleration



Time varying electric fields - RF cavities/resonators
(metal container for electromagnetic field)

The magnetic field does not accelerate at all ($F = q\vec{v} \times \vec{B}$)

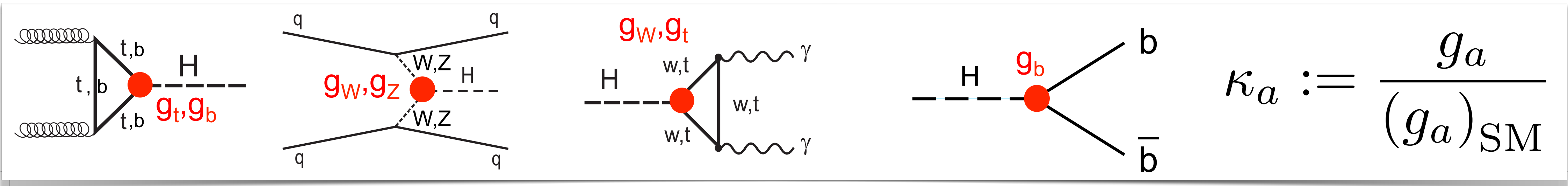
DC acceleration if not impossible ($\oint \vec{E} \cdot d\vec{l} = 0$) then is not effective (breakdown voltages)



The κ Framework



- Once Higgs boson mass is known, all other Higgs-boson parameters are fixed in the SM
- To allow for measurement deviations from SM rates, introduce coupling modifiers:



$$\begin{aligned}
 (\sigma \cdot \text{BR}) (i \rightarrow H \rightarrow f) &= \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} \\
 &= \sigma_{\text{SM}} (i \rightarrow H) \cdot \text{BR}_{\text{SM}} (H \rightarrow f) \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}
 \end{aligned}$$

Assumption:

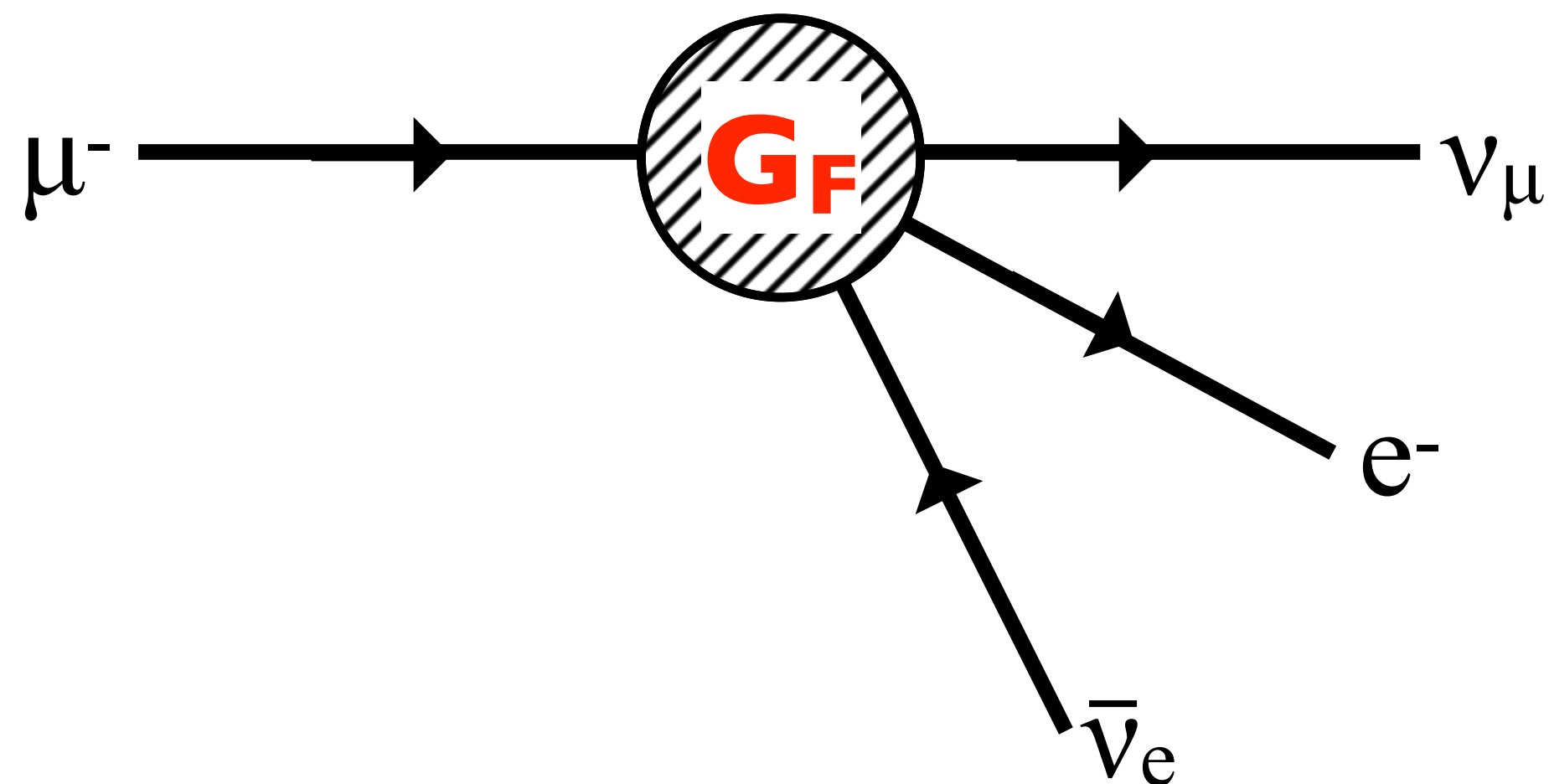
- Only one SM Higgs-like state at ~ 125 GeV with negligible width



Effective Field Theories: Muon Decay GA

Fermi-Theory (1933)

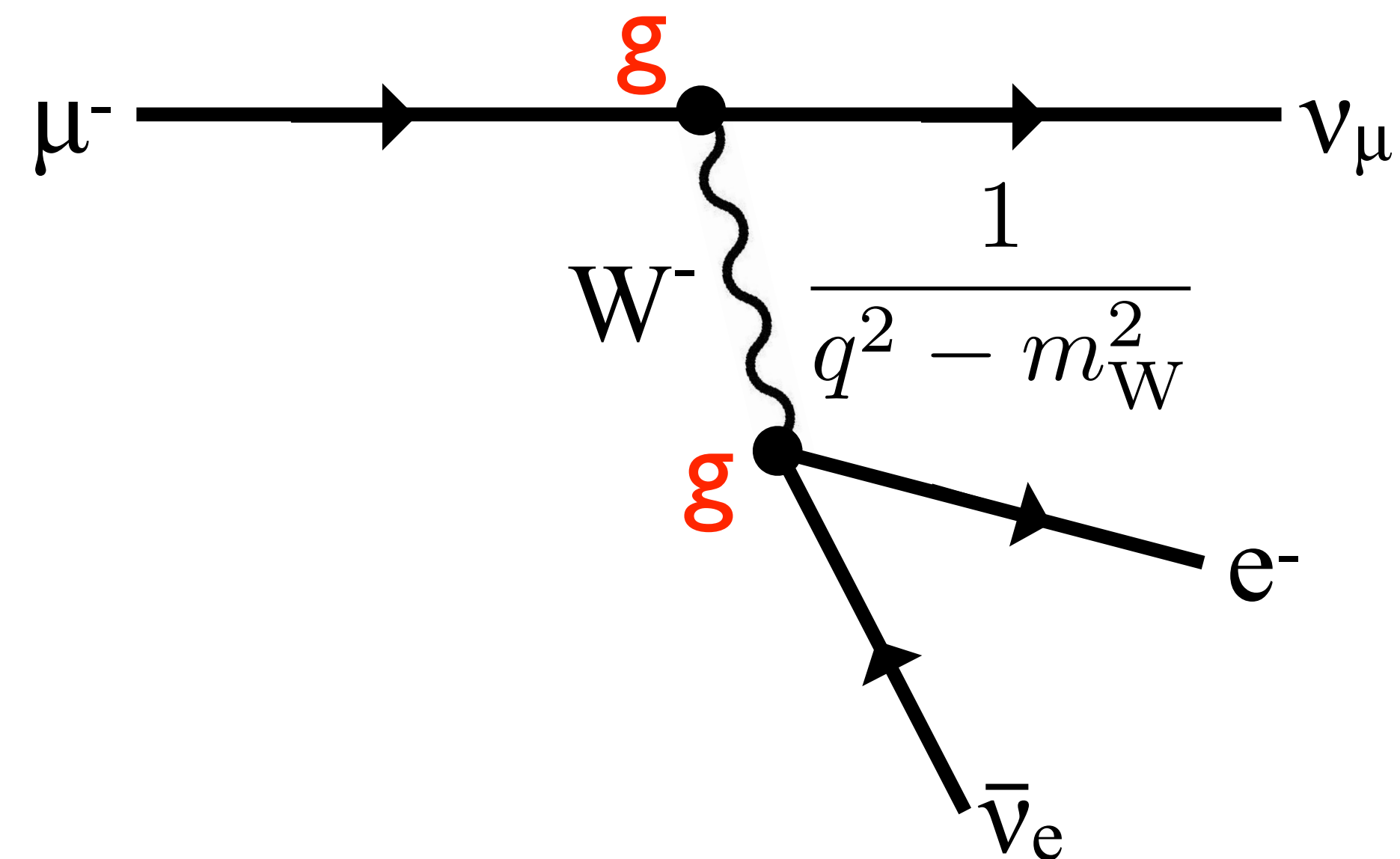
Effective Field Theory



For $q^2 \ll m_W^2$ is $\frac{1}{q^2 - m_W^2} \rightarrow \frac{1}{-m_W^2}$ and $\frac{g^2}{8m_W^2} \rightarrow \frac{G_F}{\sqrt{2}}$

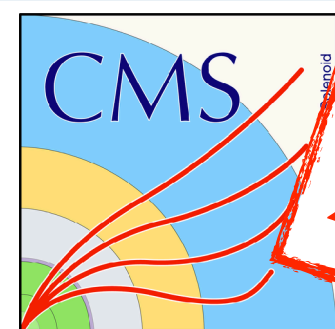
Theory of Weak Interaction

“Full” Field Theory





Higgs Boson Mass



Sep
2024

$$H \rightarrow ZZ^* \rightarrow 4\ell$$

CMS

Run 2: 138 fb⁻¹ (13 TeV)

Run 1: 5.1 fb⁻¹ (7 TeV) + 19.7 fb⁻¹ (8 TeV)

— Total Stat. Only

Total (Stat. Only)

4μ 124.90^{+0.15}_{-0.15} (+0.14)_{-0.14} GeV

4e 124.70^{+0.53}_{-0.51} (+0.49)_{-0.47} GeV

2e2μ 125.50^{+0.27}_{-0.26} (+0.25)_{-0.24} GeV

2μ2e 125.20^{+0.29}_{-0.27} (+0.27)_{-0.26} GeV

Run 2 125.04^{+0.12}_{-0.12} (+0.11)_{-0.11} GeV

Run 1 125.60^{+0.46}_{-0.45} (+0.43)_{-0.41} GeV

Run 1 + Run 2 125.08^{+0.12}_{-0.12} (+0.10)_{-0.10} GeV

122 124 126 128 130
 m_H (GeV)

$$m_H = 125.08 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}) \text{ GeV}$$



Aug
2023

$$H \rightarrow \gamma\gamma \text{ and } H \rightarrow ZZ^* \rightarrow 4\ell$$

ATLAS

— Total Stat. Syst. Combination

Run 1: $\sqrt{s} = 7-8$ TeV, 25 fb⁻¹, Run 2: $\sqrt{s} = 13$ TeV, 140 fb⁻¹

Run 1 $H \rightarrow \gamma\gamma$ 126.02 ± 0.51 (± 0.43 ± 0.27) GeV

Run 1 $H \rightarrow 4\ell$ 124.51 ± 0.52 (± 0.52 ± 0.04) GeV

Run 2 $H \rightarrow \gamma\gamma$ 125.17 ± 0.14 (± 0.11 ± 0.09) GeV

Run 2 $H \rightarrow 4\ell$ 124.99 ± 0.19 (± 0.18 ± 0.04) GeV

Run 1+2 $H \rightarrow \gamma\gamma$ 125.22 ± 0.14 (± 0.11 ± 0.09) GeV

Run 1+2 $H \rightarrow 4\ell$ 124.94 ± 0.18 (± 0.17 ± 0.03) GeV

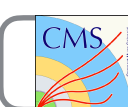
Run 1 Combined 125.38 ± 0.41 (± 0.37 ± 0.18) GeV

Run 2 Combined 125.10 ± 0.11 (± 0.09 ± 0.07) GeV

Run 1+2 Combined 125.11 ± 0.11 (± 0.09 ± 0.06) GeV

123 124 125 126 127 128
 m_H [GeV]

$$m_H = 125.11 \pm 0.09(\text{stat}) \pm 0.06(\text{syst}) \text{ GeV}$$



arXiv:2409.13663

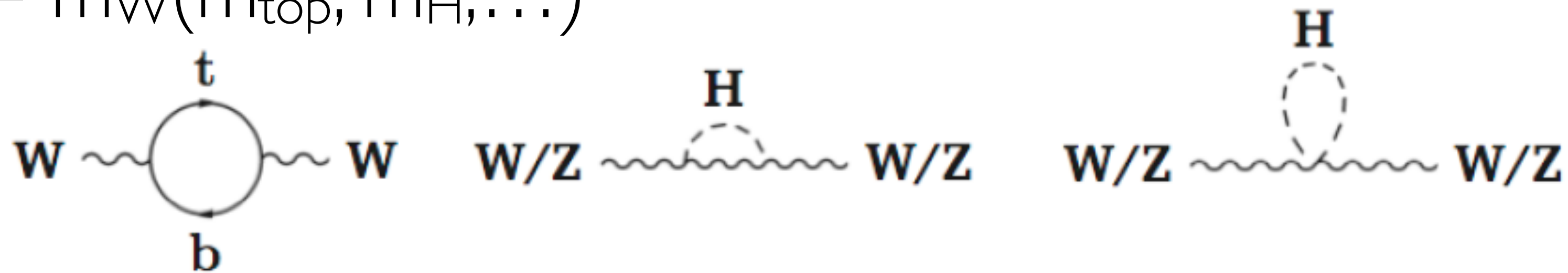




Impact of m_H



- In SM: $m_W = m_W(m_{\text{top}}, m_H, \dots)$



- Measurement uncertainty: $\Delta m_W = 9 \text{ MeV}$
- Impact on m_W in electroweak fit: $\Delta m_W(\text{Top}) = \pm 2.7 \text{ MeV}$, $\Delta m_W(H) = \pm 0.1 \text{ MeV}$

- Impact of Δm_H on cross-sections and branching fractions very small:

	Δ_{theo}	Δ_{exp}	Δm_H
BR(ZZ)	$\pm 1\%$	$\sim 10\%$	$\pm 1\%$
σ_{VBF}	$\pm 2\%$	$\sim 11\%$	$\pm 0.1\%$

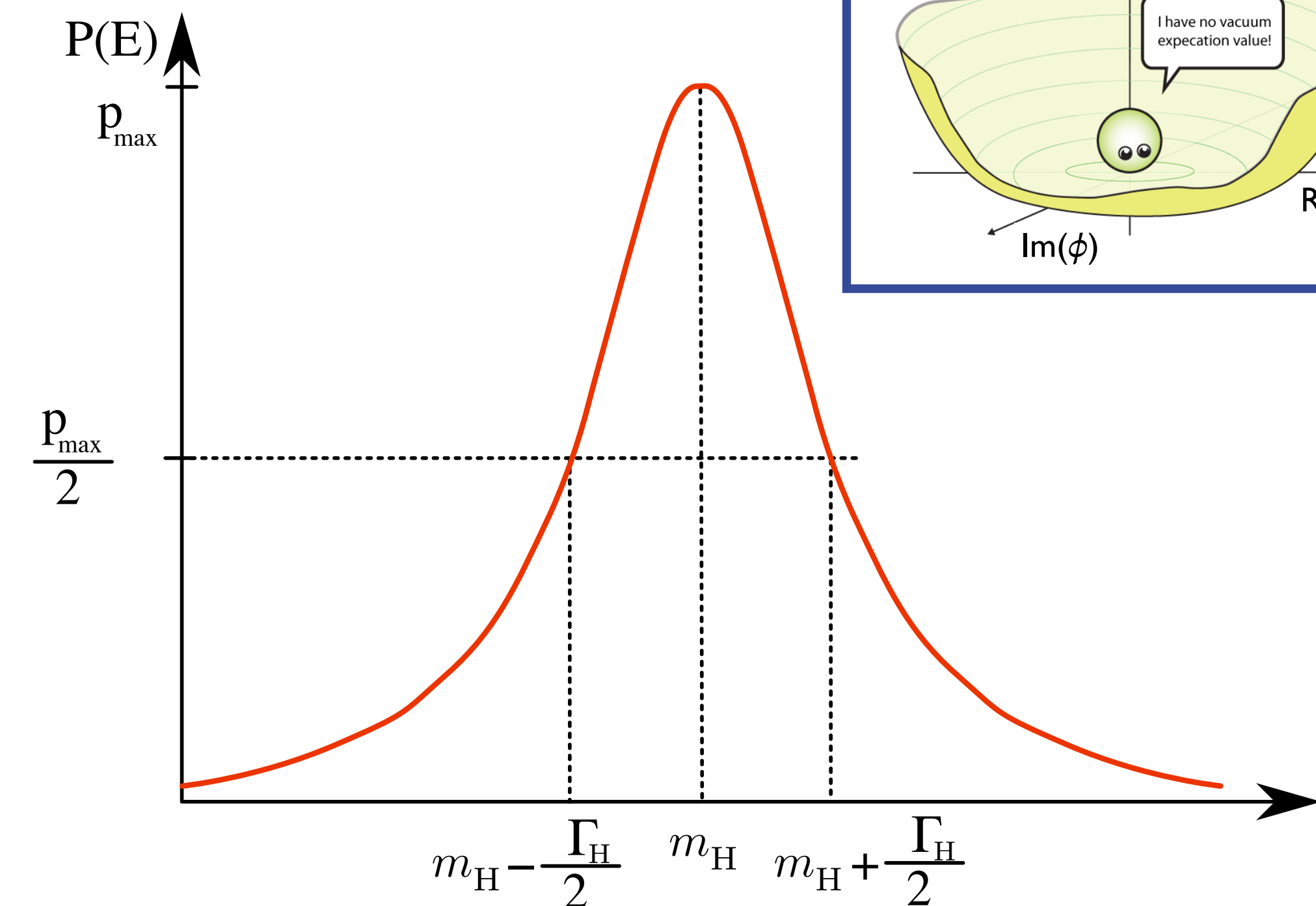
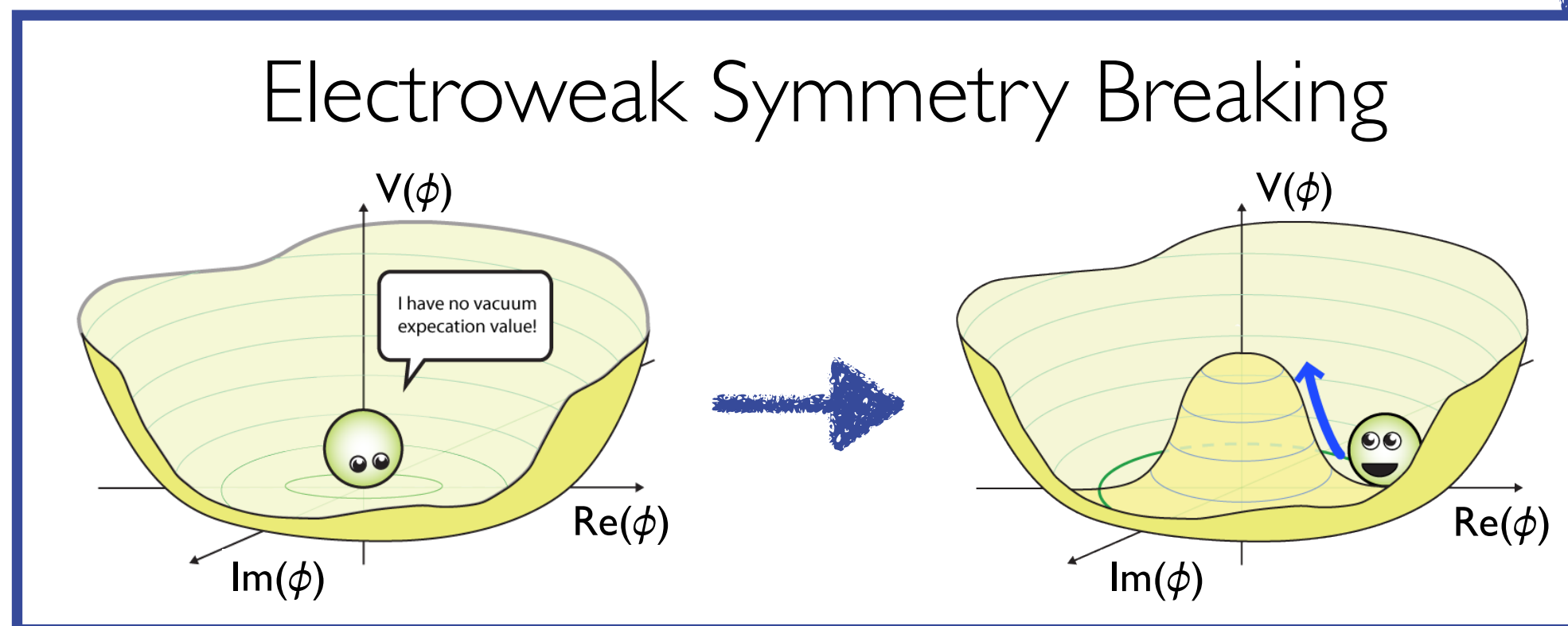
- $\Rightarrow$ Measurement precision of m_H good enough for this
- but precise measurement important!



I. Higgs Boson Width



$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^2 \boxed{-\mu^2 \phi^2 - \lambda \phi^4} + y_f \phi \bar{\psi} \psi$$



$$\mathcal{L} \ni -\boxed{\lambda v^2 H^2} - \lambda v H^3 - \frac{\lambda}{4} H^4$$

$$m_H = \sqrt{2\lambda} v$$

not predicted!



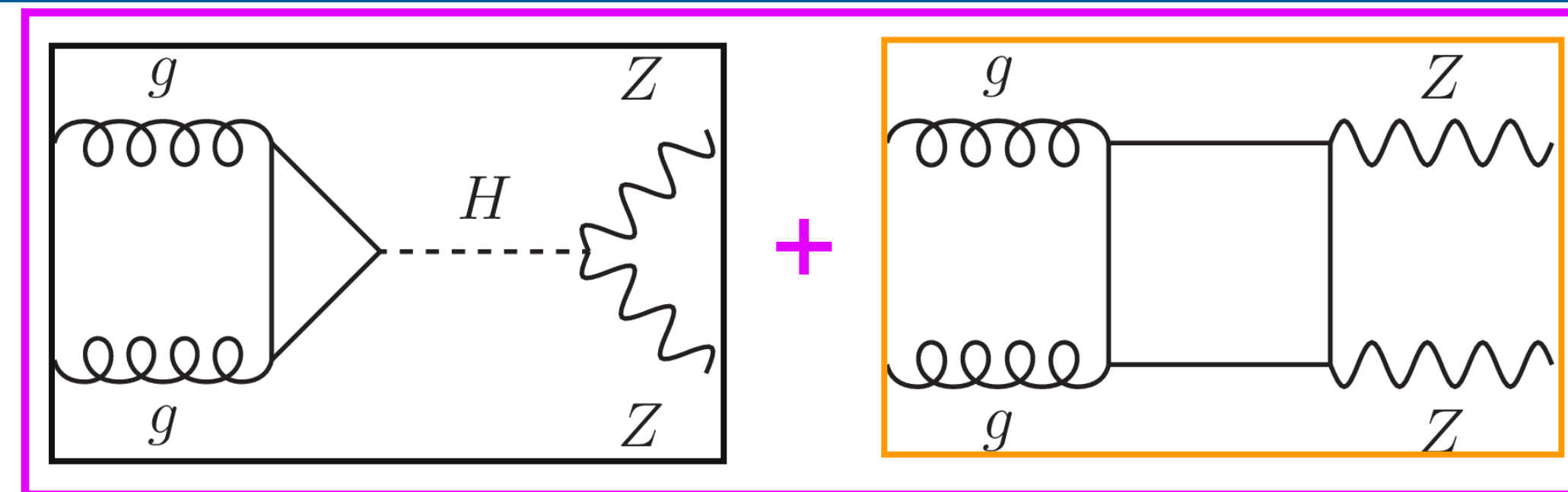
Higgs Boson Width



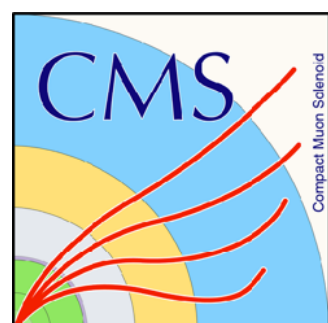
- Expected width: $\Gamma_{H,SM} = 4.1 \text{ MeV}$
 - Direct limit: $\Gamma_H < 50 \text{ MeV @ 68\% CL}$ ($< 330 \text{ MeV @ 95\% C.L.}$)
 - Lifetime too short to measure:
 $\Gamma_H > 3.5 \times 10^{-9} \text{ MeV @ 95\% CL}$

 [arXiv:2409.13663](https://arxiv.org/abs/2409.13663)

 [Phys. Rev. D 92, 072010 \(2015\)](https://arxiv.org/abs/1507.07201)



- Use $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $2\ell 2\nu$



- Evidence for off-shell production: 3.6σ

$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$$

Feb
2022

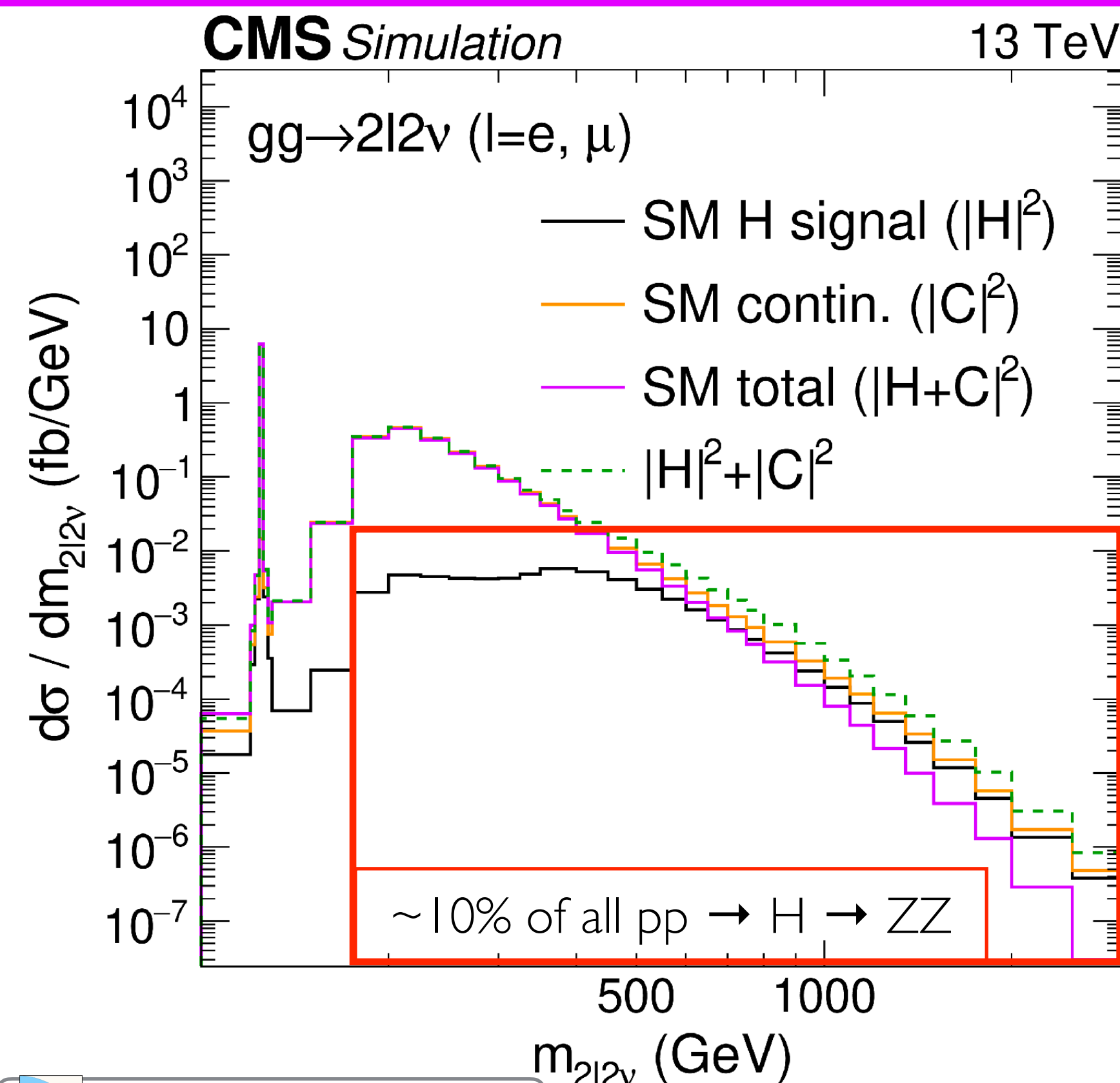


- Evidence for off-shell production: 3.3σ

$$\Gamma_H = 4.3^{+2.7}_{-1.9} \text{ MeV}$$

Dec
2024

 [arXiv:2412.01548](https://arxiv.org/abs/2412.01548)



[Nat. Phys. 18 \(2022\) 1329](https://arxiv.org/abs/2205.12601)

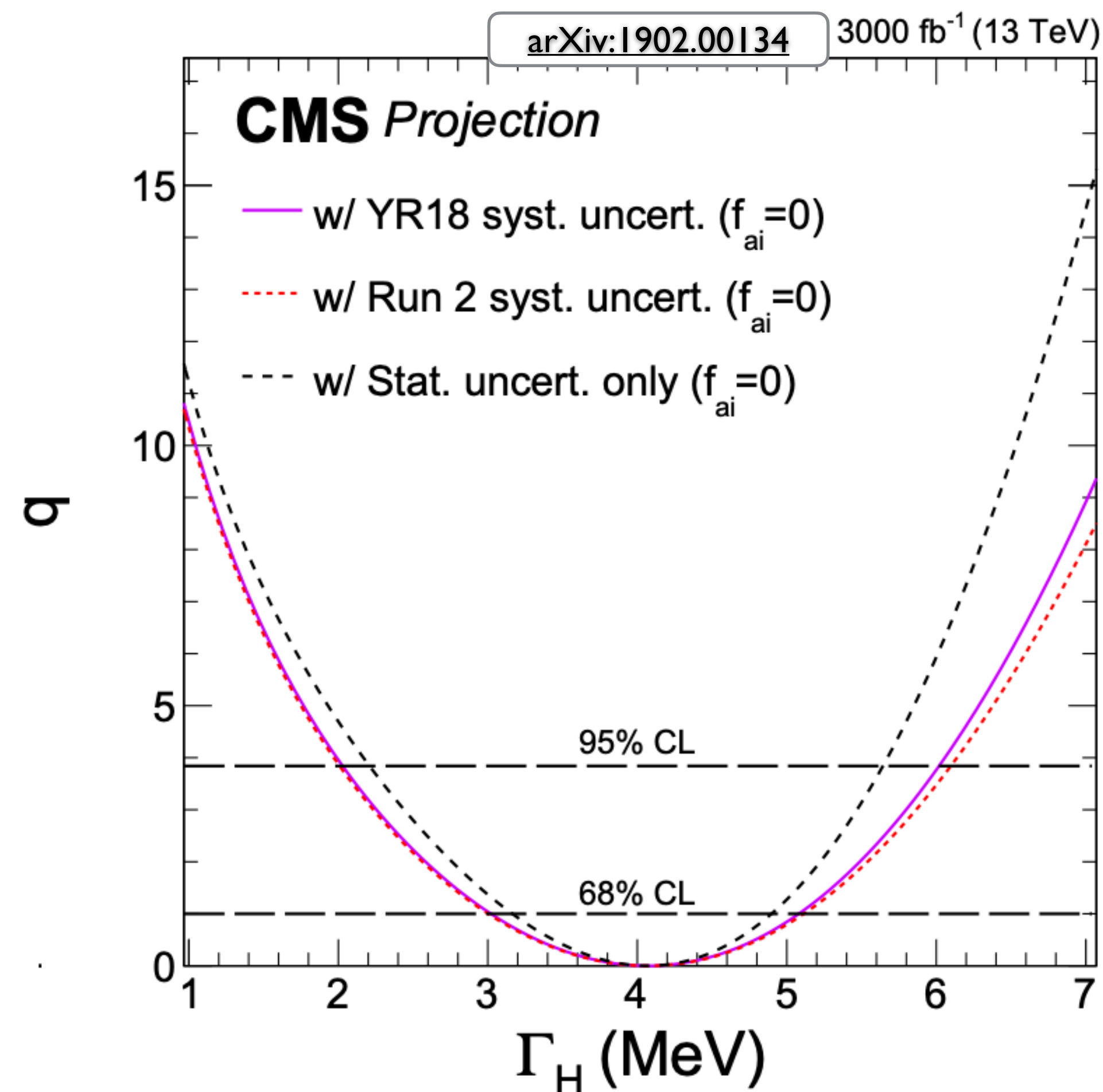
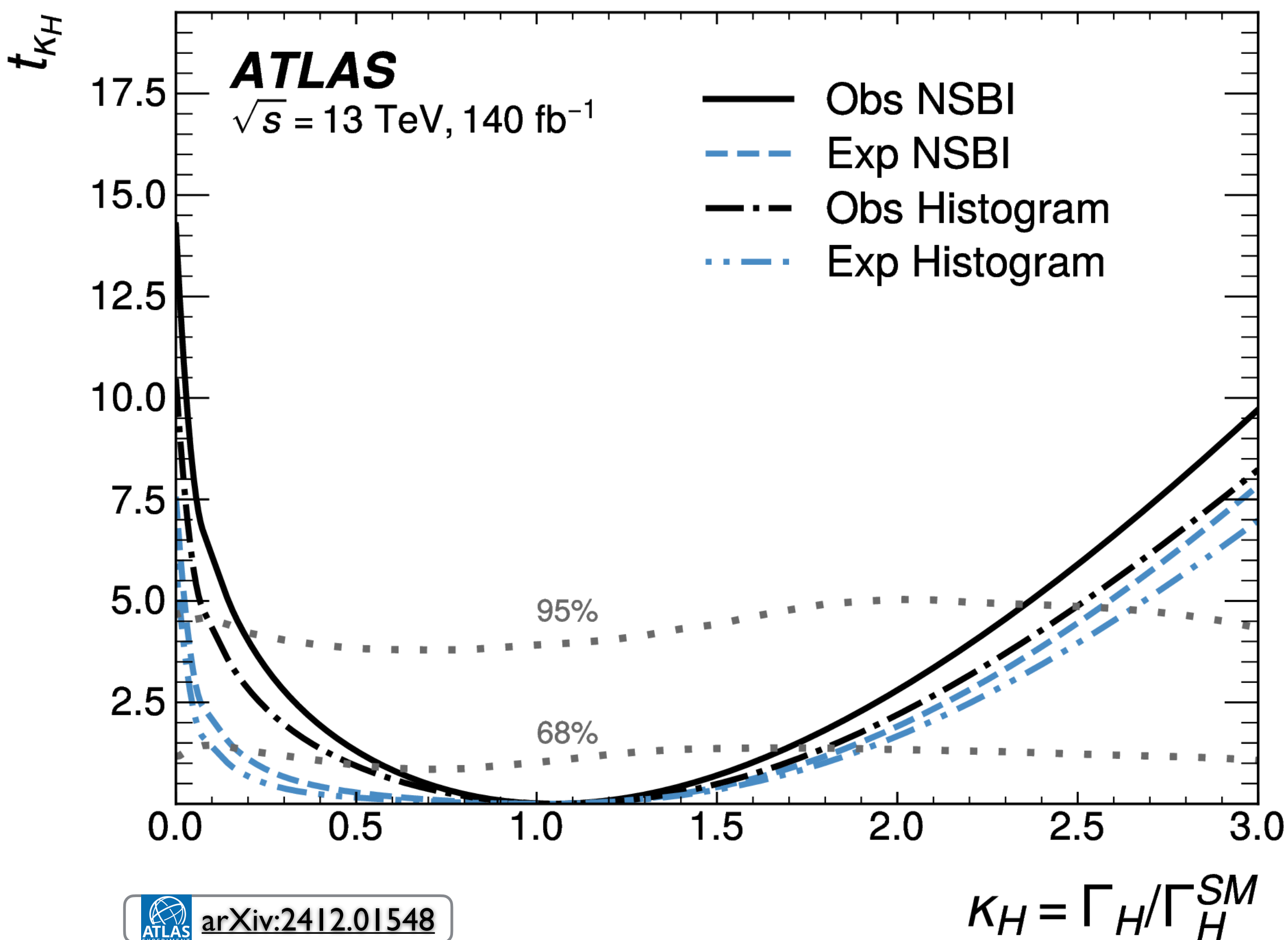


Higgs Boson Width



- HL off-shell Higgs boson production using a neural simulation-based inference technique

- HL-LHC with combined ATLAS+CMS:
 - $\Gamma_H = 4.1 \pm 0.8 \text{ MeV}$





$$H \rightarrow ZZ^* \rightarrow 4\ell$$



- $BR_{SM}(H \rightarrow ZZ^*) \approx 2.6\%$

- $BR_{SM}(Z \rightarrow \ell\ell) \approx 3.4\%$

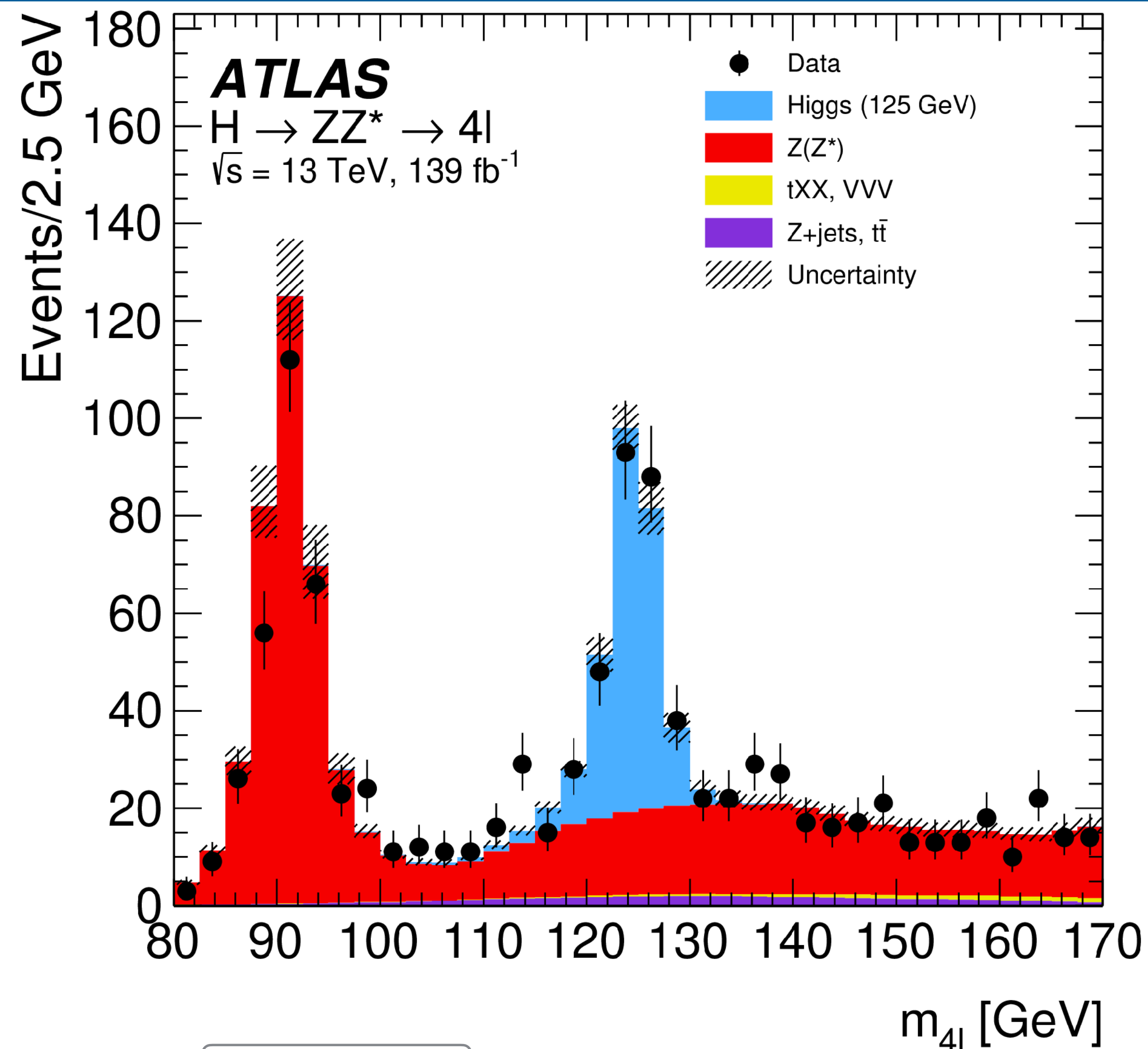
$$\Rightarrow BR_{SM}(H \rightarrow ZZ^* \rightarrow 4\ell) = 0.016\%$$

$$\Rightarrow \sim 1200 H \rightarrow ZZ^* \rightarrow 4\ell \text{ events in } 139 \text{ fb}^{-1}$$

- Expect to see **206 signal events** ($A \cdot \epsilon$)
- Excellent signal reconstruction and S/B

- Fiducial cross-section measurement:

- Observed: $\sigma_{fid}(H \rightarrow ZZ^* \rightarrow 4\ell) = 3.28 \pm 0.32 \text{ fb}$
- Expected: $\sigma_{fid,SM}(H \rightarrow ZZ^* \rightarrow 4\ell) = 3.41 \pm 0.18 \text{ fb}$





$$H \rightarrow ZZ^* \rightarrow 4\ell$$

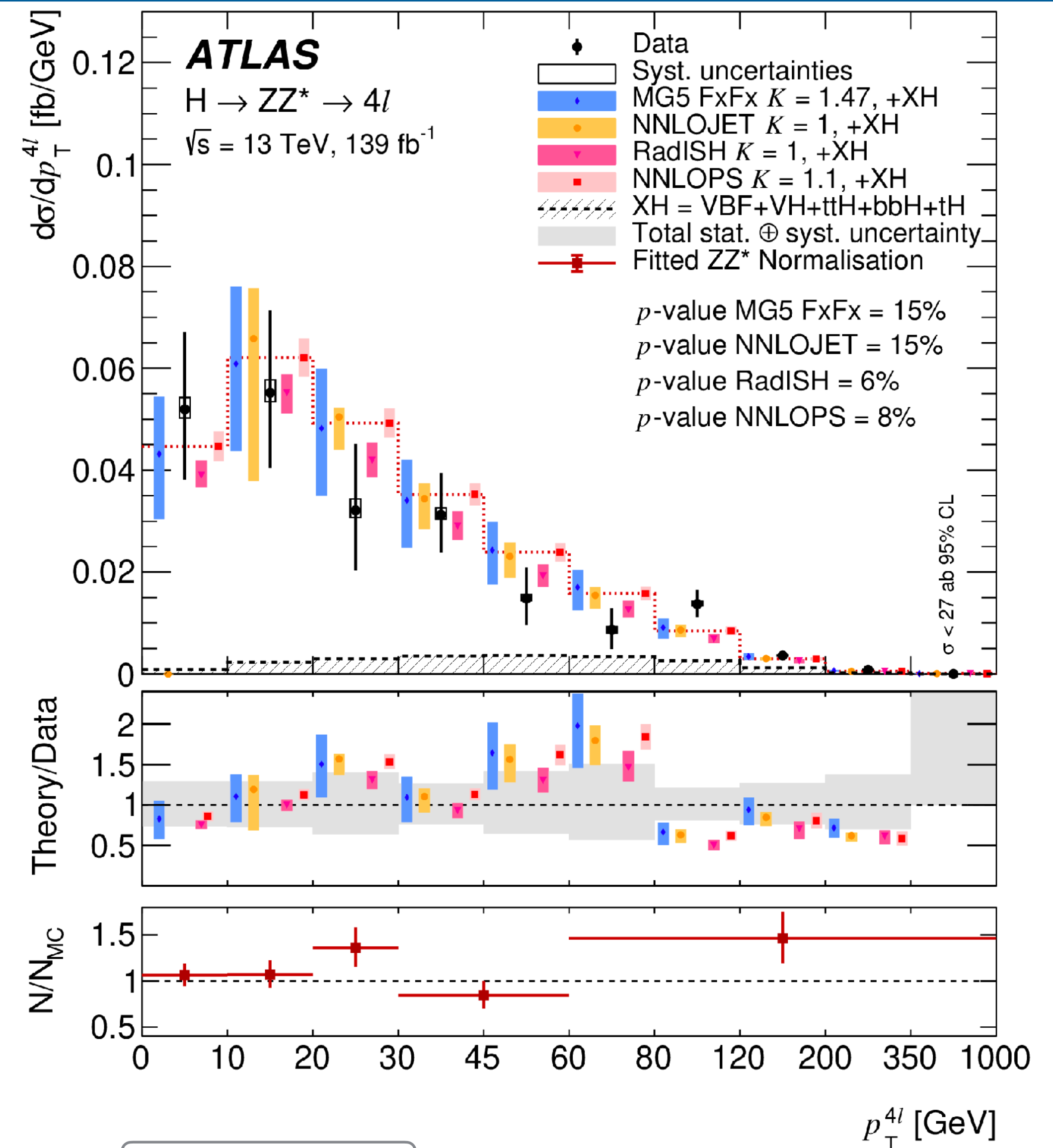


- $BR_{SM}(H \rightarrow ZZ^*) \approx 2.6\%$
 - $BR_{SM}(Z \rightarrow \ell\ell) \approx 3.4\%$

$$\Rightarrow BR_{SM}(H \rightarrow ZZ^* \rightarrow 4\ell) = 0.016\%$$

$$\Rightarrow \sim 1200 H \rightarrow ZZ^* \rightarrow 4\ell \text{ events in } 139 \text{ fb}^{-1}$$
 - Expect to see **206 signal events** ($A \cdot \epsilon$)
 - Excellent signal reconstruction and S/B
- Fiducial cross-section measurement:
 - Observed: $\sigma_{fid}(H \rightarrow ZZ^* \rightarrow 4\ell) = 3.28 \pm 0.32 \text{ fb}$
 - Expected: $\sigma_{fid,SM}(H \rightarrow ZZ^* \rightarrow 4\ell) = 3.41 \pm 0.18 \text{ fb}$
$$\Rightarrow \text{Differential cross-section measurements;}$$

$$\text{Comparison with theory predictions}$$



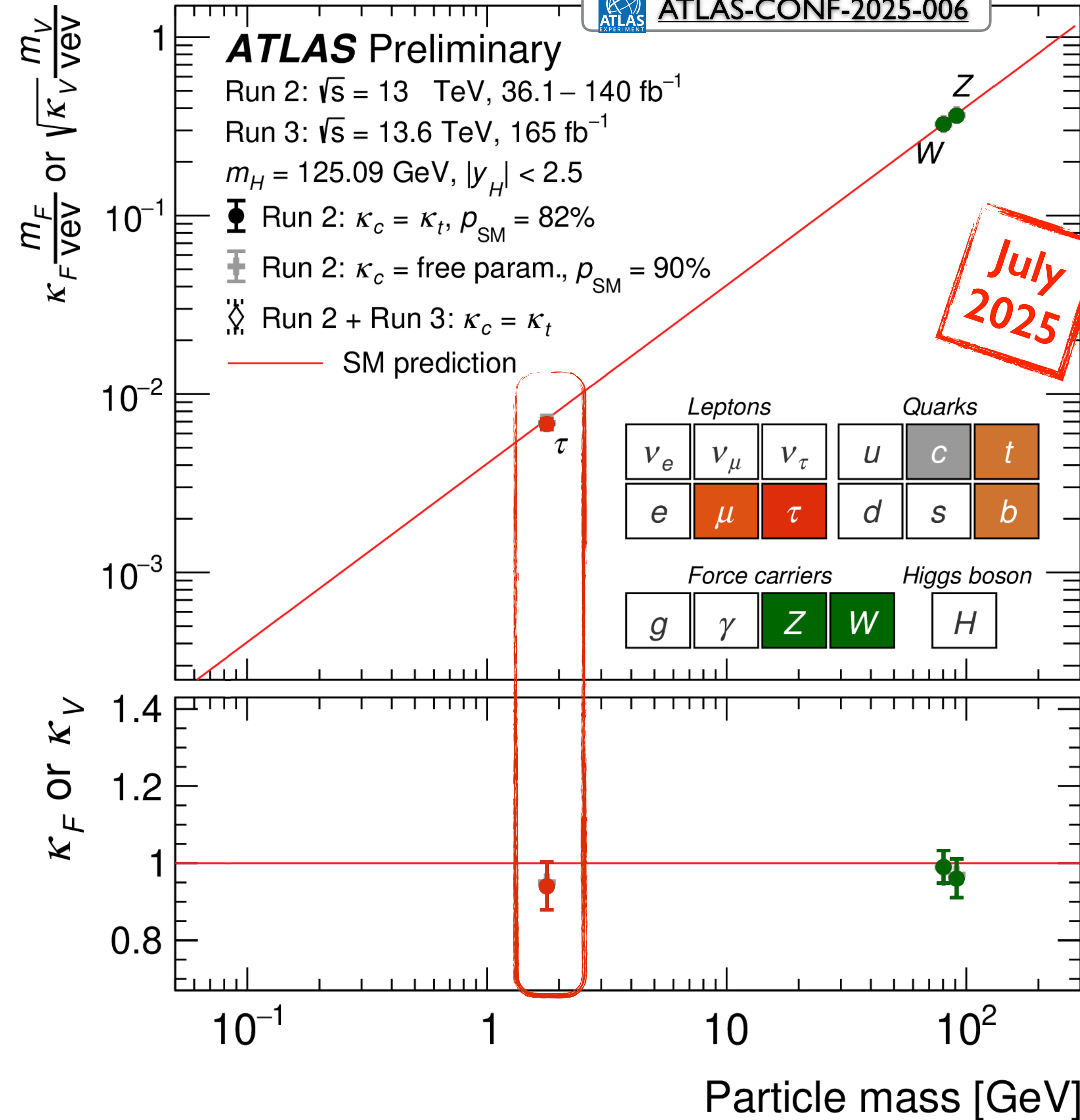
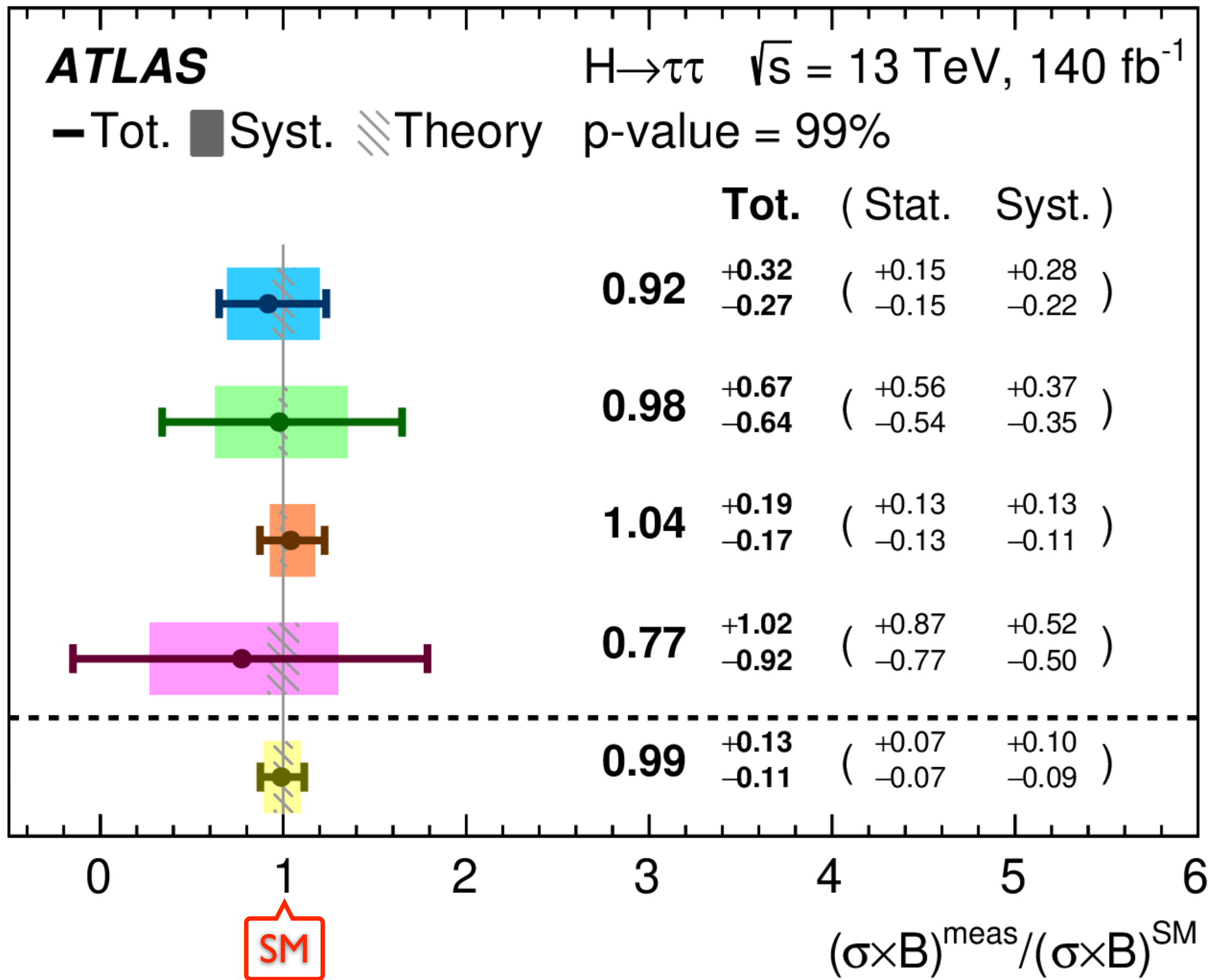


$H \rightarrow \tau\tau$



July 2024

$$\mathcal{B}_{\text{SM}}(H \rightarrow \tau\tau) = 6.3\%$$



July 2025



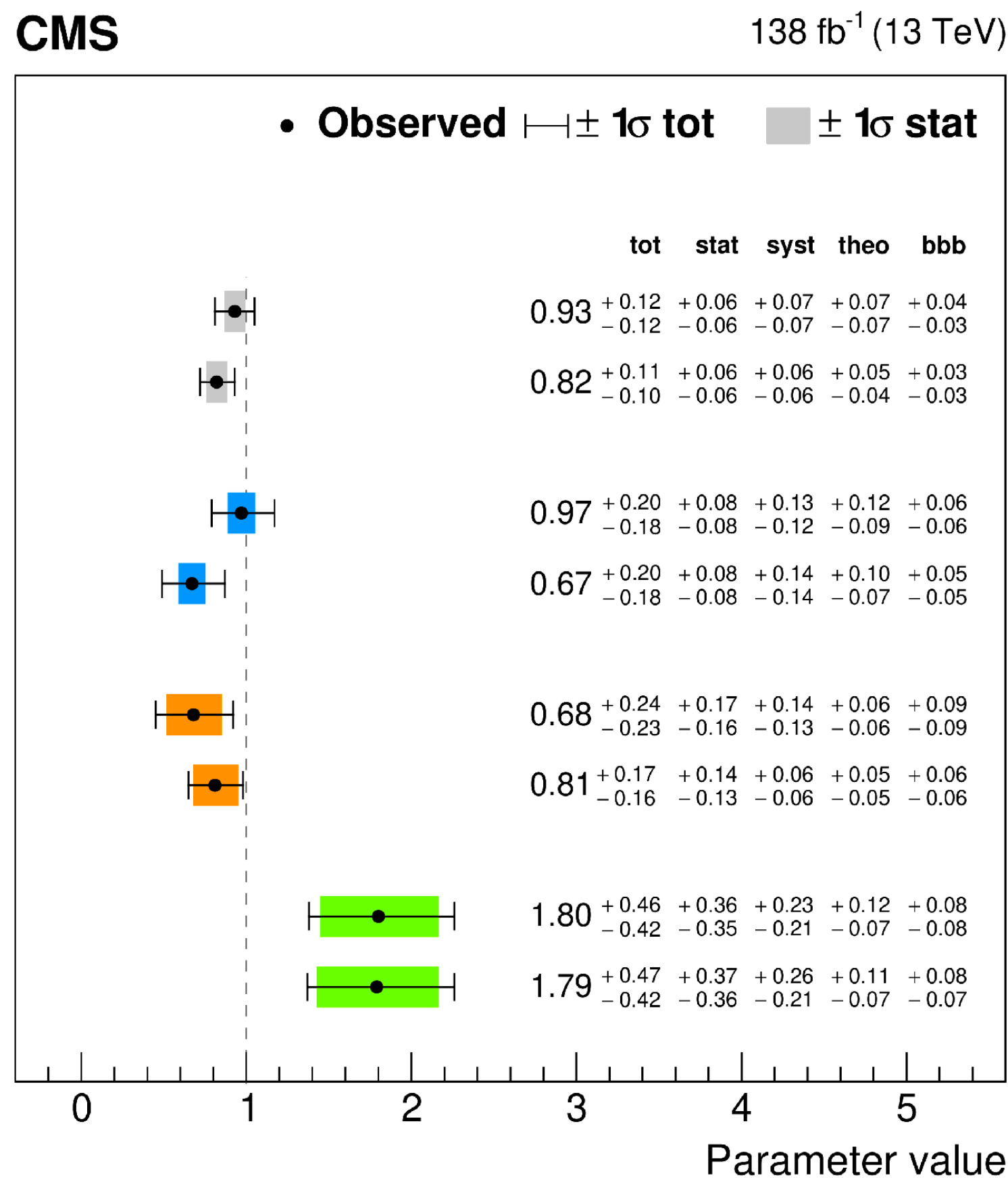
April
2022

$$H \rightarrow \tau\tau$$



Eur. Phys. J. C 83 (2023) 562

- Strongest coupling to leptons
 - $BR_{SM}(H \rightarrow \tau\tau) = 6.3\% \Rightarrow \sim 485\,000\, H \rightarrow \tau\tau$ events
- Cut-based (CB) & multiclass neural-network (NN) analyses
- 16 (15) STXS bins in NN (CB) analysis

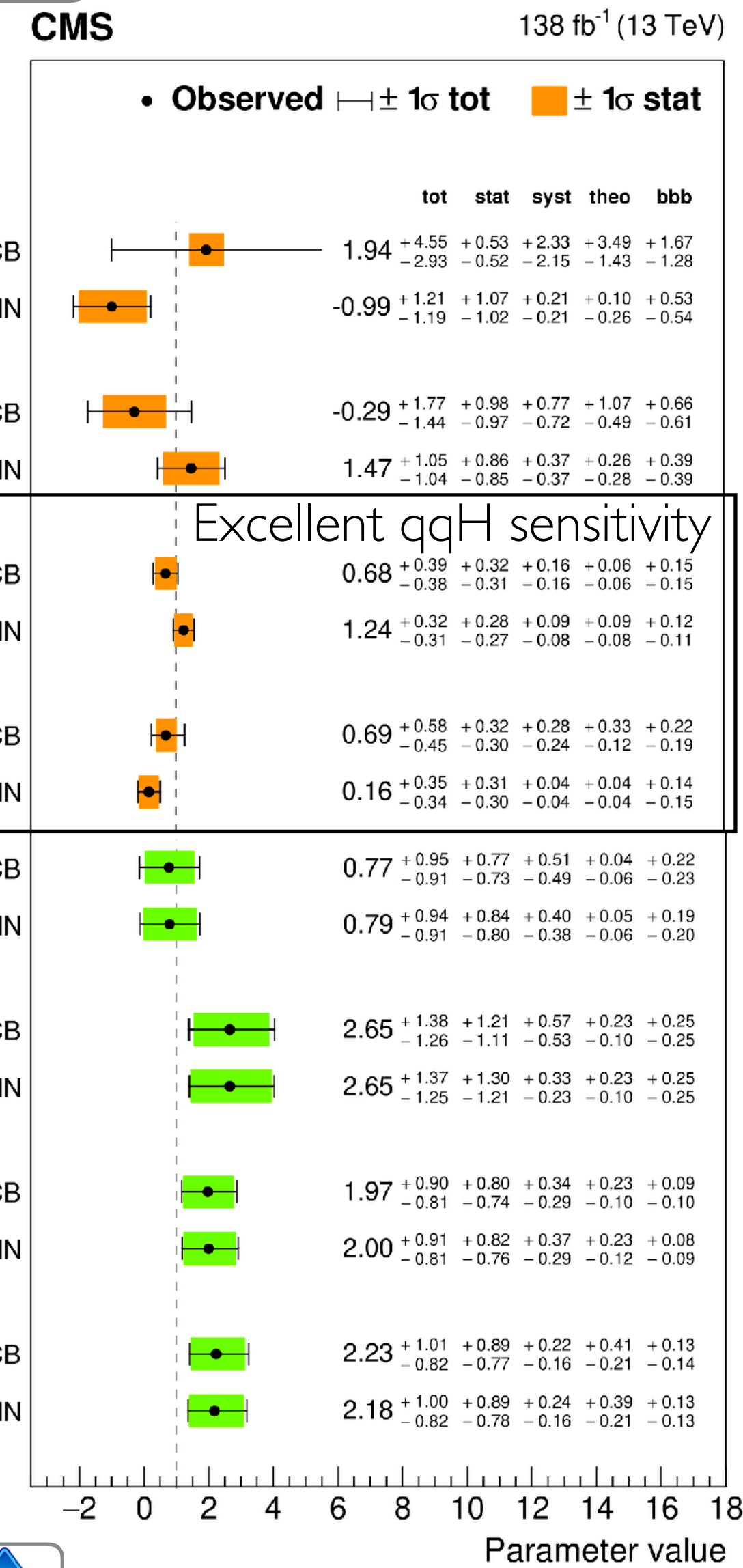
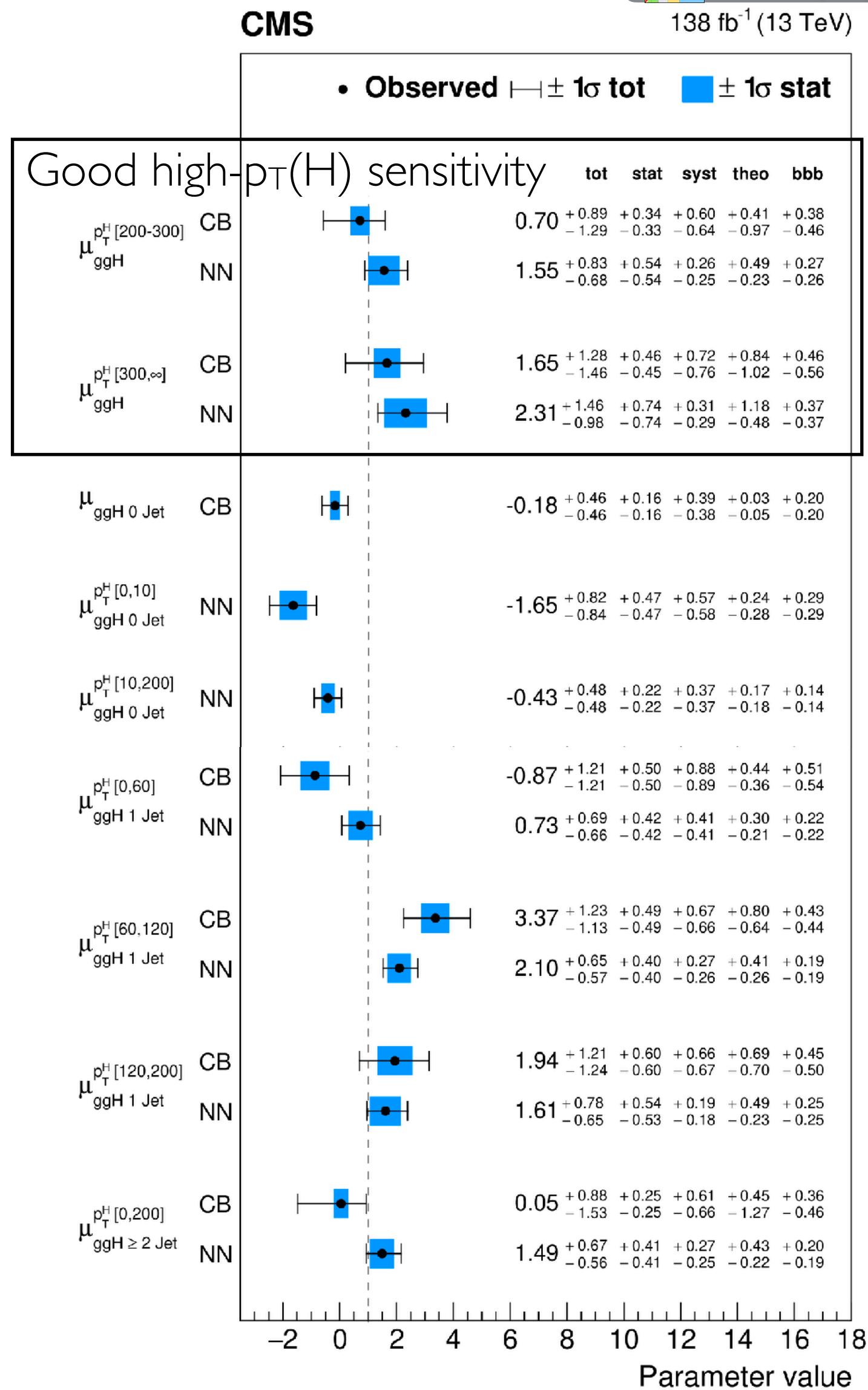


Expected uncertainty
NN (CB)
[symmetrized]
12% (13%)

25% (23%)

17% (24%)

39% (39%)



⇒ Back



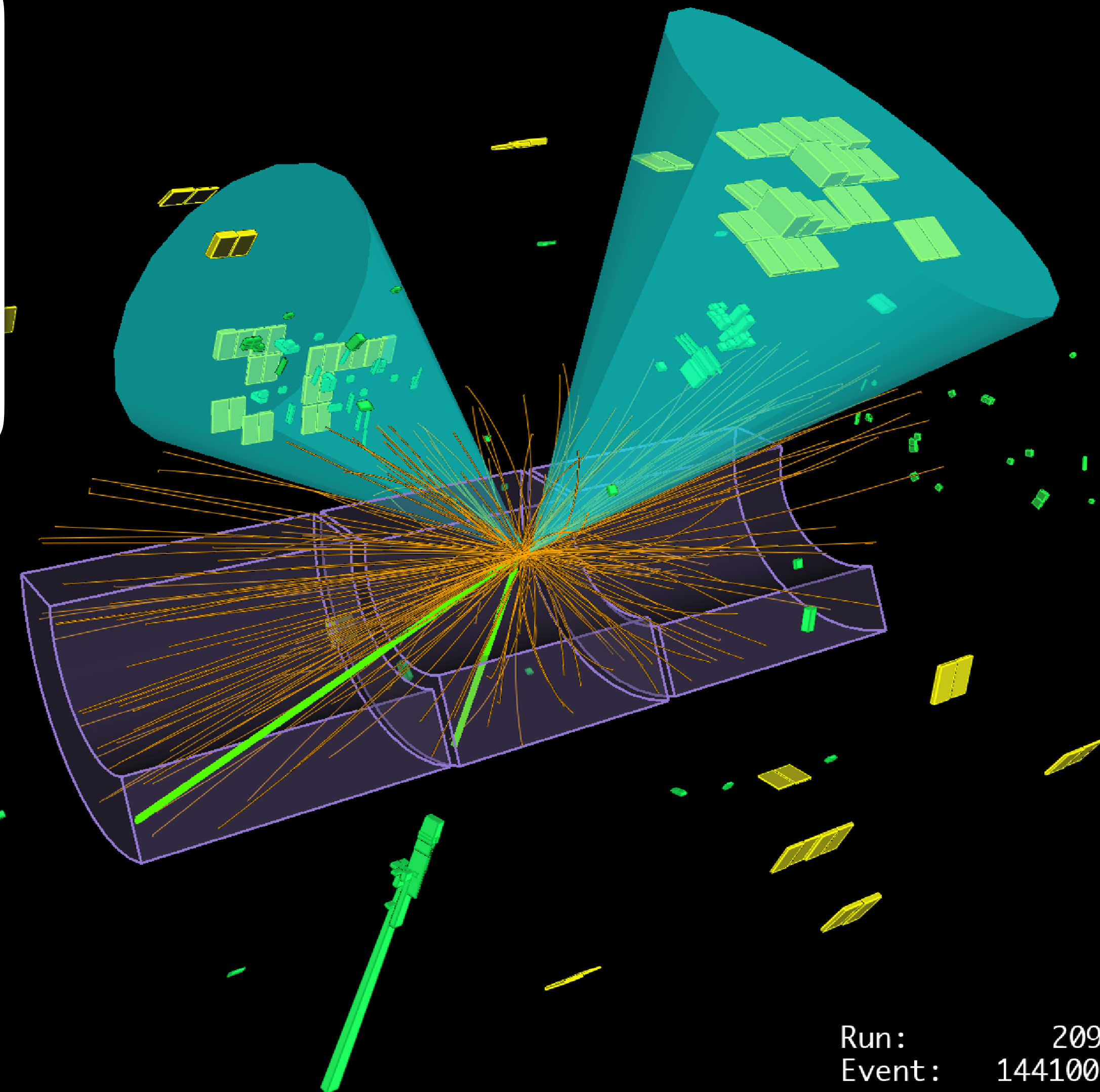
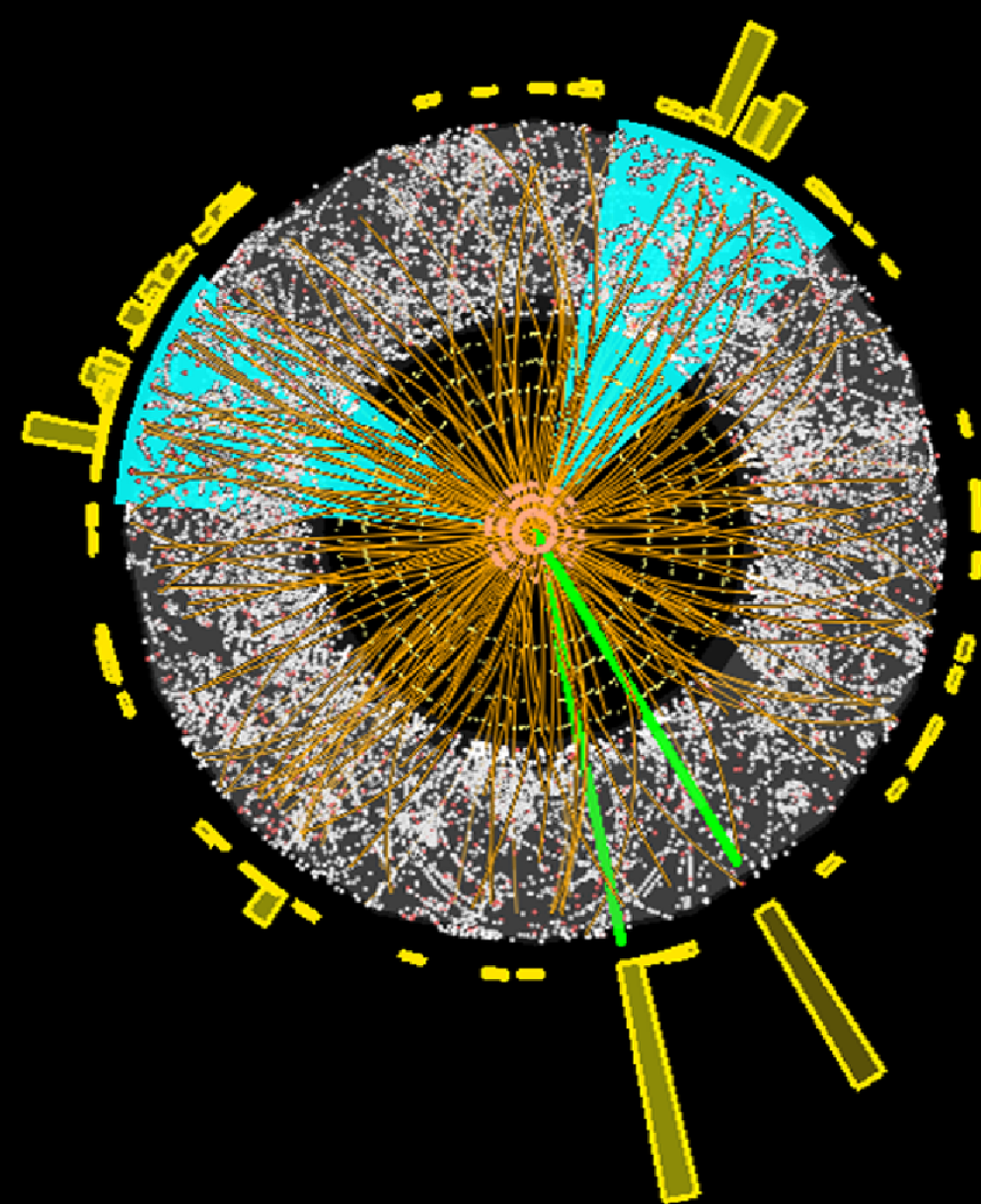
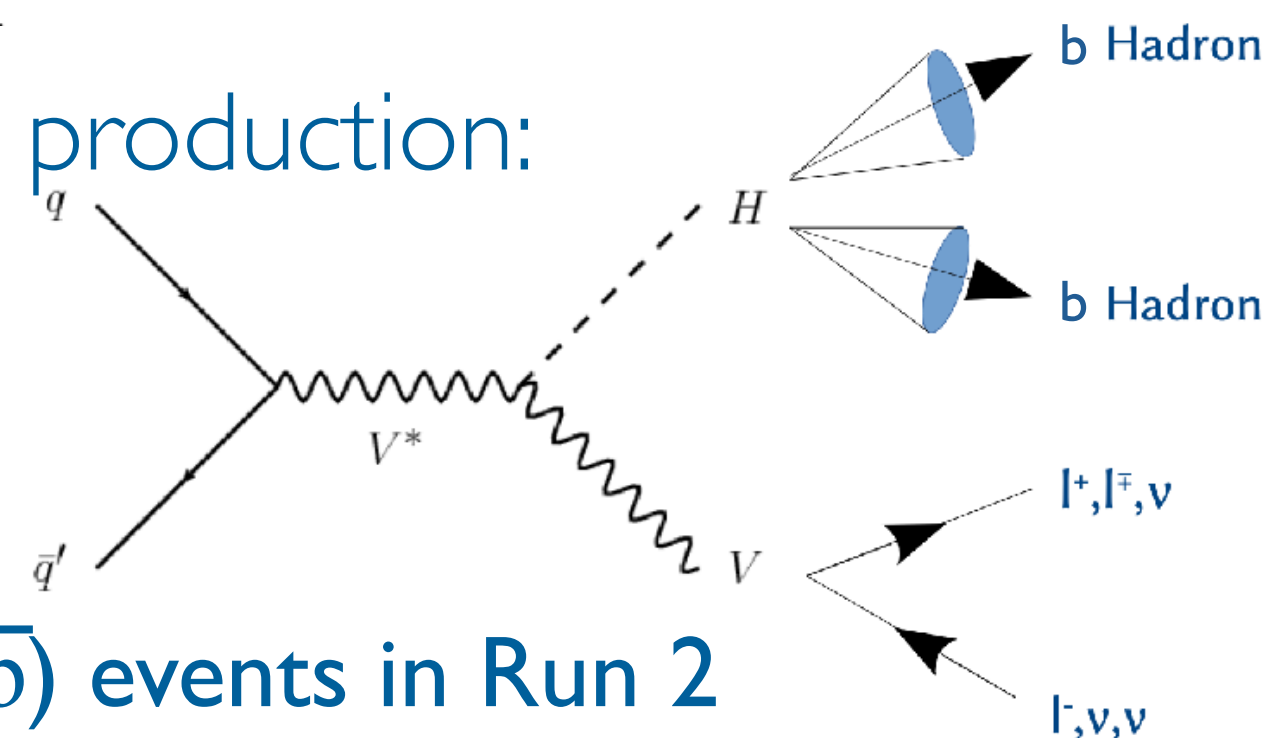
$$H \rightarrow b\bar{b}$$



- $\mathcal{B}_{\text{SM}}(H \rightarrow b\bar{b}) = 58\%$
- VH (V=W or Z) associated production:

- 0 lepton ($Z \rightarrow \nu\nu$)
- 1 lepton ($W \rightarrow \ell\nu$)
- 2 lepton ($Z \rightarrow \ell\ell$)

$\Rightarrow \sim 30000$ V($\rightarrow$ leptons)H($\rightarrow b\bar{b}$) events in Run 2





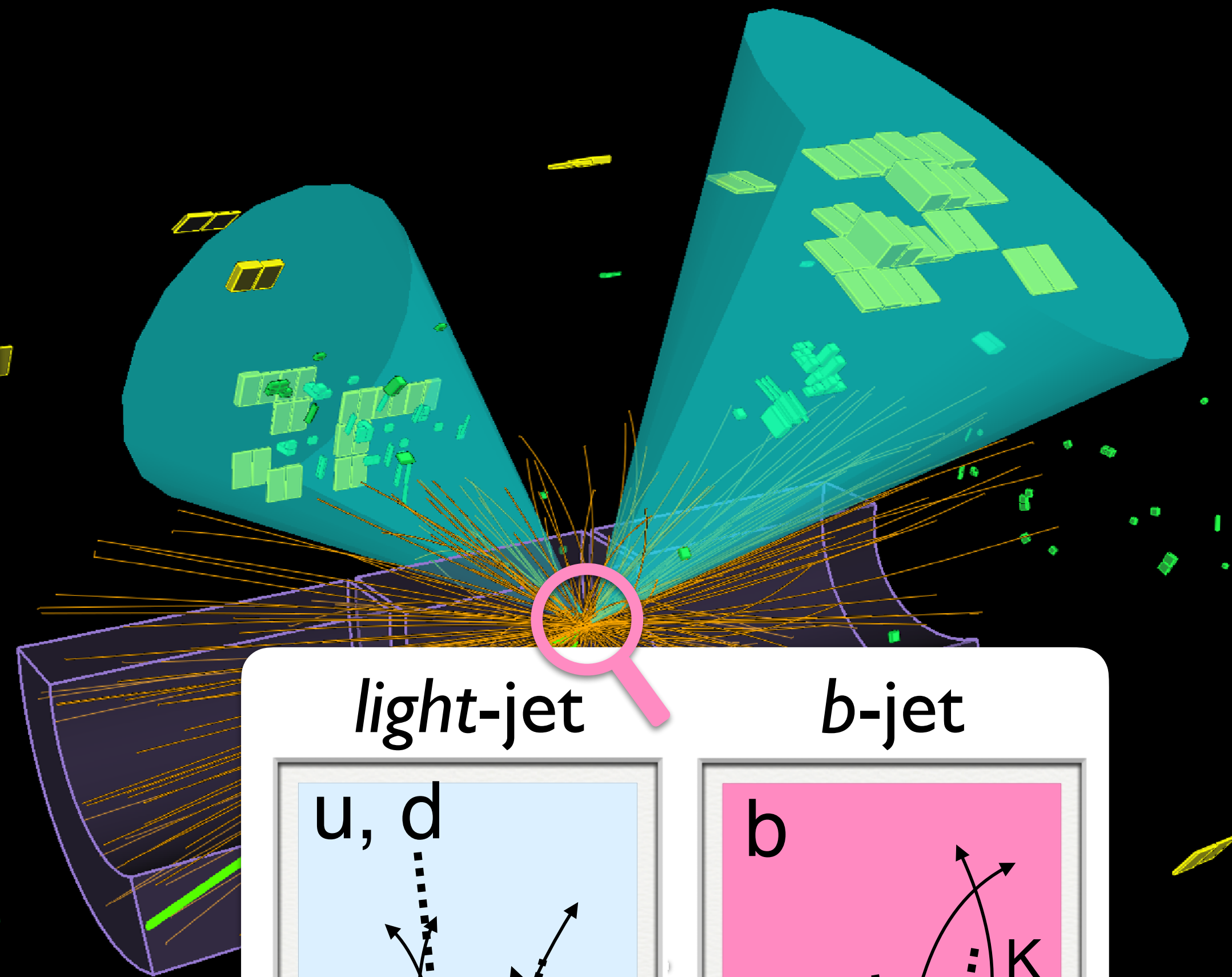
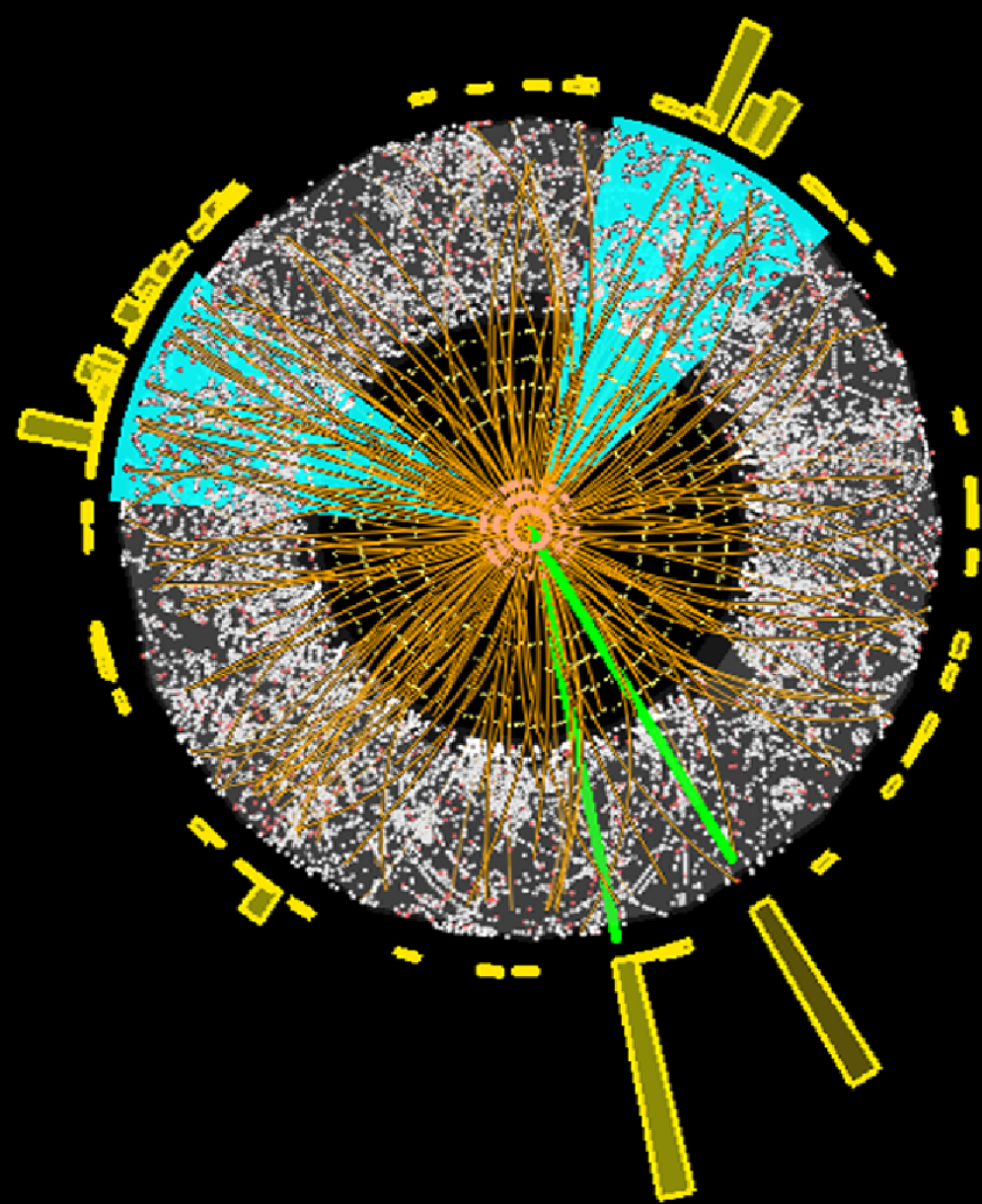
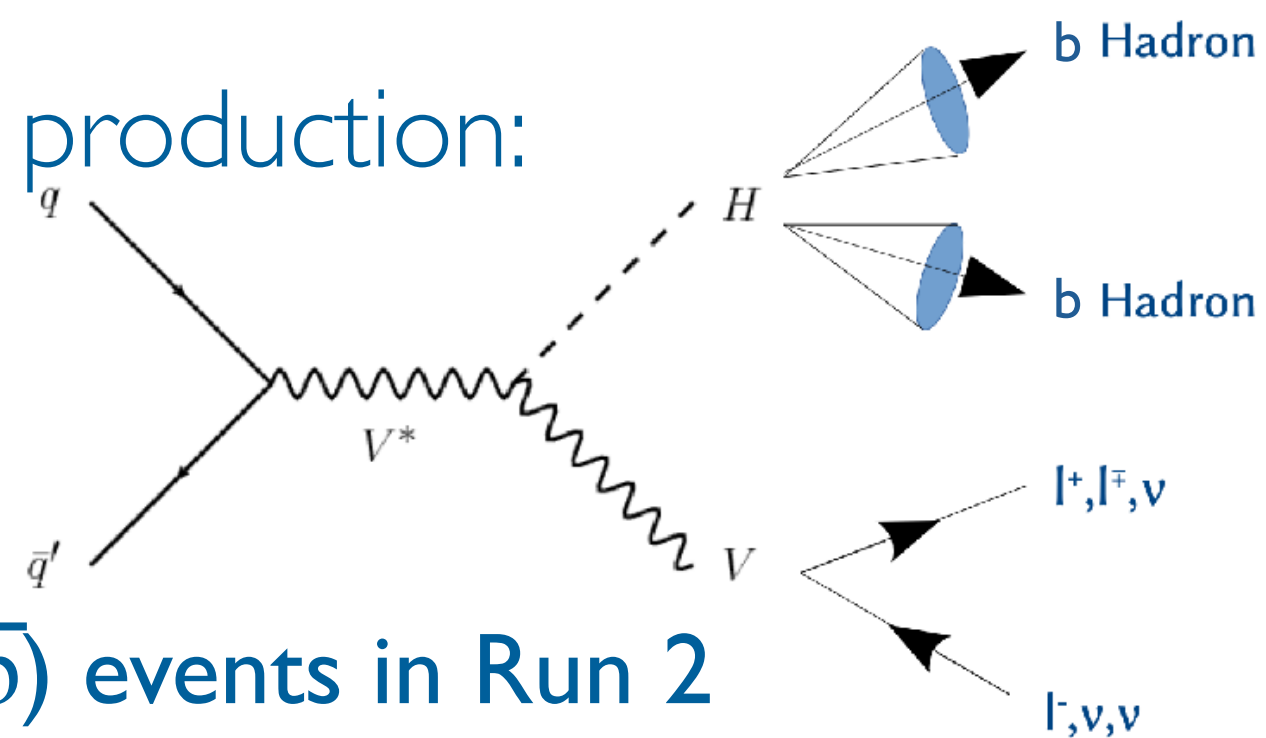
$$H \rightarrow b\bar{b}$$



- $\mathcal{B}_{\text{SM}}(H \rightarrow b\bar{b}) = 58\%$
- VH (V=W or Z) associated production:

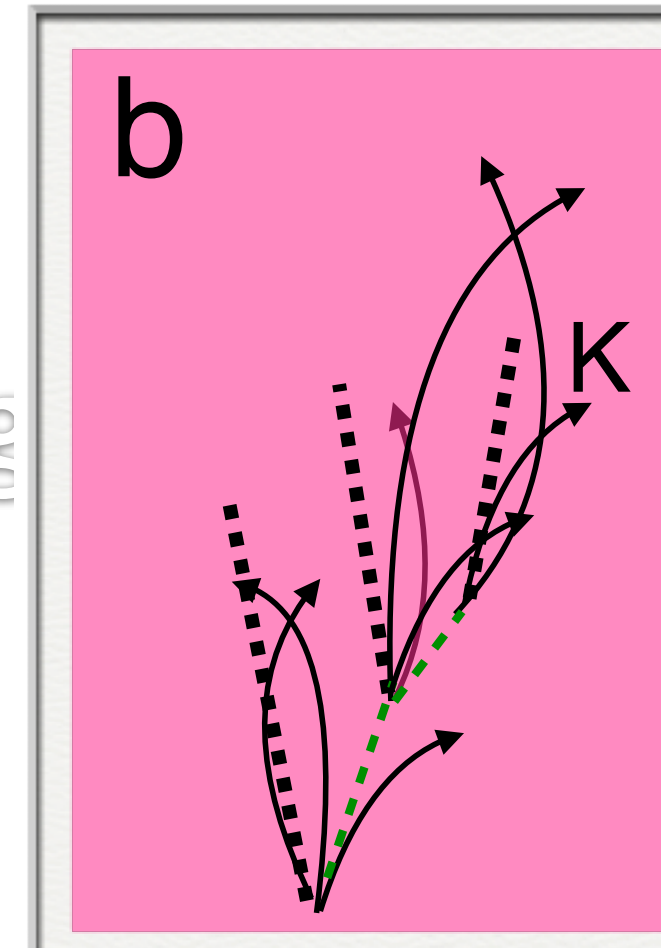
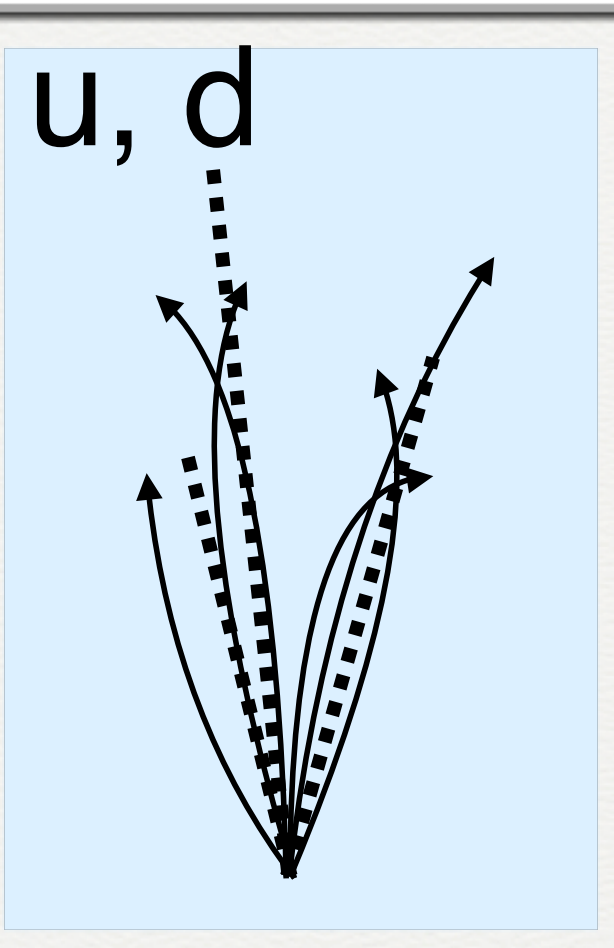
- 0 lepton ($Z \rightarrow \nu\nu$)
- 1 lepton ($W \rightarrow \ell\nu$)
- 2 lepton ($Z \rightarrow \ell\ell$)

$\Rightarrow \sim 30000$ V($\rightarrow$ leptons)H($\rightarrow b\bar{b}$) events in Run 2



light-jet

b-jet





$$H \rightarrow b\bar{b}$$

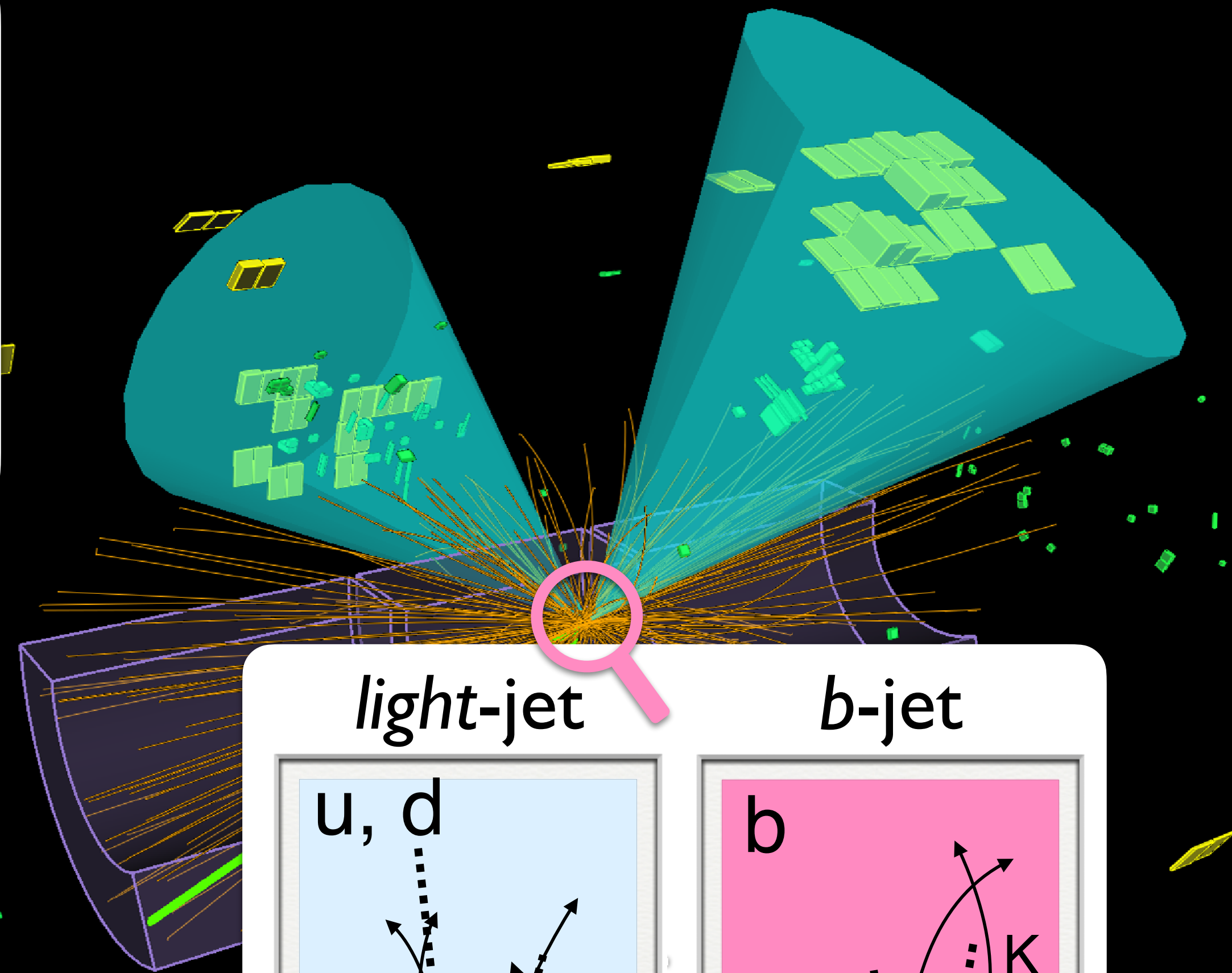
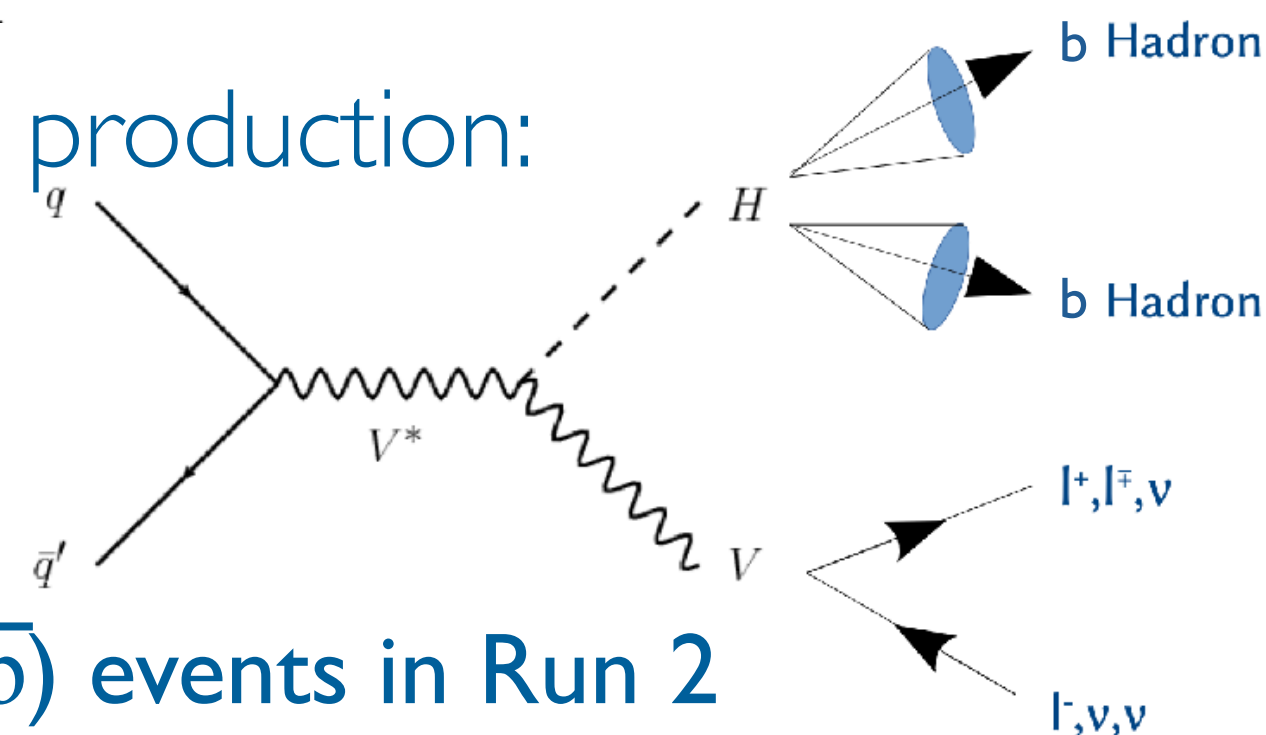


- $\mathcal{B}_{\text{SM}}(H \rightarrow b\bar{b}) = 58\%$

- VH (V=W or Z) associated production:

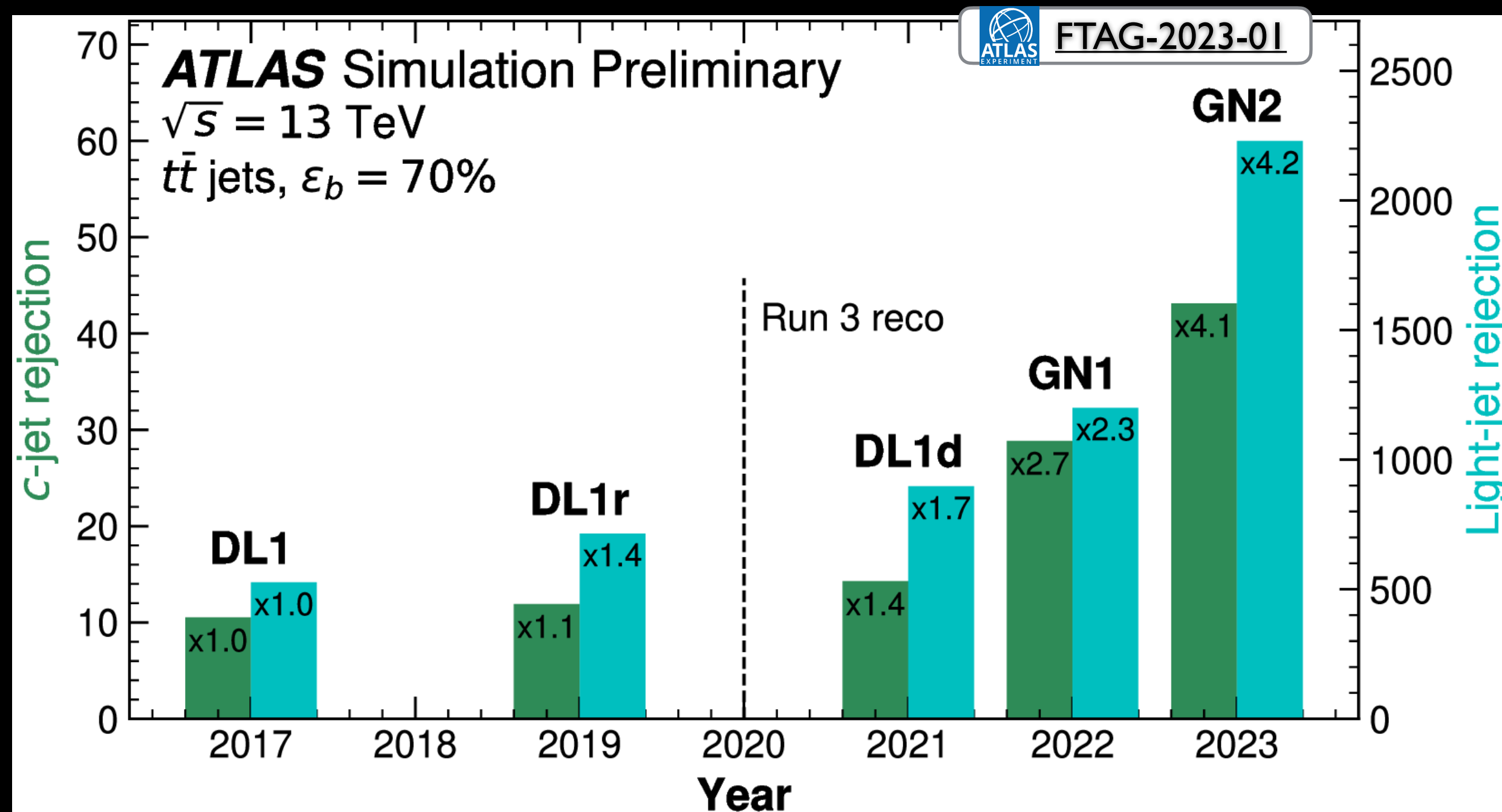
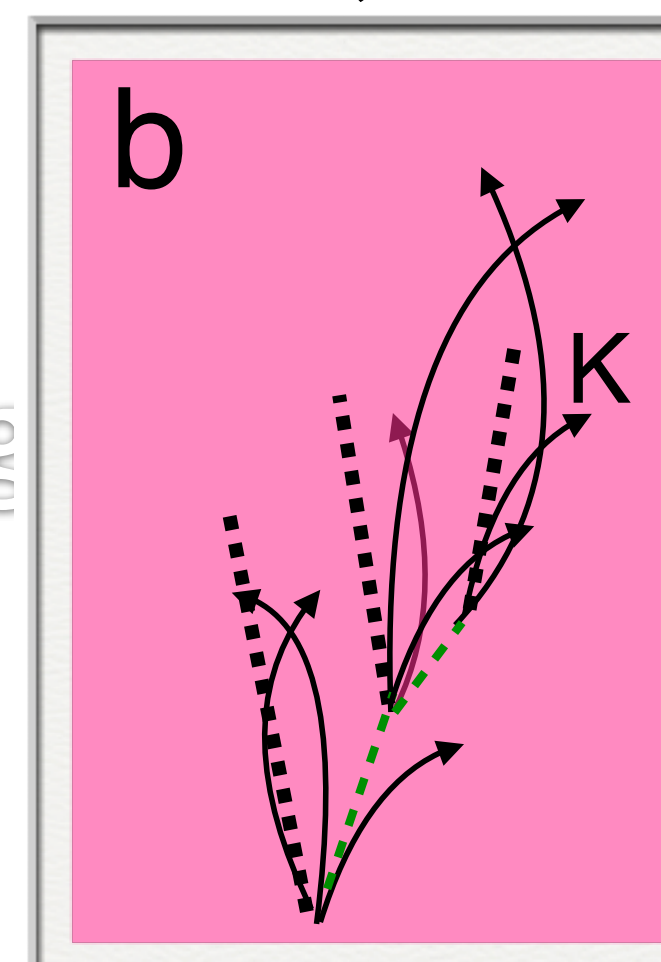
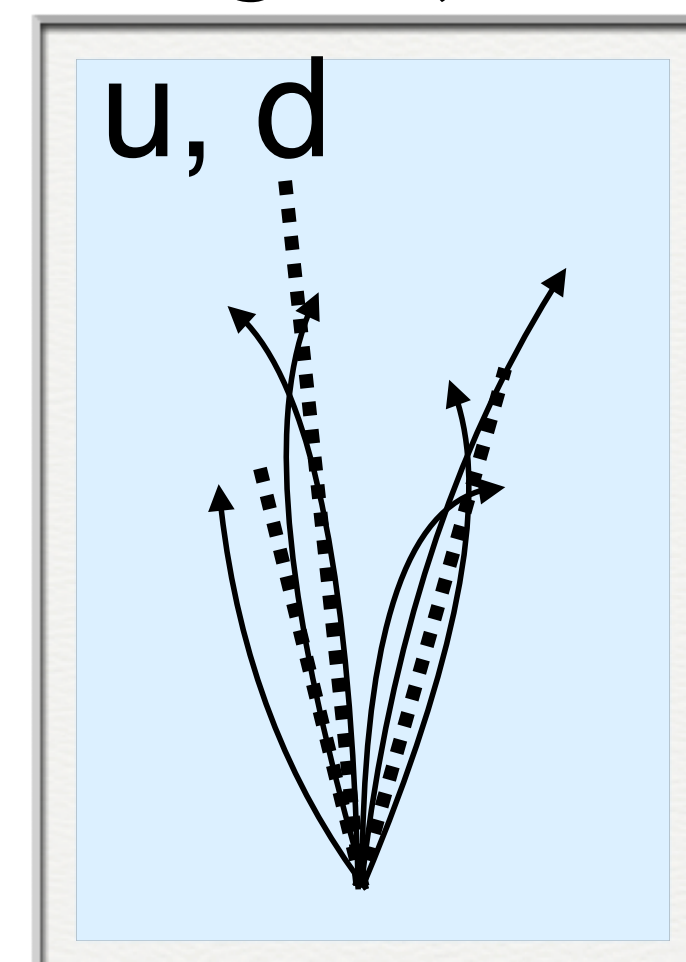
- 0 lepton ($Z \rightarrow \nu\nu$)
- 1 lepton ($W \rightarrow \ell\nu$)
- 2 lepton ($Z \rightarrow \ell\ell$)

$\Rightarrow \sim 30000$ V($\rightarrow$ leptons)H($\rightarrow b\bar{b}$) events in Run 2

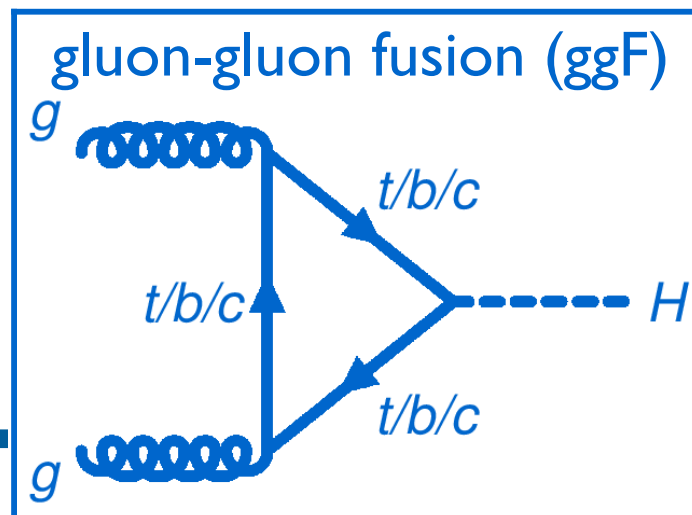


light-jet

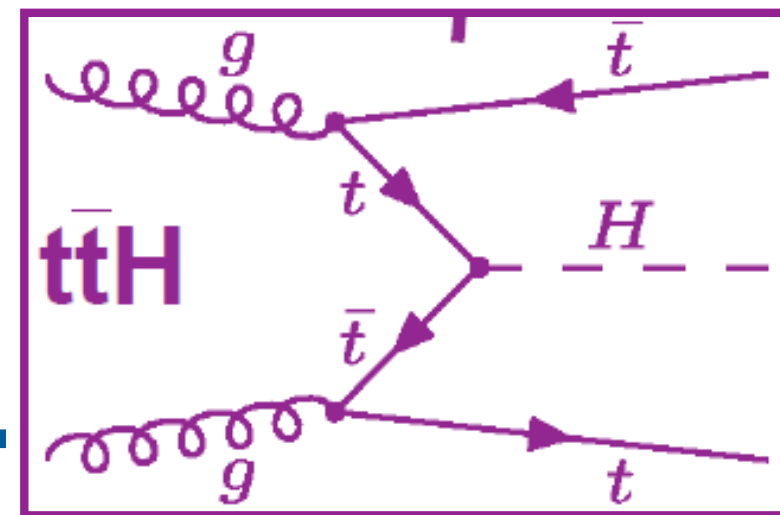
b-jet



209787
144100666
2012-09-05
15:57:49 UTC

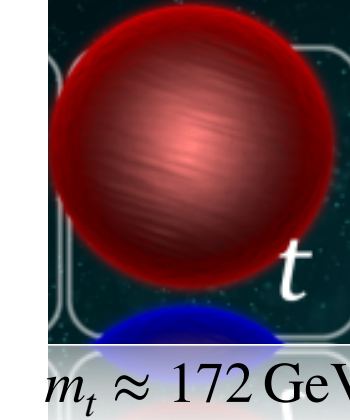


$\sigma_{\text{ggF}} = 48.5 \text{ pb (87 \%)}$



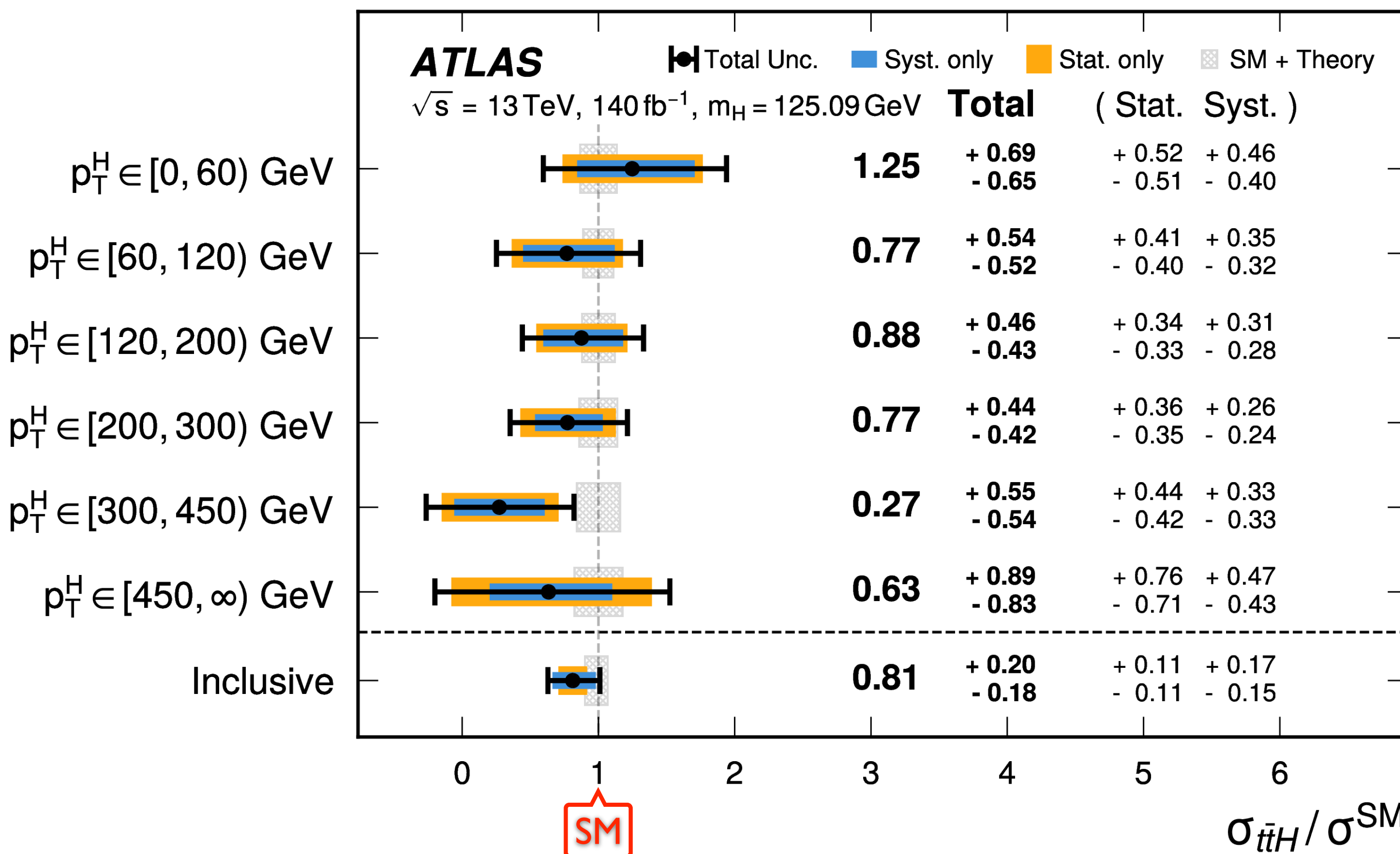
$\sigma_{\text{ttH}} = 0.5 \text{ pb (0.9 \%)}$

$$t\bar{t}H, H \rightarrow b\bar{b}$$



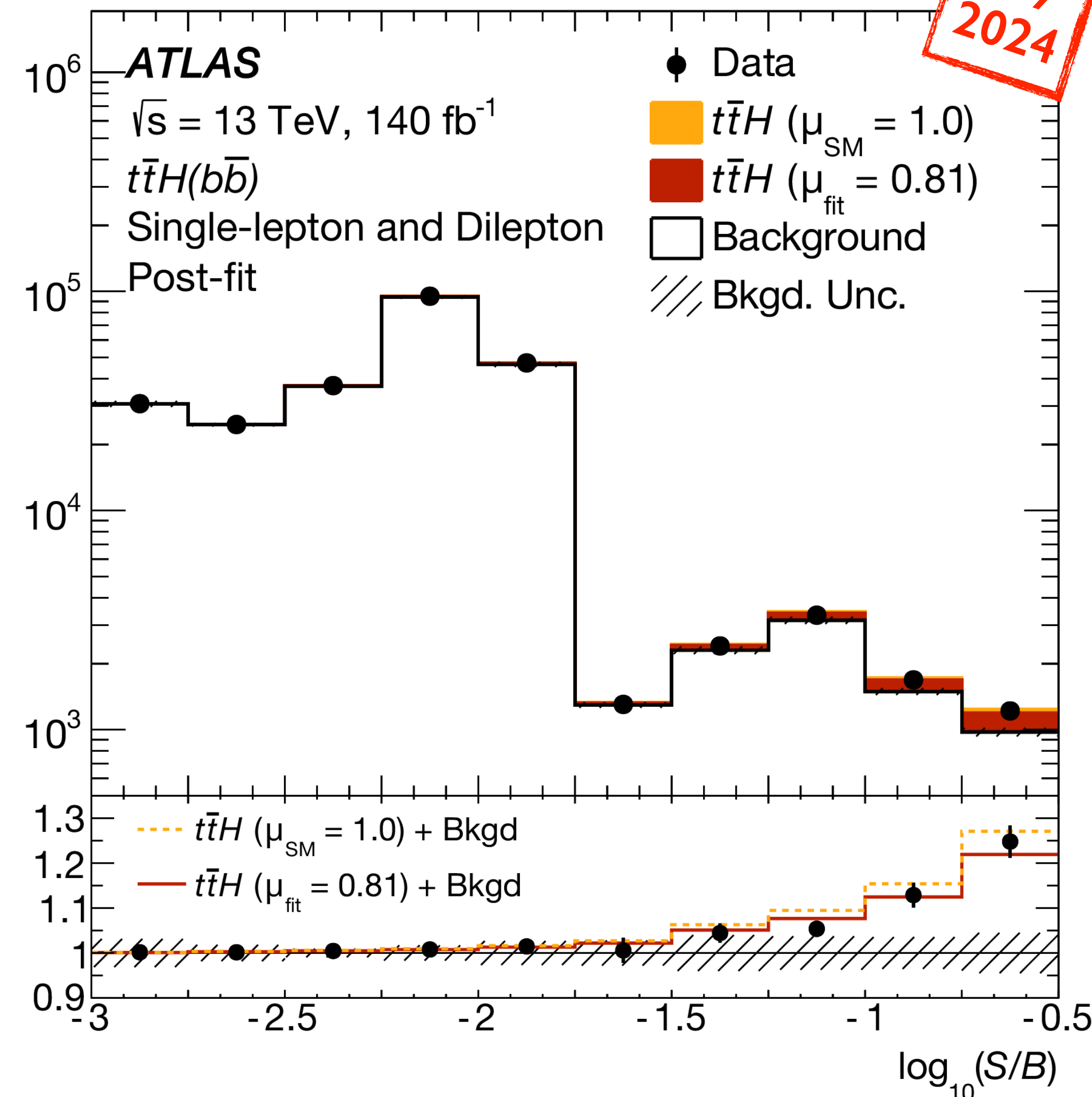
- **Tree-level top-Yukawa** measurement

- Very difficult to predict and model dominant $t\bar{t}b\bar{b}$ background
- **ATLAS** obs. (exp.) significance: **4.6 (5.4) σ**



Events

Data / Bkgd



July 2024

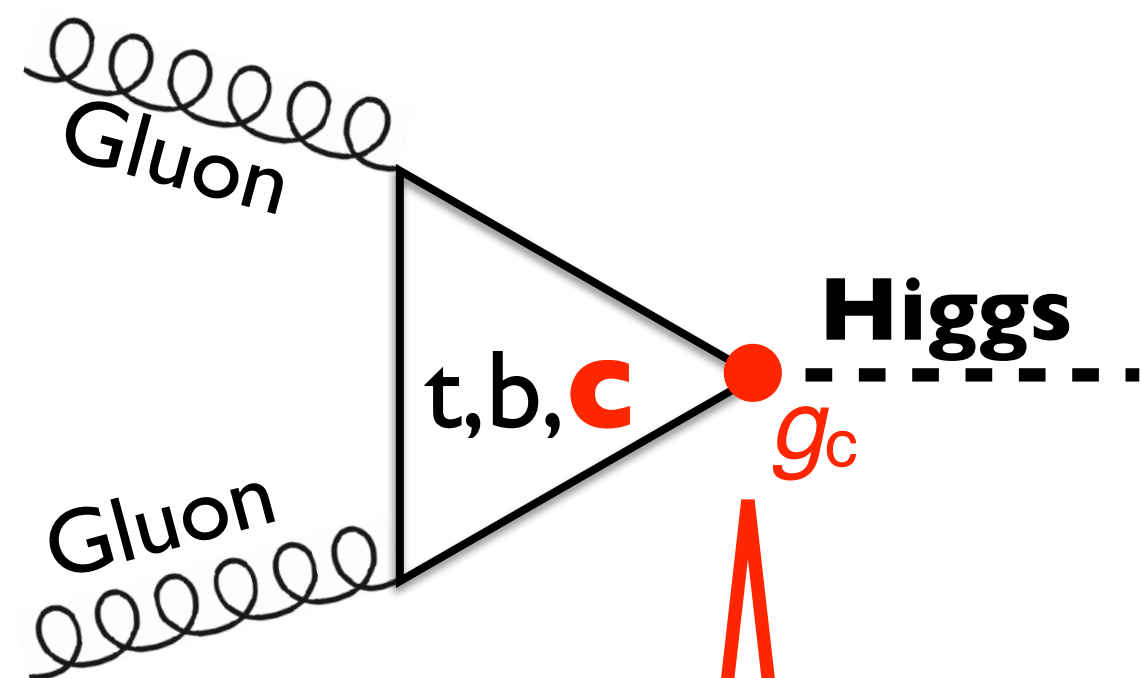


Extracting coupling modifiers



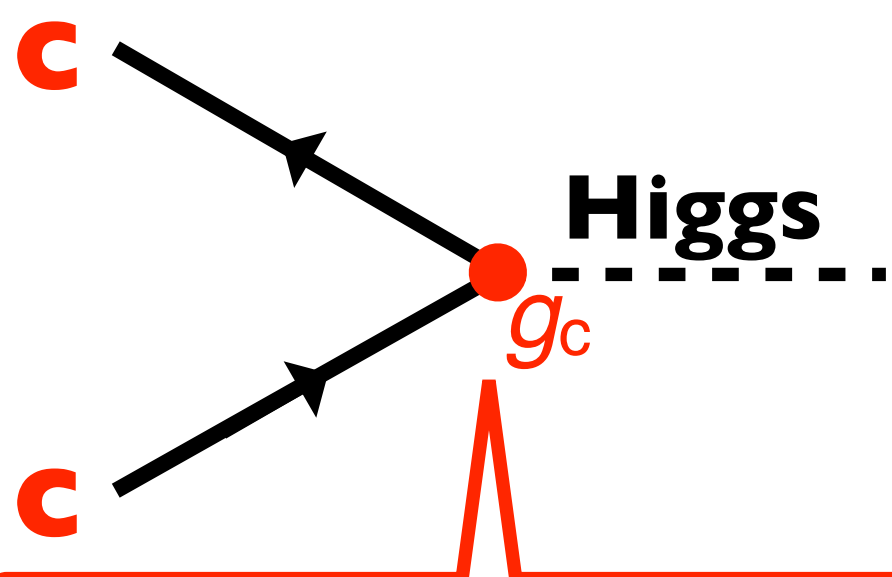
- **Idea:** $p_T(H)$ sensitiv to Charm-Yukawa coupling:

- Interference between Charm-, Bottom-, and Top-quark loop in ggF



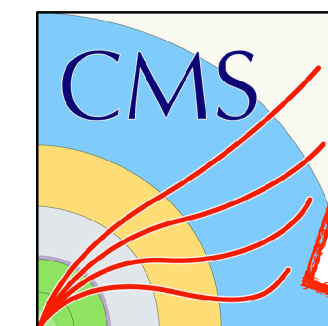
Charm-Higgs coupling strength modifier κ_c

- Direct $cc \rightarrow H$ production



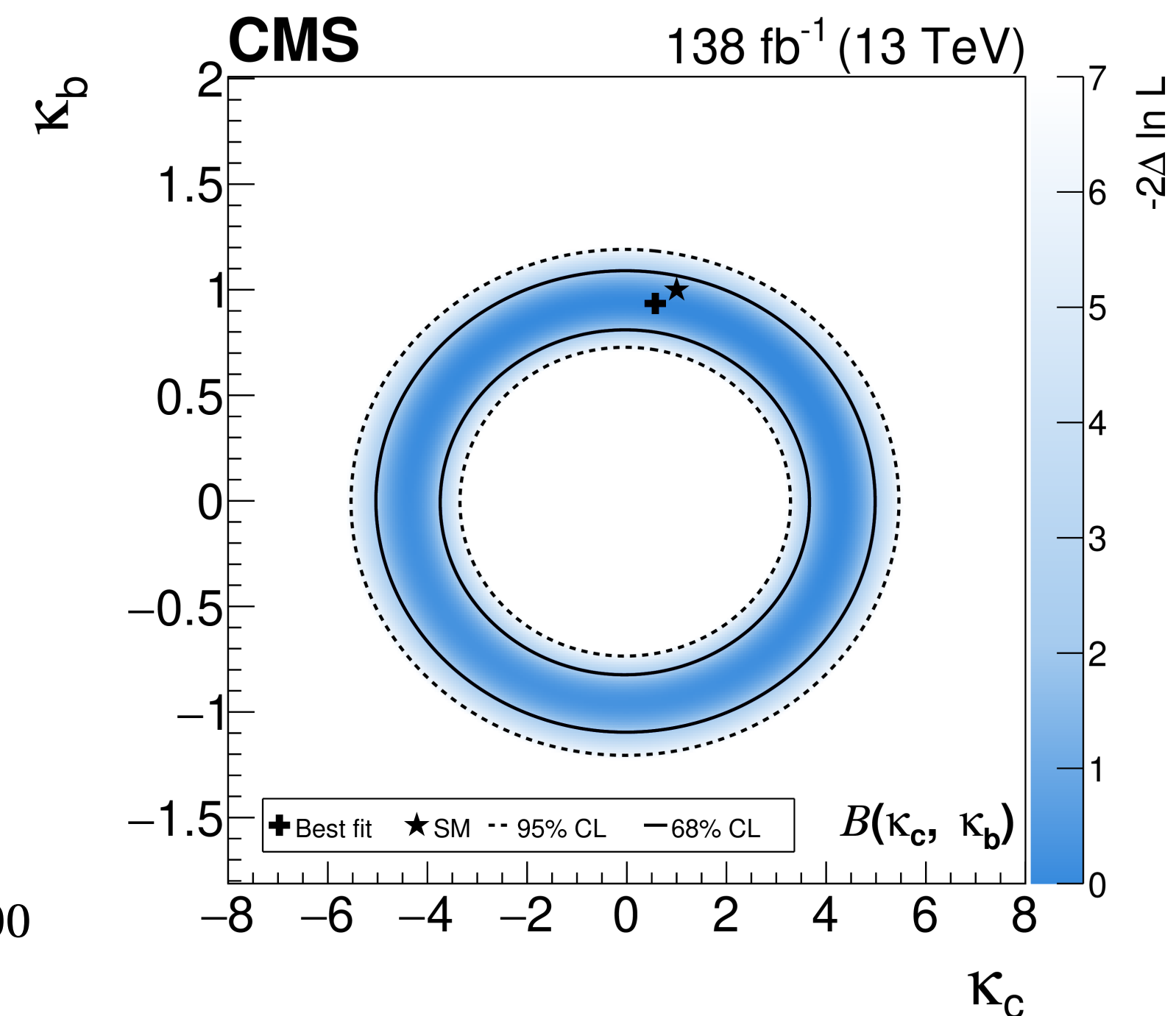
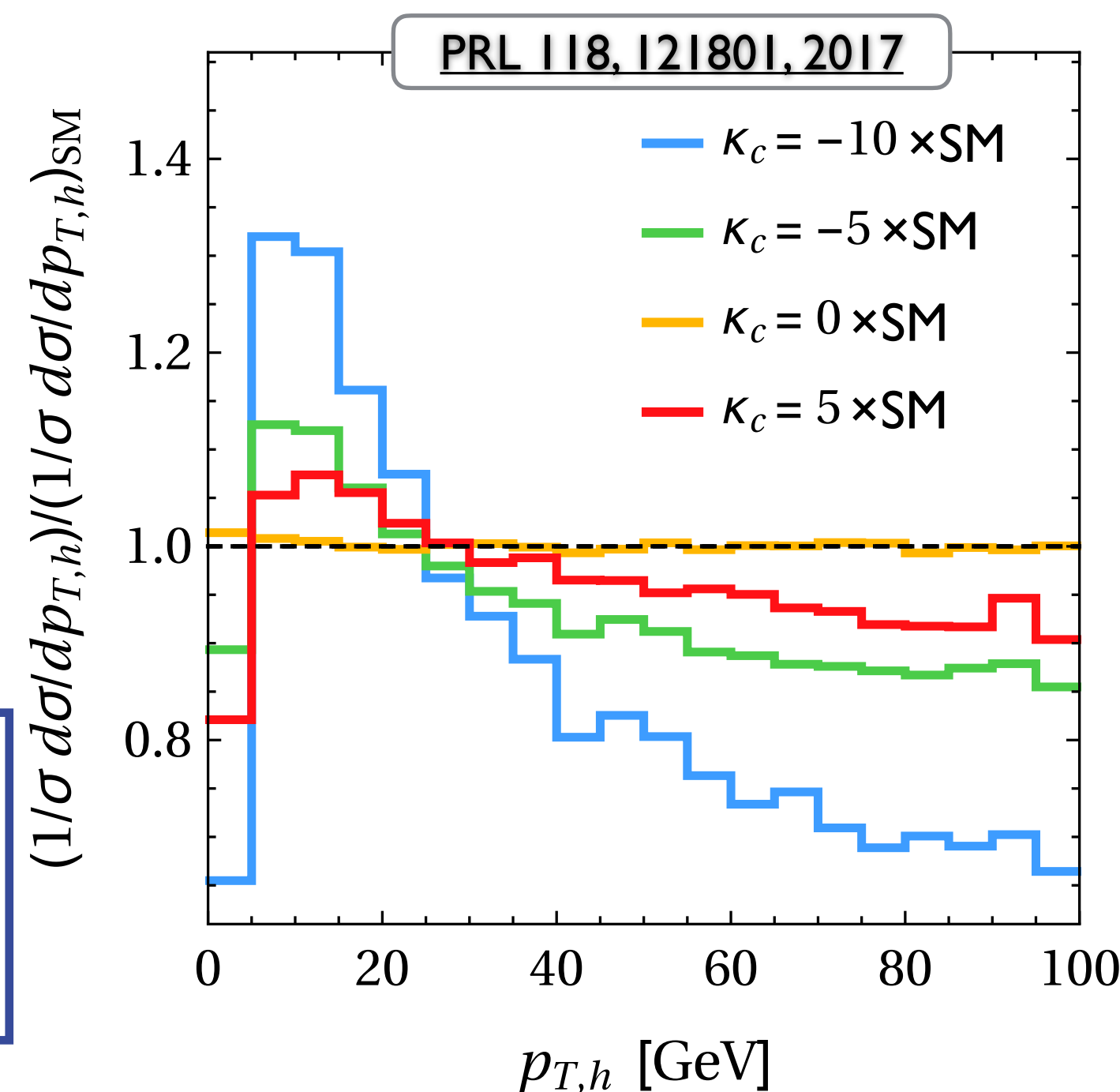
$$\kappa_c := \frac{g_c}{(g_c)_{\text{SM}}}$$

Charm-Higgs coupling strength modifier κ_c



Interpretation from $p_T(H)$ distributions with $H \rightarrow ZZ^* \rightarrow 4\ell$

Shape & coupling dependent on BR

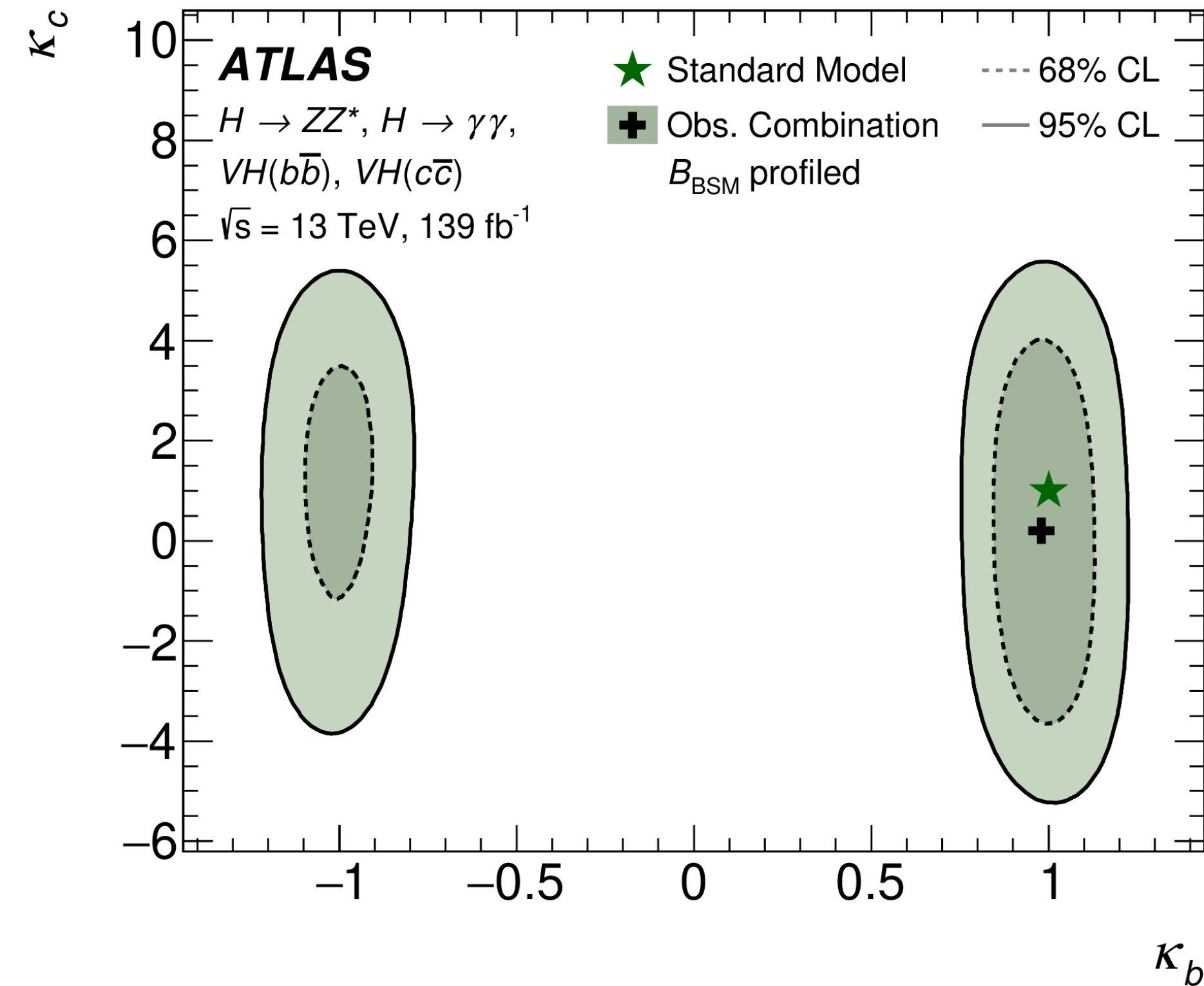
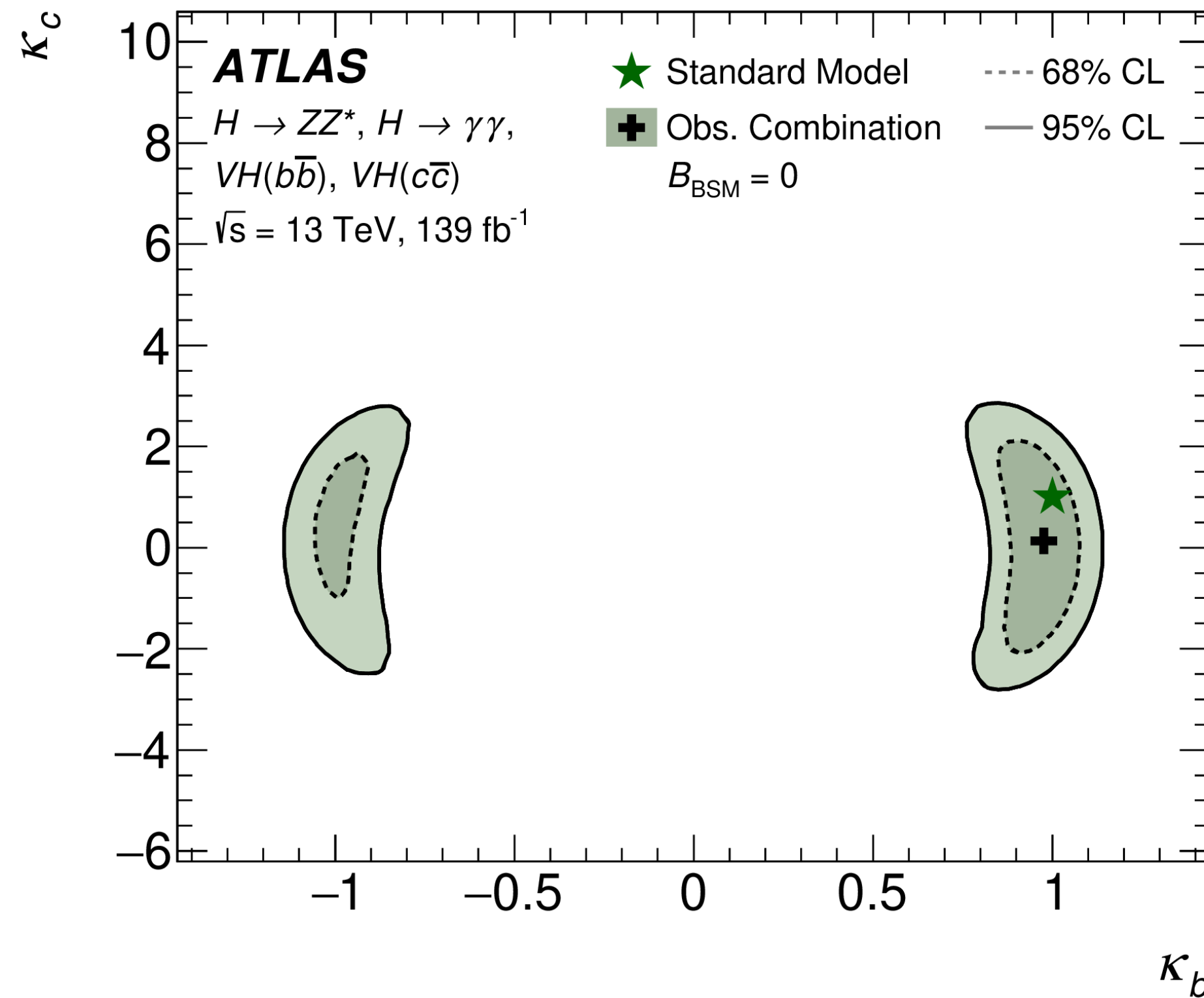




Combined κ_b and κ_c extraction



- Combine information from $p_T(H)$ with $VH(bb)$ and $VH(cc)$:



July
2022

Scenario	Observed	Observed
	68% confidence interval	95% confidence interval
$B_{\text{BSM}} = 0$	$[-1.61, 1.70]$	$[-2.47, 2.53]$
No assumption on B_{BSM}	$[-2.63, 3.01]$	$[-4.46, 4.81]$

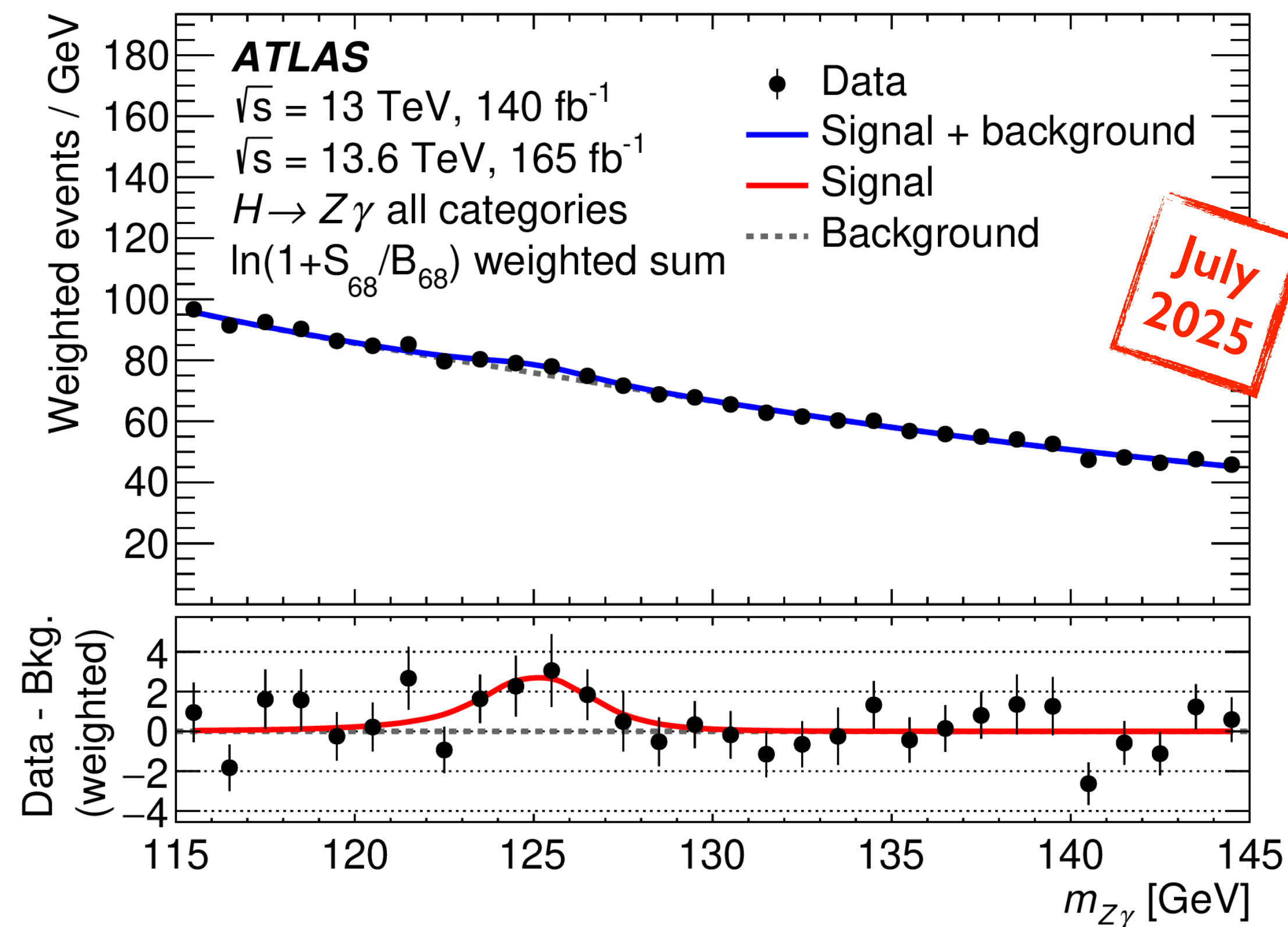
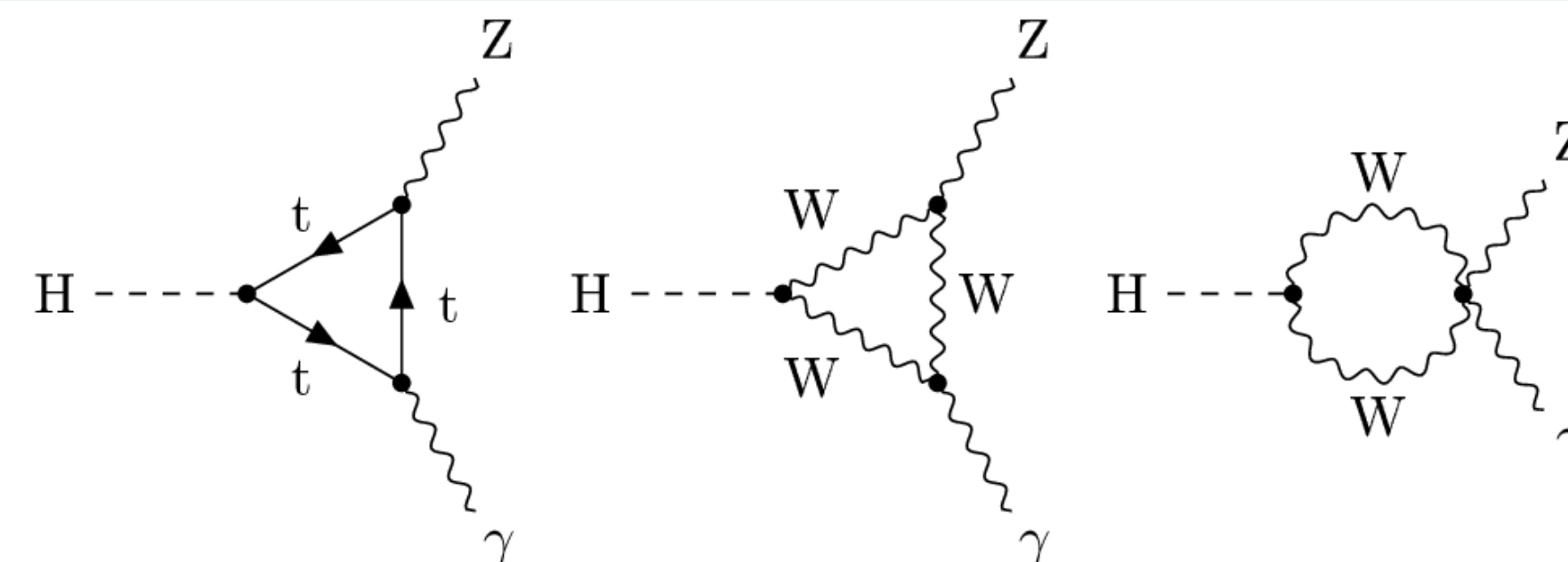


$H \rightarrow Z\gamma$



- Small $\text{BR}_{\text{SM}}(H \rightarrow Z\gamma) \approx 0.15\%$
 - $\text{BR}_{\text{SM}}(Z \rightarrow \ell\ell) \approx 3.4\%$
 $\Rightarrow \text{BR}_{\text{SM}}(H \rightarrow Z\gamma \rightarrow \ell\ell\gamma) = \mathbf{0.01\%}$
- $\Rightarrow \sim 765 H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ events in 140 fb^{-1}
and difficult kinematics

- Run 2 + partial Run 3 result:
 - Observed signal strength $\mu = 1.3^{+0.6}_{-0.5}$
 - Observed (expected) significance: $\mathbf{2.5 \sigma}$ (1.9σ)



$\Rightarrow$  combined Run 2: obs. (exp.): $\mathbf{3.4 \sigma}$ (1.6σ)

$\Rightarrow$  ATLAS $H \rightarrow \ell\ell\gamma$ result: obs. (exp.): $\mathbf{3.2 \sigma}$ (2.1σ)



$H \rightarrow Z\gamma$



- Small $\text{BR}_{\text{SM}}(H \rightarrow Z\gamma) \approx 0.15\%$

- $\text{BR}_{\text{SM}}(Z \rightarrow \ell\ell) \approx 3.4\%$

- $\Rightarrow \text{BR}_{\text{SM}}(H \rightarrow Z\gamma \rightarrow \ell\ell\gamma) = \mathbf{0.01\%}$

$\Rightarrow \sim 765 H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ events in 140 fb^{-1}
and difficult kinematics

- First evidence from ATLAS+CMS combination:

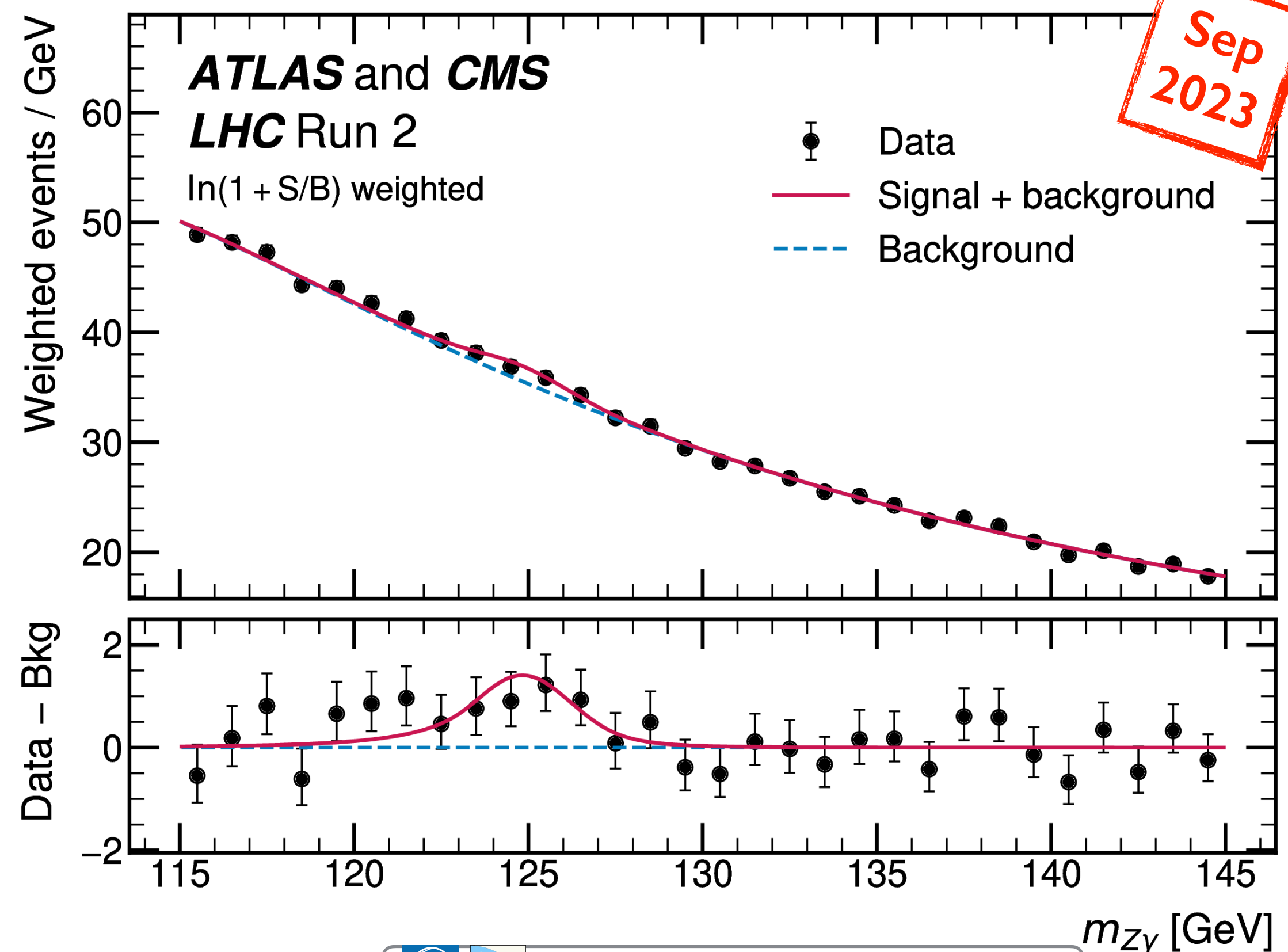
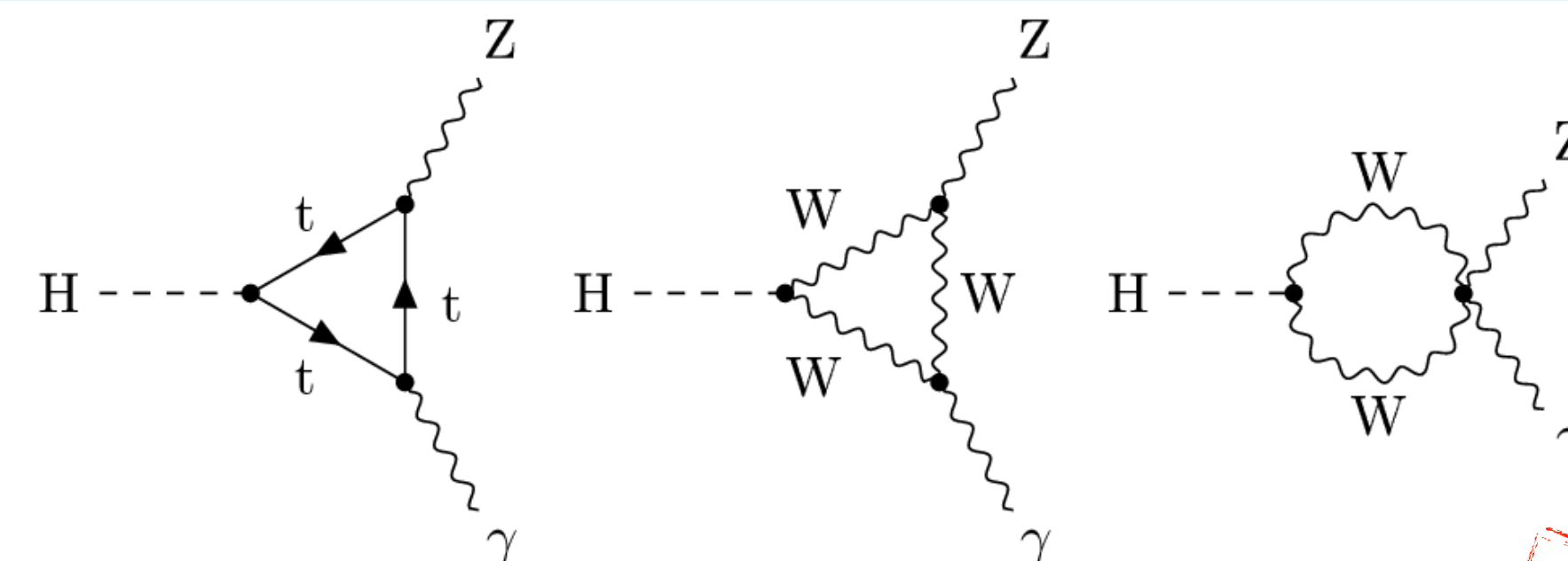
$$\text{Signal strength } \mu := \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\text{SM}}} = \frac{\text{observed rate}}{\text{expected rate}}$$

- Observed signal strength $\mu = 2.2 \pm 0.7$
 - Observed (expected) significance: 3.4σ (1.6σ)

$\Rightarrow$  ATLAS $H \rightarrow \ell\ell\gamma$ result: obs. (exp.): 3.2σ (2.1σ)

(ℓ = electron or muon)

Karsten Köneke



Phys. Rev. Lett. 132 (2024) 021803



$H \rightarrow \ell\ell\gamma$

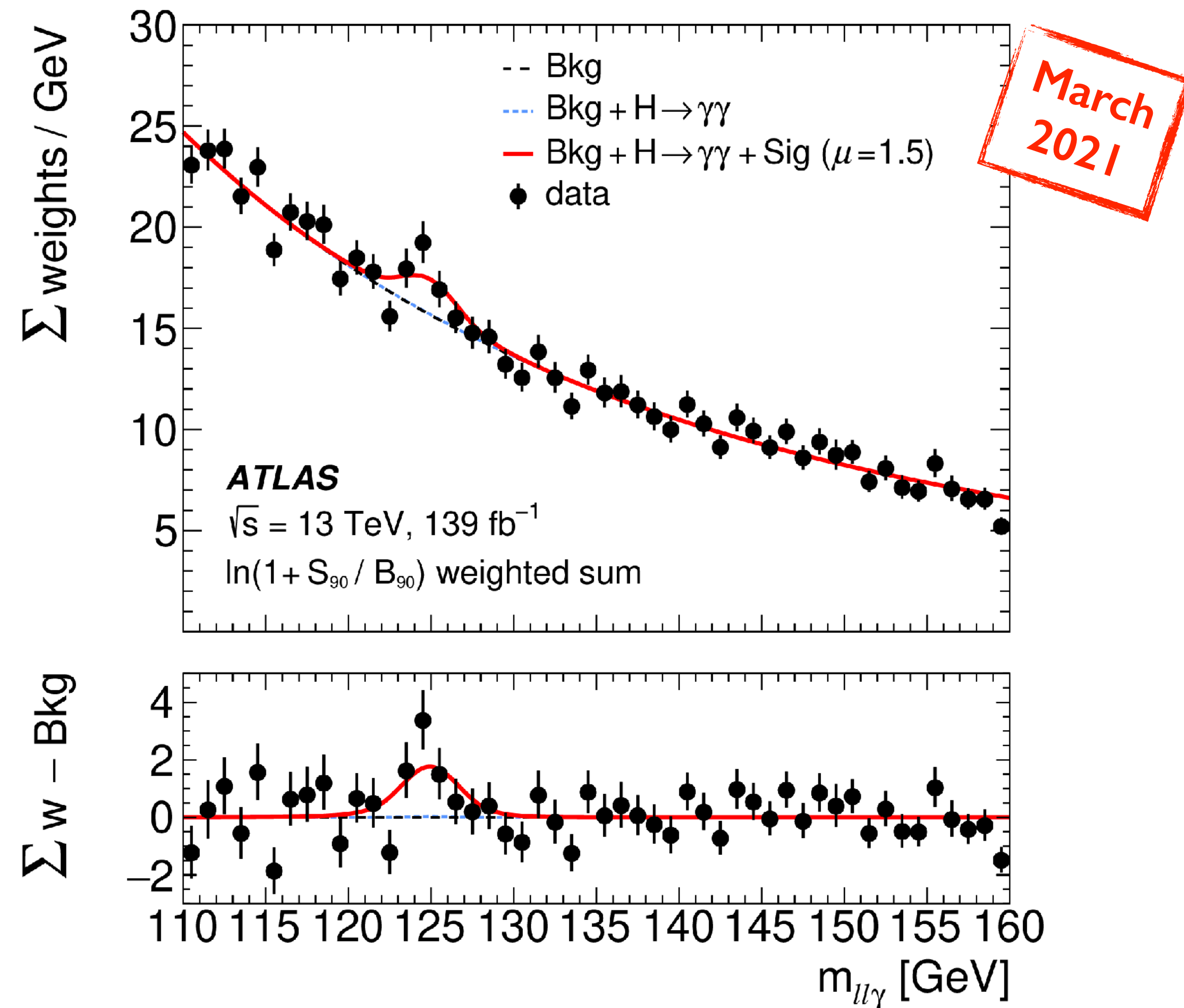
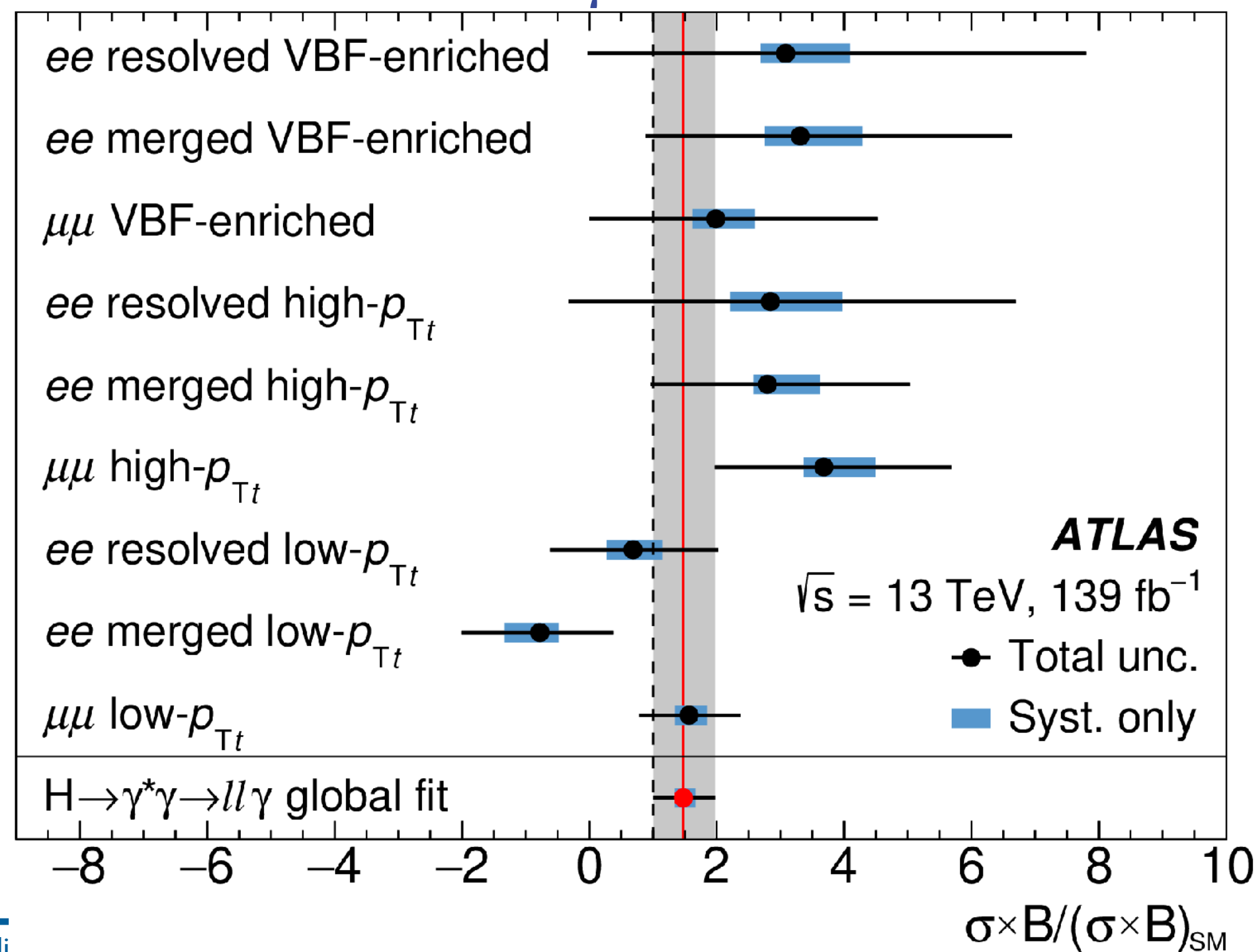


- Tiny branching fractions:**

- $BR_{SM}(H \rightarrow ee\gamma)|_{m_{\ell\ell} < 30 \text{ GeV}} = 7.20 \times 10^{-5}$

- $BR_{SM}(H \rightarrow \mu\mu\gamma)|_{m_{\ell\ell} < 30 \text{ GeV}} = 3.42 \times 10^{-5}$

- $\sim 1200 H \rightarrow \ell\ell\gamma$ events in 139 fb^{-1}



- Observed (expected) significance: **3.2 σ** (2.1 σ)



κ Coupling Modifiers



ATLAS-CONF-2025-006

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$, $36.1 - 140 \text{ fb}^{-1}$
 $m_H = 125.09 \text{ GeV}$, $|y_H| < 2.5$

Leptons			Quarks		
ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b
Force carriers				Higgs boson	
g	γ	Z	W	H	

$\approx 5\%$

κ_Z

$\approx 5\%$

κ_W

$\approx 9\%$

κ_t

$\approx 10\%$

κ_b

$\approx 6\%$

κ_τ

$\approx 25\%$

κ_μ

$\approx 6\%$

κ_g

$\approx 6\%$

κ_γ

$\approx 25\%$

$\kappa_{Z\gamma}$

$\approx 5\%$

$\approx 4\%$

$\approx 5\%$

$\approx 10\%$

$\approx 6\%$

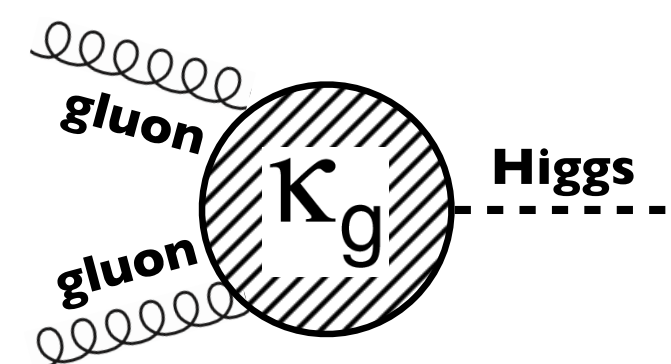
$\approx 25\%$

— Effective $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$, $p_{\text{SM}} = 89\%$
- - - Resolved $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$, $p_{\text{SM}} = 82\%$
— SM prediction

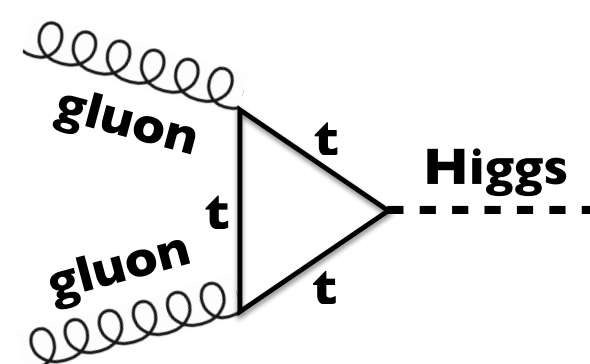
Parameter value

“Effective”
coupling
modifiers

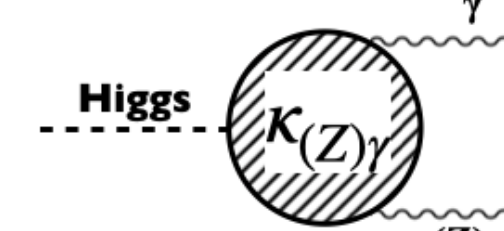
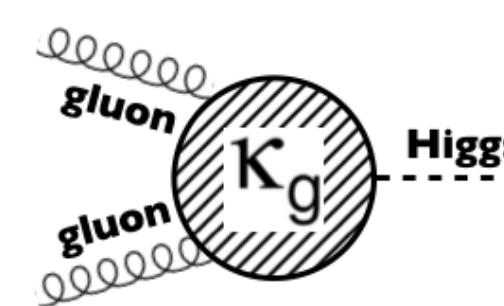
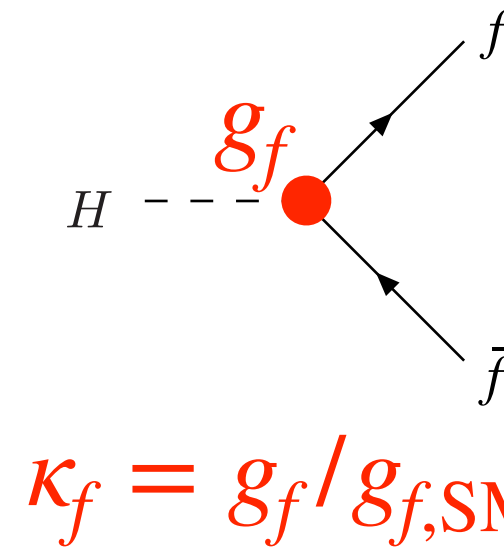
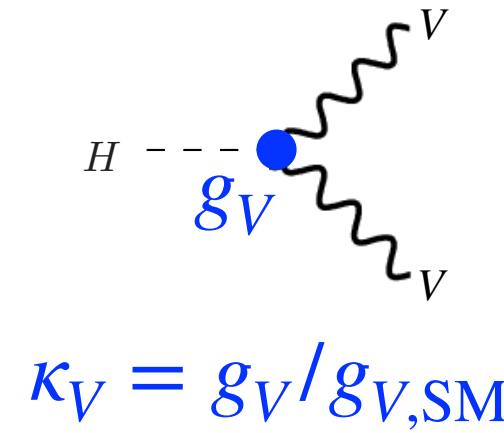
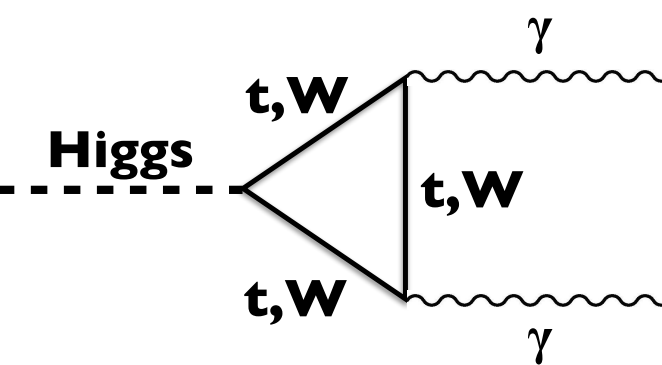
“Resolved”
coupling
modifiers



?

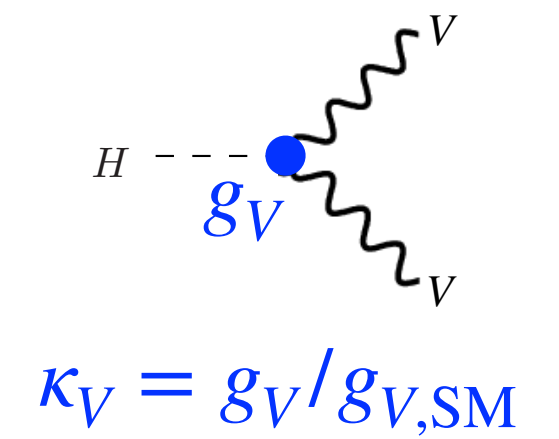


?



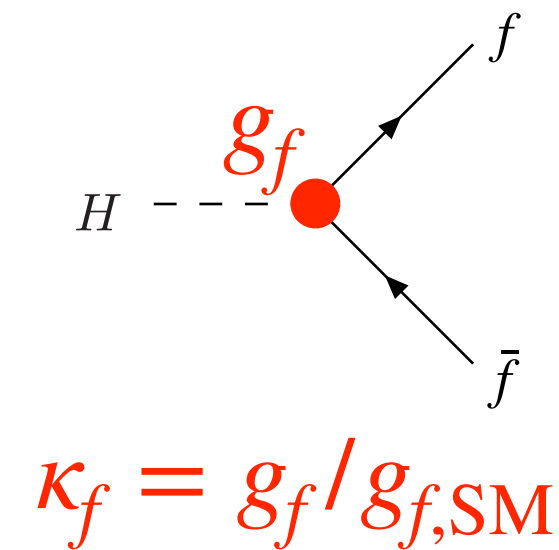


κ Coupling Modifiers



$\approx 5\%$

κ_Z



$\approx 5\%$

κ_W

$\approx 9\%$

κ_t

$\approx 10\%$

κ_b

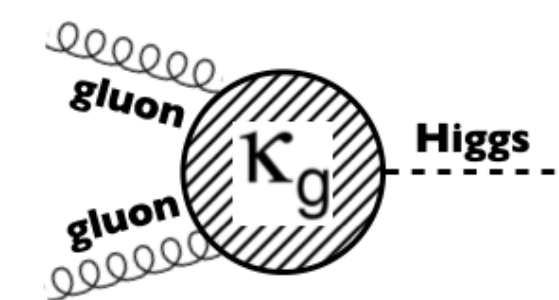
$\approx 6\%$

κ_τ

$\approx 25\%$

κ_μ

$\approx 14\%$



$\approx 6\%$

κ_g



$\approx 6\%$

κ_γ

$\approx 25\%$

$\kappa_{Z\gamma}$

$\approx 21\%$

ATLAS-CONF-2025-006

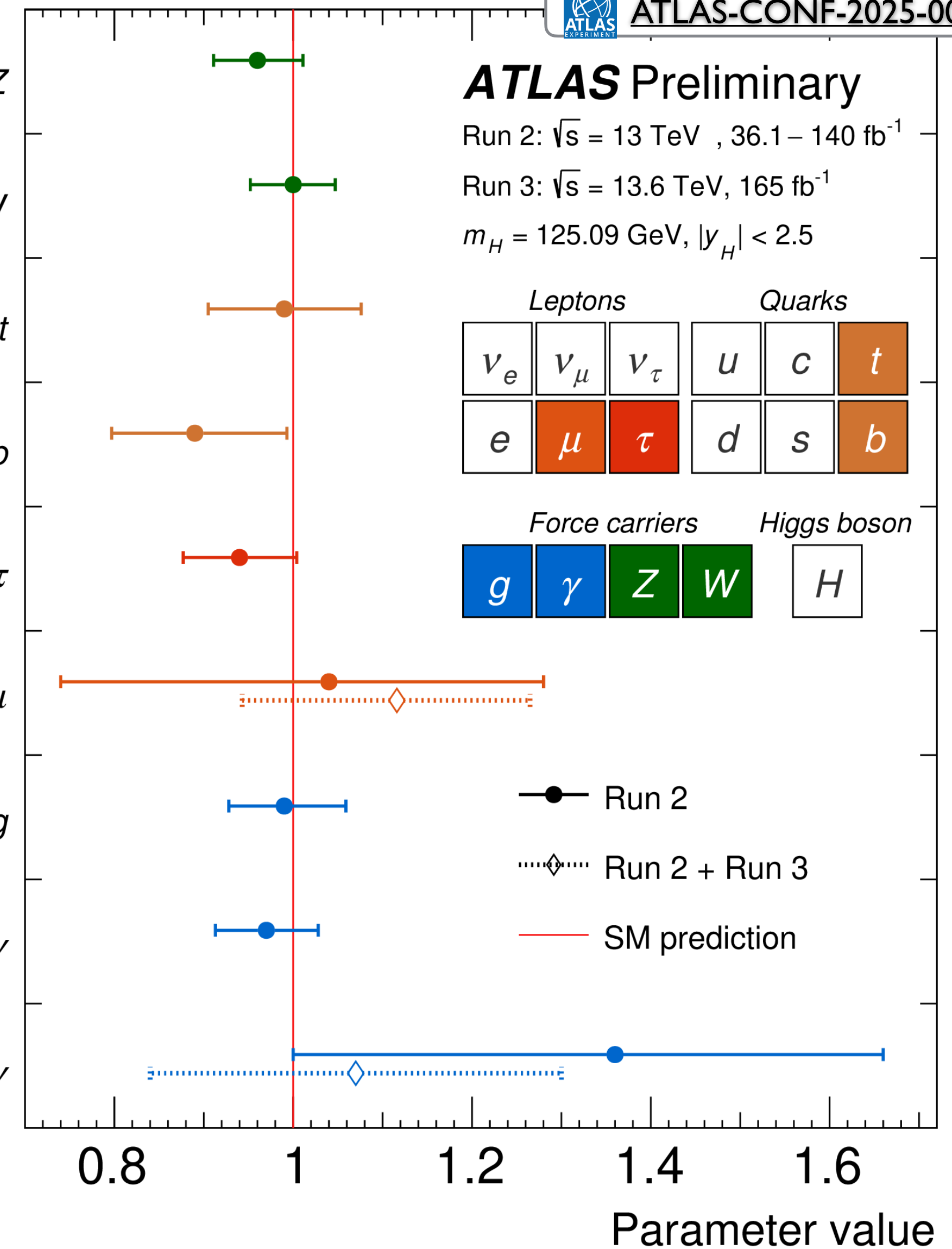
ATLAS Preliminary

Run 2: $\sqrt{s} = 13$ TeV, 36.1 – 140 fb⁻¹

Run 3: $\sqrt{s} = 13.6$ TeV, 165 fb⁻¹

$m_H = 125.09$ GeV, $|y_H| < 2.5$

Leptons			Quarks		
ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b
Force carriers				Higgs boson	
g	γ	Z	W	H	

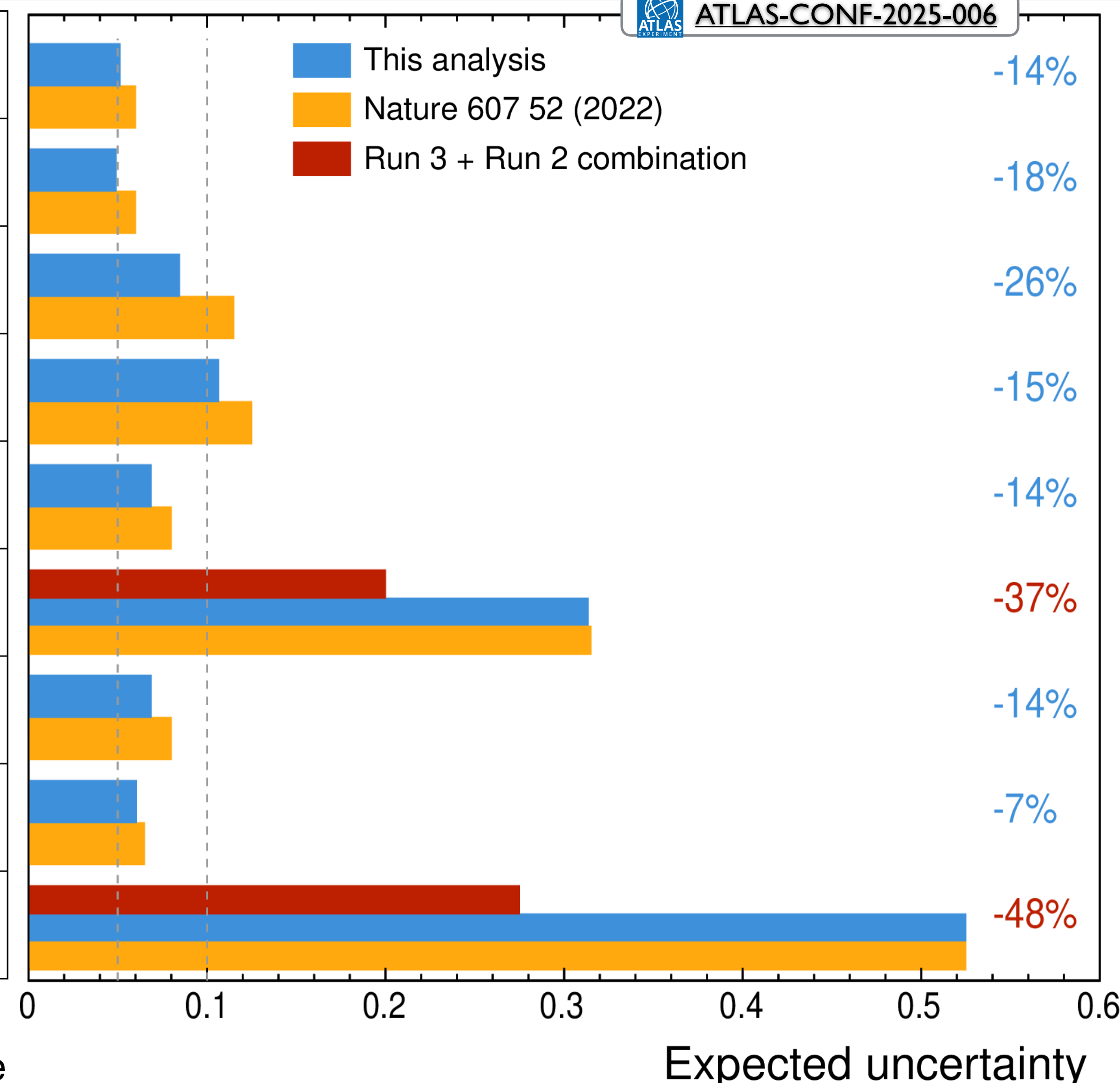
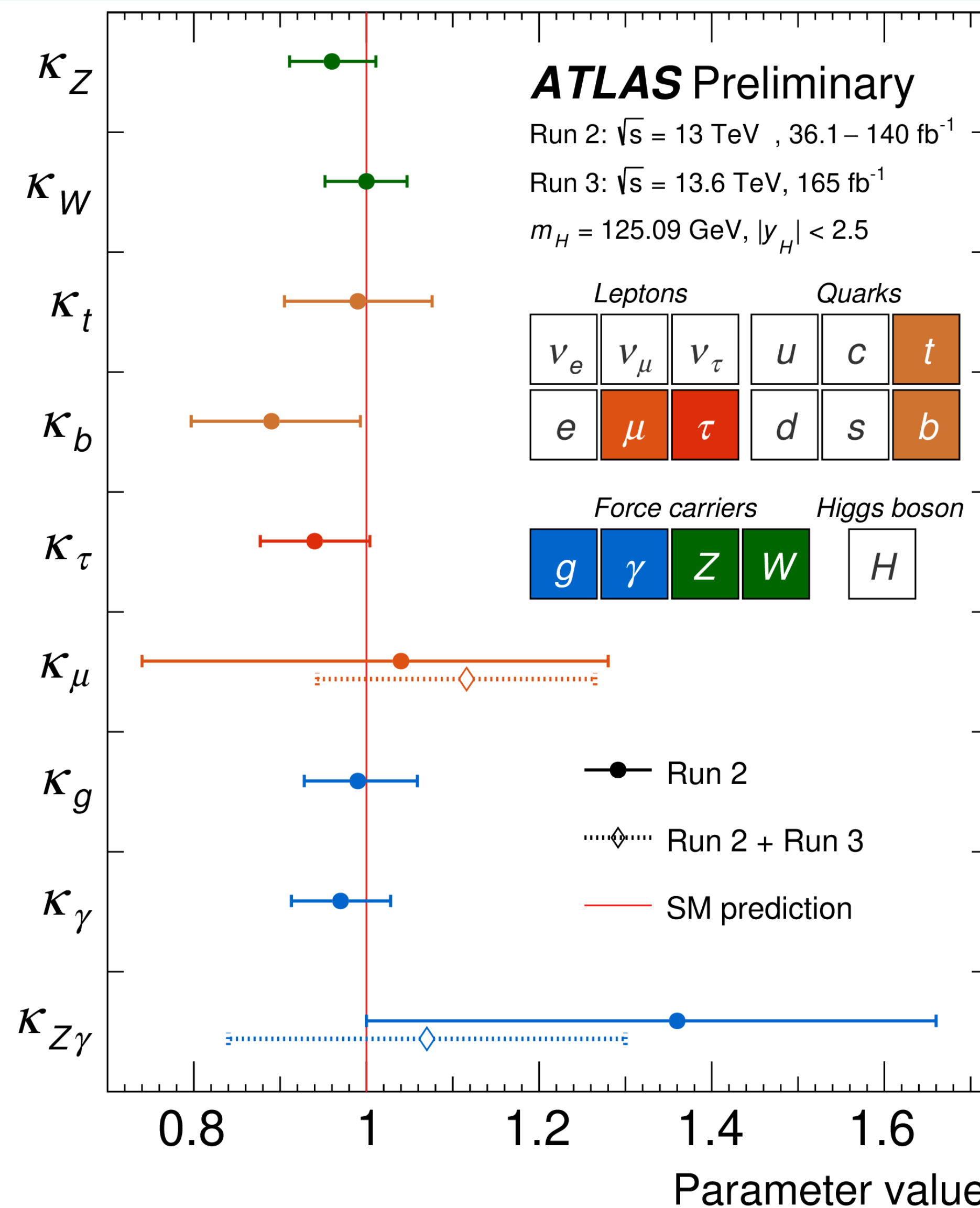




Further Coupling Strength Checks



ATLAS-CONF-2025-006



Assume:
No BSM
contributions
($B_{\text{inv}} = B_{\text{undet}} = 0$)

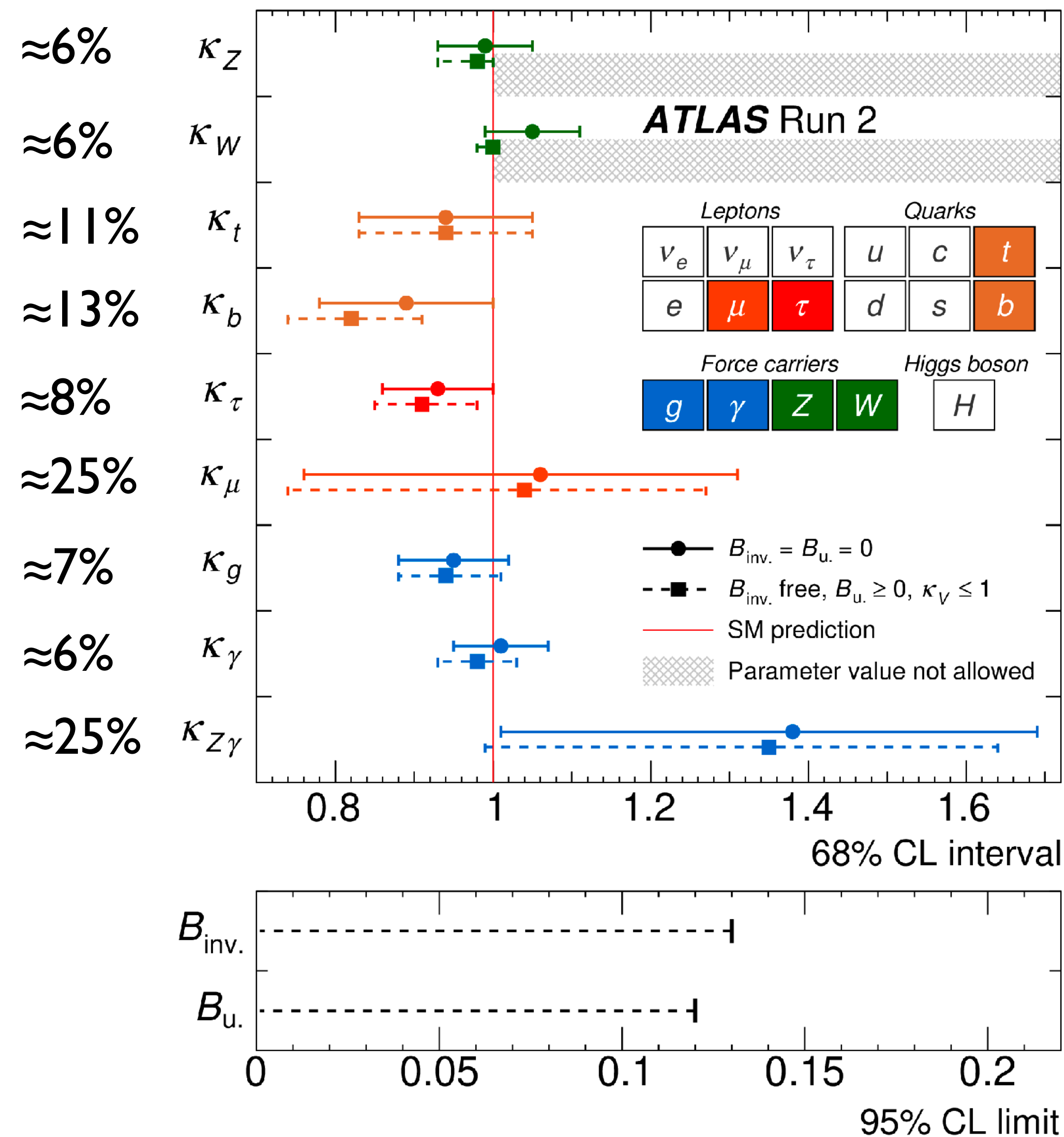


κ Coupling Modifiers



ATLAS EXPERIMENT Nature 607, 52–59 (2022)

Assume:
No BSM
contributions
($B_{\text{inv}} = B_{\text{undet}} = 0$)



Assume:
 B_{inv} and B_{undet} are
free parameters.
Constrain $\kappa_W \leq 1$
and $\kappa_Z \leq 1$

Add:
VBF $H \rightarrow$ invisible

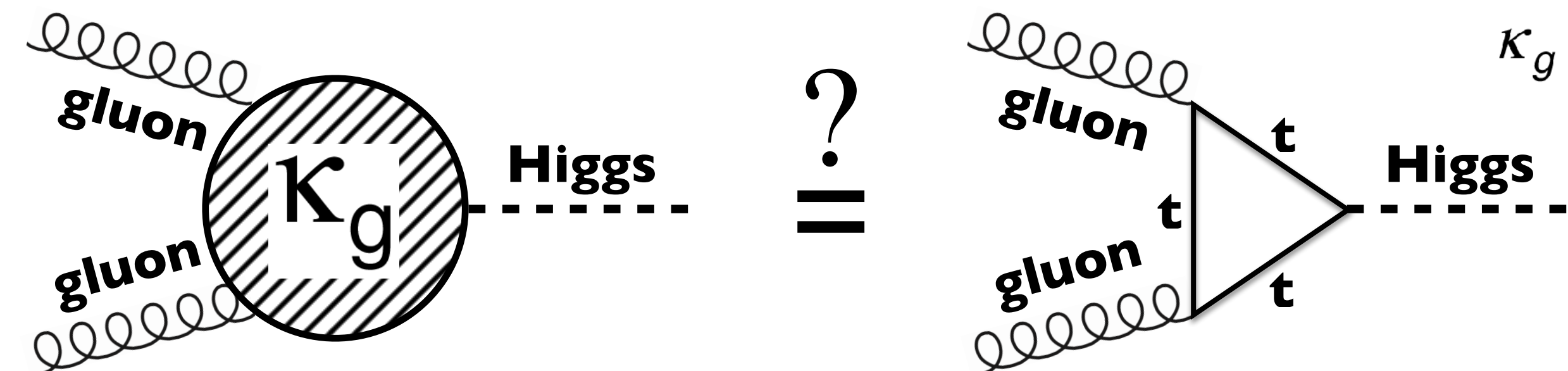
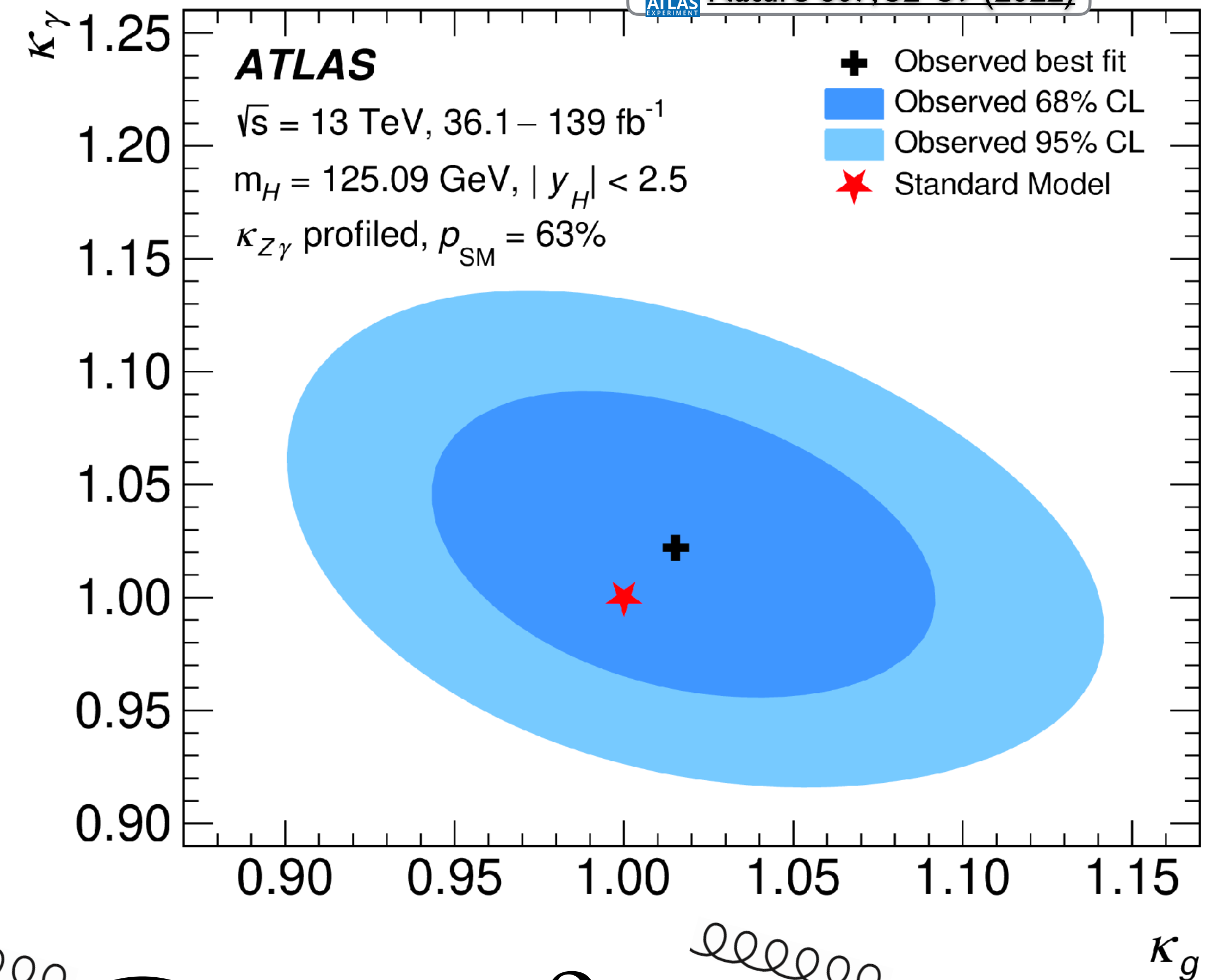
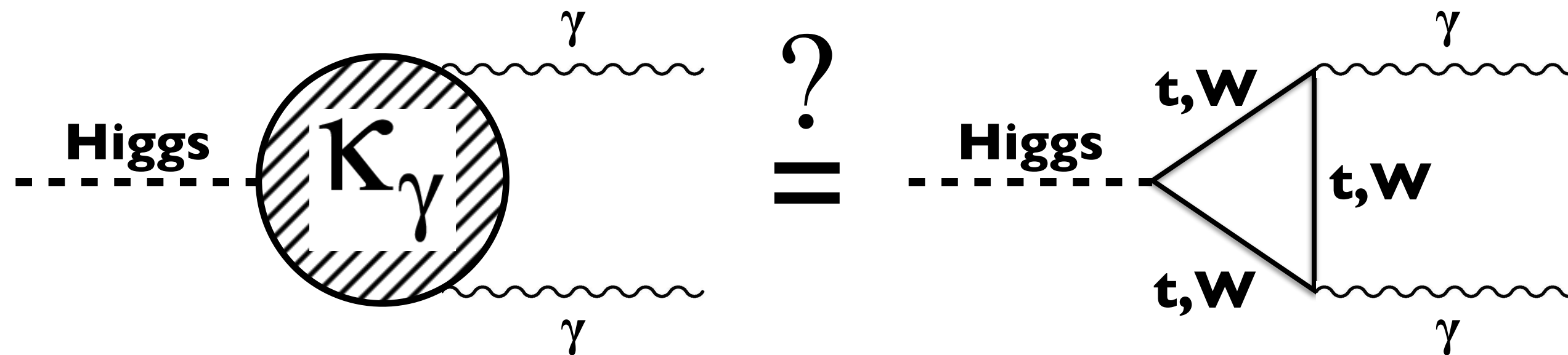


Loop-induced Couplings



Nature 607, 52–59 (2022)

- SM: ggF and $H \rightarrow \gamma\gamma$ are loop-induced
 - New particles could participate in the loop
- $\Rightarrow$ Contributions of BSM?
- $\Rightarrow$ Test effective coupling factors for photons (κ_γ) and gluons (κ_g)





Ratio of Coupling Modifiers



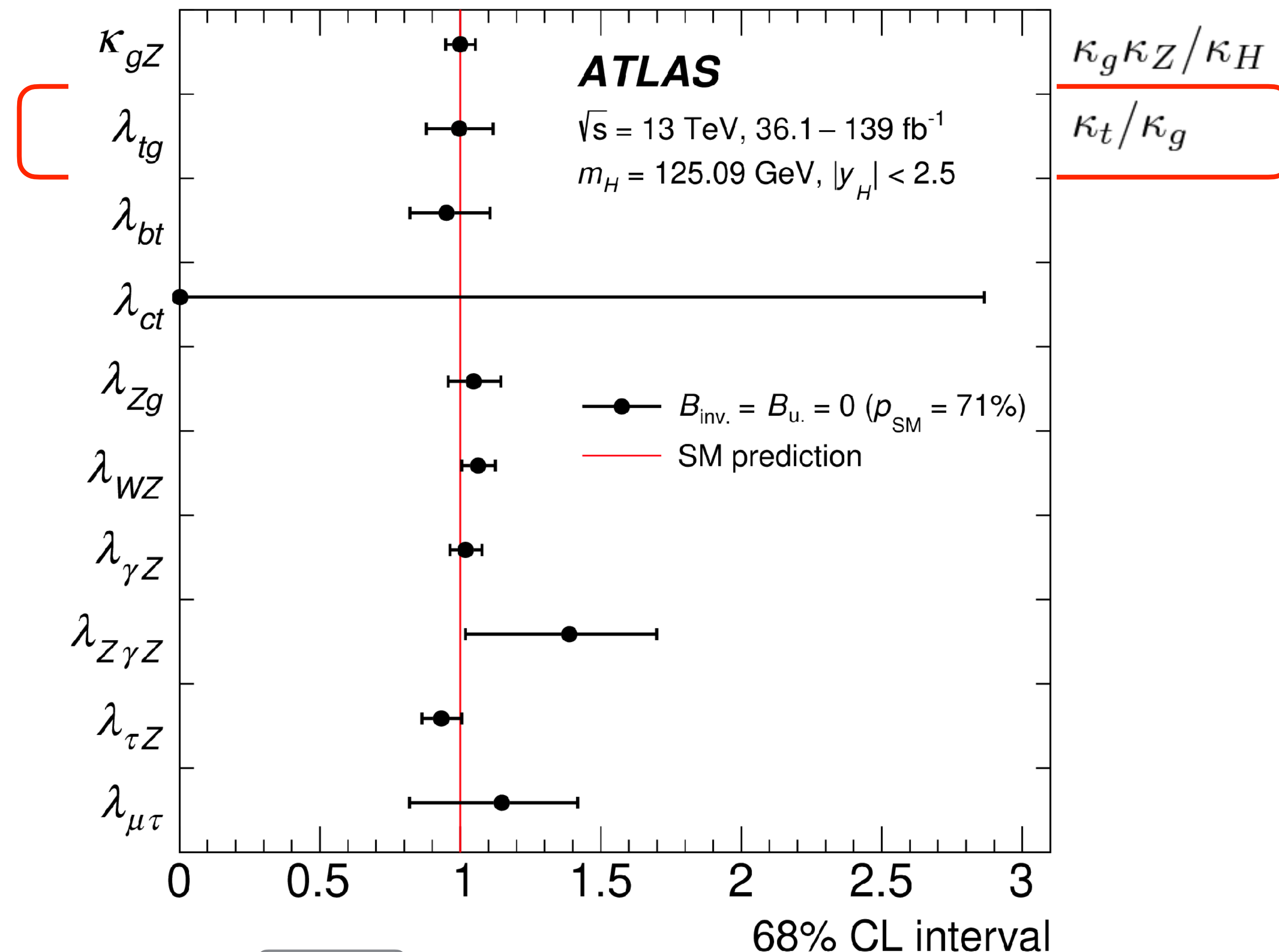
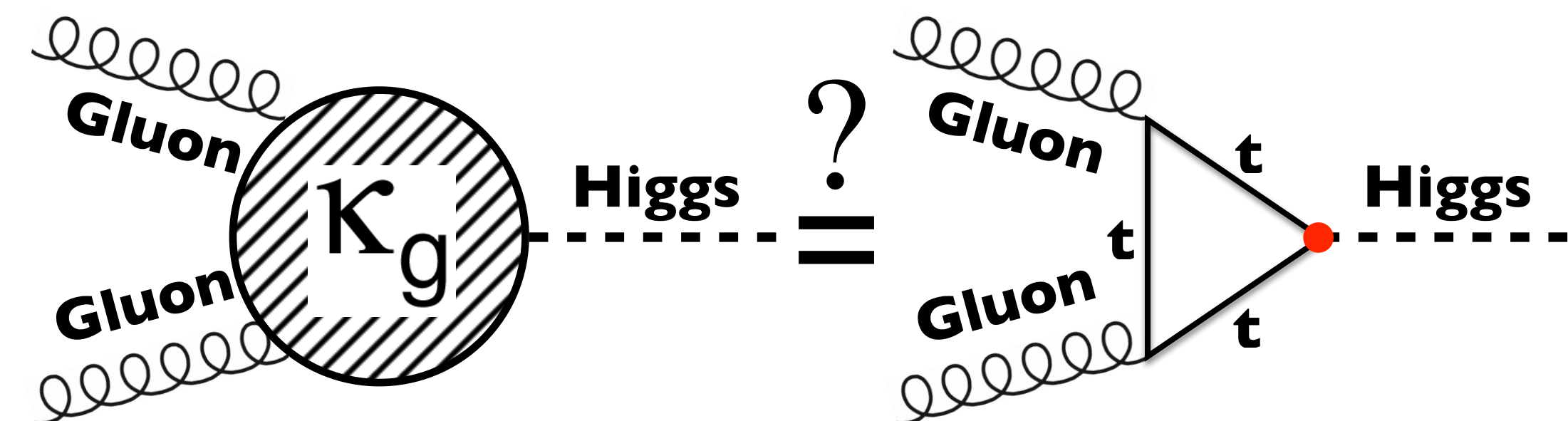
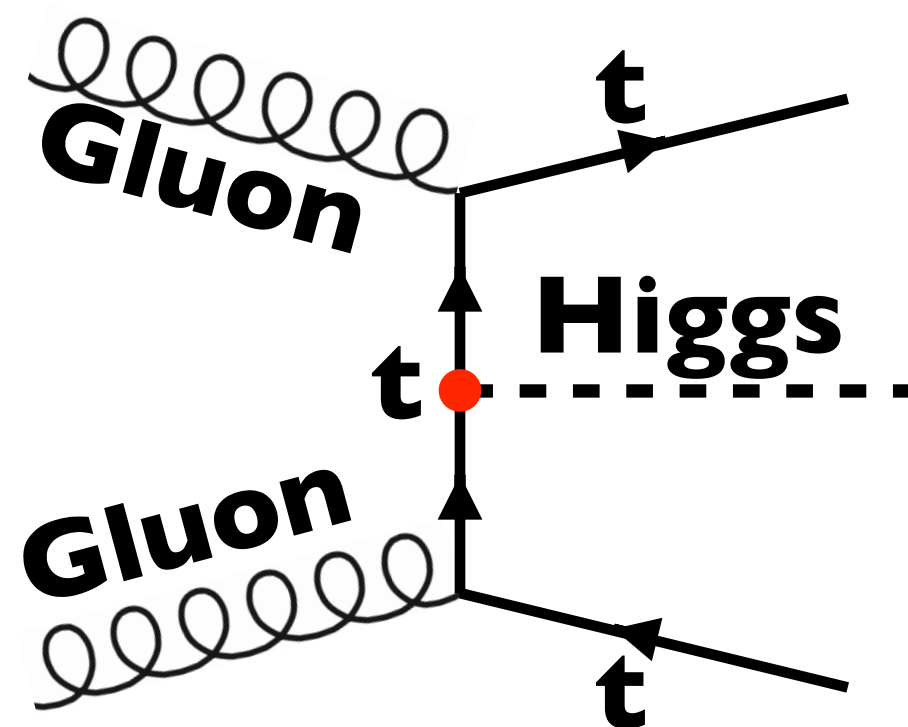
ATLAS EXPERIMENT Nature 607, 52–59 (2022)

- No assumption on total width needed; assume all parameters >0

- With $t\bar{t}H$ measurement:

⇒ Test compatibility between

- direct $t\bar{t}H$ coupling (κ_t) and
- coupling in ggF loop, i.e. effective coupling modifier for gluons (κ_g)





Combined STXS Measurement

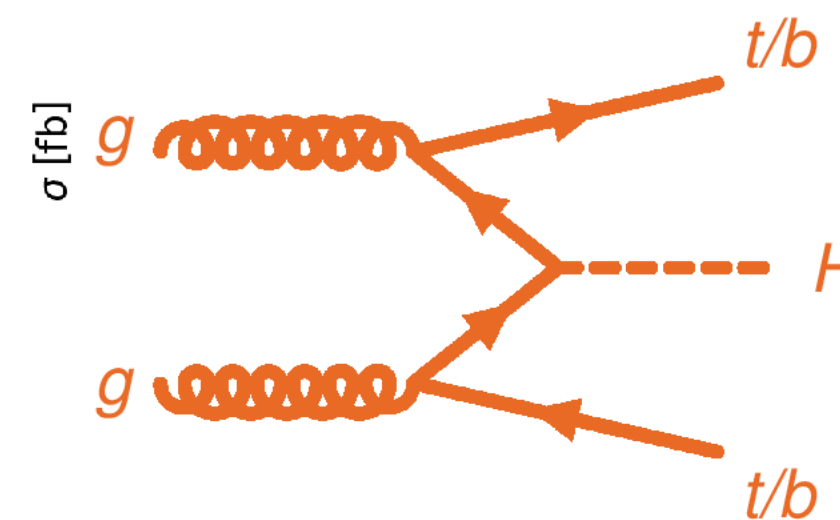
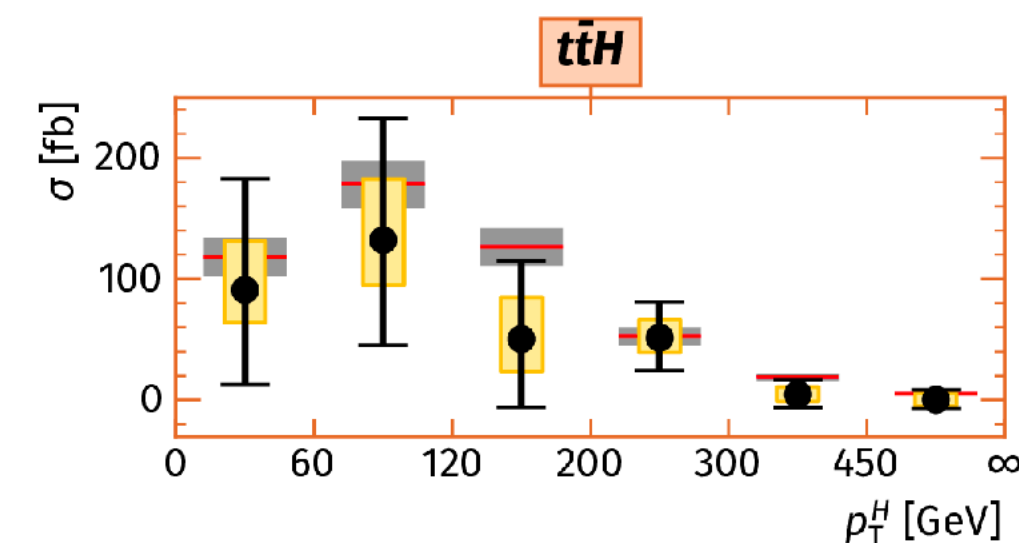
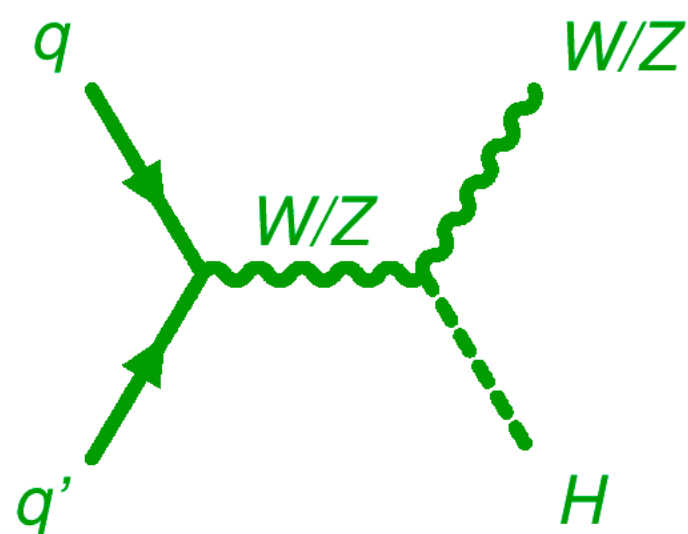
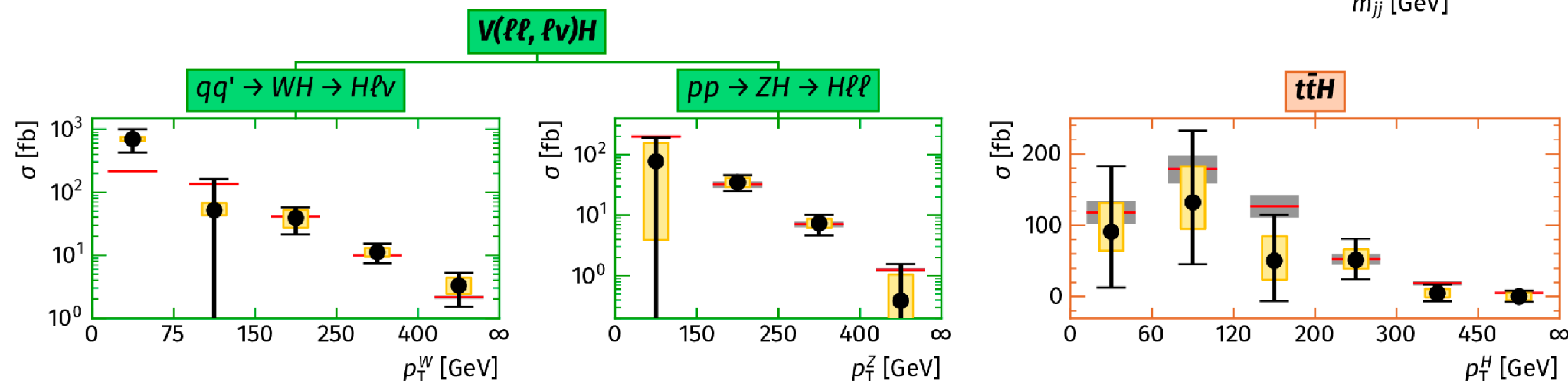
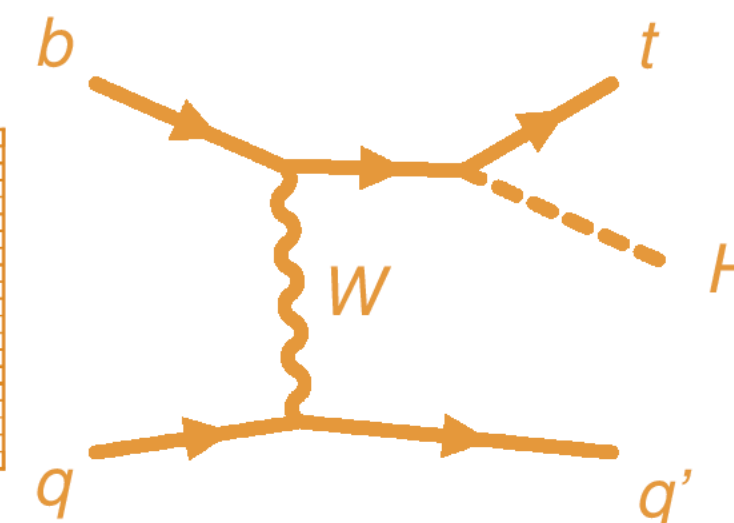
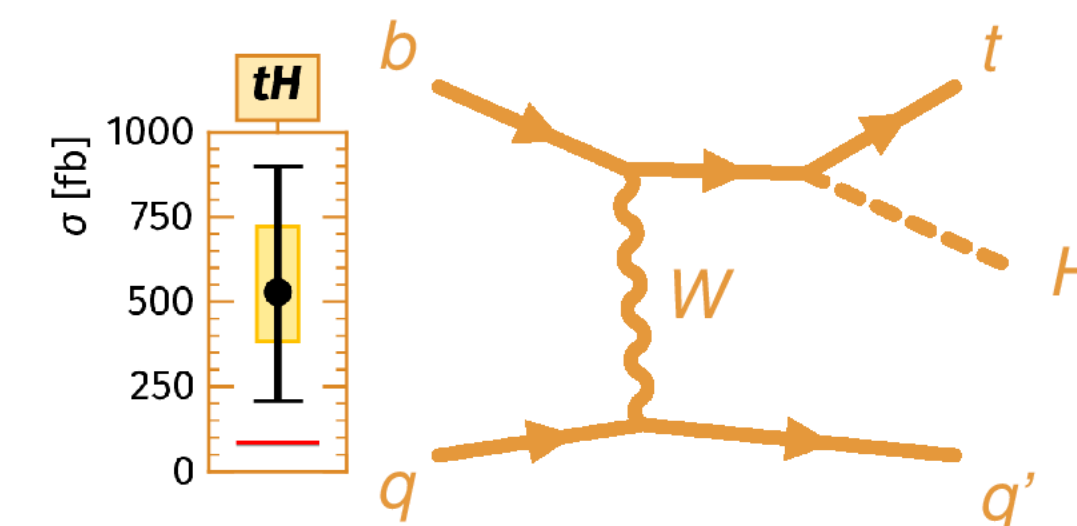
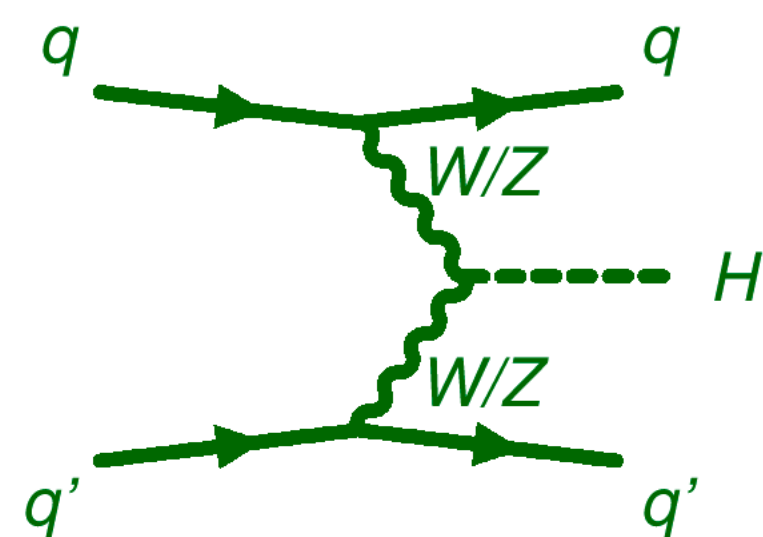
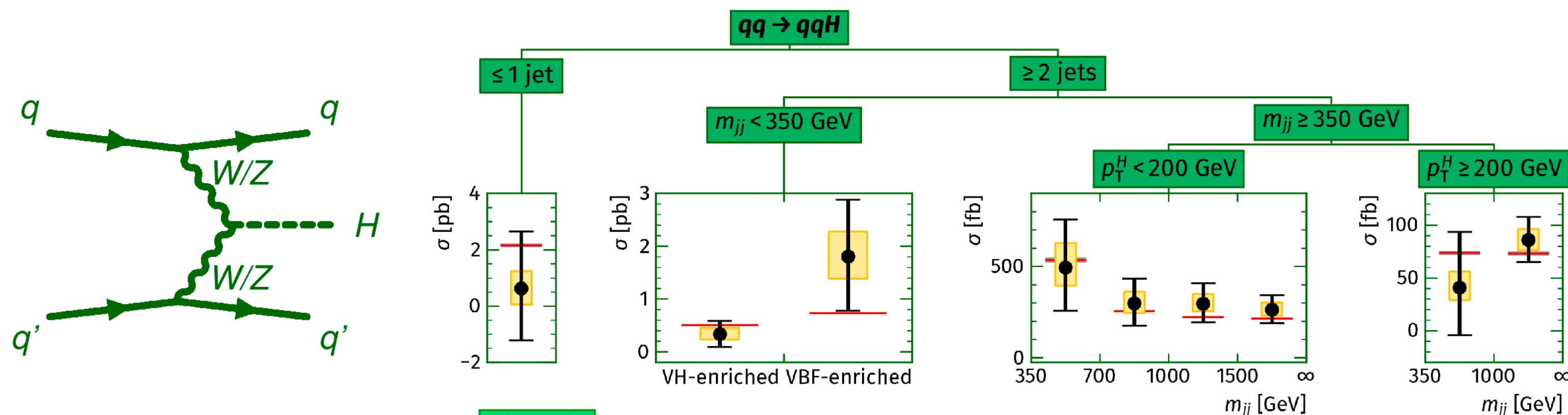
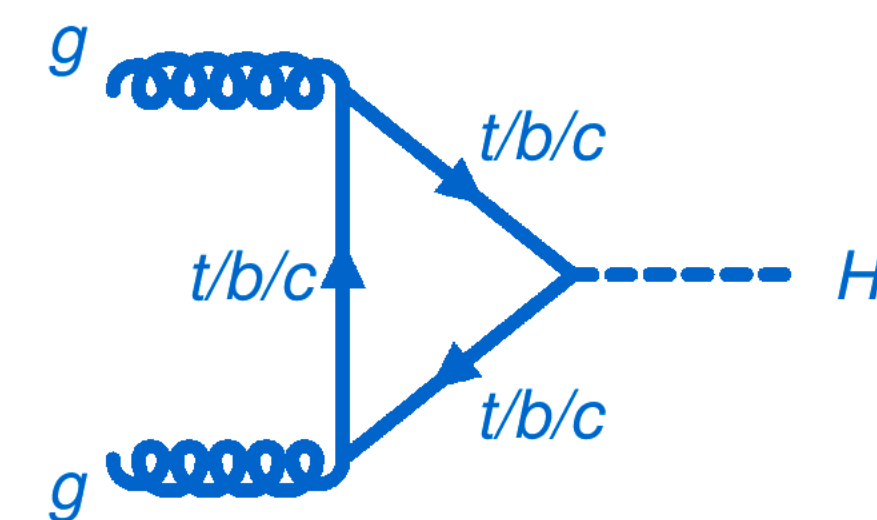
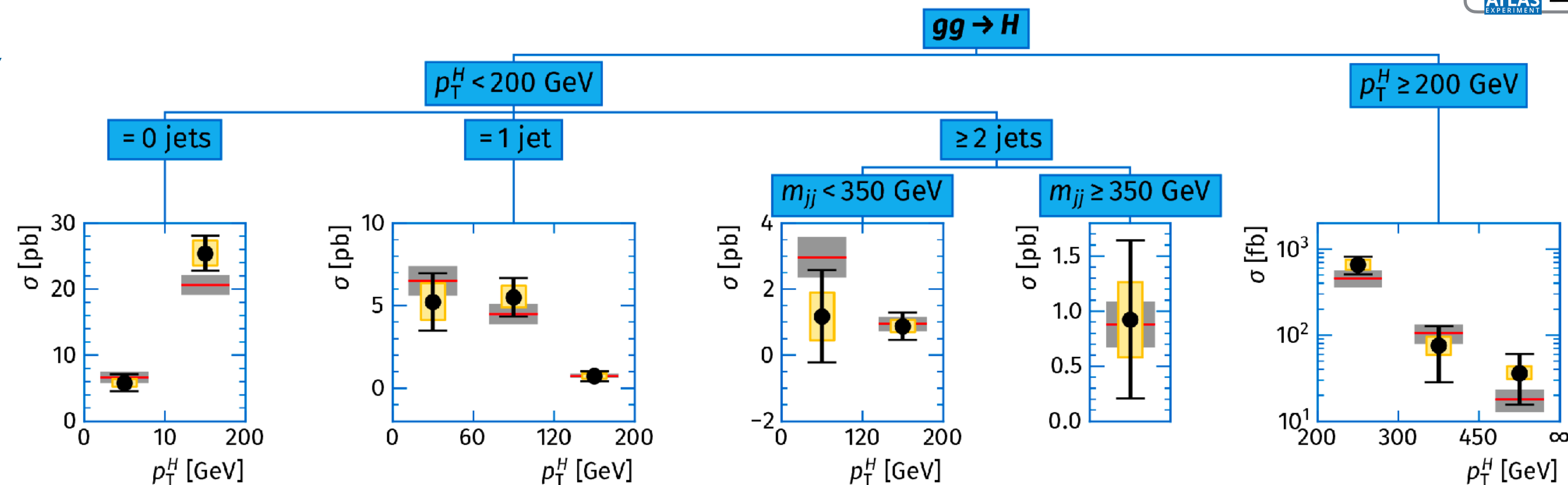


ATLAS EXPERIMENT Nature 607, 52–59 (2022)

Measurements in many kinematic regions

ATLAS Run 2

- Data (Total uncertainty)
- Syst. uncertainty
- SM prediction



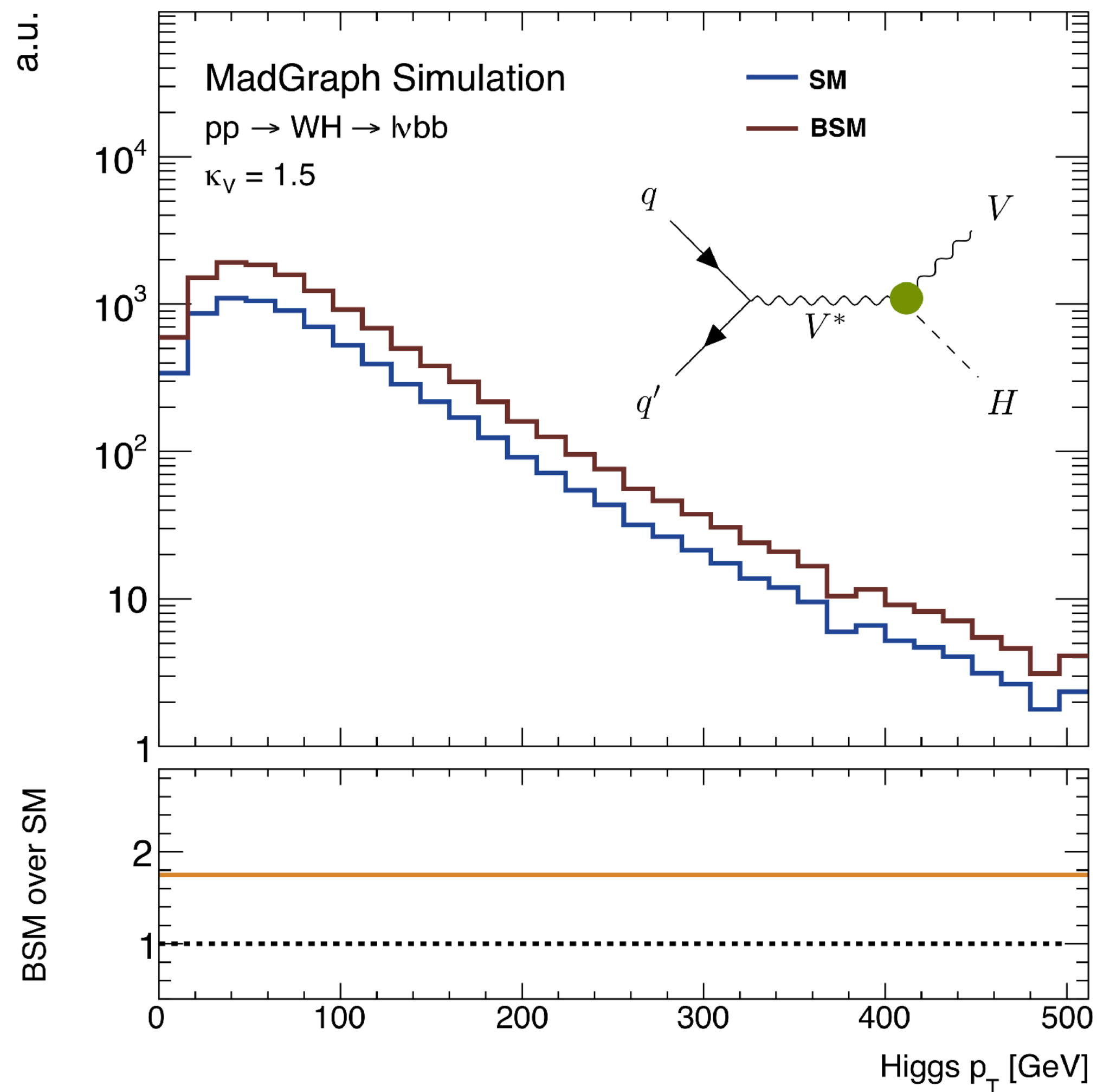
July 2022



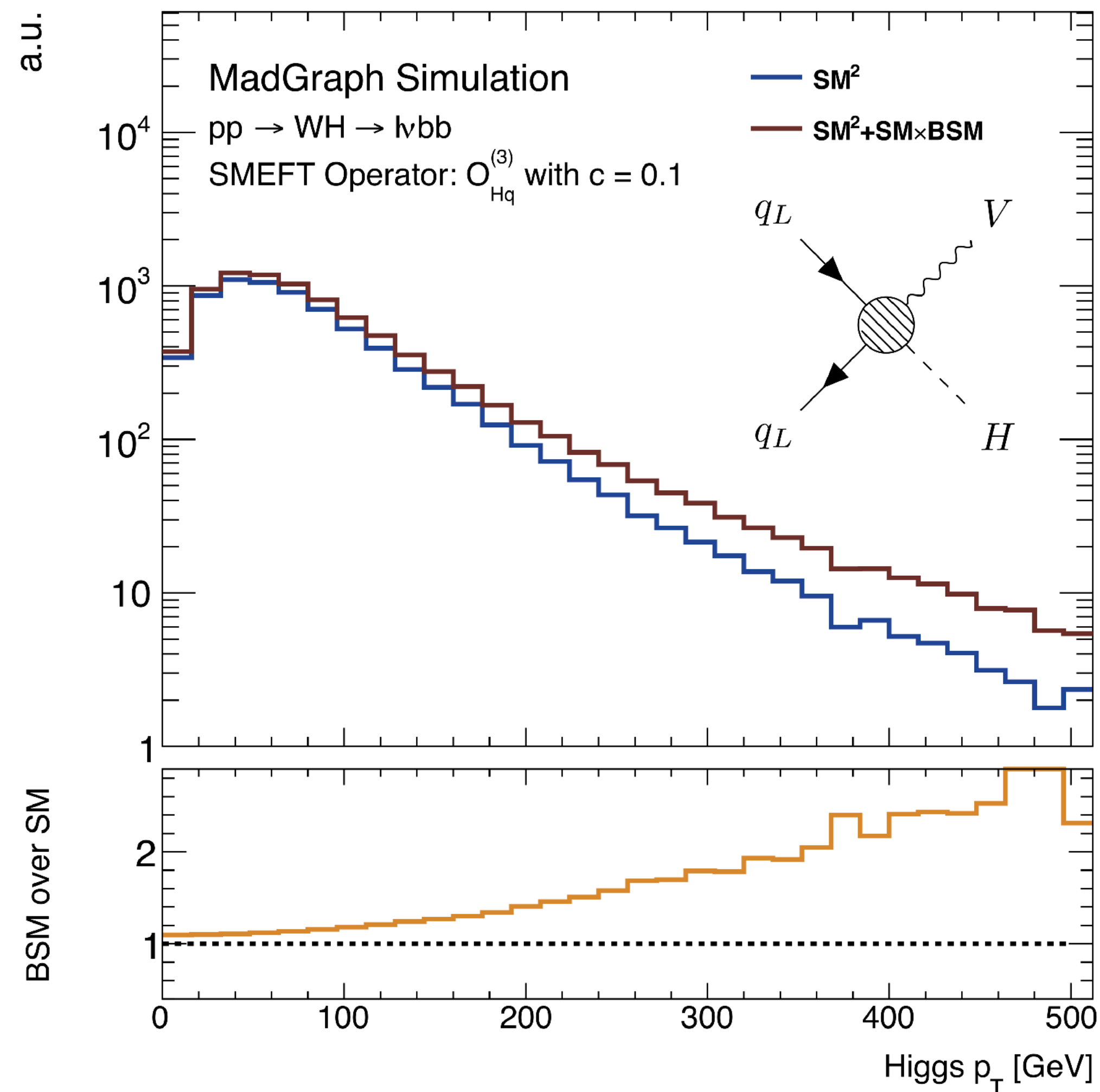
κ Framework vs. EFT Example



κ -framework: $\kappa_V = 1.5$



SMEFT: $O_{Hq}^{(3)} = 0.1$





SMEFT



Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{H} G_{\mu\nu}^A$	
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{H} W_{\mu\nu}^I$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{H} B_{\mu\nu}$	
$c_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	
c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c_{qq}^{(31)}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$	
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	
$c_{uu}^{(1)}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$	
$c_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$	
$c_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
$c_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$	
$c_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
c_G	$f^{ABC} G_\mu^A G_\nu^B G_\rho^C$	

Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	

Coefficient	Operator	Example process
$c_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	



Effective Field Theory Interpretations



Extend SM with new physics operators:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$

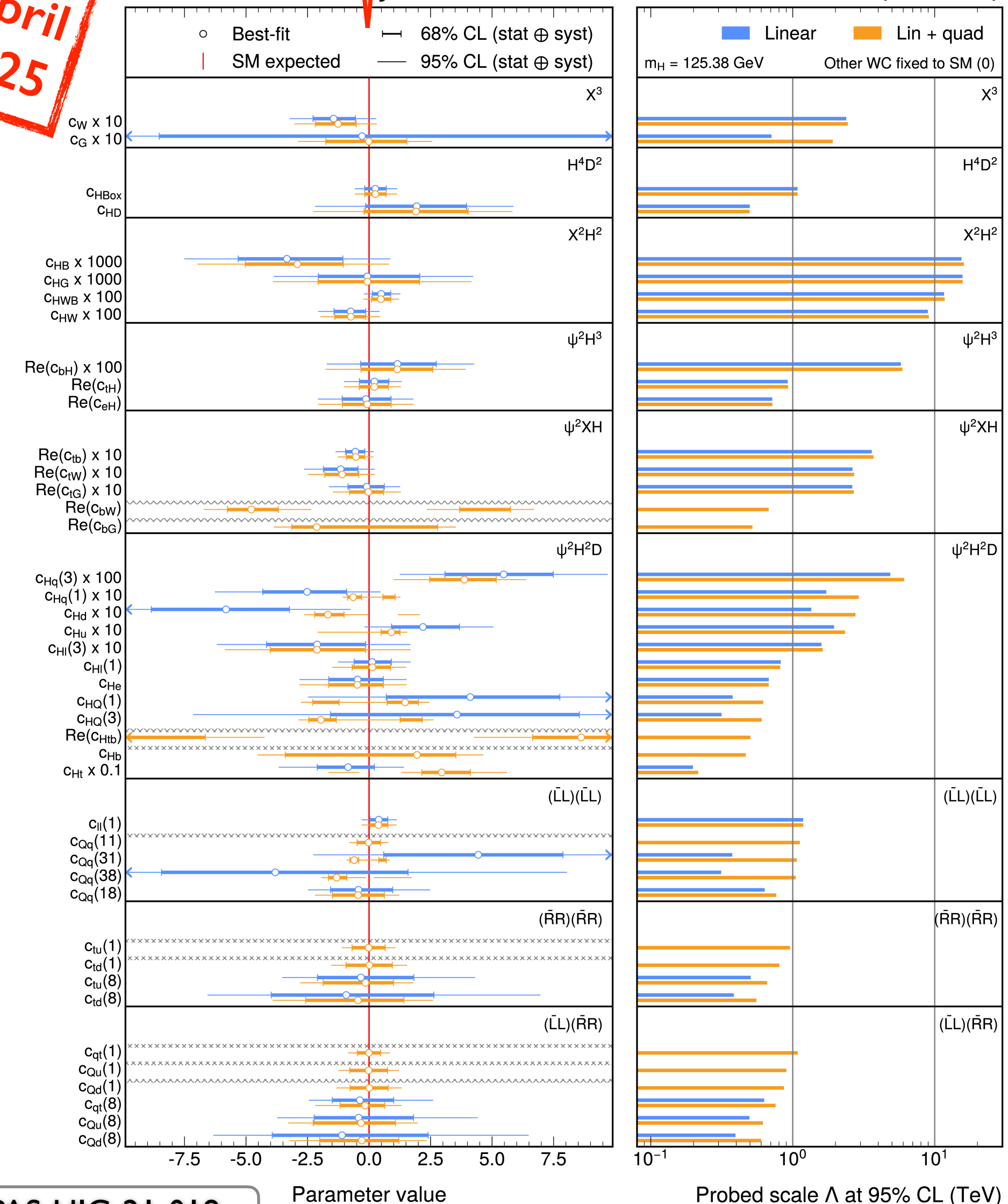
(assumes no new particles below $\Lambda = 1 \text{ TeV}$)

- 43 EFT parameters fitted, one at a time

Opens the window to global combined analyses!

April 2025

CMS Preliminary



CMS-PAS-HIG-21-018

Parameter value

Probed scale Λ at 95% CL (TeV)



Effective Field Theory Interpretations GA

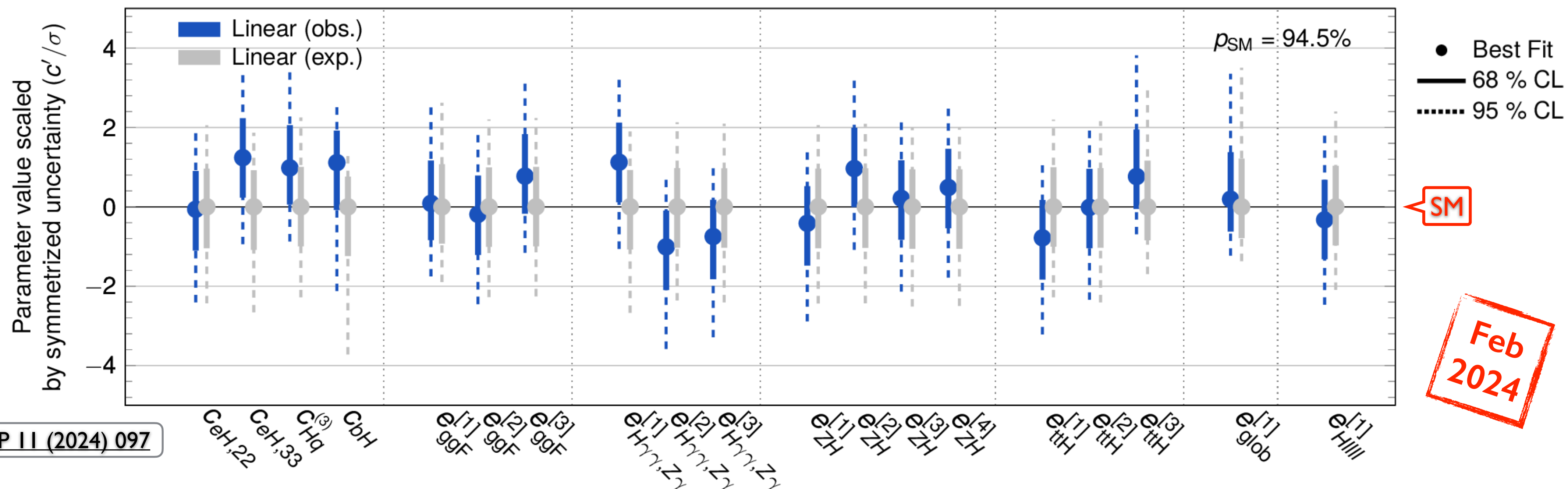
Extend SM with new physics operators:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$

(assumes no new particles below $\Lambda = 1 \text{ TeV}$)

- EFT interpretation of “Nature” combination
- 19 EFT parameters fitted simultaneously!
 - Eigenvector rotation
(to remove insensitive directions)

Opens the window to global combined analyses!





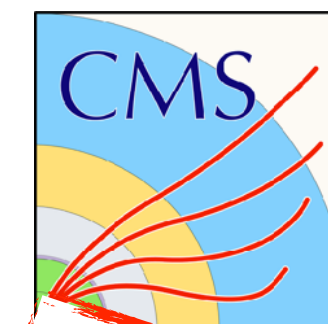
CP Measurement in HVV Coupling

CP-violation through interference of SM $\mathcal{M}_{\text{SM}}$ (CP-even) with dim-6 CP-odd $\mathcal{M}_{\text{CP-odd}}$:

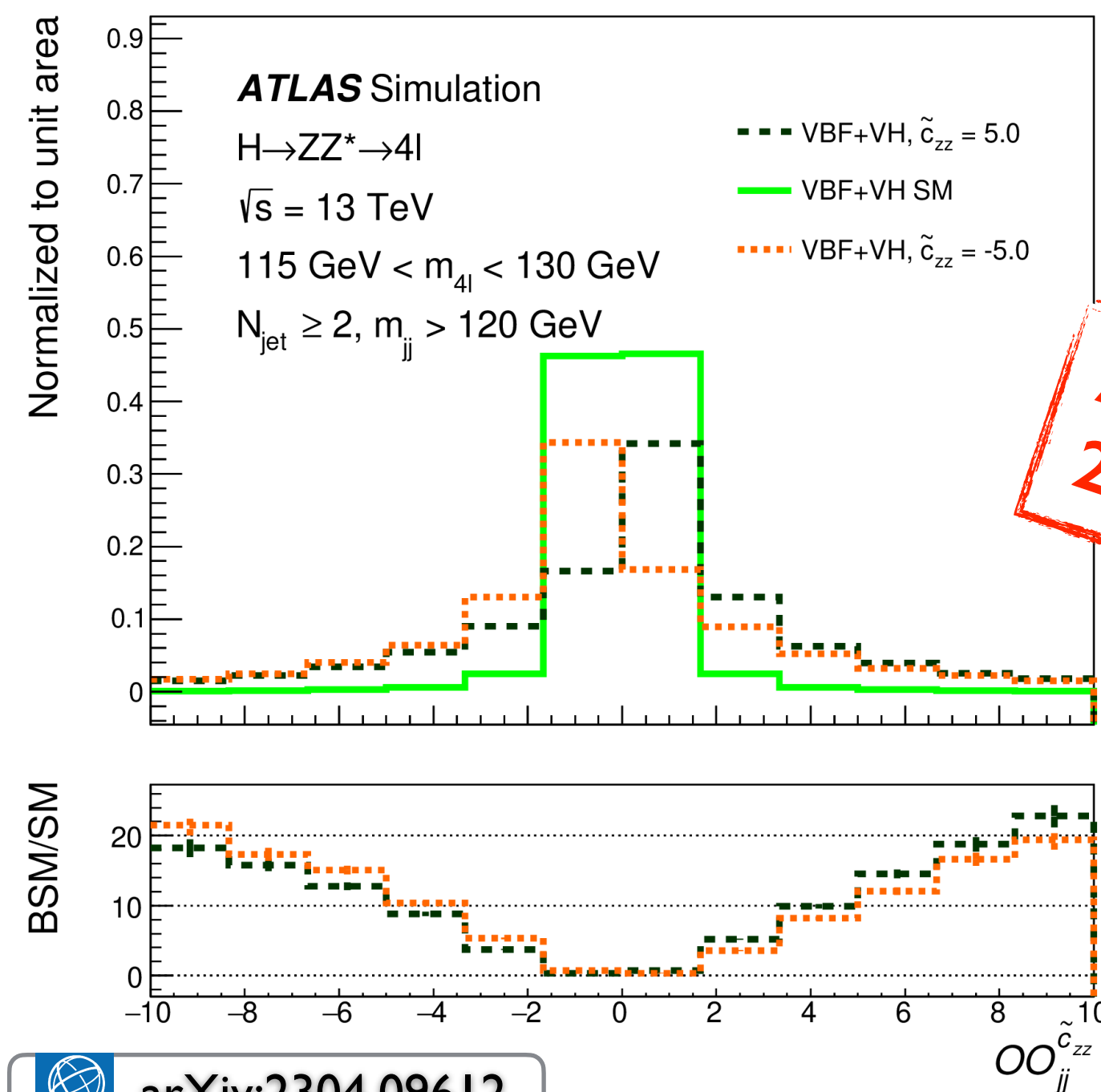
Optimal Observable:
 $OO = 2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}}) / |\mathcal{M}_{\text{SM}}|^2$



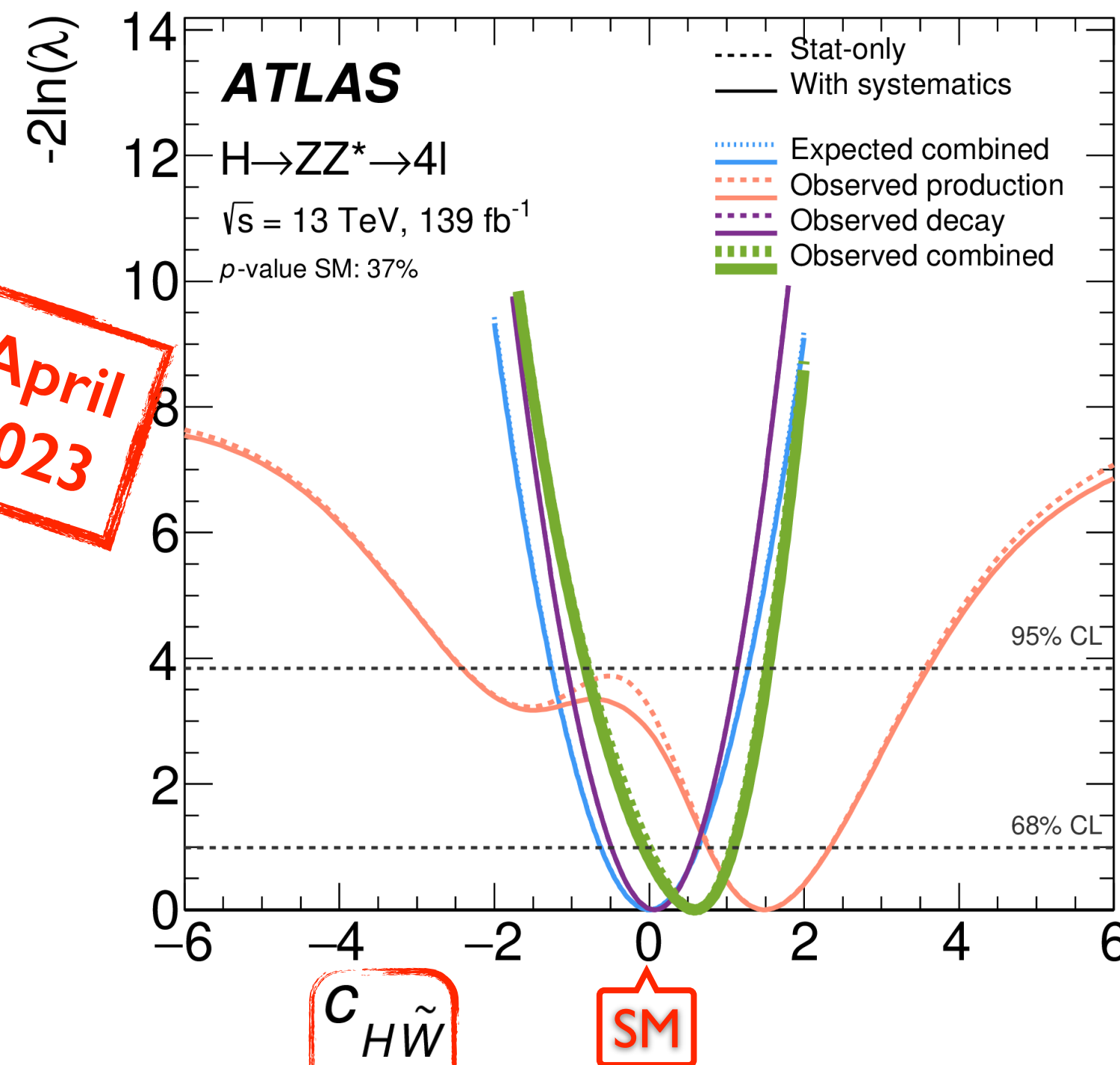
VBF production and
 $H \rightarrow ZZ^* \rightarrow 4\ell$ decay



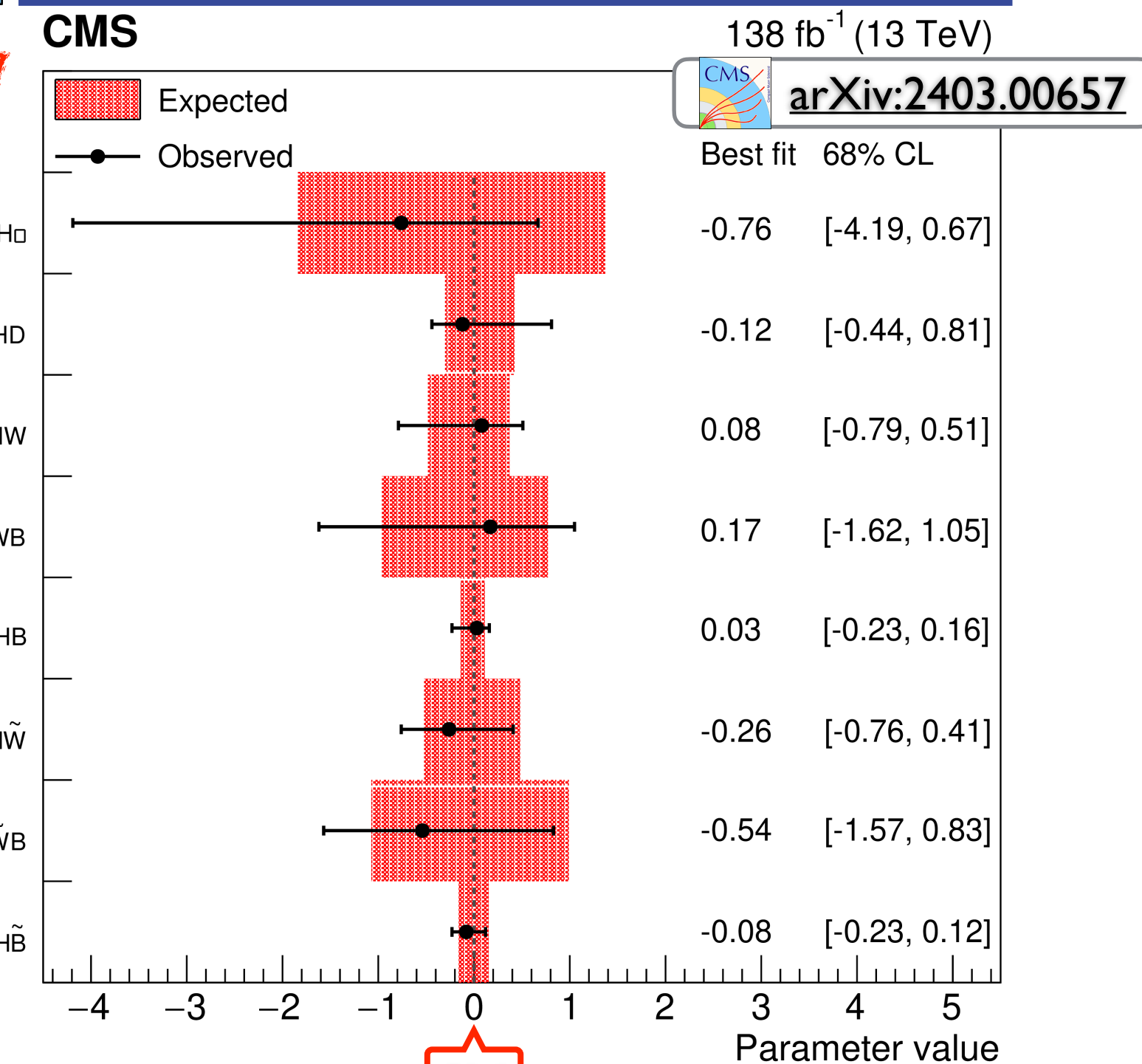
ggF, VBF, VH production and
 $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay



April 2023



March 2024

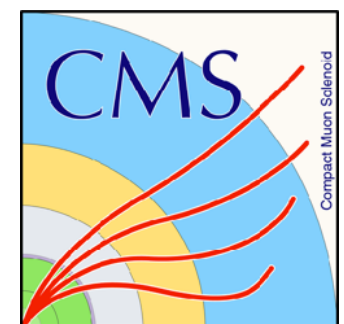


$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2c_i \text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}}) + c_i^2 |\mathcal{M}_{\text{CP-odd}}|^2$$



CP Measurement in $t(t)H$ Production

- CP-odd in Higgs-Gauge interactions need higher-order operators
- CP-odd in Higgs-fermion interactions (**top-Yukawa**) can be **tree-level**

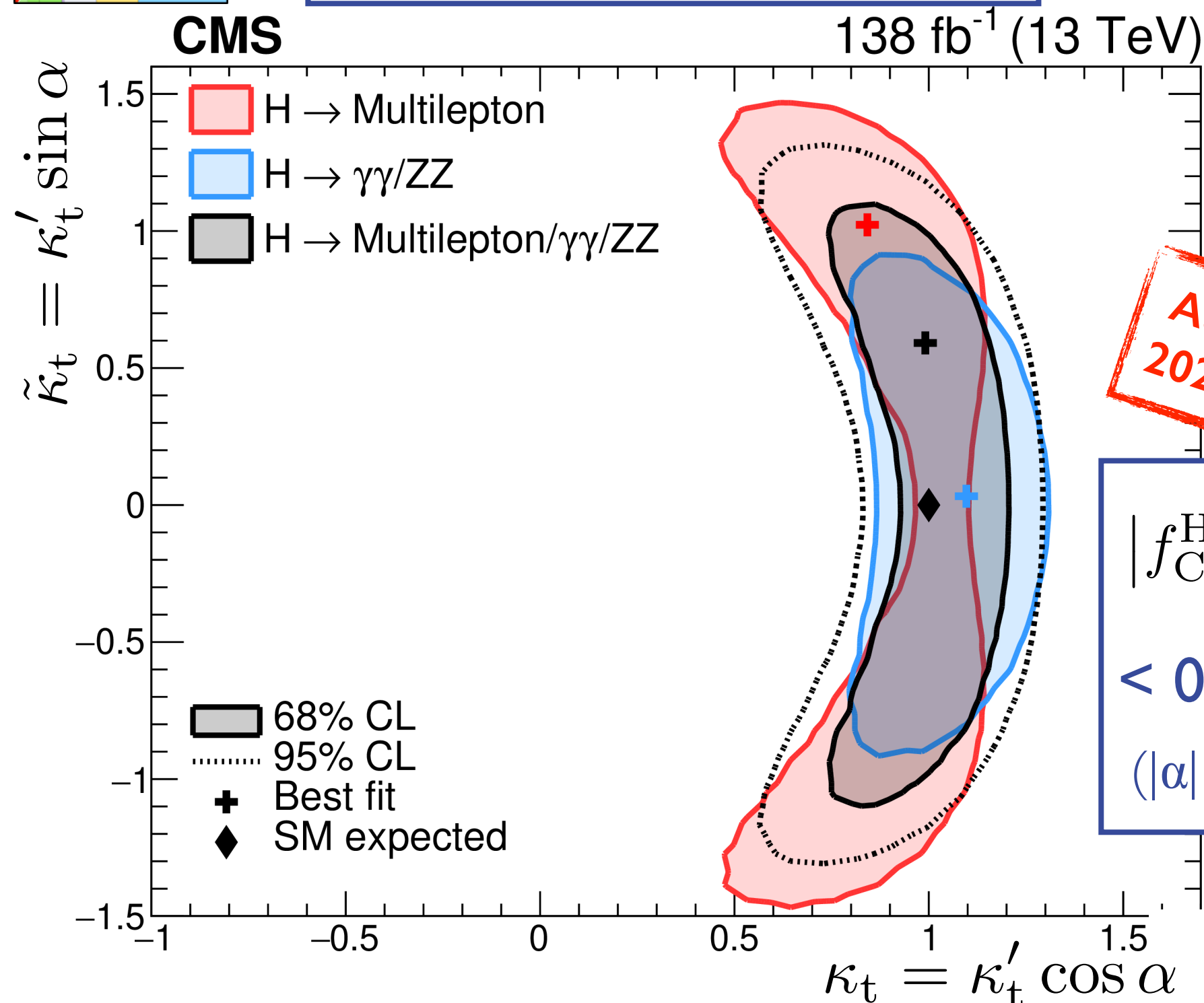


“multilepton” topology
Combine with $\gamma\gamma$ and ZZ^*

$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2} \bar{\psi}_t (\kappa_t + i\gamma_5 \tilde{\kappa}_t) \psi_t H = -\kappa'_t y_t \phi \bar{\psi}_t (\cos \alpha + i\gamma_5 \sin \alpha) \psi_t$$

SM $t\bar{t}H$ coupling: CP-even
($\tilde{\kappa}_t = 0$ or $\alpha = 0^\circ$)

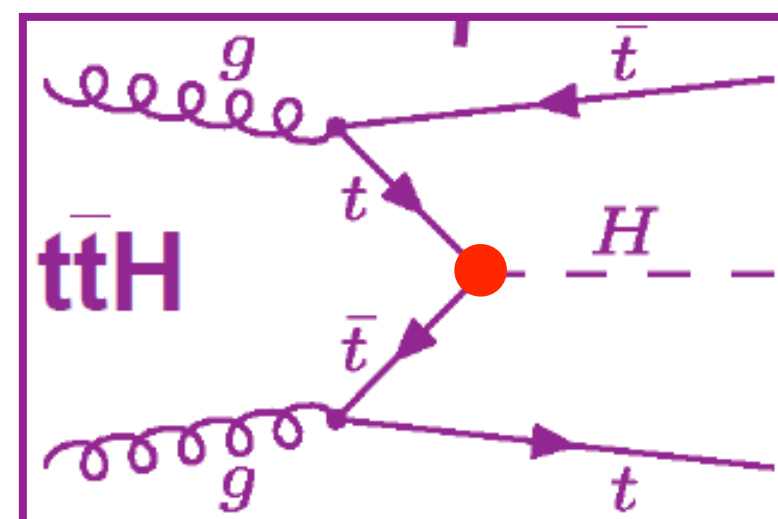
$t\bar{t}H, H \rightarrow \gamma\gamma$ topology



Aug 2022

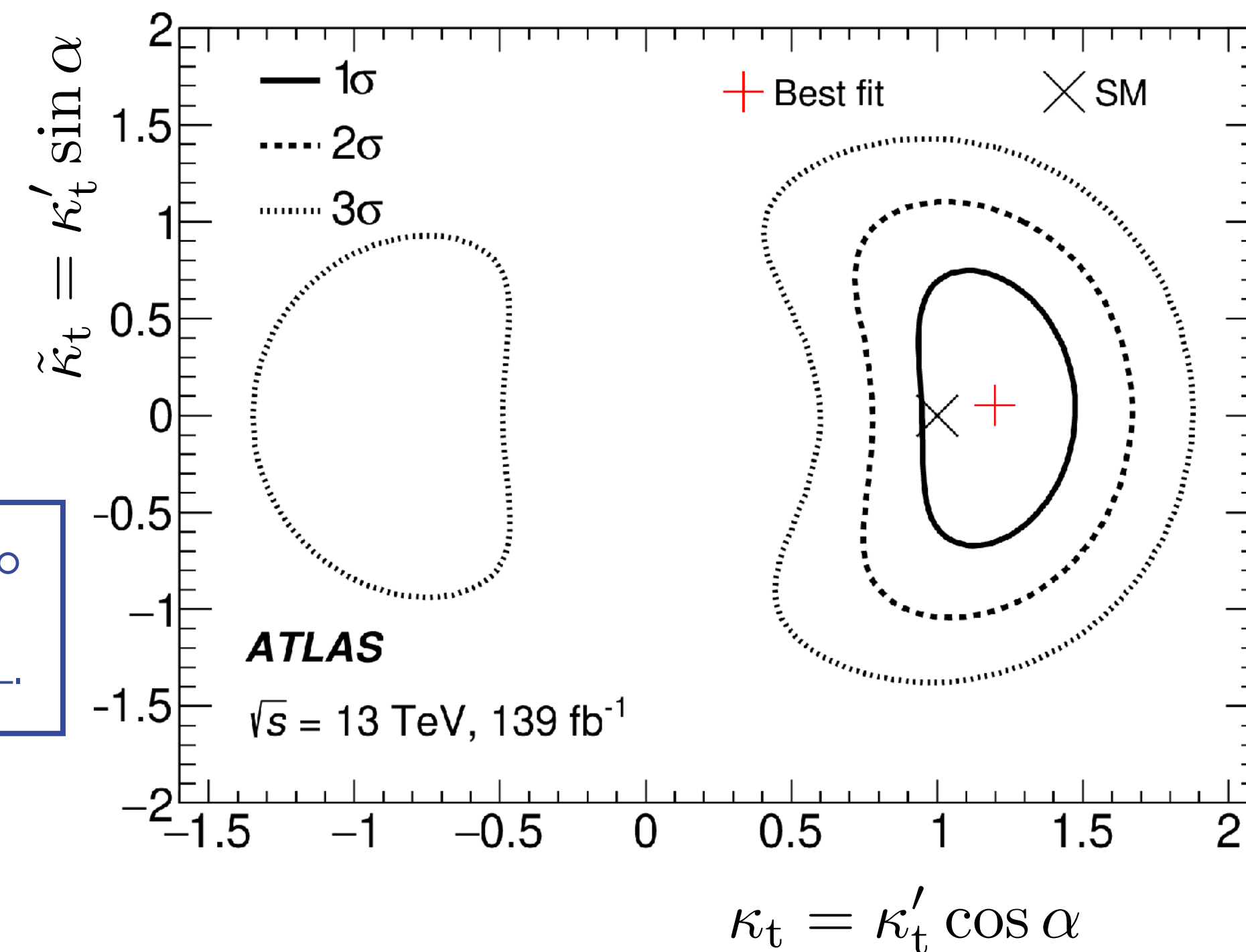
$$|f_{CP}^{Htt}| = \left| \frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2} \right|$$

< 0.55 @ 68% C.L.
($|\alpha| < 48^\circ$ @ 68% C.L.)



$$|\alpha| < 43^\circ$$

@ 95% C.L.



- Pure CP-odd coupling excluded at **3.7 σ** ...

...at **3.9 σ**

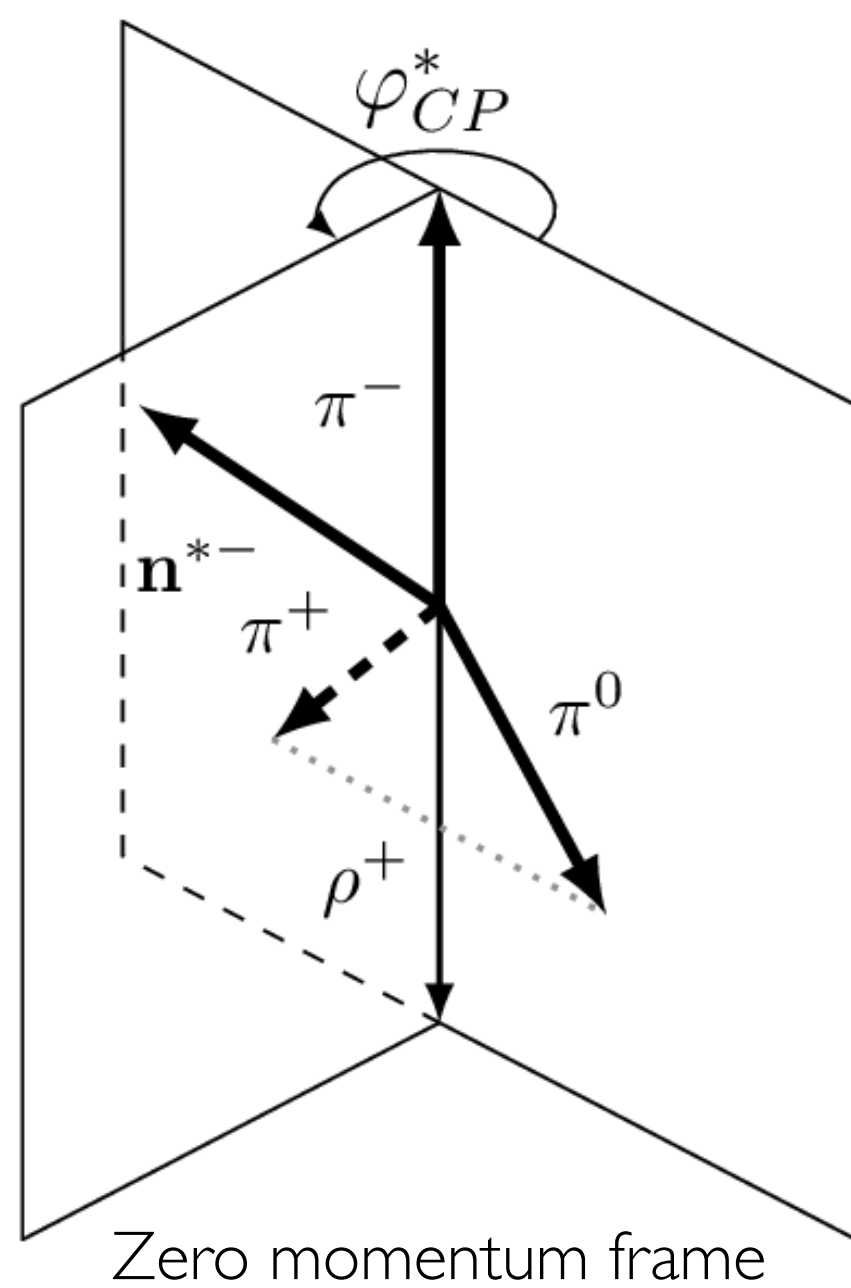


CP Measurement in $H \rightarrow \tau\tau$ Decay GA

Parametrize **τ -Yukawa** coupling: $\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v} \kappa_\tau (\cos \phi_\tau \bar{\tau}\tau + \sin \phi_\tau \bar{\tau}i\gamma_5\tau)H$ SM $H\tau\tau$ coupling: CP-even ($\phi_\tau = 0^\circ$)

- CP-odd in Higgs-Gauge interactions need higher-order operators
- CP-odd in Higgs-fermion interactions (**τ -Yukawa**) can be **tree-level!**
- Reconstruct τ decay modes
- Observable: signed acoplanarity angle between τ decay planes
 - spanned by impact parameter and/or decay products ($\pi^\pm, \pi^0$)

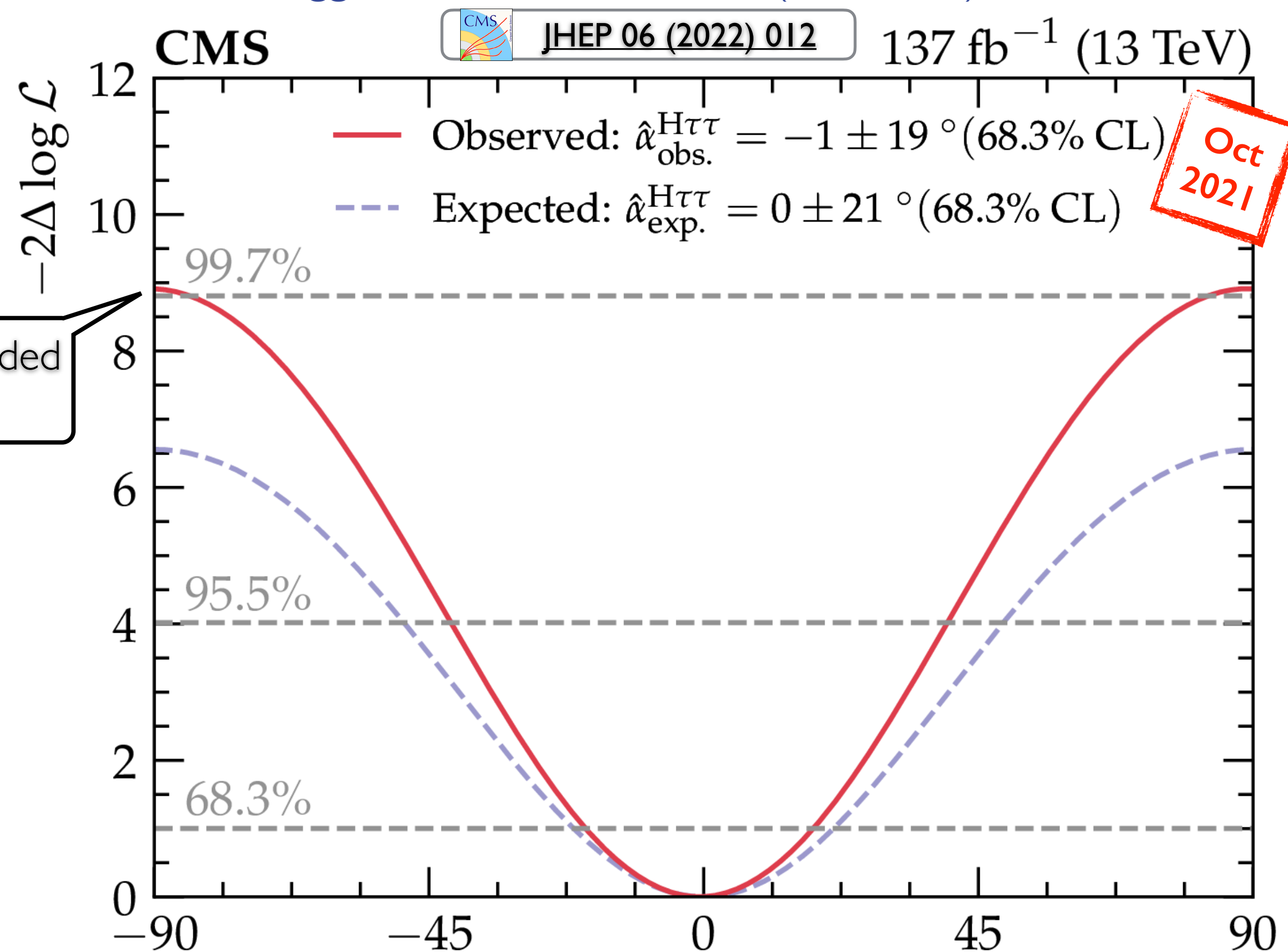
$$H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu \pi^-\nu$$



Pure **CP-odd** excluded
at **3.0 σ** (2.6 σ)

$$\alpha^{H\tau\tau} = -1 \pm 19 \text{ (stat)} \pm 1 \text{ (syst)} \pm 2 \text{ (bin-by-bin)} \pm 1 \text{ (theo)}^\circ$$

$$\alpha^{H\tau\tau} \text{ (degrees)}$$





Higgs couplings different?



July
2025

- SM: Higgs interactions CP-even → test for CP-odd contributions

ATLAS
EXPERIMENT
ATL-PHYS-PUB-2025-031

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$, 139-140 fb⁻¹

$\Lambda = 1 \text{ TeV}$

95% confidence level

Expected • Observed

Best Fit

95% CL

VBF $H \rightarrow \tau\tau$ (prod.)

arXiv:2506.19395

WH, $H \rightarrow bb$ (prod.)

ATL-PHYS-PUB-2025-022

$H \rightarrow WW^*$ (prod.)

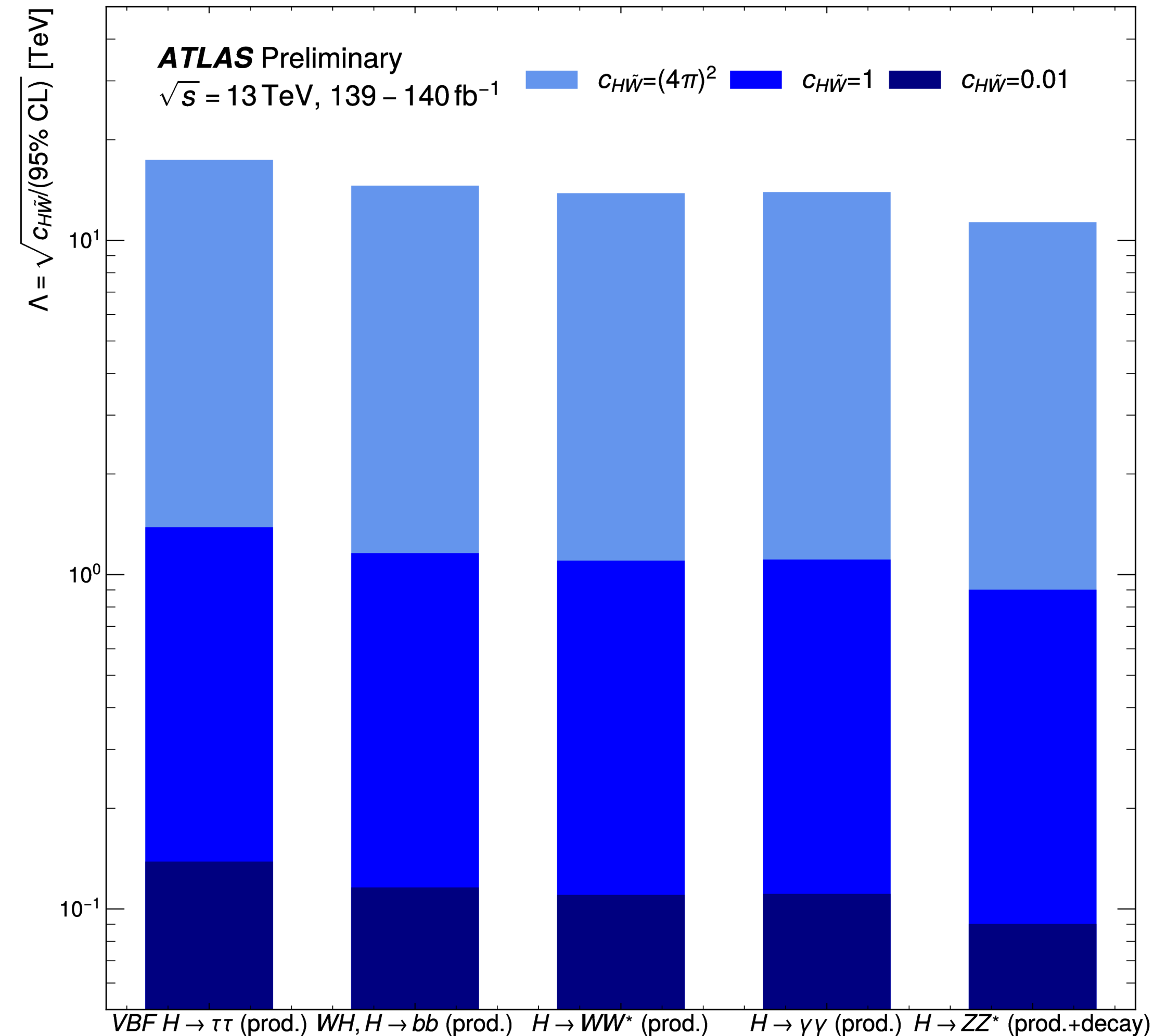
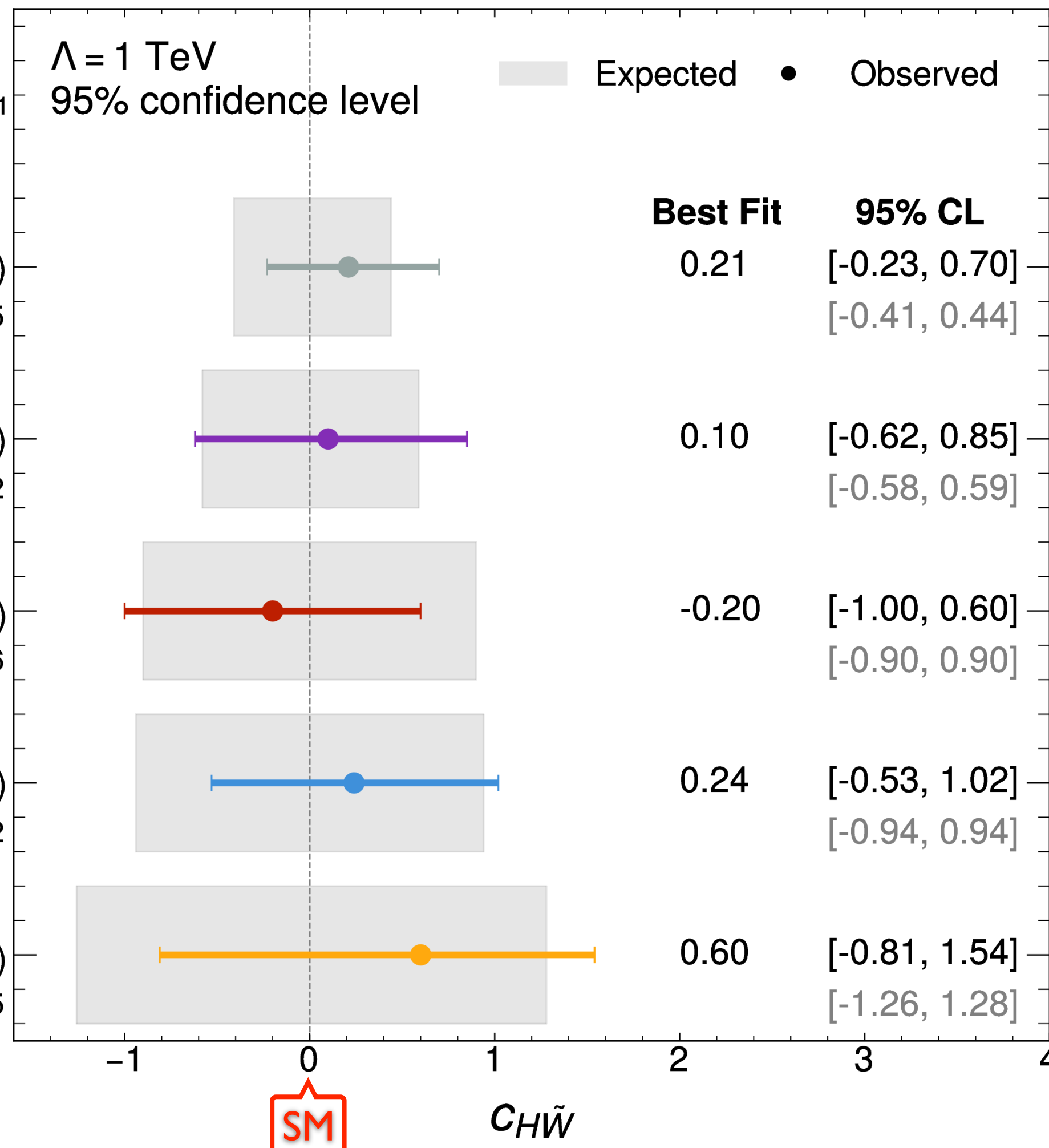
arXiv:2504.07686

$H \rightarrow \gamma\gamma$ (prod.)

Phys. Rev. Lett. 131 (2023) 061802

$H \rightarrow ZZ^*$ (prod.+decay)

JHEP 05 (2024) 105

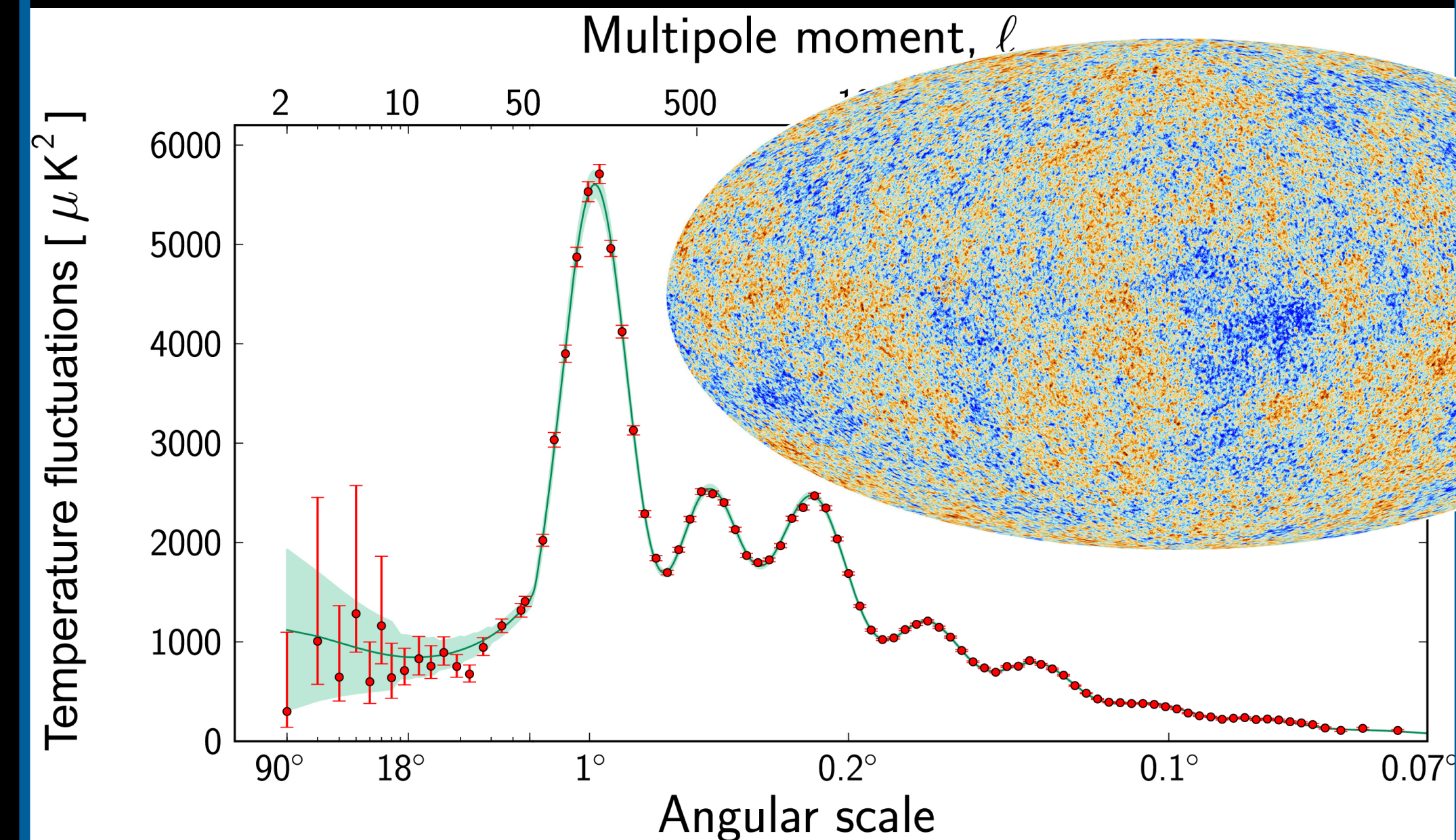




Dark Matter (DM)



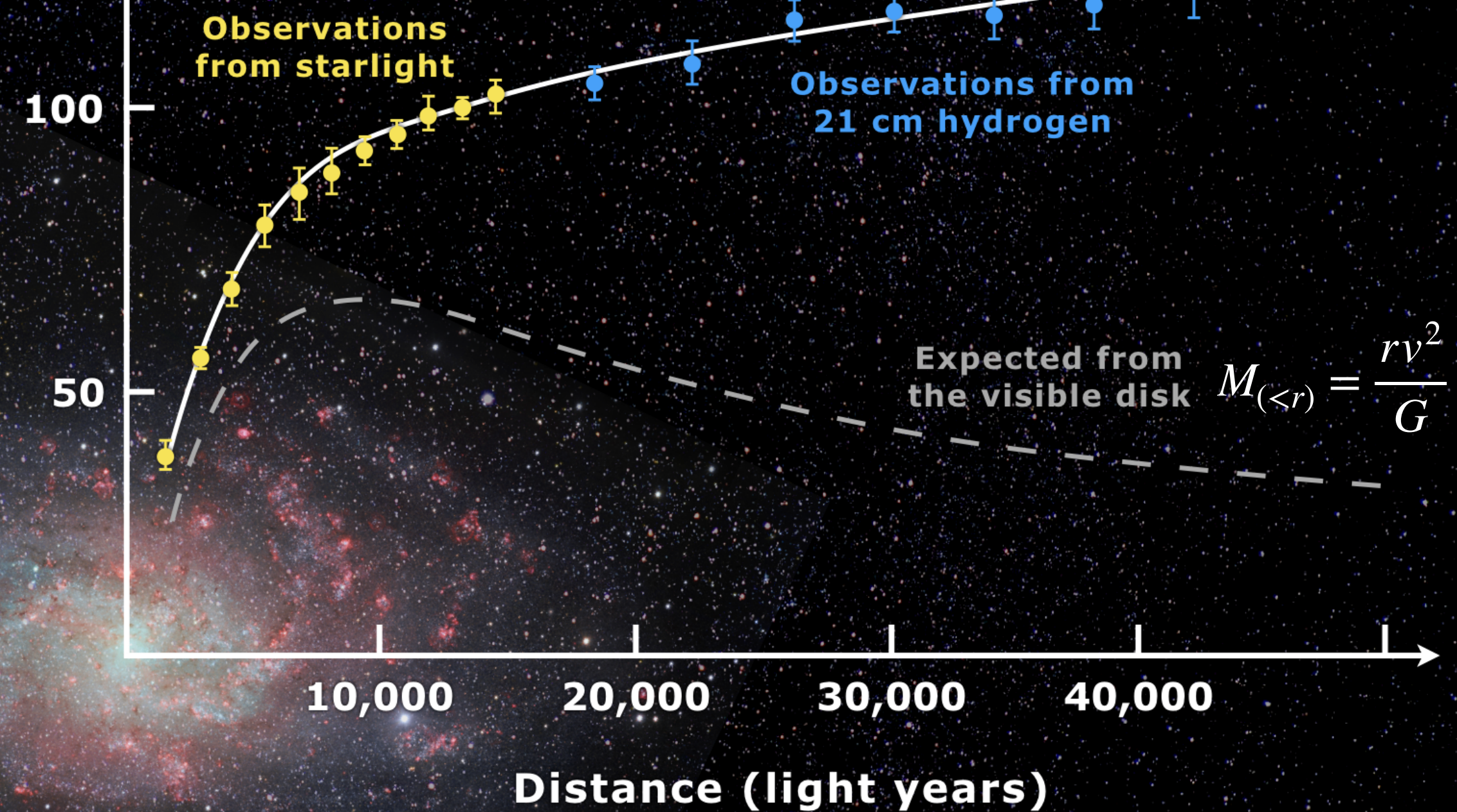
Cosmic Microwave Background



Vera Rubin

Velocity
(km s^{-1})

Galaxy rotation curves



~27% of total energy in Universe is DM

No perfect DM candidate in SM!

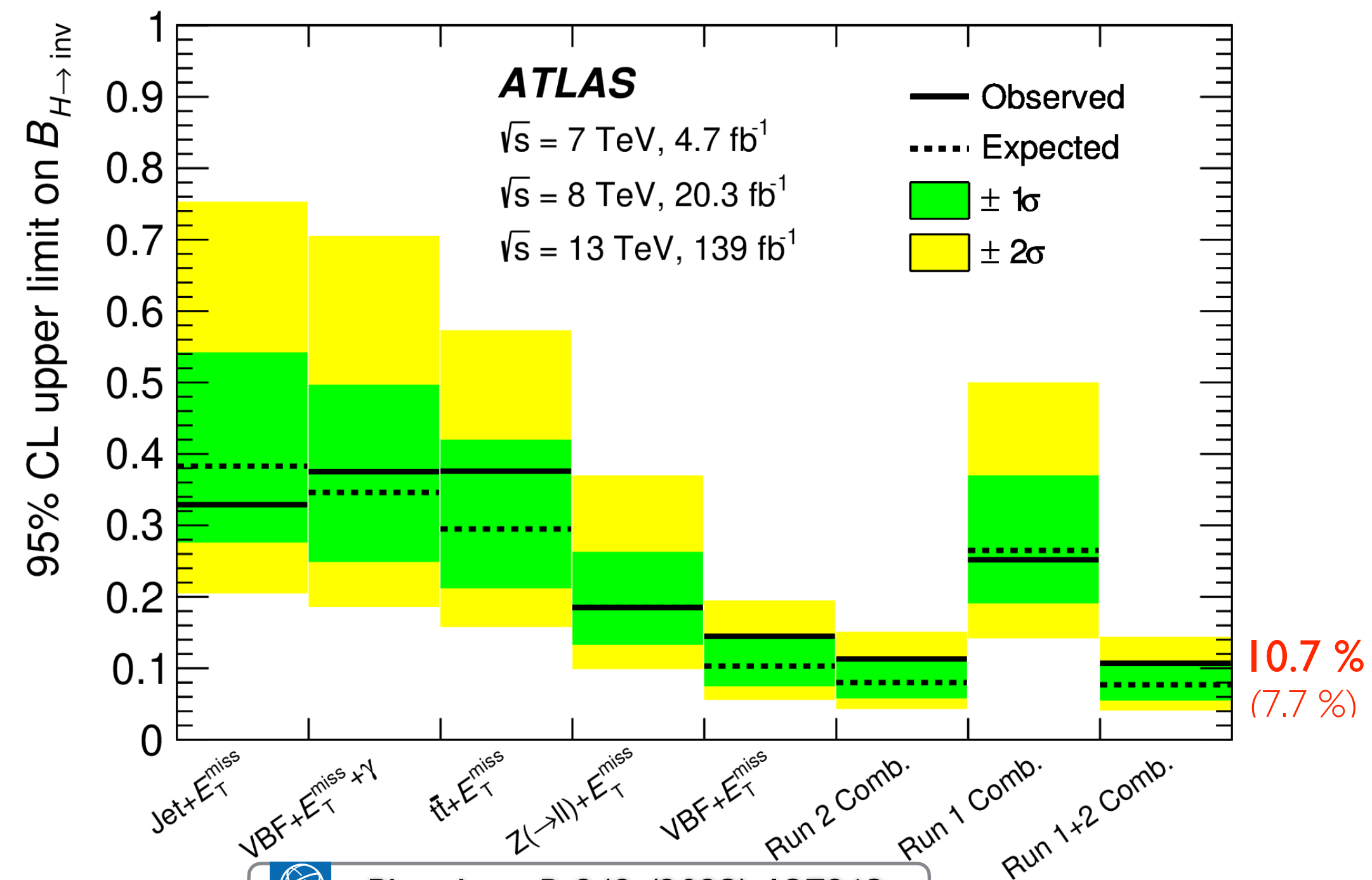


Invisible Higgs Boson Decays

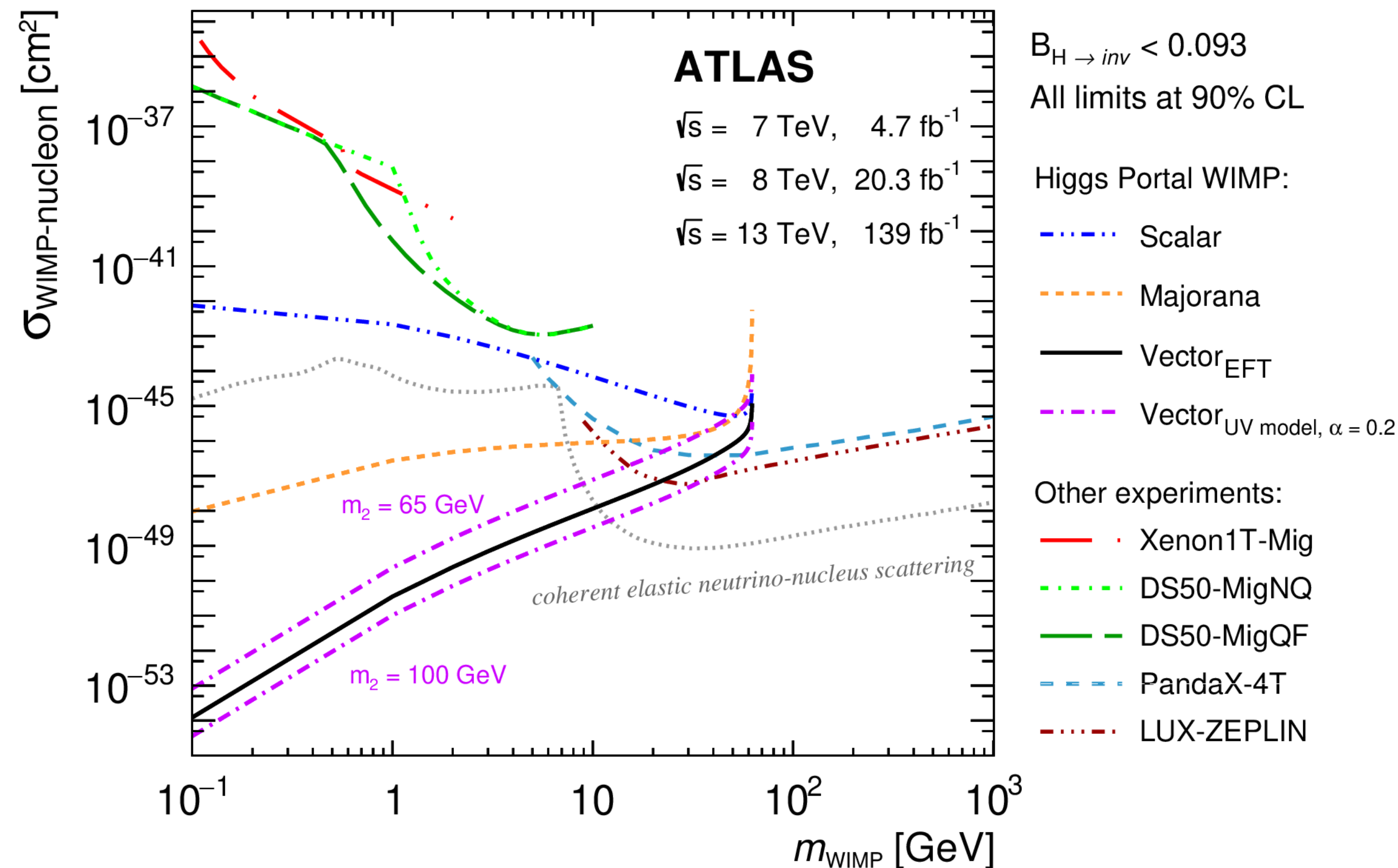
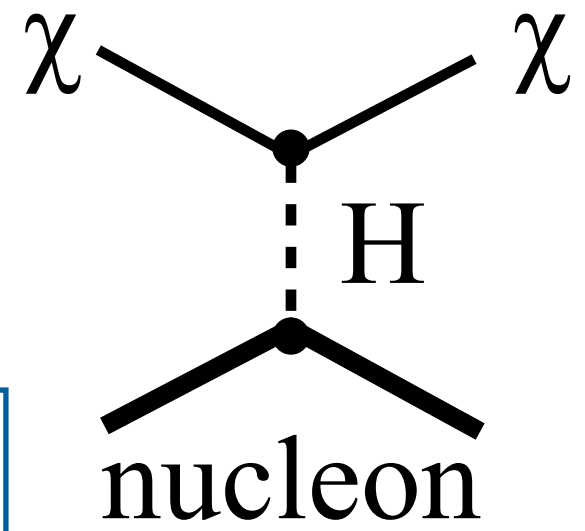


- Search for invisible decays of Higgs boson: addition to Γ_H ?

- SM: $\mathcal{B}(H \rightarrow ZZ^{(*)} \rightarrow 4\nu) \approx 0.1\%$



Interpretation as decay into Dark Matter



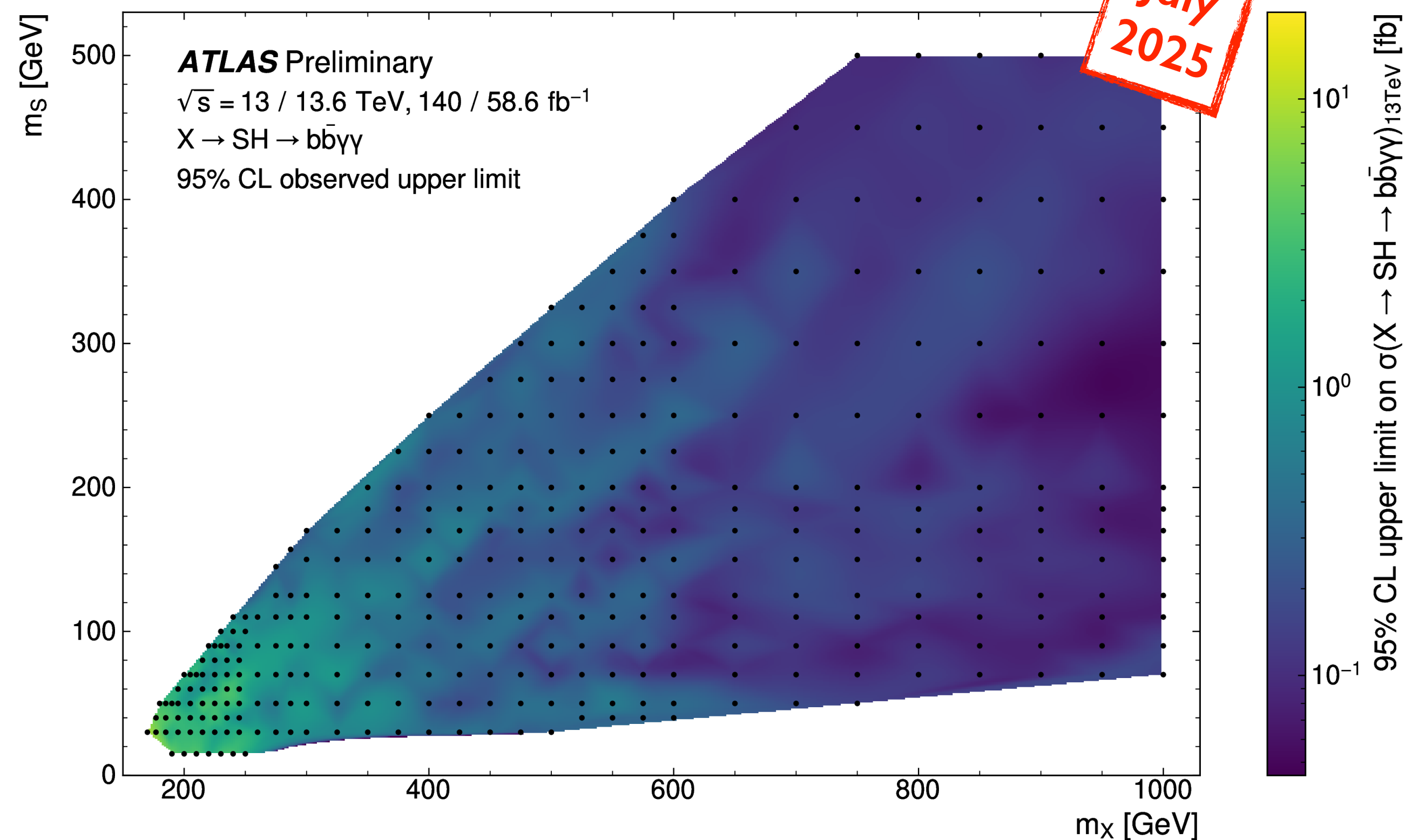
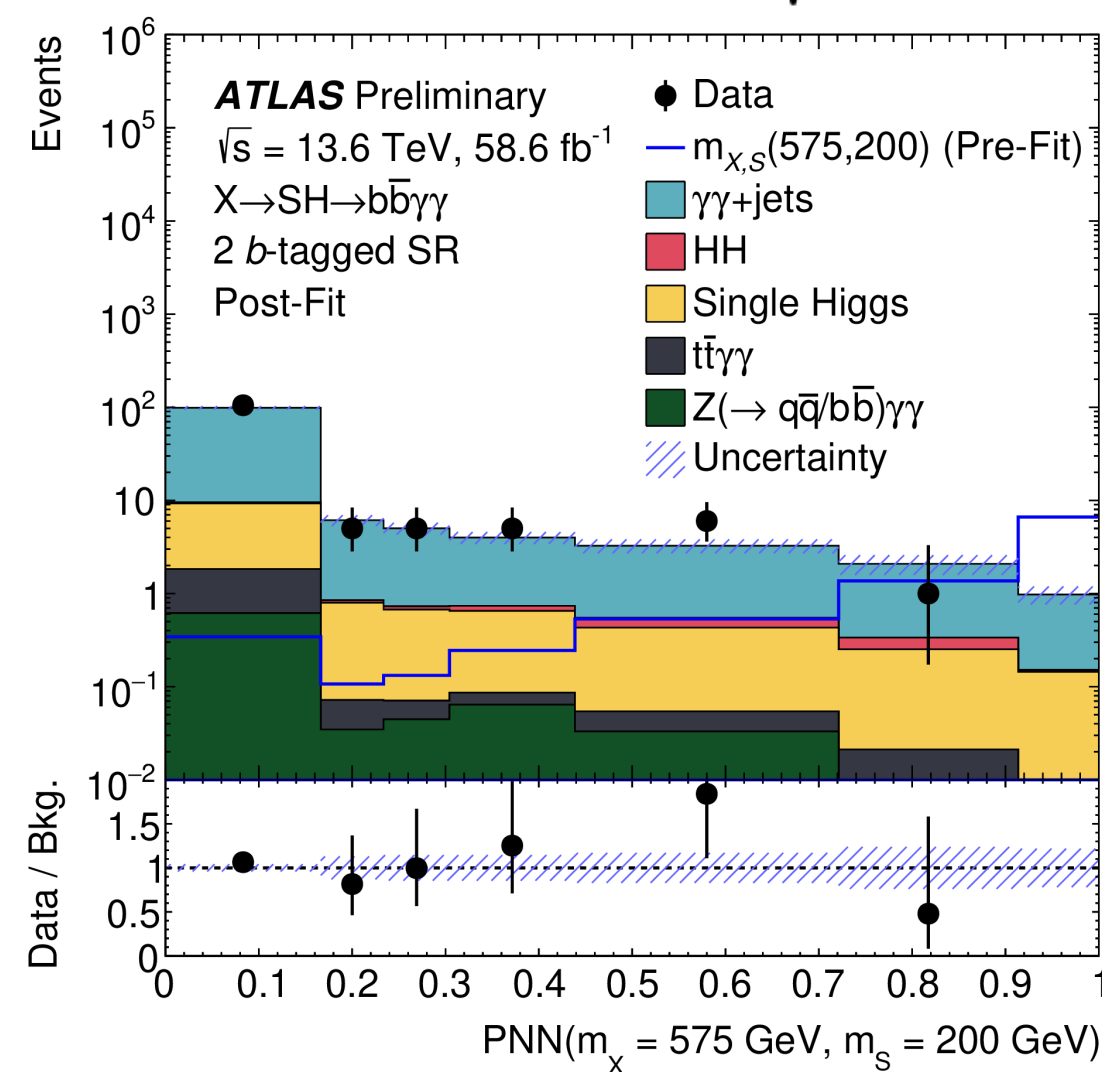
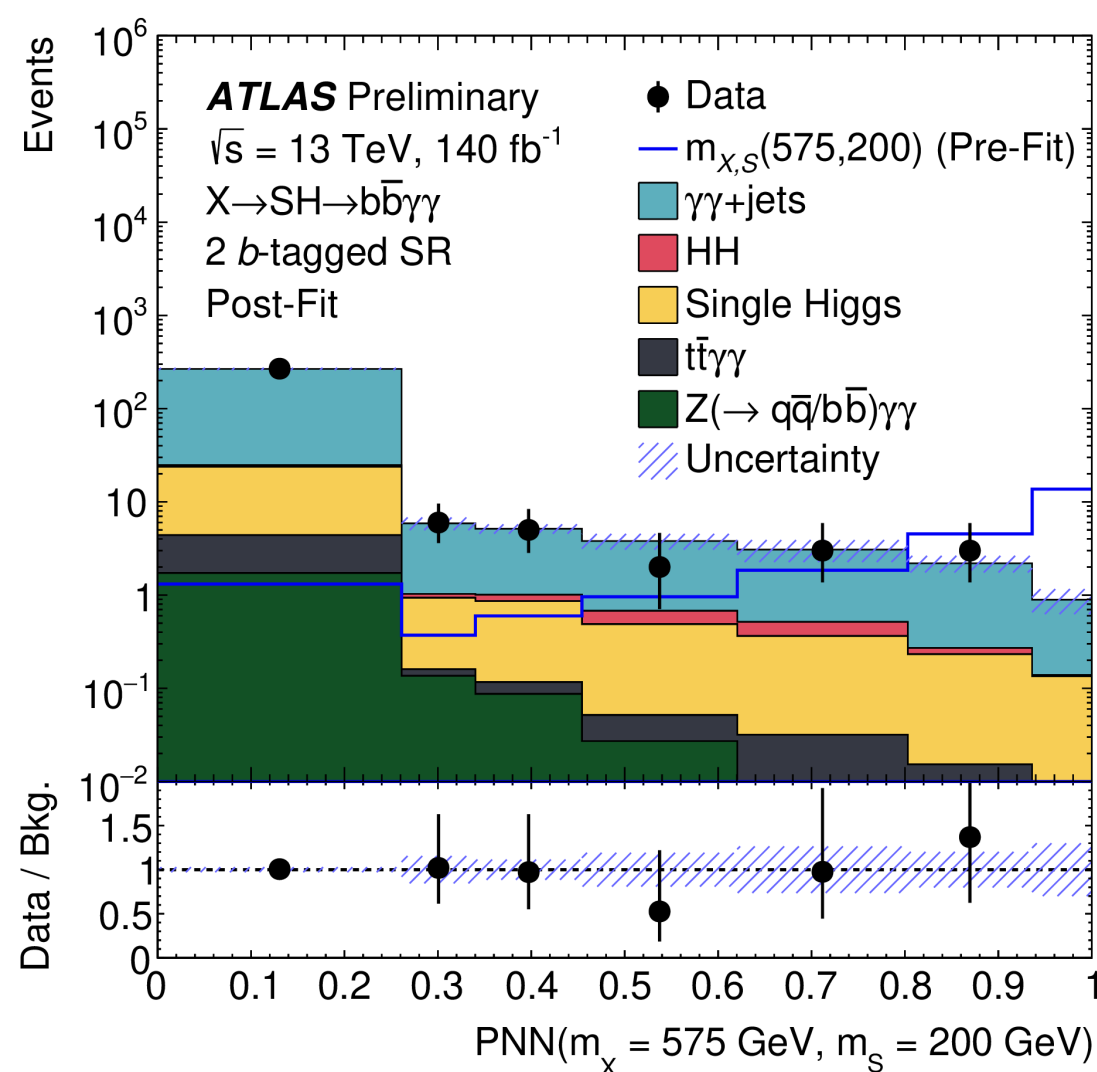
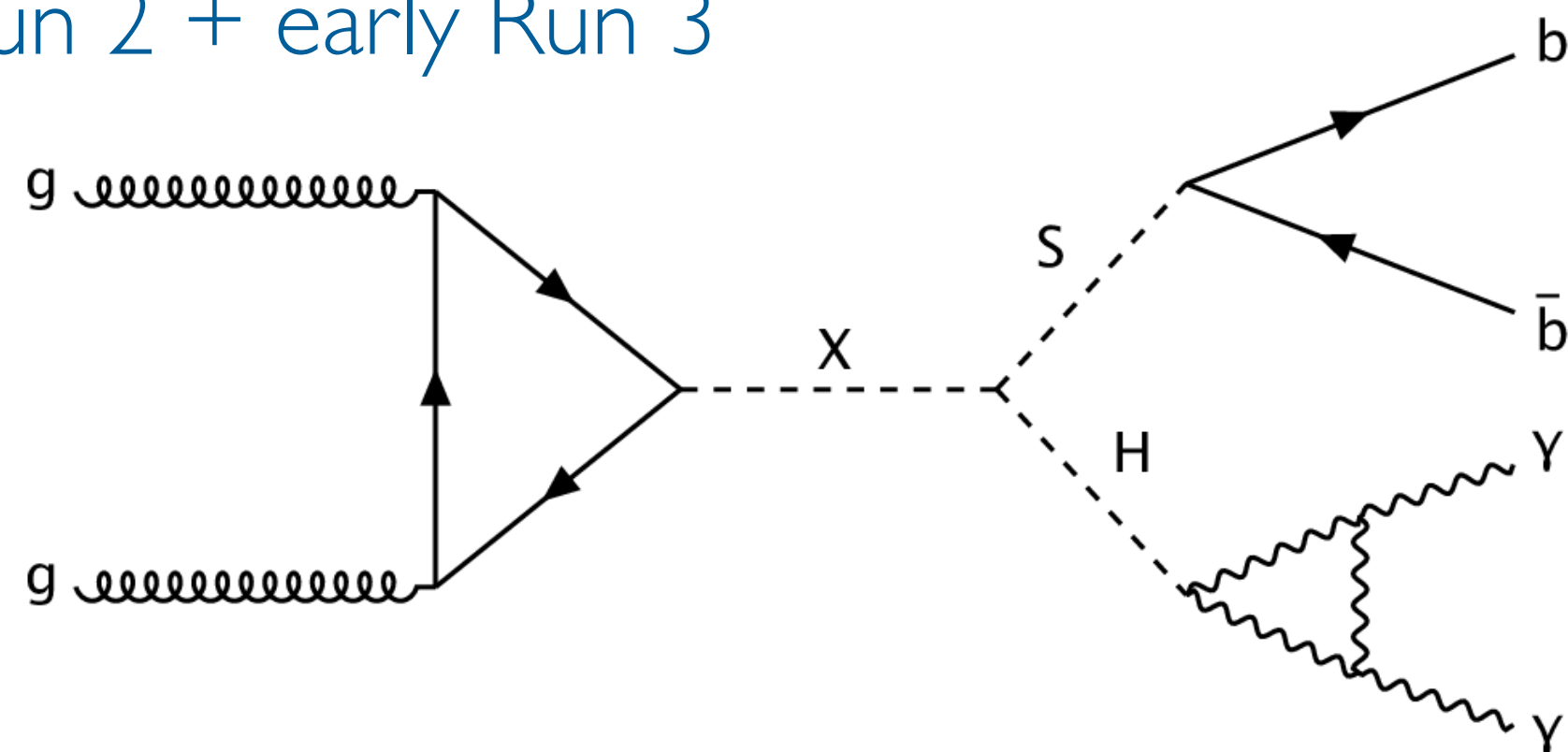


Additional Scalar/Higgs Bosons?



- Search: heavy scalar resonance X decaying to light scalar resonance S and H_{125} boson

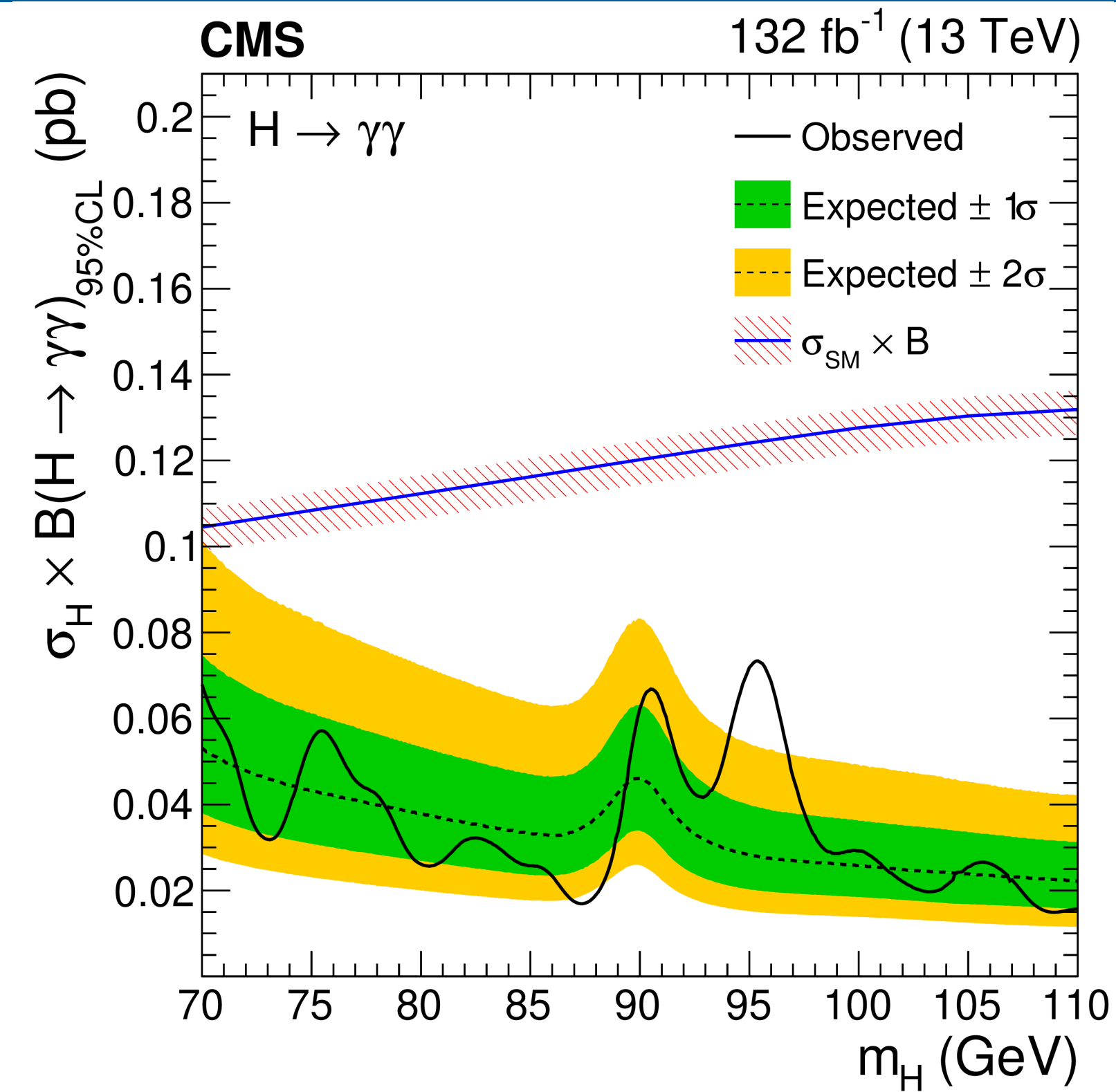
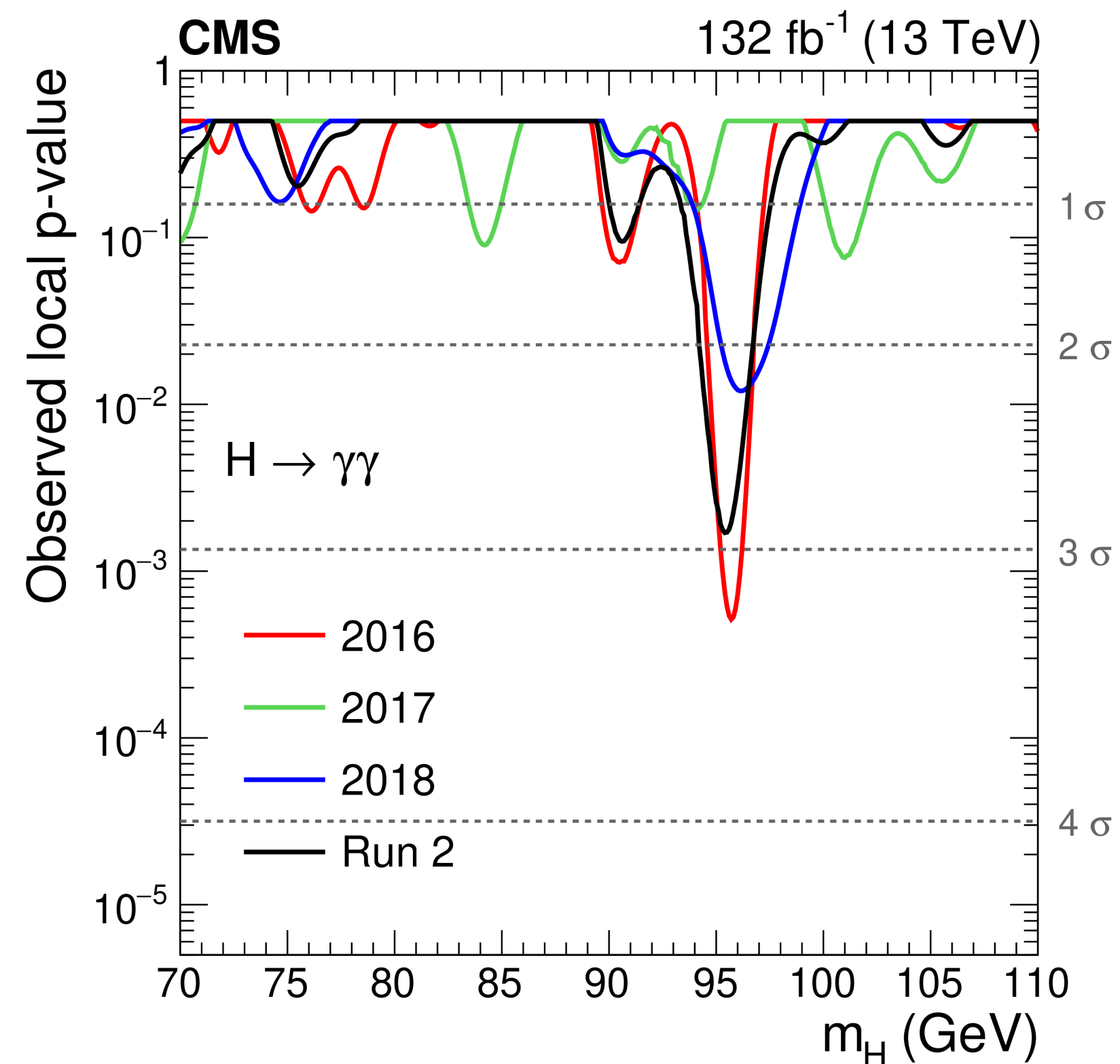
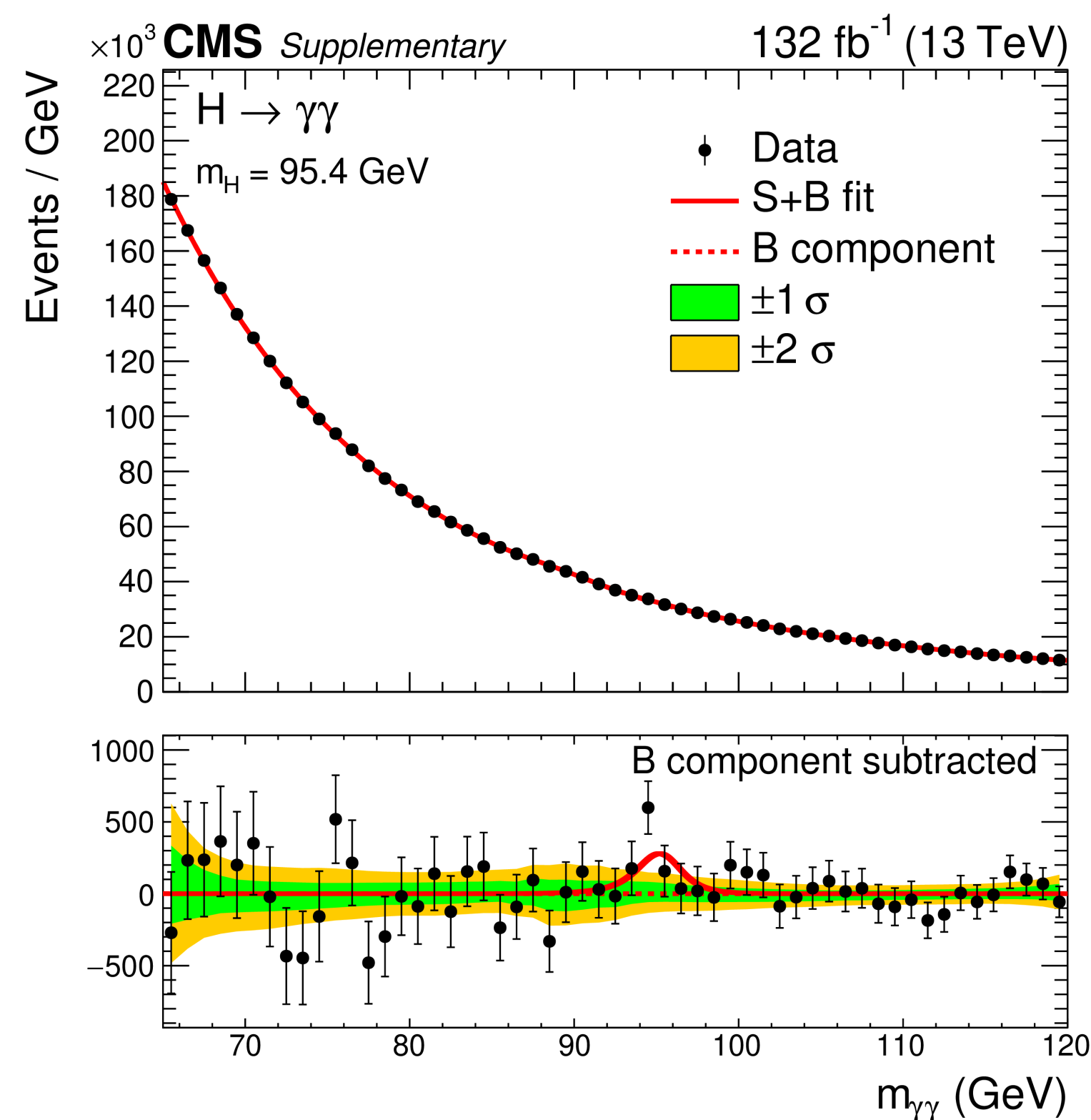
- Run 2 + early Run 3



- Largest excess in $\sigma_{13\text{ TeV}}(pp \rightarrow X) \mathcal{B}(X \rightarrow SH \rightarrow b\bar{b}\gamma\gamma)$ at $(m_X, m_S) = (235, 60)$ GeV: 2.0σ local
- Previous ATLAS deviation at $(m_X, m_S) = (235, 60)$ GeV with 3.5σ (2.0σ) local (global) not confirmed



$H \rightarrow \gamma\gamma$



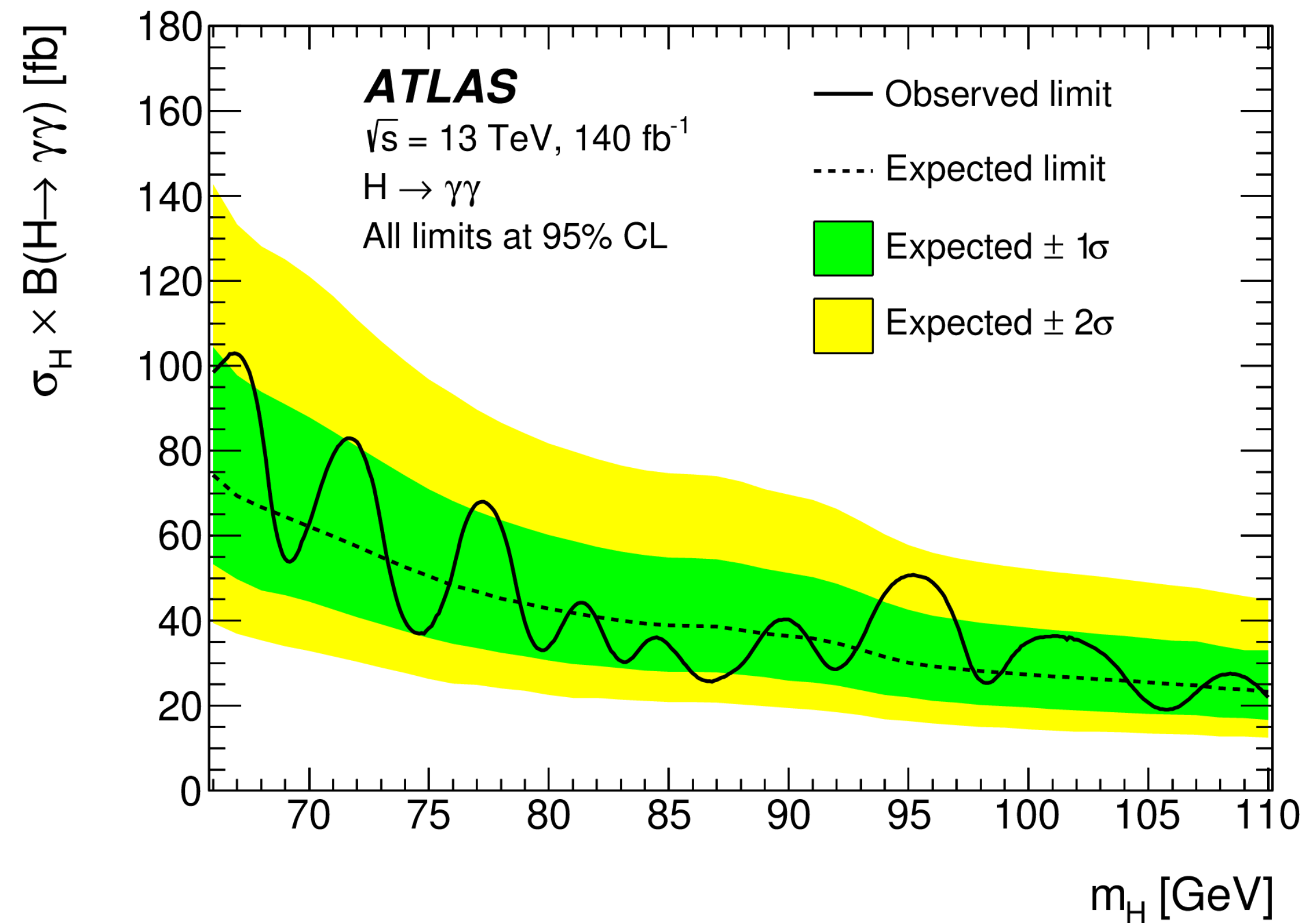
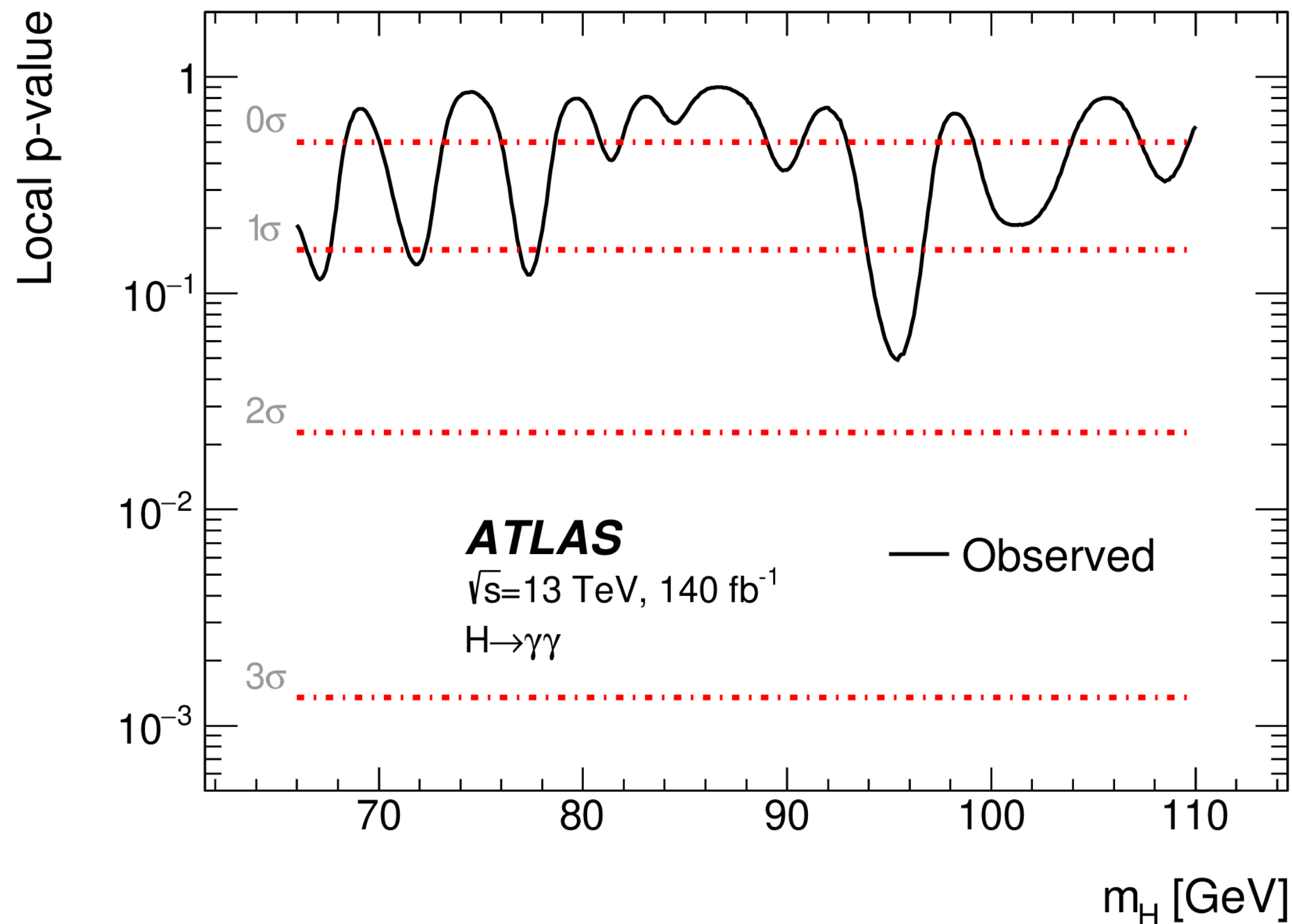
- Search below $m_H = 125$ GeV in $\gamma\gamma$ mass spectrum
- Largest excess at $m_H = 95.4$ GeV: 2.9 σ local, 1.3 σ global
 - $\sigma \times BR(H \rightarrow \gamma\gamma) \Big|_{m_H=95.4 \text{ GeV}} < 73 \text{ fb @ 95\% C.L.}$
 - Present in different production modes: ggF+ttH, VBF, VH



$H \rightarrow \gamma\gamma$



- Model independent (generic spin-0, fiducial σ) and model dependent (SM-like Higgs, total σ) search in 66-110 GeV
 - 3 categories of un/converted photons
 - MVAs used for SM-like analysis to both mitigate background processes and classify events



- Largest excess at $m_H = 95.4 \text{ GeV}$: 1.7σ local
 - $\sigma \times BR(H \rightarrow \gamma\gamma) \Big|_{m_H=95.4 \text{ GeV}} \approx 50 \text{ fb @ } 95\% \text{ C.L.}$

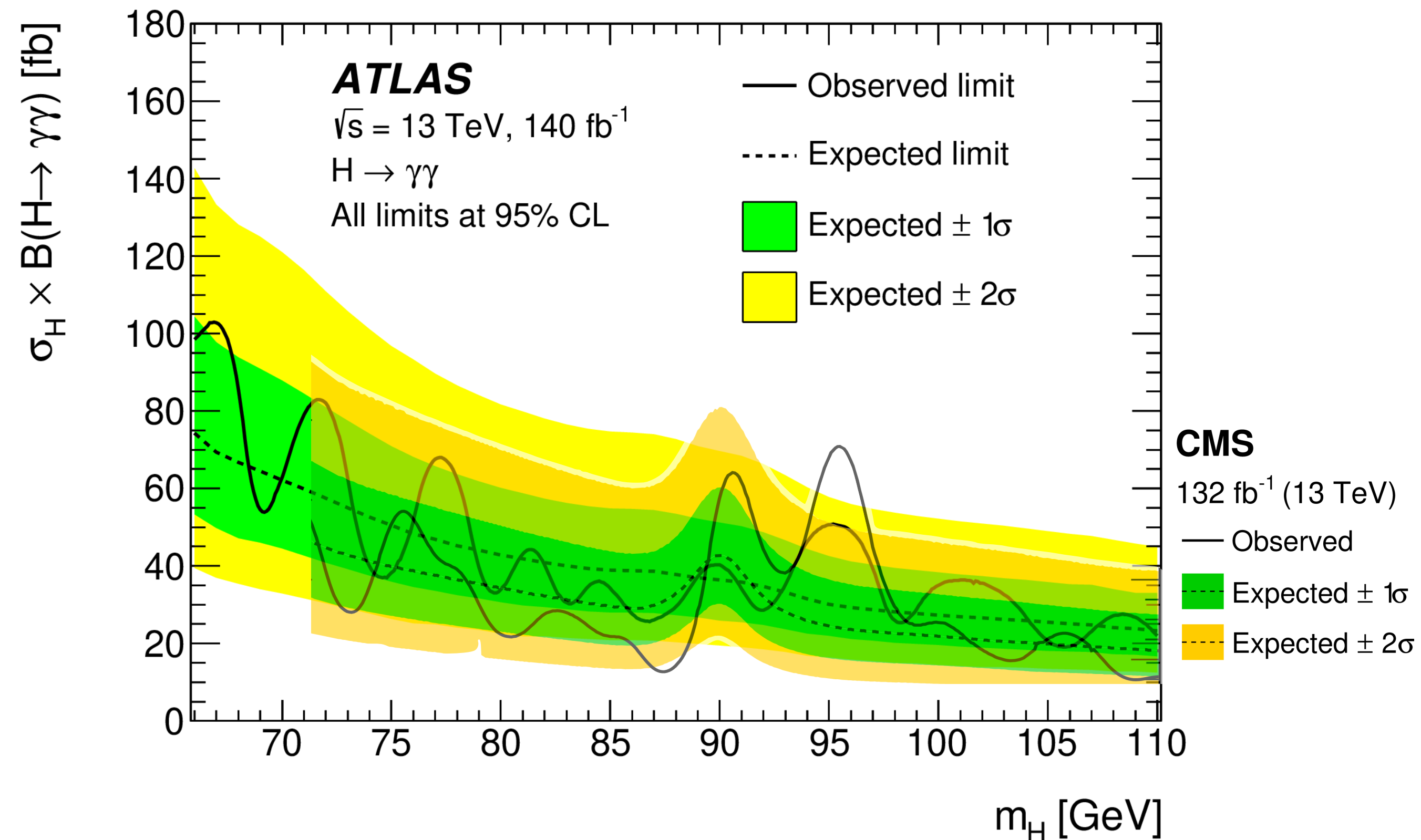


$H \rightarrow \gamma\gamma$



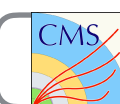
- Model independent (generic spin-0, fiducial σ) and model dependent (SM-like Higgs, total σ) search in 66-110 GeV
 - 3 categories of un/converted photons
 - MVAs used for SM-like analysis to both mitigate background processes and classify events

- Intriguing to see small bump at same mass...
 - Quite low significances though...
- Let's see what Run 3 has to say...



- Largest excess at $m_H = 95.4 \text{ GeV}$: 2.9σ local, 1.3σ global
 - $\sigma \times BR(H \rightarrow \gamma\gamma) \Big|_{m_H=95.4 \text{ GeV}} < 73 \text{ fb @ 95\% C.L.}$

- Largest excess at $m_H = 95.4 \text{ GeV}$: 1.7σ local
 - $\sigma \times BR(H \rightarrow \gamma\gamma) \Big|_{m_H=95.4 \text{ GeV}} \approx 50 \text{ fb @ 95\% C.L.}$





$$\phi \rightarrow \tau^+ \tau^-$$



- $\phi \rightarrow \tau\tau$ search, 60-3500 GeV:

- Final states:

$e\mu, e\tau_{\text{had}}, \mu\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$

$m_\phi = 95 \text{ GeV:}$

- 2.6σ local, 2.3σ global;
- Best fit $\sigma_{\text{gg}\phi} \mathcal{B}(\phi \rightarrow \tau\tau) = (7.8^{+3.9}_{-3.1}) \text{ pb}$

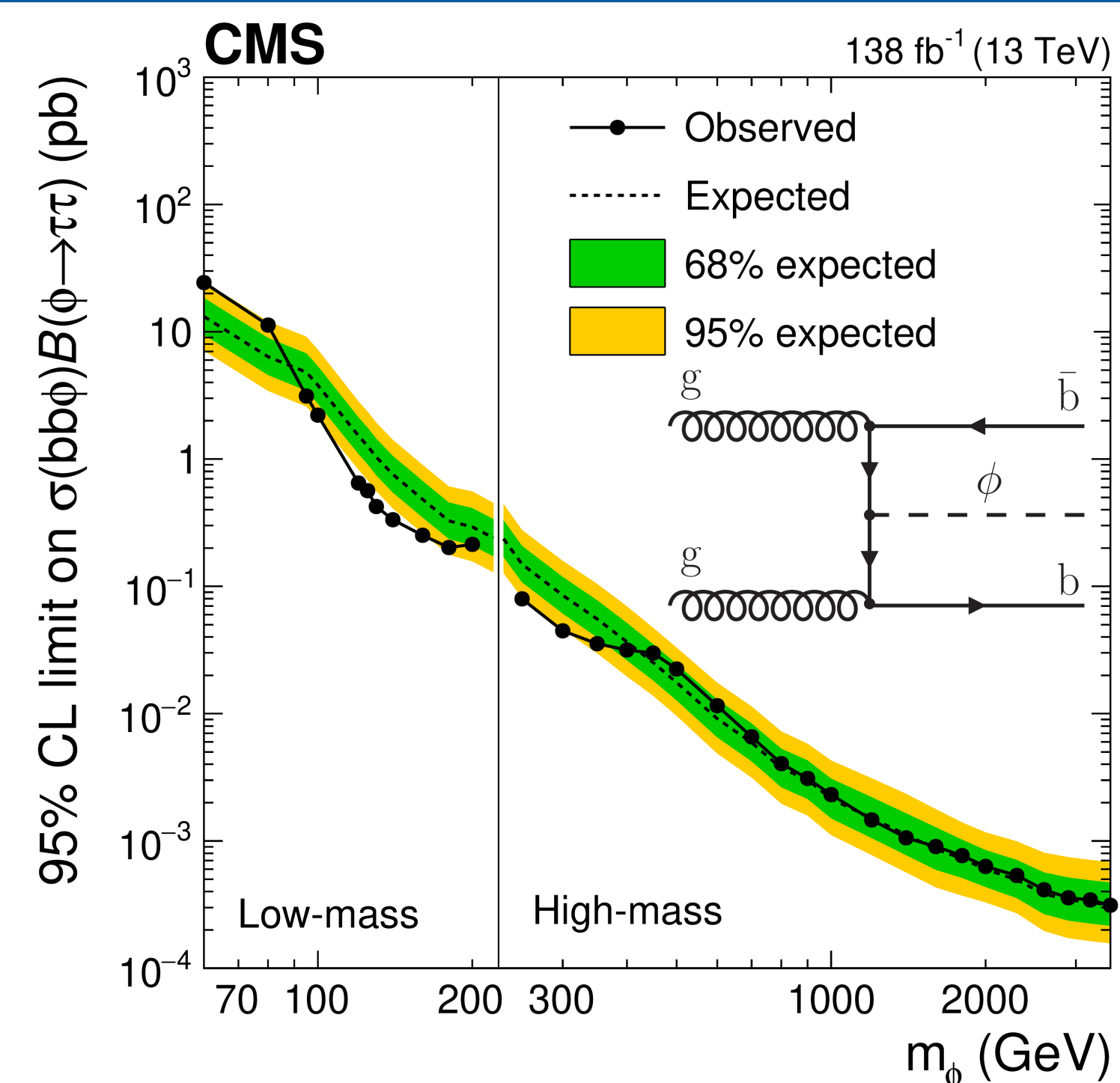
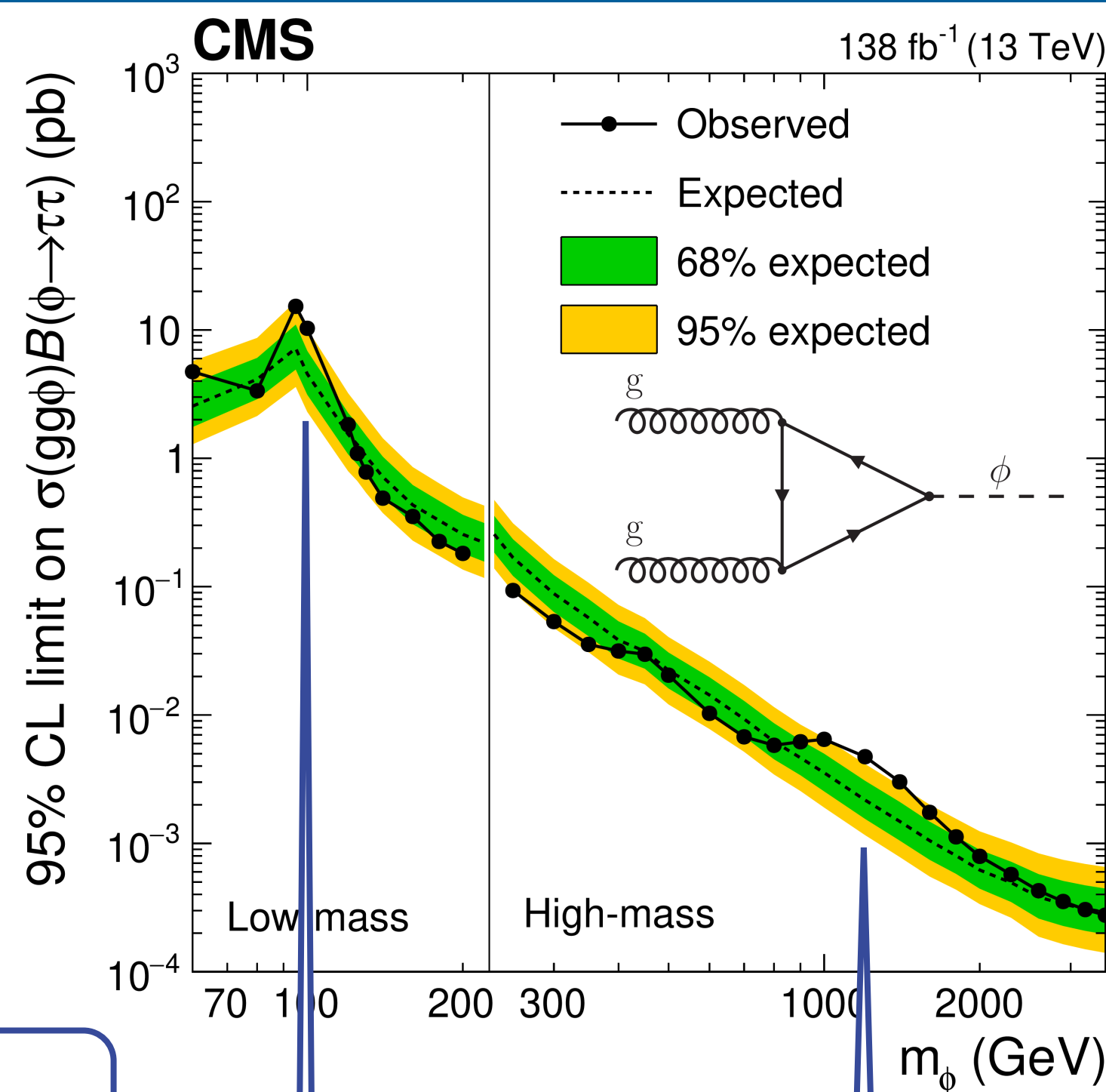
- Not seen in $bb\phi$ production
- No ATLAS counterpart yet (also not clearly seen in SM $H \rightarrow \tau\tau$ measurement)

$m_\phi = 100 \text{ GeV:}$

- 3.1σ local, 2.7σ global;
- Best fit $\sigma_{\text{gg}\phi} \mathcal{B}(\phi \rightarrow \tau\tau) = (5.8^{+2.5}_{-2.0}) \text{ pb}$
- p-value 50% (58%) for compatibility across $\tau\tau$ final states (data-taking years).

$m_\phi = 1200 \text{ GeV:}$

- 2.8σ local, 2.2σ global;
- Best fit $\sigma_{\text{gg}\phi} \mathcal{B}(\phi \rightarrow \tau\tau) = (3.1^{+1.0}_{-1.1}) \text{ fb}$
- p-value 11% (63%) for compatibility across $\tau\tau$ final states (data-taking years).
- Excluded by **ATLAS** full Run-2 ($200 < m_\phi < 2500 \text{ GeV}$) [[Phys. Rev. Lett. 125 \(2020\) 051801](#)];
95% C.L. obs. (exp.) upper limit: $\sim 1.7 \text{ fb}$ ($\sim 2.7 \text{ fb}$)

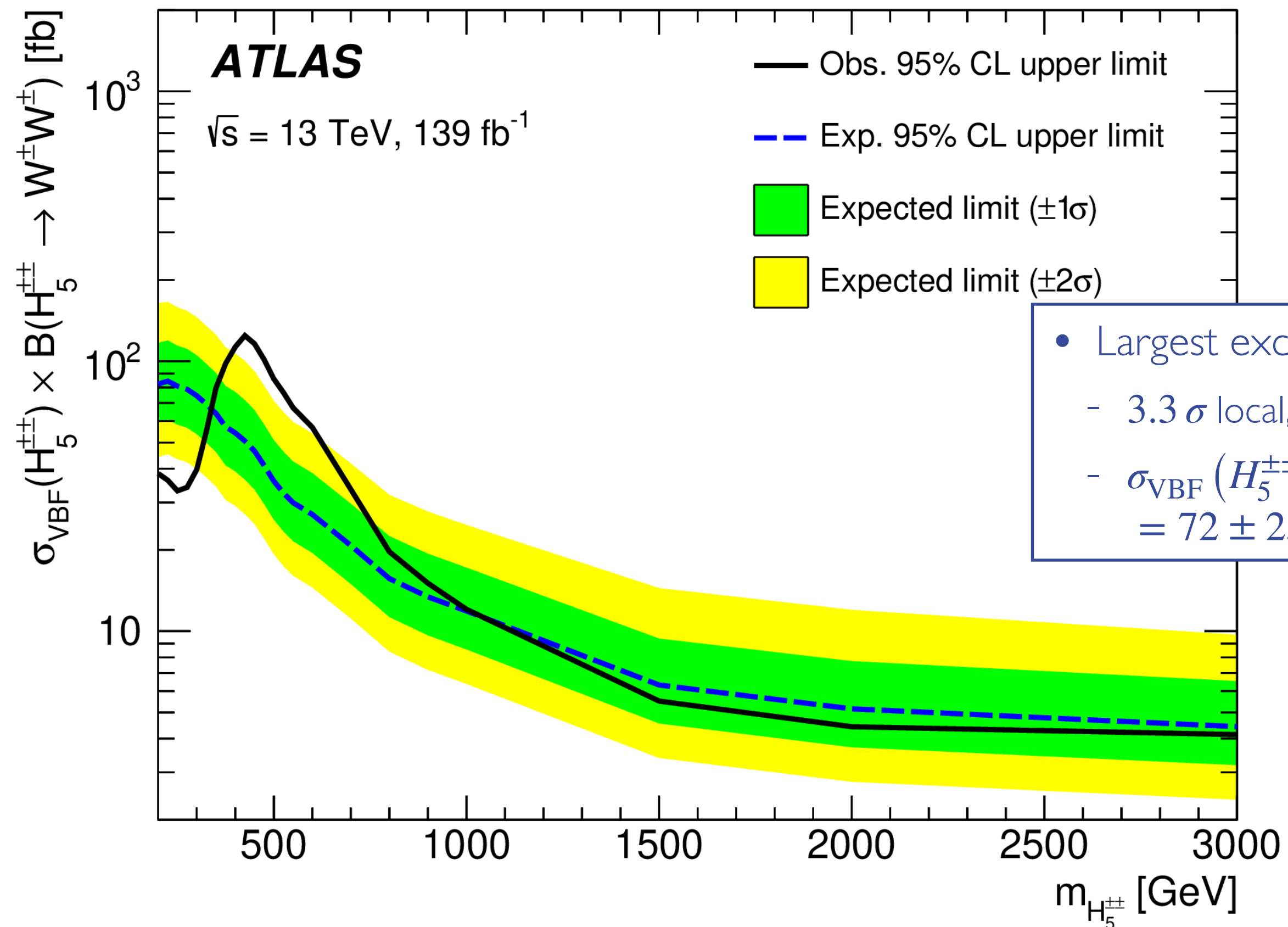
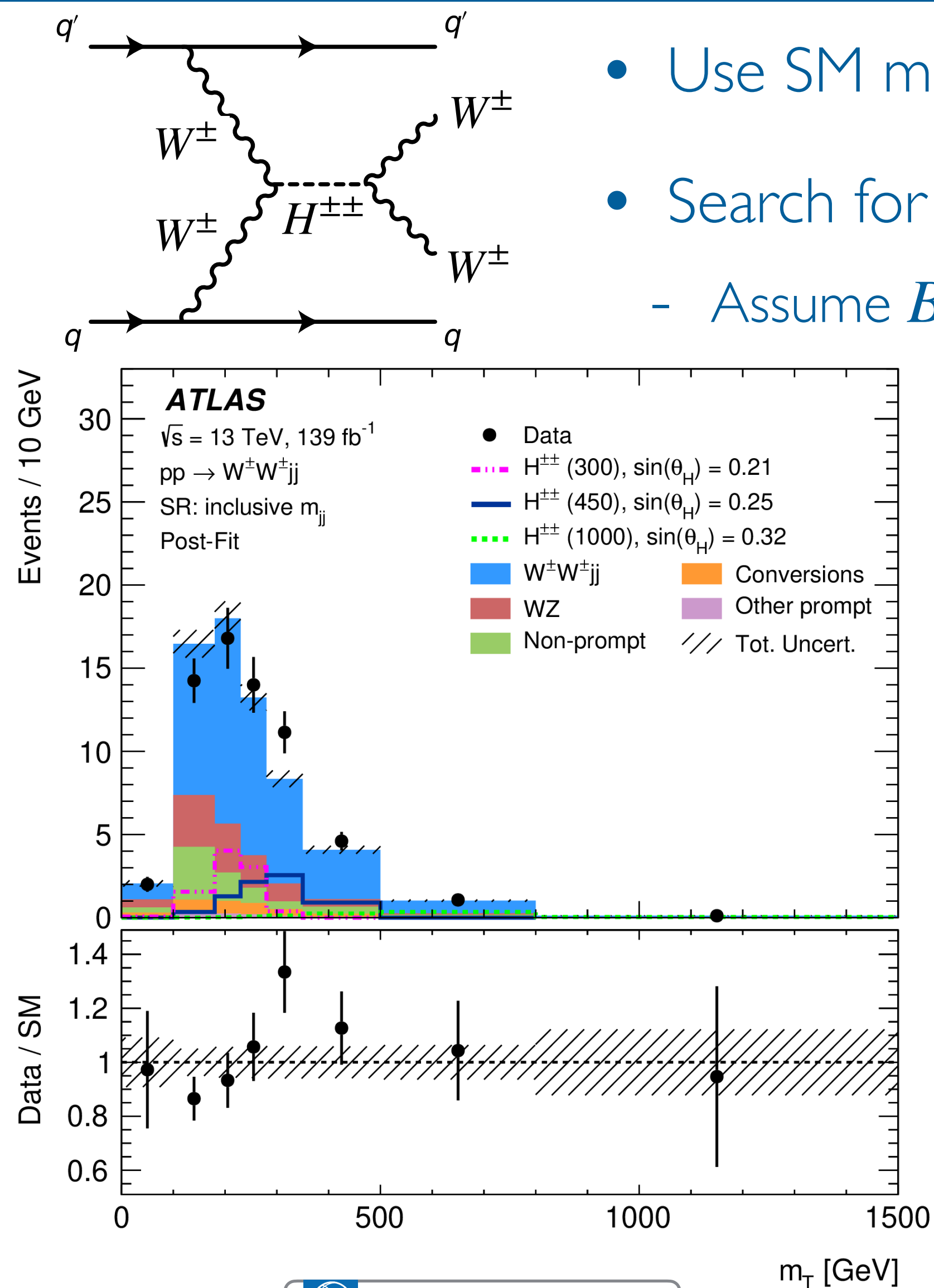




$$H^{++}jj \rightarrow W^+W^+jj \rightarrow \ell\nu\ell\nu jj$$



- Use SM measurement of EW $W^\pm W^\pm jj$ production
- Search for $H^{\pm\pm}$ production in context of Georgi-Machacek model
 - Assume $BR(H_5^{\pm\pm} \rightarrow W^\pm W^\pm) = 100\%$



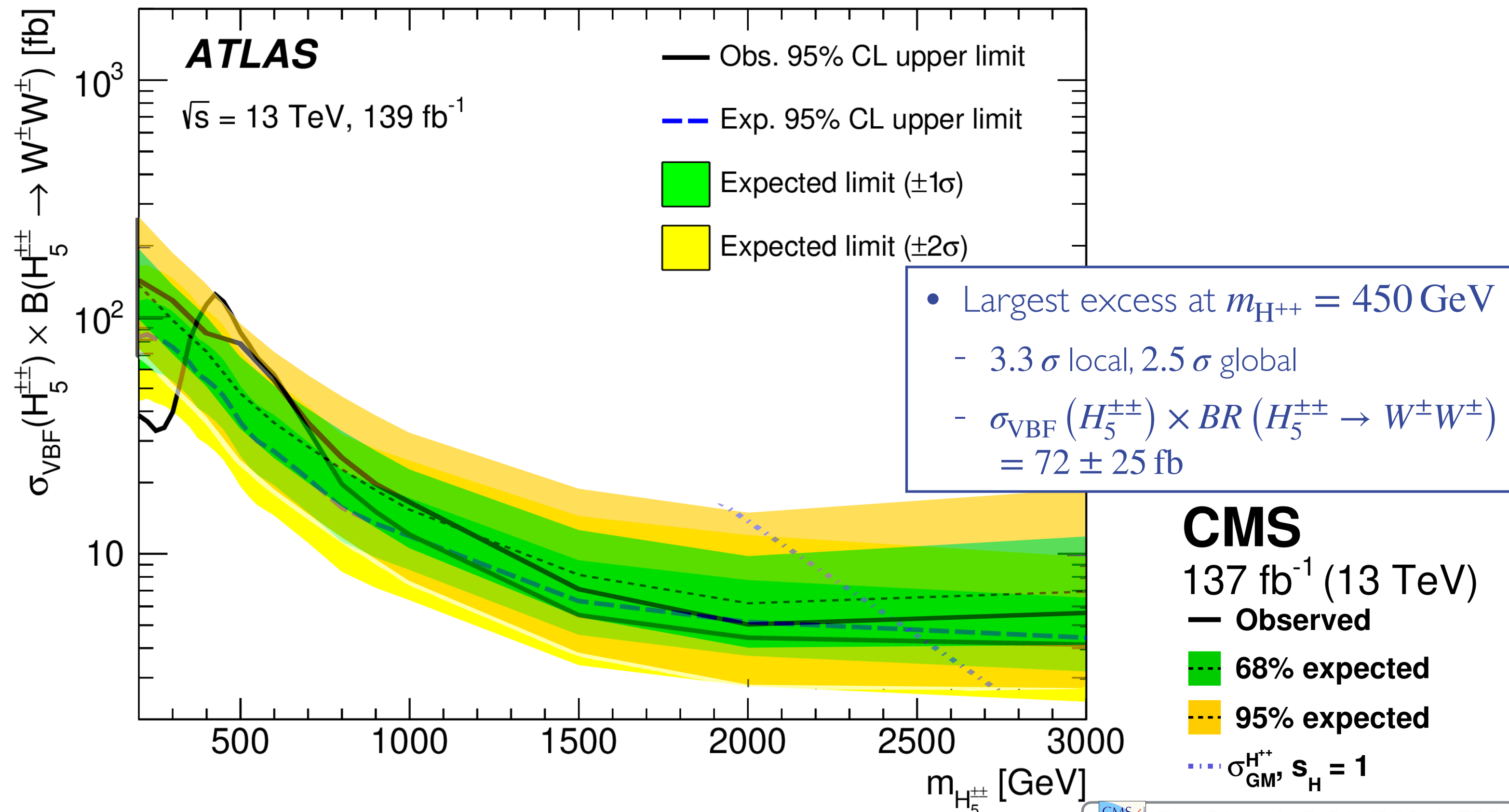
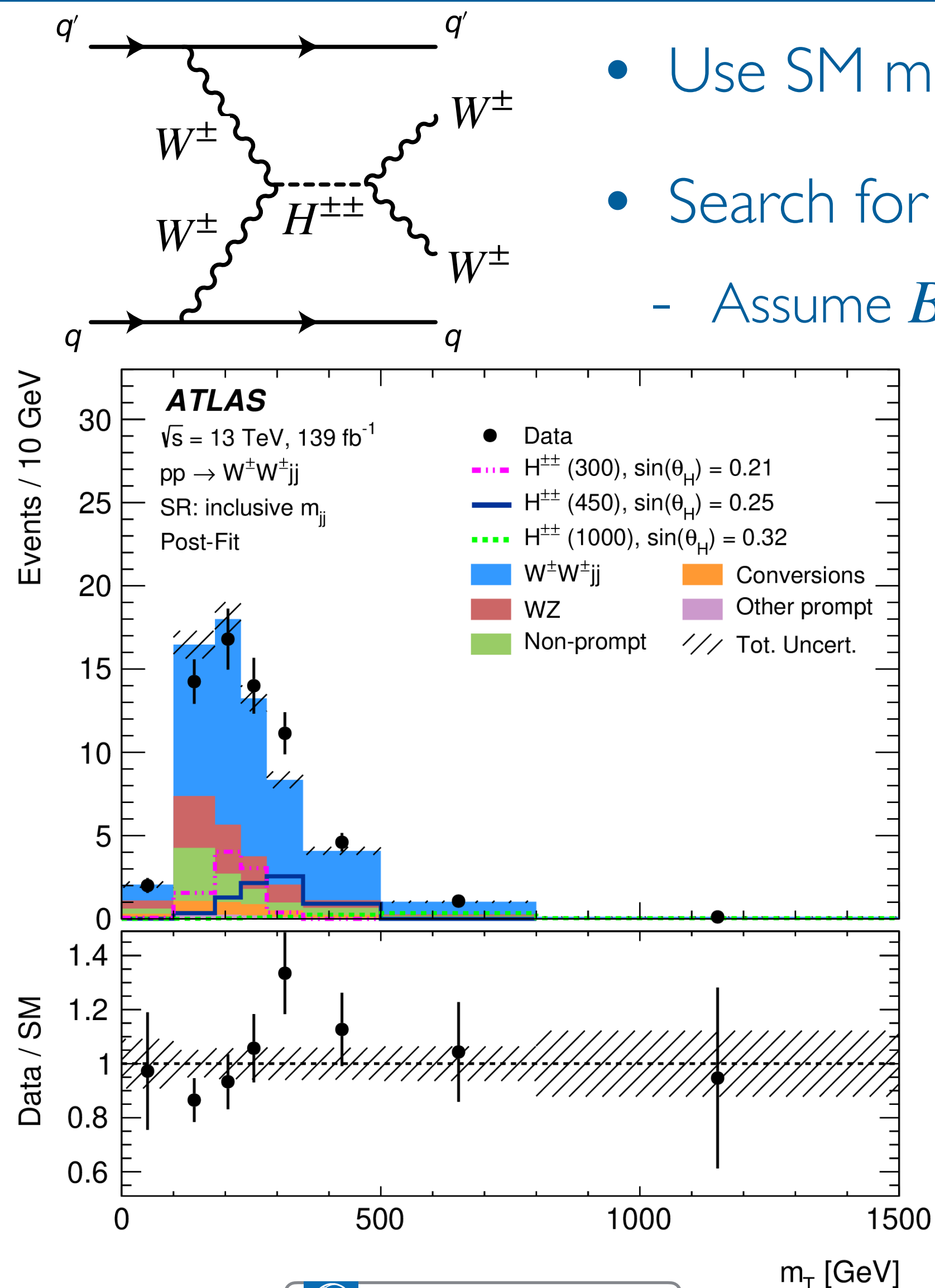
- Largest excess at $m_{H^{++}} = 450 \text{ GeV}$
 - 3.3σ local, 2.5σ global
 - $\sigma_{\text{VBF}}(H_5^{\pm\pm}) \times BR(H_5^{\pm\pm} \rightarrow W^\pm W^\pm) = 72 \pm 25 \text{ fb}$



$$H^{++}jj \rightarrow W^+W^+jj \rightarrow \ell\nu\ell\nu jj$$



- Use SM measurement of EW $W^\pm W^\pm jj$ production
- Search for $H^{\pm\pm}$ production in context of Georgi-Machacek model
 - Assume $BR(H_5^{\pm\pm} \rightarrow W^\pm W^\pm) = 100\%$





HH Production

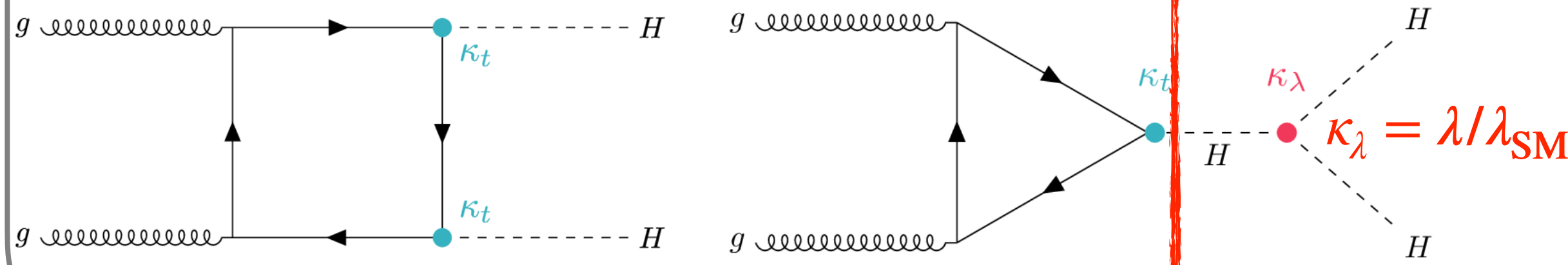


- Map out Higgs potential

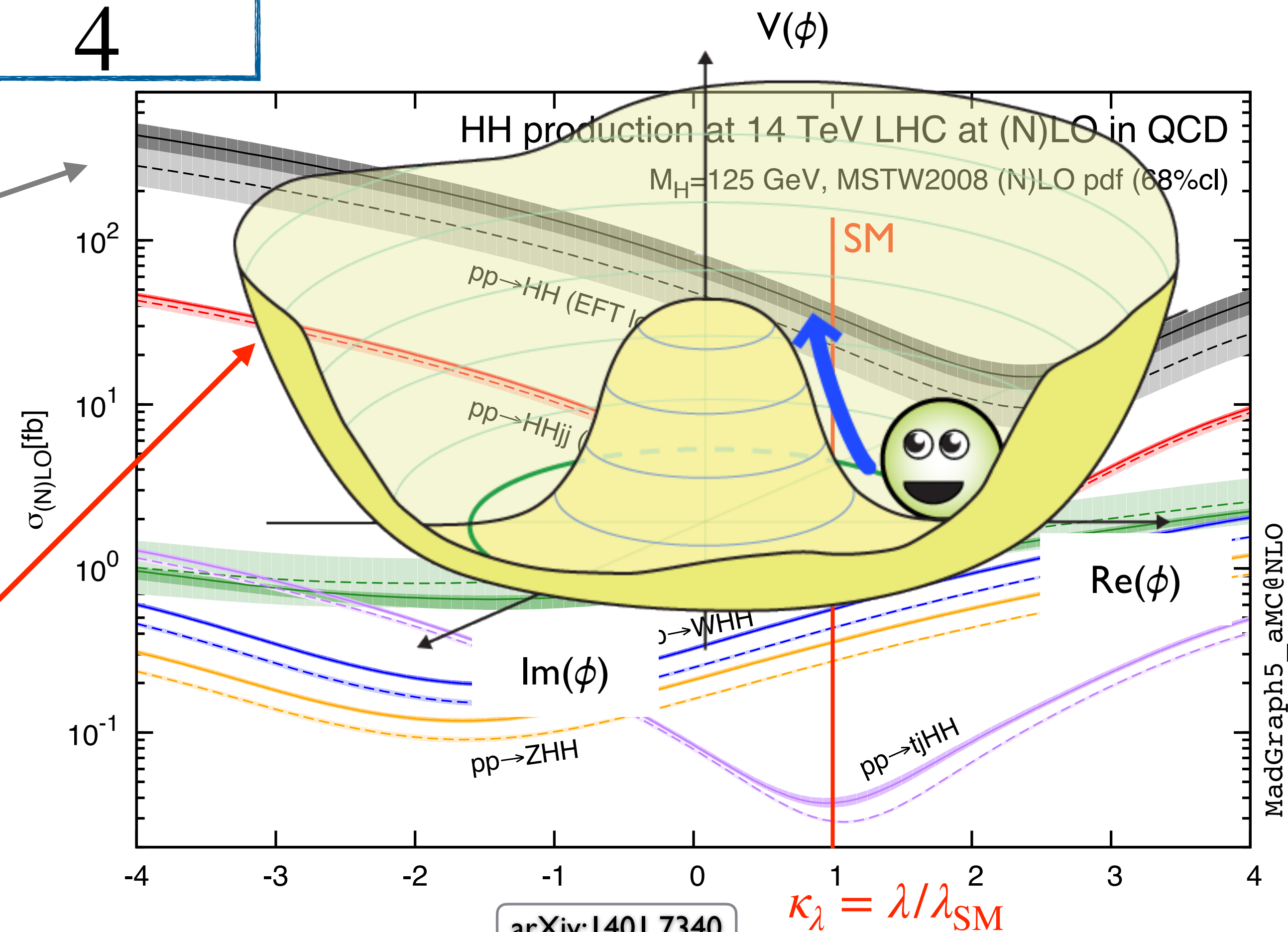
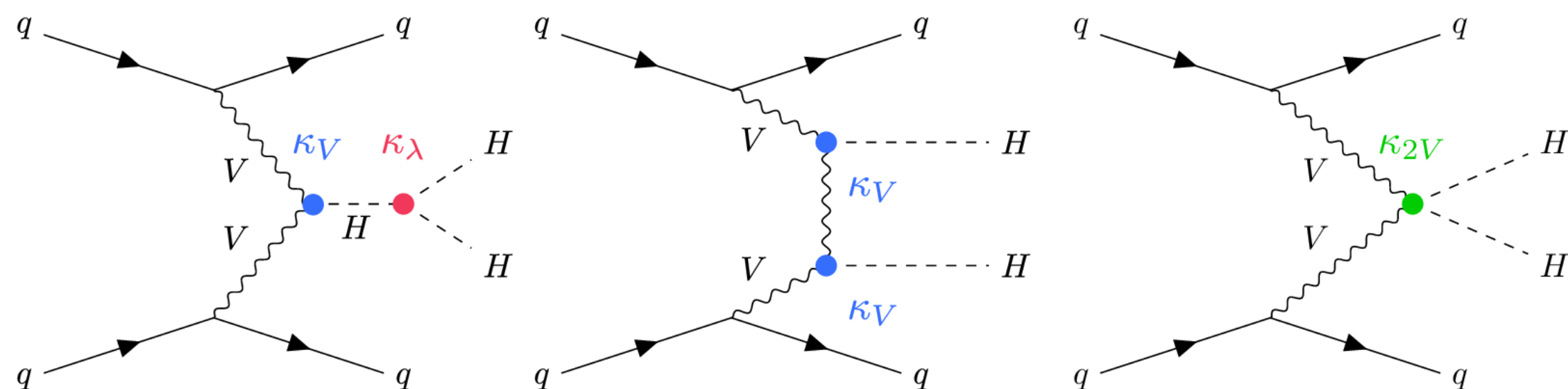
$$\mathcal{L} \ni -\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

H self interactions

$$\sigma(gg \rightarrow HH) = 31.05 \text{ fb}$$



$$\sigma(\text{VBF } HH) = 1.726 \text{ fb}$$



arXiv:1401.7340

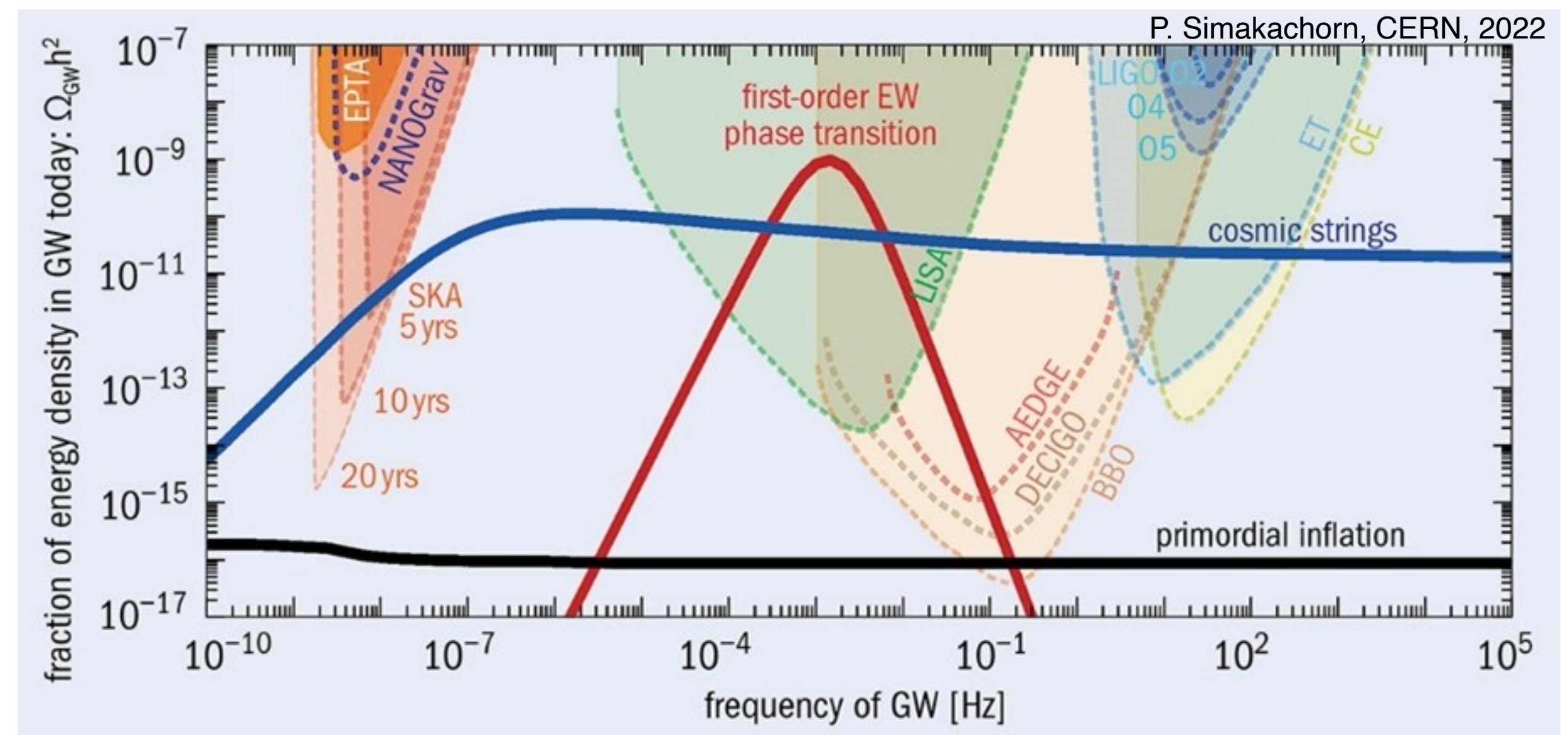
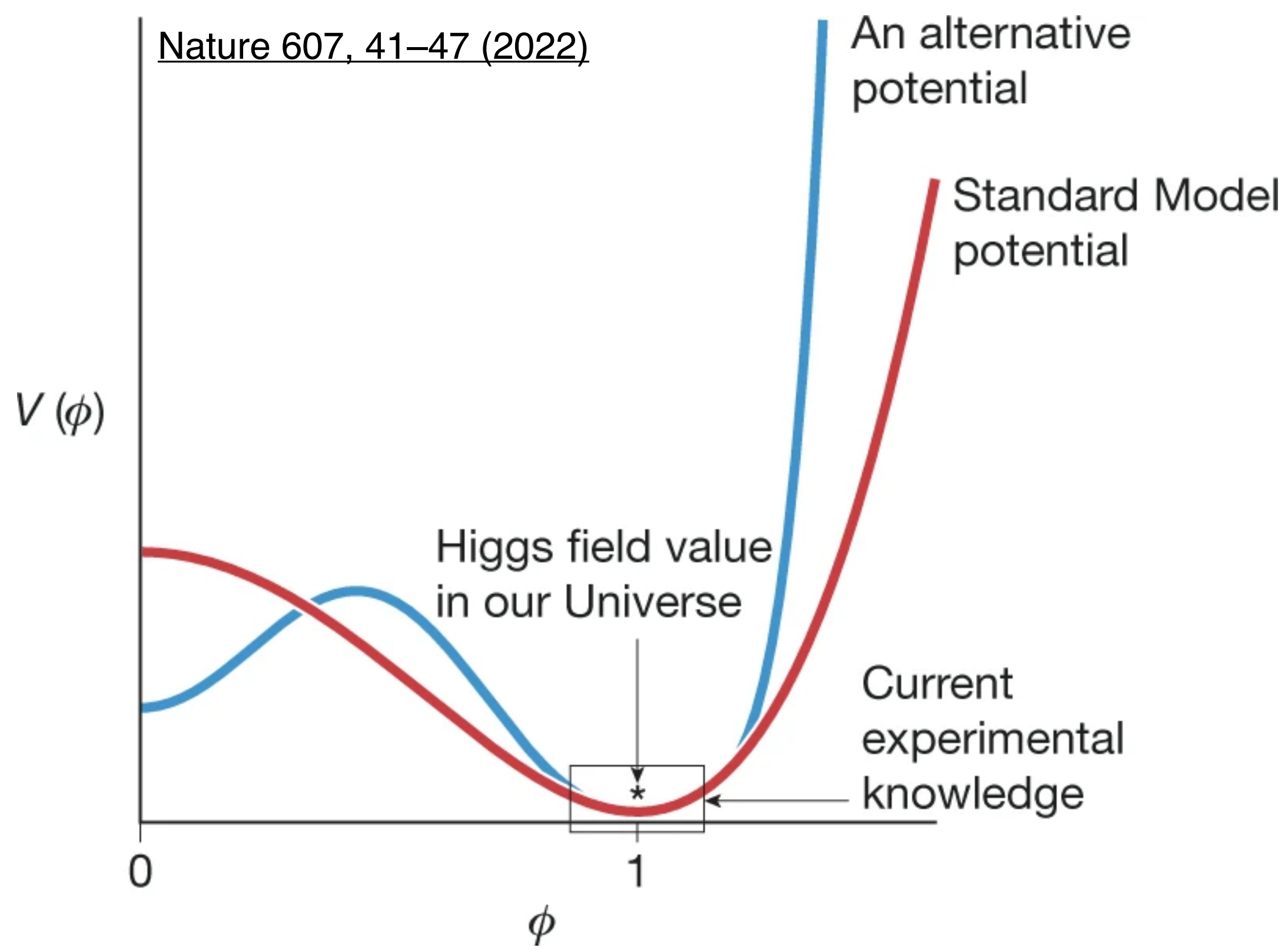
$$\kappa_\lambda = \lambda/\lambda_{\text{SM}}$$



Tripple Higgs and our Universe



Nature 607, 41–47 (2022)



P. Simakachorn, CERN, 2022

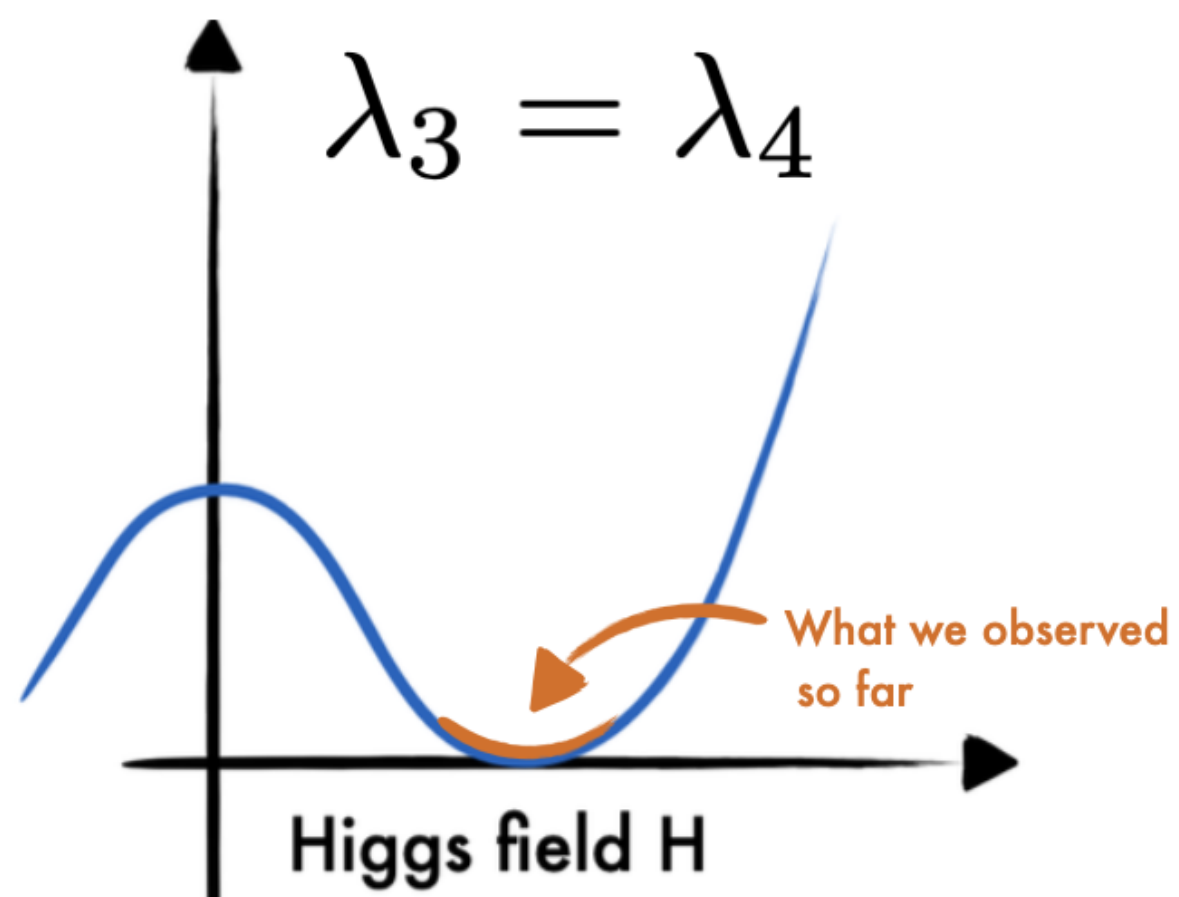


The Fate of our Universe

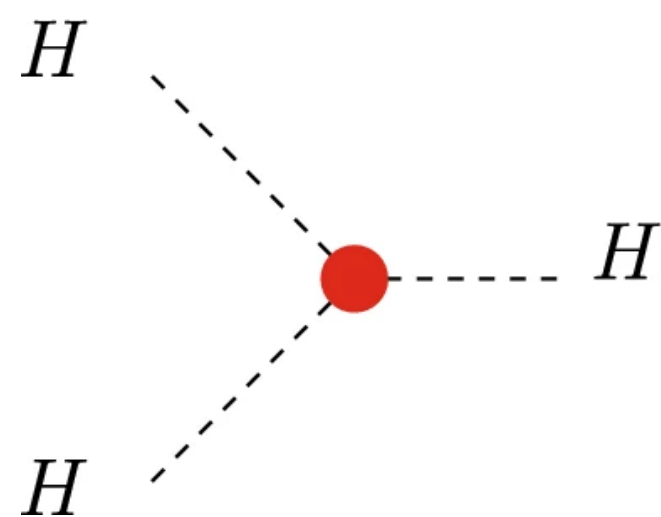


arXiv:2407.03015

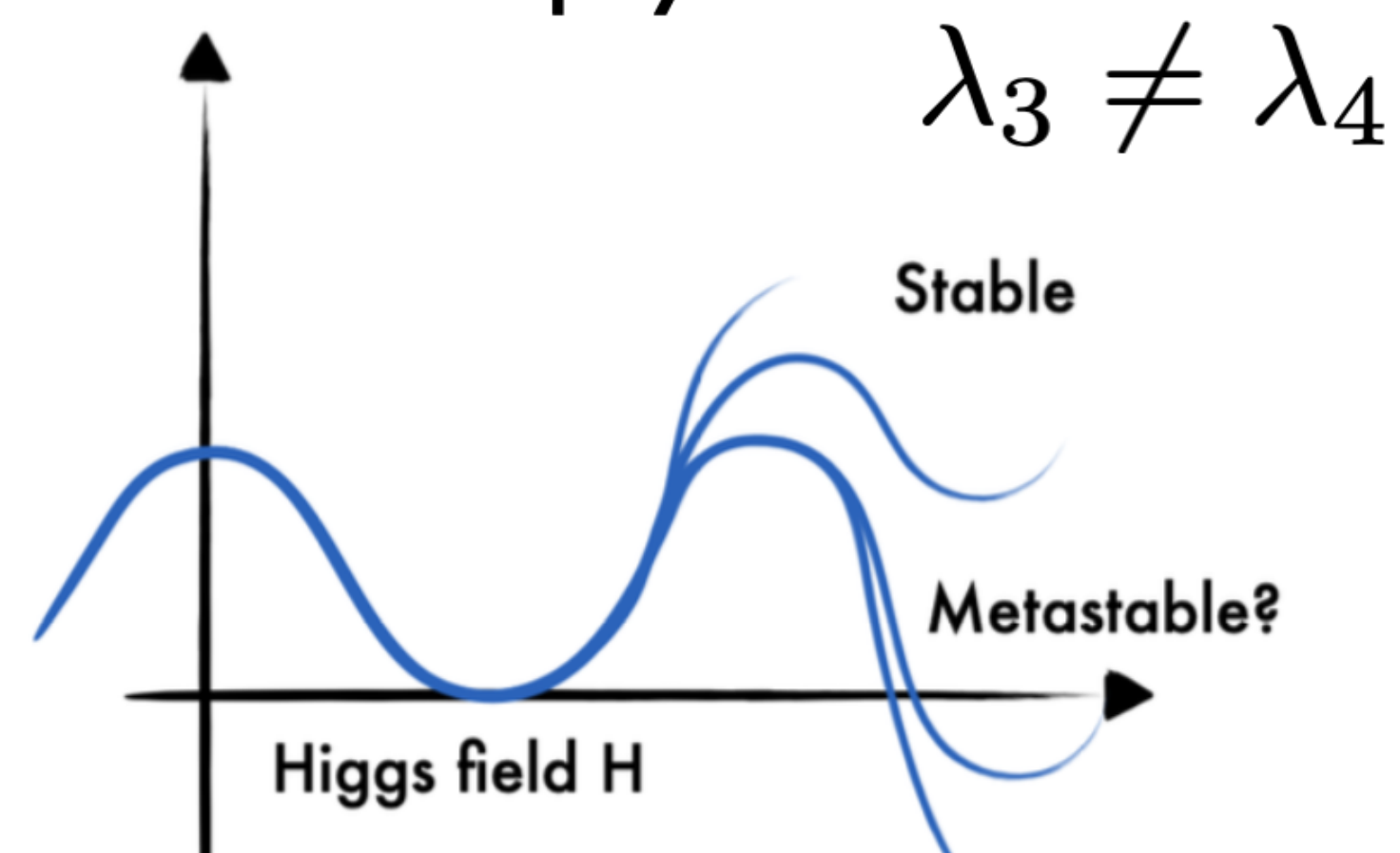
Standard Model



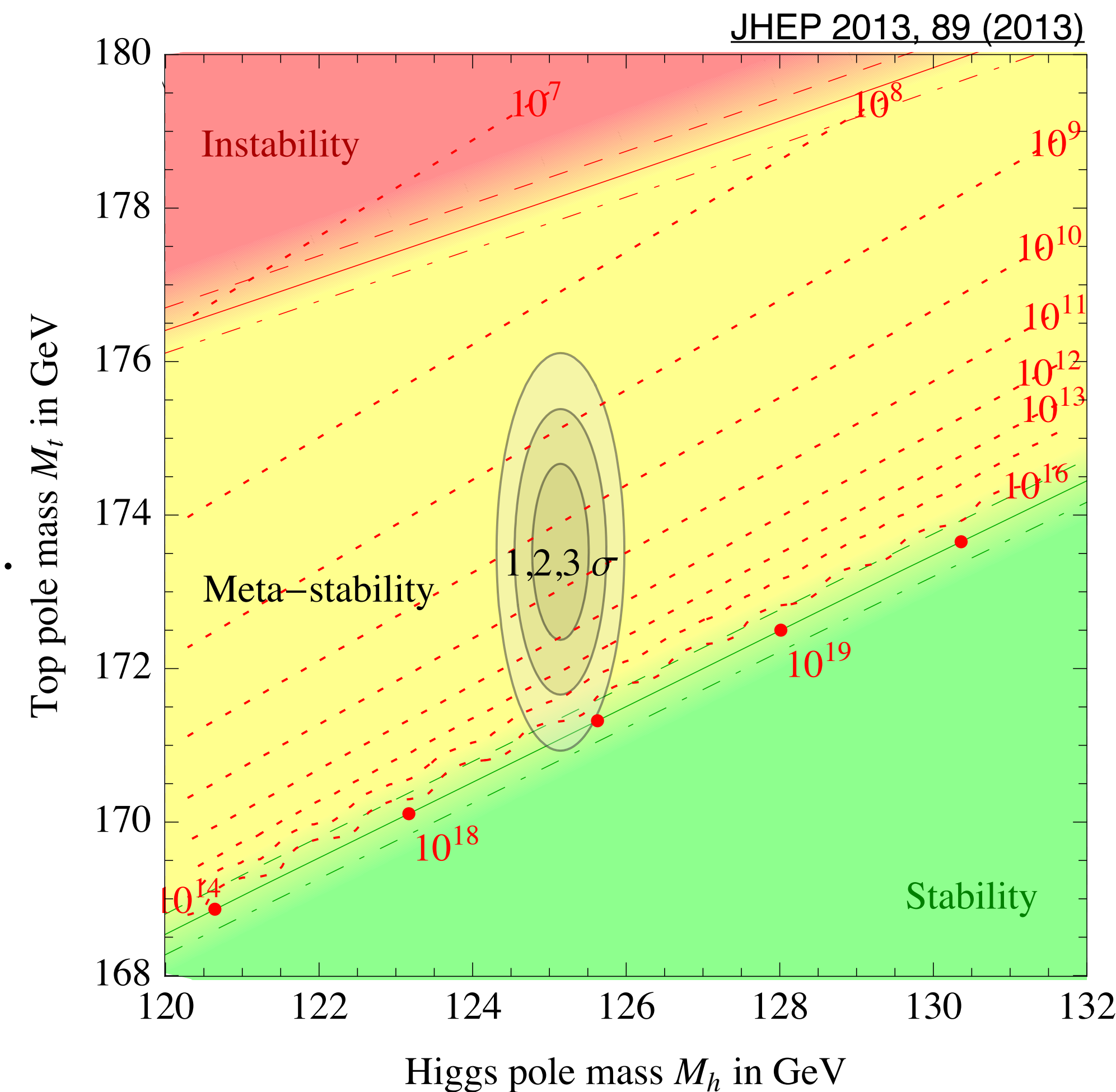
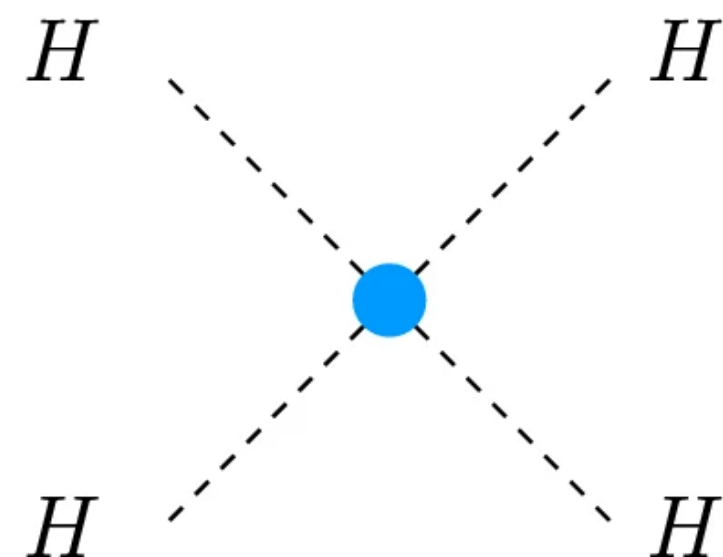
$$\mathcal{L} \ni -\frac{1}{2}m_H^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$



New physics



$$\mathcal{L} \ni -\frac{1}{2}m_H^2 H^2 - \lambda_3 v H^3 - \frac{\lambda_4}{4} H^4 \dots$$





Progress in TH Prediction (in a tiny nutshell) GA

Gavin Salam

the master formula

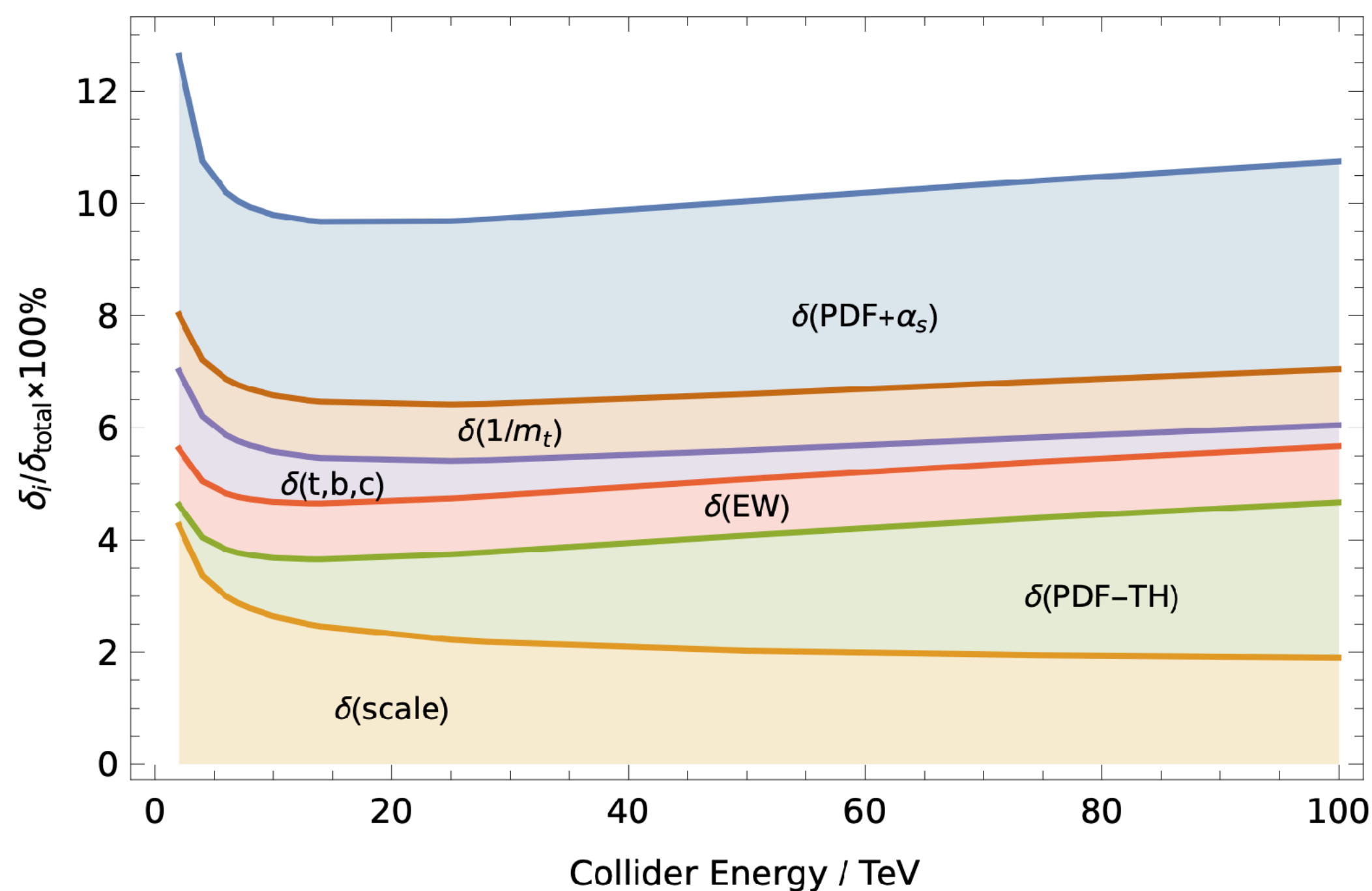
$$\sigma = \sum_{i,j} \int dx_1 dx_2 f_{i/p}(x_1) f_{j/p}(x_2) \hat{\sigma}(x_1 x_2 s) \times [1 + \mathcal{O}(\Lambda/M)^p]$$

α_s Improvements in precision from the Lattice (until FCC-ee Z hadronic)

$$\sigma_{ggF} = 48.68 \pm 3.9 \text{ (scales)} \pm 1.9 \text{ (PDF)} \pm 2.6 \text{ (}\alpha_s\text{)} \text{ Pb}$$

PDFs already at 1% (CT18 - NNPDF)
Discussions ongoing

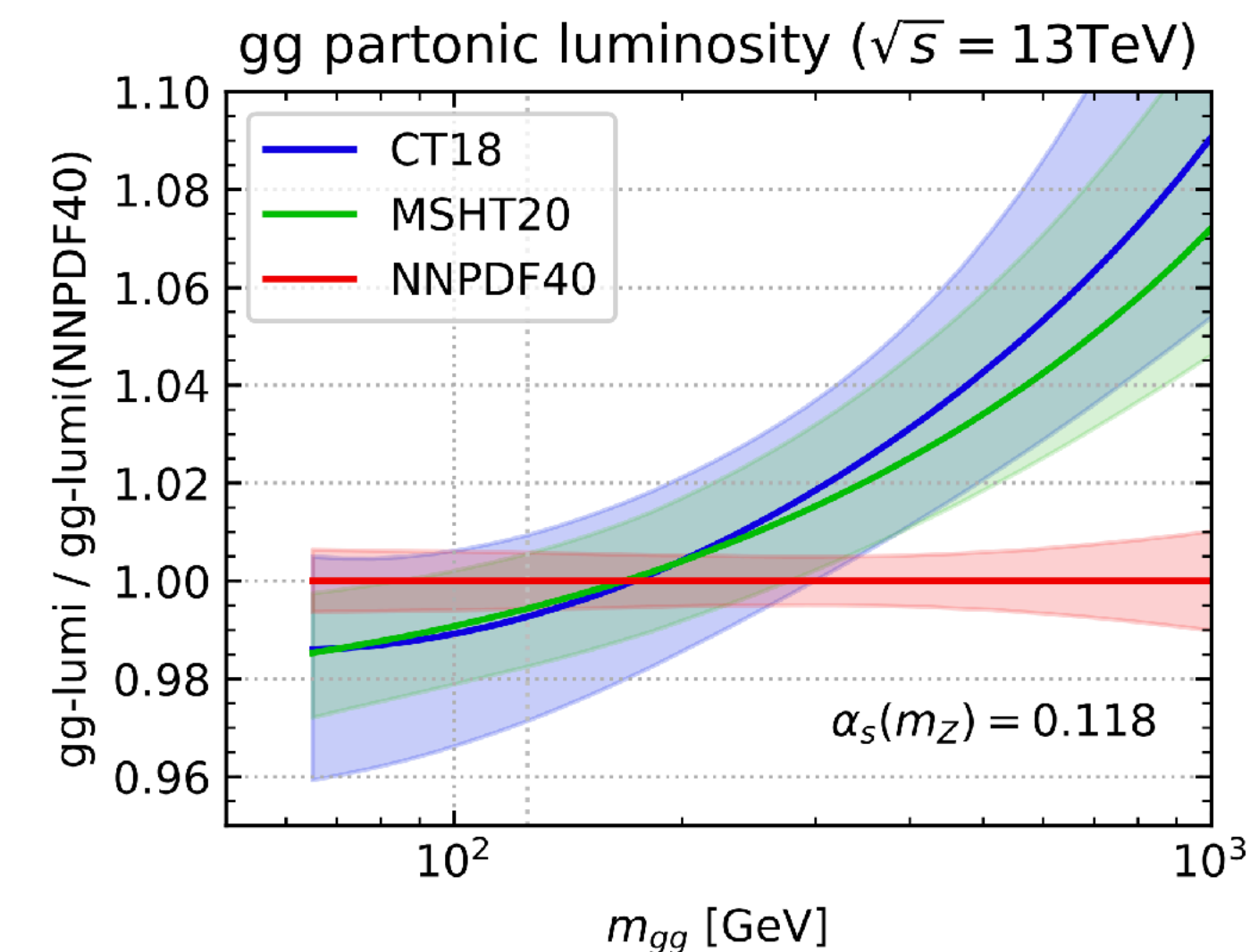
Gavin Salam



Alexander Huss

- PDF and α_s
- Finite quark masses effects
- Missing EW and mixed EW-QCD corrections
- Mismatch in the PDF (NNLO) and perturbative order N3LO
- Missing HO beyond N3LO

Many more signal processes!



Modelling of signal and background key!

- NLO QCD and EW predictions matched to PS
- NNLO PS matching
- CPU time challenge

Simon Plätzer

Frank Siegert

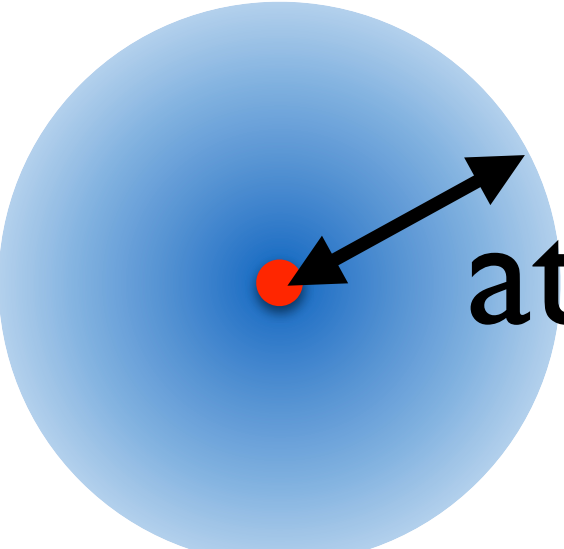
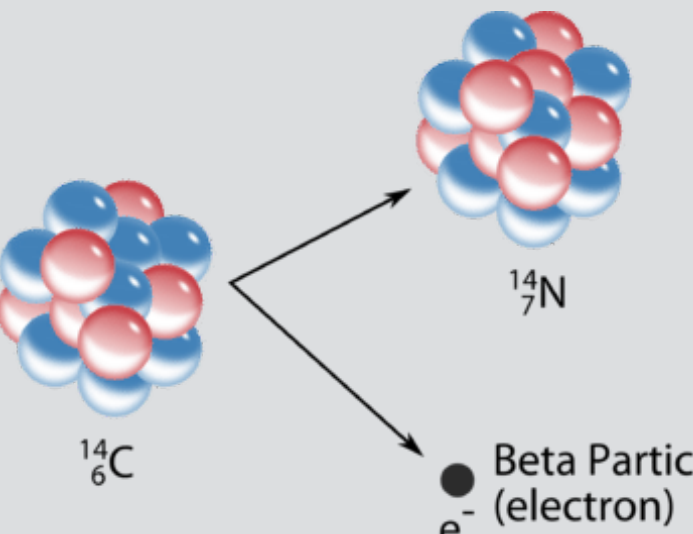
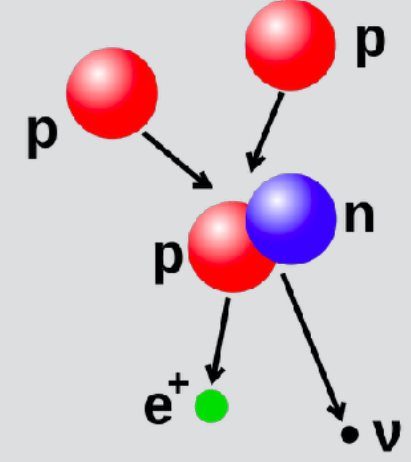
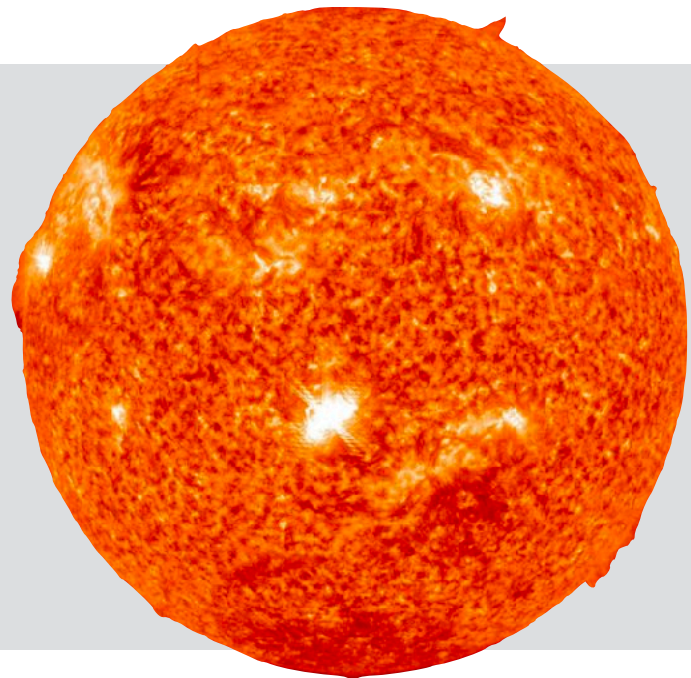
Marumi Kado



Higgs and our Universe



- Higgs-boson interactions set the quark, electron, and W-boson masses with important consequences

Role of elementary particle masses	Consequence	Higgs role established?
Up quarks (mass ~ 2.2 MeV) <i>lighter than</i> down quarks (mass ~ 4.7 MeV) Proton (up up down)  : $2.2 + 2.2 + 4.7$ MeV + EM+strong force = 938.3 MeV Neutron (up down down)  : $2.2 + 4.7 + 4.7$ MeV + EM+strong force = 939.6 MeV	Proton lighter than Neutron $\Rightarrow$ Protons are stable $\Rightarrow$ Hydrogen atom	No
 atomic radius $\propto \frac{1}{m_e}$	Electron mass (m_e) sets size of atoms & energy levels of chemical reactions	No
 $^{14}_6\text{C}$ $\rightarrow$ $^{14}_7\text{N}$ + Beta Particle (electron) e^- Neutron (blue circle) Proton (red circle) rate $\propto \frac{1}{m_W^4}$  	W-boson mass (m_W) sets rate of radioactive β-decay and burning of the sun	Yes