

Summary of Higgs 2024



Introduction

- Conference on Higgs physics:
 - Plenary sessions and parallel sessions split between:
 - Precision measurements & calculations
 - Higgs boson pairs and Higgs potential
 - BSM Higgs physics
 - Higgs physics at future colliders
- Discussions between ATLAS, CMS and theorists

*Many different results and aspects of Higgs physics shown,
we will provide a small, biased selection...*



<https://indico.cern.ch/event/higgs2024>

IGGS 2024

Uppsala, Sweden
4-8 November 2024

International Advisory Committee

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Sponsors: CARL TRYGGERS STIFTELSE FOR VETENSKAPLIG FORSKNING, Wenner-Gren Foundations, EPJ C, Uppsala kommun, ScandiNova





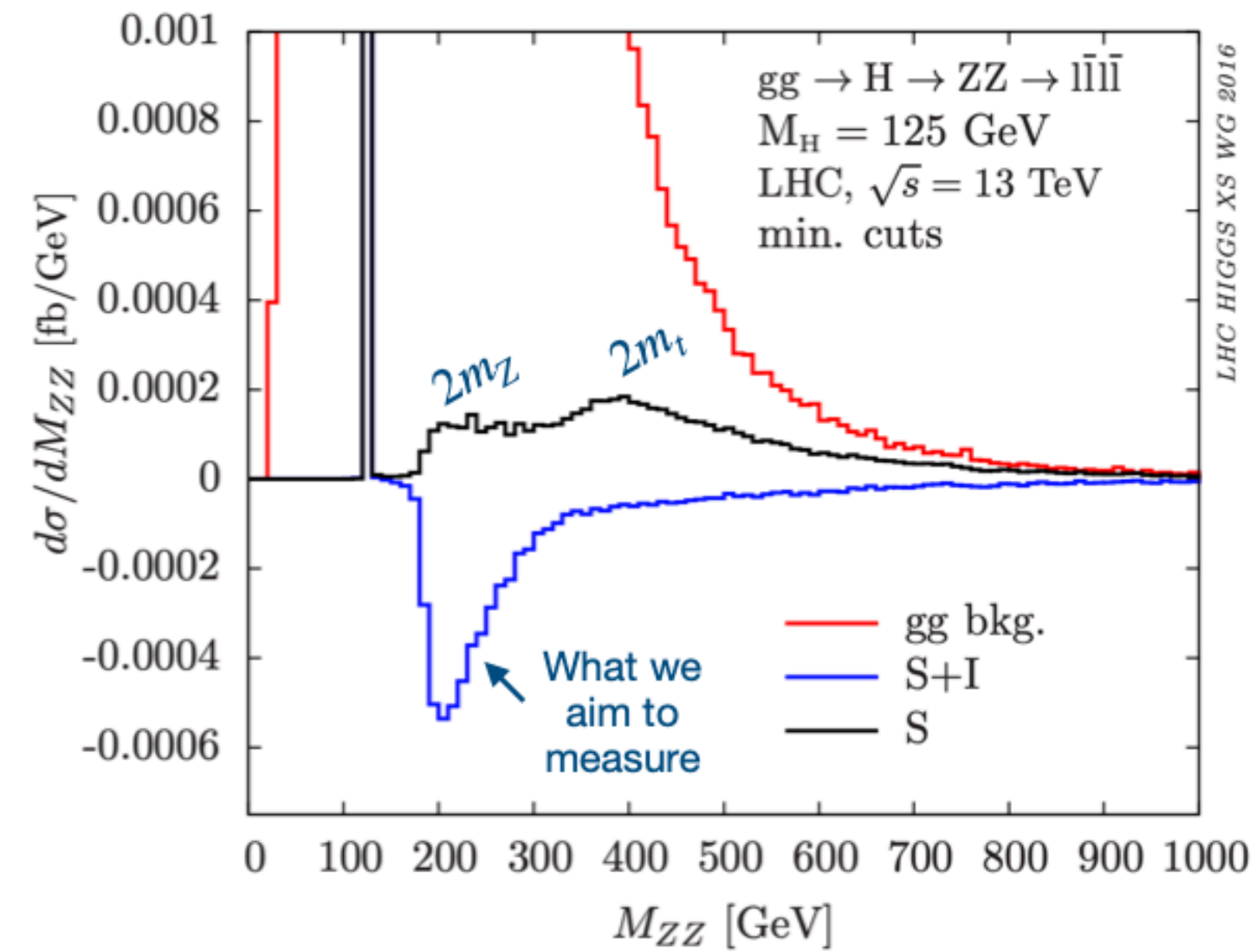
HIGGS

Higgs results

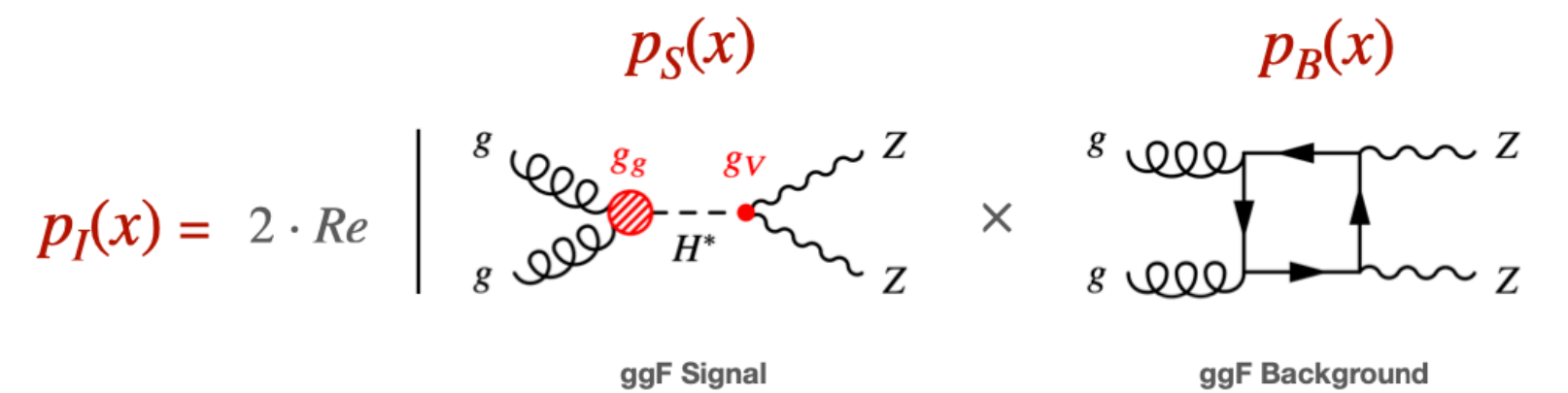
All the details have been discussed on
Oct, 11th by Wouter: [link](#)



Measurement of off-shell Higgs boson production $H \rightarrow ZZ$ using NSBI

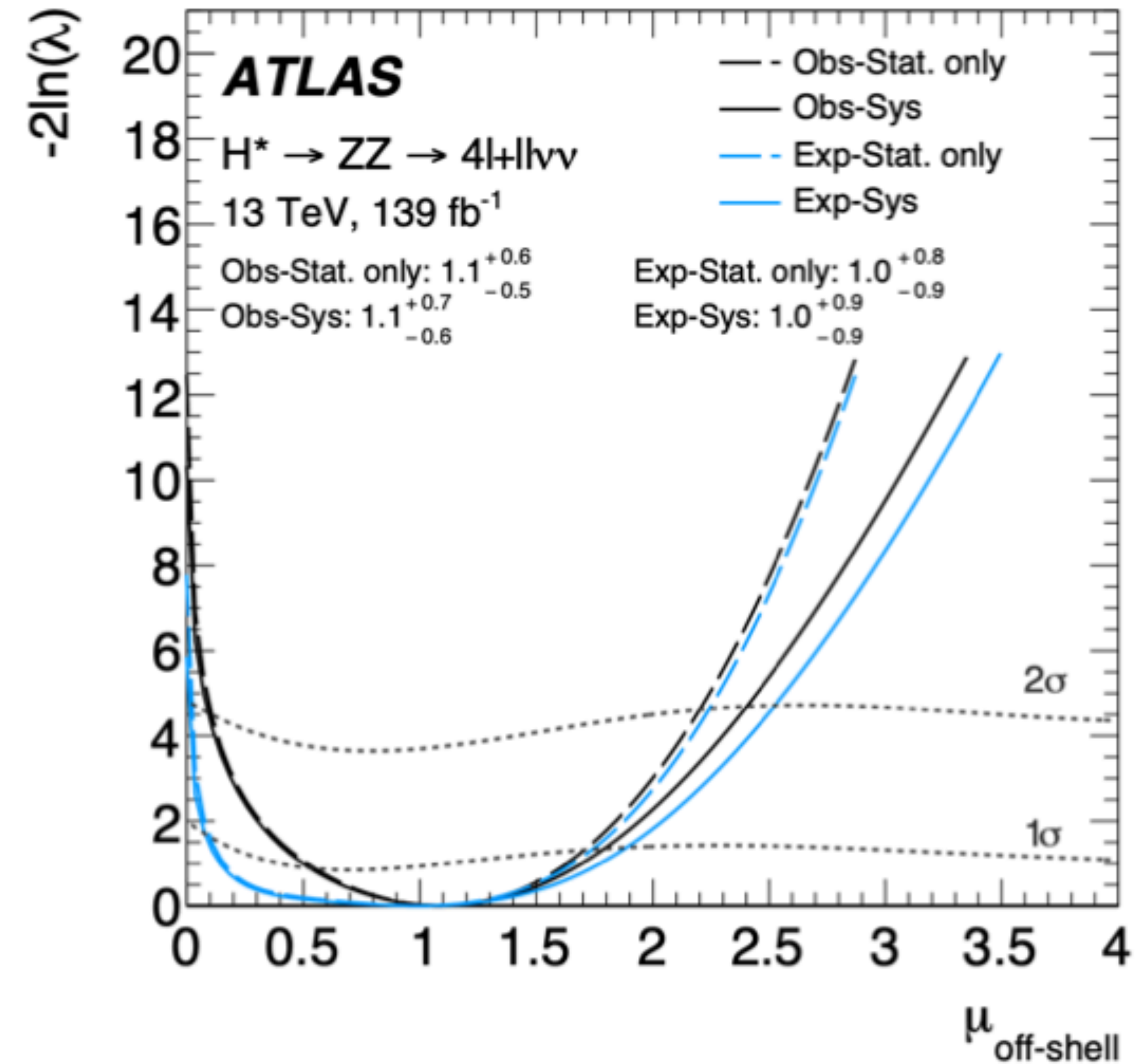


Off-shell Higgs signal (S) strongly interferes (S+I) with background (gg bkg.) and thus cannot be measured independently.



Interfering background

[Link to talk](#)



Higgs results

Measurement of off-shell Higgs boson production $H \rightarrow ZZ$ using NSBI



New Measurement

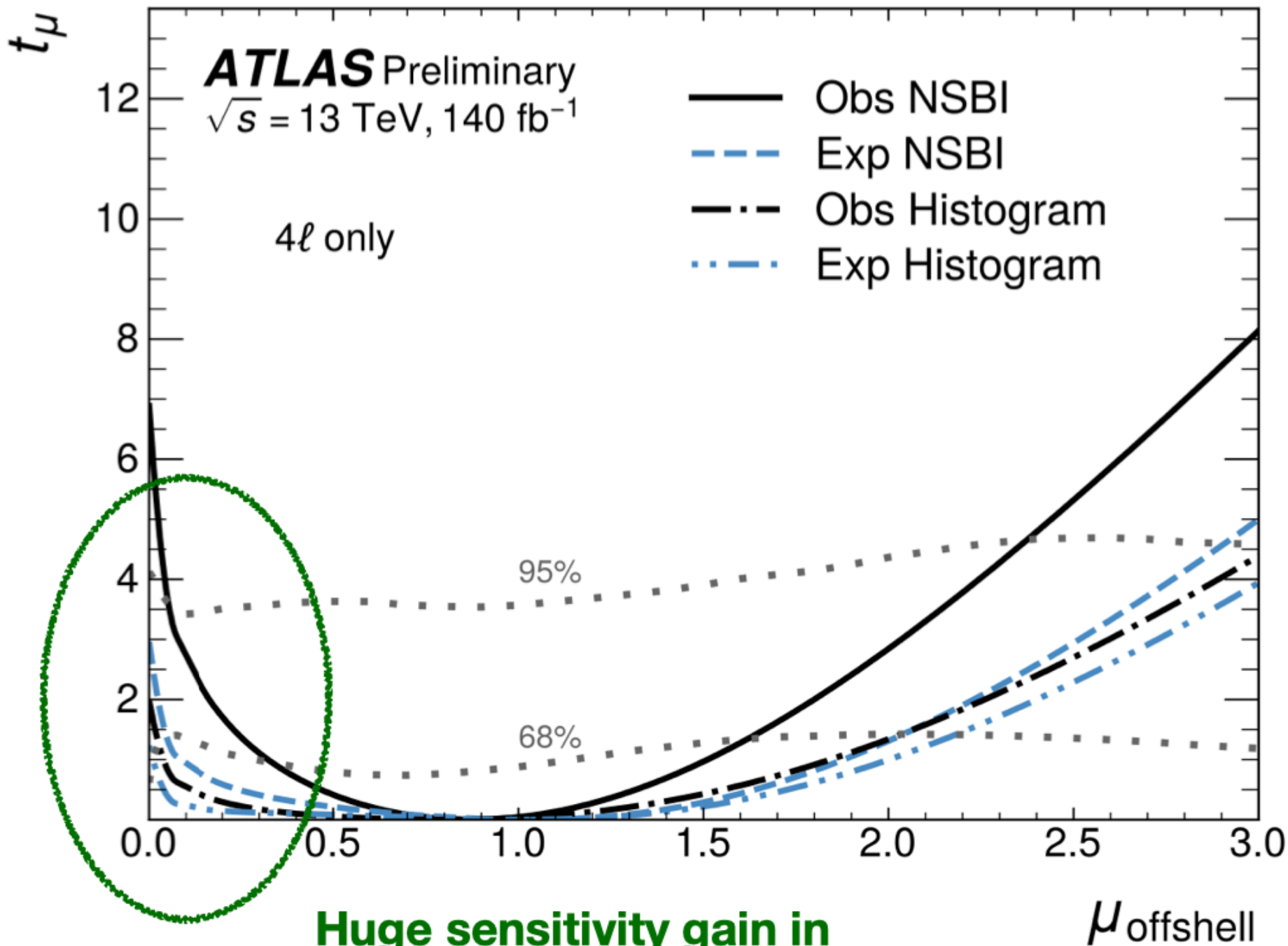
Carefully trained **parameterized per-event density ratios** are now used to build the test statistic:

$$t_\mu \sim -2 \cdot \sum_{i=1}^{N_{obs}} \log \frac{p(x_i | \mu)}{p(x_i | \hat{\mu})}$$

No fixed observable - maximal optimality throughout μ space.

Neyman pearson lemma ✓

Additional sensitivity from unbinned nature (no Poisson fits) ✓



Huge sensitivity gain in interference rich regions $\sqrt{\mu} \cdot p_I(x) \gg \mu \cdot p_S(x)$

[Link to talk](#)

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Rep. Prog. Phys.

[Link](#)

CERN-EP-2024-305
December 3, 2024

An implementation of neural simulation-based inference for parameter estimation in ATLAS

The ATLAS Collaboration

Neural simulation-based inference is a powerful class of statistical inference that naturally handles high-dimensional data. It allows for the estimation of probability density ratios, which enables the use of a large number of simulated events to estimate the finite number of events in training samples, develop intervals, and demonstrates a series of intermediate data to validate the robustness of the method. As an example, the method is applied to the measurement of the Higgs boson production in the $H^* \rightarrow ZZ \rightarrow 4\ell$ decay channel. The method is assessed on simulated data for a simplified coupling measurement in the four-lepton final states. The results are compared to the standard statistical methodology used by the experiment and can benefit many physics analyses.

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Rep. Prog. Phys.

[Link](#)

CERN-EP-2024-298
December 3, 2024

Measurement of off-shell Higgs boson production in the $H^* \rightarrow ZZ \rightarrow 4\ell$ decay channel using a neural simulation-based inference technique in 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A measurement of off-shell Higgs boson production in the $H^* \rightarrow ZZ \rightarrow 4\ell$ decay channel is presented. The measurement uses 140 fb⁻¹ of proton-proton collisions at $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the Large Hadron Collider and supersedes the previous result in this decay channel using the same dataset. The data analysis is performed using a neural simulation-based inference method, which builds per-event likelihood ratios using neural networks. The observed (expected) off-shell Higgs boson production signal strength in the $ZZ \rightarrow 4\ell$ decay channel at 68% CL is $0.87^{+0.75}_{-0.54}$ ($1.00^{+1.04}_{-0.92}$). The evidence for off-shell Higgs boson production using the $ZZ \rightarrow 4\ell$ decay channel has an observed (expected) significance of 2.5σ (1.3σ). The expected result represents a significant improvement relative to that of the previous analysis of the same dataset, which obtained an expected significance of 0.5σ . When combined with the most recent ATLAS measurement in the $ZZ \rightarrow 2\ell 2\nu$ decay channel, the evidence for off-shell Higgs boson production has an observed (expected) significance of 3.7σ (2.4σ). The off-shell measurements are combined with the measurement of on-shell Higgs boson production to obtain constraints on the Higgs boson total width. The observed (expected) value of the Higgs boson width at 68% CL is $4.3^{+2.7}_{-1.9}$ ($4.1^{+3.5}_{-3.4}$) MeV.

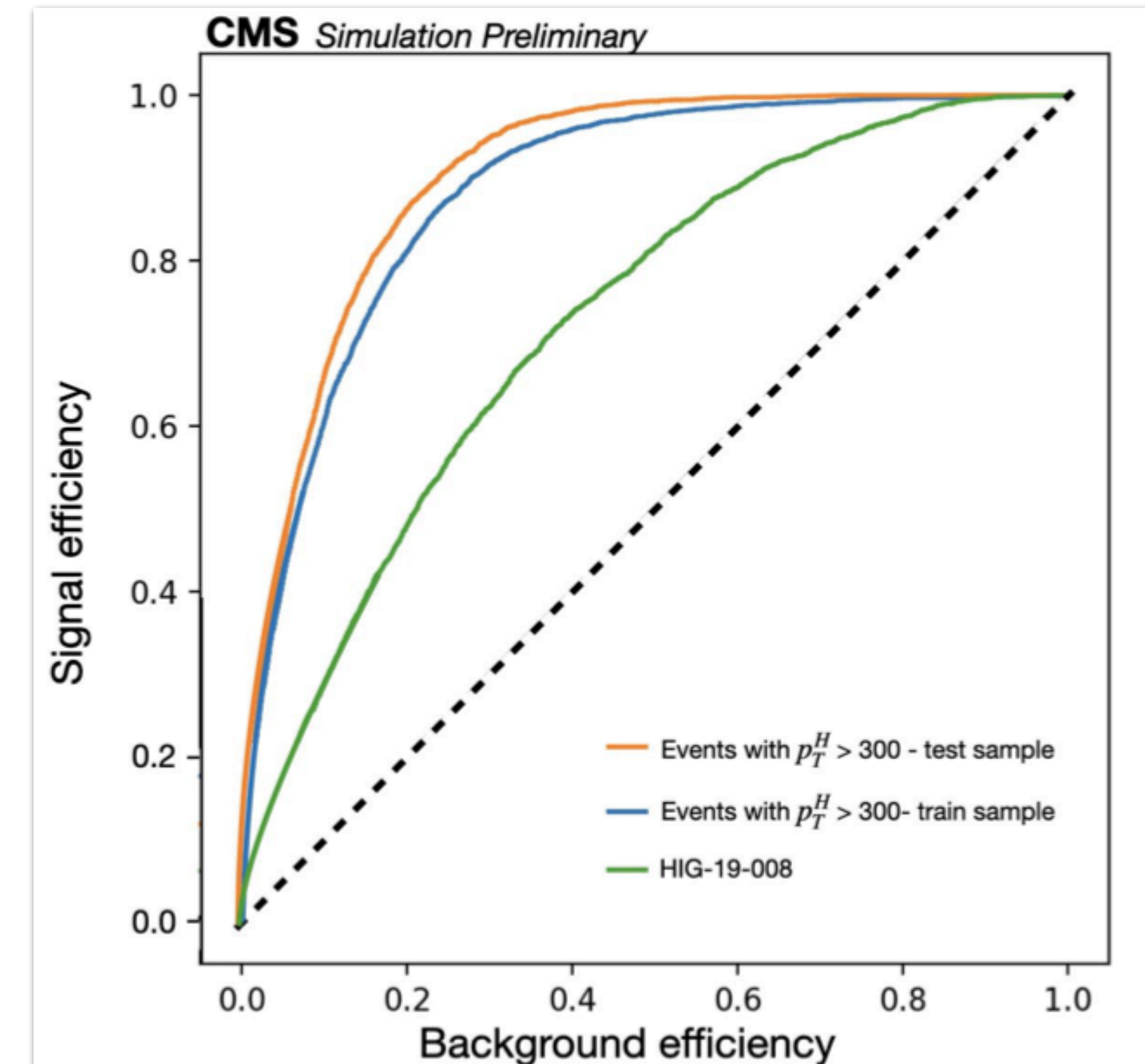
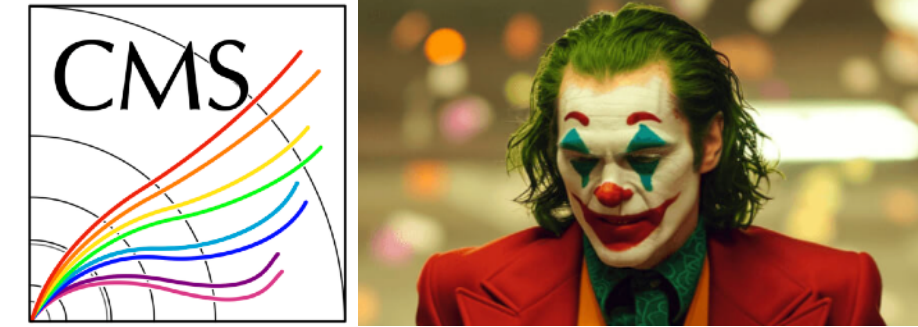
ttH(multileptons) analysis

-
- The diagram illustrates the production and decay of a Higgs boson (H) via gluon fusion. On the left, two incoming gluons (g , represented by curly lines) interact through a triangular loop of top quarks (t and $\bar{t}$). The top quark lines are solid with arrows indicating the flow of fermion number. The Higgs boson (H , represented by a dashed line) is produced at the top vertex of this loop. On the right, the Higgs boson decays through another triangular loop, this time involving charged leptons (ℓ^+ and ℓ^-). The lepton lines are solid with arrows. The decay products are two photons (γ , represented by curly lines). Various intermediate states are labeled: W^+ and W^- for the gauge bosons, and ν_ℓ for the neutrinos. The final state particles are labeled b , $\bar{b}$, q , and $\bar{q}$.

Higgs results

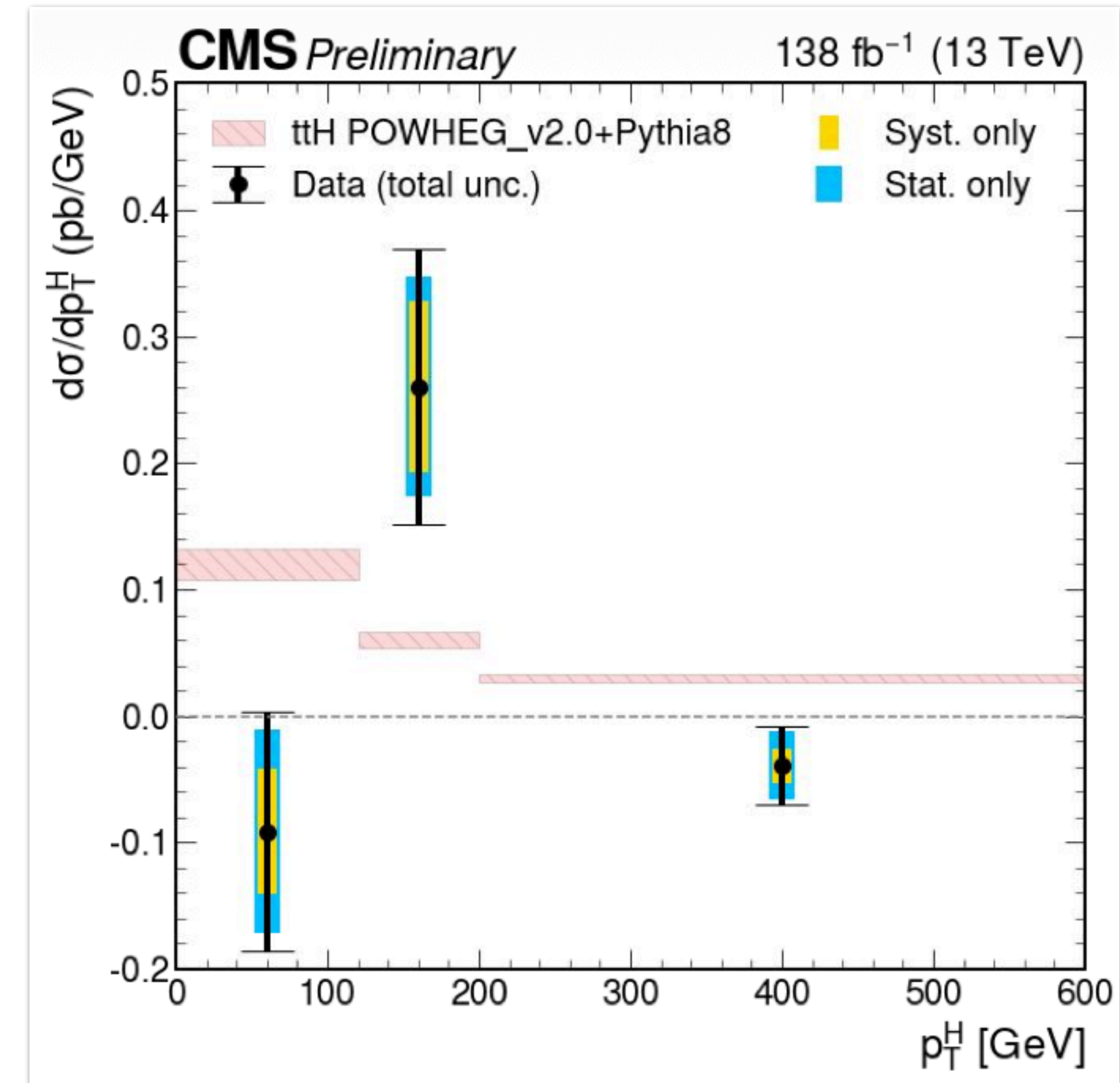
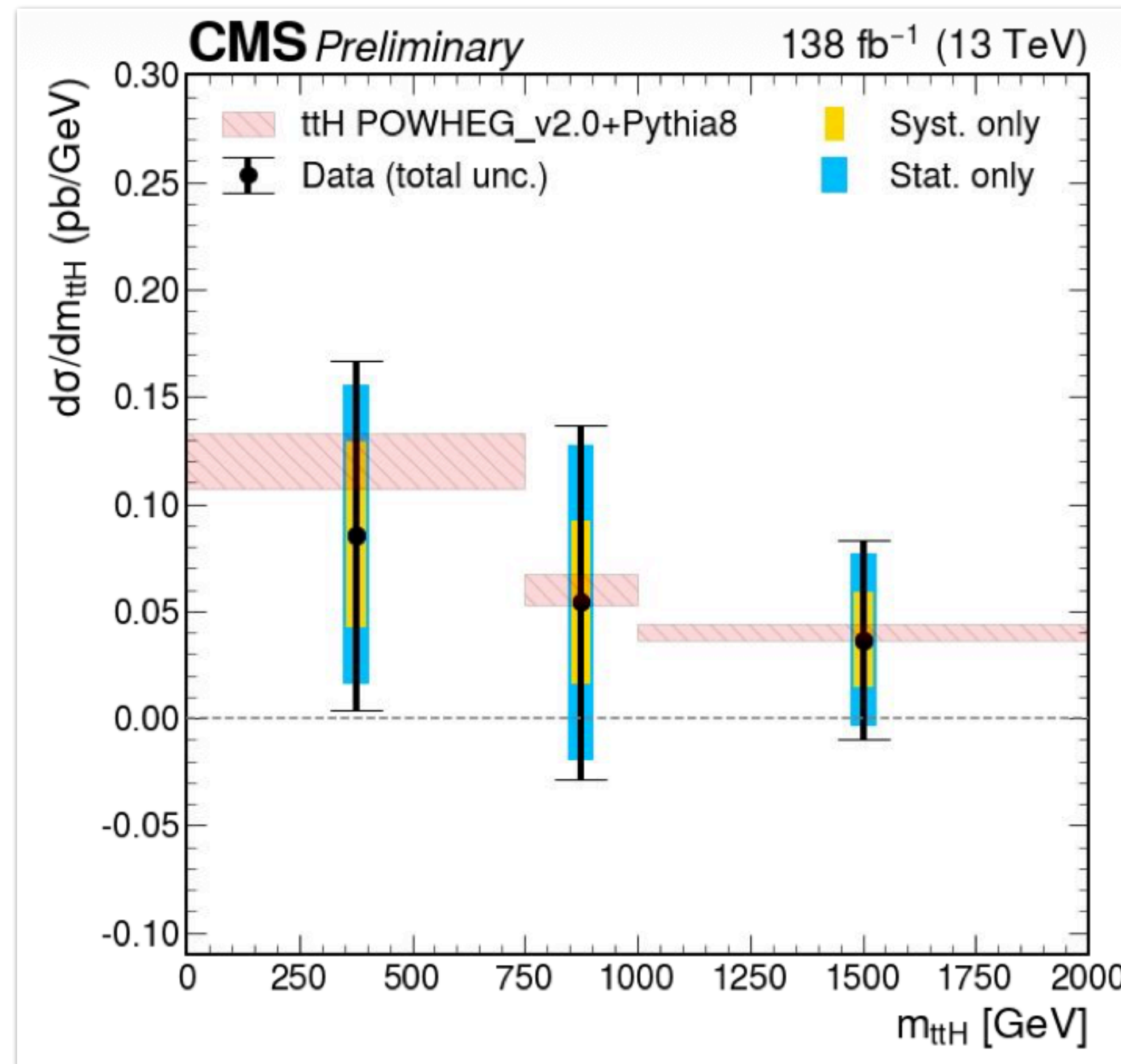
ttH(multileptons) analysis

- Target $H \rightarrow WW$ (leptonic/semi-leptonic) and $H \rightarrow \tau\tau$ (hadronic/leptonic)
- Focus on the most sensitive channels $2l_{ss} + 0\tau/1\tau$, $3l + 1\tau$
- **Main backgrounds**
 - Irreducible ttW/ttZ - shape estimate from MC, norm from CR
 - Reducible tt and W+jets - data-driven methods
- DNN multi classifier to distinguish ttH from bkg
- **[NEW]** DNN regression to reconstruct Higgs p_T (*low and high*)
- Maximum likelihood fit in SRs, 3l CR and 4l CR



Higgs results

ttH(multileptons) analysis



ATLAS ttH(ML) Run 2 analysis is on-going [under unblinding approval]

Higgs results

VH(bb) SMEFT analysis

[Link to talk](#)

- New Run2 analysis designed to target SMEFT effects

- Constraints on c_{Hq}^3 , c_{Hq}^1 , c_{Hu} , c_{Hd} , g_2^{ZZ} , g_4^{ZZ}

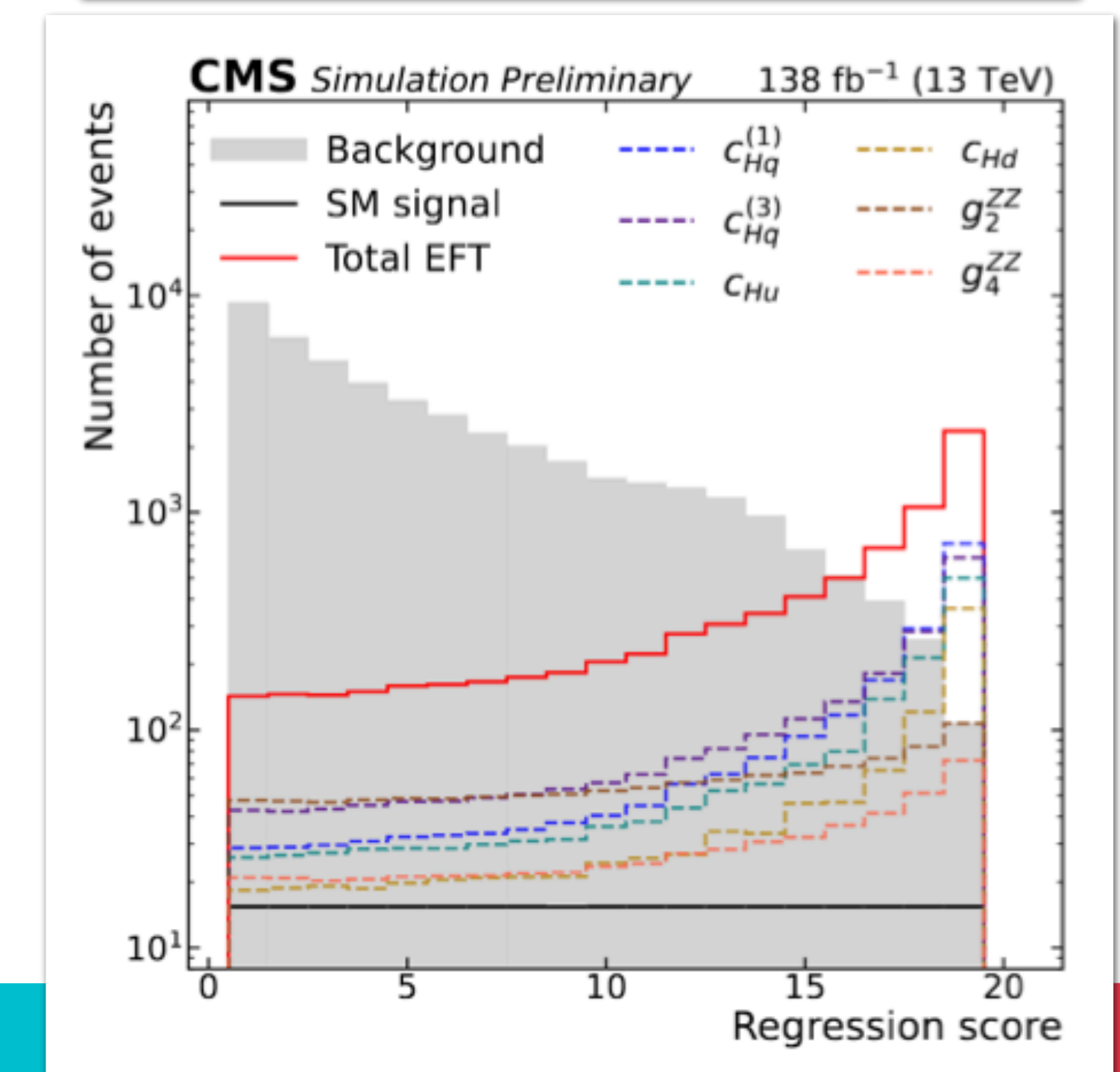
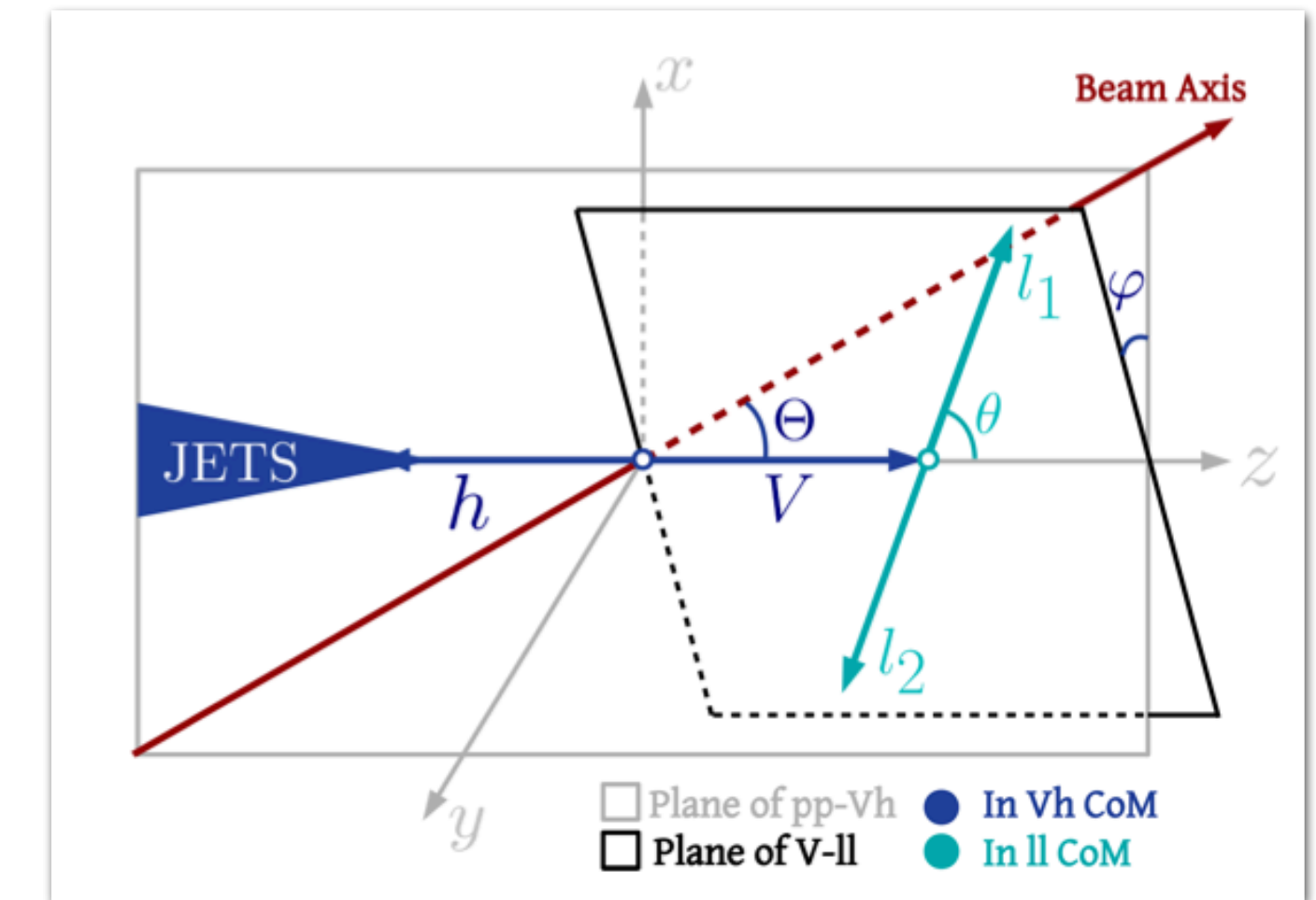
- Analysis targeting V(llep)H(bb) events

- Both boosted and resolved regimes (p_T split 250 GeV)



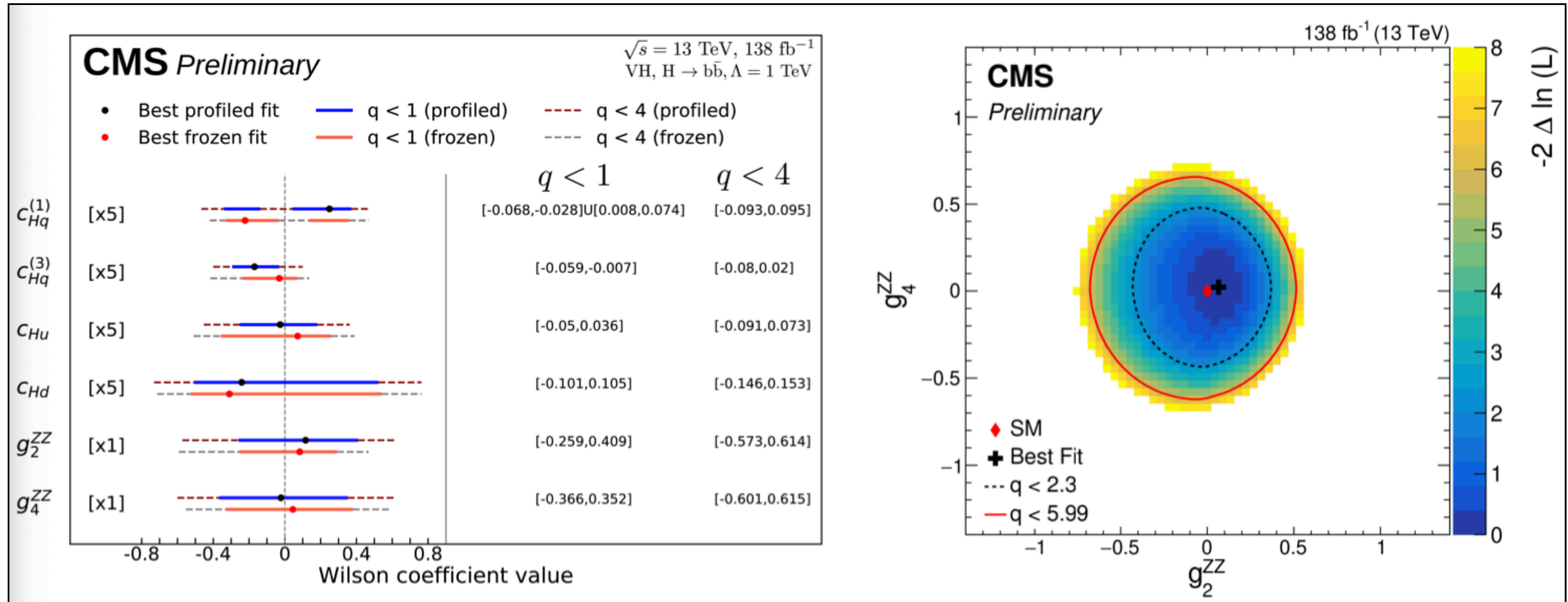
- Boosted Information Tree (BIT) to separate EFT effects from SM signal and background

- Using angular observables sensitive to interference effects



Higgs results

VH(bb) SMEFT analysis

[Link to talk](#)


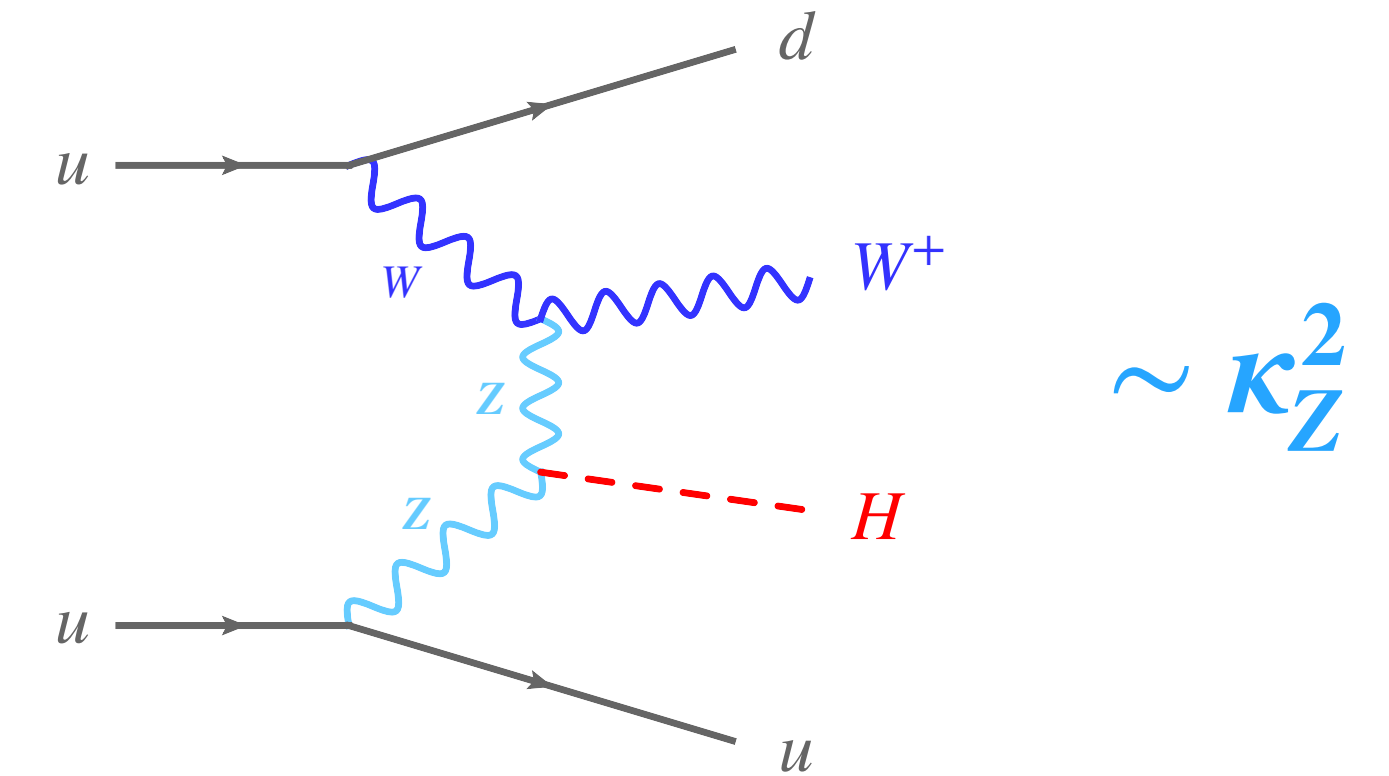
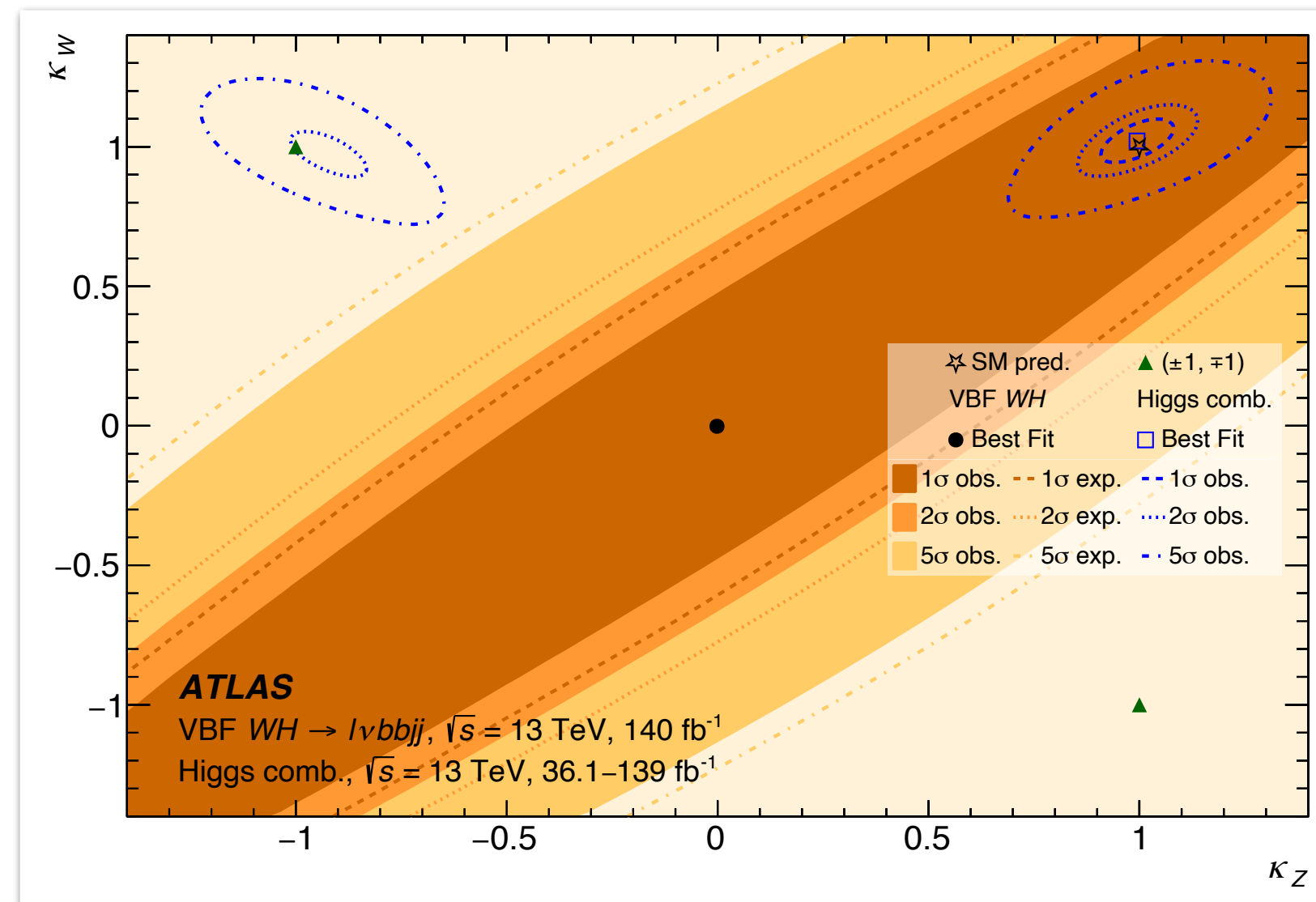
Higgs results

Relative sign of κ_W and κ_Z

- First VBF WH analysis $\rightarrow$ Unique sensitivity to the relative sign of $|\lambda_{WZ}| = \kappa_W/\kappa_Z$

$$\begin{aligned}\sigma_{\text{VBF},WH} &\propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2 \kappa_Z \kappa_W \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W] \\ &= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2 \kappa_Z^2 \lambda_{WZ} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]\end{aligned}$$

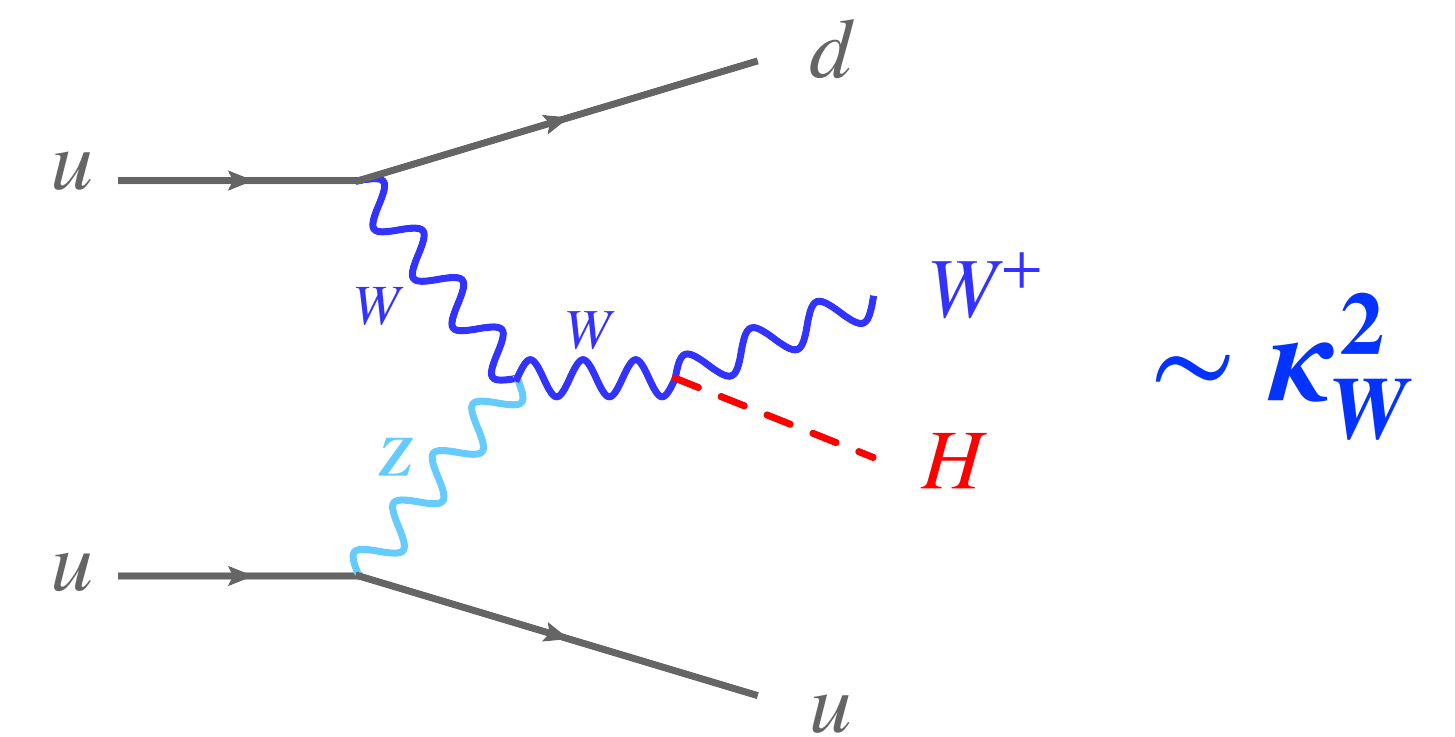
- Exclusion of opposite sign for κ_W and κ_Z with significance $>5\sigma$



+

Interference

$\sim \kappa_W \kappa_Z$



Uppsala





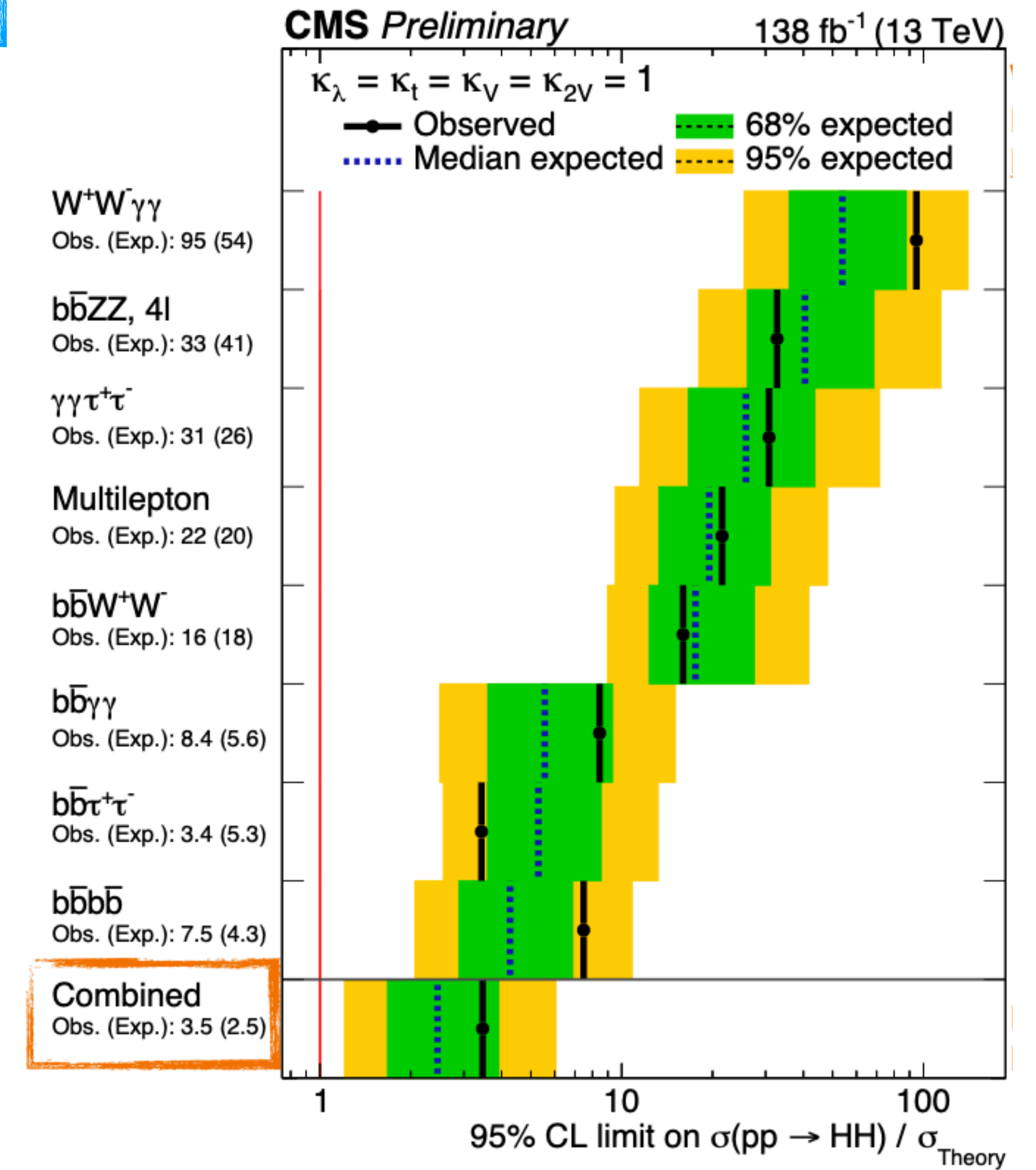
Di- and
Triple-Higgs

Di-Higgs results

CMS - HH combination

- New results added for this combination:

Published for Higgs
2024



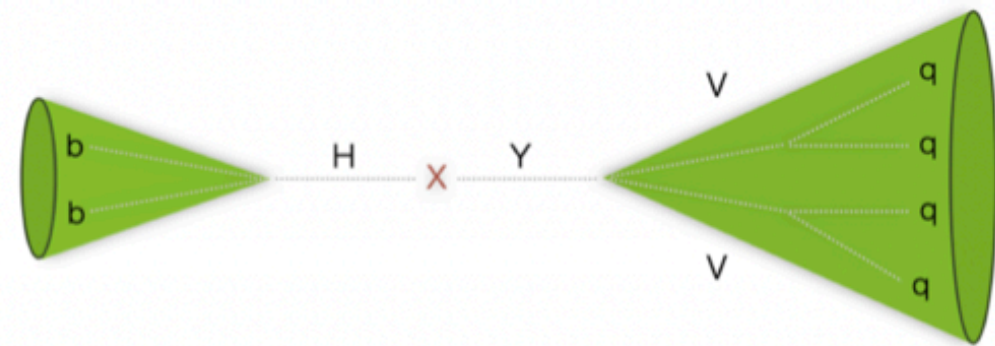
Di-Higgs results

CMS - HH combination

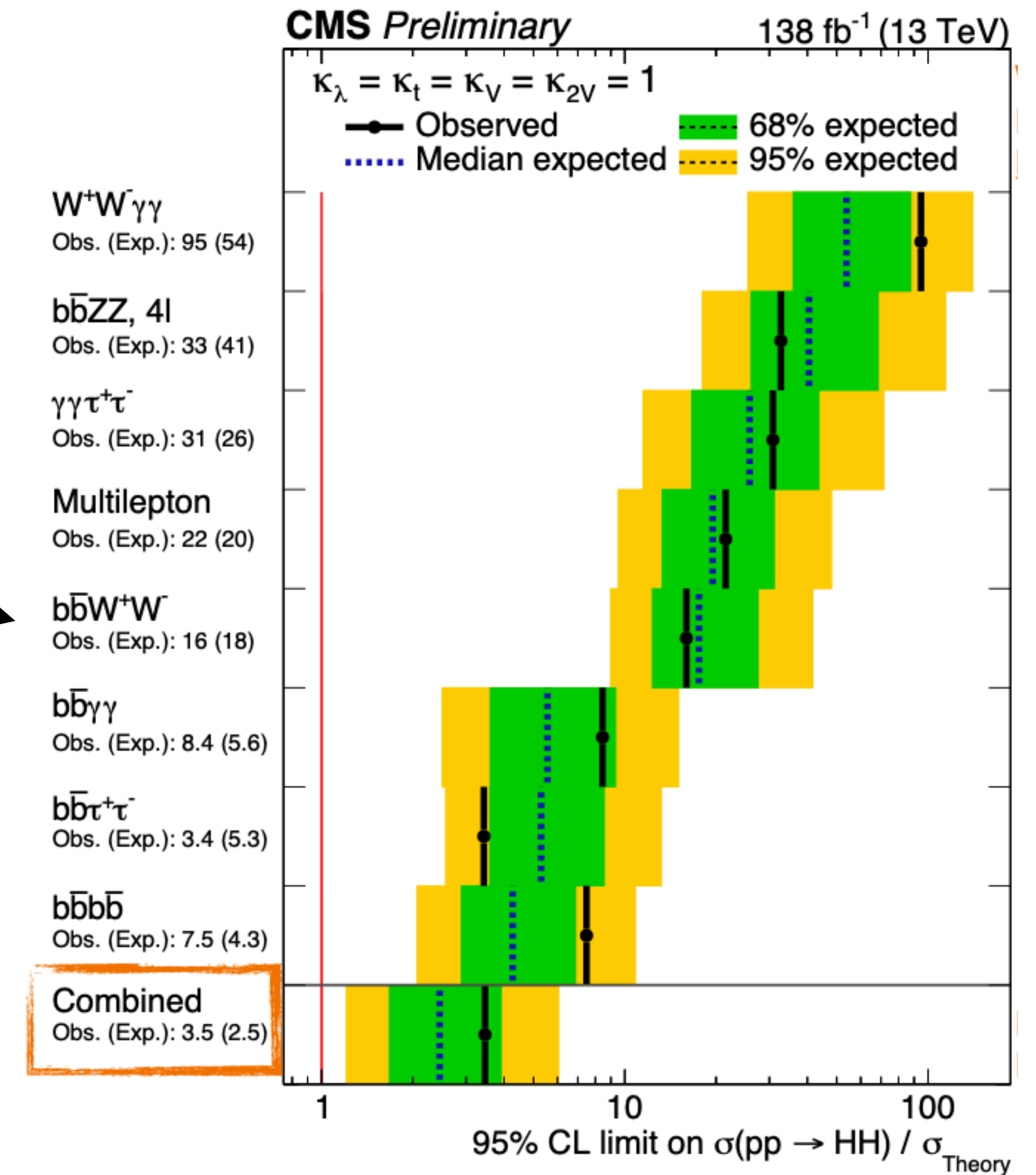
- New results added for this combination: bbVV

New since Higgs2023

bbVV:



- Jets ID with deep neural network
- BDT to separate signal (ggF/VBF) from backgrounds
- Fit m_{bb}



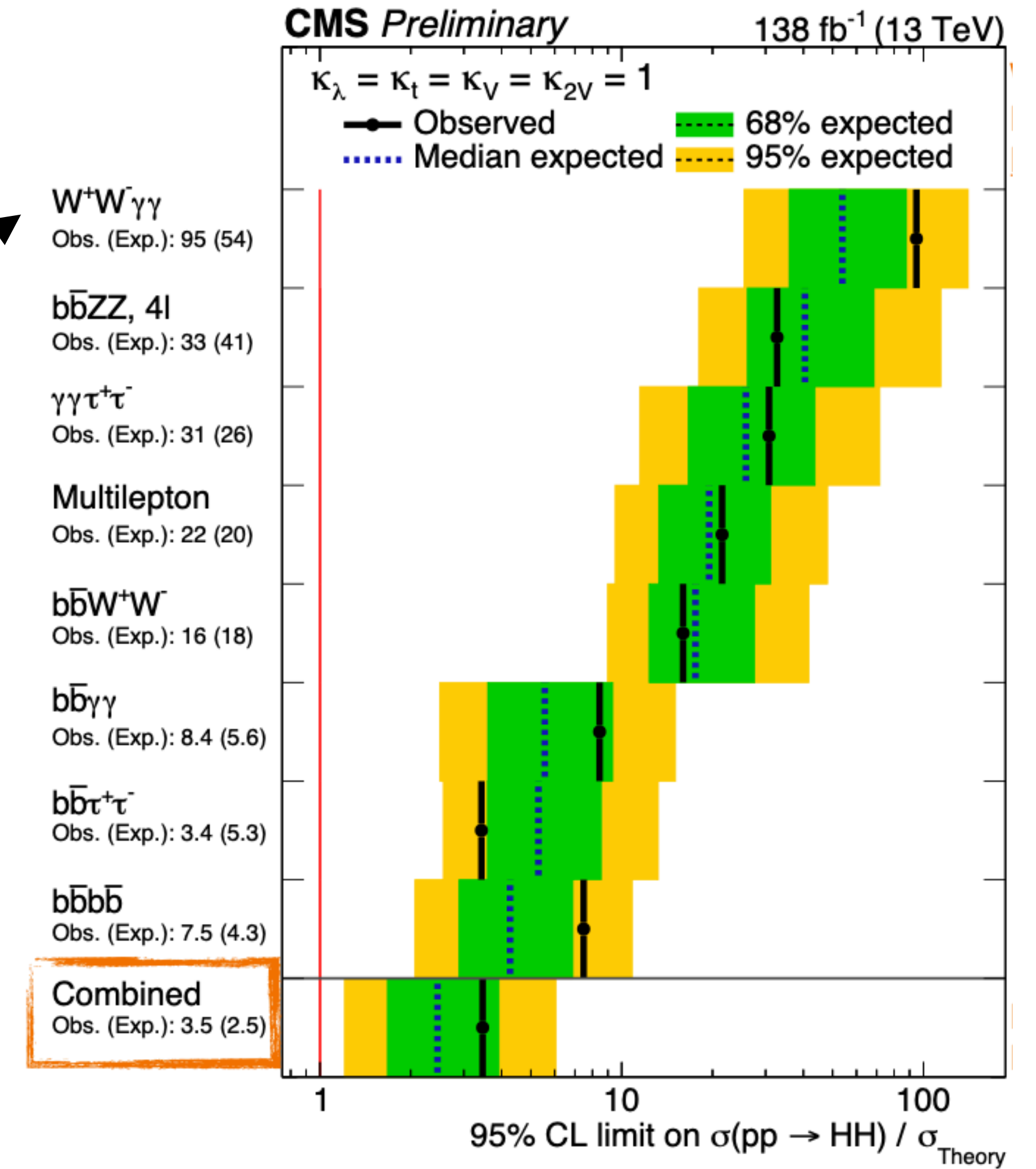
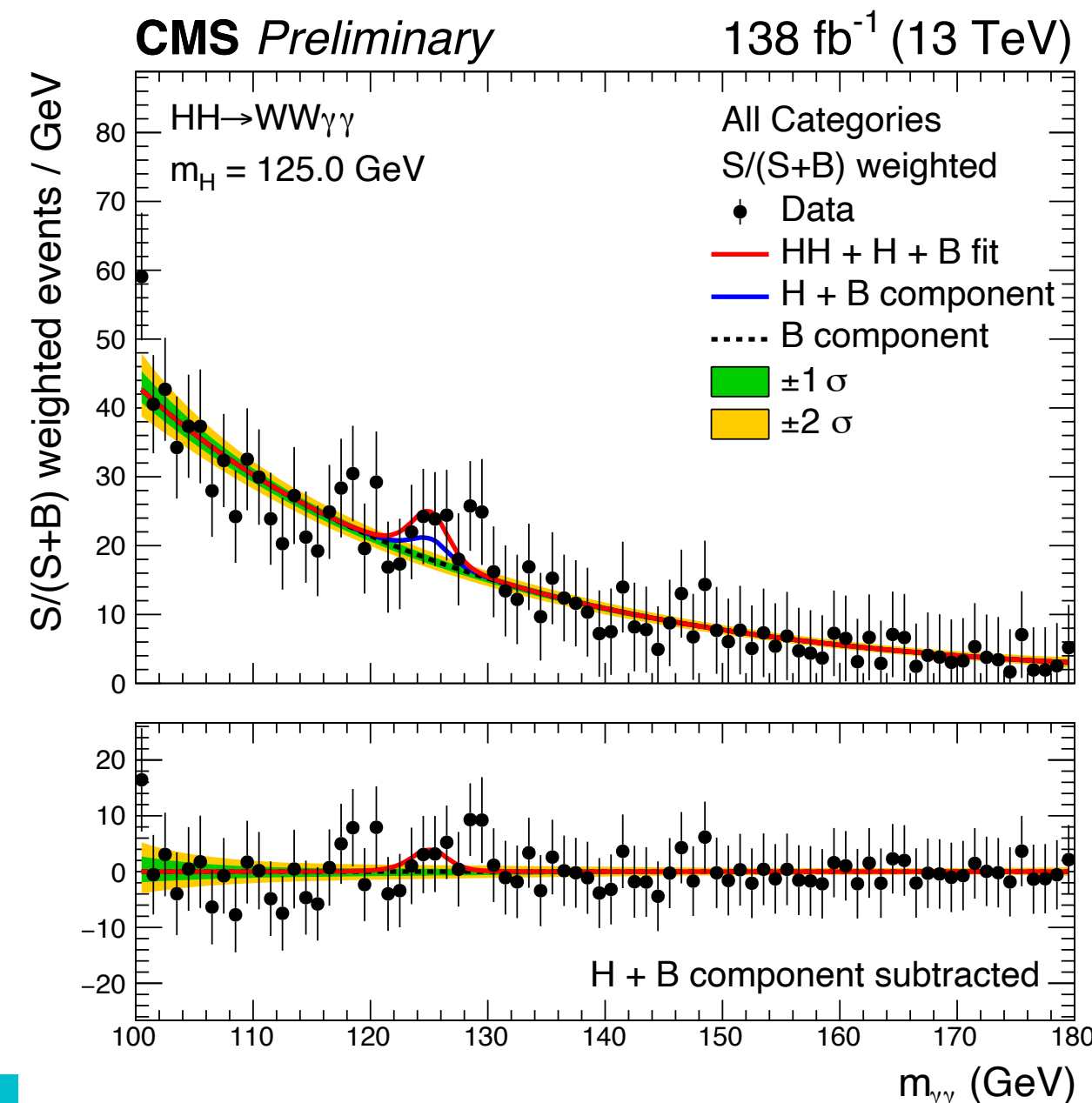
Di-Higgs results

CMS - HH combination

- New results added for this combination: $bbVV$, $WW\gamma\gamma$

$WW\gamma\gamma$:

- BDT to separate signal from background
- Fit $m_{\gamma\gamma}$



Di-Higgs results

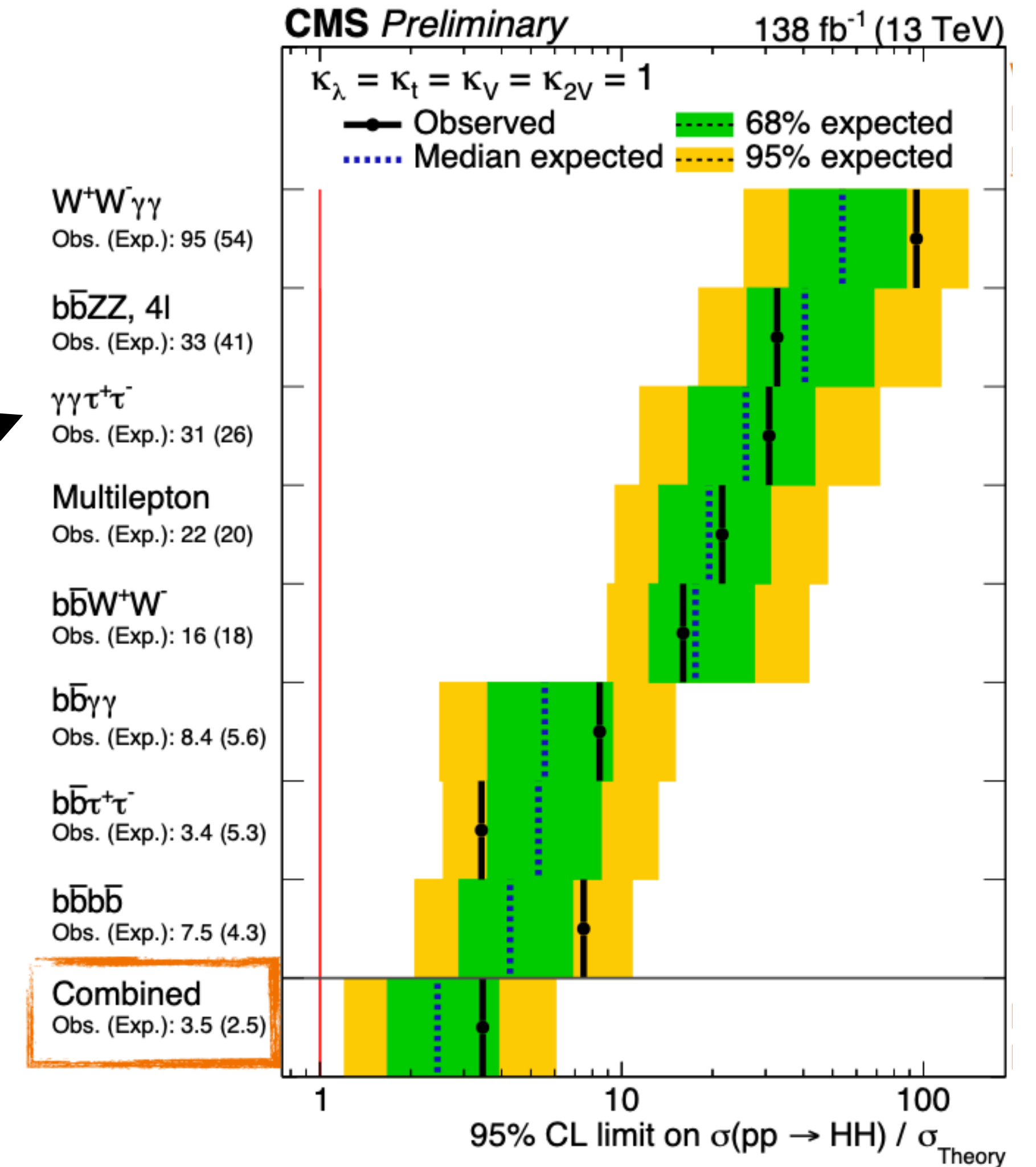
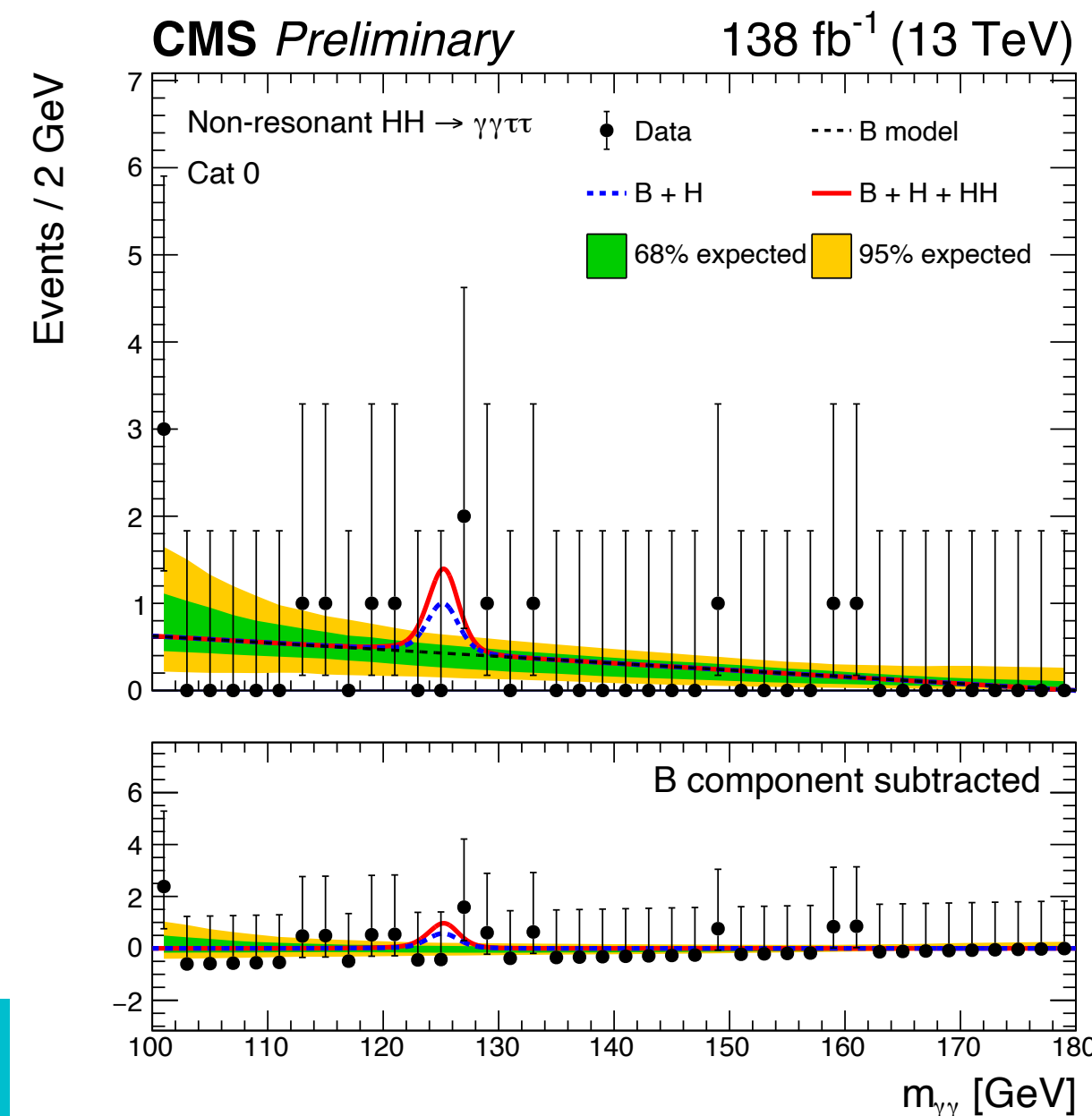
CMS - HH combination

- New results added for this combination: $bbVV$, $WW\gamma\gamma$ and $\tau\tau\gamma\gamma$

$\tau\tau\gamma\gamma$: BR = 0.03%

- τ ID with deep neural network and good $m_{\gamma\gamma}$ resolution
- BDT to separate signal from background
- Fit $m_{\gamma\gamma}$

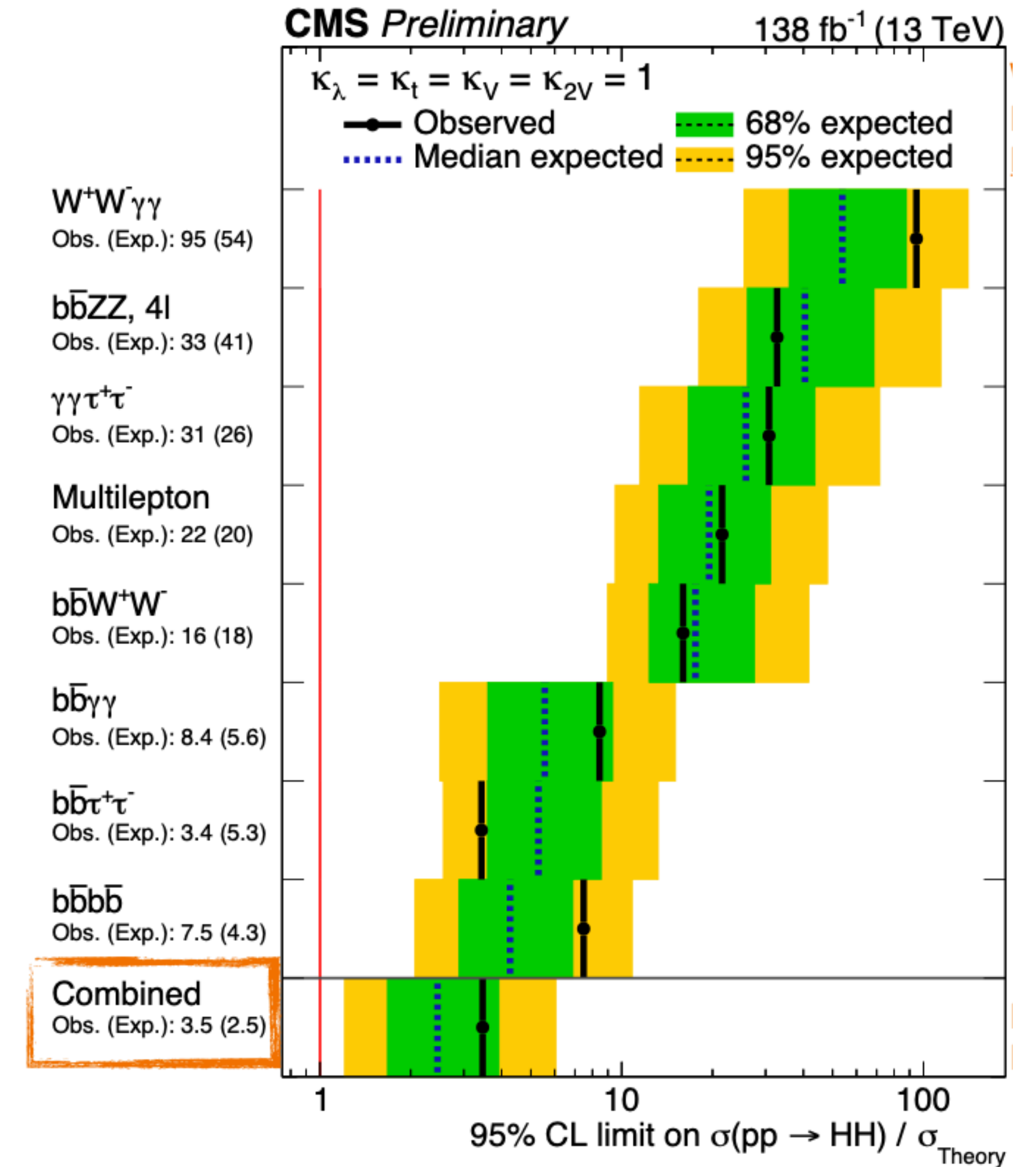
New since Higgs2023



Di-Higgs results

CMS - HH combination

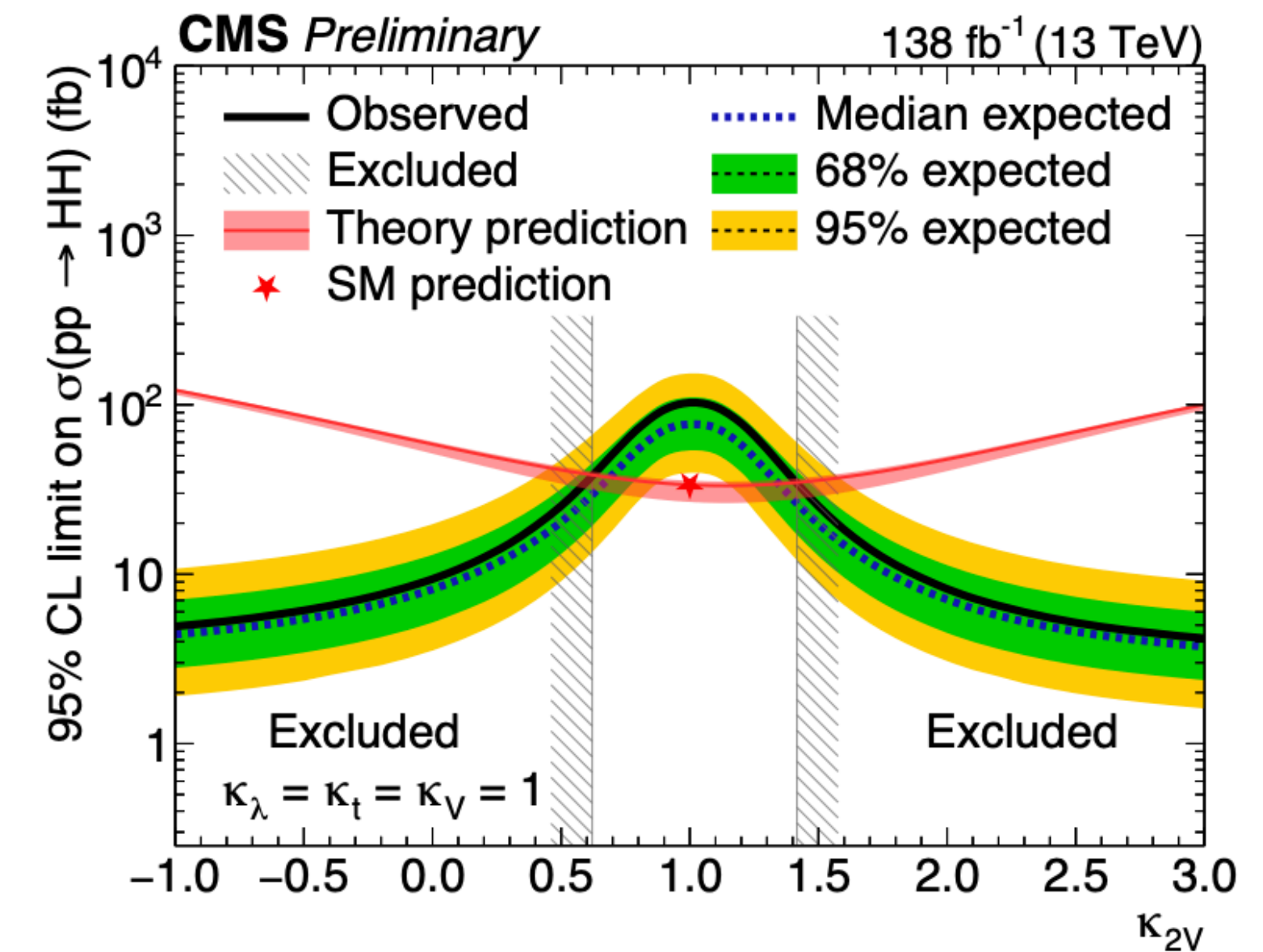
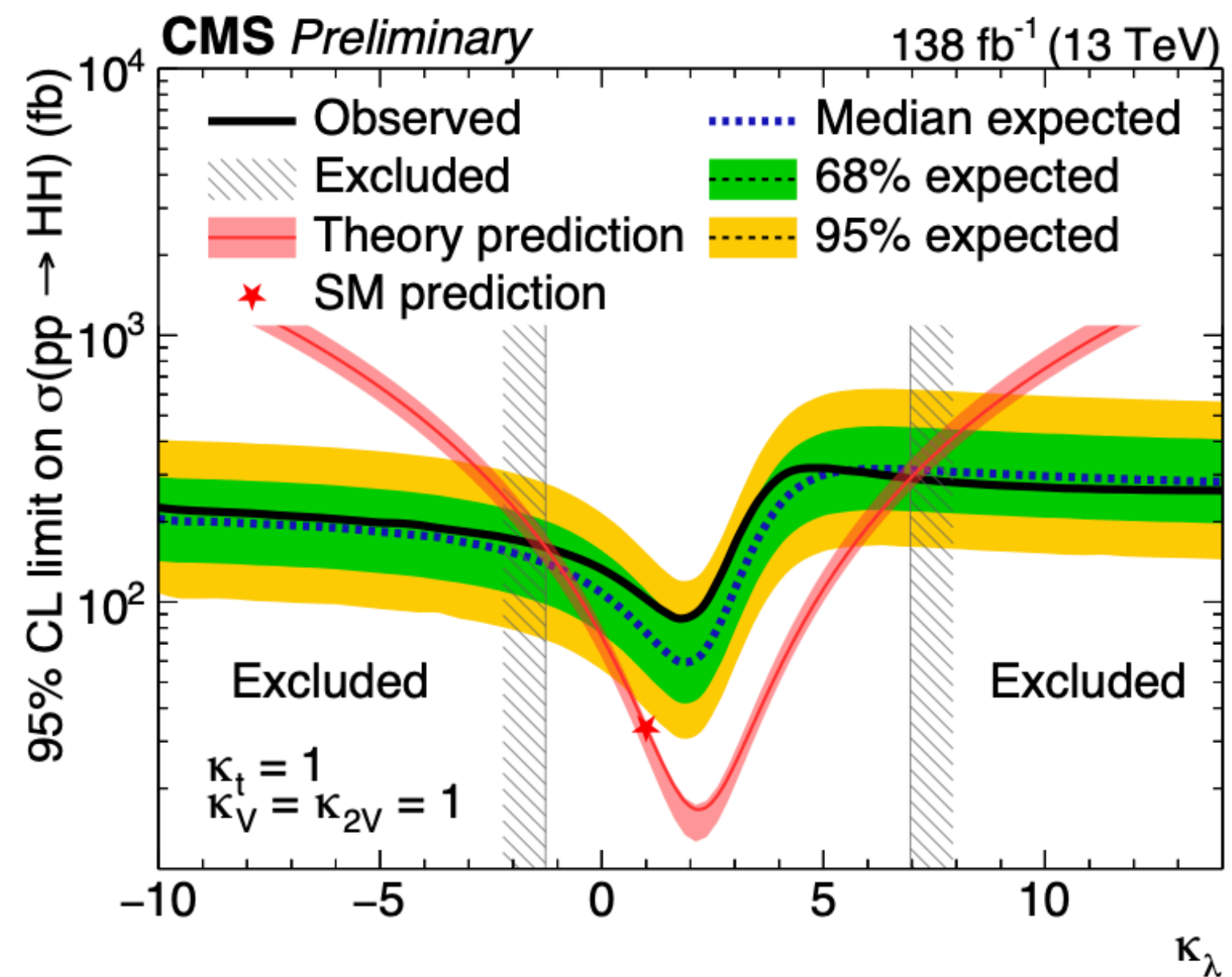
- New results added for this combination: $bbVV$, $WW\gamma\gamma$ and $\tau\tau\gamma\gamma$
- Results slightly higher for this round due to the new signal recommendation from LHC WG and new overlap removal procedure
 - Results for Combined are almost identical than the [previously](#) → Obs. (Exp.): 3.4 (2.5)
 - [ATLAS results](#) → Obs. (Exp.): 2.9 (2.4)



Di-Higgs results

CMS - HH combination

- Updated numbers for Higgs self-coupling and VHH coupling



Observed : $\kappa_{2V} \in [0.62, 1.42]$

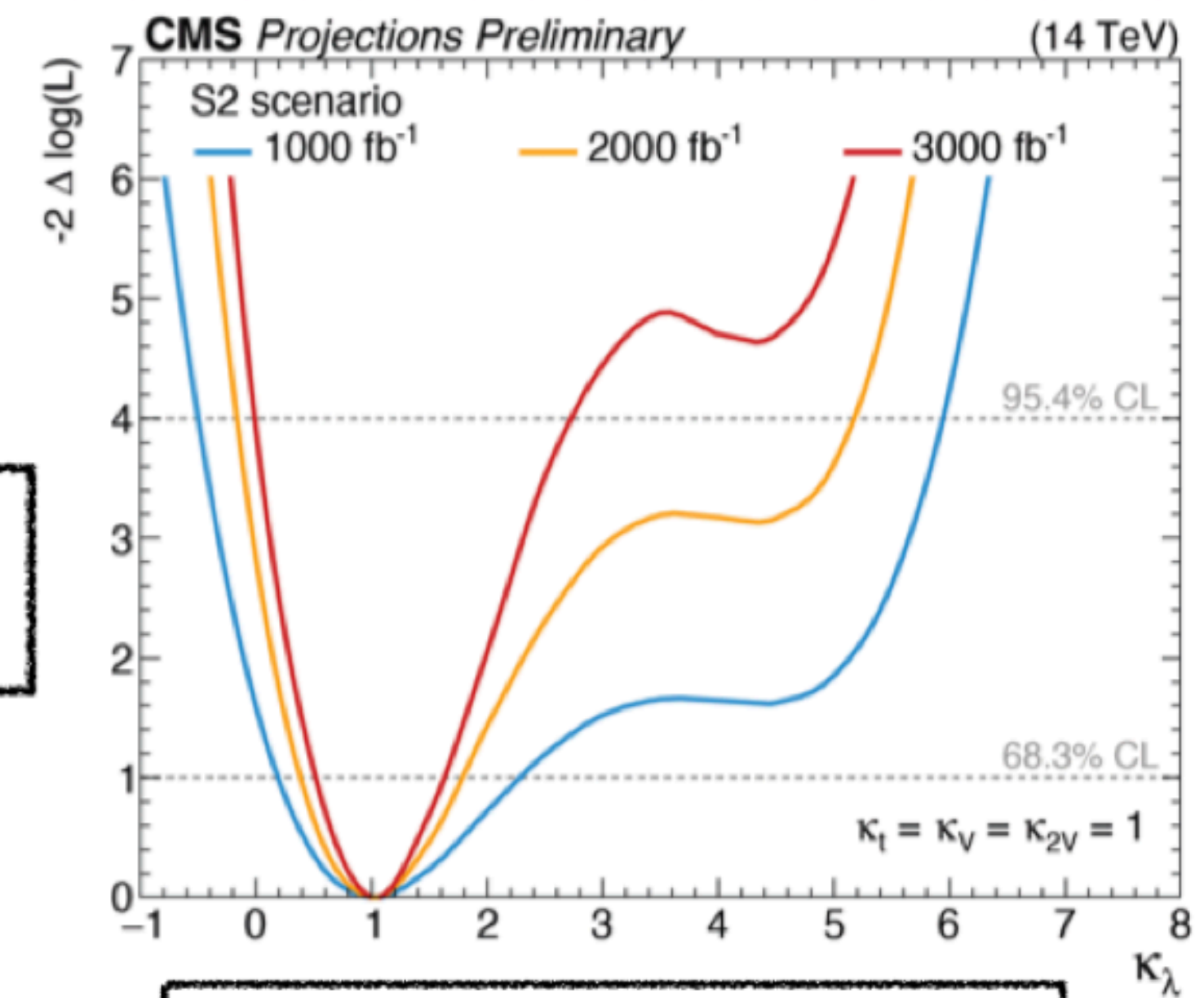
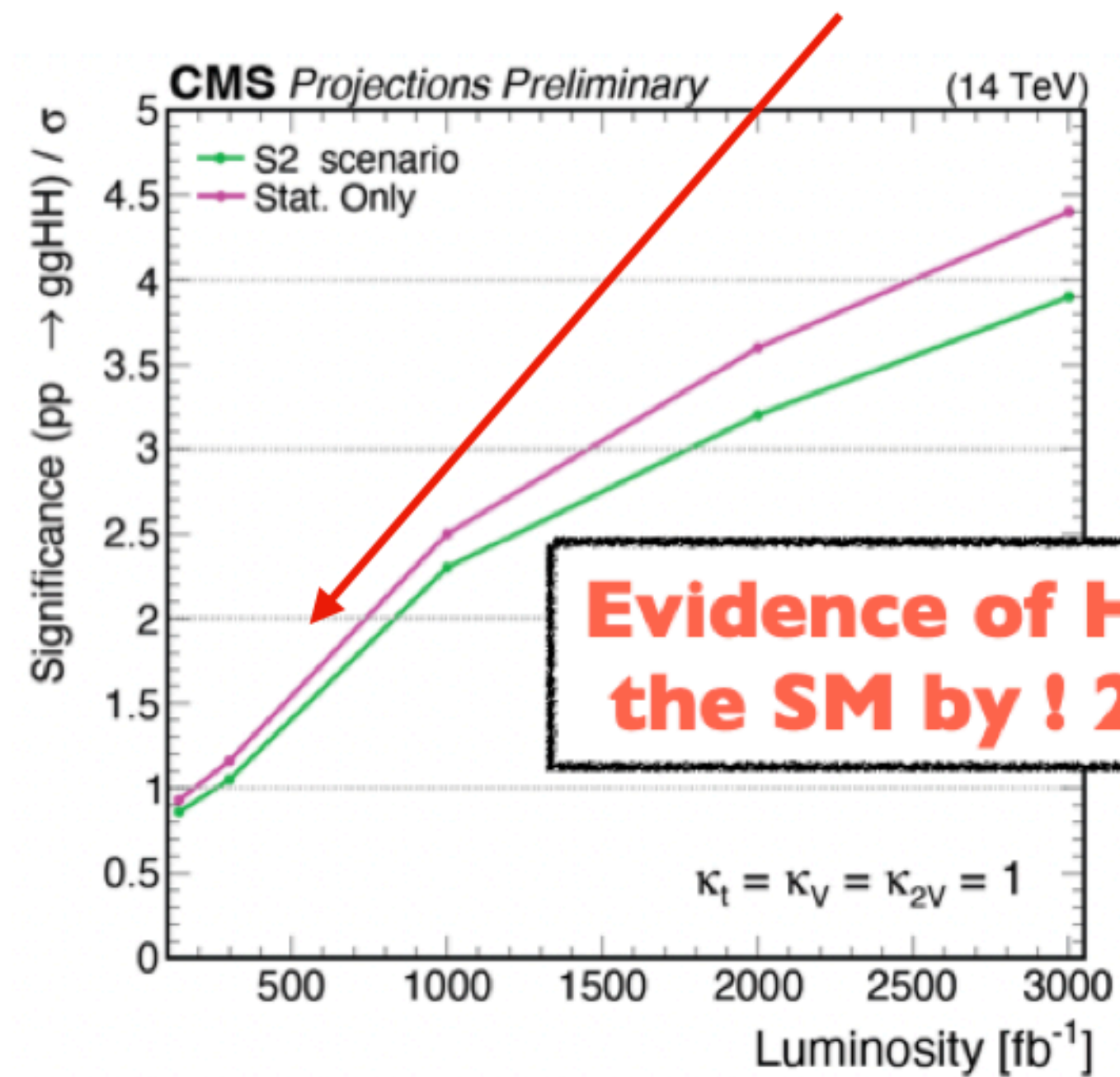
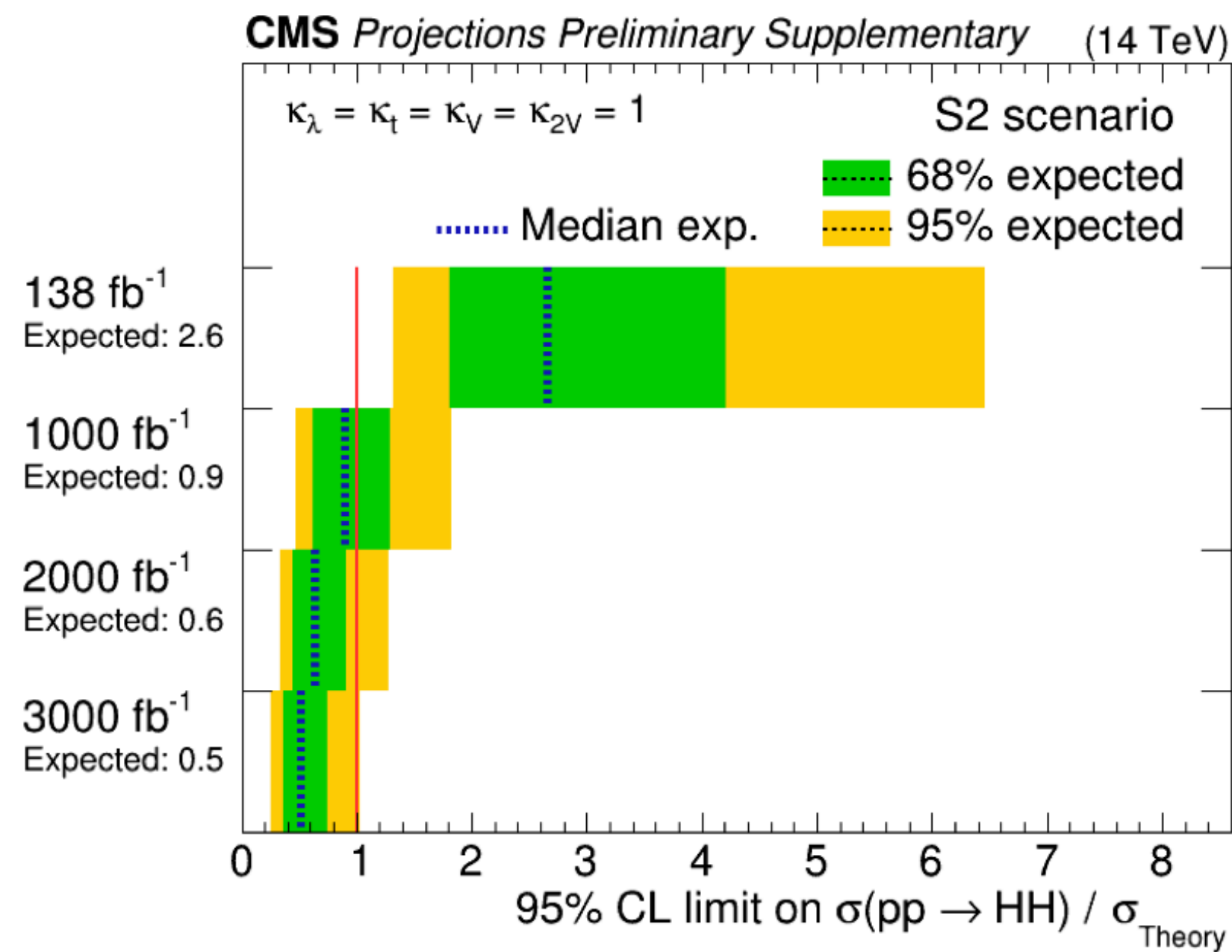
Expected : $\kappa_{2V} \in [0.69, 1.35]$

VHH coupling established at $\sim 7\sigma$ significance

Di-Higgs results

CMS - HH combination

- Updated numbers also for the HL-LHC extrapolation:
 - $bb\gamma\gamma$ and $bb\tau\tau$ lead the combination with 0.9 expected at the end of the HL-LHC
 - More than 30% improvement compared to previous results



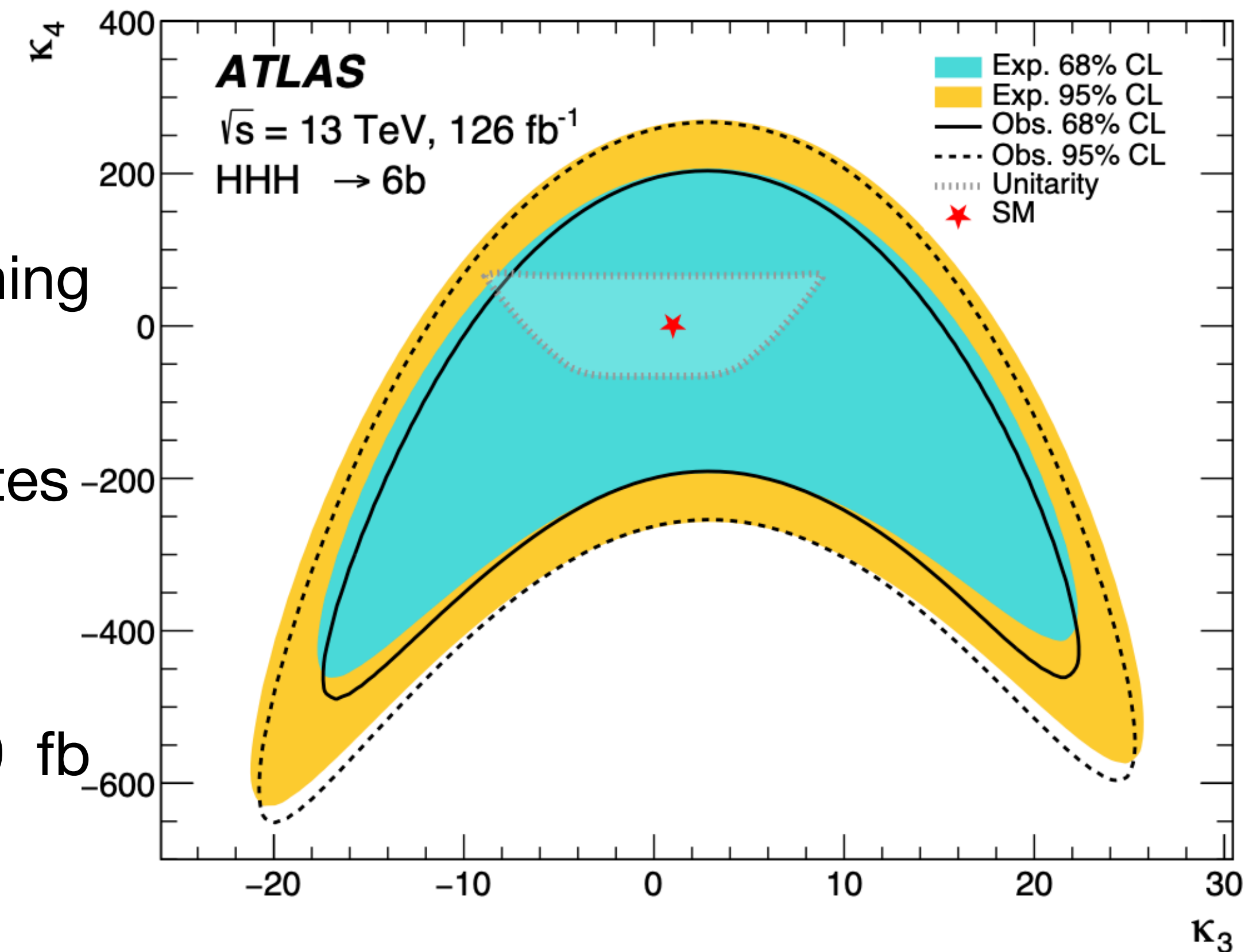
Best fit on κ_λ between [0.5, 1.6] @ 68% CL by the end of the HL-LHC run

First HHH results

ATLAS - HHH $\rightarrow$ 6b

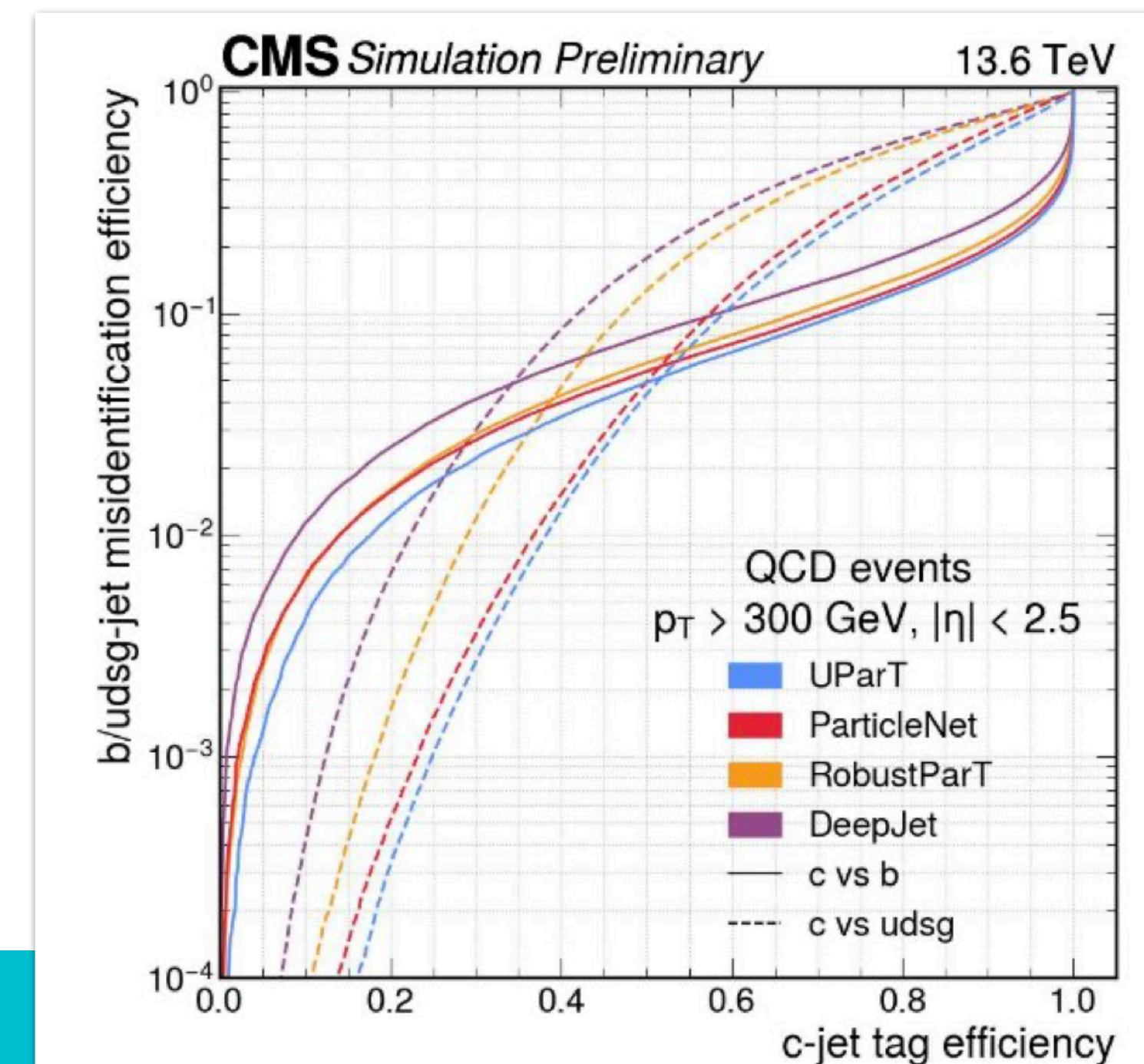
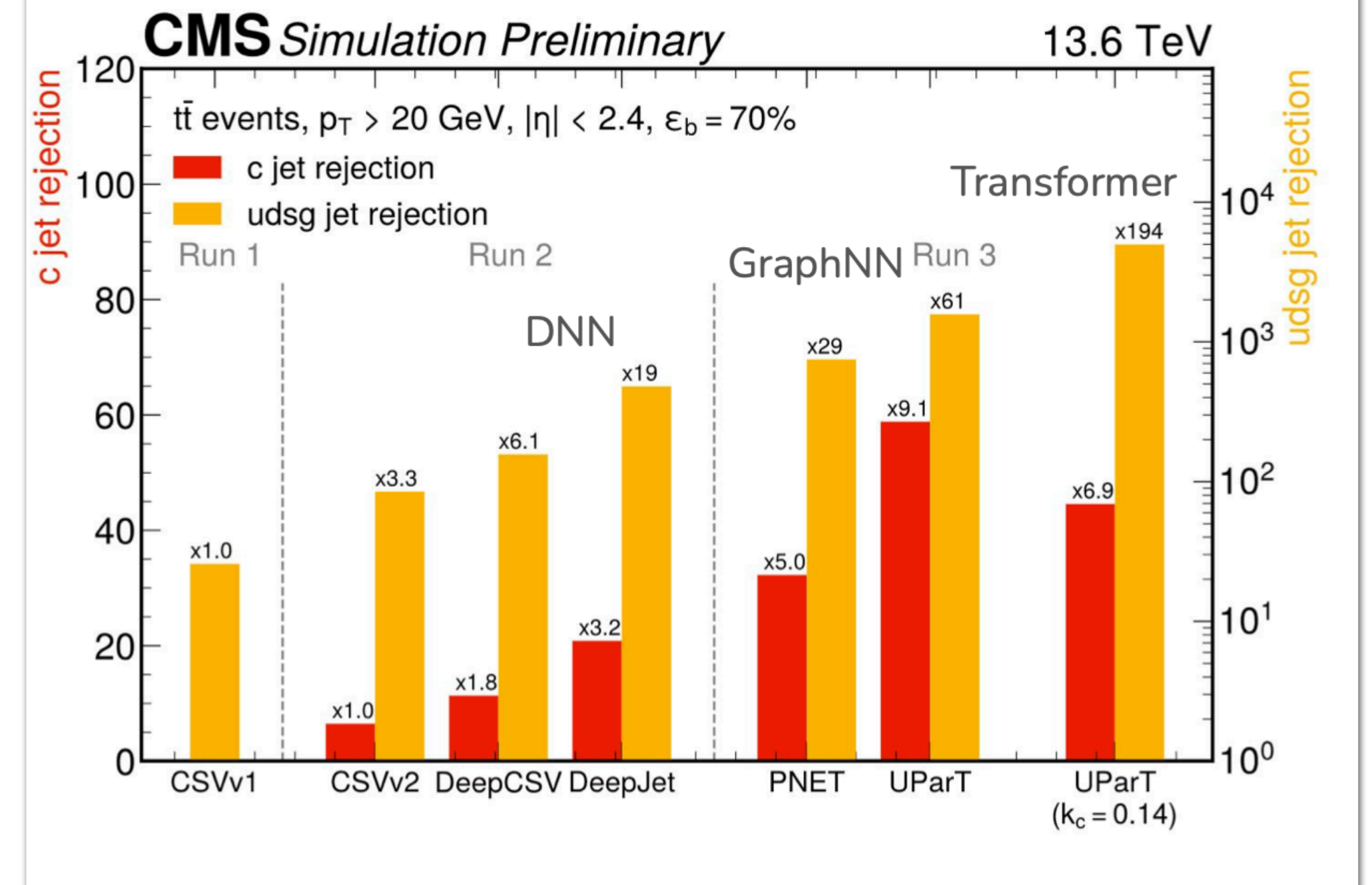
Great talk by Carlo last week (see [slides](#))

- Sensitivity to trilinear and quartic couplings
- Analysis in a nutshell:
 - 6b in the final states because of the large branching fraction
 - Pair jets based on consistency of Higgs candidates
 - DNN to discriminate signal from background
- Limit on the cross-section at 95% CL: $\sigma_{HHH} < 59 \text{ fb}$ ($\mu_{HHH} < 750$) and couplings:
 - $-11 < k_3 < 17$, $k_4=1$
 - $-230 < k_4 < 240$, $k_3=1$

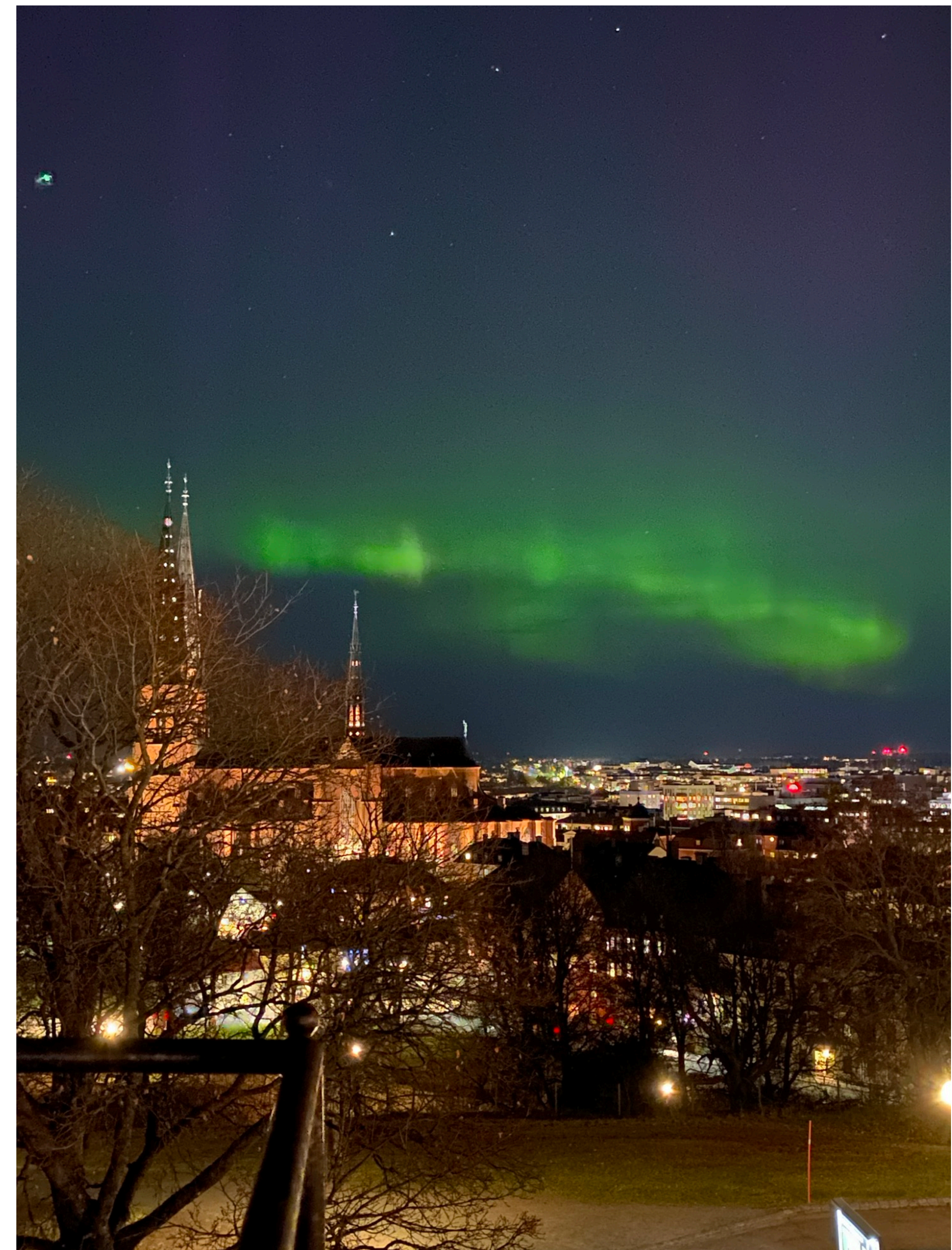


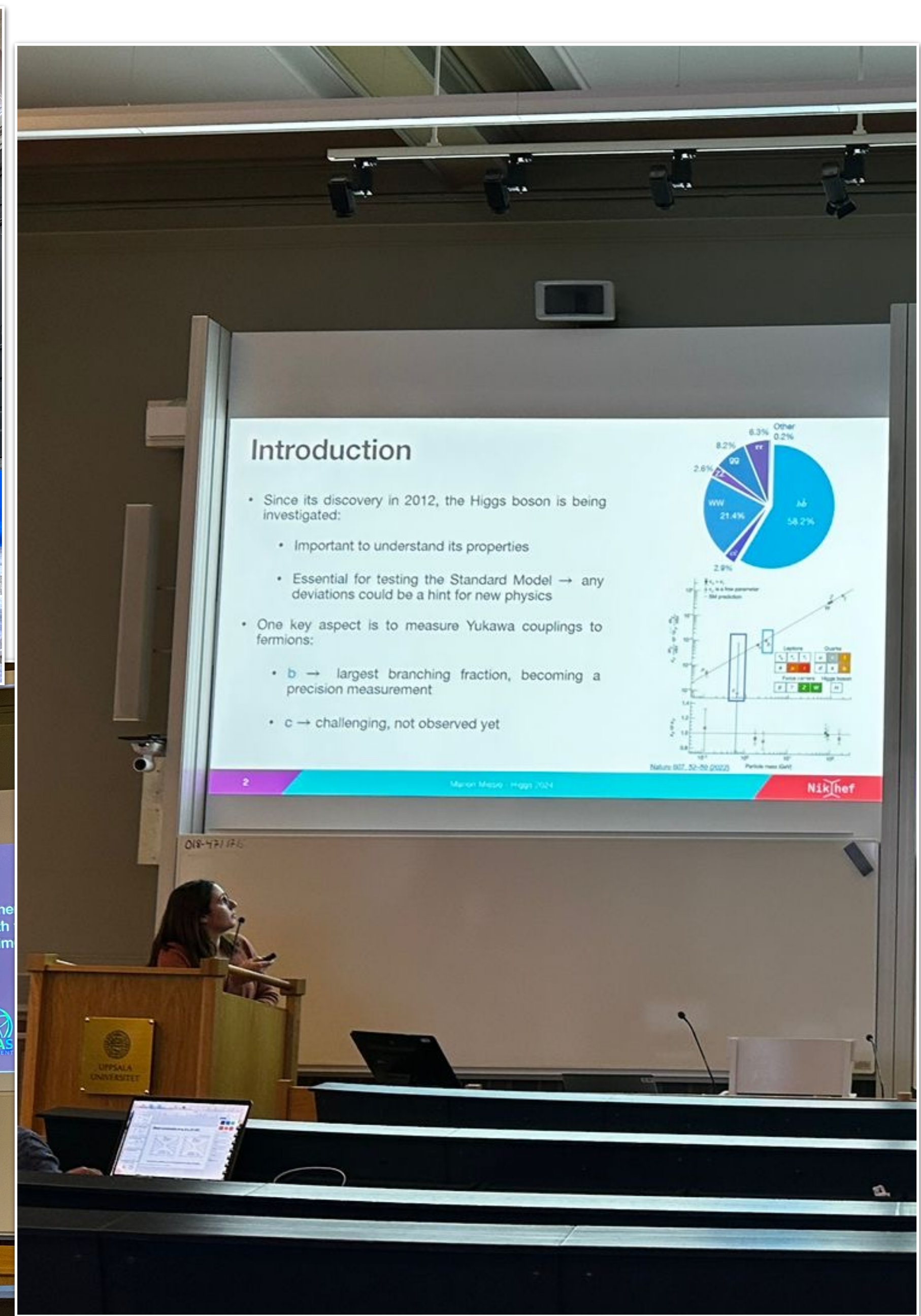
Flavour tagging

- UParT: new tagger for Run3
 - ParticleTransformer for small-R jet
 - Introduce a s-tagger → consider as a “unified” tagger
 - Also do τ_h identification but was already the case with ParticleNet
- ATLAS: ~ 4 times improvement for b- and c-tagging between Run2 and Run3 taggers



Northern light

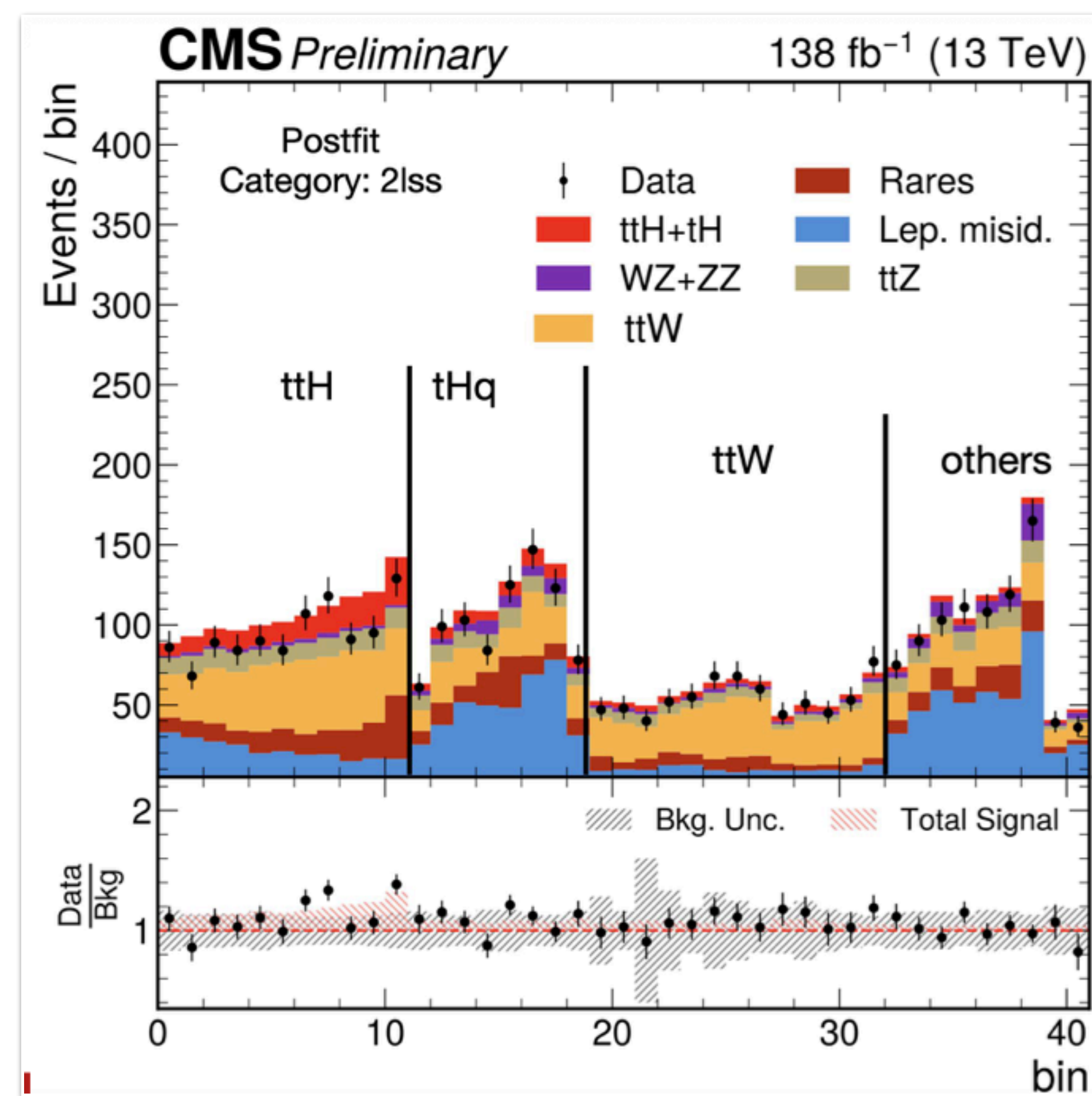
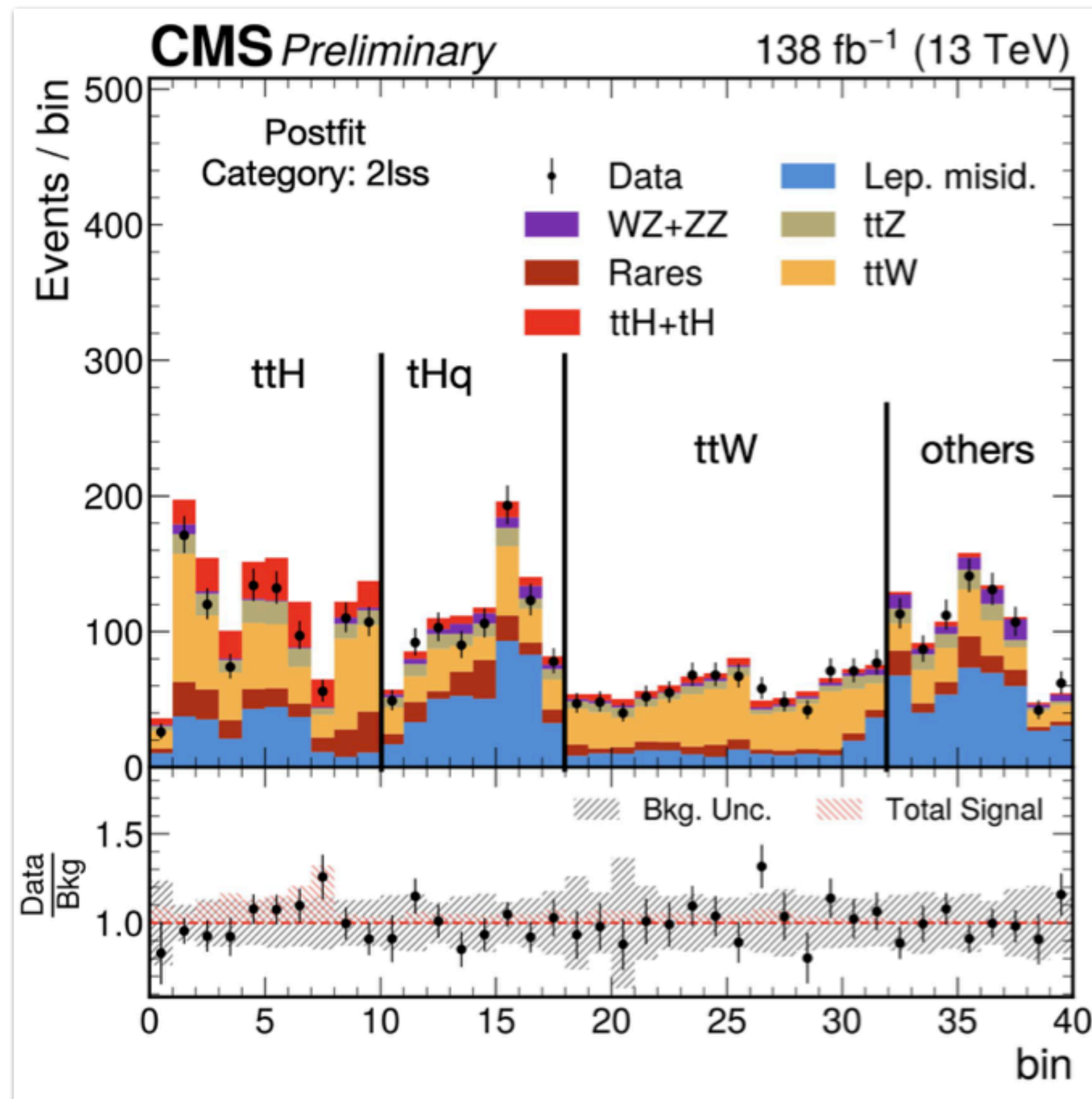
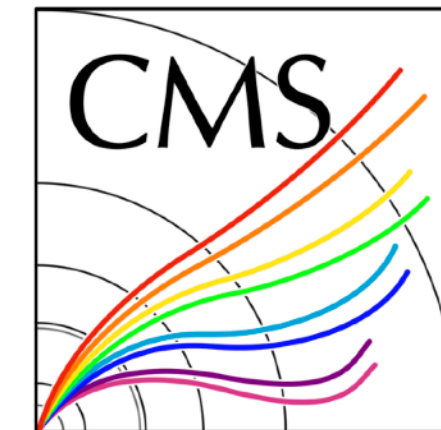




The end

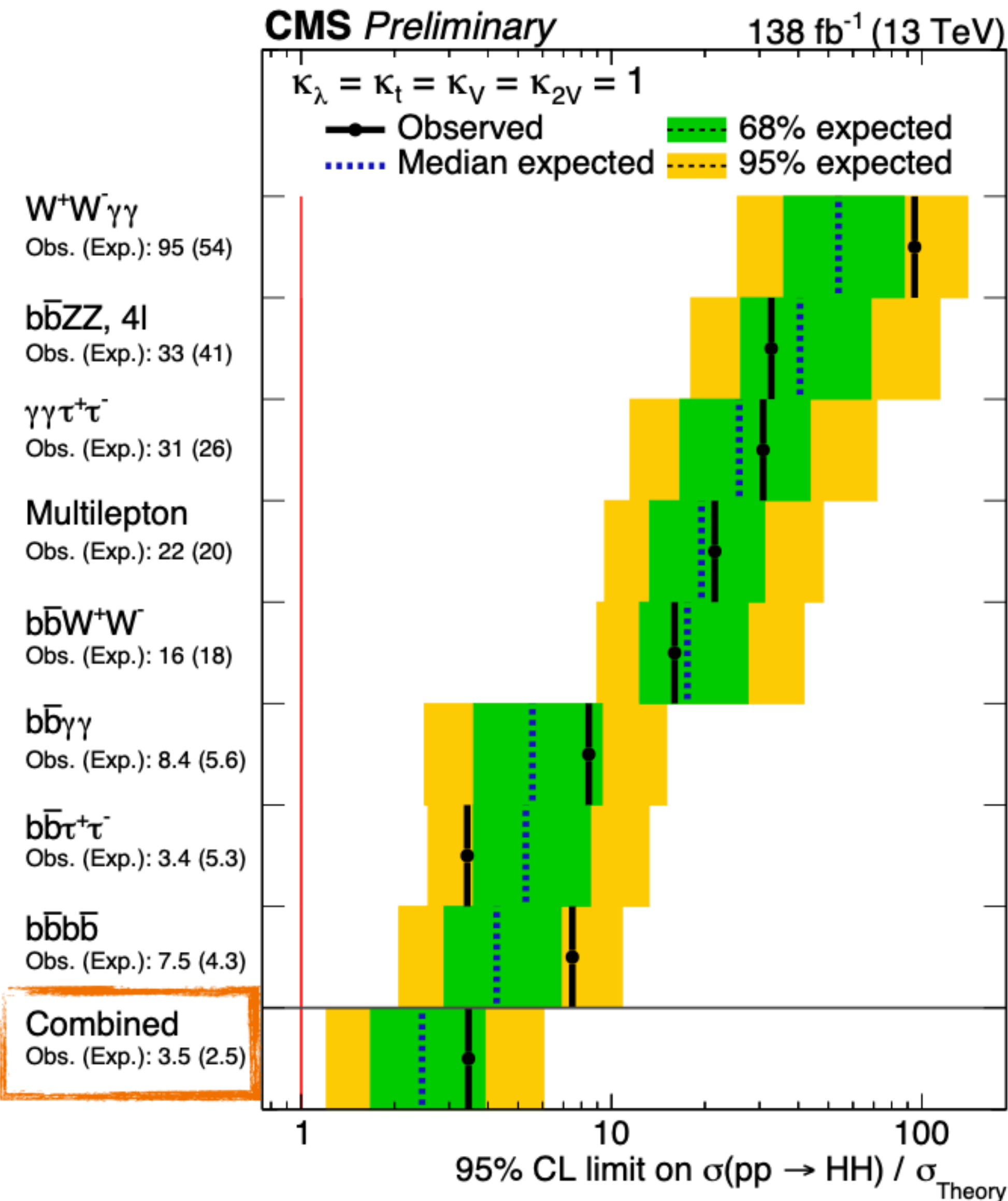
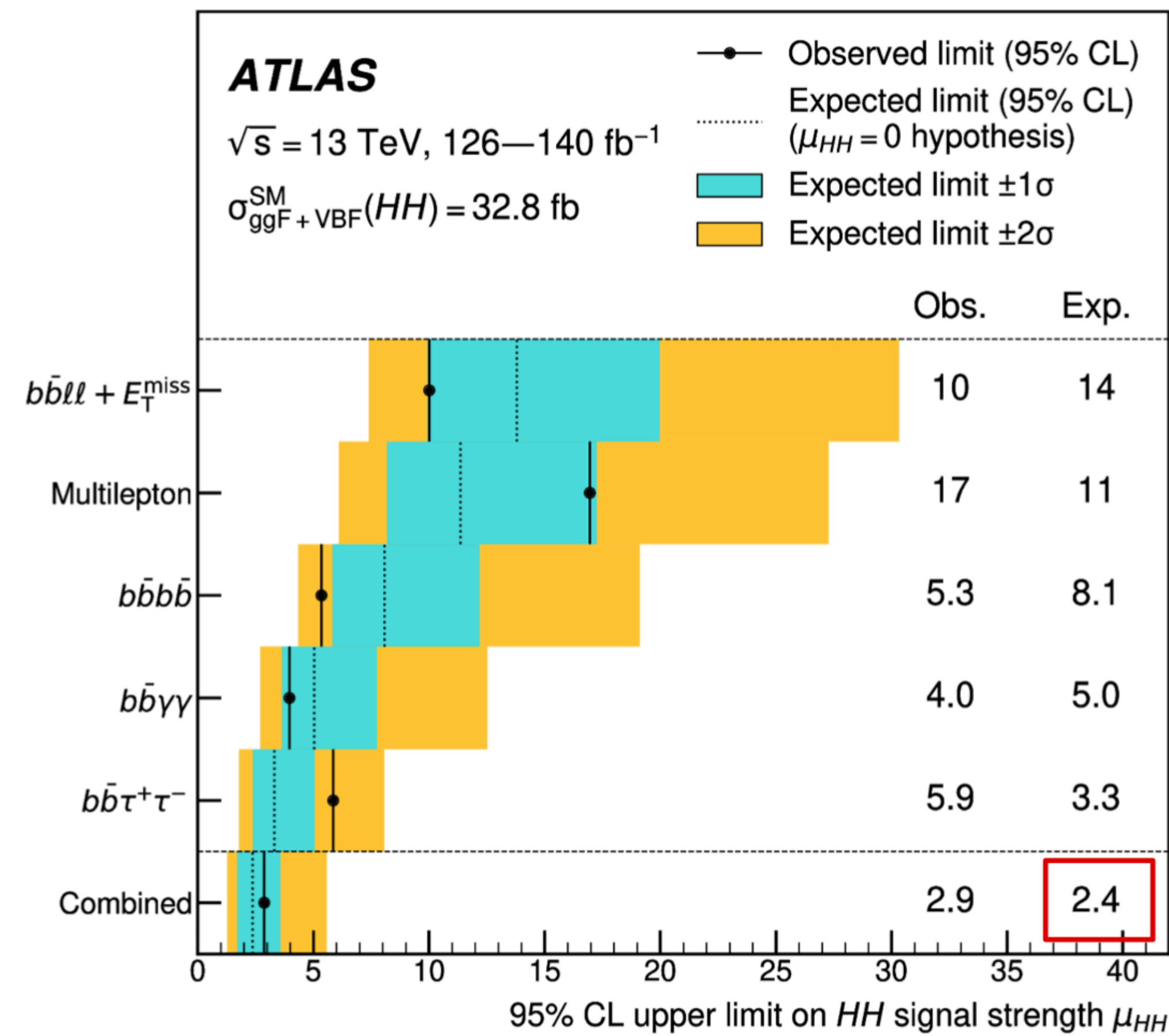
Higgs results

ttH(multileptons) analysy



Di-Higgs results

ATLAS vs CMS - HH combination



Flavour tagging

ATLAS vs CMS

All numbers for a fixed b-jet identification efficiency of 70%

