Search for new heavy resonances decaying to Higgs boson pairs in boosted bbττ final states

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on behalf of the CMS collaboration

Lepton Photon 2025

SM

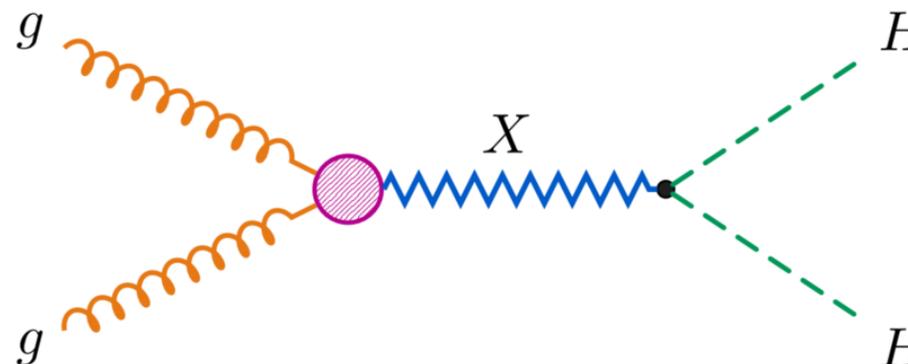**BSM**

What if HH production is facilitated by physics beyond SM ??

- Several motivated scenarios, e.g. Extra dimensions Models (spin-0/spin-2), 2HDM
- Presence of heavy resonances that decay to HH
- Production XS enhanced!
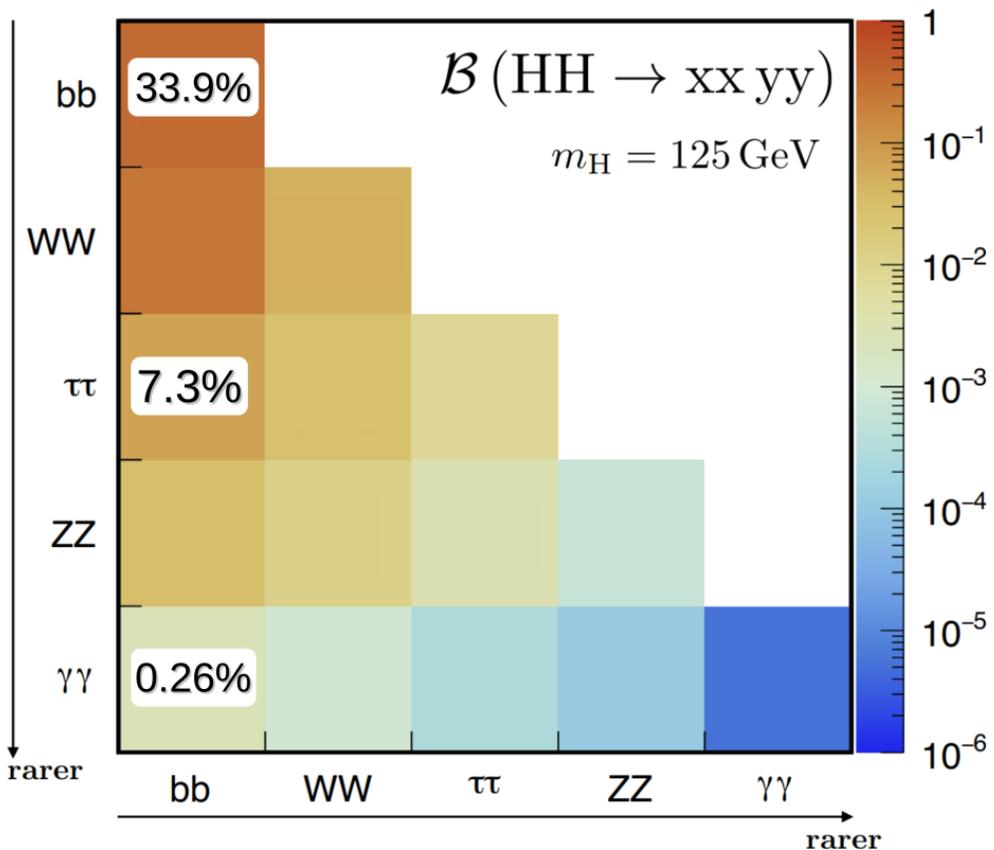

HH signatures for SM are key :

- Access to Higgs self coupling
- Shape of the Higgs potential
- Very small XS

Analysis as model independent as possible:
  o Spin 0/2 : search strategy independent of spin
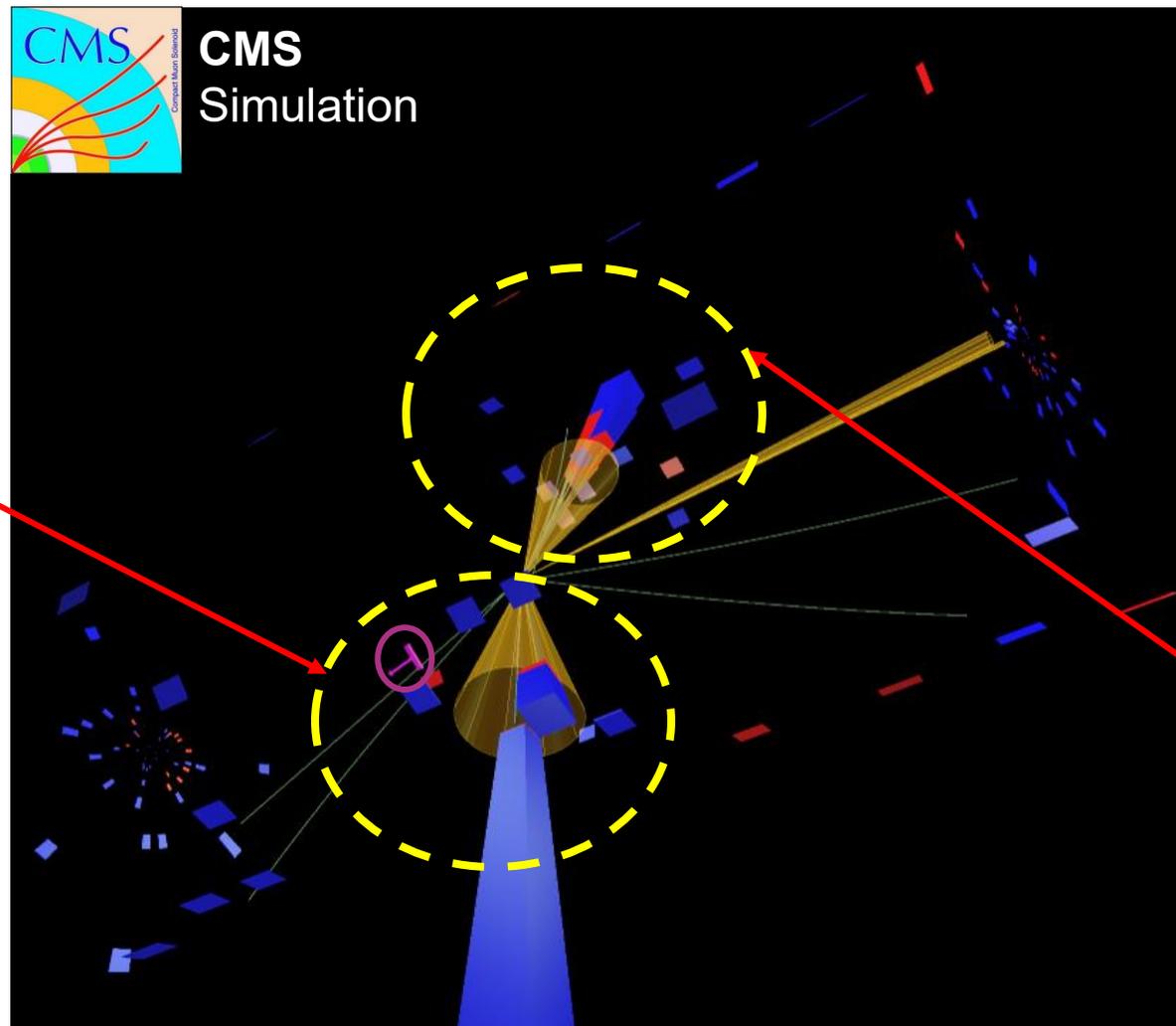
Assume narrow width resonances

bb𝜏𝜏 final state

$\mathcal{B}(HH \to xx\,yy)$
$m_H = 125\,\text{GeV}$

bb 33.9%
ττ 7.3%
γγ 0.26%

- H → bb has the highest BR
- H → ττ has relatively clean leptonic signature
  - Fully hadronic decays ($\tau_h\tau_h$)
  - Semi-leptonic decays ($\ell\tau_h$)
- Massive resonances ⇒ H carry large momentum
  - τ decay contain ν (registers as missing E_T)
  - Trigger and select events with large missing E_T (> 180 GeV)
  - Large boost brings forth challenges in reconstruction and Identification

With improvements in experimental techniques, it's possible to probe signatures for resonances with masses > 1 TeV

Summary plots for other search channels [back up]

We are looking for....

Collimated visible decay products of the ditau system. Missing E_T aligned with visible products

CMS
Simulation

H → bb jet on the opposite side of the event

Event display of a simulated signal event
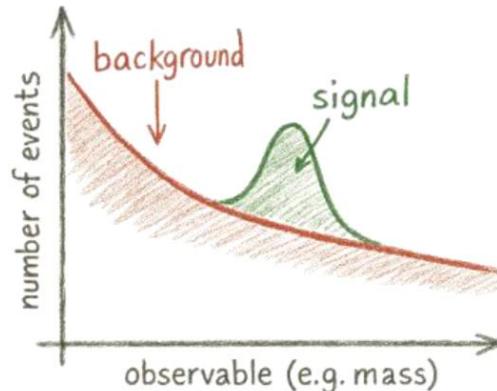
Search stratergy

$H \to \tau\tau$

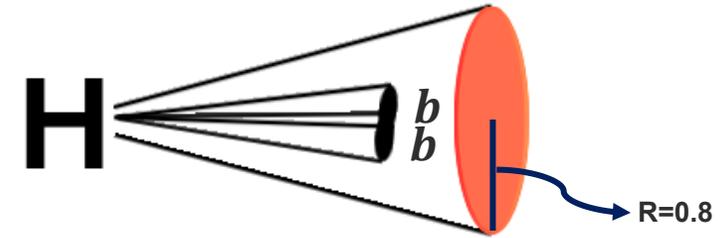**Hadron plus strip - "HPS" reconstruction (details later) and DeepTau [link]**

Special boosted "HPS" reconstruction and Boosted DeepTau (details later)

- Higgs reconstructed using dynamical likelihood approach (accounts for missing ν info)

- Channels categorized by highest p_T lepton pair type
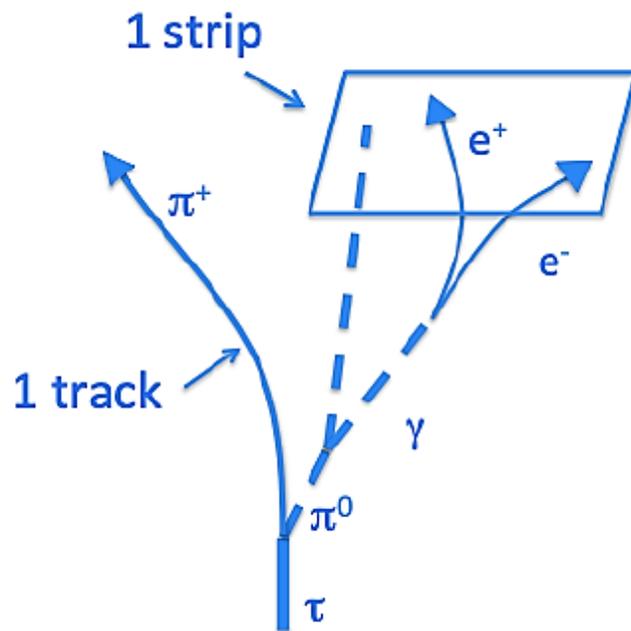
Perform a bump hunt!

$H \to bb$

Tagged using "ParticleNet" tagger- successfully used in boosted $X \to HH \to 4b$ search [link]. Additional material in back up

- Higgs reconstructed using corrected standard large radius jet (R=0.8)

- Veto events with additional small radius (R=0.4) b-tagged jets (reduce $t\bar{t}$ background)

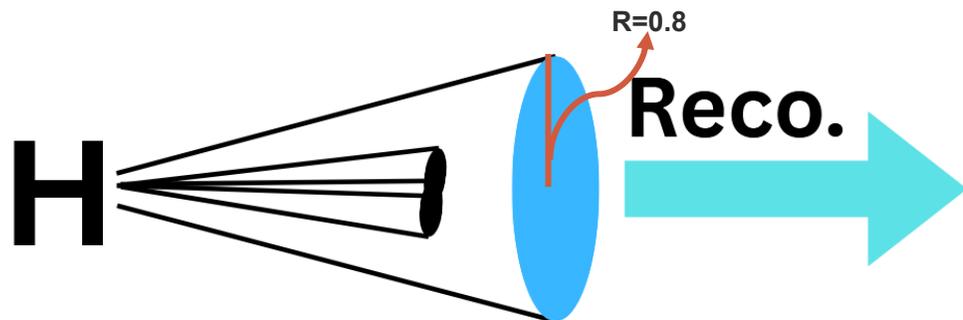**Final discriminant : Reconstructed Resonance Mass (M_X)**

Recall : Standard tau reconstruction in CMS

Hadron Plus Strip (HPS)

- Algorithm (link) to reconstruct τ_h with high purity and efficiency
  - Seeded by small radius (R=0.4) jets

- Particle Categorization:
  - Hadrons: Particles depositing energy both in HCAL and ECAL
  - Strips: Clusters of photons and electrons in ECAL – from π^0

- Combine hadrons and strip into various **modes of decay (DM)** of hadronic tau that match the τ_h kinematics

- DM 0: $\tau^{\pm} \rightarrow \pi^{\pm}\nu_{\tau}$ (1-prong)
- DM 1: $\tau^{\pm} \rightarrow \pi^{\pm}\pi^0\nu_{\tau}$ (1-prong)
- DM 10: $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$ (3-prong)
- DM 11: $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\pi^0\nu_{\tau}$ (3-prong)
- DM 5, 6: 3 prong τ_h but one track is lost during reconstruction

Boosted H → ττ

"Boosted DeepTau"

Train a CNN (vsJets)

CMS-DP-2025-047

Individual reco. boostedtaus

Individual reco. + ID boostedtaus
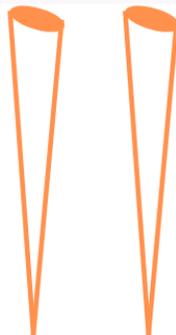
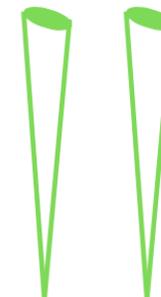Boosted Boson

Reconstruction challenges of boosted topology

- Standard HPS reco. loses efficiency due to decay products overlapping

- Boosted reco. : HPS seeded by cross cleaned subjets of a large radius (R=0.8) jet

- Produces individual reco. τ_h ("boosted taus") from a ditau system

- Works for both $\tau_h\tau_h$ and $\ell\tau_h$ decay of tau pairs

Boosted DeepTau

- Convolutional neural network (CNN) trained on individual boostedtaus – leverages the boosted reco.

- Important high-level input: tau kinematics, isolation, lifetime, average energy deposition in the event

- Low level detector information

- The training samples shuffled and merged
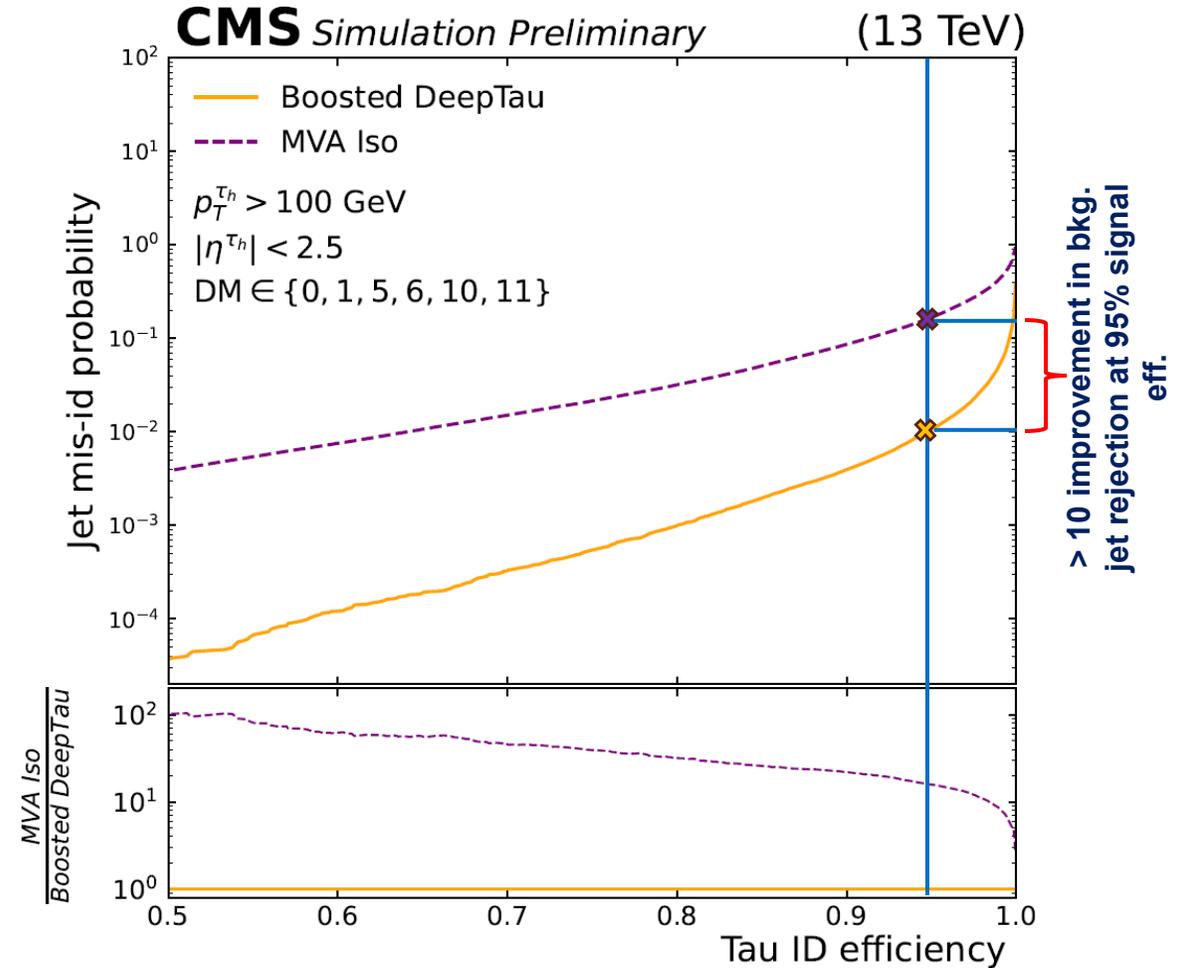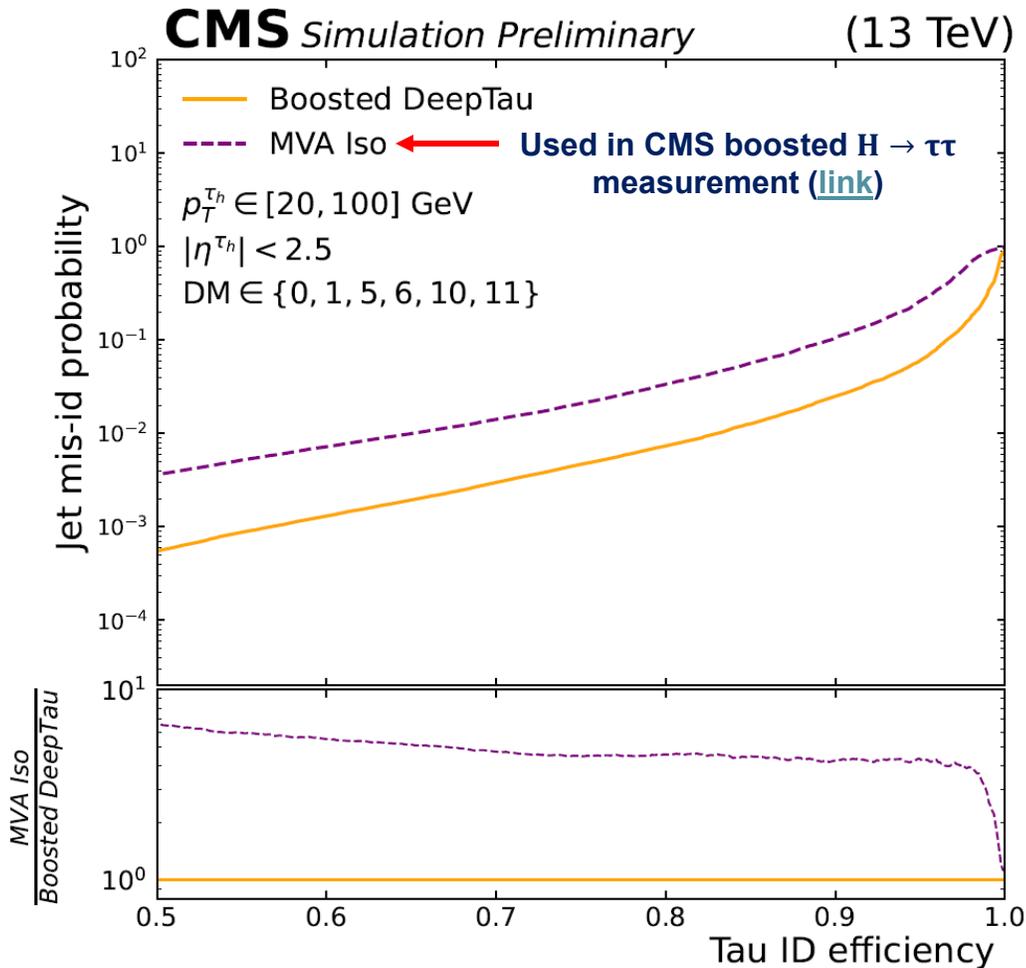 - Balances data population across p_T, η, tau types, different physics phase spaces.
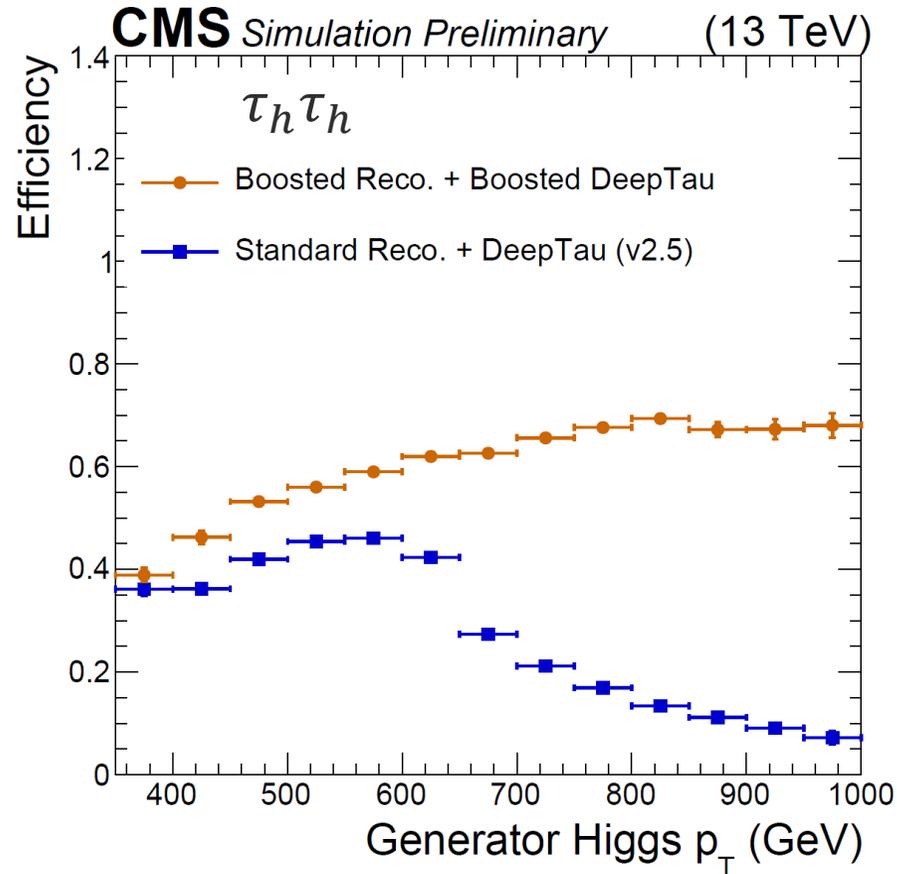
NEW!

ROC plots inclusive of all possible modes of decay of τ_h

Boosted DeepTau: factor 2-4 improvement in performance vsJets $p_T^{\tau_h} \leq 100$ GeV
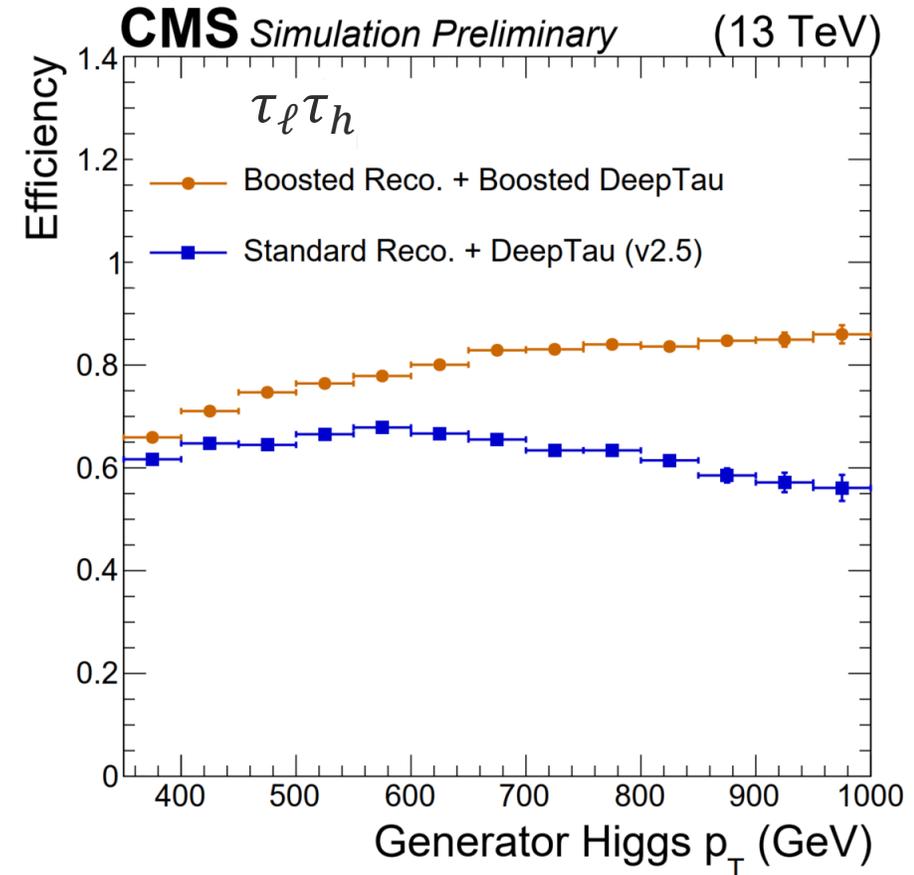
Boosted DeepTau: Order of magnitude improvement vsJets $p_T^{\tau_h} > 100$ GeV

Ditau system reconstruction + Id efficiency

Fully Hadronic channel

Semi-leptonic channel

- The standard and boosted taus are identified with the respective algos using a score with signal eff. > 95 %

- The drop-off in efficiency for standard reco. at ~ 600 GeV for Higgs $\Rightarrow$ The decay products overlapping

- Boosted reco. + Boosted DeepTau recovers efficiency at higher Higgs p_T $\Rightarrow$ extending the sensitivity in boosted event topologies
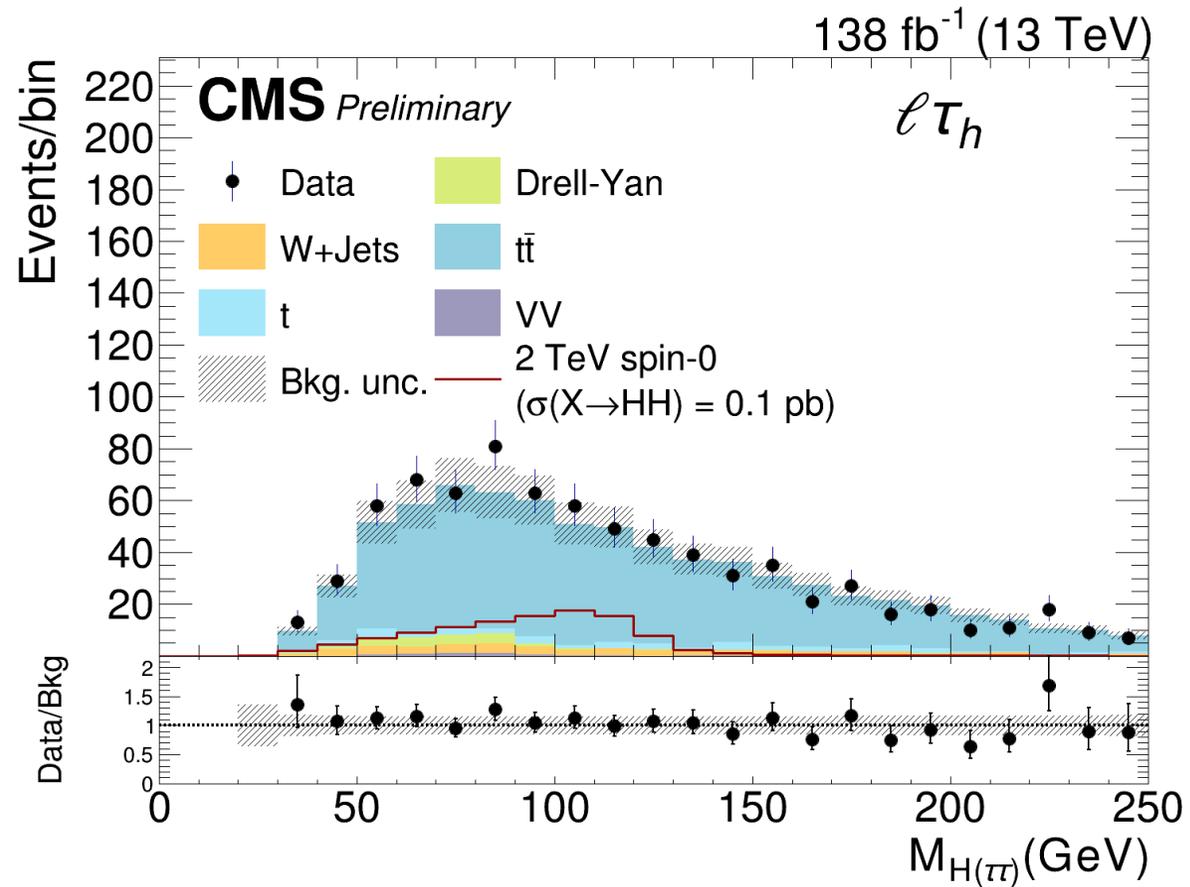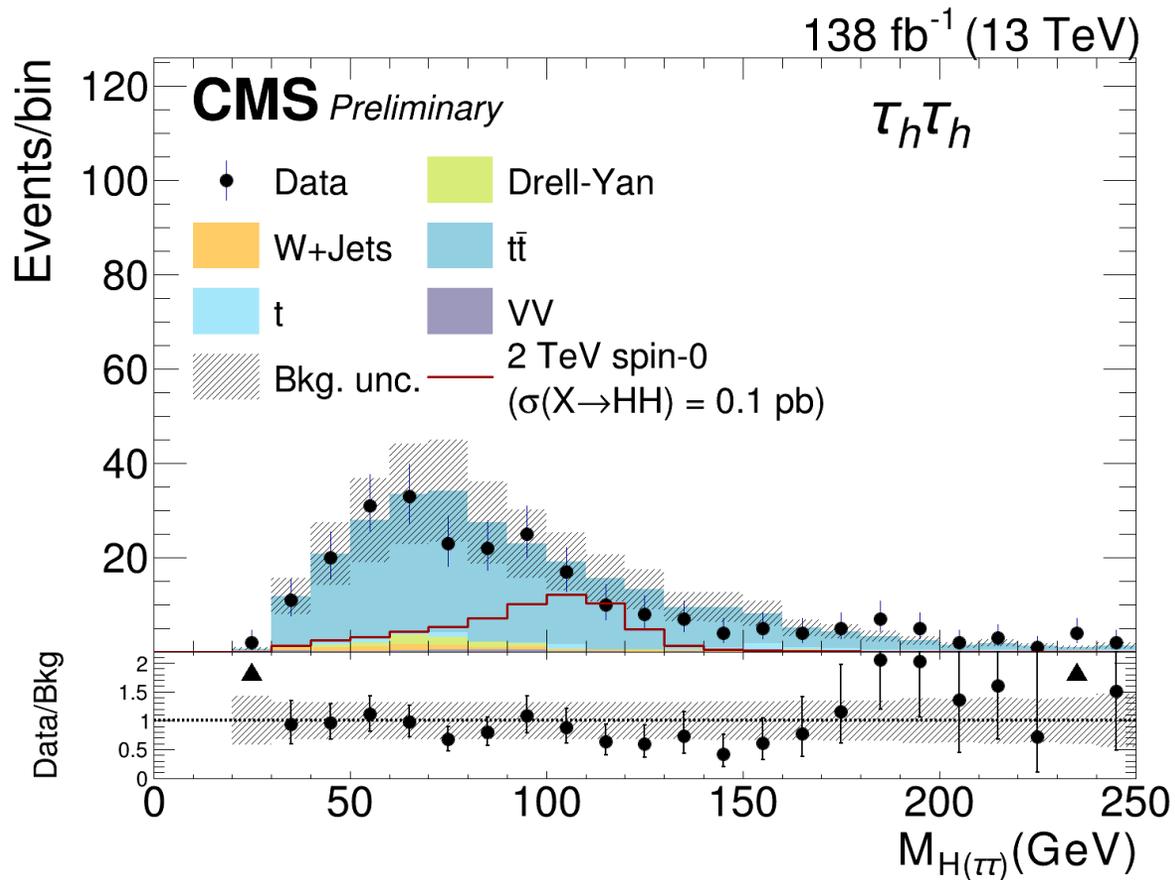
- Select events with missing E_T > 180 GeV

- Reconstruct two Higgs bosons (and ultimately the resonance X)
  - Using the discussed techniques for boosted topologies!

- Selections to further reduce background (event veto with additional b-tagged small radius jets)

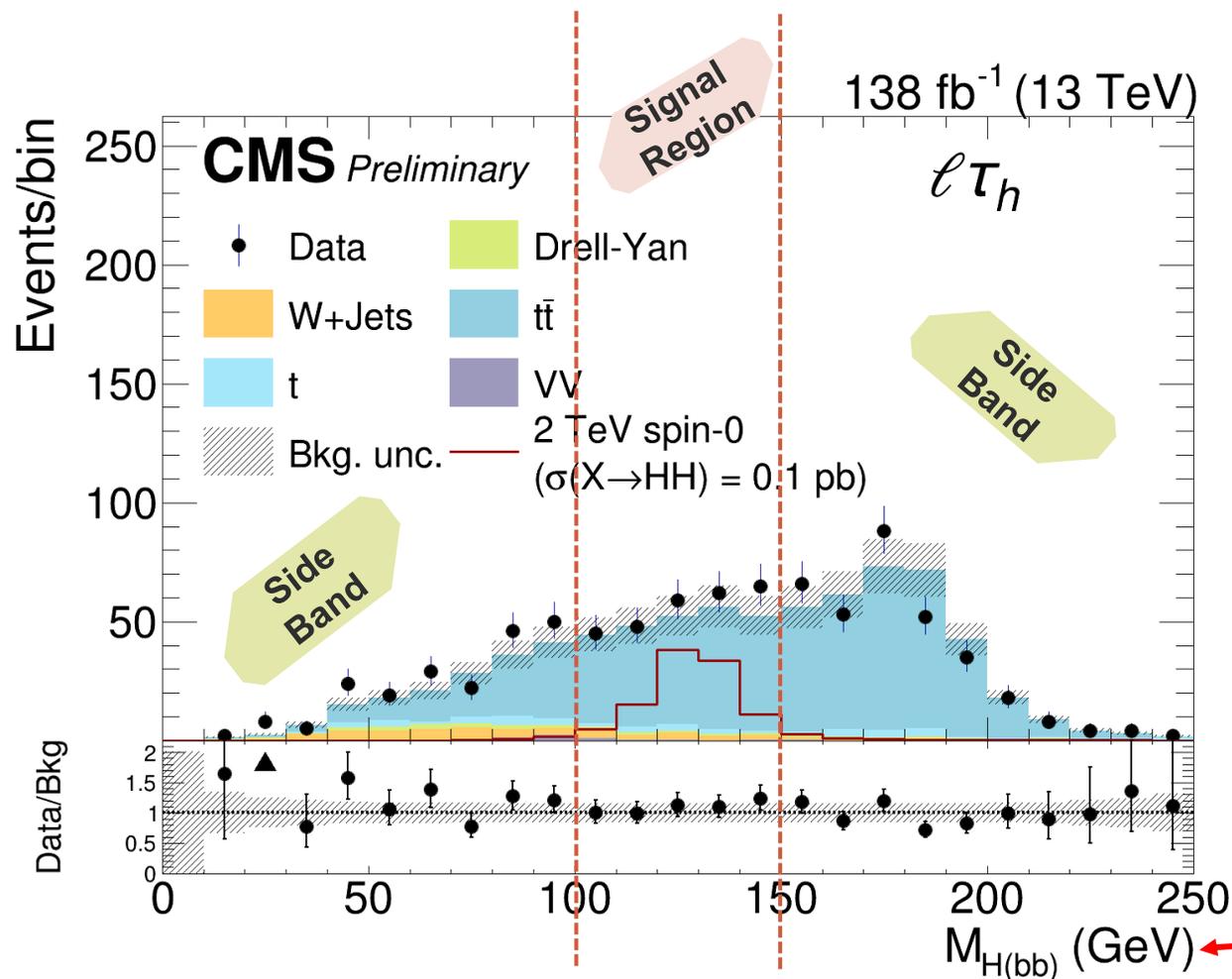**Top ($t\bar{t}$ + t) is the major background**

- Signal samples : ggF spin-0 and spin-2 resonances ($X \rightarrow HH \rightarrow bb\tau\tau$)
  - Small additional contributions from $X \rightarrow HH \rightarrow bbVV$ considered (signatures with τ in final states indistinguishable from $bb\tau\tau$)

- $M_{H(\tau\tau)}$: Invariant mass of the $H \to \tau\tau$ system taking into account the neutrinos

- The $t\bar{t}$ + t rates are scaled with average nominal postfit values of most important fit parameters for visualization

ParticleNet Regressed Mass

Same for $\tau_h\tau_h$

Signal Region (SR) Definition:

$$100\,\text{GeV} \leq M_{H(bb)} \leq 150\,\text{GeV}$$
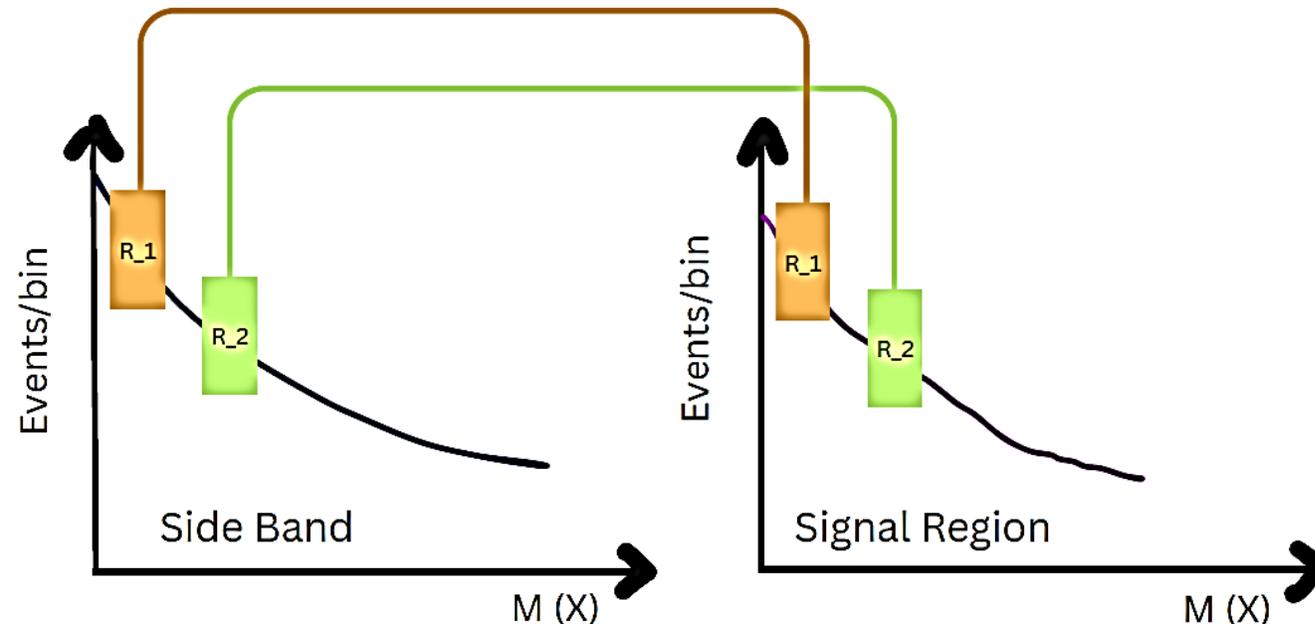
Side Band (SB) Definition:
used for Bkg. Estimation

$$(M_{H(bb)} < 100\,\text{GeV}) \,||\, (M_{H(bb)} > 150\,\text{GeV})$$

- Simultaneous maximum likelihood fit of the reconstructed resonance mass (M_X) in both the signal region (SR) and the Side Band (SB).

- Normalization of the primary background (Top) is modeled using unconstrained multiplicative parameter (**rateParam**), which links the SR and the SB

- For given bin of (M_X) in the SR, a corresponding rateParams for the Top background is linked to the same bin in the SB
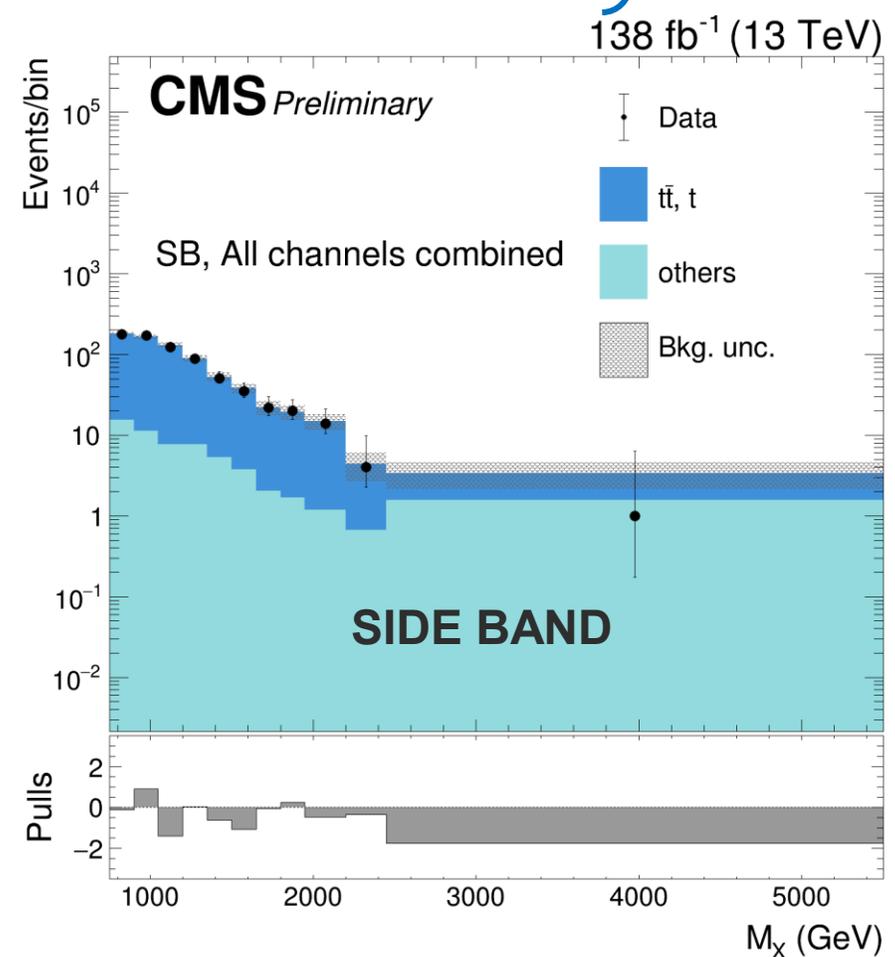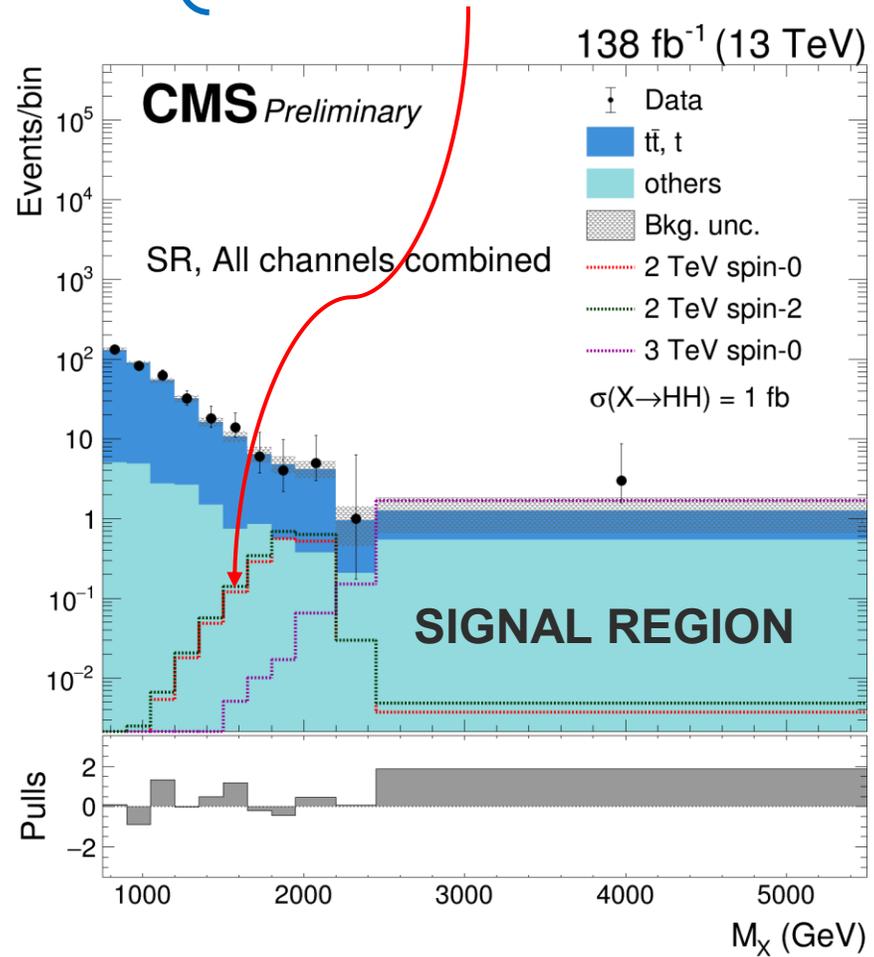
R_1, *R_2* .... : rateParams linking the bins between SR and SB
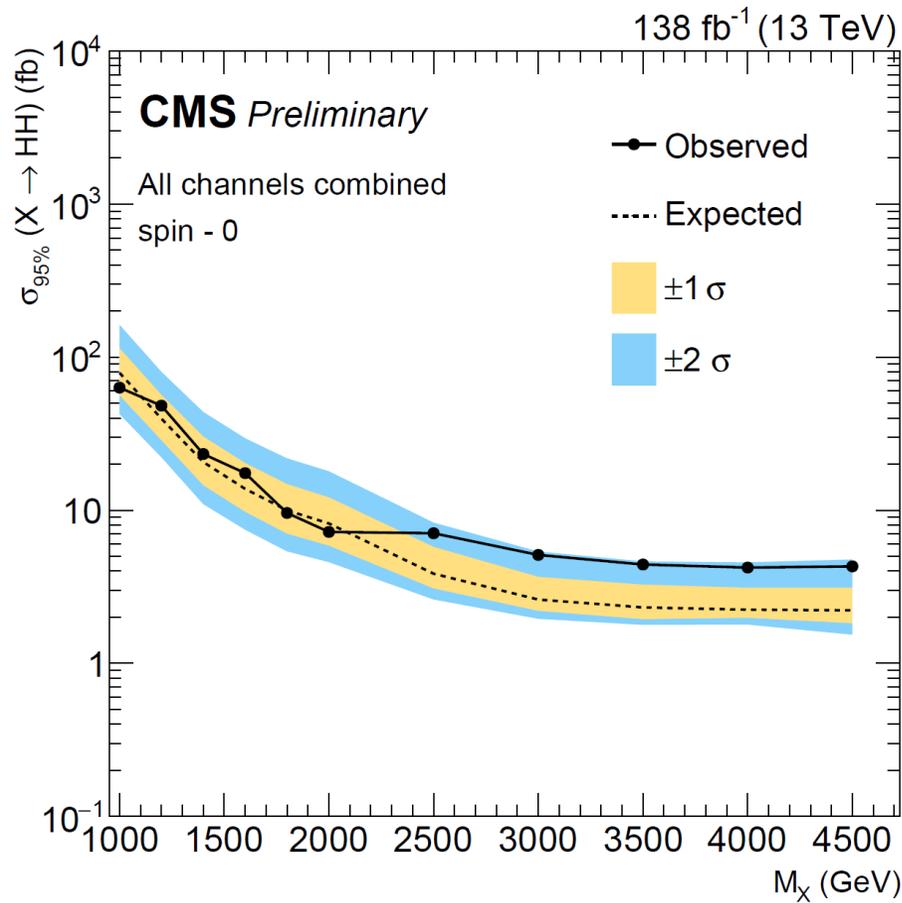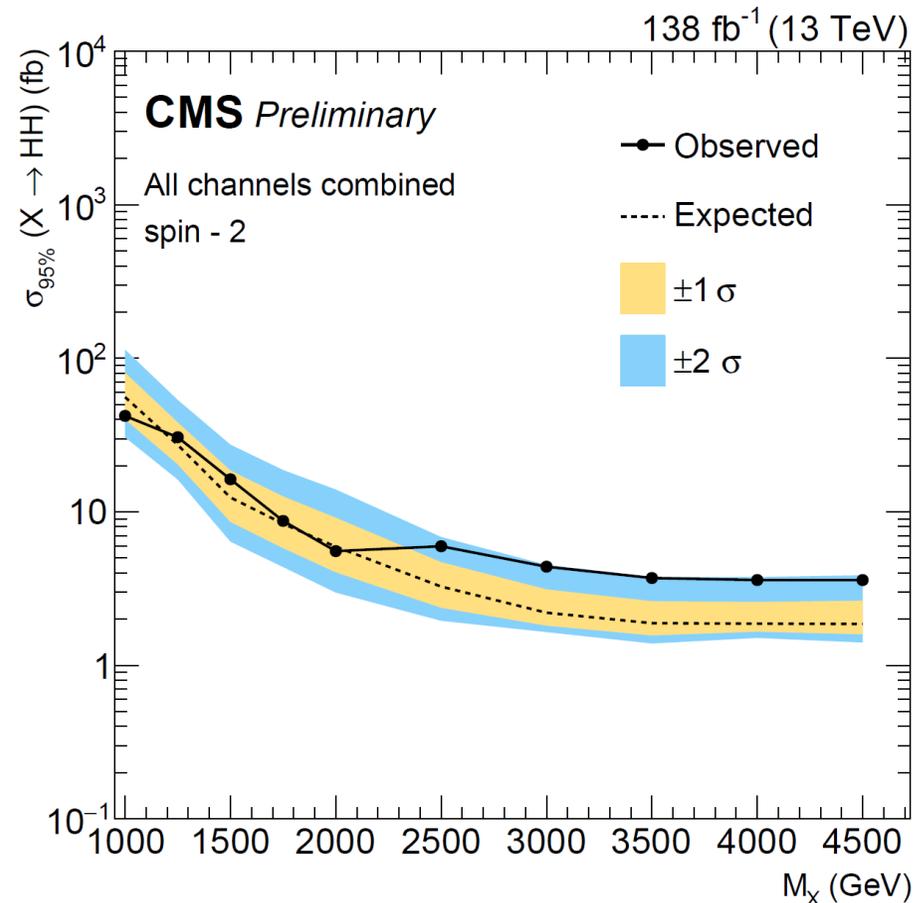
o Constrains both norm. and the shape

- **Spin-0 and spin-2 templates superimposed for visualization only**

- **Shapes of the two models same. Spin-2 has slightly higher signal acceptance**

The data agree with the standard model prediction

Results

Spin 0

Spin 2

- Improved limits for spin-2 due to slightly higher signal acceptance

- **Most sensitive limits to date on the production of $X \to HH \to bb\tau\tau$ at LHC from 1.4 TeV to 4.5 TeV**

Summary

- Presented the latest CMS result for a search for massive resonance in $bb\tau\tau$ final state using Run 2 data

- The analysis strategy is model independent

- Improved boosted reconstruction and identification (Boosted DeepTau) techniques developed and used!
    o Boosted DeepTau can also be used in measurements (e.g. Boosted $H \to \tau\tau$)

- No significant deviation from the SM prediction was observed

- Most sensitive limits to date on the production of $X \to HH \to bb\tau\tau$ at LHC from 1.4 TeV to 4.5 TeV

What's Next....

- We have started looking at Run-3!

- Ongoing improvements in methods and fresh ideas will expand our search capabilities

- Combining multiple search channels : comprehensive picture and highest potential for discovery!
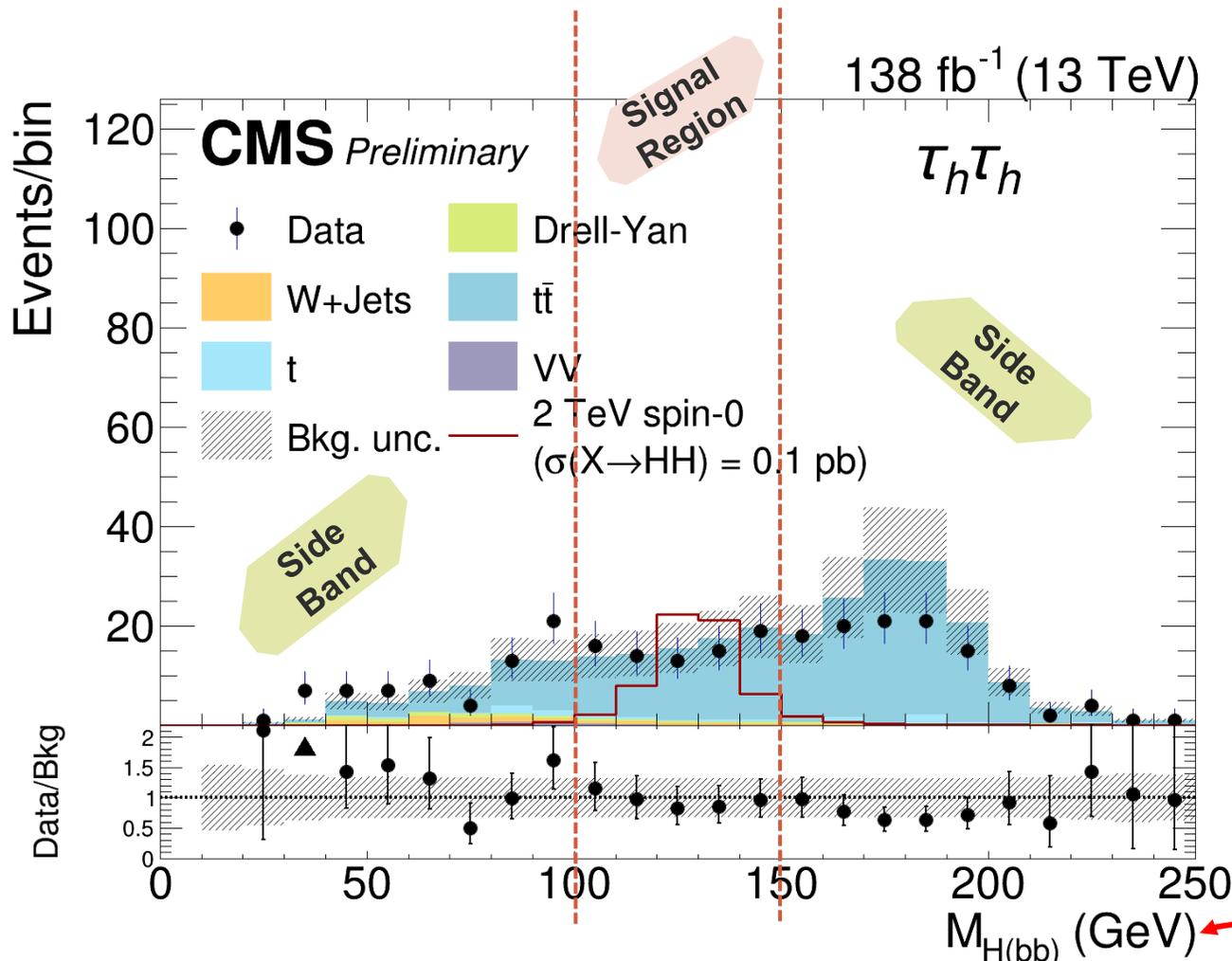......
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Hoping to see many more such interesting events in data !

Back Up Slides

ParticleNet Regressed Mass

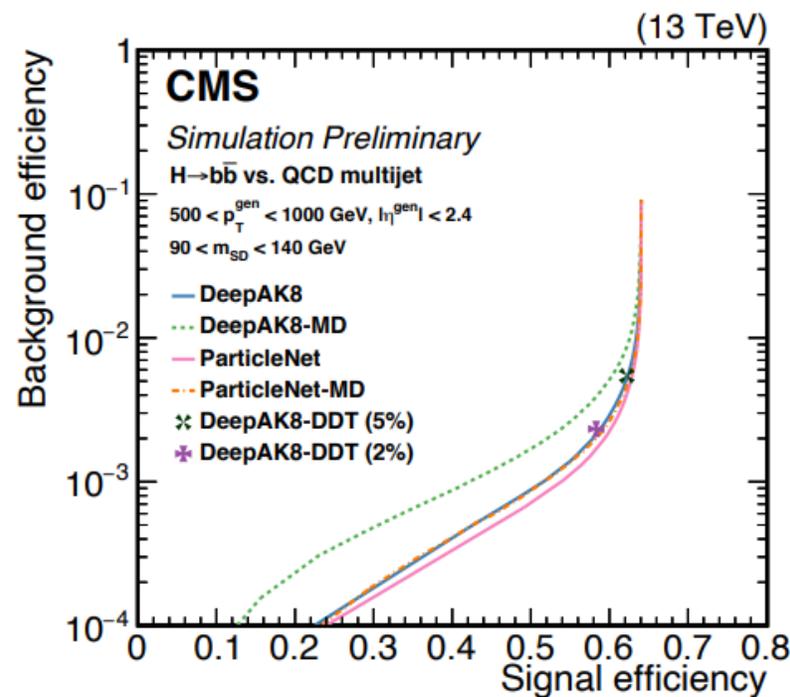**Same for $\ell\tau_h$**

Signal Region (SR) Definition:

$$100\,\text{GeV} \leq M_{H(bb)} \leq 150\,\text{GeV}$$

Side Band (SB) Definition:

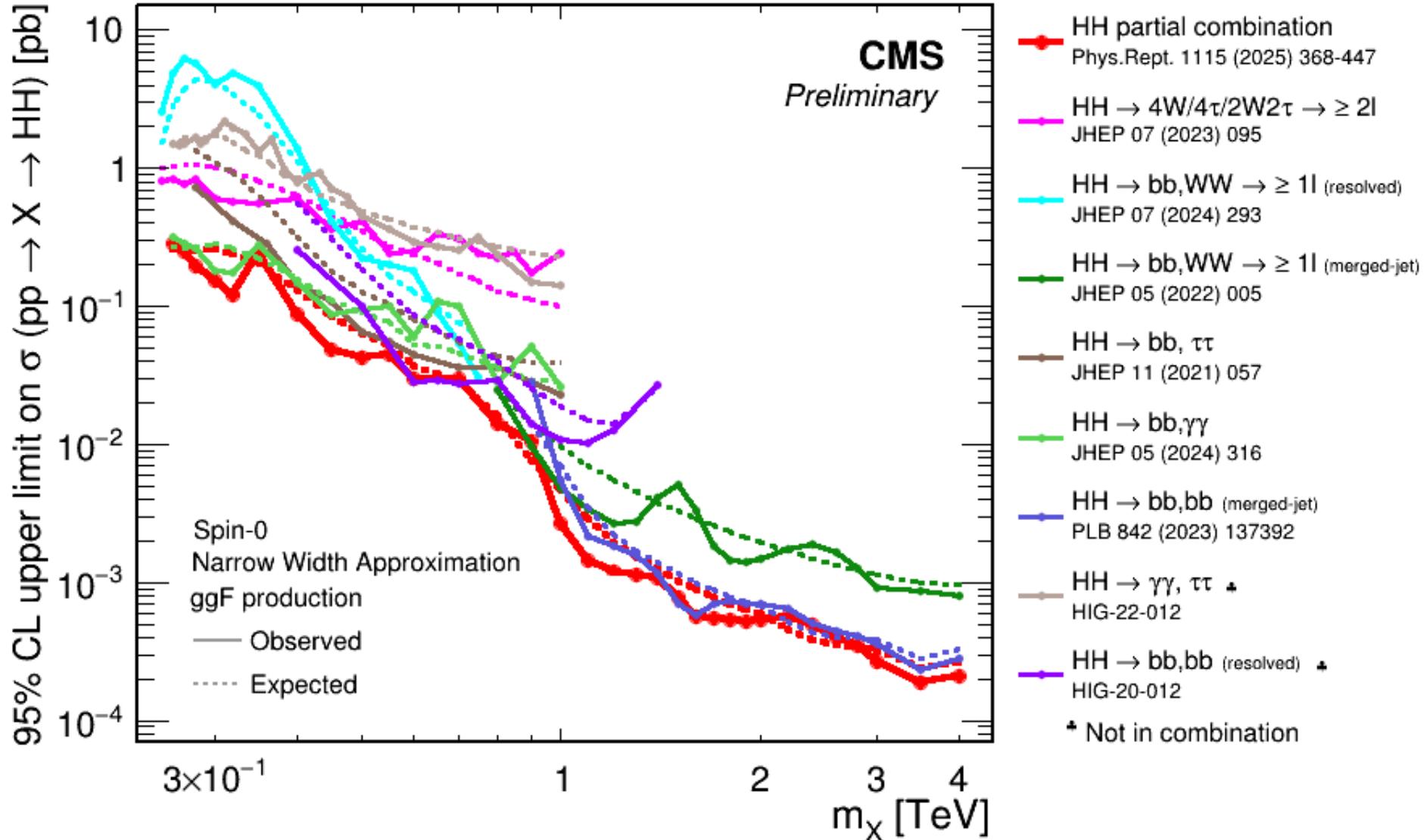$$(M_{H(bb)} < 100\,\text{GeV})\,||\,(M_{H(bb)} > 150\,\text{GeV})$$

ParticleNet H → bb

- Algorithm based on a graph neural network (GNN) using an unordered set of jet constituent particles as the input ([1], [2])

- Distinguishes Higgs decays into b quark pairs from background jets by leveraging the properties of jet constituents as input features
  - displaced tracks and secondary vertices are among the most important features
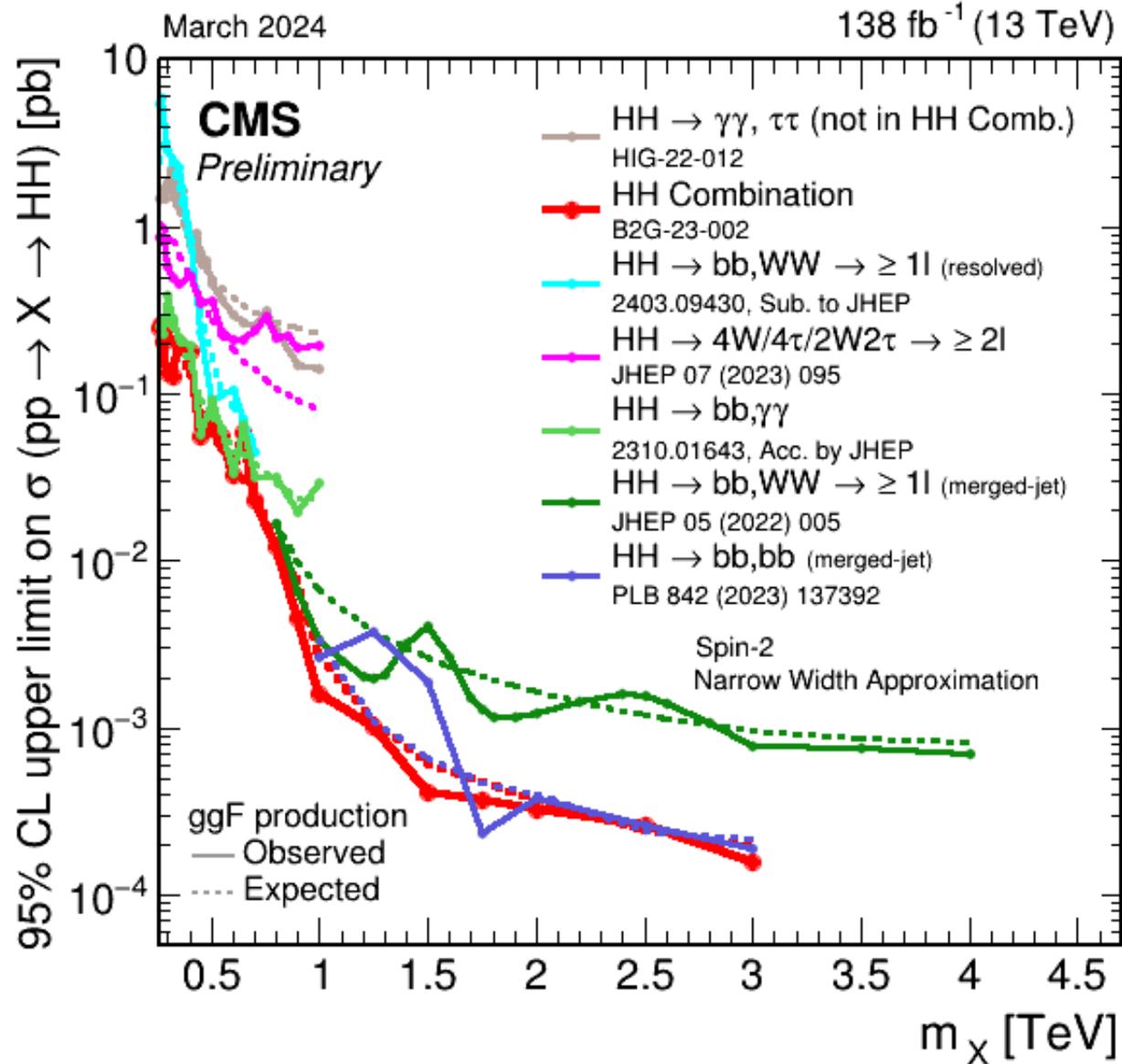 - mass-decorrelated particle identification algorithm

Spin 0

Spin 2

X → HH → bbττ (ATLAS)
Spin 0

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