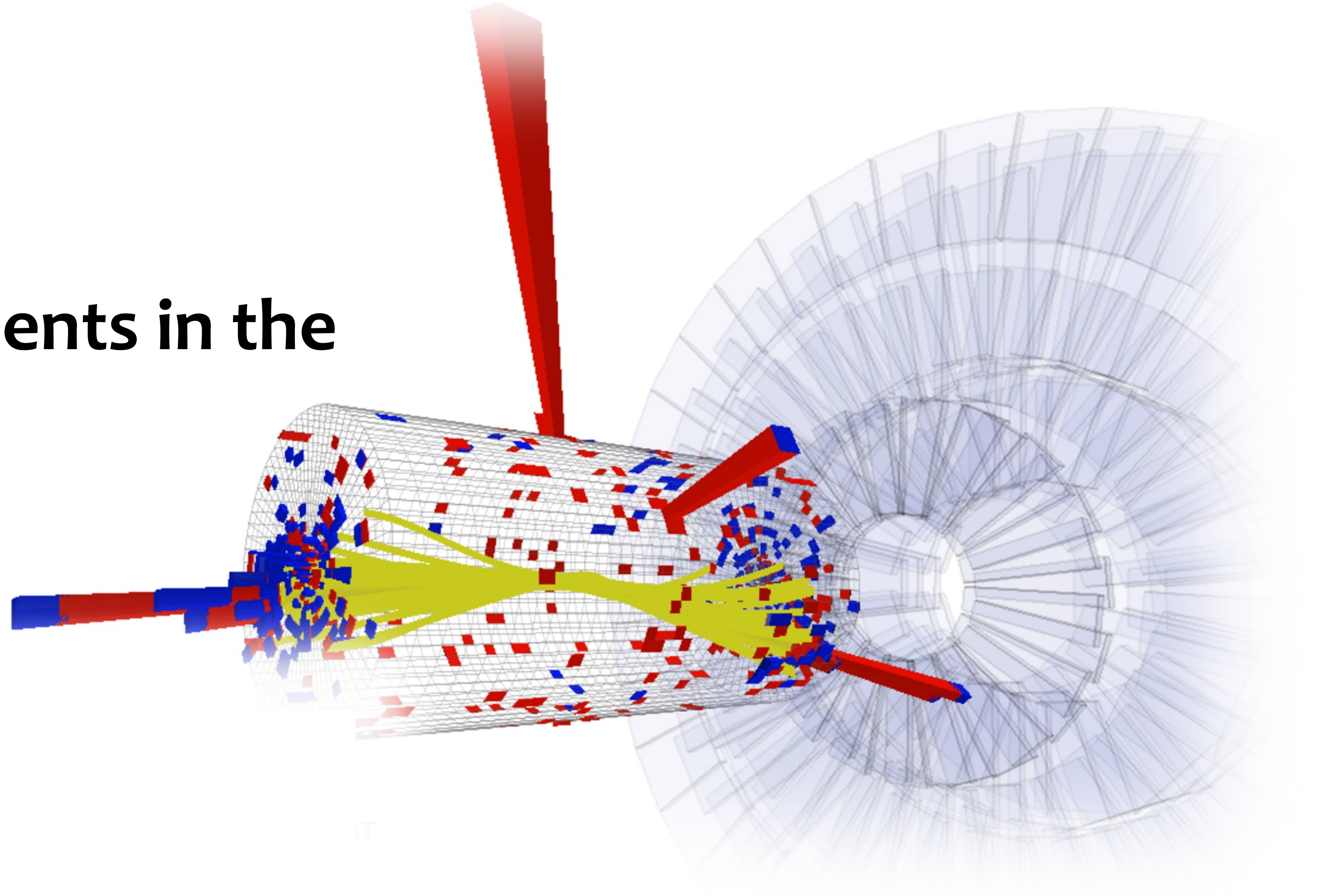
Over 10 years of measurements in the Higgs Sector with CMS

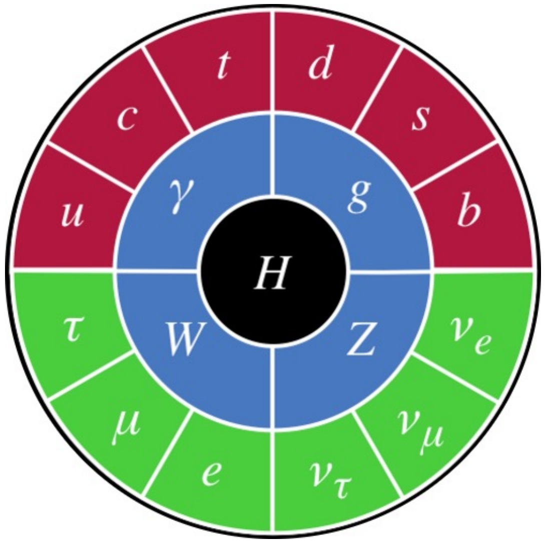


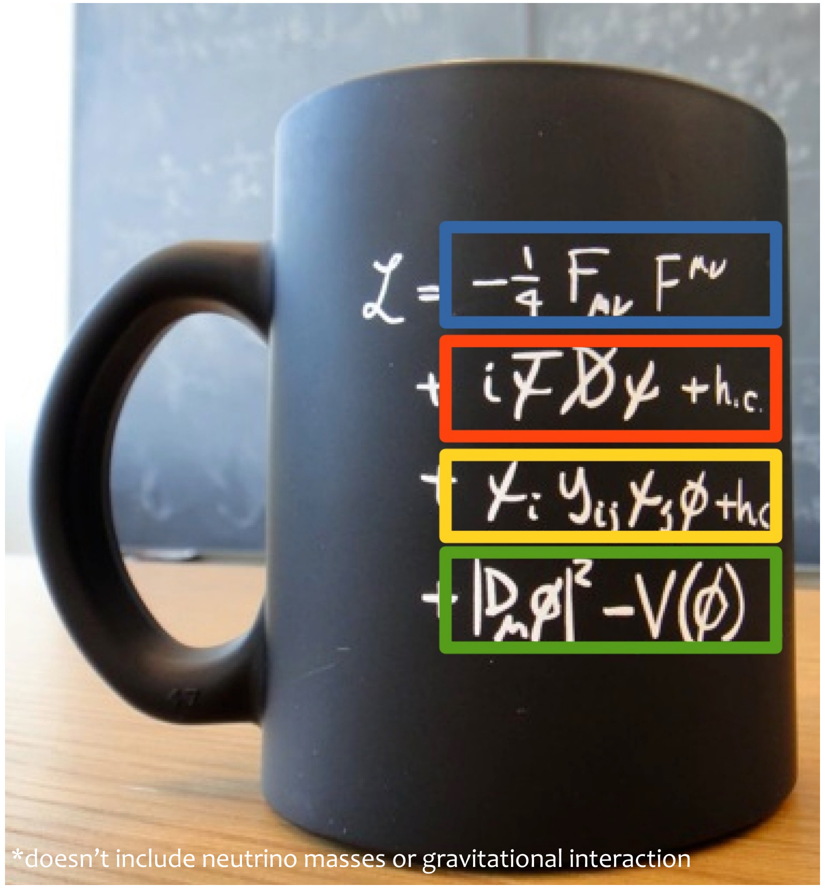
Nicholas Wardle
Imperial College London

INFN Seminar
Sapienza U. of Rome, 02/12/2024

The Standard Model

The Standard Model (**SM**) of particle physics is a (set of) quantum field theory(ies) that describe the ***fundamental* particles of nature and their interactions***





*doesn't include neutrino masses or gravitational interaction

Propagation of force-carriers (spin-1 boson)

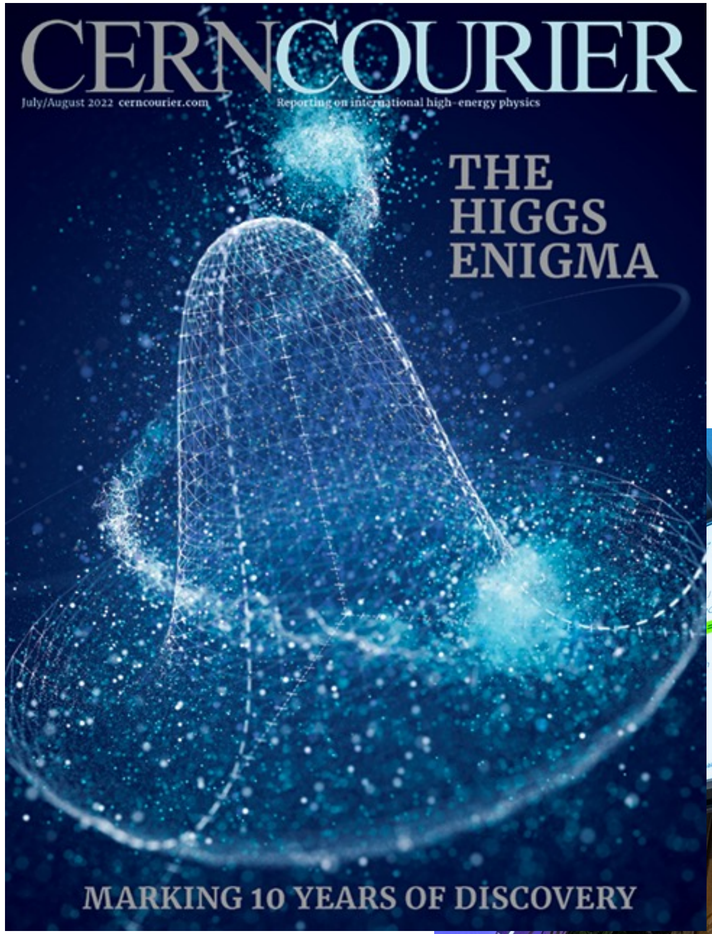
Interactions of matter particles (spin-1/2 fermions)

Masses of matter particles

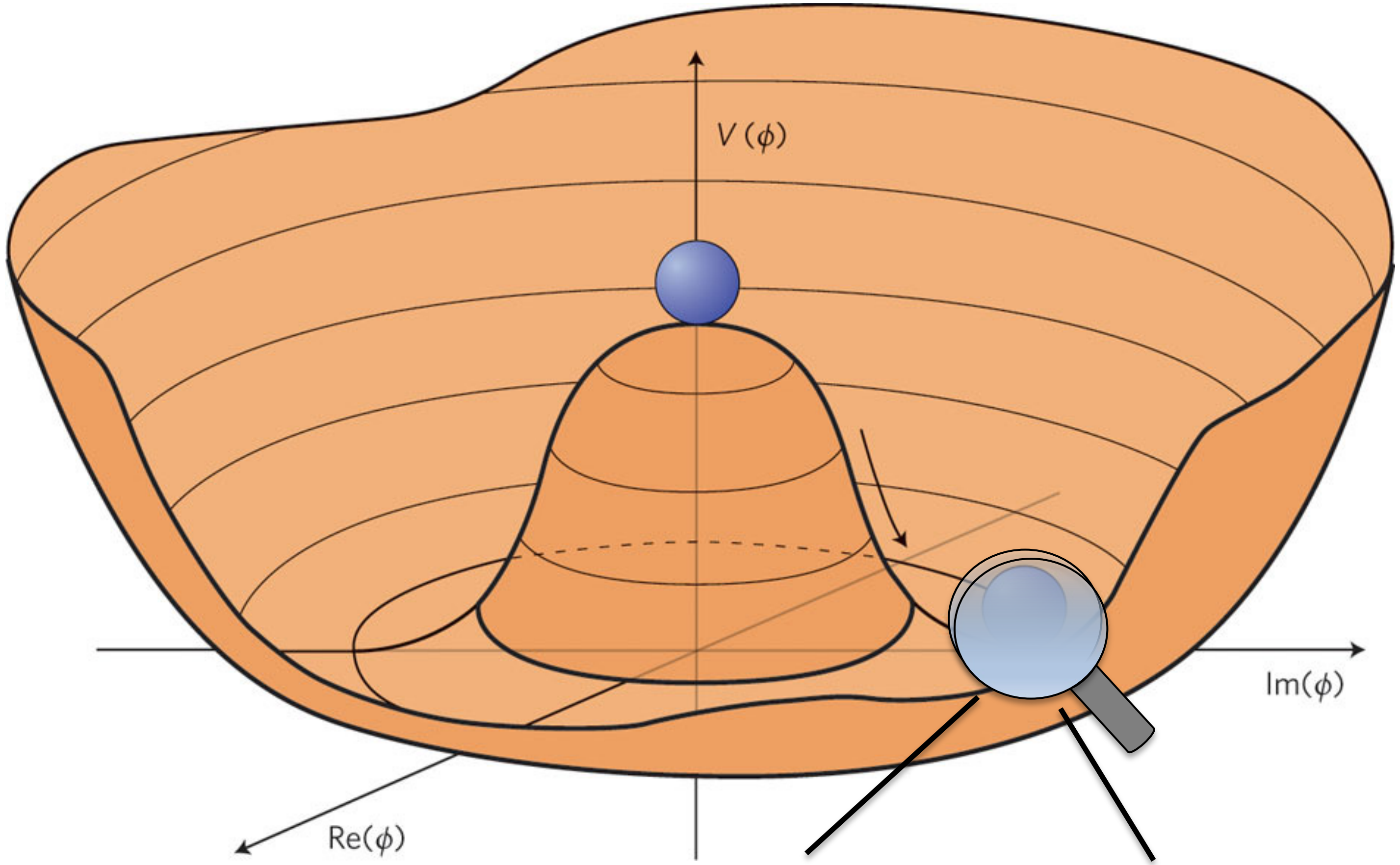
Higgs interactions and mass of force carriers

July 4th 2022

CERN 10 years HIGGS boson discovery



The Higgs boson



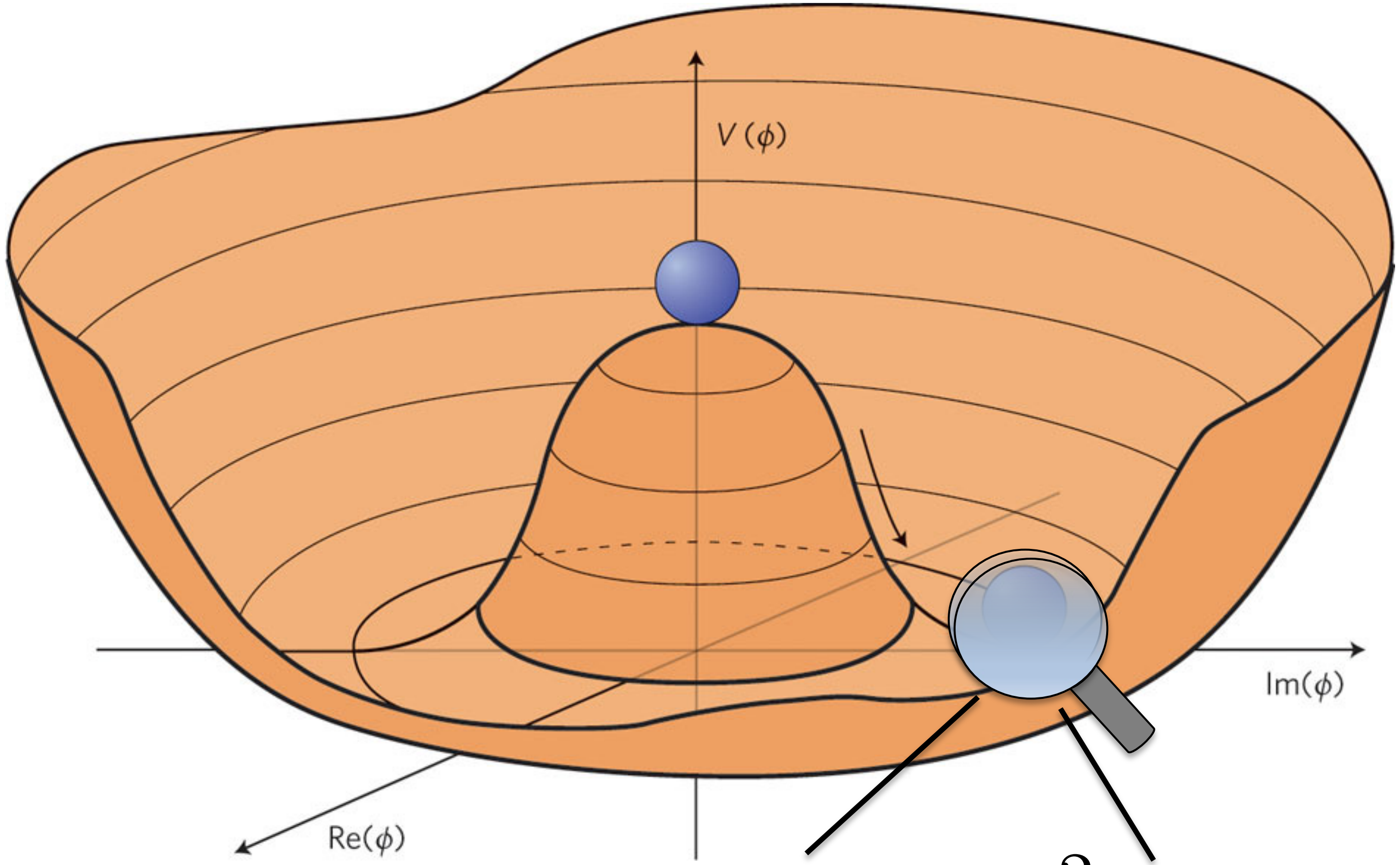
Expanding around **potential minimum** (ignoring linear H)…
→ **3 parameters** v, m_H and λ
→ Relationships between them fixed in the SM

$$V(H) = \frac{1}{2}m_H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4 + \text{const}$$

$$\lambda = \frac{m_H^2}{2v^2}$$

The Higgs boson

Low energy probes (muon decay lifetime) fixes the **vacuum expectation value**



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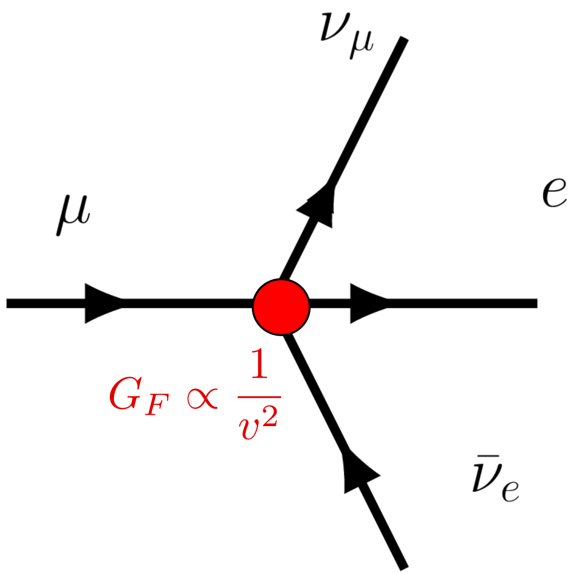
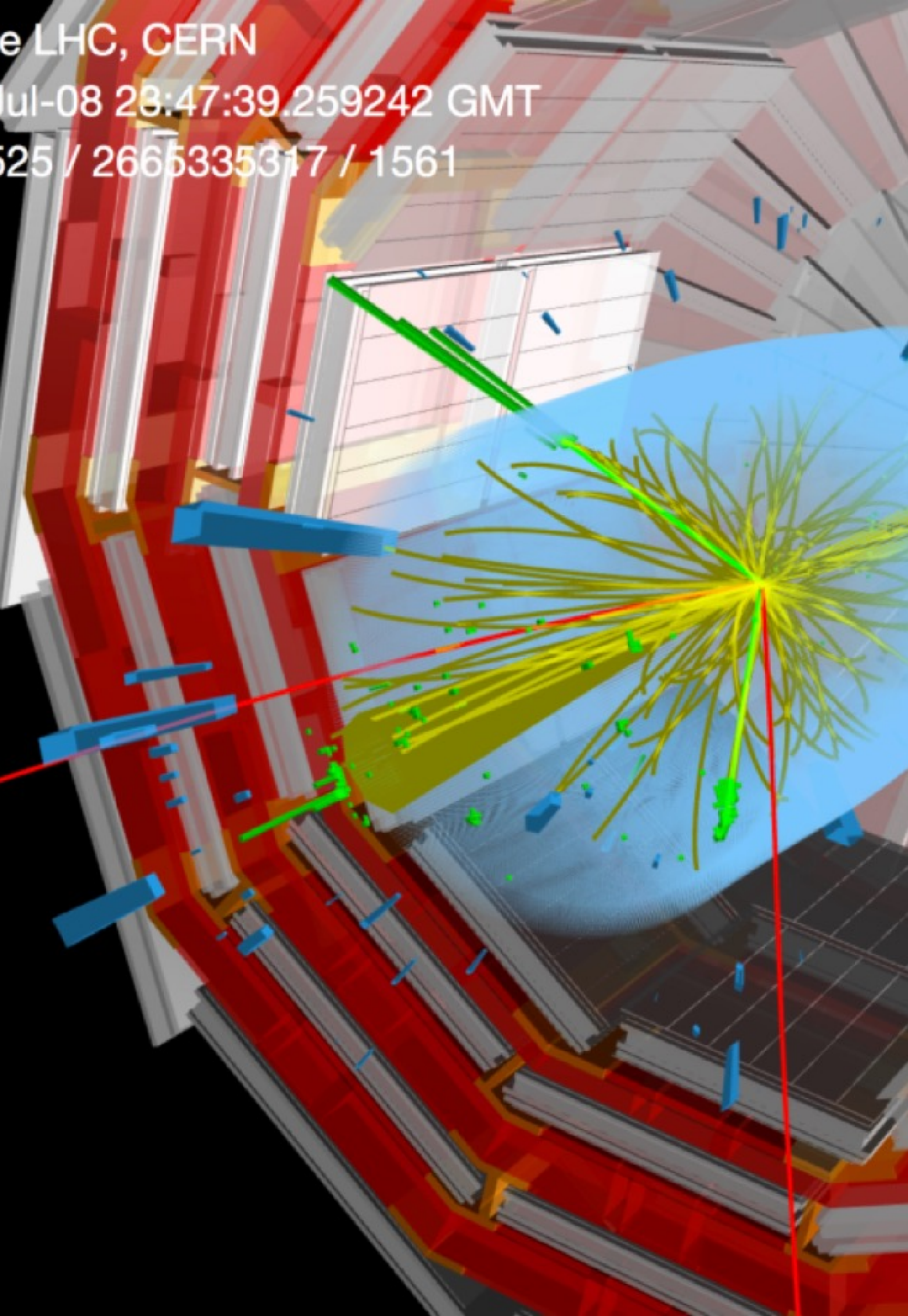


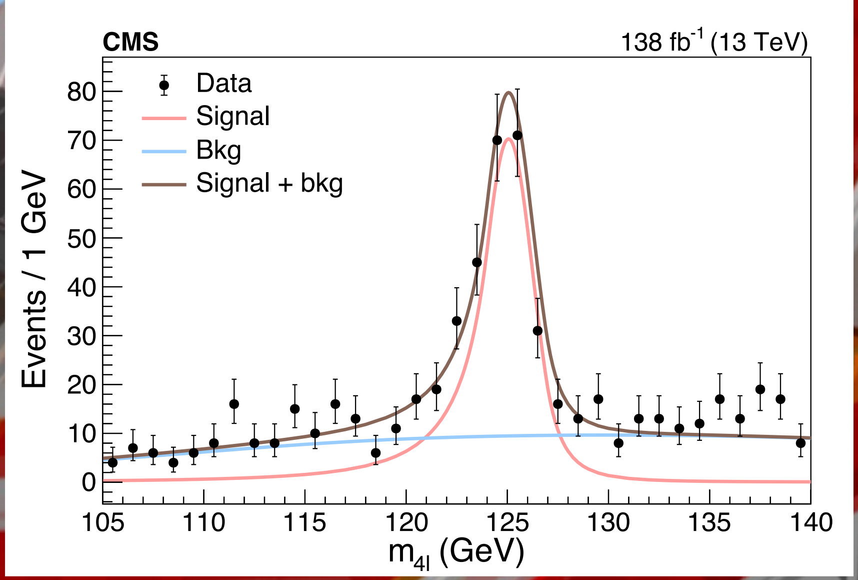
$$\frac{1}{\tau_\mu} = \Gamma_\mu \propto \frac{m_\mu^5}{v^4}$$

Higgs boson mass (m_H) remains the only free parameter …

Precision in Higgs boson mass at the level of ~0.1% with Run-1 & Run-2 data



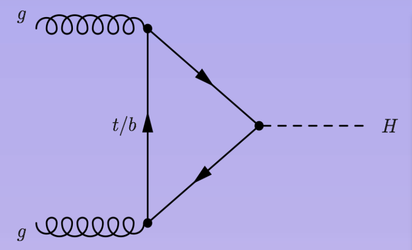
$125.08^{+0.12}_{-0.12}\ (^{+0.10}_{-0.10})$ GeV



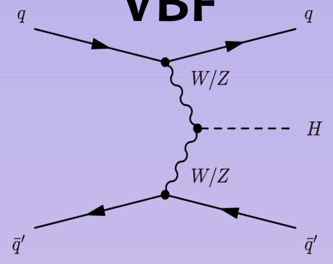
Nicholas Wardle

Higgs Production and Decay

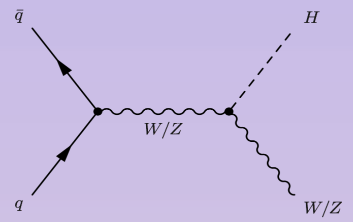
ggH

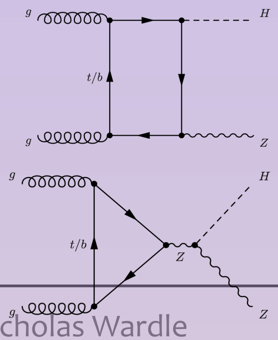


VBF

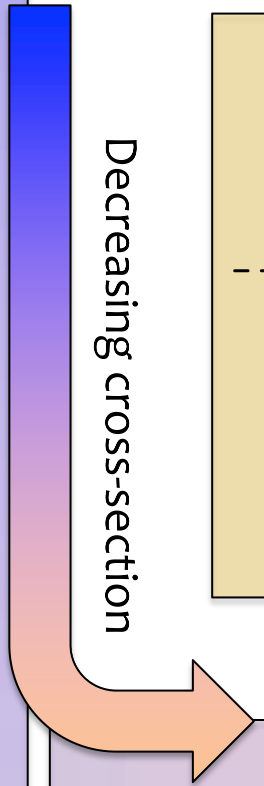


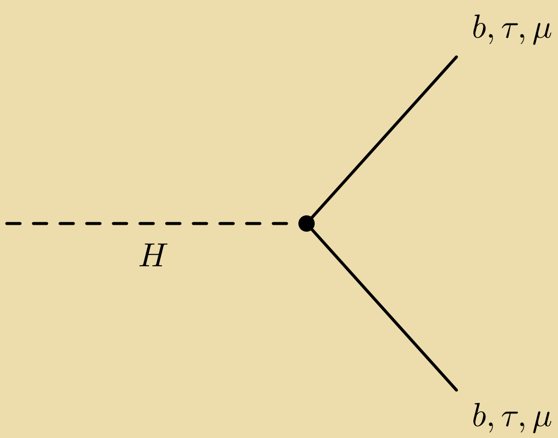
WH / ZH



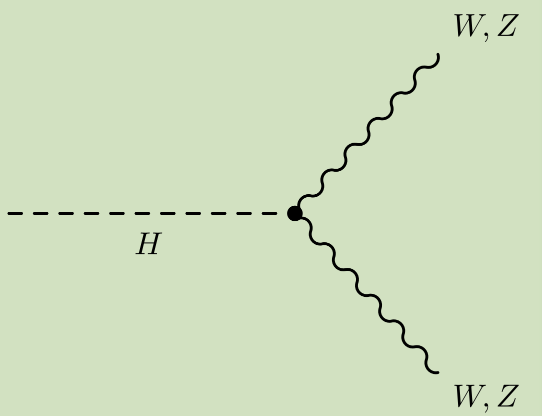


gg→ZH

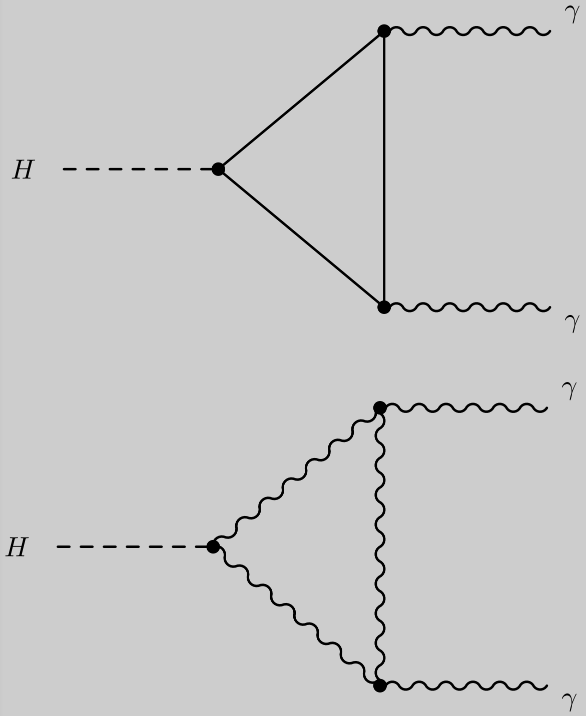




H→ff

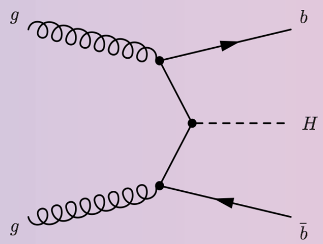


H→VV

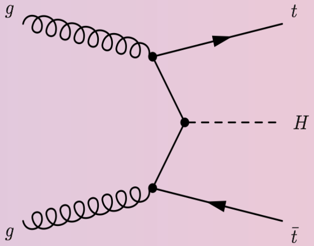


H→γγ

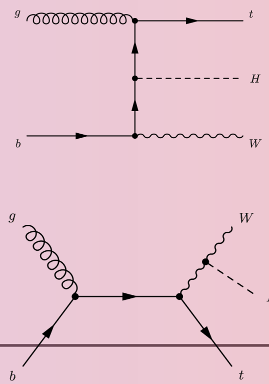
bbH



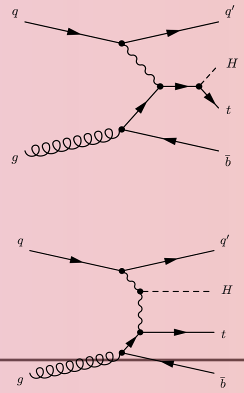
ttH



gb→tHW

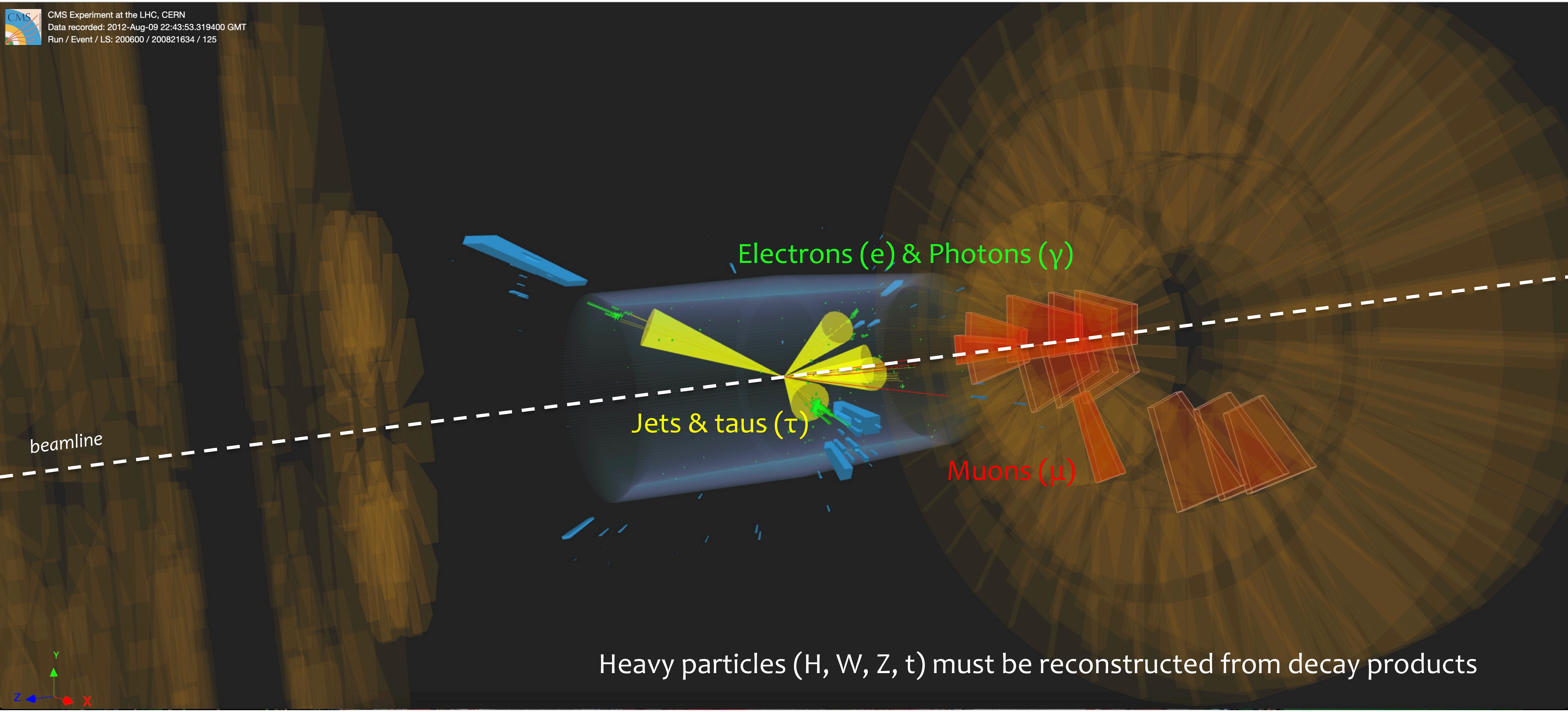


qg→tHq



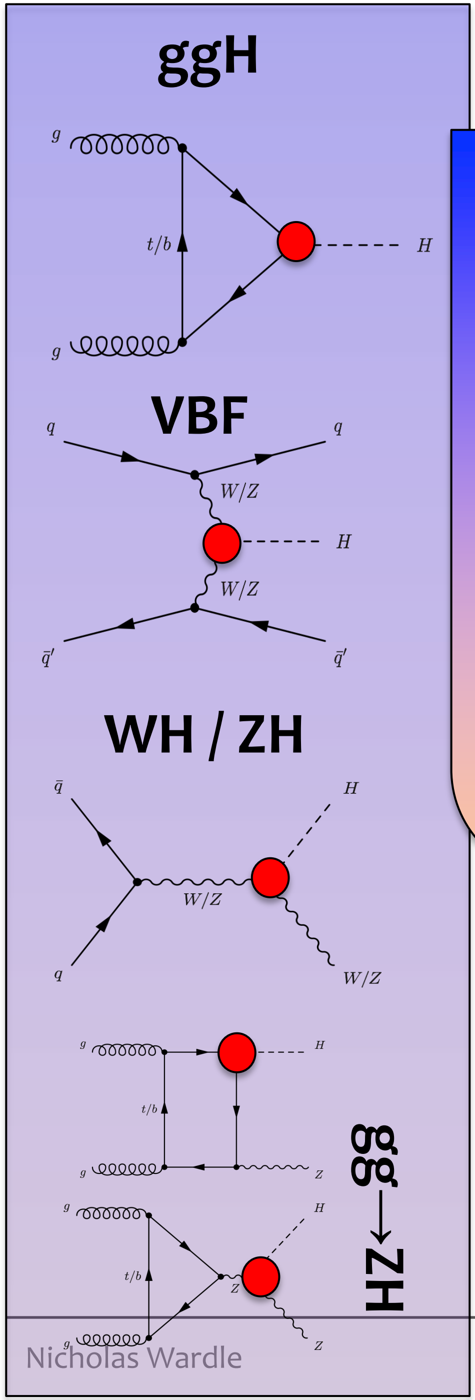
Many production and decay modes to study Higgs for m_H~125 GeV

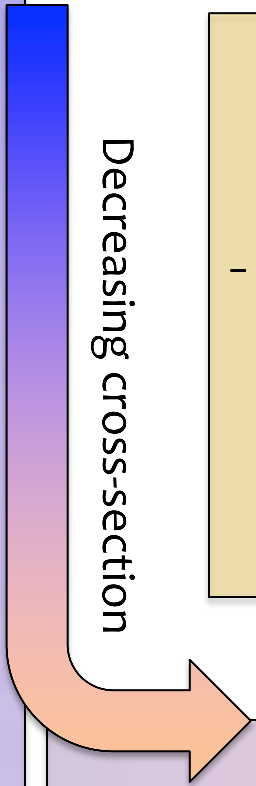
CMS as a Higgs boson camera

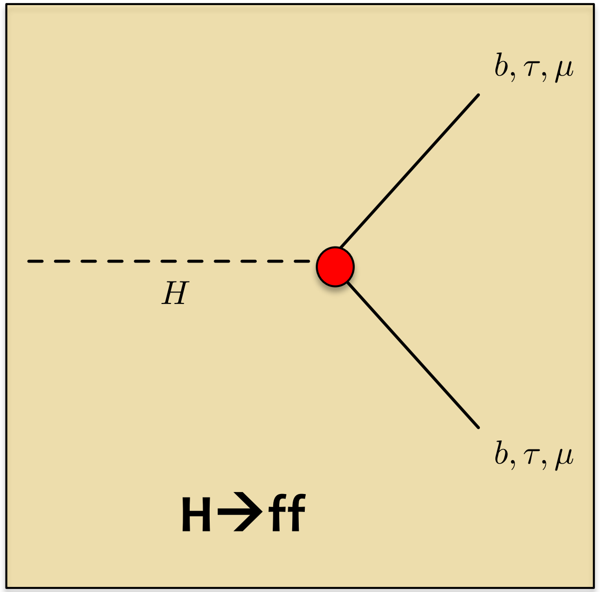


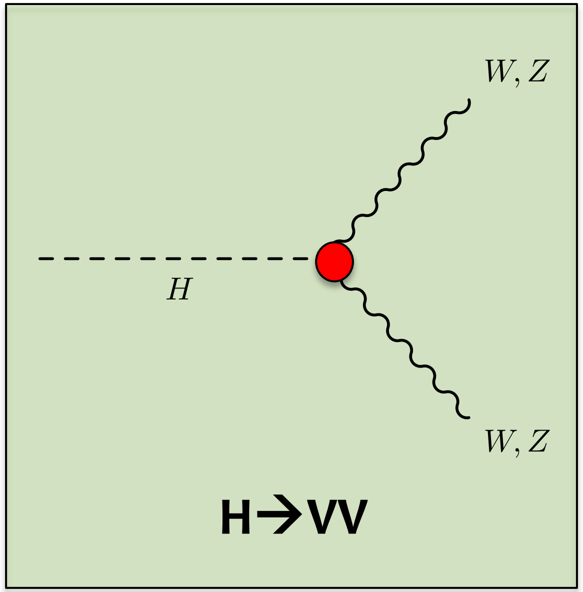
Heavy particles (H, W, Z, t) must be reconstructed from decay products

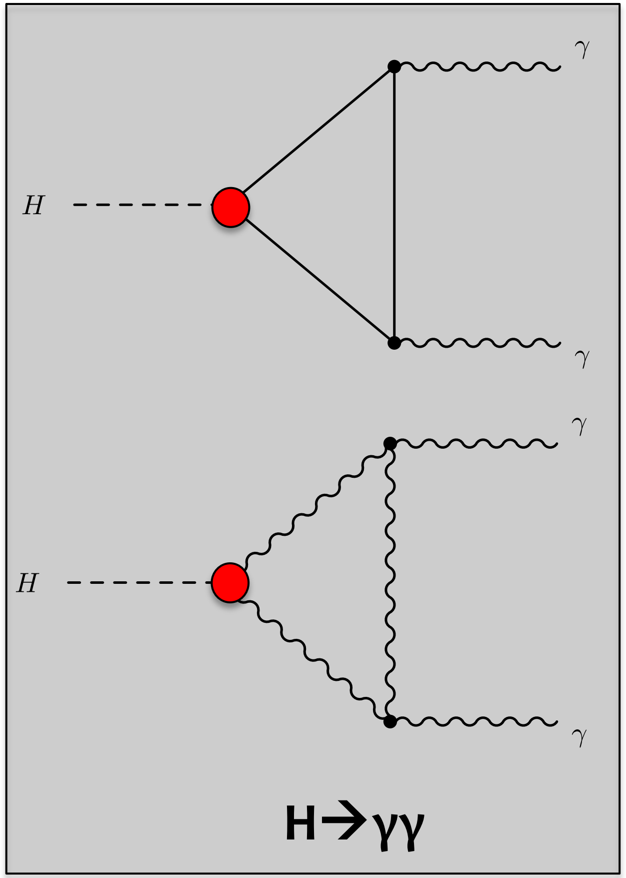
Higgs Production and Decay

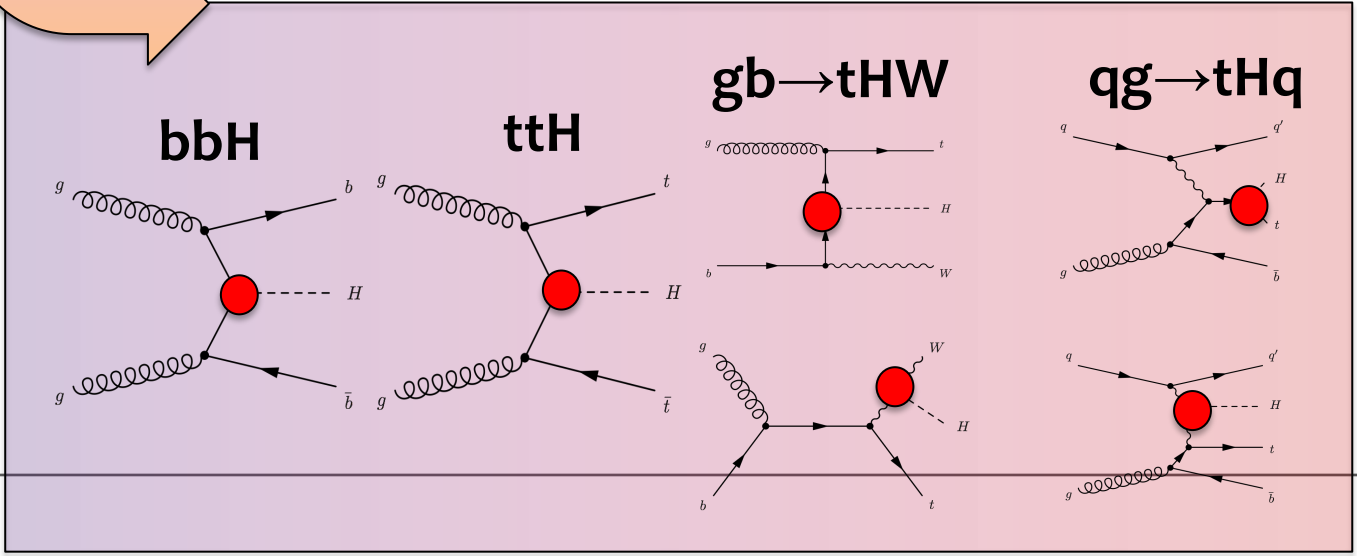






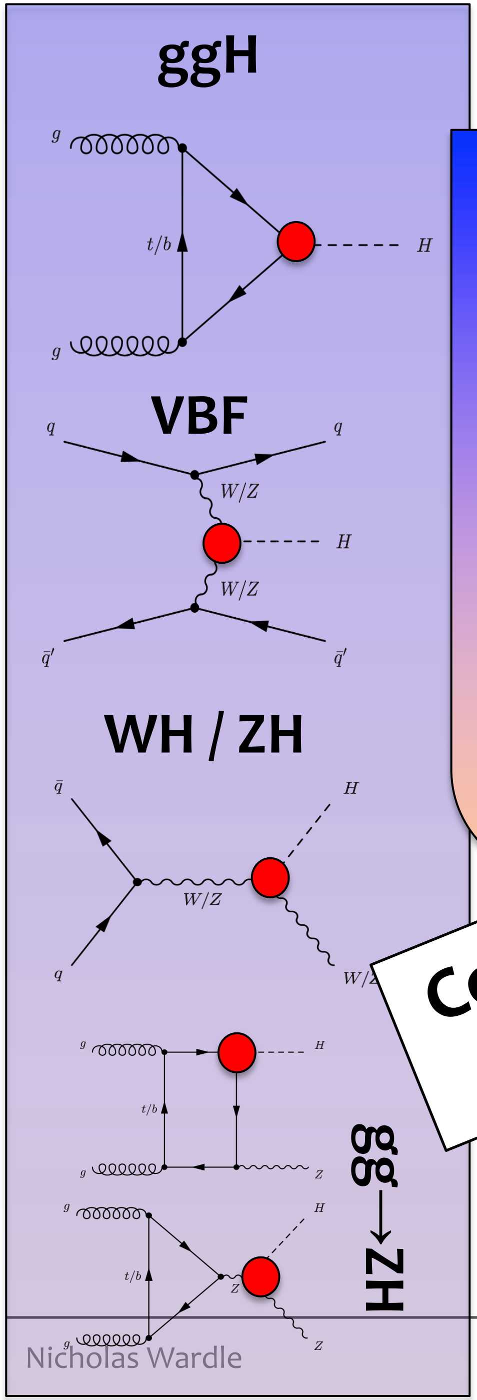


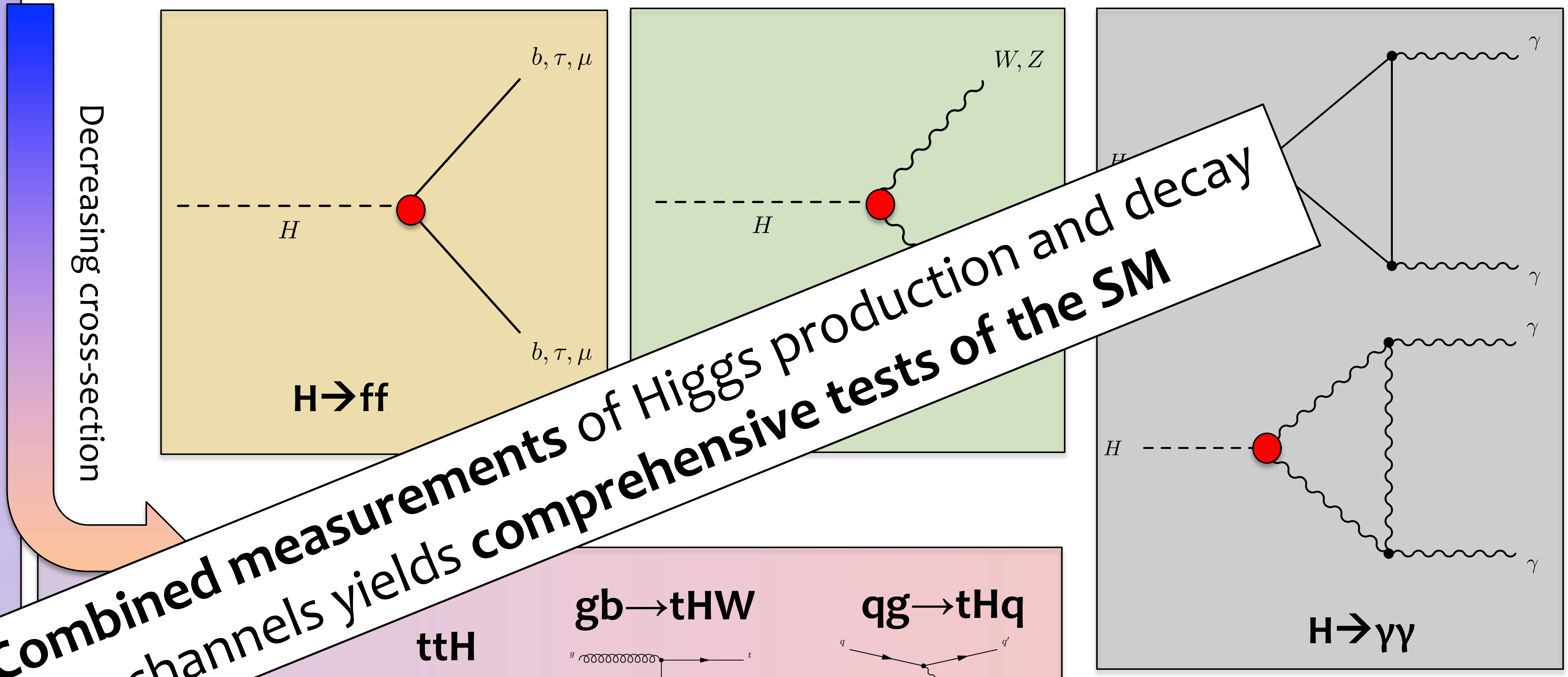


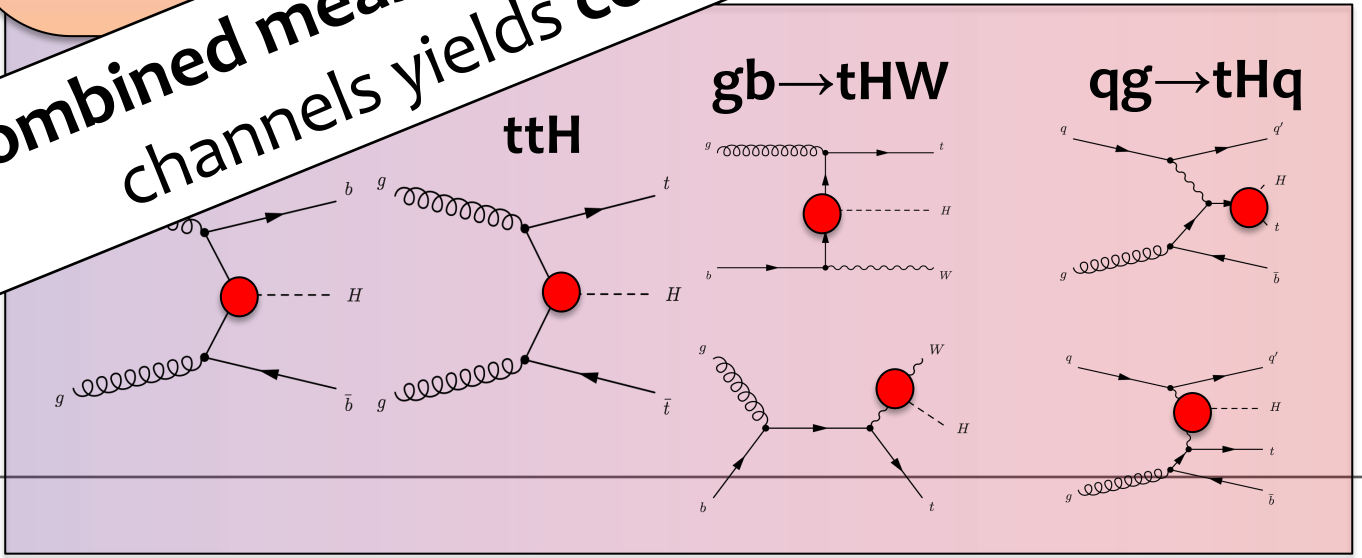


Many production and decay modes to study Higgs for m_H~125 GeV … access to many **Higgs-SM couplings**

Higgs Production and Decay







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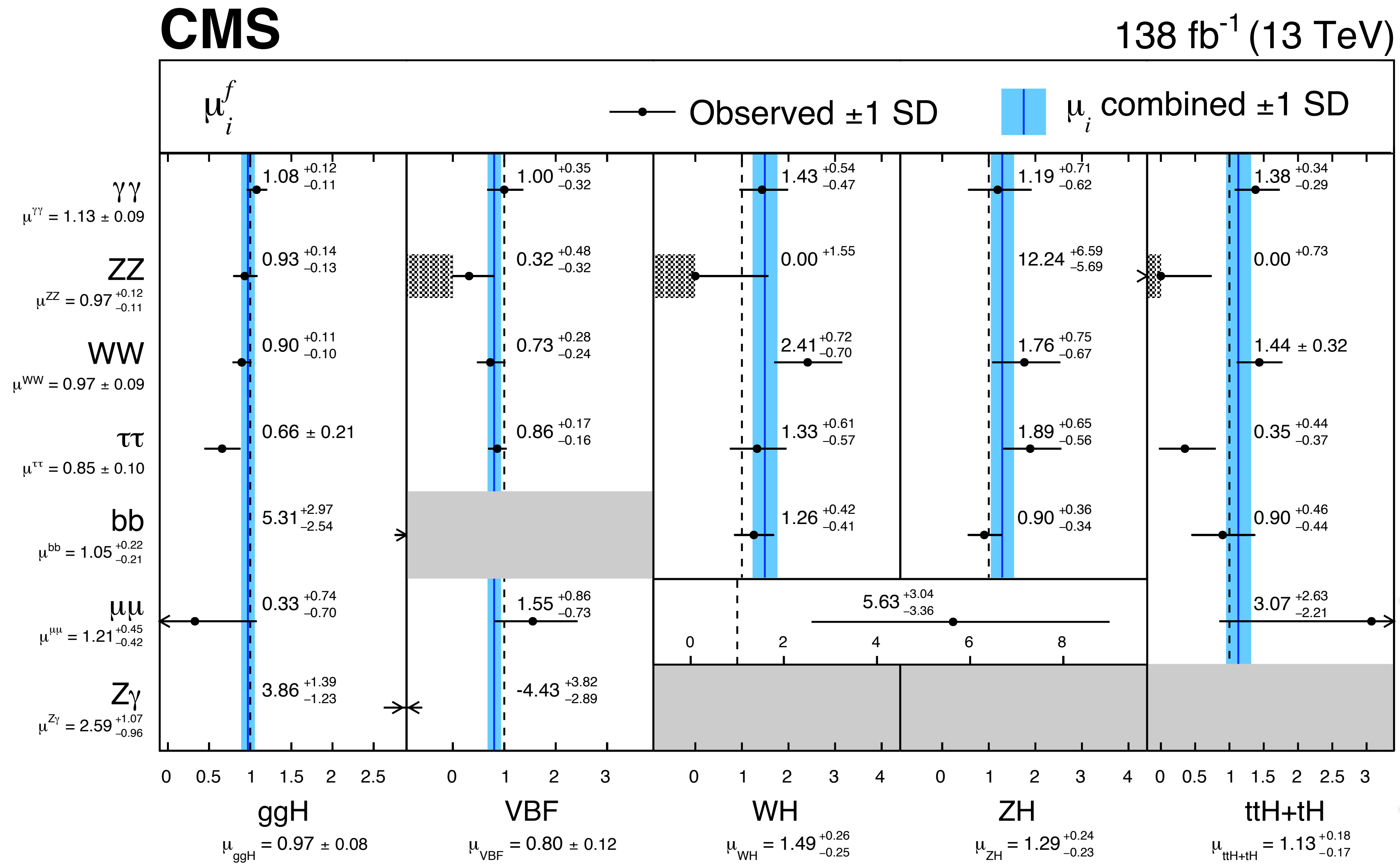
We construct a likelihood to interpret the combined datasets from across Higgs channels … .

$$L(\vec{\mu},\vec{\nu}) = \prod_n p\left(x_n; \sum_{i,f} \boxed{\mu_i \mu^f} S^f_{i,n}(\vec{\nu}) + \sum_k B_k(\vec{\nu}) \right) \cdot \prod_i p(y_i;\nu_i)$$

"**Signal strengths**" parameterization

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{(\mathrm{BR}^f)_{\mathrm{SM}}}.$$

Extracting the results

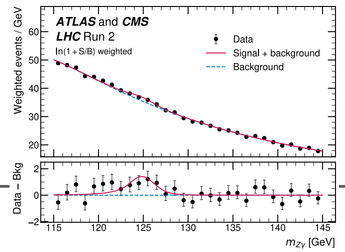


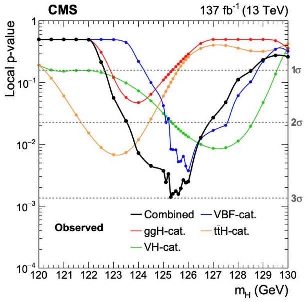
Latest CMS combination:
[Nature 607 (2022) 60-68]

~850 channels
(categories for data)

~9500 parameters
in the model (mostly constrained nuisance parameters)

Evidence for **Rare decays**
(H→μμ, H→Zγ)





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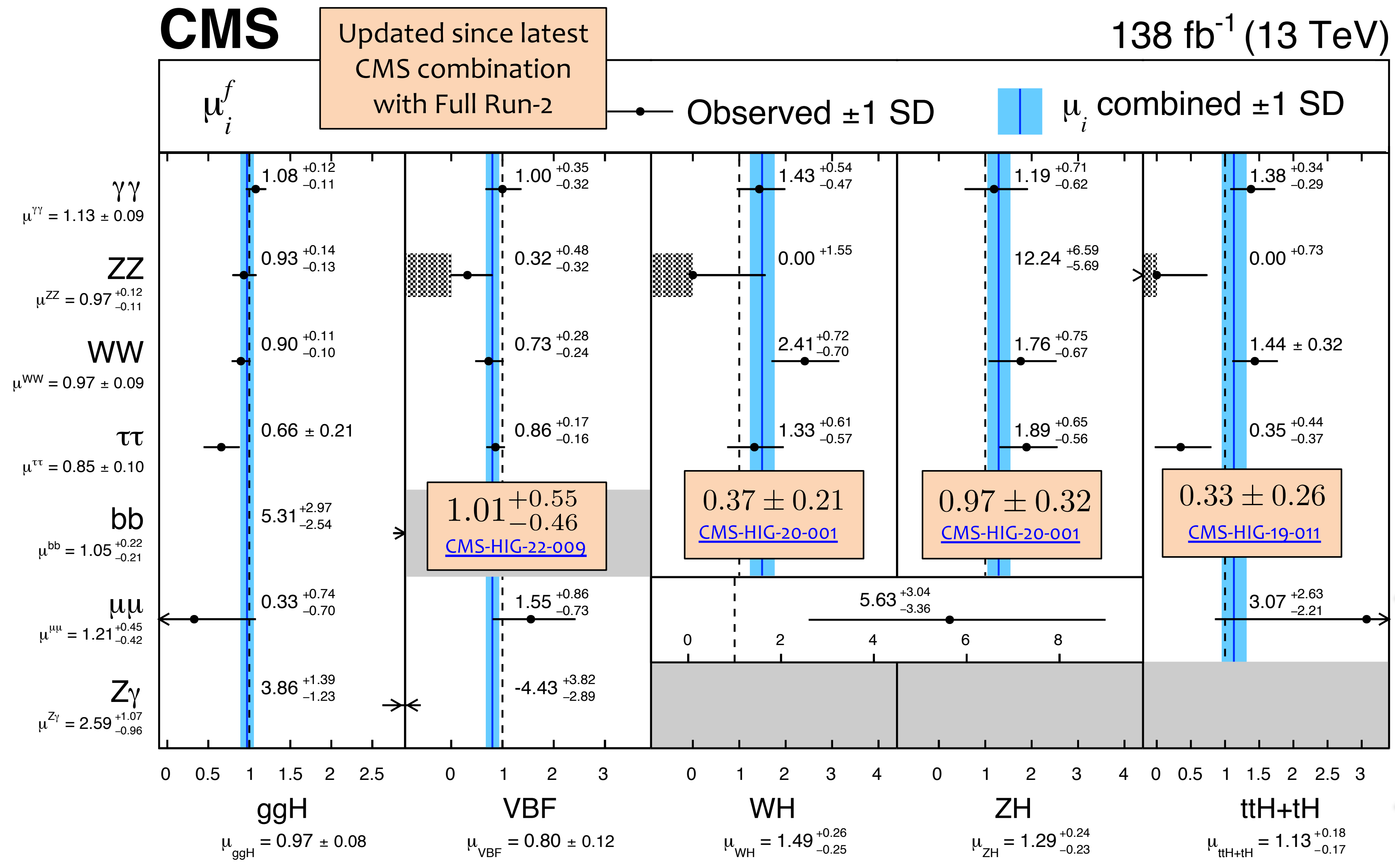

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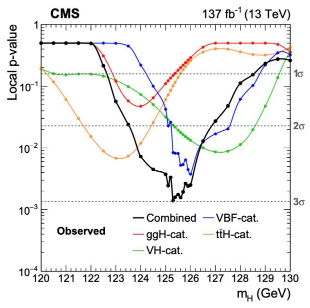

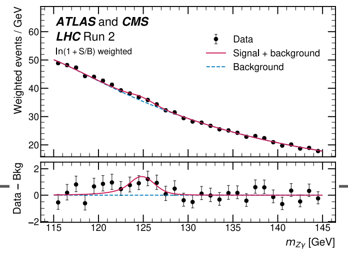

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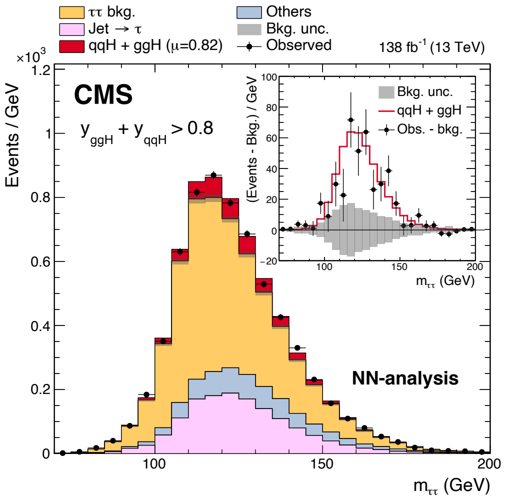
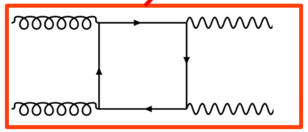
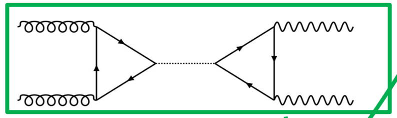
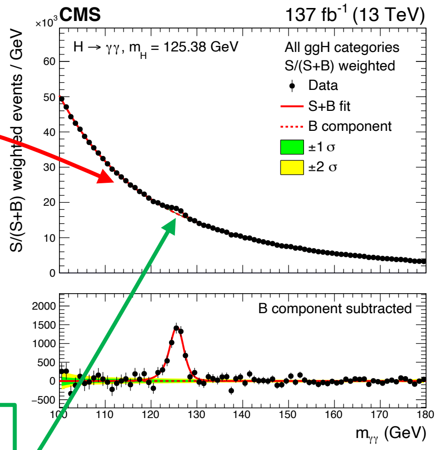
The "**data**" in each channel









Decompose expectation into ***signal*** and ***background*** contributions

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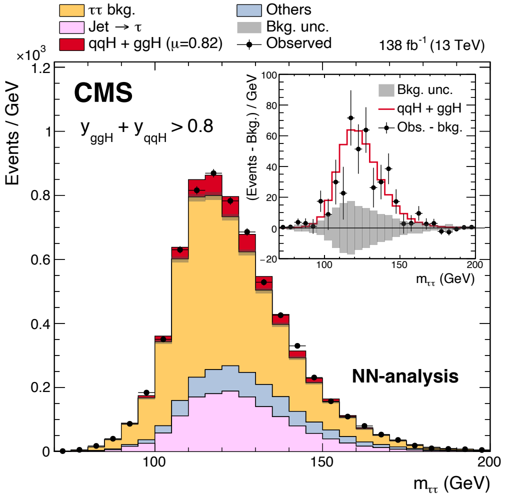
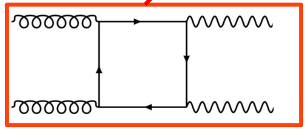
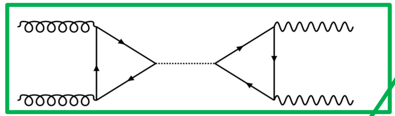
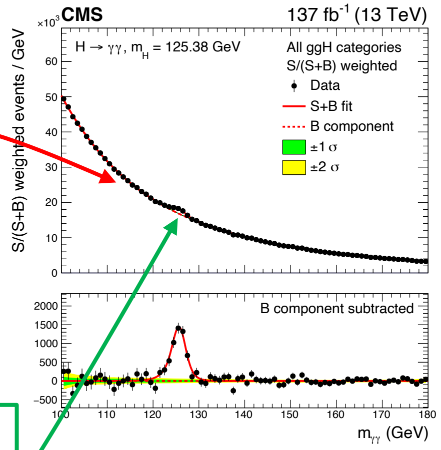


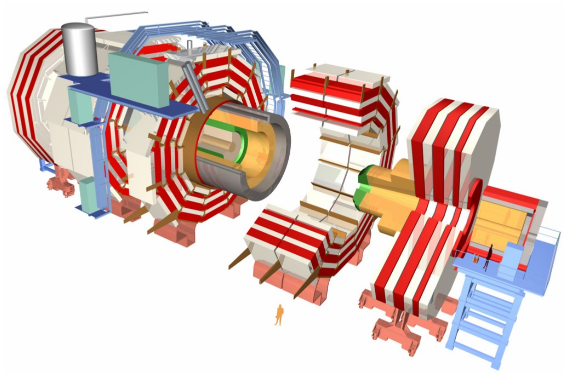






Decompose expectation into ***signal*** and ***background*** contributions

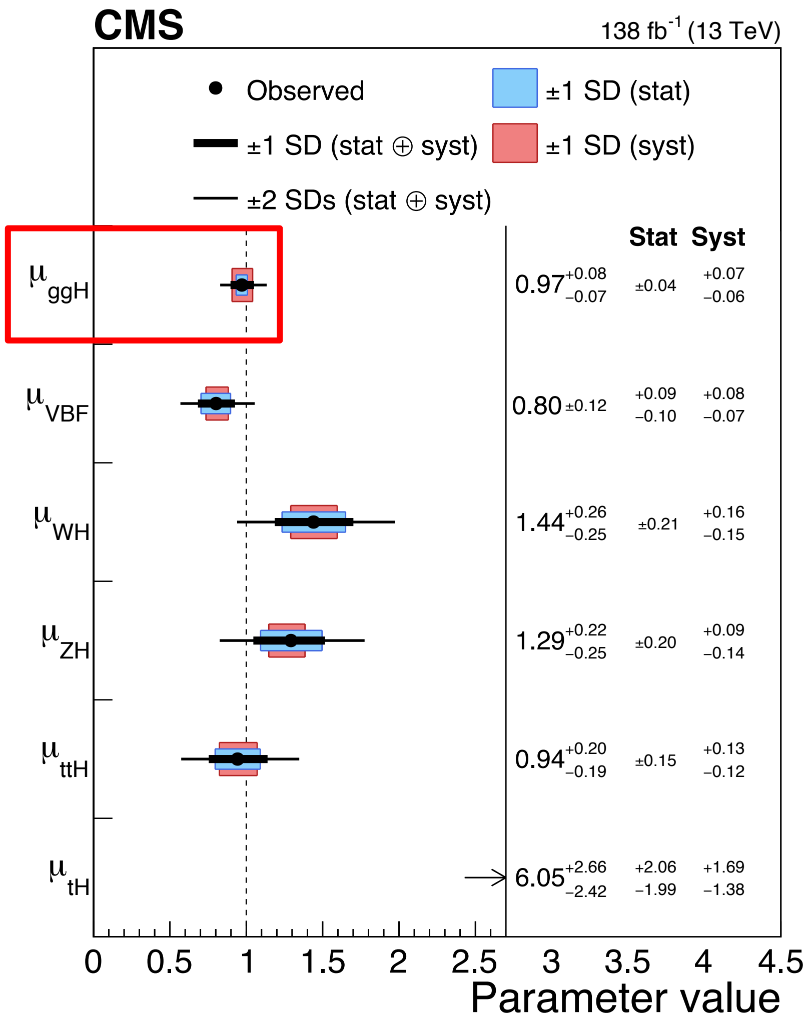
Nuisance parameters parameterize experimental/theoretical **systematic uncertainties**

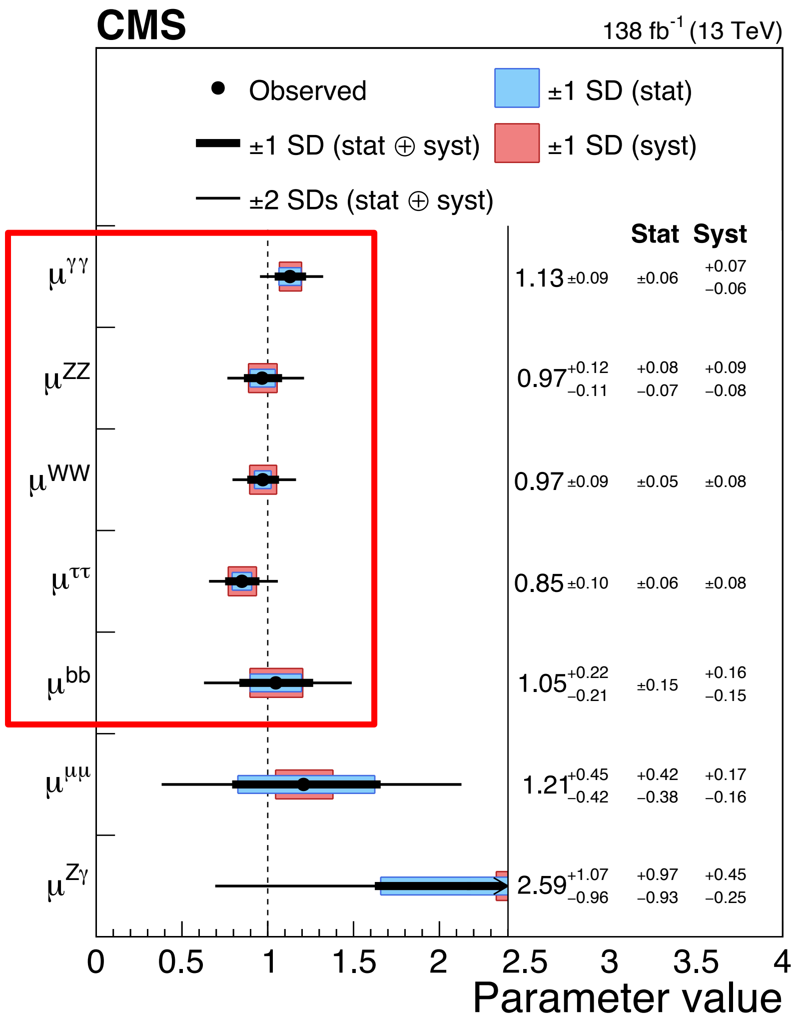


Extracting the results

Systematic uncertainties began dominate the sensitivity in certain measurements!

- Uncertainty in measurements of **largest production and decay modes** already comparable/larger than statistical uncertainties
- Inclusive measurements suffer from theoretical and experimental systematics (extrapolation etc)
  → Differential measurements needed to push sensitivity (see next talk)





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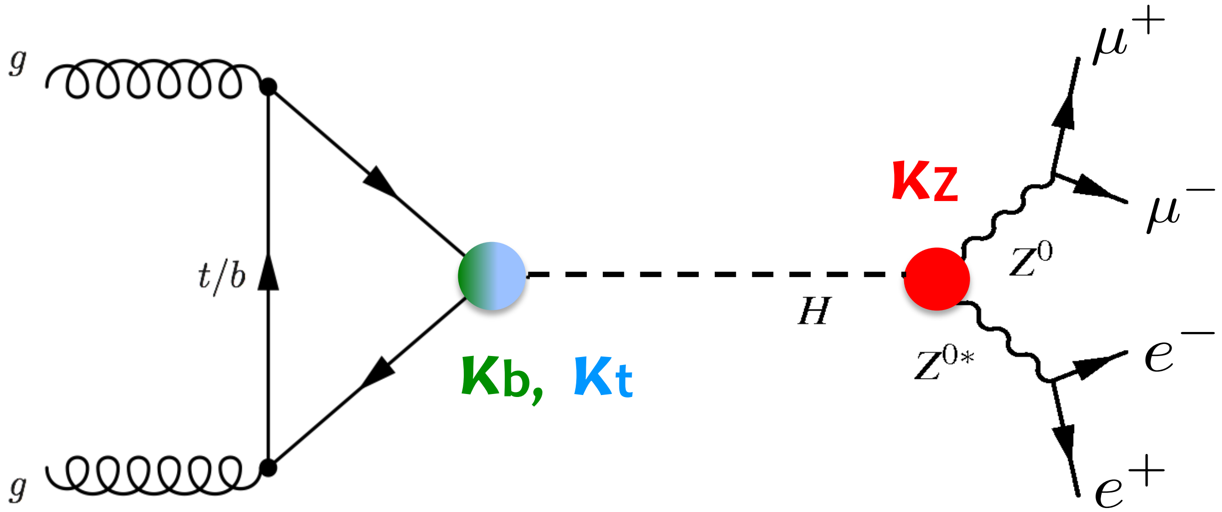
"**Signal strengths**" parameterized in terms of "coupling modifiers" **κ**

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \quad \text{and} \quad \mu^f = \frac{{\rm BR}^f}{({\rm BR}^f)_{\rm SM}}.$$

$$\mu \rightarrow \mu(\boldsymbol{\kappa})$$

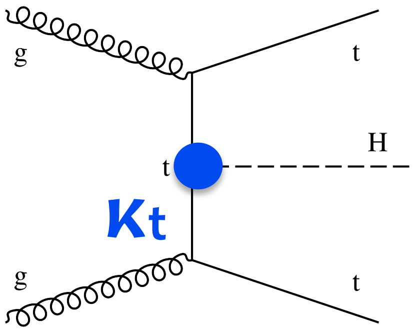
Standard model defined by $\boldsymbol{\kappa} = 1$ and $\mu(1) = 1$

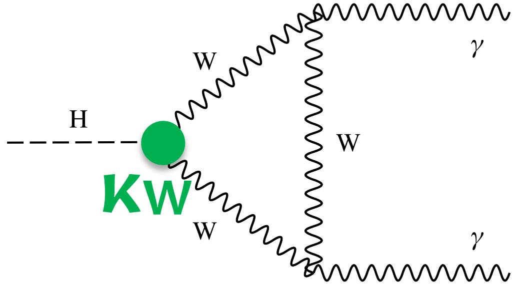


$$\mu_{ggH} \cdot \mu^{ZZ} \sim \frac{(1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\kappa_Z^2}{\kappa_H^2}$$

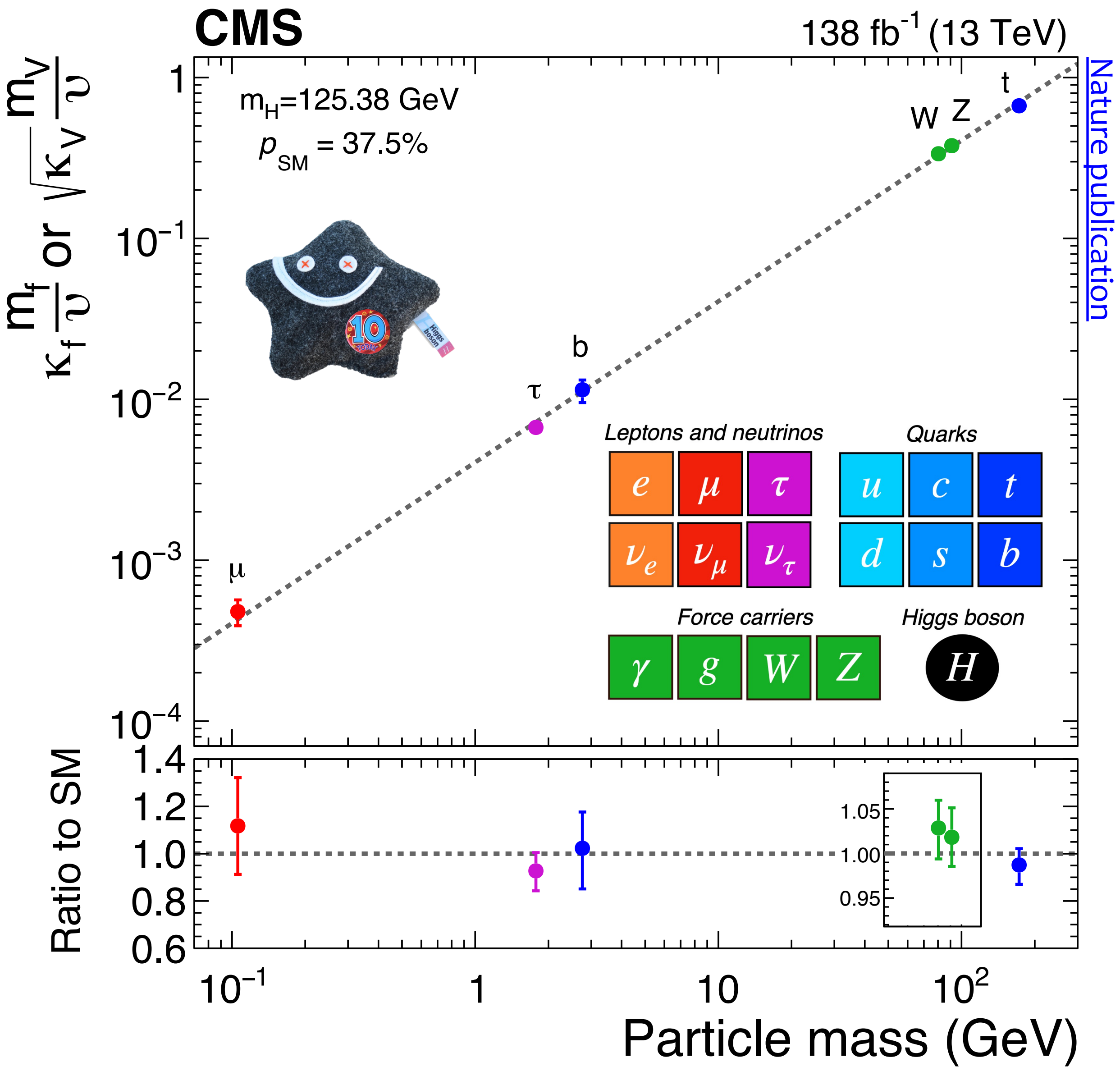
Putting it all together

In the SM - Higgs interaction strengths (**couplings**) to SM particles are **proportional to mass** of those particles





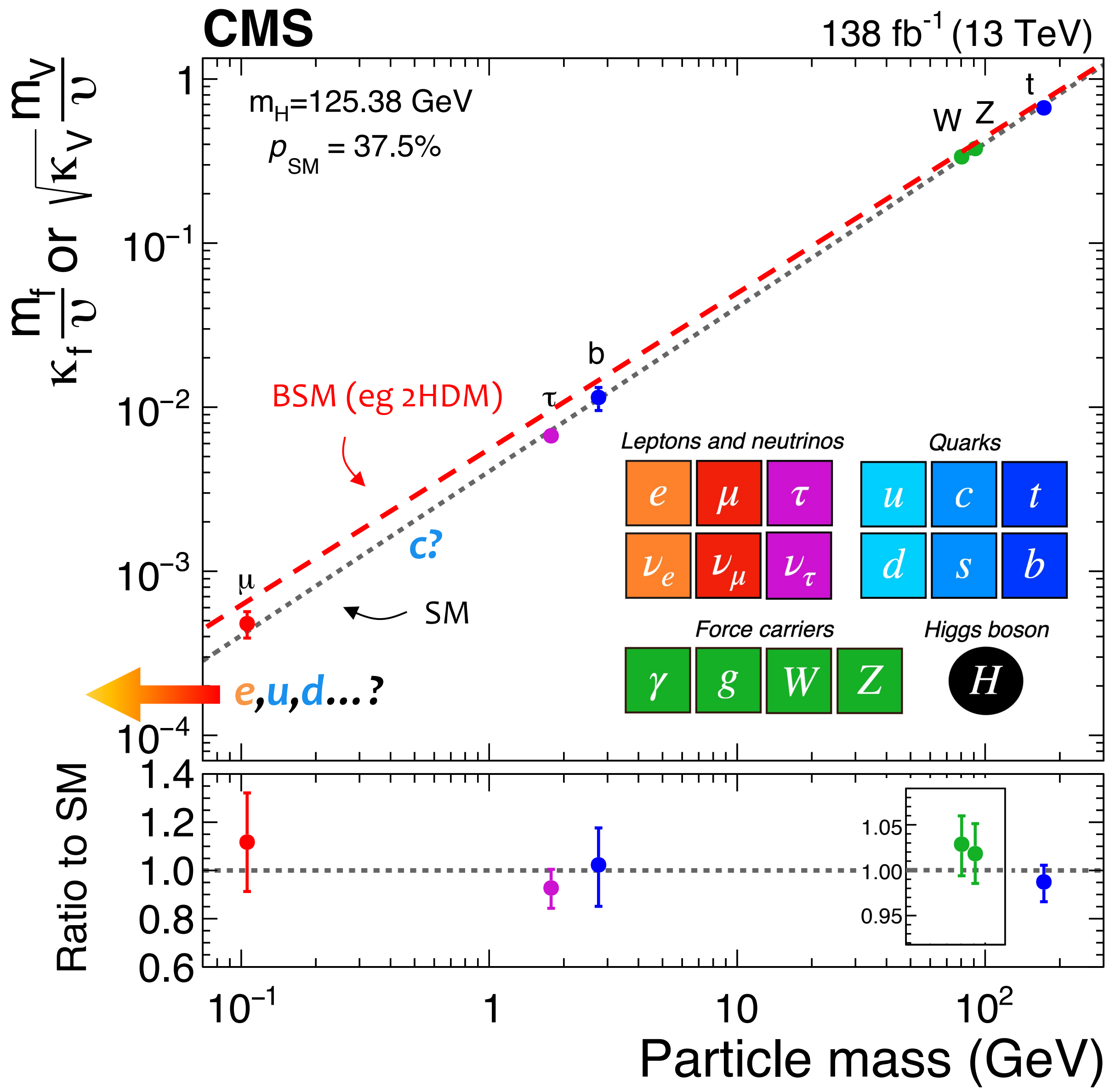
Through a **combination** of the different production and decay processes, we can extract the couplings to SM particles **and compare to the trend predicted in the SM**



So, aren't we done?

The **Higgs boson** was the **missing piece of the SM** and we've had it now for 10 years …

- **Is the Higgs sector SM-like ?** → Do all the SM particles lie on that line?



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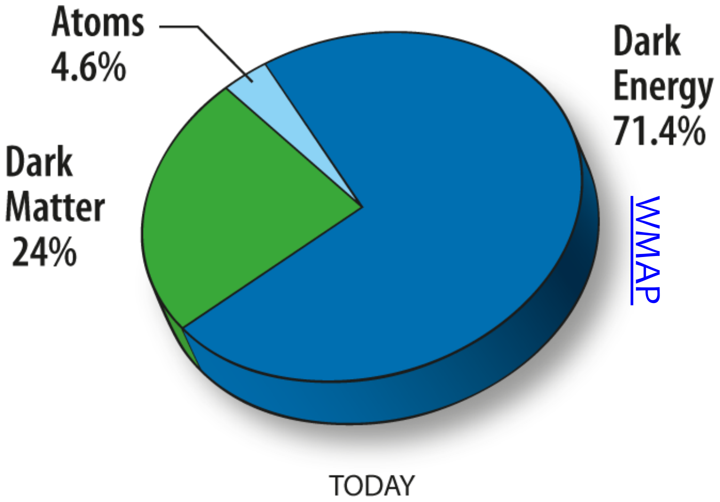
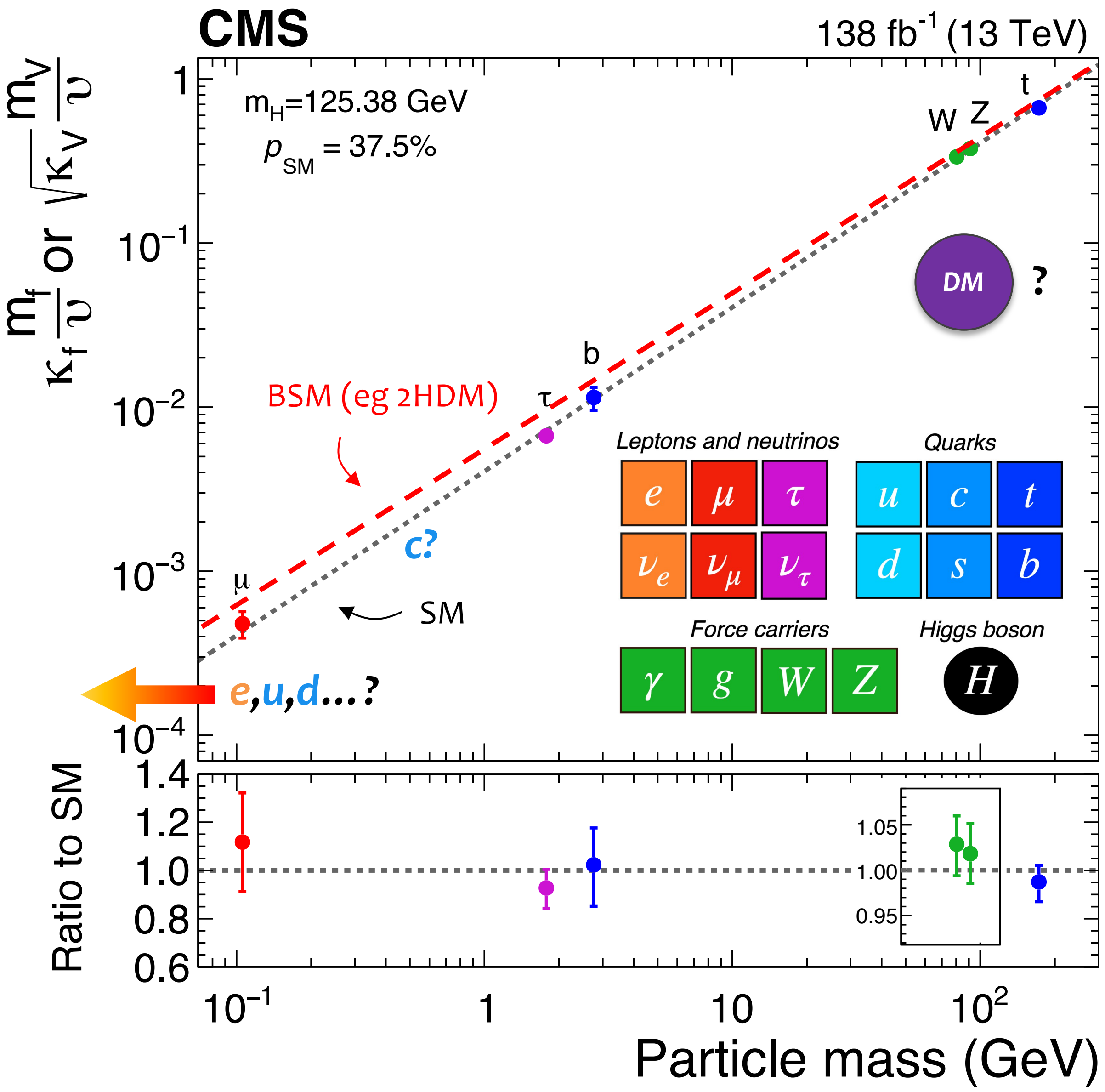
- **What does Dark Matter (DM) fit in ?** → if DM are massive particles, wouldn't they couple to the Higgs too?



WMAP



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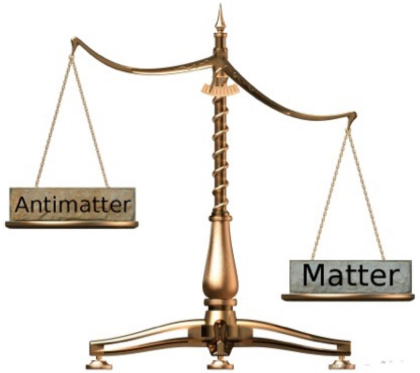

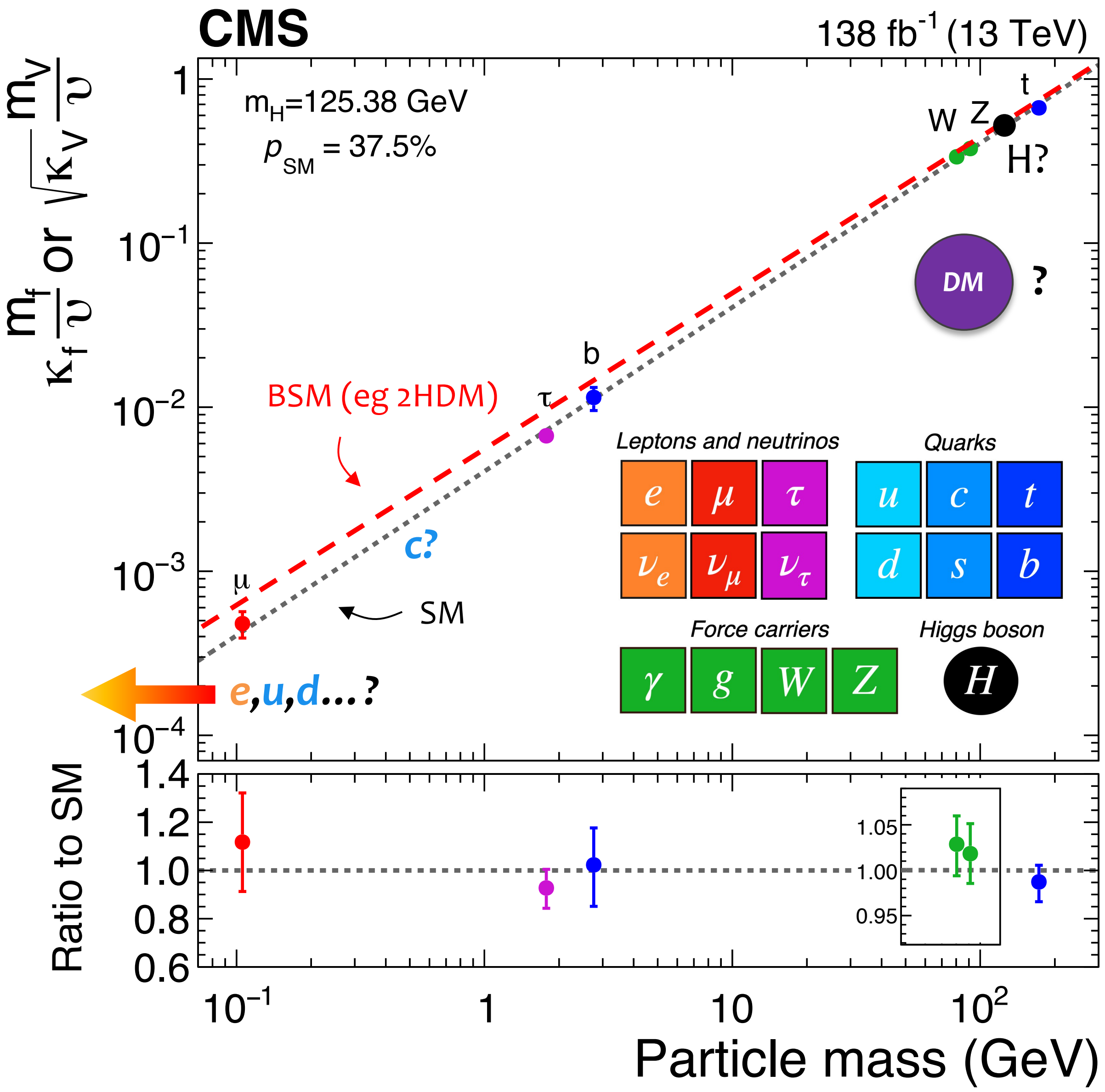

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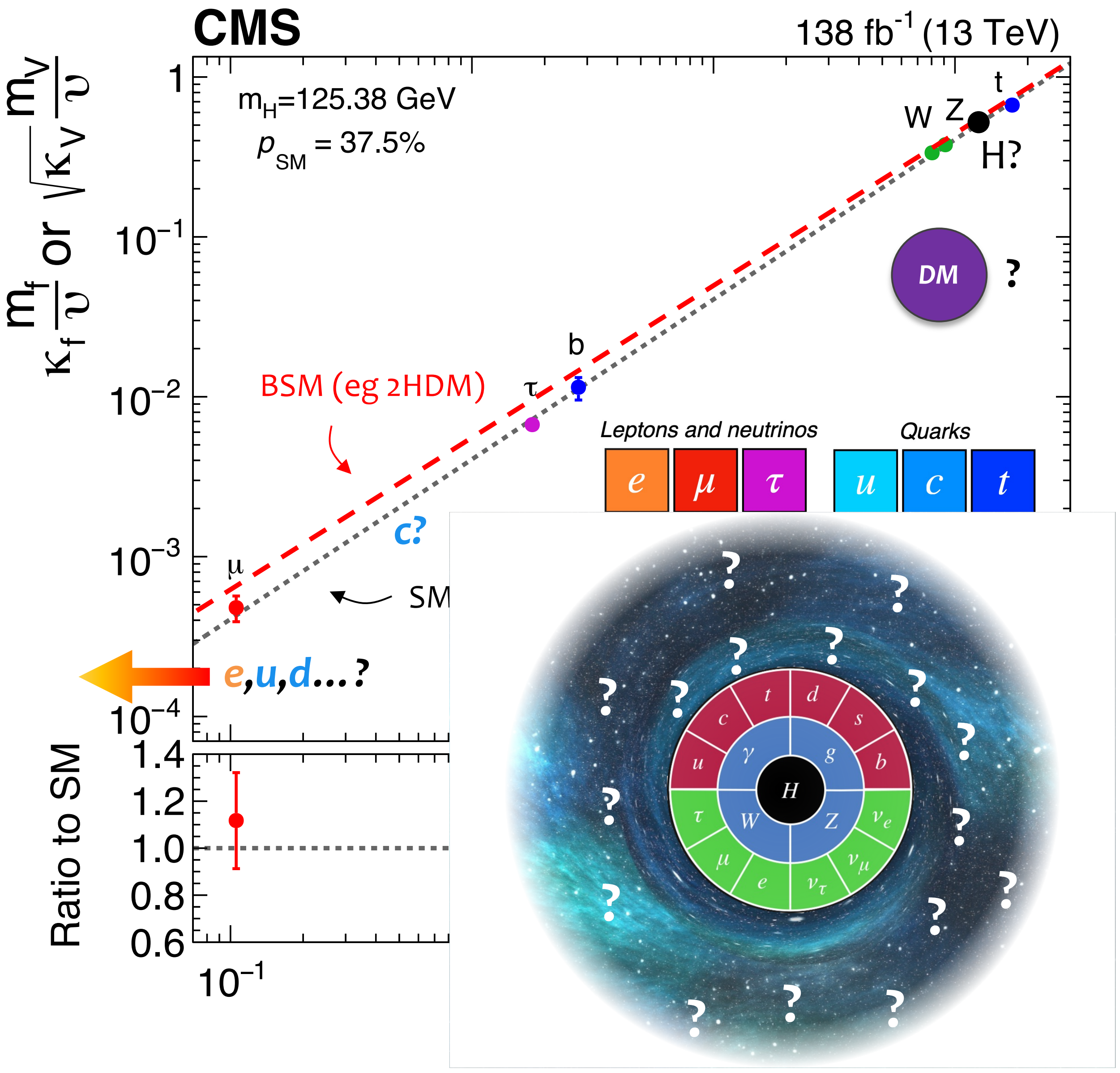
These are **fundamental questions** in physics
→ The **Higgs boson** is a unique tool to search for **physics Beyond the SM** (BSM)



Precision measurements for discovery

Examples from the past have taught us that precision measurements can lead to ***revolutionary discoveries…***

Herschel 1781

Uranus discovery
"as a planet" **(1781)**

Precise measurements of position
revealed deviations from expected orbit
→ new planet predicted **(1845/46)**

Slide heavily inspired by J. Liu (Cambridge)

Precision measurements for discovery

Examples from the past have taught us that precision measurements can lead to ***revolutionary discoveries…***

Herschel 1781

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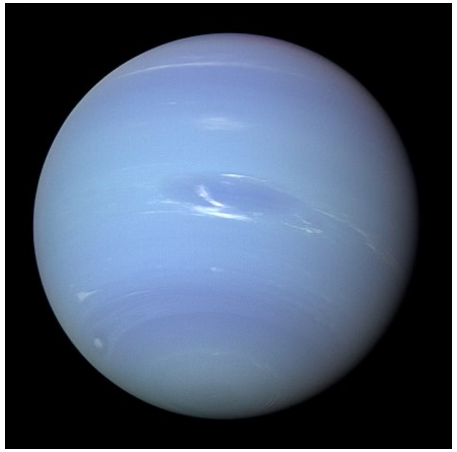
Le Verrier, Galle, d'Arrest 1846



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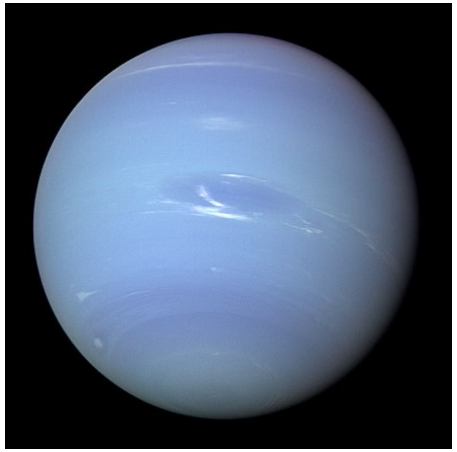

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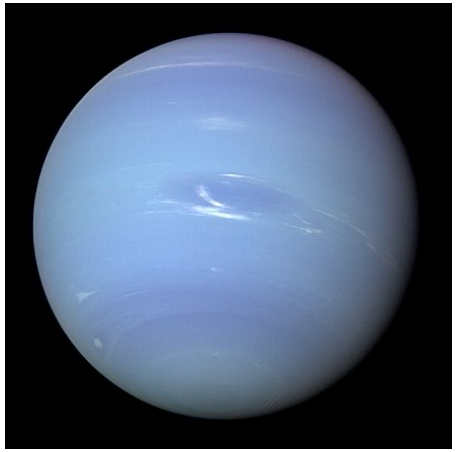

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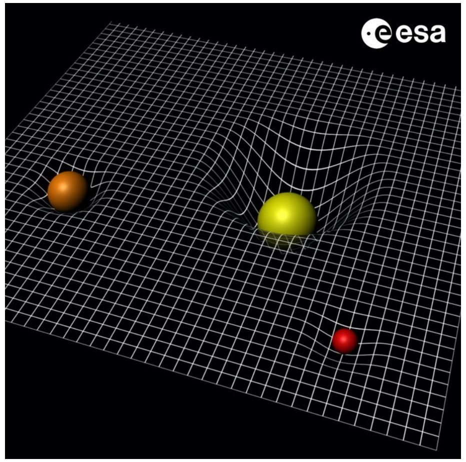
Le Verrier 1859, Einstein 1915

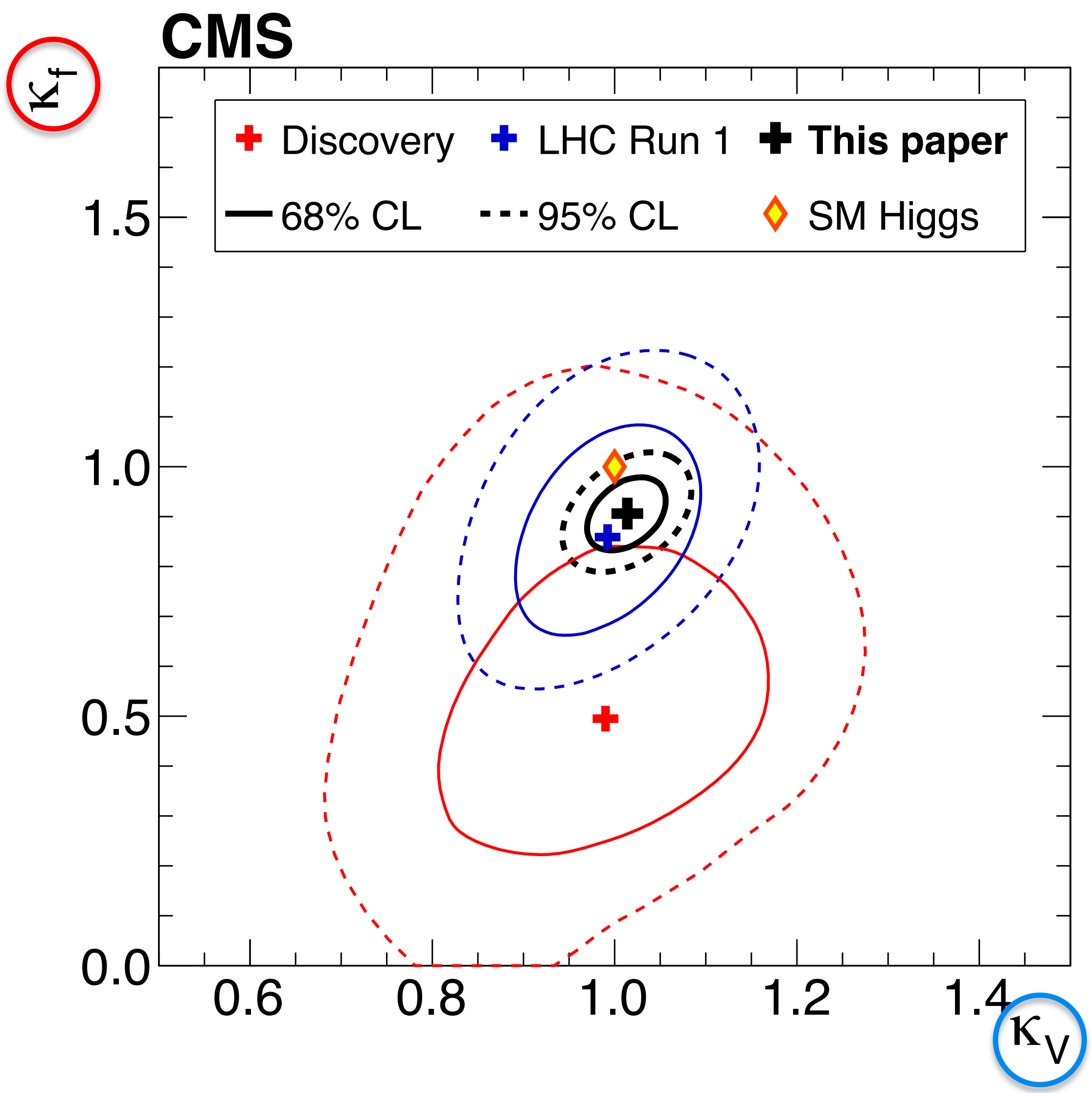


General relativity solves
anomaly and changes view
of space & time (**1915**)

Slide heavily inspired by J. Liu (Cambridge)

…History has a habit of repeating itself 🤞 …

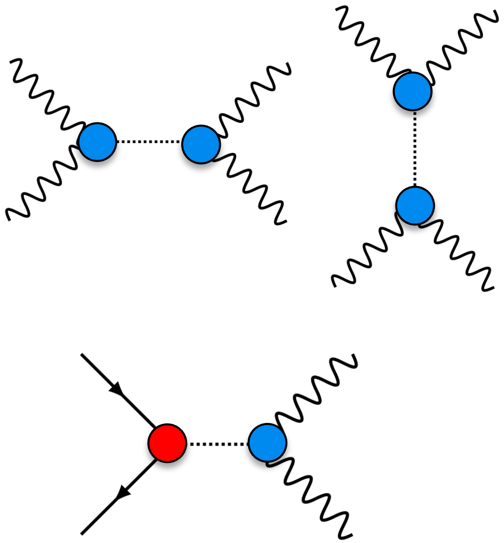
Higgs couplings for BSM physics



In the **SM, the Higgs regulates longitudinal WW** scattering at high energies

$$W_L^+W_L^- \to W_L^+W_L^- \sim \frac{g^2}{4m_W^2}(s+t)\left(1-\kappa_V^2\right)$$

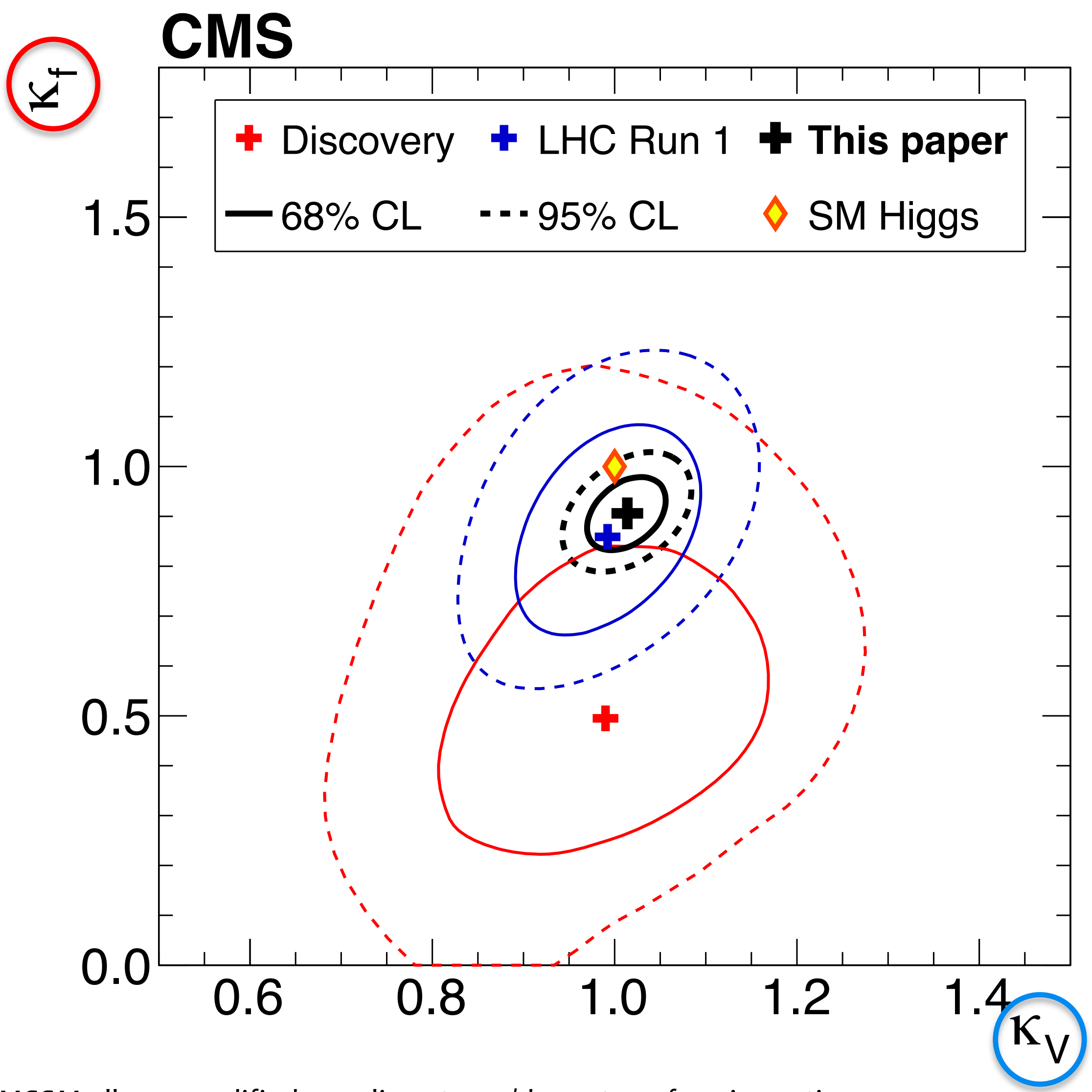
$$\psi\bar{\psi} \to W_L^+W_L^- \sim \frac{m_\psi\sqrt{s}}{v^2}\left(1-\kappa_F\kappa_V\right)$$



If couplings to vector bosons and fermions are SM-like Scattering amplitudes don't diverge

→ Measuring these couplings is a **strict test of SM at higher energies**

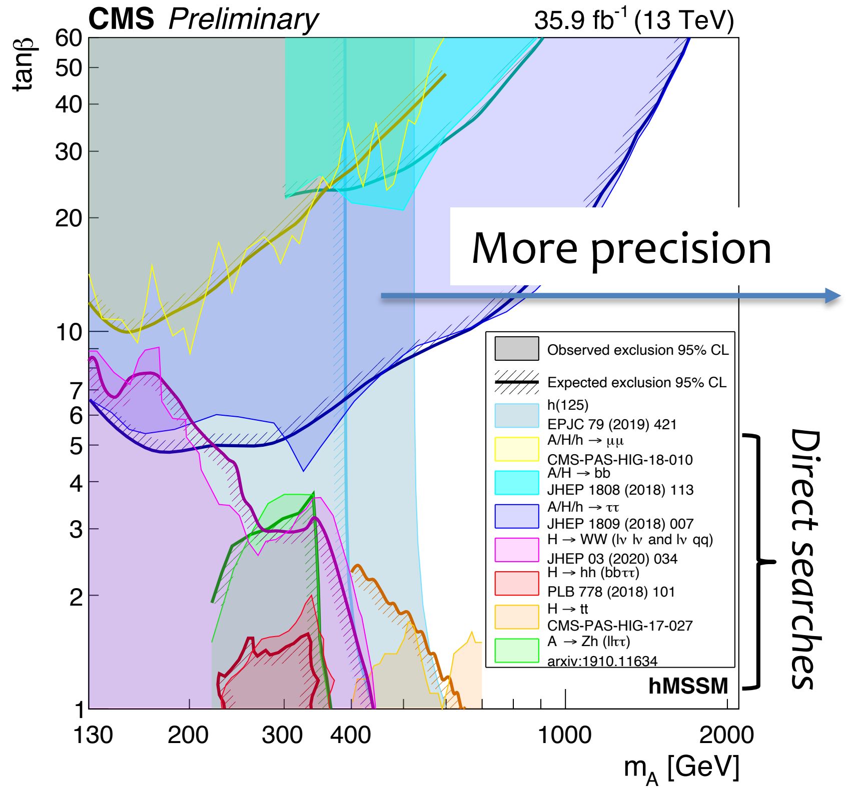
Higgs couplings for BSM physics



In extended Higgs sectors (e.g two 2HDM), couplings to vector bosons and fermions can be modified from SM

→ Measuring these couplings is a **direct probe of extended Higgs sector models**

→ **Complementary** approach **to direct searches*** for additional Higgs bosons

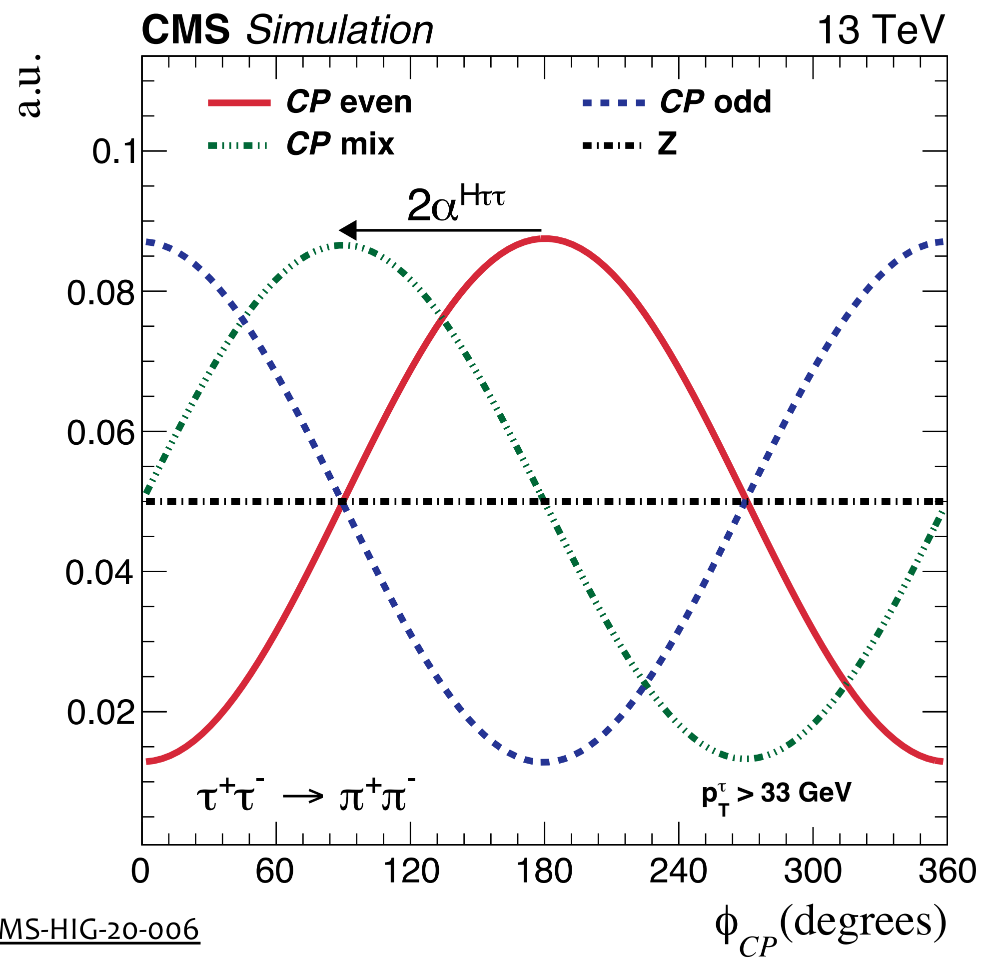


*hMSSM allows modified couplings to up/down type fermion ratio

Higgs couplings for BSM physics

Measure $H \rightarrow \tau\tau$ decays differentially in Φ_{CP} to access potential **CP-odd** contributions to H-τ coupling

$$\mathcal{L}_Y = -\frac{m_\tau}{v} H \left(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau \right)$$



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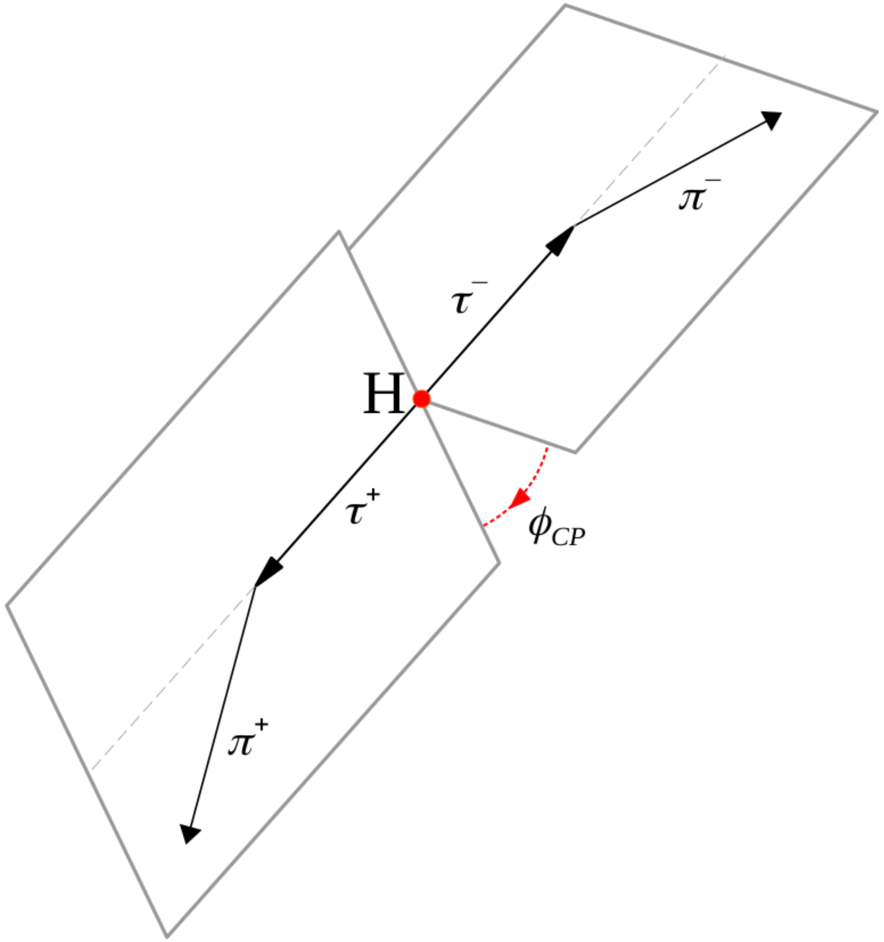
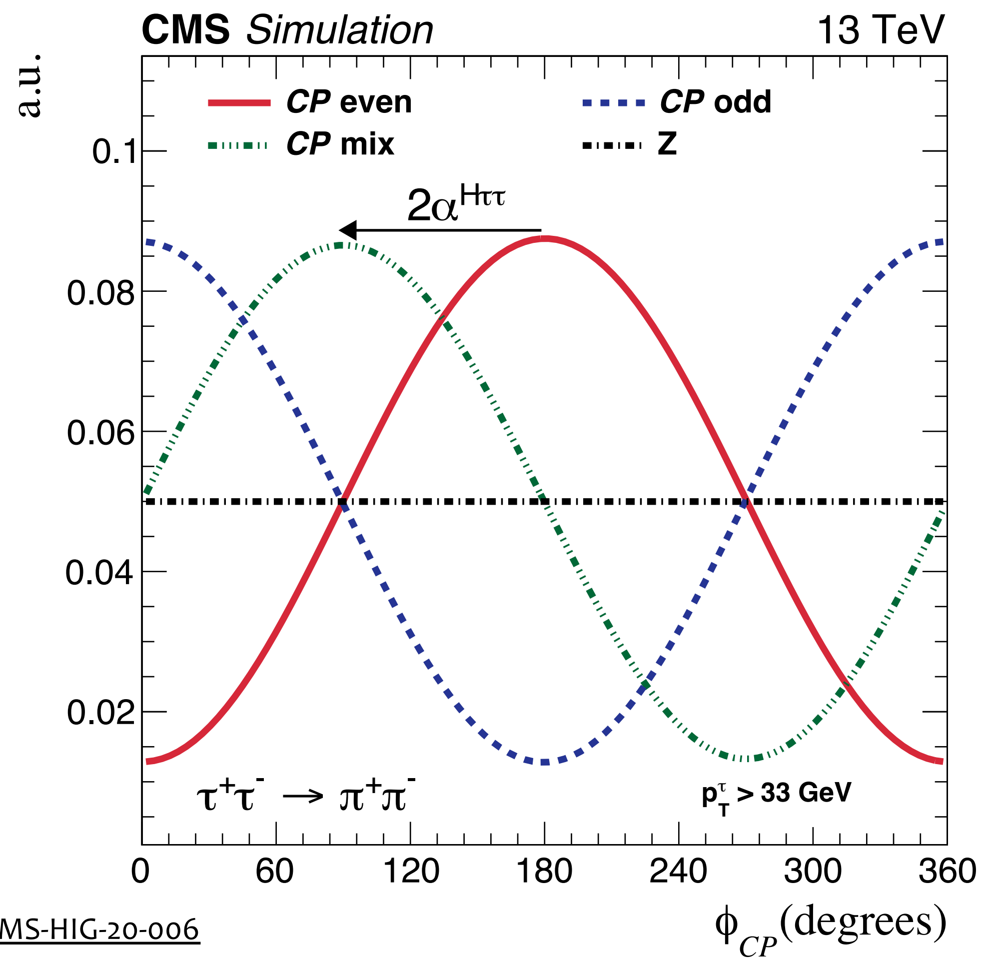


Higgs couplings for BSM physics

Measure $H\rightarrow\tau\tau$ decays differentially in Φ_{CP} to access potential CP-odd contributions to H-τ coupling

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



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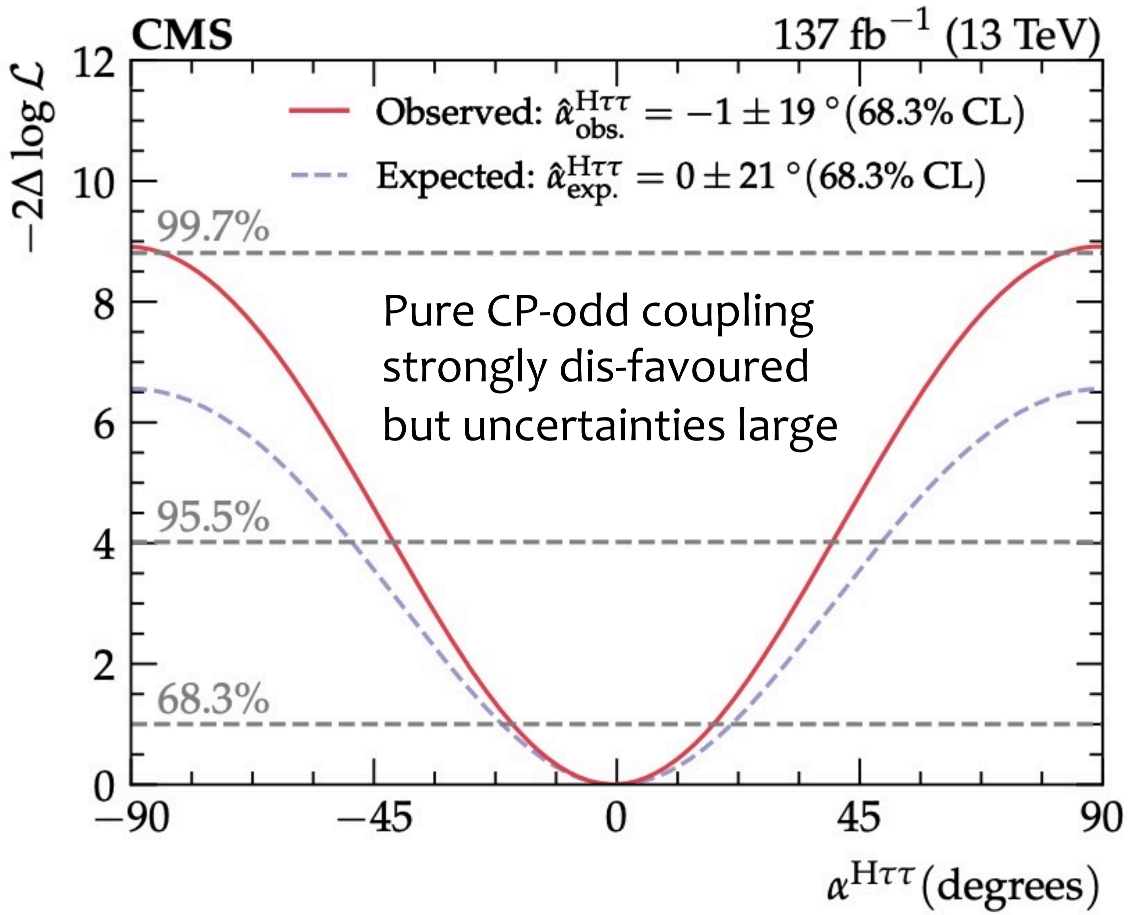


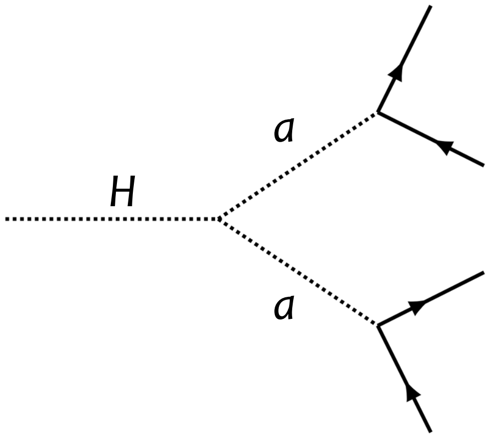
Pure CP-odd coupling strongly dis-favoured but uncertainties large

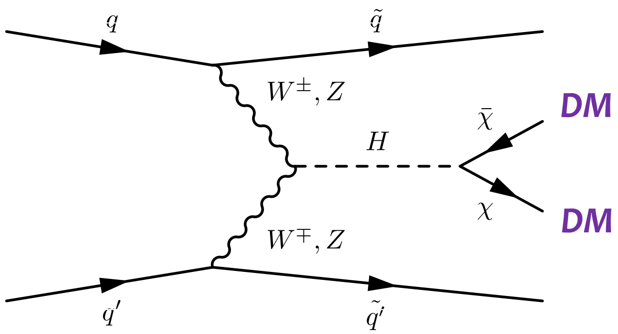
Higgs as a portal to new physics

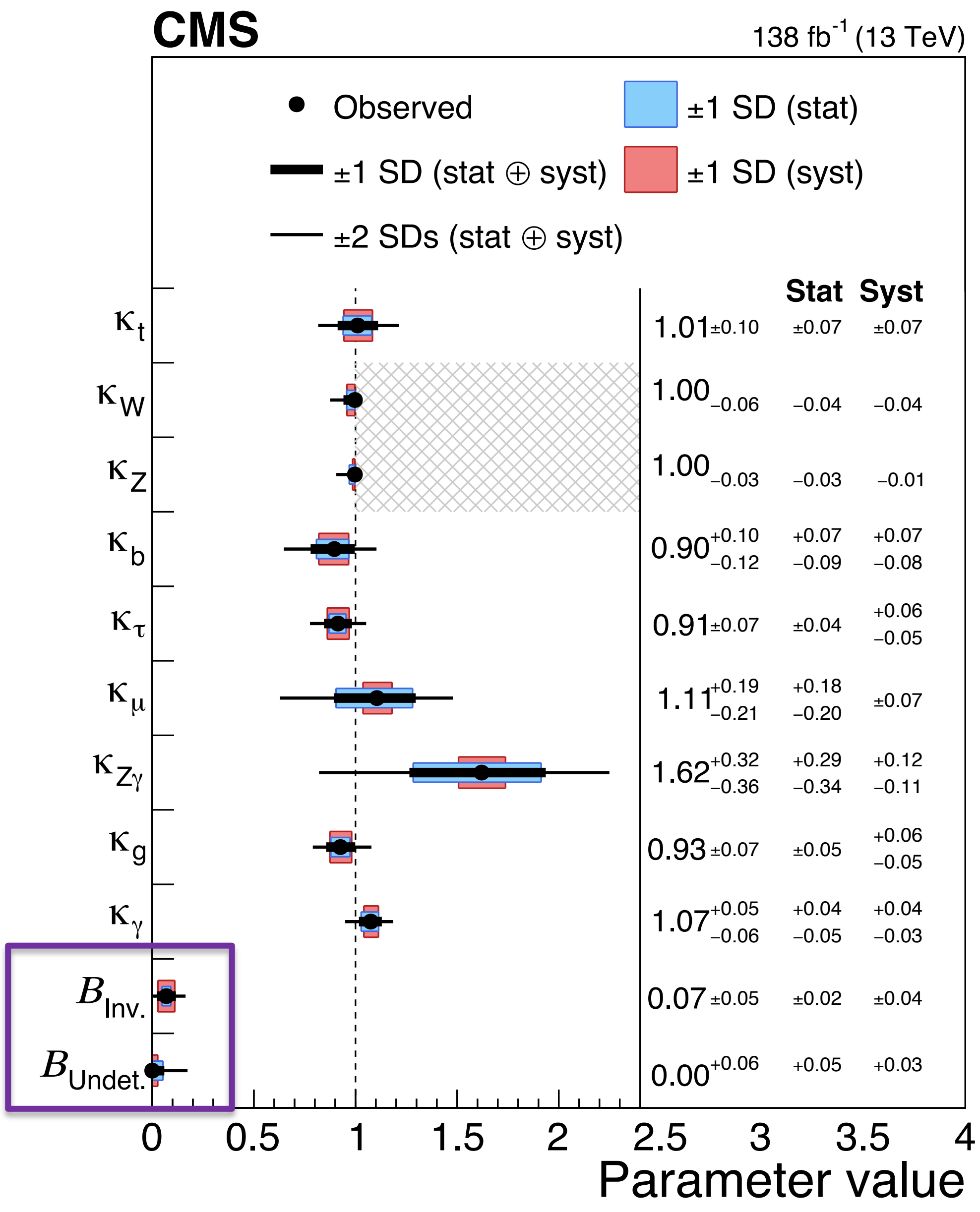
Current measurements of Higgs boson couplings allow for **“missing” decay modes to light particles**

Higgs boson decays to **BSM particles** modify the total width through

- undetected modes (2HDM+s, nMSSM…)
- **invisible particles** (Dark Matter)

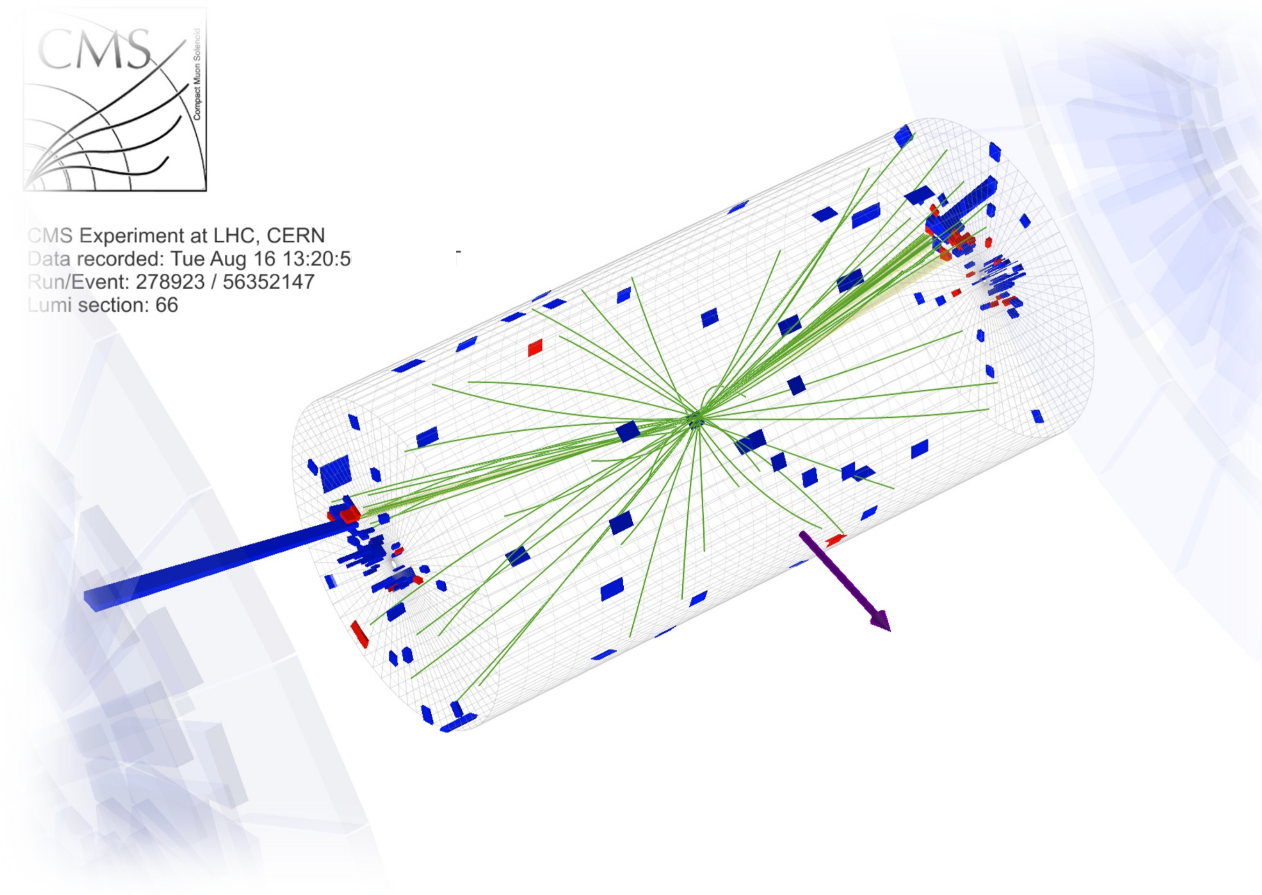


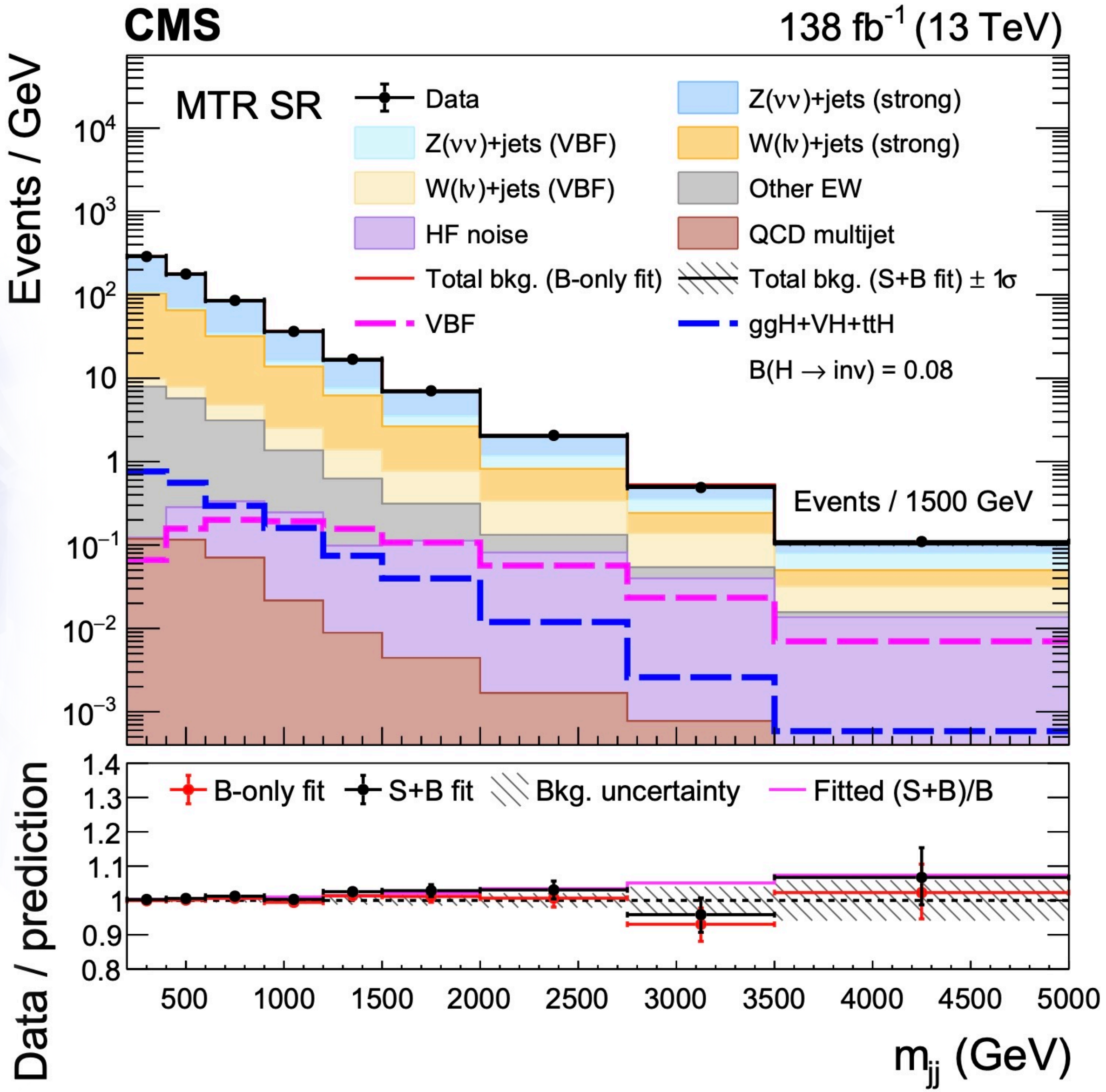




Higgs as a portal to new physics

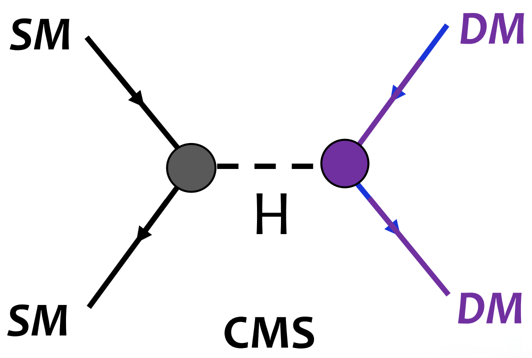
Invisible Higgs branching fraction measurements require very good understanding of energy resolution and SM background contributions

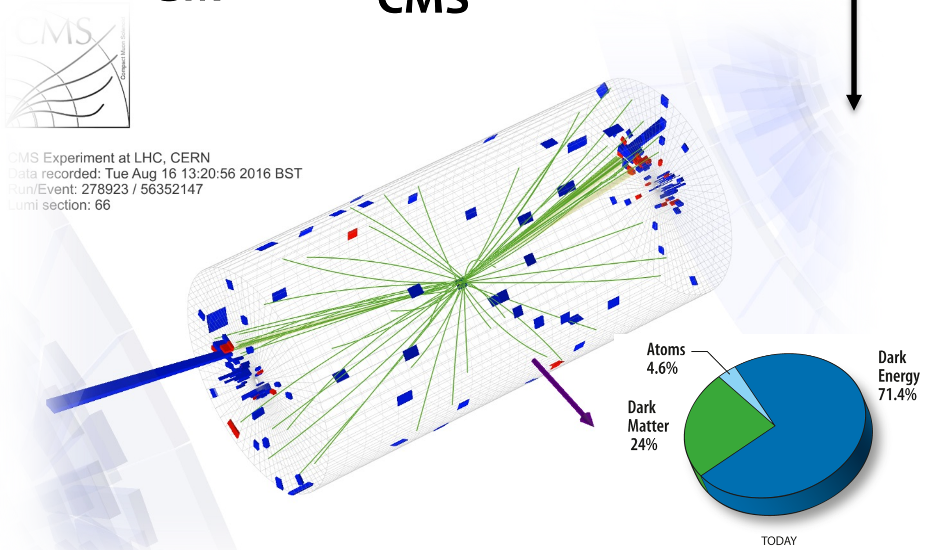




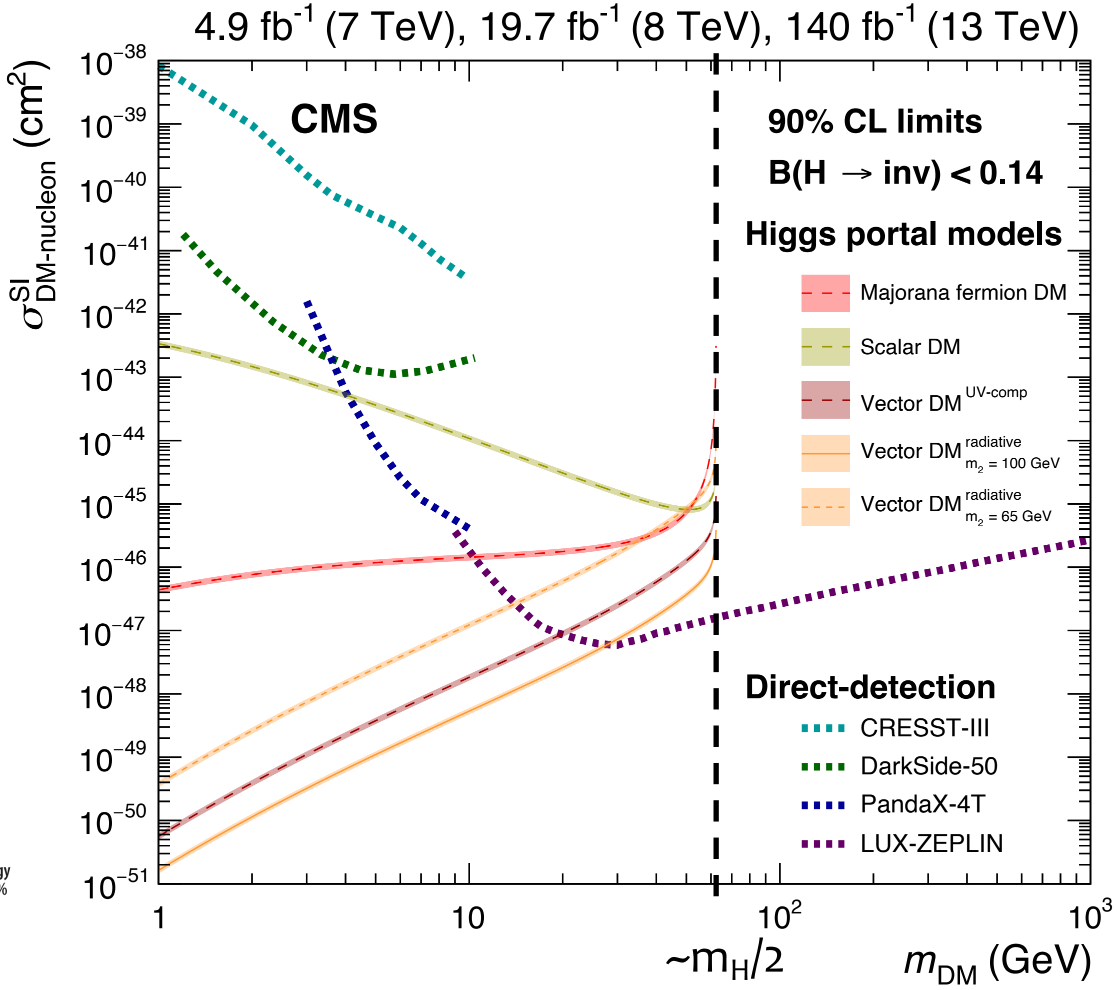
Higgs as a portal to new physics

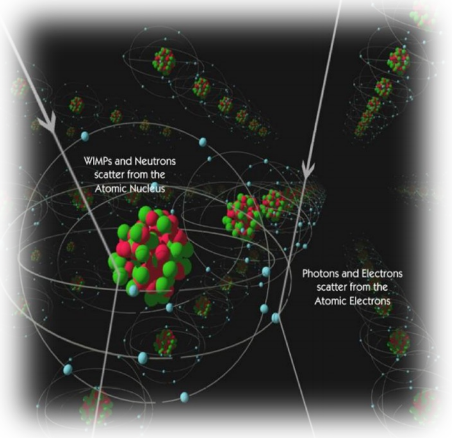
Invisible Higgs branching fraction measurements complementary to direct searches for Dark Matter!



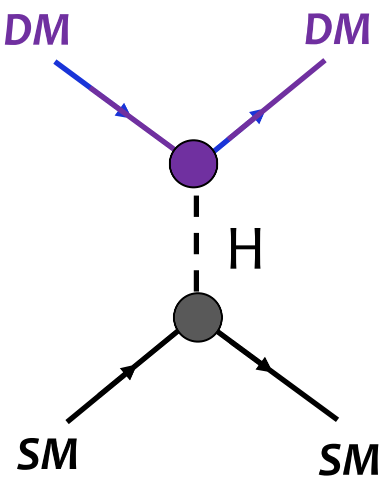


Better Sensitivity





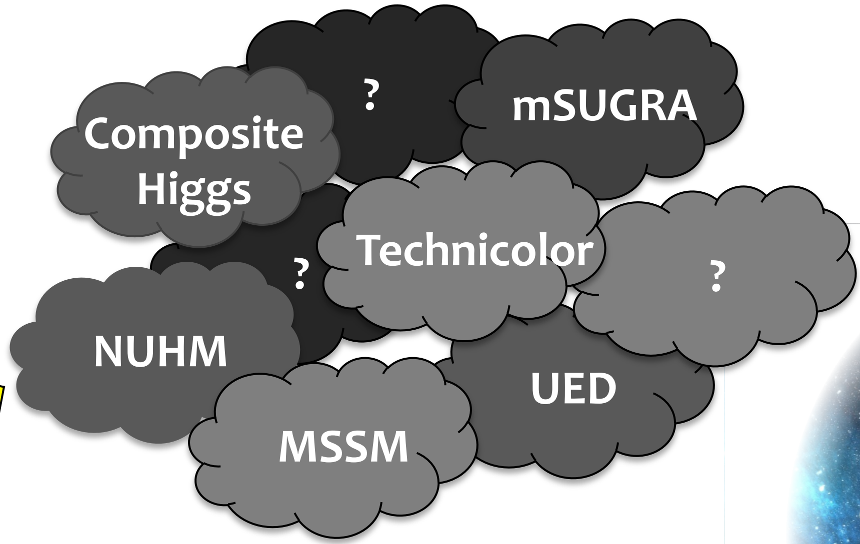
Direct DM detectors

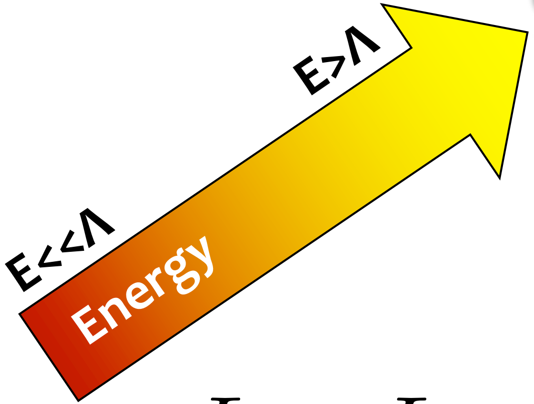


Higgs couplings as BSM physics

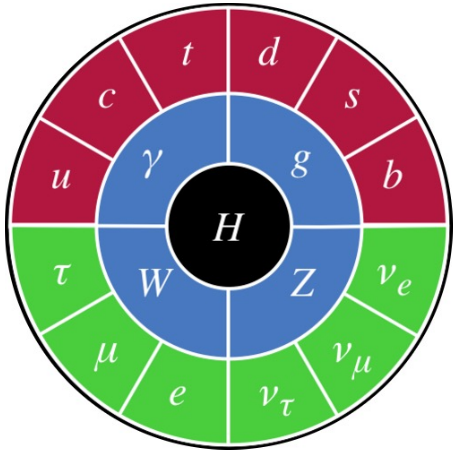
How to cope **with large space of potential models** for **BSM physics**?

New Physics models

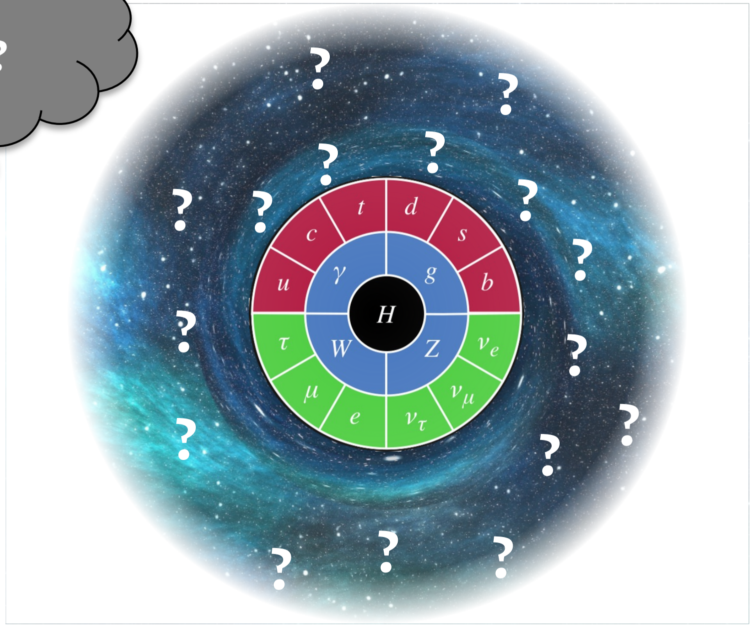




Standard Model



$$L = L_{SM} + \frac{1}{\Lambda}\sum_k \mathcal{O}_k + \dots$$



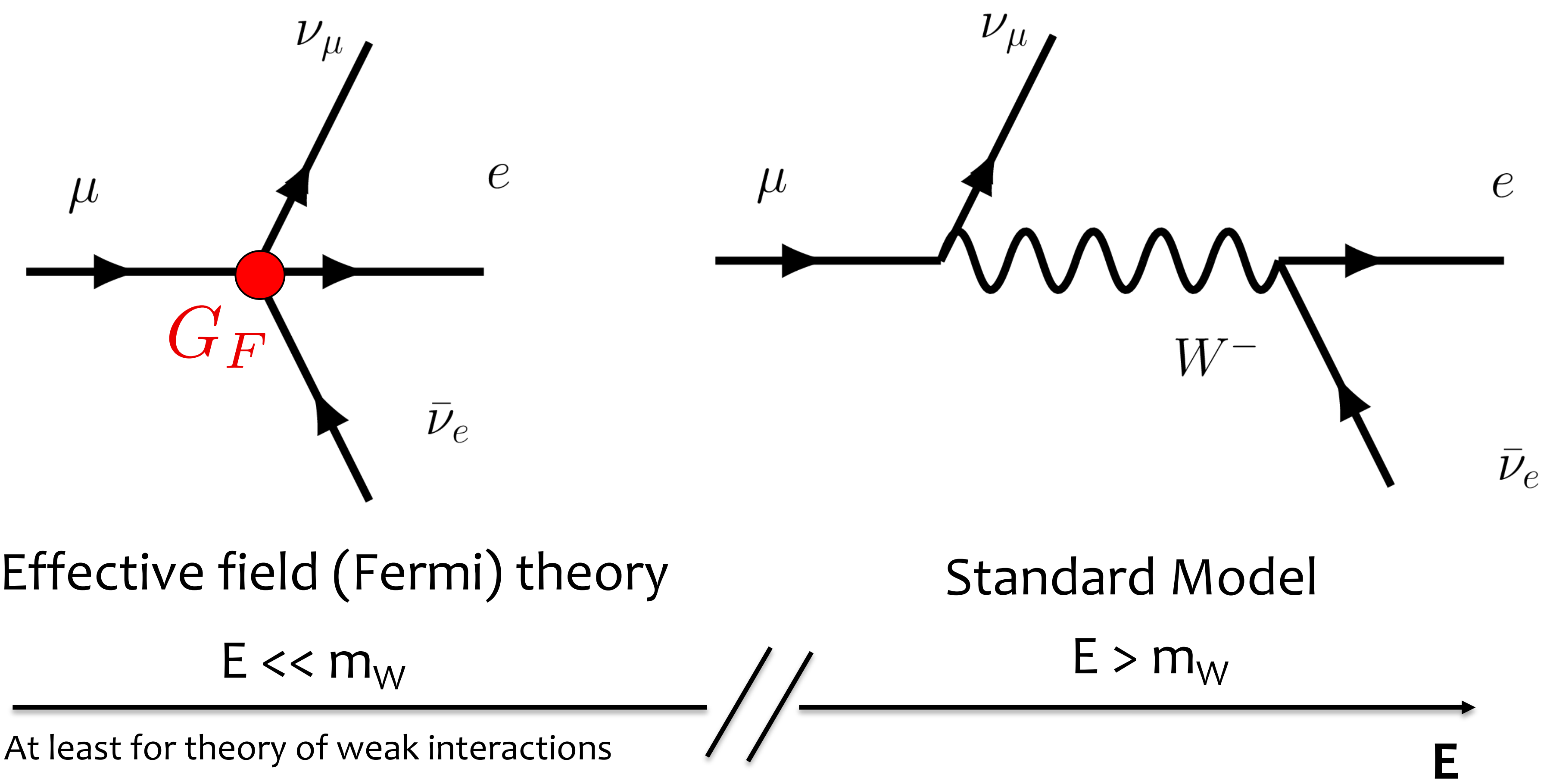
Effective Field Theories (**EFT**) allow to **systematically probe** space of new physics (**NP**) models

→ Valid for **E below NP scale Λ**

→ Match NP models to EFT parameters to **constrain possible BSM scenarios**

Effective couplings

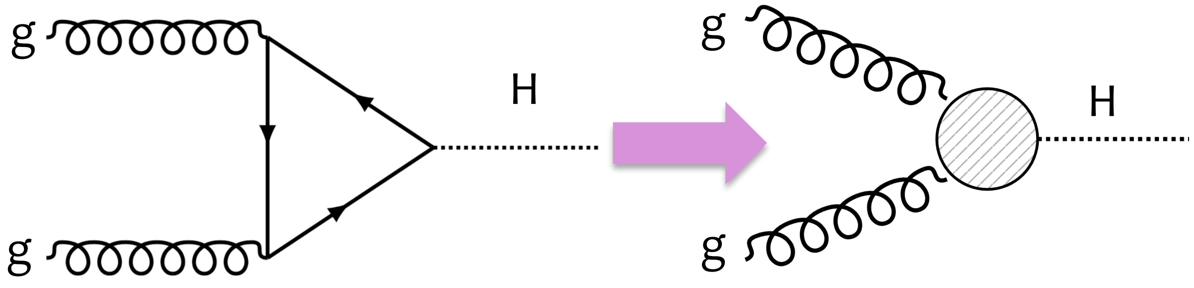
In Fermi theory for the muon decay, **low energy measurements are to constrain the SM parameters** → Fermi theory an **EFT** for the SM!*



* At least for theory of weak interactions

Effective couplings

Higgs boson production and decay mechanisms that proceed by loops can be treated as **effective couplings**



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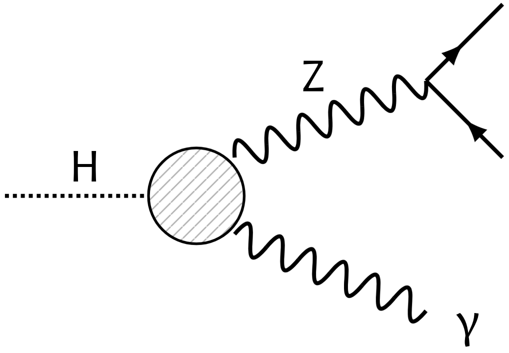
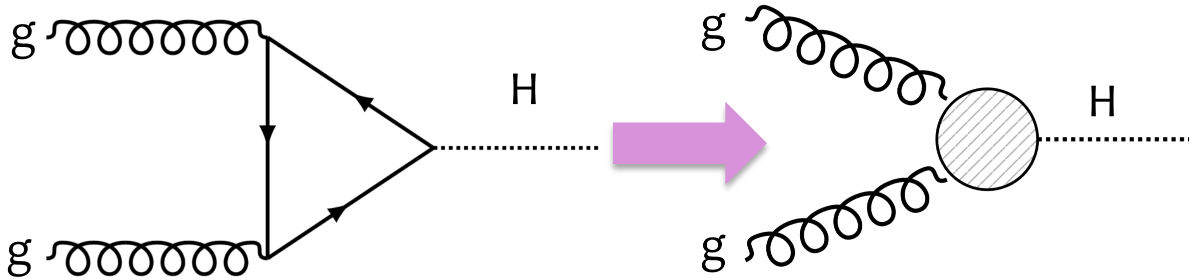
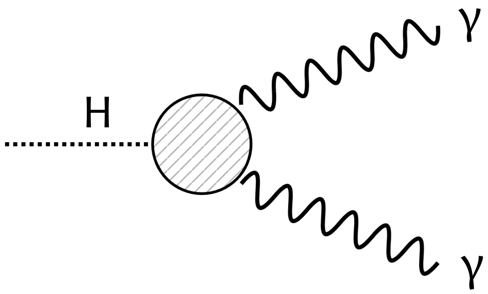
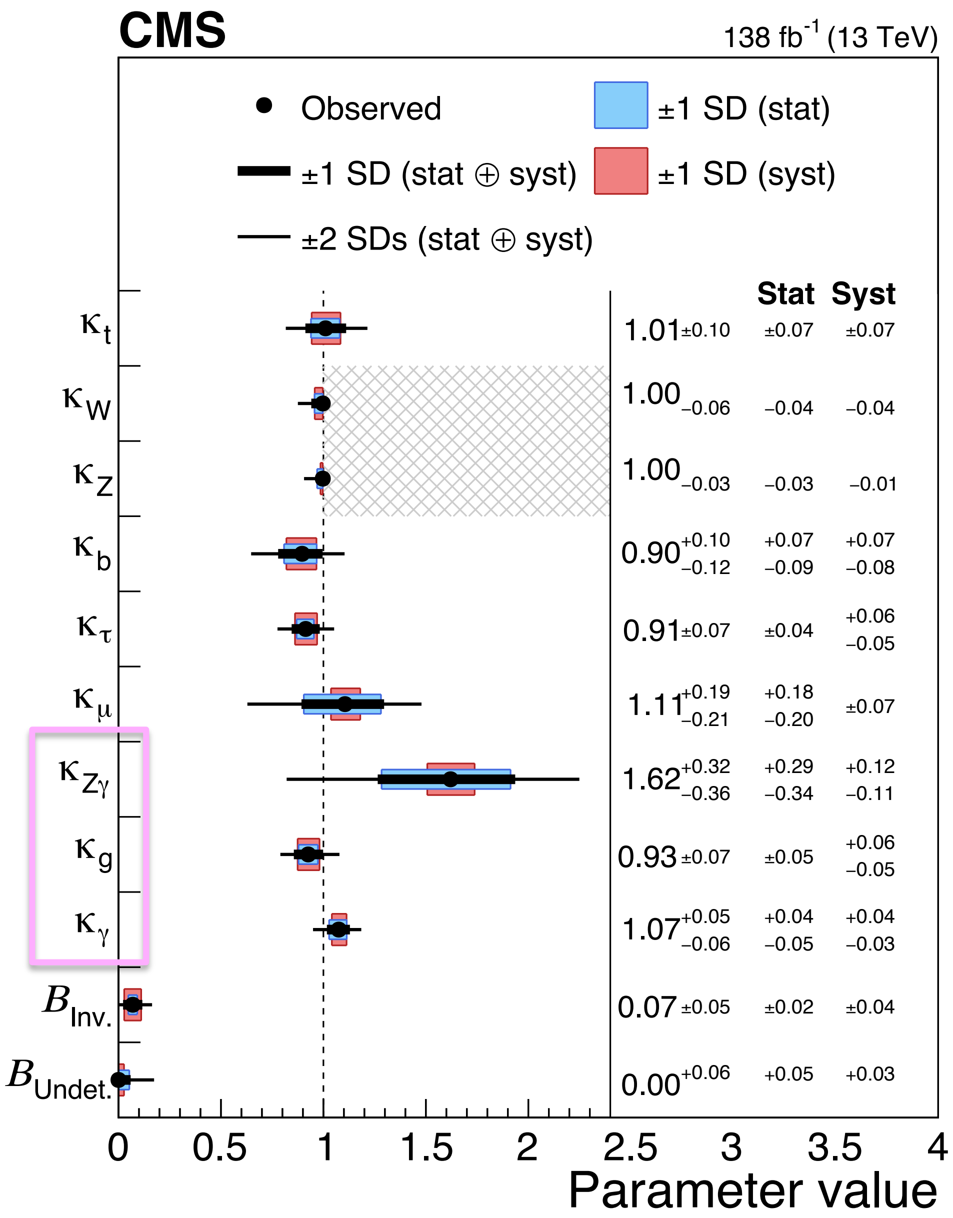




New heavy particles can appear in these loops leading to large deviation in the effective coupling:

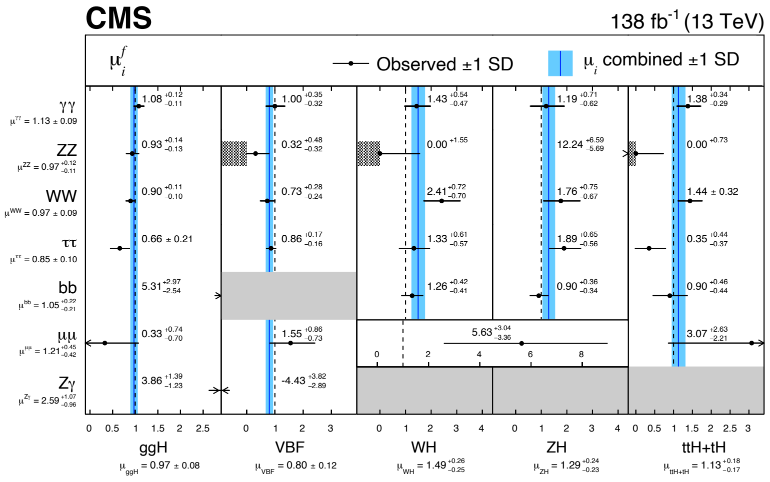
H-Zγ, H-g, H-γ





Effective field theories

On-shell

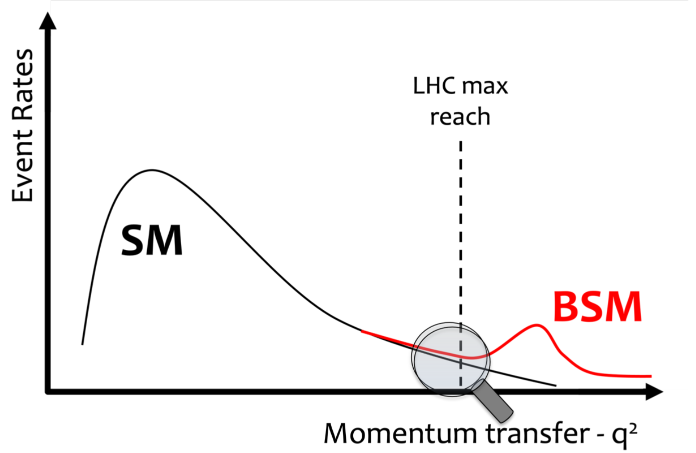


$$\delta \sim \left(\frac{v}{\Lambda}\right)^2$$

Inclusive κ : high-precision yields precision on new physics scale

δ_μ = 1% → Λ ~ 2.5 TeV

Off-shell / large q^2



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

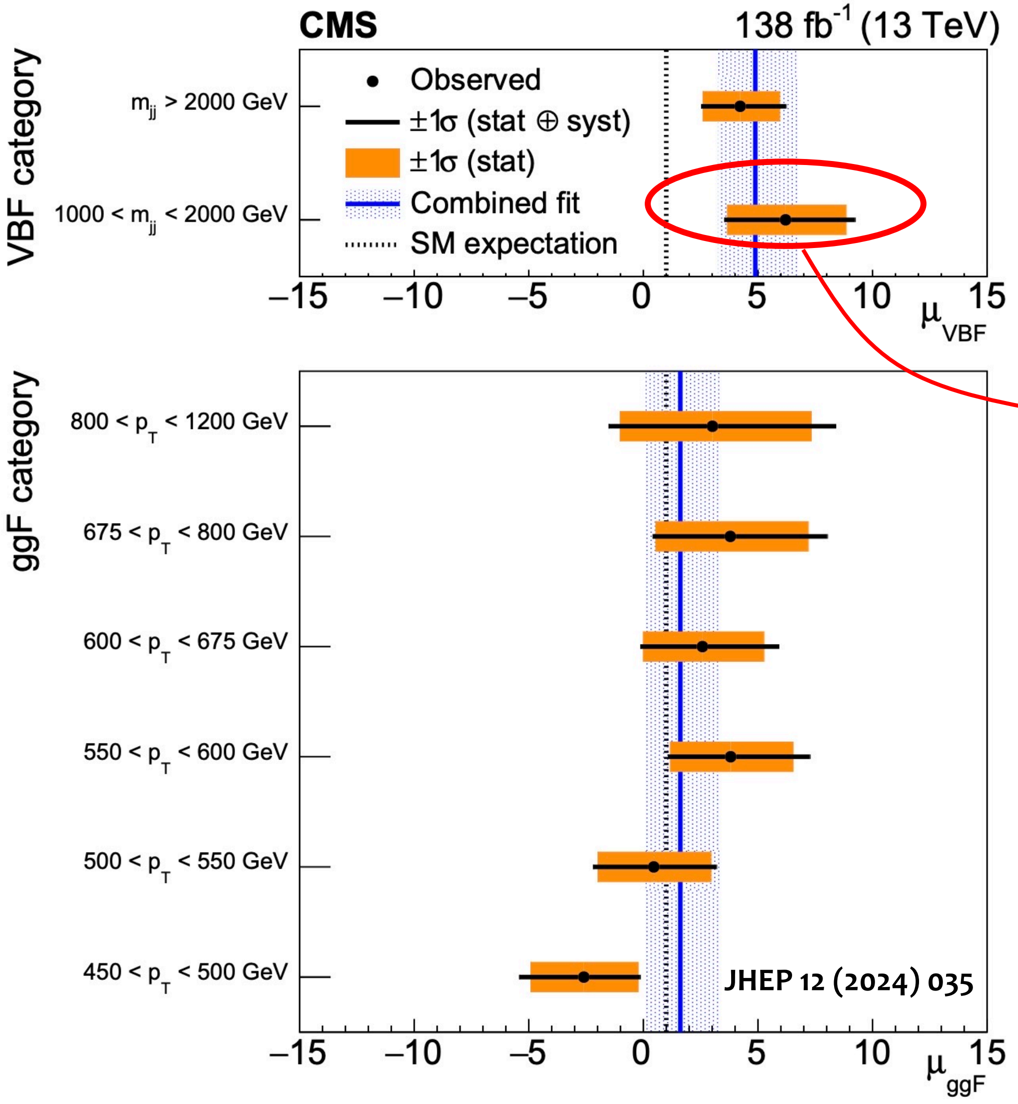
Differential: High momentum production sensitive to new physics

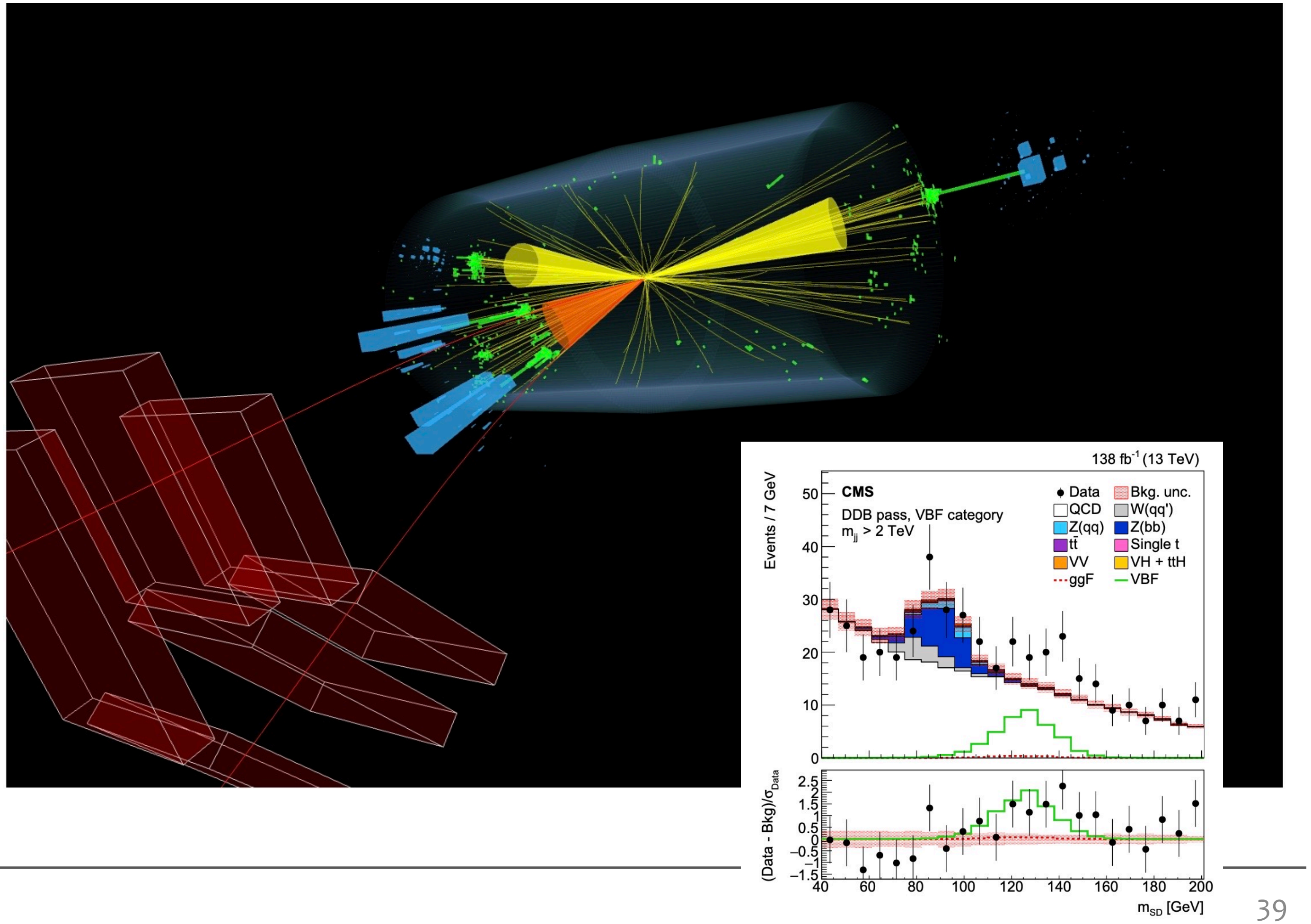
δ_σ = 15% (q=1TeV) → Λ ~ 2.5 TeV

Pushing into the tails

With **increasing datasets,** we can probe tails of distributions that could be more sensitive to BSM physics!

Use specialized reconstruction and analysis tools for these kinds of measurements at the LHC

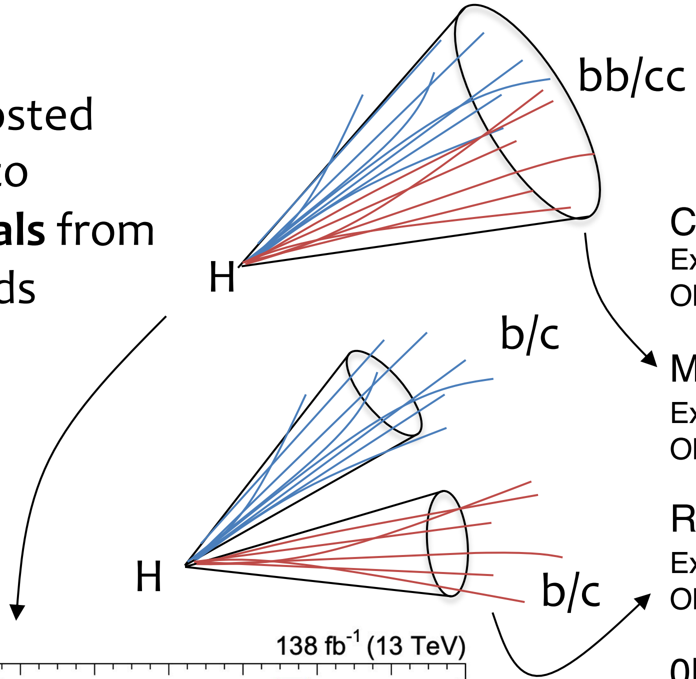


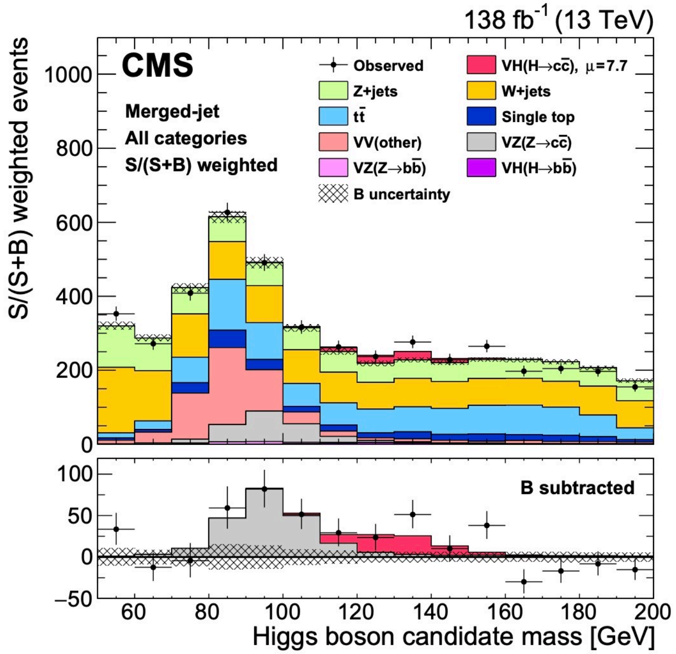


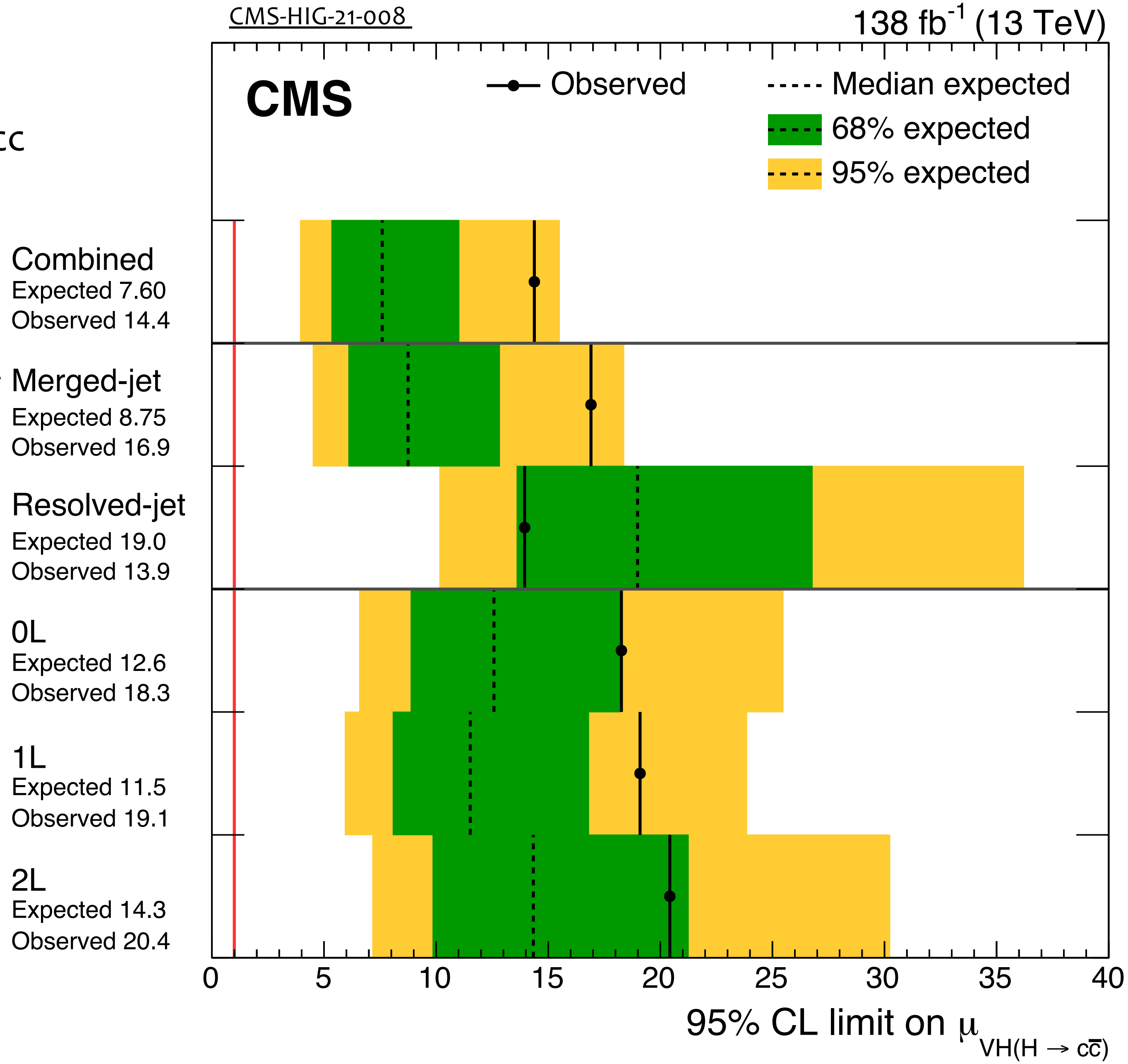
Rarer decay modes

Concentrating on boosted topologies allows us to disentangle **rare signals** from very large backgrounds

Hcc ~ 20x smaller than Hbb!







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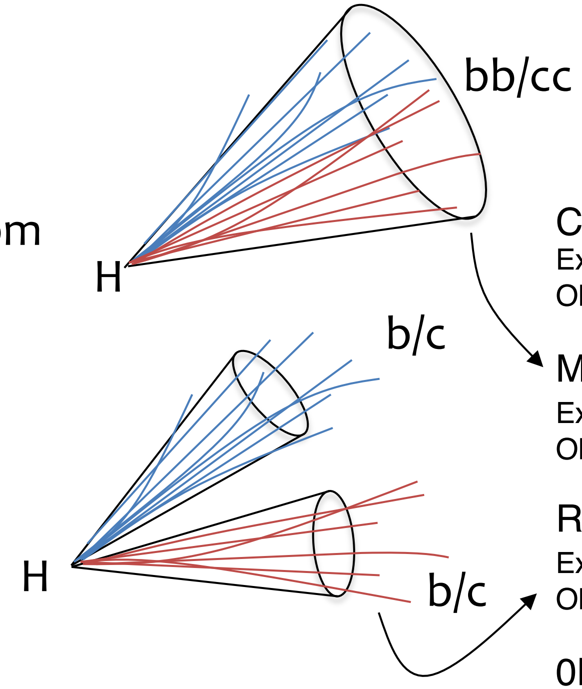
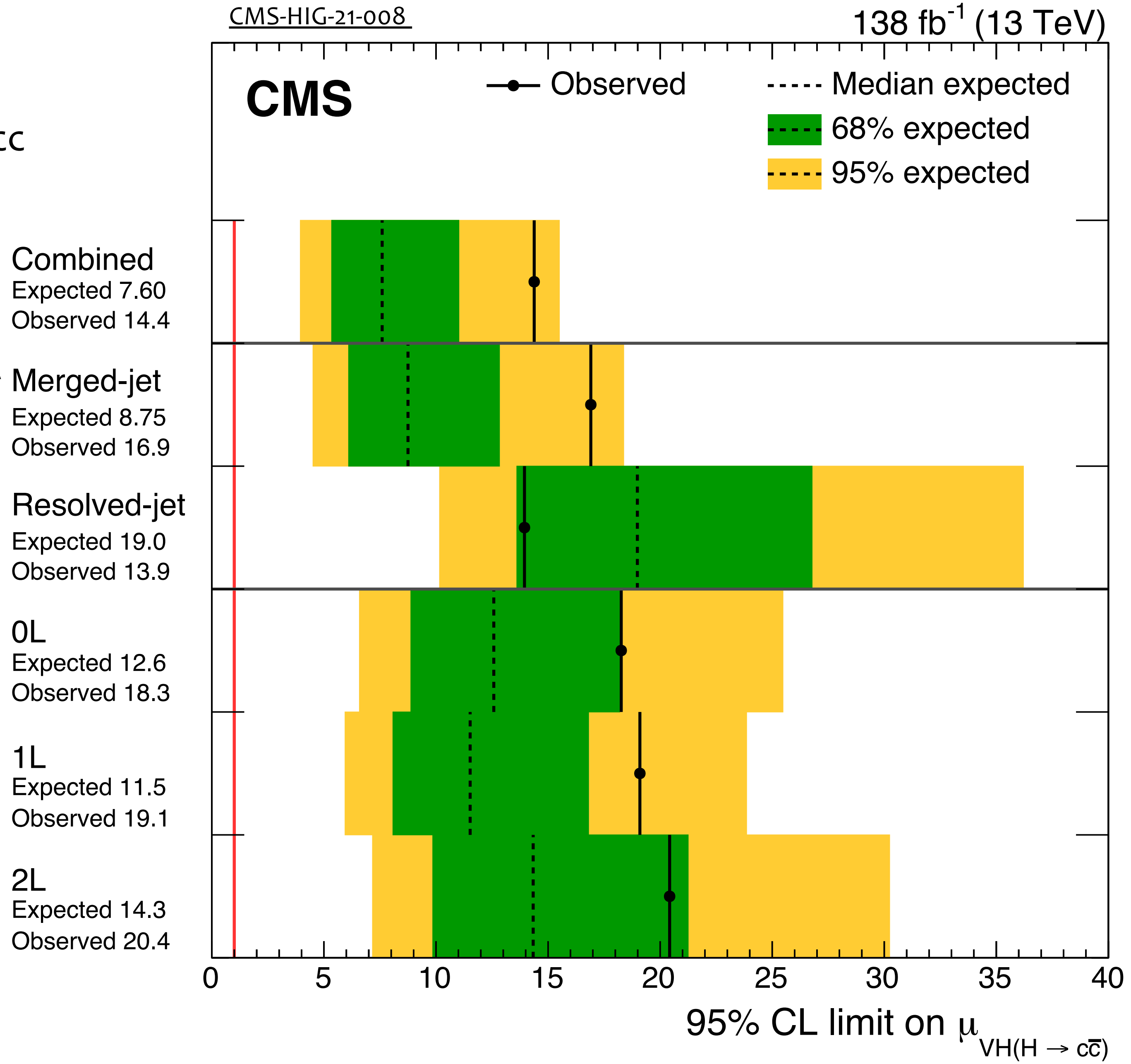
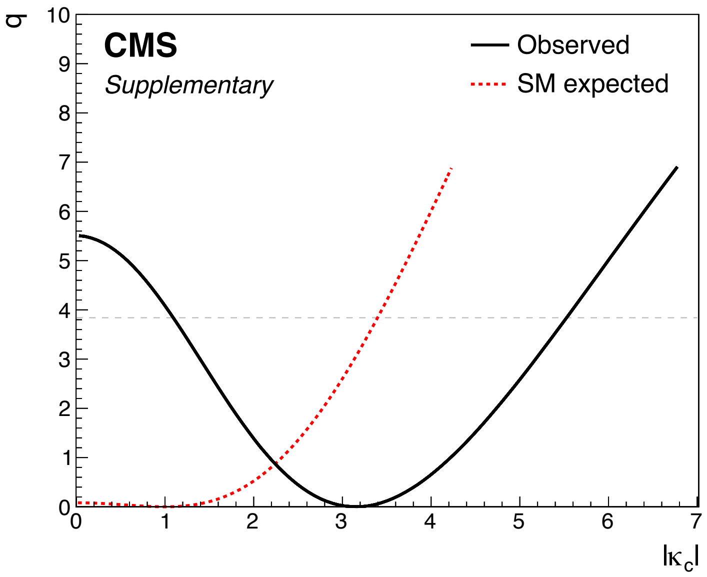




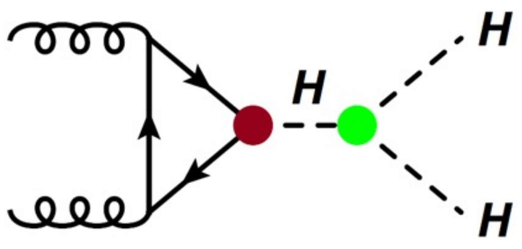


Higgs boson self-coupling

Remember in the SM, the **Higgs potential** includes ***H*^{3}** terms

$$V(H) = \frac{1}{2}m_H^2 + \boxed{\lambda v H^3} + \frac{1}{4}\lambda H^4 + \text{const}$$

"self-coupling" generates **Higgs-Higgs** interactions



→ Direct searches for **Double Higgs (HH)** production to constrain the Higgs boson self-coupling!

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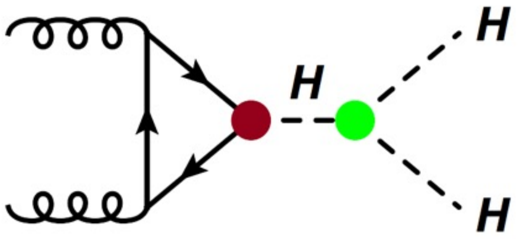

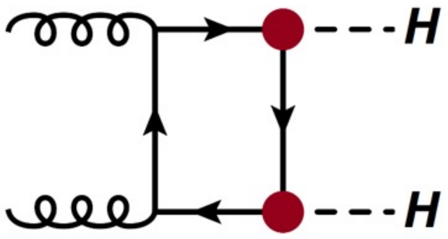

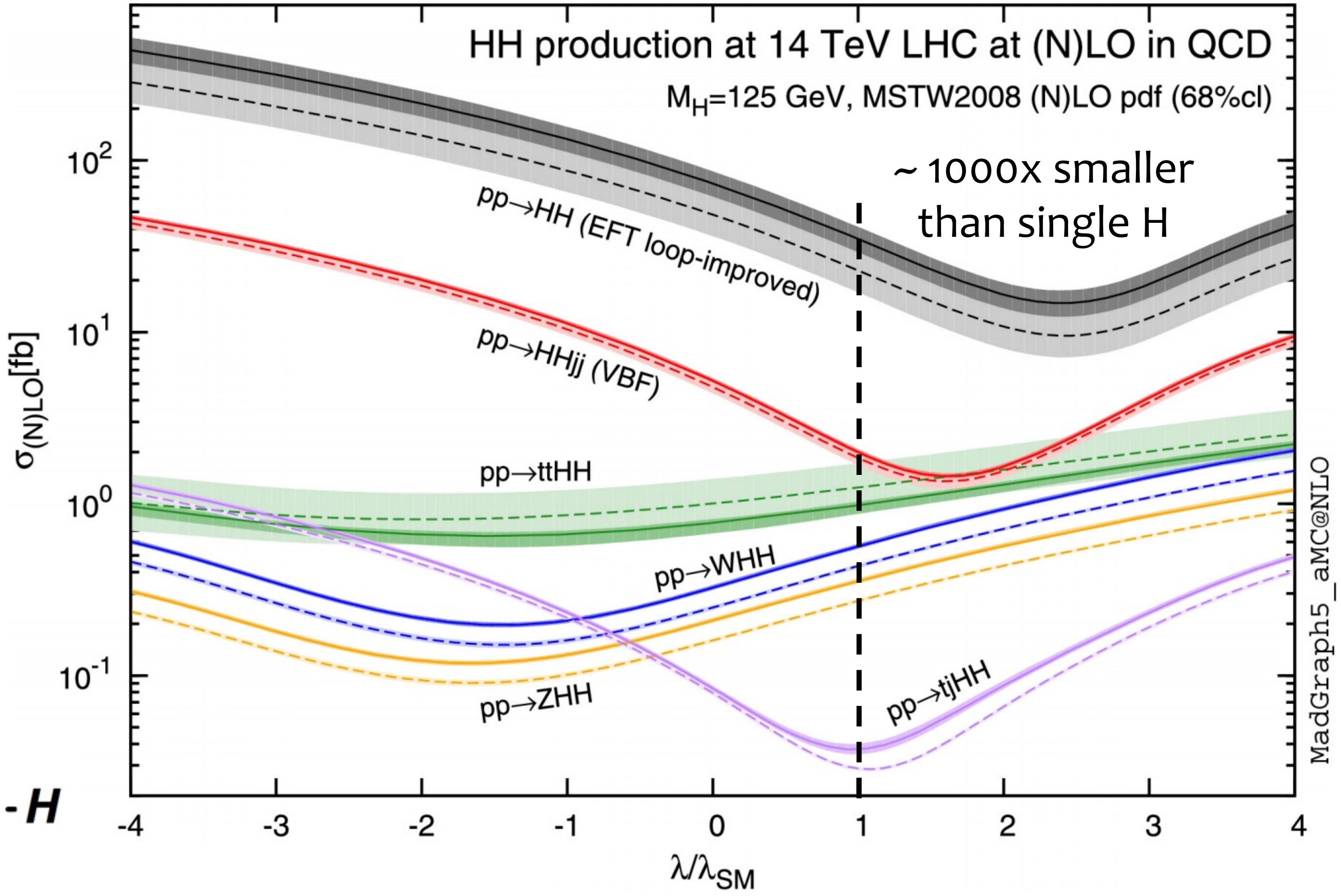

Interference with **other SM HH** diagrams makes searches for HH extremely challenging!

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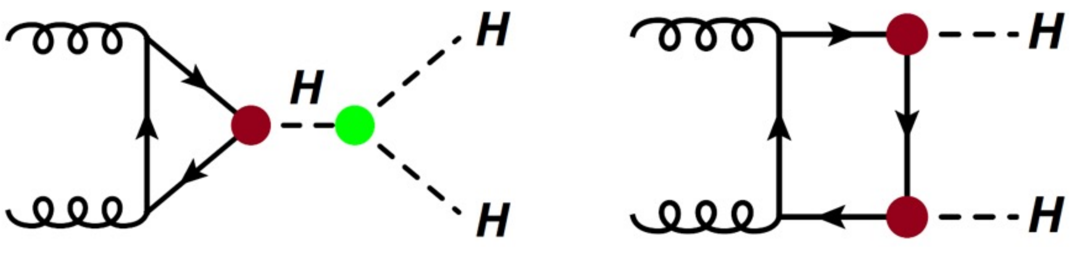
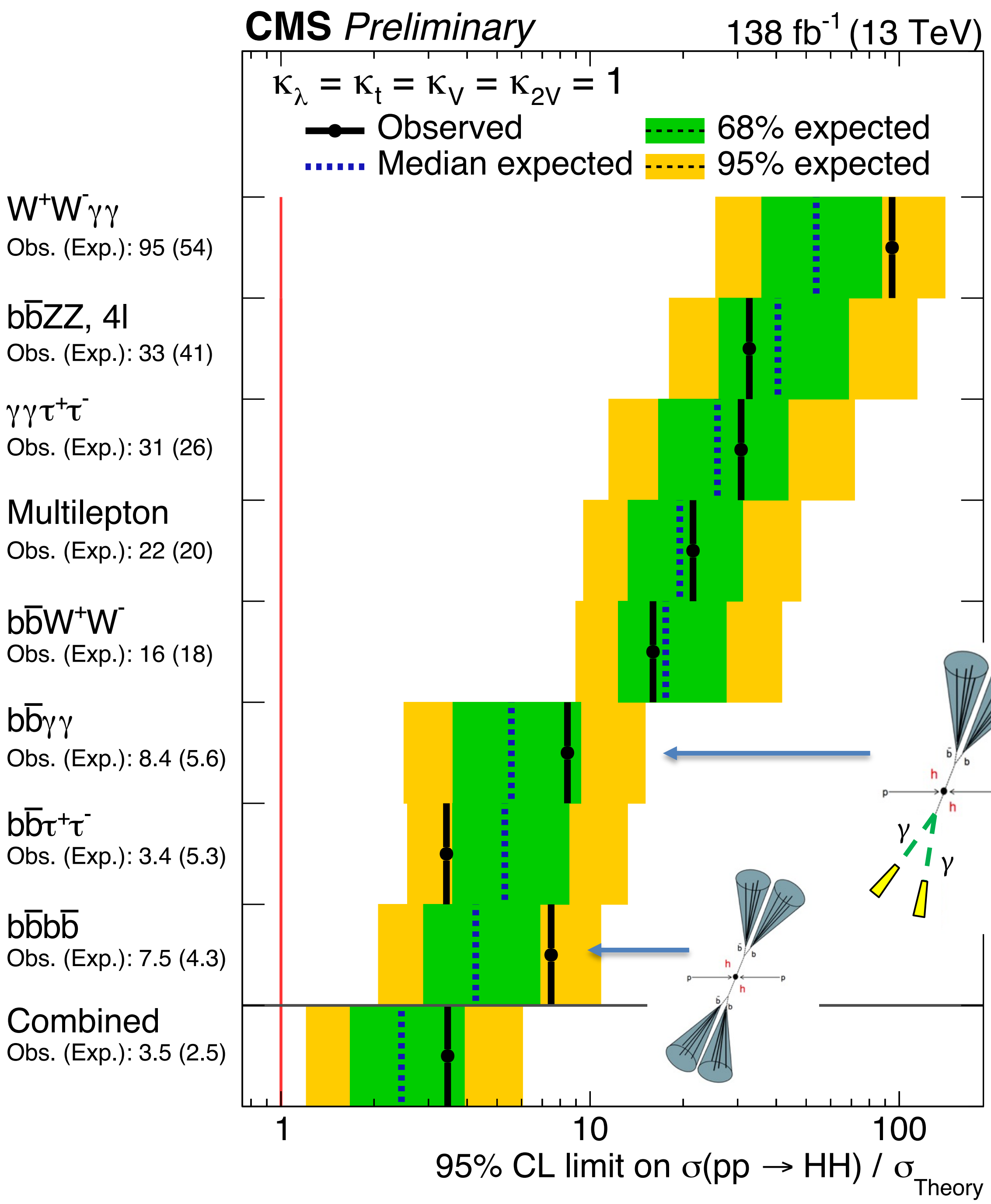


Combinations of **multiple search channels** just as important for 2xHiggs compared to single Higgs



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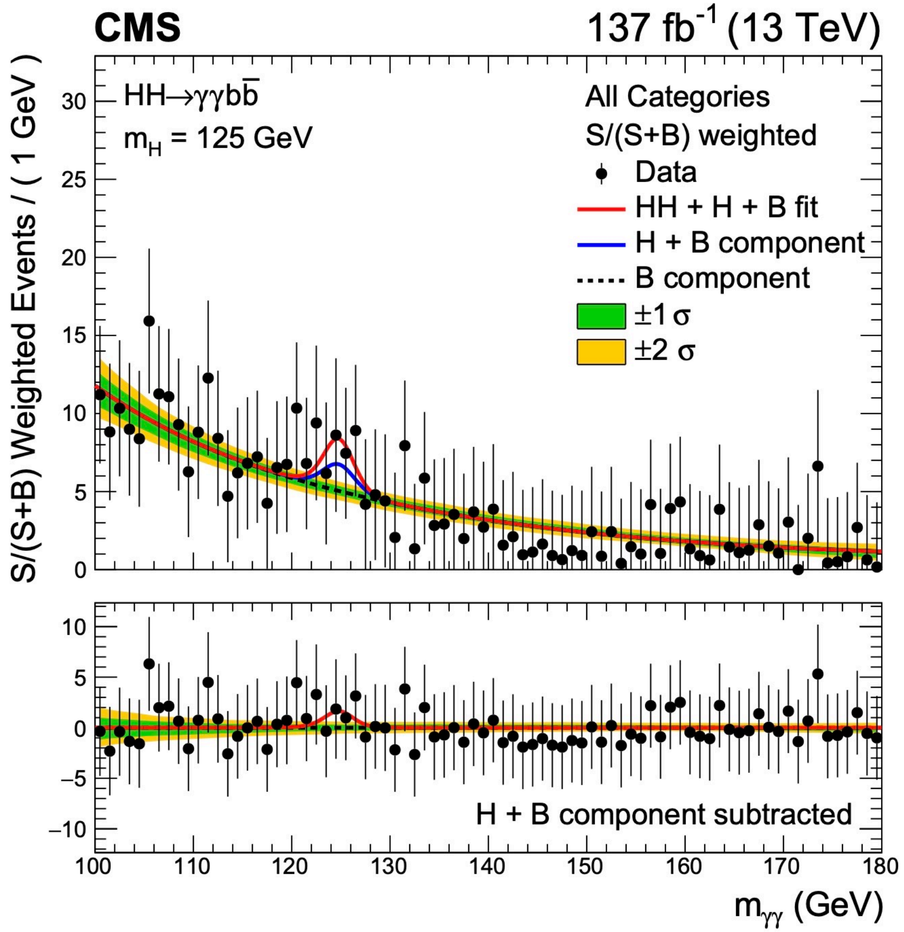
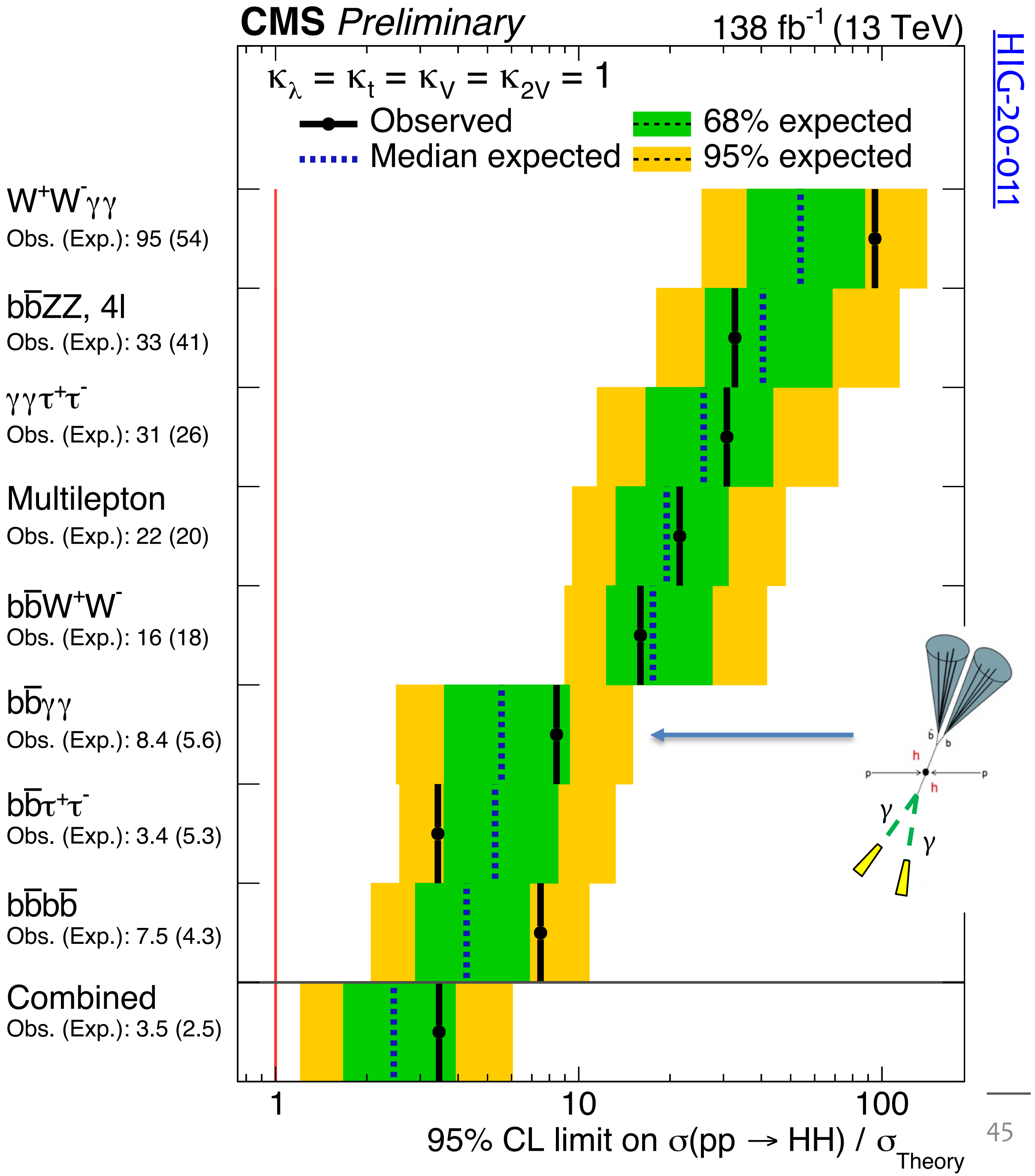
Higgs boson self-coupling



Yesterday's Higgs signal is today's HH background!



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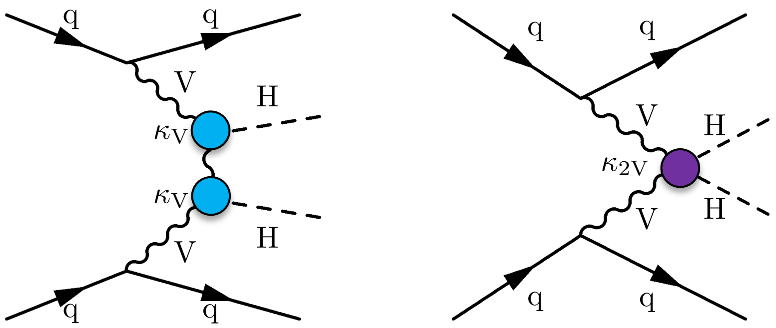
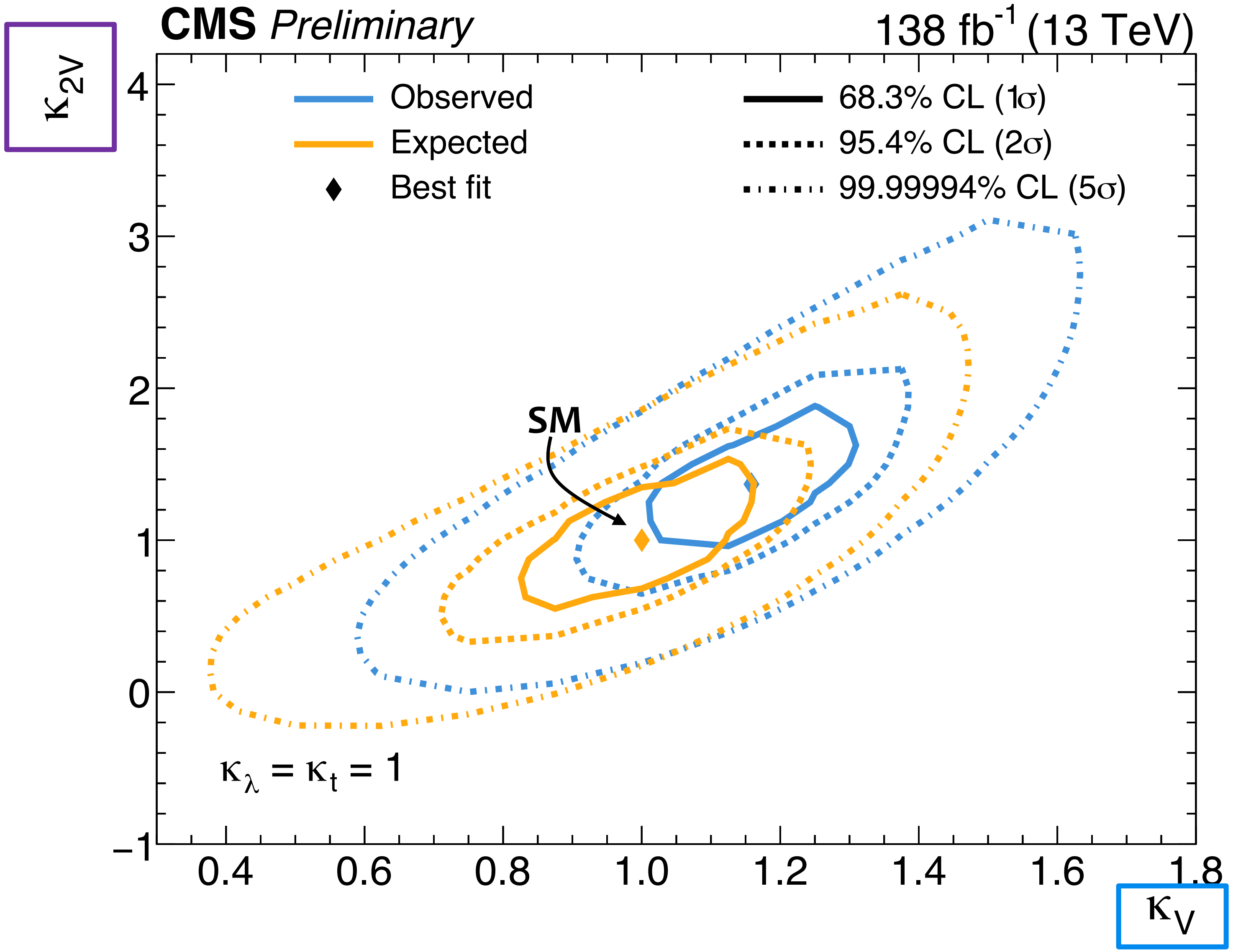
Tests of SM-structure

In SM, we'd expect $\kappa_{2V} = \kappa_V = 1$





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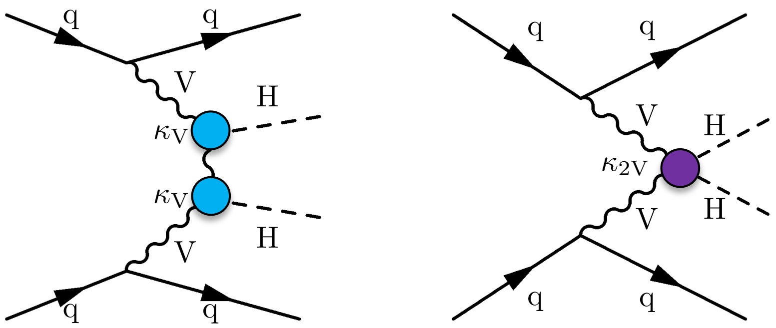
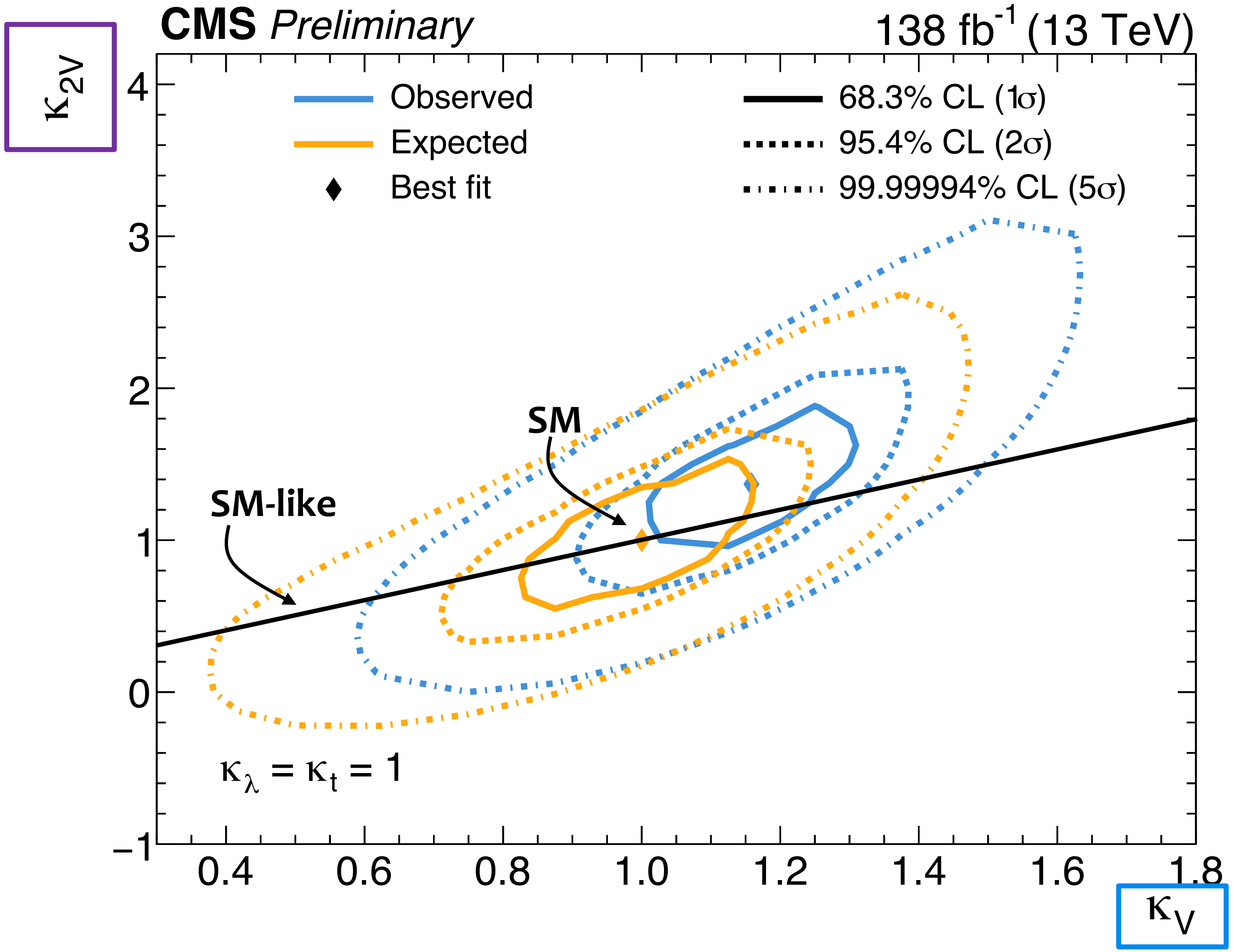


In "SM-like" extensions (eg SM-EFT) we can relax to **κ_{2V} = κ_V**

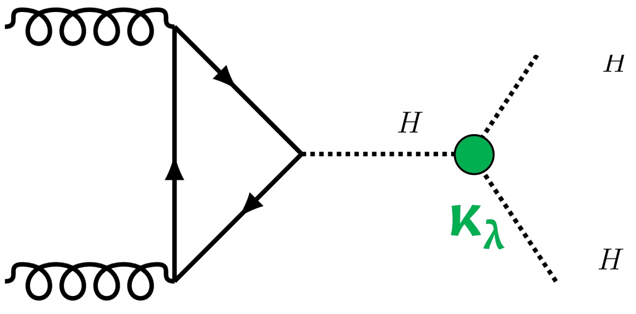
→ Test of the *nature* of effective SM-extensions through double Higgs measurements!

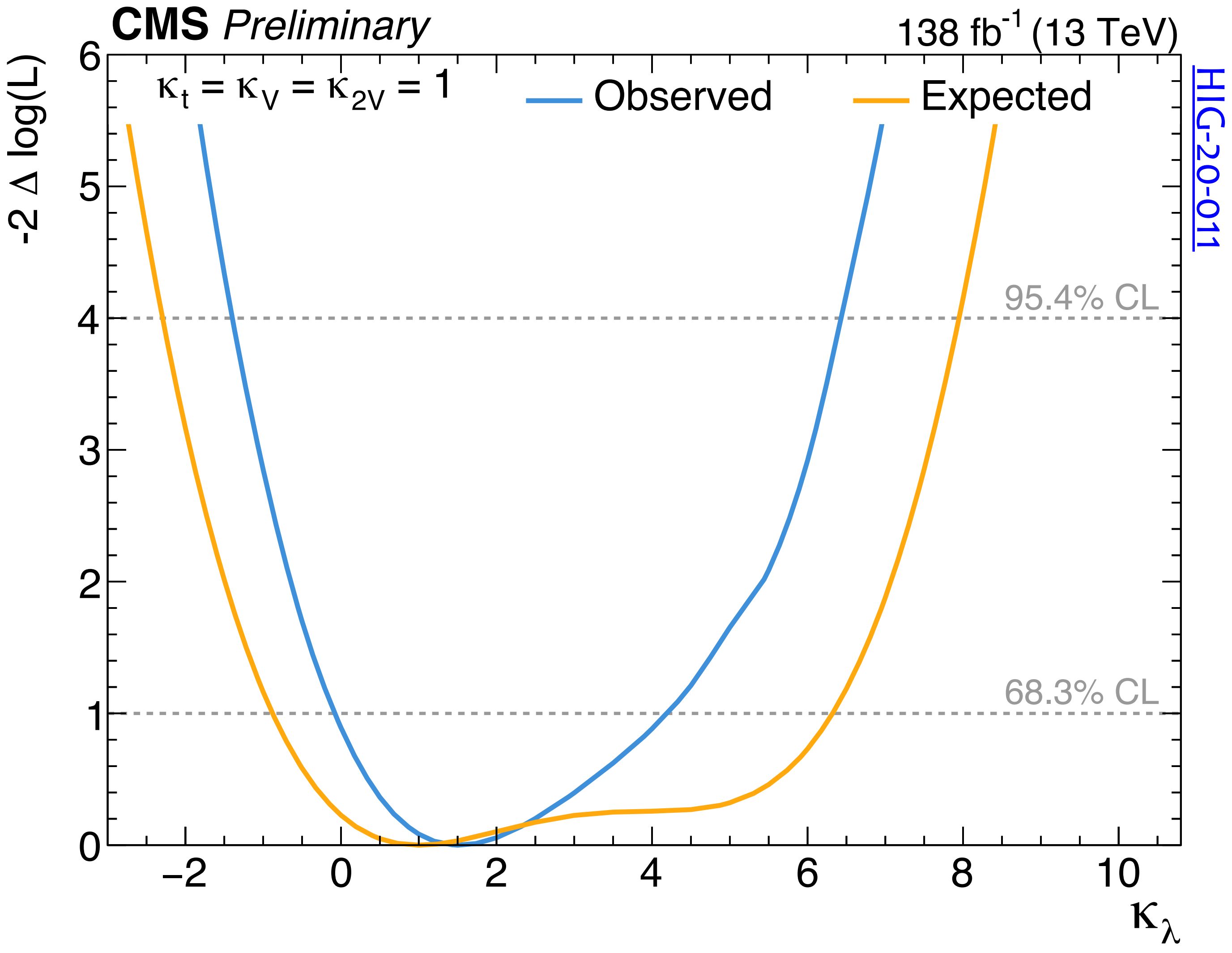


Higgs boson self-coupling

Extract self-coupling relative to SM prediction

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$



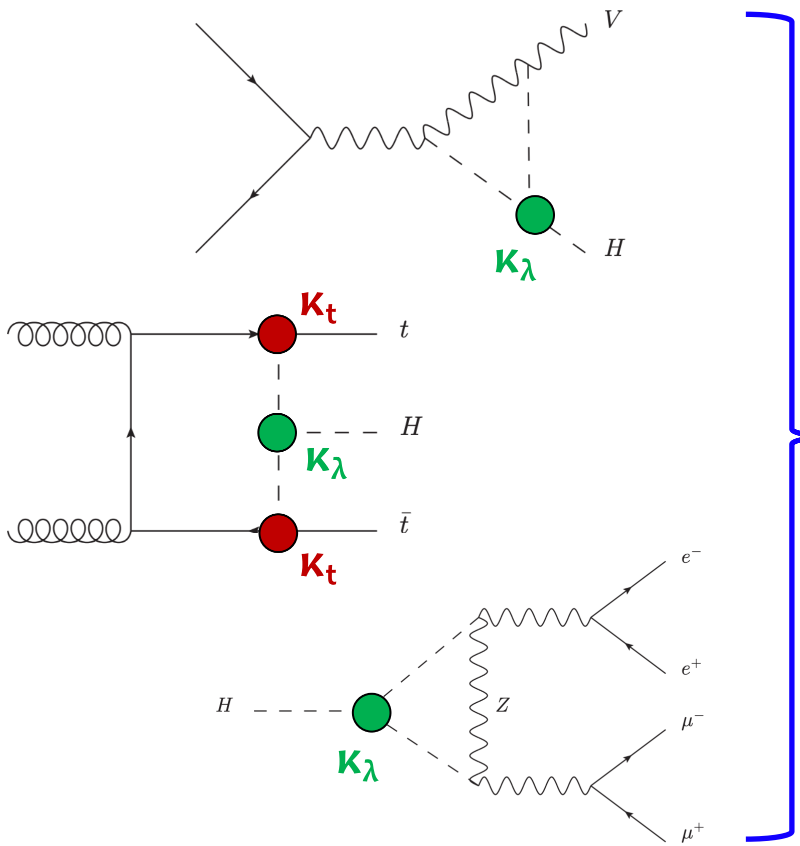


Combination of HH searches yields most stringent limit on Higgs boson self-coupling

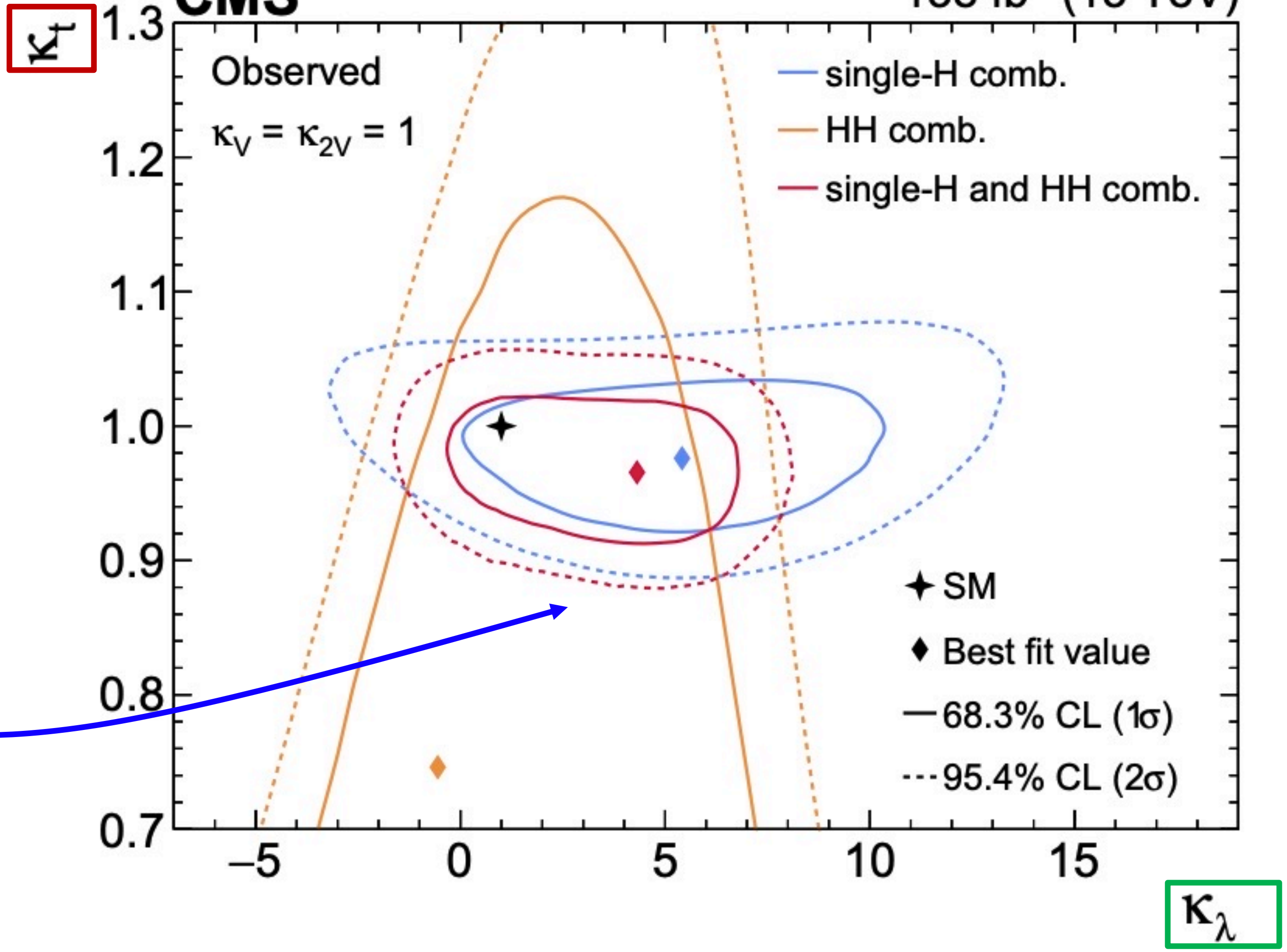
$$0.08 < \kappa_\lambda < 4.2$$ @ 68% CL

Higgs boson self-coupling

Loop corrections to **single-Higgs boson** production and decay involve **Higgs self-coupling** [1]



[HIG-23-006](HIG-23-006)



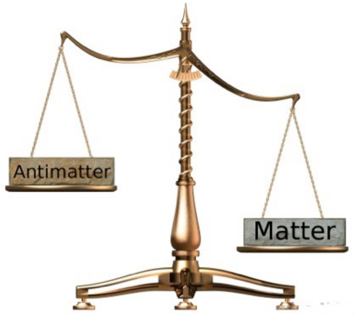
Precision (single) **Higgs boson measurements** also sensitive to **Higgs self-coupling!** Lift degeneracies with other Higgs couplings

[1] Eur. Phys. J. C (2017) 77: 887

Why do we care?

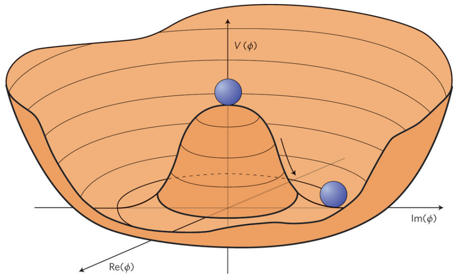
The universe today is **matter** (baryon)-**dominated,**

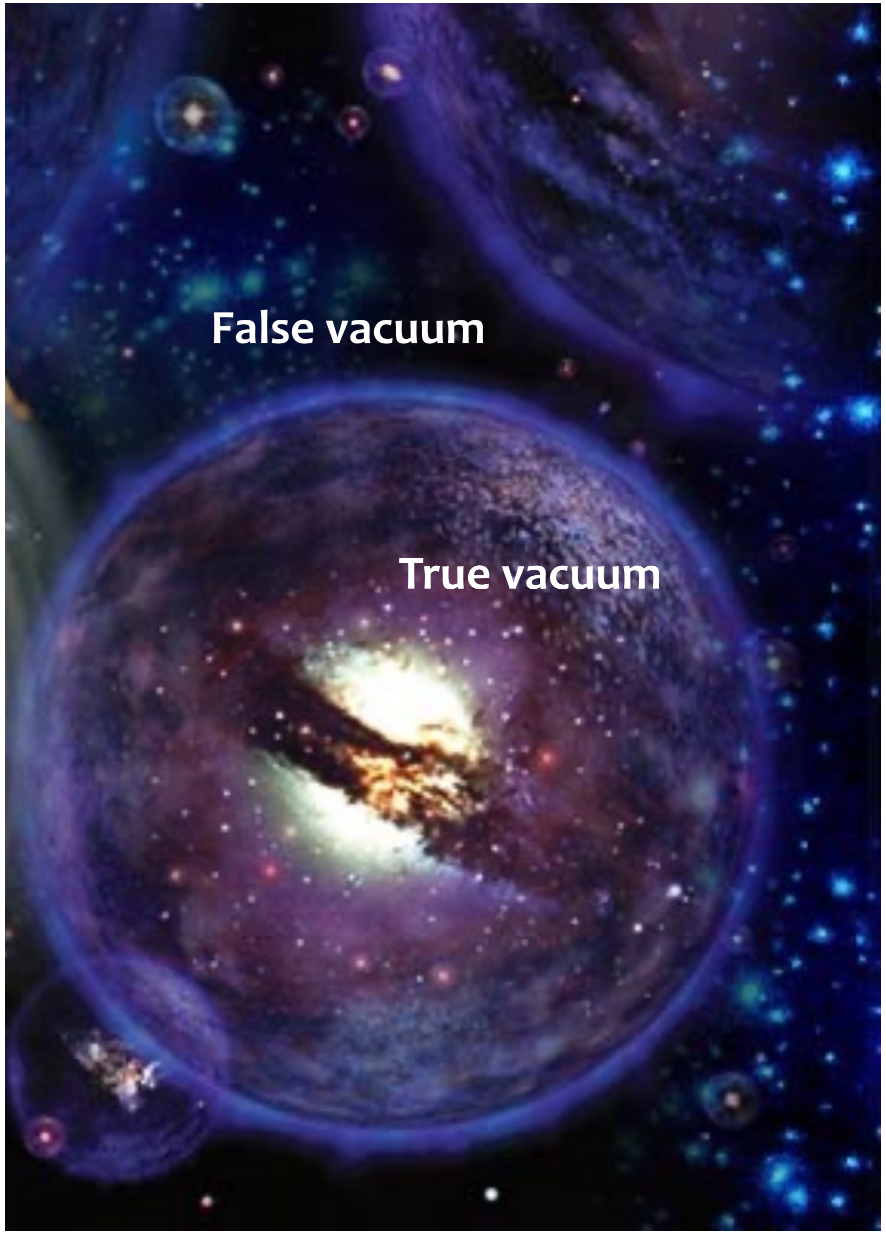
$$n_B >> n_{\bar{B}}$$



Essential ingredient for **Baryogenesis** (production of B-asymmetry) :

→ **First order phase transition** [1]





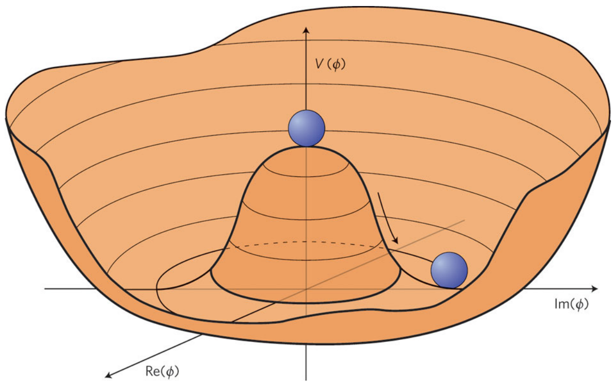
[1] A. D. Sakharov, JETP Lett. 5, 24 (1967)

Modified Higgs potential and Baryogenesis

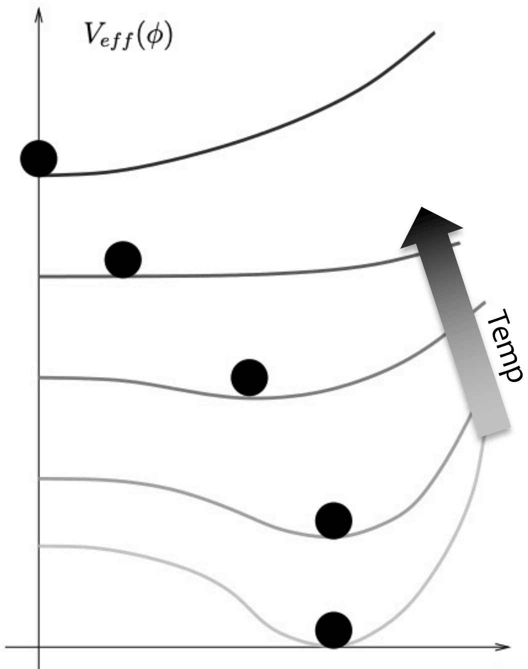
Higgs potential could be the solution?

$$V(H) = \frac{\mu^2}{2}(v+H)^2 + \frac{\lambda}{4}(v+H)^4$$

SM



$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} = 1$$



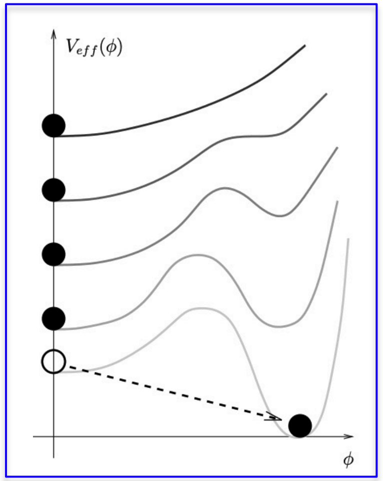
arXiv:1504.03587

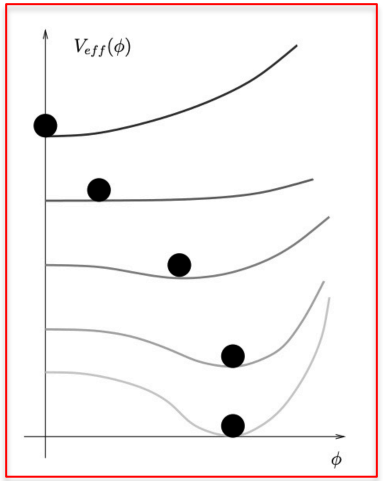
In the SM, since the Higgs mass is known (~125 GeV), we get a smooth transition between minima (2nd order PT) from the potential

Modified Higgs potential and Baryogenesis

BSM physics in **Higgs potential** could be the solution!

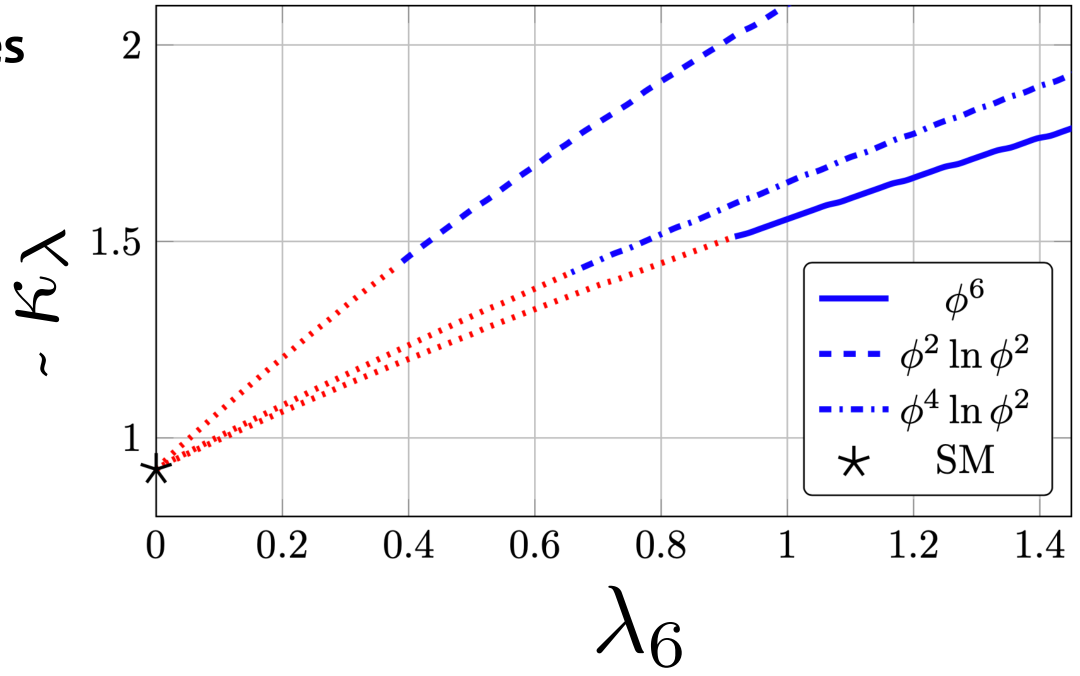
$$V(H) = \underbrace{\frac{\mu^2}{2}(v+H)^2 + \frac{\lambda}{4}(v+H)^4}_{\text{SM}} + \underbrace{\frac{\lambda_6}{\Lambda^2}(v+H)^6}_{\text{BSM}}$$





Inclusion of **Dimension-6 (BSM)** term in potential **changes the relationships between** the fundamental Higgs **parameters**

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



Phys. Rev. D 97, 075008 (2018)

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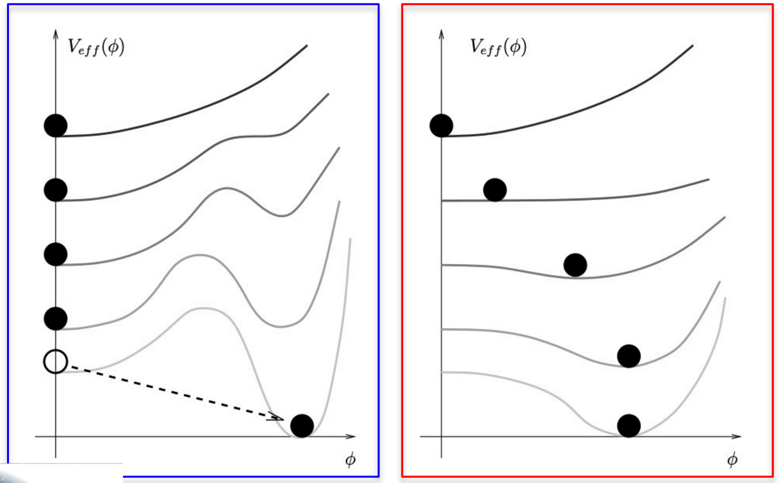

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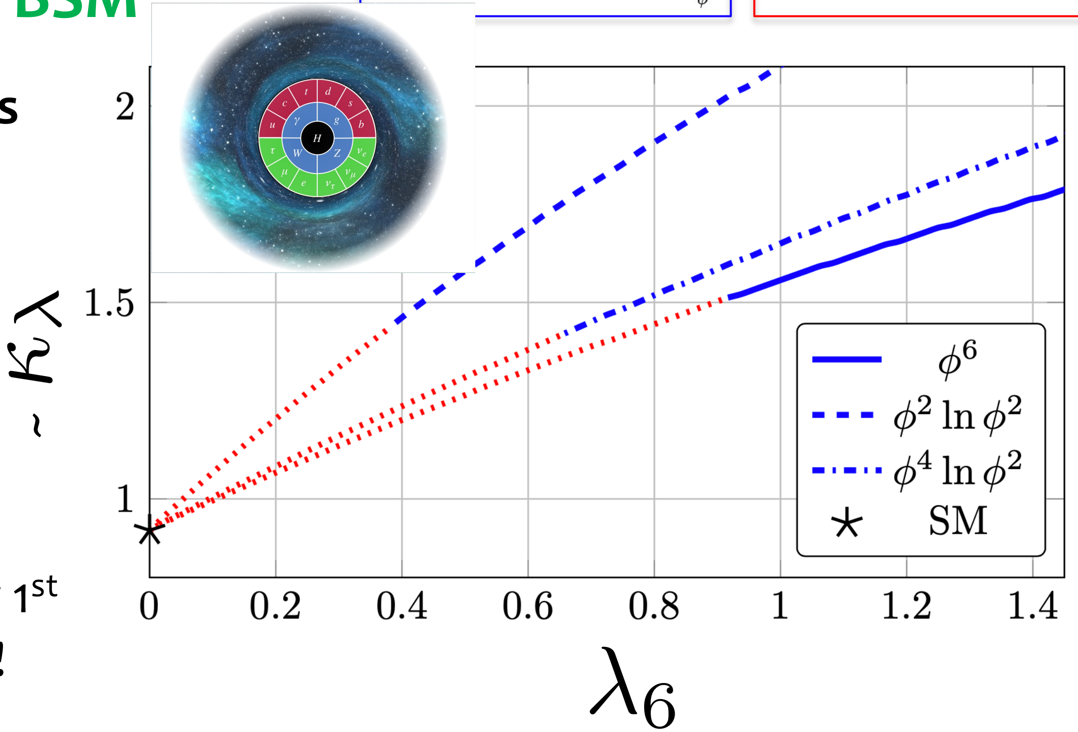


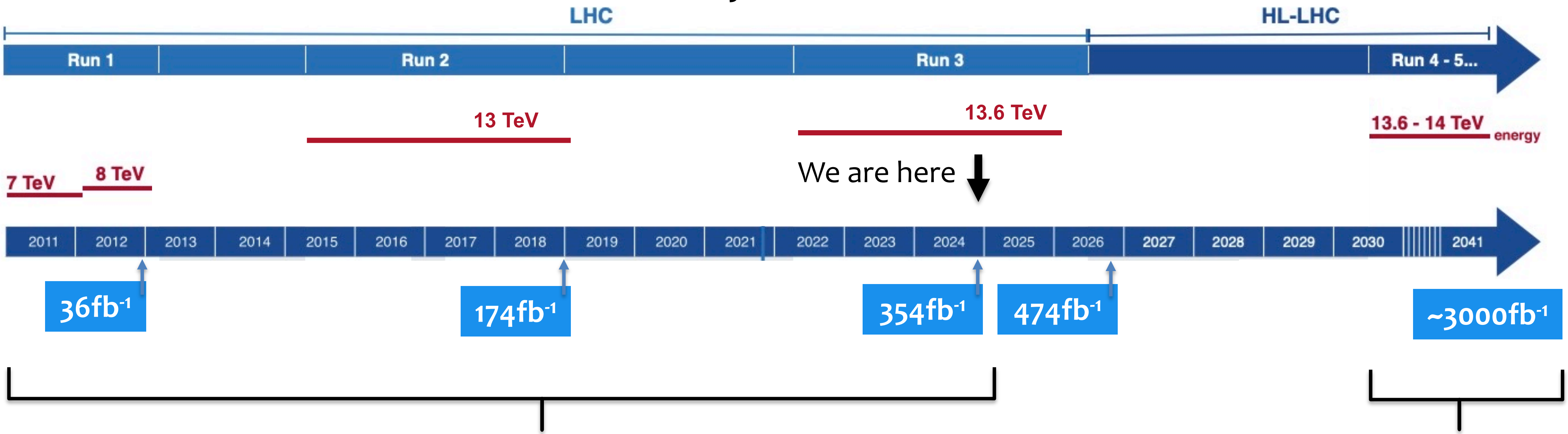
Phys. Rev. D 97, 075008 (2018)

50% increase in self-coupling could hint at mechanism for 1st order EWK phase-transition → measure the self-coupling!

The future of the LHC

After Run-3 of the LHC, the next phase is the **high-luminosity** (HL)-LHC

~20x the data we have today!



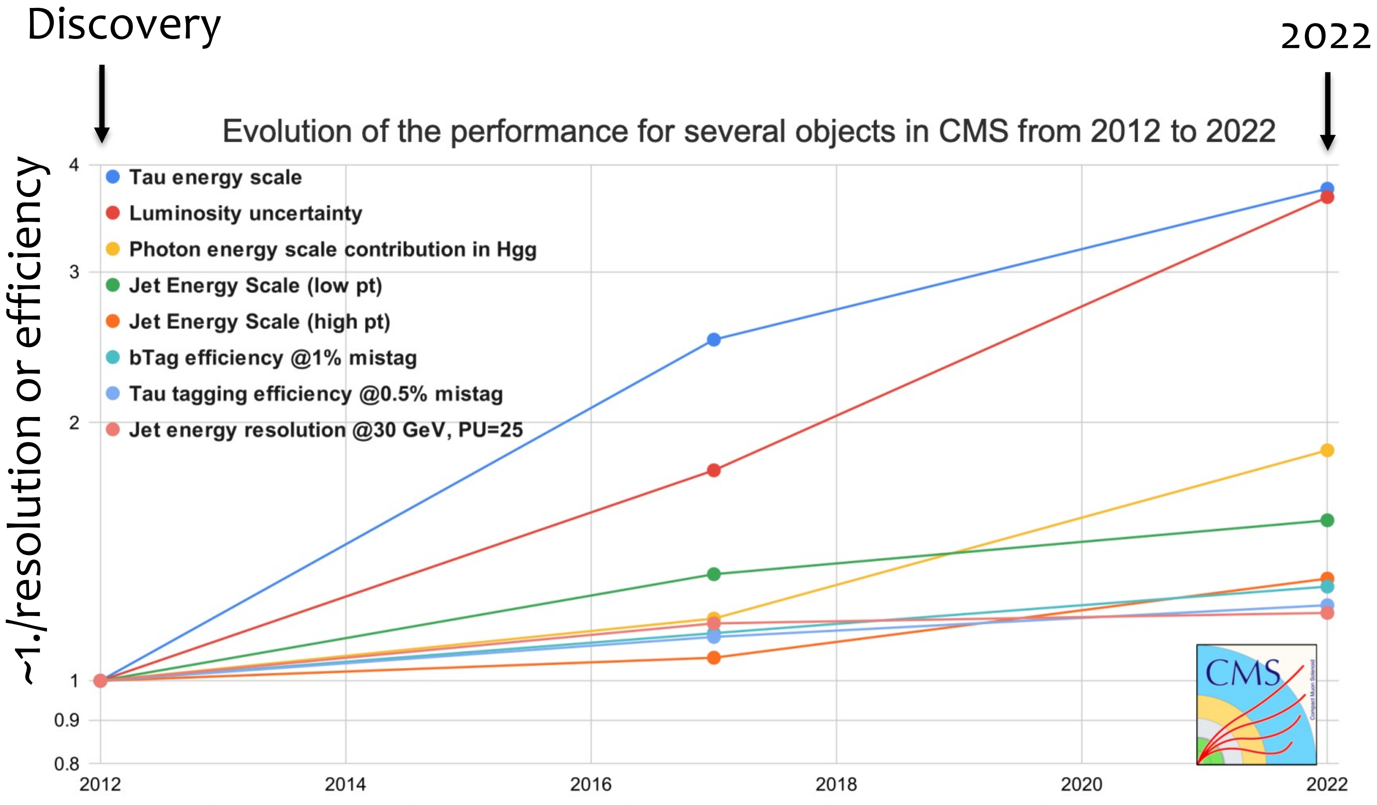
LHC

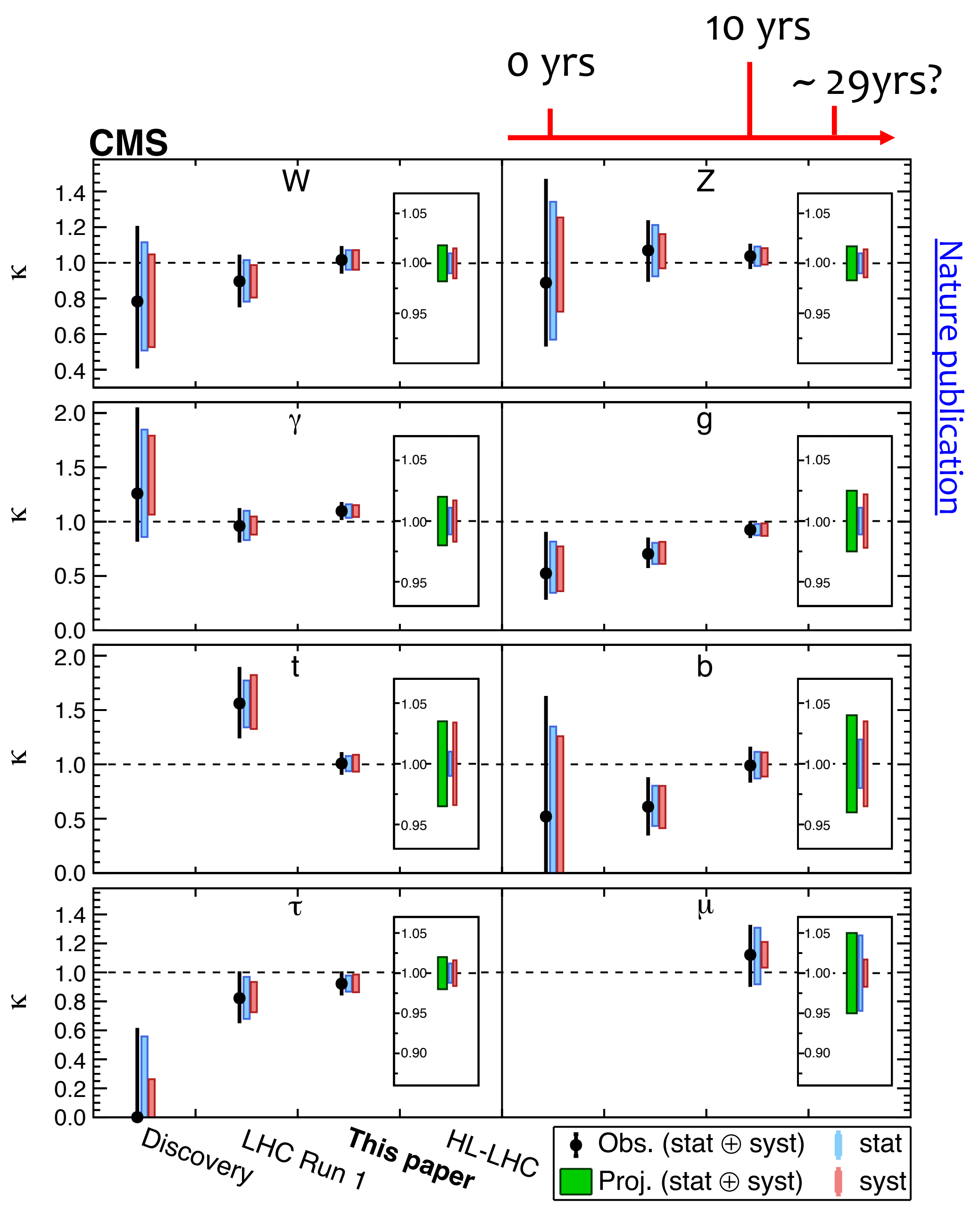
HL-LHC

Expect **> 160M H-bosons / 120k HH pairs** at CMS by the end of the **HL-LHC** !

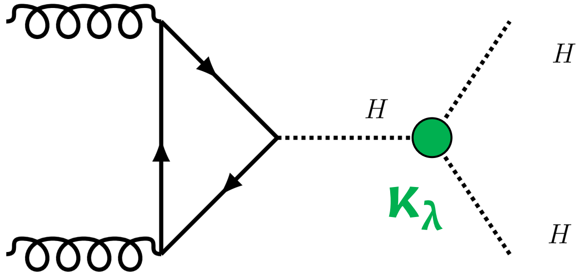
Higgs couplings @ HL-LHC

Precision measurements require more than just more data
→ Improvements in reconstruction techniques & calibrations will be needed for few % precision couplings @HL-LHC

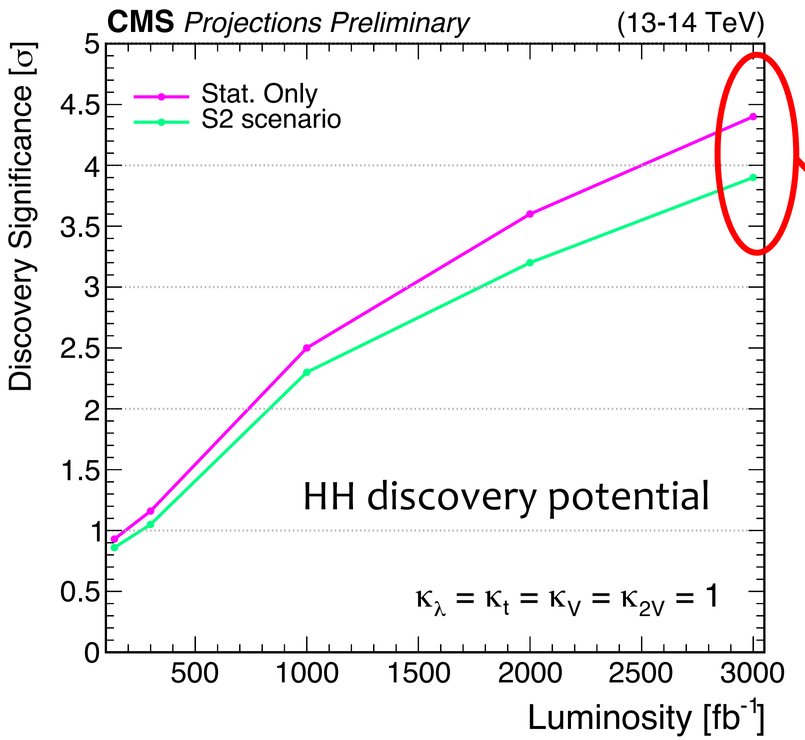


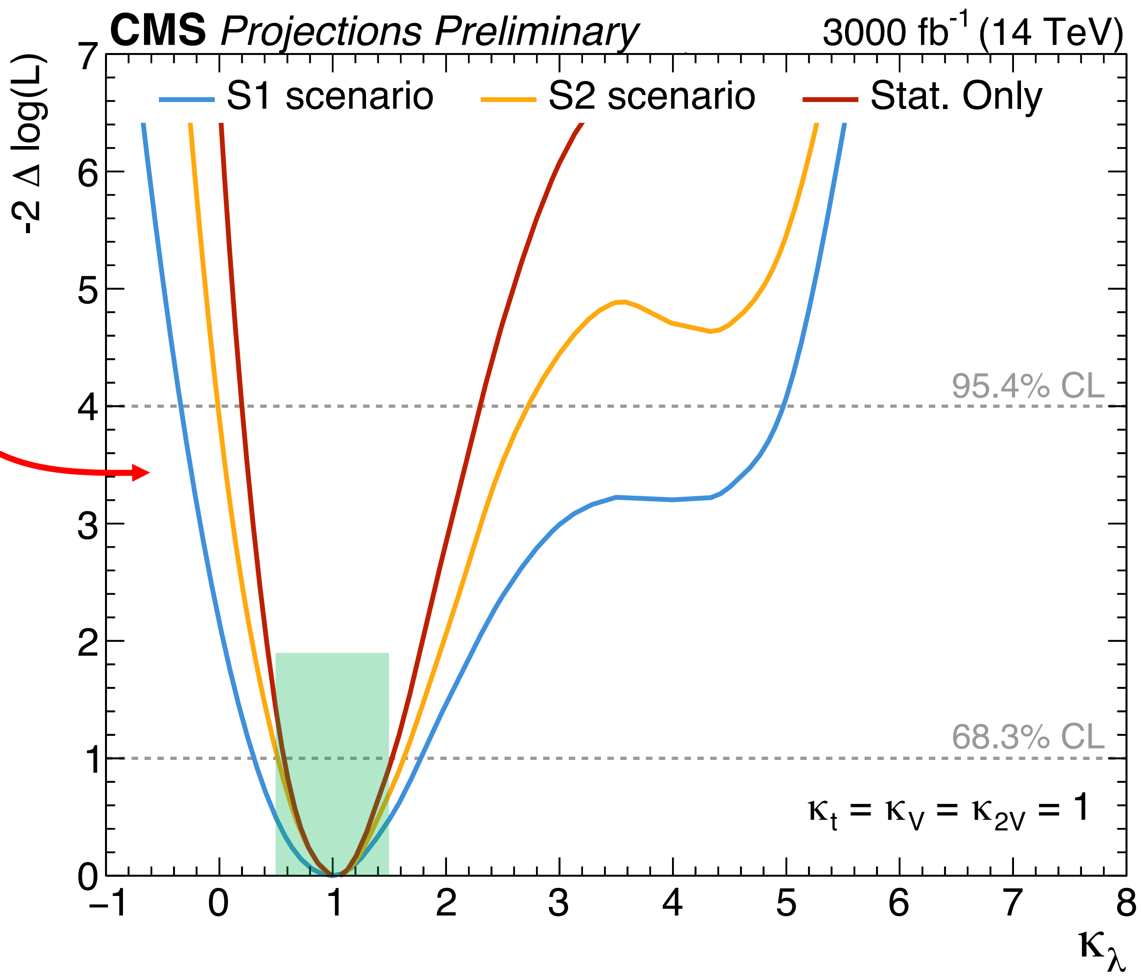


Higgs boson self-coupling @ HL-LHC



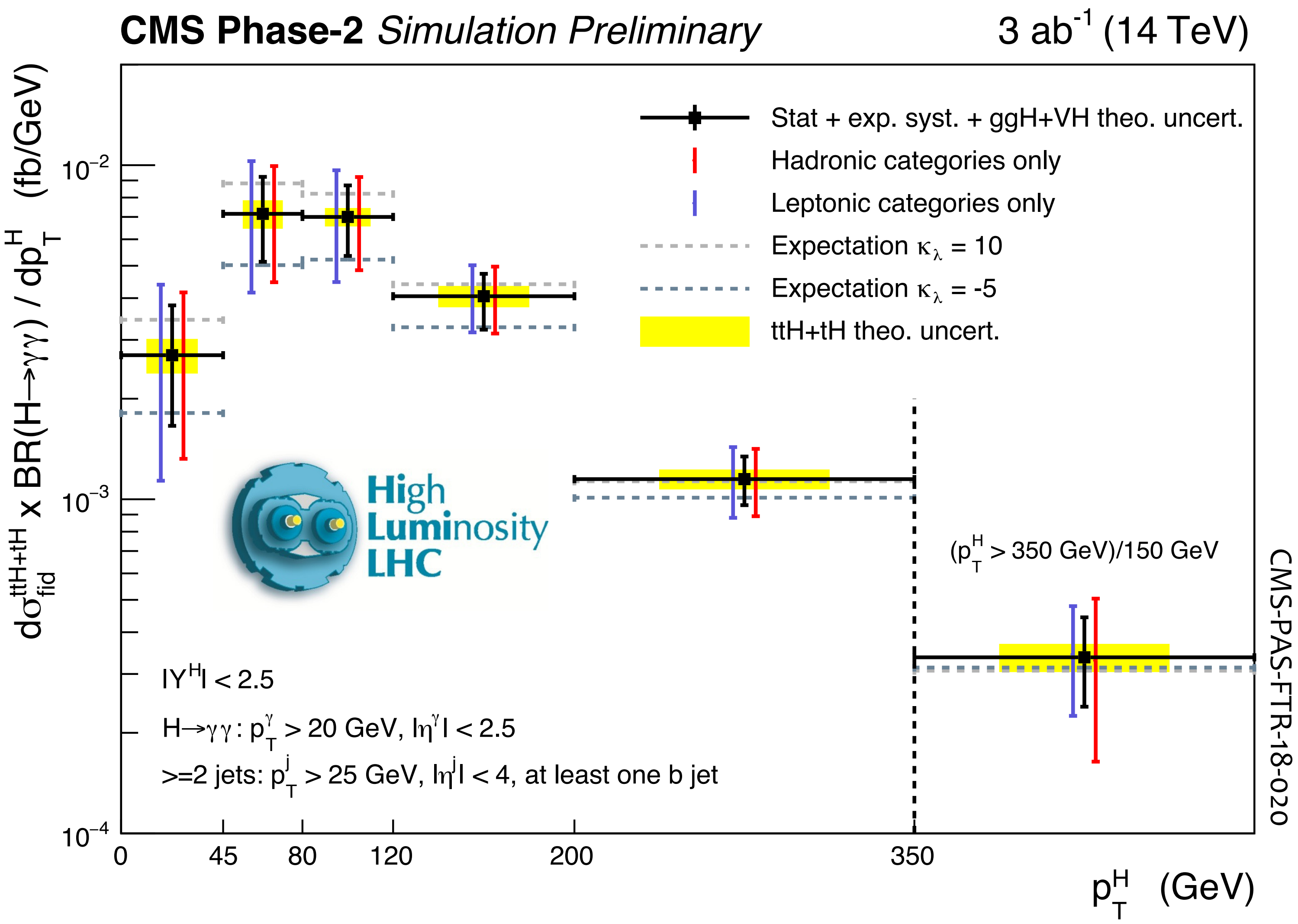
Approx 10x size data set available to **CMS** at the end of the HL-LHC
→ Combined searches for HH production to approach **~50% uncertainty in κ_λ?**

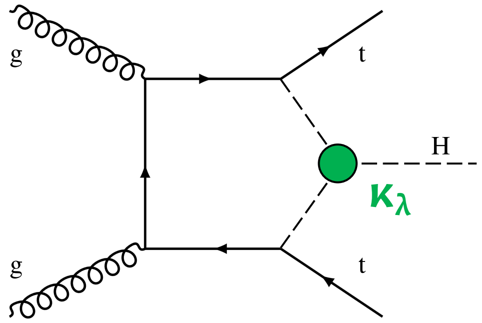




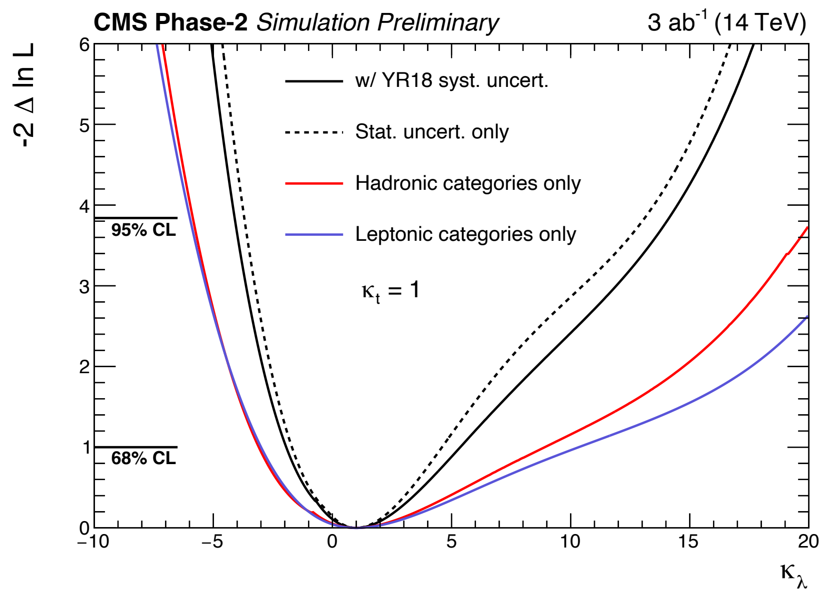
HIG-20-011

Higgs boson self-coupling @ HL-LHC



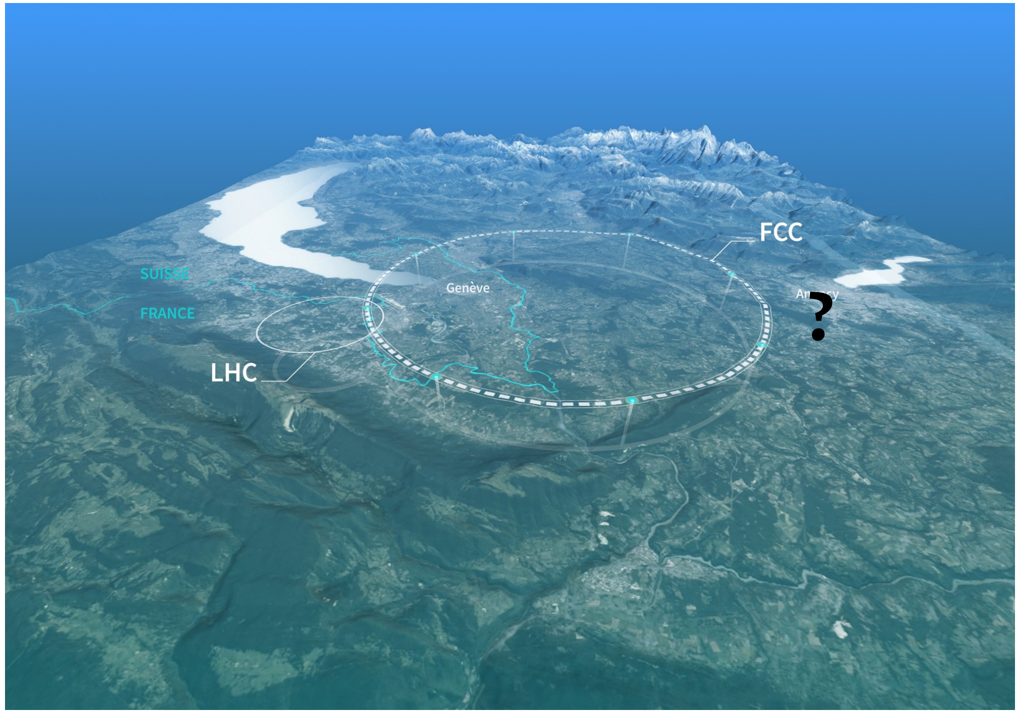


Combinations with **precision differential measurements** of **Higgs production** will push sensitivity even further!



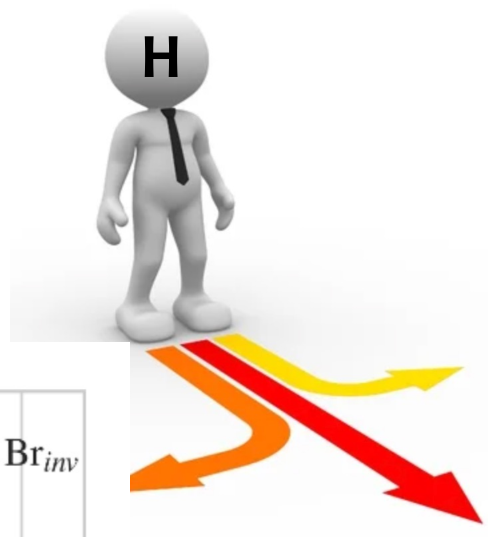
Higgs beyond the HL-LHC?

Future collider a "***High-priority future initiative***" (2020 update)



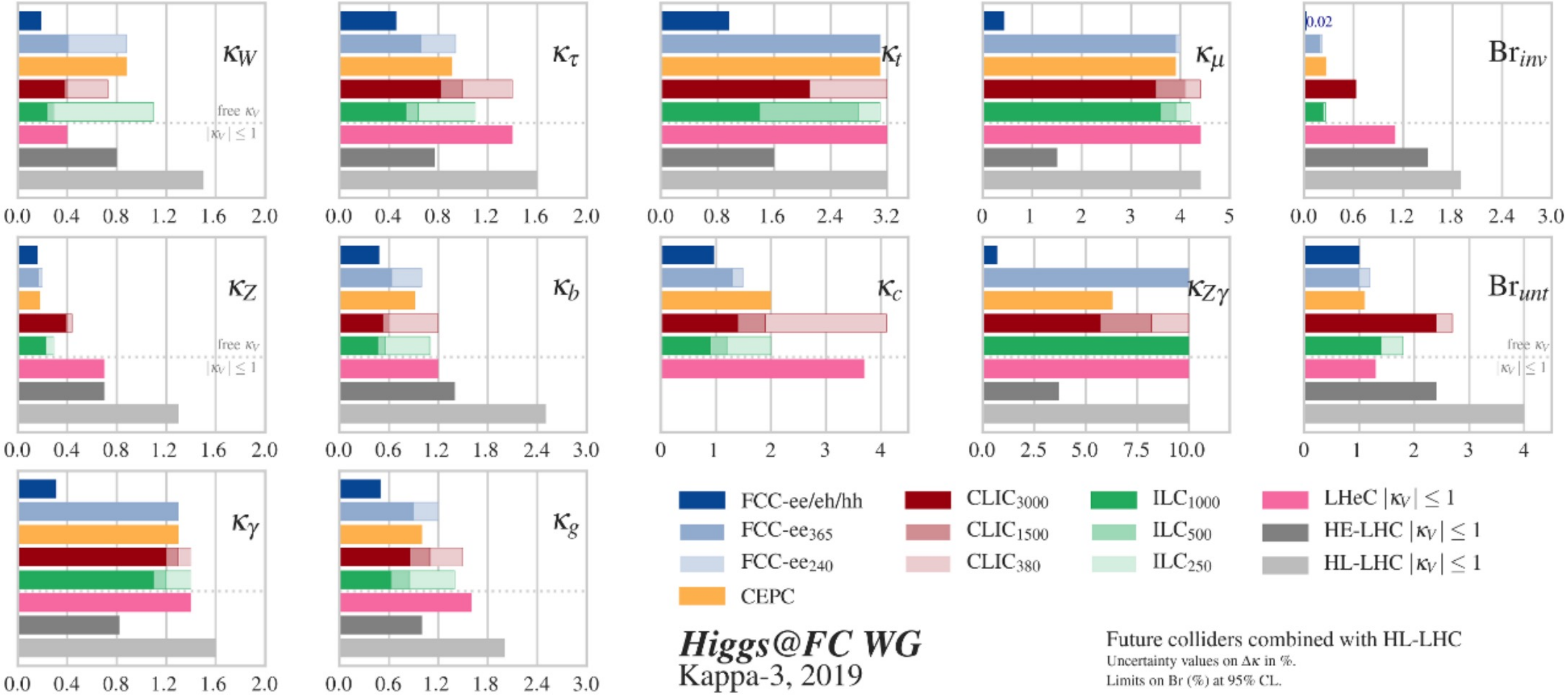
"*Europe, …, should* ***investigate the technical and financial feasibility*** *of a* ***future hadron collider*** *at CERN with a centre-of-mass energy of* ***at least 100 TeV*** *…*

Higgs boson couplings beyond the HL-LHC



The **long road ahead** for the Higgs has many potential options but all lead to high **precision (O(1)% level) characterization** of the Higgs boson couplings

JHEP 139 (2020)



Higgs boson couplings beyond the HL-LHC

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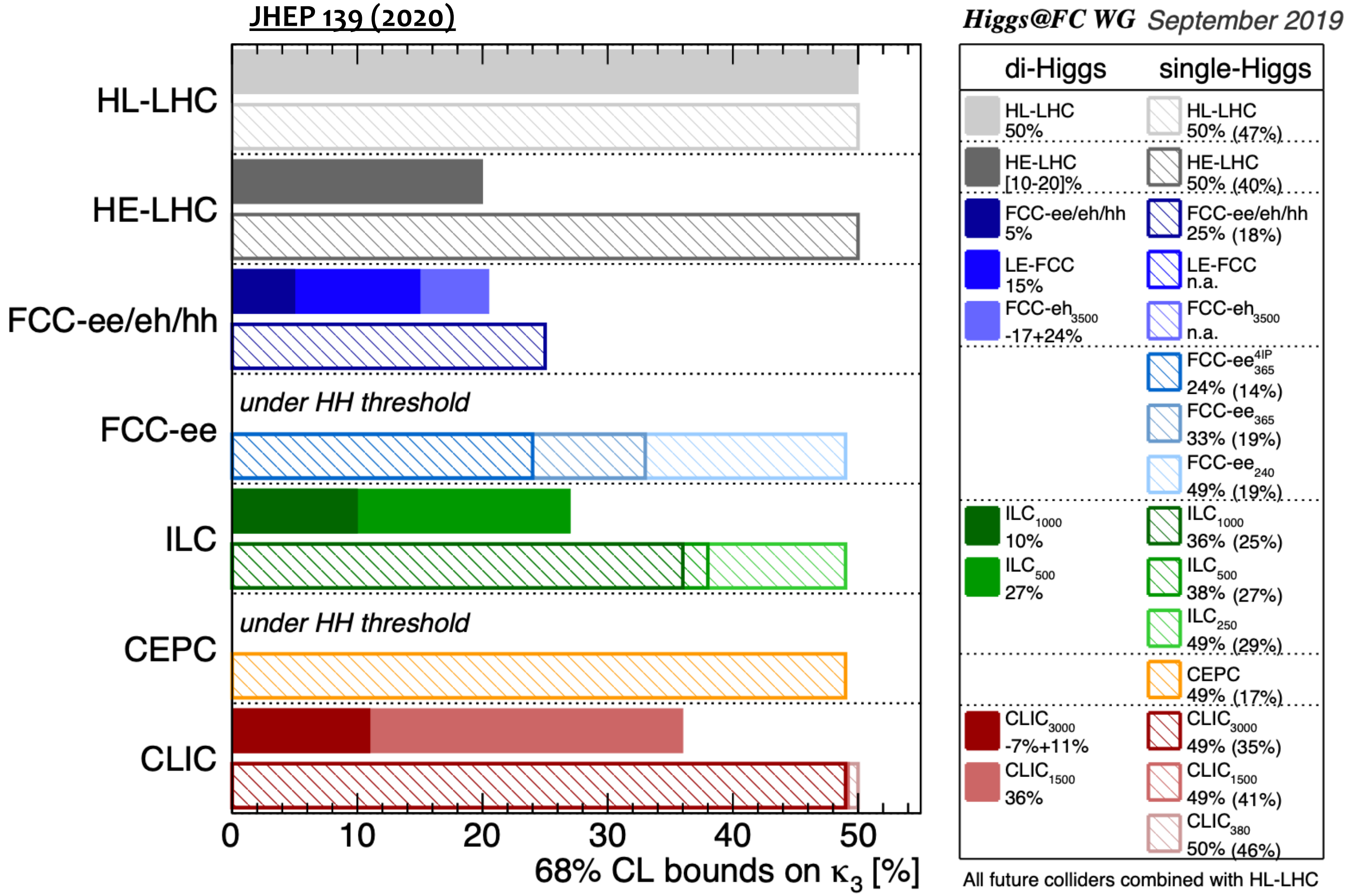
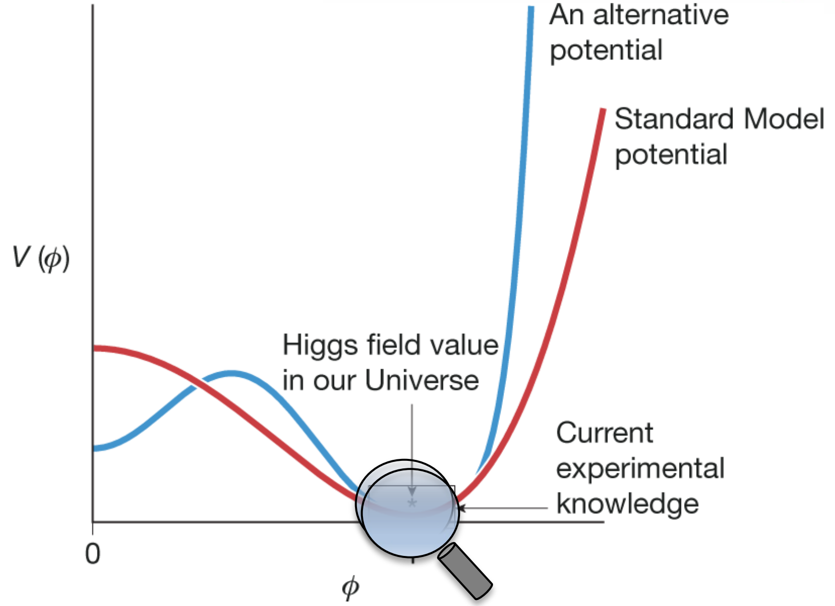
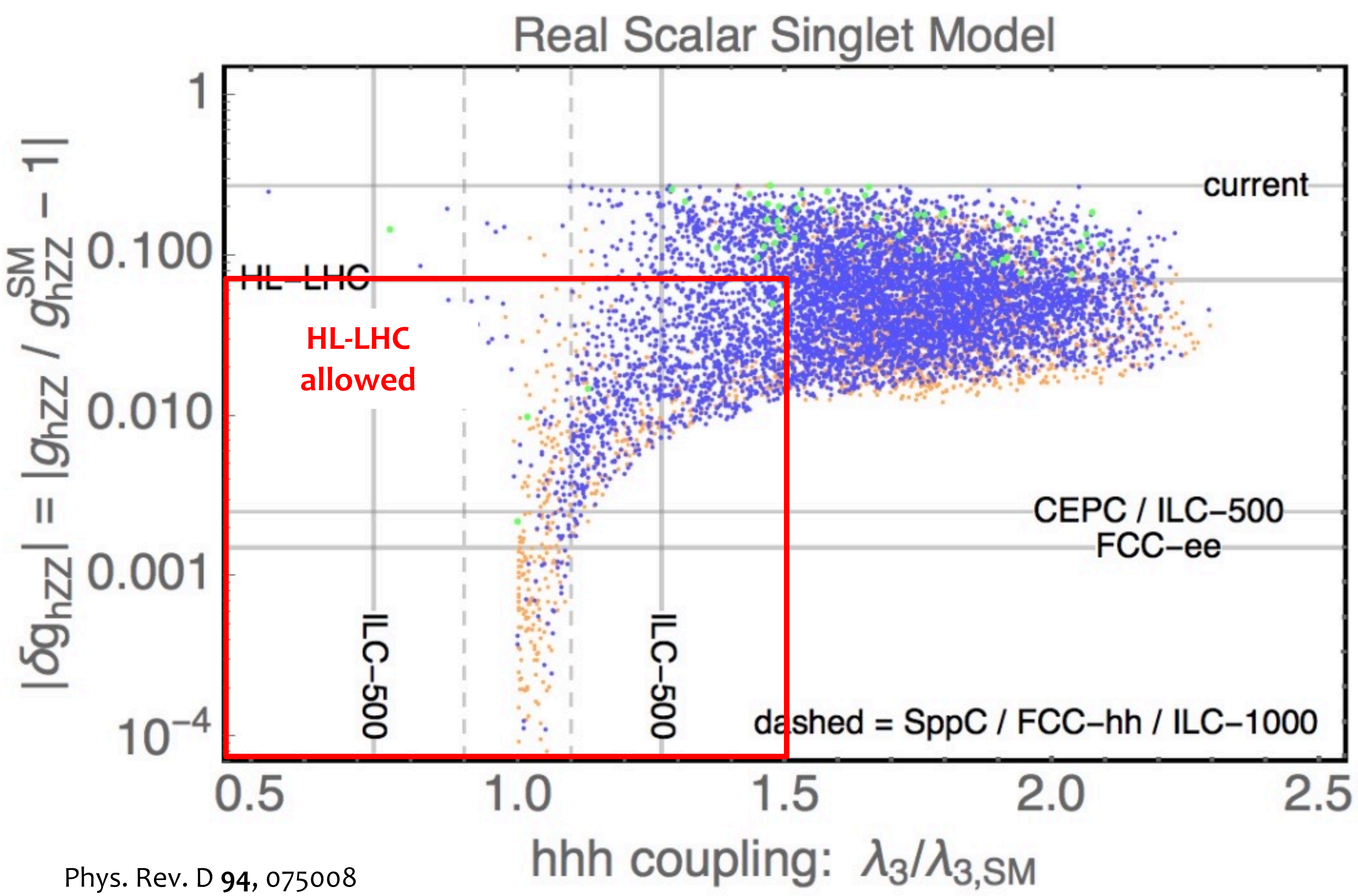
JHEP 139 (2020)





Higgs boson **self-coupling** requires **high energy** machine for % level

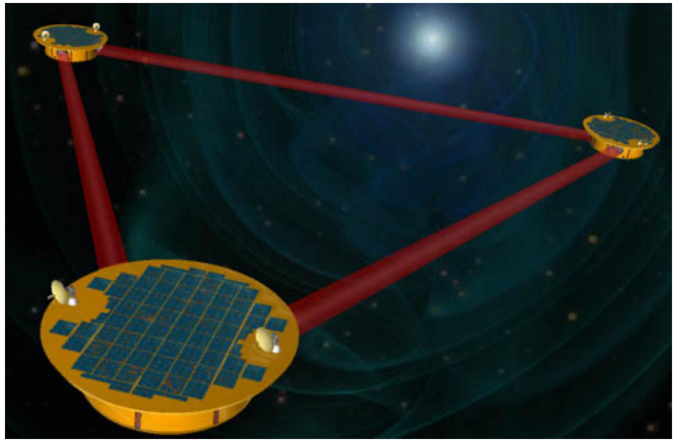
Higgs and the Universe beyond the HL-LHC



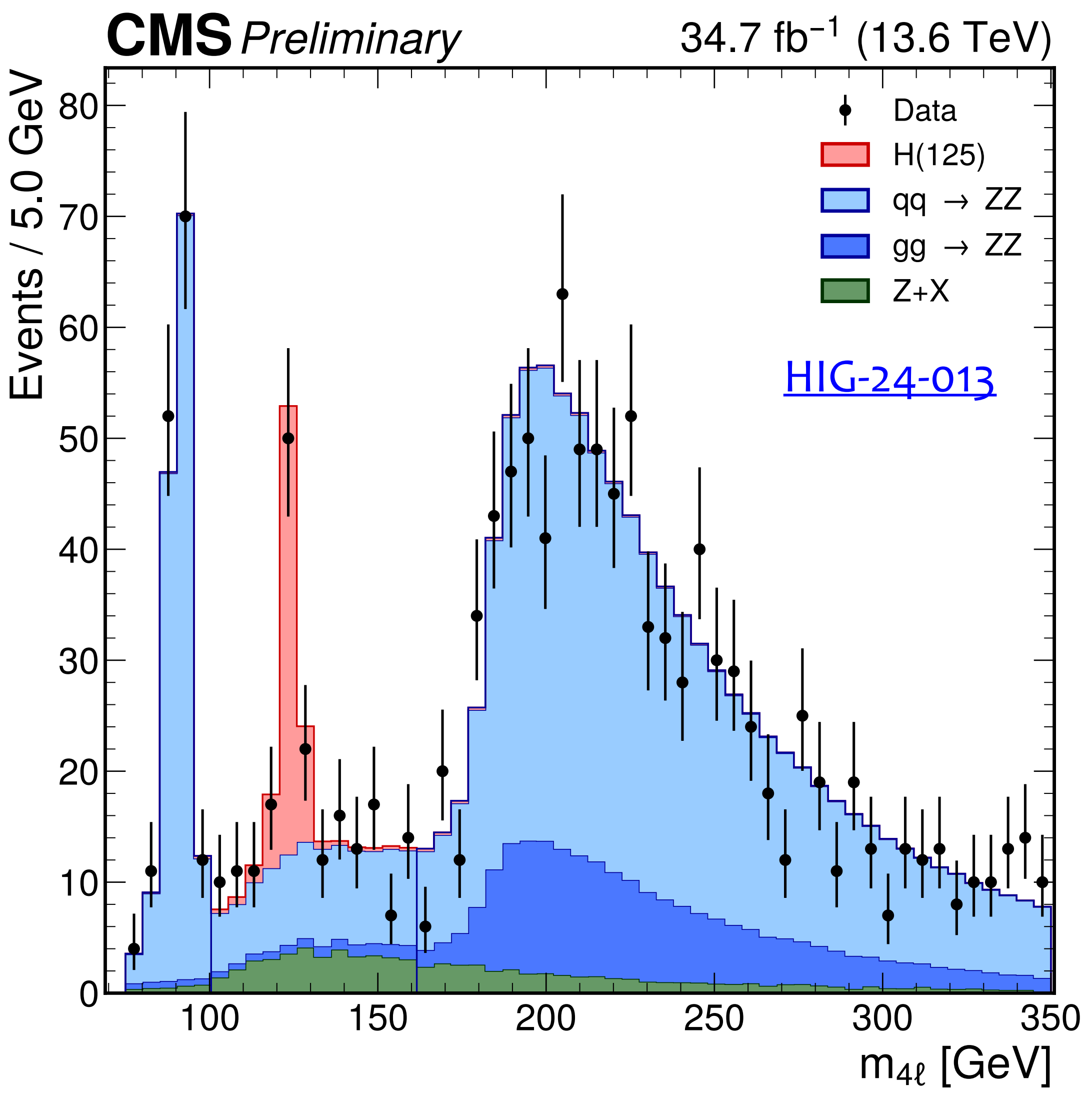
Phys. Rev. D **94**, 075008

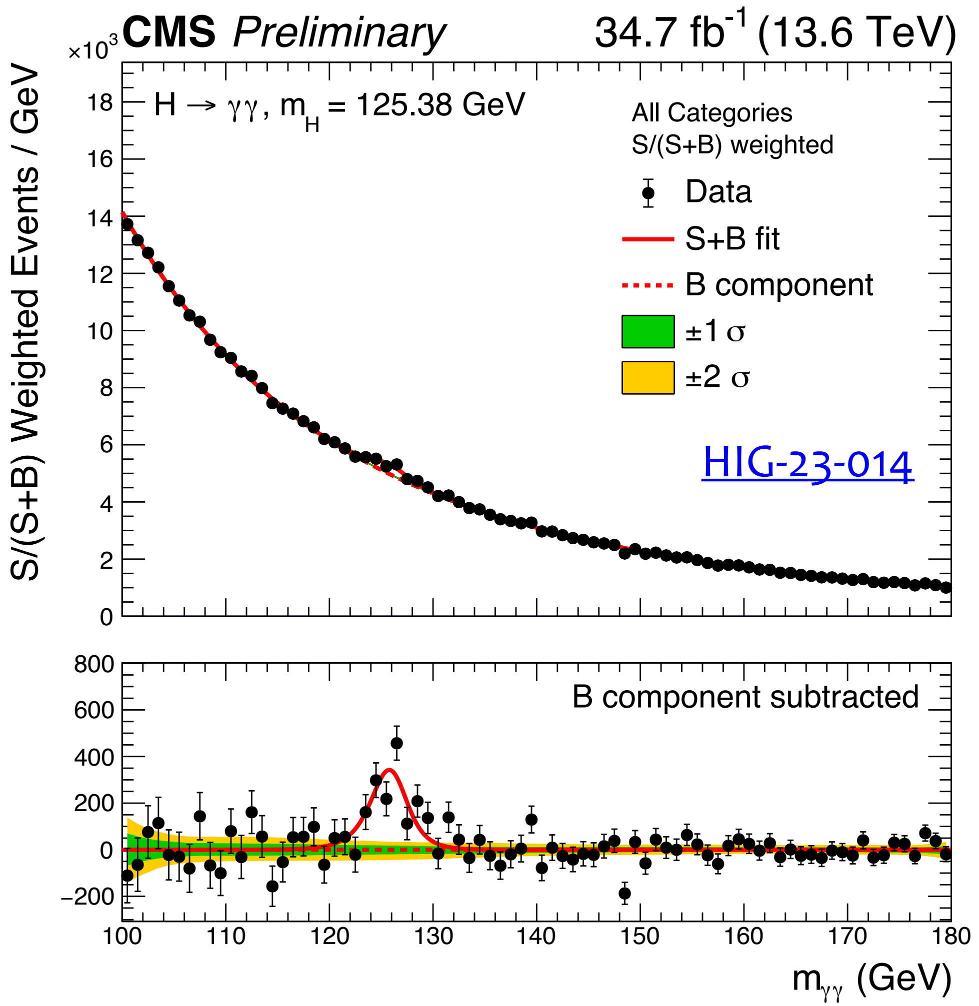
Modified Higgs potentials can result in 1st order electroweak phase transition
→ **required for baryogenesis**

- Strong first order PT (electroweak baryogenesis viable)
- Could be detected at GW detectors (eLISA)



We're not there yet – still plenty to do now





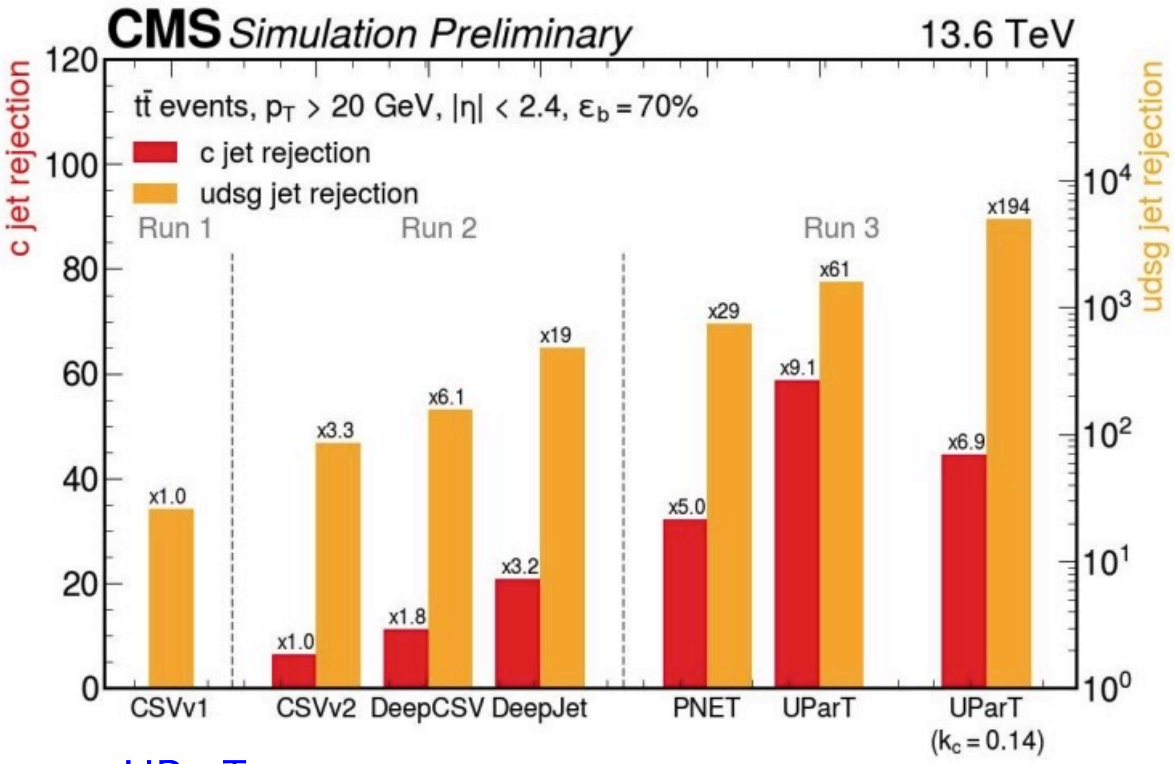
New results already with **early 13.6 TeV data** (from 2022)

→ Lots more data available since then in **Run-3!**

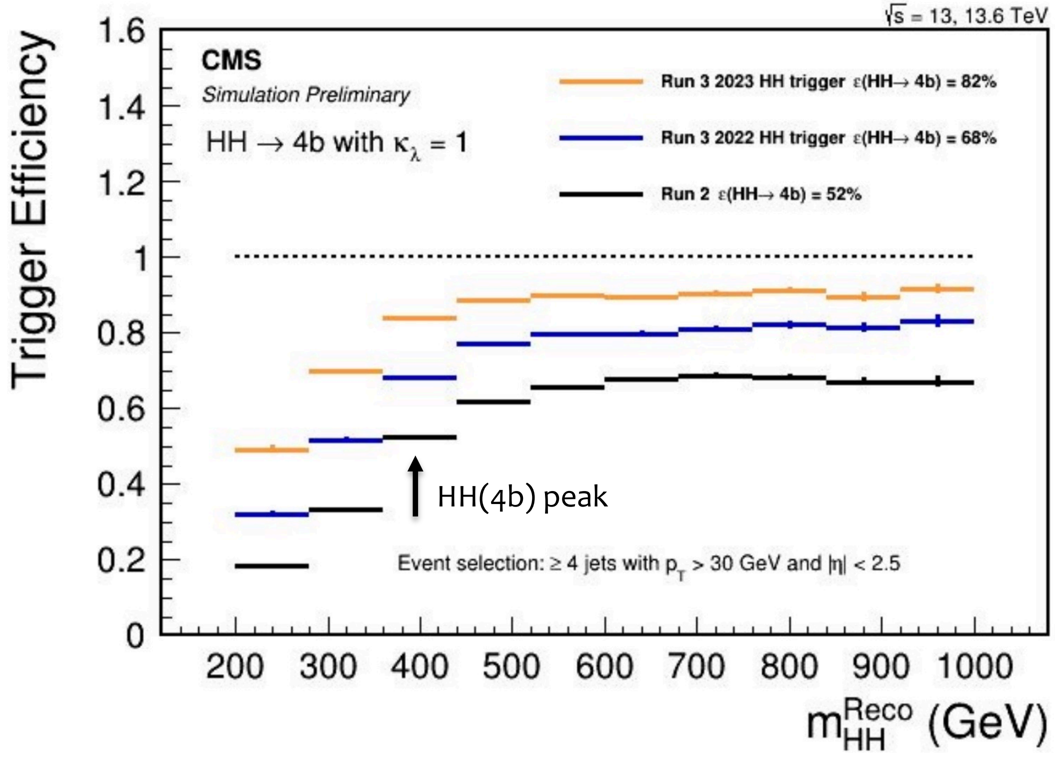
We're not there yet – and have new ideas in the pipeline

Methods constantly evolving to **improve on what we can do** with the data we have

→ Do better than scaling with statistics!

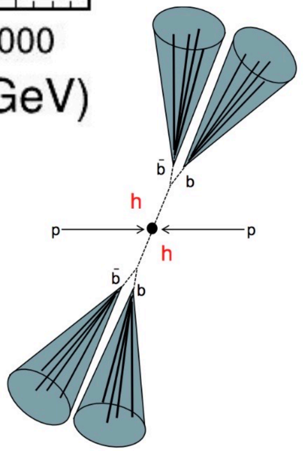


[UParT]



Machine learning plays a huge role in making the most of our data

→ New people with **new ideas always needed** to ensure the future of precision Higgs measurements

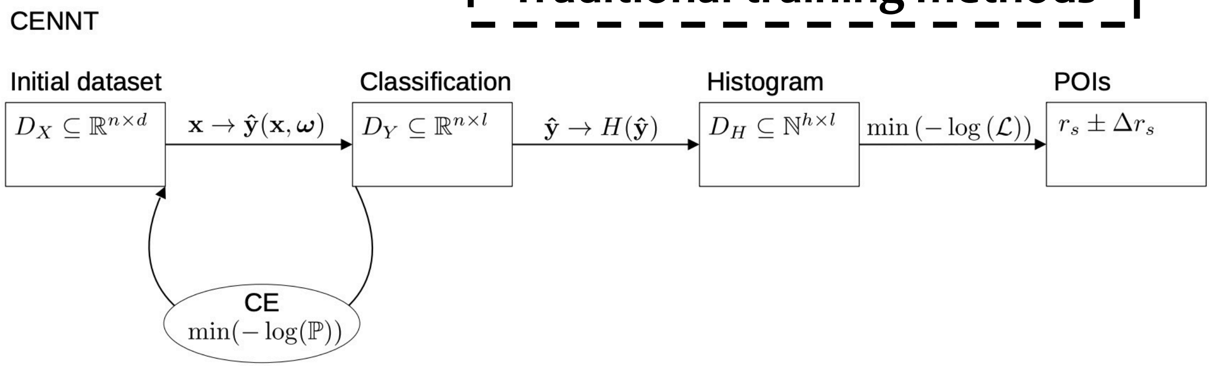


We're not there yet – and have new ideas in the pipeline

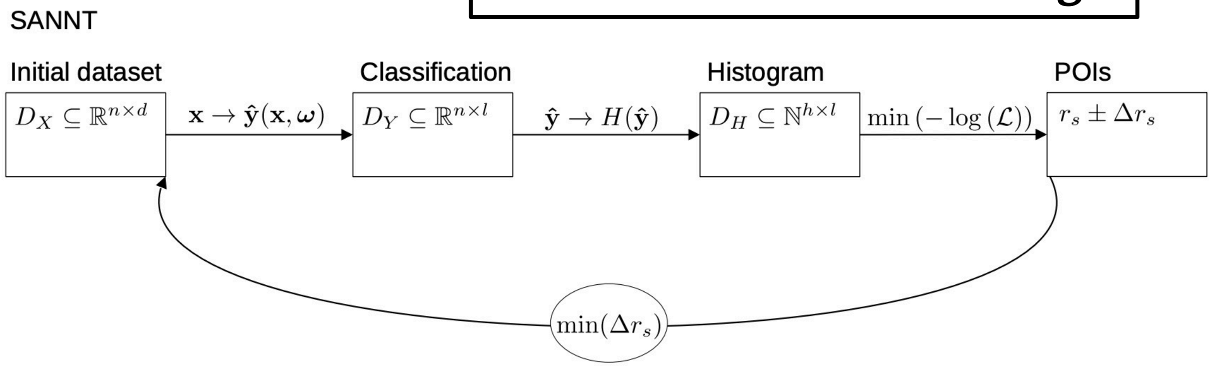
Evolving **the way we use machine learning** in the analysis could also bring significant improvements to our Higgs measurements!

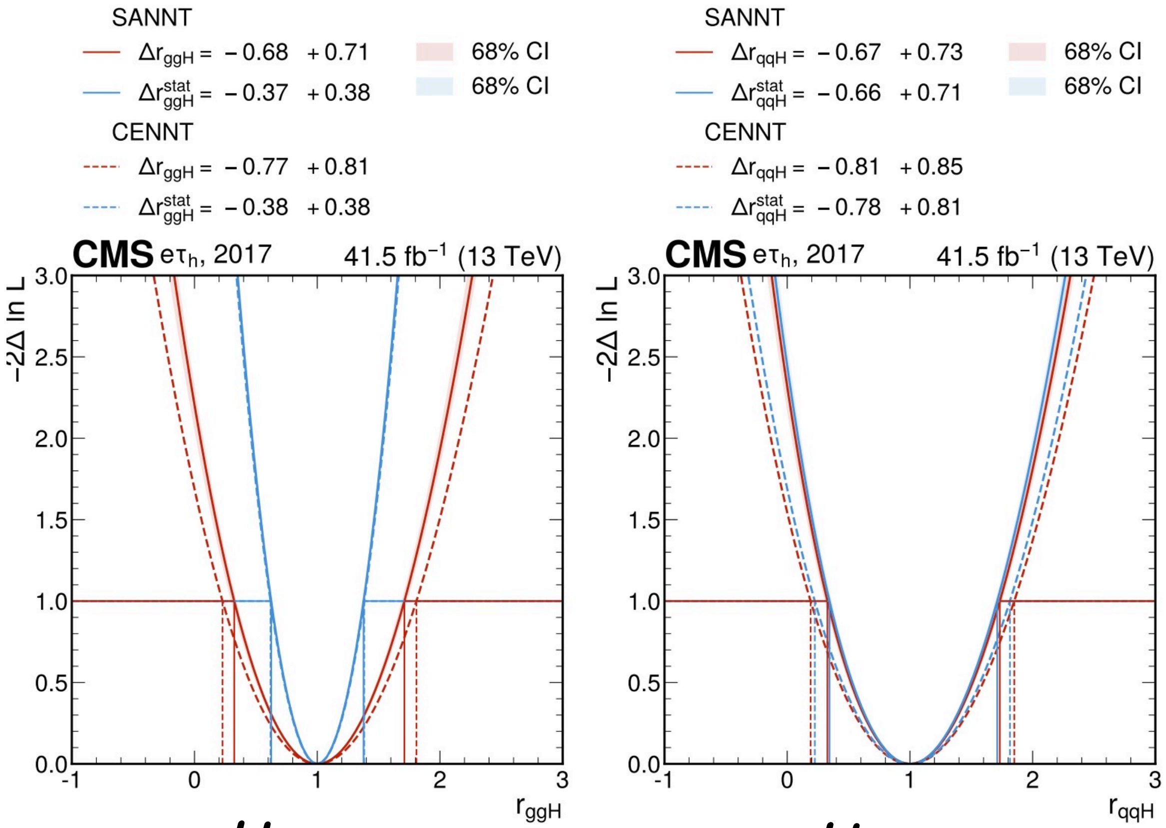
Potential for measurements in H → ττ

Traditional training methods



"Inference-aware" training





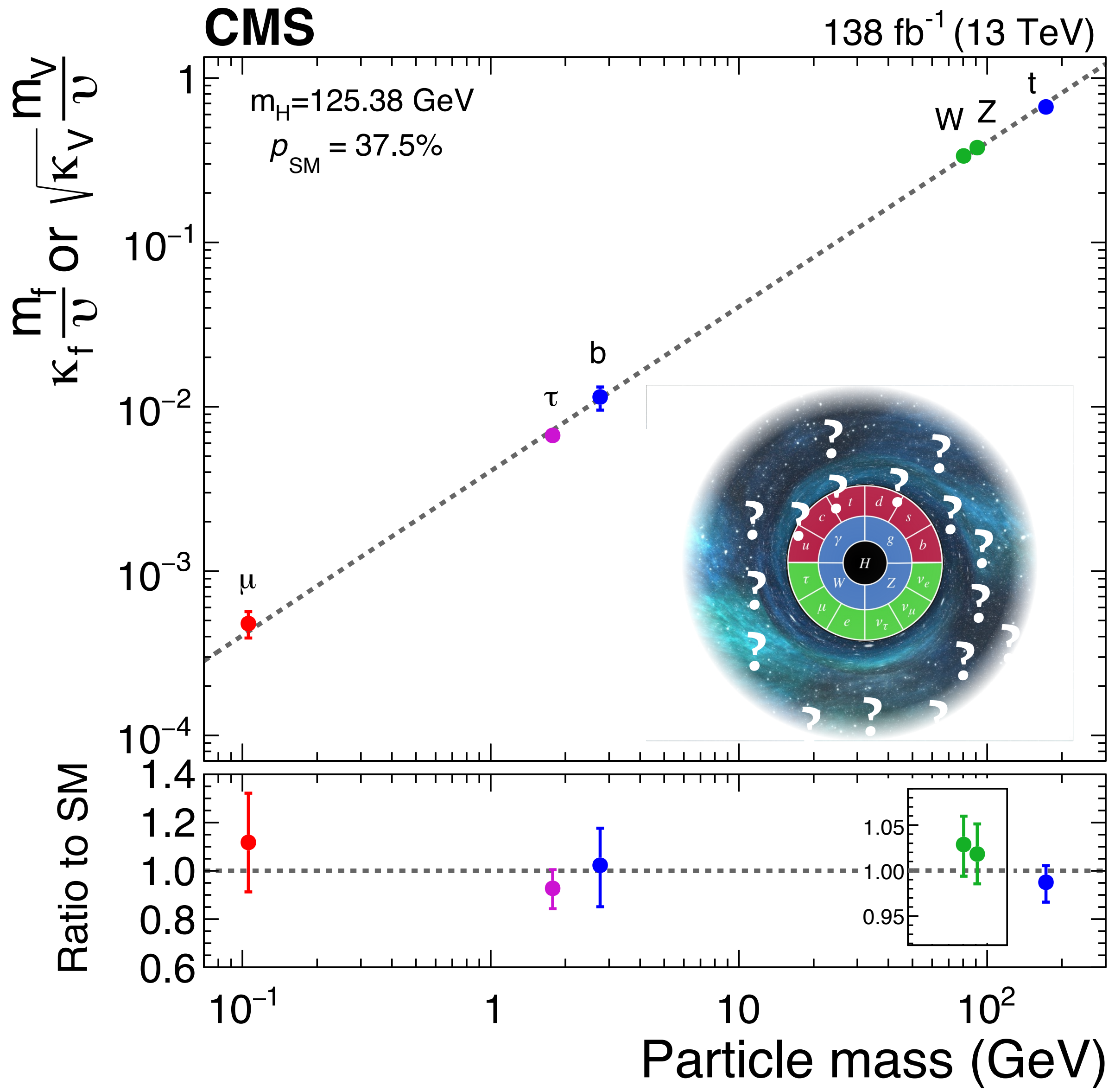
μ_{ggH} μ_{qqH}

[MLG-23-005]

Summary

Higgs boson a corner stone of the Standard Model

- **So far**, all measured properties look **SM-like,** but that's ok, who said nature would be easy to unravel?



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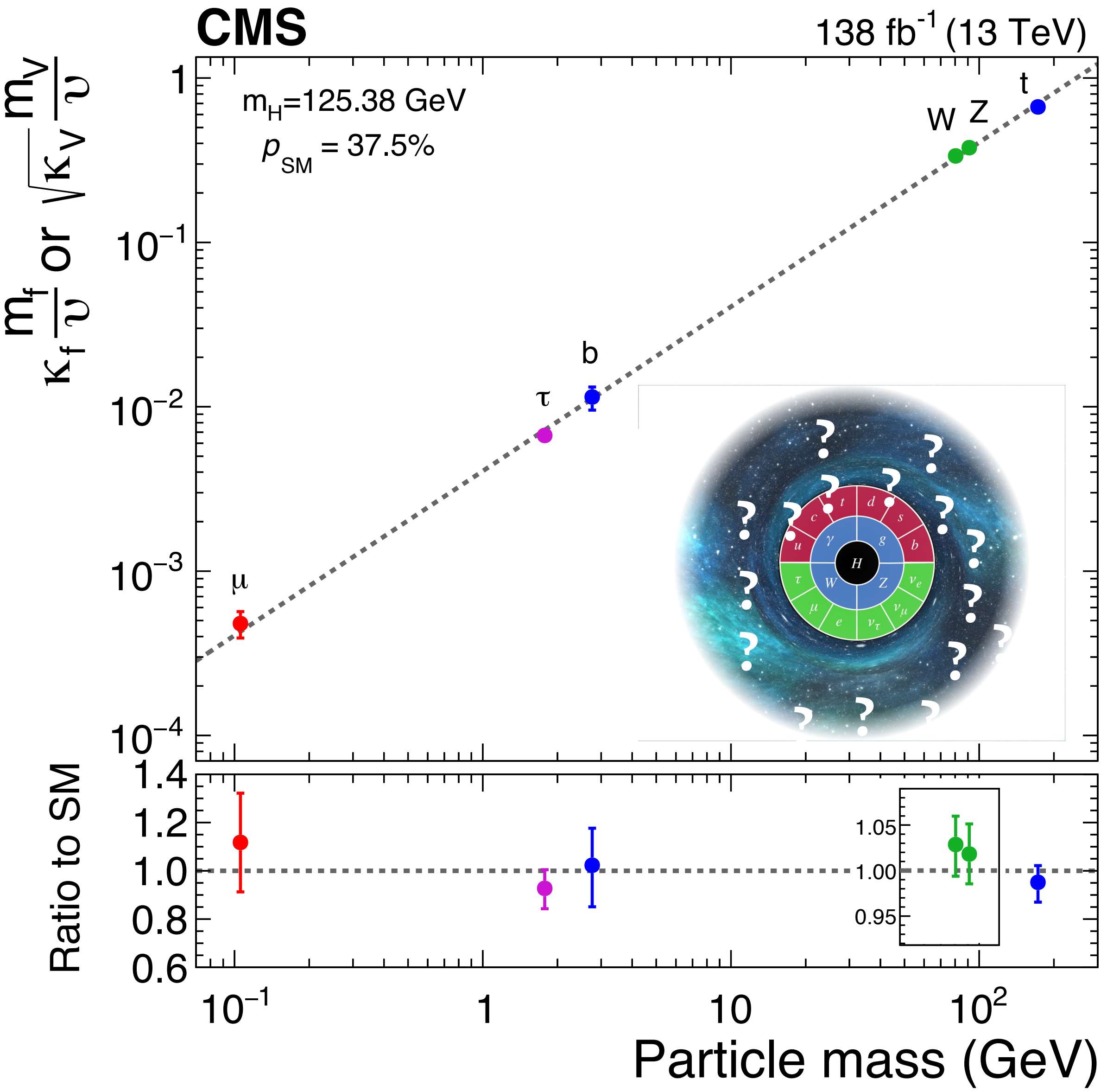
Precision Higgs boson coupling measurements offer a unique insight into BSM physics & **complimentary to direct searches**

- Measurements of **B(H→inv)** complements direct searches for **Dark Matter**!

Differential measurements crucial to make the most of LHC data

- Exploit different kinematic regions to **constrain Effective Field Theories**
- **Higgs self-coupling** from H and HH production – connections with **early universe evolution**



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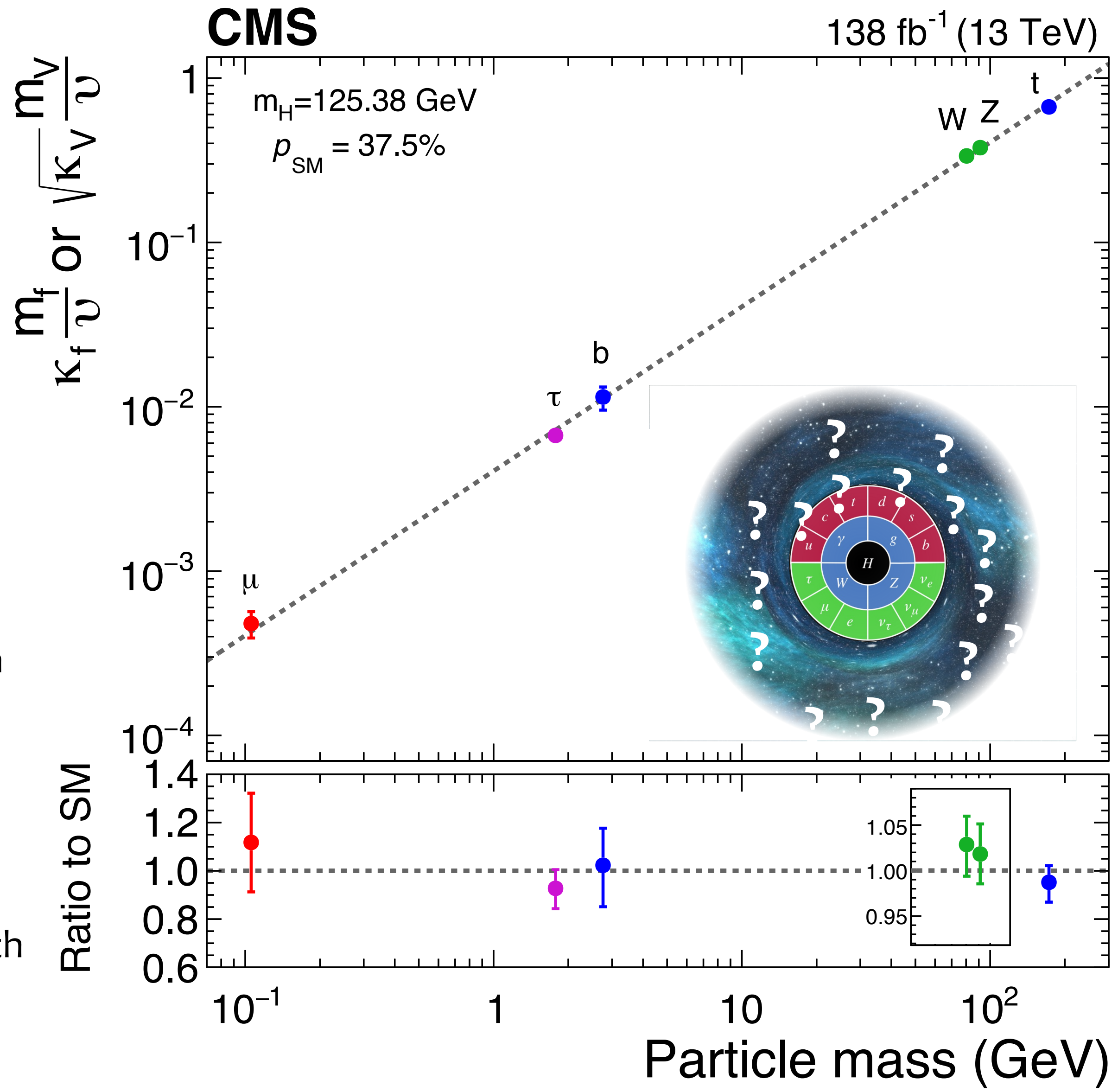
Things I didn't talk about

- Direct searches for heavy Higgs/extended Higgs sectors/res-HH
- CP-odd couplings to vector bosons & flavor violating Higgs decays
- Rare decays in the SM (1st generation couplings) & Higgs total width



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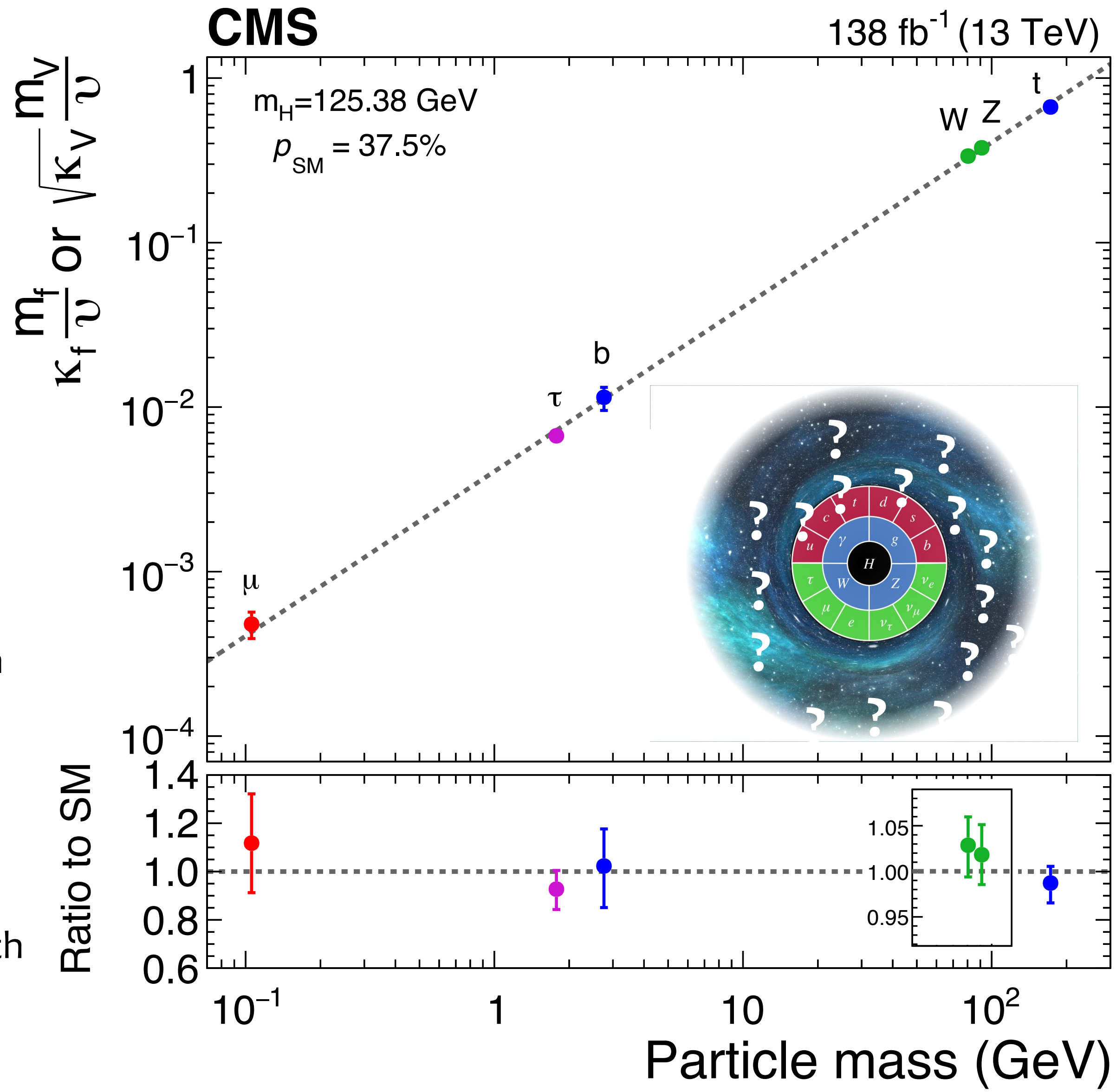


We are **only 10 years** in so far!

- **20x more data** by the end of the **HL-LHC**
- **Future colliders** will bring ultimate precision for **Higgs boson measurements in the search for new physics!**

Precision measurements for discovery

Higgs boson
discovery **(2012)**

Precision measurements for discovery

Higgs boson discovery **(2012)**

12 years of measurements **(2024)**

Precision measurements for discovery

Higgs boson discovery **(2012)**

12 years of measurements **(2024)**

Run-3/HL-LHC/Future collider ? (**20XX?**)

Time/precision

Thanks!

Backup Slides

CMS Higgs Observation statistical model

16/04/2024

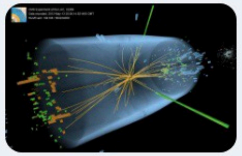
CERN
416,893 followers
2h •

CMS releases #HiggsBoson discovery data to the public

The CMS Collaboration has recently released, in electronic format, the combination of the measurements that contributed to establishing the discovery of the Higgs boson in 2012.

This release coincides with the publication of the Combine software – the statistical analysis tool that CMS developed during the first run of #LHC, to search for the unique particle, which has since been adopted throughout the collaboration.

Find out more: https://lnkd.in/gq_Tb5UB



CMS releases Higgs boson discovery data to the public
home.cern • 3 min read

https://new-cds.cern.ch/records/c2948-e8875

Full statistical model from CMS Higgs observation and code to use it made public in **April this year (it only took 12 years ☺)**

Full **statistical model** + **data** = **public experimental likelihood!**

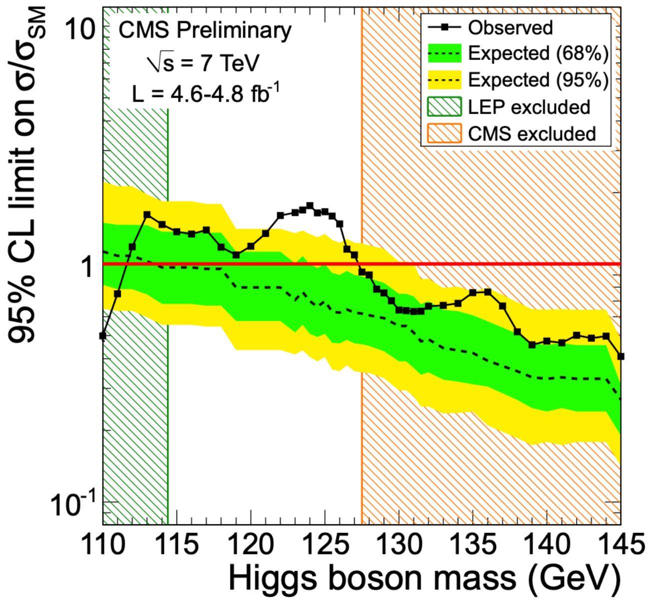
```
combine 125.5/comb.txt --mass 125.5 -M Significance

 -- Significance --
Significance: 4.87557
Done in 1.76 min (cpu), 1.76 min (real)
```

Can reproduce results from 2012 **on your laptop**!

New CMS policy to “routinely” provide this information for analyses, including **more recent Higgs combinations**

Pre-discovery …

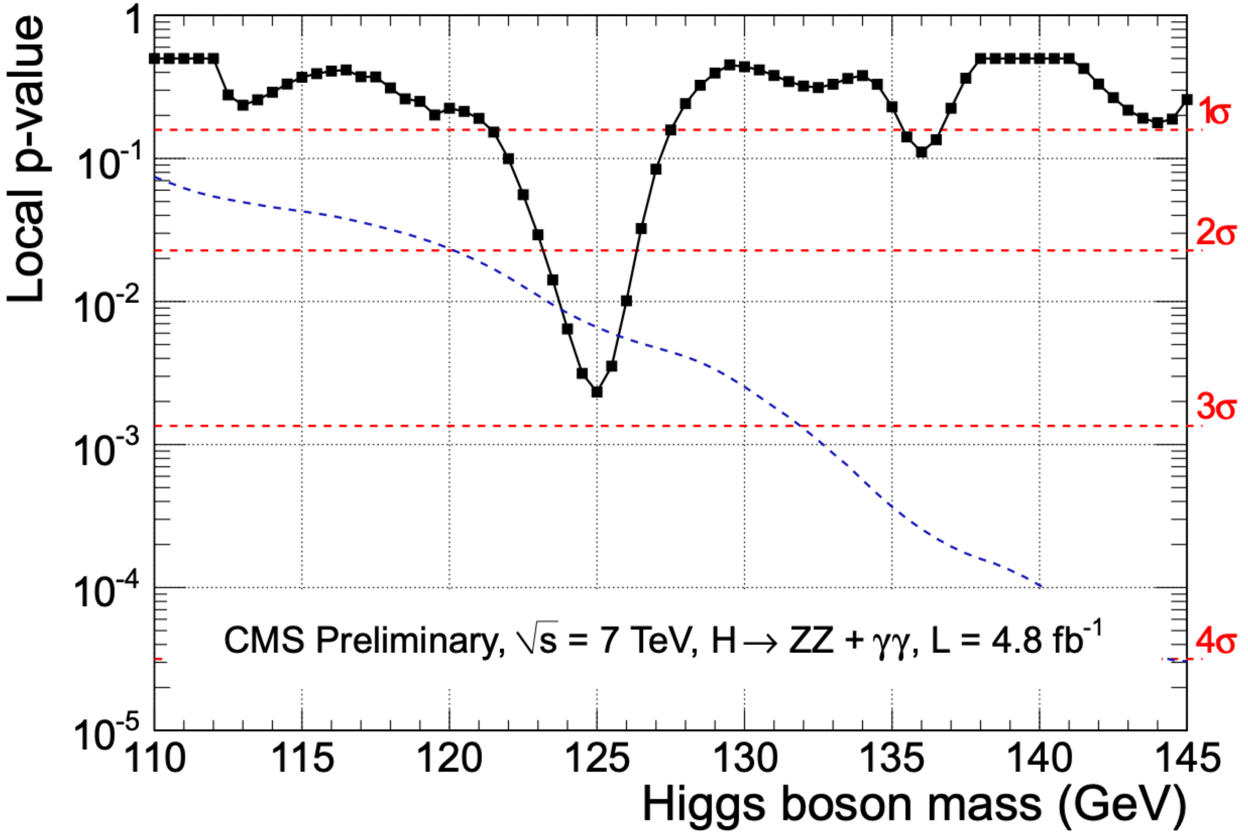
R. Heuer (4th June)



Status ~ today

SM Higgs boson excluded with 95% cl up to a mass of 600 GeV except for the window **122.5 to 127.5** GeV

"interesting fluctuations" around masses of **124 to 126** GeV

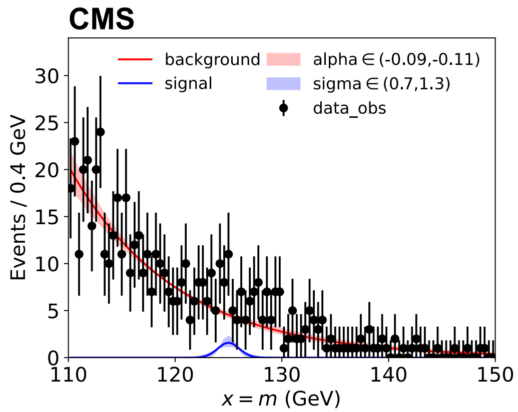


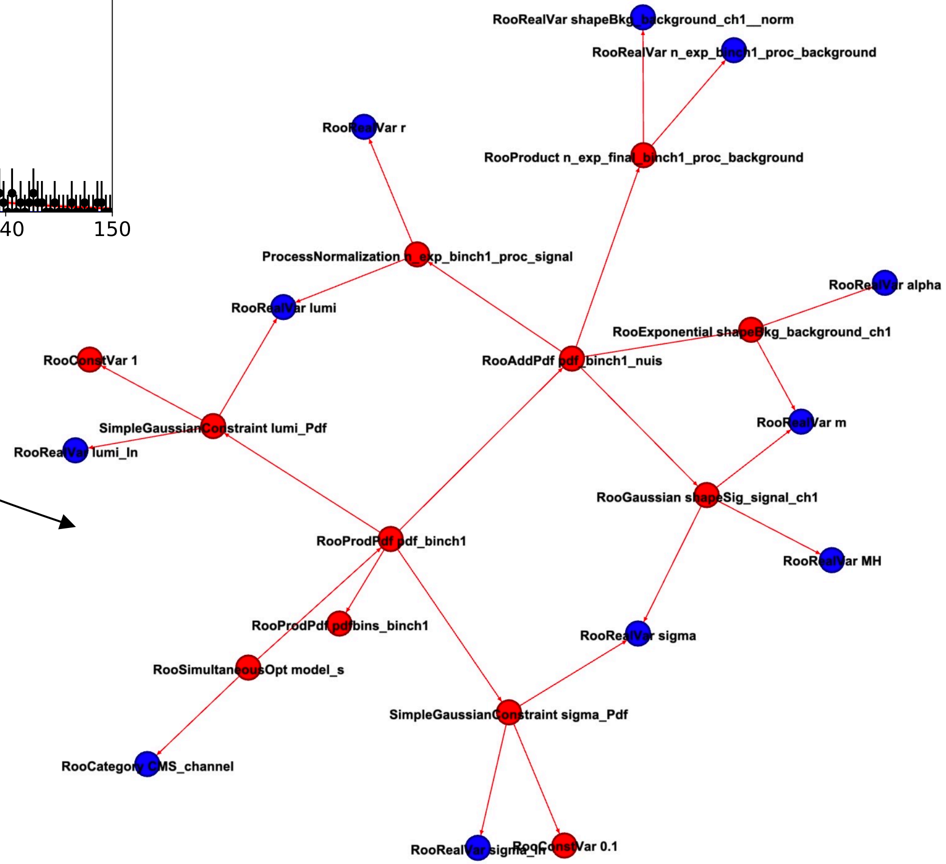
N. Wardle (8th June)

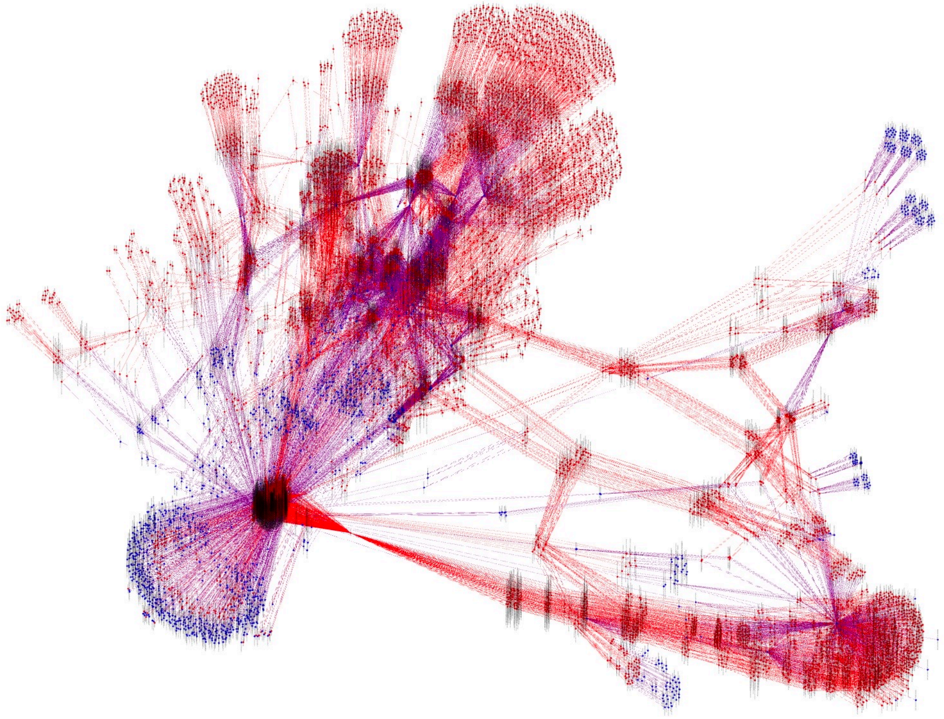
- **Excess observed at** $125\ GeV$**, local significance** 2.8σ **(**1.6σ **with LEE)**
- **CMS will continue to run in 2012 at 8 TeV. Can expect to be sensitive to SM this year**

Simple Model vs Combination

Simple parametric statistical model

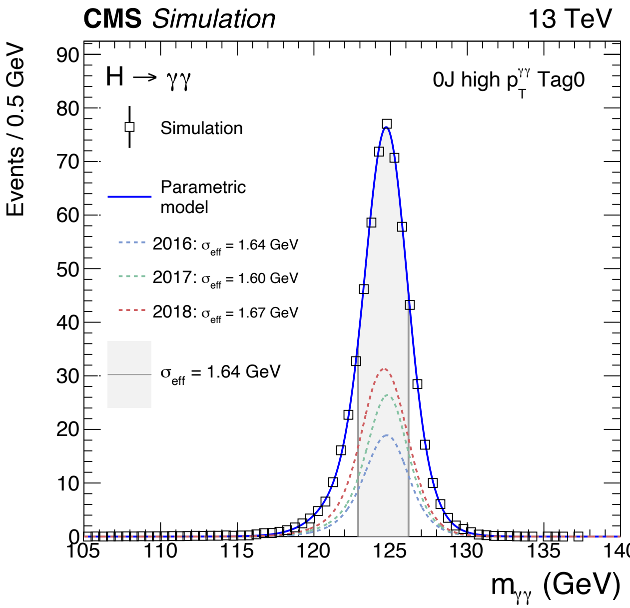




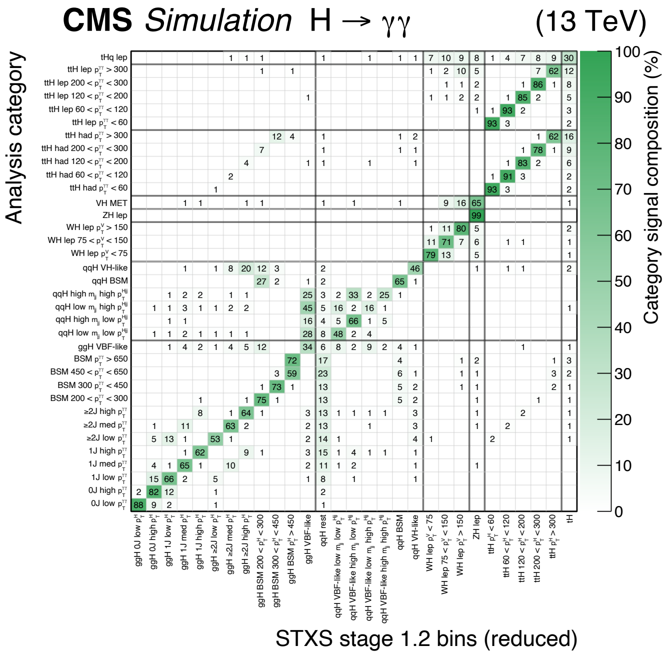


CMS Higgs observation combination statistical model

$$L(\vec{\mu},\vec{\nu}) = \prod_n p\left(x_n; \sum_{i,f} \mu_i \mu^f S_{i,n}^f(\vec{\nu}) + \sum_k B_k(\vec{\nu})\right) \cdot \prod_i p(y_i;\nu_i)$$



$\times$

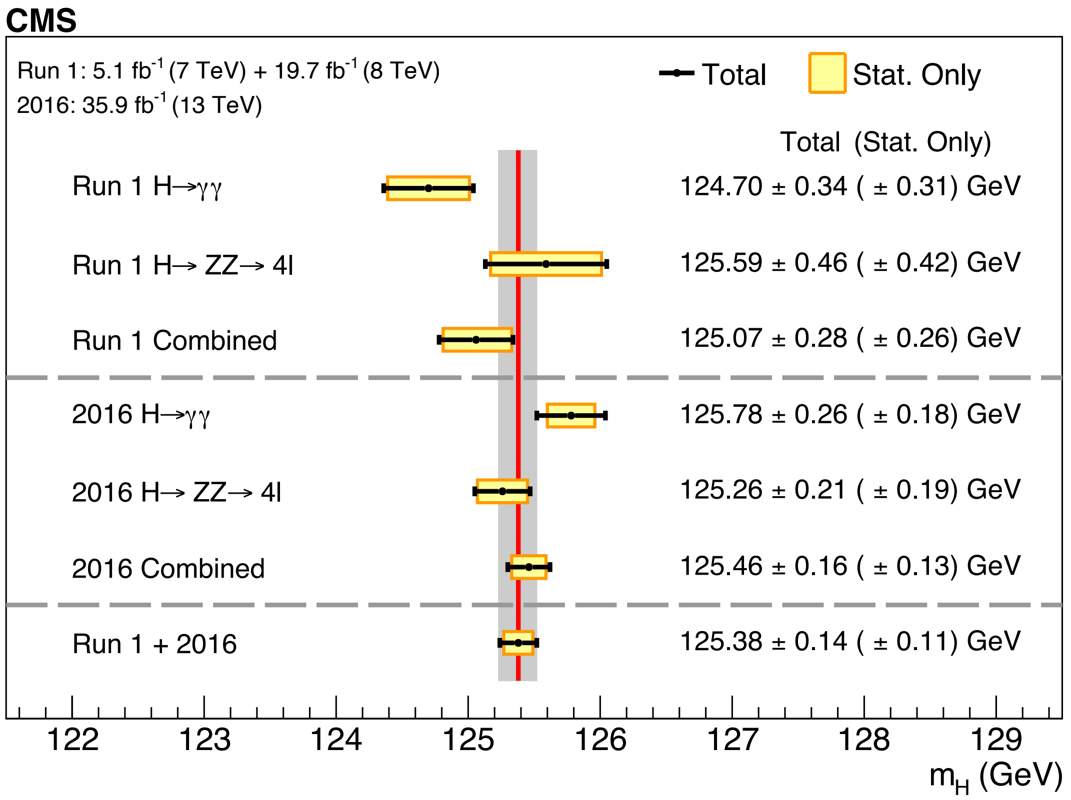


$\times \mathcal{L} \times \varepsilon \times A$

Signal model, accounts for "**shape**" of signal processes

- Relative composition across signal regions
- Overall Efficiency x acceptance

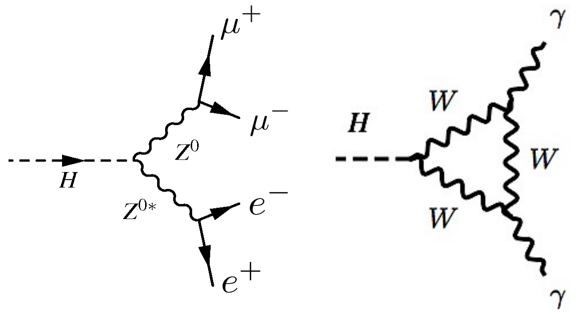
CMS combined m_H



Phys. Lett. B 805 (2020) 135425

Most precise measurement of m_H from **CMS** 2016 (Run-2 13 TeV) **dataset**

Combination of 4l and γγ decay channels

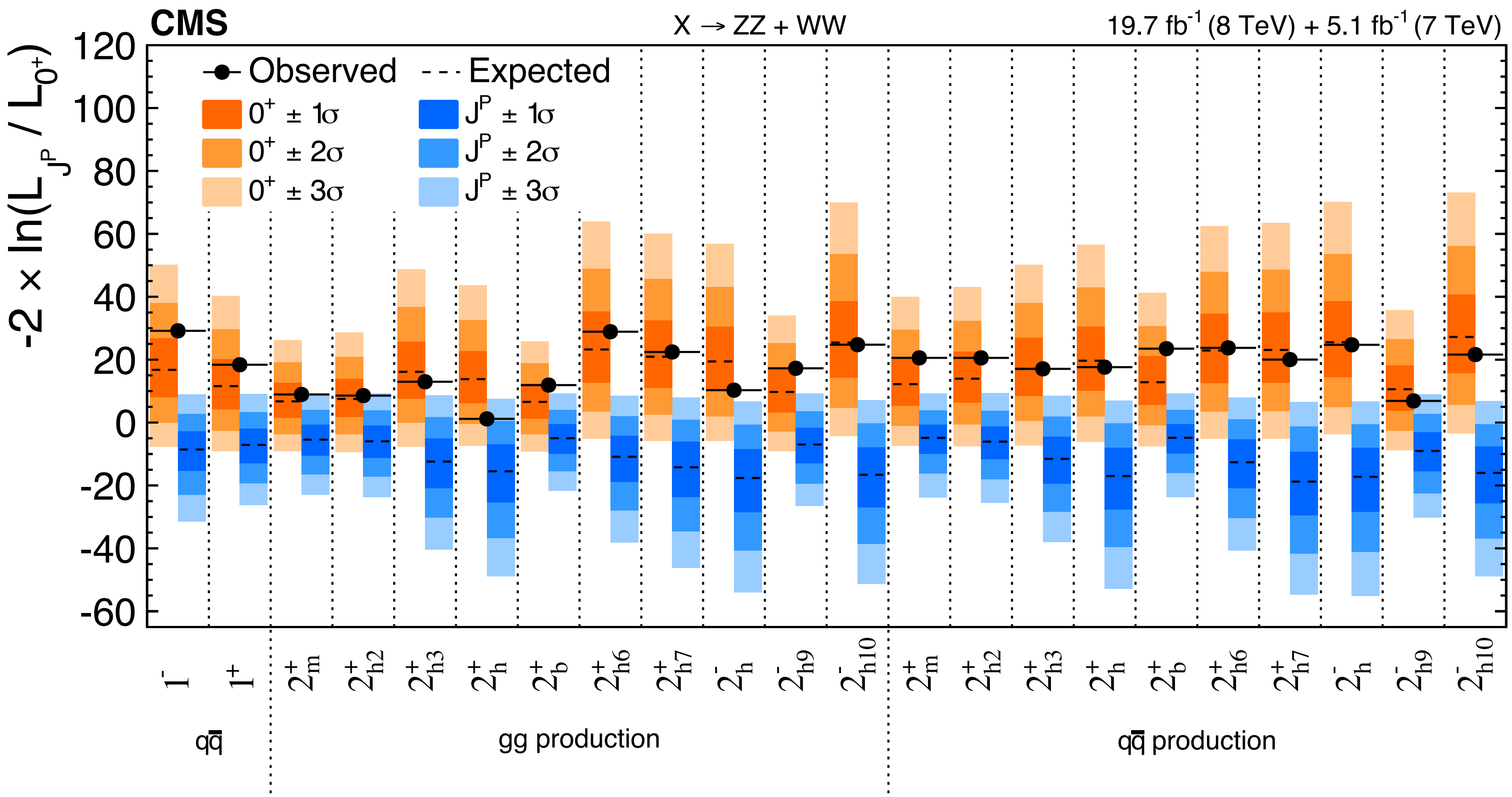


Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

Systematic uncertainty in γγ dominates, mostly due to details of **ECAL calibration and shower modelling**

~~No~~ Zero - Spin zone

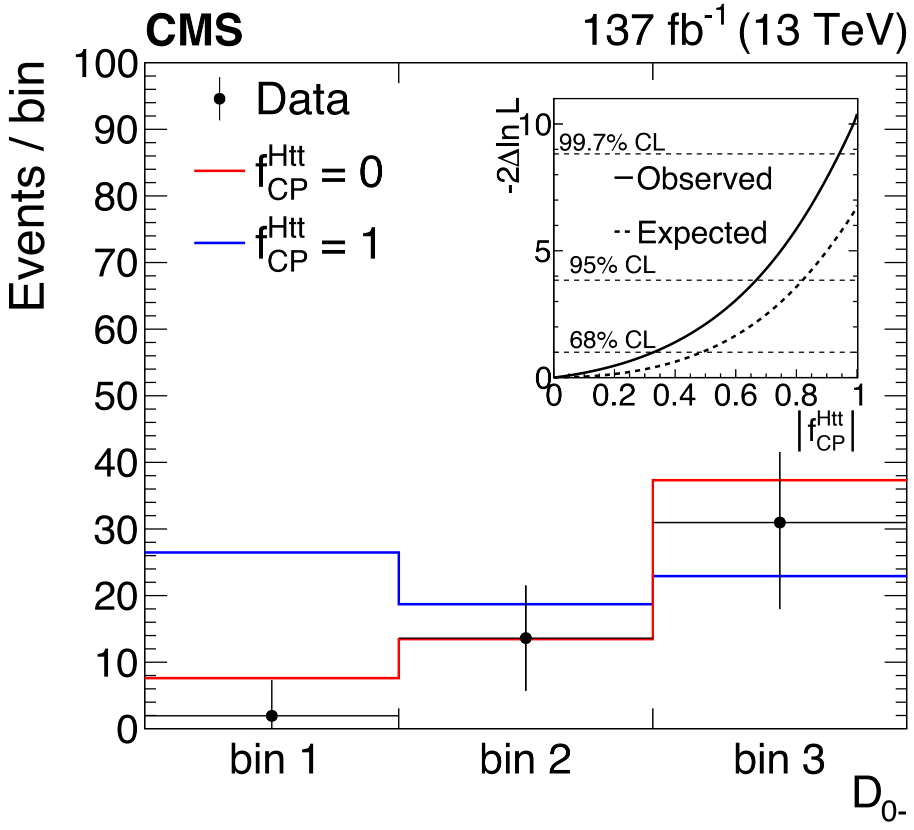
Hypothesis tests for ***non-nested models*** used to distinguish O⁺ from other J^{CP} states.

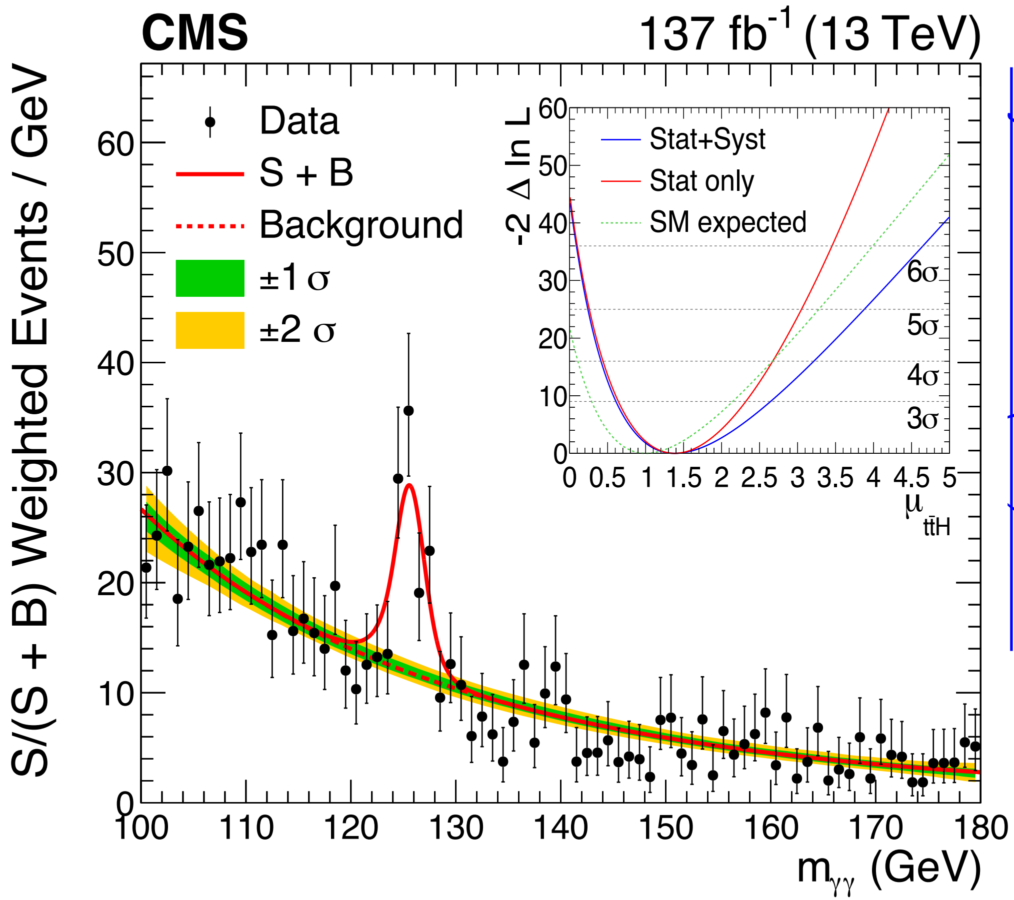


Run-1 data is already enough to rule out spin-2 (and many other J^P states) at > 99.9% confidence level

Matter-vs-anti-matter

Measurements of top-H coupling in different kinematic regionscould reveal **charge-parity odd** processes in Higgs-fermion couplings





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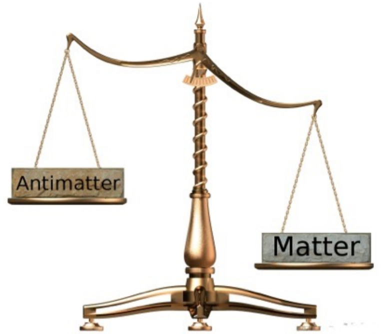
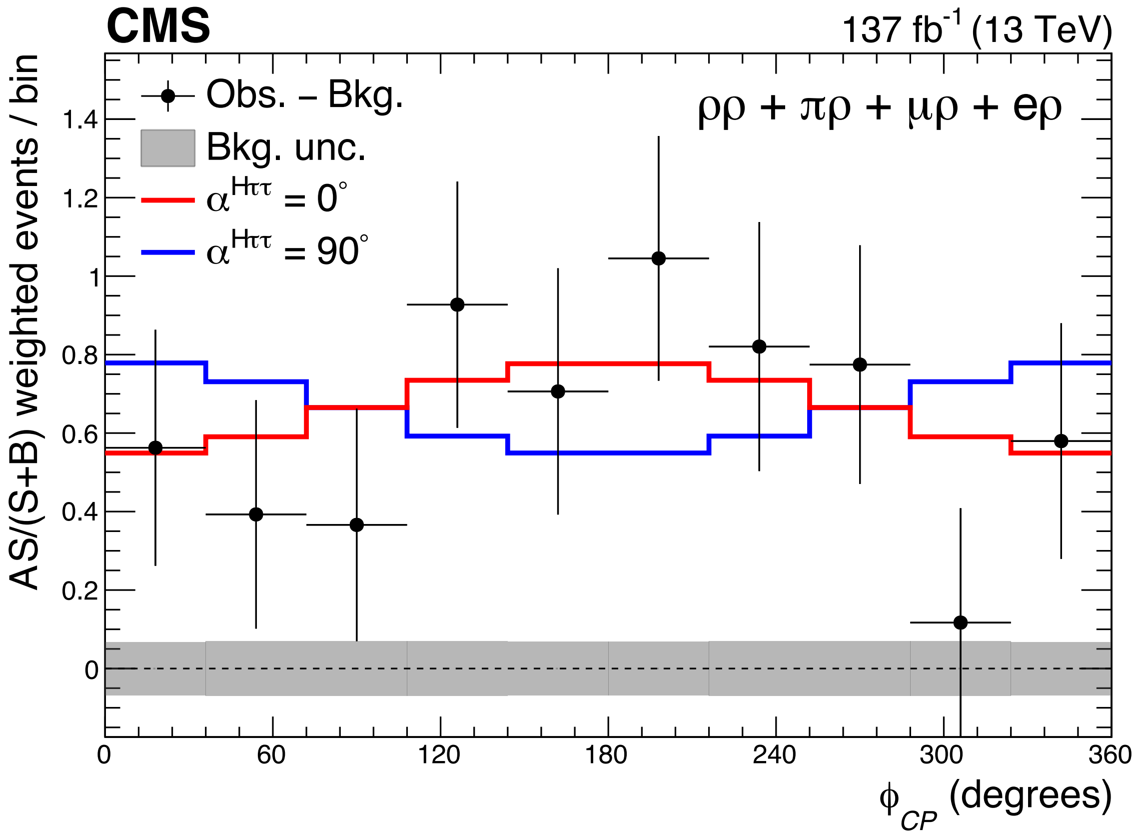
$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\overline{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t,$$

$$f_{CP}^{\mathrm{Htt}} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t).$$



Matter-vs-anti-matter

Differential measurements of tau-decay products in H→ττ constrains **CP-odd contributions** to Higgs-tau coupling



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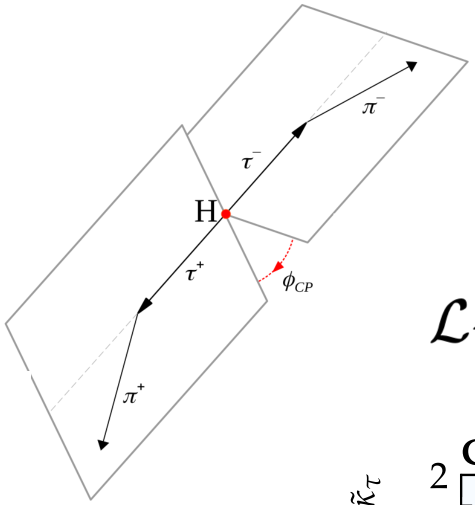
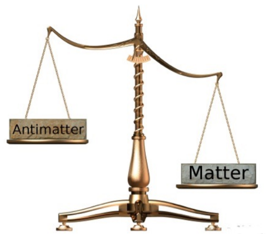
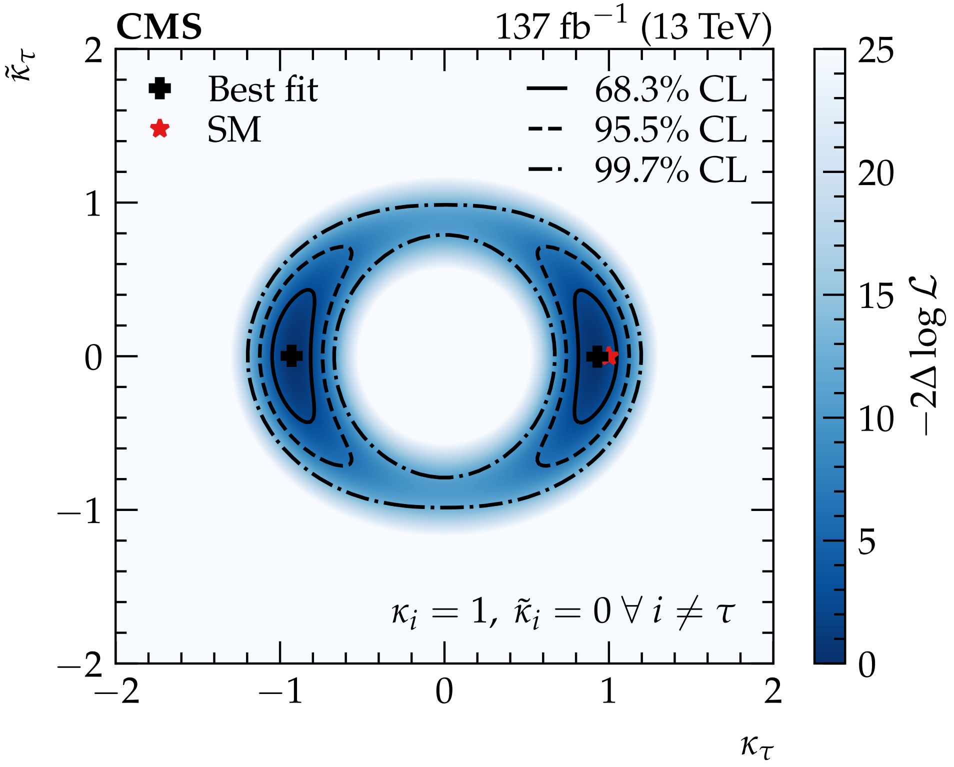




$$\mathcal{L}_Y = -\frac{m_\tau H}{v}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

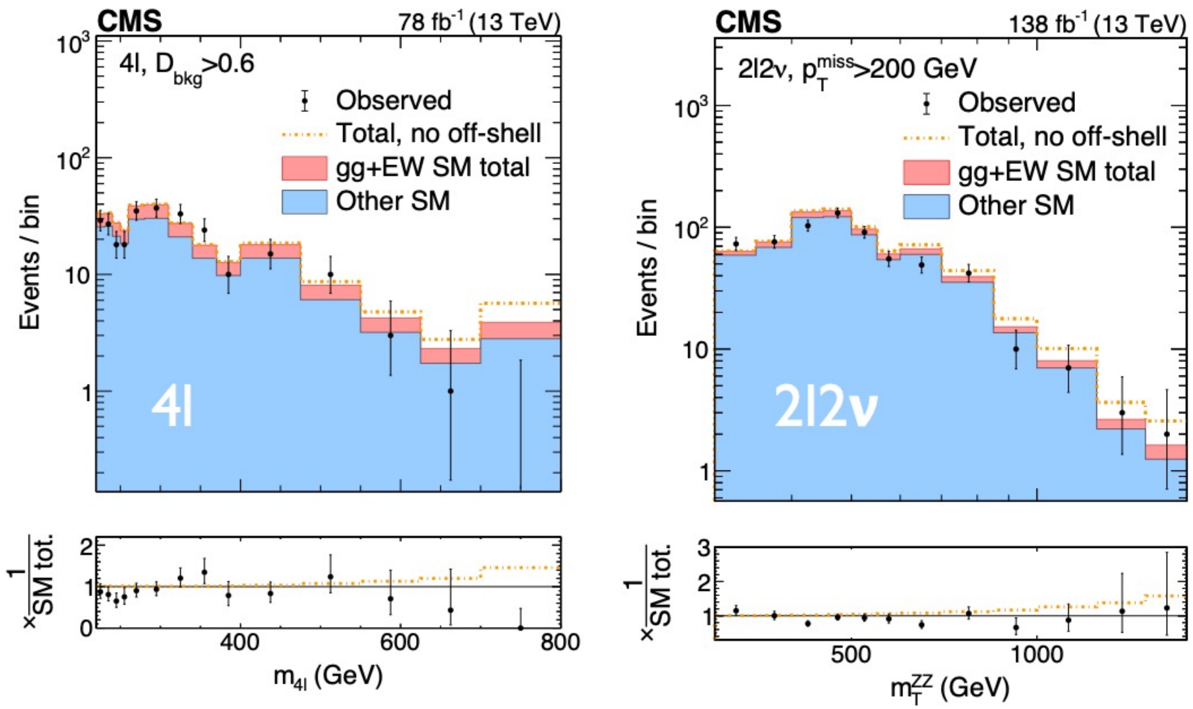


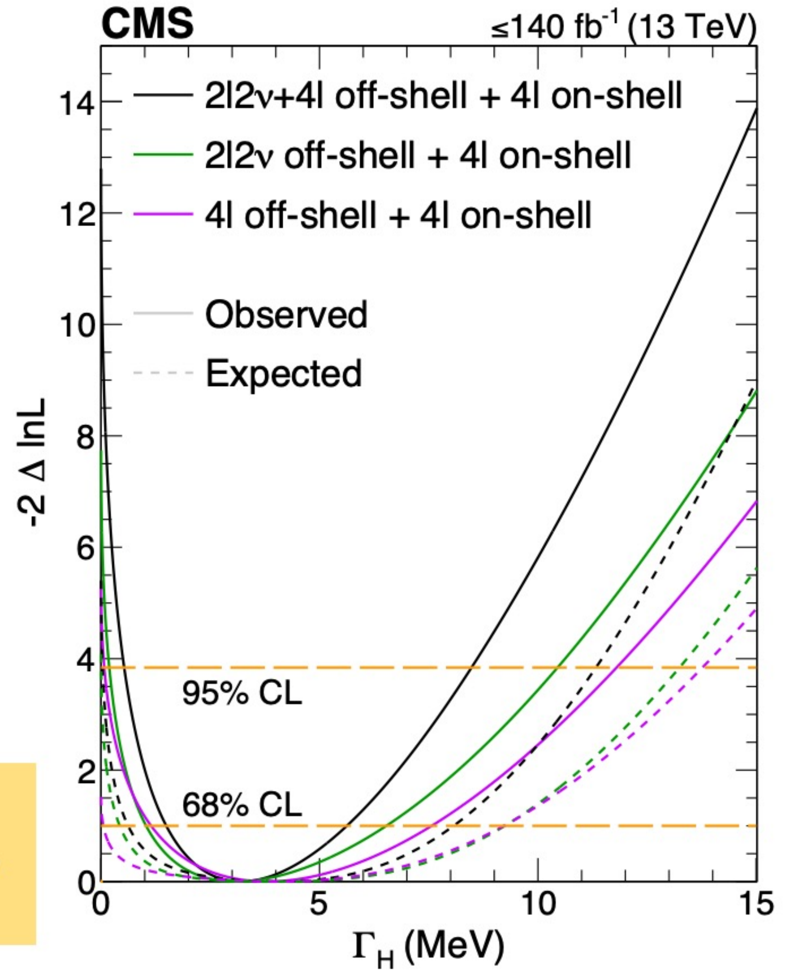
Higgs width

Measurements of the Higgs width from off-shell production

Measurements in 4l and 2l2ν final states and for different production modes (CMS: ttH, VH, VBF, ggH)

arXiv:2202.06923





Slide by M. Delmastro

140 fb^{-1} on-shell 4l
78 fb^{-1} off-shell 4l
138 fb^{-1} off-shell 2l2ν

3.6 σ evidence for off-shell H production

CMS $\Gamma_H = 3.2^{+2.5}_{-1.7}$ MeV

Higgs boson width

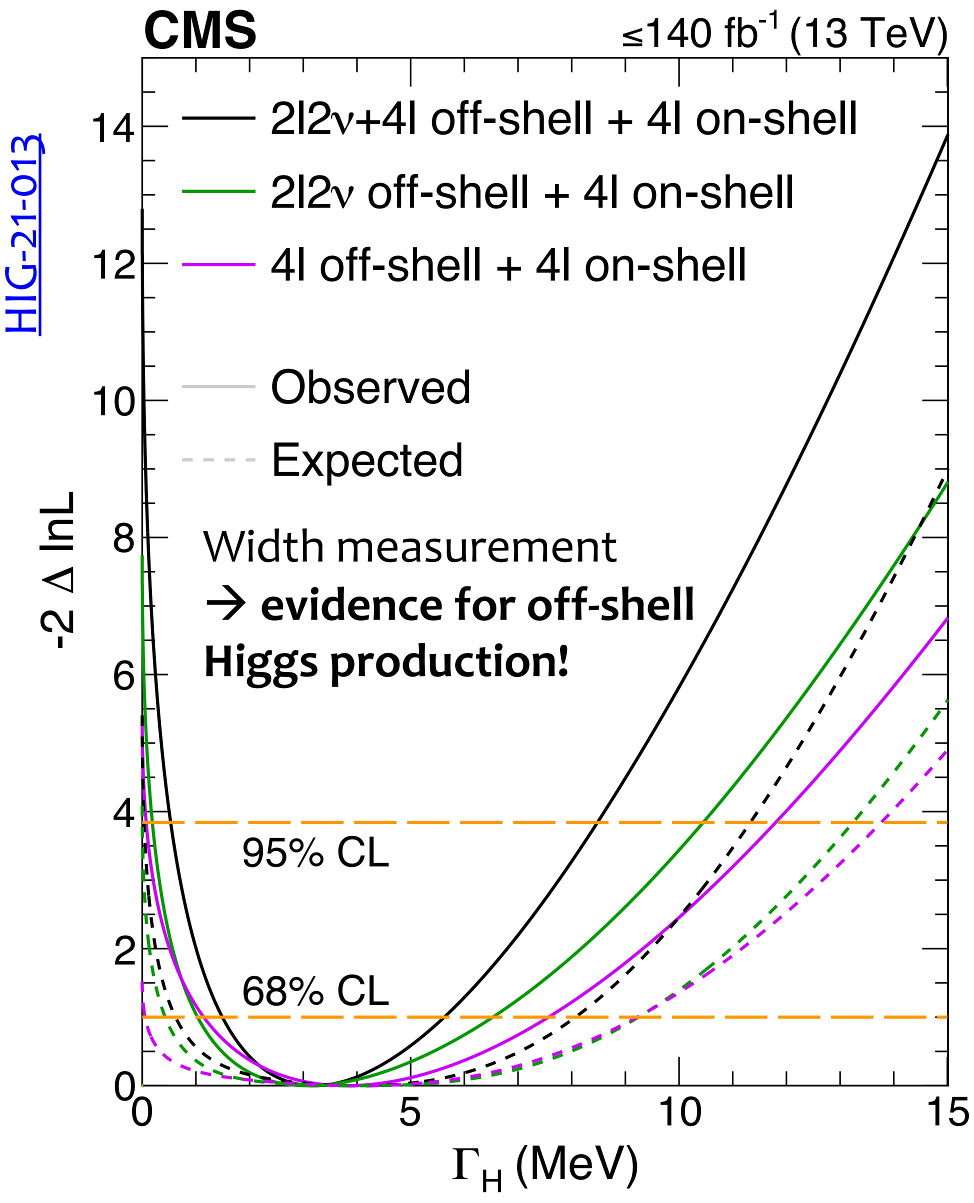
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H},$$

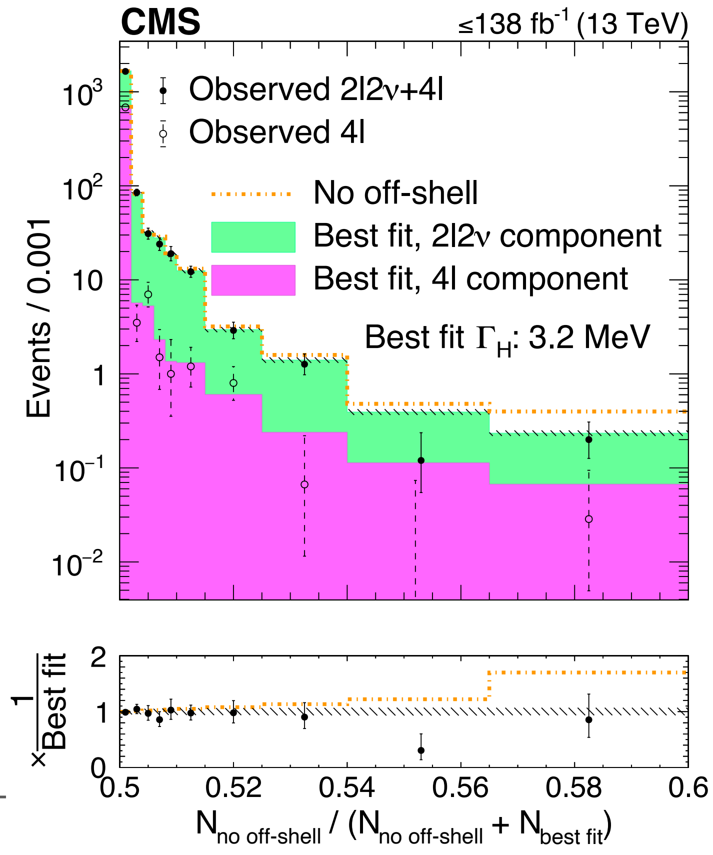
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}.$$

$m_{ZZ} \sim m_H$
(On-shell production)

$m_{ZZ} > m_{ZZ}$
(Off-shell production)

HIG-21-013

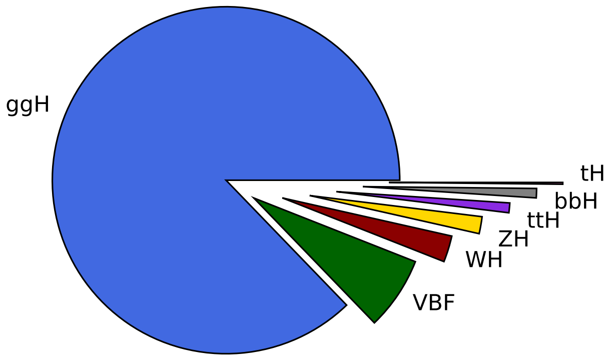


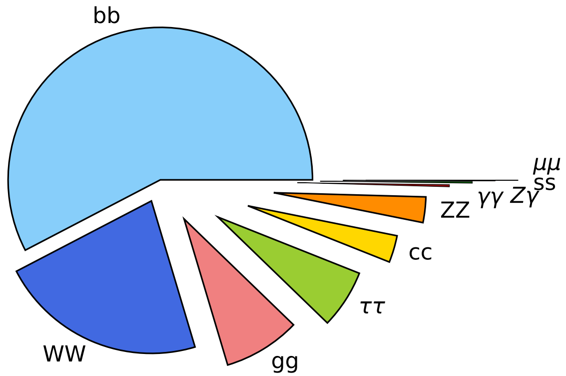


Higgs prod & decay

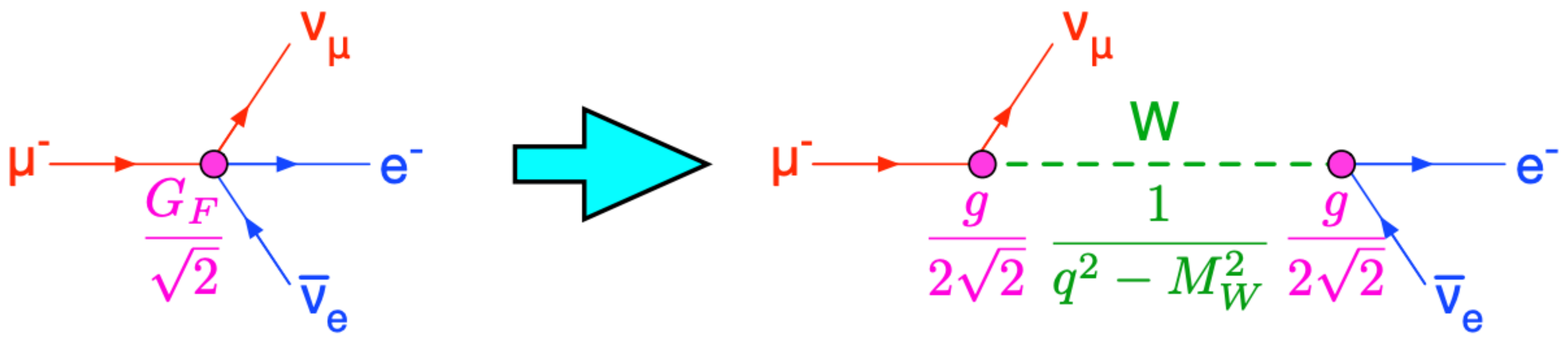
Production mode	Cross section (pb)
ggH	48.31 ± 2.44
VBF	3.771 ± 0.807
WH	1.359 ± 0.028
ZH	0.877 ± 0.036
ttH	0.503 ± 0.035
bbH	0.482 ± 0.097
tH	0.092 ± 0.008

Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
$\tau\tau$	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
$\gamma\gamma$	0.227 ± 0.005
$Z\gamma$	0.157 ± 0.009
ss	0.025 ± 0.001
$\mu\mu$	0.0216 ± 0.0004





Fermi theory & the muon decay

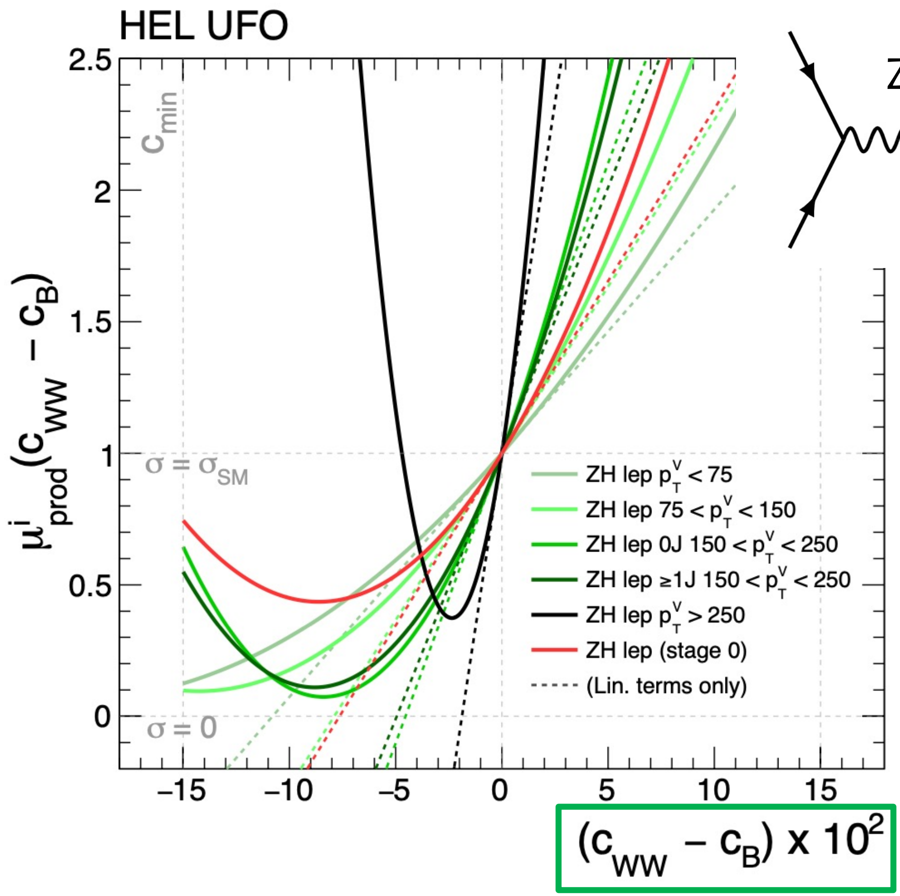


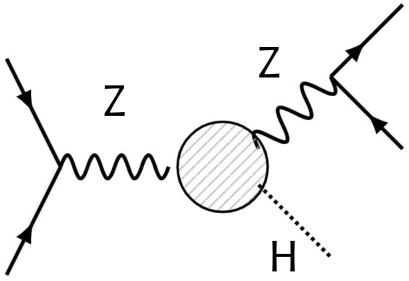
In the limit $q^2 \rightarrow 0$, fermi constant is completely determined by the Higgs vacuum expectation value ν

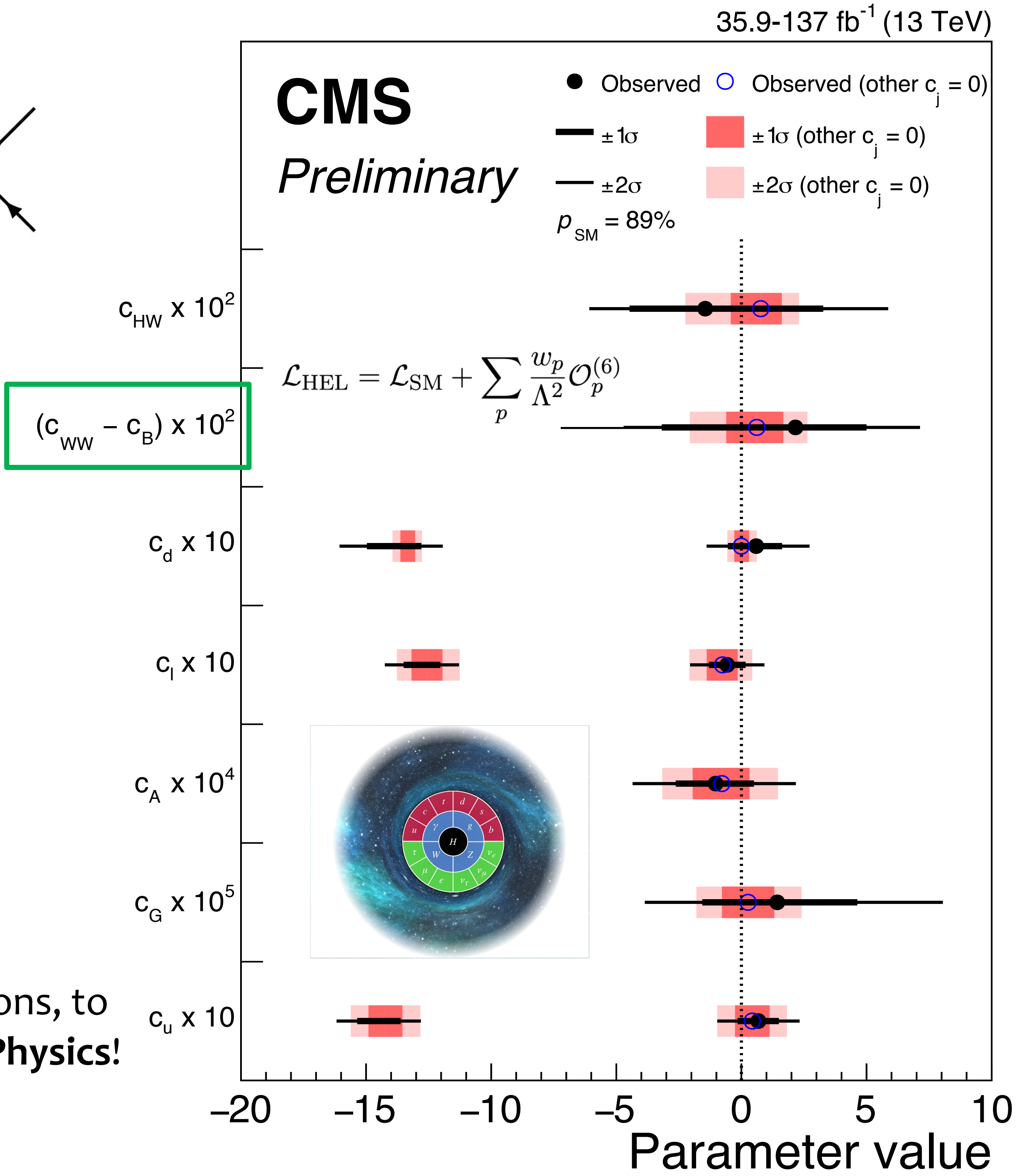
$$\frac{G_F}{\sqrt{2}} = \left[\frac{g}{2\sqrt{2}}\right]^2 \frac{1}{M_W^2} = \frac{g^2}{8M_W^2} = \frac{g^2}{8(gv/2)^2} = \frac{1}{2v^2}$$

$$\Gamma_\mu = \frac{\hbar}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} = \frac{m_\mu^5}{384\pi^3 v^4}$$

Effective field theories







EFTs allow us to coherently correlate measurements across different production & decay, from different kinematic regions, to pick out coherent BSM effcts → **guide** on the path **to New Physics**!

Table 7.6: The dimension-6 operator subset, $\{\mathcal{O}\}$, considered in the Warsaw basis parametrisation shown in Appendix I. An example Feynman diagram of the corresponding contact interaction is shown for each operator. The quantity, $\sigma^{\mu\nu}$, is defined by the gamma matrices relation: $\sigma^{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. A $U^3(5)$ flavour symmetry is assumed, such that in the diagrams, u, d and ℓ represent all up-type quarks, all down-type quarks, and all charged leptons, respectively.

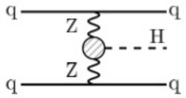
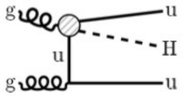
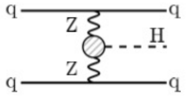
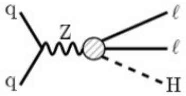
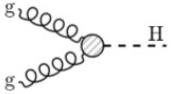
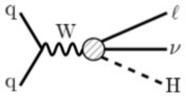
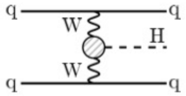
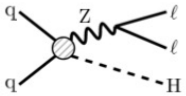
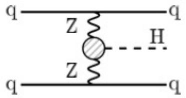
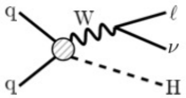
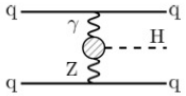
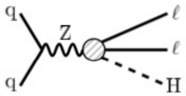
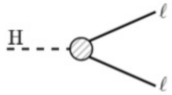
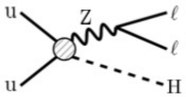
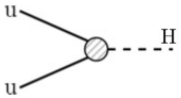
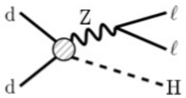
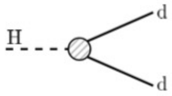
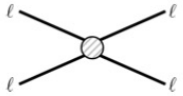
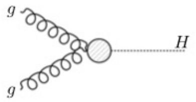
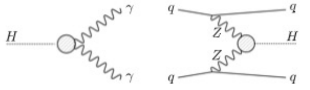
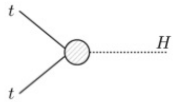
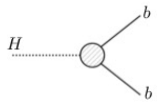
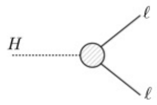
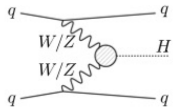
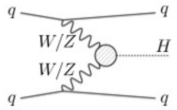
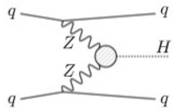
Parameter	Operator definition	Example diagram	Parameter	Operator definition	Example diagram
$C_{H\text{Box}}$	$(H^\dagger H)\Box(H^\dagger H)$		$\lvert C_{uG}\rvert$	$(\bar{Q}_L\sigma^{\mu\nu}T^a u_R)(\tilde{H}G^{a,\mu\nu})$	
C_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$		$C^{(1)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$	
C_{HG}	$(H^\dagger H)(G^a_{\mu\nu}G^{a,\mu\nu})$		$C^{(3)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{L}_L\sigma^i\gamma^\mu L_L)$	
C_{HW}	$(H^\dagger H)(W^i_{\mu\nu}W^{i,\mu\nu})$		$C^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$	
C_{HB}	$(H^\dagger H)(B_{\mu\nu}B^{\mu\nu})$		$C^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{Q}_L\sigma^i\gamma^\mu Q_L)$	
C_{HWB}	$(H^\dagger\sigma^i H)(W^i_{\mu\nu}B^{\mu\nu})$		C_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}_R\gamma^\mu\ell_R)$	
$\lvert C_{eH}\rvert$	$(H^\dagger H)(\bar{L}_L\ell_R H)$		C_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	
$\lvert C_{uH}\rvert$	$(H^\dagger H)(\bar{Q}_L u_R\tilde{H})$		C_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	
$\lvert C_{dH}\rvert$	$(H^\dagger H)(\bar{Q}_L d_R H)$		$C^{(1)}_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	

Table 7.1: The dimension-6 operator subset, $\{\mathcal{O}\}$, considered in the HEL interpretation. The definition of each operator is provided in terms of the SM field tensors. In addition, the corresponding HEL parameter is defined in terms of the nominal EFT Wilson coefficients. The final two columns show the affected Higgs boson interaction vertices and an example Feynman diagram of the EFT interaction.

Operator	Definition	HEL Parameter	Relevant vertices	Example diagrams
$\mathcal{O}_G$	$\lvert H\rvert^2 G^a_{\mu\nu}G^{a,\mu\nu}$	$c_G = \frac{m_W^2}{g_s^2}\frac{w_G}{\Lambda^2}$	Hgg	
$\mathcal{O}_A$	$\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$c_A = \frac{m_W^2}{g'^2}\frac{w_A}{\Lambda^2}$	H$\gamma\gamma$, HZZ	
$\mathcal{O}_u$	$\lambda_u\lvert H\rvert^2\bar{Q}_L H^\dagger u_R + \text{h.c.}$	$c_u = -v^2\frac{w_u}{\Lambda^2}$	Htt	
$\mathcal{O}_d$	$\lambda_d\lvert H\rvert^2\bar{Q}_L H^\dagger d_R + \text{h.c.}$	$c_d = -v^2\frac{w_d}{\Lambda^2}$	Hbb	
$\mathcal{O}_\ell$	$\lambda_\ell\lvert H\rvert^2\bar{L}_L H^\dagger \ell_R + \text{h.c.}$	$c_\ell = -v^2\frac{w_\ell}{\Lambda^2}$	H$\tau\tau$	
$\mathcal{O}_{HW}$	$i(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$c_{HW} = \frac{m_W^2}{2g}\frac{w_{HW}}{\Lambda^2}$	HWW, HZZ	
$\mathcal{O}_{WW}$	$i(H^\dagger\sigma^a D^\mu H)D^\nu W^a_{\mu\nu}$	$c_{WW} = \frac{m_W^2}{g}\frac{w_{WW}}{\Lambda^2}$	HWW, HZZ	
$\mathcal{O}_B$	$i(H^\dagger D^\mu H)\partial^\nu B_{\mu\nu}$	$c_{WW} = \frac{2m_W^2}{g'}\frac{w_B}{\Lambda^2}$	HZZ	

Inputs to the combination

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]	$e\mu/ee/\mu\mu$	ggH $\leq$ 2-jets
		VBF
	$\mu\mu$+jj/ee+jj/$e\mu$+jj	VH hadronic
	3ℓ	WH leptonic
	4ℓ	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]	$W(\ell\nu)H(bb)$	WH leptonic
	$Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$	ZH leptonic
	bb	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
Higgs boson pair production		
$HH \to bbbb$ [57, 58]	H(bb)H(bb)	ggHH, VBFHH (resolved, boosted)
$HH \to bb\tau\tau$ [59]	$H(bb)H(\tau\tau)$	ggHH, VBFHH
$HH \to$ leptons [60]	$H(WW)H(WW)$, $H(WW)H(\tau\tau)$, $H(\tau\tau)H(\tau\tau)$	ggHH, VBFHH
$HH \to bb\gamma\gamma$ [61]	$H(bb)H(\gamma\gamma)$	ggHH, VBFHH
$HH \to bbZZ$ [62]	H(bb)H(ZZ)	ggHH

Differential combination(s)

<table>
<tr><th>Channel</th><th>$H \to \gamma\gamma$</th><th>$H \to ZZ^{(*)} \to 4\ell$</th><th>$H \to W^+W^{-(*)} \to e^{\pm}\mu^{\mp}\nu_1\bar{\nu}_1$</th><th>$H \to \tau^+\tau^-$</th><th>$H \to \tau^+\tau^-$ boosted</th></tr>
<tr><td rowspan="20">p_T^H bin boundaries (GeV)</td><td>0 - 5</td><td rowspan="2">0 - 10</td><td rowspan="6">0 - 30</td><td rowspan="8">0 - 45</td><td rowspan="18"></td></tr>
<tr><td>5 - 10</td></tr>
<tr><td>10 - 15</td><td rowspan="2">10 - 20</td></tr>
<tr><td>15 - 20</td></tr>
<tr><td>20 - 25</td><td rowspan="2">20 - 30</td></tr>
<tr><td>25 - 30</td></tr>
<tr><td>30 - 35</td><td rowspan="2">30 - 45</td><td rowspan="2">30 - 45</td></tr>
<tr><td>35 - 45</td></tr>
<tr><td>45 - 60</td><td>45- 60</td><td rowspan="2">45 - 80</td><td rowspan="2">45 - 80</td></tr>
<tr><td>60 - 80</td><td>60 - 80</td></tr>
<tr><td>80 - 100</td><td rowspan="2">80 - 120</td><td rowspan="2">80 - 120</td><td rowspan="2">80 - 120</td></tr>
<tr><td>100 - 120</td></tr>
<tr><td>120 - 140</td><td rowspan="3">120 - 200</td><td rowspan="3">120 - 200</td><td>120 - 140</td></tr>
<tr><td>140 - 170</td><td>140 - 170</td></tr>
<tr><td>170 - 200</td><td>170 - 200</td></tr>
<tr><td>200 - 250</td><td rowspan="5">200 - ∞</td><td rowspan="5">200 - ∞</td><td rowspan="2">200 - 350</td></tr>
<tr><td>250 - 350</td></tr>
<tr><td>350 - 450</td><td>350 - 450</td></tr>
<tr><td rowspan="2">450 - ∞</td><td rowspan="2">450 - ∞</td><td>450 - 600</td></tr>
<tr><td>600 - ∞</td></tr>
</table>

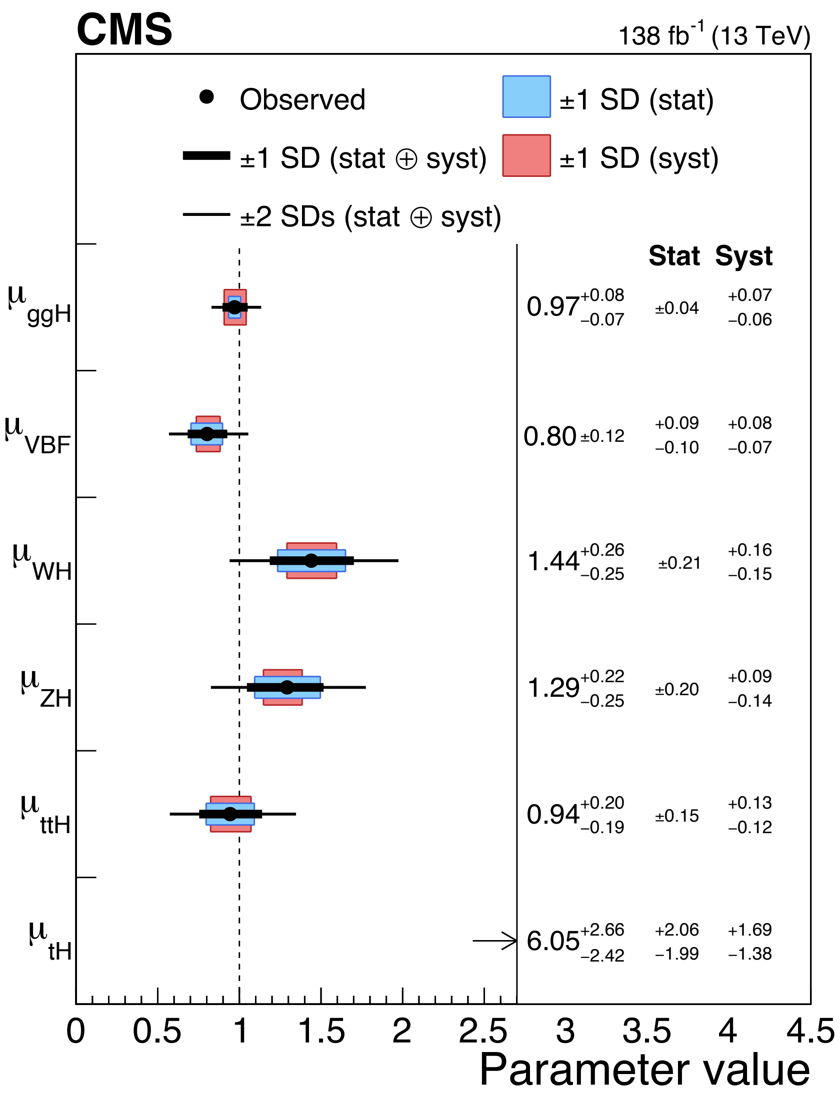
Table 1: p_T^H bin boundaries used in the combination.

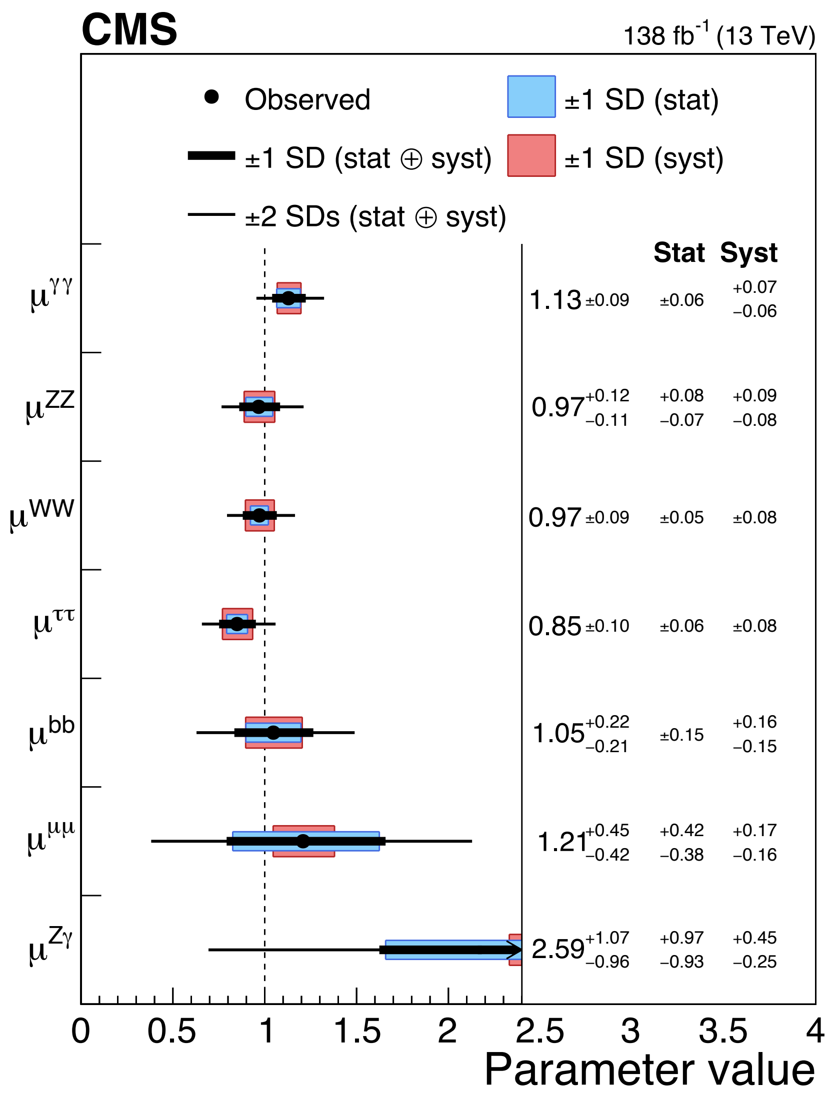
Signal strengths (stat/syst)

Decay mode	ggH				VBF				WH				ZH				ttH			
	Best fit value	Uncertainty			Best fit value	Uncertainty			Best fit value	Uncertainty			Best fit value	Uncertainty			Best fit value	Uncertainty		
			stat	syst			stat	syst			stat	syst			stat	syst			stat	syst
$H \to bb$	5.31	$^{+2.97}_{-2.54}$	$^{+2.09}_{-2.09}$	$^{+2.11}_{-1.45}$	–				1.26	$^{+0.42}_{-0.41}$	$^{+0.33}_{-0.32}$	$^{+0.26}_{-0.26}$	0.90	$^{+0.36}_{-0.34}$	$^{+0.27}_{-0.26}$	$^{+0.25}_{-0.21}$	0.90	$^{+0.46}_{-0.44}$	$^{+0.24}_{-0.24}$	$^{+0.40}_{-0.37}$
		$\left(^{+2.52}_{-2.47}\right)$	$\left(^{+2.09}_{-2.09}\right)$	$\left(^{+1.41}_{-1.31}\right)$	–					$\left(^{+0.43}_{-0.41}\right)$	$\left(^{+0.33}_{-0.32}\right)$	$\left(^{+0.27}_{-0.26}\right)$		$\left(^{+0.32}_{-0.31}\right)$	$\left(^{+0.26}_{-0.26}\right)$	$\left(^{+0.18}_{-0.17}\right)$		$\left(^{+0.47}_{-0.44}\right)$	$\left(^{+0.24}_{-0.24}\right)$	$\left(^{+0.40}_{-0.37}\right)$
$H \to \tau\tau$	0.66	$^{+0.21}_{-0.21}$	$^{+0.09}_{-0.09}$	$^{+0.19}_{-0.18}$	0.86	$^{+0.17}_{-0.16}$	$^{+0.14}_{-0.14}$	$^{+0.09}_{-0.09}$	1.33	$^{+0.61}_{-0.57}$	$^{+0.51}_{-0.49}$	$^{+0.34}_{-0.29}$	1.89	$^{+0.65}_{-0.56}$	$^{+0.54}_{-0.51}$	$^{+0.36}_{-0.25}$	0.35	$^{+0.44}_{-0.37}$	$^{+0.30}_{-0.28}$	$^{+0.32}_{-0.23}$
		$\left(^{+0.25}_{-0.23}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.24}_{-0.21}\right)$		$\left(^{+0.18}_{-0.17}\right)$	$\left(^{+0.14}_{-0.14}\right)$	$\left(^{+0.10}_{-0.09}\right)$		$\left(^{+0.59}_{-0.56}\right)$	$\left(^{+0.50}_{-0.48}\right)$	$\left(^{+0.31}_{-0.28}\right)$		$\left(^{+0.54}_{-0.46}\right)$	$\left(^{+0.48}_{-0.44}\right)$	$\left(^{+0.24}_{-0.14}\right)$		$\left(^{+0.49}_{-0.43}\right)$	$\left(^{+0.32}_{-0.31}\right)$	$\left(^{+0.38}_{-0.30}\right)$
$H \to WW$	0.90	$^{+0.11}_{-0.10}$	$^{+0.05}_{-0.05}$	$^{+0.09}_{-0.09}$	0.73	$^{+0.28}_{-0.24}$	$^{+0.20}_{-0.19}$	$^{+0.19}_{-0.15}$	2.41	$^{+0.72}_{-0.70}$	$^{+0.52}_{-0.51}$	$^{+0.50}_{-0.48}$	1.76	$^{+0.75}_{-0.67}$	$^{+0.66}_{-0.62}$	$^{+0.36}_{-0.27}$	1.44	$^{+0.32}_{-0.32}$	$^{+0.29}_{-0.29}$	$^{+0.14}_{-0.13}$
		$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.06}_{-0.06}\right)$	$\left(^{+0.10}_{-0.09}\right)$		$\left(^{+0.30}_{-0.27}\right)$	$\left(^{+0.22}_{-0.21}\right)$	$\left(^{+0.21}_{-0.17}\right)$		$\left(^{+0.60}_{-0.57}\right)$	$\left(^{+0.46}_{-0.45}\right)$	$\left(^{+0.37}_{-0.34}\right)$		$\left(^{+0.65}_{-0.52}\right)$	$\left(^{+0.60}_{-0.49}\right)$	$\left(^{+0.25}_{-0.17}\right)$		$\left(^{+0.32}_{-0.31}\right)$	$\left(^{+0.29}_{-0.28}\right)$	$\left(^{+0.13}_{-0.13}\right)$
$H \to ZZ$	0.93	$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.10}$	$^{+0.11}_{-0.09}$	0.32	$^{+0.48}_{-0.32}$	$^{+0.44}_{-0.32}$	$^{+0.18}_{-0.01}$	0.00	$^{+1.55}_{+0.00}$	$^{+1.50}_{-0.00}$	$^{+0.40}_{-0.00}$	12.24	$^{+6.59}_{-5.69}$	$^{+4.40}_{-4.13}$	$^{+4.91}_{-3.91}$	0.00	$^{+0.73}_{+0.00}$	$^{+0.68}_{-0.00}$	$^{+0.27}_{-0.00}$
		$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.09}_{-0.09}\right)$	$\left(^{+0.11}_{-0.09}\right)$		$\left(^{+0.54}_{-0.44}\right)$	$\left(^{+0.52}_{-0.42}\right)$	$\left(^{+0.15}_{-0.12}\right)$		$\left(^{+2.01}_{-0.96}\right)$	$\left(^{+1.94}_{-0.96}\right)$	$\left(^{+0.53}_{-0.08}\right)$		$\left(^{+4.55}_{-1.17}\right)$	$\left(^{+3.77}_{-1.17}\right)$	$\left(^{+2.54}_{-0.02}\right)$		$\left(^{+1.44}_{-0.71}\right)$	$\left(^{+1.39}_{-0.71}\right)$	$\left(^{+0.38}_{-0.06}\right)$
$H \to \gamma\gamma$	1.08	$^{+0.12}_{-0.11}$	$^{+0.09}_{-0.09}$	$^{+0.08}_{-0.07}$	1.00	$^{+0.35}_{-0.32}$	$^{+0.32}_{-0.29}$	$^{+0.15}_{-0.11}$	1.43	$^{+0.54}_{-0.47}$	$^{+0.53}_{-0.47}$	$^{+0.09}_{-0.05}$	1.19	$^{+0.71}_{-0.62}$	$^{+0.70}_{-0.61}$	$^{+0.14}_{-0.07}$	1.38	$^{+0.34}_{-0.29}$	$^{+0.28}_{-0.26}$	$^{+0.19}_{-0.12}$
		$\left(^{+0.11}_{-0.11}\right)$	$\left(^{+0.08}_{-0.08}\right)$	$\left(^{+0.08}_{-0.06}\right)$		$\left(^{+0.34}_{-0.31}\right)$	$\left(^{+0.30}_{-0.29}\right)$	$\left(^{+0.17}_{-0.12}\right)$		$\left(^{+0.52}_{-0.47}\right)$	$\left(^{+0.51}_{-0.47}\right)$	$\left(^{+0.08}_{-0.05}\right)$		$\left(^{+0.71}_{-0.60}\right)$	$\left(^{+0.69}_{-0.59}\right)$	$\left(^{+0.14}_{-0.06}\right)$		$\left(^{+0.29}_{-0.25}\right)$	$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.14}_{-0.08}\right)$
$H \to \mu\mu$	0.33	$^{+0.74}_{-0.70}$	$^{+0.71}_{-0.69}$	$^{+0.20}_{-0.12}$	1.55	$^{+0.86}_{-0.73}$	$^{+0.75}_{-0.69}$	$^{+0.40}_{-0.24}$			5.63	$^{+3.36}_{-3.04}$	$^{+3.28}_{-3.01}$	$^{+0.71}_{-0.45}$			3.07	$^{+2.63}_{-2.21}$	$^{+2.50}_{-2.20}$	$^{+0.81}_{-0.19}$
		$\left(^{+0.76}_{-0.73}\right)$	$\left(^{+0.75}_{-0.72}\right)$	$\left(^{+0.16}_{-0.07}\right)$		$\left(^{+0.81}_{-0.70}\right)$	$\left(^{+0.73}_{-0.66}\right)$	$\left(^{+0.36}_{-0.23}\right)$				$\left(^{+2.75}_{-2.44}\right)$	$\left(^{+2.73}_{-2.43}\right)$	$\left(^{+0.33}_{-0.19}\right)$				$\left(^{+2.17}_{-1.82}\right)$	$\left(^{+2.15}_{-1.82}\right)$	$\left(^{+0.27}_{-0.11}\right)$
$H \to Z\gamma$	3.86	$^{+1.39}_{-1.23}$	$^{+1.26}_{-1.18}$	$^{+0.60}_{-0.36}$	−4.43	$^{+3.82}_{-2.89}$	$^{+3.77}_{-2.68}$	$^{+0.60}_{-1.08}$	–				–				–			
		$\left(^{+1.23}_{-1.20}\right)$	$\left(^{+1.20}_{-1.18}\right)$	$\left(^{+0.30}_{-0.19}\right)$		$\left(^{+3.31}_{-3.88}\right)$	$\left(^{+3.19}_{-3.85}\right)$	$\left(^{+0.92}_{-0.43}\right)$	–				–				–			

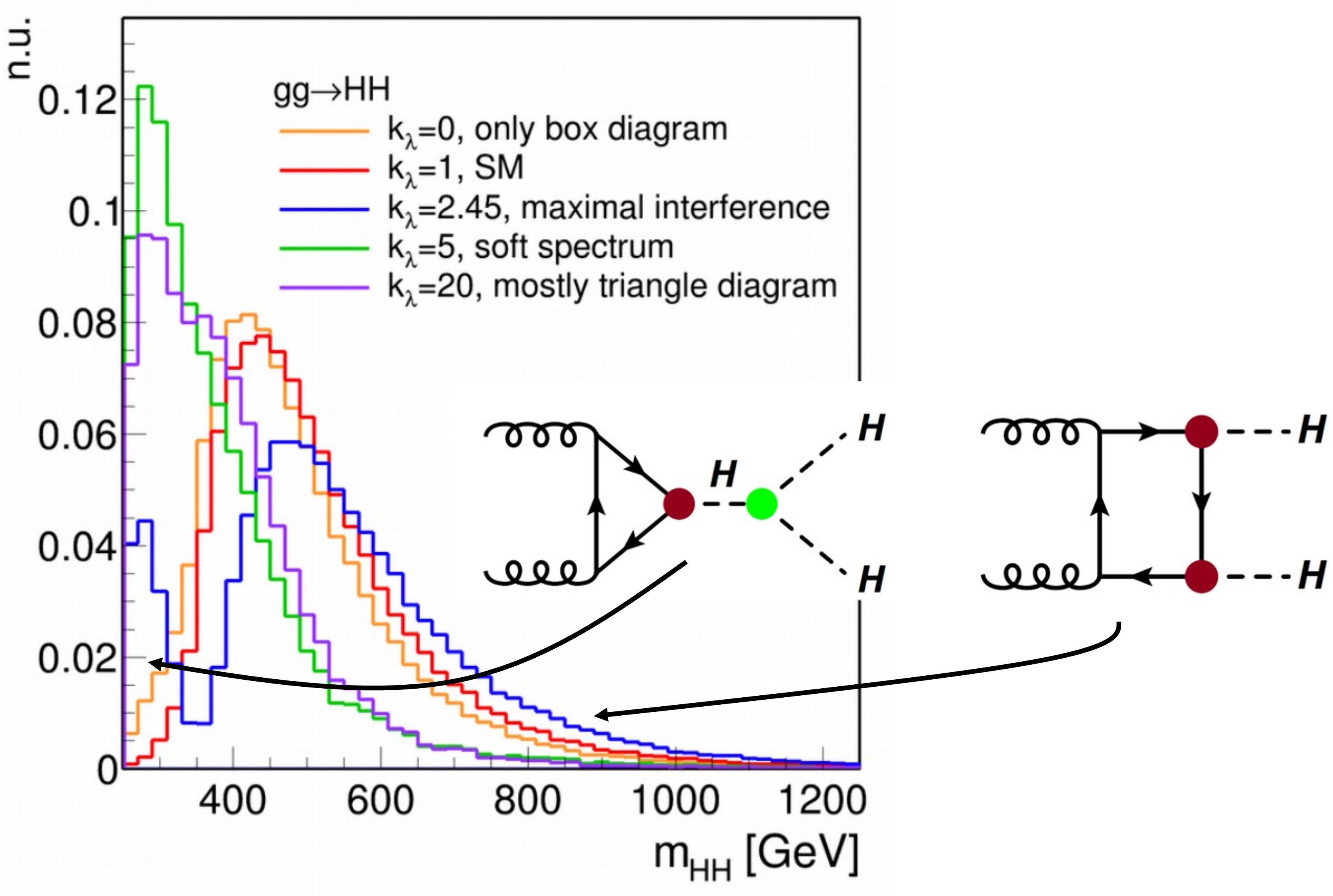
Extracting the results

Systematic uncertainties dominate the sensitivity in certain measurements

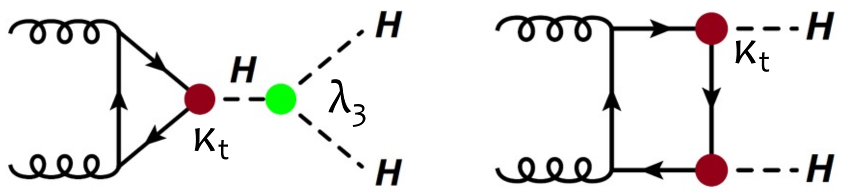


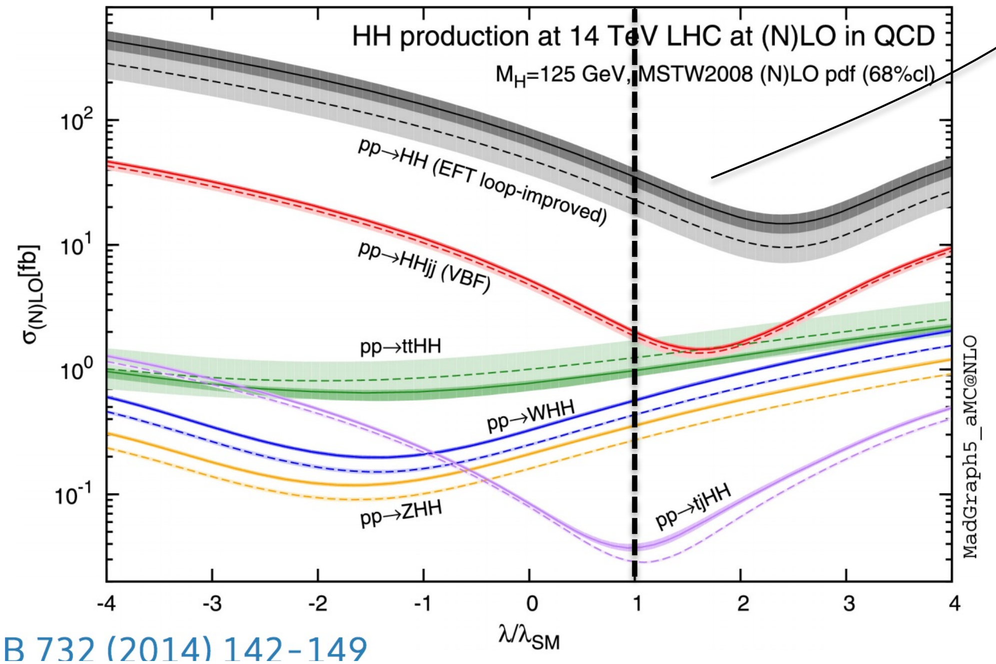


Sensitivity to self-coupling in HH



Double Higgs double challenge!





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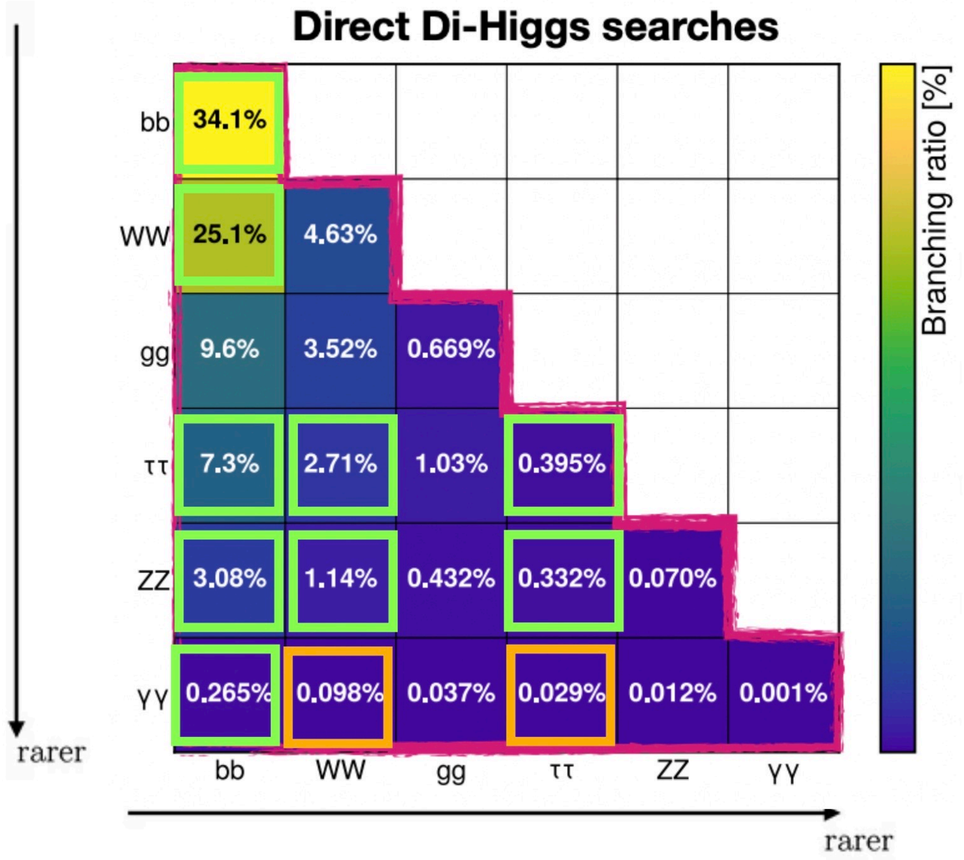
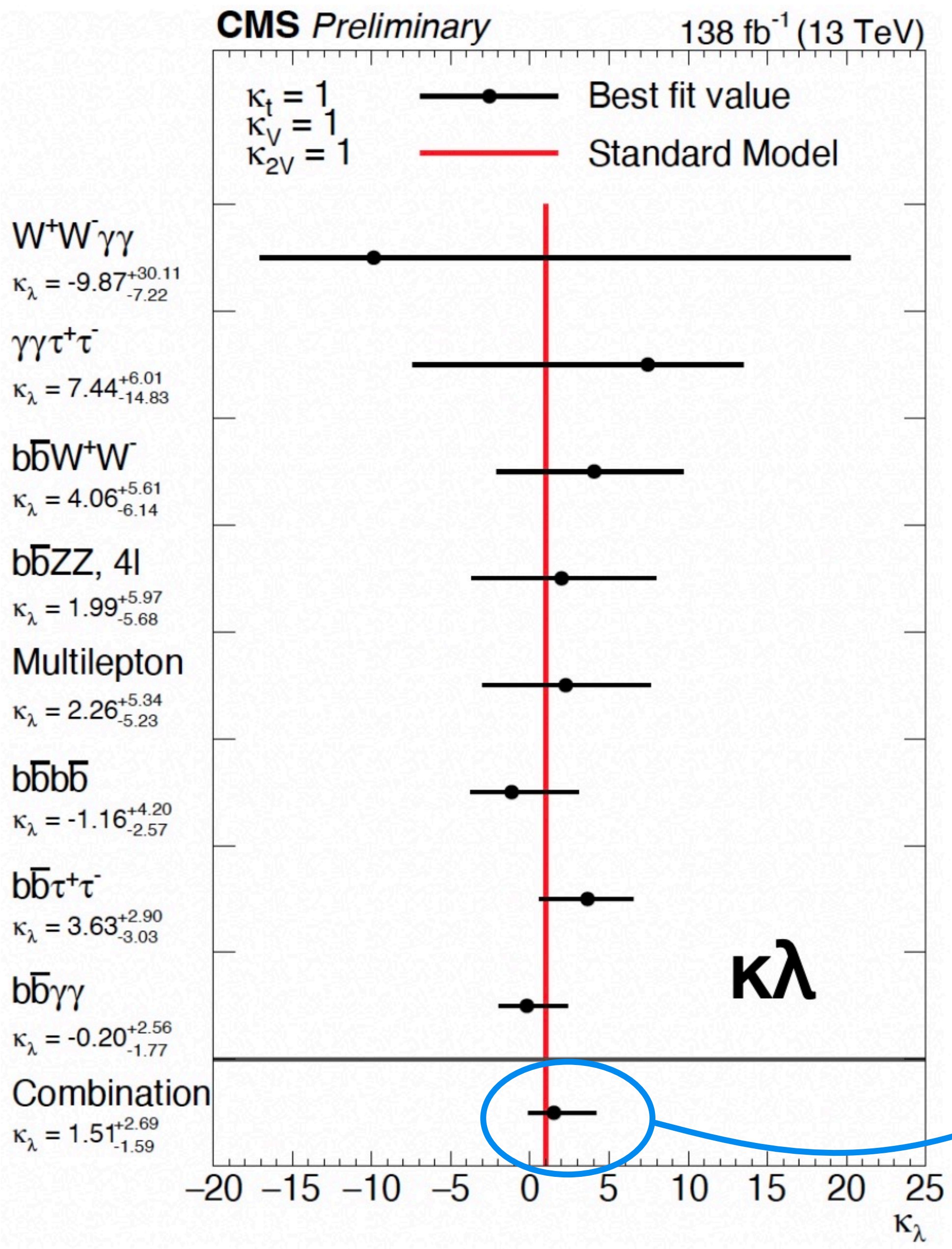
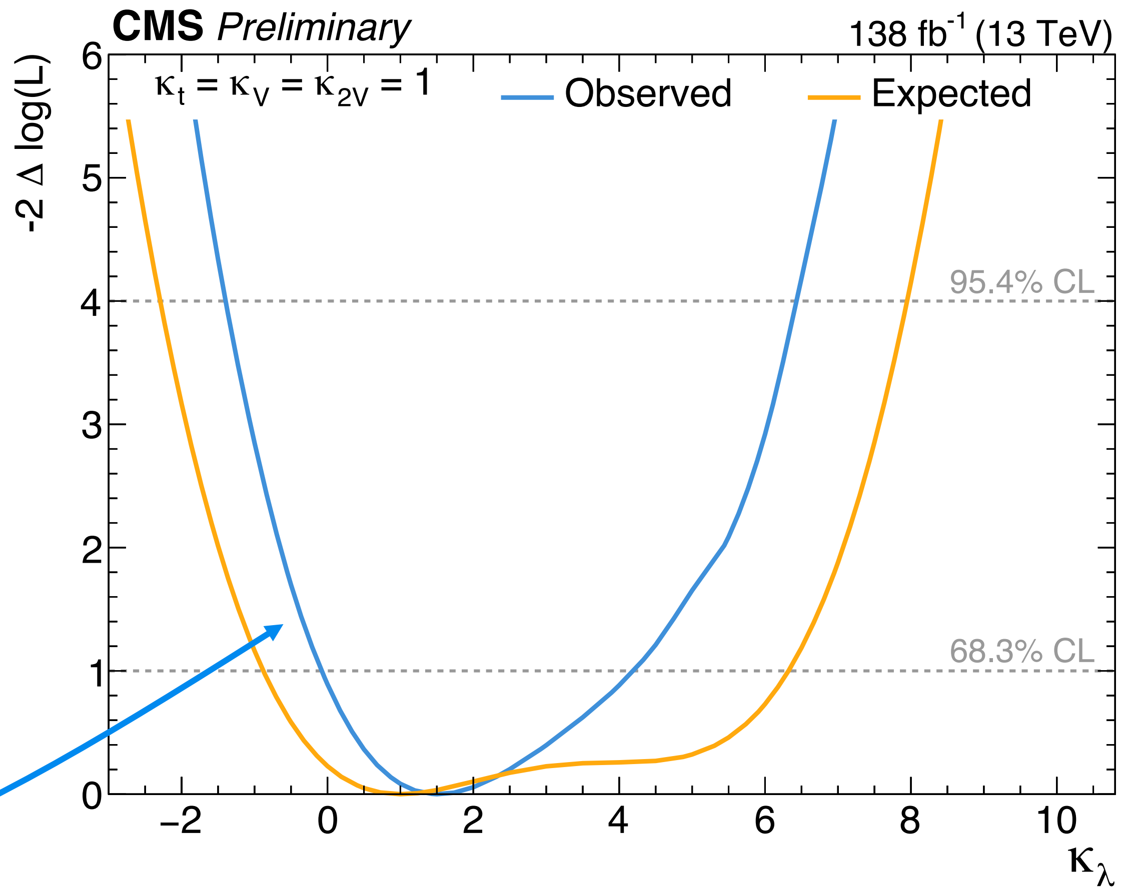
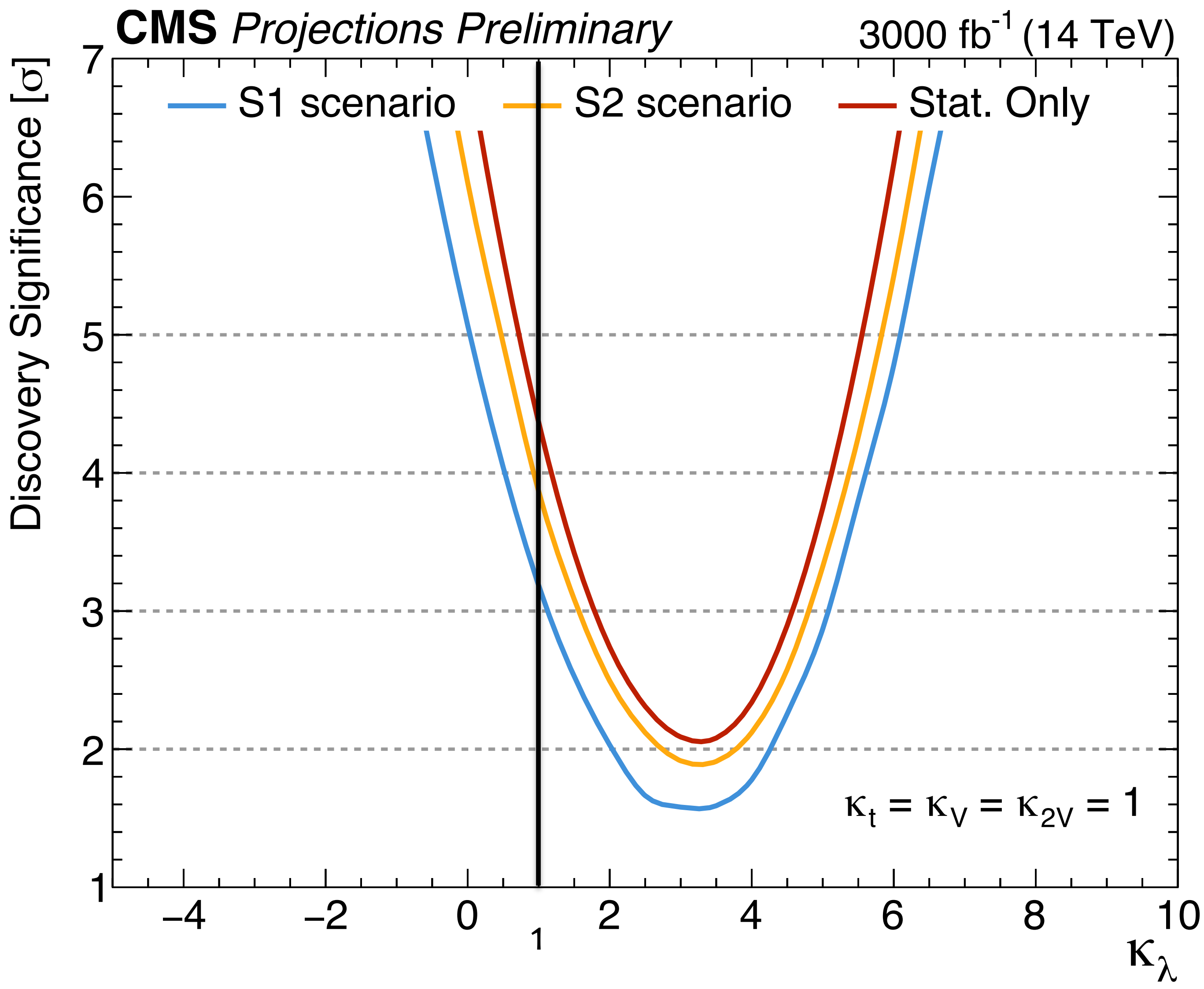


Per-channel self-coupling measurements





Non-SM HH discovery potential



Simple D6 term in Higgs potential

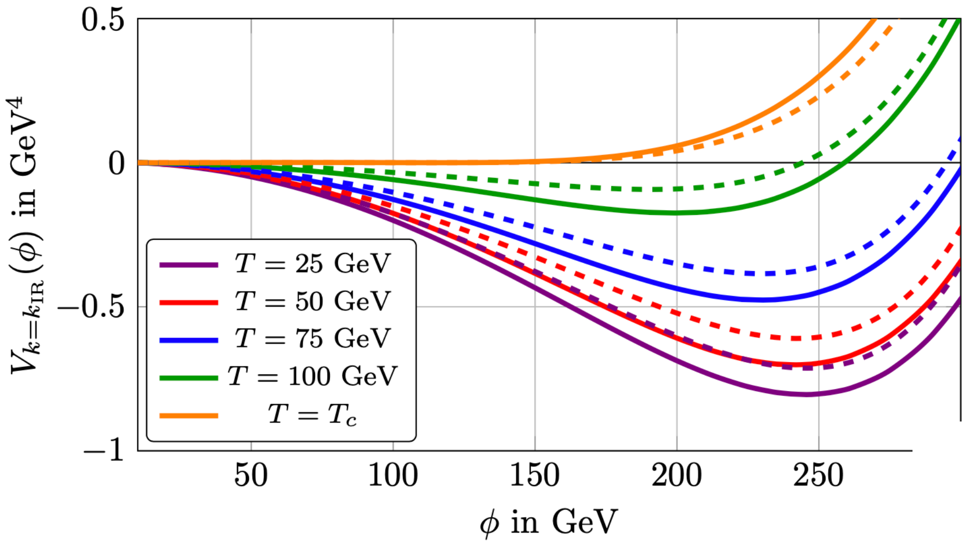
$$V = \frac{\mu^2}{2}(v+H)^2 + \frac{\lambda_4}{4}(v+H)^4 + \frac{\lambda_6}{\Lambda^2}(v+H)^6 .$$

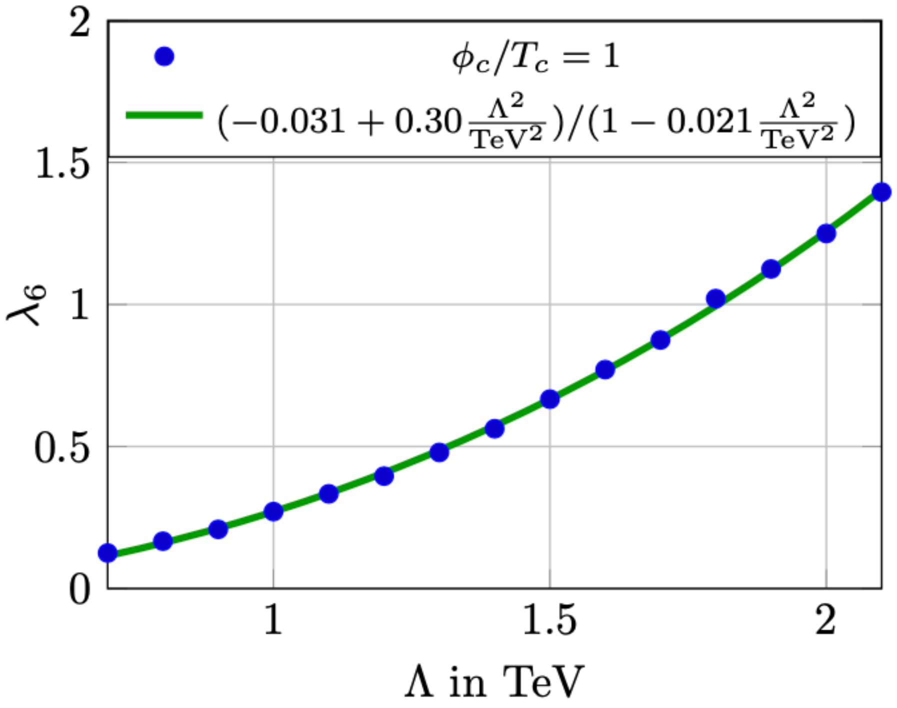
$$m_H = \sqrt{2\lambda_4}\, v \left(1 + 12\frac{\lambda_6 v^2}{\lambda_4 \Lambda^2}\right) ,$$

$$\lambda_{H^3} = \frac{3m_H^2}{v}\left(1 + \frac{16\lambda_6 v^4}{m_H^2 \Lambda^2}\right) \equiv \lambda_{H^3,0}\left(1 + \frac{16\lambda_6 v^4}{m_H^2 \Lambda^2}\right) ,$$

$$\lambda_{H^4} = \frac{3m_H^2}{v^2}\left(1 + \frac{96\lambda_6 v^4}{m_H^2 \Lambda^2}\right) \equiv \lambda_{H^4,0}\left(1 + \frac{96\lambda_6 v^4}{m_H^2 \Lambda^2}\right) .$$

Temperature dependence





For D6, above 7TeV we end up with strong couplings (perturbativity breaks down)

$$\Lambda_6^{\rm crit} = 7.0\,\mathrm{TeV},$$

MSSM SM-like couplings

	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

$$s_u = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{(m_Z^2+m_A^2\tan^2\beta-m_H^2(1+\tan^2\beta))^2}}}$$

$$s_d = s_u\frac{(m_A^2+m_Z^2)\tan\beta}{m_Z^2+m_A^2\tan^2\beta-m_H^2(1+\tan^2\beta)}$$

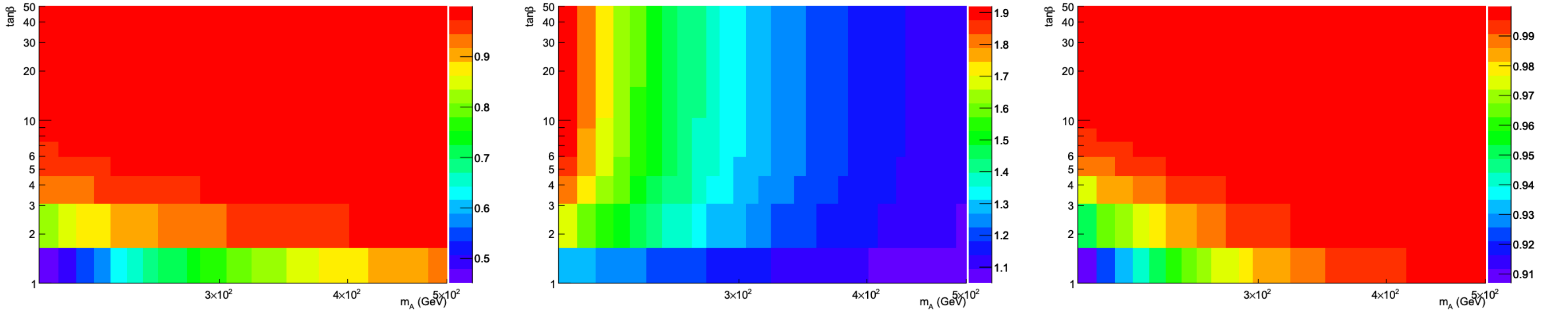
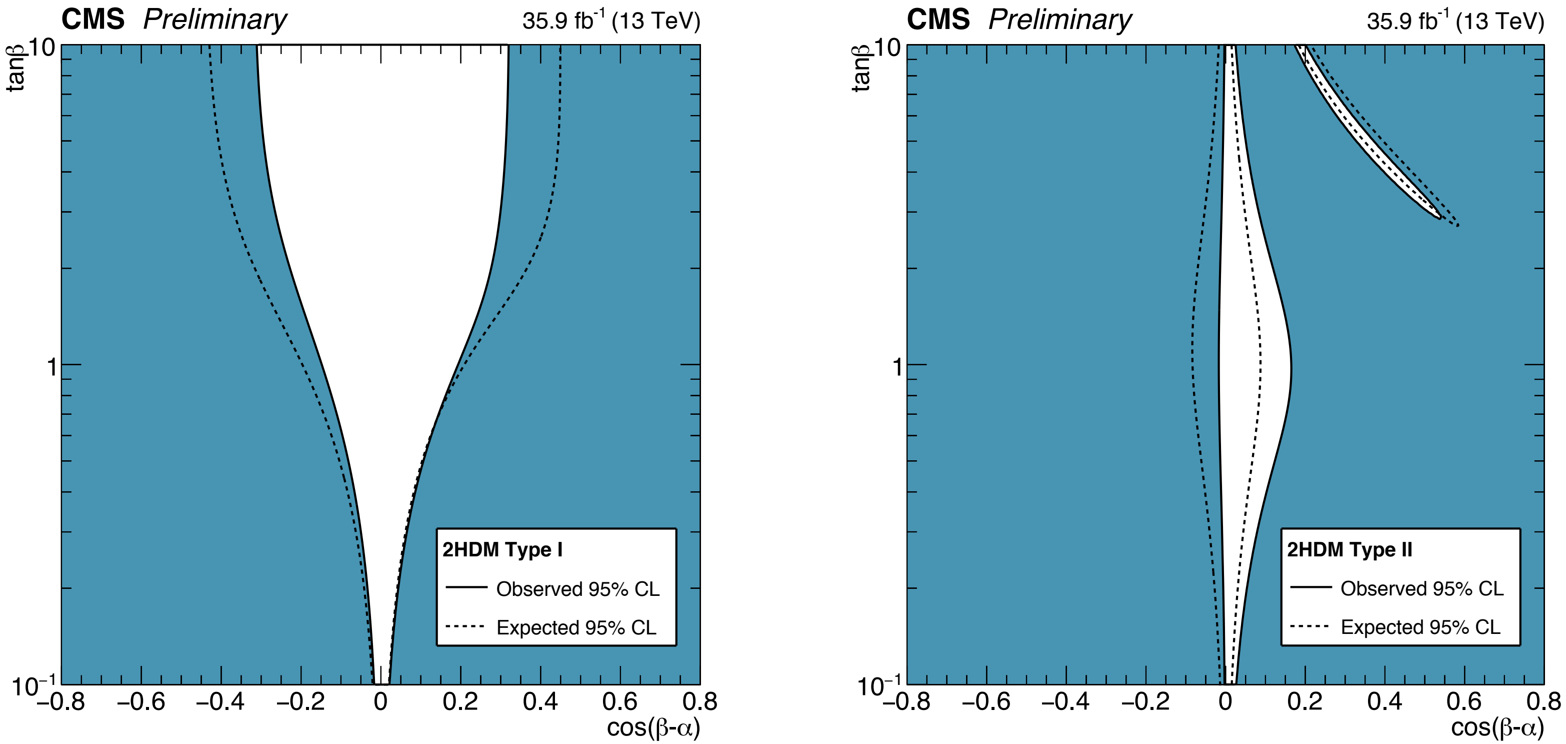


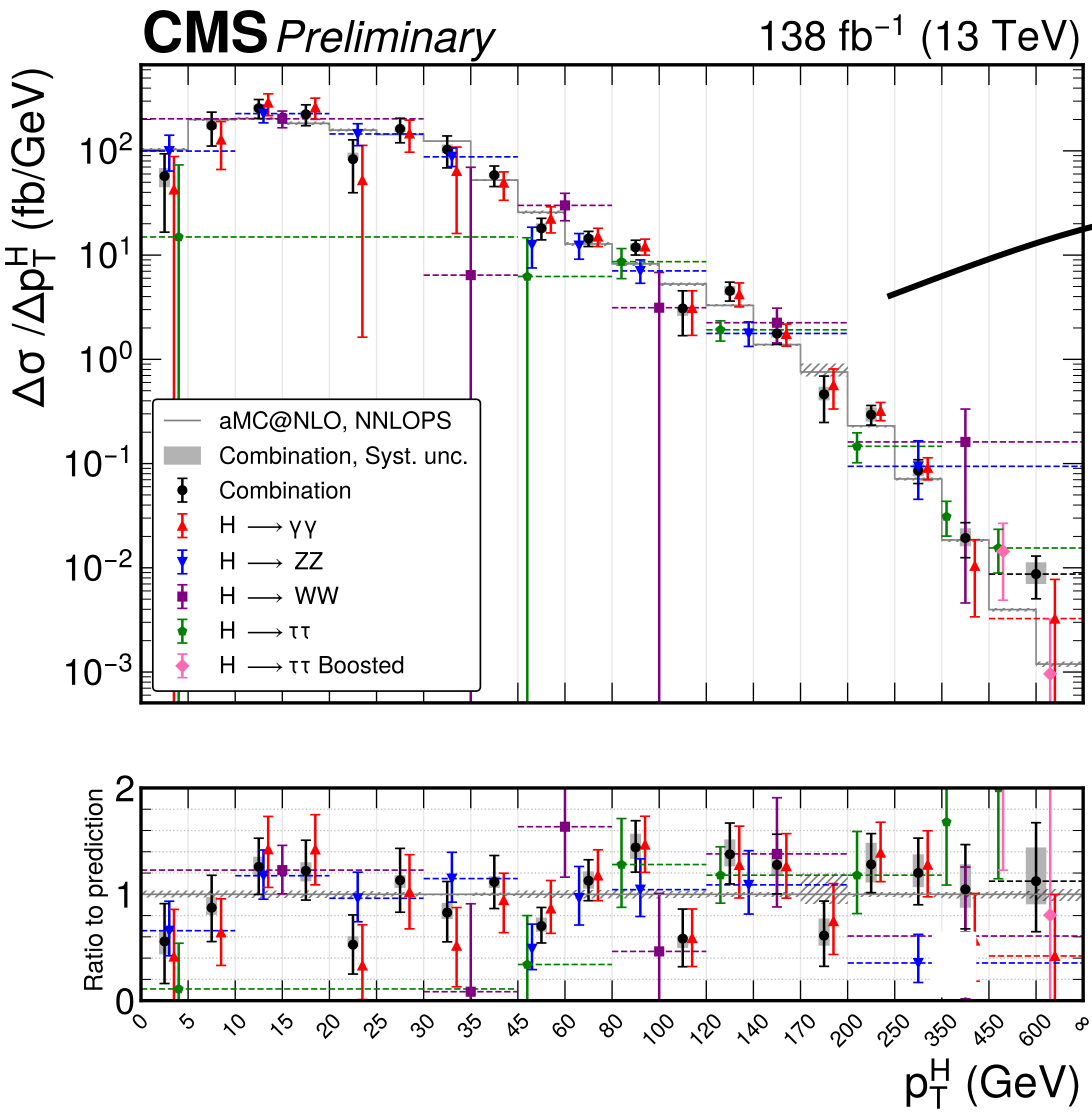
Figure 6: Scan of coupling modifiers κ_u (left), κ_d (centre) and κ_V (right) as a function of the MSSM parameters m_A and $\tan(\beta)$.

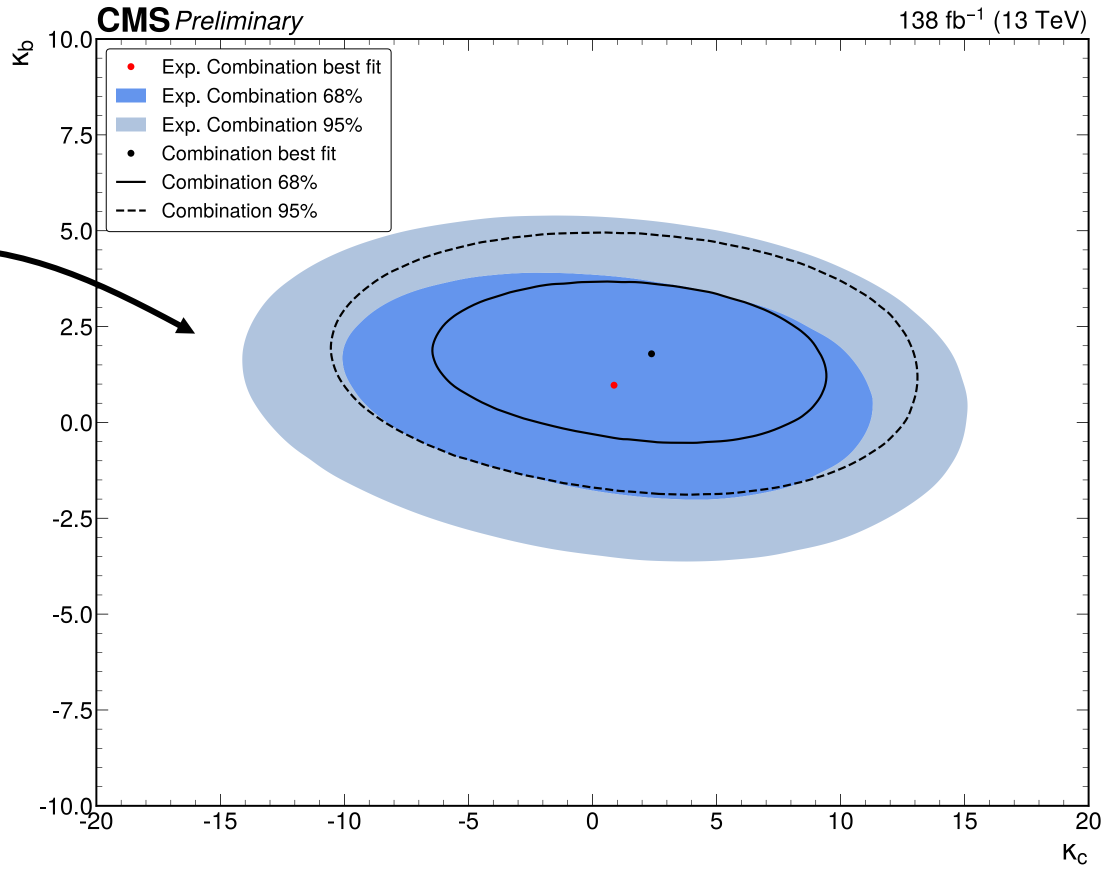
2HDM SM-like couplings

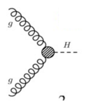
	2HDM				hMSSM
	Type I	Type II	Type III	Type IV	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$



Differential results for couplings



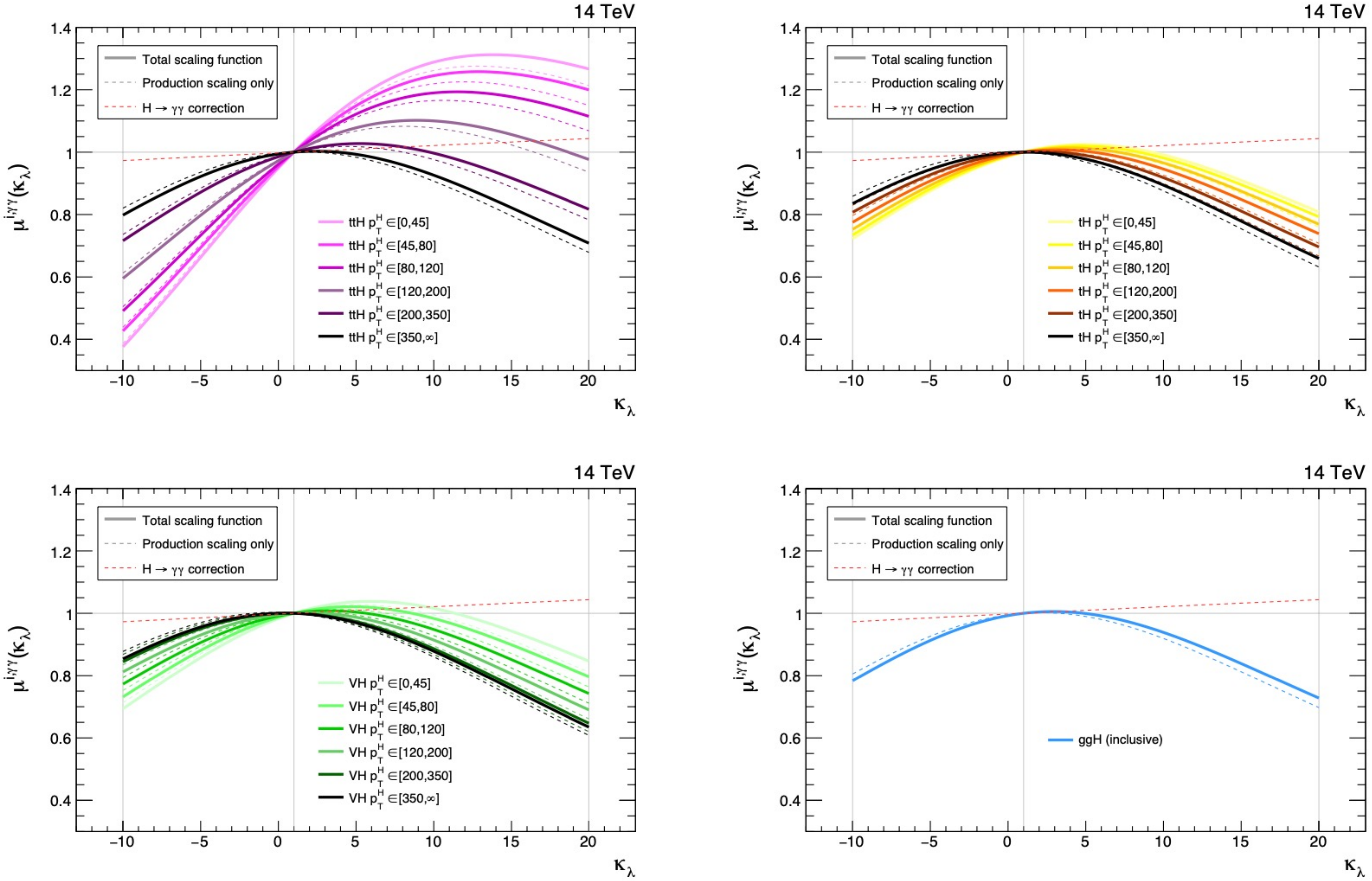




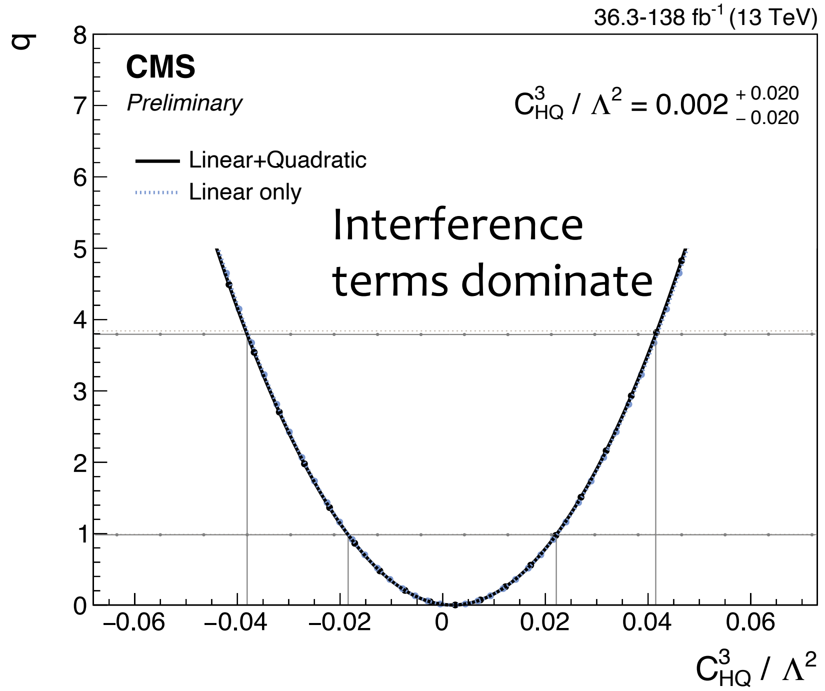
$$\mathcal{O}_1 = |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}\,, \quad \mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.\,, \quad \mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c.$$

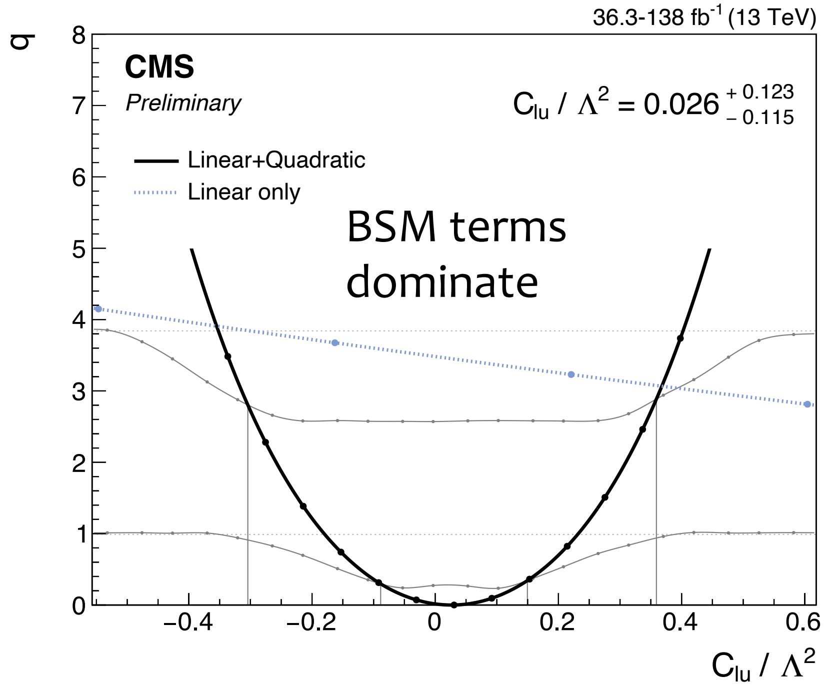
Yukawas

https://arxiv.org/abs/1705.05143

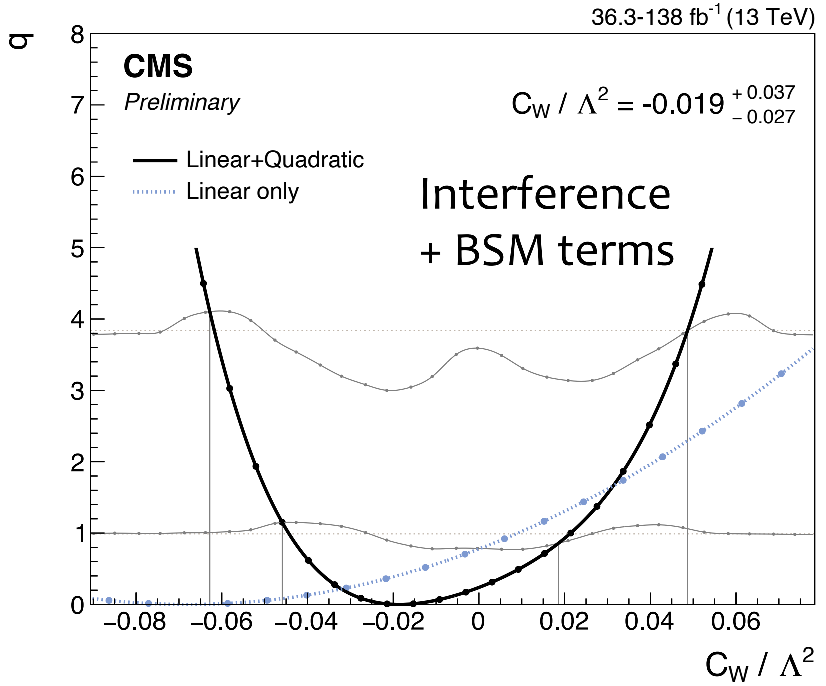

14 TeV
Total scaling function
Production scaling only
H → γγ correction
ttH $p_T^H \in$[0,45]
ttH $p_T^H \in$[45,80]
ttH $p_T^H \in$[80,120]
ttH $p_T^H \in$[120,200]
ttH $p_T^H \in$[200,350]
ttH $p_T^H \in$[350,∞]
$\mu^{i,\gamma\gamma}(\kappa_\lambda)$
κ_λ
14 TeV
Total scaling function
Production scaling only
H → γγ correction
tH $p_T^H \in$[0,45]
tH $p_T^H \in$[45,80]
tH $p_T^H \in$[80,120]
tH $p_T^H \in$[120,200]
tH $p_T^H \in$[200,350]
tH $p_T^H \in$[350,∞]
$\mu^{i,\gamma\gamma}(\kappa_\lambda)$
κ_λ
14 TeV
Total scaling function
Production scaling only
H → γγ correction
VH $p_T^H \in$[0,45]
VH $p_T^H \in$[45,80]
VH $p_T^H \in$[80,120]
VH $p_T^H \in$[120,200]
VH $p_T^H \in$[200,350]
VH $p_T^H \in$[350,∞]
$\mu^{i,\gamma\gamma}(\kappa_\lambda)$
κ_λ
14 TeV
Total scaling function
Production scaling only
H → γγ correction
ggH (inclusive)
$\mu^{i,\gamma\gamma}(\kappa_\lambda)$
κ_λ

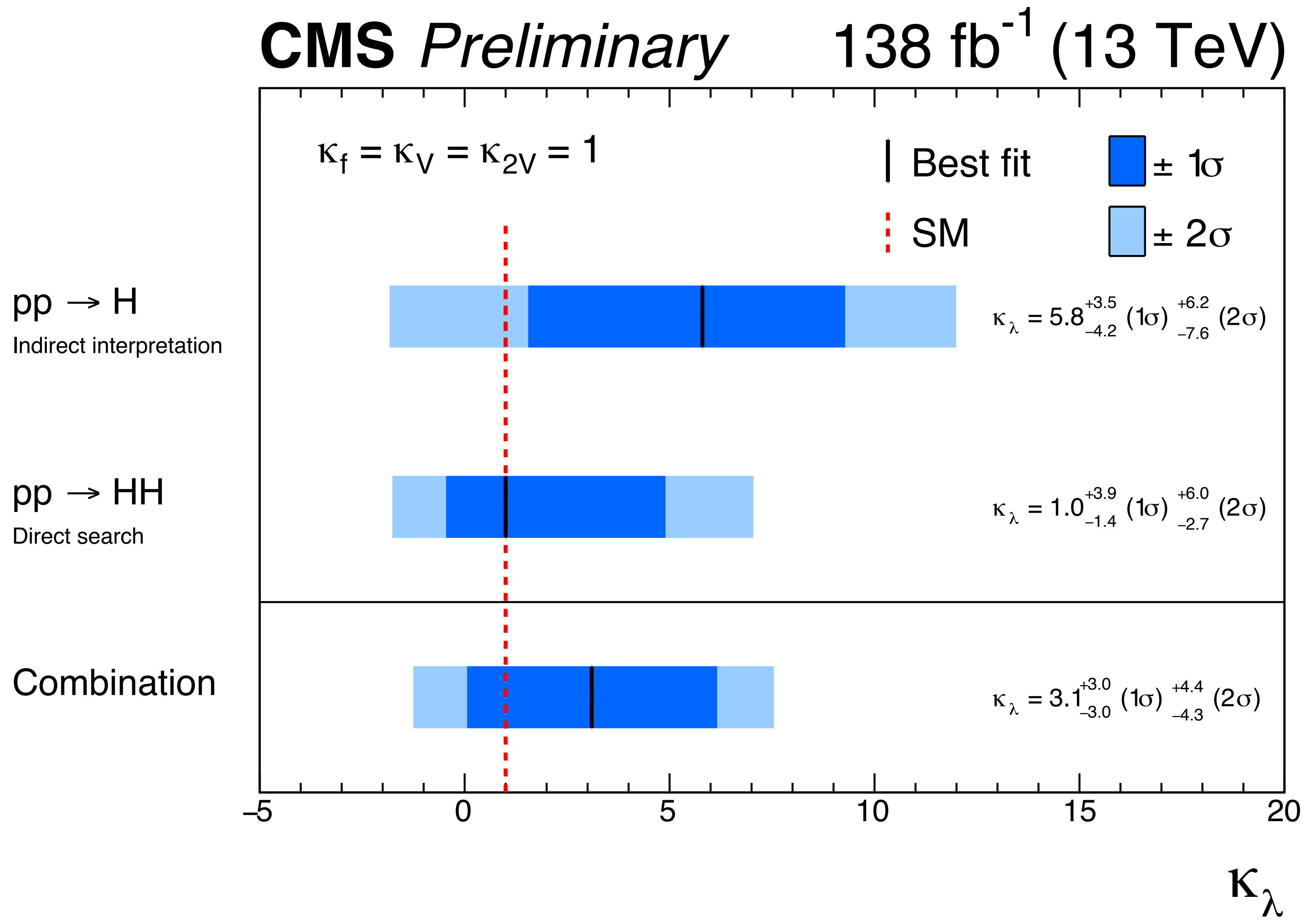
Wilks & EFT





$$\sigma^i_{p,\text{SMEFT}} = \sigma^i_{p,\text{SM}} + \sigma^i_{p,\text{int.}}(\vec{c}) + \sigma^i_{p,\text{BSM}}(\vec{c}) = \sigma^i_{p,\text{SM}} \left(1 + \sum_j A^i_{p,j} \frac{c_j}{\Lambda^2} + \sum_{j,k} B^i_{p,jk} \frac{c_j c_k}{\Lambda^4}\right)$$





CMS Preliminary
138 fb^{-1} (13 TeV)
$\kappa_f = \kappa_V = \kappa_{2V} = 1$
Best fit
SM
± 1σ
± 2σ
pp → H
Indirect interpretation
$\kappa_\lambda = 5.8^{+3.5}_{-4.2}$ (1σ) $^{+6.2}_{-7.6}$ (2σ)
pp → HH
Direct search
$\kappa_\lambda = 1.0^{+3.9}_{-1.4}$ (1σ) $^{+6.0}_{-2.7}$ (2σ)
Combination
$\kappa_\lambda = 3.1^{+3.0}_{-3.0}$ (1σ) $^{+4.4}_{-4.3}$ (2σ)
–5
0
5
10
15
20
κ_λ

EFT Interpretations – caveat 1.

STXS measurements don't include relevant information about decay of the Higgs

- Angular information (eg in 4l final state) sensitive to BSM effects
- ATLAS/CMS use MELA/BDT to exploit this information

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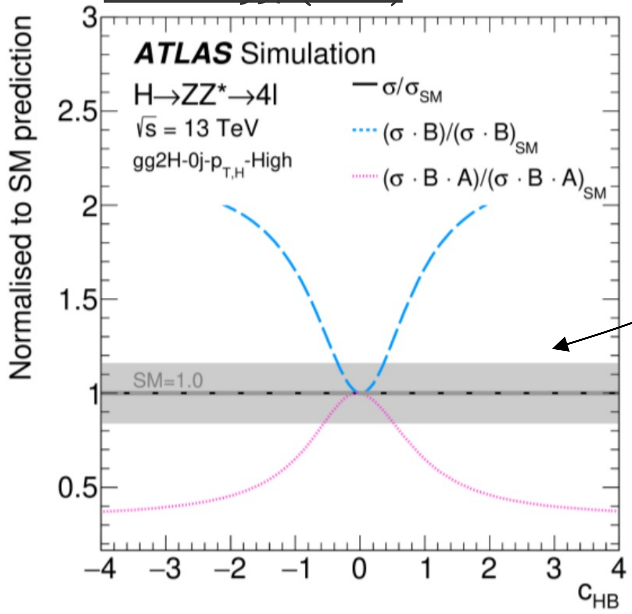

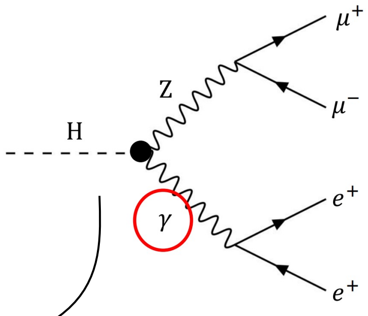

Need to account for non-SM acceptance when interpreting STXS measurements!

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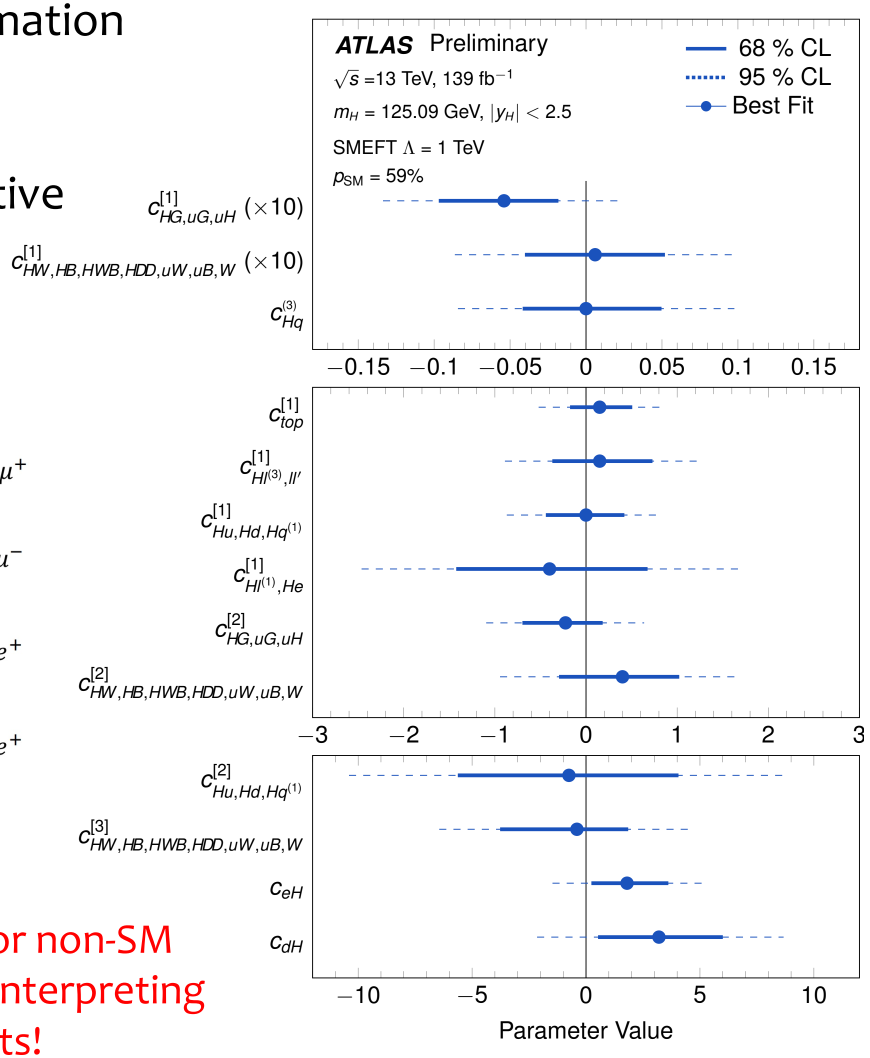

EFT Interpretations – caveat 2.

CMS/ATLAS are used to thinking of **Signal** / **Background** → But EFT is a global approach!

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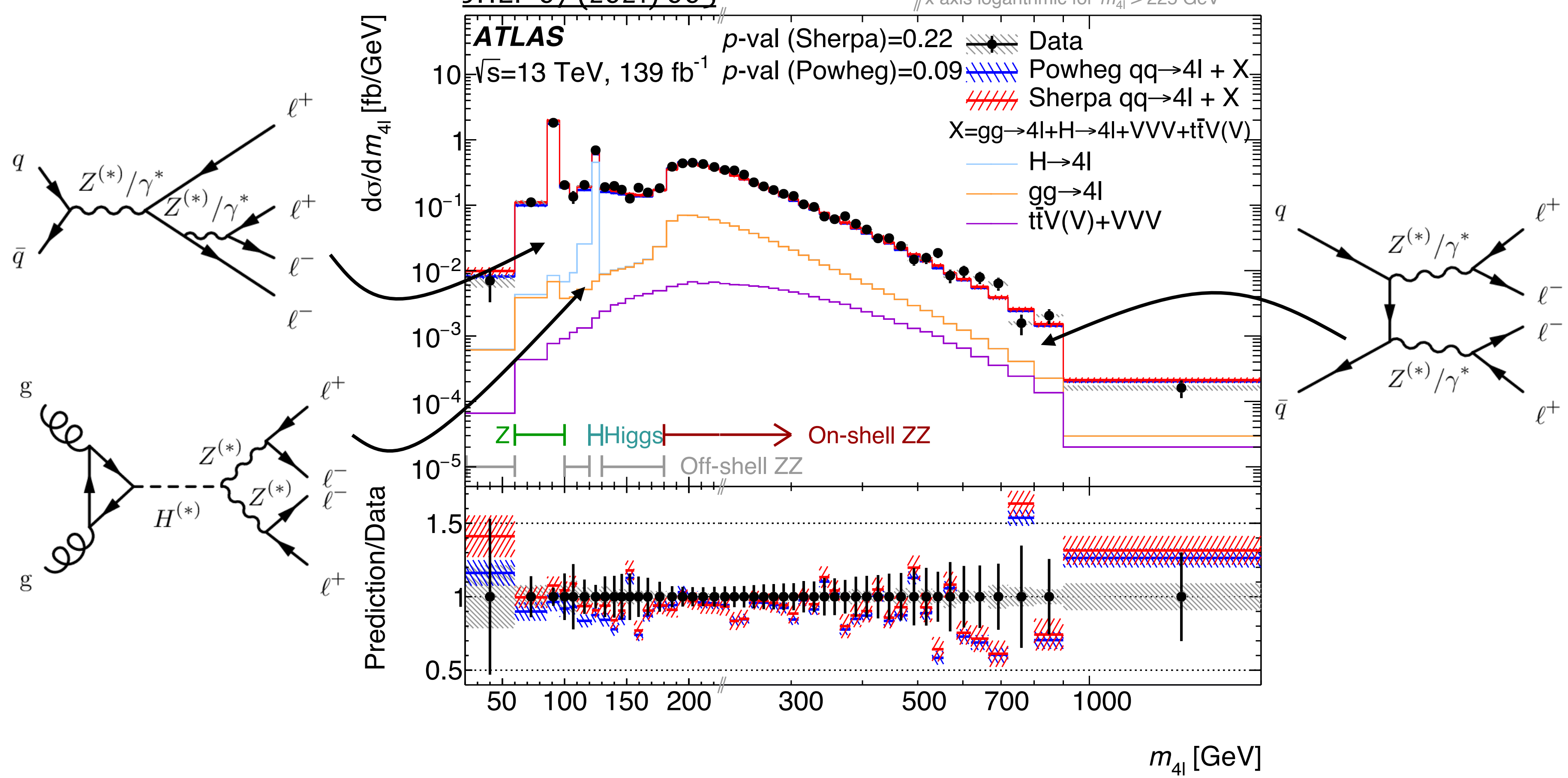


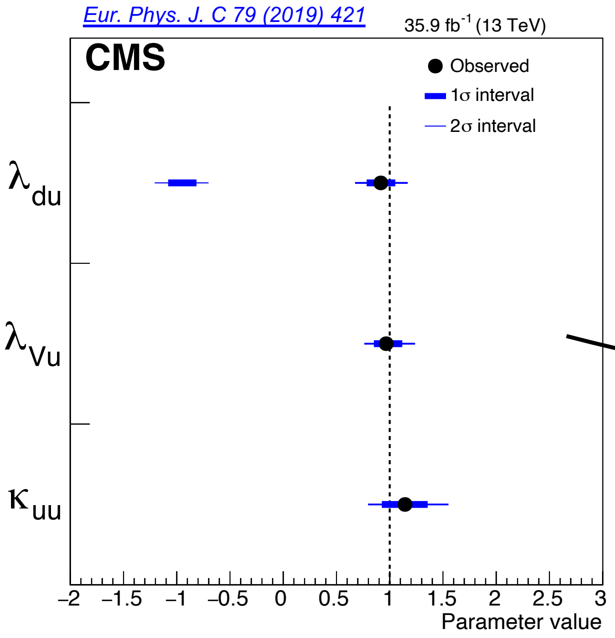
Full pp→4l combinations are the correct way to interpret the data

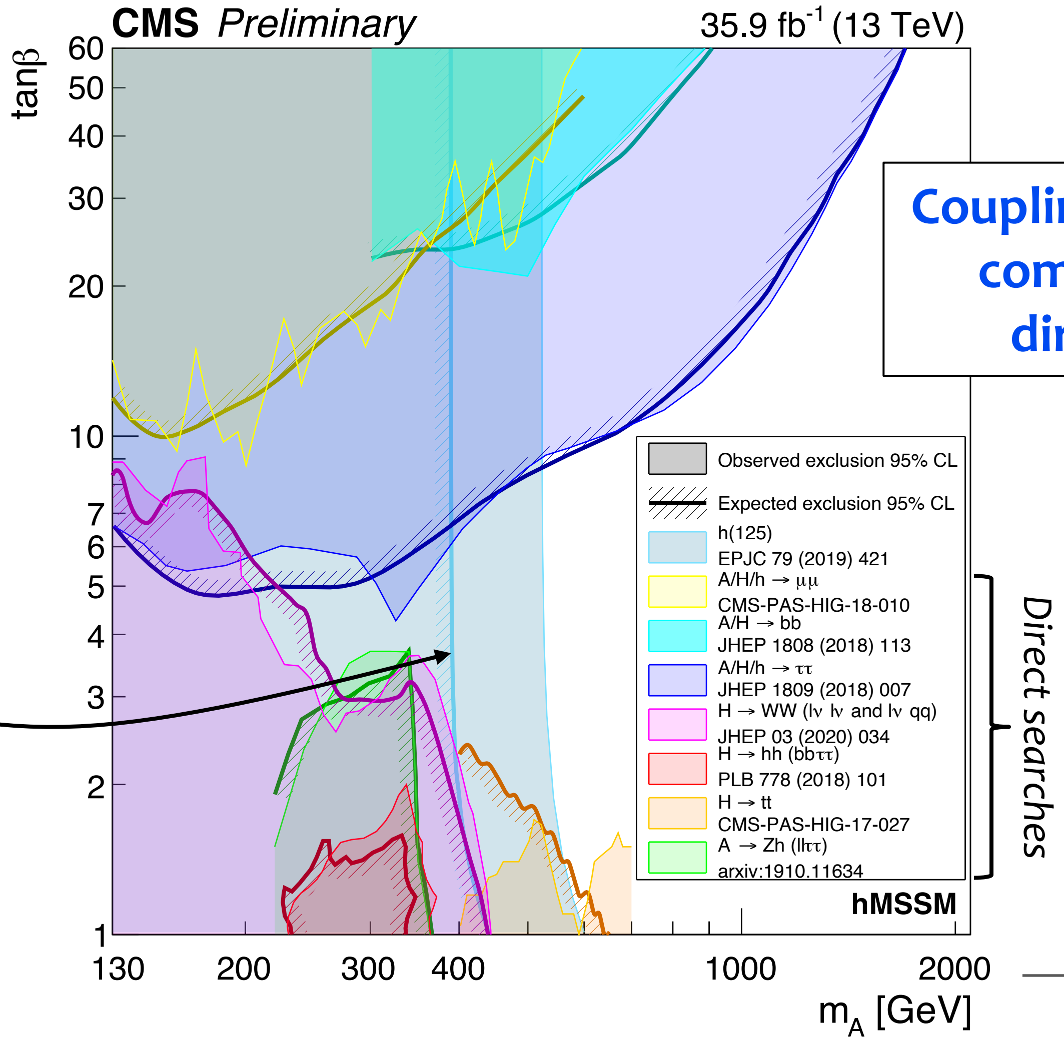
→Need to consider all contributions together to fully exploit our data

Complementarity to BSM searches

Beyond SM (BSM) Higgs models predict **modifications in couplings** between **up and down** type fermions and the Higgs boson

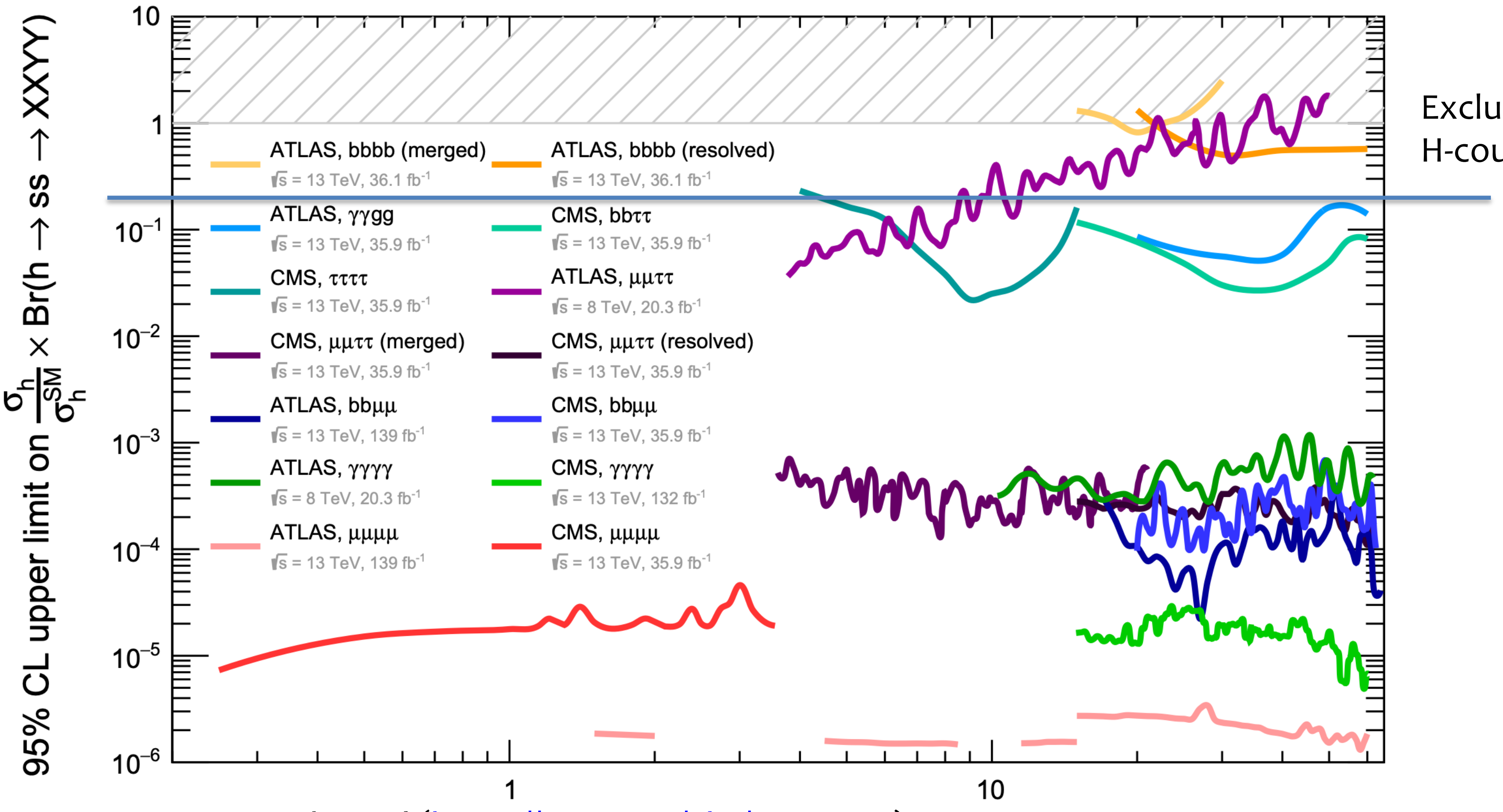
Supersymmetry (SUSY) is a popular extension of the SM…
→ Two Higgs doublets ϕ_u, ϕ_d
→ 5 Higgs bosons (A, H, h, $H^{+/-}$)





Coupling constraints are complementary to direct searches!

Complementarity to BSM searches



Excluded by H-couplings

M. Cepeda et al (https://arxiv.org/abs/2111.12751)

Higgs Couplings @ HL-LHC

Expect to reach O(%)-level precision in many couplings!

Assumes trigger & detector performance / reconstruction similar to Run-2

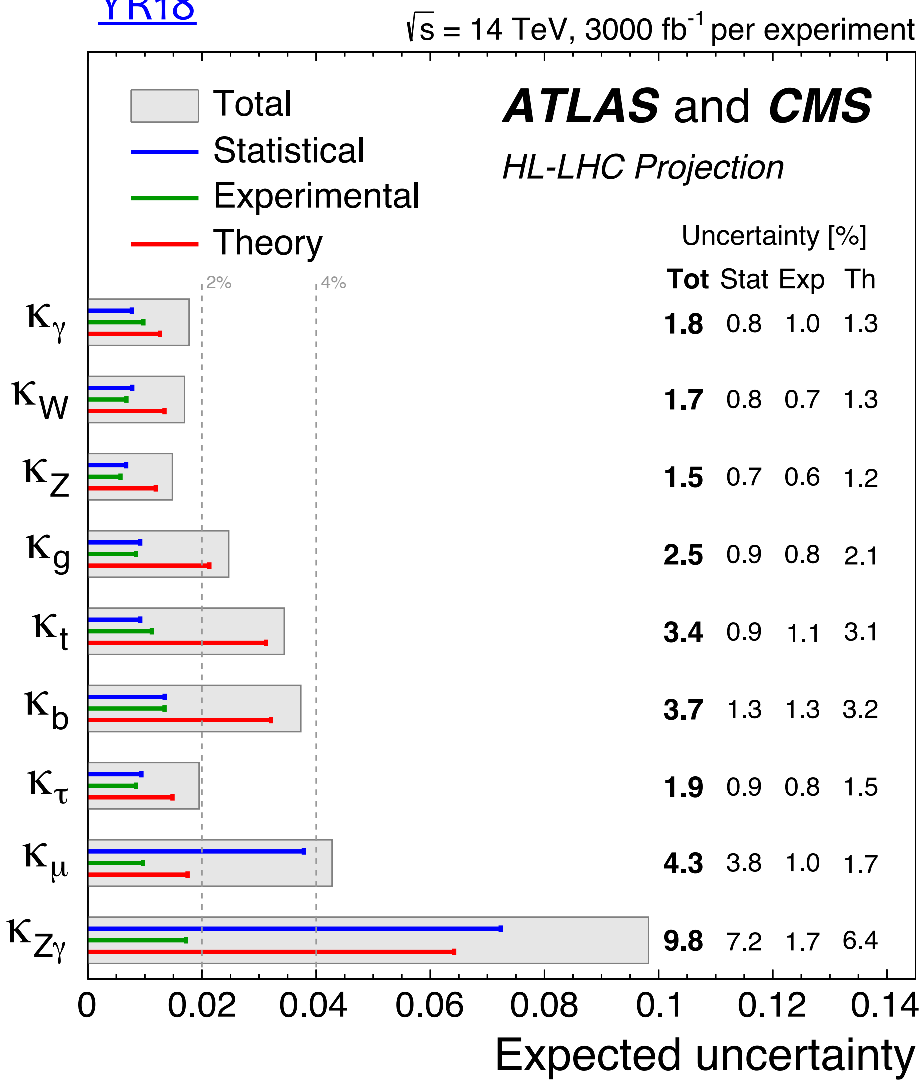
Uncertainty scaling:

Statistical Uncertainties	$\propto 1/\sqrt{L}$
Experimental Uncertainties	$\propto 1/\sqrt{L}$ Until floor reached
Theoretical Uncertainties	x 0.5

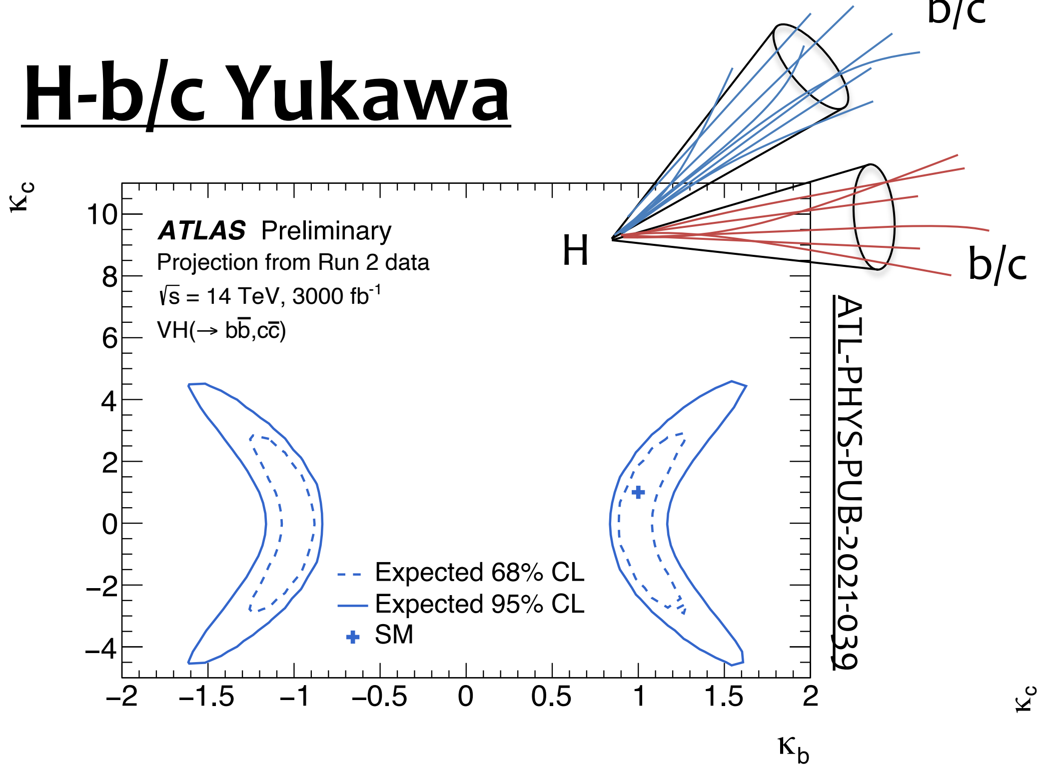
Uncertainty dominated by systematic components in many cases for coupling (inclusive) measurements

Caveat! Higgs boson couplings based on partial Run-2 data - Represents only ~few % of total expected HL-LHC dataset.

YR18



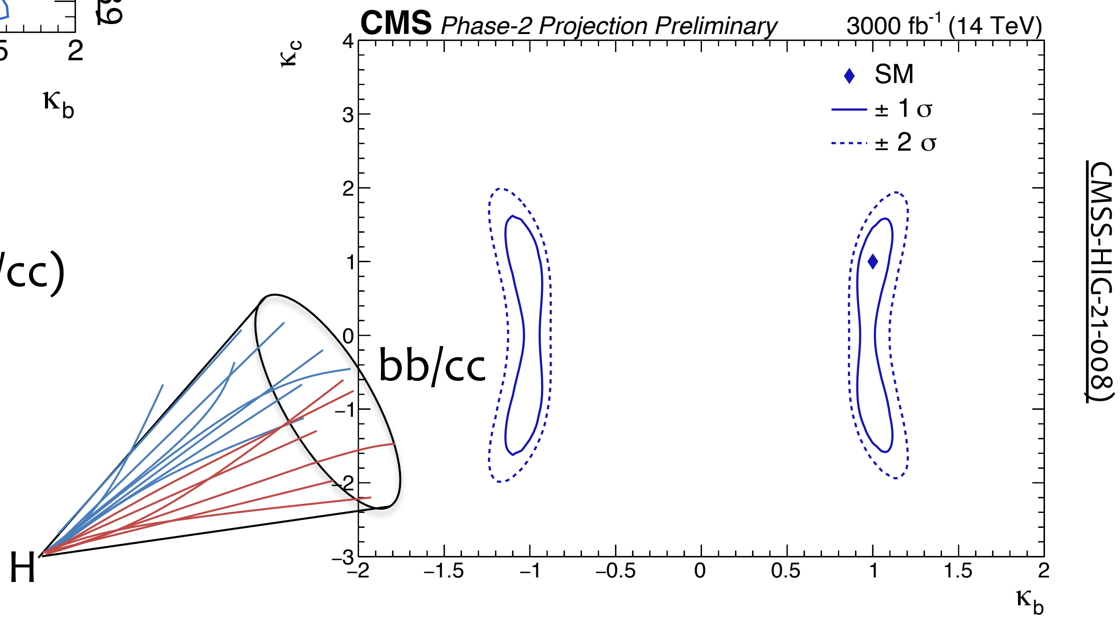
H-b/c Yukawa



VH→bb/cc measurements sensitive to b-quark and c-quark couplings

Expected measurements of κ_b-κ_c at HL-LHC from STXS VH→bb (STXS measurement) and VH→cc (inclusive search) in resolved di-jet events (ATLAS)…

…and in boosted events (p_T>200 GeV) using ParticleNet [1,2] H(bb/cc) merged-jet tagging

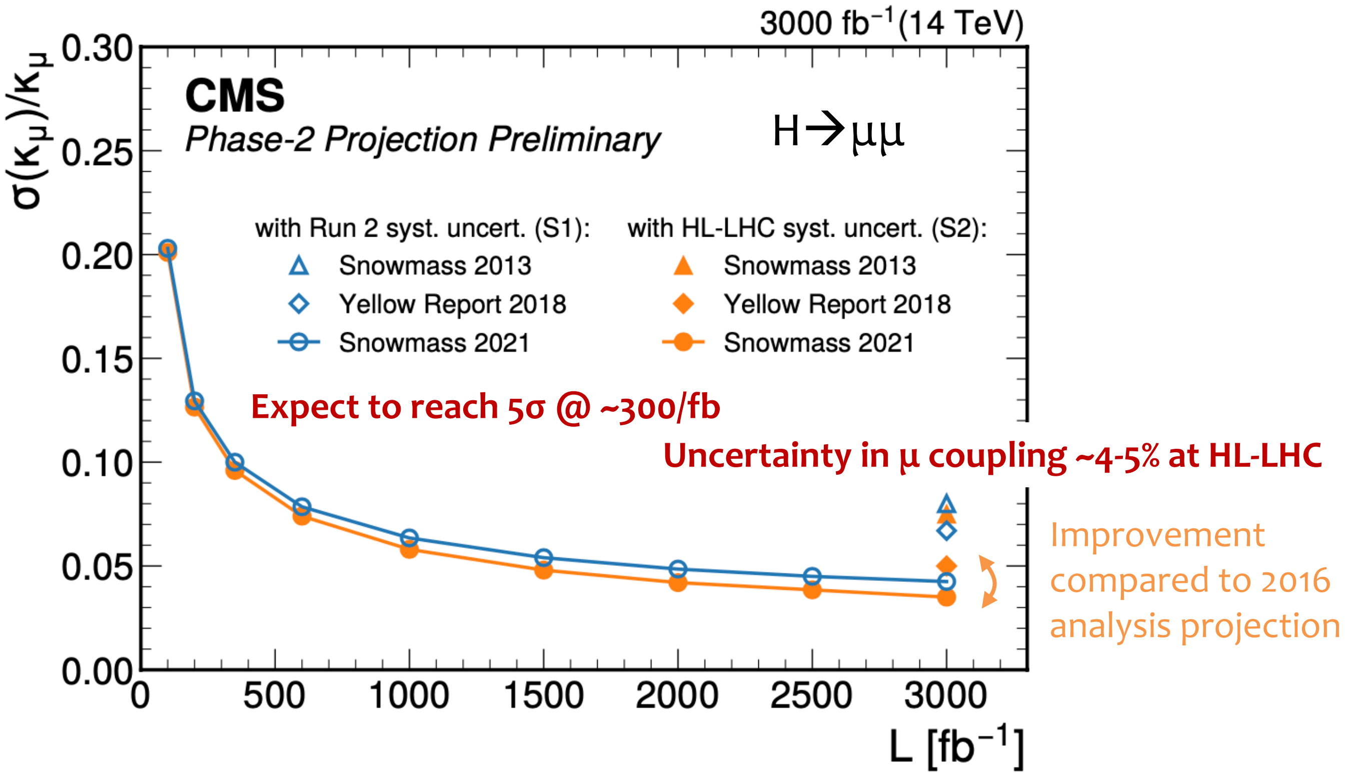


[1] CERN-CMS-DP-2020-002

[2] PRD **101,** 056019

Higgs boson 2nd generation couplings

Updates in 2022 (Snowmass) for key decay channels where projections now use analyses based only **full Run-2 datasets & improved analysis methods**

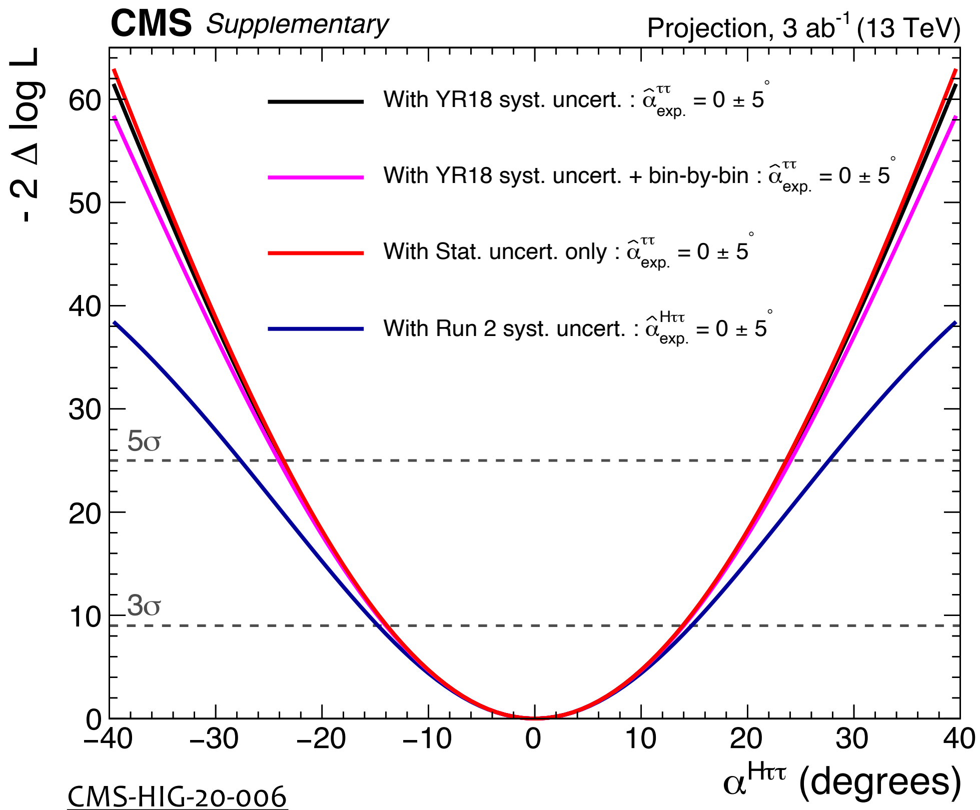


Reminder that projections are often pessimistic as **analysis strategies improve with each iteration**

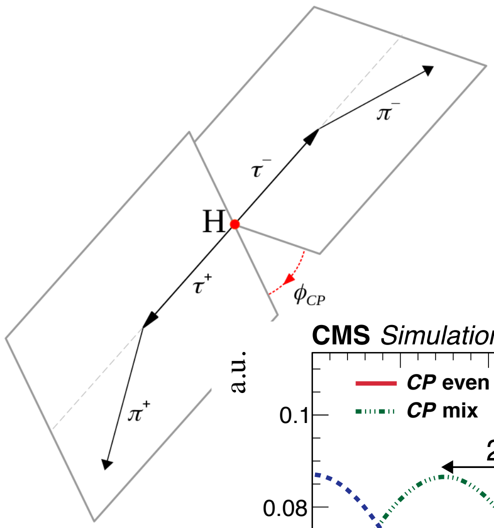
CP in H→ττ

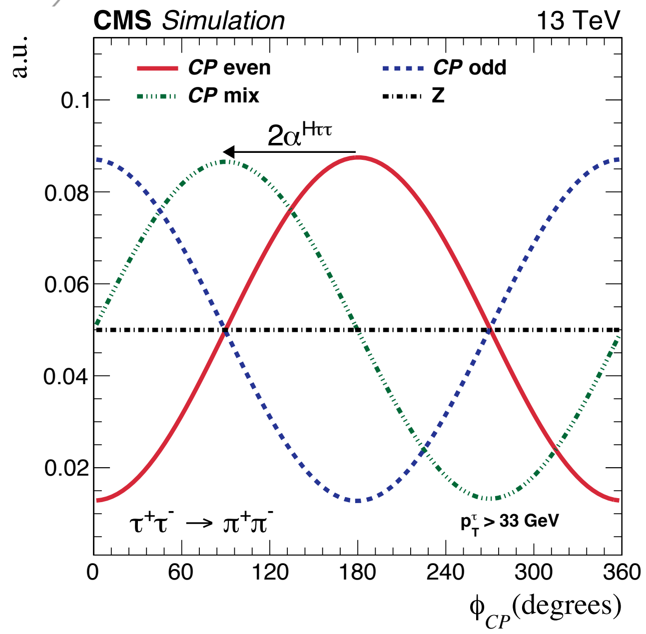
Measure H→ττ decays differentially in Φ_{CP} to access potential CP-odd contributions to H-τ coupling

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



CMS-HIG-20-006



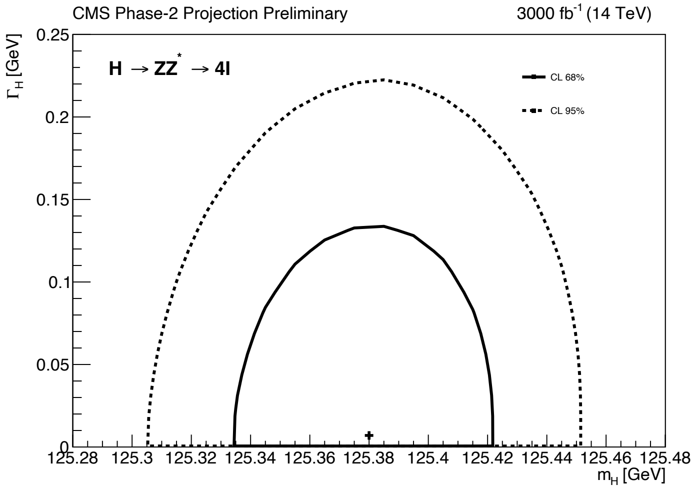


Projection of Run-2 analysis at CMS
→ Expect to constrain CP-mixing angle ($\alpha^{H\tau\tau}$) to 5 degrees at HL-LHC!

BSM in Higgs decays

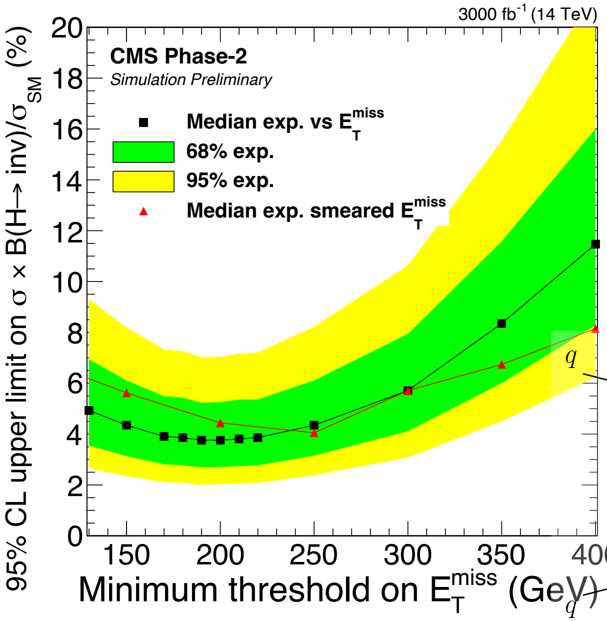
Additional (BSM) decays of the Higgs boson results in modified Higgs boson width

- Indirect from total width from coupling measurements (+ offshell) measurements
- Direct measurement from H→4l mass peak
- Limited by experimental resolution ($\Gamma_H \sim 4$ MeV in SM)!

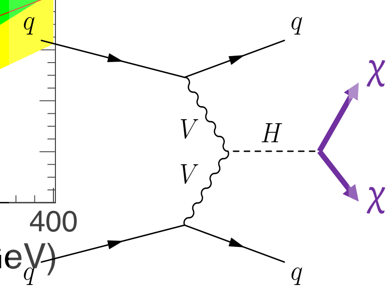


CMS-PAS-FTR-21-007

Γ_H expected upper limit (MeV)	Projection	Optimistic	Pessimistic
Total	177	155	177
Syst impact	150	123	150
Stat only	94		



CMS-PAS-FTR-18-016



Direct searches for VBF H→invisible decays benefit from improved forward tracking & calorimetry

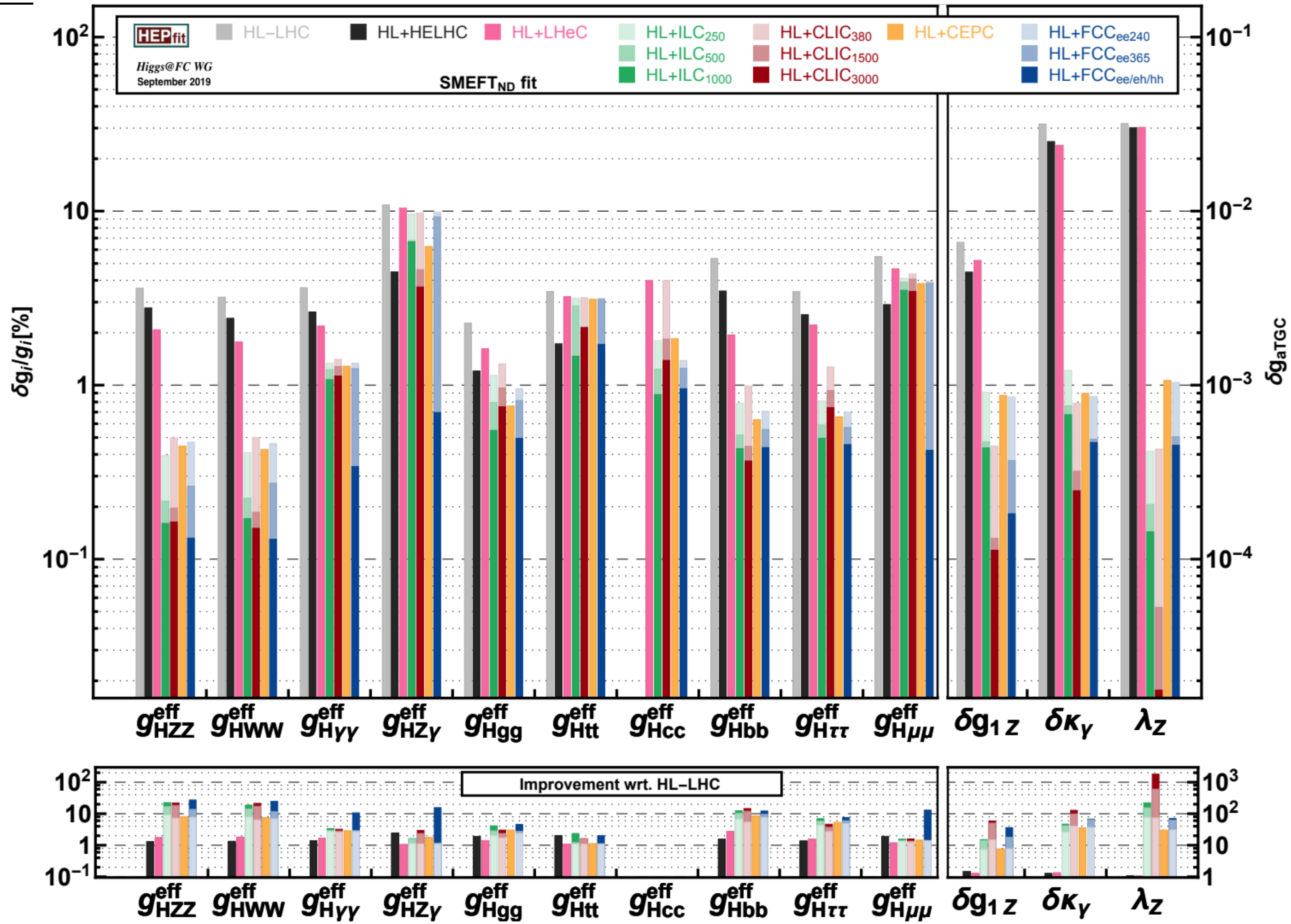
→ Sensitivity limited by trigger/selection thresholds achievable at HL-LHC

→ Need to get smarter to maintain or do better than sqrt(L)!

Future Colliders

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] [e^-/e^+]	N(Det.)	$\mathscr{L}_{\text{inst}}$ [10^{34}] cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[13]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[13]	HE-LHC
FCC-hh$^{(*)}$	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 14]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5	[4]	ILC$_{1000}$
							(+1-2)		(1-2y SD after 500 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[15]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[12]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

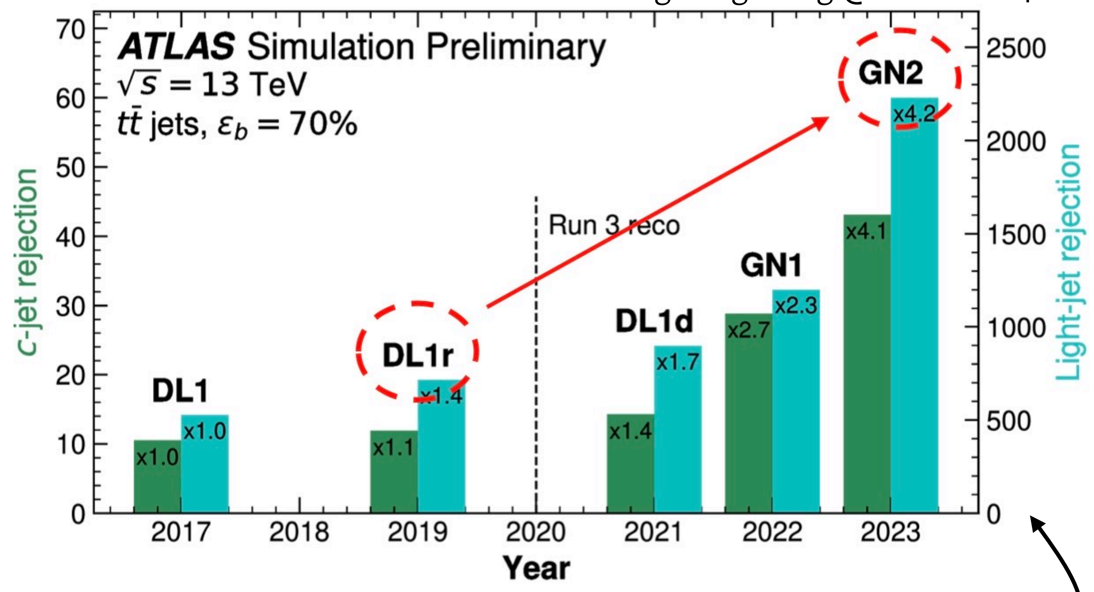
Future colliders & EFT



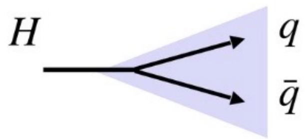
Exploiting new ideas

(FTAG-2023-01)

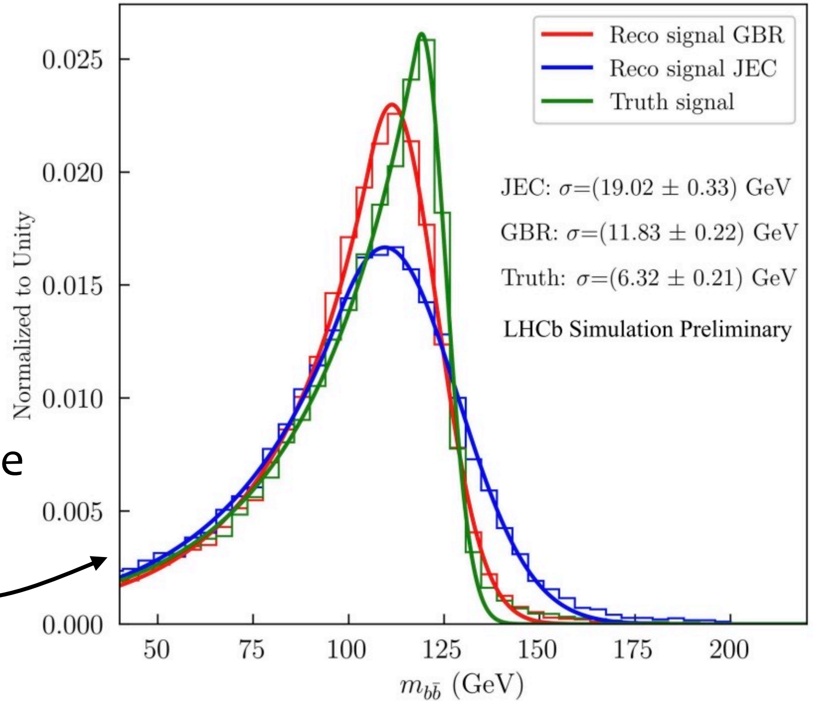
Song-Ming Wang @ ICHEP 2024



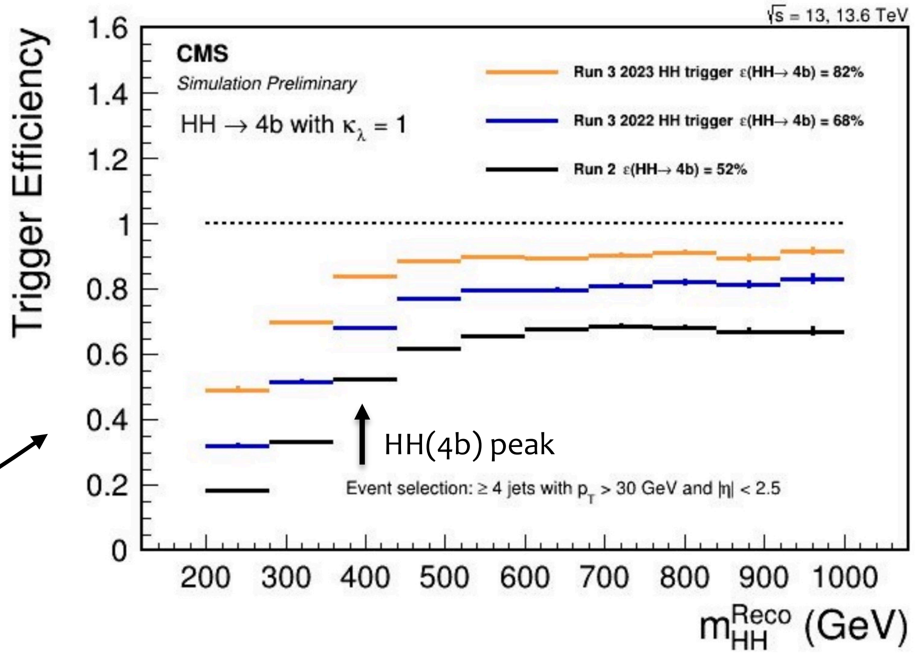
Smarter algorithms (enhanced with Graph-based ML) to identify jet-flavor → **VH(bb), HH→4b**

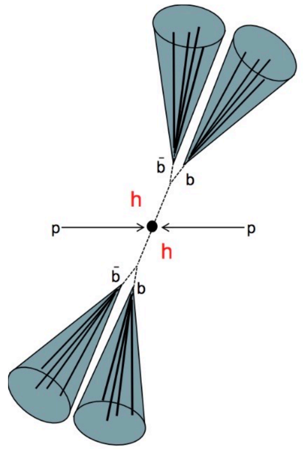


Gradient boosted regressor to improve $m_{bb/cc}$ resolution for **H→bb/cc**



LHCB-FIGURE-2023-029

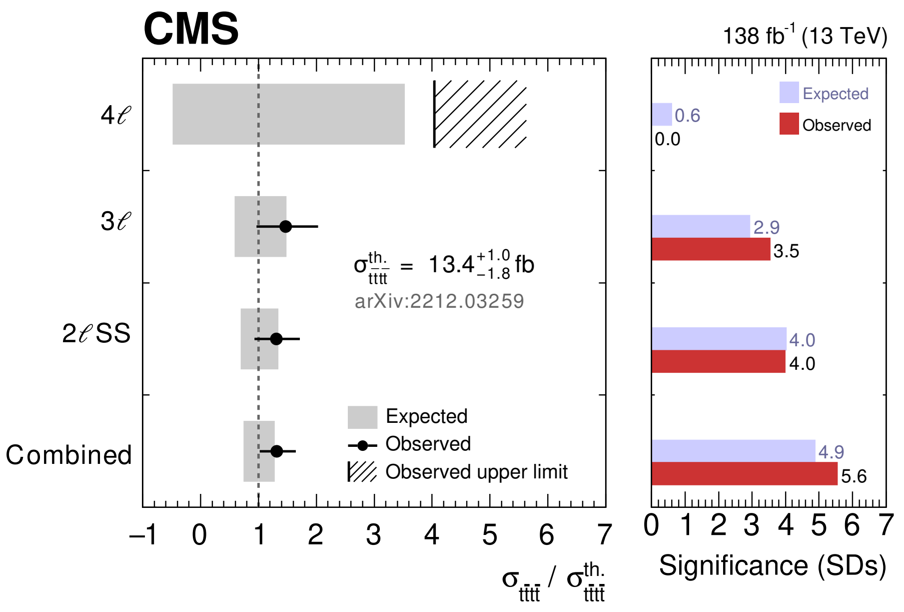




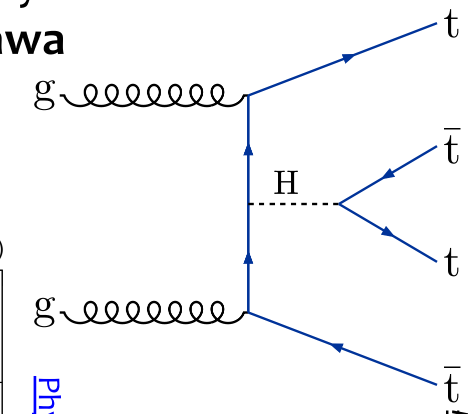
New dedicated triggers for **HH searches** (both for 4b and 2b2τ final states) to improve signal efficiency in Run-3!

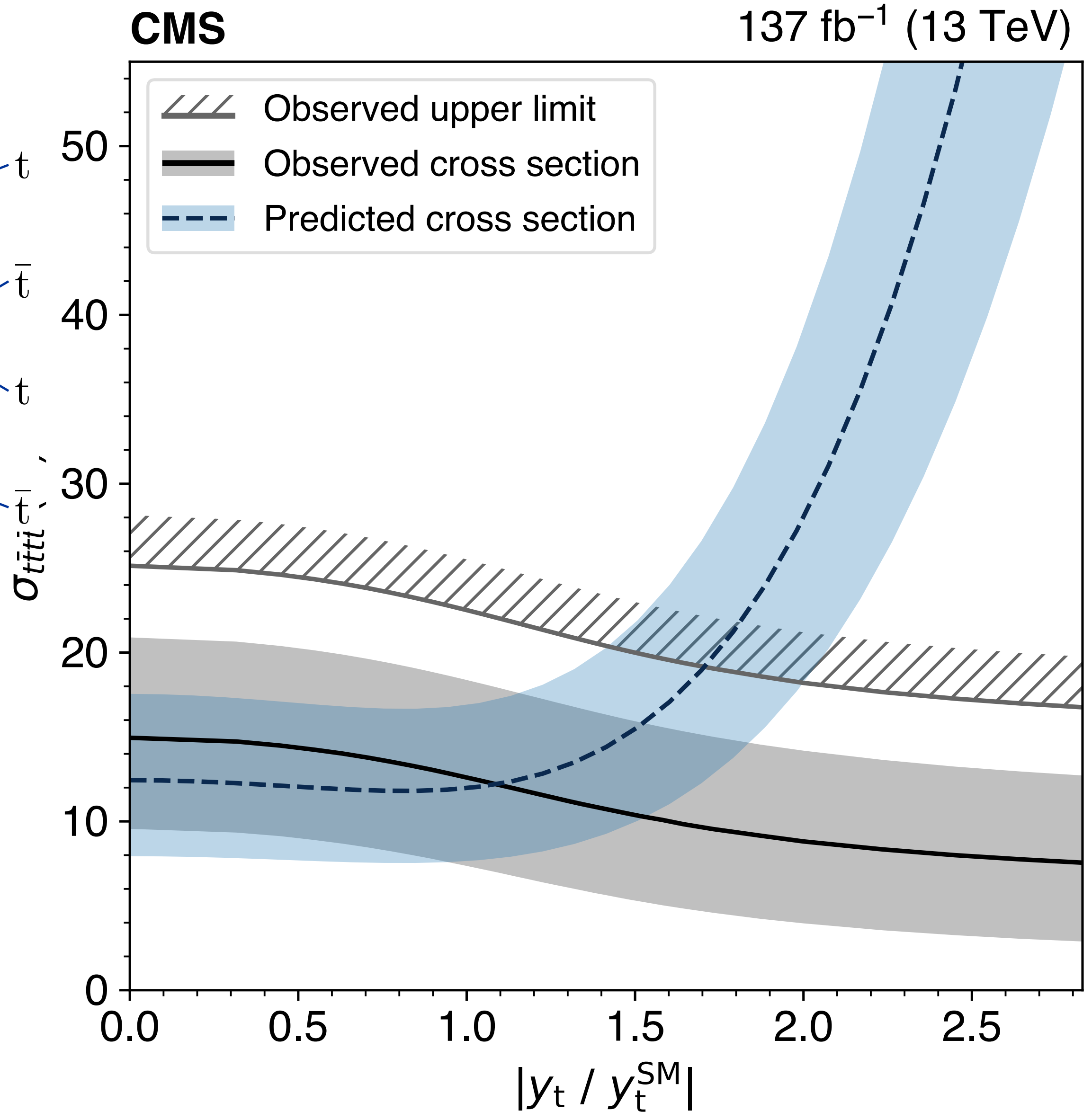
Looking beyond the Higgs?

Search for 4-tops provides complementary approach to constraining **Higgs-top Yukawa** coupling!



Phys. Lett. B 847 (2023) 138290





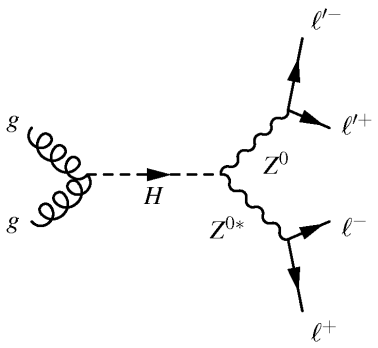
CMS-TOP-18-003

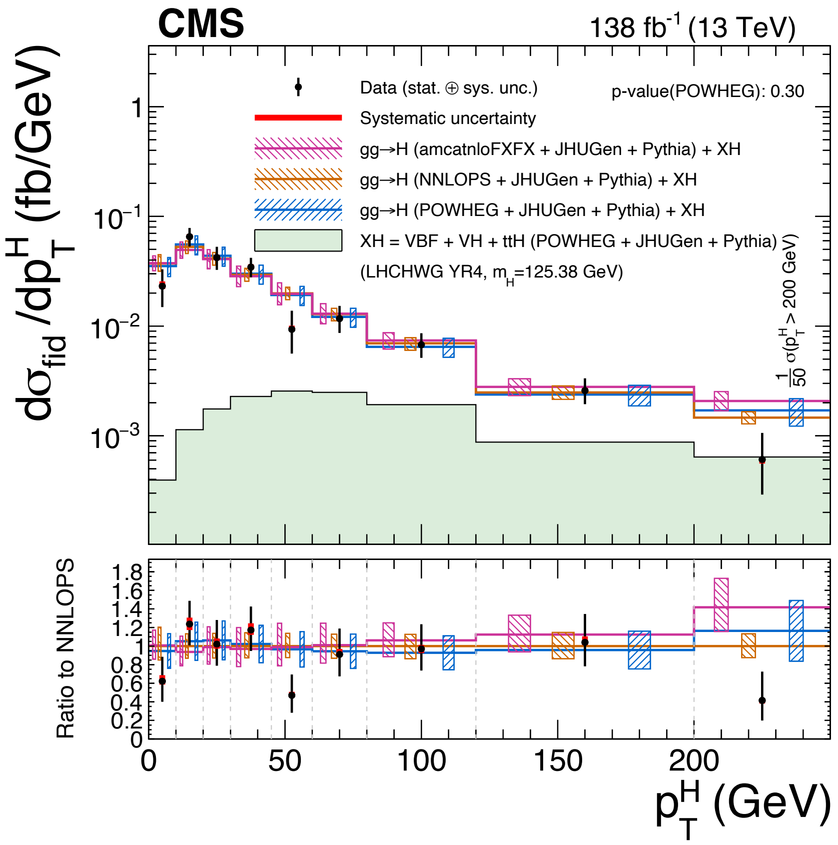
Full Run-2 analysis yields 4-top observation

Combined significance **5.9σ (5.1σ) !**

Looking beyond the signal strenghts

Huge datasets available in Run-2 (and being collected in Run-3) allow to measure Higgs boson properties differentially





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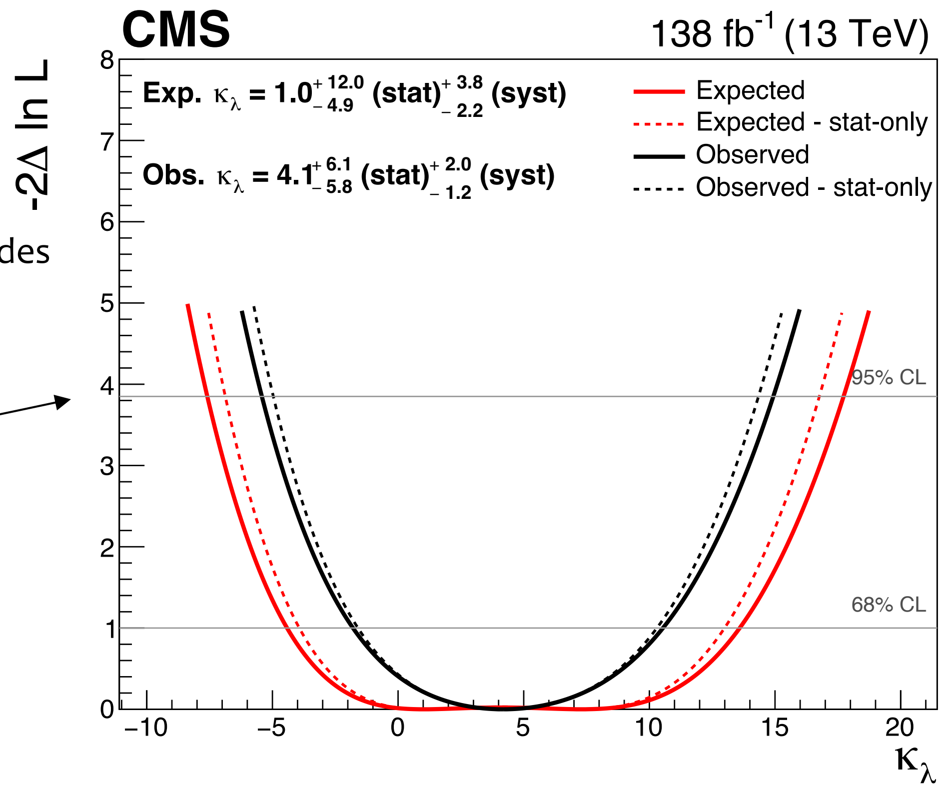
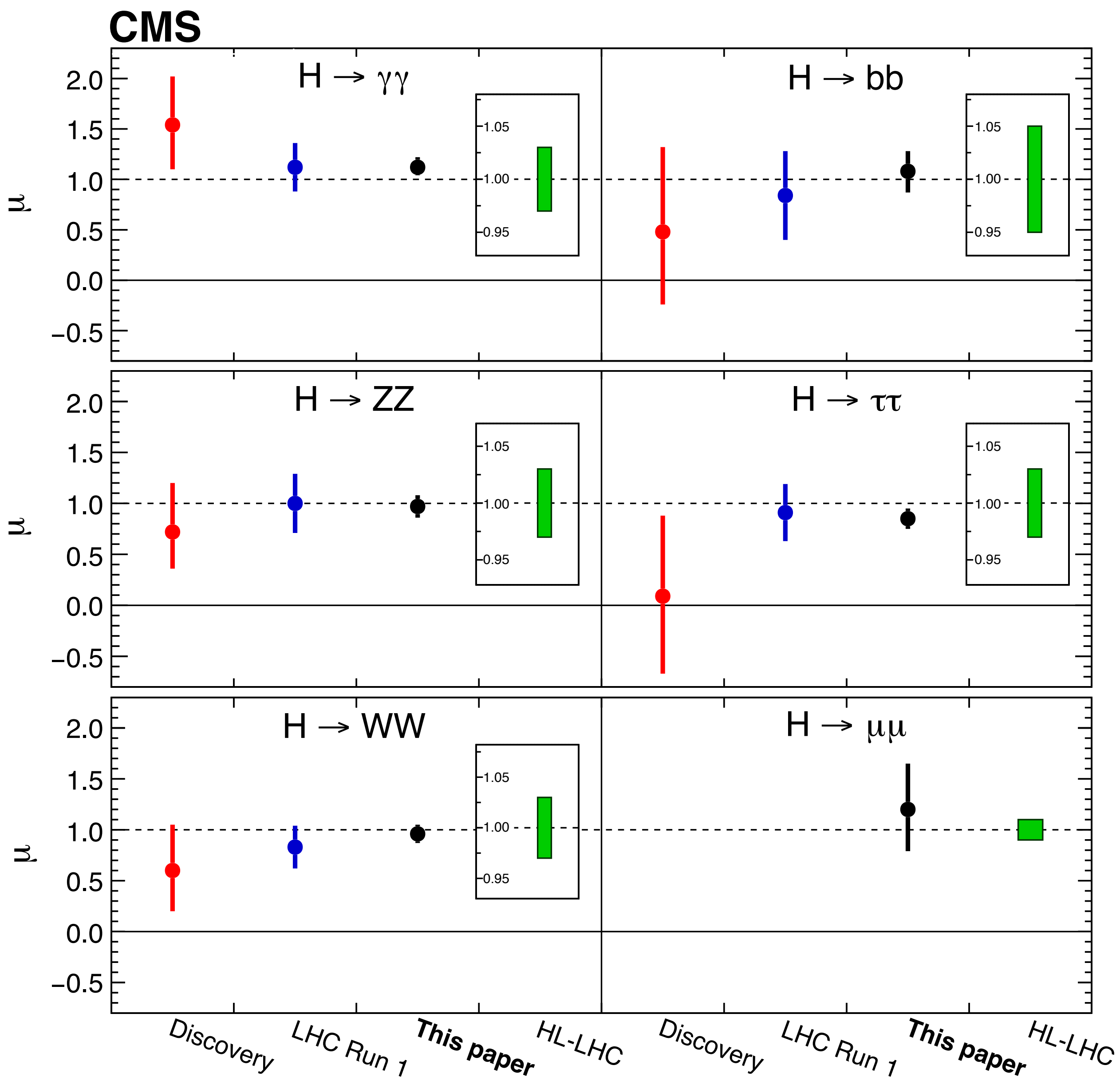
Differential information provides additional handles on Higgs boson (self) couplings

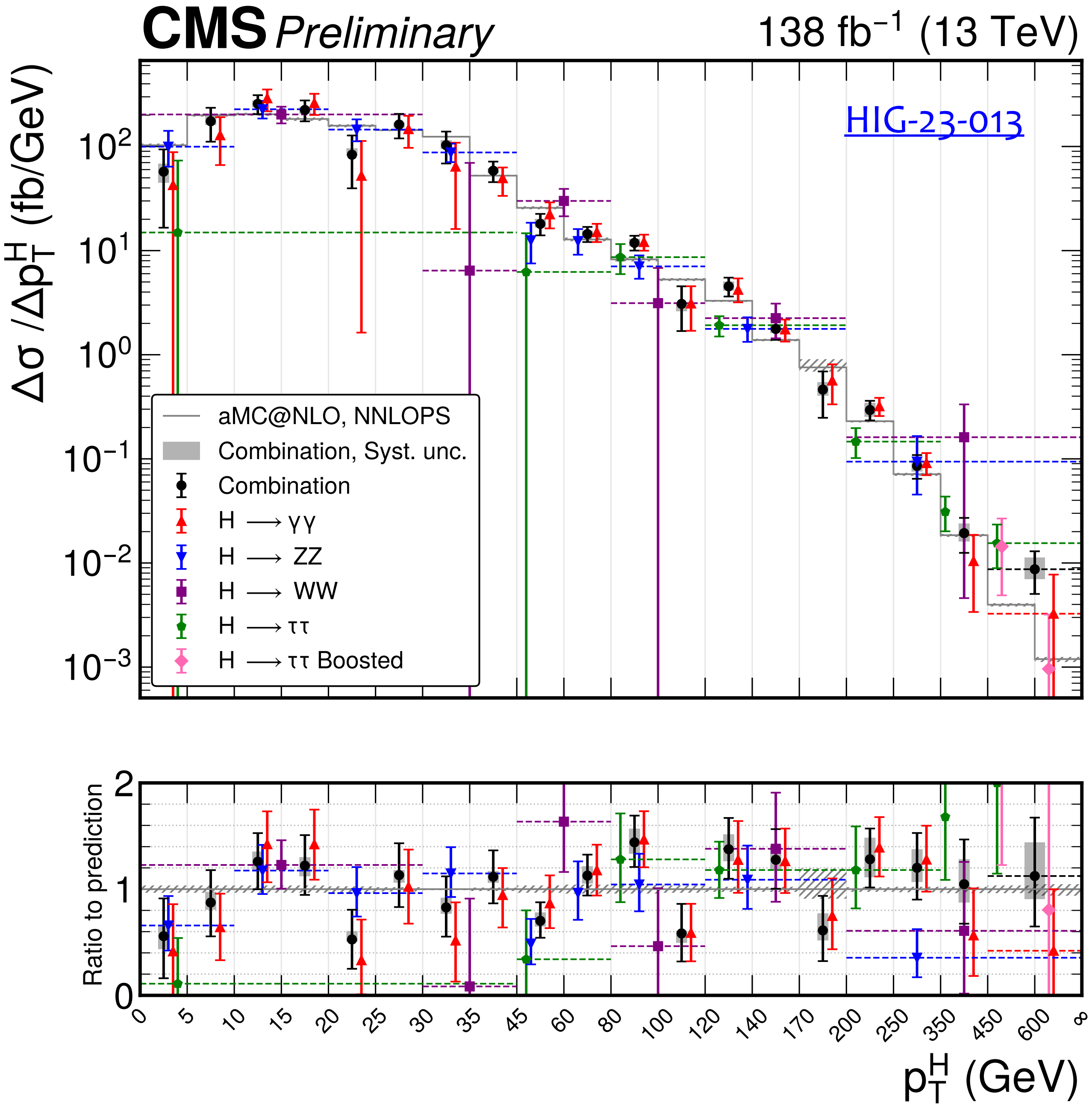


Projection of signal strengths



Differential measurements

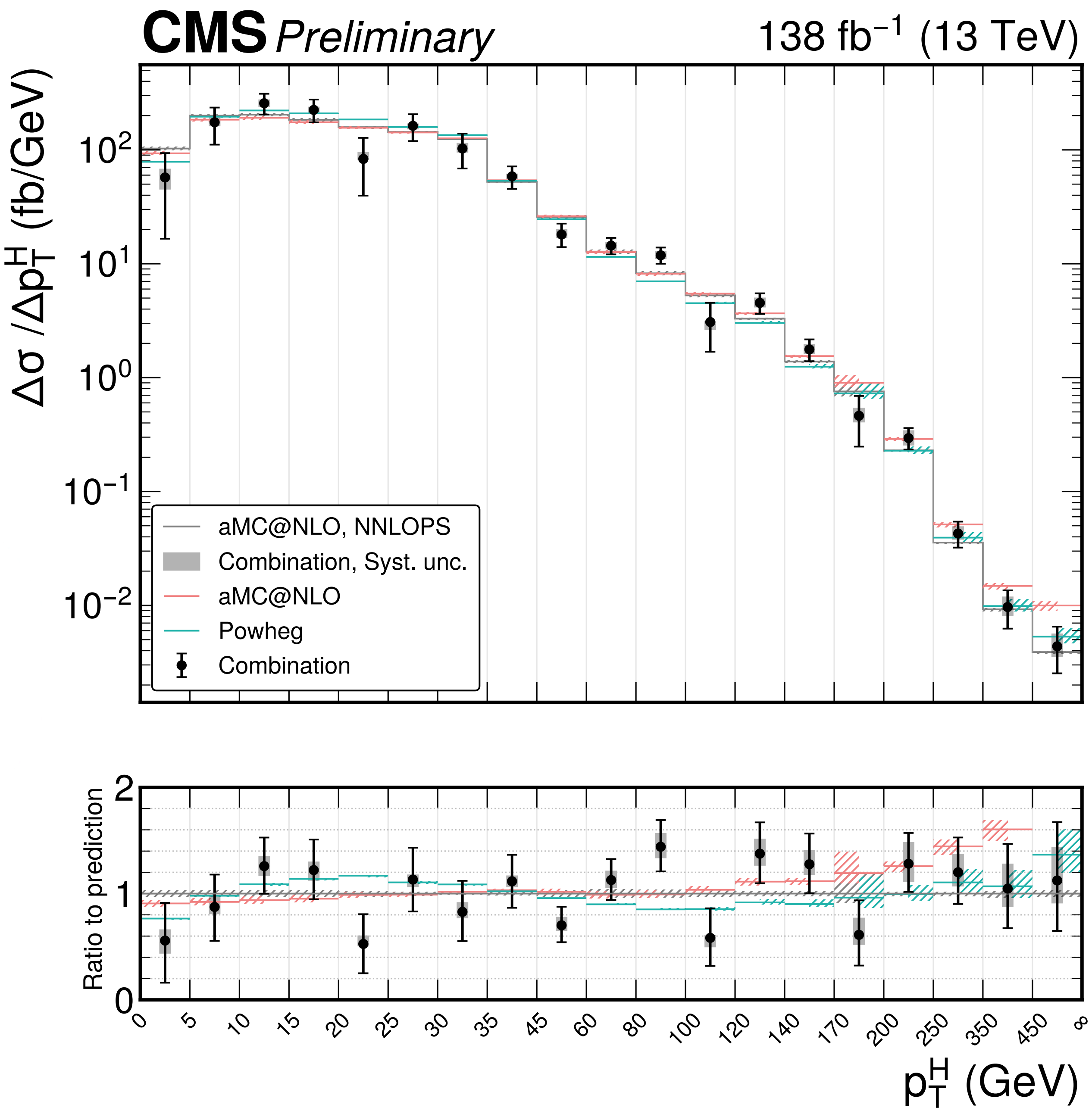
With the data collected in Run-2 we have enough Higgs bosons to **explore high momentum regions** and probe potential hiding places for new (heavy) physics!



Differential measurements

With the data collected in Run-2 we have enough Higgs bosons to **explore high momentum regions** and probe potential hiding places for new (heavy) physics!

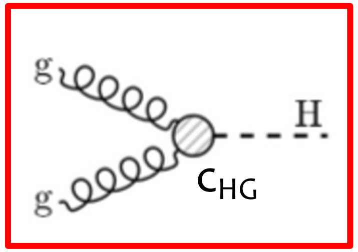
Combinations of decay channels provides most stringent tests of SM Higgs (and our understanding of the SM Higgs!)

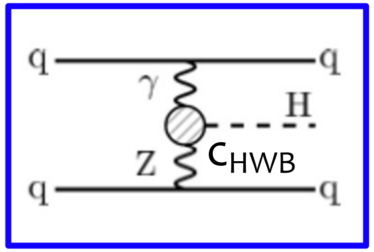


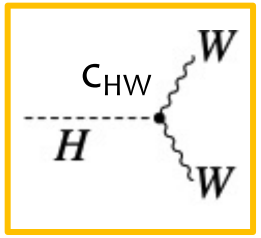
Differential measurements for EFT

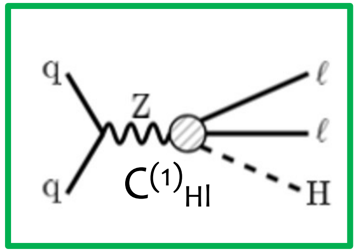
Similarly to SM couplings measurements, can express differential cross-section measurements in terms of EFT couplings (Wilson Coefficients)

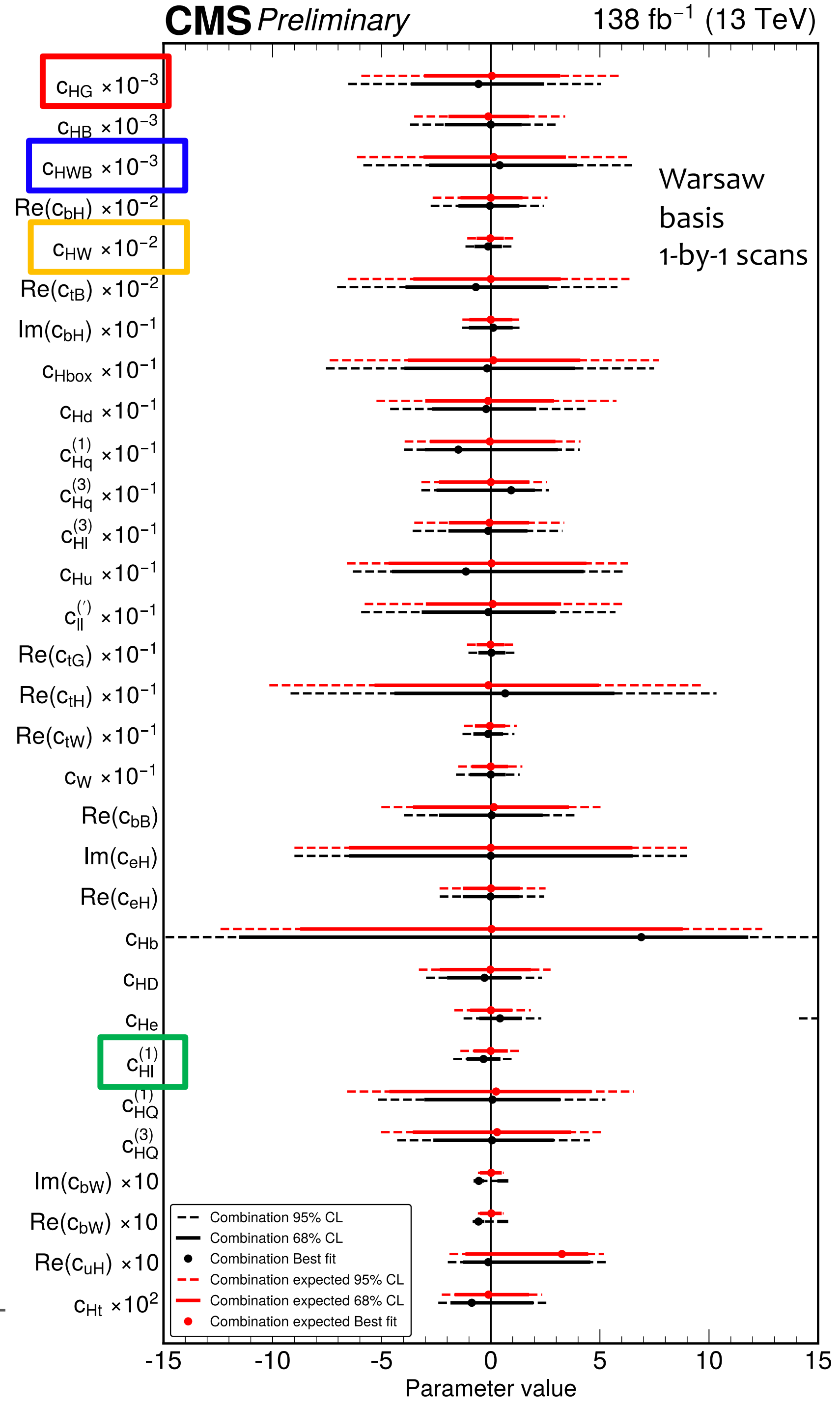
$$\mu_i \rightarrow \mu_i(\boldsymbol{c}) \qquad \mu^f \rightarrow \mu^f(\boldsymbol{c})$$



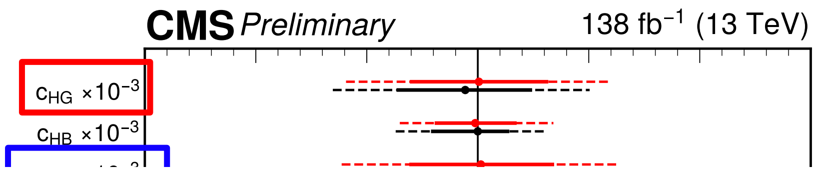






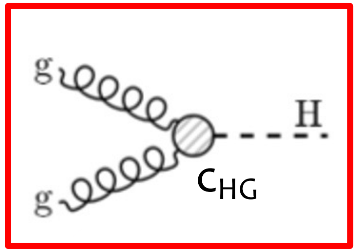


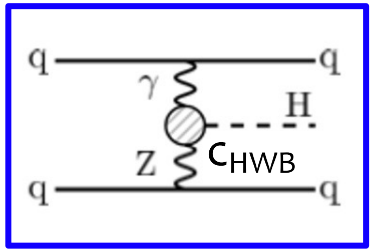
Differential measurements for EFT

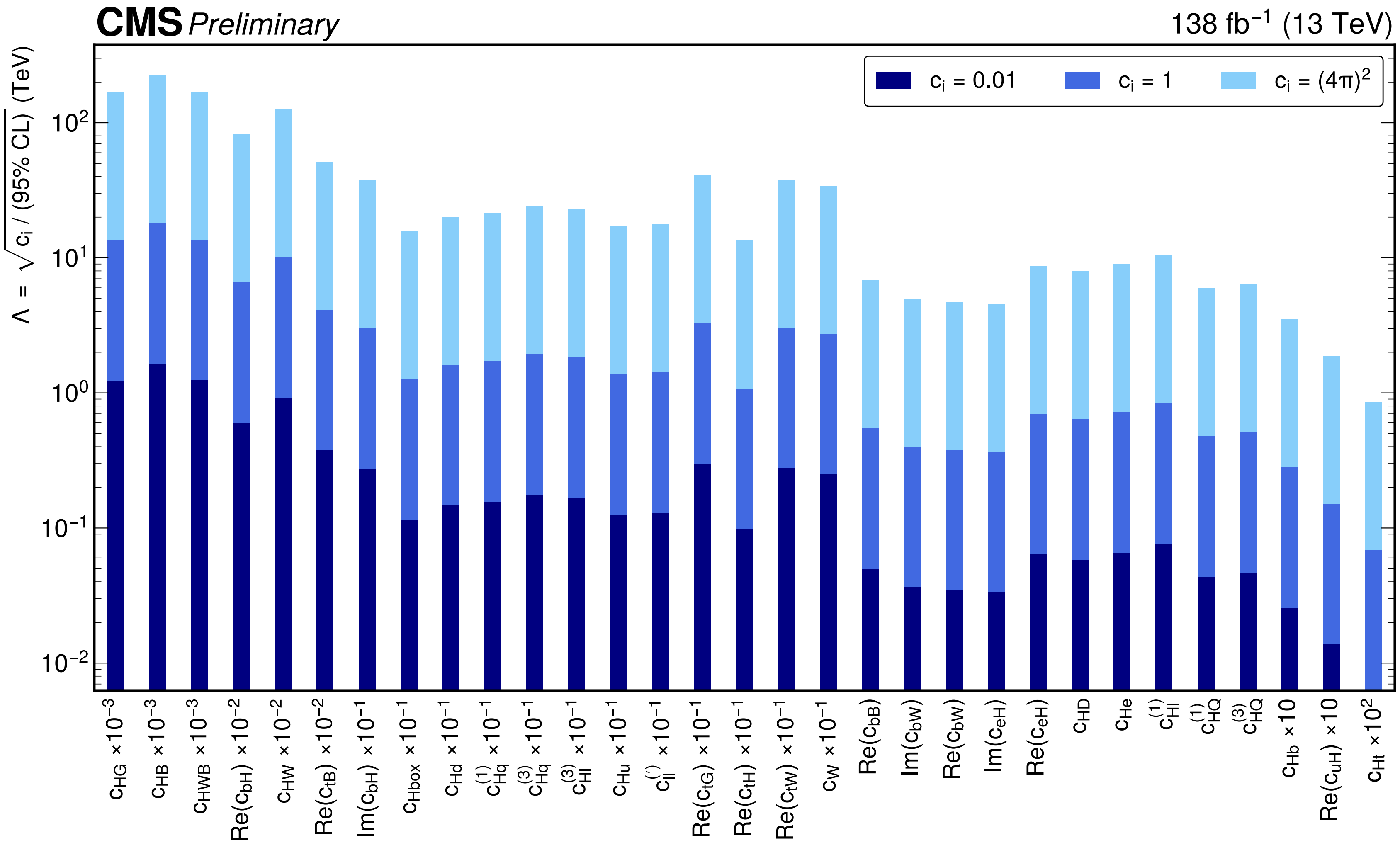


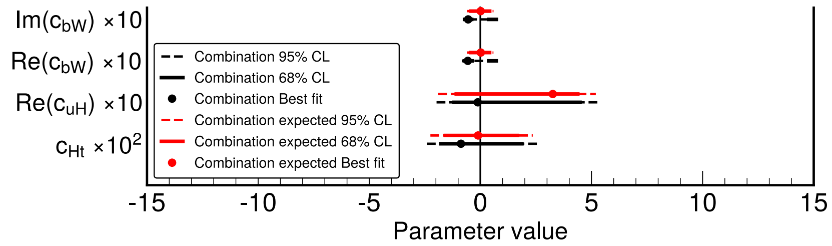
Conversion to lower bounds on New Physics scale **Λ**

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,j} \frac{c_j^{(d)}}{\Lambda^{d-4}} Q_j^{(d)}$$









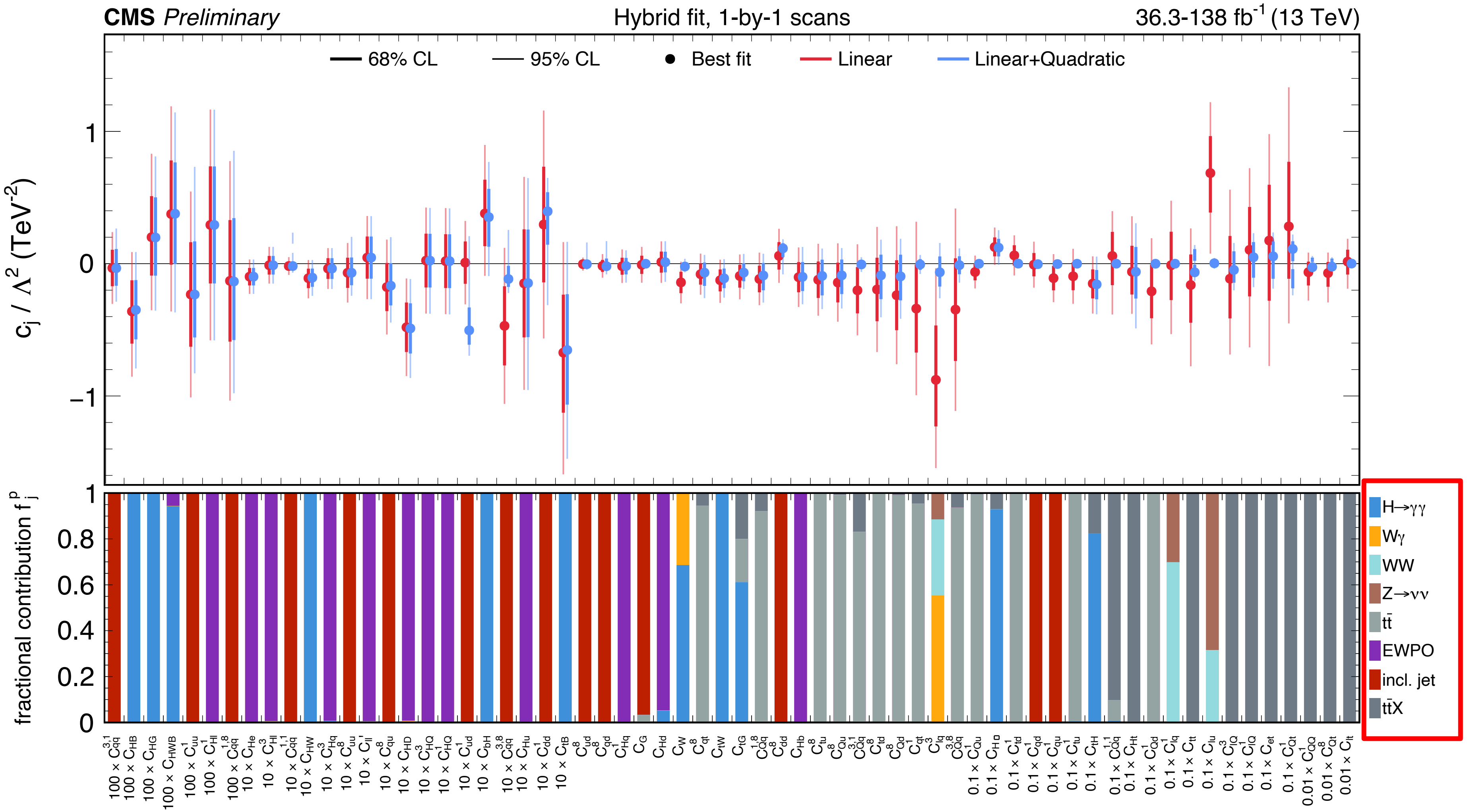
EFTs allow us to indirectly probe higher energy scales

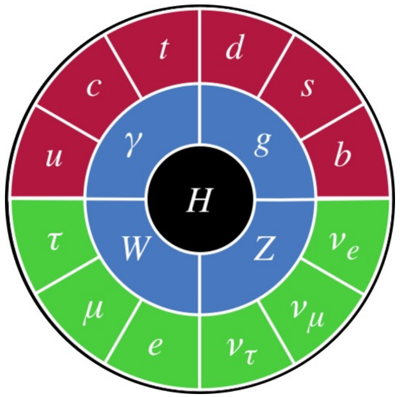
→ **Guide** on the path **to New Physics**!

Differential measurements for EFT

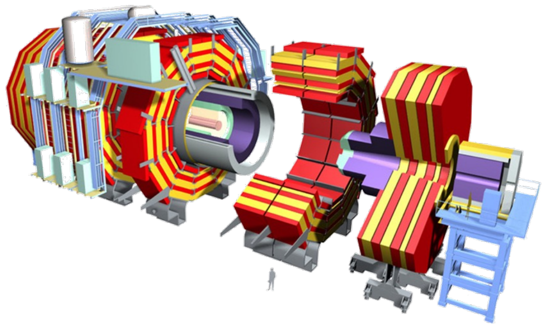
SMP-24-003

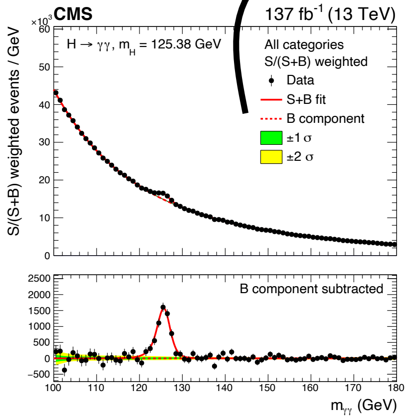
EFT provides consistent framework to combine measurements **across different sectors of the SM**

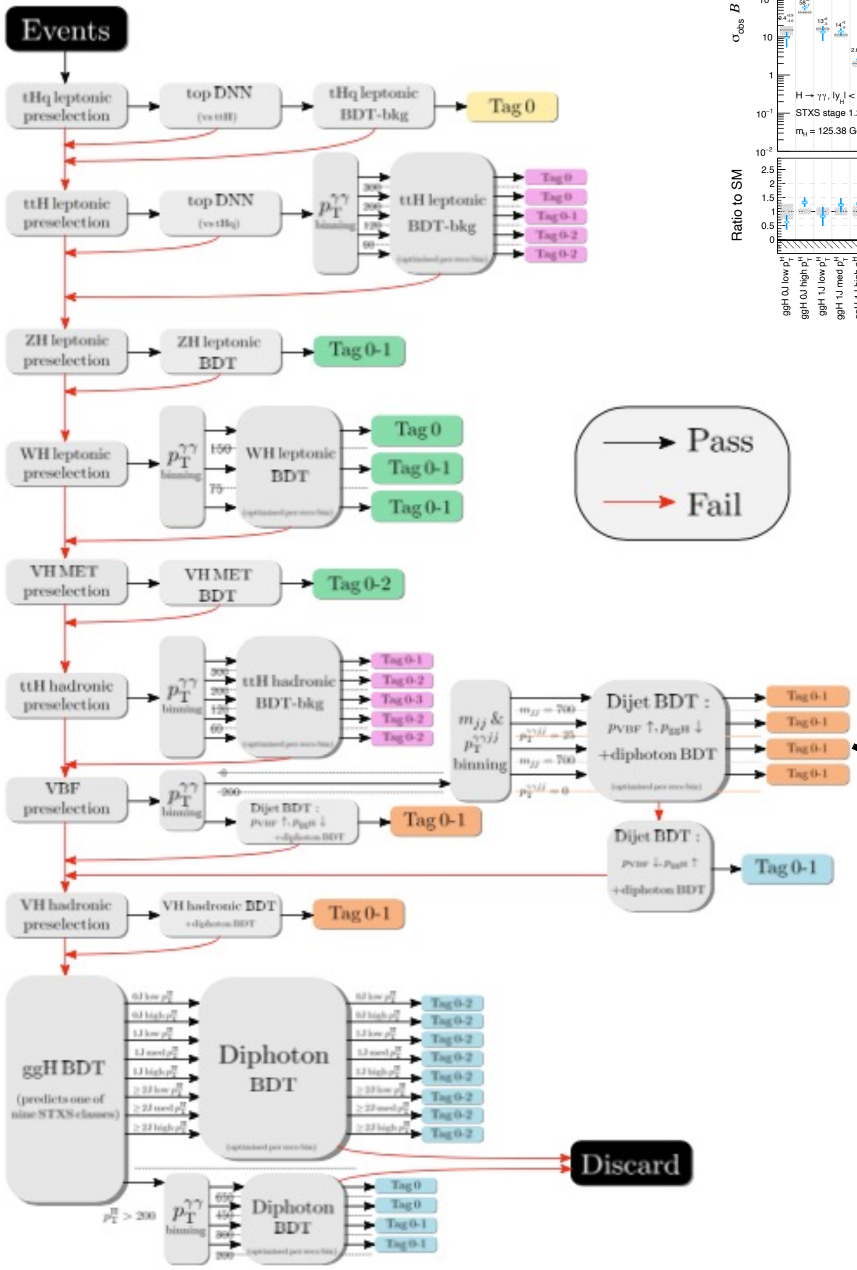


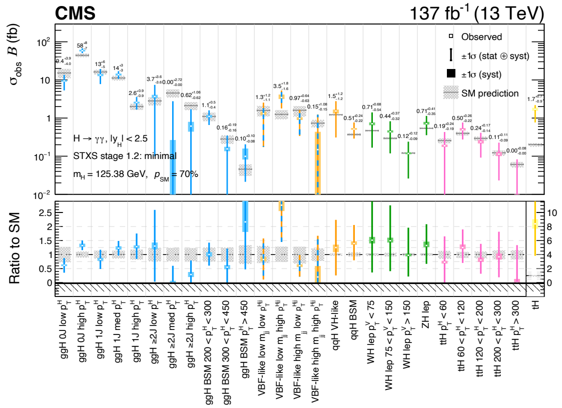


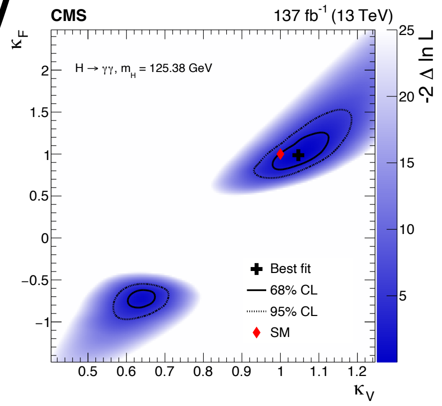
A Real CMS analysis selection flow



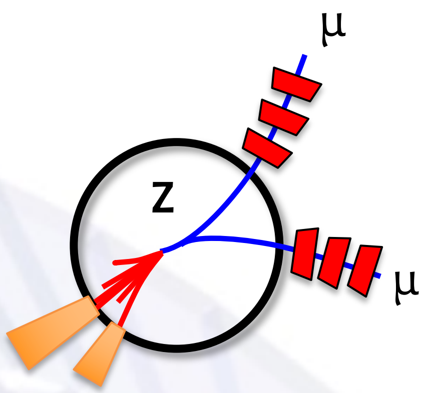


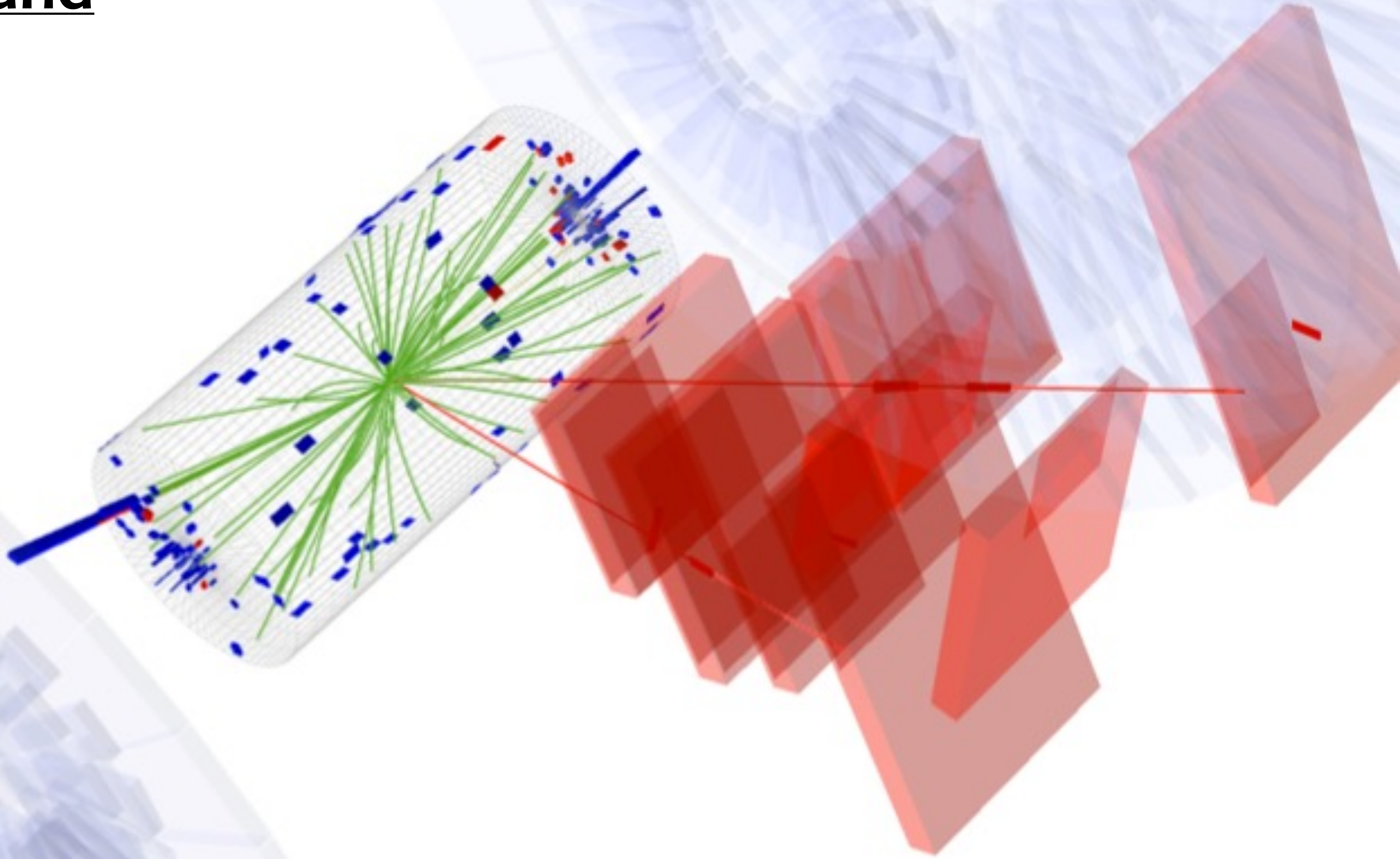






Data-driven background



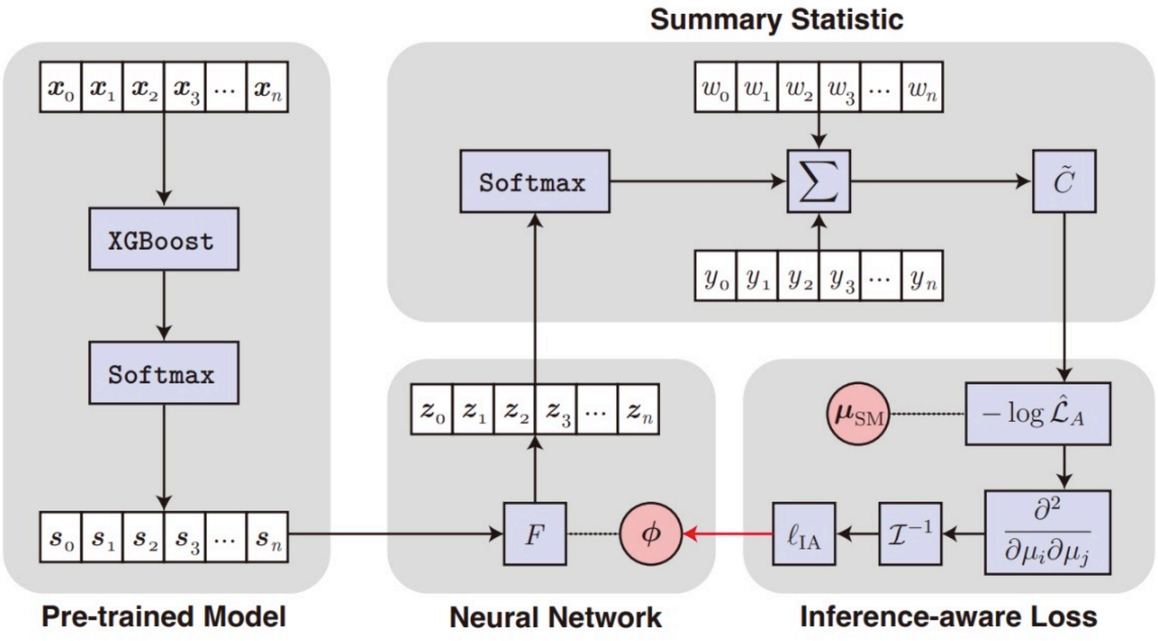


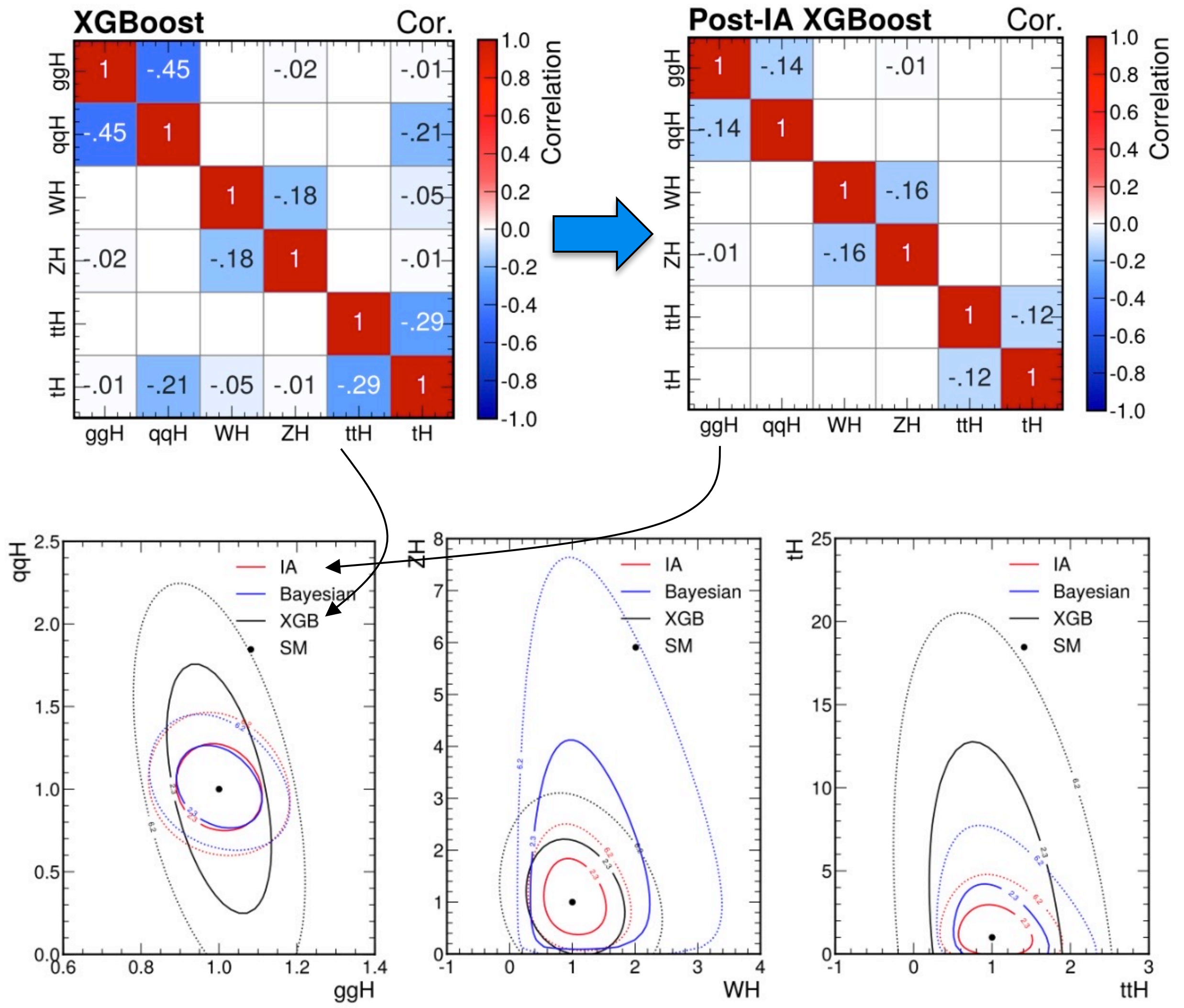
Estimate the normalization of the
Z→neutrinos background using data!

$$N_{Z(\to\nu\nu)} \approx N_{Z(\to\mu\mu)} \frac{B(Z\to\nu\nu)}{B(Z\to\mu\mu)} A(\mu)\epsilon(\mu)$$

We’re not there yet – and have new ideas in the pipeline

Inference aware optimization to improve sensitivity to Higgs production modes (STXS) in classification task





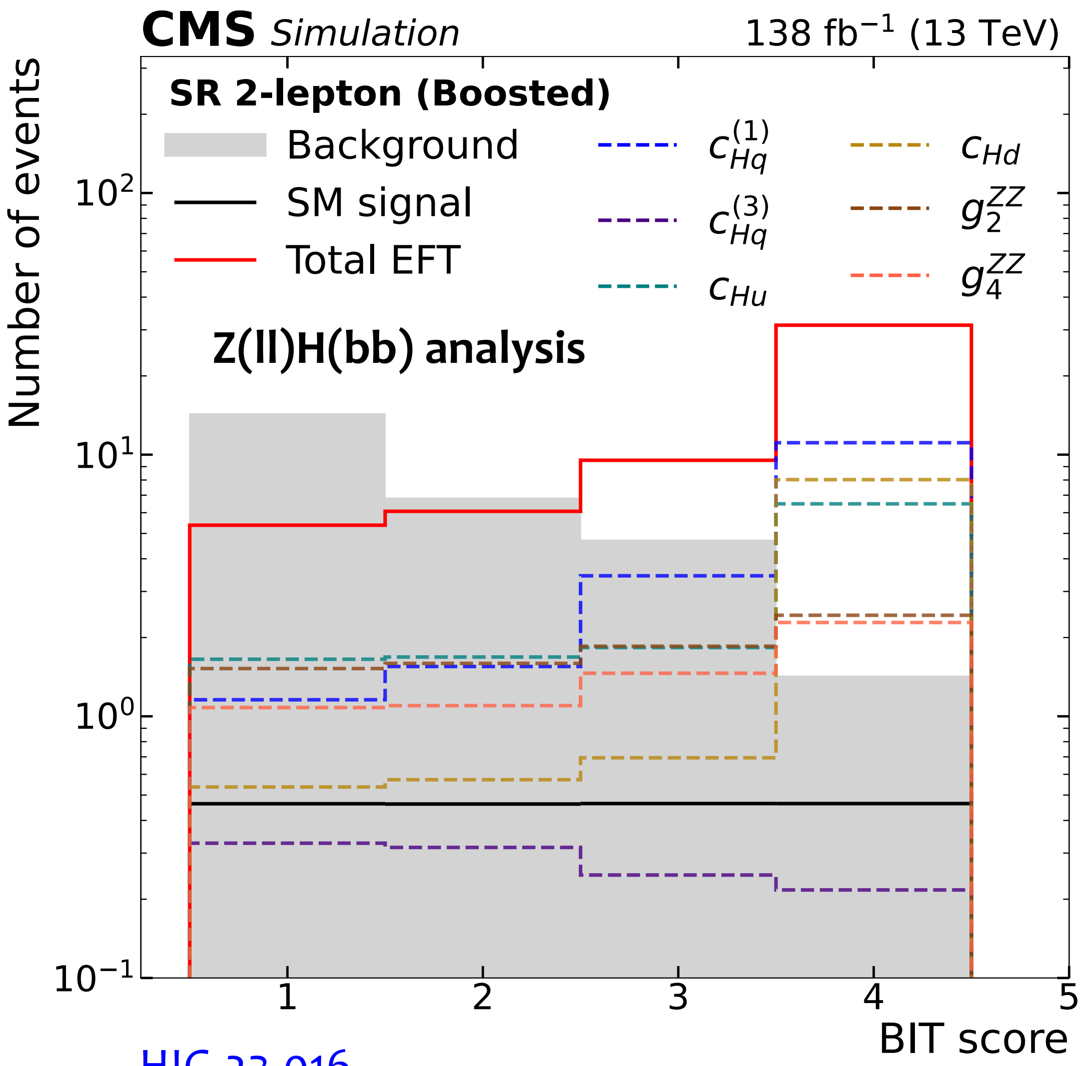
Imperial MRes Student Project

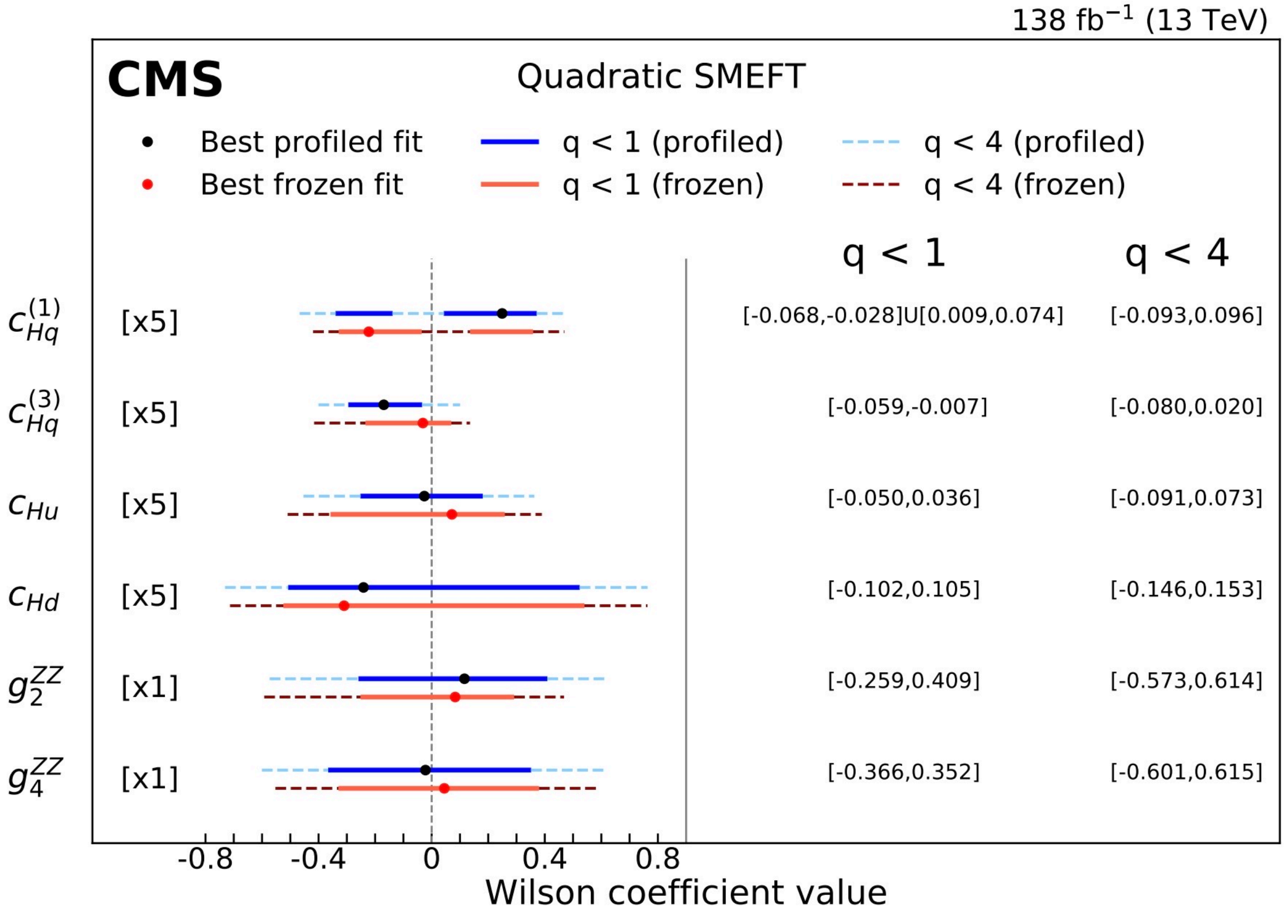
$$\mathcal{I}(\hat{\boldsymbol{\theta}})_{ij} = \mathbb{E}\left[-\frac{\partial^2}{\partial\mu_i\partial\mu_j}\mathrm{NLL}(\boldsymbol{\mu})\right]$$

Similar improvements seen in 2-parameter model in H→ττ with systematics included in training (MLG-23-005)

VHbb EFT optimized analysis

Simulation-based-inference ML approach to constrain multiple EFT coefficients at once → optimality across wide range of new physics scenarios!

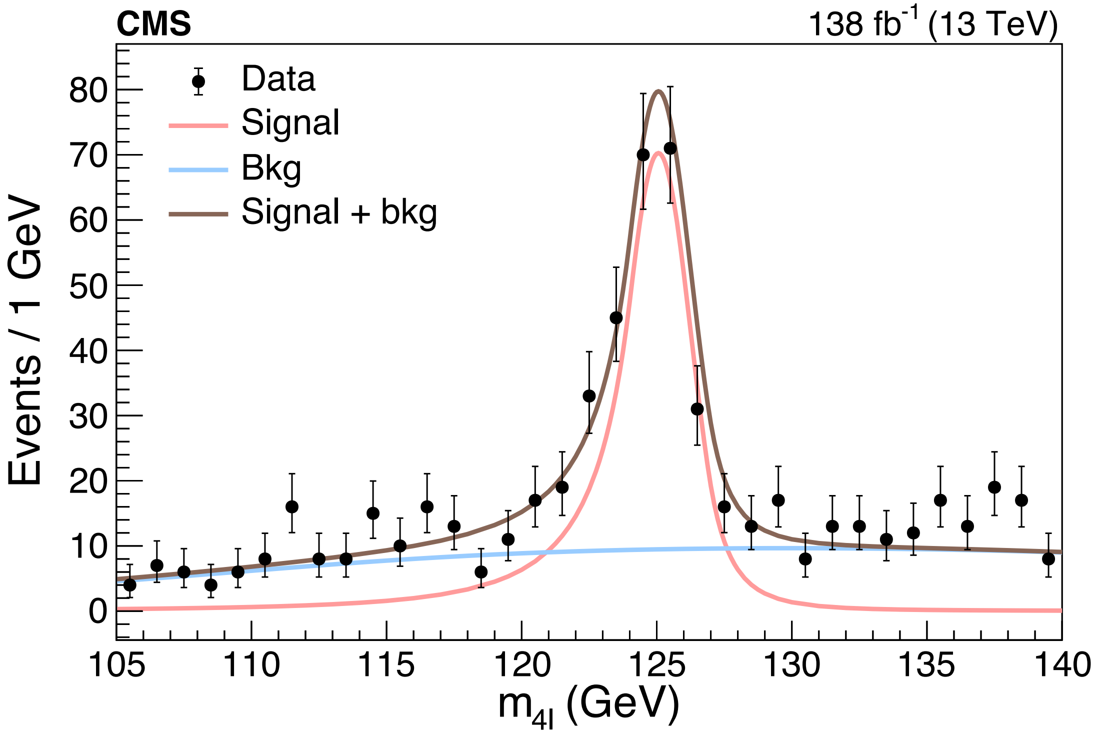


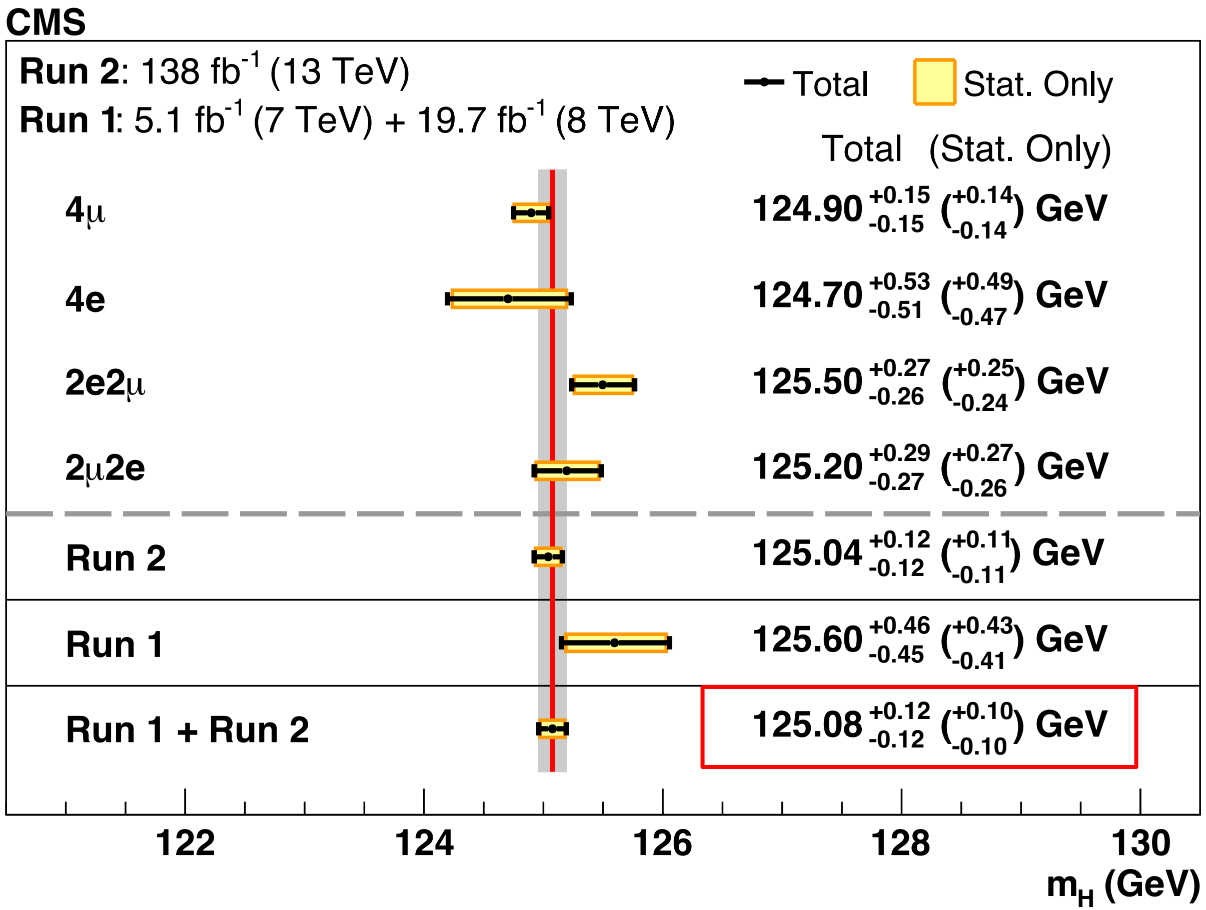


HIG-23-016

A *massive* achievement

Precision in Higgs boson mass at the level of **~0.1%** with Run-1 & Run-2 data using high resolution channels (H→4l)





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With the value of m_H known, we can make **precision tests of the SM** with the Higgs boson!