Combined measurements and interpretations of Higgs production and decay at $\sqrt{s} = 13$ TeV with CMS

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On behalf of the CMS collaboration

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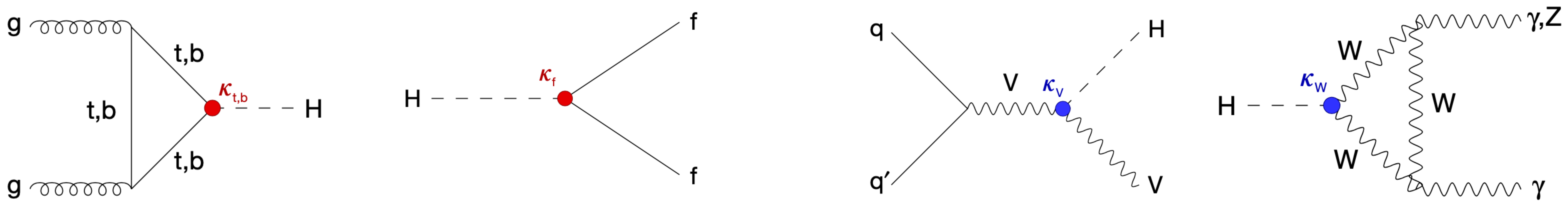
La Thuile | 29/03/2025

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Introduction

- Special place in the SM of particle physics - the only fundamental spin-0 particle in the SM
- Responsible for the mass generation for the vector bosons (spontaneous symmetry breaking) and the fermions (Yukawa interaction)
- Combinations of single Higgs measurements are very powerful
  - **Precise measurements of Yukawa and vector boson couplings**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$



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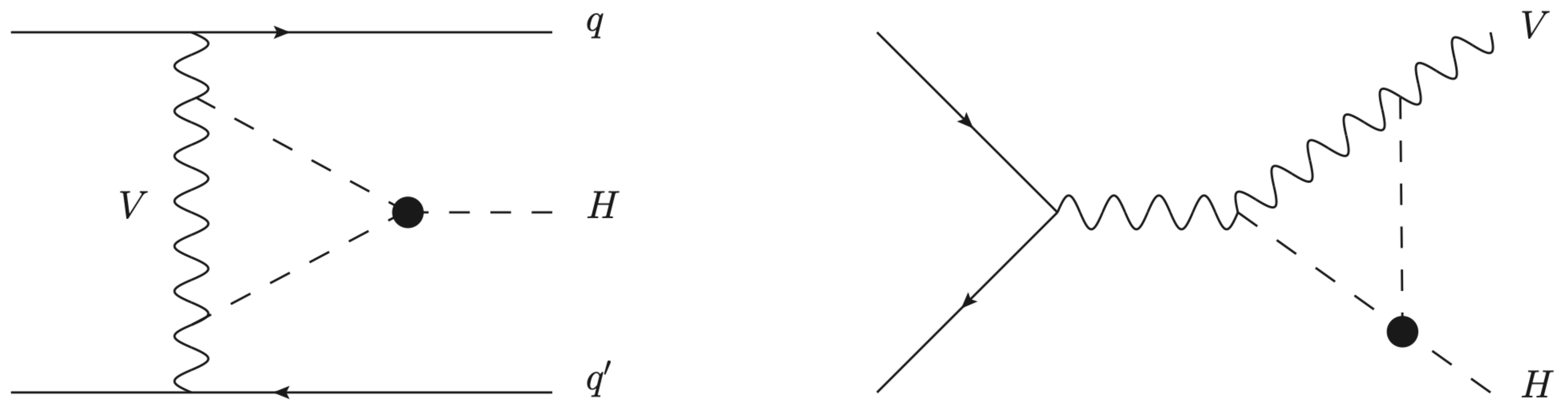
  - **Access to Higgs self coupling through EW corrections** **[Eur. Phys. J. C (2017) 77: 887]**



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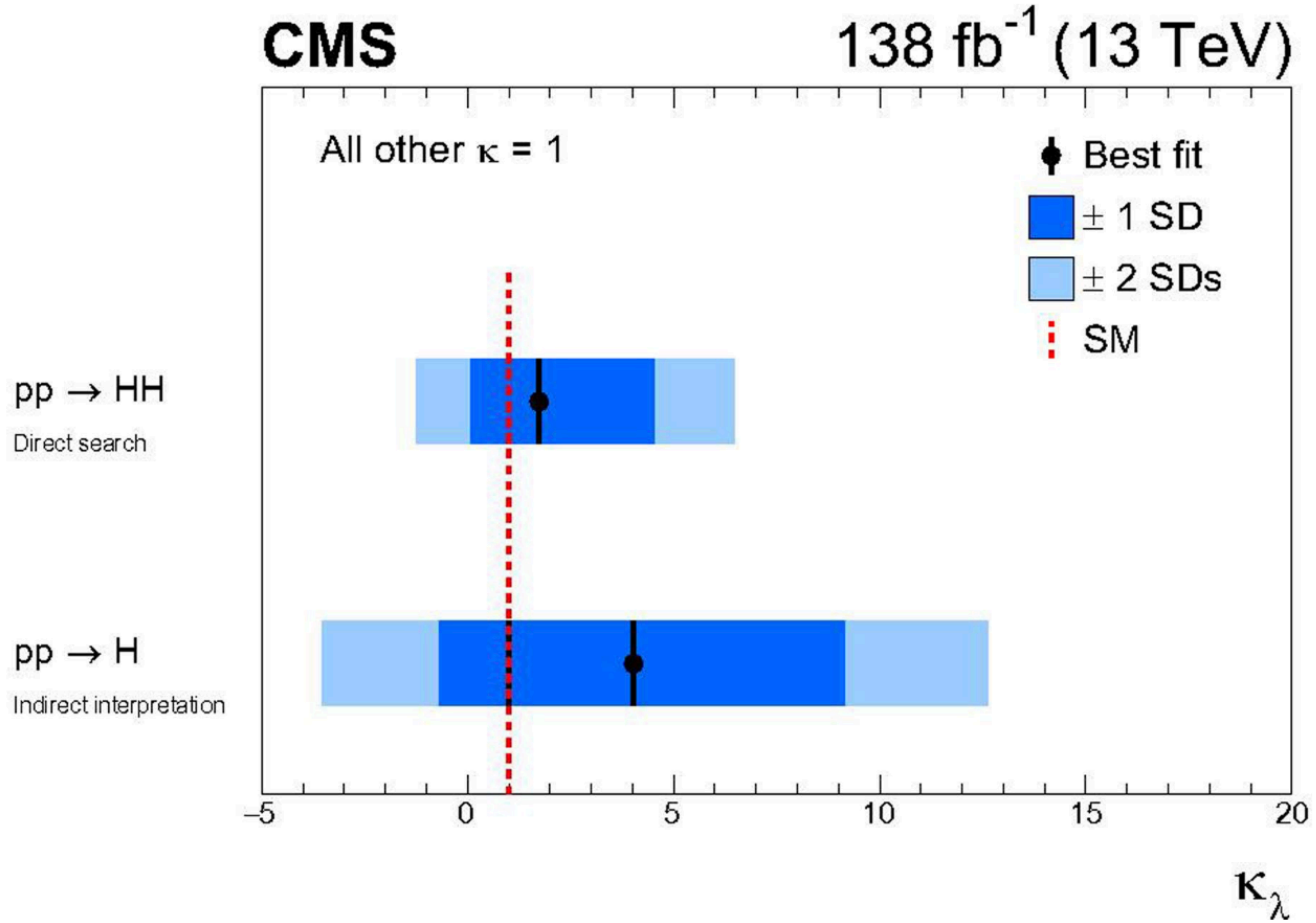

Nature 607, 60–68 (2022)

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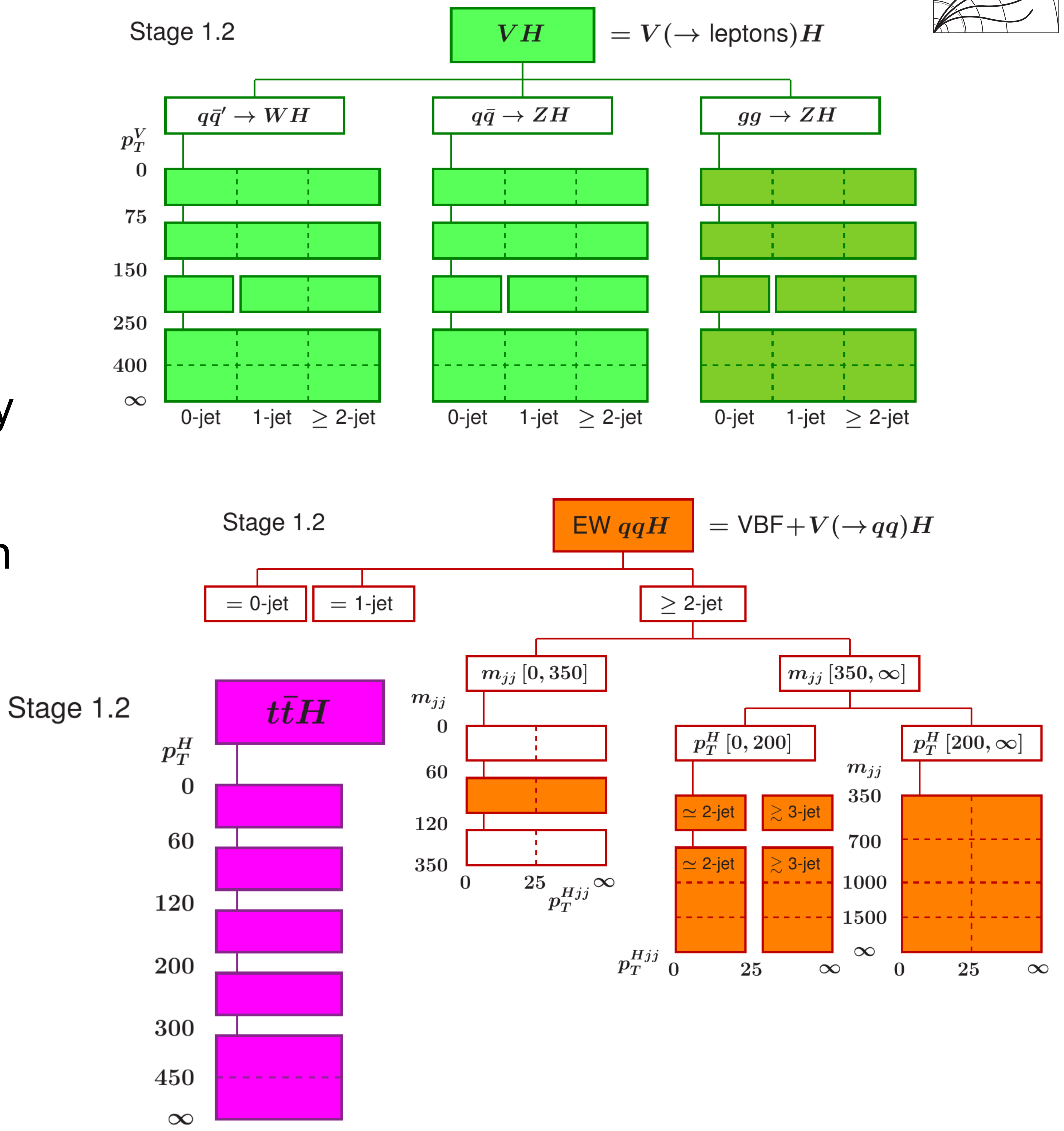

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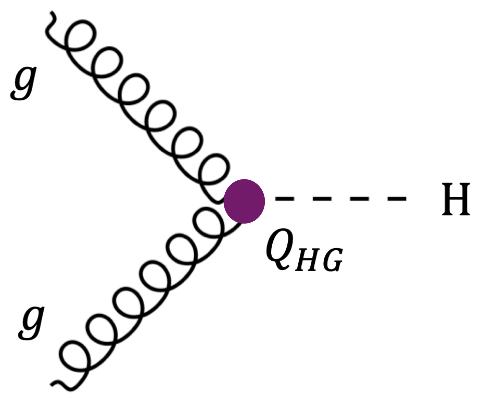
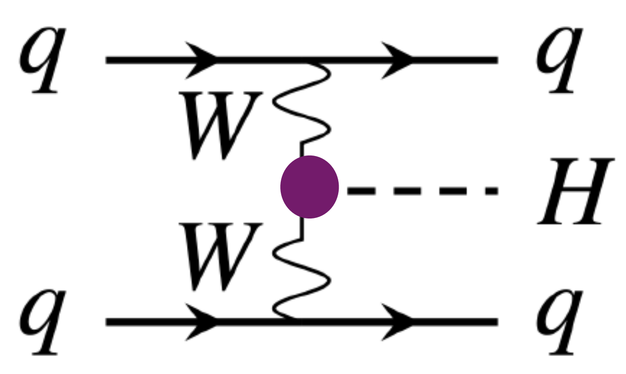
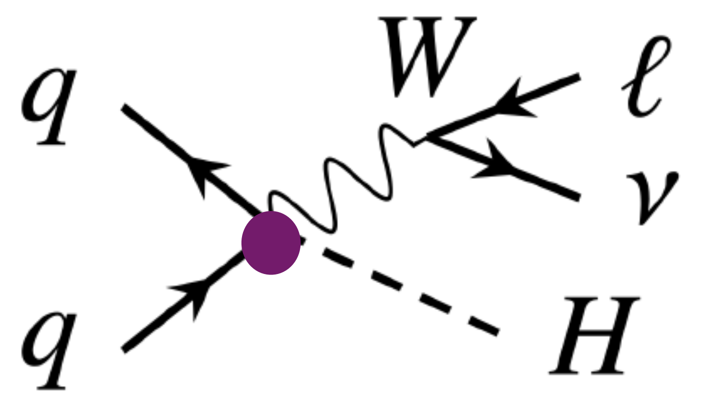
  - Access to Higgs self coupling through EW corrections
  - Differential Higgs production cross sections (STXS)
  - **Model independent searches for BSM with EFT**

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$+ \sum \frac{c_i}{\Lambda^2} O_i^{d=6}$$



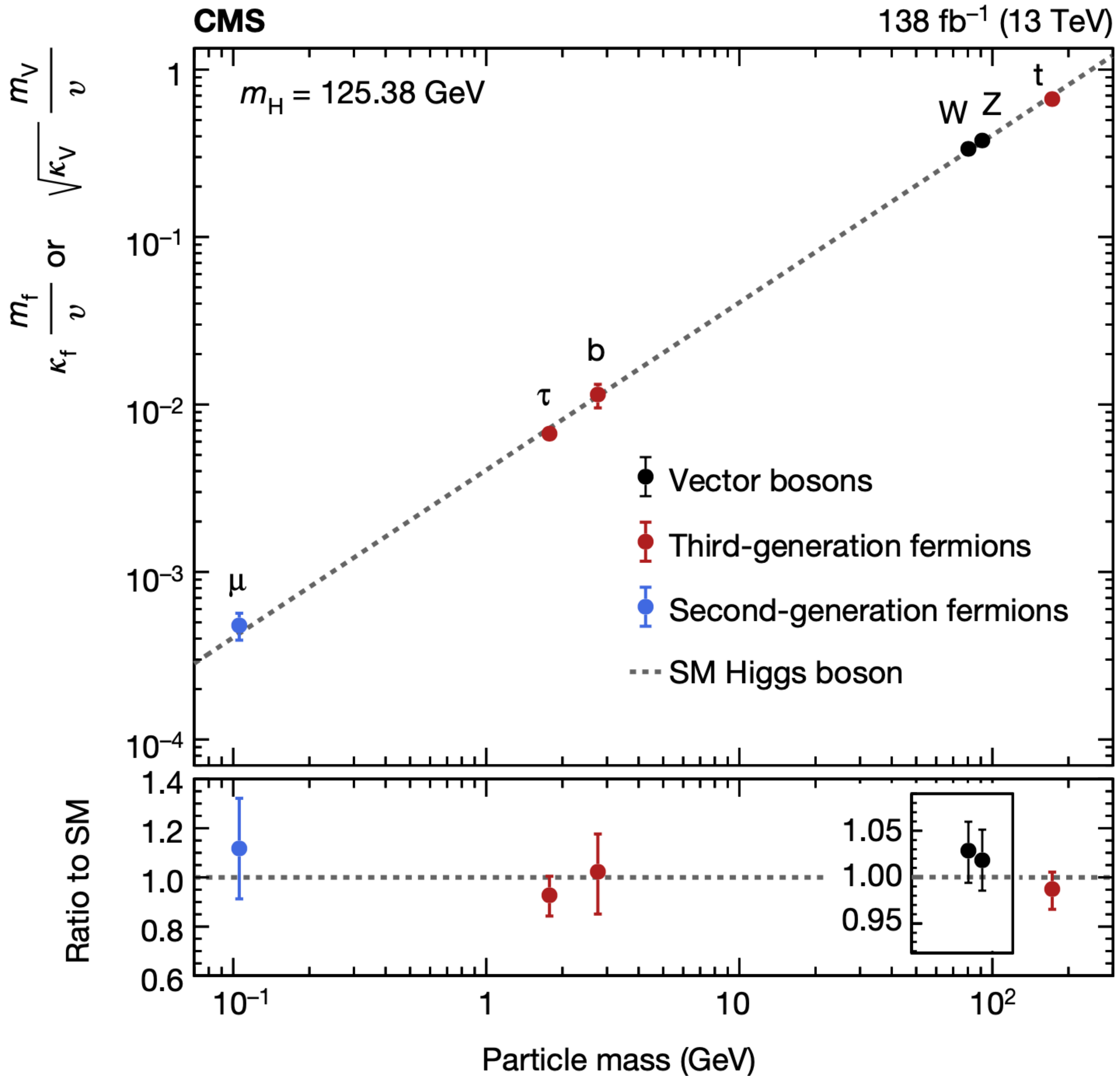




Introduction

In this talk: update of CMS single Higgs results combination since Nature 607, 60–68 (2022)

- Run 2 results ($\sqrt{s} = 13$ TeV, 138 fb^{-1}) are included for all channels
- Signal strength for **all production modes and decay channels**
- Added new interpretations
- **First STXS combination in CMS**
- All results are very fresh, released for Moriond EW, analysis summary will become available early next week [CMS-HIG-21-018]



Nature 607, 60–68 (2022)

Input channels	Update since Nature (2022)	STXS/inclusive	Contributes to	References
$H \to \gamma\gamma$		STXS	μ, κ (all), STXS 0 and 1.2	JHEP 07 (2021) 027
$H \to ZZ$		STXS	μ, κ (all), STXS 0 and 1.2	Eur. Phys. J. C 81 (2021) 488
$H \to WW$		STXS	μ, κ (all), STXS 0 and 1.2	Eur. Phys. J. C 83 (2023) 667
$H \to \tau\tau$		STXS	μ, κ (all), STXS 0 and 1.2	Eur. Phys. J. C 83 (2023) 562
Boosted $H \to b\bar{b}$	**New channel**	STXS	μ, κ (all), STXS 0 and 1.2	JHEP 12 (2024) 035
VBF $H \to b\bar{b}$	**New channel**	inclusive	μ, κ (all), STXS stage 0	JHEP 01 (2024) 173
V$H \to b\bar{b}$	**Updated with full Run 2**	STXS	μ, κ (all), STXS 0 and 1.2	Phys. Rev. D 109 (2024) 092011
$t\bar{t}H \to b\bar{b}$	**Updated with full Run 2**	STXS	μ, κ (all), STXS 0 and 1.2	JHEP 02 (2025) 097
$t\bar{t}H$ multilepton		STXS	μ, κ (all), STXS 0 and 1.2	Eur. Phys. J. C 81 (2021) 378
$H \to \mu\mu$		inclusive	μ, κ (all), STXS stage 0	JHEP 01 (2021) 148
$H \to Z\gamma$		inclusive	μ, κ (all), STXS stage 0	JHEP 05 (2023) 233
$H \to$ inv	**Added ttH and VH-had production channels**	inclusive	Effective κ (w/ $B_{\text{inv}}, B_{\text{undet}}$)	Eur. Phys. J. C 83 (2023) 933
$H \to 4l$ offshell	**New channel**	inclusive	Offshell κ interpretation	arXiv:2409.13663

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Statistical inference

[Comp. Softw. Big Sci. 8 (2024) 19]

Combined likelihood

$$L(\vec{x}; \vec{\alpha}, \vec{\theta}) = \prod_r L_r(\vec{x}; \vec{\alpha}, \vec{\theta}) \prod_l p_l(y_l; \theta_l)$$

Interpretations are performed by scaling the SM predictions with POI equation

$$s_r^{if}(\vec{\alpha}, \vec{\theta}) = \boxed{\mu^{if}(\vec{\alpha})} \cdot \left[\sigma^i \times \mathcal{B}^f\right]_{\mathrm{SM,HO}}(\vec{\theta}_{\mathrm{th,norm}}) \cdot \epsilon^{if}_{r,\mathrm{SM}}(\vec{\theta}_{\mathrm{th,acc}}, \vec{\theta}_{\mathrm{exp}}) \cdot \mathscr{L}(\vec{\theta}_{\mathrm{lumi}})$$

$\vec{\alpha}$: signal strengths μ, Higgs couplings modifiers κ, SMEFT parameters c_i

Parameter estimation

$$q(\vec{x}; \vec{\alpha}) = -2\ln\left(\frac{L(\vec{x}; \vec{\alpha}, \hat{\hat{\vec{\theta}}}_{\vec{\alpha}})}{L(\vec{x}; \hat{\vec{\alpha}}, \hat{\vec{\theta}})}\right);$$

SM compatibility p-value

$$p_{SM} = 1 - F_{\chi^2_n}(q(\vec{\alpha}_{SM}))$$

Inclusive signal strength μ

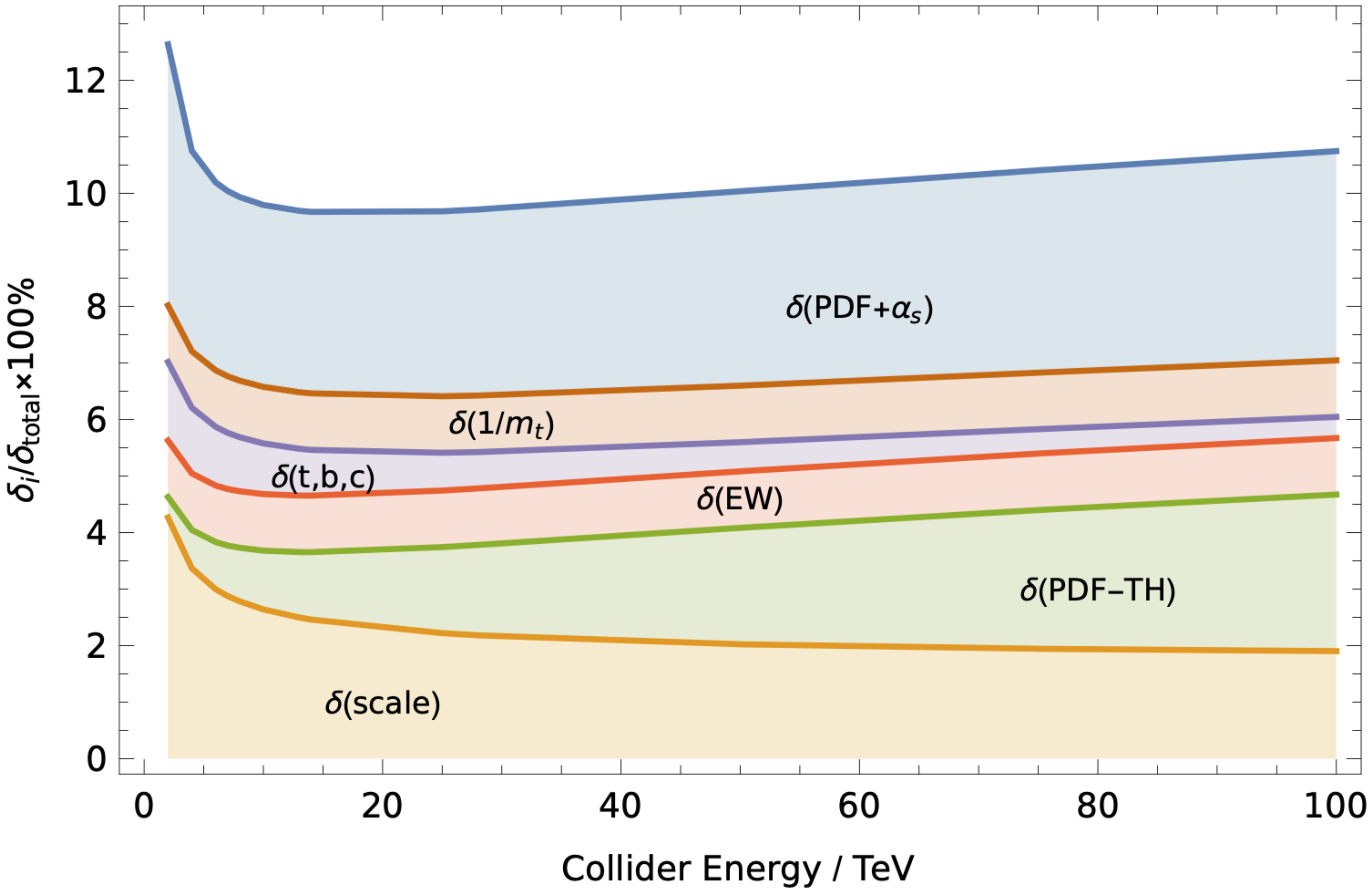
- The most constraining fit (single parameter linearly scaling all onshell and SM input channels)

$$\mu = 1.014^{+0.055}_{-0.053} = 1.014^{+0.040}_{-0.039}(\text{theory})^{+0.025}_{-0.024}(\text{exp}) \pm 0.028(\text{stat})$$

SM compatibility p-value

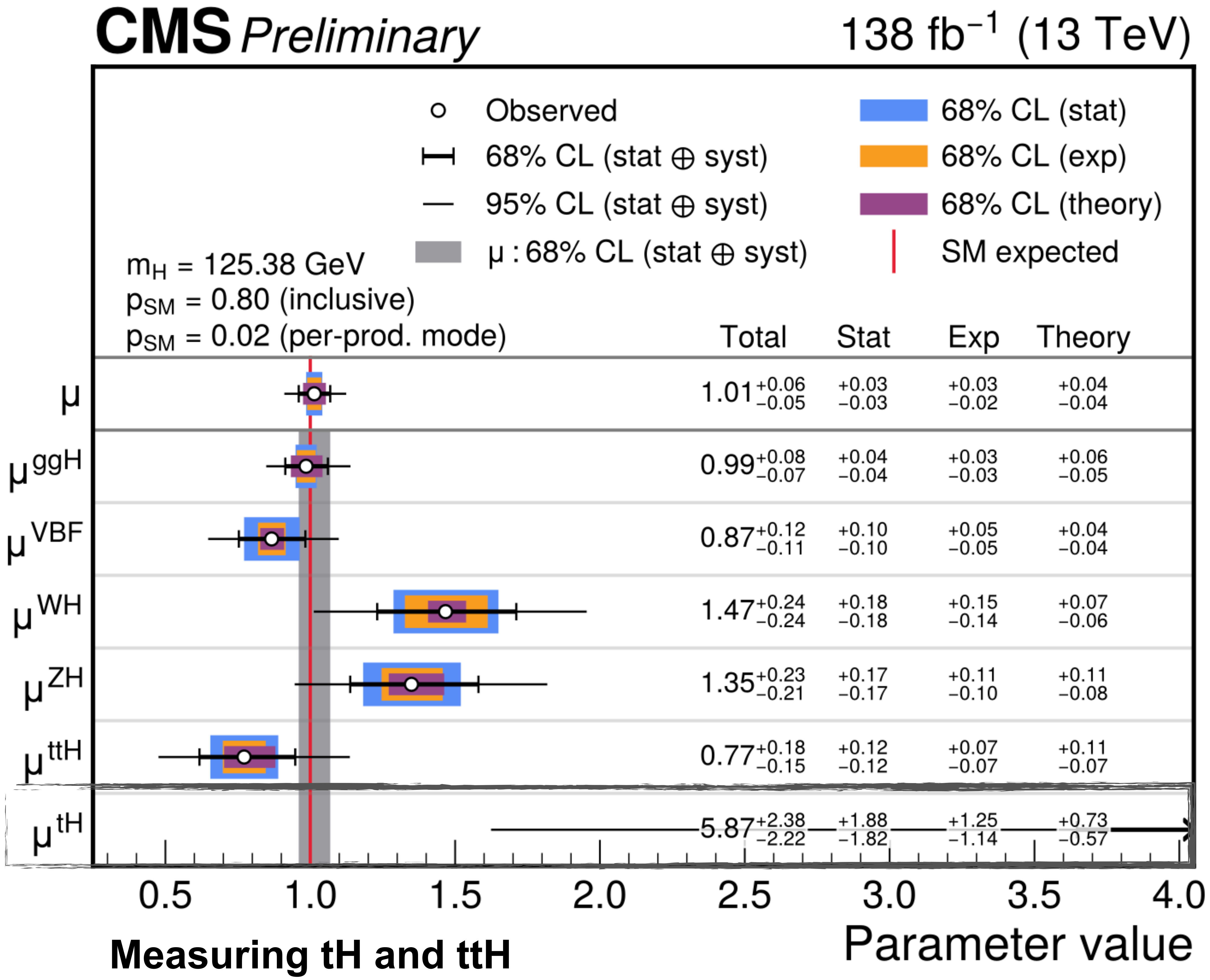
$$p_{SM} = 1 - F_{\chi^2_n}(q(\vec{\alpha}_{\rm SM})) = 0.80$$

- Total uncertainty is dominated by theoretical uncertainty on the Higgs production (μ_R, μ_F variations)
- Leading sources of experimental uncertainty are due to background modeling and simulation statistics



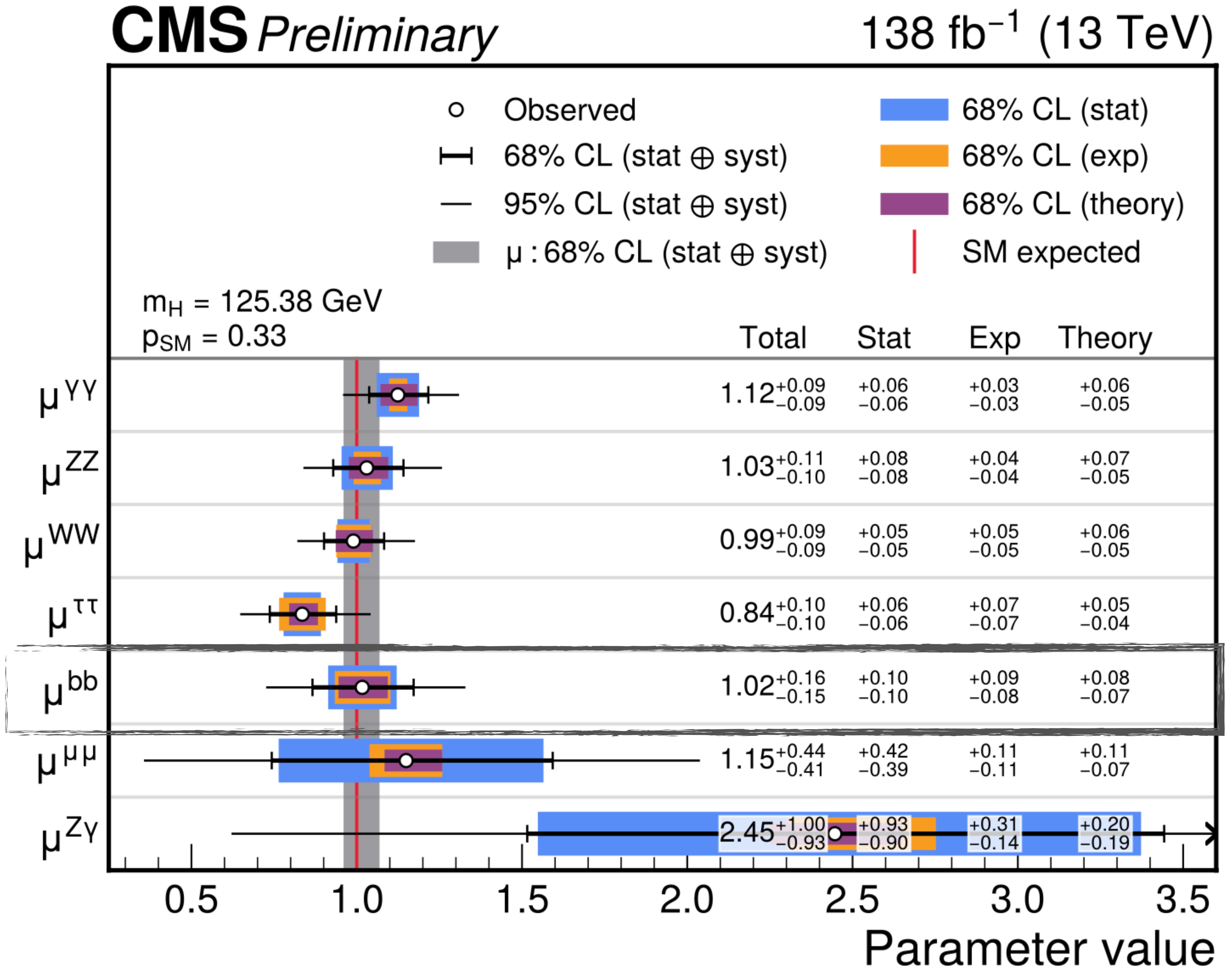
Production and decay signal strengths μ^i and μ_f

Assigned POI for each production mode μ^i, p_{SM} = 2%



Measuring tH and ttH separately for the first time

For each decay channel μ_f , p_{SM} = 33%



Production × decay signal strengths $\mu^{i,f}$

[CMS-HIG-21-018]

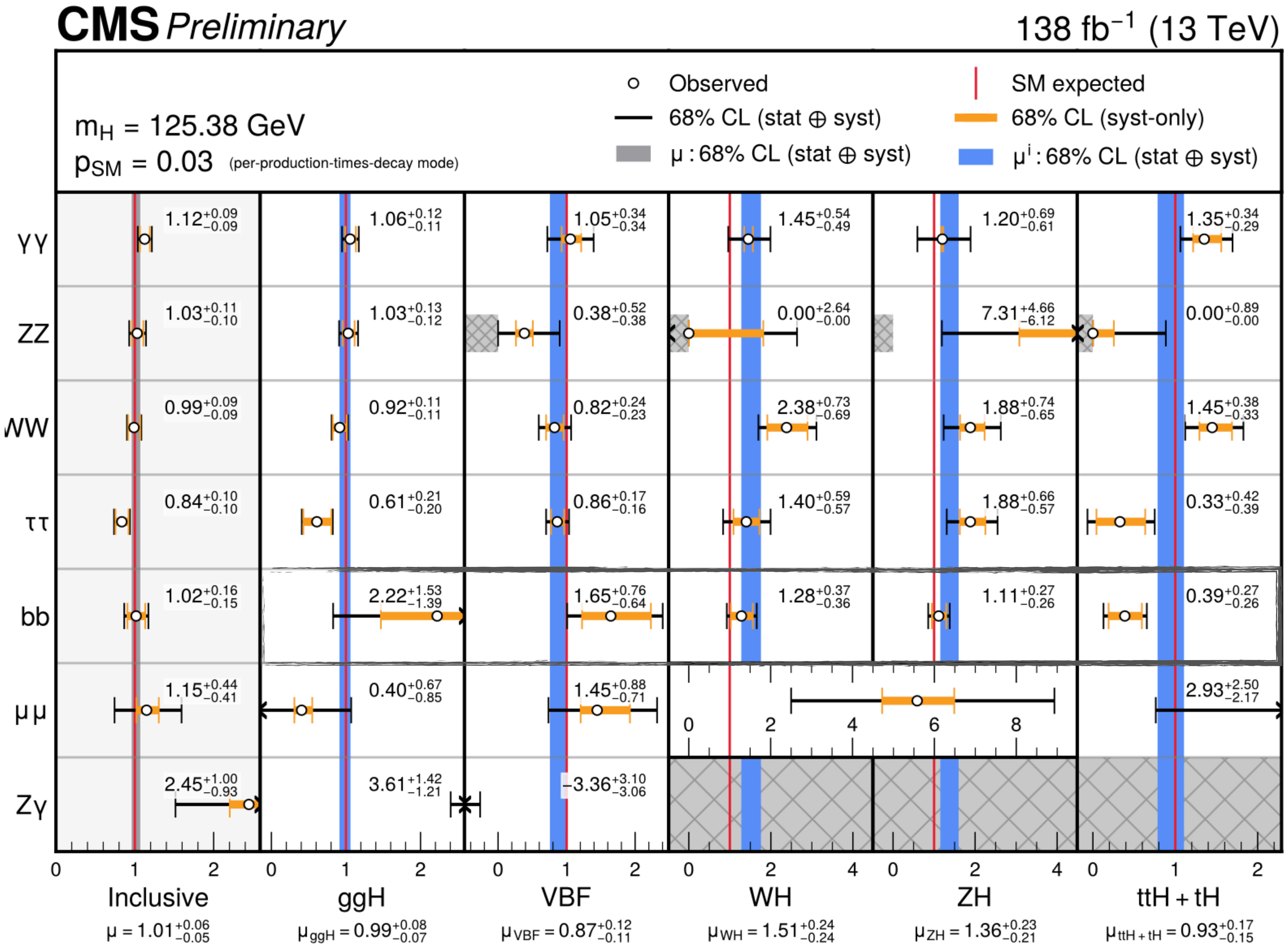
Assigned parameters linearly scaling the predicted yields for each decay channel and production mode

$$\mu^{i,f}(\vec{\alpha}) = \mu^{i,f}$$

New/updated channels:

$H \rightarrow b\bar{b}$ in VBF, tt̄H, ggH, VH production modes

p_{SM} = 3 %



STXS stage 1.2 measurements

[CMS-HIG-21-018]

First STXS combination in CMS

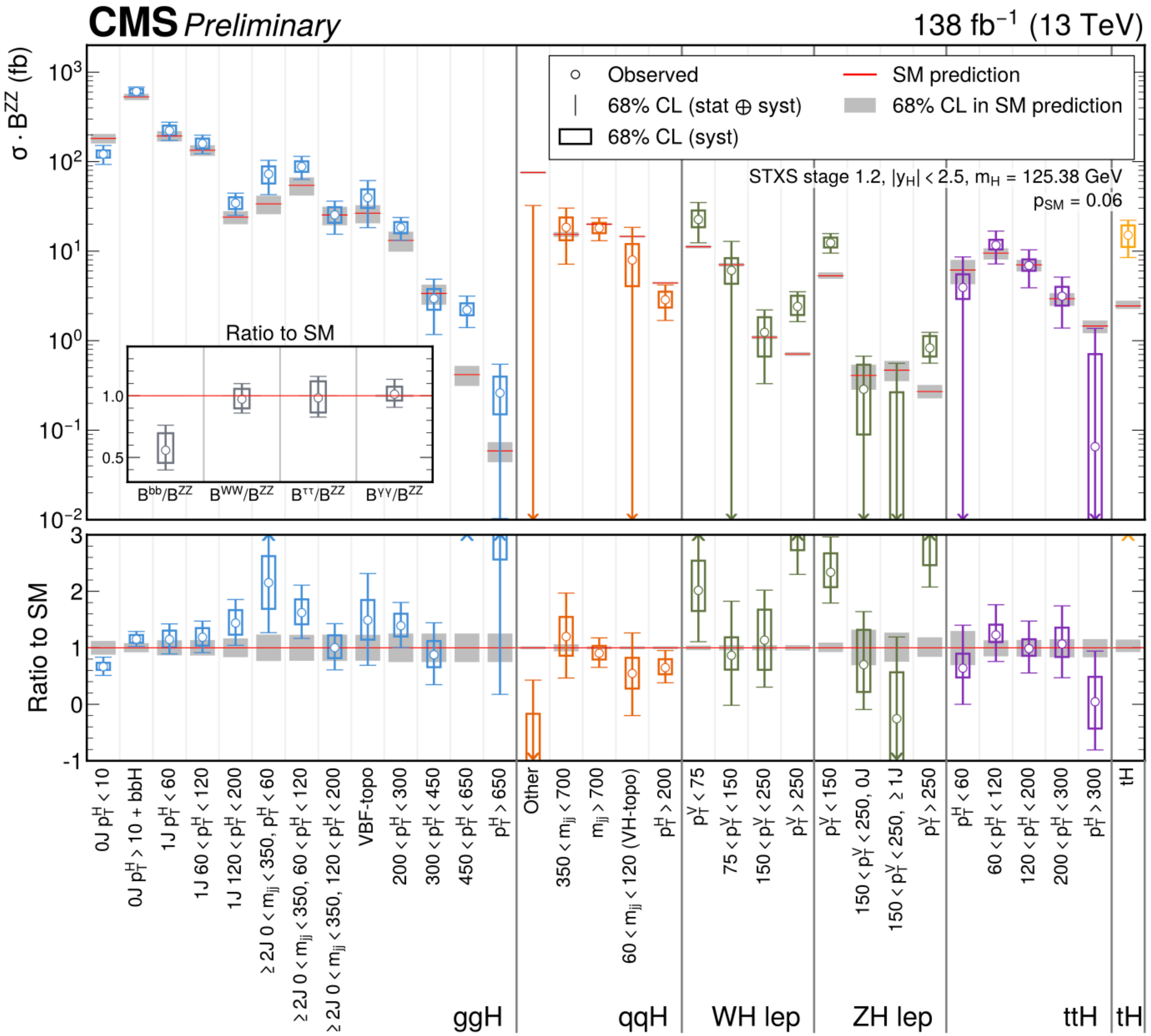
- Extracting differential Higgs production cross sections with STXS (32 parameters)
- To avoid SM assumptions for BF extending the fit to extract the Higgs decay branching fraction ratios wrt $H \rightarrow ZZ$ (+ 4 parameters)

$$\mu^{i,ZZ} = \frac{\left[\sigma^i \times \mathcal{B}^{ZZ}\right]_{obs}}{\left[\sigma^i \times \mathcal{B}^{ZZ}\right]_{\mathrm{SM,HO}}(\vec{\theta}'_{\mathrm{th,norm}})}$$

- For all other channels

$$\mu^{i,f} = \mu^{i,ZZ} \cdot R^{f/ZZ} \qquad R^{f/ZZ} = \frac{\mathcal{B}^f_{\mathrm{obs}} / \mathcal{B}^f_{\mathrm{SM,HO}}(\vec{\theta}'_{\mathrm{th,norm}})}{\mathcal{B}^{ZZ}_{\mathrm{obs}} / \mathcal{B}^{ZZ}_{\mathrm{SM,HO}}(\vec{\theta}'_{\mathrm{th,norm}})}$$

p_{SM} = 6 %



Interpretations with κ framework

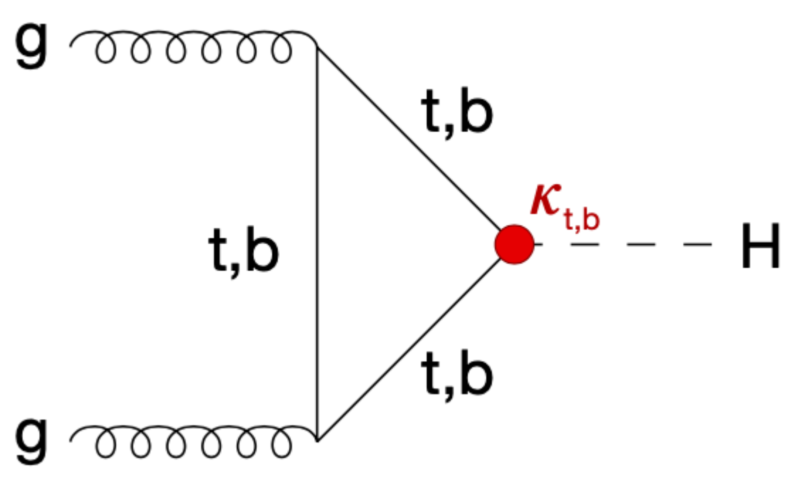
[CMS-HIG-21-018]

$$\mu^{i,f}(\vec{\kappa}) = \sigma^i(\vec{\kappa}) \cdot \mathcal{B}^f(\vec{\kappa})$$

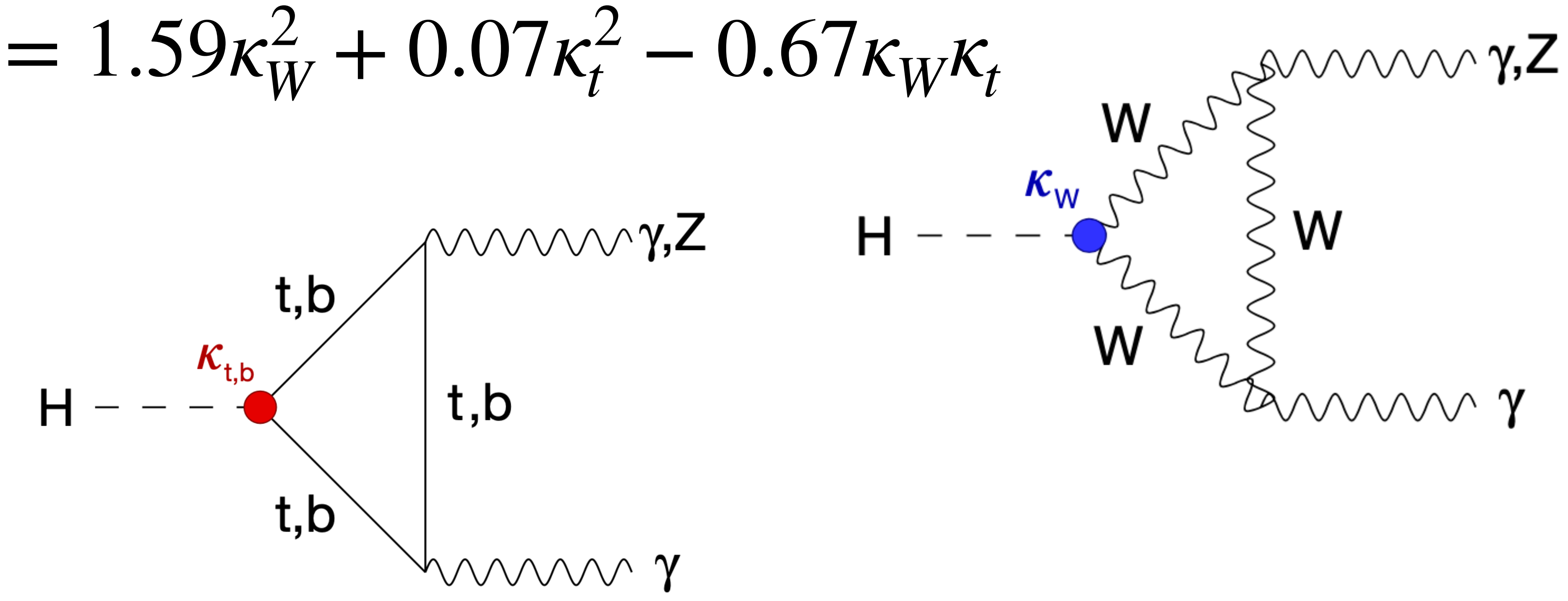
$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \text{ or } \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

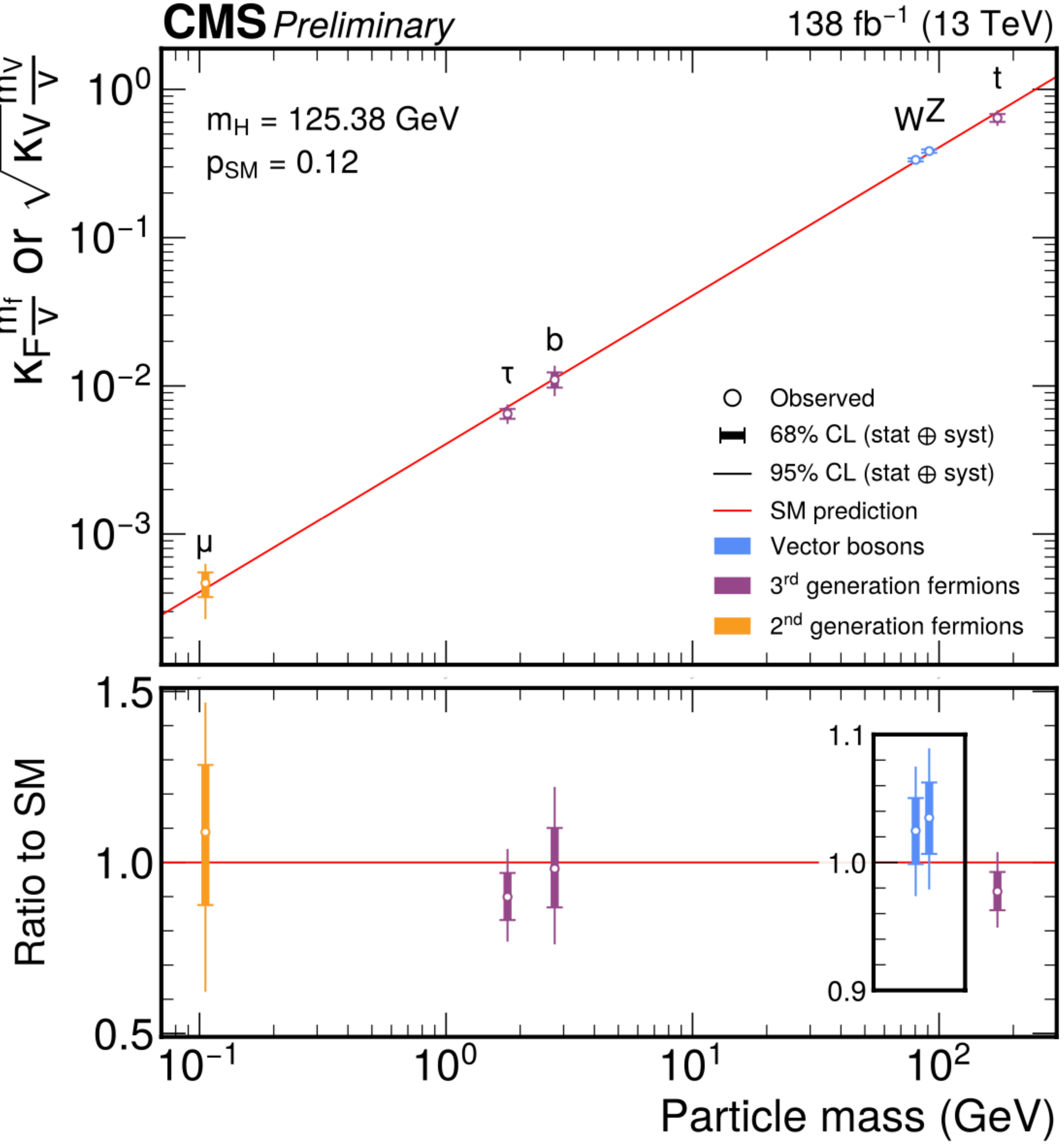
For loop processes ggH, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ including contributions from SM particles only

$$\mu^{ggH} = 1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$$



$$\mu^{H\rightarrow\gamma\gamma} = 1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$$



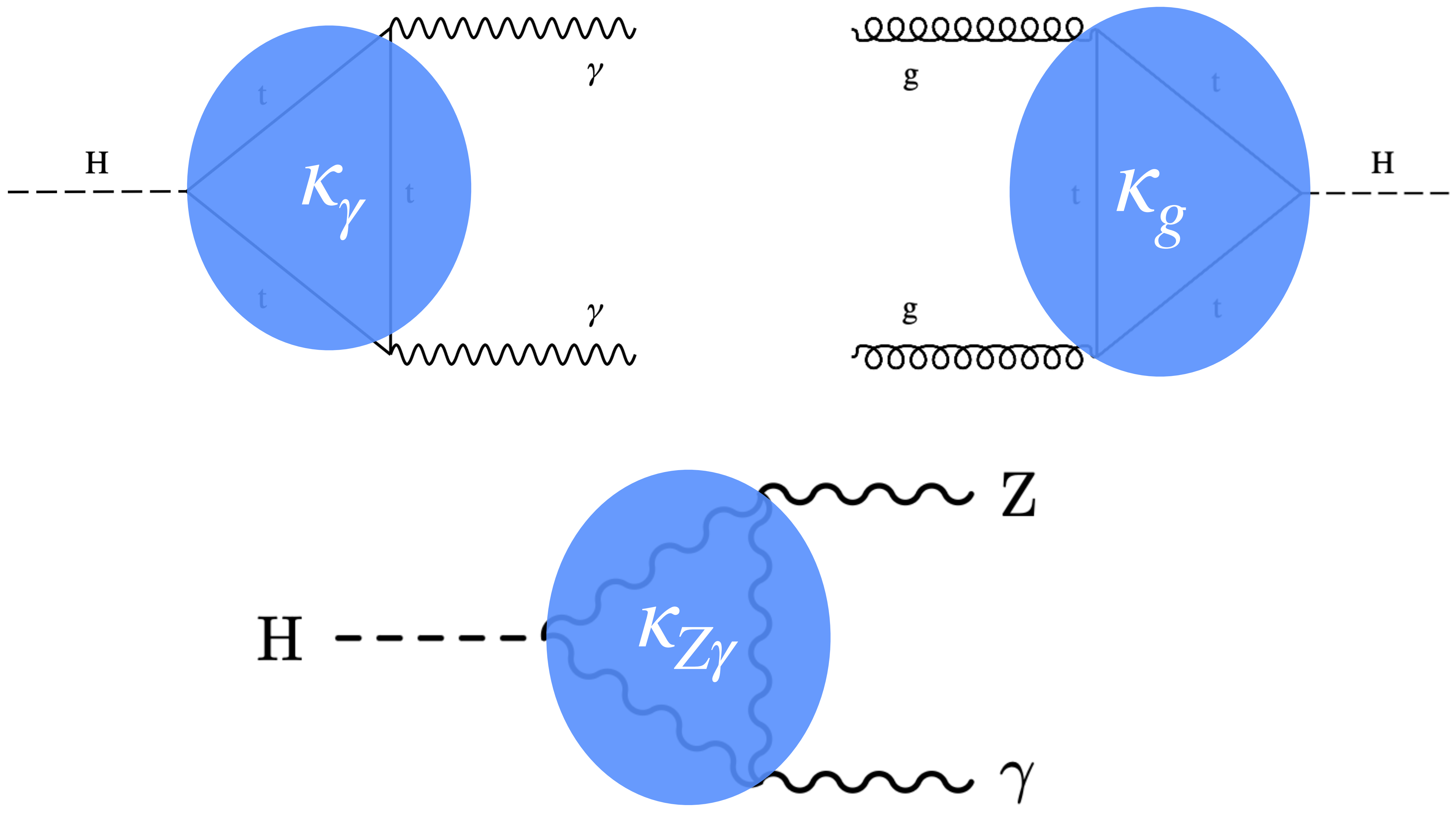


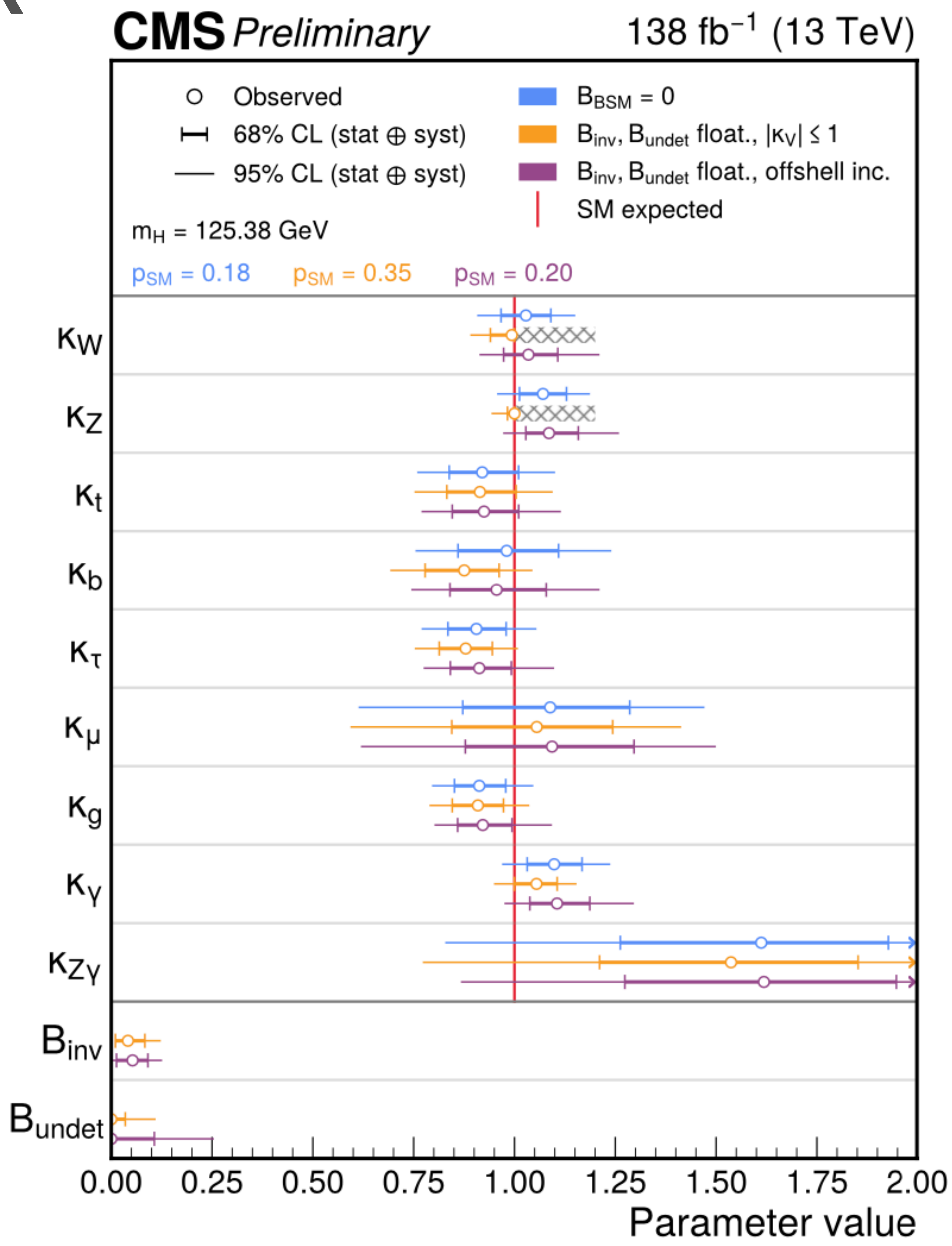
Interpretations with κ framework

[CMS-HIG-21-018]

$$\mu^{i,f}(\vec{\kappa}) = \sigma^i(\vec{\kappa}) \cdot \mathcal{B}^f(\vec{\kappa}) \quad \kappa_j^2 = \sigma_j/\sigma_j^{SM} \text{ or } \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

Add effective couplings κ_g, κ_γ, $\kappa_{Z\gamma}$ to scale ggH, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ effective vertices. p_{SM} = 18 %





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Add effective couplings κ_g, κ_γ, $\kappa_{Z\gamma}$ to scale ggH, $H \to \gamma\gamma$, $H \to Z\gamma$ effective vertices. p_{SM} = 18 %

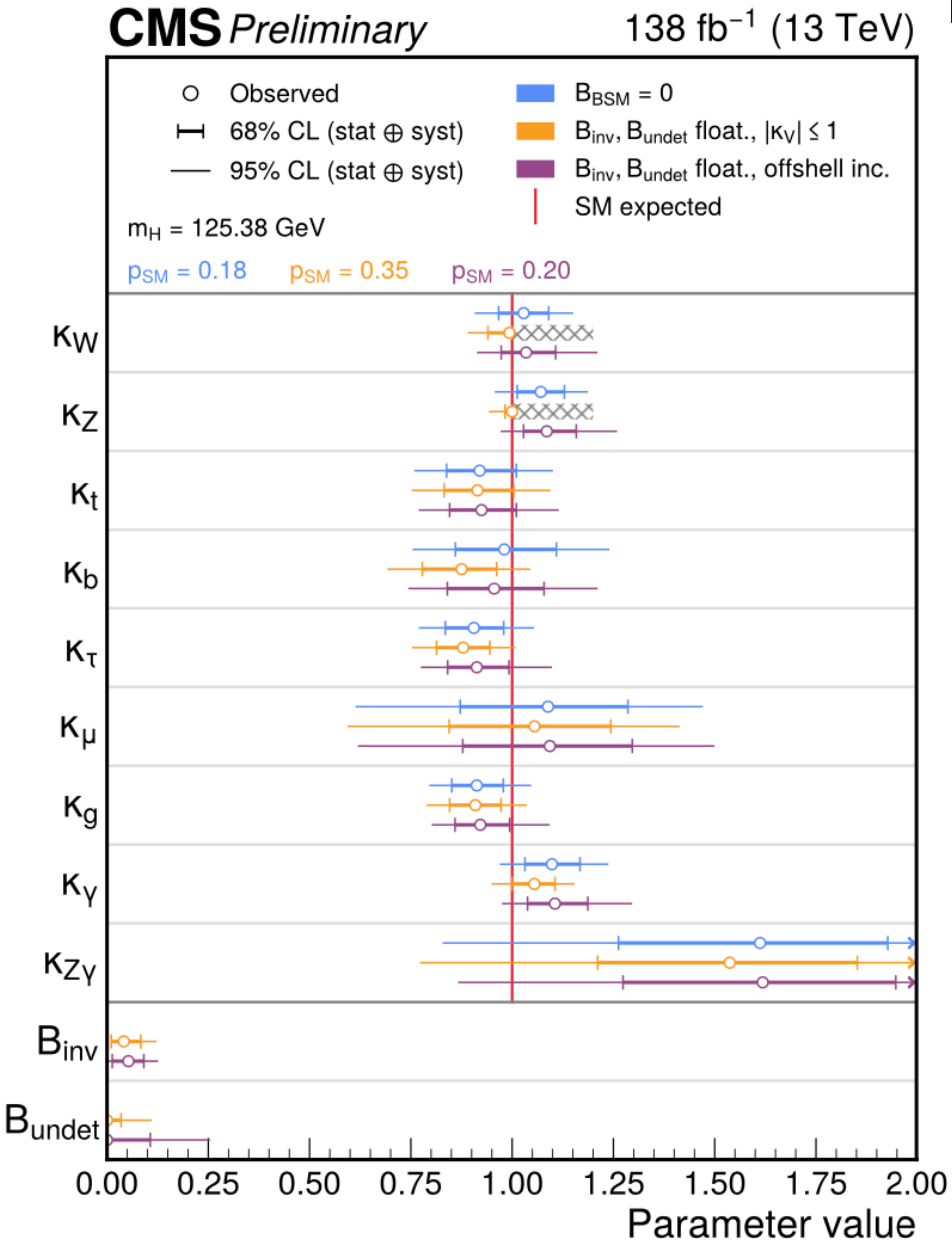
With $H \to$ inv channel: B_{inv}, B_{undet} are included

$$\frac{\Gamma_H}{\Gamma_{H,SM}} = \frac{\kappa_H^2}{1-(B_{\text{inv}}+B_{\text{undet}})} = \frac{\sum BF^i \times \kappa_i^2}{1-(B_{\text{inv}}+B_{\text{undet}})}$$

Invisible decays characterized by p_T^{miss} (DM, other neutral BSM particles). In SM $B_{\text{inv}} = 0.1\ \%$ from $H \to ZZ^* \to 4\nu$

Other undetected decays not associated with p_T^{miss}, due to the lack of dedicated channels

$\kappa_V \leq 1$ assumption is needed to resolve total width scaling degeneracy due to B_{undet}; p_{SM} = 35 %



Interpretations with κ framework

[CMS-HIG-21-018]

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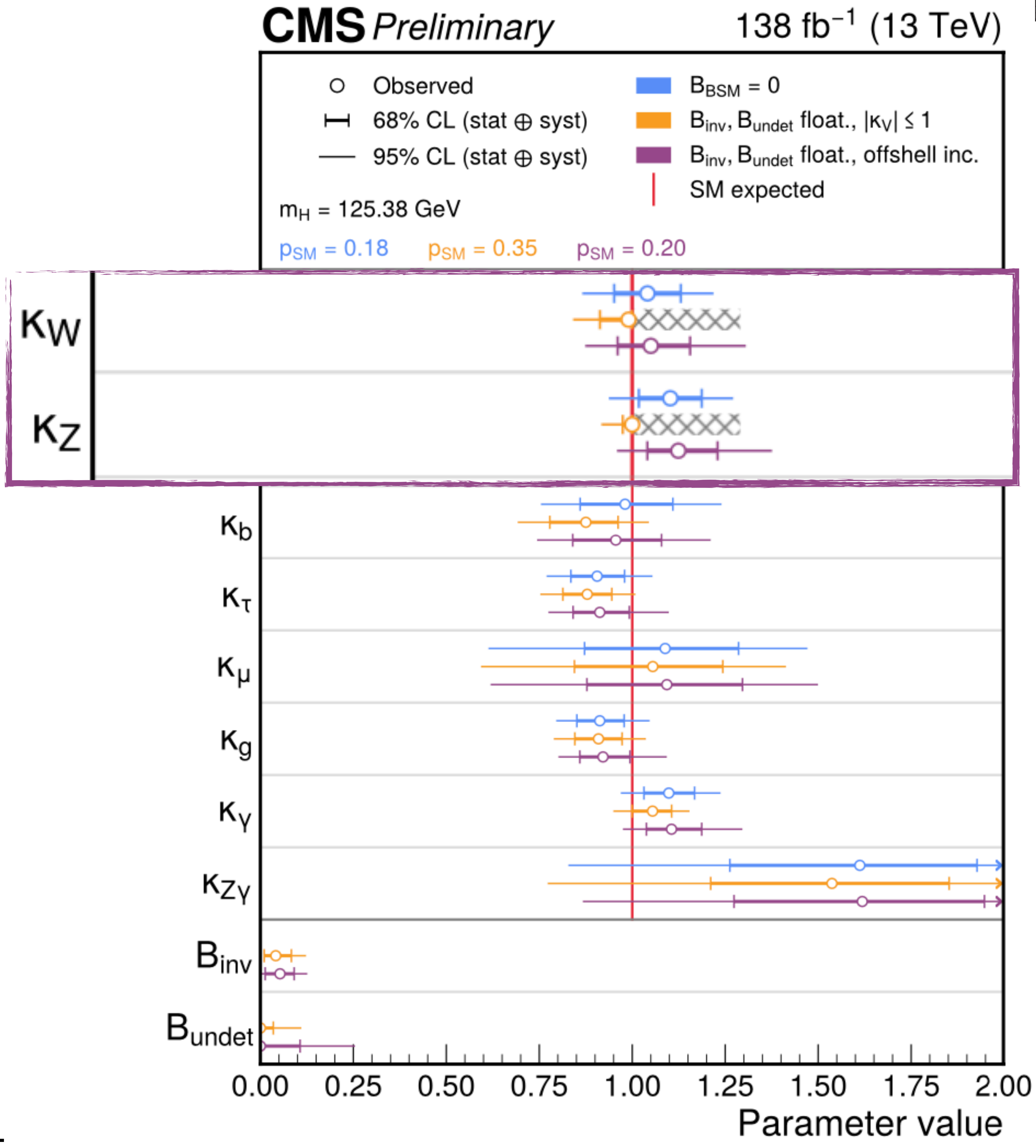
Add effective couplings κ_g, κ_γ, $\kappa_{Z\gamma}$ to scale ggH, $H \to \gamma\gamma$, $H \to Z\gamma$ effective vertices. p_{SM} = 18 %

With $H \to$ inv channel: B_{inv}, B_{undet} are included

$$\frac{\Gamma_H}{\Gamma_{H,SM}} = \frac{\kappa_H^2}{1-(B_{\text{inv}}+B_{\text{undet}})}$$

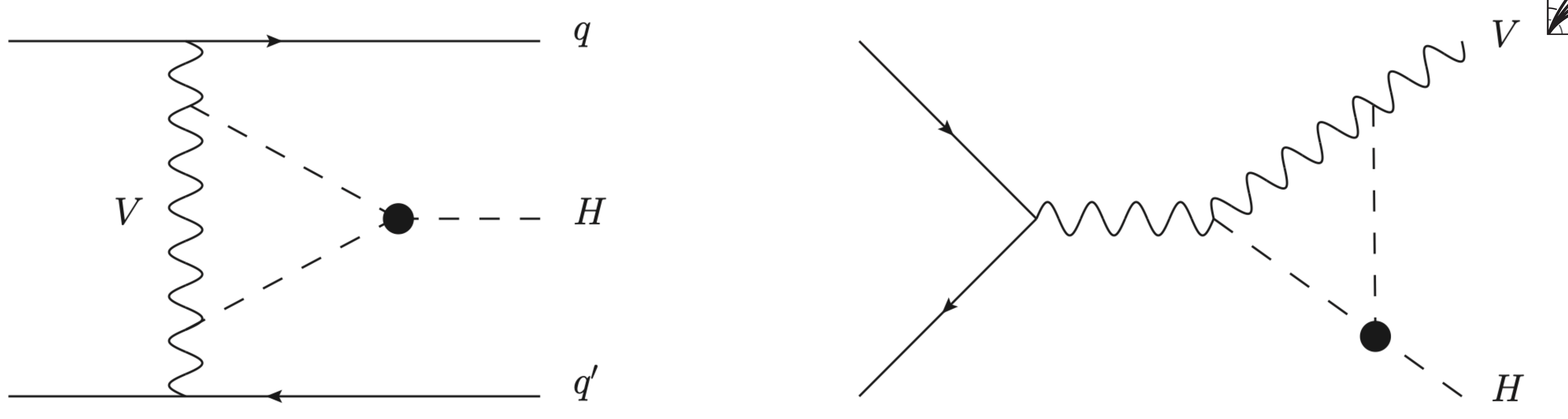
With inclusion H → 4l offshell analysis allows to release $\kappa_V \leq 1$ constraint and B_{inv}, B_{undet} at the same time (due to difference in dependence on $\kappa_{W,Z}$ for offshell and onshell Higgs production)

New since Nature 607, 60–68 (2022)



Constraints on Higgs self-coupling

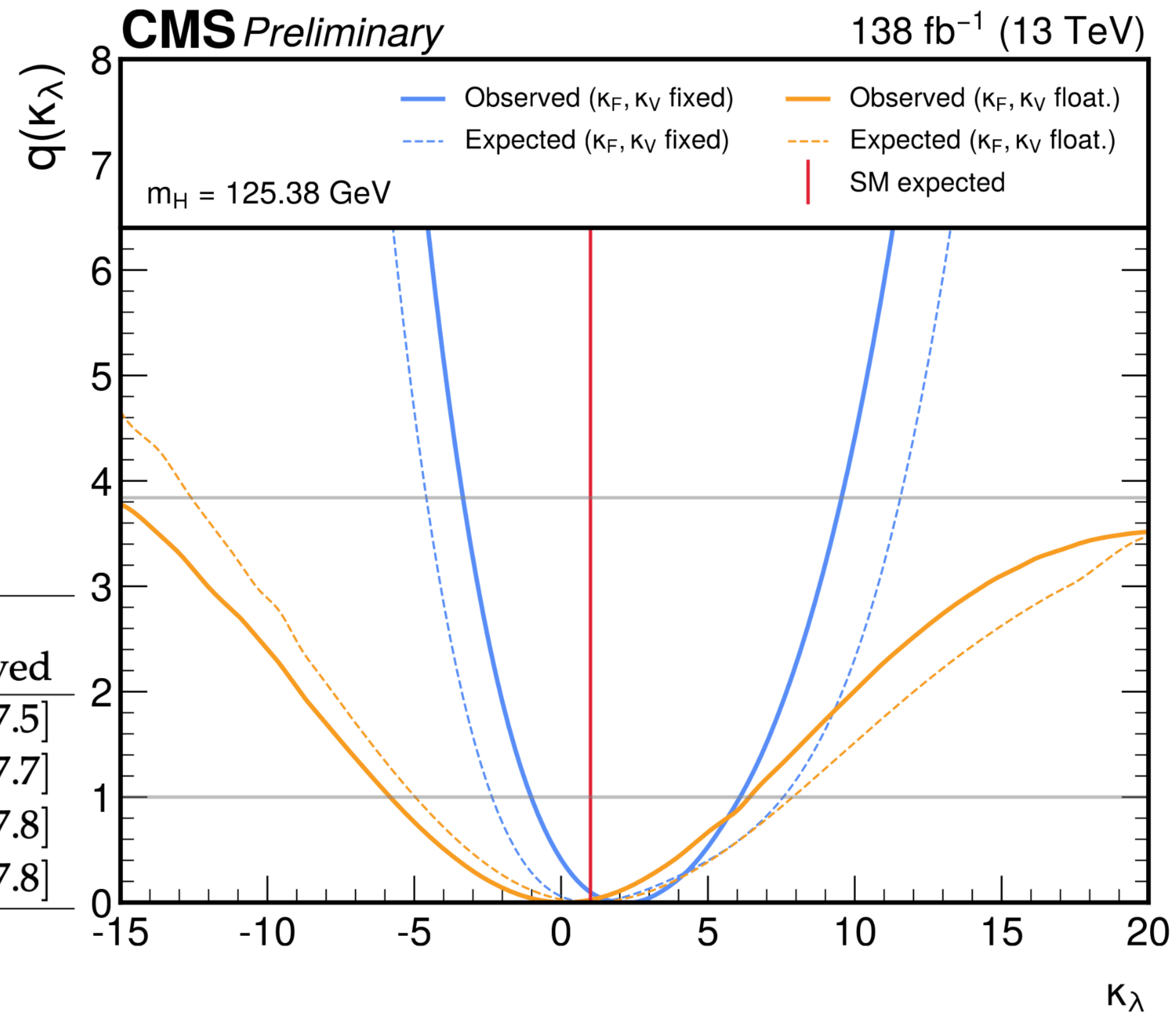
- Constraining κ_λ with in single Higgs through EW NLO corrections contributing to decay and production vertices
- Corrections depend on Higgs kinematics, parametrization is defined in STXS bins [LHCHWG-2022-002]



Assumption	Best-fit κ_λ	95% CL interval	p_{SM}
$\kappa_F = \kappa_V = 1$	$2.14^{+3.95}_{-3.16}$ $\left({}^{+6.57}_{-3.35}\right)$	$[-3.34, 9.55]$ $\left([-4.58, 11.56]\right)$	0.74

With $\kappa_F = \kappa_V = 1$ constraints are close to H + HH combination

95% CL intervals [-3.34, 9.55] (this result) vs [-1.2,7.5] (H+HH)



Hypothesis	Best fit κ_λ value $\pm 1\sigma$ Expected	Best fit κ_λ value $\pm 1\sigma$ Observed	2σ interval Expected	2σ interval Observed
Other couplings fixed to the SM prediction	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, 7.7]$	$[-1.2, 7.5]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_f)$	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, 7.8]$	$[-1.7, 7.7]$
Floating $(\kappa_V, \kappa_t, \kappa_b, \kappa_\tau)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, 7.7]$	$[-1.4, 7.8]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, 7.8]$	$[-1.4, 7.8]$

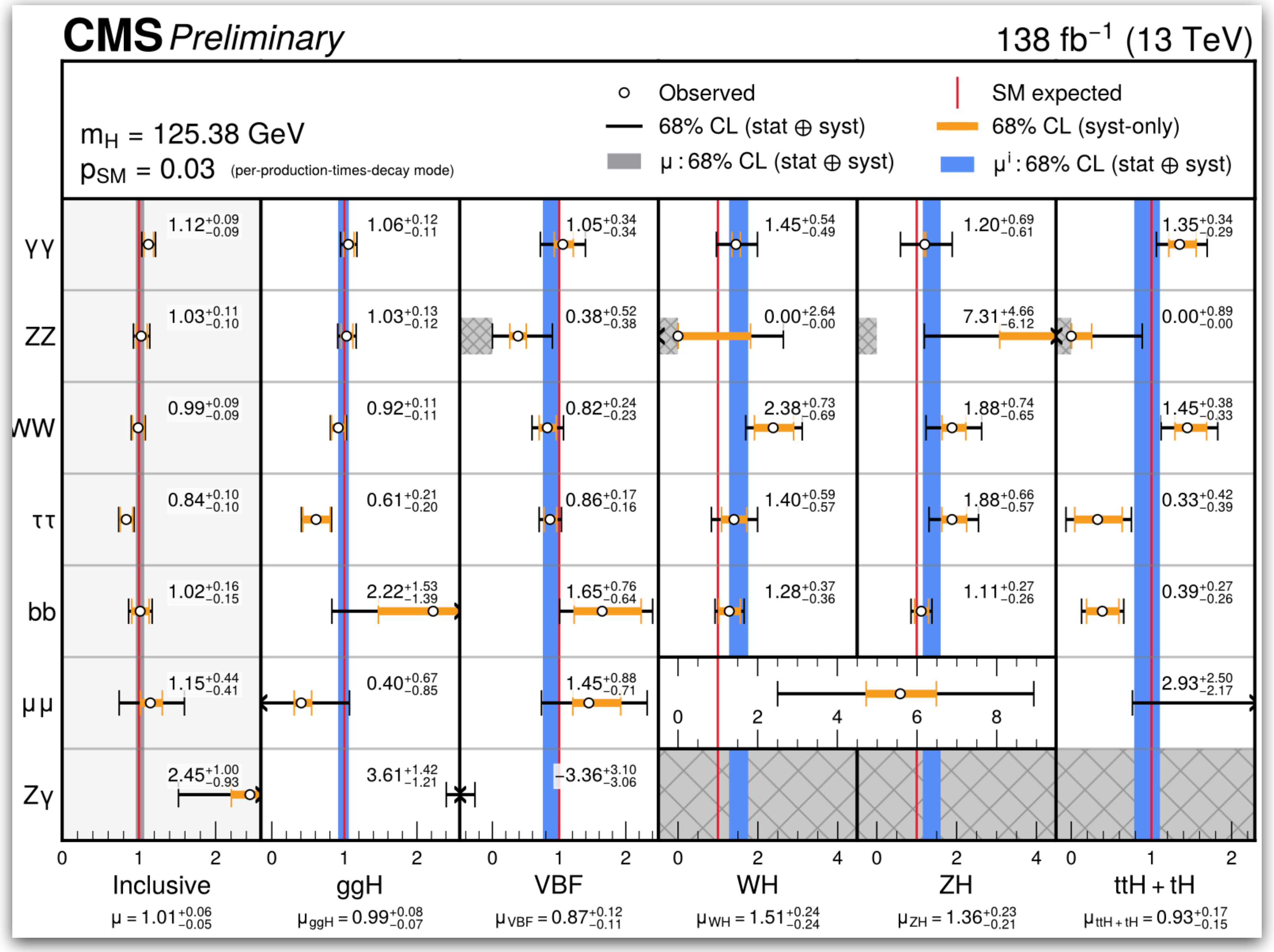
[Phys. Lett. B 861 (2025) 139210]

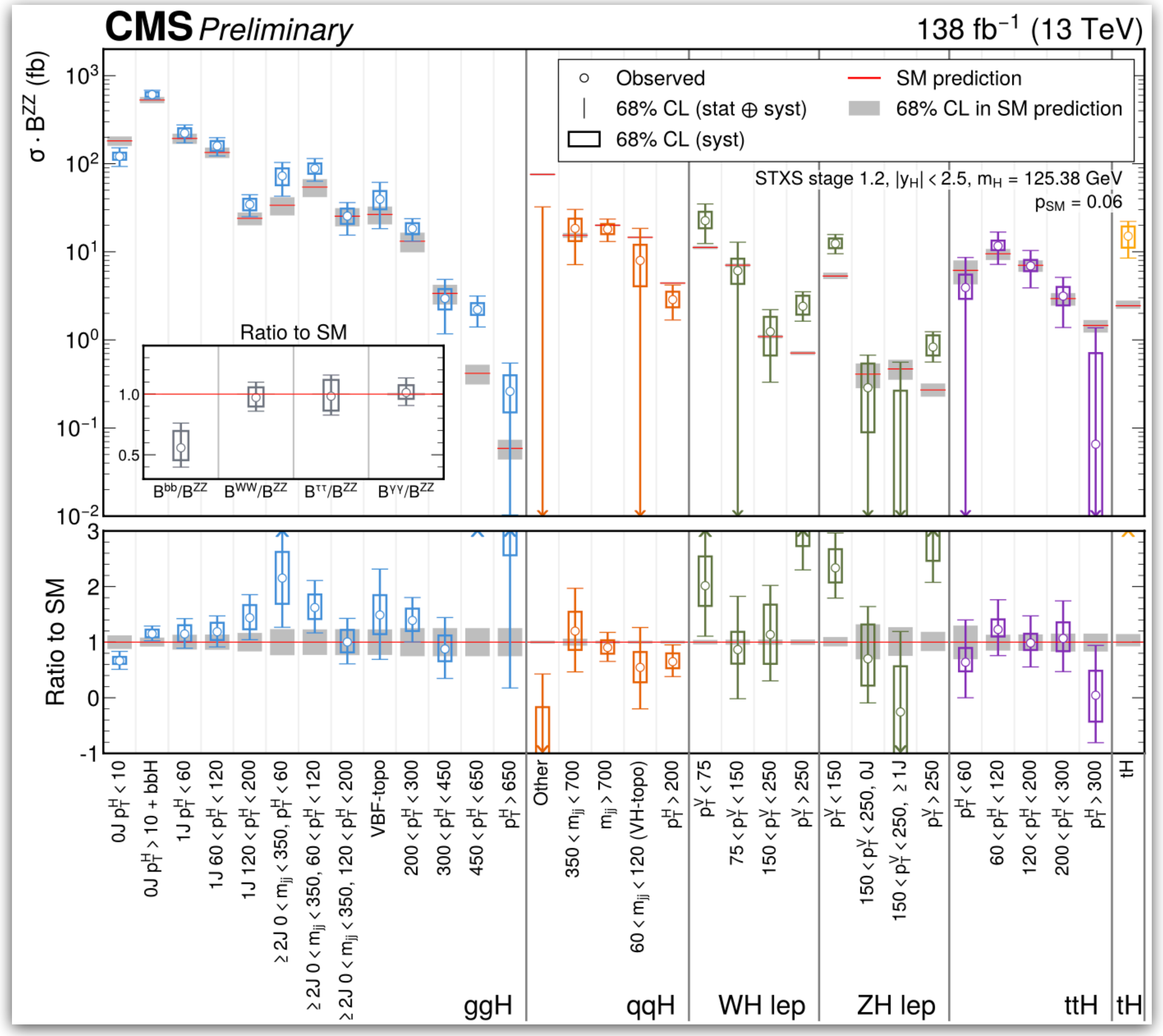
Summary

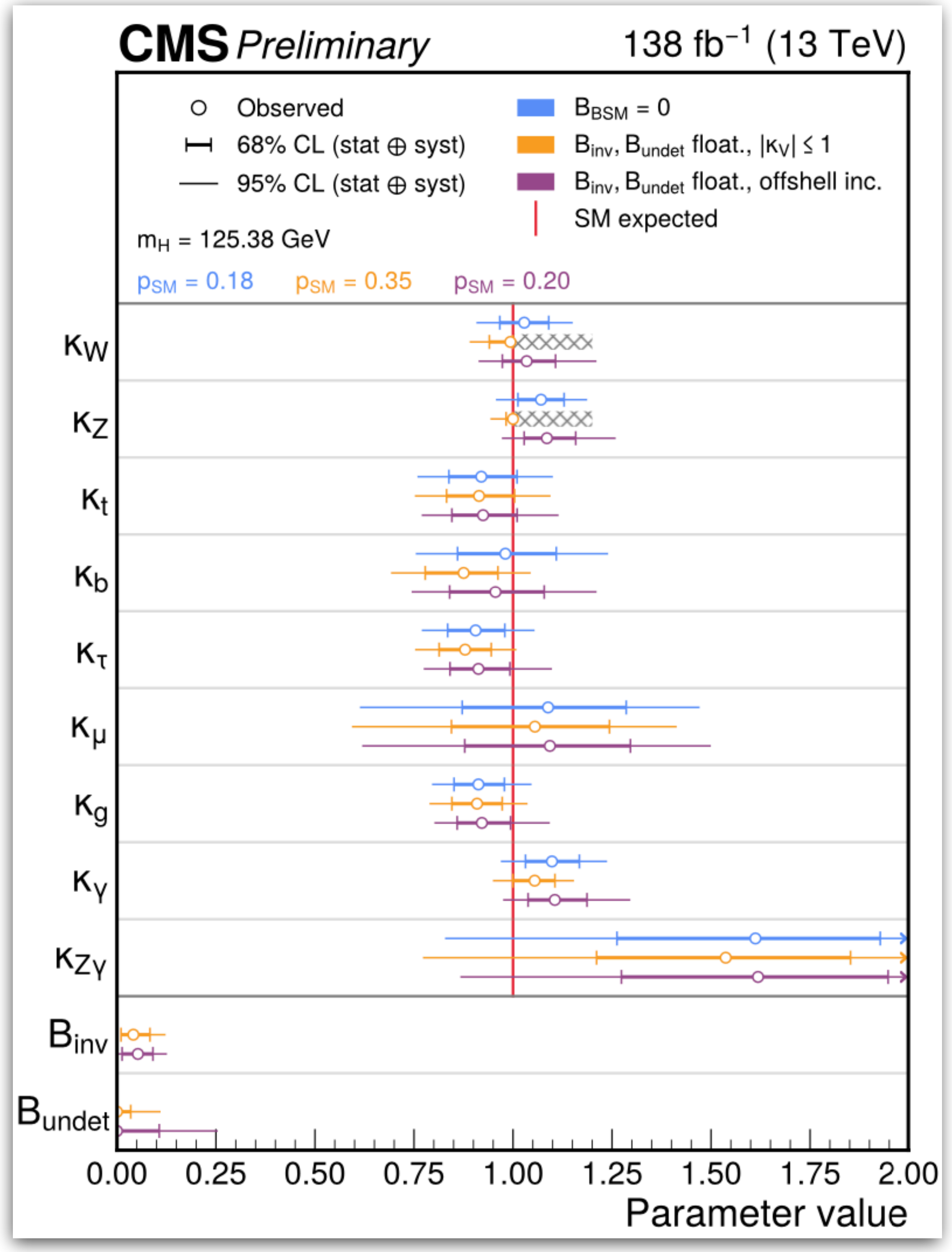
- CMS Higgs Run 2 combination provides ultimate sensitivity, targeting all production and decay modes
  - Signal strength for all production and decay channels (leading systematics - th. unc.)

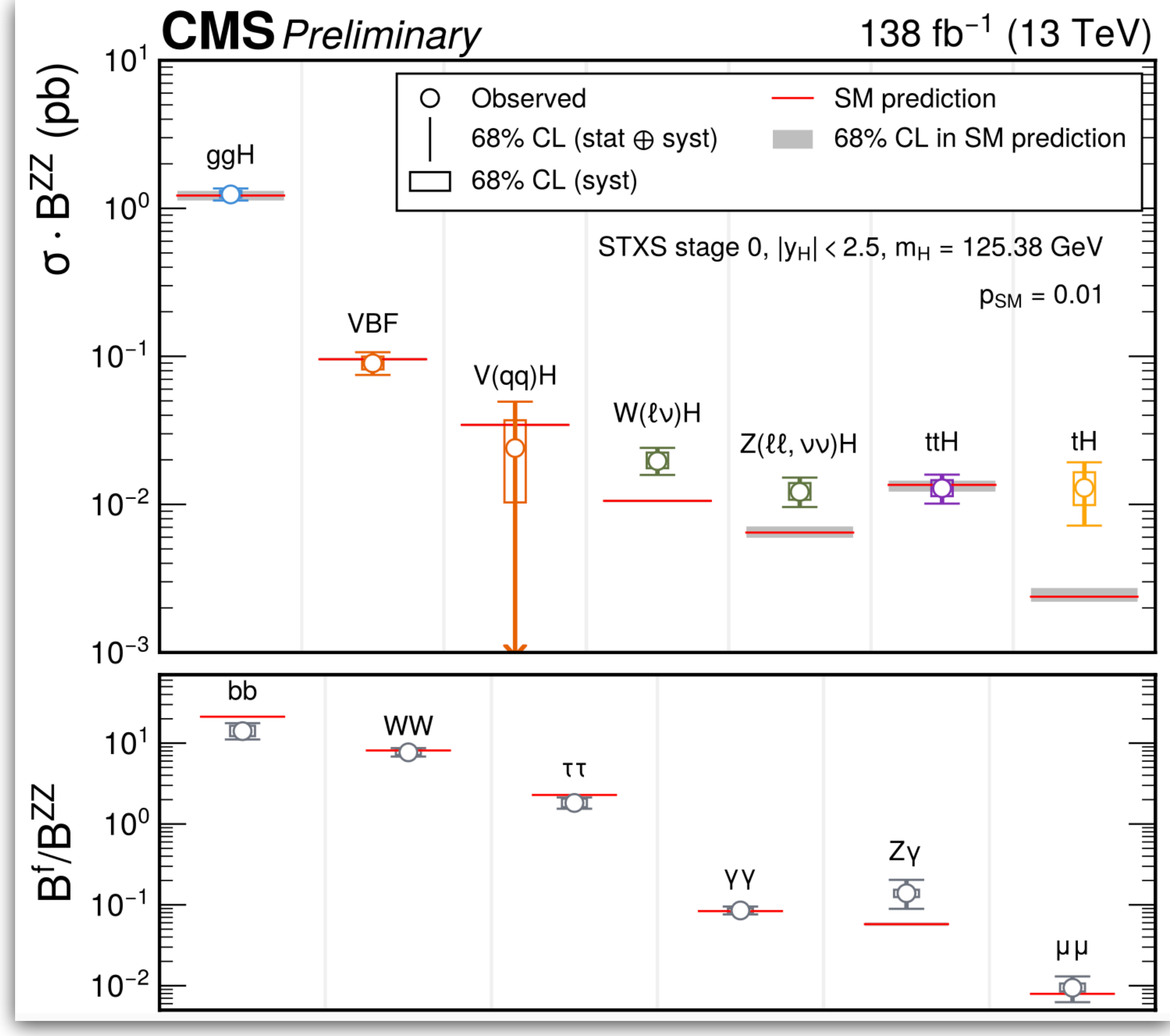
$$\mu = 1.014^{+0.055}_{-0.053}$$

  - Interpretations with coupling modifiers
  - First CMS STXS combination (stage 1.2 with 36 parameters)
- Stay tuned for more results to be released next week for Moriond QCD [CMS-HIG-21-018]
  - SMEFT interpretation, other variations of Higgs coupling models, more granular STXS results will be covered in the talk by J. Langford





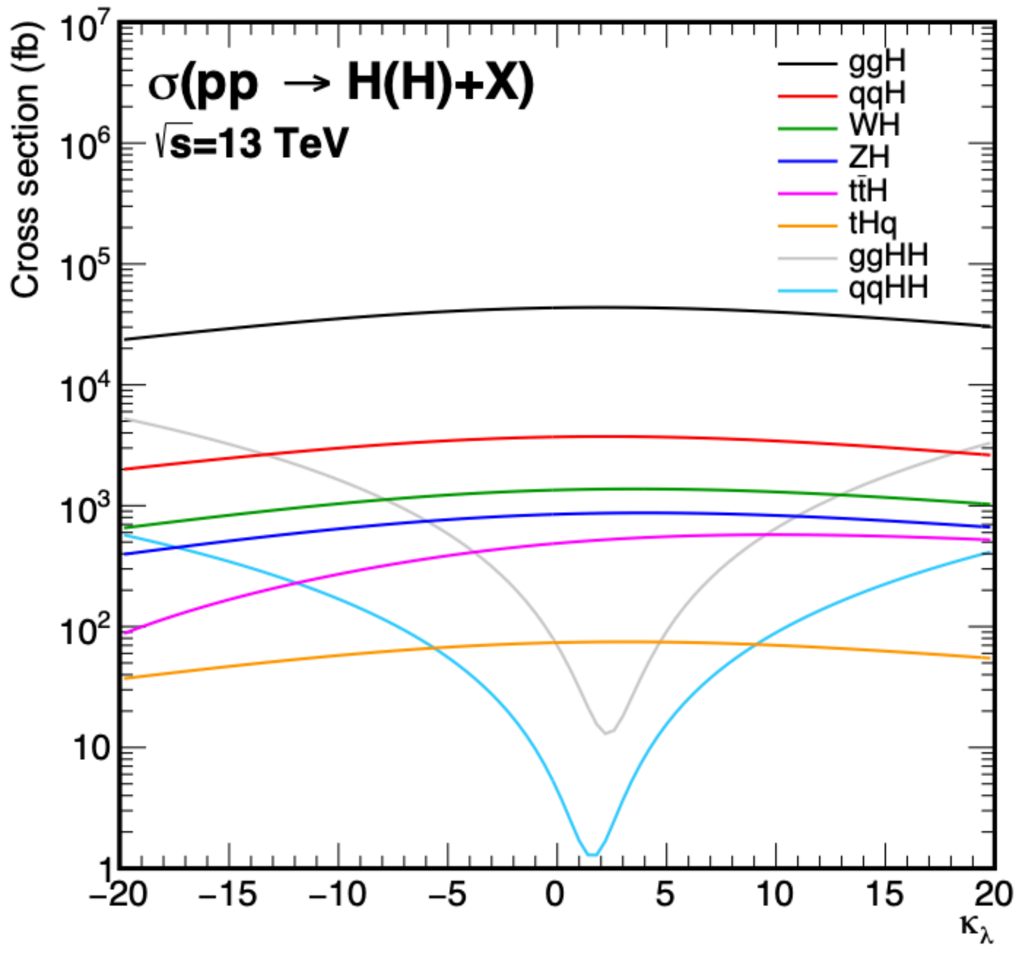


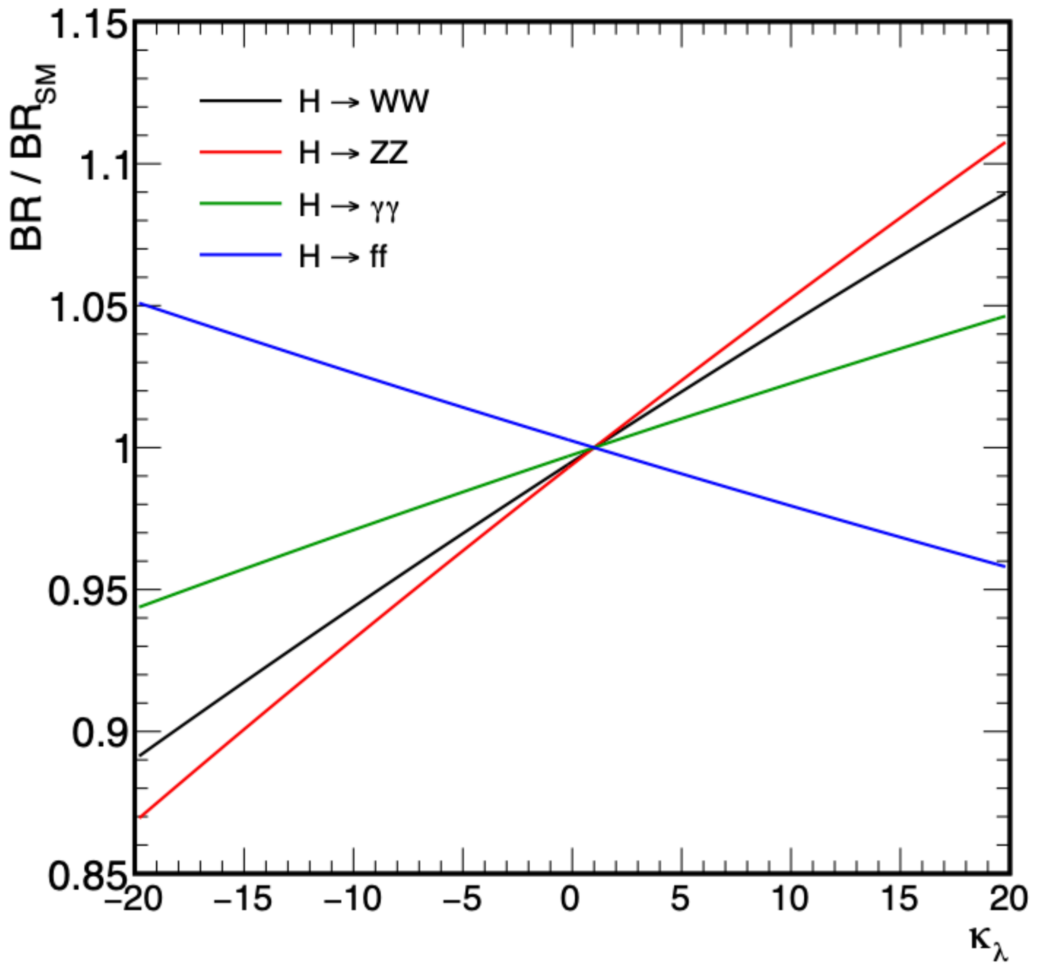


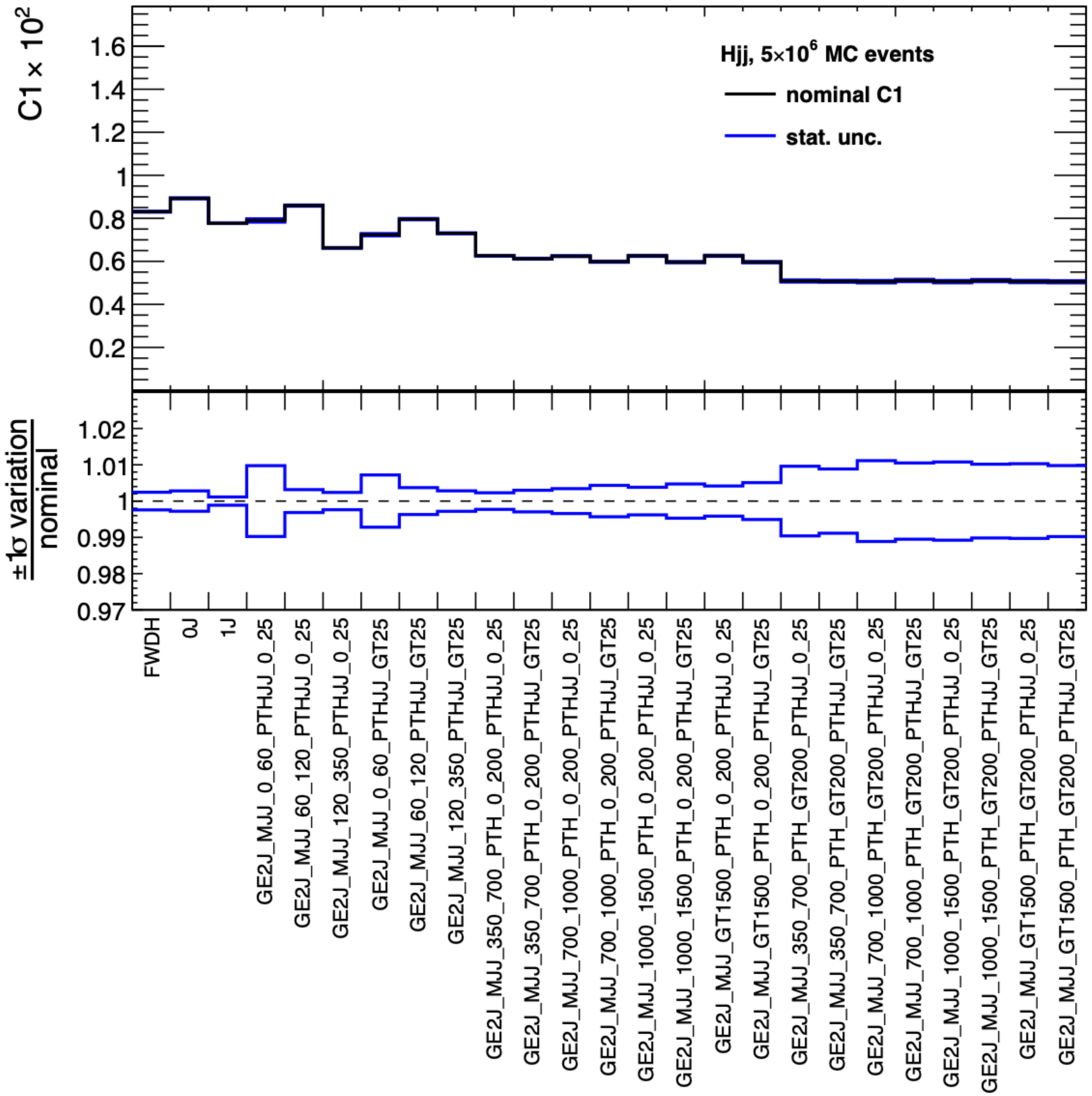
Backup

Higgs self-coupling from NLO EWK corrections

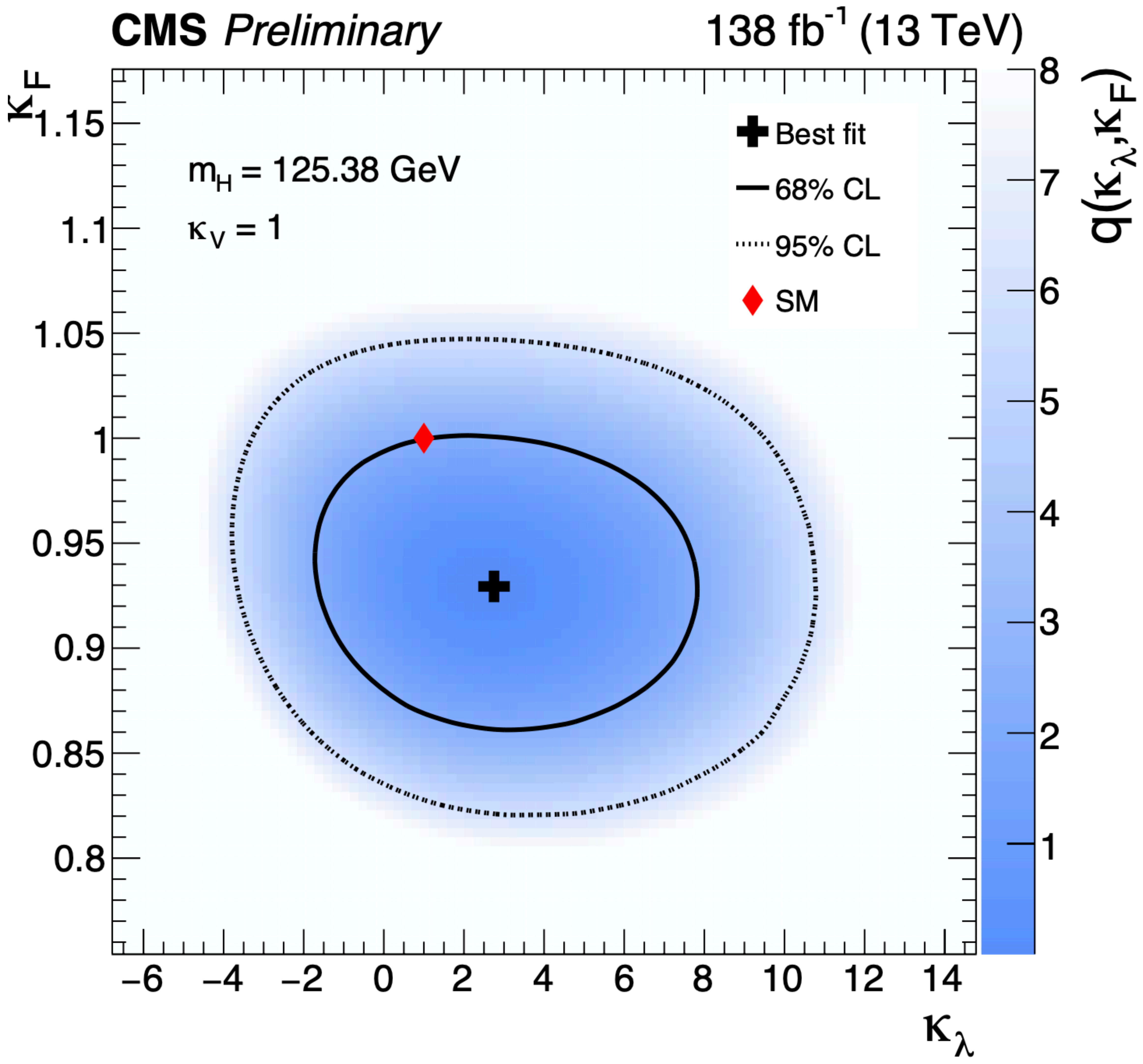
$$\frac{\sigma^{i}_{NLO_{EW}}}{\sigma^{i}_{NLO_{EW},SM}} = Z_{\mathrm{H}}^{BSM}\left[\frac{(\kappa_\lambda - 1)C_1^i}{K^i_{EW}} + \kappa_i^2\right]$$

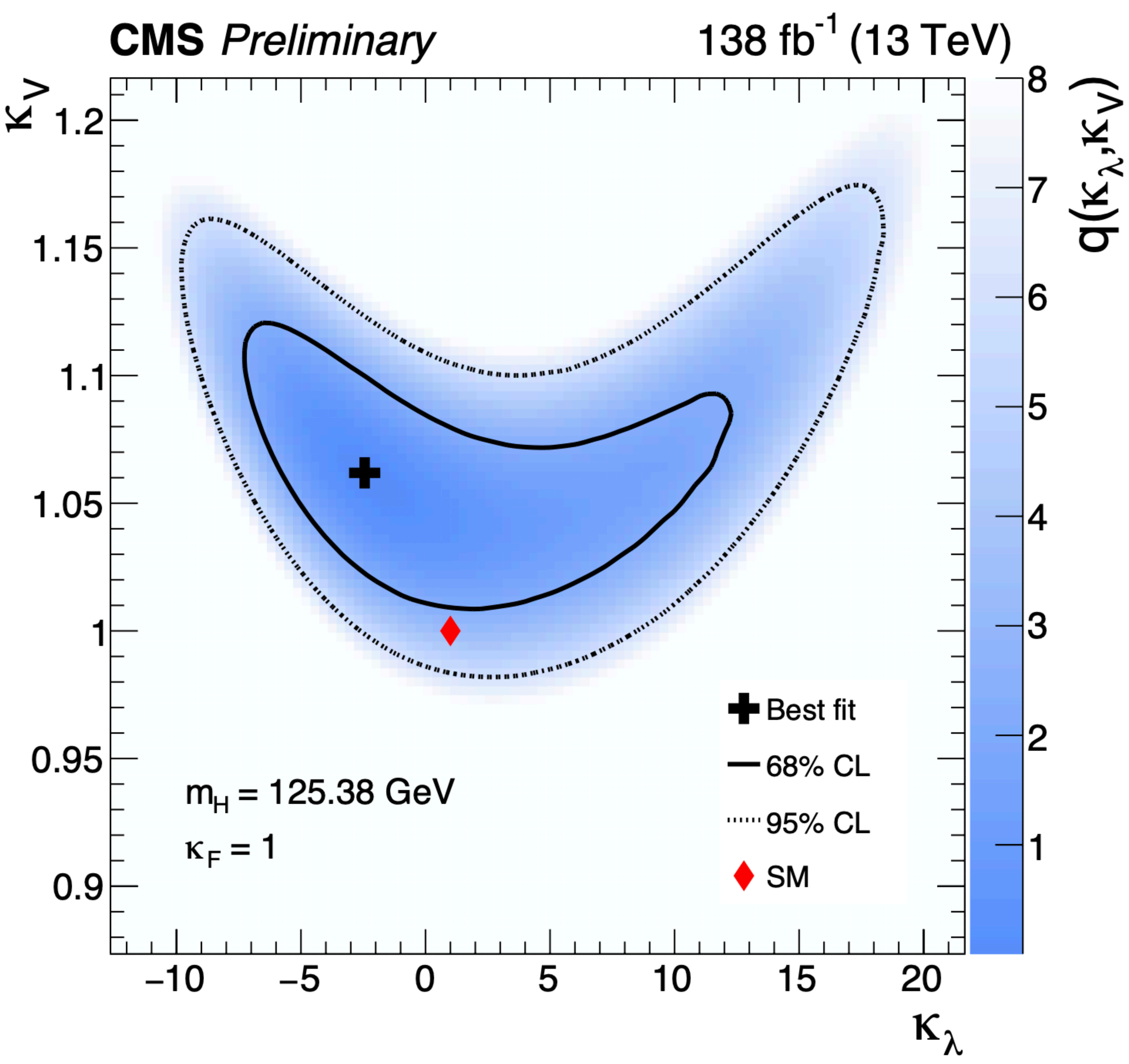






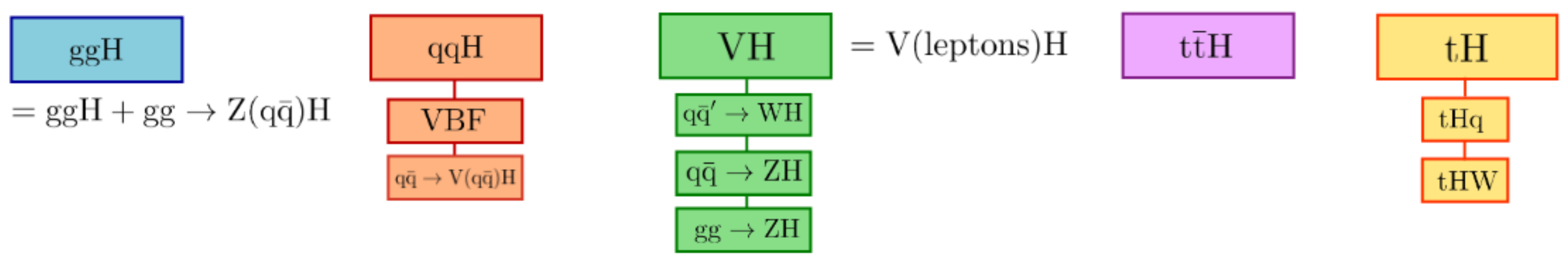
Constraints on Higgs self-coupling





STXS stage 0

First STXS combination result from CMS

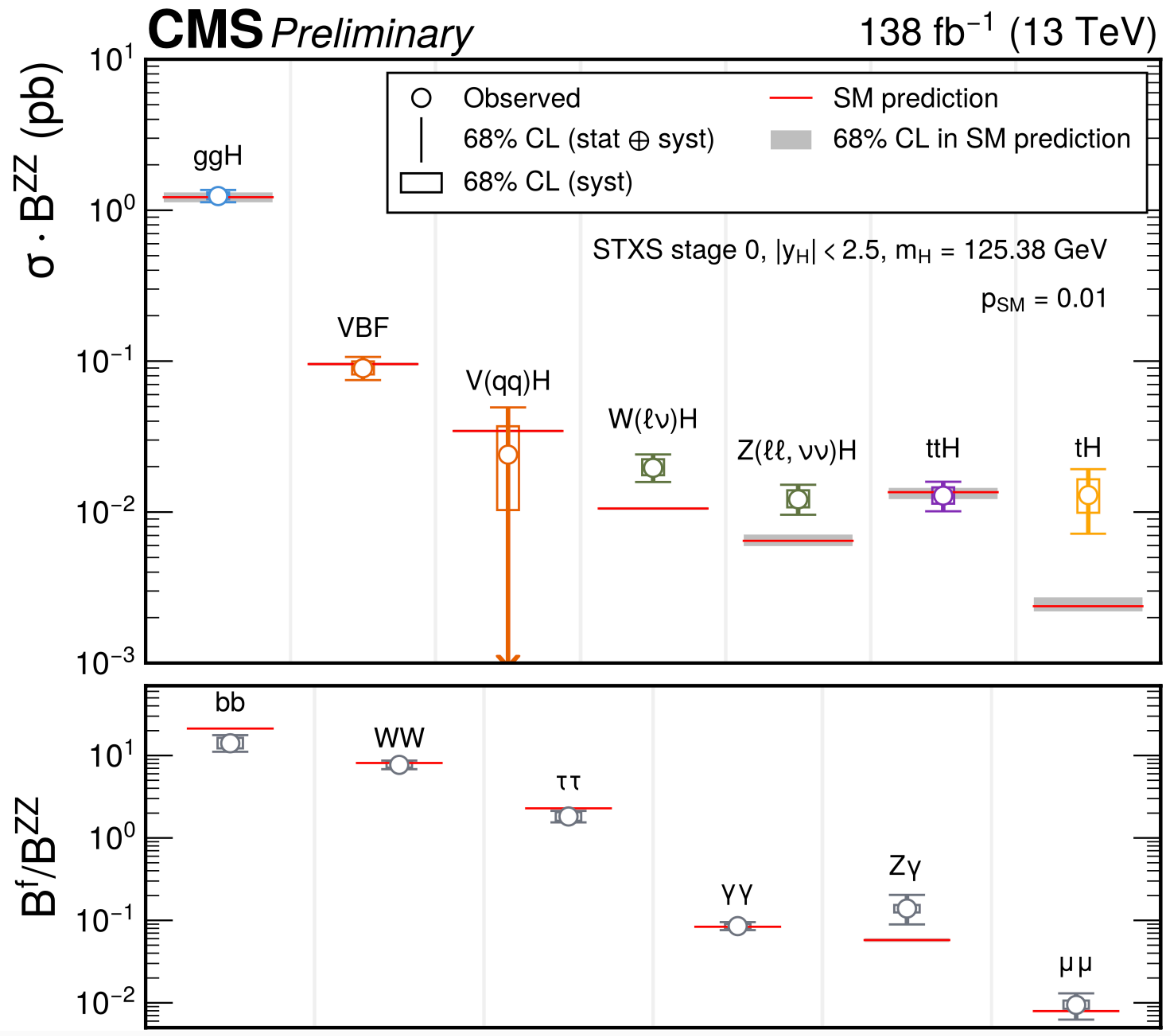


- 13 POIs: 7 for STXS cross sections
- Additional 6 parameters to extract the Higgs decay branching fraction ratios wrt $H \to ZZ$

$$\mu^{i,ZZ} = \frac{\left[\sigma^i \times \mathcal{B}^{ZZ}\right]_{obs}}{\left[\sigma^i \times \mathcal{B}^{ZZ}\right]_{\mathrm{SM,HO}}(\vec{\theta}'_{\mathrm{th,norm}})}$$

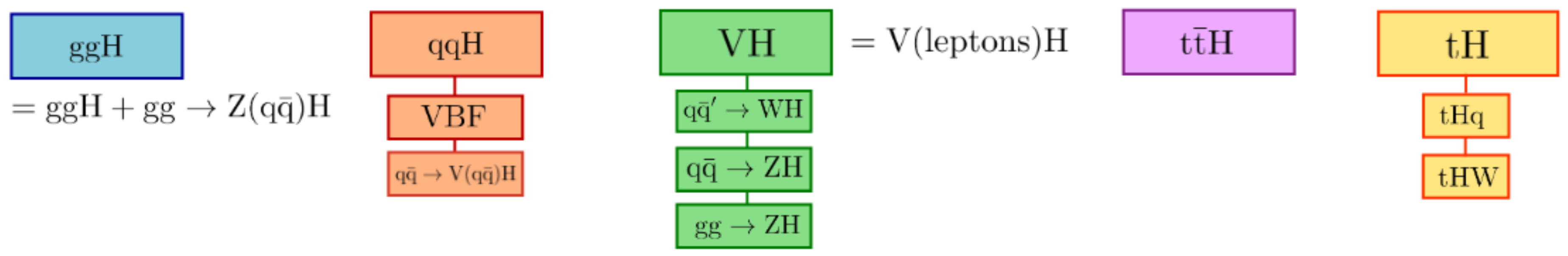
- For all other channels

$$\mu^{i,f} = \mu^{i,ZZ} \cdot R^{f/ZZ} \qquad R^{f/ZZ} = \frac{\mathcal{B}^f_{\mathrm{obs}} / \mathcal{B}^f_{\mathrm{SM,HO}}(\vec{\theta}'_{\mathrm{th,norm}})}{\mathcal{B}^{ZZ}_{\mathrm{obs}} / \mathcal{B}^{ZZ}_{\mathrm{SM,HO}}(\vec{\theta}'_{\mathrm{th,norm}})}$$

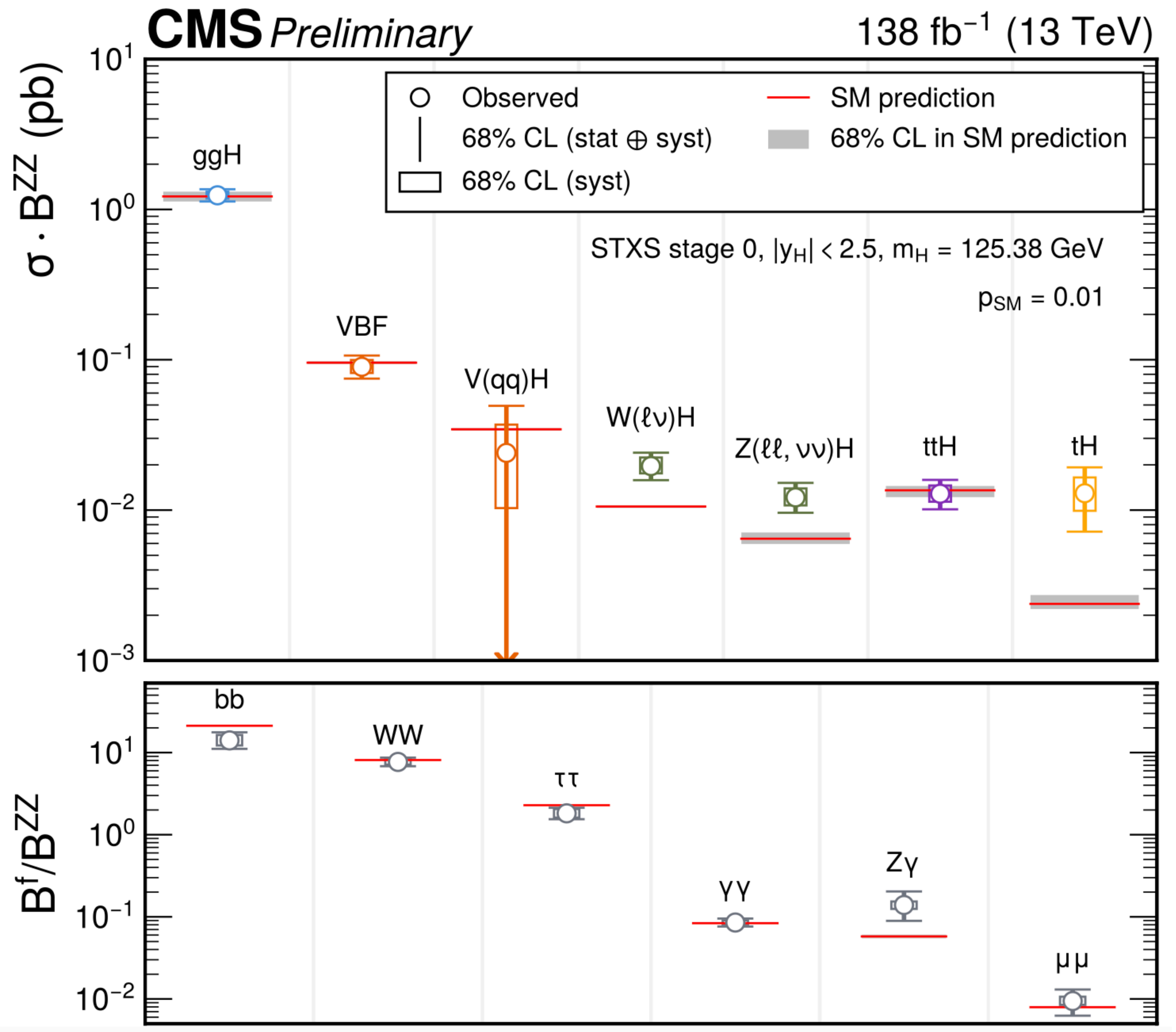


STXS stage 0

First STXS combination result from CMS



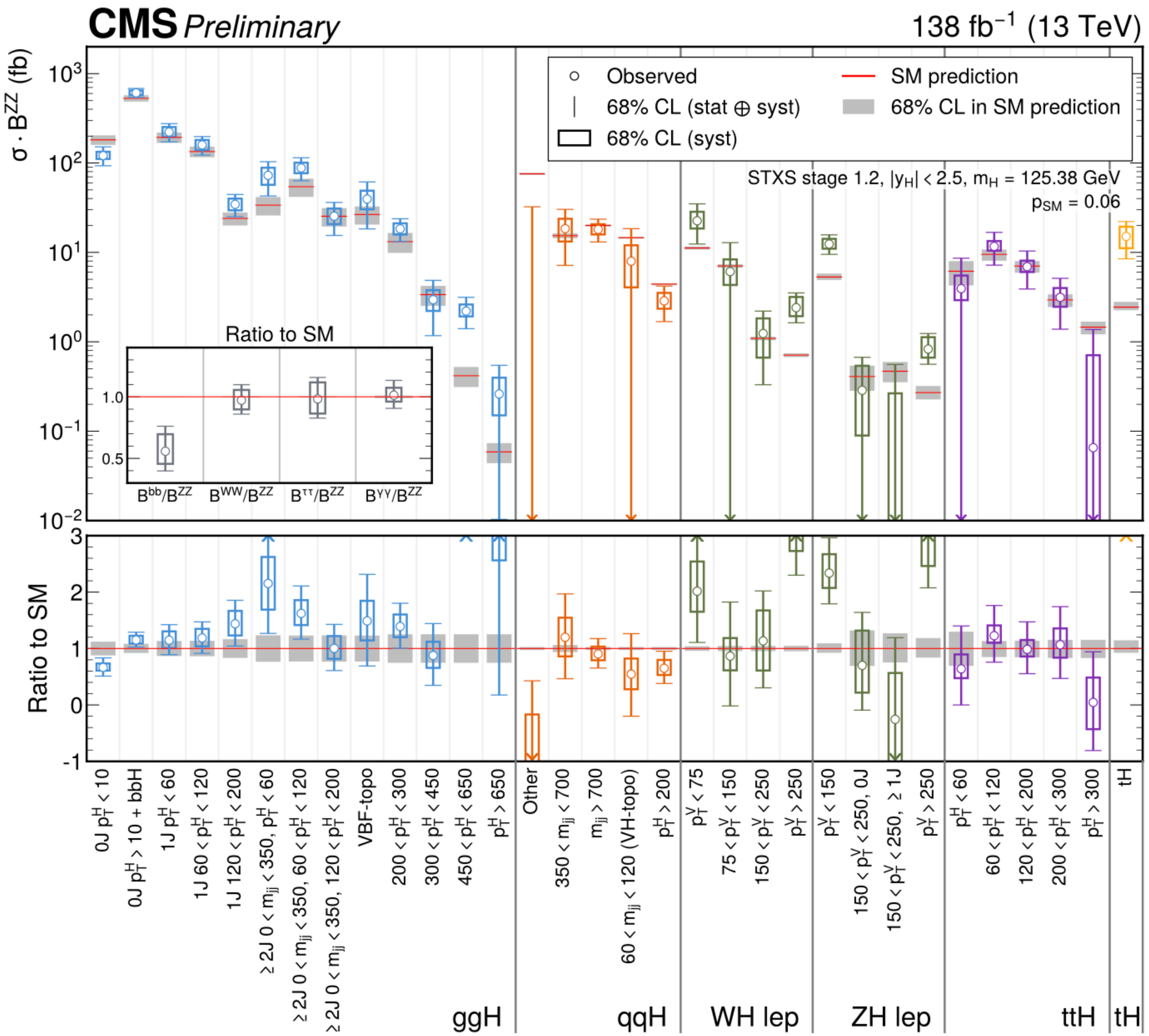
Input channels	STXS/inclusive
$H \to \gamma\gamma$	+ (STXS)
$H \to ZZ$	+ (STXS)
$H \to WW$	+ (STXS)
$H \to \tau\tau$	+ (inclusive)
Boosted $H \to b\bar{b}$	+ (inclusive)
VBF $H \to b\bar{b}$	+ (inclusive)
$VH \to b\bar{b}$	+ (STXS)
$t\bar{t}H \to b\bar{b}$	+ (inclusive)
$t\bar{t}H$ multilepton	+ (STXS)
$H \to \mu\mu$	+ (inclusive)
$H \to Z\gamma$	+ (inclusive)
$H \to$ inv	-
$H \to 4l$ offshell	-



STXS stage 1.2

Input channels	STXS/inclusive
$H \to \gamma\gamma$	+ (STXS)
$H \to ZZ$	+ (STXS)
$H \to WW$	+ (STXS)
$H \to \tau\tau$	+ (STXS)
Boosted $H \to b\bar{b}$	+ (STXS)
VBF $H \to b\bar{b}$	-
V$H \to b\bar{b}$	+ (STXS)
$t\bar{t}H \to b\bar{b}$	+ (STXS)
$t\bar{t}H$ multilepton	+ (STXS)
$H \to \mu\mu$	-
$H \to Z\gamma$	-
$H \to$ inv	-
$H \to 4l$ offshell	-

First STXS combination result from CMS



Interpretation with κ

$H \to \gamma\gamma$	+ (STXS)
$H \to ZZ$	+ (STXS)
$H \to WW$	+ (STXS)
$H \to \tau\tau$	+ (inclusive)
Boosted $H \to b\bar{b}$	+ (inclusive)
VBF $H \to b\bar{b}$	+ (inclusive)
V$H \to b\bar{b}$	+ (STXS)
$t\bar{t}H \to b\bar{b}$	+ (inclusive)
$t\bar{t}H$ multilepton	+ (STXS)
$H \to \mu\mu$	+ (inclusive)
$H \to Z\gamma$	+ (inclusive)
$H \to$ inv	+
$H \to 4l$ offshell	+

Included special model for H → 4l offshell analysis allows to release $\kappa_V \leq 1$ constraint and B_{inv}, B_{undet} at the same time

$$\kappa_g^2 = 1.035\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b + 0.979\kappa_Q^2 + 2.015\kappa_t\kappa_Q - 0.004\kappa_b\kappa_Q.$$