Higgs coupling measurements

Tiziano Bevilacqua (UZH, PSI)
On behalf of the CMS Collaboration

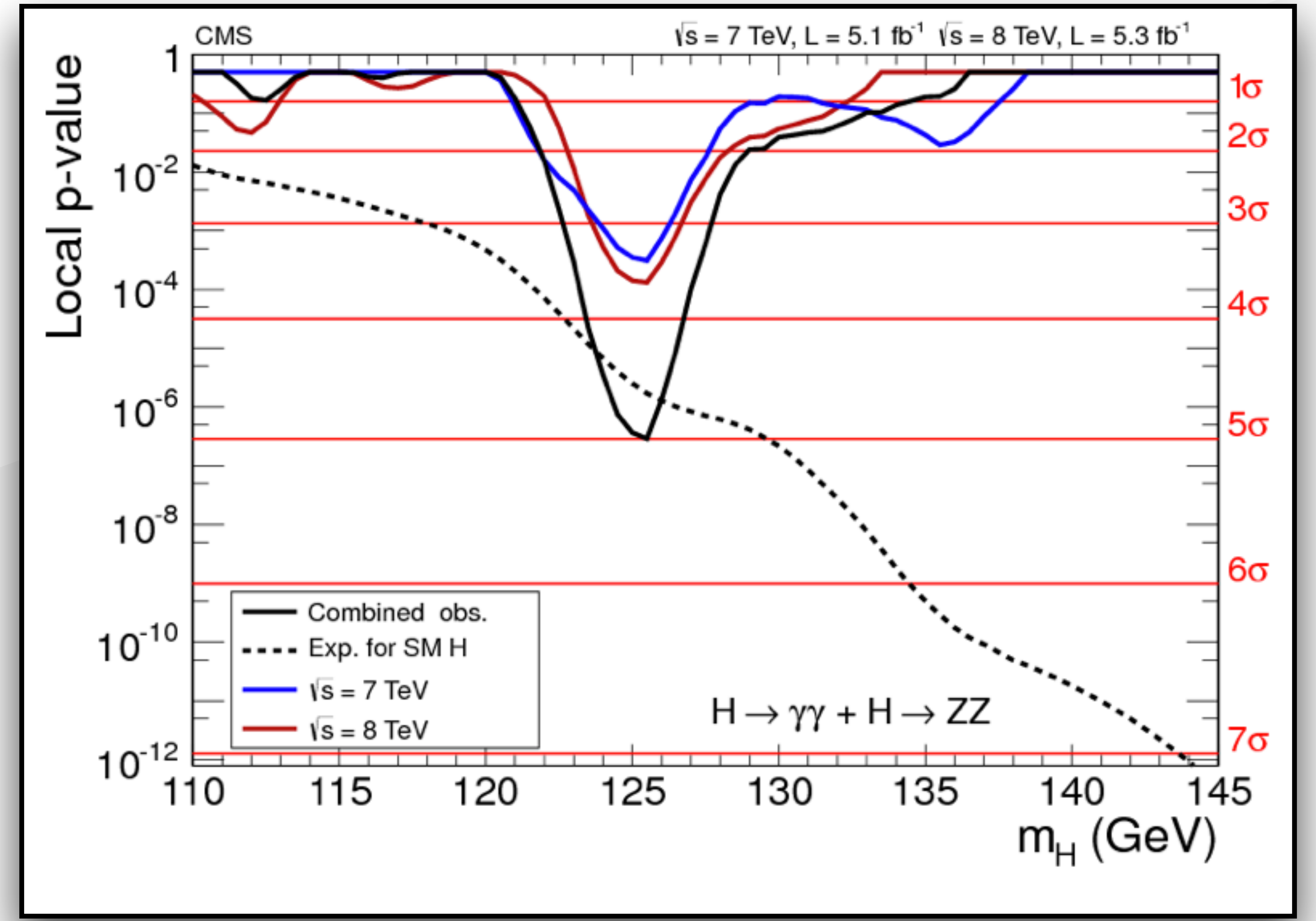
Outline

- **State of the art**:
  - Where we stand
- **Probing the Yukawa sector:**
  - H+c.
  - H+b.
- **Run 2 crowning moving towards Run 3:**
  - Run 2 combination.
  - Run 3 cross section measurements.
- **Conclusions.**

Where we stand 10+ years after

- **Run I:** Discovery of a boson in 2012 compatible with the scalar sector of the Standard Model.
  - Separate observation of the **bosonic** decay channels $O(15\%)$.
  - Spin and parity compatible with $J^P = 0^+$.

Phys. Lett. B 716 (2012) 30-61



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  - Separate observation of the **bosonic** decay channels $O(15\%)$.
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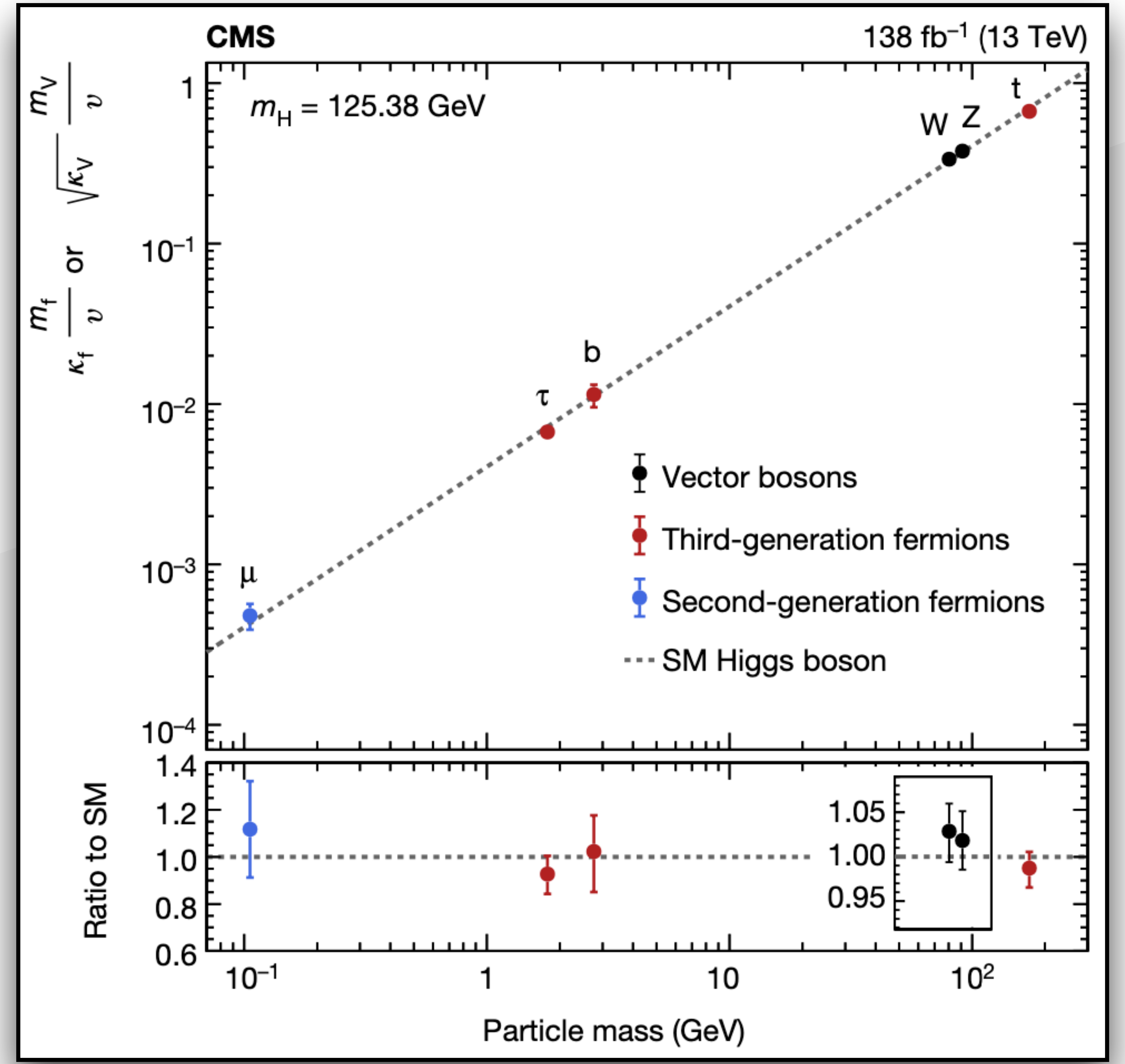
- **Run II:** Firmly established the existence of Yukawa couplings.
  - Separate observation of **vector bosons** $O(8\%)$ and **third generation fermions** couplings $O(10-20\%)$.
  - First evidence of **second generation** coupling.



Nature 607, 60–68 (2022)

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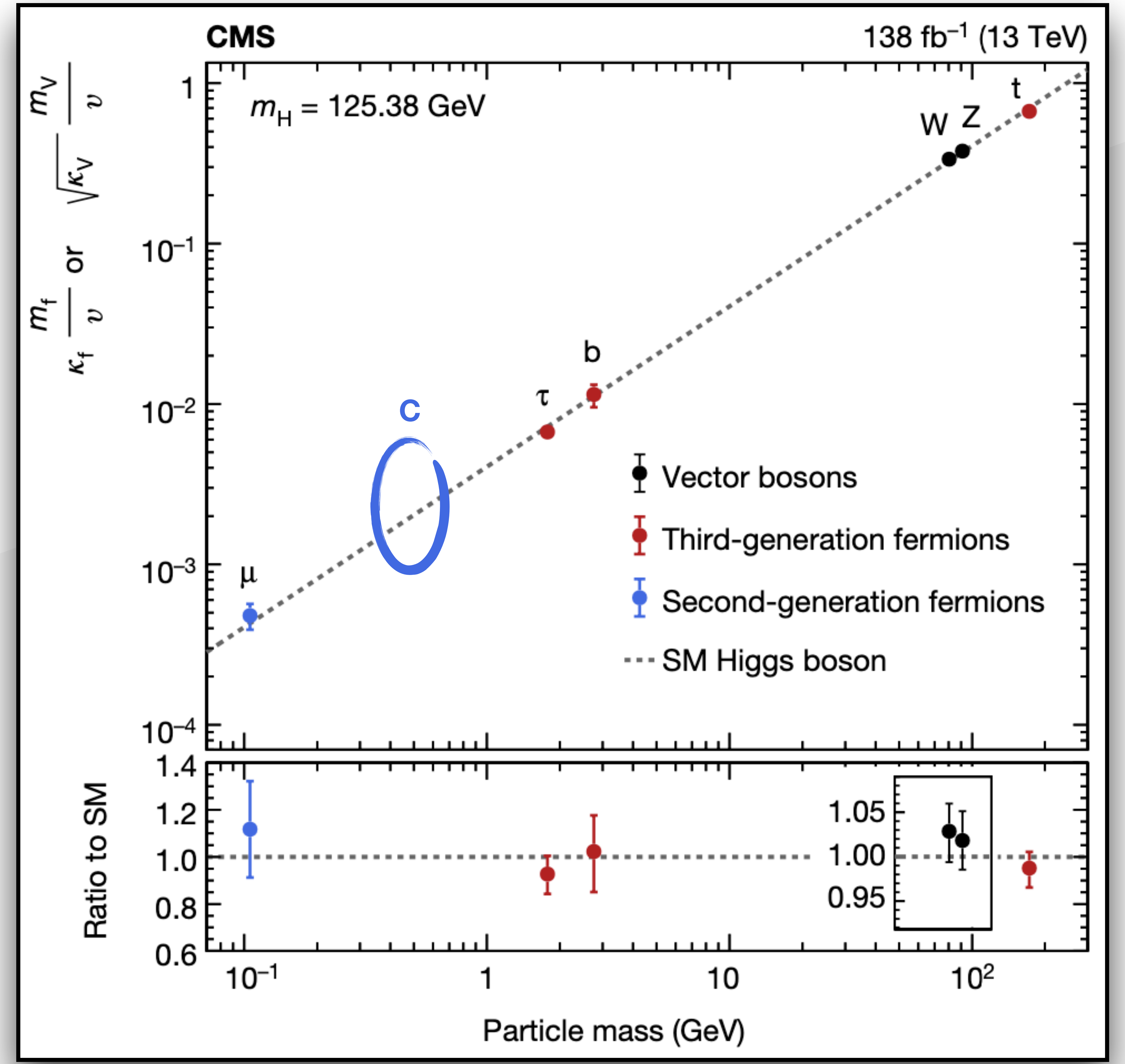
- **Run III and beyond:** Era of precision.
  - Tackle **second generation** coupling and **Higgs self coupling** to complete the picture.



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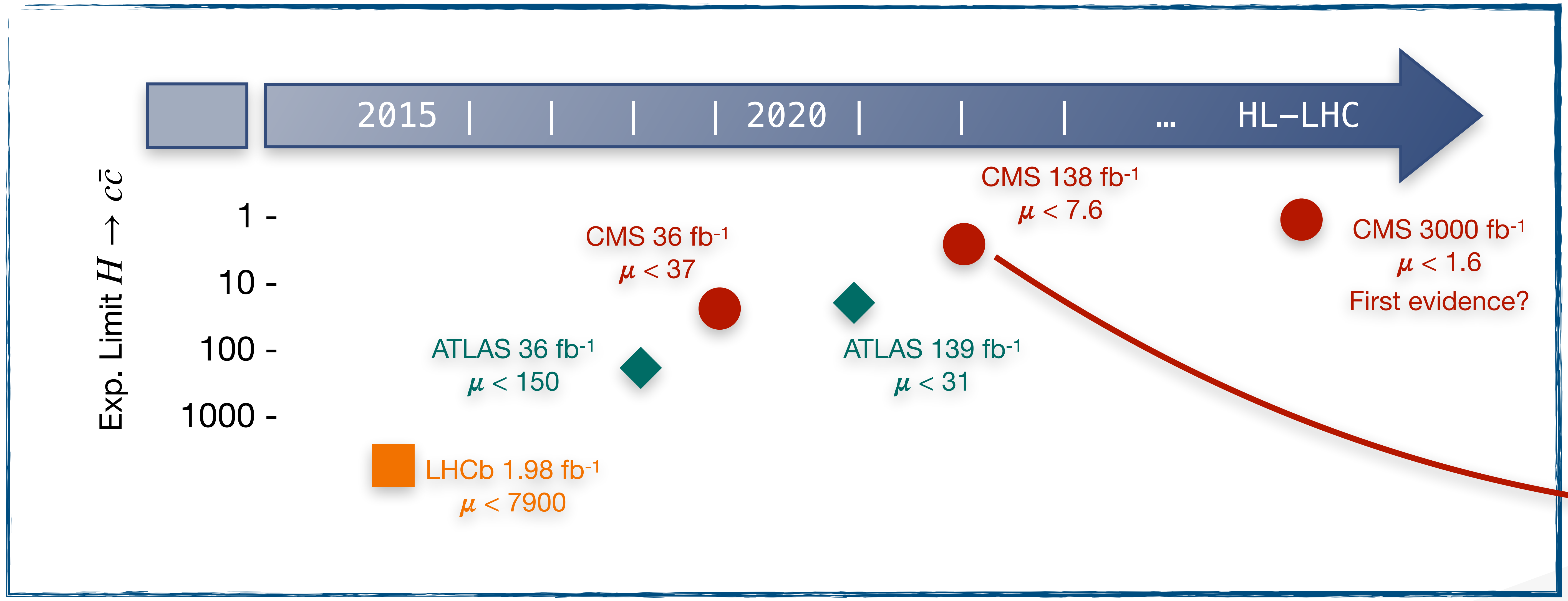
Probing the 2nd and 3rd generation Yukawas

2nd generation Yukawas: Probing y_c



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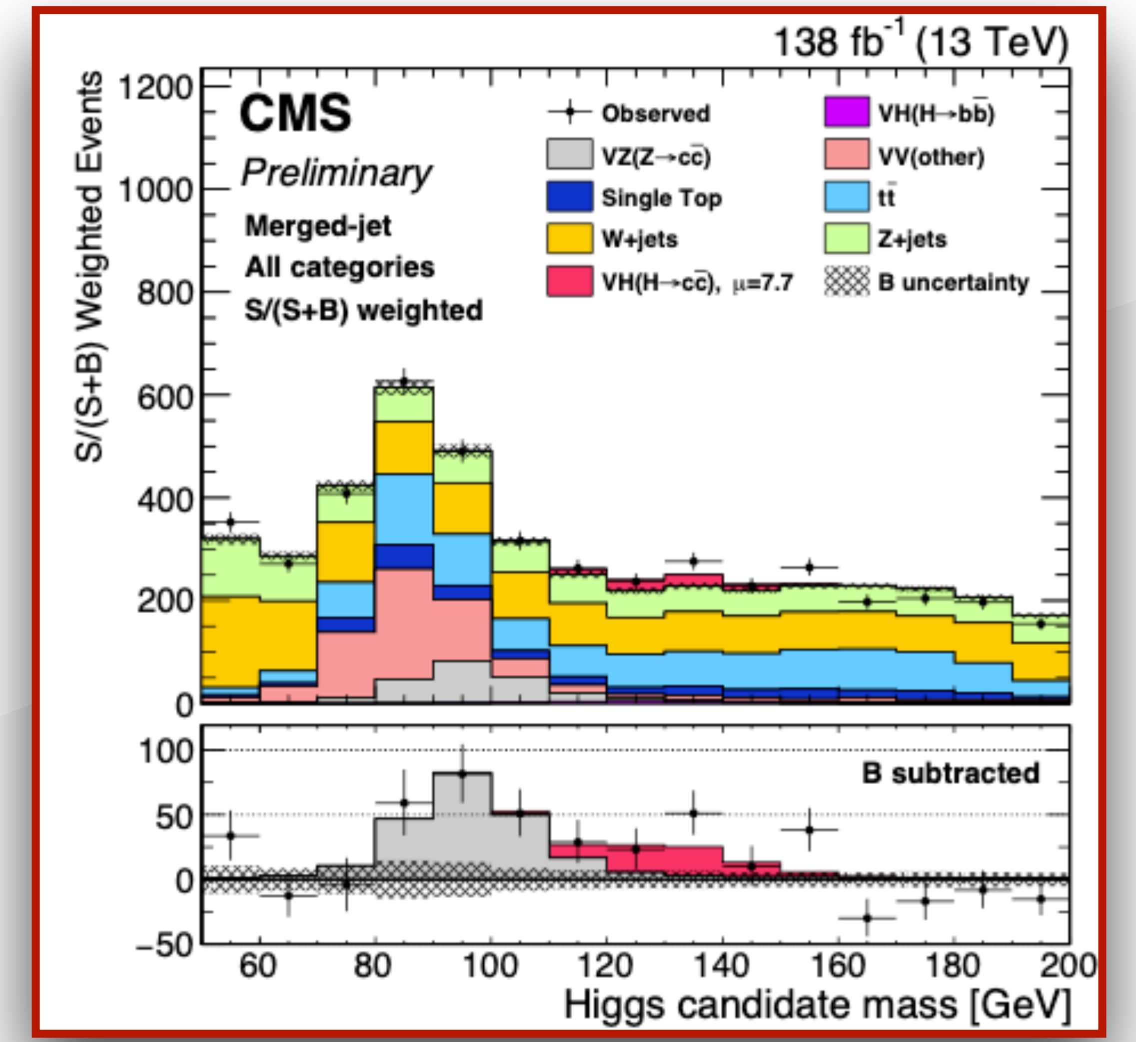
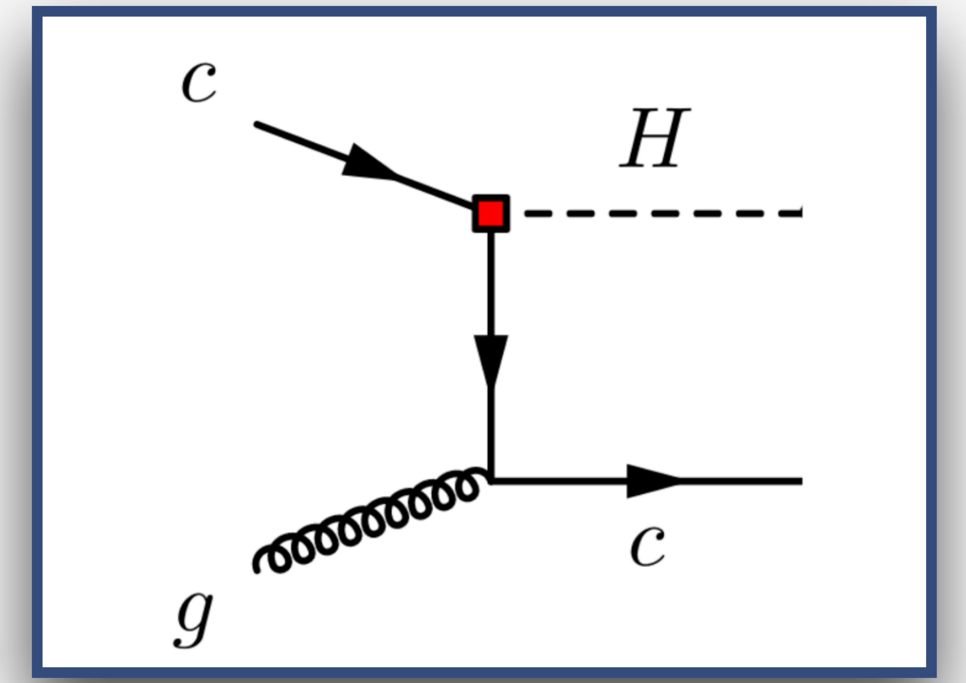


- Great improvements in the last few years.

- **Yukawa probed directly:** $VH(H \to c\bar{c})$ decay yields the most stringent (CMS) observed (exp.) limit of $\mu < 14$ (7.6).

- Indirect approaches: Exclusive rare decays, $p_T(H)$ differential measurements.

- **New attempt:** Probe y_c in the production side with associated production.



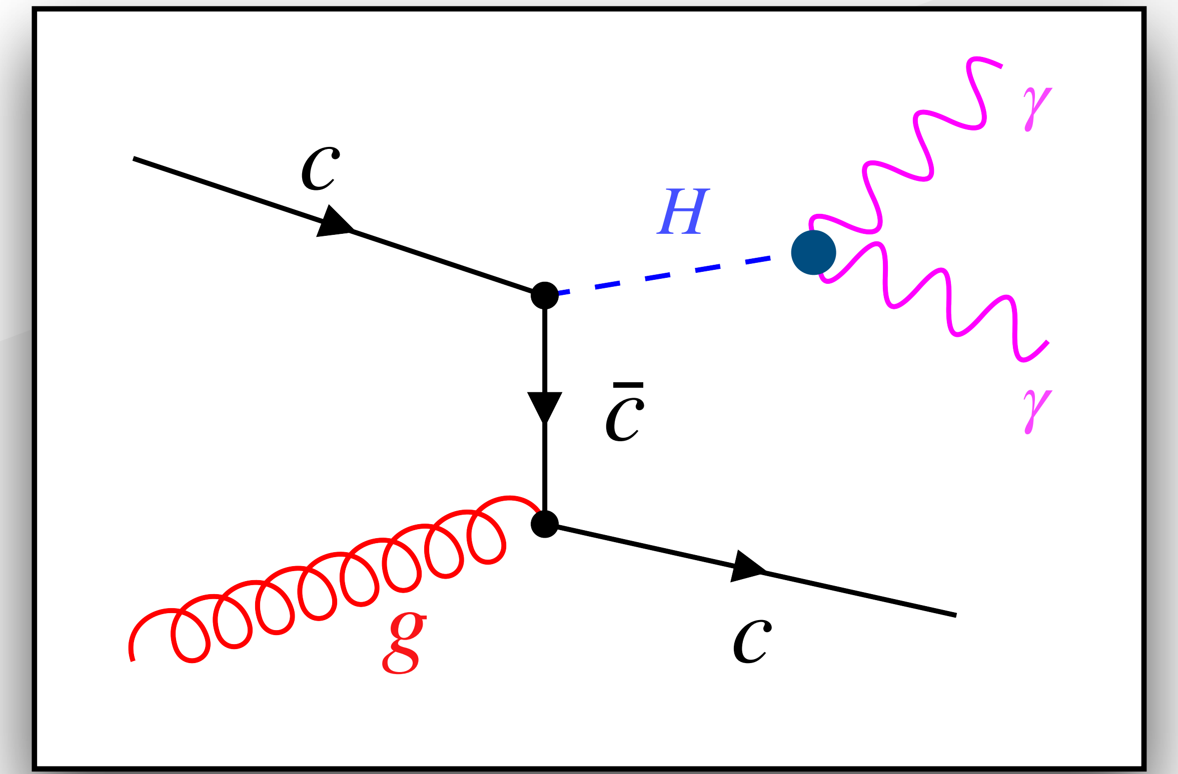
$H(\gamma\gamma) + c$ analysis

- $H \to \gamma\gamma$ decay channel.
- **Main backgrounds**:
  - ⇒ Higgs production through gluon fusion (ggH),
  - ⇒ continuous diphoton background (CB) from $\gamma\gamma$ and $\gamma + jets$ events.
- **Full Run 2 dataset** of 138 fb^{-1}:
  - Uses dedicated NLO+PS simulation of the y_c dependent H production.
  - Flavour Scheme studies to address signal generation theoretical uncertainty.
  - Kinematic based BDTs used to categorise the events.

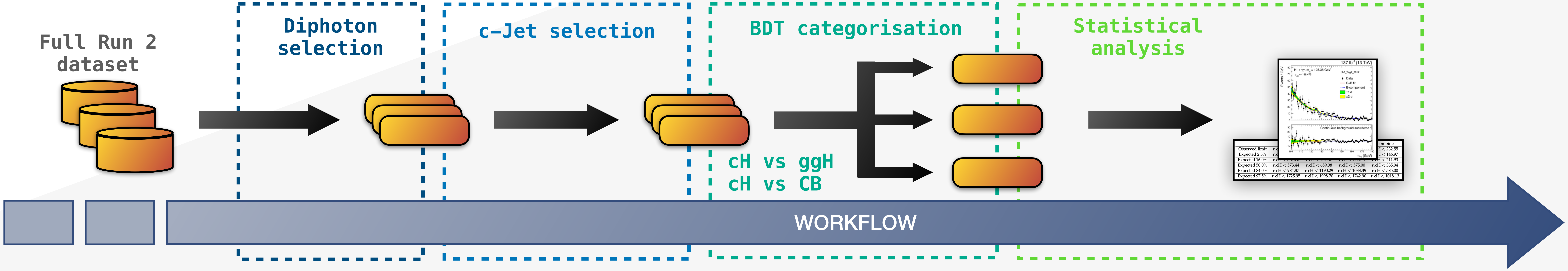
[GEN charm $p_T > 20$ GeV]

$[fb] \to A = 254.5,\ B = -3.5,\ C = 34.5$

$$\sigma(hc) = A + B \cdot y_c + C \cdot y_c^2$$



CMS-PAS-HIG-23-010



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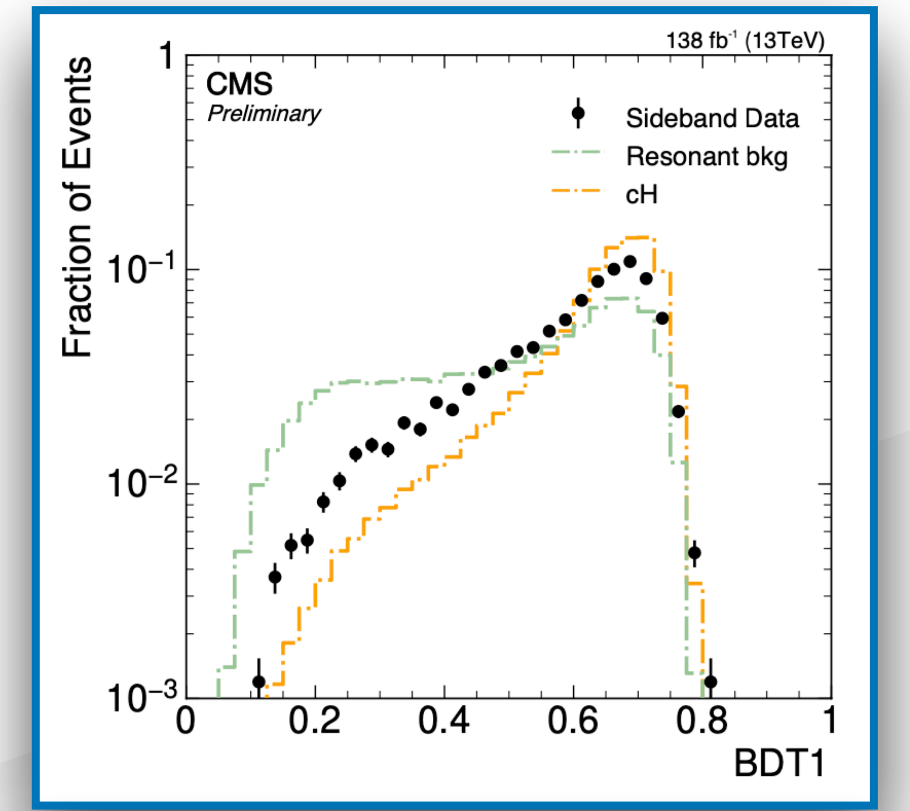
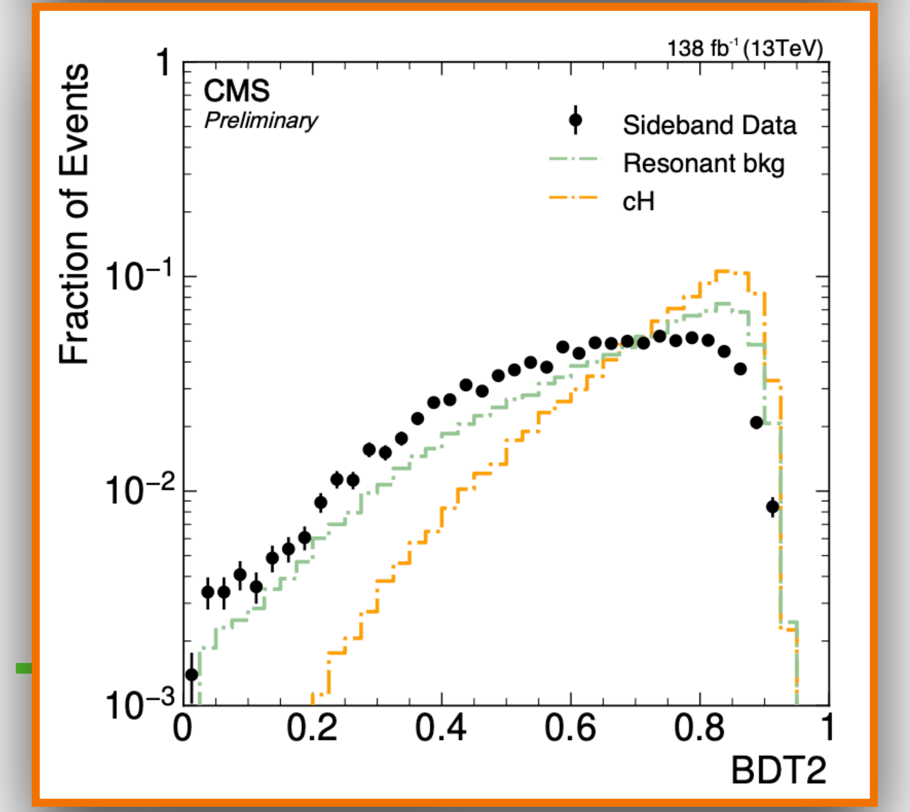
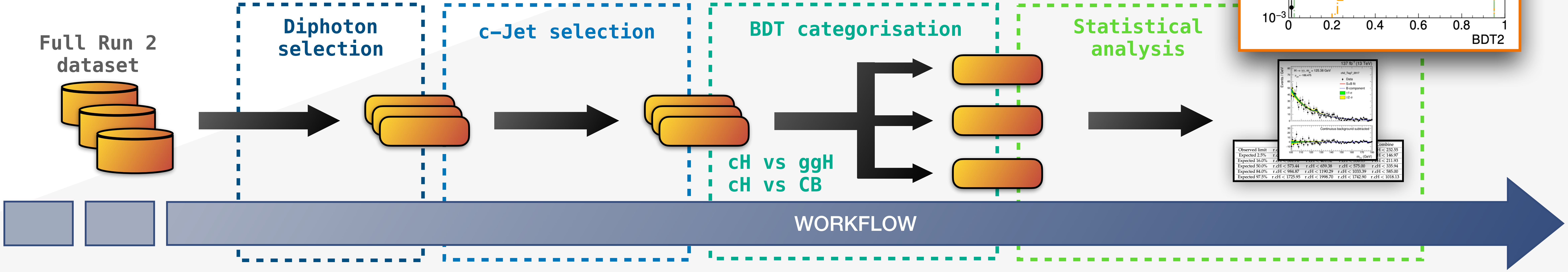
cH vs ggH



cH vs CB



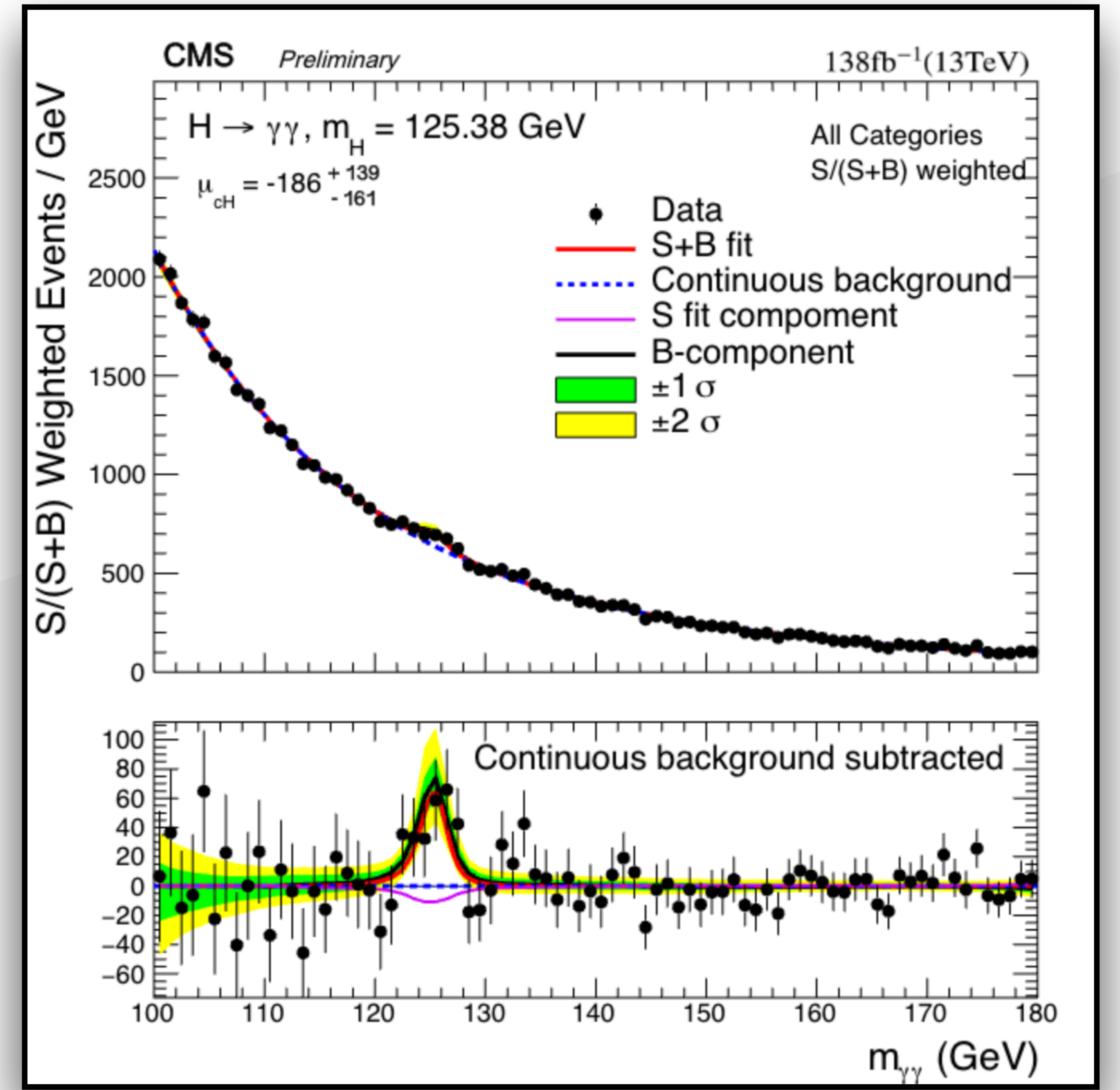


$H(\gamma\gamma)$ + c analysis

Results:

[CMS-PAS-HIG-23-010](CMS-PAS-HIG-23-010)

- μ_{cH} is extracted via a **simultaneous maximum likelihood fit** in the $m_{\gamma\gamma}$ distribution in the 27 event categories.
- Assuming the standard model (SM) cross sections times branching fractions for all other Higgs production processes.
- The **observed (expected)** upper limit at 95% confidence level on the cH signal strength is **243 (355)** times the SM prediction.
- Result interpreted considering the **"flat direction" approach** (PRD 100 (2019) 073013):
  - The **observed (expected)** allowed interval is $|\kappa_c|$ **< 38.1 (**$|\kappa_c|$ **< 72.5)** at 95% confidence level.



- Signal: cH
- Res. Bkg: ggH, ttH, VH, VBF, bH
- Cont. Bkg: $\gamma\gamma$, γ+jets

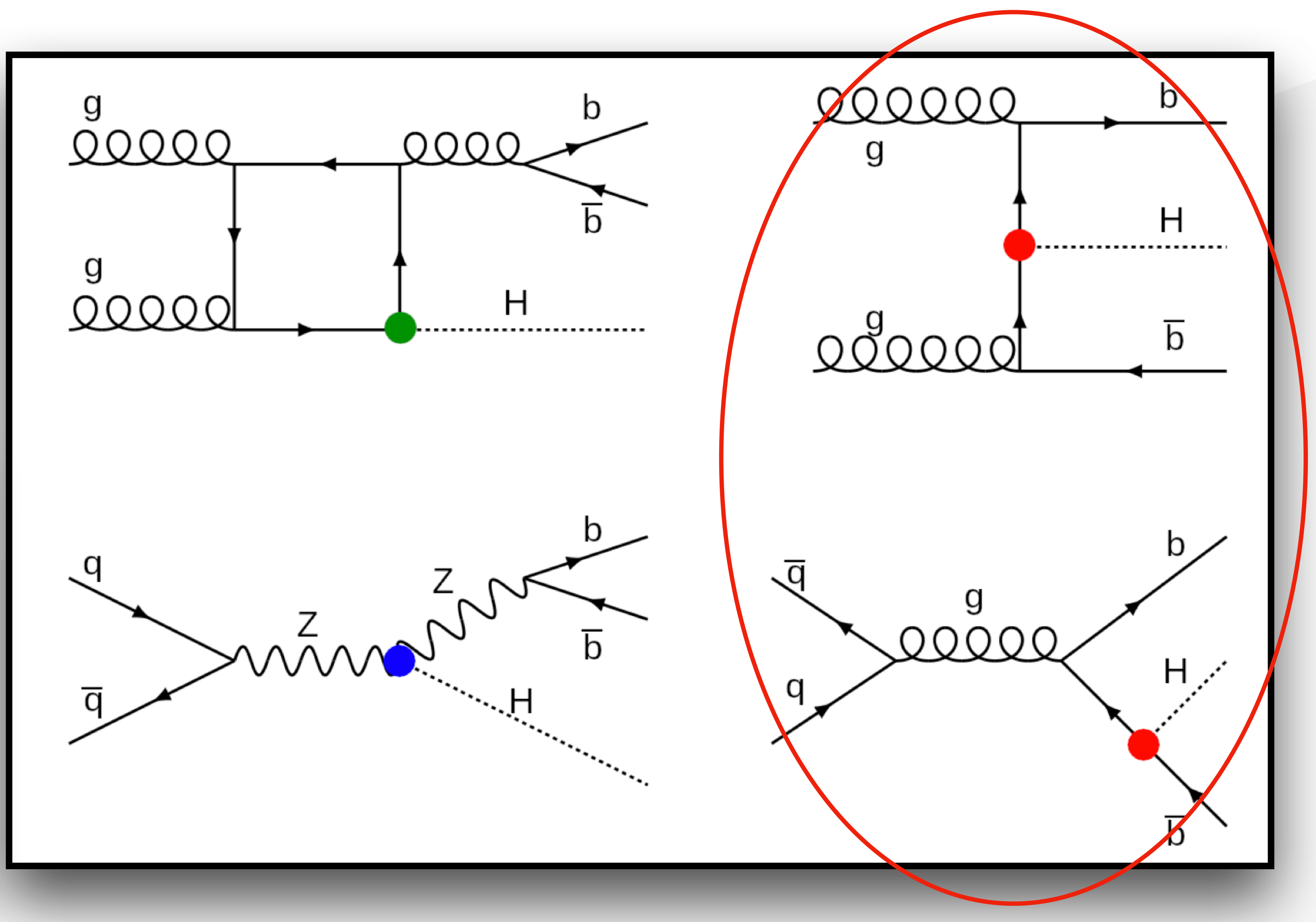
$$\mu_{cH} = \frac{\sigma_{cH}}{\sigma_{cH}^{SM}}$$

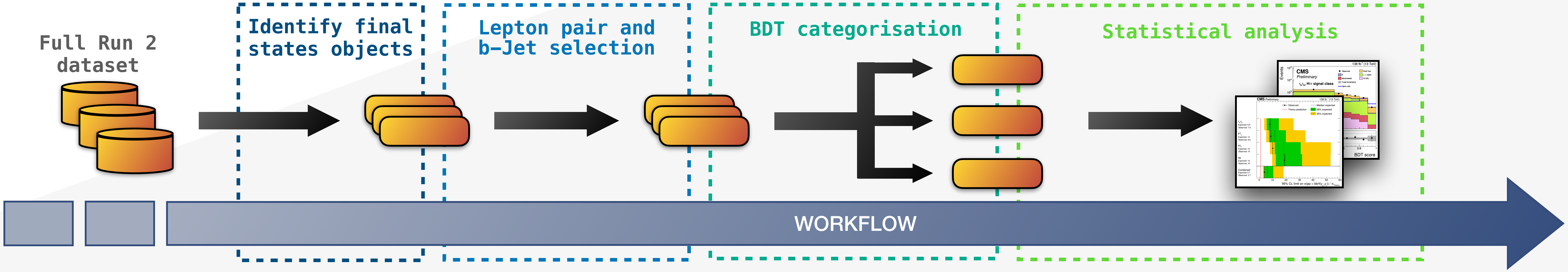
bbH associated production

- Search for b-quark associated Higgs boson production followed by decay to τ lepton pair or WW.
- Direct probe of Higgs couplings to the bottom quark (y_b) in production.
- Challenging analysis experimentally with 4 final states ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$):
  - Larger background than in the ttH channel.
  - Complex contribution of y_t dependent diagrams and interference.

term	σ(pb)
y_t^2	1.040 (+0.468 -0.489)
y_b^2	0.482 (+0.048 -0.070)
$y_b y_t$	– 0.033 (+0.007 -0.008)

Subdominant y_b dependent contribution





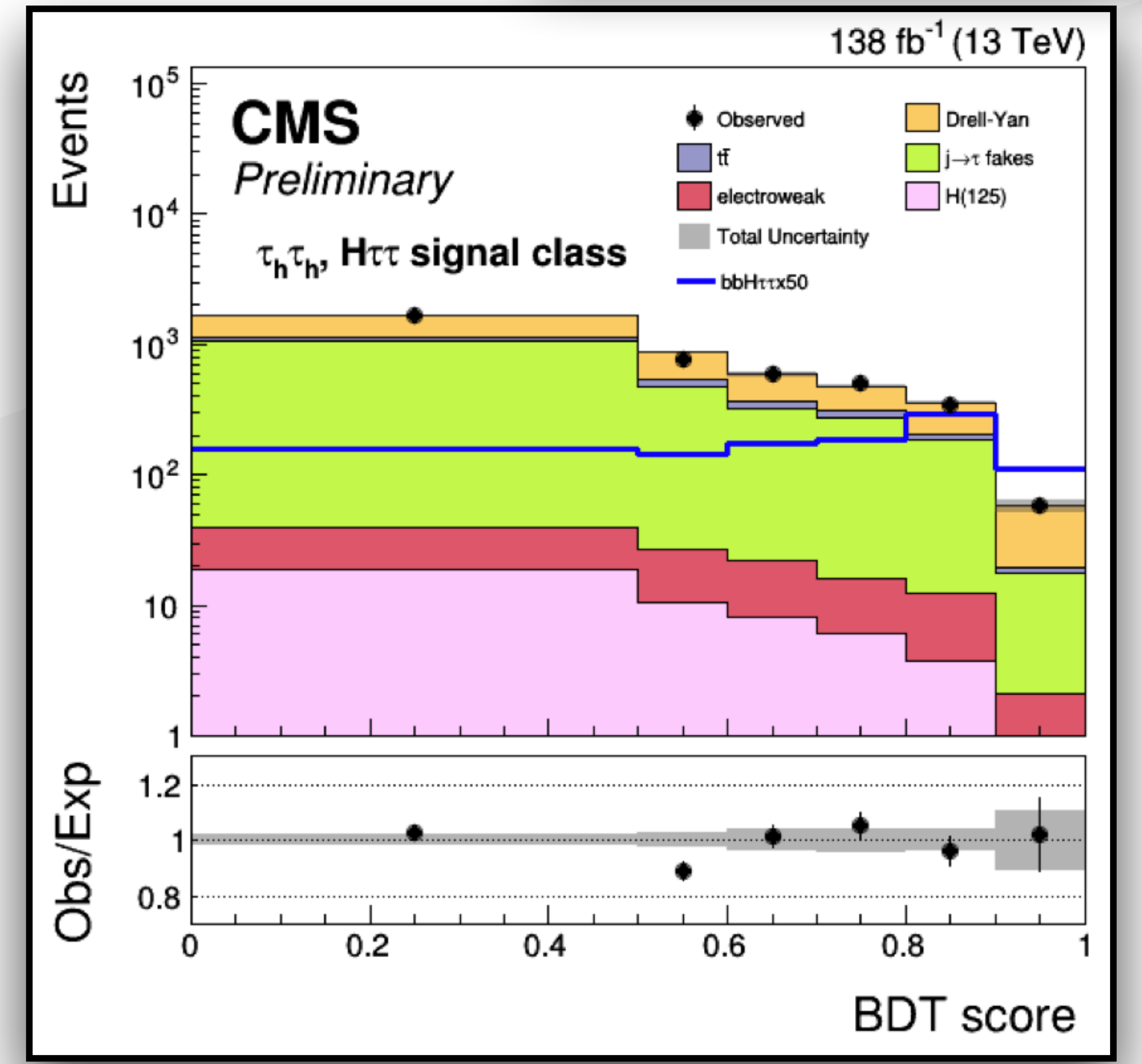
bbH associated production

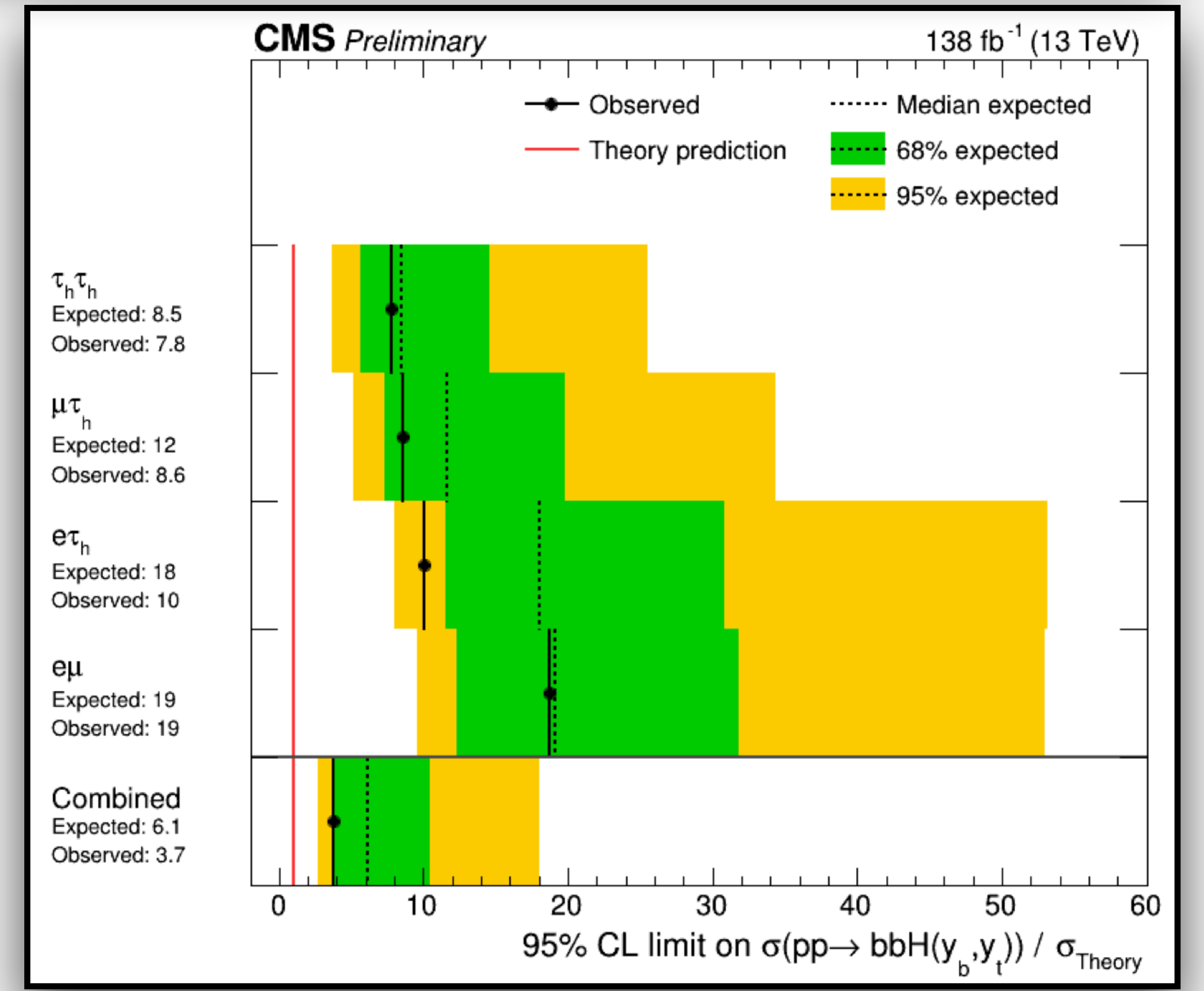
Results:

- Dominant backgrounds: $t\bar{t}$, DY, and $j \rightarrow t_h$ misidentification ⇒ require dedicated classes.
- Fit to BDT score, inclusive measurement:
  - The different contributions to the signal are scaled by varying proportionally the y_b^2, y_t^2 and $y_b y_t$ terms.

Channel	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
BDT Categories	DY, TT, bbH(→WW), bbH(→ $\tau\tau$)	DY, TT, bbH(→ $\tau\tau$)	DY, TT, bbH(→ $\tau\tau$)	DY+Higgs, TT, j→τ_h fakes, bbH(→ $\tau\tau$)

- Observed **obs (exp)** upper limits at **3.7 (6.1)** times the SM expectation.



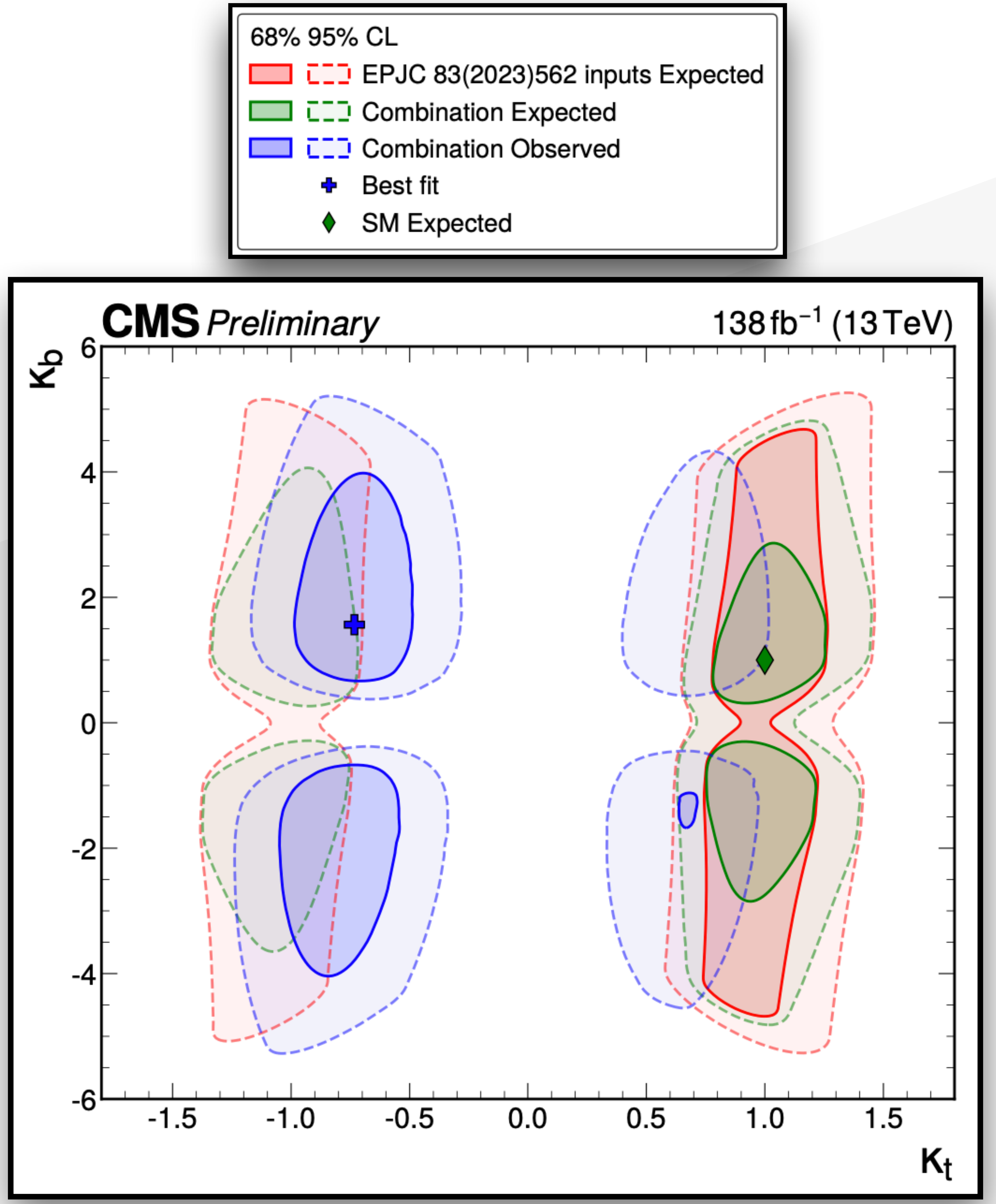


CMS PAS HIG-23-003

$H + b$ associated production

K-framework interpretation:

- Scan performed on coupling modifiers k_t and k_b, with k_τ freely floating.
- Combined with the results from STXS $H \rightarrow \tau\tau$ cross-section measurement (with veto on b-jets) to better constrain k_t.
- The best fit point is (k_t, k_b) = (-0.73,1.58)
- Limits on the couplings are **compatible with the SM** at 95% CL.

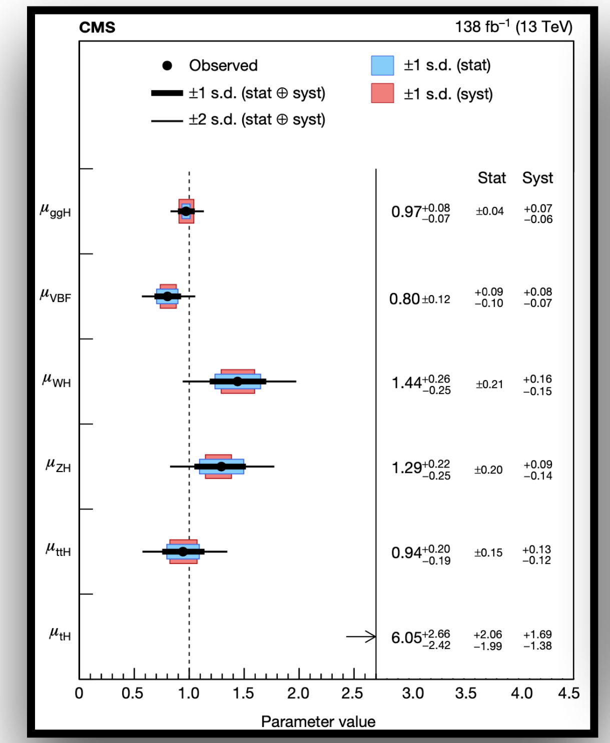


CMS PAS HIG-23-003

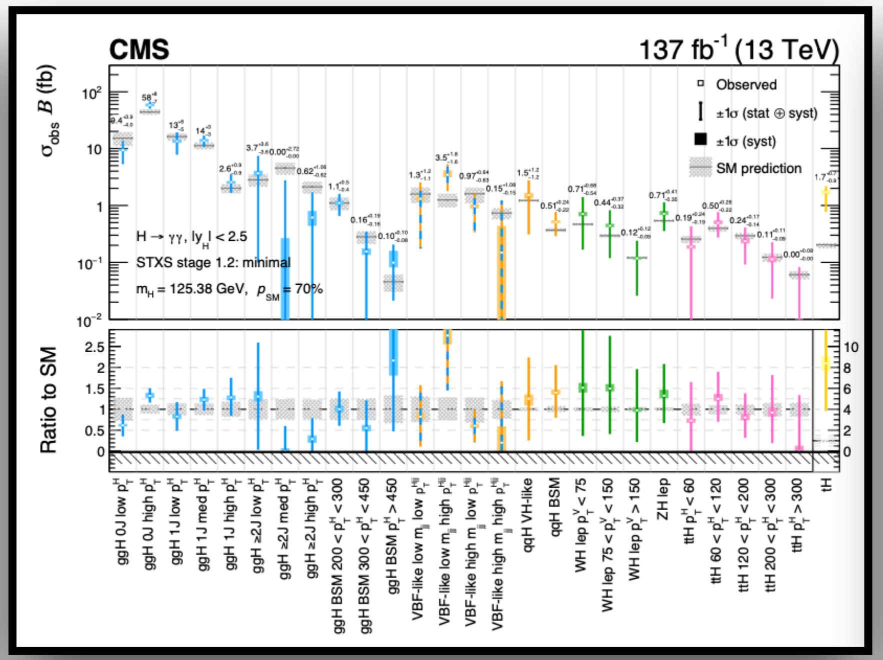
Run 2 crowning moving towards Run 3

Combination of H boson production XSections

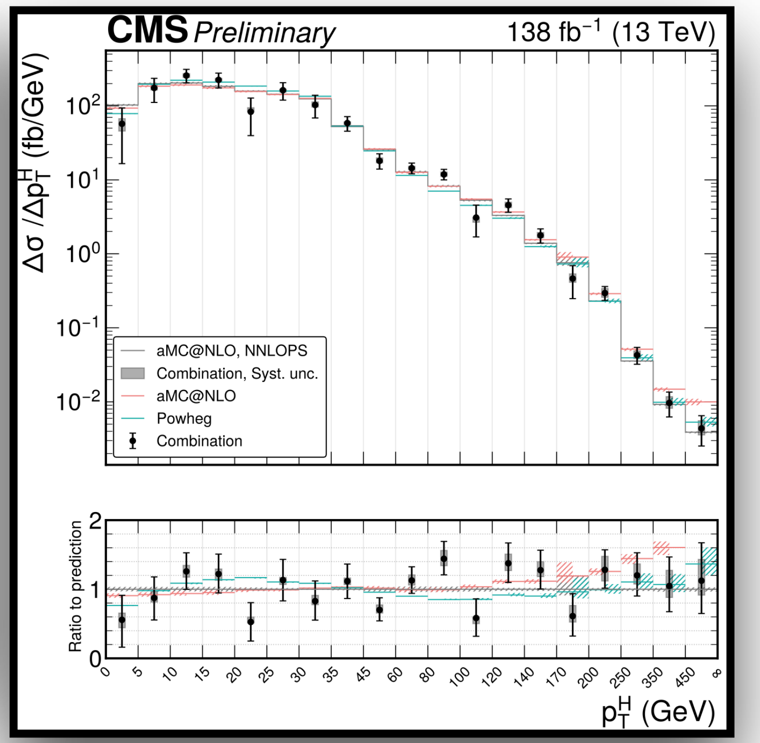
Signal strength | **STXS** | **Fid. cross section**



[1]



[2] [3]



Experimental sensitivity ←

→ **Model independence**

- **Fiducial differential cross section, most model independent approach:**
  - Fiducial regions defined by selections at generator level.
  - Each analysis performs measurements in different fiducial phase spaces.
  - Small coupling variations could lead to significant distortions of the shape of the differential observables.

- **Three main parts:**
  - ⇒ Combination of spectra (fid. diff. σ_s extrapolated to the full phase space).
  - ⇒ K-framework based interpretation.
  - ⇒ SMEFT based interpretation.

Full Run 2:

- $H \to \gamma\gamma$
- $H \to ZZ^*$
- $H \to WW^*$
- $H \to \tau\tau$
- $H \to \tau\tau$ (boosted)

Individual channels

$$\mu = \frac{\sigma_i \times BF_i \times A_i}{\sigma_{SM} \times BF_{SM} \times A_{SM}}$$

Extrapolation to inclusive phase space

Combination

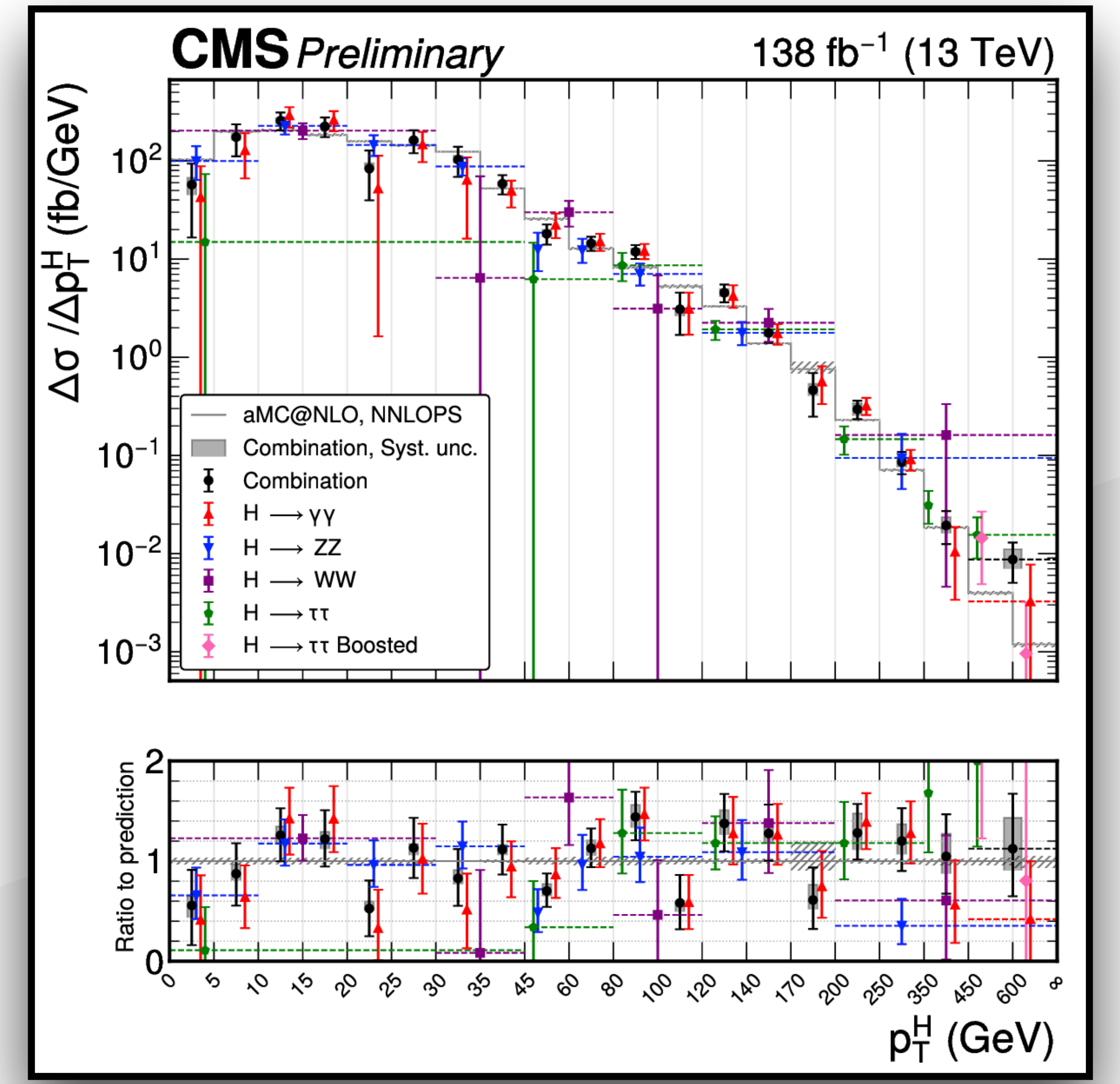
$$\mu = \frac{\sigma}{\sigma_{SM}}$$

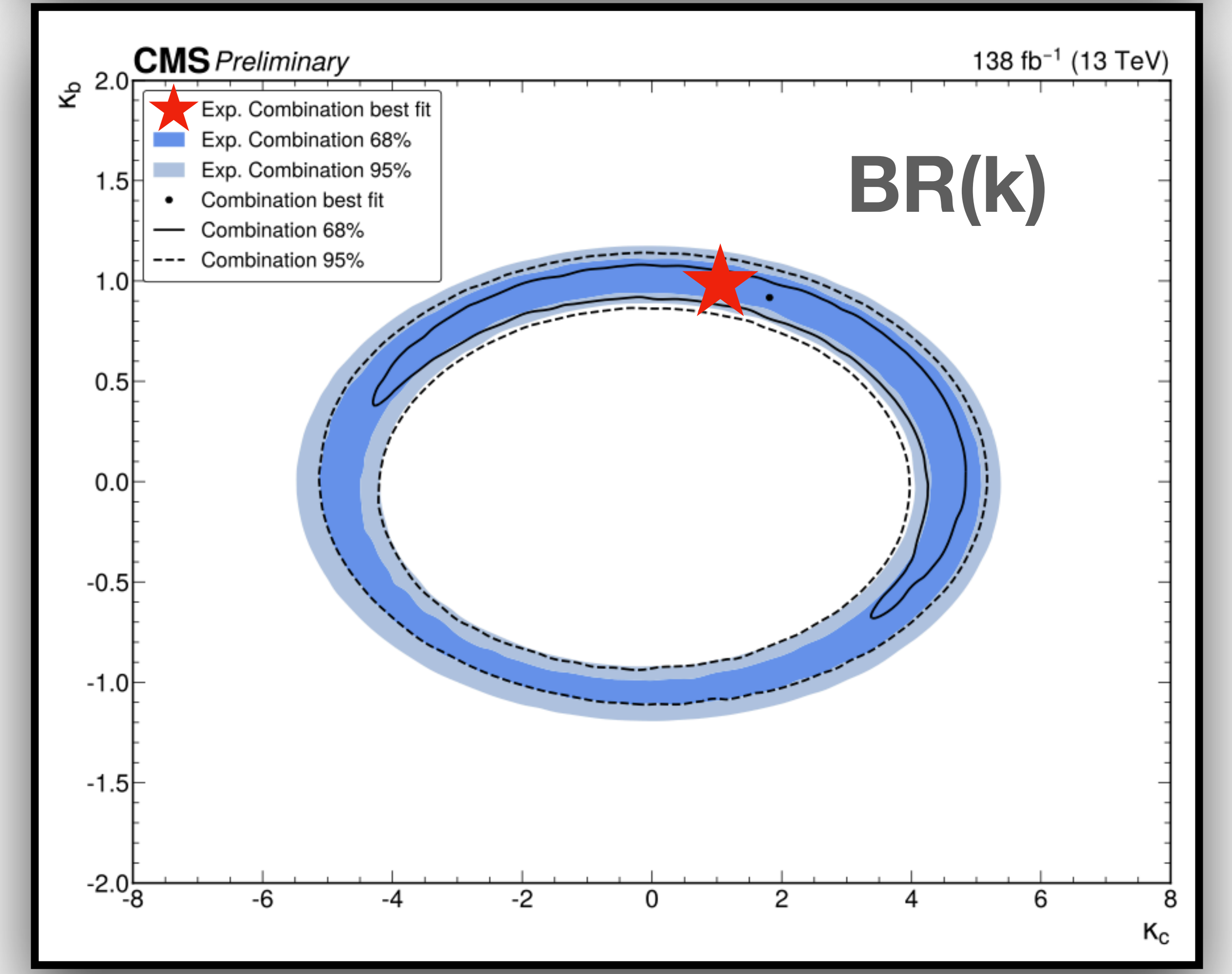
[1] Nature 607, 60–68 (2022) [2] PoS(ICHEP2022)509 [3] CMS-PAS-HIG-23-013

Combination of H boson production XSections

K framework interpretation:

- **No significant deviations** from the standard model are observed in any differential observable:
  - $p_T^H, N_{jets}\,, \,|y_H|\,, p_T^{j_1}, m_{jj}, \,|\Delta\eta_{jj}|\,, \tau_C^j.$
- The obtained $p_T(H)$ spectra are interpreted in the **κ-framework**:
  - **Constraints on the Higgs couplings using two models:**
    $\Rightarrow k_b - k_c, p_T^H$ effects from light quarks.
    $\Rightarrow k_b - k_t - c_g, c_g$ gives direct H-gluon coupling.
  - Two different treatment for BRs in the fit:
    $\Rightarrow$ BRs(k).
    $\Rightarrow$ BRs freely floating.





CMS-PAS-HIG-23-013

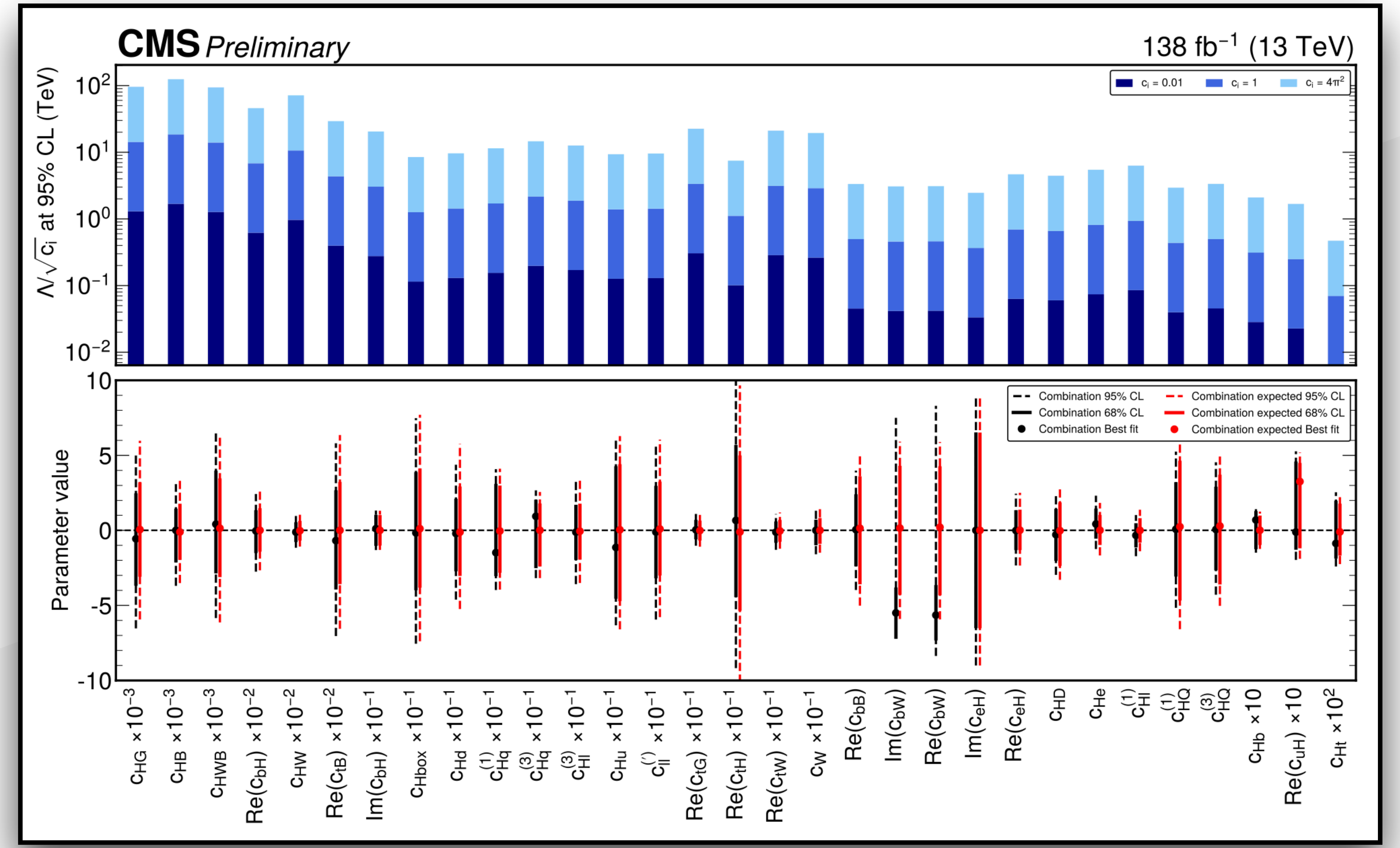
Combination of H boson production XSections

EFT interpretation:

- Interpretation with a model agnostic EFT approach.
  ⇒ No extrapolation to inclusive phase space needed!

- **Scan: fit a couple of Wilson coefficients** and the others are fixed to the SM values.
  - Results consistent with SM and the same scan performed by Atlas in the $H \to \gamma\gamma$ channel.

- **Eigenvector decomposition:**
  - Linear combinations of the original coefficients:
    ⇒ indication of their constraining power.
  - Highest constraining power ones are then left floating.
  - Results are consistent with the SM.



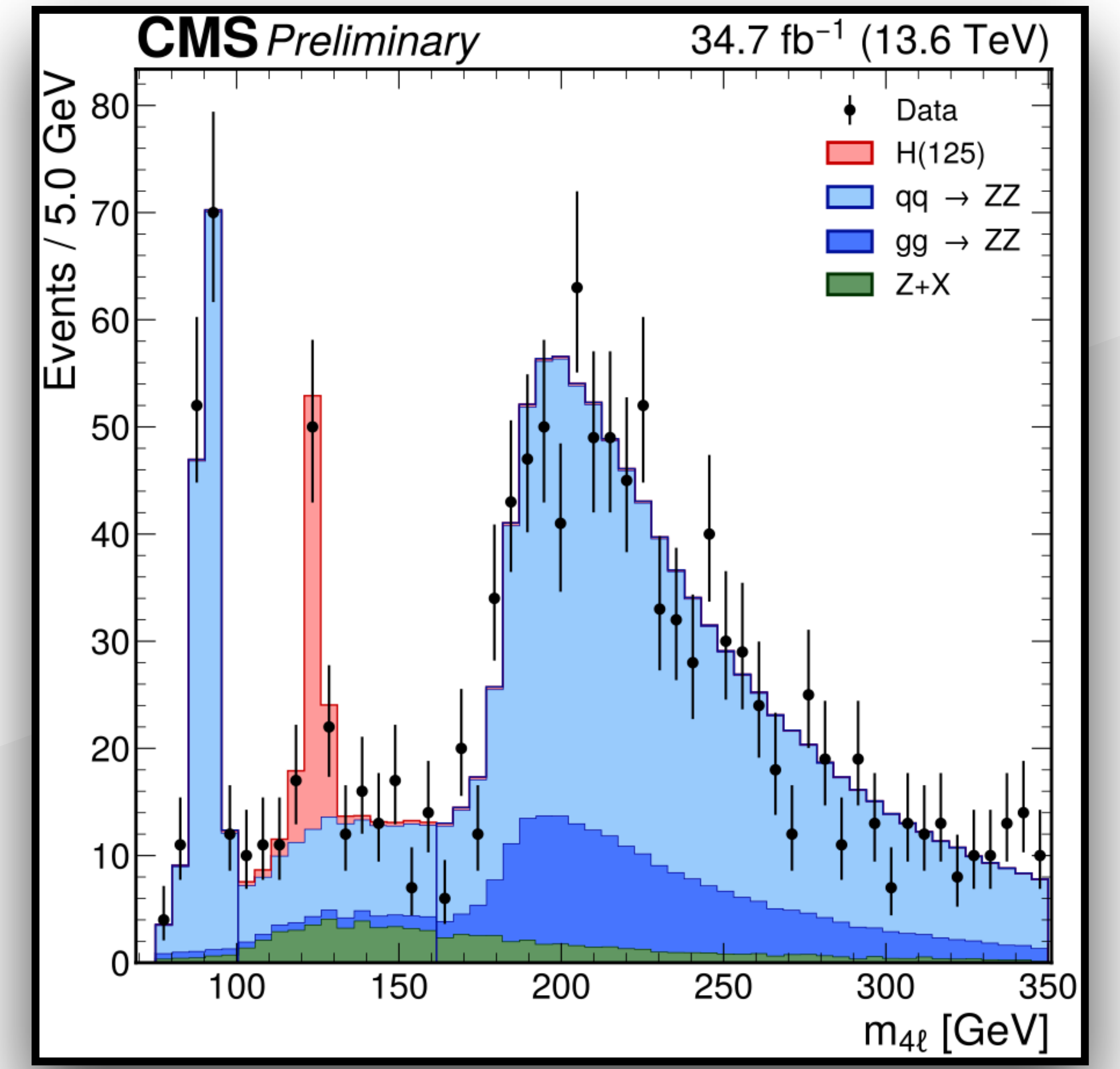
CMS-PAS-HIG-23-013

Run 3 measurements

$H\to\gamma\gamma$ and $H\to ZZ$ at 13.6 TeV:

HIG-24-013

- Inclusive and differential cross section measurements.
- Using ~ 35 fb^{-1} from 2022 → statistically limited.
- Excellent validation of muon and electron performance in CMS in Run 3.
- Old strategies, new tools!
- More in Nico's talk.

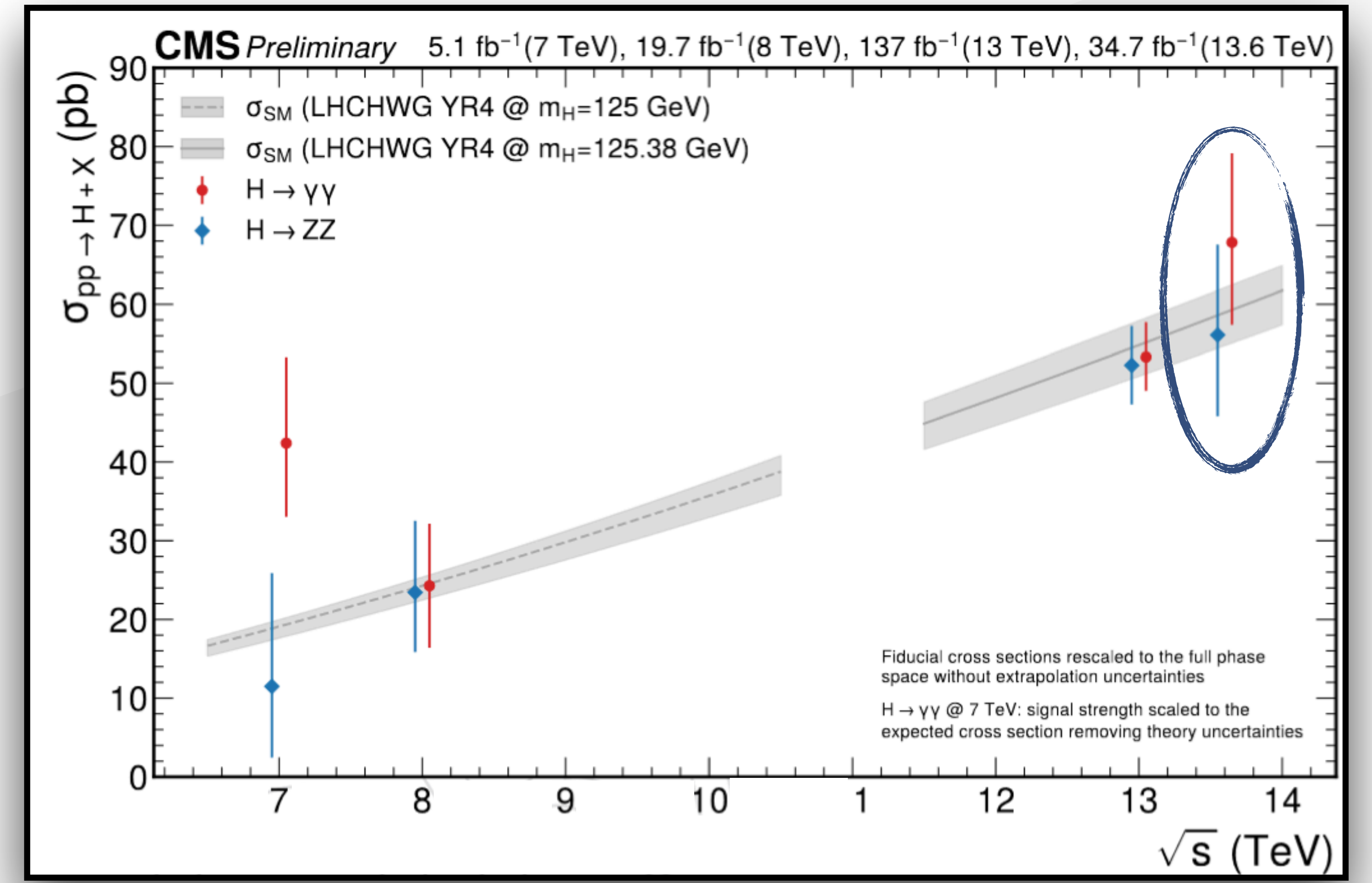


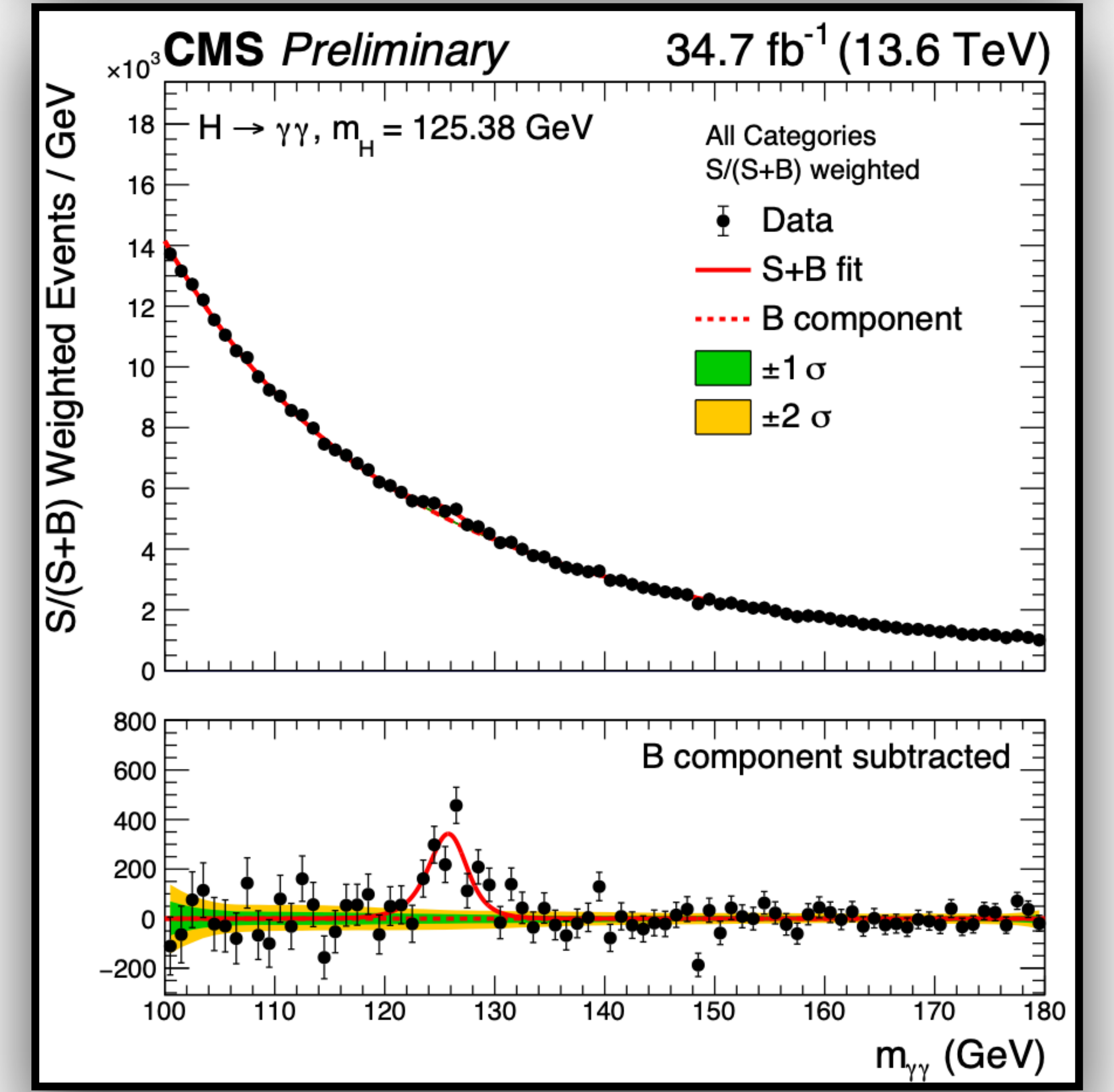
$H \to ZZ$

$$\sigma_{\text{fid}} = 2.94^{+0.53}_{-0.49}\,(\text{stat.})^{+0.29}_{-0.22}\,(\text{syst.})\,\text{fb}$$

$H \to \gamma\gamma$

$$\sigma_{\text{fid}} = 78 \pm 11\,(\text{stat.})^{+6}_{-5}\,(\text{syst.})\,\text{fb}$$

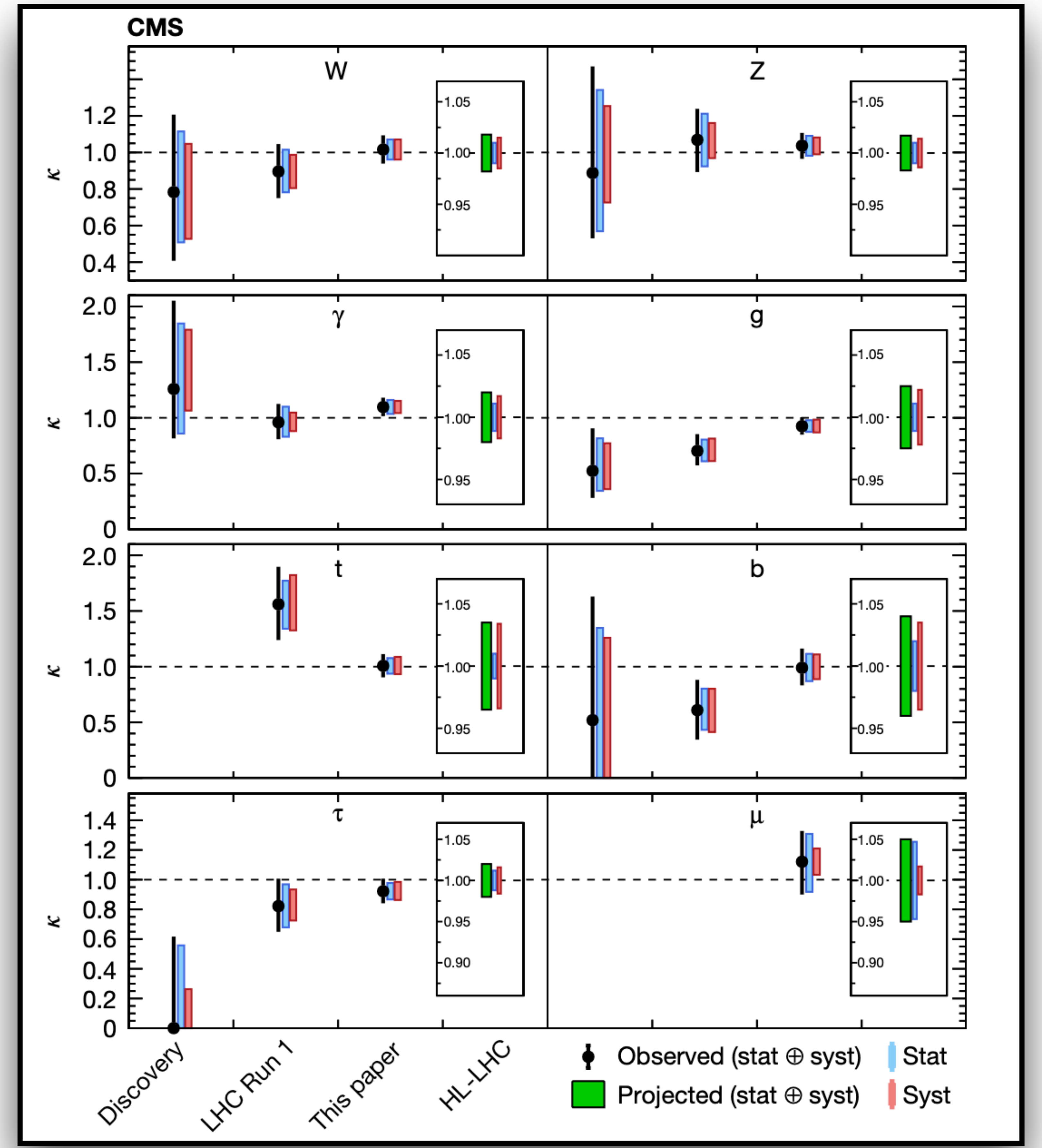




HIG-23-01

Summary

- After more than 10 years of studying the properties of the Higgs Boson we're now targeting precision measurements of its properties.
- **We've taken the most out of the Run 2 dataset:**
  - Most coupling to 3rd generation fermions and vector bosons are know with < 10% uncertainty.
  - 2nd generation couplings are becoming accessible.
- **First measurements with Run 3 are being published** and show good agreement with the SM.
- Much more to come! Looking forward to Run 3 and beyond.



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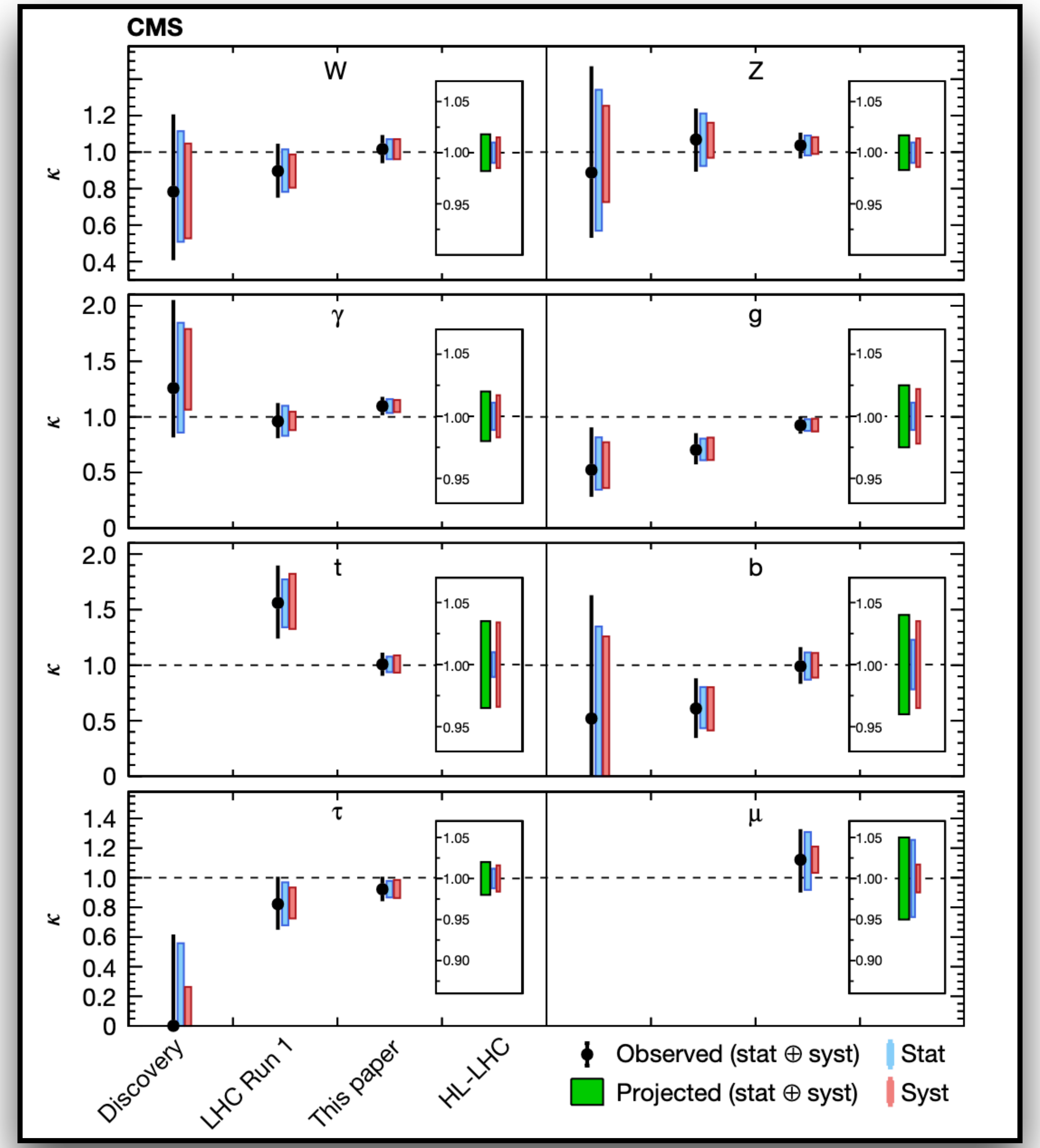

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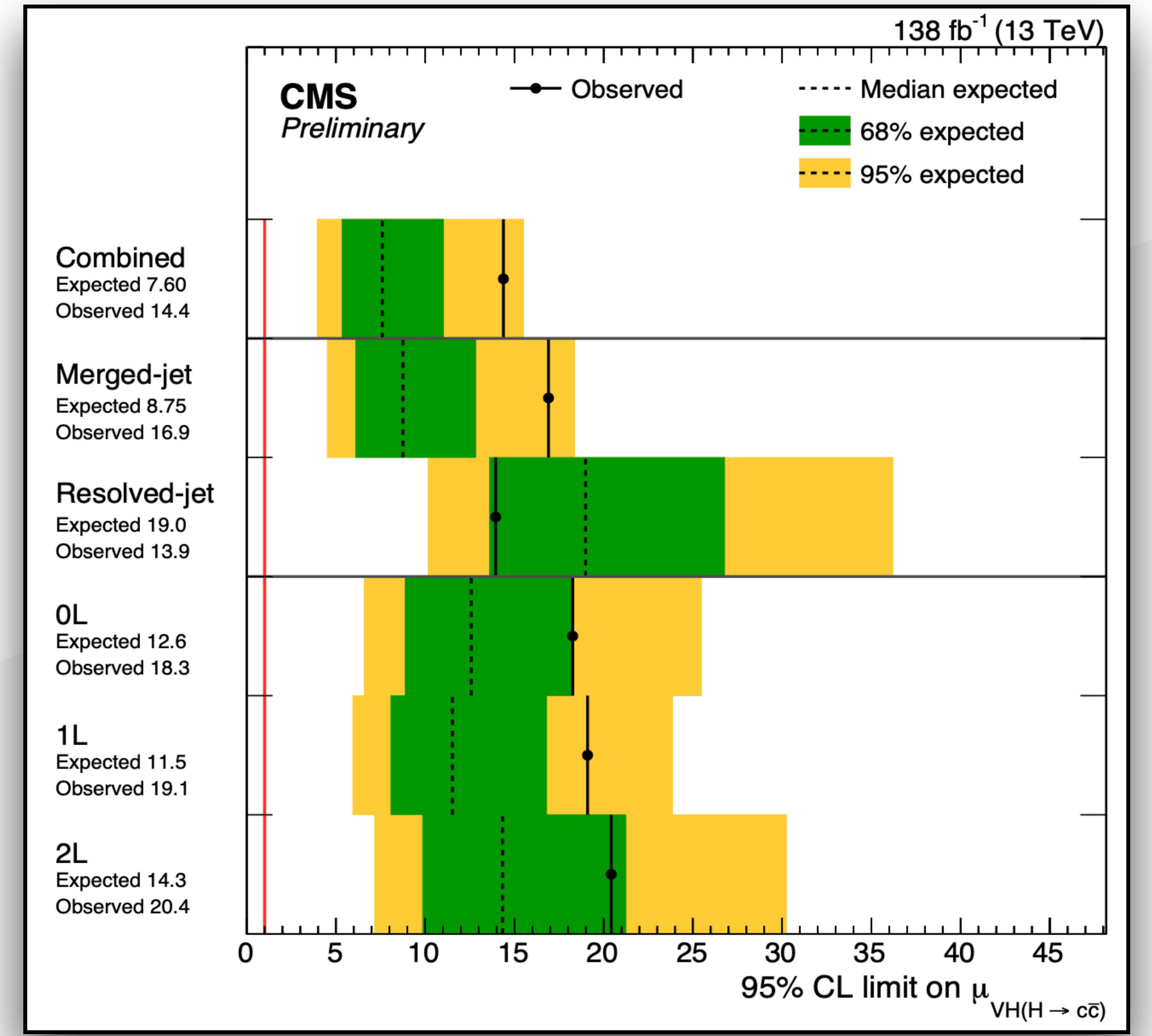
Thank you!

Back Up

Motivation

- Direct search for $VH(H \rightarrow c\bar{c})$ arXiv:2205.05550: recent improvements, most stringent limit on $H \rightarrow c\bar{c}$.
  - Upper limit $\mu_{VH(H\rightarrow c\bar{c})} < 14\ (7.6)$ observed (expected).
  - $1.1 < |k_c^{[*]}| < 5.5\ (|k_c| < 3.4)$ observed (expected) at 95% C.L.
    [ATLAS : $|k_c| < 8.5(12.4)$ obs (exp) at 95% C.L.]
  - First observation of $Z \rightarrow c\bar{c}$ at a hadron collider (5.7σ)



- Boosted $ggH(H \rightarrow c\bar{c})$ HIG-21-012:
  - $\mu < 38\ (45)$ observed (expected) at 95% C.L.

- Exclusive $H \rightarrow J/\Psi + \gamma$ decays, clean signature, $J/\Psi \rightarrow \mu\mu$ but very rare process:
  - $BR/BR_{SM} < 220\ (170)$ observed (expected) at 95% C.L.
    [ATLAS : proj. for $3\ ab^{-1}$ $\mu < \mu_{SM}$ at 95% C.L.]

- H differential measurements, variation of $p_T(H)$ as a function of k_c:
  - $-4.9 < k_c < 4.8\ (-6.1 < k_c < 6.0)$ observed (expected) at 95% C.L.

$H(\gamma\gamma) + c$ analysis

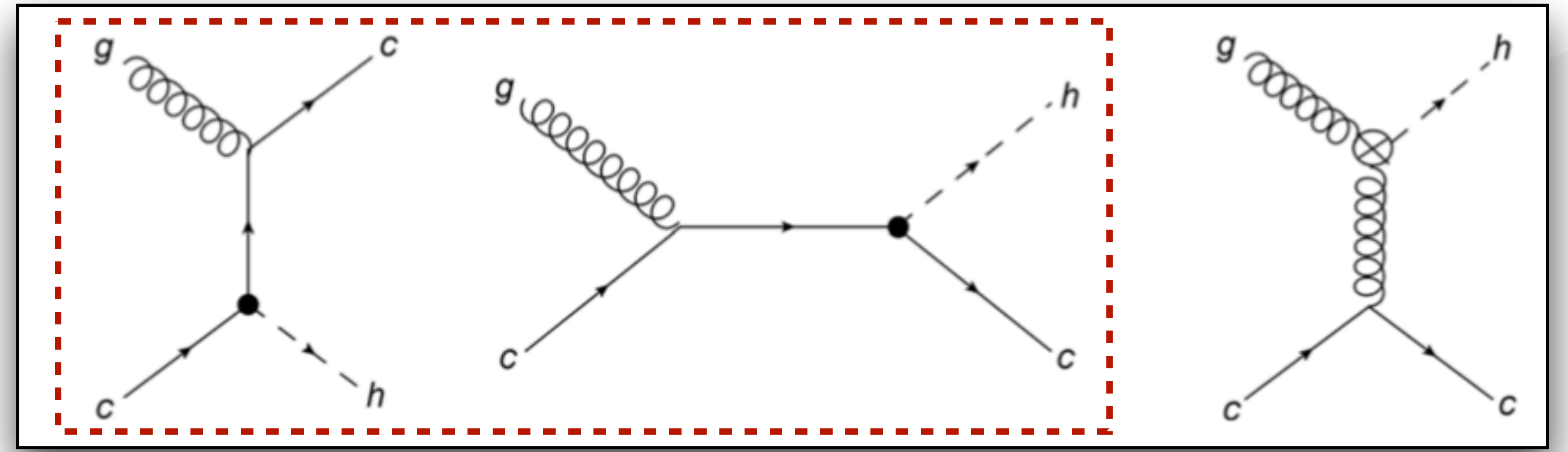
H+c signal:

- Focusing on the signal simulation for $H + c$ MC (not available in CMS up to now).

$$\sigma(hc) = A + B \cdot y_c + C \cdot y_c^2$$

	σ [fb]
A	254.5
B	-3.5
C	34.5

[GEN charm $p_T > 20$ GeV]



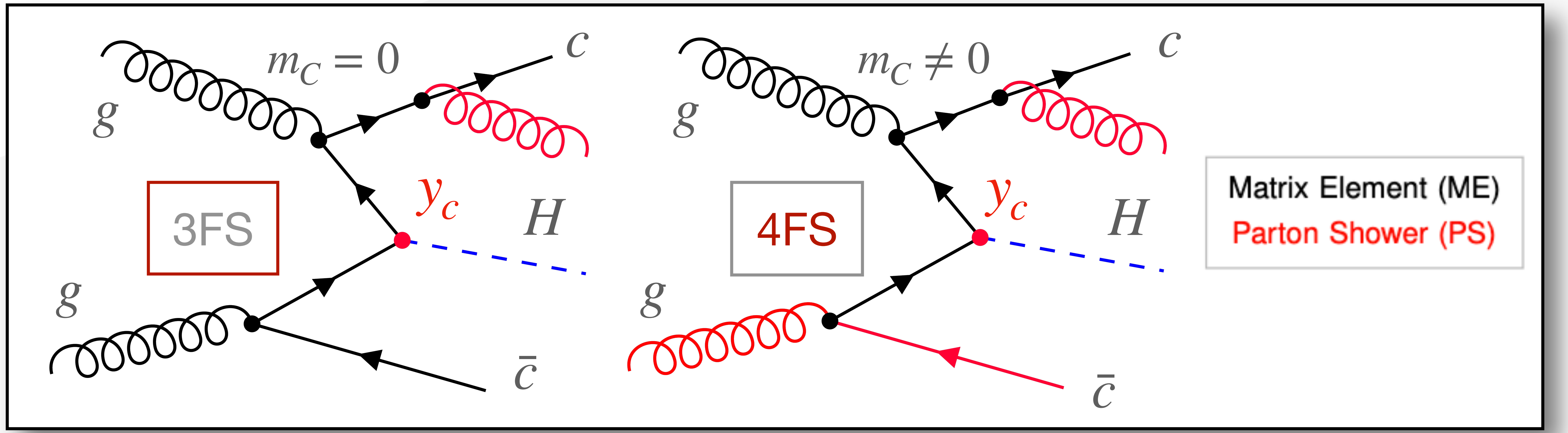
- $\sigma(hc)$ does not scale trivially with y_c, tests were run with effective ggH coupling at LO.
- Biggest contribution from the term that does not probe y_c, but small y_c proportional interference term (~10 times smaller than the y_c^2 dependent term), for sensitivity $O(10 \cdot SM)$ contribution of ~1%.
- As first approximation one can generate signal probing y_c^2 and bkgs/interference in separate MC, orthogonality with $H + jets$ MCs.

$H(\gamma\gamma)$ + c analysis

Focus on the y_c^2 term:

- Simulated with **MadGraph_aMC@NLO** ([QCD] NLO) + Pythia8 Parton Shower.
- Simulated using `loop_sm` model to have y_c in the $\overline{MS}$ renormalisation scheme and include **running of $y_c \rightarrow \overline{y}_c(\mu_R)$ and $m_c \rightarrow \overline{m}_c(\mu_R)$.**
- Simulated using **4 Flavour Scheme** (4FS), to have c-quarks in the initial state, and with FXFX-merging to **better describe the kinematics.**
  - To assess the 3FS vs 4FS theory uncertainty we **compare samples produced using both methods:**
    $\Rightarrow$ FS uncertainty $O(30\%)$ of the yields in analysis categories, dominant w.r.t. Scales, PDFs, PS.

LO diagrams

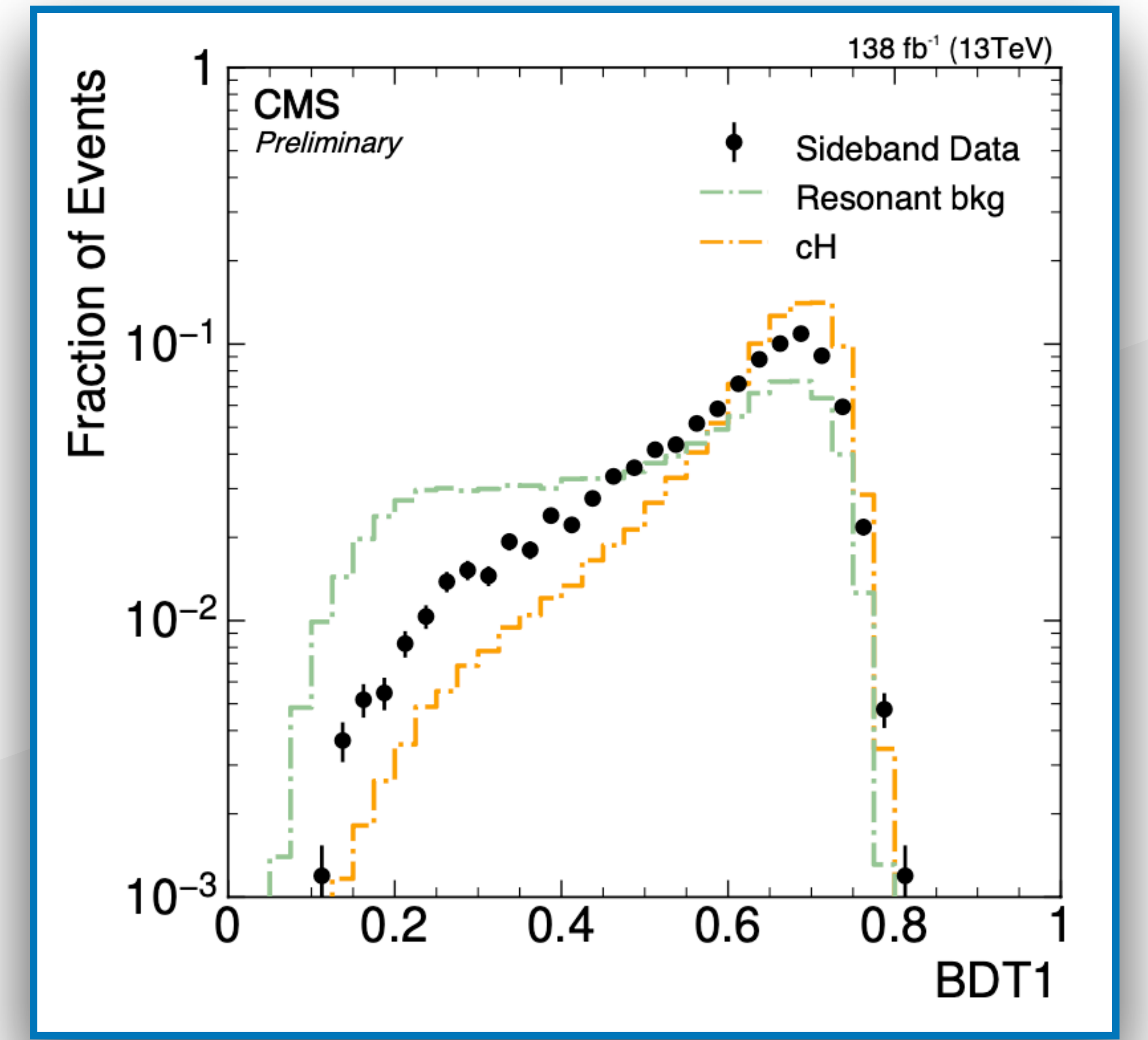


$H(\gamma\gamma) + c$ analysis

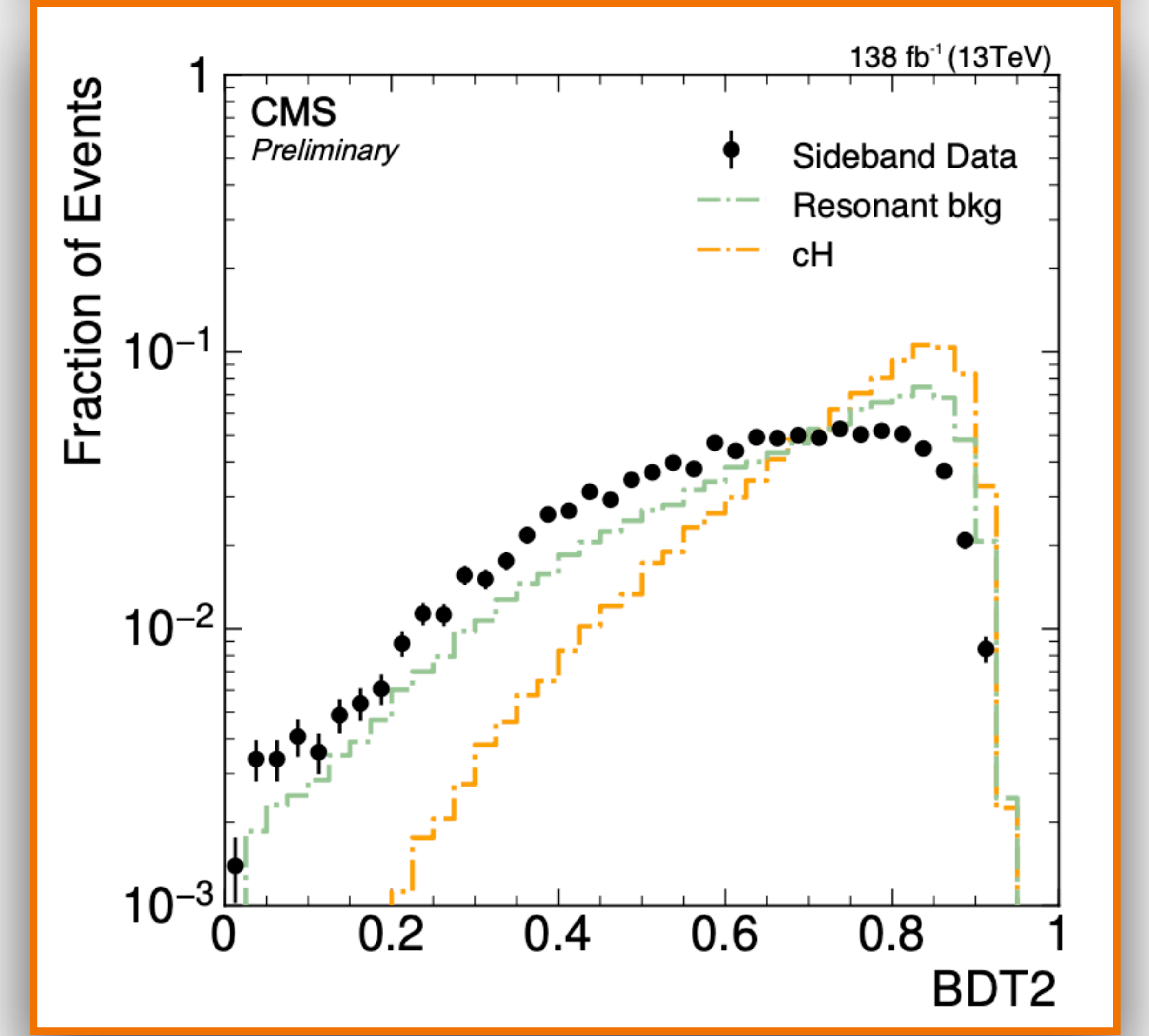
BDT training:

- We use two Boosted Decision Trees (BDT) to separate the two main backgrounds:
    - **cH vs ggH** (BDT1): cH (signal), ggH (background),
    - **cH vs CB** (BDT2): cH (signal), $\gamma\gamma$ and $\gamma + jets$ (backgrounds).
- Separation is achieved exploiting the **kinematics of the Photons and Jets** in the event.
- c-tag scores are NOT used in the training, so that $ggH + c$ fraction is stable w.r.t BDT outputs. This limits the impacts of $ggH + HF$ mismodelling.
- Training performed with the XGBoost package.

cH vs ggH



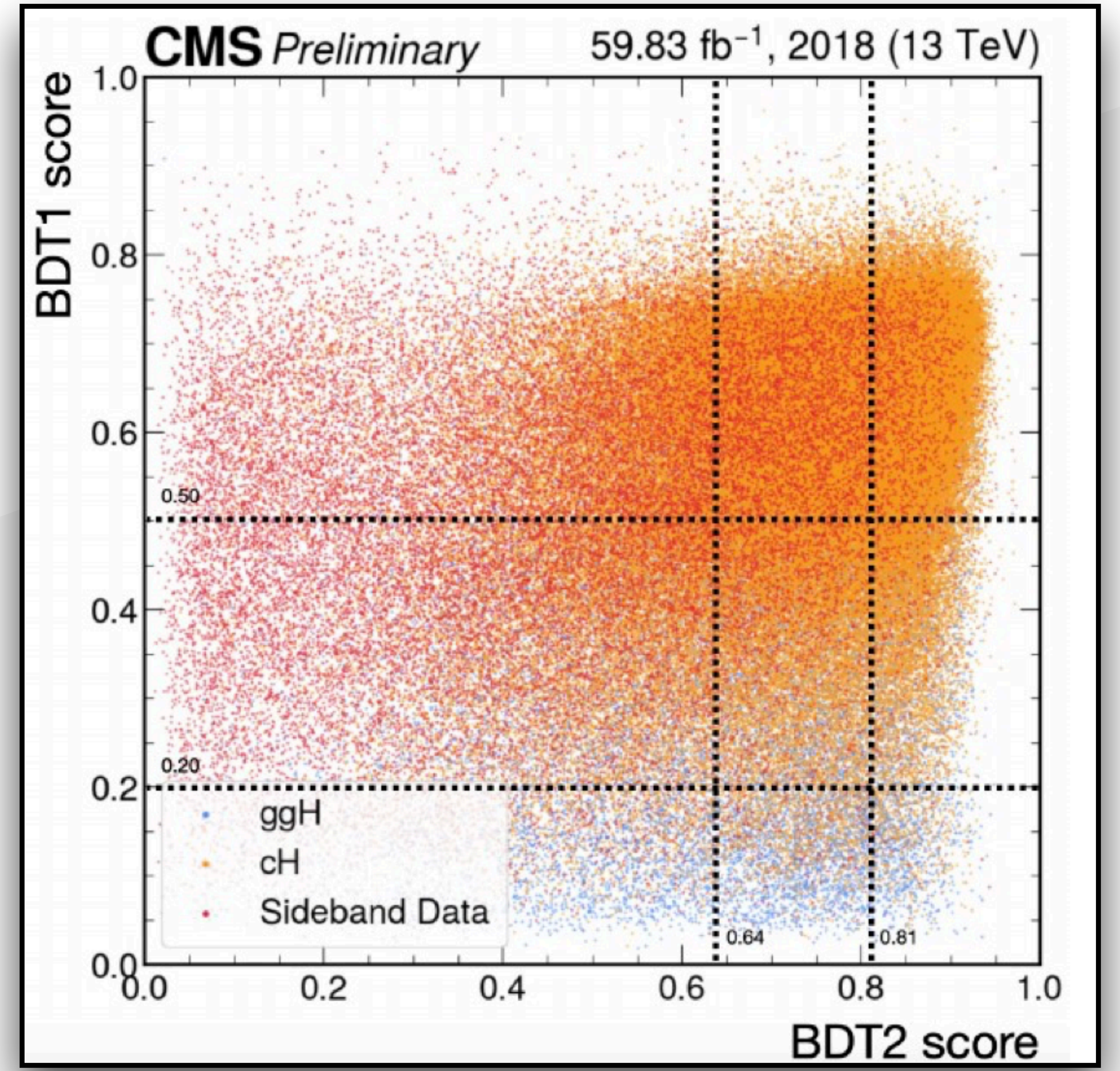
cH vs CB



$H(\gamma\gamma) + c$ analysis

Categorisation:

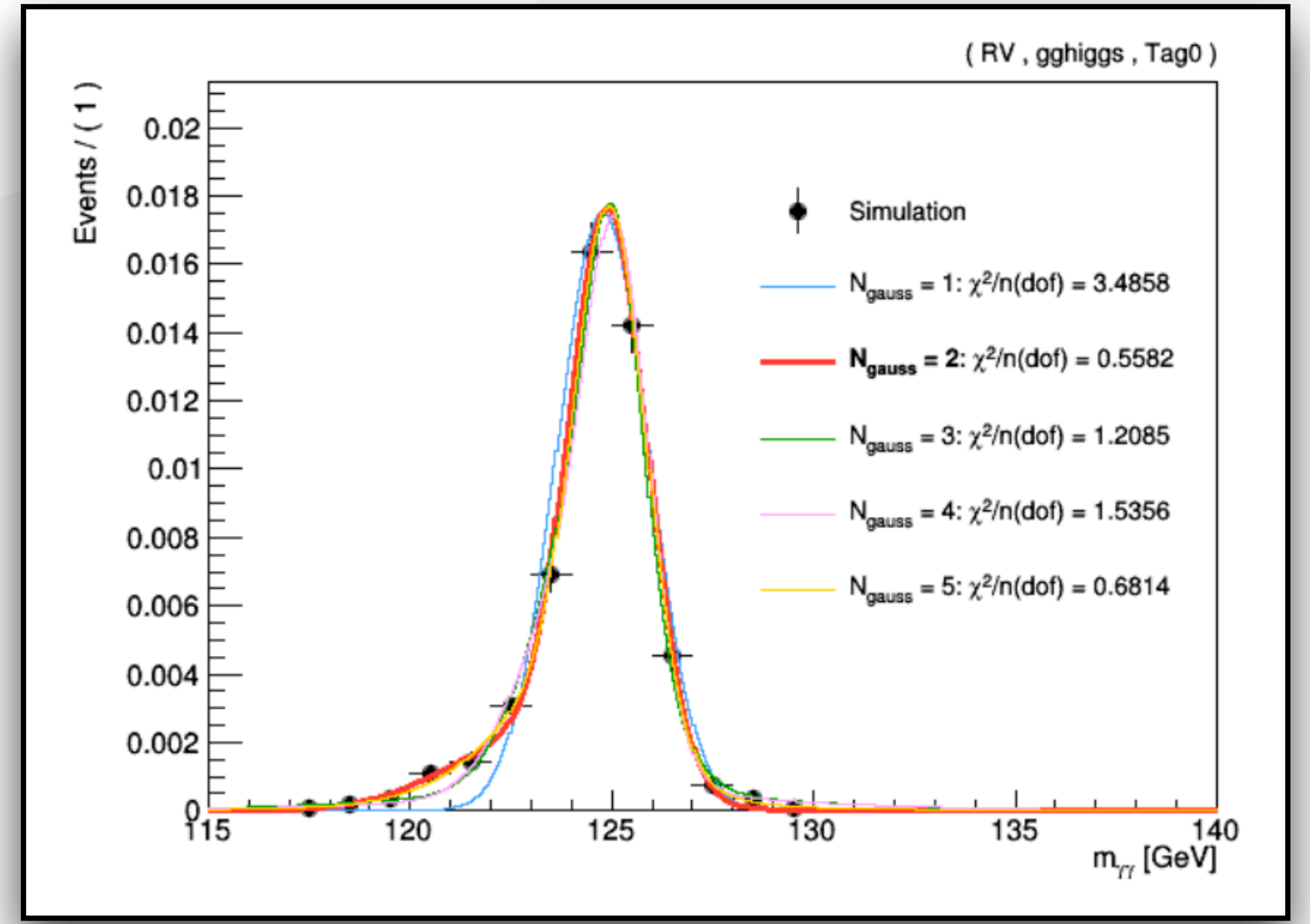
- The events are divided into **9 categories for each year**, according to the scores of BDT1 and BDT2.
- The category boundaries are simultaneously optimised using MCs:
  - To reduce the correlation between the cH and ggH processes,
  - To maximise the sensitivity.
- Boundaries are optimised separately for each year.
- Migration uncertainties and data/MC agreements are extracted from $Z \to e^+e^-$ events.



$H(\gamma\gamma) + c$ **analysis**

Higgs processes modelling:

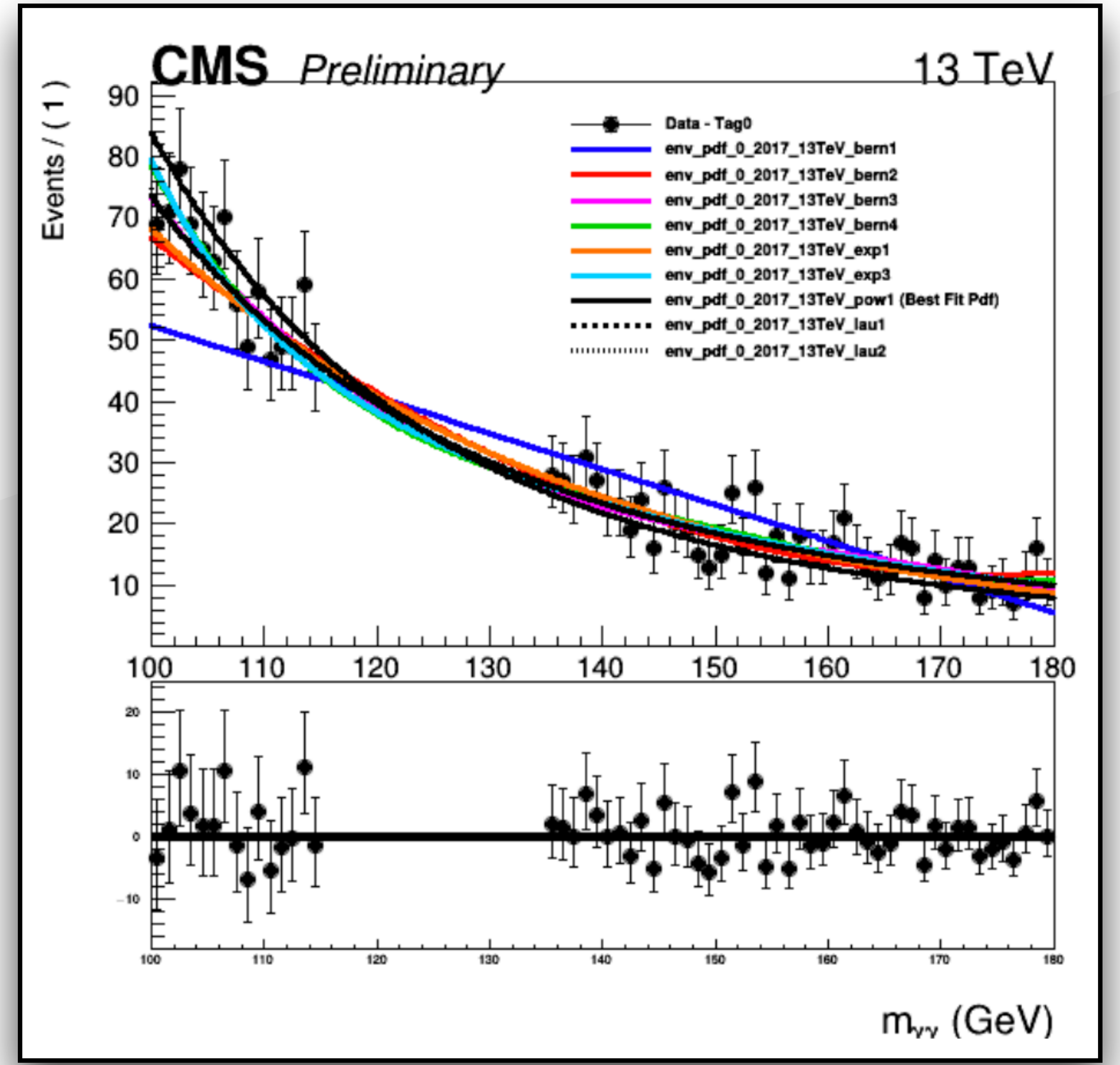
- The statistical analysis is performed with the $H \to \gamma\gamma$ FlashggFinalFit framework.
- The signal and the Higgs backgrounds are modelled with MC simulations.
- **Mass shapes** are:
  - Parametrised with **sum of multiple gaussian functions.**
  - The parametrisation is derived **independently for each process X category X vtx scenario.**
  - Yields are extracted from simulation.



$H(\gamma\gamma)$ + *c* analysis

Continuous background modelling:

- The continuous background is modelled with a **data driven approach**.
- The functional form and normalisation are extracted by fitting the data.
- An F-test is performed to chose from different orders and families of analytical functions.
- A **discrete nuisance parameter** is used to extract an uncertainty due to the choice of one functional form over the others.
- Normalisation is extracted from data.



$H + b$ associated production

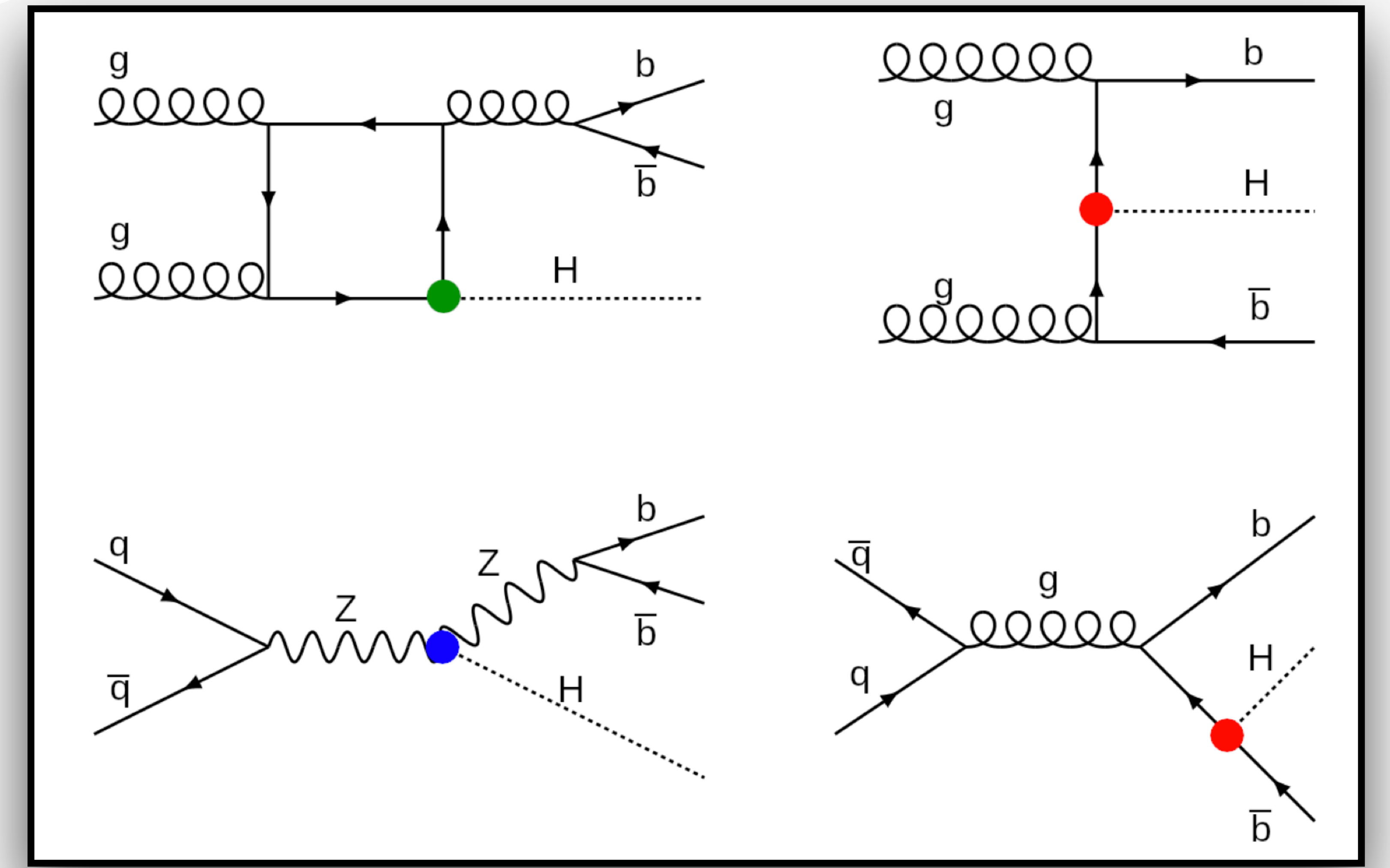
- Cross section components coming from the different processes.

- Inclusive measurement: The different contributions to the signal are scaled by varying proportionally the y_b^2, y_t^2 and $y_b y_t$ terms.

  - Infer limits on the Higgs coupling structure → done by introducing the coupling scaling parameters k_t and k_b, and performing a likelihood ratio scan over the $k_t - k_b$ parameter space.

  - b-quark contribution to the quark loop in the y_t^2 process, are accounted for by scaling it by $1.04k_t^2 - 0.04k_b k_t + 0.002k_b^2$, while the y_b^2 contribution and the interference term are scaled by k_b^2 and $k_b k_t$ respectively.

term	σ(pb)
y_t^2	1.040 (+0.468 -0.489)
y_b^2	0.482 (+0.048 -0.070)
$y_b y_t$	– 0.033 (+0.007 -0.008)



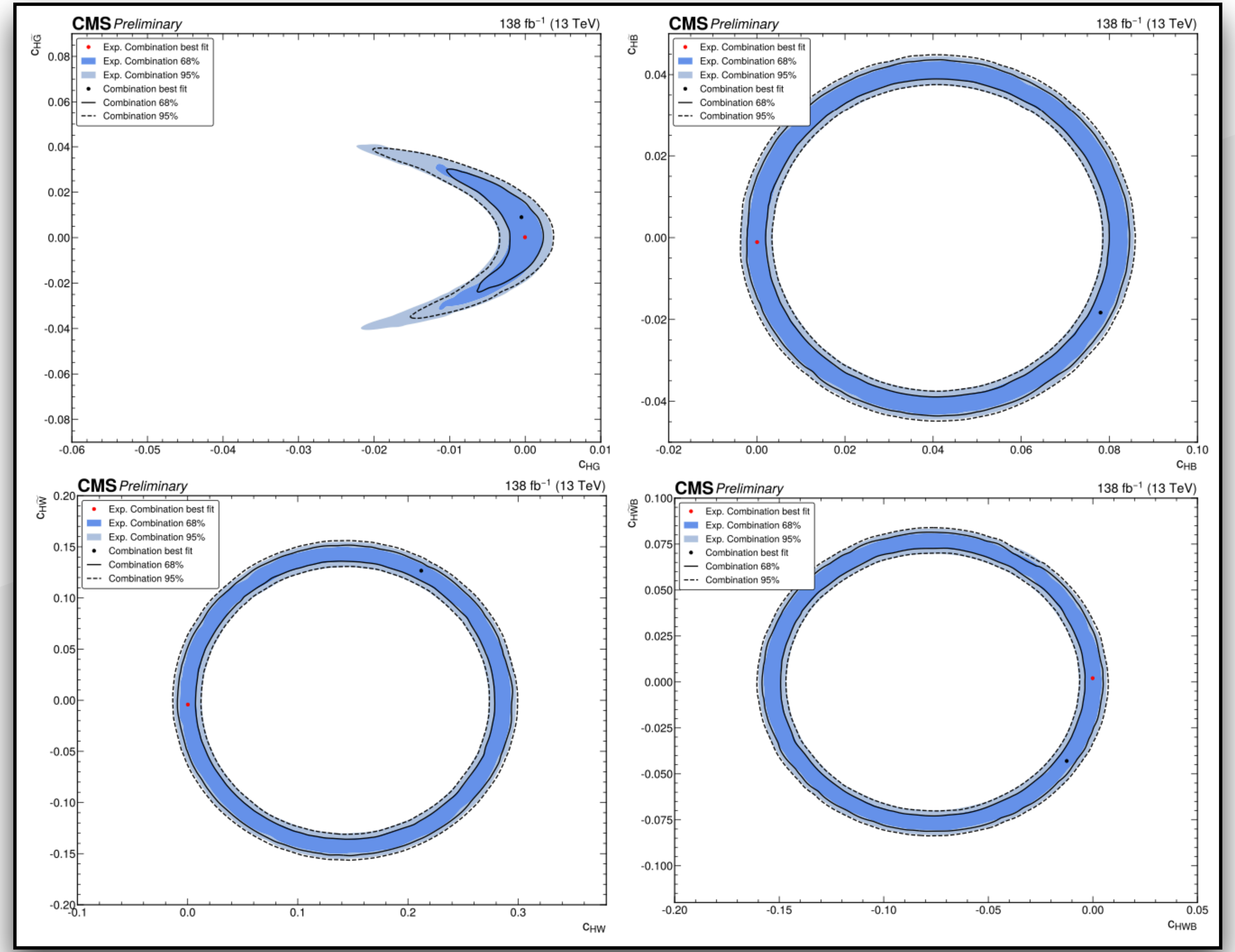
$H + b$ associated production

- The fit is performed on the BDT score distributions for both signal and background categories.
- Lower-score regions are still dominated by background processes,
- Higher BDT score regions show an increasing contribution from bbH process in final states with τ leptons or W bosons.
- There must be a $e\mu$, $e\tau_h$, $\mu\tau_h$, or $\tau_h\tau_h$ pair with opposite electric charge.
- No additional electrons or muons may be present in the event.
- The leptons and τ_h candidates must be separated by $\Delta R >$ 0.5(0.3) in the $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ ($e\mu$) channels.
- There must be at least one, and no more than two, b-tagged jet.

Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}$	×	✓	✓	✓
m_{vis}	✓	✓	✓	✓
Collinear mass	×	✓	✓	×
D_ζ	✓	✓	✓	×
$\Delta\eta$ between lepton and τ_h	×	✓	✓	×
Total transverse mass	✓	×	×	×
Di-τ p_T	✓	✓	✓	✓
Electron p_T	✓	×	×	×
Muon p_T	✓	×	×	×
p_T of leading τ_h	×	×	×	✓
p_T of trailing τ_h	×	×	×	✓
Transverse mass	×	✓	✓	×
Number of b-jets	✓	×	×	✓
p_T of leading b-jet	✓	✓	✓	✓
p_T of trailing b-jet	×	✓	✓	×
B-tag score for leading b-jet	×	✓	✓	✓
$\Delta\eta$ between di-τ p_T and leading b-jet	×	✓	✓	×
B-tag score for trailing b-jet	×	✓	✓	✓
Number of jets	✓	×	×	✓
p_T of leading jet	✓	×	×	✓
p_T of trailing jet	✓	×	×	✓
Di-jet invariant mass	×	×	×	✓
Di-jet $\Delta\eta$	✓	×	×	✓
p_T^{miss}	×	×	×	✓

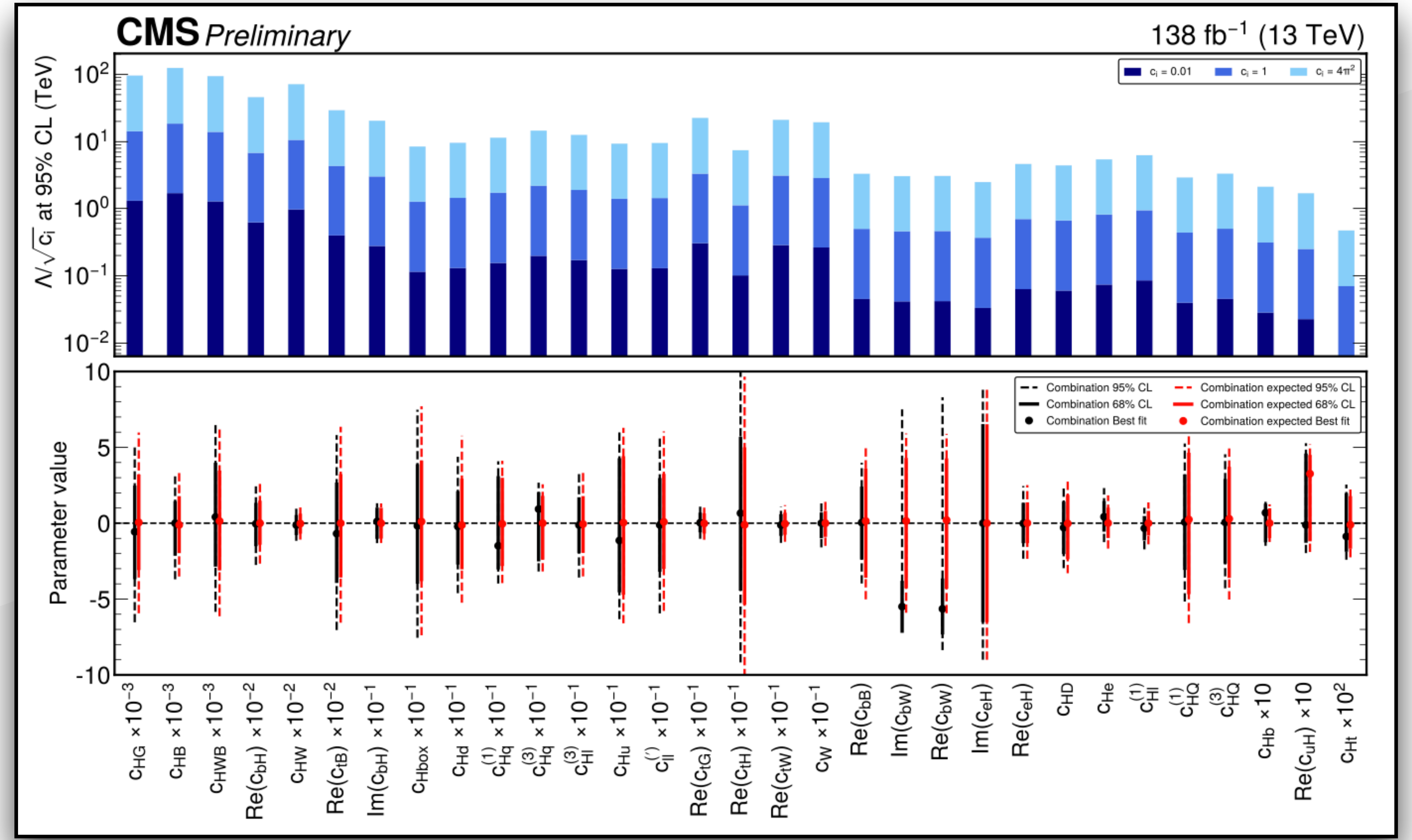
Combination of fid. diff. H boson prod. XSections

- One or two WCs left free to float, others fixed to SM value.
- Fit:
  $\Rightarrow c_{HG}, \tilde{c}_{HG},$
  $\Rightarrow c_{HB}, \tilde{c}_{HB},$
  $\Rightarrow c_{HW}, \tilde{c}_{HW},$
  $\Rightarrow c_{HWB}, \tilde{c}_{HWB}$
- Set others to 0.
- $c_{HG}, \tilde{c}_{HG}$ mostly affect ggH production.
- c_{HWB}, c_{HW}, c_{B} and their CP odd partners mostly affect VH, VBF production and the Higgs decays.



Combination of fid. diff. H boson prod. XSections

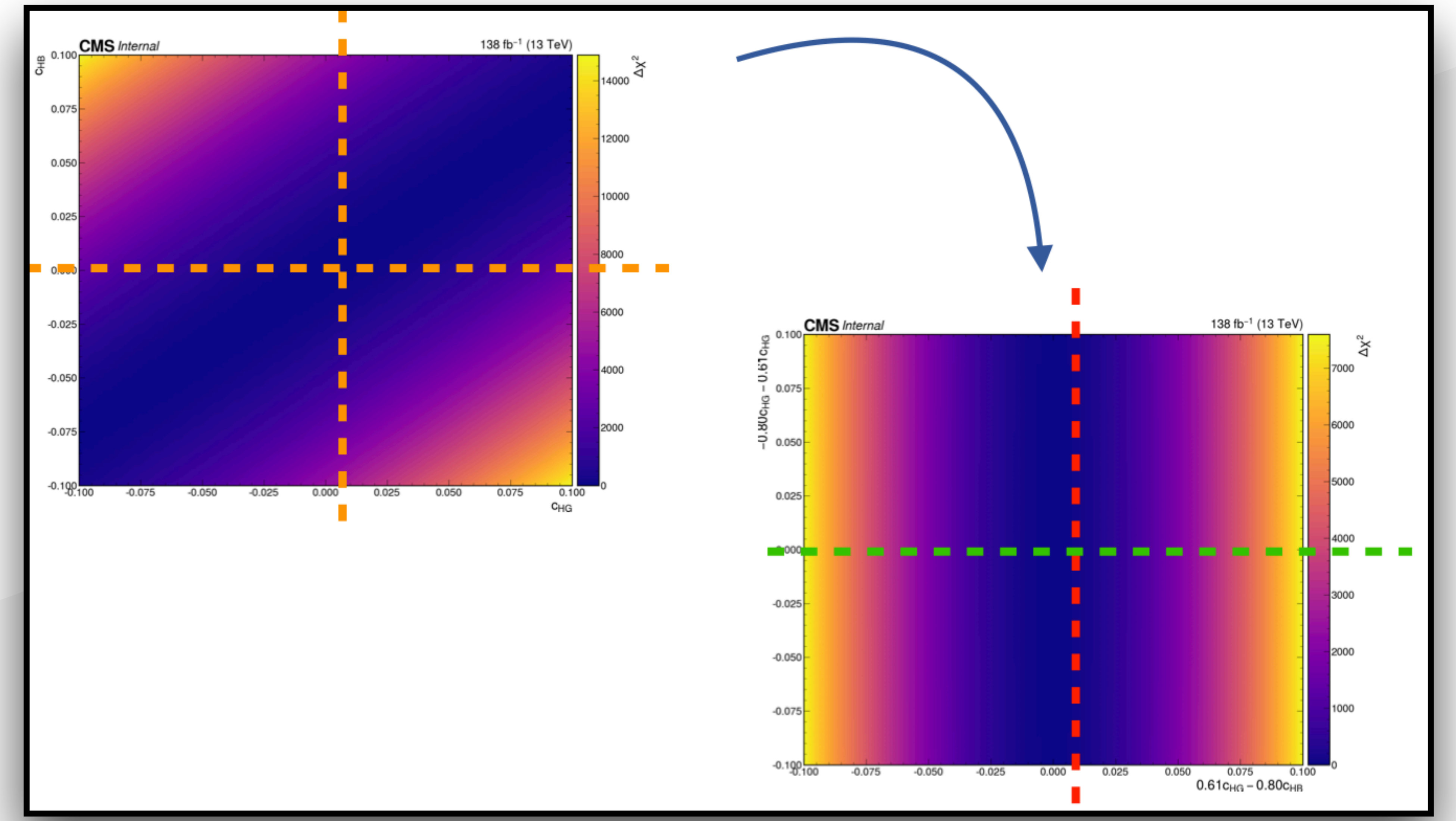
- Same procedure repeated for a wider set of coefficients.
- Derive lower bounds on the energy as a function of different operators for different coupling choices.

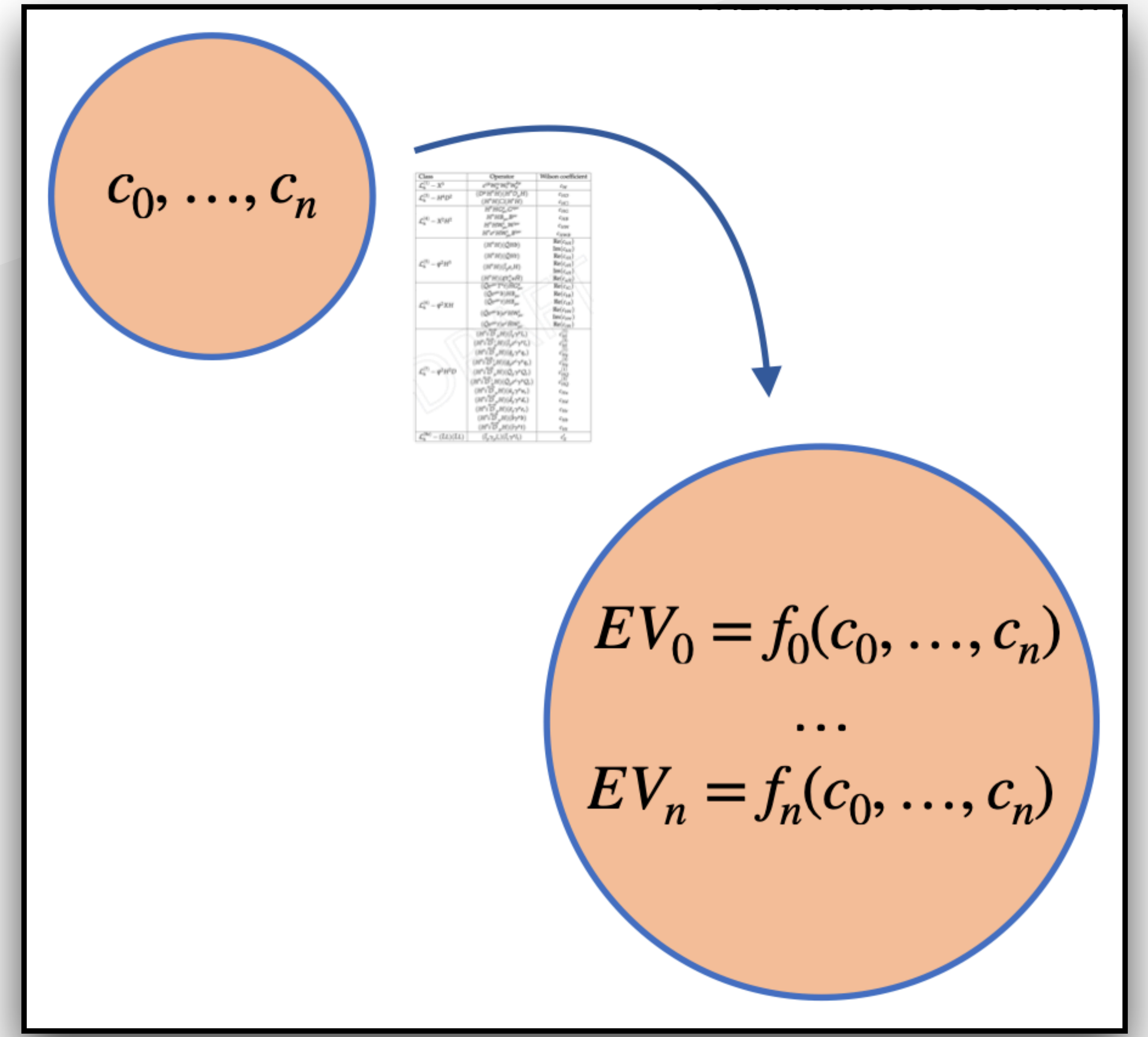


Combination of fid. diff. H boson prod. XSections

Principal Components Analysis:

- When running a fit floating all the WCs, we can't fit all directions in SMEFT basis simultaneously.
- Use PCA on the information matrix to find constrained direction in the parameter space.
- Obtain linear combination of SMEFT Wilson coefficient.
- Fit constrained directions, fix unconstrained directions to 0.
- In this case this assumption is lead by data itself.





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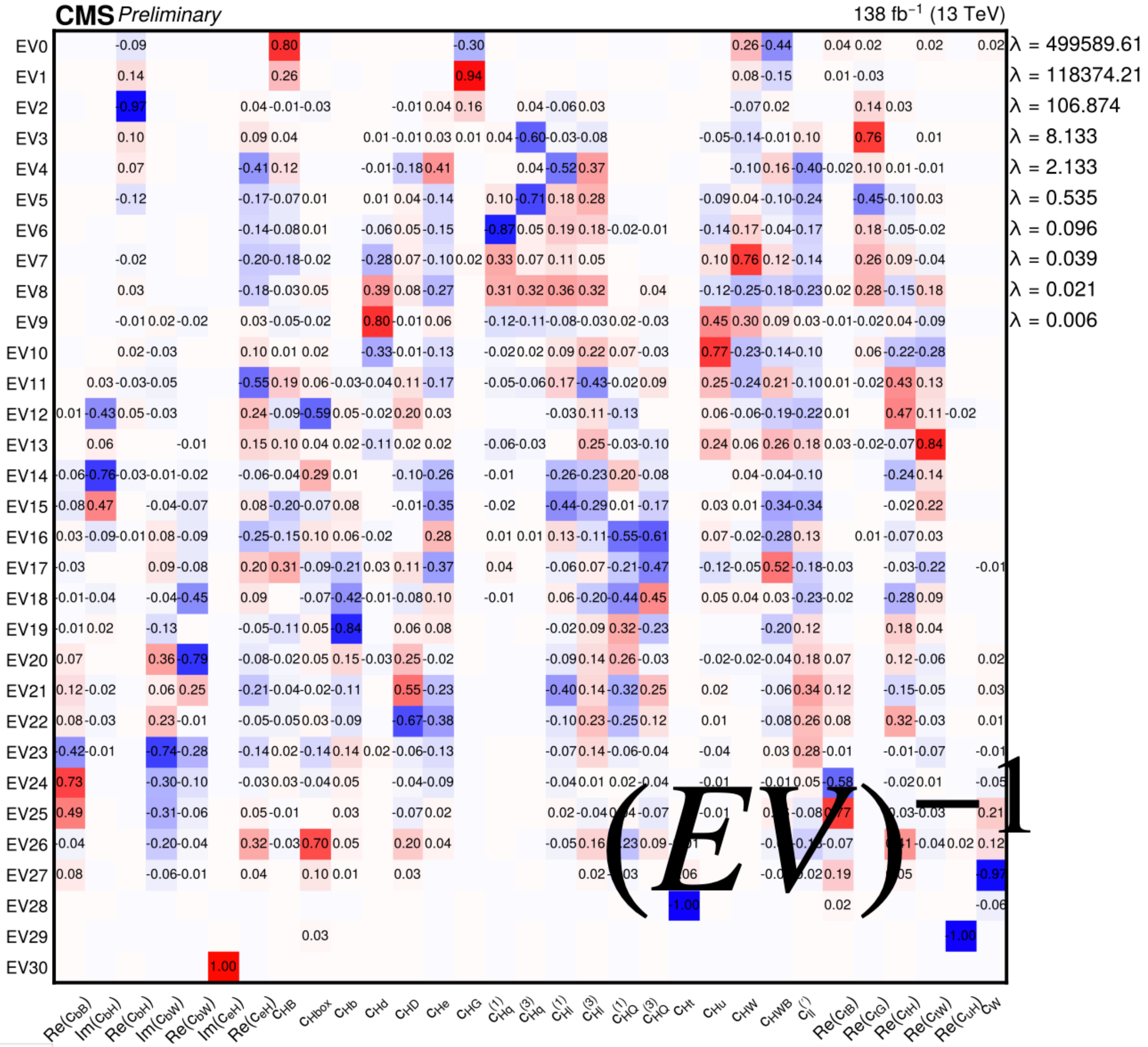
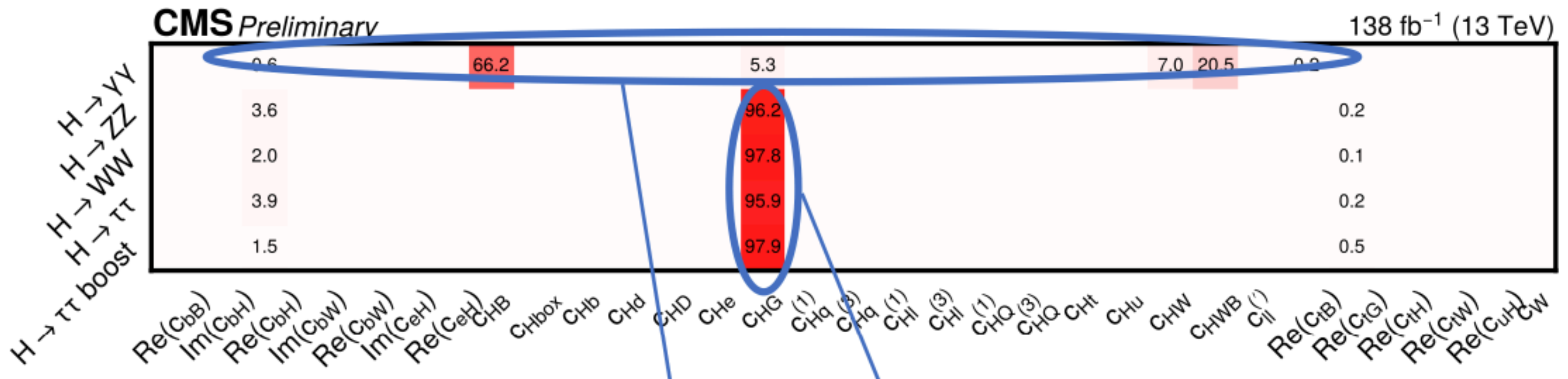
Combination of fid. diff. H boson prod. XSections

Sensitivity Studies





- Each row is the **diagonal of the expected Fisher Information Matrix** in its own decay channel analysis
- Normalization along **rows**
- Terms < 0.1 omitted

Dominated by c_{HG} because
- correction in production is two orders of magnitude higher than decay
- dominated by ggH

- Production and decay contributions are comparable
- Proportions justified by the linear terms entering rotation matrix P

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