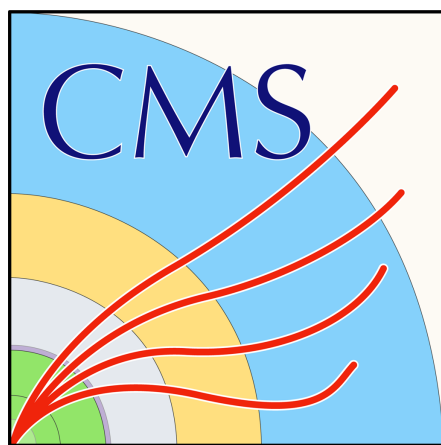
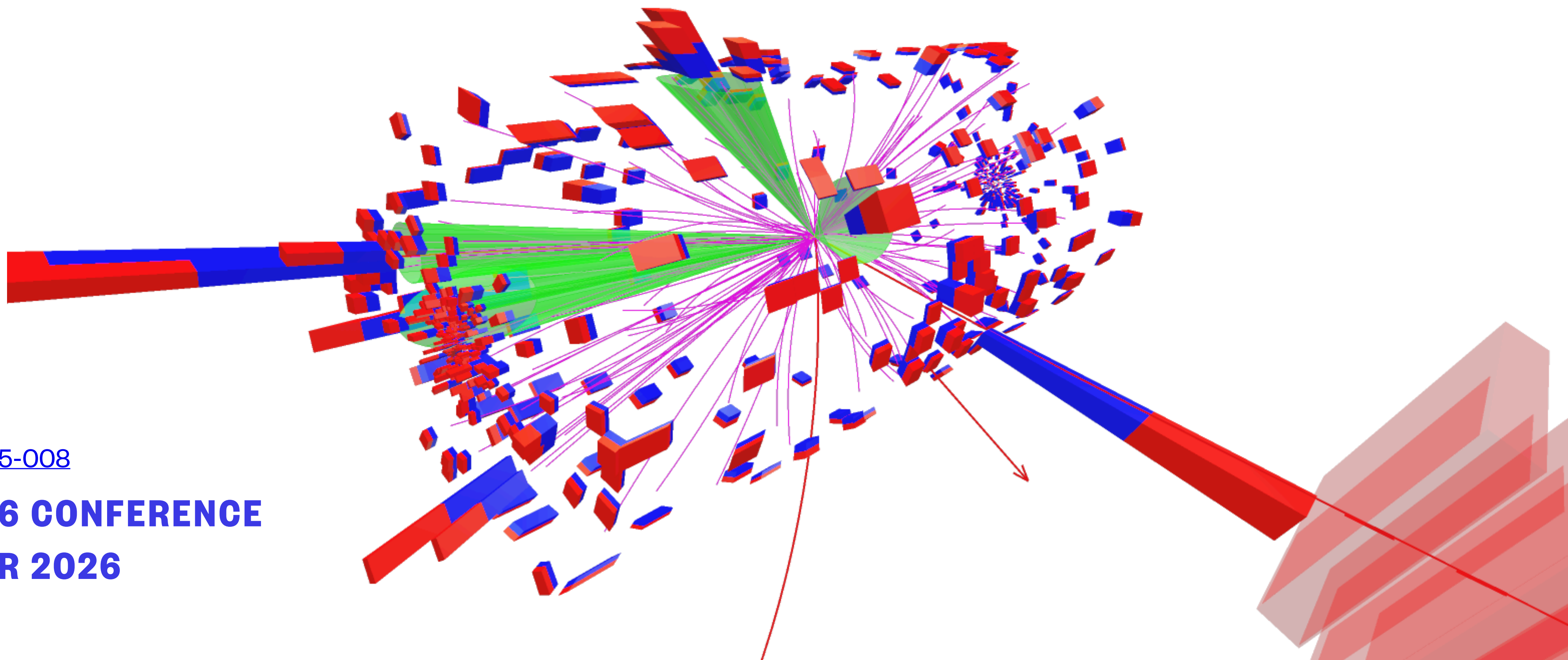




$HH \rightarrow bb\tau\tau$ new opportunities in Run 3

Marco Chiusi, on behalf of the CMS Collaboration



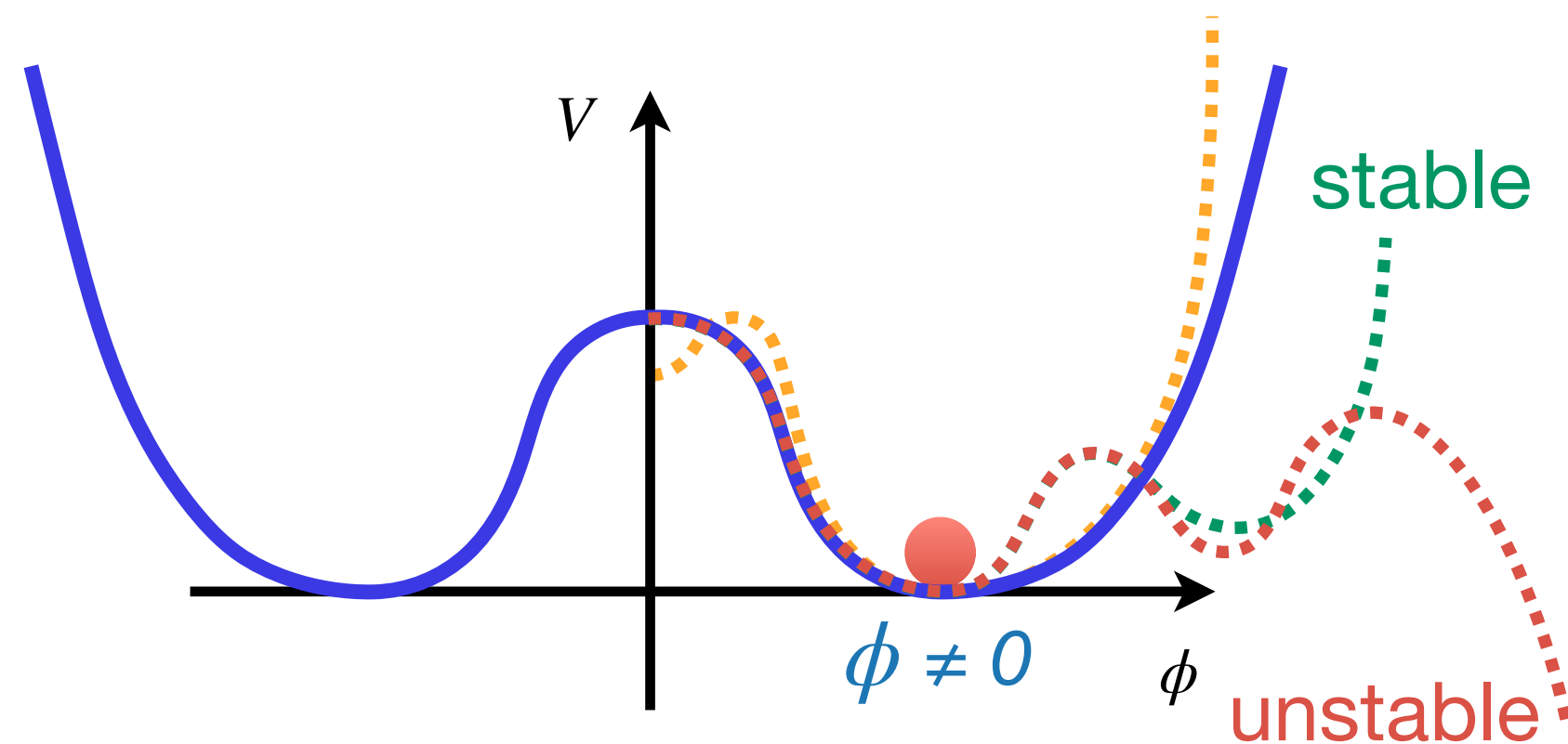
[CMS-PAS-HIG-25-008](#)

CLHCP2026 CONFERENCE
31 OCTOBER 2026

Probing the Higgs potential with HH

- HH production provides direct access to a key parameter of the SM: the **Higgs self-coupling** λ_{HHH}

1. **Probe the shape of the BEH potential**, with deep cosmological implications

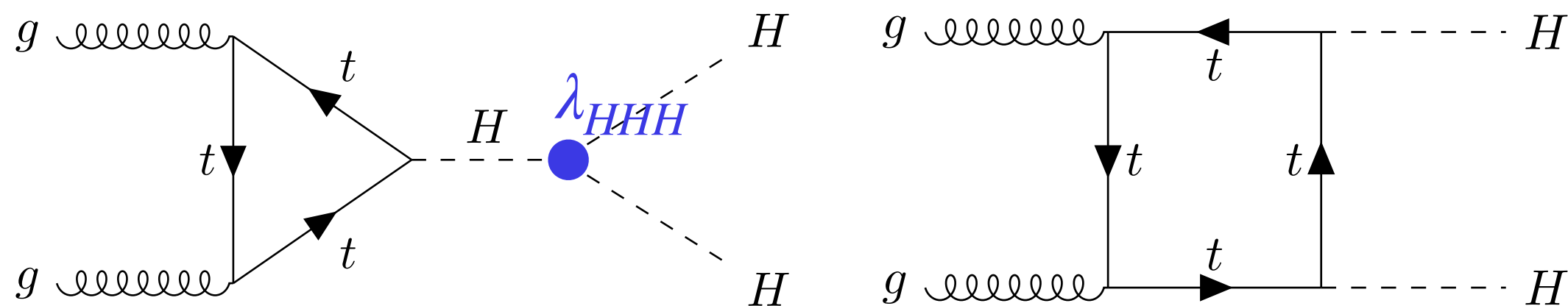


2. **Deeply test the SM**, as λ_{HHH} is linked to the **mass of the Higgs** and the vacuum expectation value:

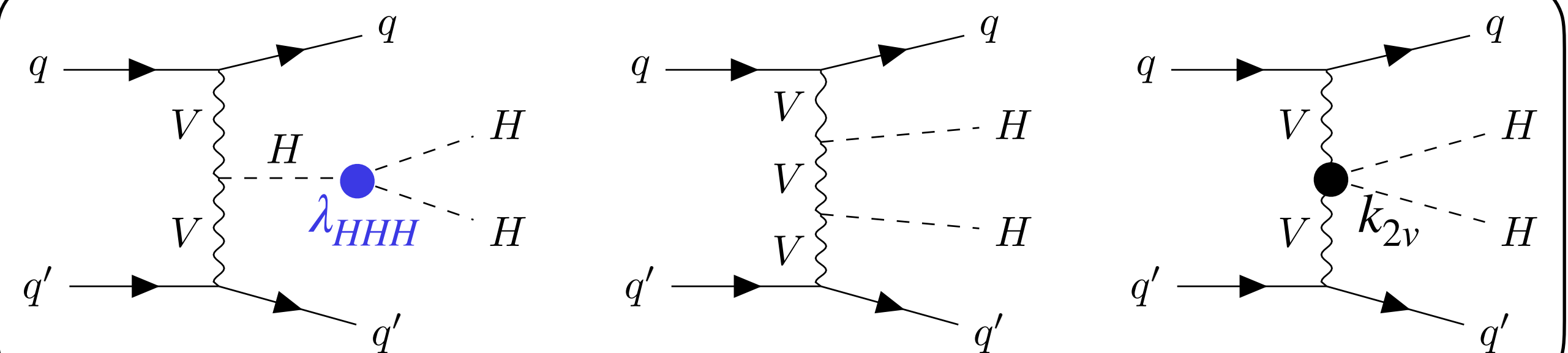
$$V(H) = \frac{m_h^2}{2} H^2 - \lambda_{HHH} v H^3 - \lambda_4 H^4$$

with $\lambda_{HHH} = \frac{m_h^2}{2v^2}$

Gluon Fusion - 34 fb

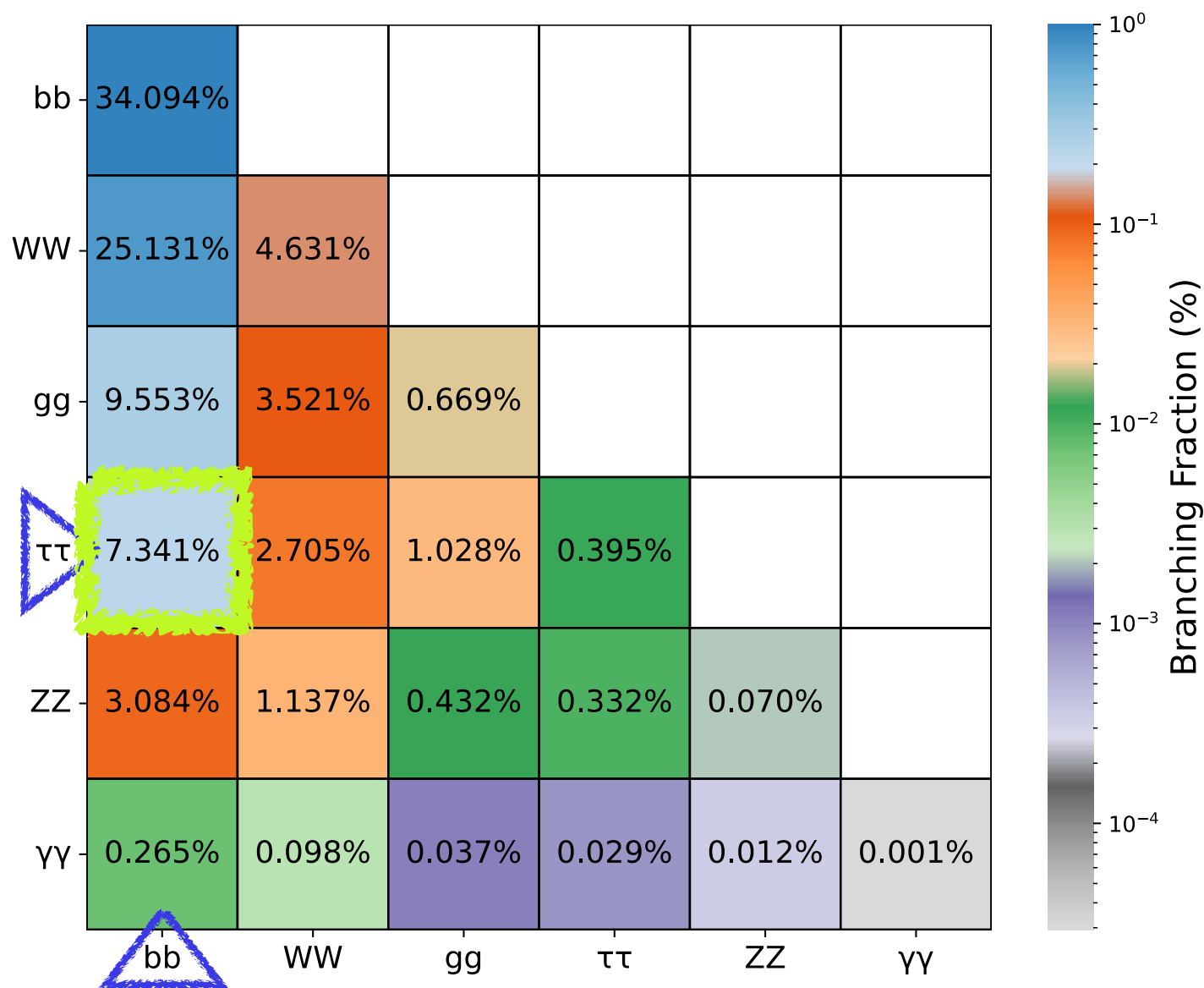
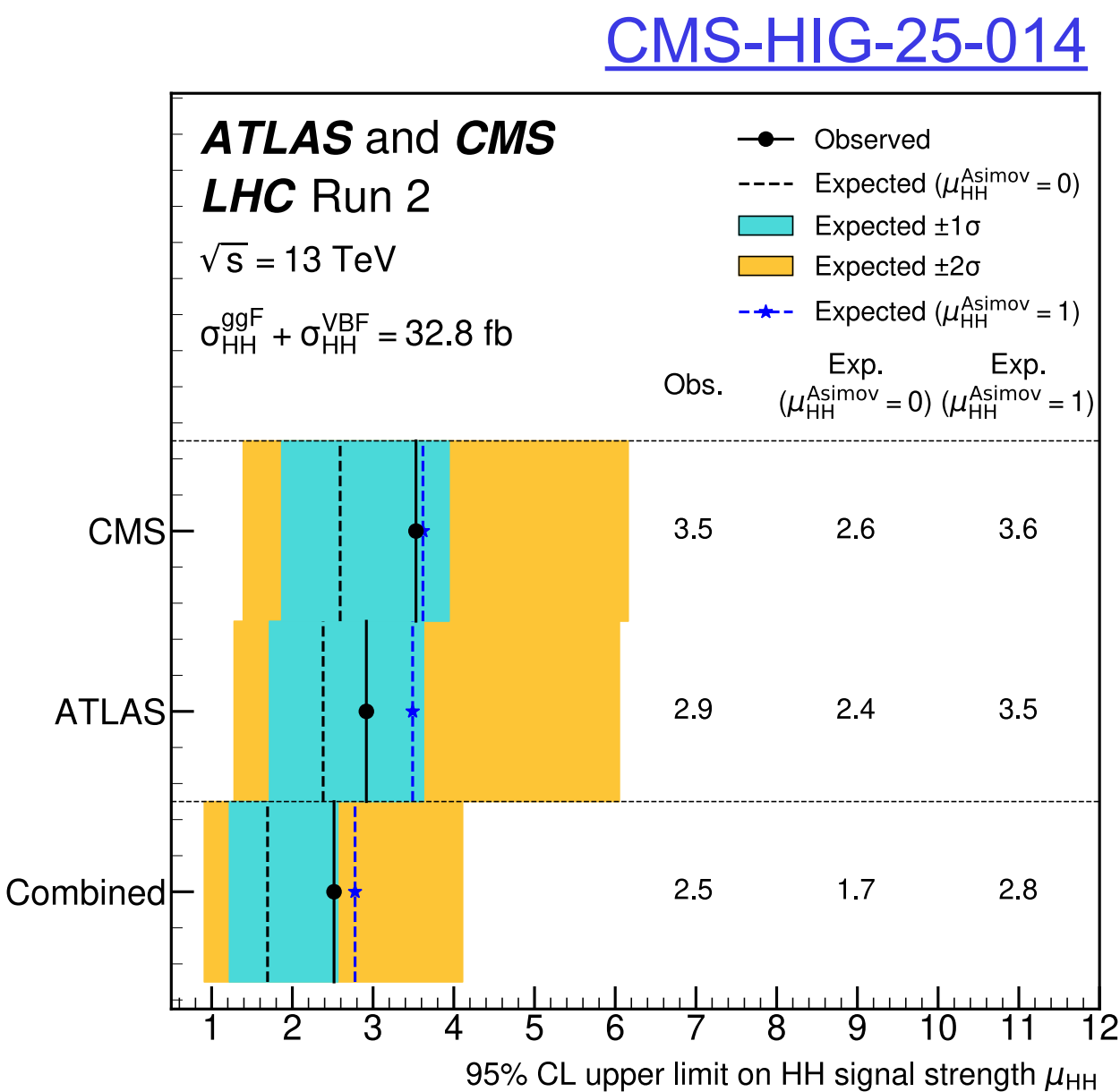


Vector Boson Fusion - 1.9 fb



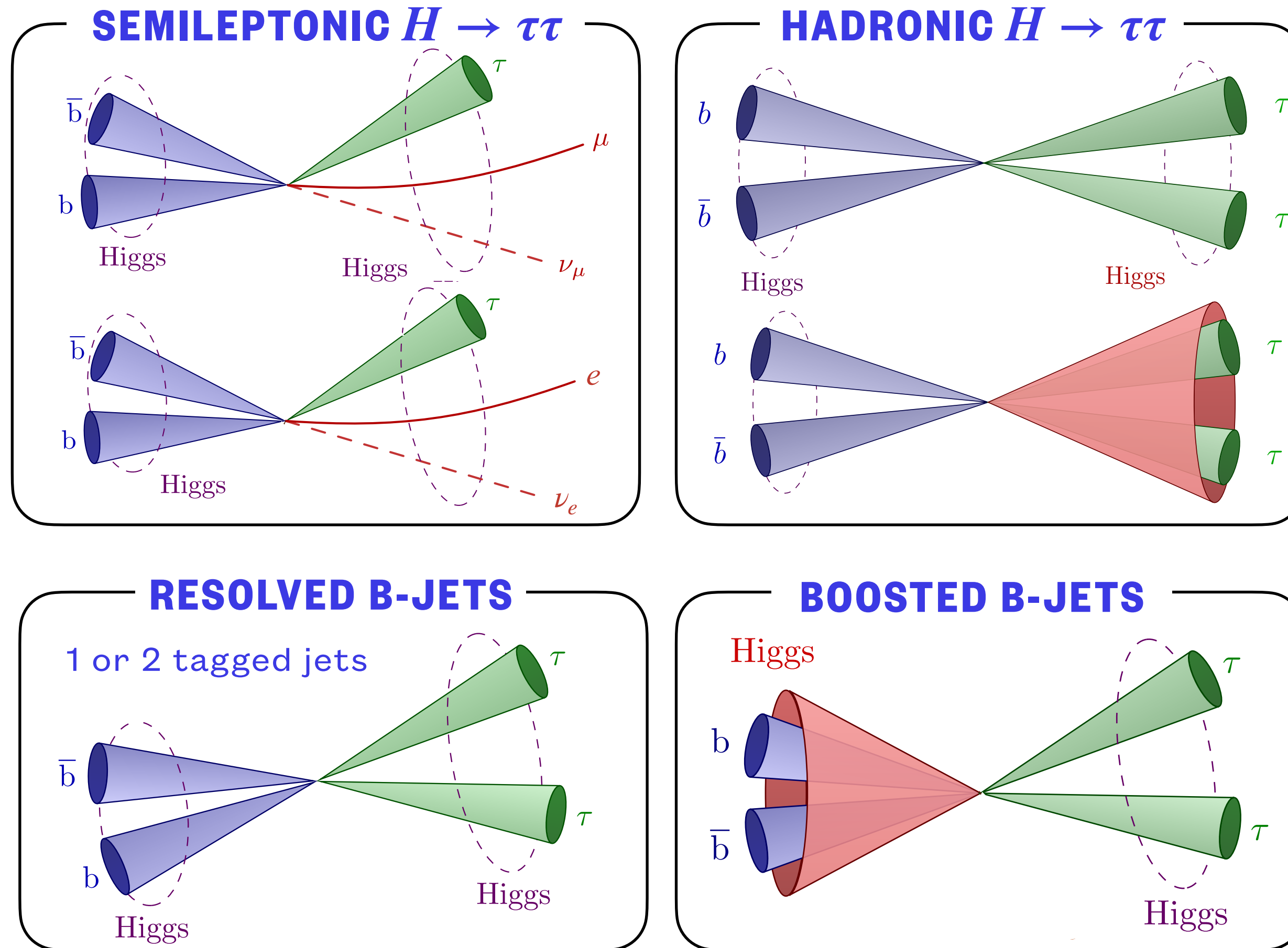
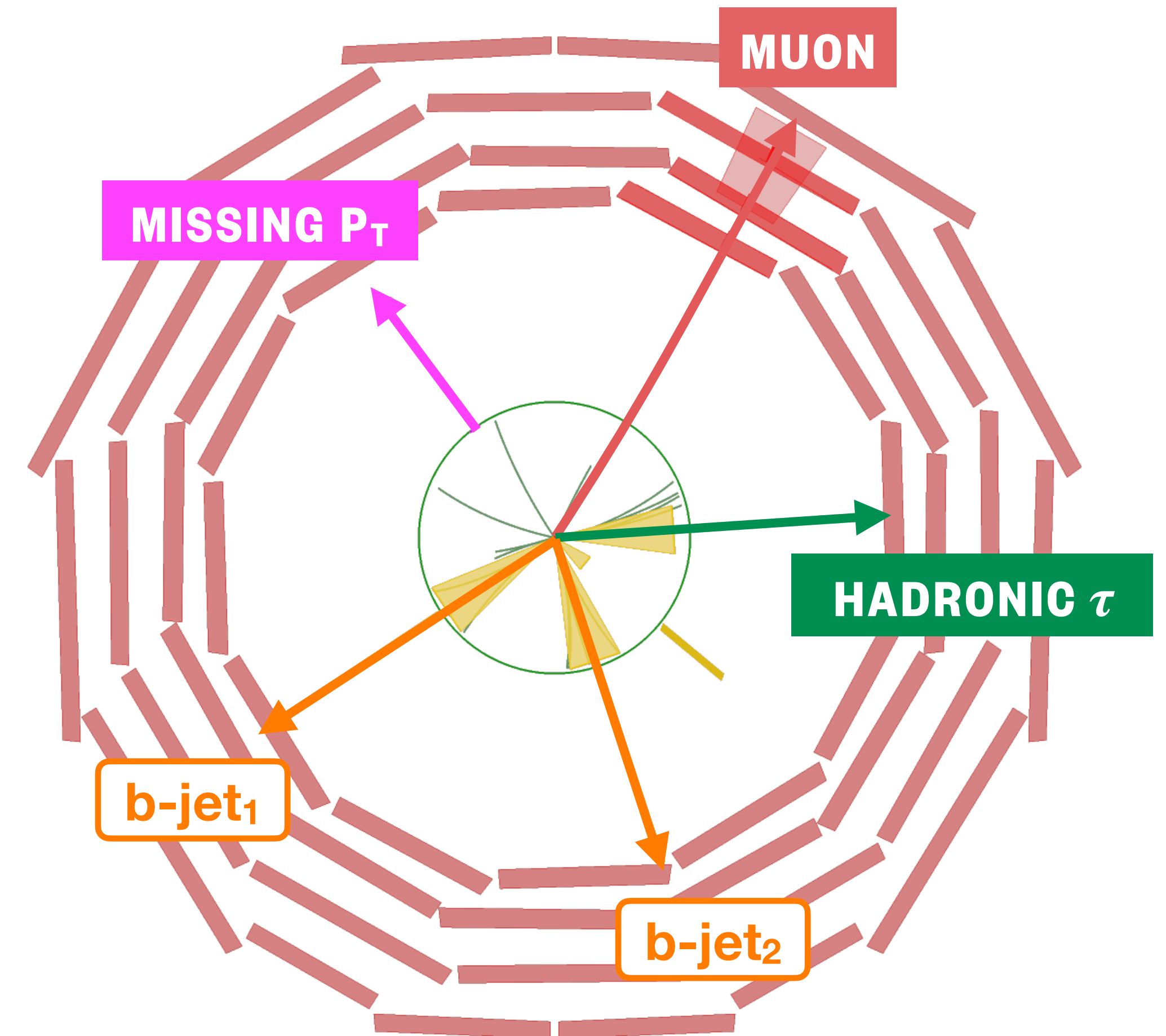
Why $bb\tau\tau$?

- The Higgs decays through **several modes**
- ATLAS and CMS are now exploring (almost) the whole phase space through multi-leptons and multi-bosons searches
- Several *silver channels*, among which (ordered by sensitivity in Run2 analyses)



Decay channel	Branching ratio	Pros	Cons	Constraint on κ_λ from Run 2
bbbb	34 %	High branching ratio	Complex QCD background	<u>CMS-HIG-20-005</u> [−2.3, 9.4]
$bb\tau\tau$	7.3%	Compromise between branching ratio and background discrimination (tau purity)		<u>CMS-HIG-20-010</u> [−1.7, 8.7]
$bb\gamma\gamma$	0.27%	Easy to trigger, reconstruct	Low branching ratio	<u>CMS-HIG-19-018</u> [−3.3, 8.5]

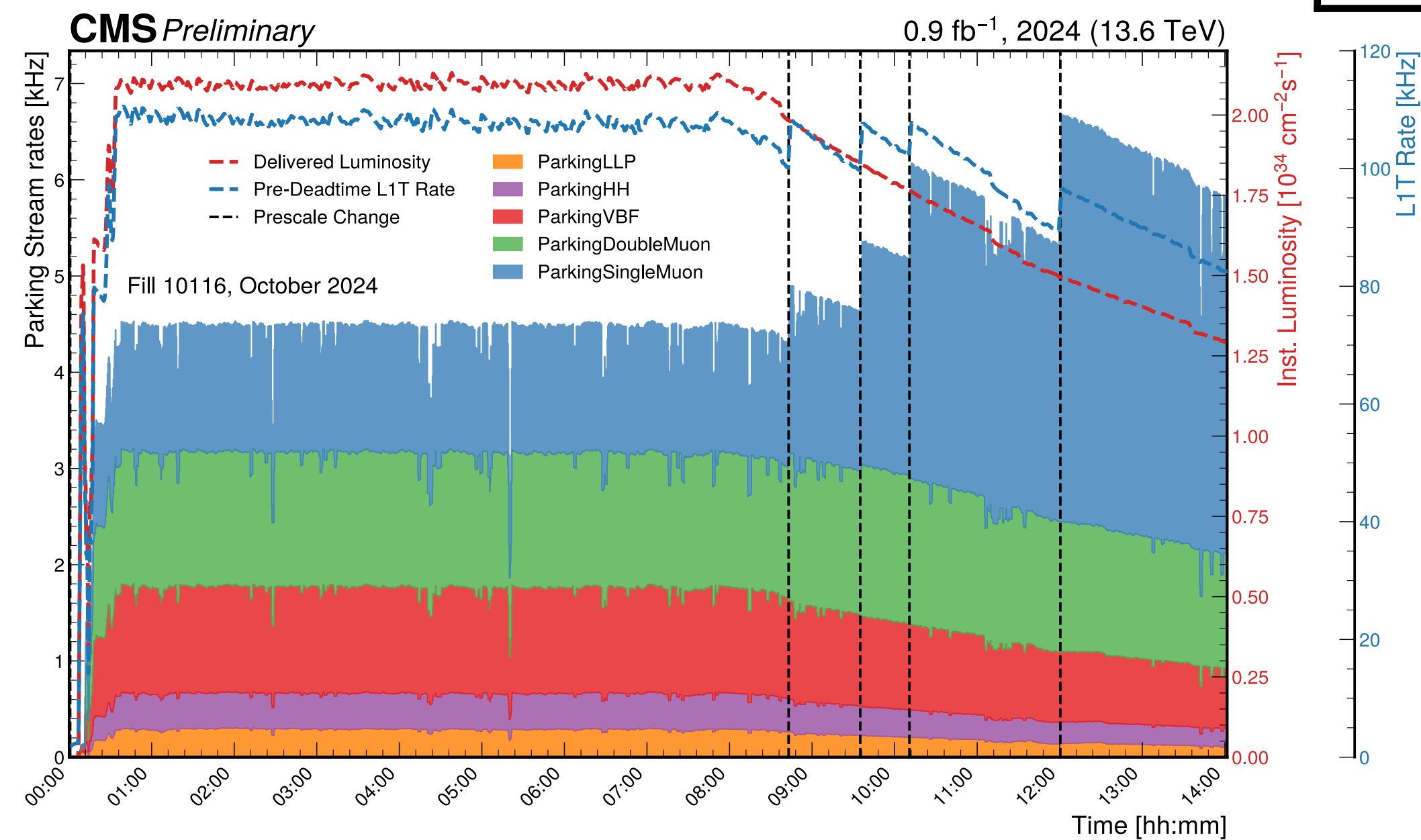
Several topologies and.. challenges



Beyond standard triggers

- Trigger strategy aims to **maximise the signal acceptance**
 - **Baseline (Run 2): lepton-based triggers** (single and cross lepton)
 - Major Run 3 improvements

Introduced	Triggering on	Signal acceptance gain wrt Run2
2022	DiTau + Jet	+13 % on DiTau trigger
	BoostedTau pair	New topology
2023	VBF (+ lepton/tau)	>20% on lepton triggers
2024	QuadJet + b-jet + tau	+15 % on DiTau trigger



Data Parking:

- Exploits the available HLT bandwidth as the instantaneous luminosity decreases → increase signal acceptance
- Dedicated HH and VBF parking streams in Run 3

Defining signal regions

- Improved reconstruction of $H \rightarrow bb$ and $H \rightarrow \tau\tau$ candidates using advanced algorithms
 - Better background rejection
 - More precise inputs for the final discriminator

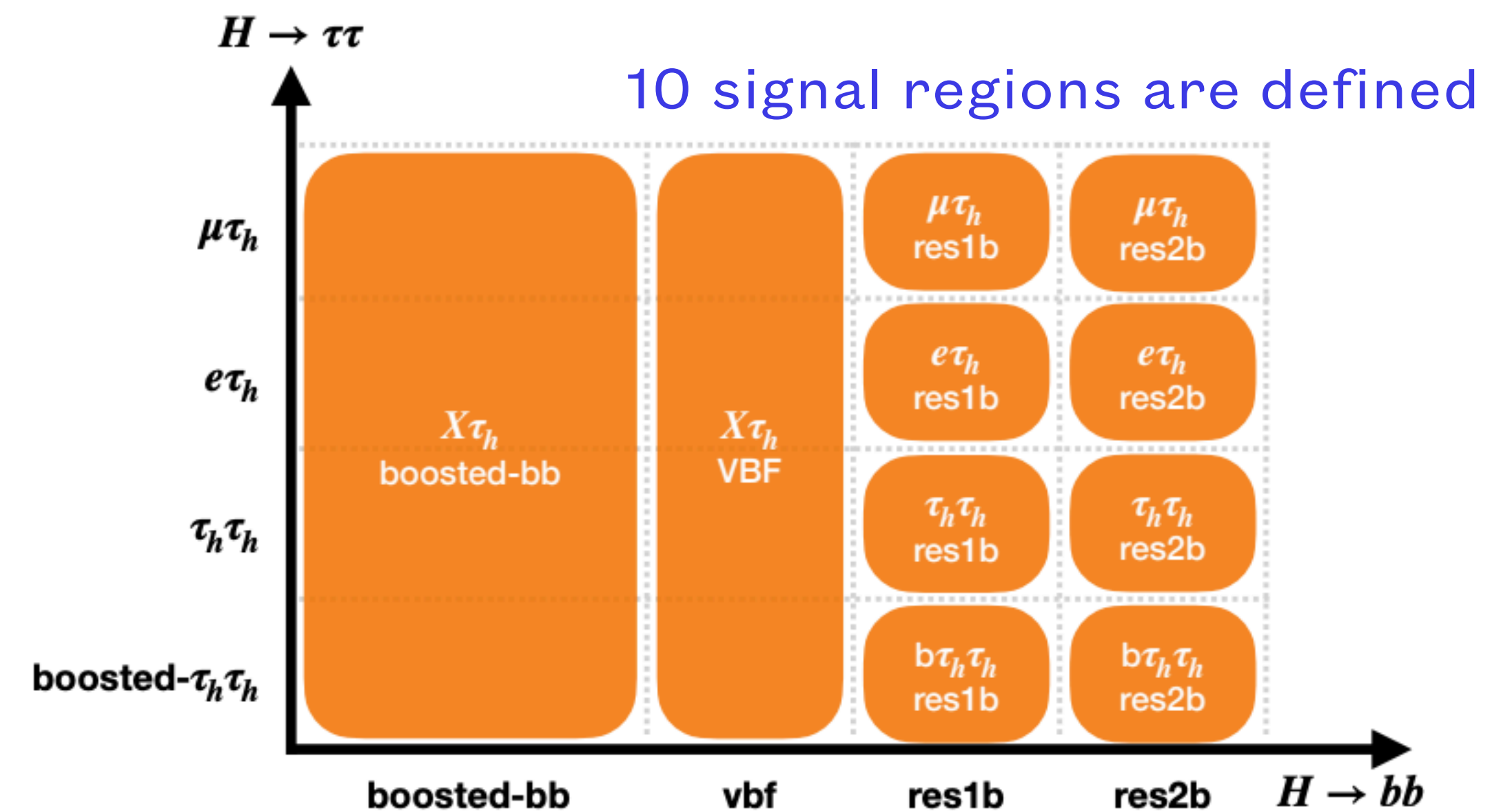
1. $H \rightarrow \tau\tau$ candidate:

- τ -pair reconstruction
- NN regression for improved $m_{\tau\tau}$ resolution and background rejection (30%) wrt Run 2



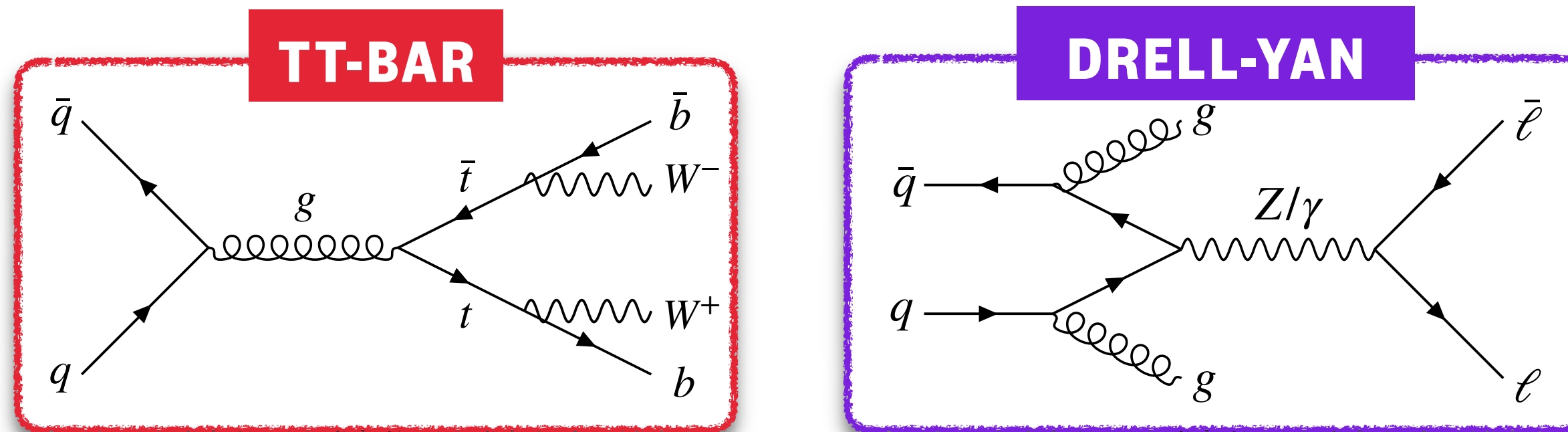
2. $H \rightarrow bb$ candidate:

- Advanced b-tagging: ParticleNet / UParT
- Higgs b-jet assignment (HHBTag) reaches >95% purity in HH events
- VBF, boosted and resolved jet topologies are identified



Background modelling

- All processes are obtained **from MC simulations**, except for data-driven fake τ background

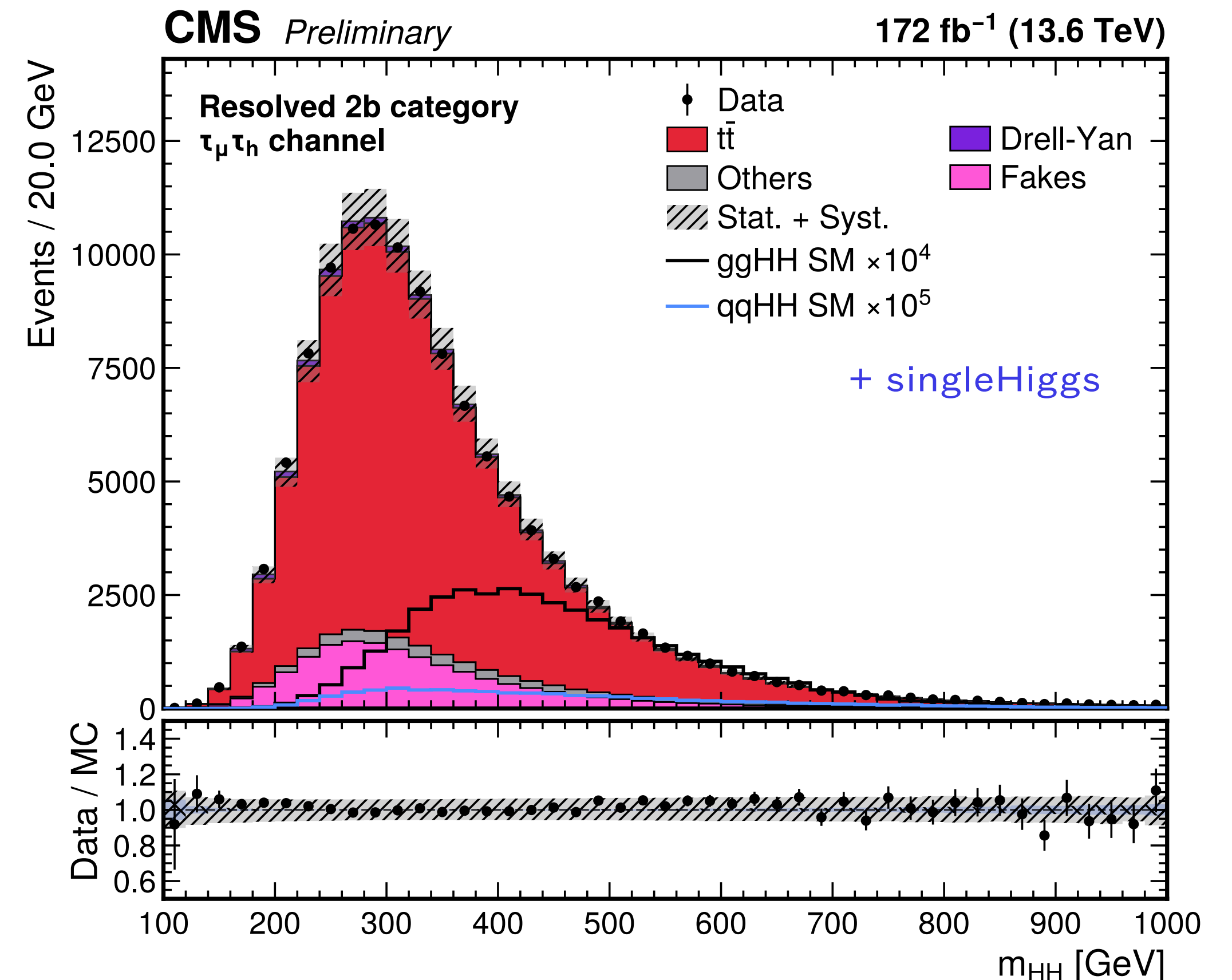


FAKE τ

Events where a jet is reconstructed as τ

Dedicated method for FFs derivation:

- Define CRs in QCD, $t\bar{t}$ and W+jets, binned in (p_T, η)
- In each CR, **transfer factor** $FF^p = \frac{\text{events } \tau \text{ ID}}{\text{events anti-}\tau \text{ ID}}$
- $FF^{SR} = \sum r_p FF^p$, r fraction of process p in anti-ID SR



Signal extraction

EVENT INFO

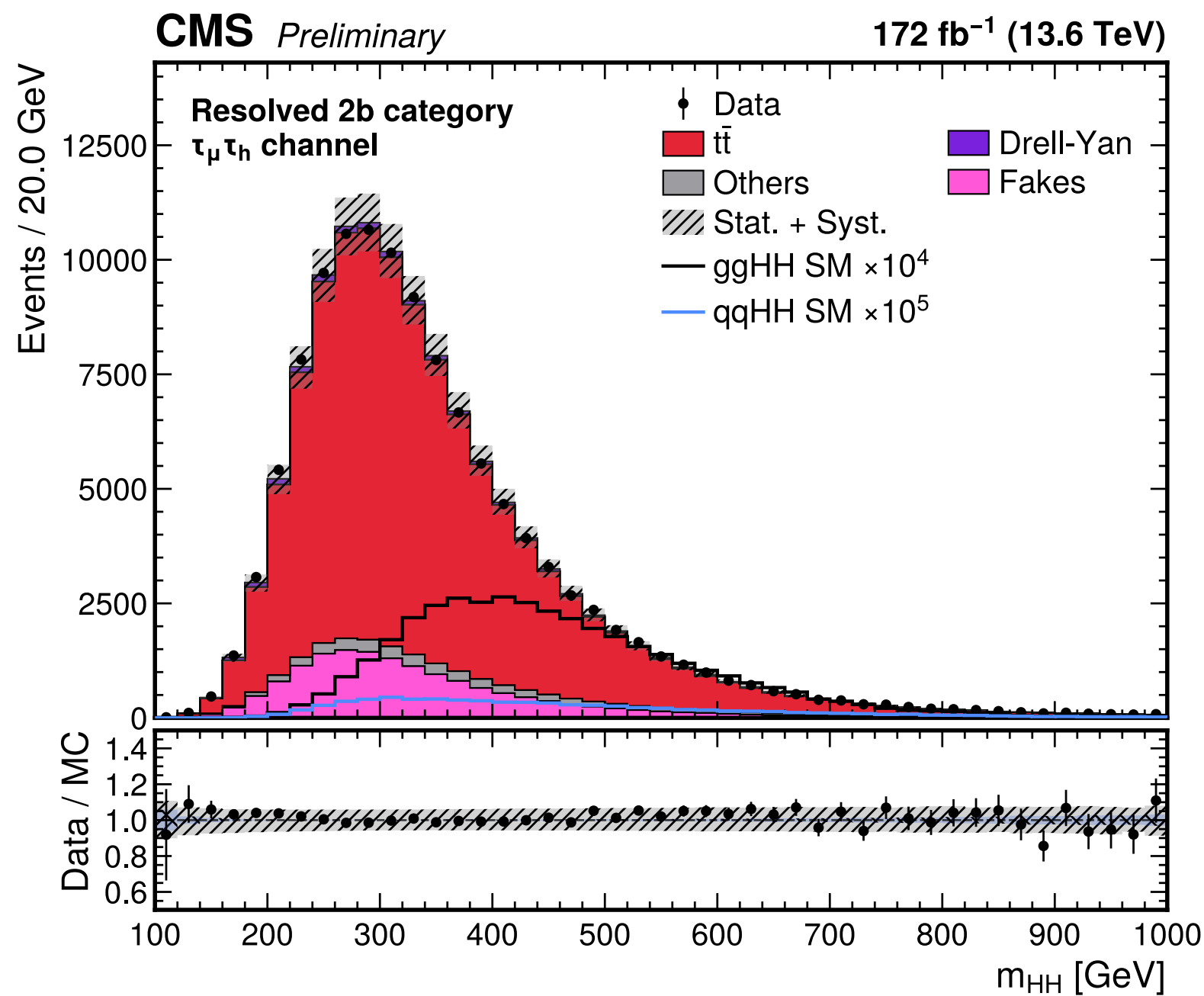
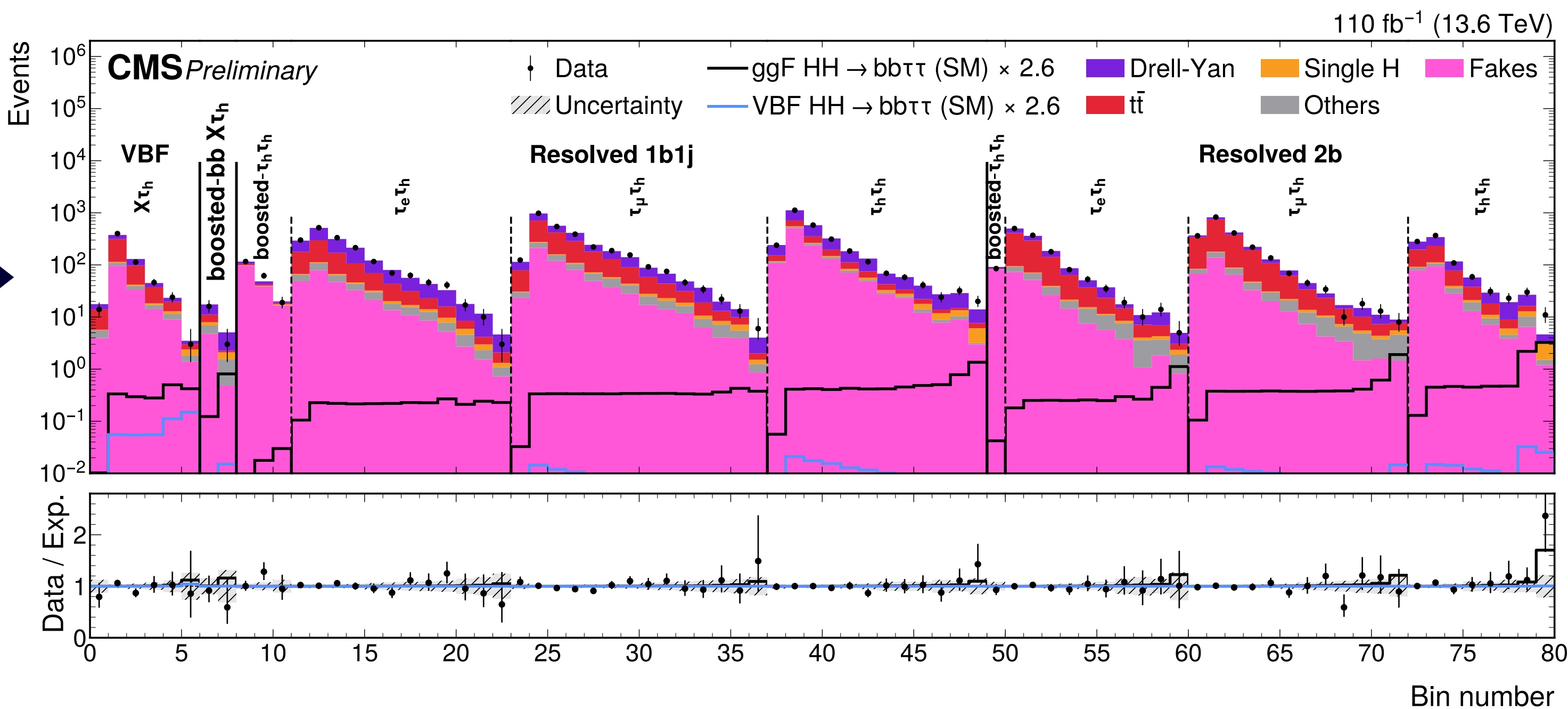
Leptons	Kinematics, decay modes, charges;
Jets	AK4/AK8 pT; b-tagging, HHBTag scores
Higgs pairs	$H \rightarrow \tau\tau$; $H \rightarrow bb$; HH system kinematics
Event-level	MET; neutrino momenta from NN

CLASSIFIER

HH / DY / $t\bar{t}$
reco objects and
event-level variables

FIT

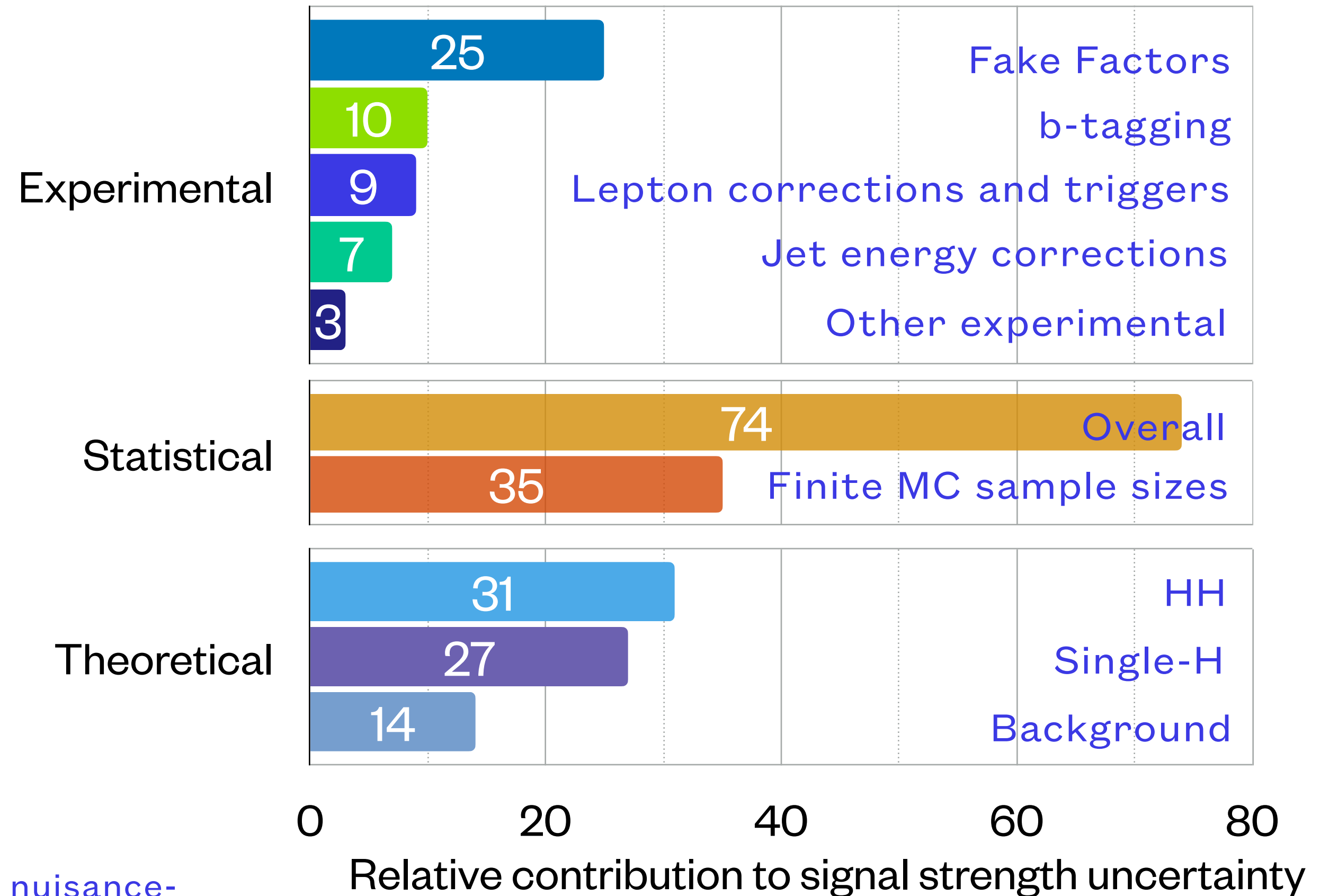
Simultaneous
binned likelihood
fit across all SRs



What limits the measurement?

- The analysis remains statistically limited, but systematics still play a significant role

- Statistical uncertainties** still dominate:
 - Statistics (74%)
 - Finite MC sample sizes, mainly DY and $t\bar{t}$ (35%)
- Theory modelling** remains significant
 - HH uncertainties (31%)
 - Large single-Higgs + HF: (dedicated simulations under investigations)
- Fake-factor uncertainties** (25%) are the leading experimental limitation
 - Significant is also b-tagging (10%)

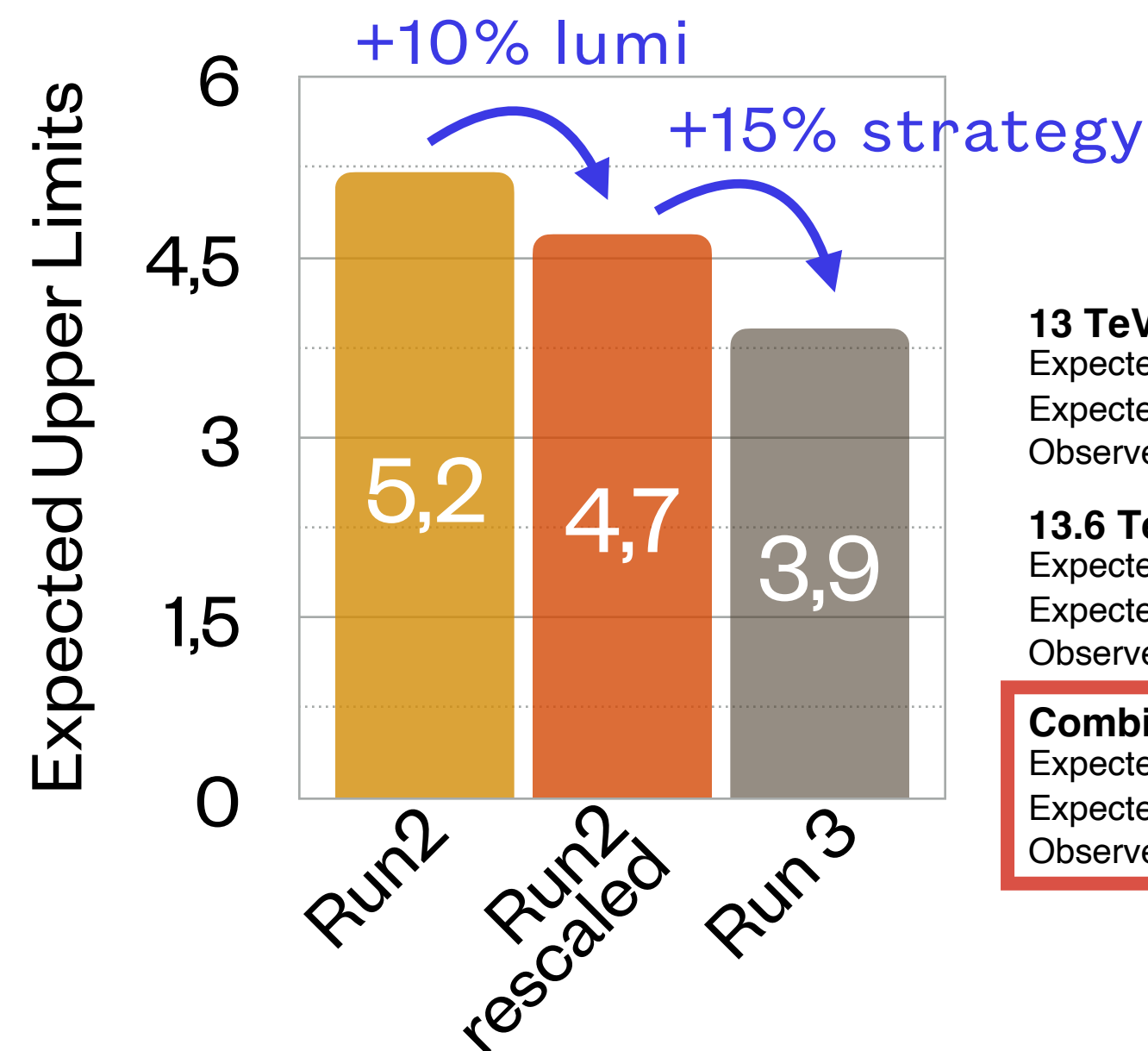
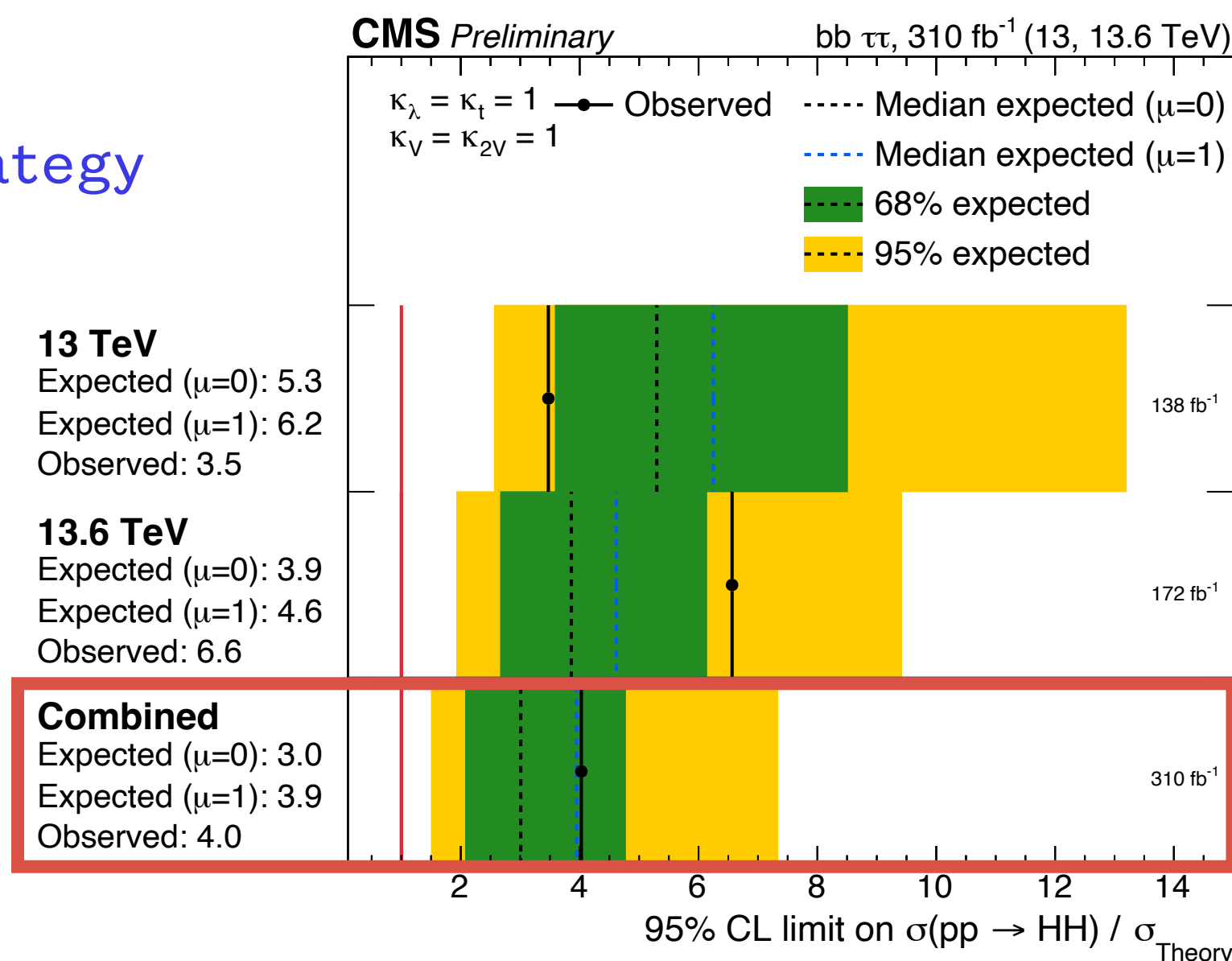


Contributions estimated by freezing nuisance-parameter groups in the likelihood fit

Improved HH sensitivity in Run 3

[CMS-PAS-HIG-25-008](#)

- **25% improvement** in expected sensitivity wrt Run 2 analysis ($5.2 \rightarrow 3.9 \times \text{SM}$)
- Observed (expected) **6.6 (3.9) x SM** at 95% CL
- For VBF, halving the expected limit of Run 2 analysis **81 (85) x SM** at 95% CL



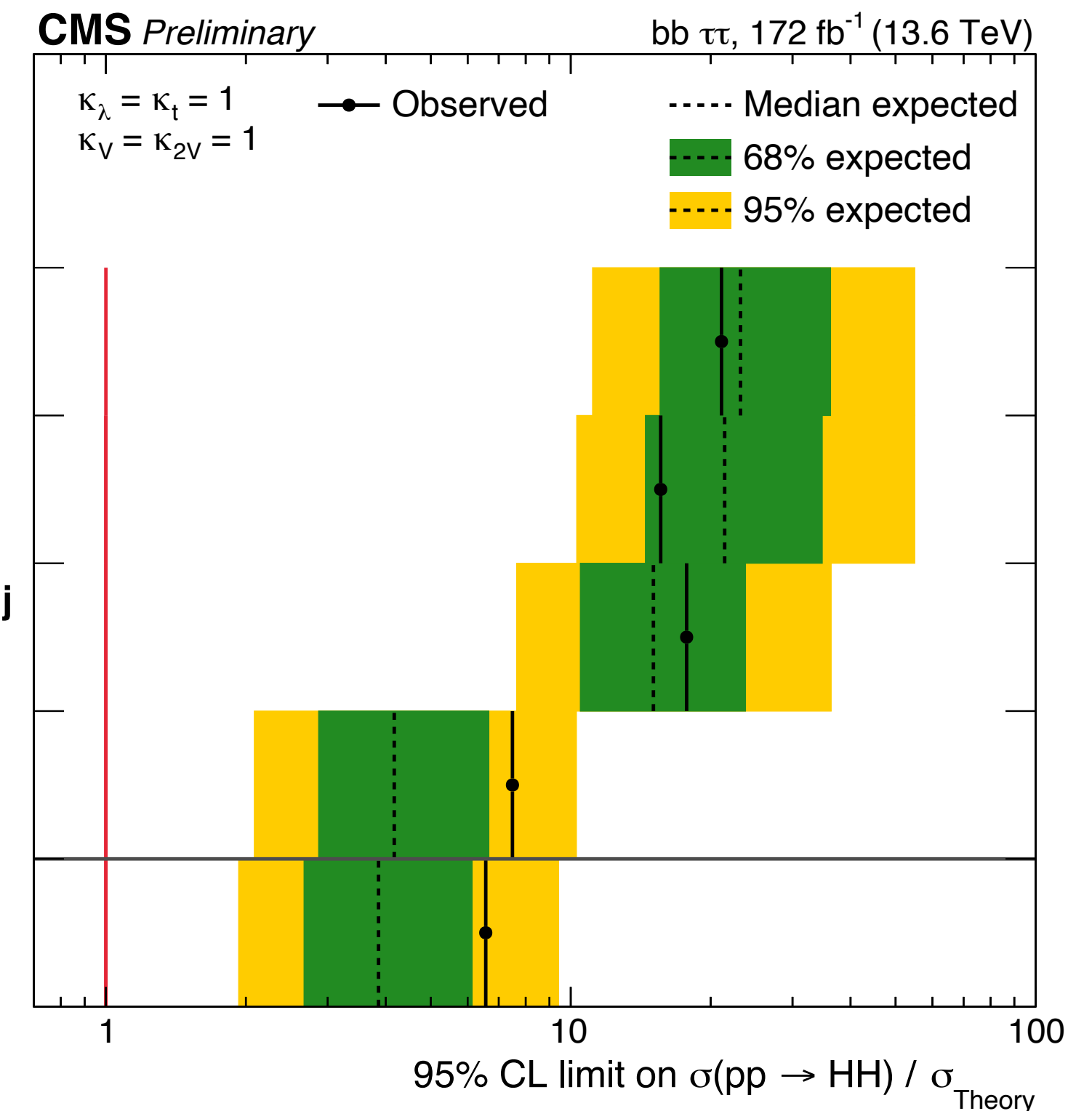
VBF
Expected: 23
Observed: 21

bb-boosted
Expected: 21
Observed: 16

resolved 1b1j
Expected: 15
Observed: 18

resolved 2b
Expected: 4.2
Observed: 7.5

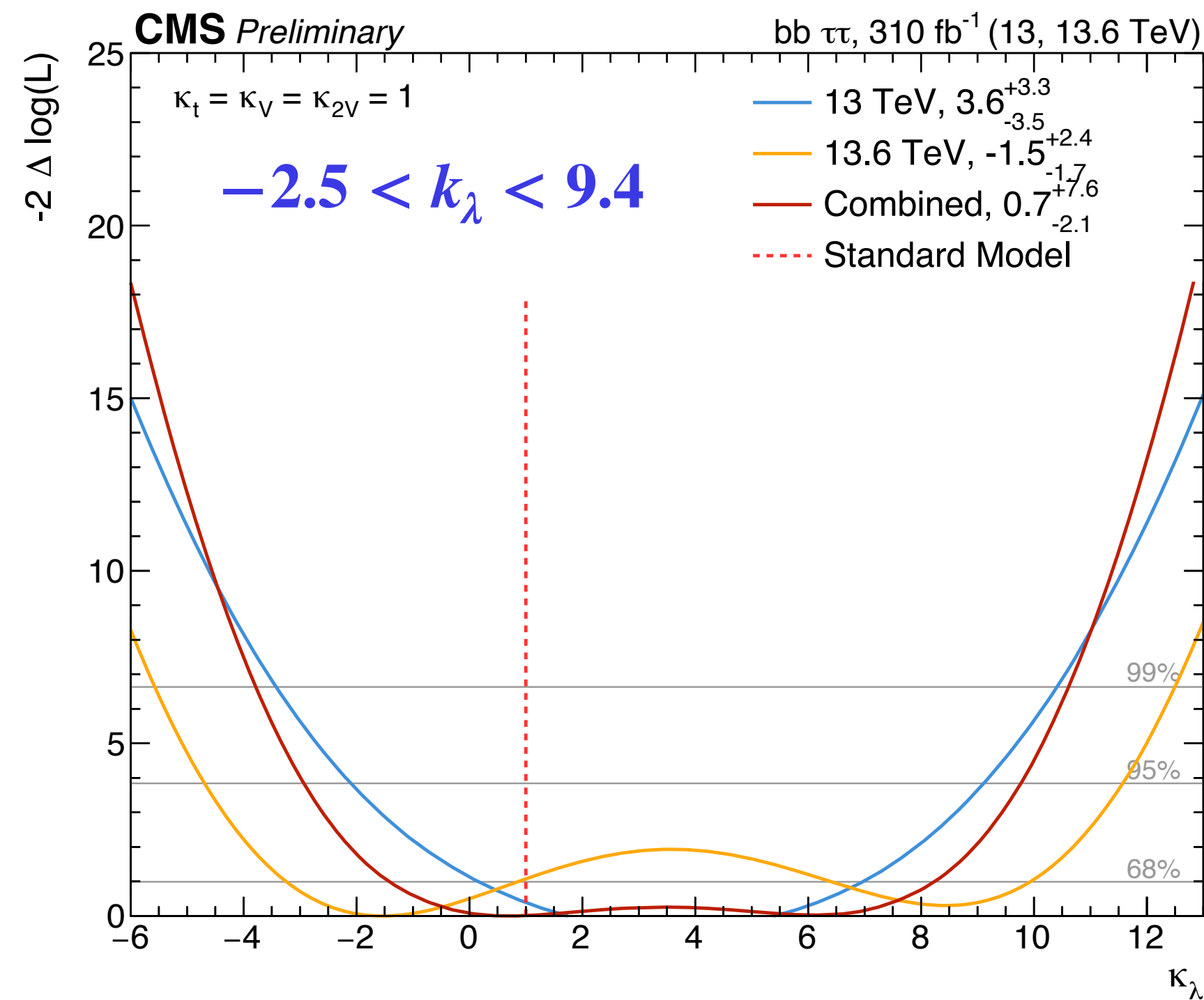
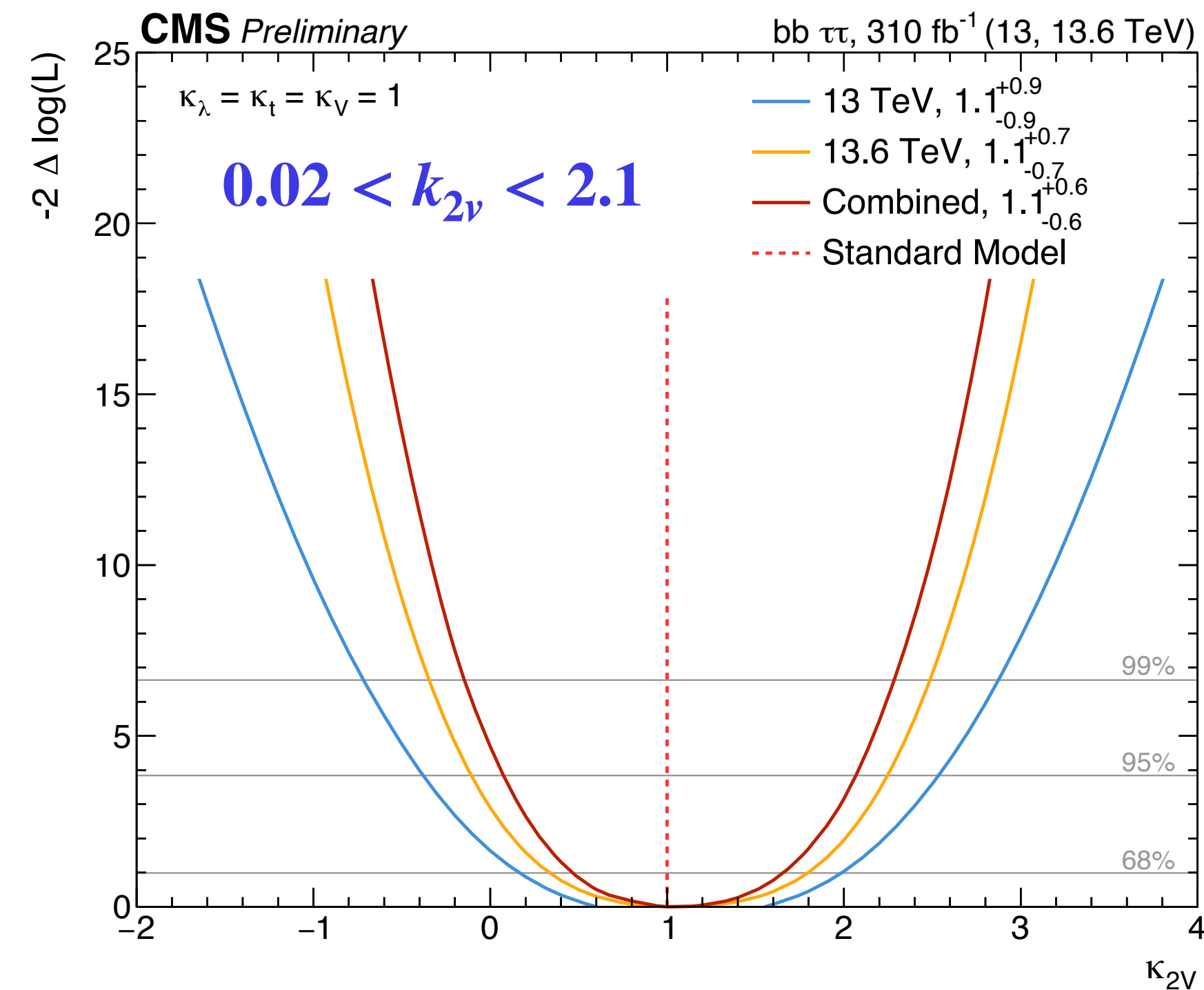
Combined
Expected: 3.9
Observed: 6.6



- **Combined Run2 and Run3** inclusive HH results: 4.0 (3.0 expected) x SM

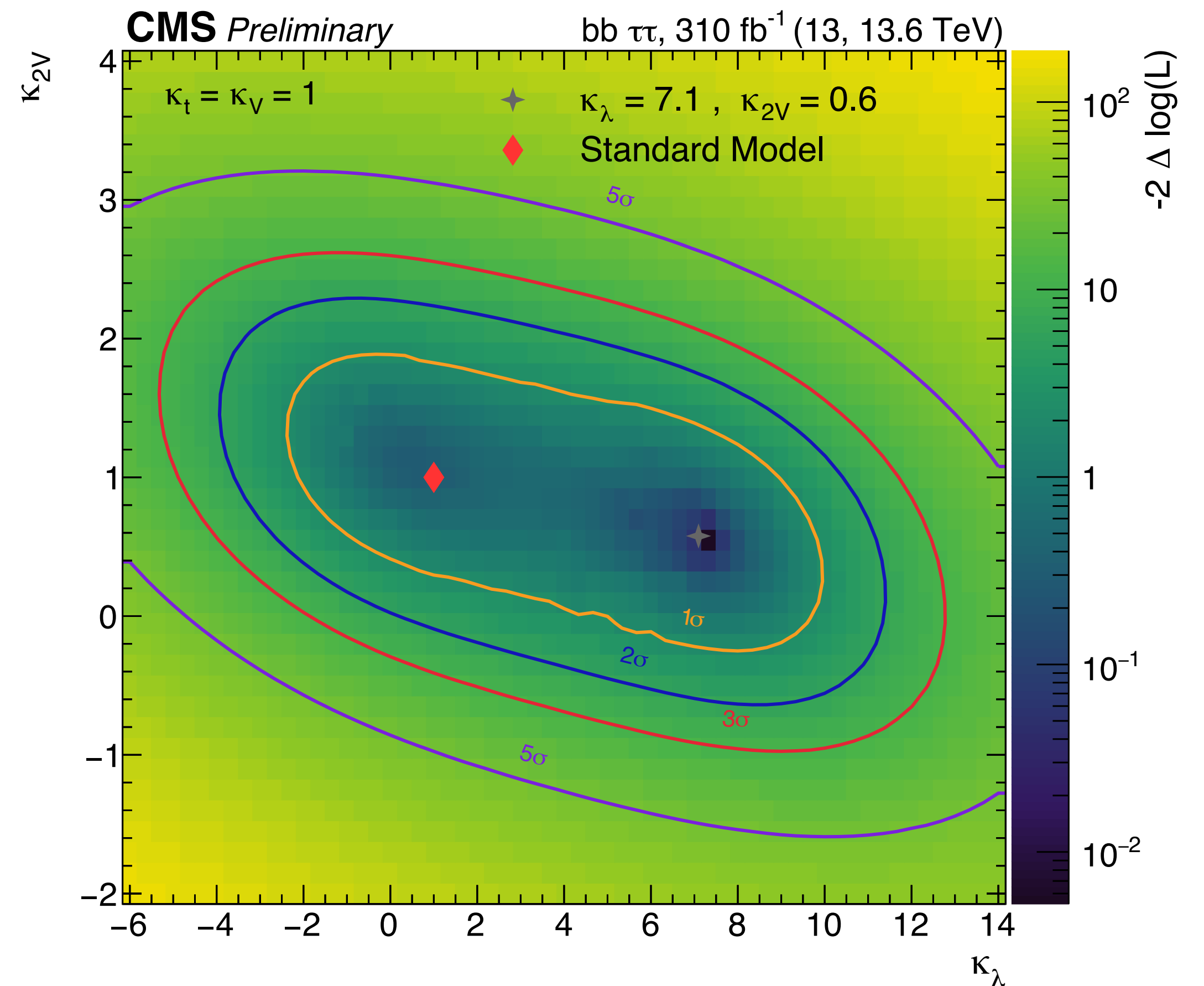
Constraining Higgs interactions

- **310 fb⁻¹ of data** collected at 13 and 13.6 TeV provide stronger constraints on the Higgs couplings
- **1D likelihood scans:**
 - +22% improvement on expected k_λ constraints compared to Run 2
 - +32% on expected $k_{2\nu}$ constraints compared to Run 2



Constraining Higgs interactions

- **310 fb⁻¹ of data** collected at 13 and 13.6 TeV provide stronger constraints on the Higgs couplings
- Improved VBF sensitivity helps disentangle k_λ and k_{2V} contributions
- **2D likelihood scans:**
 - Simultaneous fit of k_λ and k_{2V} , accounting for possible degeneracies
 - Best-fit point: $(k_\lambda, k_{2V}) = (7.1, 0.6)$
 - SM hypothesis compatible within 68% CL



Conclusions

- **CMS-PAS-HIG-25-008 brings major improvements** across the entire analysis chain: triggers, reconstruction, categorisation and signal extraction

TRIGGER

New standard triggers and new parking strategies

RECONSTRUCT

Improved b-jets, τ and boosted- τ

MODEL

Innovative data-driven fake- τ estimation

EXTRACT

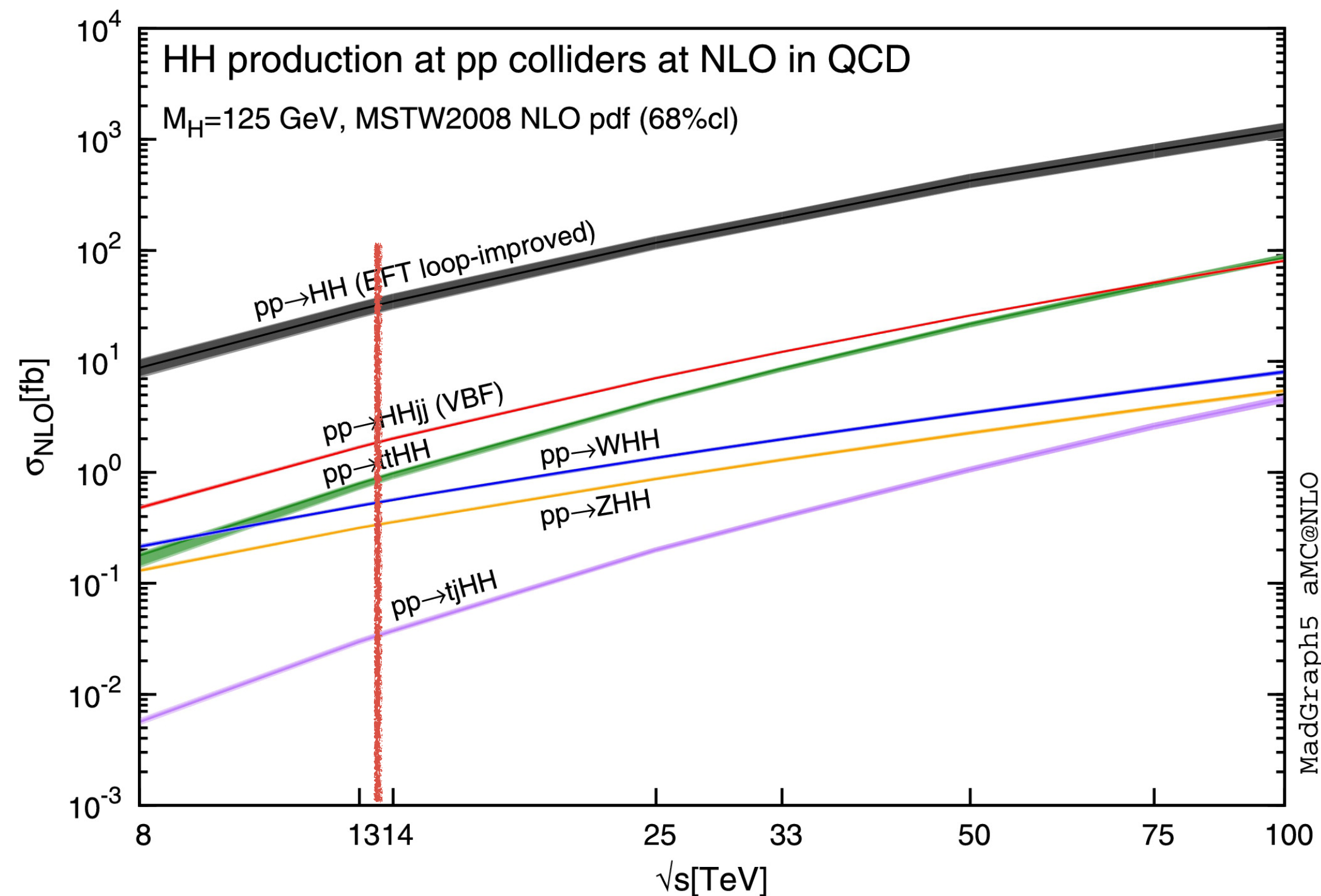
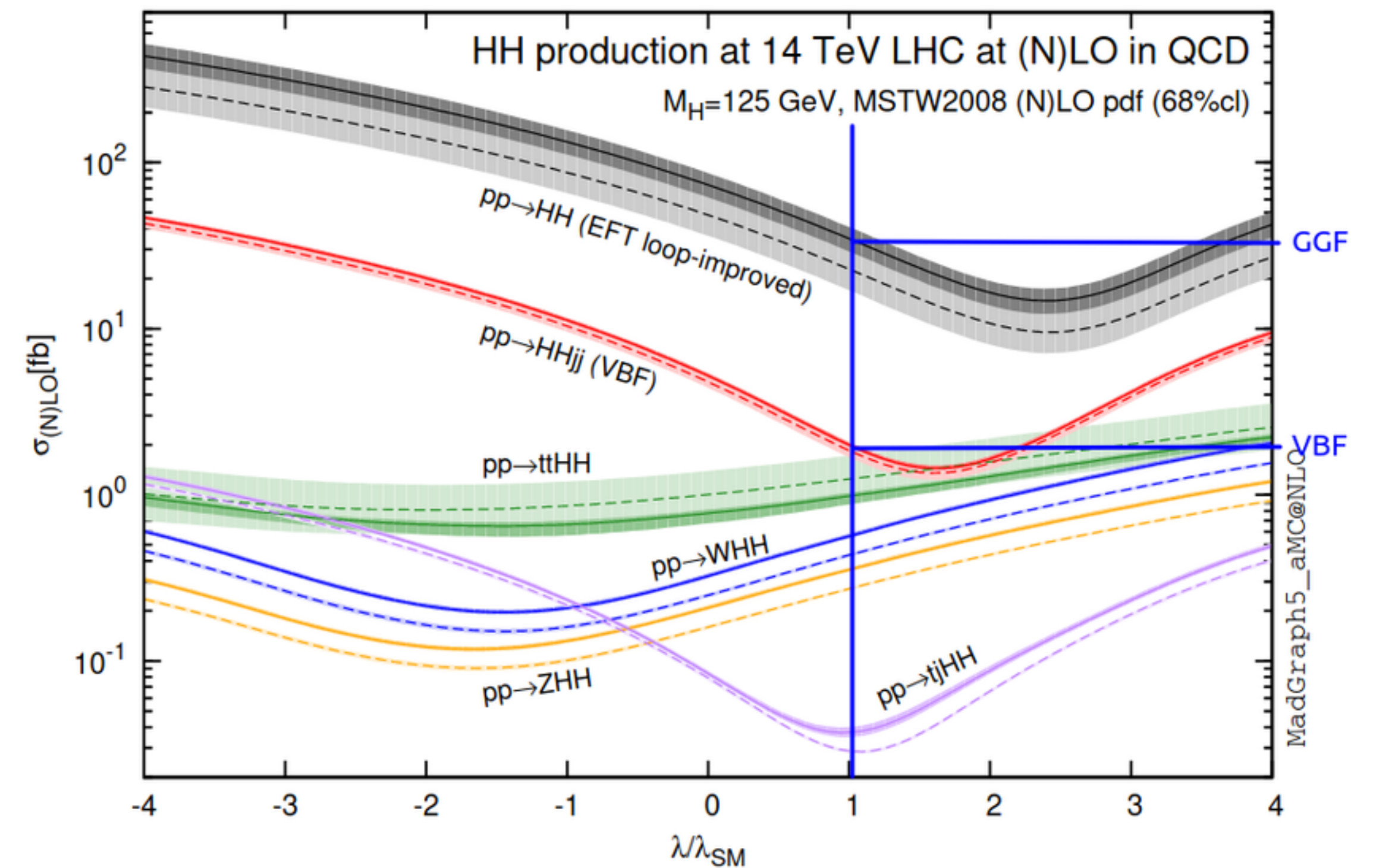
Retrained DNN, multivariate fit

- **25% lower expected HH upper limit** compared with Run 2
 - ~10% from lumi scaling, ~15% from improvements along the analysis workflow
- ... with a x2 improvement in the VBF expected upper limit
- **Run 2 + Run 3 combination** further strengthens constraints on k_λ and $k_{2\nu}$ couplings
- Towards full Run 3: more data, improved acceptance, enhanced coupling sensitivity and further optimisation of the analysis strategy..

Backup

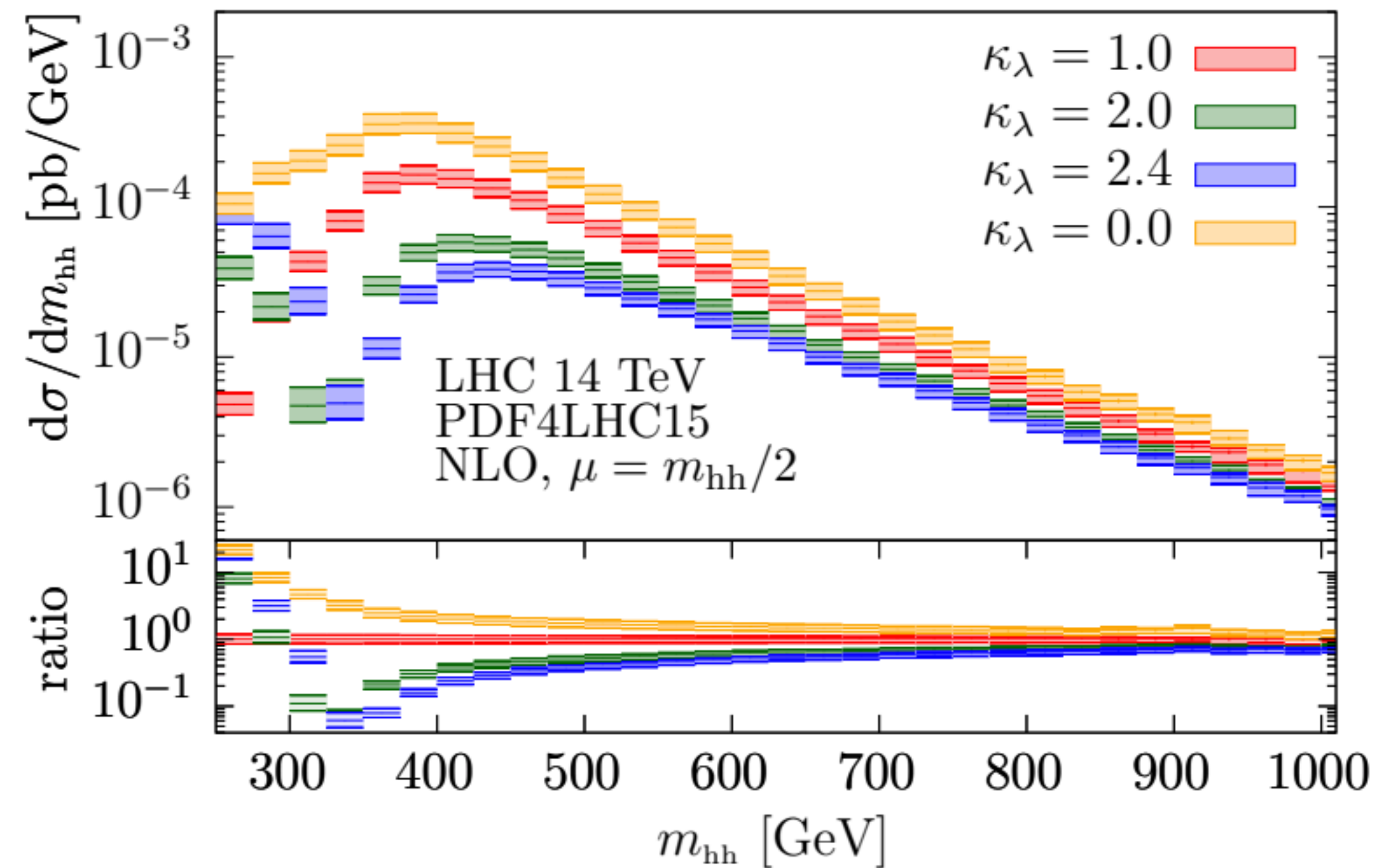
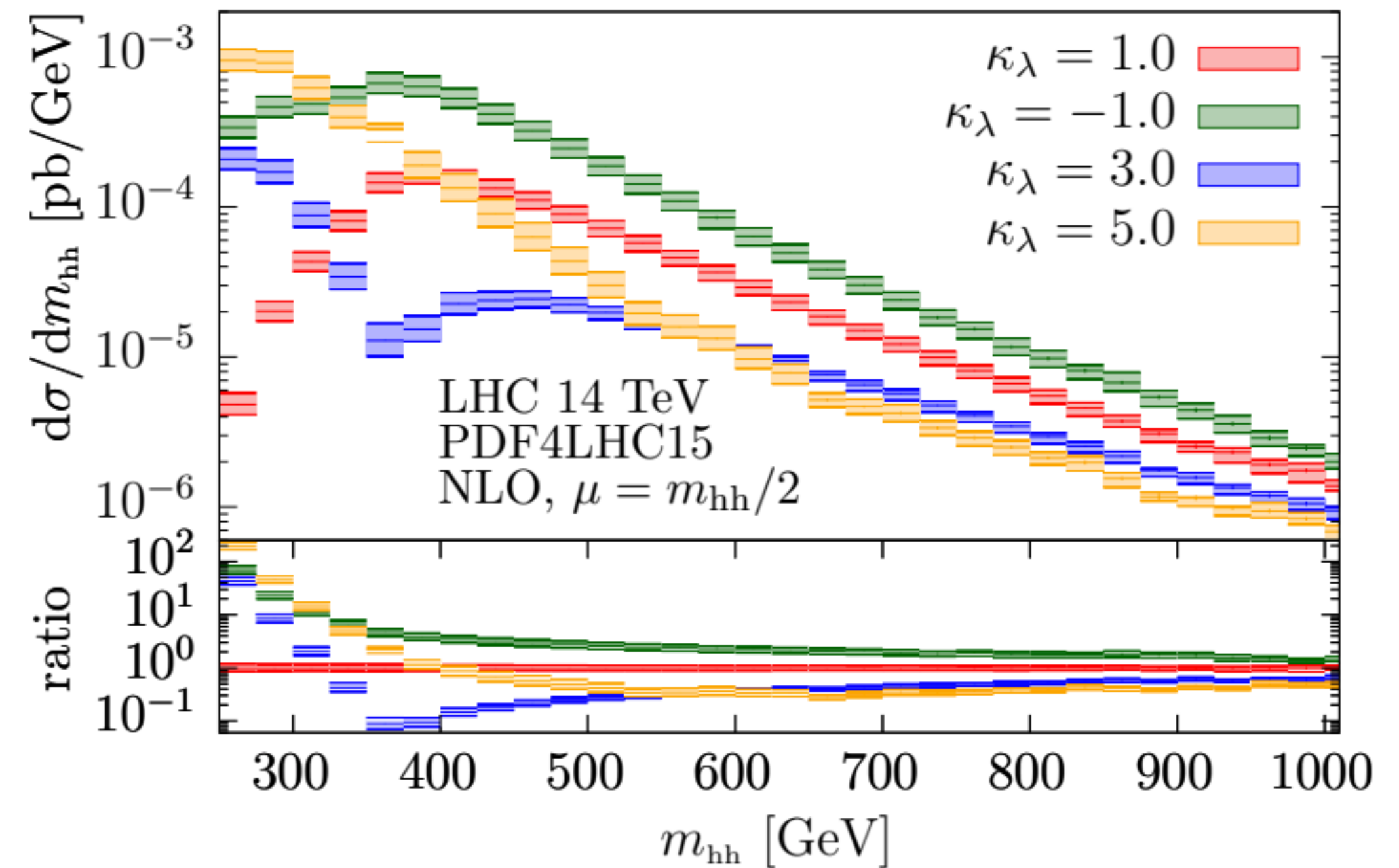
HH production process

- Gluon fusion (ggF) cross section has it minimum at 2.4 → maximum destructive interference of ggF diagrams
 - Large $|\kappa_\lambda|$: softer m_{hh} spectrum and large cross section
 - Medium $|\kappa_\lambda|$: harder m_{hh} spectrum



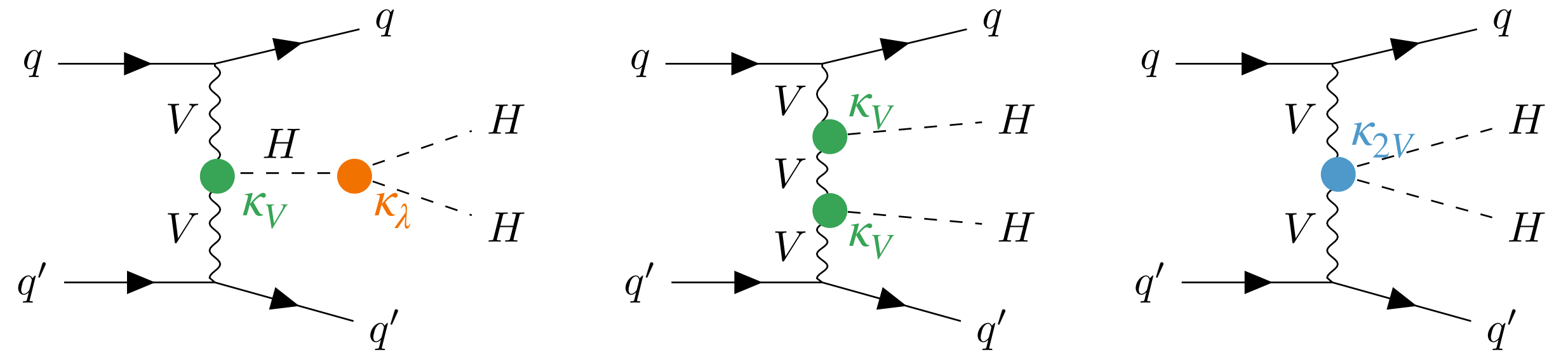
HH production process

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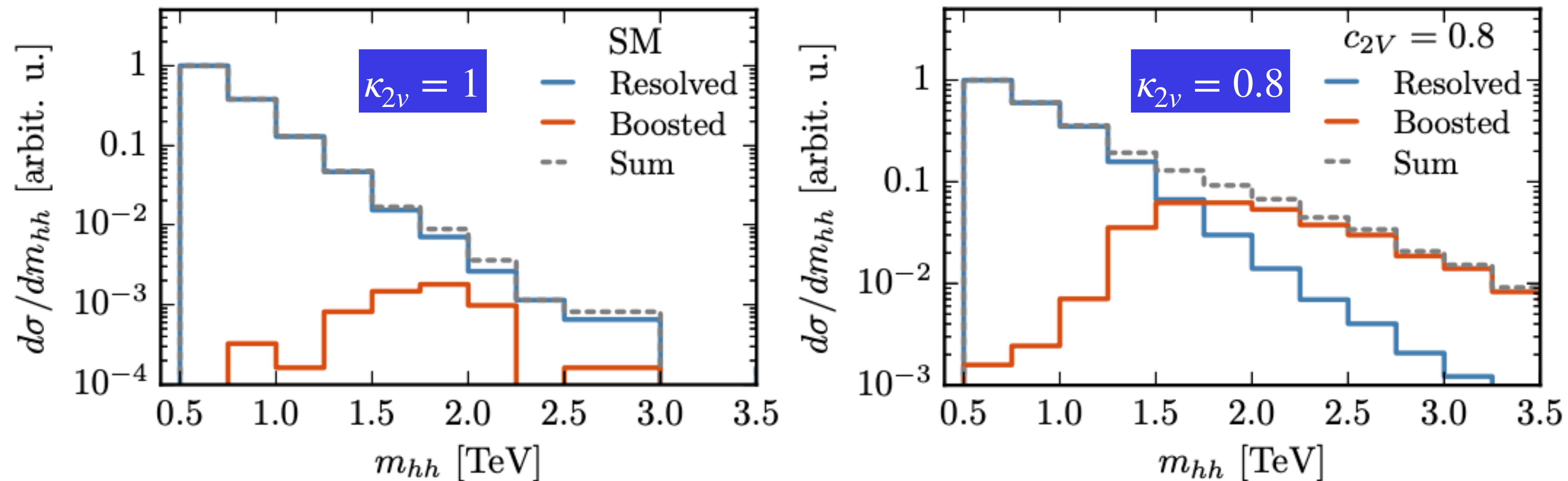


HH production process

- VBF cross section has it minimum at 1.65
 - $\kappa_{2V} \rightarrow 1$: softer m_{hh} spectrum and large cross section
 - Large $|\kappa_{2V}|$: harder m_{hh} spectrum $\rightarrow$ boosted topologies



<https://arxiv.org/pdf/1611.03860>

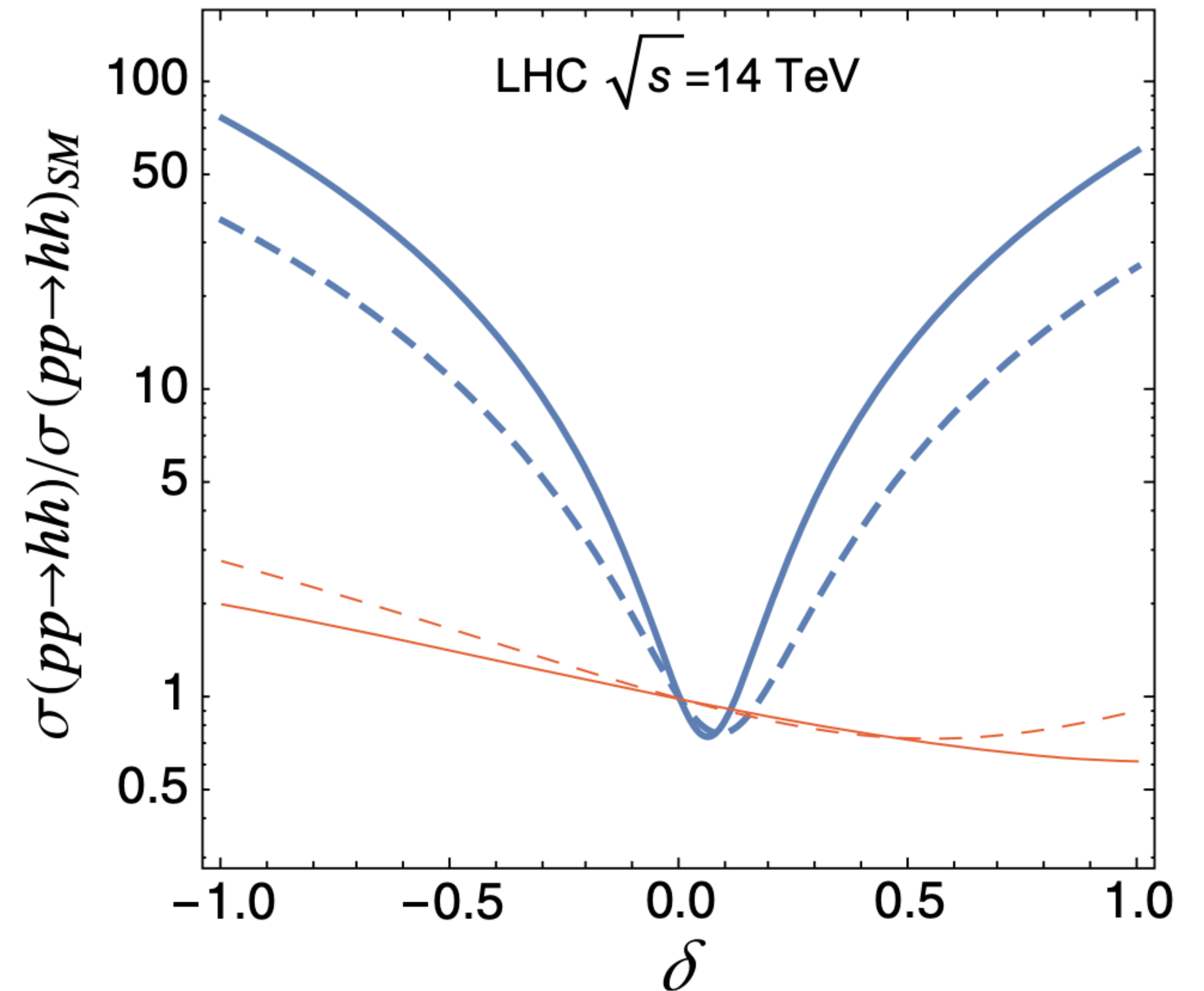


HH production process

- Cross section as a function of the κ_{HHH} and κ_{2v} :
 - Sensitivity particularly striking for $|\delta_{2v}| = 1$ where the cross section is enhanced x50
 - Sensitivity is crucial for measuring κ_{2v} with good precision (even if small rate)
 - Sensitivity comes from **events from the tail** of the m_{hh} distribution
- Sensitivity on κ_{HHH} is relatively weak :
 - Comes from events near to the Higgs threshold $m_{hh} \sim 2m_h$

$$\delta_{2v} = \kappa_{2v} - 1$$
$$\delta_{HHH} = \kappa_{HHH} - 1$$

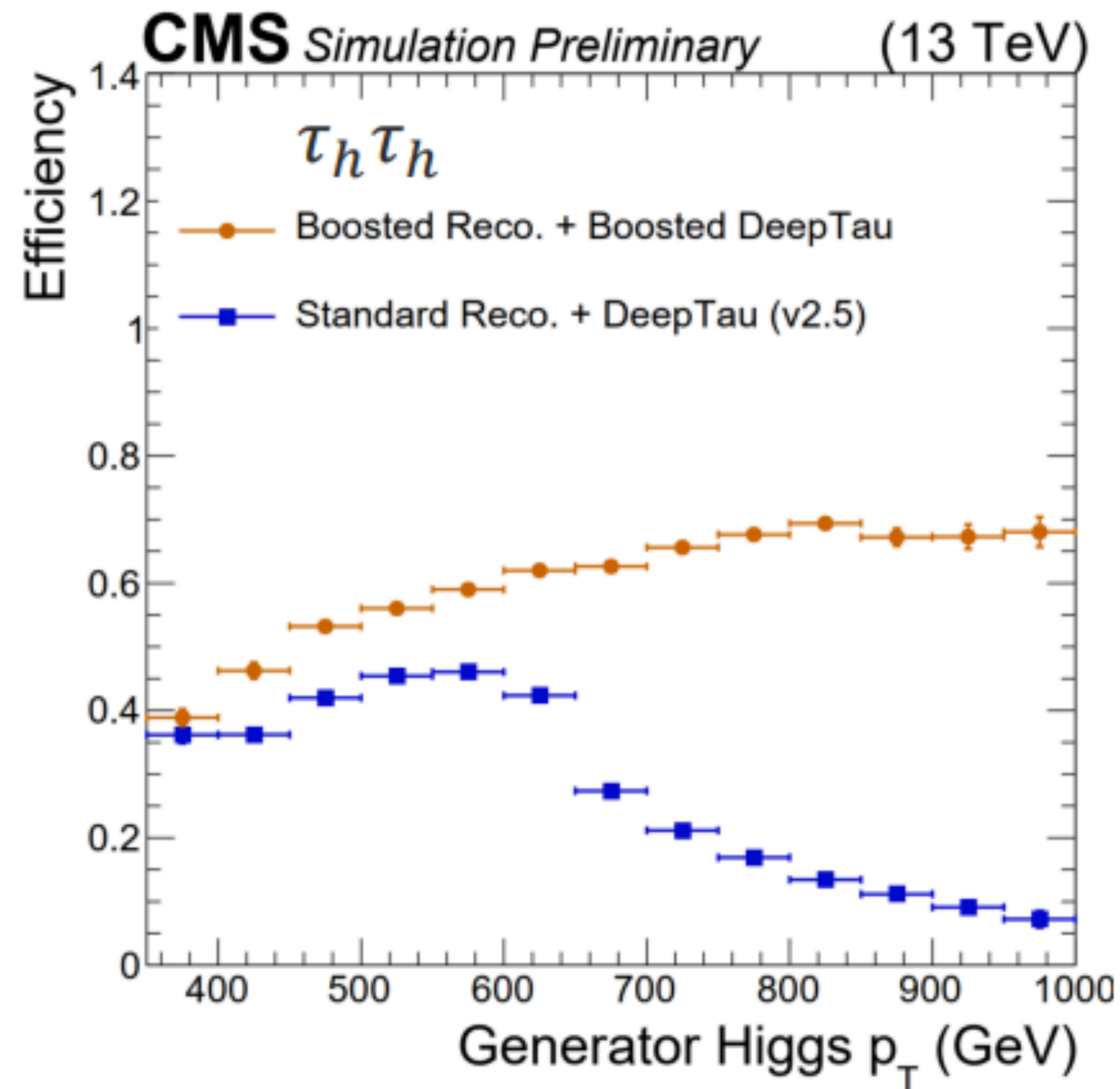
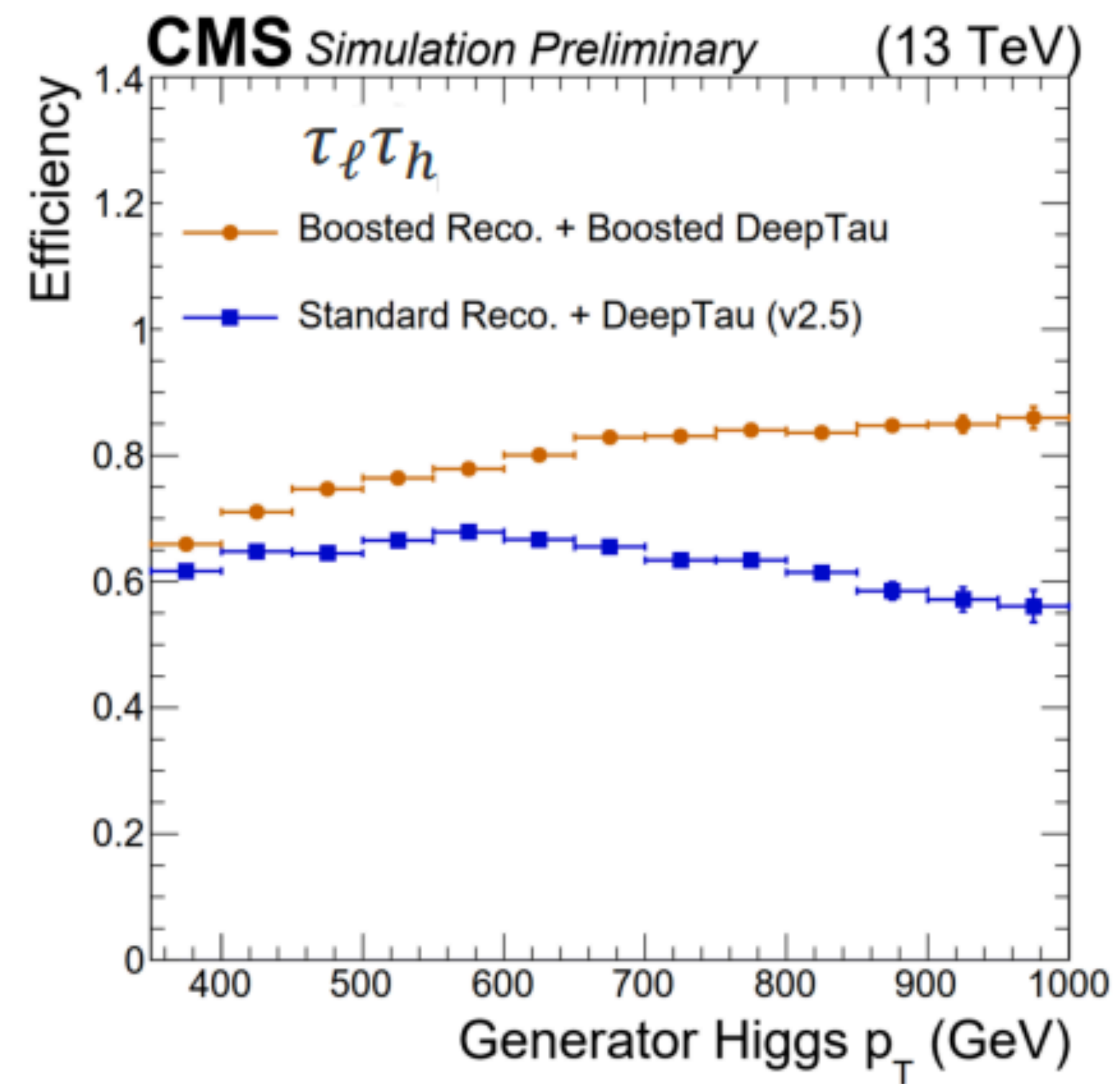
<https://arxiv.org/pdf/1611.03860>



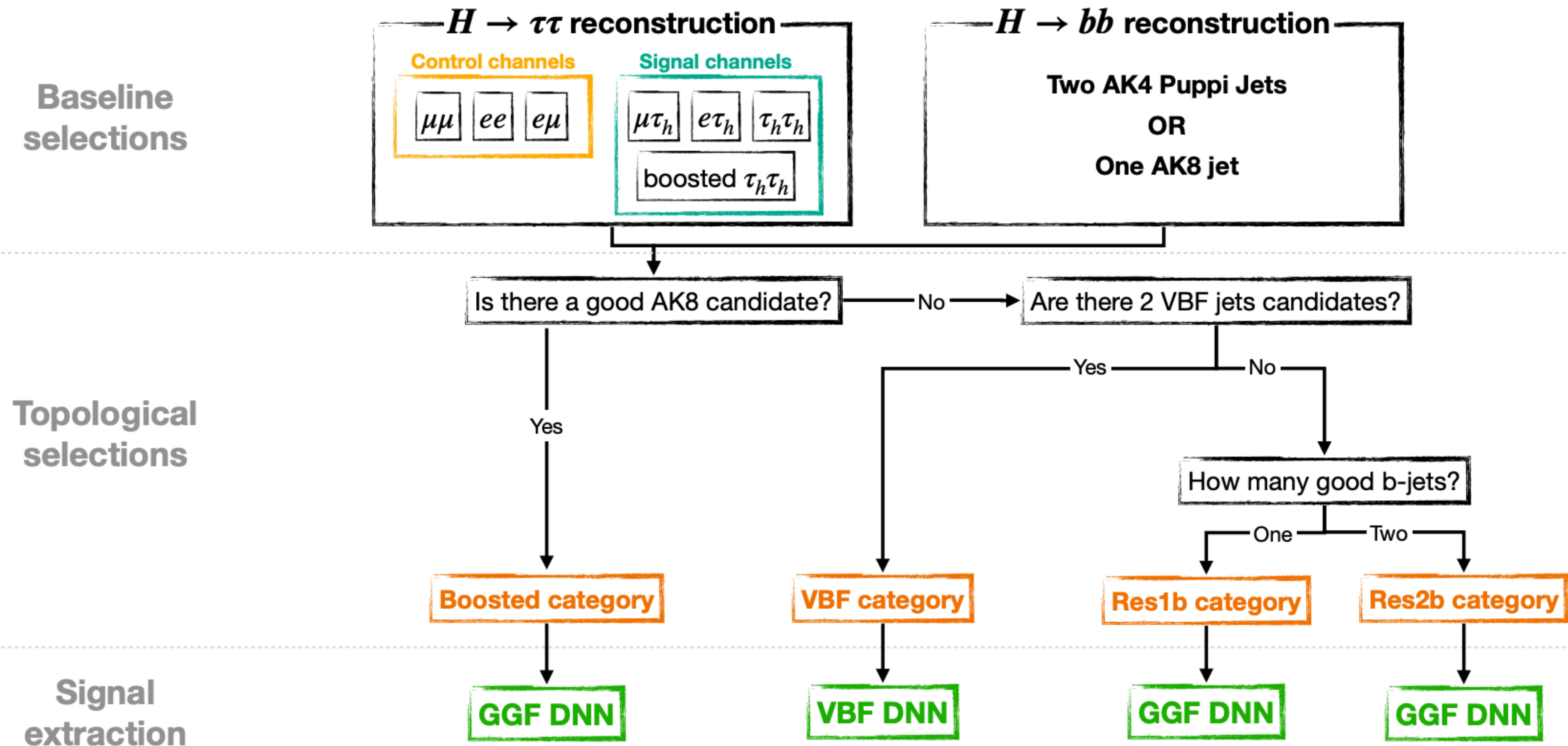
Boosted Tau reconstruction

<https://cds.cern.ch/record/2941434>

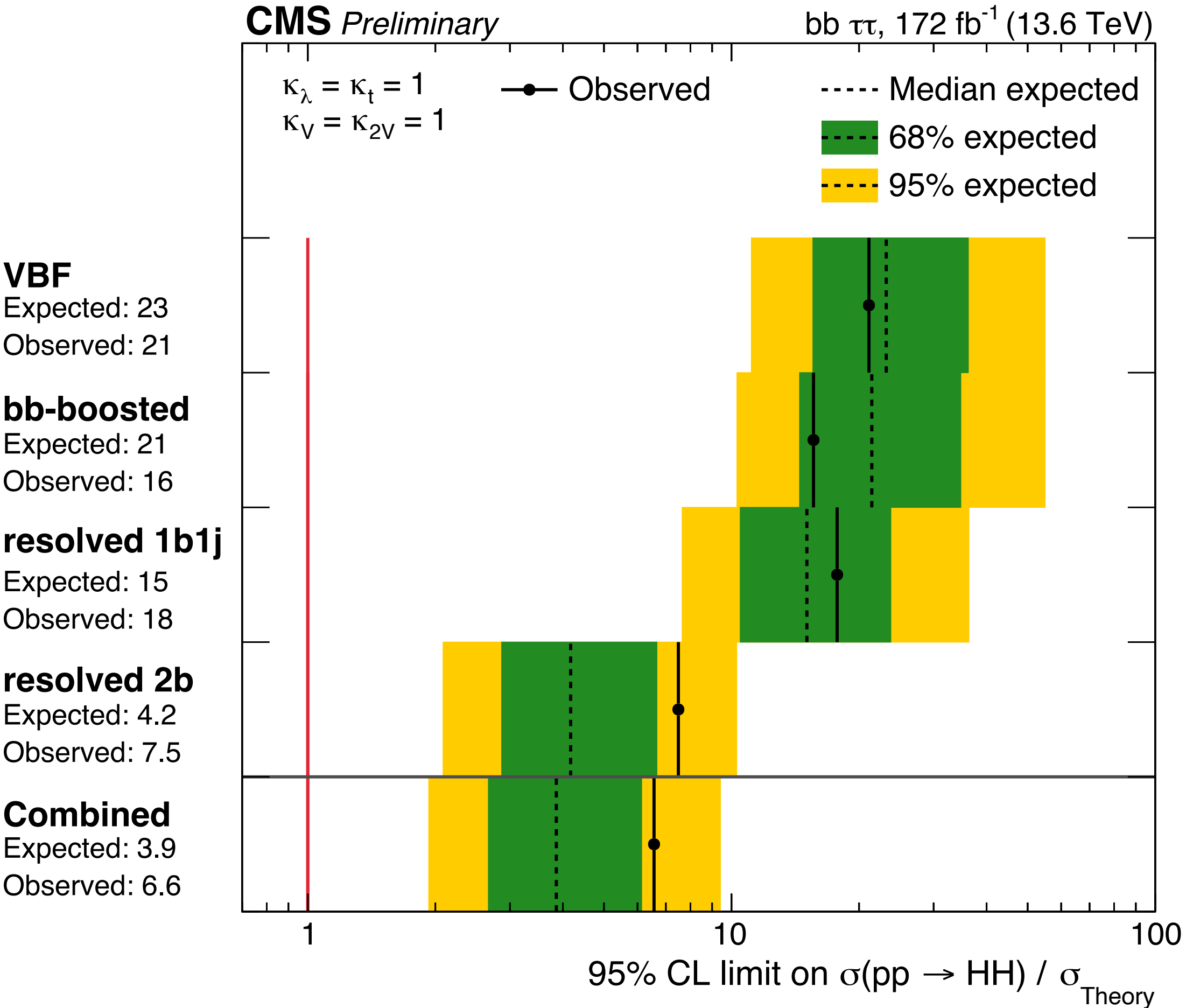
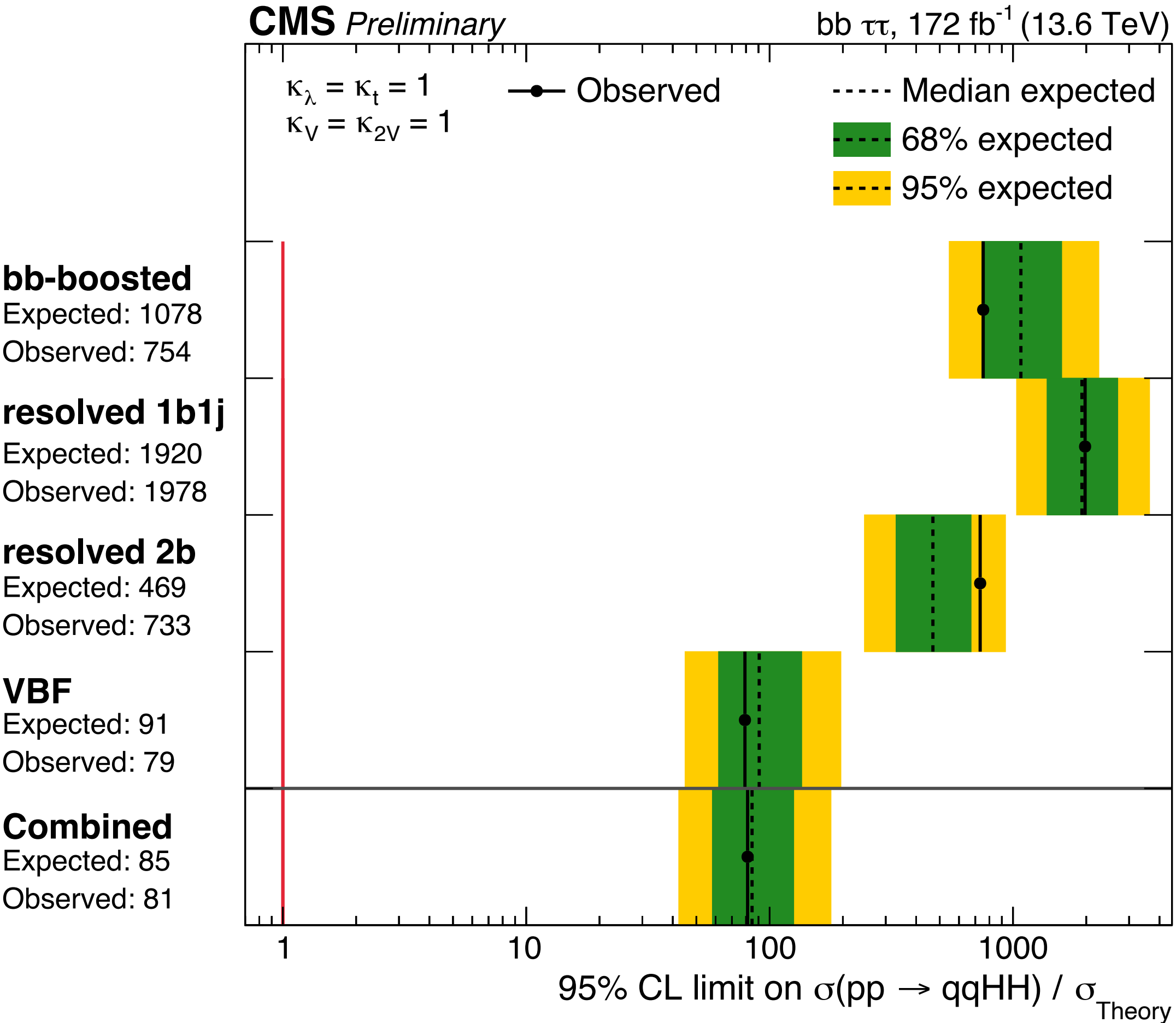
- H tt reconstruction and identification efficiency



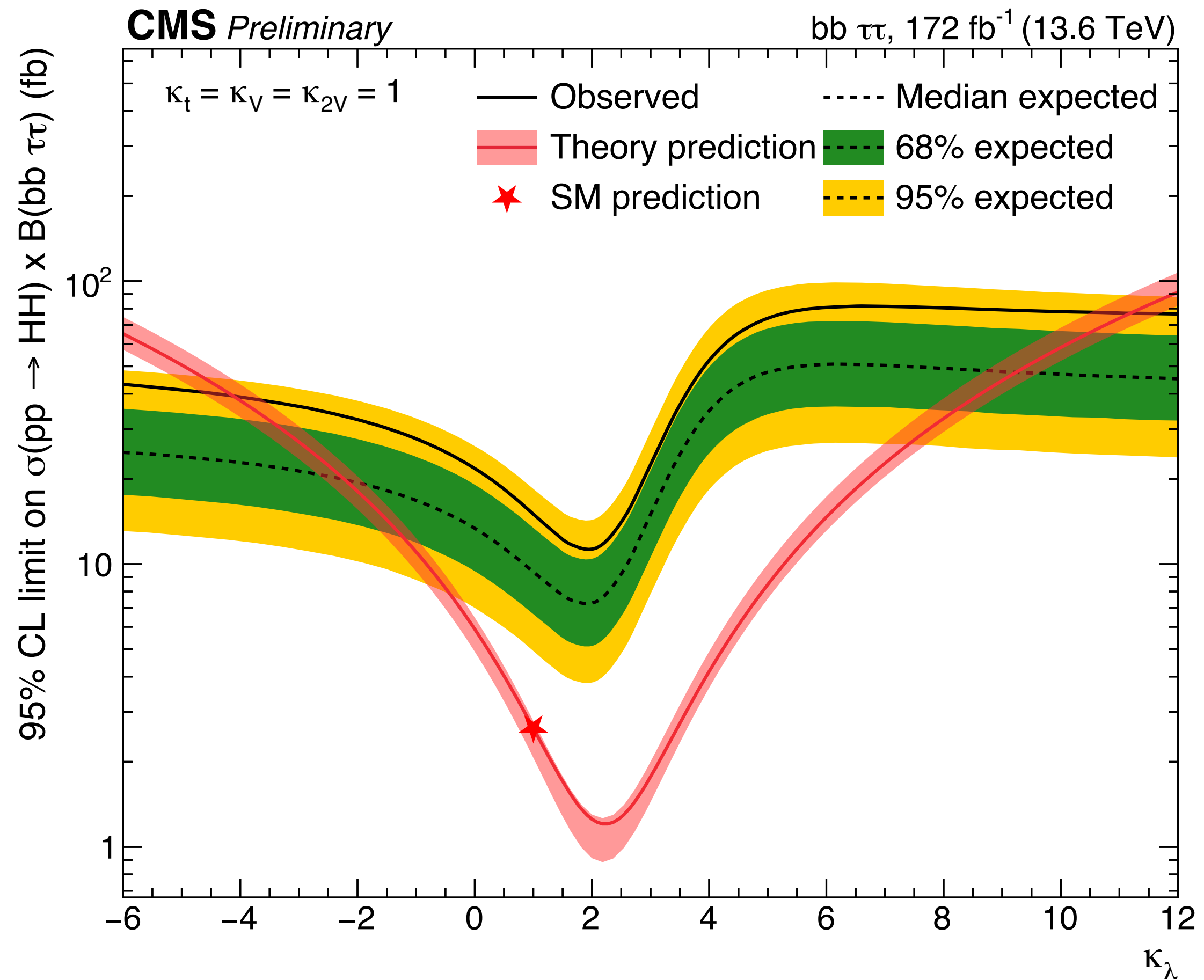
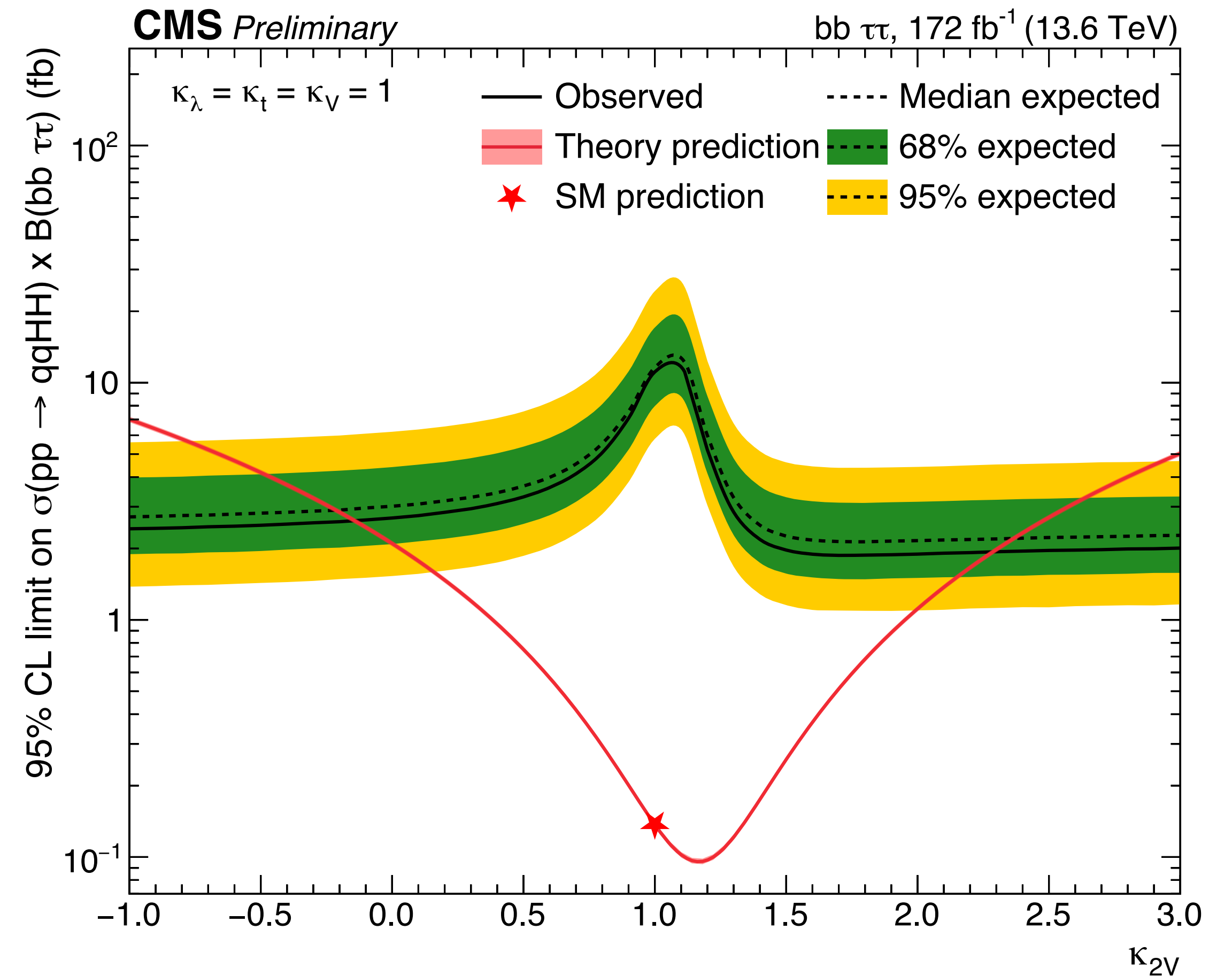
Event categorisation



SM results



1D scans

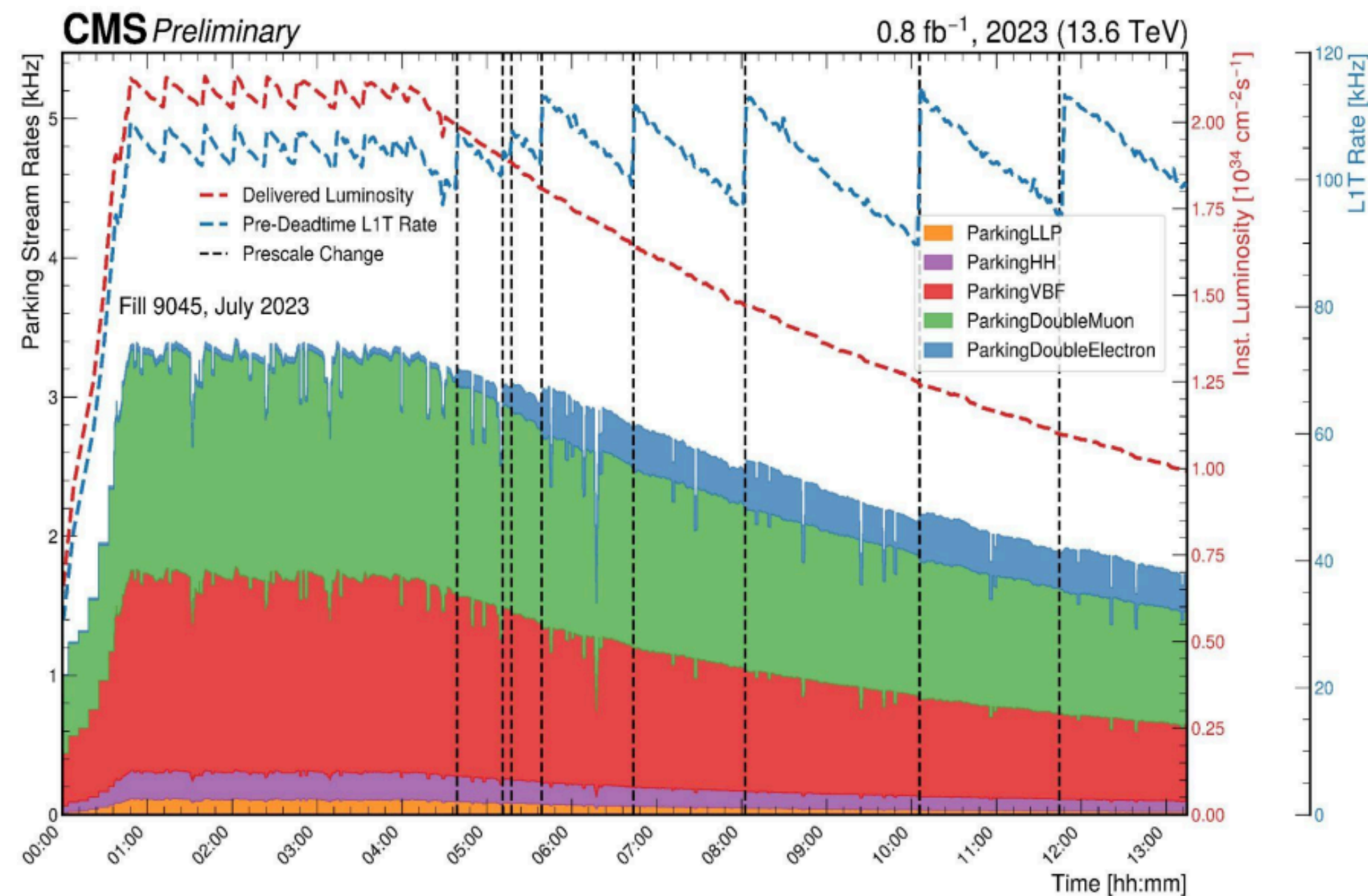
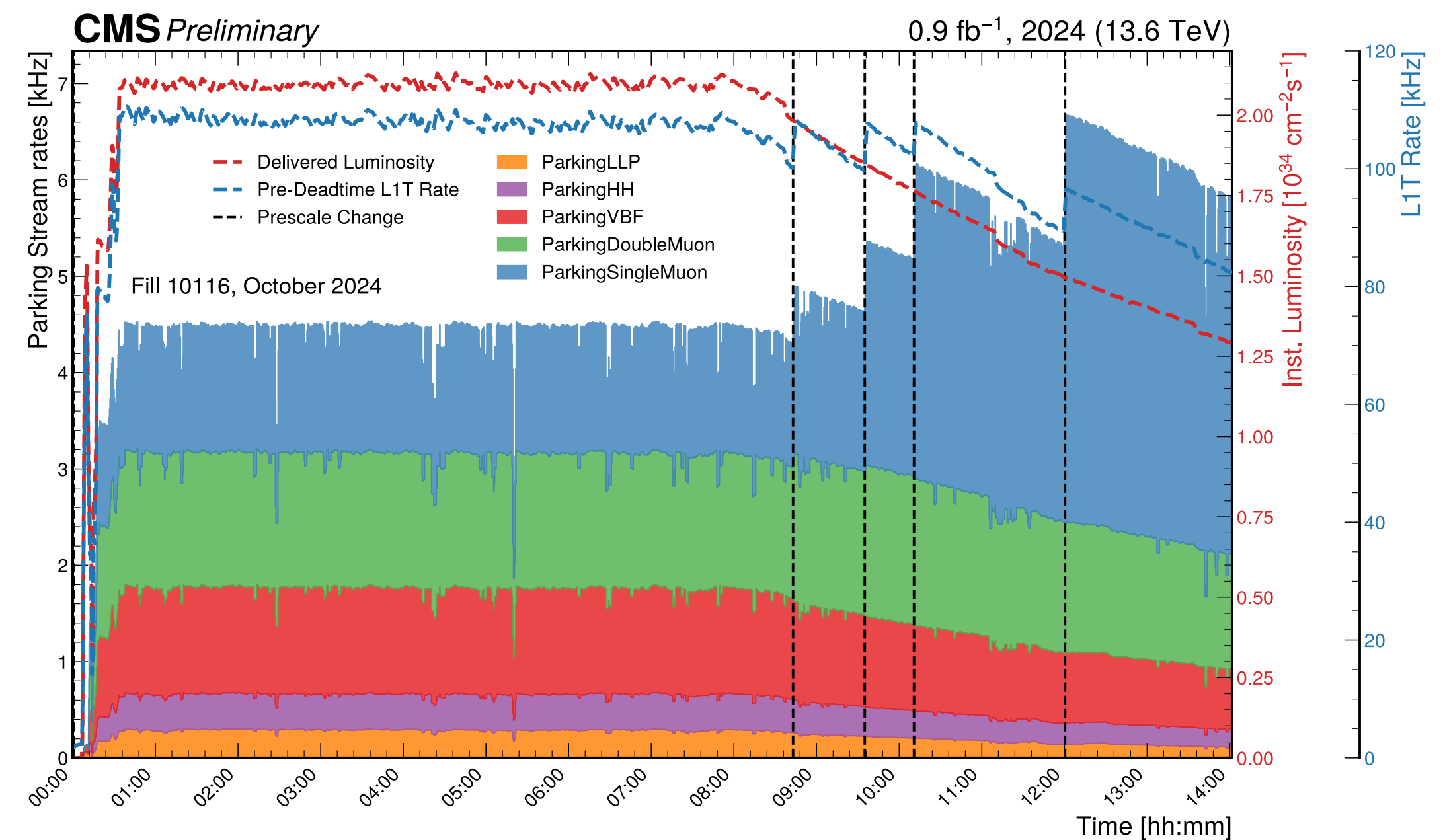


Selections applied to the $\tau\tau$ candidates

Muon	$p_T > 22/26/6$ GeV for the cross μ - τ /single μ /VBF+ μ trigger $ d_{xy} < 0.045$ cm, $ d_z < 0.2$ cm, $ \eta < 2.4$ Tight Muon ID, PF relative isolation < 0.15
Electron	$p_T > 25/31/13(18)$ GeV for the cross e- τ /single e/VBF+e trigger $ d_{xy} < 0.045$ cm, $ d_z < 0.2$ cm, $ \eta < 2.5$ Tight electron MVA Isolation+ID
Tau lepton	$\tau_h\tau_h$: double- τ : $p_T > 40(35)$ GeV, double- τ +jet: $p_T > 35(31)$ GeV, 2 jets + 1 τ + 1 b-jet : $p_T > 25(25)$ GeV $\tau_\mu\tau_h$: $p_T > 32$ GeV $\tau_e\tau_h$: $p_T > 35$ GeV $ d_z < 0.2$ cm, $ \eta < 2.5$ DEEPTAU ID working points: D_{jet}^τ Medium, D_e^τ VVLoose, D_μ^τ VLoose/Tight
Boosted- τ	$p_T > 20$ GeV , $ \eta < 2.5$ BOOSTED DEEPTAU vsJet score requirement
Lepton pair	opposite electric charge, resolved $\tau\tau$: $\Delta R > 0.5$, boosted- $\tau_h\tau_h$: $\Delta R < 0.8$
Additional	additional lepton veto

Evolution of Parking stream in CMS

- With respect to the 2022, several new triggers have been deployed online in 2023 and 2024:
 - In 2023, new parking streams were added in order to increase trigger acceptance for HH production, LLP signatures, and VBF
 - In 2024, new triggers optimised for low-pT single-muon signatures for B-physics measurements and new-physics searches were introduced



Advances in object reconstruction

- Improved **b-jet** and **tau** reconstruction with state-of-the-art algorithms

- $H \rightarrow bb$ candidate **b-tagging** (PNet / UParT):
 - > 95% b-jets purity in simulated HH events
 - Higher tagging performance in collimated $H \rightarrow bb$ events
- $m_{\tau\tau}$ **reconstruction**:
 - 50% improvement in $m_{\tau\tau}$ resolution
 - 30% improvement in background rejection

