Measurements of Higgs differential cross-sections at CMS

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Co-funded by the Horizon 2020 Framework Programme of the European Union

Outline

Introduction

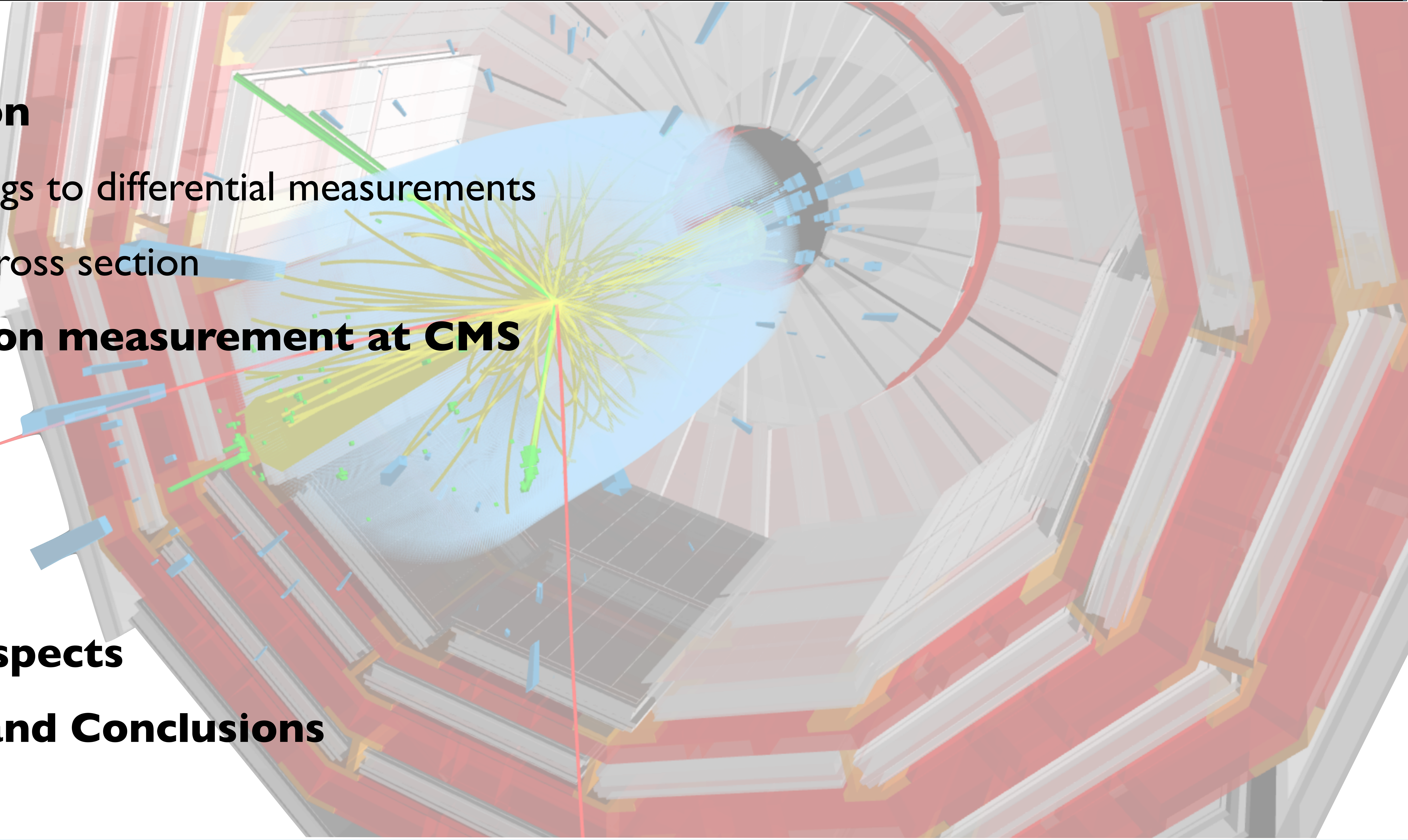
- From couplings to differential measurements
- Differential cross section

Cross section measurement at CMS

- $H \to ZZ$
- $H \to \gamma\gamma$
- Combination

Future prospects

Summary and Conclusions



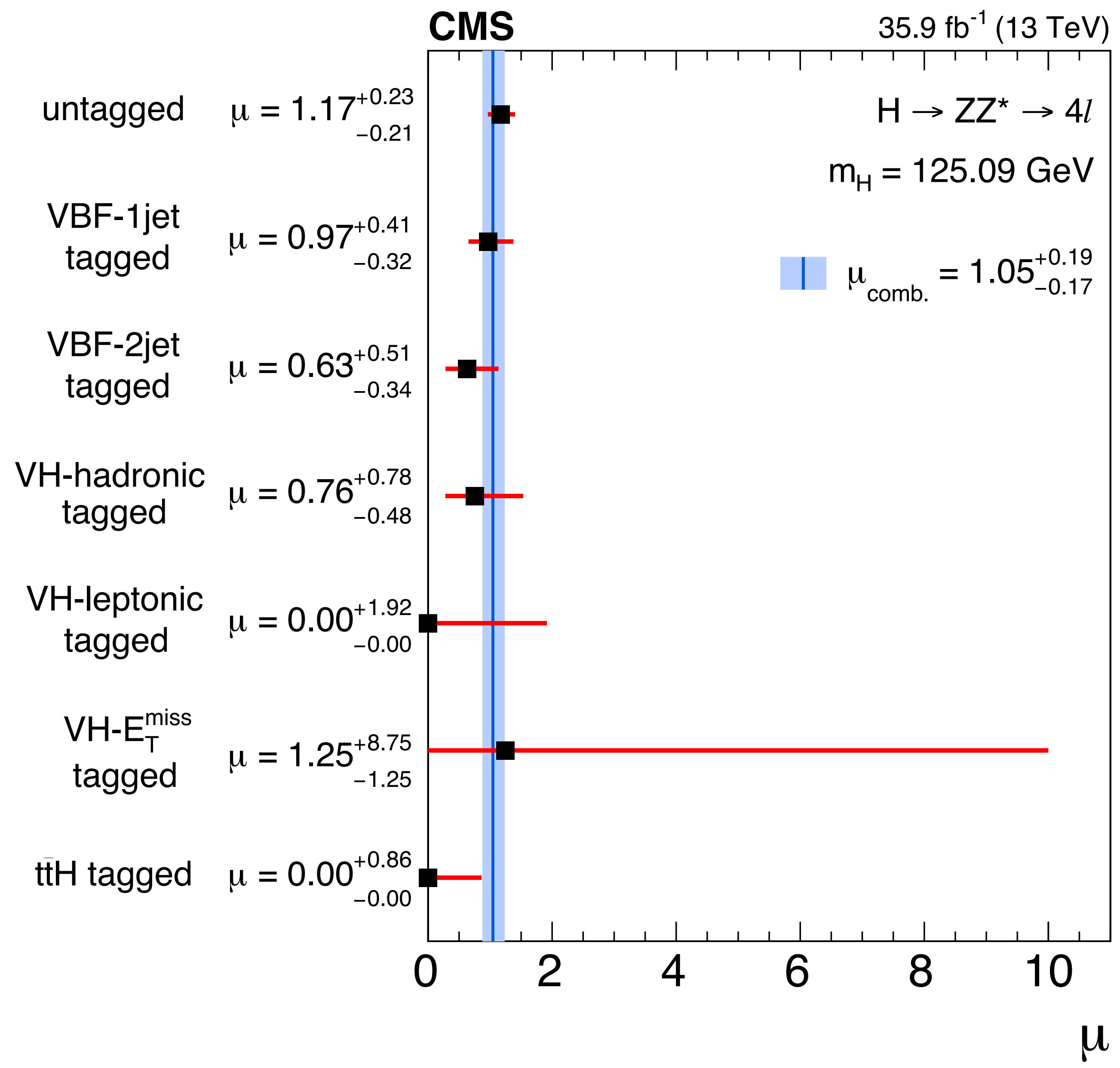
Higgs couplings

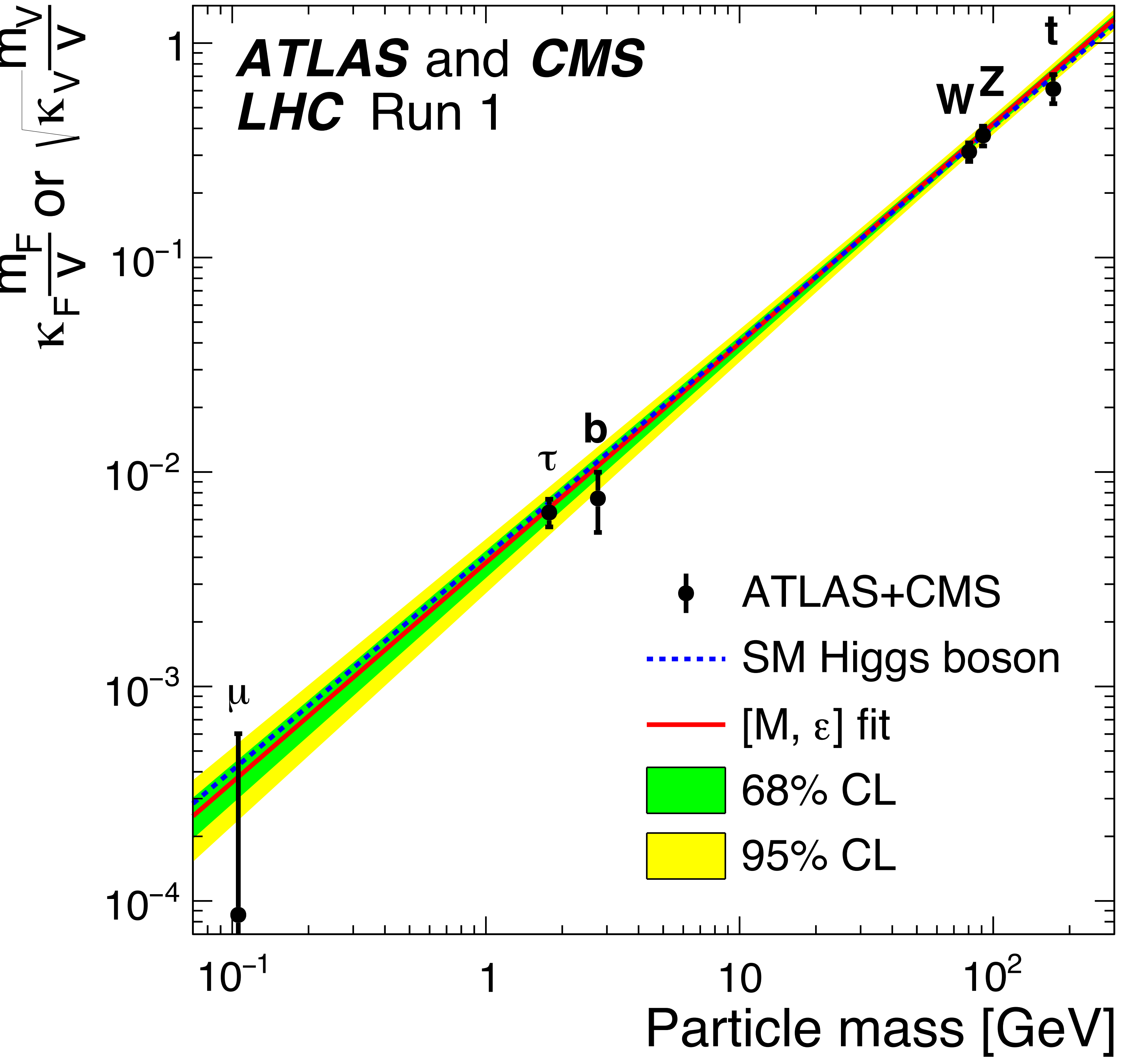
LHC run1&2 allowed to study the Higgs boson properties

Main focus: mass and **couplings**

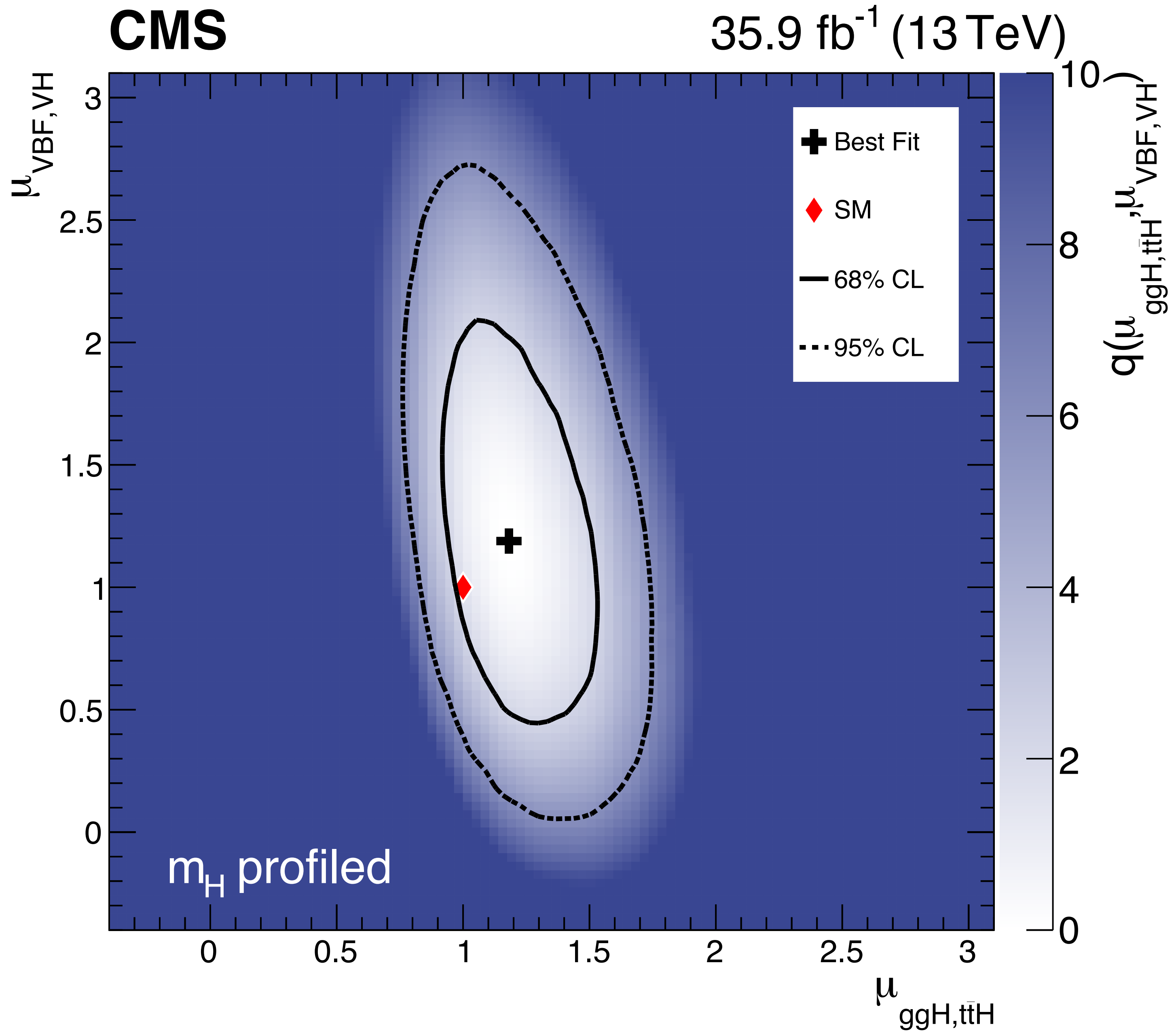
- Signal strengths, k-framework, anomalous couplings used to quantify possible BSM effects

General strategy: identify selection/categories sensitive to different production/decay modes

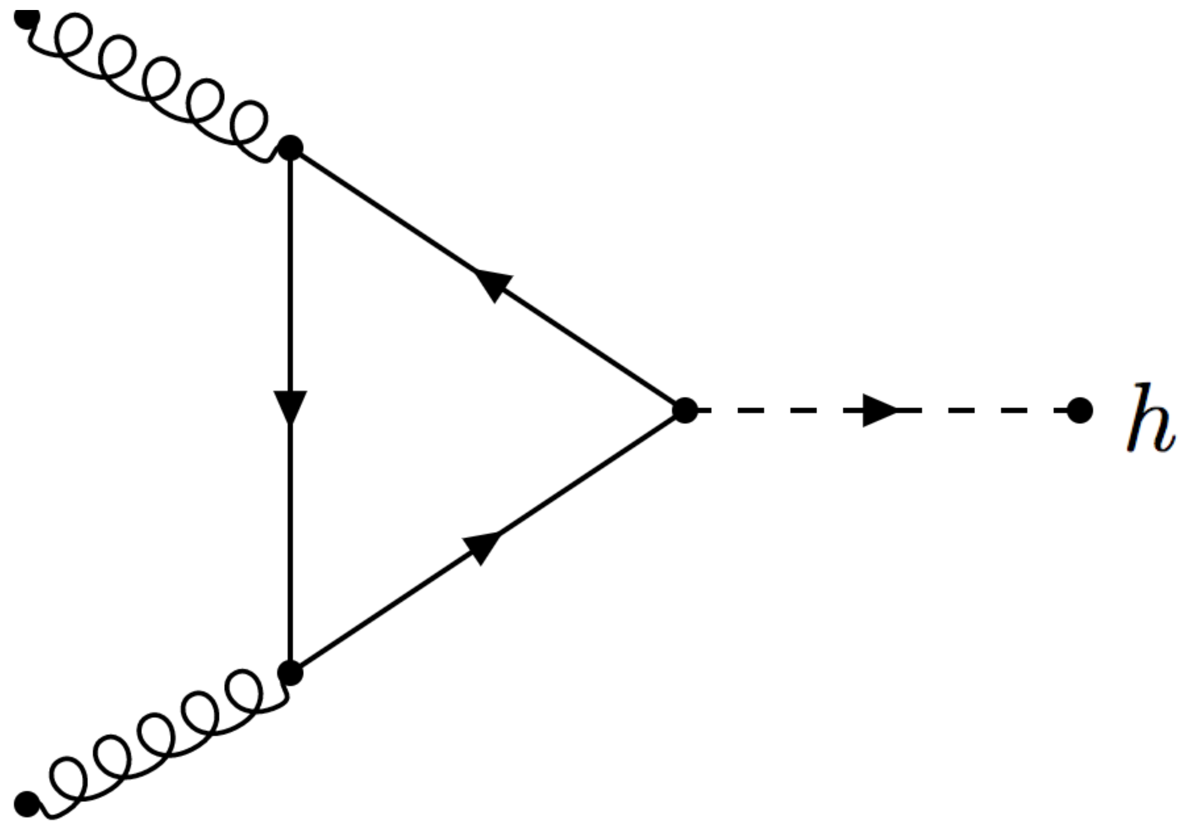


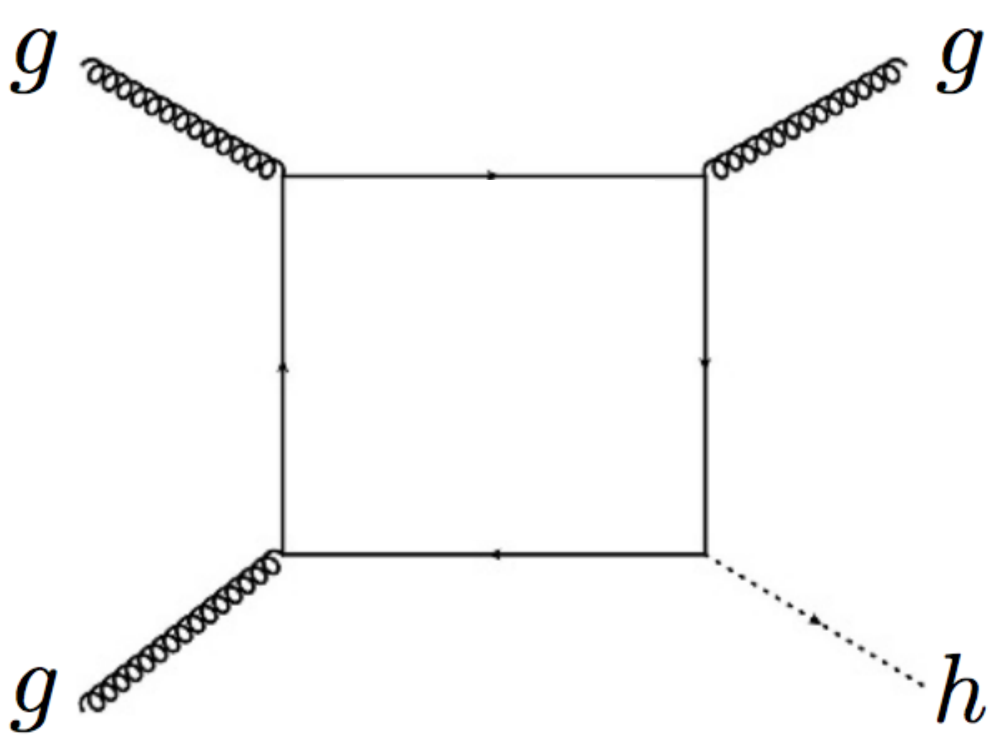


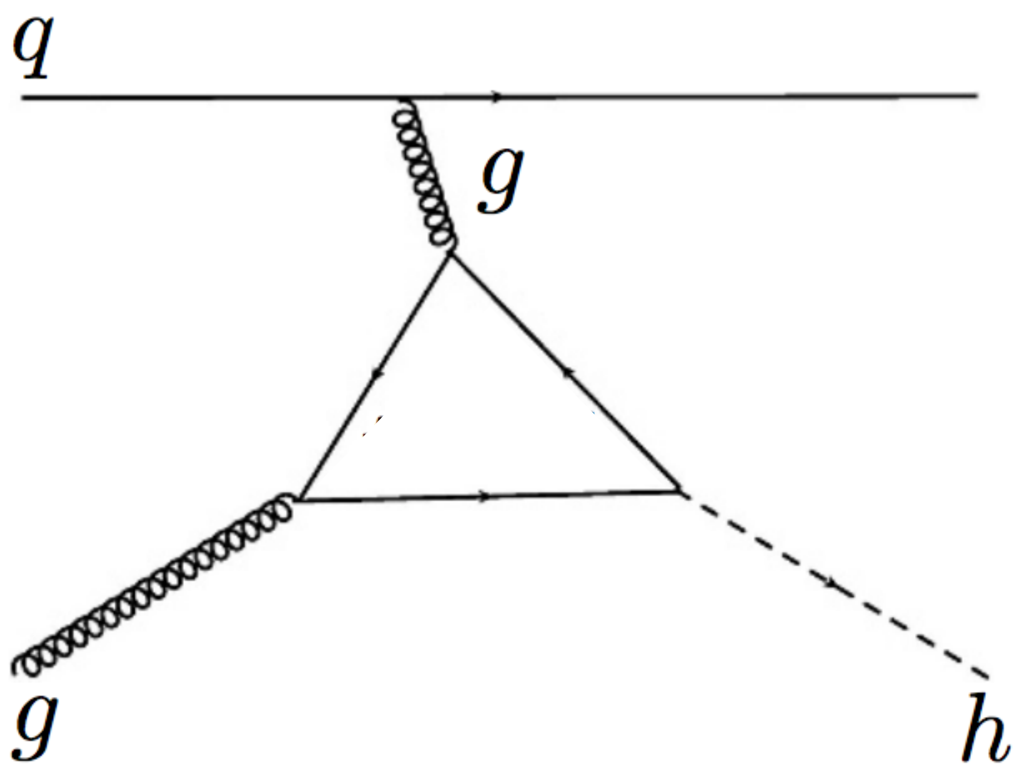
Overall picture from couplings highly consistent with the Standard Model expectations



Differential measurements: why







Couplings are only sensitive to modification of the inclusive cross-section of a measurement

New physics might affect the shape of Higgs distributions, without affecting its overall production

Differential measurements are needed to identify such effects

Transverse momentum $p_T(H)$

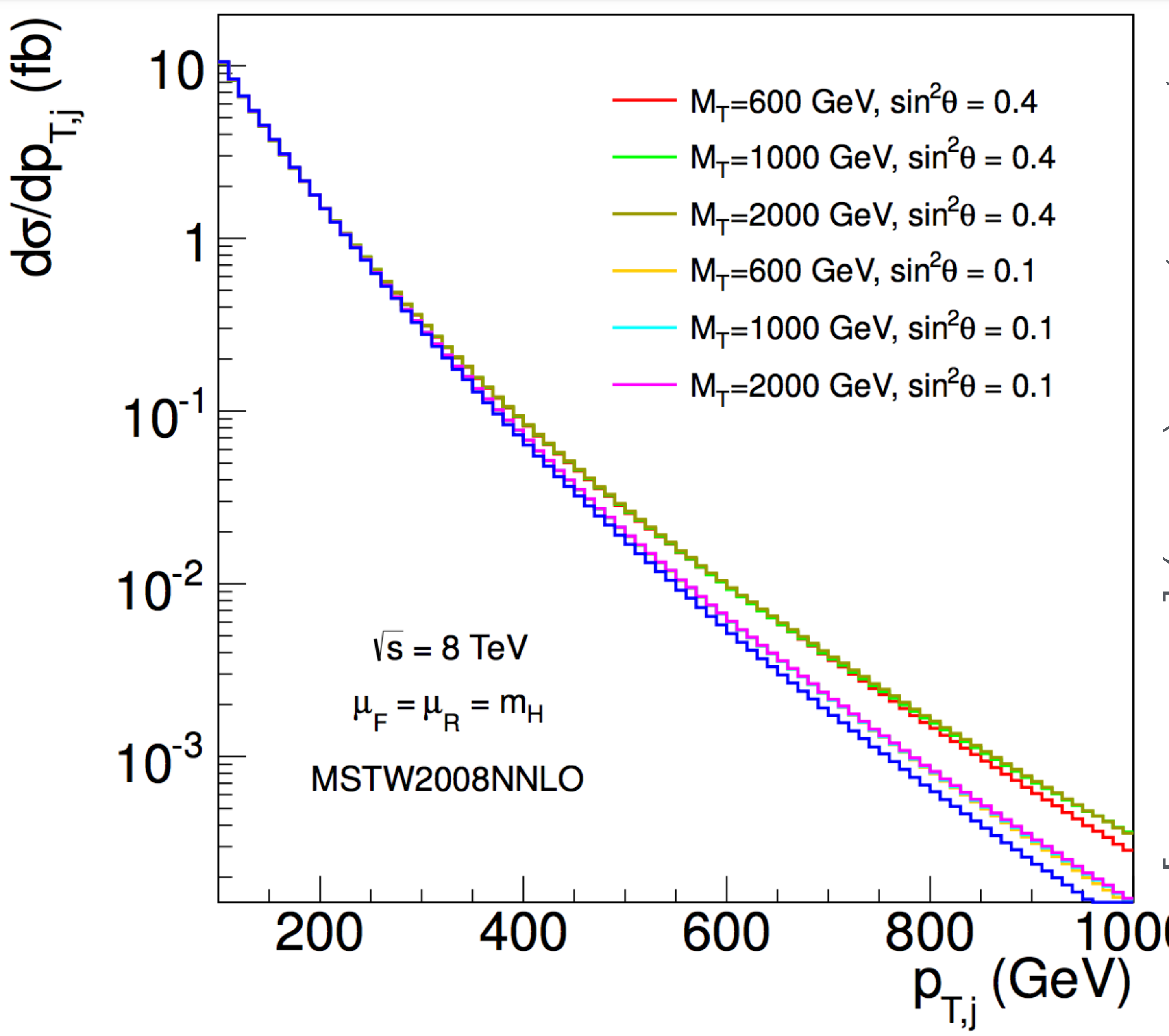
- Sensitive to modifications of effective Higgs Yukawa couplings
- Sensitivity to finite top mass effects

Jet multiplicity and p_T

- New physics in the quark loop (especially at high jet p_T)

Higgs rapidity:

- Effects on gluon PDF



Banfi, Martin, Sanz (2014) [1308.4771]

Differential measurements: how

Fiducial Volume

Defined by experimental and analysis constraints

Observables and binning

Probe production and decay kinematics. Binning compromise between statistics, resolution and migration

Response matrix

Relates the number of truth values and the expected number of reconstructed values (usually from MC)

Unfolding

Correct for detector effects

Interpretation

Fiducial and Simplified template cross-section

Fiducial cross-section

- Optimized for maximal theoretical independence
- Fiducial in Higgs decay
- Smallest acceptance corrections
- Simple signal cuts
- "Exact" fiducial volume
- Targeted object definitions
- Agnostic to production mode

Can be done with single and differential distributions

Only feasible in HZZ,H$\gamma\gamma$,HWW

Combination not straightforward

Simplified templates cross section

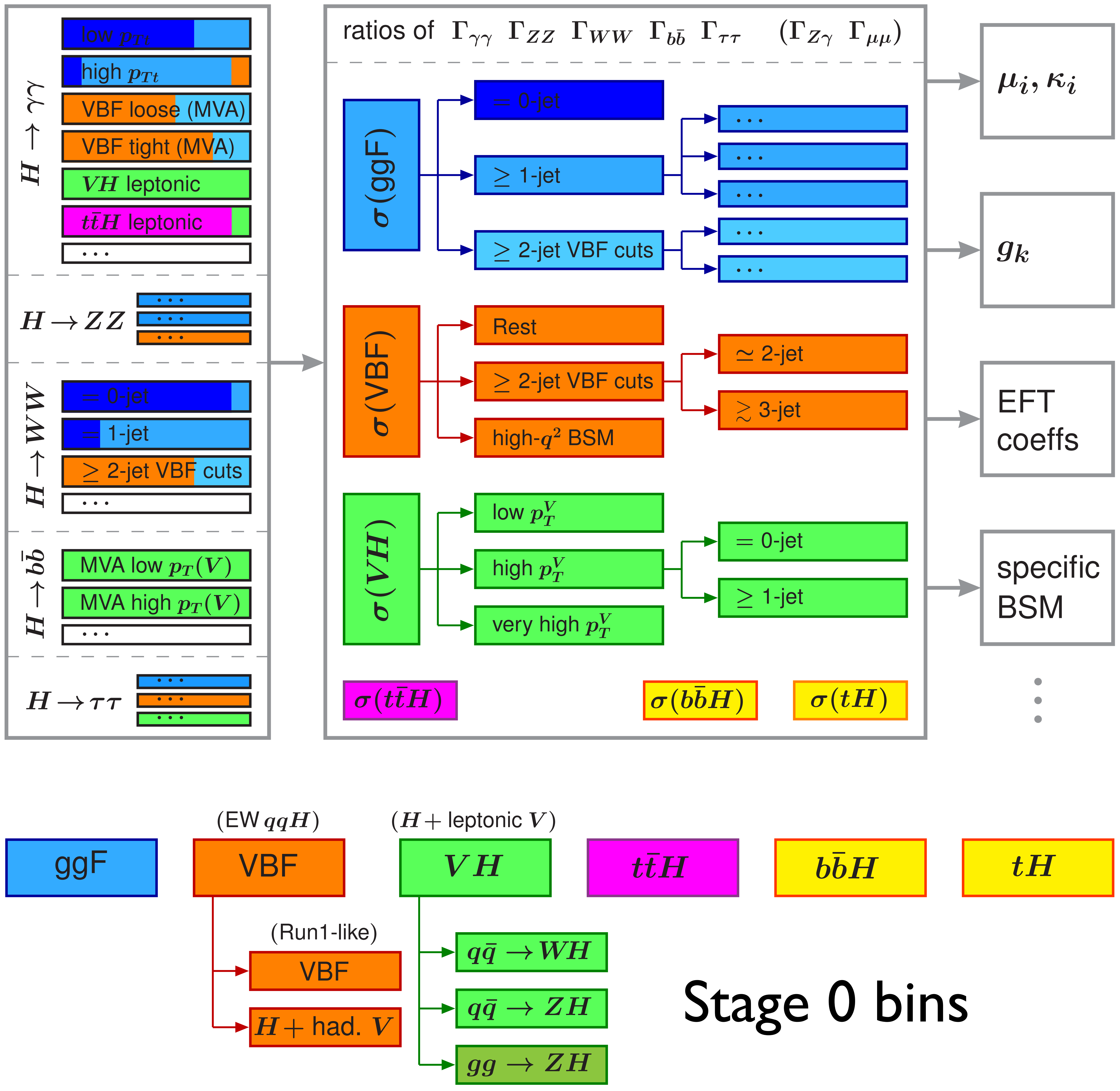
- Target maximum sensitivity, while keeping theoretical dependence as small as possible
- Cross section split by production mode
- Cross section divided in **exclusive** regions of phase space (bins)
- Larger acceptance corrections
- Abstracted fiducial volumes
- Inclusive in Higgs decay
- Allows complex event selections, categorisation

Common abstracted object definitions

Can be done in all decay modes

Explicitly designed for combination

Fiducial and Simplified template cross-section



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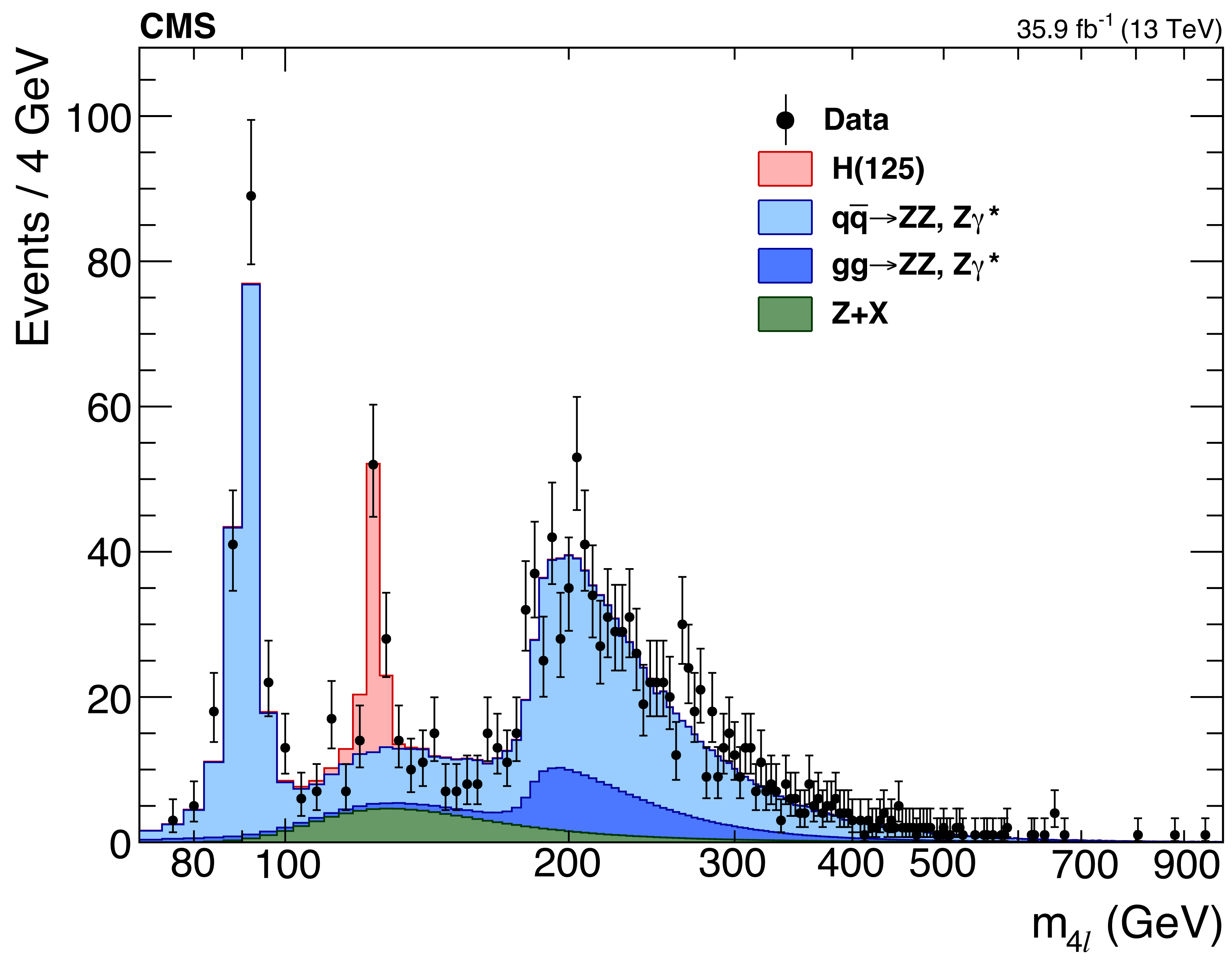
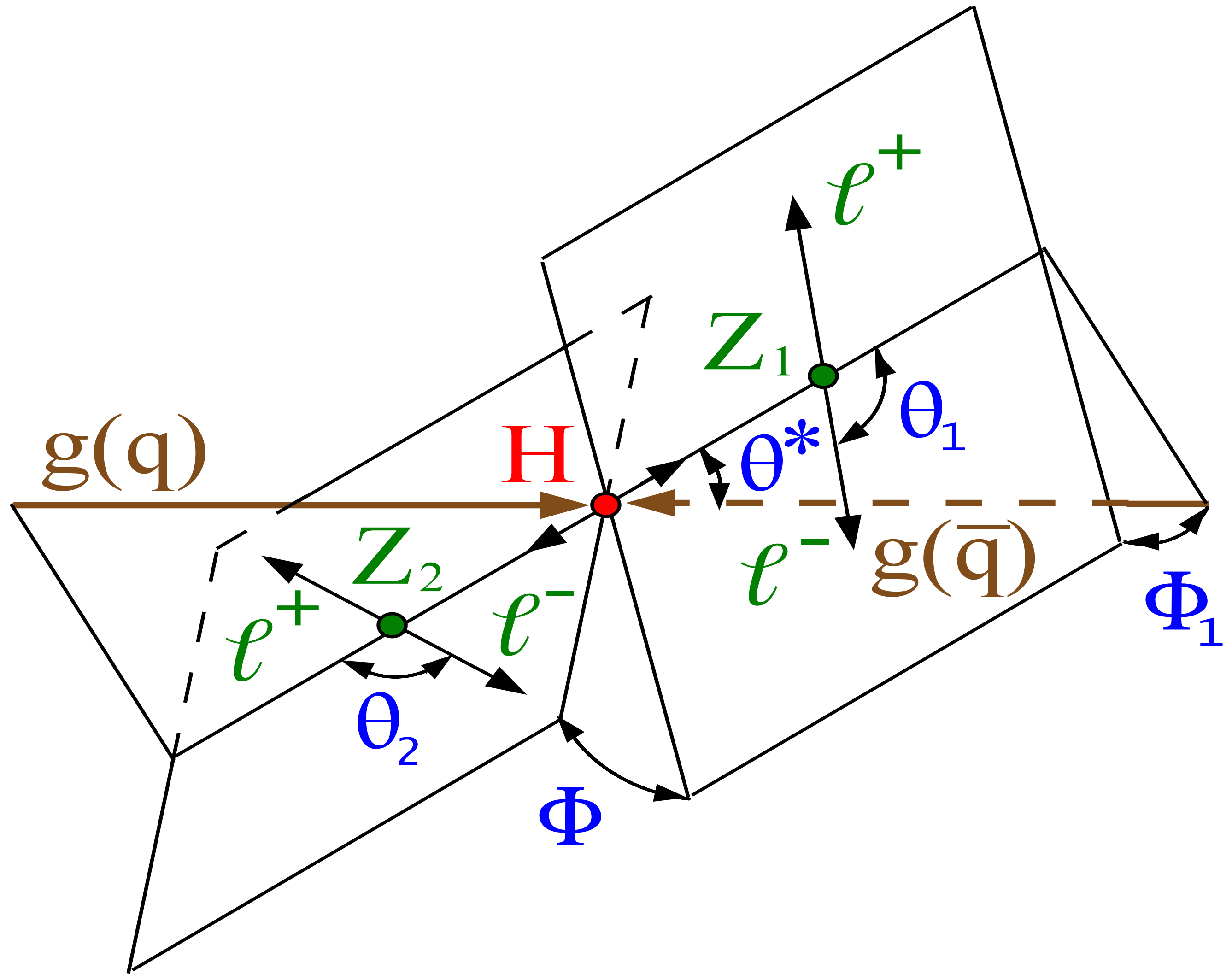
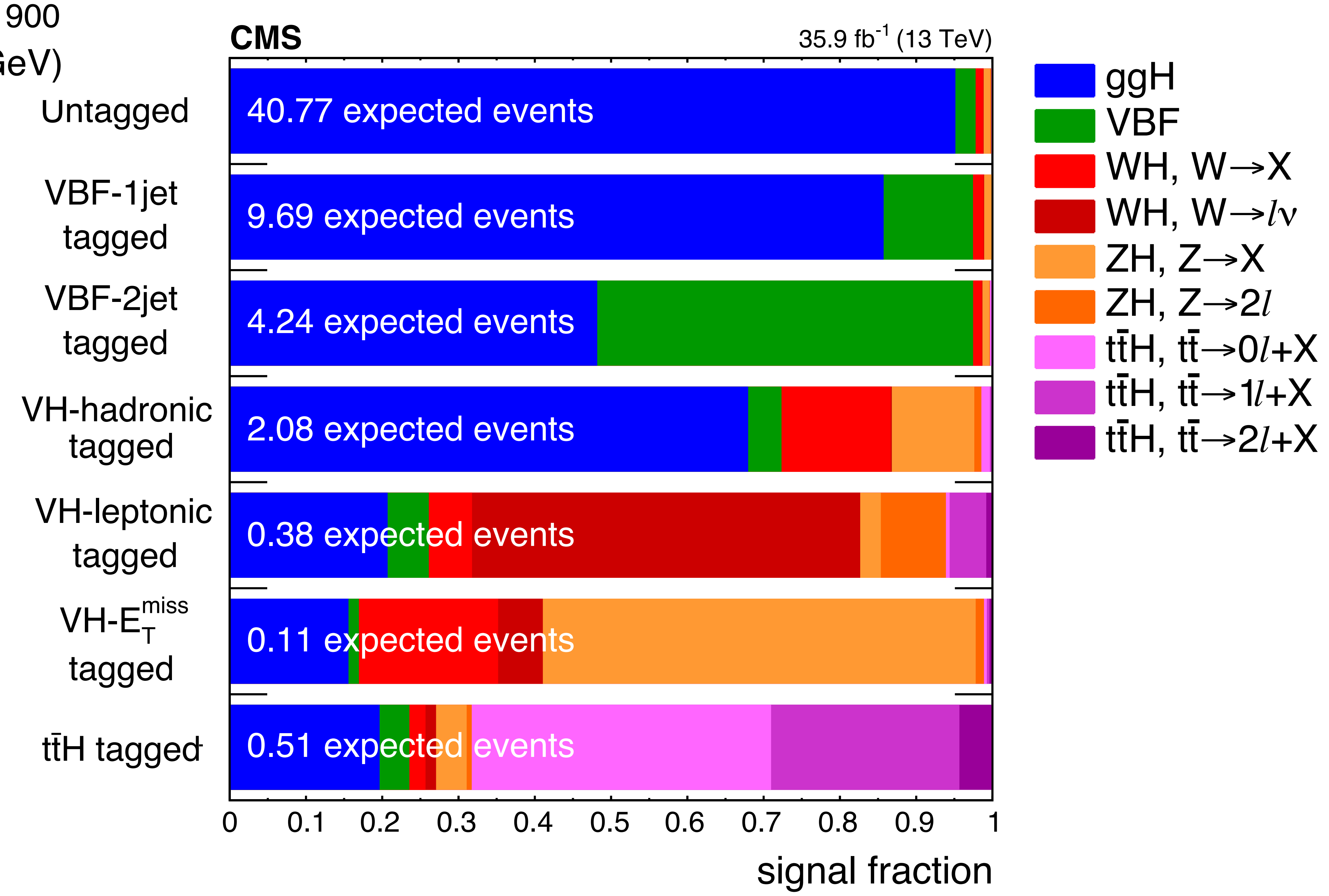
H→ZZ*→4l



Low signal rate, but very clear topology with a small background (mainly qqZZ, Z+jets)

- 4 isolated leptons in final state combined in 2 Z pairs
- Can exploit kinematical information (matrix element KD discriminants) to separate signal and background and categorise events in different production modes.
- Can probe 4 different production modes (ggH, VBF, ttH, VH)





Untagged events

4leptons+1jet+high KD

4leptons+{2,3,4}non b-jets+high KD

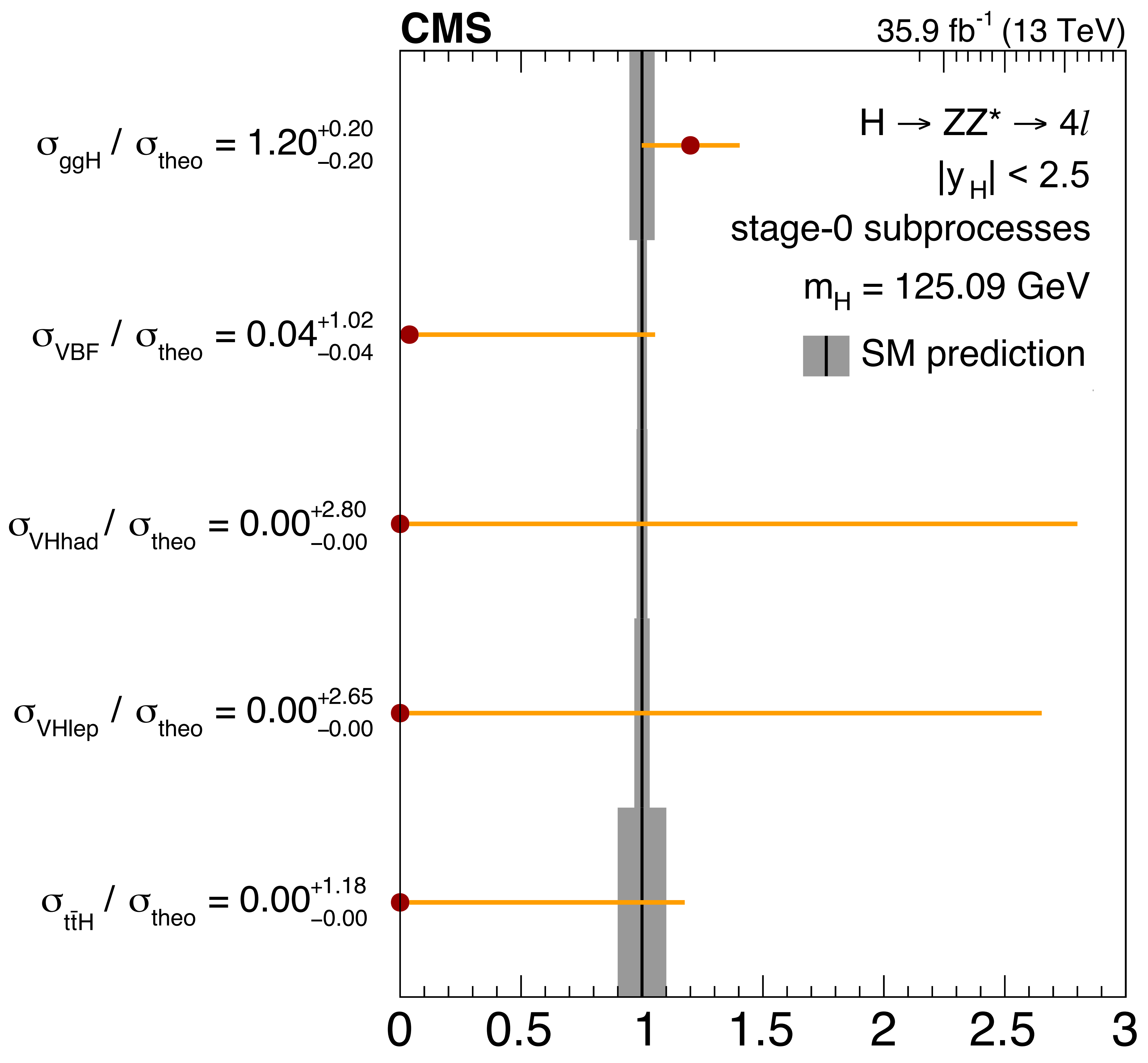
5-6leptons+≤3 non-b jets

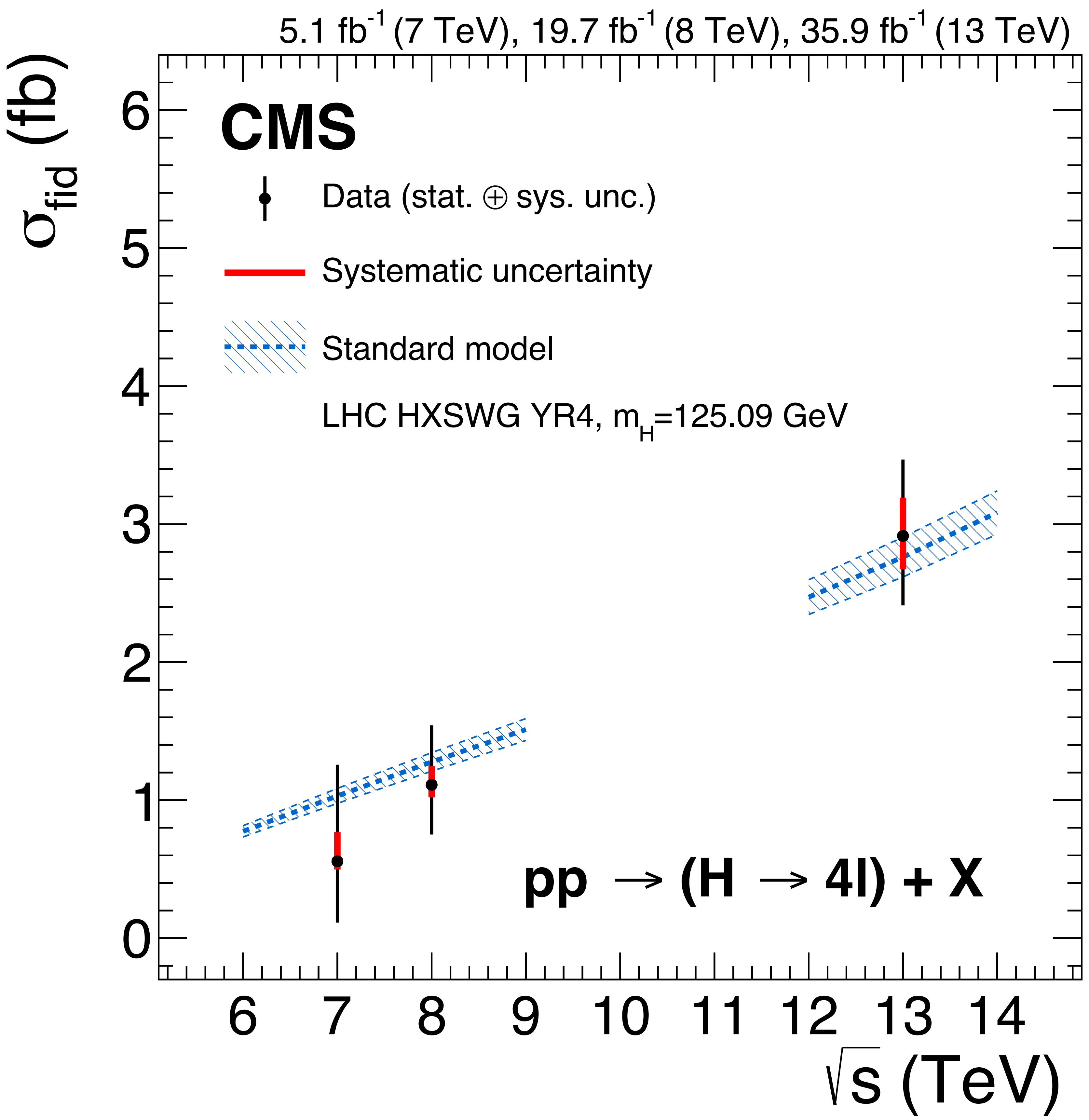
4leptons +{2,3,4}non b-jets+high KD

4leptons + <2 jets + E_T^{miss}>100GeV

4leptons+4 jets (≥1b-tag) or 1 lepton

Cross sections





Good agreement between prediction and observation

Slight overfluctuation in ggH→ZZ forces the other production modes to ~0

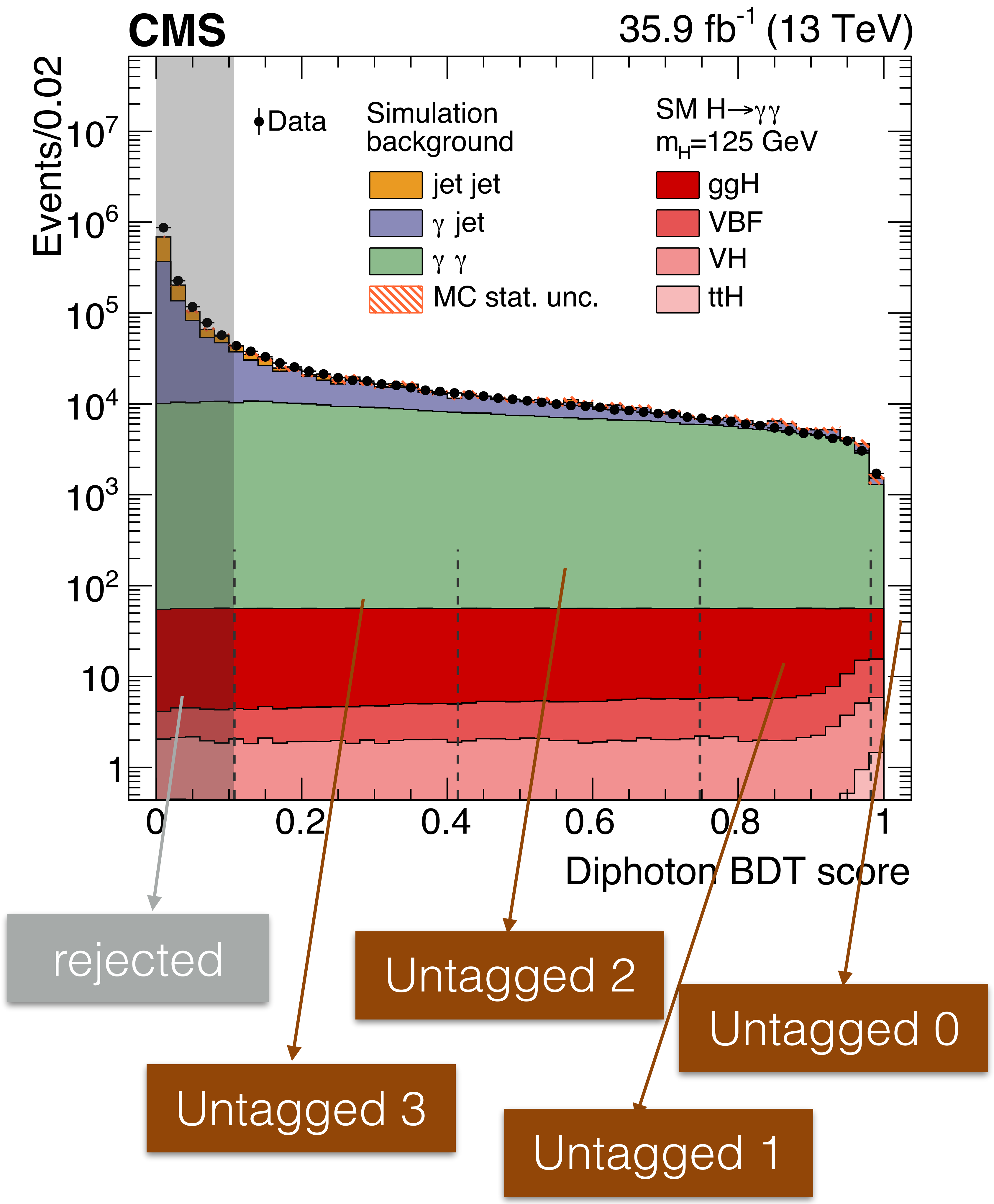
JHEP 11 (2017) 047

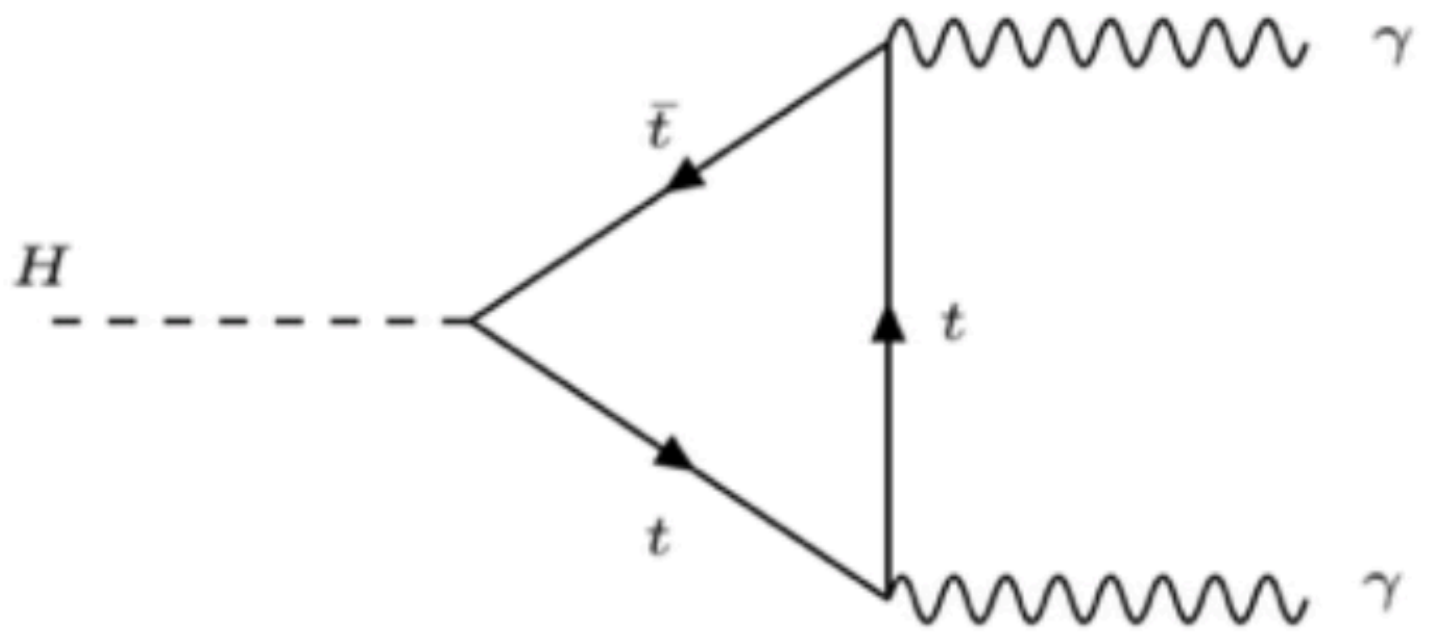
Differential distributions

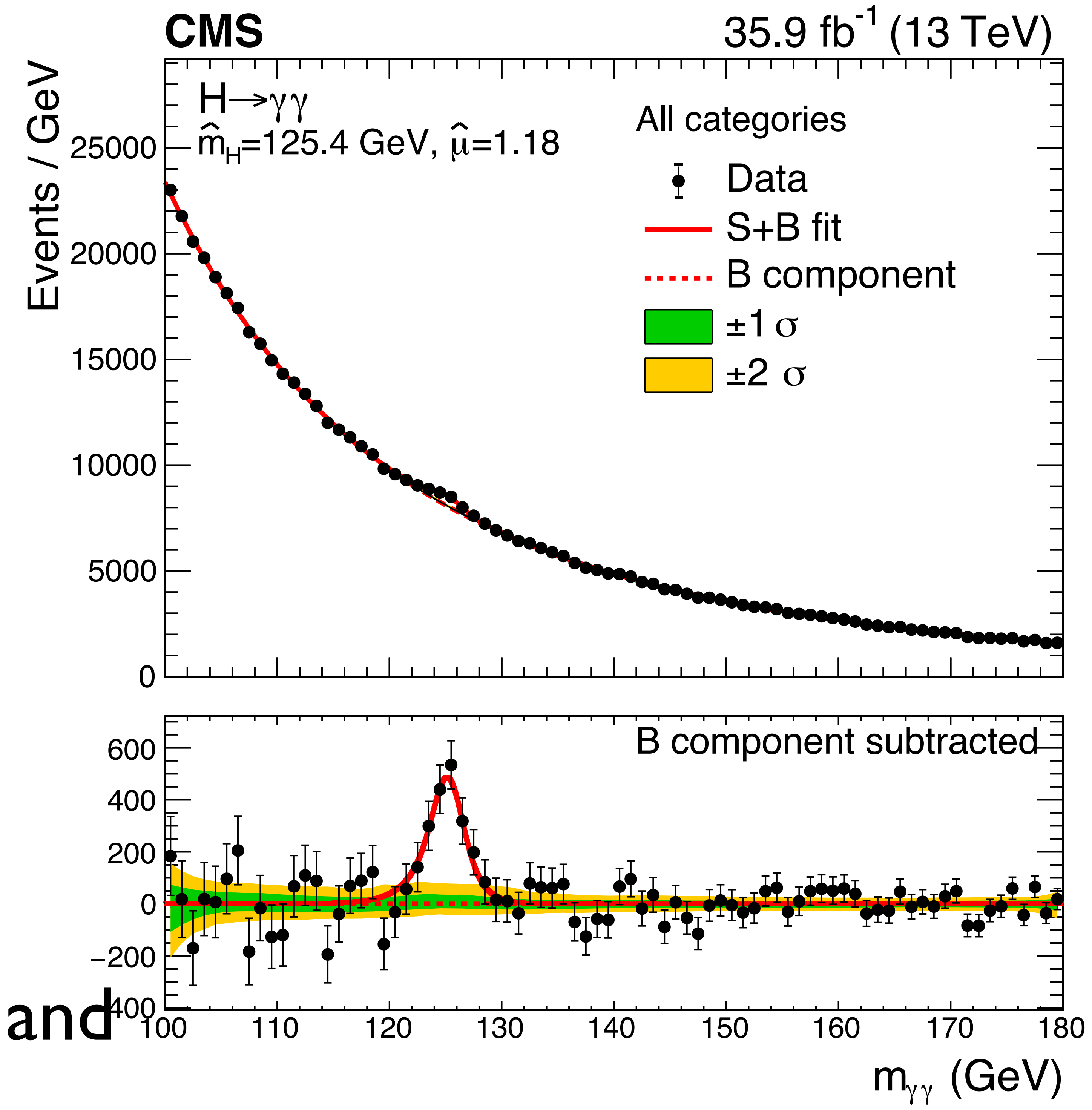
No significant deviation from SM predictions

Experimental uncertainties are reaching NLO theoretical uncertainties (in the 0-jet bin)

The H→γγ channel







Very clean channel for discovery and signal strength measurements

Search strategy: peak over (abundant) and regular background

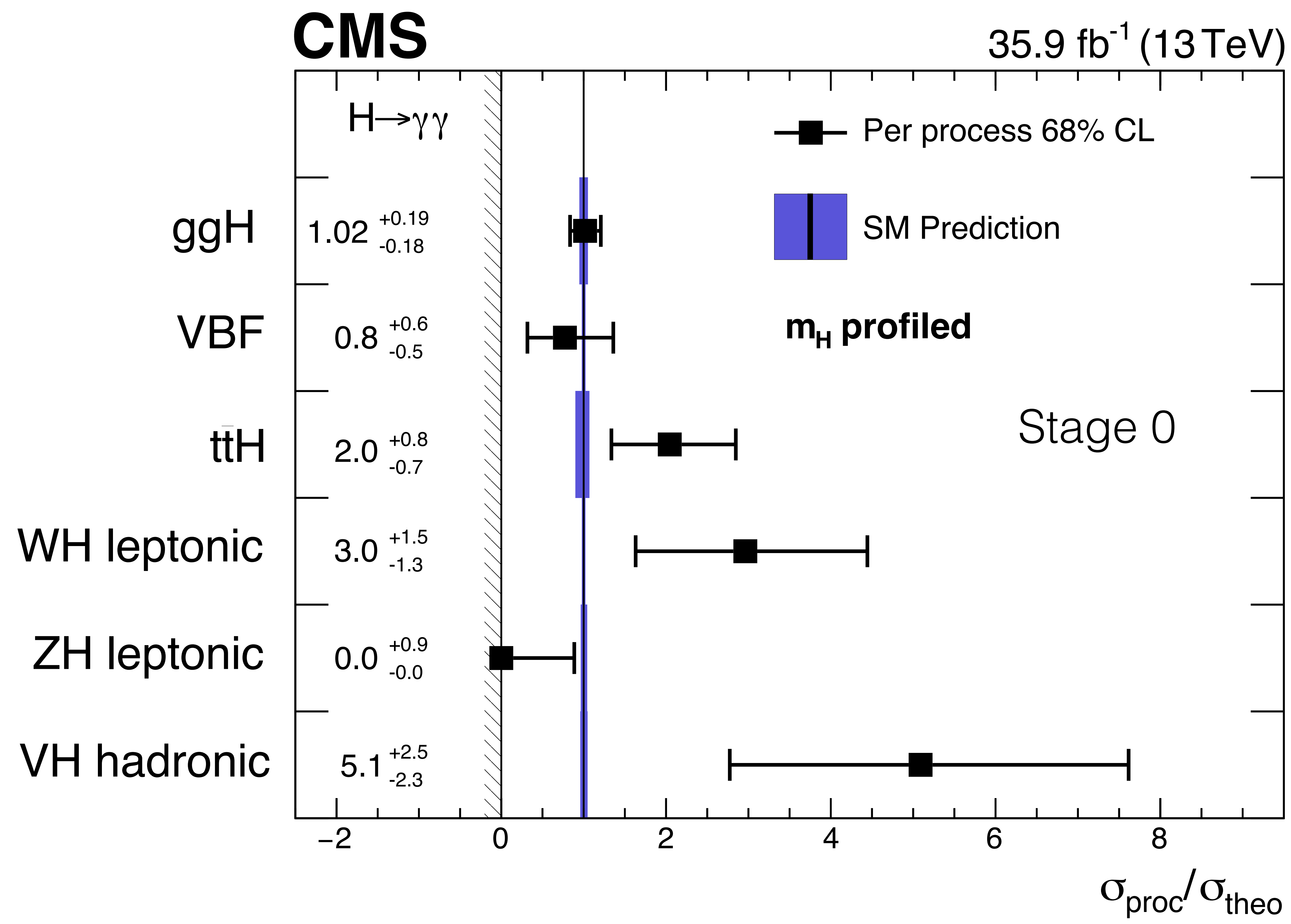
Vertex+photonID+kinematic BDT to select and classify the events

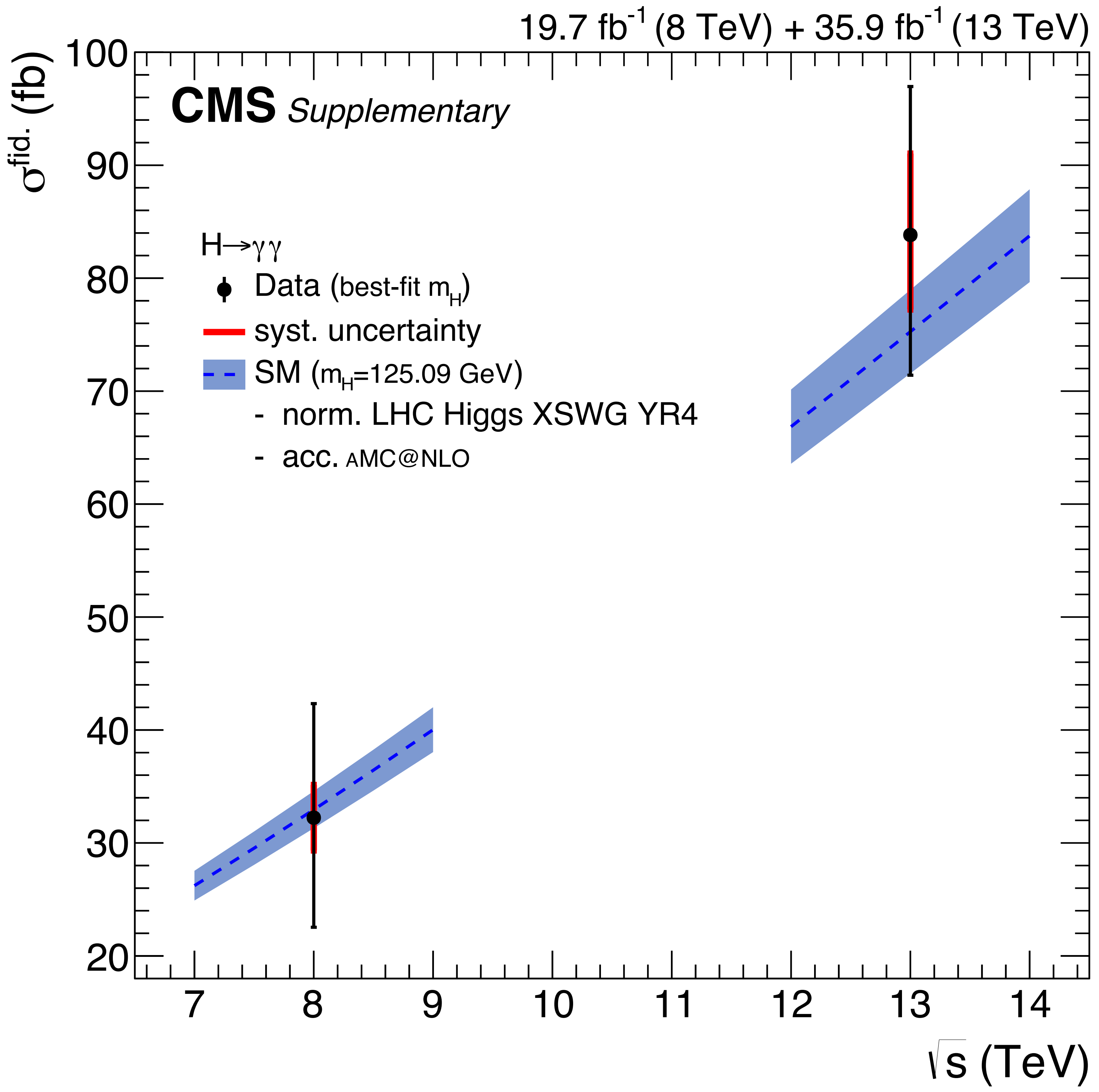
Indirect probe of coupling through production loops

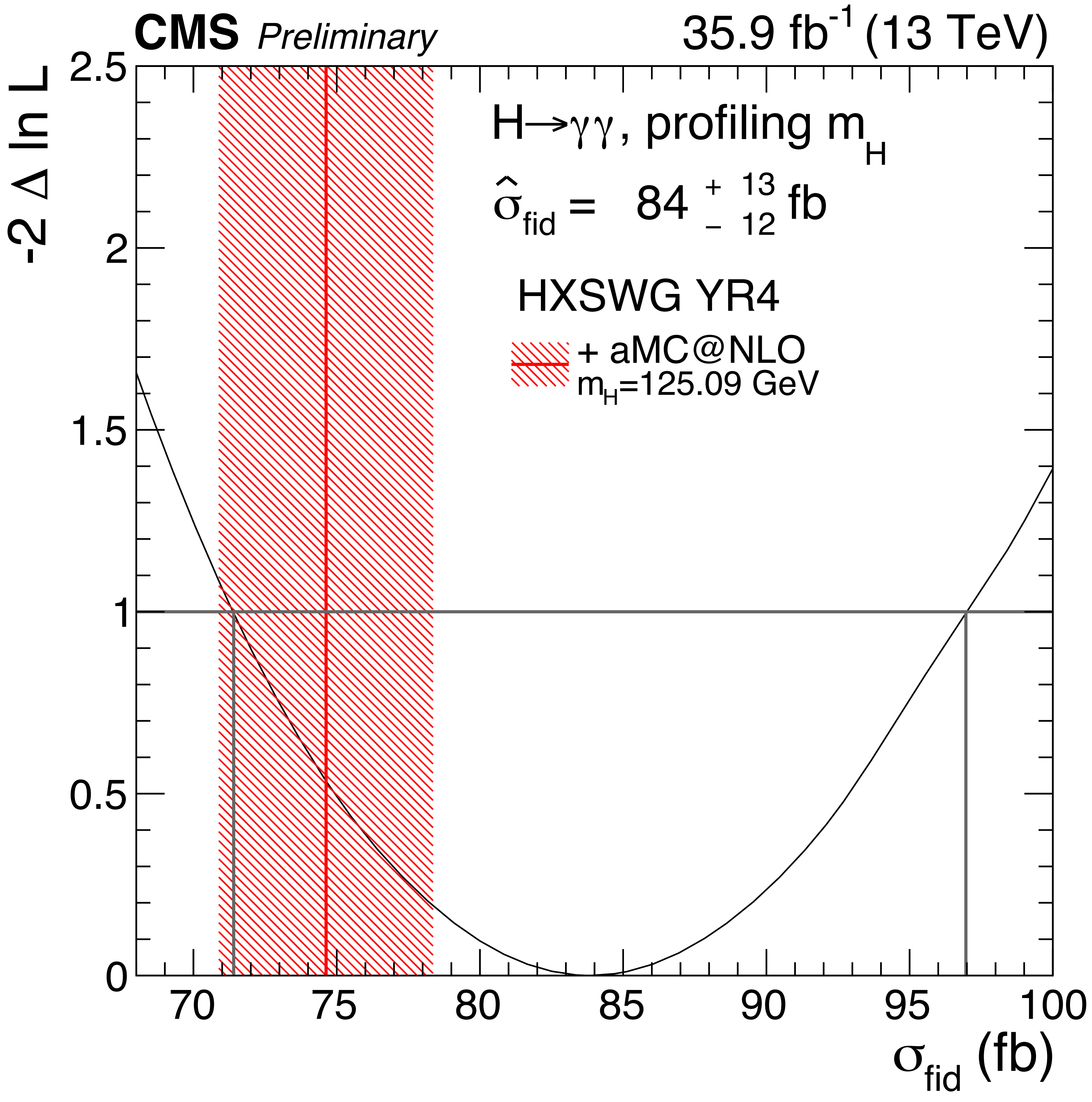
Categorisation (for STXS analysis):

- 4 untagged categories with different relative contributions of VH/ggH
- 2 ttH-tagged categories leptonic/hadronic top decay
- 3 VBF-tagged categories BDT-based
- 5 VH categories W/Z H leptonic, VH hadronic, VH+MET, VH lept. loose

$H\rightarrow\gamma\gamma$ Results, fiducial and STXS







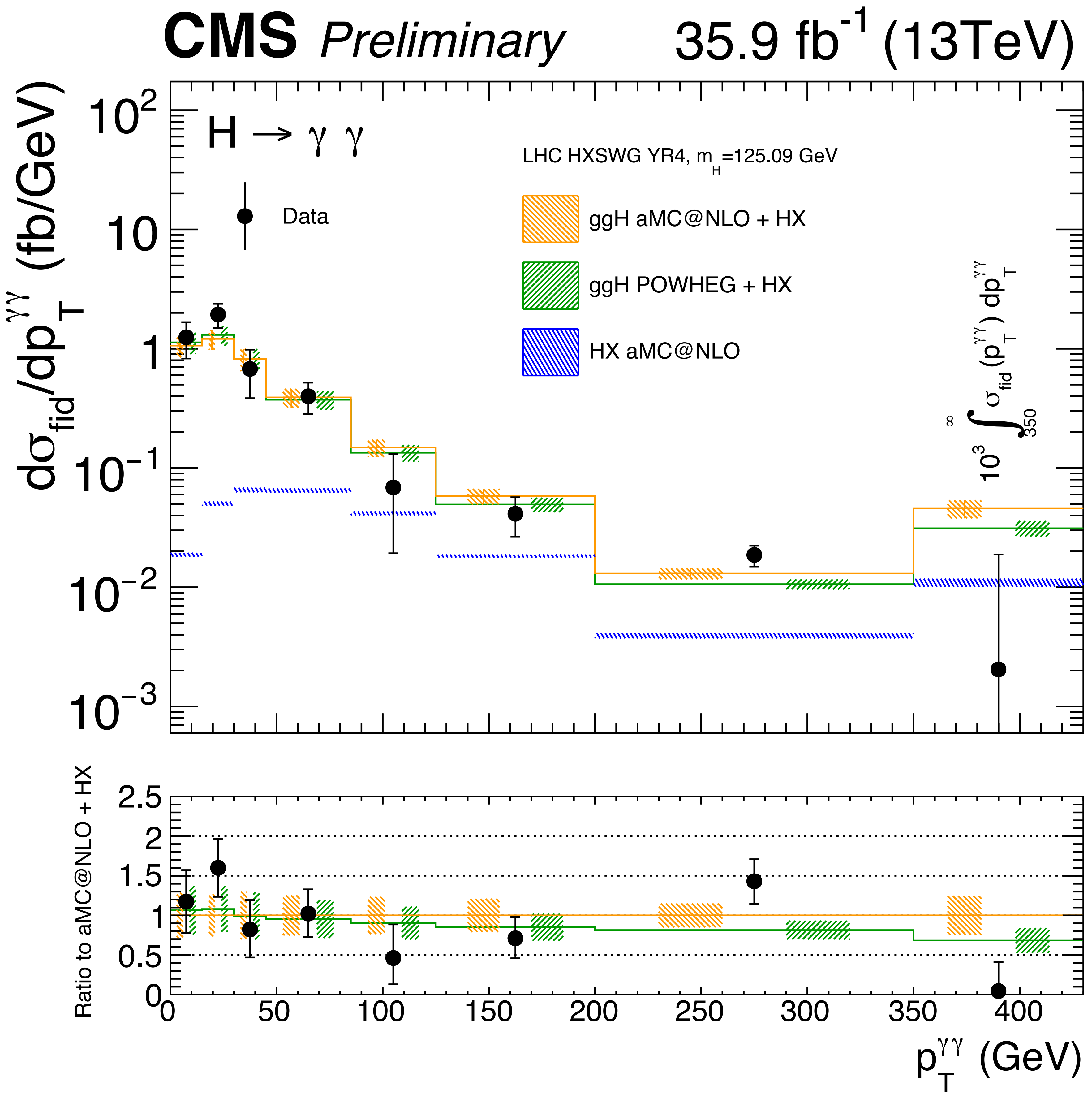
Fiducial cross section measurement phase space:

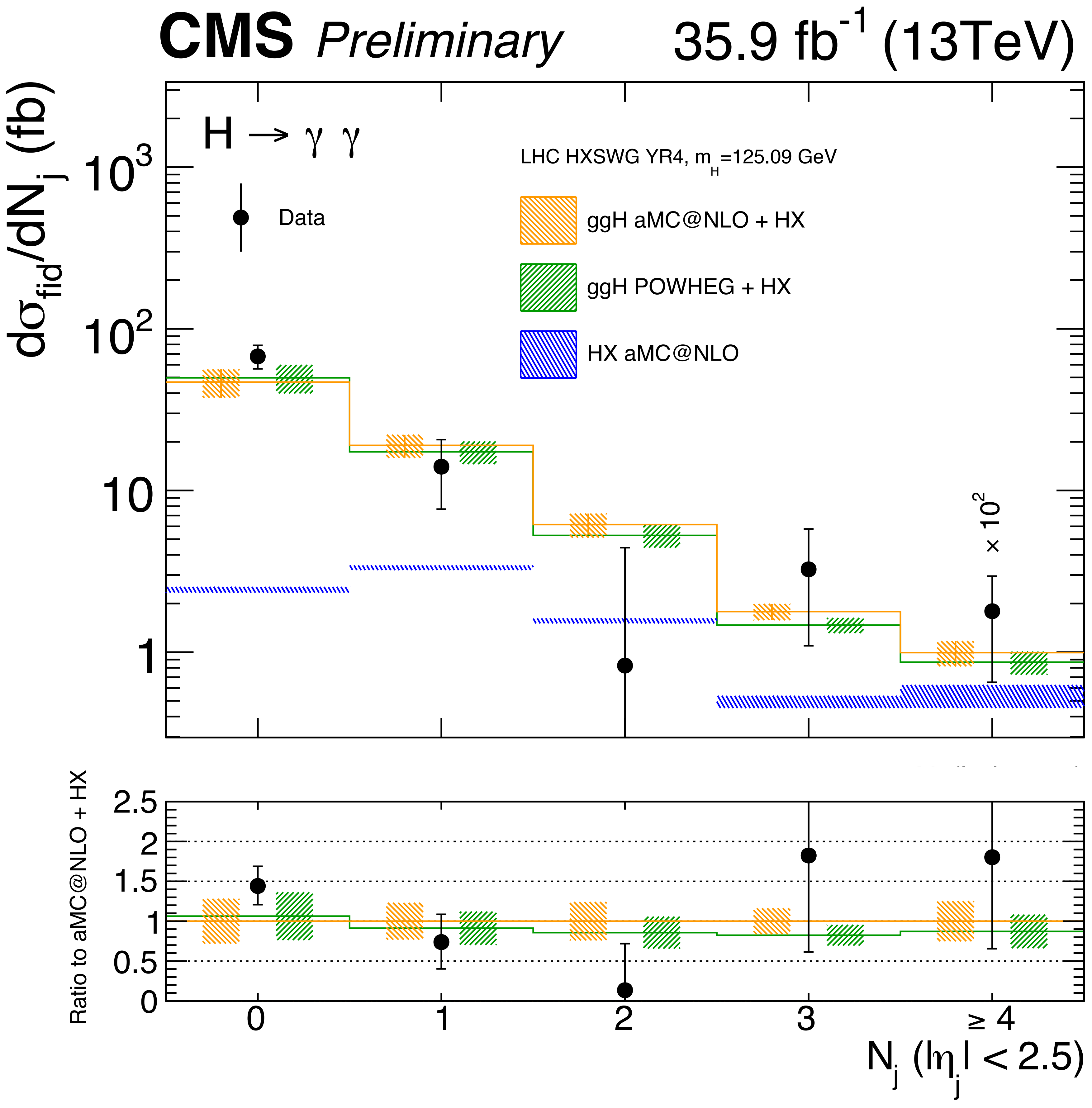
- 2 isolated photons, $|\eta| < 2.5$, $p_T^{1(2)}/m_{\gamma\gamma} > 1/3(4)$
- 3 categories based on σ_m/m_{decorr}

Both fiducial and STXS result in good agreement with SM expectations

CMS-PAS-HIG-17-015

H→γγ Results, differential





No deviations observed in the differential distributions

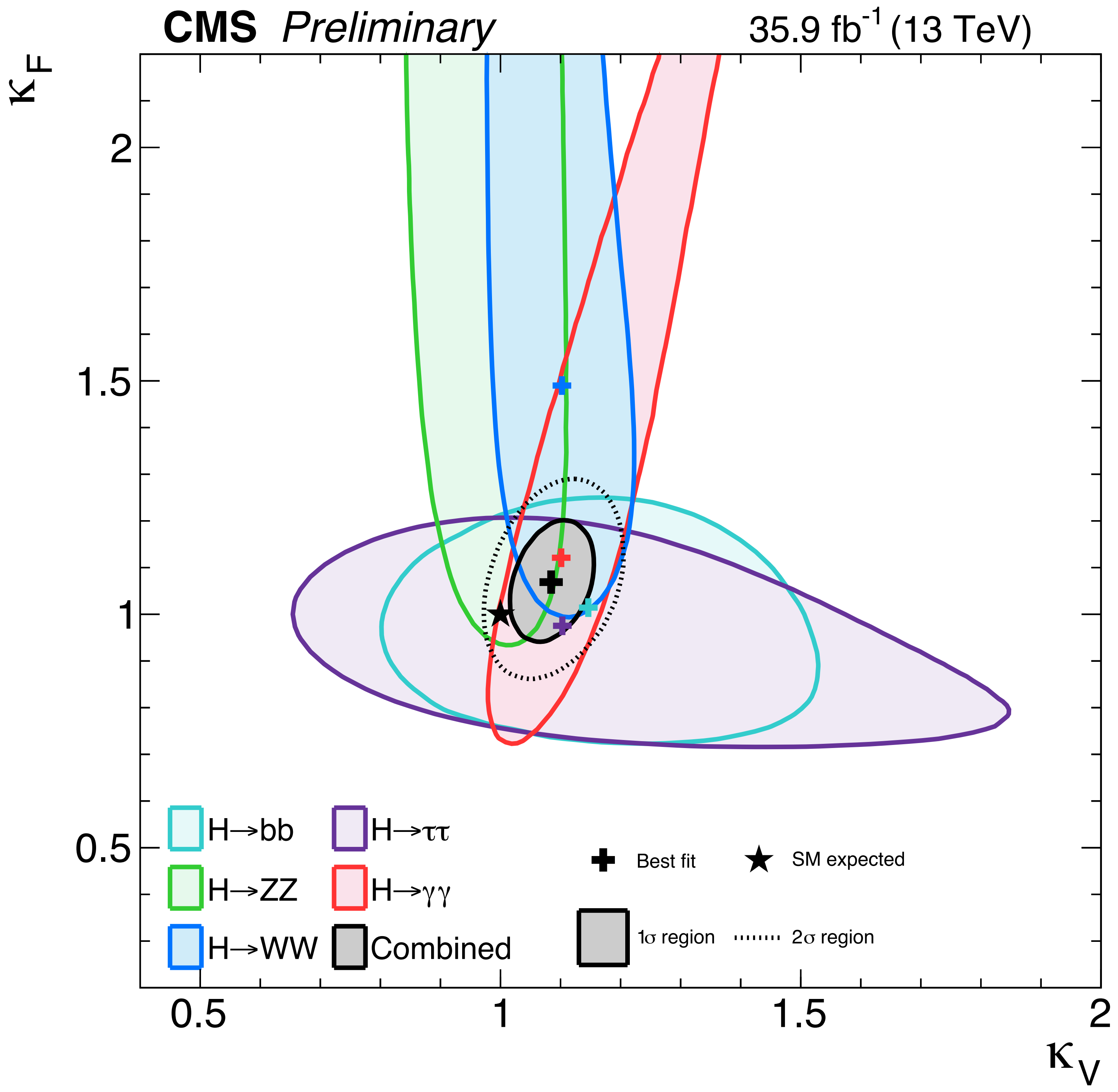
CMS-PAS-HIG-17-031

Combination of Higgs channels

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

Combination of all Higgs channels
Most general parametrisation: product of production x decay signal strength with all parameters floating

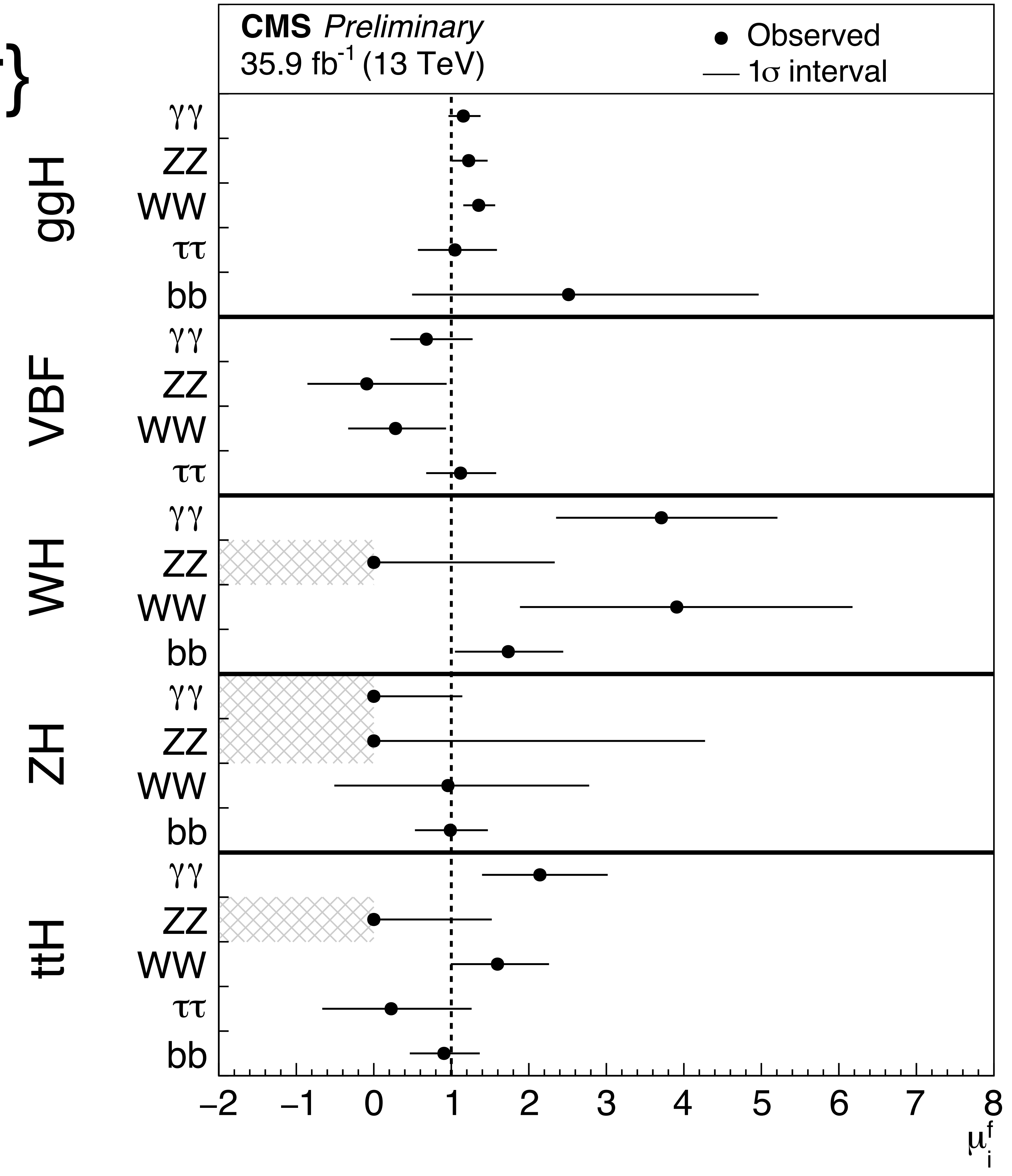
- 5x5 matrix μ_i={ggH, VBF, WH, ZH, ttH} x μ^f={**γγ**, ZZ, WW, bb, ττ}
- 22/25 measurements available



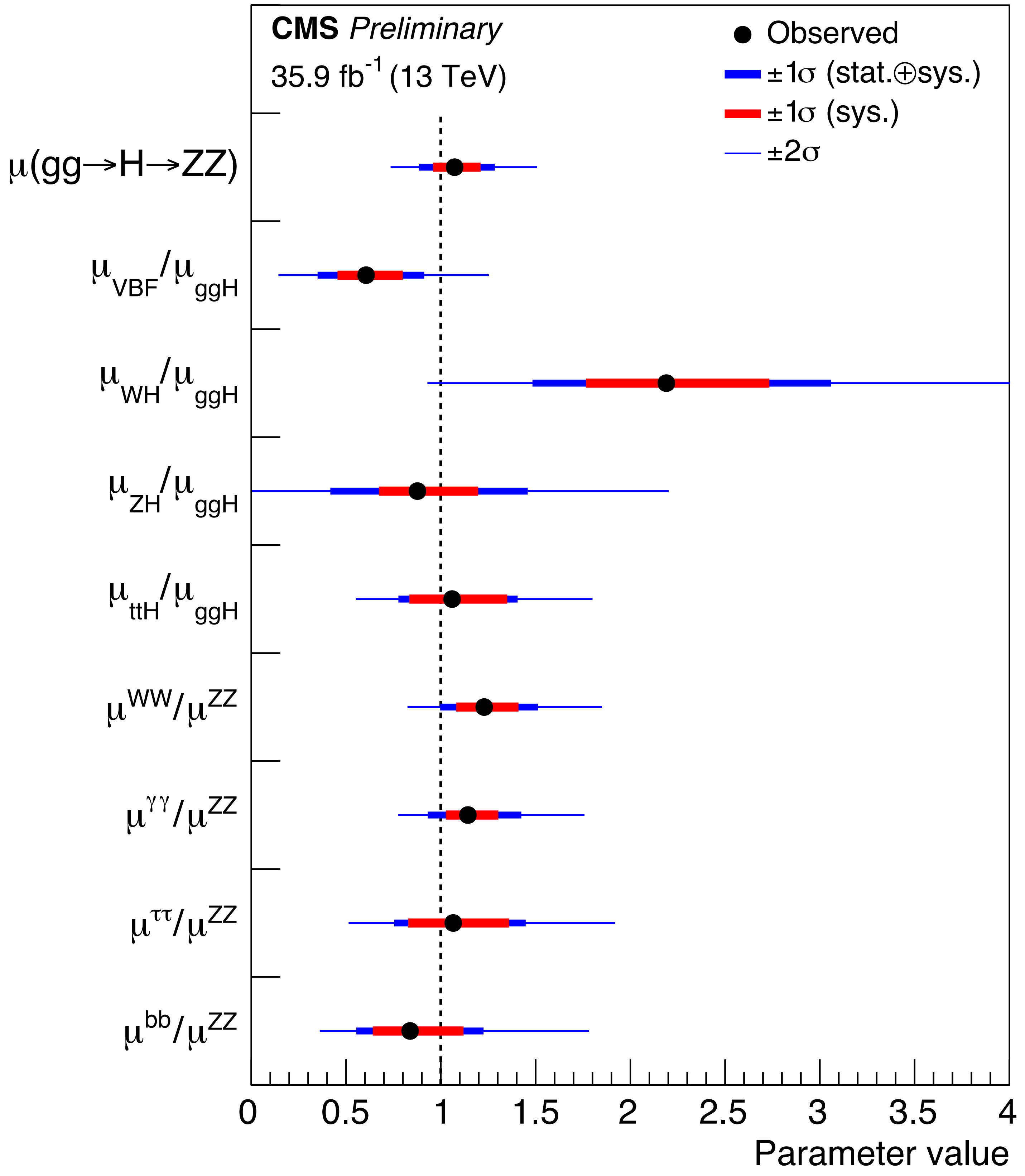
Different interpretations possible by applying constraints on μ_i, μ^f, i.e. STXS, ratios of cross sections

Global signal strength: μ=1.17±0.10

Picture consistent with SM expectations



Combination Result



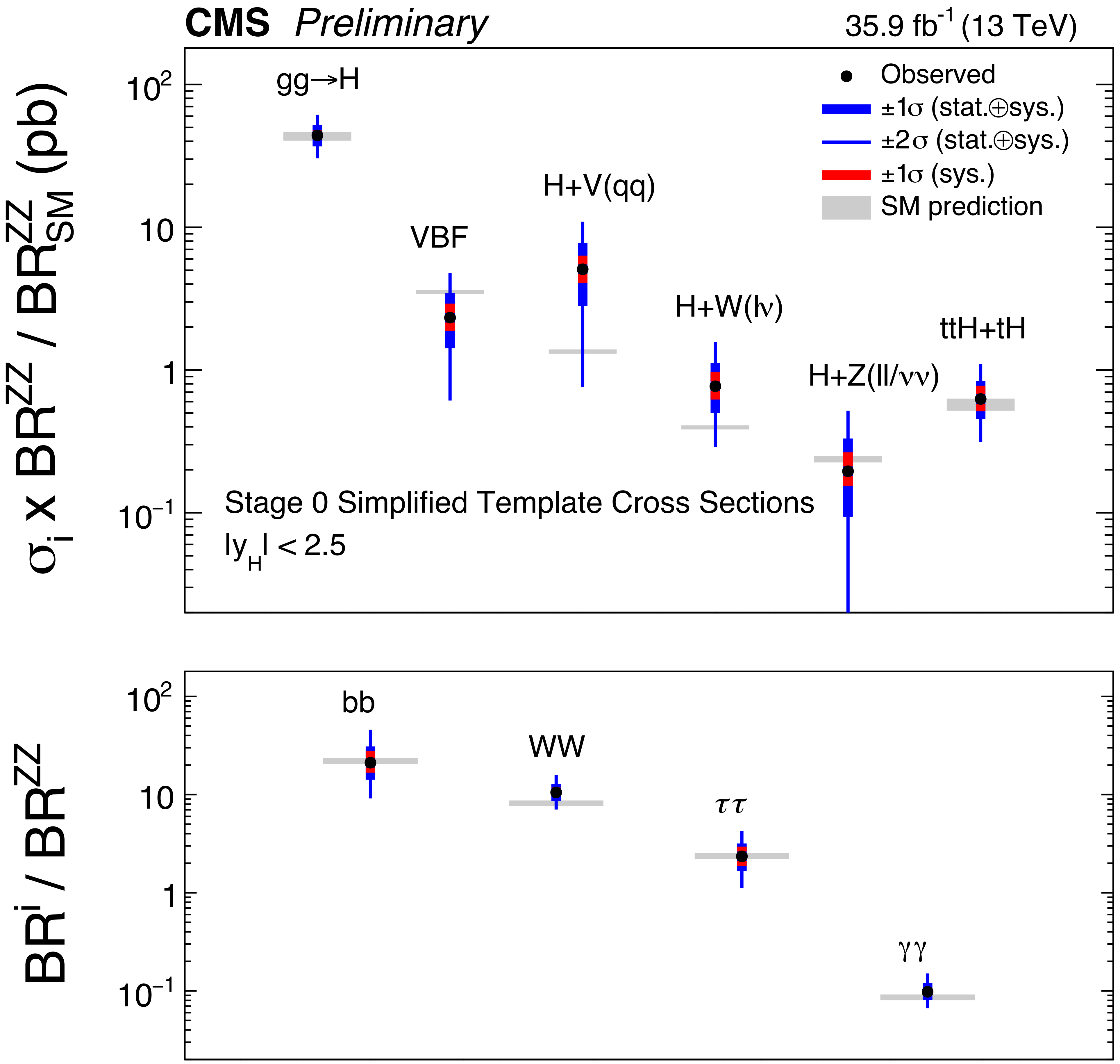
Ratio of signal strengths: helps reducing systematic uncertainties.

ggH→ZZ used as a reference as it is the most precise

Combined results STXS interpretation also provided (in the Stage-0 bins)

BRs are allowed to float in the fit

Measurement performed in fiducial region $|y_H|<2.5$



Future prospects: HL-LHC

Projection of $p_T(H)$ differential distribution at $3ab^{-1}$

H→ZZ channel only

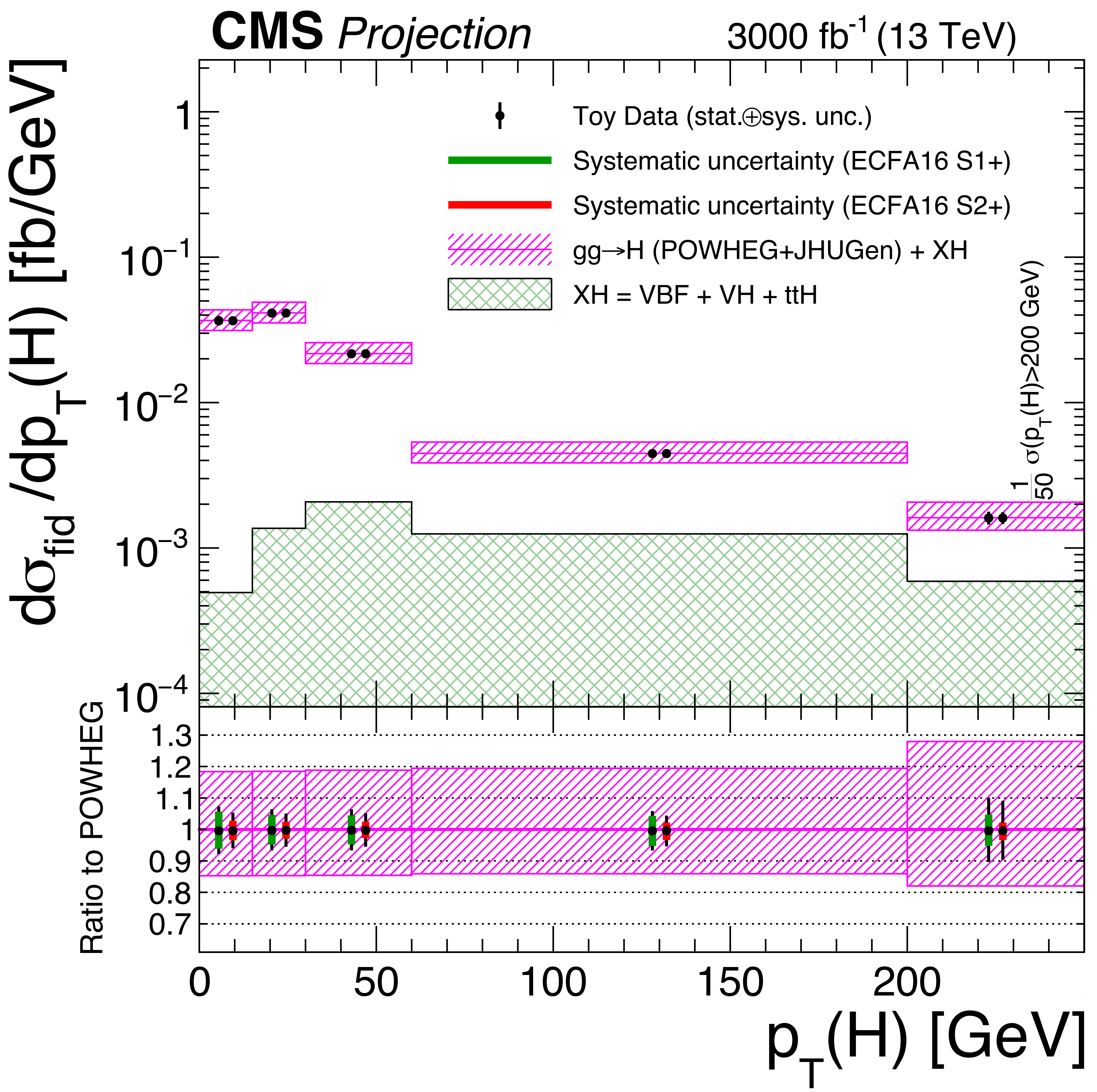
Uncertainties in each bin in the order of 5-10%

Slight dependence on the systematics scenarios

Still significant statistical component

Much better than current theoretical uncertainties

Correct th. uncertainties reached at ~$300fb^{-1}$



Summary and Conclusions

The CMS Collaboration is producing its first results on differential Higgs distributions at 13TeV

Fiducial and differential cross-section measurements have been reported in the $H\to ZZ$ and $H\to\gamma\gamma$ channels

The simplified template cross-section measurement has been reported for individual CMS channels and for their combination, displaying a nice agreement with SM expectations

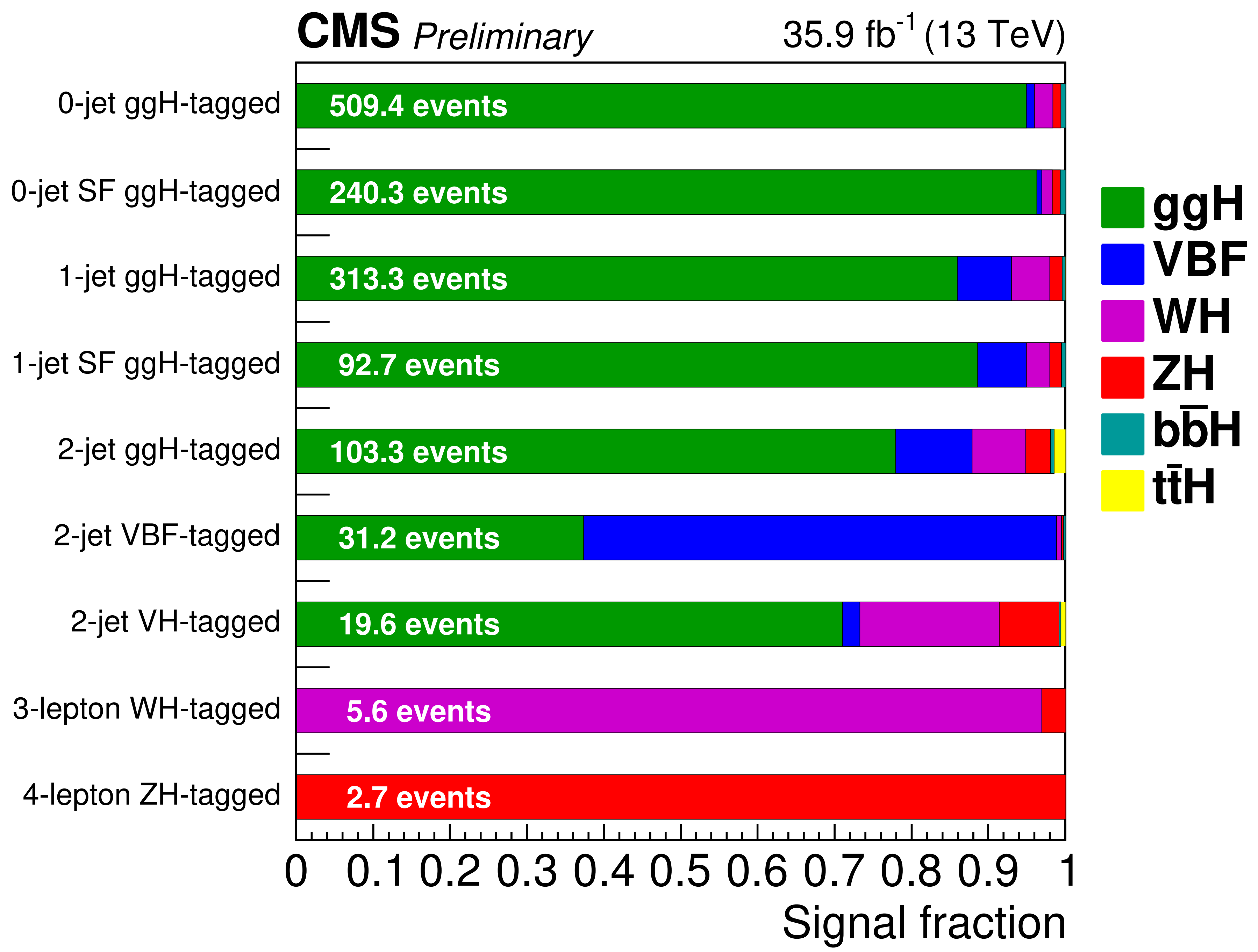
Combination of the differential results is underway

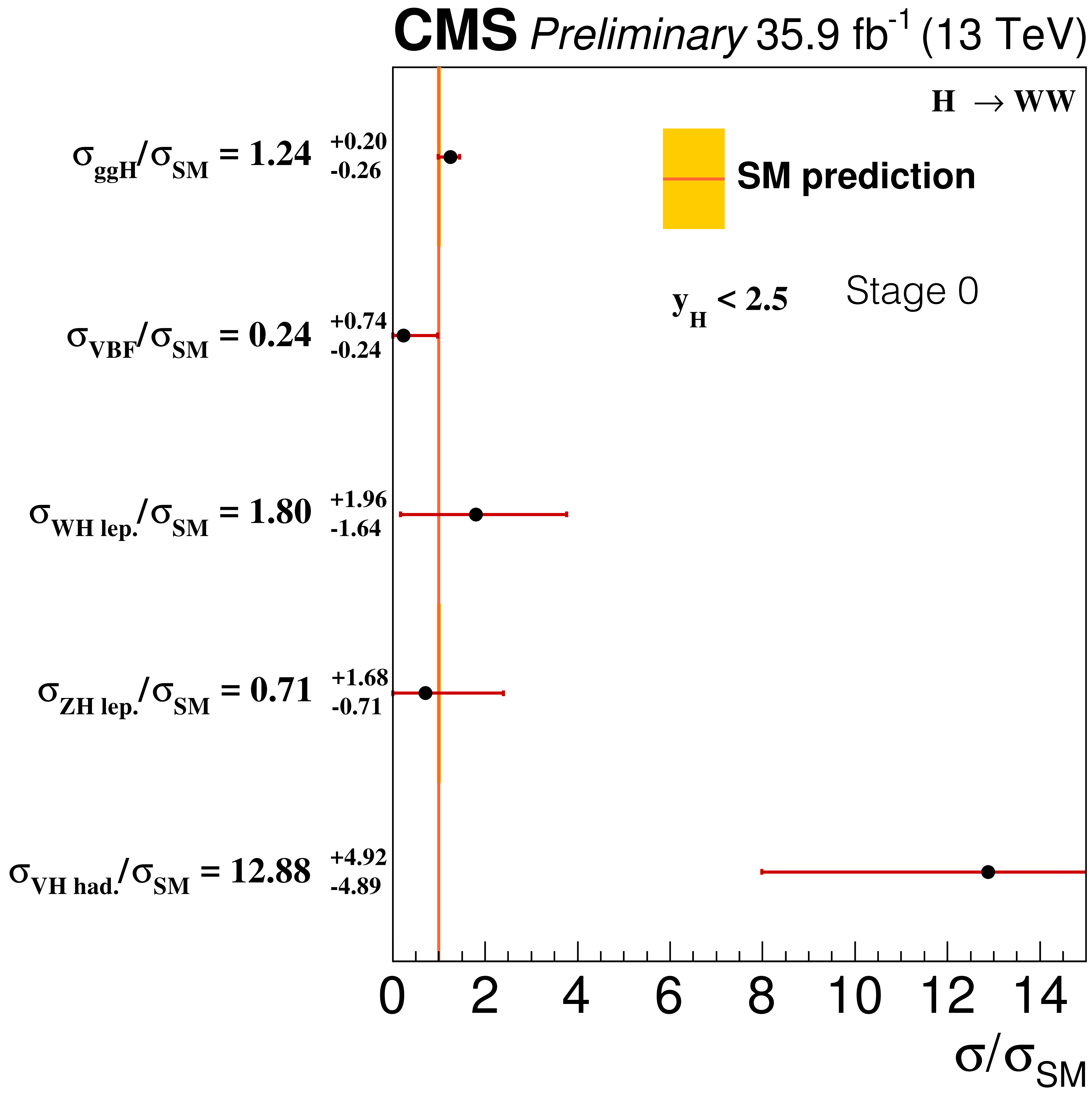
Experimental sensitivity in (some) differential observables is reaching the NLO precision

No significant deviations from the SM prediction have (yet?) been observed

Backup

H→WW, STXS





Differential H observables are still out of reach

Stage-0 STXS analysis shows general agreement with the SM predictions

2σ excess in VH-hadronic bin, mostly driven by 3-leptons WH-tagged category

K-framework and PO

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\rm SM} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{\rm SM}$$

$$\sigma_i \cdot {\rm BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\rm H}},$$

Total width determined as

$$\Gamma_{\rm H} = \frac{\kappa_H^2 \cdot \Gamma_H^{\rm SM}}{1 - {\rm BR}_{\rm BSM}}$$

Where

$$\kappa_H^2 = \sum_j {\rm BR}^j_{\rm SM} \kappa_j^2$$

At first, signal strengths μ (ratio of observed cross-section to SM predictions)

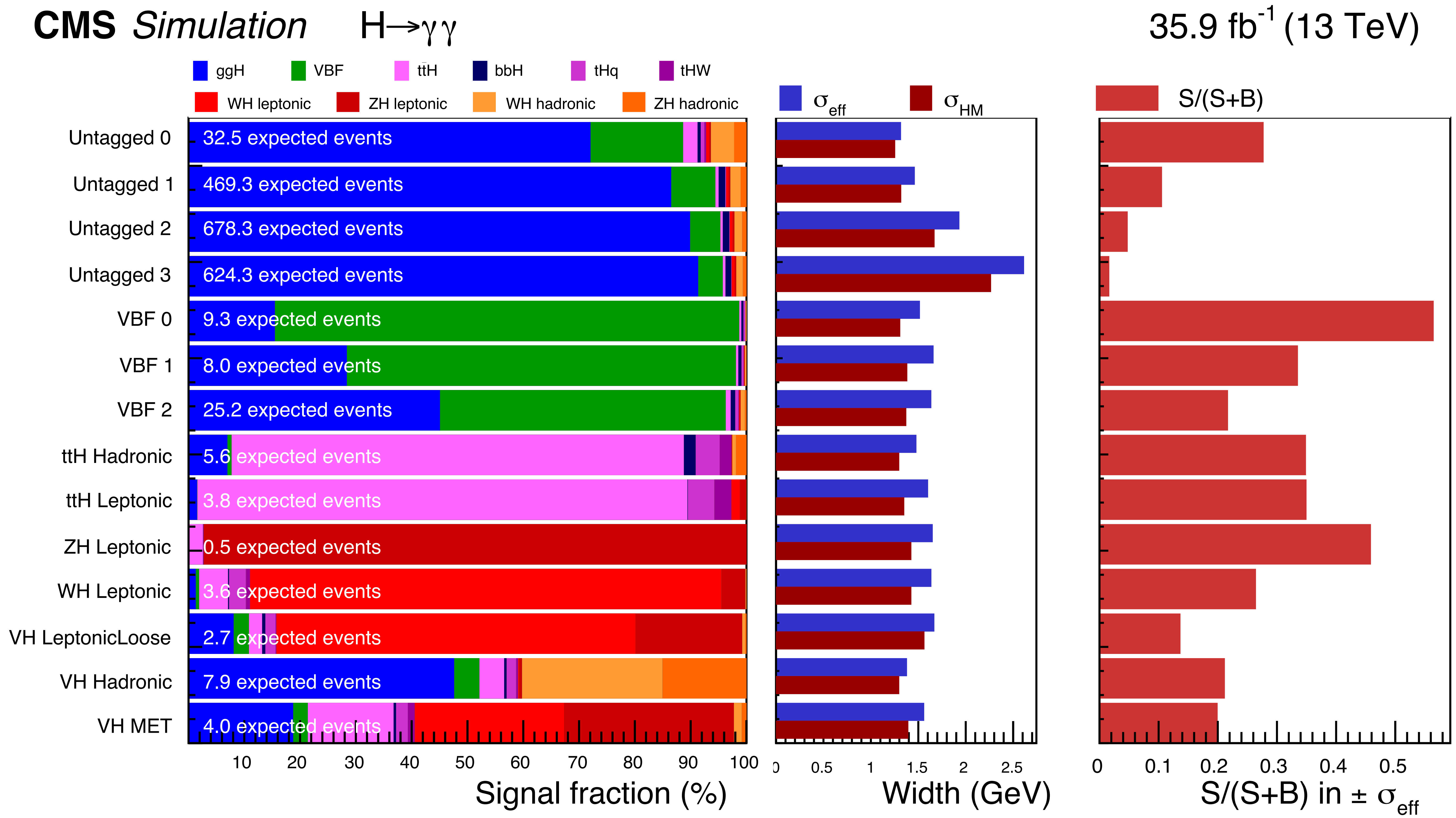
- Good to verify H(125) properties and to check compatibility with SM
- Not ideal parametrization when introducing NP

Second step, K-framework:

- Disentangles production and decay mechanisms. Notation $k_f = \{k_t, k_b, k_\tau\}$; $k_V = \{k_W, k_Z\}$
- Effective coupling modifiers for processes with loops (k_g, k_γ, k_H…)
- Also possible to describe as coupling modifier ratios $\lambda_{ij}=\kappa_i/\kappa_j$
- Production processes: ggF, VBF, WH, ZH, ttH
- Decay channels: HZZ,WW,$\gamma\gamma$,$\tau\tau$,bb,$\mu\mu$

Next step: PseudoObservables (not for this talk)

H→γγ



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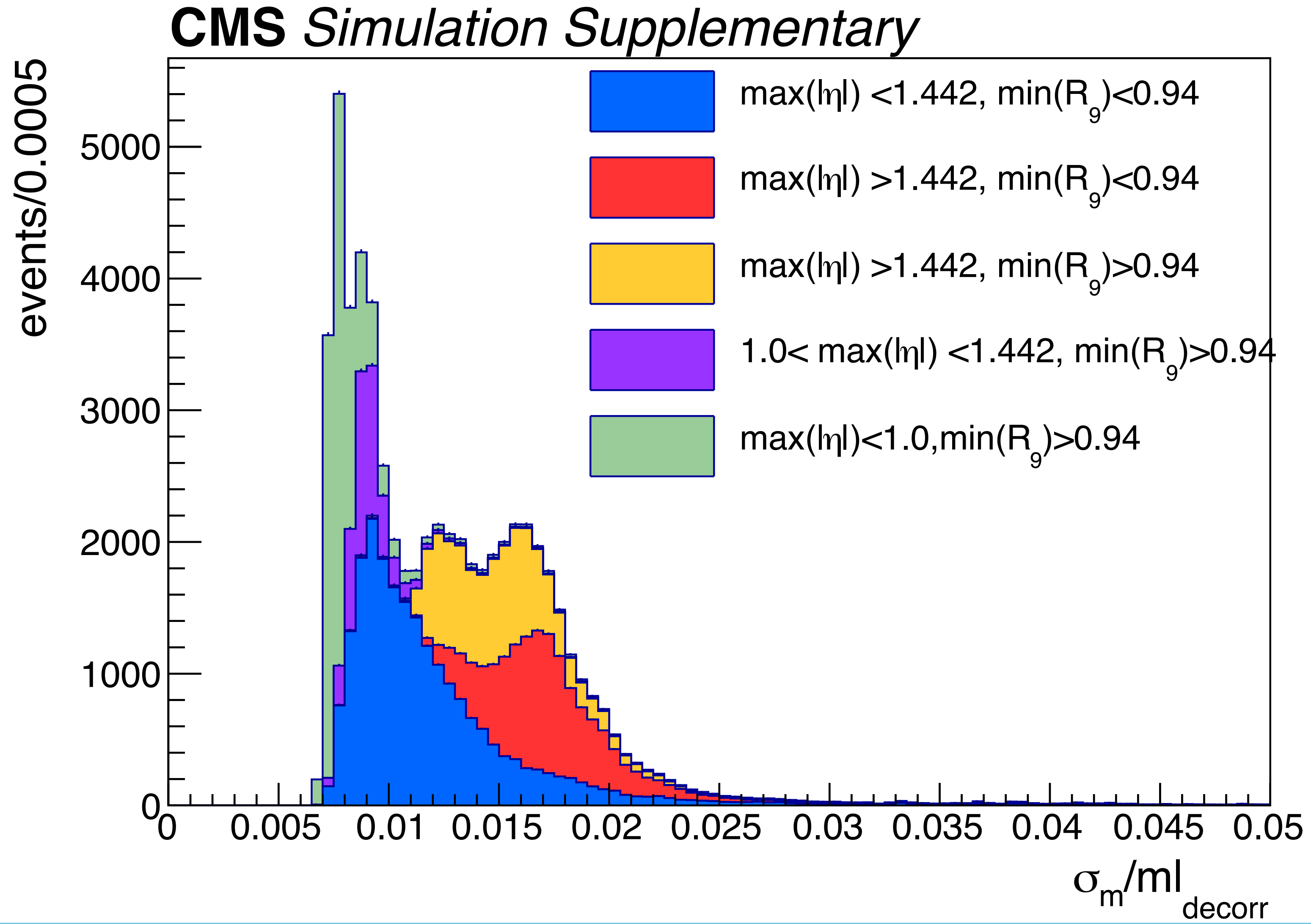

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HWW, yields

	Category				
	2-jet ggH-tagged	2-jet VBF-tagged	2-jet VH-tagged	3-lepton WH-tagged	4-lepton ZH-tagged
ggH	80.4 (100.6)	11.6 (14.6)	13.9 (17.4)	< 0.1 (< 0.1)	< 0.1 (< 0.1)
VBF	10.3 (13.3)	19.2 (24.5)	0.4 (0.6)	< 0.1 (< 0.1)	< 0.1 (< 0.1)
WH	7.2 (9.3)	0.2 (0.2)	3.6 (4.6)	5.4 (7.2)	< 0.1 (< 0.1)
ZH	3.3 (4.3)	< 0.1 (< 0.1)	1.5 (2.1)	0.2 (0.2)	2.7 (3.5)
$t\bar{t}H$	1.6 (2.1)	< 0.1 (< 0.1)	0.1 (0.2)	< 0.1 (< 0.1)	< 0.1 (< 0.1)
$b\bar{b}H$	0.6 (0.7)	< 0.1 (0.1)	< 0.1 (< 0.1)	< 0.1 (< 0.1)	< 0.1 (< 0.1)
Signal	103 (130)	31 (40)	20 (25)	5.6 (7.4)	2.7 (3.5)
± total unc.	(± 16)	(± 3)	(± 3)	(± 0.7)	(± 0.3)
WW	1048.3 (860.1)	69.4 (46.0)	52.0 (33.5)	< 0.1 (< 0.1)	< 0.1 (< 0.1)
top	5196.9 (5186.9)	157.0 (158.3)	229.9 (229.2)	< 0.1 (< 0.1)	0.3 (0.3)
Nonprompt	358.8 (305.0)	29.8 (20.0)	41.5 (37.1)	19.2 (21.2)	< 0.1 (< 0.1)
DY	110.2 (112.4)	20.4 (18.5)	28.9 (30.0)	< 0.1 (< 0.1)	< 0.1 (< 0.1)
$VZ/V\gamma^*$	136.0 (137.1)	7.1 (6.9)	10.5 (10.4)	< 0.1 (< 0.1)	< 0.1 (< 0.1)
$V\gamma$	58.8 (52.6)	2.8 (2.8)	4.2 (4.6)	3.8 (9.6)	< 0.1 (< 0.1)
Other diboson	2.1 (2.3)	0.3 (0.3)	1.2 (1.3)	28.6 (32.8)	12.7 (12.6)
Triboson	15.2 (15.3)	0.3 (0.3)	2.0 (2.0)	2.1 (2.1)	0.4 (0.4)
Background	6926 (6672)	287 (253)	370 (348)	57 (70)	13.3 (13.3)
± total unc.	(± 502)	(± 17)	(± 37)	(± 7)	(± 0.6)
Data	6802	285	386	85	15

CMS-PAS-HIG-17-031

Combination Result, stage 0

Parameter	Best fit	Uncertainty Stat.	Uncertainty Syst.	Parameter	Best fit	Uncertainty Stat.	Uncertainty Syst.
$\sigma_{ggH} \cdot BR^{ZZ}$	$1.00^{+0.19}_{-0.16}$ $\left(^{+0.18}_{-0.16}\right)$	$^{+0.16}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.09}_{-0.07}$ $\left(^{+0.09}_{-0.07}\right)$	BR^{bb}/BR^{ZZ}	$0.96^{+0.45}_{-0.32}$ $\left(^{+0.58}_{-0.38}\right)$	$^{+0.32}_{-0.25}$ $\left(^{+0.40}_{-0.29}\right)$	$^{+0.31}_{-0.20}$ $\left(^{+0.42}_{-0.25}\right)$
$\sigma_{VBF} \cdot BR^{ZZ}$	$0.66^{+0.32}_{-0.26}$ $\left(^{+0.40}_{-0.32}\right)$	$^{+0.27}_{-0.22}$ $\left(^{+0.33}_{-0.28}\right)$	$^{+0.17}_{-0.13}$ $\left(^{+0.22}_{-0.16}\right)$	$BR^{\tau\tau}/BR^{ZZ}$	$0.99^{+0.35}_{-0.29}$ $\left(^{+0.36}_{-0.28}\right)$	$^{+0.24}_{-0.20}$ $\left(^{+0.26}_{-0.21}\right)$	$^{+0.25}_{-0.20}$ $\left(^{+0.26}_{-0.19}\right)$
$\sigma_{H+V(qq)} \cdot BR^{ZZ}$	$3.77^{+2.00}_{-1.69}$ $\left(^{+1.66}_{-1.06}\right)$	$^{+1.76}_{-1.51}$ $\left(^{+1.50}_{-1.06}\right)$	$^{+0.93}_{-0.75}$ $\left(^{+0.72}_{-0.00}\right)$	BR^{WW}/BR^{ZZ}	$1.29^{+0.29}_{-0.24}$ $\left(^{+0.24}_{-0.20}\right)$	$^{+0.24}_{-0.20}$ $\left(^{+0.20}_{-0.16}\right)$	$^{+0.17}_{-0.13}$ $\left(^{+0.14}_{-0.11}\right)$
$\sigma_{H+W(\ell\nu)} \cdot BR^{ZZ}$	$1.94^{+0.89}_{-0.68}$ $\left(^{+0.68}_{-0.53}\right)$	$^{+0.72}_{-0.57}$ $\left(^{+0.56}_{-0.44}\right)$	$^{+0.51}_{-0.37}$ $\left(^{+0.40}_{-0.29}\right)$	$BR^{\gamma\gamma}/BR^{ZZ}$	$1.14^{+0.26}_{-0.20}$ $\left(^{+0.23}_{-0.18}\right)$	$^{+0.22}_{-0.18}$ $\left(^{+0.21}_{-0.17}\right)$	$^{+0.13}_{-0.09}$ $\left(^{+0.11}_{-0.08}\right)$
$\sigma_{H+Z(\ell\ell/\nu\nu)} \cdot BR^{ZZ}$	$0.83^{+0.58}_{-0.43}$ $\left(^{+0.70}_{-0.47}\right)$	$^{+0.49}_{-0.39}$ $\left(^{+0.56}_{-0.41}\right)$	$^{+0.30}_{-0.17}$ $\left(^{+0.43}_{-0.22}\right)$			-	
$\sigma_{ttH} \cdot BR^{ZZ}$	$1.08^{+0.37}_{-0.29}$ $\left(^{+0.38}_{-0.31}\right)$	$^{+0.26}_{-0.22}$ $\left(^{+0.28}_{-0.24}\right)$	$^{+0.26}_{-0.19}$ $\left(^{+0.26}_{-0.20}\right)$			-	

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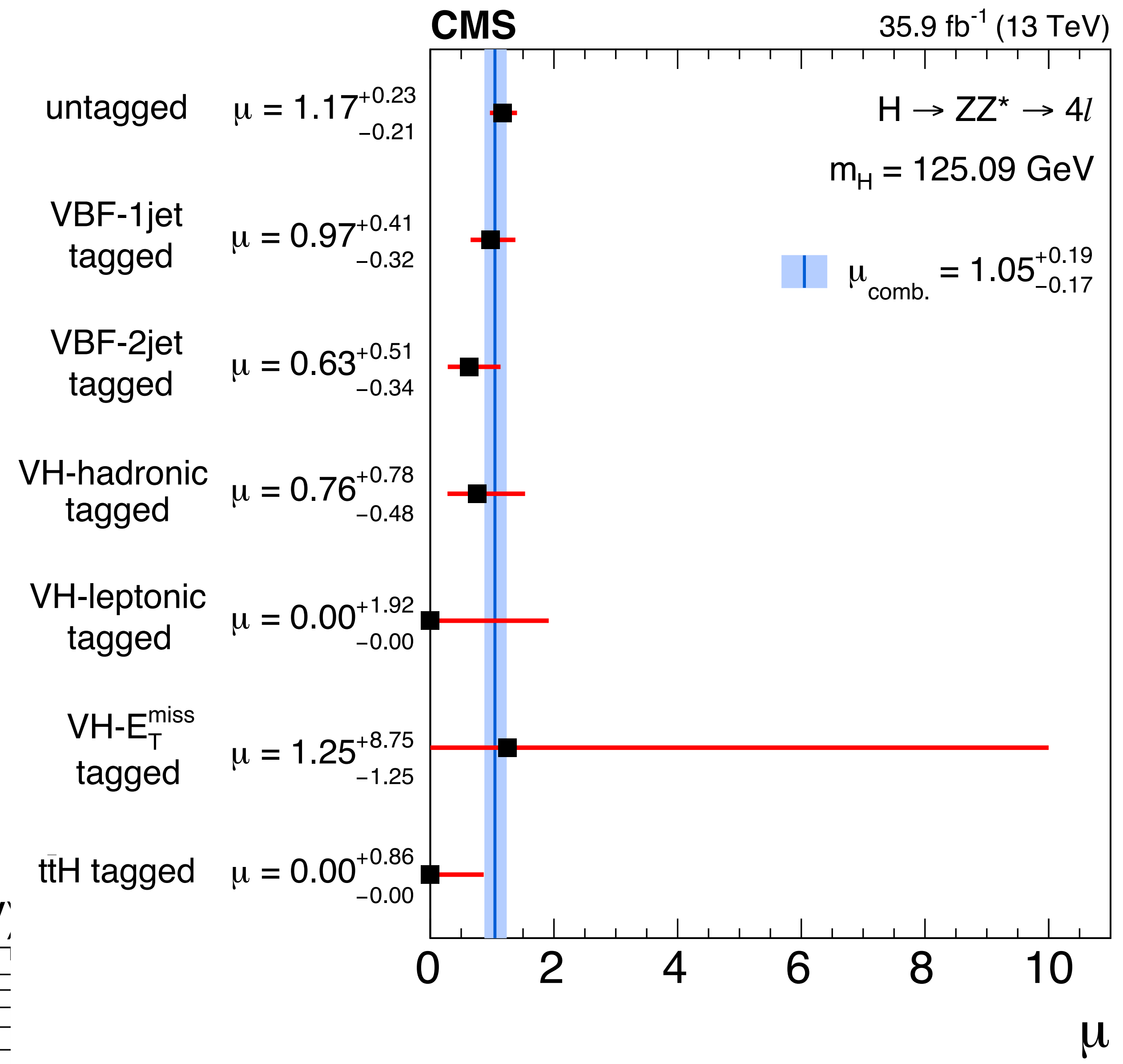
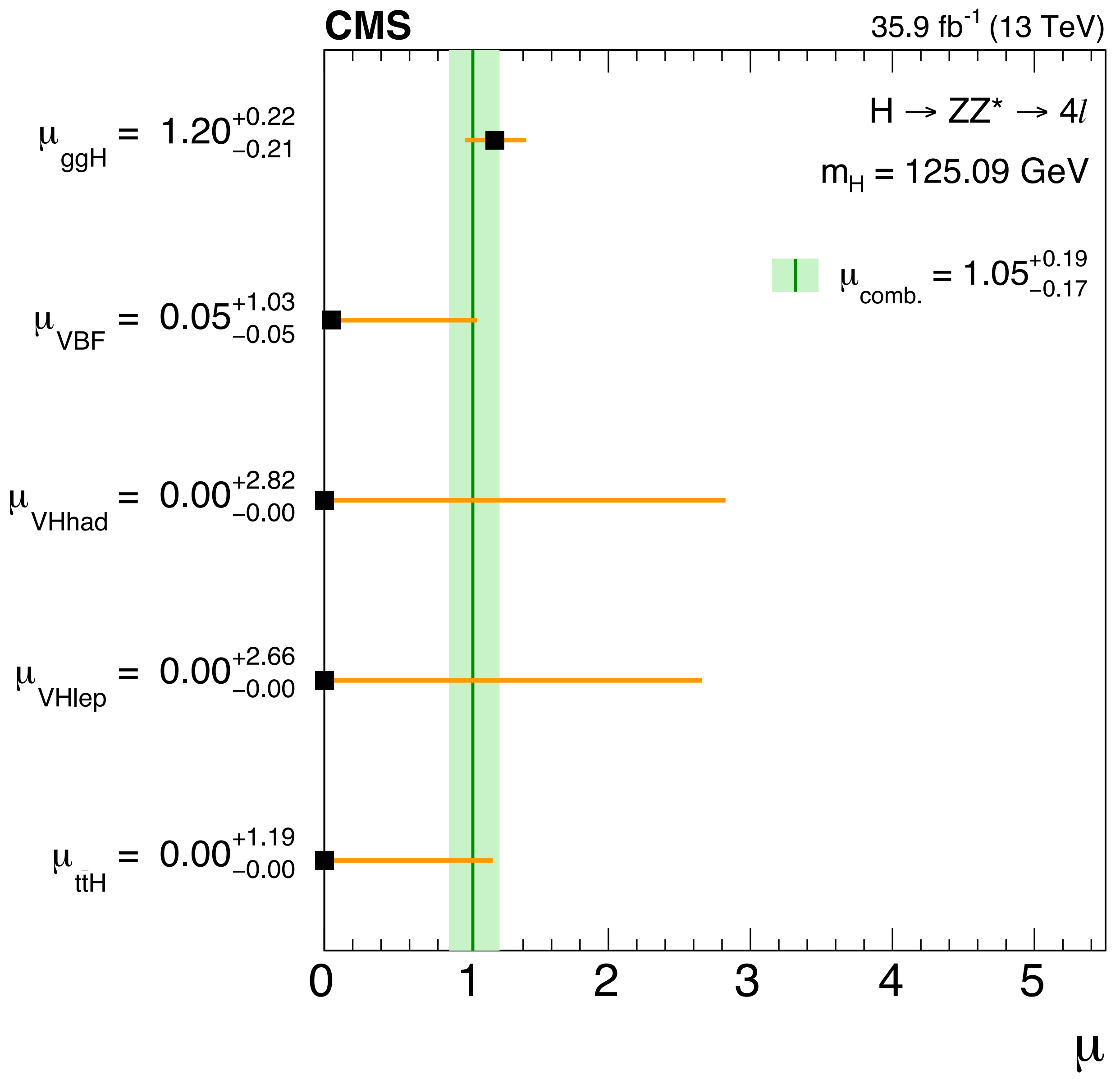
Higgs properties

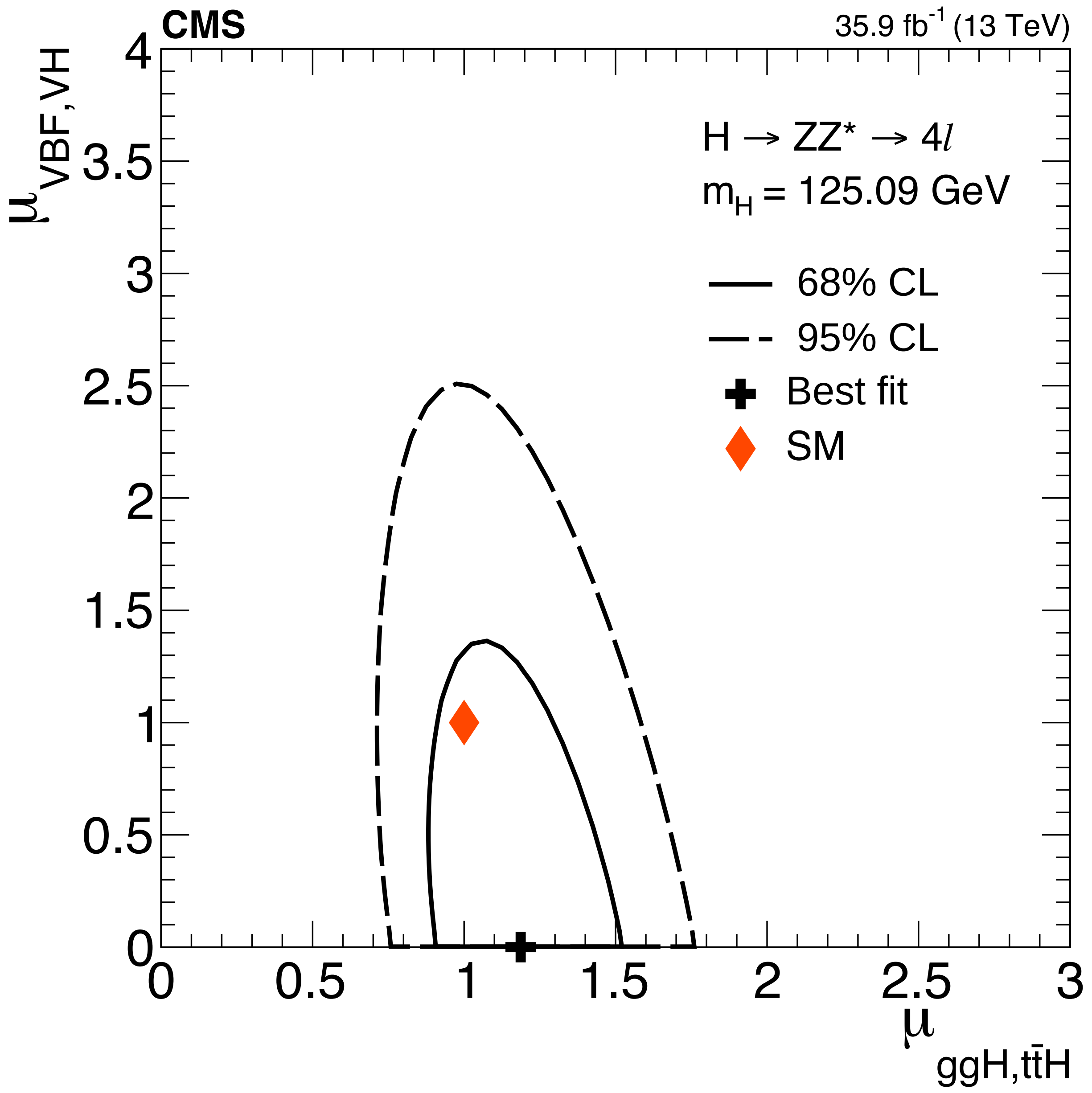
The excellent resolution and high S/B ratio makes the HZZ4l channel one of the best we have to determine the Higgs properties

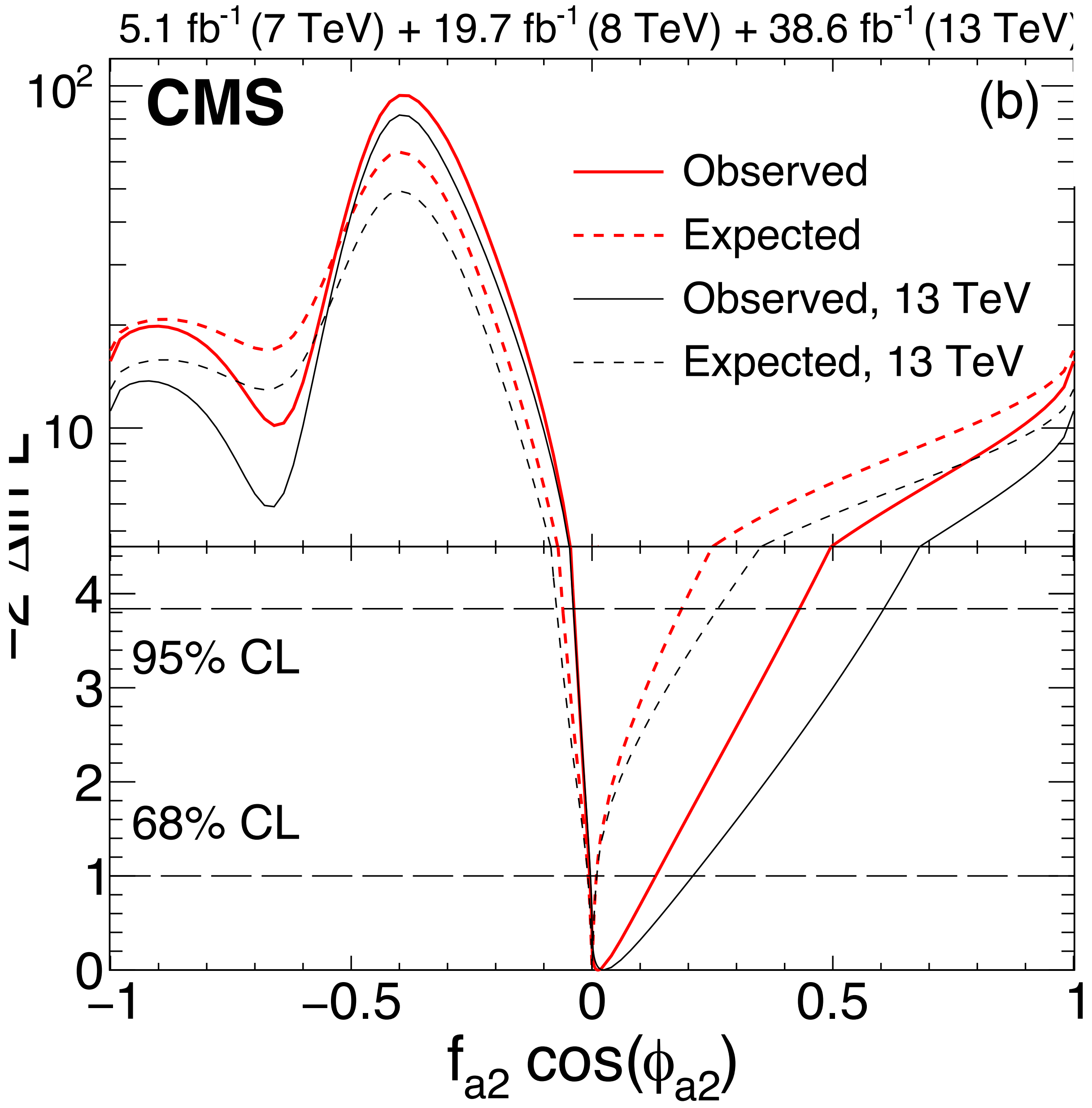




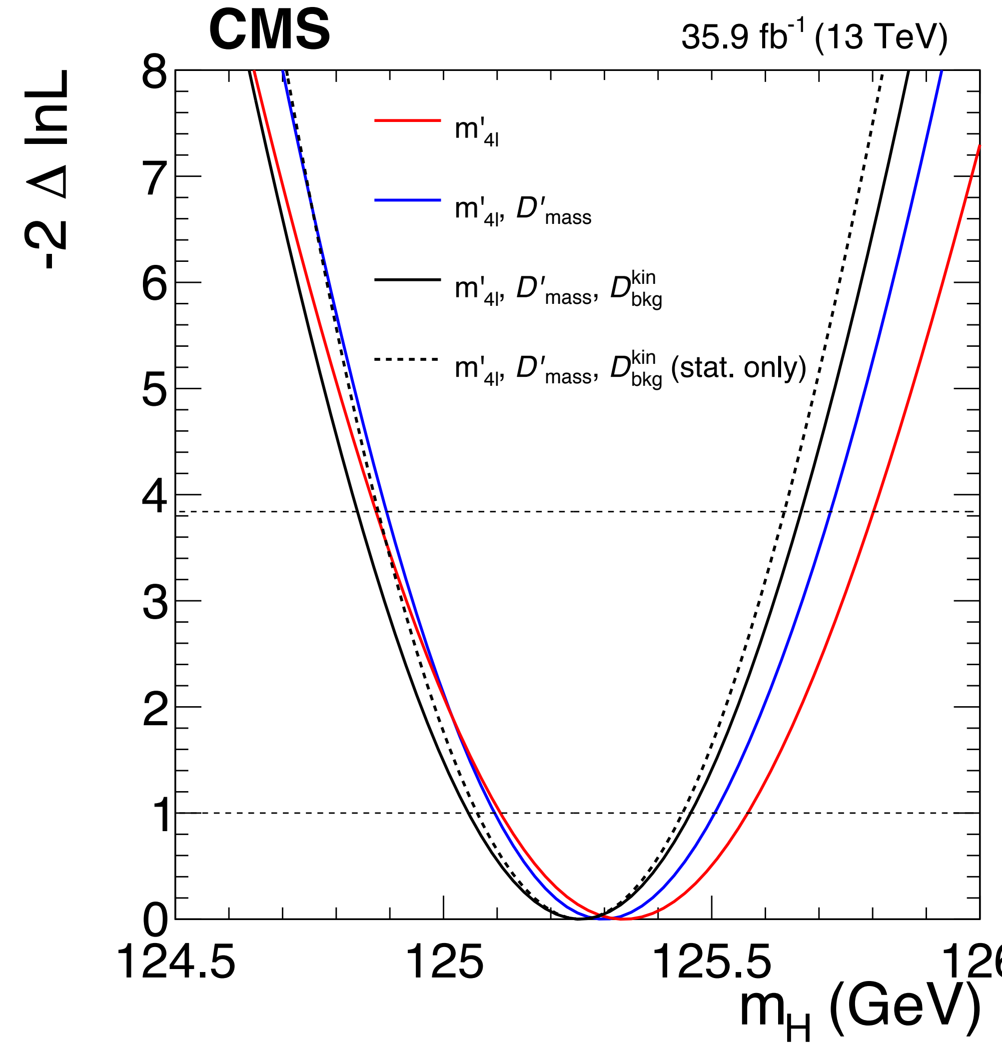
Signal strengths in run2 are consistent with SM expectations

ttH production is being reported for the first time by CMS in the ZZ channel



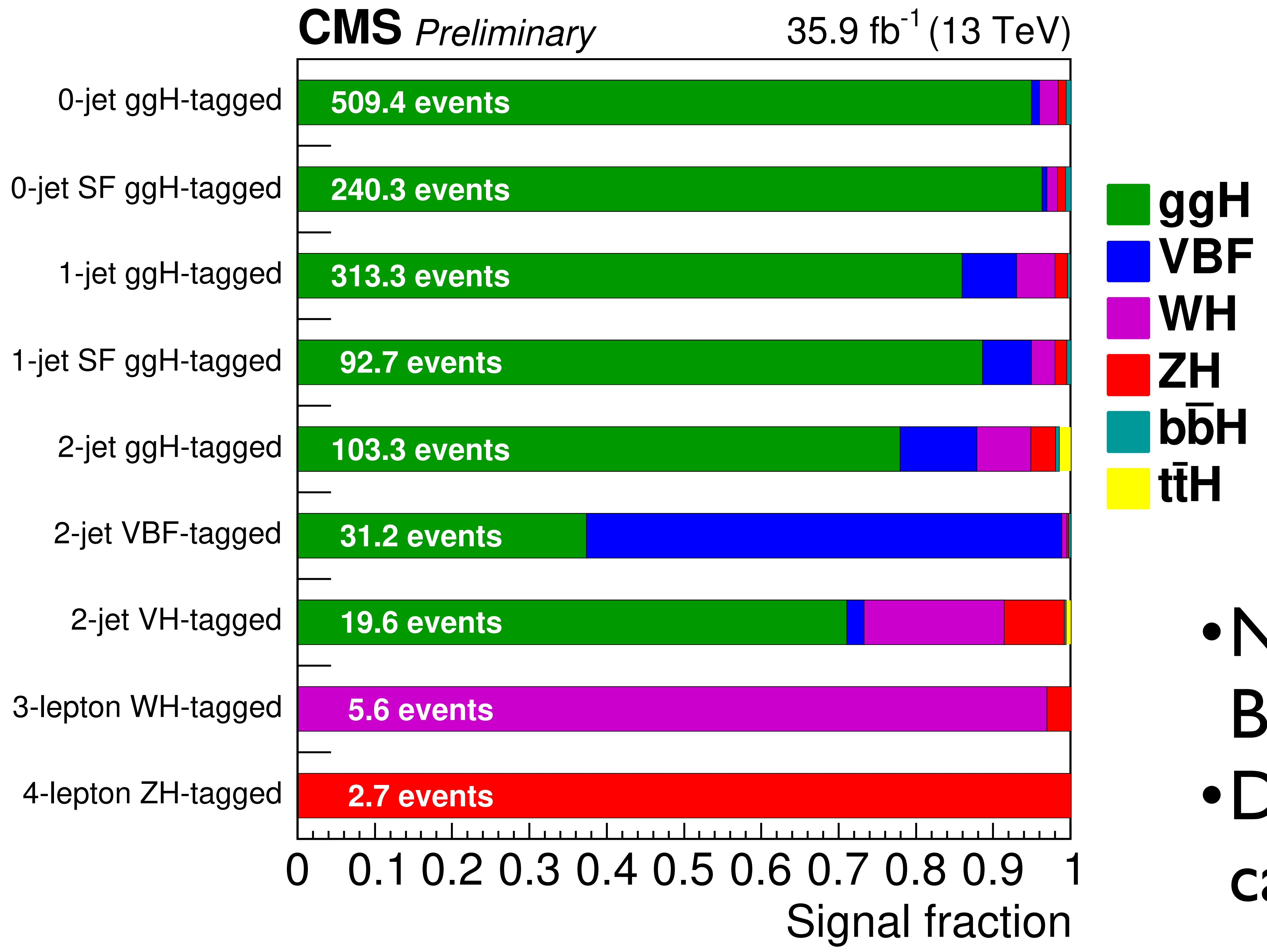


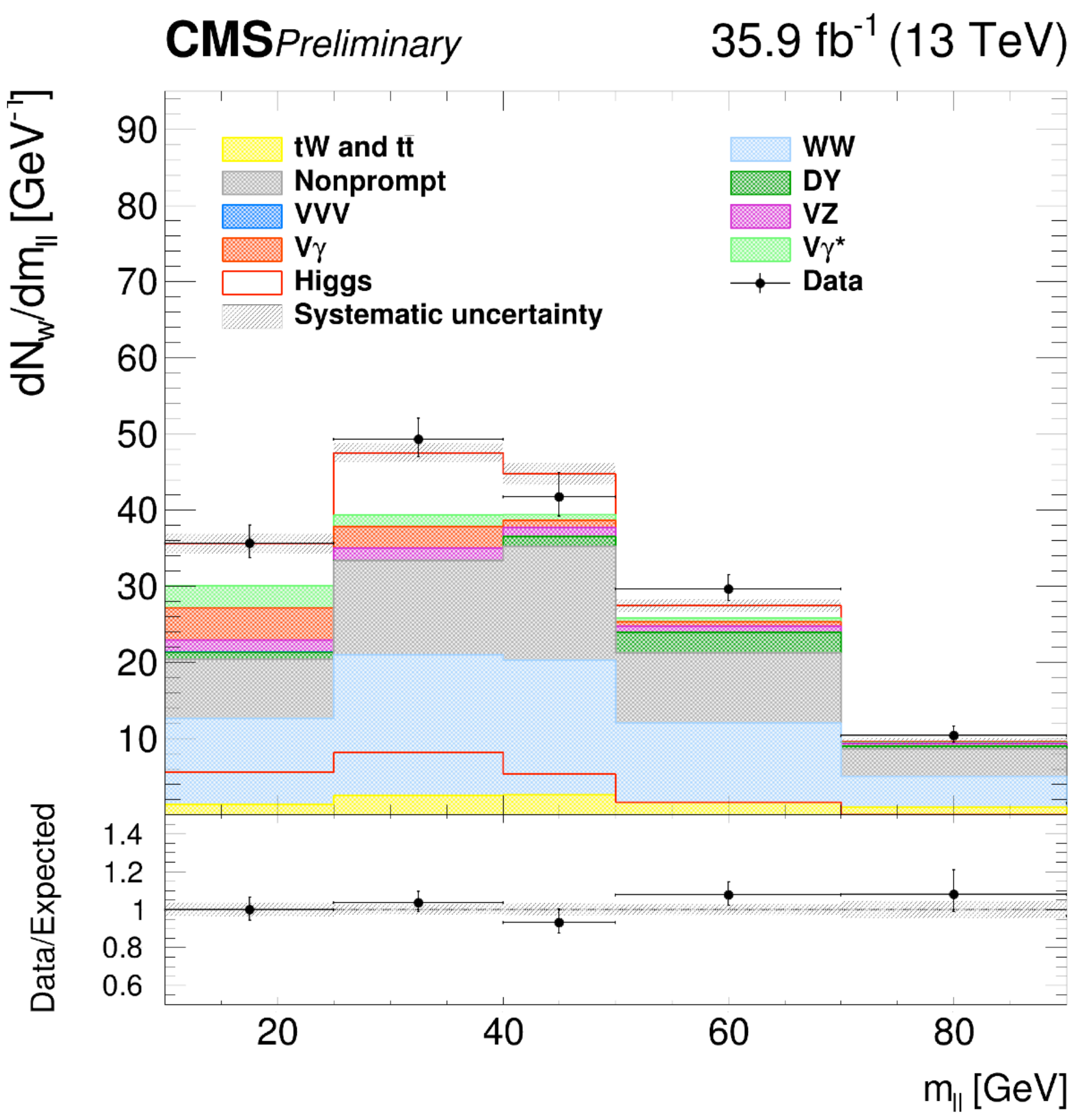
No evidence for anomalous HZZ couplings so far



H→WW

- Signature: at least two opposite sign leptons + large E_T^{miss}
- Subcategories based on leading lepton pT, lepton flavours
- Separate eμ/μe categories to exploit differences in fake rate





- Neutrinos in the final state: poor resolution, but larger BR wrt ZZ
- Different discriminant variables used in various categories