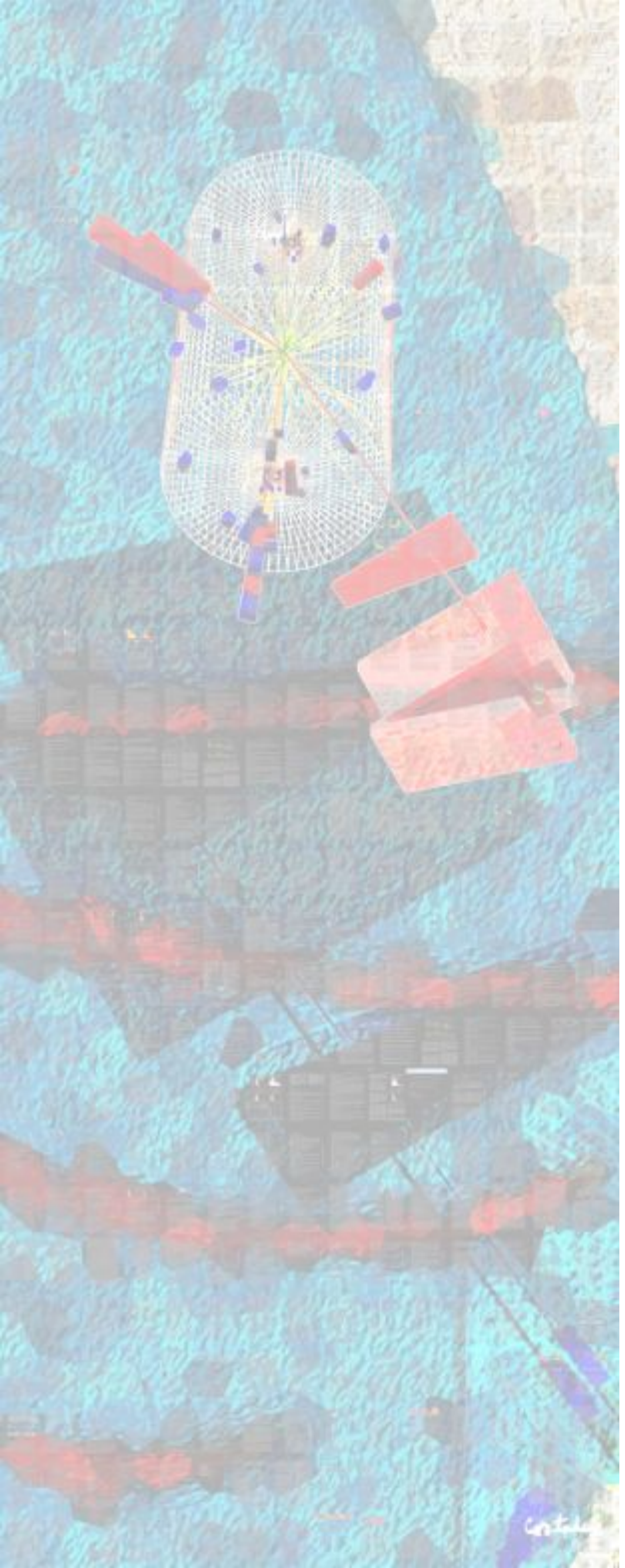
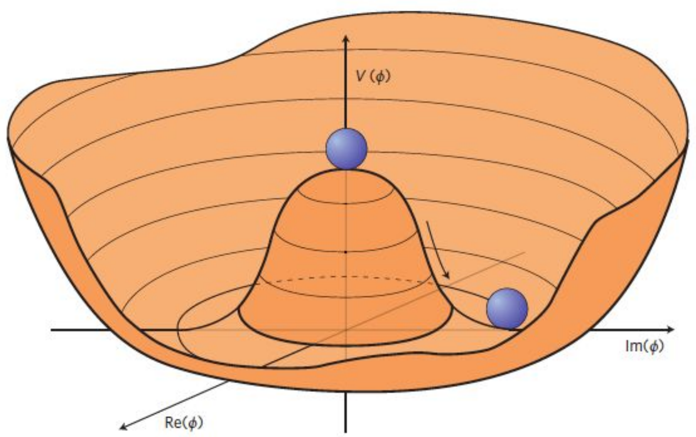




Higgs boson combinations at CMS

UoB Particle Physics Seminar

Dr. Jonathon Langford

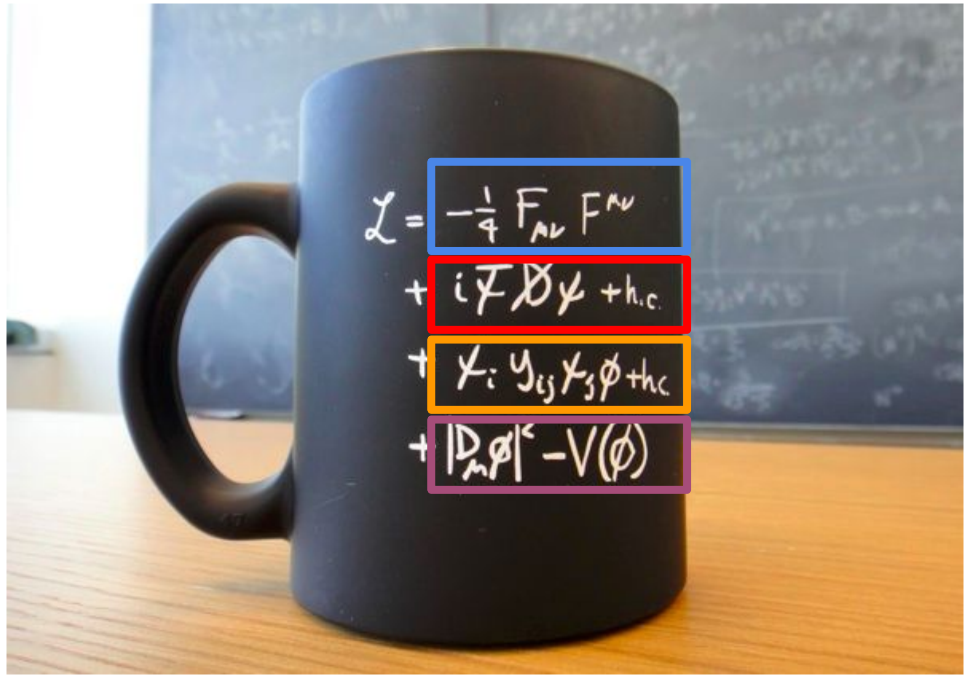
27th November 2024

Imperial-X

CMS

Higgs & the standard model

- SM = set of quantum field theories that describe fundamental particles and their interactions

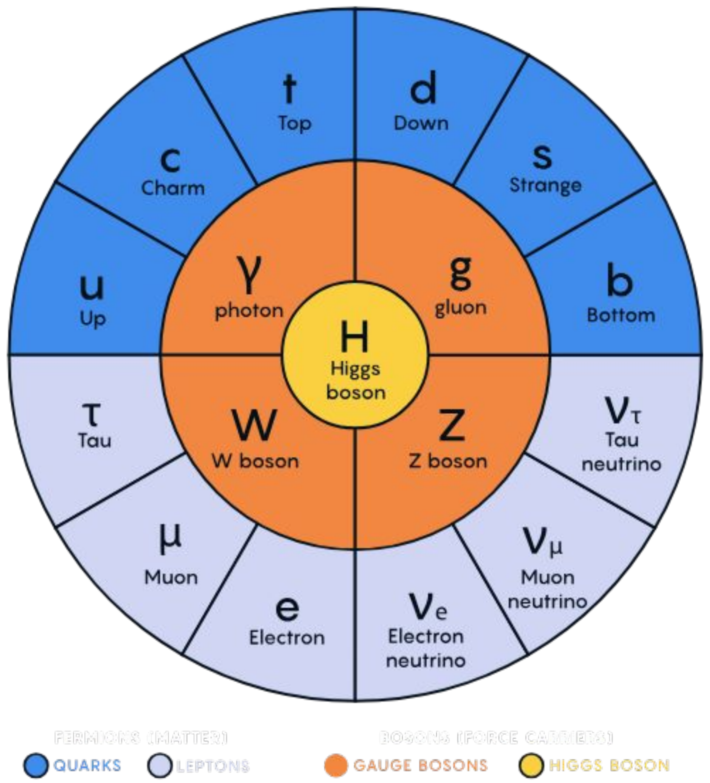


Propagation of force carriers (spin-1 bosons)

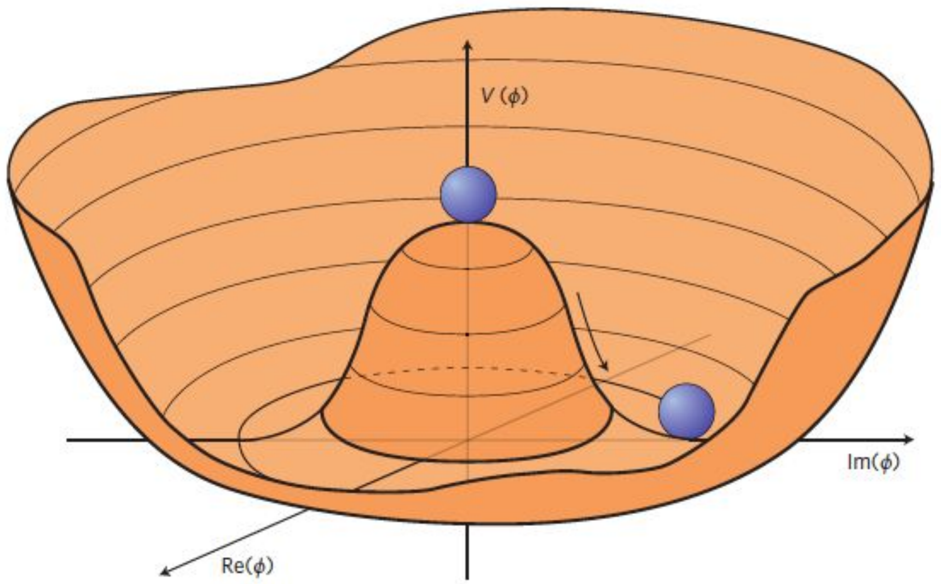
Interactions of matter particles (spin-½ fermions)

Masses of matter particles (Yukawa)

Higgs interactions & masses of force carriers



- Higgs mechanism plays a major role in the SM

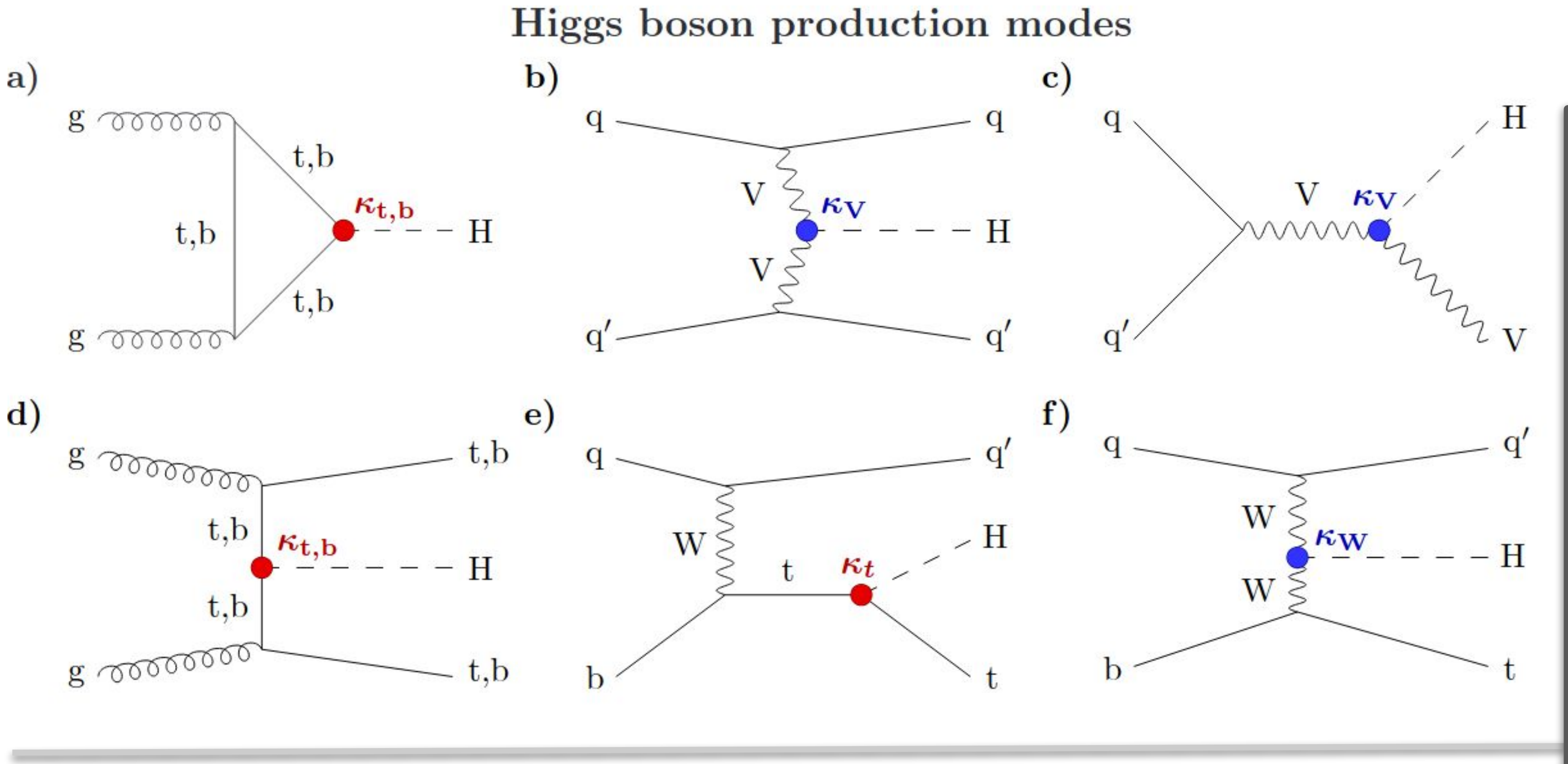


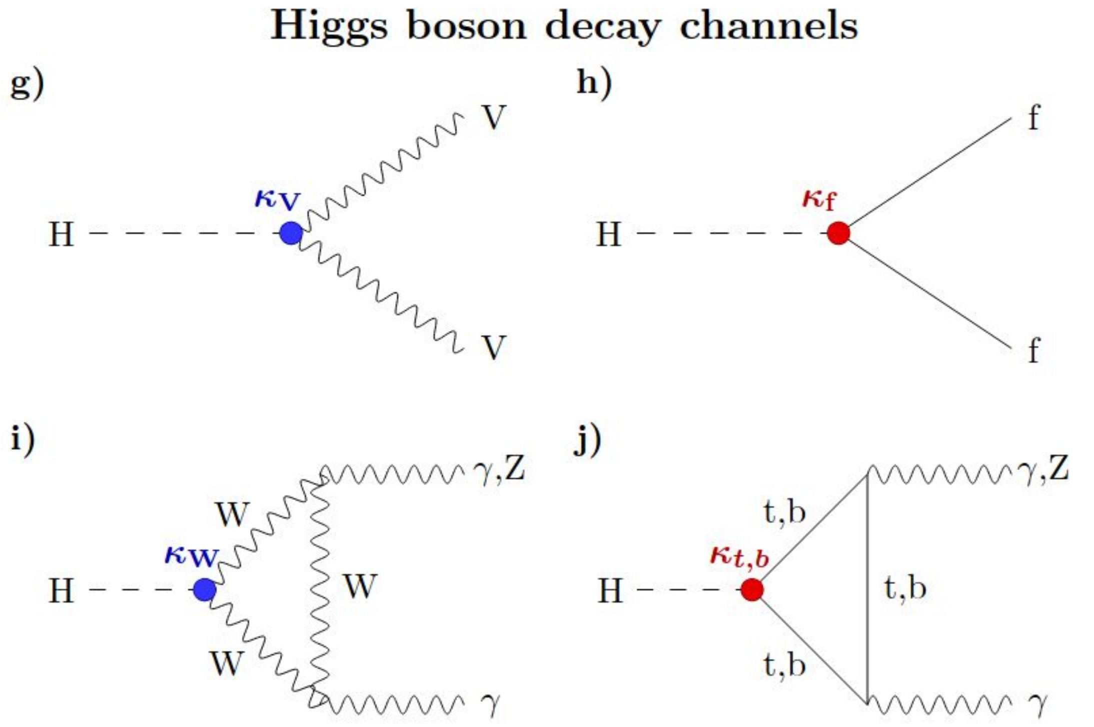
Explains how:

- *W and Z bosons acquire mass*
- *Quarks and charged leptons acquire mass*

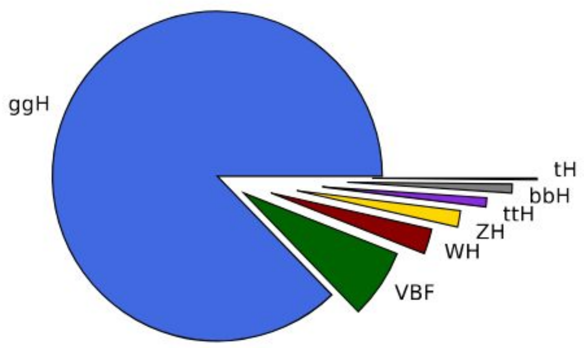
Prediction of new scalar particle → **Higgs boson**

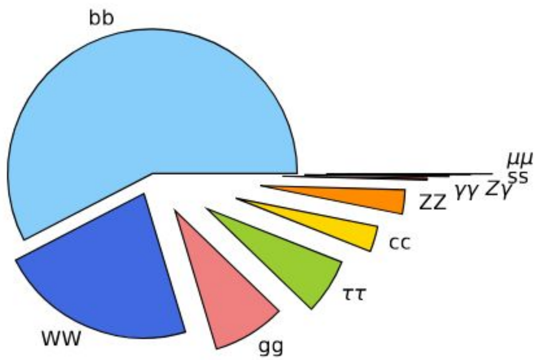
Higgs boson production & decay @ LHC





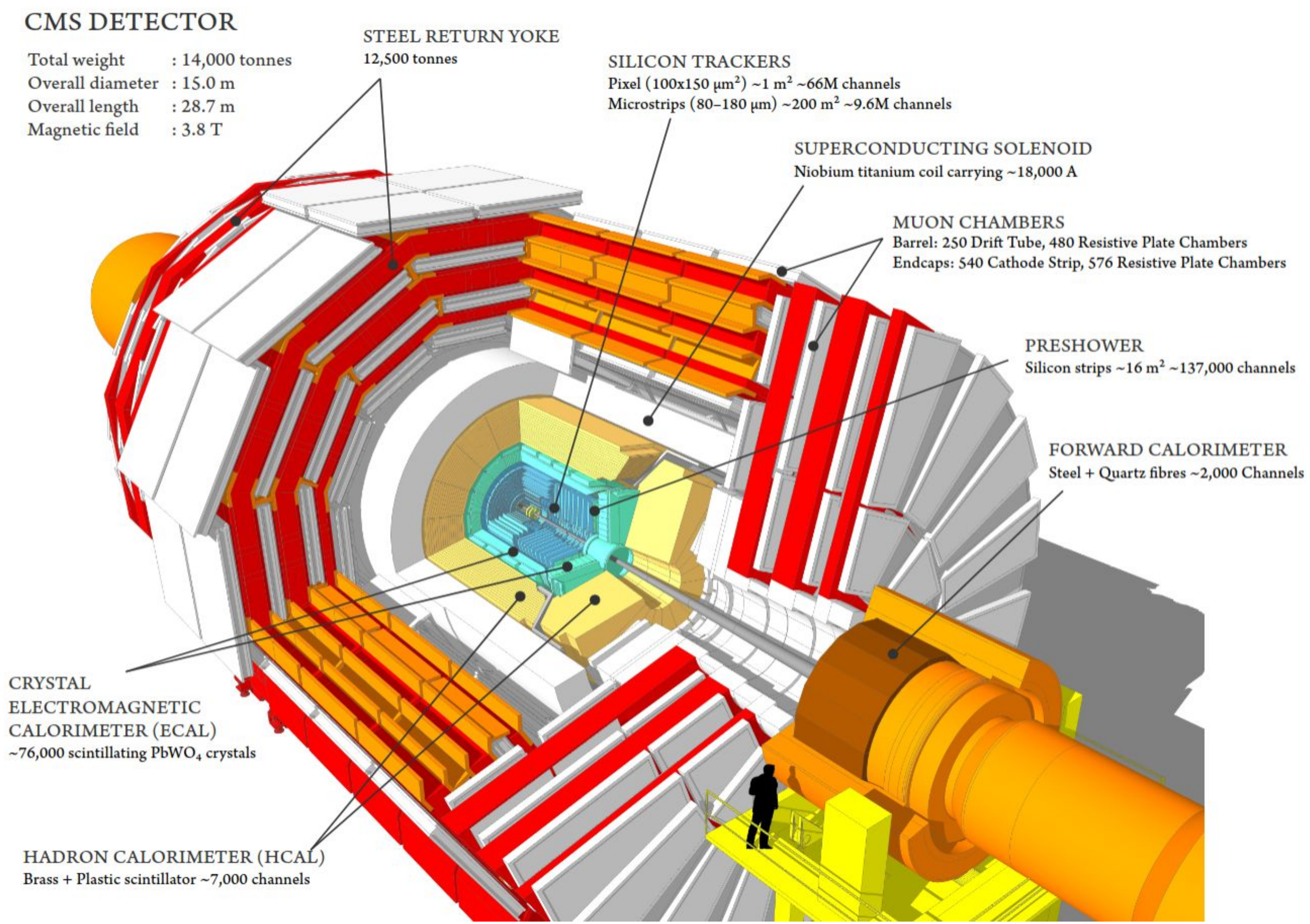
Production mode	Cross section (pb)	Decay channel	Branching fraction (%)
ggH	48.31 ± 2.44	bb	57.63 ± 0.70
VBF	3.771 ± 0.807	WW	22.00 ± 0.33
WH	1.359 ± 0.028	gg	8.15 ± 0.42
ZH	0.877 ± 0.036	$\tau\tau$	6.21 ± 0.09
ttH	0.503 ± 0.035	cc	2.86 ± 0.09
bbH	0.482 ± 0.097	ZZ	2.71 ± 0.04
tH	0.092 ± 0.008	$\gamma\gamma$	0.227 ± 0.005
		$Z\gamma$	0.157 ± 0.009
		ss	0.025 ± 0.001
		$\mu\mu$	0.0216 ± 0.0004



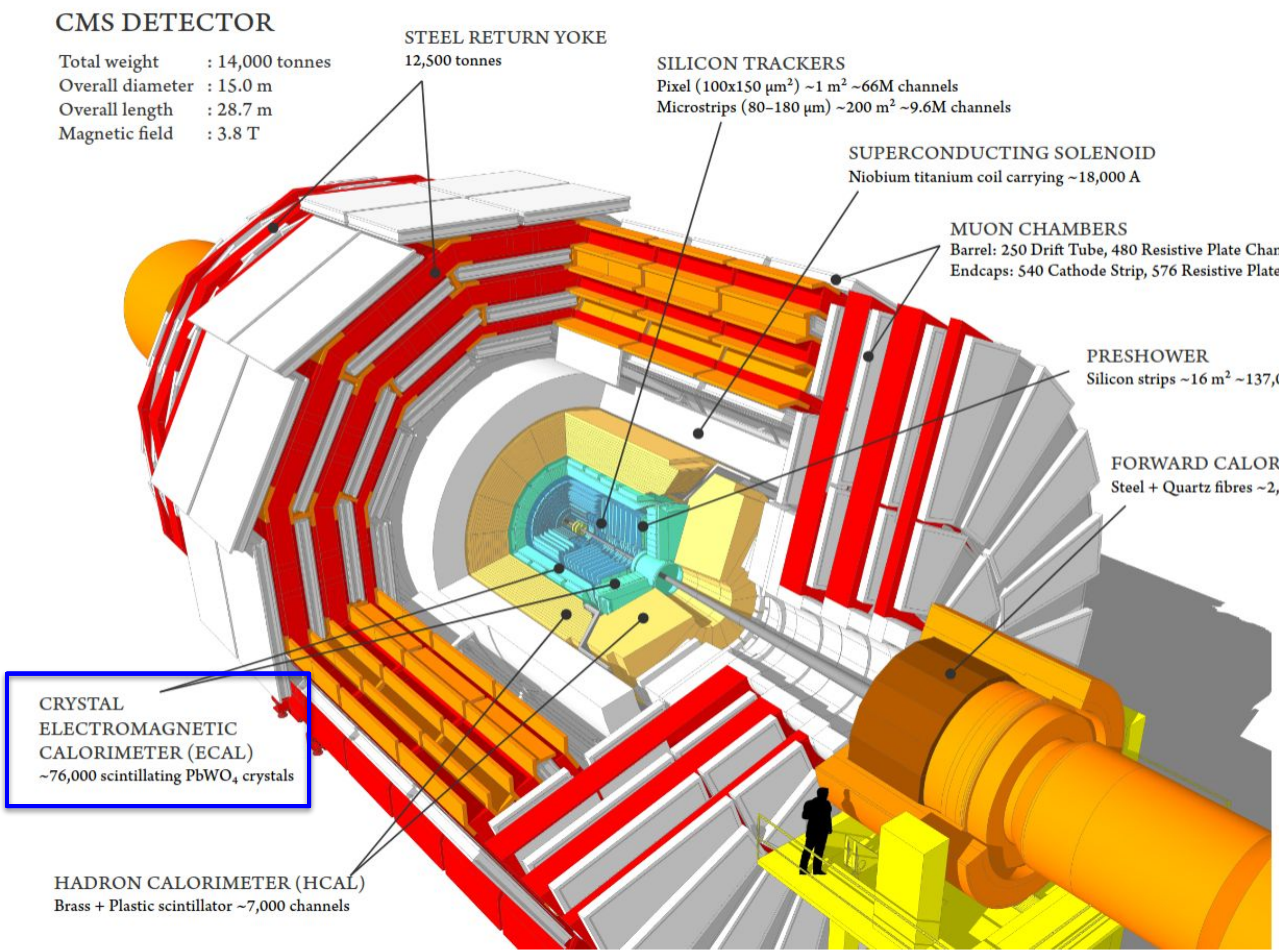


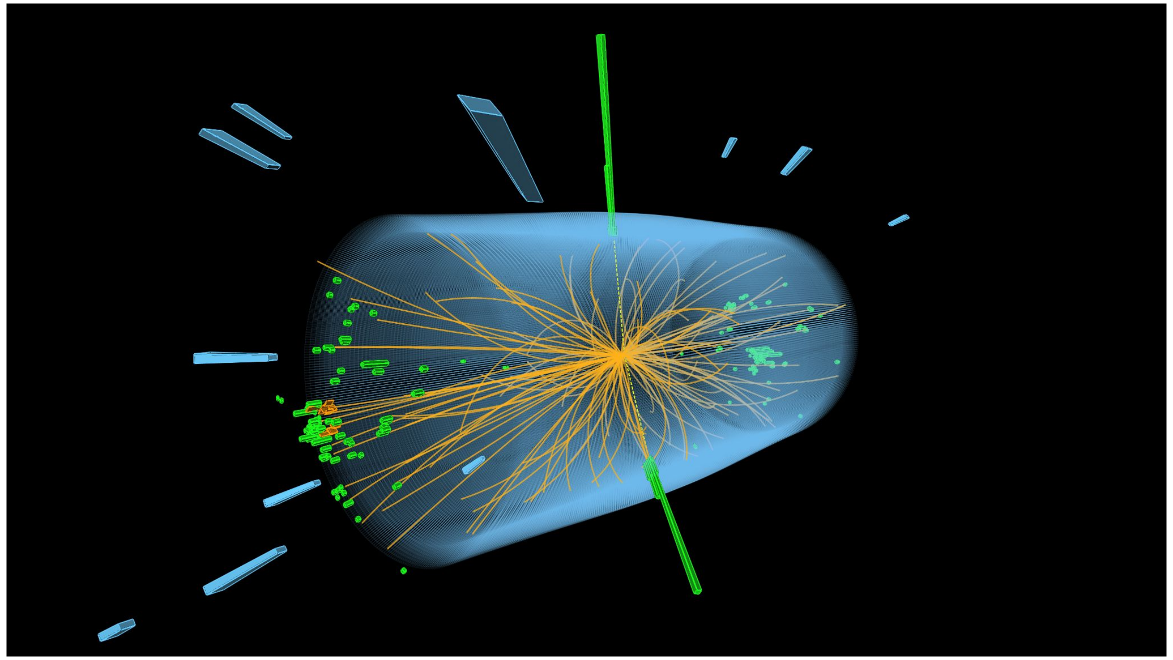
Higgs boson offers unique tool to probe many different interactions

CMS experiment



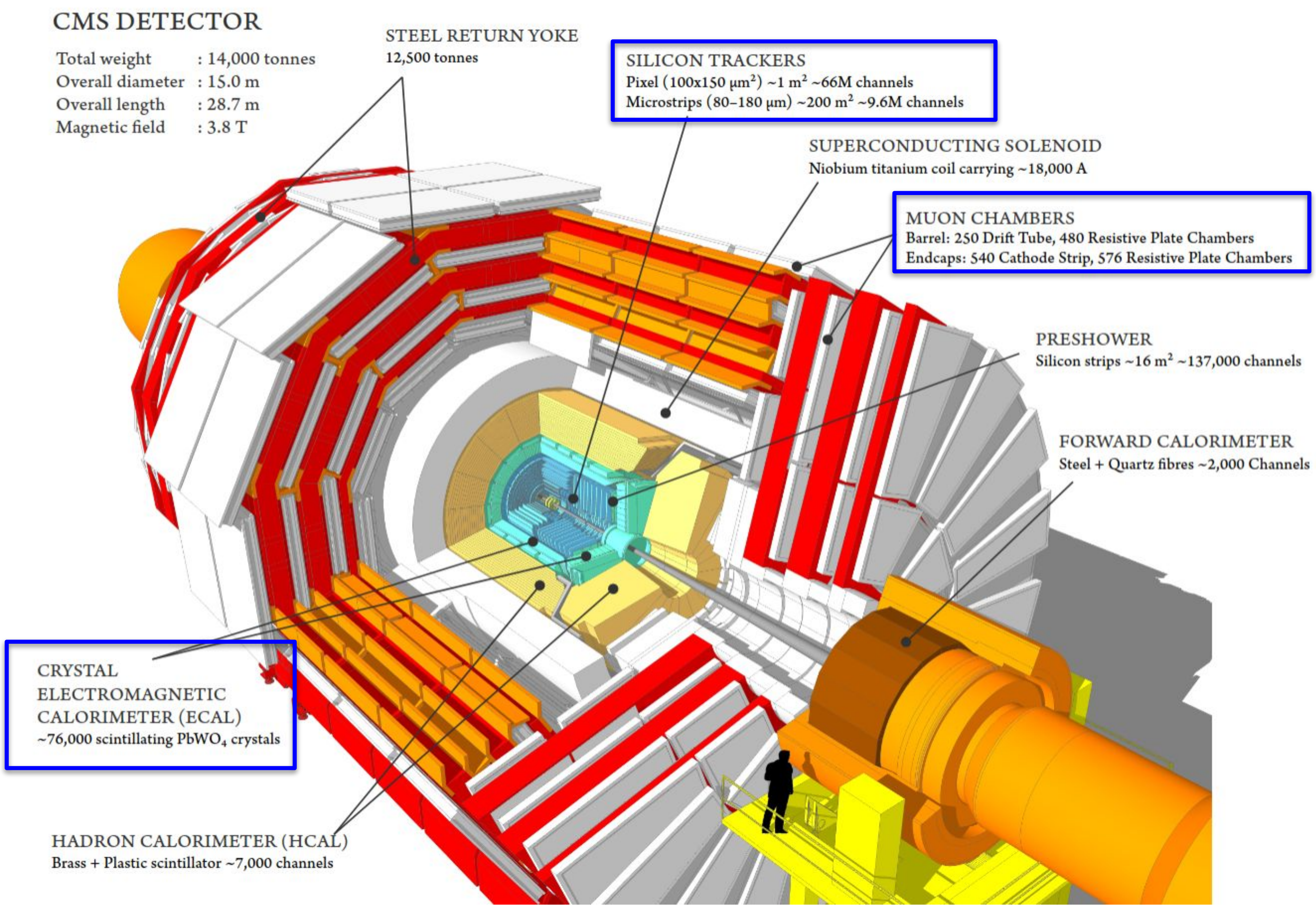
CMS experiment

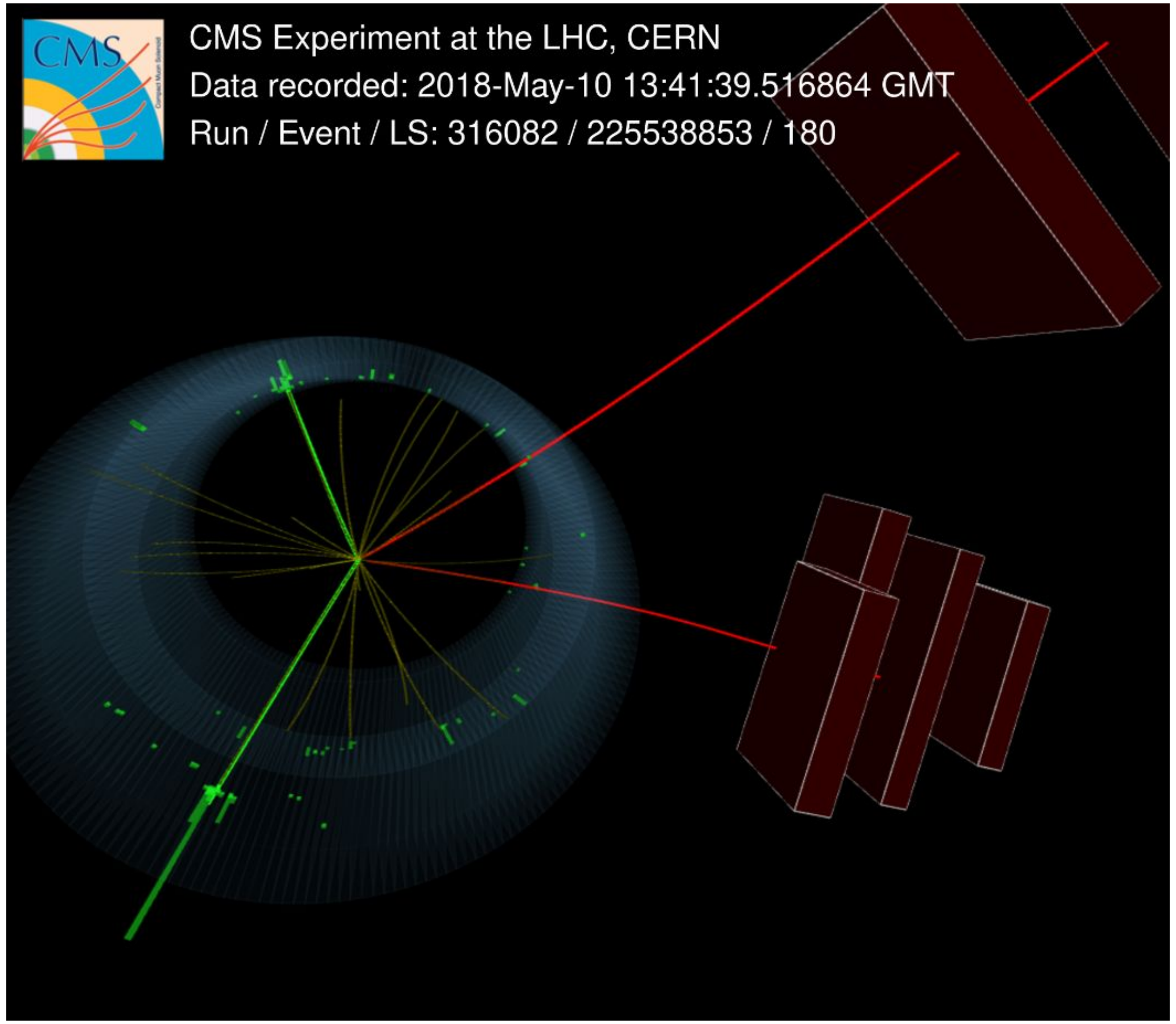




$H \to \gamma\gamma$ candidate

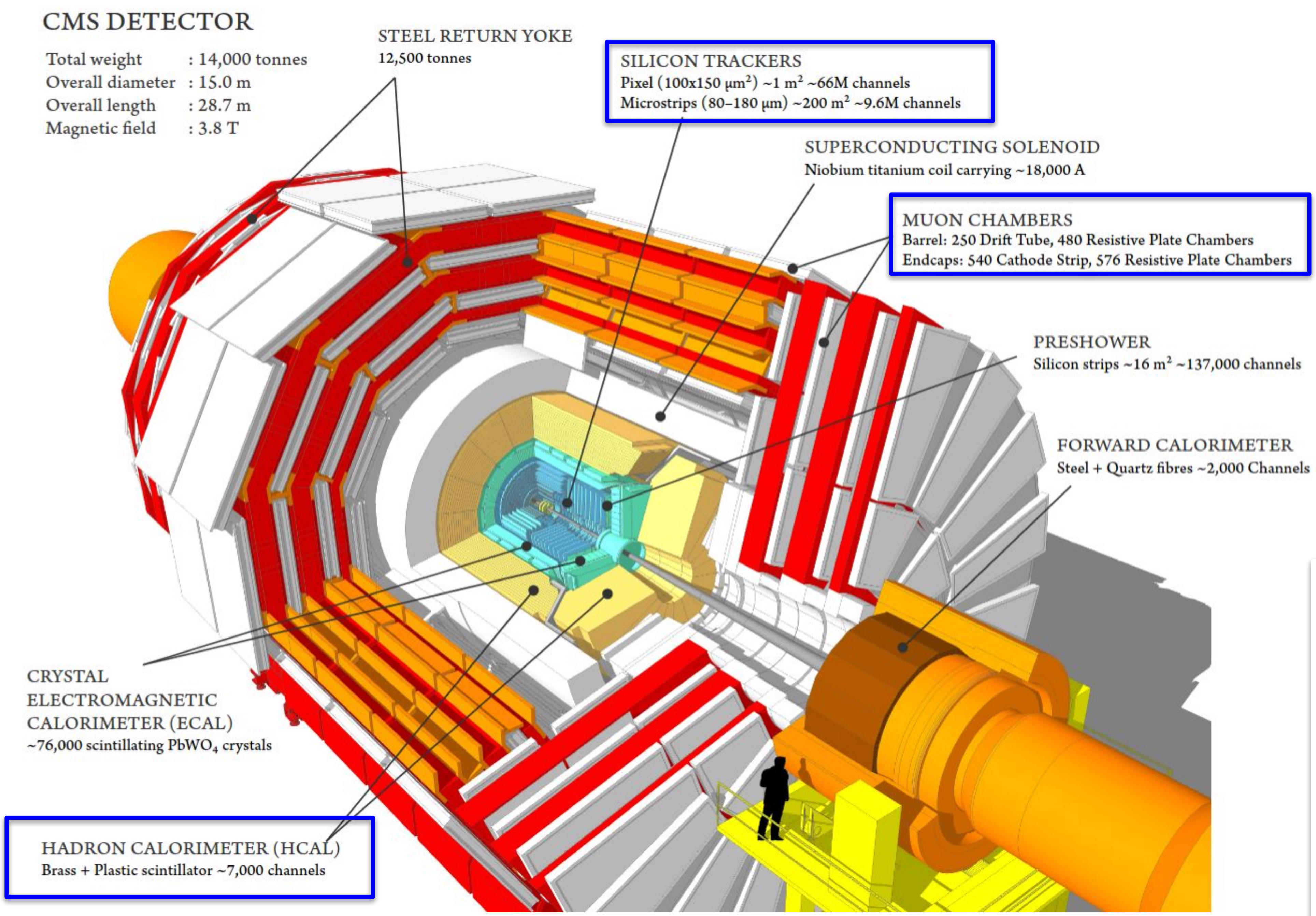
CMS experiment

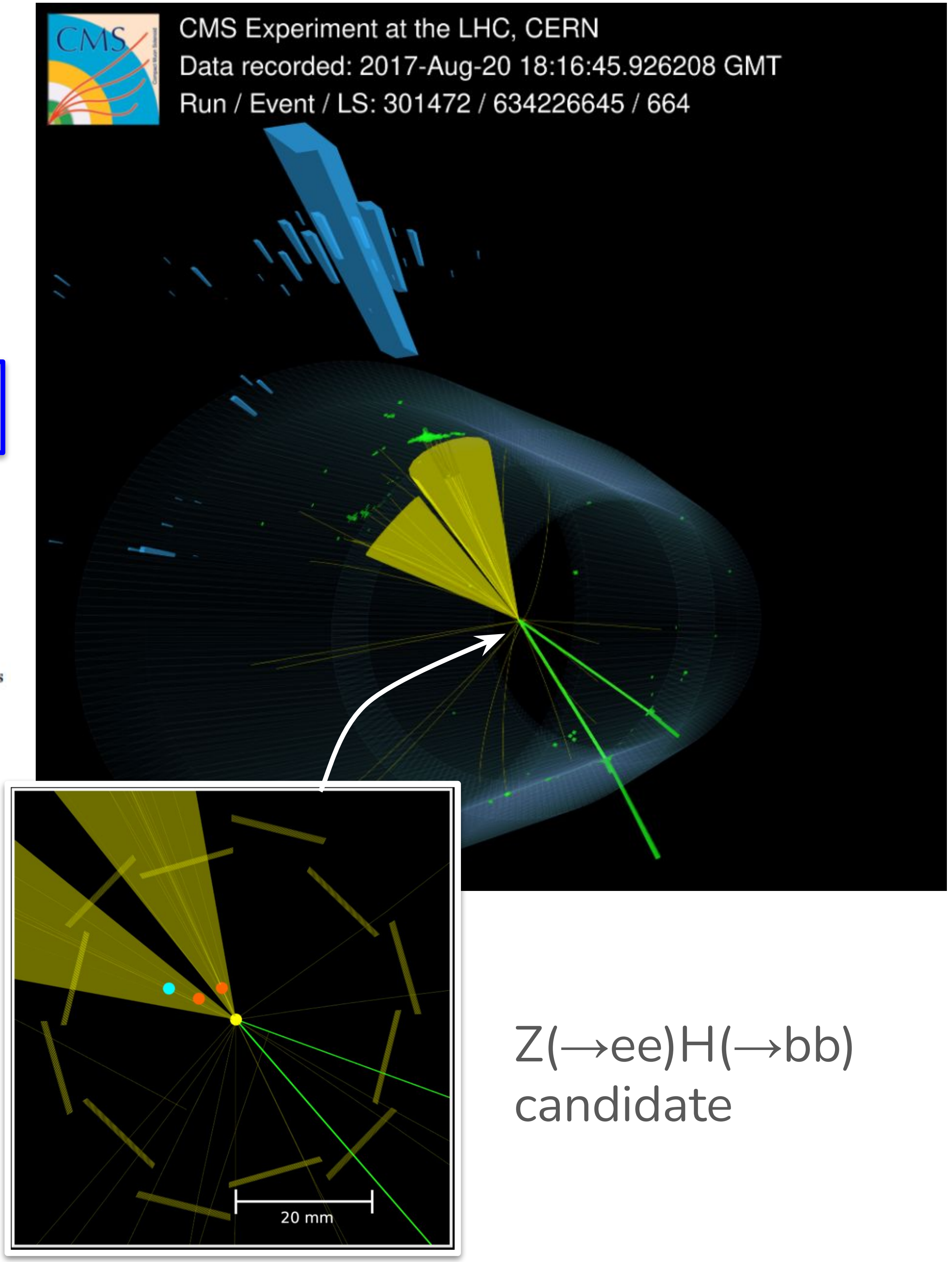




$H \to ZZ^* \to ee\mu\mu$ candidate

CMS experiment





Z(→ee)H(→bb) candidate

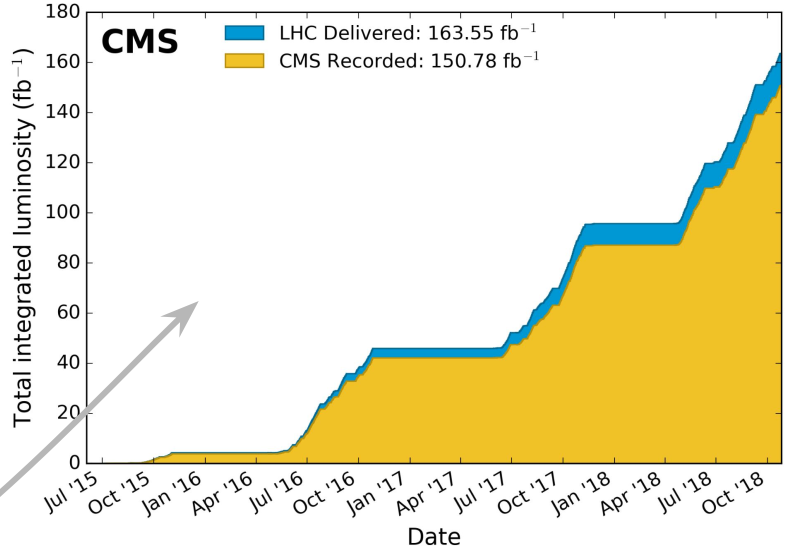
Twelve years since discovery

- Since discovery we have collected significantly more data

~200k H-bosons

Twelve years since discovery

- Since discovery we have collected significantly more data



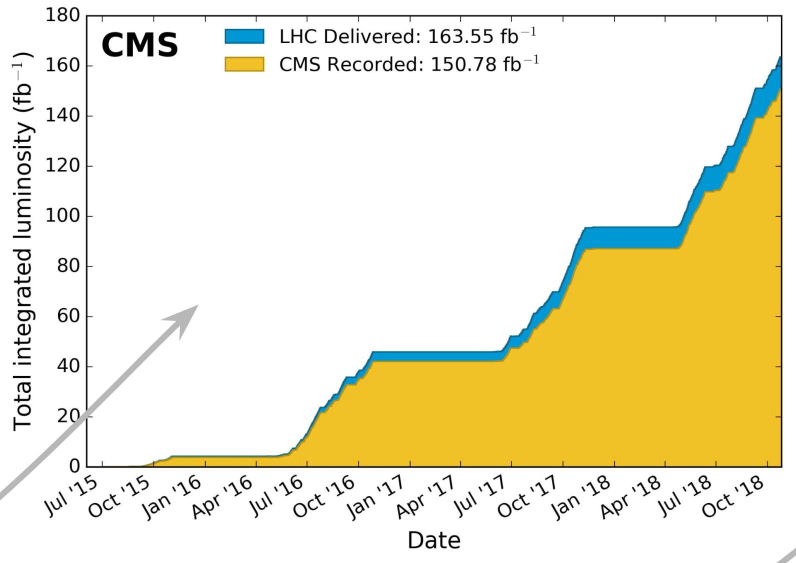
~200k H-bosons

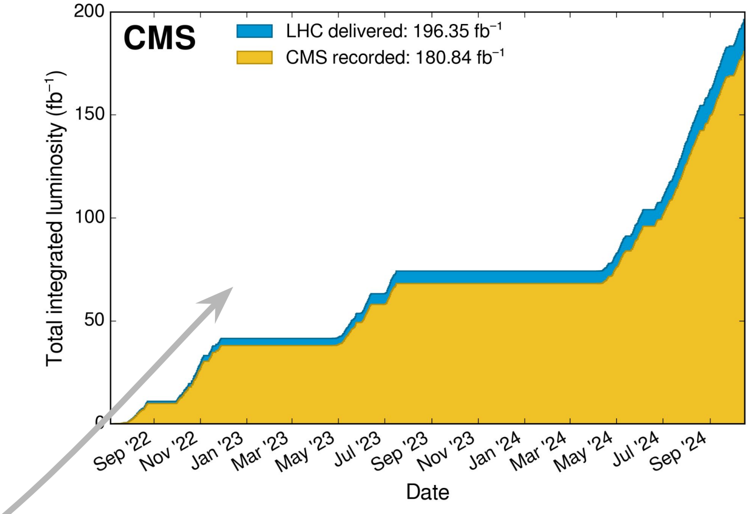
~7.7M H-bosons

- Entered era of precision measurements in the Higgs sector

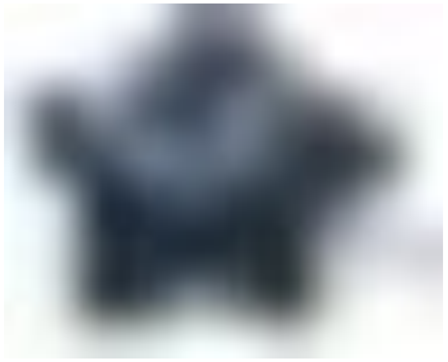
Twelve years since discovery

- Since discovery we have collected significantly more data





~200k H-bosons



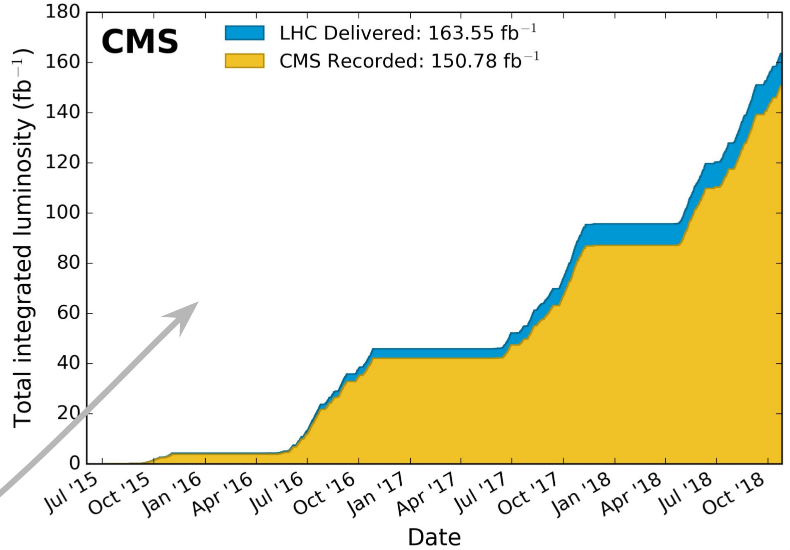
~7.7M H-bosons

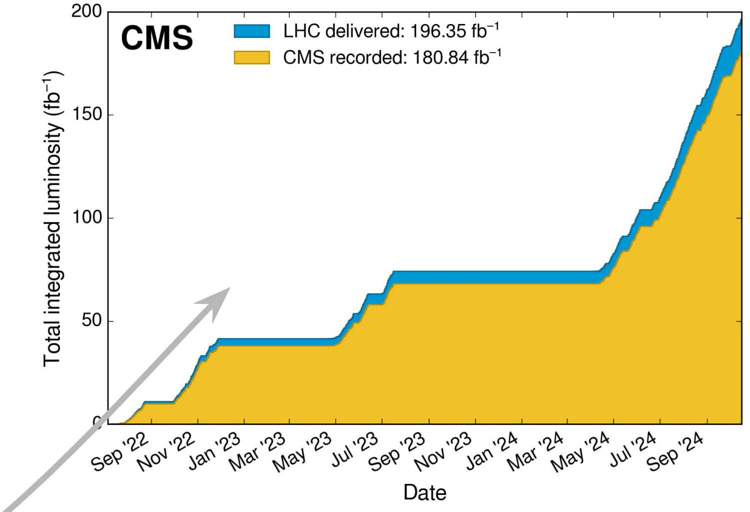
~21.5M H-bosons

- Entered era of precision measurements in the Higgs sector

Twelve years since discovery

- Since discovery we have collected significantly more data





~200k H-bosons

~7.7M H-bosons

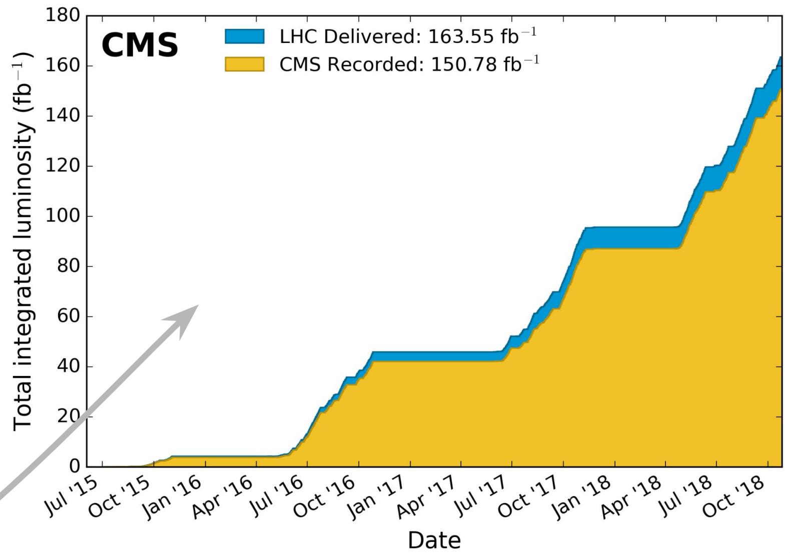
~21.5M H-bosons

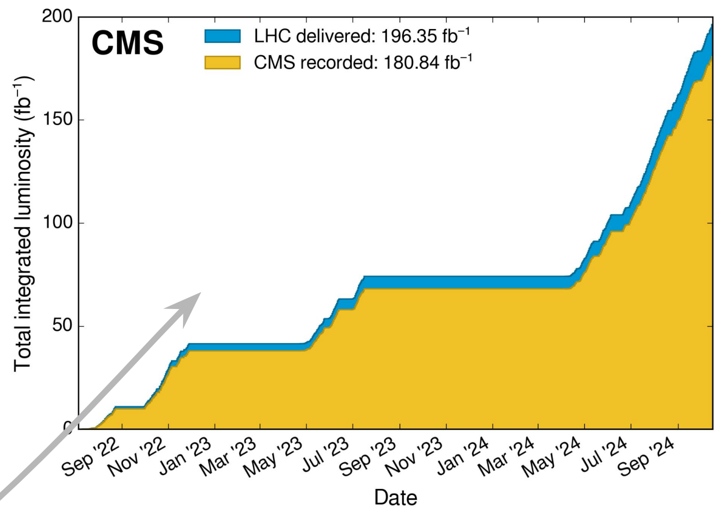
~170M H-bosons

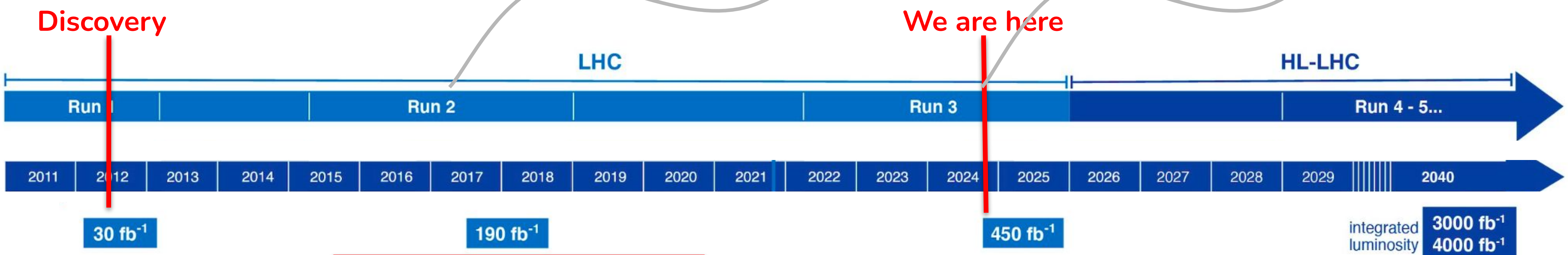
- Entered era of precision measurements in the Higgs sector → Still much more to come!

Twelve years since discovery

- Since discovery we have collected significantly more data







~200k H-bosons

~7.7M H-bosons

~21.5M H-bosons

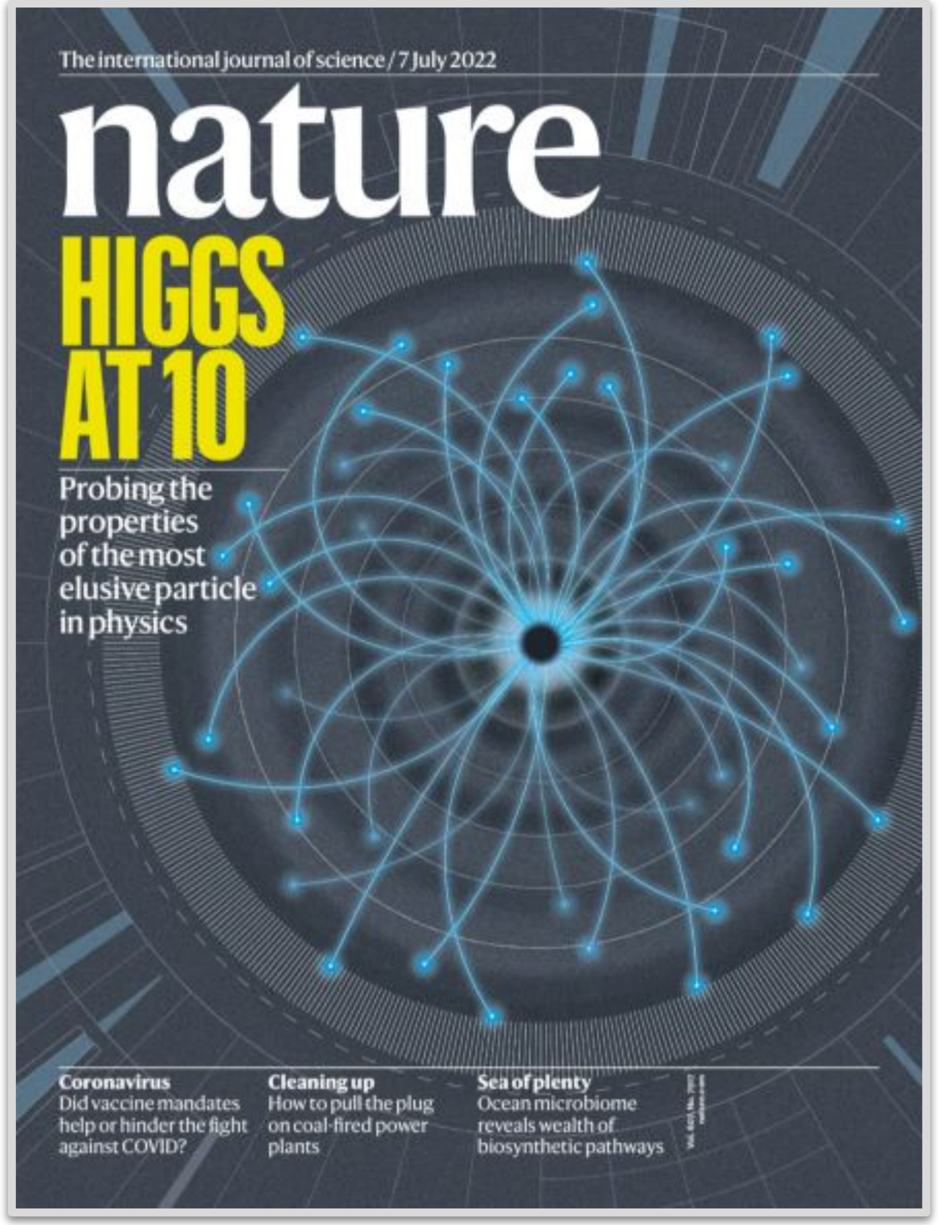
~170M H-bosons

- Entered era of precision measurements in the Higgs sector → Still much more to come!

Higgs boson combination

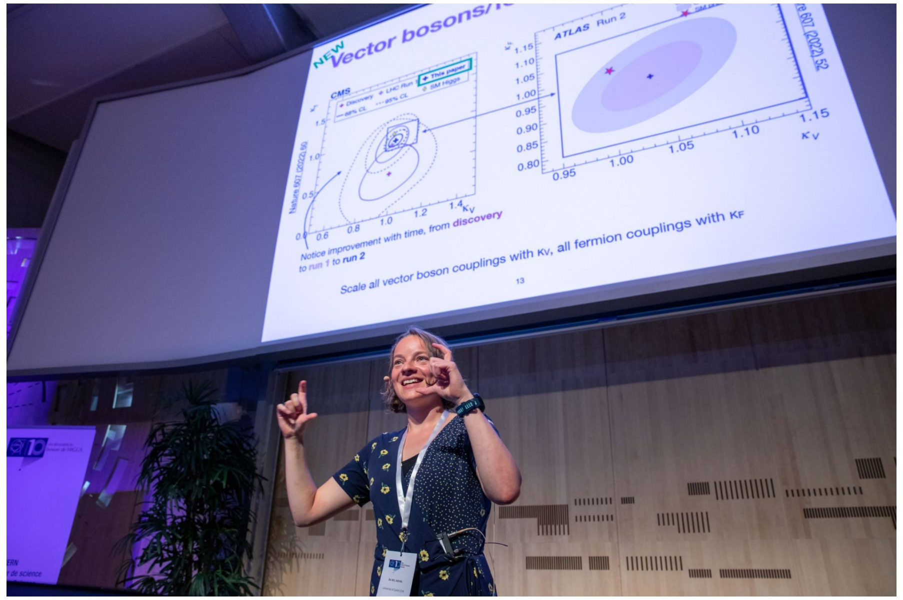
July 4th 2022

- **Ultimate precision comes from statistically combining Higgs boson analyses across different decay channels**
- Celebrated ten years since discovery with statistical combination paper in [Nature 607 (2022) 60-68]



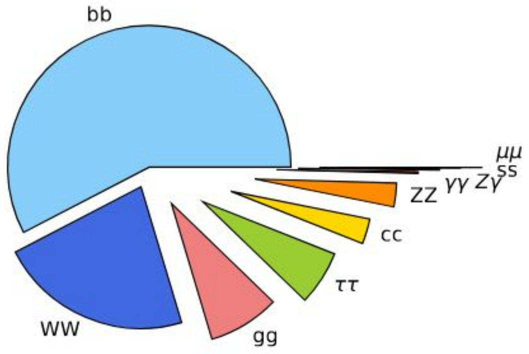
Papers from ATLAS and theory community in same journal edition

CERN 10 years HIGGS boson discovery

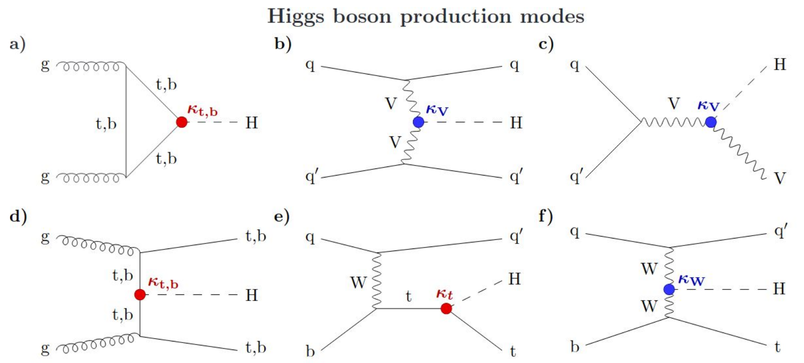


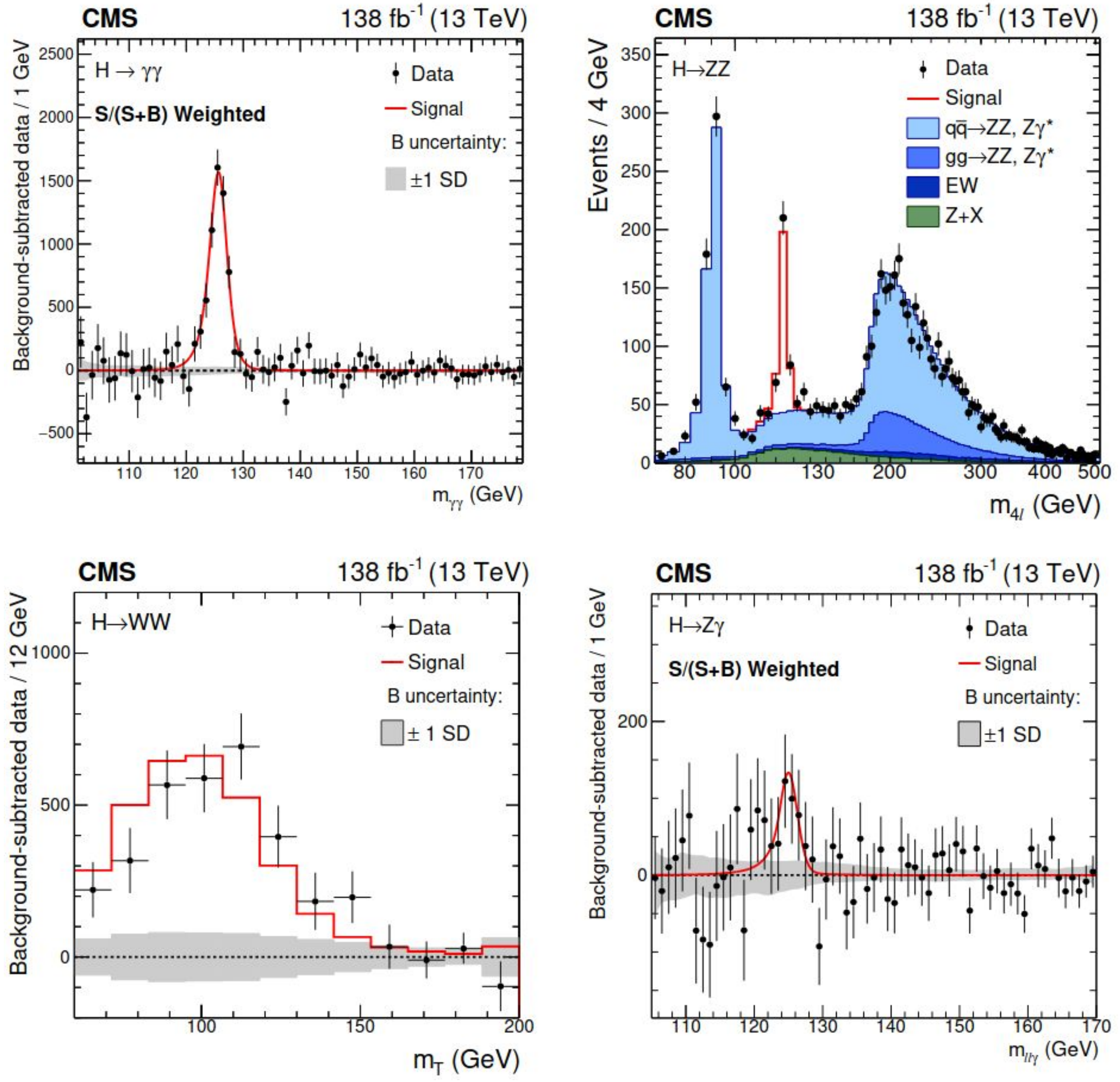
Nature input analyses [Nature 607 (2022) 60-68]

- Combination of Higgs boson analyses using the full Run 2 dataset (2016-2018) = 138 fb^{-1}

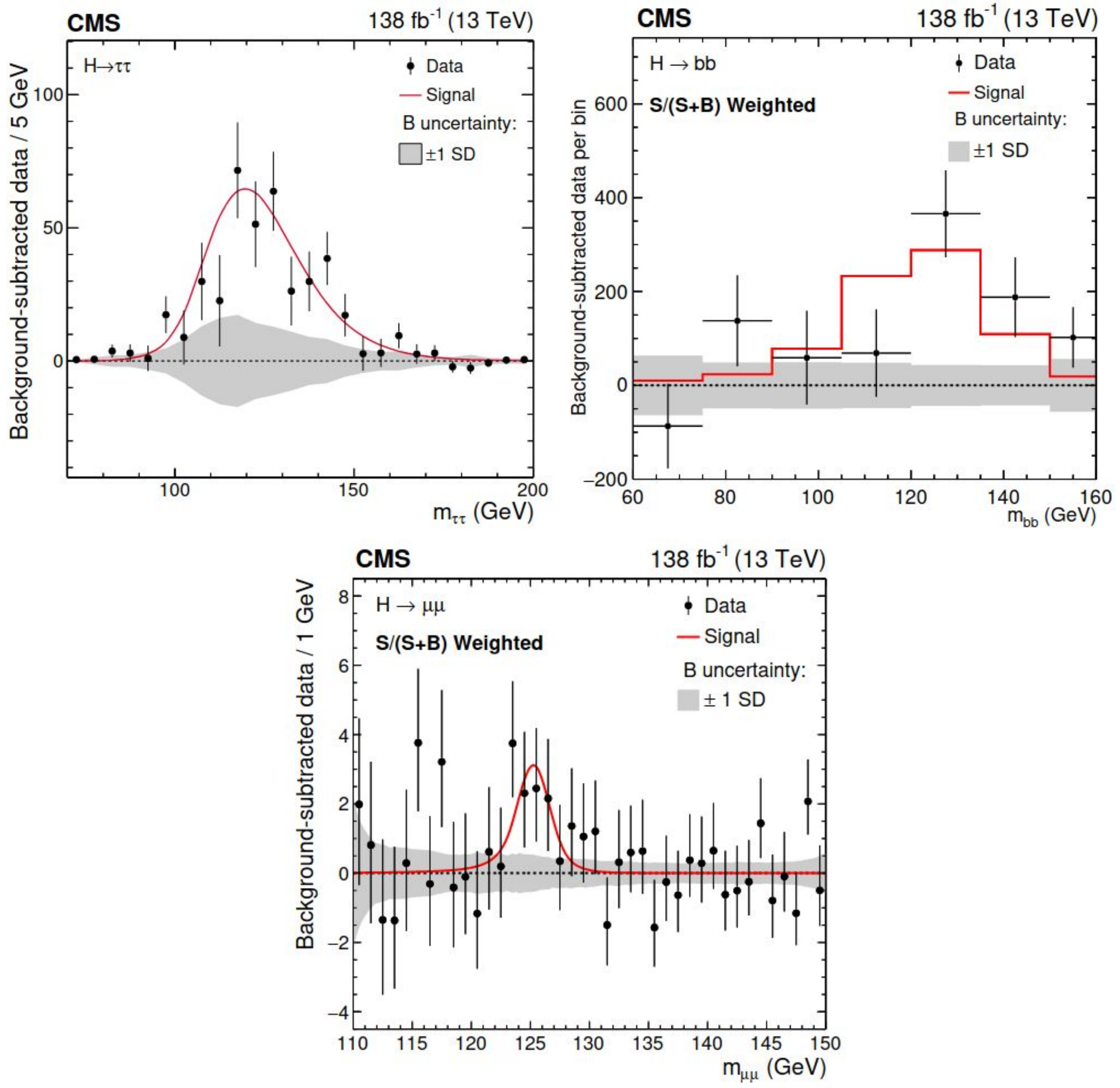


Analysis	Decay tags	Production tags
Single Higgs boson production		
$H \to \gamma\gamma$ [42]	$\gamma\gamma$	ggH, $p_T(H) \times N_j$ bins VBF/VH hadronic, $p_T(Hjj)$ bins WH leptonic, $p_T(V)$ bins ZH leptonic ttH $p_T(H)$ bins, tH
$H \to ZZ \to 4\ell$ [43]	4μ, $2e2\mu$, 4	ggH, $p_T(H) \times N_j$ bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH
$H \to WW \to \ell\nu\ell\nu$ [44]	$e\mu/ee/\mu\mu$ $\mu\mu$+jj/ee+jj/$e\mu$+jj 3ℓ 4ℓ	ggH $\leq$ 2-jets VBF VH hadronic WH leptonic ZH leptonic
$H \to Z\gamma$ [45]	$Z\gamma$	ggH VBF
$H \to \tau\tau$ [46]	$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	ggH, $p_T(H) \times N_j$ bins VH hadronic VBF
$H \to bb$ [47–51]	$W(\ell\nu)H(bb)$ $Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$ bb	VH, high-$p_T(V)$ WH leptonic ZH leptonic ttH, $\to 0, 1, 2\ell +$ jets ggH, high-$p_T(H)$ bins
$H \to \mu\mu$ [52]	$\mu\mu$	ggH VBF
ttH production with $H \to$ leptons [53]	2ℓ SS, 3ℓ, 4 $1\ell + \tau_h$, 2ℓ SS+$1\tau_h$ τ_h	ttH
$H \to$ Inv. [71, 72]	p_T^{miss}	ggH VBF VH hadronic ZH leptonic





Bosonic decay channels



Fermionic decay channels

Building the likelihood

- Analysis region = selected set of p-p collision data events, d_r → (1) Signal region (SR) designed to be enriched in Higgs boson events
  (2) Control region (CR) designed to control background predictions in SR

- **Define likelihood for each analysis region:**

$$x_{r,d} \in d_r$$

$$\mathcal{L}_r(d_r|\boldsymbol{\mu},\boldsymbol{\nu}) = \prod_d \mathrm{Prob}\Big(x_{r,d}\,\Big|\,\sum_{i,f}\mu^{i,f}S^{i,f}_{r,d}(\boldsymbol{\nu}) + \sum_k B_k(\boldsymbol{\nu})\Big)$$

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Parameters of interest, μ

Nuisance parameters, $\boldsymbol{\nu}$

Observation

Expectation

Building the likelihood

- Analysis region = selected set of p-p collision data events, d_r → (1) Signal region (SR) designed to be enriched in Higgs boson events
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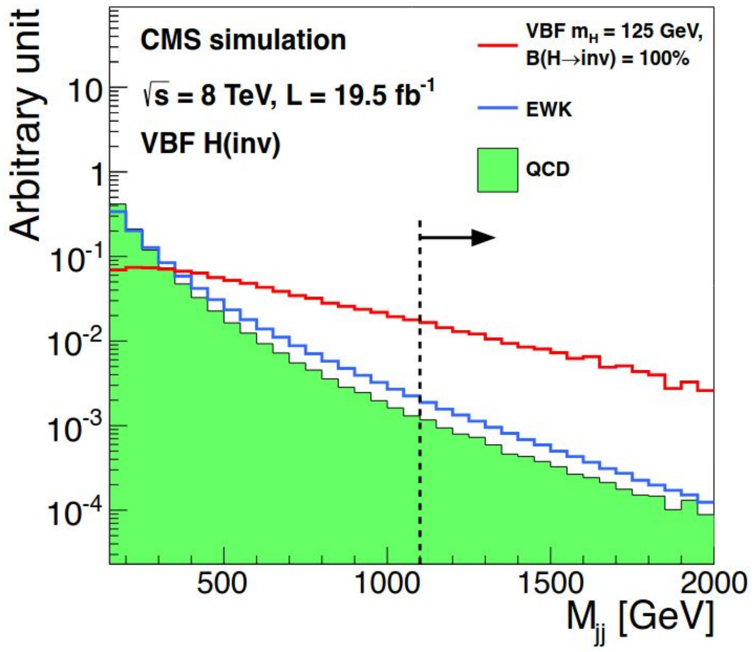
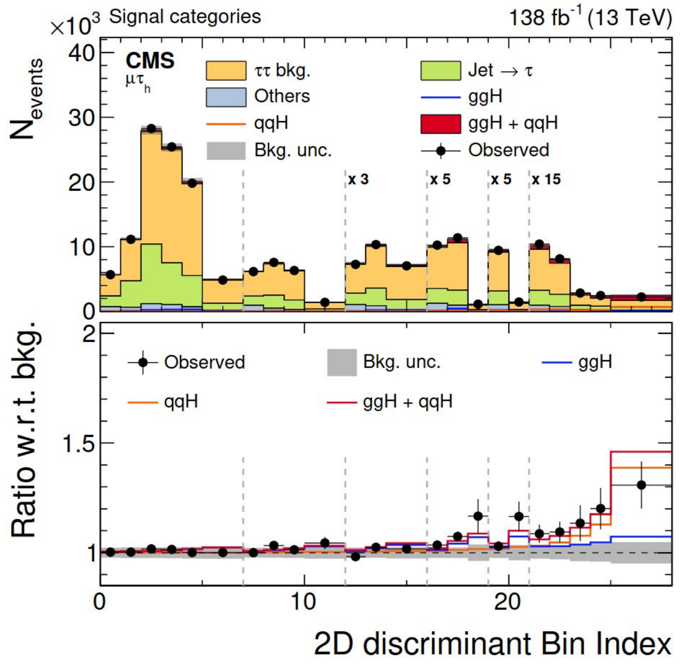
- The **data** (d_r) in each analysis region can be...



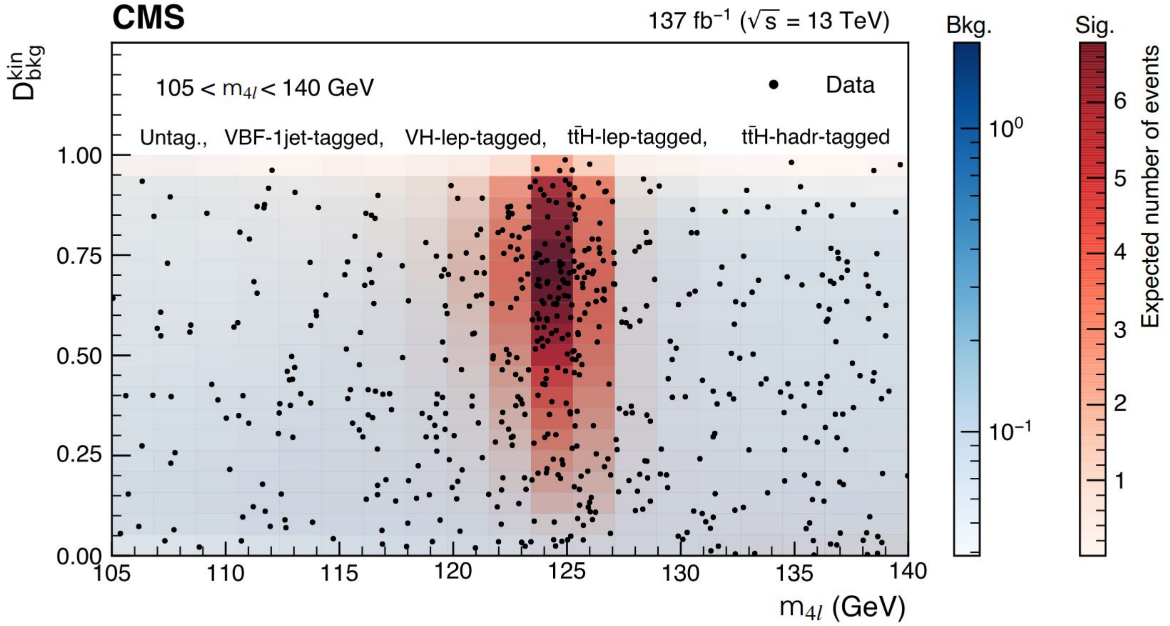
Cut-and-count:

L_r = single Poisson term



Binned (histogram):

L_r = product of Poisson terms over bin counts



Unbinned observables:

L_r = (extended) product of Poisson terms over events

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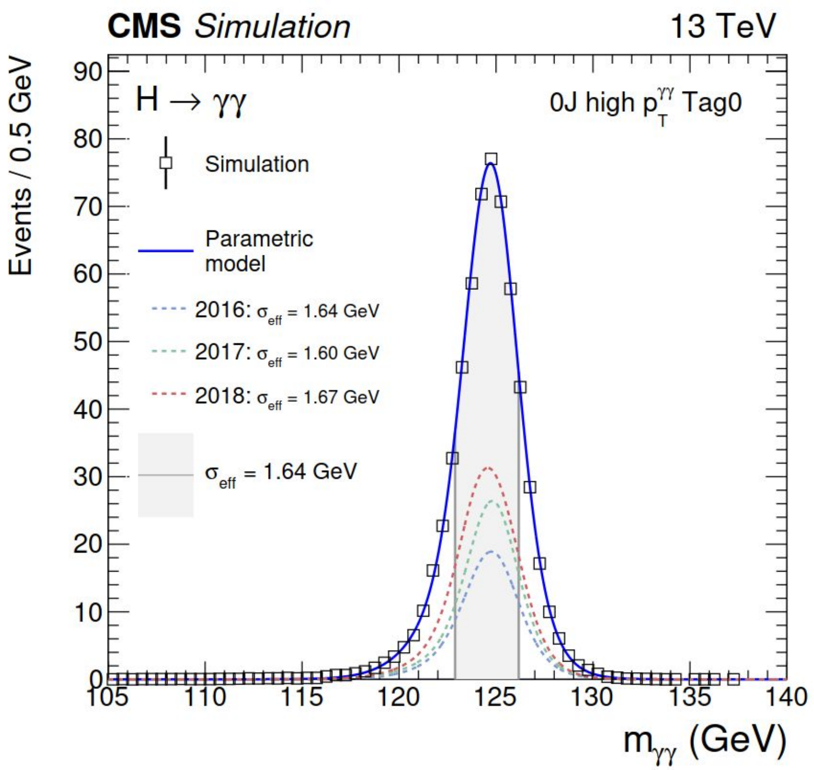
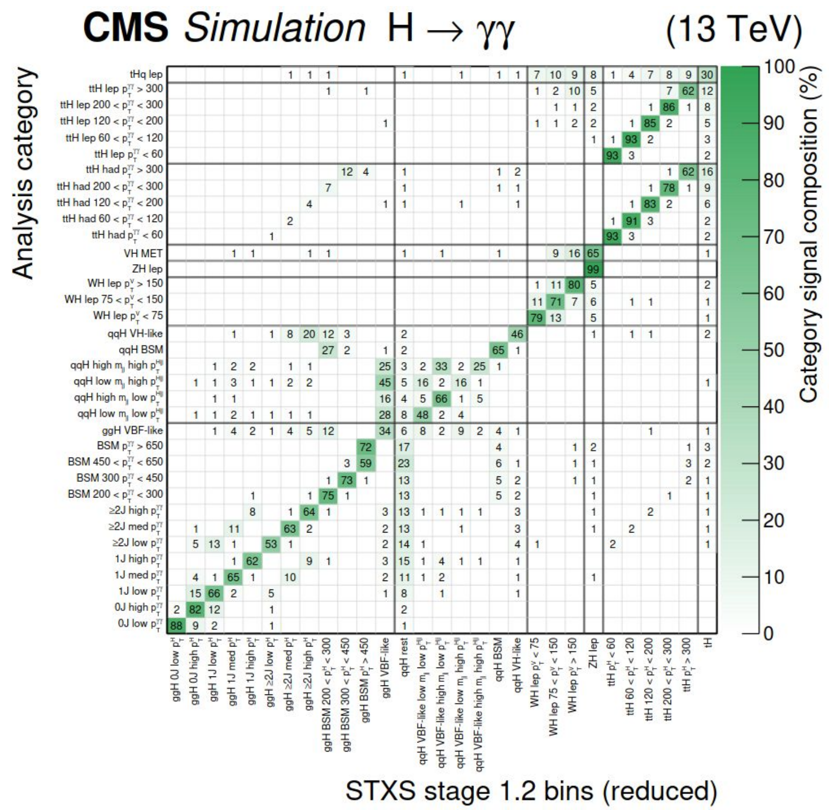
- **Signal model** for Higgs boson production process **i**, in decay channel **f** (derived from Monte-Carlo simulation)



X



X Efficiency X Acceptance X Luminosity

Shape

Composition in analysis region, r

Building the likelihood

- Analysis region = selected set of p-p collision data events, d_r $\longrightarrow$ (1) Signal region (SR) designed to be enriched in Higgs boson events
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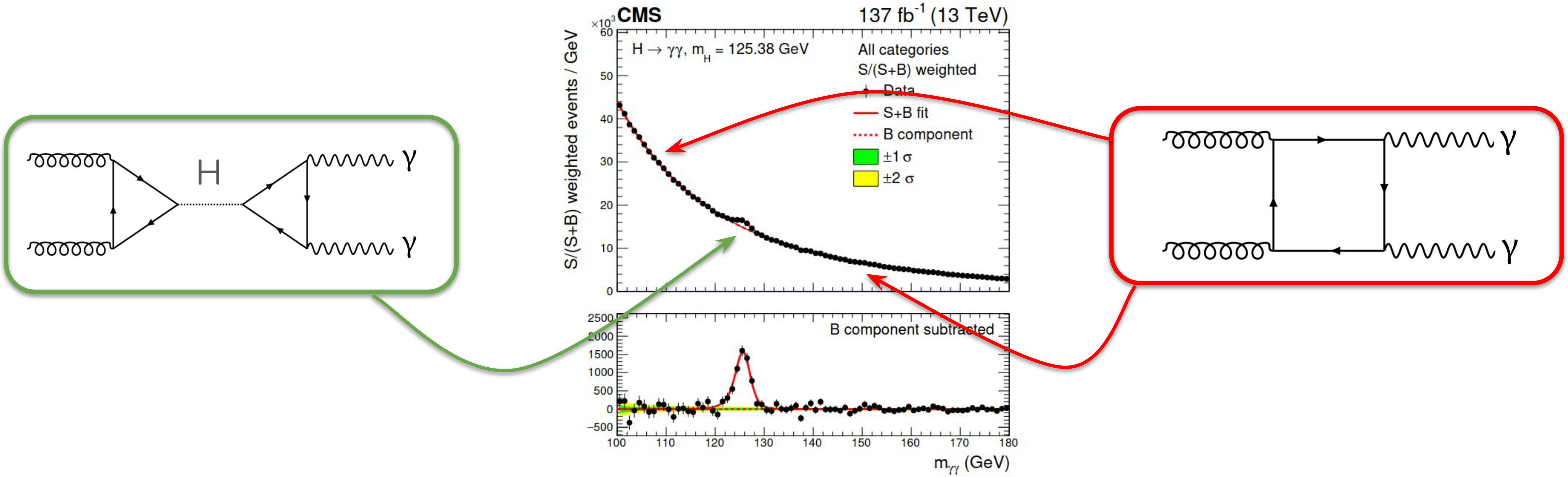
- **Background model:** majority are data-driven e.g. mass sidebands to estimate background under signal



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- **Parameters of interest:** "signal-strength" formalism measures rate relative to SM prediction

$$\mu^{i,f} = \mu^i \cdot \mu^f = \frac{\sigma^i}{\sigma^i_{\mathrm{SM}}} \cdot \frac{\mathcal{B}(H \to f)}{\mathcal{B}(H \to f)_{\mathrm{SM}}}$$

Building the likelihood

- Analysis region = selected set of p-p collision data events, $d_r \rightarrow$ (1) Signal region (SR) designed to be enriched in Higgs boson events
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- **Define likelihood for each analysis region:**

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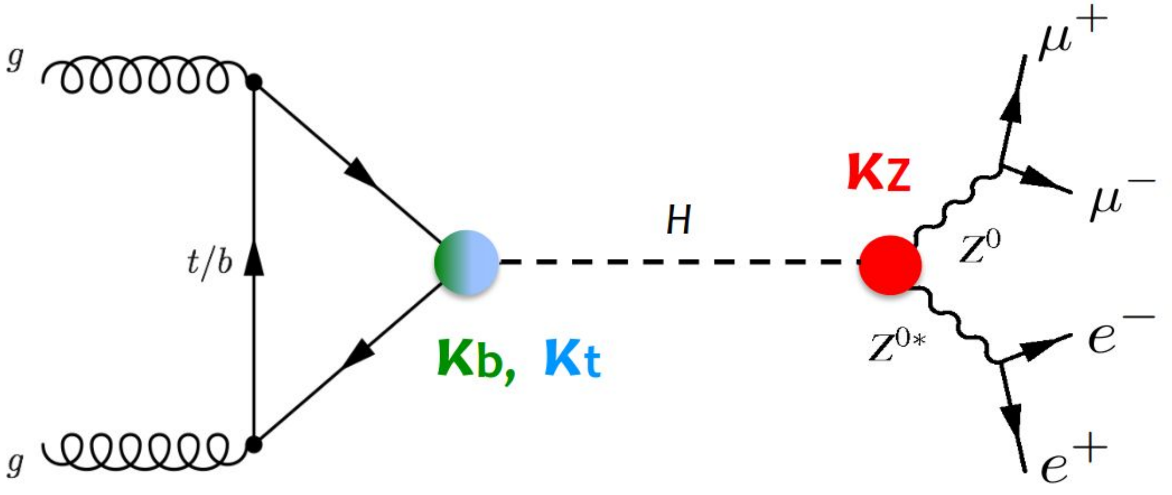
- **Extract different interpretations by parameterising signal strengths**
  - E.g. Coupling modifiers (kappa-framework):

$$\mu \longrightarrow \mu(\vec{\kappa})$$



$$\mu_{ggH} \cdot \mu^{ZZ} \sim \frac{(1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\kappa_Z^2}{\kappa_H^2}$$

SM defined by: $\vec{\kappa} = 1 \longrightarrow \mu(1) = 1$

Building the likelihood

$$\mathcal{L}_r(d_r|\boldsymbol{\mu},\boldsymbol{\nu}) = \prod_d \mathrm{Prob}\Big(x_{r,d}\,\Big|\,\sum_{i,f}\mu^{i,f}S^{i,f}_{r,d}(\boldsymbol{\nu}) + \sum_k B_k(\boldsymbol{\nu})\Big)$$

- Combination likelihood calculated as the product of likelihoods across analysis regions

$$\mathcal{L}(\mathcal{D}|\boldsymbol{\mu},\boldsymbol{\nu}) = \prod_r \mathcal{L}_r \times \mathrm{Gauss}(\tilde{\boldsymbol{\nu}}|\boldsymbol{\nu})$$

Building the likelihood

$$\mathcal{L}_r(d_r|\boldsymbol{\mu},\boldsymbol{\nu}) = \prod_d \mathrm{Prob}\left(x_{r,d} \,\middle|\, \sum_{i,f} \mu^{i,f} S^{i,f}_{r,d}(\boldsymbol{\nu}) + \sum_k B_k(\boldsymbol{\nu})\right)$$

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- Crucial ingredient: **nuisance parameters** → Account for systematic uncertainty in signal/background normalisation and shape

Building the likelihood

$$\mathcal{L}_r(d_r|\boldsymbol{\mu},\boldsymbol{\nu}) = \prod_d \mathrm{Prob}\left(x_{r,d} \,\middle|\, \sum_{i,f} \mu^{i,f} S^{i,f}_{r,d}(\boldsymbol{\nu}) + \sum_k B_k(\boldsymbol{\nu})\right)$$

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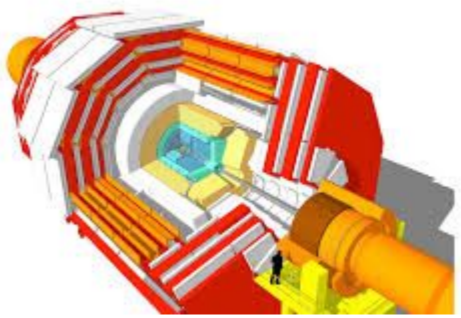
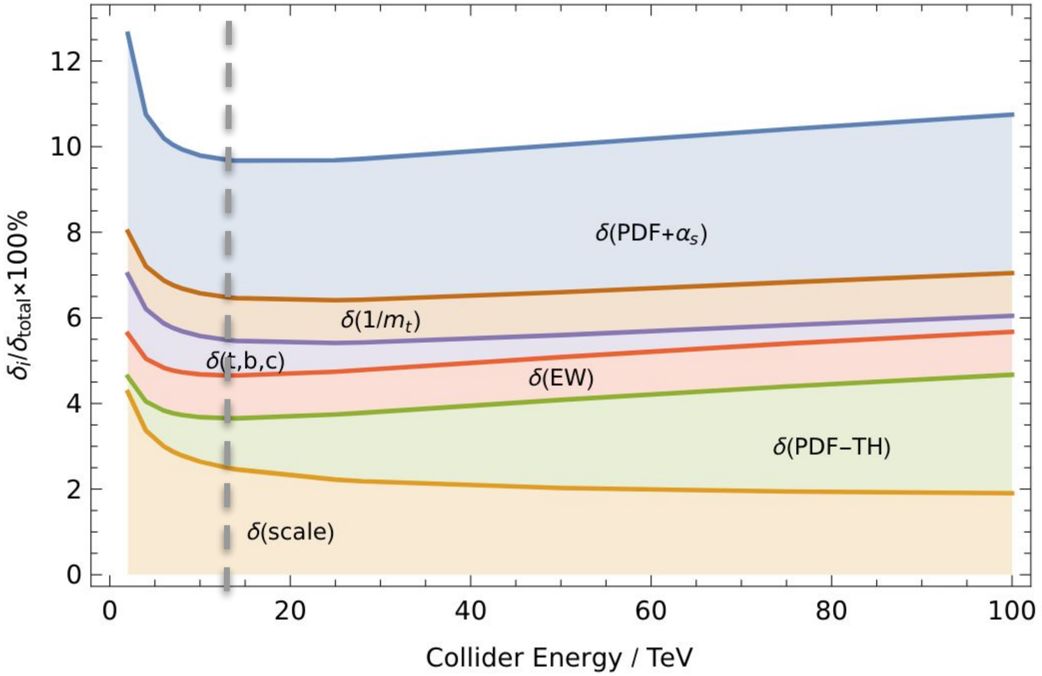
- Crucial ingredient: **nuisance parameters** → Account for systematic uncertainty in signal/background normalisation and shape

1. **Experimental/detector systematics:**
   Object efficiencies, energy scales, luminosity, …



2. **Signal theory uncertainties:**
   Inclusive x-section, QCD scale, PDF, UEPS, branching fraction, …

3. **Background theory uncertainties:**
   Cover extrapolation from CR to SR phase space for data-driven estimates



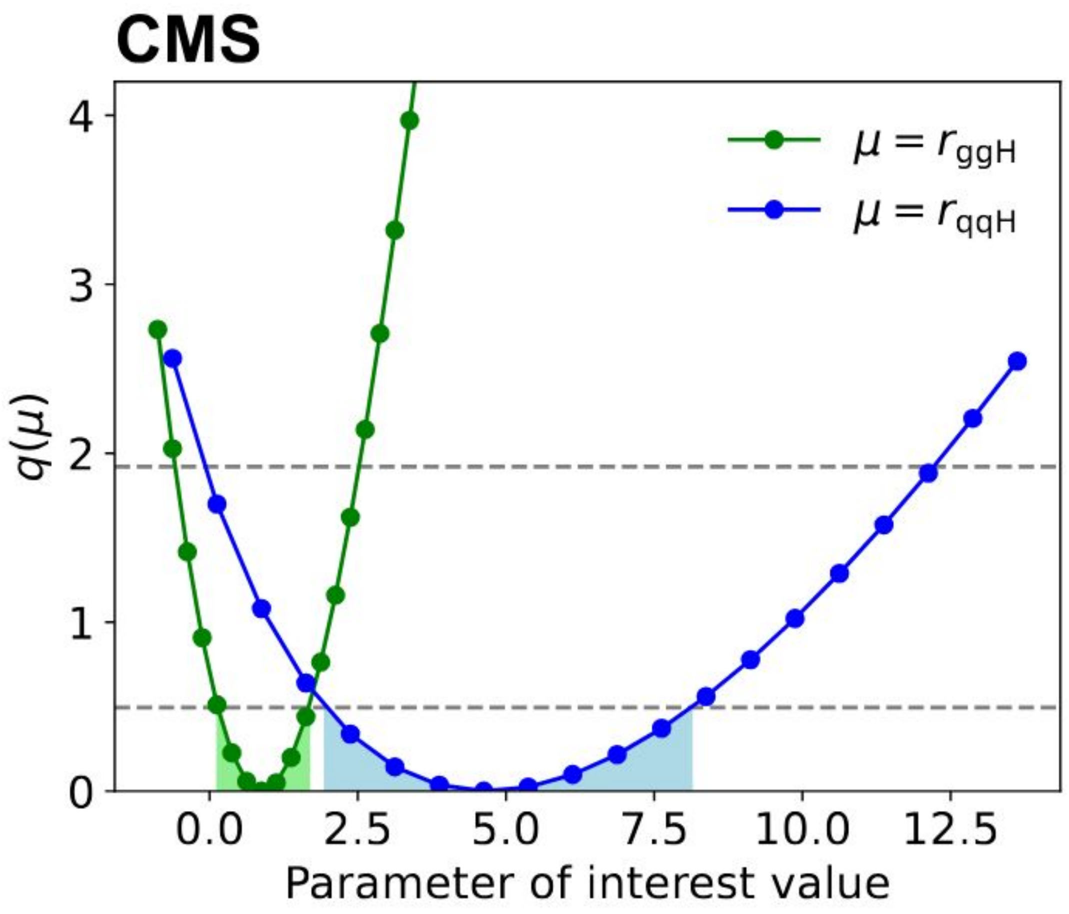
- Combinations typically have O(1000)'s nuisance parameters → **Correlate effects across different input channels**

A computational challenge

- Nature combination has **~850 analysis regions** and **~9500 parameters** in the model (mostly constrained nuisance params)
- Fitting the likelihood is a computationally expensive task:
  - ~30 Gb to build likelihood, (~10 Gb, ~10 hours) to fit per parameter point
  - Parallelisation is key!

$$\mathcal{L}(\mathcal{D}|\boldsymbol{\mu},\boldsymbol{\nu}) \longrightarrow q(\boldsymbol{\mu}) = -2\ln\left(\frac{\mathcal{L}(\mathcal{D}|\boldsymbol{\mu},\hat{\hat{\boldsymbol{\nu}}}_{\boldsymbol{\mu}})}{\mathcal{L}(\mathcal{D}|\hat{\boldsymbol{\mu}},\hat{\boldsymbol{\nu}})}\right)$$

Profiled likelihood ratio



A computational challenge

- Nature combination has **~850 analysis regions** and **~9500 parameters** in the model (mostly constrained nuisance params)
- Fitting the likelihood is a computationally expensive task:
  - ~30 Gb to build likelihood, (~10 Gb, ~10 hours) to fit per parameter point
  - Parallelisation is key!

$$\mathcal{L}(\mathcal{D}|\boldsymbol{\mu},\boldsymbol{\nu}) \longrightarrow q(\boldsymbol{\mu}) = -2\ln\left(\frac{\mathcal{L}(\mathcal{D}|\boldsymbol{\mu},\hat{\hat{\boldsymbol{\nu}}}_{\boldsymbol{\mu}})}{\mathcal{L}(\mathcal{D}|\hat{\boldsymbol{\mu}},\hat{\boldsymbol{\nu}})}\right)$$

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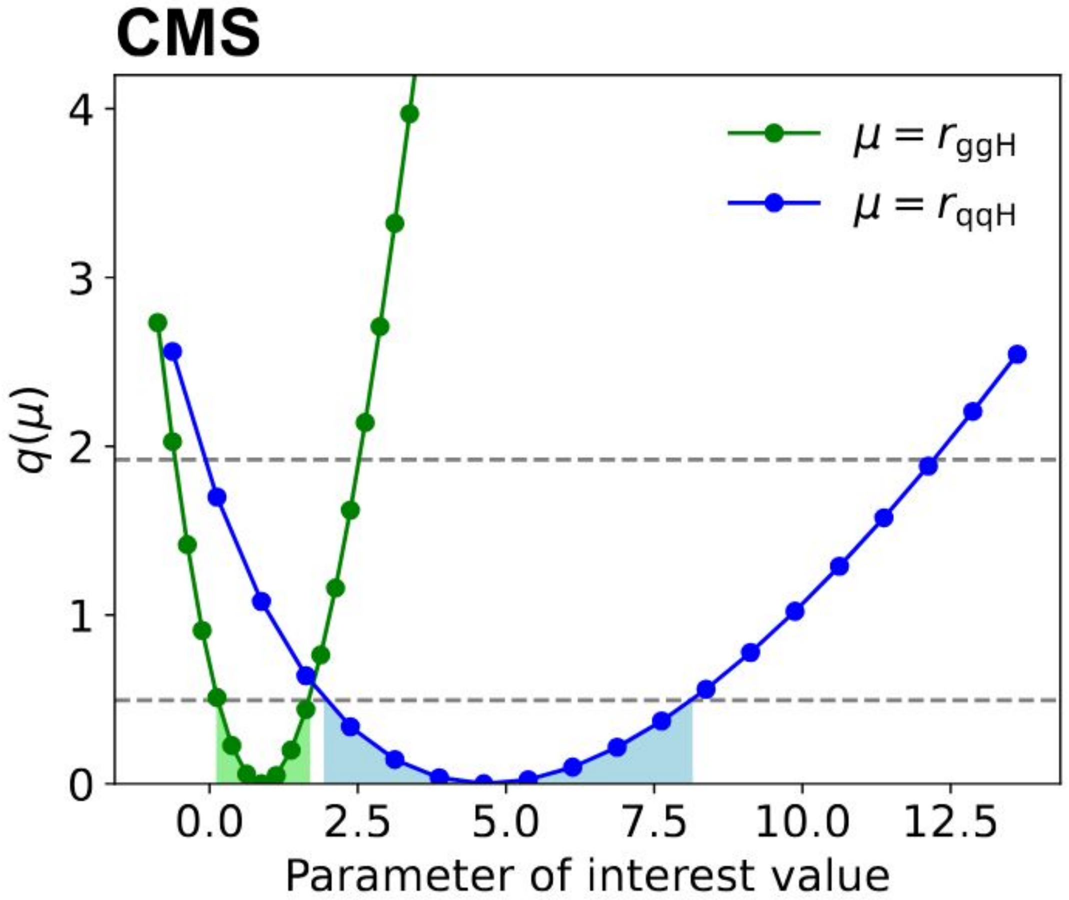
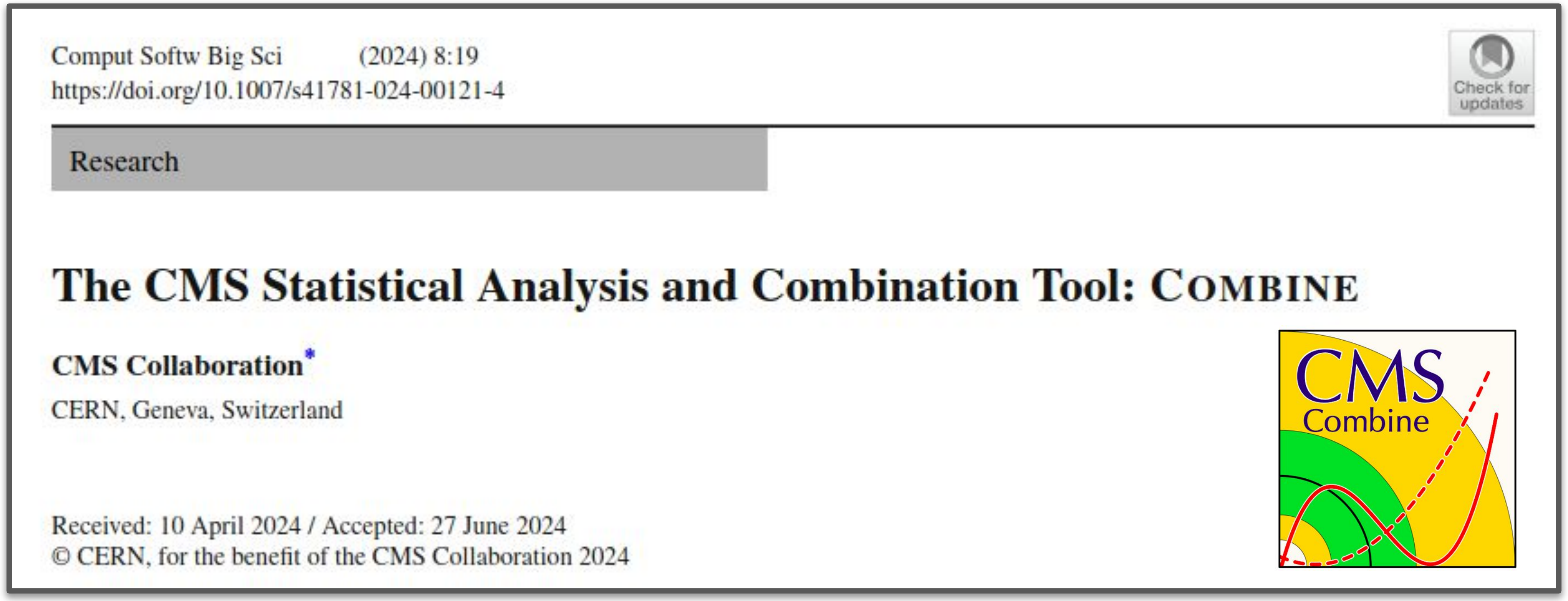


Combine: statistical fitting tool developed in CMS



Comput Softw Big Sci (2024) 8:19
https://doi.org/10.1007/s41781-024-00121-4

Research

The CMS Statistical Analysis and Combination Tool: COMBINE

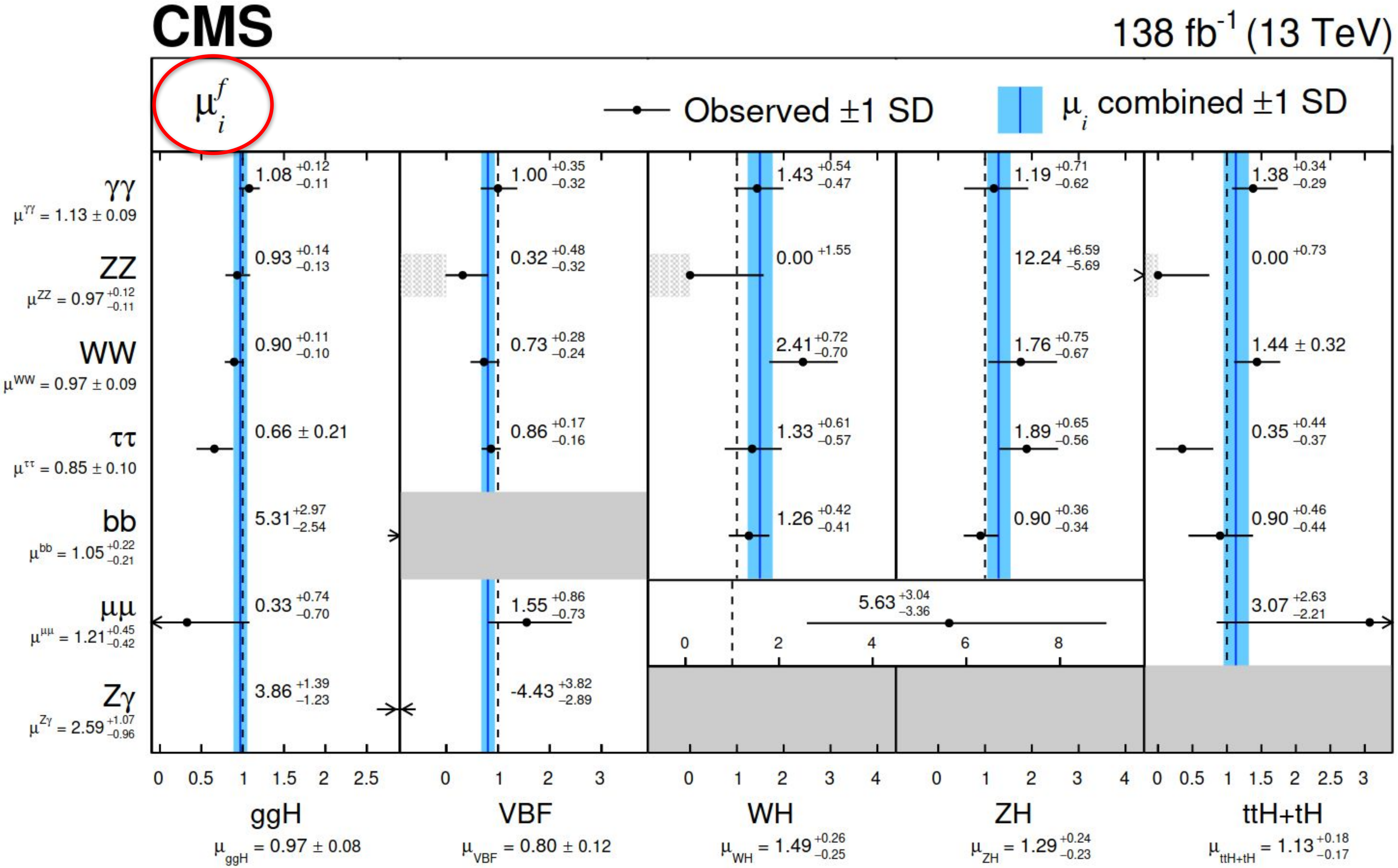
CMS Collaboration*
CERN, Geneva, Switzerland

Received: 10 April 2024 / Accepted: 27 June 2024

Now being used outside of the collaboration!

A combined fit

[Nature 607 (2022) 60-68]



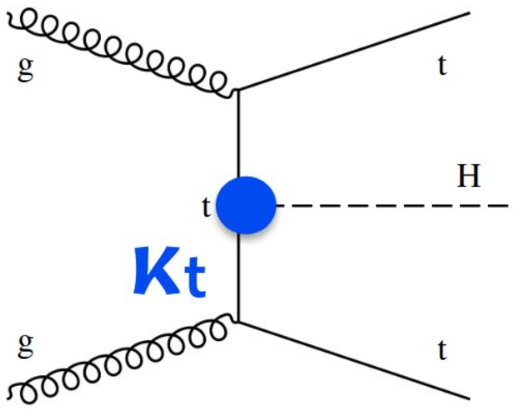
Higgs boson couplings

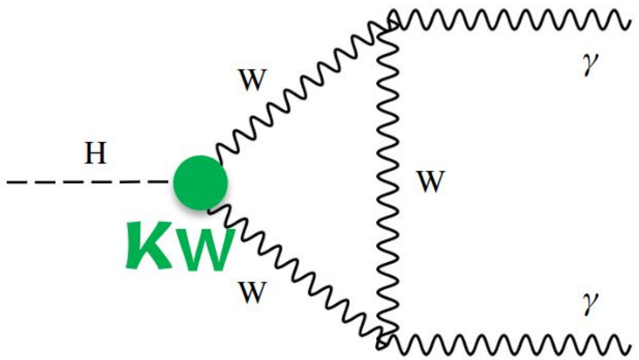
[Nature 607 (2022) 60-68]

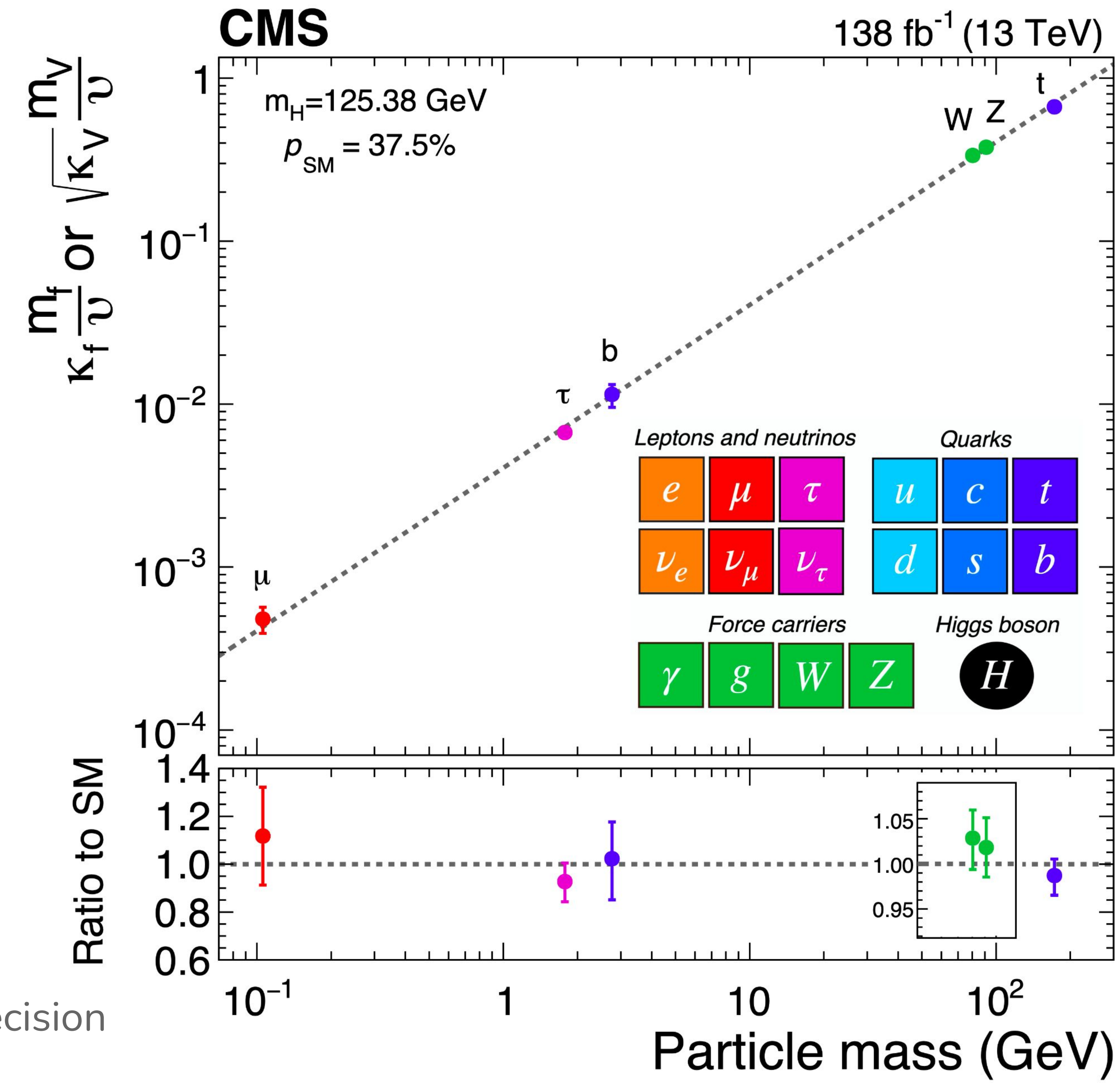
- In SM → Higgs interactions strengths (couplings) to SM particles are proportional to mass of those particles

- Probe this relationship with the **kappa-framework**

$$\mu \longrightarrow \mu(\vec{\kappa})$$



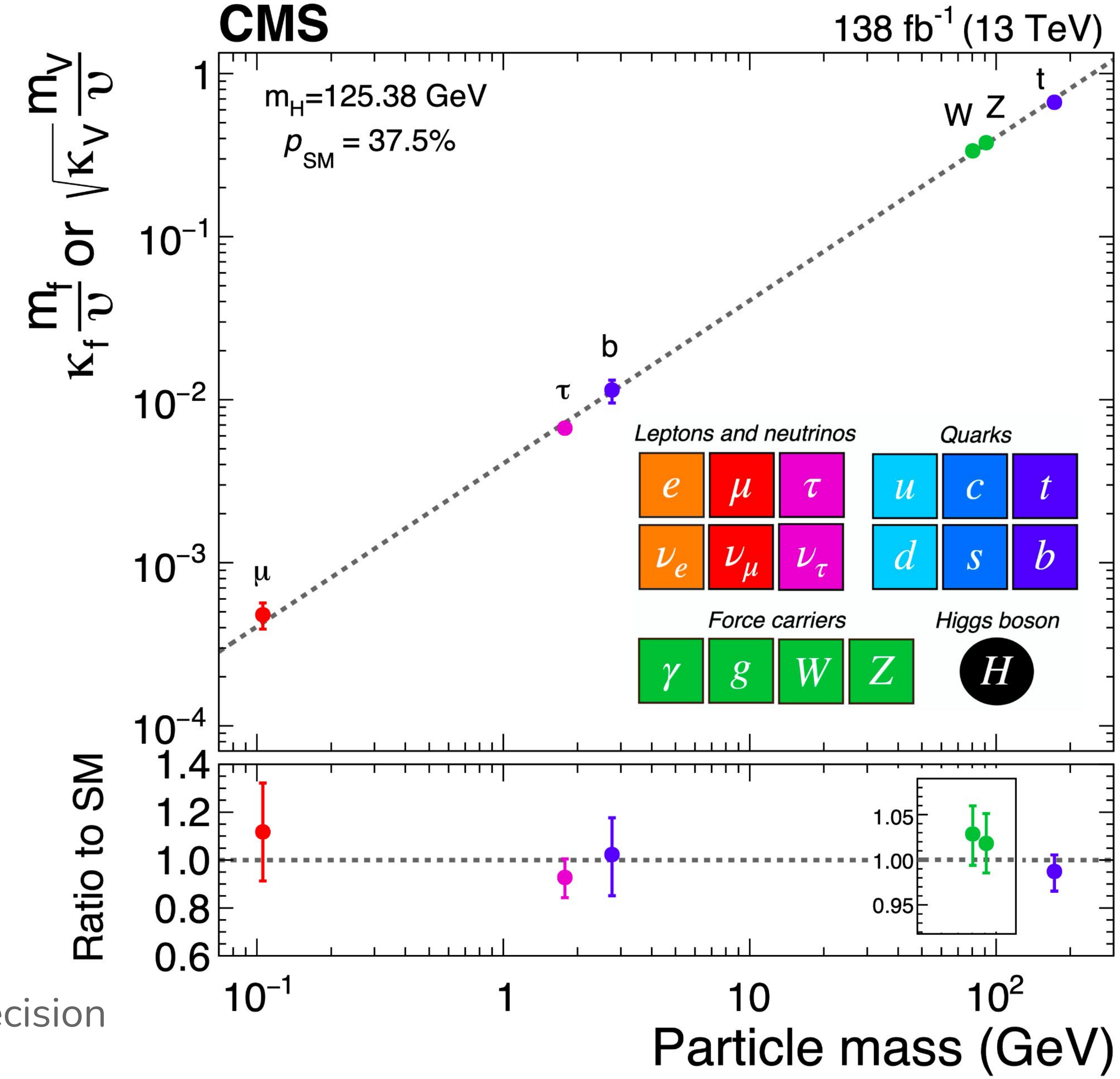




- Measurements are in good agreement with SM with good precision

Higgs boson couplings

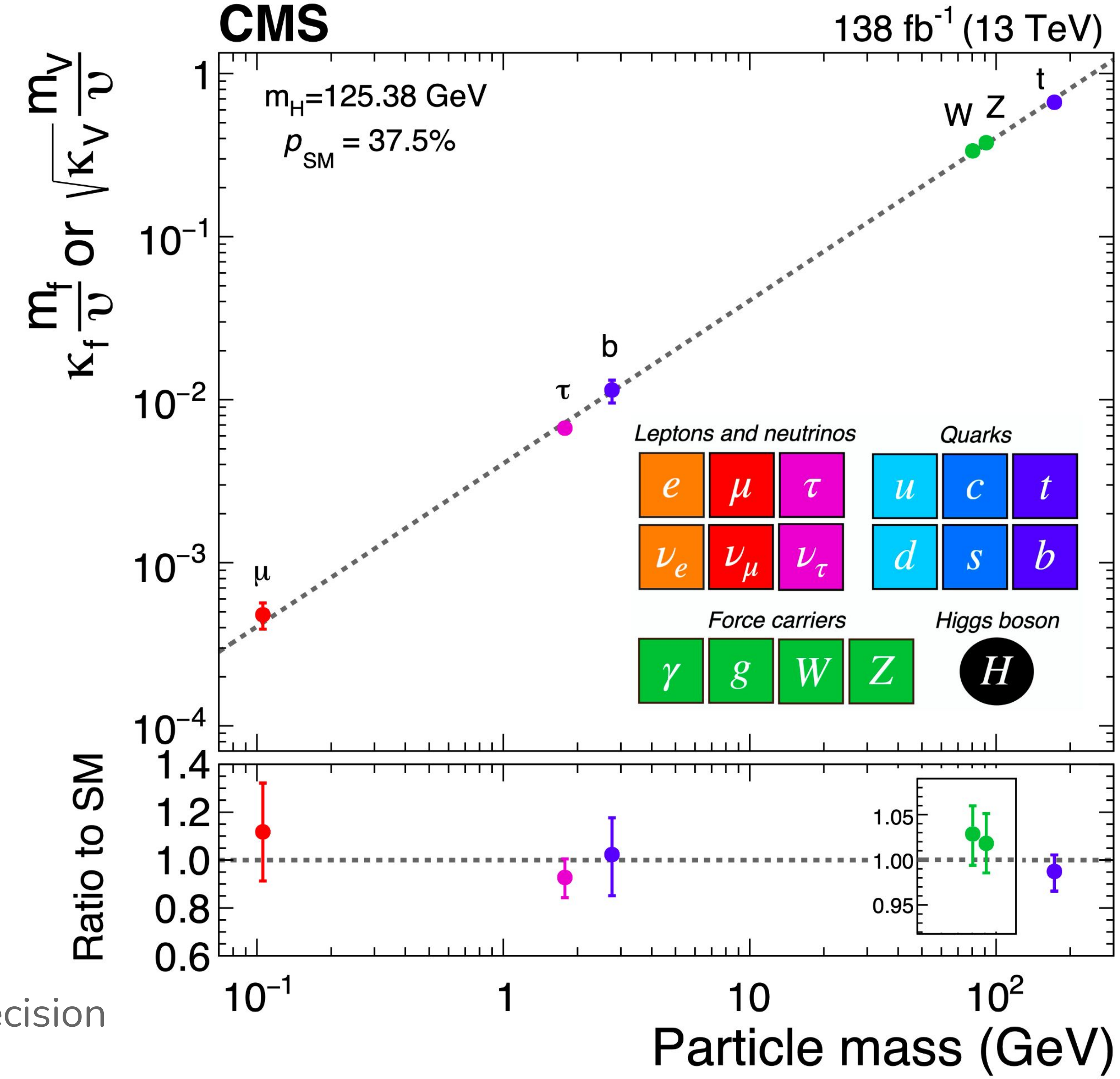
[Nature 607 (2022) 60-68]



- Measurements are in good agreement with SM with good precision
- **Are we not done?**

Higgs boson couplings

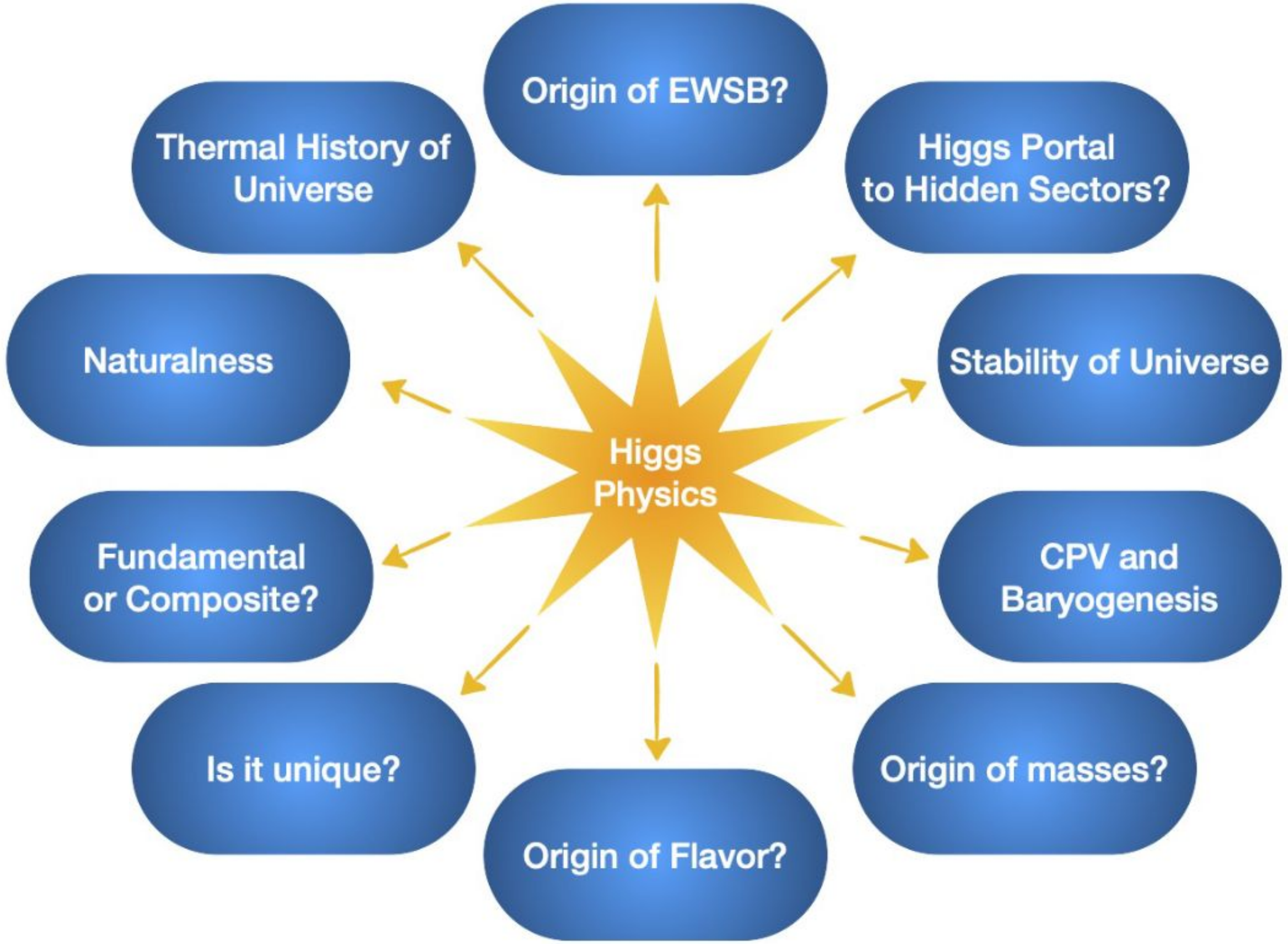
[Nature 607 (2022) 60-68]



- Measurements are in good agreement with SM with good precision
- **Are we not done?**

The open questions

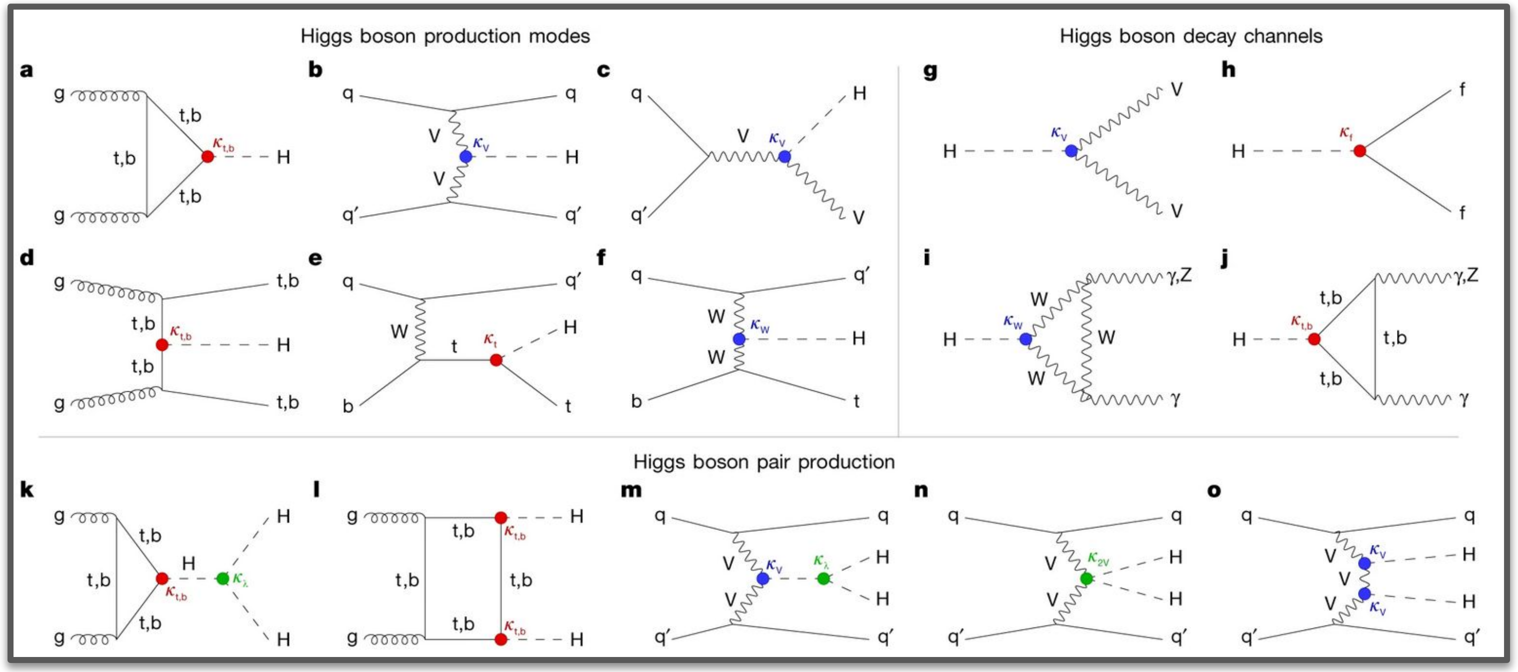
- “Almost every problem of the Standard Model originates from Higgs boson interactions”



Taken from G. Salam slides @ FCC Week 2023

$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour ($y H \psi \bar{\psi}$) — *naturalness* ($\mu^2 |H|^2$) — *stability* ($\lambda |H|^4$) — *cosmological constant* (V_0)

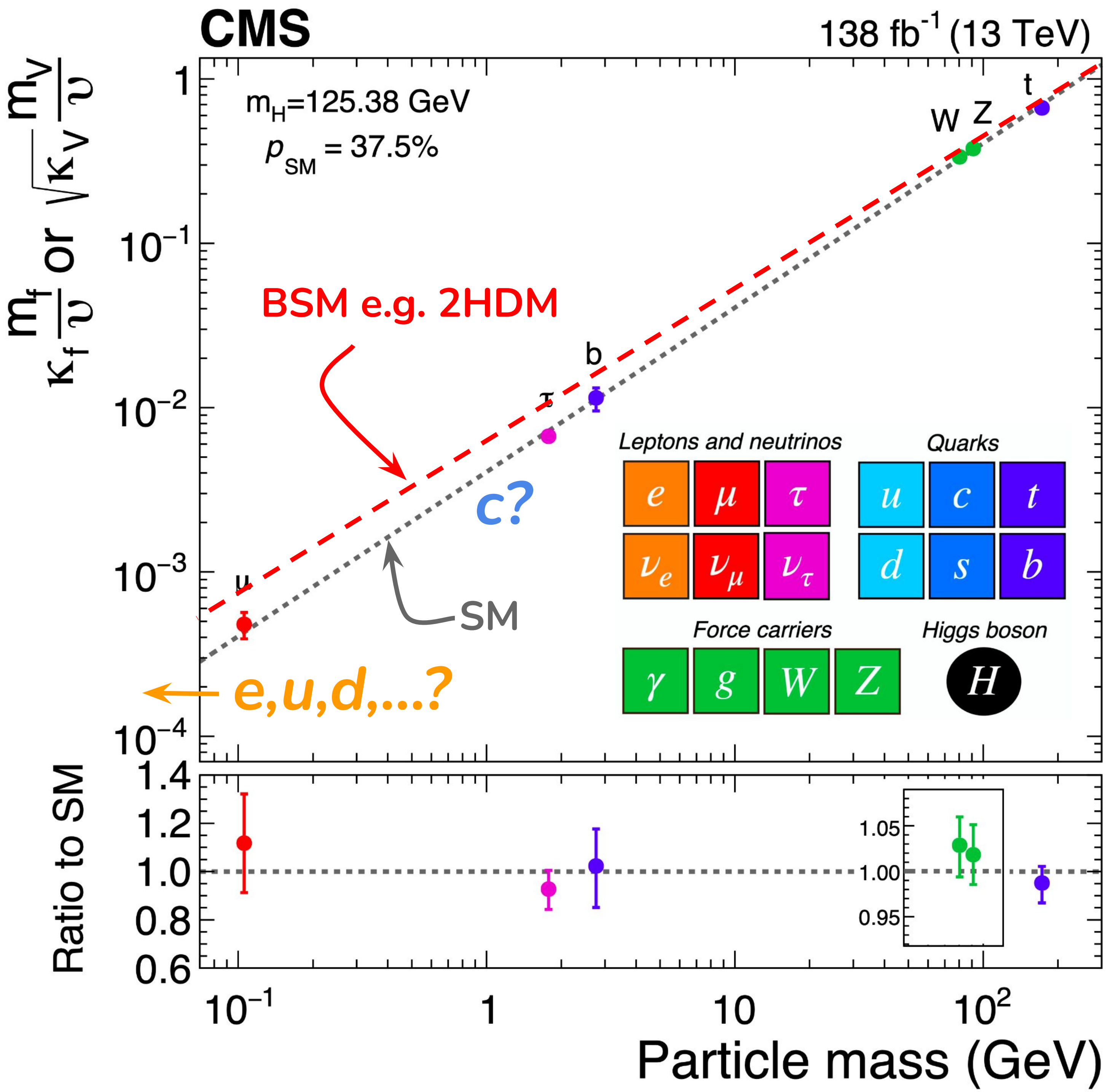


- Precision measurements of Higgs boson offer a **unique tool to search for new fundamental physics**

The open questions

- **Are the Higgs interactions SM-like?**

  Do all SM particles lie on that line?



Overview of analyses

1. [CMS-PAS-HIG-23-013]: ★

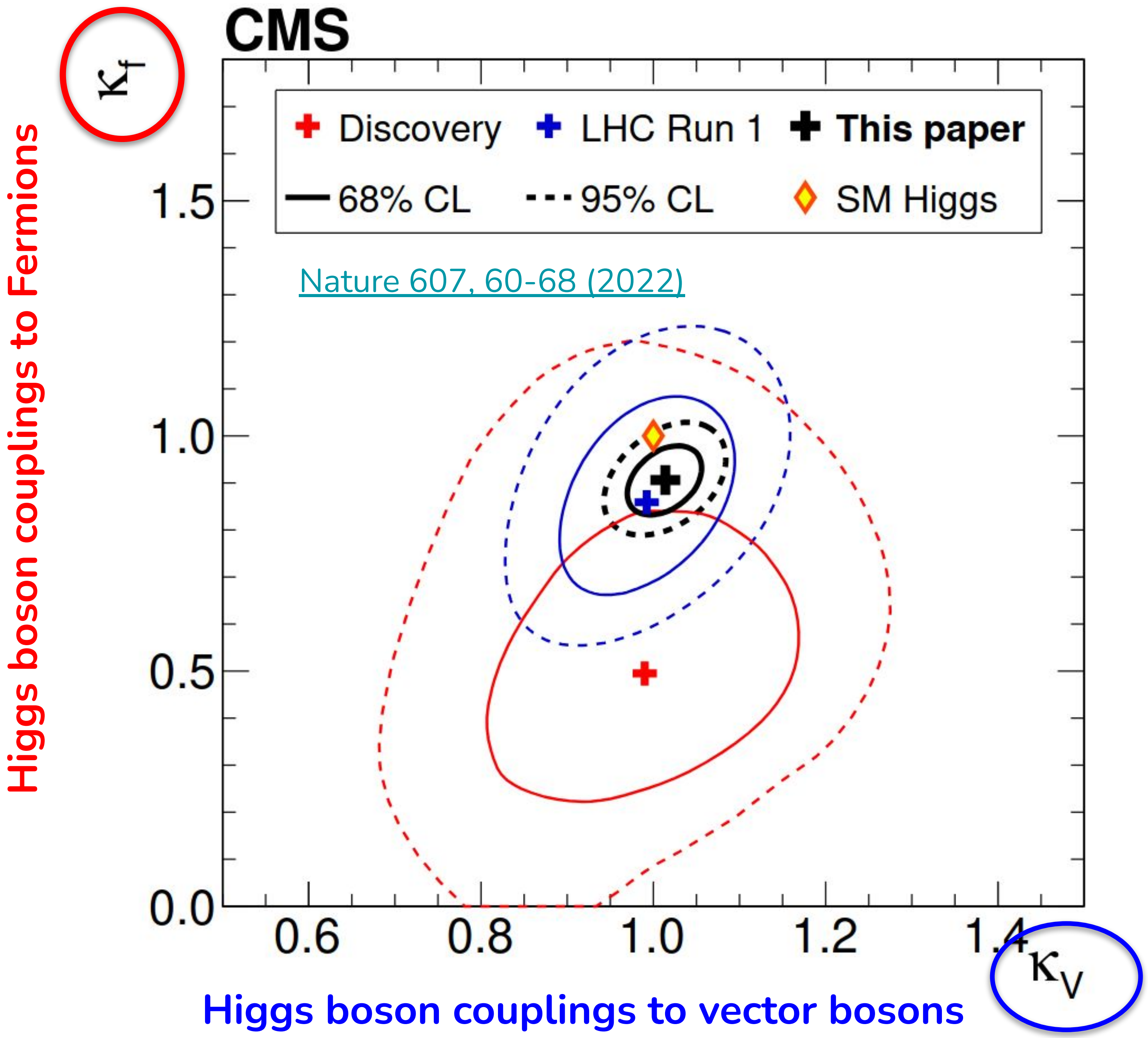
   Combination and interpretation of fiducial differential Higgs boson production cross sections at $\sqrt{s}$ = 13 TeV

2. [CMS-PAS-SMP-24-003]:

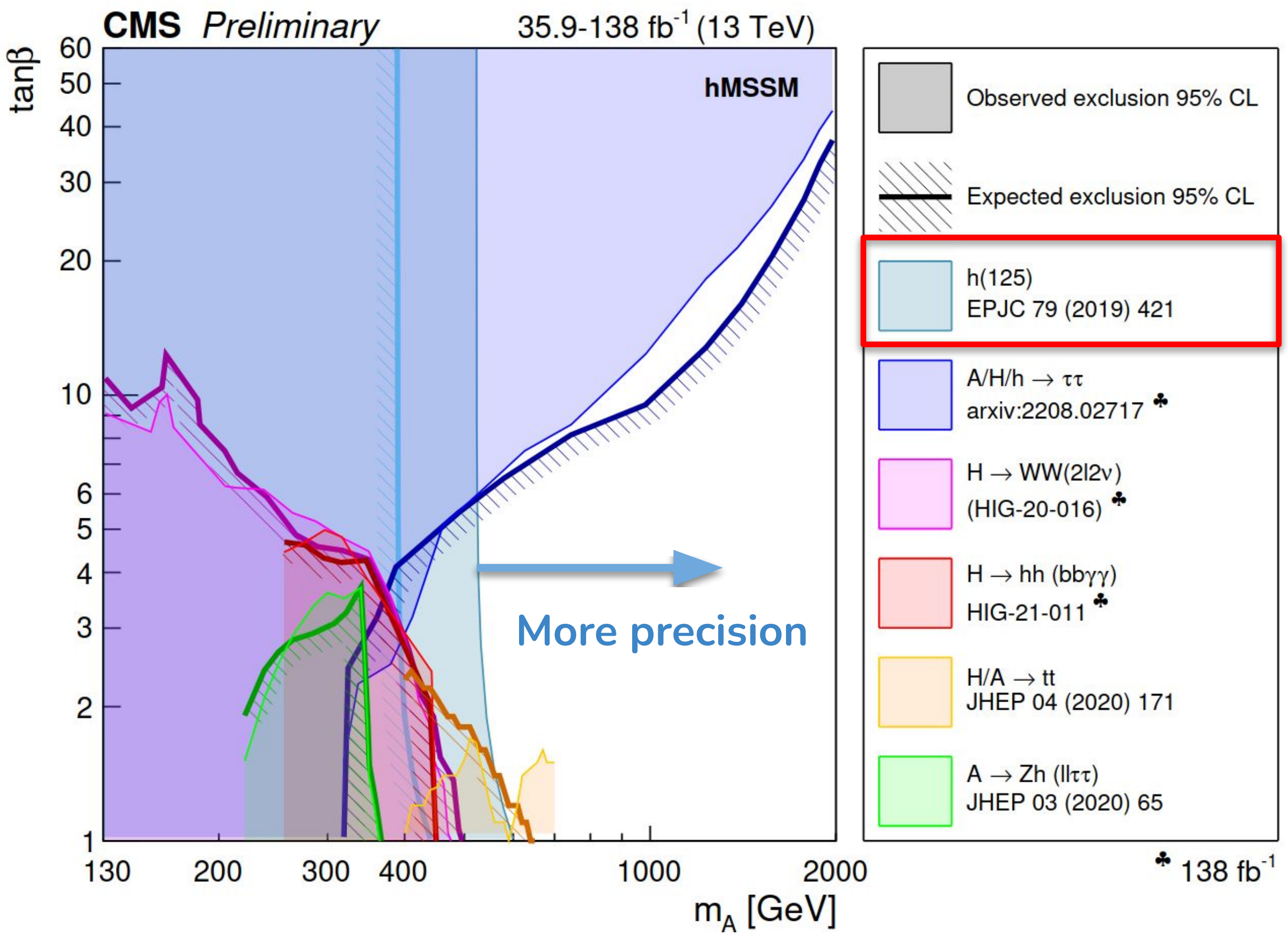
   Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark and multi-jet measurements

Higgs couplings to probe BSM physics

- Precision measurements of Higgs boson interactions provide complimentary approach to direct searches



In extended sectors (e.g. hMSSM) couplings to vector bosons and fermions can be modified from the SM



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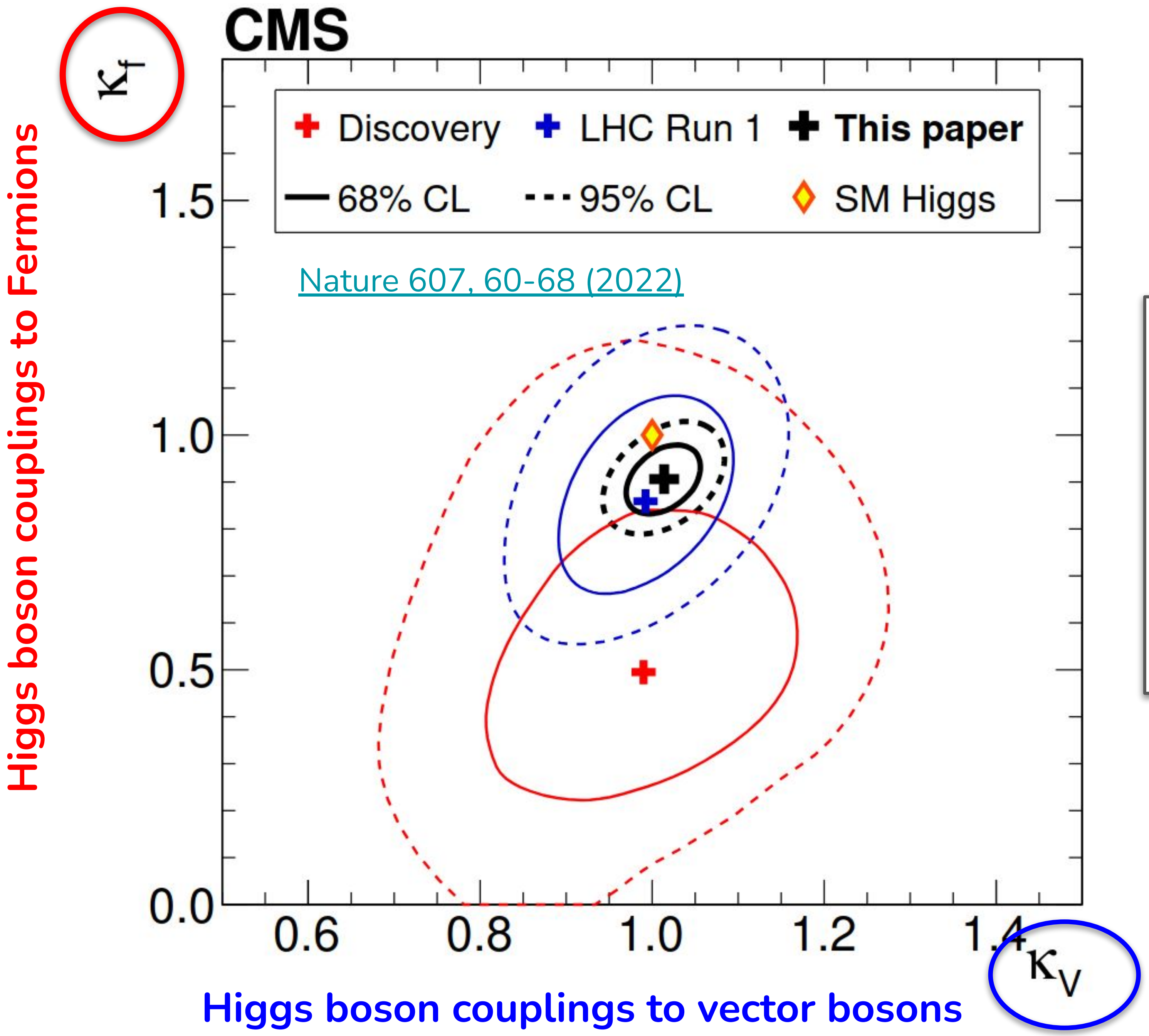


In extended sectors (e.g. hMSSM) couplings to vector bosons and fermions can be modified from the SM

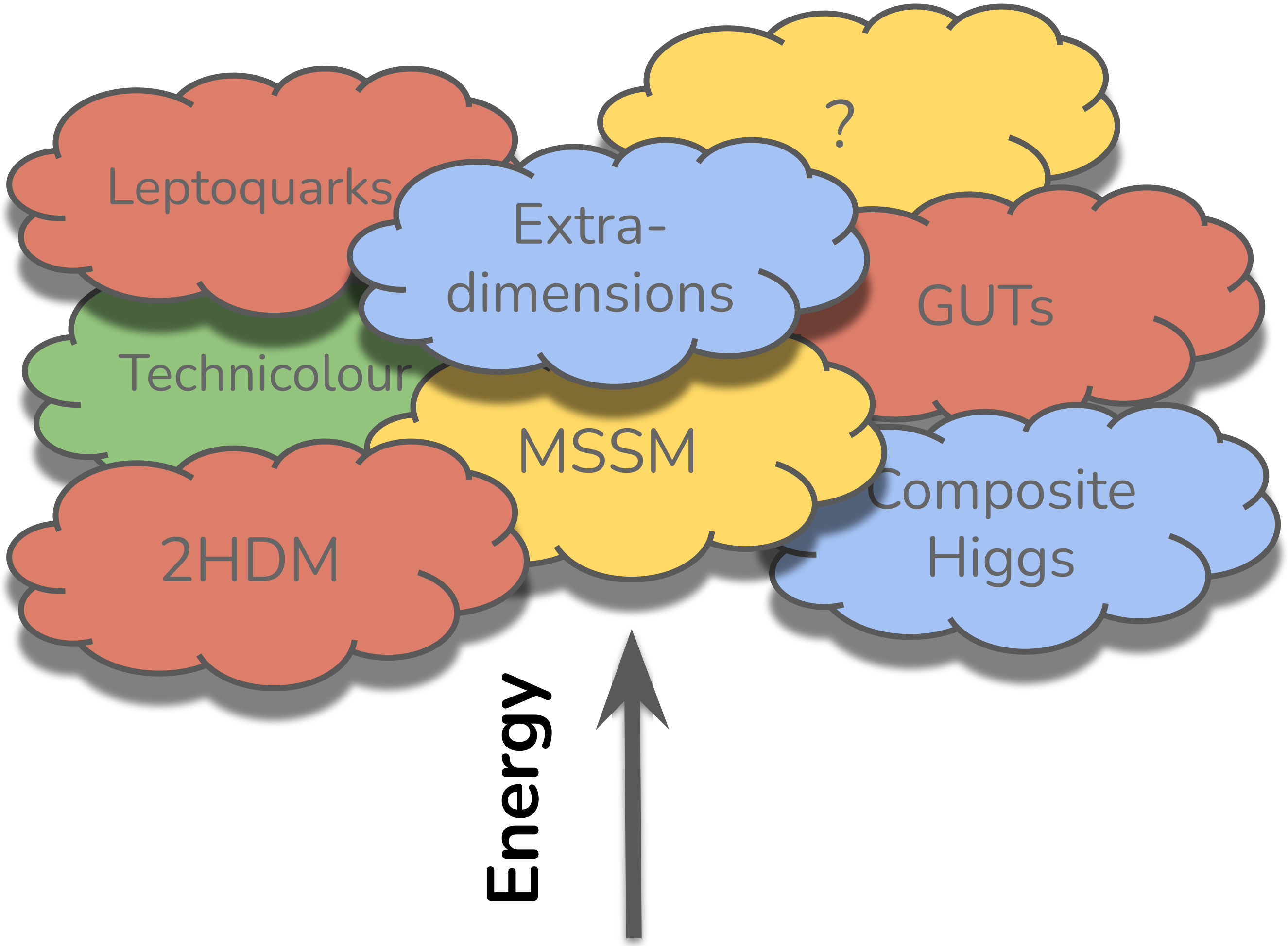
Table 1-8. *Generic size of Higgs coupling modifications from the Standard Model values when all new particles are $M \sim 1$ TeV and mixing angles satisfy precision electroweak fits. The Decoupling MSSM numbers assume $\tan\beta = 3.2$ and a stop mass of 1 TeV with $X_t = 0$ for the κ_γ prediction.*

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

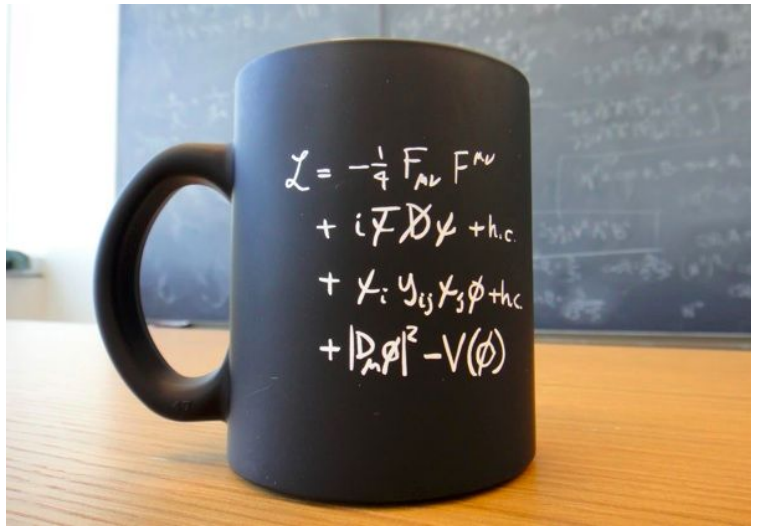
arXiv:1310.8361

Cannot rule out new physics with current precision (~10%)

A model agnostic search



SM



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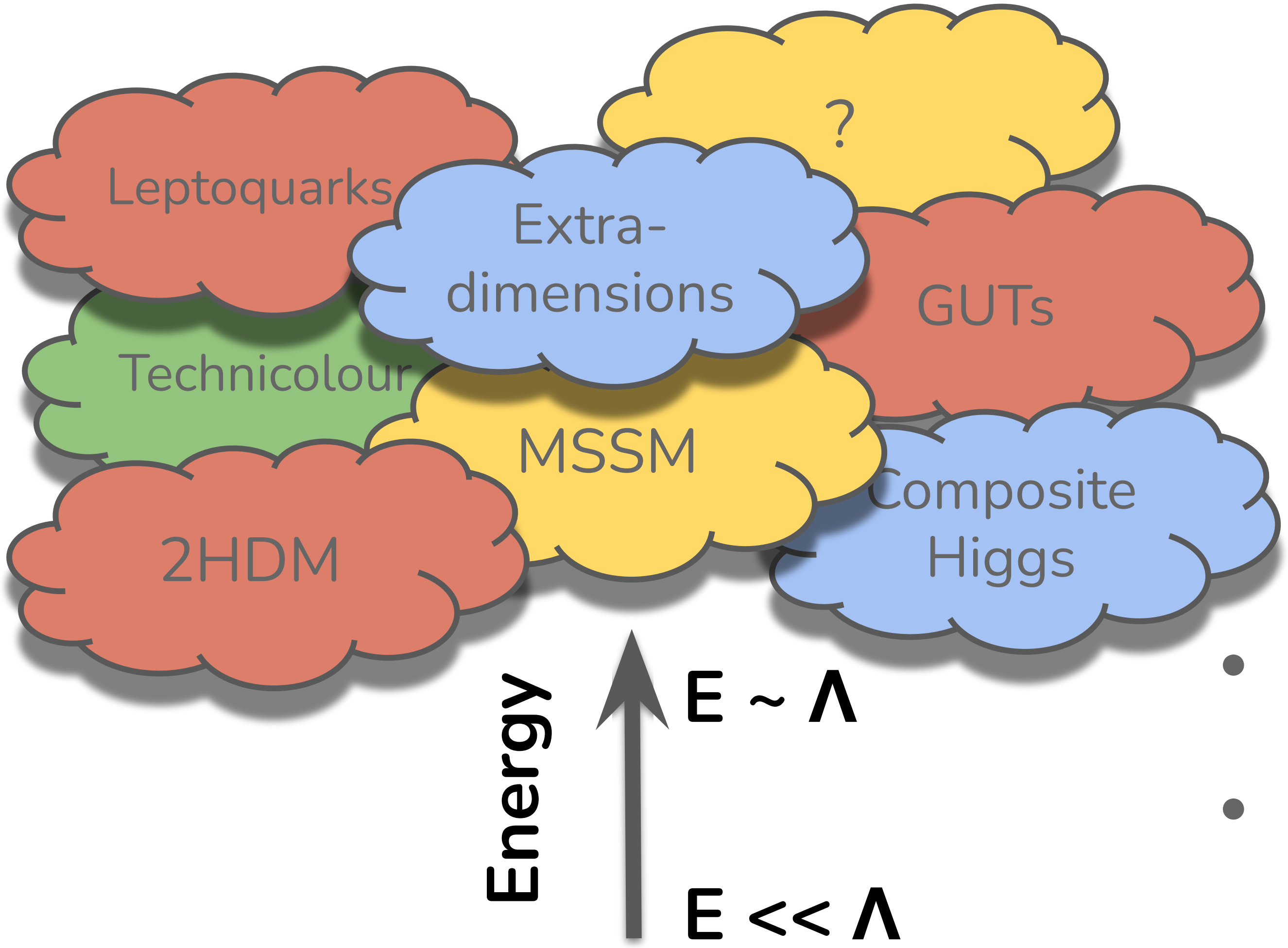

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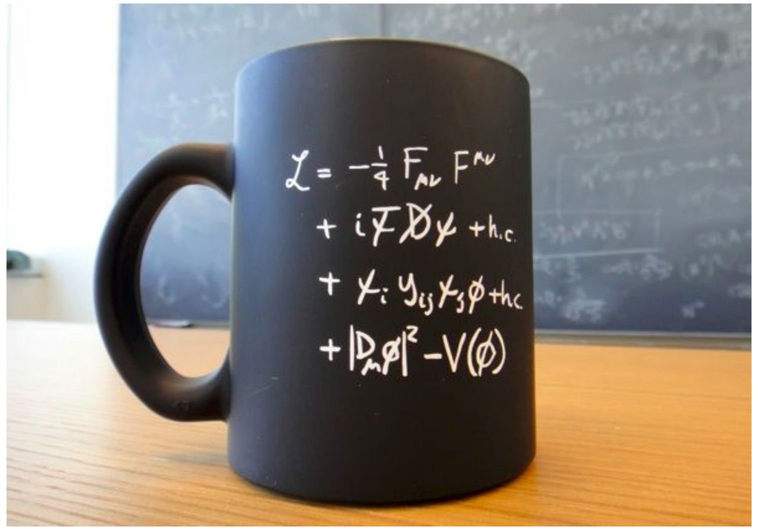


With no direct observation of new physics (NP) at the LHC we turn to:

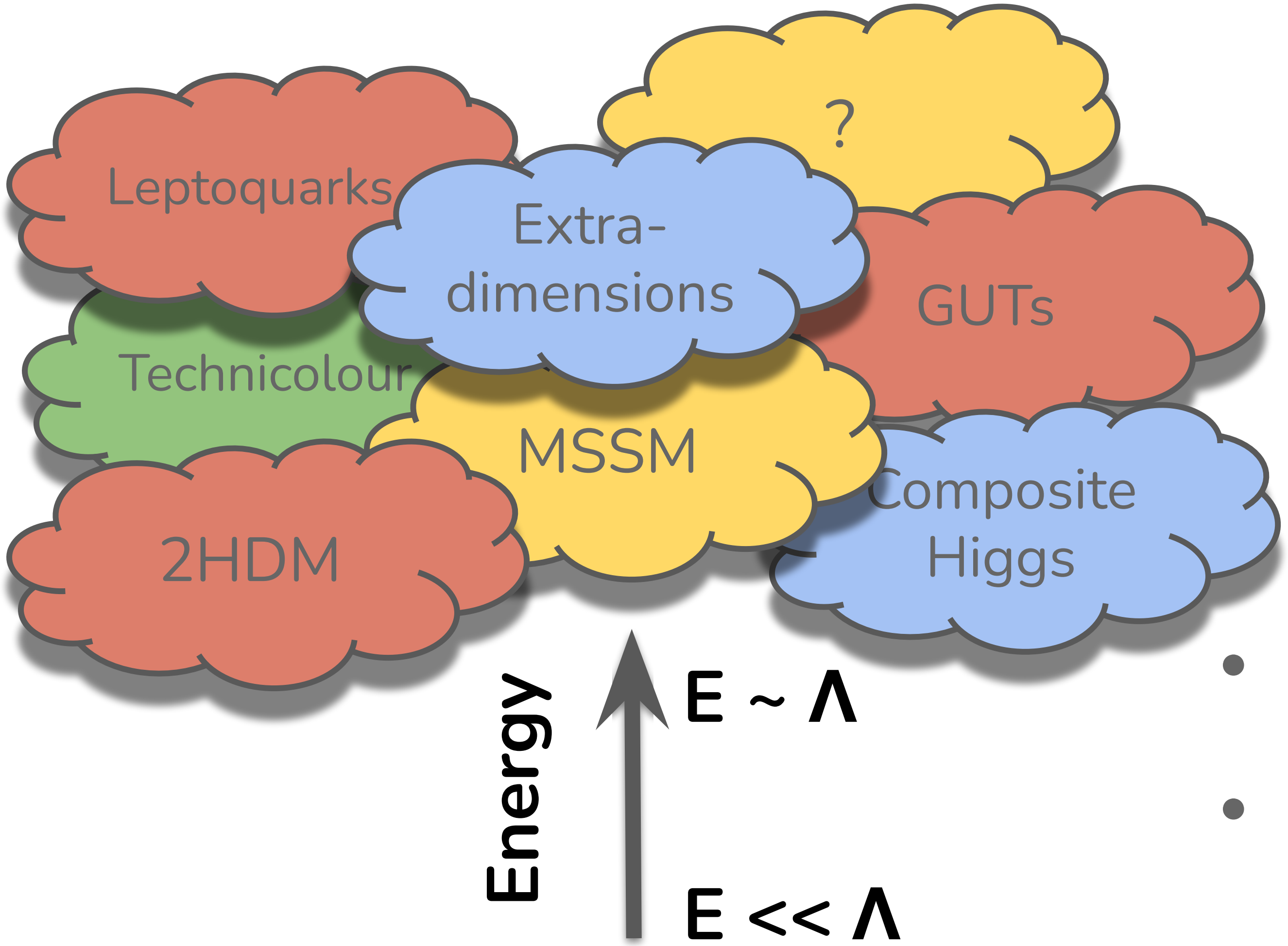
Effective Field Theory

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

- Assume NP exists at a **mass scale**, Λ, beyond energy-reach of collider
- **Coherent expansion in 1/Λ of SM Lagrangian** to include higher-dim operators
  - Integrate out short-distance new physics
  - Look for imprints in SM interactions
  - **Systematically probe space of BSM theories**
- Model-independent approach (*)

(*) - Valid for E<Λ. Assumes some flavour scheme. Obeys SM symmetries

A model agnostic search



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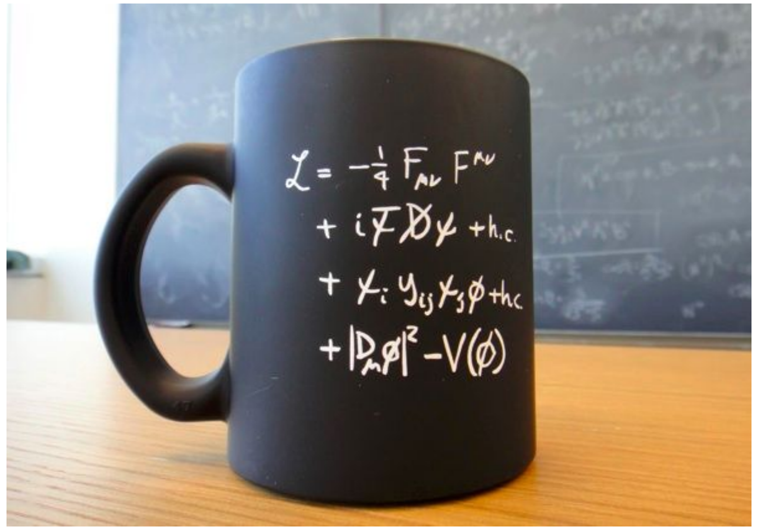

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Odd terms violate B-L conservation

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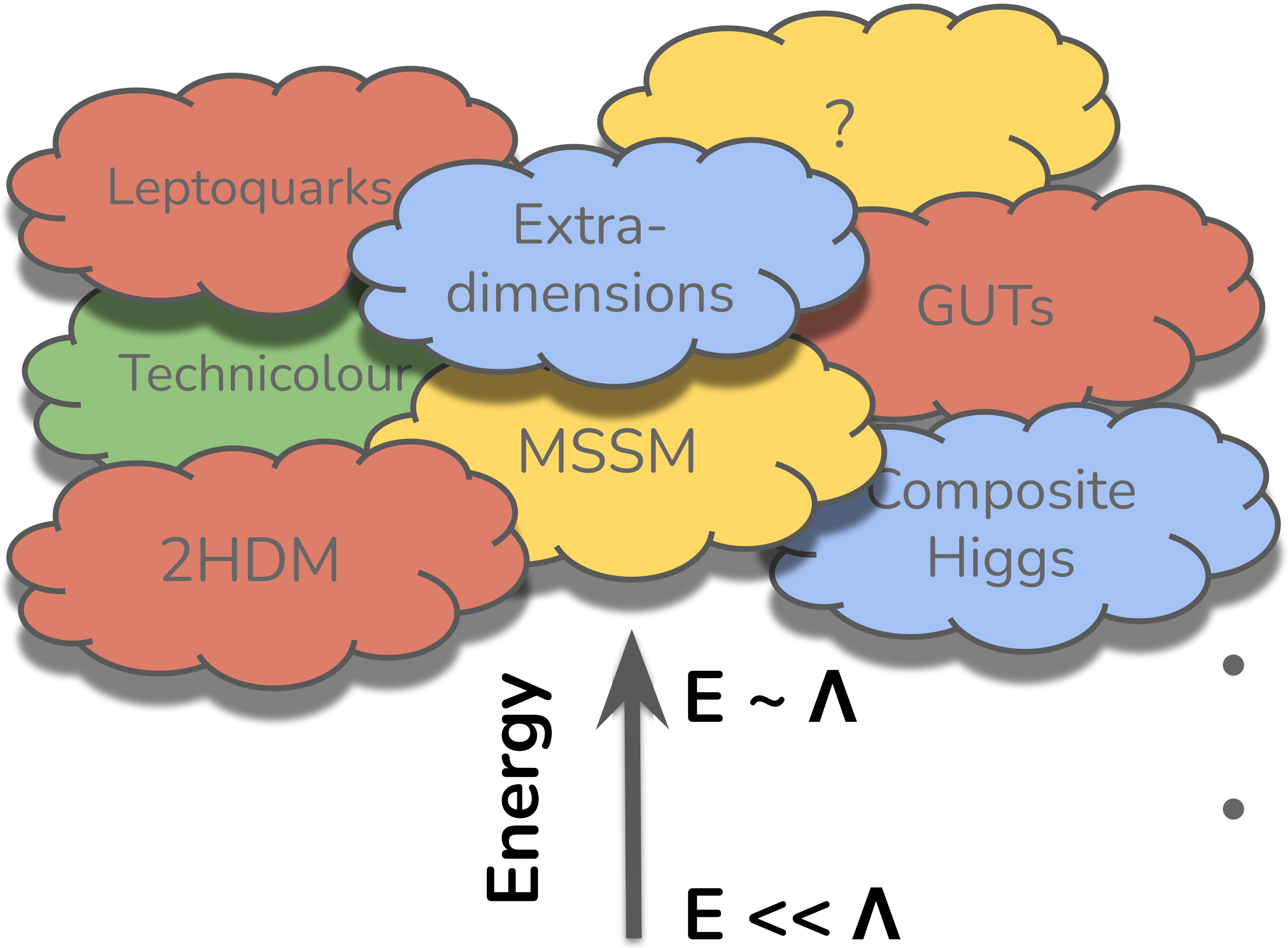

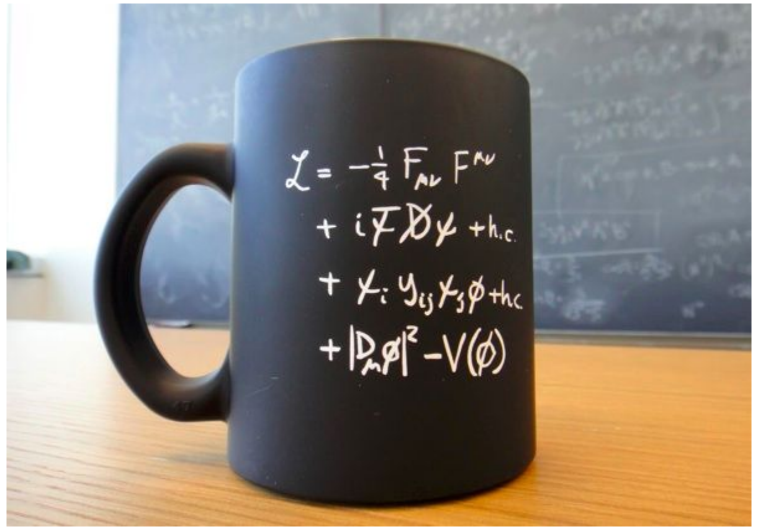

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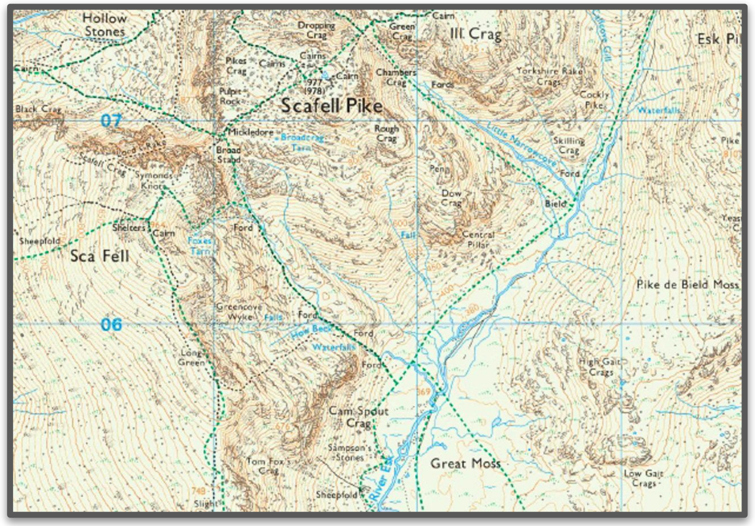
A hiker's guide to EFT

Complete theory: map of mountain range down to details of cracks in rock

- A hiker does not need this level of detail
- Introduce 10m grid on terrain and use average values for each square



Effective theory:

- Discard information with length scale below some cut-off
- But capture relevant physics!

A hiker's guide to EFT

(*) Compare with Fermi-theory for muon decay. Fermi-theory is an EFT for the SM

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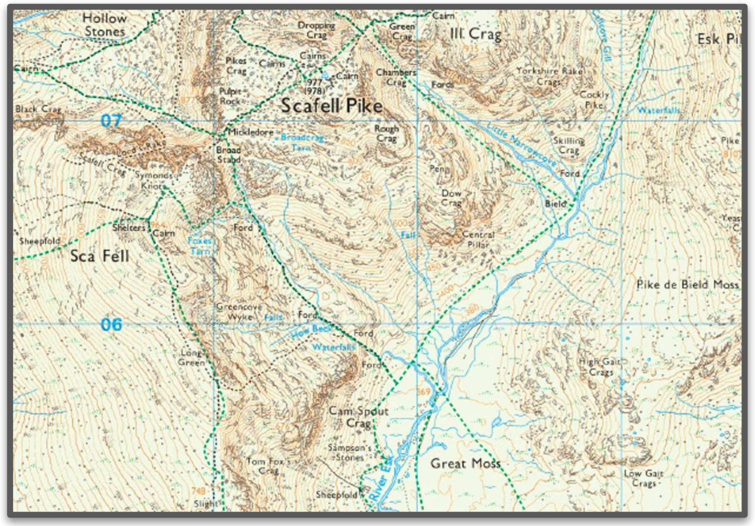

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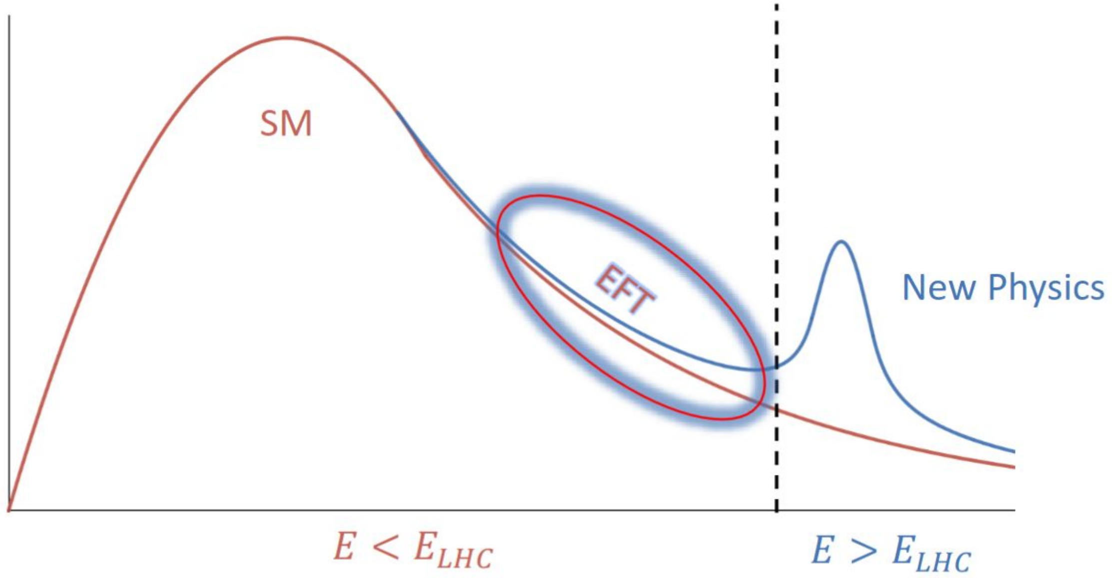
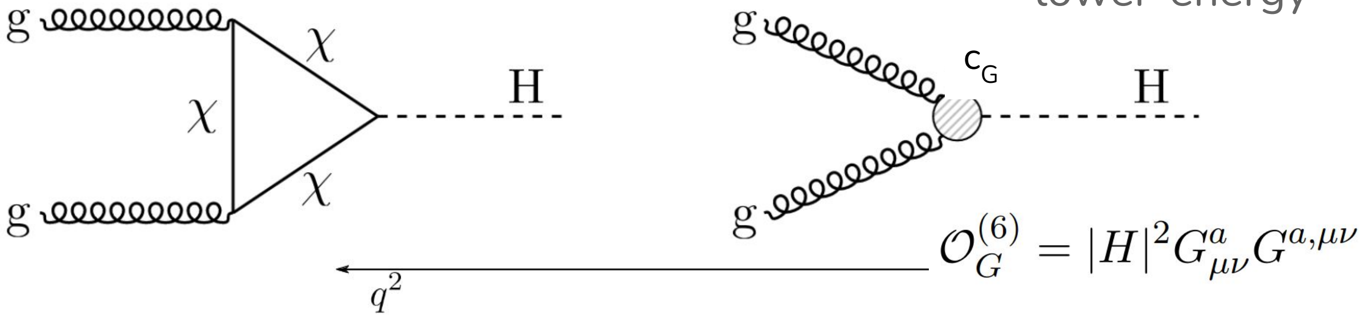
Apply same principle to TeV+ scale physics



Short-distance, high-energy

Contact interaction, lower-energy



$$\mathcal{L}^{(d)} = \sum_j^{N^{(d)}} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{O}_j^{(d)}$$

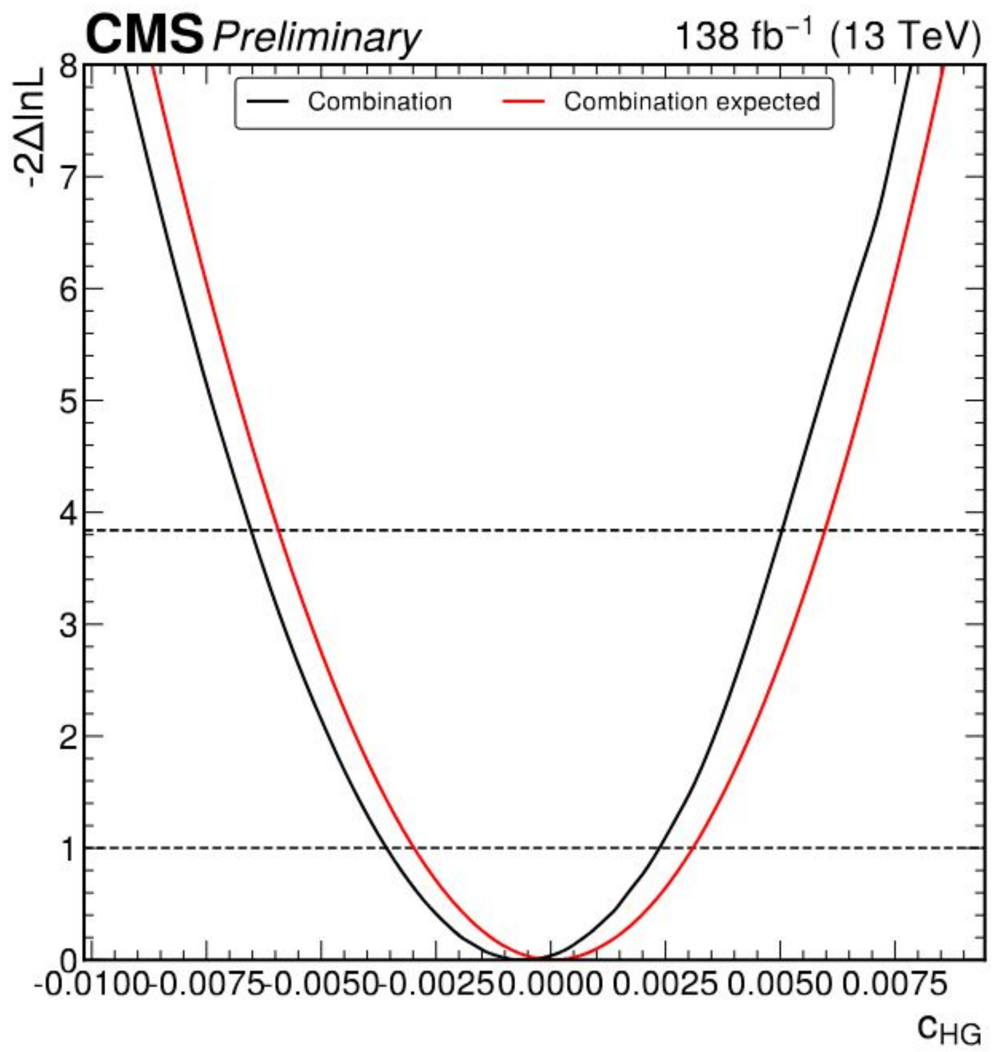
Wilson coefficients

Higher-dim operator

Mass-scale suppression

A hiker's guide to EFT

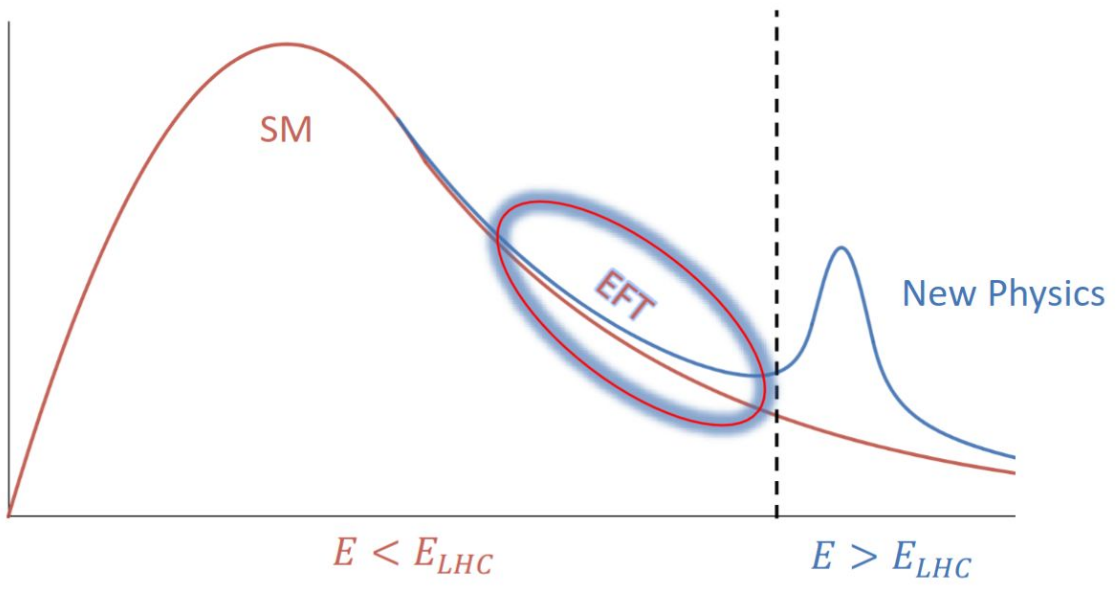
(*) Compare with Fermi-theory for muon decay. Fermi-theory is an EFT for the SM



Measure Wilson coefficients, c_j

- Deviations from zero are a smoking gun for BSM physics
- And tells us where to look i.e. what kind of interactions!

Apply same principle to TeV+ scale physics



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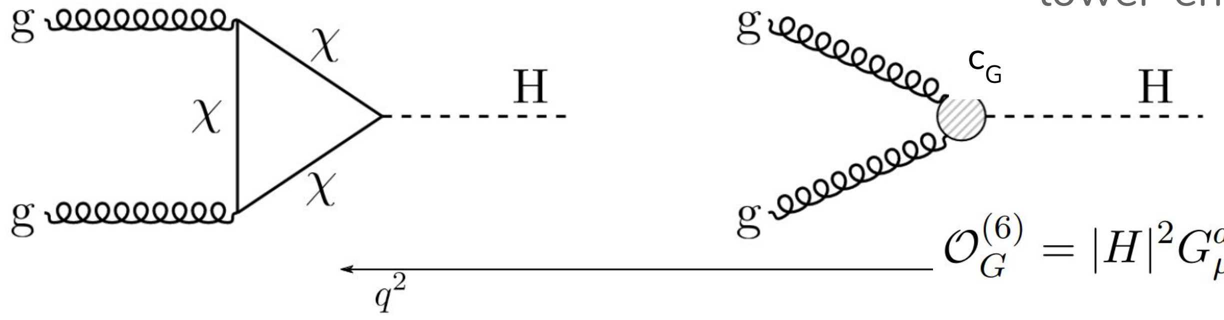

$$\mathcal{O}_G^{(6)} = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\mathcal{L}^{(\mathrm{d})} = \sum_j^{N^{(\mathrm{d})}} \frac{c_j^{(\mathrm{d})}}{\Lambda^{d-4}} \mathcal{O}_j^{(\mathrm{d})}$$

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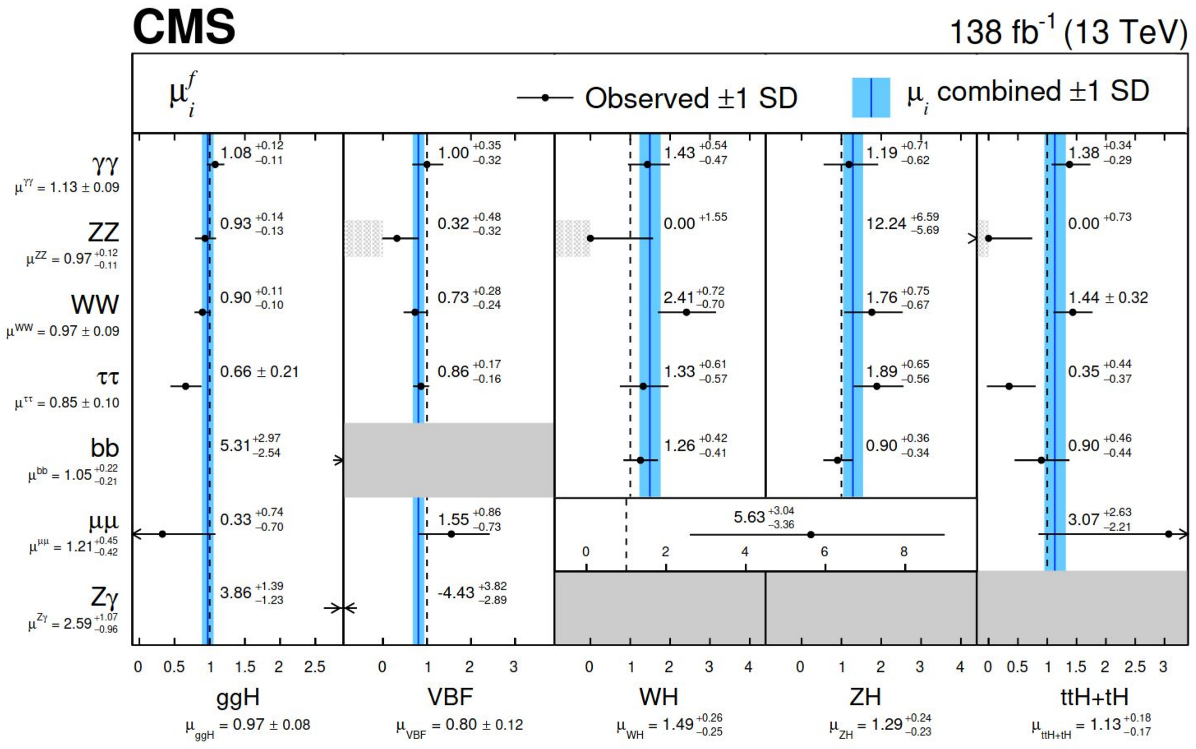
Mass-scale suppression

Importance of going differential

Onshell production



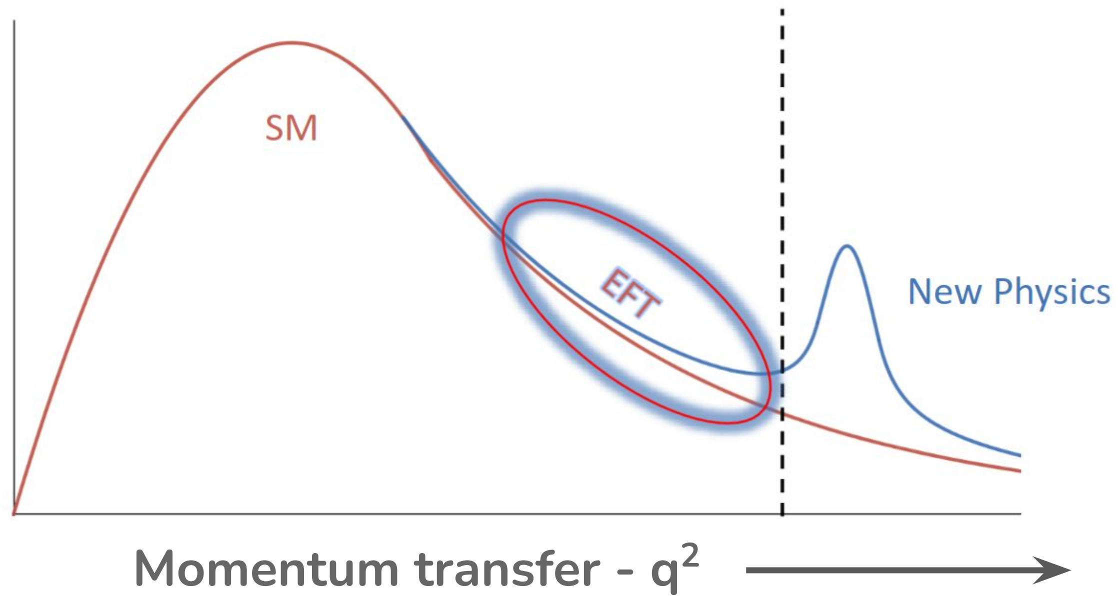
$$\delta = \left(\frac{v}{\Lambda}\right)^2$$

Inclusive measurements (in bulk)

High precision yields precision on new physics scale

δ~1% → Λ ~ 2.5 TeV

Offshell production, high-q^2



$$\delta = \left(\frac{q}{\Lambda}\right)^2$$

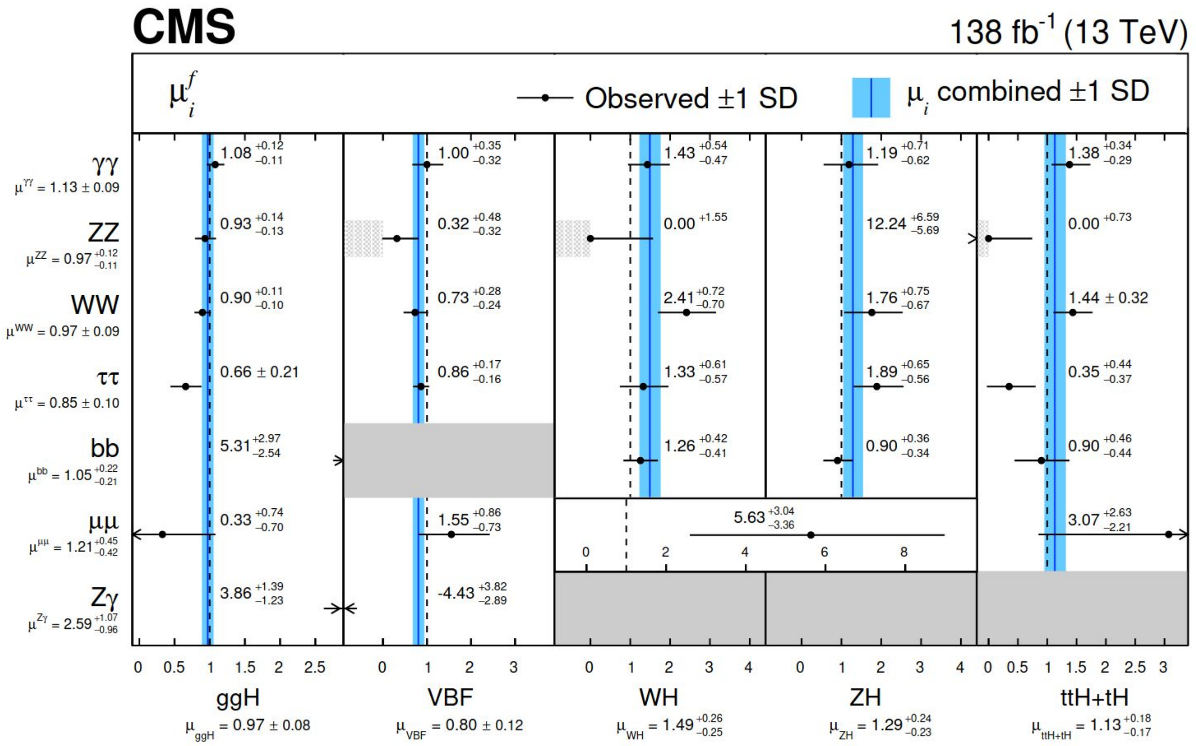
Differential measurements (in tail)

High momentum production is sensitive to new physics

δ~15% (q=1 TeV) → Λ ~ 2.5 TeV

Importance of going differential

Onshell production



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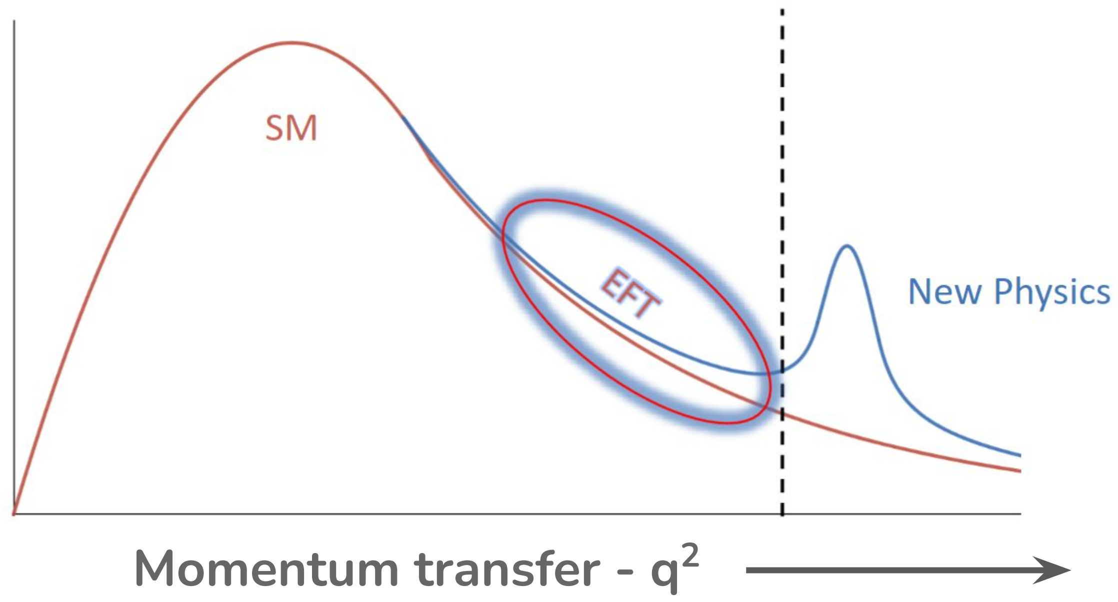


$$\delta = \left(\frac{q}{\Lambda}\right)^2$$

Differential measurements (in tail)

High momentum production is sensitive to new physics

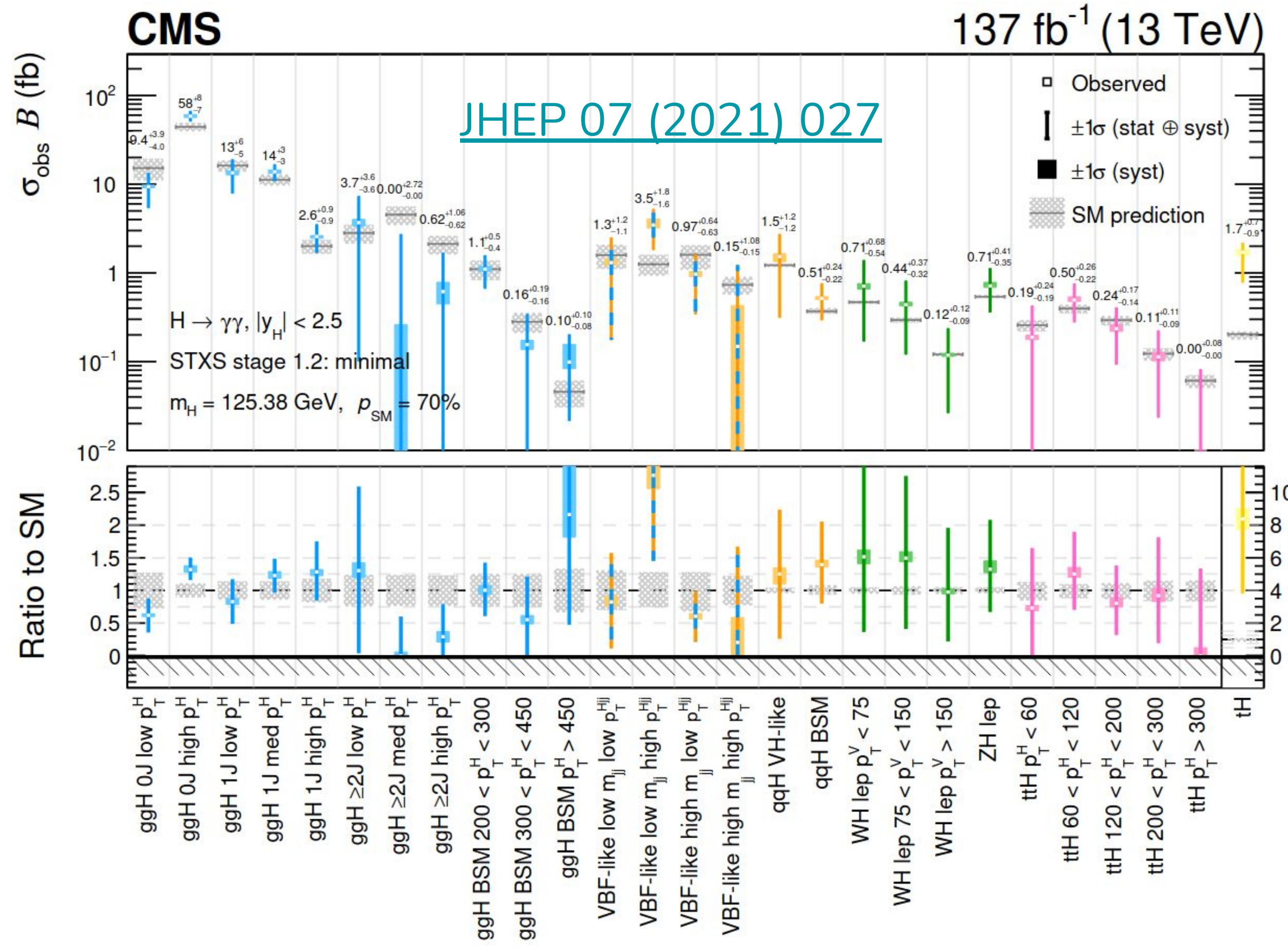
δ~15% (q=1 TeV) → Λ ~ 2.5 TeV

Use differential Higgs boson measurements to exploit sensitivity to EFT

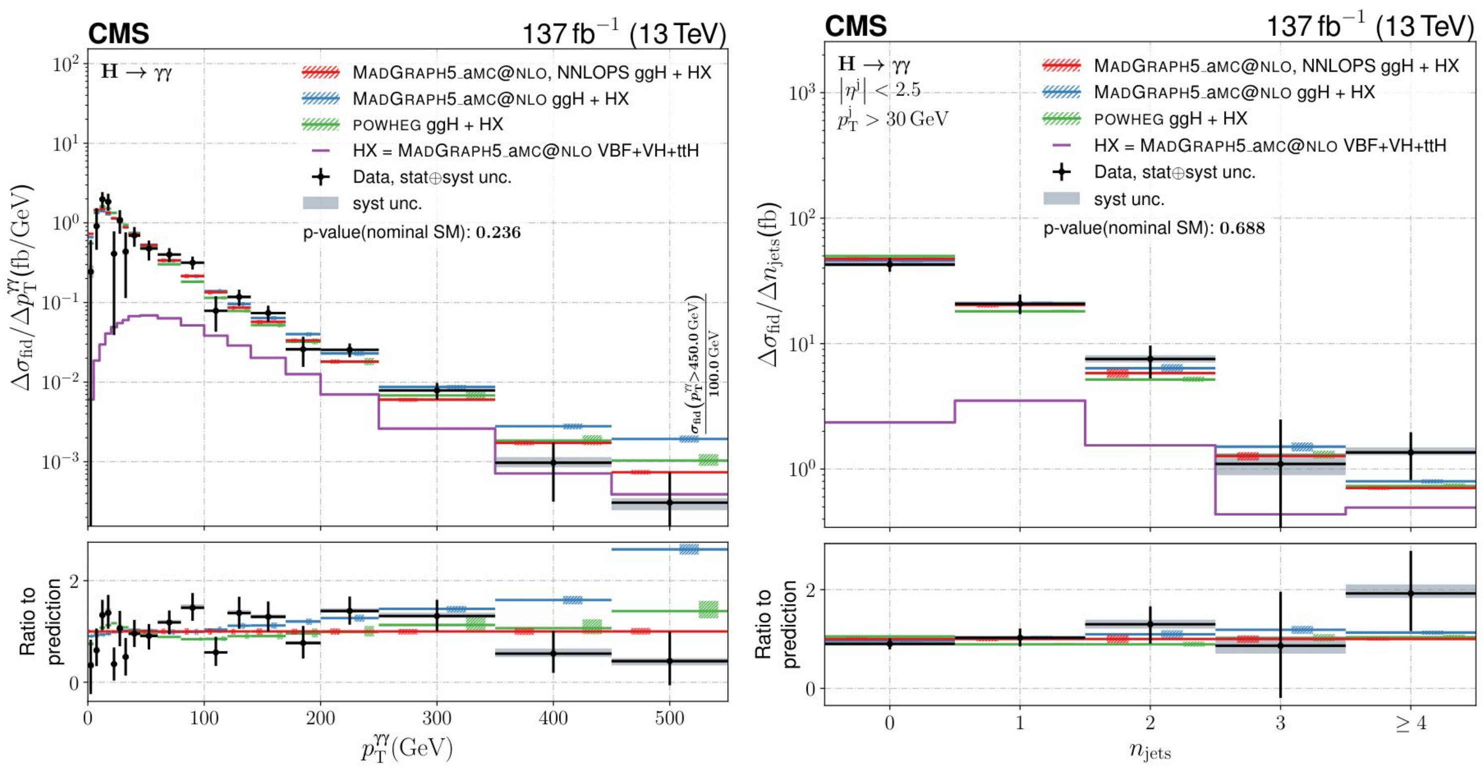
Differential Higgs boson measurements

H → γγ

- Large Run 2 dataset has paved the way for precise differential Higgs boson measurements



Simplified template cross sections (STXS)



Fiducial differential cross sections

Larger model-dependence ⟷ Most model-independent

Differential Higgs boson measurements

$H \to \gamma\gamma$

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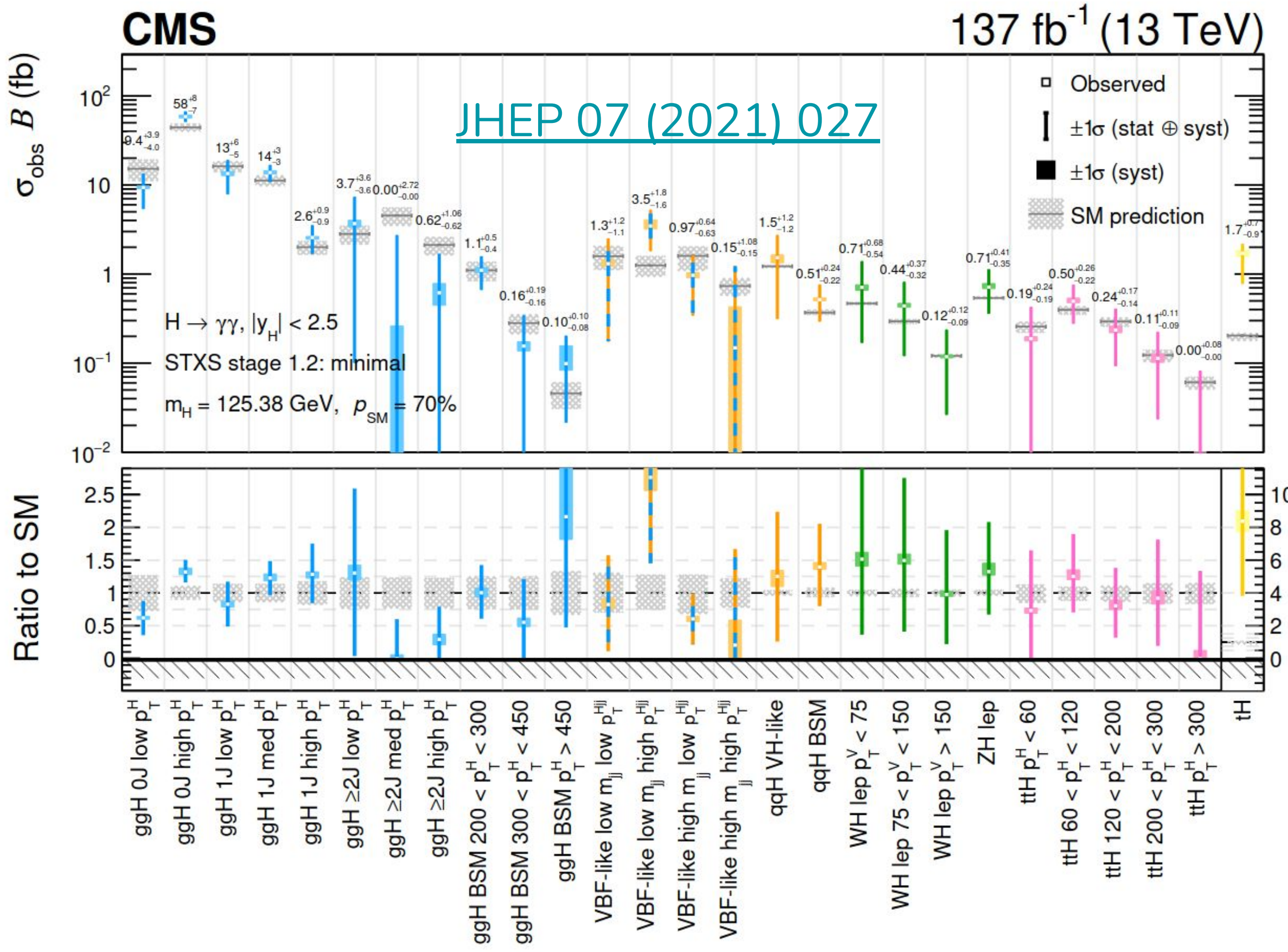
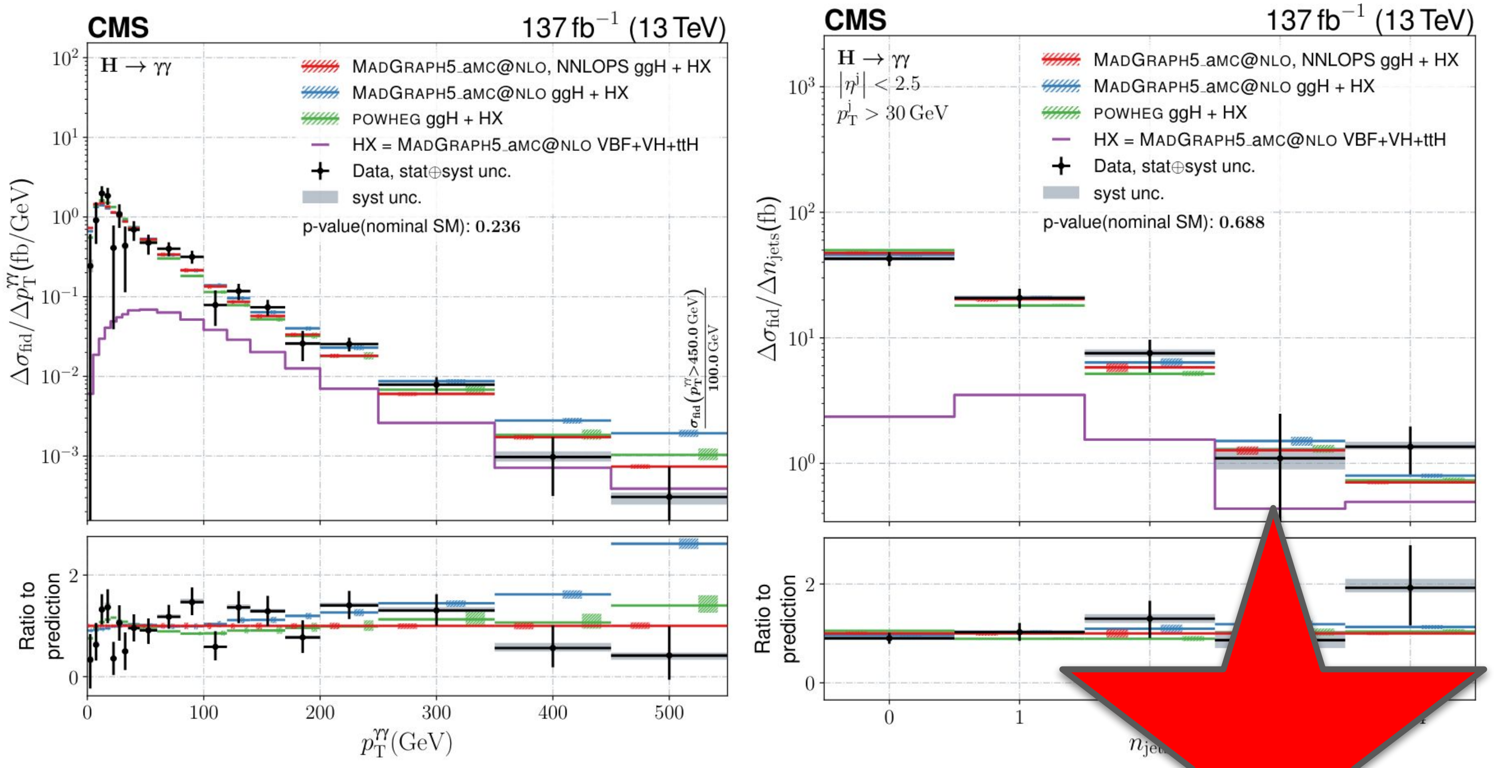


JHEP 07 (2021) 027

Simplified template cross sections (STXS)



JHEP 07 (2023) 091

Fiducial differential cross sections

Larger model-dependence ⟷ Most model-independent

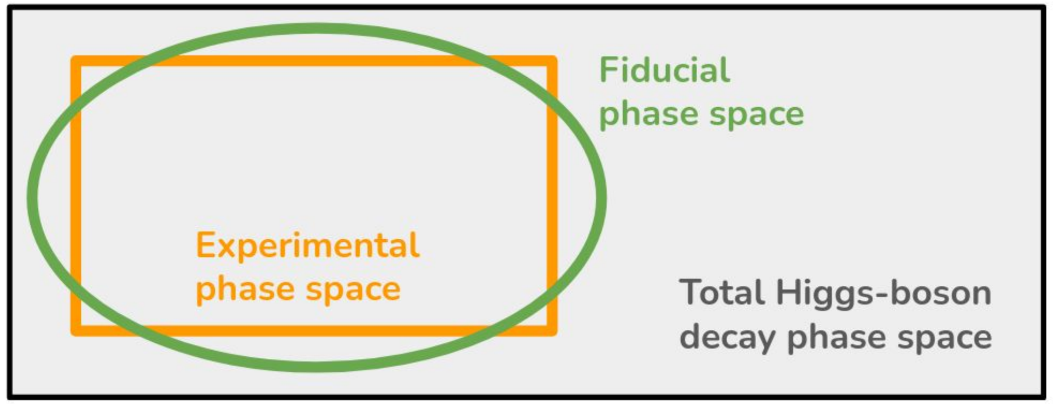
Combination of fiducial differential cross sections

NEW JULY 24

[CMS-PAS-HIG-23-013]

- "Fiducial" = measurements performed in specific fiducial phase space, designed to be close to experimental phase space
  - For example: H→$\gamma\gamma$

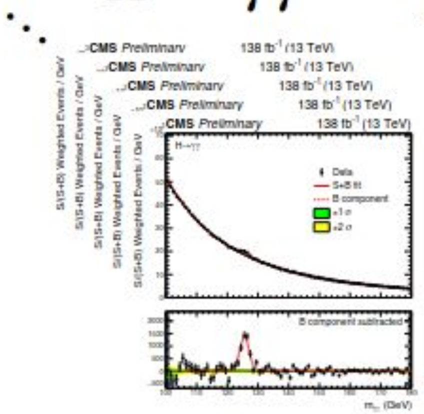
Observable	Selection
$p_{\mathrm{T}}^{\gamma_1}/m_{\gamma\gamma}$	$>1/3$
$p_{\mathrm{T}}^{\gamma_2}/m_{\gamma\gamma}$	$>1/4$
$\mathcal{I}_{\mathrm{gen}}^{\gamma}$	$<10\,\mathrm{GeV}$
$\lvert\eta^{\gamma}\rvert$	<2.5



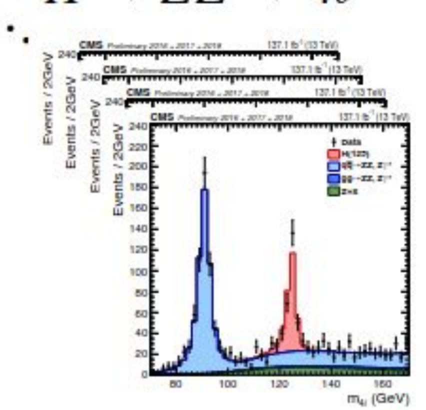
- H→$\gamma\gamma$ JHEP 07 (2023) 091, H→ZZ*→4l JHEP 08 (2023) 040, H→WW* →eμ$\nu\nu$ JHEP 03 (2021) 003, H→$\tau\tau$ Phys. Rev. Lett. 128 (2022) 081805 and H→$\tau\tau$ (boosted) Phys. Lett. B 857 (2024) 138964
  - Analyses use full dataset collected 2016–2018 corresponding to 138 fb^{-1}
  - Fiducial regions defined by loose selections → measurements are mostly sensitive to ggH production
- Differential cross sections extracted through **simultaneous maximum likelihood fit**
  - Common parameters of interest (μ = dσ/dσ_{SM}) for all channels with correlated nuisance parameter scheme
  - Measurements: $p_T^H, N_{\mathrm{jets}}, |y_H|, p_T^{j1}, m_{jj}, |\Delta\eta_{jj}|, \tau_C^j$

Combination of fiducial differential cross sections

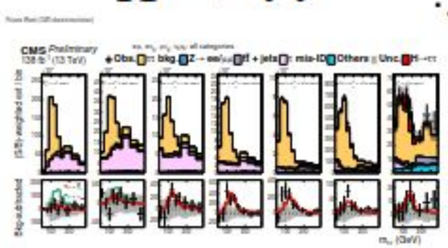
$H \to \gamma\gamma$



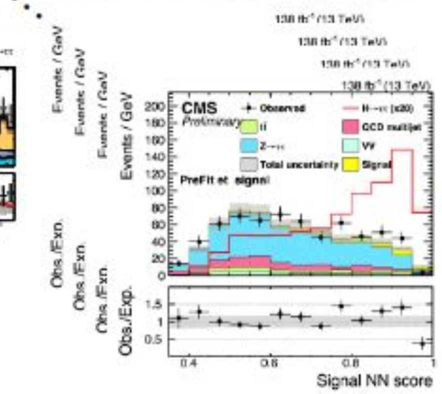
$H \to ZZ \to 4\ell$



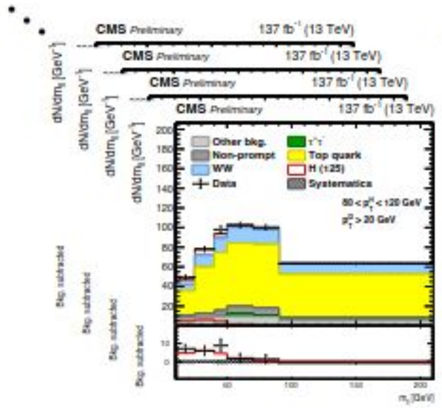
$H \to \tau\tau$



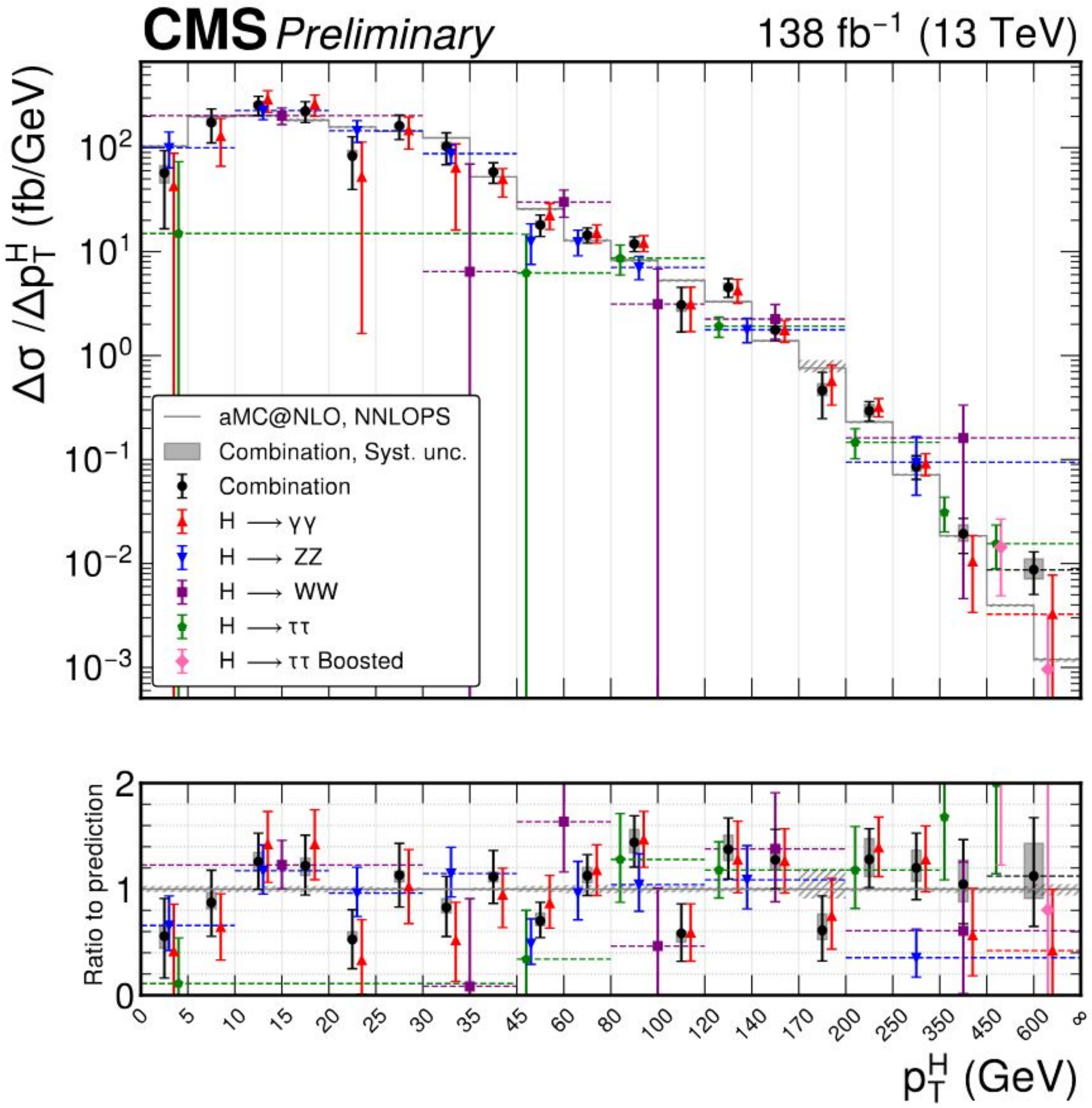
$H \to \tau\tau(\text{boosted})$



$H \to WW$



$$\mathcal{L}(\mathcal{D}|\mu_i, \nu)$$



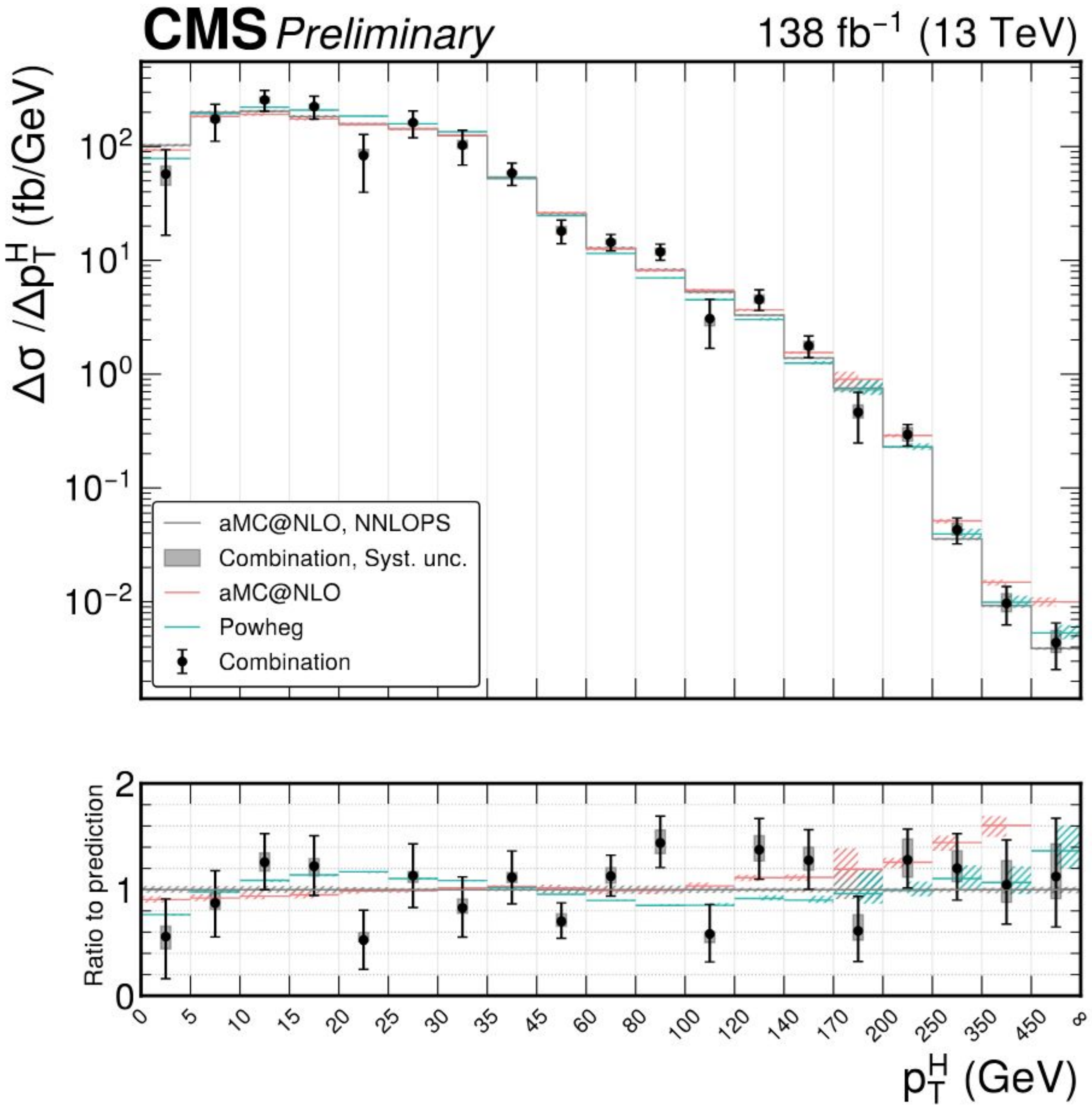
(*) Fitted observables

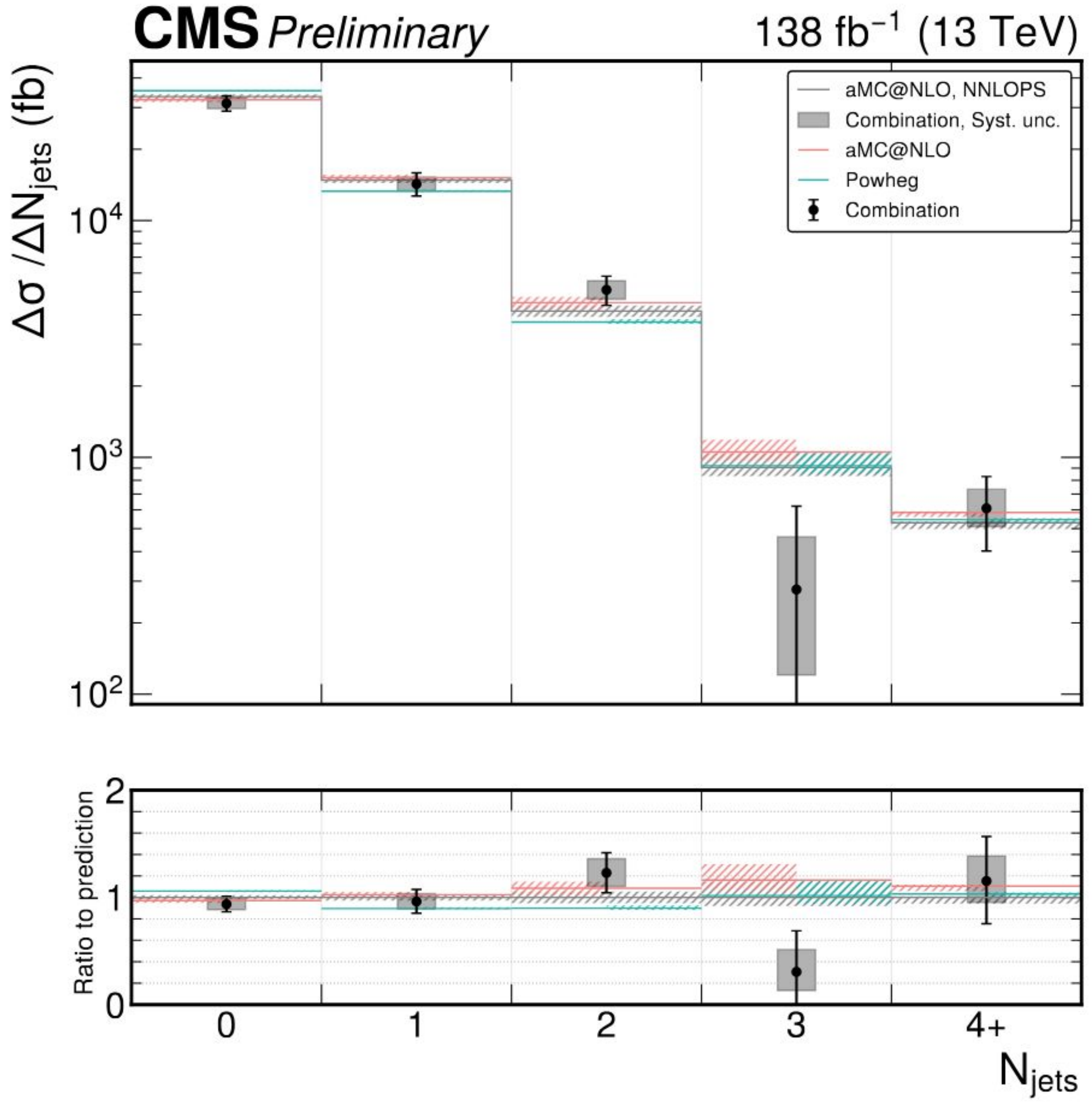
In bins of measured spectra

Likelihood-based unfolding

(*) Combination requires extrapolation to full Higgs boson decay phase space (unavoidable model dependence)
Additional systematic uncertainties from scale variations are included to cover this extrapolation

Combined spectra





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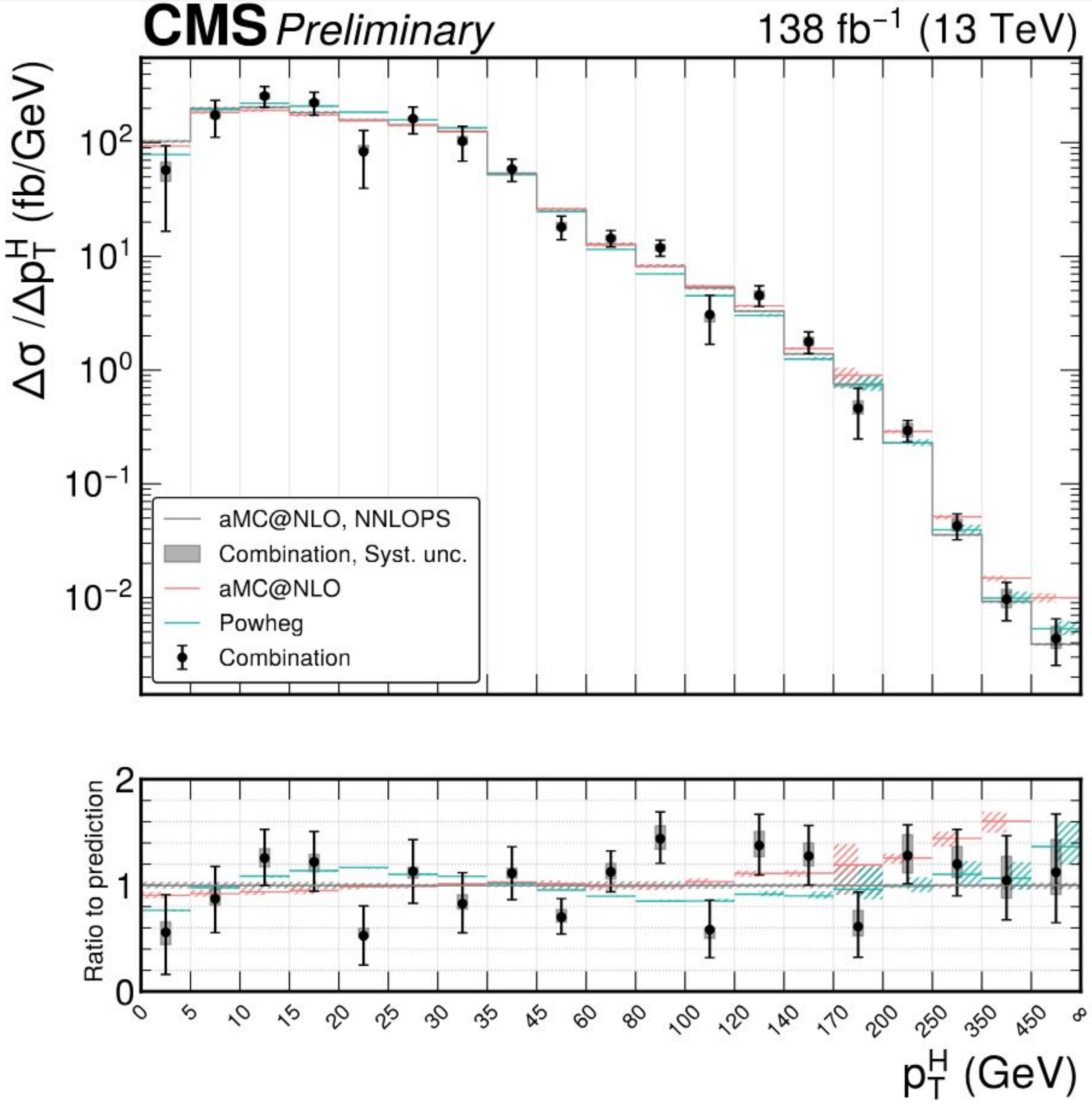

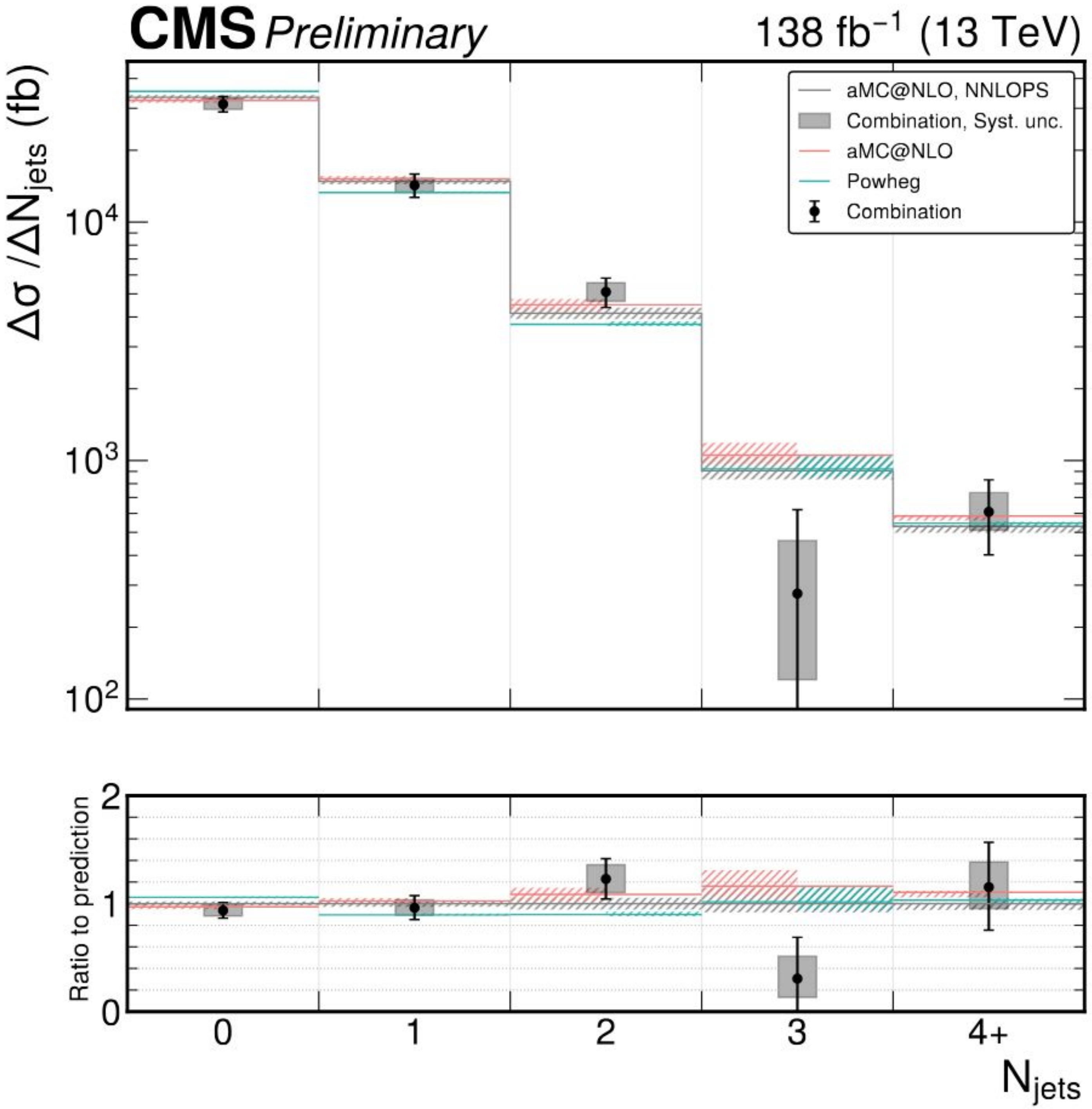

- **Shape distortions in measured pTH spectra used to constrain EFT Wilson coefficients**

SMEFT interpretation

- Standard Model Effective Field Theory (SMEFT)
  - Used to **parametrise distortions** in p_T^H spectrum
  - Flavour symmetry: $\mathcal{U}(2)^3_{q,u,d} \times \mathcal{U}(3)^2_{l,e}$
  - Consider all relevant CP-even operators for Higgs boson interactions

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{j=0} \frac{c_j^{(6)}}{\Lambda^2} O_j^{(6)}$$

Class	Operator	Wilson coefficient
$\mathcal{L}_6^{(1)} - X^3$	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$	c_W
$\mathcal{L}_6^{(3)} - H^4 D^2$	$(D^\mu H^\dagger H)(H^\dagger D_\mu H)$	c_{HD}
	$(H^\dagger H)\Box(H^\dagger H)$	$c_{H\Box}$
$\mathcal{L}_6^{(4)} - X^2 H^2$	$H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$	c_{HG}
	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	c_{HB}
	$H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	c_{HW}
	$H^\dagger \sigma^i H W^i_{\mu\nu} B^{i\mu\nu}$	c_{HWB}
$\mathcal{L}_6^{(5)} - \psi^2 H^3$	$(H^\dagger H)(\bar{Q} H b)$	$\text{Re}(c_{bH})$
		$\text{Im}(c_{bH})$
	$(H^\dagger H)(\bar{Q} H t)$	$\text{Re}(c_{tH})$
	$(H^\dagger H)(\bar{l}_p e_r H)$	$\text{Re}(c_{eH})$
		$\text{Im}(c_{eH})$
	$(H^\dagger H)(\bar{q} Y_u^\dagger u \tilde{H})$	$\text{Re}(c_{uH})$
$\mathcal{L}_6^{(6)} - \psi^2 X H$	$(\bar{Q}\sigma^{\mu\nu} T^a t)\tilde{H} G^a_{\mu\nu}$	$\text{Re}(c_{tG})$
	$(\bar{Q}\sigma^{\mu\nu} b) H B_{\mu\nu}$	$\text{Re}(c_{bB})$
	$(\bar{Q}\sigma^{\mu\nu} t) H B_{\mu\nu}$	$\text{Re}(c_{tB})$
	$(\bar{Q}\sigma^{\mu\nu} b)\sigma^i H W^i_{\mu\nu}$	$\text{Re}(c_{bW})$
		$\text{Im}(c_{bW})$
	$(\bar{Q}\sigma^{\mu\nu} t)\sigma^i \tilde{H} W^i_{\mu\nu}$	$\text{Re}(c_{tW})$
$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	$c_{Hl}^{(1)}$
	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$	$c_{Hl}^{(3)}$
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$c_{Hq}^{(1)}$
	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$	$c_{Hq}^{(3)}$
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	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{Q}_p \sigma^i \gamma^\mu Q_r)$	$c_{HQ}^{(3)}$
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	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	c_{Hd}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	c_{He}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{b} \gamma^\mu b)$	c_{Hb}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t} \gamma^\mu t)$	c_{Ht}
$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	c'_{ll}

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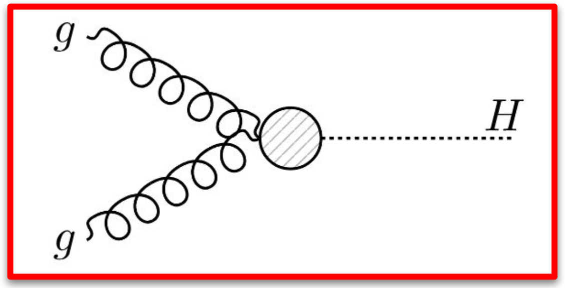

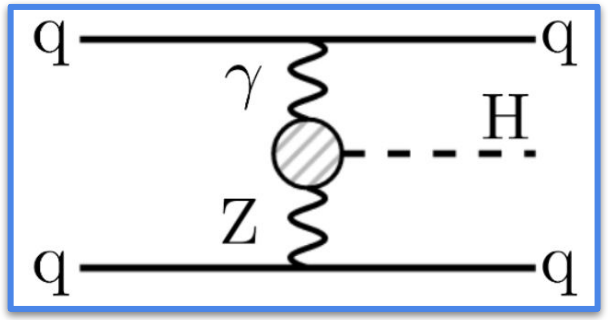

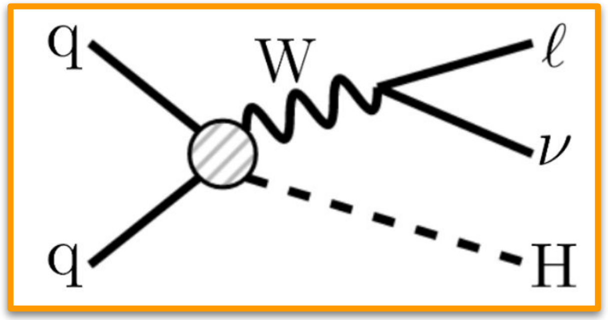

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	$(\bar{Q}\sigma^{\mu\nu} b) H B_{\mu\nu}$	$\mathrm{Re}(c_{bB})$
	$(\bar{Q}\sigma^{\mu\nu} t) H B_{\mu\nu}$	$\mathrm{Re}(c_{tB})$
	$(\bar{Q}\sigma^{\mu\nu} b)\sigma^i H W^i_{\mu\nu}$	$\mathrm{Re}(c_{bW})$ $\mathrm{Im}(c_{bW})$
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	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$	$c_{Hq}^{(3)}$
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_p \gamma^\mu Q_r)$	$c_{HQ}^{(1)}$
	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{Q}_p \sigma^i \gamma^\mu Q_r)$	$c_{HQ}^{(3)}$
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	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{b} \gamma^\mu b)$	c_{Hb}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t} \gamma^\mu t)$	c_{Ht}
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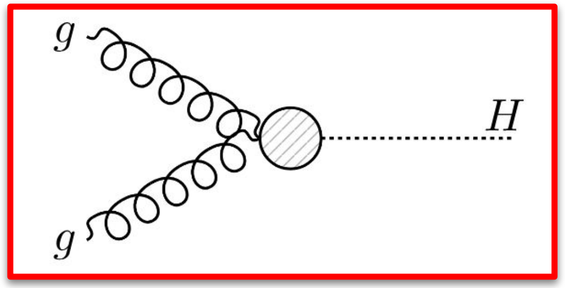

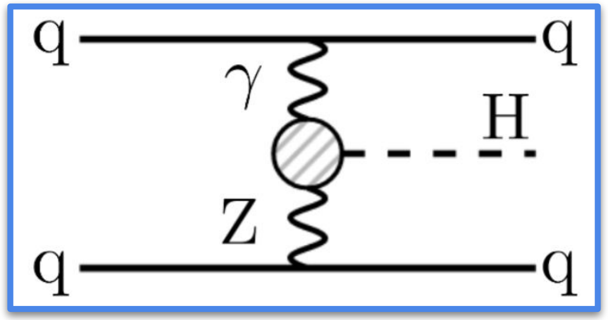

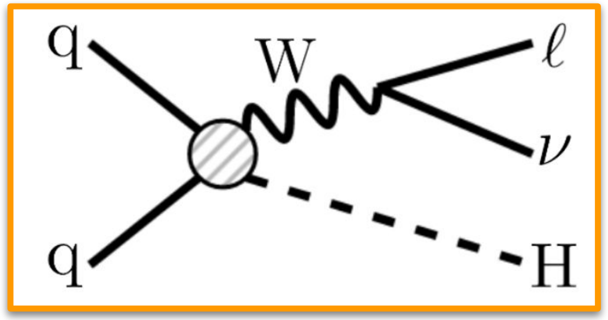

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	$(H^\dagger H)(\bar{Q}\tilde{H}t)$	$\text{Re}(c_{tH})$
	$(H^\dagger H)(\bar{l}_p e_r H)$	$\text{Re}(c_{eH})$, $\text{Im}(c_{eH})$
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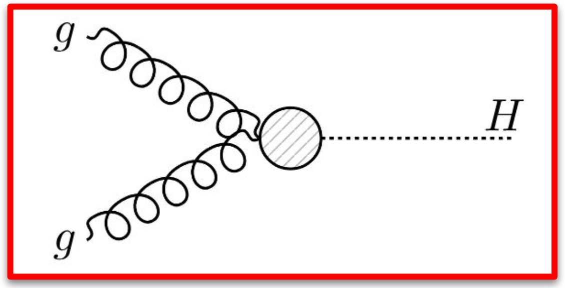

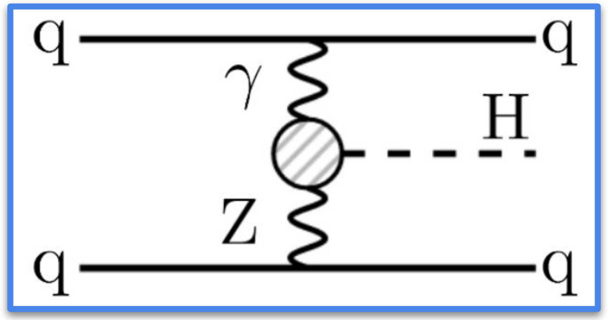

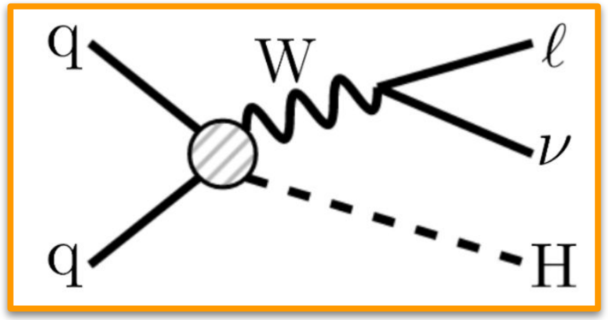

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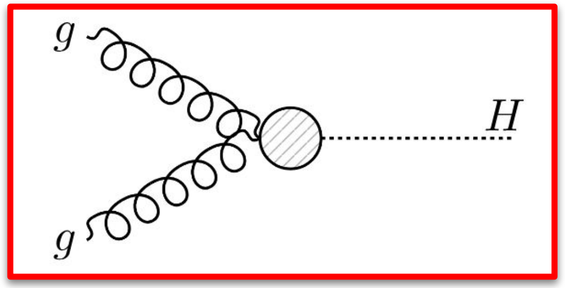
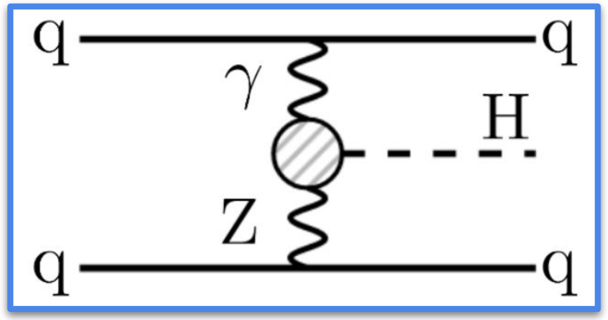
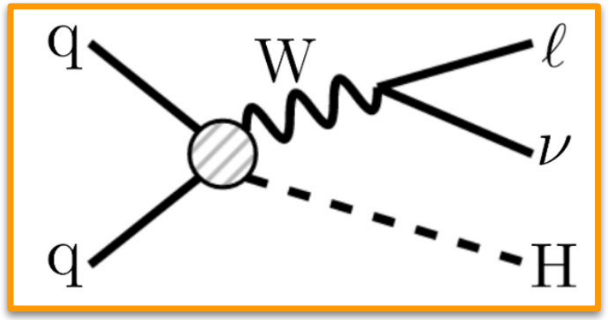
$$\mu = 1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j$$







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	$(\bar{Q}\sigma^{\mu\nu} b)\sigma^i H W^i_{\mu\nu}$	$\text{Re}(c_{bW})$, $\text{Im}(c_{bW})$
	$(\bar{Q}\sigma^{\mu\nu} t)\sigma^i \tilde{H} W^i_{\mu\nu}$	$\text{Re}(c_{tW})$
$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	$c_{Hl}^{(1)}$
	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$	$c_{Hl}^{(3)}$
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$c_{Hq}^{(1)}$
	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$	$c_{Hq}^{(3)}$
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_p \gamma^\mu Q_r)$	$c_{HQ}^{(1)}$
	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{Q}_p \sigma^i \gamma^\mu Q_r)$	$c_{HQ}^{(3)}$
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	c_{Hu}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	c_{Hd}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	c_{He}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{b} \gamma^\mu b)$	c_{Hb}
	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t} \gamma^\mu t)$	c_{Ht}
$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	c'_{ll}

SMEFT interpretation

$$\mu = 1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j$$

- Higgs boson production (differential) cross sections and decay rates are quadratic functions of Wilson coefficients
  - Parameterised by A_i (linear interference term) and B_{ij} (quadratic BSM term) factors
  - Derived numerically with Monte Carlo tools using SMEFTsim and SMEFT@NLO models [EFT2Obs]
  - Decay scaling calculated within fiducial phase space of each channel
- Narrow-width approximation:

$$\mu_i^X(c_j) = \frac{(\sigma \times \mathcal{B})^{i,H\rightarrow X}}{(\sigma \times \mathcal{B})^{i,H\rightarrow X}_{\text{SM}}}$$

$$\mu_i^X(c_j) = (1 + \sum_j A_j^{pp\rightarrow H} c_j + \sum_{jk} B_{jk}^{pp\rightarrow H} c_j c_k) \cdot \frac{(1 + \sum_j A_j^{H\rightarrow X} c_j + \sum_{jk} B_{jk}^{H\rightarrow X} c_j c_k)}{(1 + \sum_j A_j^{tot} c_j + \sum_{jk} B_{jk}^{tot} c_j c_k)}$$

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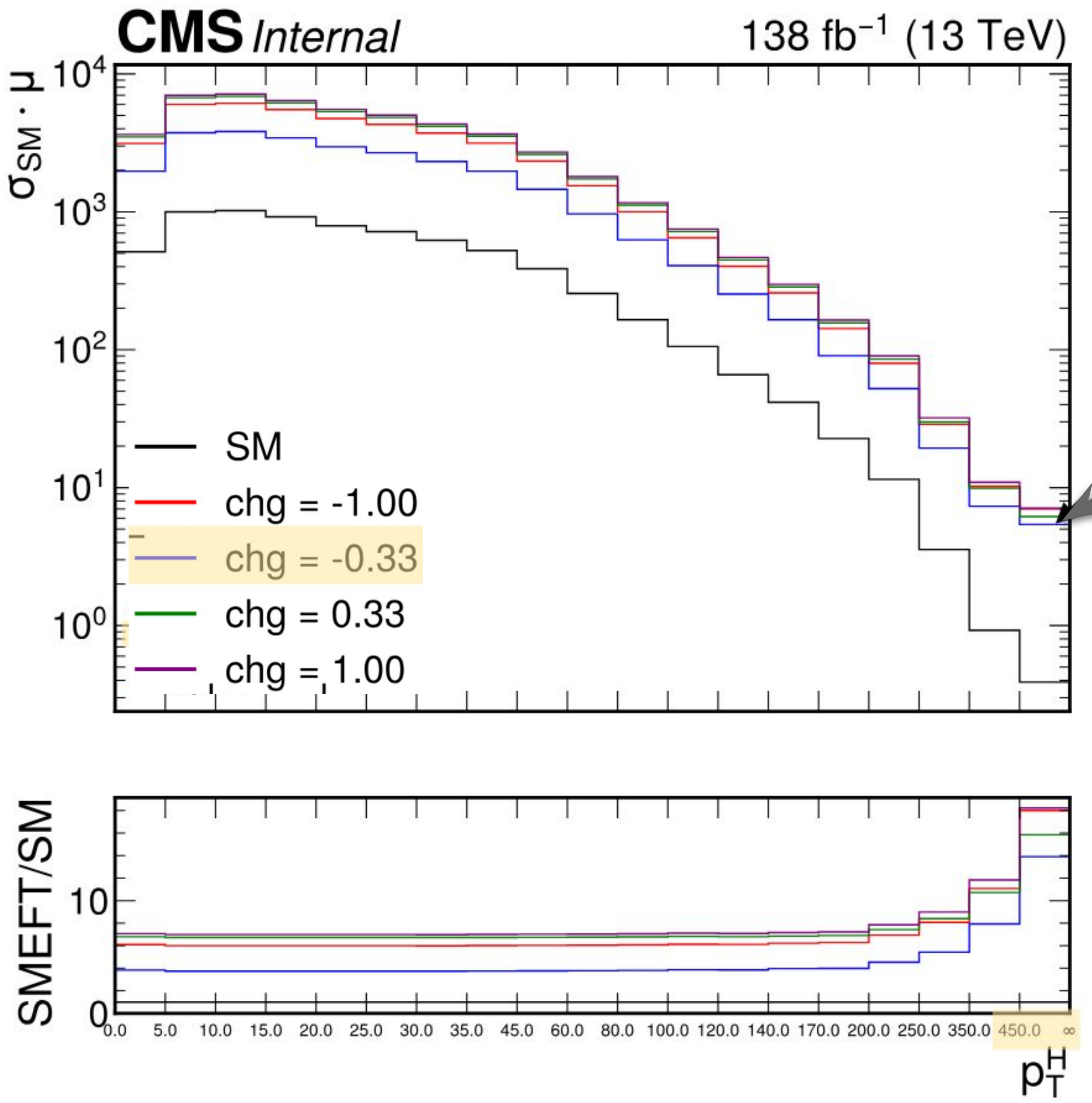
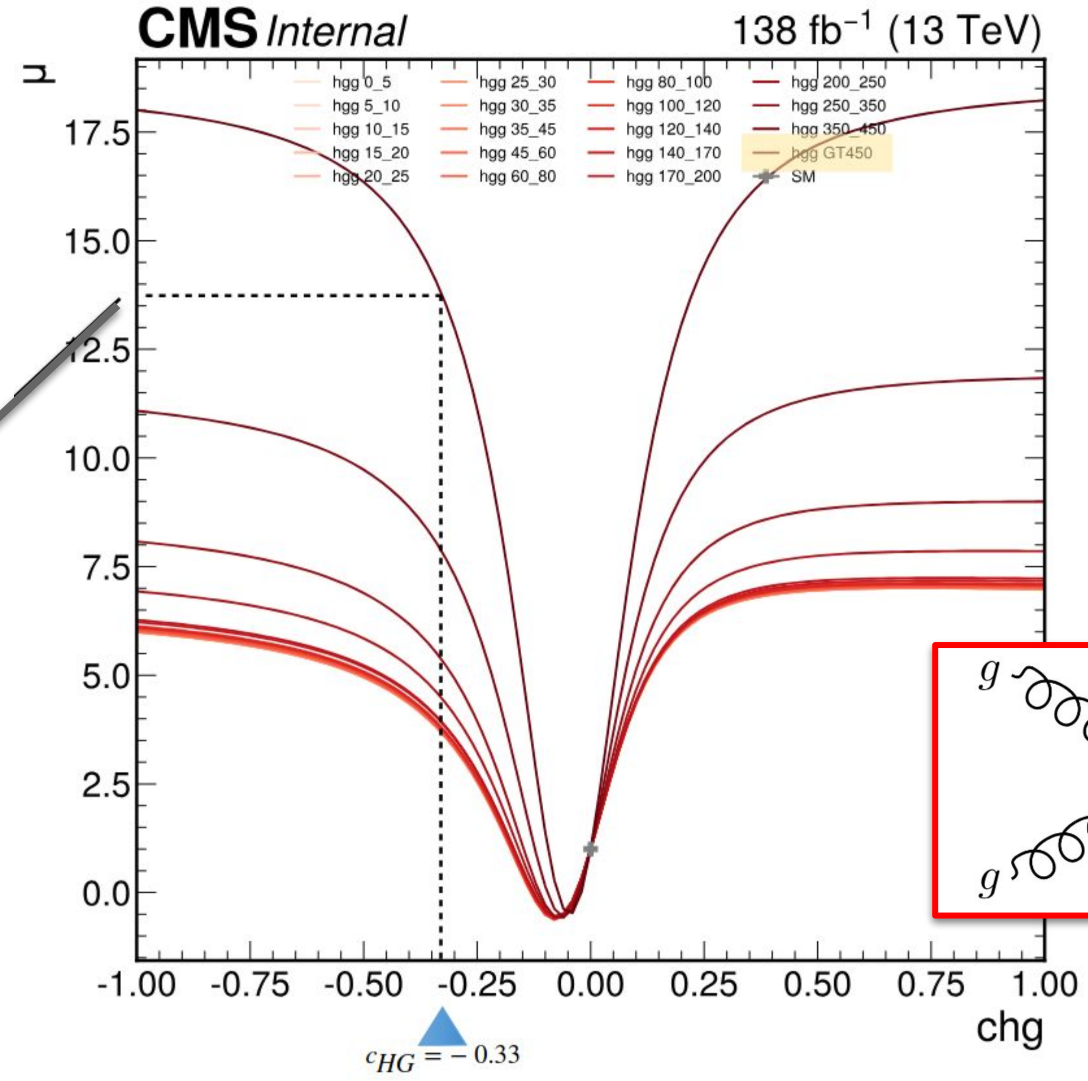
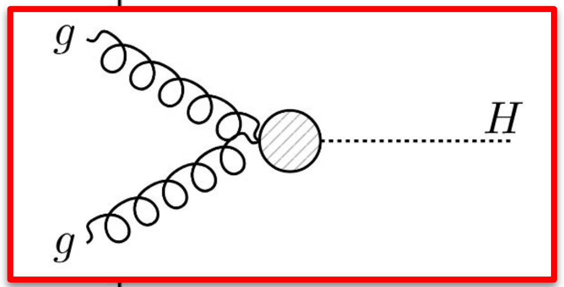
Higgs boson production ($d\sigma/d\sigma_{SM}$)

Total width scaling

SMEFT interpretation







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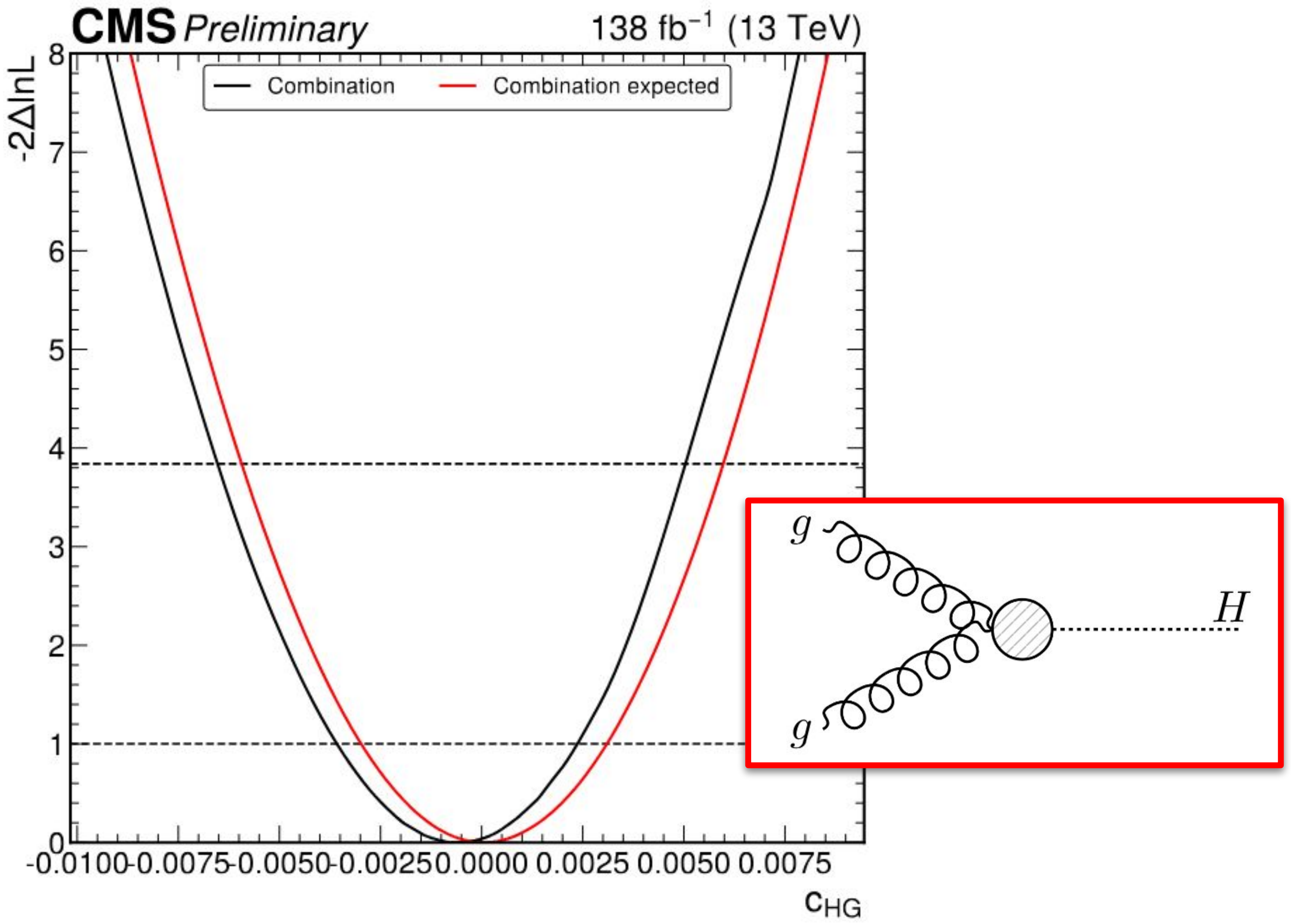

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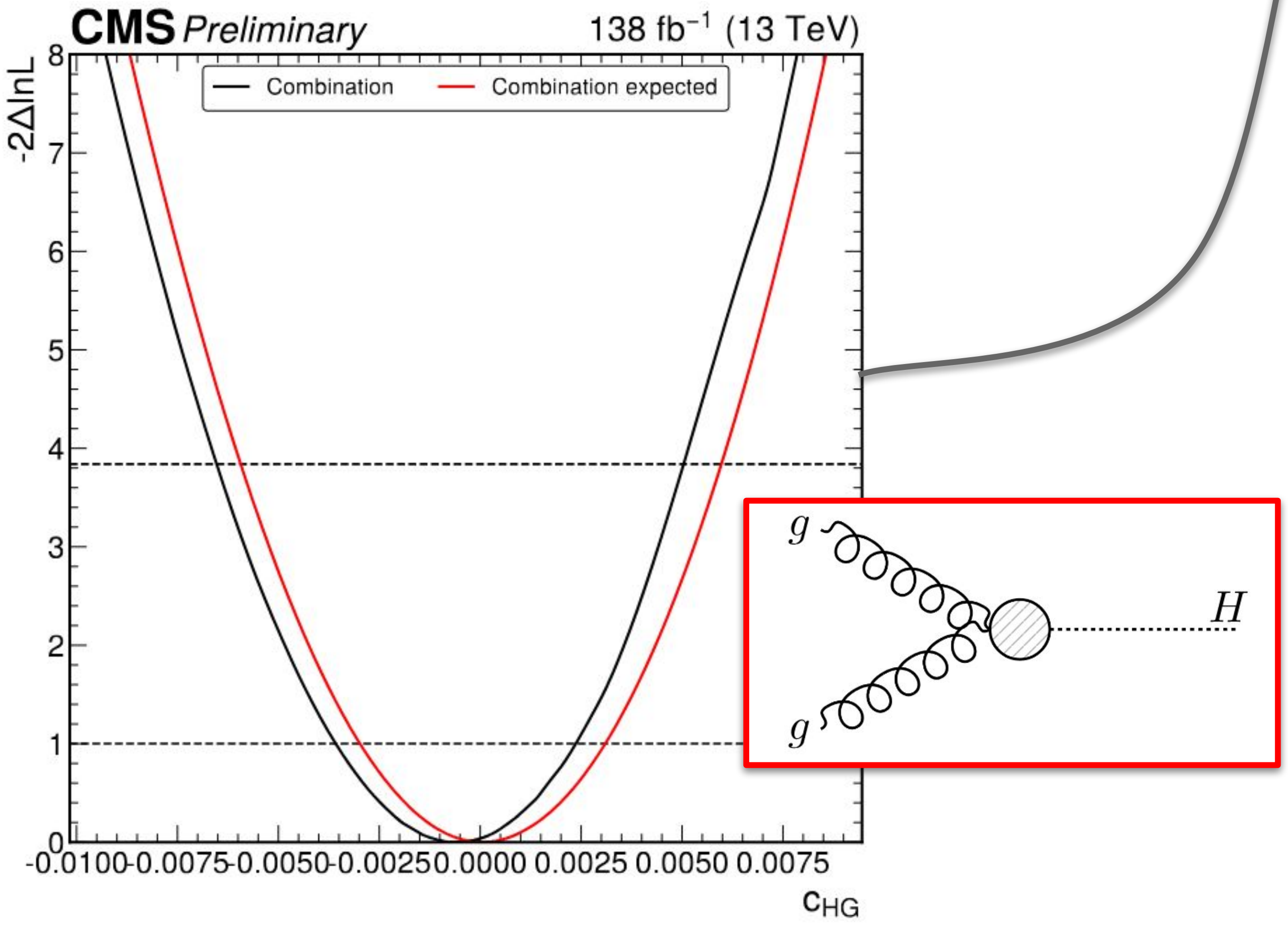
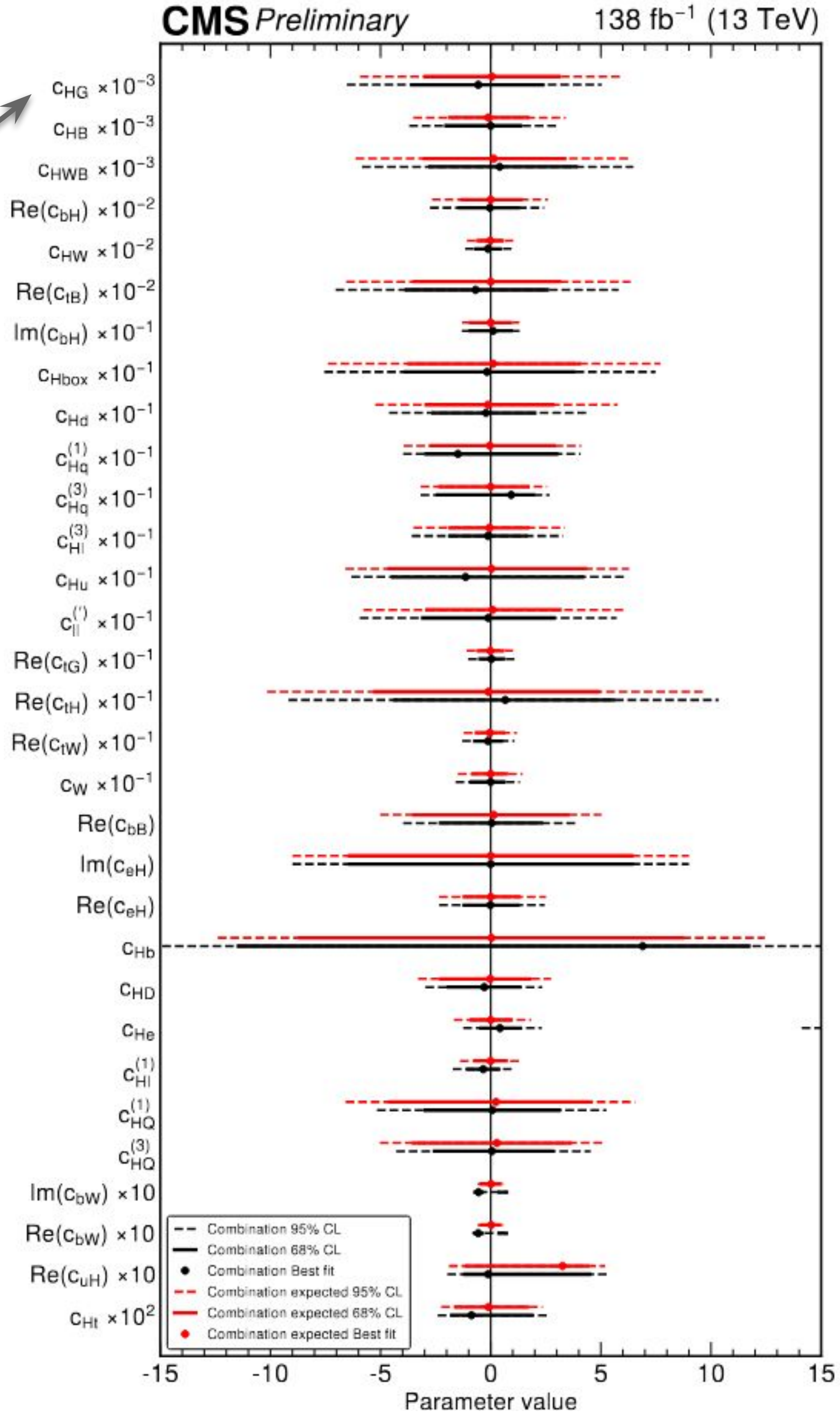
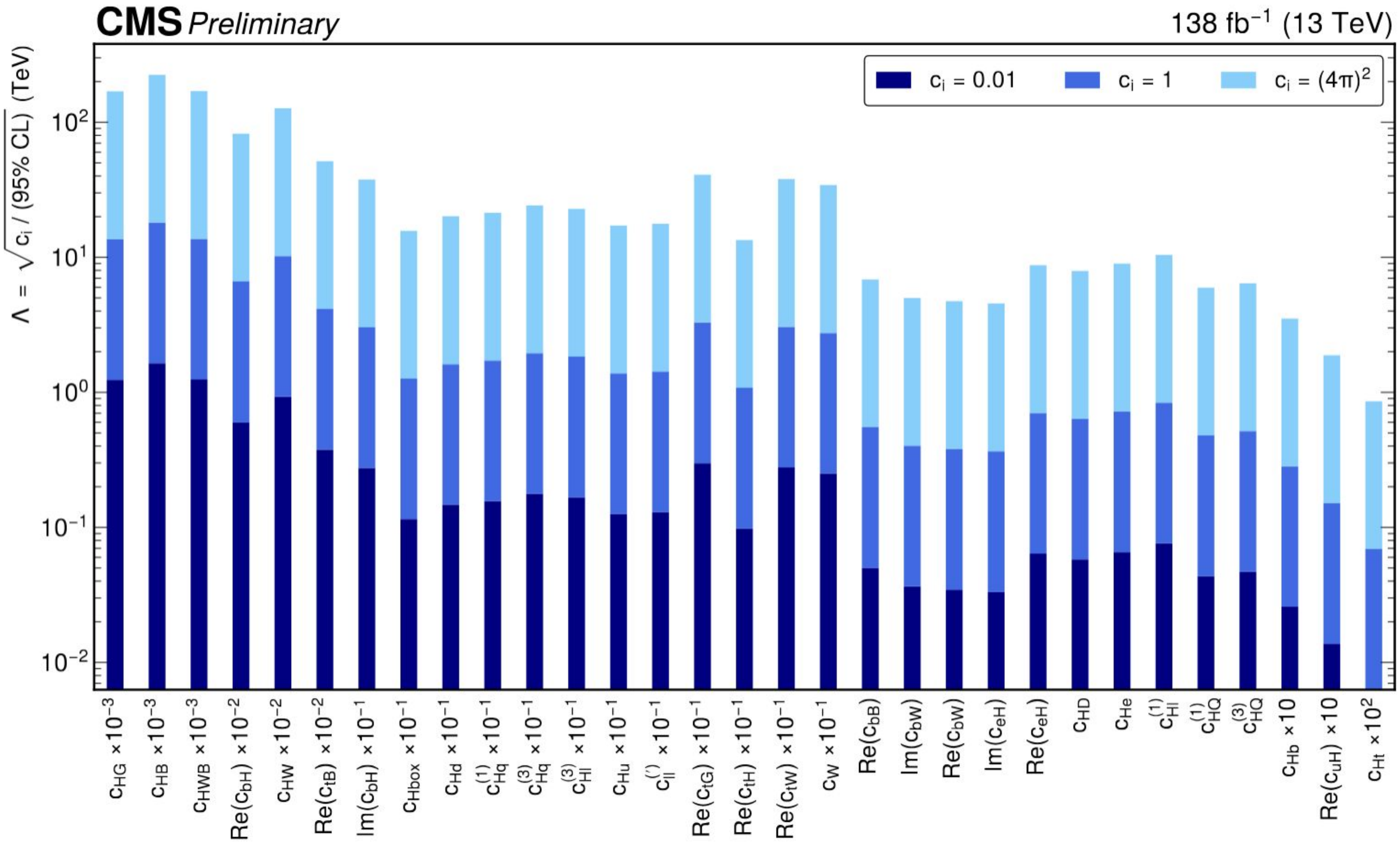




$$\mathcal{L}^{(\mathrm{d})} = \sum_{j}^{N^{(\mathrm{d})}} \frac{c_j^{(\mathrm{d})}}{\Lambda^{d-4}} \mathcal{O}_j^{(\mathrm{d})}$$



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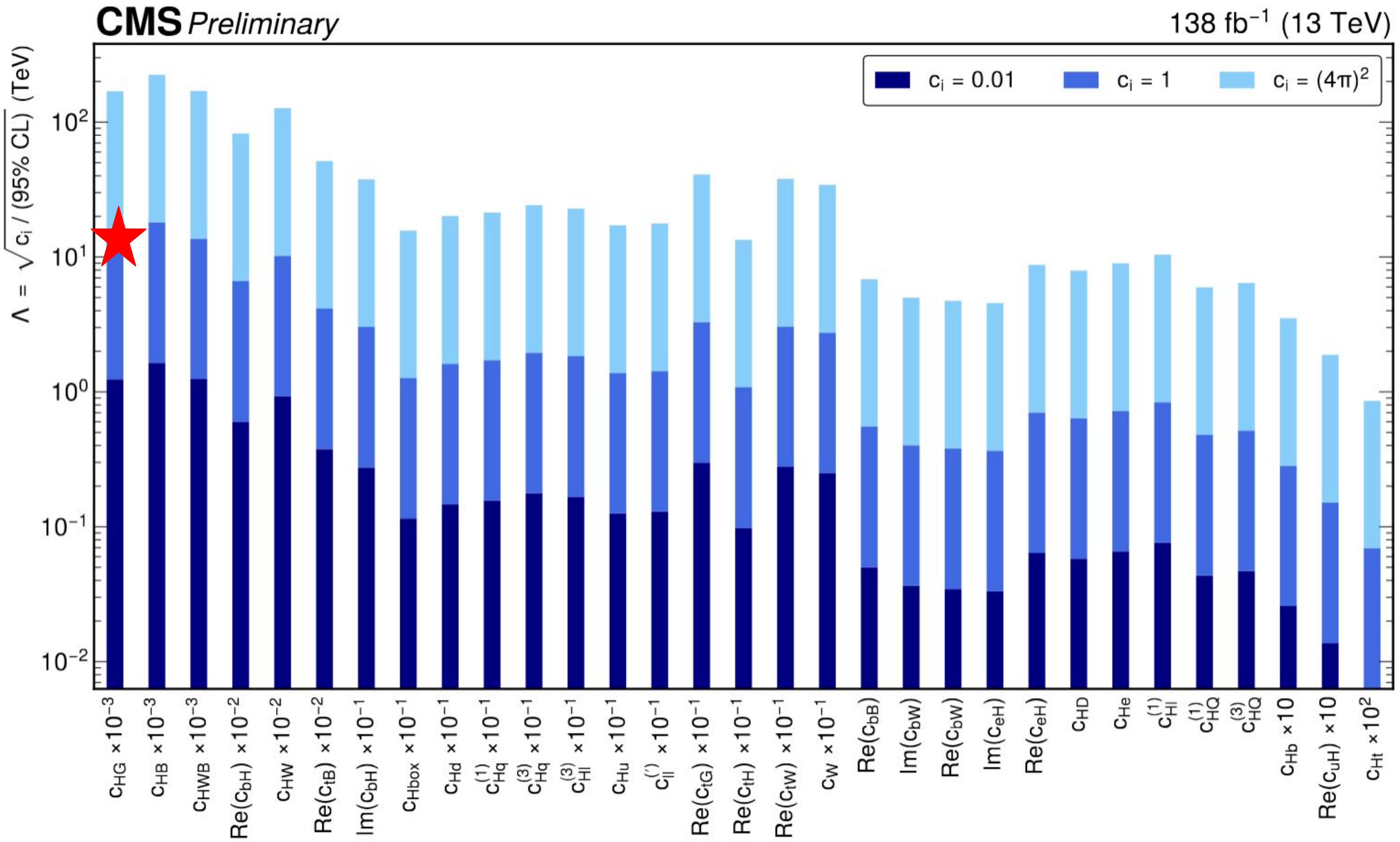

Principal component analysis (PCA)

- Available data do not contain enough information to constrain all coefficients simultaneously → flat directions in likelihood
- **PCA:** eigenvector decomposition of Fisher information matrix to find constrained (and unconstrained) direction in WC space
  - Obtain **linear combinations of SMEFT WCs**
  - Fit constrained directions and fix unconstrained directions to zero(*)

(*) Minimal loss of generality in fit by fixing flat directions in likelihood

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Use Asimov dataset

$$\mathcal{L}(\mathcal{D}|\mu_i^{\gamma\gamma},\nu) \longrightarrow \mathcal{I}_{\text{diff}}^{\gamma\gamma} = \left[-\frac{\partial^2 \ln \mathcal{L}(\mathcal{D}|\mu_i^{\gamma\gamma},\nu)}{\partial\theta_k \partial\theta_l} \right]$$

Under Gaussian Approximation:

$$\mathcal{I}_{\gamma\gamma,\text{diff}} = \mathcal{H}_{\gamma\gamma,\text{diff}} = C^{-1}_{\gamma\gamma,\text{diff}}$$

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Rotation to SMEFT basis:

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$$C^{-1}_{\gamma\gamma,\text{SMEFT}} = P^{\gamma\gamma T} C^{-1}_{\gamma\gamma,\text{diff}} P^{\gamma\gamma}$$

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Perform Eigenvector decomposition:

$$C^{-1}_{\gamma\gamma,\text{SMEFT}} = (EV_{\gamma\gamma})\Lambda_{\gamma\gamma}(EV_{\gamma\gamma})^{-1}$$

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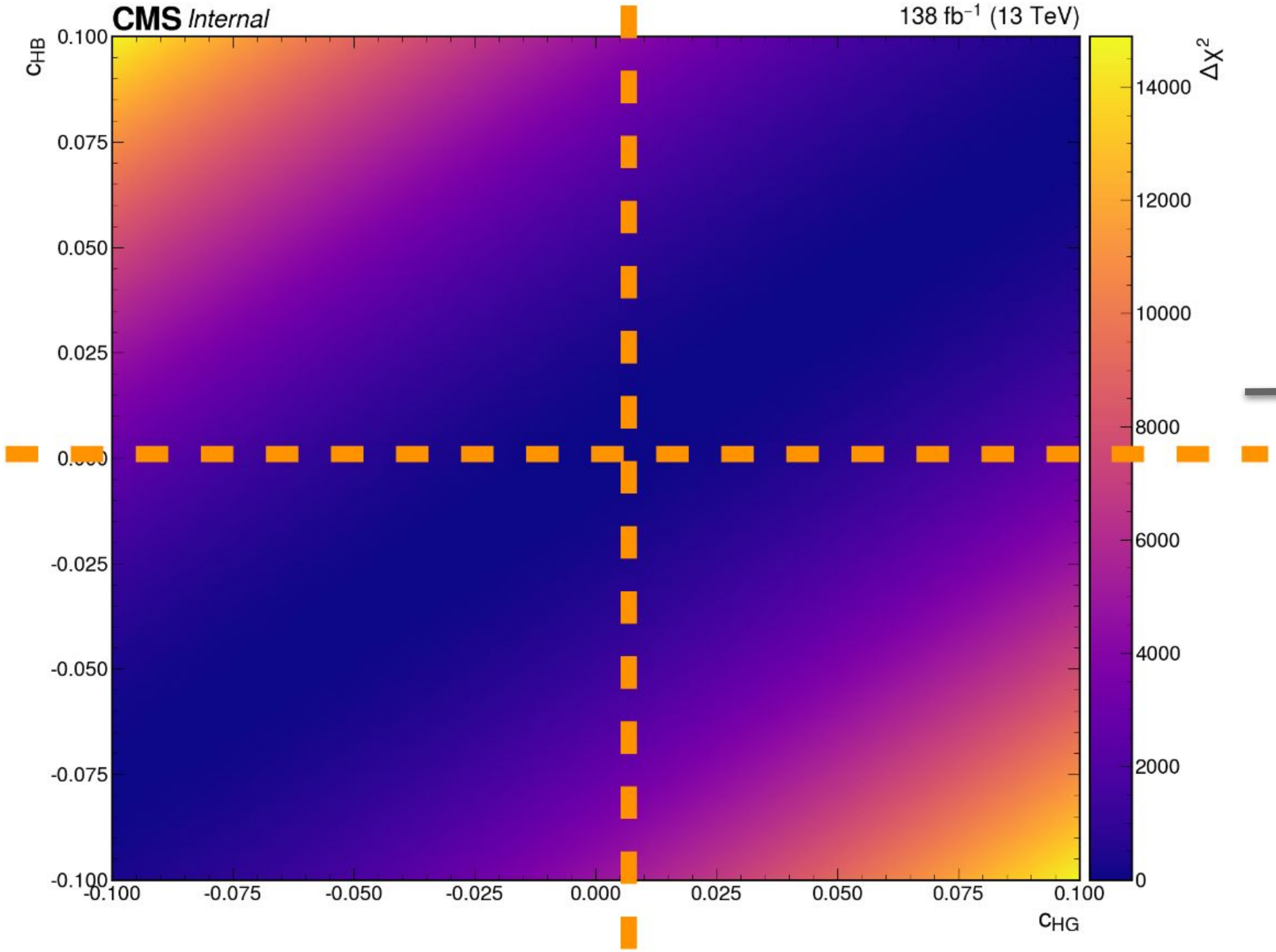
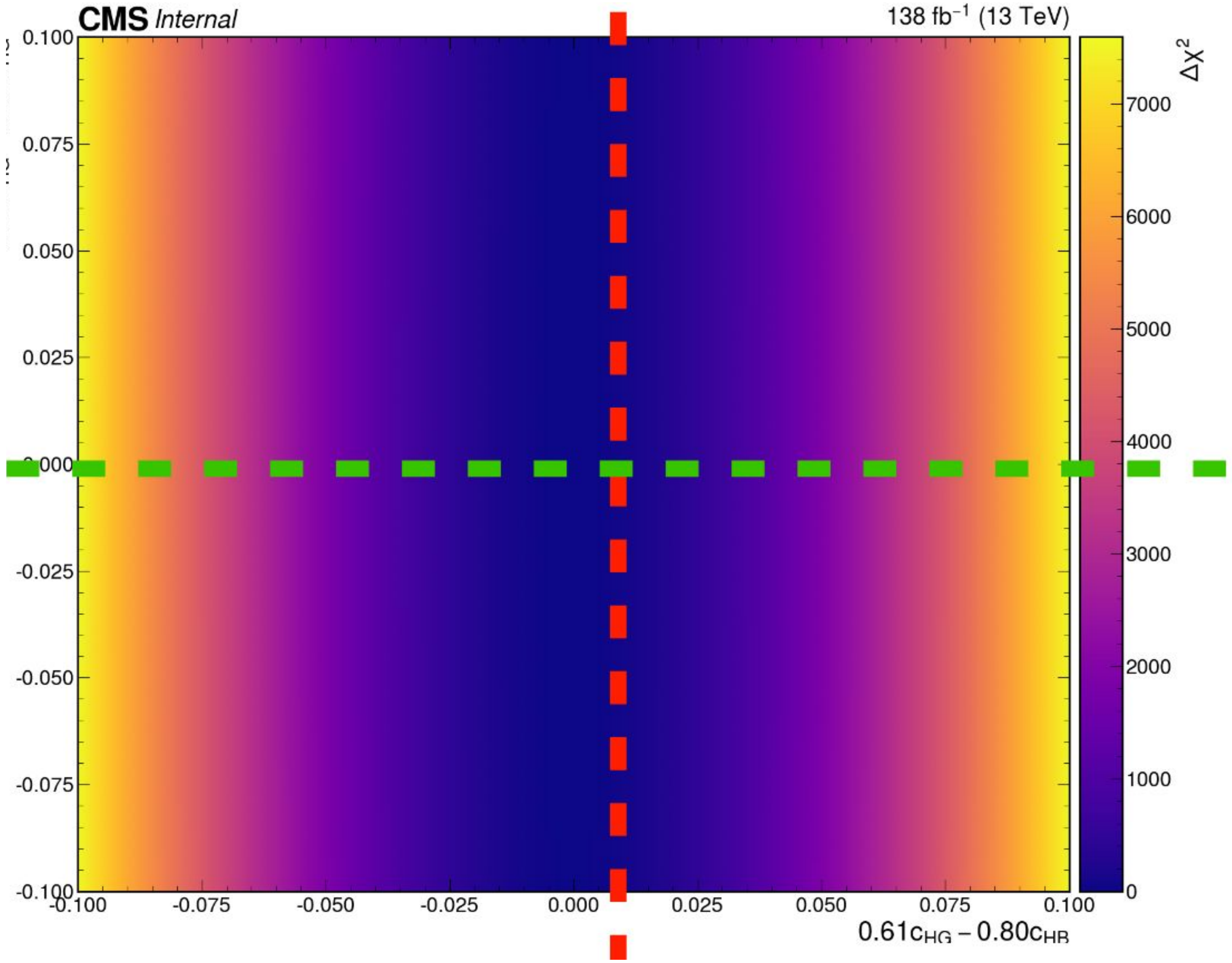
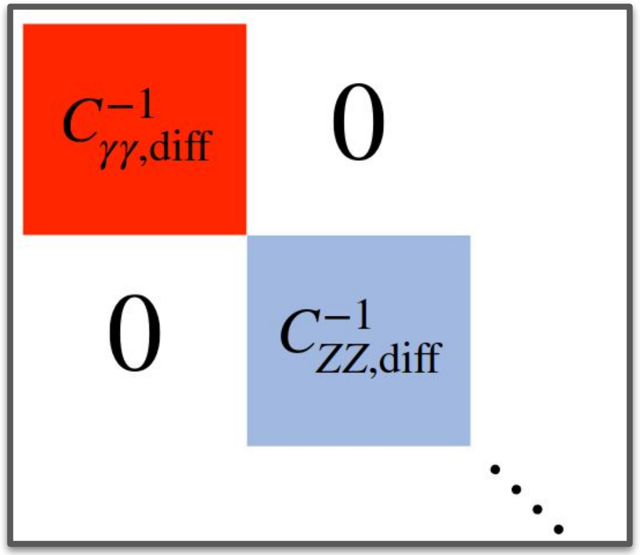
Principal component analysis (PCA)

- Two-dimension example: $C^{-1}_{\gamma\gamma,\text{SMEFT}} = (EV_{\gamma\gamma})\Lambda_{\gamma\gamma}(EV_{\gamma\gamma})^{-1}$



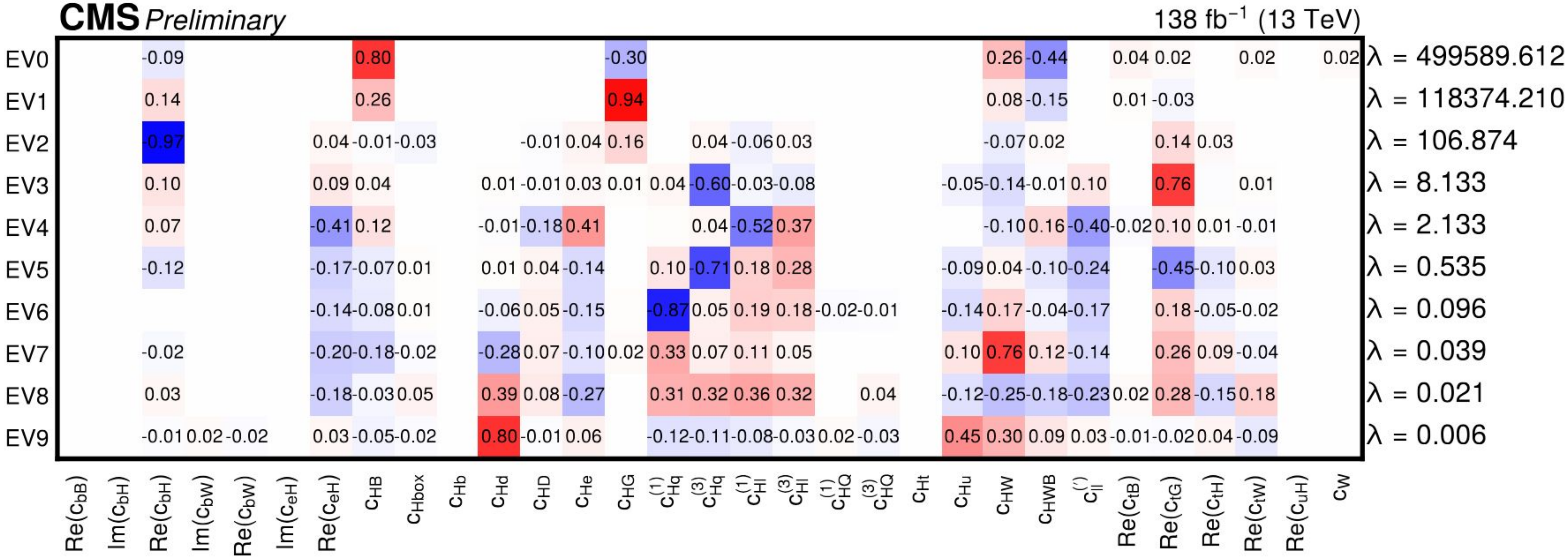


Principal component analysis (PCA)



- **Extend basis rotation to full combination:** build block-diagonal information matrix

$$C^{-1}_{\mathrm{SMEFT}} = (EV)\,\Lambda\,(EV)^{-1}$$



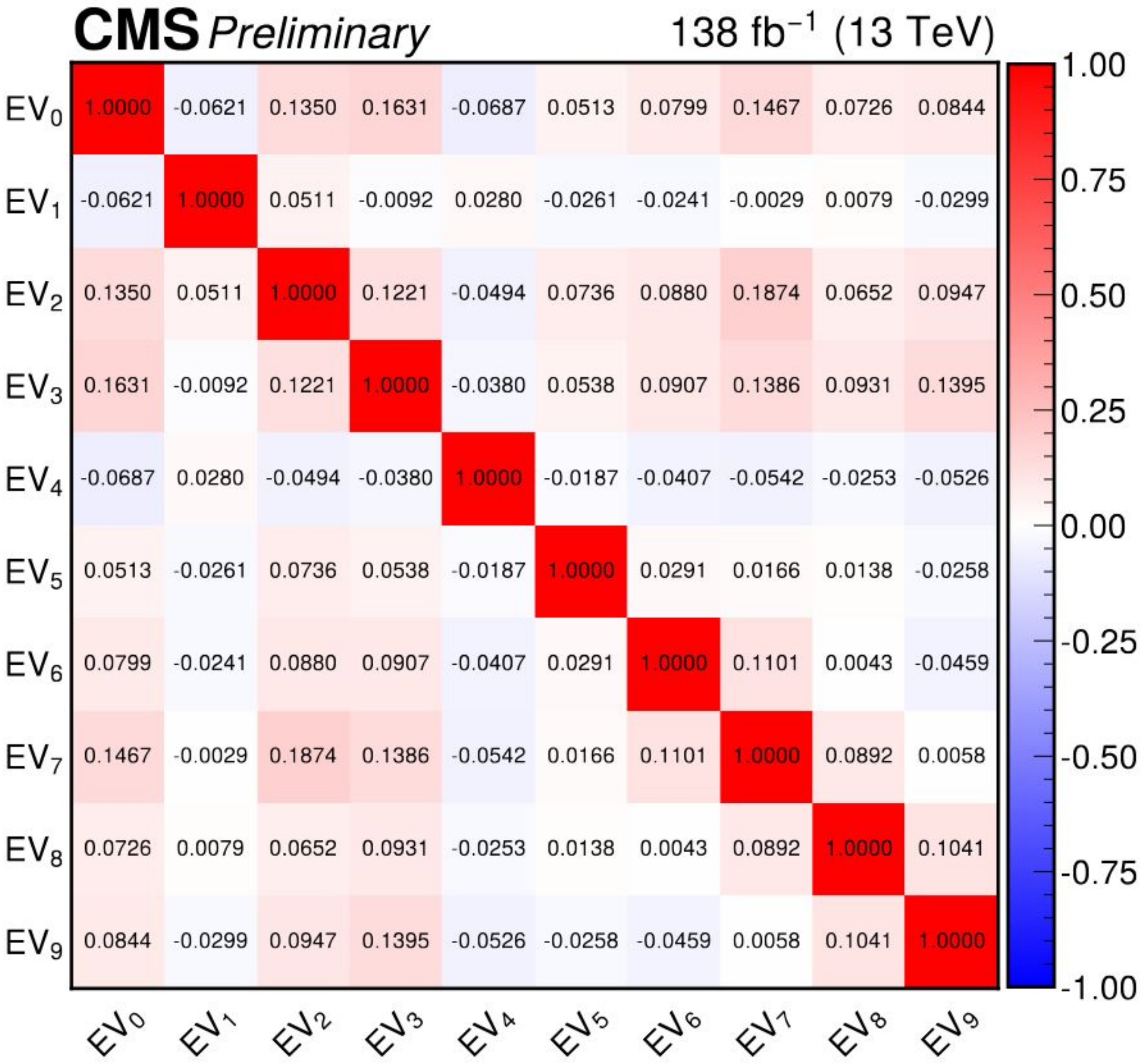
- **Consider only 10 eigenvectors with highest eigenvalues** (most sensitive directions) → Others fixed to zero

Simultaneous SMEFT constraints

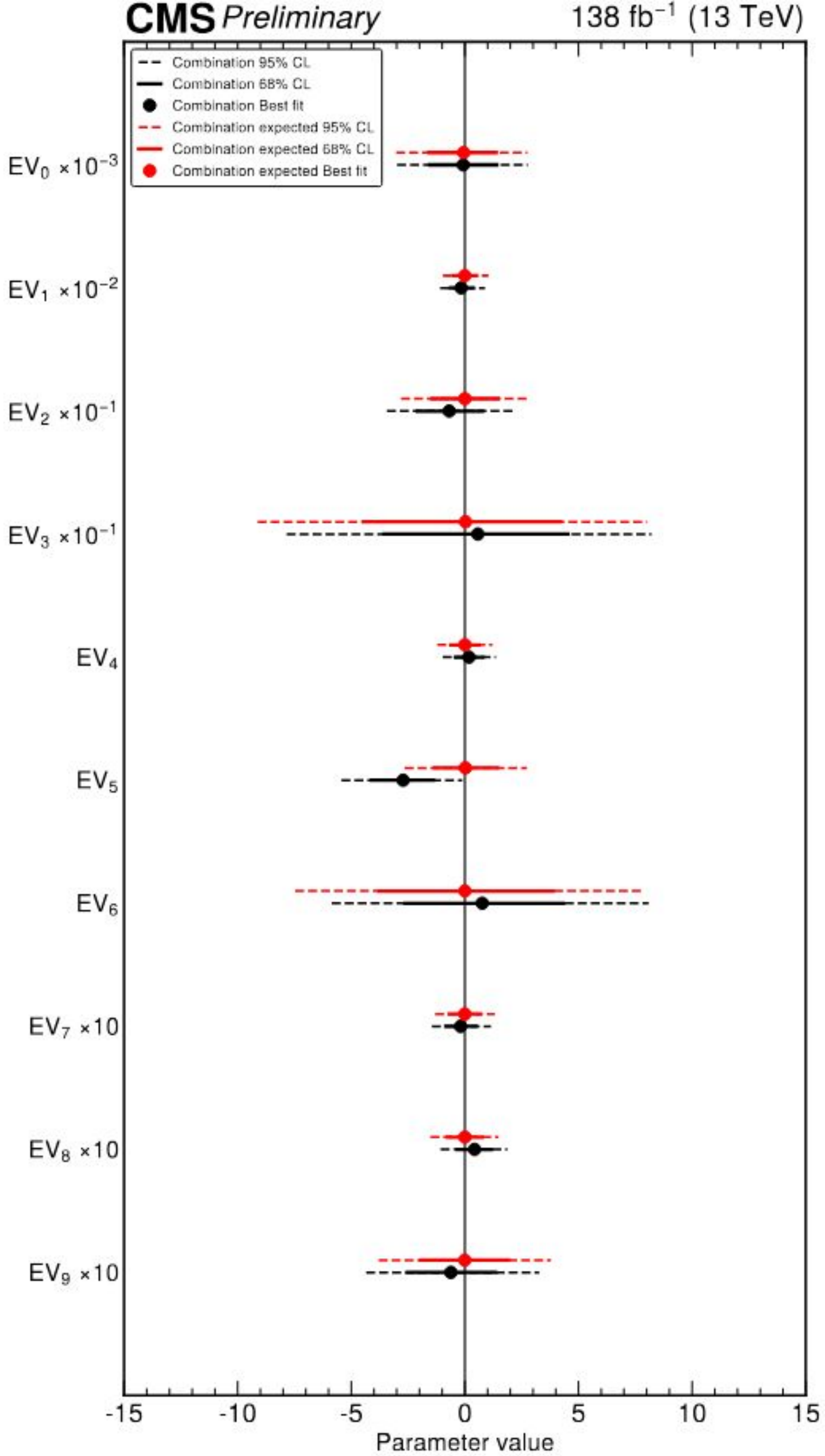
- Simultaneous fit to ten linear combinations of Wilson coefficients:

$$\mathcal{L}(\mathcal{D}|\mu_i^X, \nu) \longrightarrow \mathcal{L}(\mathcal{D}|\mu_i^X(EV), \nu)$$

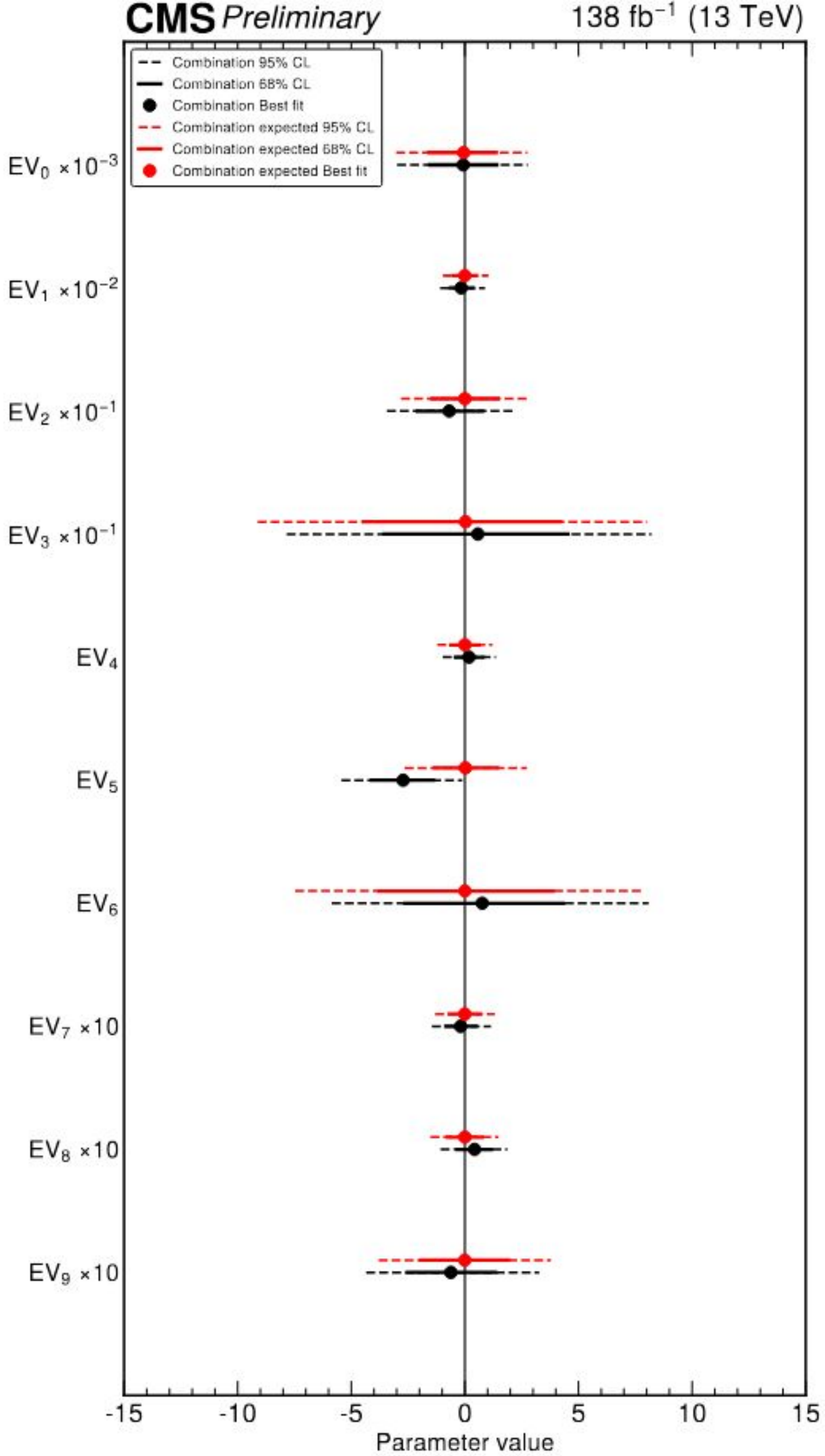
Generally obtain small correlations between eigenvectors with this approach



	EV_0	EV_1	EV_2	EV_3	EV_4	EV_5	EV_6	EV_7	EV_8	EV_9
EV_0	1.0000	-0.0621	0.1350	0.1631	-0.0687	0.0513	0.0799	0.1467	0.0726	0.0844
EV_1	-0.0621	1.0000	0.0511	-0.0092	0.0280	-0.0261	-0.0241	-0.0029	0.0079	-0.0299
EV_2	0.1350	0.0511	1.0000	0.1221	-0.0494	0.0736	0.0880	0.1874	0.0652	0.0947
EV_3	0.1631	-0.0092	0.1221	1.0000	-0.0380	0.0538	0.0907	0.1386	0.0931	0.1395
EV_4	-0.0687	0.0280	-0.0494	-0.0380	1.0000	-0.0187	-0.0407	-0.0542	-0.0253	-0.0526
EV_5	0.0513	-0.0261	0.0736	0.0538	-0.0187	1.0000	0.0291	0.0166	0.0138	-0.0258
EV_6	0.0799	-0.0241	0.0880	0.0907	-0.0407	0.0291	1.0000	0.1101	0.0043	-0.0459
EV_7	0.1467	-0.0029	0.1874	0.1386	-0.0542	0.0166	0.1101	1.0000	0.0892	0.0058
EV_8	0.0726	0.0079	0.0652	0.0931	-0.0253	0.0138	0.0043	0.0892	1.0000	0.1041
EV_9	0.0844	-0.0299	0.0947	0.1395	-0.0526	-0.0258	-0.0459	0.0058	0.1041	1.0000

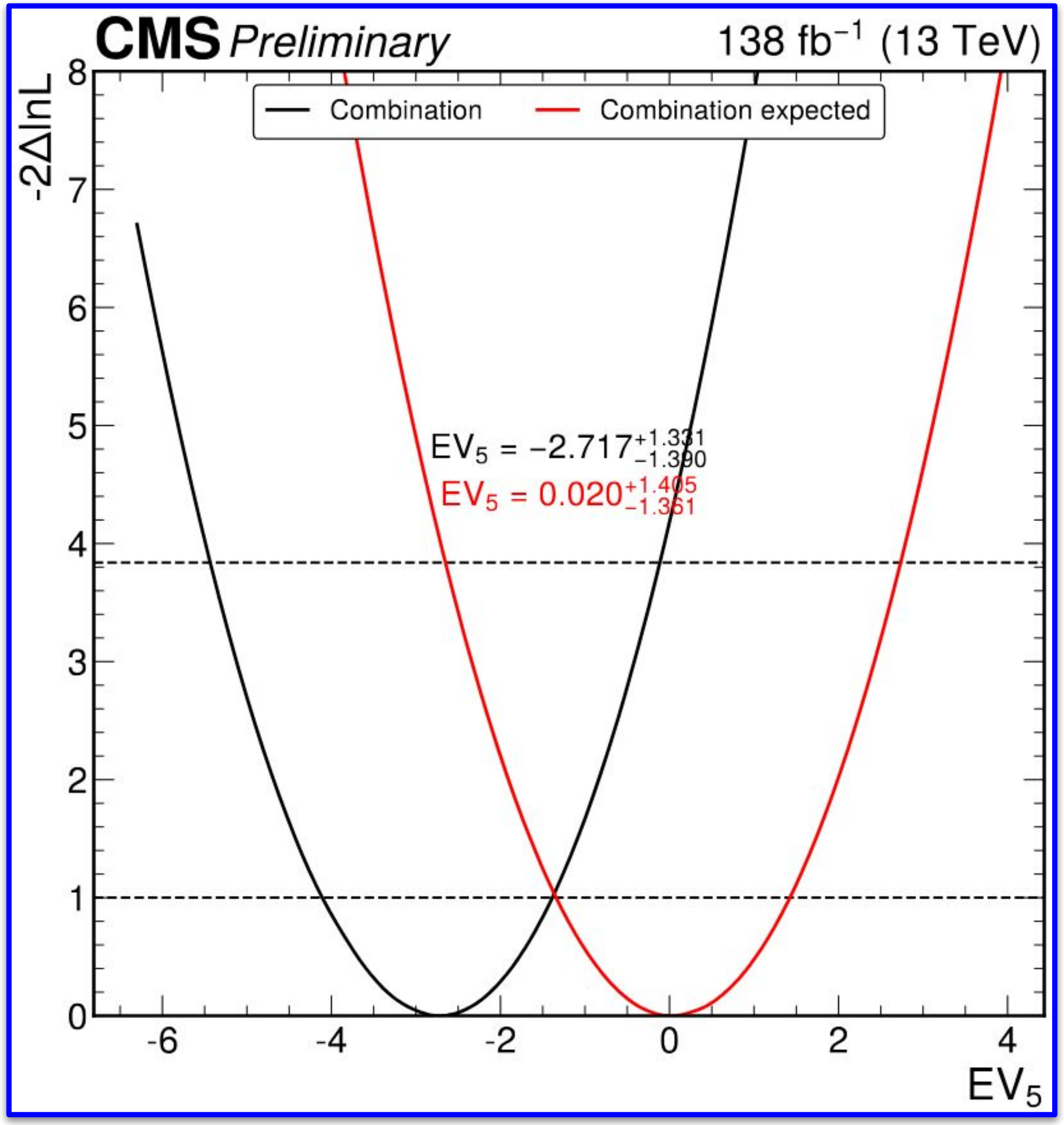


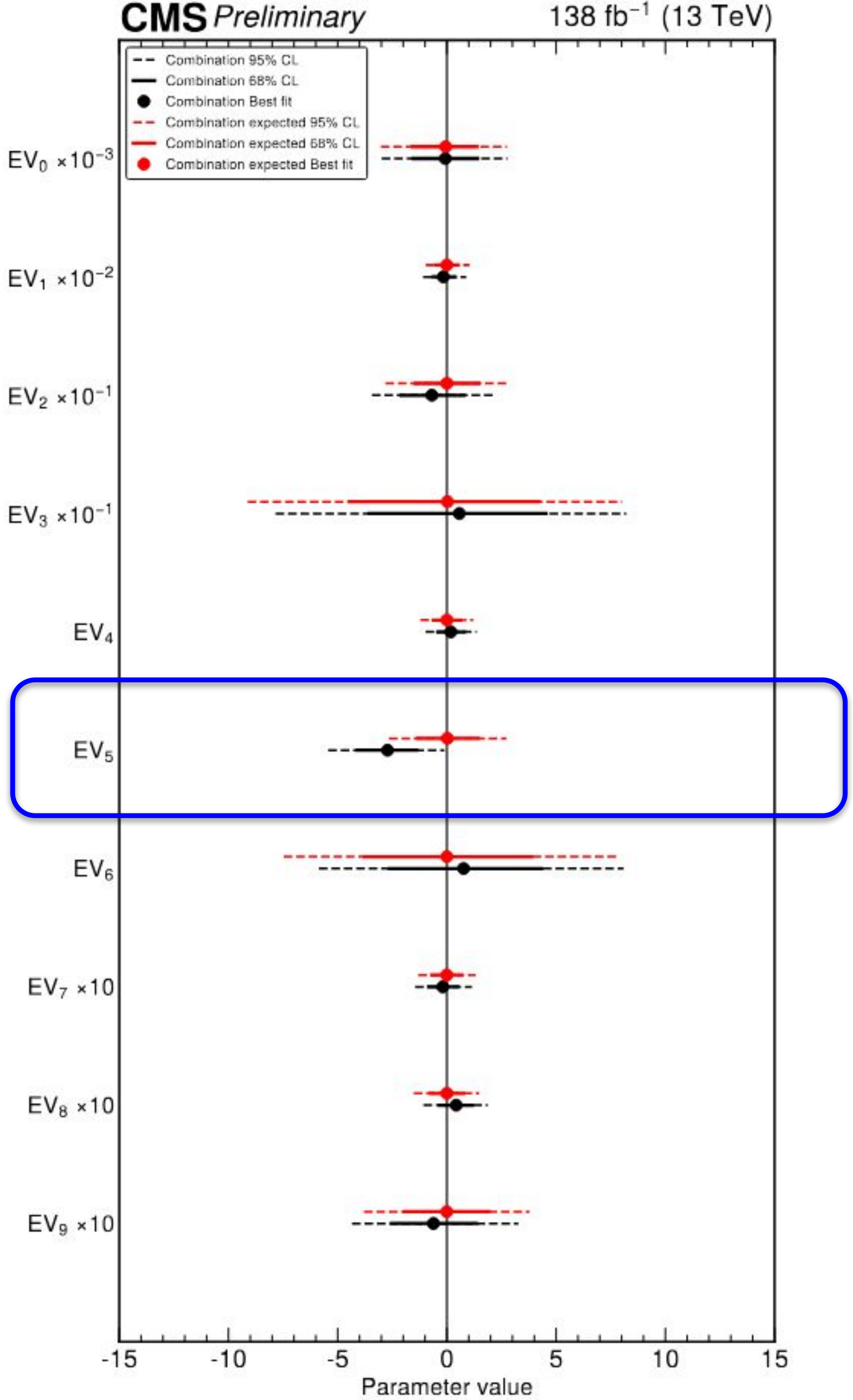
How to interpret these results?



How to interpret these results?

- Observe ~2σ deviation from SM in EV_5





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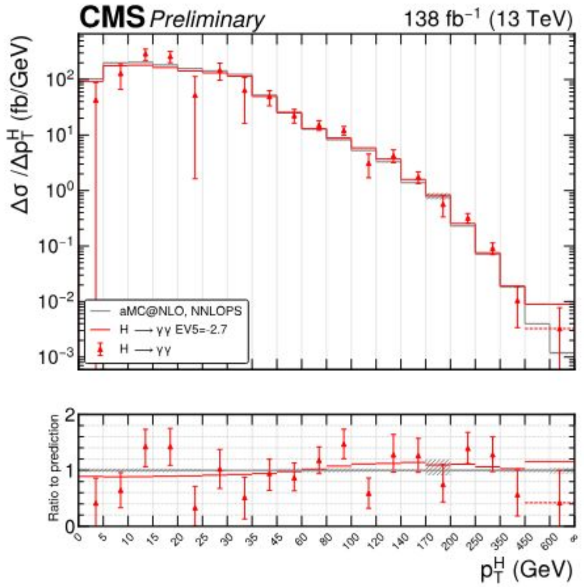

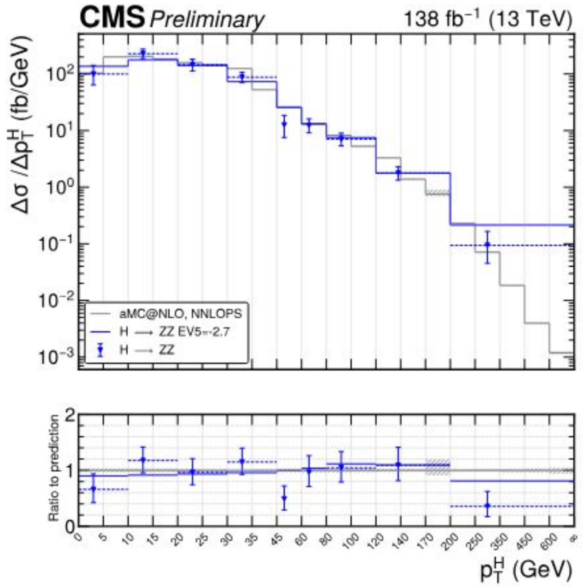

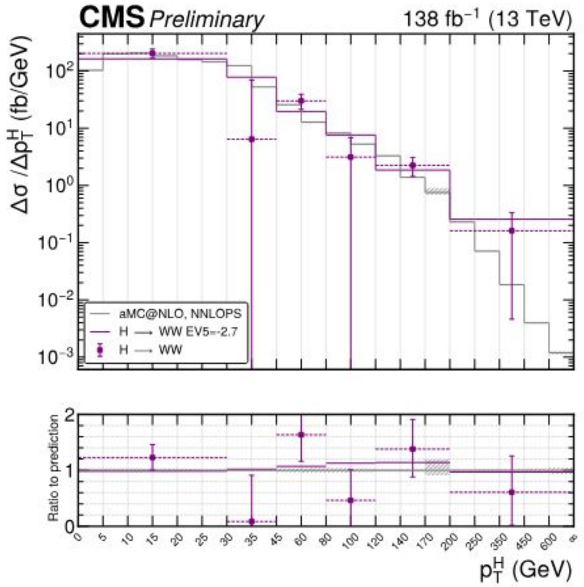

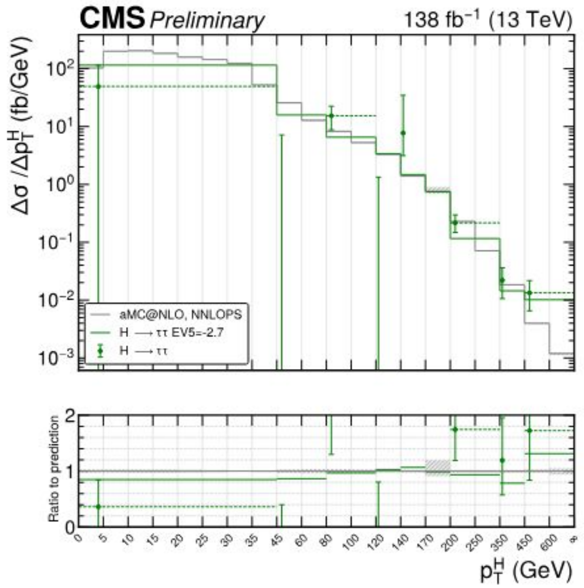

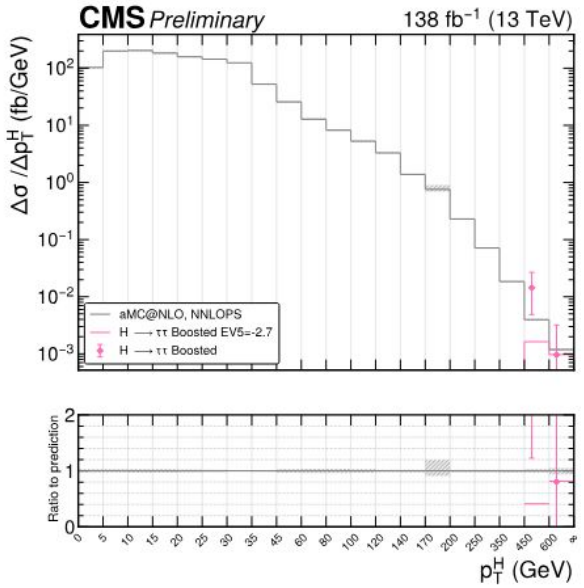

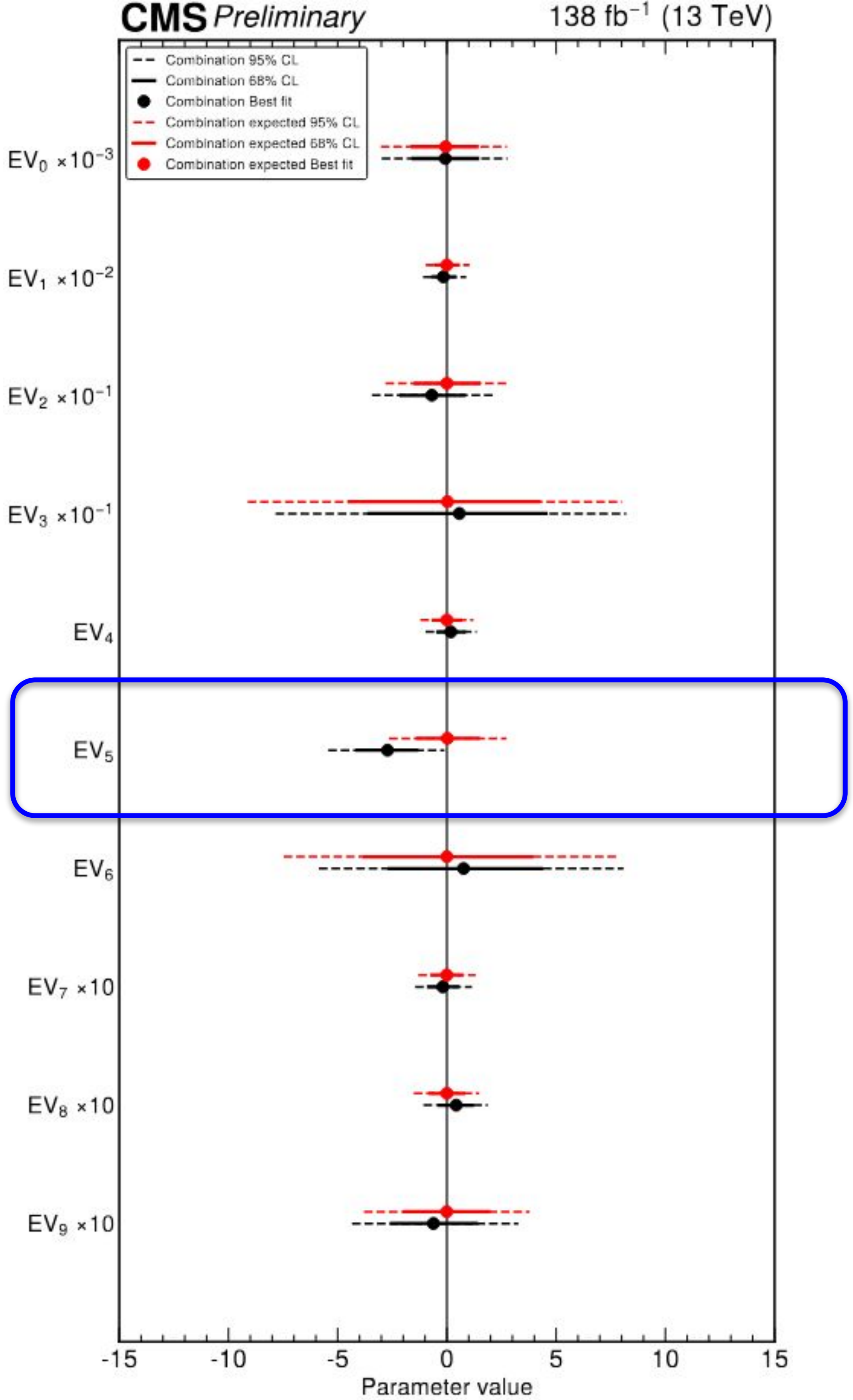

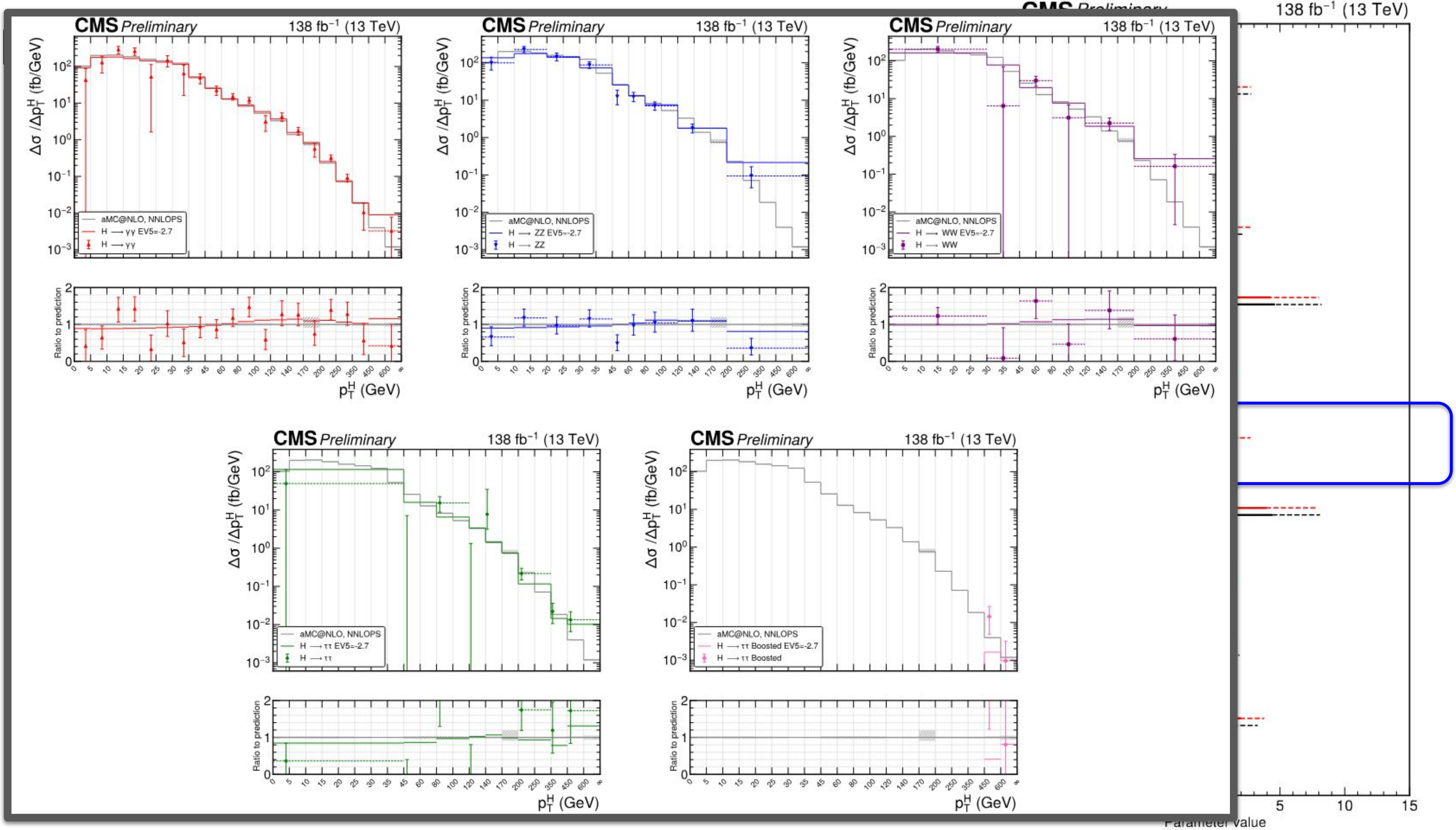

CMS Preliminary
138 fb^{-1} (13 TeV)
Δσ /Δp$_T^H$ (fb/GeV)
Ratio to prediction
p$_T^H$ (GeV)
aMC@NLO, NNLOPS
H ⟶ γγ EV5=-2.7
H ⟶ γγ
H ⟶ ZZ EV5=-2.7
H ⟶ ZZ
H ⟶ WW EV5=-2.7
H ⟶ WW
H ⟶ ττ EV5=-2.7
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Parameter value

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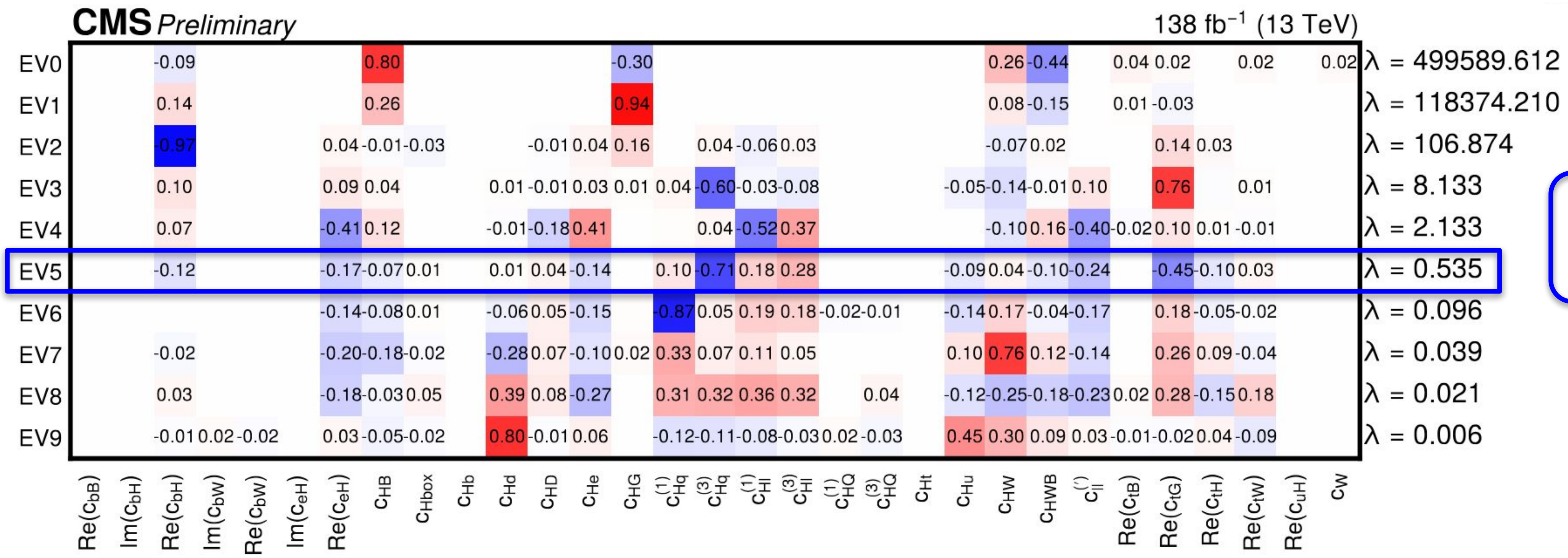

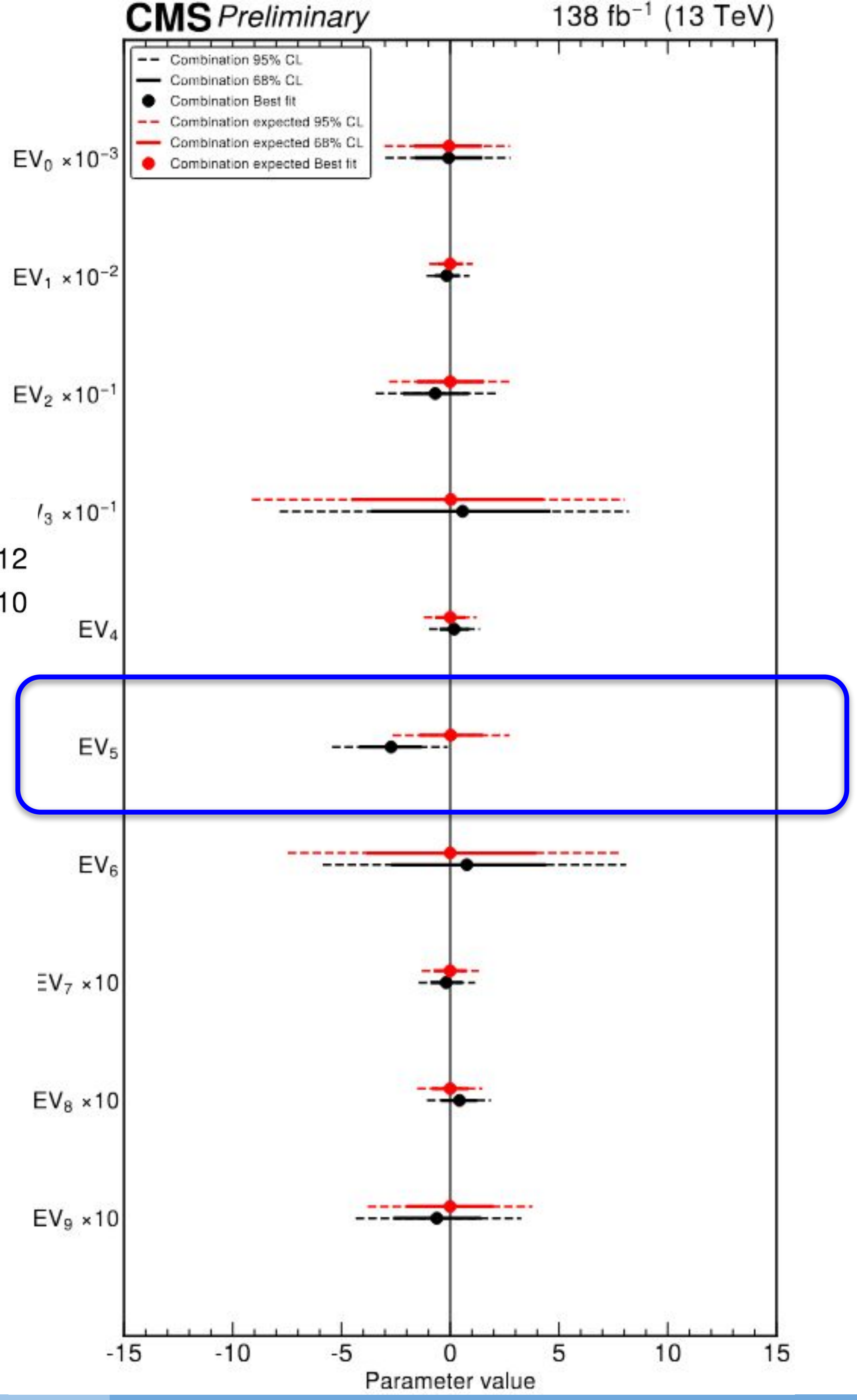

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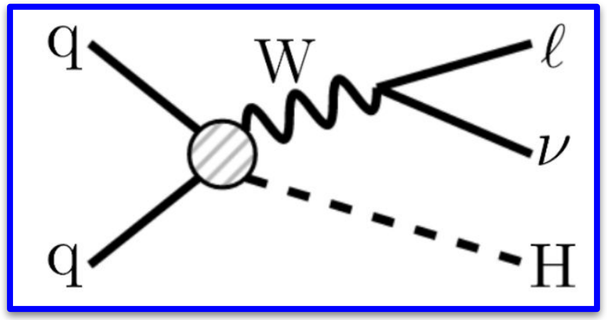
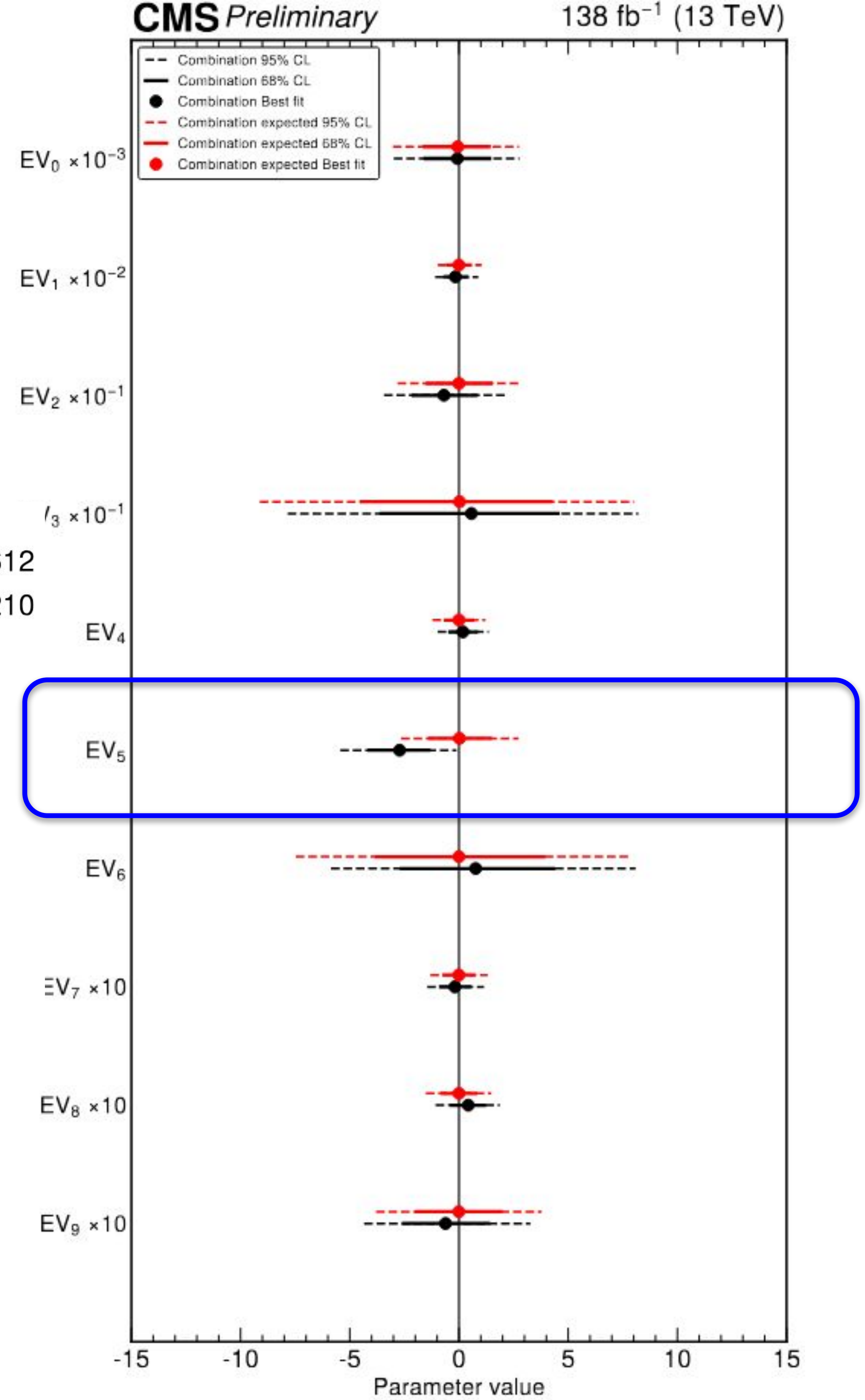
CMS *Preliminary* — 138 fb^{-1} (13 TeV)

	Re(c_{bB})	Im(c_{bH})	Re(c_{bH})	Im(c_{pW})	Re(c_{pW})	Im(c_{eH})	Re(c_{eH})	c_{HB}	c_{Hbox}	c_{Hb}	c_{Hd}	c_{HD}	c_{He}	c_{HG}	$c_{Hq}^{(1)}$	$c_{Hq}^{(3)}$	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	$c_{HQ}^{(1)}$	$c_{HQ}^{(3)}$	c_{Ht}	c_{Hu}	c_{HW}	c_{HWB}	$c_{ll}^{(')}$	Re(c_{tB})	Re(c_{tG})	Re(c_{tH})	Re(c_{tW})	Re(c_{uH})	c_W	λ
EV0			-0.09					0.80						-0.30									0.26	-0.44		0.04	0.02		0.02		0.02	λ = 499589.612
EV1			0.14					0.26						0.94									0.08	-0.15		0.01	-0.03					λ = 118374.210
EV2			-0.97				0.04	-0.01	-0.03			-0.01	0.04	0.16		0.04	-0.06	0.03					-0.07	0.02			0.14	0.03				λ = 106.874
EV3			0.10				0.09	0.04			0.01	-0.01	0.03	0.01	0.04	-0.60	-0.03	-0.08				-0.05	-0.14	-0.01	0.10		0.76		0.01			λ = 8.133
EV4			0.07				-0.41	0.12			-0.01	-0.18	0.41			0.04	-0.52	0.37					-0.10	0.16	-0.40	-0.02	0.10	0.01	-0.01			λ = 2.133
EV5			-0.12				-0.17	-0.07	0.01		0.01	0.04	-0.14		0.10	-0.71	0.18	0.28				-0.09	0.04	-0.10	-0.24		-0.45	-0.10	0.03			λ = 0.535
EV6							-0.14	-0.08	0.01		-0.06	0.05	-0.15		-0.87	0.05	0.19	0.18	-0.02	-0.01		-0.14	0.17	-0.04	-0.17		0.18	-0.05	-0.02			λ = 0.096
EV7			-0.02				-0.20	-0.18	-0.02		-0.28	0.07	-0.10	0.02	0.33	0.07	0.11	0.05				0.10	0.76	0.12	-0.14		0.26	0.09	-0.04			λ = 0.039
EV8			0.03				-0.18	-0.03	0.05		0.39	0.08	-0.27		0.31	0.32	0.36	0.32		0.04		-0.12	-0.25	-0.18	-0.23	0.02	0.28	-0.15	0.18			λ = 0.021
EV9			-0.01	0.02	-0.02		0.03	-0.05	-0.02		0.80	-0.01	0.06		-0.12	-0.11	-0.08	-0.03	0.02	-0.03		0.45	0.30	0.09	0.03	-0.01	-0.02	0.04	-0.09			λ = 0.006

- Largest contribution from: $c_{Hq}^{(3)}$

$$(H^{\dagger} i \overleftrightarrow{D}^{i}_{\mu} H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$$





How to re-interpret these results?

(*) - Valid for E<Λ. Assumes some flavour scheme. Obeys SM symmetries. Rotated basis truncation

- EFT is a model-agnostic(*) approach to search for new physics → **UV-complete matching**

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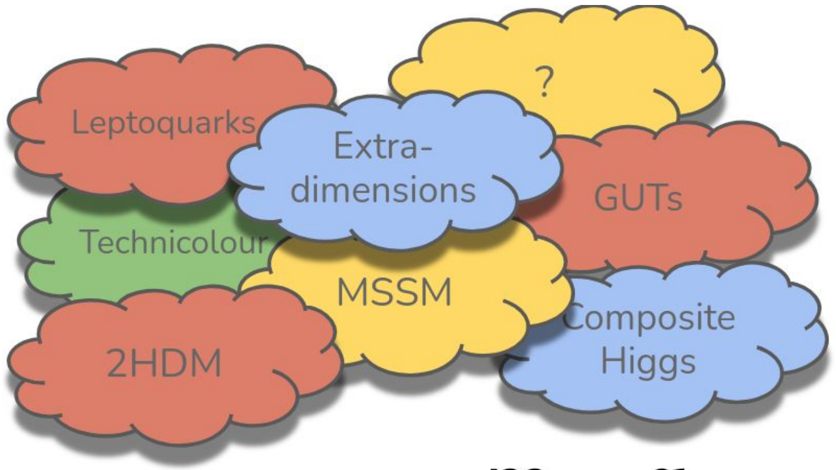

Parameters: $m_\chi, g_\chi, \dots$

1. Favourite UV-complete theory

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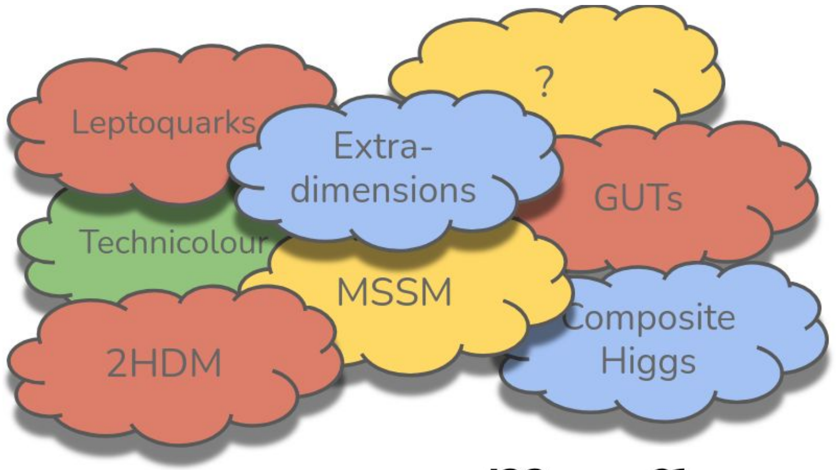

Parameters: $m_\chi, g_\chi, \ldots$

1. Favourite UV-complete theory

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{j=0} \frac{c_j^{(6)}}{\Lambda^2} O_j^{(6)}$$

$$c_j^{(6)}(m_\chi, g_\chi, \ldots)$$

[LHCEFTWG-2022-002]

2. "Matching" to EFT Wilson Coeffs

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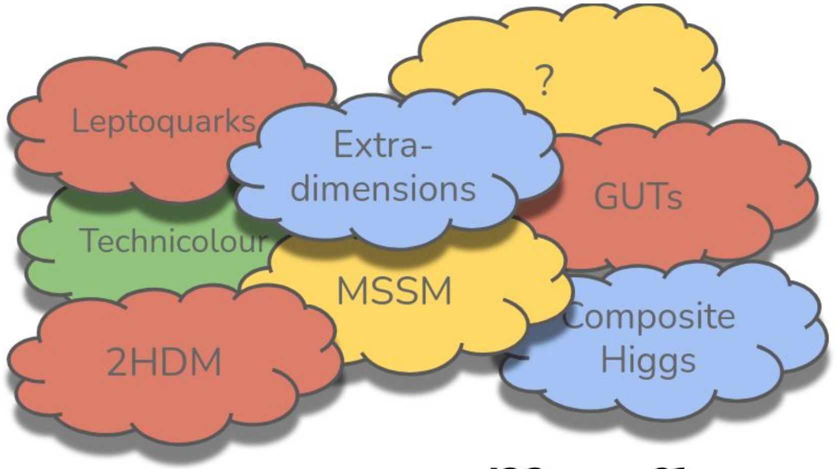

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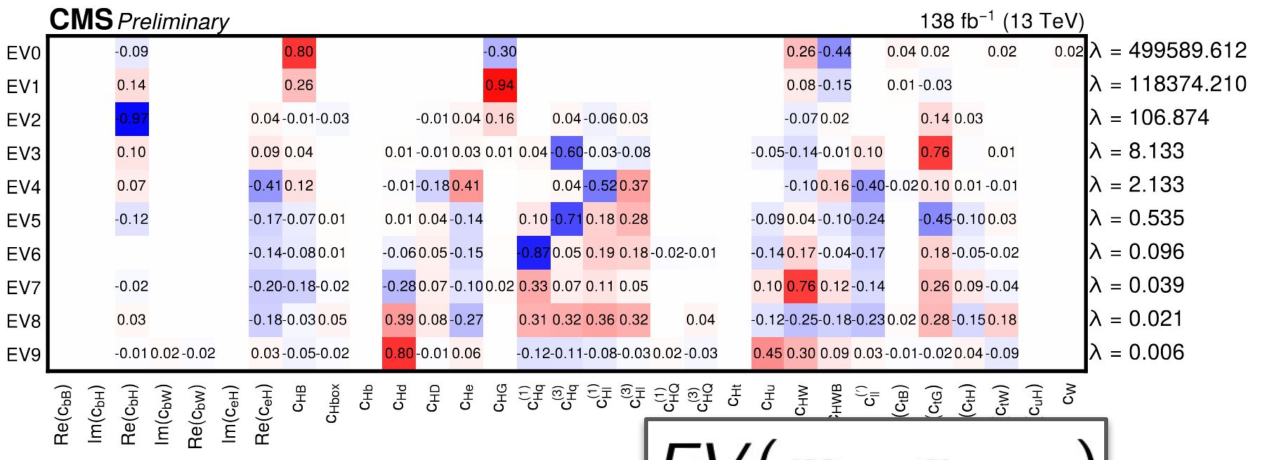

$EV(m_\chi, g_\chi, \ldots)$

3. Rotate relations to EV basis

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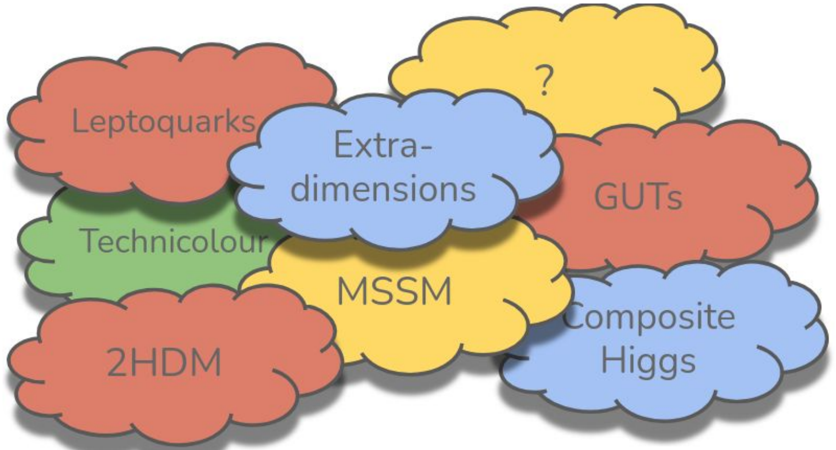

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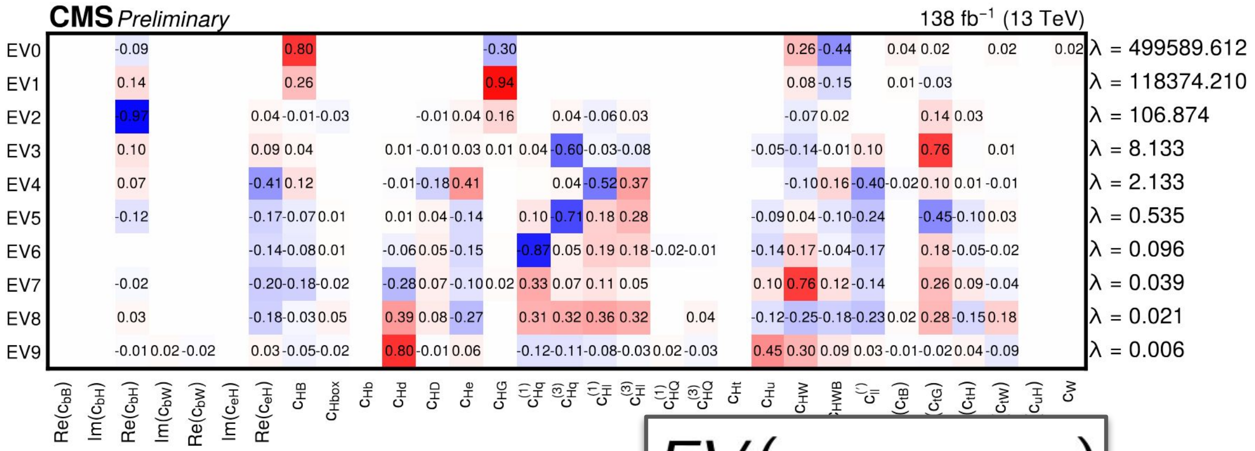
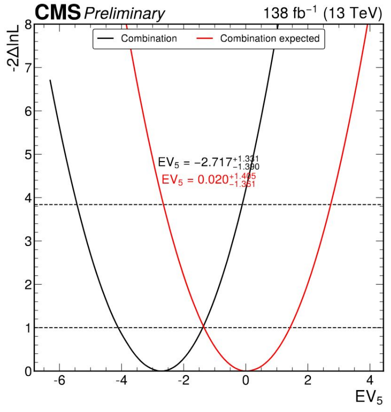
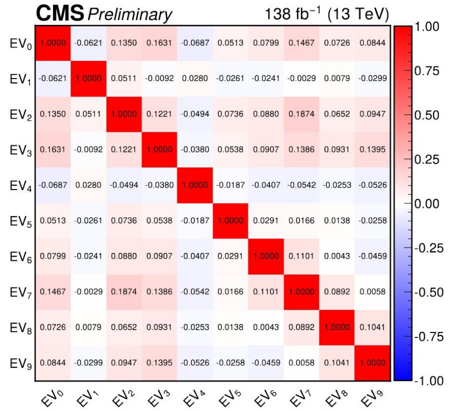


$$EV(m_\chi, g_\chi, \ldots)$$

3. Rotate relations to EV basis

$$V_{ij} = \rho_{ij}\sigma_i\sigma_j$$





$$\chi^2(m_\chi, g_\chi) = (\hat{EV} - EV(m_\chi, g_\chi))^T V^{-1} (\hat{EV} - EV(m_\chi, g_\chi))$$

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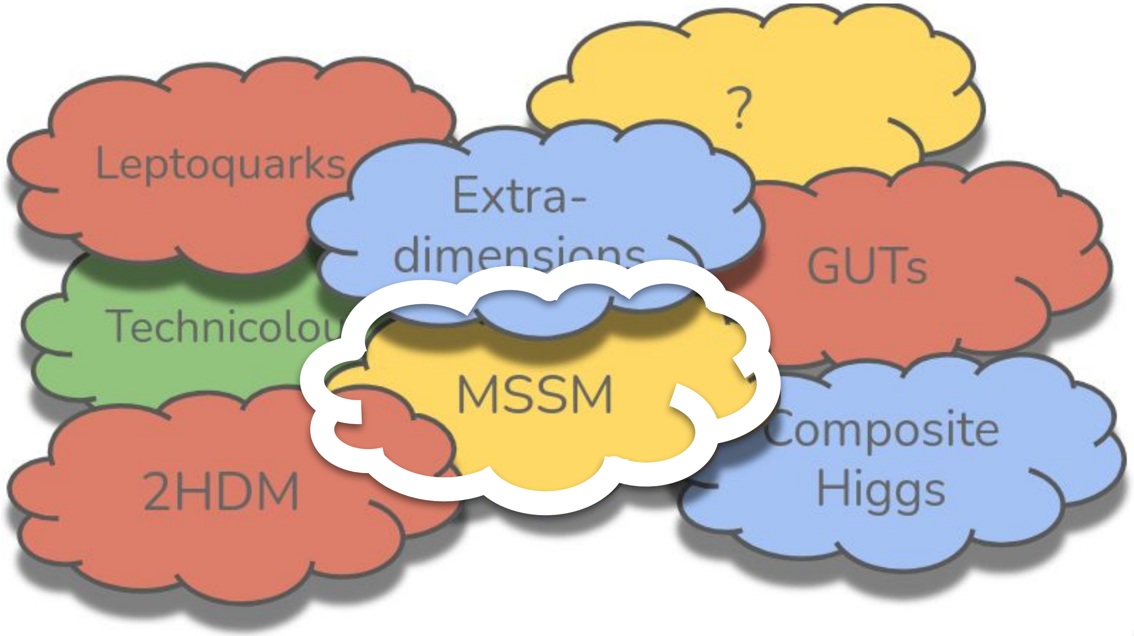

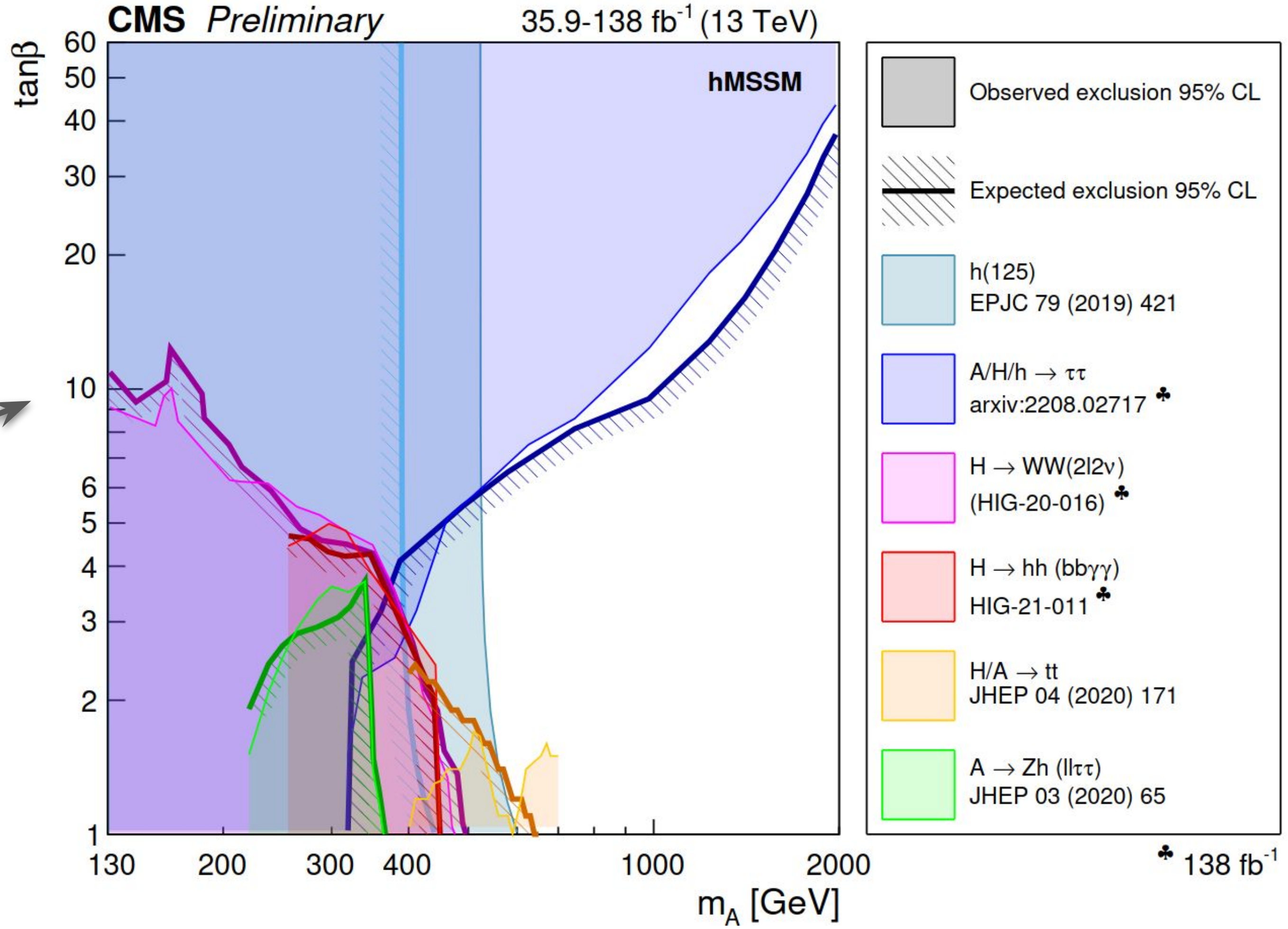

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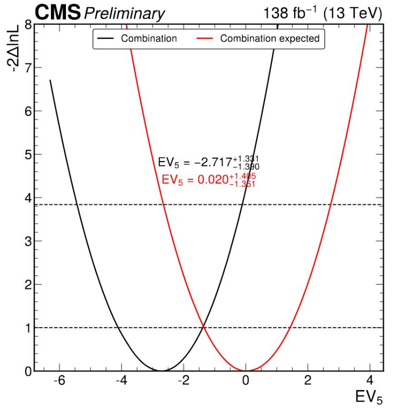

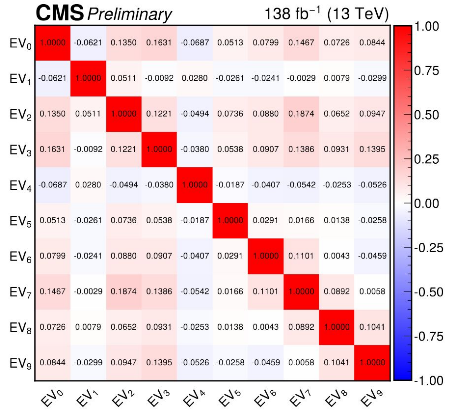

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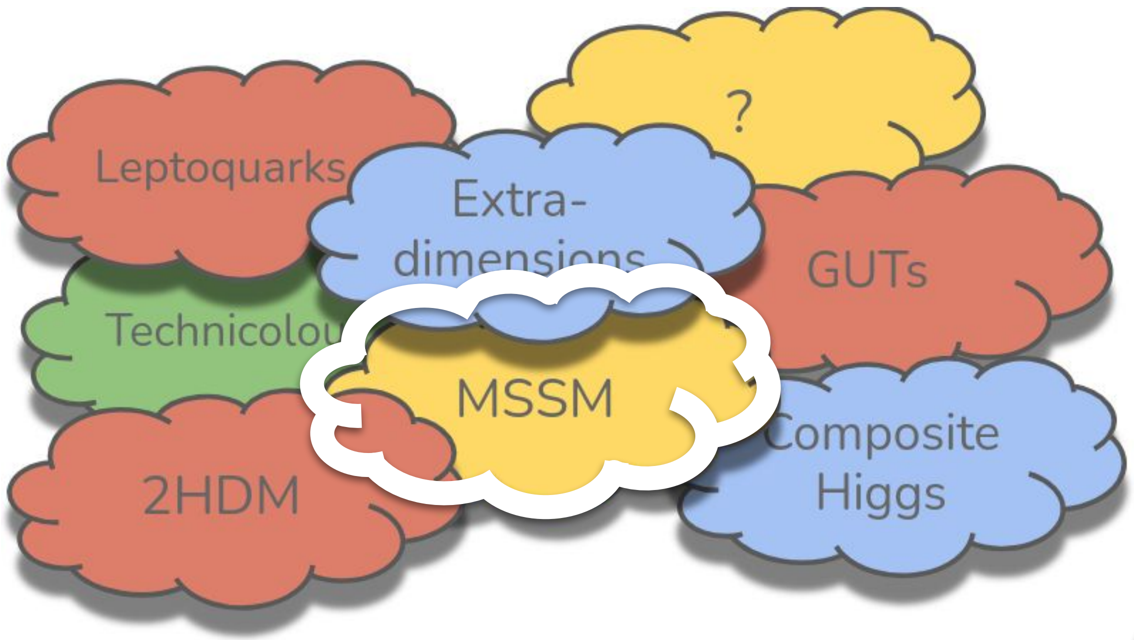

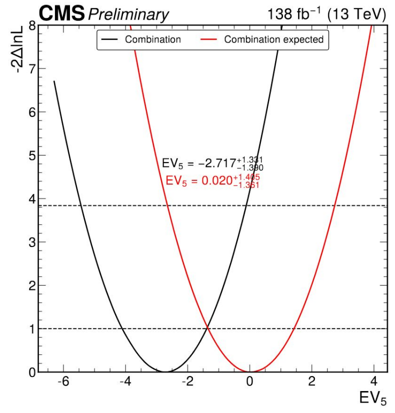

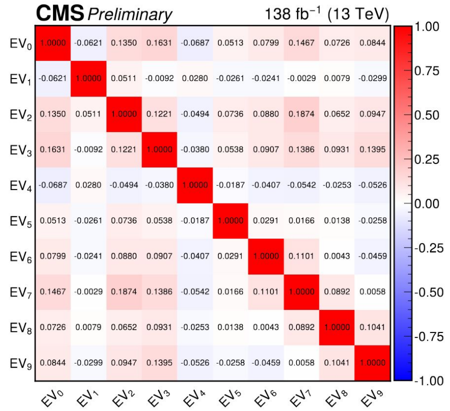

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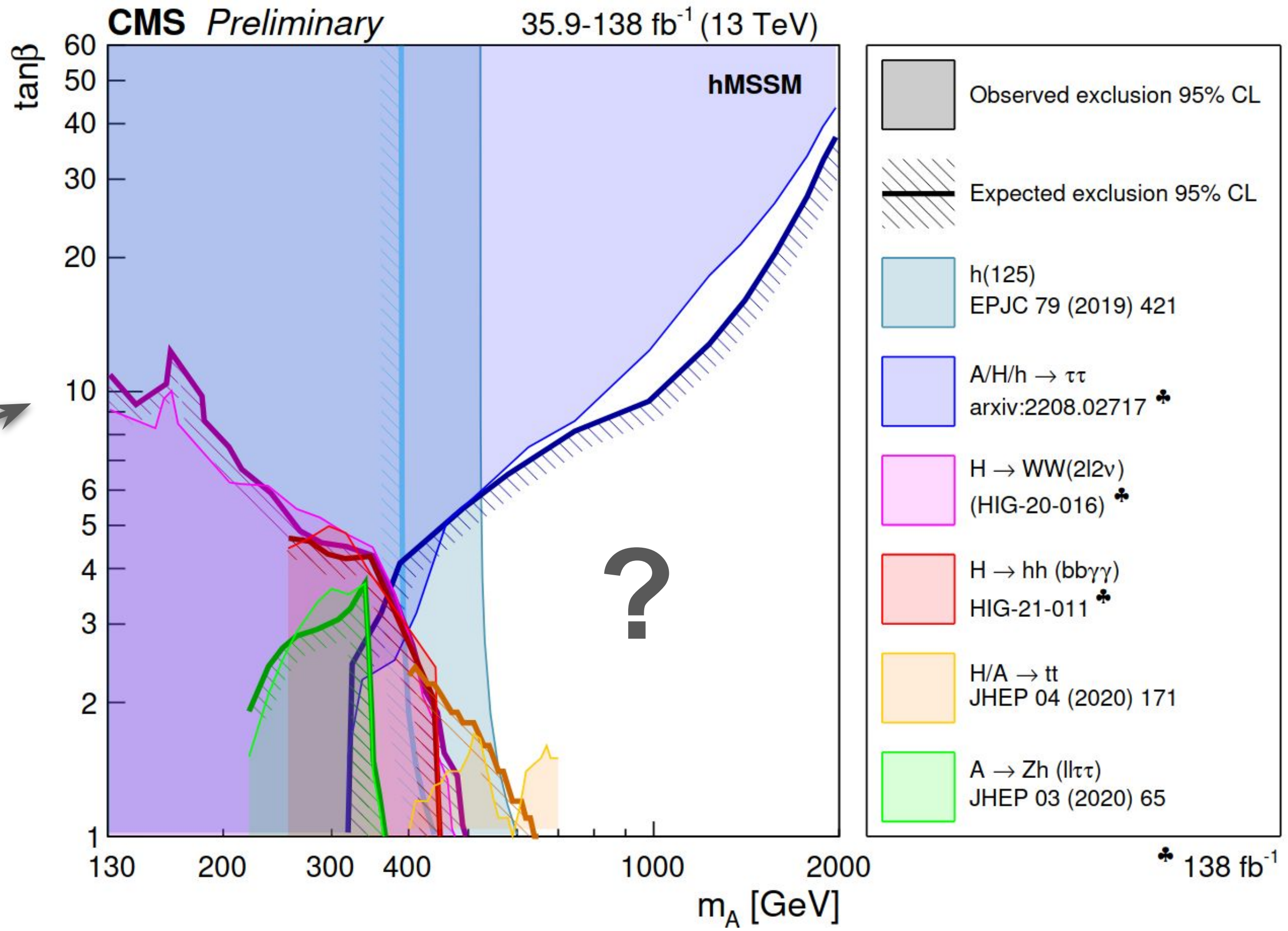


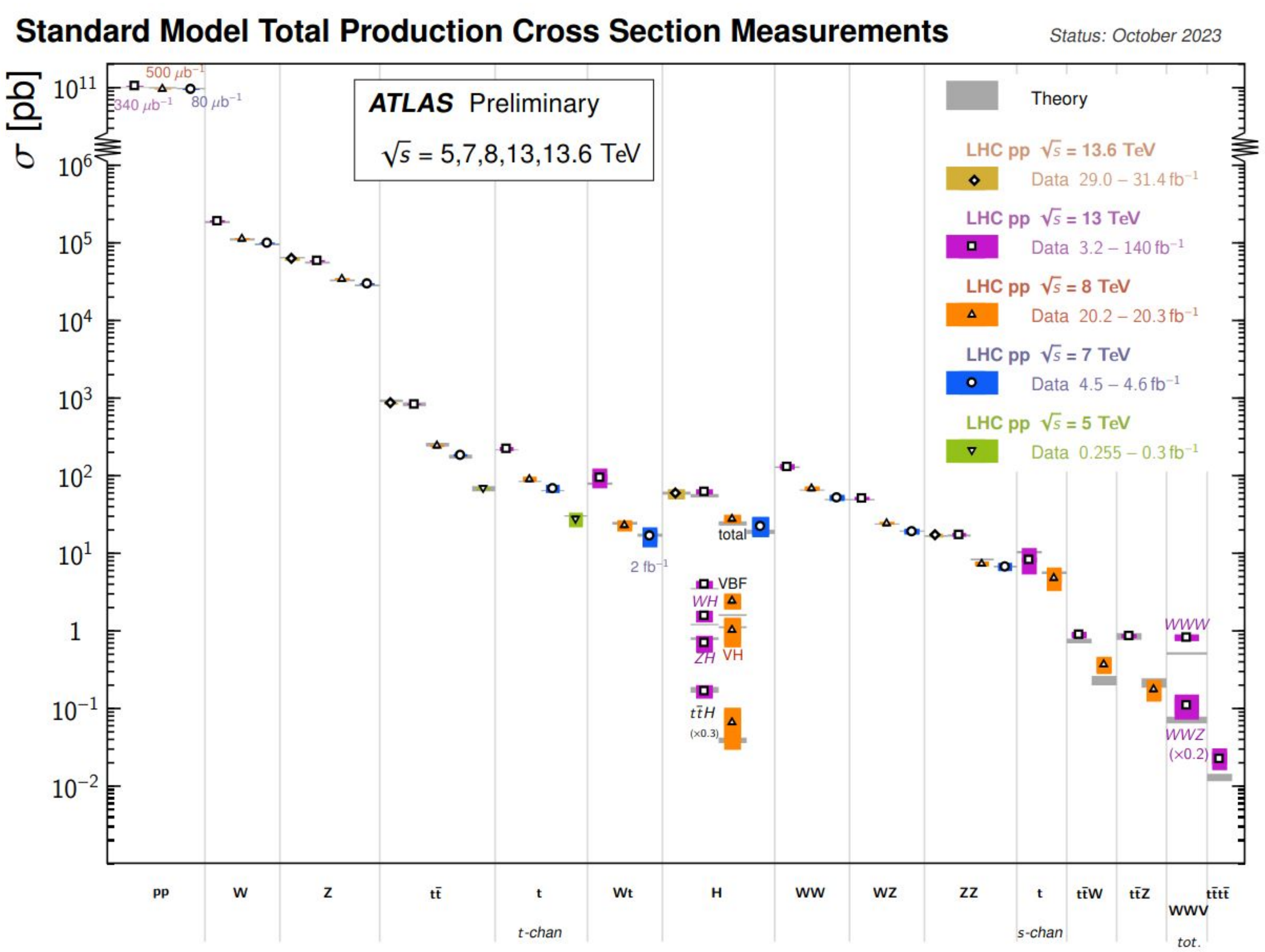
We need to do better at this part of the EFT workflow

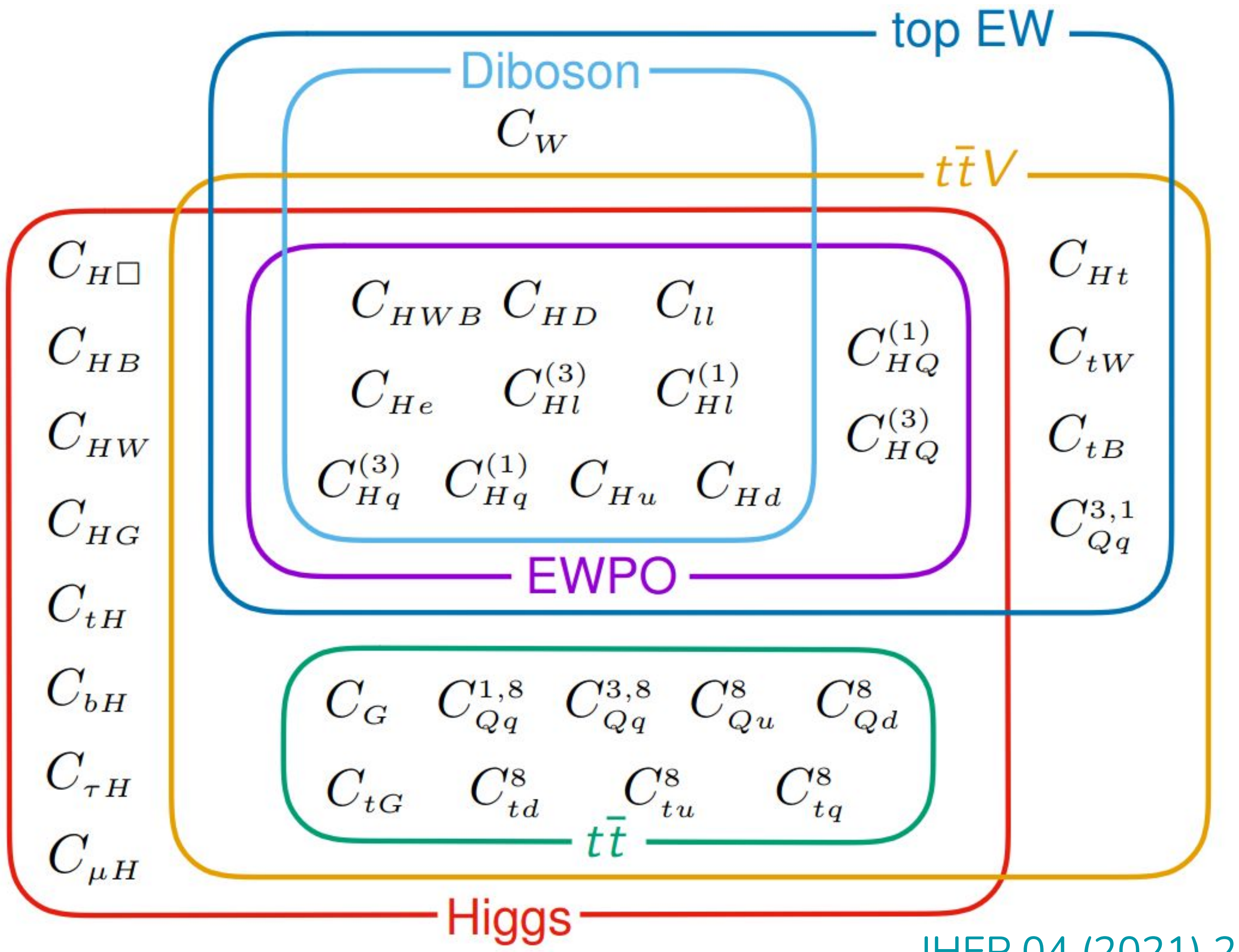
The tools exist: MATCHETE MEFT ...

Encourage theorists to test models with plethora of EFT constraints

Towards a global SMEFT fit

- Beauty of EFT is it's a fully consistent expansion of the SM → **coherently correlate BSM effects across different processes**





[JHEP 04 (2021) 279]

- Global EFT fit by combining measurements of many different processes

Combined EFT interpretation of CMS data

NEW SEPT 24

- [CMS-PAS-SMP-24-003]: **Higgs boson, electroweak vector boson, top quark and multi-jet measurements**
  - First attempt at a global EFT fit from CMS:

Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]	✓
$W\gamma$	Fid. diff. cross sections	$p_T^{\gamma} \times \lvert\phi_f\rvert$	✓
WW	Fid. diff. cross sections	$m_{\ell\ell}$	✓
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^Z	✓
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A^{0,\ell}_{FB}$, $A^{0,c}_{FB}$, $A^{0,b}_{FB}$	×
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$	×
$t\bar{t}X$	Direct EFT	Yields in regions of interest	✓

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$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$	×
EWPO	Pseudo-observables	$\Gamma_Z,\ \sigma^0_{had},\ R_\ell,\ R_c,\ R_b,\ A^{0,\ell}_{FB},\ A^{0,c}_{FB},\ A^{0,b}_{FB}$	×
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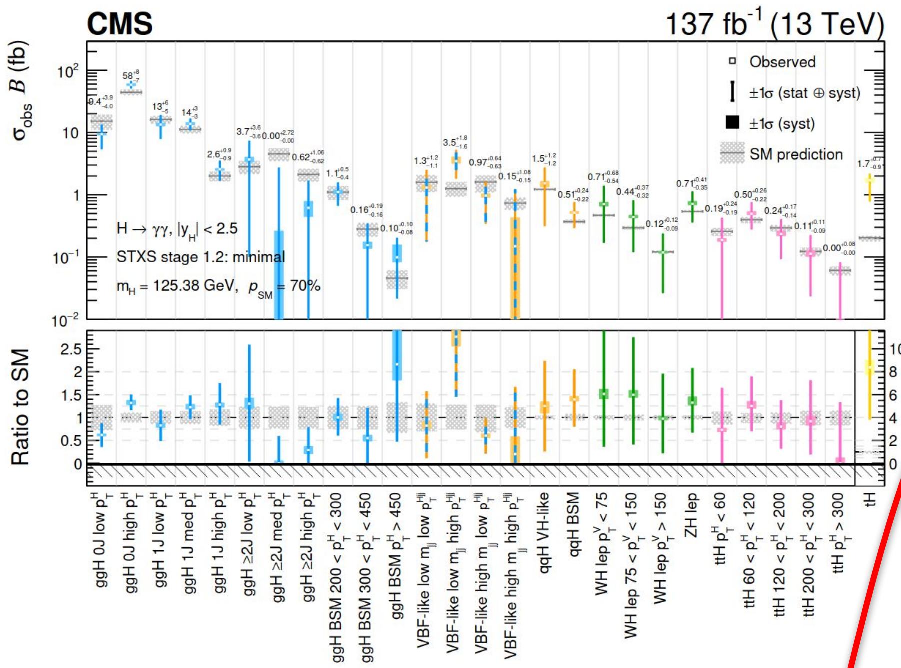
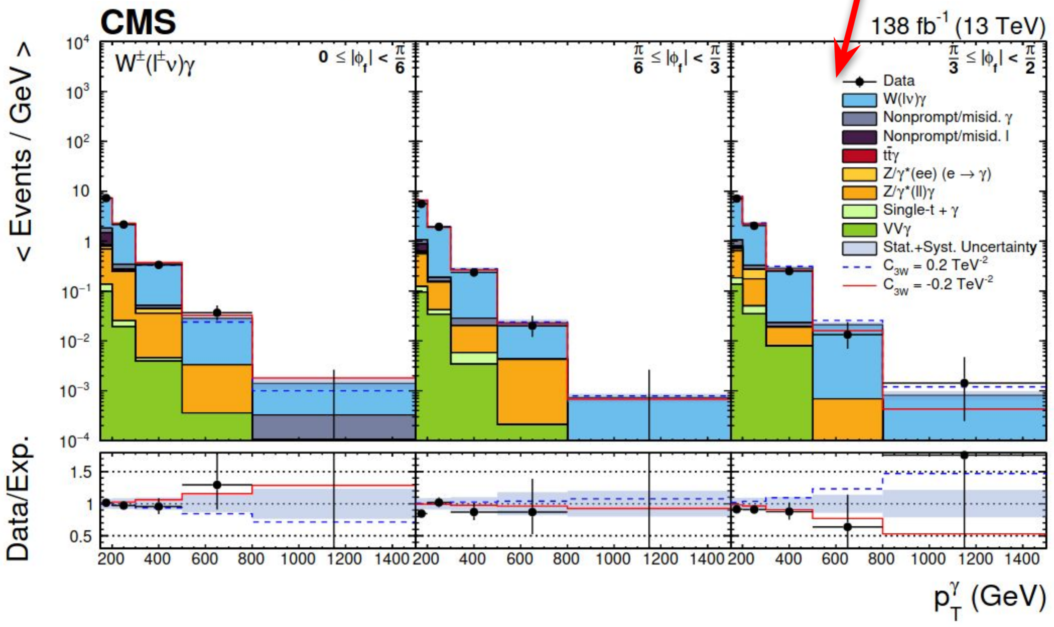
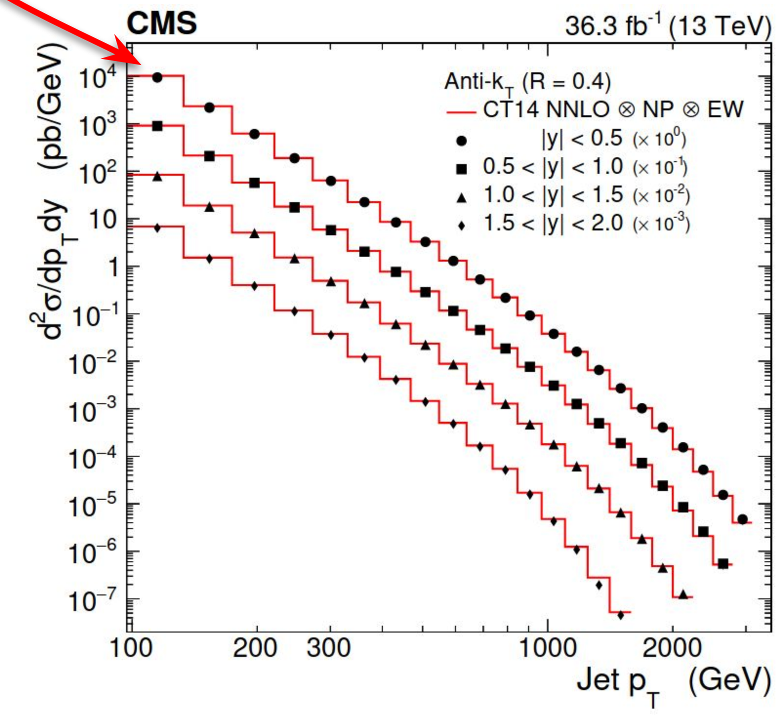
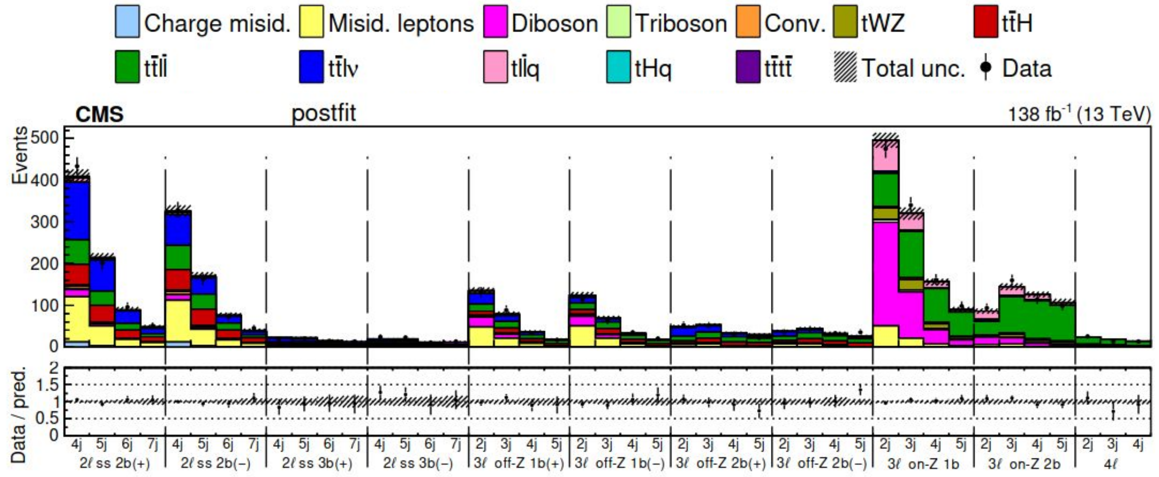




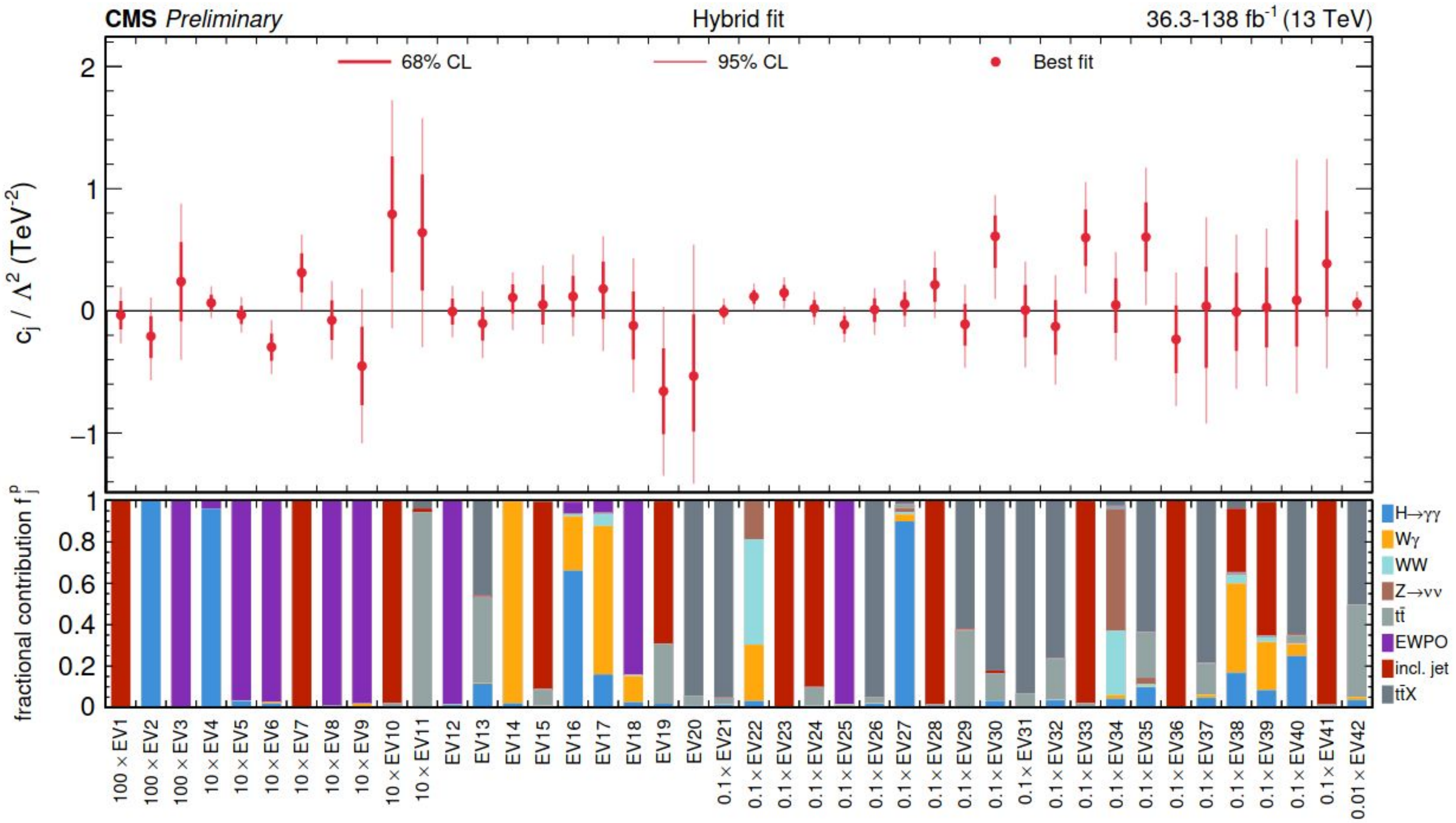




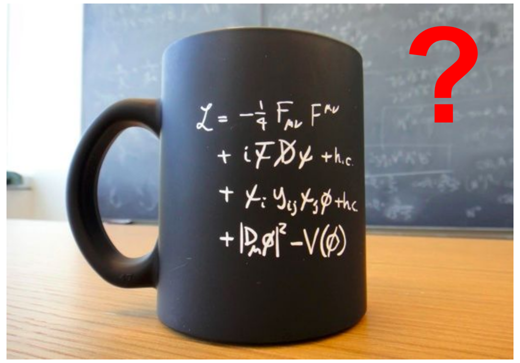
NEW SEPT 24

Combined EFT interpretation of CMS data

- Again use PCA to find constrained directions → Many more compared to using only Higgs differential measurements

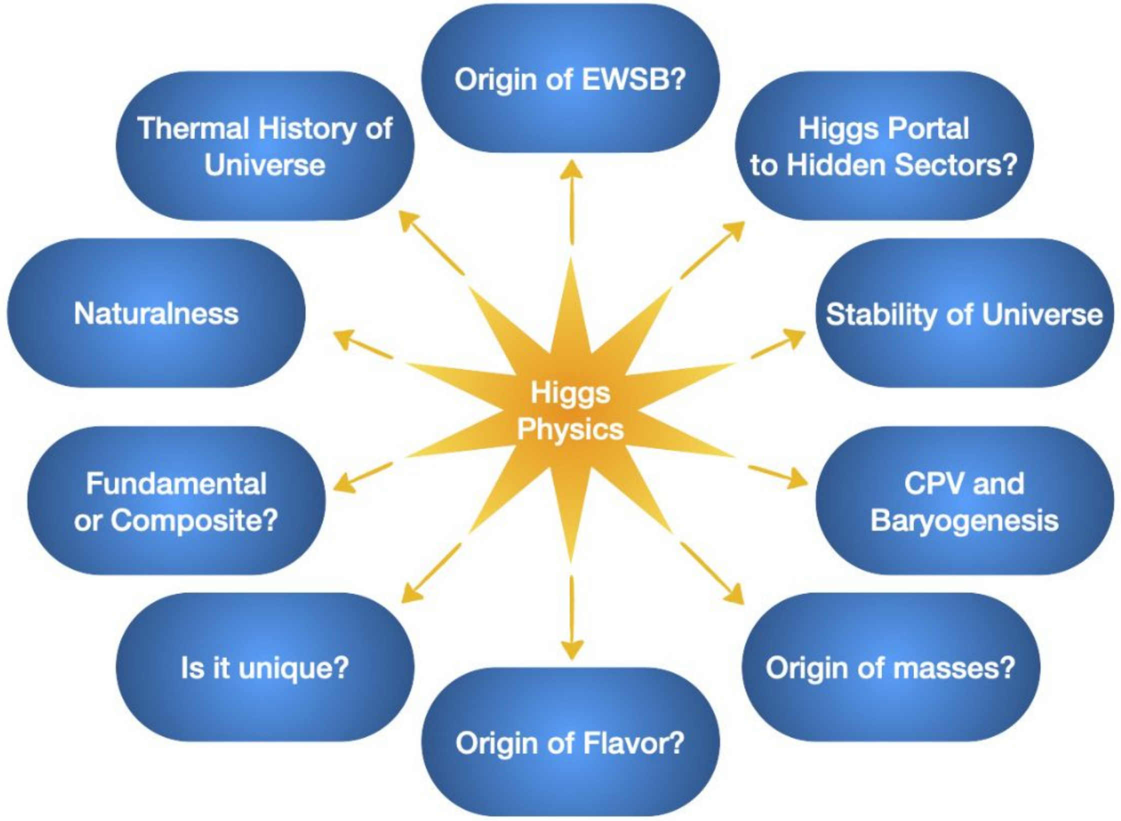


Breakdown of sensitivity from different channels

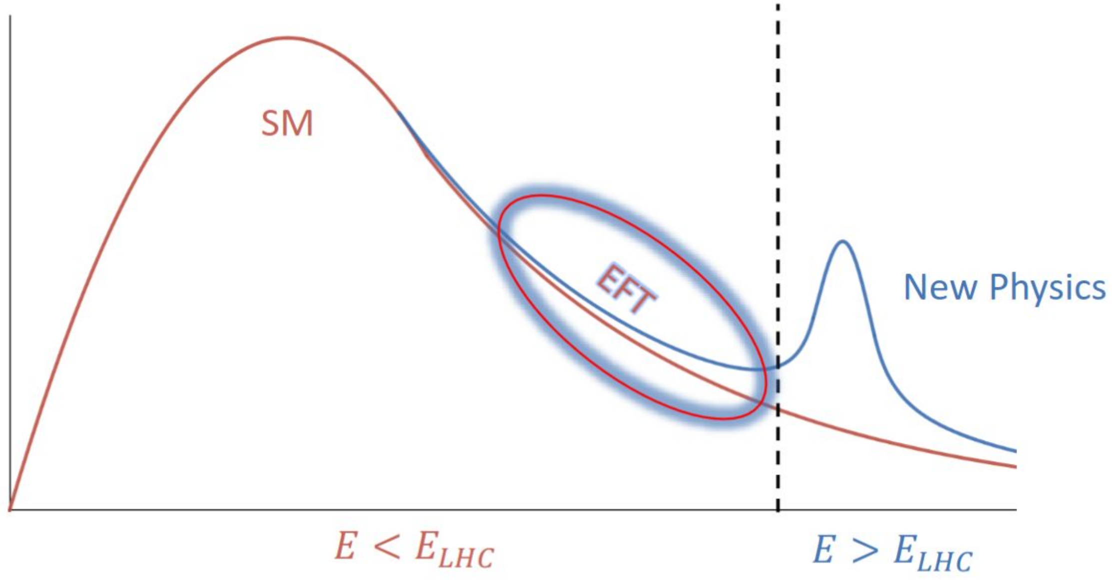


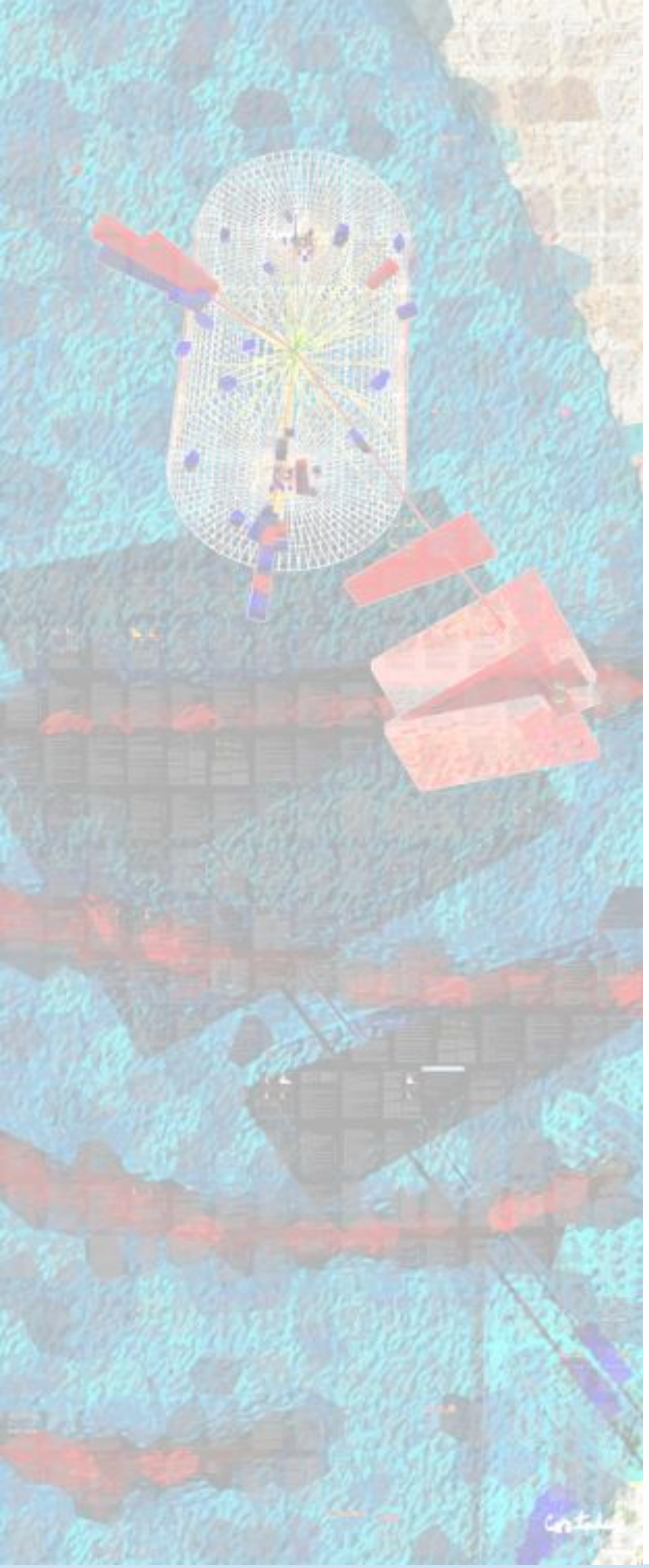
- Flavour of what is to come in Run 3 → **Ultimate consistency test of the SM @ LHC using global EFT fits**

Summary



- "Almost every problem of the SM originates from Higgs boson interactions"
  - Probe answers with **precision Higgs boson measurements**
- Large Run 2 dataset has opened the door to more sophisticated analyses
  - Going differential!
- Ultimate precision via **Higgs boson statistical combinations**
  - Differential combination → SMEFT interpretation
- Global EFT fits for ultimate SM consistency tests

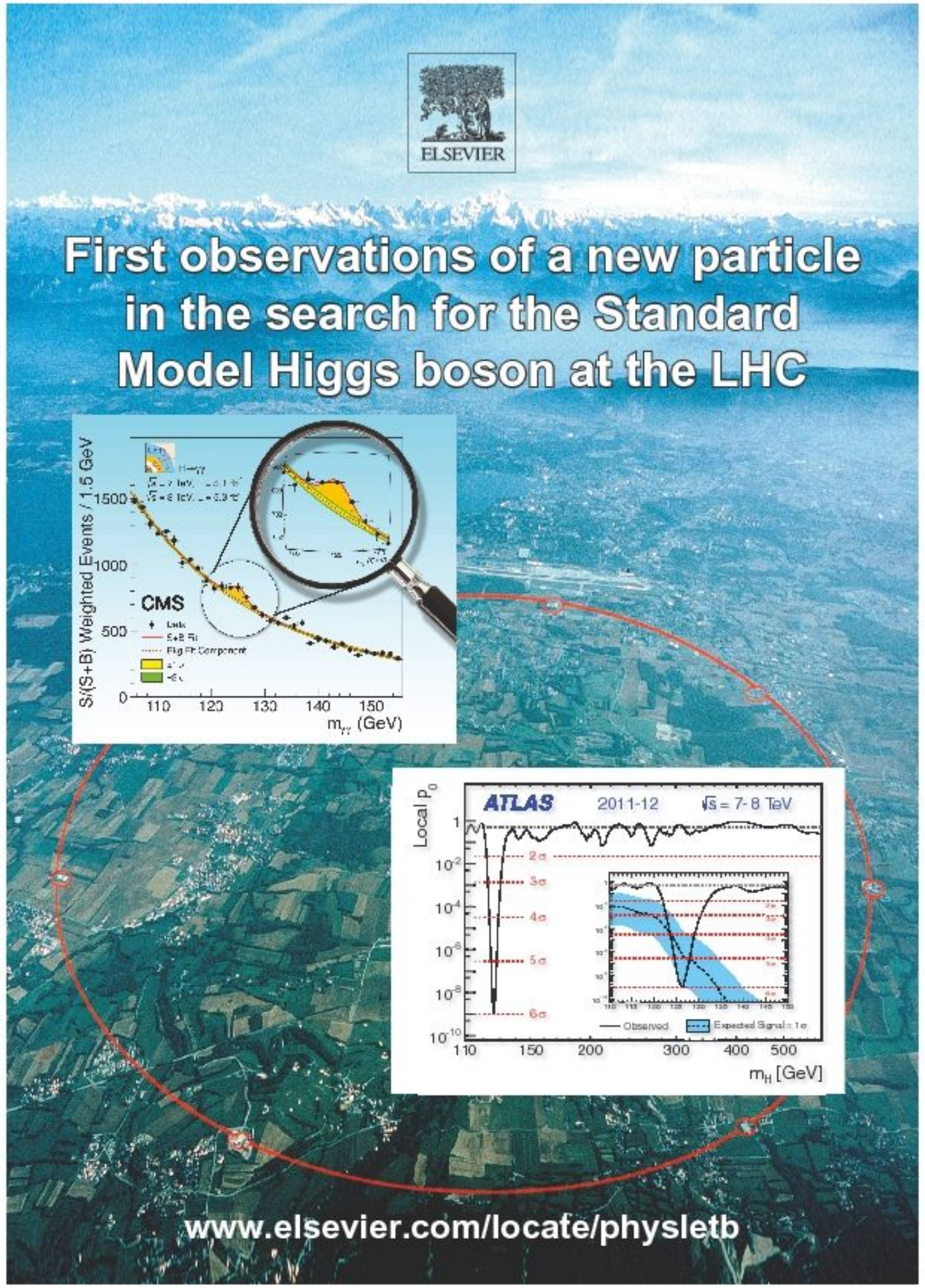


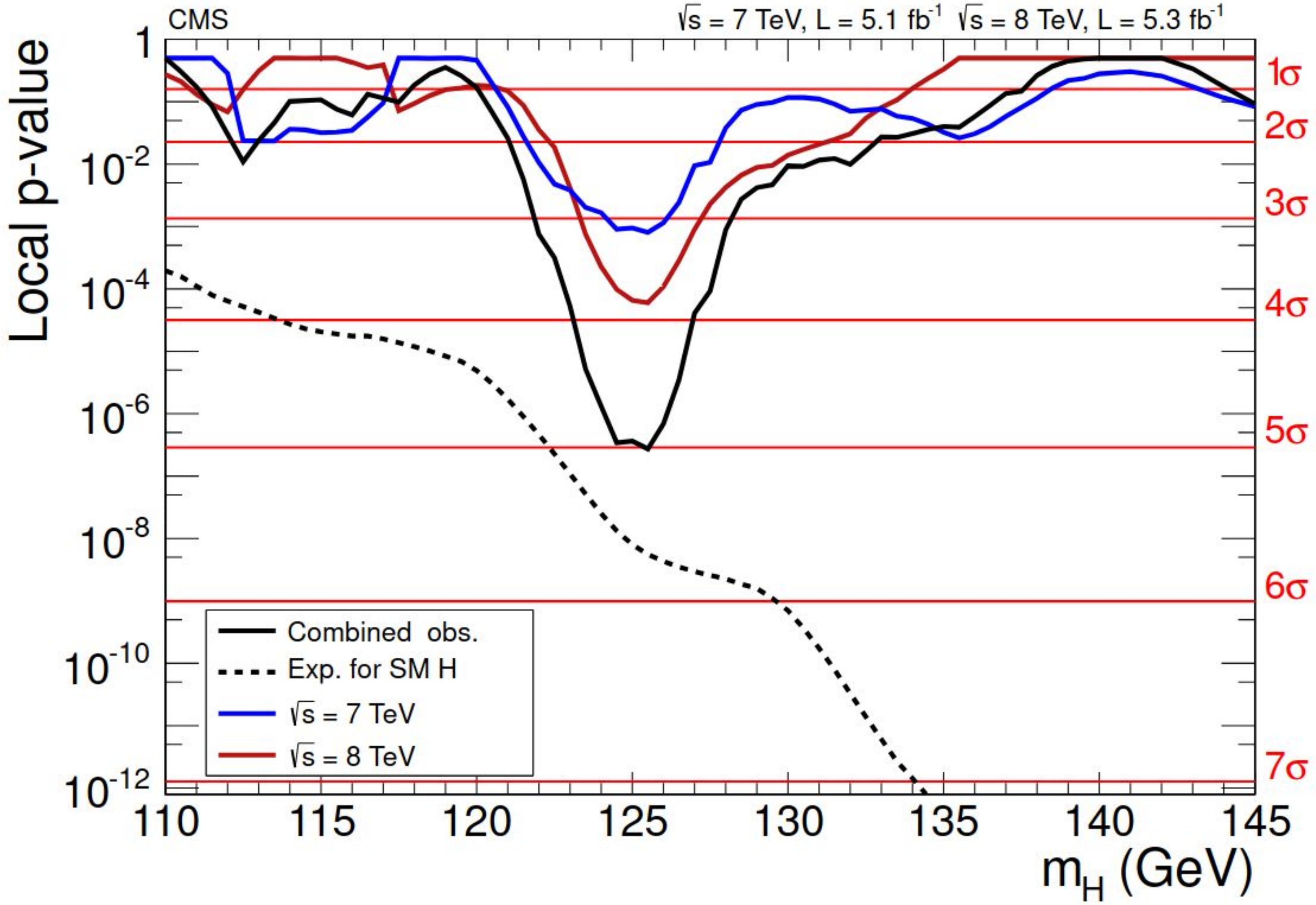


Back-Up

Discovery

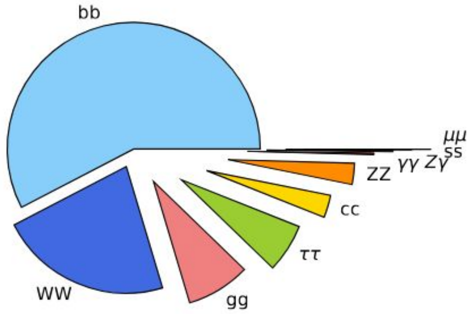
July 4th 2012





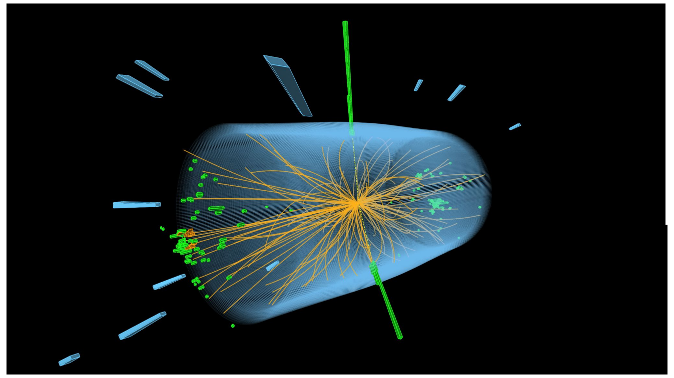
Nature input analyses

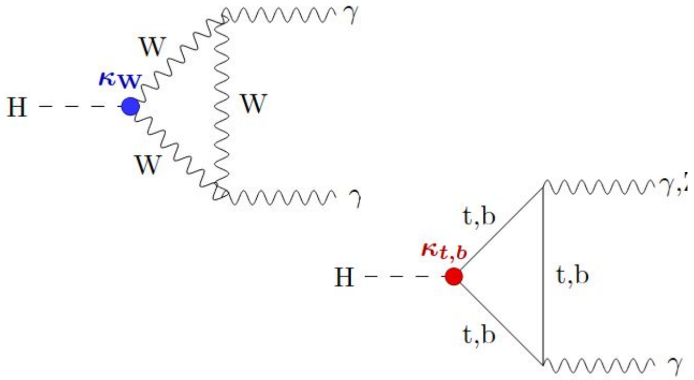
[Nature 607 (2022) 60-68]



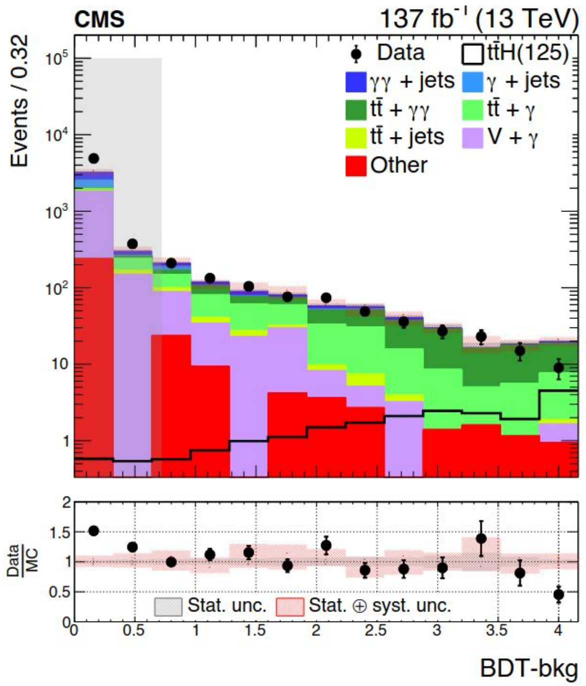
- Combination of Higgs boson analyses using the full Run 2 dataset (2016-2018) = 138 fb^{-1}

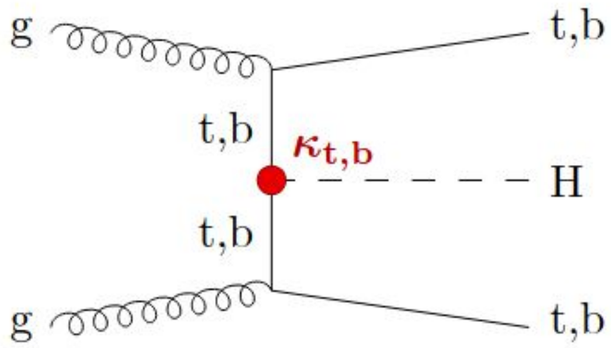
Select two isolated photons consistent with H boson decay





Categorise events according to kinematic properties to target different production modes (STXS bins)

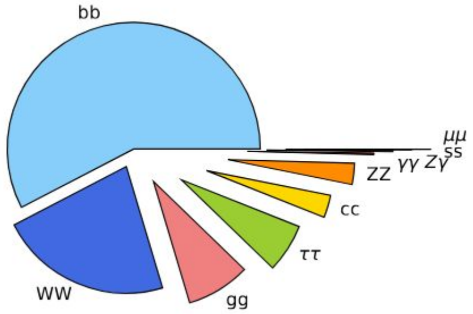




Analysis	Decay tags	Production tags
Single Higgs boson production		
$H \to \gamma\gamma$ [42]	$\gamma\gamma$	ggH, $p_T(H) \times N_j$ bins VBF/VH hadronic, $p_T(Hjj)$ bins WH leptonic, $p_T(V)$ bins ZH leptonic ttH $p_T(H)$ bins, tH
$H \to ZZ \to 4\ell$ [43]	4μ, $2e2\mu$, $4e$	ggH, $p_T(H) \times N_j$ bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH
$H \to WW \to \ell\nu\ell\nu$ [44]	$e\mu/ee/\mu\mu$ $\mu\mu$+jj/ee+jj/$e\mu$+jj 3ℓ 4ℓ	ggH $\leq$ 2-jets VBF VH hadronic WH leptonic ZH leptonic
$H \to Z\gamma$ [45]	$Z\gamma$	ggH VBF
$H \to \tau\tau$ [46]	$e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$	ggH, $p_T(H) \times N_j$ bins VH hadronic VBF VH, high-$p_T(V)$
$H \to bb$ [47–51]	$W(\ell\nu)H(bb)$ $Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$ bb	WH leptonic ZH leptonic ttH, $\to 0, 1, 2\ell$ + jets ggH, high-$p_T(H)$ bins
$H \to \mu\mu$ [52]	$\mu\mu$	ggH VBF
ttH production with $H \to$ leptons [53]	$2\ell SS$, 3ℓ, 4ℓ, $1\ell + \tau_h$, $2\ell SS + 1\tau_h$, $3\ell + 1\tau_h$	ttH
$H \to$ Inv. [71, 72]	p_T^{miss}	ggH VBF VH hadronic ZH leptonic

Nature input analyses

[Nature 607 (2022) 60-68]



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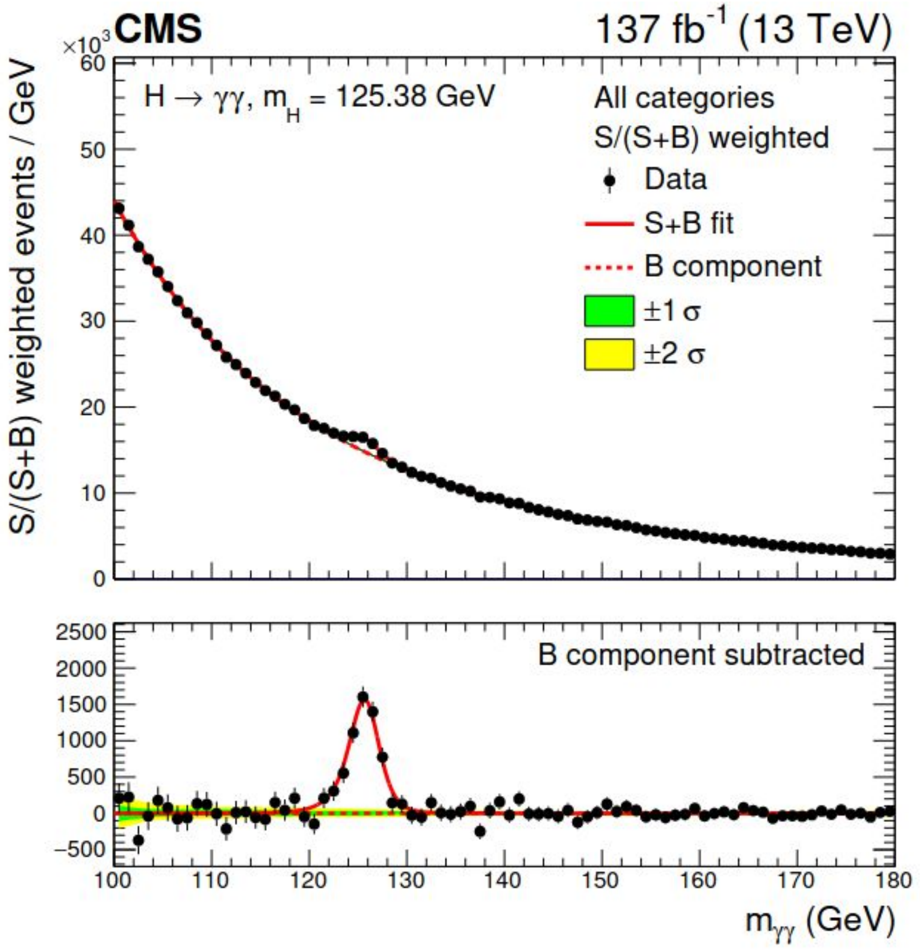
Excellent photon energy resolution of CMS ECAL



Extract signal with fit to diphoton mass spectrum

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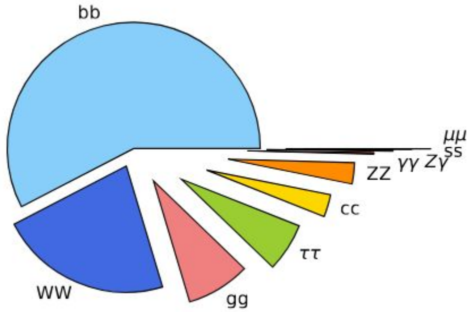

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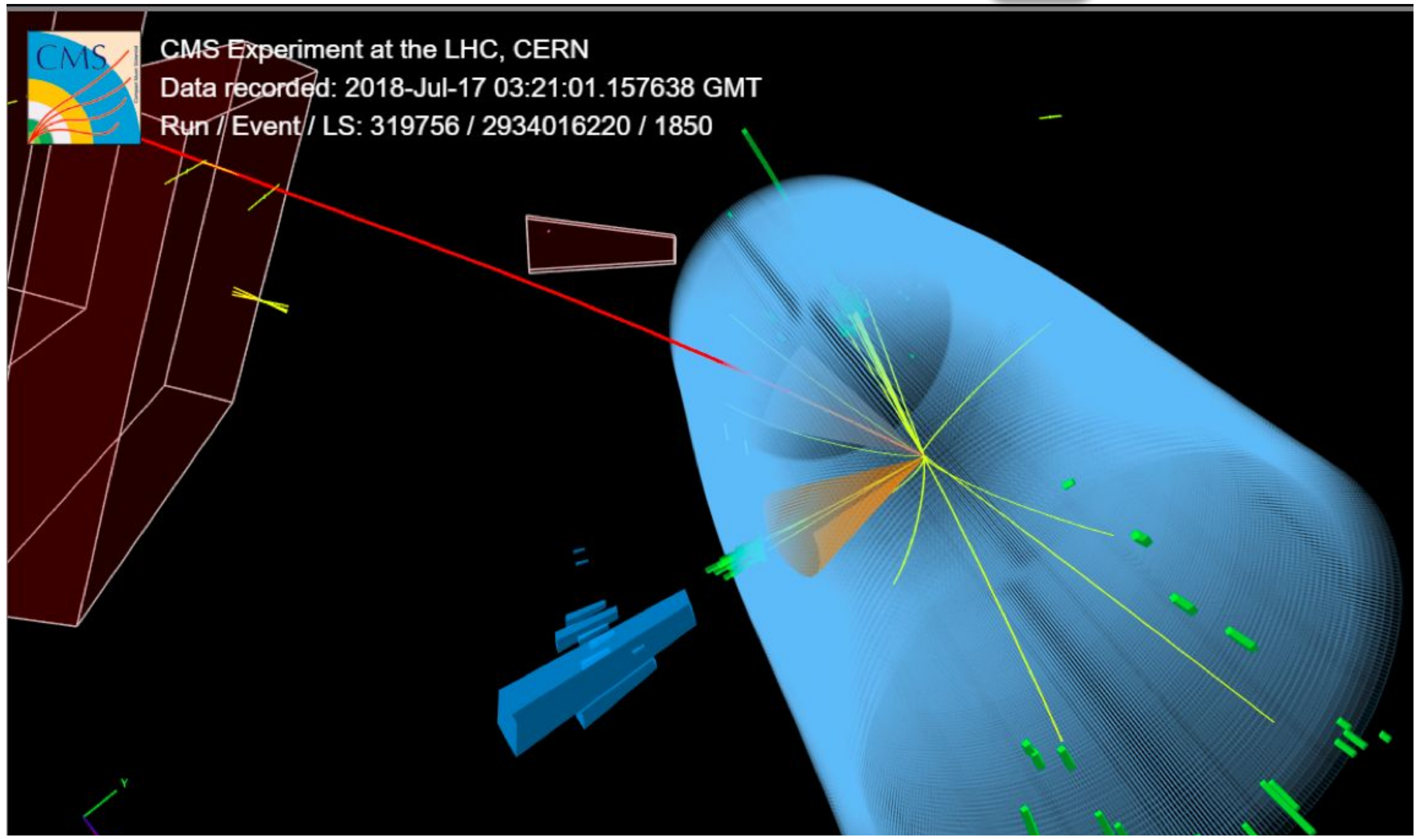
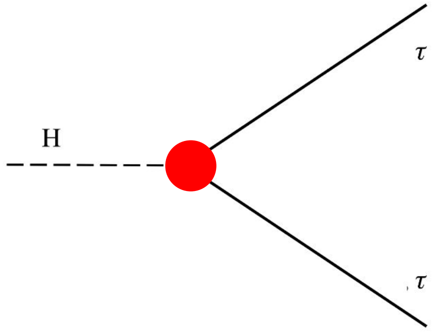
Study four different di-τ final states: eμ, eτ_h, μτ_h, $\tau_h\tau_h$



Benefit from clean leptonic final states + good τ_h identification



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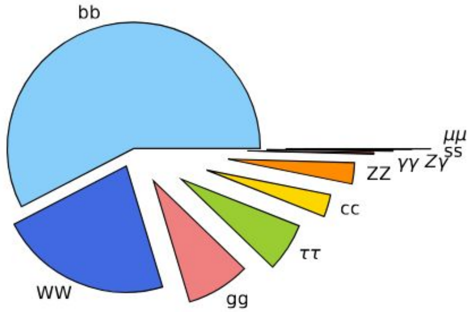
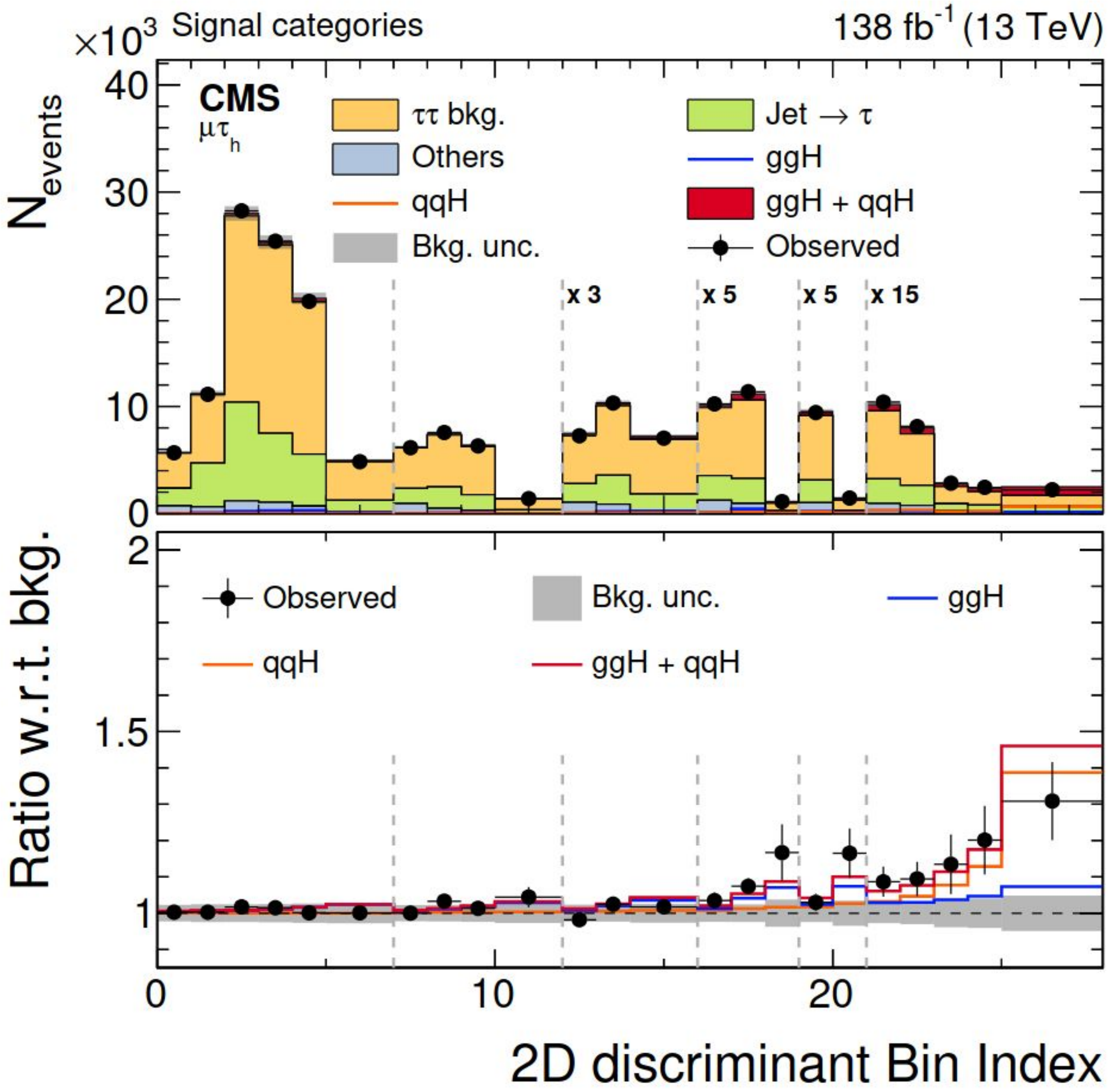
$H \to Z\gamma$ [45]	$Z\gamma$	ggH VBF
$H \to \tau\tau$ [46]	$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	ggH, $p_T(H) \times N_j$ bins VH hadronic VBF VH, high-$p_T(V)$
$H \to bb$ [47–51]	$W(\ell\nu)H(bb)$ $Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$ bb	WH leptonic ZH leptonic ttH, $\to 0, 1, 2\ell$ + jets ggH, high-$p_T(H)$ bins
$H \to \mu\mu$ [52]	$\mu\mu$	ggH VBF
ttH production with $H \to$ leptons [53]	2ℓSS, 3ℓ, 4ℓ, $1\ell + \tau_h$, 2ℓSS+$1\tau_h$, $3\ell + 1\tau_h$	ttH
$H \to$ Inv. [71, 72]	p_T^{miss}	ggH VBF VH hadronic ZH leptonic

Nature input analyses [Nature 607 (2022) 60-68]

- Combination of Higgs boson analyses using the full Run 2 dataset (2016-2018) = 138 fb^{-1}



Extract ggH, VBF (and VH production) with fit to DNN output



Analysis	Decay tags	Production tags
Single Higgs boson production		
$H \to \gamma\gamma$ [42]	$\gamma\gamma$	ggH, $p_T(H) \times N_j$ bins VBF/VH hadronic, $p_T(Hjj)$ bins WH leptonic, $p_T(V)$ bins ZH leptonic ttH $p_T(H)$ bins, tH
$H \to ZZ \to 4\ell$ [43]	4μ, $2e2\mu$, $4e$	ggH, $p_T(H) \times N_j$ bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH
$H \to WW \to \ell\nu\ell\nu$ [44]	$e\mu/ee/\mu\mu$ $\mu\mu$+jj/ee+jj/$e\mu$+jj 3ℓ 4ℓ	ggH $\leq$ 2-jets VBF VH hadronic WH leptonic ZH leptonic
$H \to Z\gamma$ [45]	$Z\gamma$	ggH VBF
$H \to \tau\tau$ [46]	$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	ggH, $p_T(H) \times N_j$ bins VH hadronic VBF
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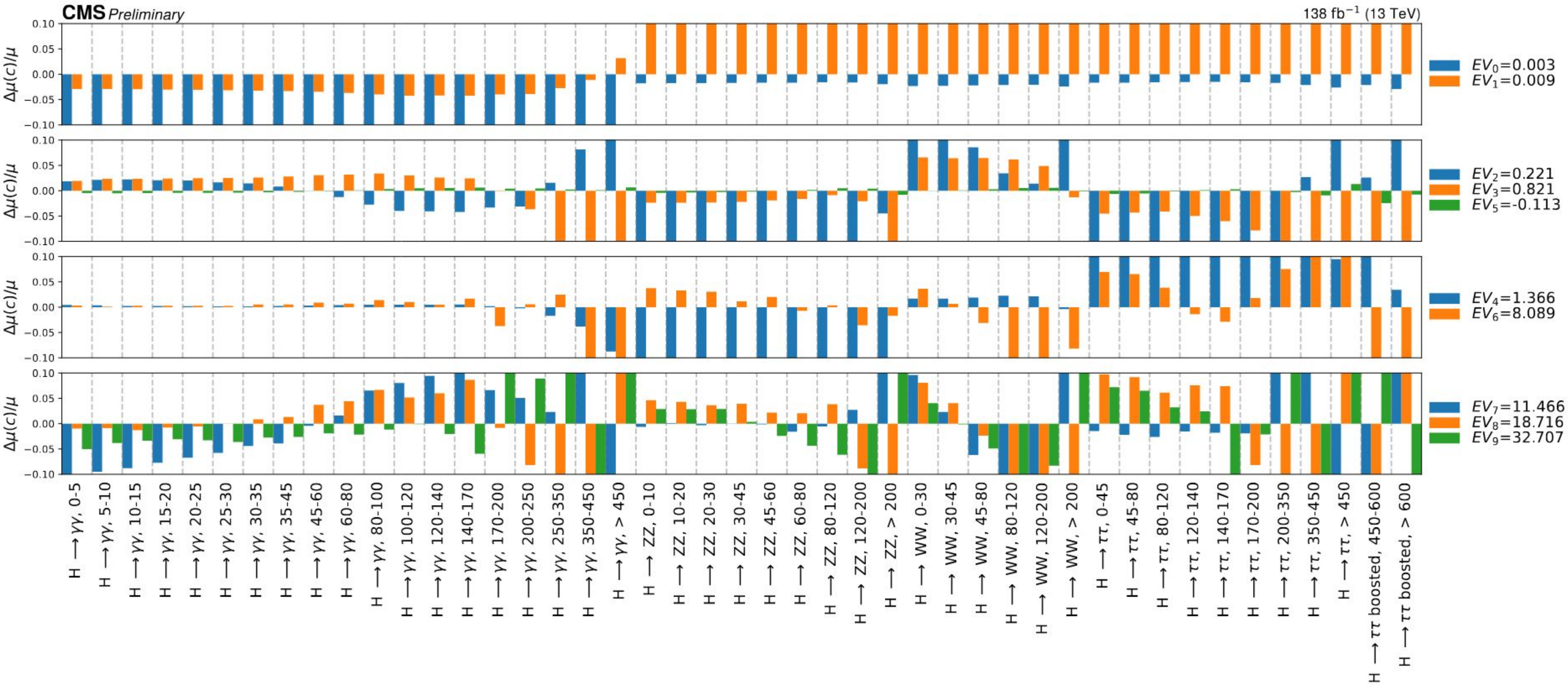
Rotated basis parametrisation




“And now for something ~~completely~~ quite different”

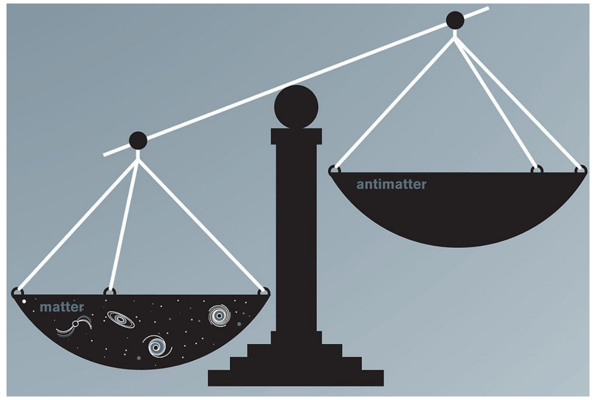
The open questions

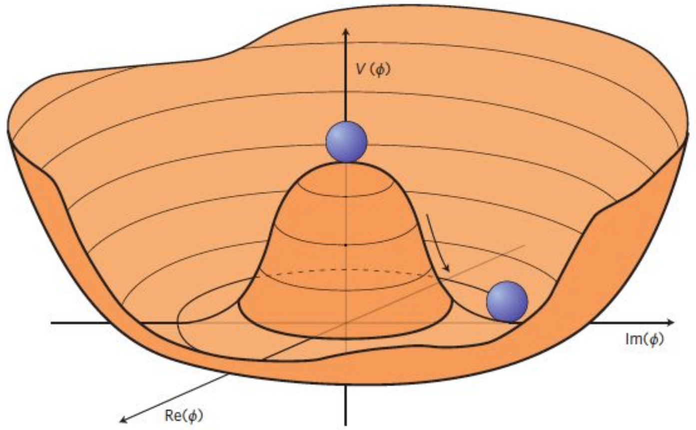
- **Is the Higgs sector SM-like?**

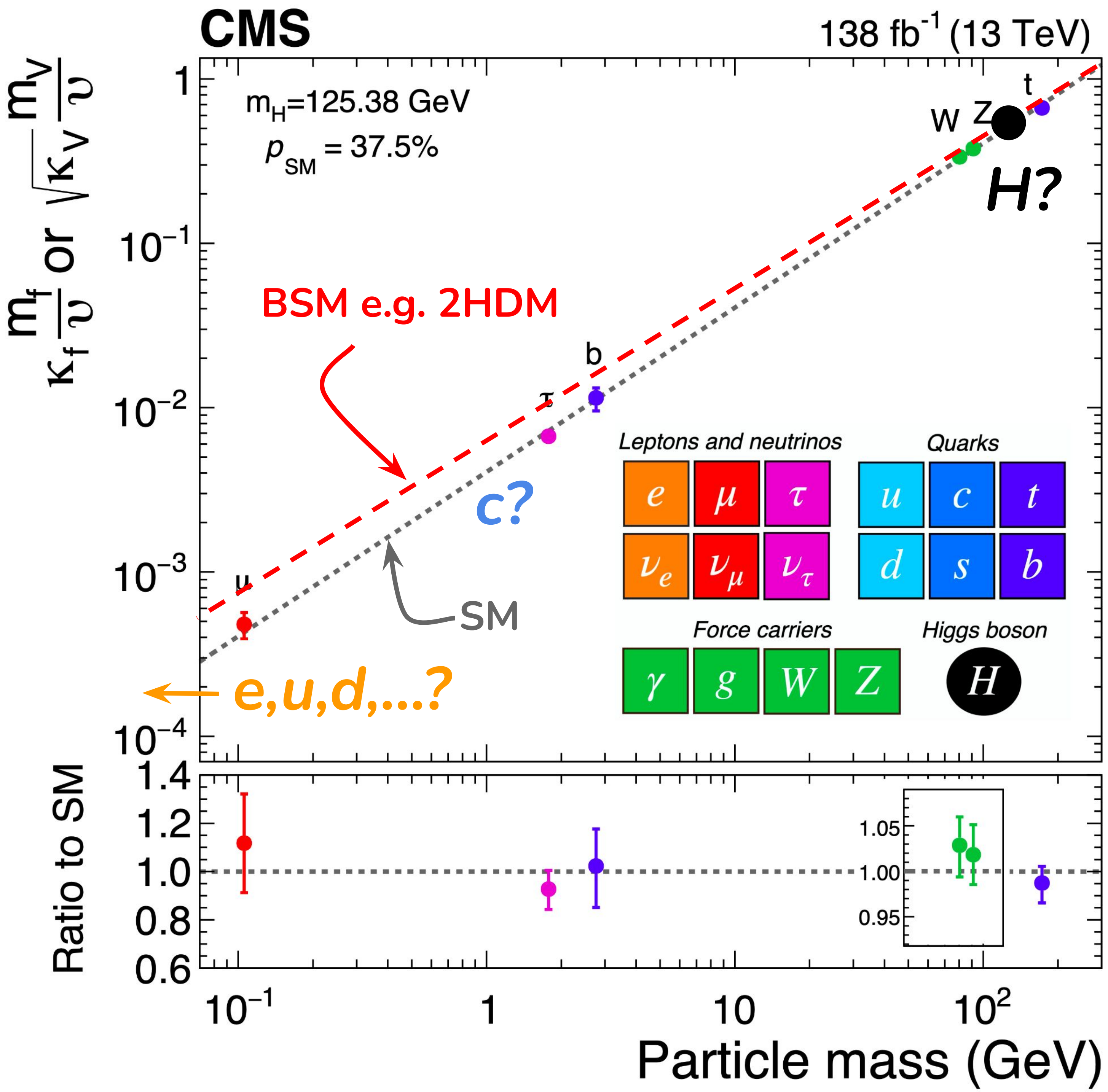
  Do all SM particles lie on that line?

- **Why is the universe matter dominated?**

  Can the Higgs boson self-coupling explain baryogenesis in the early universe?







Overview of analyses

- Rest of talk: present **recent Run 2 CMS Higgs boson combinations** and explain how they address the open questions

1. [CMS-PAS-HIG-23-013]:

   Combination and interpretation of fiducial differential Higgs boson production cross sections at √s = 13 TeV

2. [CMS-PAS-SMP-24-003]:

   Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark and multi-jet measurements

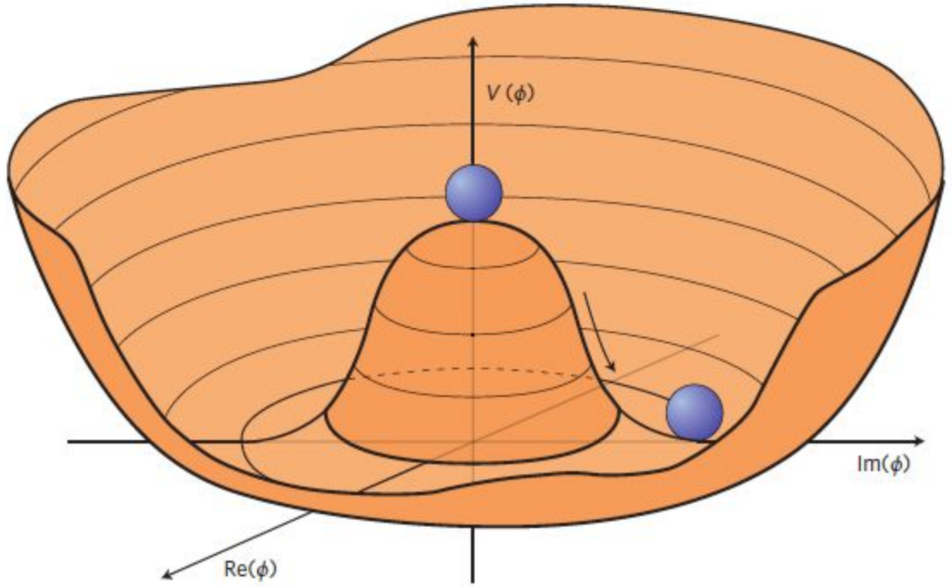
3. [CMS-PAS-HIG-20-011]:

   Combination of searches for nonresonant Higgs boson pair production in p-p collisions at √s = 13 TeV

4. [CMS-HIG-23-006, submitted to Phys. Lett. B]:

   Constraints on the Higgs boson self-coupling with combination of single and double Higgs boson production

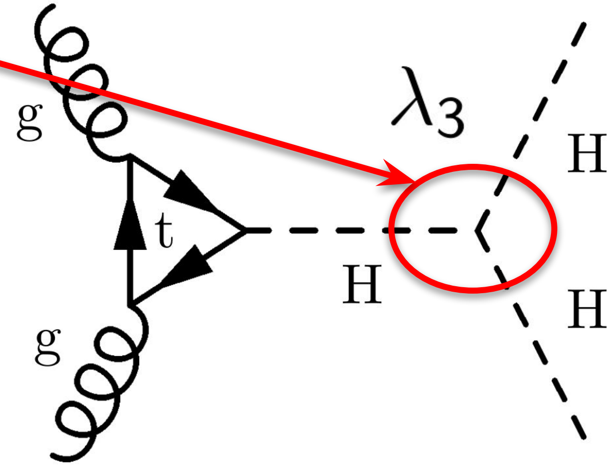
Probing the Higgs potential



- Dynamics of electroweak-symmetry breaking are defined by shape of Higgs potential

$$V(H) = \frac{1}{2} m_H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

- H^3 term generates Higgs-Higgs interactions → Higgs boson self-coupling



- In the SM: $$\lambda_3 = 4\lambda_4 = \frac{m_H^2}{v^2}$$
   - Only parameter regulating shape of potential + fully predicted when mH and v are measured

- Measurements of the Higgs boson self coupling are of the highest priority in the field (see European strategy)
   1. λ_3 is not a free parameter → closure test of the SM
   2. λ_3 regulates shape of potential → test of EWSB and vacuum stability
   3. λ_3 deviations from SM would enable first-order EWSB transition → Could provide mechanism for EW baryogenesis

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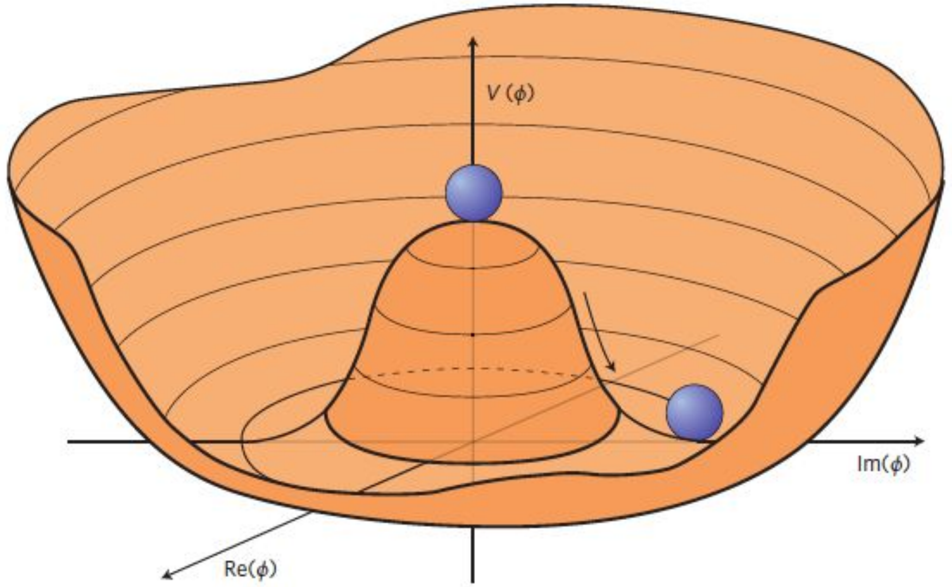

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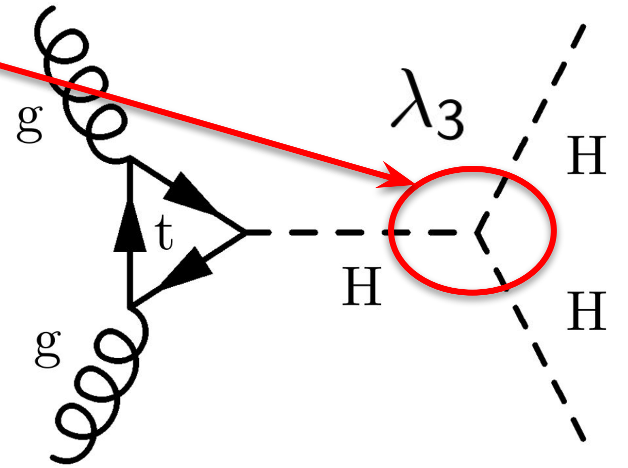

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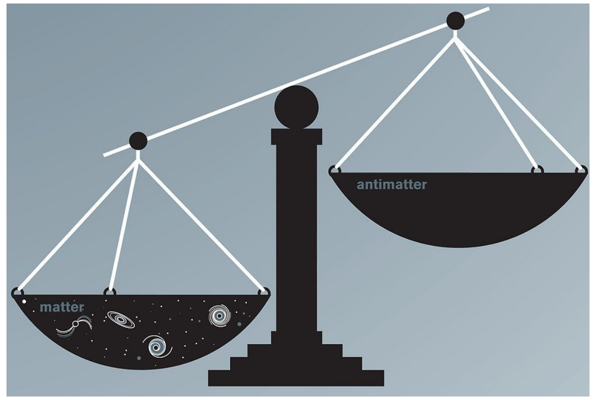
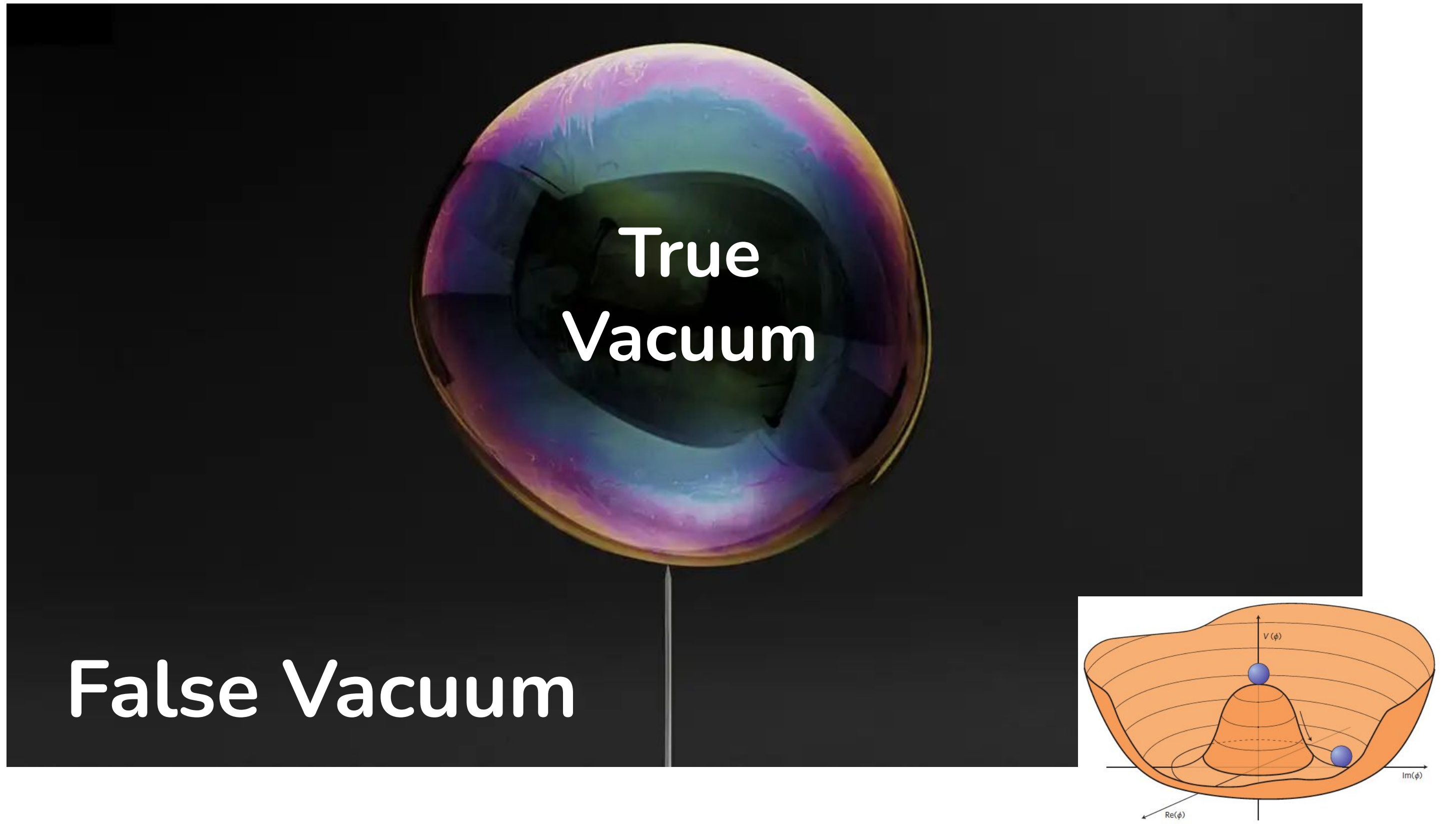
Baryogenesis

- Universe is **matter (baryon) dominated**

$$n_B >> n_{\bar{B}}$$





- **First order phase transition:** essential ingredient for production of B-asymmetry (Baryogenesis) [A. D. Sakharov, *ETP Lett.* 5 (1967) 24-27]
    - Sharp discontinuity in state of Universe → nucleation of "bubbles" of the new phase within old phase (out-of-equilibrium)
- **Electroweak Baryogenesis?** Bubbles of Higgs field true vacuum in background of false vacuum
    - As bubbles expand → create regions where CP-violating interactions occur at bubble walls → B-asymmetry
    - A smooth second-order transition would not generate required asymmetry

Electroweak baryogenesis

- To achieve first-order phase transition in EWSB we **need a modified Higgs potential**

$$V = \underbrace{\frac{\mu^2}{2}(v+H)^2 + \frac{\lambda_4}{4}(v+H)^4}_{\text{SM}} + \underbrace{\frac{\lambda_6}{\Lambda^2}(v+H)^6}_{\text{BSM}}$$

SM

BSM

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- Inclusion of dim-6 (BSM) term in potential changes relationship between fundamental Higgs parameters

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}} = 1 + \frac{16\lambda_6 v^4}{m_H^2\Lambda^2}$$

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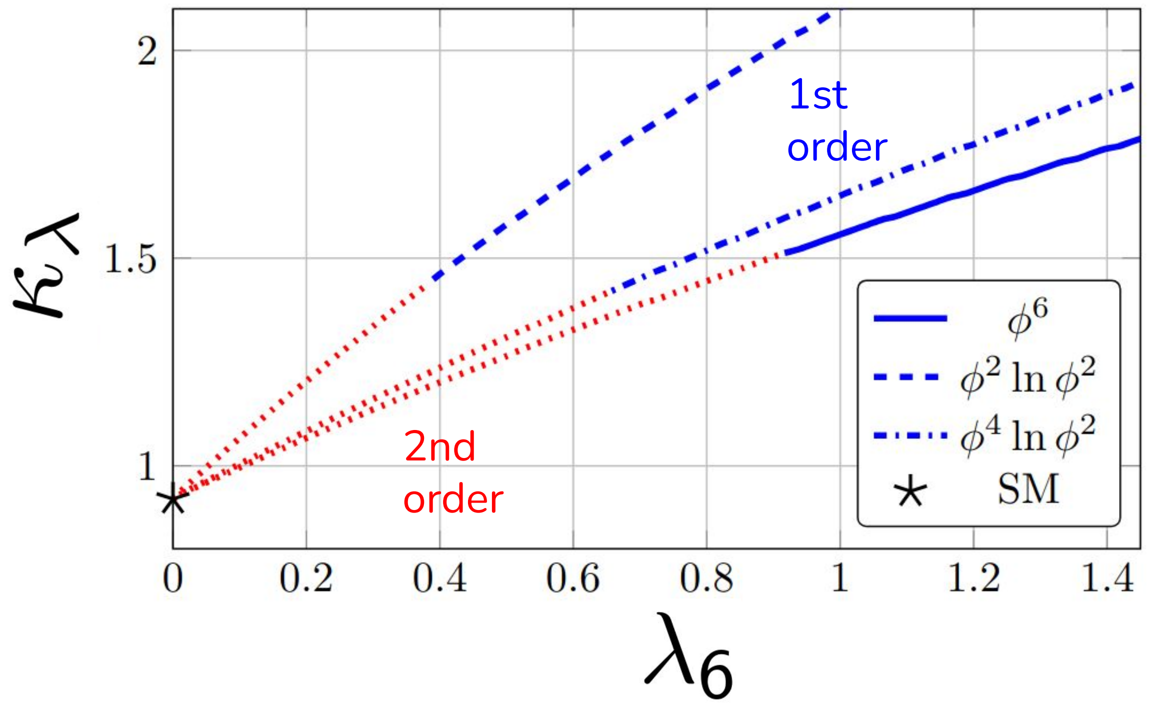
[Phys. Rev. D 97, 075008 (2018)]



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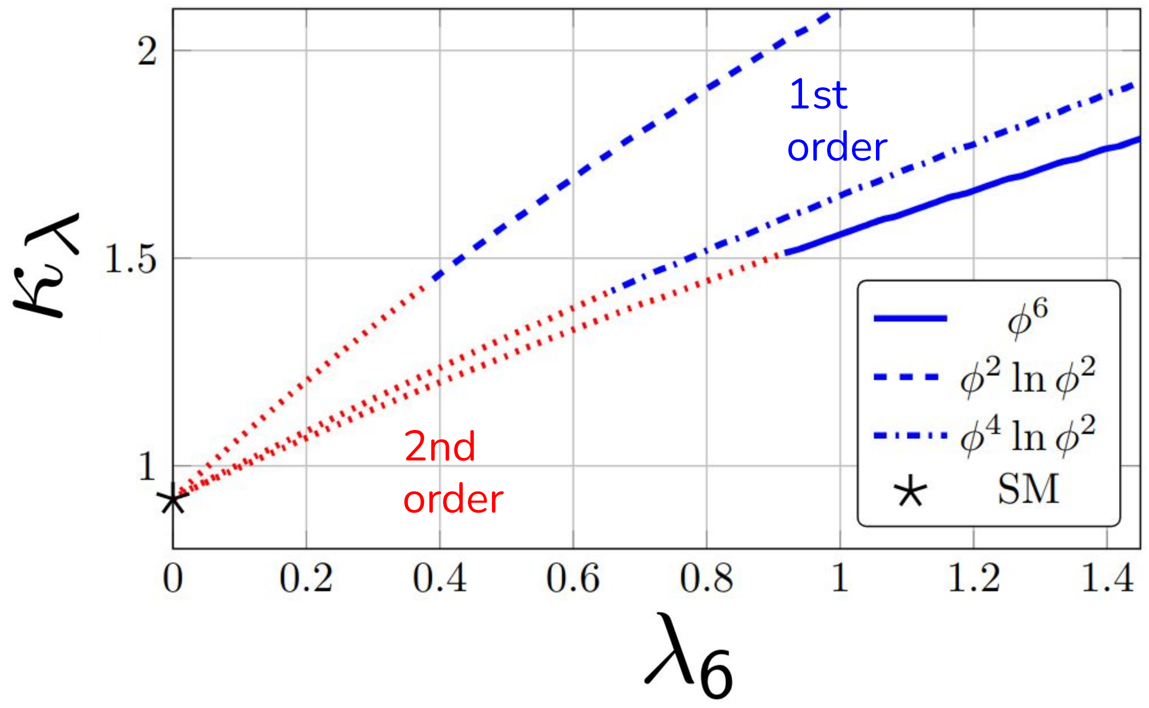

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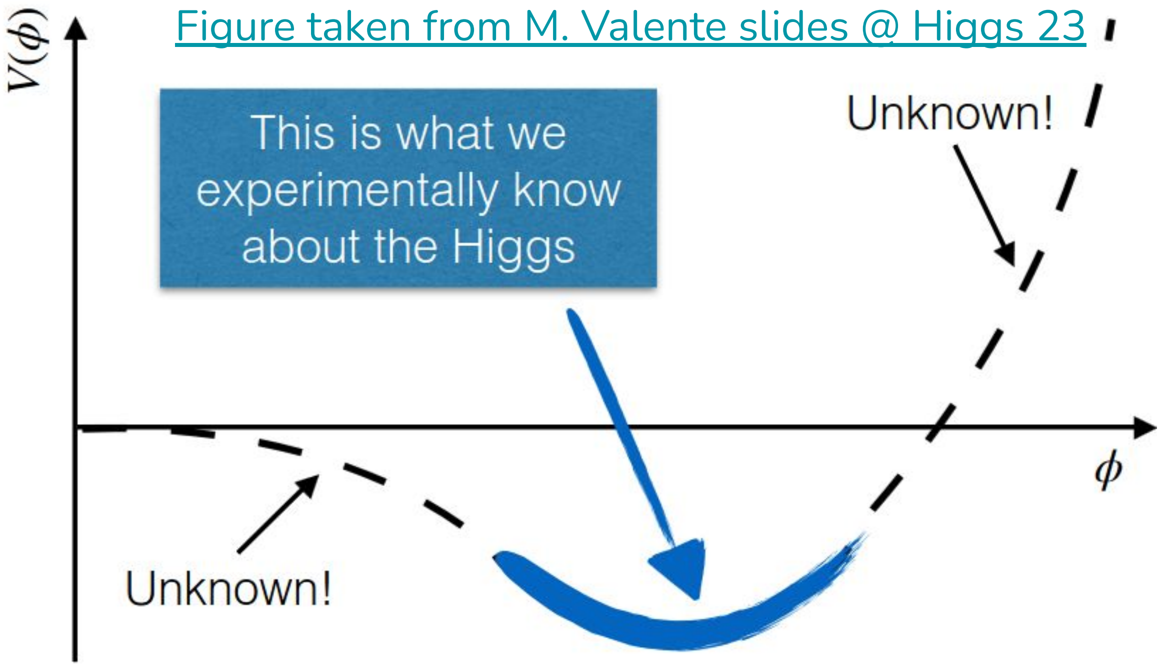
Figure taken from M. Valente slides @ Higgs 23

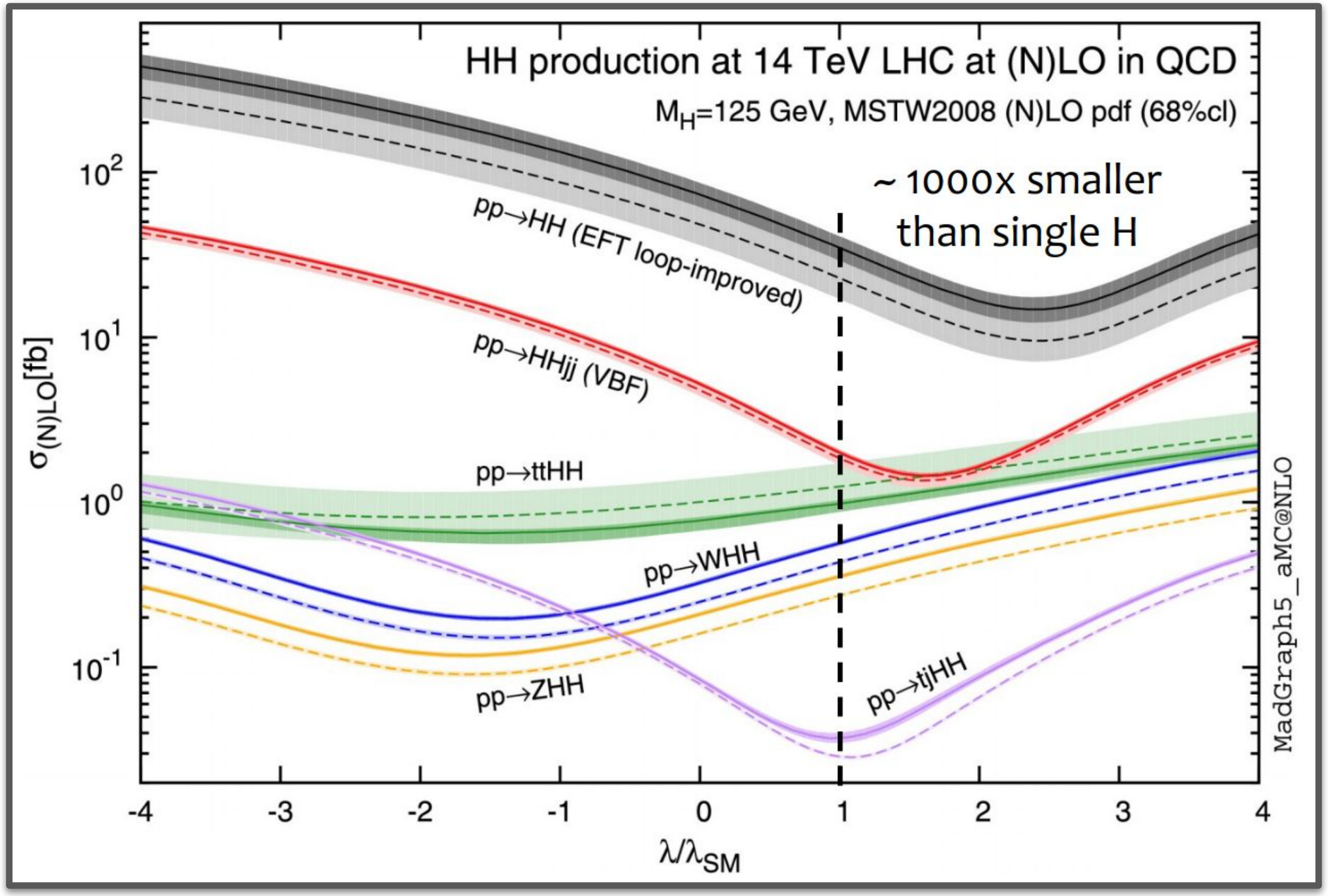


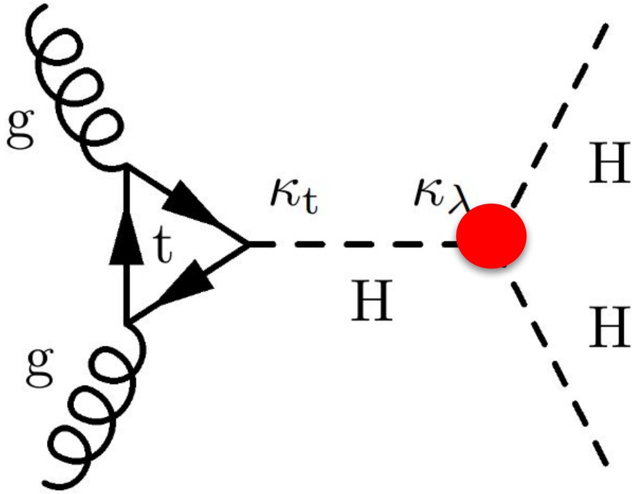
- **50% increase in self-coupling → Provides mechanism for first-order EW phase transition**
  - Increasing our precision on λ_3 is of paramount important to understanding evolution of the early Universe!

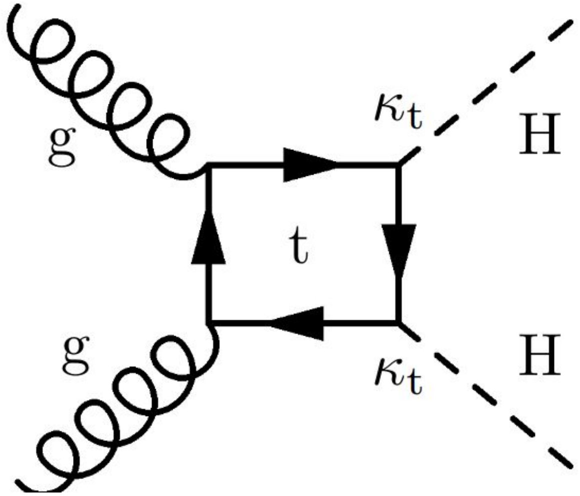
Di-Higgs production

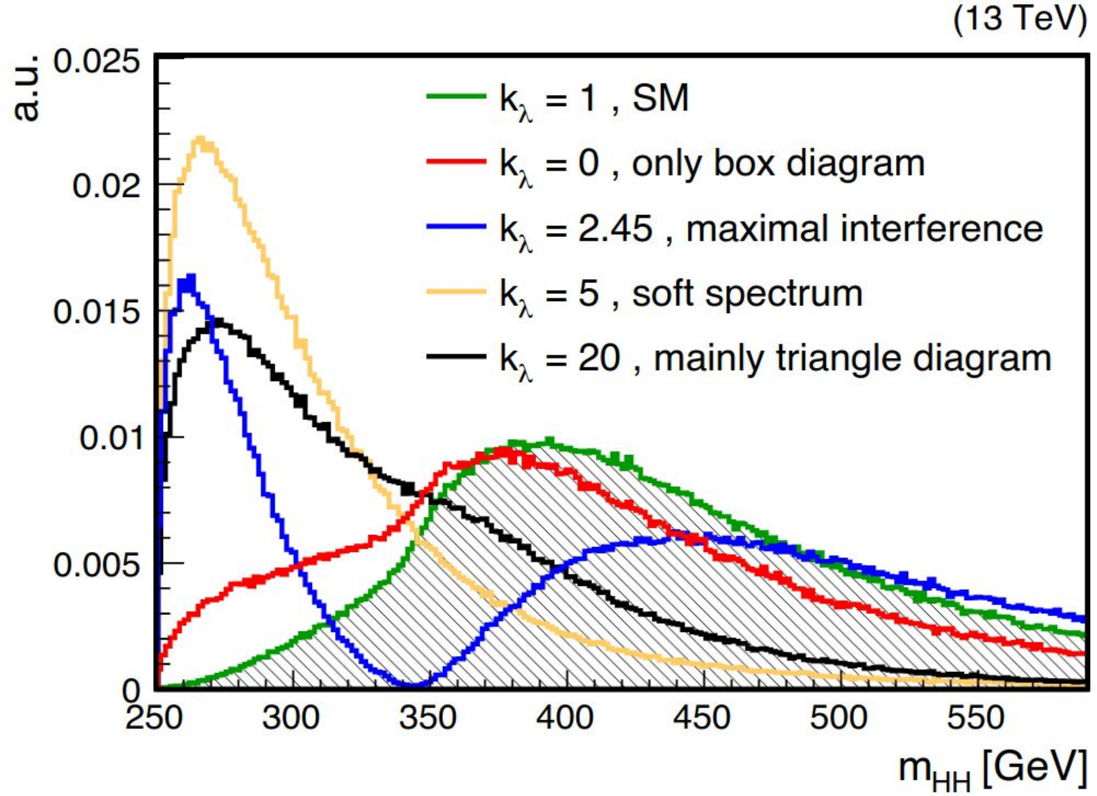
$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

- How to probe the Higgs self-coupling? → Only direct method via search for **non-resonant Higgs boson pair production**





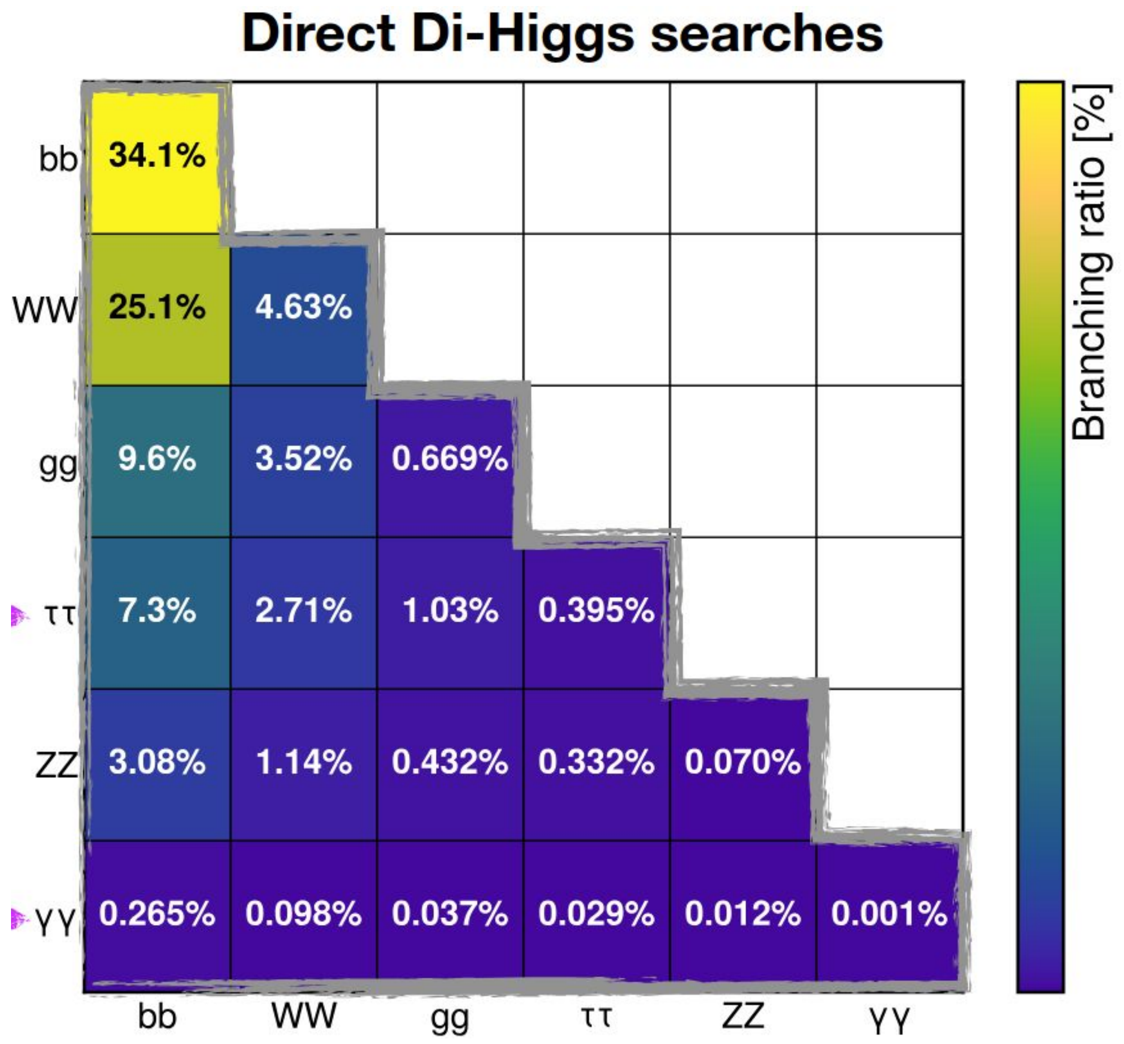




- Cross section: $\sigma_{ggHH} = 31.05 \text{ fb}$
- Destructive interference between triangle and box diagrams

A big step in Run 2

- Large statistics of Run 2 dataset has enabled CMS to gain significant ground in measuring this rare process
- Plethora of HH final states offers a fun experimental challenge



[Taken from Jona Motta slides @ Higgs 24]()

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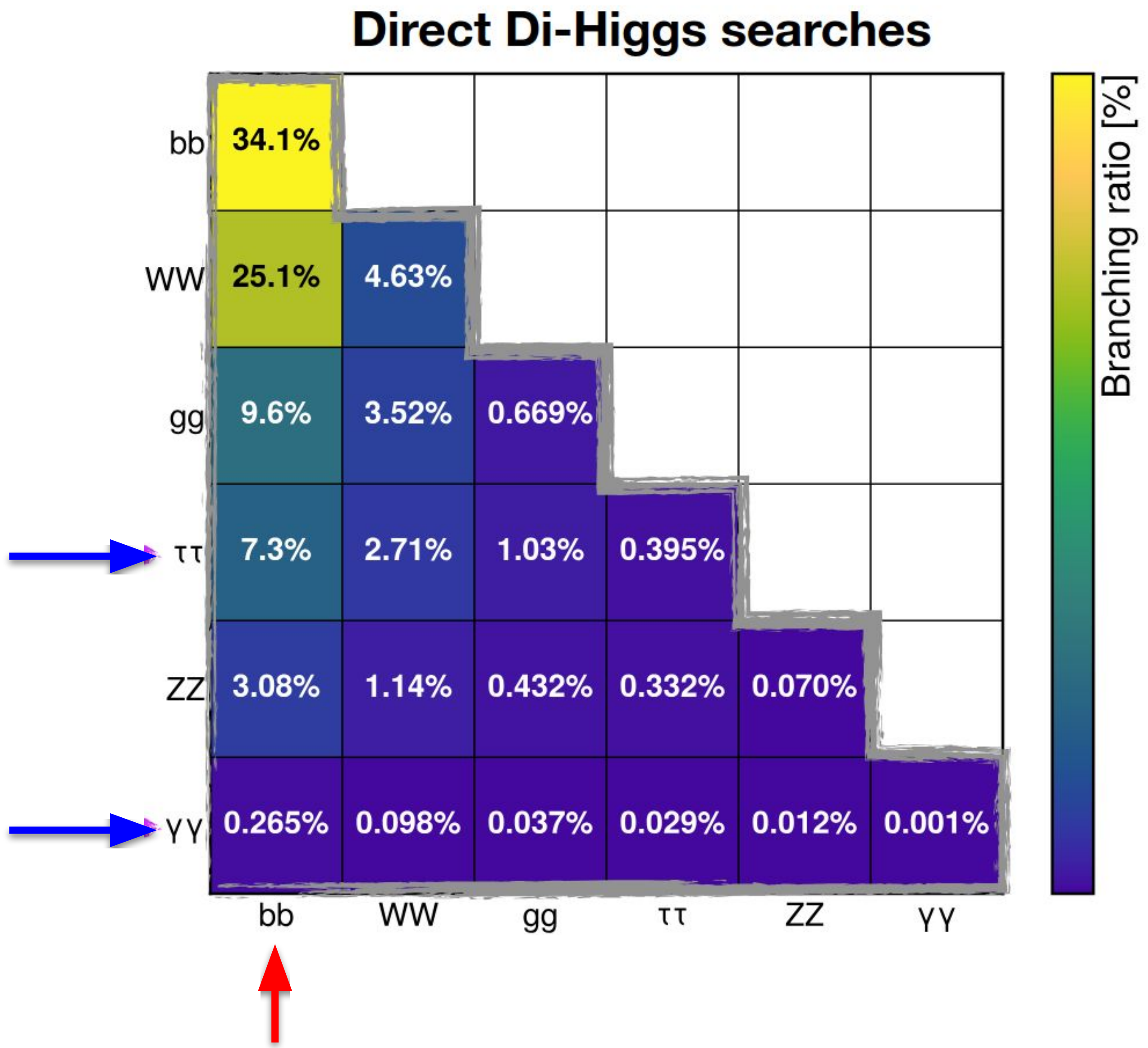

Taken from Jona Motta slides @ Higgs 24

Given current luminosity and large backgrounds we typically leverage:

1. **Large branching fraction**
2. **Good selection purity**
3. **Combination of (1) and (2)**

Three “main” channels: HH→4b, HH→bb$\tau\tau$, HH→bb$\gamma\gamma$

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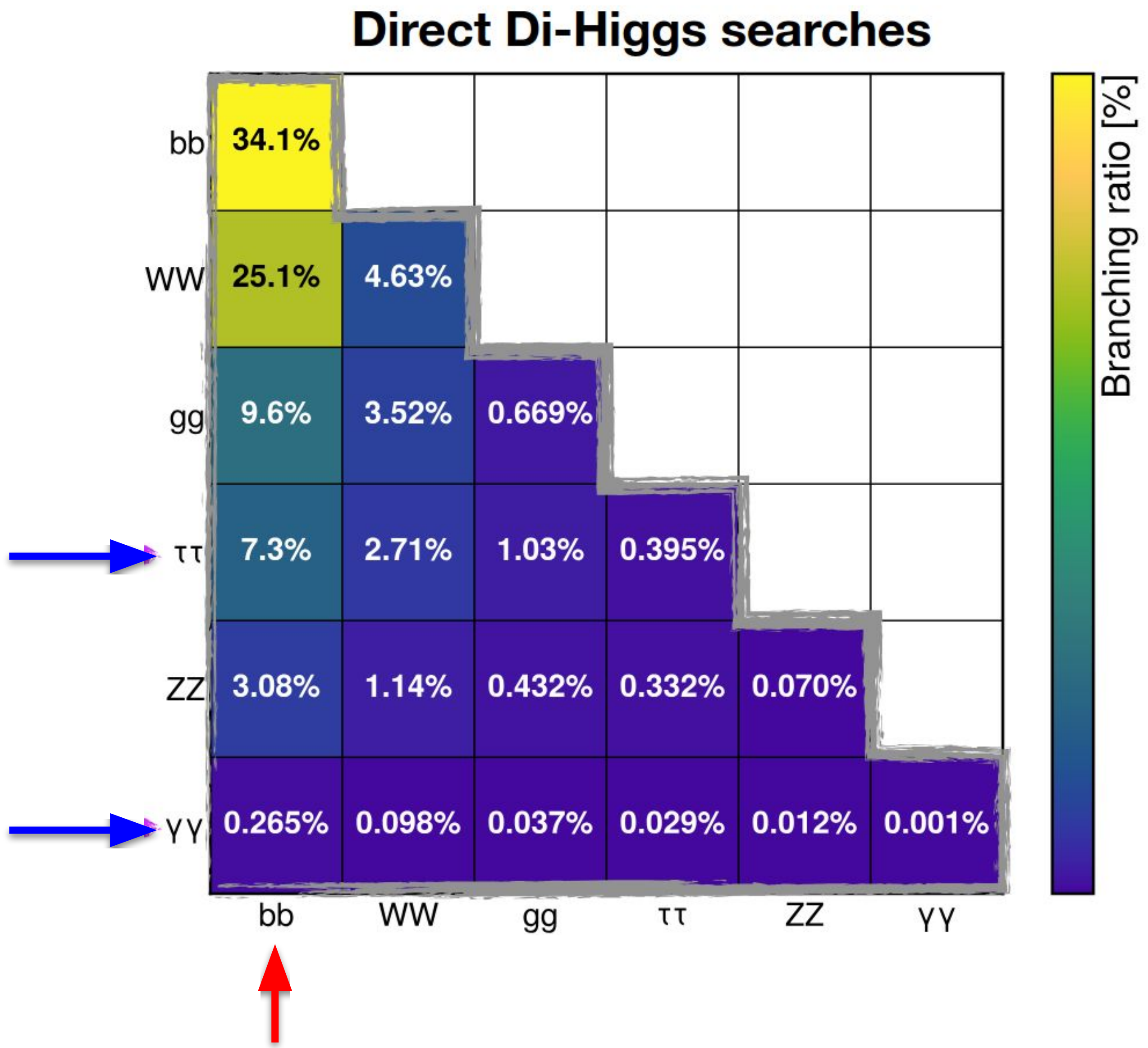

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Significant advancements in reconstruction and identification techniques (e.g. Machine Learning) has allowed us to move away from these constraints…

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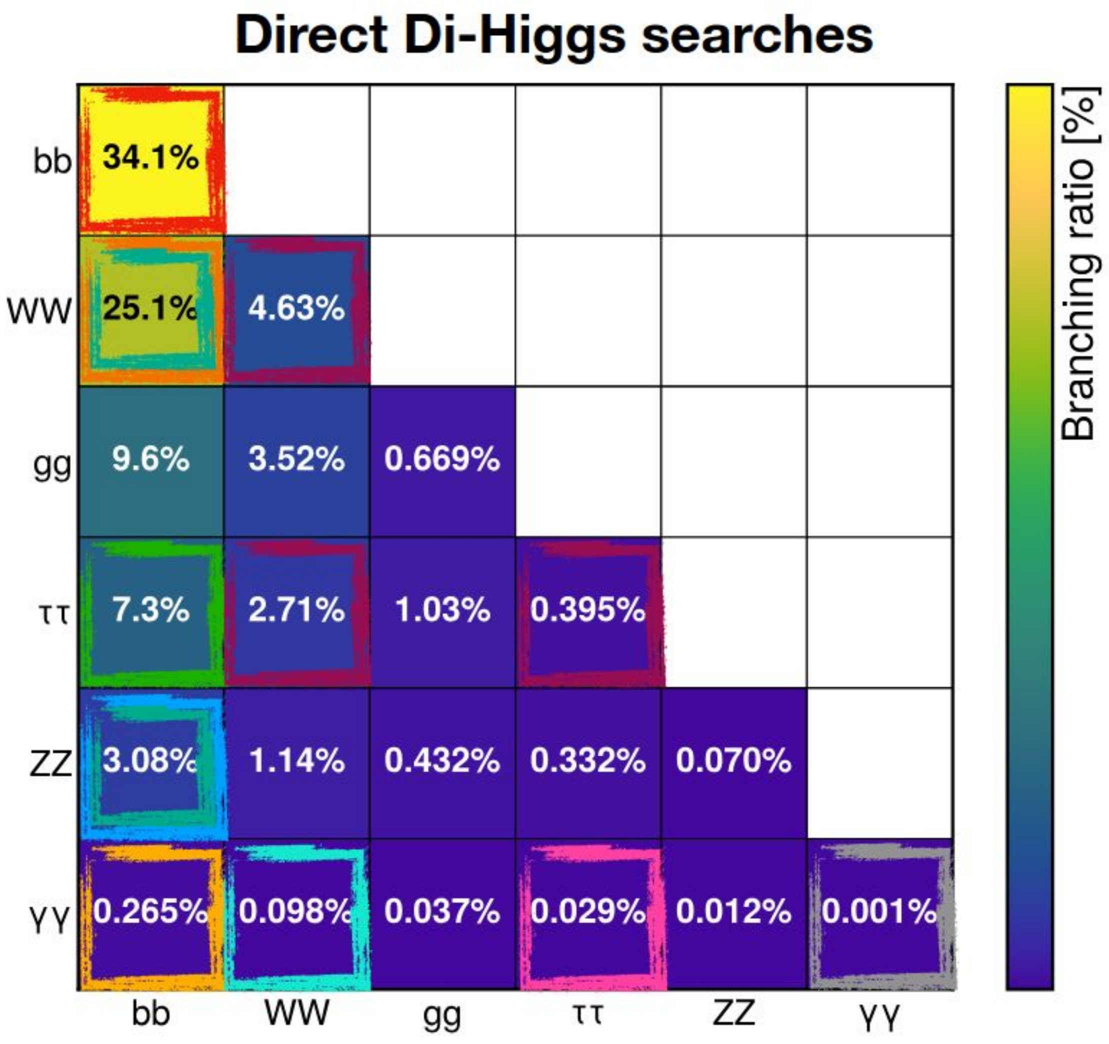


Taken from Jona Motta slides @ Higgs 24

HH → bbbb Non-resonant, resolved topology Phys. Rev. Lett. 129.081802
Non-resonant, boosted topology Phys. Rev. Lett. 131.041803
Non-resonant, VHH production CMS-PAS-HIG-22-006
Resonant X→YH Phys. Lett. B 842.137392

HH → bb$\tau\tau$ Non-resonant Phys. Lett. B 842.137531
Resonant X→YH JHEP 11 (2021) 057

HH → bb$\gamma\gamma$ Non-resonant JHEP 03 (2021) 257
Resonant X→YH CMS-PAS-HIG-21-011

HH → bbZZ Non-resonant JHEP 06 (2023) 130
Resonant Phys. Rev. D. 102.032003

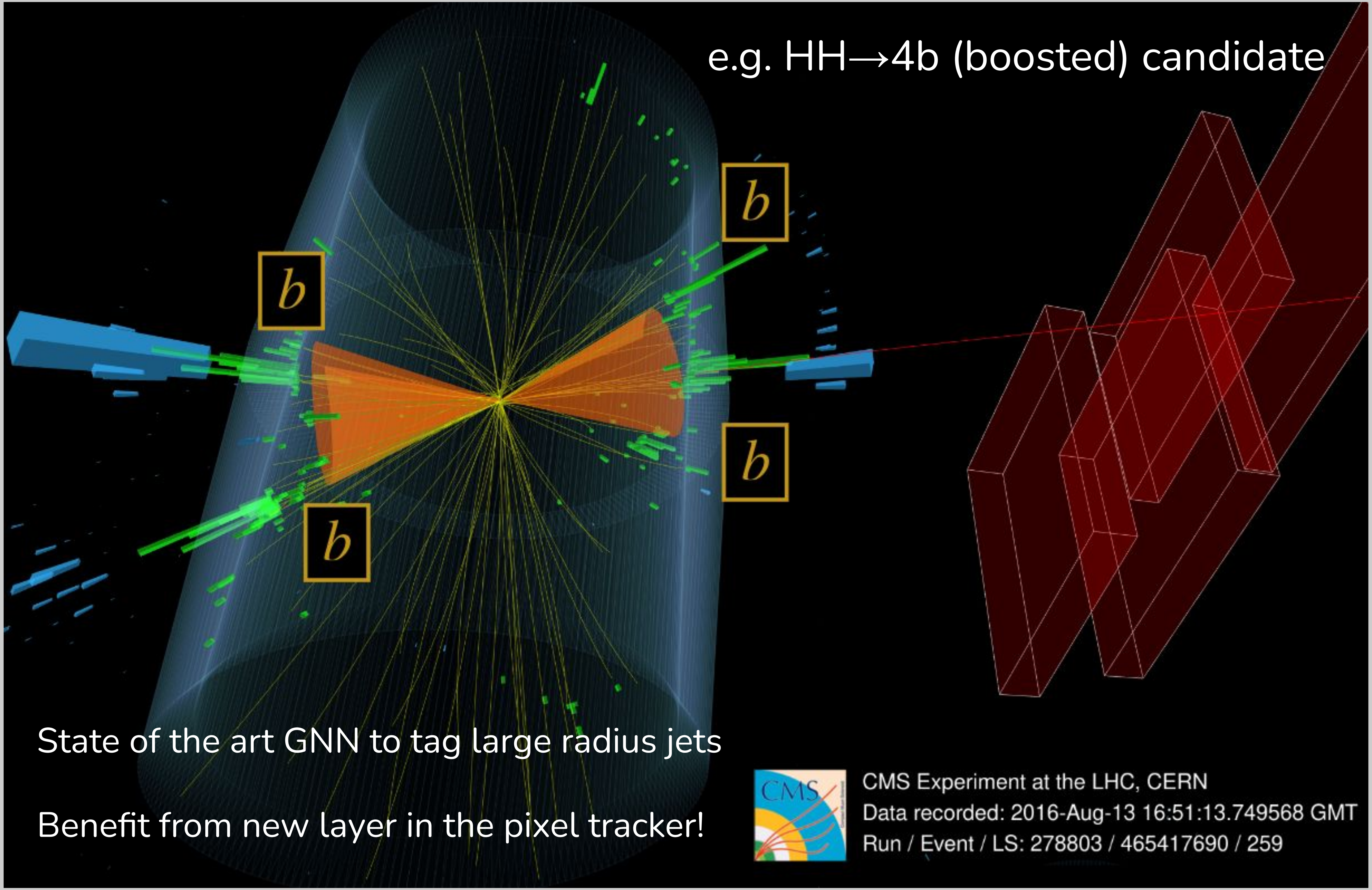
HH → bbWW Non-resonant + Resonant JHEP 07 (2024) 293
Resonant JHEP 05 (2022) 005

HH → bbVV Non-resonant, fully hadronic boosted topology CMS-PAS-HIG-23-012

HH → WW$\gamma\gamma$ Non-resonant CMS-PAS-HIG-21-014

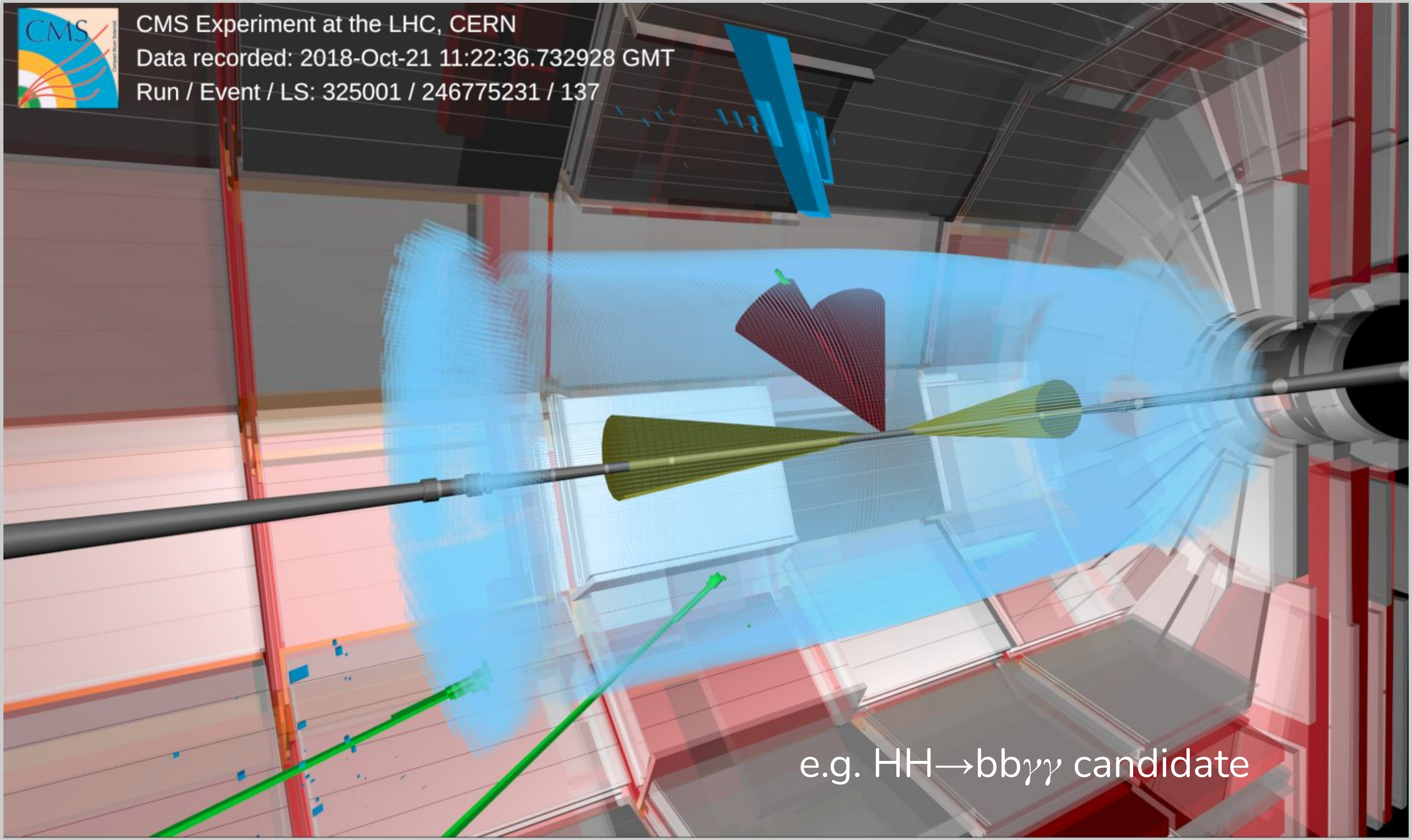
HH → $\gamma\gamma\tau\tau$ Non-resonant + Resonant CMS-PAS-HIG-22-012

HH → WWWW + WW$\tau\tau$ + $\tau\tau\tau\tau$ Non-resonant + Resonant JHEP 07 (2023) 095 e.g. HH→4b (boosted) candidate



State of the art GNN to tag large radius jets

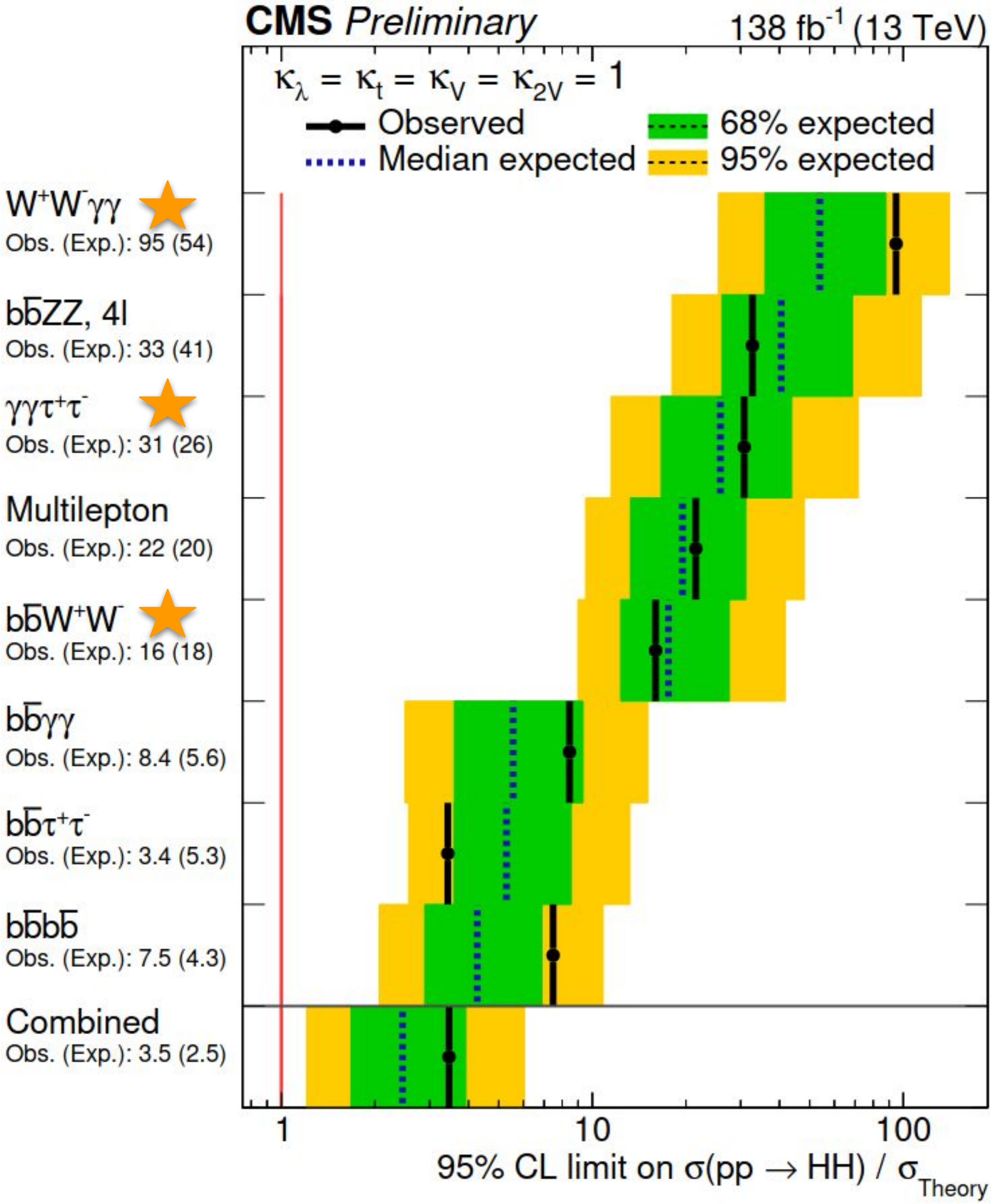
Benefit from new layer in the pixel tracker!


CMS Experiment at the LHC, CERN
Data recorded: 2018-Oct-21 11:22:36.732928 GMT
Run / Event / LS: 325001 / 246775231 / 137
e.g. HH→bbγγ candidate

Combination of non-resonant HH production

NEW NOV 24

- Brand new result from ~two weeks ago [HIG-20-011]
- Updated HH combination from Nature 607 (2022) 60-68
  - **Additional channels**, more interpretations, expanded projections



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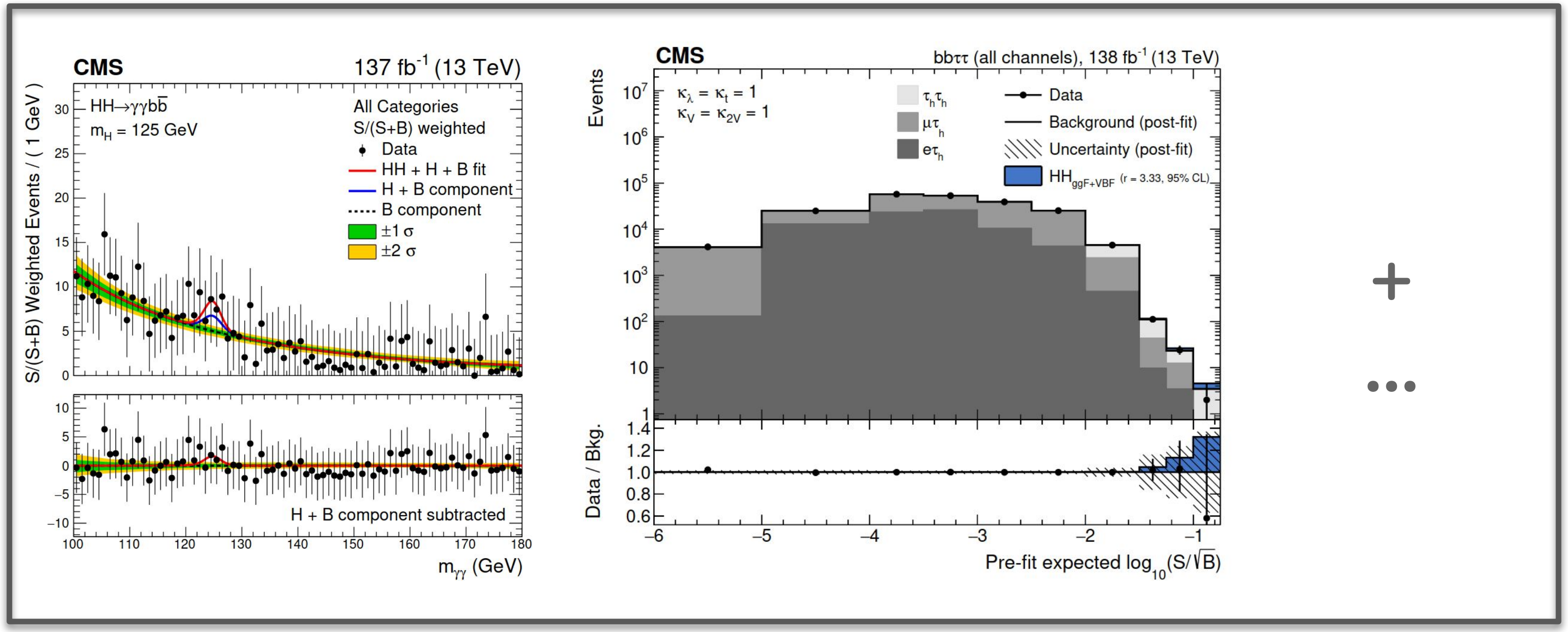
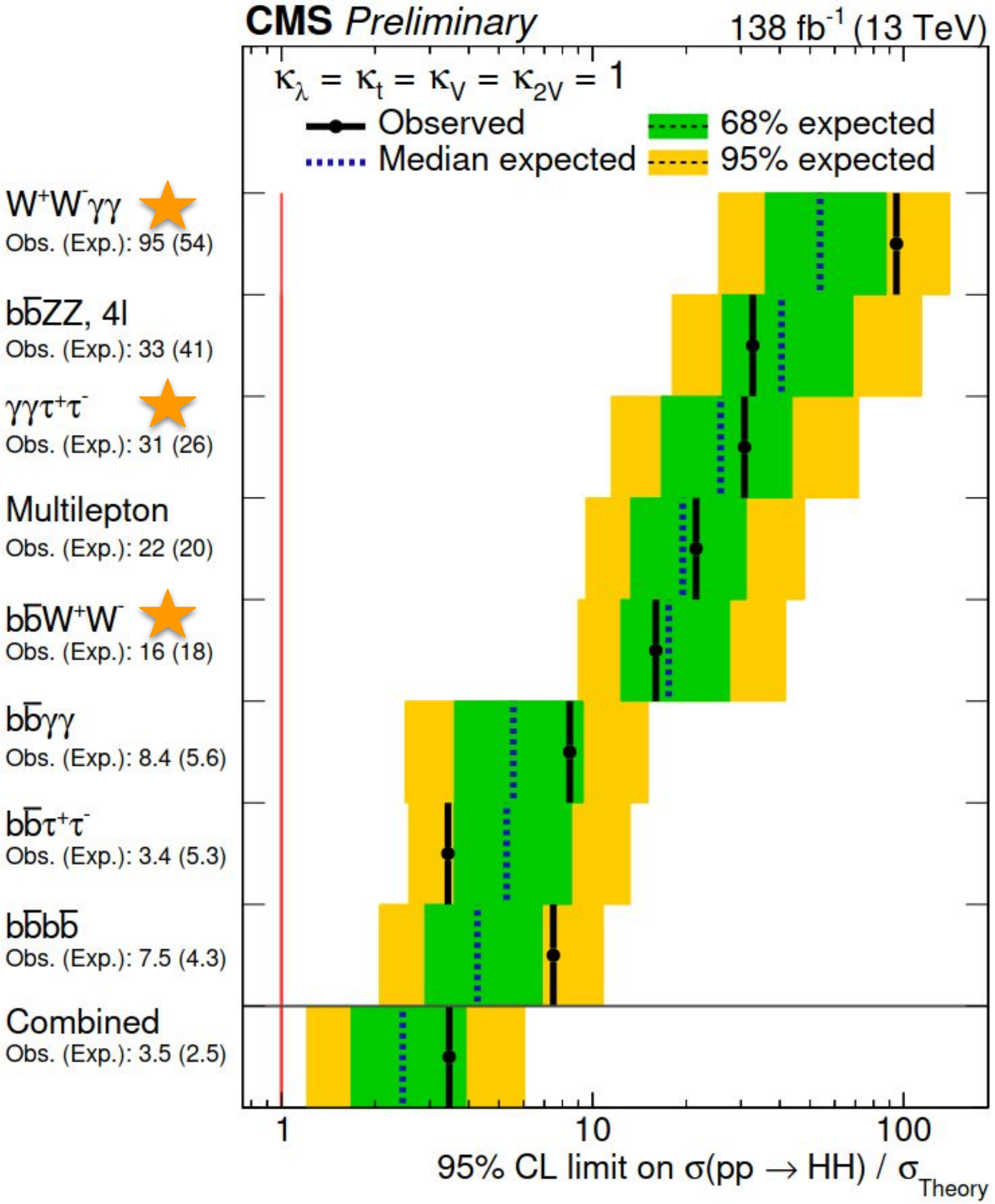
Parameters of interest e.g. κ_λ

Nuisance parameters with correlation scheme





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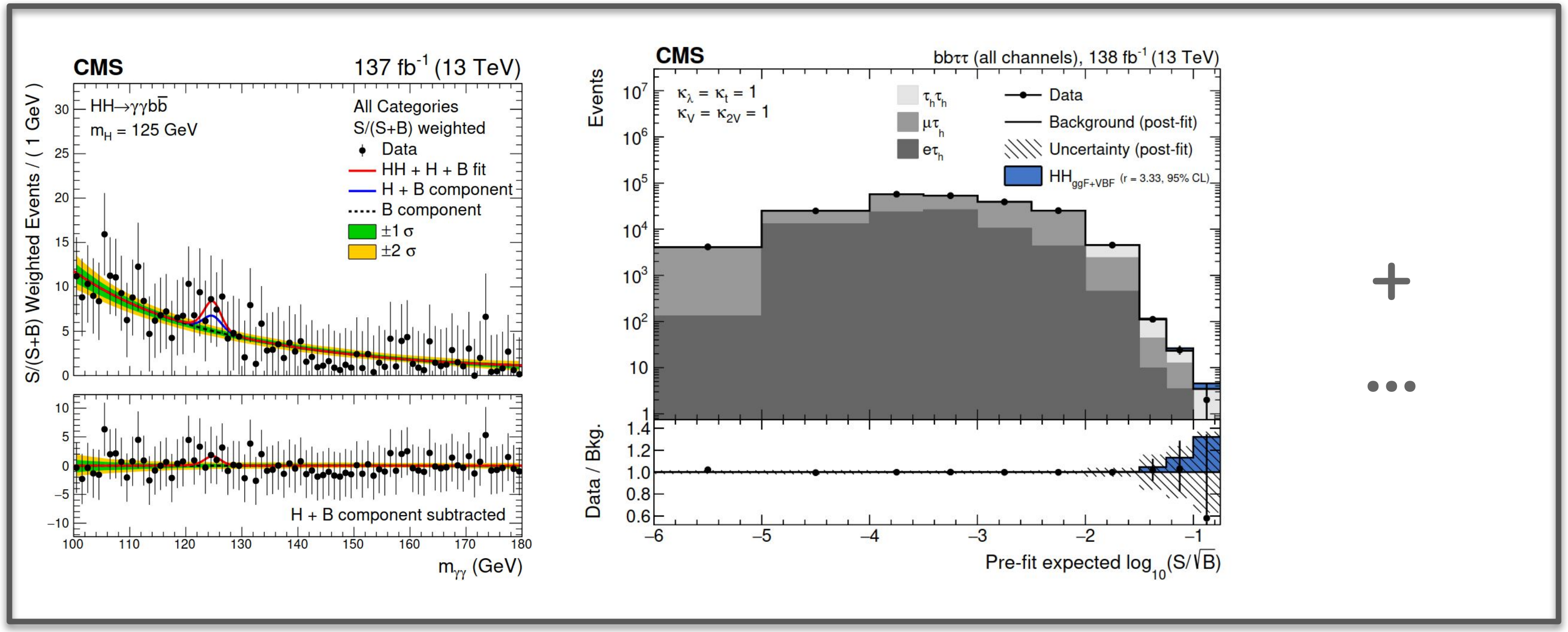
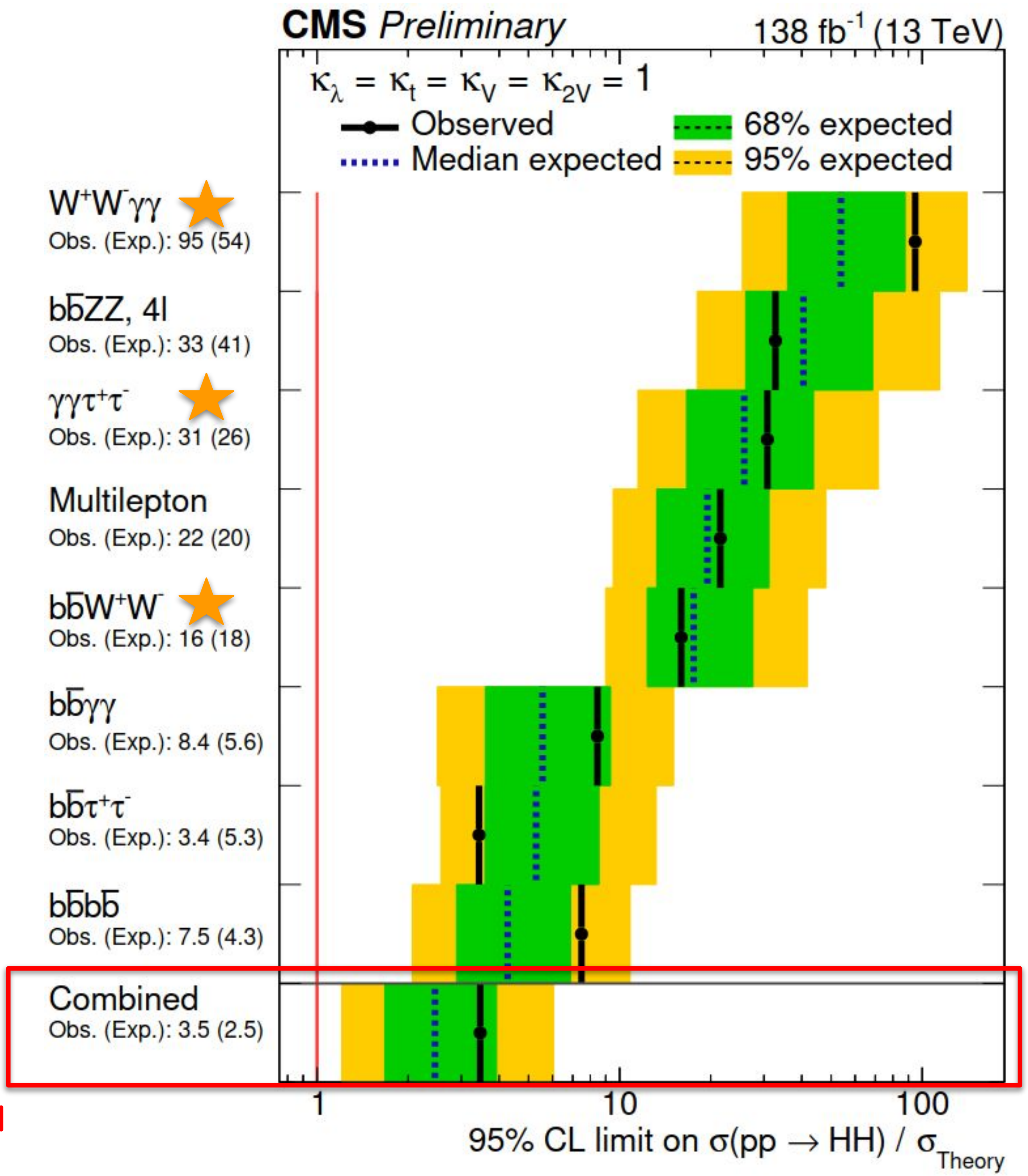


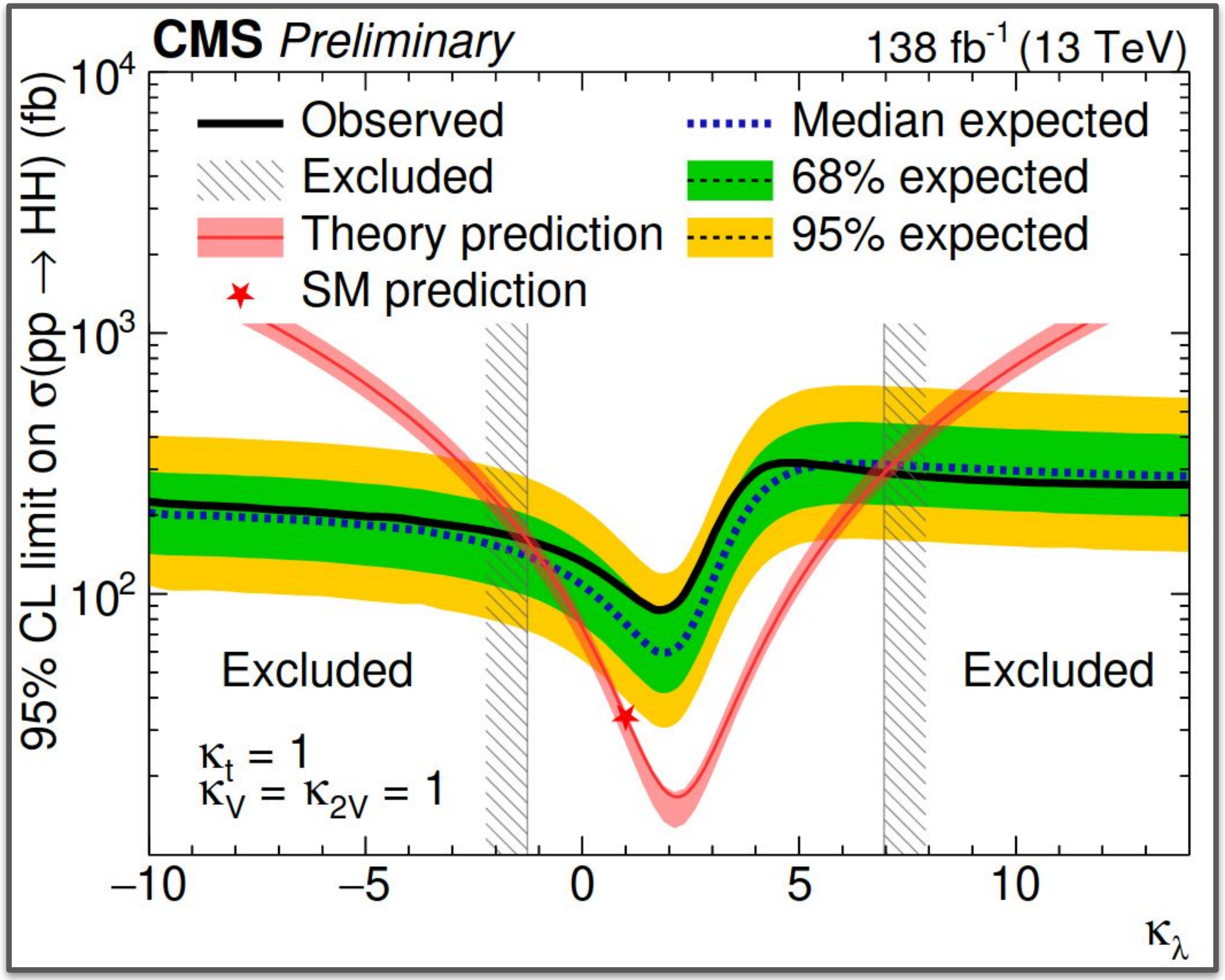


Observed (expected) upper limit on SM HH cross section: 3.5 (2.5) times SM

Self-coupling sensitivity

$$\sigma(\kappa_\lambda, \kappa_t) = \kappa_\lambda^2 \kappa_t^2 t + \kappa_t^4 b + \kappa_\lambda \kappa_t^3 i$$

- ggHH signal dependence on $(\kappa_\lambda, \kappa_t)$ modelled using linear combination of three simulated data samples



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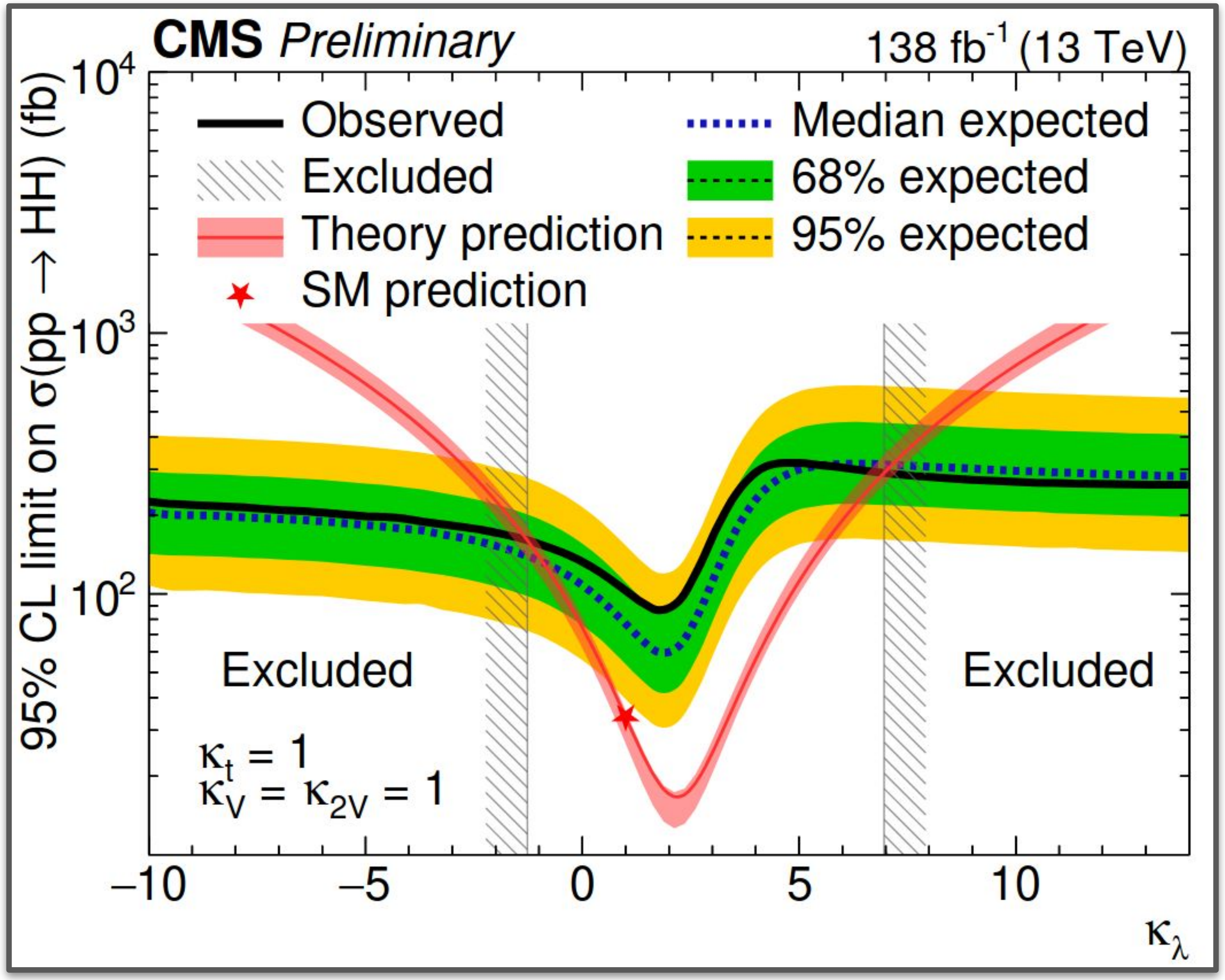

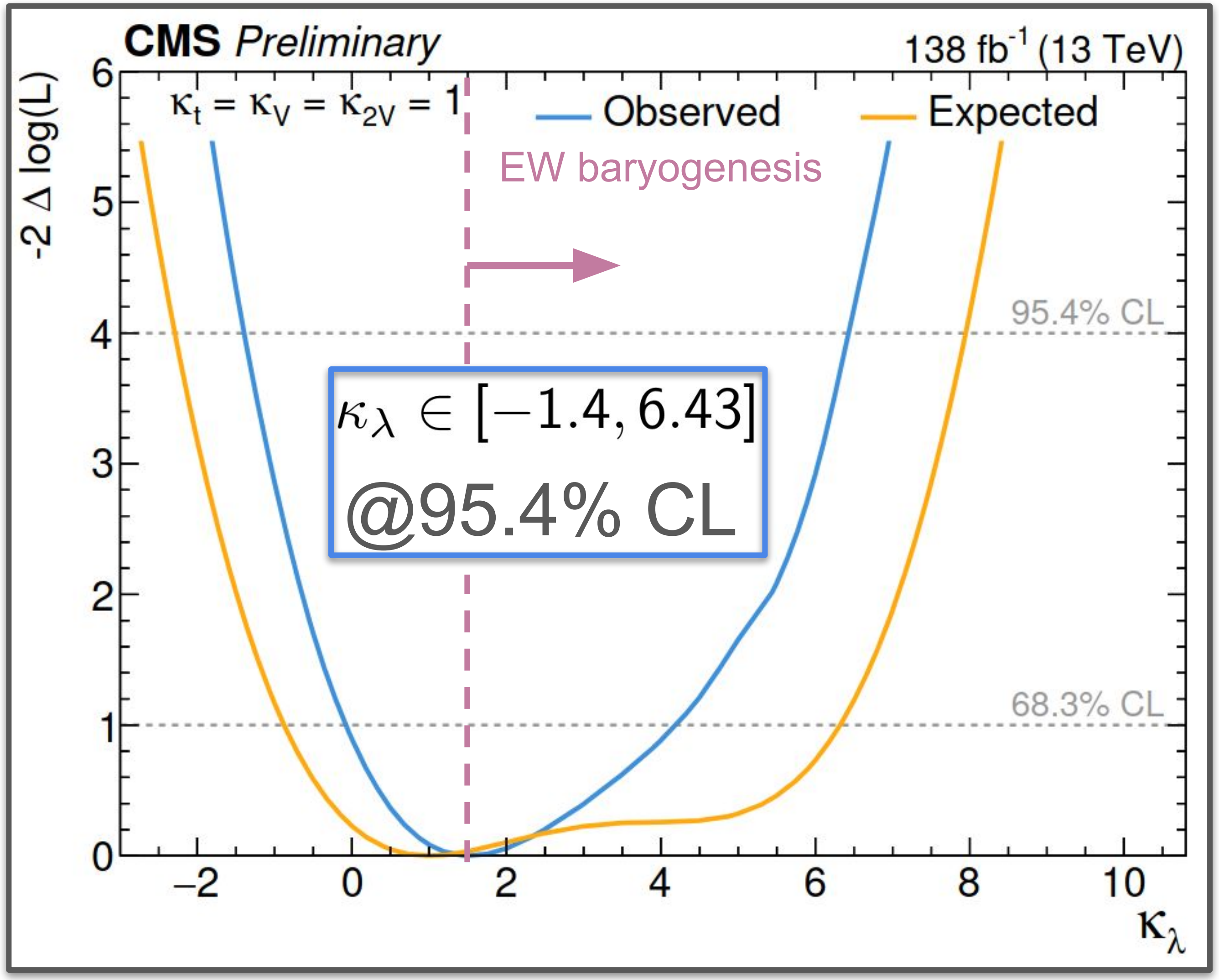

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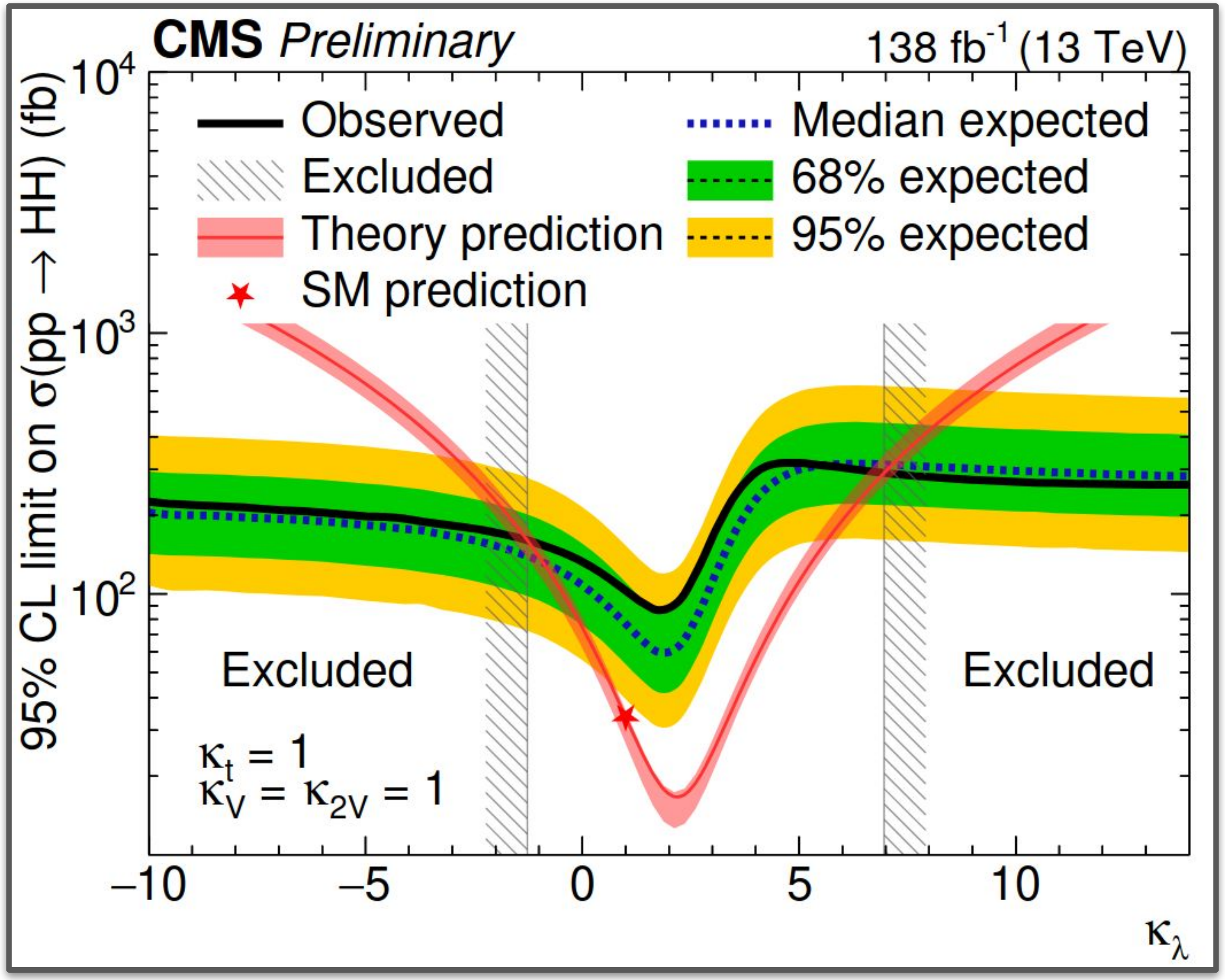
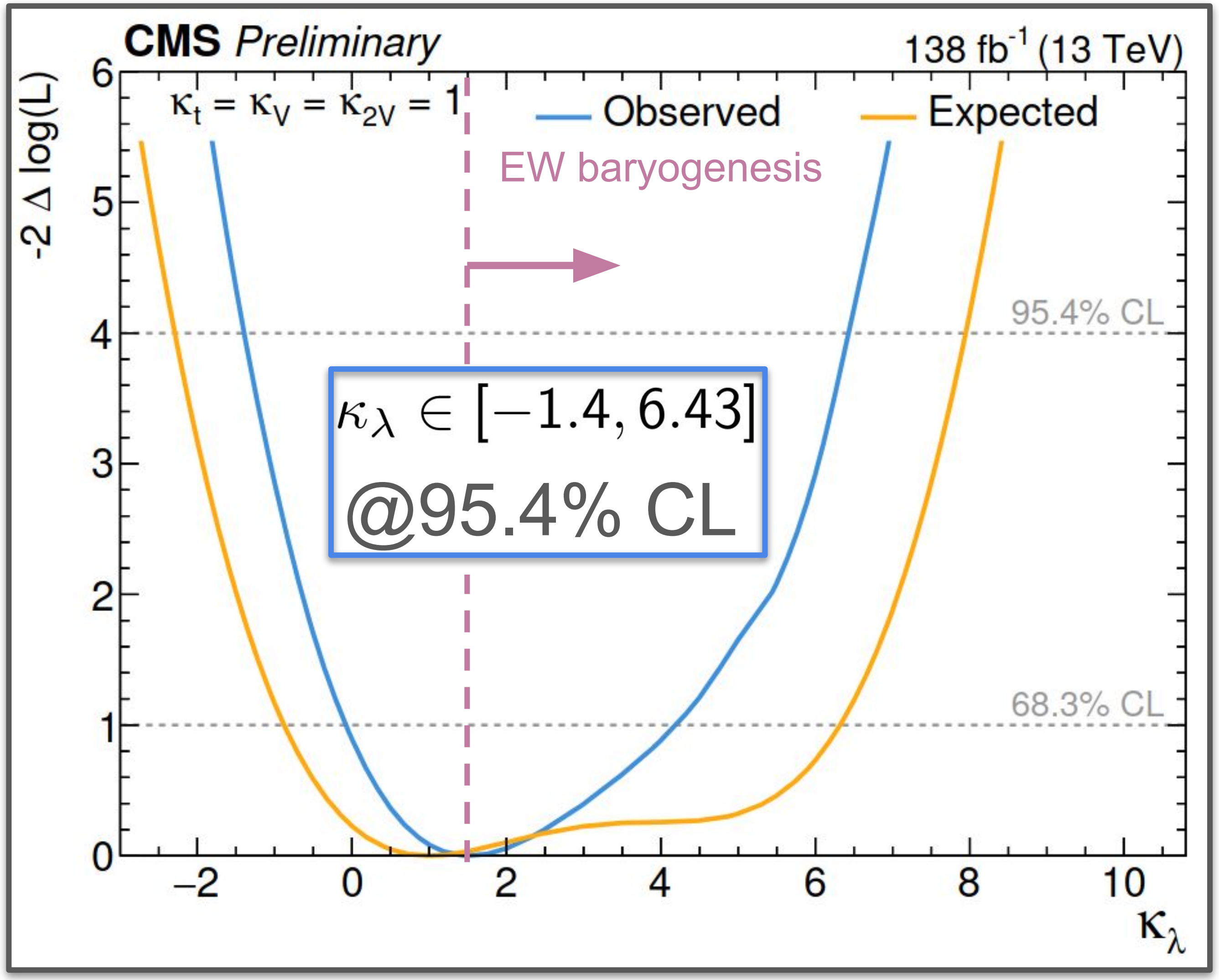


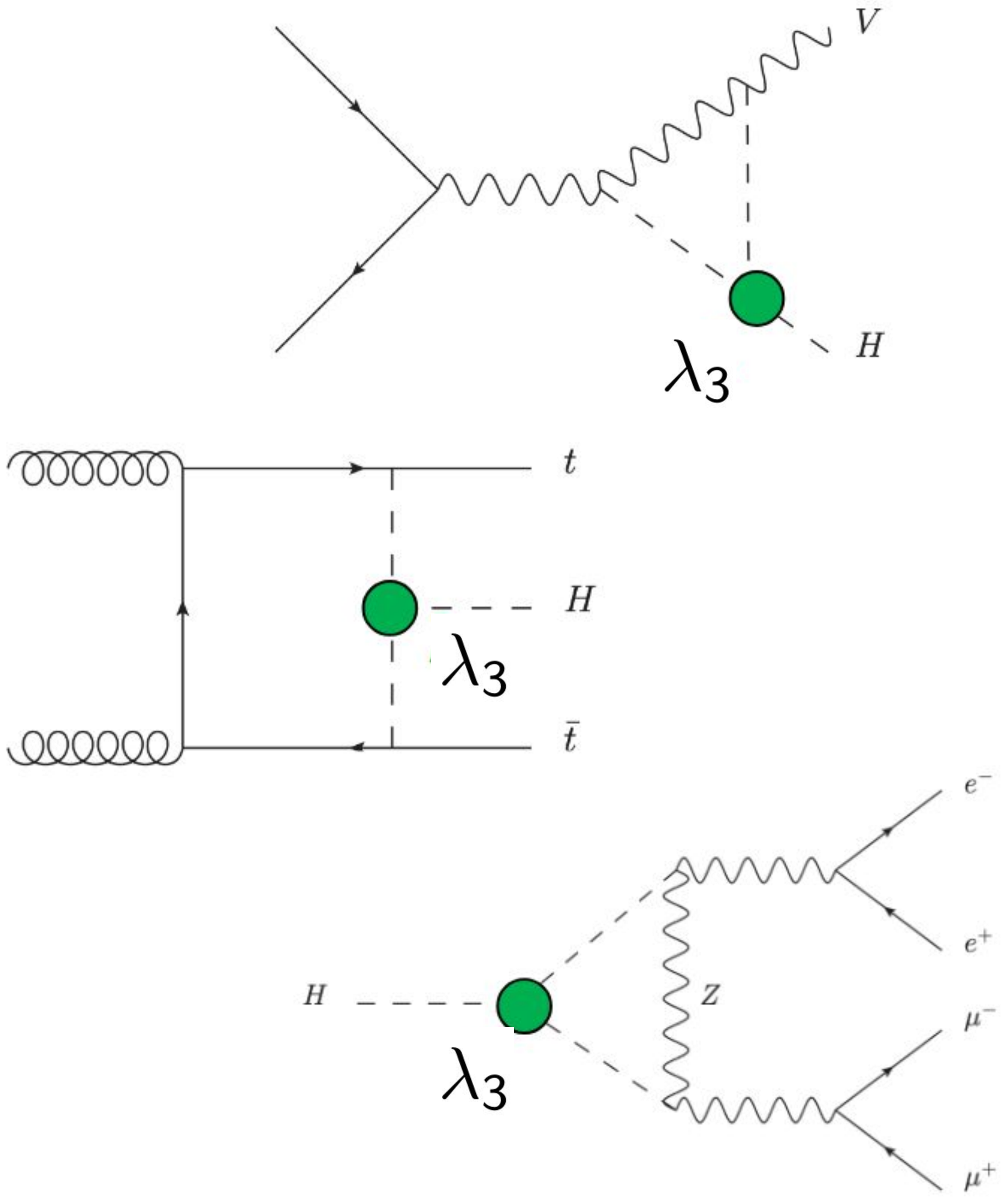


- **Vast improvements to 2016-only results**: ~5x stronger constraints (expect to be ~2x from increase in statistics alone)
  - Driven by advancements in analysis techniques e.g. GNN for b-jet tagging
- Many more interpretations in note: VBFHH production and κ_{2V} constraints, HEFT benchmarks, c2, UV-complete, ...

Combination of H and HH production

PAPER SUBMITTED JULY 24

- Ultimate κ_λ sensitivity comes by combining with indirect constraint from single-Higgs production
- NLO EW corrections to single Higgs boson production and decay involve **Higgs self-coupling**



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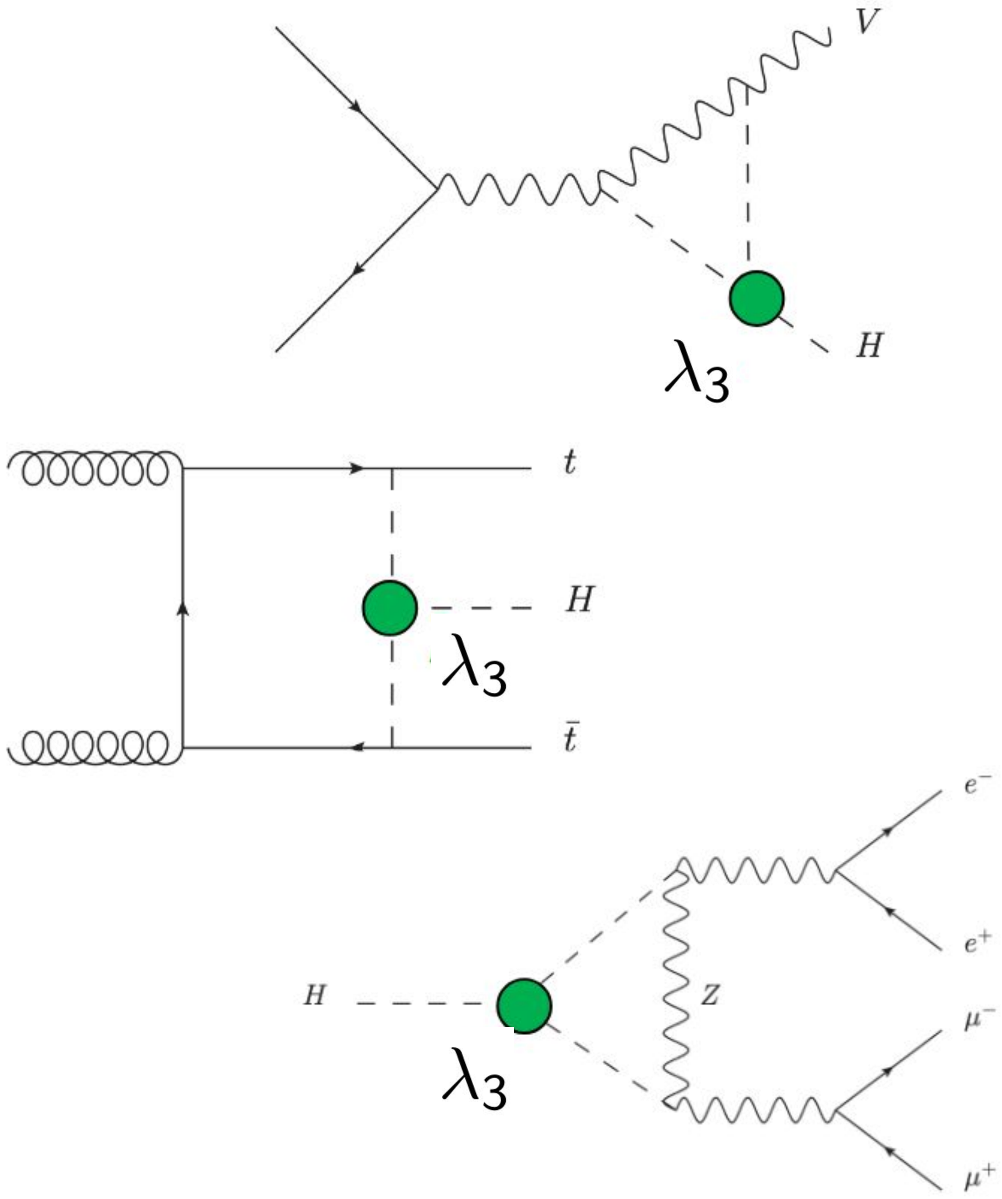
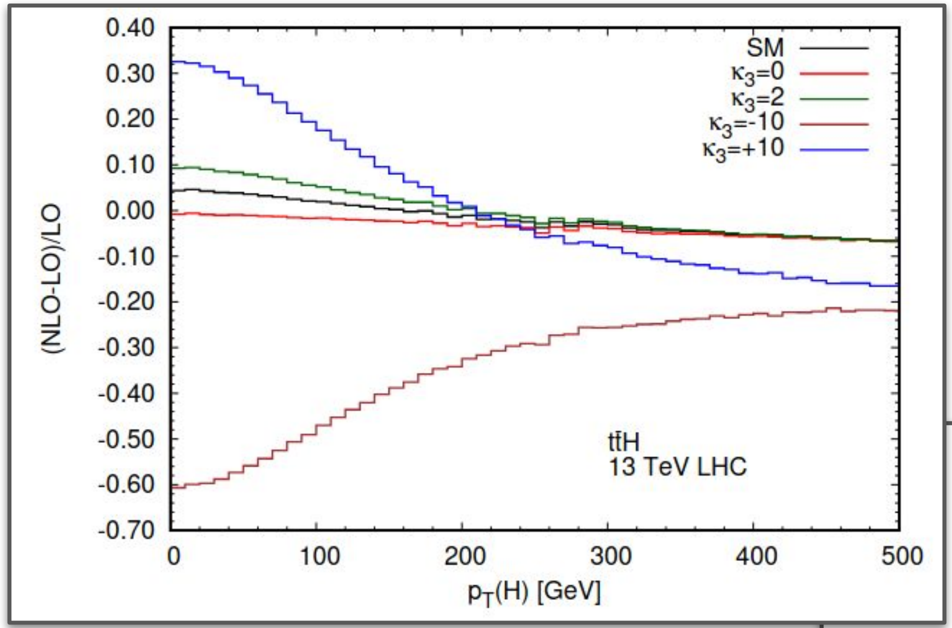
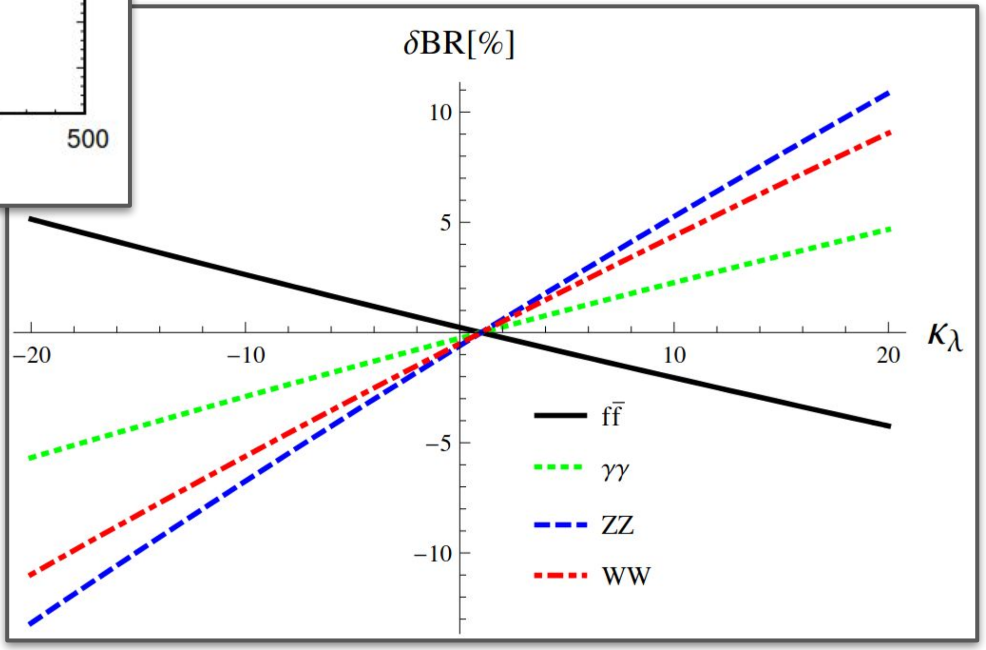






Precision measurements of (differential) Higgs boson production and decay rates are also sensitive to λ_3

Combination of H and HH production

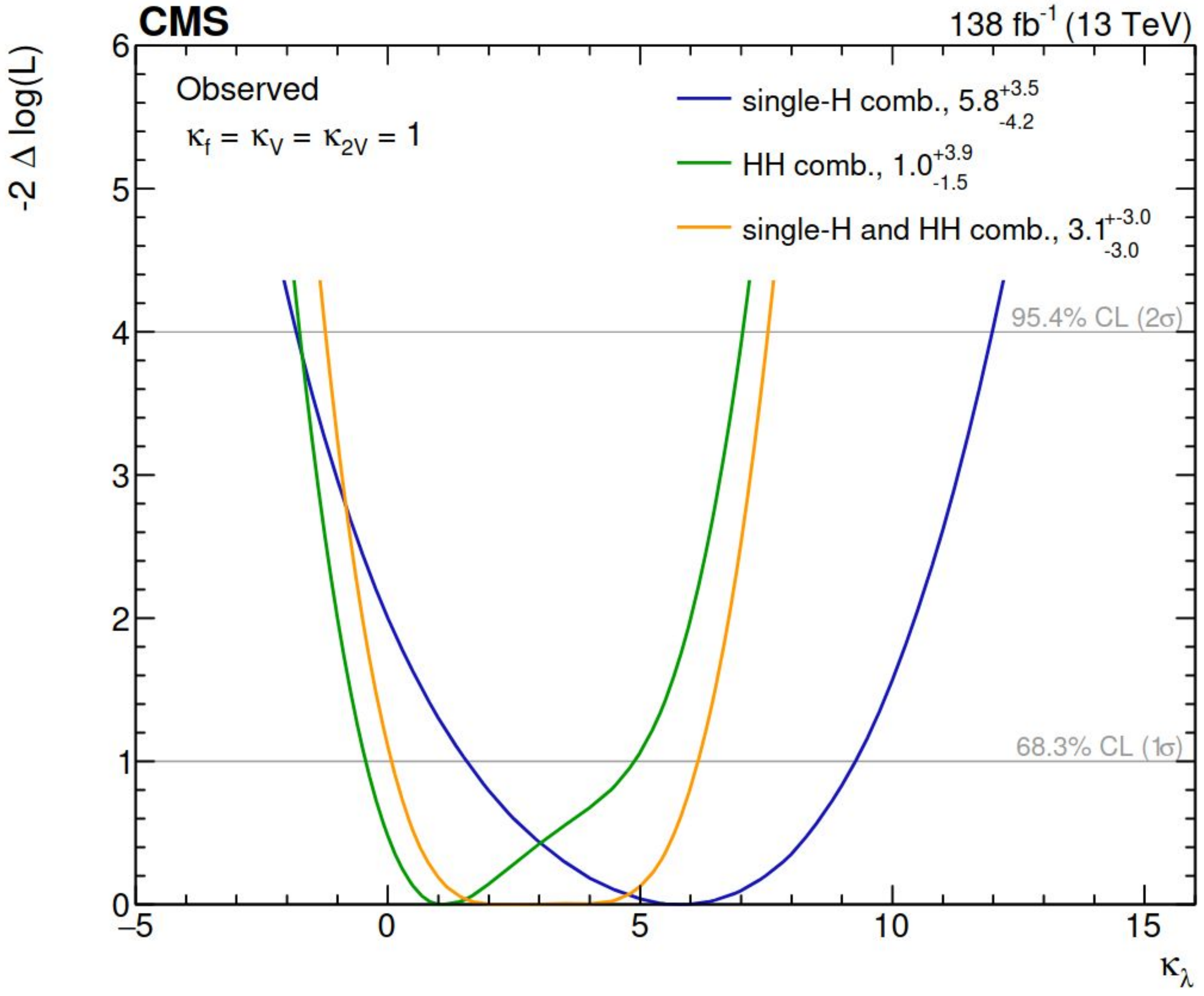
PAPER SUBMITTED JULY 24

- Ultimate κ_λ sensitivity comes by combining with indirect constraint from single-Higgs production
- NLO EW corrections to single Higgs boson production and decay involve **Higgs self-coupling**

Analysis	Integrated luminosity (fb^{-1})	Maximum granularity
$H \to 4l$	138	STXS 1.2
$H \to \gamma\gamma$	138	STXS 1.2
$H \to WW$	138	STXS 1.2
$H \to$ leptons ($t\bar{t}H$)	138	Inclusive
$H \to b\bar{b}$ (ggH)	138	Inclusive
$H \to b\bar{b}$ (VH)	77	Inclusive
$H \to b\bar{b}$ ($t\bar{t}H$)	36	Inclusive
$H \to \tau\tau$	138	STXS 1.2
$H \to \mu\mu$	138	Inclusive

Analysis	Int. luminosity (fb^{-1})	Targeted production modes
$HH \to \gamma\gamma b\bar{b}$	138	ggHH and qqHH
$HH \to \tau\tau b\bar{b}$	138	ggHH and qqHH
$HH \to 4b$	138	ggHH, qqHH and VHH
$HH \to$ leptons	138	ggHH
$HH \to WWb\bar{b}$	138	ggHH and qqHH

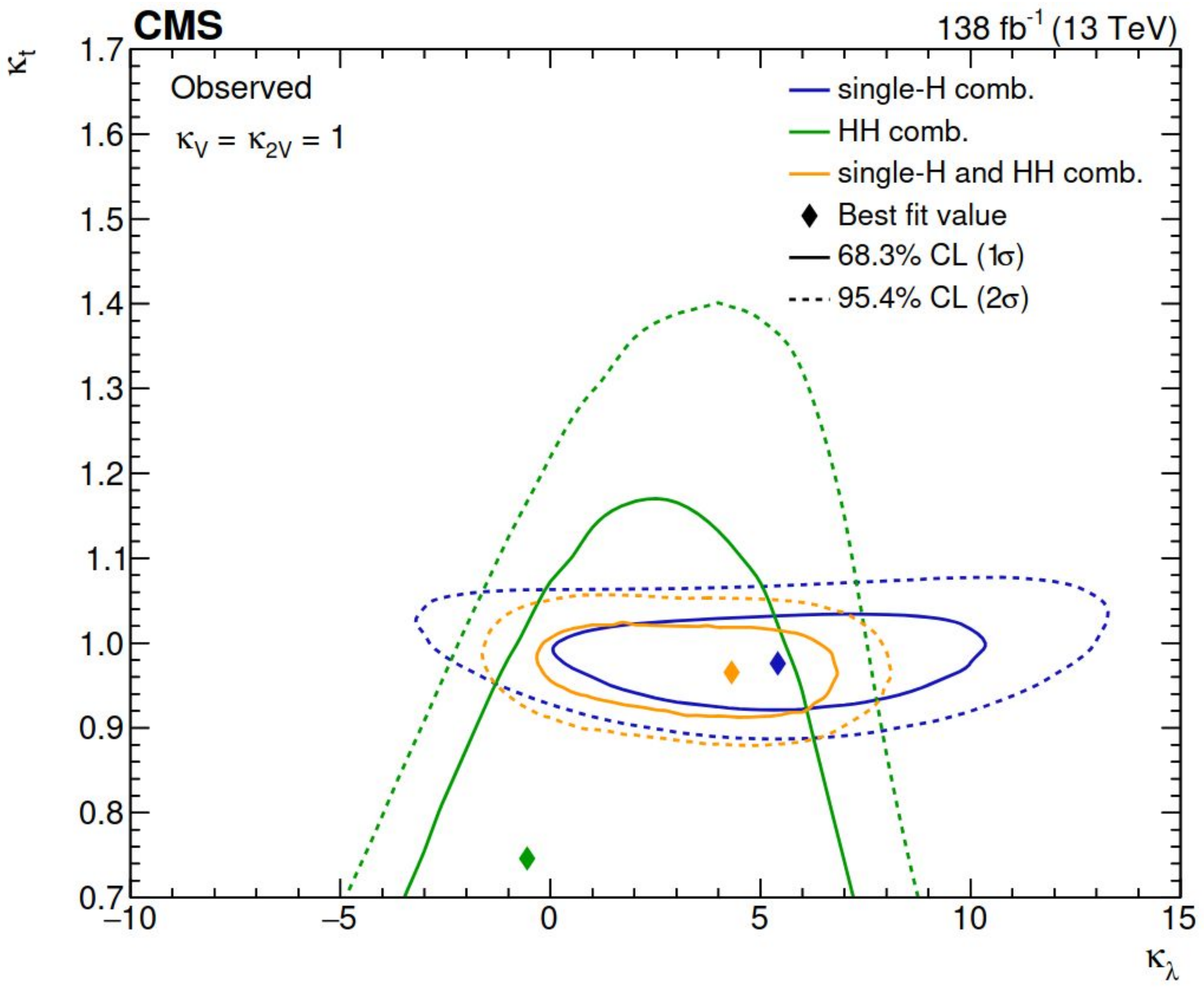
Combination

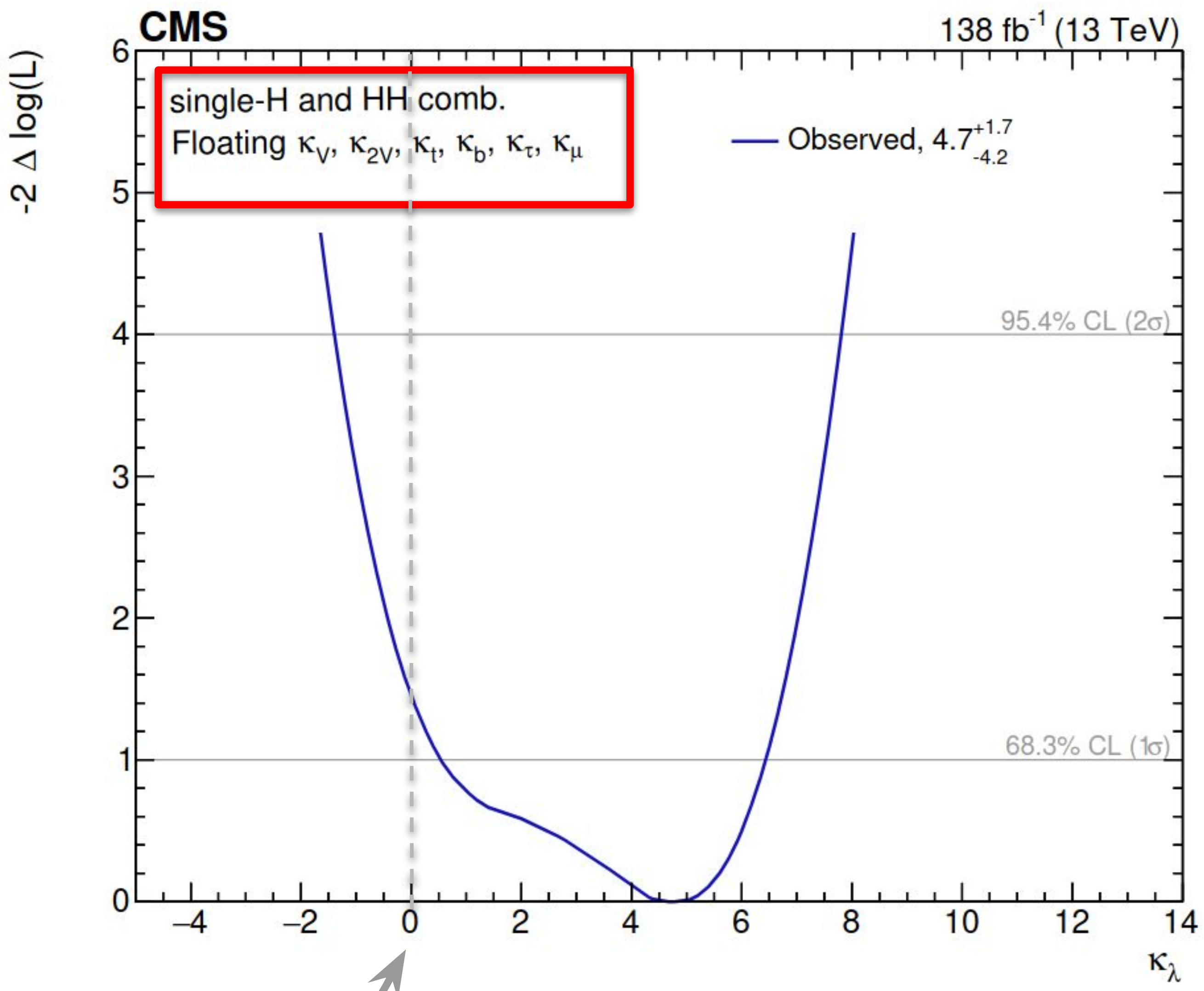


Combination of H and HH production

****PAPER SUBMITTED JULY 24****

- Ultimate κ_λ sensitivity comes by combining with indirect constraint from single-Higgs production
- NLO EW corrections to single Higgs boson production and decay involve **Higgs self-coupling**
- **Key benefit:** relax SM assumptions on other couplings without large degradation in sensitivity





Rapidly approaching exclusion of $\kappa_\lambda = 0$

Outlook: Run 3 improvements

- **More luminosity** (~300 fb^{-1}), **more energy** (+10% HH cross sections at 13.6 TeV)
- HH is within touching distance → We are not taking our foot off the gas...

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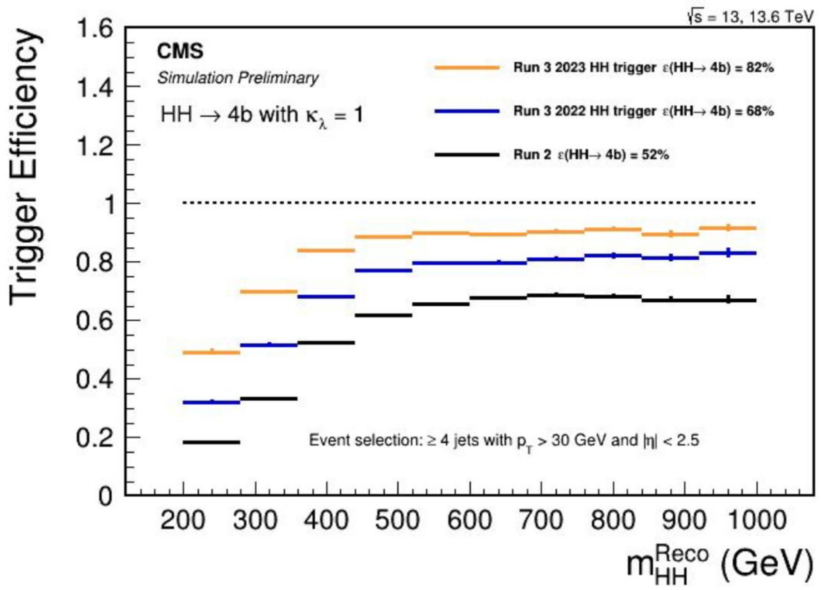

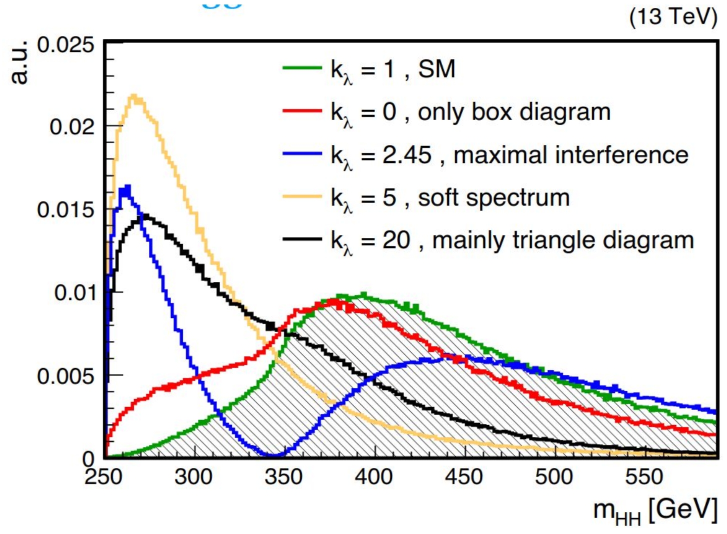

[CMS-DP-2023-050]

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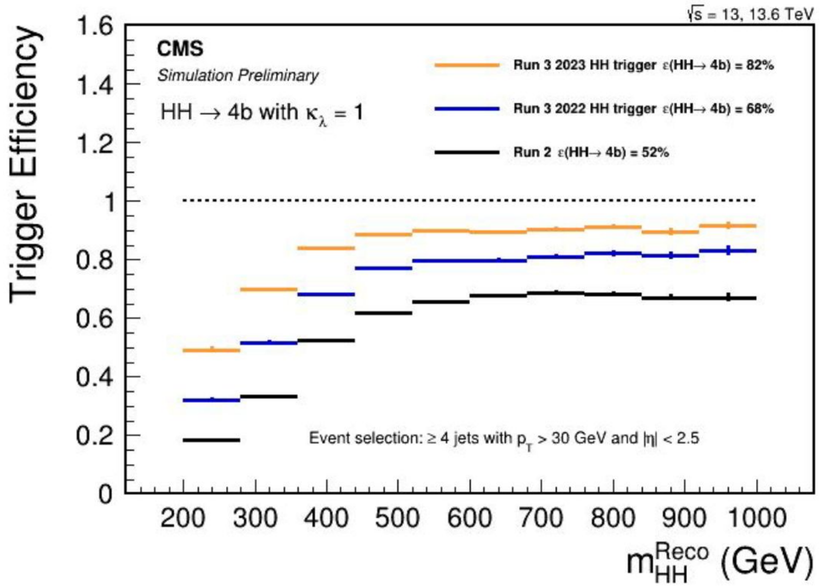

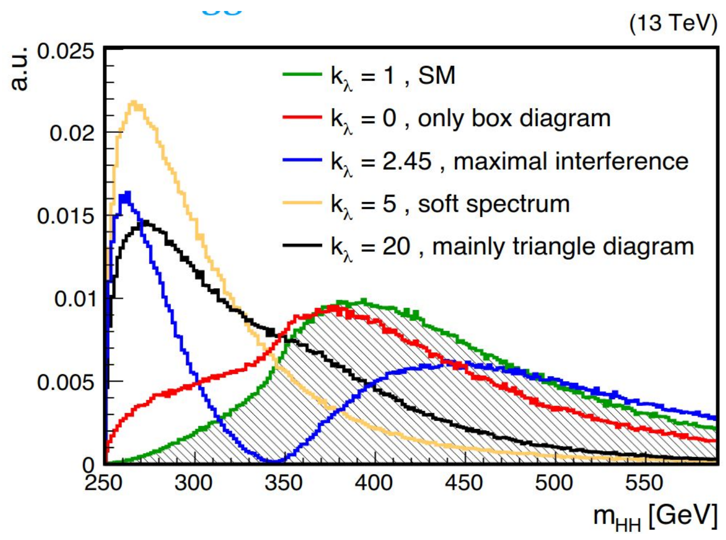

[CMS-DP-2023-050]

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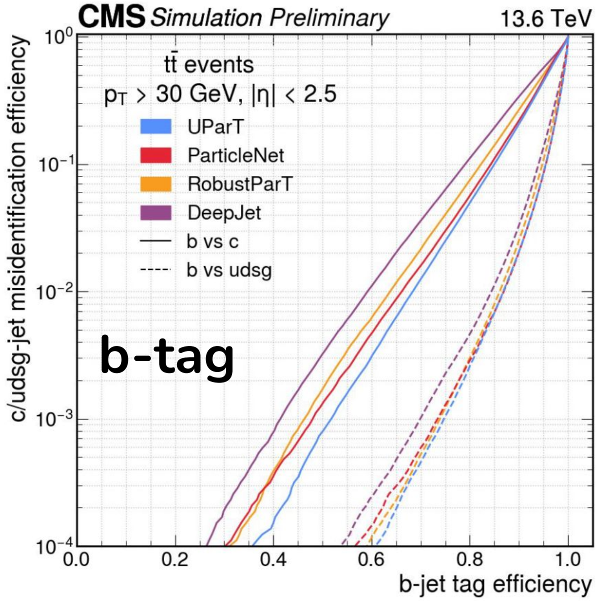

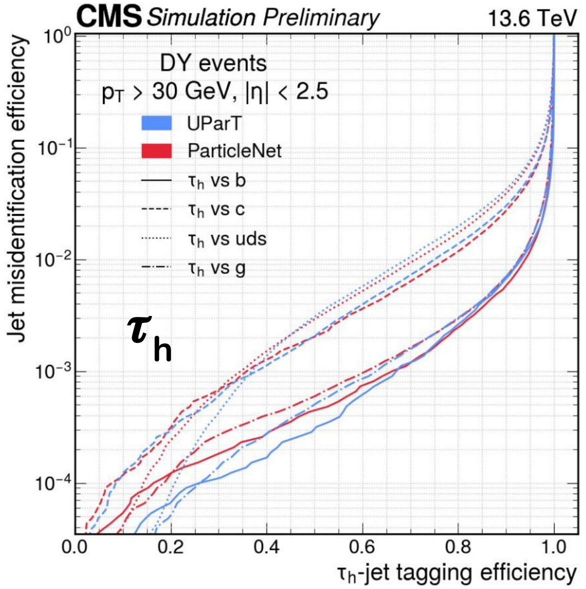

[CMS-DP-2024-066]

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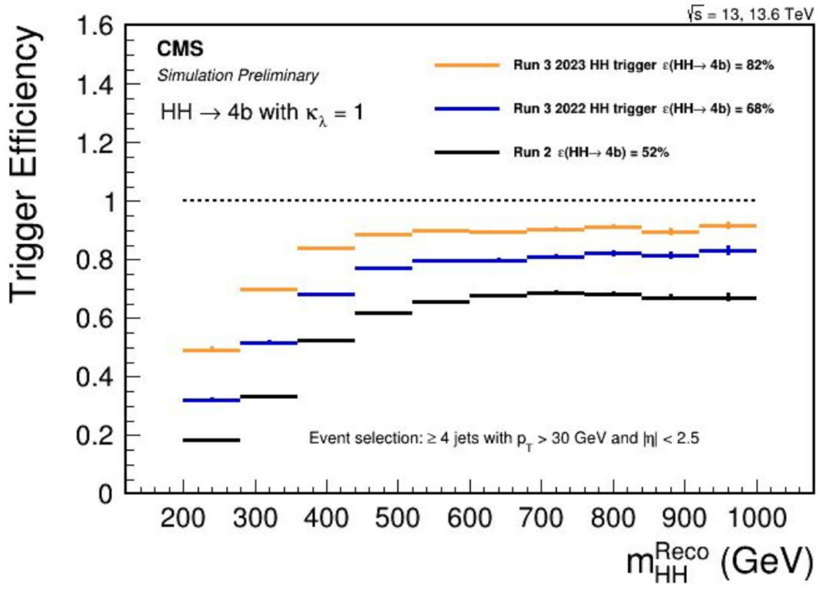

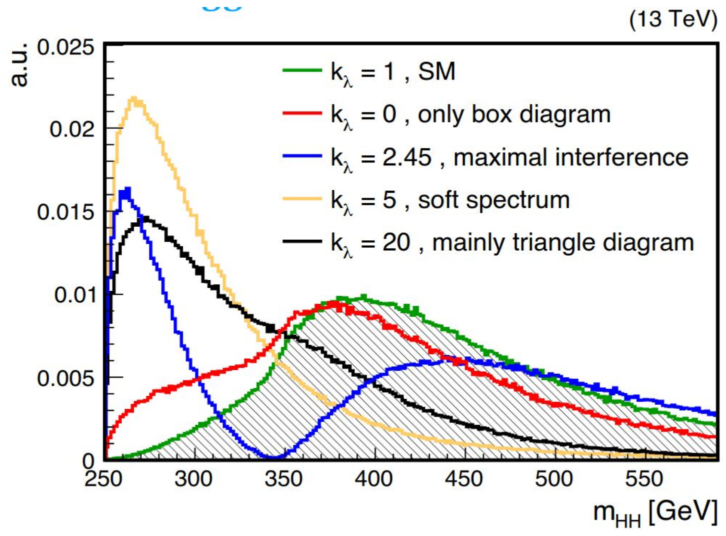

[CMS-DP-2023-050]

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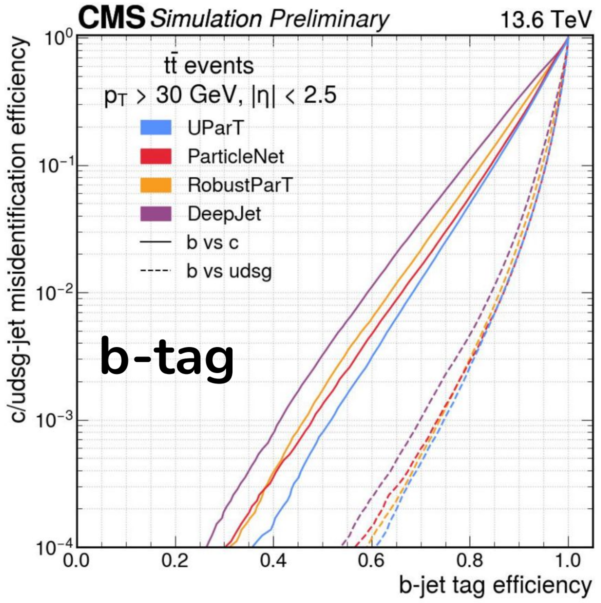
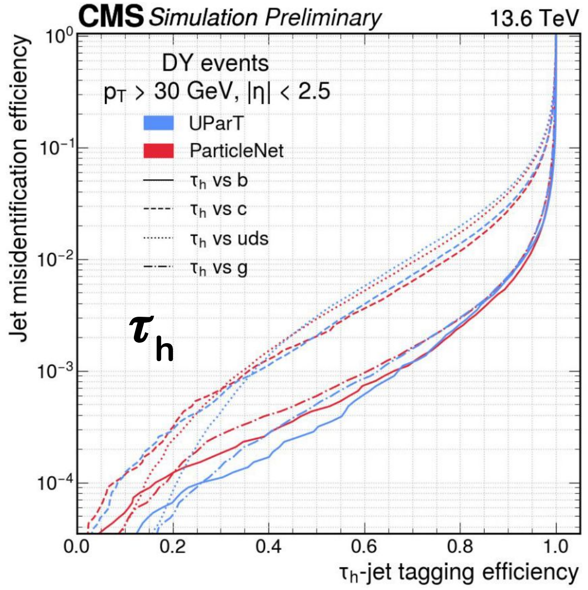
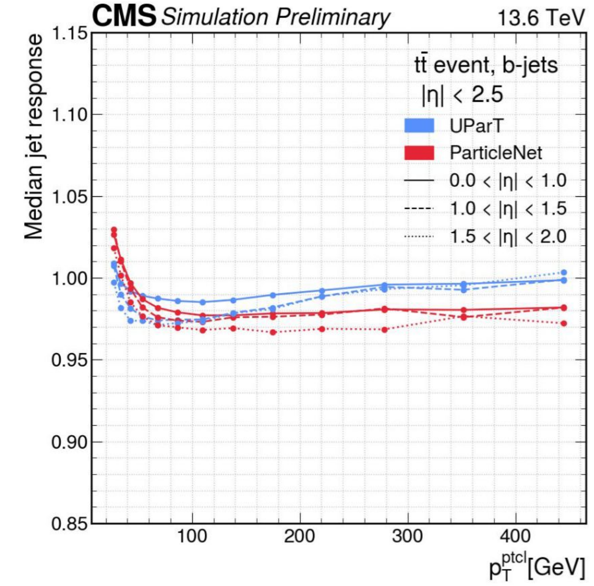
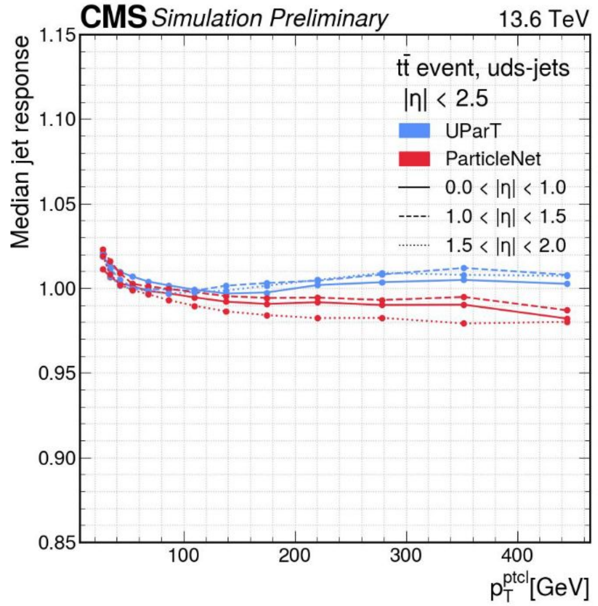




[CMS-DP-2024-066]

New pT regressions





[CMS-DP-2024-066]

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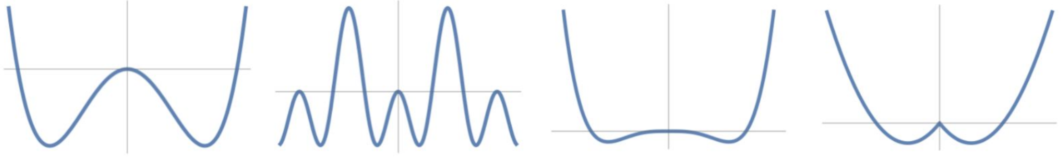
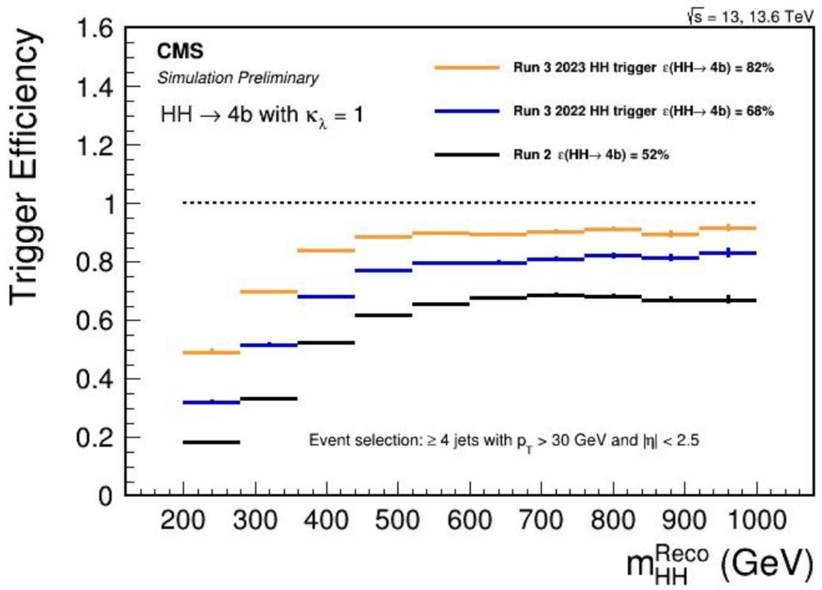
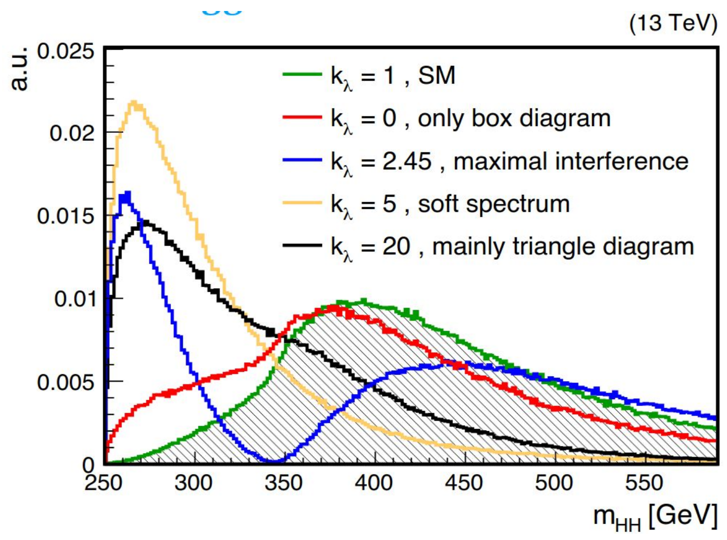


Landau-Ginzburg Higgs   Nambu-Goldstone Higgs   Coleman-Weinberg Higgs   Tadpole-Induced Higgs

- HH is within touching distance: $\mu_{\mathrm{SM}}^{95\%\mathrm{CL}} \sim 1$
  - New innovative ideas could bring it closer → **If something is very BSM-like in Higgs potential, we might see it in Run 3!**

New triggers





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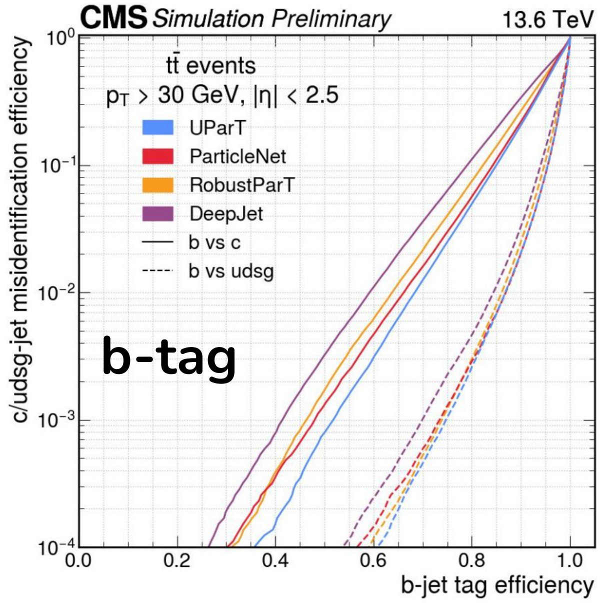

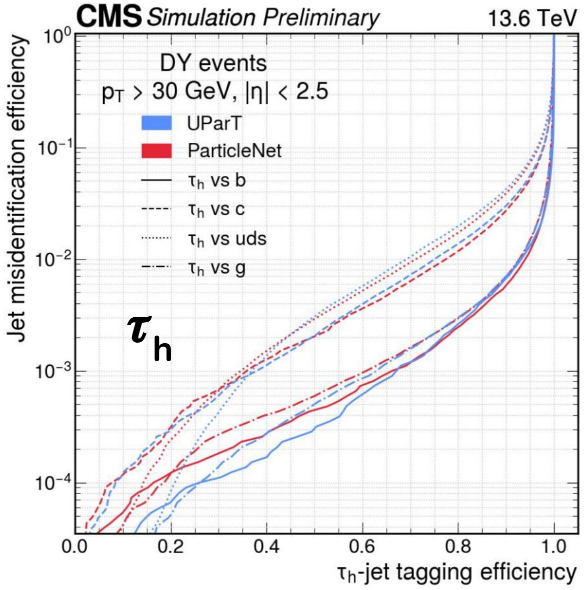

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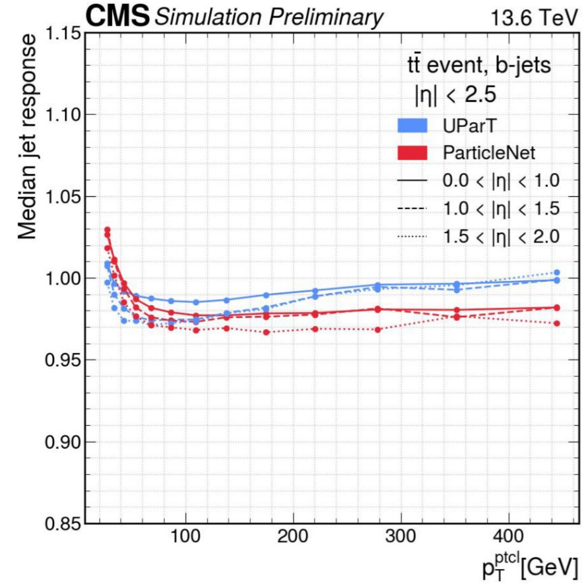
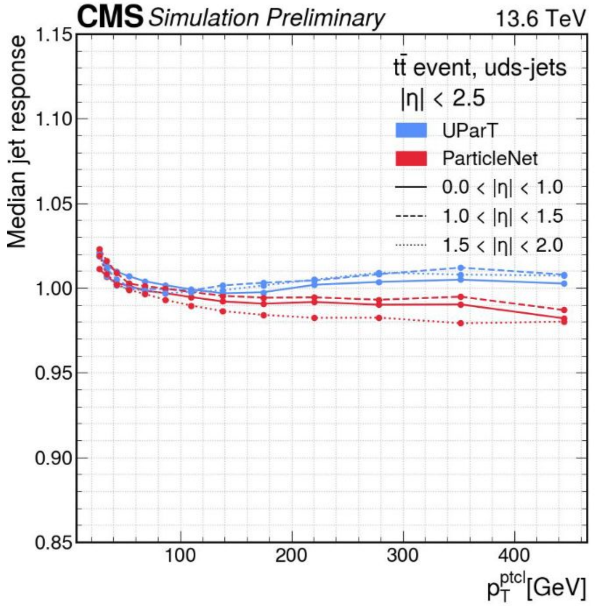


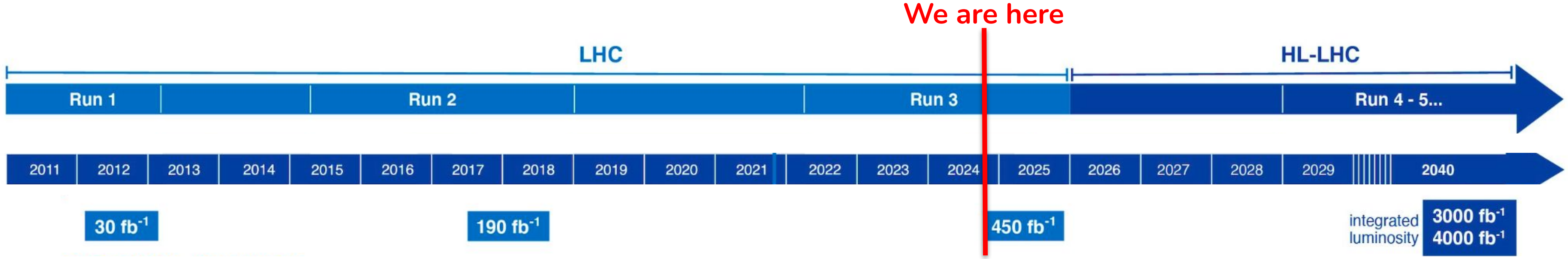


[CMS-DP-2024-066]

Outlook: HL-LHC projections

(*) Projection of Run 2 results → Conservative as do not include Run 3 improvements

- [HIG-20-011]: included detailed projection study for HL-LHC sensitivity(*)



~8k HH pairs

~18k HH pairs

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HiLumi HL-LHC PROJECT

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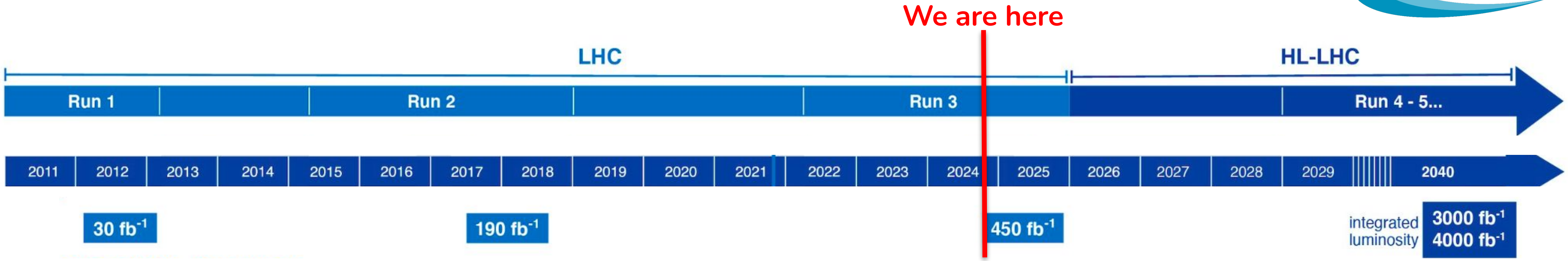

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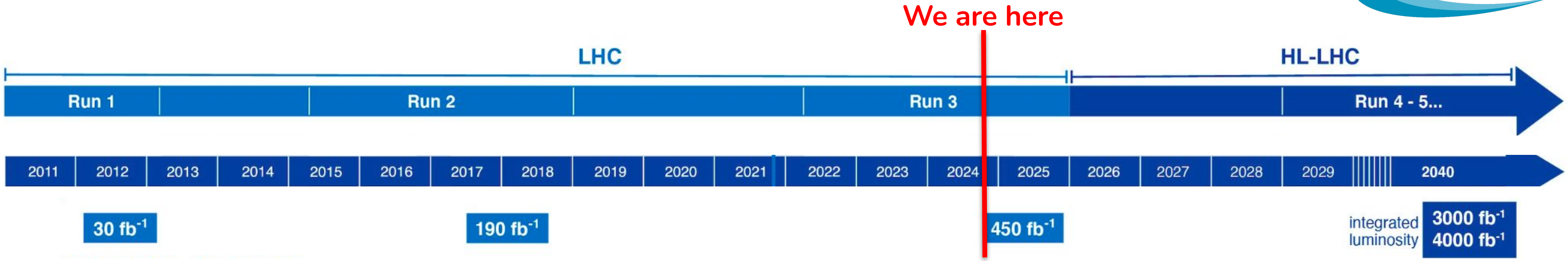

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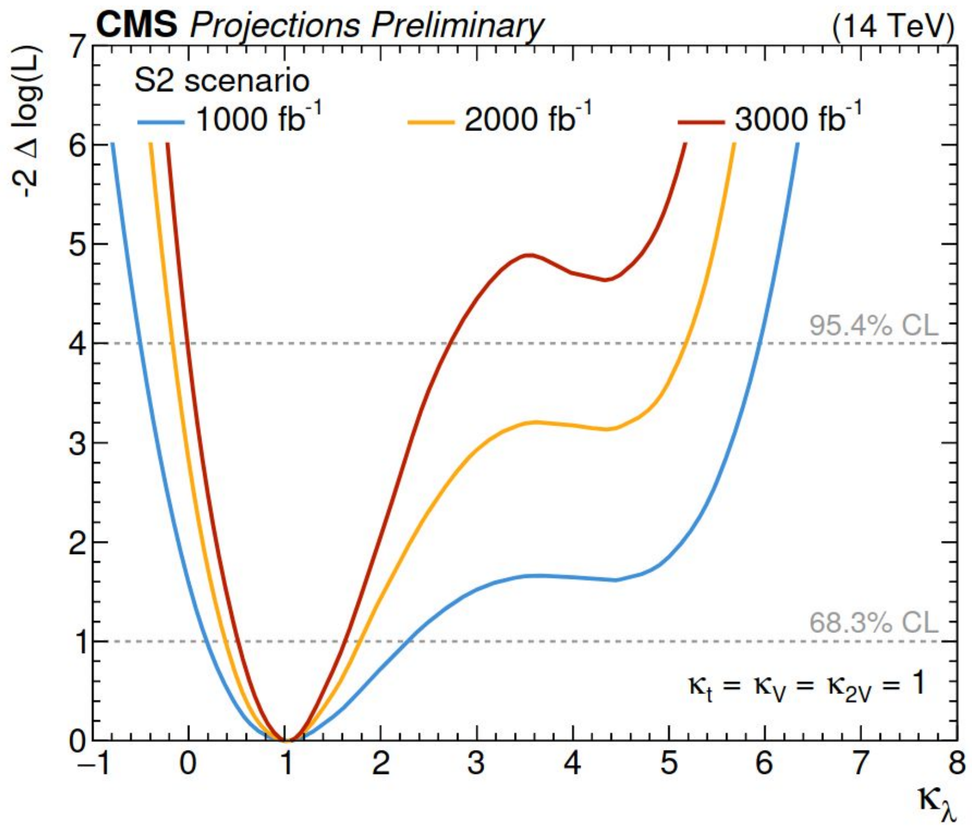

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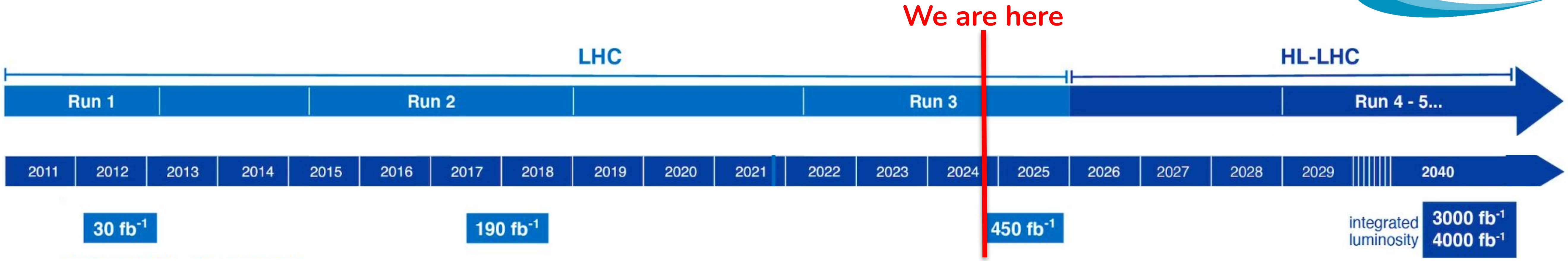

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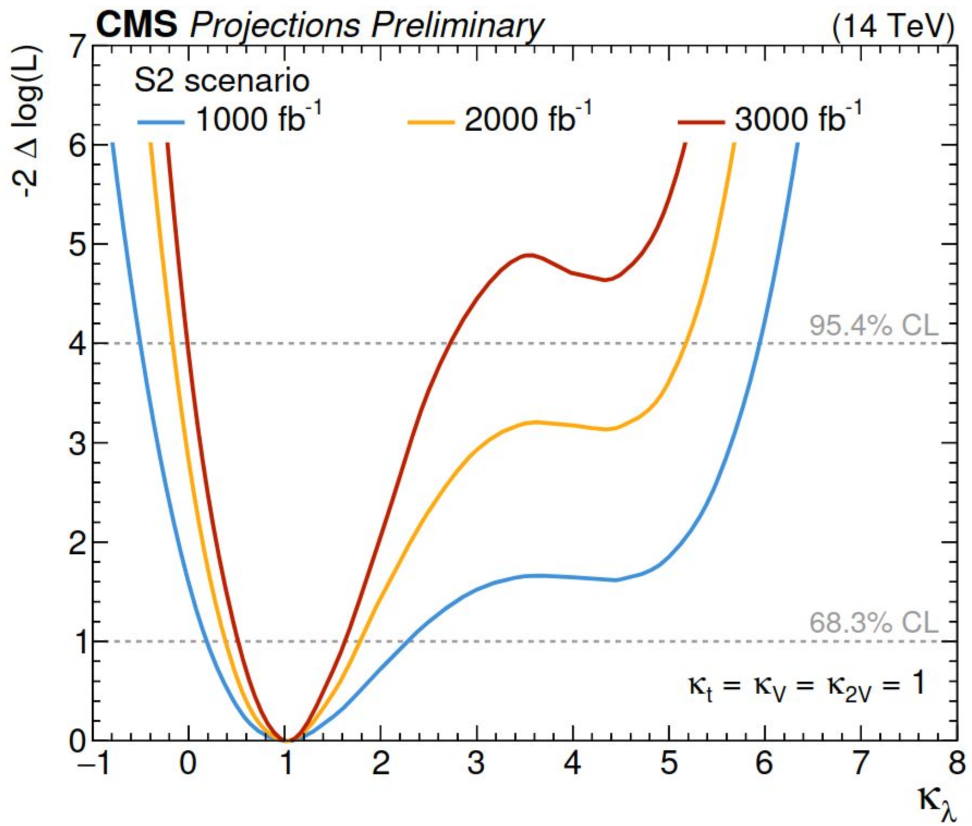

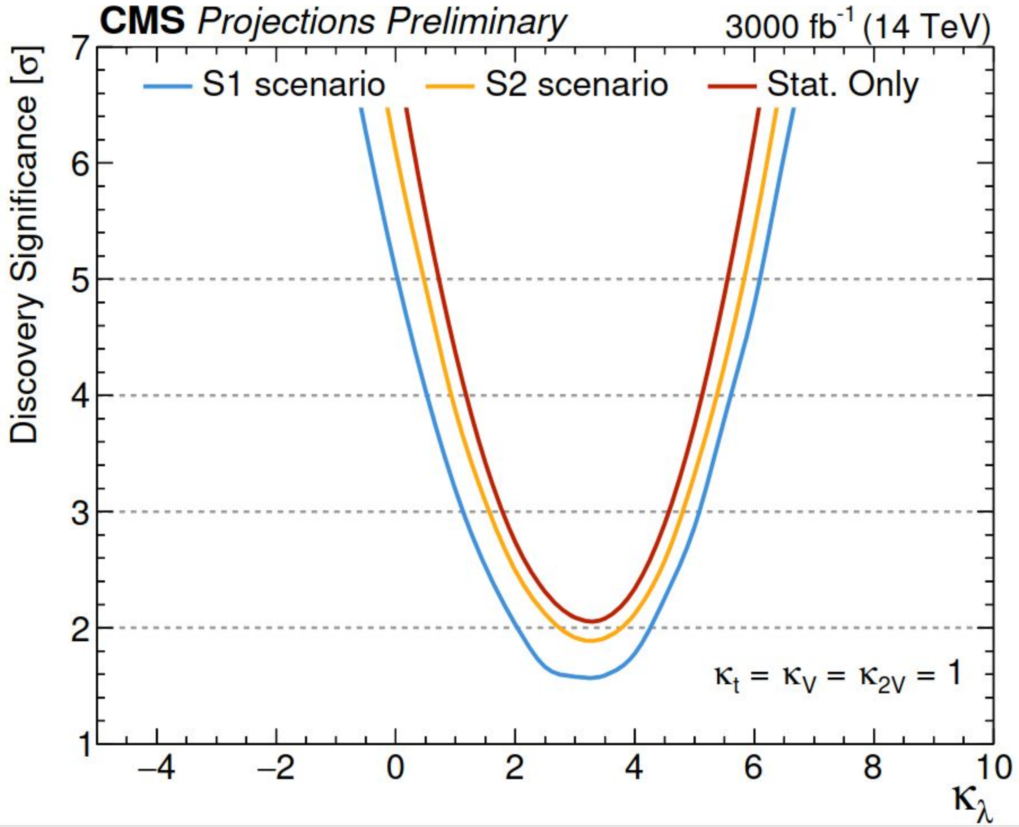

Expected sensitivity is sufficient to establish (SM) HH existence at 3-4σ with CMS alone

Depending on systematics scenario

Achieve 5σ observation combining with ATLAS!

Elucidate early Universe dynamics

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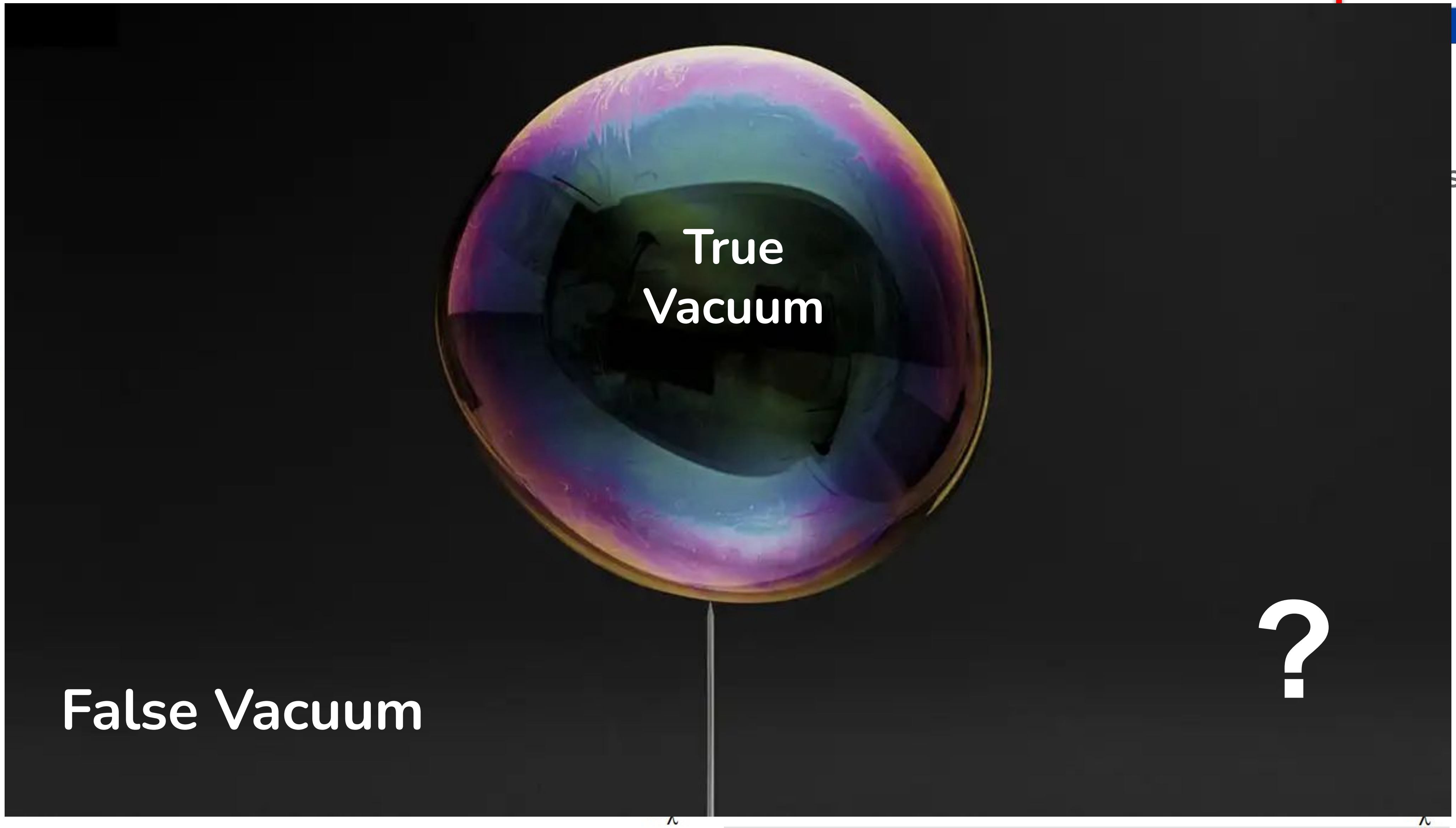

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