Higgs2023
November 27- December 1, 2023, Beijing-China

Higgs boson cross-section measurements in fermionic final states with the CMS detector

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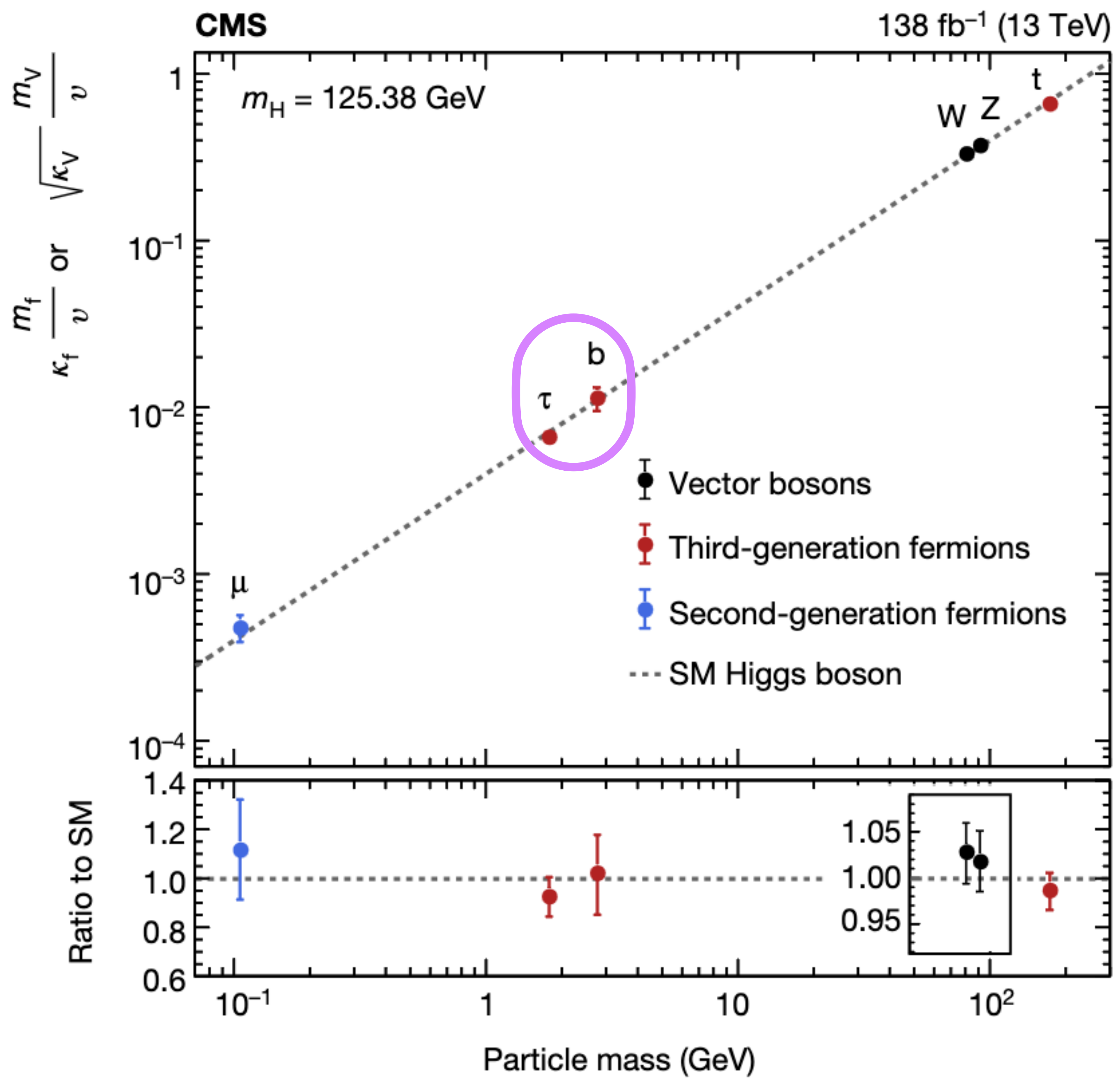
On behalf of the **CMS collaboration**

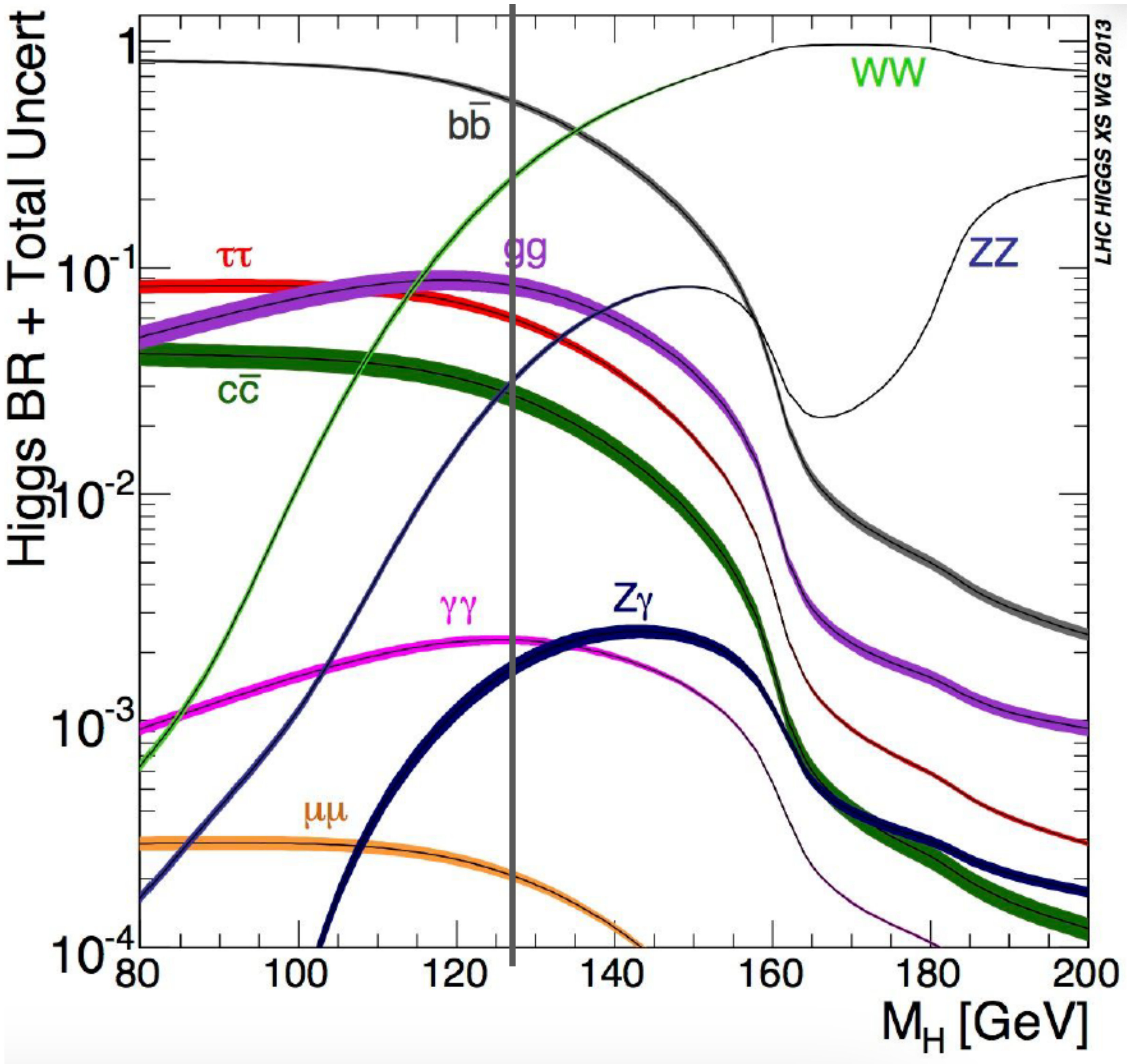
Overview

See Palmer's talk on coupling measurements

- ✳Higgs boson discovered in 2012 at CERN
- ✳Its properties have been measured with evolving precision since the discovery
  - Couplings, cross-section and etc.
- ✳Several decay modes studied so far.

https://doi.org/10.1038/s41586-022-04892-x





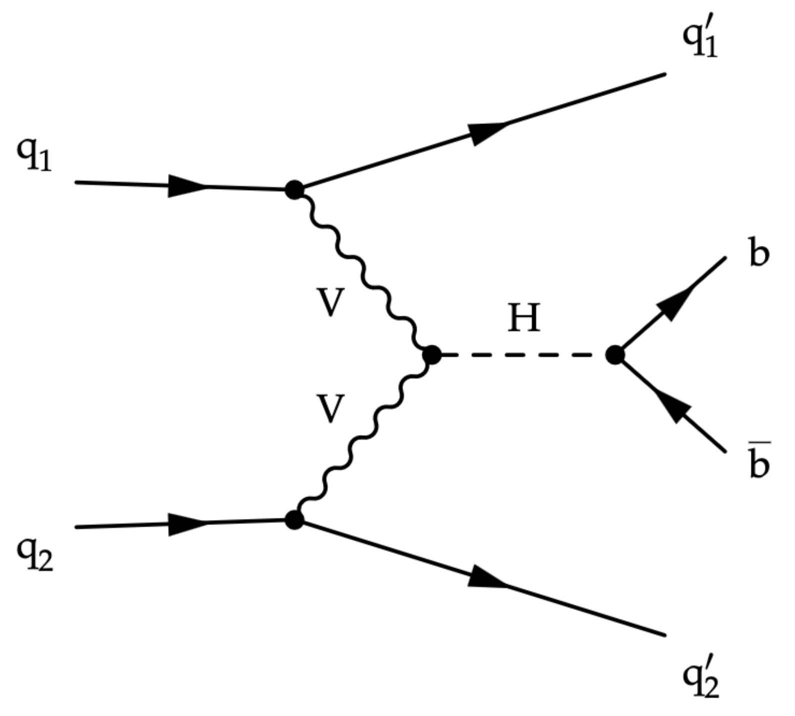
Today's talk:

- ✳$H \to bb$
  - Inclusive Signal Strengths, STXS
- ✳$H \to \tau\tau$
  - Inclusive Signal Strengths, STXS, inclusive and differential XS (resolved and boosted)

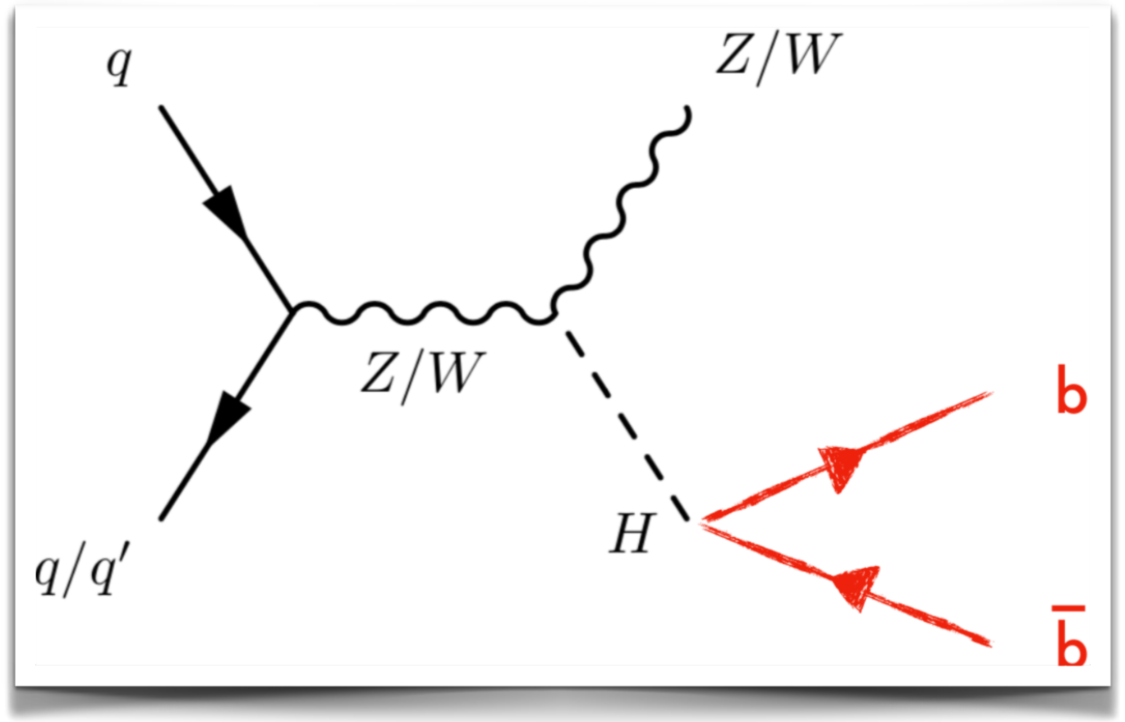
Higss production in bb final state

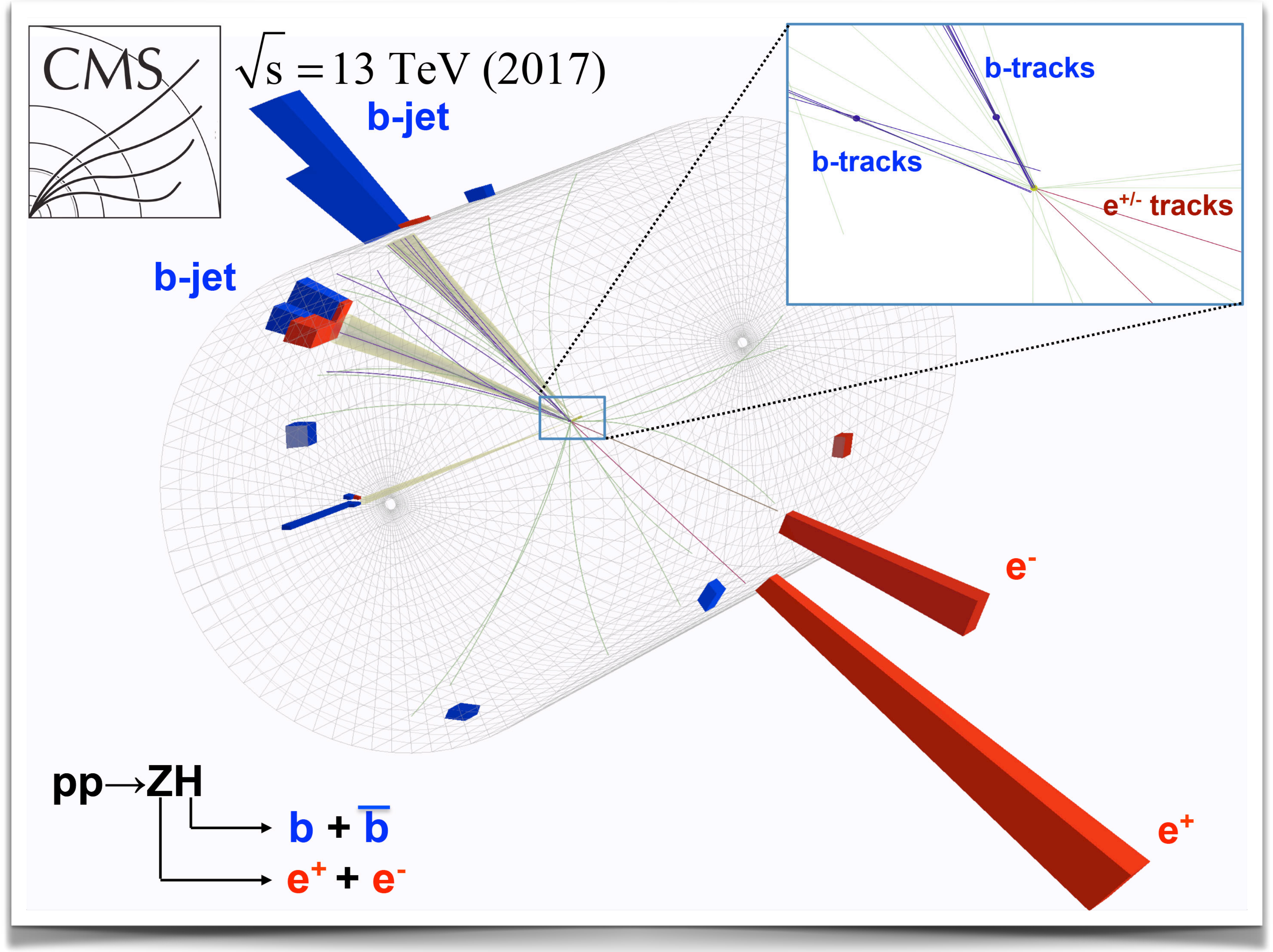
- $H \rightarrow bb$
  - Signal Strengths, STXS

VBF

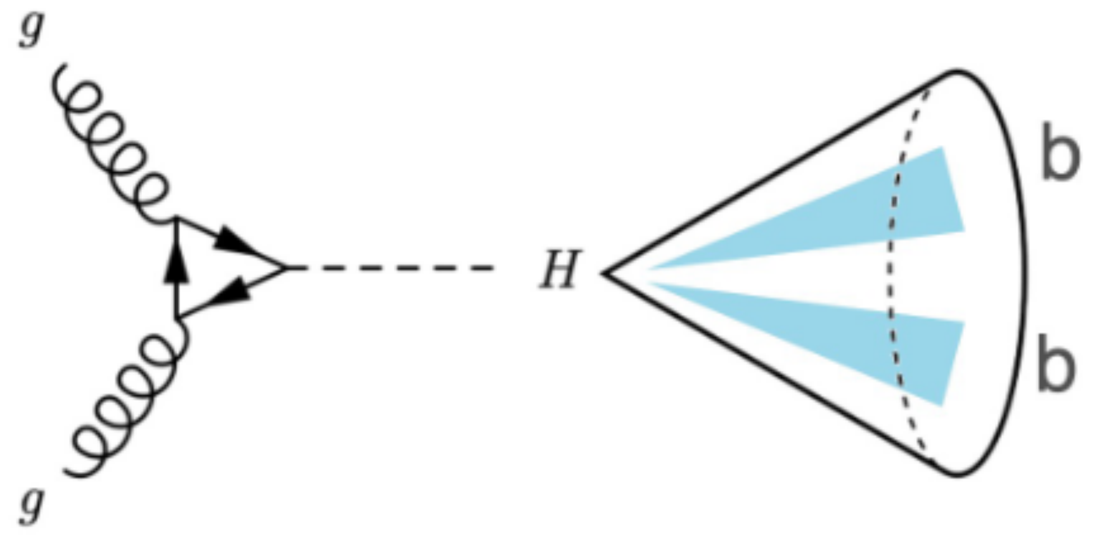


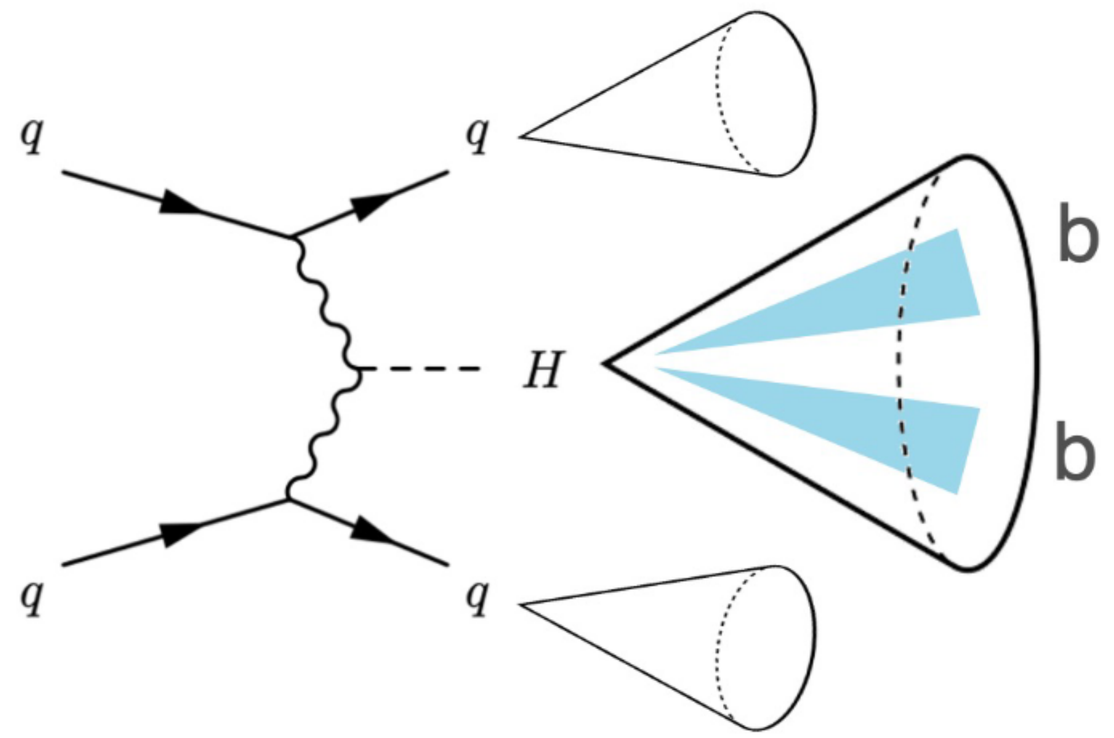
VH



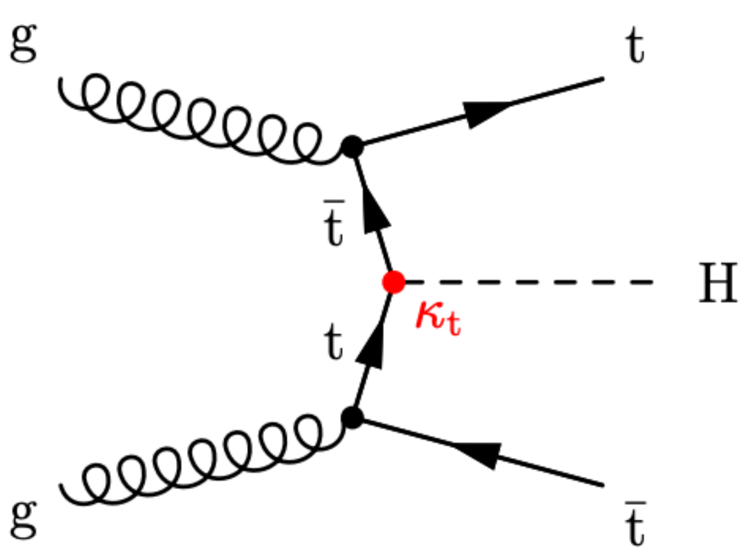


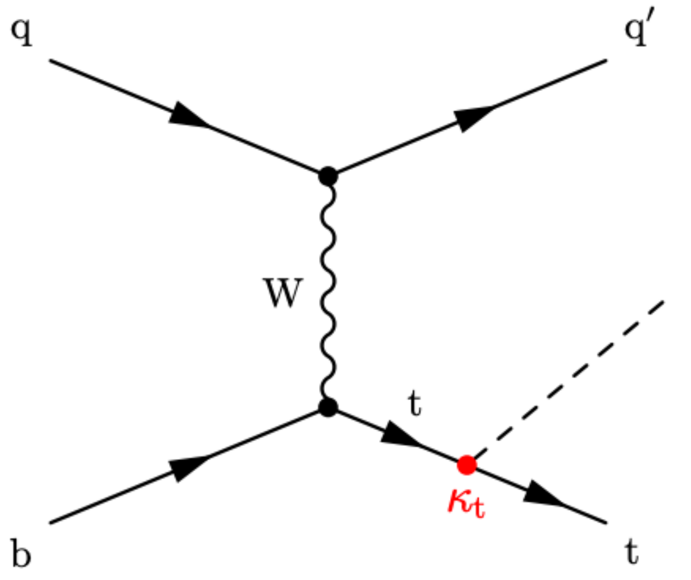
Boosted ggH/VBF

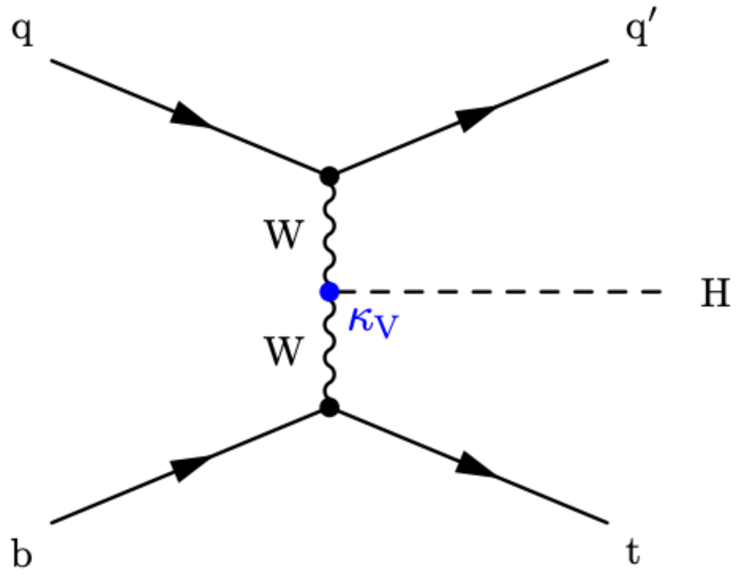




tH/ttH







[CMS-PAS-HIG-21-020], [CMS-PAS-HIG-19-011], [CMS-PAS-HIG-22-009], [CMS-PAS-HIG-20-001] , [CMS-PAS-HIG-22-011]

(VBF) $H \rightarrow bb$

https://arxiv.org/abs/2308.01253
sub. to JHEP

✳ Events categorization in Loose and Tight VBF with BDT Classifier

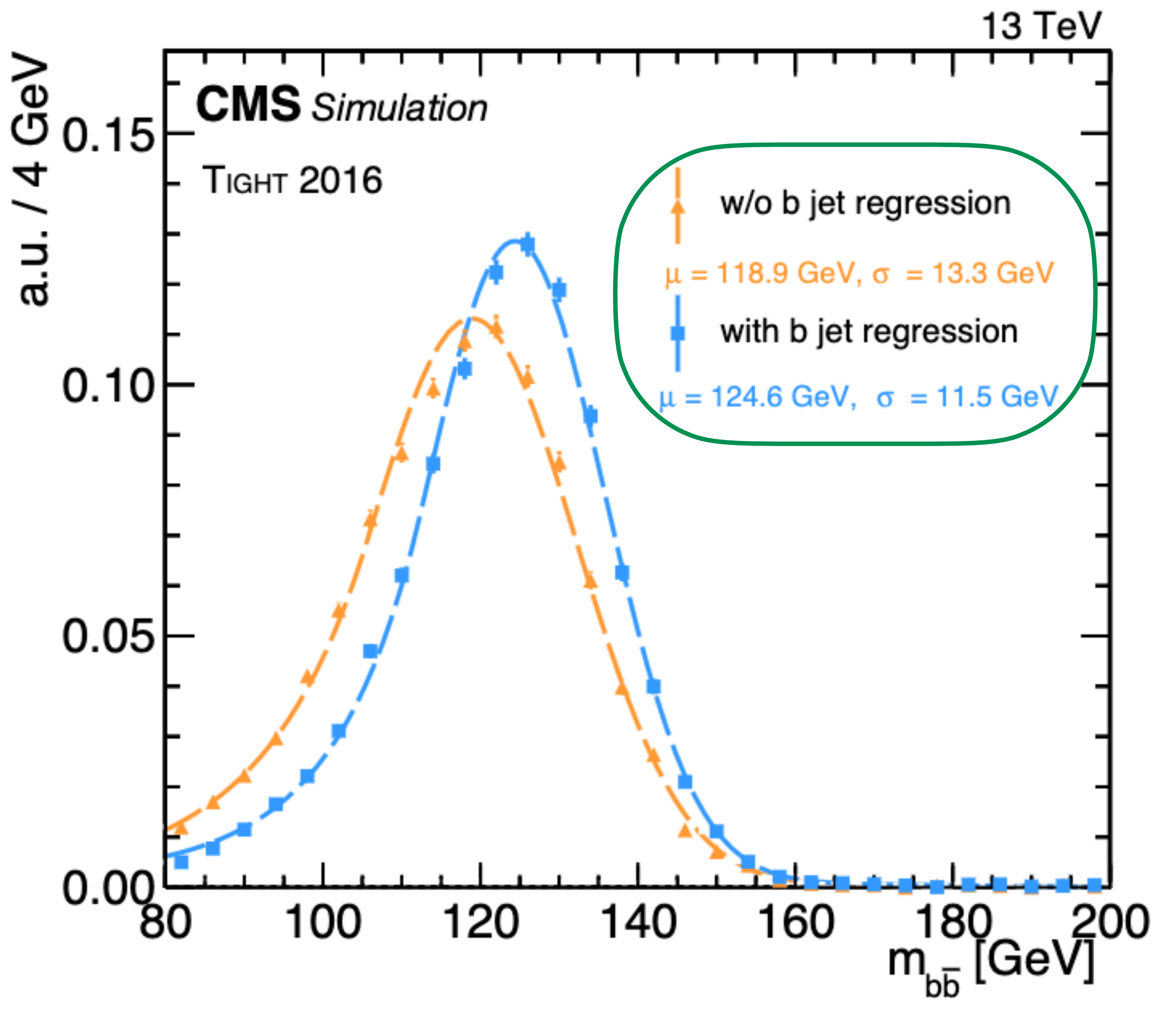
✳ Scale and Smearing corrections applied to DeepNN-based regressed b-jets

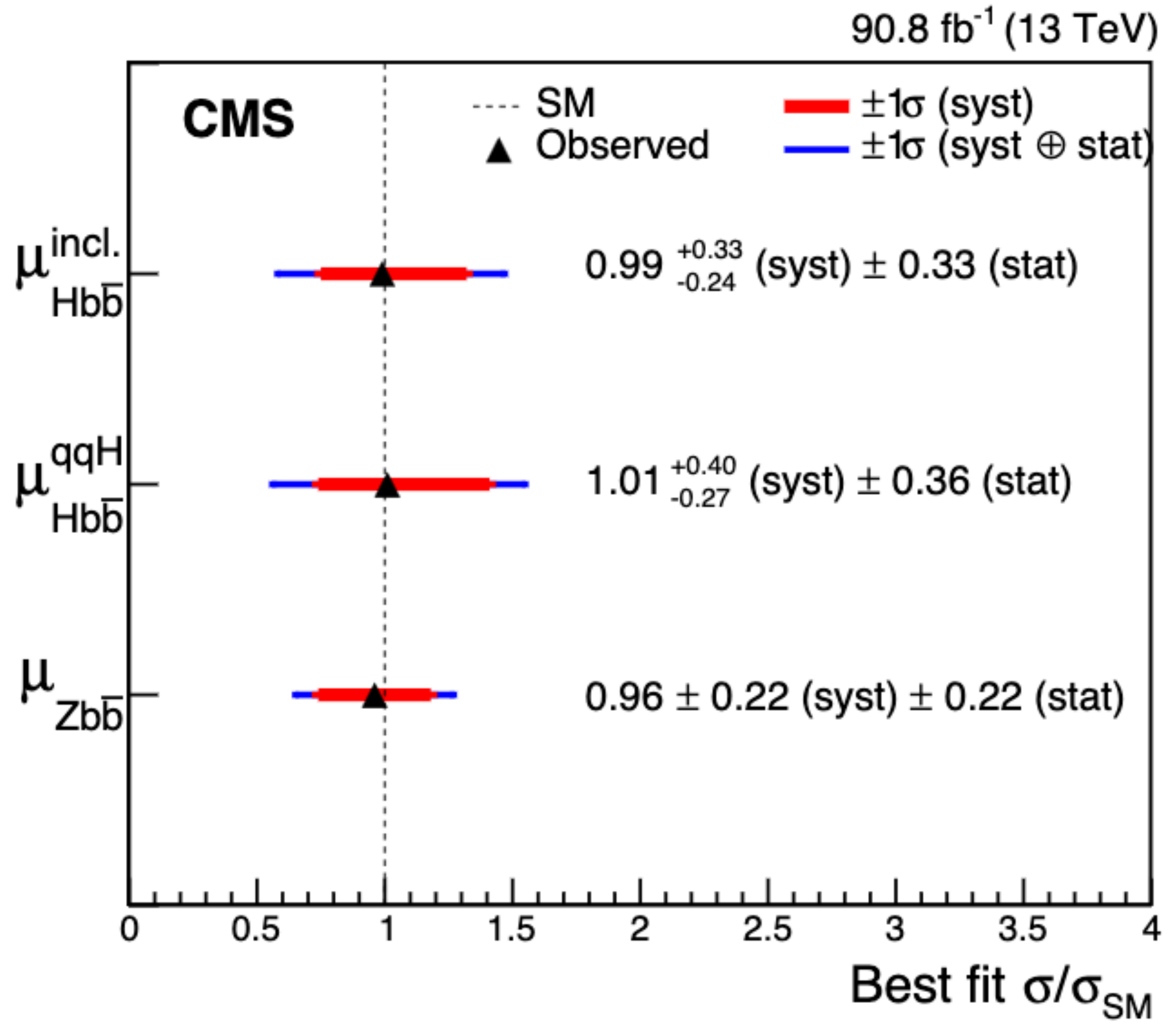
✳ Background estimation:

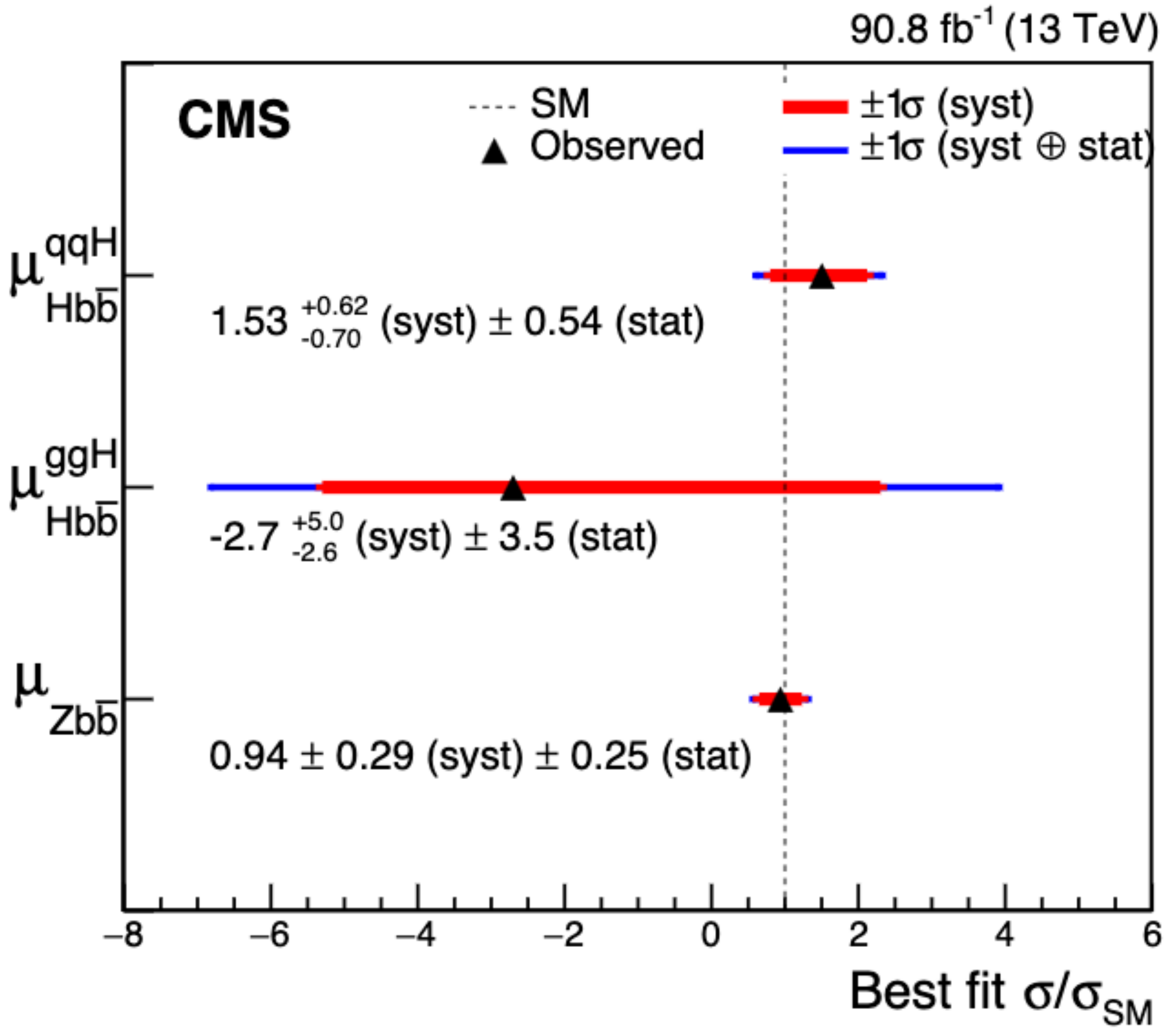
- Resonant Z(bb) + jets [DY & EWK] (simulation)
- Continuum QCD multijet production (fit to data) [80, 104] & [146, 200] GeV

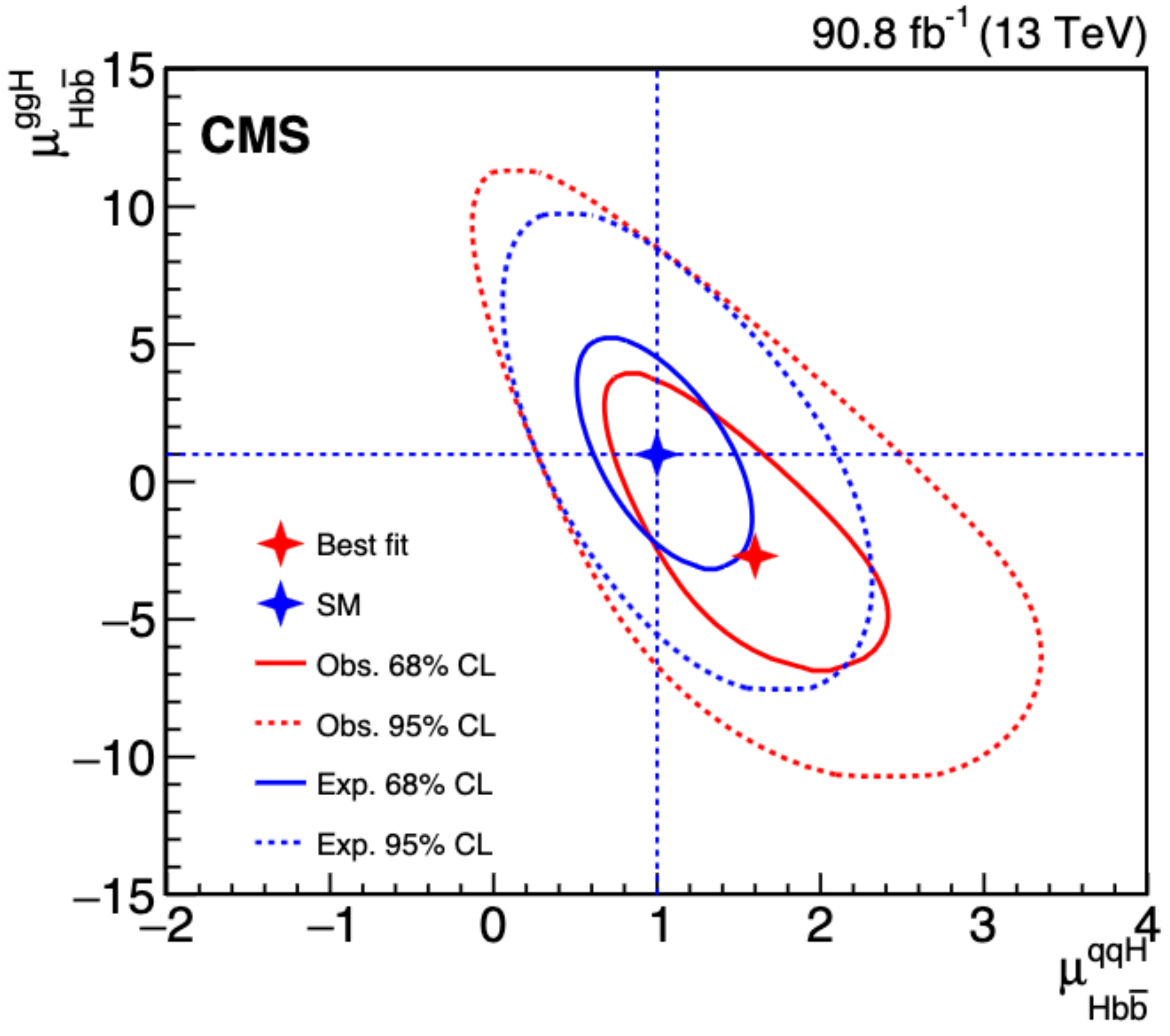
✳ VBF Parton shower and JES being leading systematic sources

✳ Simultaneous fit to $m_{b\bar{b}}$ extract signal









$V(W/Z \rightarrow leptons)\ H \rightarrow bb$

[CMS-PAS-HIG-20-001]

✳Inclusive measurement of VH (WH+ZH) production

✳3 channels are considered for V:

- 0-lepton ($Z \rightarrow \nu\nu$)
- 1-lepton ($W \rightarrow \ell\nu$)
- 2-lepton ($Z \rightarrow \ell\ell$); kinematic fit applied

✳Fit to SR and orthogonal control regions (CRs):

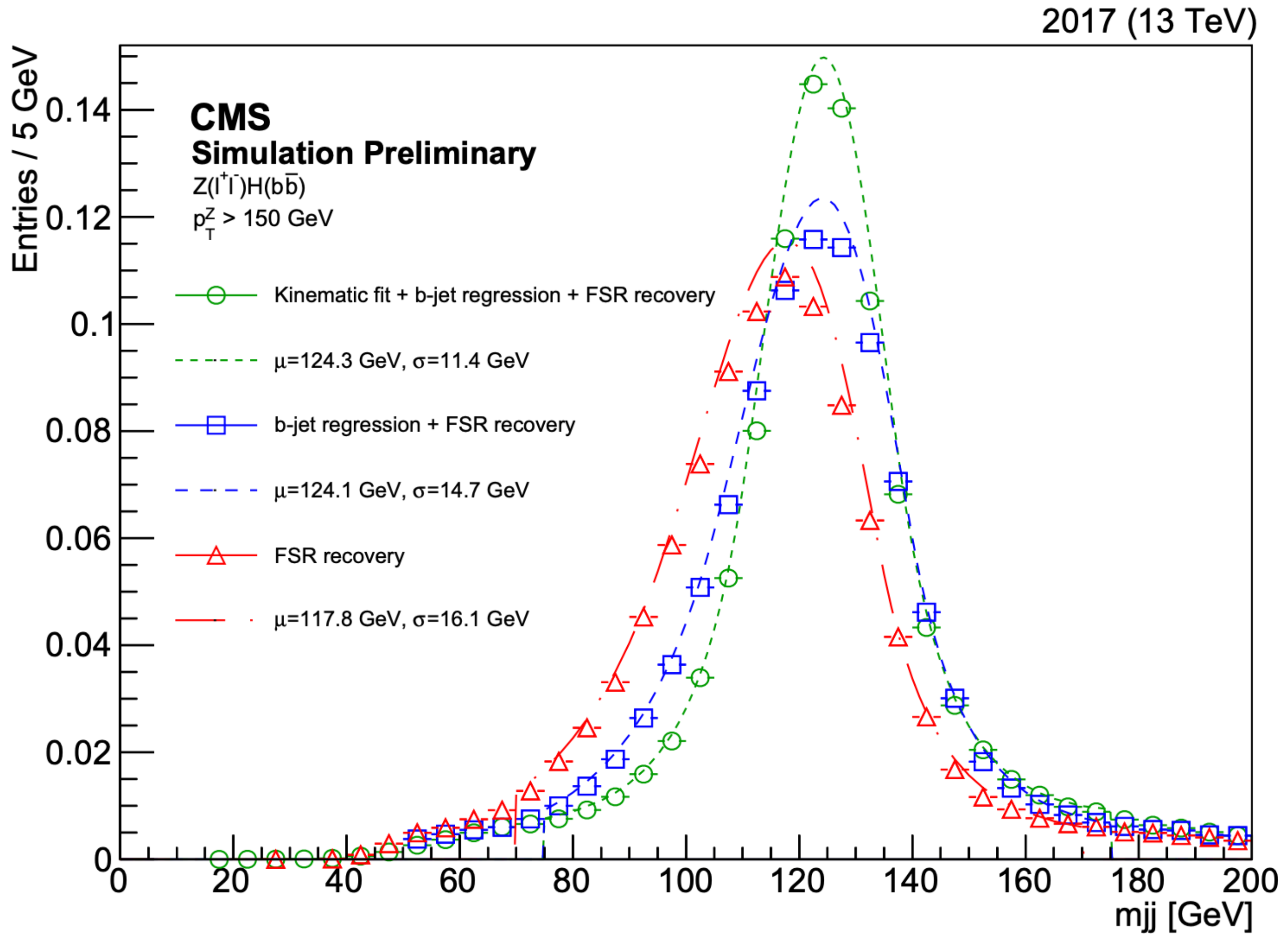
- tt
- V+HF(heavy flavor)
- V+LF (light flavors)

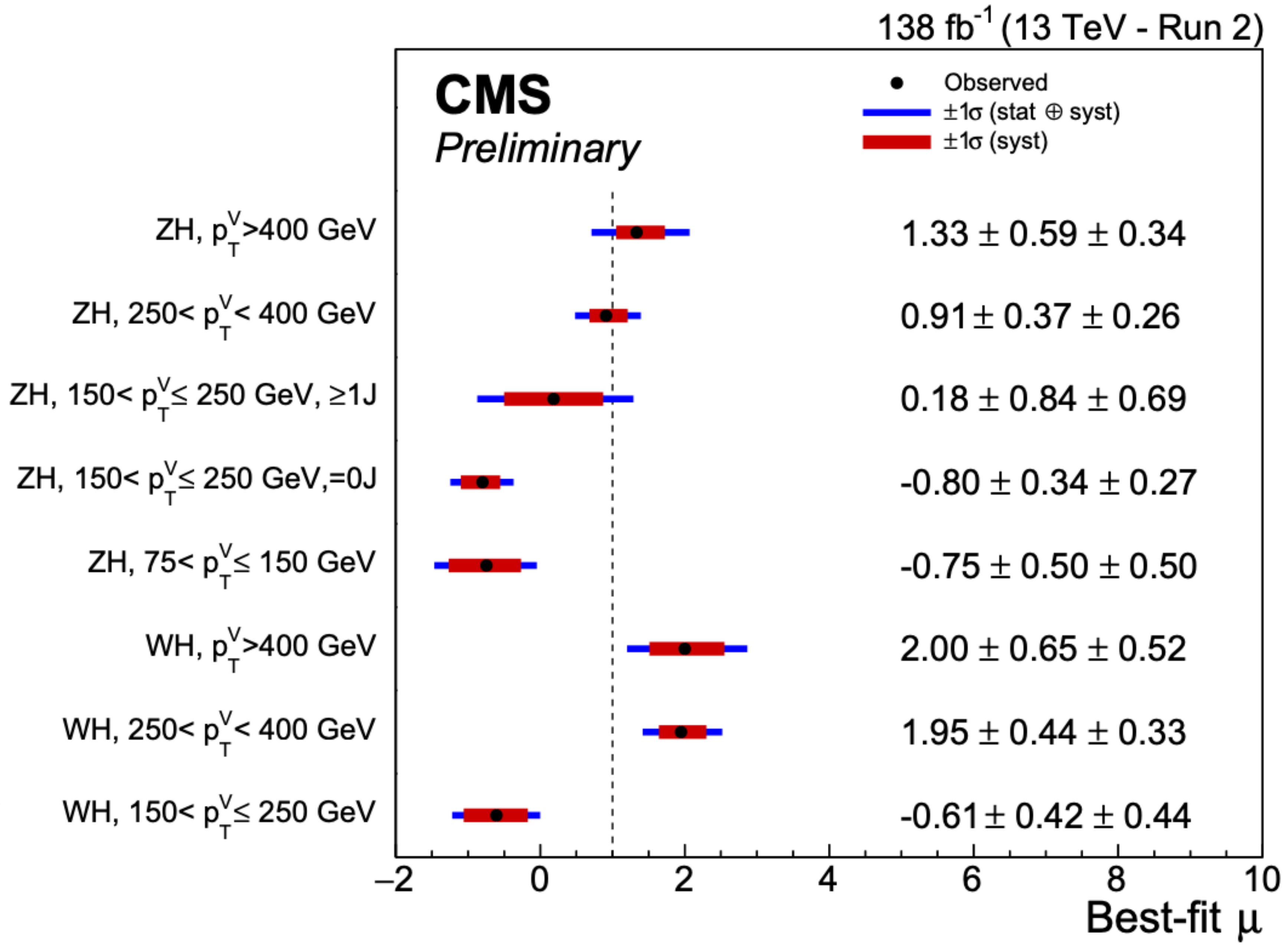
✳Multi-category DNN in V+HF CR

✳DNN for signal classification and extraction

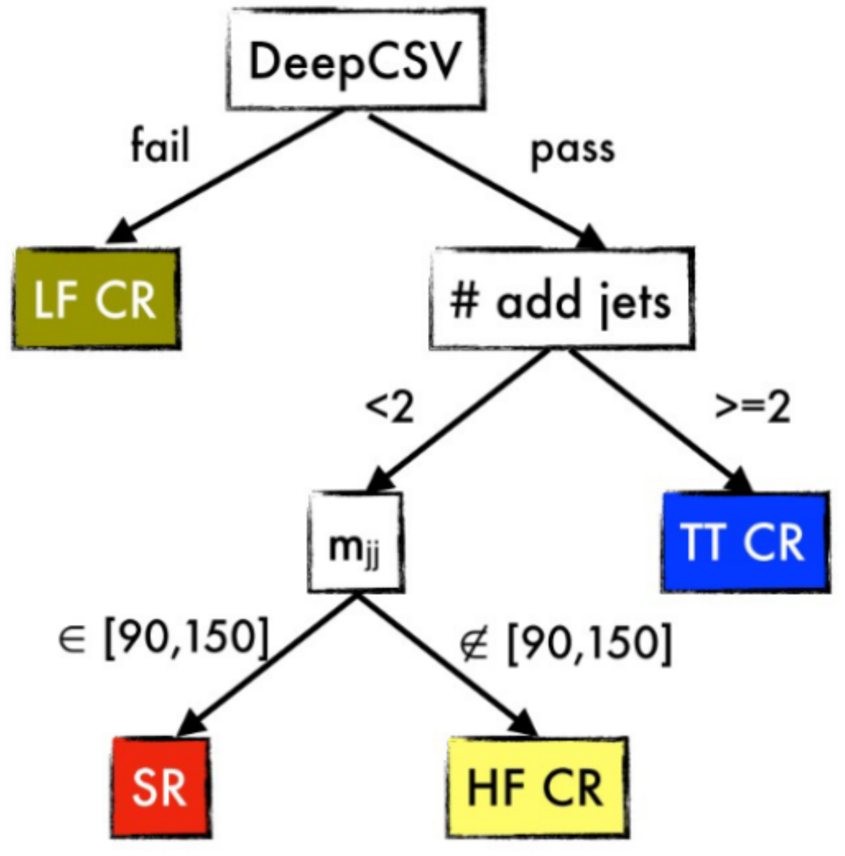
- 8 VH categories (pT and jet multiplicity; 5 ZH & 3 WH)

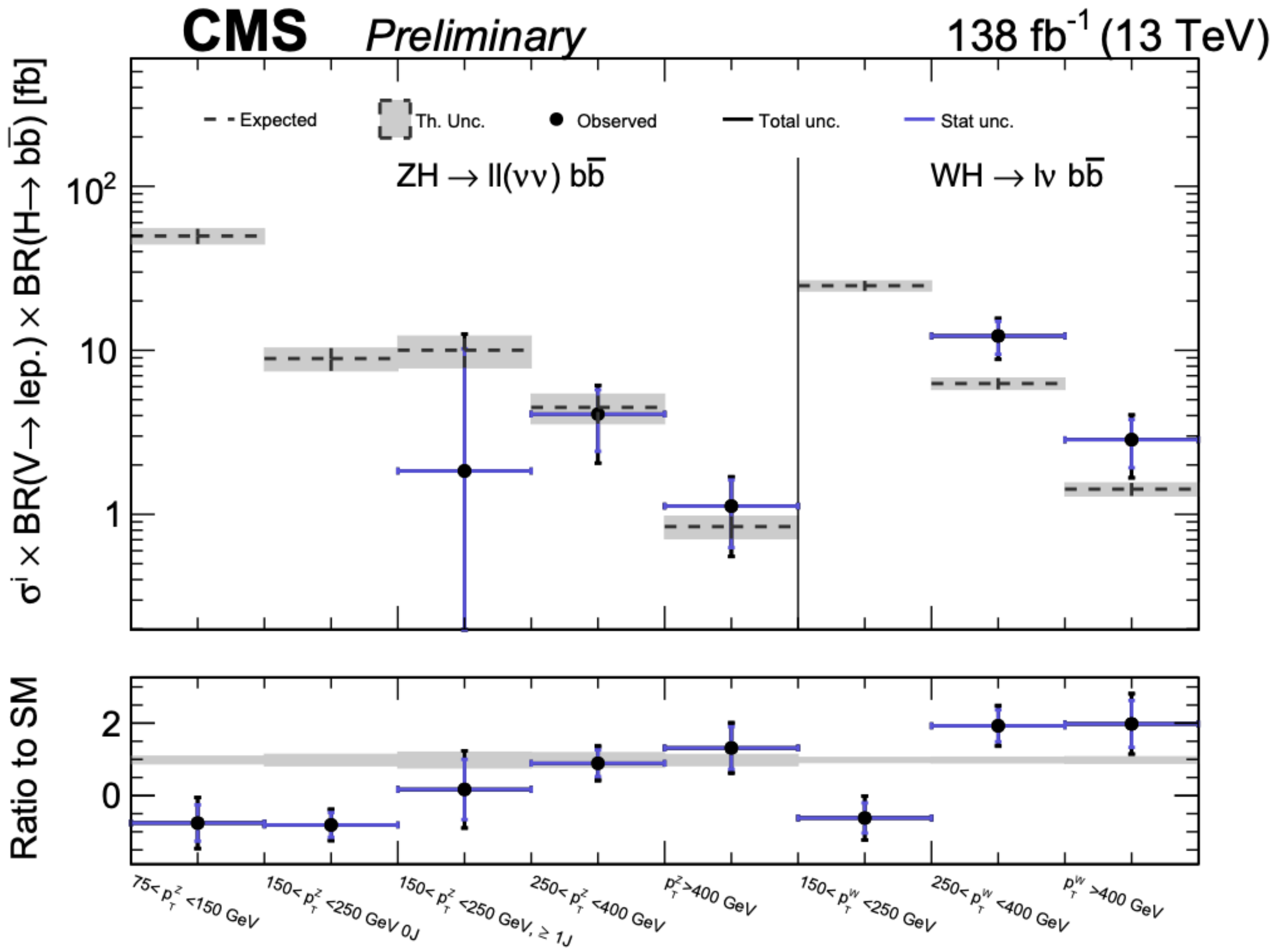
✳Sim. Modeling, b-tagging, JER being leading systematic sources





1-lepton example





(Boosted VBF/ggH) $H \to bb$: Analysis Strategy

[CMS-PAS-HIG-21-020]

✳ Higgs at large pT (>450 GeV considered)

- To probe BSM effects in scalar sector, test higher-order EW radiative corrections in H production

✳ Generalized energy correlation functions for 2-prong (W/Z/H) tagging [JHEP 1612 (2016) 53]

- Mass-decorrelated version; using the Designed Decorrelated Tagger method [JHEP 1605 (2016) 156]

✳ Updated multivariate Deep Double B-Tagger (DDB)

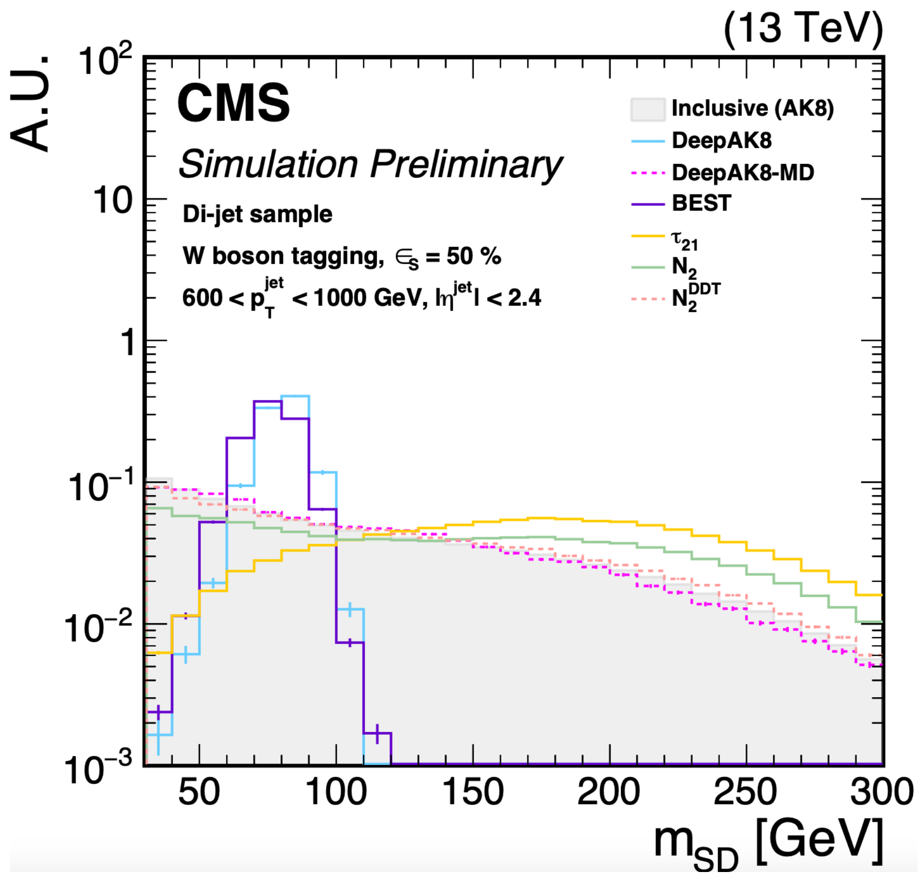
- Signal significance increased by twice

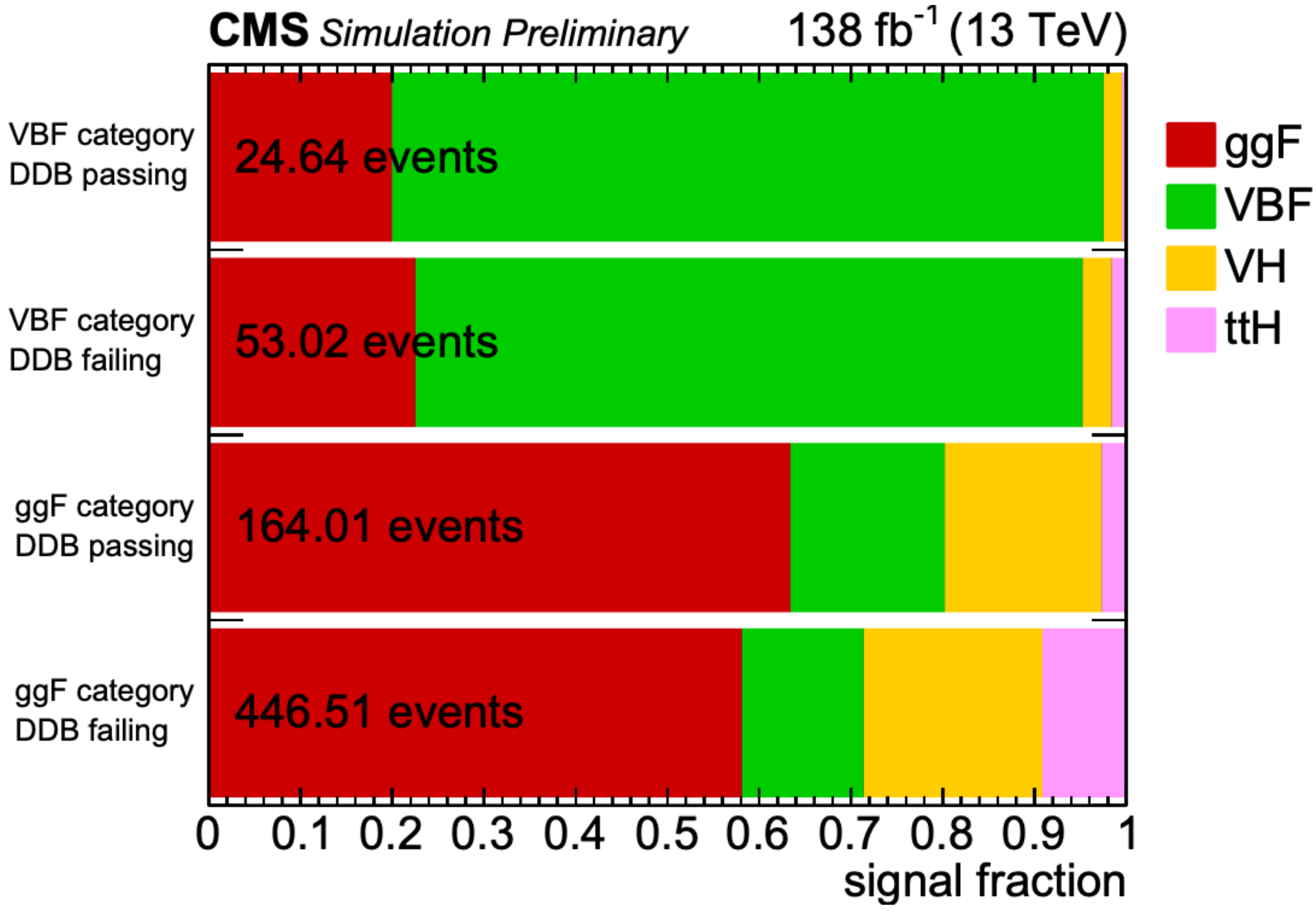
✳ Jet substructure and novel b-tagging (DDB fail region) to reject QCD

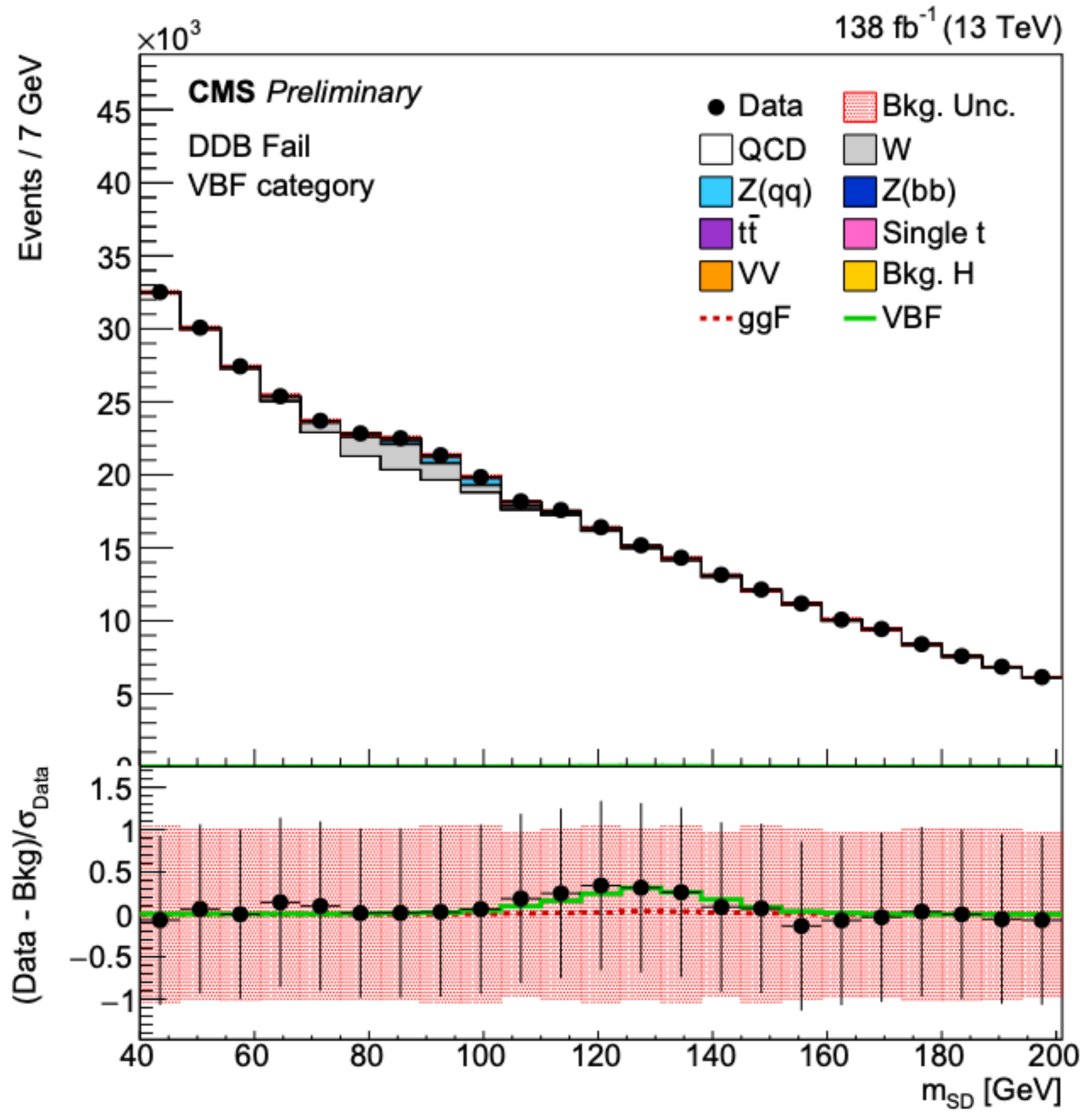
✳ ML fit to the observed m_{SD} distributions for ggH and VBF

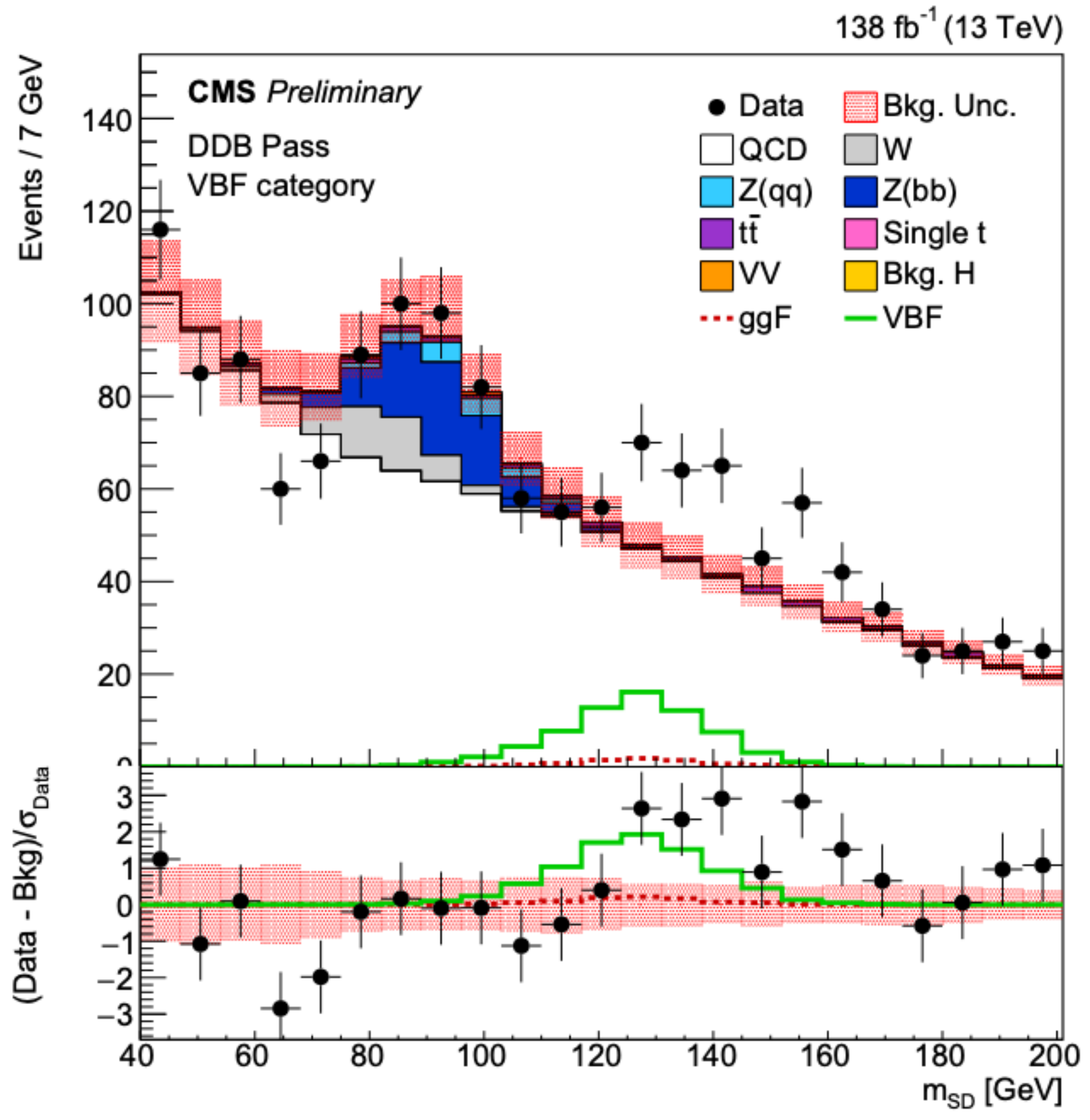
✳ W and Z boson resonances used to constraint syst. unc.

CMS-PAS-JME-18-002









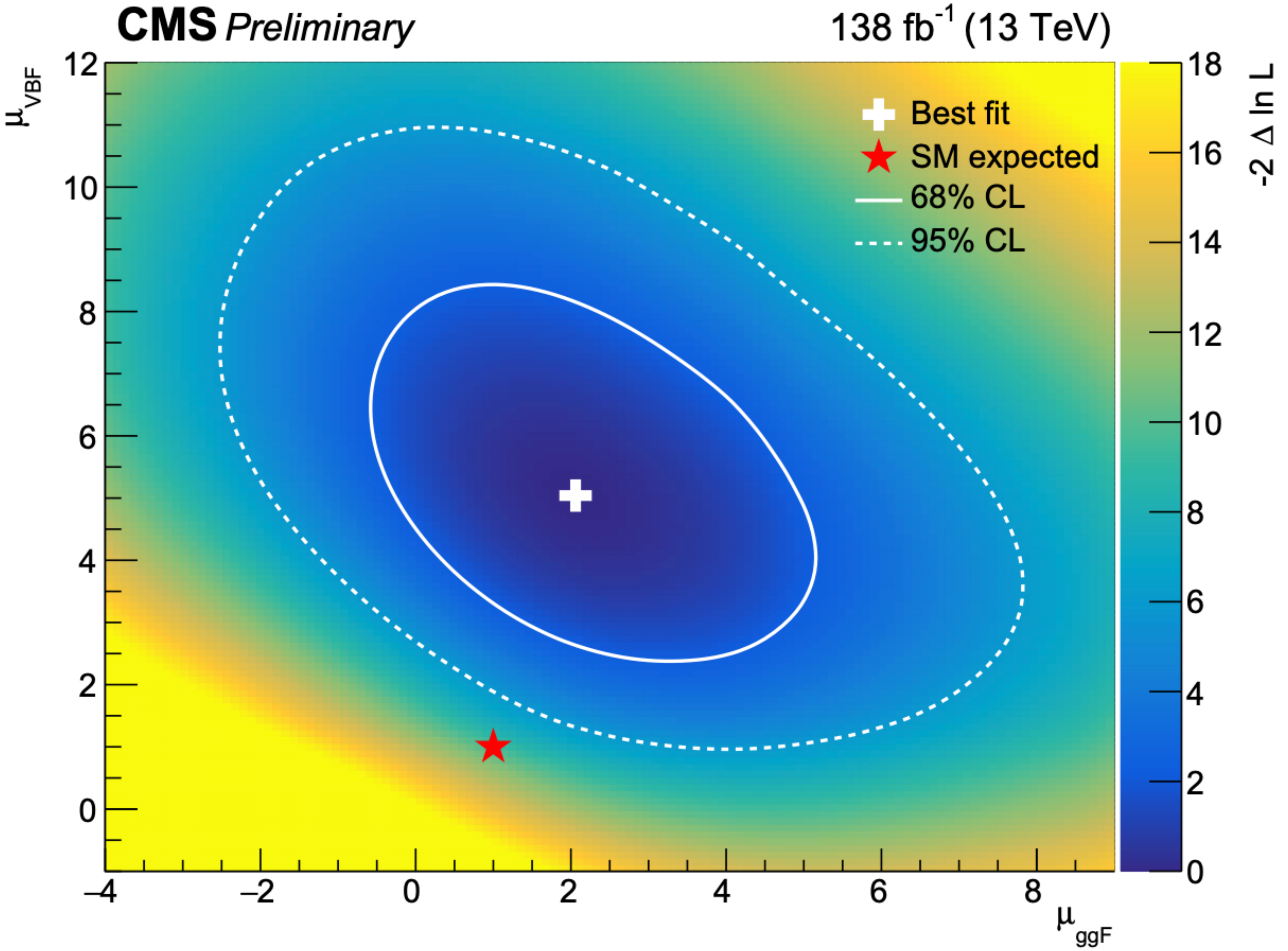
(Boosted VBF/ggH) $H \to bb$: Results

✳ Observed inclusive Signal Strengths:

- VBF process: $5.0^{+2.1}_{-1.8}$
  - Significance: obs(exp.) $\to 3.0\sigma$ (0.9σ)
- ggF process: $2.1^{+1.9}_{-1.7}$
  - Significance: obs(exp.) $\to 1.2\sigma$ (0.9σ)

✳ Observed differential Signal strengths:

- In p_T bins for ggF
- Inv. mass of forward jets for VBF



(Boosted VBF/ggH) $H \rightarrow bb$: Results

[CMS-PAS-HIG-21-020]

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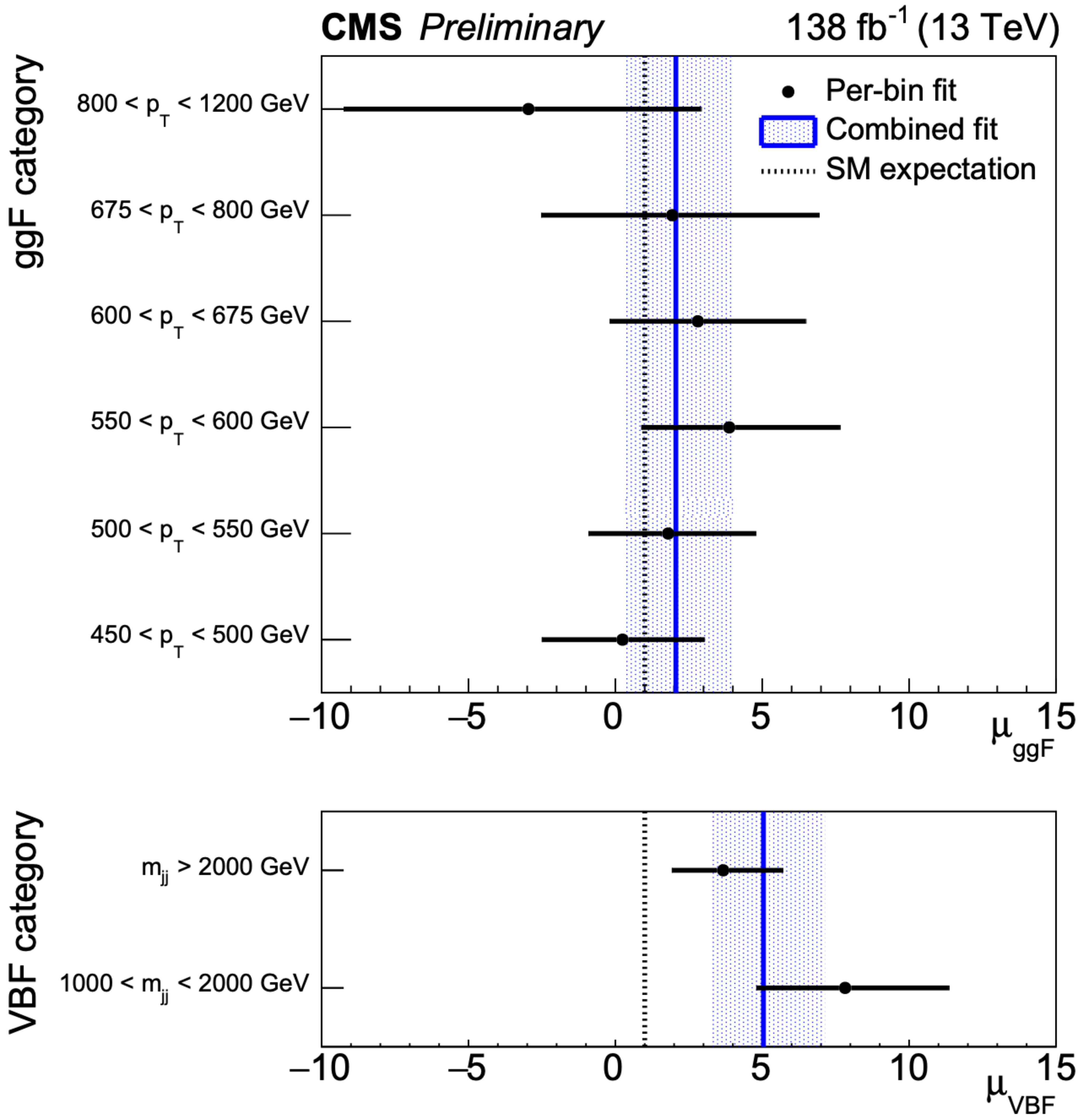


$t\bar{t}H/tH$, with $H \to bb$: Analysis Strategy

More details, see Abhisek's talk

[CMS-PAS-HIG-19-011]

✶ **3 channels** are considered:

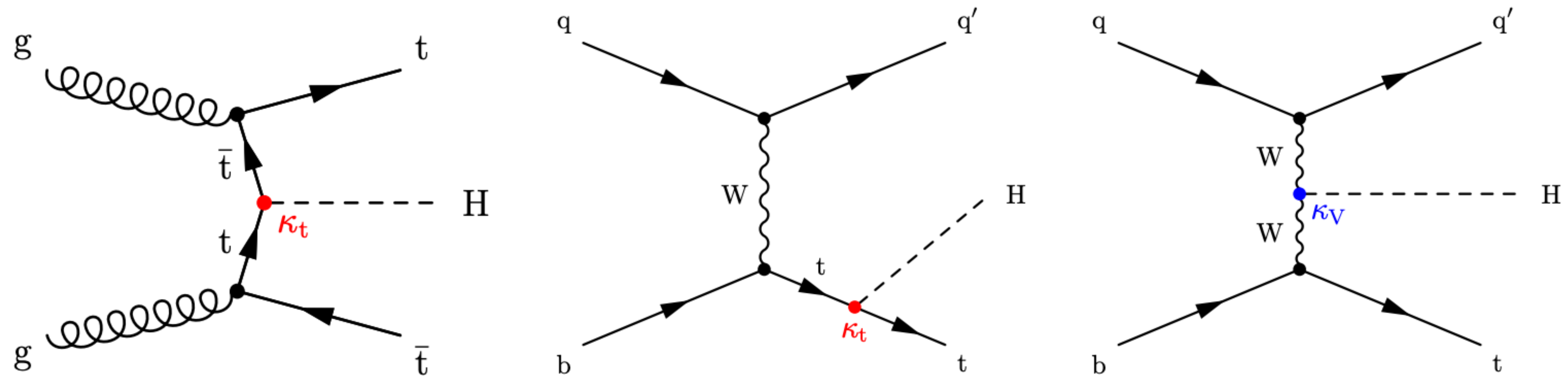
- Fully Hadronic (FH): 0-leptons ($W \to q\bar{q}$)
- Semi leptonic (SL): 1-lepton ($W \to \ell\nu$)
- Dileptonic (DL): 2-leptons (2 x $W \to \ell\nu$)

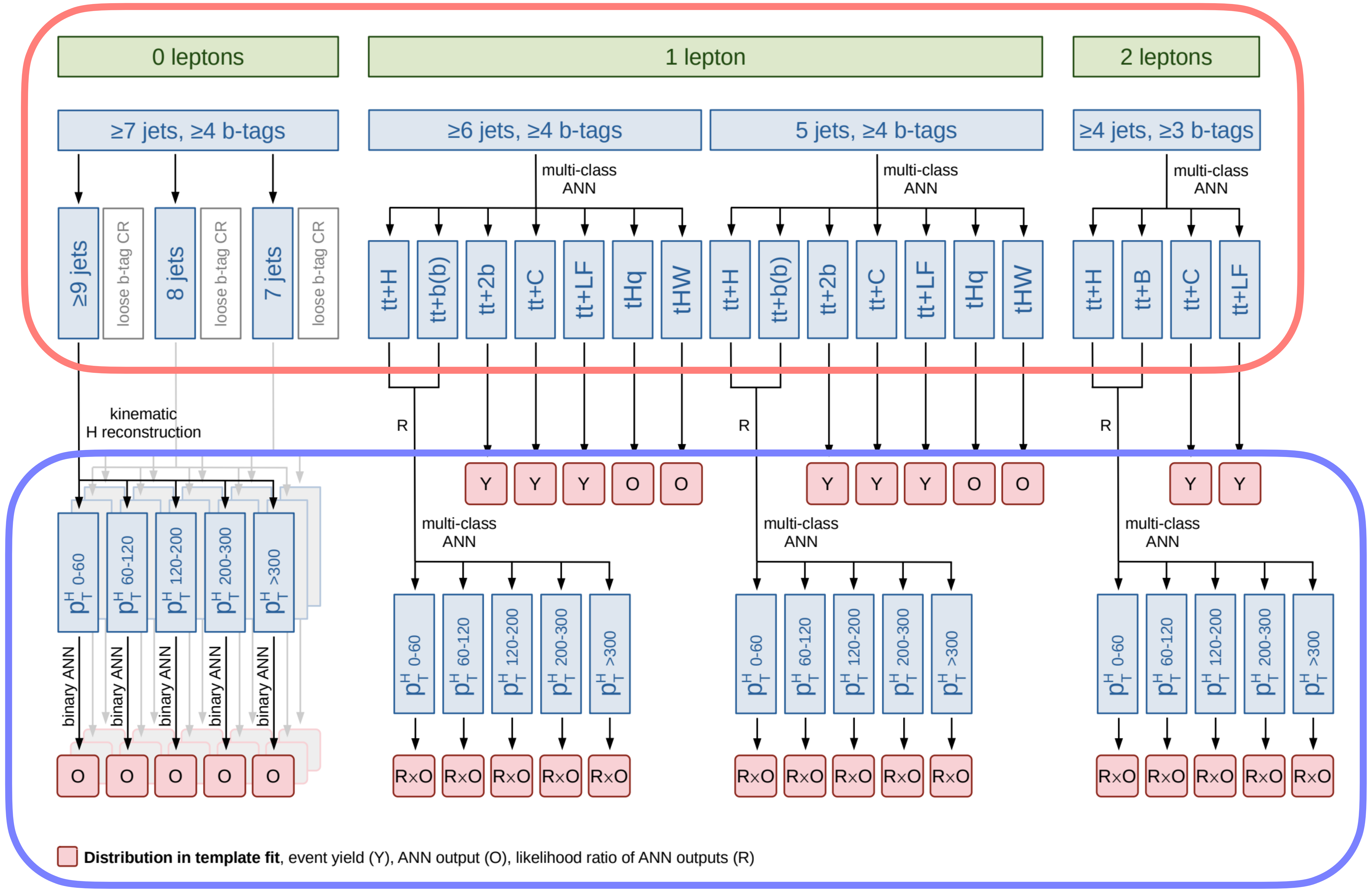
✶ categorization done with *jet* and b-tag multiplicity (inclusive, STXS).

✶ **ANNs** trained for sig./bkg. separation, further categorization, and building **discriminants**

✶ Improvements w.r.t. (CMS-PAS-HIG-18-030):

- dominant QCD bkg. estimation (FH); data-driven
- (Refined) neural network classifiers
- DeepJet b tagging algorithm





$t\bar{t}H/tH$, with $H \to bb$: Results

[CMS-PAS-HIG-19-011]

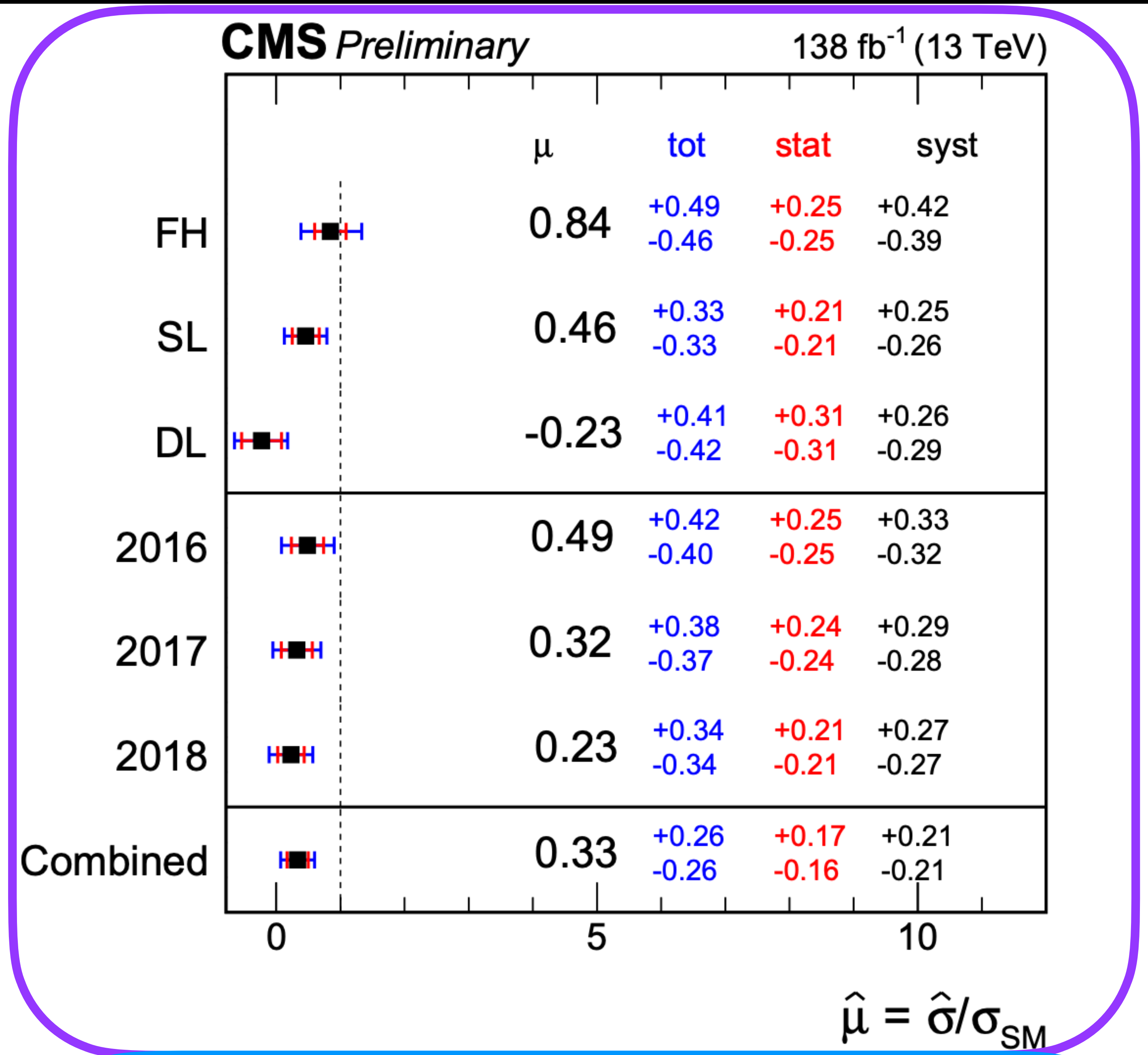
✳ $t\bar{t}H$:

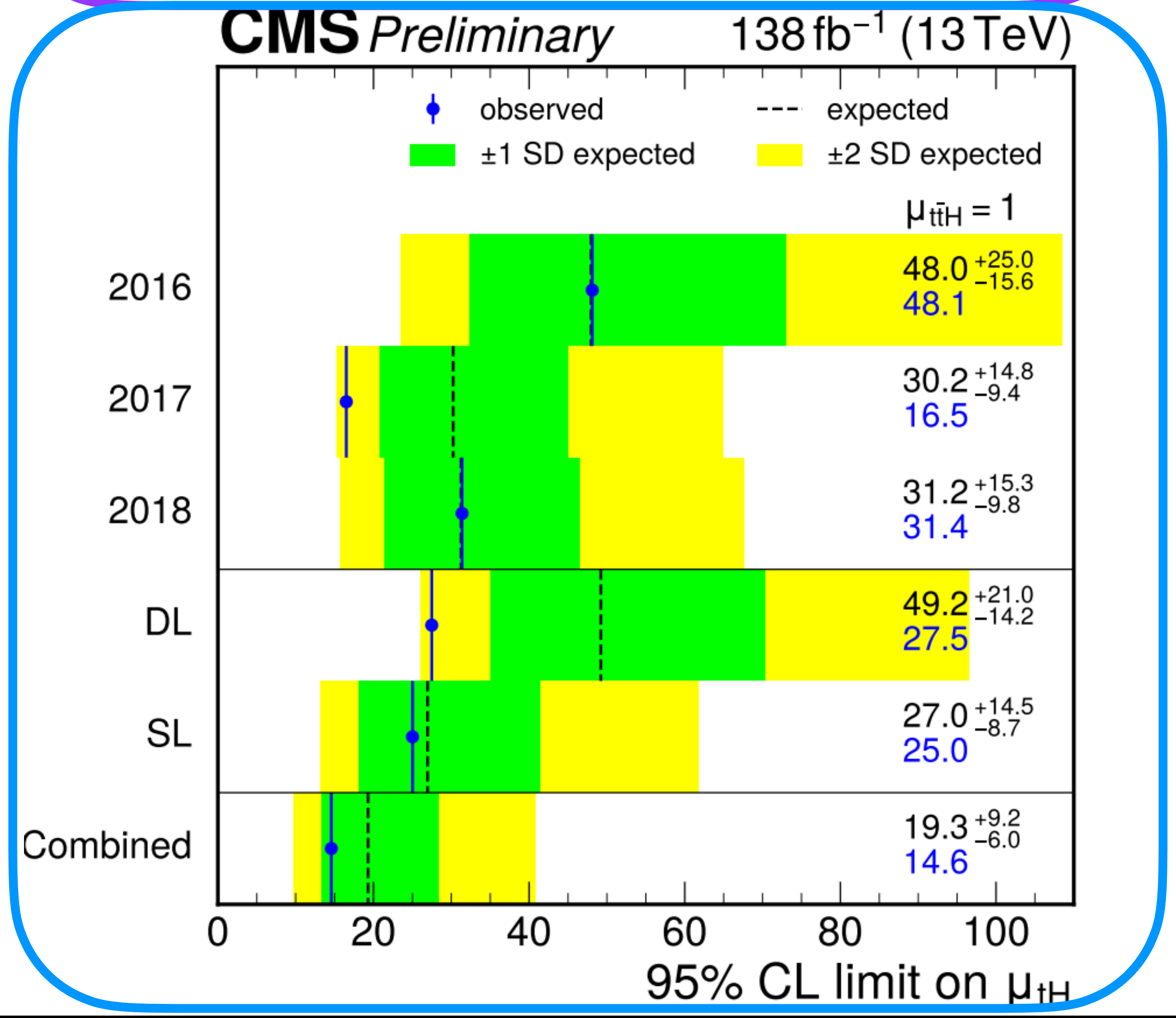
- inclusive
  - $\mu_{t\bar{t}H} = 0.33 \pm 0.26$

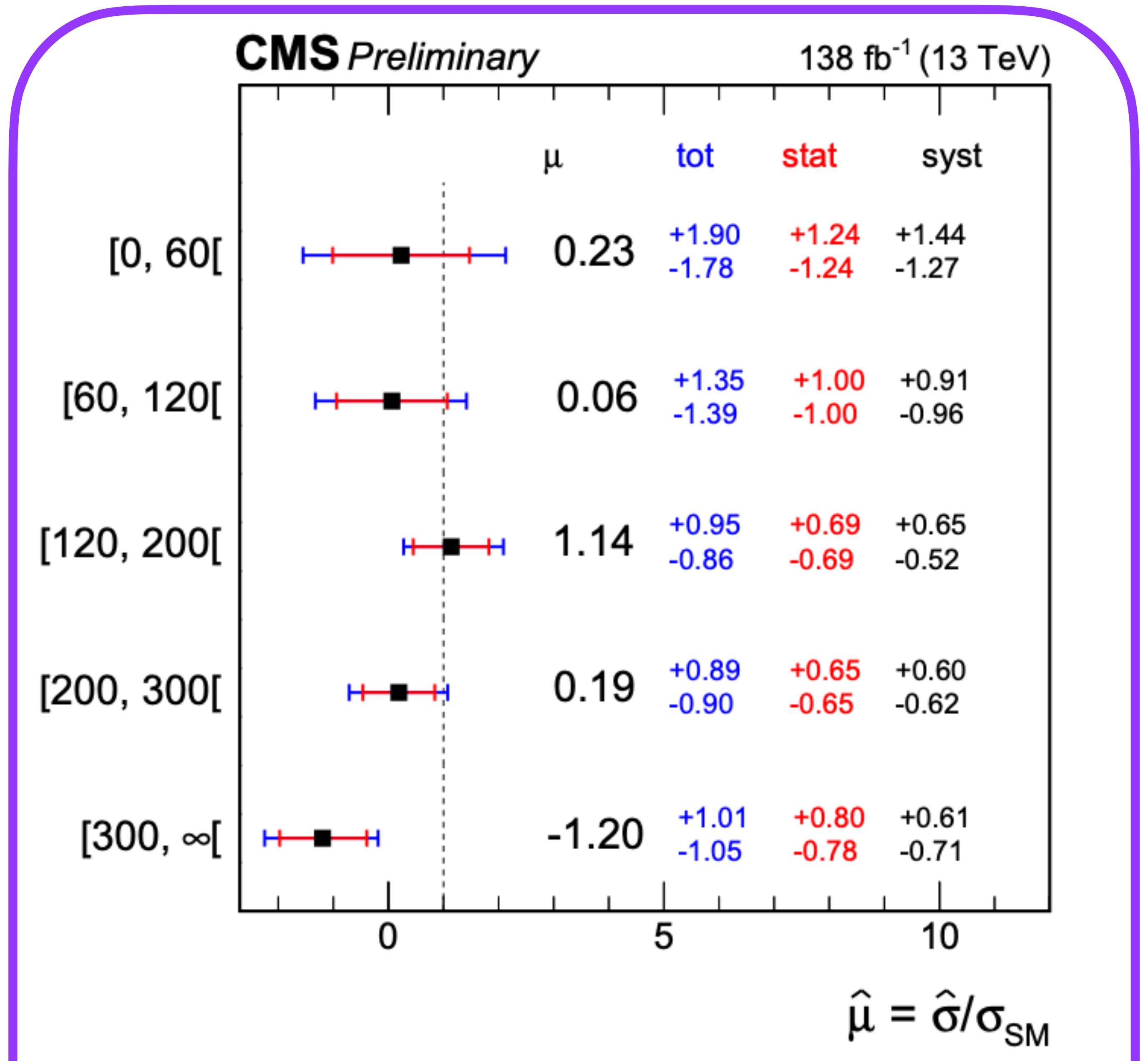
    significance: obs.(exp.) 1.3σ (4.1σ)
  - Background normalization $(t\bar{t}B, t\bar{t}C)$
- exclusive in p_T bins

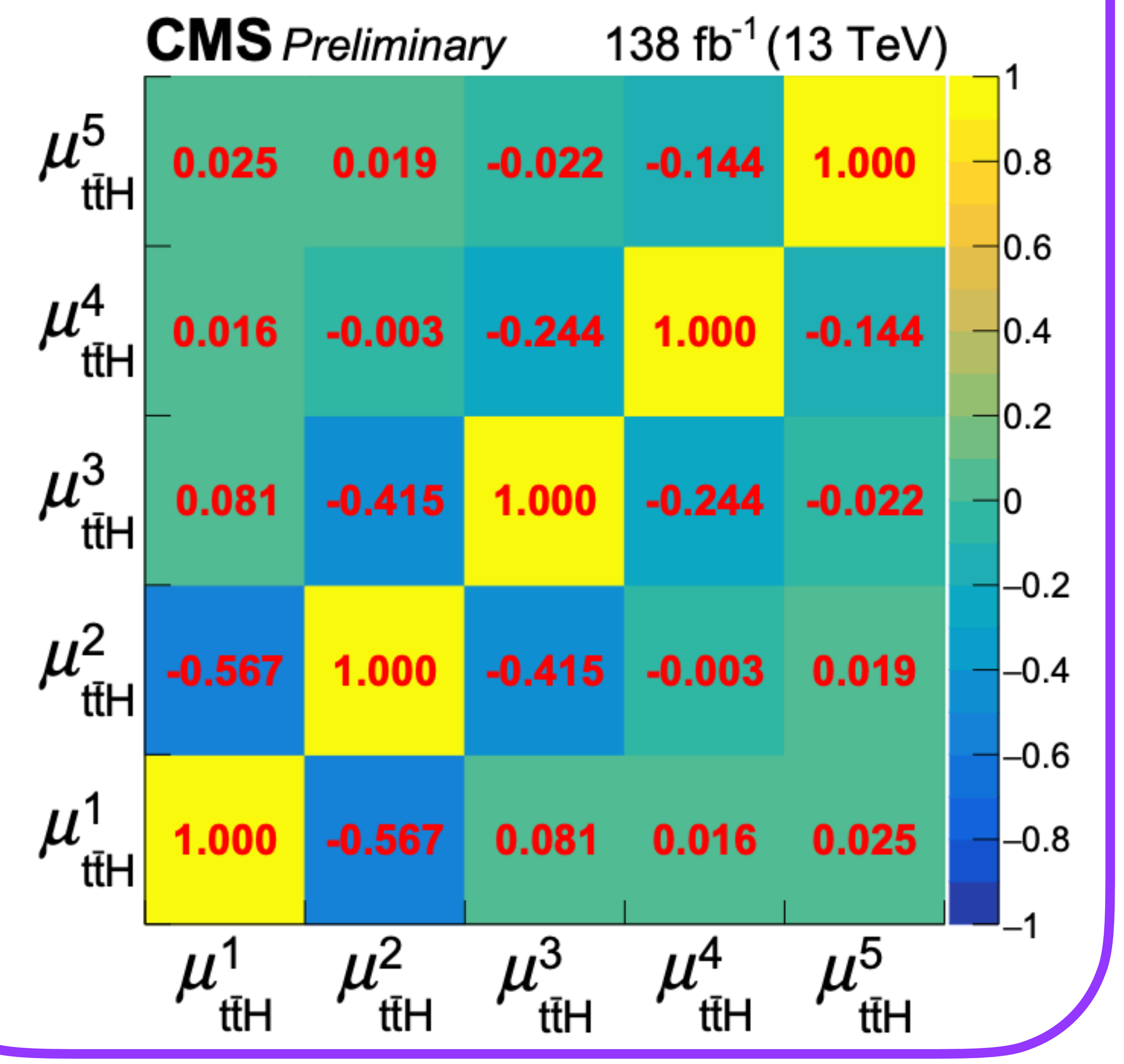
✳ tH (inclusive):

- Expected and observed 95% CL upper limits
- Simultaneous with $t\bar{t}H$









$ZZ/ZH \rightarrow 4b$

[CMS-PAS-HIG-22-011] **New**

✳ A search for ZZ and ZH production in the $b\bar{b}b\bar{b}$ final state

- larger XS than HH

✳ Multi-class multivariate classifier (4b)

- Extract the signal and background model

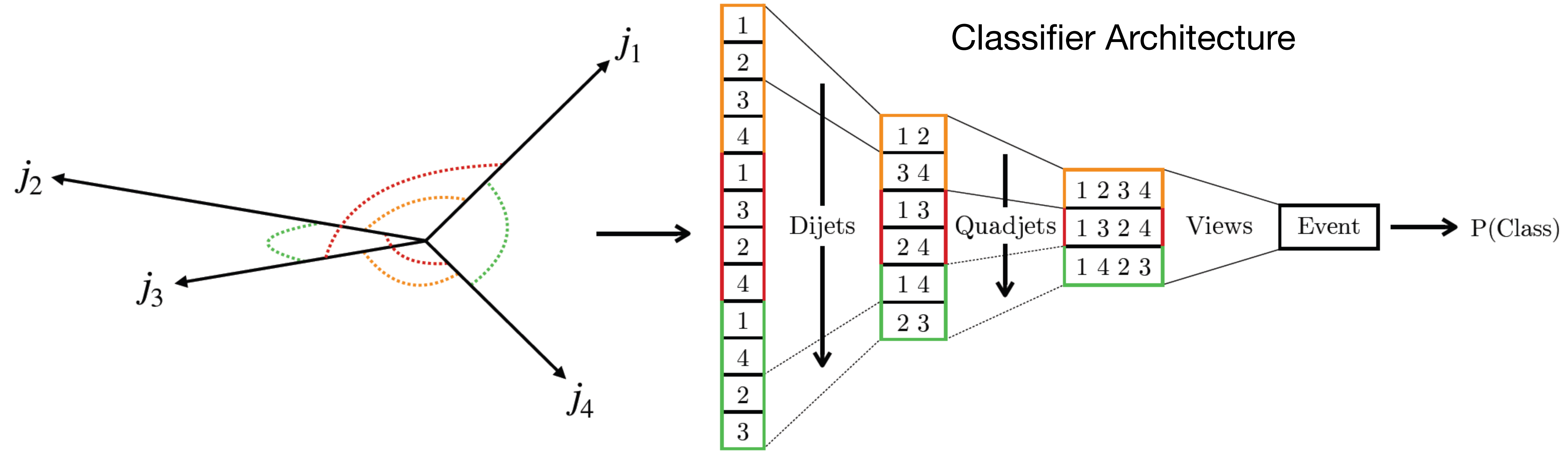
✳ Major (multi-jet) background estimated from data

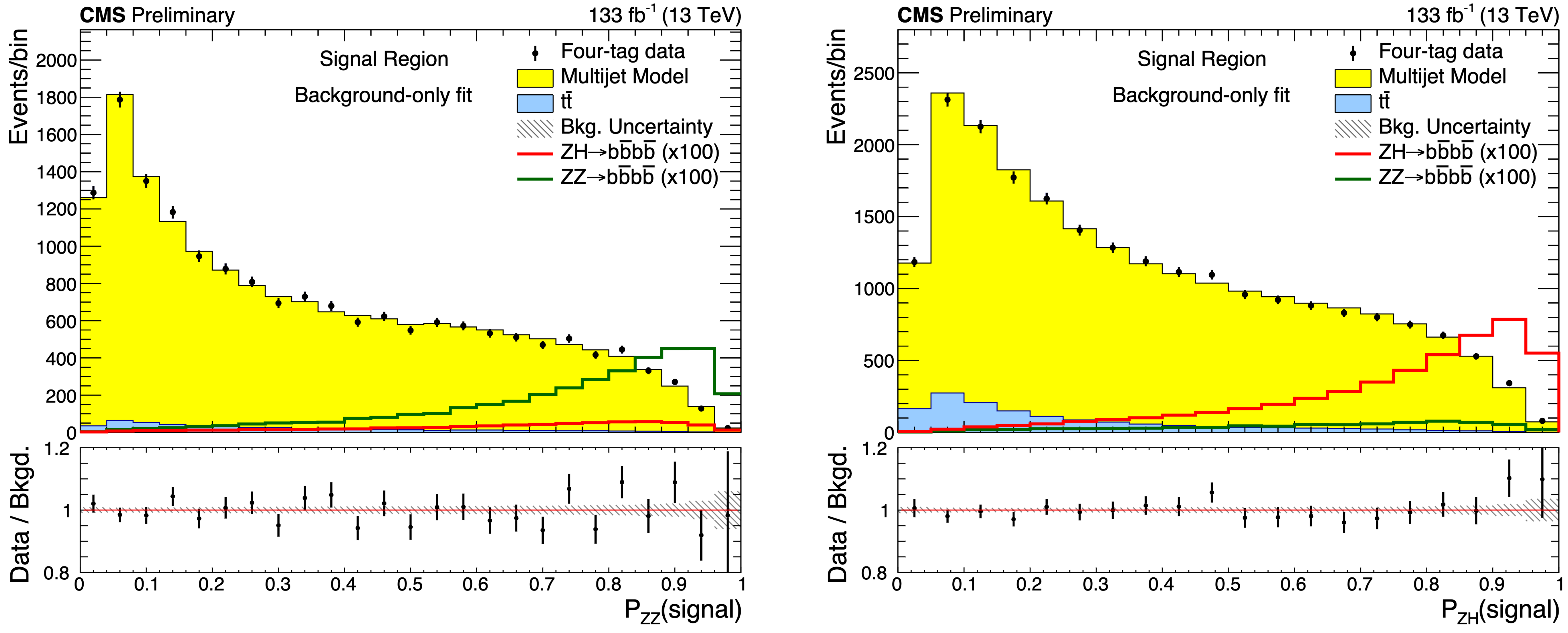
✳ Novel approach to validate the background model

- Using synthetic data

✳ Signal vs Background **probabilities**

- Combined fit in ZZ and ZH regions



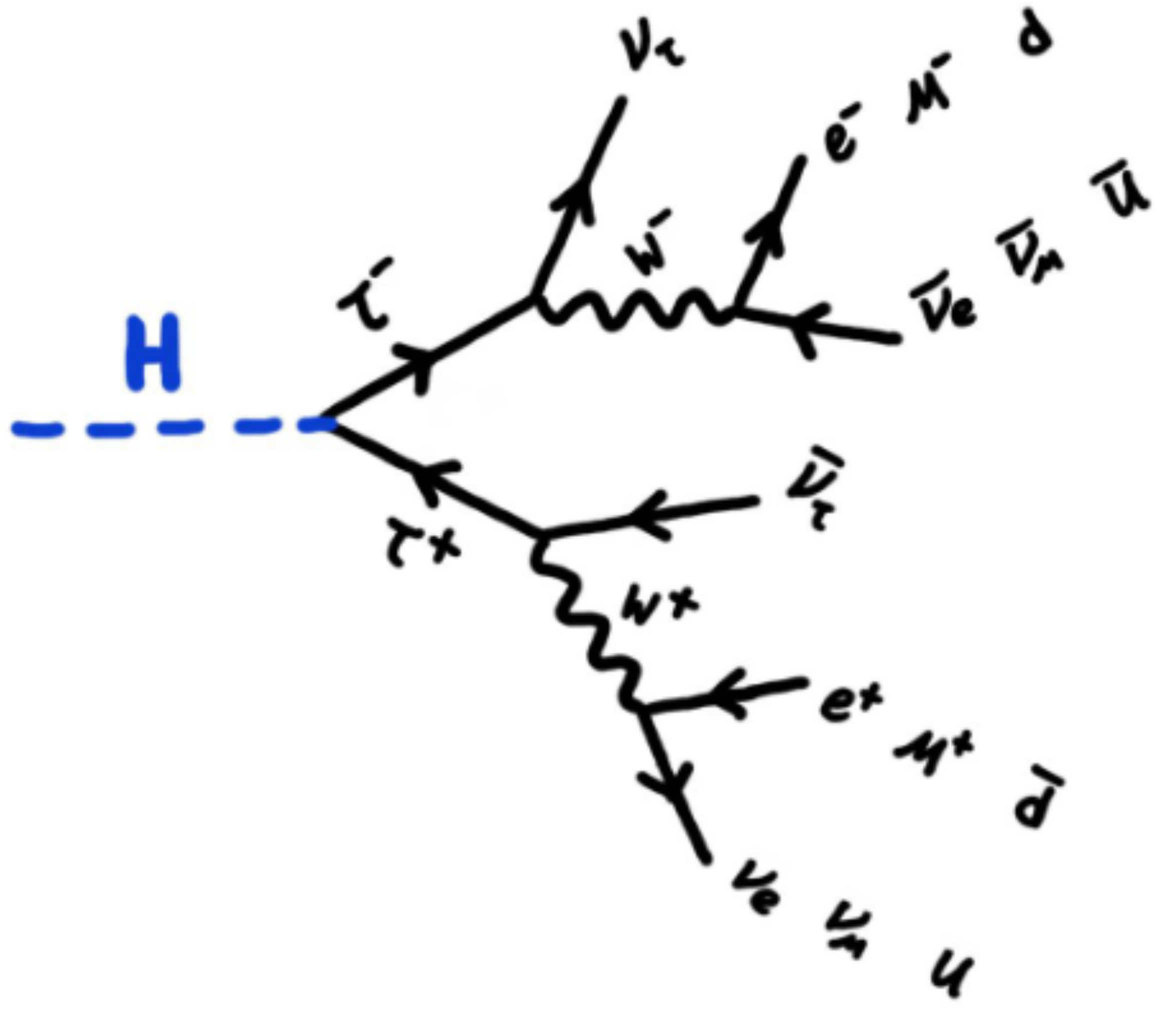


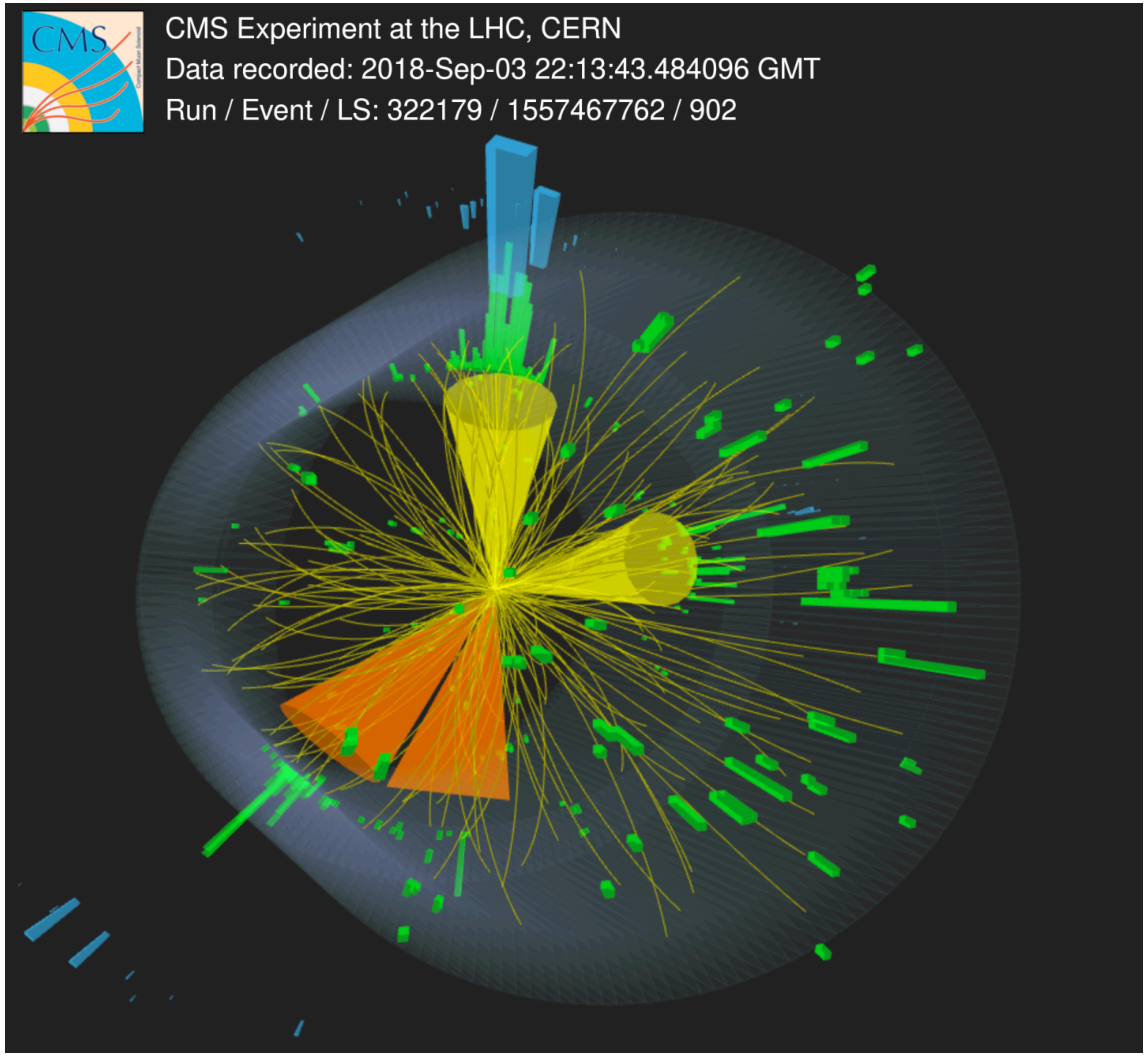
	ZZ	ZH
Signal strength expected (stat-only)	$1^{+1.9}_{-1.7}$ $(1^{+1.4}_{-1.3})$	$1^{+1.5}_{-1.4}$ $(1^{+1.1}_{-1.1})$
Signal strength observed	$0.0^{+2.0}_{-1.7}$	$2.2^{+0.9}_{-0.8}$
Expected Limit at 95% CL (stat-only)	3.8 (2.8)	2.9 (2.3)
Observed Limit at 95% CL	3.8	5.0

Higss production in $\tau\tau$ final state

$\ast H \rightarrow \tau\tau$

- Signal Strengths, STXS, inclusive and differential (resolved and boosted)





10.1140/epjc/s10052-023-11452-8
10.1103/PhysRevLett.128.081805
CMS-PAS-HIG-21-017

$H \to \tau\tau$: Analysis Strategy

10.1140/epjc/s10052-023-11452-8
10.1103/PhysRevLett.128.081805
CMS-PAS-HIG-21-017

✳ SS, STXS and differential cross-sections

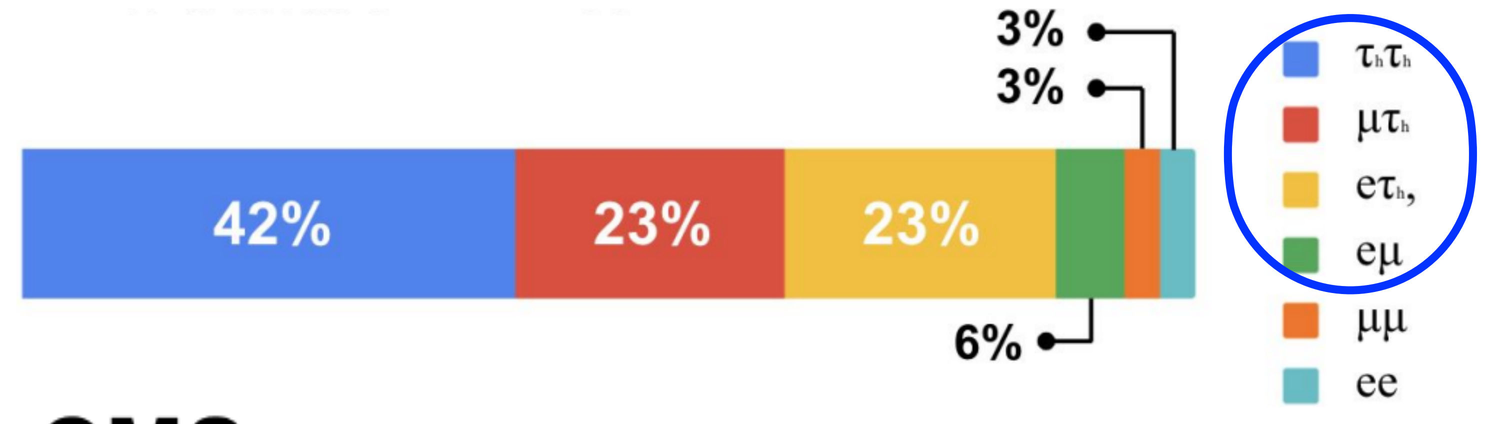
✳ 4 channels considered in ggF and VBF productions:

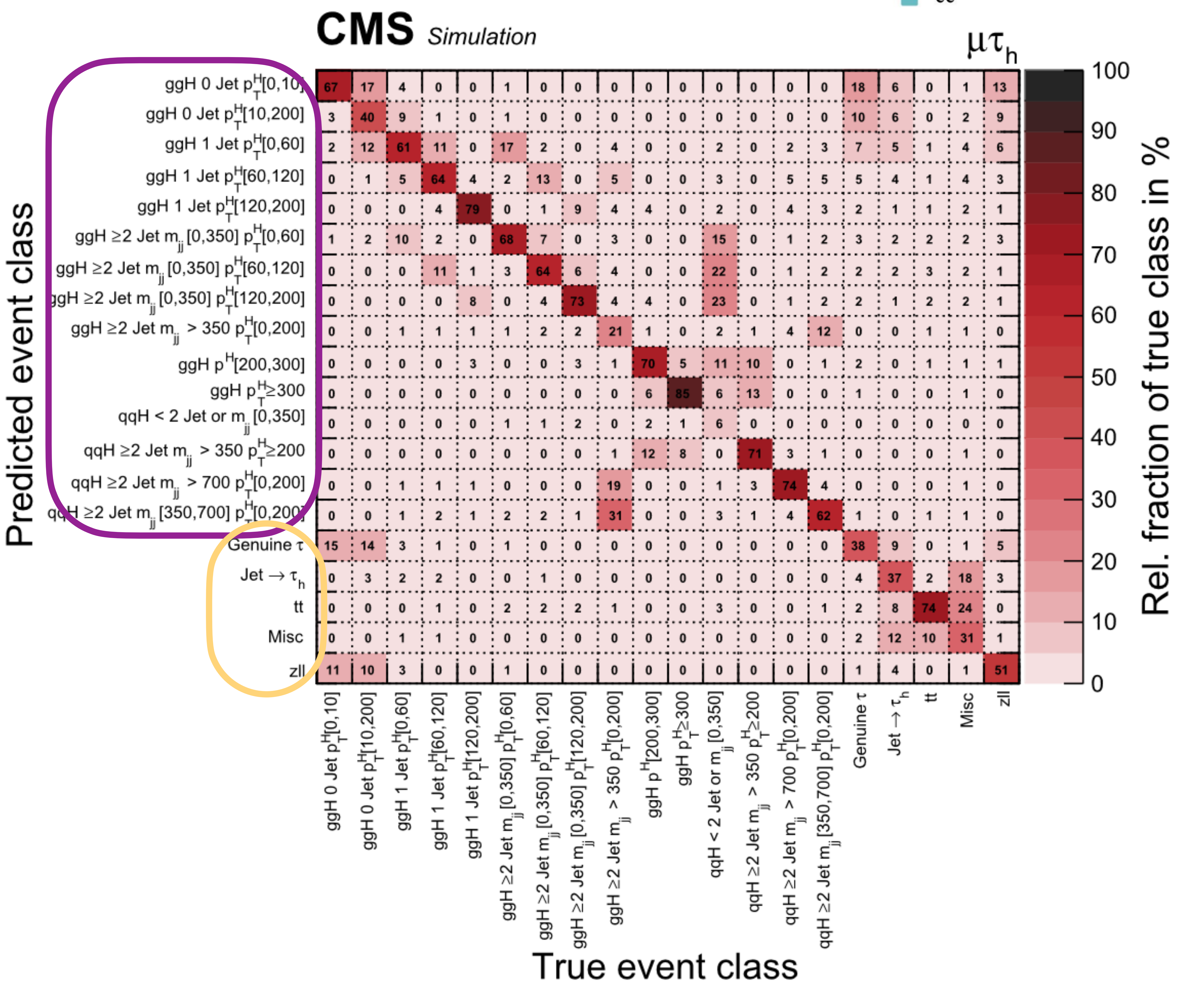
- $\tau_h\tau_h, \mu\tau_h, e\tau_h, e\mu$

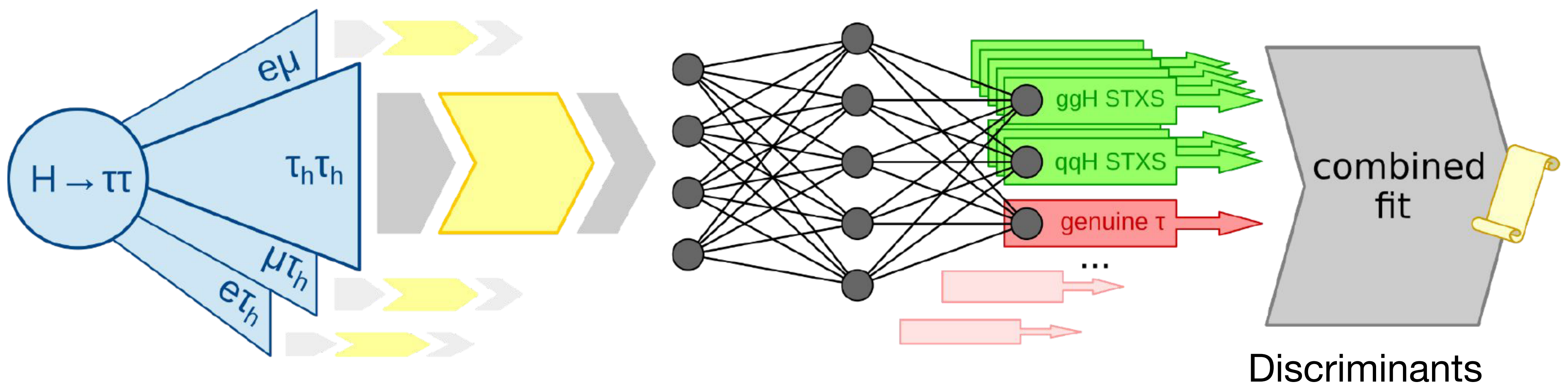
✳ Events categorized according to jets' p_T and the multiplicity (**NN** multiclassification for signal and background)

✳ Majority of background estimated from data

- Genuine $\tau\tau$ events: estimated using Tau Embedding
- Jet misidentified as τ_h: Fake factor (F_F) Method







$H \to \tau\tau$: Results (differential)

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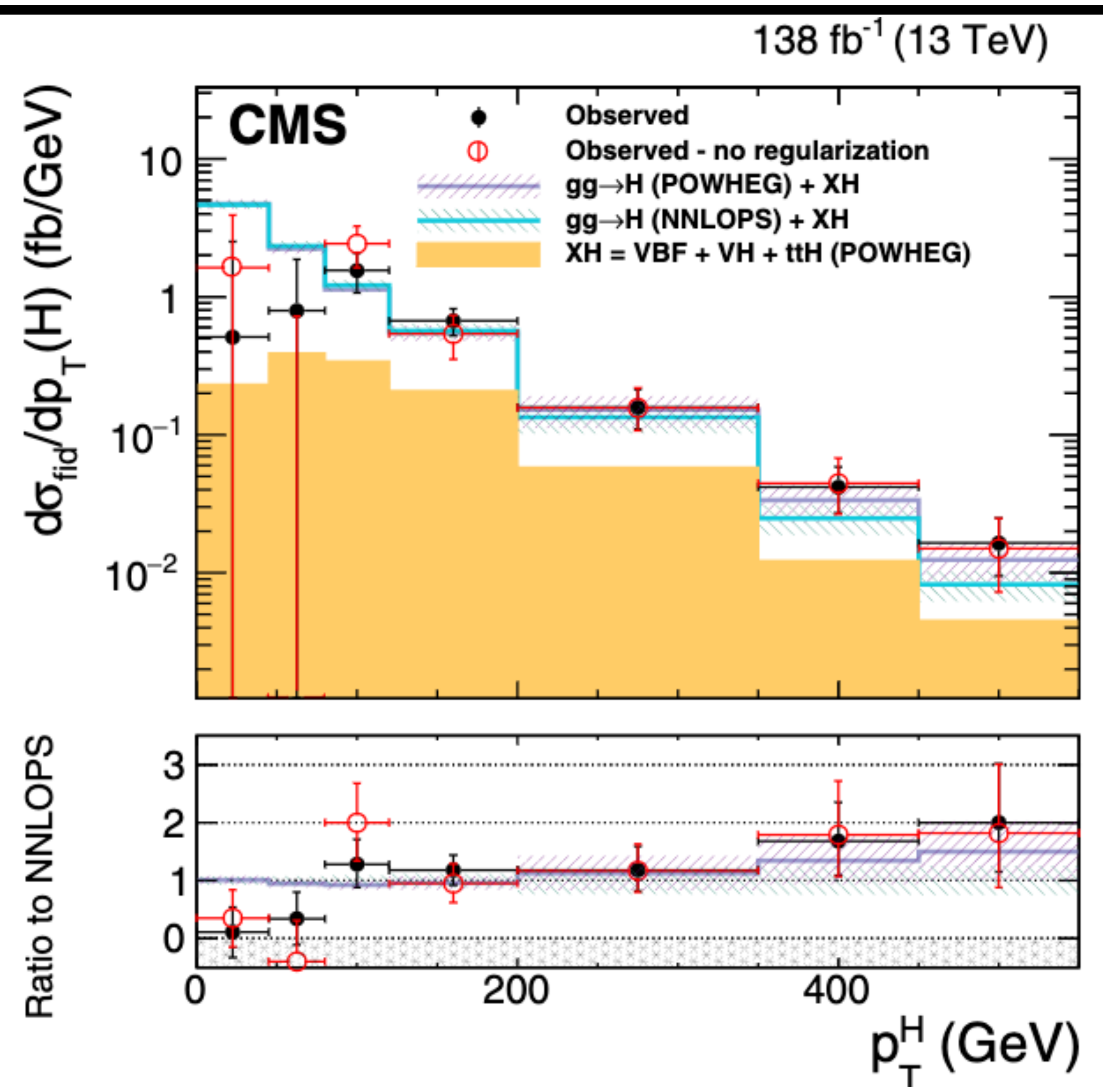
CMS-PAS-HIG-21-017

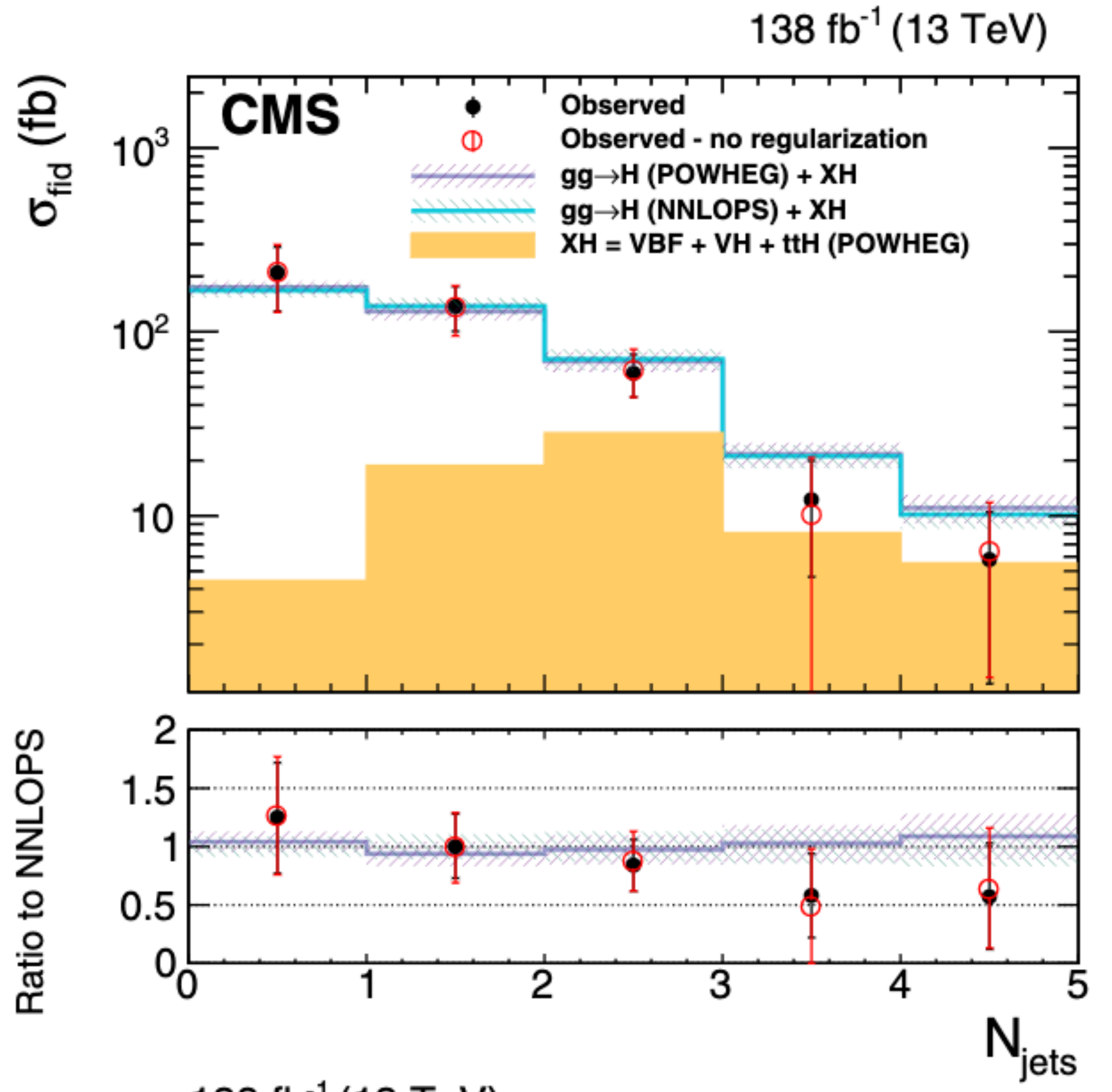
✳ Measured in fiducial region defined to match the offline selection for each decay channel

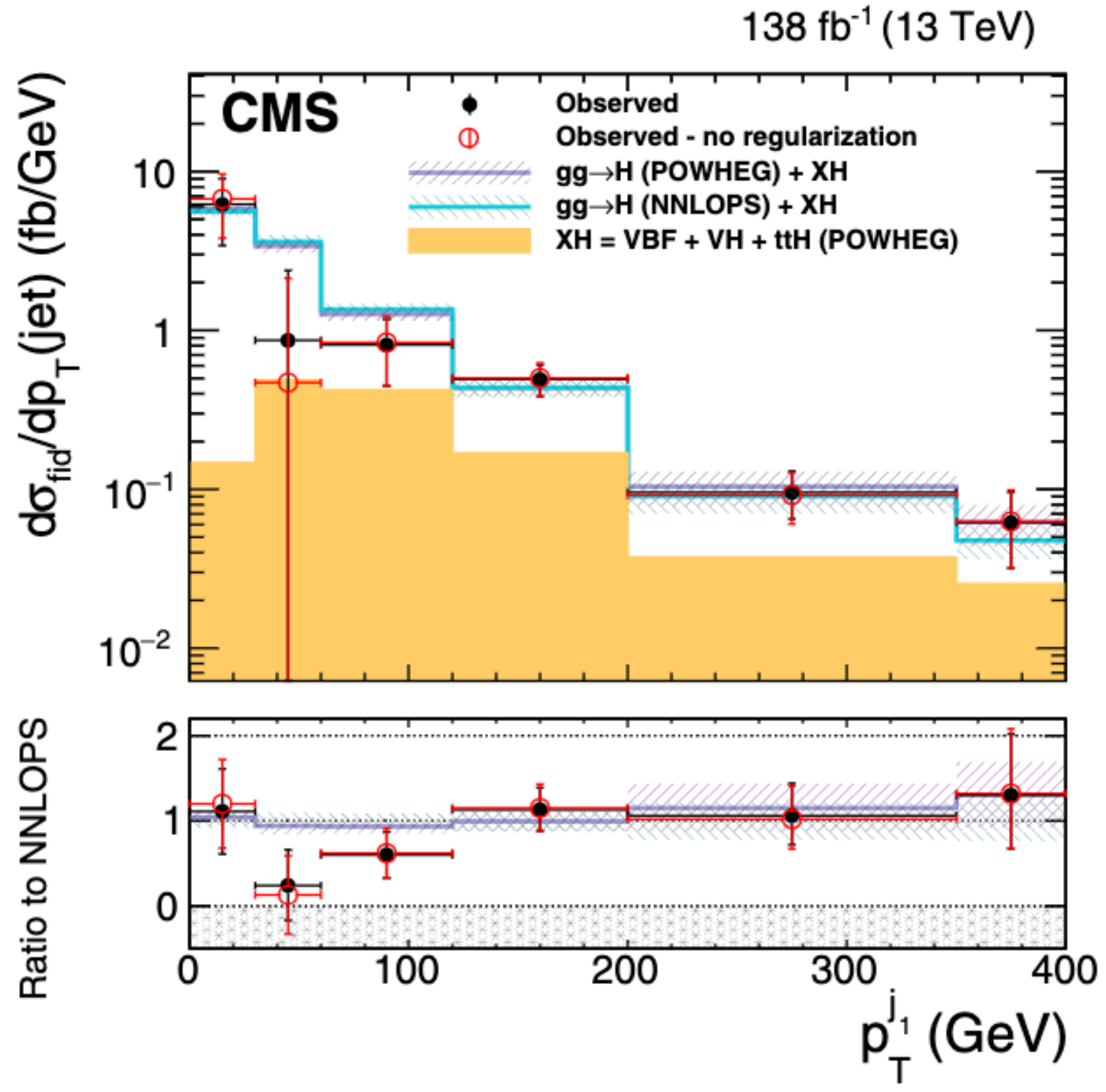
- "OutsideAcceptance" events fixed to SM and treated as background

✳ Reported Differential measurements

- Observables (resolved) : p_T^H, N_{jets} and p_T^{j1}
- Observables (boosted): p_T^H, $p_T^{j_1}$
  - Final observable is NN output
- In agreement with SM







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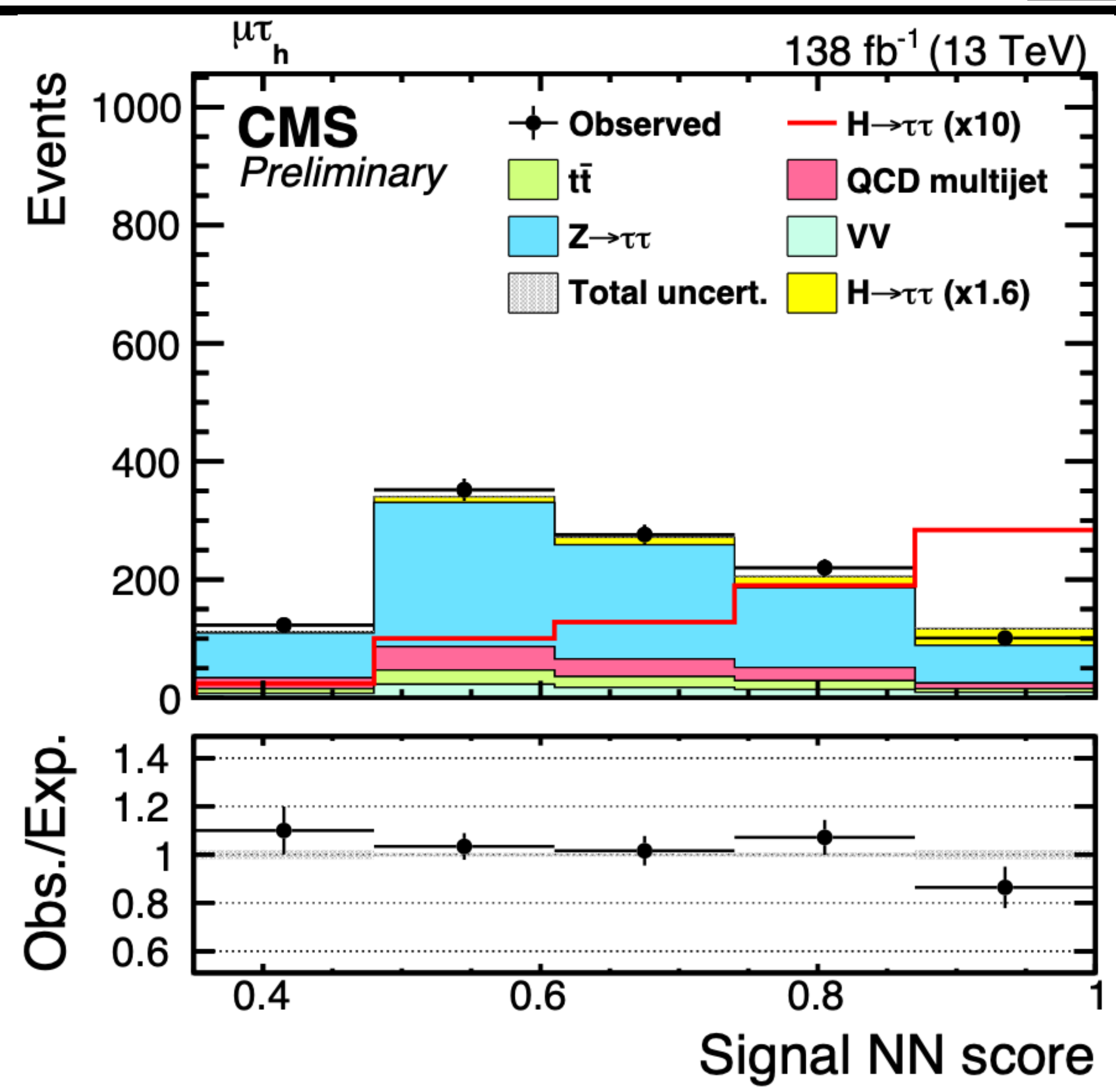
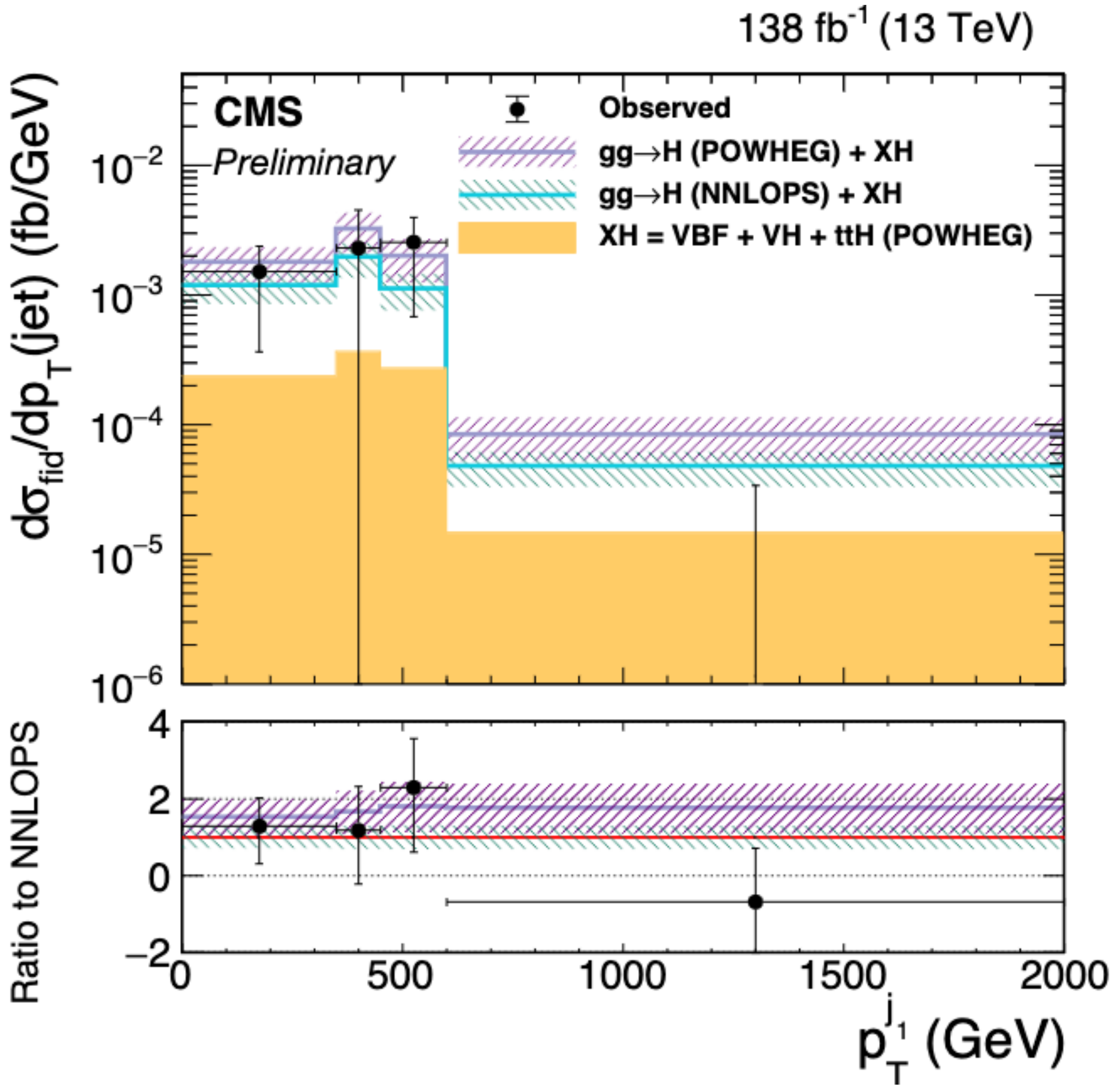
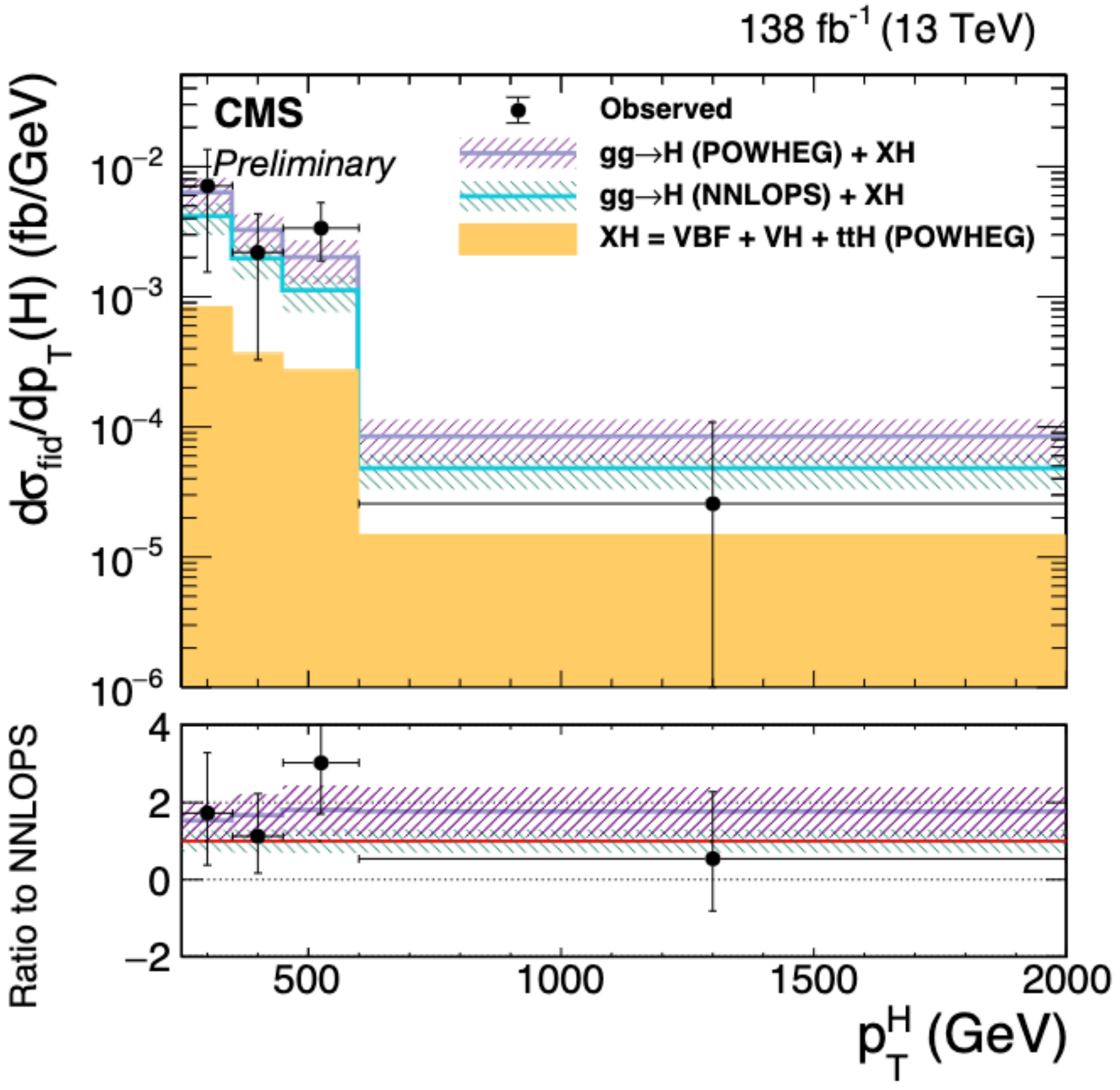






Summary

✳Presented the recent Higgs cross sections measured in fermionic final states

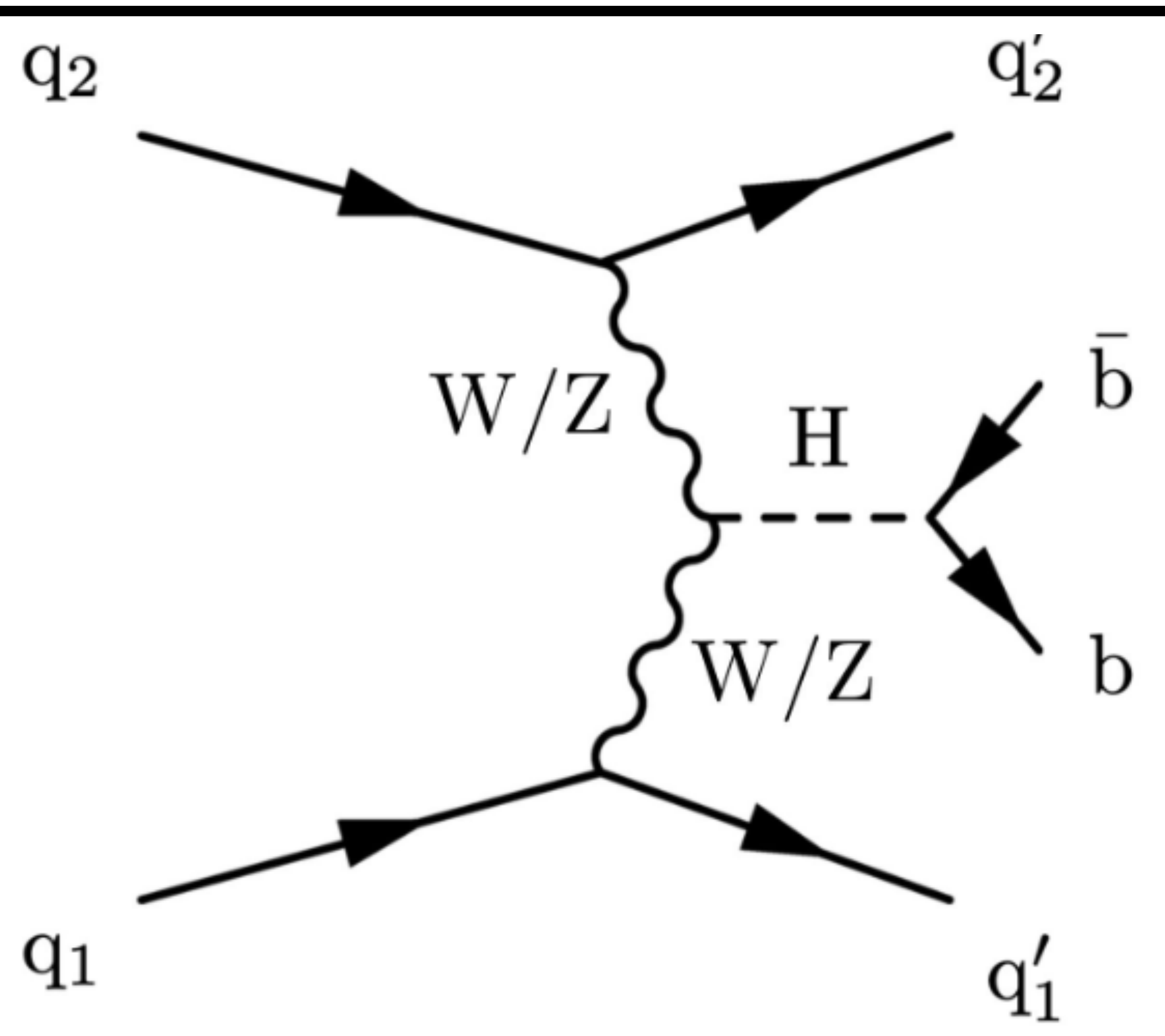
- Run 2 CMS data
- Several fronts explored in $H \to bb$ and $H \to \tau\tau$ decay modes:
  - SS, $STXS$, differential (compared with theory predictions)

✳Run 3 data would provide us the opportunity to explore more fine granularity to see the BSM effects (if any) in this regime


Thank
you

BACKUP SLIDES

VBF



Vector Boson Fusion (VBF) process: second most dominant Higgs production @LHC

cross section ~ 3.78 pb @ $\sqrt{s}$ = 13 TeV with N^{2}LO QCD & NLO EWK accuracy.

→ Br(H→ bb) : largest, ~ 58%

→ VBFHbb process at tree level probes C_V **(HVV) coupling at the production** and **y_b (Hbb) coupling at the decay**.

Hbb coupling established already via VH process→ allowed strength varies over considerably large range.

Experimental challenges

→ Overwhelming QCD multijet background

→ Large resonant Z→ bb background (overlapping with the signal in the higher tail of the Z peak)

→ Triggering VBFHbb events with high efficiency at reasonable rate

Signatures of VBF process:

→ **Two forward-backward** jets from the outgoing scattered partons

→ Mostly with moderate p_T => positioned at the higher $|\eta|$ region, reasonably large rapidity gap ($\Delta\eta_{jj}$)

→ High dijet invariant mass (m_{jj})

→ jet pair termed as **VBF jets**

Strategy (Resolved analysis dealing with AK4 jets : 2 b-jets from Higgs decay + 2 VBF jets)

→ **Dedicated HLT Triggers** based on the **VBF & b-tag requirements**

→ **Multivariate analysis techniques (MVA)** to discriminate signal against major backgrounds

→ Reconstructed Higgs candidate mass **(invariant mass of two b jets, m_{bb})** distribution is used to extract signal.

$t\bar{t}H/tH$, with $H \to bb$: Results

[CMS-PAS-HIG-19-011]

$\ast\, t\bar{t}H$:

- inclusive
  - $\mu_{t\bar{t}H} = 0.33 \pm 0.26$

    significance: obs.(exp.) 1.3σ (4.1σ)
  - Background normalization ($t\bar{t}B, t\bar{t}C$)
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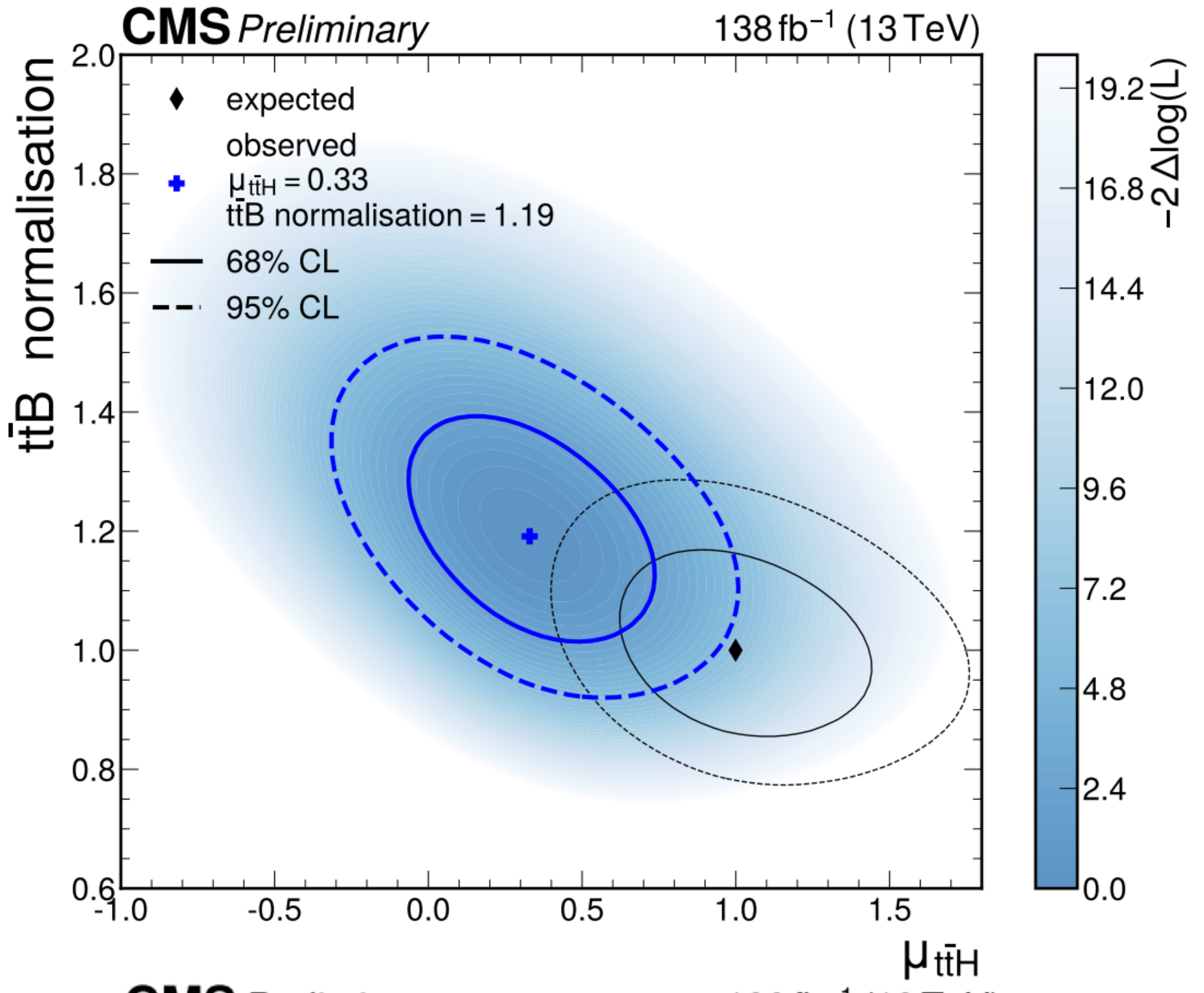
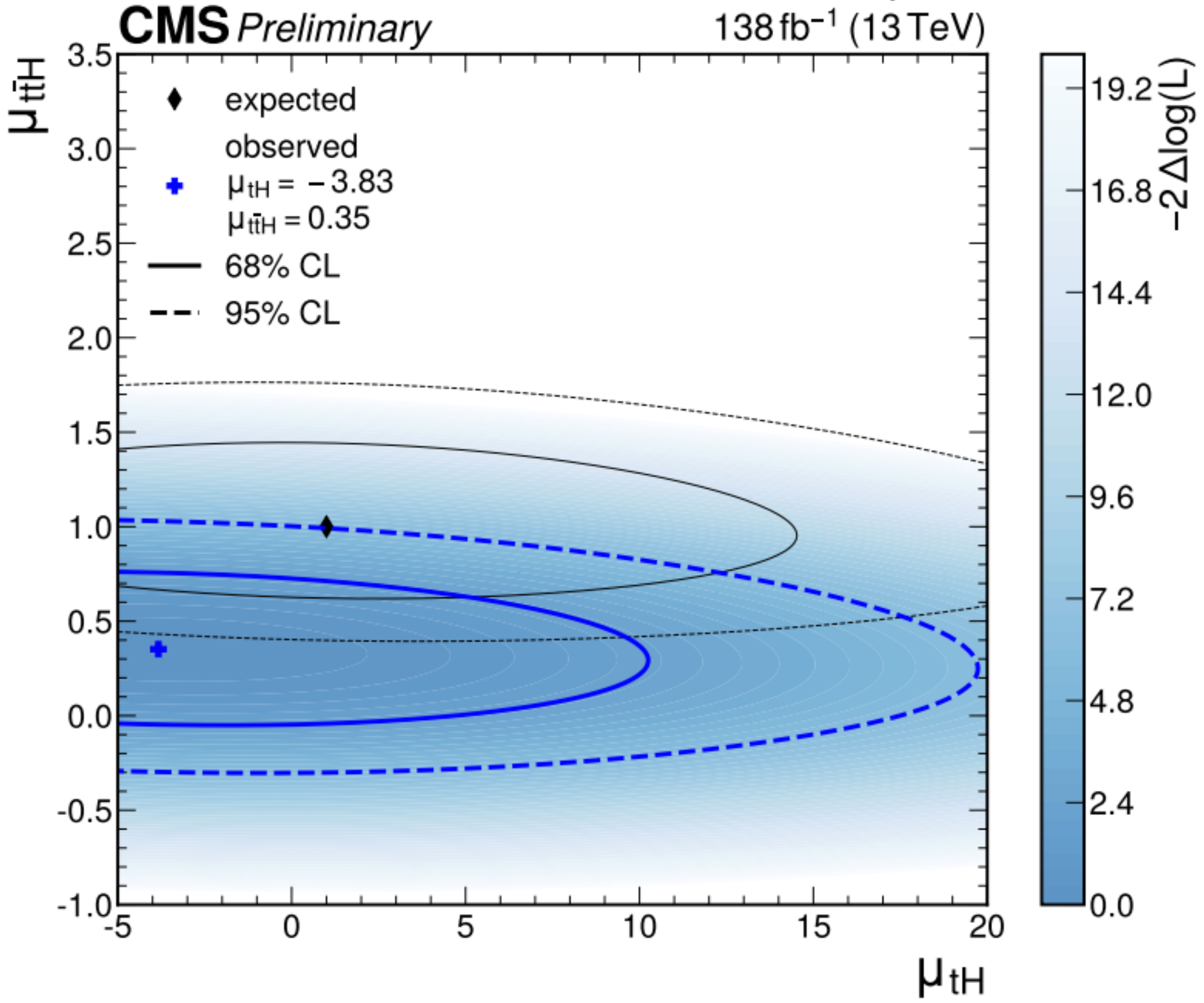
- Simultaneous with $t\bar{t}H$

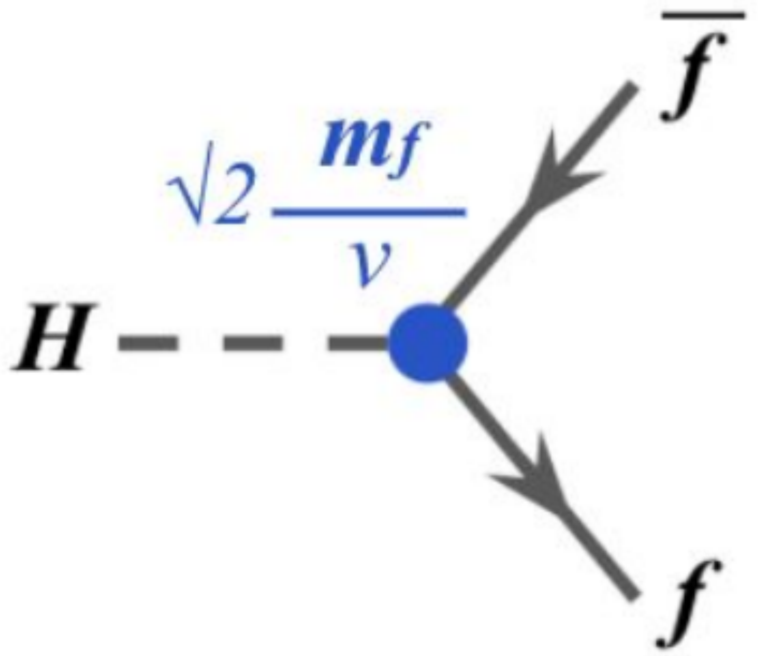




$H \rightarrow \tau\tau$

Why are we interested in Higgs couplings to fermions?

- In the **SM**, fermions interact with Higgs boson via Yukawa couplings
- In the many **BSM** theories, deviations of the couplings of the observed Higgs boson to down-type fermions is implied

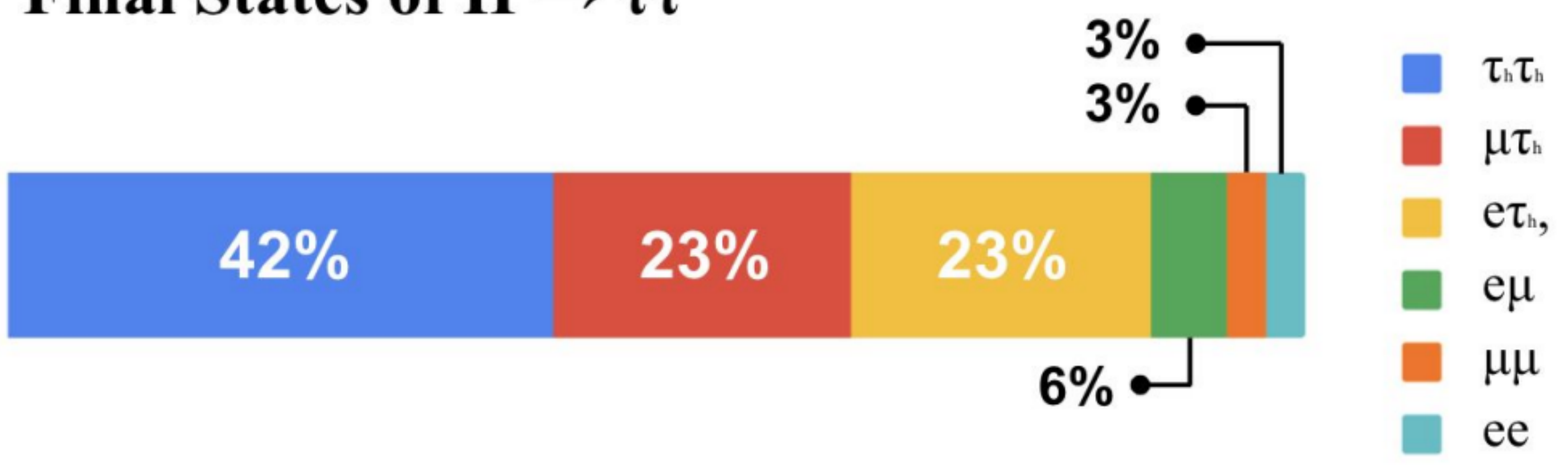


Why do we use H→ττ?

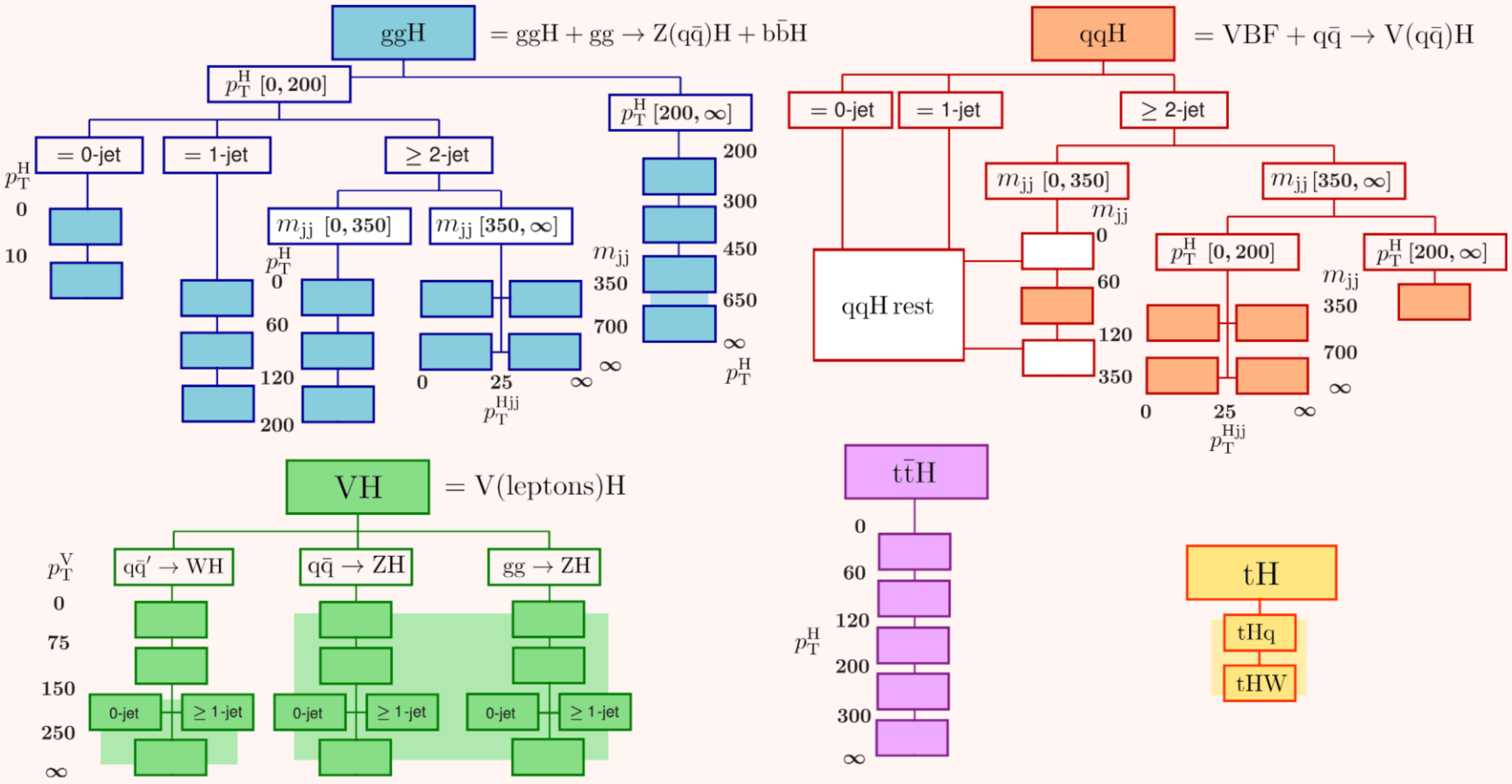
- The H→ττ decay allows to demonstrate direct coupling of the H boson to fundamental fermions
- Particularly sensitive to the Higgs boson production at high p_T^{Higgs} and with jets

Analysis targets

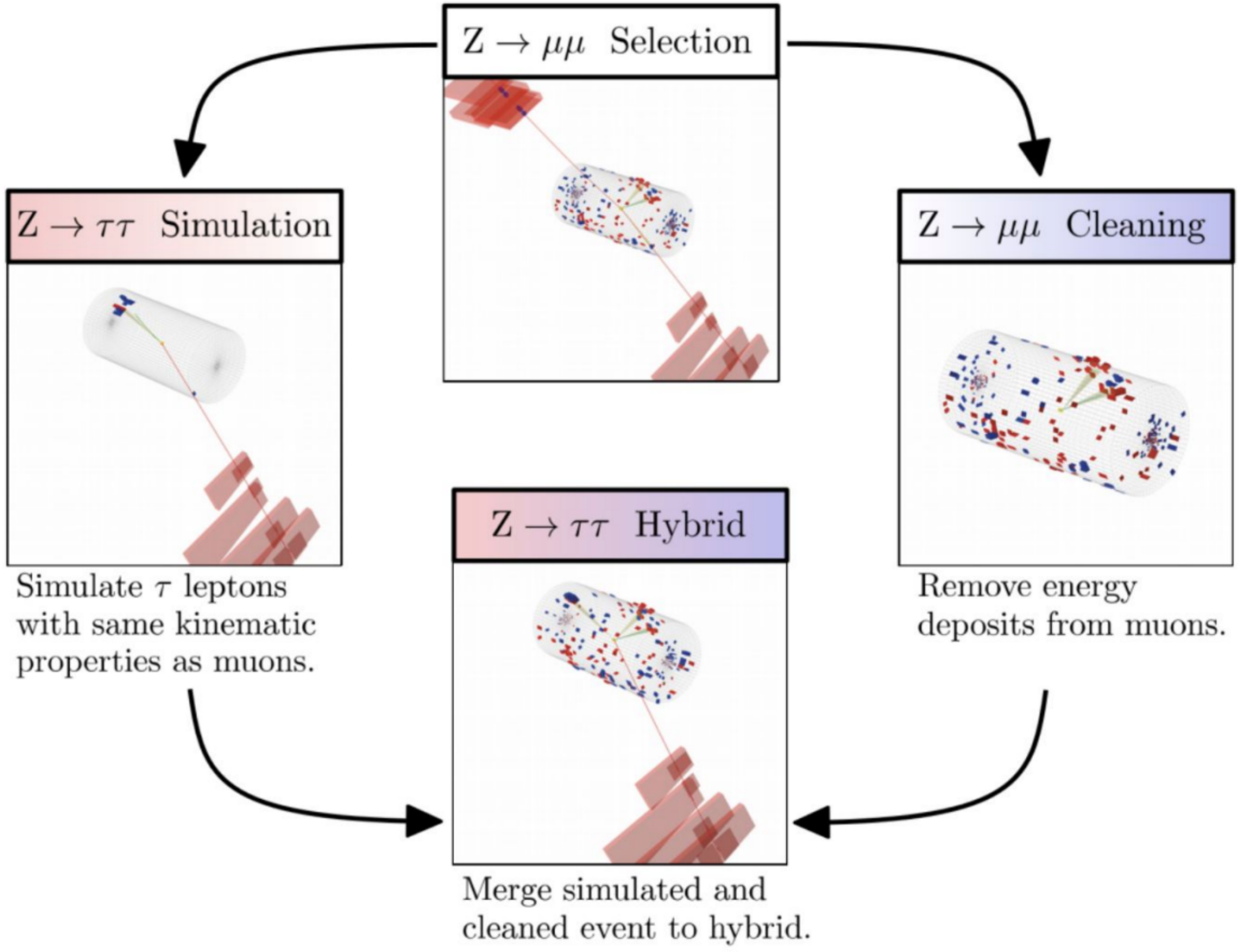
- **ggF** and **VBF** productions using $H \rightarrow \tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$ final states to measure $\boldsymbol{\mu}$ and $\boldsymbol{\sigma}$**×BR**(H→ττ)



STXS



- Higgs kinematics can be sensitively modified by BSM physics
- "Simplified Template Cross Sections" approach: Measure cross sections separated into production modes, inclusively over the Higgs decays, in specific regions of phase-space ("bins"), defined in terms of specific kinematic variables (p_T^H, m_{jj}, p_T^{Hjj}, p_T^V)
- STXS provide a largely model-independent way to test for BSM deviations in kinematic distributions.
- Specific bins defined in coordination with the theoretical community



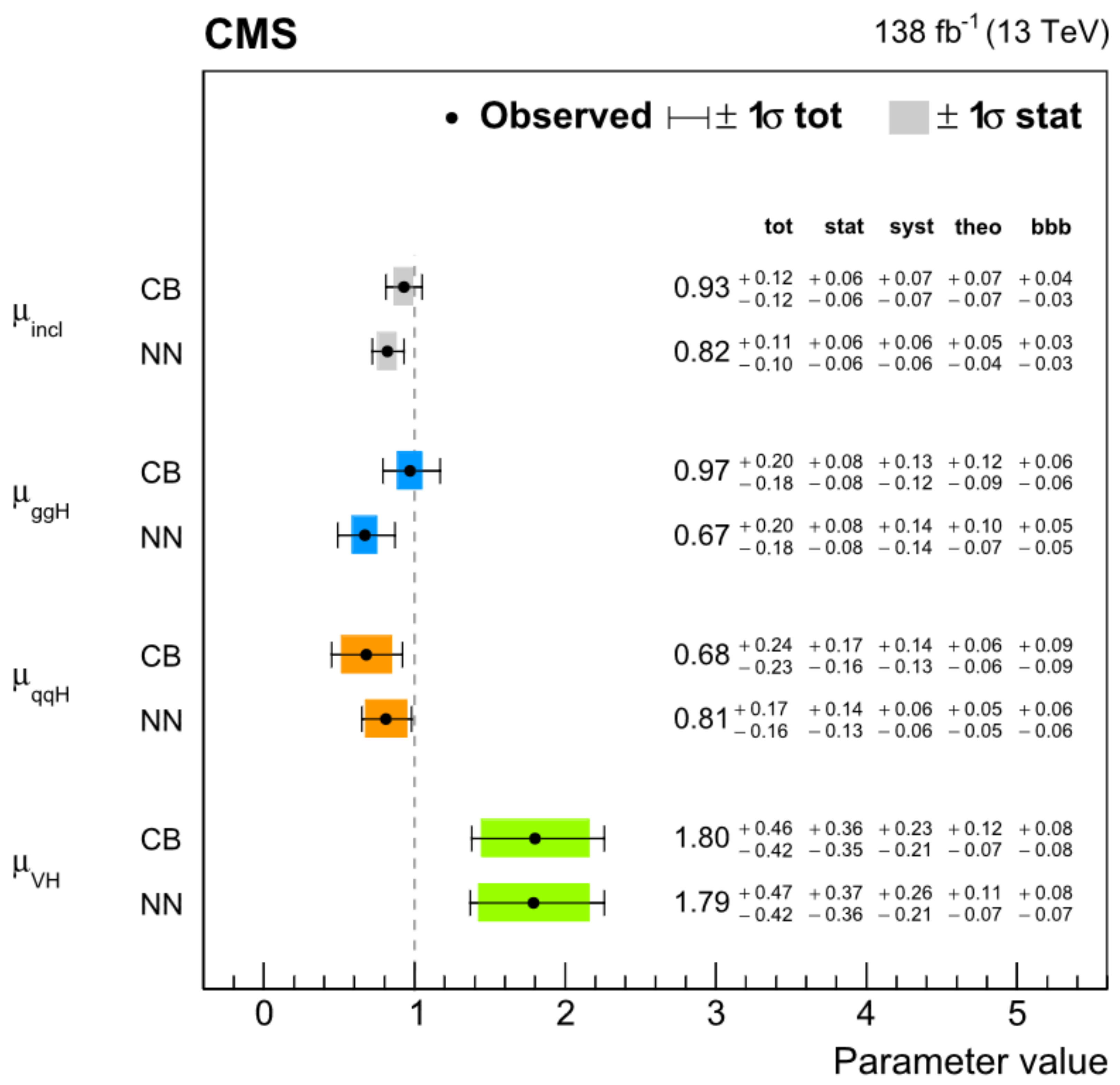
- Estimate all **backgrounds with two real τ**
- Select di-muon events from data, remove muon hits
- Muons are replaced by simulated taus with the same kinematics
- Advantages
  - Decent description of jet and underlying event
  - Less systematic uncertainties
- Used in HIG-18-032

Note:

MET covariance matrix issue does not effect on this analysis

Table 9 Tabulated values of the STXS stage-0 and -1.2 signal strengths for the combination of the (CB) CB-, resp. (NN) NN-analysis with the VH-analysis. The upper four lines refer to the inclusive and STXS stage-0 measurements. The values in braces correspond to the expected 68% confidence intervals for an assumed SM signal. The products of cross sections and branching fraction to τ leptons as expected from the SM with the uncertainties as discussed in Sect. 10.4 are also given

				SM (fb)	μ_s (CB)	μ_s (NN)
Inclusive				3422.28 ± 0.05	$0.93 \pm^{0.12}_{0.12}$ $(^{0.13}_{0.13})$	$0.82 \pm^{0.11}_{0.10}$ $(^{0.12}_{0.11})$
ggH				3051.34 ± 0.05	$0.97 \pm^{0.20}_{0.18}$ $(^{0.24}_{0.22})$	$0.67 \pm^{0.20}_{0.18}$ $(^{0.27}_{0.23})$
qqH				328.68 ± 0.03	$0.68 \pm^{0.24}_{0.23}$ $(^{0.24}_{0.23})$	$0.81 \pm^{0.17}_{0.16}$ $(^{0.17}_{0.17})$
VH				44.19 ± 0.03	$1.80 \pm^{0.46}_{0.42}$ $(^{0.41}_{0.37})$	$1.79 \pm^{0.47}_{0.42}$ $(^{0.41}_{0.37})$
	N_{jet}	$p_{\mathrm{T}}^{\mathrm{H}}$ (GeV)				
ggH	$= 0$	0–10		423.58 ± 0.13	$-0.18 \pm^{0.46}_{0.46}$ $(^{0.45}_{0.44})$	$-1.65 \pm^{0.82}_{0.84}$ $(^{0.84}_{0.83})$
		10–200		1329.36 ± 0.07		$-0.43 \pm^{0.48}_{0.48}$ $(^{0.49}_{0.48})$
		0–60		451.09 ± 0.14	$-0.87 \pm^{1.21}_{1.21}$ $(^{1.06}_{0.99})$	$0.73 \pm^{0.69}_{0.66}$ $(^{0.68}_{0.64})$
	$= 1$	60–120		287.68 ± 0.14	$3.37 \pm^{1.23}_{1.13}$ $(^{0.90}_{0.83})$	$2.10 \pm^{0.65}_{0.57}$ $(^{0.54}_{0.50})$
		120–200		50.04 ± 0.19	$1.94 \pm^{1.21}_{1.24}$ $(^{1.04}_{0.90})$	$1.61 \pm^{0.78}_{0.65}$ $(^{0.68}_{0.60})$
	≥ 2	0–200		306.26 ± 0.23	$0.05 \pm^{0.88}_{1.53}$ $(^{0.83}_{0.71})$	$1.49 \pm^{0.67}_{0.56}$ $(^{0.66}_{0.56})$
		200–300		27.51 ± 0.42	$0.70 \pm^{0.89}_{1.29}$ $(^{0.91}_{0.77})$	$1.55 \pm^{0.83}_{0.68}$ $(^{0.76}_{0.65})$
		300–∞		7.19 ± 0.47	$1.65 \pm^{1.28}_{1.46}$ $(^{1.20}_{0.96})$	$2.31 \pm^{1.46}_{0.98}$ $(^{1.10}_{0.86})$
	N_{jet}	$p_{\mathrm{T}}^{\mathrm{H}}$ (GeV)	m_{jj} (GeV)			
qqH		0–200	350 –700	34.43 ± 0.04	$-0.29 \pm^{1.77}_{1.44}$ $(^{1.31}_{1.32})$	$1.47 \pm^{1.05}_{1.04}$ $(^{1.03}_{1.03})$
	≥ 2	0–200	700–∞	47.48 ± 0.04	$0.68 \pm^{0.39}_{0.38}$ $(^{0.39}_{0.38})$	$1.24 \pm^{0.32}_{0.31}$ $(^{0.31}_{0.30})$
		200–∞	350–∞	9.90 ± 0.03	$0.69 \pm^{0.58}_{0.45}$ $(^{0.45}_{0.43})$	$0.16 \pm^{0.35}_{0.34}$ $(^{0.37}_{0.35})$
	$N_{\mathrm{jet}} < 2$ or m_{jj} [0, 350] GeV			209.46 ± 0.03	$1.94 \pm^{4.55}_{2.93}$ $(^{2.15}_{2.16})$	$-0.99 \pm^{1.21}_{1.19}$ $(^{1.23}_{1.18})$
		$p_{\mathrm{T}}^{\mathrm{V}}$ (GeV)				
WH		0–150		20.57 ± 0.03	$0.77 \pm^{0.95}_{0.91}$ $(^{0.90}_{0.85})$	$0.79 \pm^{0.94}_{0.91}$ $(^{0.90}_{0.85})$
		150–∞		3.30 ± 0.05	$2.65 \pm^{1.38}_{1.26}$ $(^{1.26}_{1.15})$	$2.65 \pm^{1.37}_{1.25}$ $(^{1.26}_{1.15})$
ZH		0–150		11.99 ± 0.06	$1.97 \pm^{0.90}_{0.81}$ $(^{0.79}_{0.71})$	$2.00 \pm^{0.91}_{0.81}$ $(^{0.79}_{0.71})$
		150–∞		2.55 ± 0.10	$2.23 \pm^{1.01}_{0.82}$ $(^{0.78}_{0.61})$	$2.18 \pm^{1.00}_{0.82}$ $(^{0.78}_{0.61})$



✳ Inclusive signal strength

- $\mu_{incl} = 0.82 \pm 0.11$
  - p-value for compatibility of incl. with SM: 0.10
  - Correlation b/w μ_{ggH} and μ_{qqH} : -0.35