Search for di-Higgs at CMS

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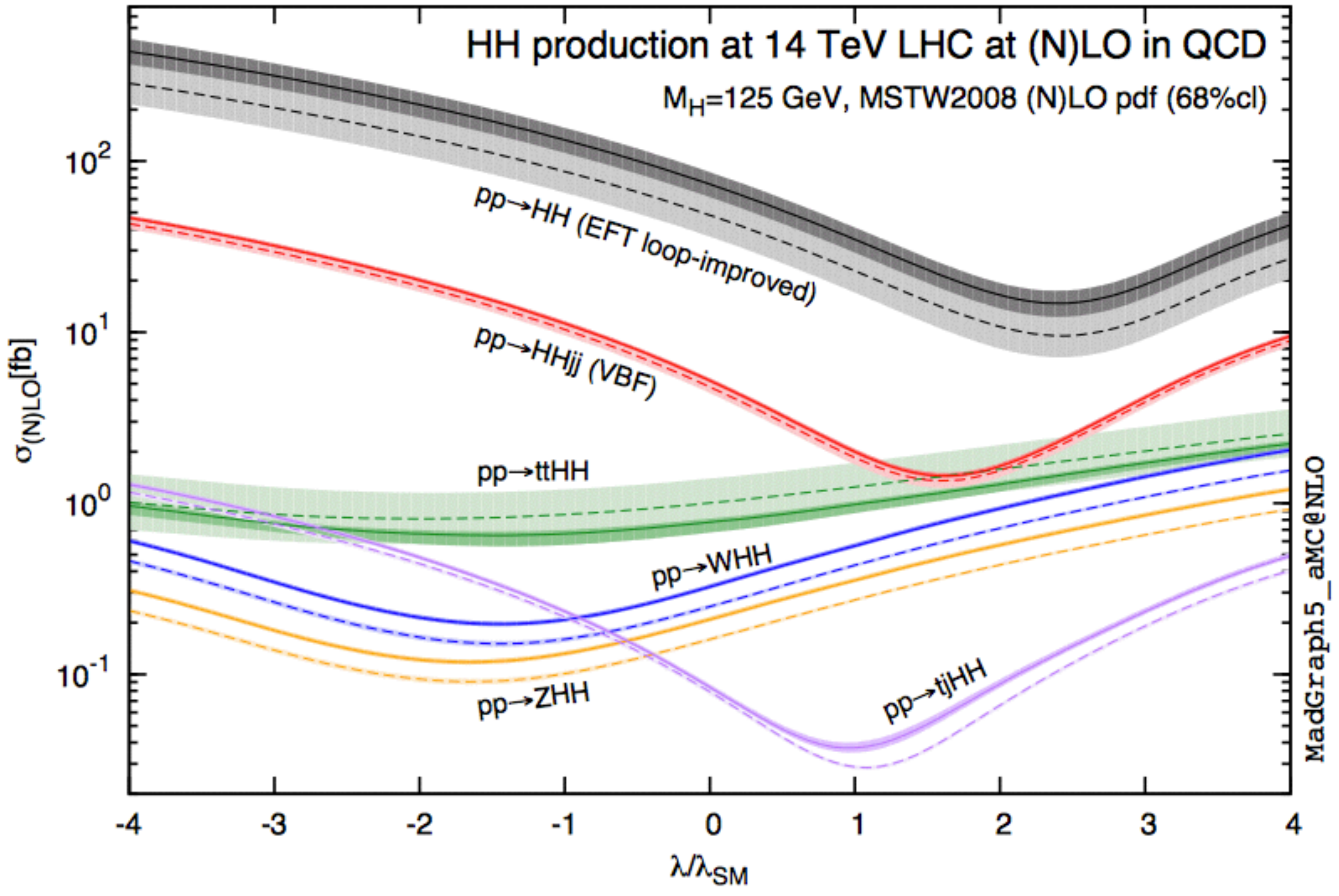
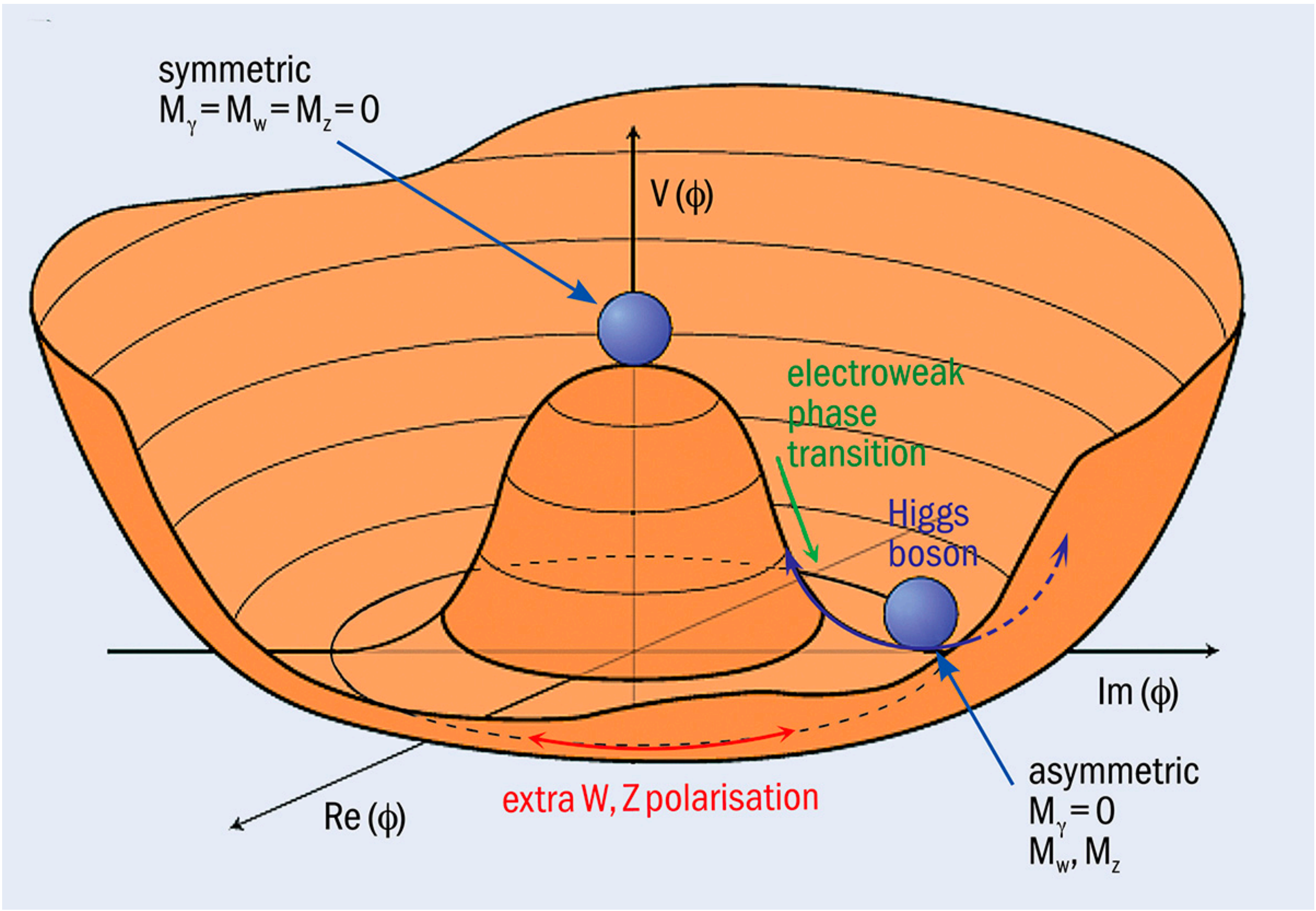
DiHiggs and Higgs self-coupling

- The shape of the Higgs potential determined by the self-coupling λ

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

- Trilinear self-coupling λ can be probed directly via HH production, extremely challenging to measure at LHC

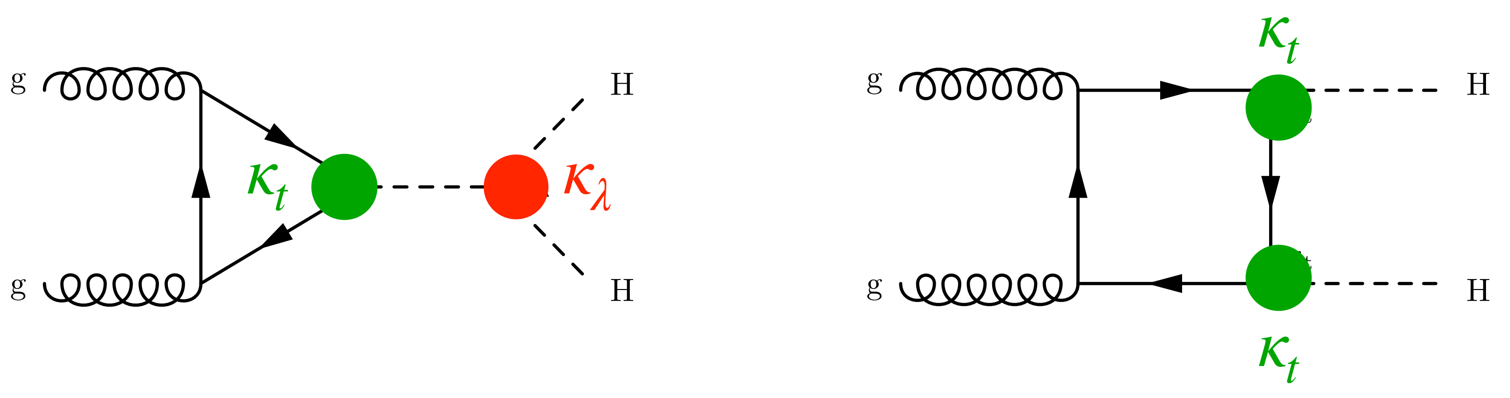


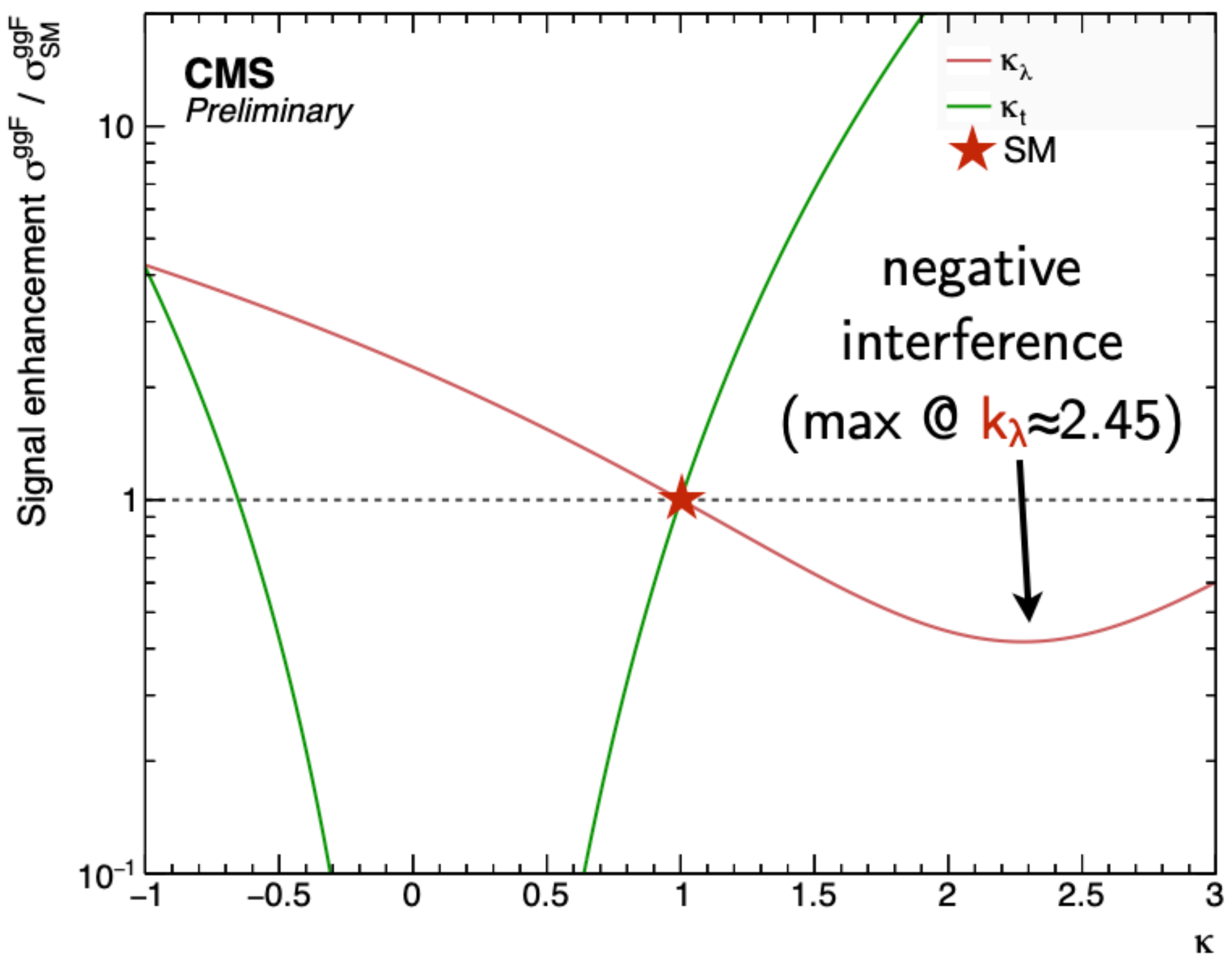


R.Frederix et al: Phys.Lett. B732 (2014) 142-149

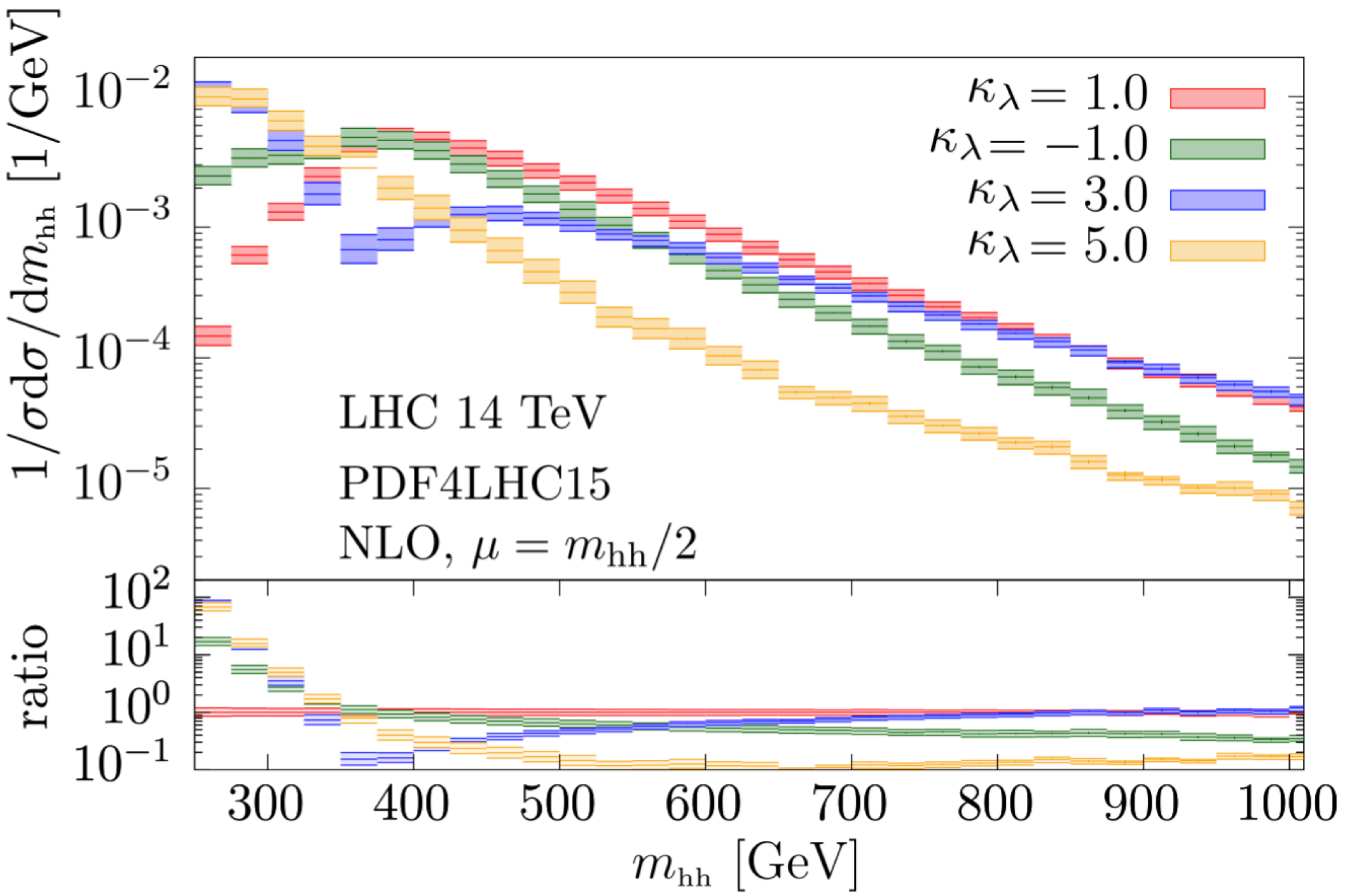
Gluon fusion HH production at the LHC

- Dominant gluon-gluon fusion (ggF) production mode (σ_{ggF} = 31.05 fb) gives best access to H self-coupling



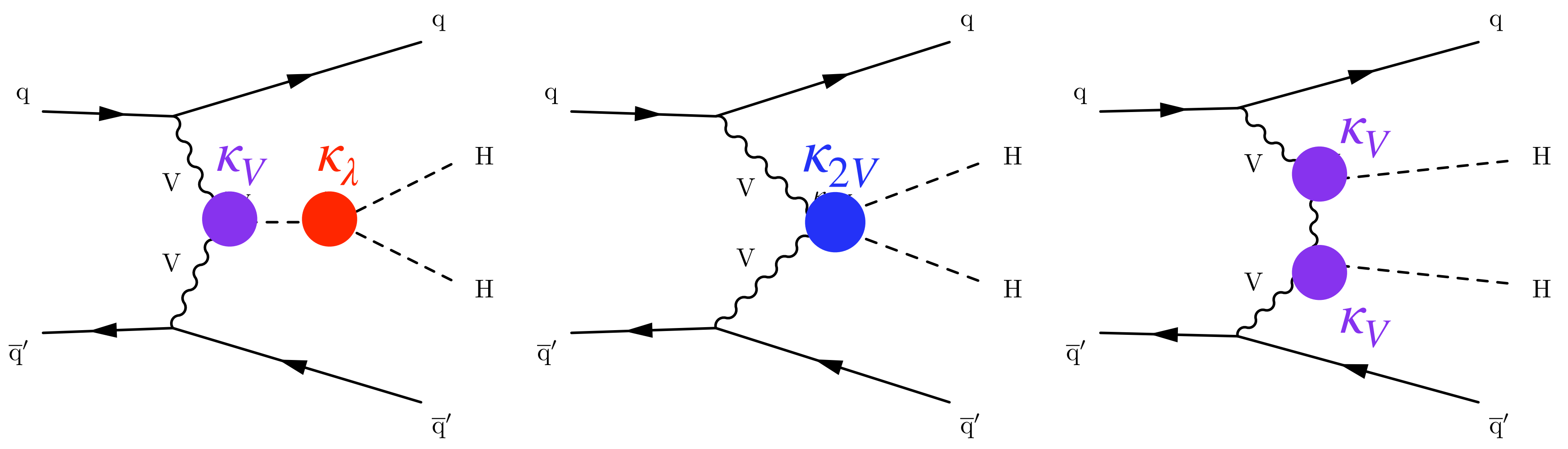


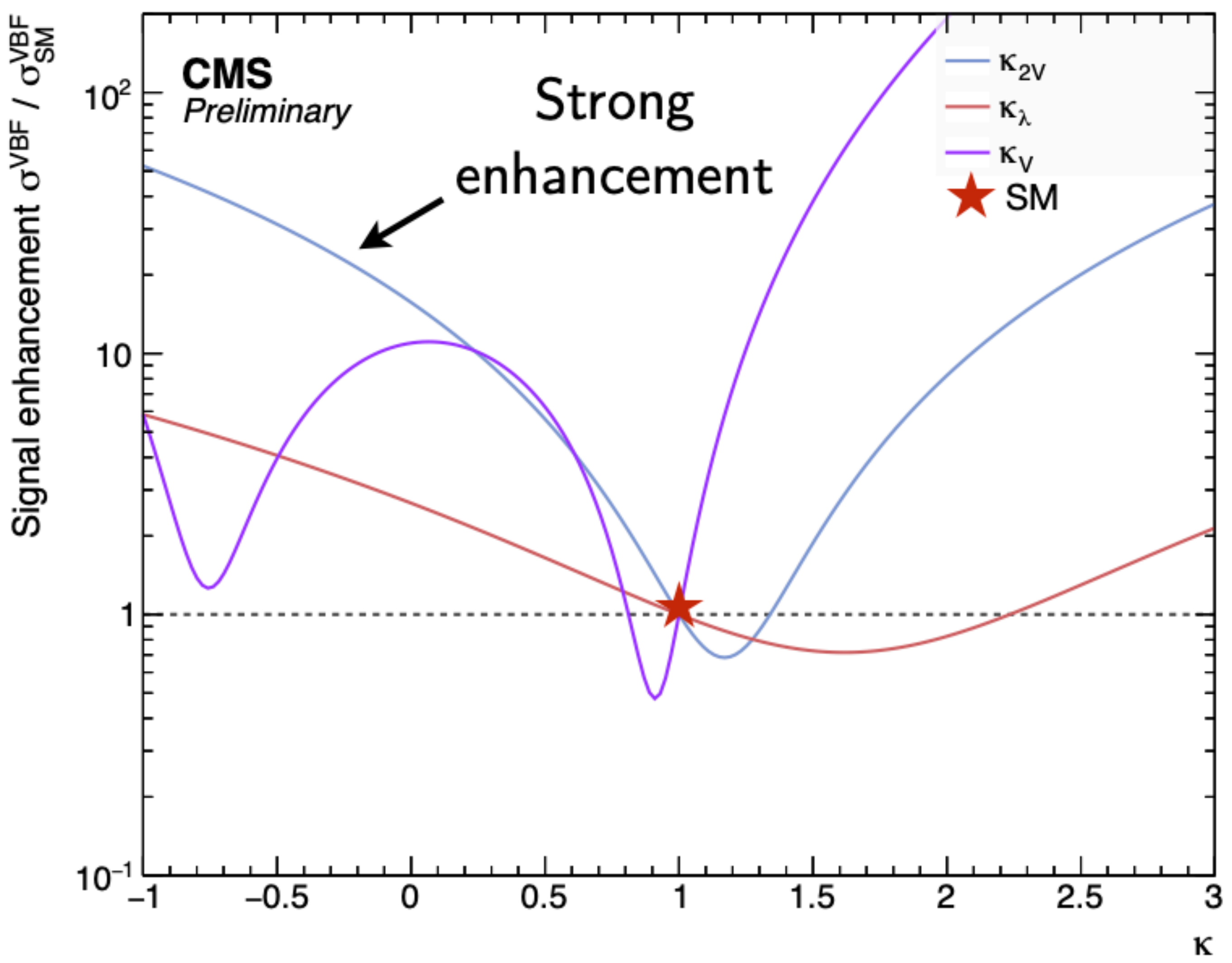
- Spectrum of m_{HH} depends on κ_λ



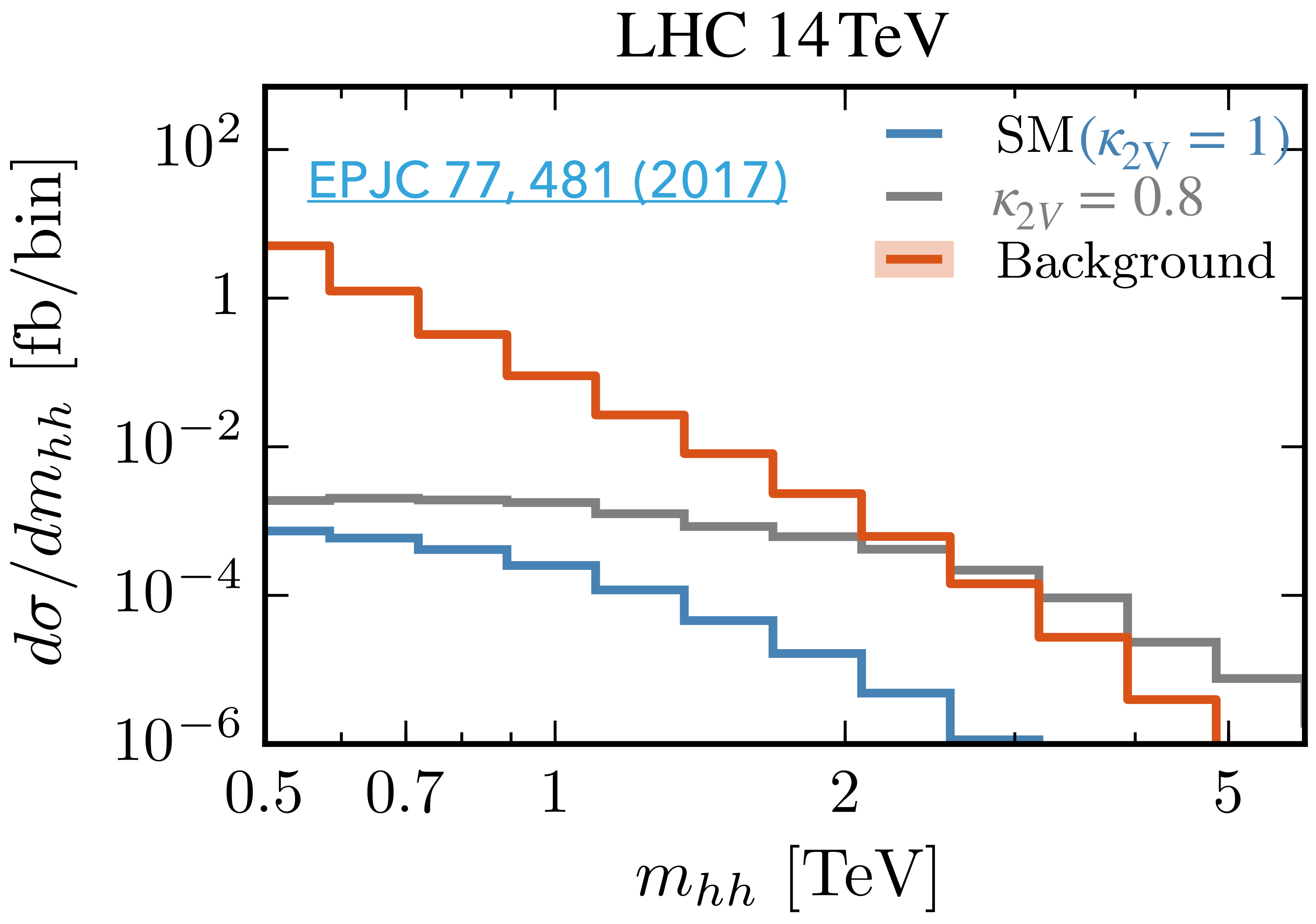
VBF HH Production at the LHC

- Vector boson fusion (VBF) (σVBF = 1.73 fb) sensitive to HHVV coupling

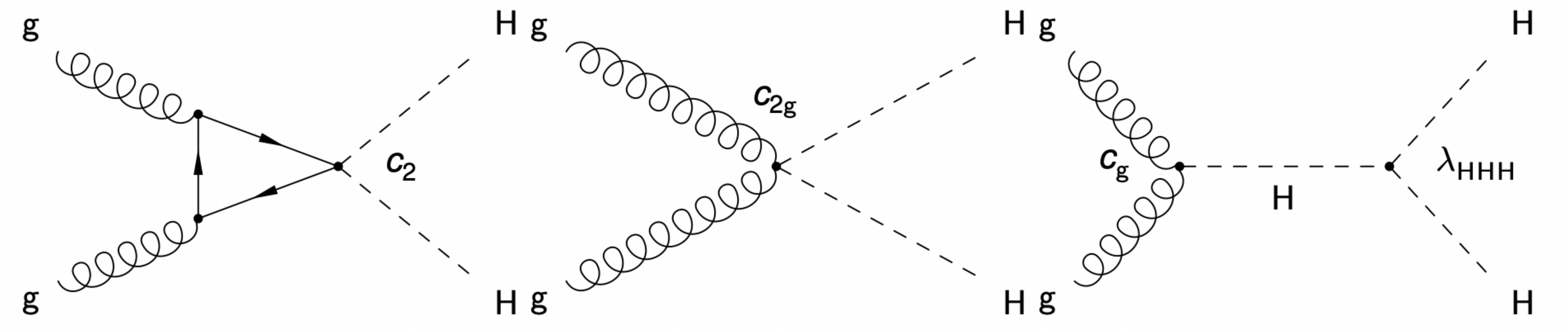




- smaller κ_{2V} leads to larger cross section, harder m_{HH} spectrum, and boosted VBF signatures



EFT studies with HH



- The HEFT Lagrangian as a function of the anomalous coupling modifiers

$$\Delta\mathcal{L}_{\mathrm{HEFT}} = -m_{\mathrm{t}}\left(\kappa_{\mathrm{t}}\frac{h}{v} + c_2\frac{h^2}{v^2}\right)\bar{t}t - \kappa_\lambda\frac{m_{\mathrm{H}}^2}{2v}h^3 + \frac{\alpha_{\mathrm{S}}}{8\pi}\left(c_{\mathrm{g}}\frac{h}{v} + c_{2\mathrm{g}}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

- Considering operators up to dimension 6, the tree-level interactions of the Higgs boson are modeled by five parameters κ_λ, κ_t, c_2, c_g, c_{2g}
  - c_g, c_{2g}, c_2: interactions between two gluons and one H boson, two gluons and two H bosons, and two top quarks and two H bosons

Nonresonant HH searches in Run 2 in CMS

Analysis	μ	κ_λ	κ_{2V}	HEFT
$b\bar{b}b\bar{b}$, resolved jets	3.9 (7.8)	$[-2.3, 9.4]$	$[-0.1, 2.2]$	✓
$b\bar{b}b\bar{b}$, merged jets	9.9 (5.1)	$[-9.9, 16.9]$	$[0.62, 1.41]$	✓
VHH, HH $\rightarrow b\bar{b}b\bar{b}$	$\mu_{\mathrm{VHH}} < 294$ (124)	$[-37.7, 37.2]$	$[-12.2, 8.9]$	—
$b\bar{b}\tau\tau$	3.3 (5.2)	$[-1.7, 8.7]$	$[-0.4, 2.6]$	✓
$b\bar{b}\gamma\gamma$	7.7 (5.2)	$[-3.3, 8.5]$	$[-1.3, 3.5]$	✓
$b\bar{b}$WW, WW $\rightarrow \ell\nu qq/2\ell 2\nu$	14 (18)	$[-7.2, 13.8]$	$[-8.7, 15.2]$	✓
$b\bar{b}$WW, WW $\rightarrow$ 4q	141 (69)	—	$[-0.04, 2.05]$	—
HH multilepton	21.3 (19.4)	$[-6.9, 11.1]$	—	✓
$\tau\tau\gamma\gamma$	33 (26)	$[-13, 18]$	—	—
$b\bar{b}$ZZ	32.4 (39.6)	$[-8.8, 13.4]$	—	—
WW$\gamma\gamma$	97 (53)	$[-25.8, 14.4]$	—	✓

- multilepton (e, μ, τ_h), HH → WWWW + WWττ + ττττ

Table from arXiv:2510.07527 submitted to ROPP

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

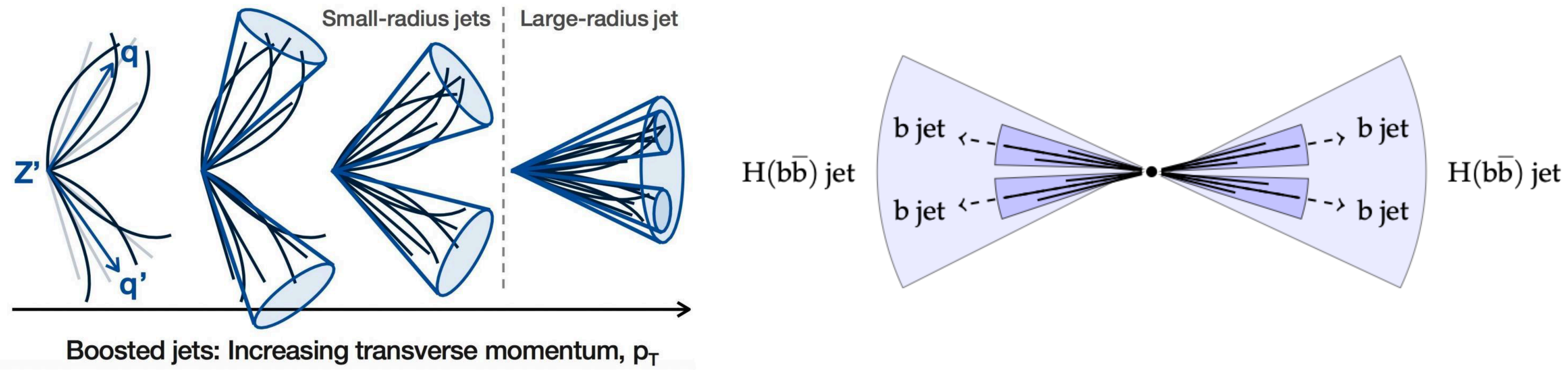
References:

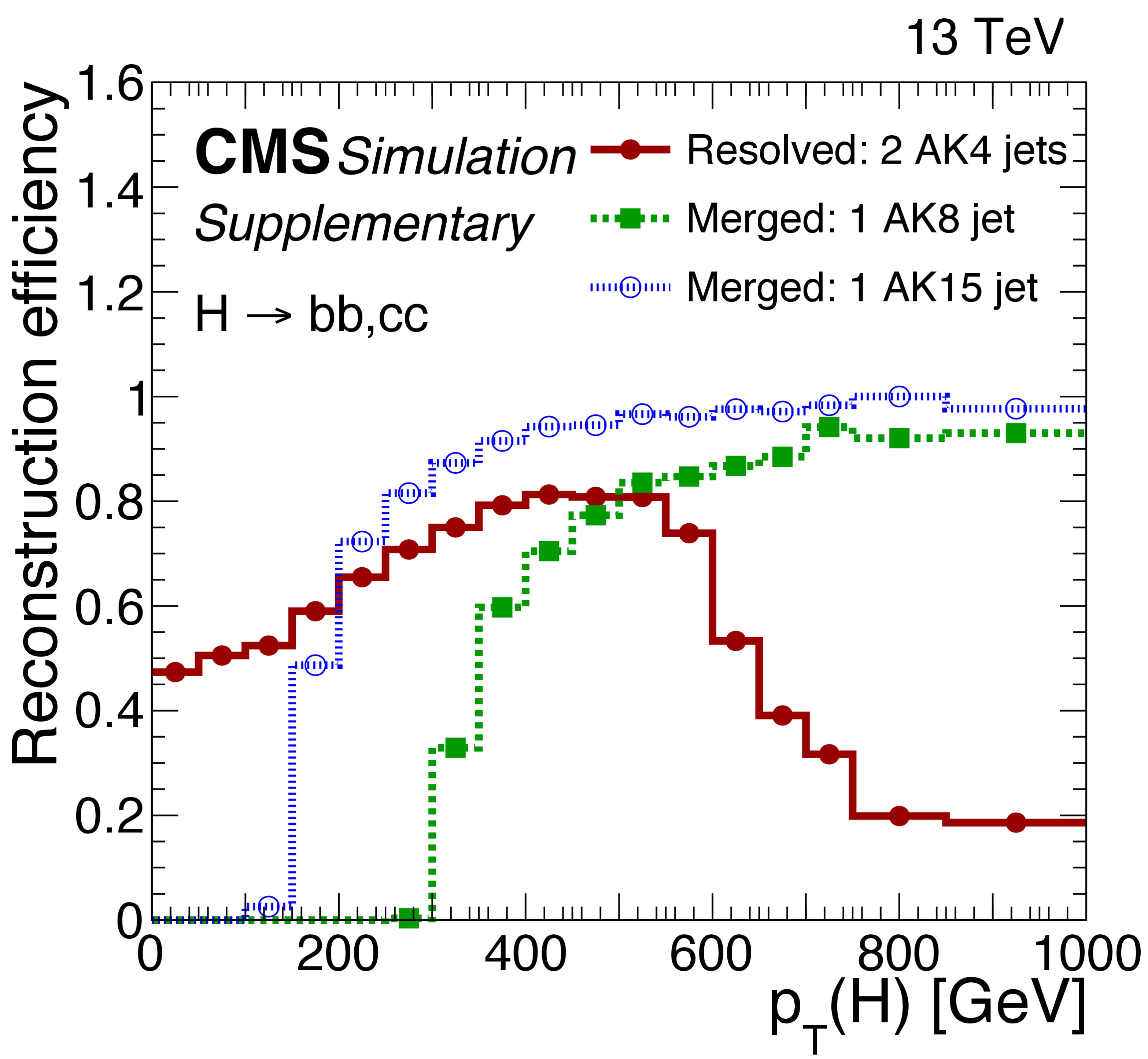
bbbb resolved (Phys. Rev. Lett. 129, 081802 (2022))
bbbb boosted (Phys. Rev. Lett. 131, 041803 (2023))
bbττ (Phys. Lett. B 842, 137531 (2023))
bbγγ (JHEP03(2021)257)
bbZZ(4l) (JHEP06(2023)130)
Multilepton: WWWW WWττ ττττ (JHEP07(2023)095)
bbWW (JHEP07(2024)293)
WWγγ (CMS-PAS-HIG-21-014 (2022))
γγττ (CMS-PAS-HIG-22-012 (2024))
HH combination (arXiv:2510.07527 submitted to ROPP)
H+HH combination (Phys. Lett. B 861, 139210 (2024))

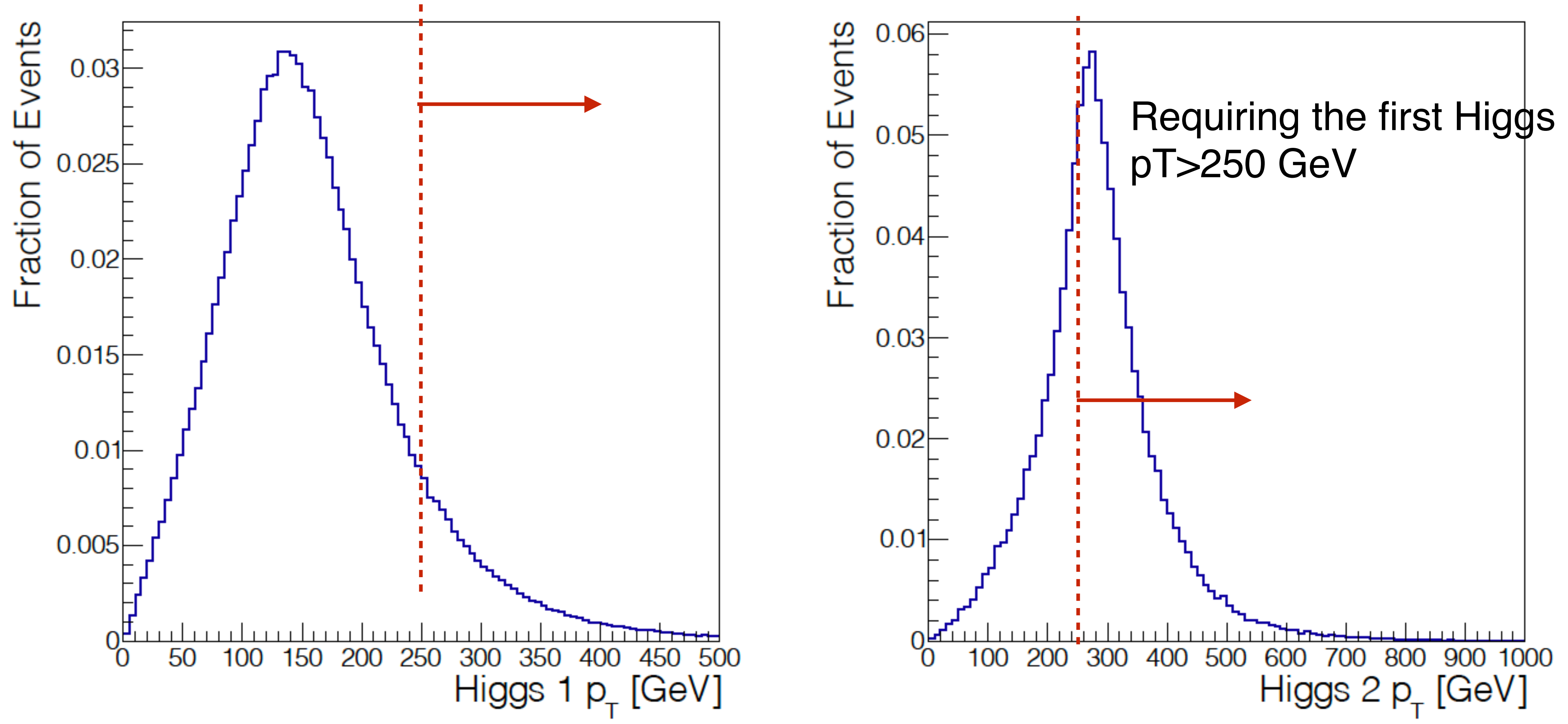
Search for HH using boosted Higgs bosons in HH → bbbb channel

Phys. Rev. Lett. 131, 041803

- **HH→4b decay** channel has **largest branching ratio (34%)**
- **1.5k** HH→4b events produced in Run 2
- **15%** HH→4b events with two boosted Higgs (Anti-k_T algorithm with R=0.8 (AK8) jets, pT > 250 GeV)
  - Among the first analyses to use ParticleNet GNN algorithm to discriminate between H → bb and QCD-induced jets







~20% acceptance for the first Higgs to have high pT > 250 GeV

Requiring first Higgs pT>250 GeV, large acceptance (75%) for having a second boosted Higgs

ParticleNet Jet tagger for AK8 jets

ParticleNet: A multi-class jet classifier for top,

Higgs, W or Z tagging for large radius jets

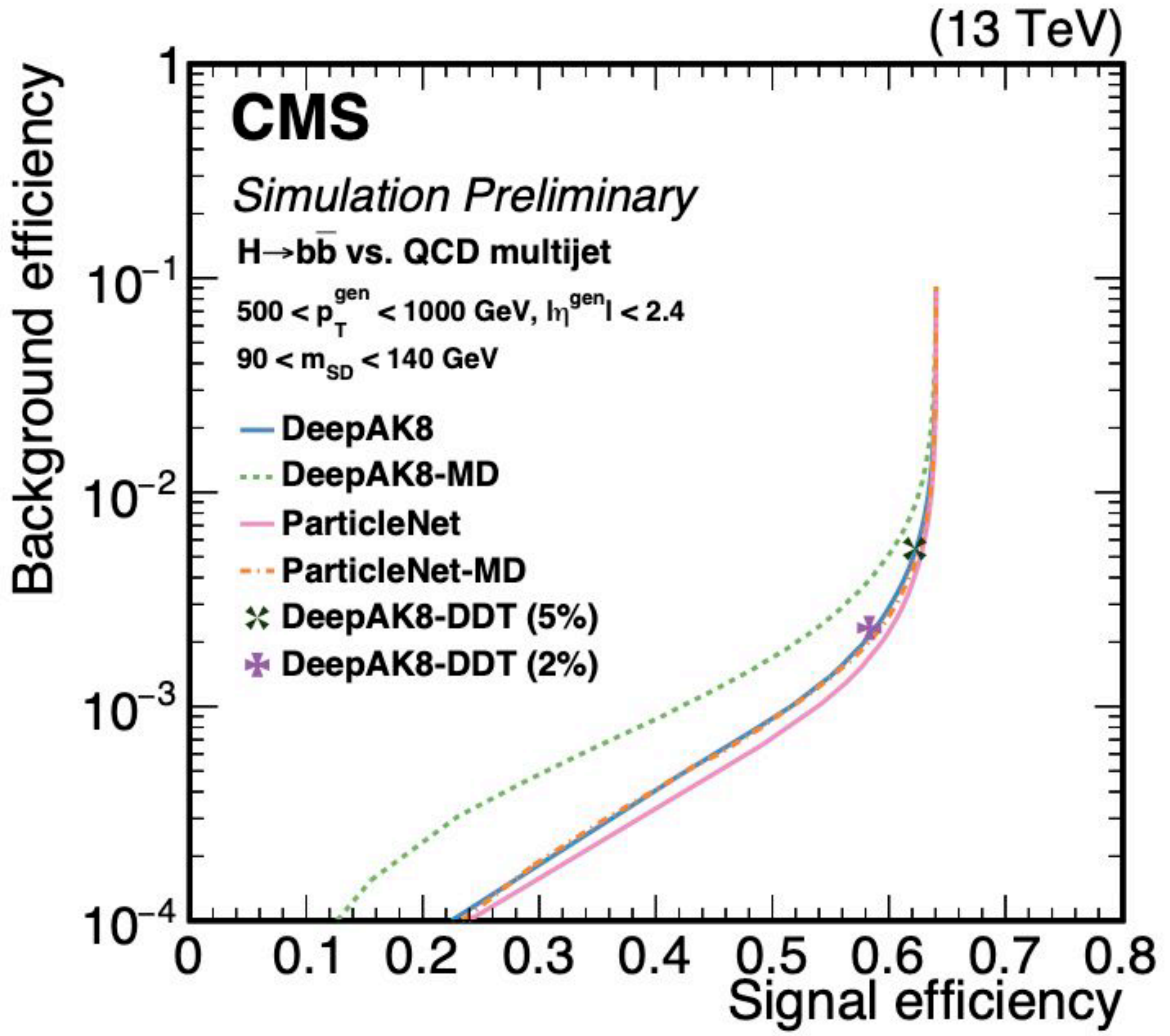
● low-level jet information (PF objects, secondary

vertices from b-quark decays etc.) as inputs

● Dynamic Graph Convolutional Neural Networks

(DGCNN) as ML architecture, details in Phys.

Rev. D 101, 056019

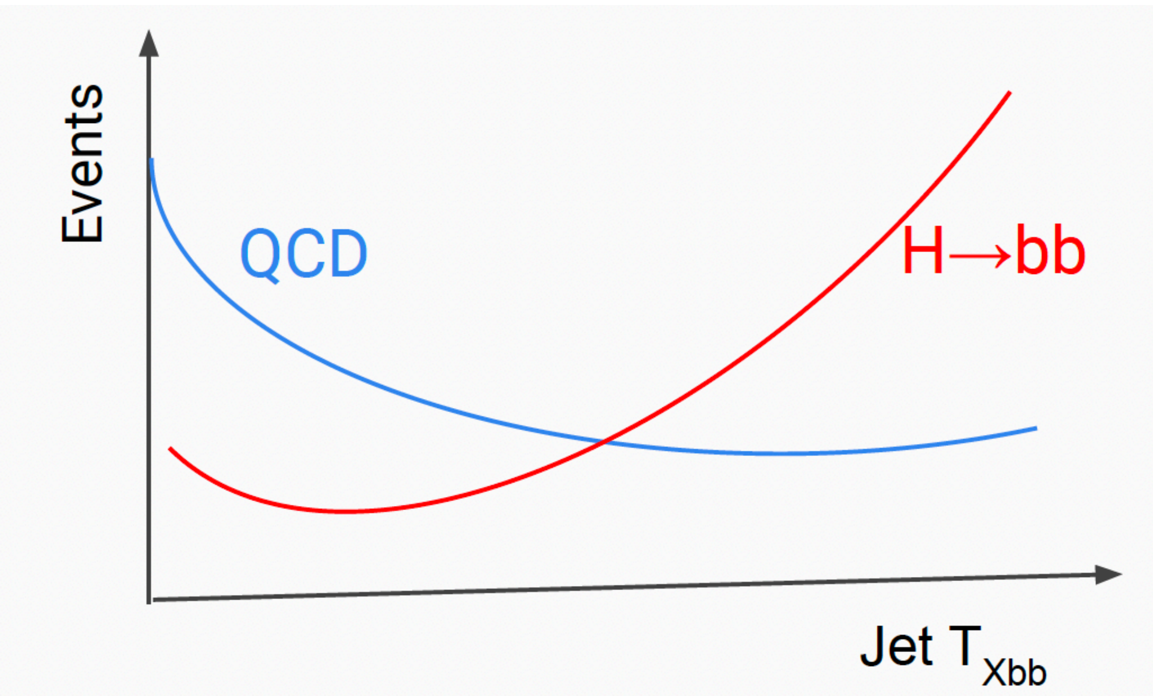


ParticleNet output scores: X→bb, X→cc, X→light quarks,QCD jets

- In this di-Higgs search: discriminate X→bb vs QCD jets:

$$T_{Xbb} = \frac{P_{Xbb}}{P_{Xbb} + P_{QCD}}$$

- The discriminant (called T_{xbb} or D_{bb}) is calibrated using data and simulated samples dominated by QCD multijet events



Mass decorrelated ParticleNet-MD:

Background efficiency of ~0.1% for signal efficiency of 50%

● Compare to DeepAK8-MD, background

rejection improved by a factor of ~2 per jet

- PRD 101, 056019 (Huilin Qu & Loukas Gouskos)
- CMS Collaboration, Identification of highly Lorentz- boosted heavy particles using graph neural networks and new mass decorrelation techniques, CMS Detector Performance Note Report CMS-DP-2020-002 (Congqiao Li and Huilin Qu are key authors)
- Calibration of the mass-decorrelated ParticleNet tagger for boosted bb and cc jets using LHC Run 2 data, CMS Detector Performance Note Report CMS-DP-2022-005 (Congqiao Li and Huilin Qu are key authors)

Search for HH using boosted Higgs bosons in HH → bbbb channel

Phys. Rev. Lett. 131, 041803

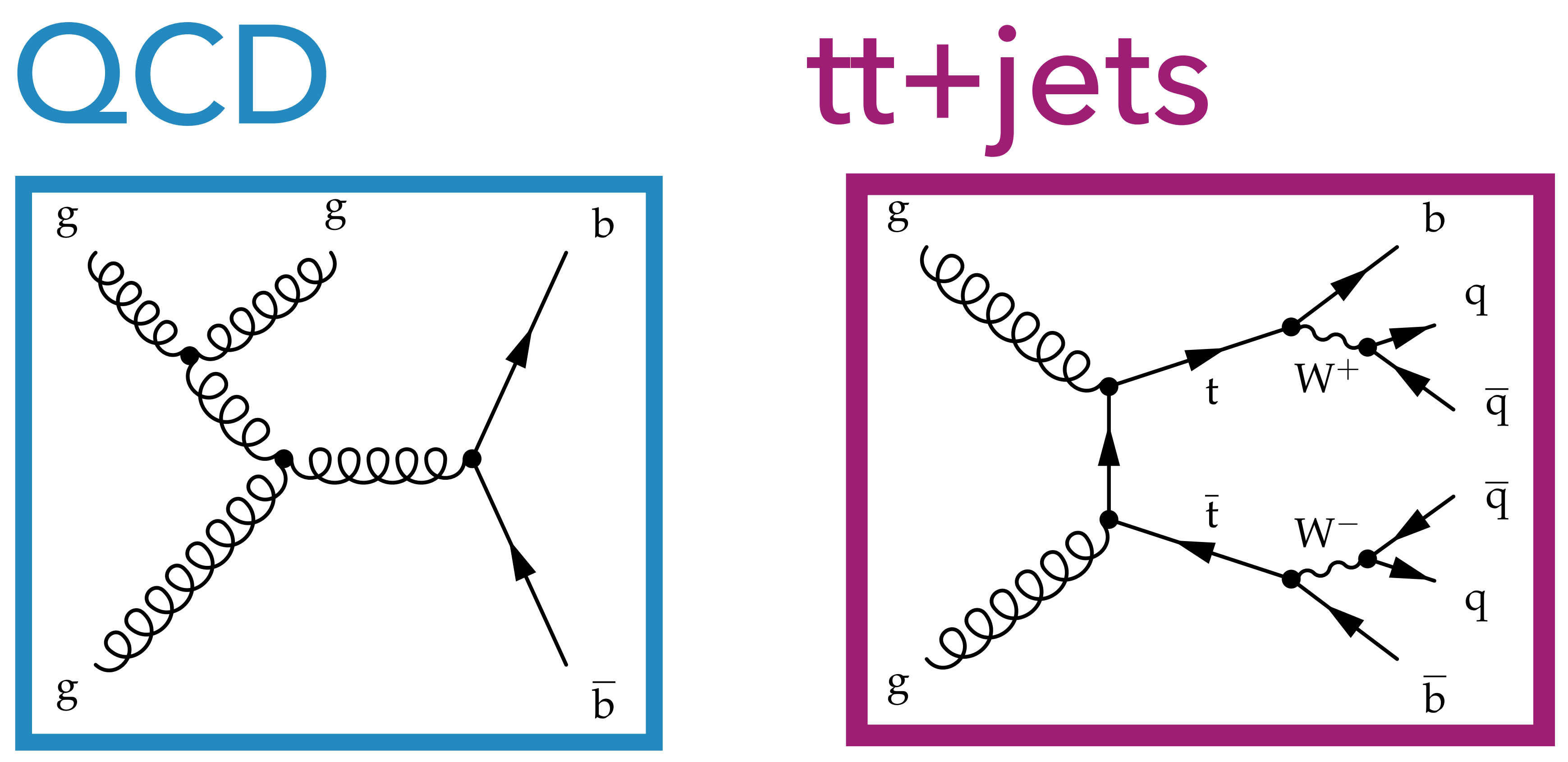
- Trigger:
  - A combination of several trigger algorithms, all requiring the total hadronic transverse energy (H_T) or jet pT to be above a given threshold. A minimum triggering threshold on the jet mass is also imposed
  - Trigger efficiency: 10% to 95% for jets with pT from 300 to 450 GeV, fully efficient for jets with pT > 500 GeV

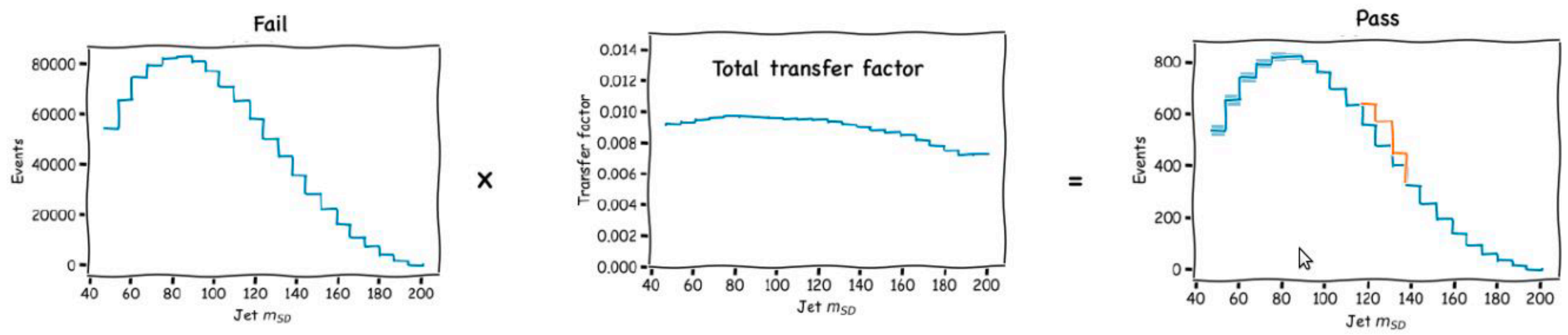
- Two complementary analyses targeting ggF and VBF HH events:
  - based on the characteristic VBF signature of two additional small-radius jets (anti-k_T algorithm with R=0.4) in opposite forward regions: m(jj) > 500 GeV, $\Delta\eta$ (jj) > 4.0
  - ggF analysis: sensitive to SM HH production cross section and Higgs self-coupling
  - VBF analysis: sensitive for HHVV coupling

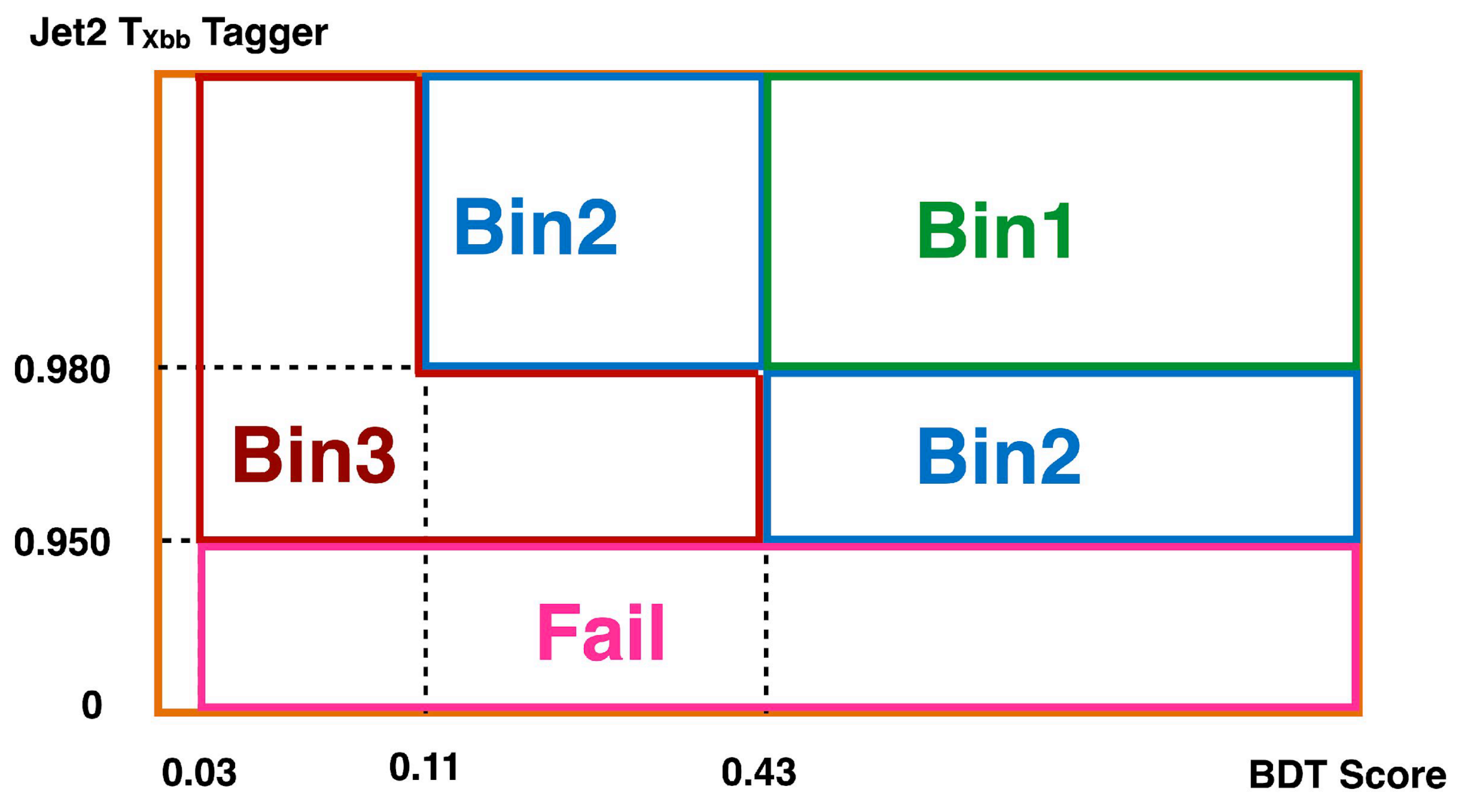
Search for HH using boosted Higgs bosons in HH → bbbb channel

[Phys. Rev. Lett. 131, 041803]

- Two highly Lorentz-boosted high-p_T Higgs candidate jets：
  - Ordered by ParticleNet H→bb tagger T_{xbb}
  - ParticleNet regressed jet mass m_{reg} > 50 GeV for subleading jet
  - Soft-drop mass m_{reg} > 50 GeV for leading jet
- BDT for major background tt and QCD rejection
- Main backgrounds estimation:
  - tt+jets: simulation with corrections derived in data control regions
  - QCD: parametric fit to data in control region



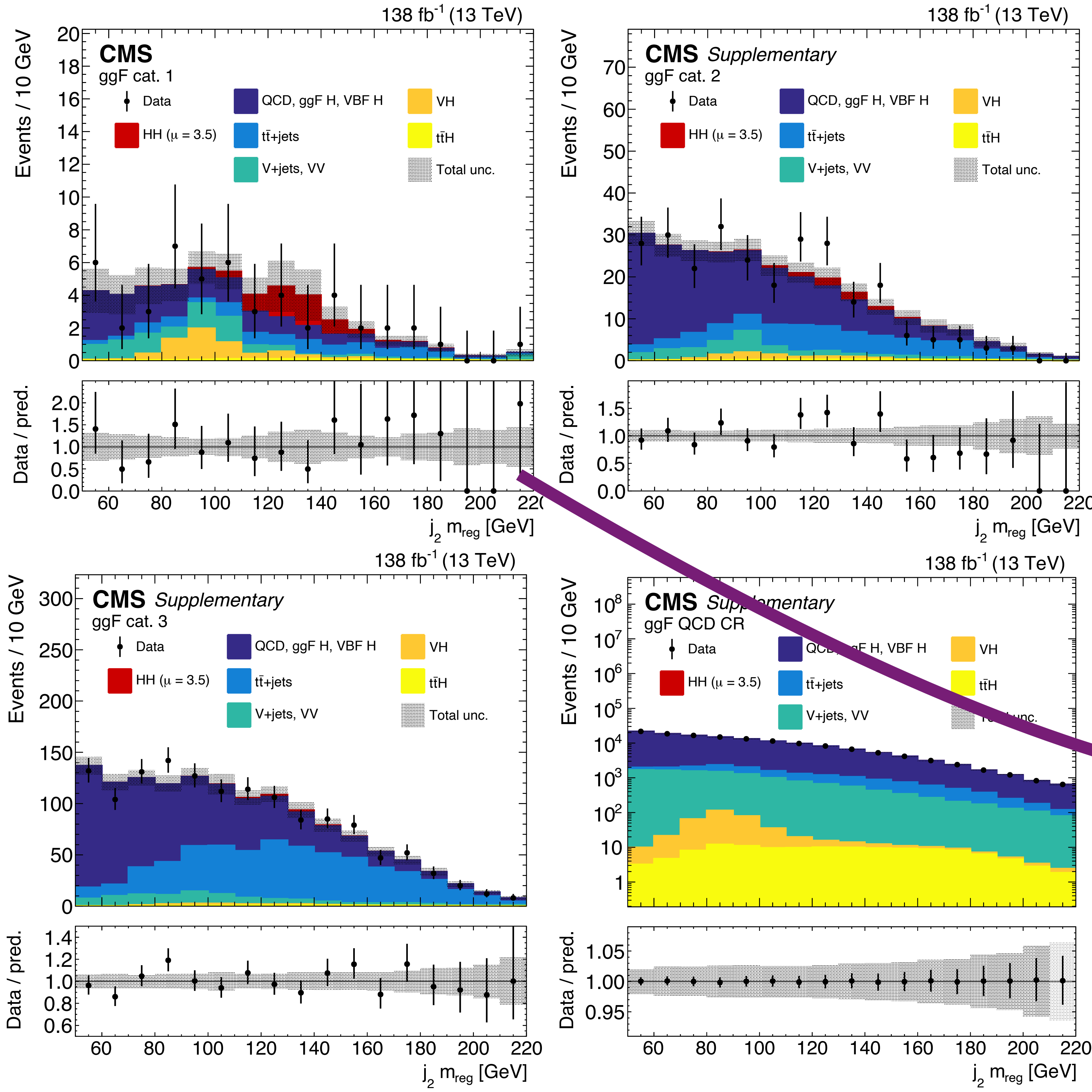


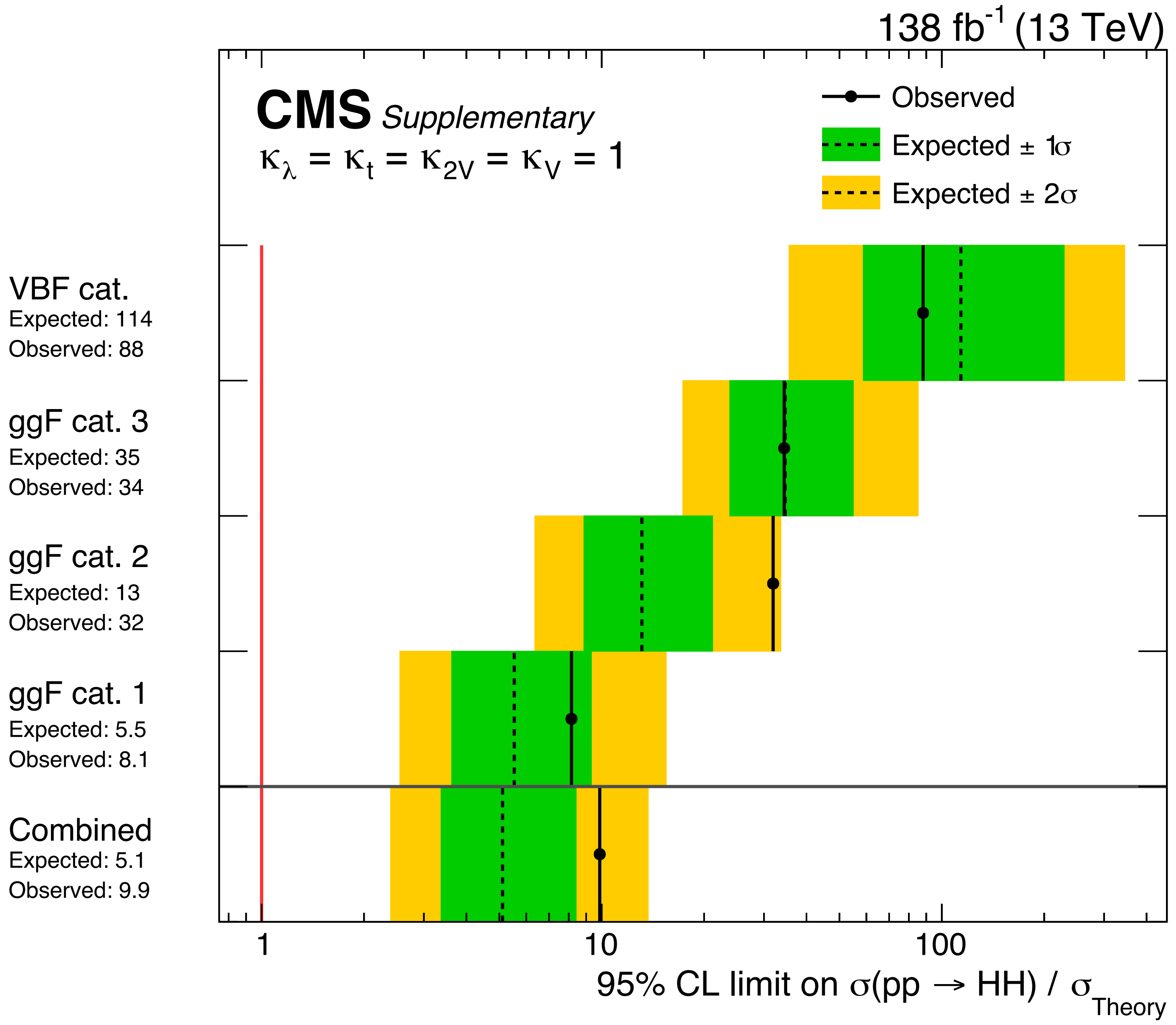


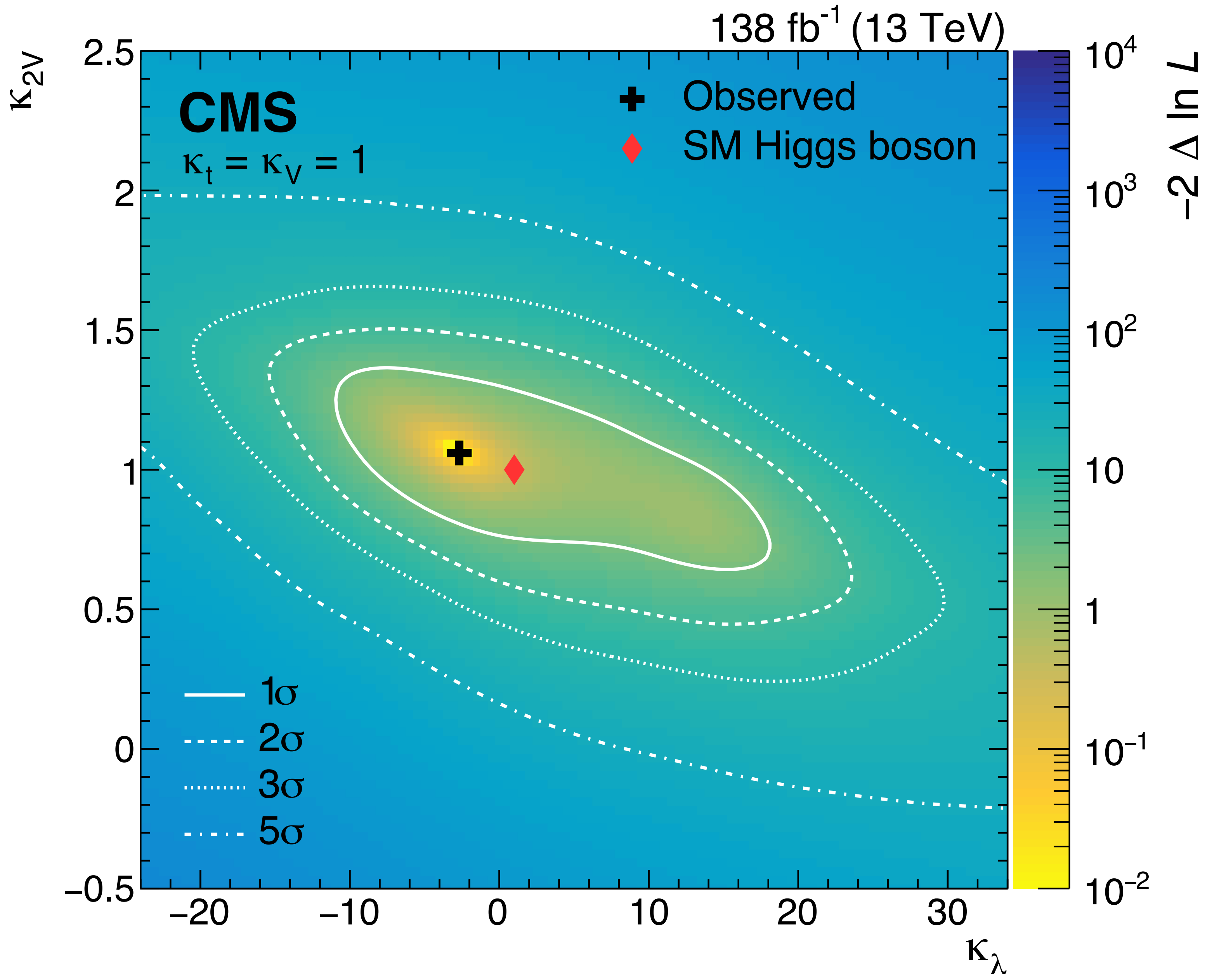
Search for HH using boosted Higgs bosons in HH → bbbb channel

Phys. Rev. Lett. 131, 041803

- Observed (expected) upper limit at 95% CL on HH cross section: 9.9 (5.1) × SM, by ggF analysis
- κ_{2V}=0 excluded at 6.3σ, assuming other Higgs couplings to be SM values, by VBF analysis

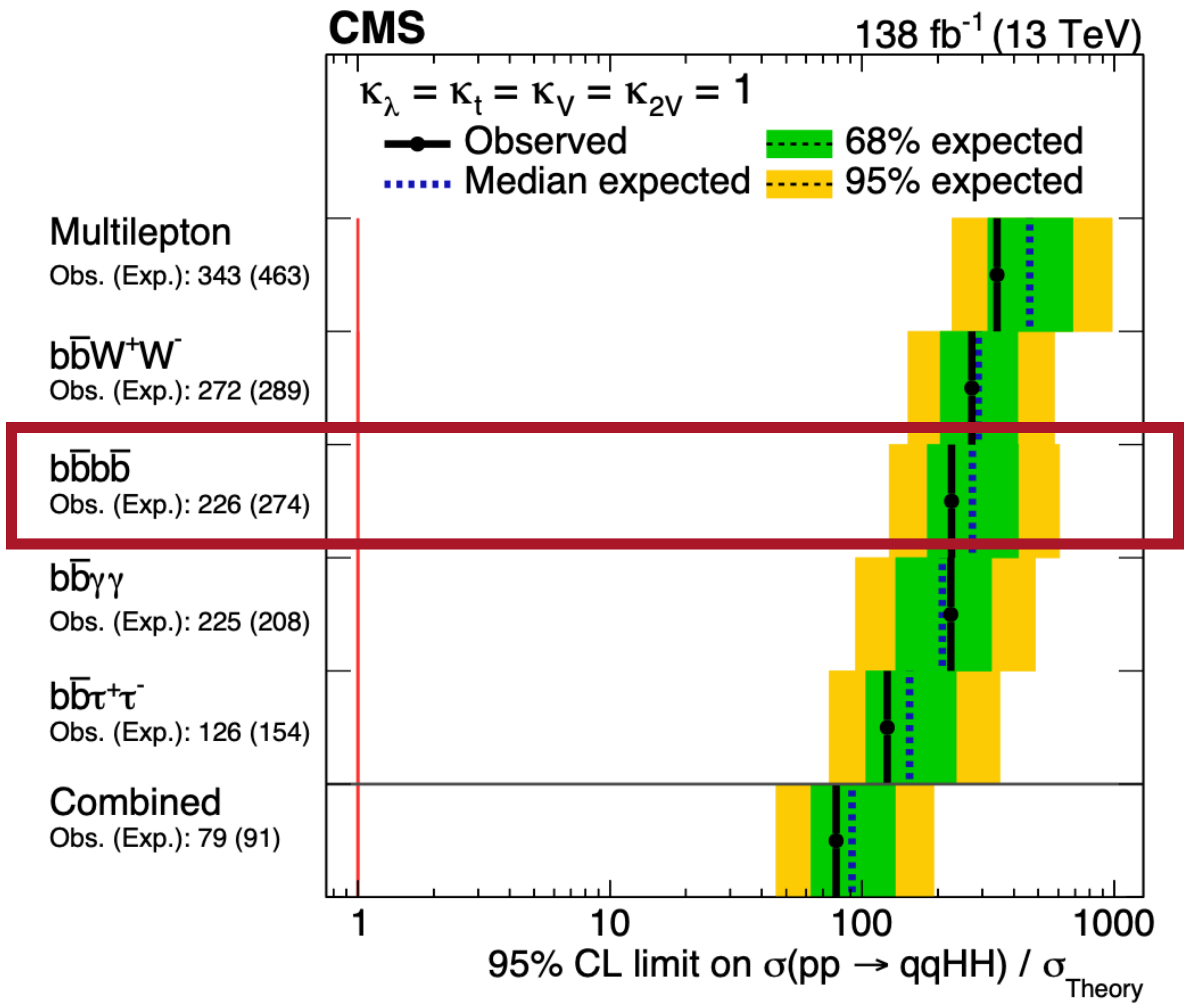




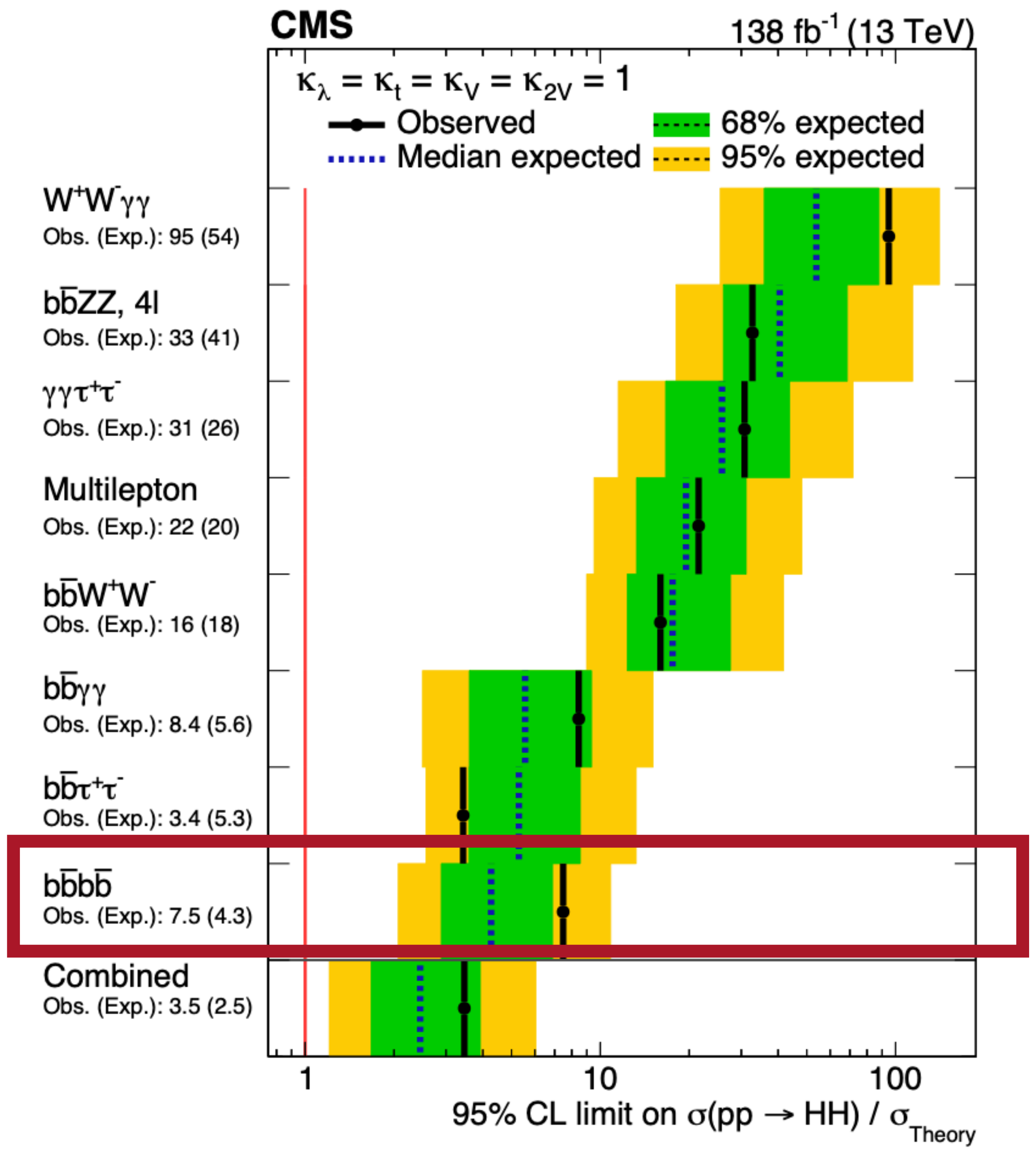


HH combination Run 2

arXiv:2510.07527 submitted to ROPP



combined VHH4b, boosted and resolved 4b analyses

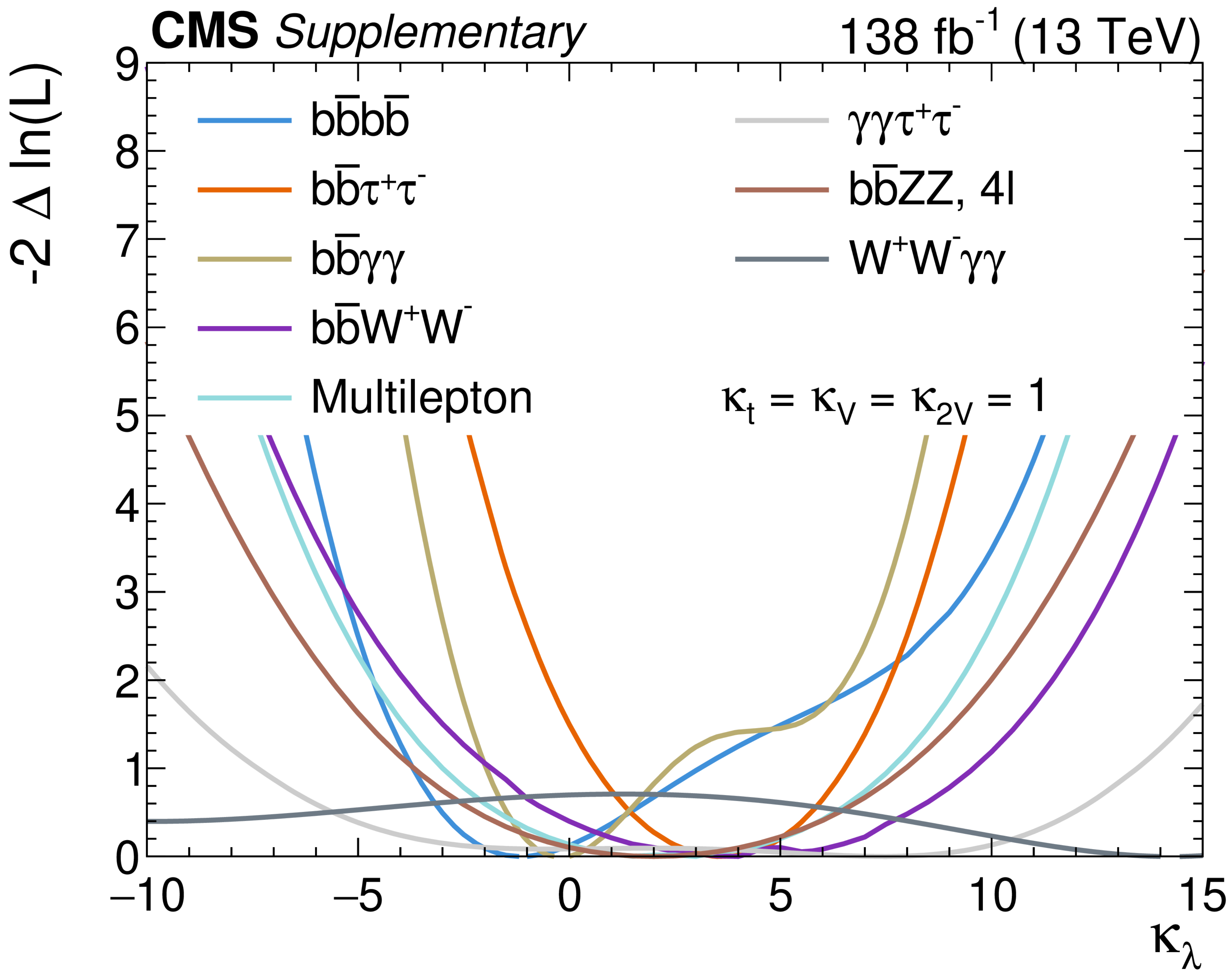


HH combination Run 2

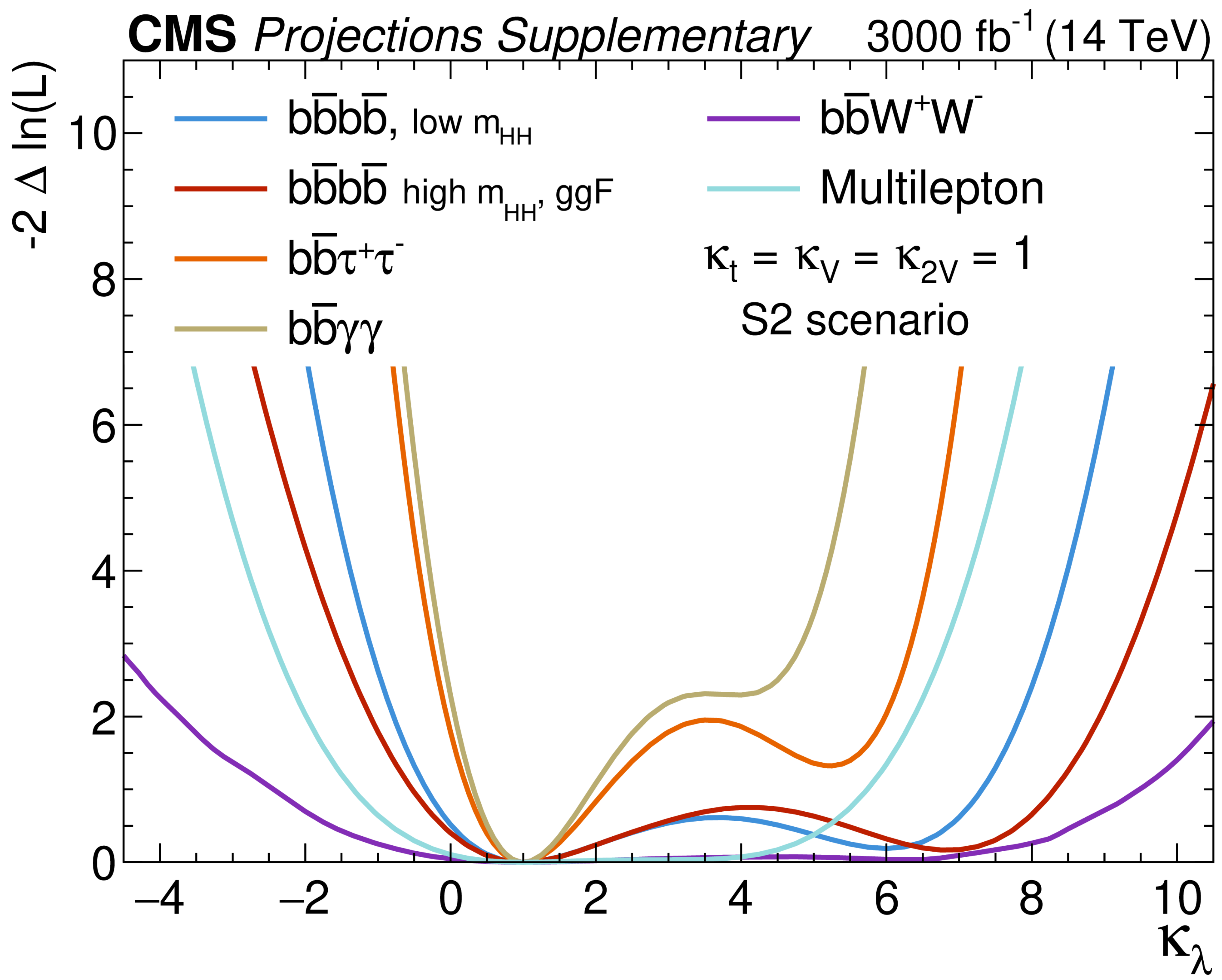
arXiv:2510.07527 submitted to ROPP

Method	κ_λ observed (expected)	κ_{2V} observed (expected)
$-2\Delta\ln(L)$ scan, 68% CL	$[-0.07, 4.18]$ ($[-0.87, 6.31]$)	$[0.81, 1.23]$ ($[0.77, 1.26]$)

Observed



Expected



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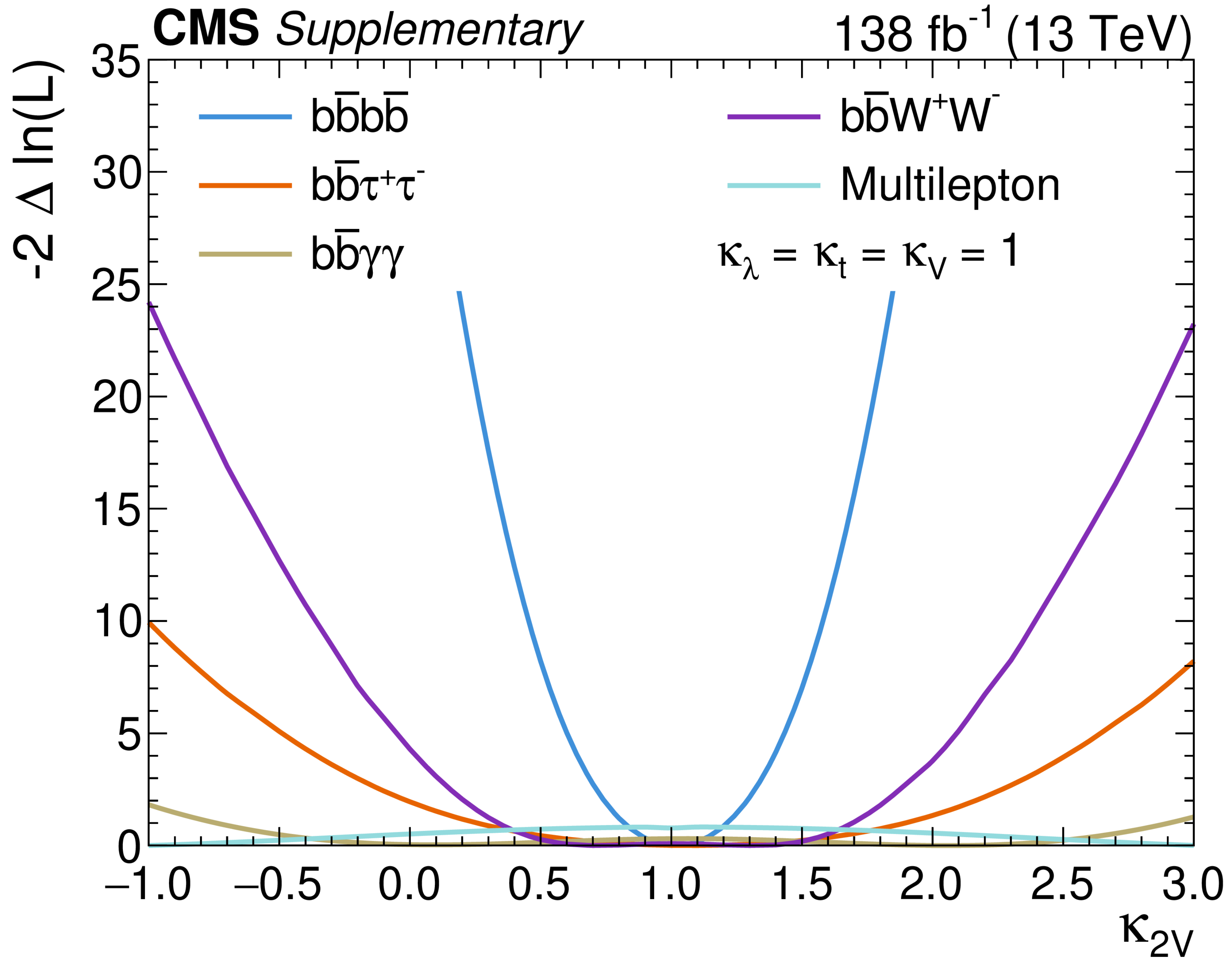
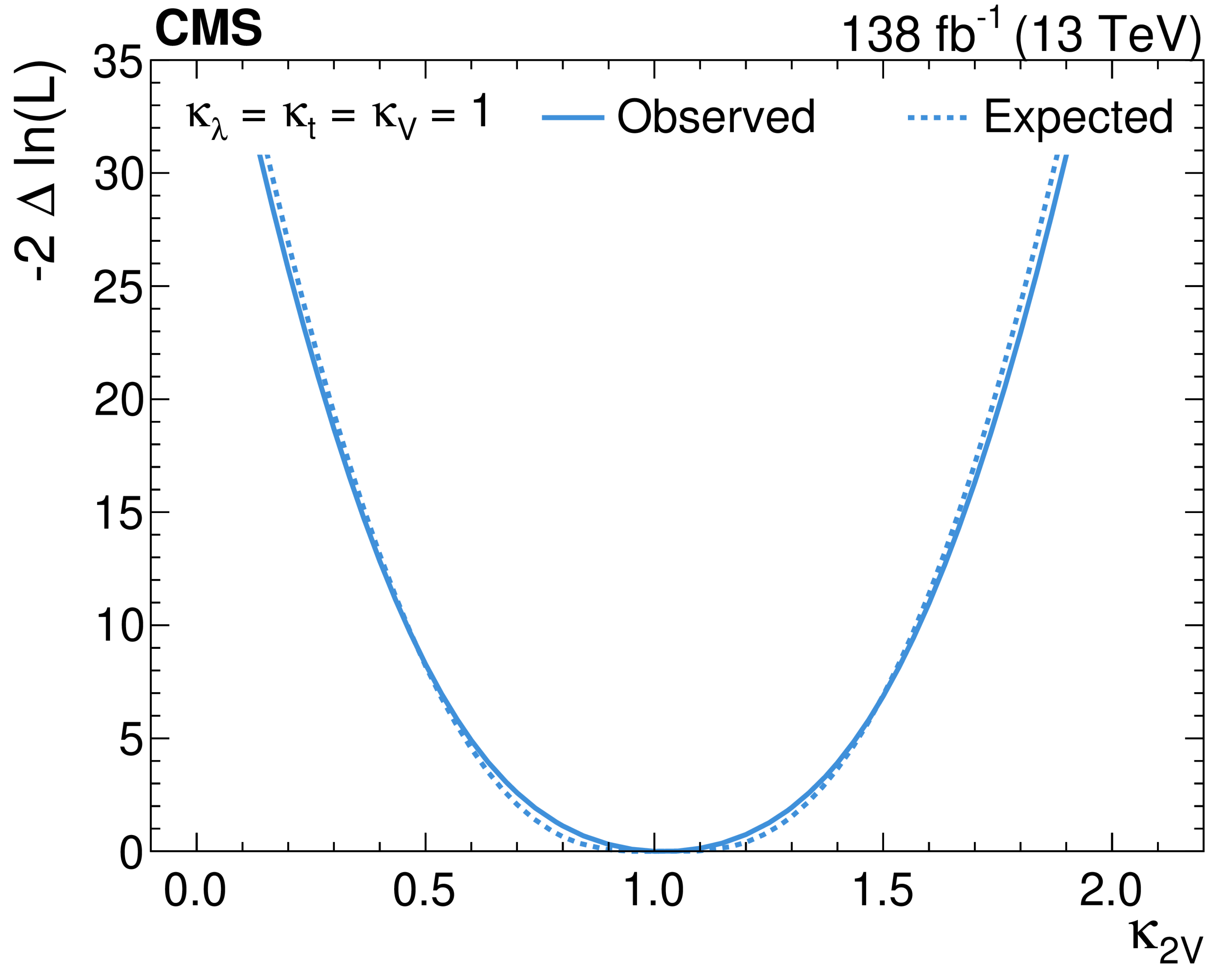
Observed

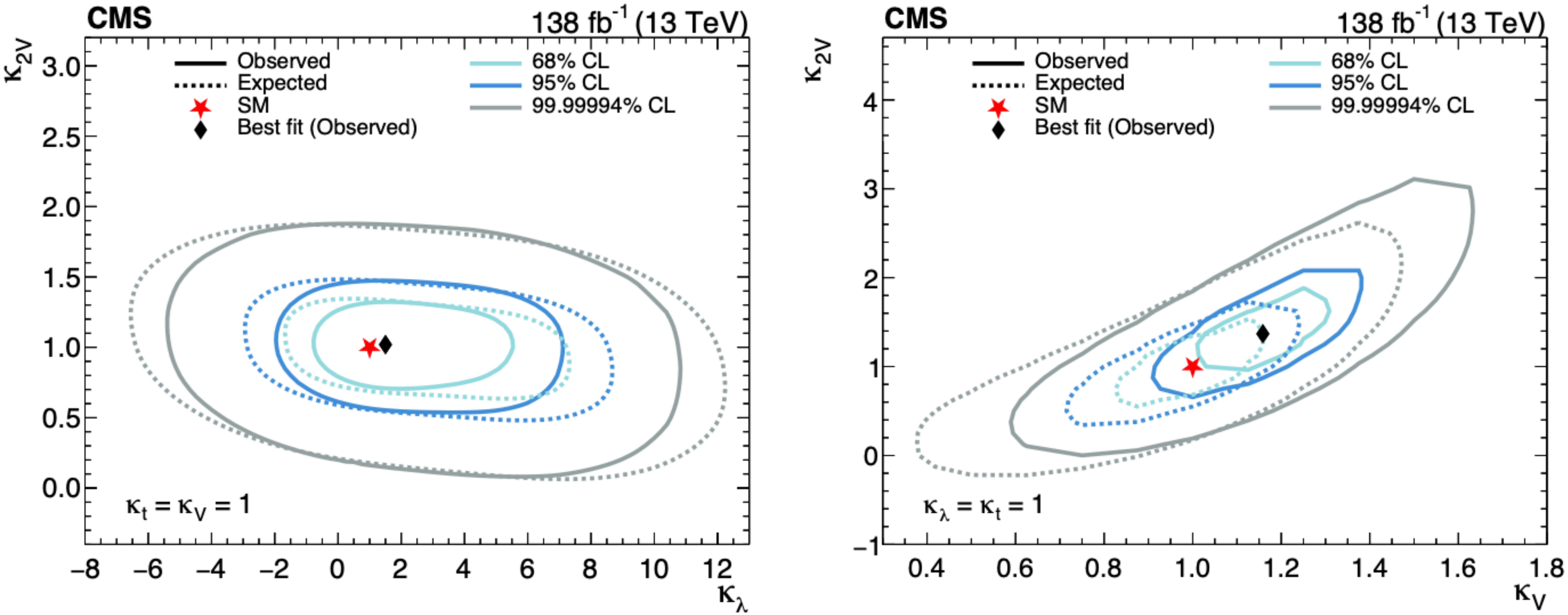


Observed and Expected



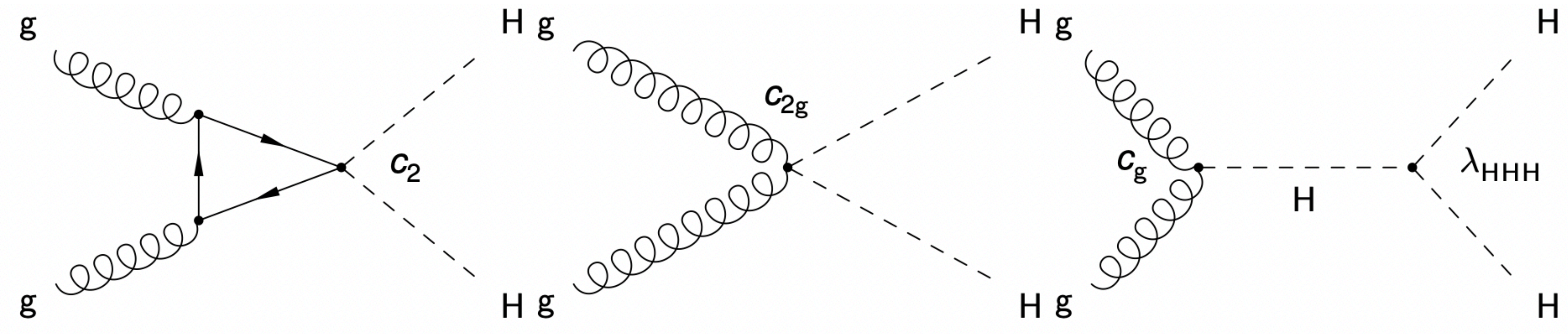
HH combination Run 2

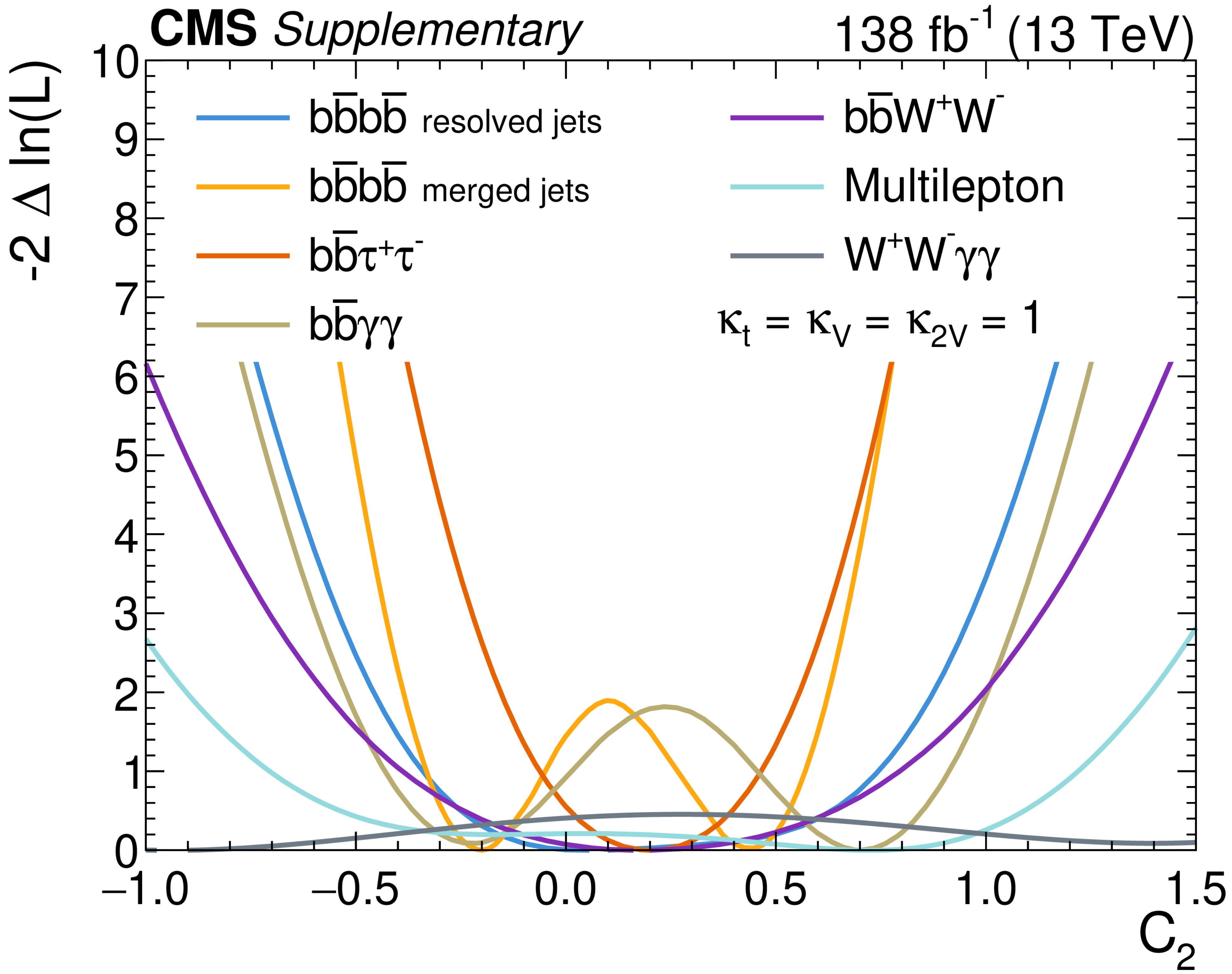
arXiv:2510.07527 submitted to ROPP

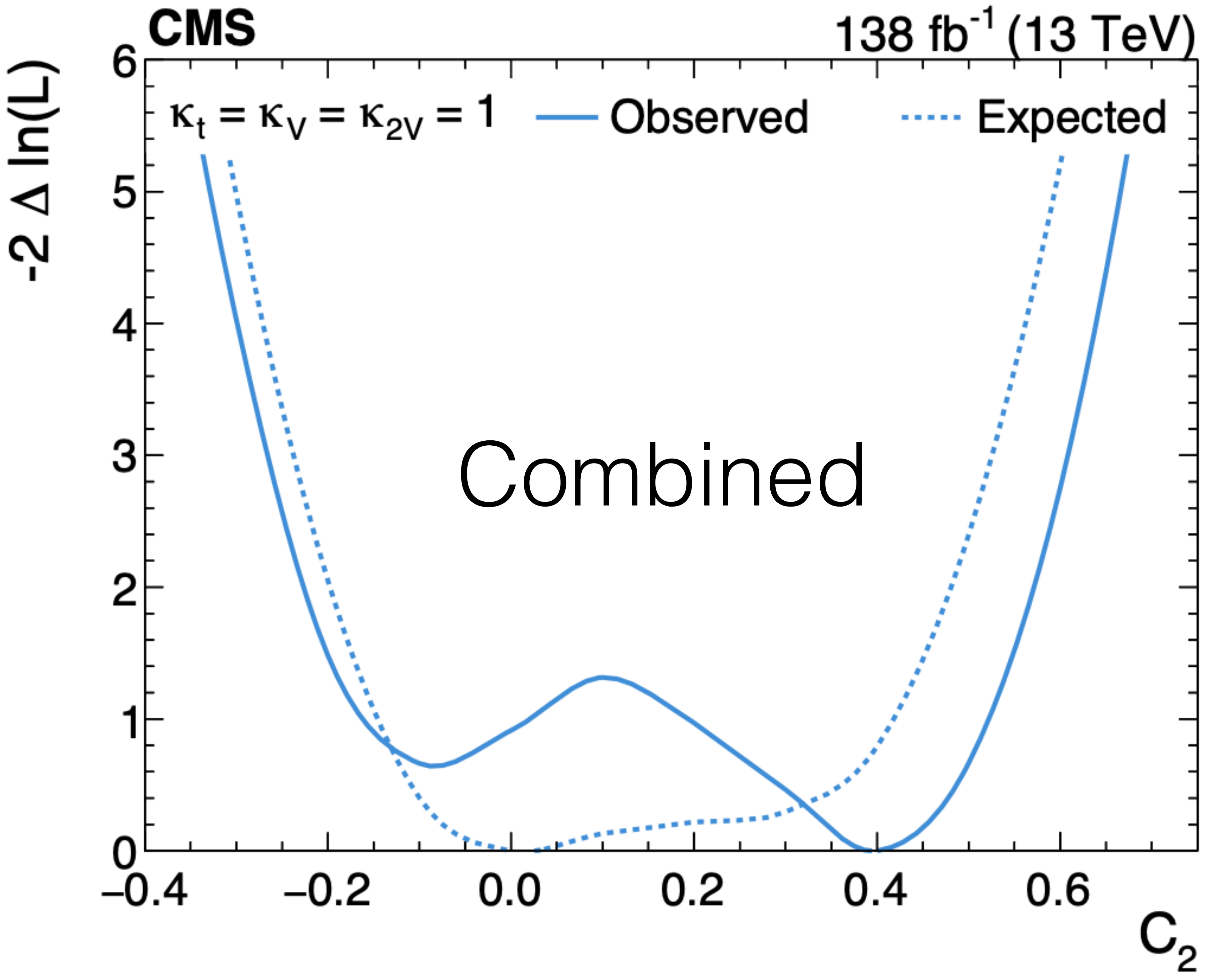


HH combination Run 2： HEFT

arXiv:2510.07527 submitted to ROPP





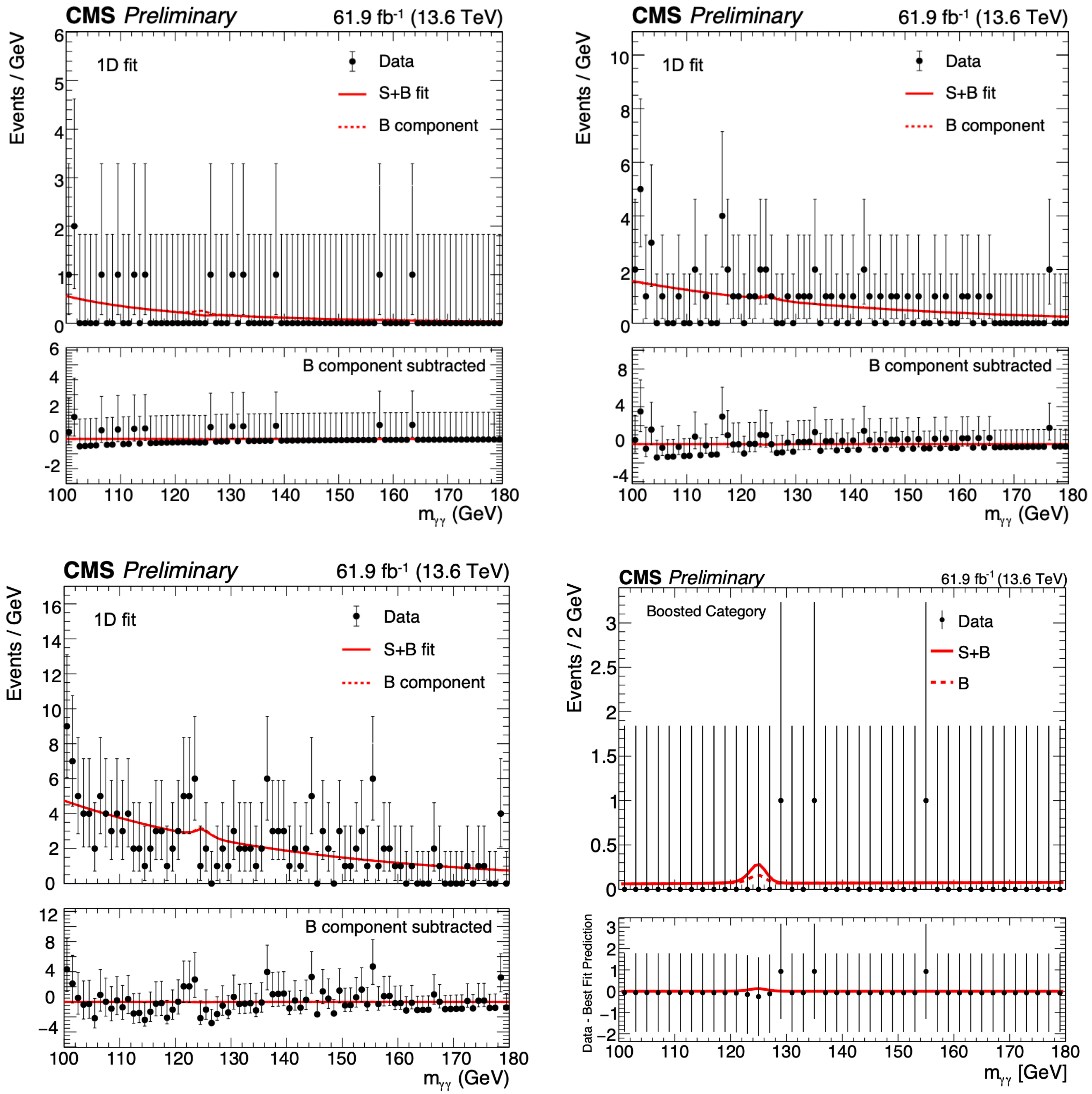


Preliminary result: HH→bbγγ search 2022 + 2023 Run 3 data

CMS-PAS-HIG-25-007

Analysis strategy:

- Two isolated photons
- Two AK4 jets with highest ParticleNet b-tagging score
  - Regression to improve the mass resolution of the reconstructed m(Hbb) developed on top of the ParticleNet b-jet pT regression (10-20% improvement on m(Hbb) resolution
- One AK8 jet with highest ParticleNet Hbb score
- Dedicated classifiers to reject diphoton and ttH backgrounds
- m(γγ) 1D or m(γγ) x m(bb) 2D fit strategies



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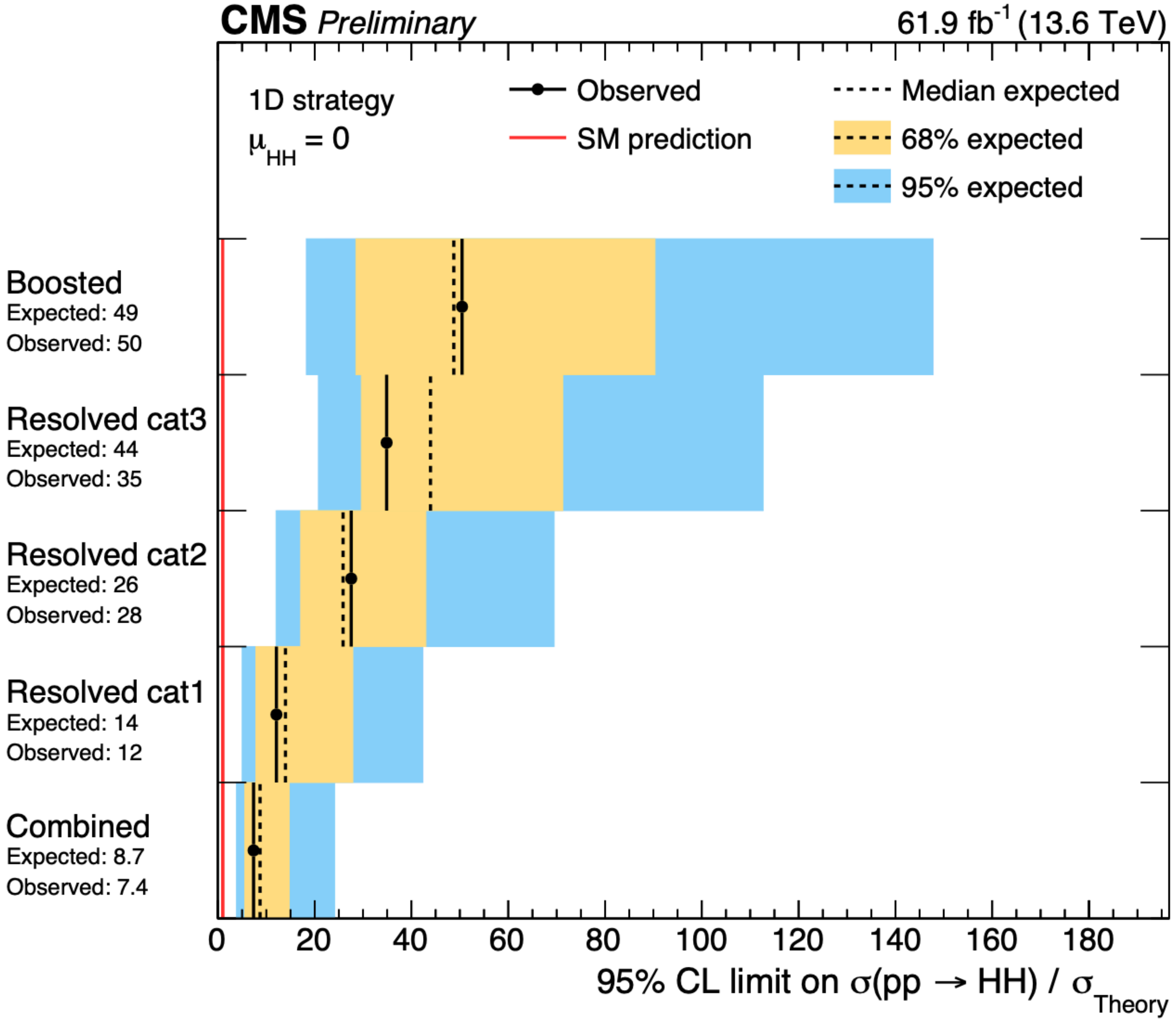
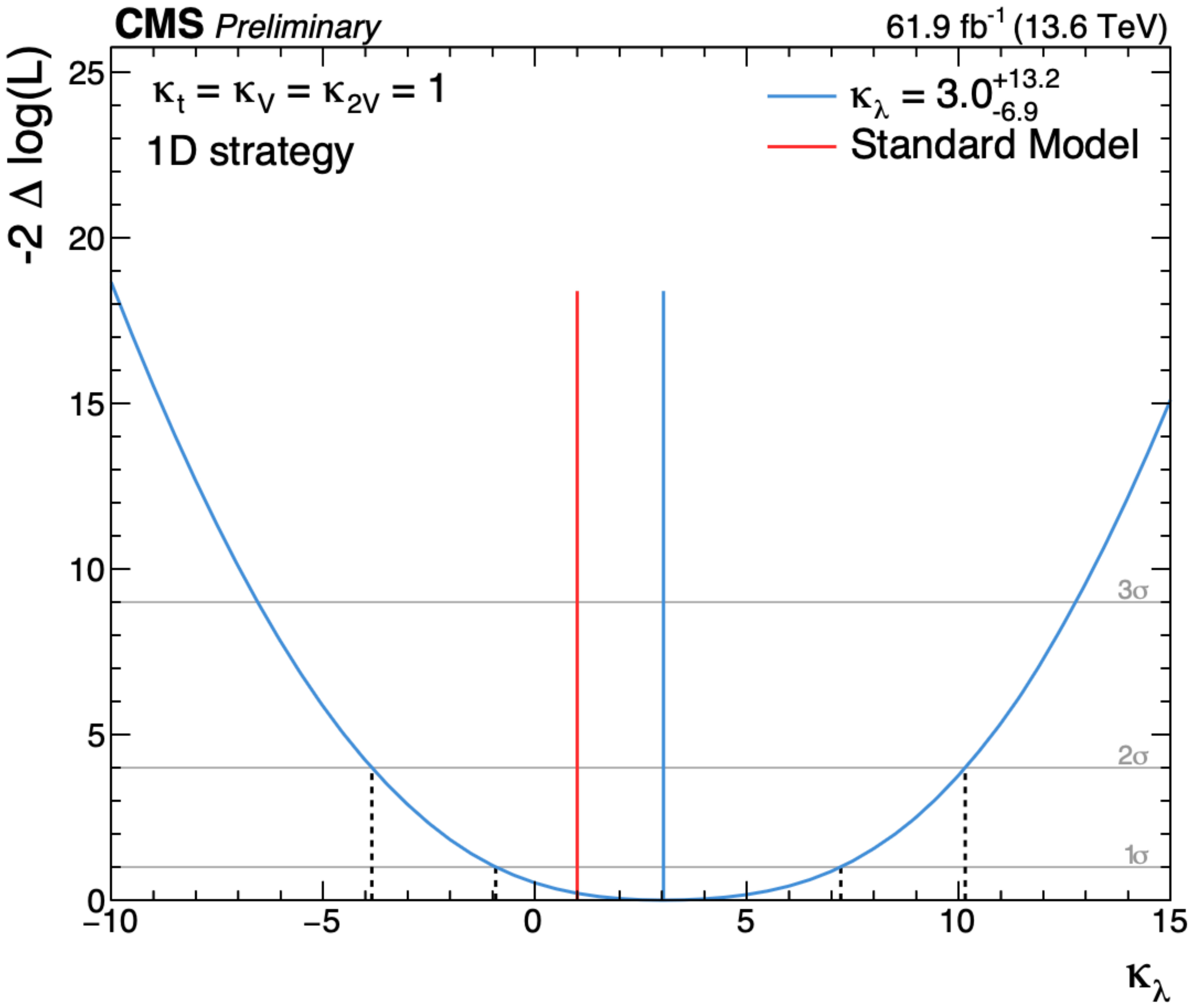
CMS-PAS-HIG-25-007





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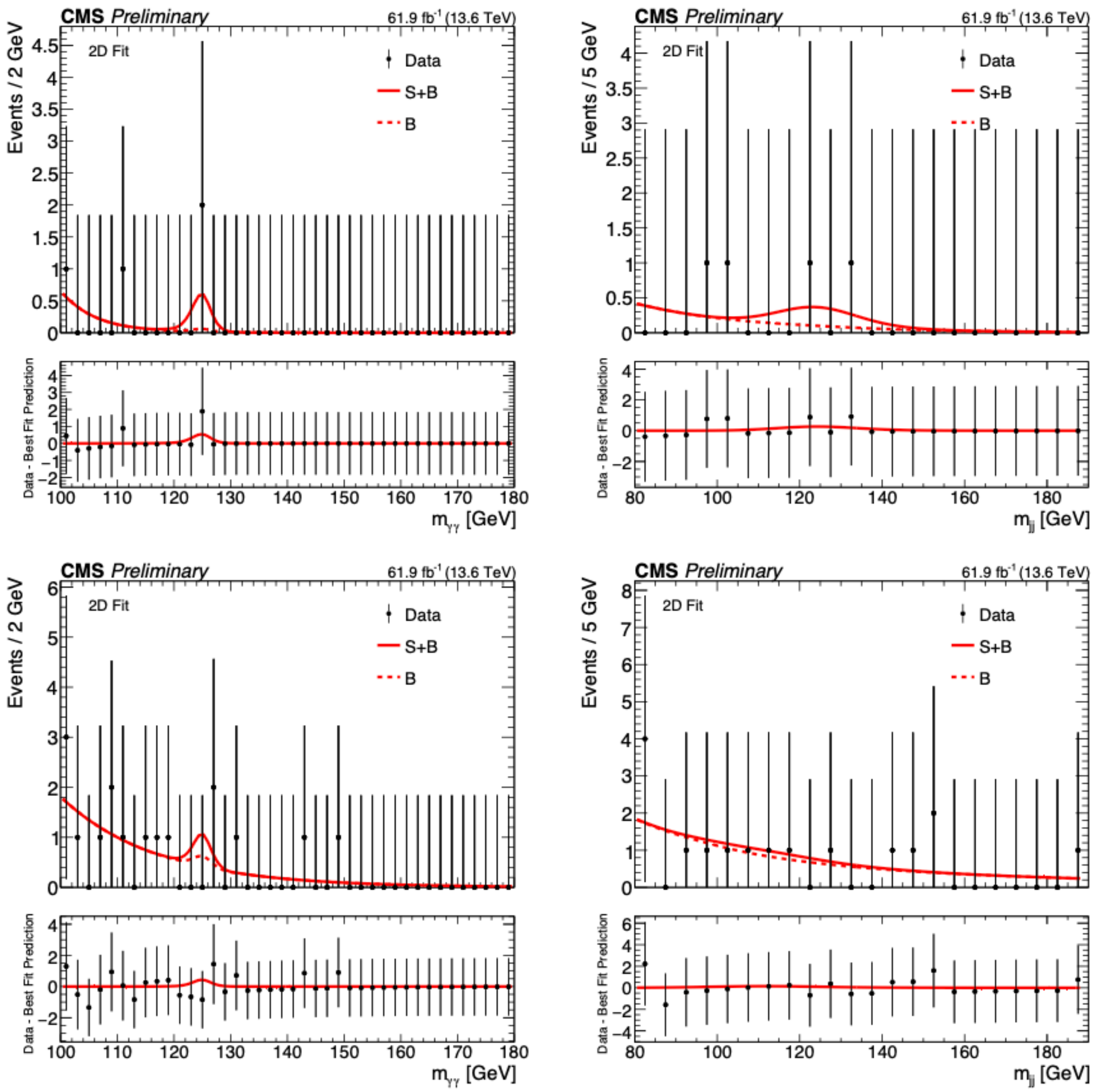
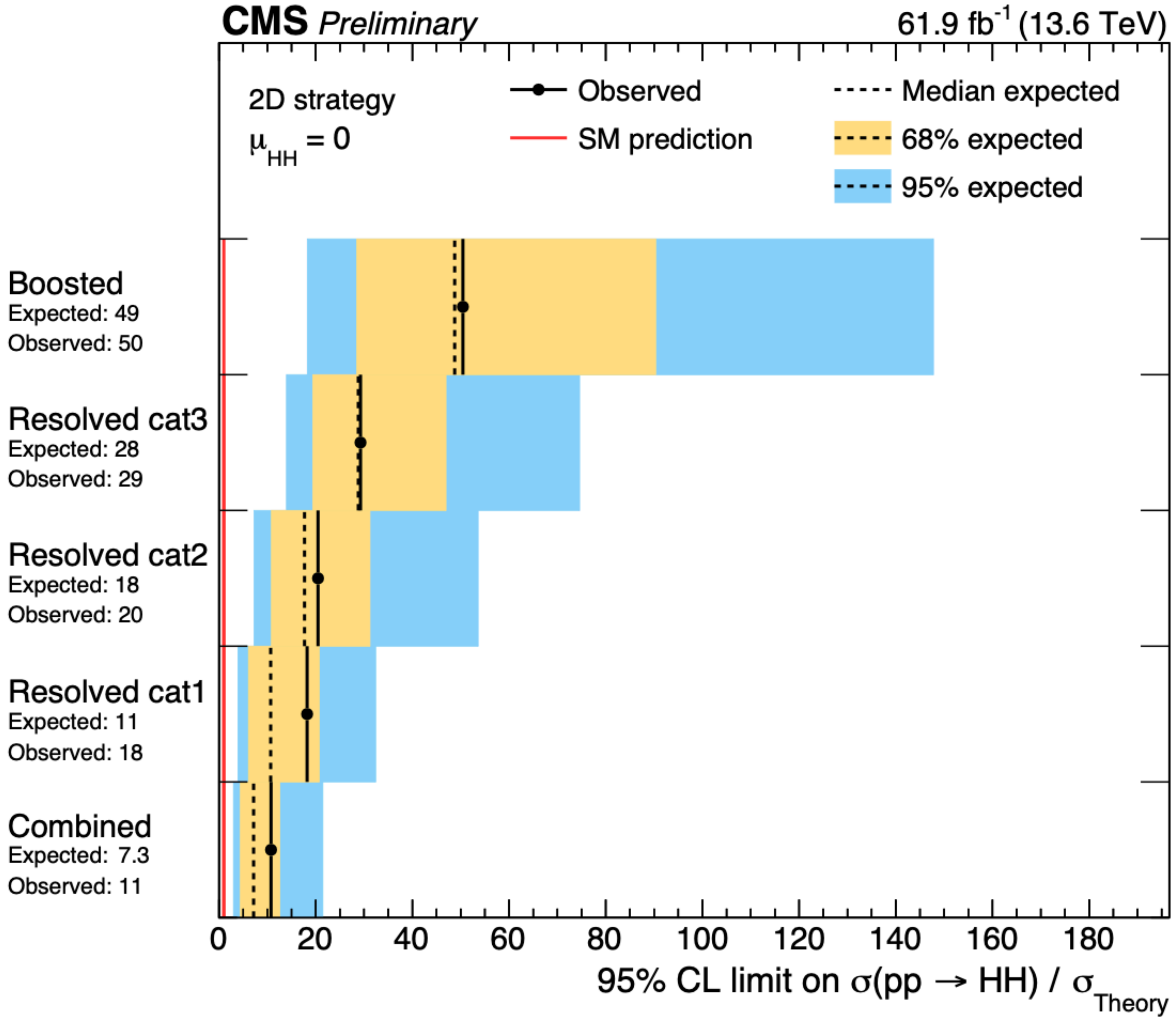
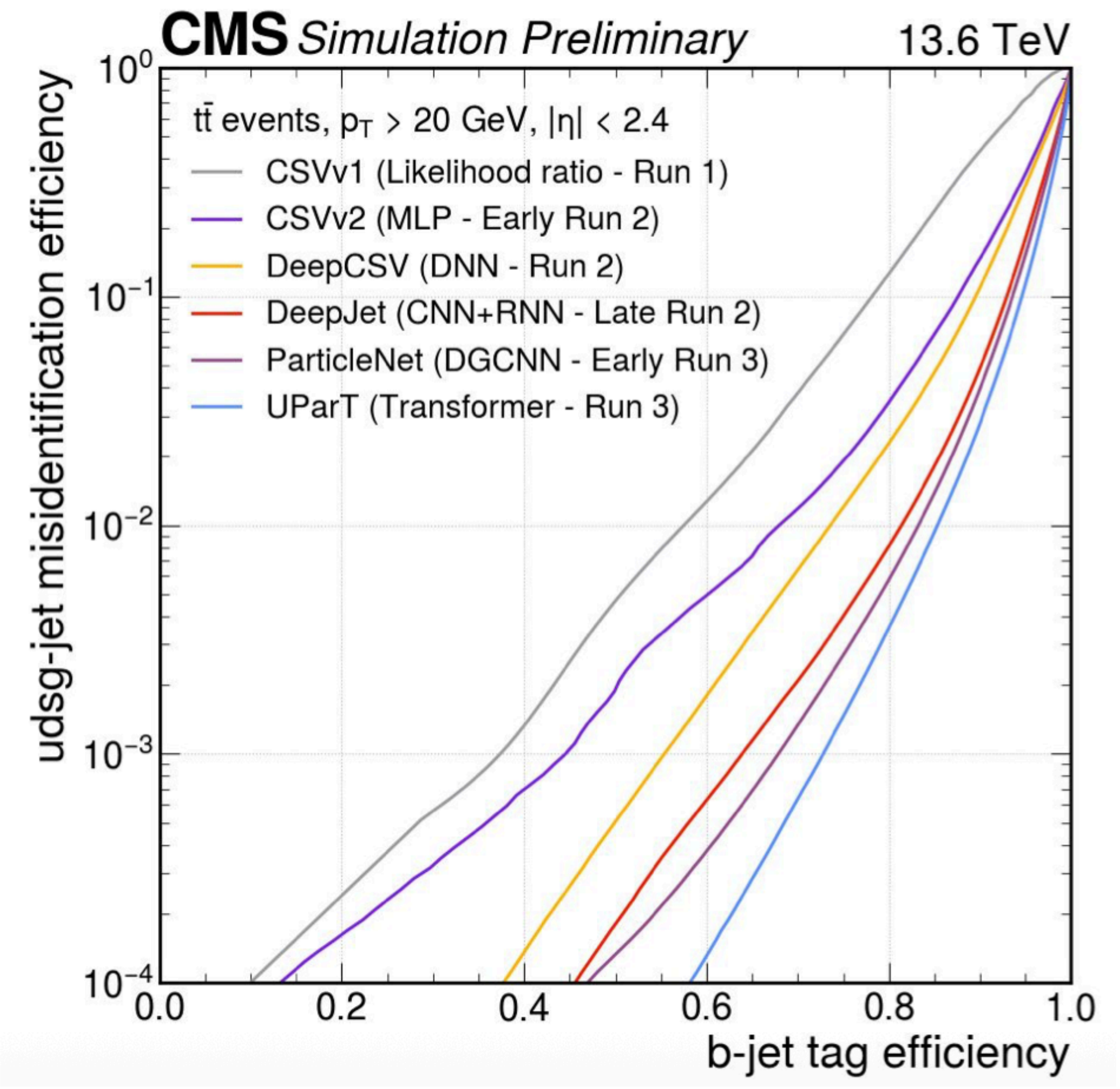
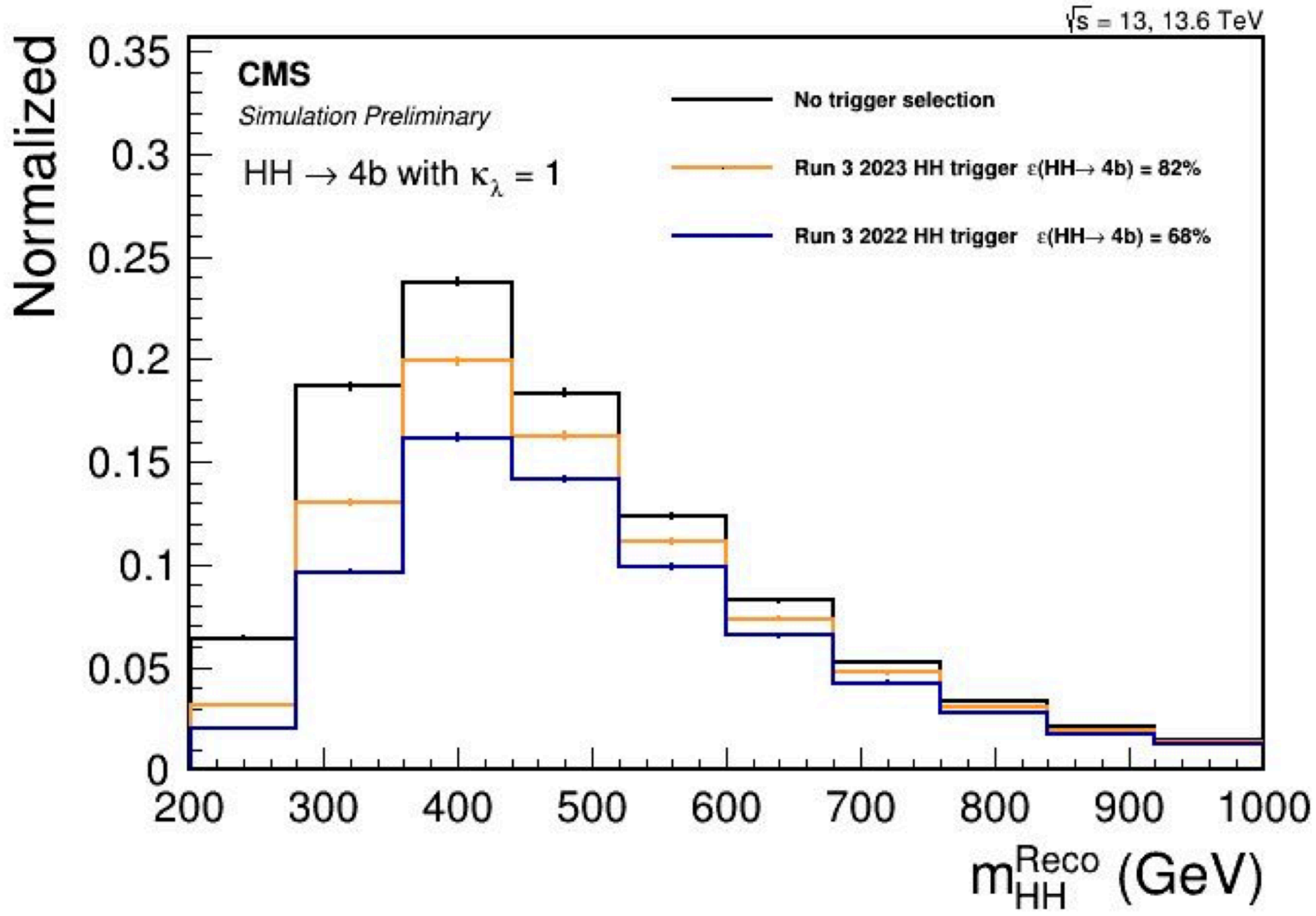




Outlook for Run 3

Machine learning to improve b-tagging and jet energy regression, HLT trigger



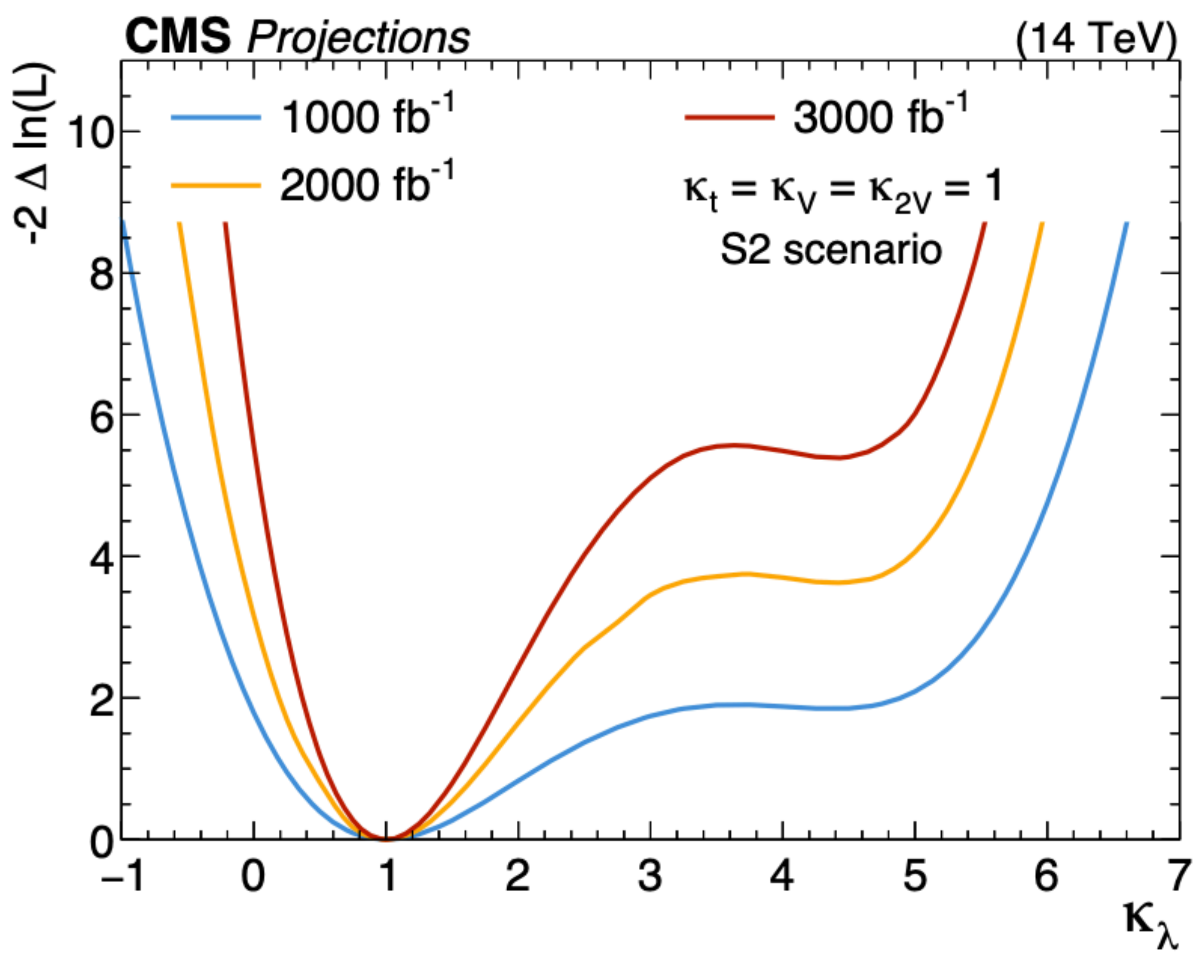


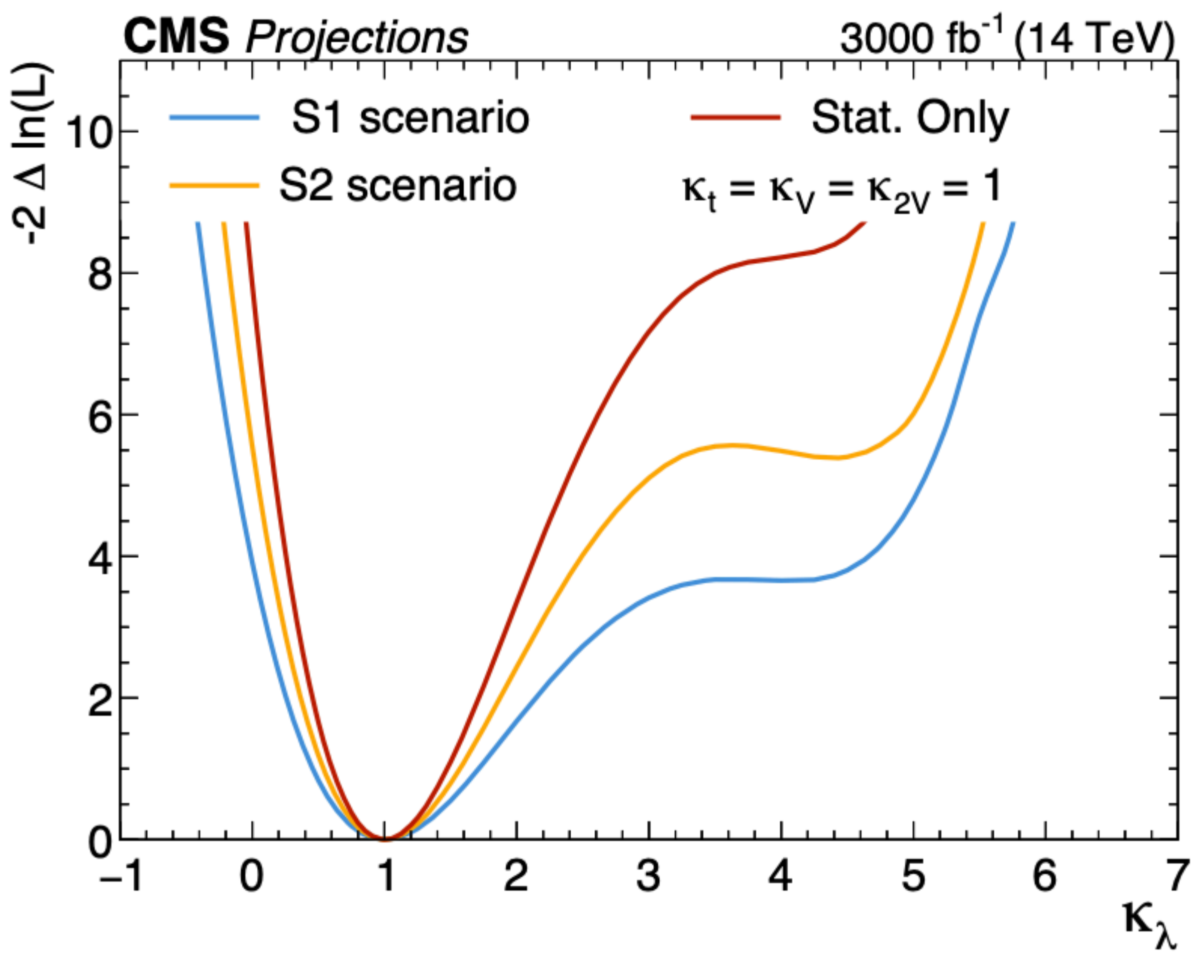
CMS Collaboration, A unified approach for jet tagging in Run 3 at √s =13.6 TeV in CMS CMS DP-2024/066

CMS Collaboration, Novel strategy targeting HH and HHH production at High Level Trigger in Run 3 CMS DP-2023/050

HL-LHC prospect

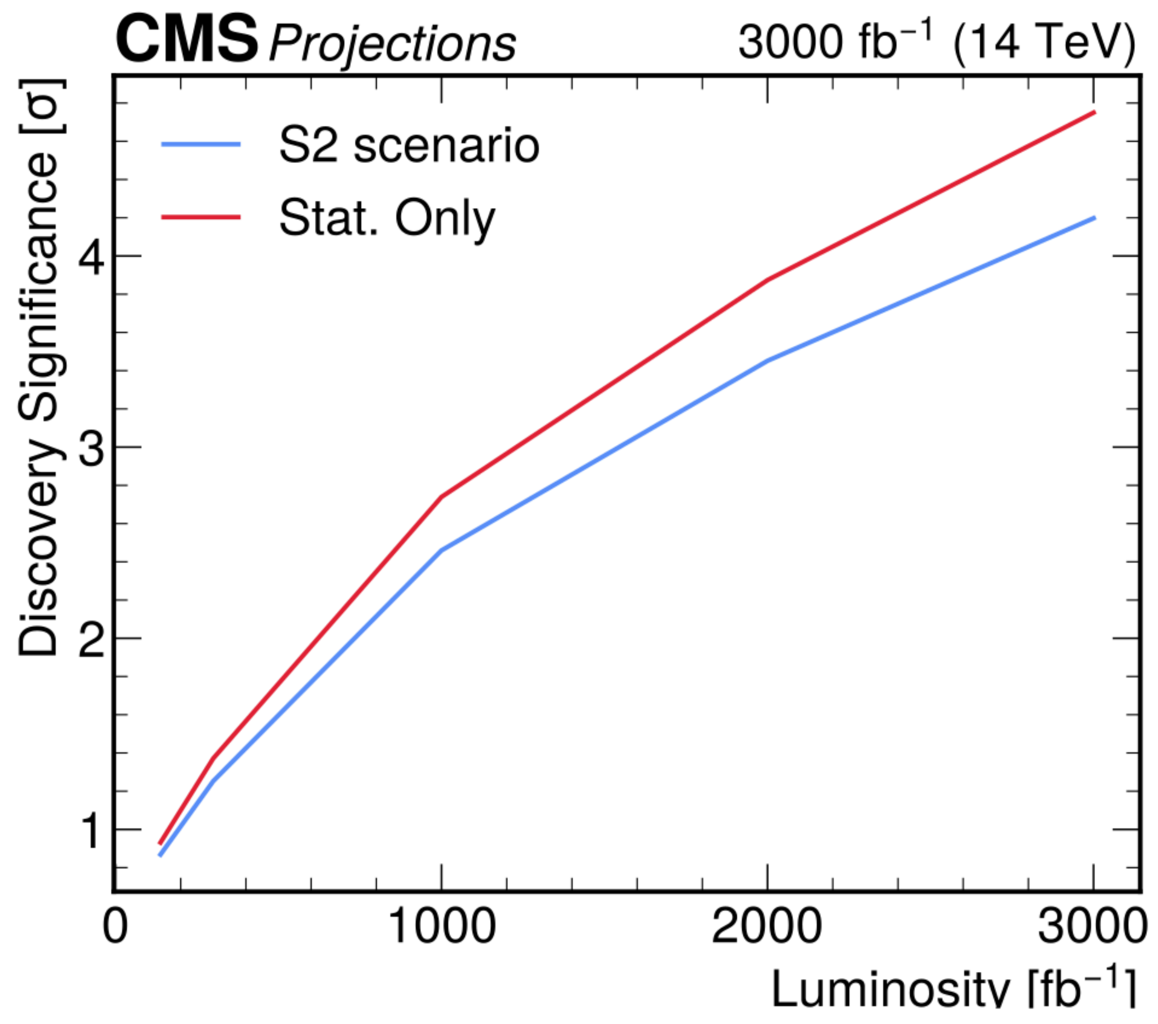
arXiv:2510.07527 submitted to ROPP





- Systematics uncertainty scenario:
  - Stats only
  - S1 scenario: same as Run 2
  - S2 scenario: estimated scenario for HL-LHC

Uncertainty	Scaling with respect to Run 2
Theoretical uncertainties	1/2
Stat. uncertainties in MC simulation	Removed
b-tagging efficiency stat. component	$1/\sqrt{k_L}$
b-tagging efficiency (nonstat. component)	Unchanged
AK4 jet absolute energy scale	$\max(0.3, 1/\sqrt{k_L})$
AK4 jet energy scale dependence on flavour	$\max(0.5, 1/\sqrt{k_L})$
AK4 jet relative energy scale	$\max(0.2, 1/\sqrt{k_L})$
AK4 jet energy scale method	$1/\sqrt{k_L}$
AK4 jet energy resolution	$\max(0.5, 1/\sqrt{k_L})$
E_T^{miss}	$\max(0.5, 1/\sqrt{k_L})$
Luminosity	0.6
τ_h ID	Unchanged
τ_h energy scale	Unchanged
Pileup	Unchanged
Run-2 issues	Removed



	Significance (σ) at 2000 fb^{-1}		Significance (σ) at 3000 fb^{-1}	
	S2	Stat. only	S2	Stat. only
$b\bar{b}b\bar{b}$ resolved jets	1.0	1.4	1.2	1.7
$b\bar{b}b\bar{b}$ merged jets	1.8	1.9	2.2	2.3
$b\bar{b}\tau\tau$	1.9	2.1	2.4	2.6
$b\bar{b}\gamma\gamma$	2.0	2.0	2.4	2.5
$b\bar{b}WW$	0.3	0.8	0.3	1.0
HH multilepton	0.4	0.6	0.5	0.8
Combination	3.5	3.9	4.2	4.8

S2 scenario:

- κλ [0.5,1.6] @3000 fb-1, [0.4,1.8] @2000 fb-1
- HH signal significance 4.2σ @3000 fb-1, 3.5σ@2000 fb-1
- CMS and ATLAS combination would achieve observation at HL-LHC

Summary

- The Discovery of the Higgs boson and the study of its properties have expanded our vision of particle physics
- The shape of the Higgs potential needs to be verified
  - CMS Run 2 HH combination: observed (expected) upper limit at 95% CL on HH cross section: 3.5 (2.5) $\times$ SM
  - Opportunities with CMS Run 3 data:
    - First preliminary result in $HH \rightarrow bb\gamma\gamma$ channel on CMS 2022 + 2023 data
    - Many more analyses to come with new HLT triggers, Transformer Algorithm AK4 b jet tagging, boosted Higgs tagging, with the potential to significantly improve HH sensitivity
  - ATLAS and CMS combination shall achieve HH observation at HL-LHC
- Looking forward to LHC Run 3 and beyond

Apologies for all I could not cover

Thank you!

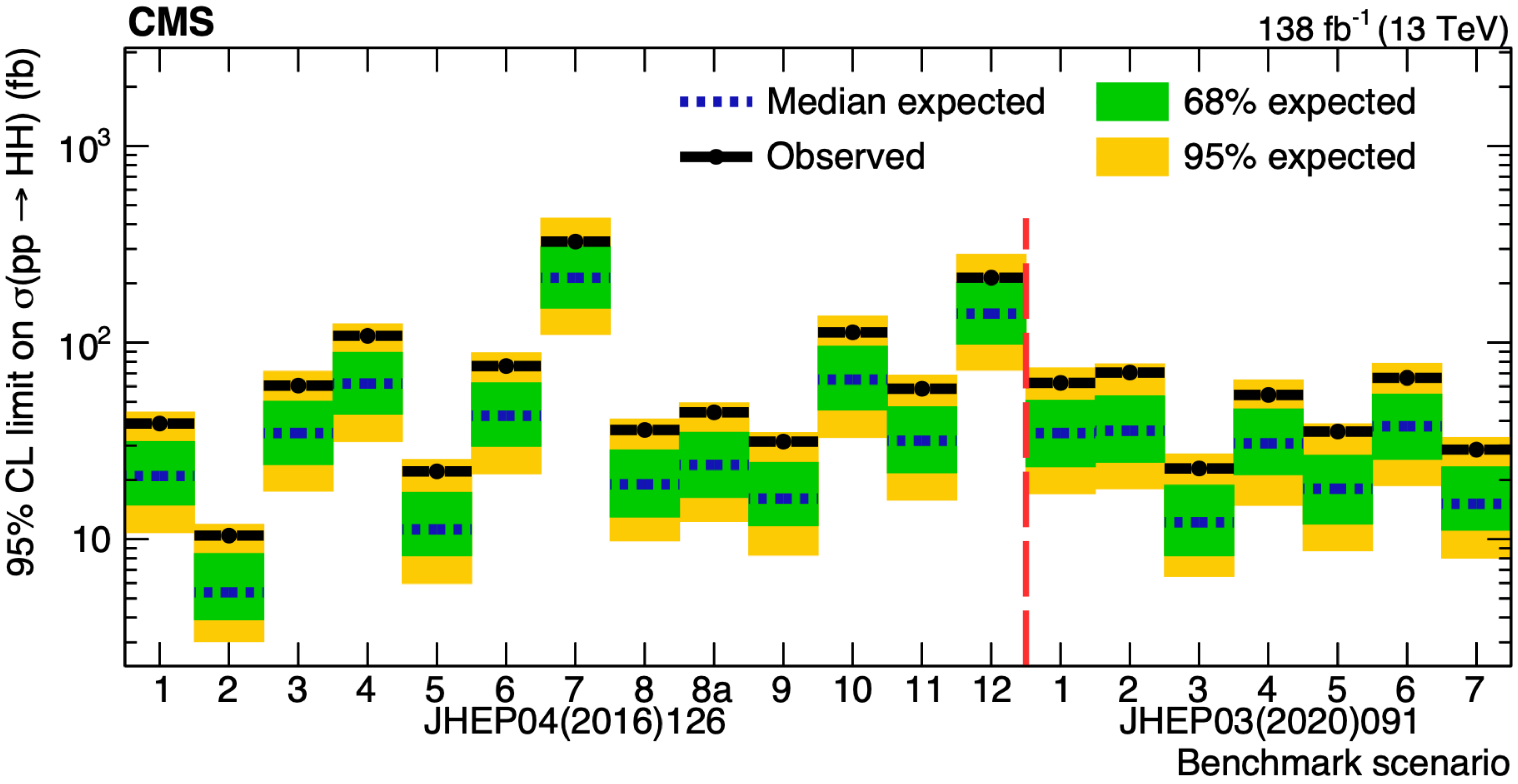
backup slides

HH combination Run 2： HEFT

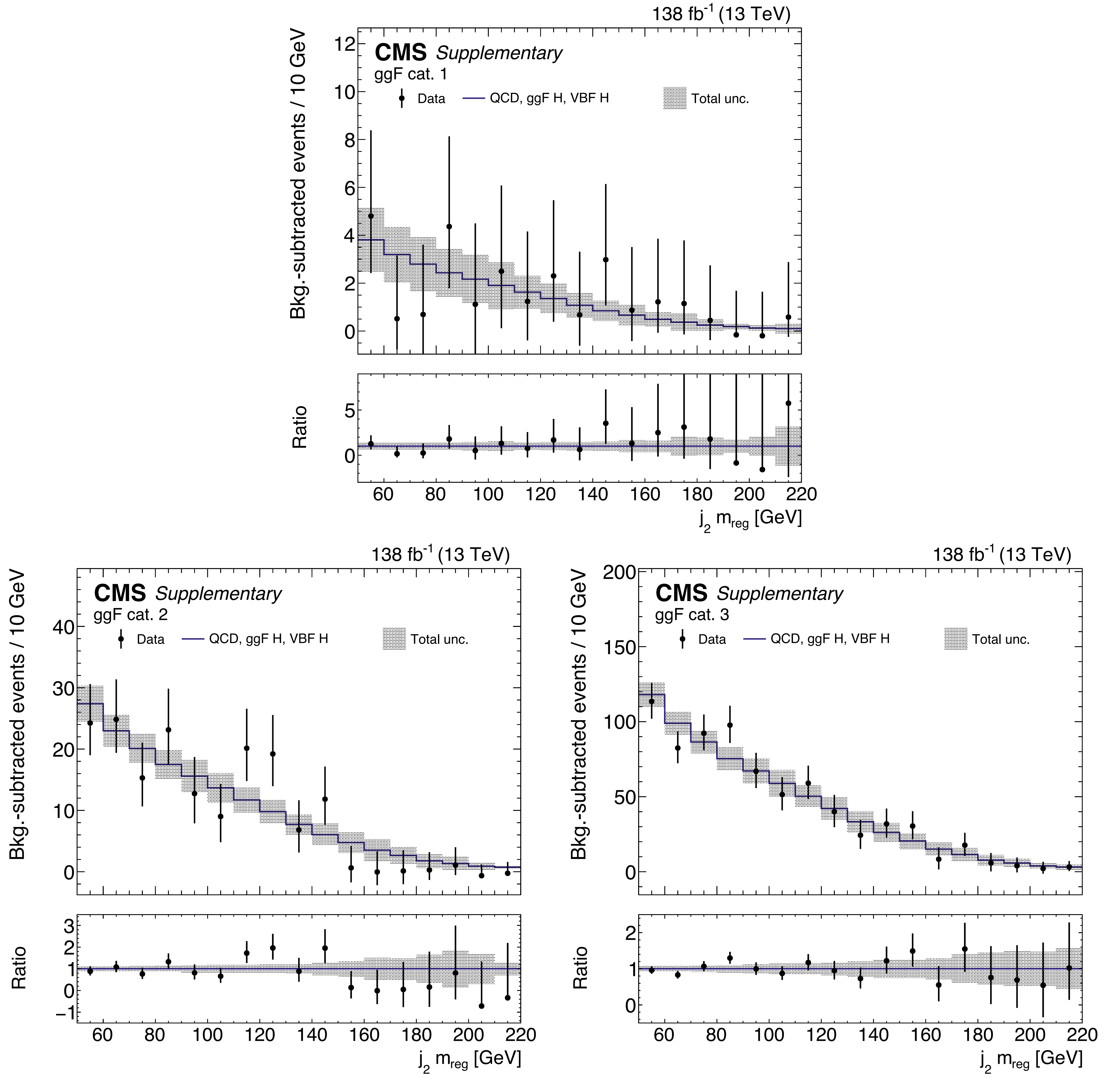
arXiv:2510.07527 submitted to ROPP

	1	2	3	4	5	6	7	8	9	10	11	12	8a
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.5
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.27
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0

	1	2	3	4	5	6	7
κ_λ	3.94	6.84	2.21	2.79	3.95	5.68	−0.10
κ_t	0.94	0.61	1.05	0.61	1.17	0.83	0.94
c_2	−0.33	0.33	−0.33	0.33	−0.33	0.33	1.0
c_g	0.75	0.0	0.75	−0.75	0.25	−0.75	0.25
c_{2g}	−1	1	−1.5	−0.5	1.5	−1	1

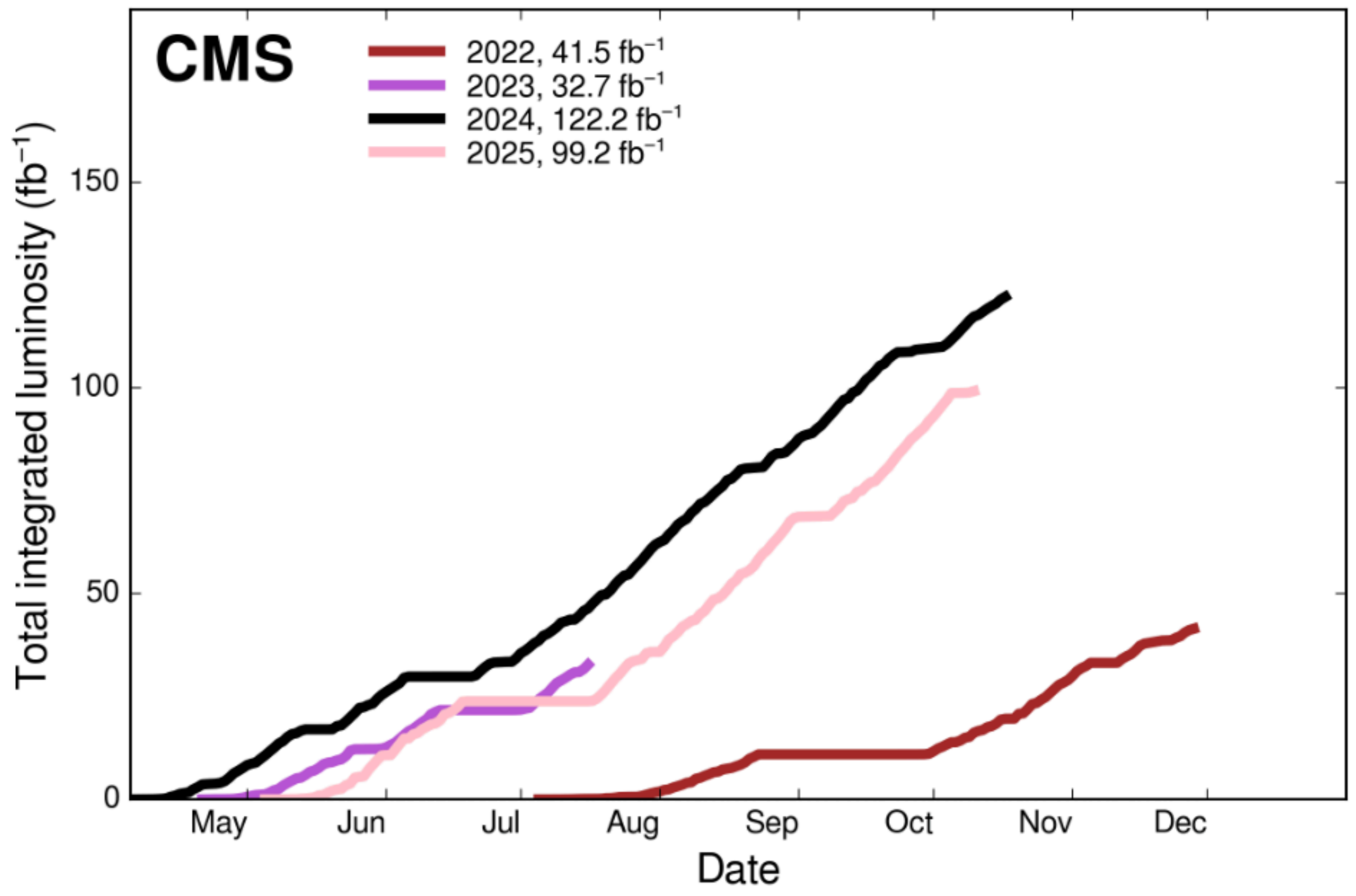


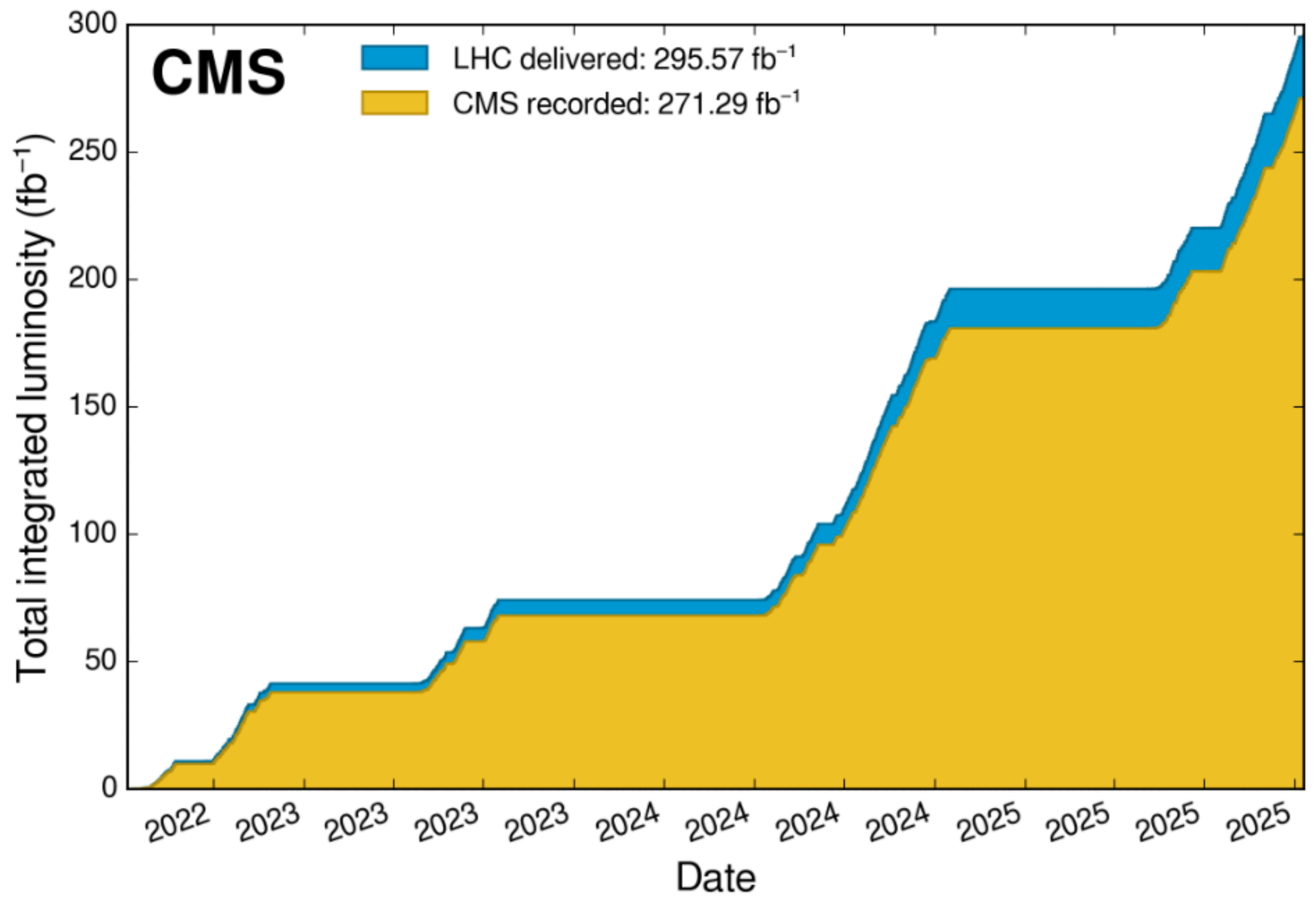
QCD Background modeling

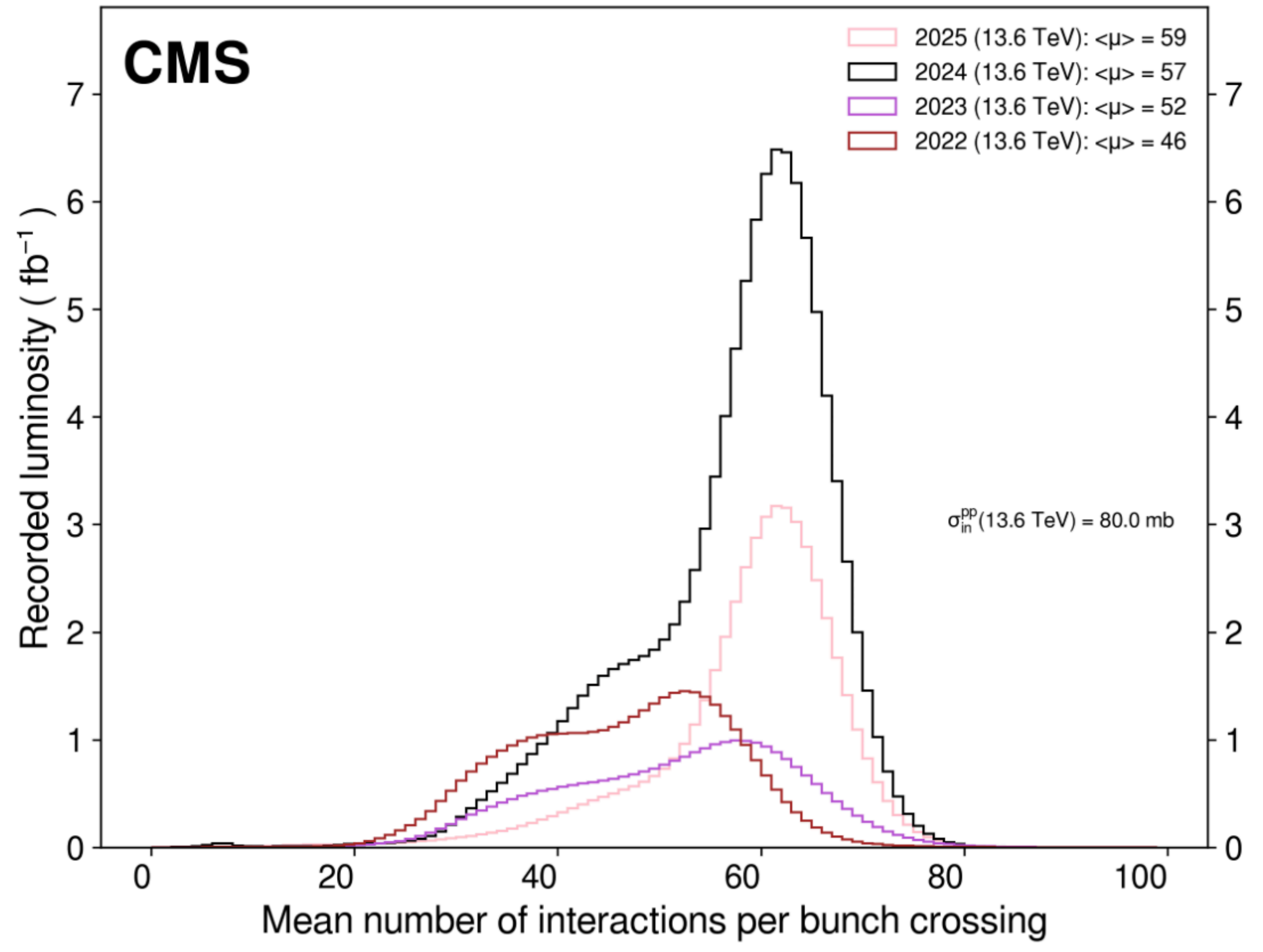


data after subtracting the non-QCD backgrounds, agrees well with QCD background prediction in the sideband regions

Run 3 data-taking

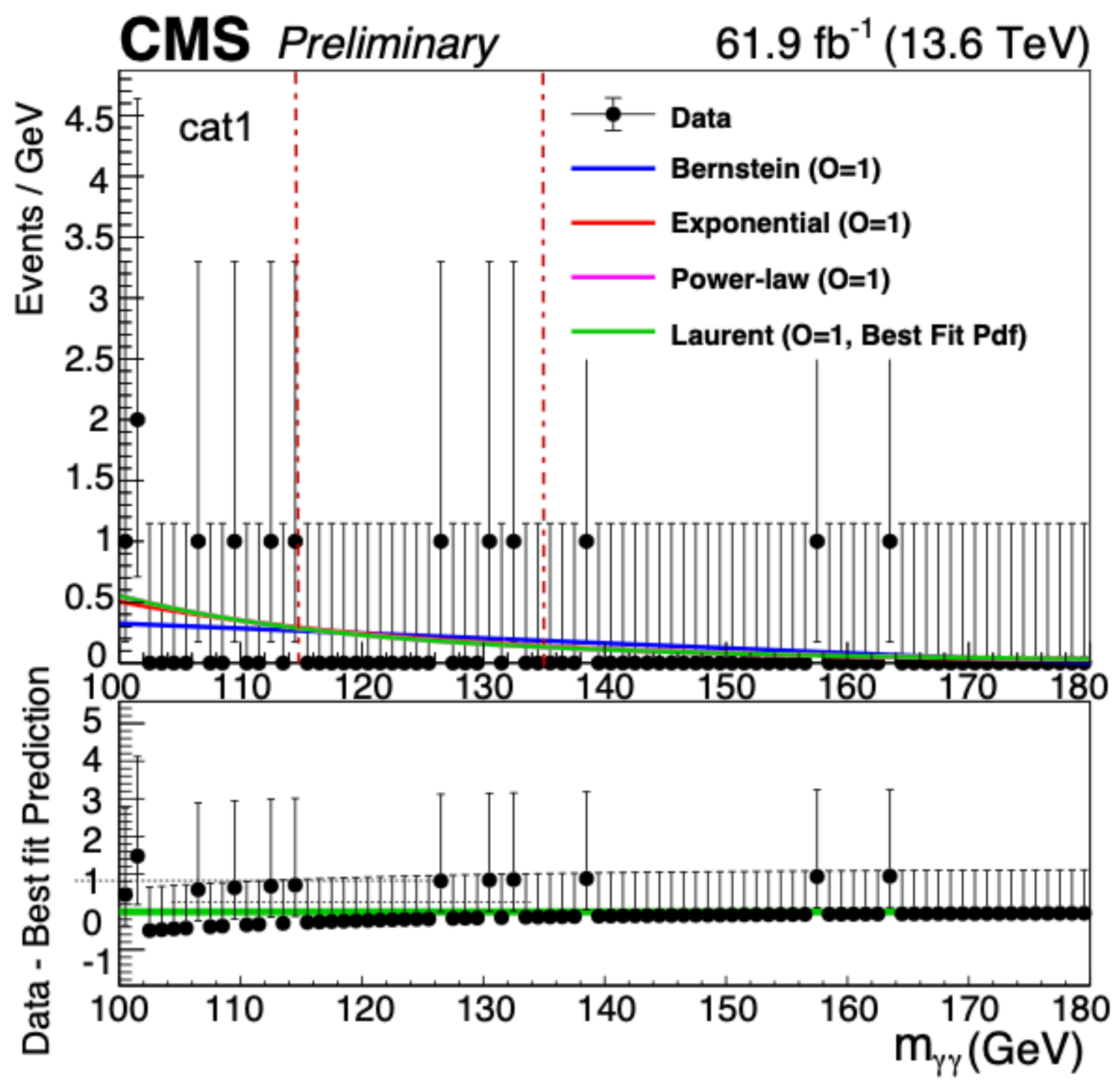


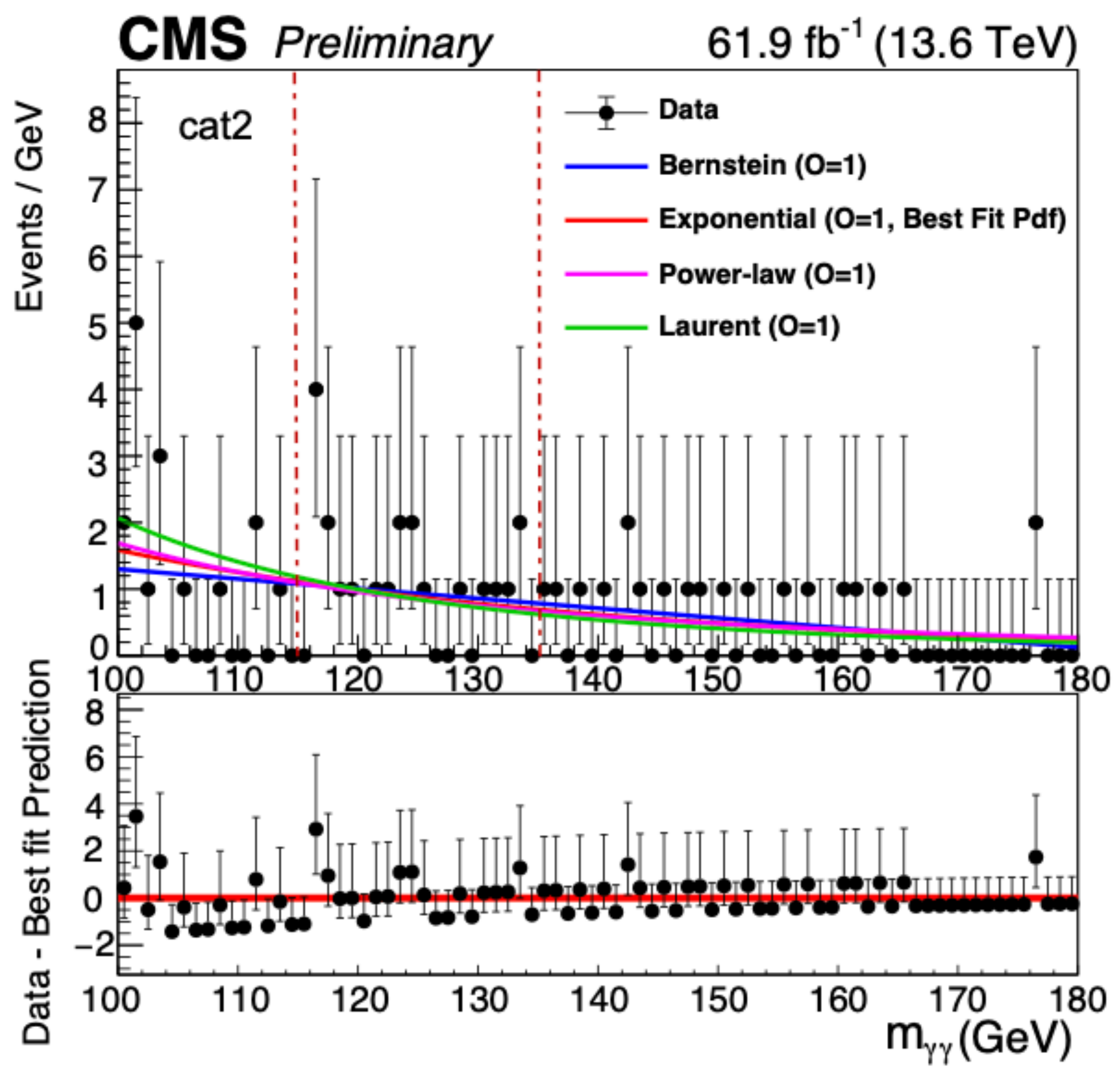


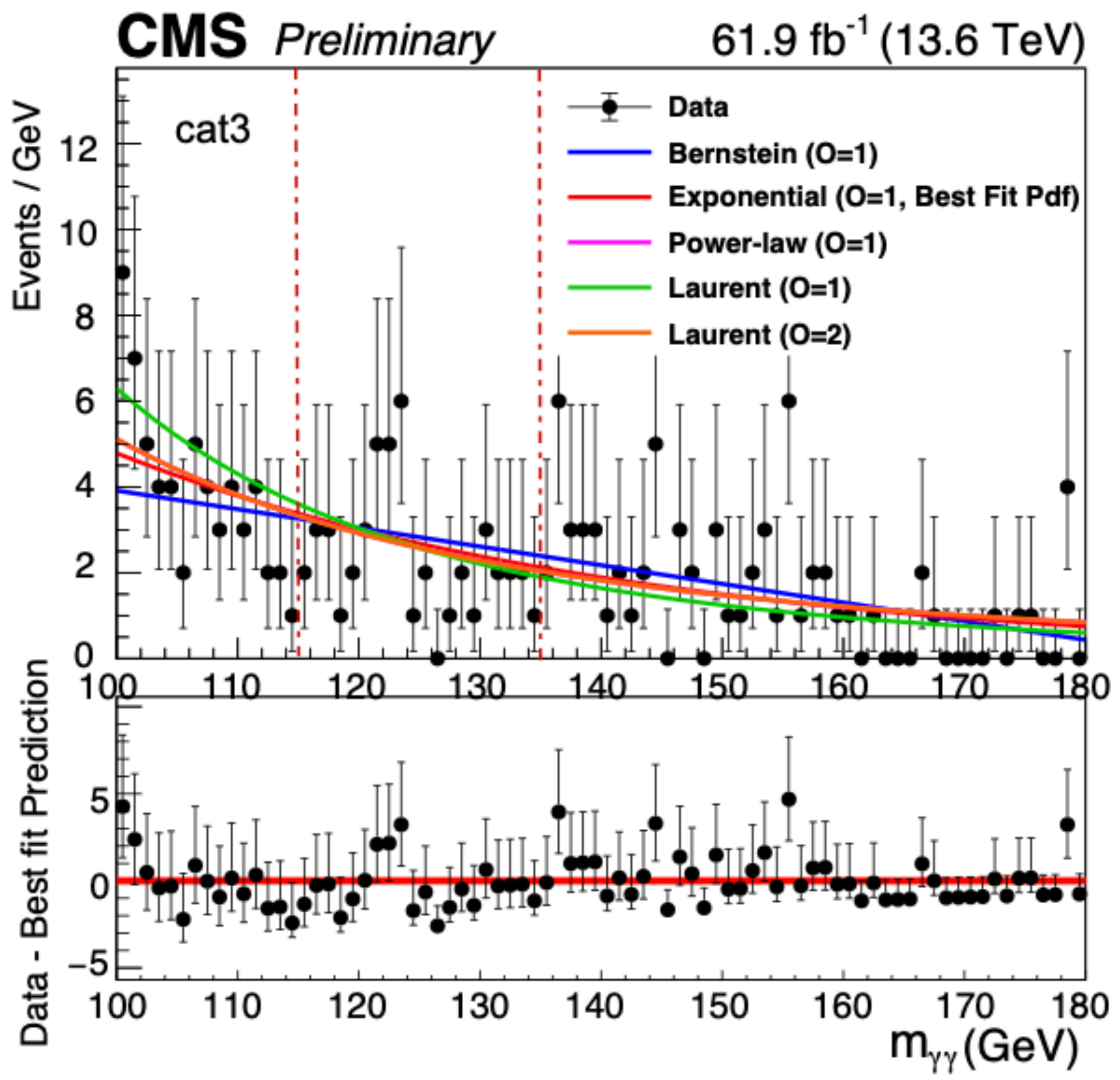


HH→bbγγ search 2022 + 2023 Run 3 data

CMS-PAS-HIG-25-007







discrete profiling method is employed to account for systematic uncertainty of the choice of the family of functional forms