Measurements of Higgs Boson Cross Sections and Differential Distributions, and Searches for Lepton Flavor Violating Decays in Leptonic Final States at CMS

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On behalf of the CMS collaboration

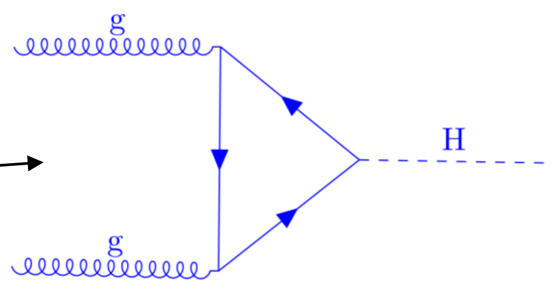
Overview

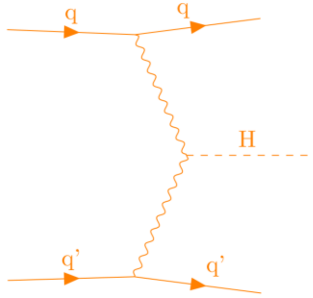
Analysis	Link To Documentation
$H\tau\tau$ Simplified Template Cross Section Analysis	CMS-PAS-HIG-19-010
$H\tau\tau$ Differential Cross Section Analysis	CMS-PAS-HIG-20-015
$H\mu\tau/He\tau$ Lepton Flavor Violation Search	HIG-20-009, ArXiv Link

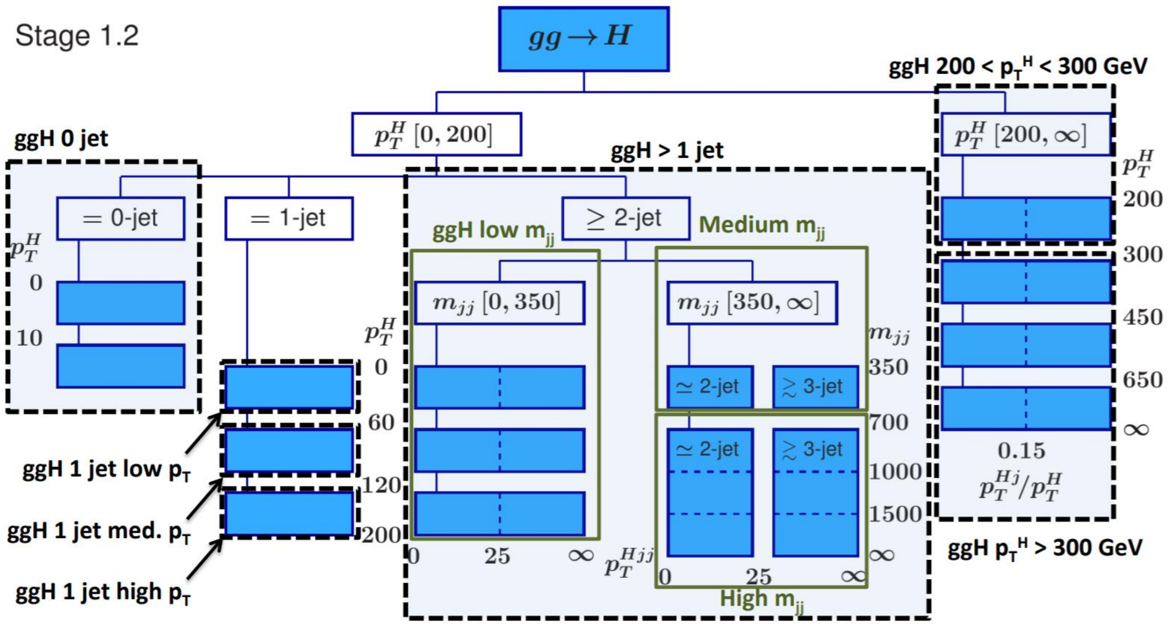
- Why look at leptonic final states of the Higgs boson decay?
- $H \rightarrow \tau\tau$ decays…
  - … provide direct observation of the yukawa coupling
  - … have a high branching fraction that allows for measurements of rarer parts of Higgs Phase space (high transverse momentum, large jet multiplicity, etc)
- H lepton flavor violating decay modes would be evidence of BSM physics
- Note: Silvio Donato will cover the $H \rightarrow \mu\mu$ channel in his talk **here**

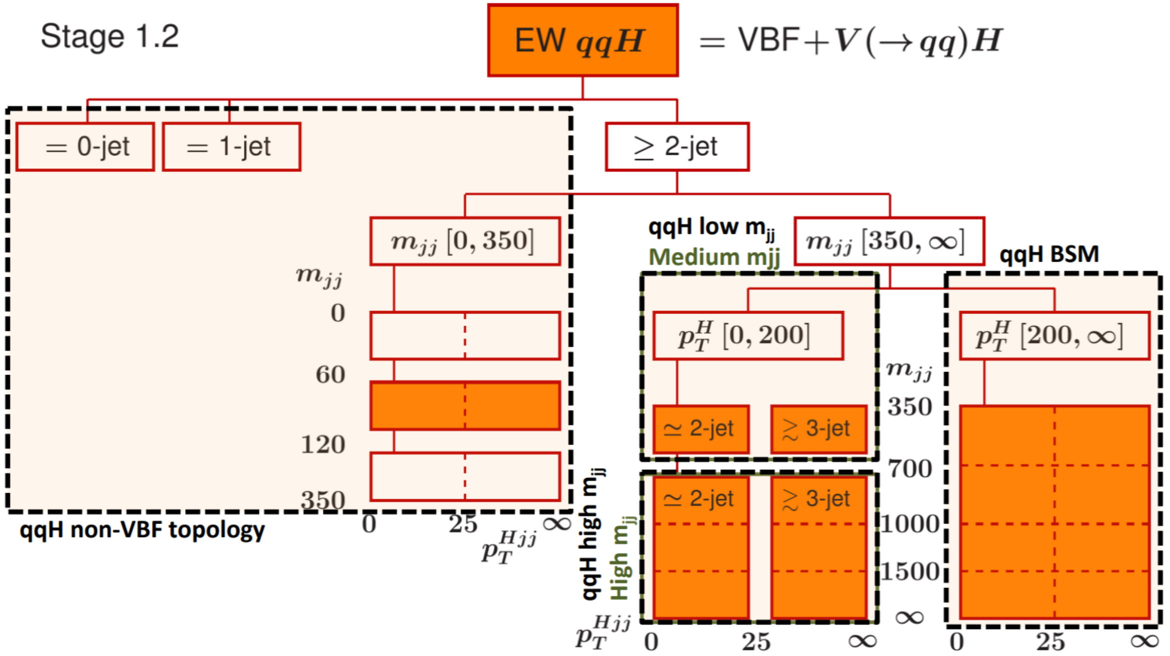
Simplified Template Cross Section Framework

- Simplified Template Cross Section (STXS) framework:
  - Sensitive fine-grained measurements
  - Reduction of theoretical uncertainties
- Inclusive: All higgs signal
- Stage 0: ggH and VBF
- Stage 1.2: below









STXS ggH/VBF framework with merging of gen-level bins measured at CMS. HIG 19-010

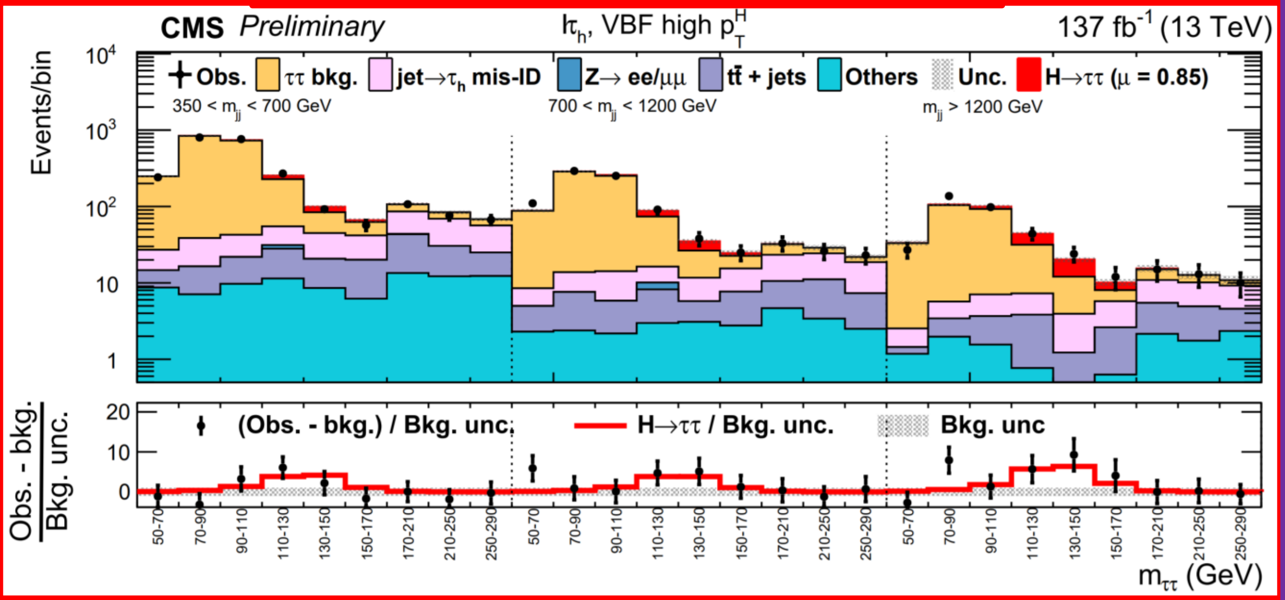
CMS STXS Measurement Strategy

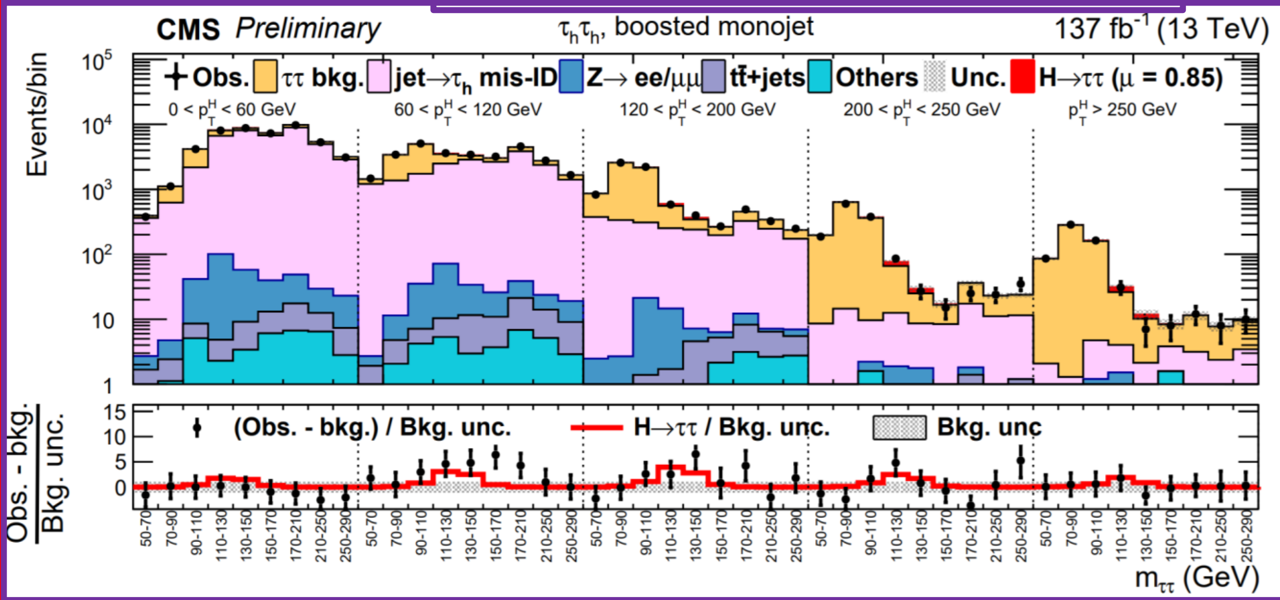
- The Di-Tau decay is picked up in 4 channels: $\tau_h\tau_h, \mu\tau_h, e\tau_h, e\mu$
  - Hadronic taus are reconstructed via the Hadrons Plus Strips (HPS) algorithm, and identified via the DeepTau machine learning algorithm

- VBF:
  - High Higgs Pt
  - Low Higgs Pt

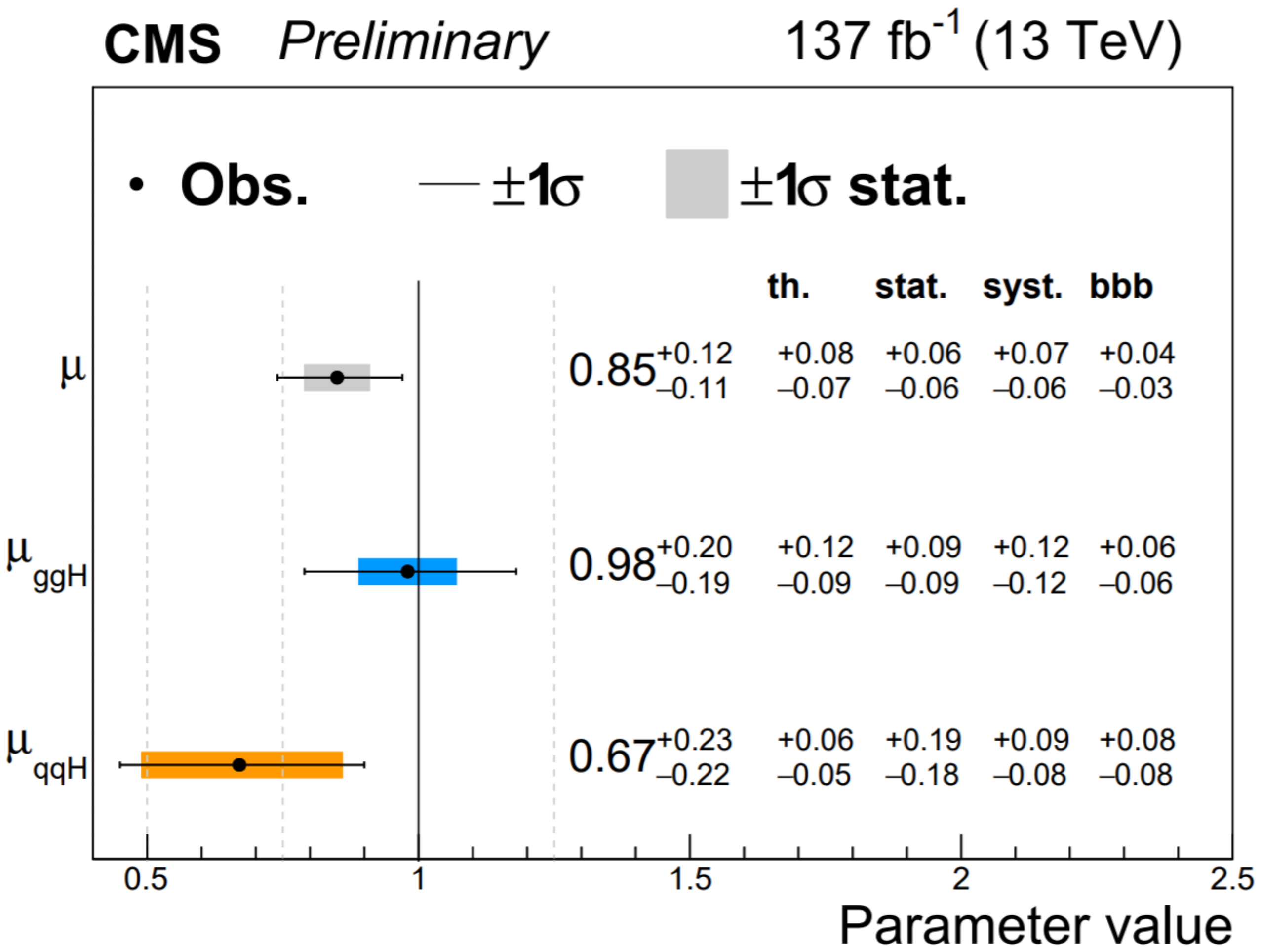
- 0 Jet (Not shown)

- Boosted:
  - Monojet
  - MultiJet

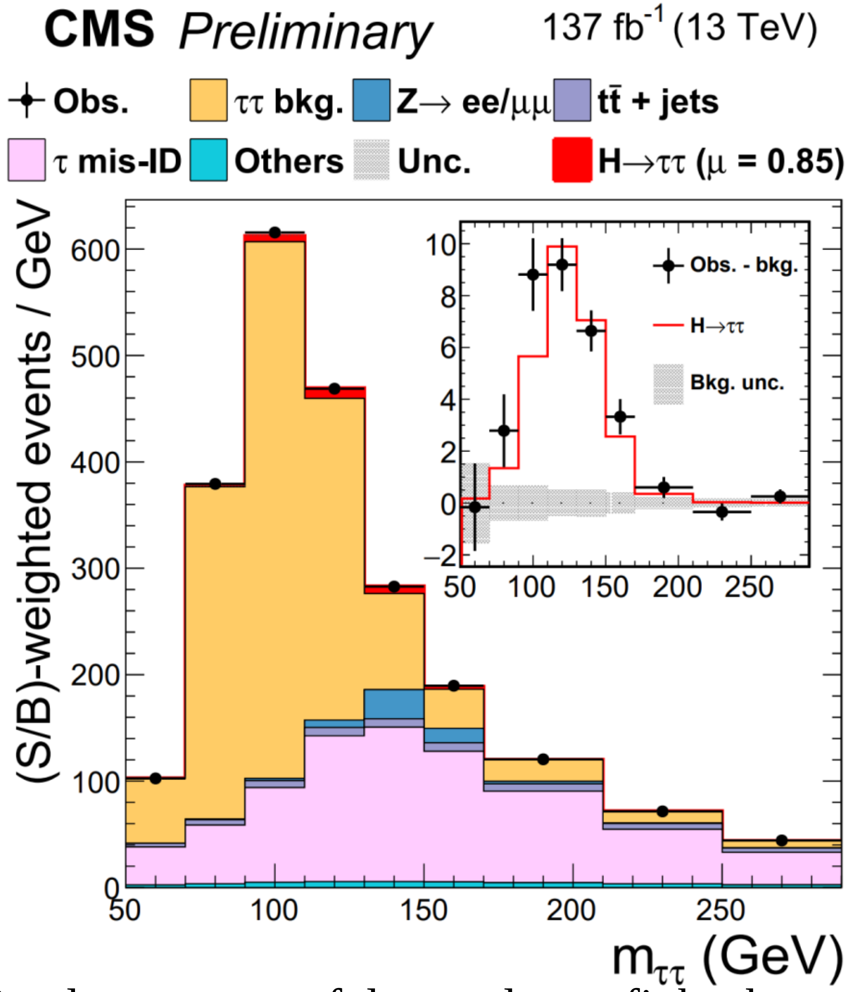




Signal Strengths: Stage 0



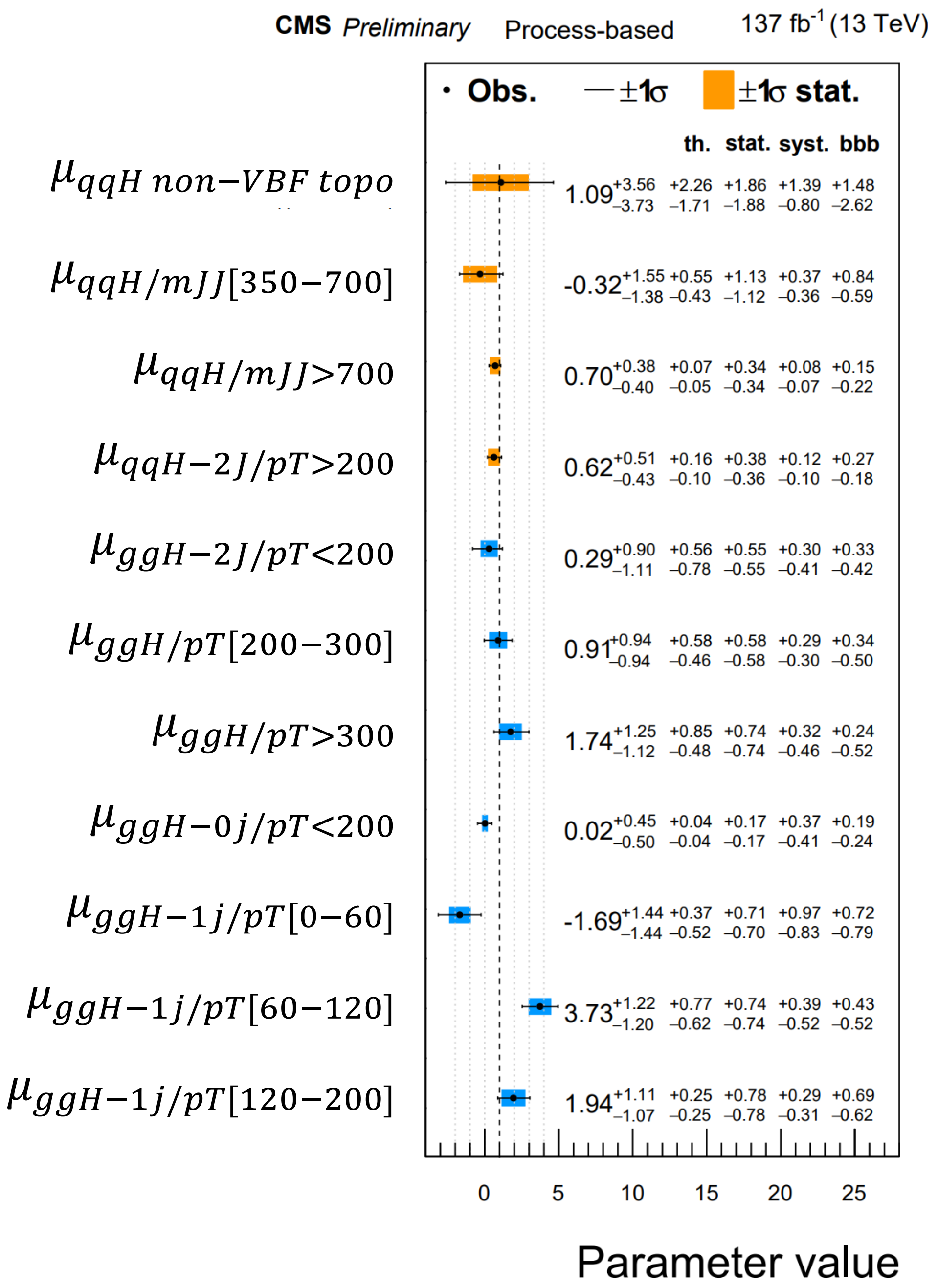
Theory and systematic uncertainties now larger than statistical uncertainties for Inclusive and ggH measurements



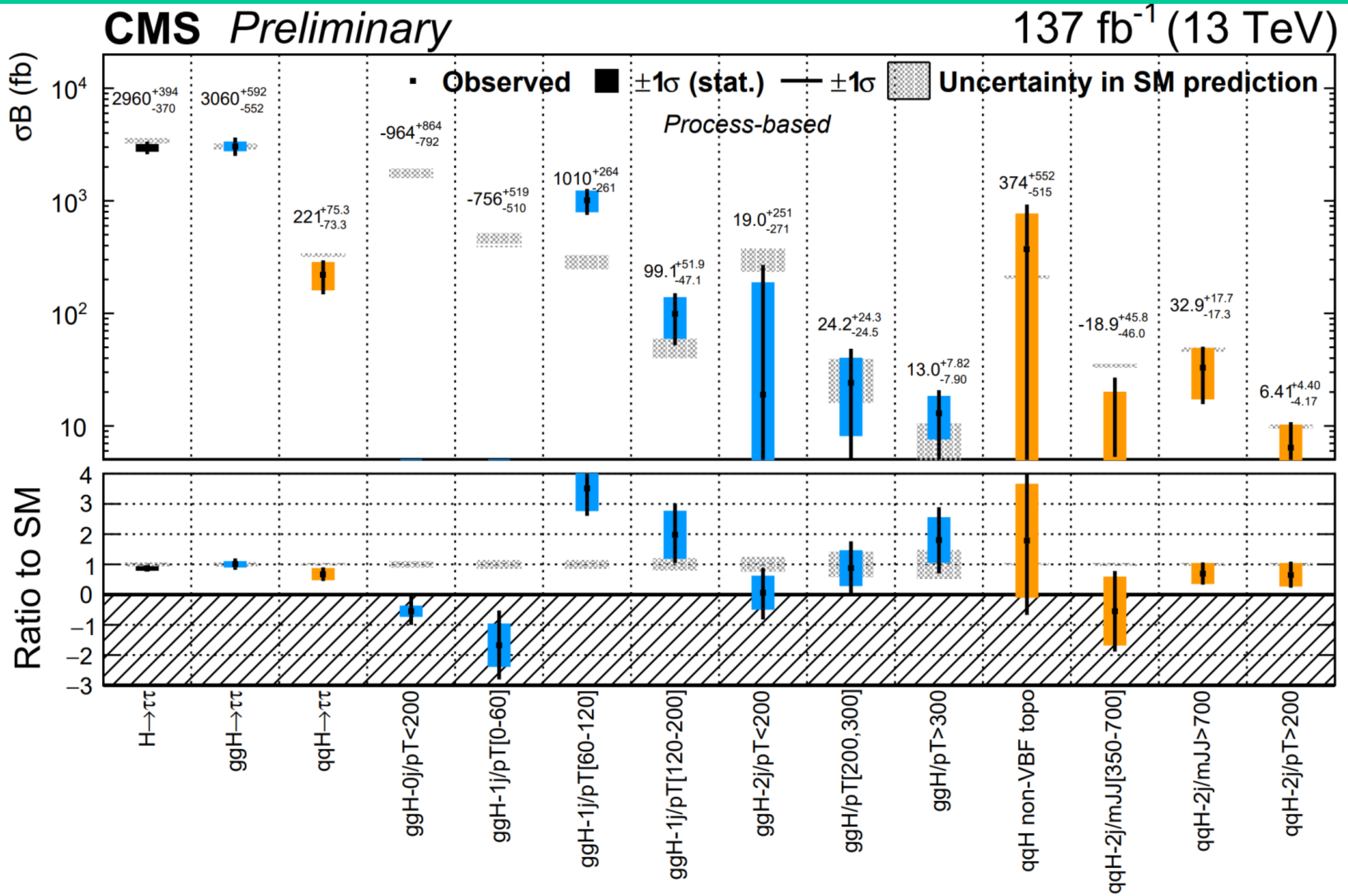
Good agreement of data and post-fit background subtracted signal peak, Peak well situated at 125 GeV

Signal Strengths: Stage 1.2

- Signal strengths computed for certain merging schemes of STXS bins
- Good overall agreement of parameters with SM



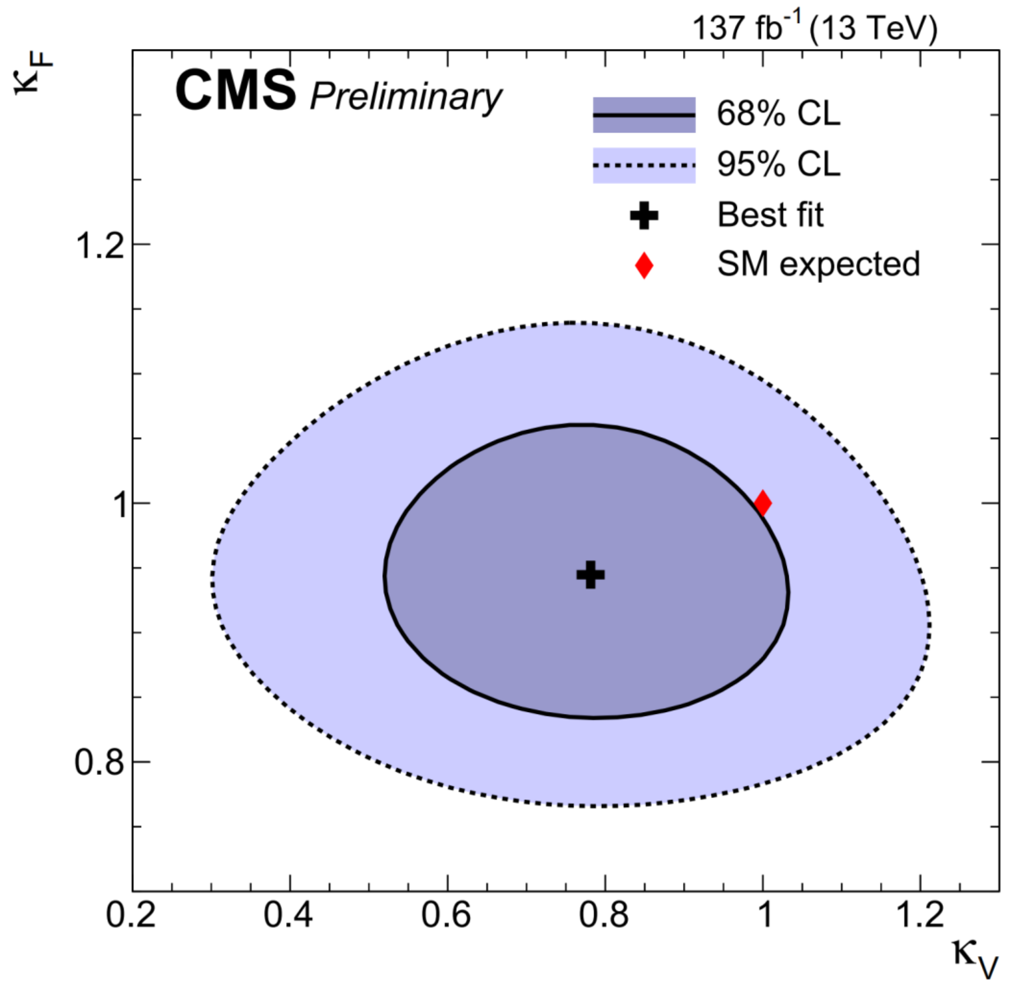
Cross Section Measurements: Stage 1.2

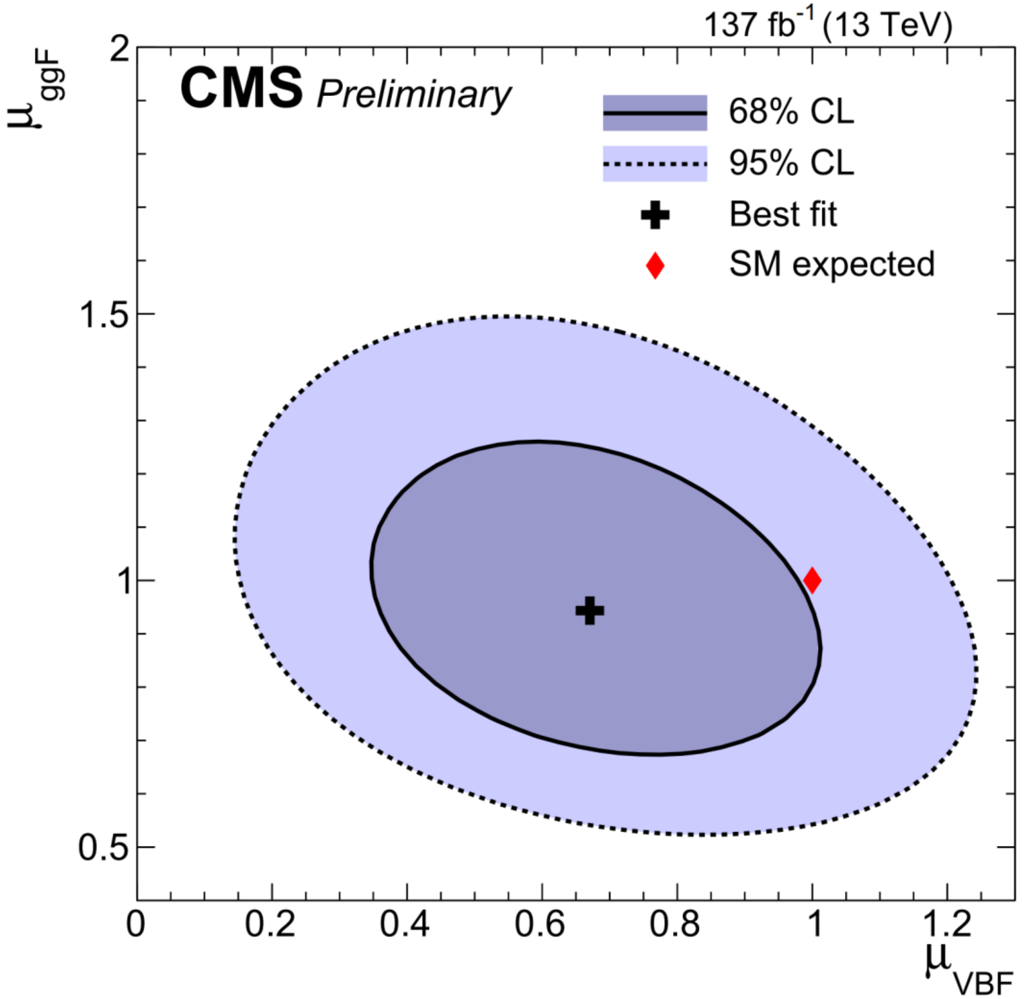


As a reminder:
- ggH
- VBF/qqH

$\kappa_v\kappa_f$ and ggH vs. VBF.

- Both close to 1σ agreement with SM





Differential Analysis

- This analysis targets an inclusive and differential fiducial higgs XS measurement using $H \rightarrow \tau\tau$ decays
  - Provides a more model independent way to look at Higgs physics in secondary variables than the STXS scheme, but integrates over production modes

- Three variables are considered that provide the most interesting measurements and where the $H \rightarrow \tau\tau$ channel can contribute

  - Higgs Pt ← **Offers particularly good probe of BSM Physics**
  - Jet Multiplicity
  - Leading Jet Pt

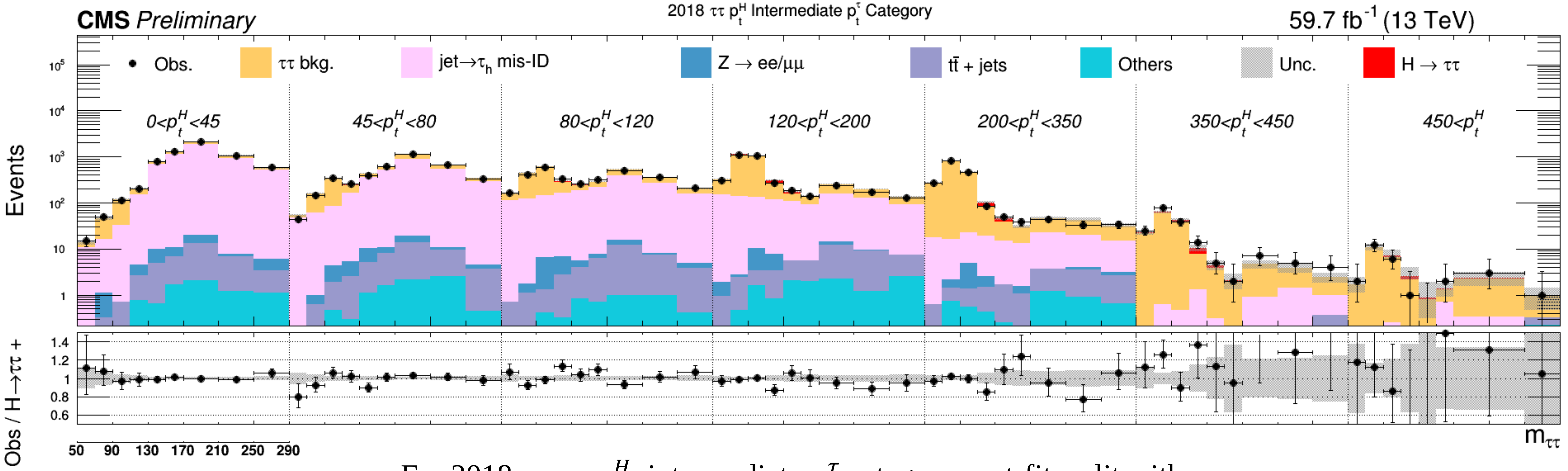
- The $H \rightarrow \tau\tau$ channel offers a good way to examine low cross section regions of phase space
  - High branching fraction to massive taus
- This is the first time that a differential analysis has been performed for the $H \rightarrow \tau\tau$ channel at the LHC

Differential Analysis Strategy

- The Di-Tau decay is picked up in 4 channels: $\tau_h\tau_h, \mu\tau_h, e\tau_h, e\mu$
- Fiducial region defined similarly to offline selection
- In order to maintain independence from the three differential variables, the analysis is categorized based on tau pt
  - S/B increases with p_t^τ
  - $e\mu$ left uncategorized
- Three categories are used:
  - Low p_t^τ: 30-50 GeV (40-50 GeV for $\tau_h\tau_h$)
  - Intermediate p_t^τ: 50-70 GeV
  - High p_t^τ: 70+ GeV

Categorization and Signal Extraction

- Categories use di-tau mass as a primary observable
  - Categories also split further with each observable parameter given a bin, except where statistics do not permit it



Ex. 2018 $\tau_h\tau_h$, p_t^H, intermediate p_t^τ category post-fit, split with one reconstruction p_t^H bin for each signal p_t^H bin

Likelihood Fitting

- Results are extracted as a simultaneous fit maximizing the likelihood function of the form:

Signal Strength Modifier

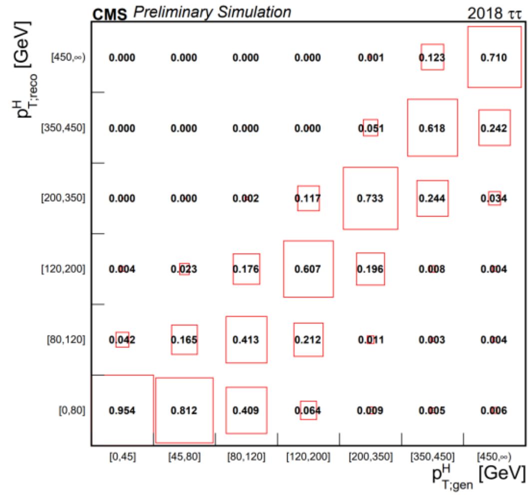
$$\mathcal{L} = \prod_i Poisson\left(n_i \sum_j [R_{ij}(\boldsymbol{\theta})\mu_j] + b_i\right) \cdot \mathcal{C}(\theta_i(\mu))$$

Observed Events

Response matrix:

Nuisance Constraints

Reconstructed Background



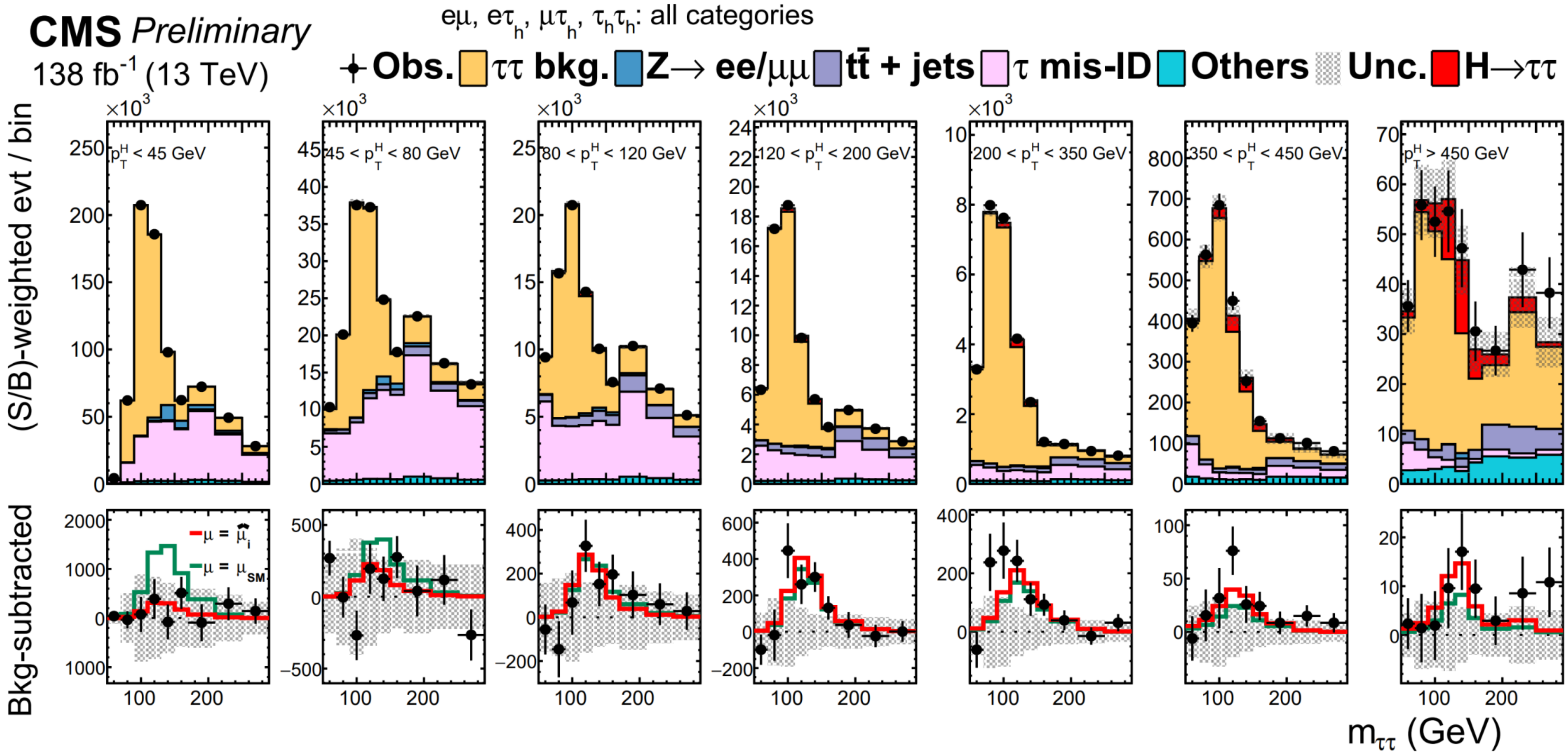
Regularization

- To remove unphysical (statistical) fluctuations of parameters, regularization is employed
- A penalty term of the form:

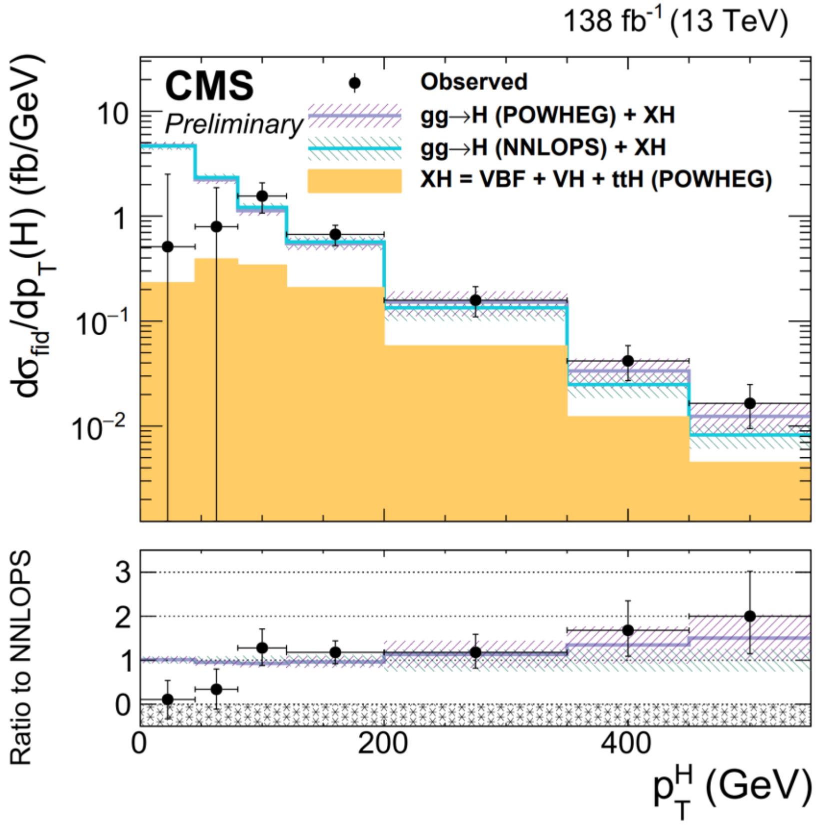
$$\mathcal{K}(\boldsymbol{\mu}) = \prod_{j=1}^{M-2} \exp\left(\frac{-\left[\left(\mu_{j+1} - \mu_j\right) - \left(\mu_j - \mu_{j-1}\right)\right]^2}{2\delta^2}\right)$$

  Where M is the number of bins, and δ controls the strength of the regularization is multiplied in the likelihood function
- δ is optimized to minimize mean global correlation coefficient
  - $p_t^H, \delta = 1.85$
  - $N_{Jets}, \delta = 1.35$
  - $p_t^{j_1}, \delta = 2.35$

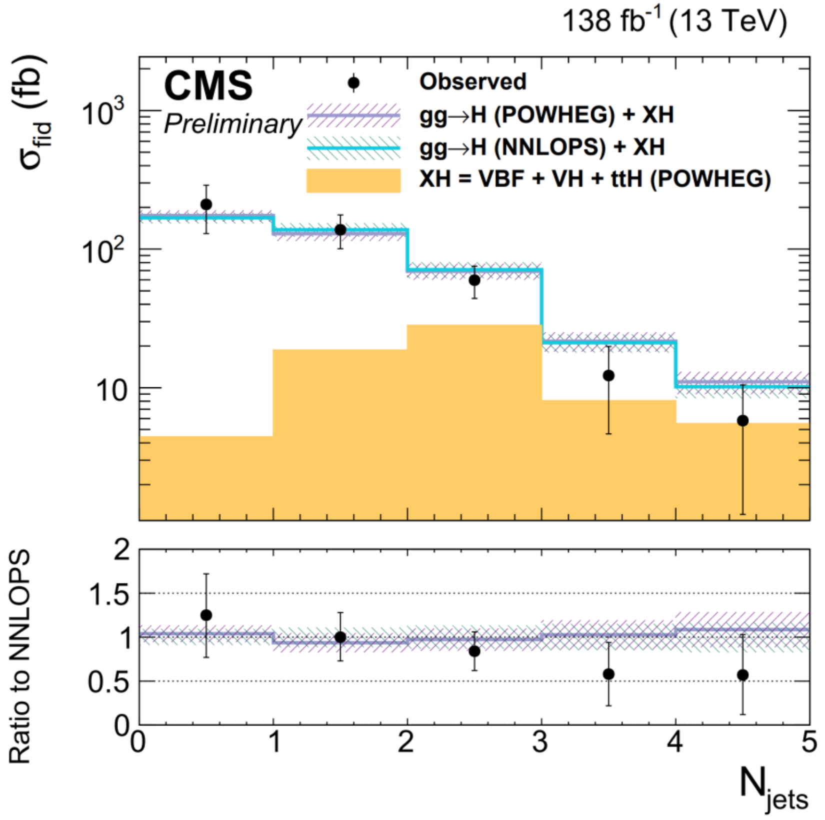
S/B Weighted Plots (p_t^H)



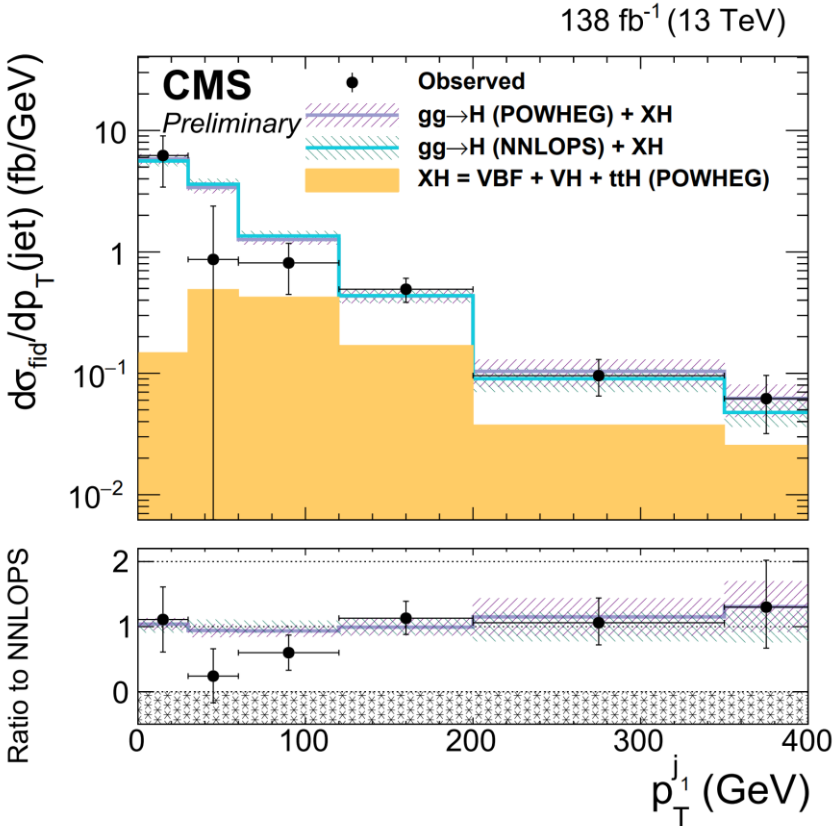
Differential X-Sec



SM P-Value: 17%



SM P-Value: 71%



SM P-Value: 45%

Differential Summary

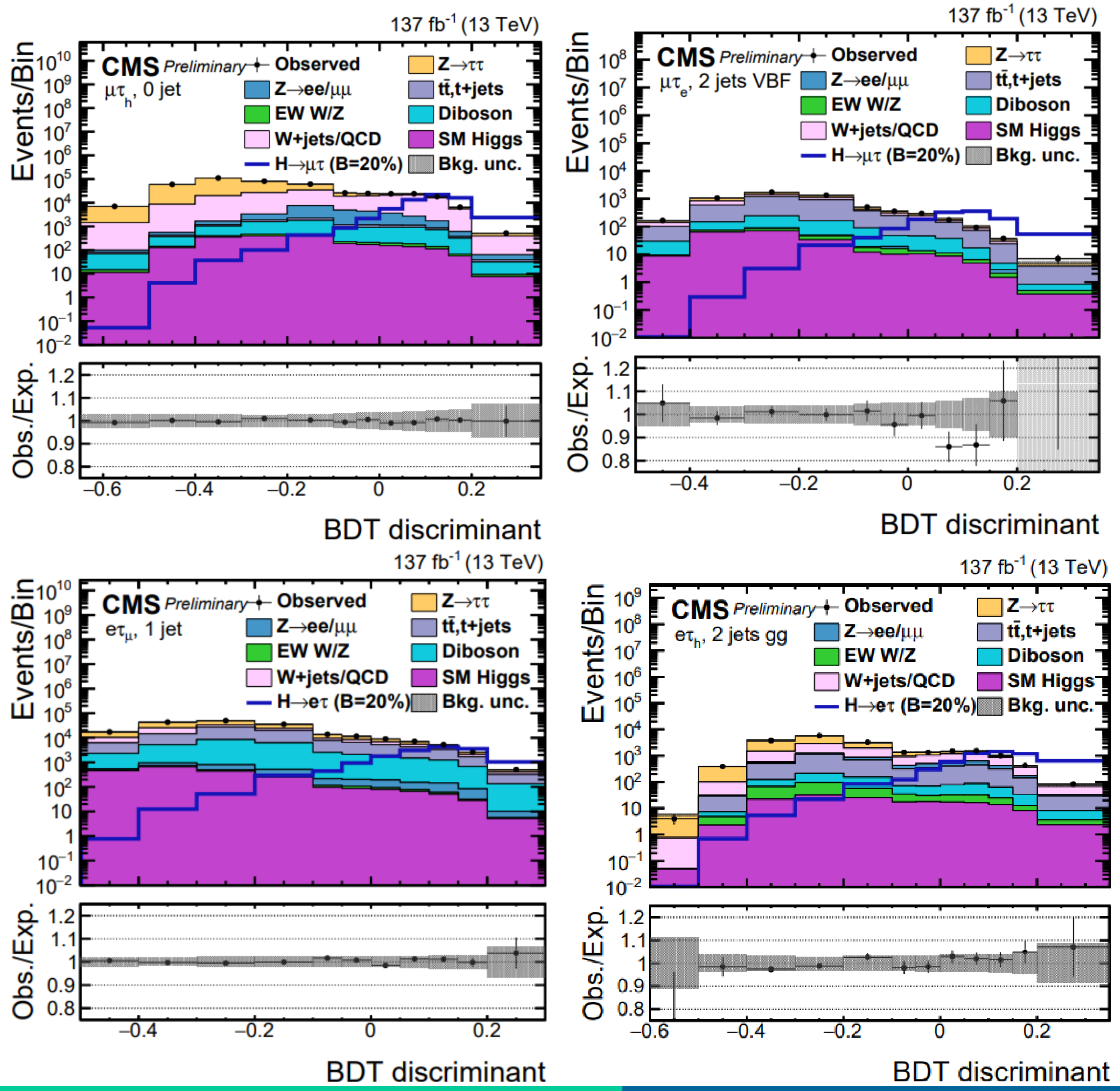
- This is the first time that a differential analysis has been performed for the $H \rightarrow \tau\tau$ channel
- The differential analysis shows good agreement with SM expectation
  - Values largely agree within uncertainties
  - P-values (with respect to SM)17%/71%/45% for $p_t^H / N_{Jets} / p_t^{j_1}$
- Particularly precise, with comparable precision in the fiducial region to CMS Run 2 differential analyses for…
  - $120\ GeV < p_t^H < 600\ GeV$
  - $N_{Jets} > 2$
  - $p_t^{j_1} > 120$

Higgs Lepton Flavor Violation

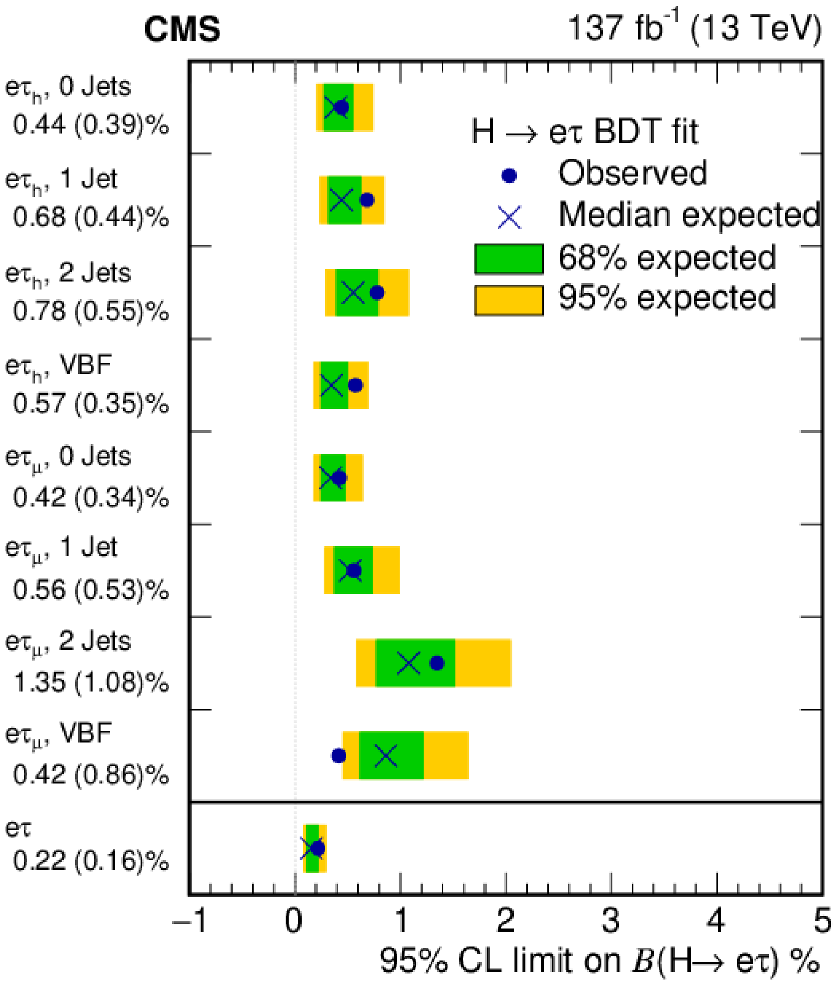
- Certain BSM models give rise to Higgs decays that do not conserve lepton flavor (multiple Higgs doublets, certain supersymmetric models, etc).
- The CMS lepton flavor violation analysis uses a Boosted Decision Tree (BDT) to discriminate between signal and background in distributions
- The analysis searches for 4 channels/decay modes: $\mu\tau_h$, $\mu\tau_e$, $e\tau_h$, $e\tau_\mu$
  - Each channel has its own BDT input variables
- The analysis also categorizes events by number of jets 0,1 and 2 jets
  - The 2 jet category is further split, with higher m_{jj} events being a part of the VBF category
- Then overall signal strength of Higgs lepton flavor violating decays is extracted from a fit to the BDT output distributions

BDT Output Score

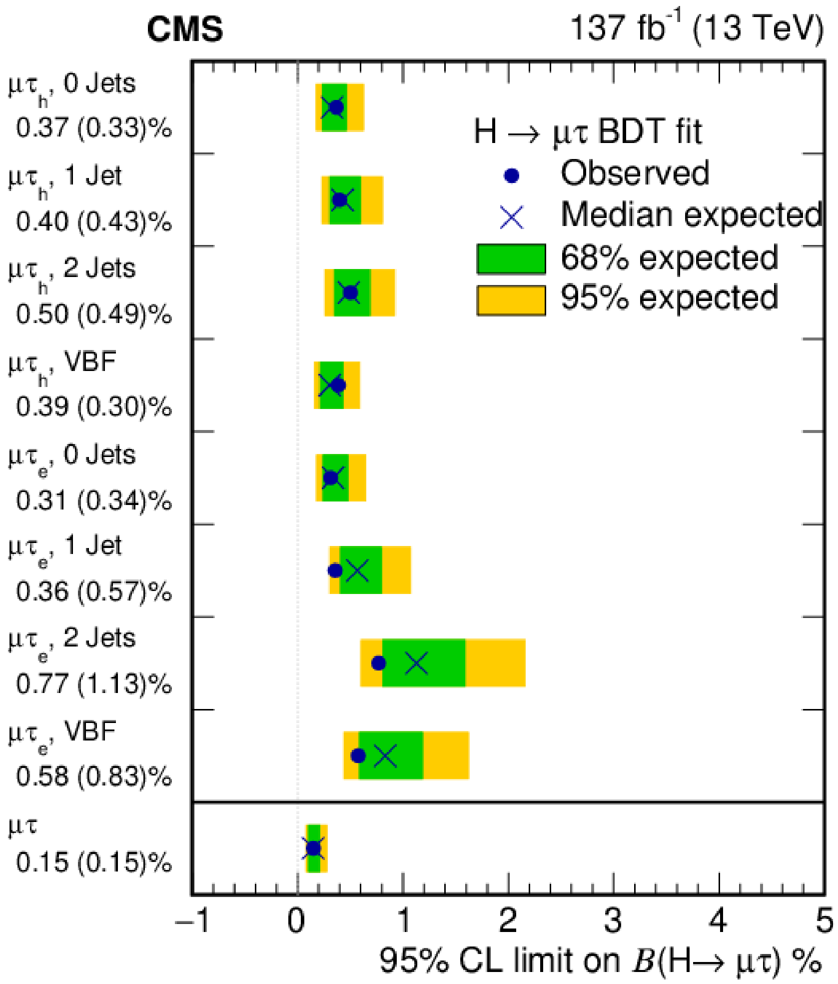
- BDT Inputs
  - p_t of the leptons
  - visible and collinear mass,
  - transverse mass,
  - $\Delta\phi$ and $\Delta\eta$ between various leptons
  - MET in the $\mu\tau_h$ channel



Higgs Lepton Flavor Violation Branching Ratio Results



- No significant excess is seen in any channel
- observed (expected) upper limits at 95% CL:
  - $\mu\tau$: 0.15(0.15)%
  - $e\tau$: 0.22(0.16)%



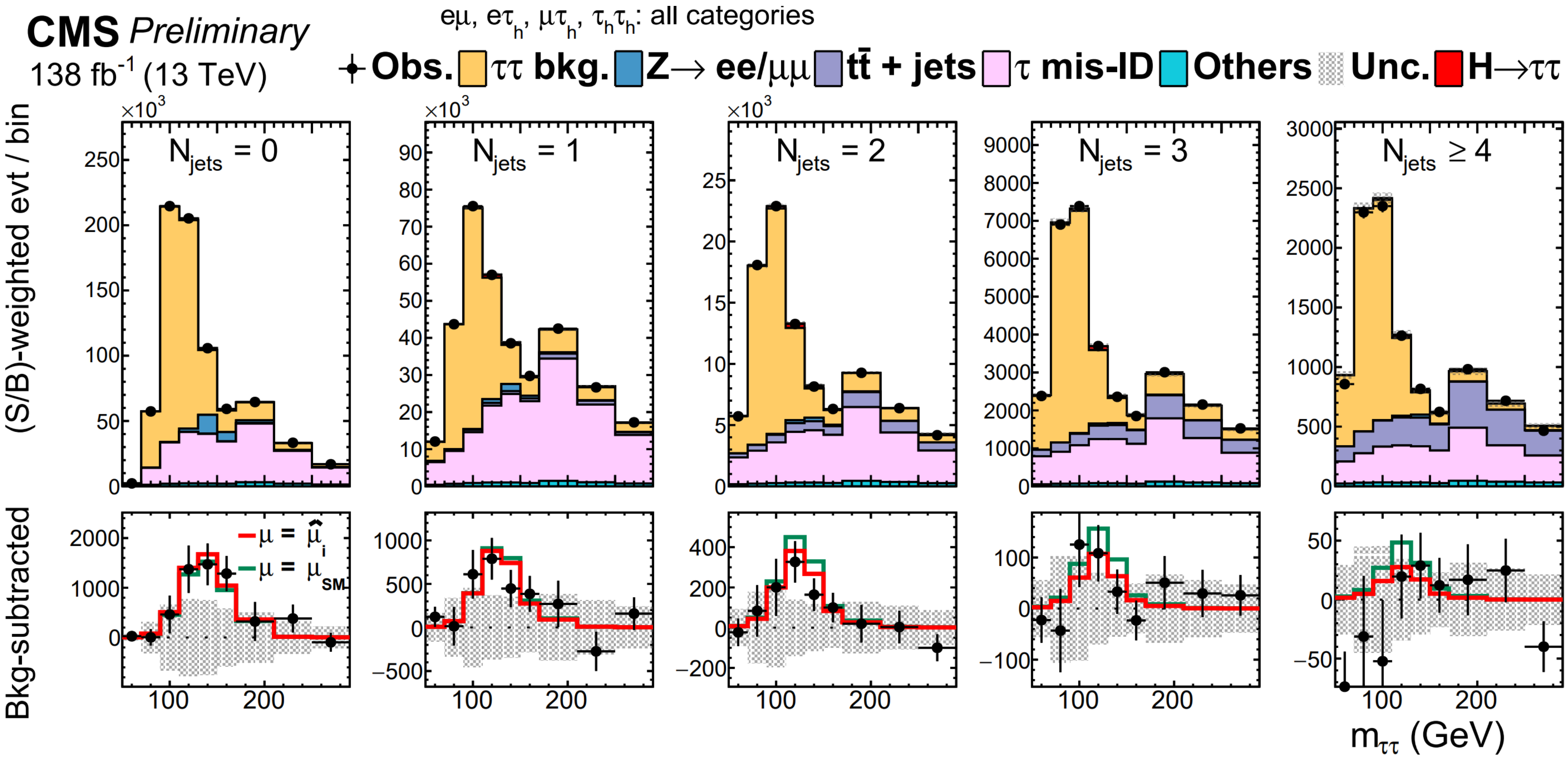
Summary

- The $H \rightarrow \tau\tau$ decay mode continues to get more precise
  - First STXS Stage 1.2 cross section measurements have been performed
  - An LHC first, differential $H \rightarrow \tau\tau$ measurements have been performed in 3 major kinematic variables
  - All cases show good agreement with SM expectations
- Higgs lepton flavor violation analyses using boosted decision trees have been performed and have found no significant excess with respect to SM expectation
  - More stringent upper limits on LFV branching fraction:
    - Observed (expected) 95% CL: $\mu\tau$: 0.15(0.15)%, $e\tau$: 0.22(0.16)%

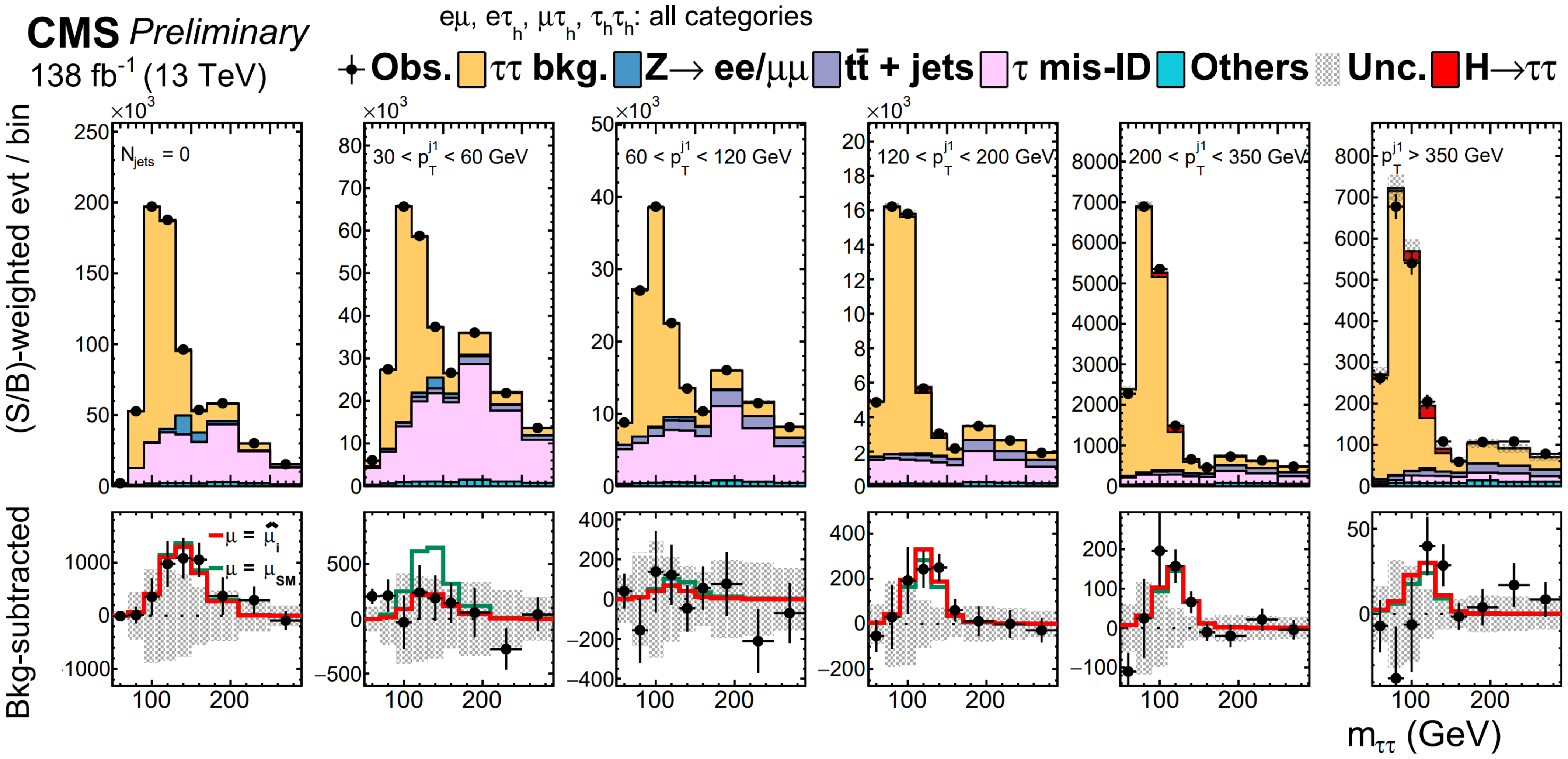
- What is next in Higgs to lepton measurements?
  - More exclusive production mode analyses
  - Boosted topologies (higher p_t^H)

Backup

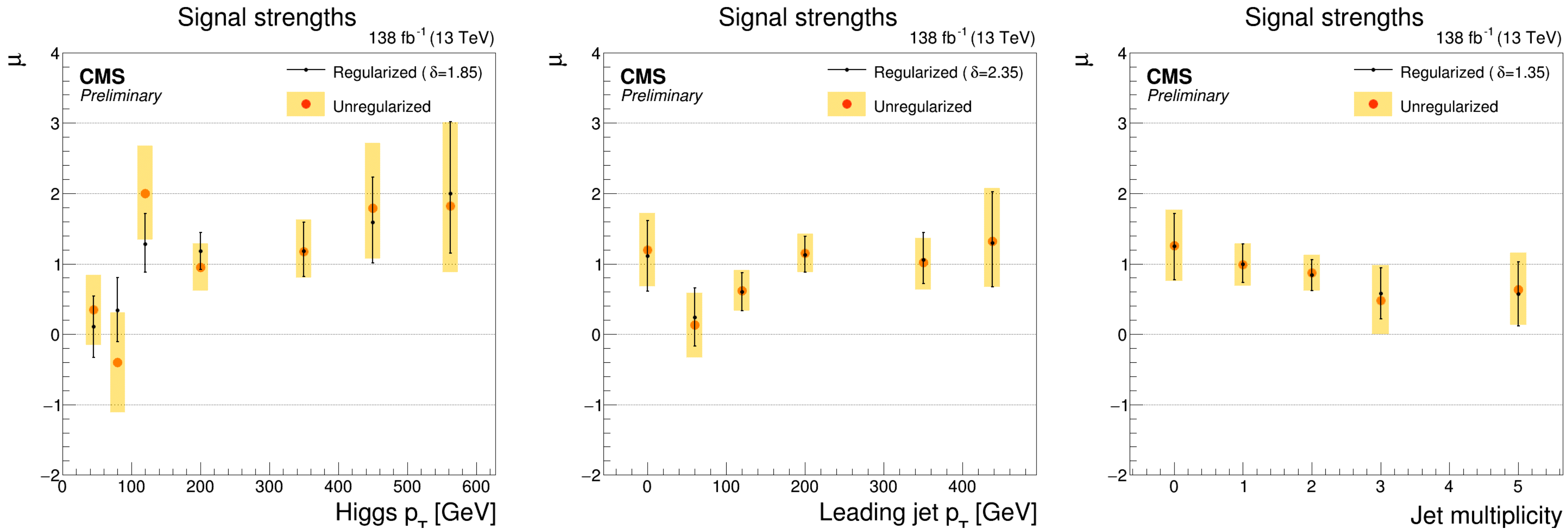
S/B Weighted Plots (N_{jets})



S/B Weighted Plots ($j_1^{p_t}$)



Differential Signal Strength



Observed Inclusive Cross Section: 426 ± 102 fb

LFV BDT Input

- Input Variables:
  - $e\tau_h$: $p_T^e, p_T^{\tau_h}, m_{col}, m_{vis}, m_T\left(\tau, \vec{p}_T^{miss}\right), \Delta\eta(e, \tau_h), \Delta\phi(e, \tau_h), \Delta\phi\left(\tau_h, \vec{p}_T^{miss}\right)$
  - $e\tau_\mu$: $p_T^\mu, p_T^e, m_{col}, m_{vis}, m_T\left(\mu, \vec{p}_T^{miss}\right), \Delta\phi(e, \mu), \Delta\phi\left(\mu, \vec{p}_T^{miss}\right), \Delta\phi\left(e, \vec{p}_T^{miss}\right)$
  - $\mu\tau_h$: $p_T^\mu, p_T^{\tau_h}, m_{col}, \vec{p}_T^{miss}, m_T\left(\tau, \vec{p}_T^{miss}\right), \Delta\eta(\mu, \tau_h), \Delta\phi(\mu, \tau_h), \Delta\phi\left(\tau_h, \vec{p}_T^{miss}\right)$
  - $\mu\tau_e$: $p_T^\mu, p_T^e, m_{col}, m_T\left(\mu, \vec{p}_T^{miss}\right), m_T\left(e, \vec{p}_T^{miss}\right), \Delta\phi(e, \mu), \Delta\phi\left(\mu, \vec{p}_T^{miss}\right), \Delta\phi\left(e, \vec{p}_T^{miss}\right)$

Coupling Constants