Higgs Combinations ATLAS & CMS

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(on behalf of the CMS & ATLAS Collaborations)
University of Freiburg

Outline

- Introduction
- Mass Measurements
- Differential Cross Sections
- Coupling Combinations and Interpretations
- Summary & Outlook

Consequences of Brout-Englert-Higgs Mechanism

- Higgs boson with mass:

$$m_{\mathrm{H}} = \sqrt{2\lambda} v$$

not predicted!

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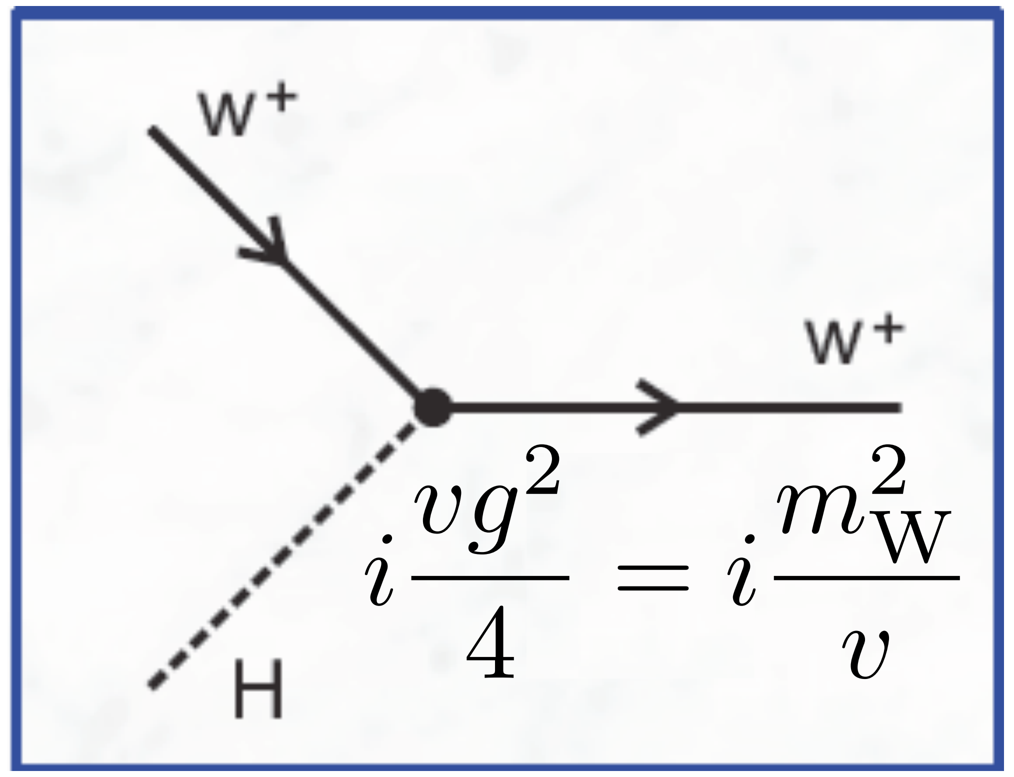
- W mass and interaction:

$$m_{\mathrm{W}} = \frac{vg}{2}$$

direct connection



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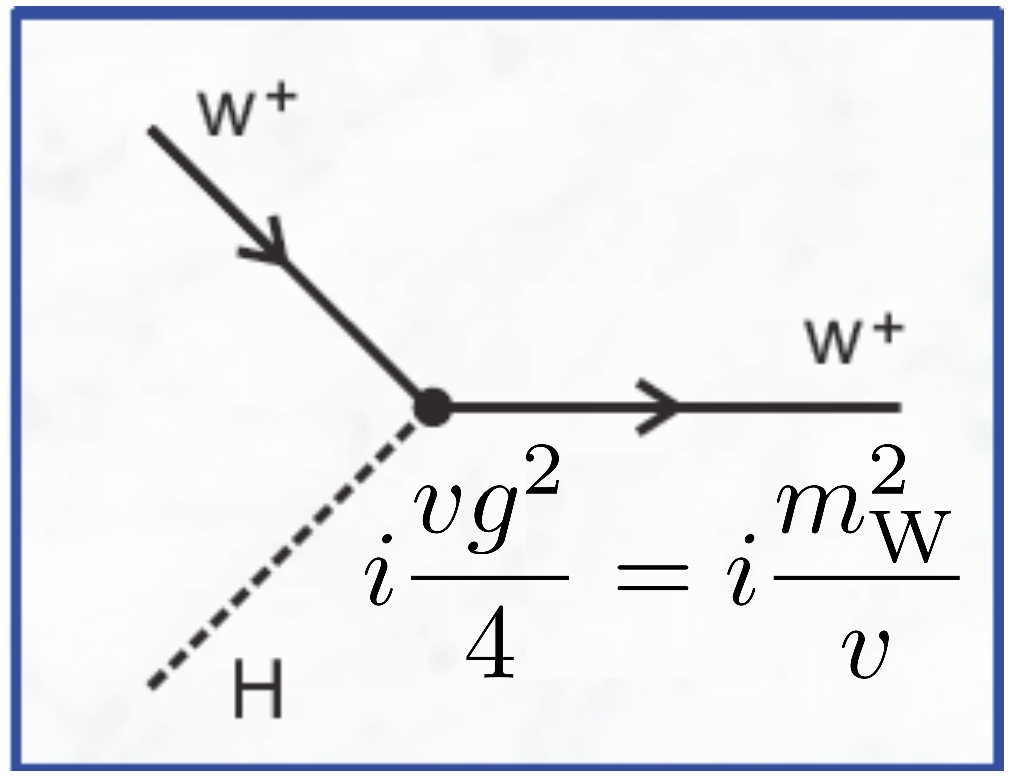
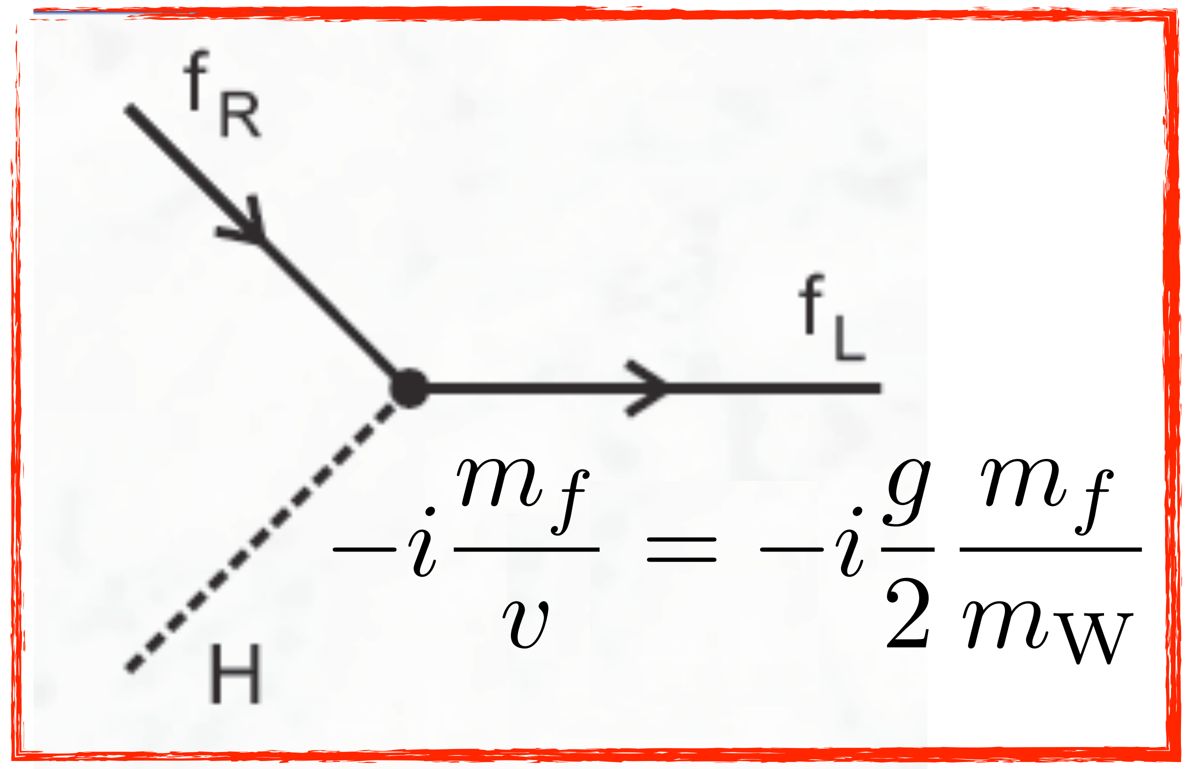


- Fermion masses and Yukawa interactions:

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

direct connection ⟷



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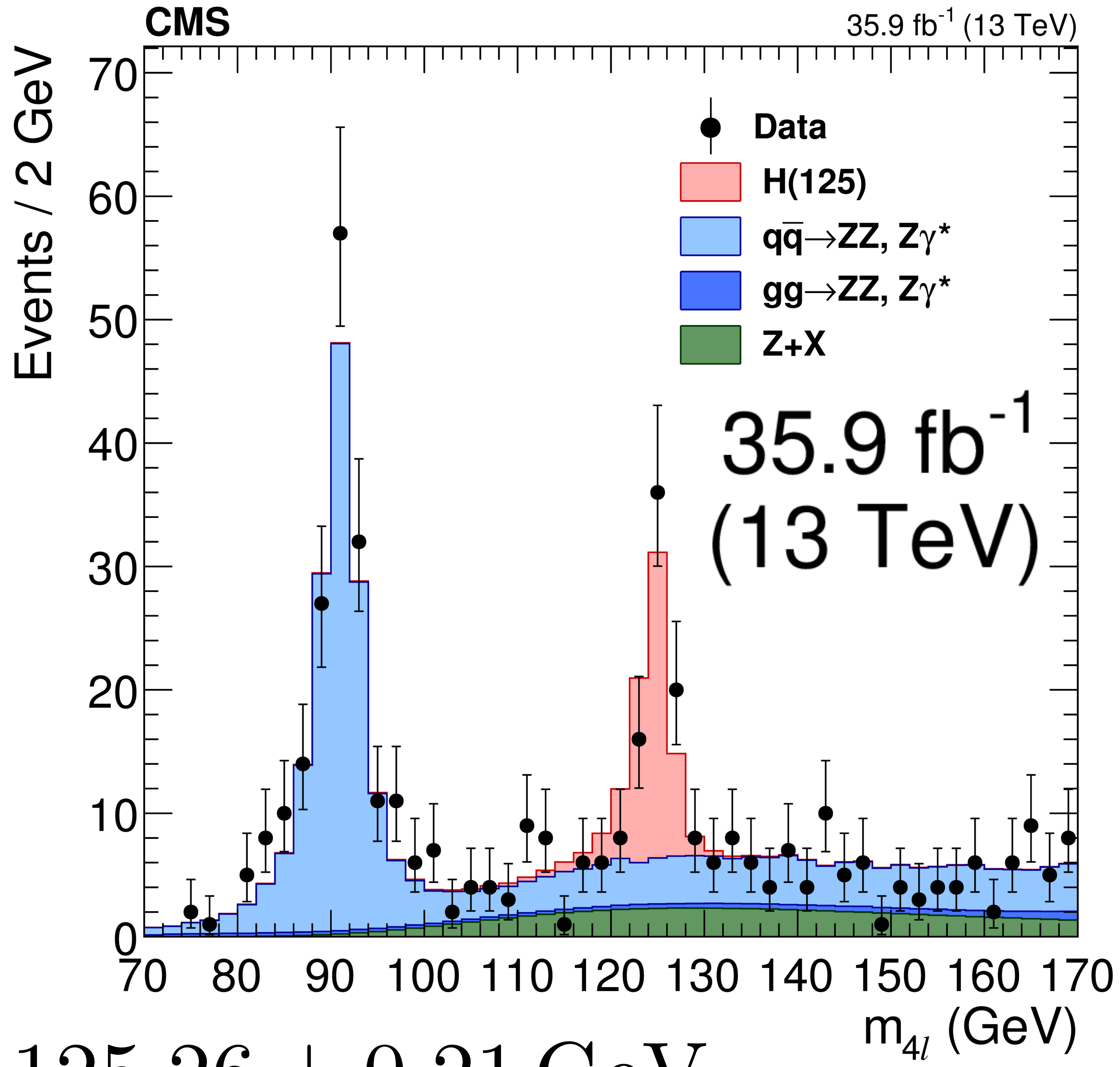
Run 2 Mass Measurement

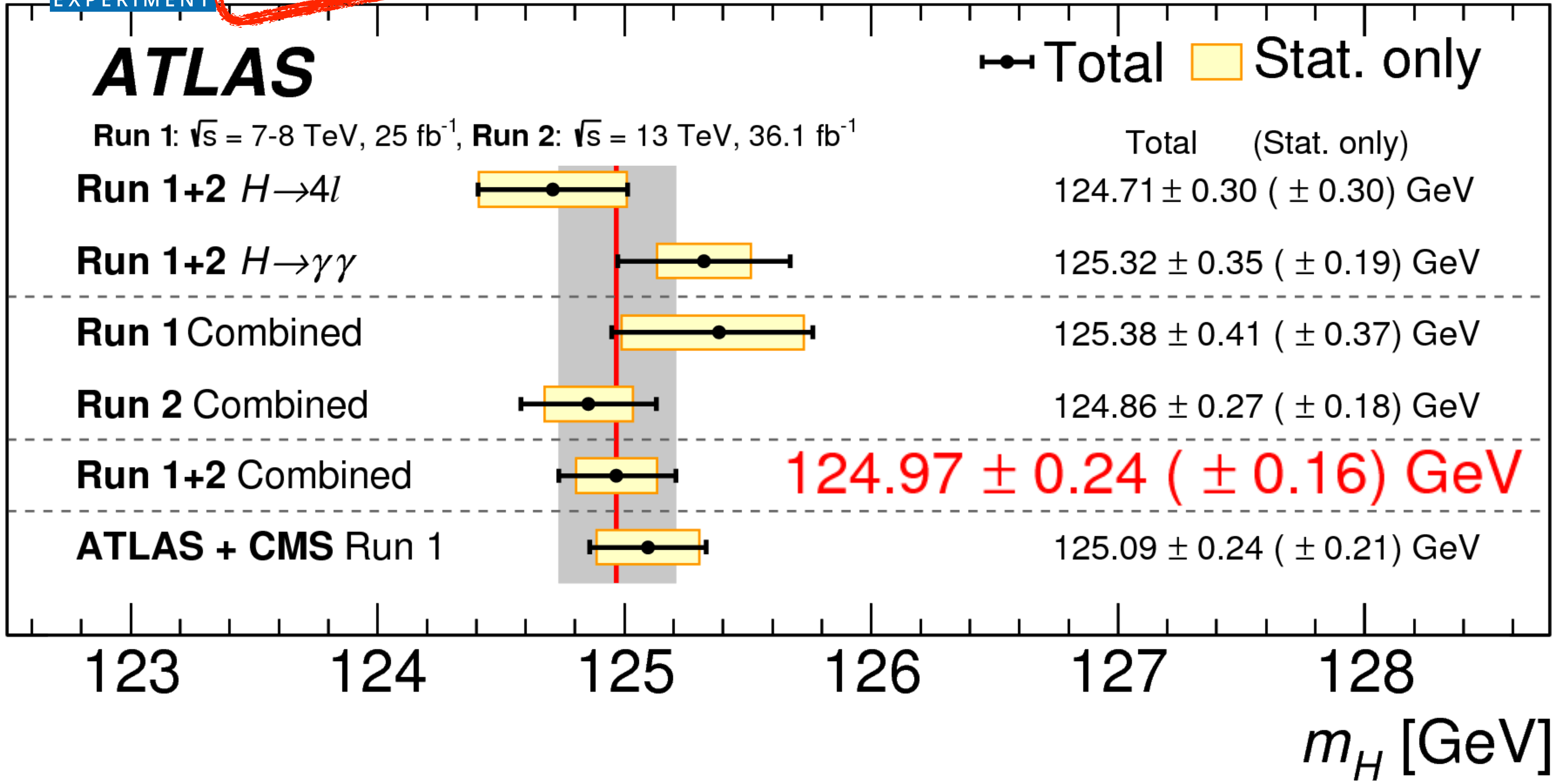
- Not predicted by SM theory ⇒ once measured by experiment, everything else is determined

From $H \to ZZ^* \to 4\ell$ (ℓ=e,μ):



May 2018

From $H \to ZZ^* \to 4\ell$ + $H \to \gamma\gamma$:



$$m_H = 125.26 \pm 0.21\,\mathrm{GeV}$$
$$= 125.26 \pm 0.20\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})\,\mathrm{GeV}$$
$$(\mathrm{expected:}\ \pm 0.23\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})\,\mathrm{GeV})$$

JHEP 11 (2017) 047

PLB 784 (2018) 345

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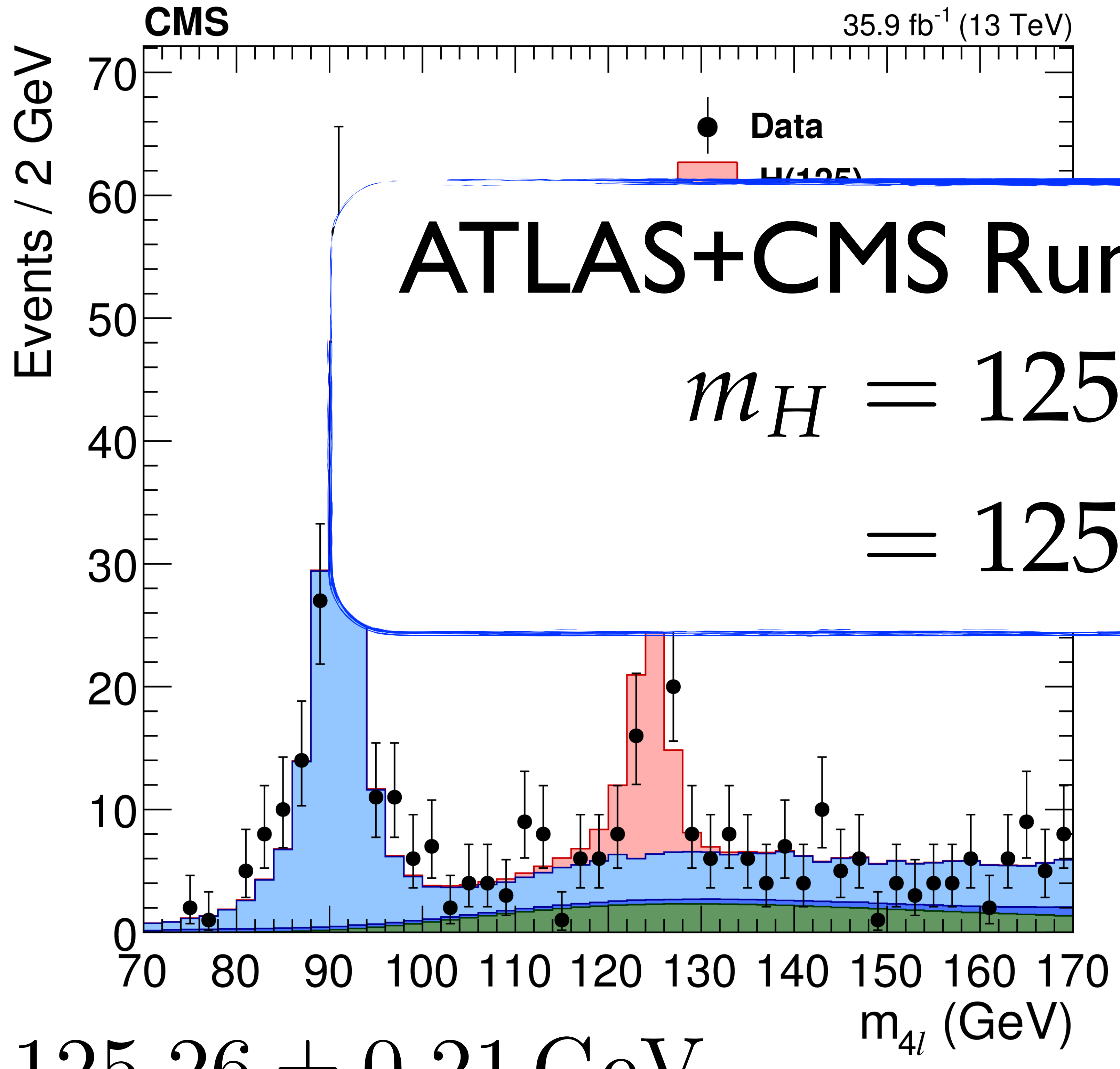

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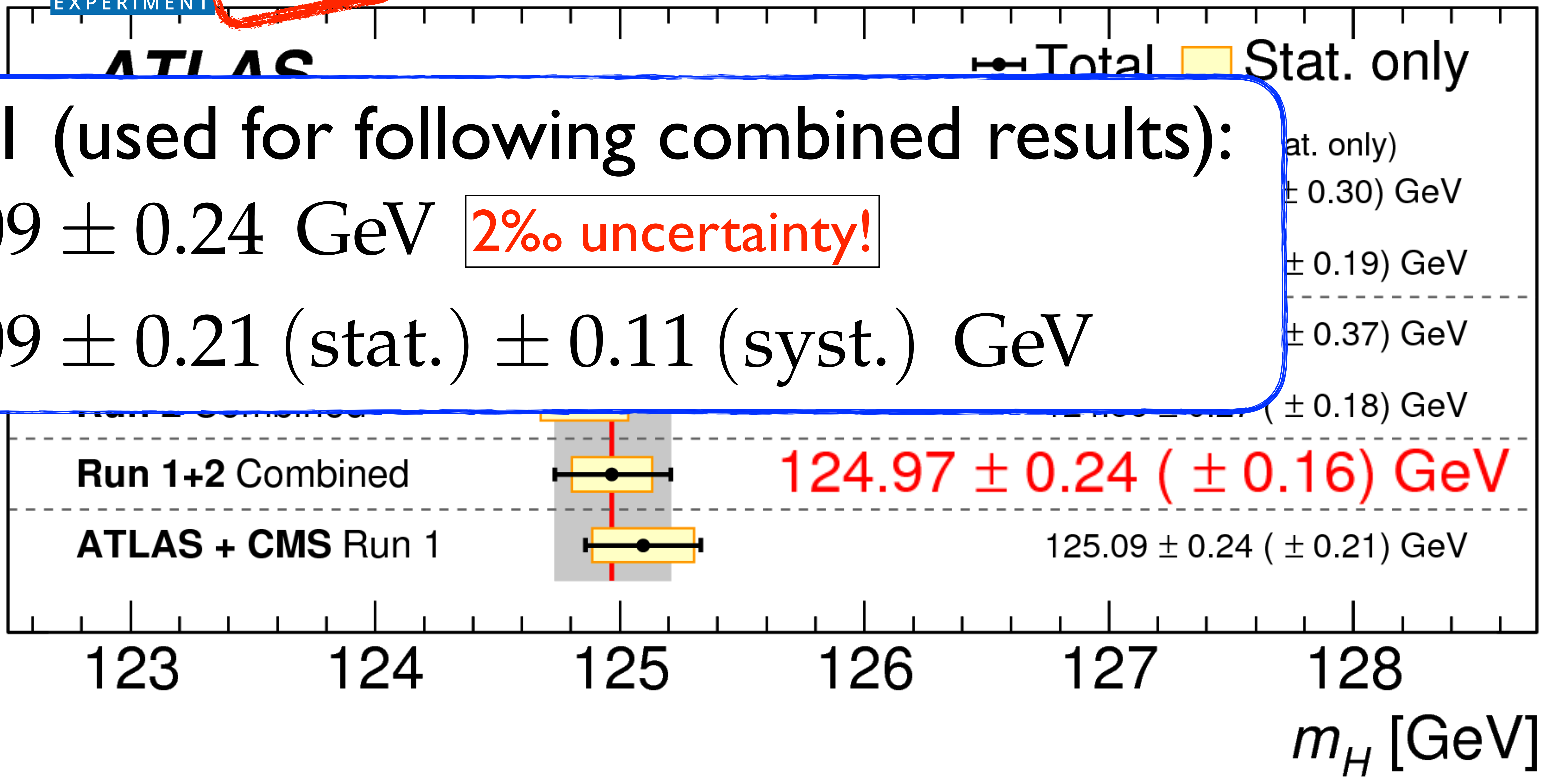
From H → ZZ* → 4ℓ + H → γγ:



ATLAS+CMS Run 1 (used for following combined results):

$$m_H = 125.09 \pm 0.24\ \mathrm{GeV}$$ 2‰ uncertainty!

$$= 125.09 \pm 0.21\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})\ \mathrm{GeV}$$

PLB 784 (2018) 345

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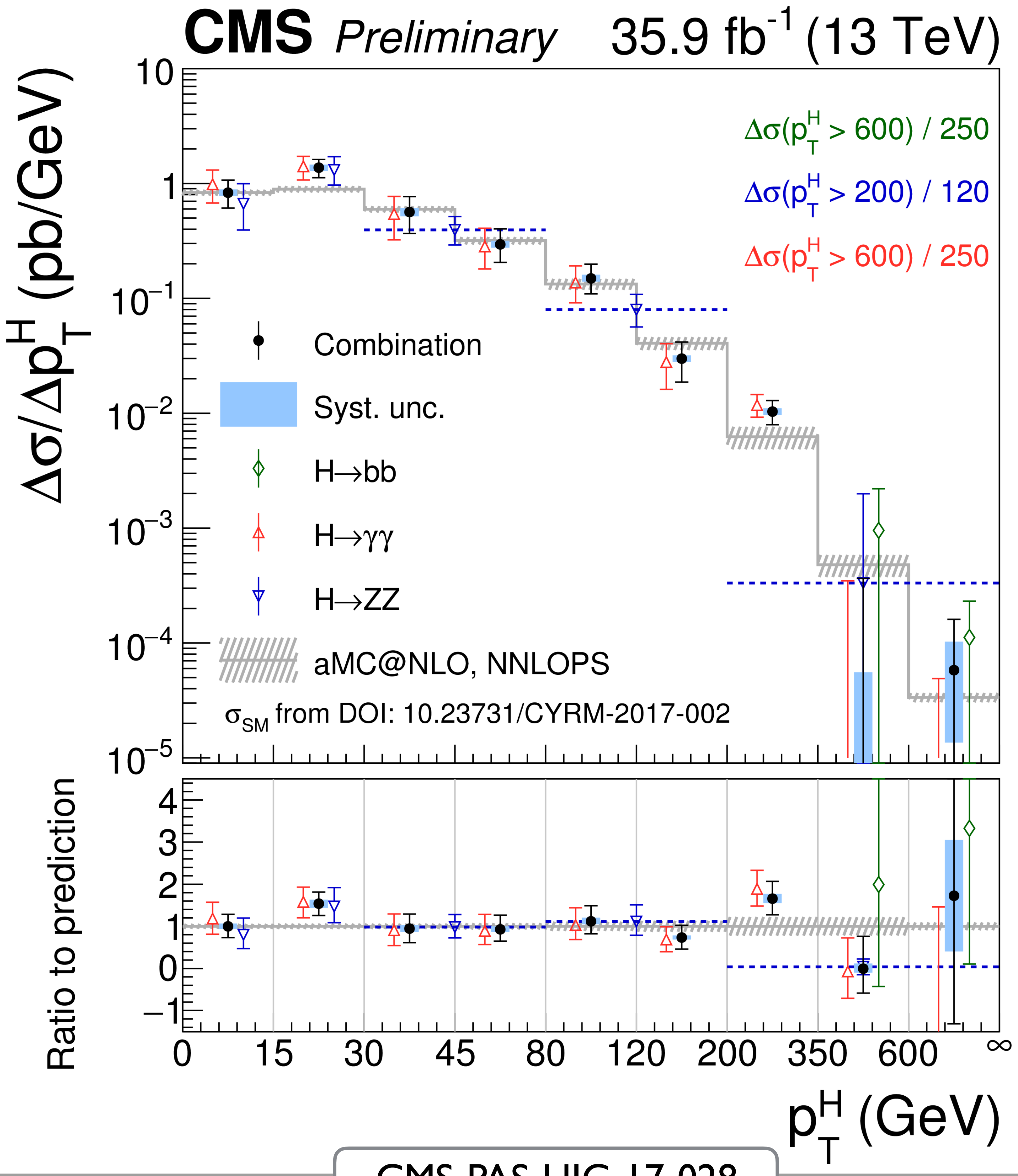
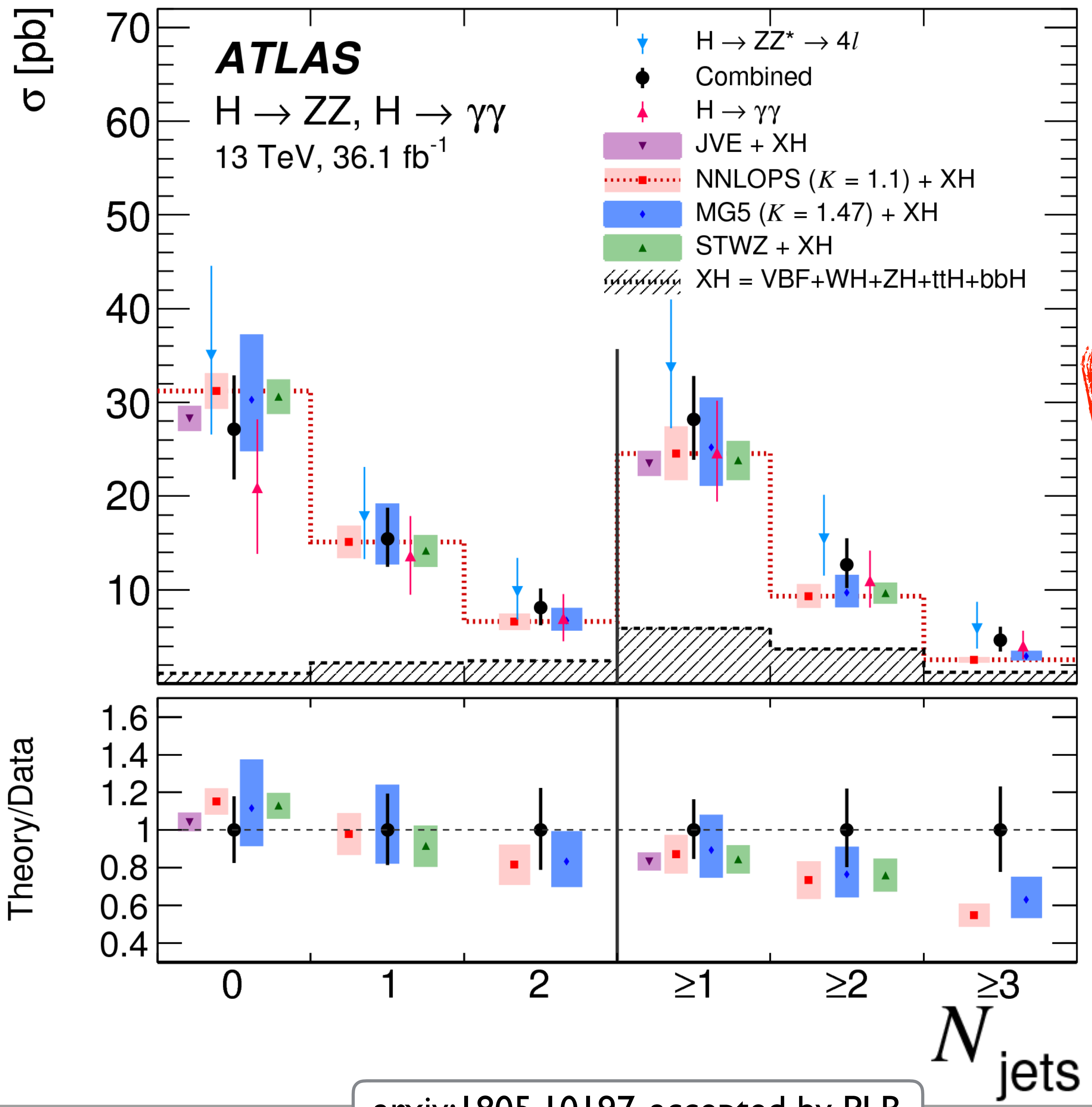
Differential Measurements

- Probe kinematic properties of Higgs boson production
  - Fiducial regions matched between experiment and theory
  - Compare with available predictions ⇒ Input for improvement of predictions

July 2018



CMS-PAS-HIG-17-028

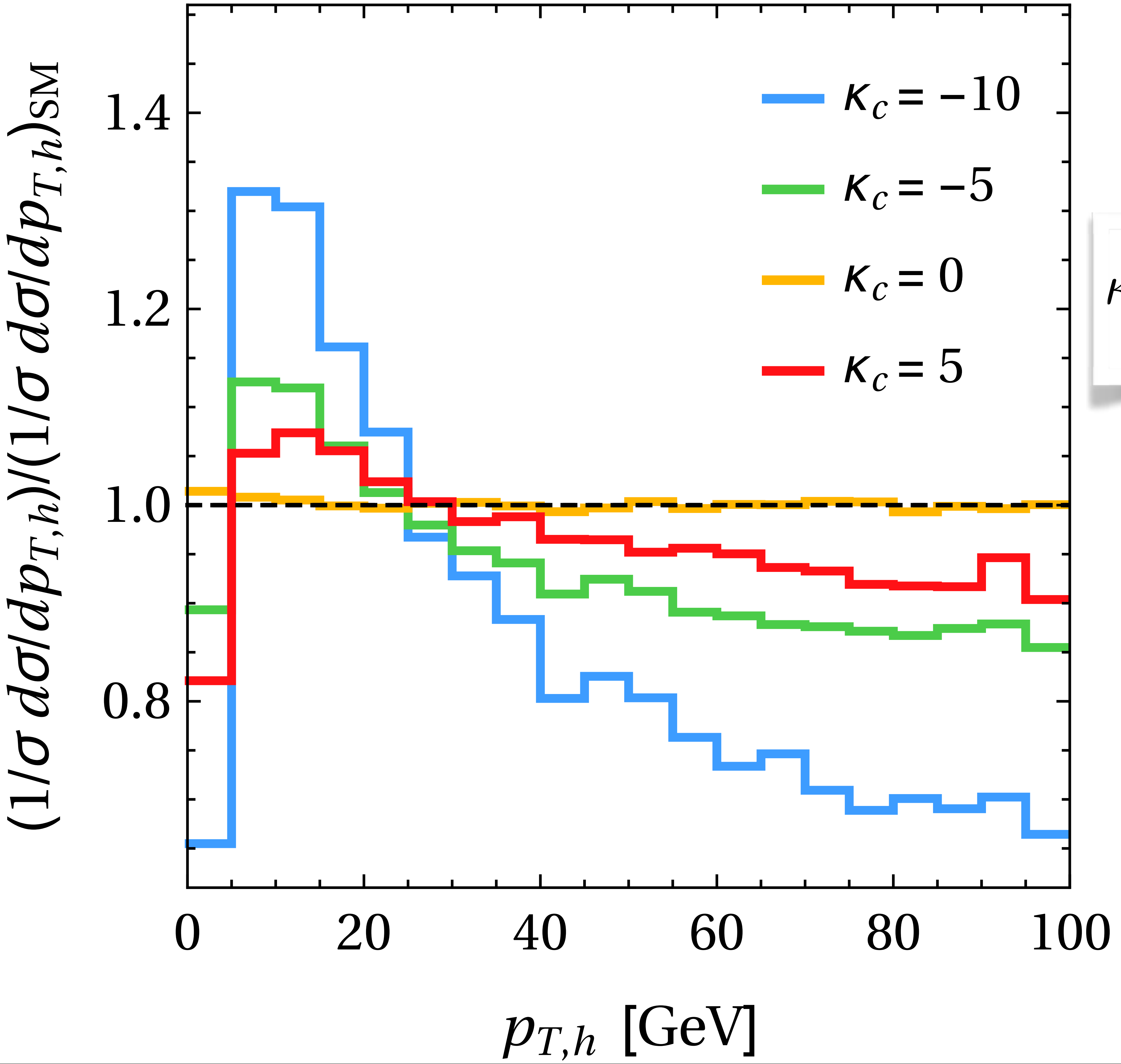


May 2018

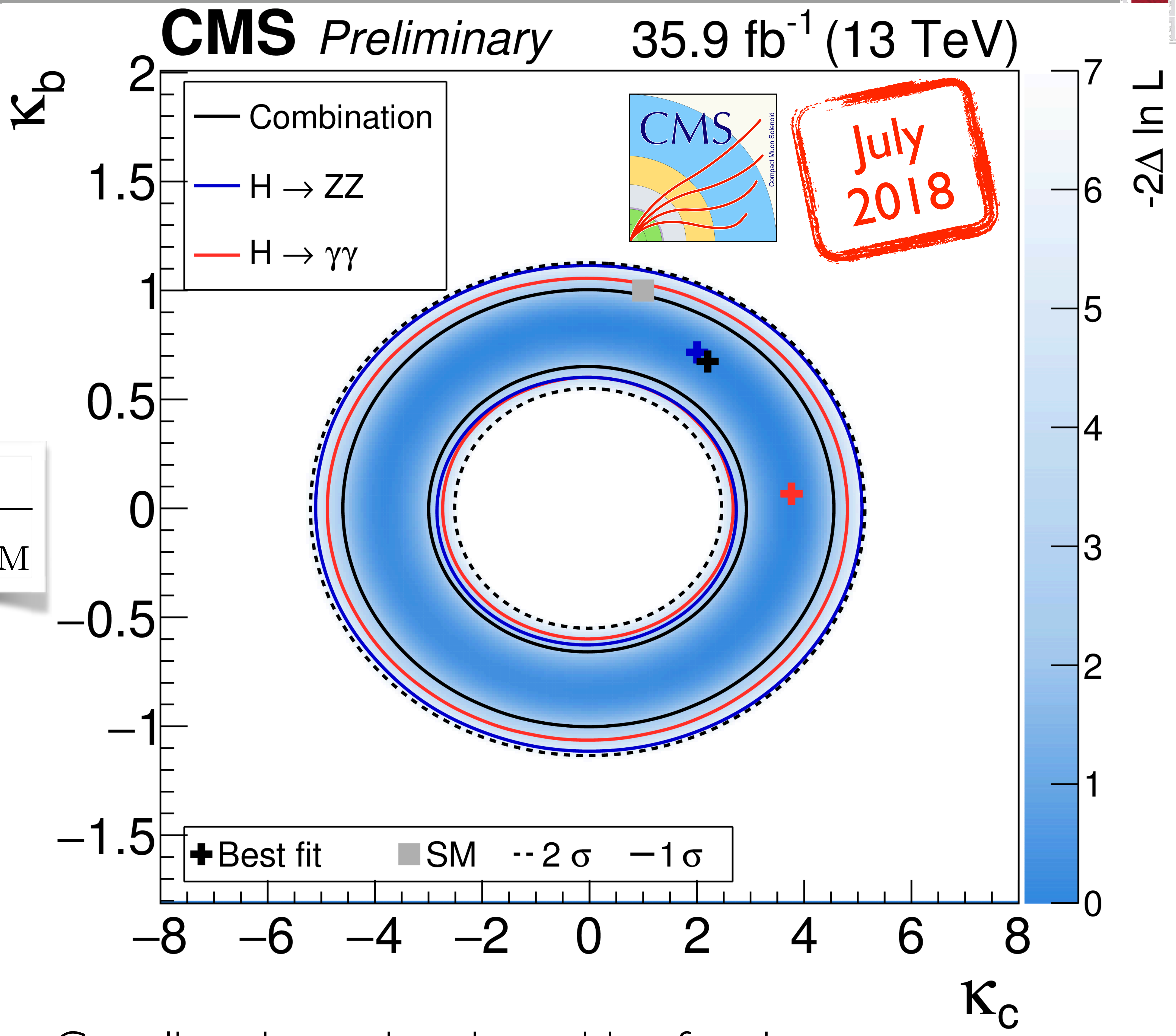
arxiv:1805.10197, accepted by PLB

Extracting Light-Quark Couplings from $p_T(H)$

- **Idea** (PRL **118**, 121801, 2017):
  - $p_T(H)$ sensitive to charm-Yukawa due to interference between charm- and top-mediated contributions in ggF



$$\kappa_a := \frac{g_a}{(g_a)_{SM}}$$



- Coupling-dependent branching fractions
  - Total width and overall normalization largely contribute to constraint

CMS-PAS-HIG-17-028

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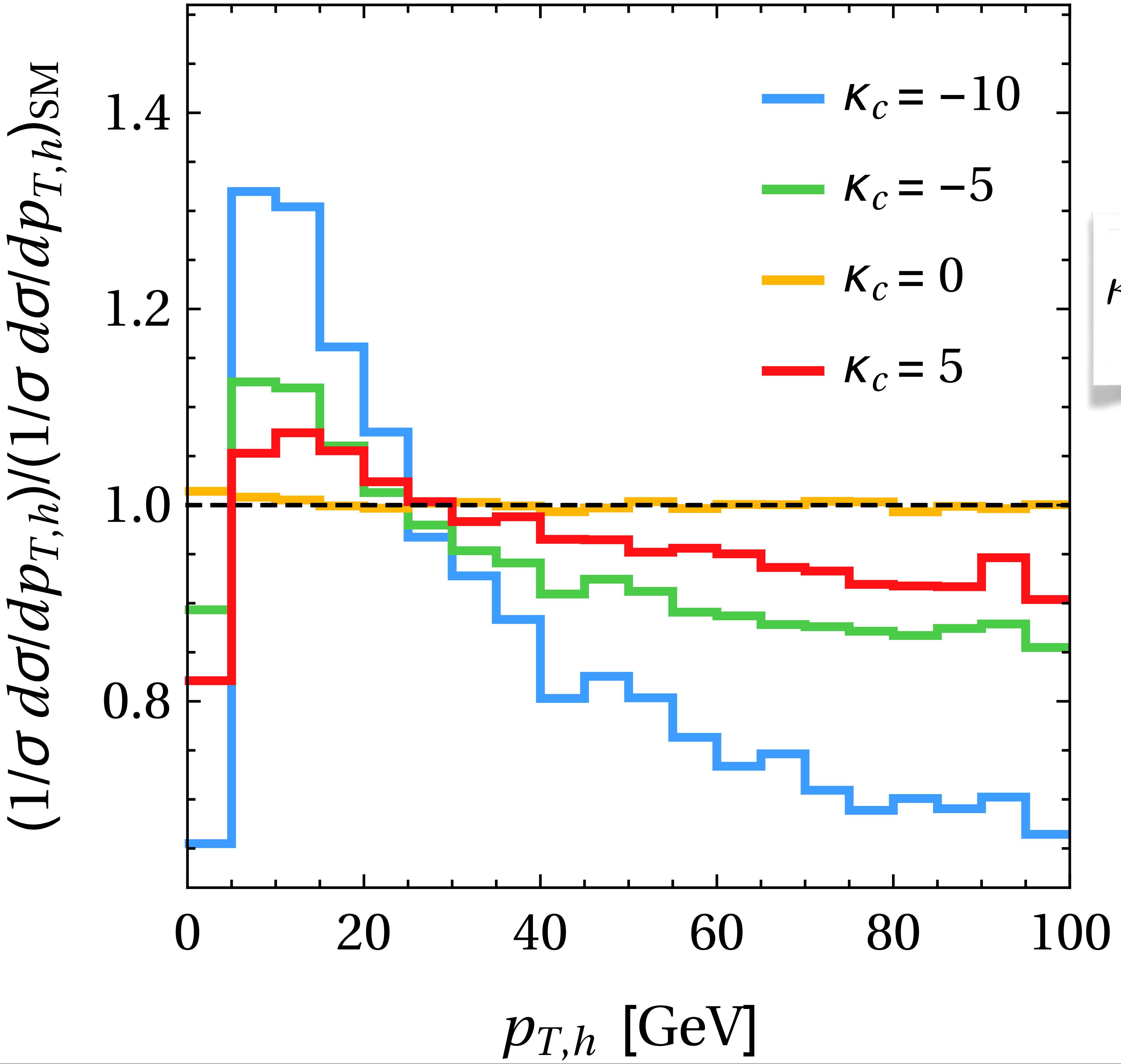

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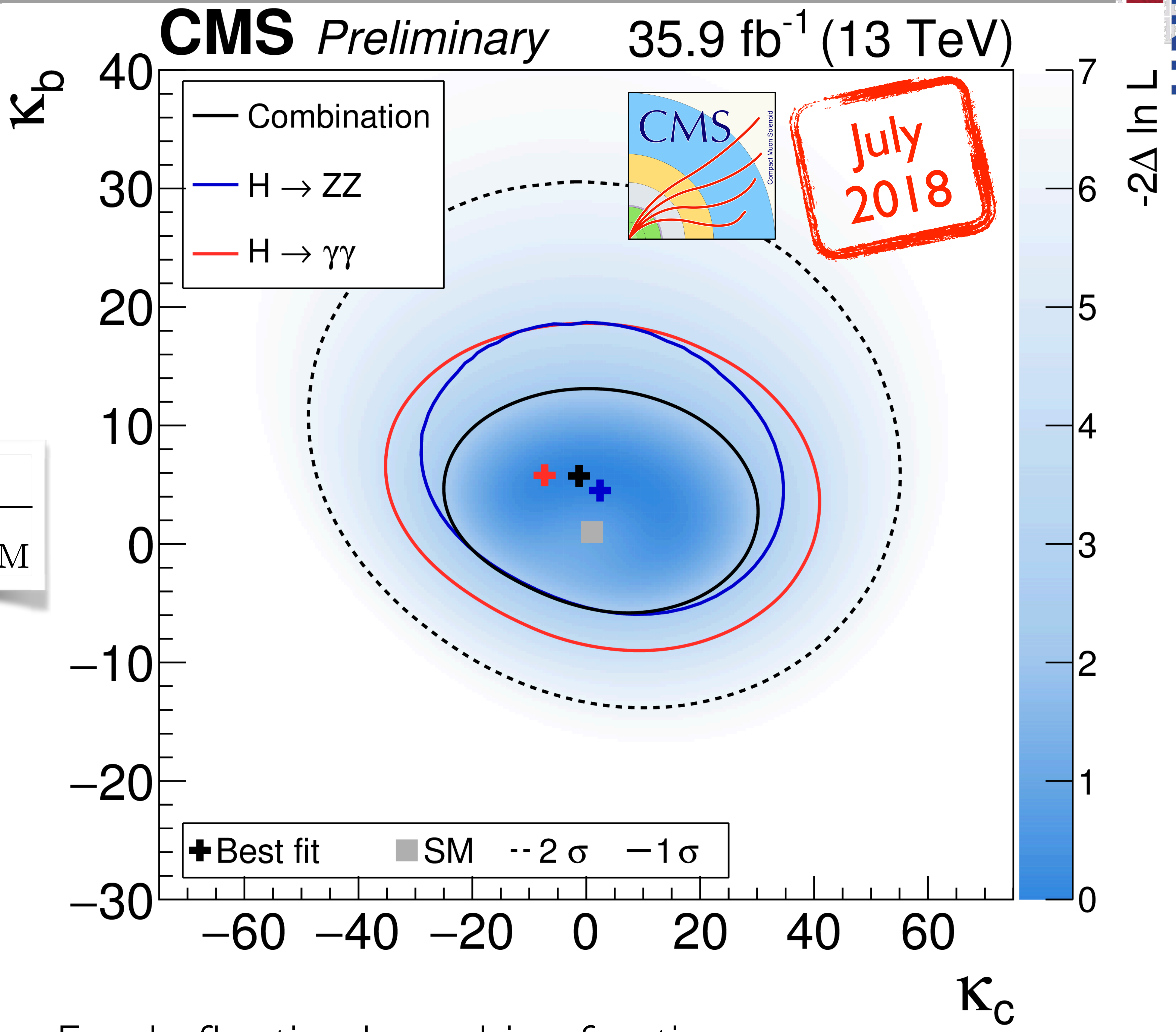

- Freely-floating branching fractions

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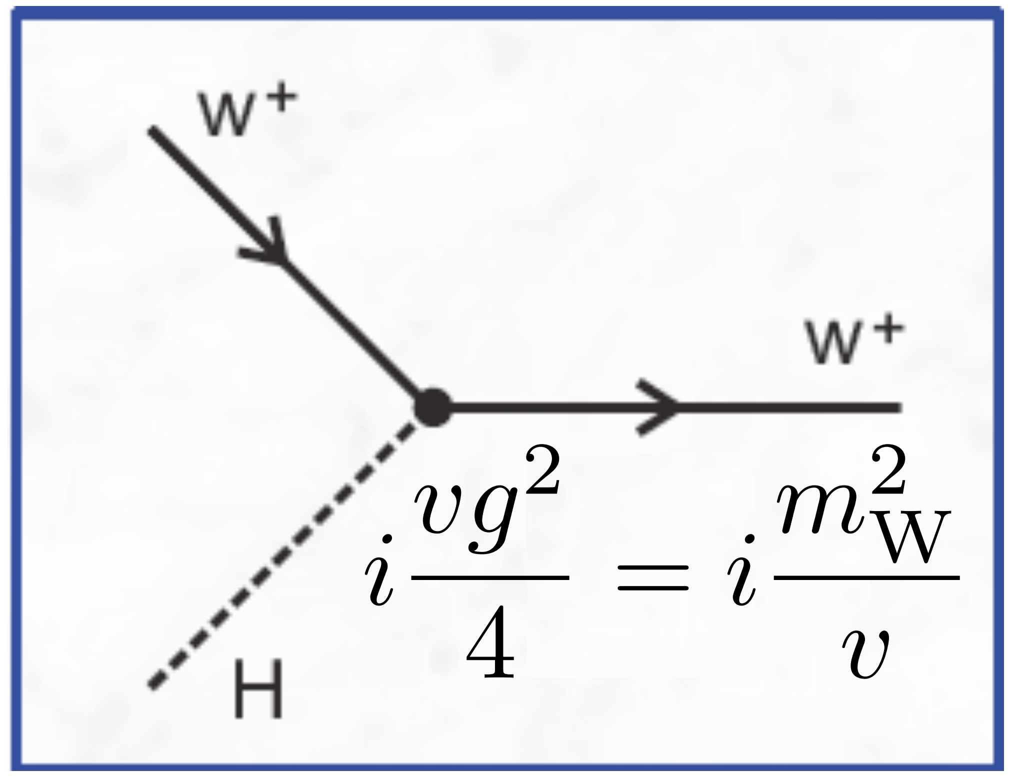
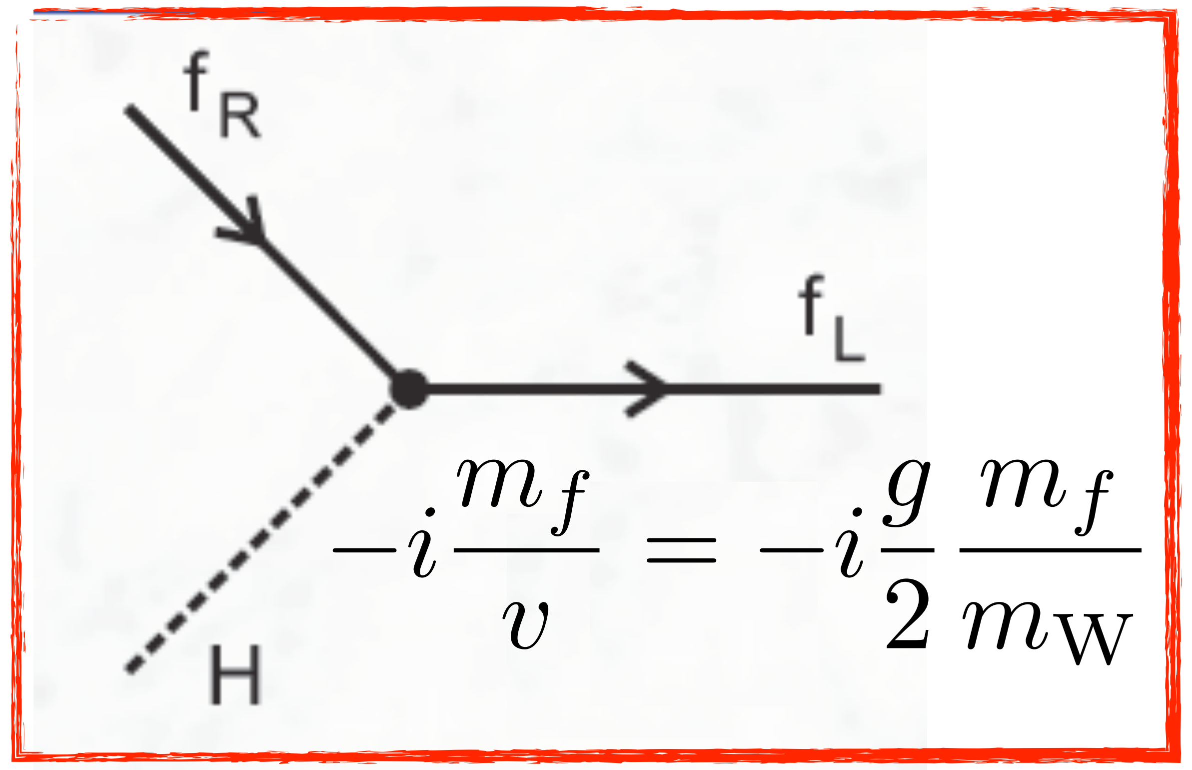
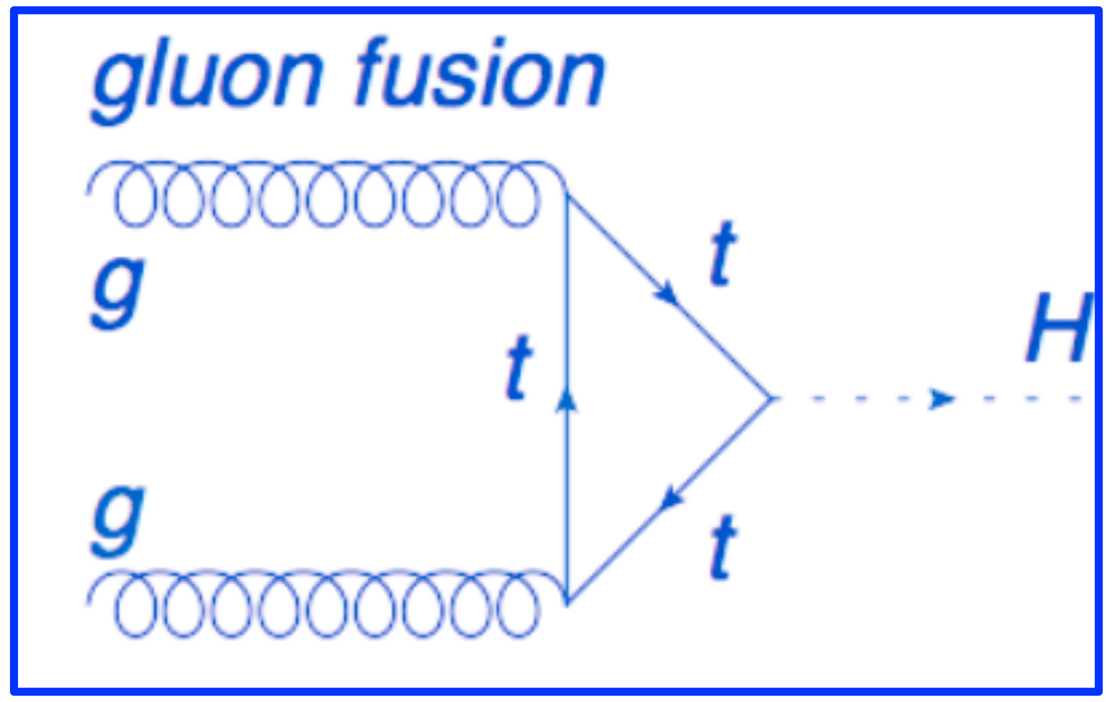
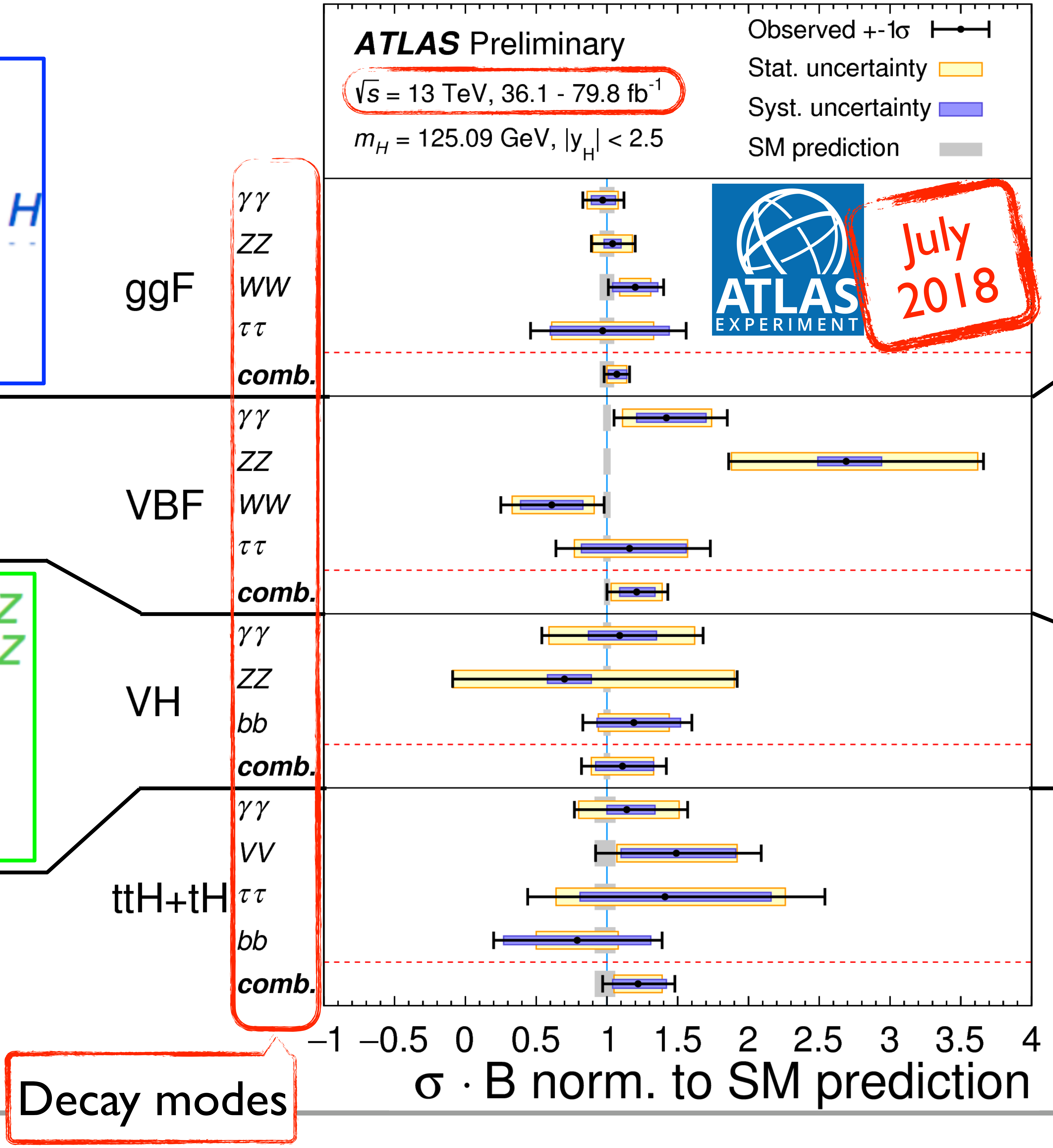
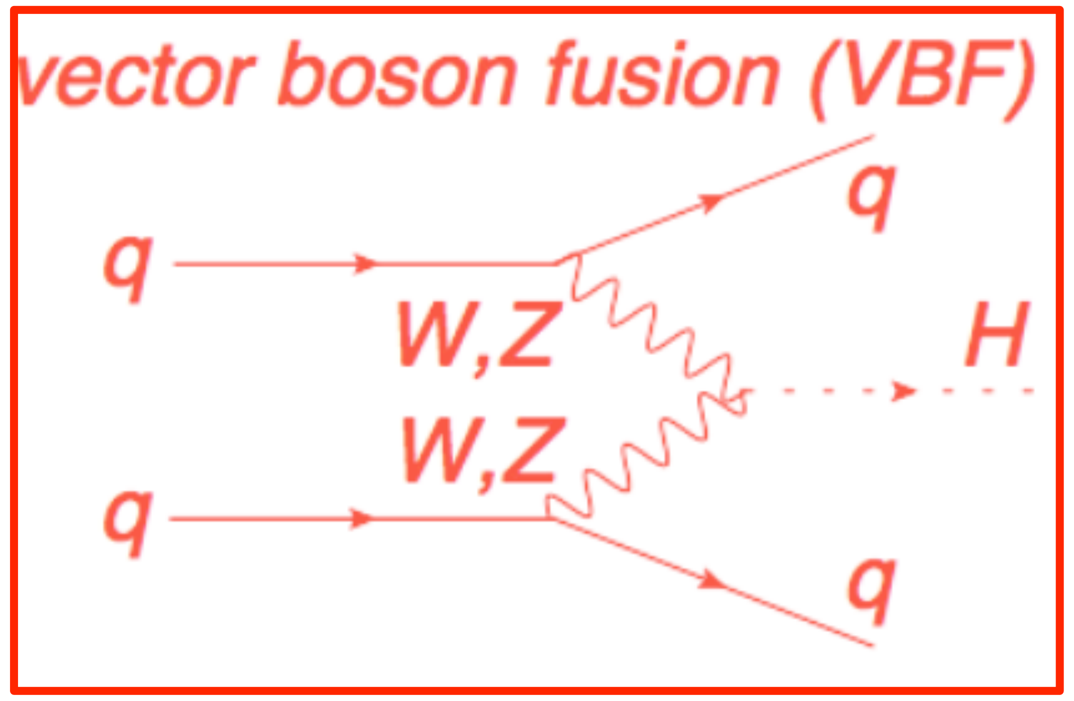


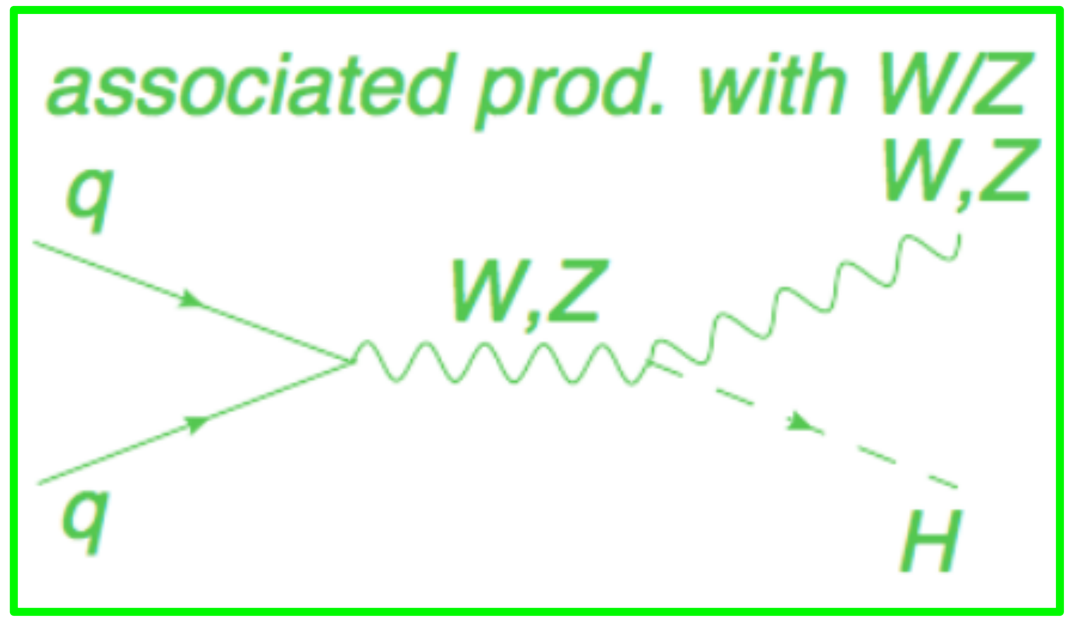


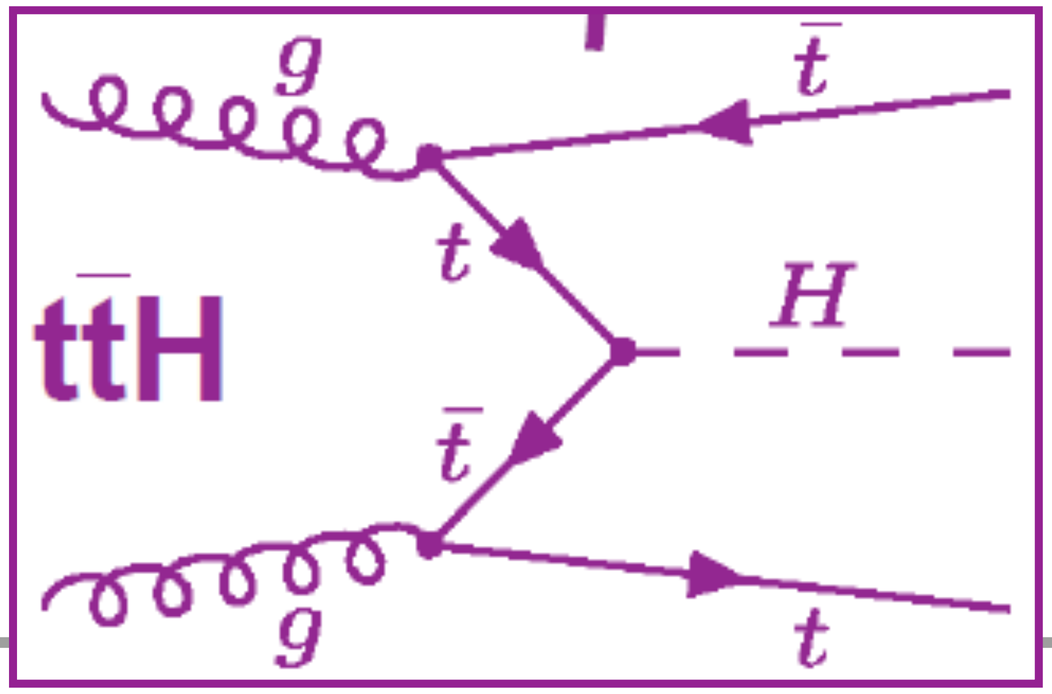
Production and Decay Modes

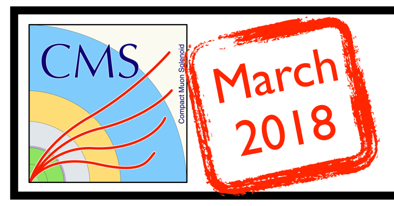












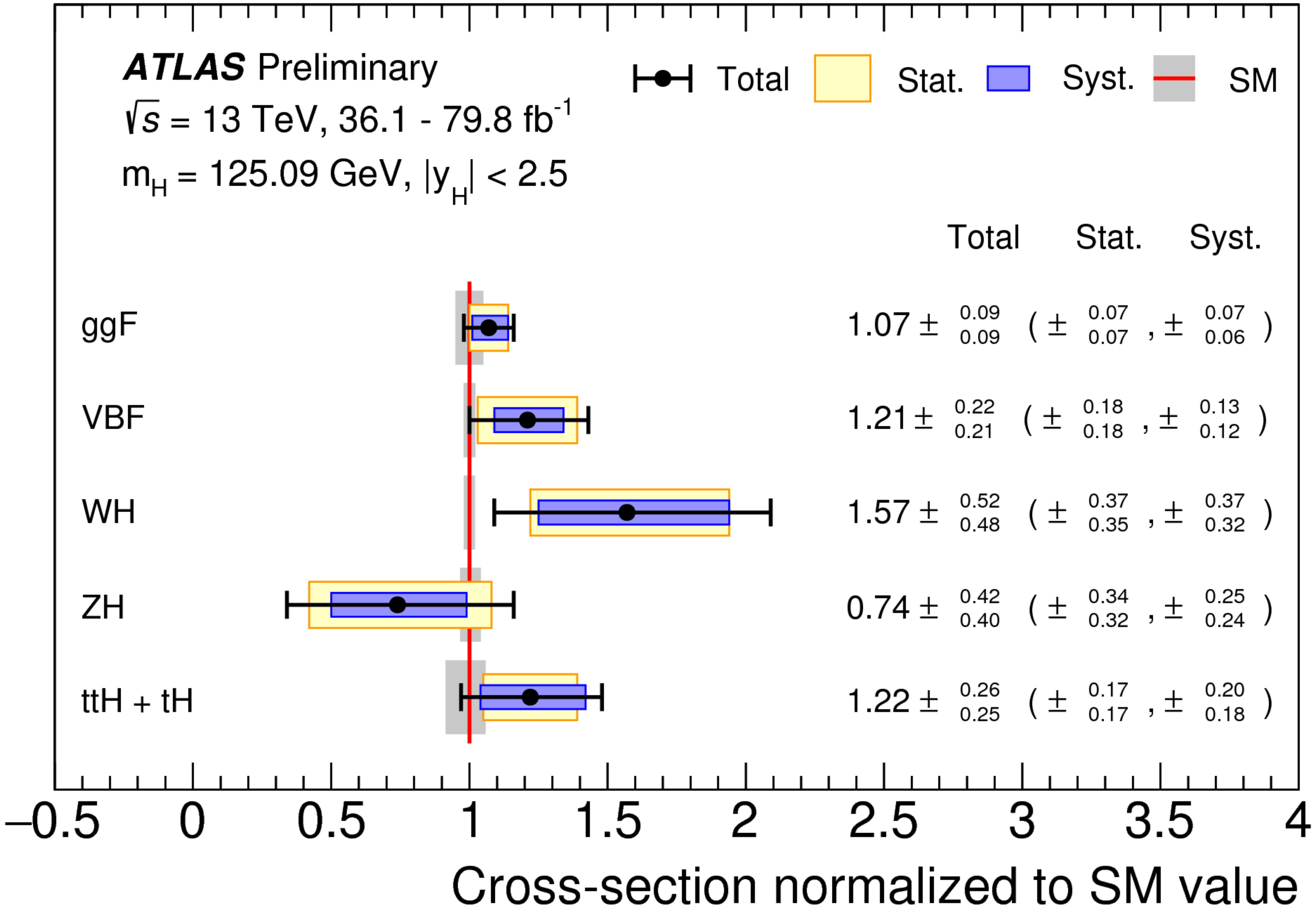
See backup

Production and Decay Modes

ATLAS-CONF-2018-031

July 2018

Production Cross-Sections
(assume SM decay BRs)



Process ($\lvert y_H \rvert < 2.5$)	Significance obs. (exp.)
ggF	-
VBF	6.5 (5.3)
WH	4.1 (3.7)
ZH	
$t\bar{t}H+tH$	5.8 (5.3)

Production and Decay Modes

- Define for $i \to H \to f$:

$$\mu_i := \frac{\sigma_i}{(\sigma_i)_{\text{SM}}}$$

$$\mu^f := \frac{\mathcal{B}^f}{(\mathcal{B}^f)_{\text{SM}}}$$

- Signal strength:

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

$$= \frac{\text{observed rate}}{\text{expected rate}}$$

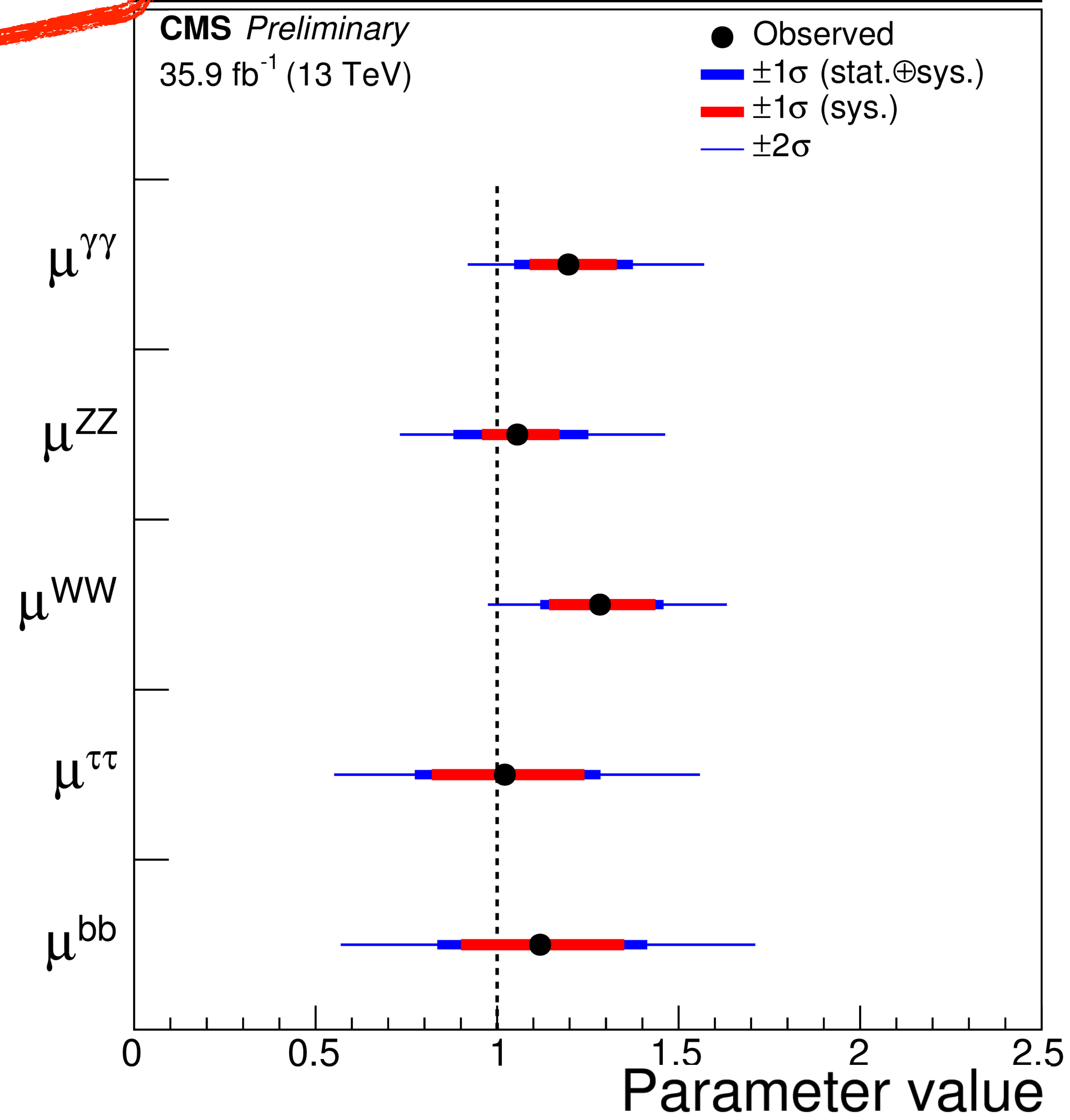
$\Rightarrow$ Includes total signal theory uncertainty!

CMS-PAS-HIG-17-031

March 2018

Decay μ

(assume SM production μ_i = 1)

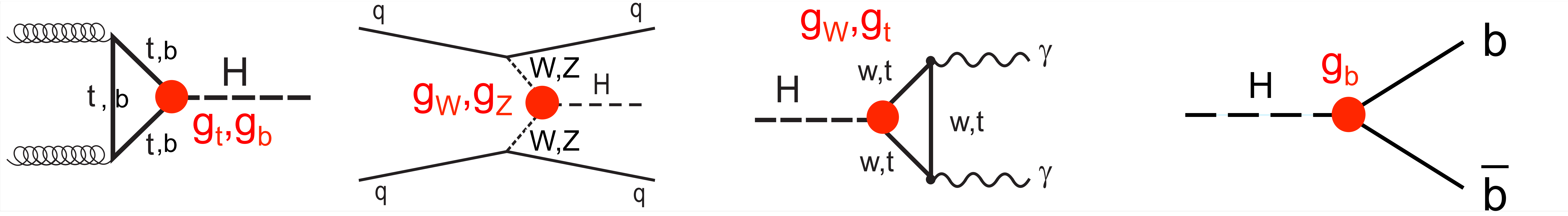


Global signal strength:	CMS (36 fb⁻¹)	$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\ ^{+0.06}_{-0.05}\,(\text{sig. th.})\ ^{+0.06}_{-0.06}\,(\text{other sys.})$
	ATLAS (36-80 fb⁻¹)	$\mu = 1.13^{+0.09}_{-0.08} = 1.13 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{exp.})\ ^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$

The κ Framework

Model and fit 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 scale factors:



$$\kappa_a := \frac{g_a}{(g_a)_{\mathrm{SM}}}$$

$$(\sigma \cdot \mathrm{BF})\,(i \to H \to j) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

$$= \sigma_{\mathrm{SM}}\,(i \to H) \cdot \mathrm{BF}_{\mathrm{SM}}\,(H \to f) \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

Assumption:

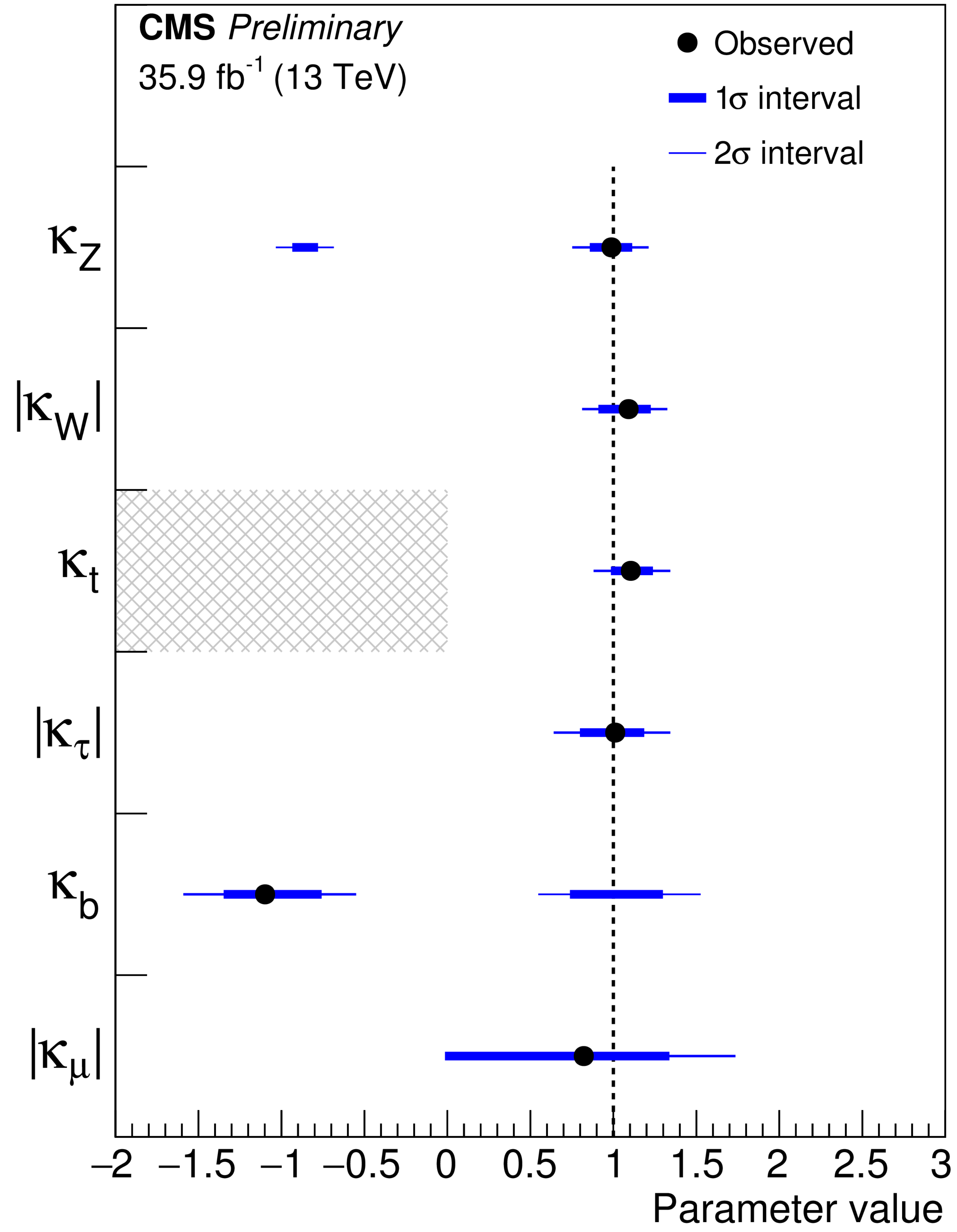
- Only one SM Higgs-like state at ~125 GeV with negligible width

LHC Higgs XS WG (arxiv:1307.1347)

Mass ~ Coupling Strength?

Assume: SM Higgs only couples to SM particles (no new physics)

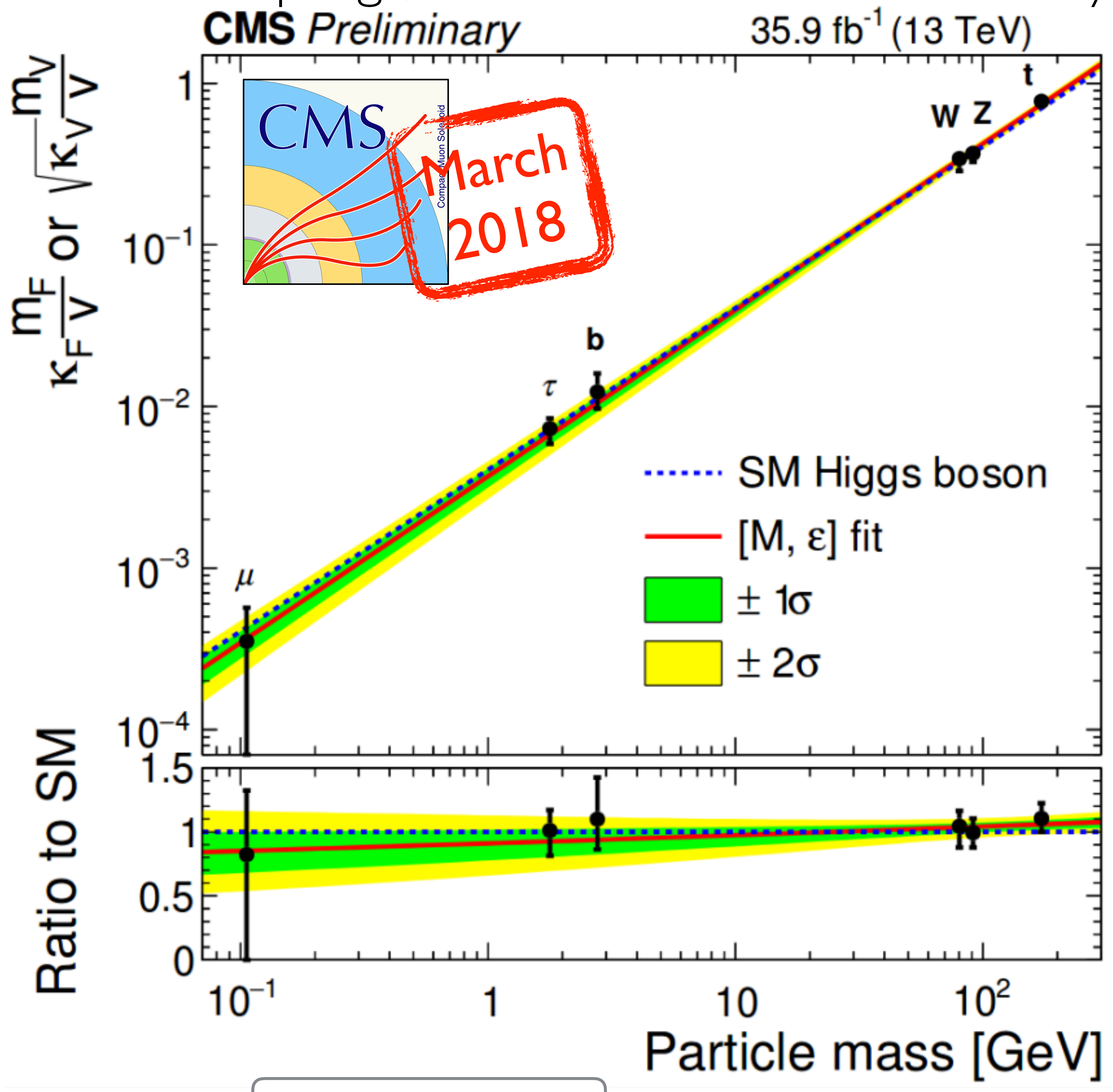
- express effective couplings to photons, gluons, and Higgs width only via SM couplings; no BSM contribution in decays



$\Rightarrow$

Include limit on $H \rightarrow \mu\mu$

Not model-independent measurement!



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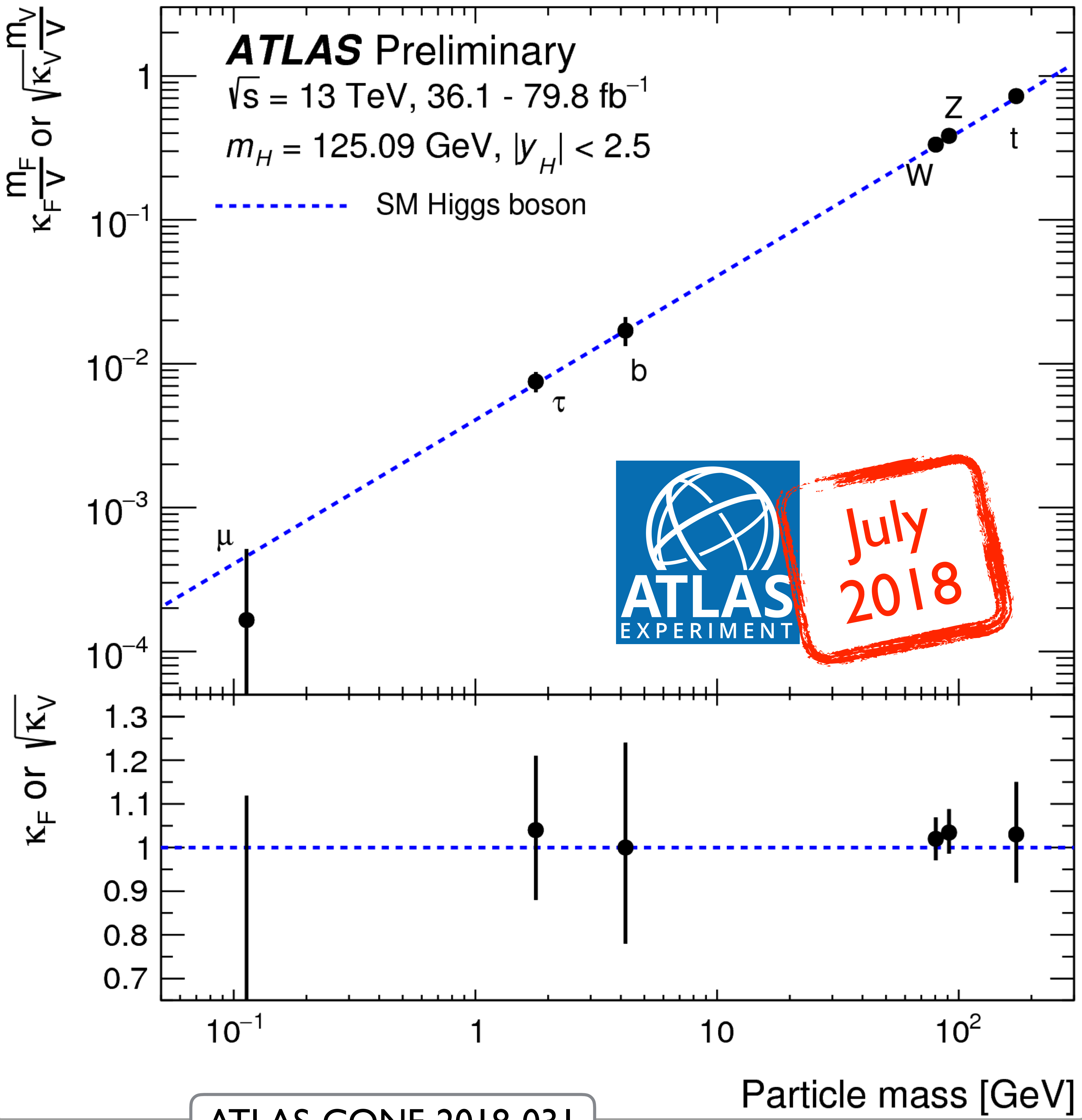

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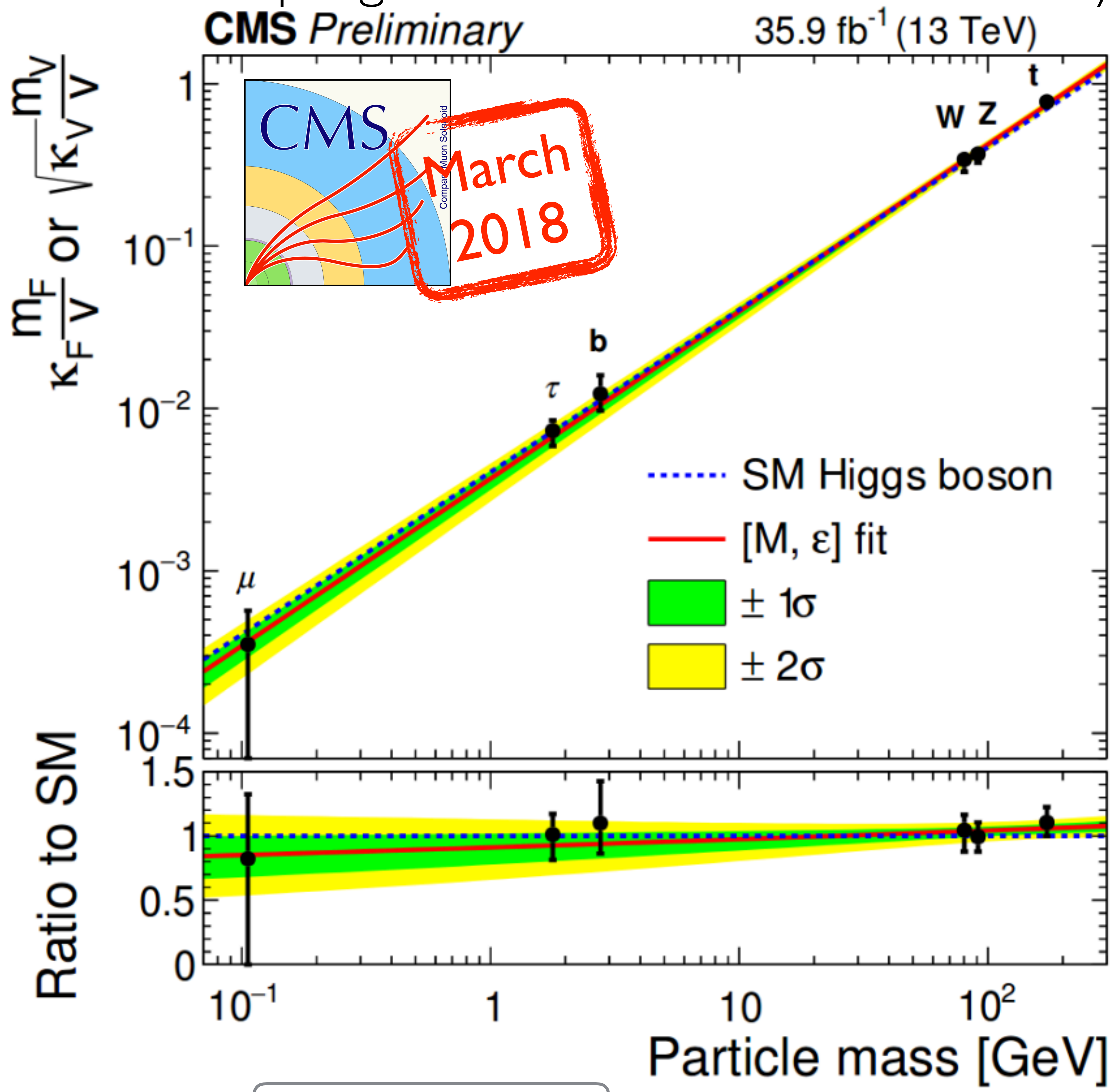


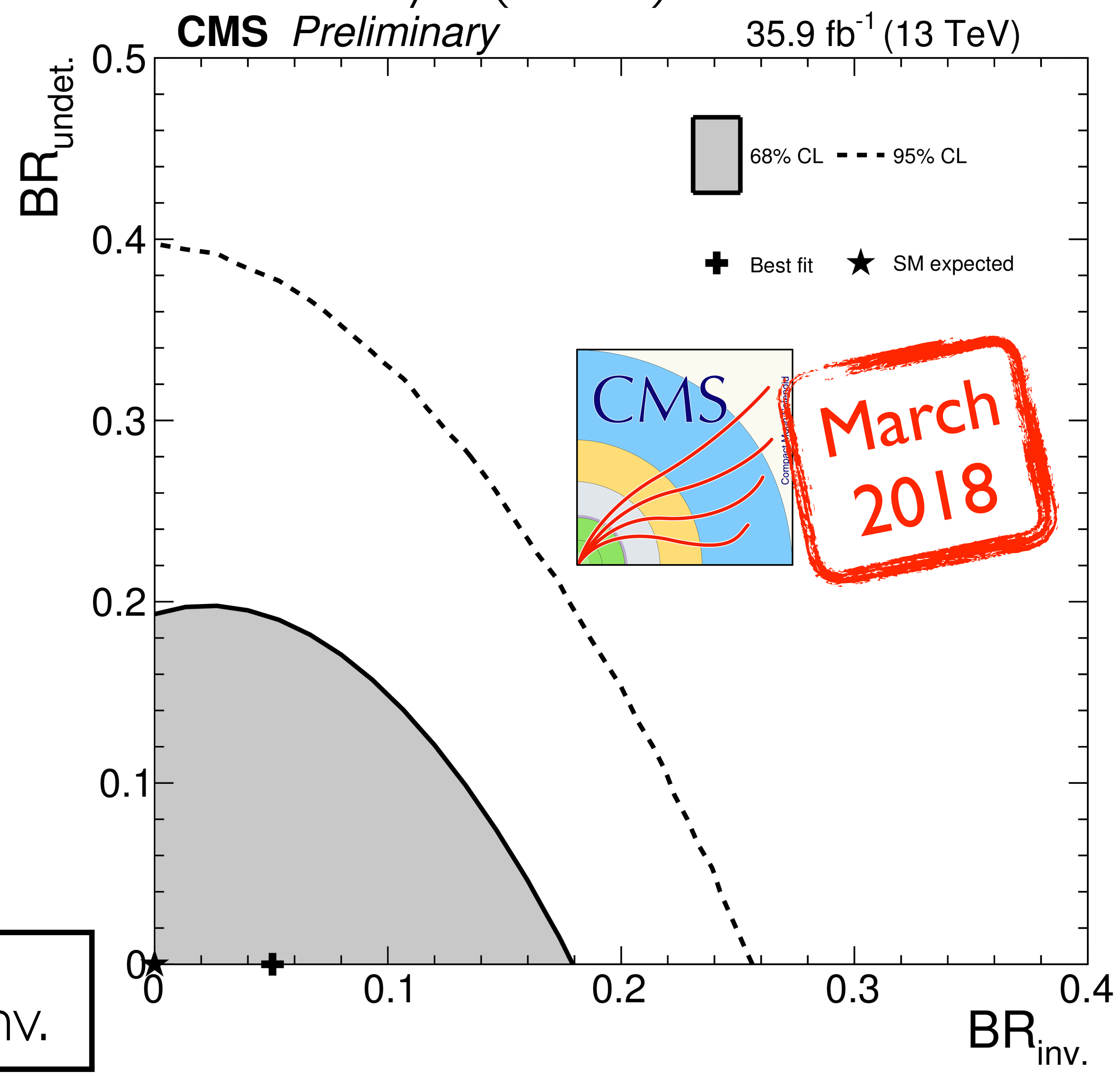
ATLAS-CONF-2018-031

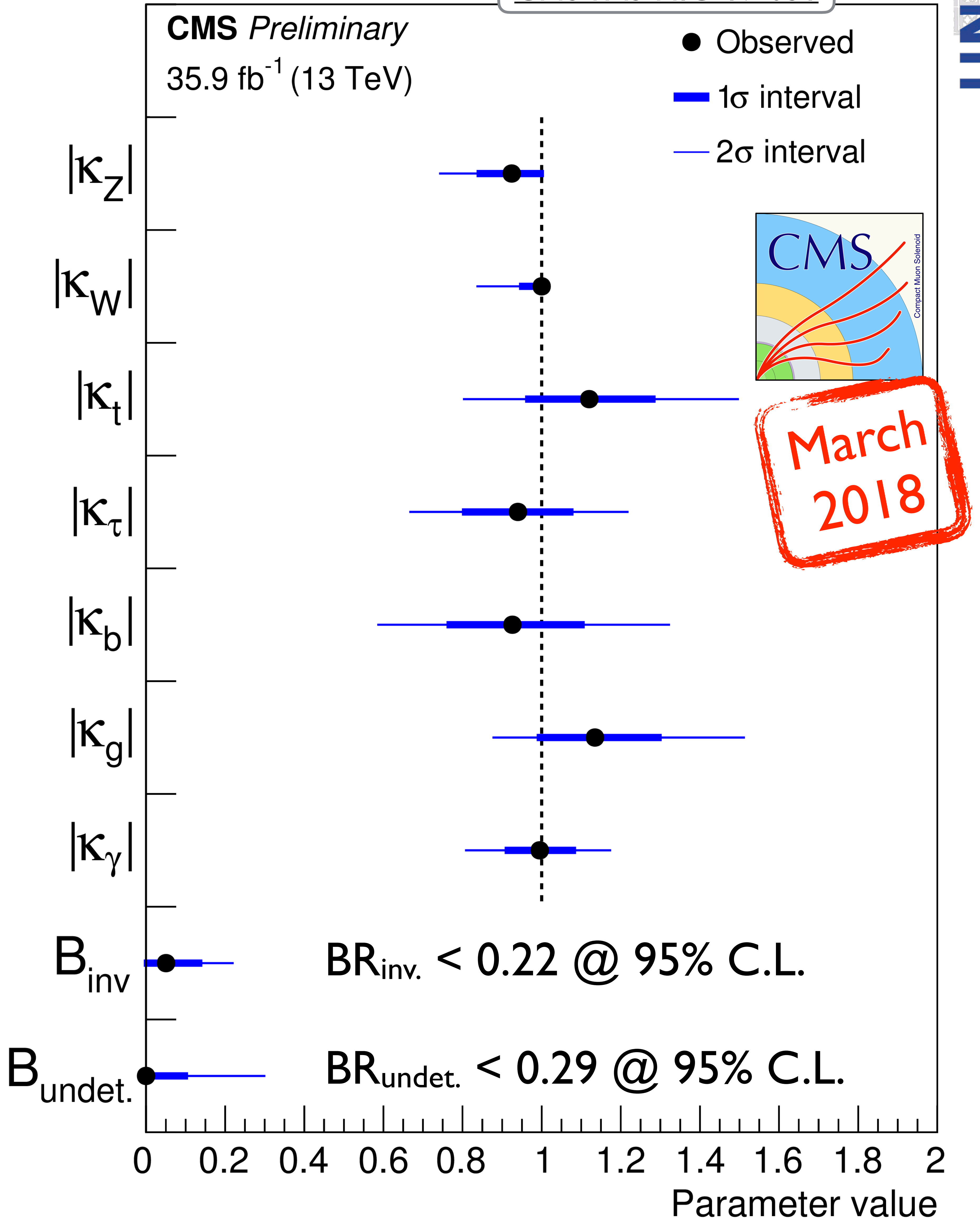
CMS-PAS-HIG-17-031

Invisible Decays of the Higgs Boson

- Use effective coupling modifiers to gluons (κ_g) and photons (κ_γ)
- Assume $|\kappa_Z| \leq 1$ and $|\kappa_W| \leq 1$
- Include direct searches for invisible decays (CMS)

CMS-PAS-HIG-17-031





$BR_{inv.} < 0.22$ @ 95% C.L.

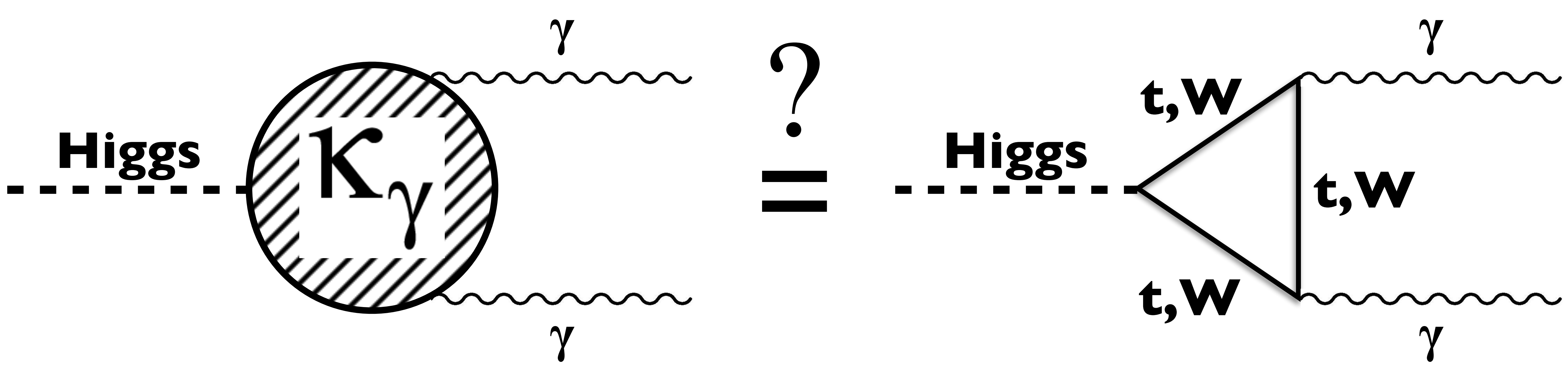
$BR_{undet.} < 0.29$ @ 95% C.L.

$BR_{BSM} = BR_{undet.} + BR_{inv.}$

ATLAS July 2018: $BR_{BSM} < 0.26$ @ 95% C.L., more in backup

Loop-induced Couplings

- In SM, ggF and H → γγ are loop-induced
  - New Particles could contribute inside loop
  - ⇒ Test effective coupling modifiers to photons and (κ_γ) gluons (κ_g)



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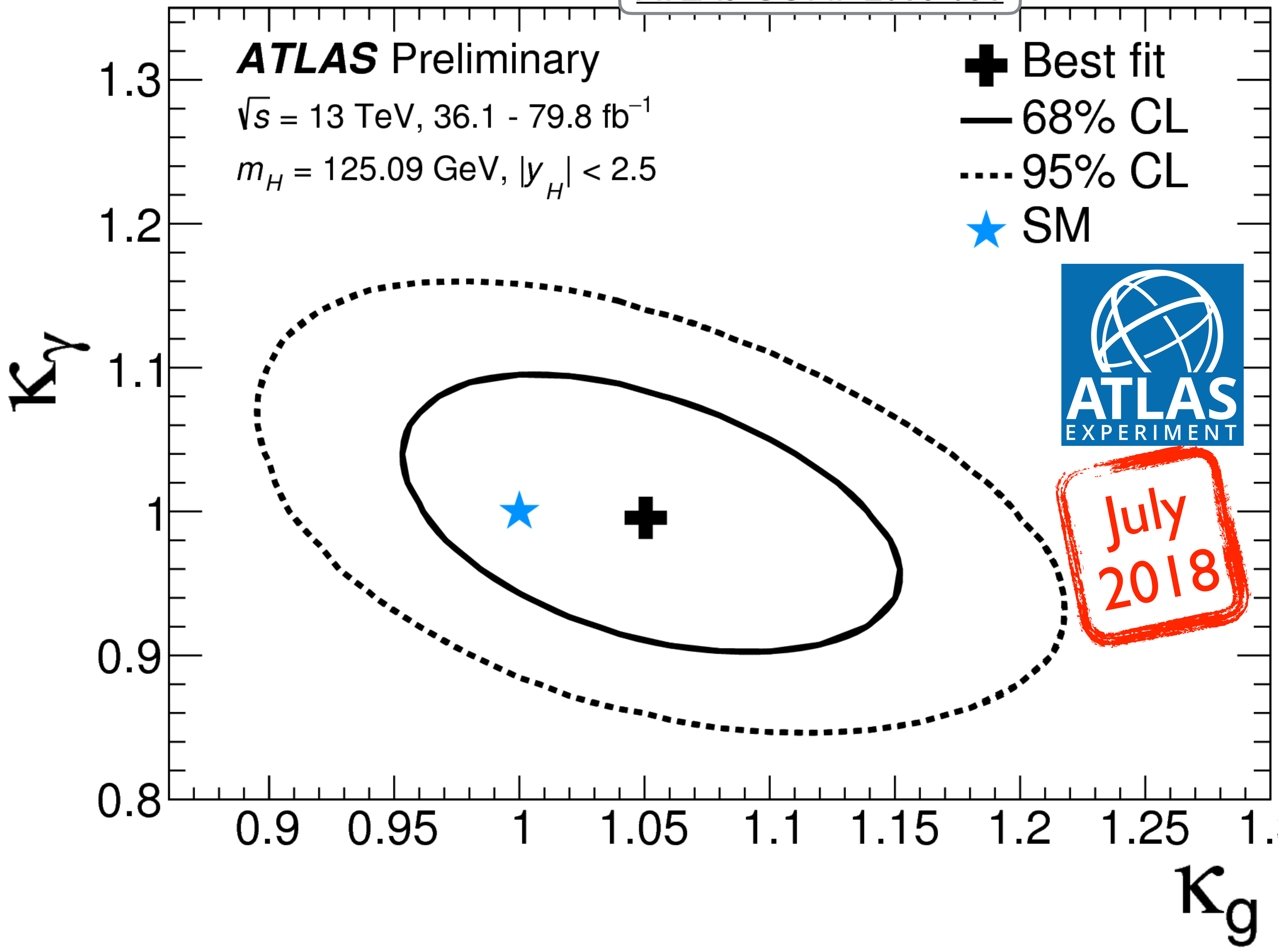
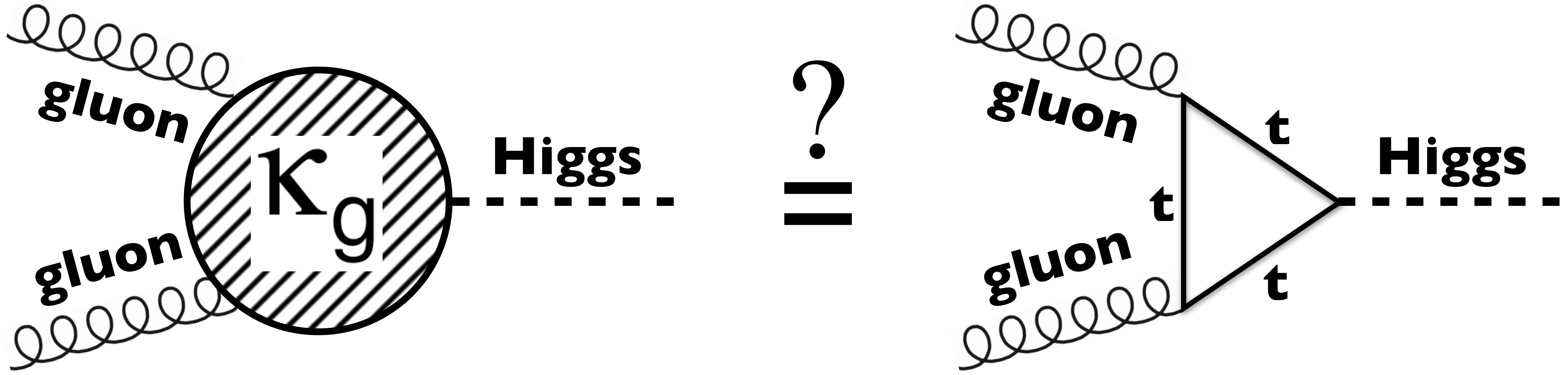
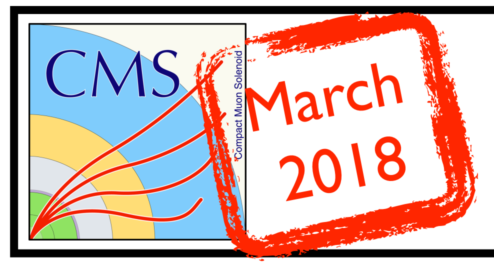




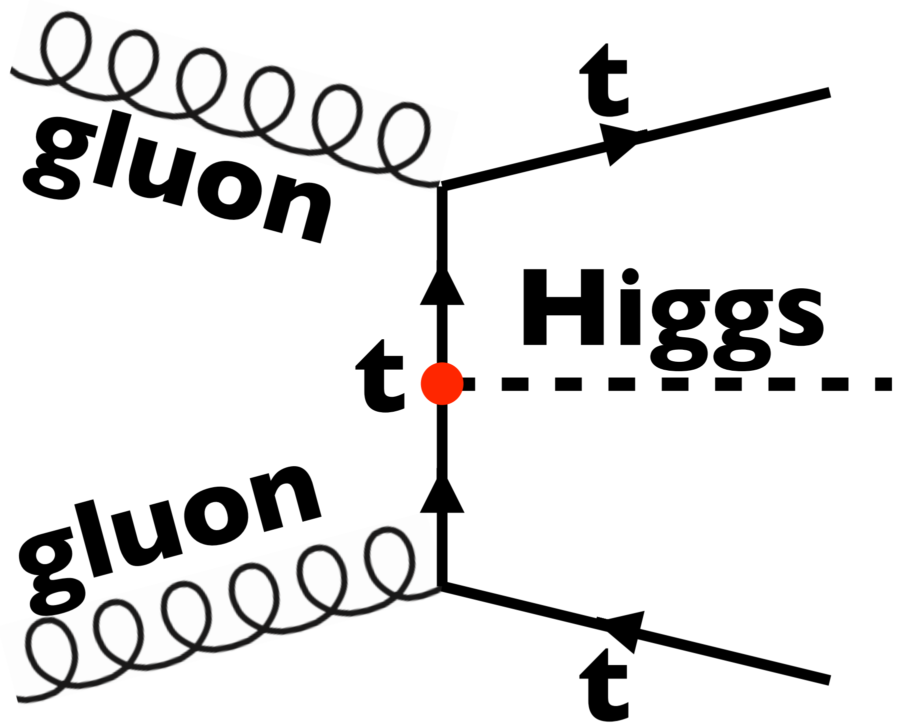


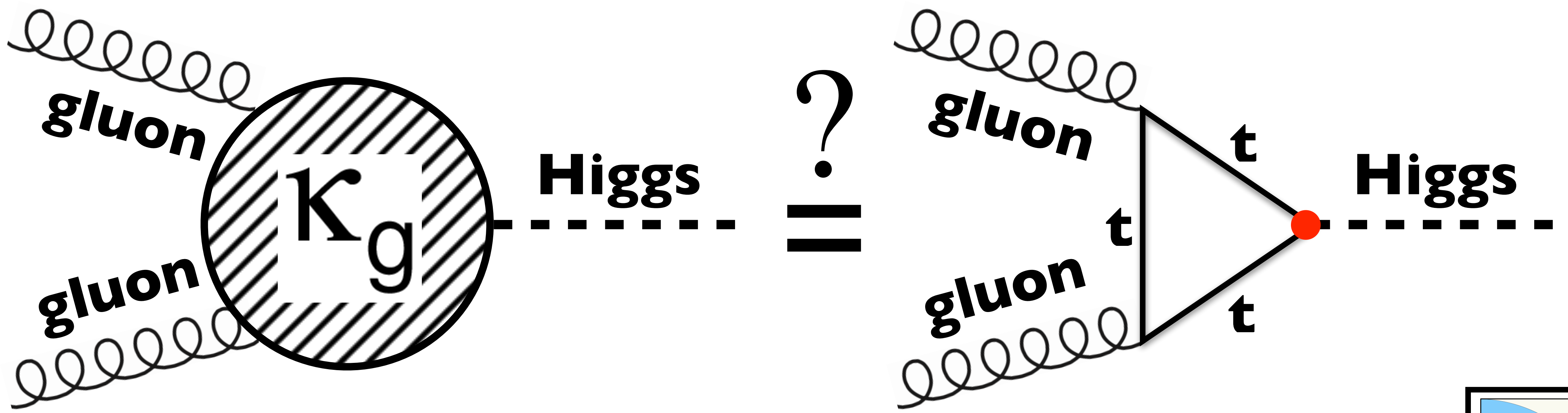
See backup

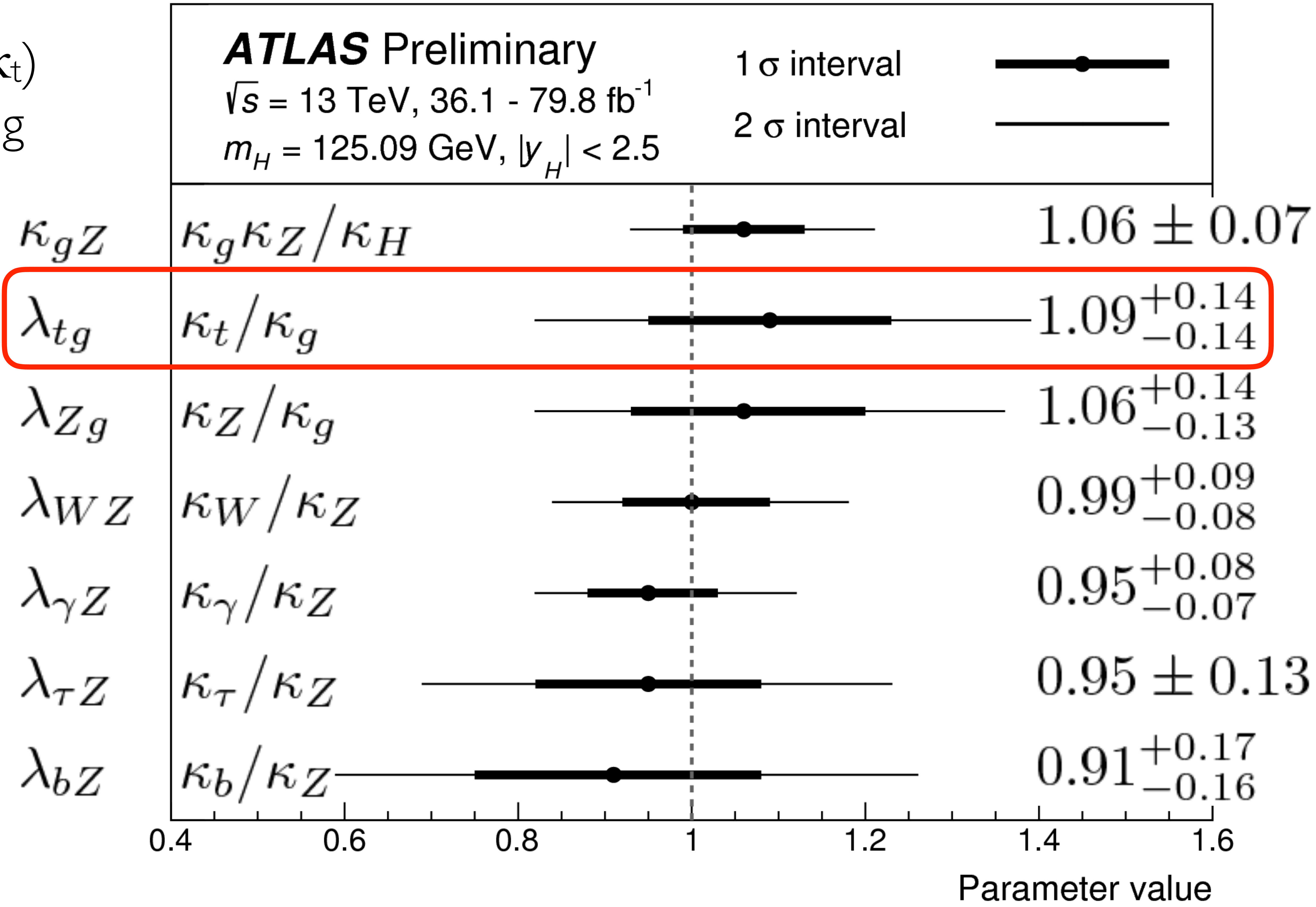
Ratios of Coupling Modifiers

ATLAS-CONF-2018-031

- Requires no assumption on total width of Higgs boson; assume all parameters >0
- New ttH result:
  - ⇒ Test compatibility between direct ttH coupling (κ_t) and coupling inside ggF loop, *i.e.*, effective coupling modifier to gluons (κ_g)





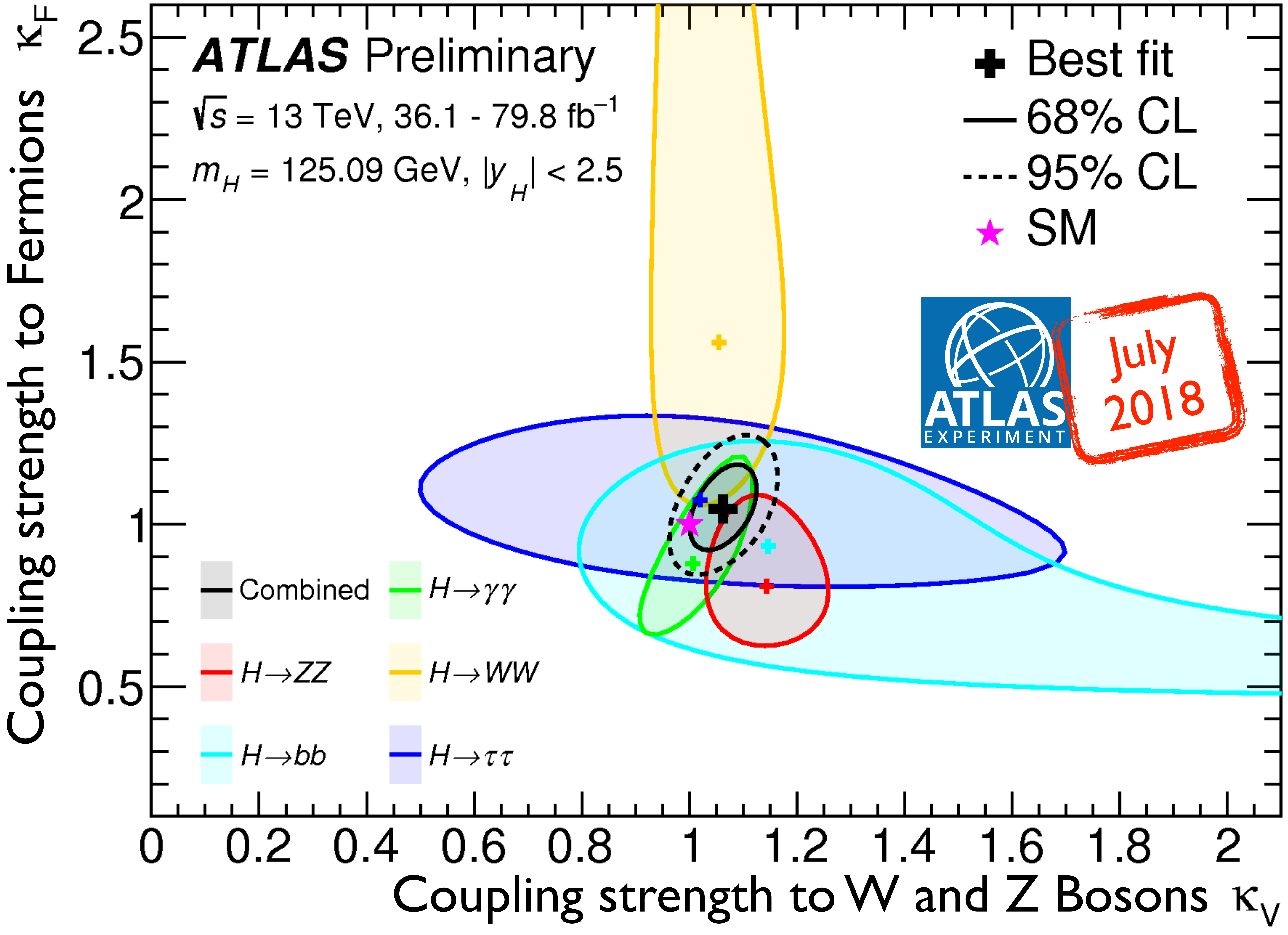


CMS March 2018: $\lambda_{tg} = 0.96\,^{+0.16}_{-0.15}$, more in backup

Coupling to Fermions and Bosons

ATLAS-CONF-2018-031

- Scale all fermionic couplings and all bosonic couplings to Higgs boson by same modifier (κ_F, κ_V)
  - Good agreement amongst individual results and with SM

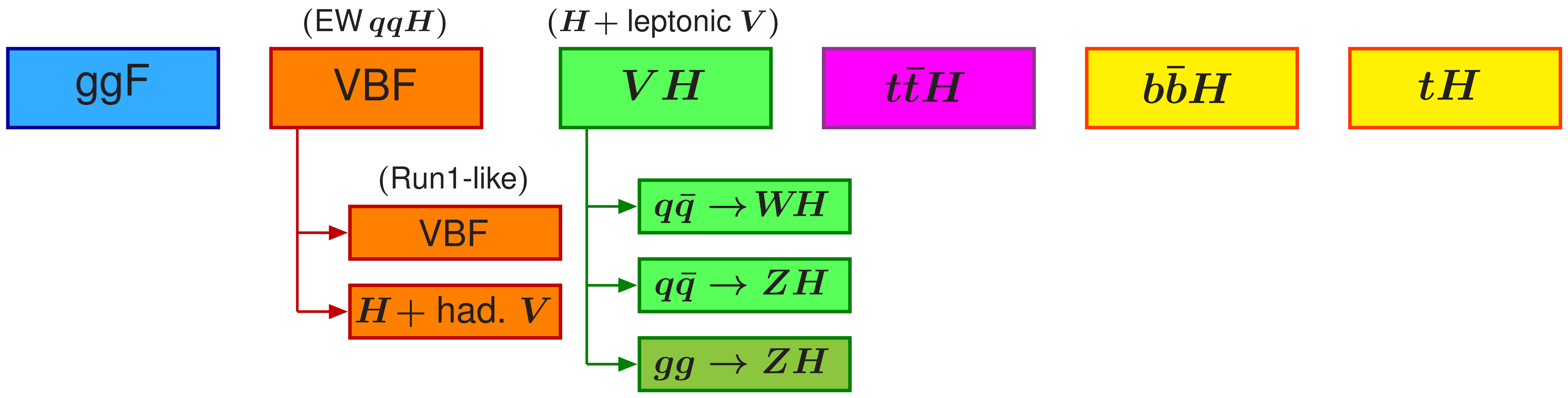


See backup

Simplified Template Cross Sections (STXS)

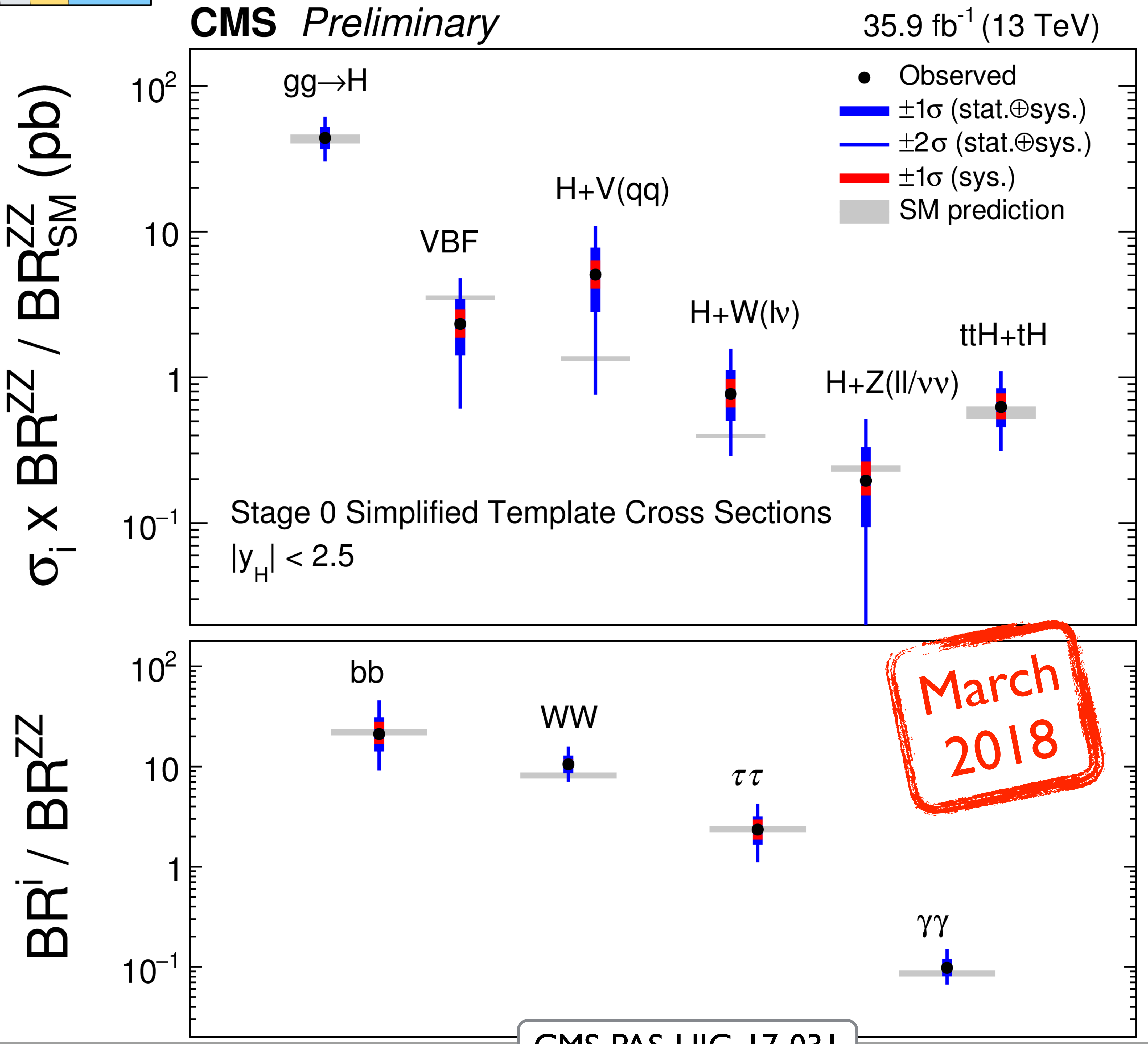
- Evolution of Run 1 coupling framework
  - Measure ***cross sections***, instead of signal strengths
- Allows for combination across all decay modes

Stage-0 categories: separated into production modes



arxiv:1610.07922

Stage-0 analysis:
Combination of main channels



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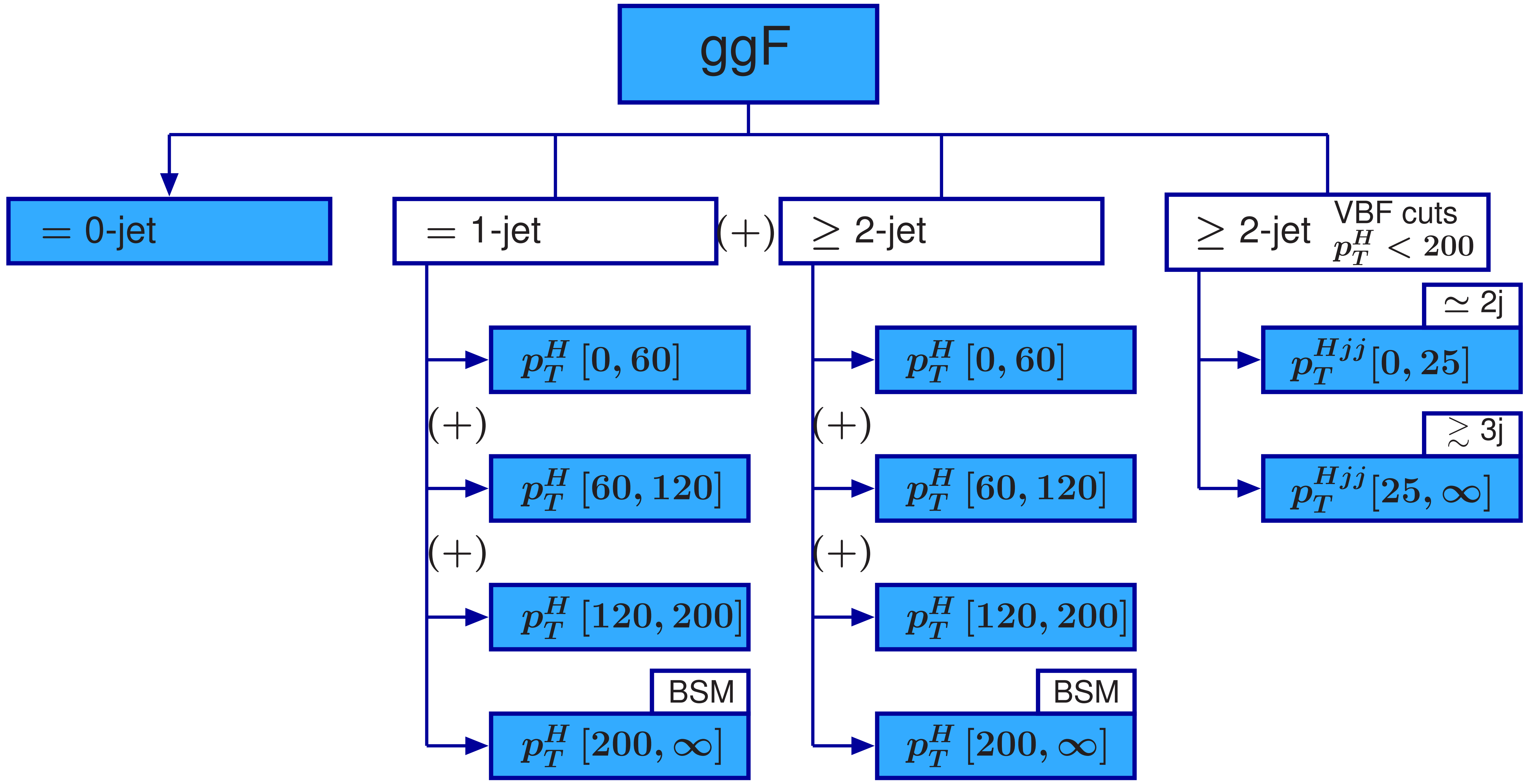
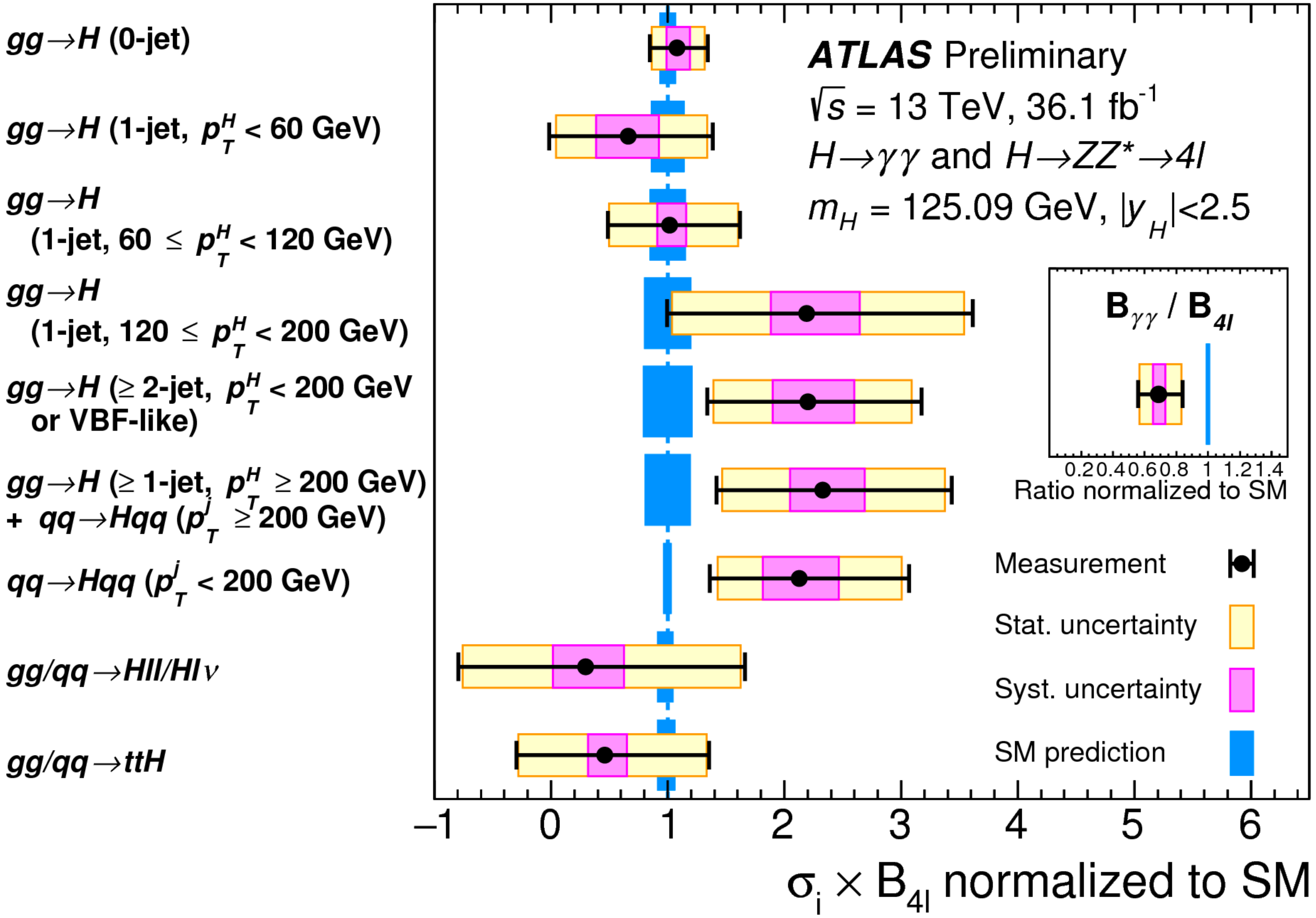
Simplified Template Cross Sections (STXS)

Stage-1 ggF categories: exclusive phase spaces



arxiv:1610.07922

Stage-1 analysis: Combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$



ATLAS-CONF-2017-047

Effective Field Theory Interpretation

ATL-PHYS-PUB-2017-018

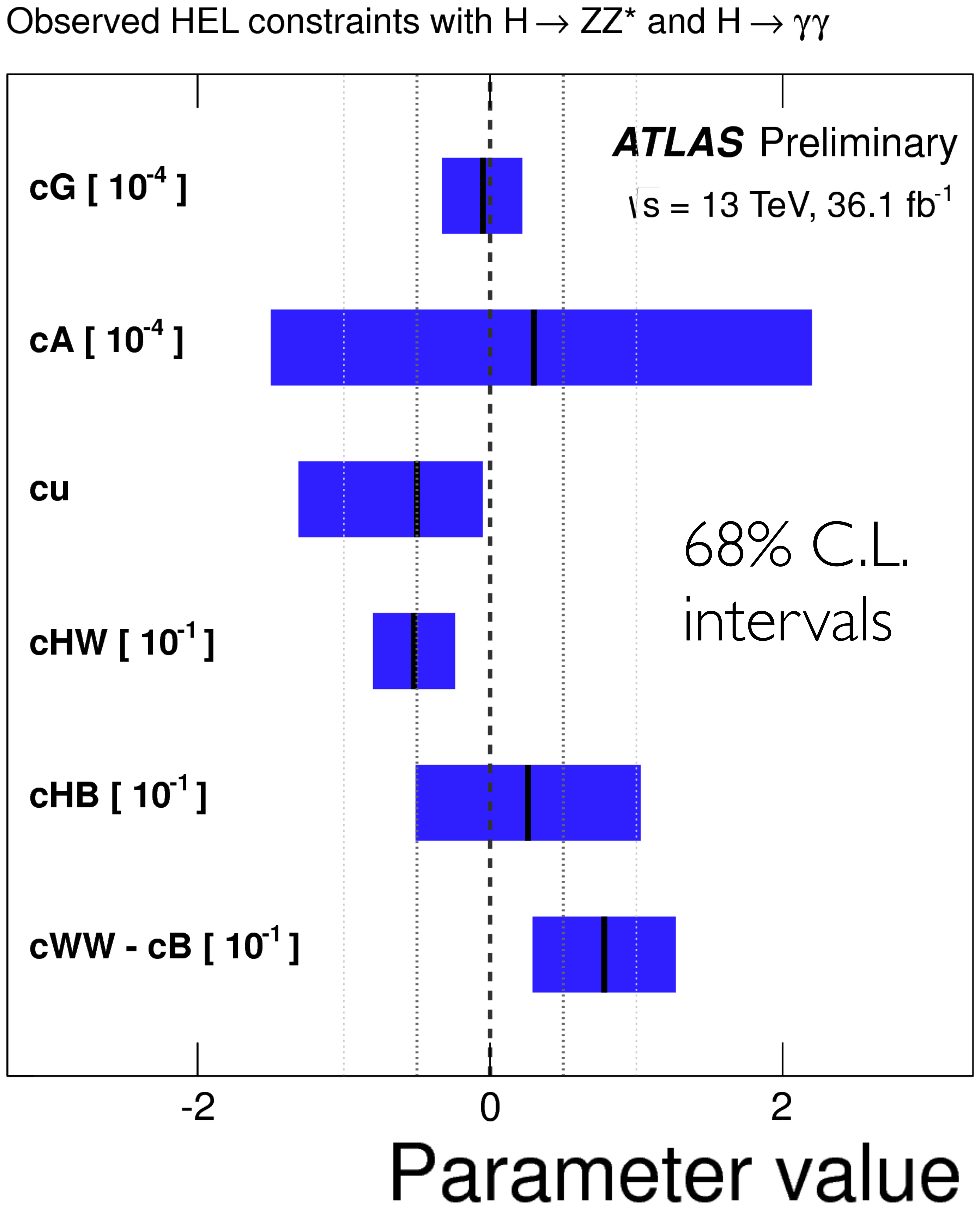
- Extend SM with new Operators:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$$

  - Assumes no new particles below Λ=1 TeV

- Use **Stage-1 STXS $\gamma\gamma$+4ℓ combination**:

Vertices
Hgg
Hγγ, HZZ
Htt
HWW, HZZ
HZZ
HWW, HZZ



Summary & Outlook

What we know about the Higgs boson

- **2‰ precision** on **m_H** measurements
- **All measured properties consistent with SM expectations**
- Many more $\sqrt{s}$ = 13 TeV results could not be discussed here

Significant advances in theory, crucial for interpretation of measurements

- e.g., improvement in ggF cross-section calculation (N^3LO QCD): theory uncertainty: 8.5% ⟶ 5.0%

Entering new era of interpretation of precise results

- with **~10 million produced Higgs bosons in 150 fb^{-1} during Run 2**
- Differential cross sections
- Simplified Template Cross Sections
- Effective Field Theories

And even ~20 million produced Higgs bosons in 300 fb^{-1} in Run 3…

Total Cross Section

- Combination of H → $\gamma\gamma$ and H → ZZ* → 4ℓ

ATLAS EXPERIMENT — May 2018

$$57.0^{+6.0}_{-5.9}\,(\text{stat.})\;{}^{+4.0}_{-3.3}\,(\text{syst.})\ \text{pb}$$

arxiv:1805.10197, accepted by PLB

CMS — July 2018

$$61.1 \pm 6.0\,(\text{stat.}) \pm 3.7\,(\text{syst.})\ \text{pb}$$

CMS-PAS-HIG-17-028

SM: 55.6 ± 2.5 pb

Extracting Light-Quark Couplings from $p_T(H)$

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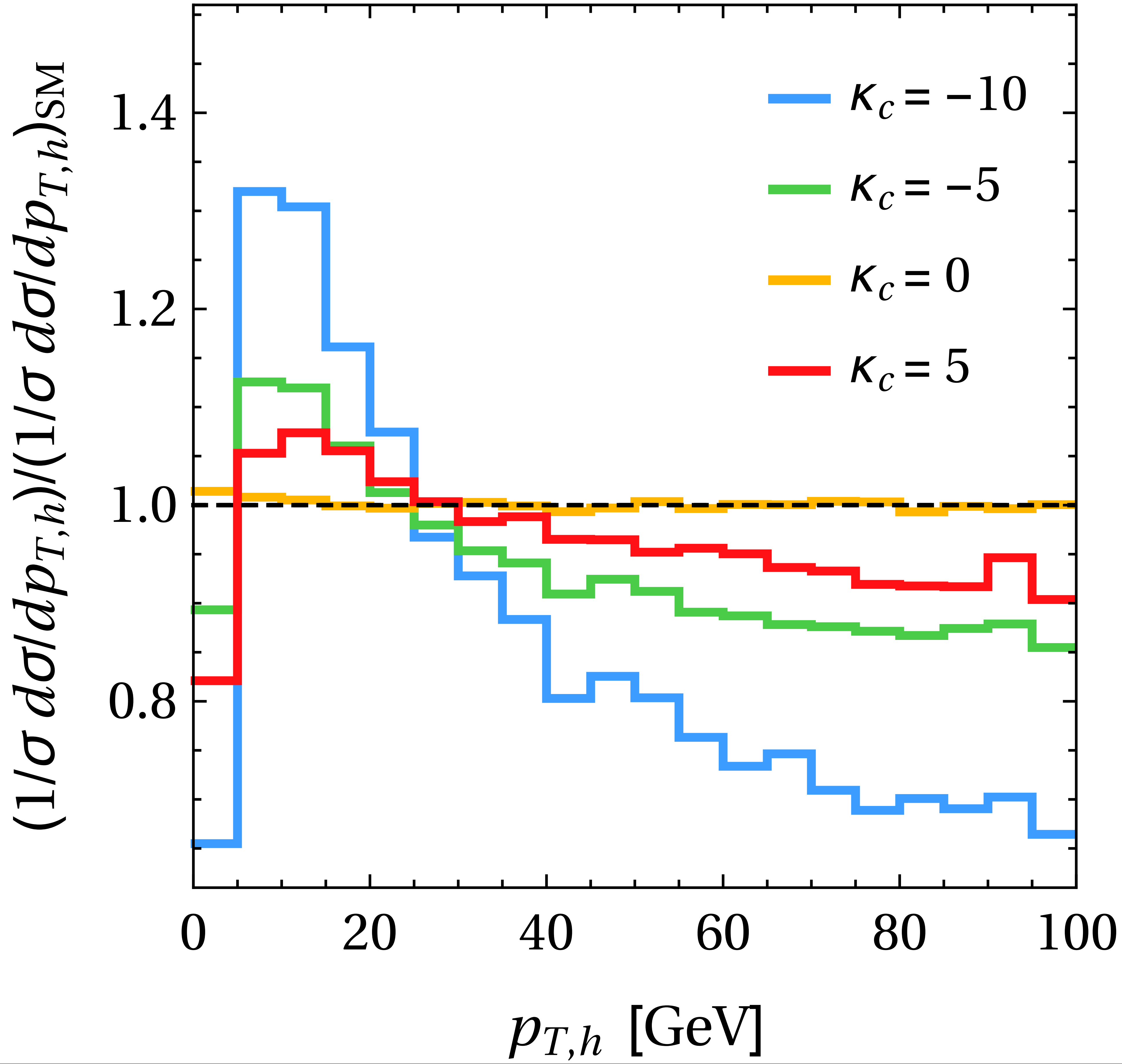


July 2018

Scan one κ_q; profile other

- Coupling-dependent branching fractions
  - Total width and overall normalization largely contribute to constraint

$$-0.9 < \kappa_b < 0.9 \quad (-1.2 < \kappa_b < 1.2 \ \text{expected})$$

$$-4.3 < \kappa_c < 4.3 \quad (-5.4 < \kappa_c < 5.3 \ \text{expected})$$

- Freely-floating branching fractions
  - Only $p_T(H)$ influence

$$-2.8 < \kappa_b < 9.9 \quad (-3.7 < \kappa_b < 7.3 \ \text{expected}),$$

$$-18.0 < \kappa_c < 22.9 \quad (-15.7 < \kappa_c < 19.3 \ \text{expected})$$

- Branching fractions fixed to SM

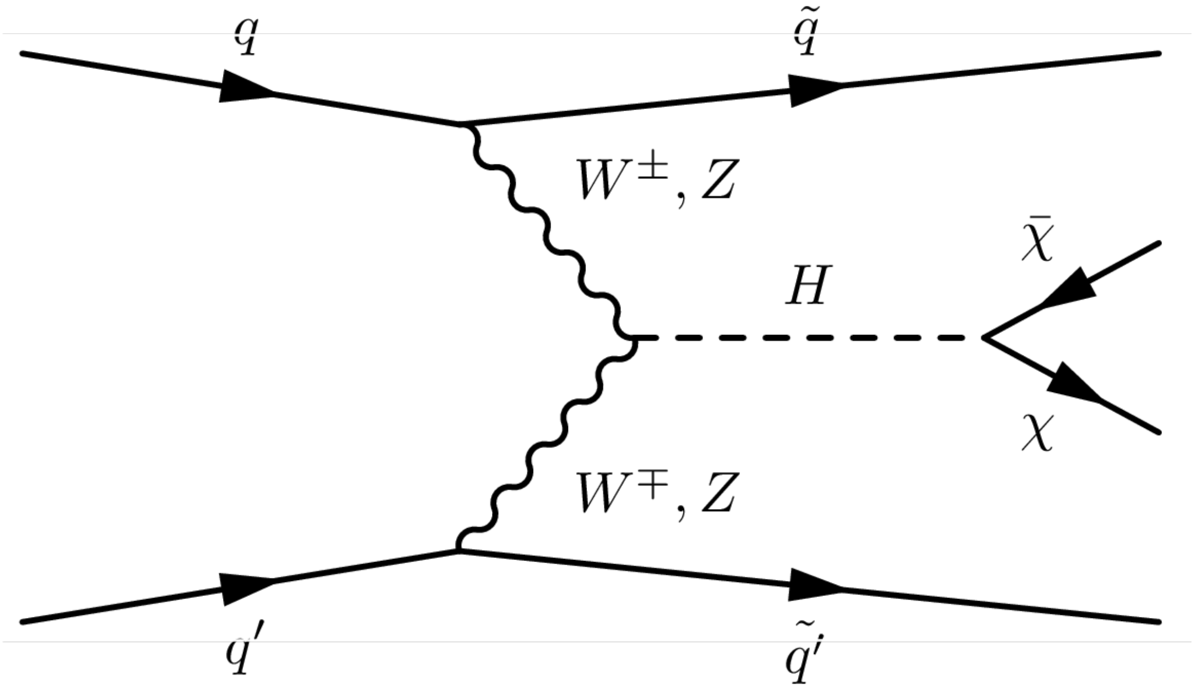
$$-1.9 < \kappa_b < 2.9 \ (\text{expected})$$

$$-8.7 < \kappa_c < 10.6 \ (\text{expected})$$

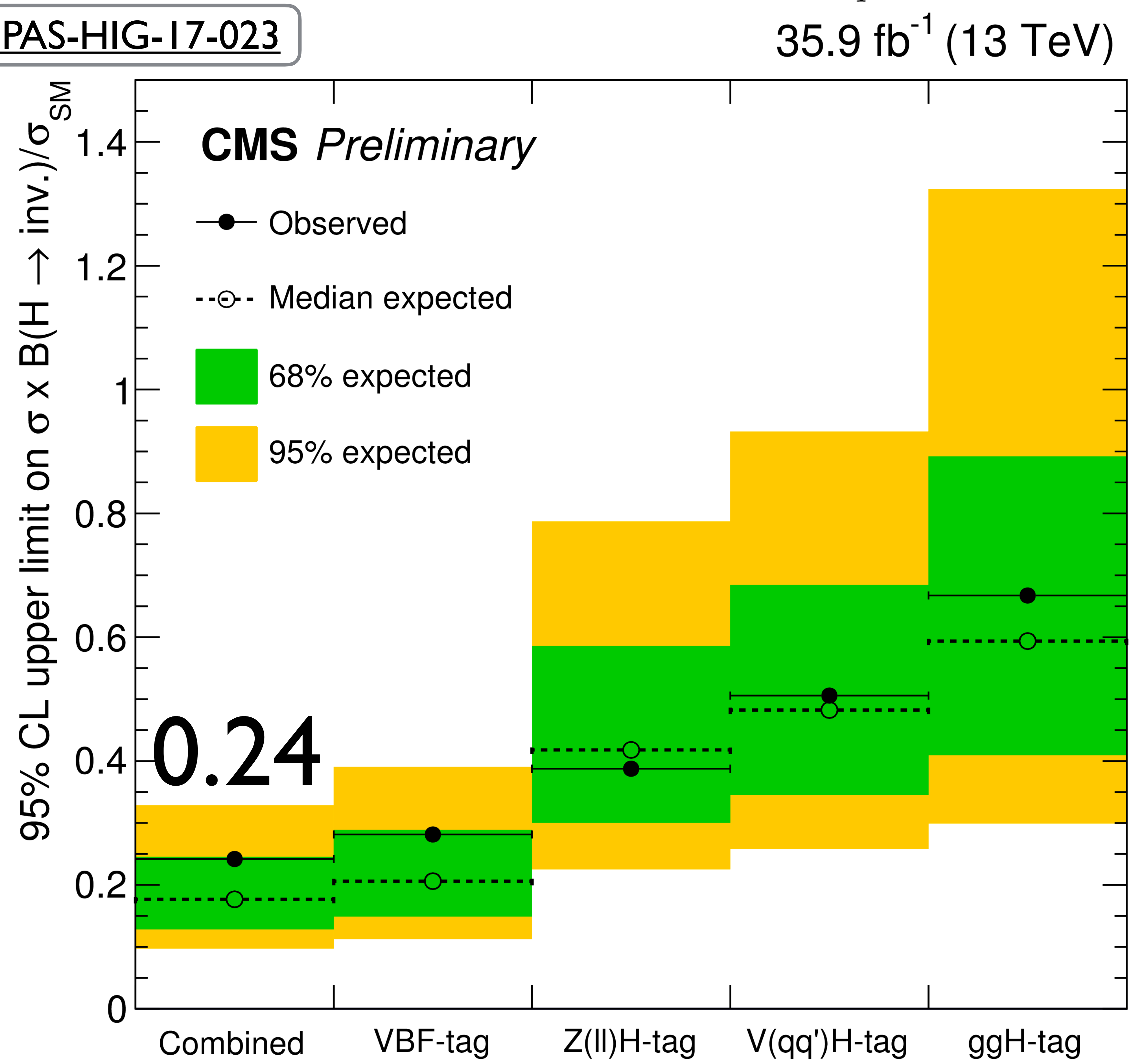
CMS-PAS-HIG-17-028

Invisible Decays of the Higgs Boson

- Search for new invisible decays
  - e.g., VBF topology:

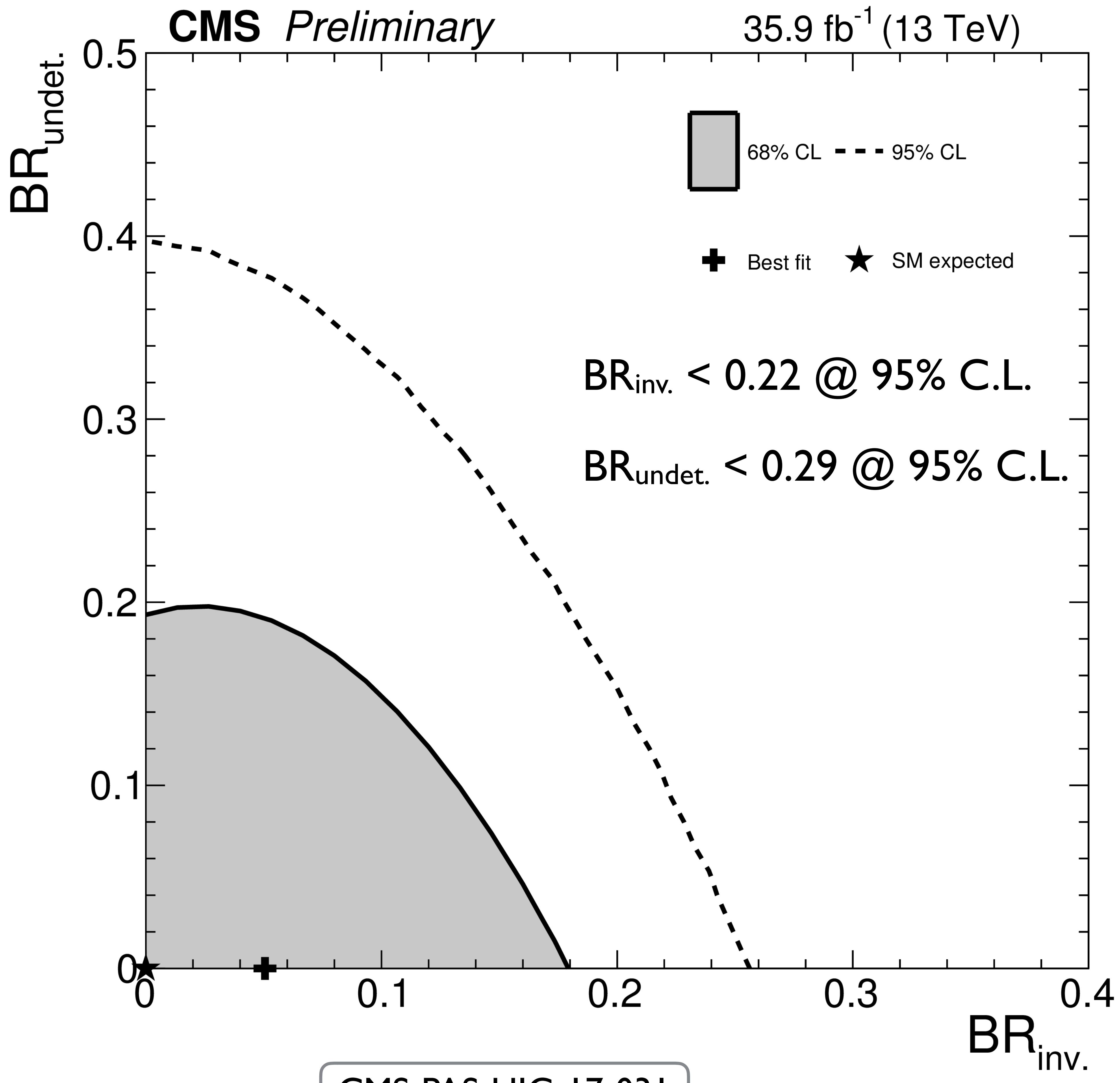


CMS-PAS-HIG-17-023



March 2018

- or combined analysis
  - with assumptions

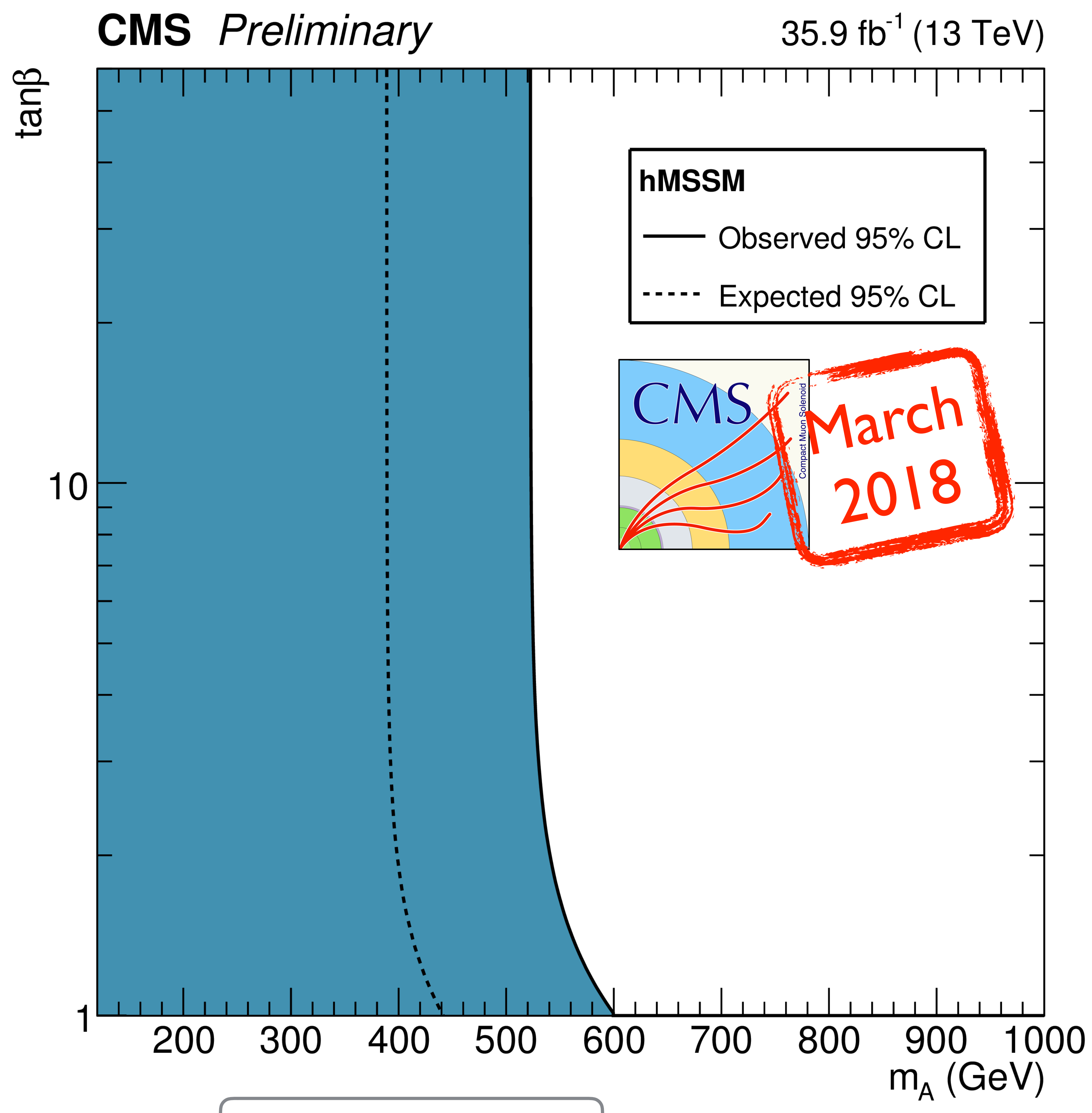


CMS-PAS-HIG-17-031

BSM Interpretations

- Models with second Higgs doublet without tree-level FCNC
- Assume: Higgs boson with m_H = 125 GeV is lightest CP-even neutral Higgs boson

⇒ Production and decay rates are (at tree level) only sensitive to α and β.

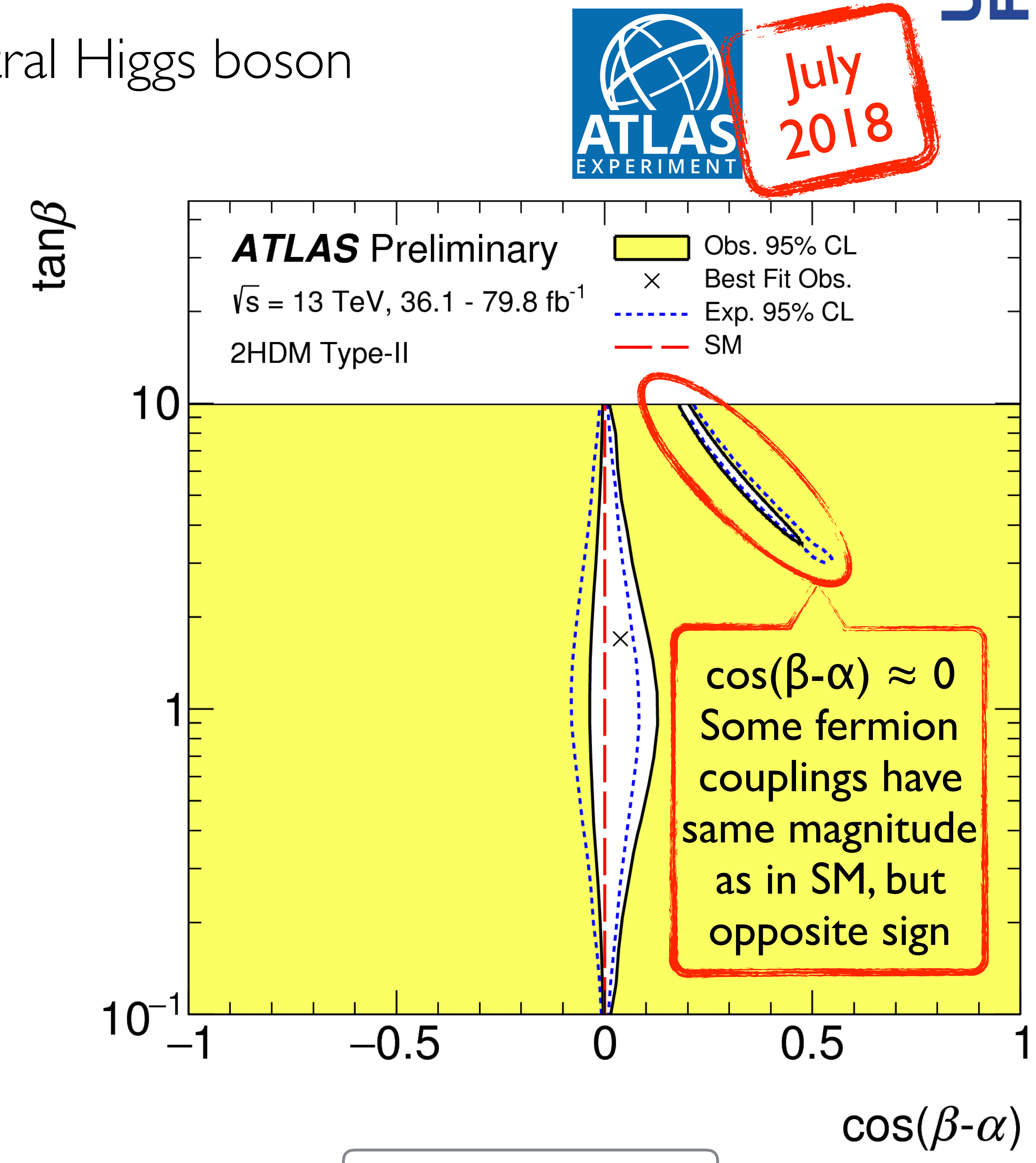


CMS-PAS-HIG-17-031

tan β = ratio of vevs

α = mixing angle between h and H

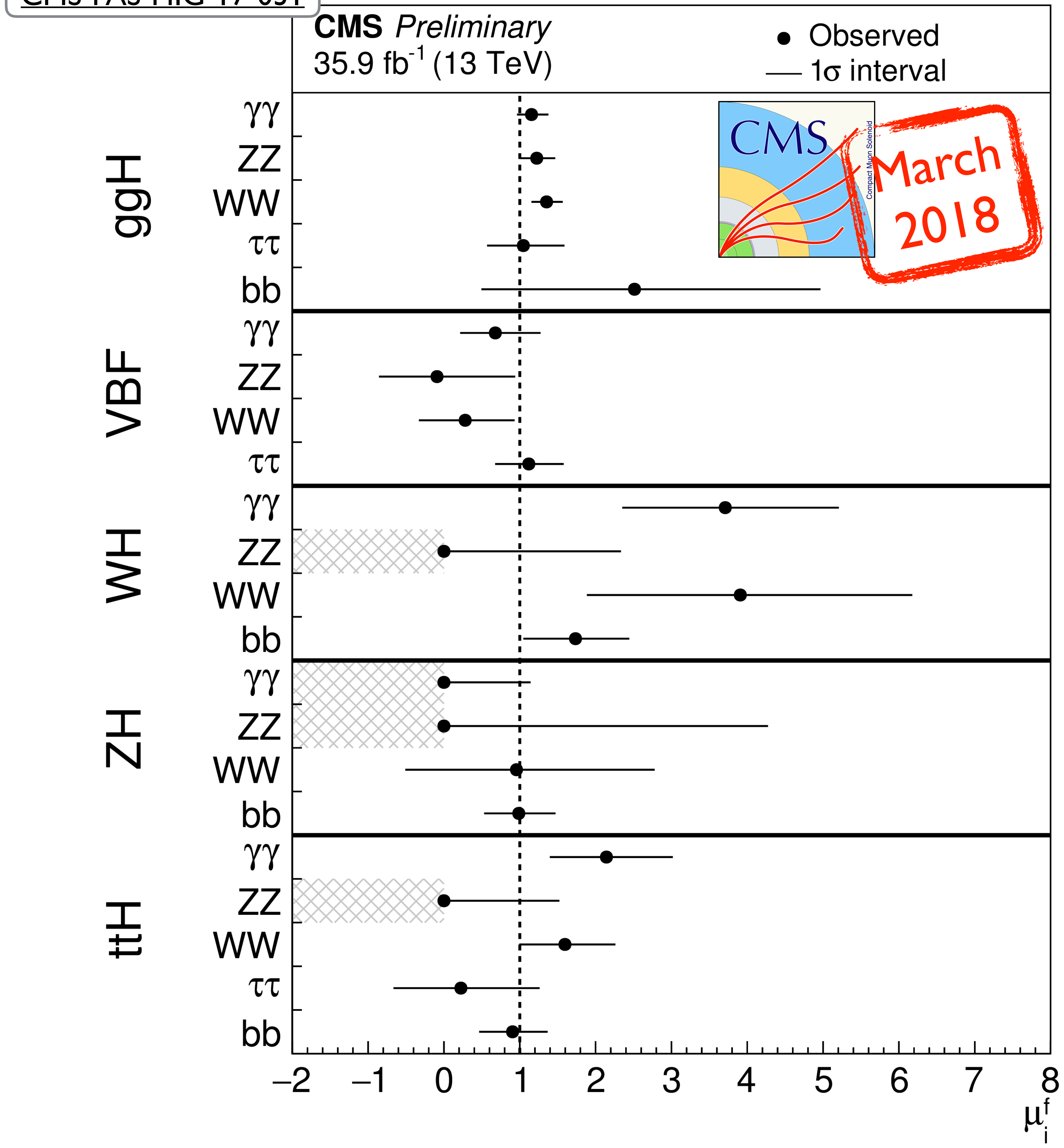
m_A = mass of CP-odd Higgs boson



ATLAS-CONF-2018-031

Production and Decay Modes

CMS-PAS-HIG-17-031



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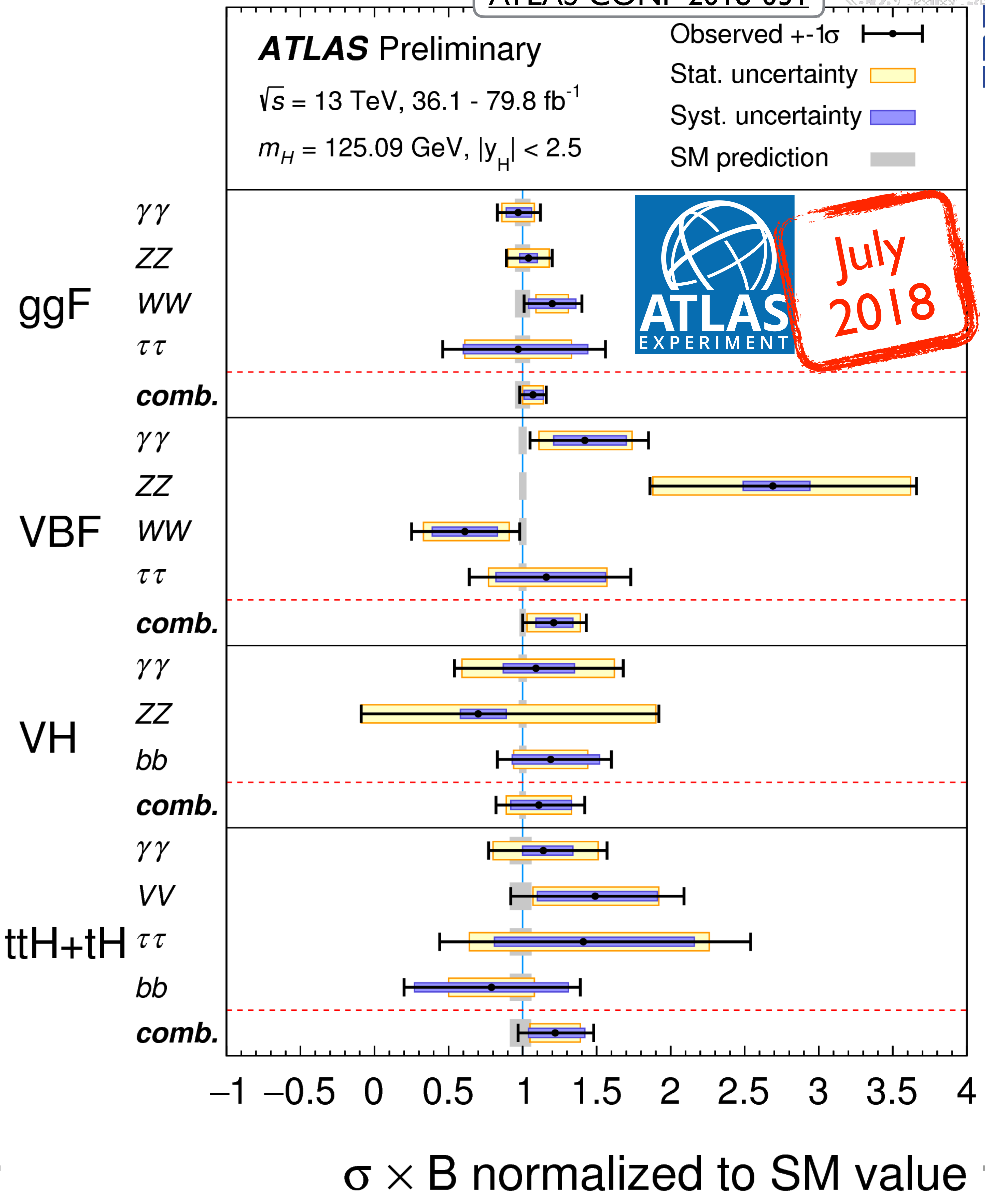

Ratios of Cross-Sections and Branching Fractions

CMS-PAS-HIG-17-031

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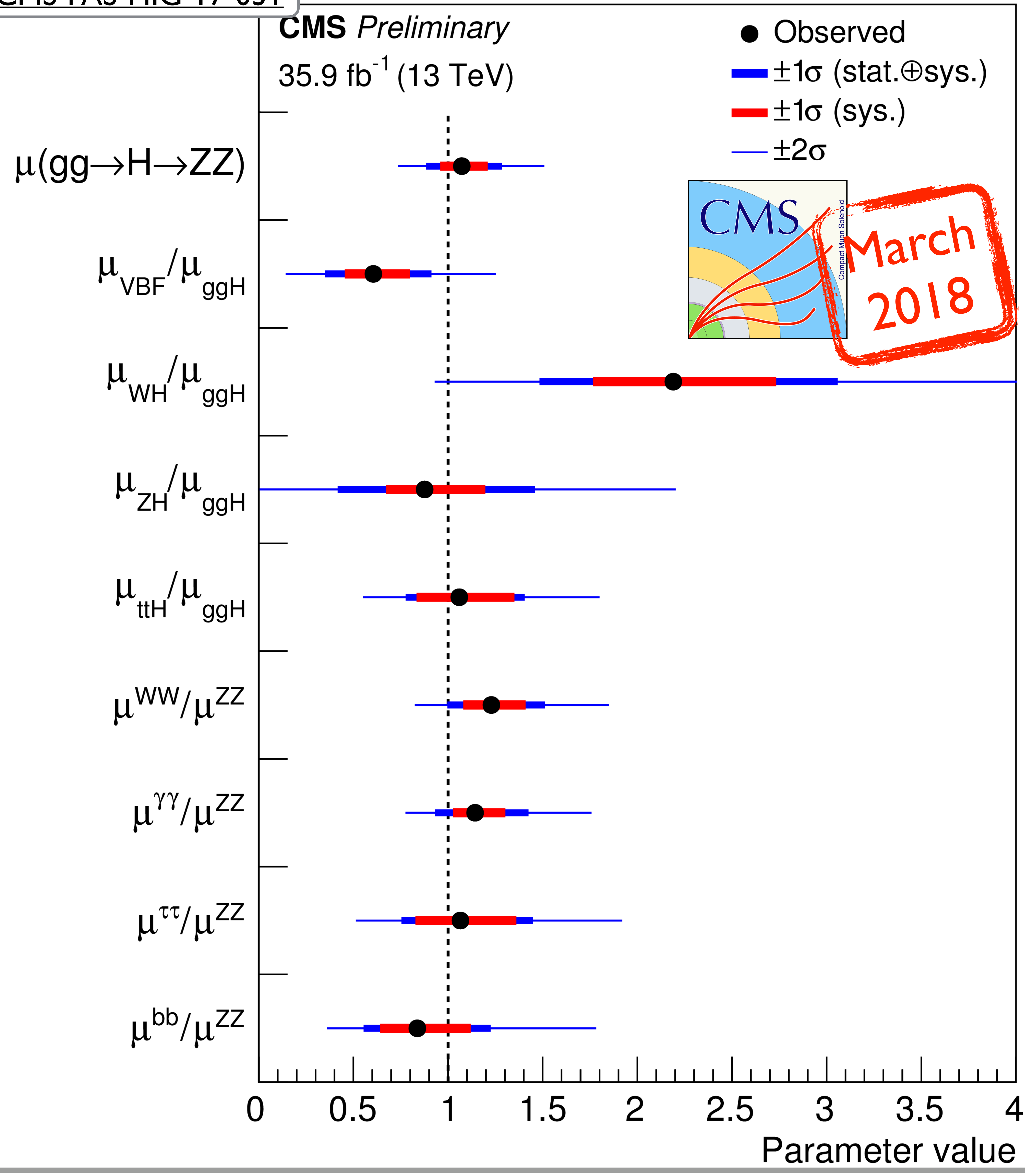
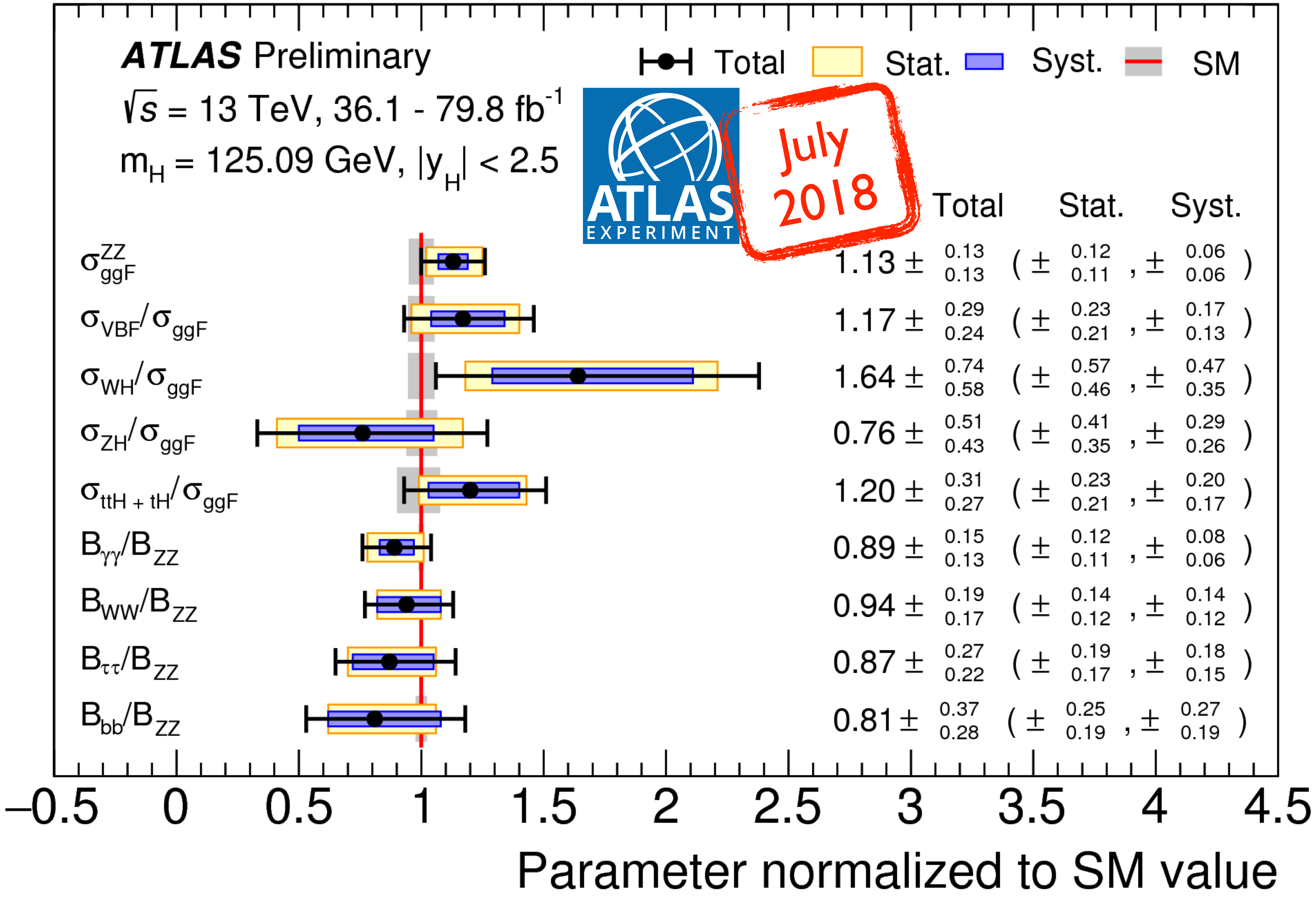


- No assumption on total width of Higgs boson
- Partial cancelation of systematics

$$(\sigma \times \mathrm{B})_{if} = \sigma^{ZZ}_{\mathrm{ggF}} \cdot \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \cdot \left(\frac{\mathrm{B}_f}{\mathrm{B}_{ZZ}}\right)$$



Branching Fractions

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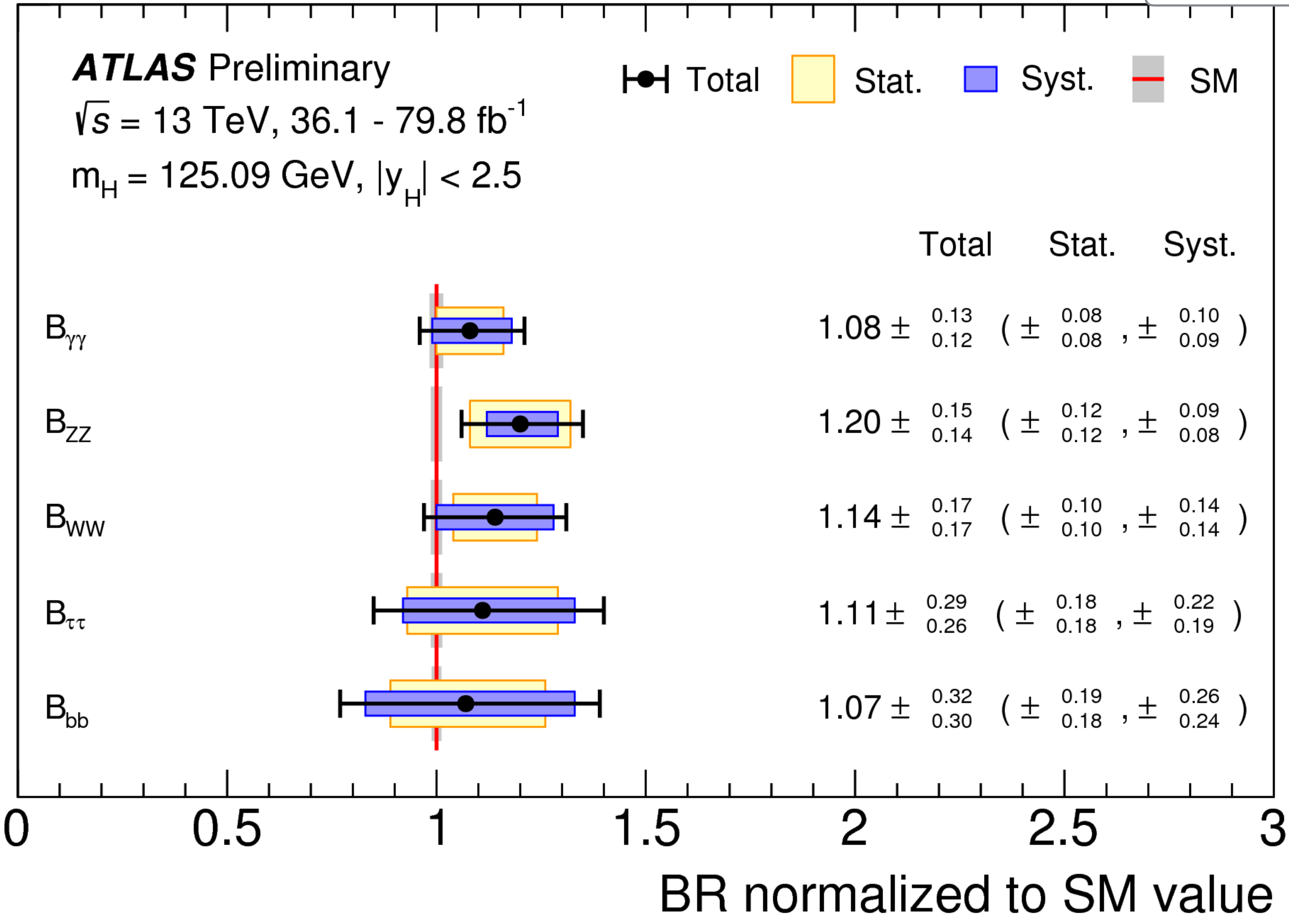
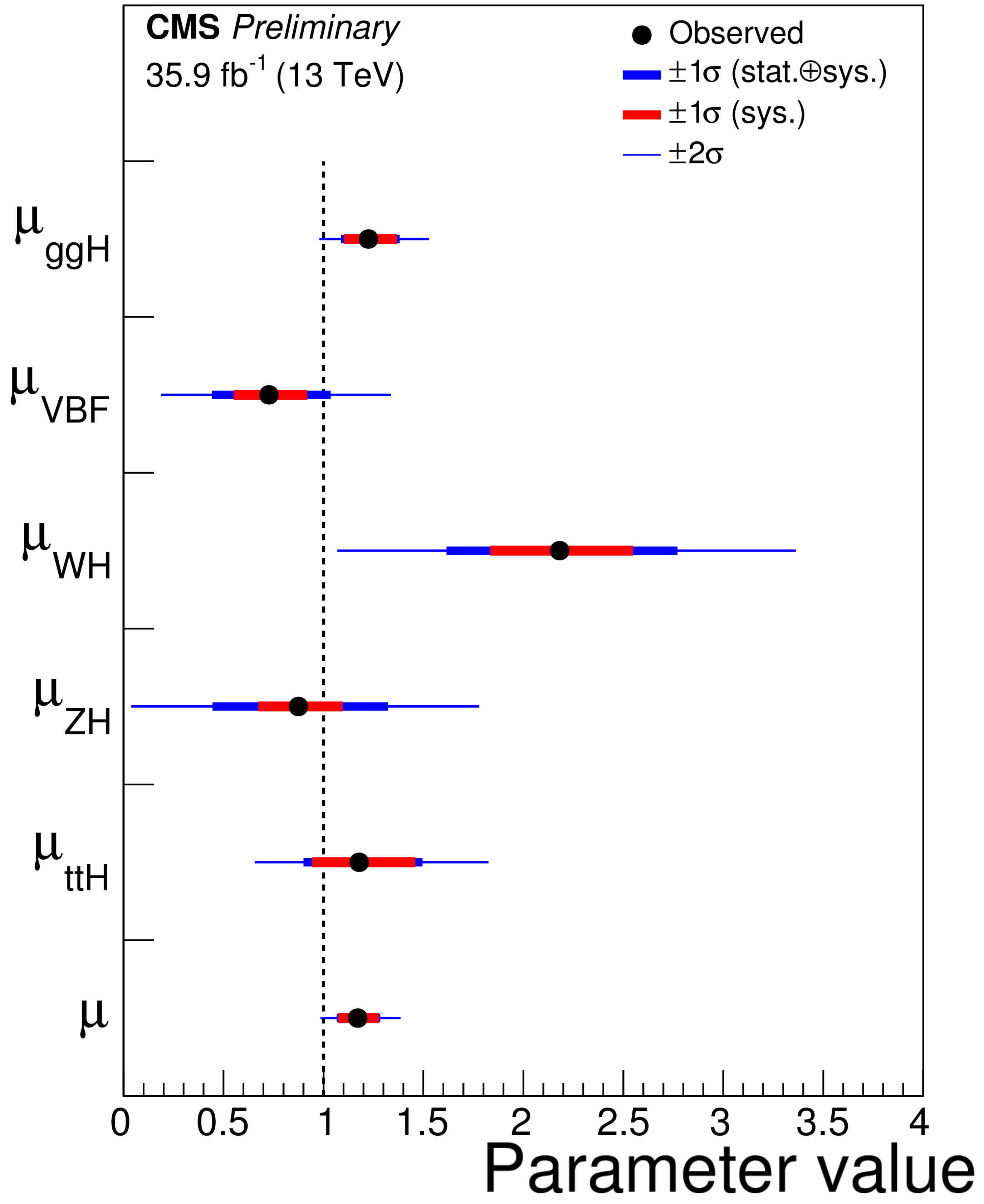


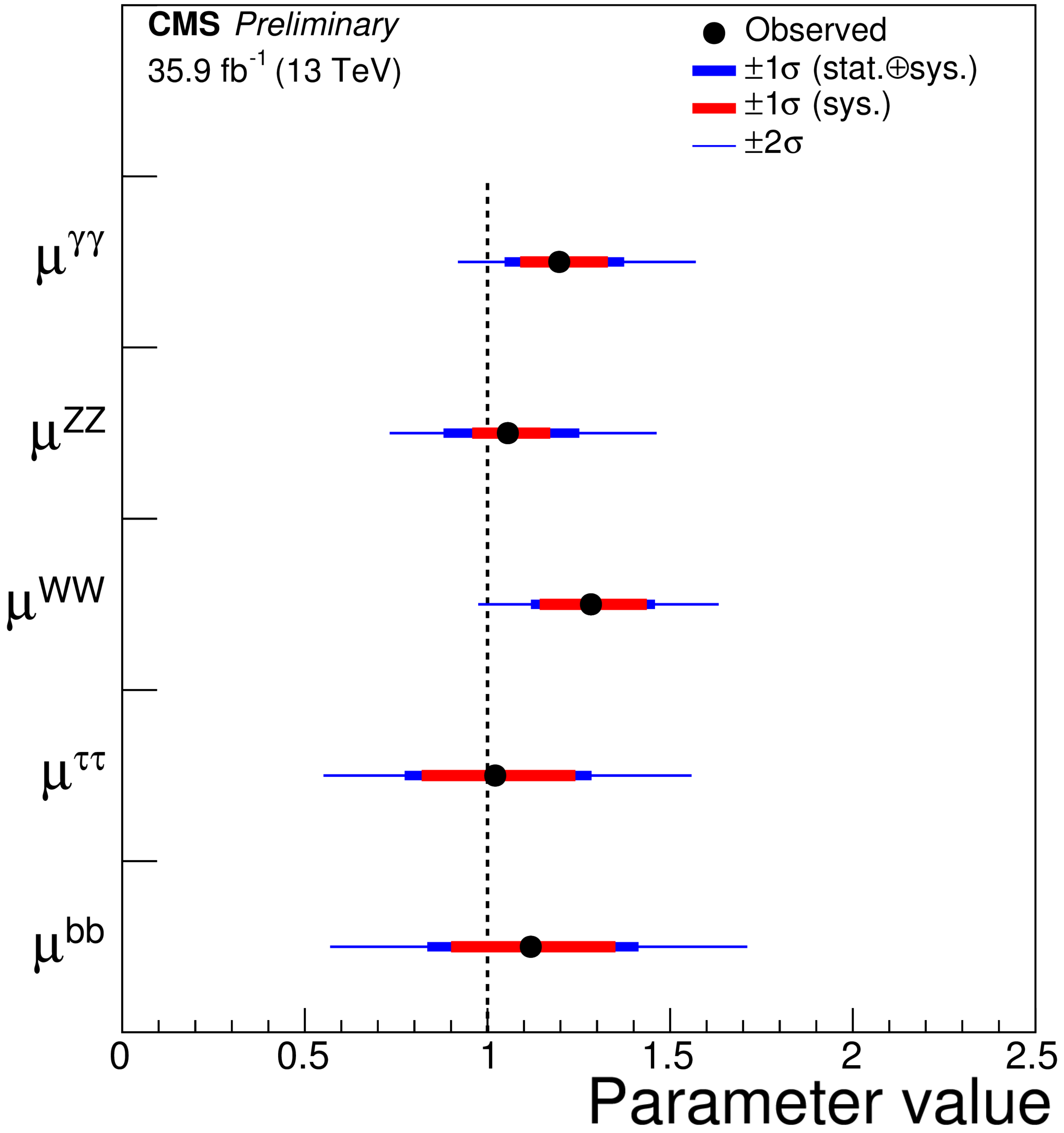
Production and Decay Modes

CMS-PAS-HIG-17-031

Production μ
(assume SM decay BRs μ^f = 1)



Decay μ
(assume SM production μ_i = 1)



- Define for $i \to H \to f$:

$$\mu_i := \frac{\sigma_i}{(\sigma_i)_{\text{SM}}} \qquad \mu^f := \frac{\mathcal{B}^f}{(\mathcal{B}^f)_{\text{SM}}}$$

- Signal strength:

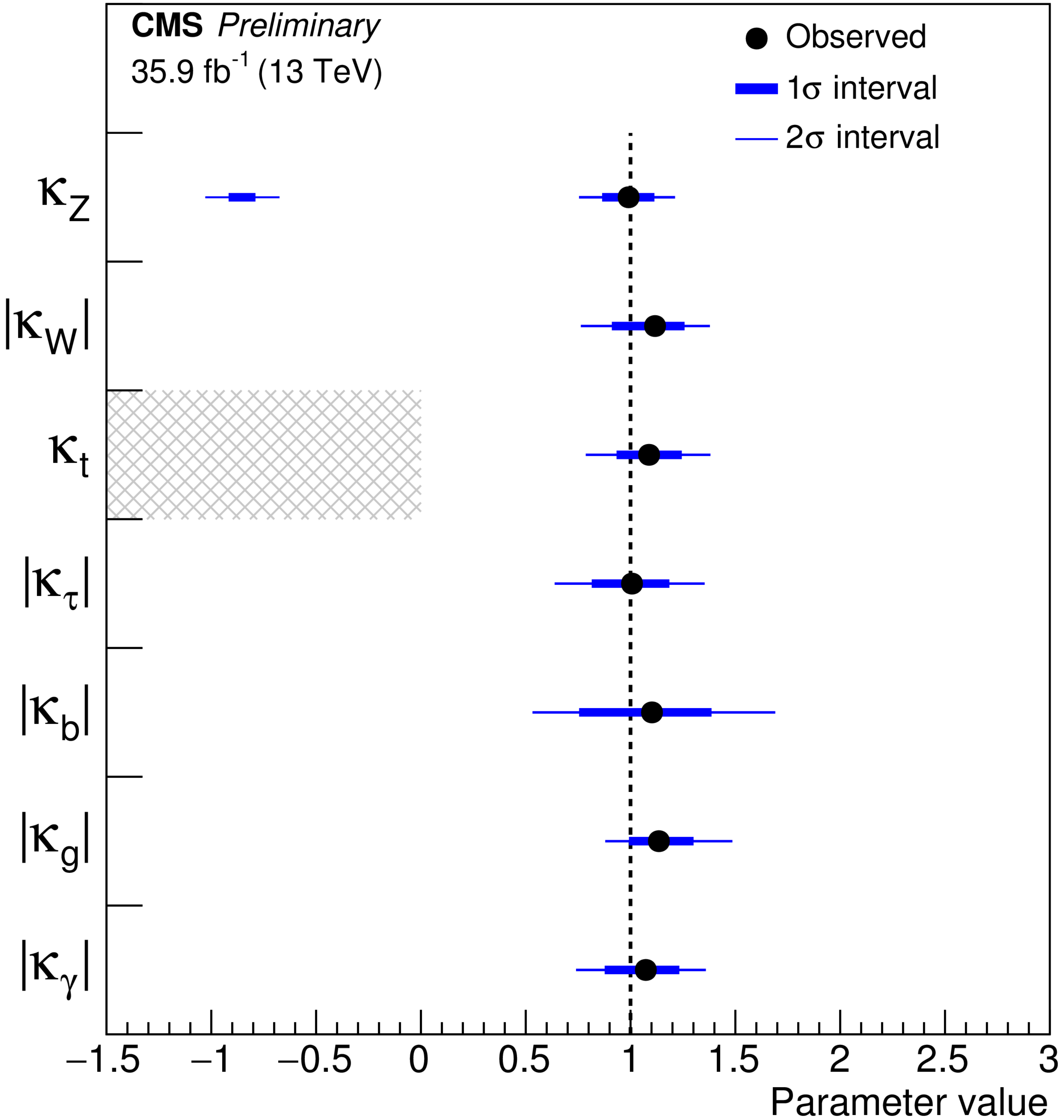
$$\mu := \mu_i \cdot \mu^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\text{SM}}}$$

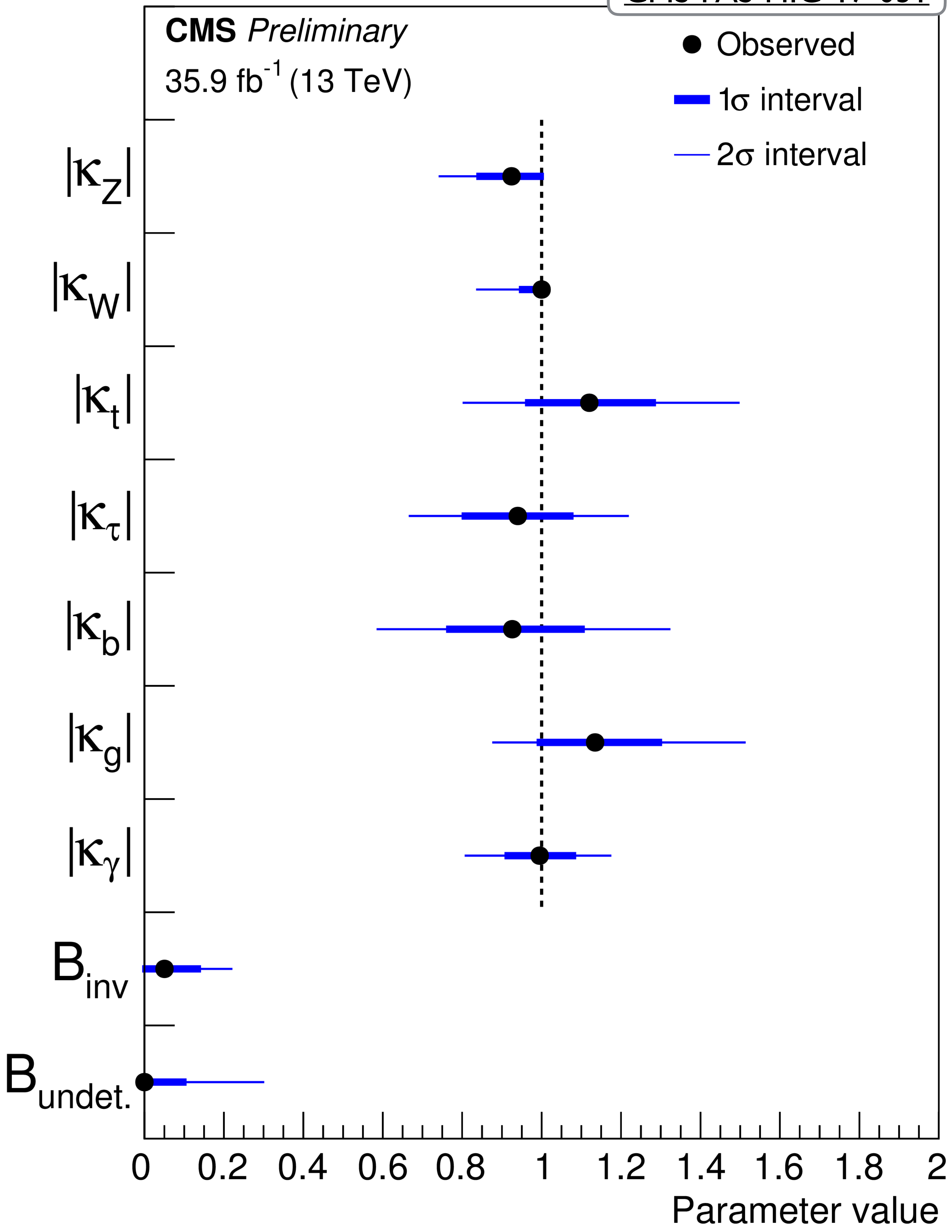
$$= \frac{\text{observed rate}}{\text{expected rate}}$$

Global signal strength: $\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$

Models with effective Gluon and Photon Couplings

CMS-PAS-HIG-17-031





Models with effective Gluon and Photon Couplings

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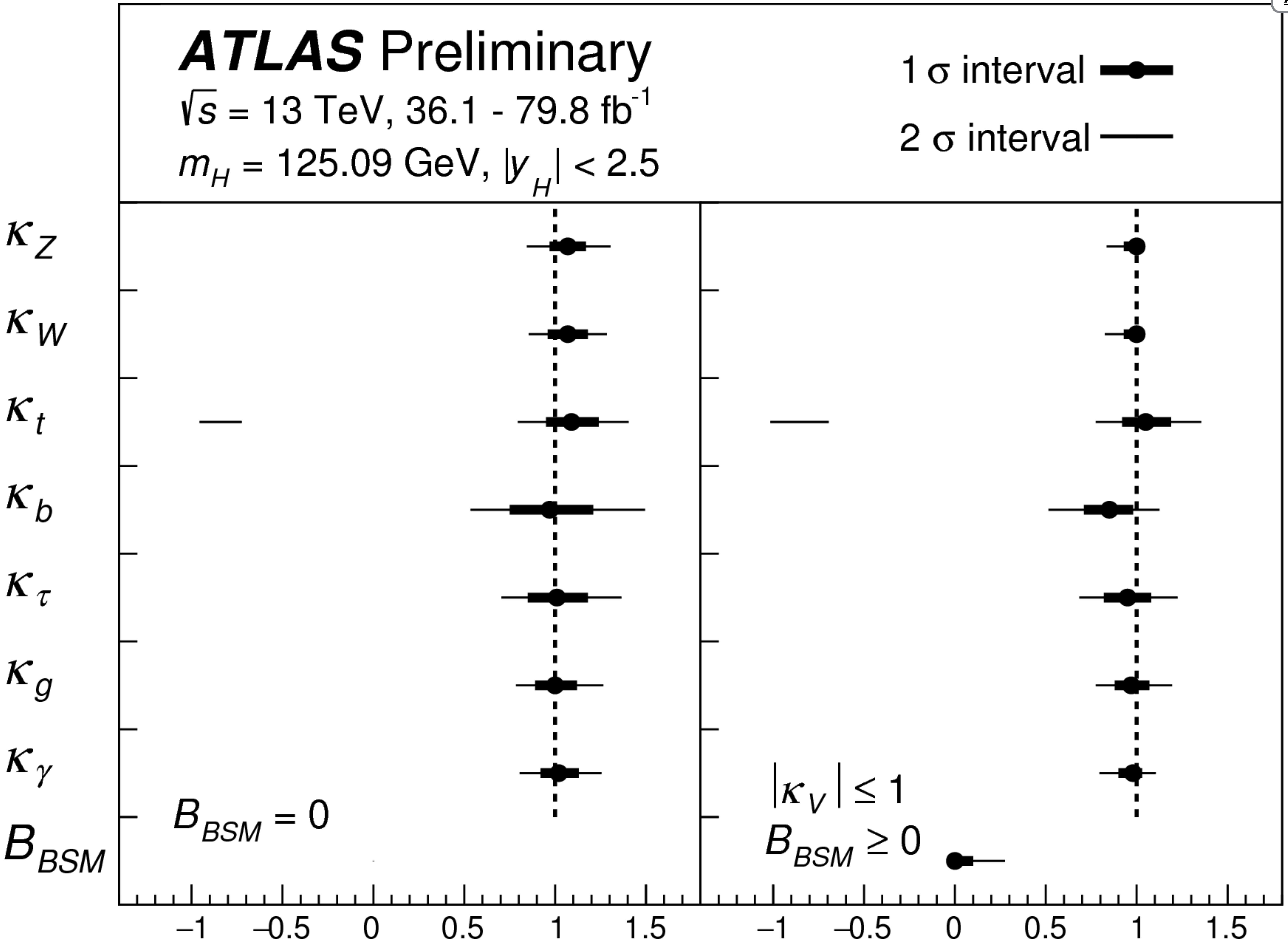

< 0.26 at 95% CL

Ratios of Coupling Modifiers

CMS-PAS-HIG-17-031

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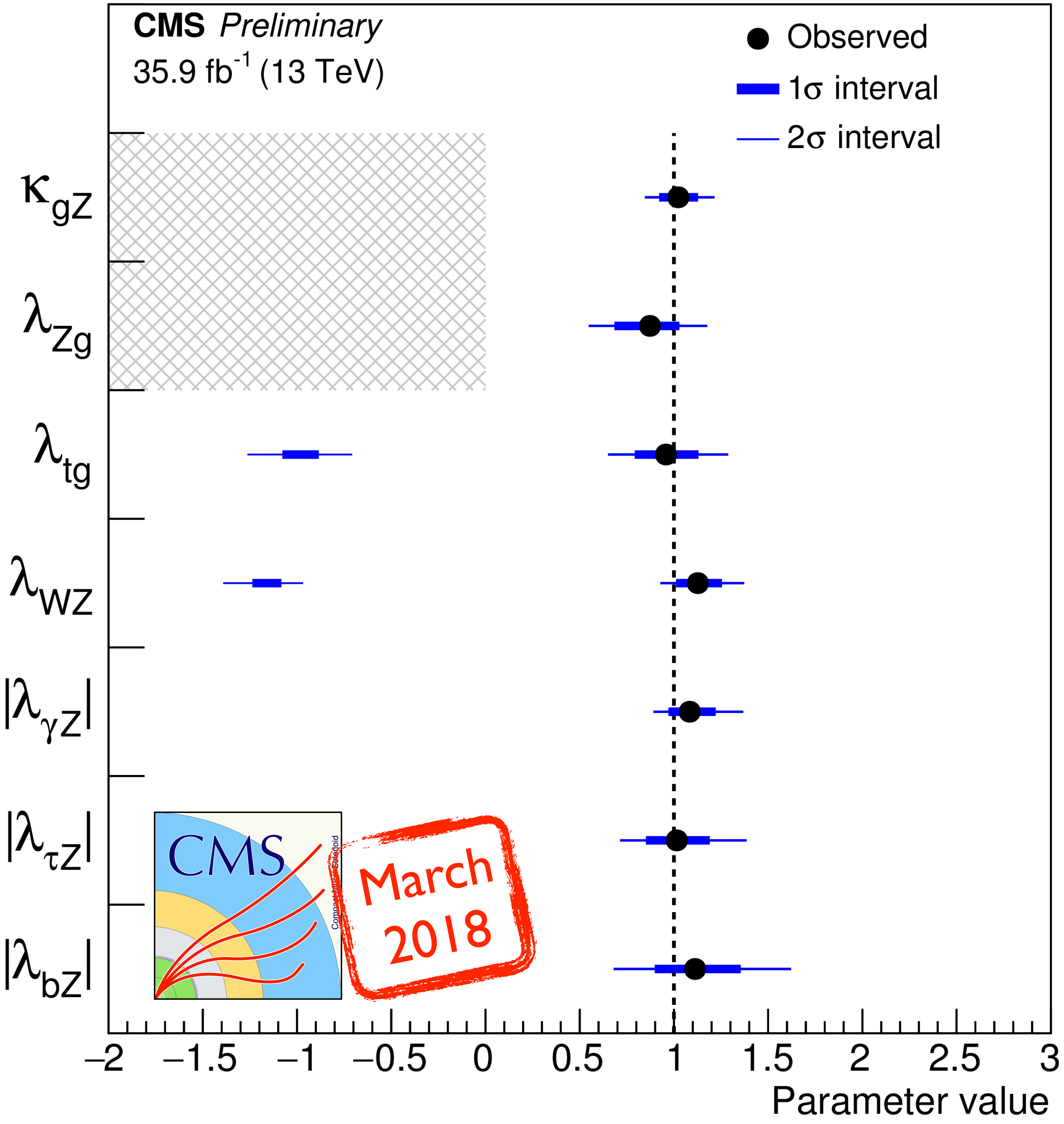
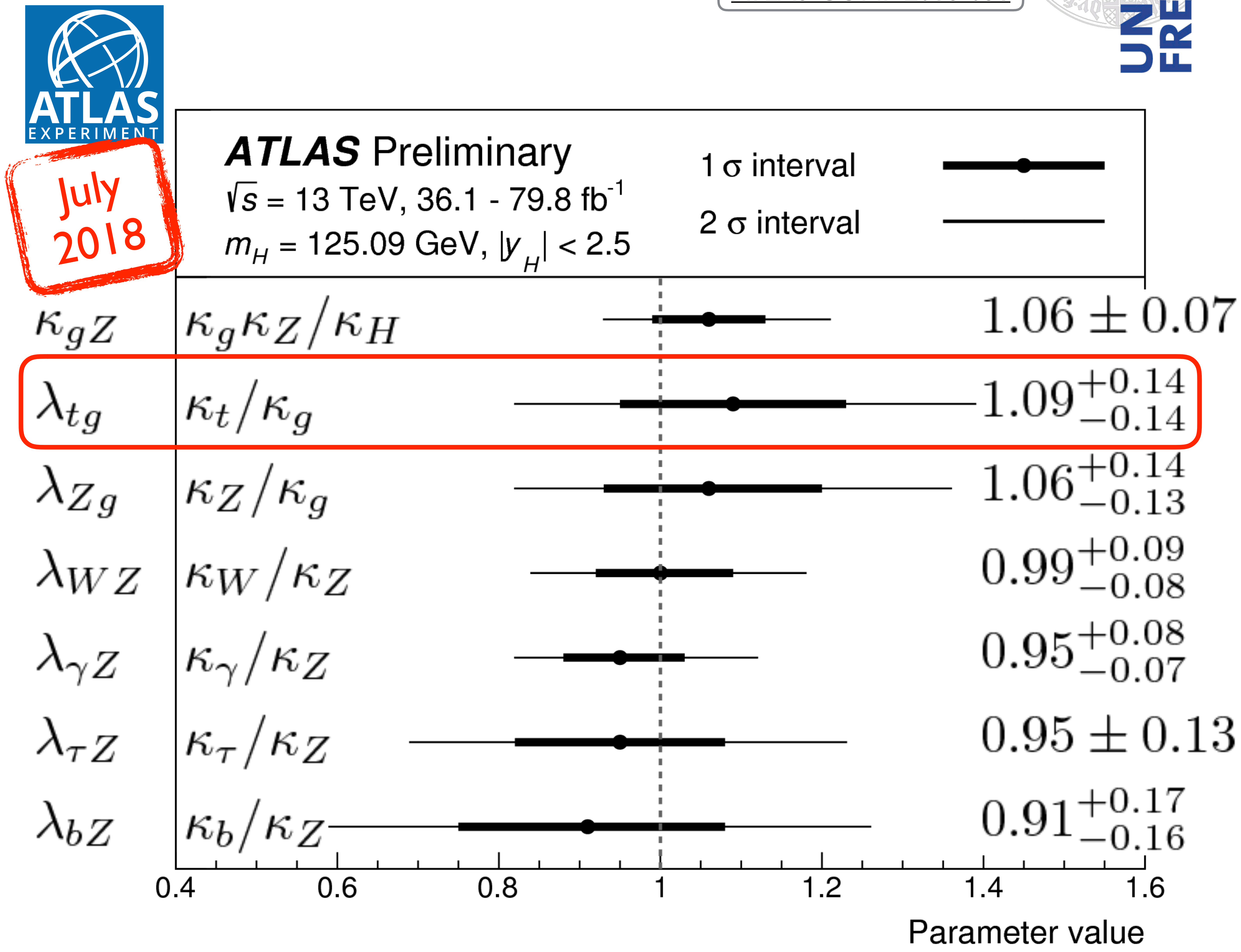
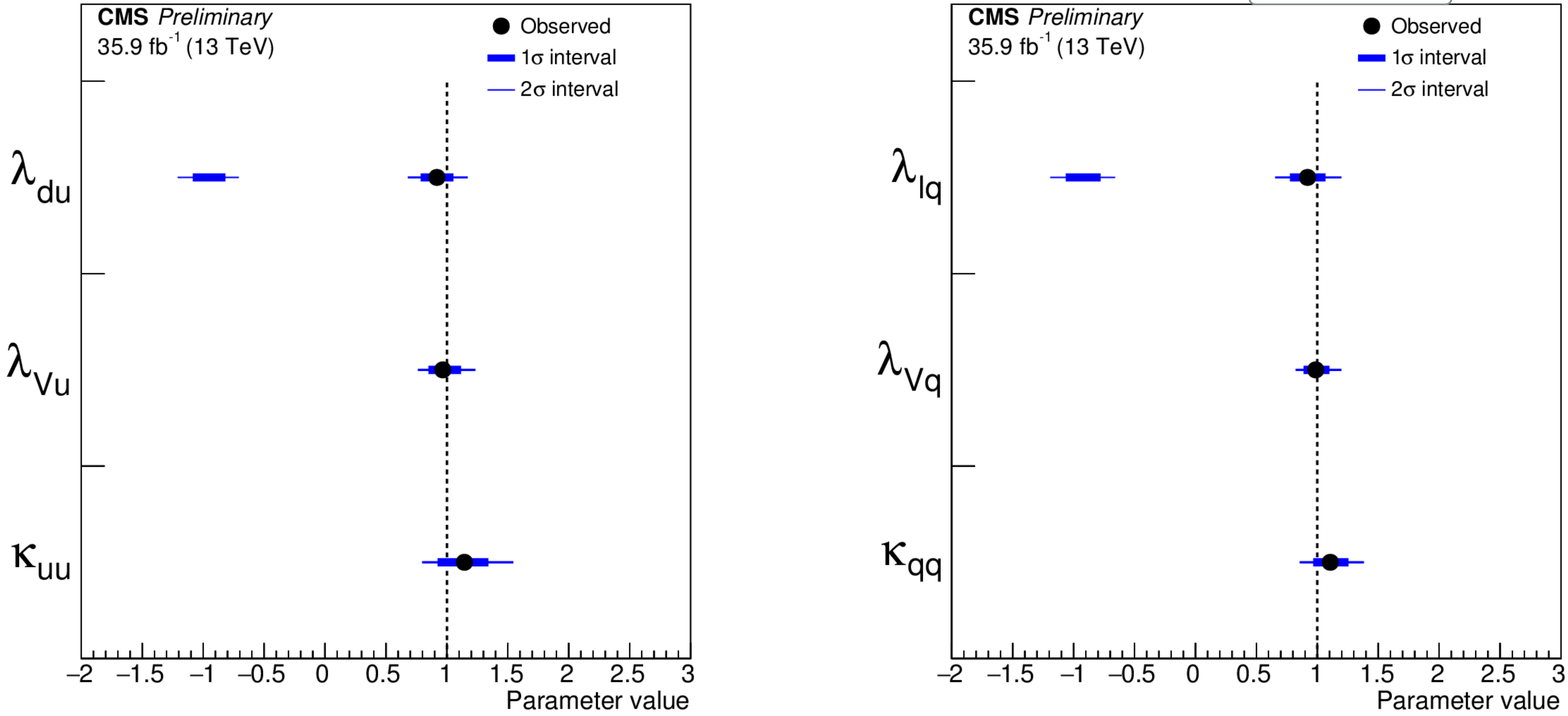




Separate Up- and Down-Type Quark Couplings; Separate Quark- and Lepton Couplings

CMS-PAS-HIG-17-031



Loop-induced Couplings

CMS-PAS-HIG-17-031

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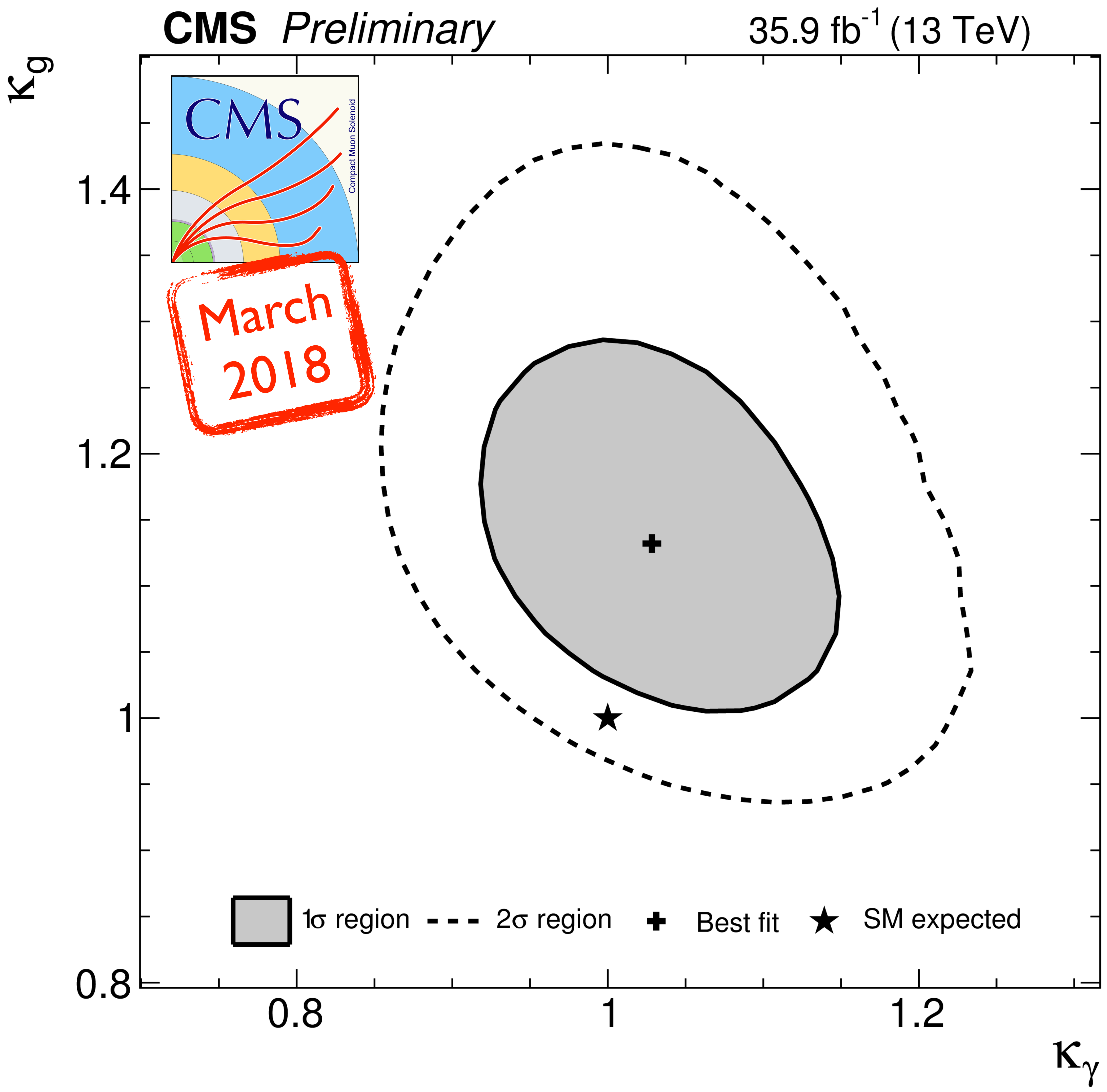
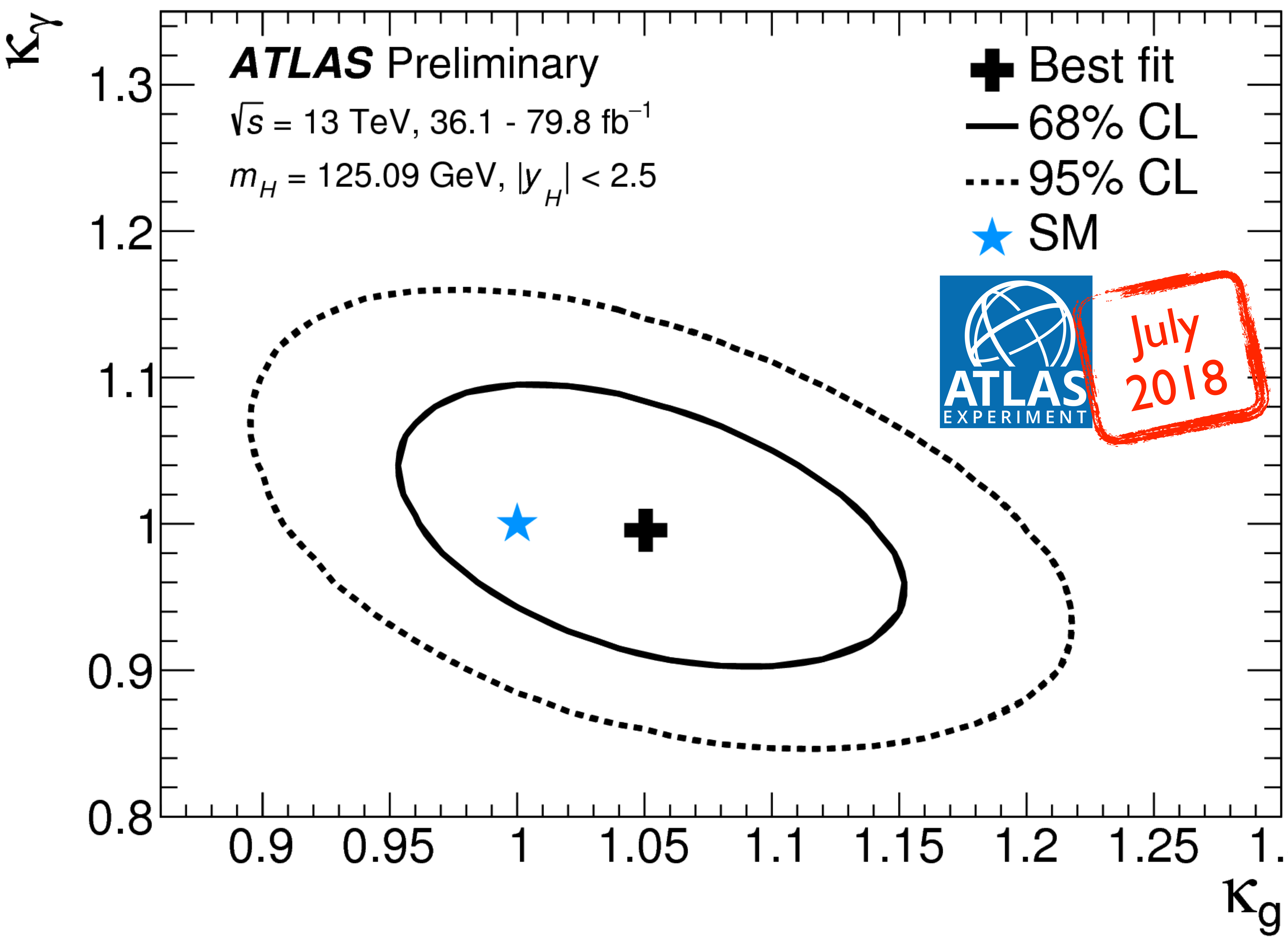
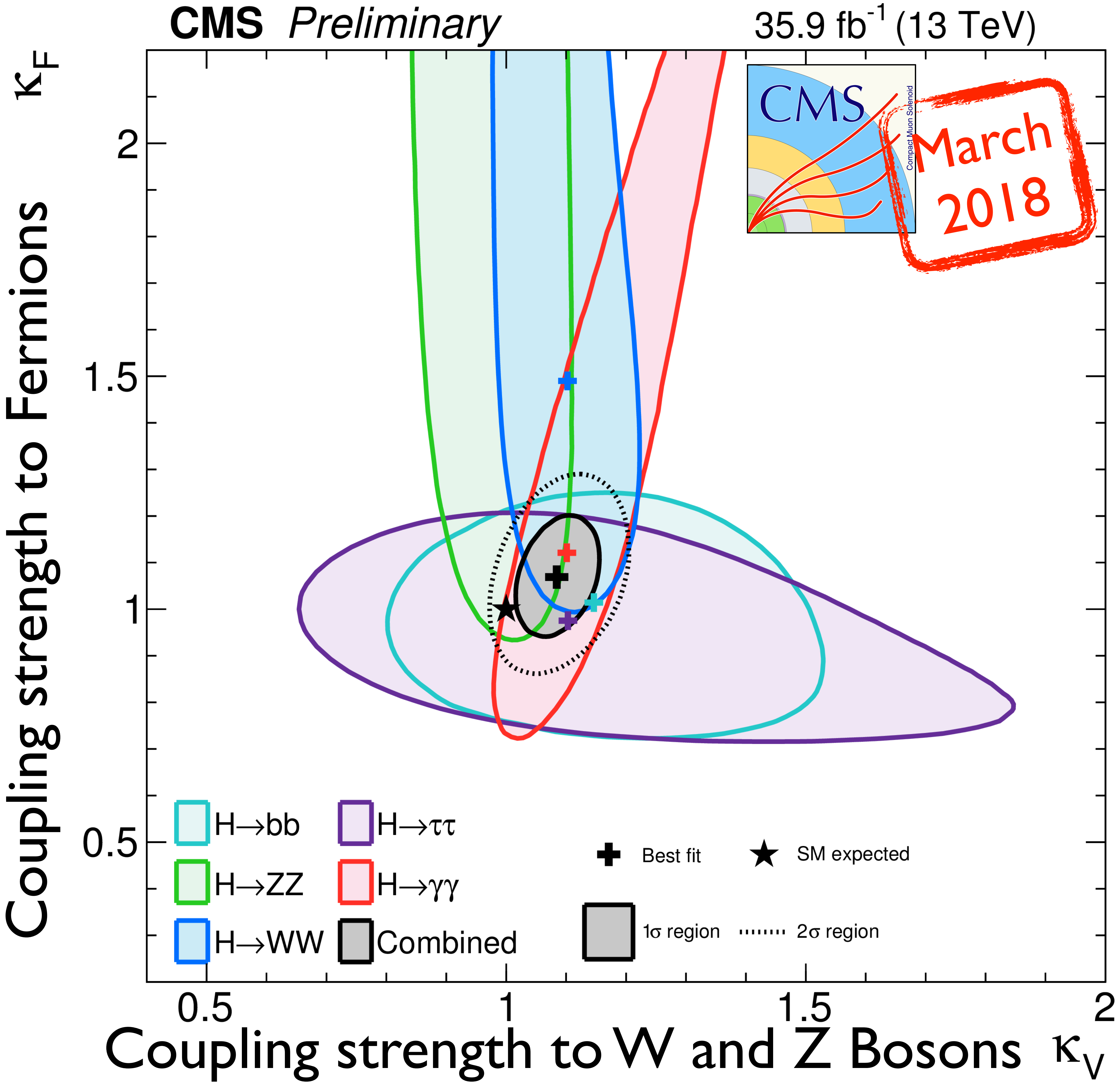


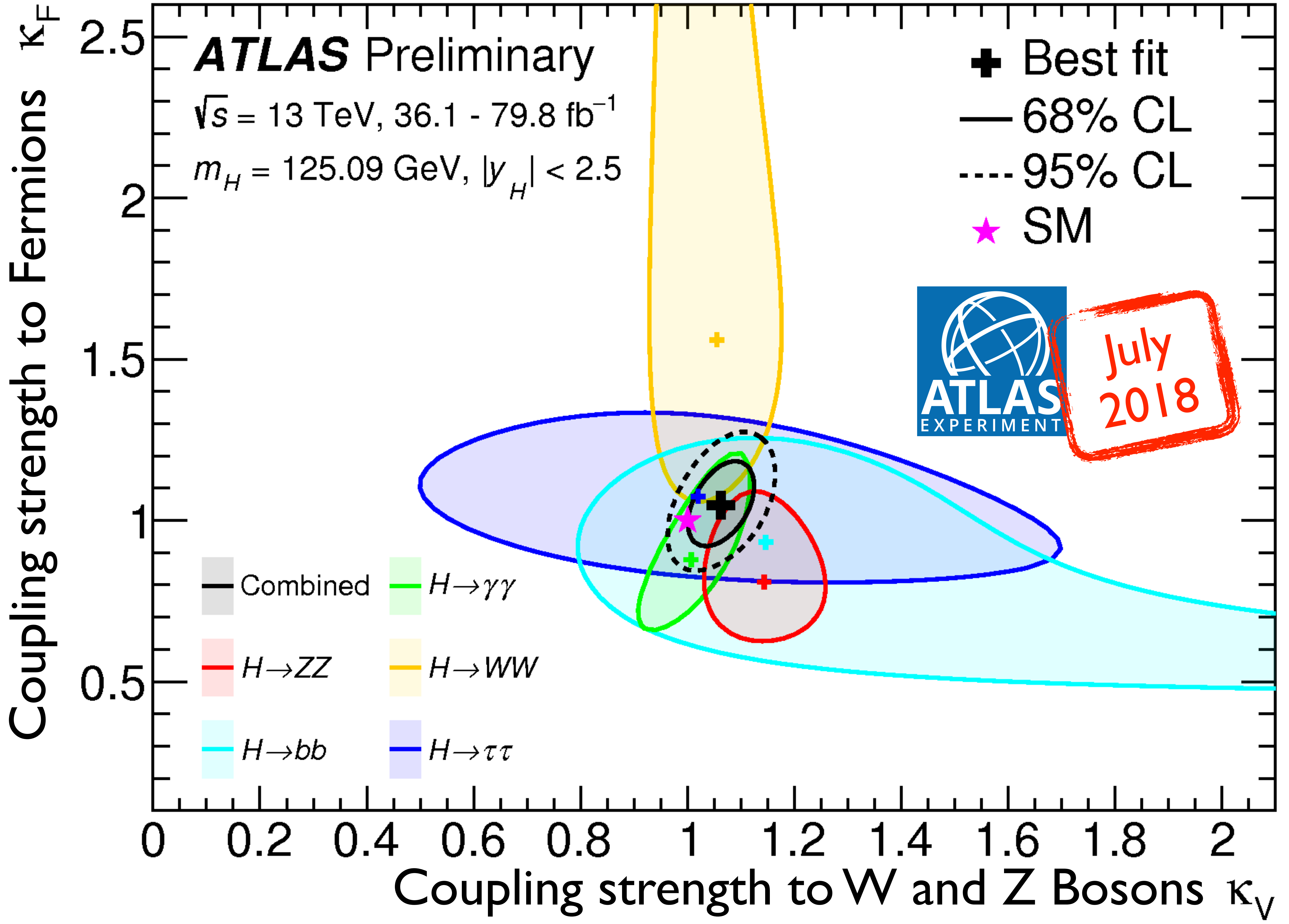


Coupling to Fermions and Bosons

CMS-PAS-HIG-17-031

ATLAS-CONF-2018-031





ggF and VBF Cross Sections

July 2018

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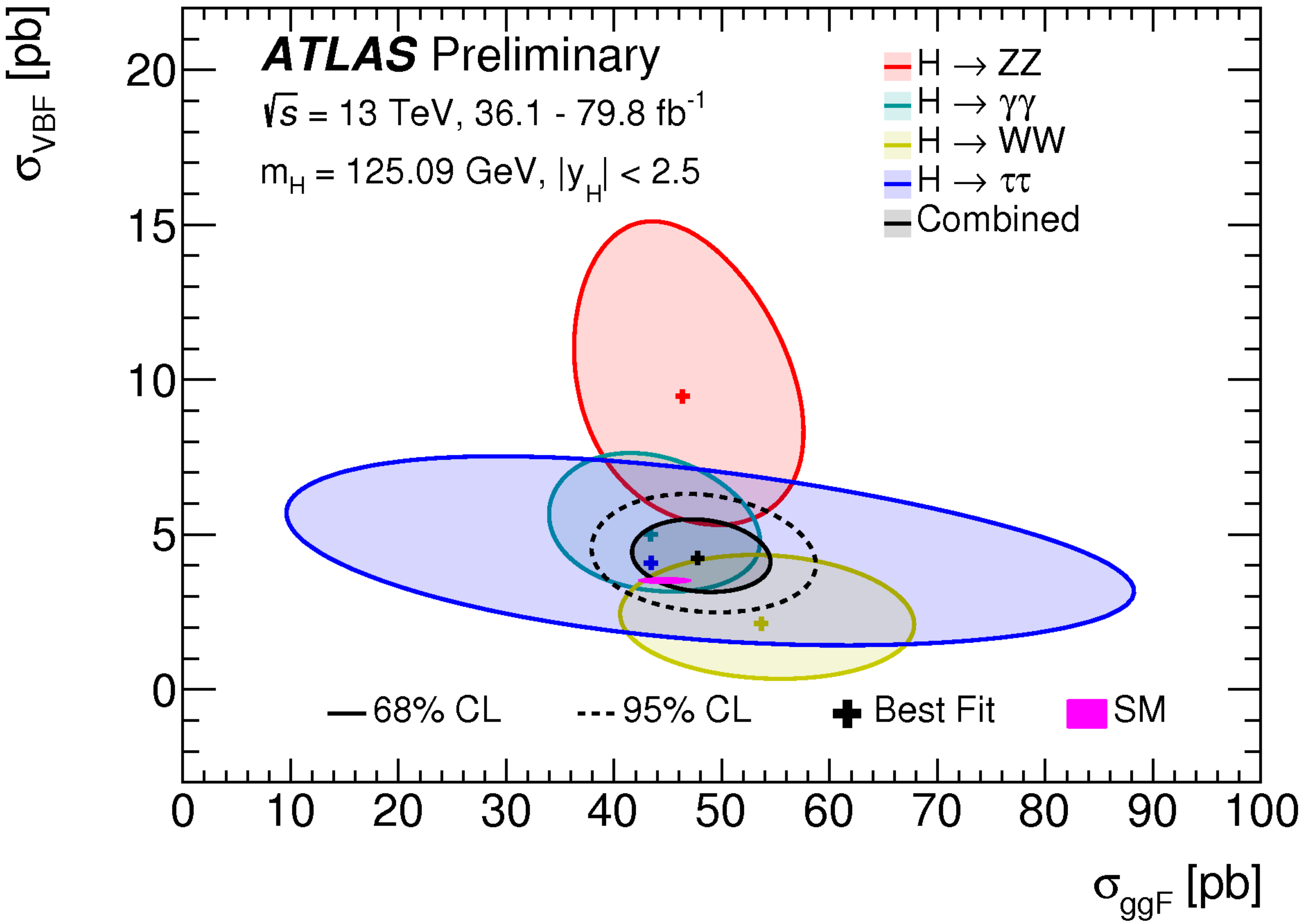
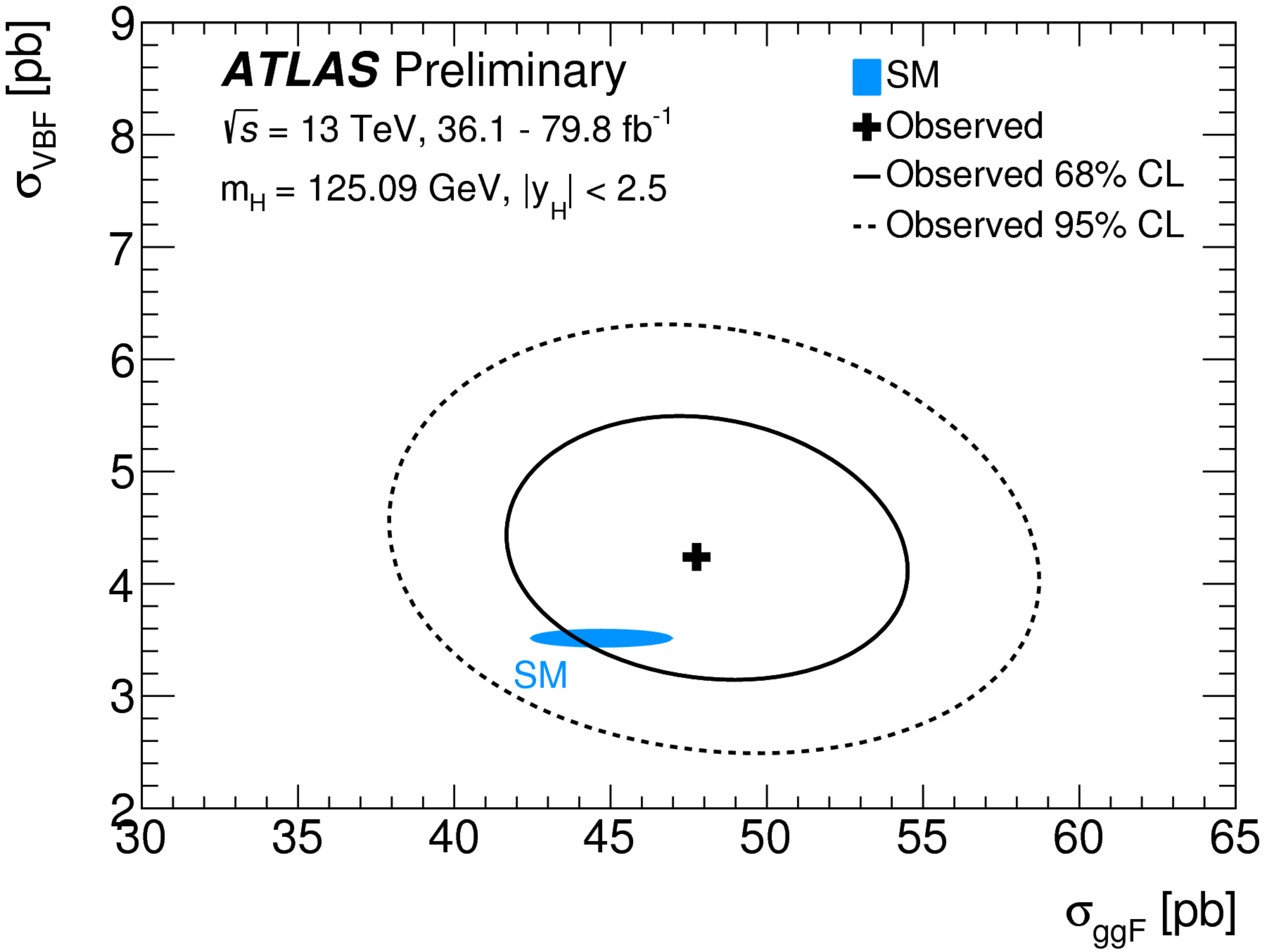


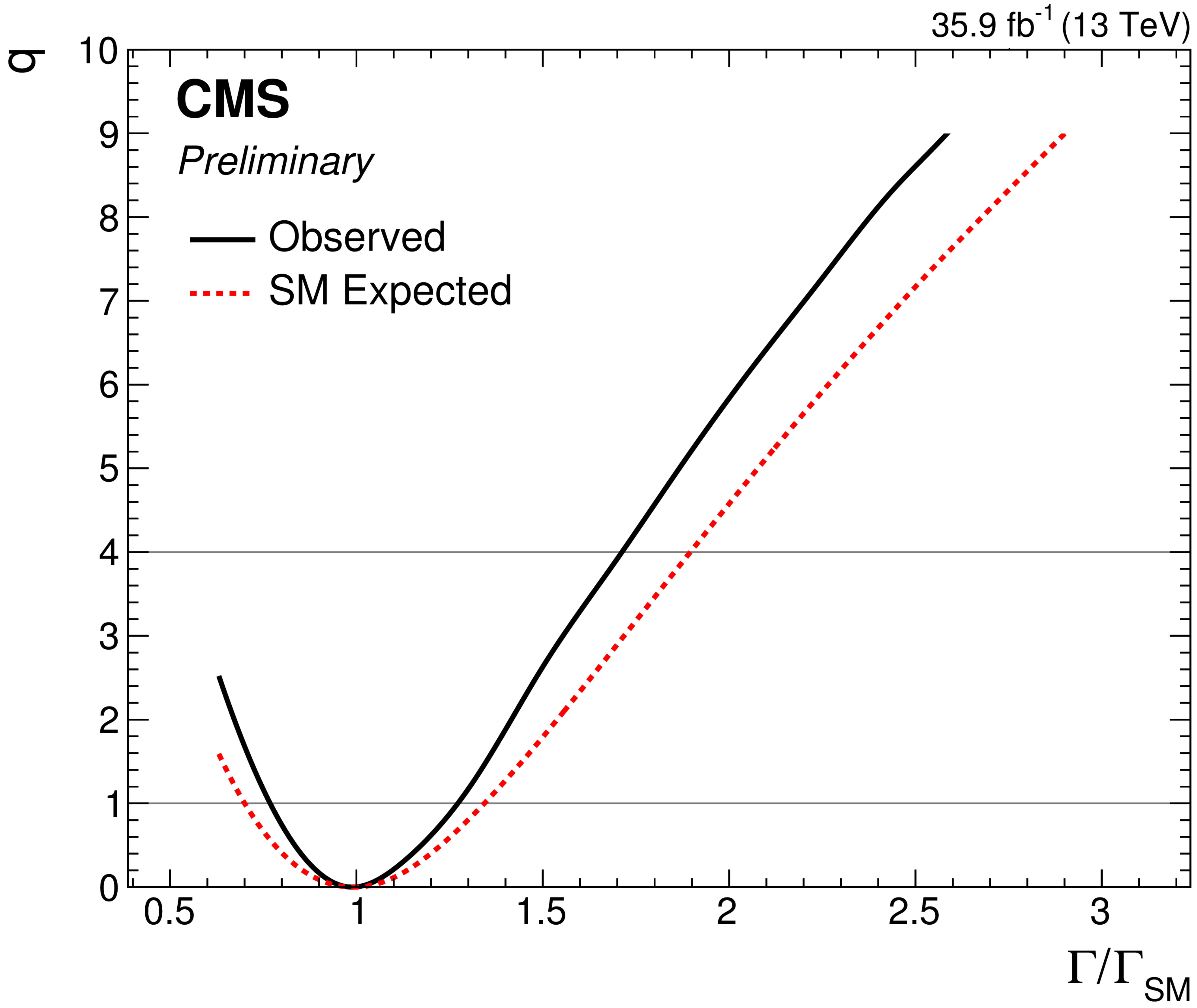


Total Width Interpretation

CMS-PAS-HIG-17-031

- Reinterpret limit on BR_{BSM} as limit on total width

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \frac{\kappa_{\mathrm{H}}^2}{1-(\mathrm{BR}_{\mathrm{undet.}}+\mathrm{BR}_{\mathrm{inv.}})}$$



Input Analyses

Analysis	Integrated luminosity (fb^{-1})
$H \rightarrow \gamma\gamma$ (including $t\bar{t}H$, $H \rightarrow \gamma\gamma$)	79.8
$H \rightarrow ZZ^* \rightarrow 4\ell$ (including $t\bar{t}H$, $H \rightarrow ZZ^* \rightarrow 4\ell$)	79.8
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$	36.1
$H \rightarrow \tau\tau$	36.1
VH, $H \rightarrow b\bar{b}$	36.1
$H \rightarrow \mu\mu$	79.8
$t\bar{t}H$, $H \rightarrow b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

Coupling Modifiers

ATLAS-CONF-2018-031

Production	Effective modifier	Resolved modifier
σ_{ggF}	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
σ_{VBF}	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma_{qq/qg\to ZH}$	-	κ_Z^2
$\sigma_{gg\to ZH}$	-	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
σ_{WH}	-	κ_W^2
$\sigma_{t\bar{t}H}$	-	κ_t^2
σ_{tHW}	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
σ_{tHq}	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma_{b\bar{b}H}$	-	κ_b^2

Partial decay width	Effective modifier	Resolved modifier
$\Gamma_{\gamma\gamma}$	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
Γ_{ZZ}	-	κ_Z^2
Γ_{WW}	-	κ_W^2
$\Gamma_{\tau\tau}$	-	κ_τ^2
Γ_{bb}	-	κ_b^2
$\Gamma_{\mu\mu}$	-	κ_μ^2
Γ_{gg}	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma_{Z\gamma}$	$\kappa_{(Z\gamma)}^2$	$1.12\,\kappa_W^2 - 0.12\,\kappa_W\kappa_t$

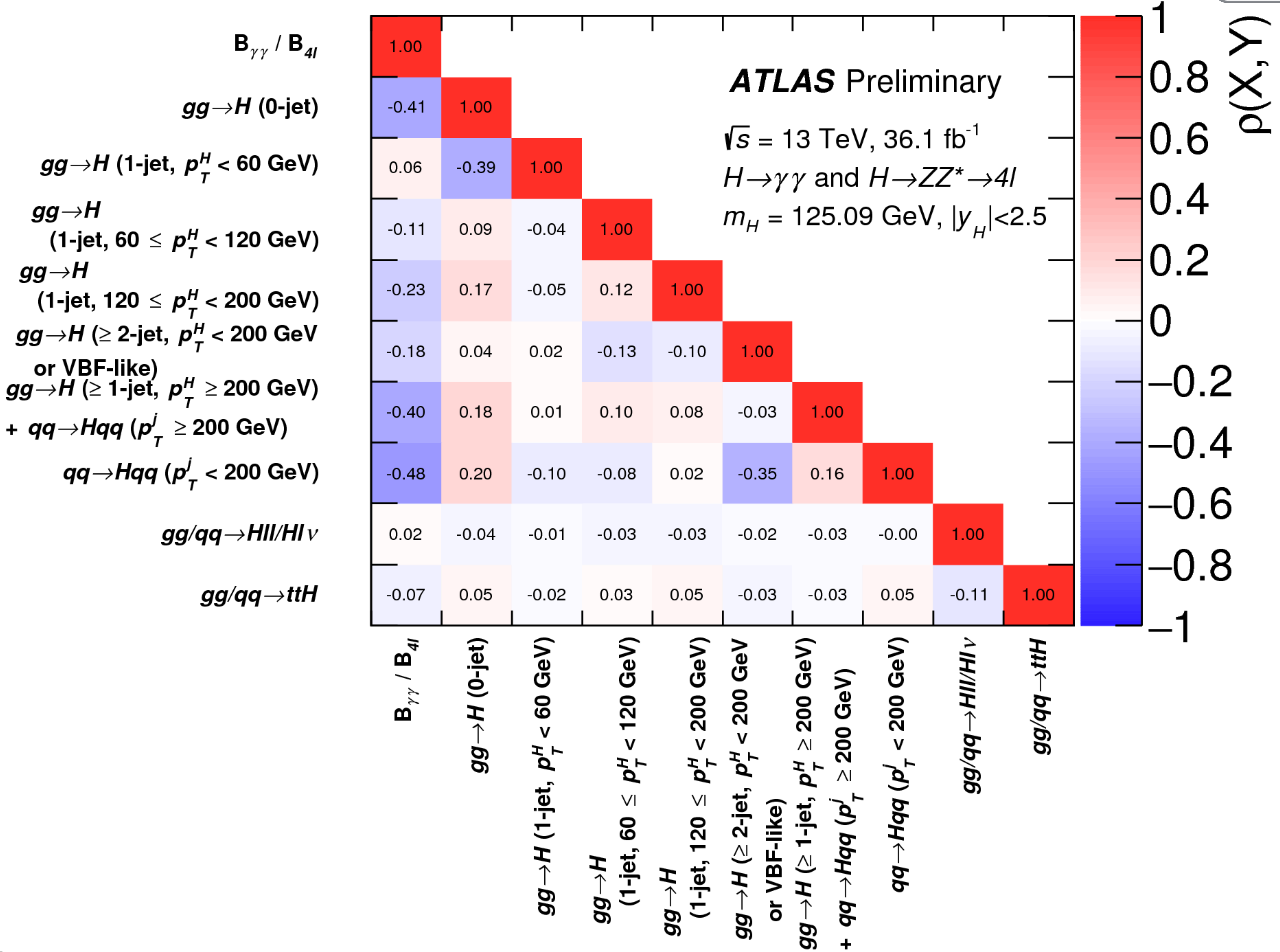
Total width	Efective modifier	Resolved modifier
Γ_H	κ_H^2	$(0.58\,\kappa_b^2 + 0.22\,\kappa_W^2 + 0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2 + 0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2 + 0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2)/(1 - \mathrm{B_{BSM}})$

Coupling Modifiers

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\mathrm{ggH})$	✓	b − t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\mathrm{WH})$	–	–		κ_W^2
$\sigma(\mathrm{qq/qg} \to \mathrm{ZH})$	–	–		κ_Z^2
$\sigma(\mathrm{gg} \to \mathrm{ZH})$	✓	Z − t		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	–	–		κ_t^2
$\sigma(\mathrm{gb} \to \mathrm{WtH})$	–	W − t		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t\kappa_W$
$\sigma(\mathrm{qb} \to \mathrm{tHq})$	–	W − t		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W − t	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $\mathrm{BR_{BSM}} = 0$				
Γ_H	✓	–	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Simplified Template Cross Sections

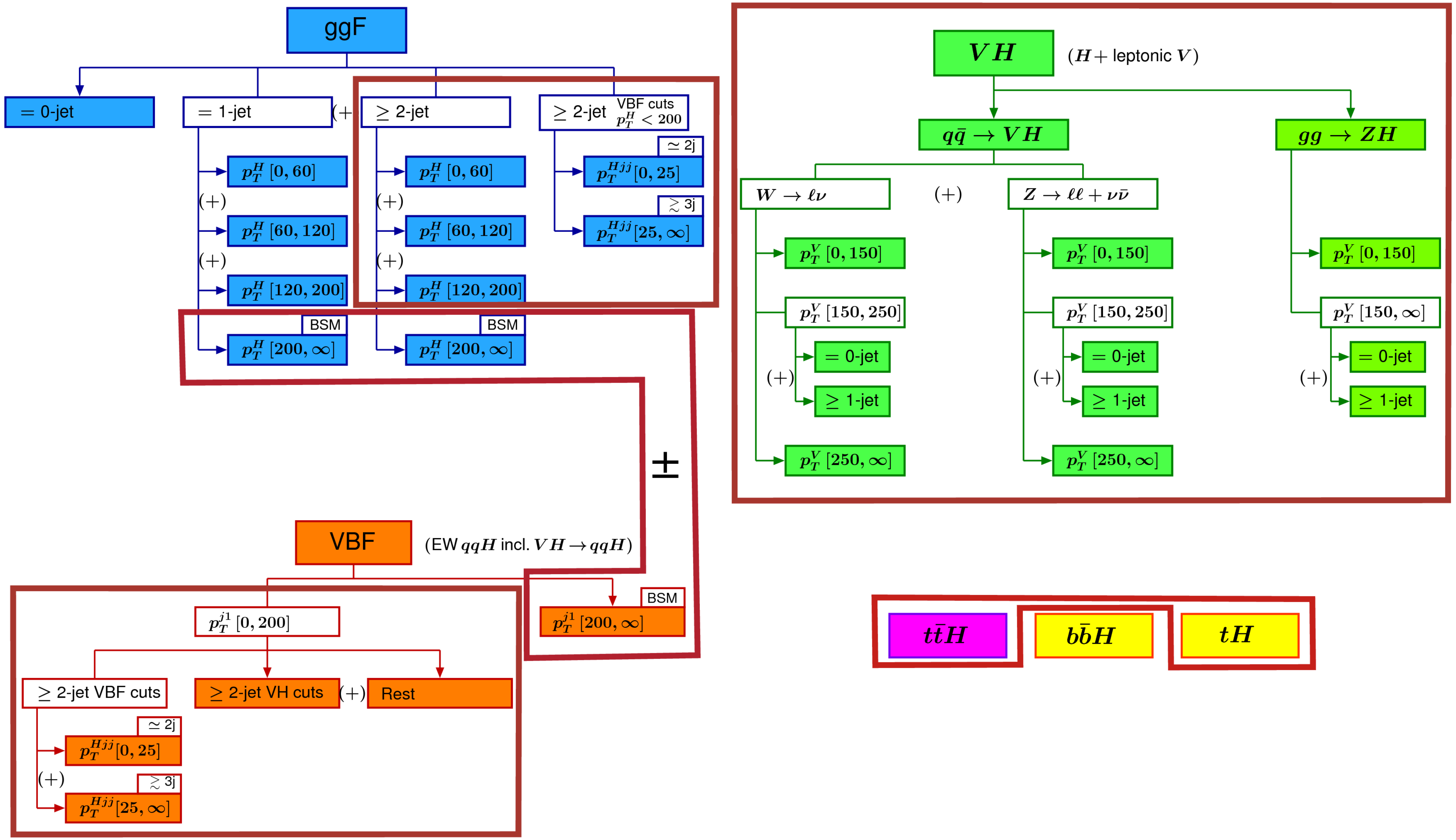
ATLAS-CONF-2017-047



Simplified Template Cross Sections

ATLAS-CONF-2017-047

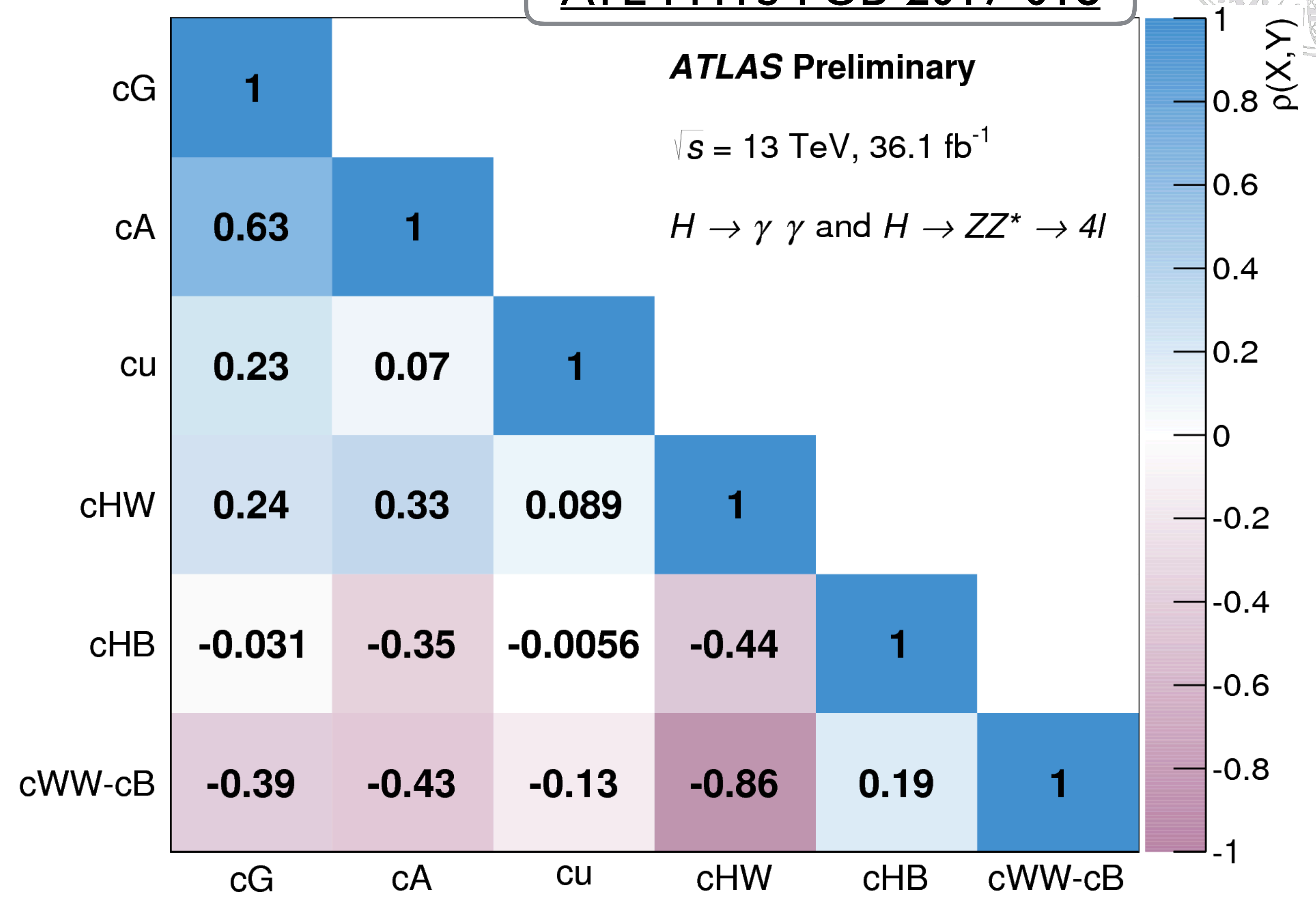
ATLAS preliminary

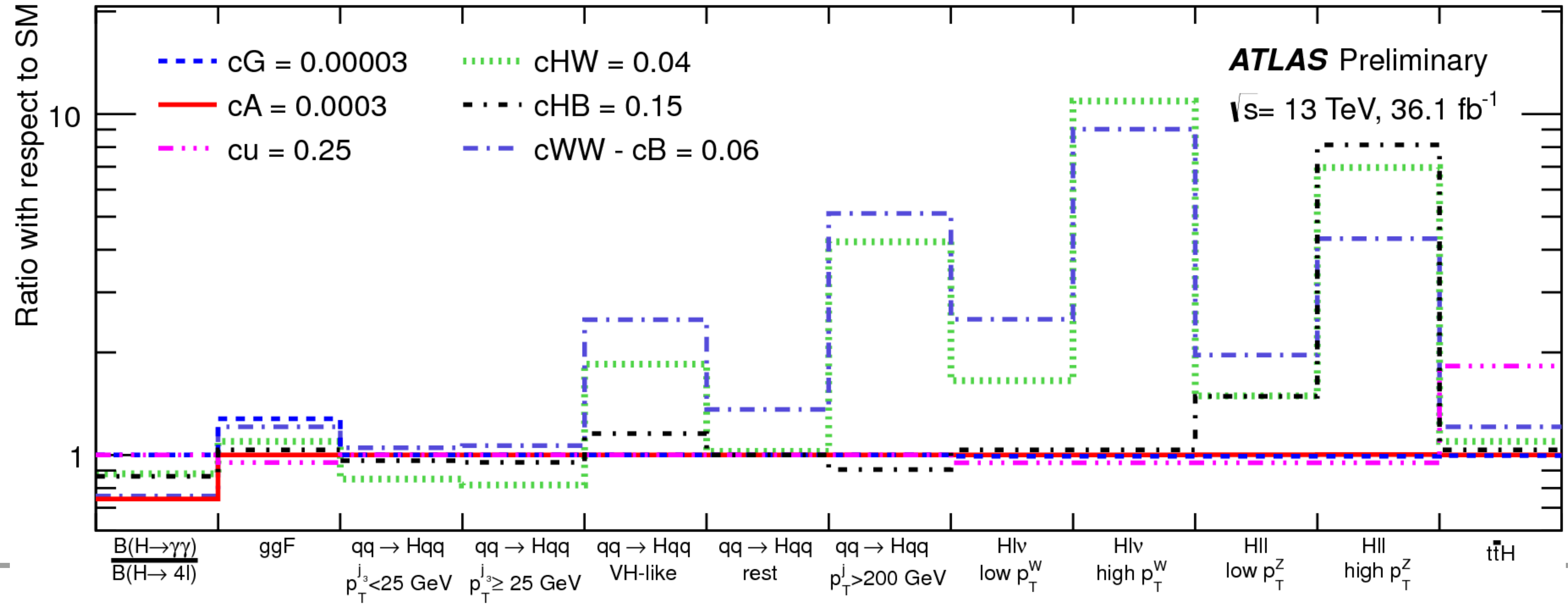


Effective Field Theory Interpretation

ATL-PHYS-PUB-2017-018

Operator	Expression	HEL coefficient	Vertices
$\mathcal{O}_g$	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\texttt{cG} = \frac{m_W^2}{g_s^2}\bar{c}_g$	Hgg
$\mathcal{O}_\gamma$	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\texttt{cA} = \frac{m_W^2}{g'^2}\bar{c}_\gamma$	$H\gamma\gamma, HZZ$
$\mathcal{O}_u$	$y_u \lvert H\rvert^2 \bar{u}_l H u_R +$ h.c.	$\texttt{cu} = v^2 \bar{c}_u$	$Ht\bar{t}$
$\mathcal{O}_{HW}$	$i\left(D^\mu H\right)^\dagger \sigma^a \left(D^\nu H\right) W^a_{\mu\nu}$	$\texttt{cHW} = \frac{m_W^2}{g}\bar{c}_{HW}$	HWW, HZZ
$\mathcal{O}_{HB}$	$i\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu}$	$\texttt{cHB} = \frac{m_W^2}{g'}\bar{c}_{HB}$	HZZ
$\mathcal{O}_W$	$i\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$	$\texttt{cWW} = \frac{m_W^2}{g}\bar{c}_W$	HWW, HZZ
$\mathcal{O}_B$	$i\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$	$\texttt{cB} = \frac{m_W^2}{g'}\bar{c}_B$	HZZ





Brout-Englert-Higgs Mechanism

- Mass in matter: ~95% due to binding energy of strong force in nucleus ($E = mc^2$)

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- **Solution:**
  (developed in 1960s by Brout, Engler, Higgs, and others)
  - Introduce complex scalar field $\boldsymbol{\phi}(\boldsymbol{x})$ with potential:

$$V(\phi) = \mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2$$

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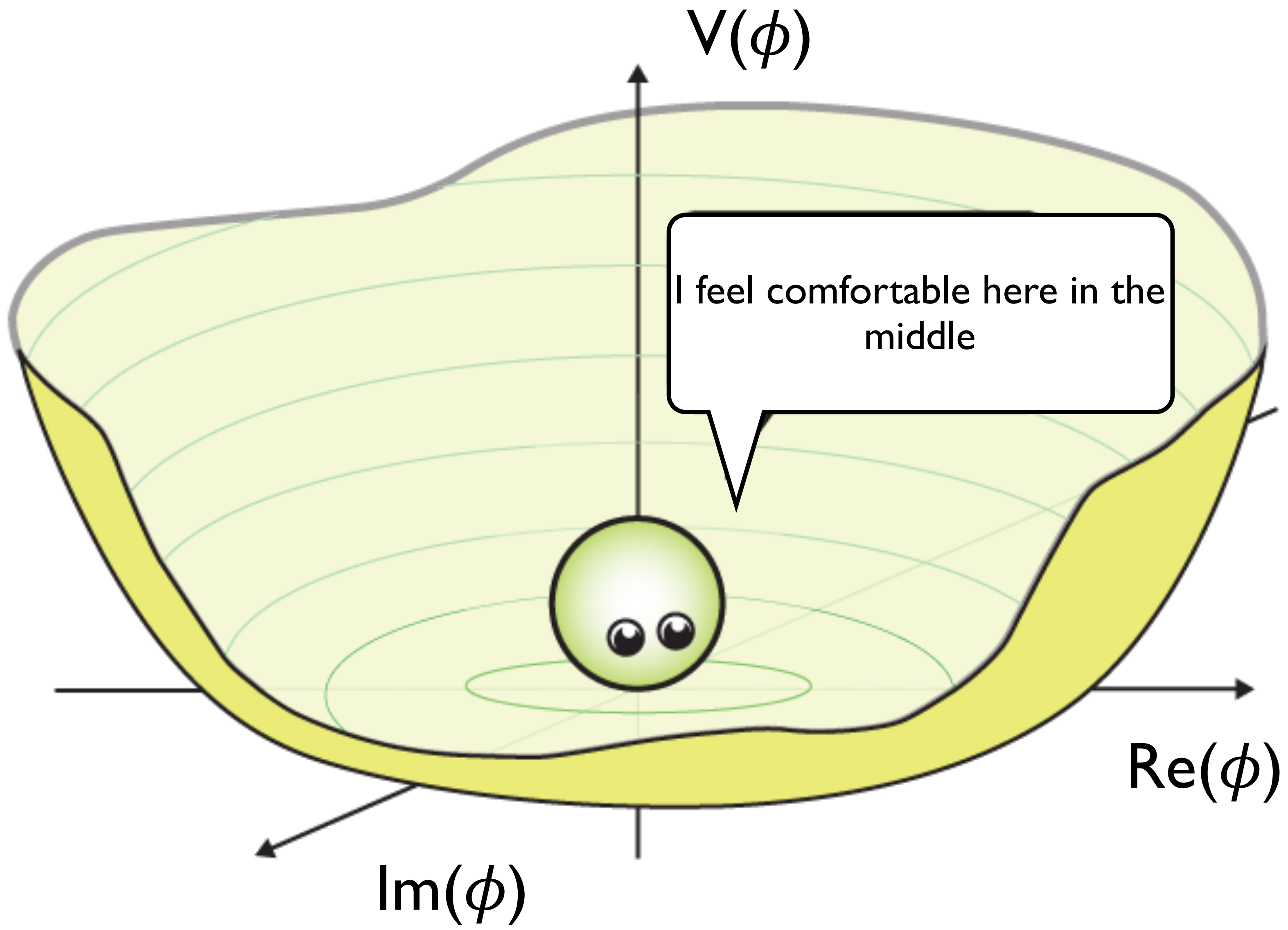
For $\lambda > 0$, $\mu^2 > 0$:



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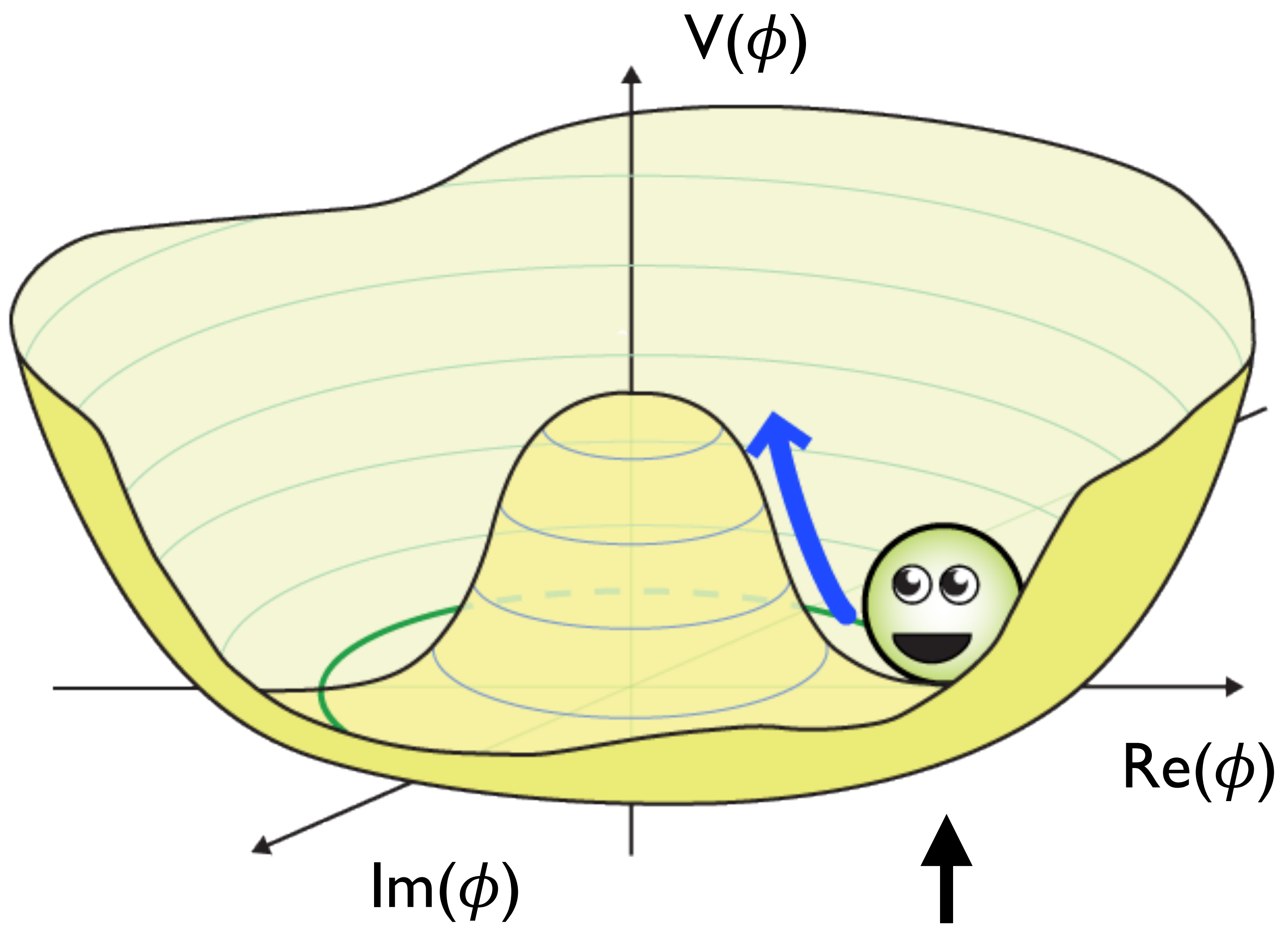
For $\lambda > 0$, $\mu^2 < 0$:
Spontaneous symmetry breaking



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

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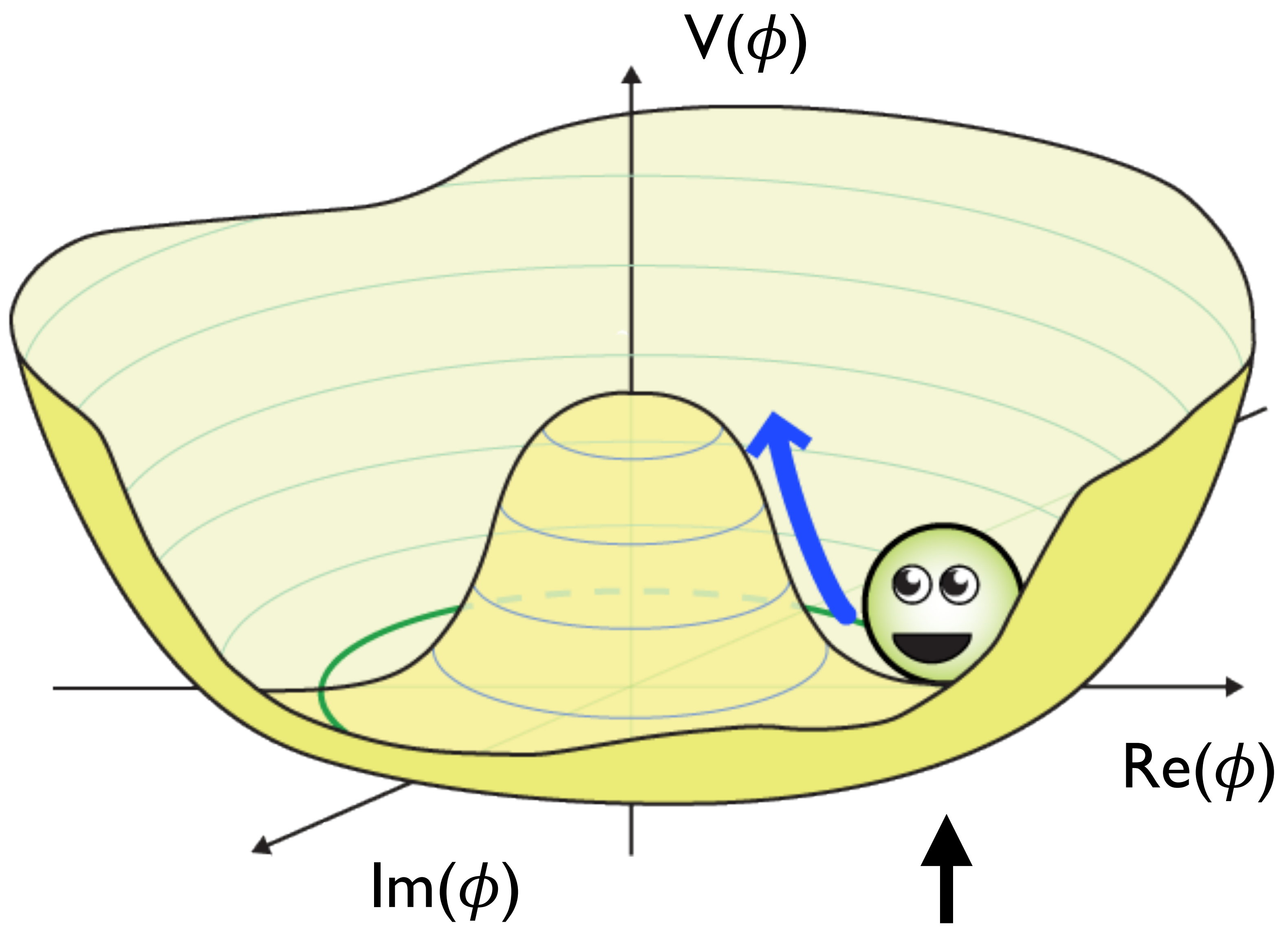
  - Introduce complex scalar field $\boldsymbol{\phi}(\boldsymbol{x})$ with potential:

$$V(\phi) = \mu^2\left(\phi^\dagger\phi\right) + \lambda\left(\phi^\dagger\phi\right)^2$$

Expand $\boldsymbol{\phi}(\boldsymbol{x})$ around new vacuum:

$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

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



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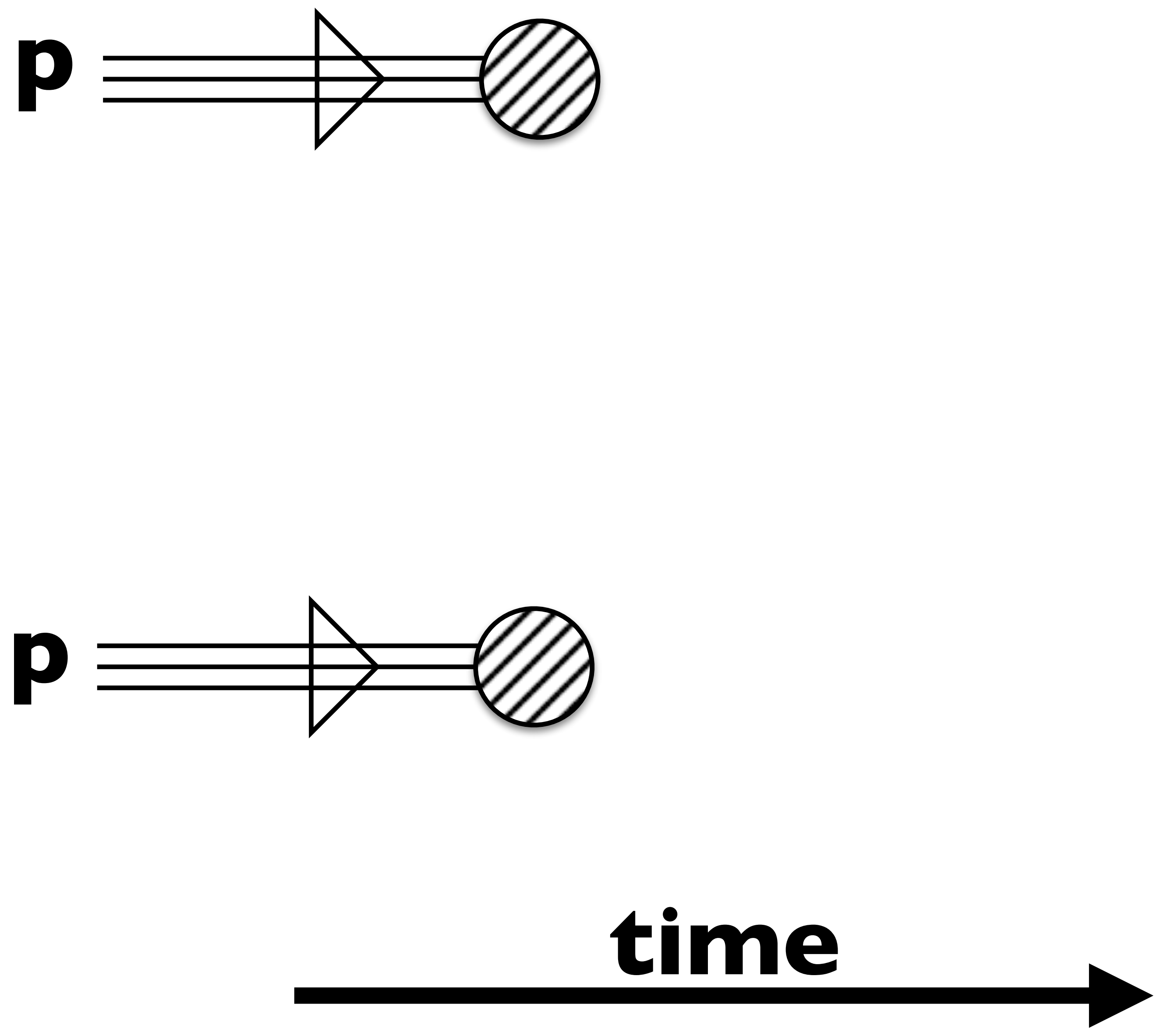
Higgs Boson Production at the LHC



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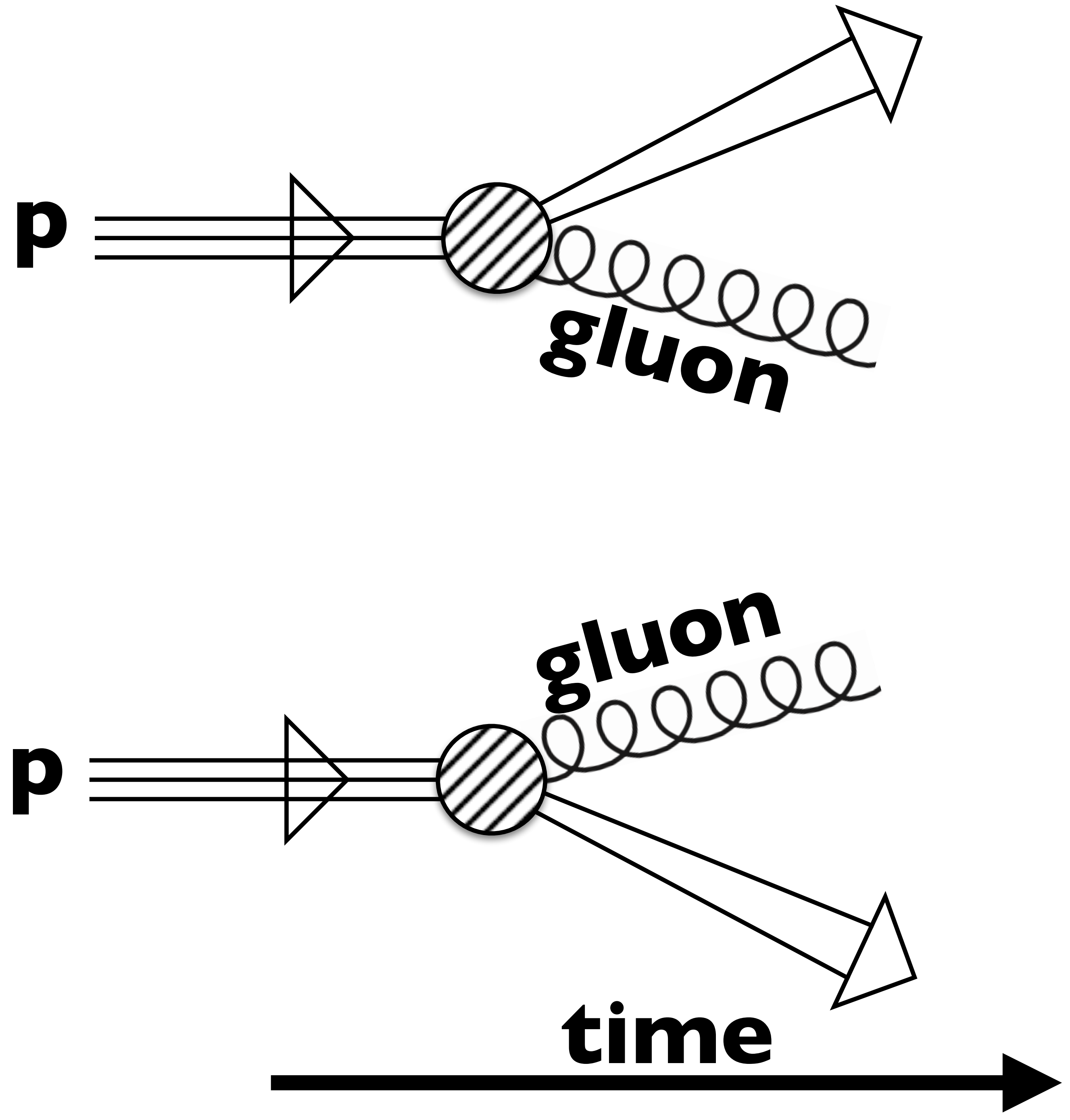

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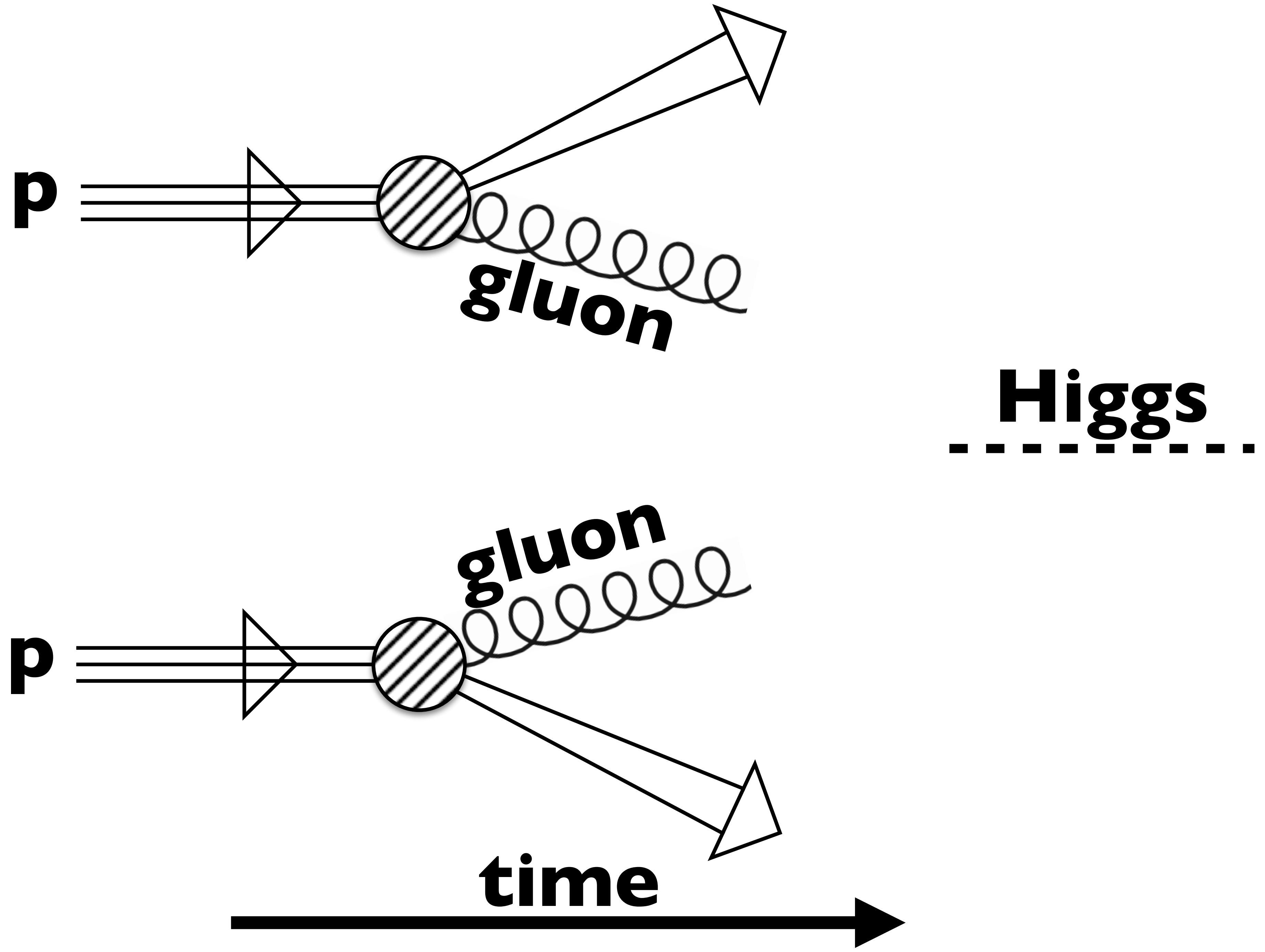

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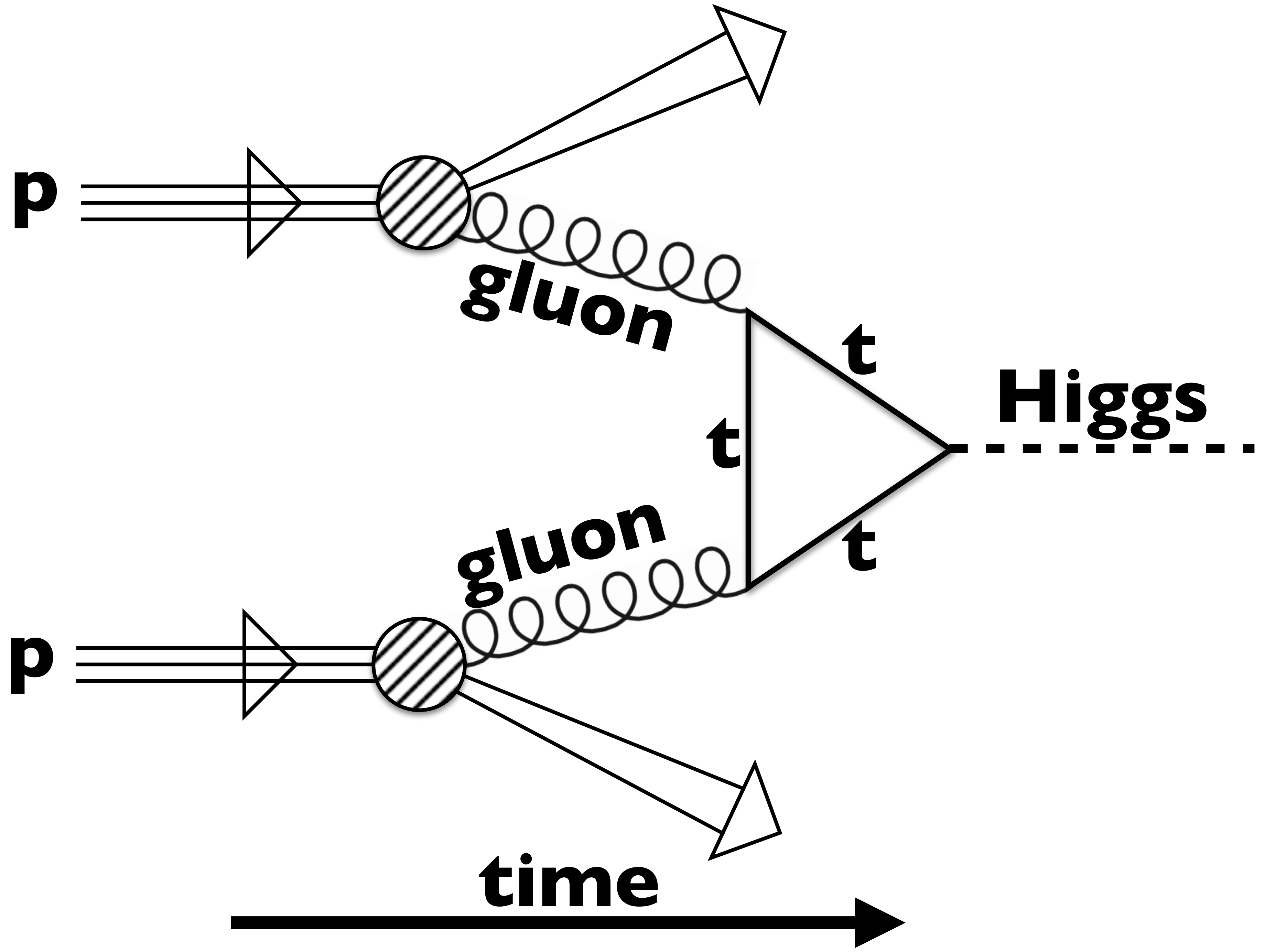
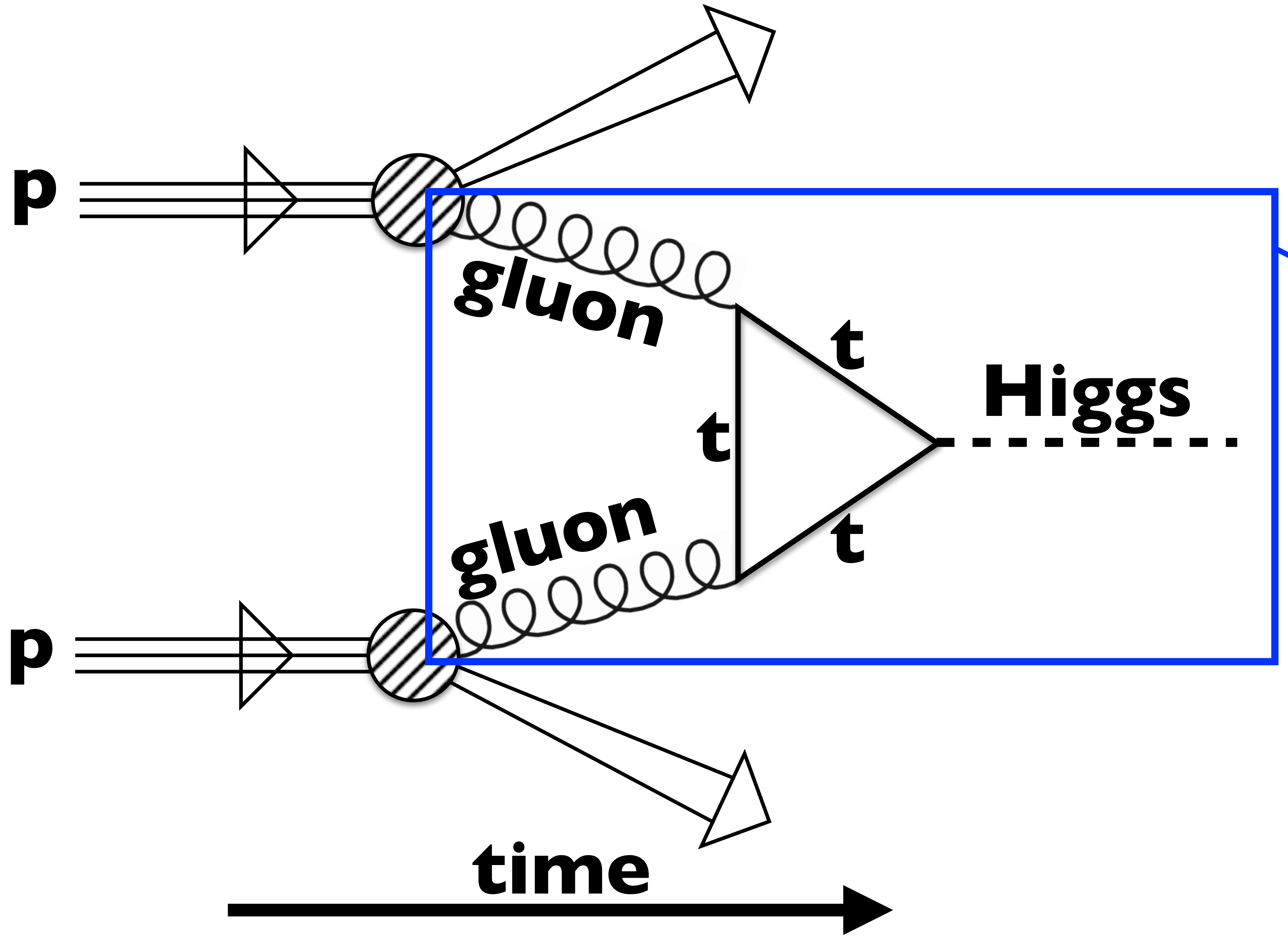
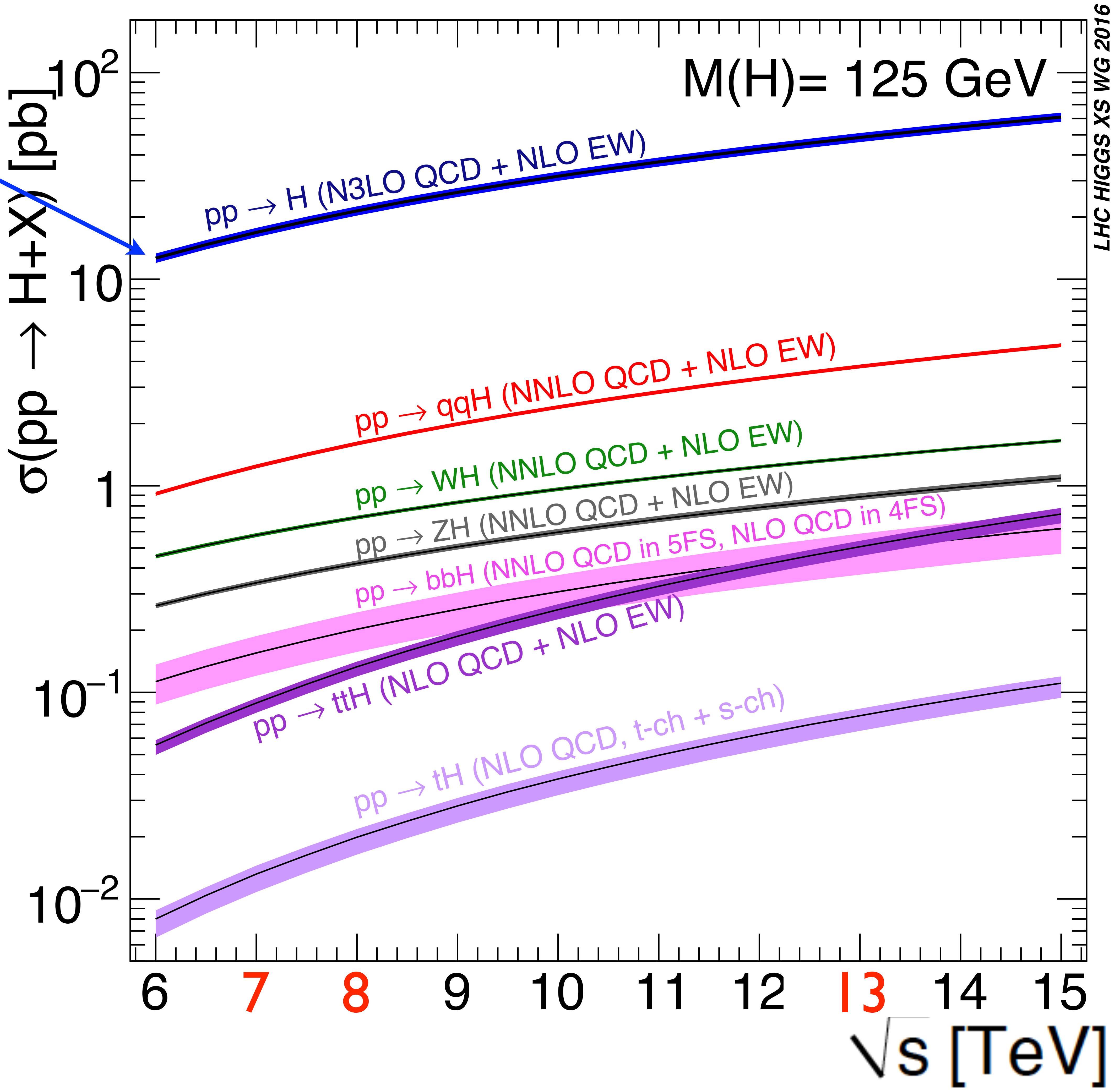


Higgs Boson Production at the LHC





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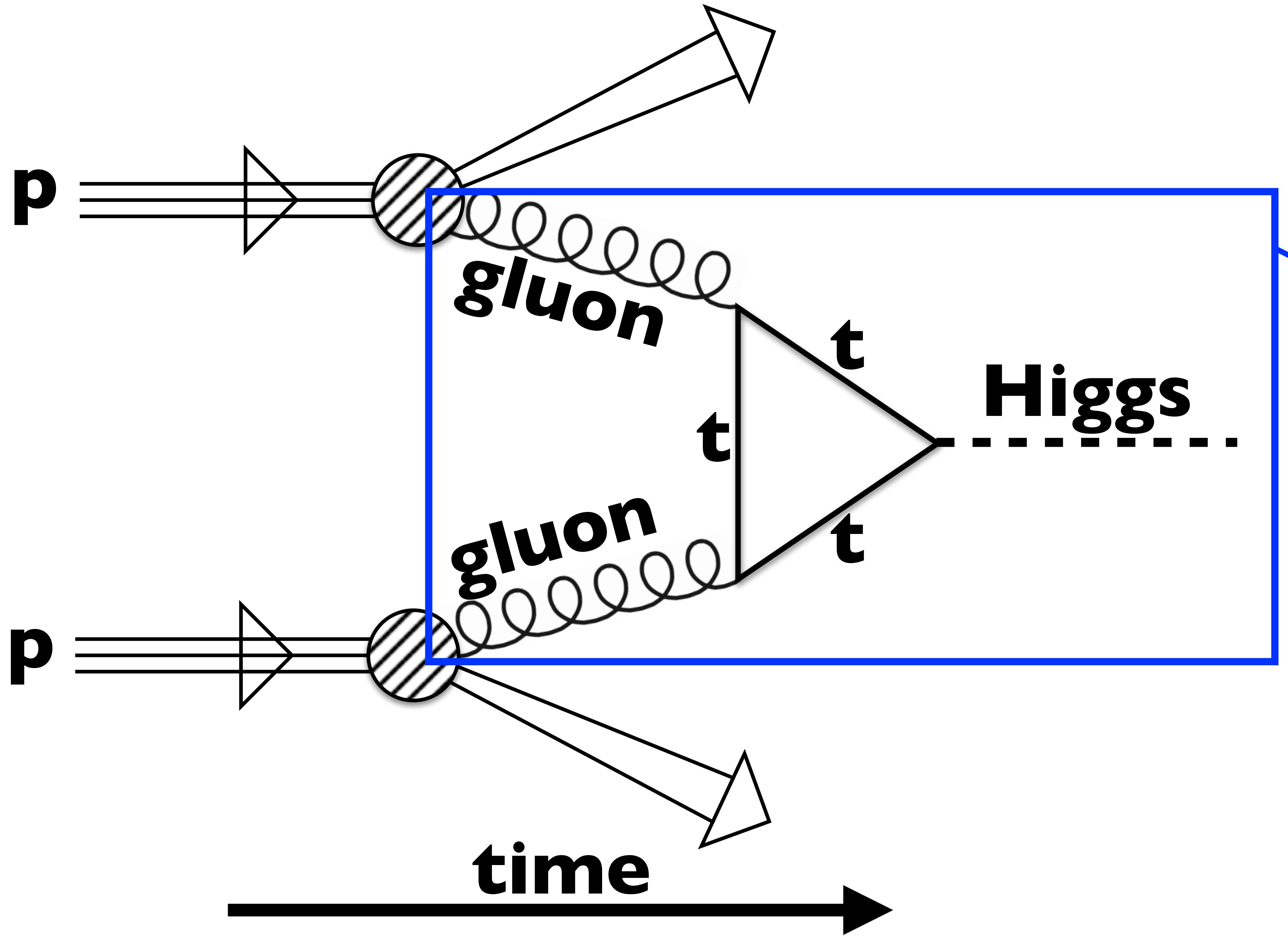
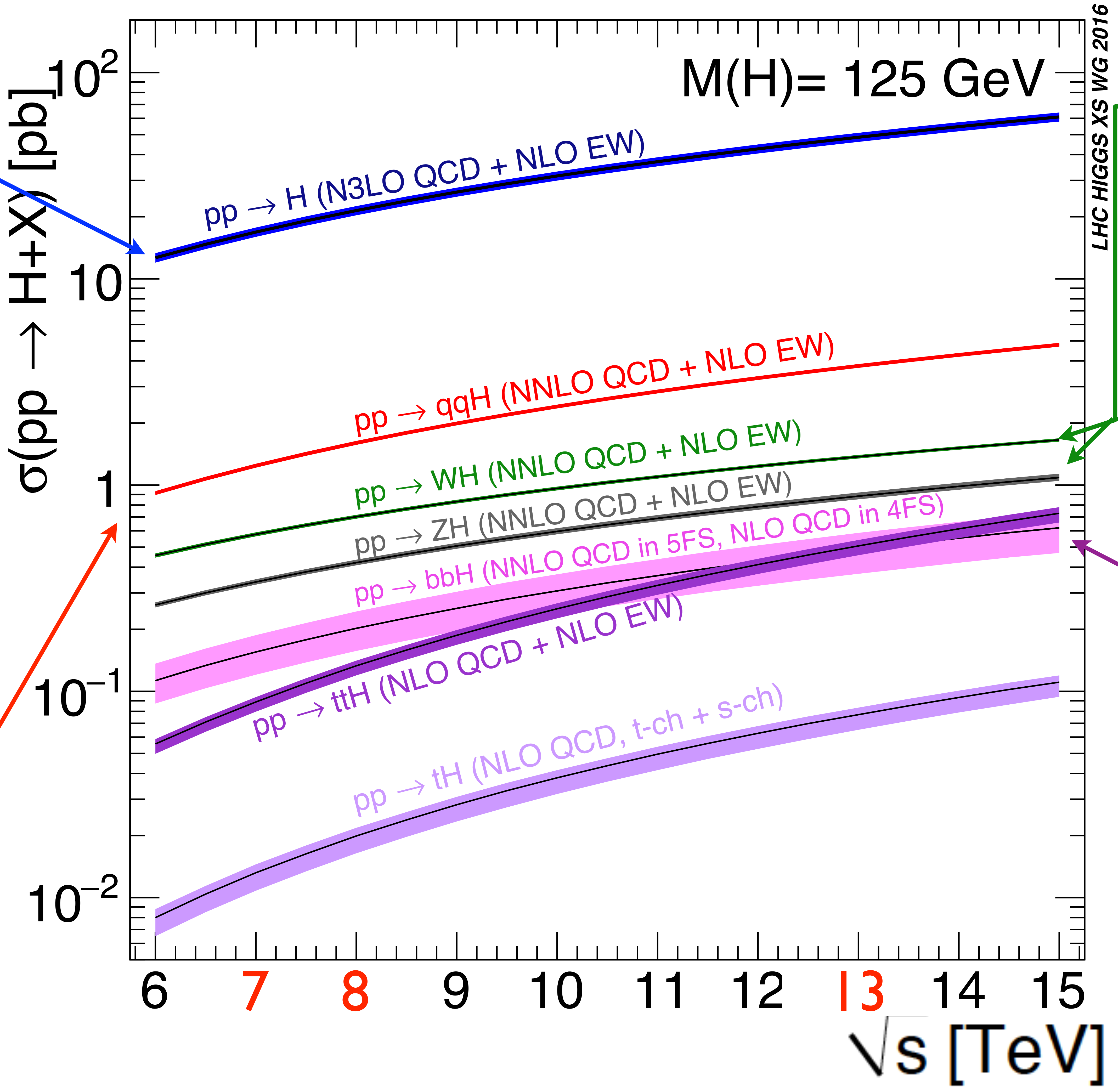
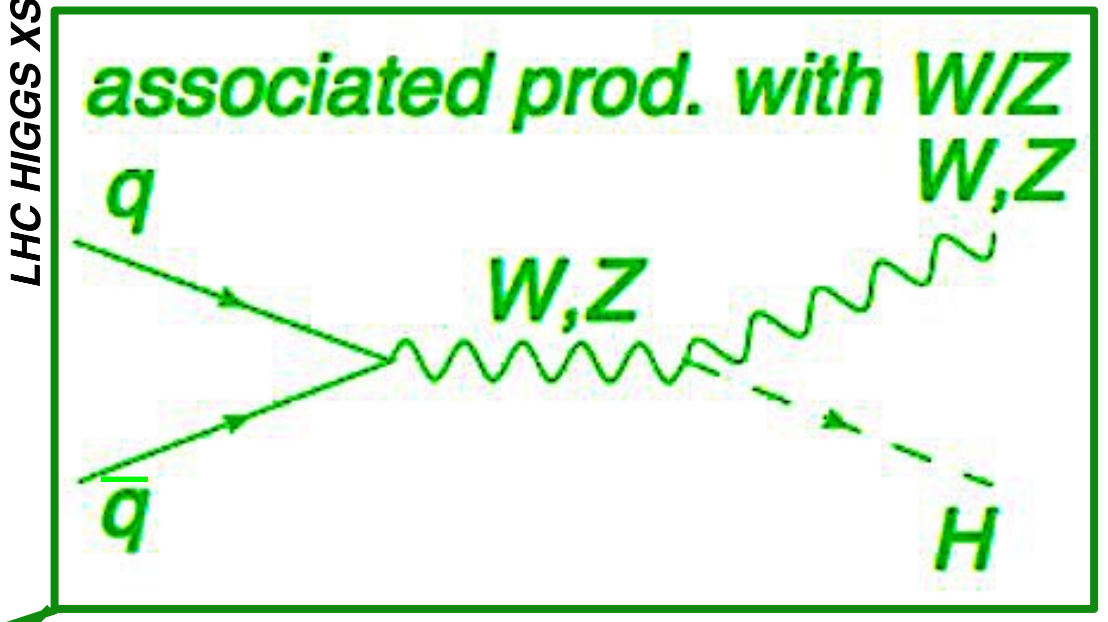
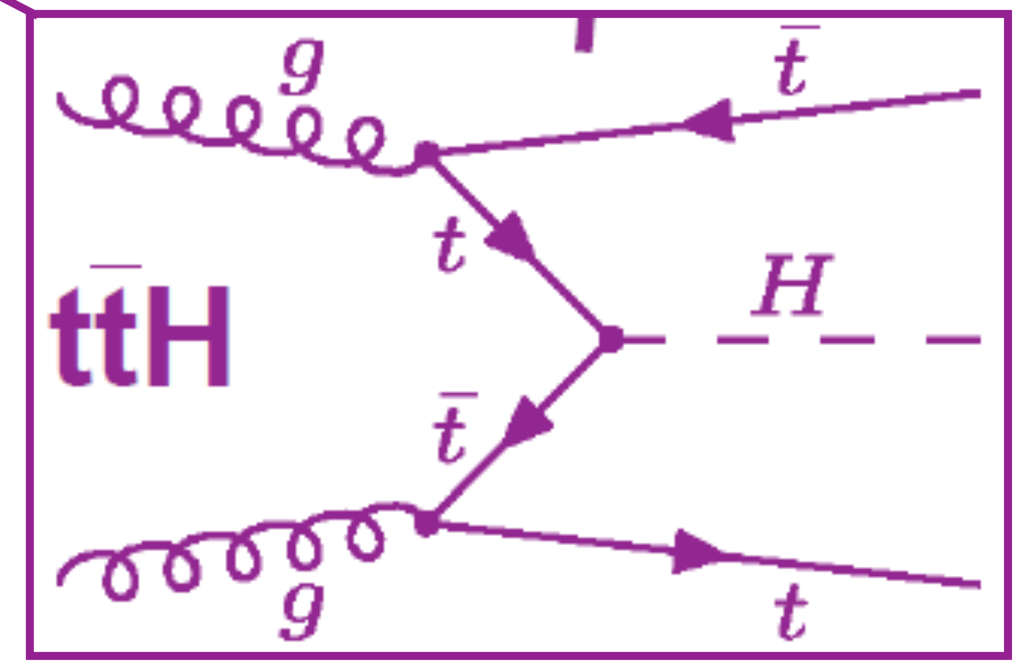
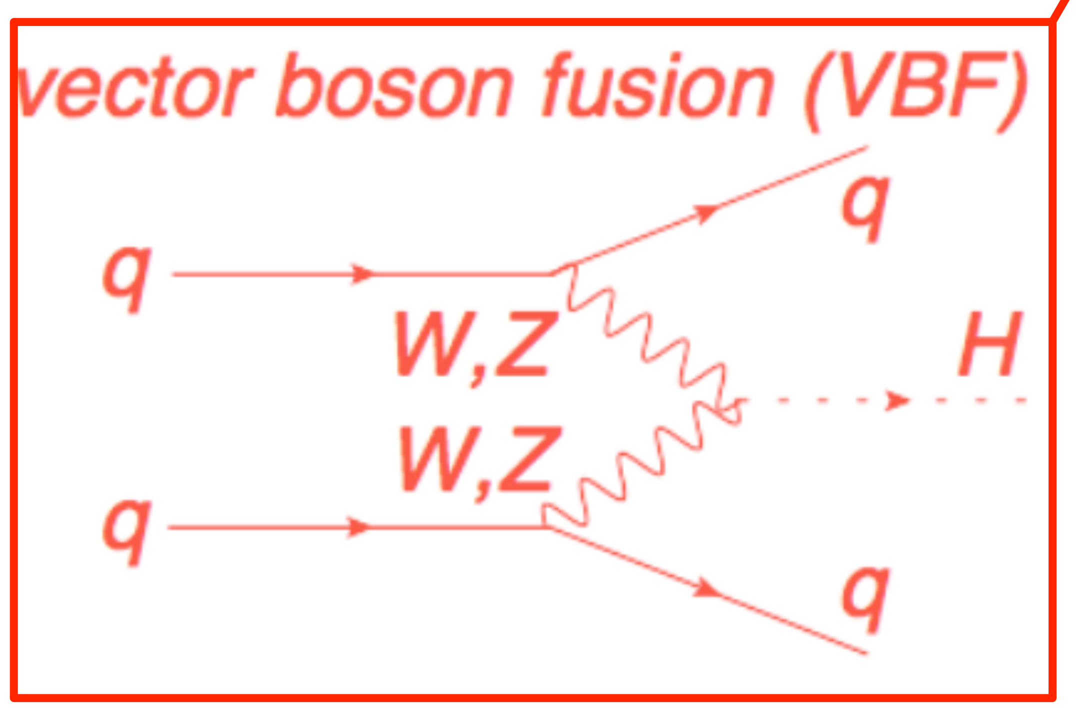


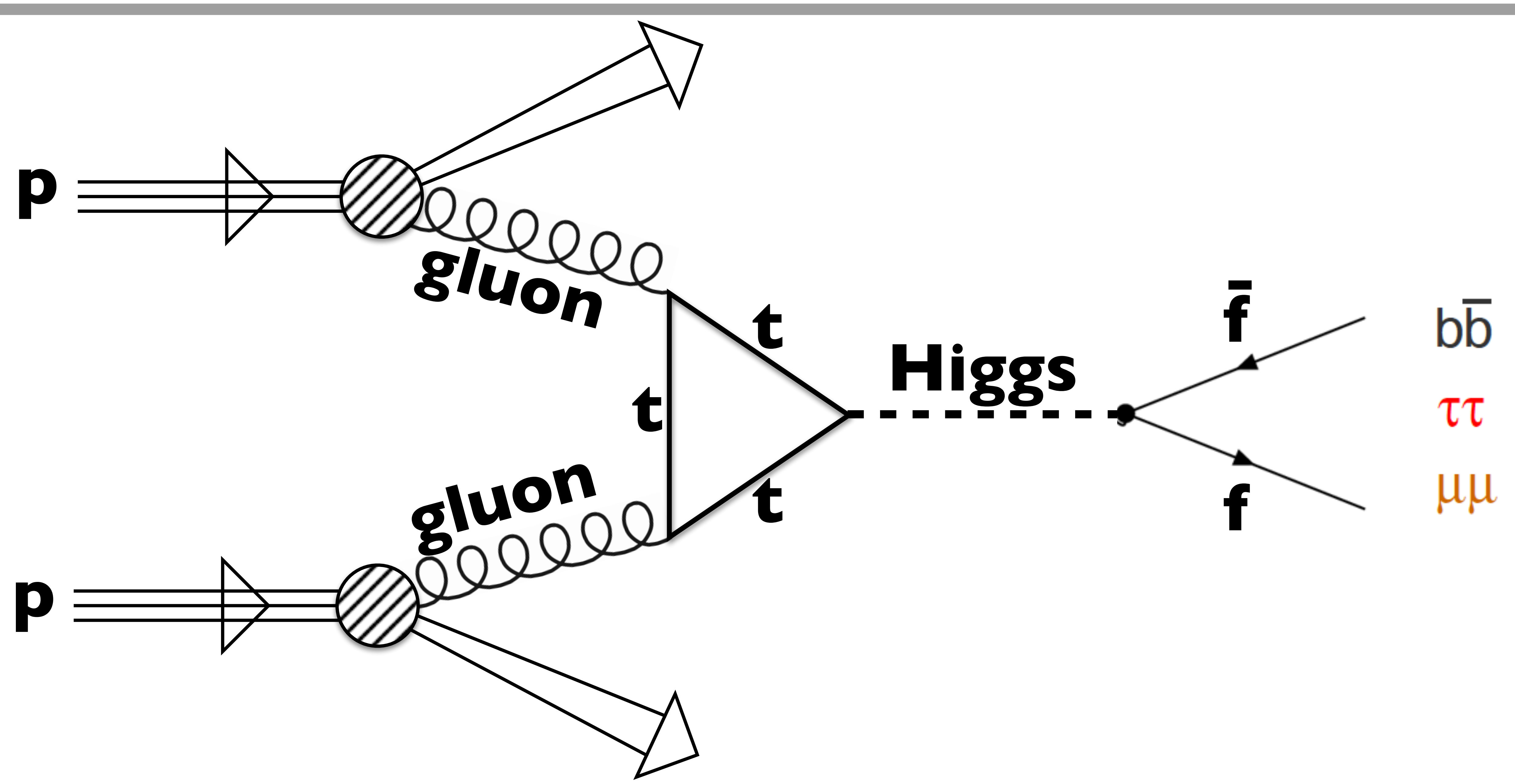


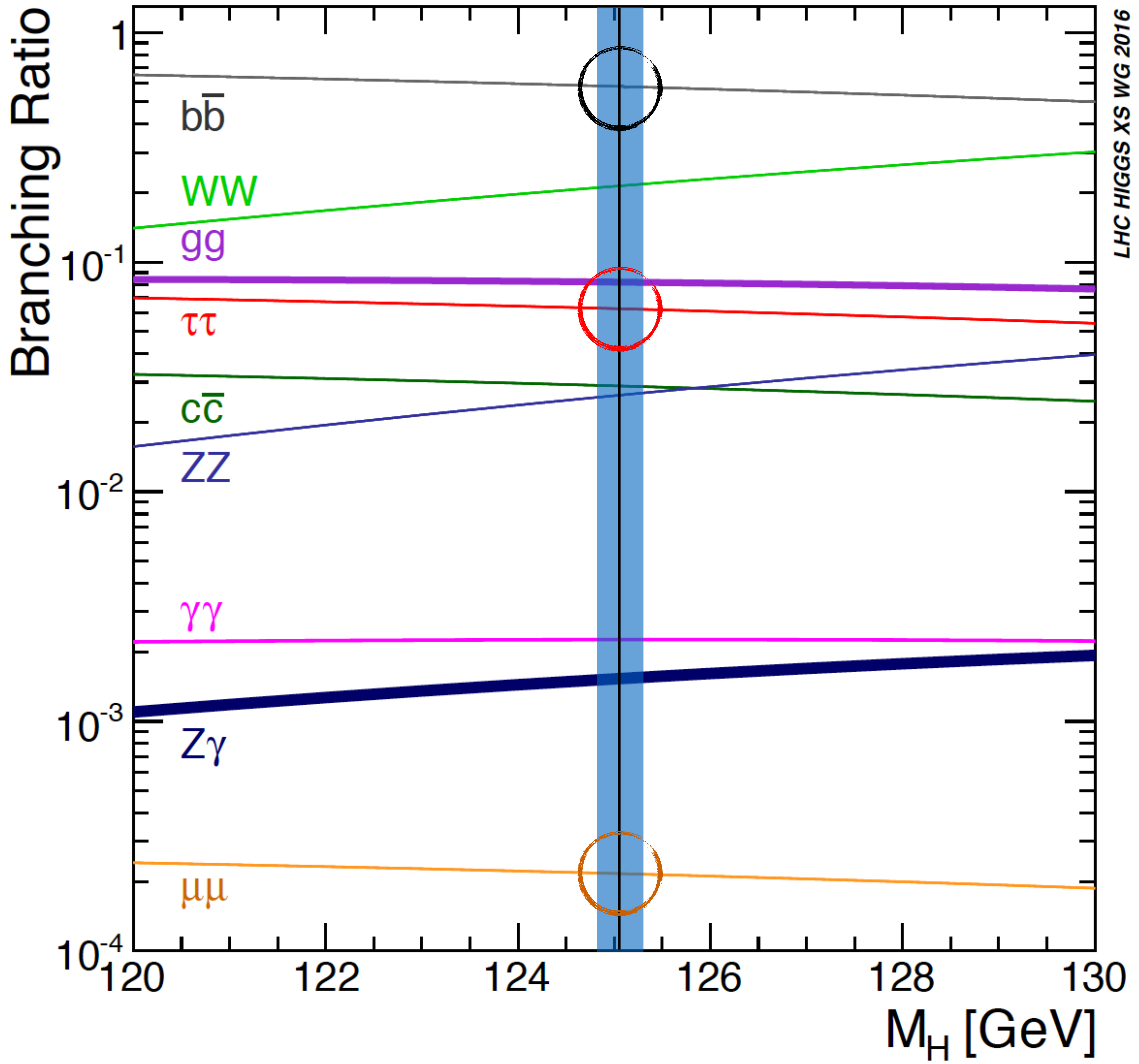






Higgs Boson Decay





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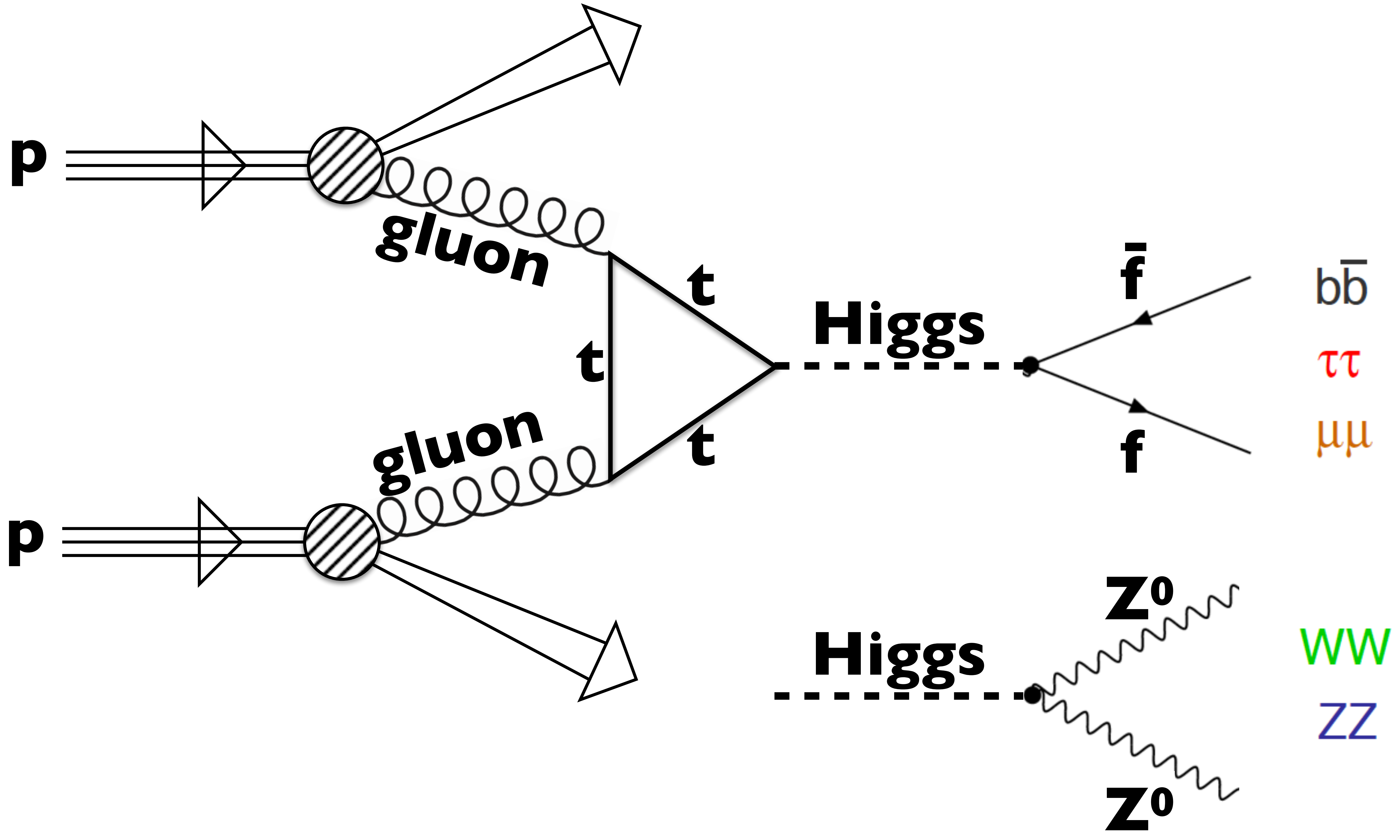

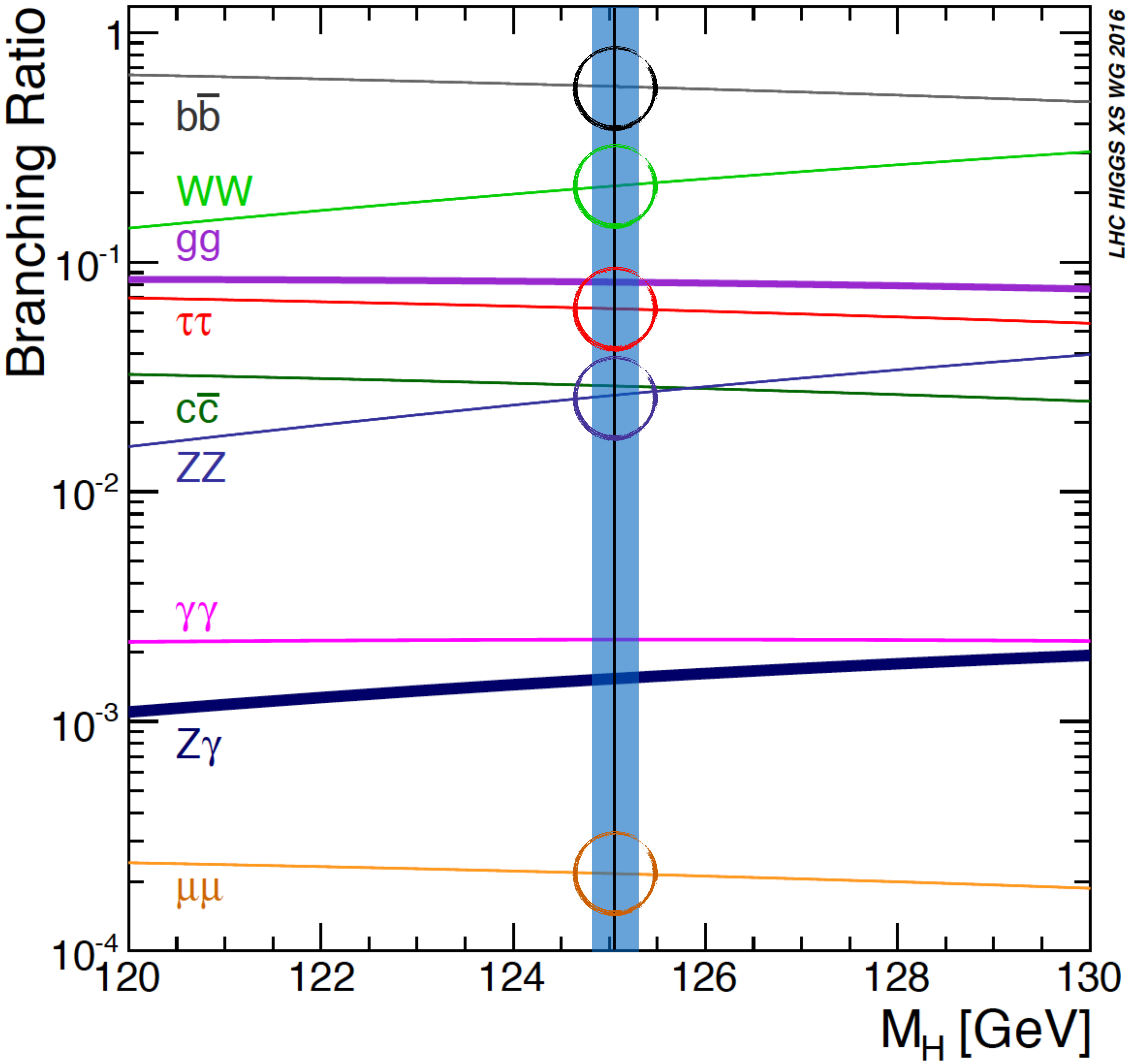

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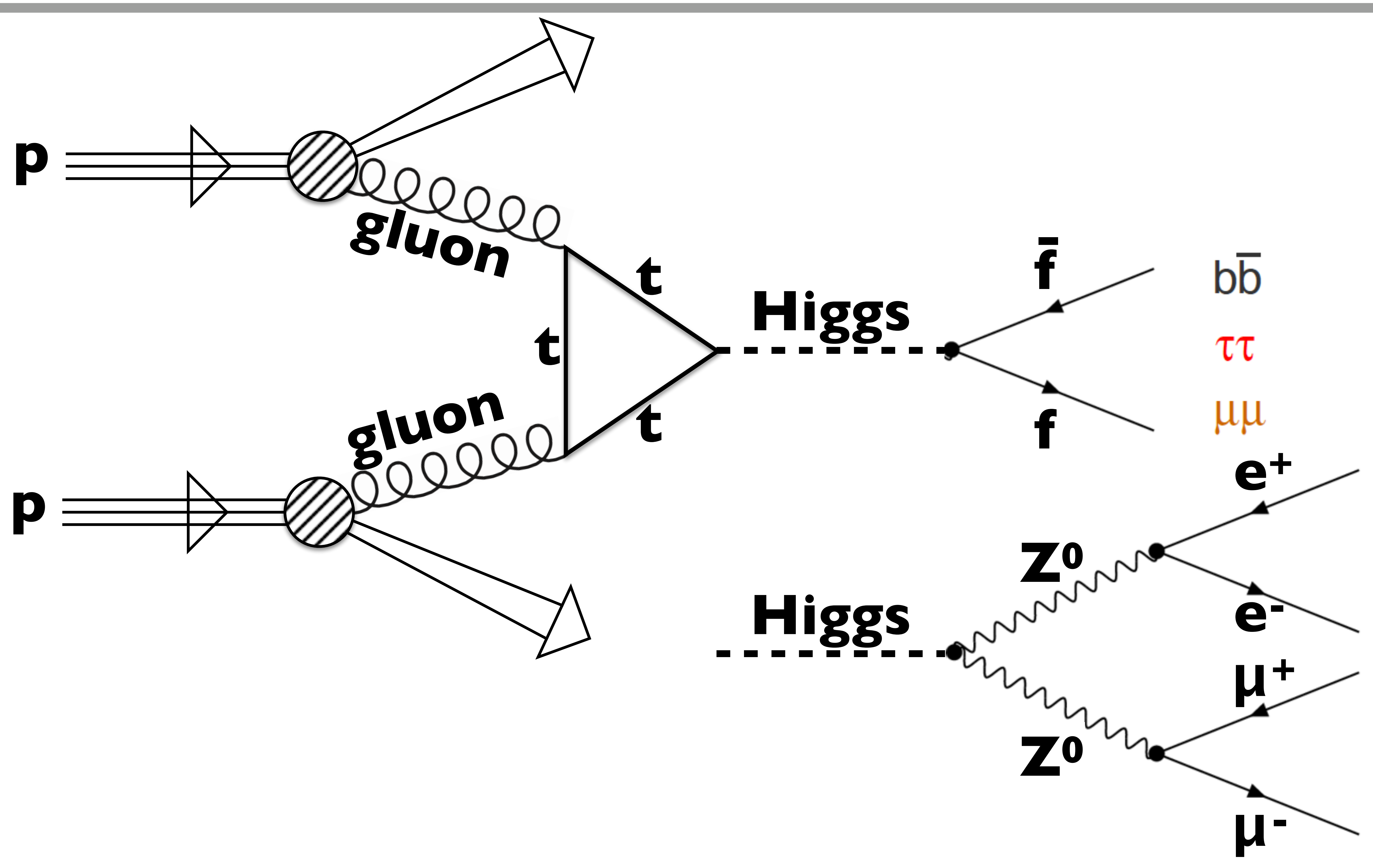

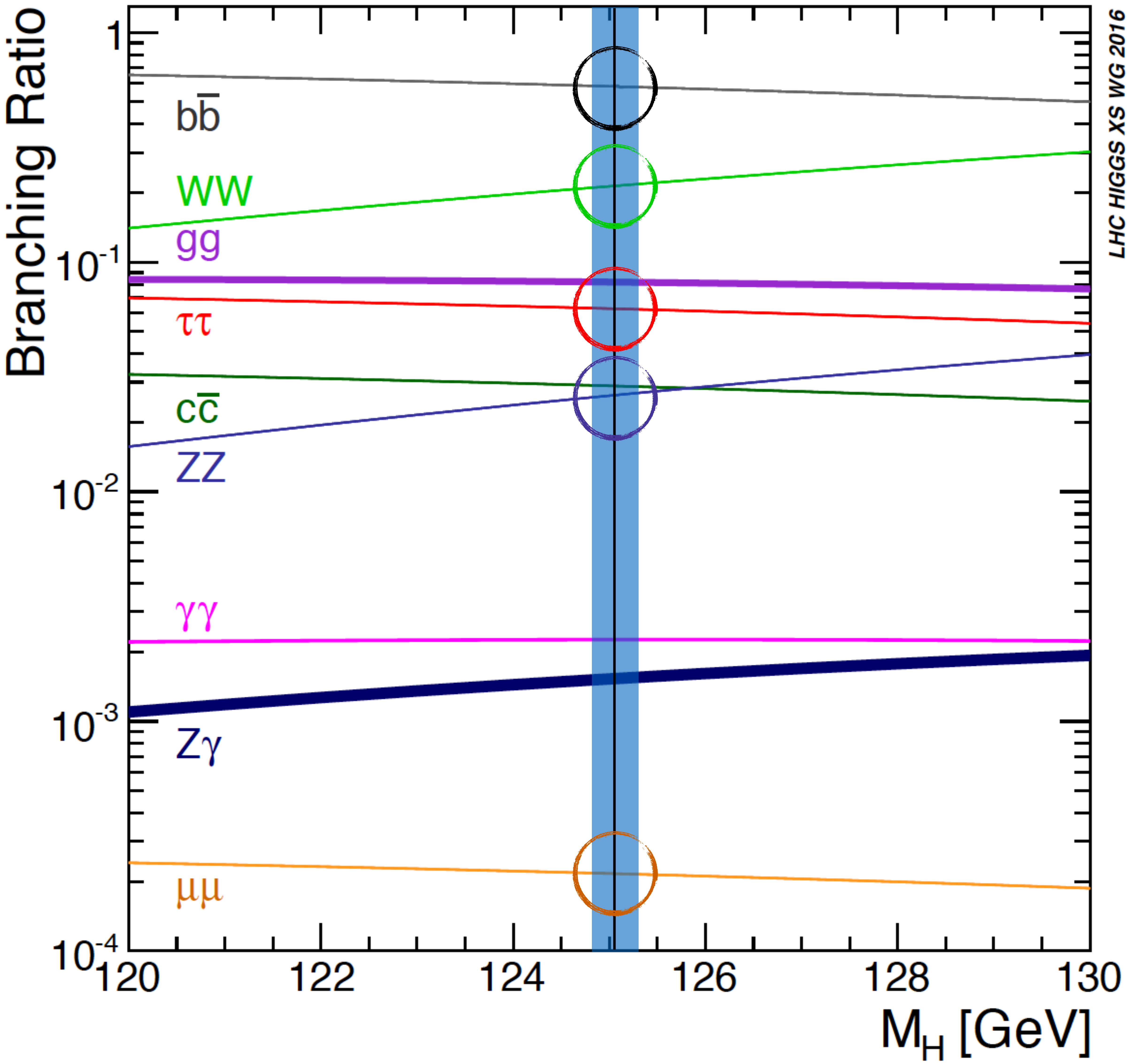

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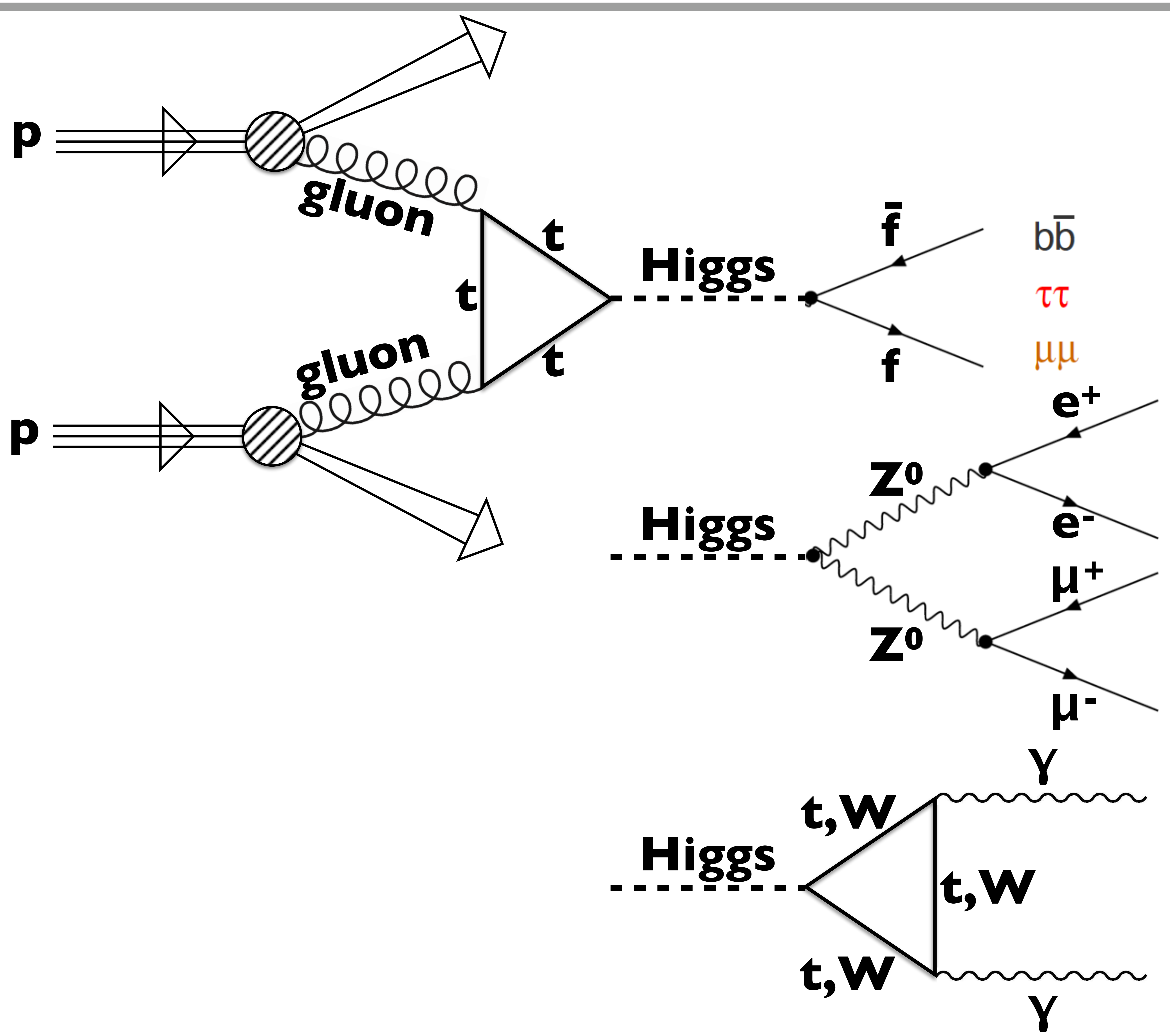
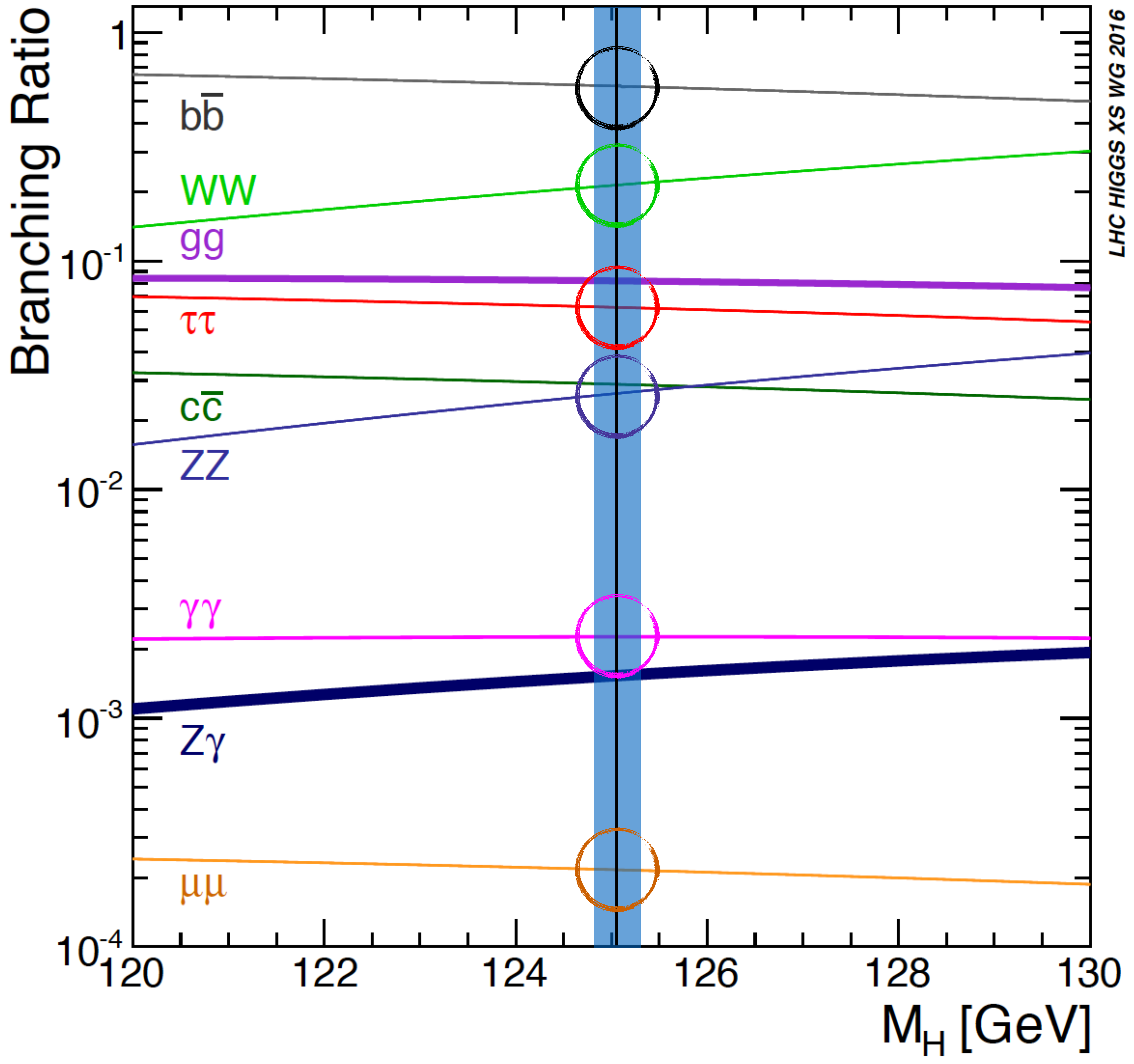
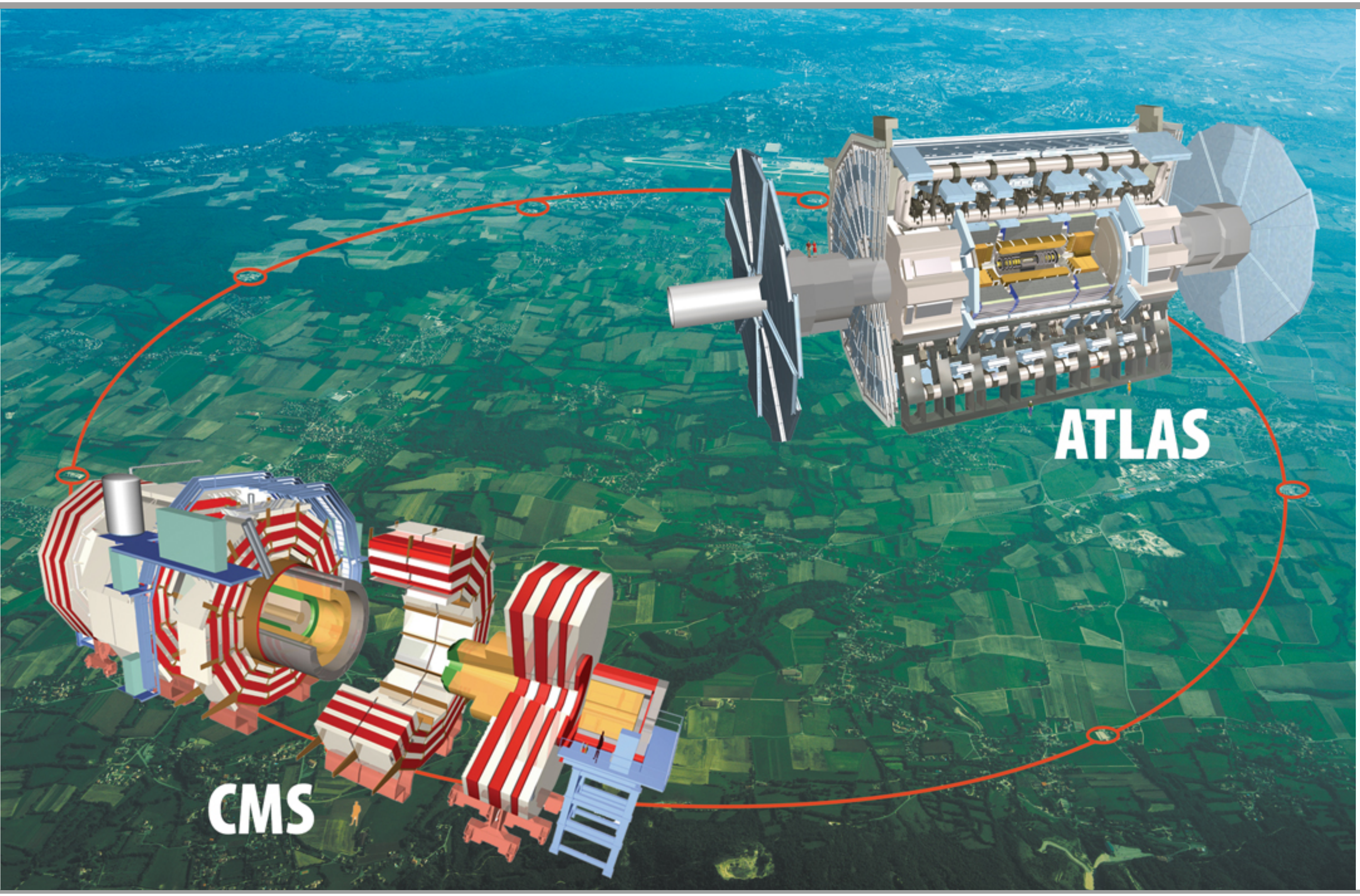




The LHC with ATLAS & CMS



LHC bunch-crossing rate: 40 MHz

Up to 60 pp collisions
per bunch-crossing on average

⇒ ~2 billion pp collisions per second

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- Proton-proton collision energy $E_{CM} \equiv \sqrt{s}$
  - 7 TeV (2011), 8 TeV (2012): "Run 1"
  - 13 TeV (2015-2018): "Run 2"
- Luminosity
  - Integrated Luminosity $L = \int \mathscr{L}\, dt$

ATLAS

CMS

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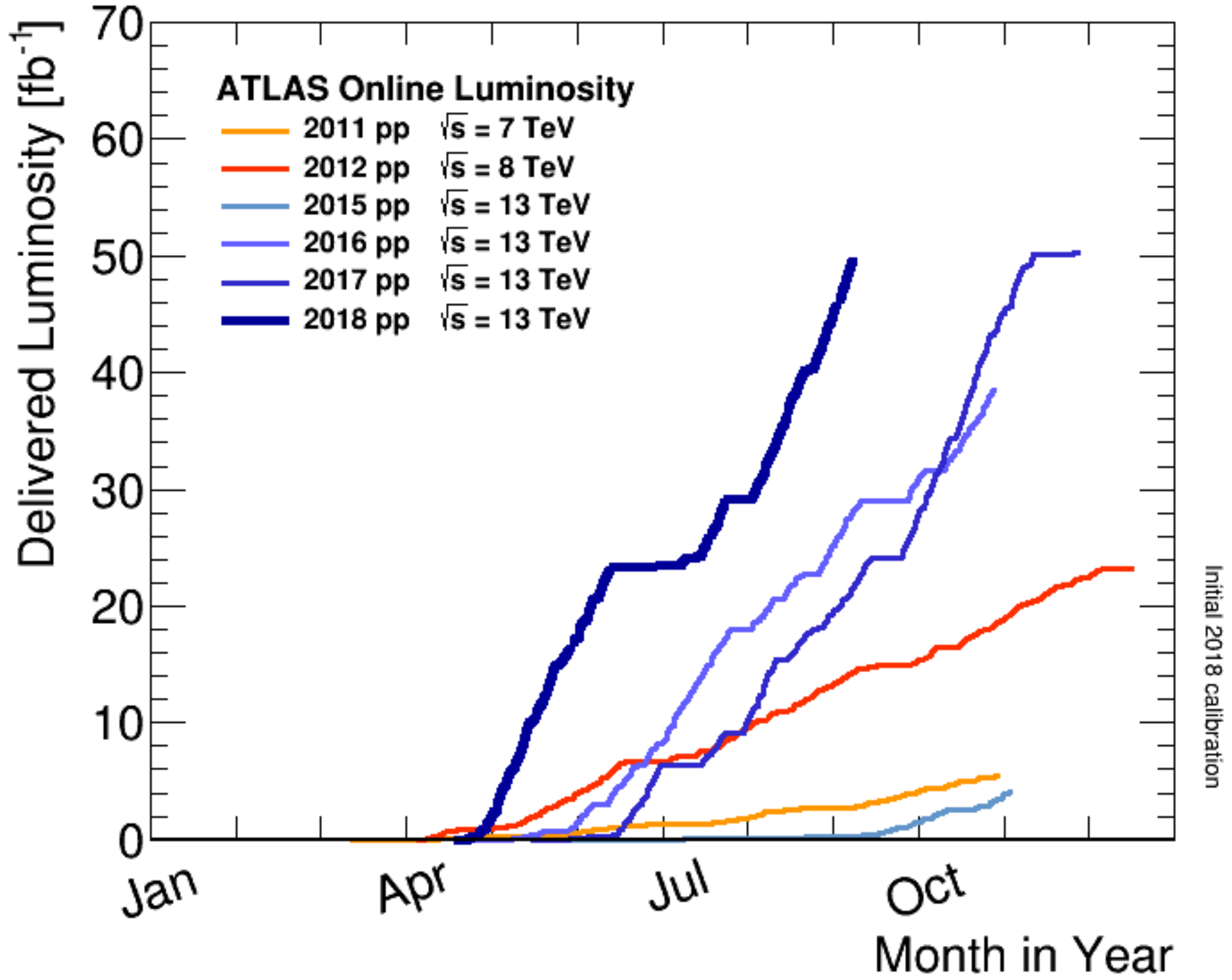

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- Number of produced events $N = \sigma \cdot L$
  - ***Run 1***: $\sigma_{Higgs} \approx 25$ pb

    $\Rightarrow \mathbf{N_{Higgs}} \approx 25\text{ pb} \cdot 25\text{ fb}^{-1} =$ **625 000**
  - ***Run 2***: $N_{Higgs} \approx 55\text{ pb} \cdot 36\text{ fb}^{-1} =$ **2 000 000**

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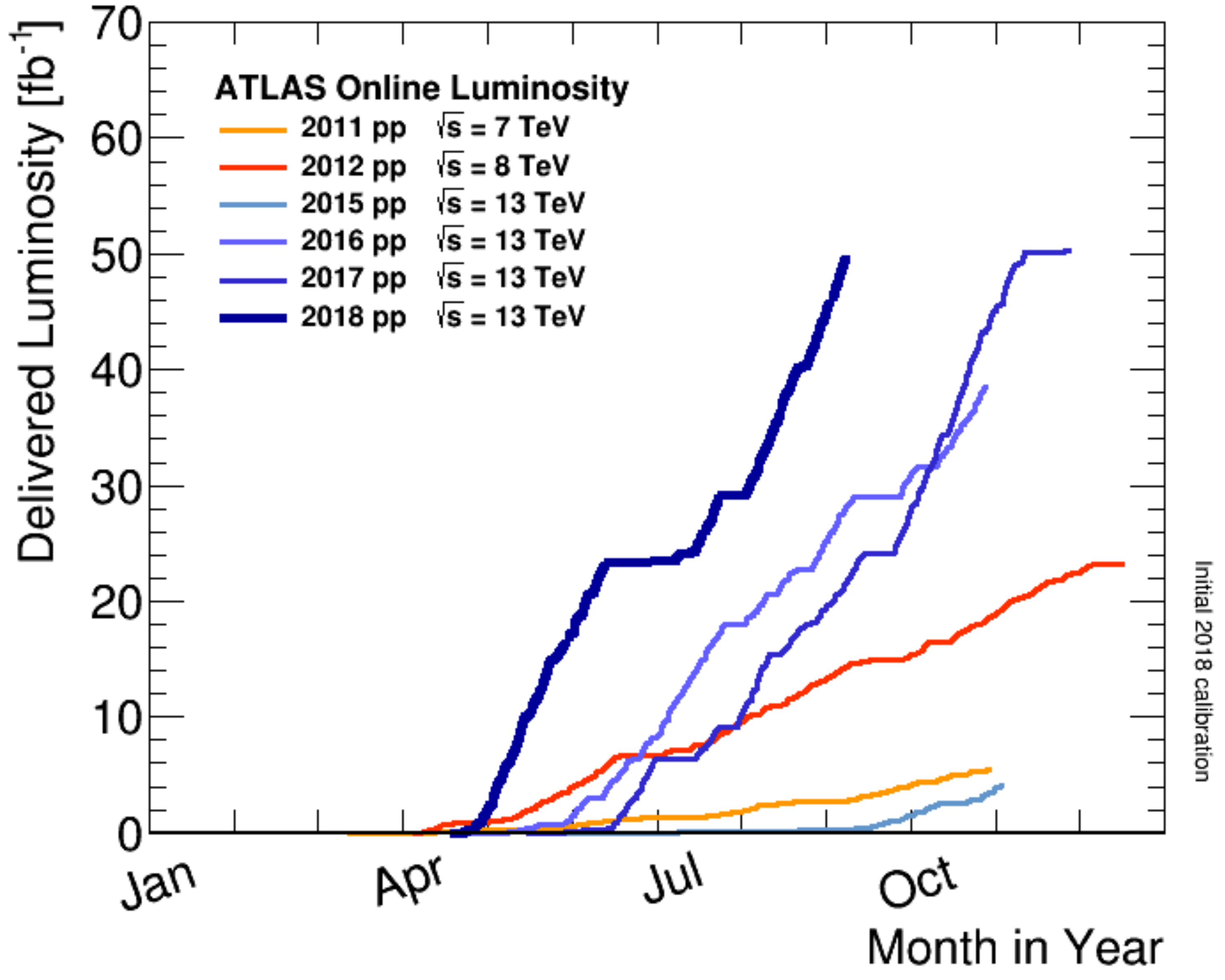
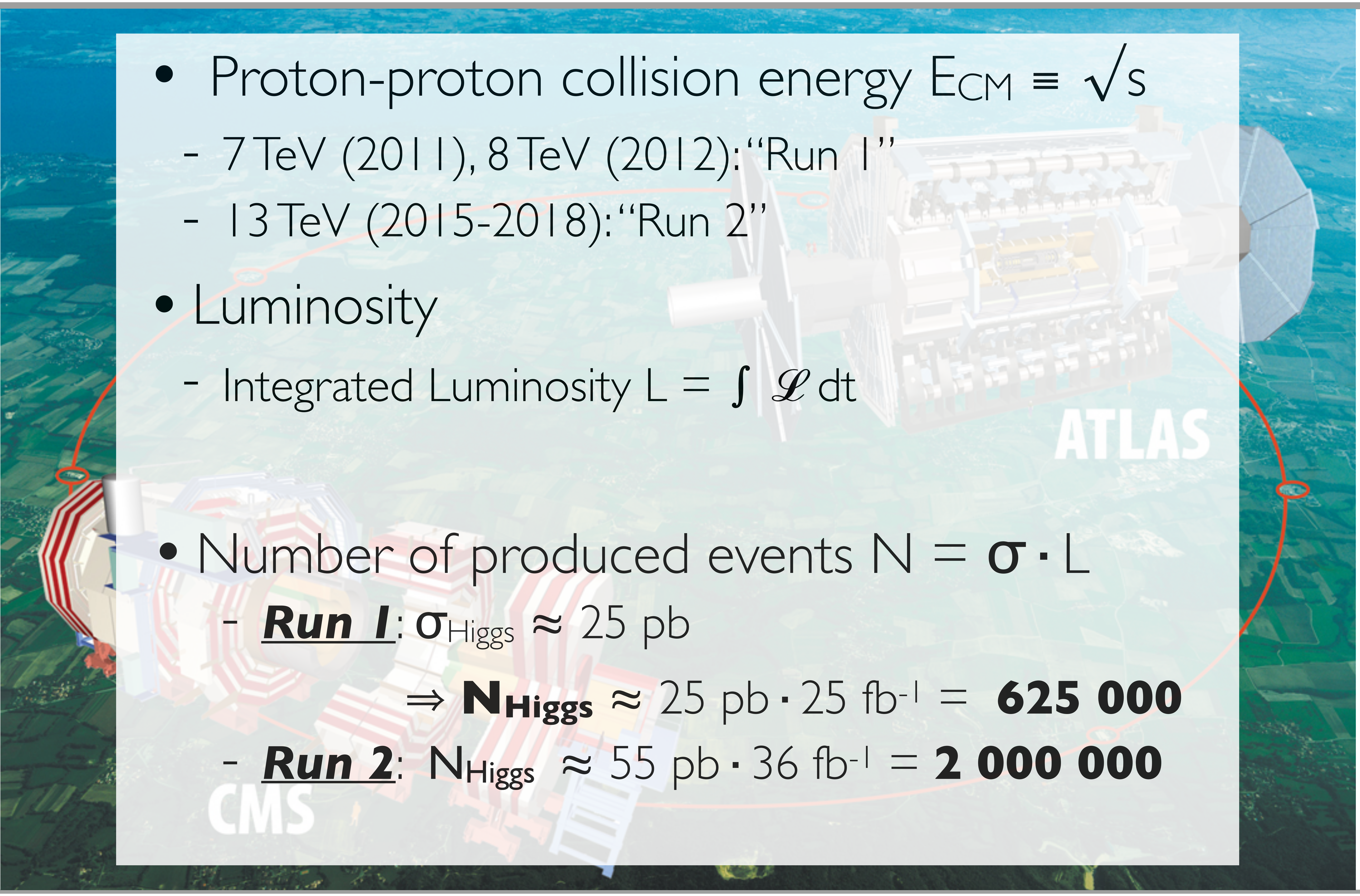


The LHC with ATLAS & CMS



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LHC bunch-crossing rate: 40 MHz

Up to 60 pp collisions per bunch-crossing on average

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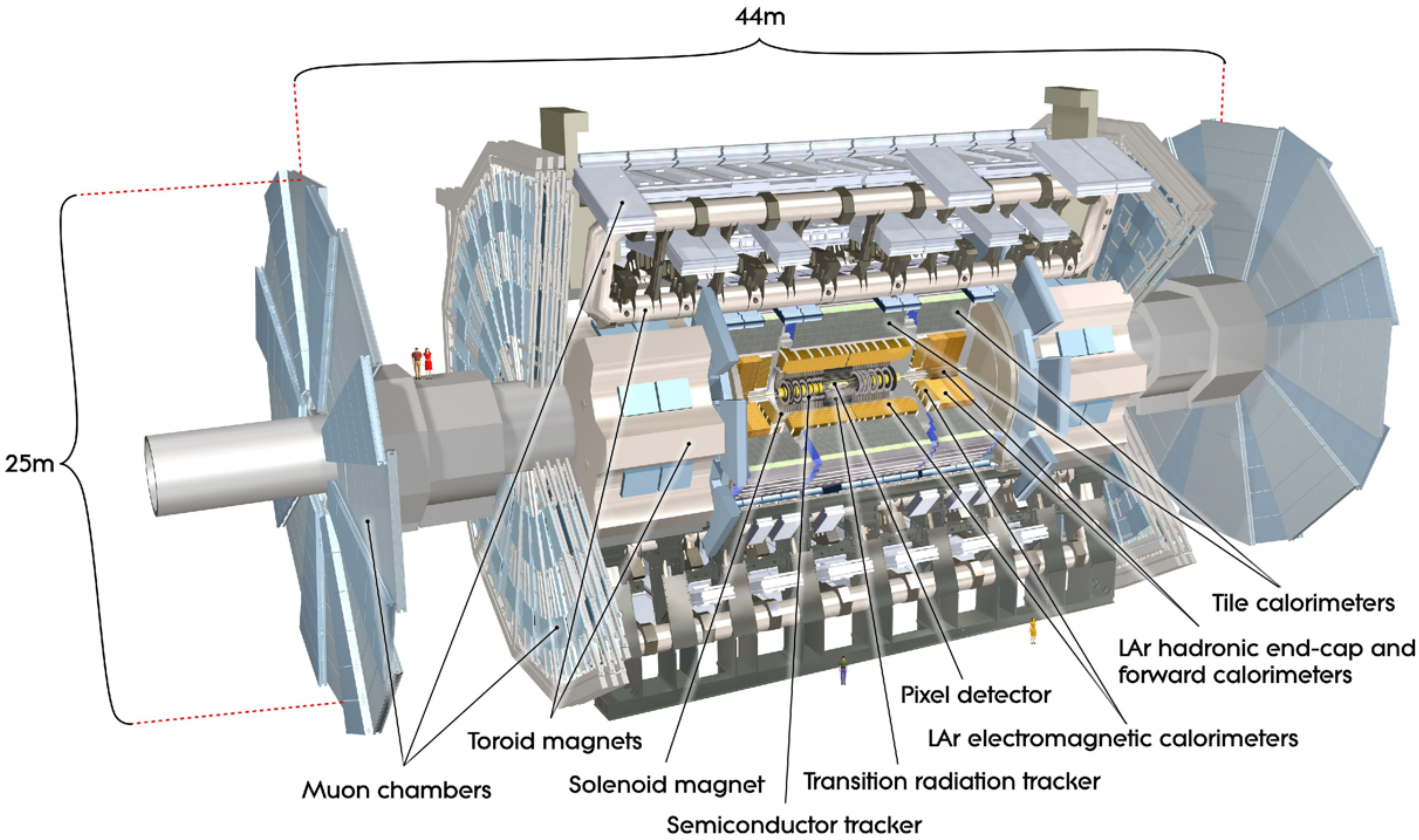
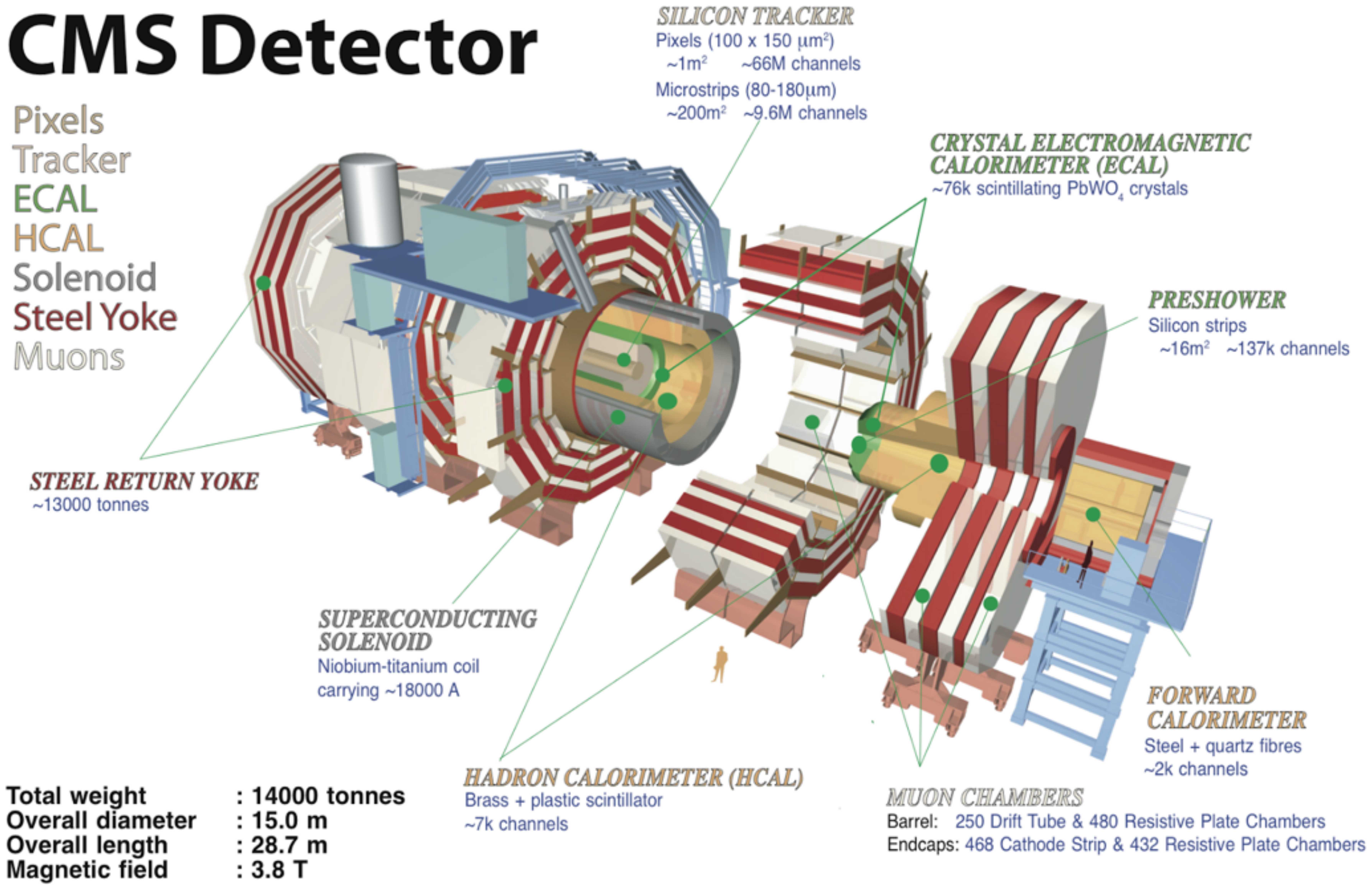
A Higgs boson is produced in only 1 out of 10^9 events

The ATLAS Detector



The CMS Detector

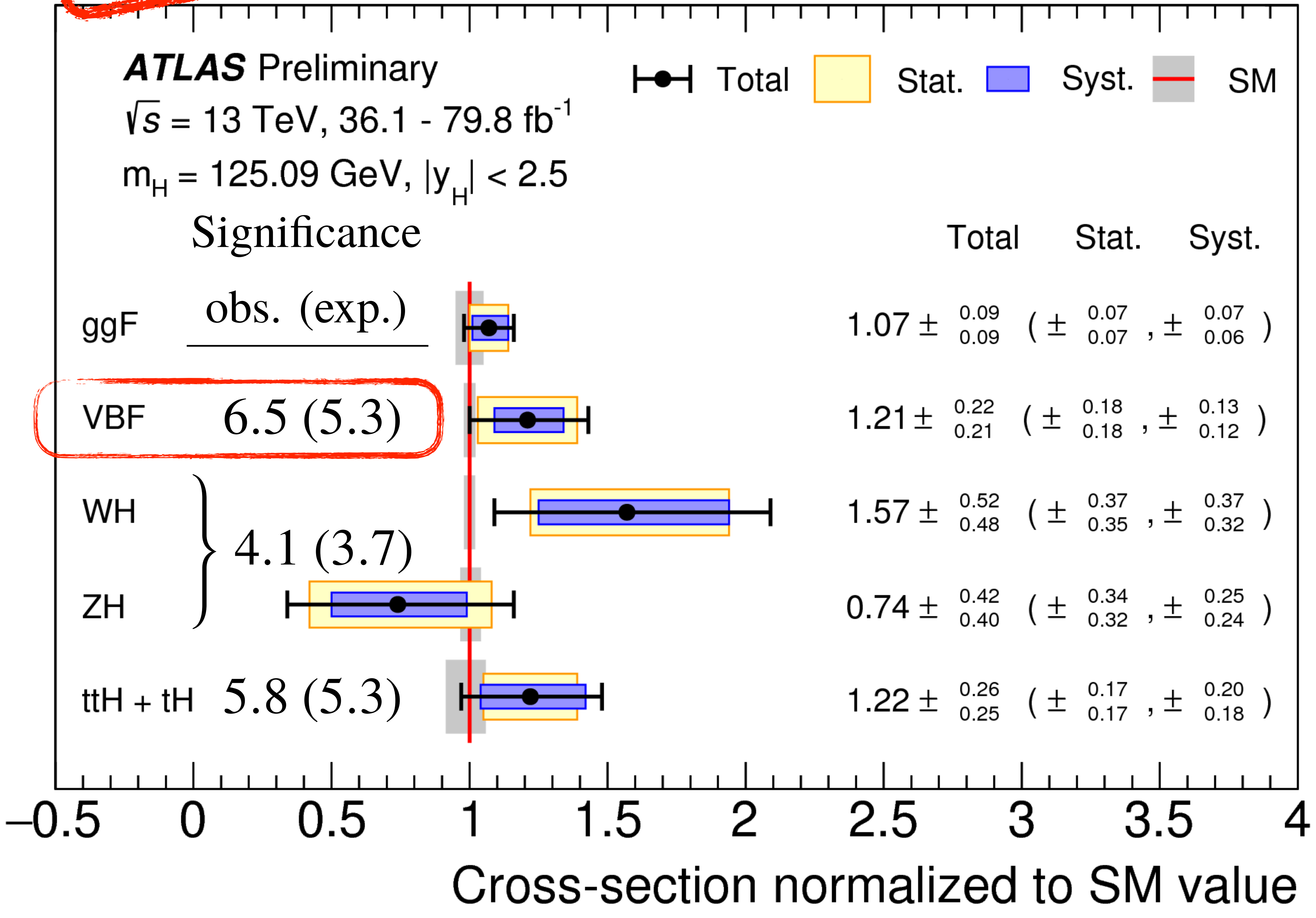


Production and Decay Modes

ATLAS-CONF-2018-031

July 2018

Production Cross-Sections
(assume SM decay BRs)



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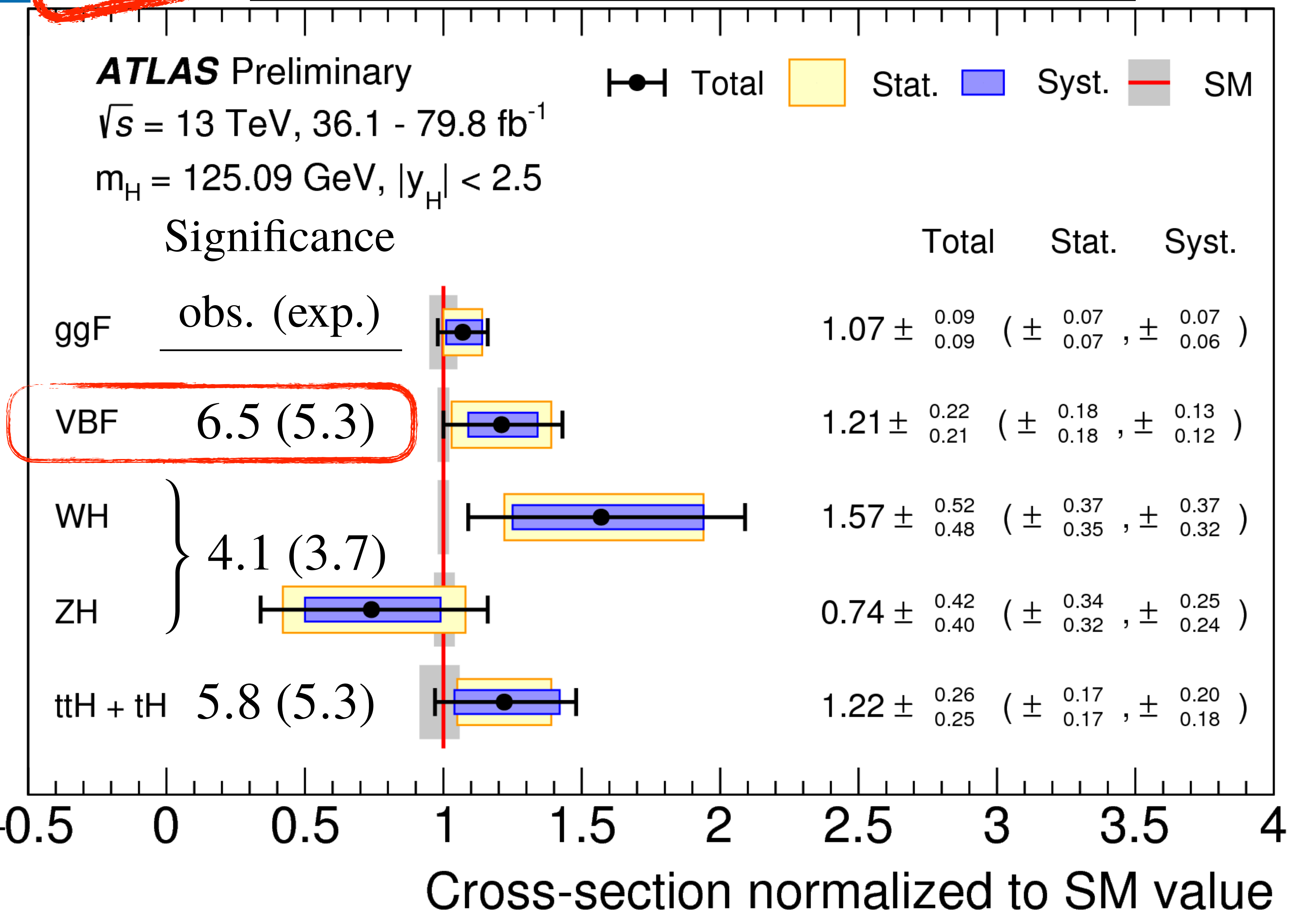

- Define for $i \to H \to f$:

$$\mu_i := \frac{\sigma_i}{(\sigma_i)_{\text{SM}}}$$

$$\mu^f := \frac{\mathcal{B}^f}{(\mathcal{B}^f)_{\text{SM}}}$$

- Signal strength:

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

$$= \frac{\text{observed rate}}{\text{expected rate}}$$

$\Rightarrow$ Includes total signal theory uncertainty!

Production and Decay Modes

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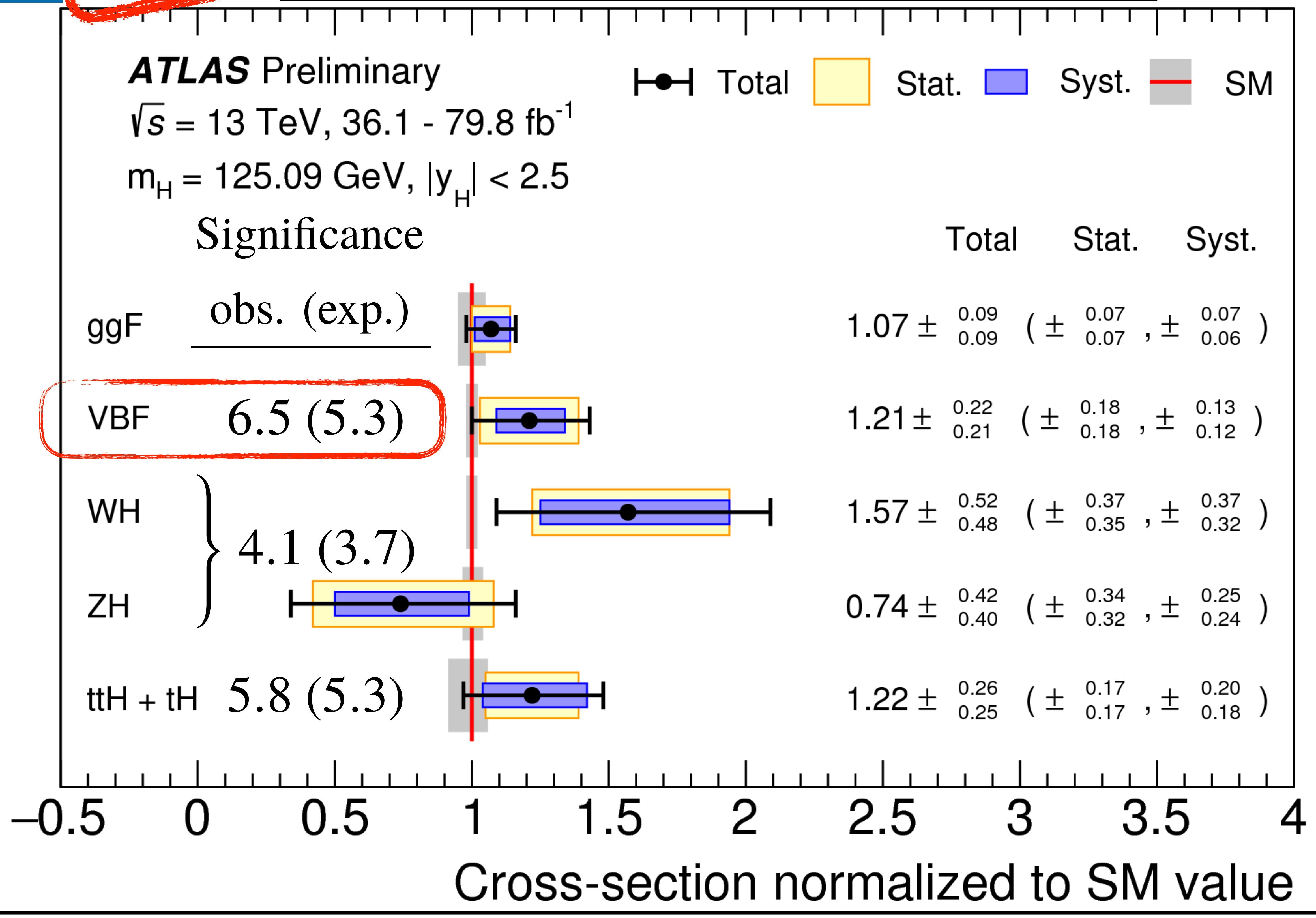
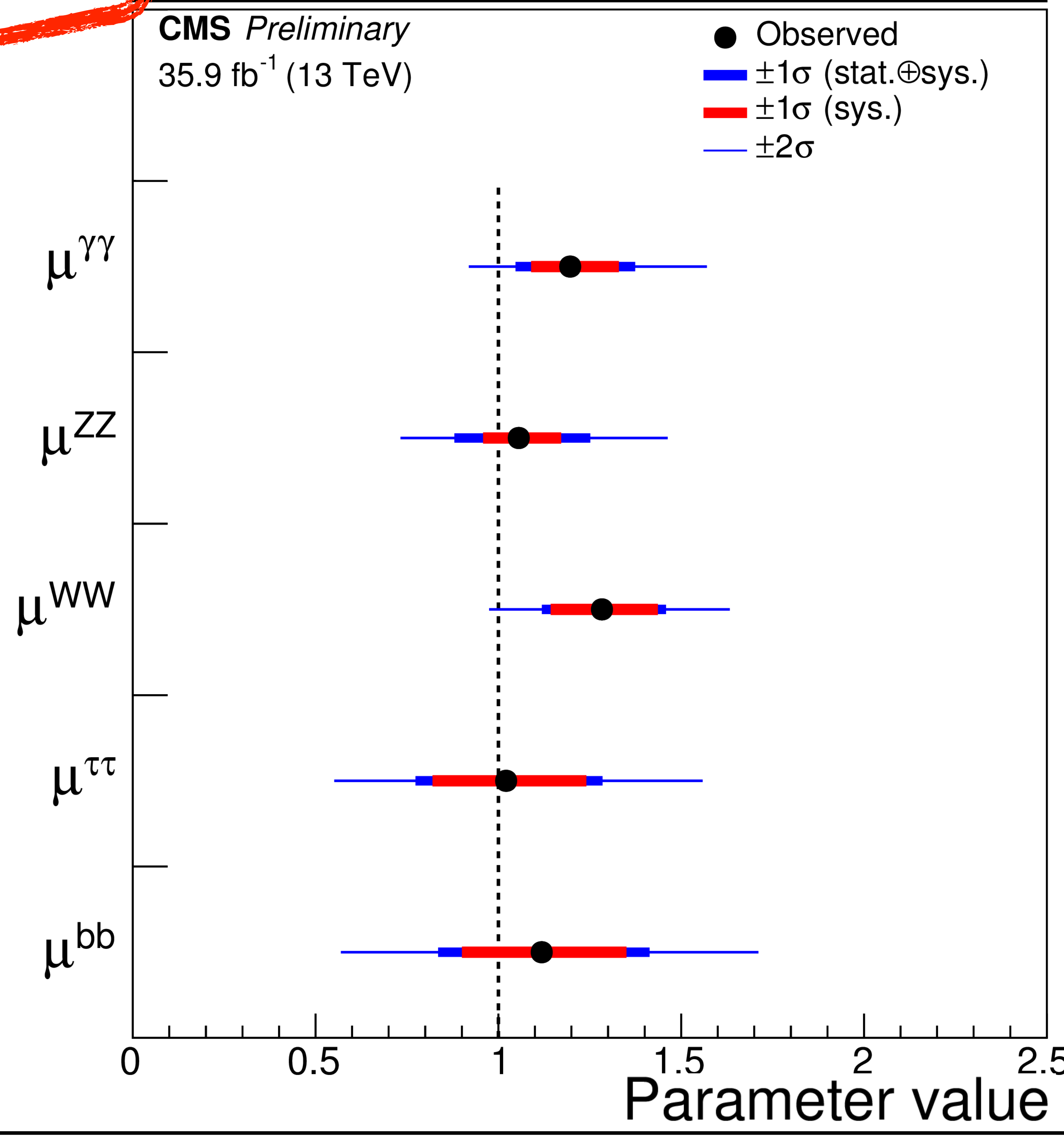


CMS-PAS-HIG-17-031

March 2018

Decay μ

(assume SM production μ_i = 1)



Global signal strength:

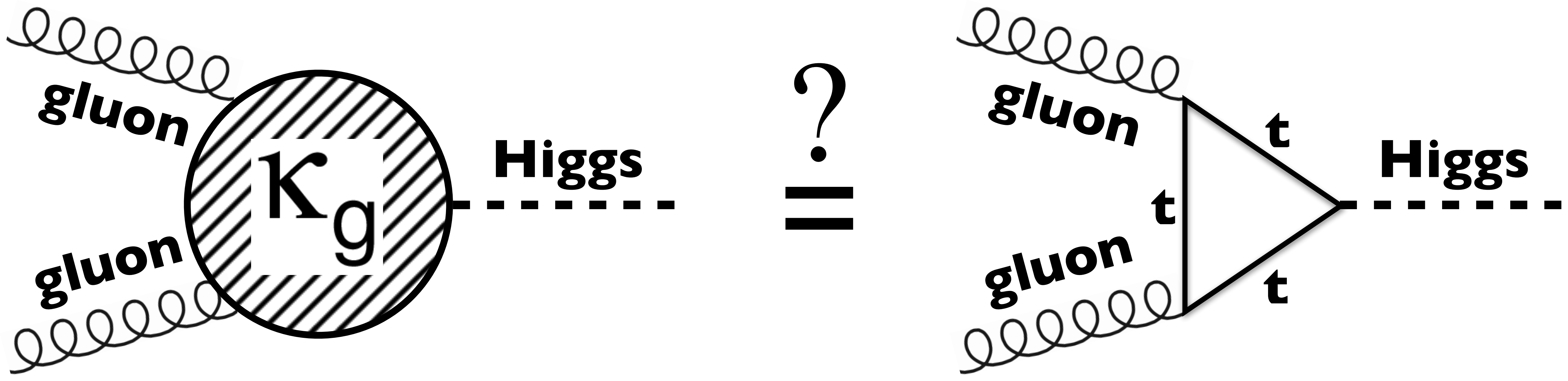
CMS (36 fb^{-1}) $\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$

ATLAS (36-80 fb^{-1}) $\mu = 1.13^{+0.09}_{-0.08} = 1.13 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$

Loop-induced Couplings

- In SM, ggF and H → γγ are loop-induced
  - New Particles could contribute inside loop

⇒ Test effective coupling modifiers to gluons (κ_g) and photons (κ_γ)



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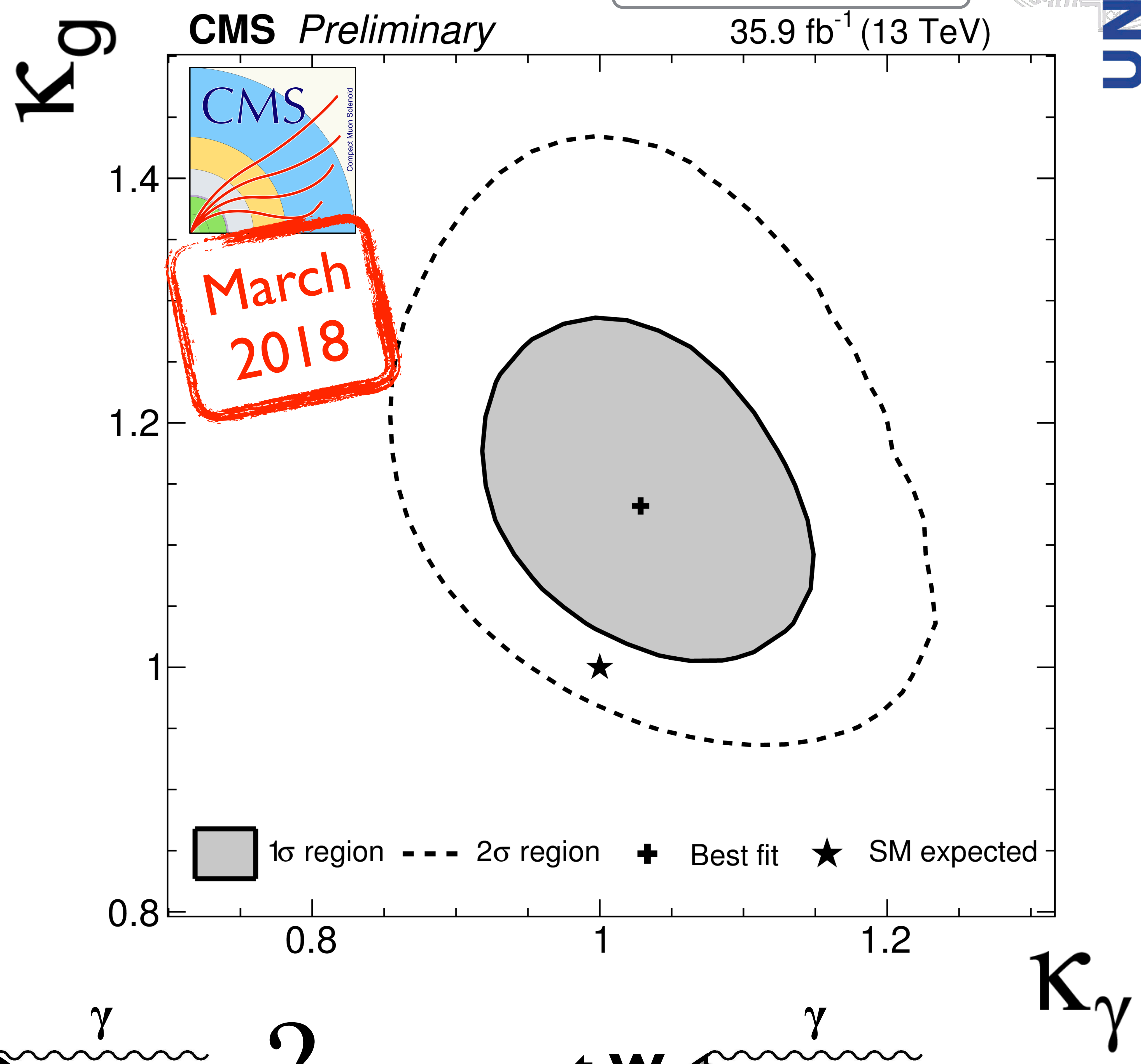

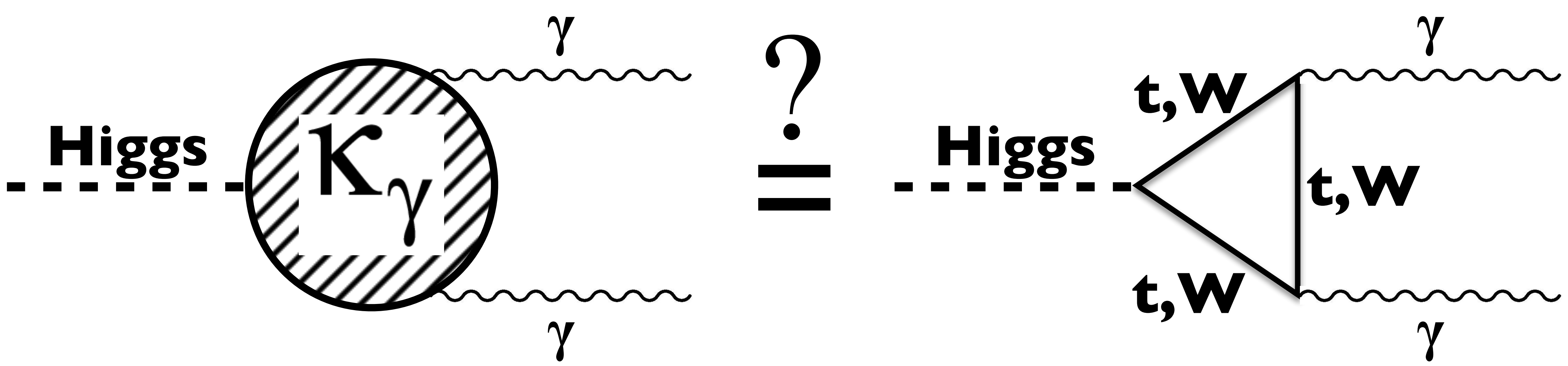

ATLAS EXPERIMENT July 2018 See backup