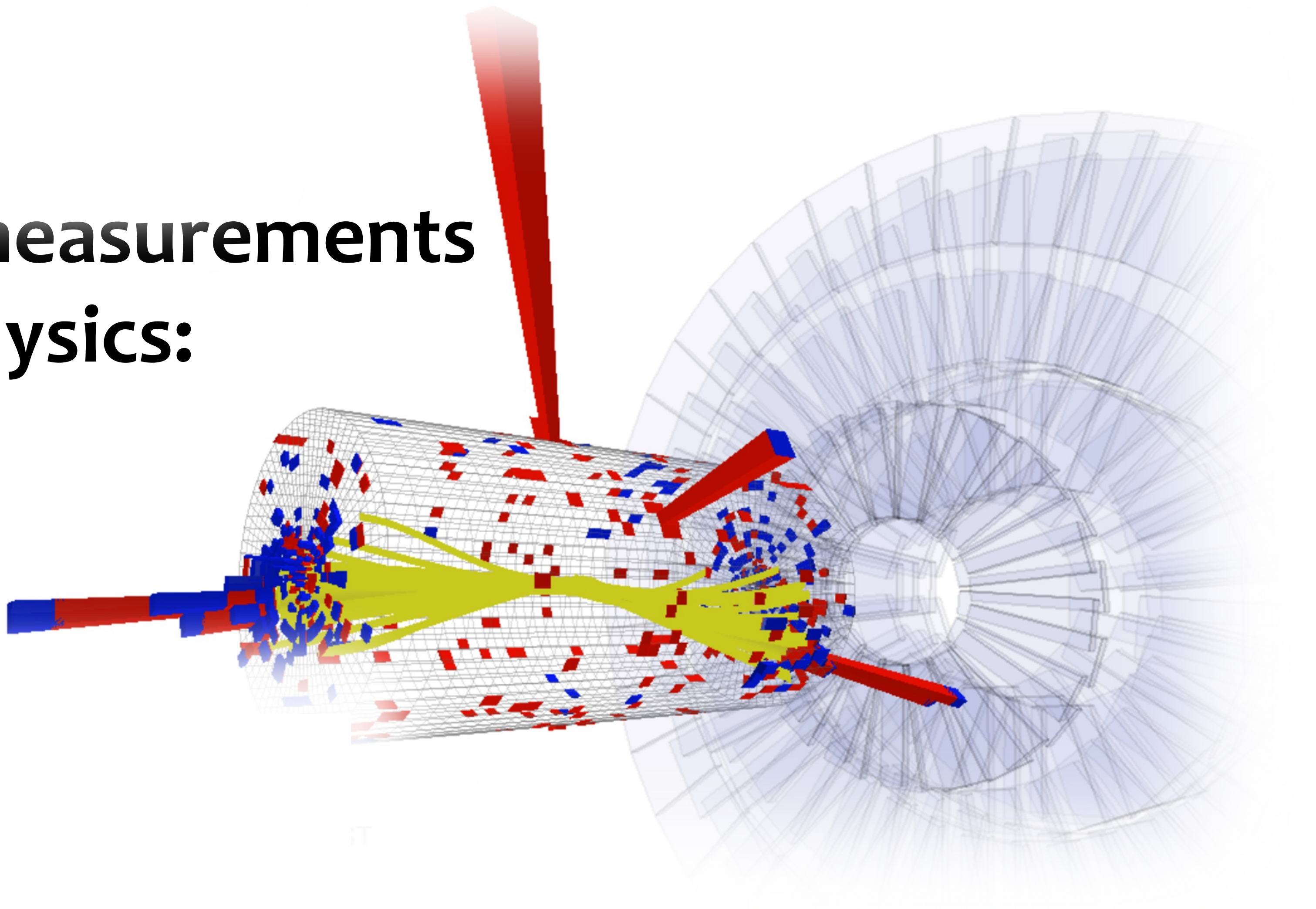
Imperial College London

Precision Higgs boson measurements in the search for new Physics:

10 years of measuring the Higgs boson



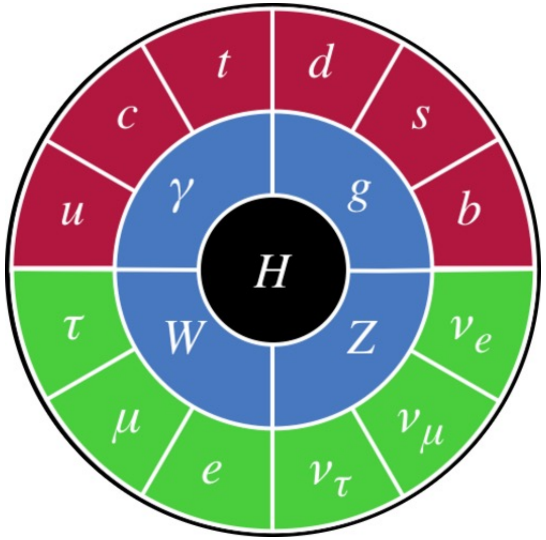
Nicholas Wardle

Imperial College London

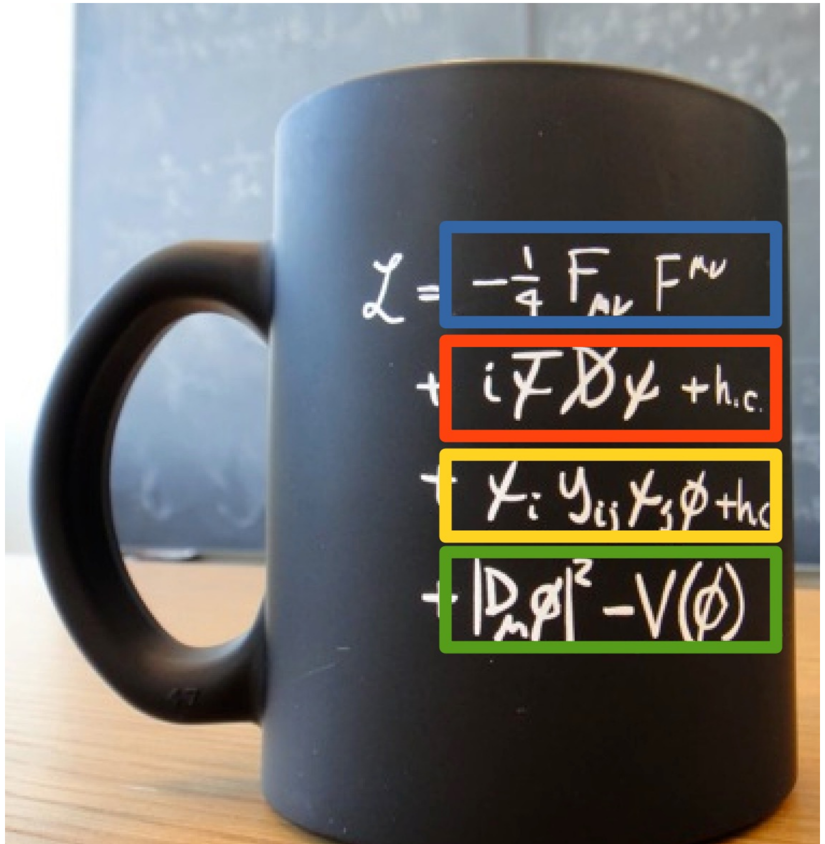
KIT Particle Physics Colloquium

19/08/2022

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)

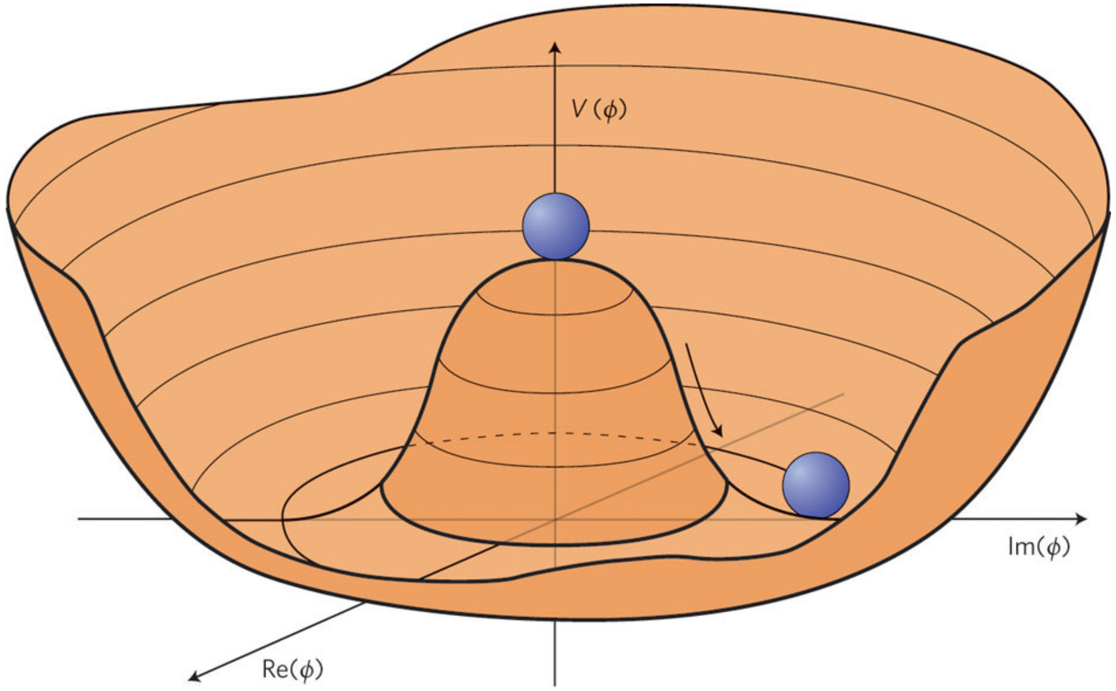
Interactions of matter particles (spin-1/2 fermions)

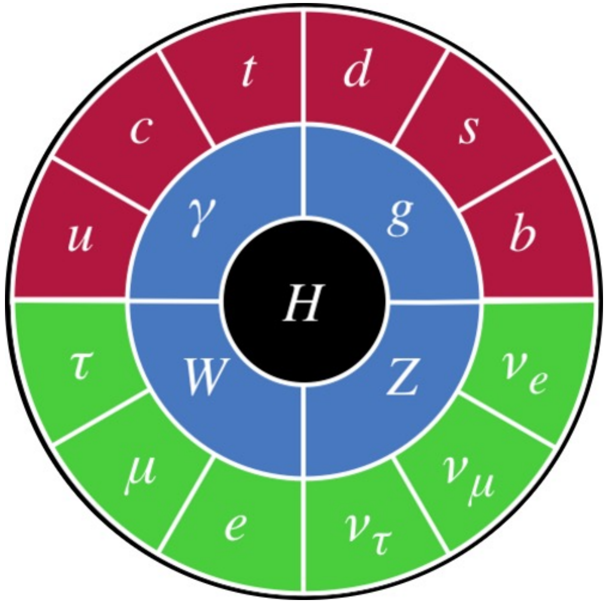
Masses of matter particles

Higgs interactions and mass of force carriers

The Higgs boson

The **Higgs boson** plays a major role in **the standard model (SM)** of particle physics …



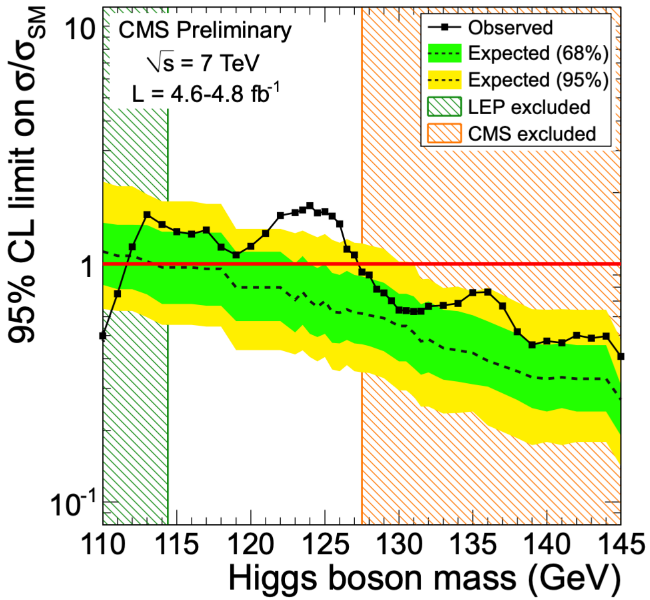


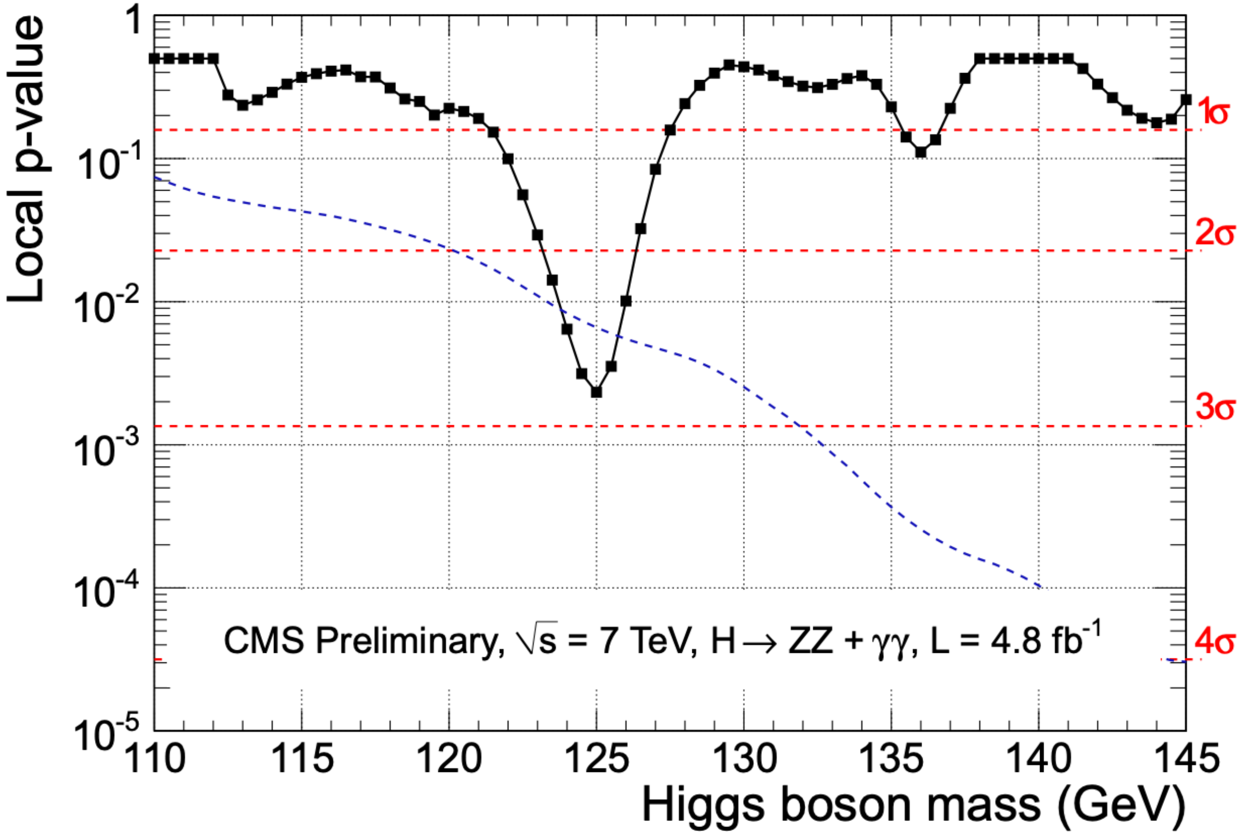
Higgs mechanism in SM:

→ **W and Z** bosons acquire **masses**
→ **quarks** and **charged leptons** acquire **mass**

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

Trying to keep our cool …





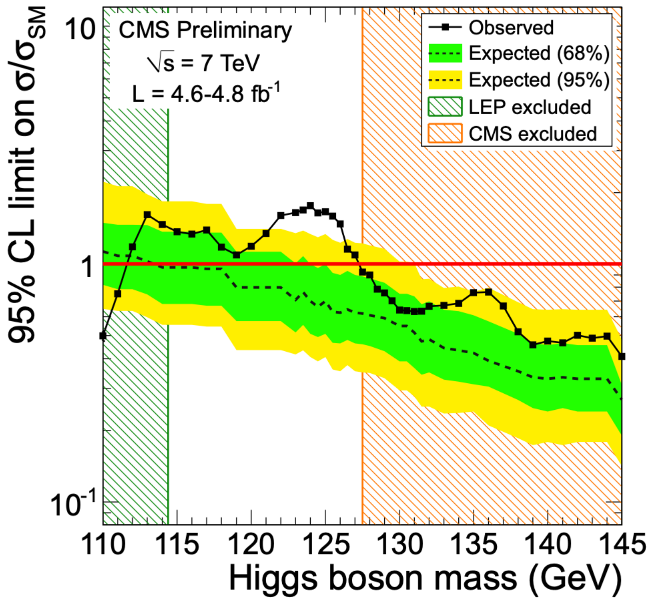
Status ~ today

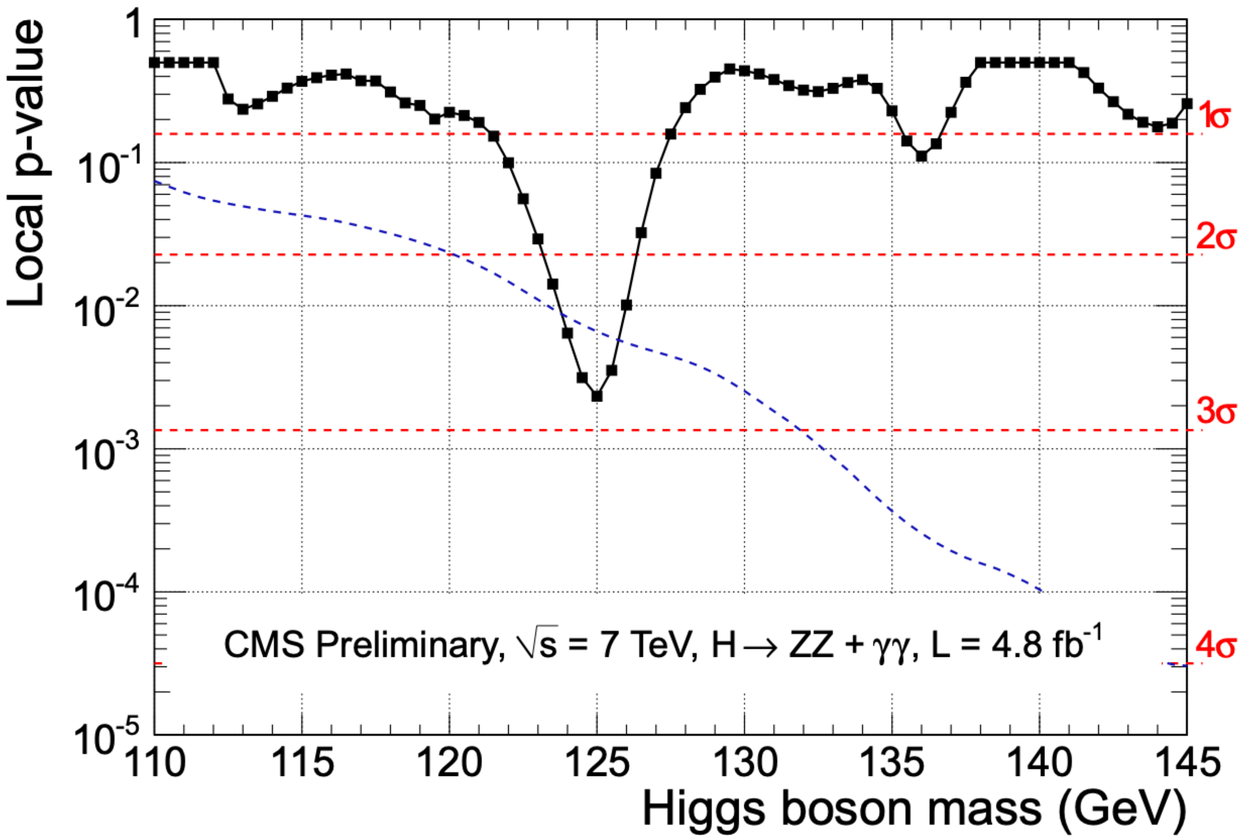
SM Higgs boson excluded with 95% cl up to a mass of 600 GeV except for the window **122.5 to 127.5** GeV

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

- **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**

Trying to keep our cool …





R. Heuer (4th June)

Status ~ today

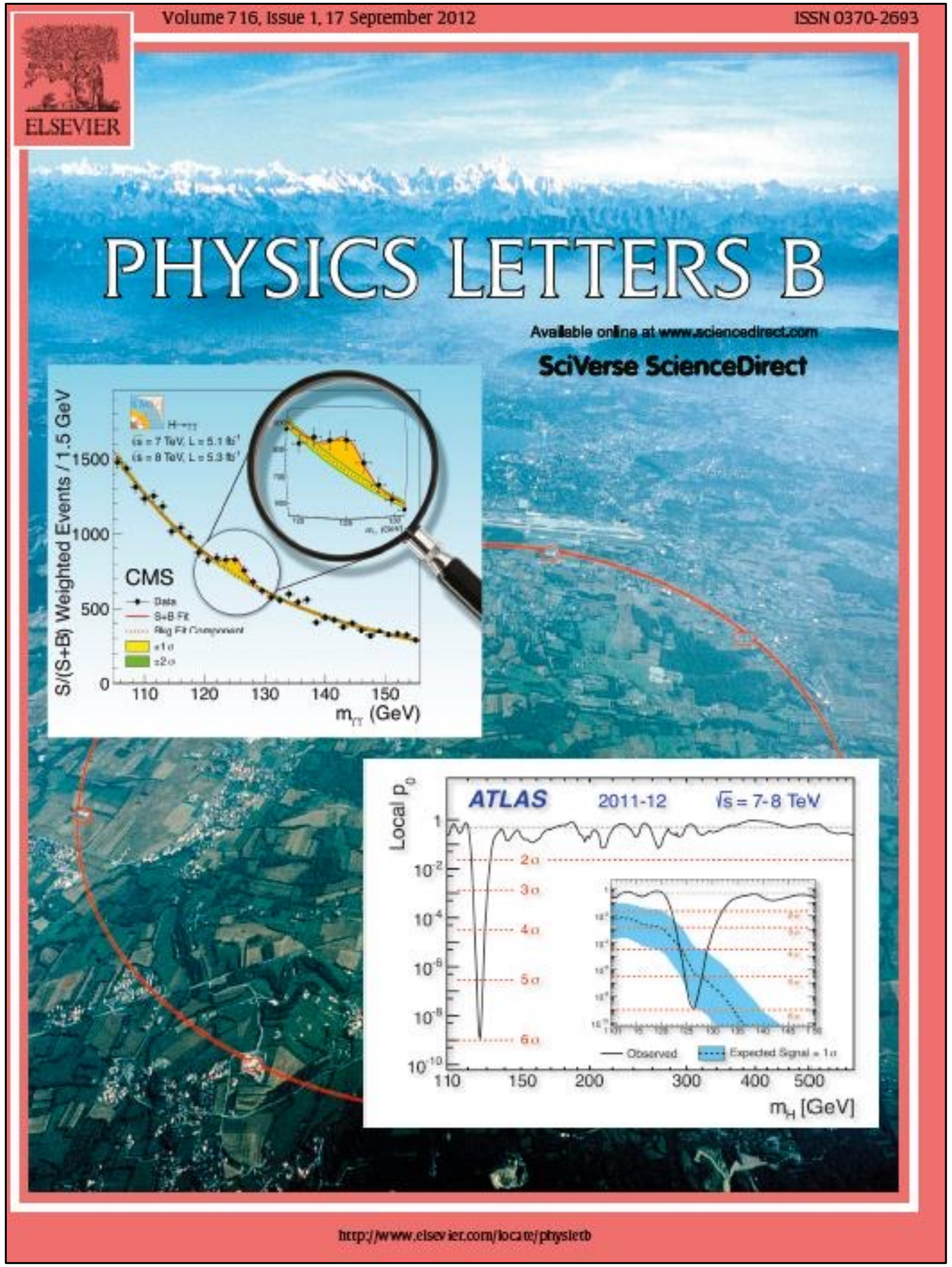
SM Higgs boson excluded with 95% cl up to a mass of 600 GeV except for the window **122.5 to 127.5** GeV

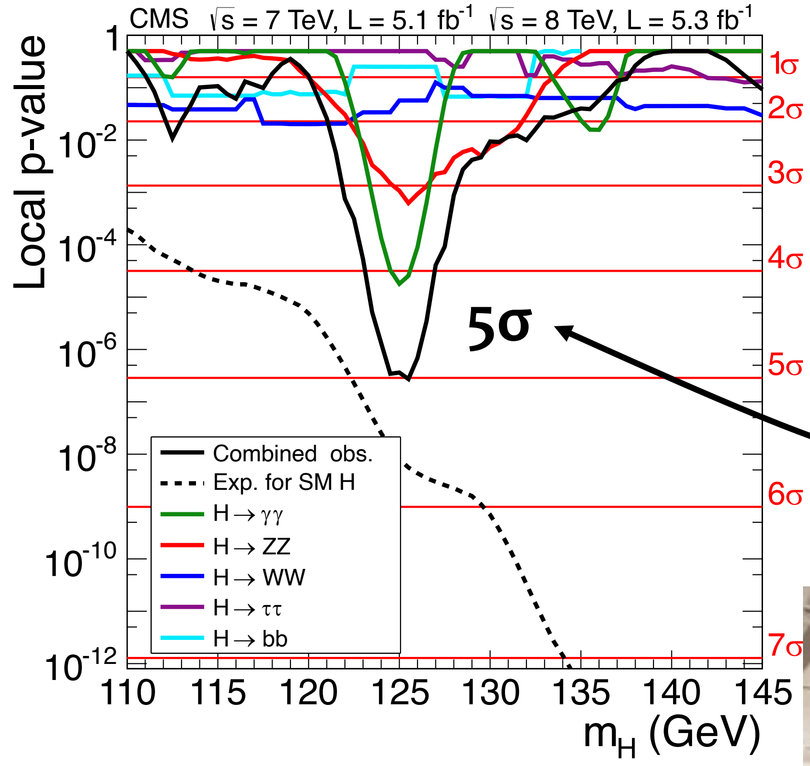
"interesting fluctuations" around masses of **124 to 126** GeV

N. Wardle (8th June)

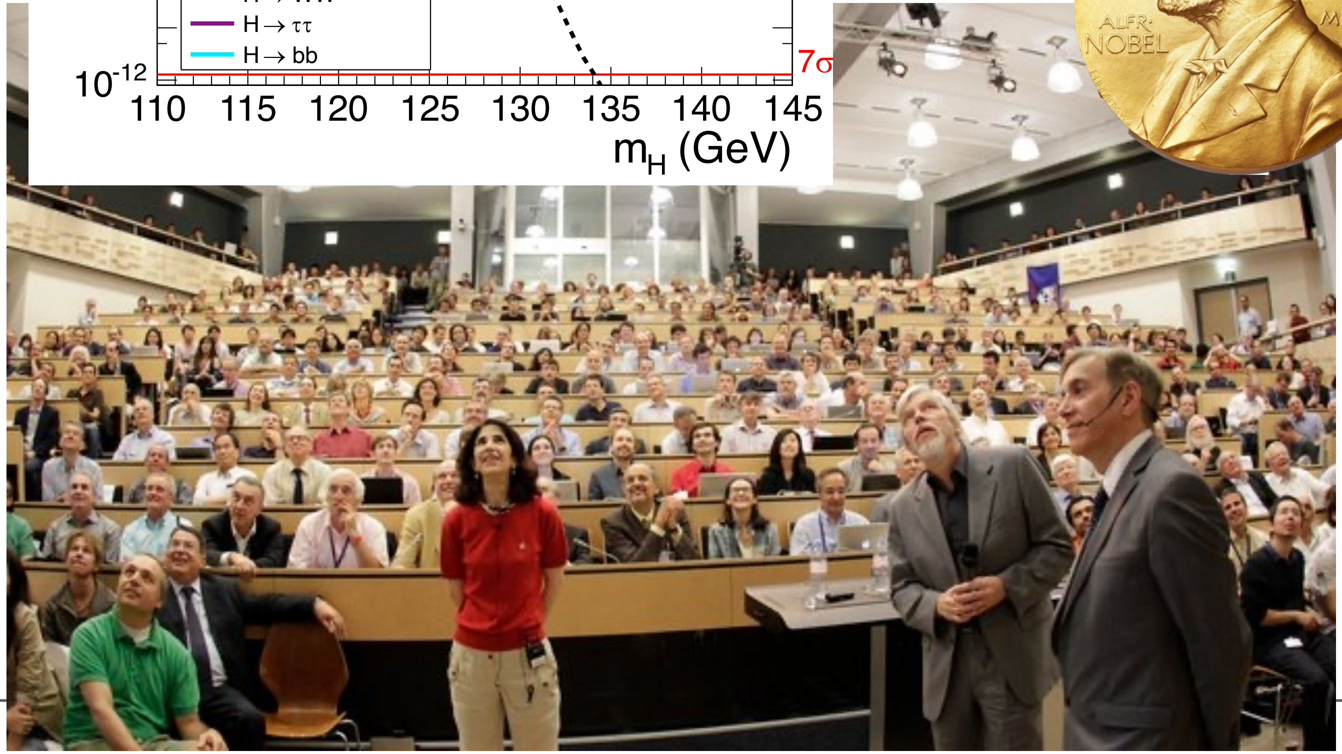
- **Excess observed at 125 GeV, local significance 2.8σ (1.6σ with LEE)**
- **CMS will continue to run in 2012 at 8 TeV. Can expect to be sensitive to SM this year**

July 4th 2012



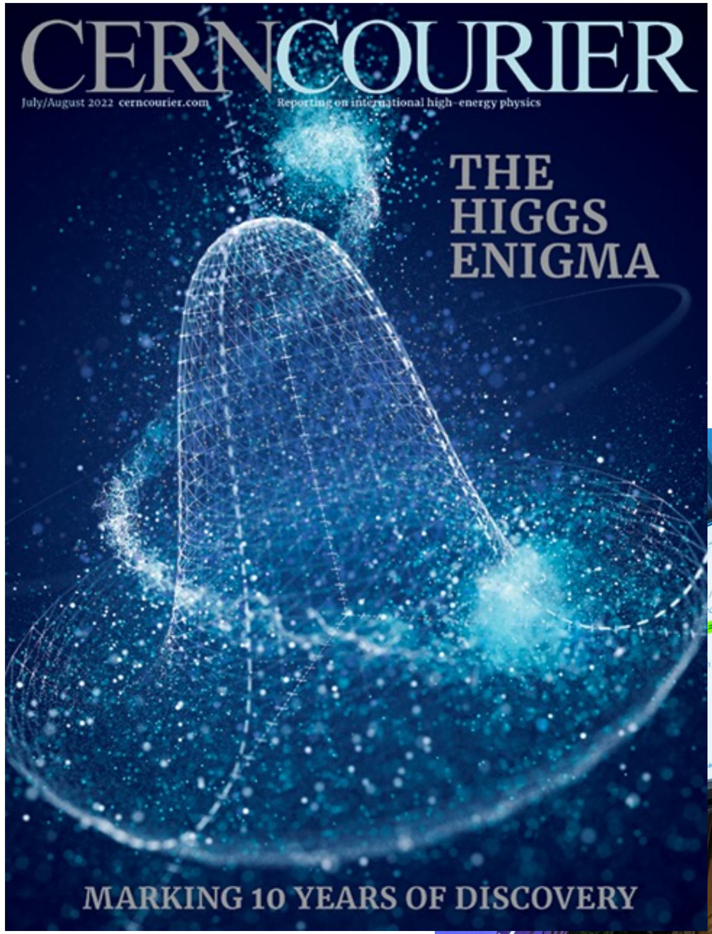


CMS combination involved 5 of the Higgs boson decay channel at the time of <u>discovery</u>!



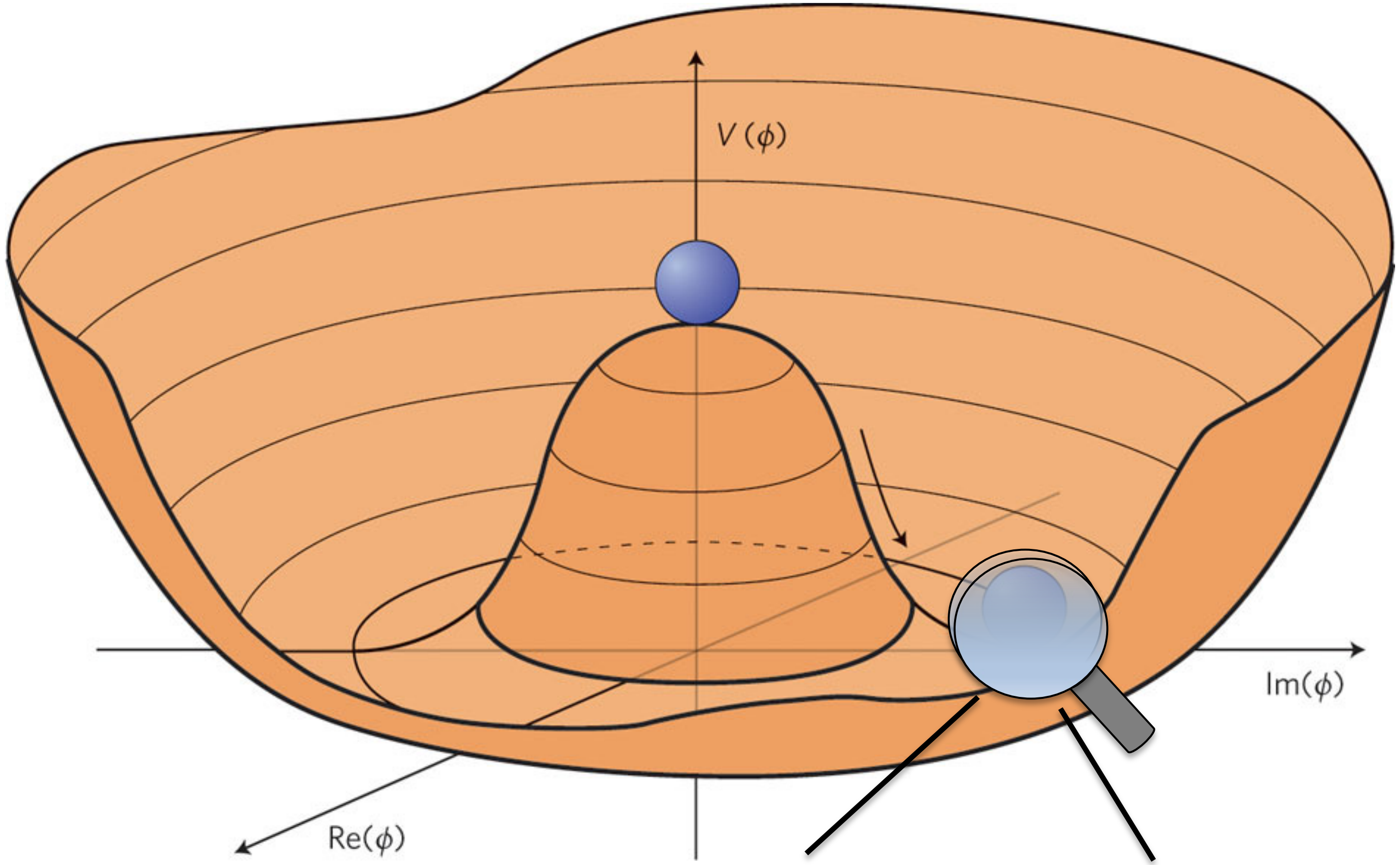
July 4th 2022

CERN 10 years HIGGS boson discovery



July 4th 2022

The Higgs boson

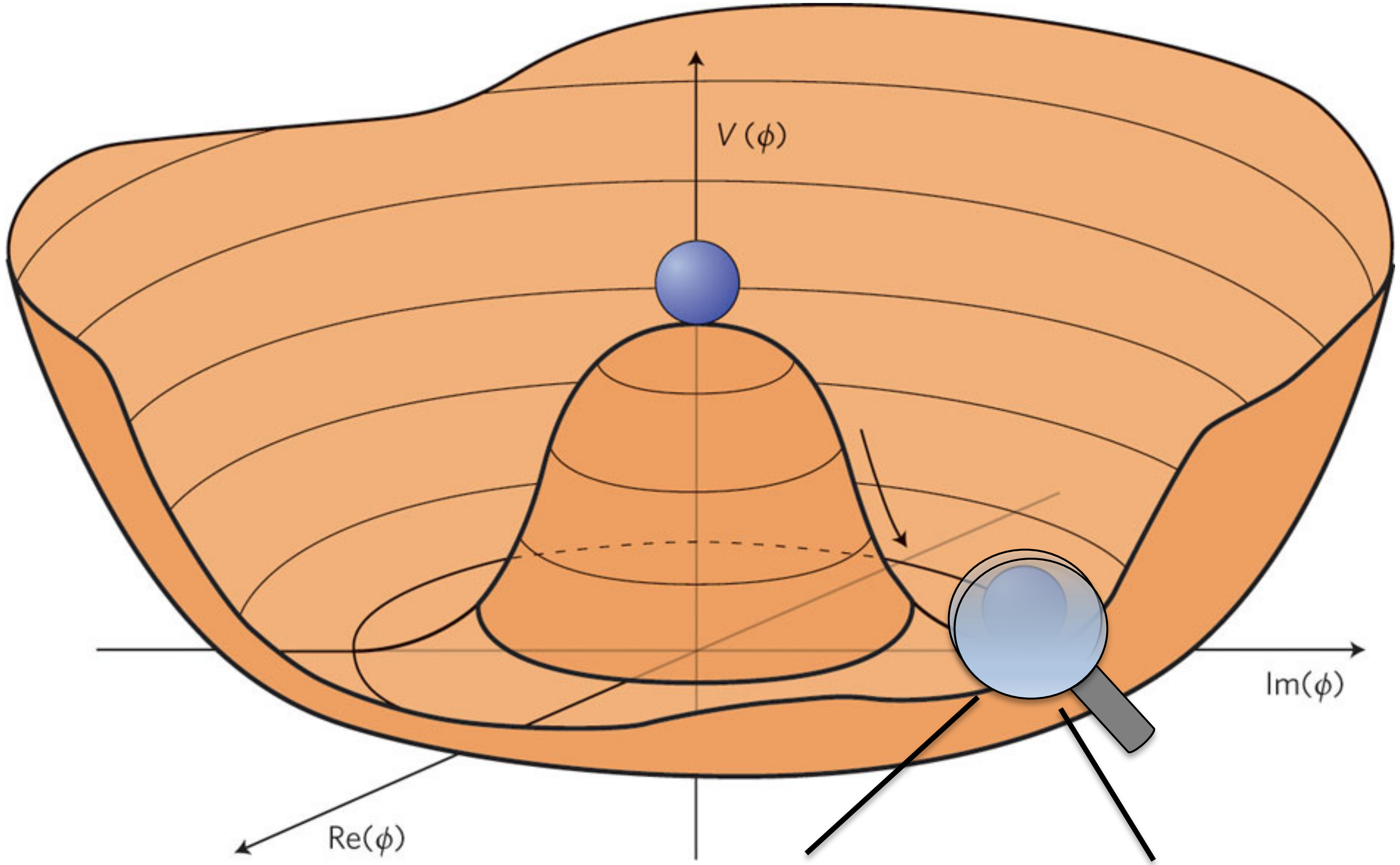


$$V(H) = \frac{m_H^2}{2}H^2 + \lambda v H^3 + \lambda H^4$$

Expanding around **potential minimum …**

→ **3 parameters** v, m_H and λ

The Higgs boson



Expanding around **potential minimum …**

→ **3 parameters** v, m_H and λ

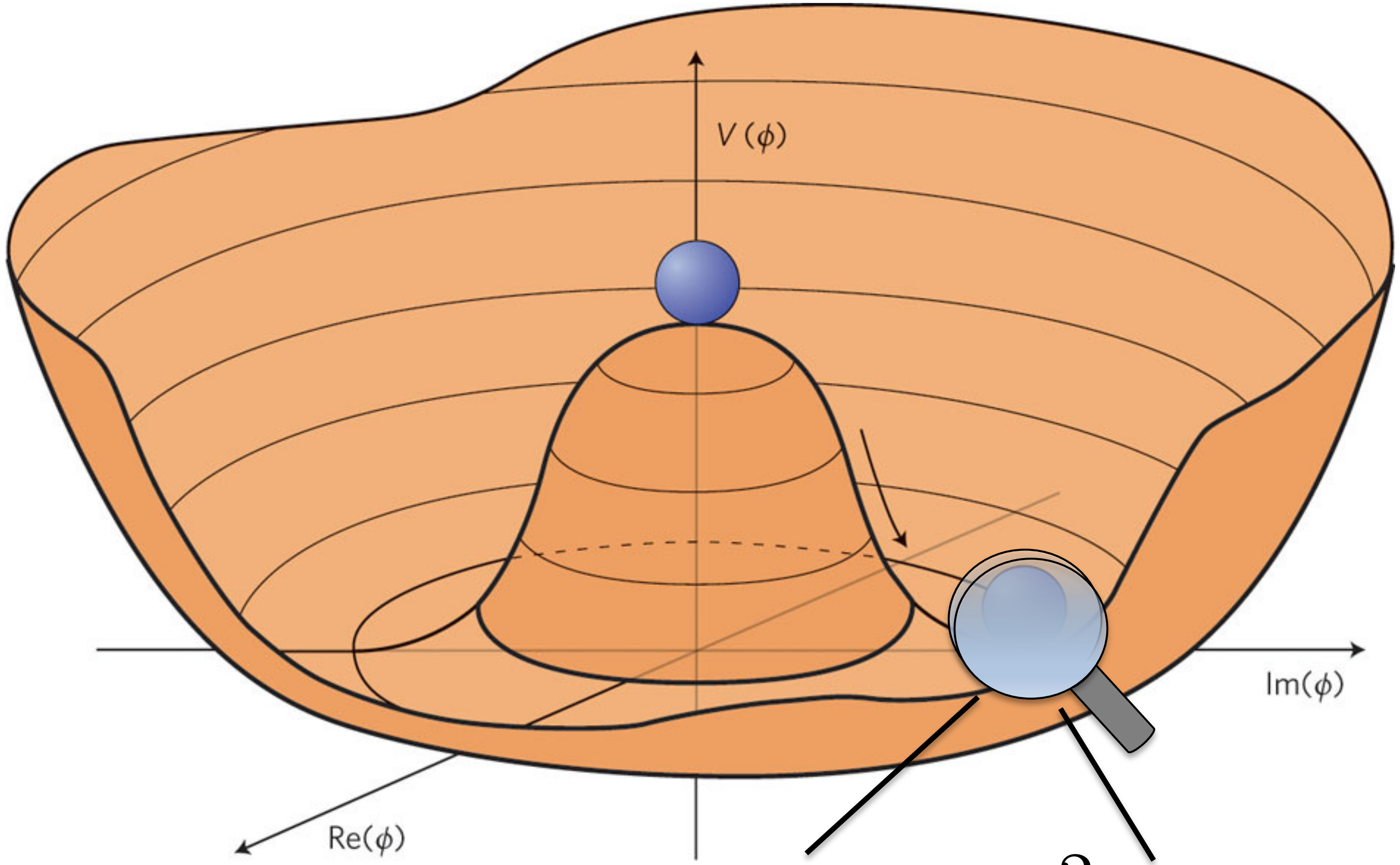
→ Relationships between them fixed in the SM

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

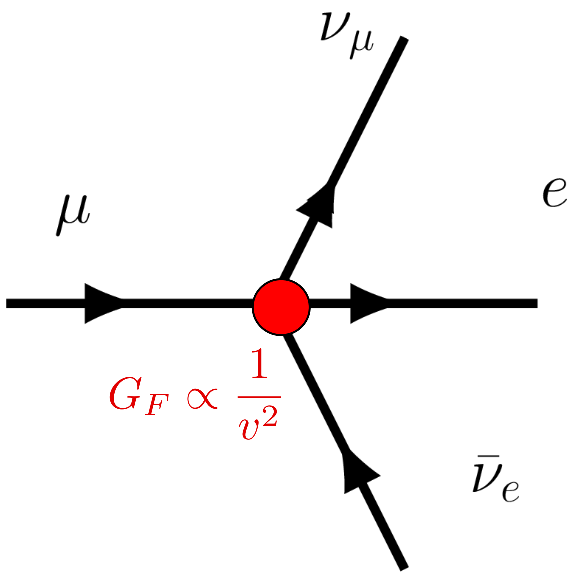
$$\lambda = \frac{m_H^2}{2v^2}$$

The Higgs boson

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



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

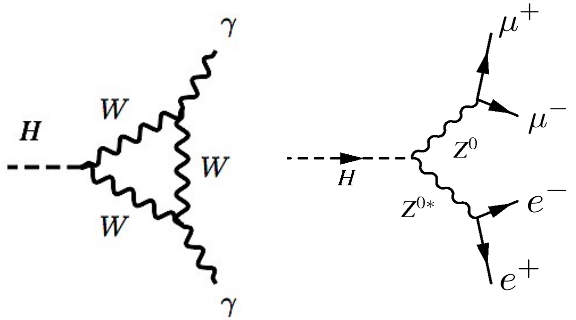


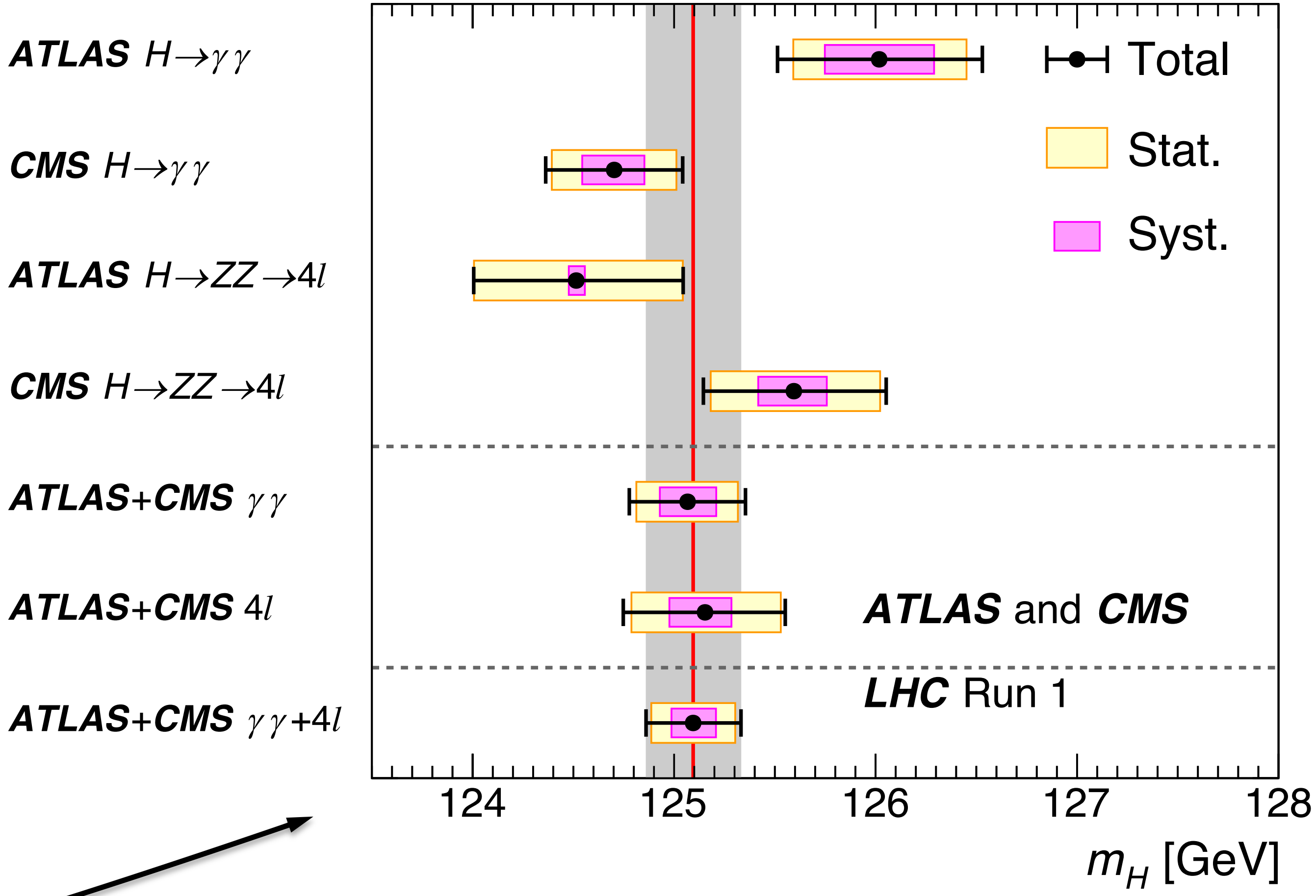
$$\frac{1}{\tau_\mu} = \Gamma_\mu \propto \frac{m_\mu^5}{v^4}$$

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

A *massive* achievement

ATLAS and CMS combined (Run-1) measurement of the Higgs boson mass **with 0.2% precision*!**



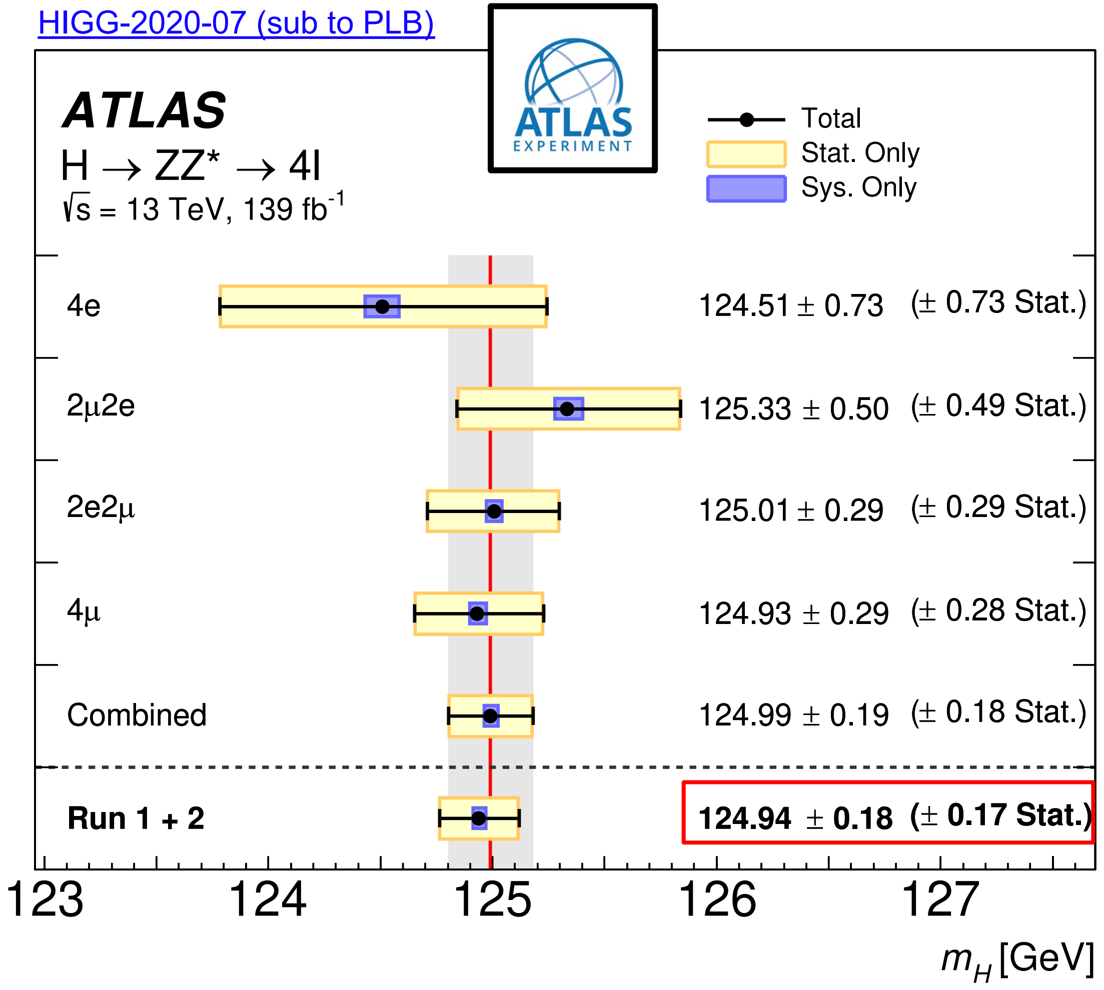


M_H = 125.09 ± 0.24 GeV

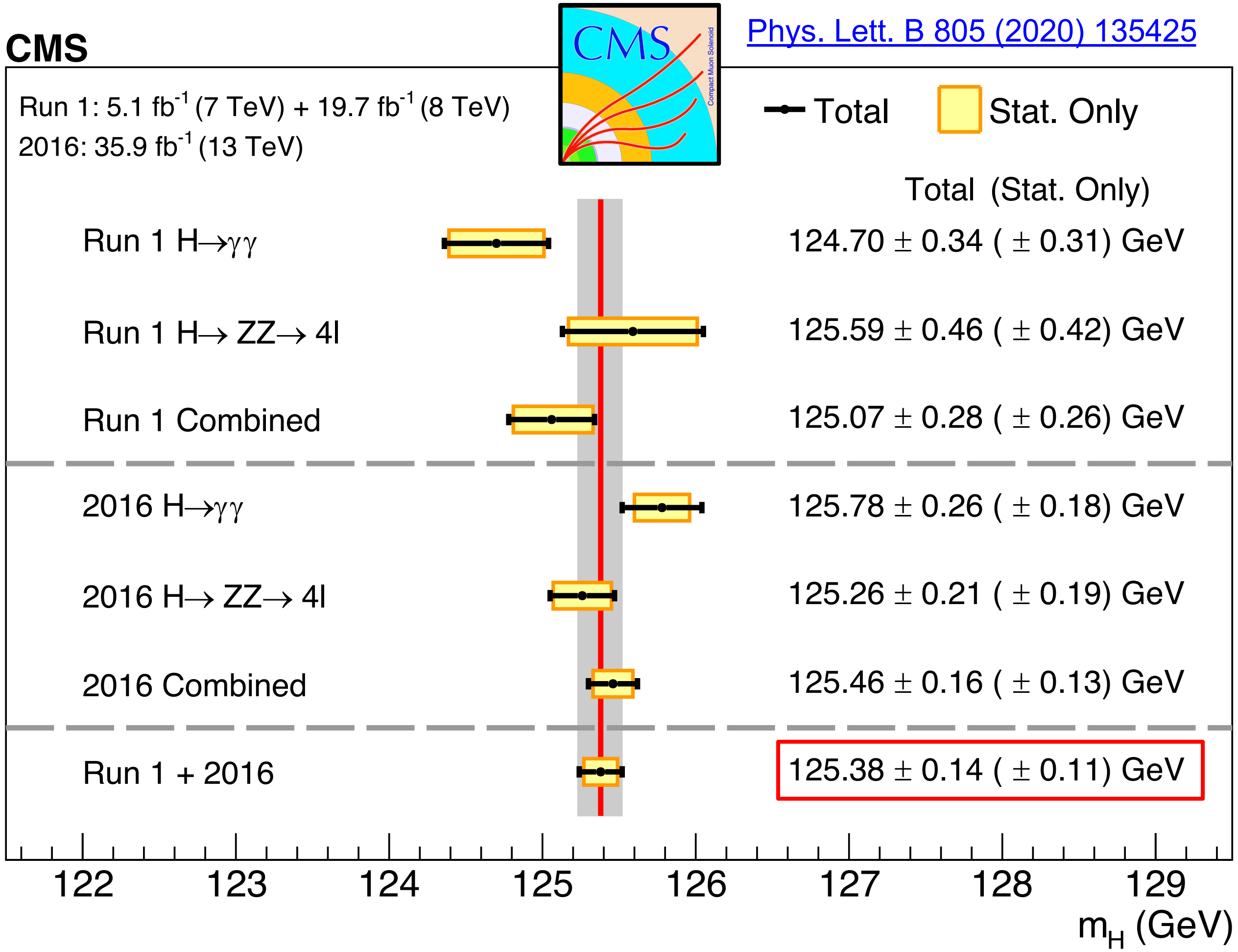
(±0.21 (stat) ±0.11(syst))

A *massive* achievement Take-II

[HIGG-2020-07 (sub to PLB)](#)



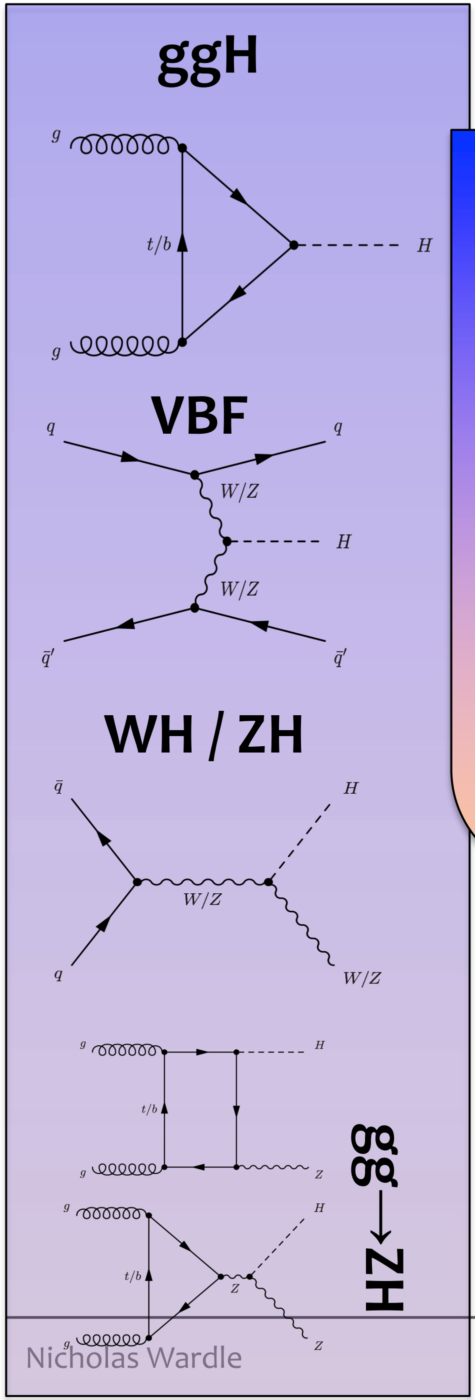
[Phys. Lett. B 805 (2020) 135425](#)

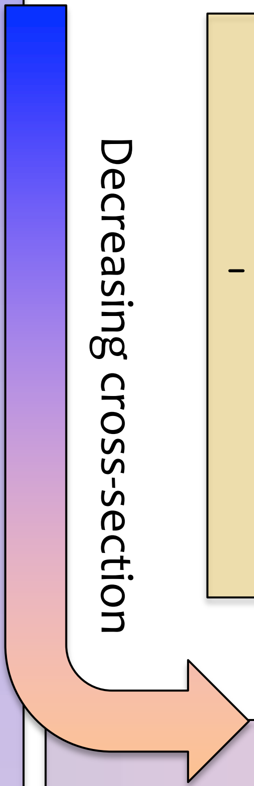


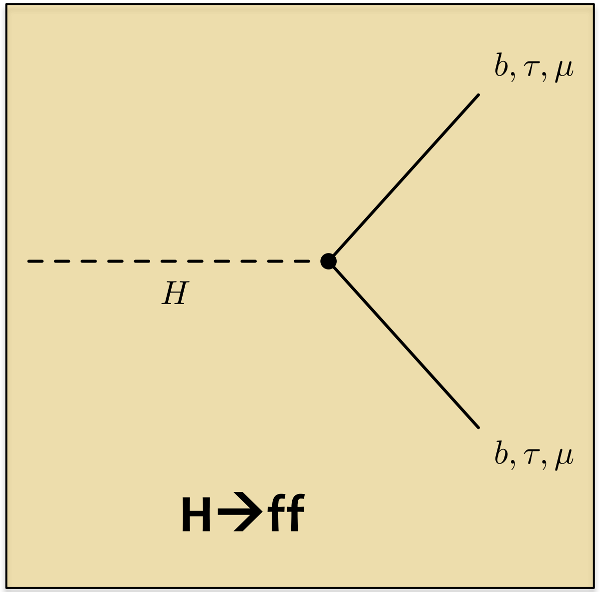
Precision in Higgs boson mass at the level of **11-14%** with the addition of Run-2 data!

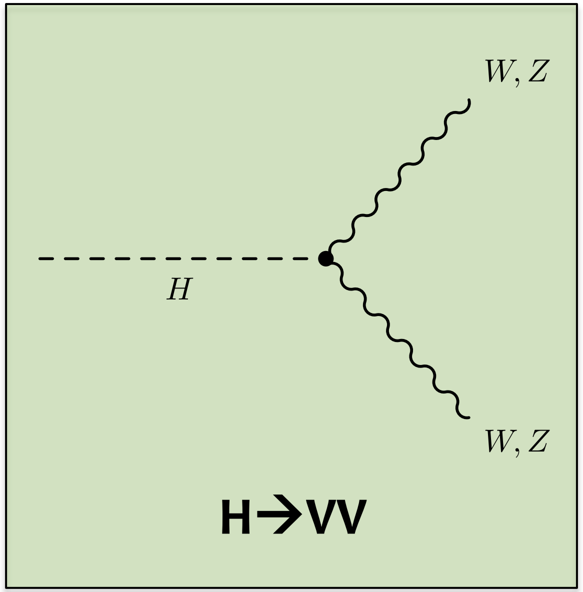
With the value of m_H known, we can make precision tests of the SM with the Higgs boson…

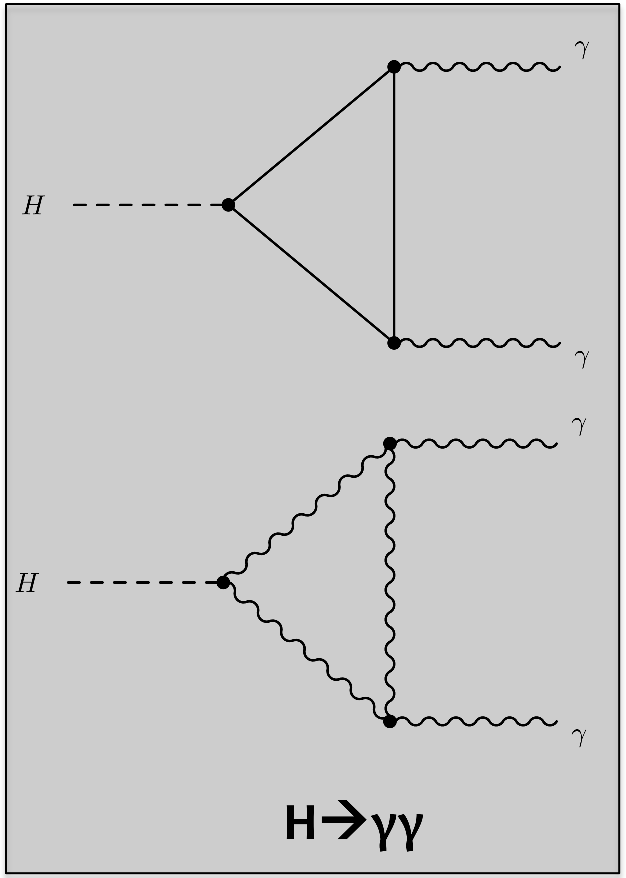
Higgs Production and Decay

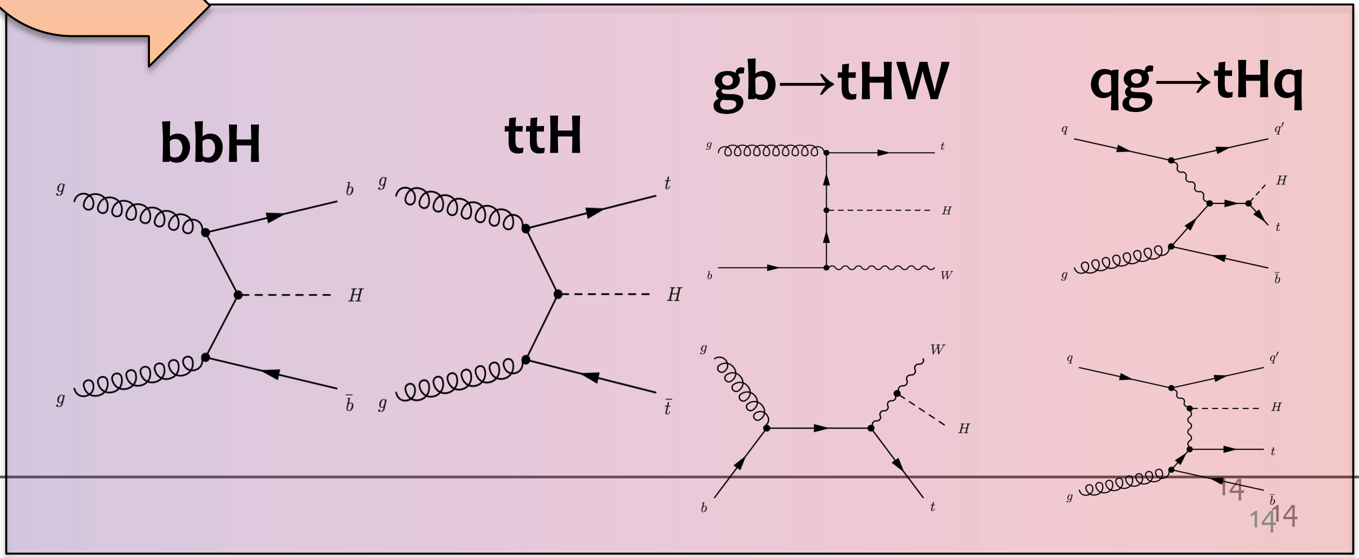






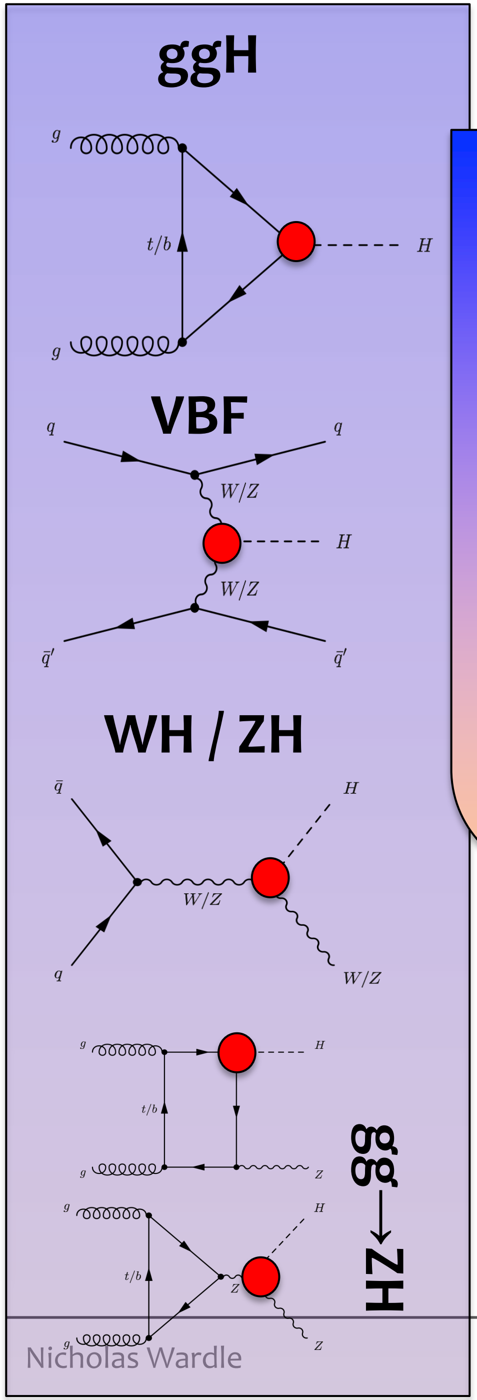


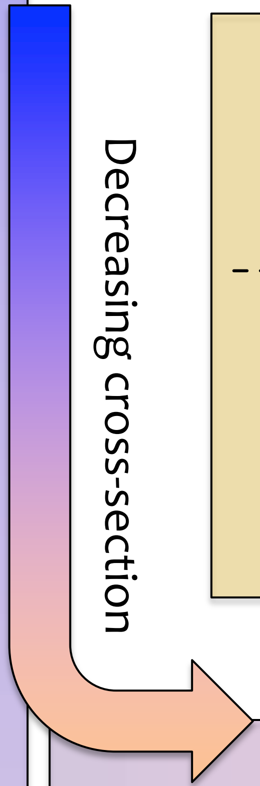


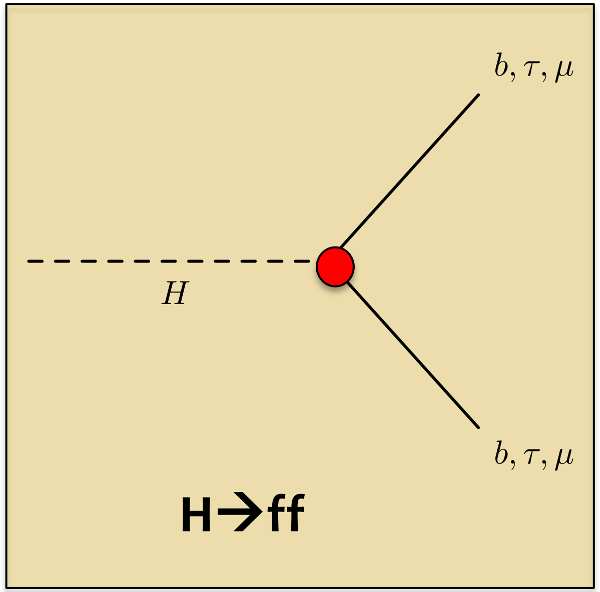


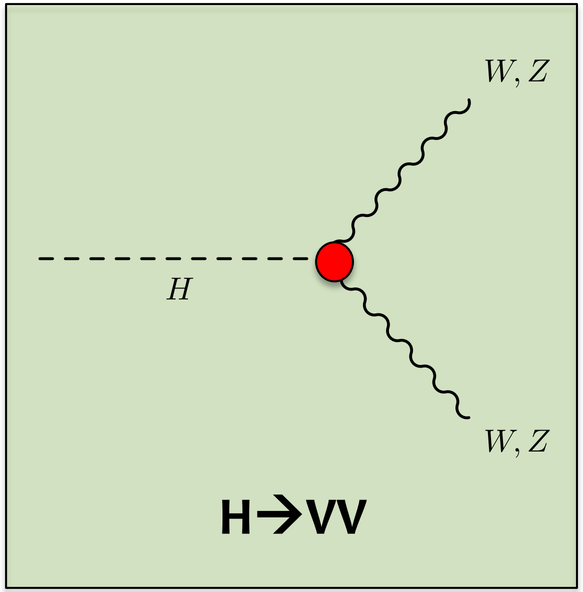
Many production and decay modes to study Higgs for m_H~125 GeV

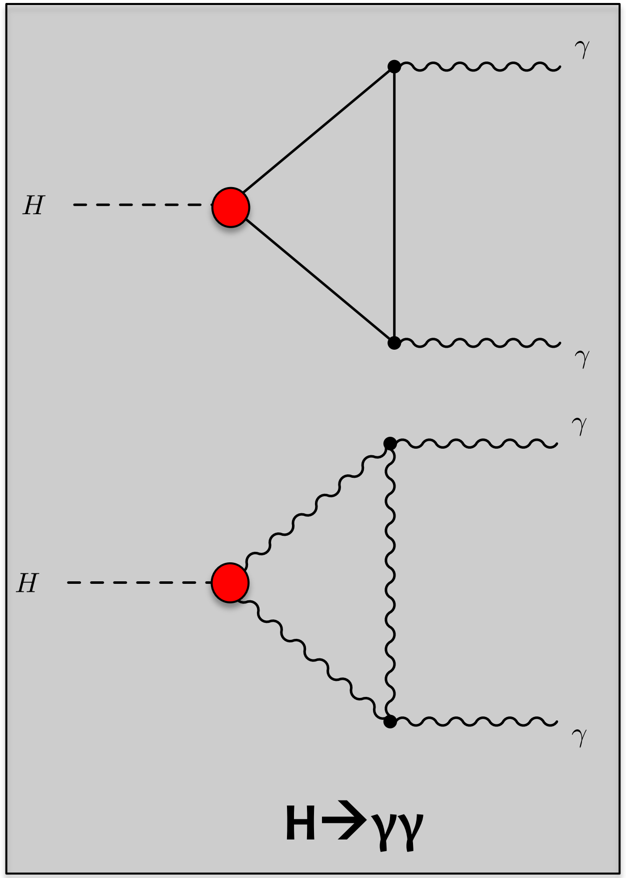
Higgs Production and Decay

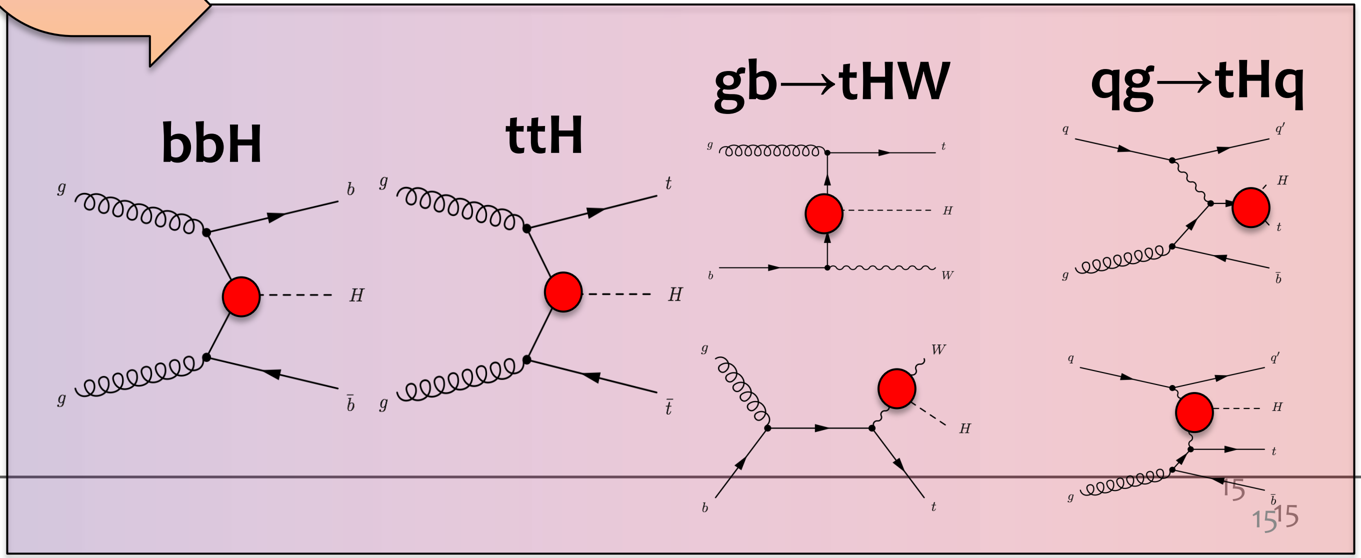






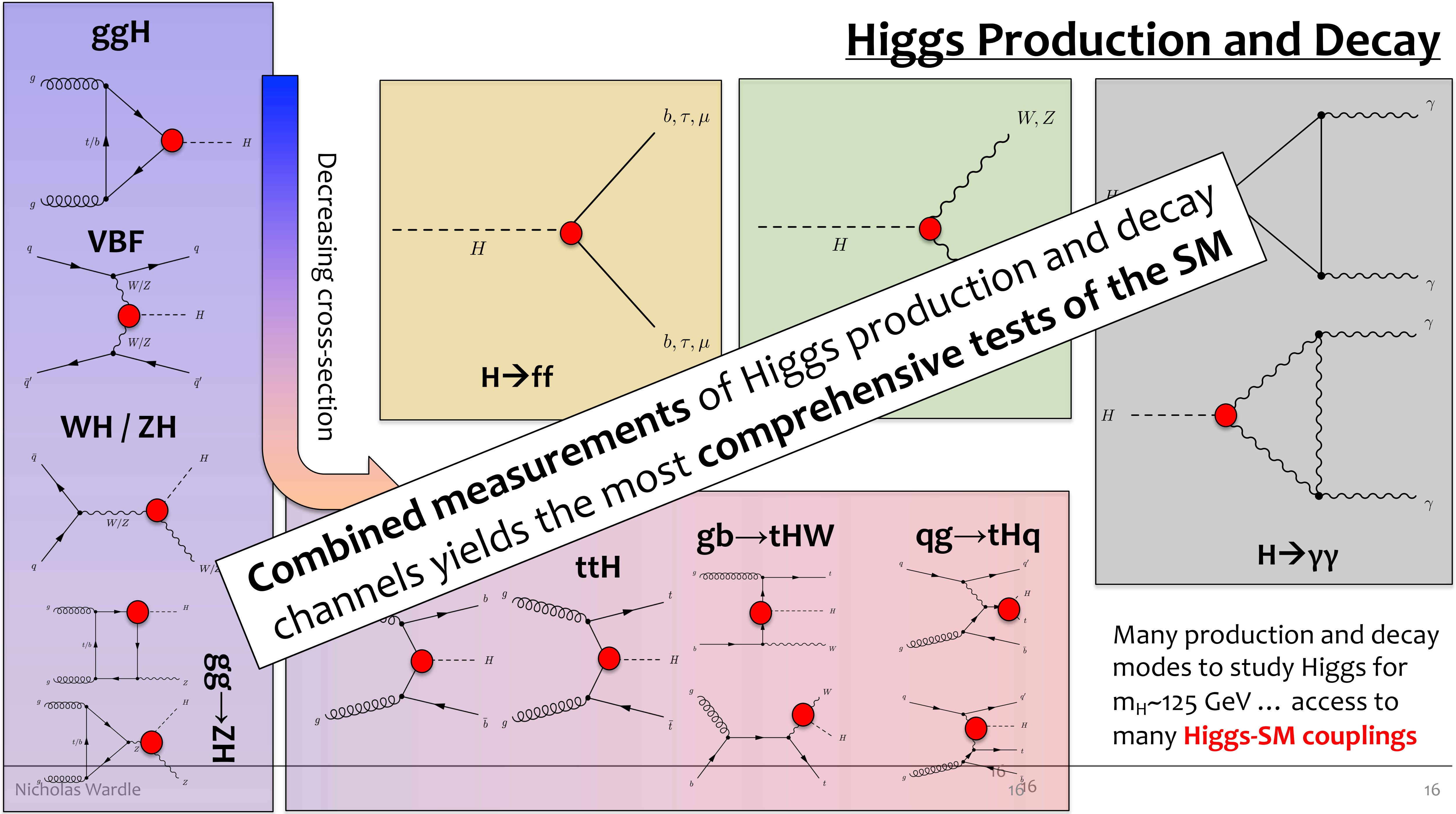






Many production and decay modes to study Higgs for m_H~125 GeV … access to many **Higgs-SM couplings**

Higgs Production and Decay



Combined measurements of Higgs production and decay channels yields the most **comprehensive tests of the SM**

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

Breaking down the likelihood

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

$$L(D|\boldsymbol{\mu},\boldsymbol{\theta}) = \prod_{n} Prob\left(d_n | \sum_{i,f} \mu_i \mu^f S^f_{i,n}(\boldsymbol{\theta}) + \sum_{k} B_k(\boldsymbol{\theta}) \right) \times Gauss(\tilde{\boldsymbol{\theta}}|\theta)$$

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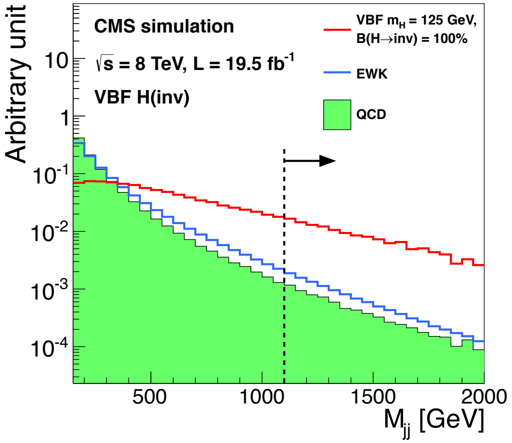
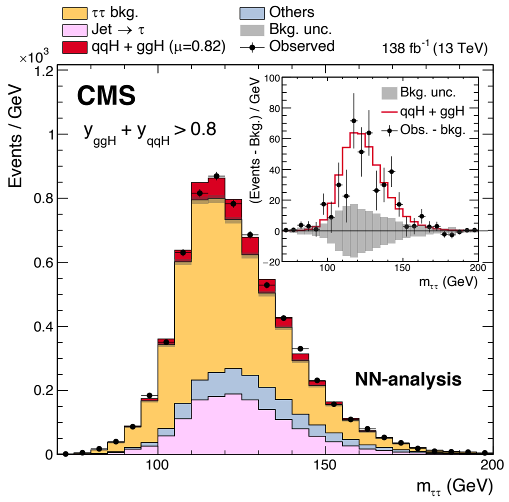
The "**data**" in each channel can be …

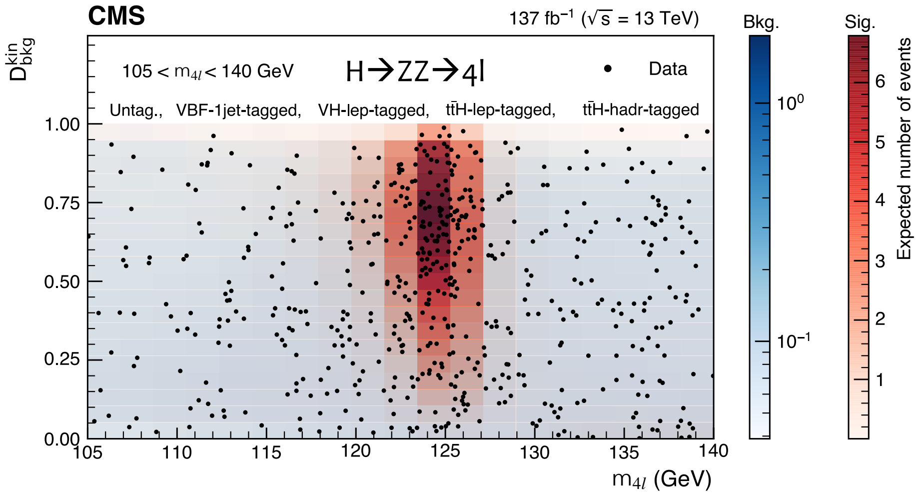
Event count(s) after some selection





Number of events in a given bin of some distribution

Multidimensional observable used to separate signal and background



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"**Signal strengths**" parameterized in terms of "coupling modifiers" $\boldsymbol{\kappa}$

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

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

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

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

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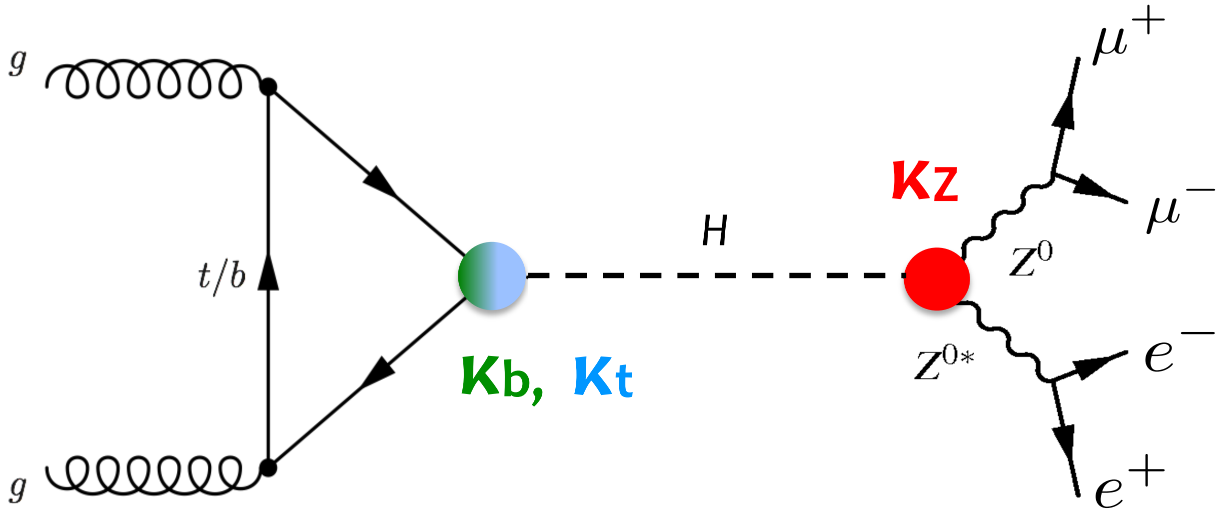

$$\mu_{ggH}\cdot\mu^{ZZ} \sim \frac{(1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\kappa_Z^2}{\kappa_H^2}$$

Breaking down the likelihood

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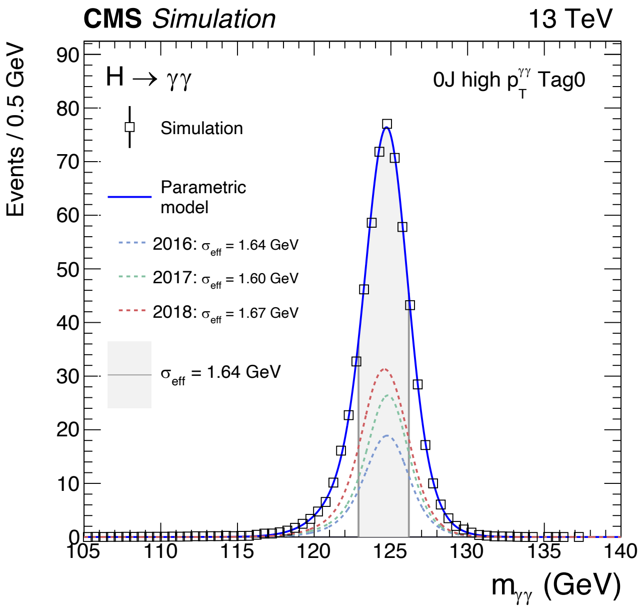
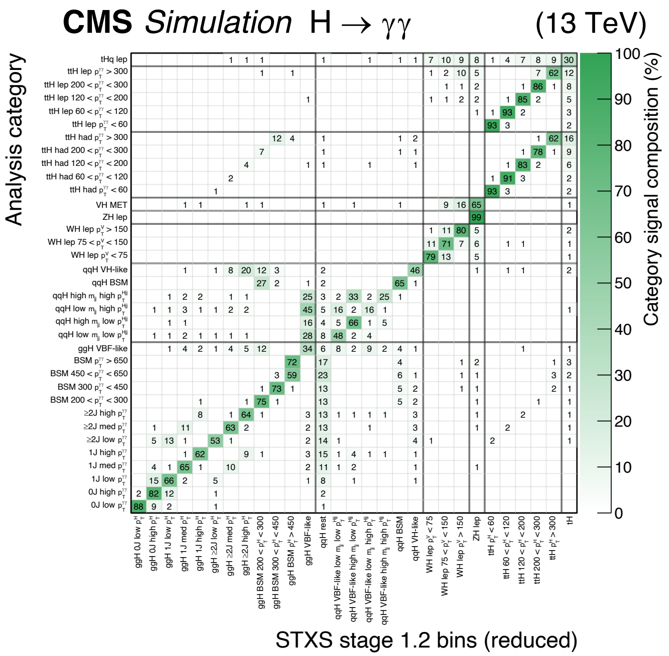


$\times$



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

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

- Relative composition across signal regions
- Overall Efficiency x acceptance

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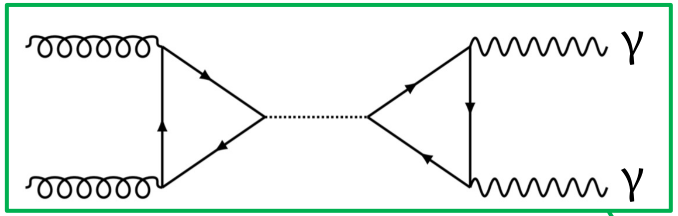
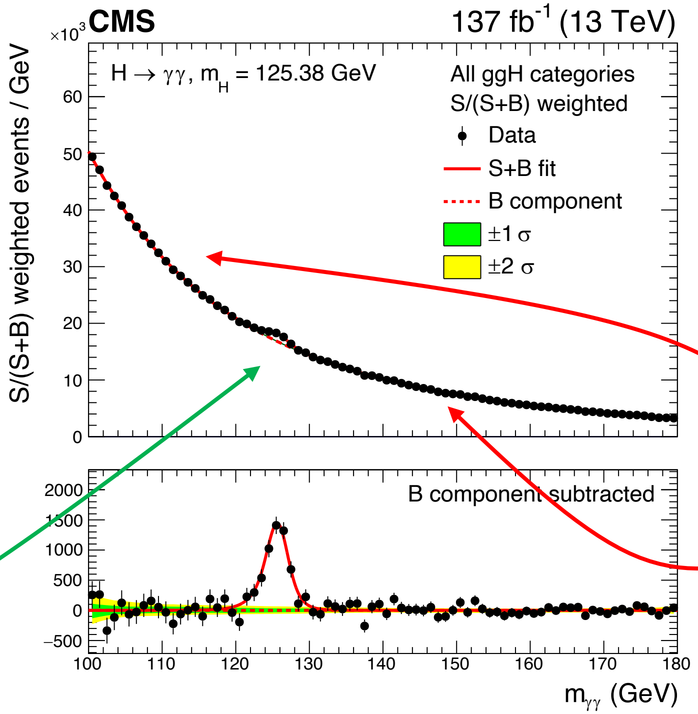
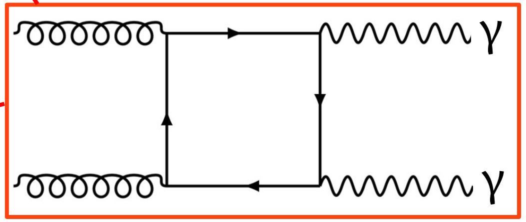
Majority of **backgrounds** are data-driven

Example: use sidebands of an invariant mass fit to estimate ***background*** contribution under the ***signal***







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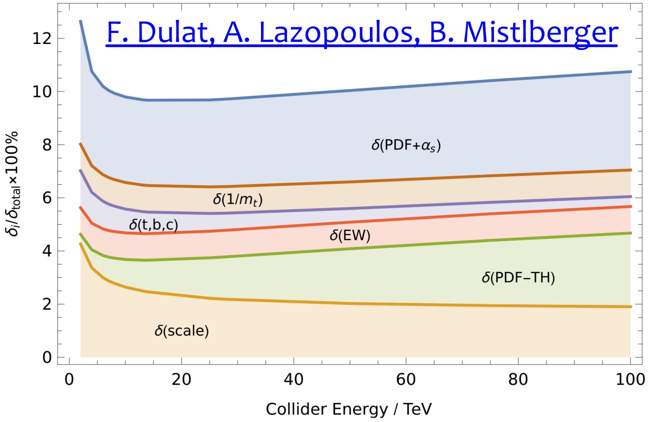
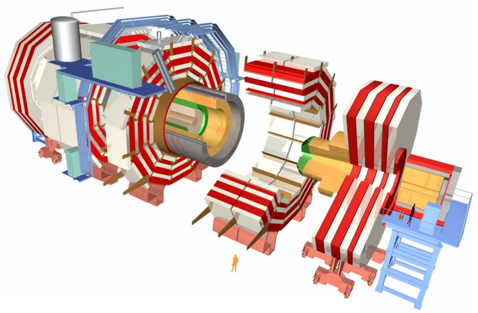
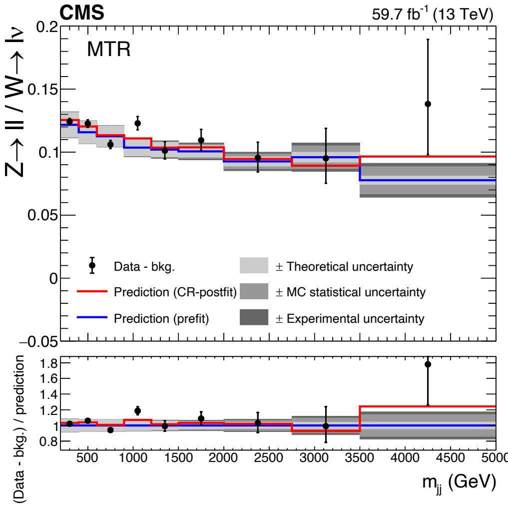


Experimental/Detector systematics:
- Object efficiencies, energy scales, luminosity



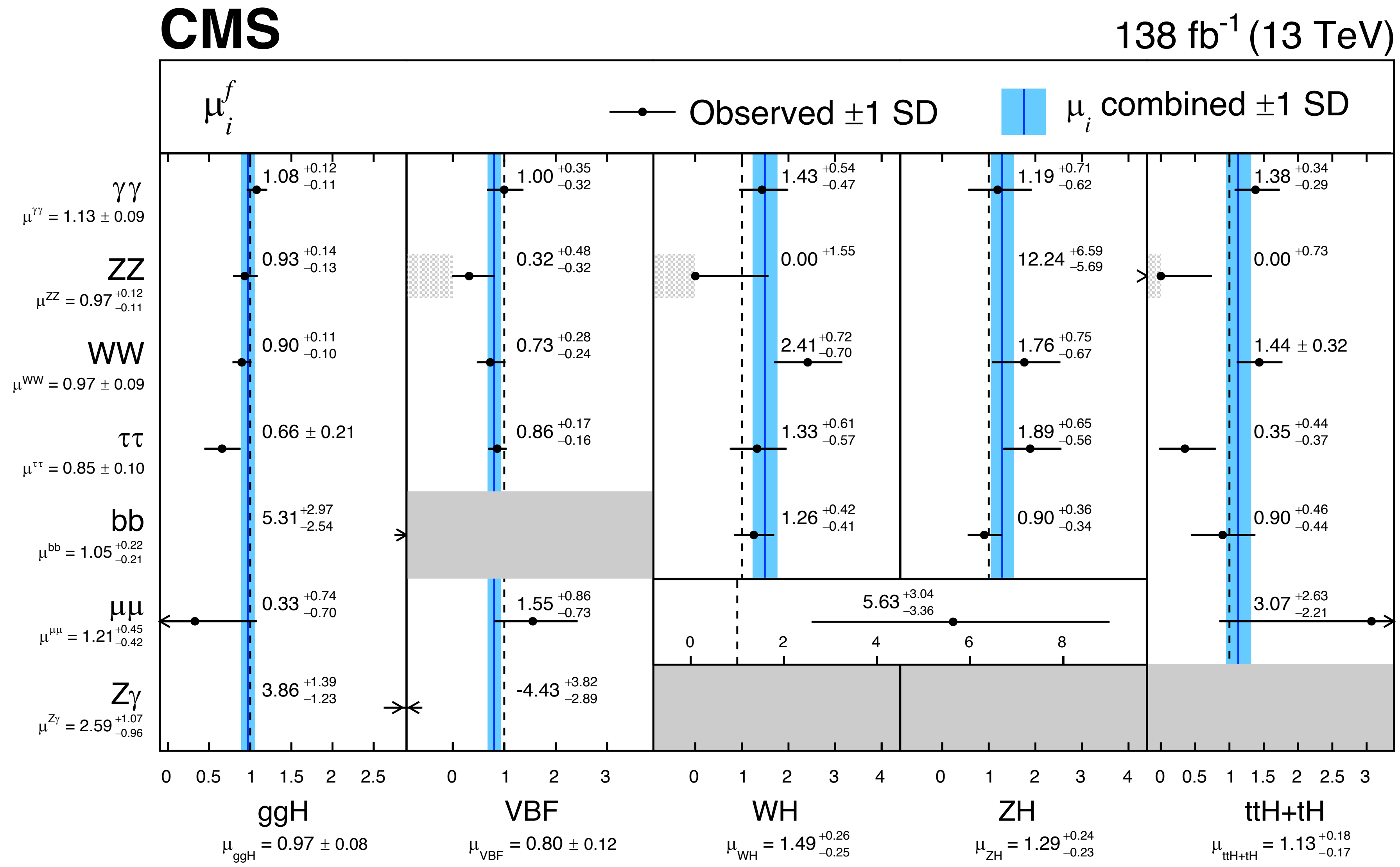
Signal theory uncertainties:
- Inclusive x-section uncertainties, QCD scale, pdf, UEPS, Branching ratios, jet counting

Background theory uncertainties:
- Often rather different phase-spaces considered for extrapolating from control regions for data-driven estimates



Combination has **O(1000)'s nuisance parameters** (sources of systematic uncertainty)

Putting it back together



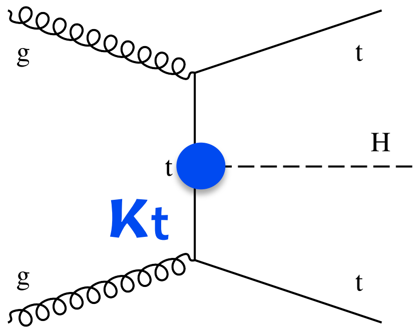
Latest CMS combination:
[Nature 607 (2022) 60-68]

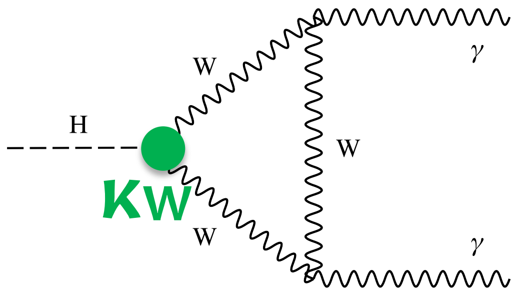
~850 channels
(categories for data)

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

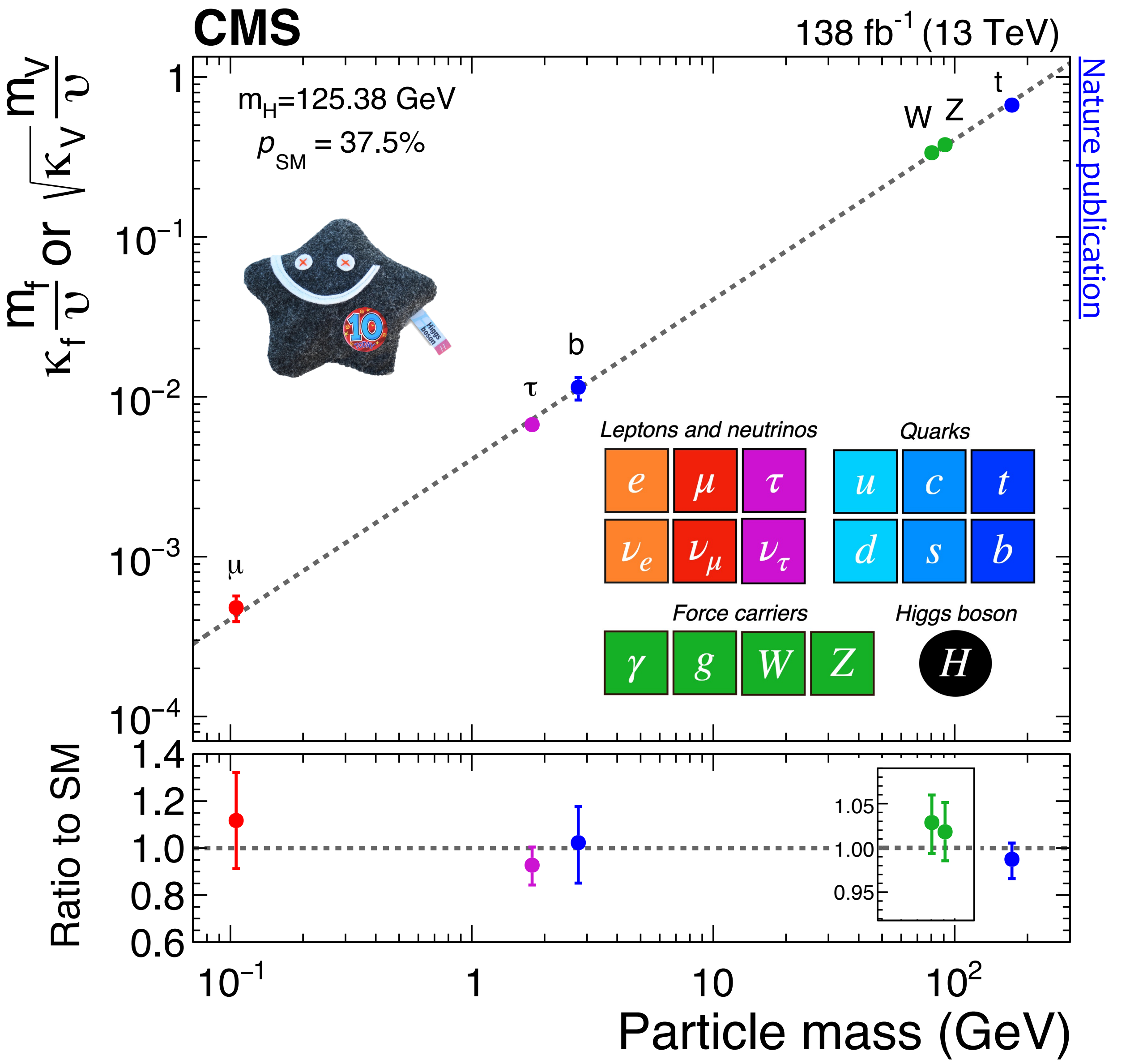
Putting it all together

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





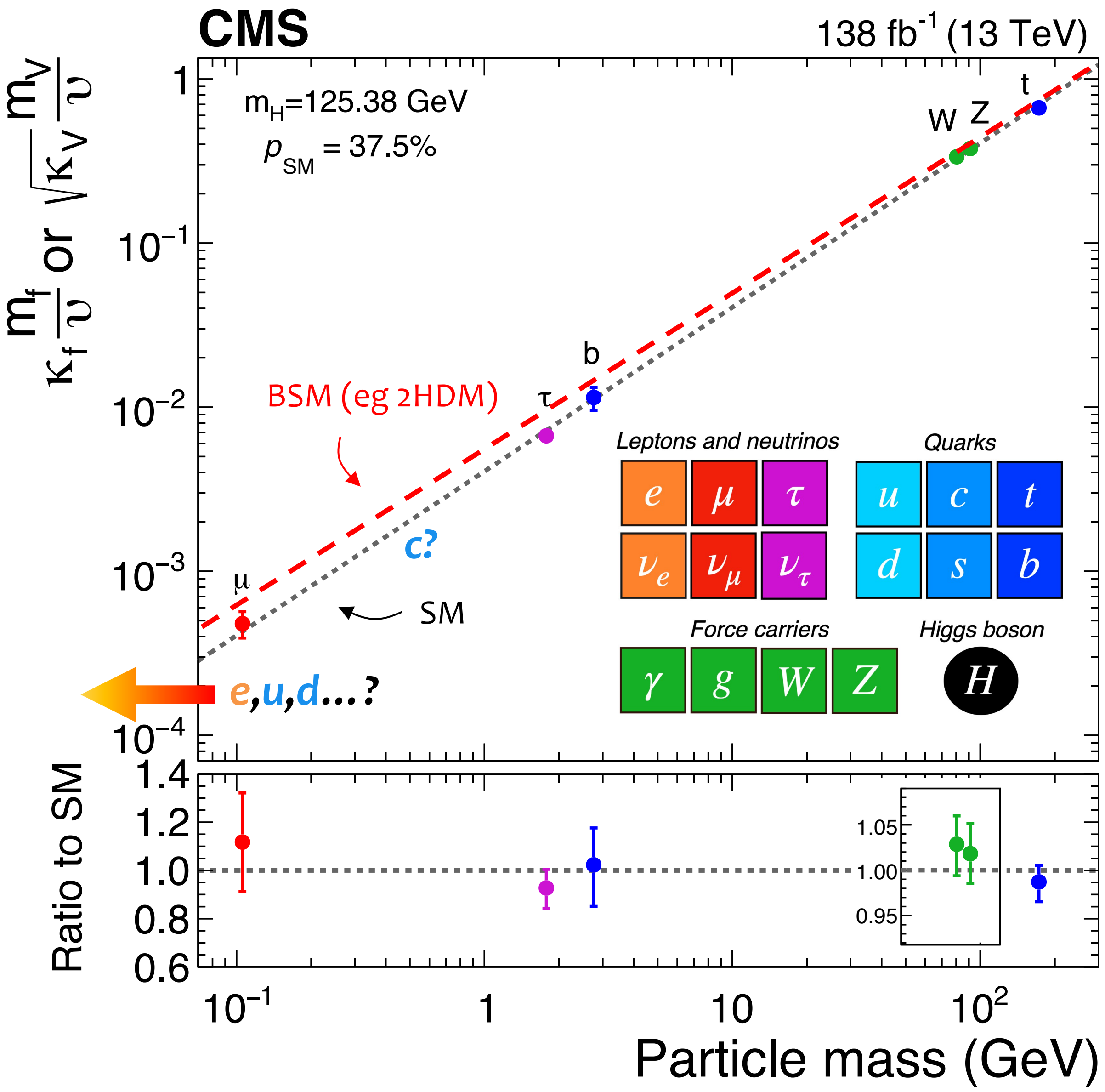
Through a **combination** of the different production and decay processes, we can extract the couplings to SM particles **and compare to the trend predicted in the SM**



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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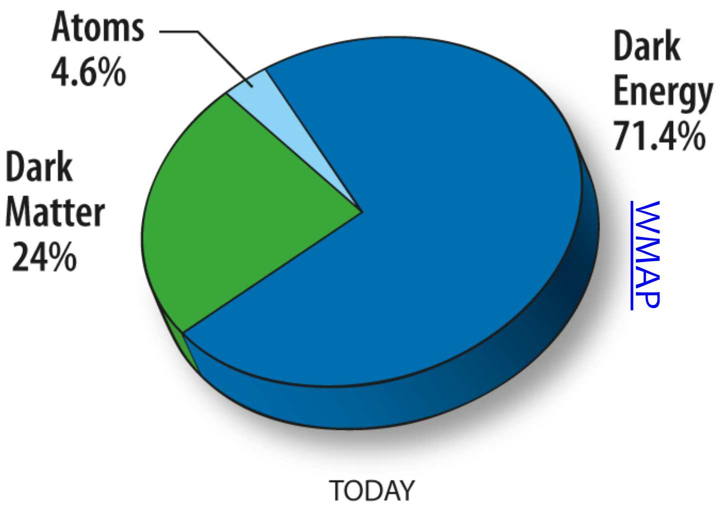
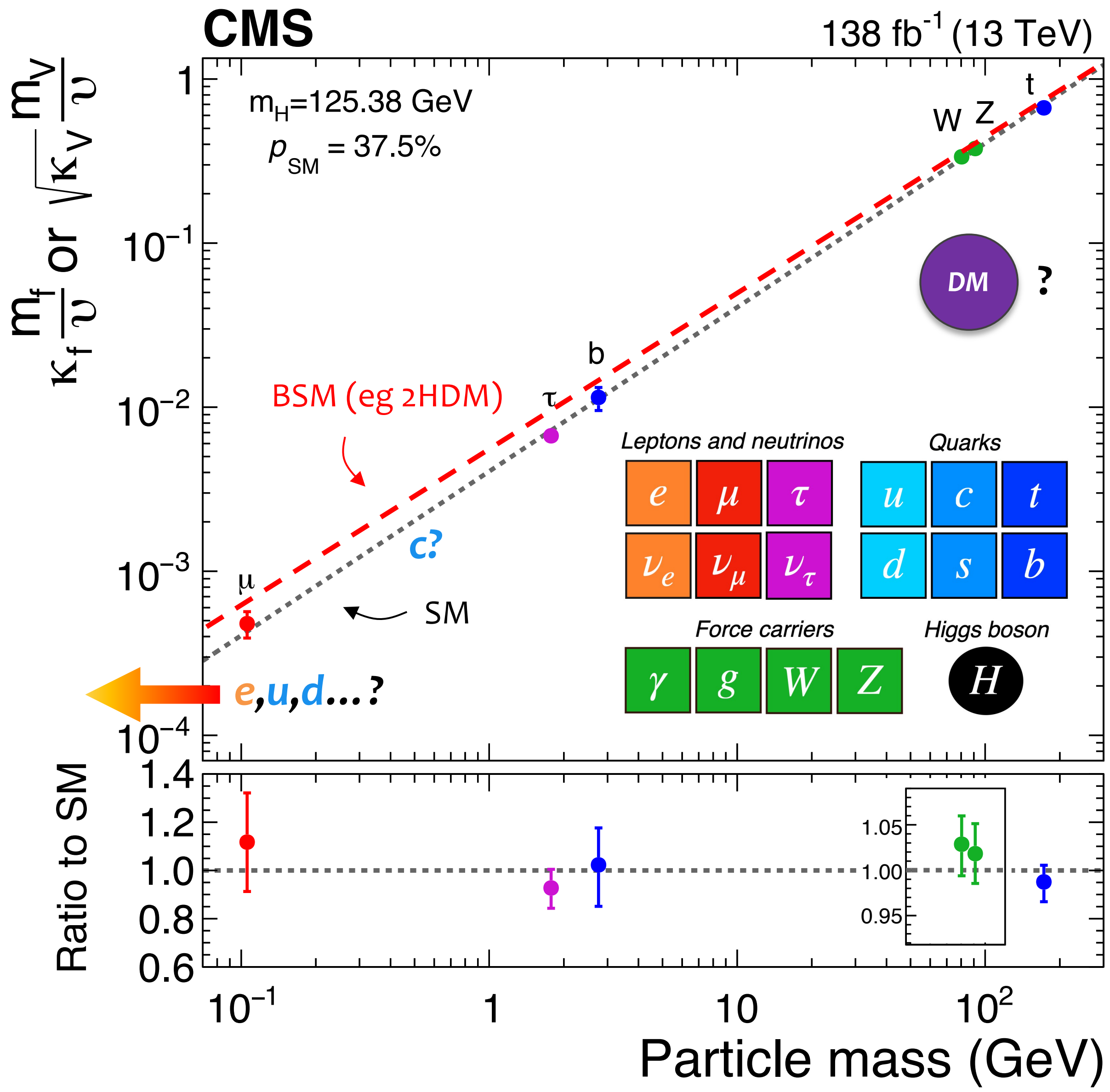
- **Is the Higgs sector SM-like ? →** Do all the SM particles lie on that line?
- **What does Dark Matter (DM) fit in ? →** if DM are massive particles, wouldn't they couple to the Higgs too?





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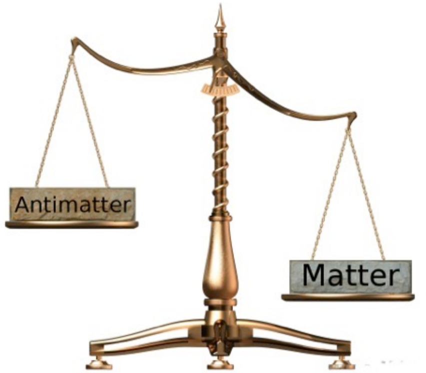

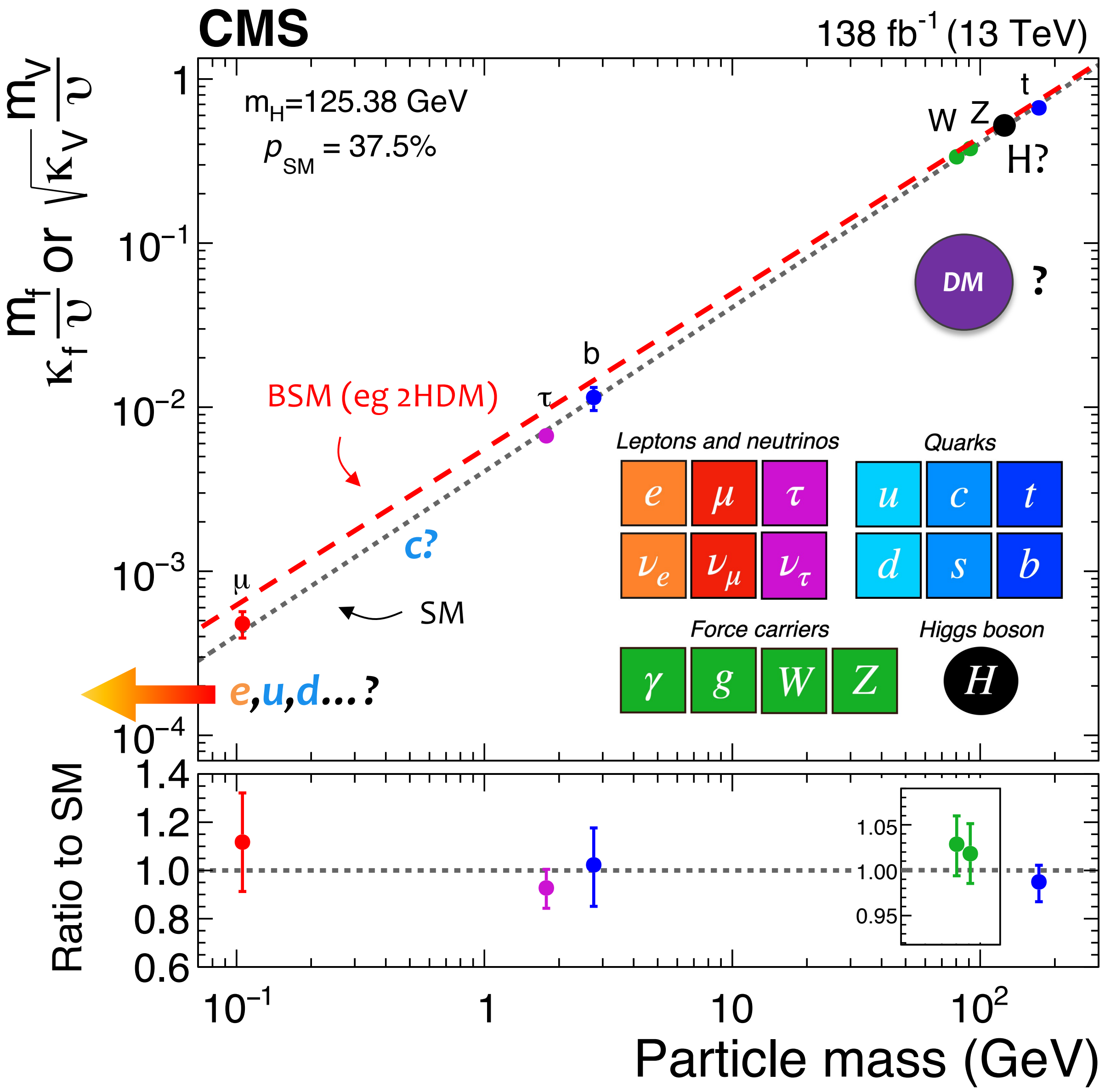

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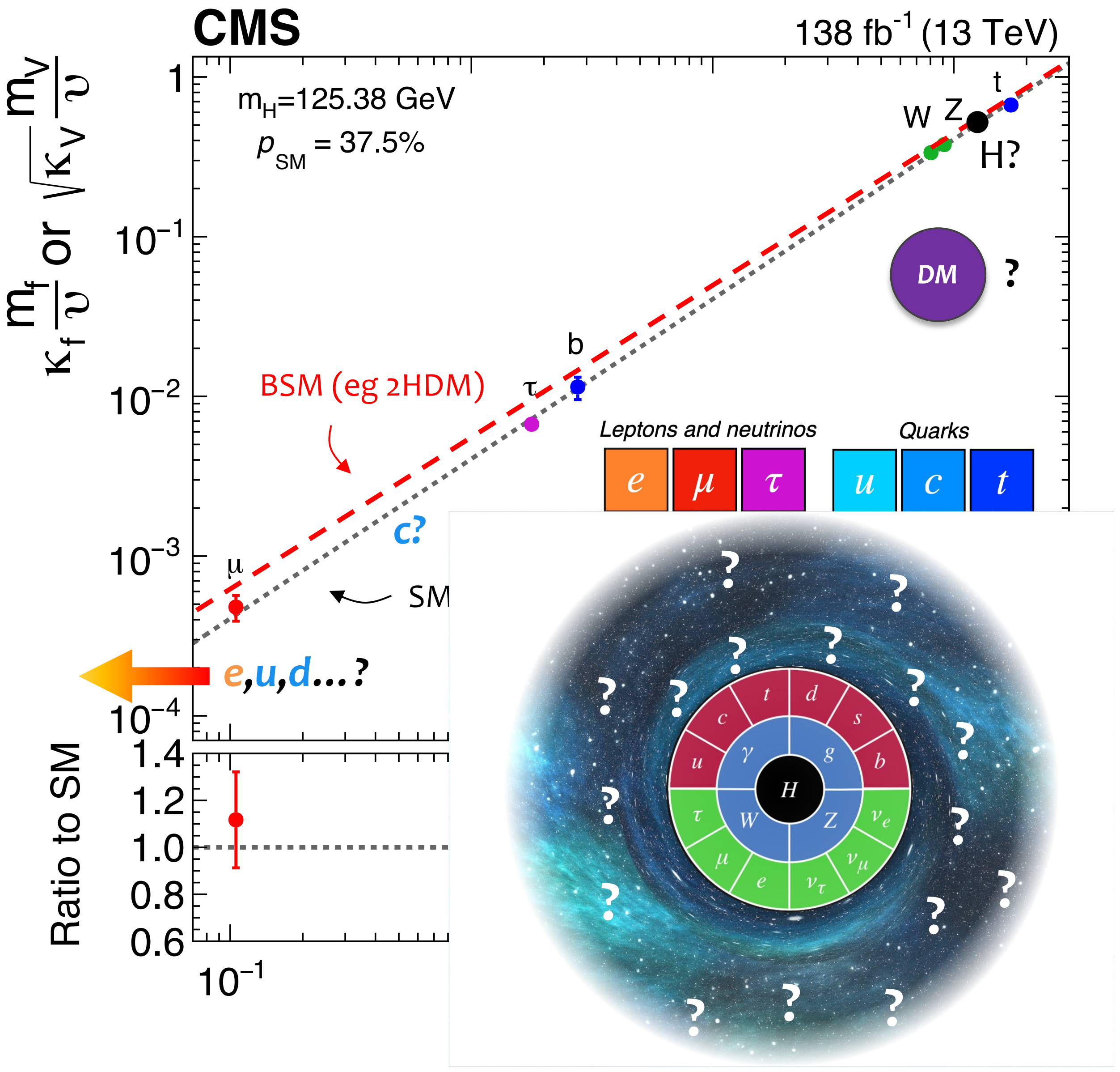
These are **fundamental questions** in physics
→ The **Higgs boson** is a unique tool to search for **physics Beyond the SM** (BSM)



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)

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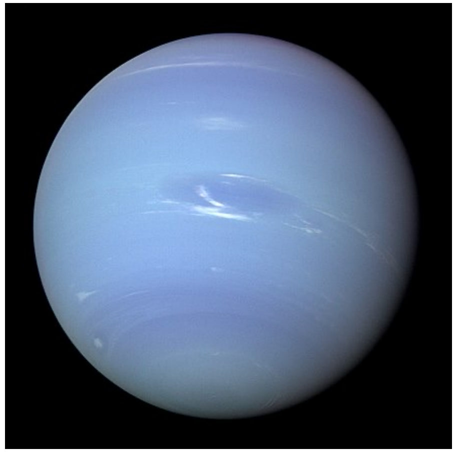

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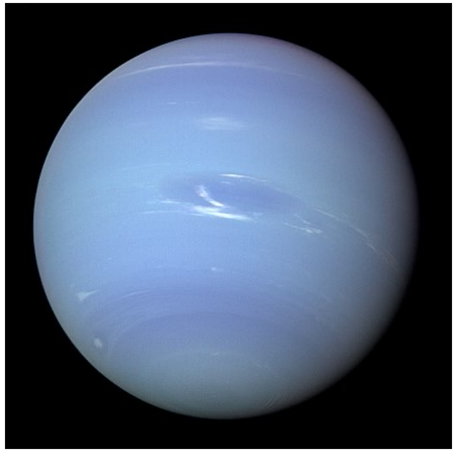

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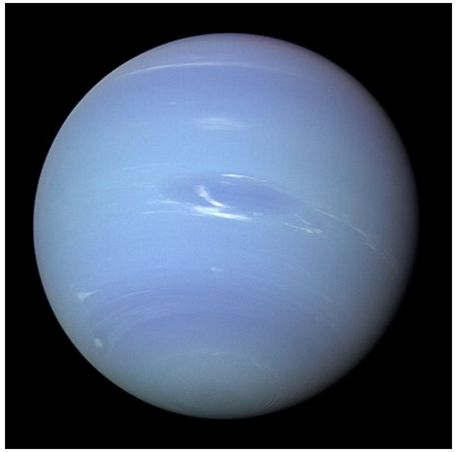
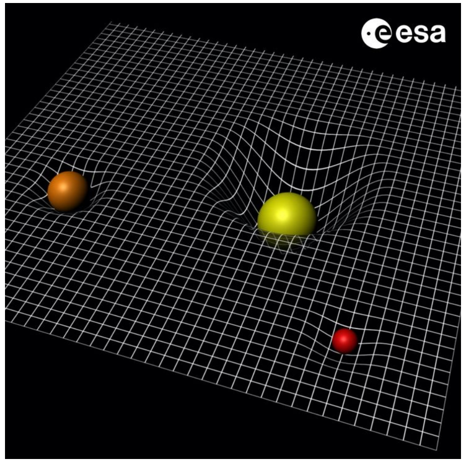


Le Verrier 1859, Einstein 1915



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

Neptune discovered with 1°
of predicted position (**1846**)

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

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

Measurements of Mercury's orbit reveals
43 arcseconds/century anomaly
→ new planet (or body) predicted (**1859**)

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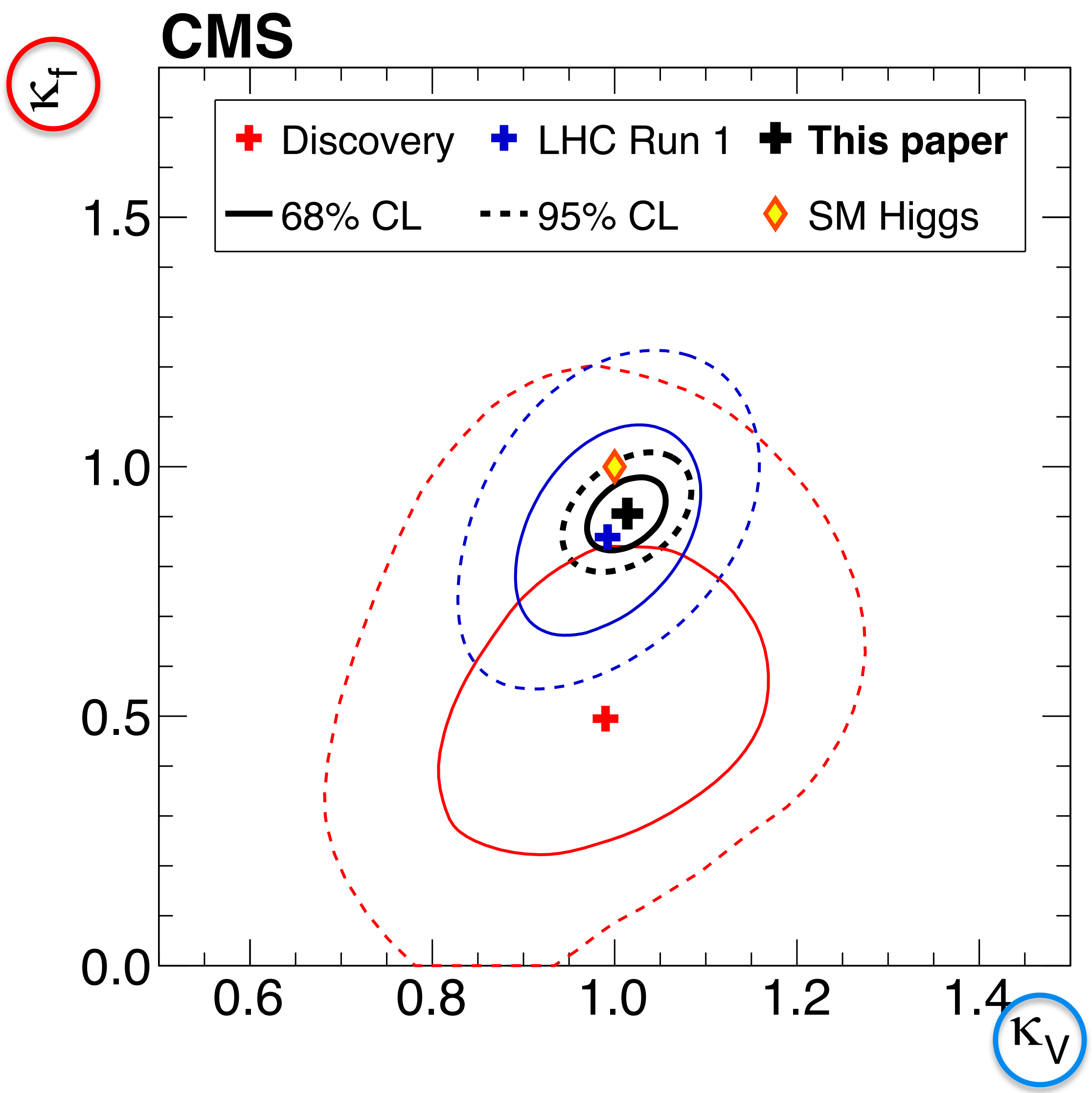
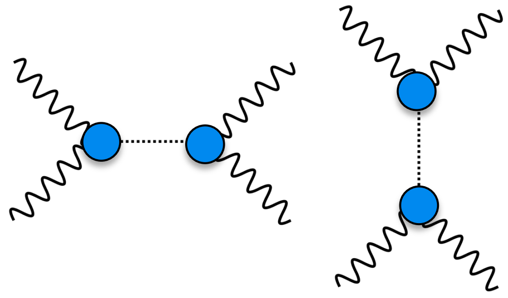
…History has a habit of repeating itself 🤞 …

Higgs couplings for BSM physics

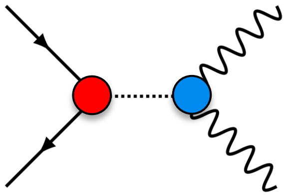


In the **SM, the Higgs regulates longitudinal WW** scattering at high energies

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



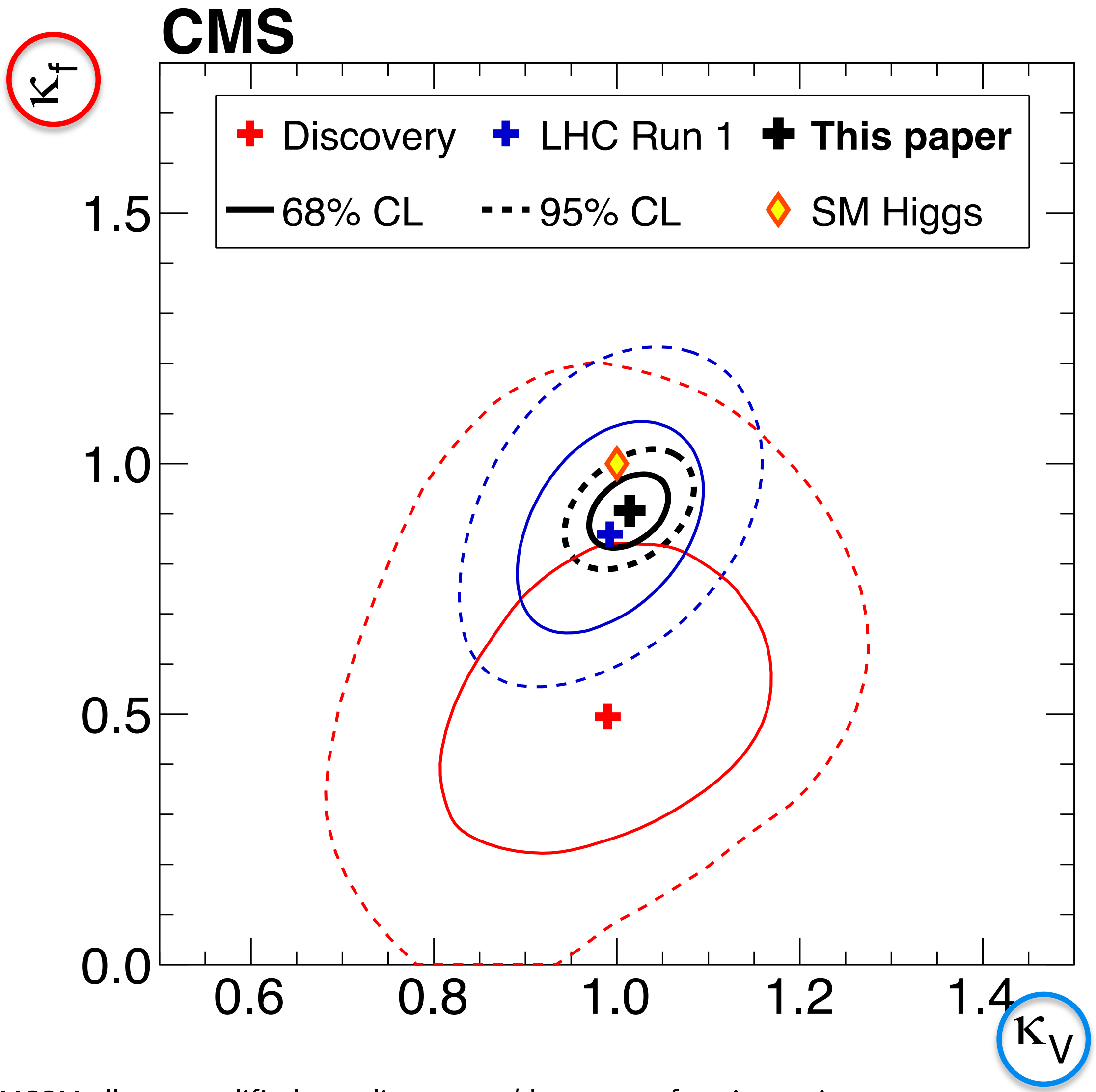
$$\psi\bar{\psi} \to W_L^+W_L^- \sim \frac{m_\psi\sqrt{s}}{v^2}\left(1-\kappa_F\kappa_V\right)$$



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**

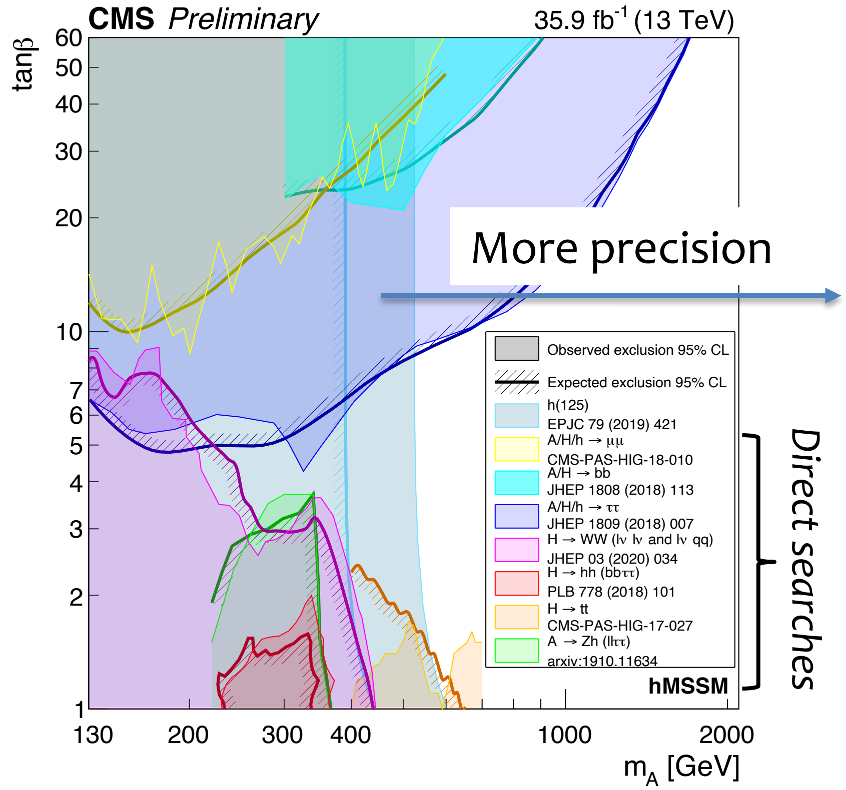
Higgs couplings for BSM physics



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



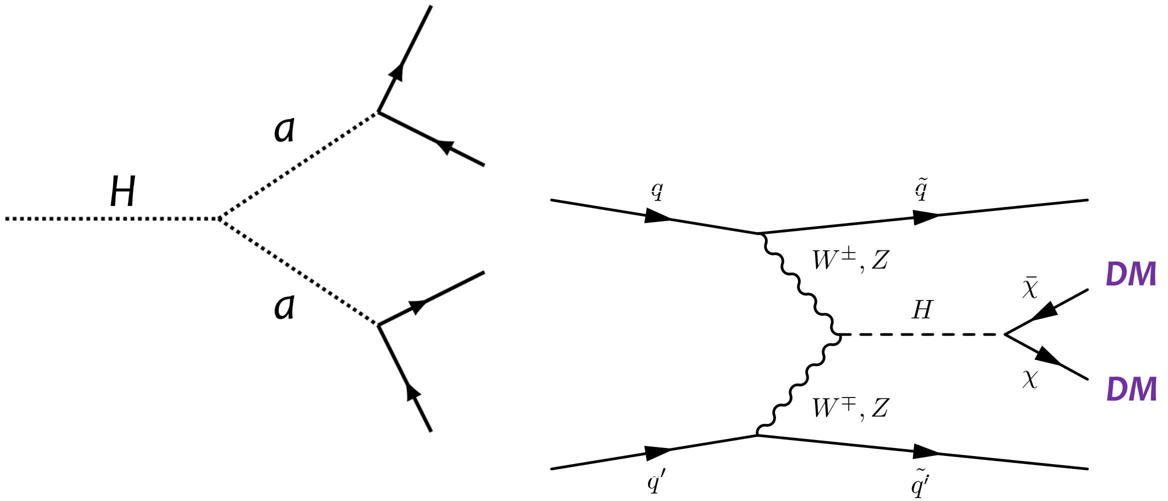
*hMSSM allows modified couplings to up/down type fermion ratio

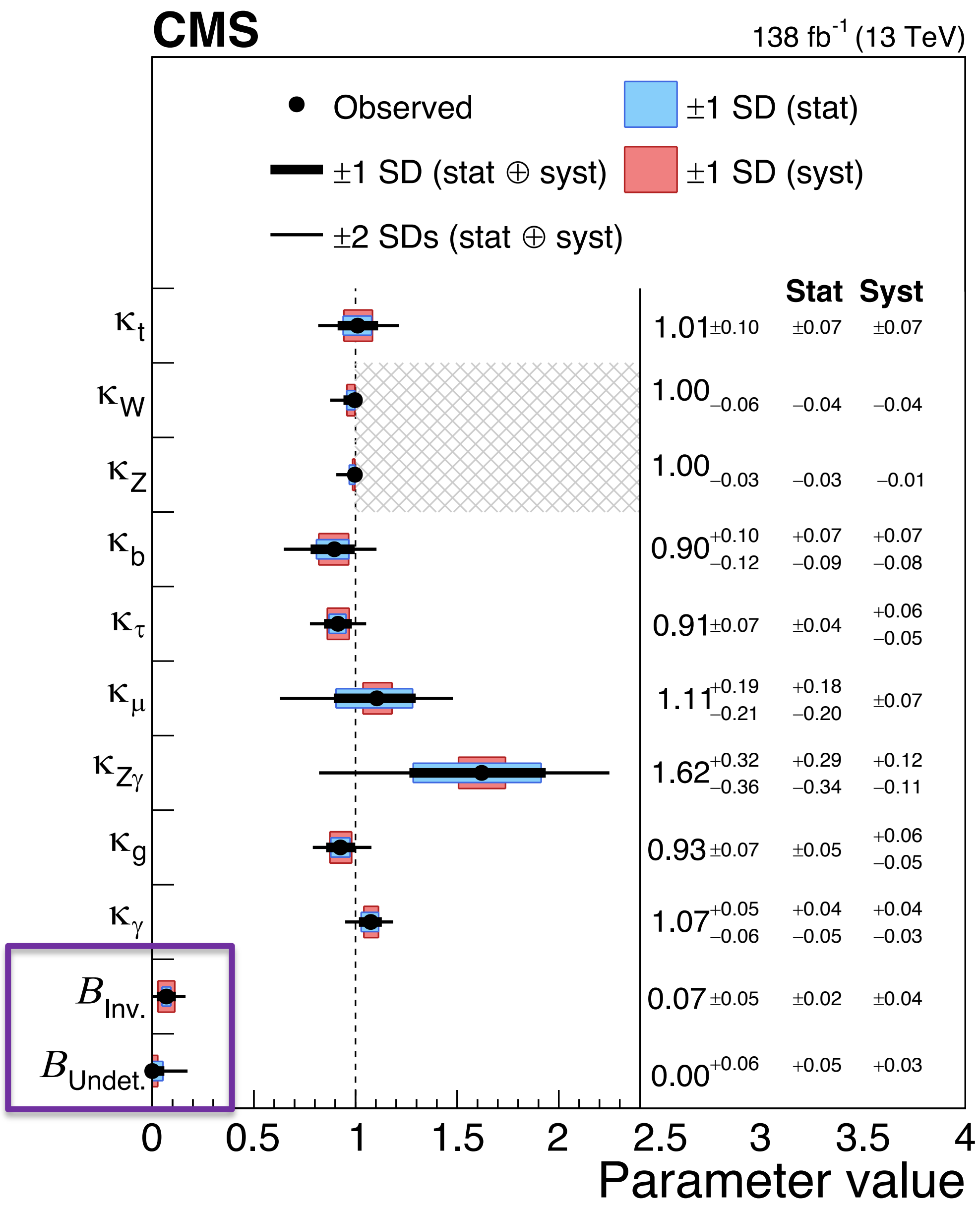
Higgs as a portal to new physics

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

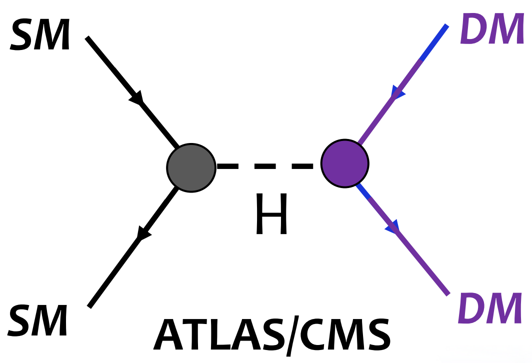
- undetected modes (2HDM+s, nMSSM…)
- **invisible particles** (Dark Matter)

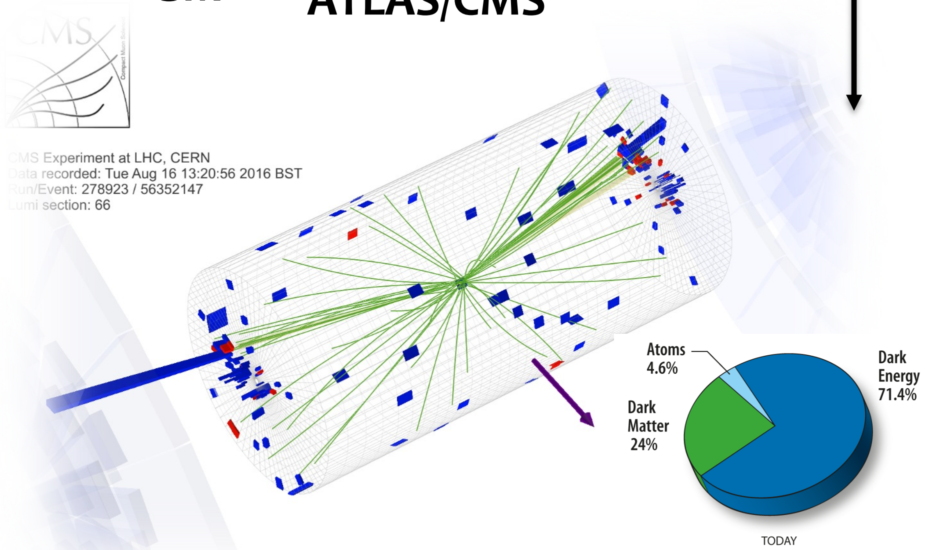


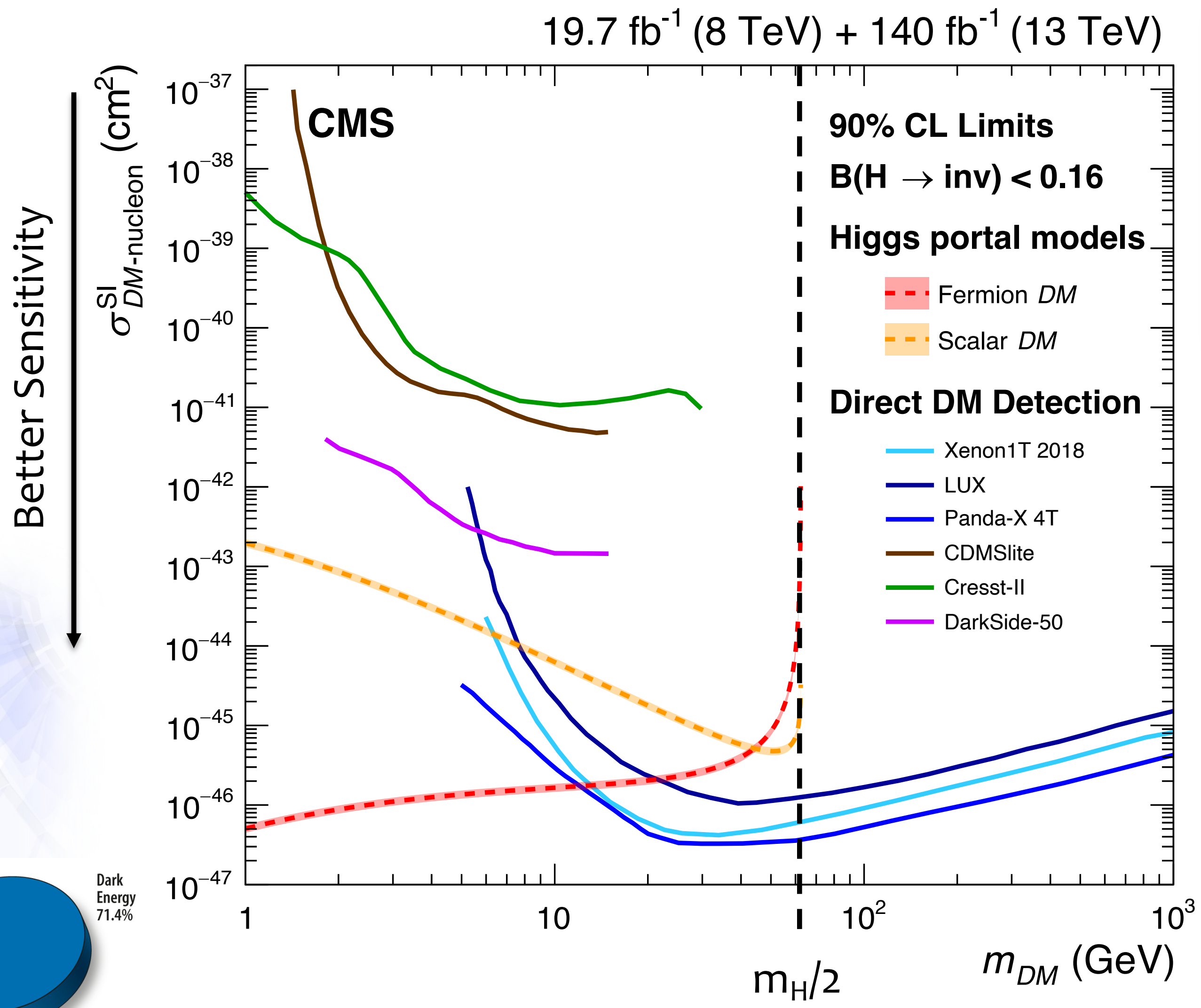


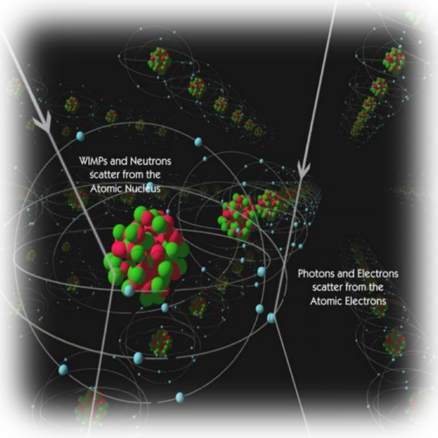
Higgs as a portal to new physics

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

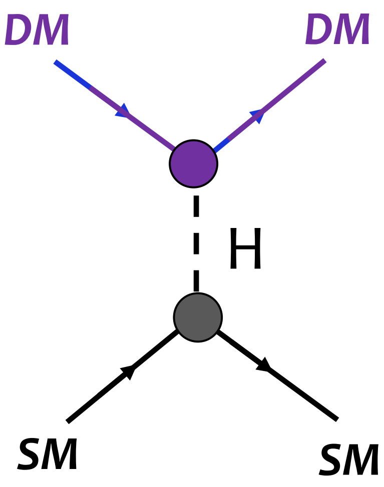






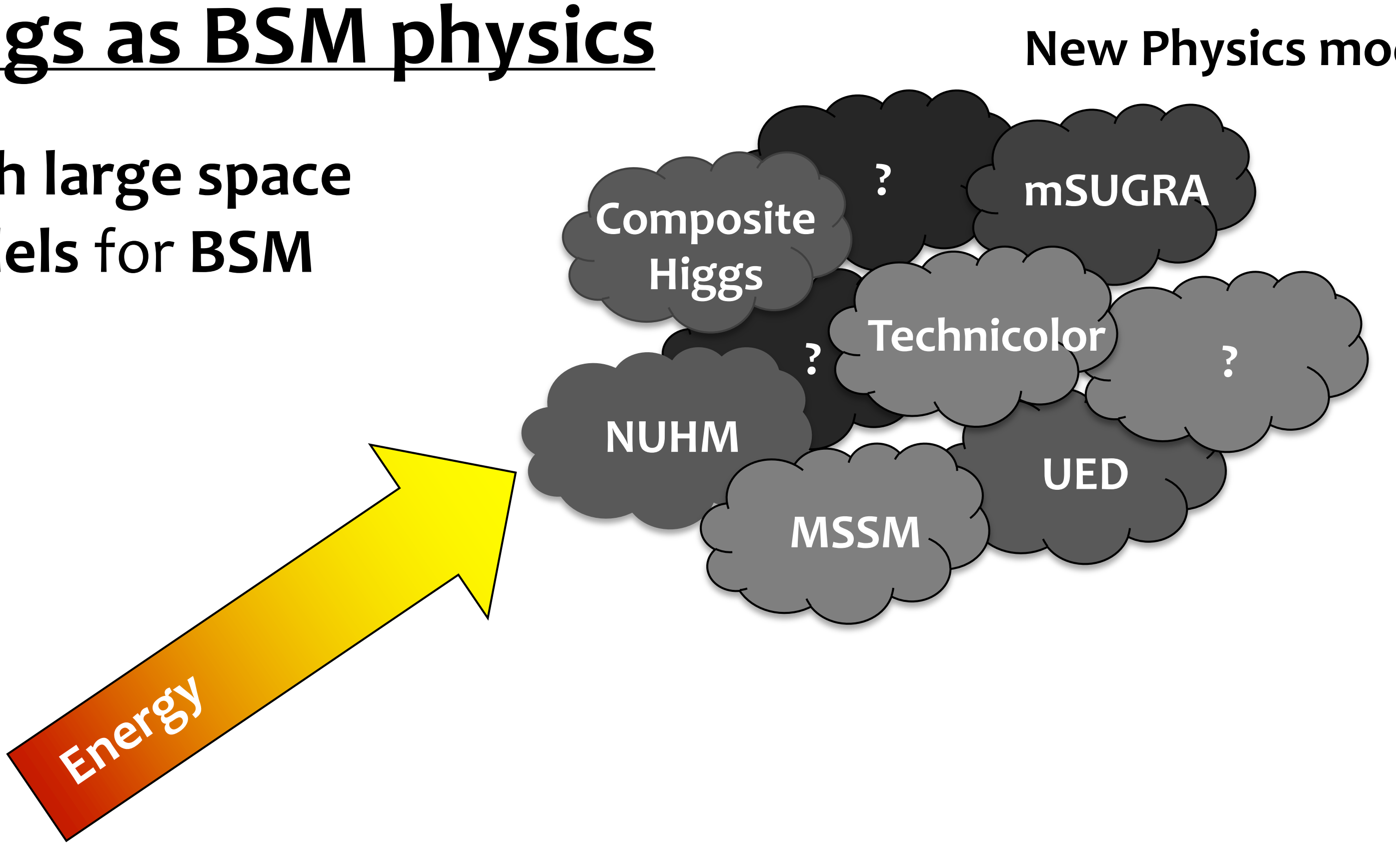


Direct DM detectors

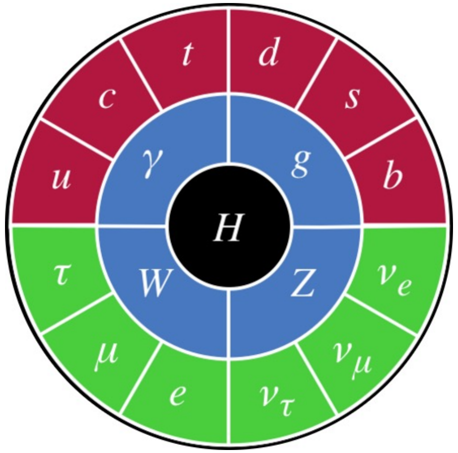


Higgs couplings as BSM physics

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



Standard Model



Higgs couplings as BSM physics

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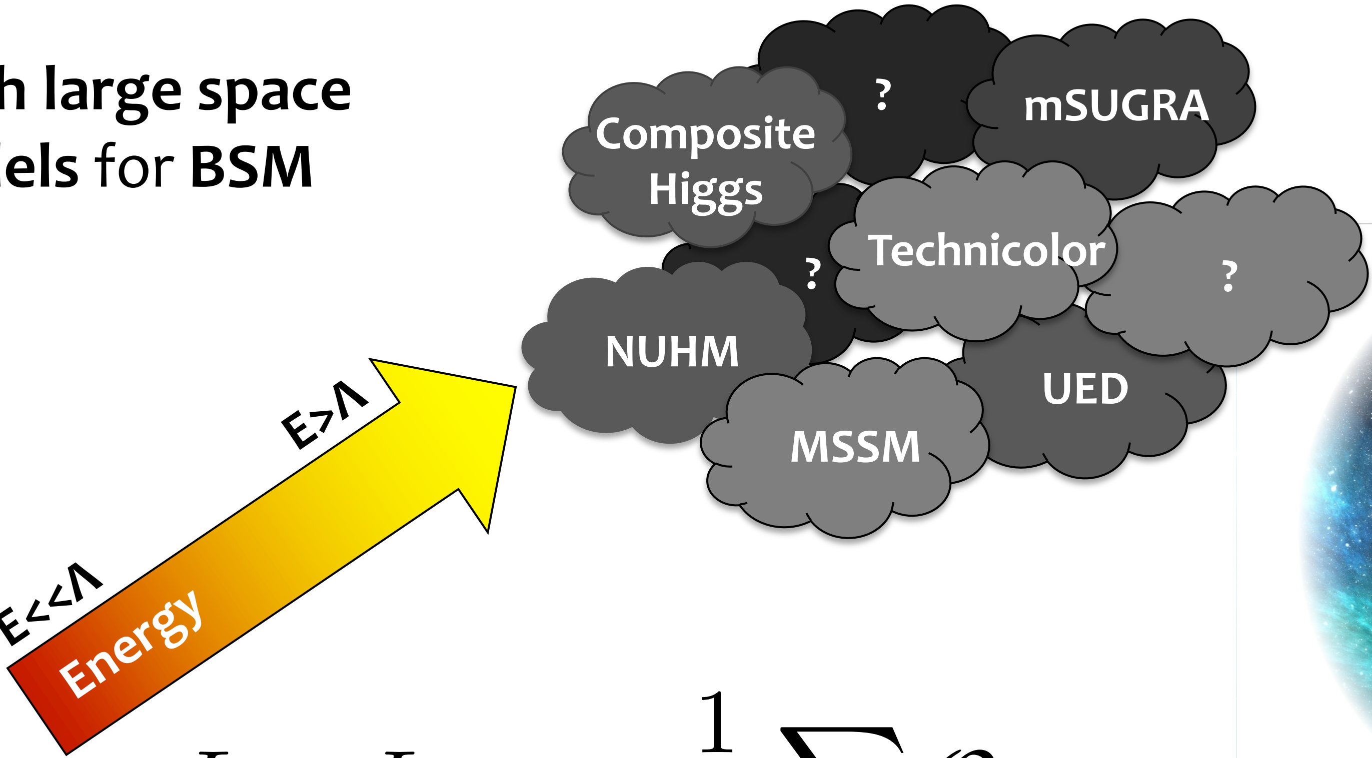
New Physics models



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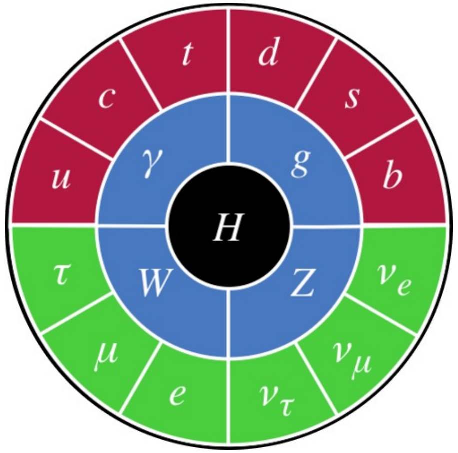
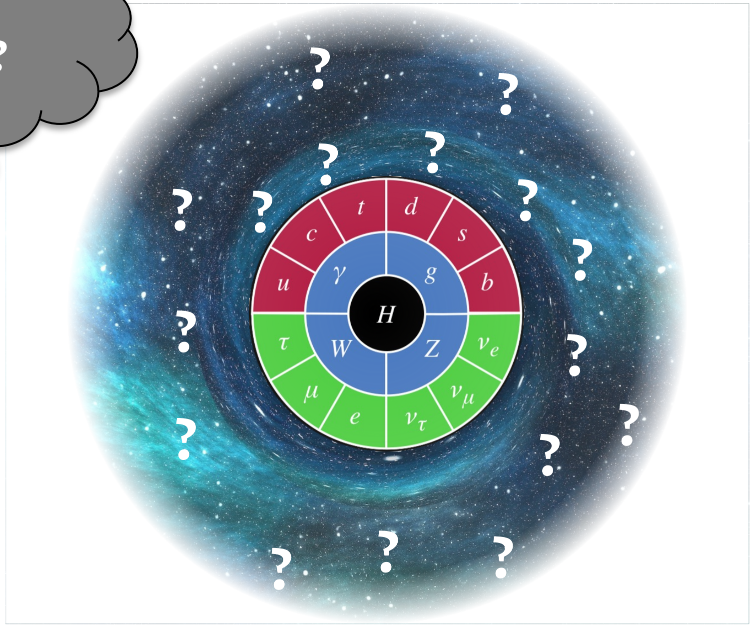


$$L = L_{SM} + \frac{1}{\Lambda}\sum_k \mathcal{O}_k + \ldots$$



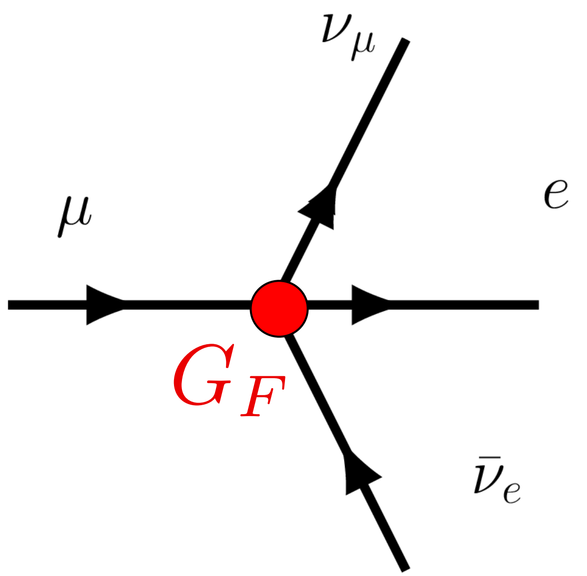
Effective Field Theories (**EFT**) allow to **systematically probe** space of new physics (**NP**) models

→ 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

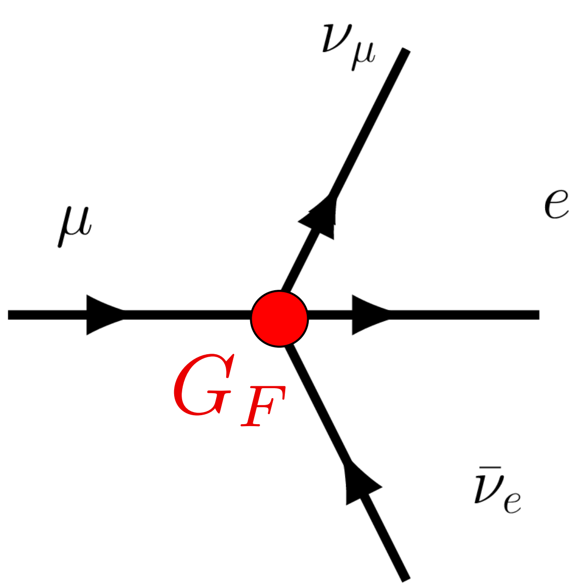


Effective field (Fermi) theory

$E << m_W$

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! *



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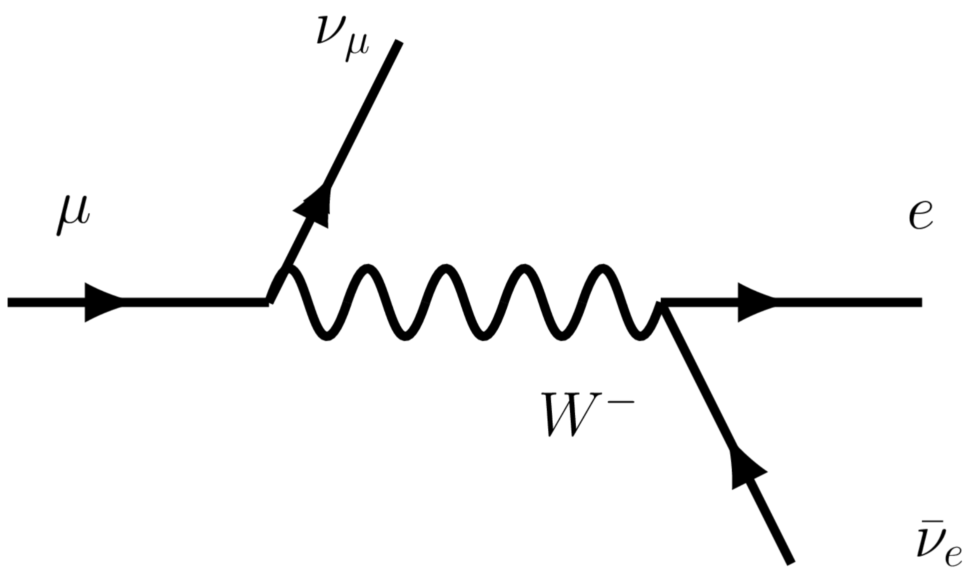


Standard Model

E << m_W

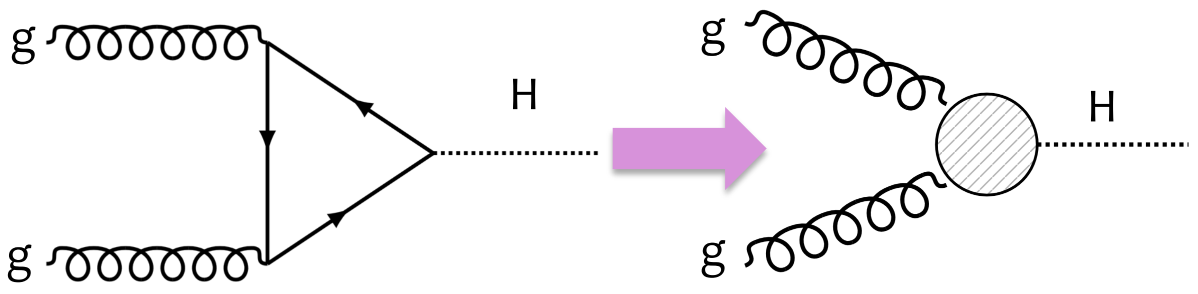
E > m_W

E

* 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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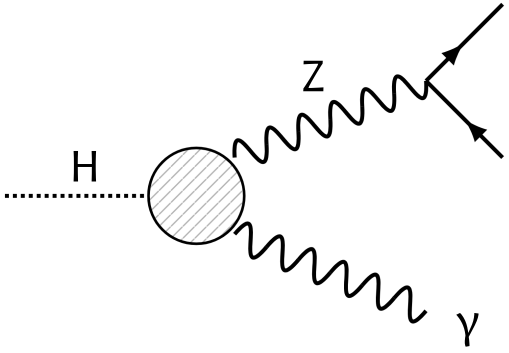
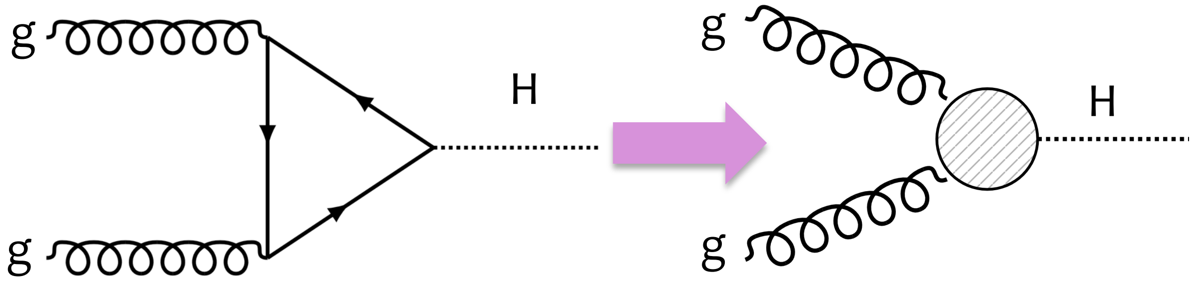
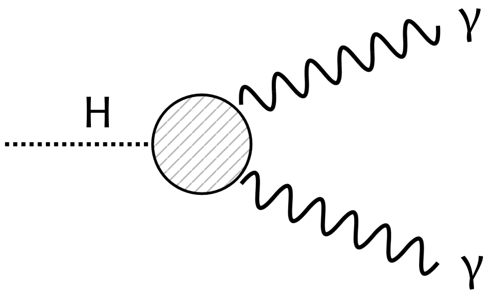
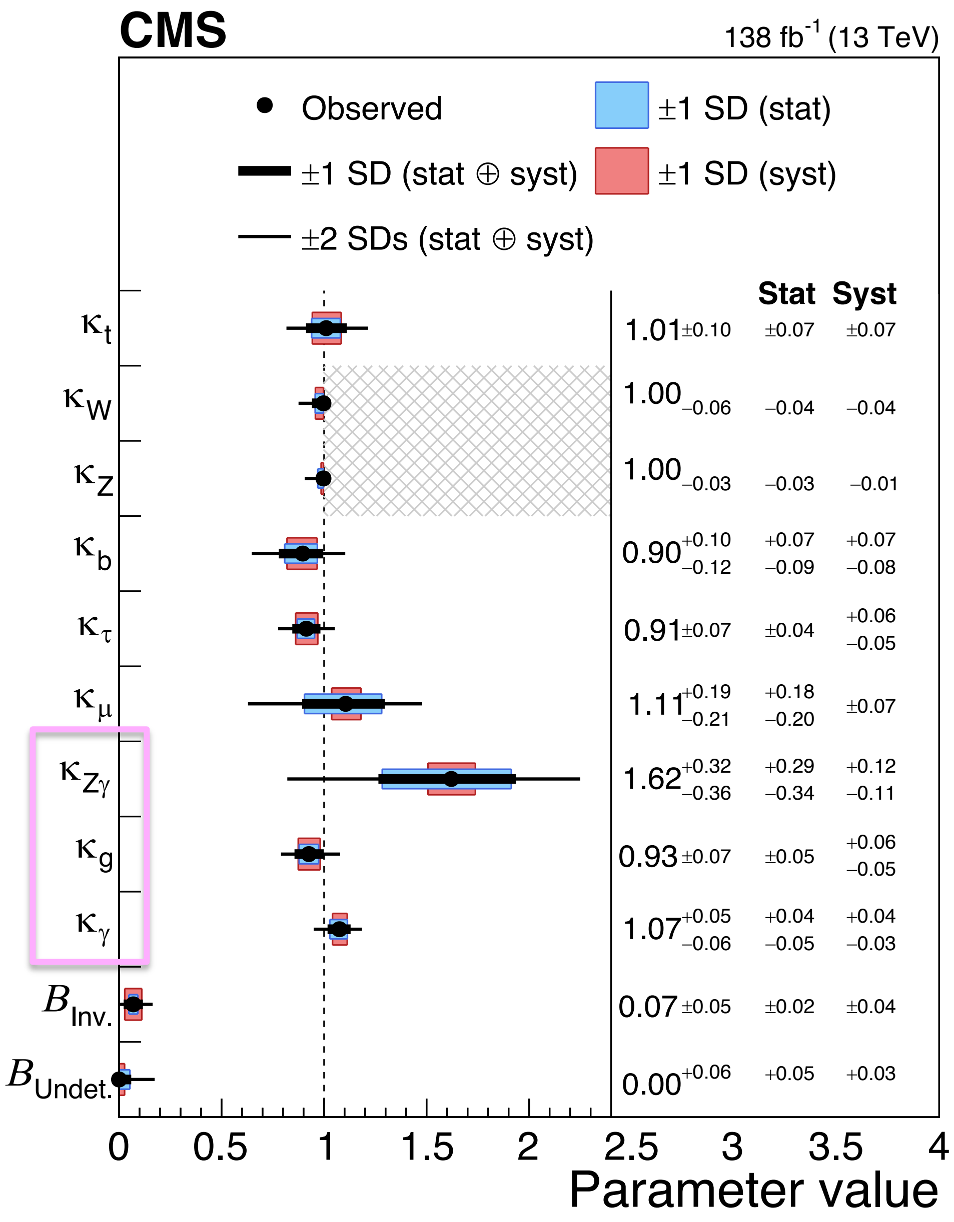




New heavy particles can appear in these loops leading to large deviation in the effective coupling:

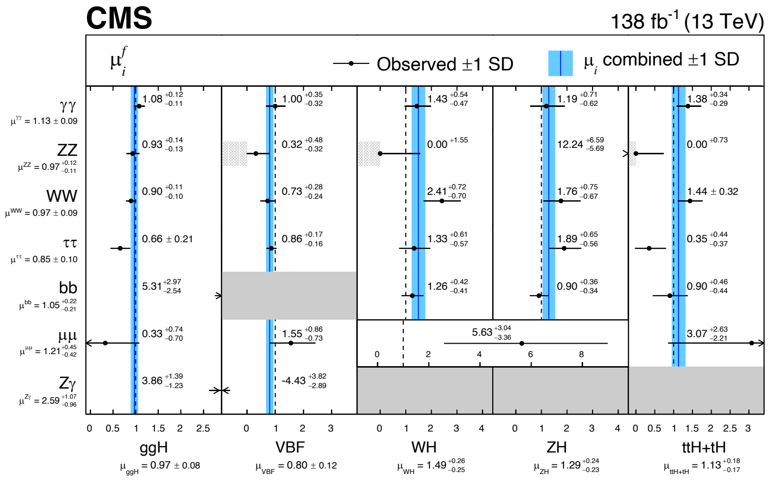
H-Zγ, H-g, H-γ





Effective field theories

On-shell

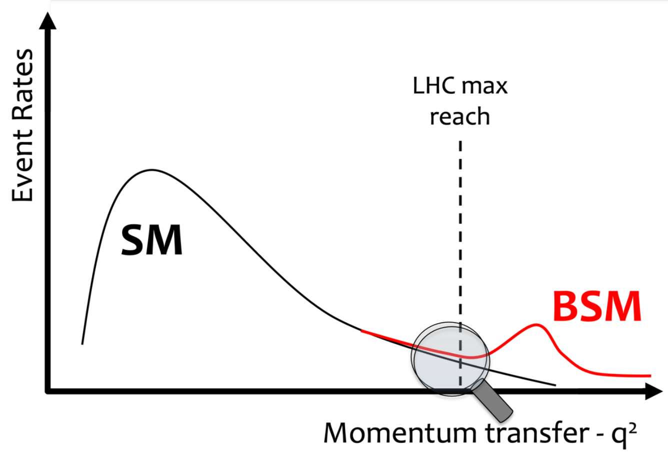


$$\delta \sim \left(\frac{v}{\Lambda}\right)^2$$

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

δ_μ = 1% → Λ ~ 2.5 TeV

Off-shell / large q^2



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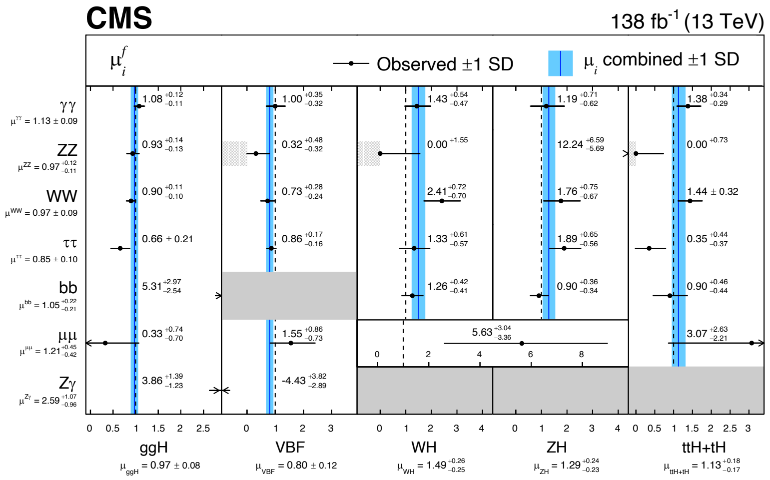
Differential: High momentum production sensitive to new physics

δ_σ = 15% (q=1TeV) → Λ ~ 2.5 TeV

Effective field theories

On-shell



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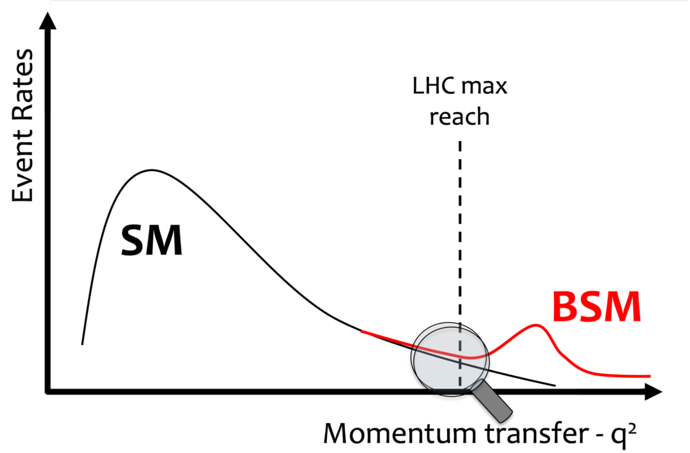

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Differential: High momentum production sensitive to new physics

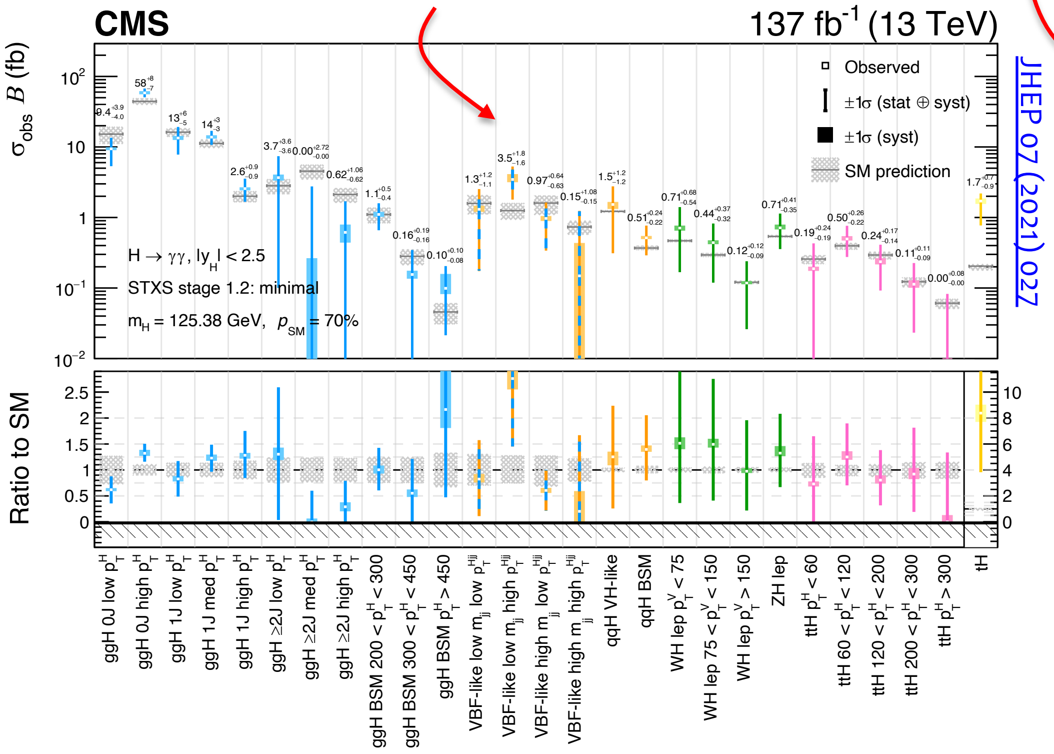
δ_σ = 15% (*q*=1TeV) → Λ ~ 2.5 TeV

Use **differential measurements** to exploit sensitivity at LHC!

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!

Run-2 CMS **H→γγ**



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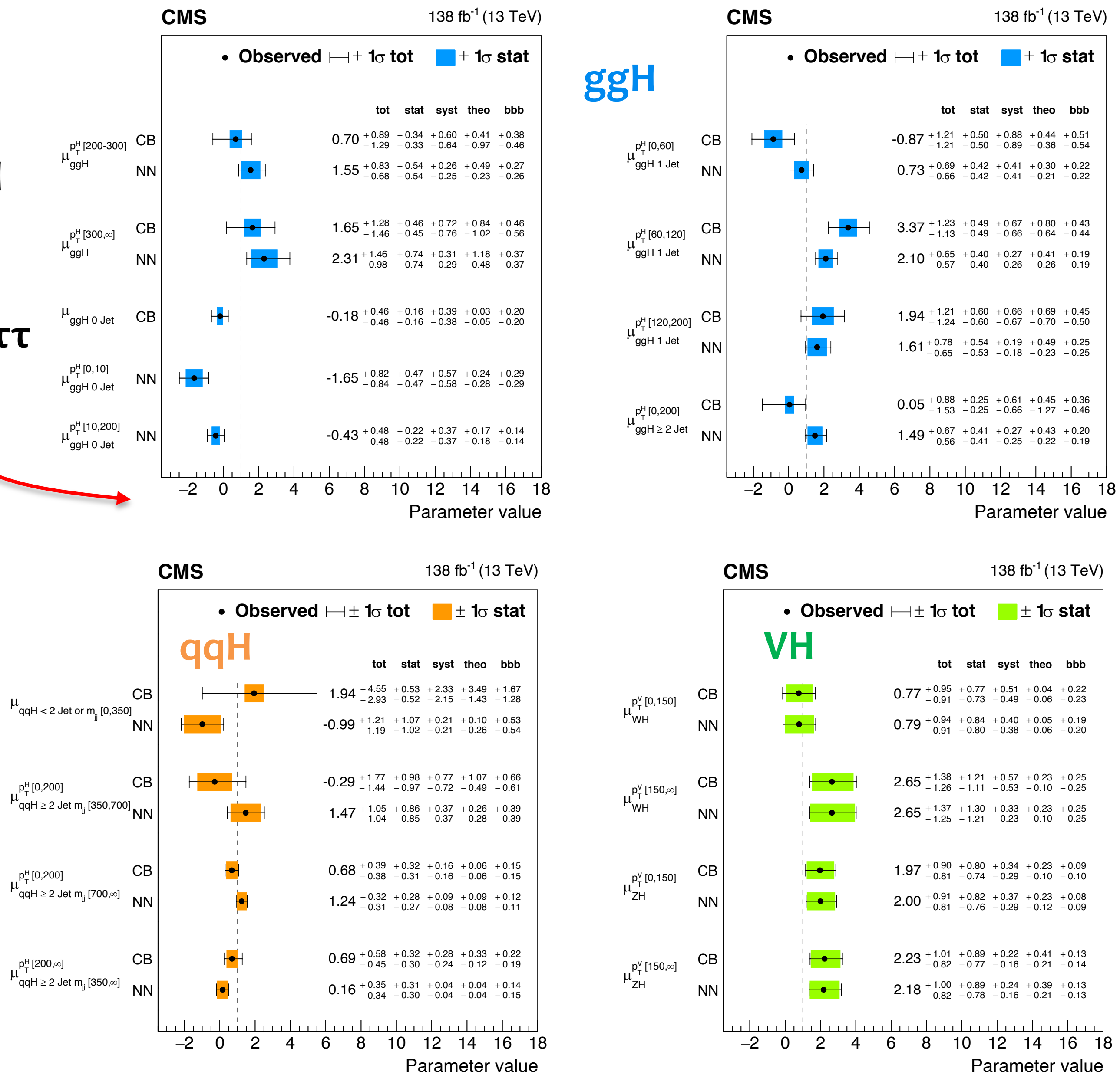
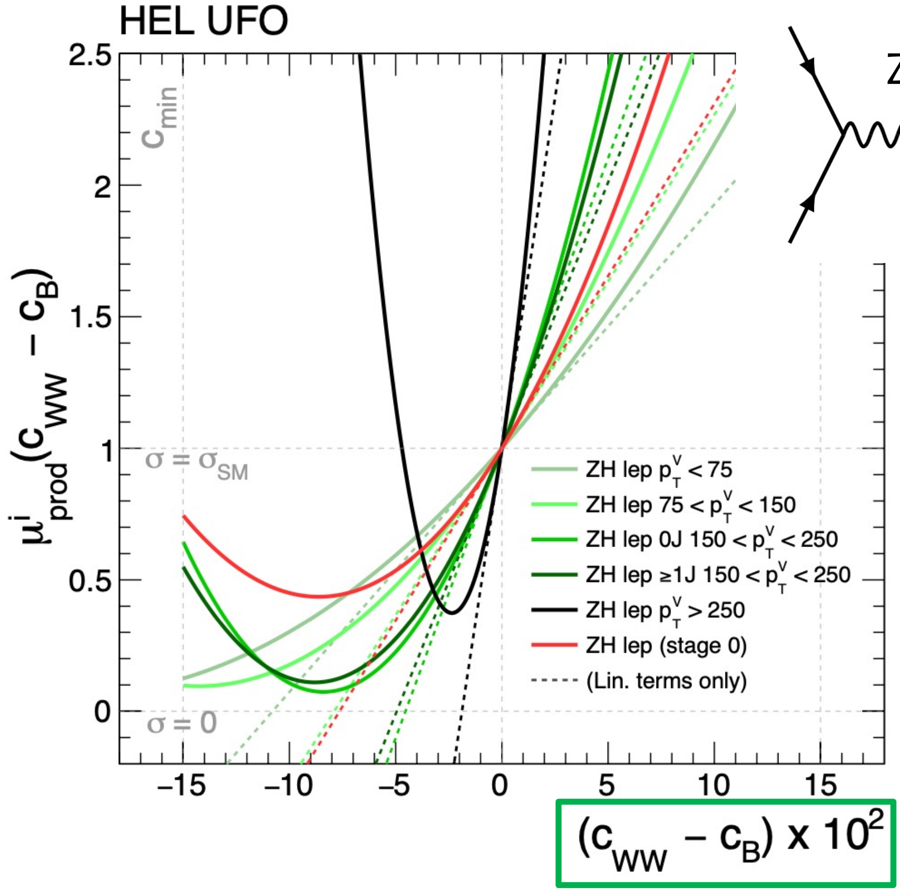
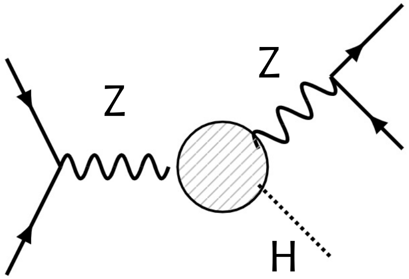
Run-2 CMS **H→ττ**

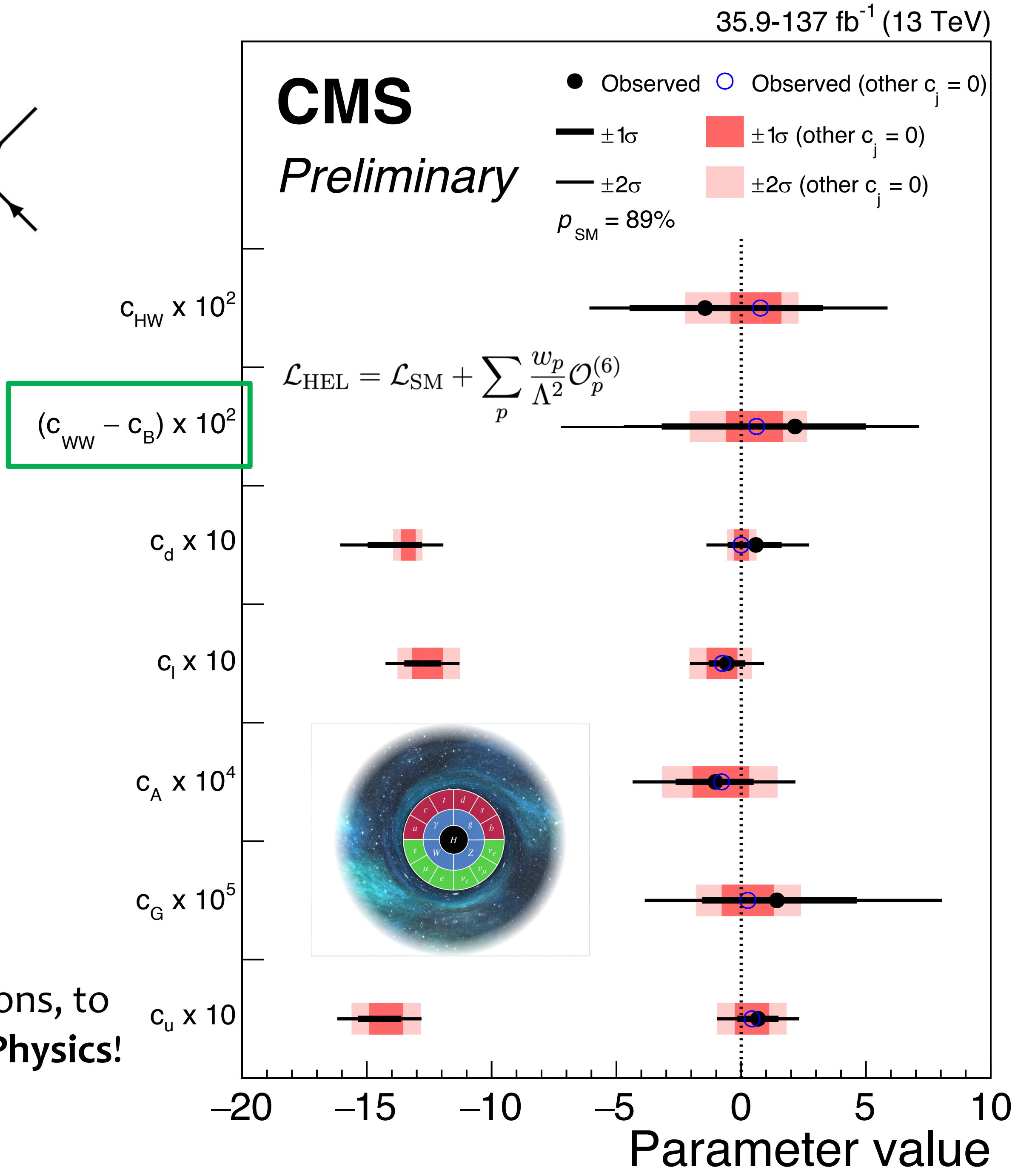


CMS-HIG-19-010 (sub to EPJC)

Effective field theories



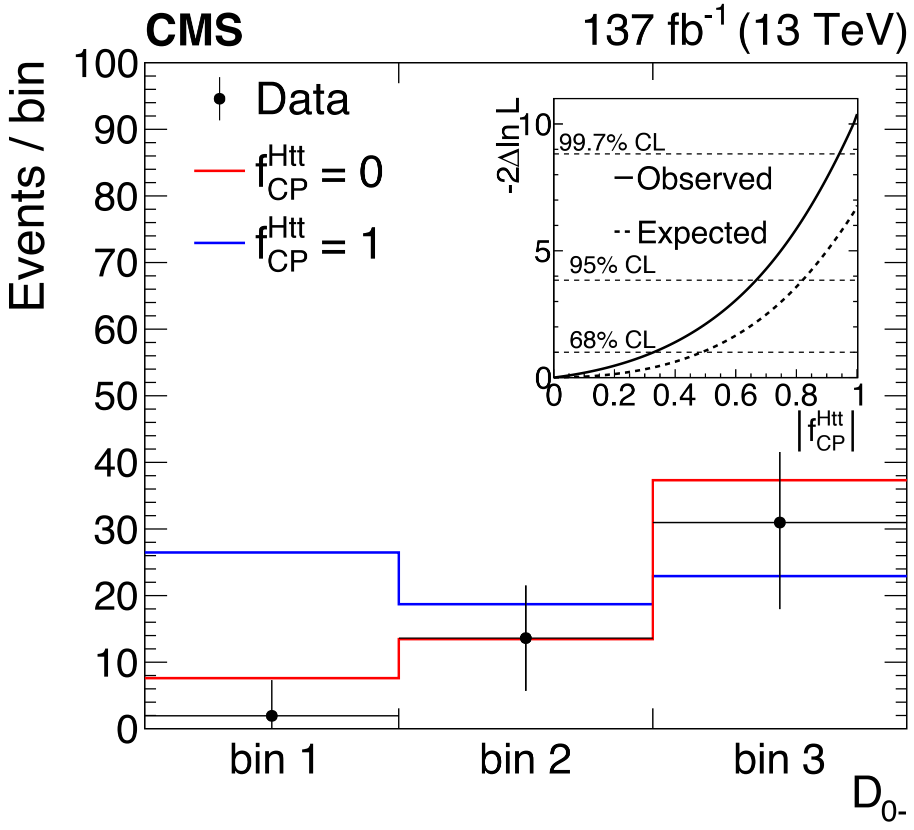


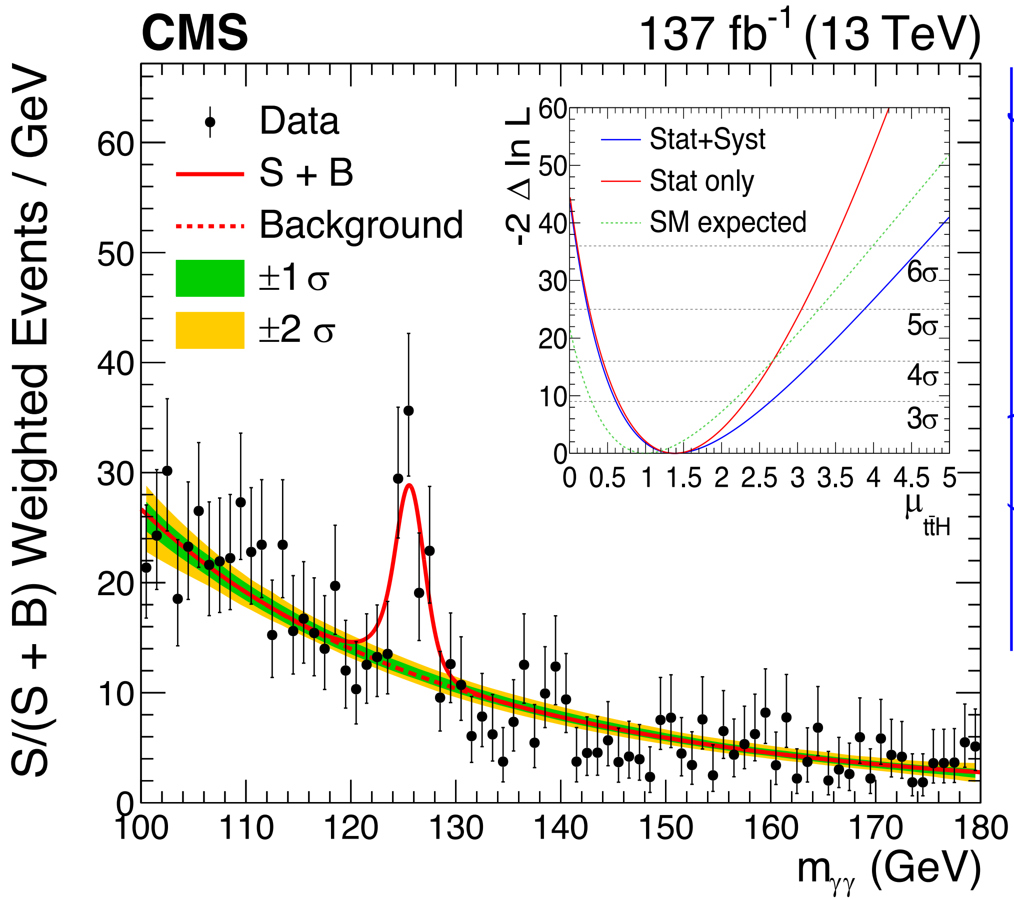


EFTs allow us to coherently correlate measurements across different production & decay, from different kinematic regions, to pick out coherent BSM effcts → **guide** on the path **to New Physics!**

Matter-vs-anti-matter

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

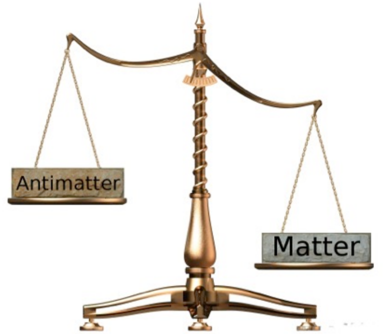




Phys. Rev. Lett. 125 (2020) 061801

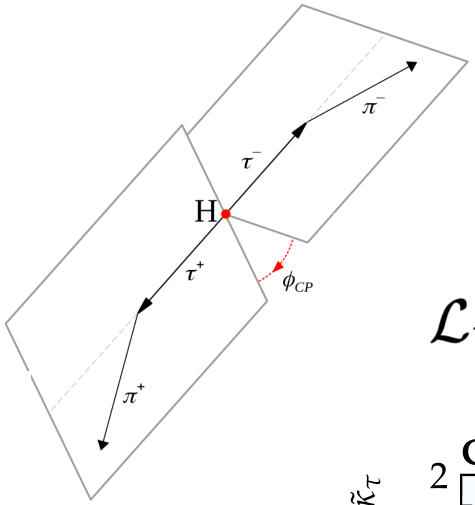
$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\overline{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t,$$

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

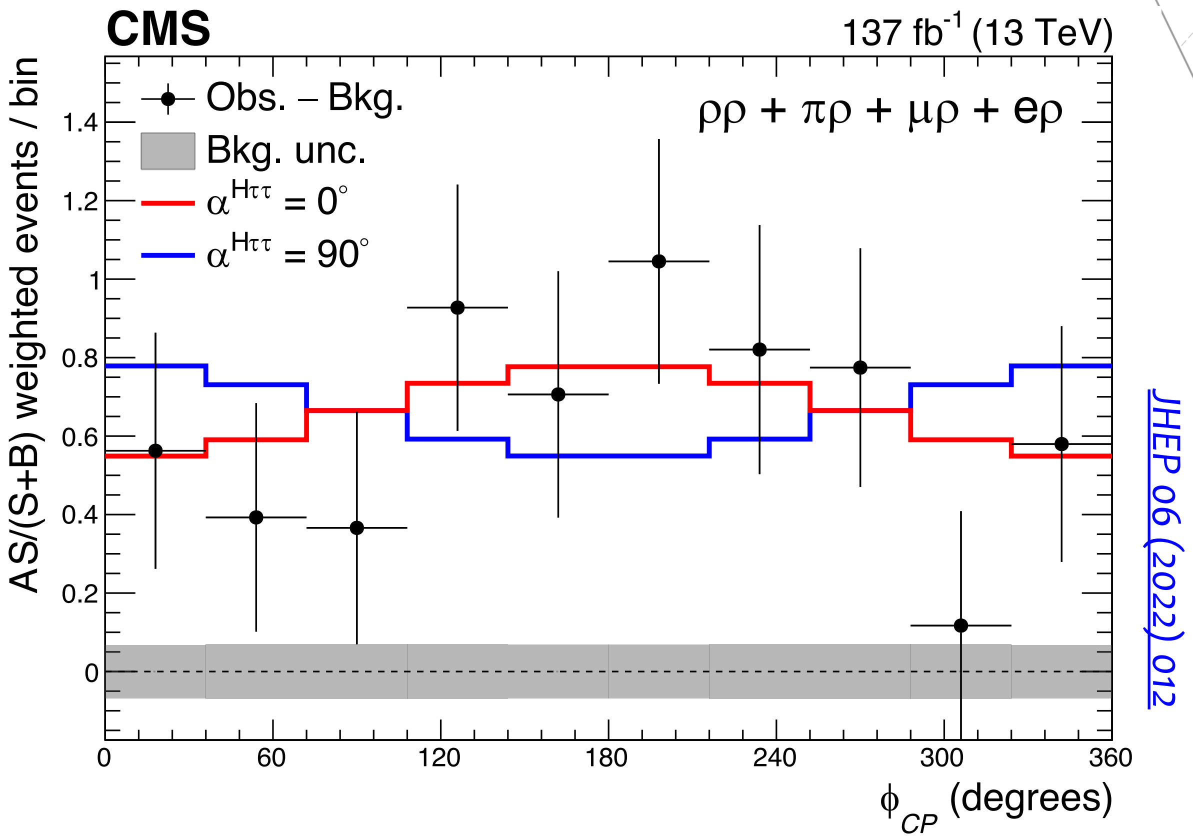


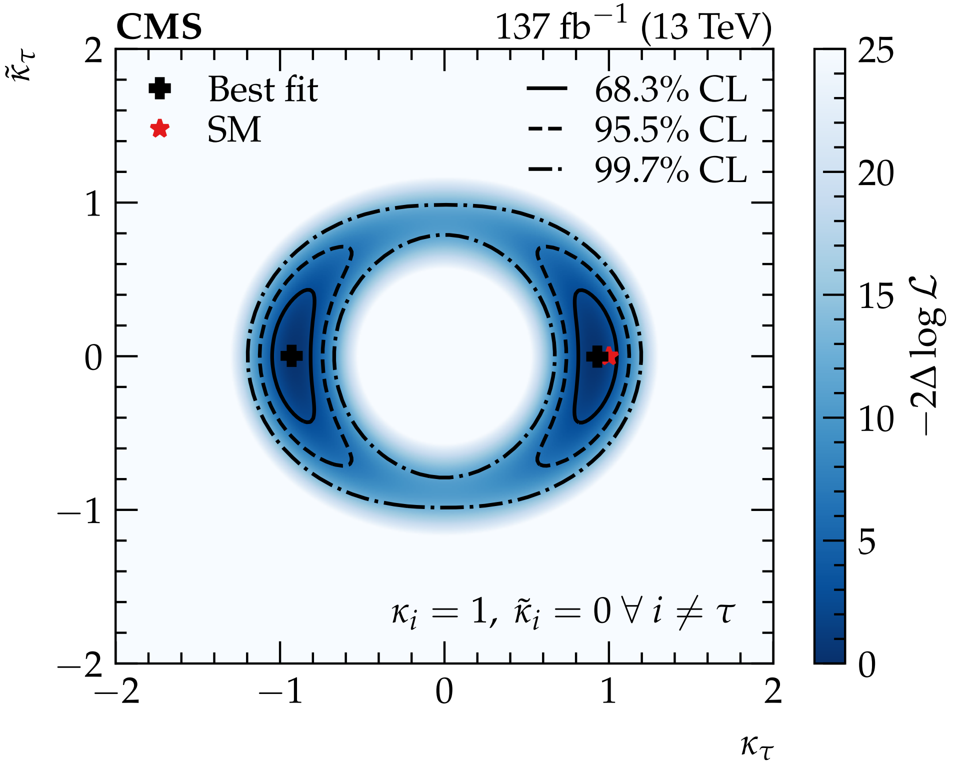
Matter-vs-anti-matter

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



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



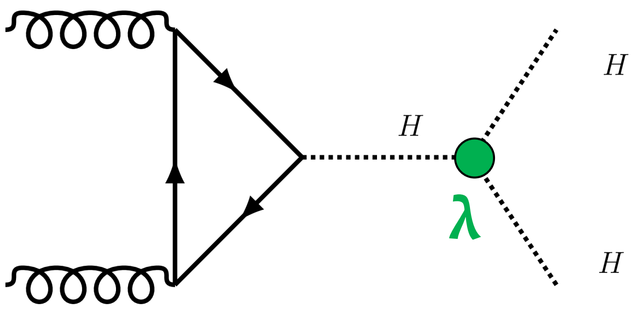


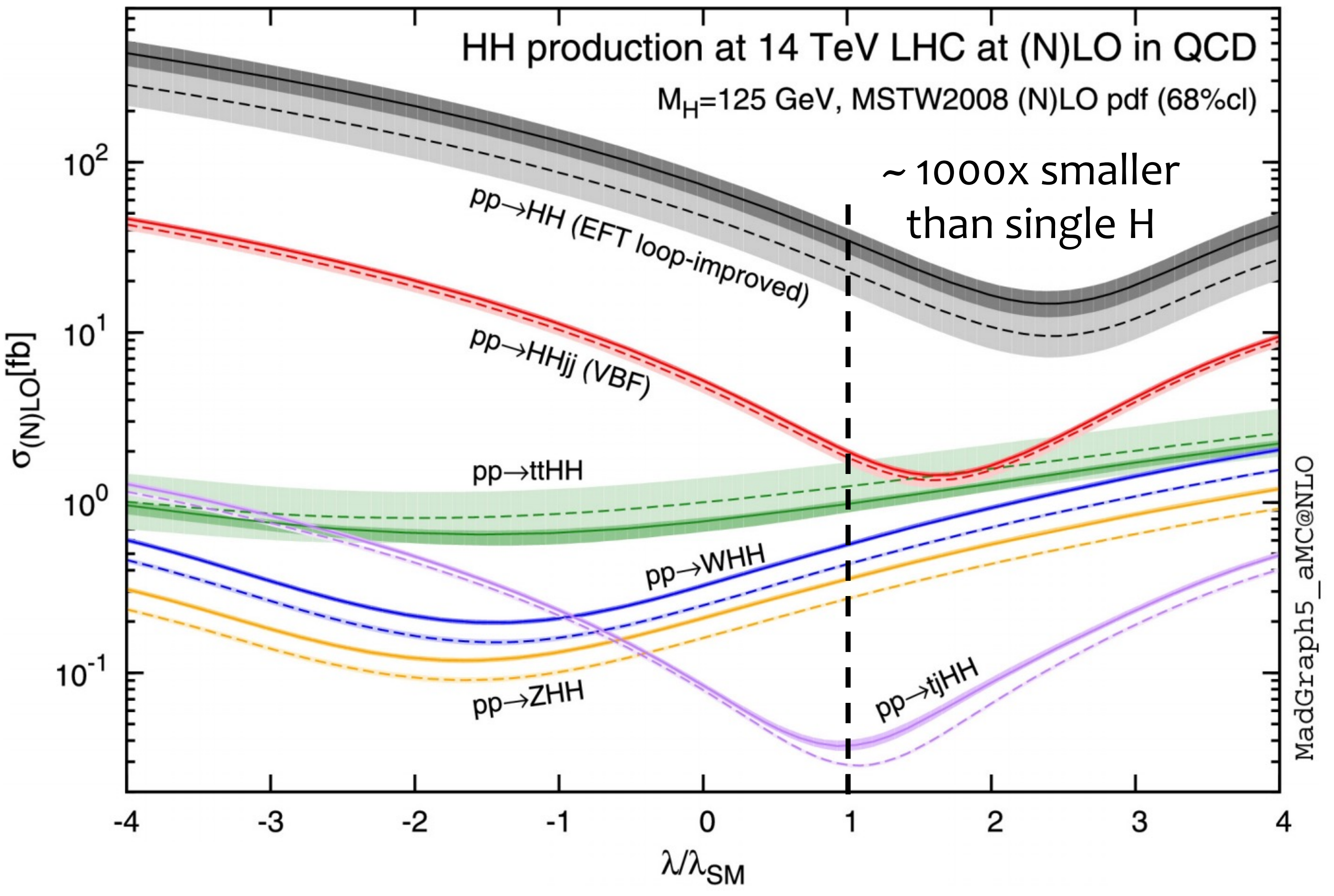
Higgs boson self-coupling

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

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

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





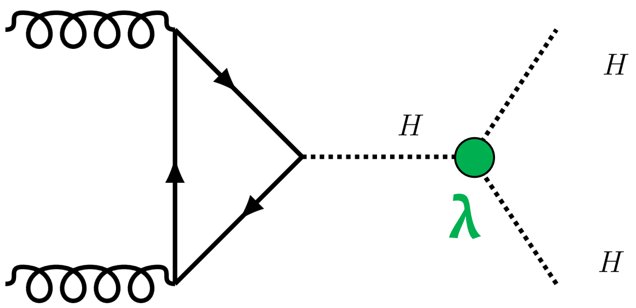
Direct searches for **Double Higgs (HH)** production one way to constrain the Higgs boson self-coupling!

Higgs boson self-coupling

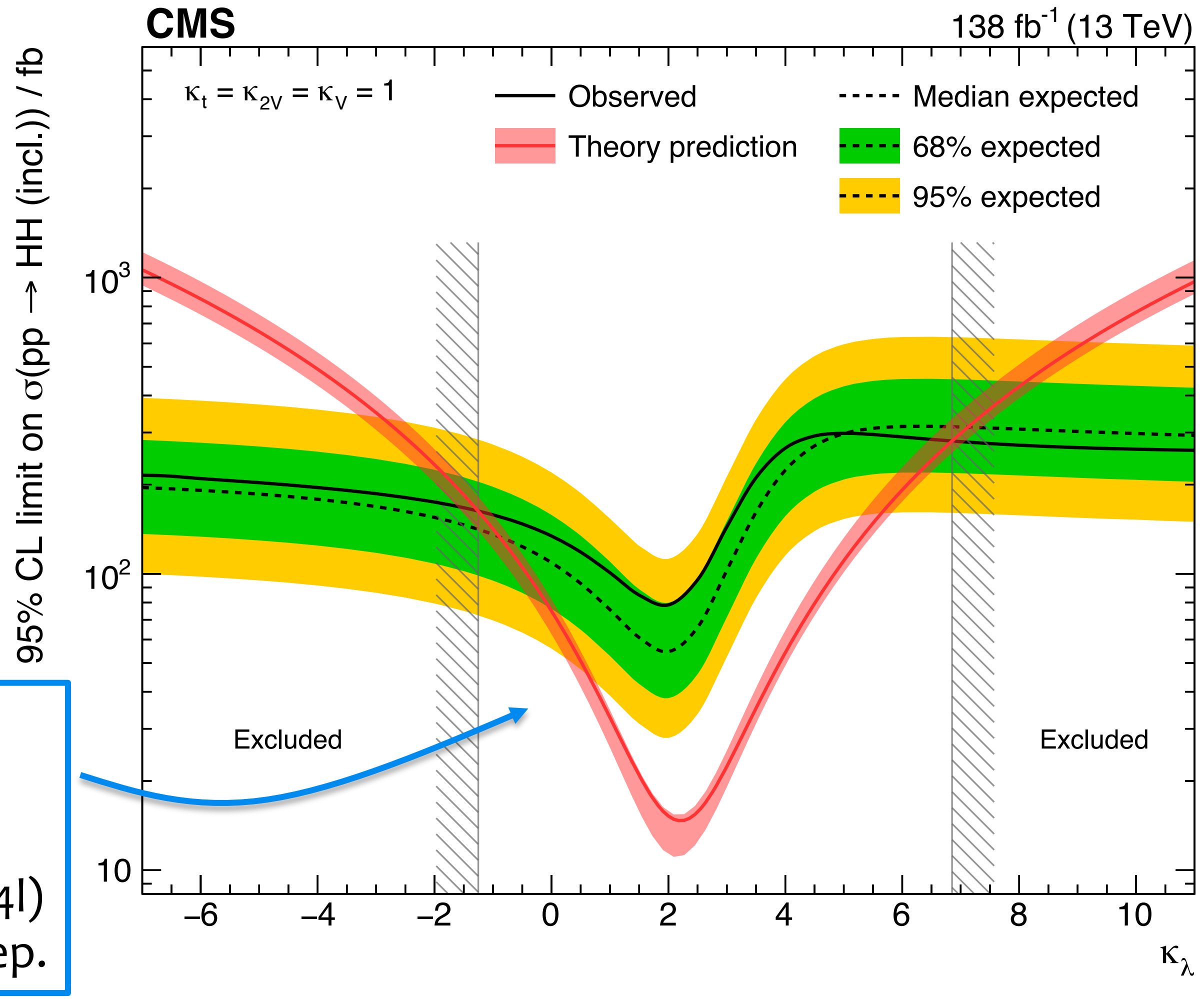
Remember in the SM, the **Higgs potential** includes ***H*³** terms

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

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



HH→bbbb,
HH→bbττ
HH→bbγγ
HH→bbZZ(4l)
HH→multilep.

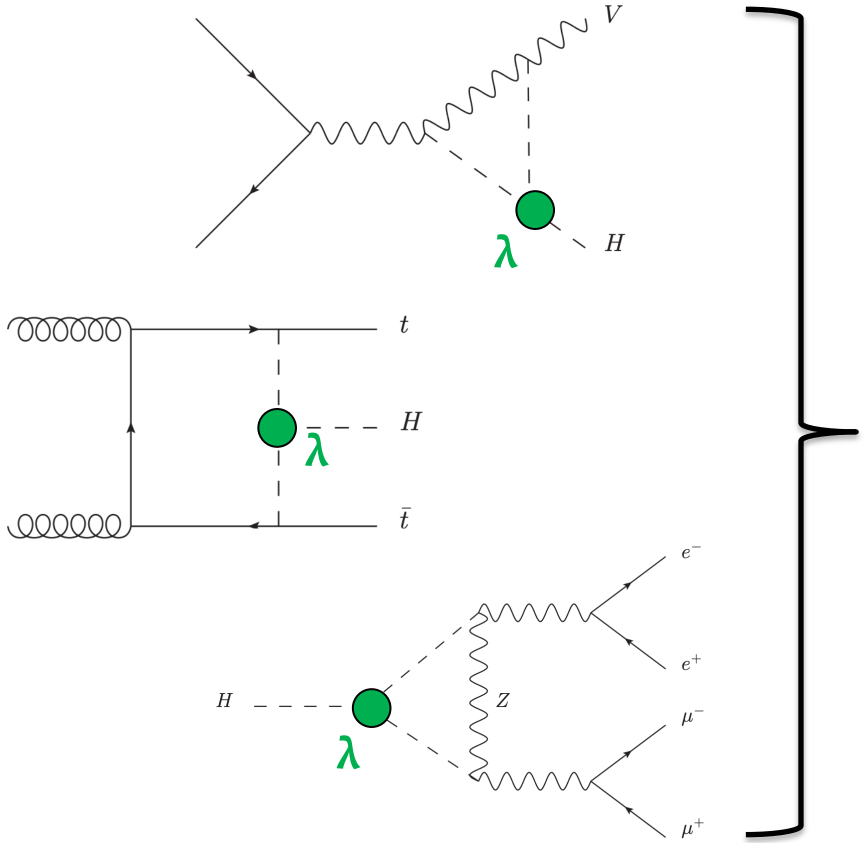


Nature publication

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

Higgs boson self-coupling

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

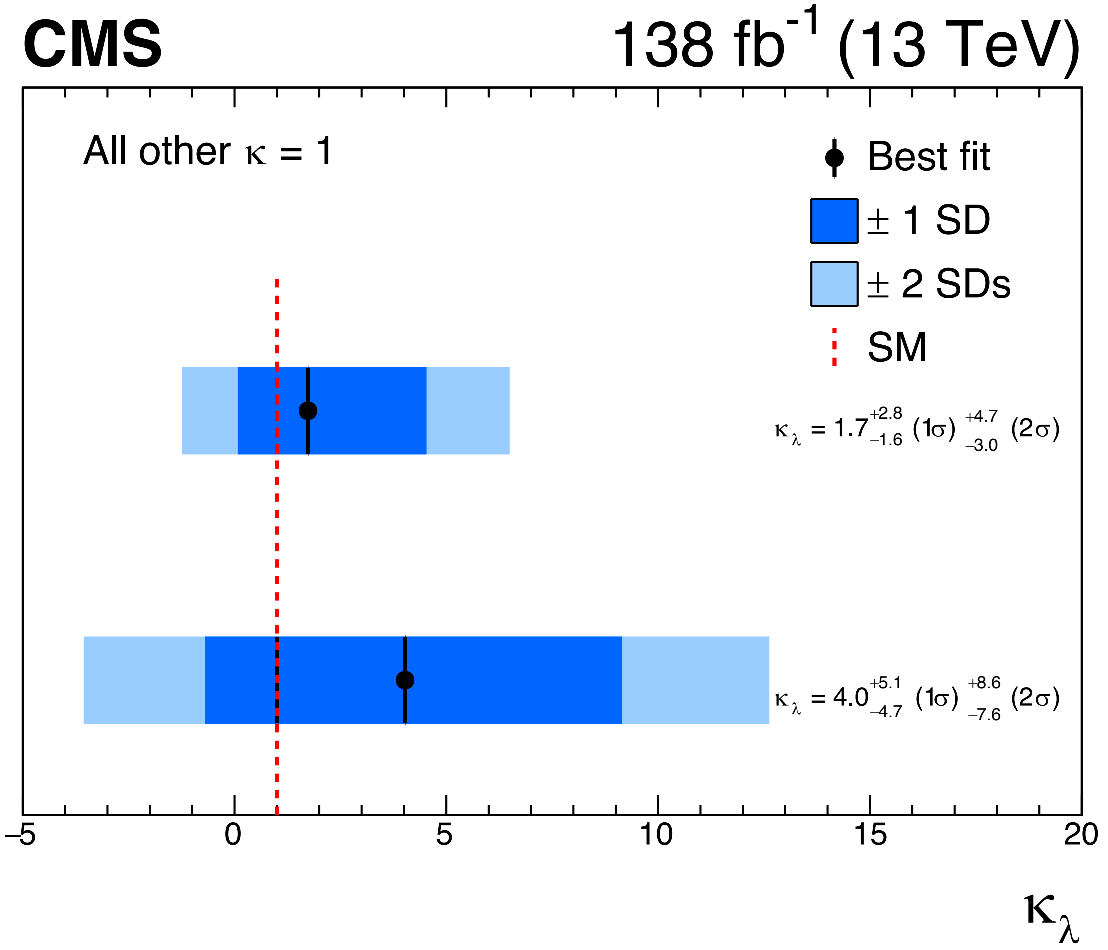


pp → HH

Direct search

pp → H

Indirect interpretation



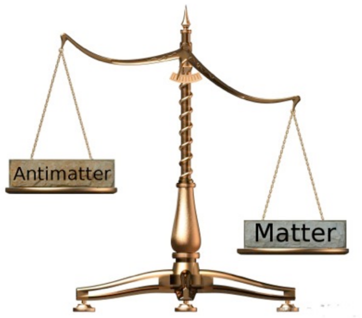
Precision (single) **Higgs boson measurements** also sensitive to **Higgs self-coupling**!

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

Why do we care?

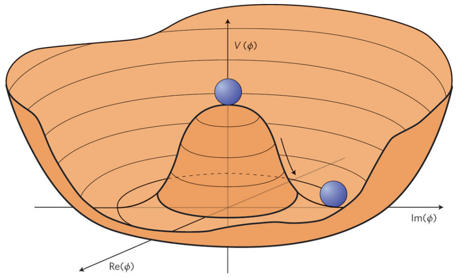
The universe today is **matter** (baryon)-**dominated,**

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

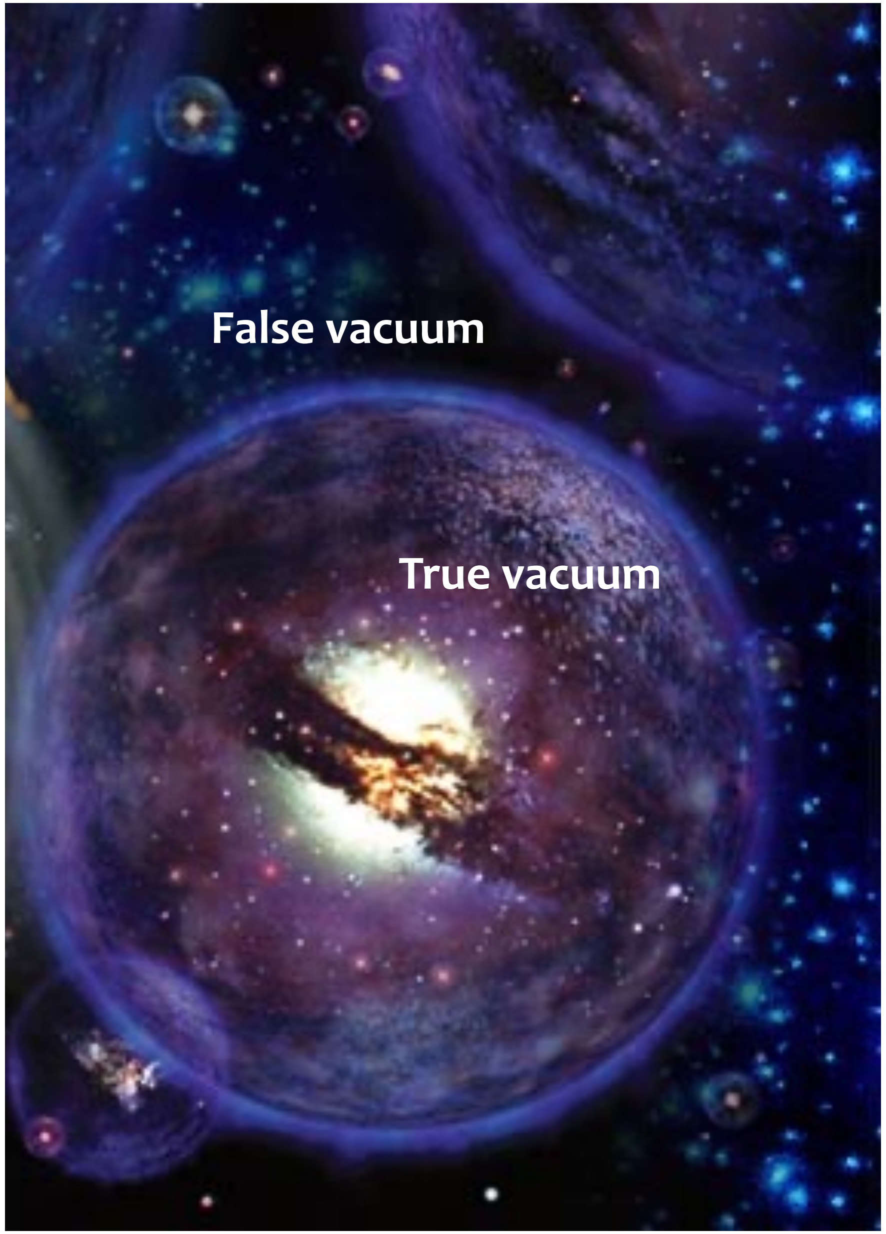


Essential ingredient for **Baryogenesis** (production of B-asymmetry) :

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



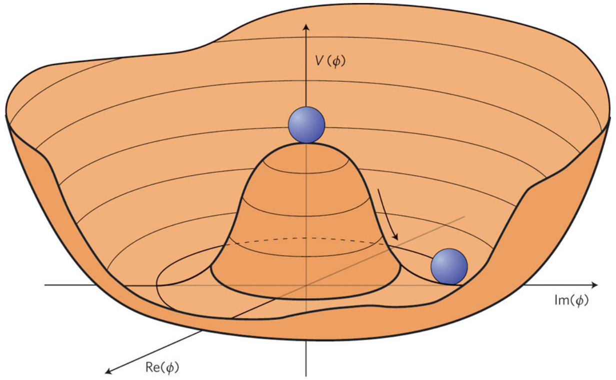
[1] A. D. Sakharov, JETP Lett. 5, 24 (1967)



Modified Higgs potential and Baryogenesis

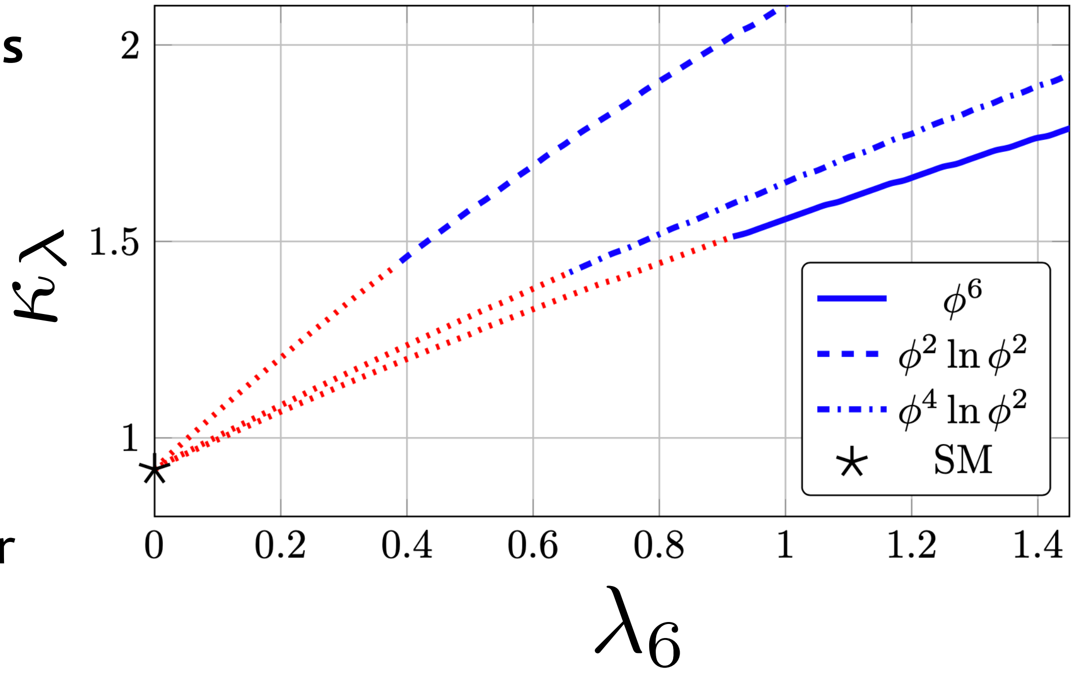
BSM physics in **Higgs potential** could be the solution!

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



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

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



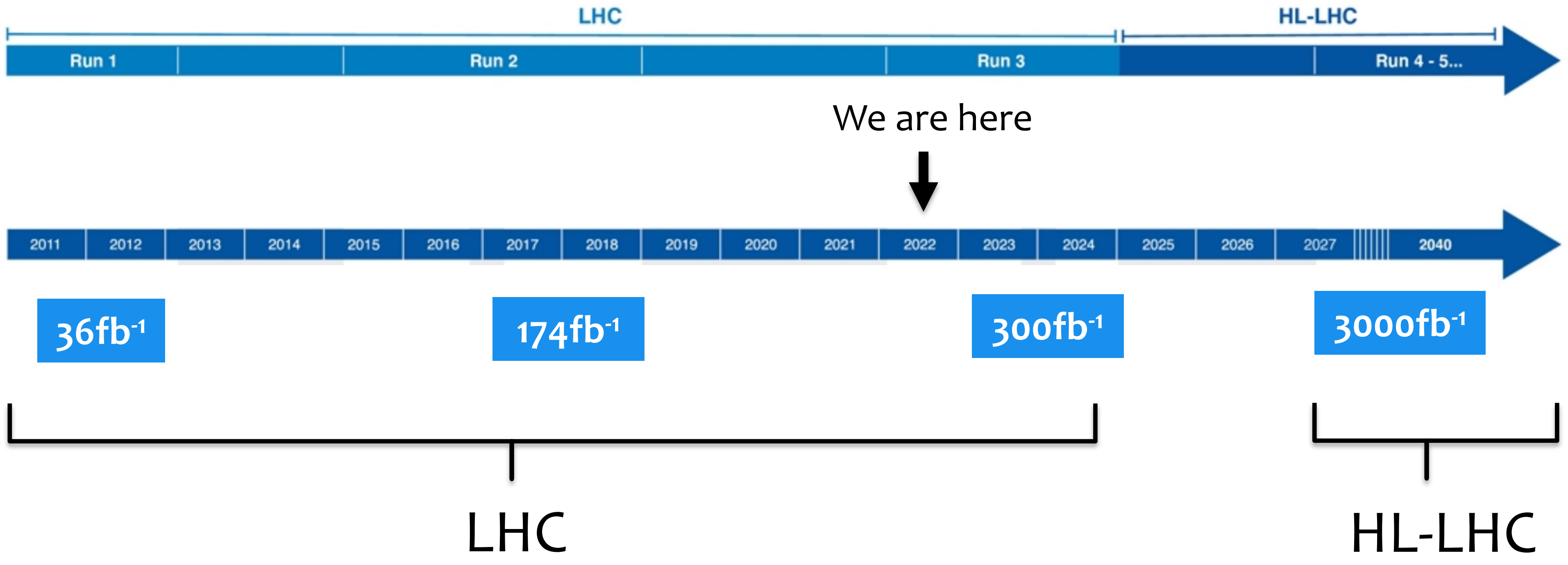
Phys. Rev. D 97, 075008 (2018)

50% increase in self-coupling could hint at mechanism for 1st order EWK phase-transition accuracy crucial goal

The future of the LHC

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

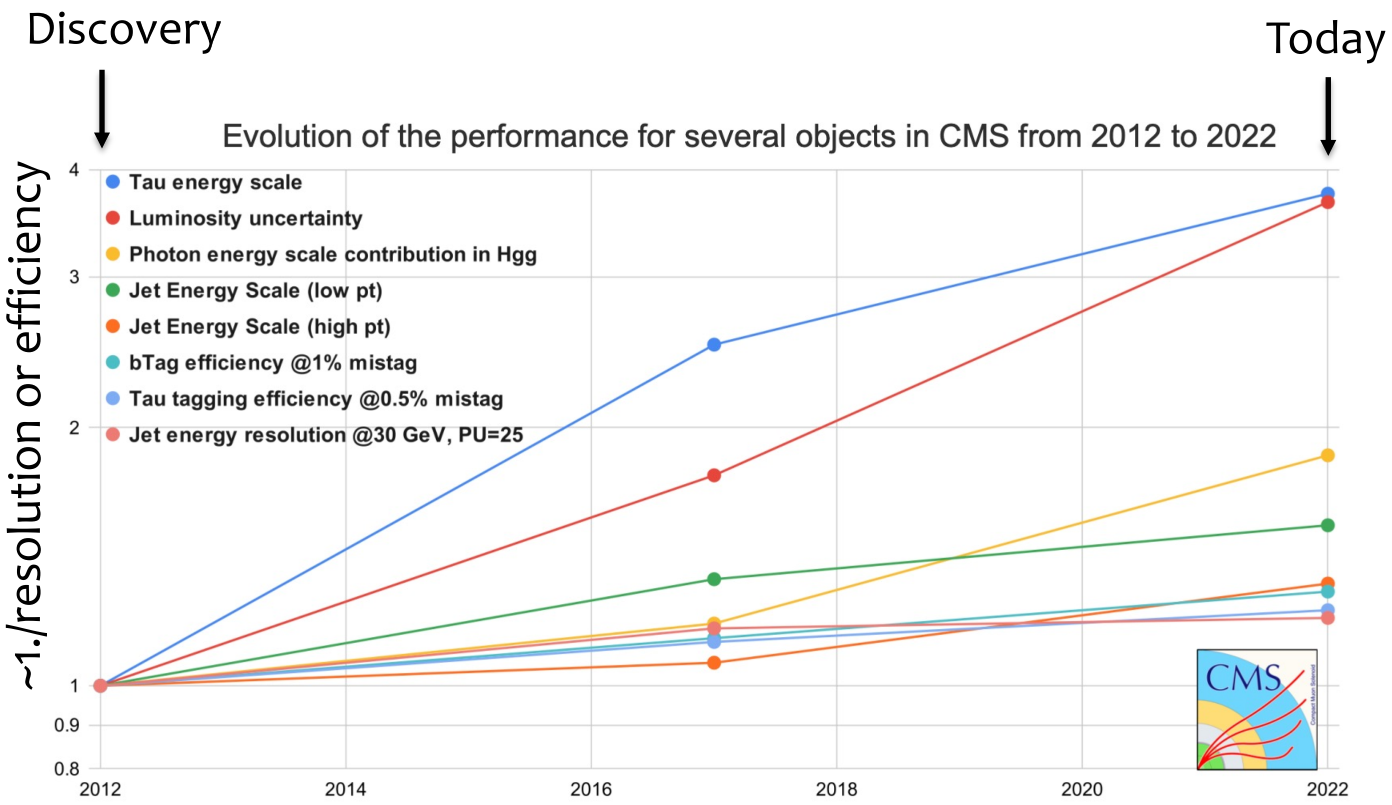
~20x the data we have today!

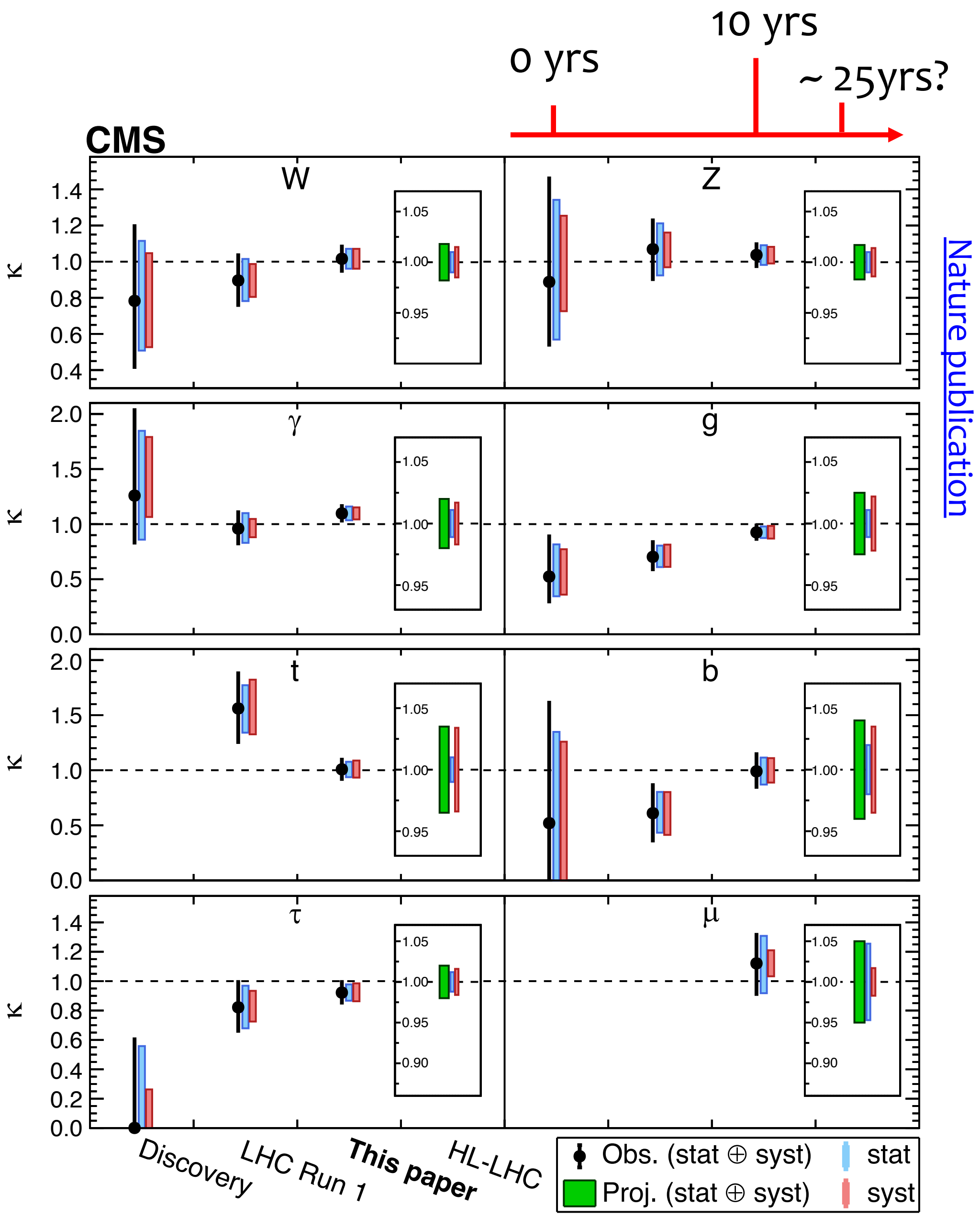


Expect **> 160M H-bosons / 120k HH pairs** at CMS by the end of the **HL-LHC** !

Higgs couplings @ HL-LHC

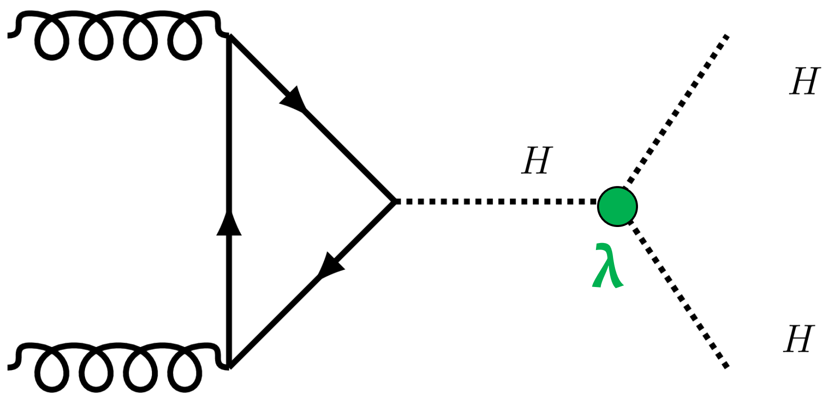
Precision measurements require more than just more data
→ Improvements in reconstruction techniques & calibrations will be needed for few % precision couplings @HL-LHC

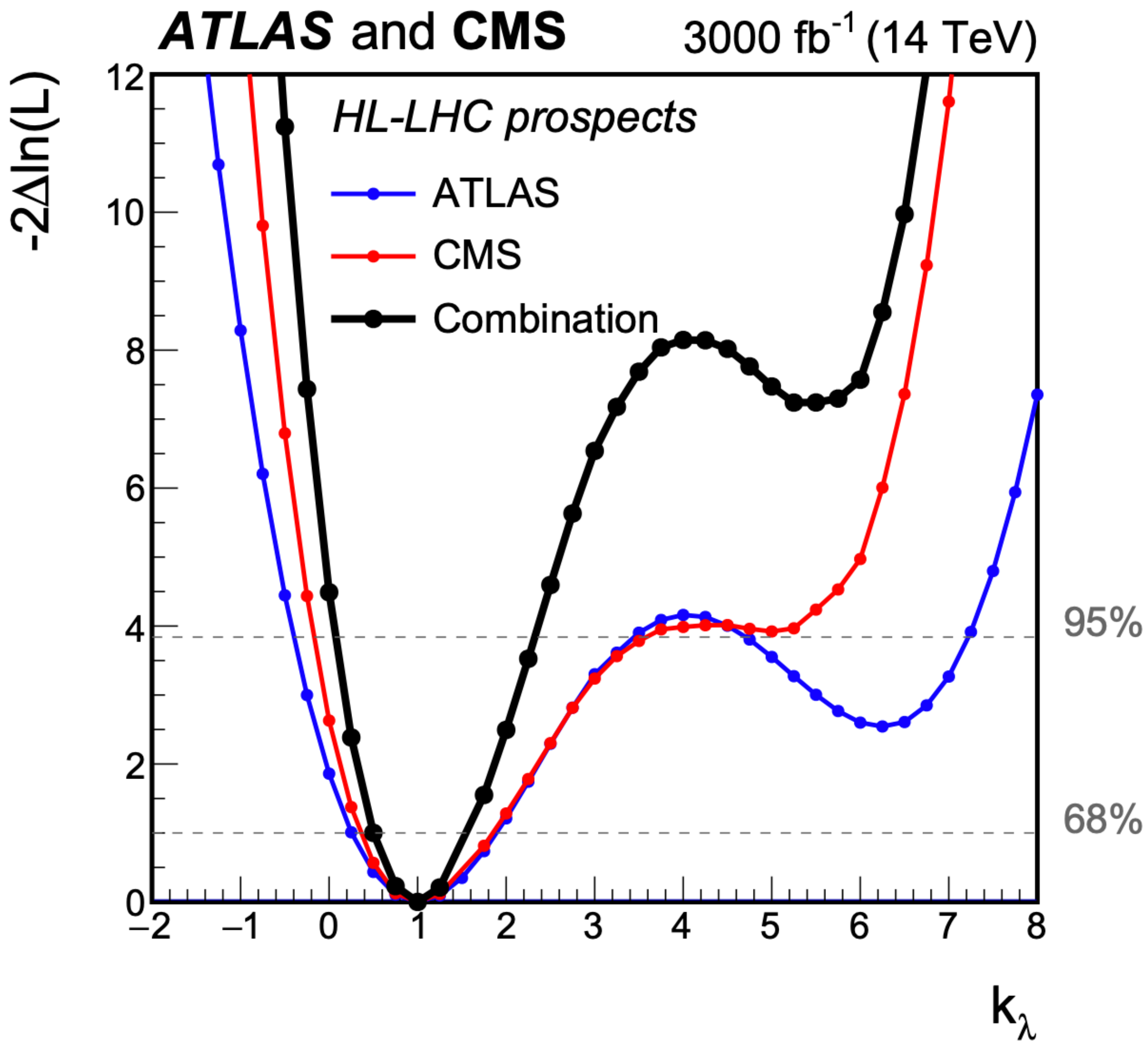




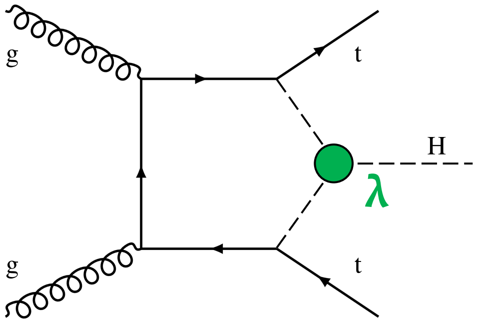
Higgs boson self-coupling @ HL-LHC

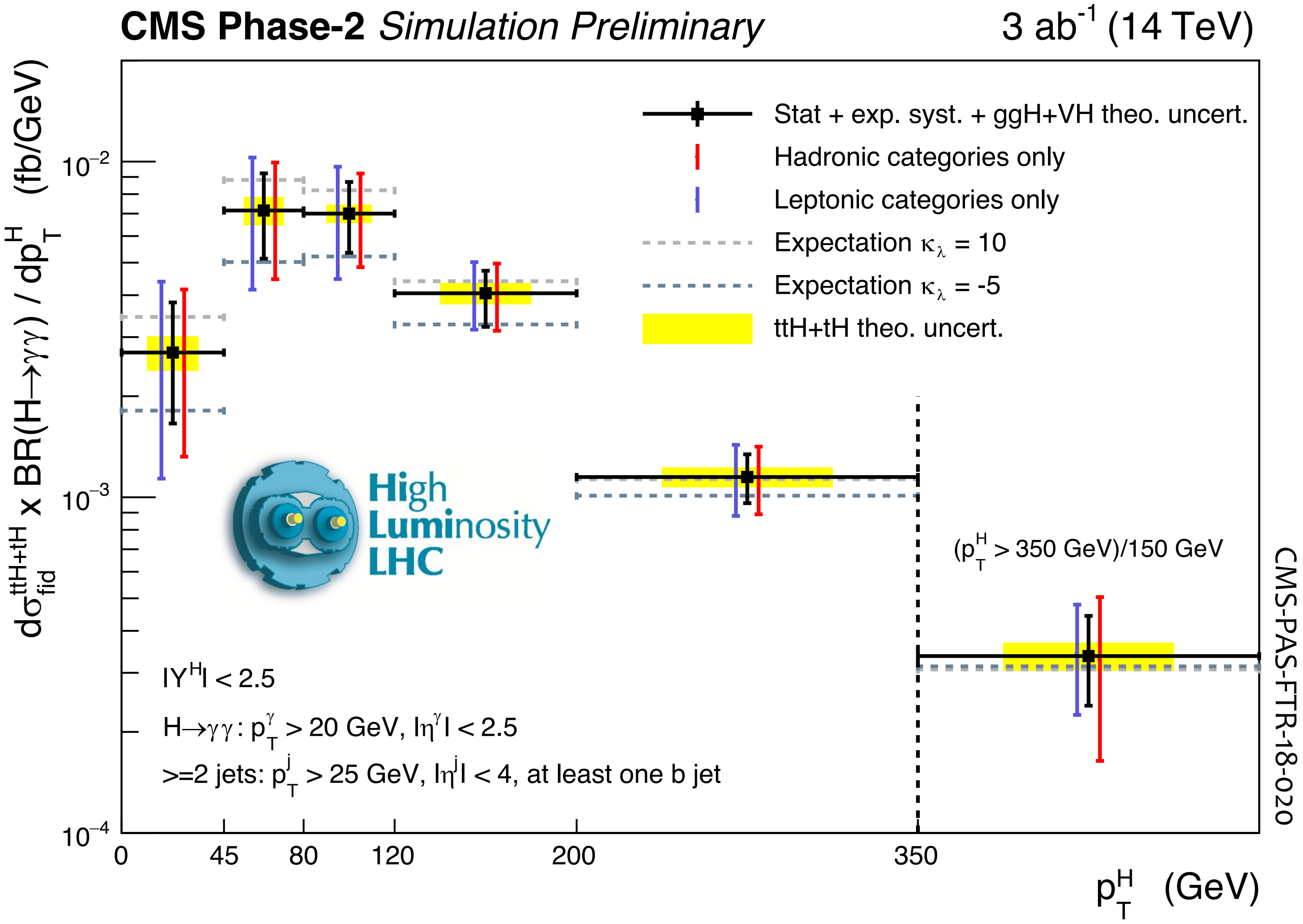
Approx 10x size data set available to **ATLAS+CMS** at the end of the HL-LHC
→ Combined searches for HH production to approach **~50% uncertainty on κ_λ**



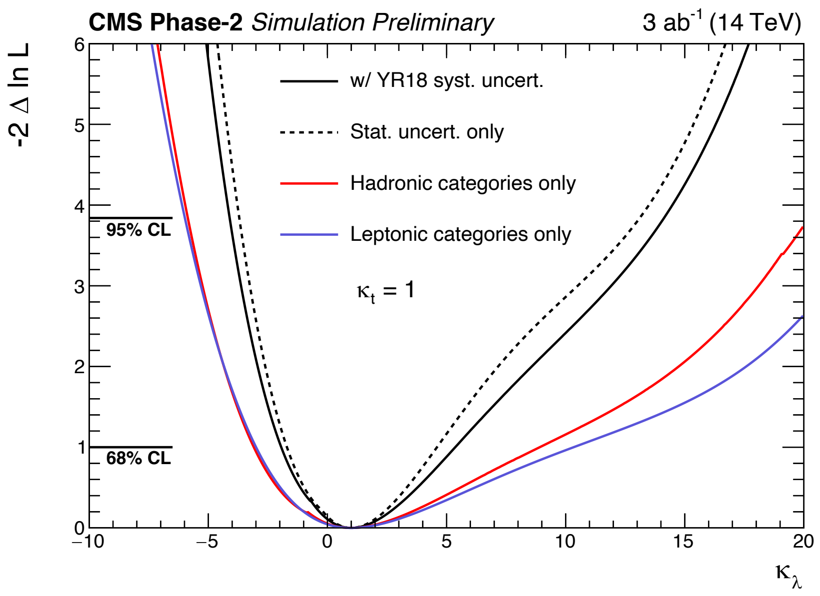


Higgs boson self-coupling @ HL-LHC



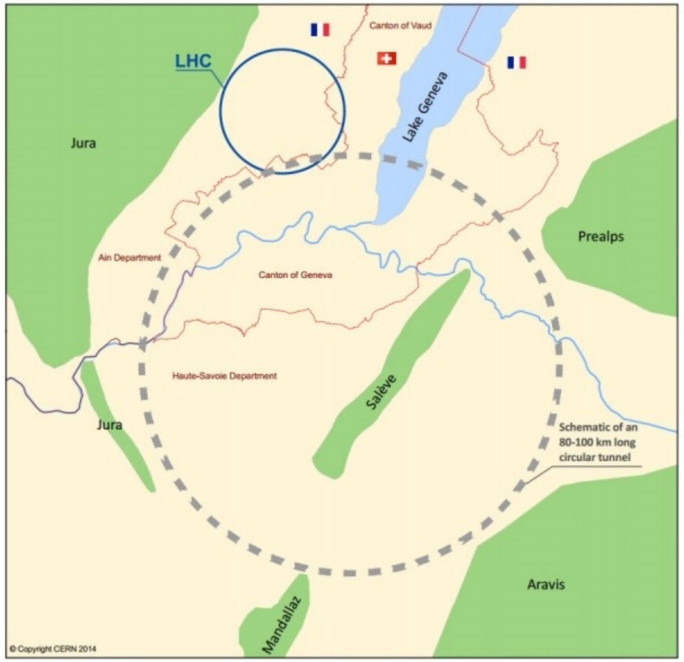


Combinations with **precision differential measurements** of **Higgs production** will push sensitivity even further!



Higgs beyond the HL-LHC?

Future collider a "*High-priority future initiative*"

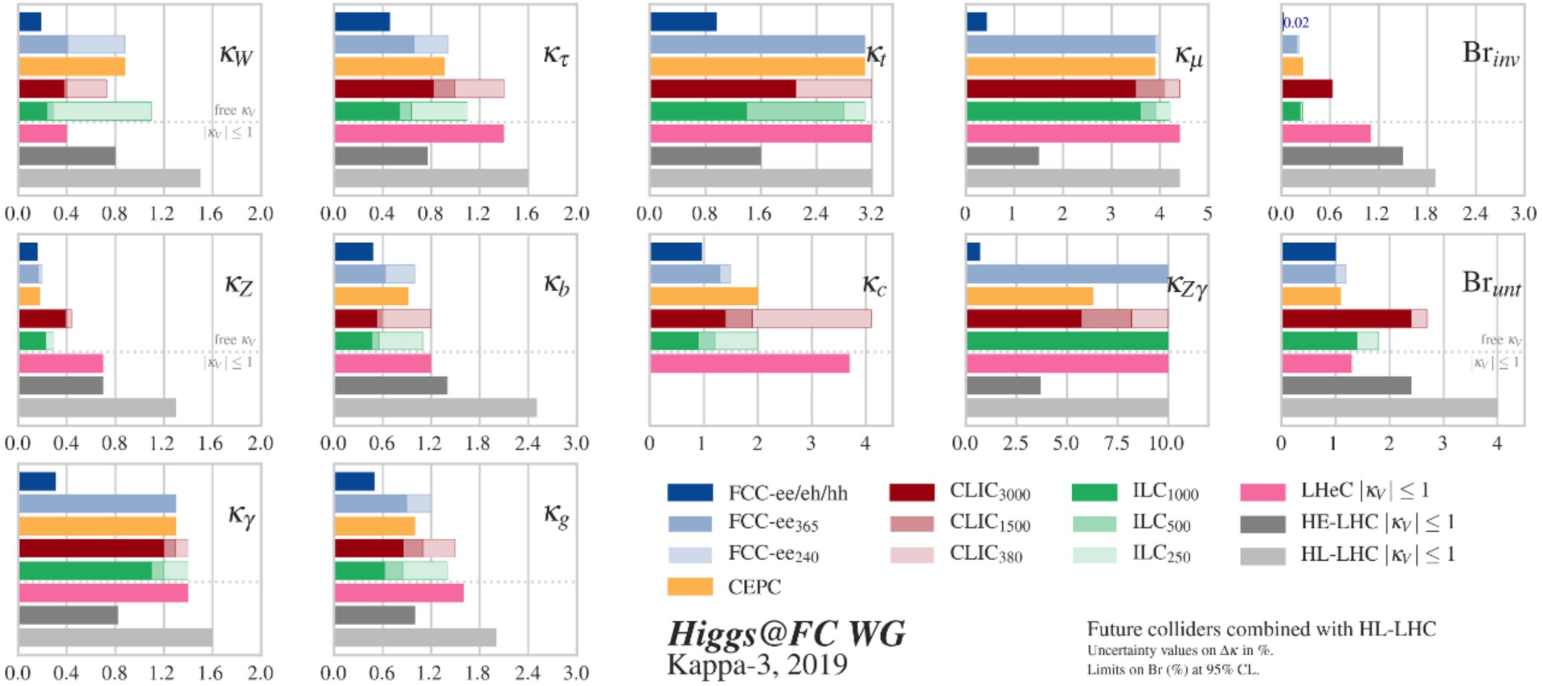


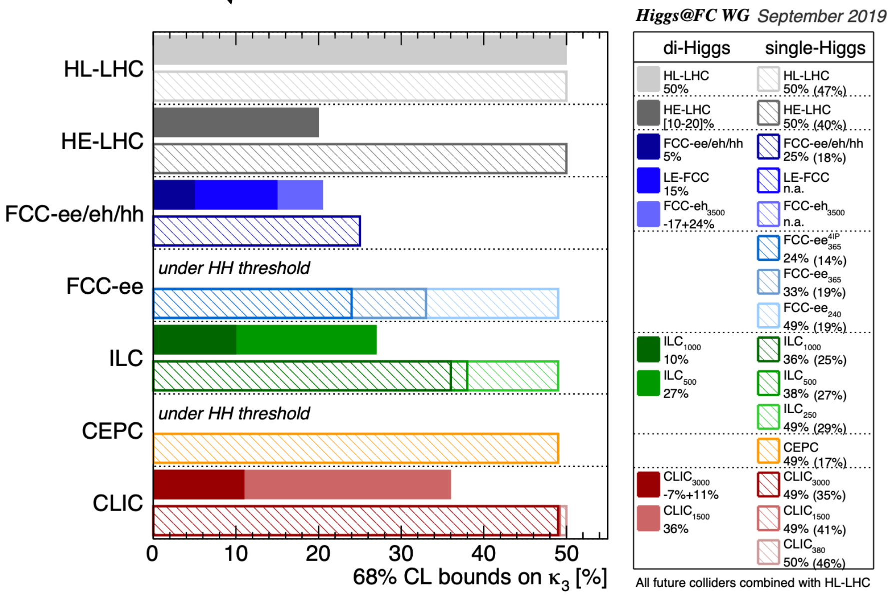
"Europe, …, should ***investigate the technical and financial feasibility*** *of a* ***future hadron collider*** *at CERN with a centre-of-mass energy of* ***at least 100 TeV*** *…*

Higgs boson couplings beyond the HL-LHC

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

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



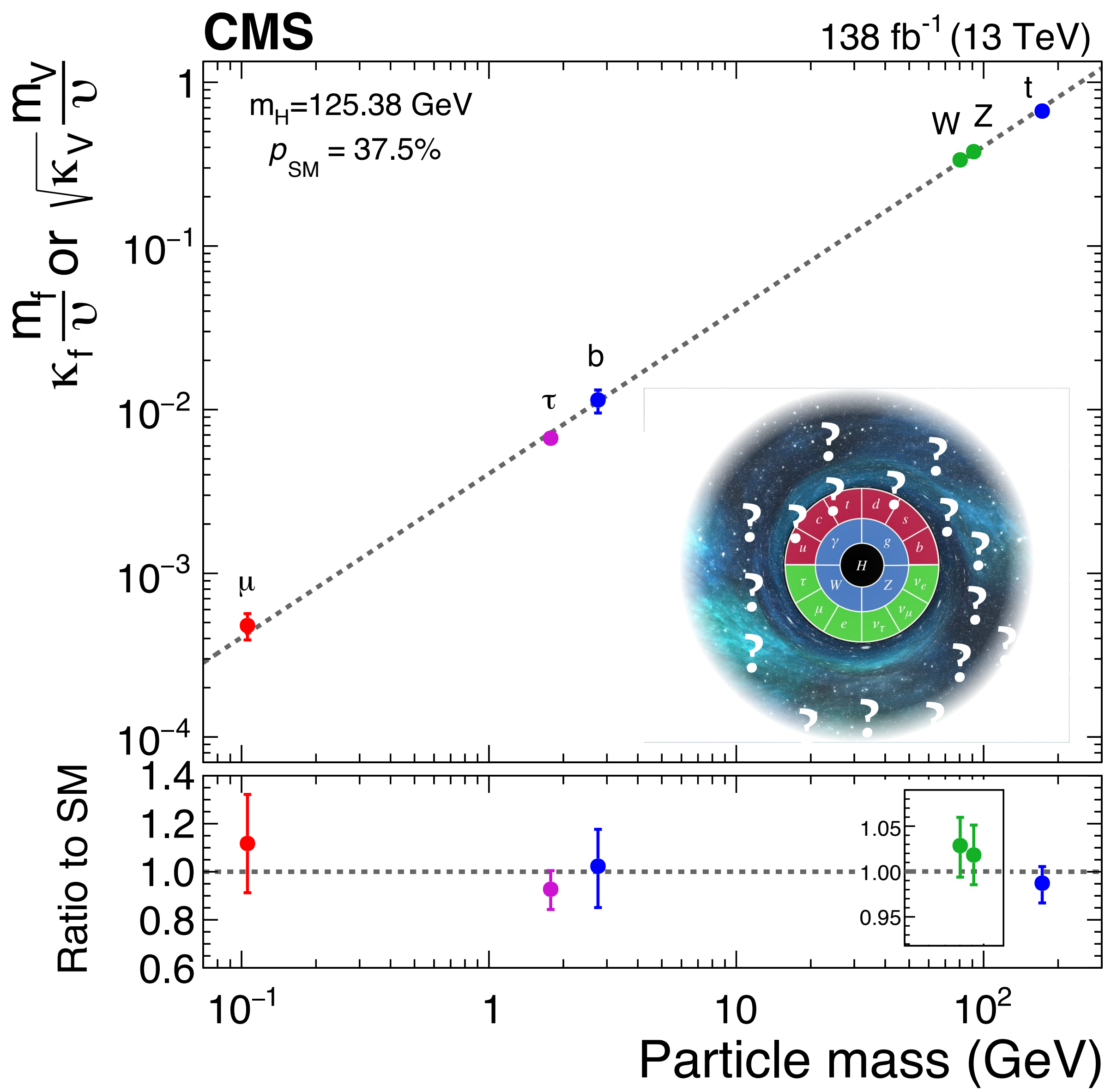


JHEP 139 (2020)

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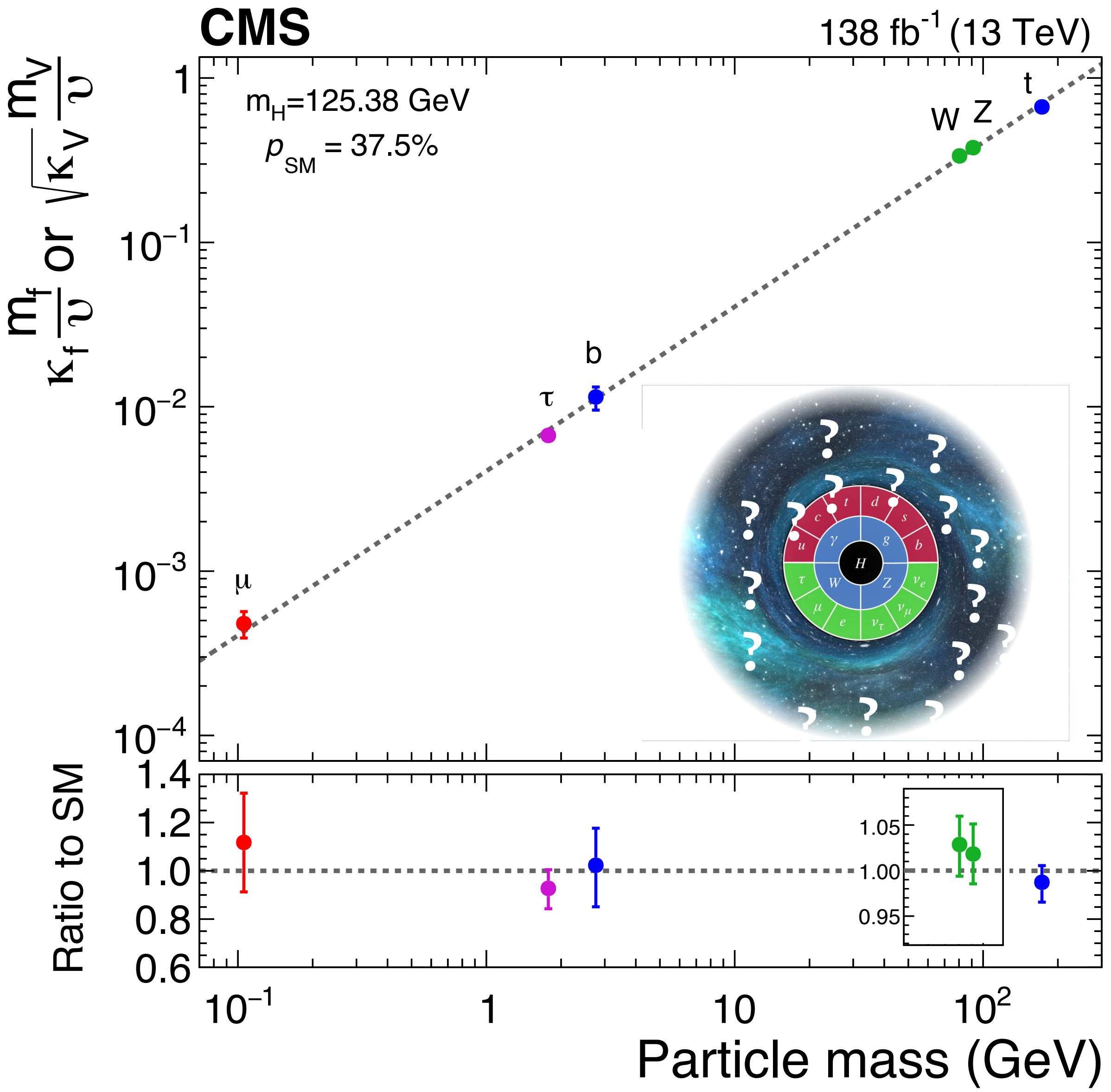
- **So far**, all measured properties look **SM-like (**but that's ok, who said nature would be easy to unravel?_

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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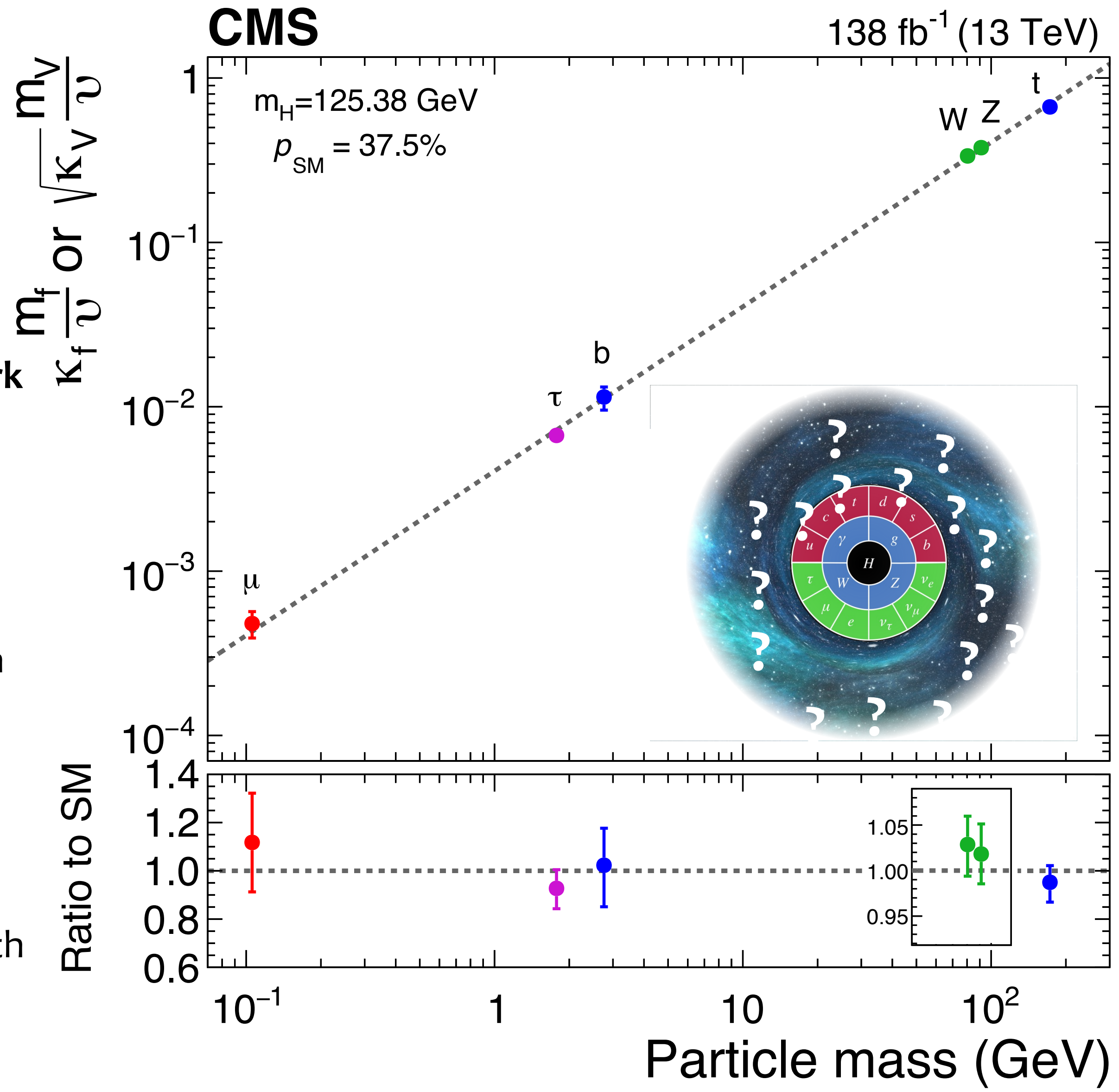
Things I didn't talk about
- Direct searches for heavy Higgs/extended Higgs sectors/res-HH
- CP-odd couplings to vector bosons & flavor violating Higgs decays
- Rare decays in the SM (1st generation couplings) & Higgs total width



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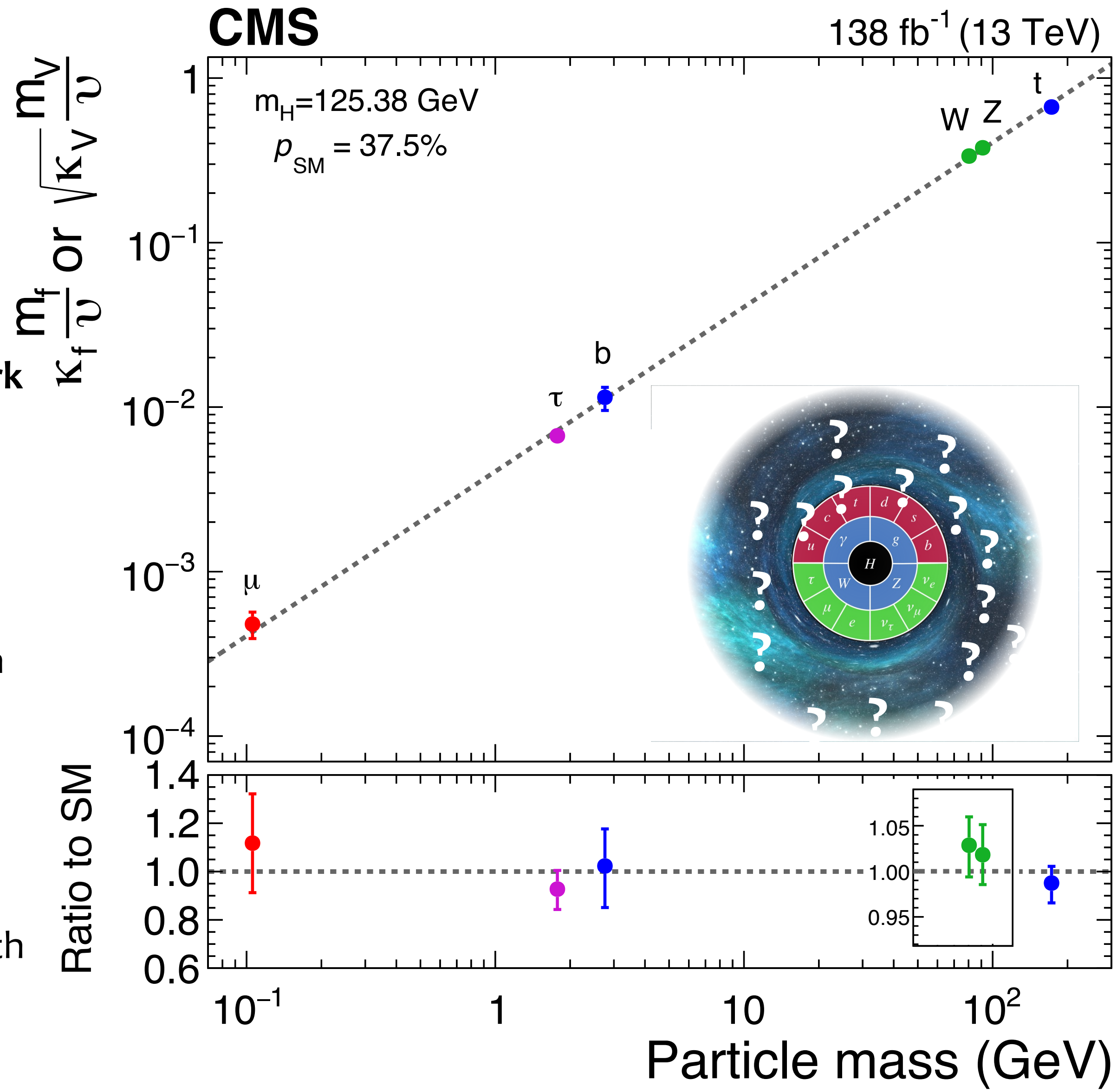


We are **only 10 years** in so far!

- **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)**

10 years of precision measurements **(2022)**

Precision measurements for discovery

Higgs boson discovery **(2012)**

10 years of precision measurements **(2022)**

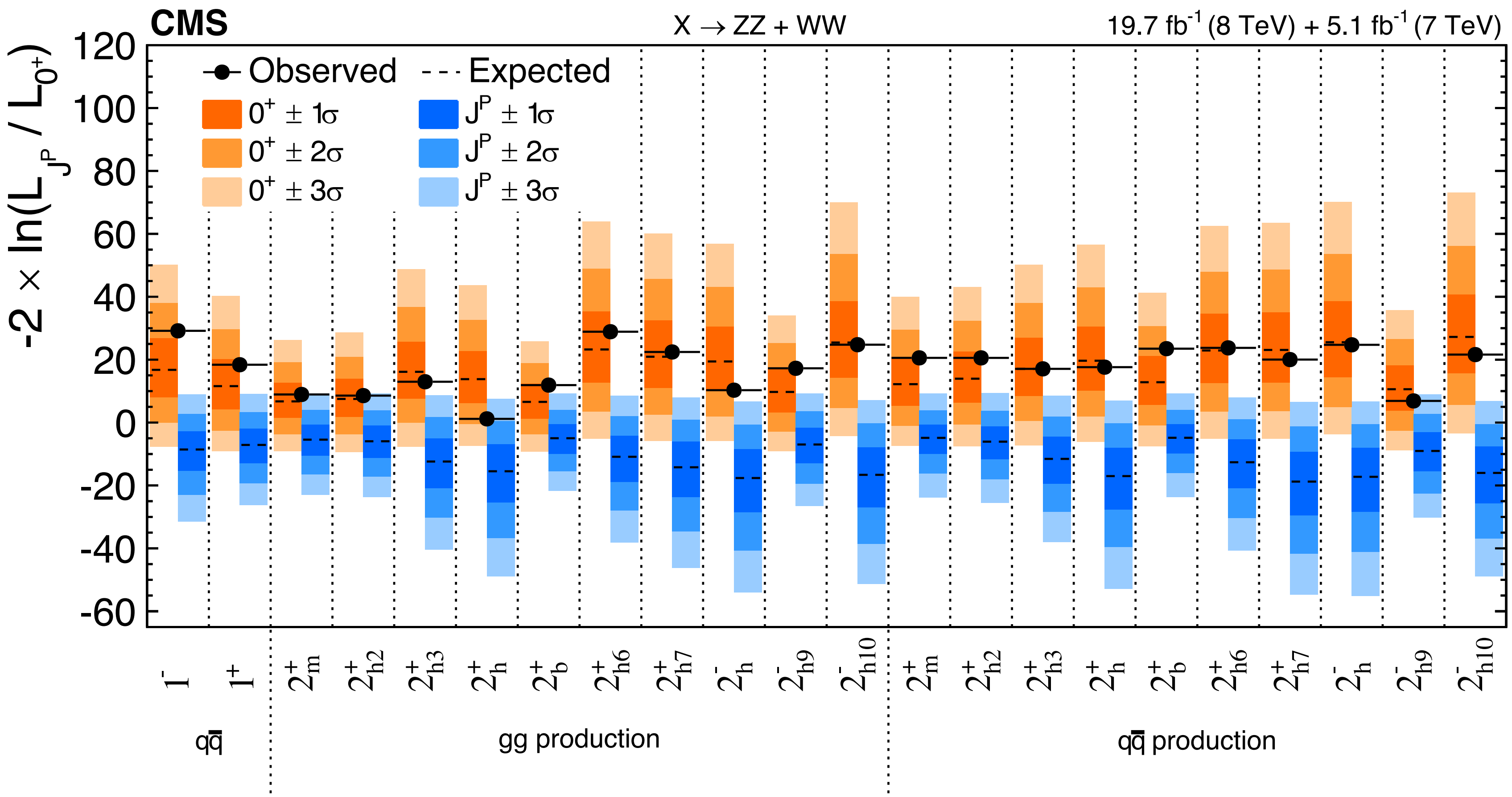
Run-3/HL-LHC/Future collider ? **(20XX?)**

Thanks!

Backup Slides

~~No~~ Zero - Spin zone

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



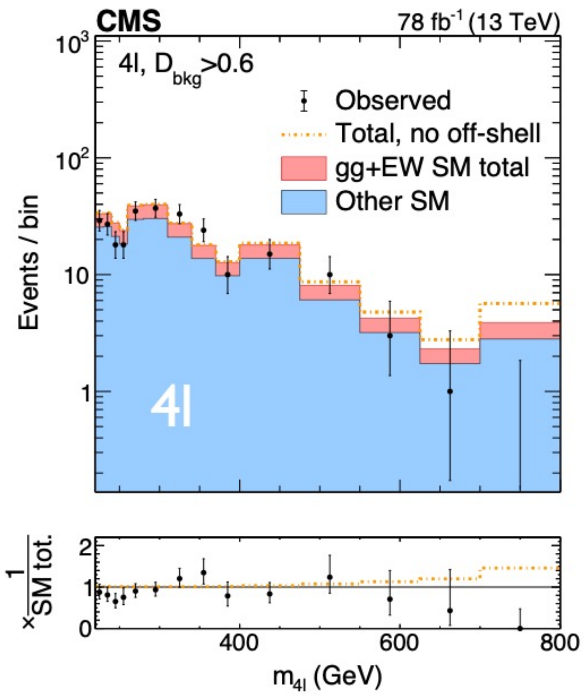
Run-1 data is already enough to rule out spin-2 (and many other J^P states) at > 99.9% confidence level

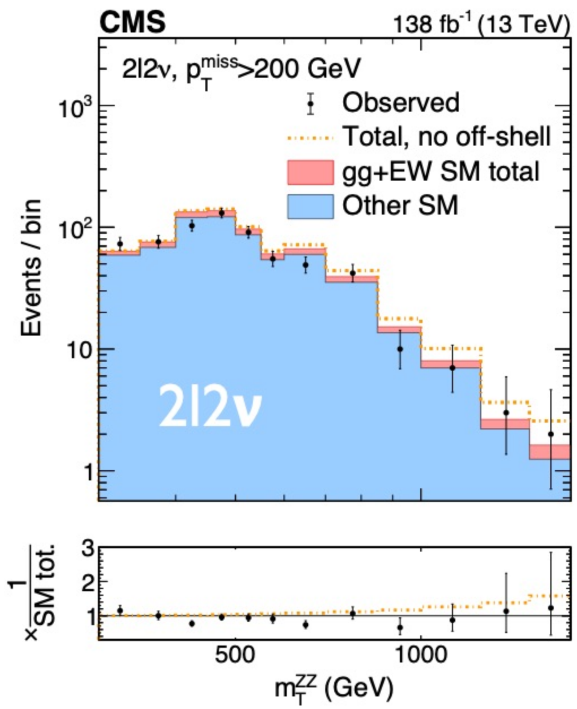
Higgs width

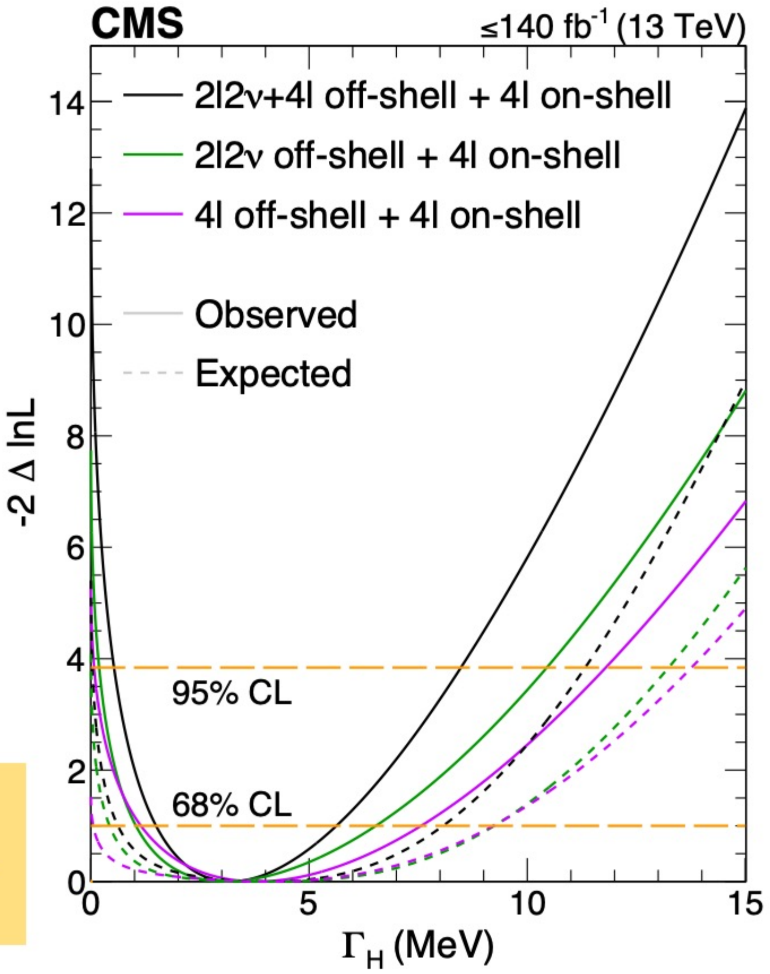
Measurements of the Higgs width from off-shell production

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

arXiv:2202.06923







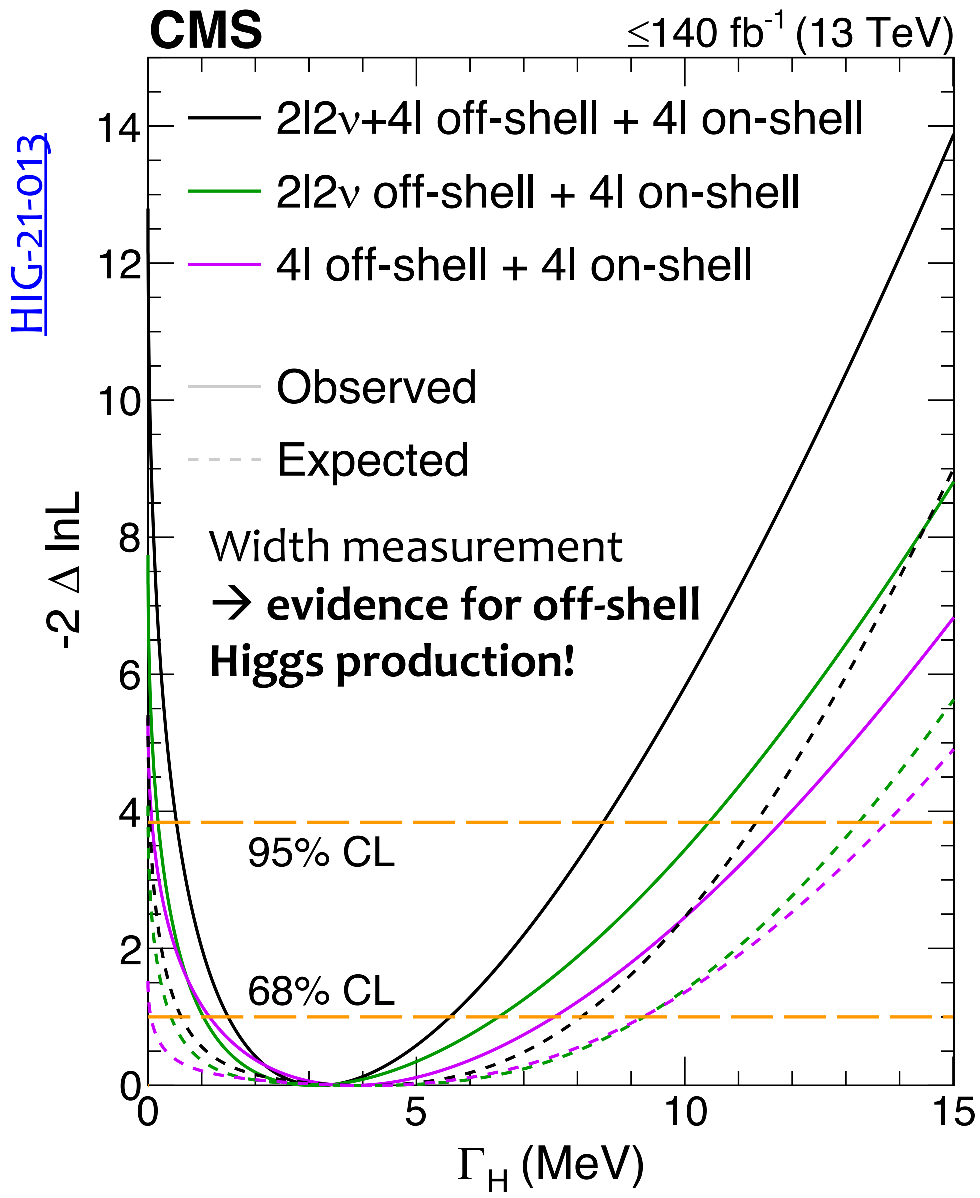
Slide by M. Delmastro

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

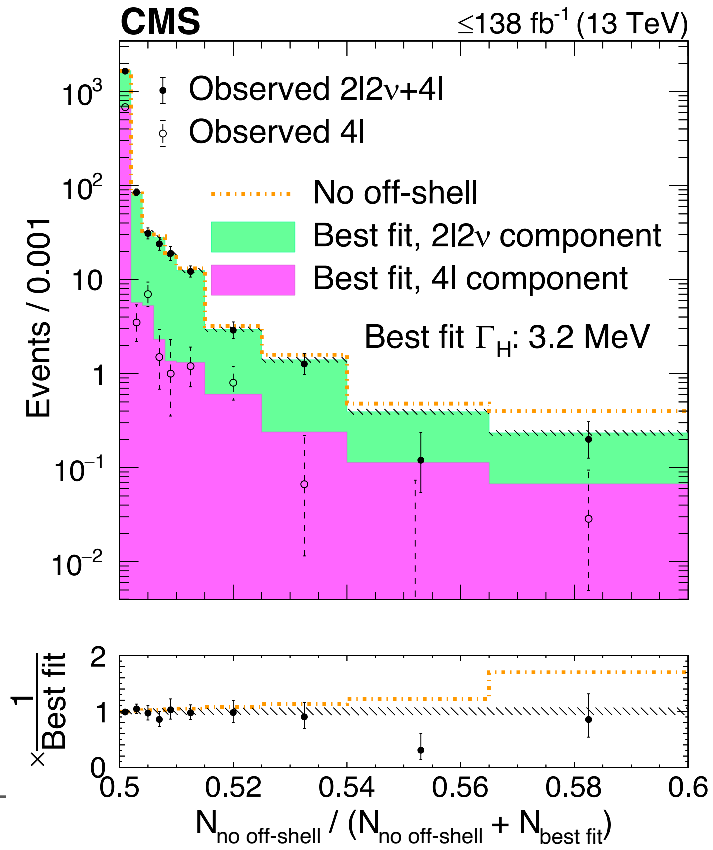


$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H},$$

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

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

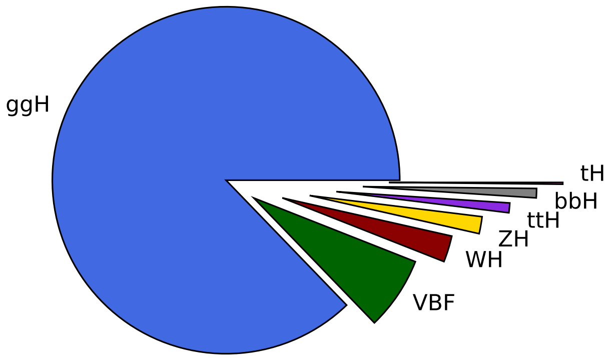
$m_{ZZ} > m_{2Z}$ *(Off-shell production)*

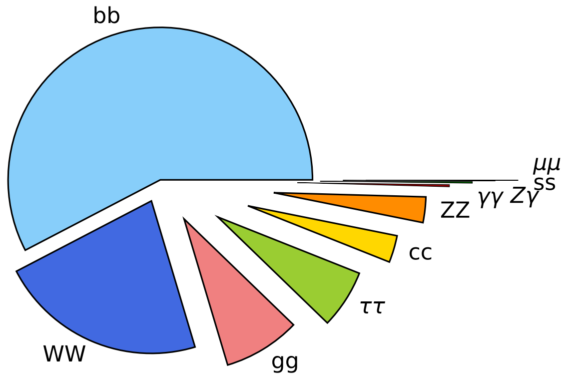


Higgs prod & decay

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





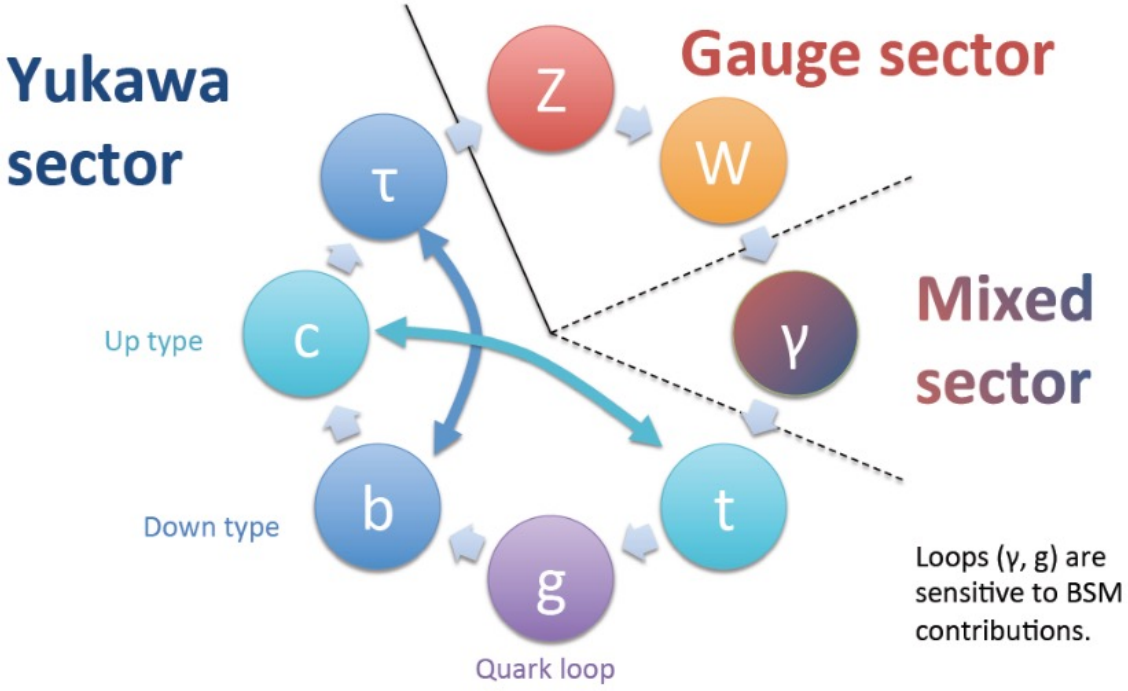
Higgs boson couplings

SM Higgs should have definite couplings to the different SM particles

Allow for a coupling modifier for each SM particle

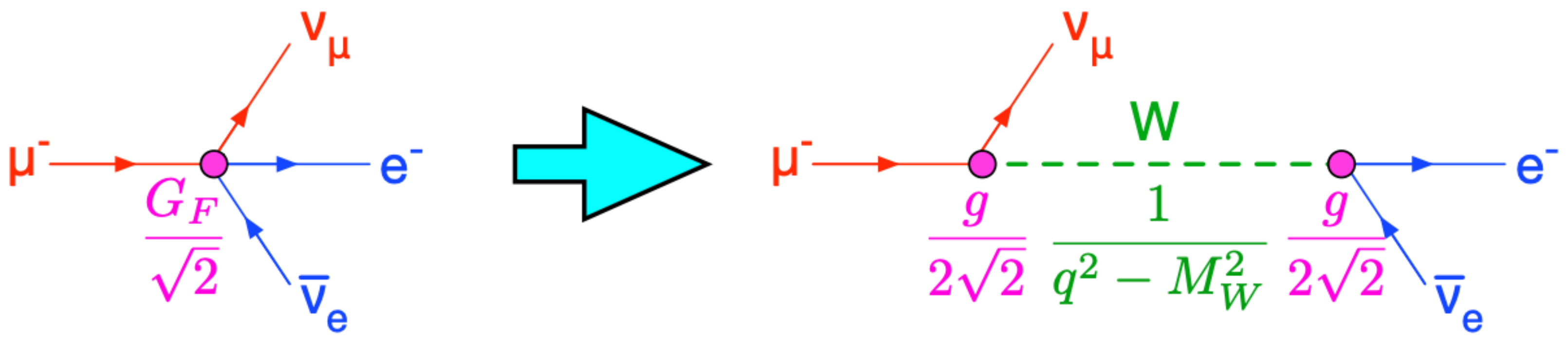
Scale Higgs boson (tree level) couplings by modifiers **κ**

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



We don't measure the couplings of the SM (they aren't inputs to the theory) but we can test ***compatibility*** ⟶ **SM: =** $\boldsymbol{\kappa} = 1$

Fermi theory & the muon decay

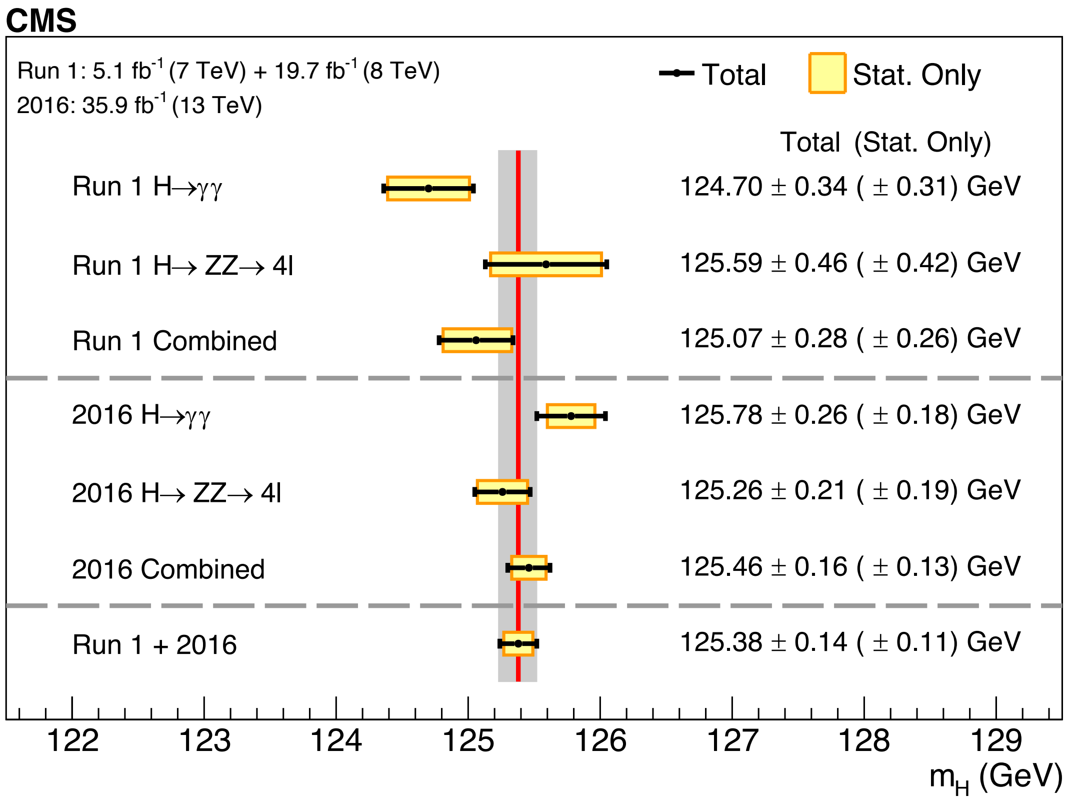


In the limit $q^2 \rightarrow 0$, fermi constant is completely determined by the Higgs vacuum expectation value ν

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

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

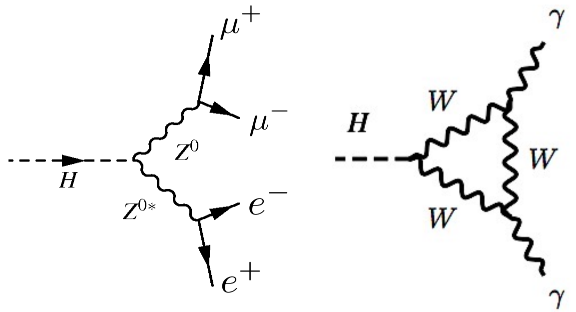
CMS m_H



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



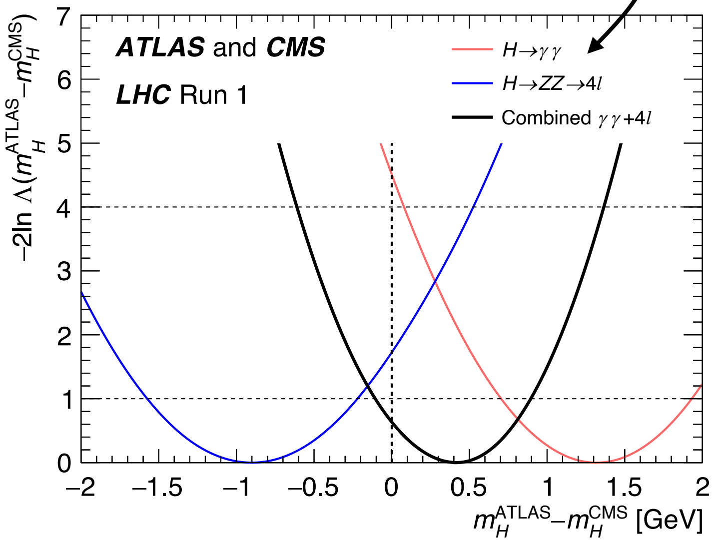
Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

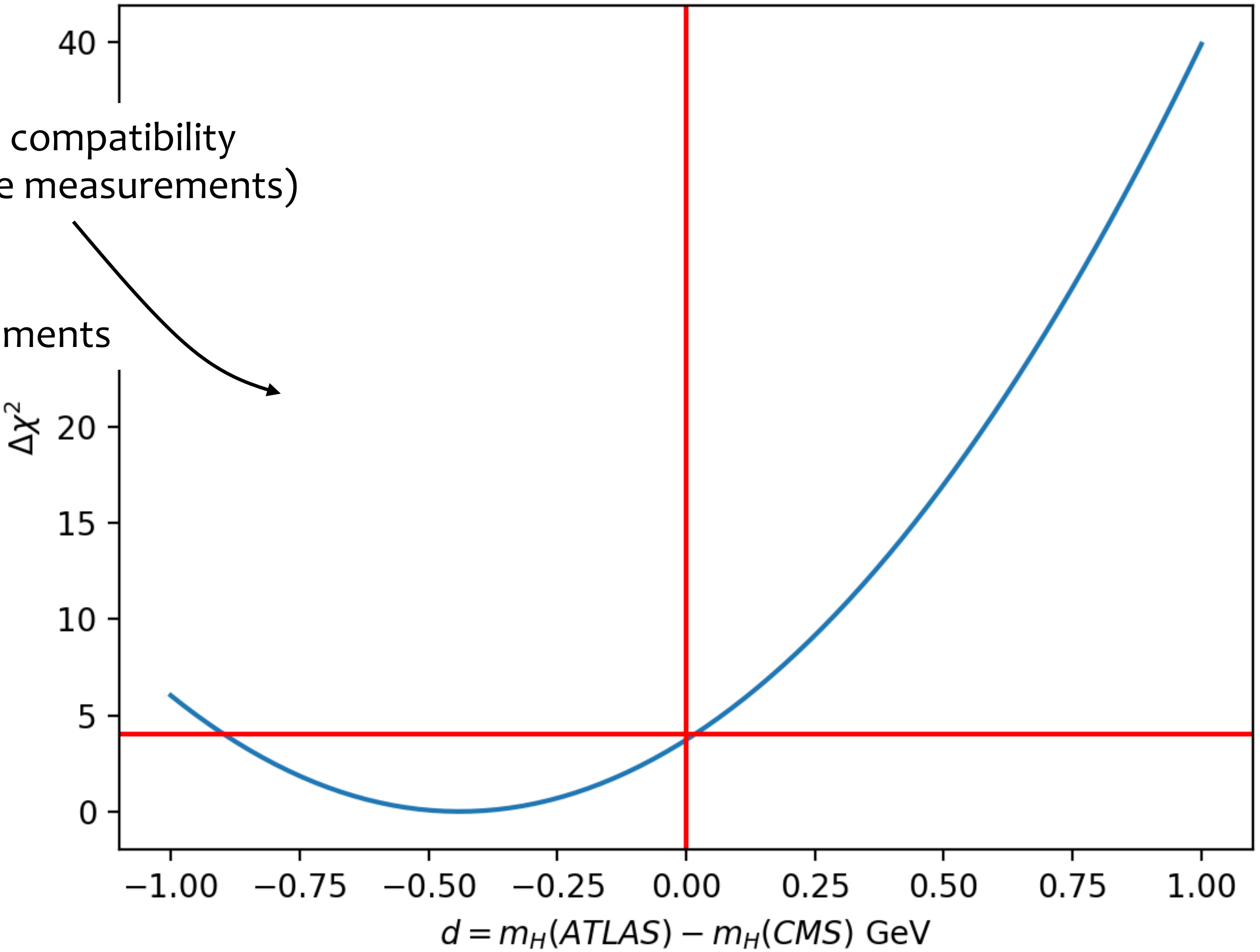
Systematic uncertainty in γγ dominates, mostly due to details of **ECAL calibration and shower modelling**

m_H : ATLAS-vs-CMS

Naive check of ATLAS and CMS mass compatibility
(assume no correlations between the measurements)

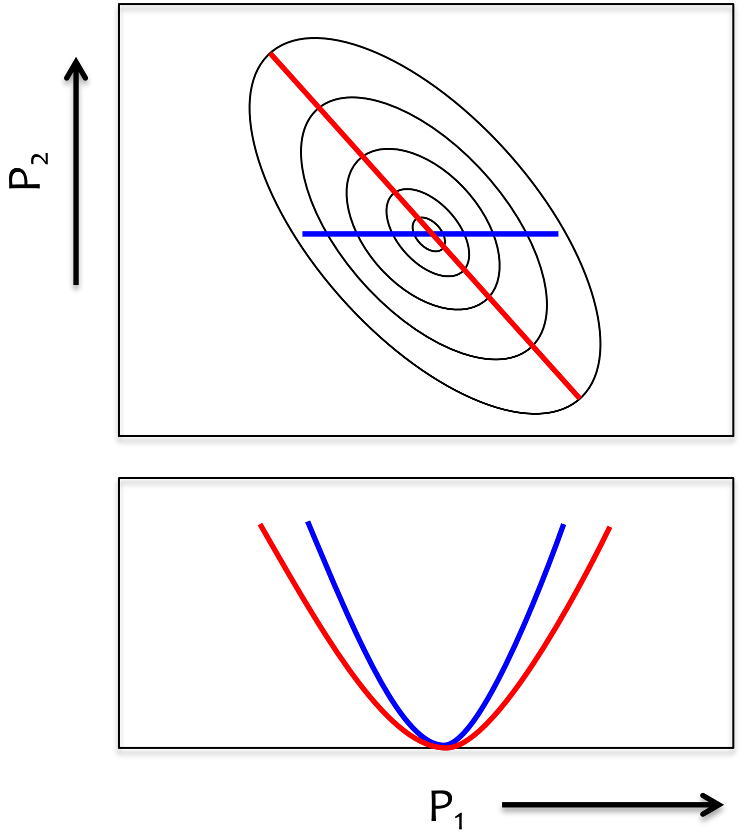
→ Latest measurements within 2σ
→ Larger tension wrt Run-1 measurements





Profiling nuisance parameters

To estimate parameters of the model (and intervals on the parameters of interest), (one or two at a time…), we eliminate parameters of likelihood via ***profiled likelihood***



$$L(P_1, P_2) \rightarrow L(P_1, \hat{\hat{P}}_2)$$

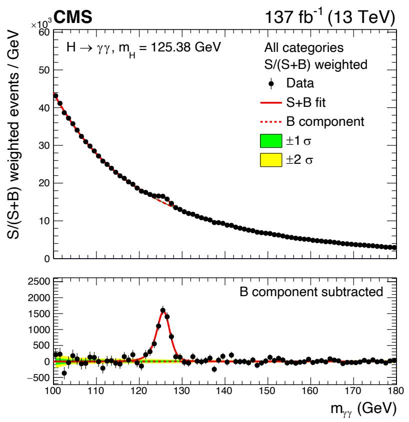
Example, say we have just 2 parameters

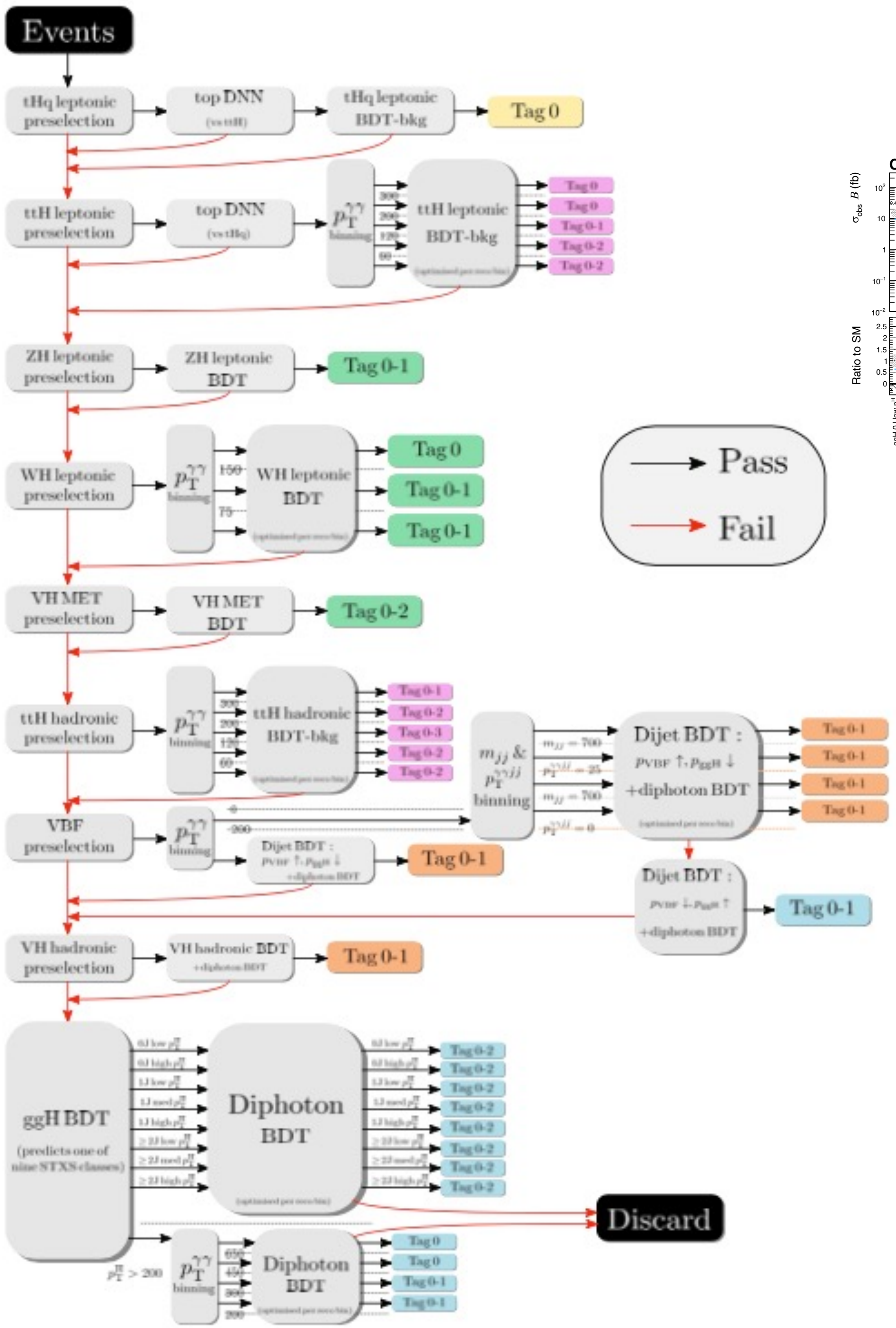
- $L(P_1,P_2)$ describes full likelihood
- Profiling out one of the parameters gives is a profiled likelihood
- We use Wilks' theorem to determine intervals from ratios of profiled log-likelihood (q)

$$q(P_1) = -2\ln\left(\frac{L(P_1, \hat{\hat{P}}_2)}{L(\hat{P}_1, \hat{P}_2)}\right)$$

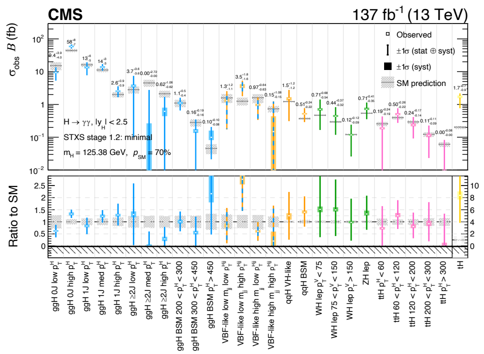
- q=0 → "best-fit" for P_1
- q≤1 → 1σ interval for P_1

Analysis workflow





J. Langford thesis

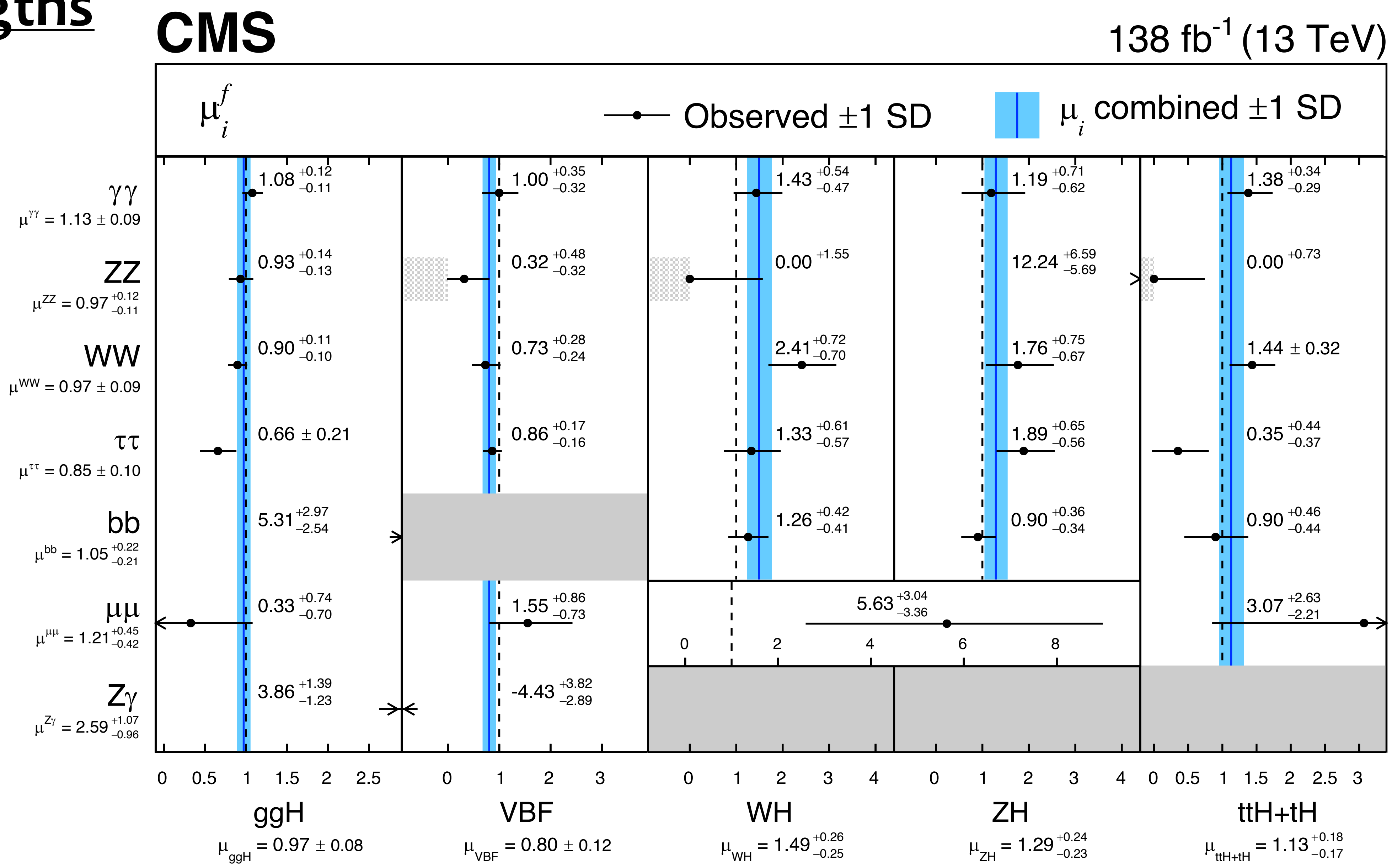


Large number of Higgs bosons available in Run-II → sophisticated analysis strategies to extract the most sensitivity out of the data we have

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
	$\mu\mu$+jj/ee+jj/$e\mu$+jj	VBF 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
$H \to bb$ [47–51]	$W(\ell\nu)H(bb)$	VH, high-$p_T(V)$ 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]	2ℓ SS, 3ℓ, 4ℓ, $1\ell + \tau_h$, 2ℓ SS+$1\tau_h$, $3\ell + 1\tau_h$	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

Signal strengths



Signal strengths (stat/syst)

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

Significances of Higgs

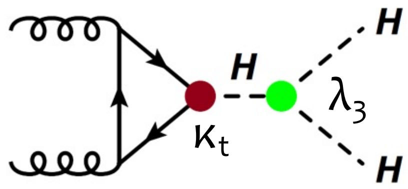
Significances	obs(exp)
VBF:	7.4σ (9.0σ)
ggFbbH:	$> 10\sigma$ ($> 10\sigma$)
WH:	6.2σ (4.5σ)
ZH:	6.2σ (5.0σ)
ttH:	5.5σ(6.1σ)
tH:	2.6σ (0.5σ)

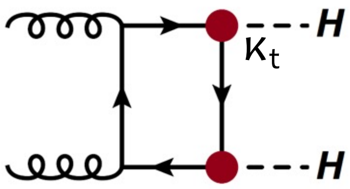
Decay mode	obs(exp) significance
HWW	$> 10\sigma$ ($> 10\sigma$)
HZZ	$> 10\sigma$ ($> 10\sigma$)
Htautau	9.8σ ($> 10\sigma$)
Hbb	5.1σ (4.9σ)
Hmm	2.96σ (2.44σ)
Hzg	2.27σ (1.14σ)

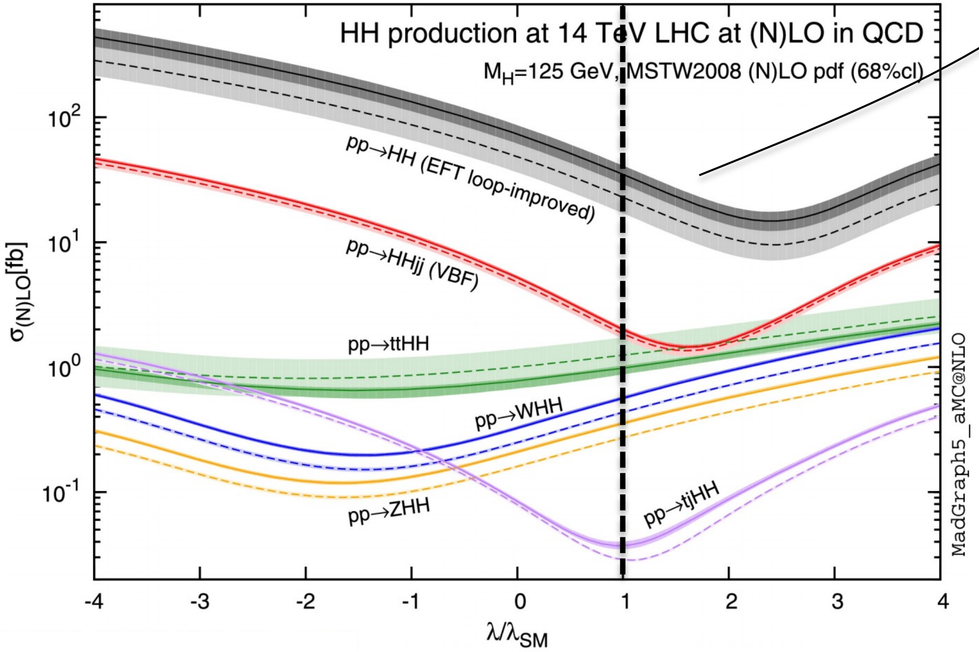
Double Higgs cross-sections

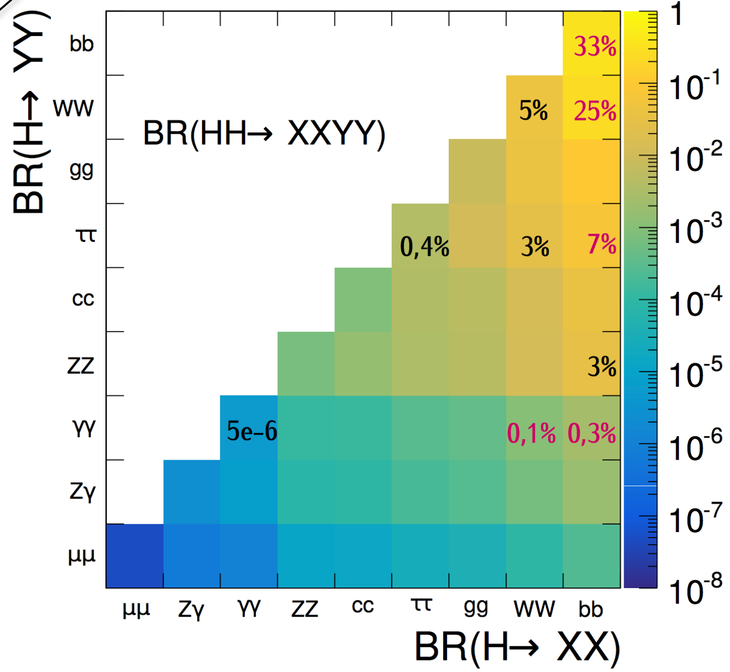
Double Higgs production very tricky at LHC

→ XS Small due to interference
→ Small BR hits twice!
→ Clean channels have smallest BR

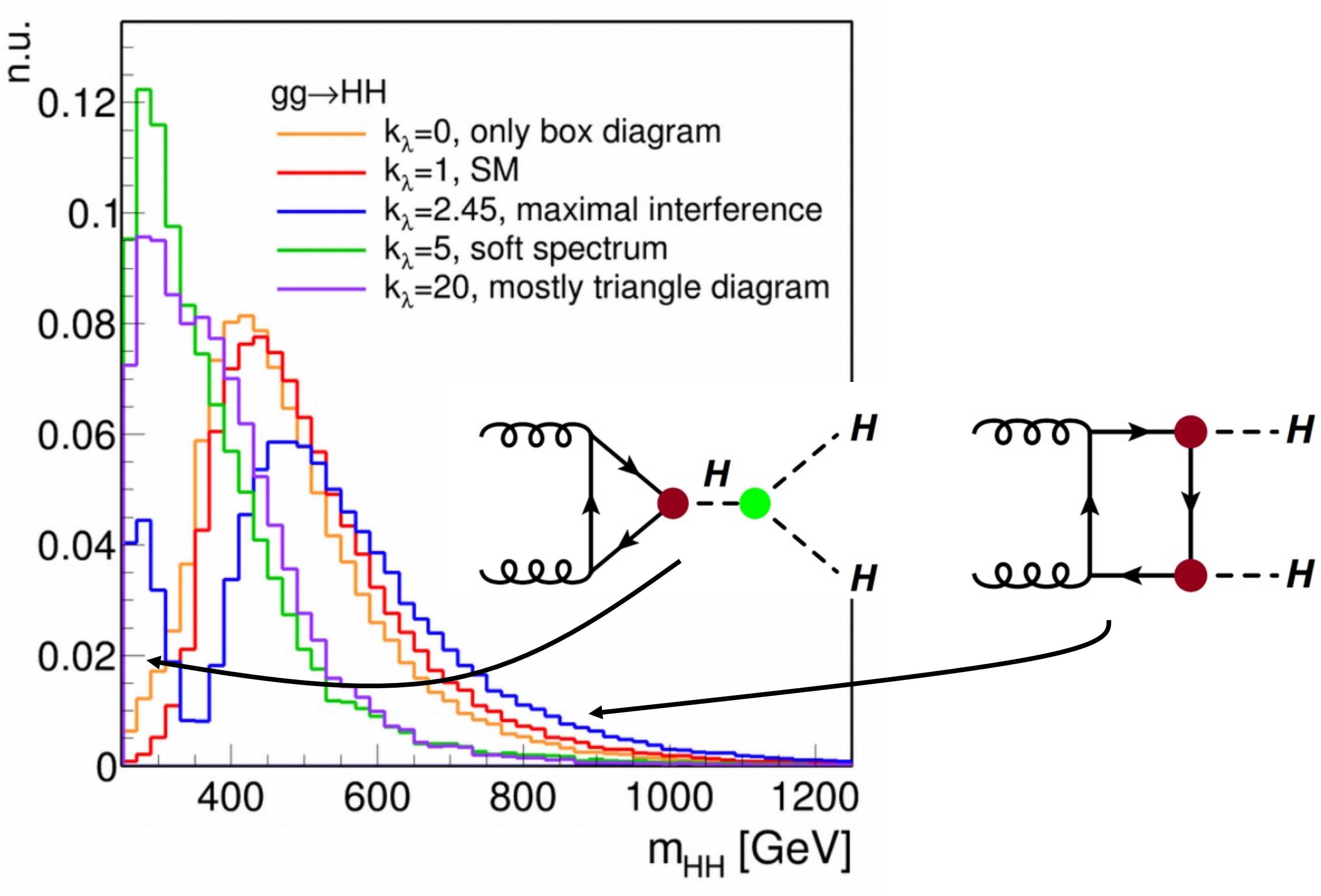




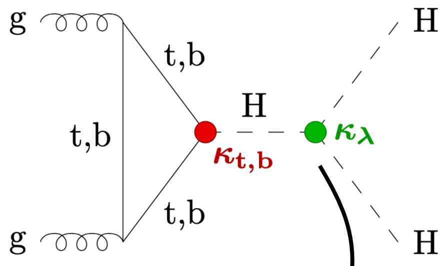


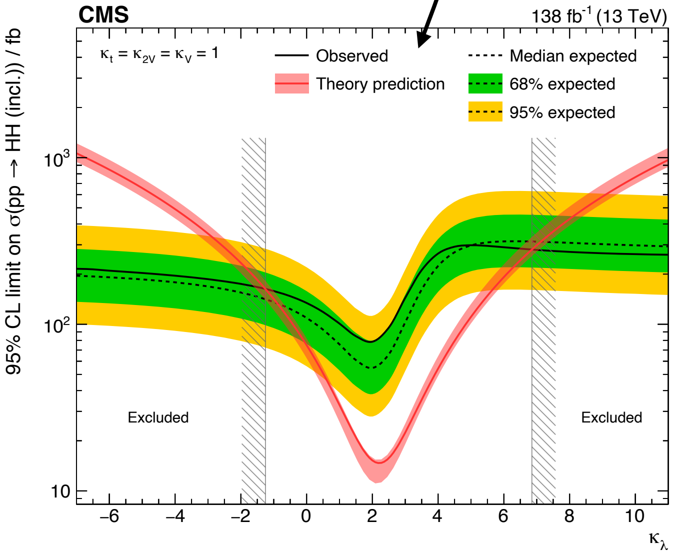


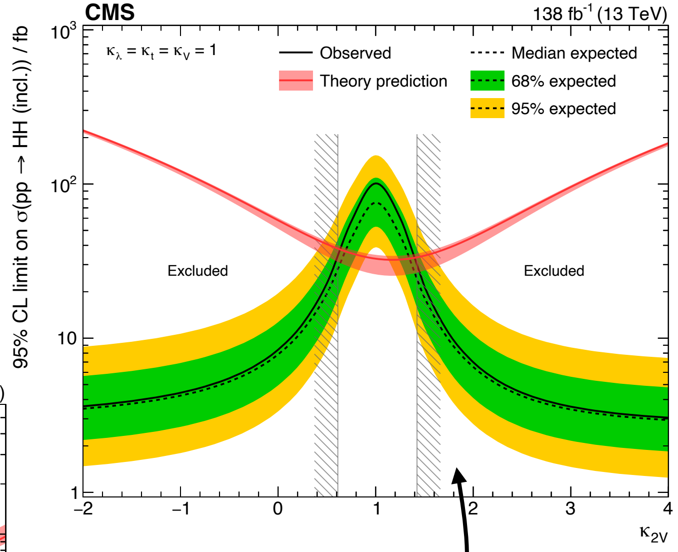
Sensitivity to self-coupling in HH

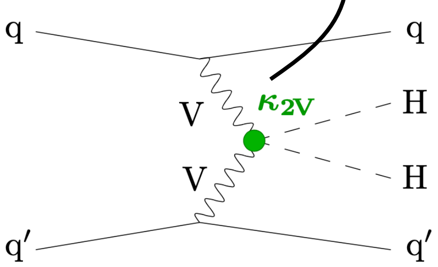


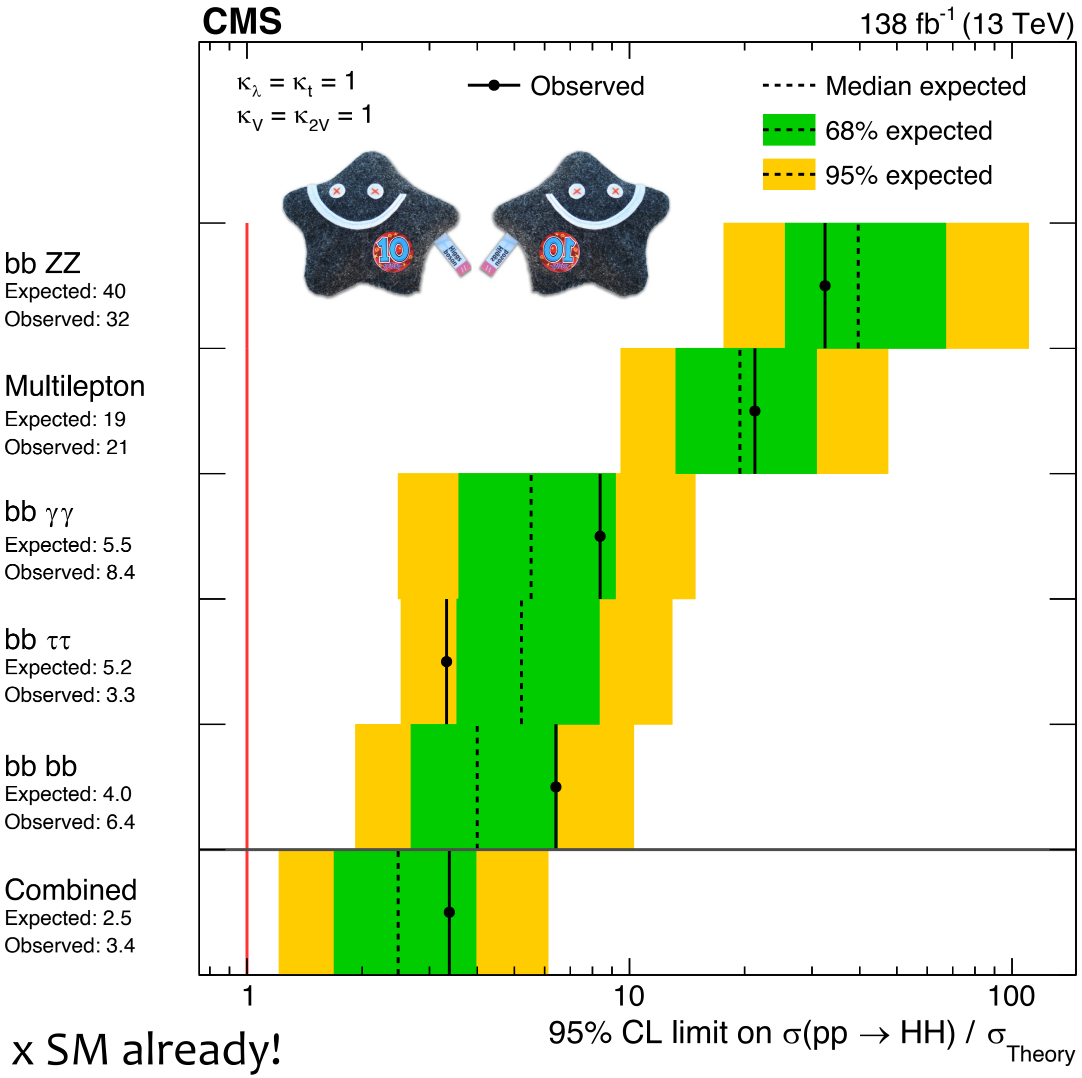
HH searches





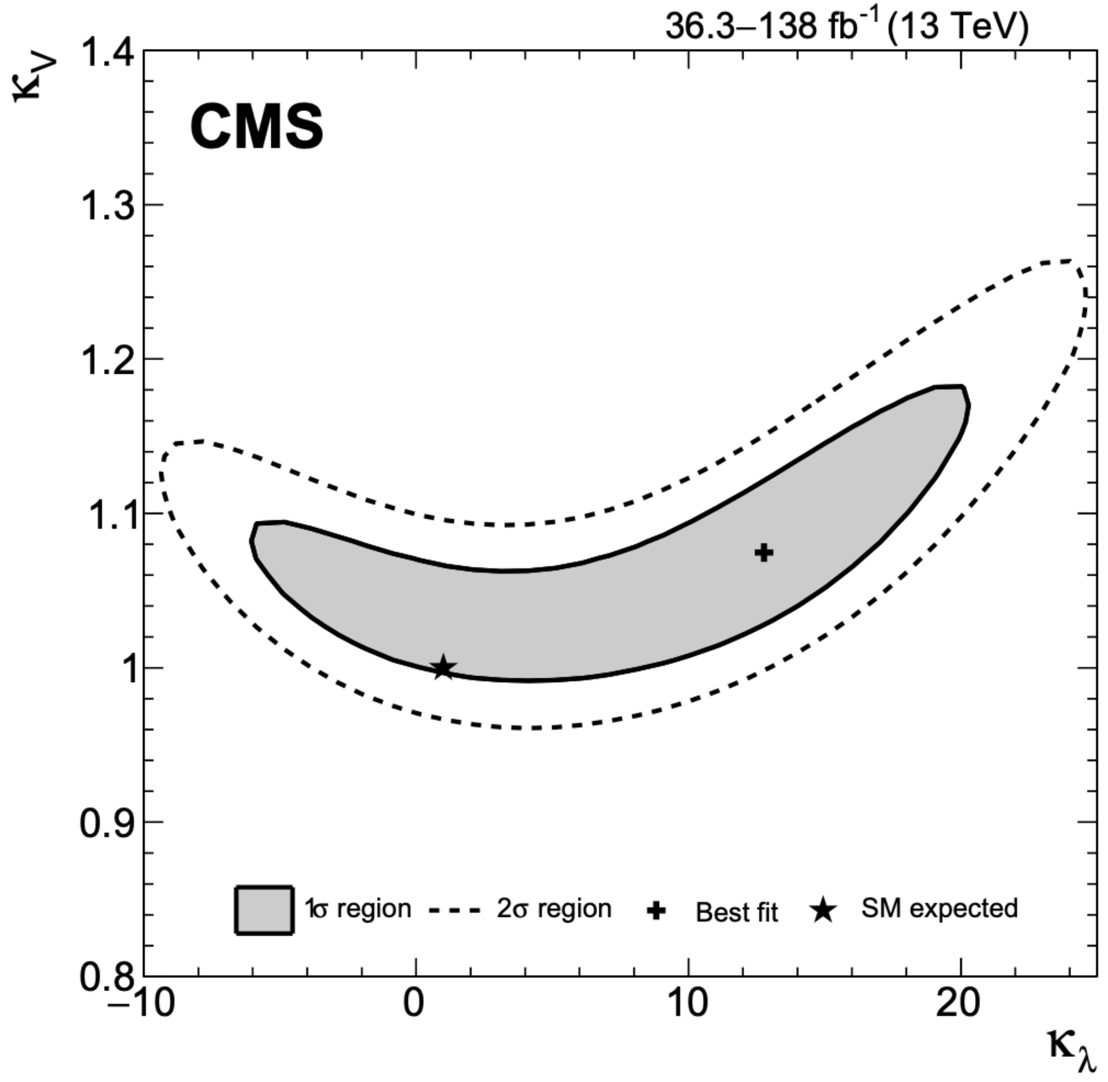


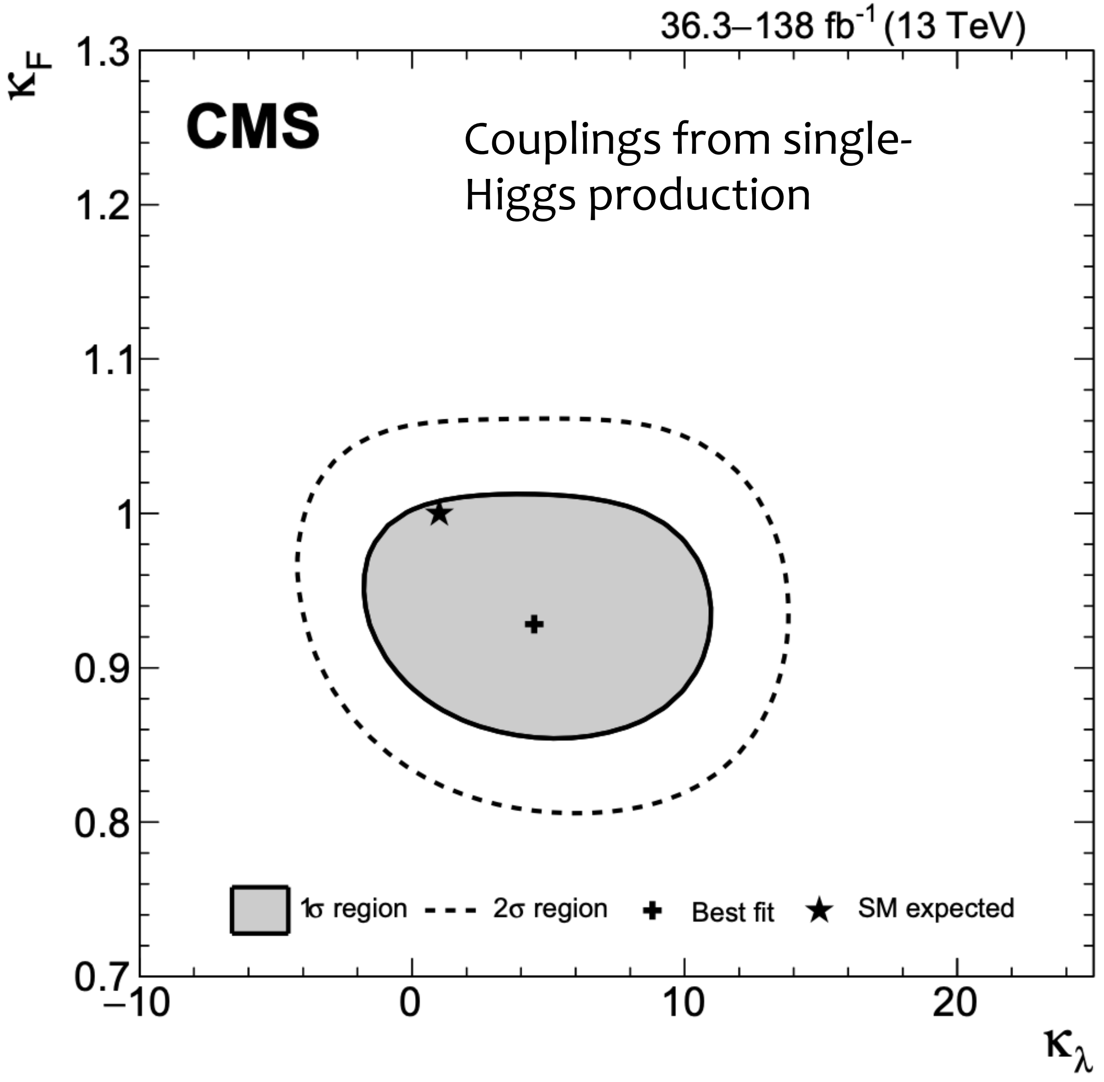




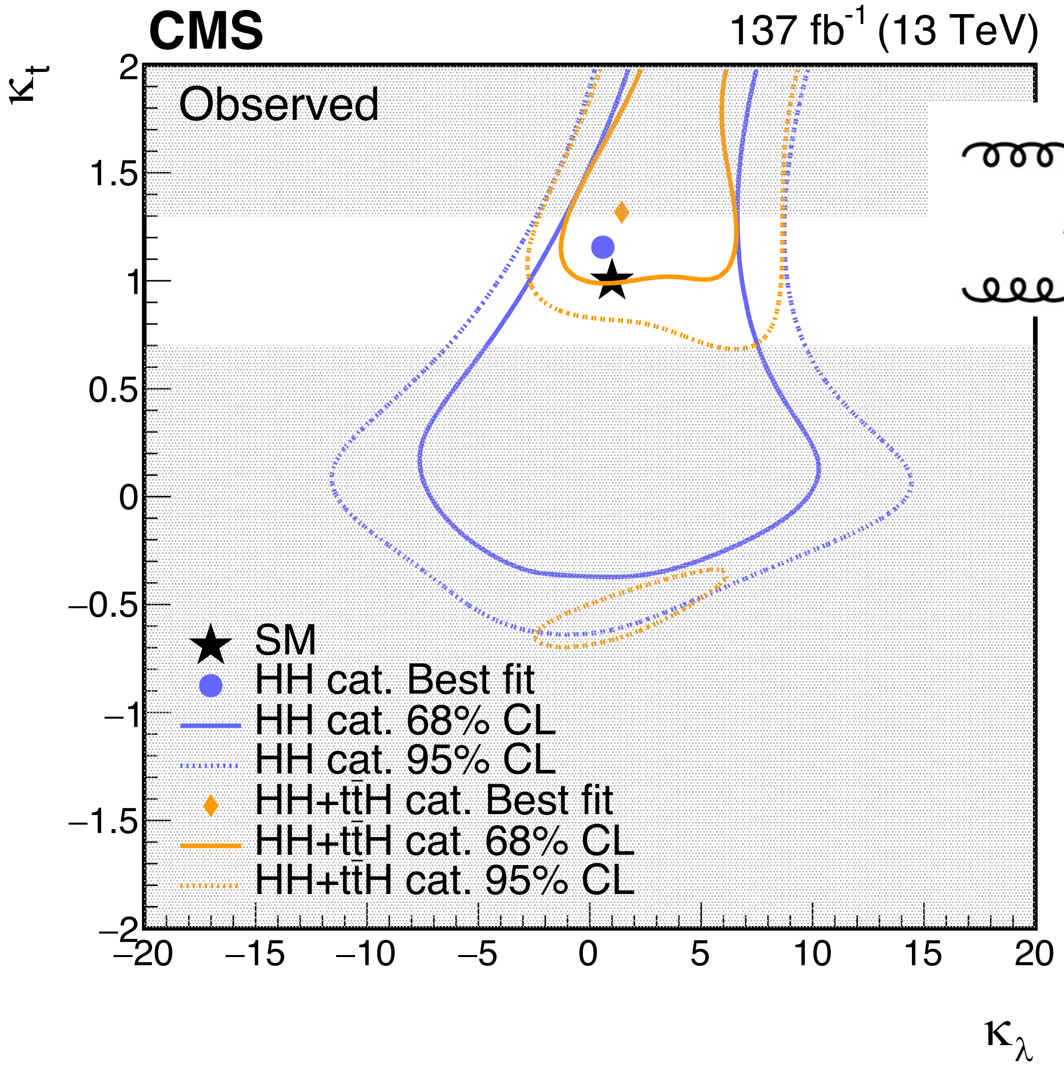
~few x SM already!

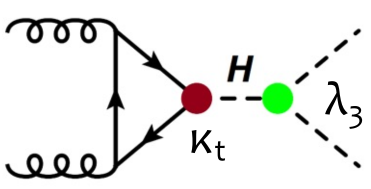
Self-couplings models

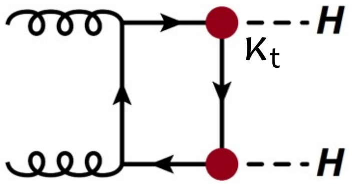


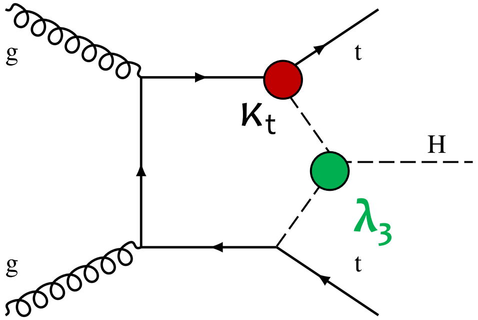


Self-coupling models H+HH









Simple D6 term in Higgs potential

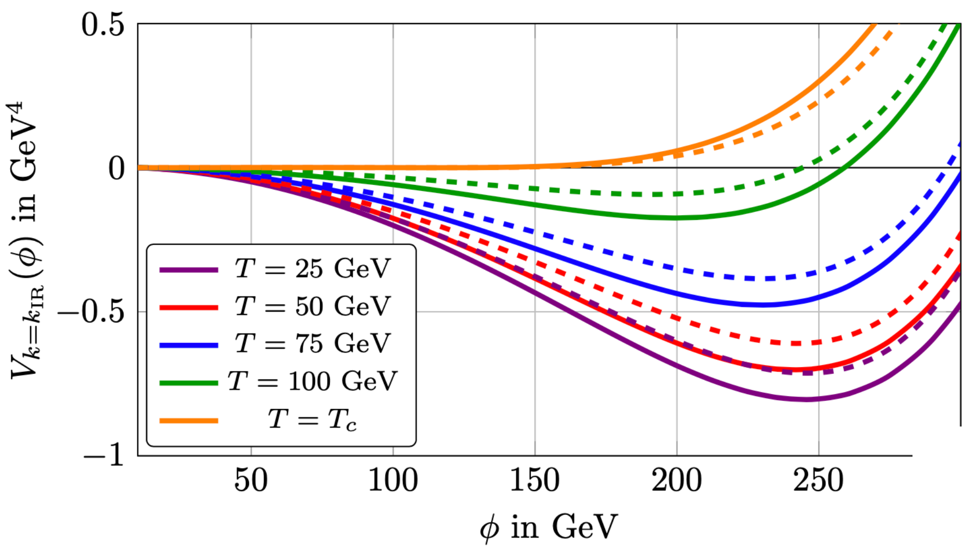
$$V = \frac{\mu^2}{2}(v+H)^2 + \frac{\lambda_4}{4}(v+H)^4 + \frac{\lambda_6}{\Lambda^2}(v+H)^6 .$$

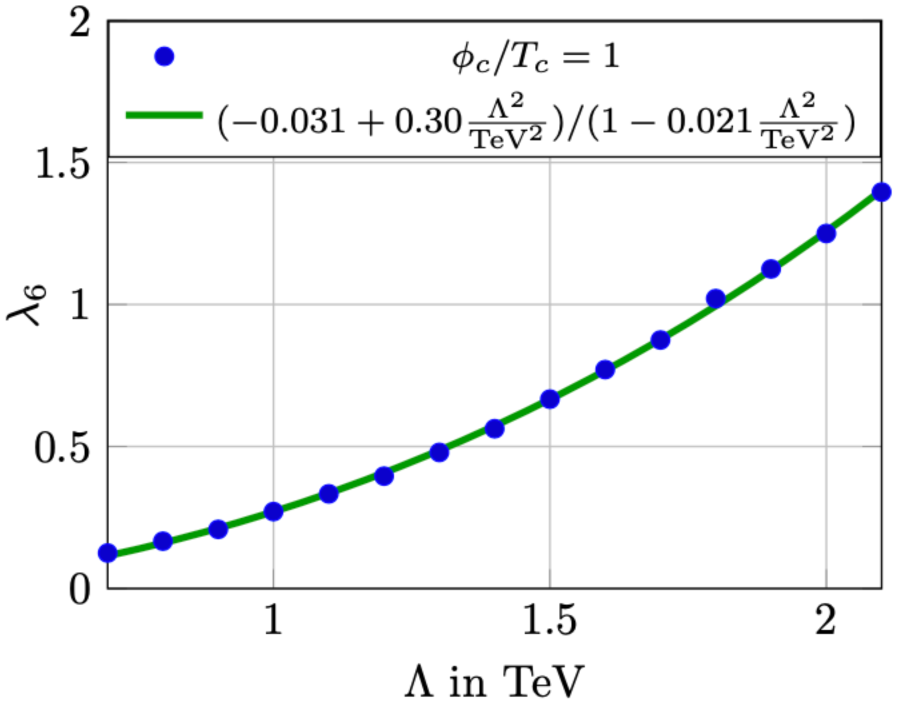
$$m_H = \sqrt{2\lambda_4}\, v \left(1 + 12\frac{\lambda_6 v^2}{\lambda_4 \Lambda^2}\right) ,$$

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

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

Temperature dependence

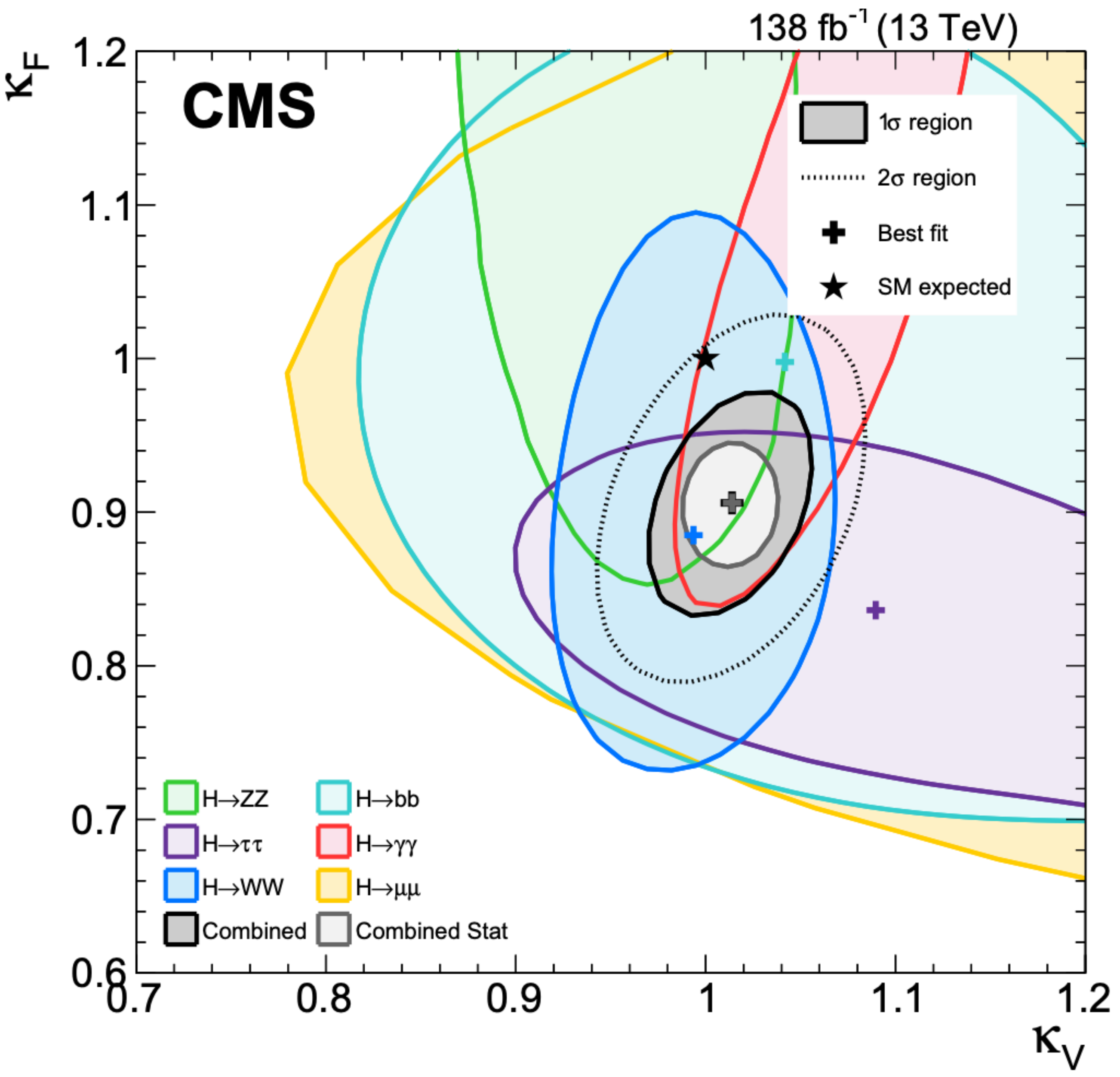




For D6, above 7TeV we end up with strong couplings (perturbativity breaks down)

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

Couplings per decay



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	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

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

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

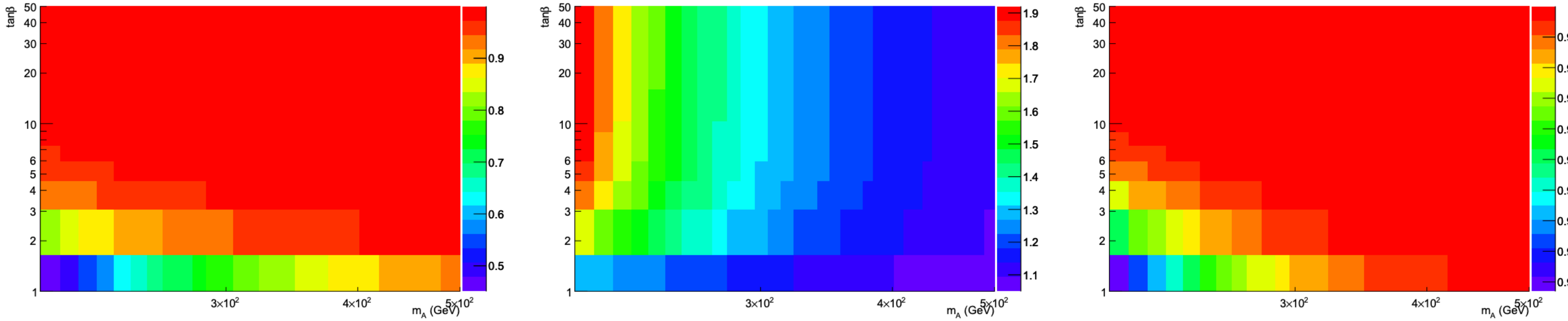
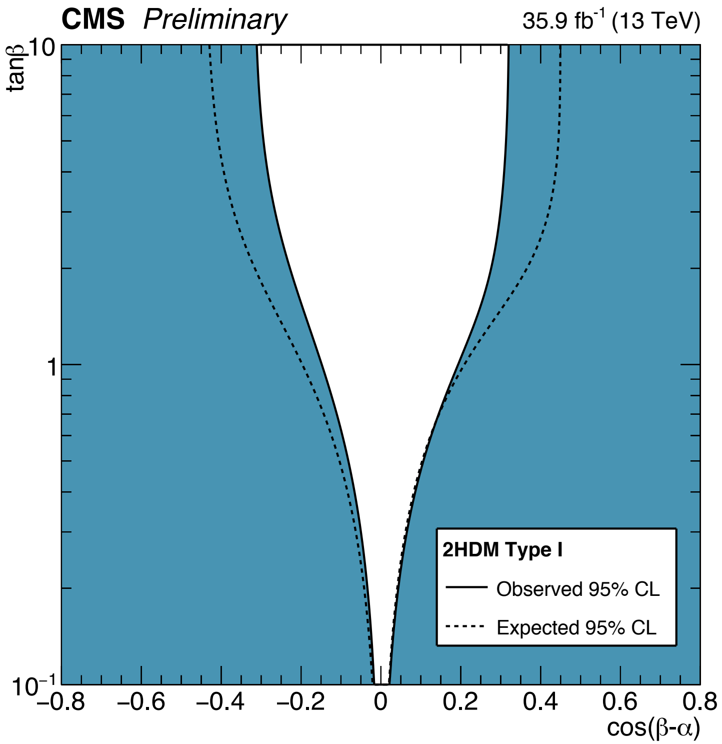
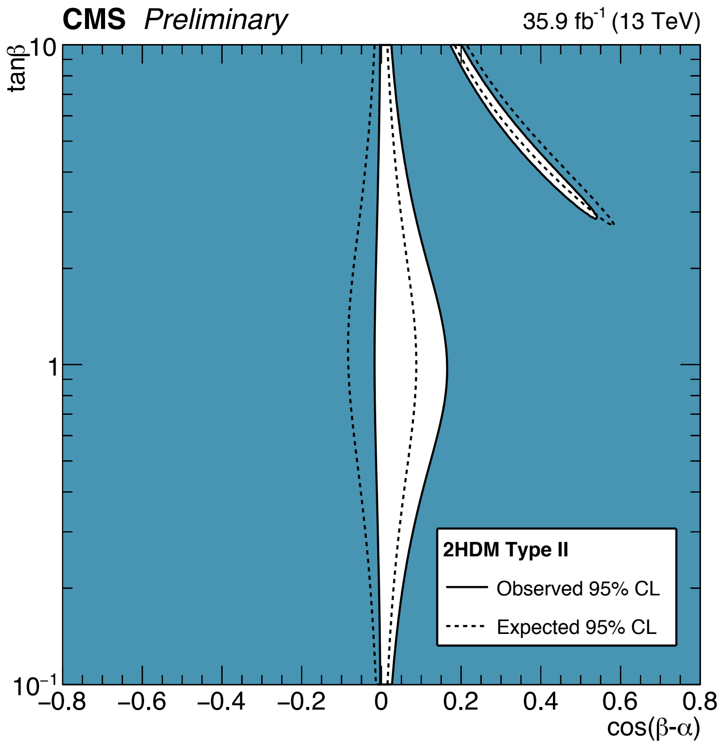


Figure 6: Scan of coupling modifiers κ_u (left), κ_d (centre) and κ_V (right) as a function of the MSSM parameters m_A and $\tan(\beta)$.

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	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

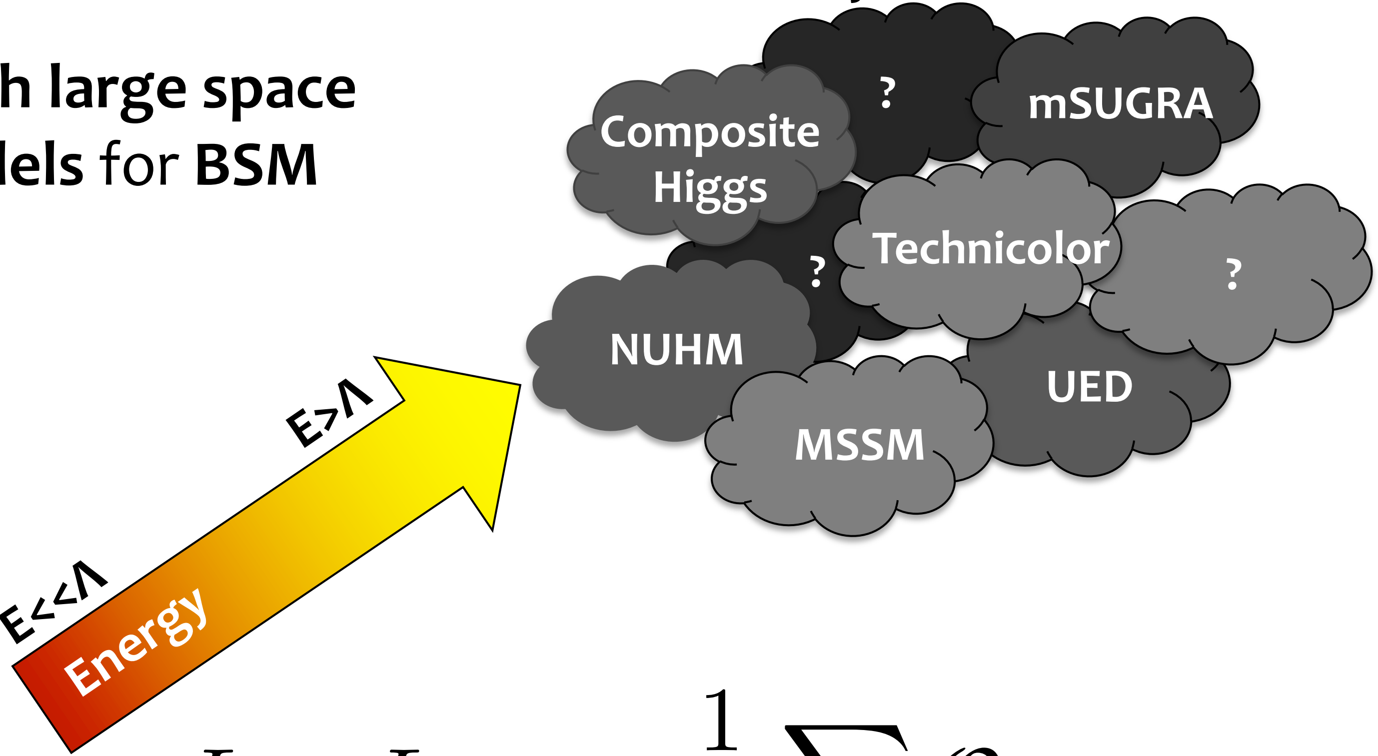




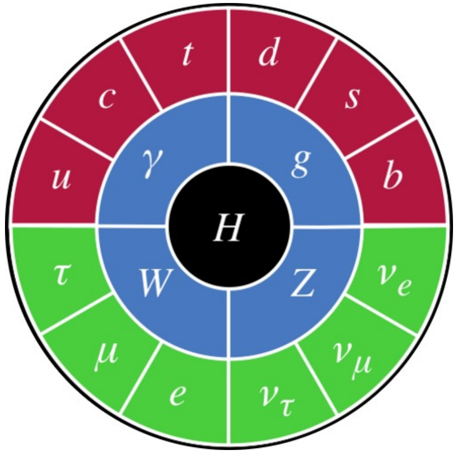
Effective field theories

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

New Physics models



Standard Model



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

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**

EFT impact on differential Higgs boson measurements

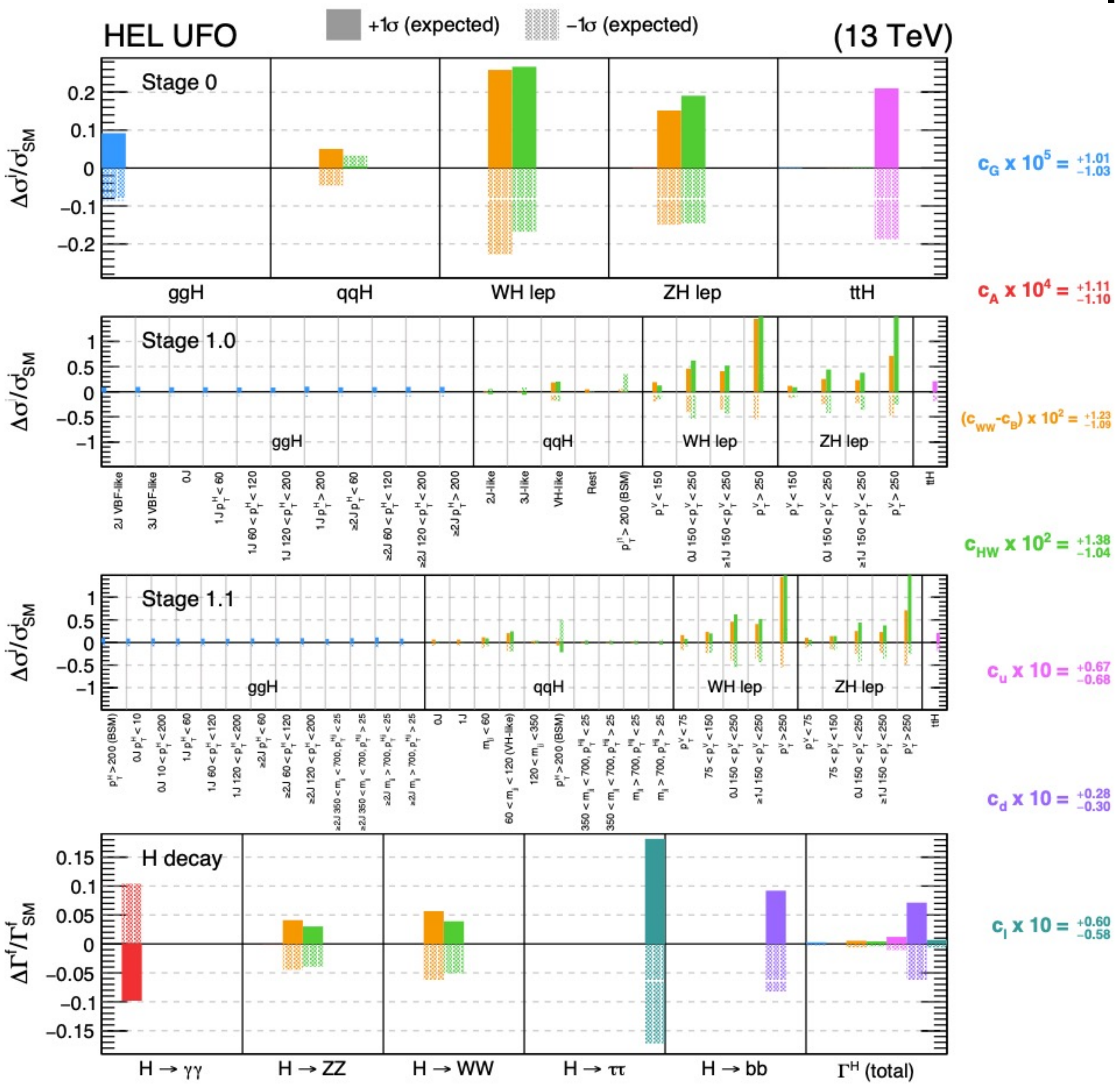


Table 7.1: The dimension-6 operator subset, $\{\mathcal{O}\}$, considered in the HEL interpretation. The definition of each operator is provided in terms of the SM field tensors. In addition, the corresponding HEL parameter is defined in terms of the nominal EFT Wilson coefficients. The final two columns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

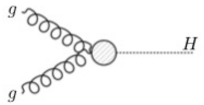
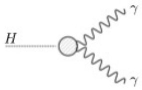
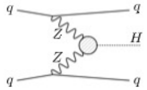
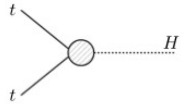
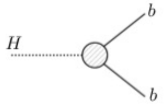
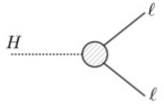
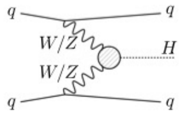
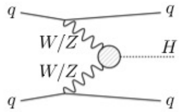
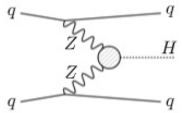
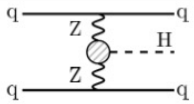
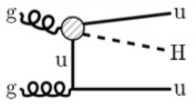
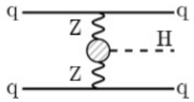
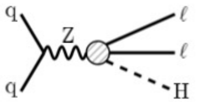
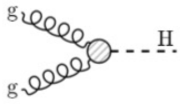
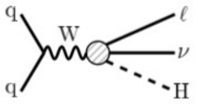
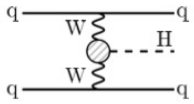
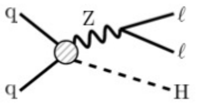
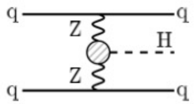
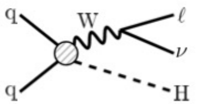
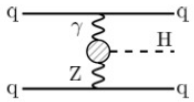
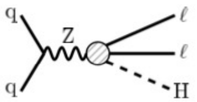
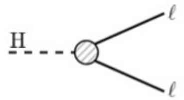
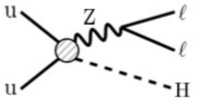
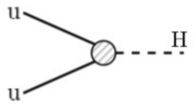
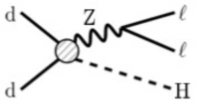
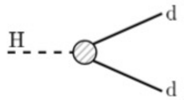
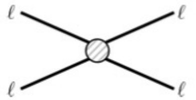
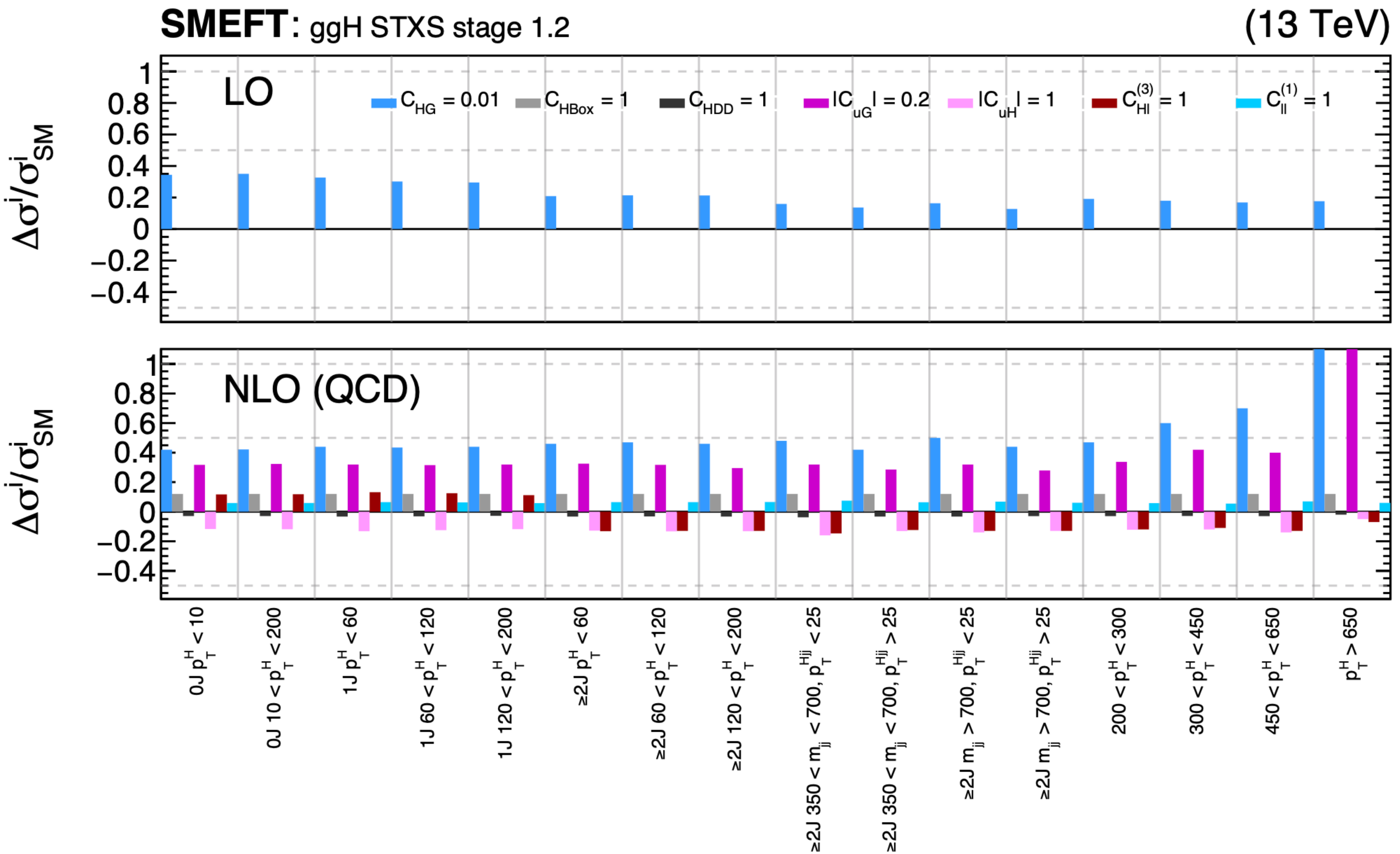
Operator	Definition	HEL Parameter	Relevant vertices	Example diagrams
$\mathcal{O}_G$	$\lvert H\rvert^2 G^a_{\mu\nu} G^{a,\mu\nu}$	$c_G = \frac{m_W^2}{g_s^2}\frac{w_G}{\Lambda^2}$	Hgg	
$\mathcal{O}_A$	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$c_A = \frac{m_W^2}{g'^2}\frac{w_A}{\Lambda^2}$	H$\gamma\gamma$, 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	

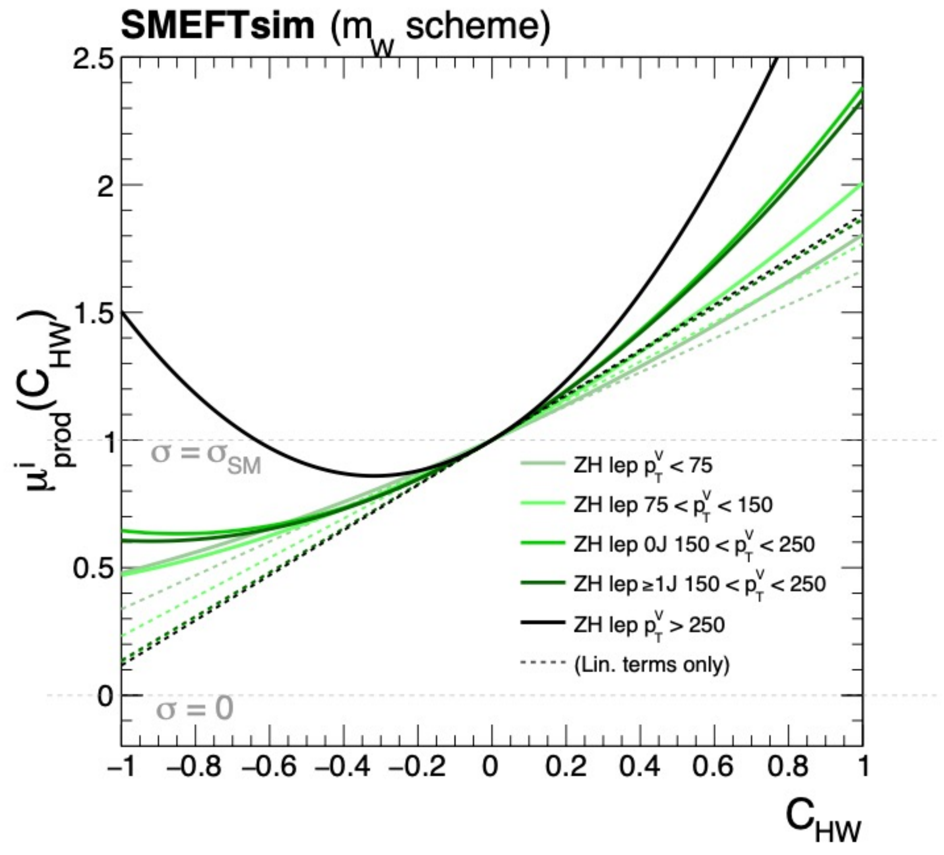
Table 7.6: The dimension-6 operator subset, $\{\mathcal{O}\}$, considered in the Warsaw basis parametrisation shown in Appendix I. An example Feynman diagram of the corresponding contact interaction is shown for each operator. The quantity, $\sigma^{\mu\nu}$, is defined by the gamma matrices relation: $\sigma^{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. 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.

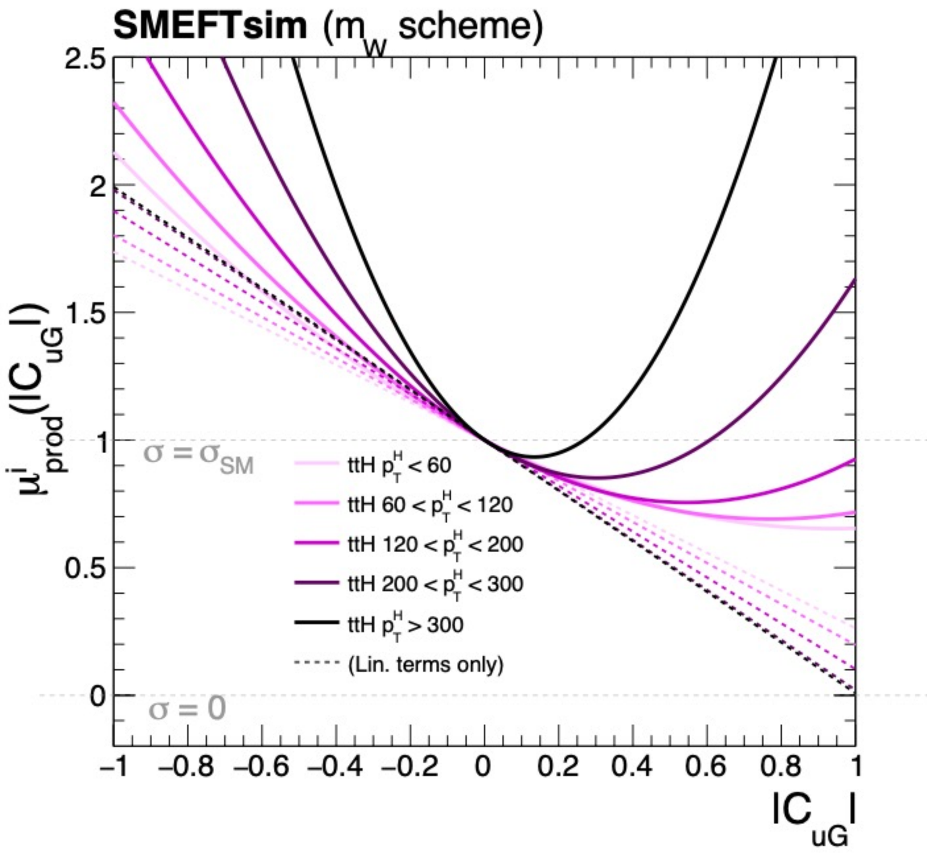
Parameter	Operator definition	Example diagram	Parameter	Operator definition	Example diagram
$C_{H\mathrm{Box}}$	$(H^\dagger H)\Box(H^\dagger H)$		$\lvert C_{uG}\rvert$	$(\bar{Q}_L\sigma^{\mu\nu}T^a u_R)(\tilde{H}G^{a,\mu\nu})$	
C_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$		$C_{H\ell}^{(1)}$	$(H^\dagger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



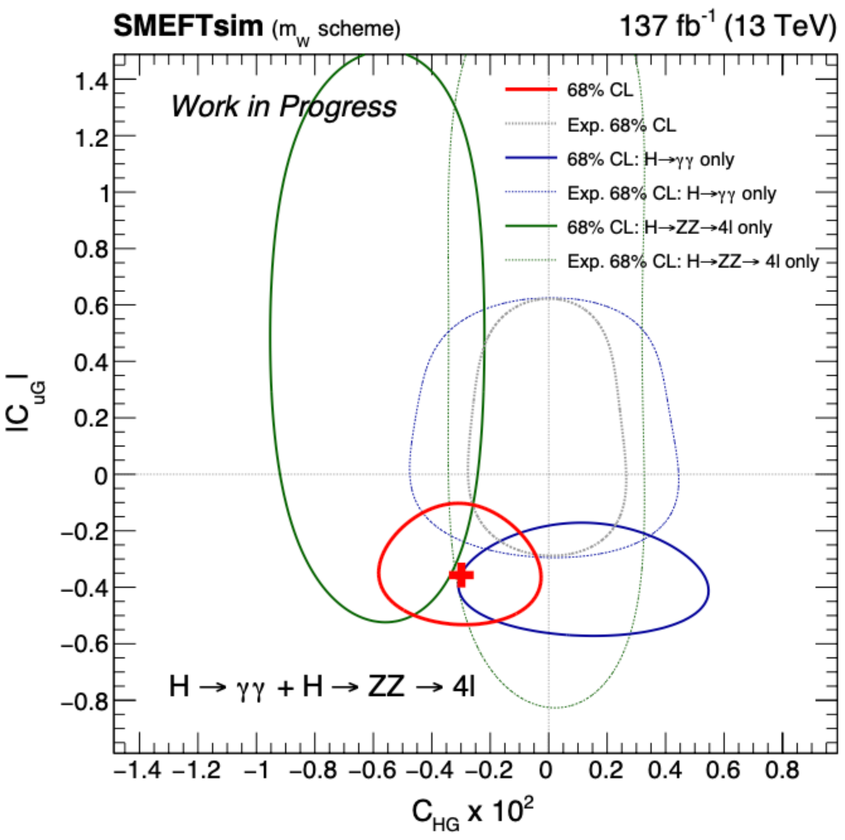
SMEFT: ggH STXS stage 1.2
(13 TeV)
LO
NLO (QCD)
$\Delta\sigma^i/\sigma^i_{SM}$
C_{HG} = 0.01
C_{HBox} = 1
C_{HDD} = 1
$|C_{uG}|$ = 0.2
$|C_{uH}|$ = 1
$C^{(3)}_{Hl}$ = 1
$C^{(1)}_{ll}$ = 1
0J p^H_T < 10
0J 10 < p^H_T < 200
1J p^H_T < 60
1J 60 < p^H_T < 120
1J 120 < p^H_T < 200
≥2J p^H_T < 60
≥2J 60 < p^H_T < 120
≥2J 120 < p^H_T < 200
≥2J 350 < m_{jj} < 700, p^{Hjj}_T < 25
≥2J 350 < m_{jj} < 700, p^{Hjj}_T > 25
≥2J m_{jj} > 700, p^{Hjj}_T < 25
≥2J m_{jj} > 700, p^{Hjj}_T > 25
200 < p^H_T < 300
300 < p^H_T < 450
450 < p^H_T < 650
p^H_T > 650

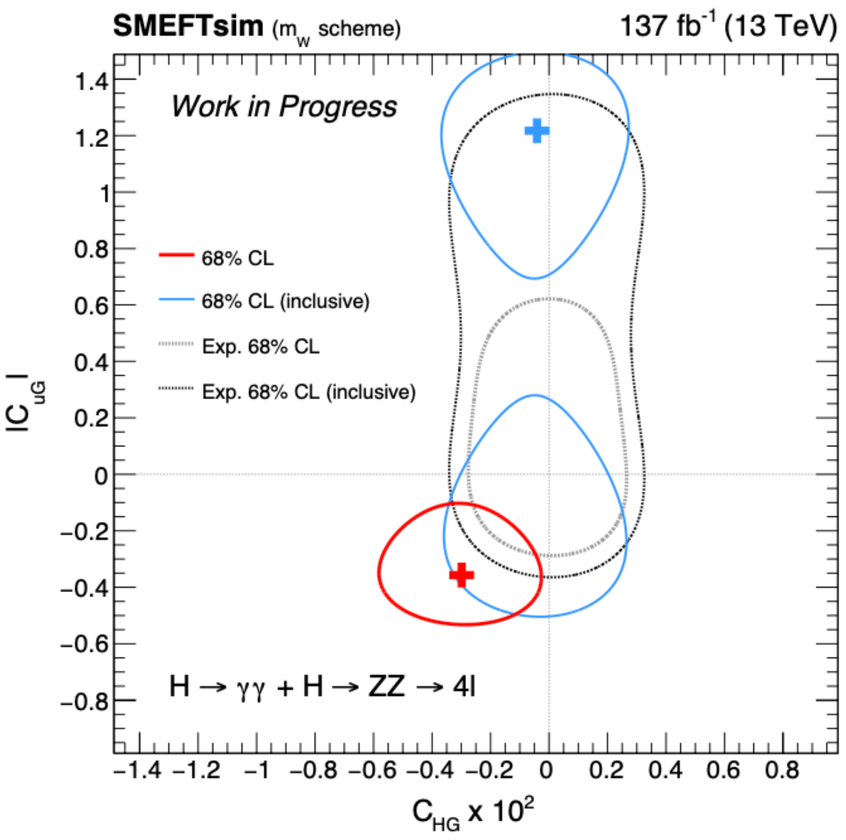
The Higgs boson as a tool for New Physics searches



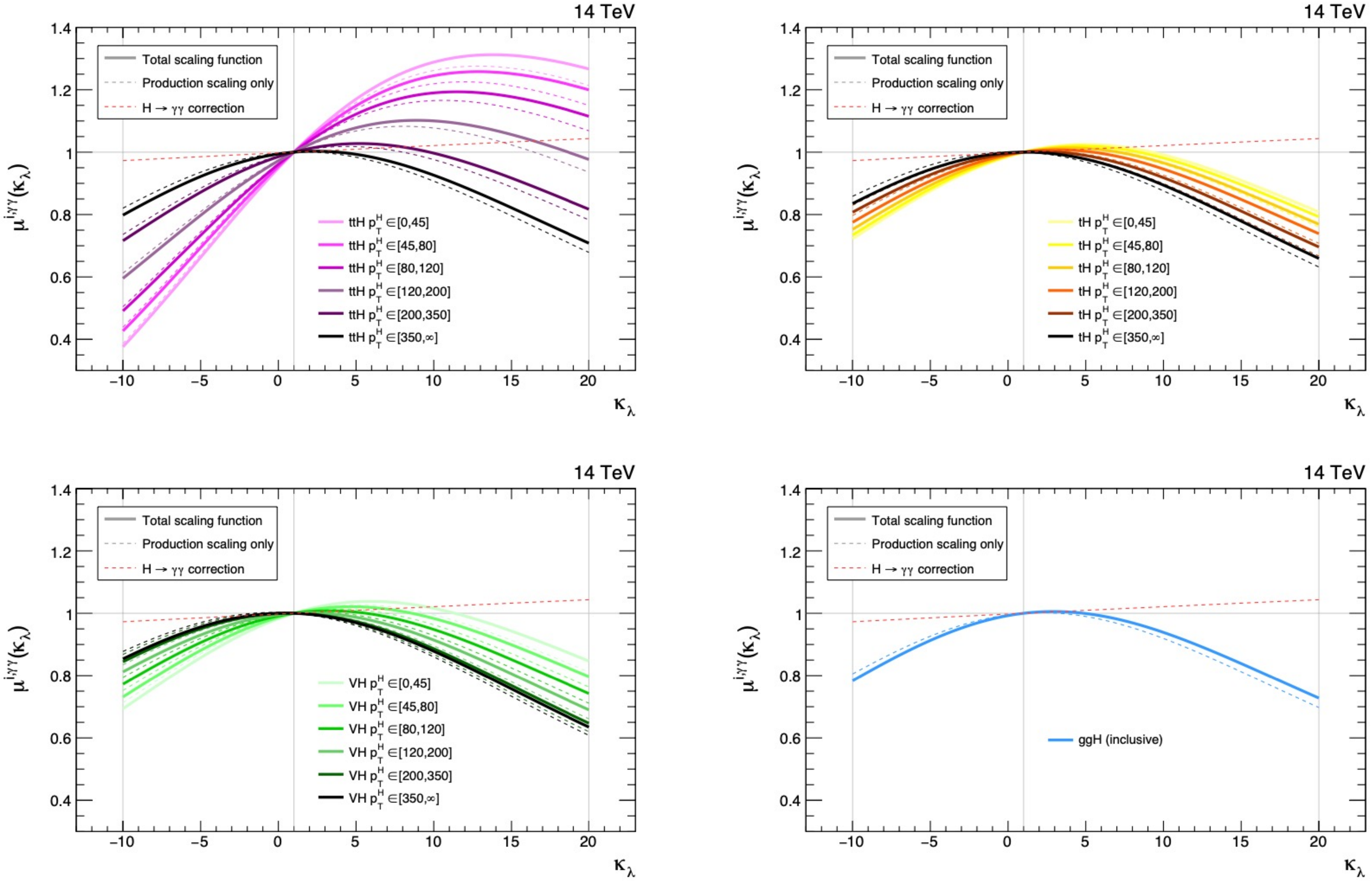


The Higgs boson as a tool for New Physics searches





J. Langford Thesis

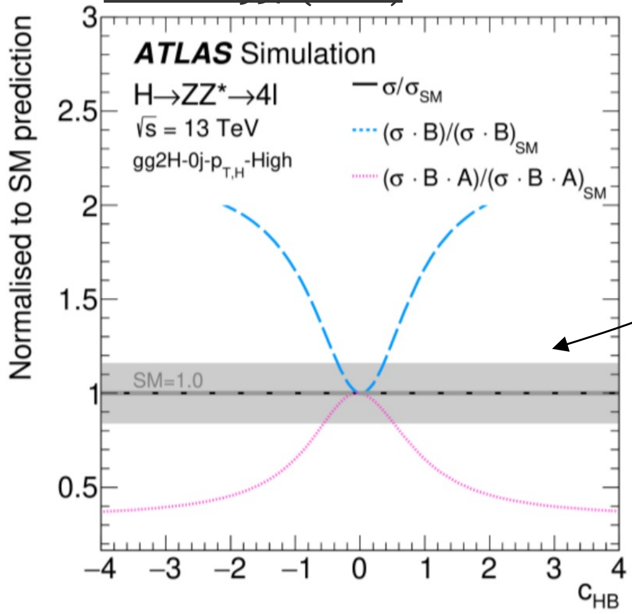

14 TeV
Total scaling function
Production scaling only
H → γγ correction
ttH $p_T^H \in$[0,45]
ttH $p_T^H \in$[45,80]
ttH $p_T^H \in$[80,120]
ttH $p_T^H \in$[120,200]
ttH $p_T^H \in$[200,350]
ttH $p_T^H \in$[350,∞]
tH $p_T^H \in$[0,45]
tH $p_T^H \in$[45,80]
tH $p_T^H \in$[80,120]
tH $p_T^H \in$[120,200]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

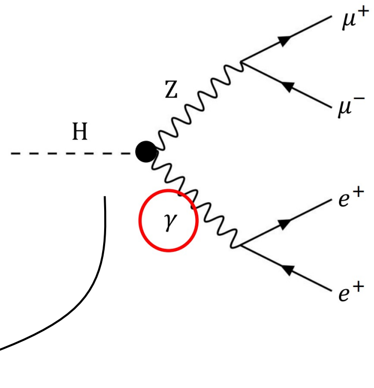
EFT Interpretations – caveat 1.

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

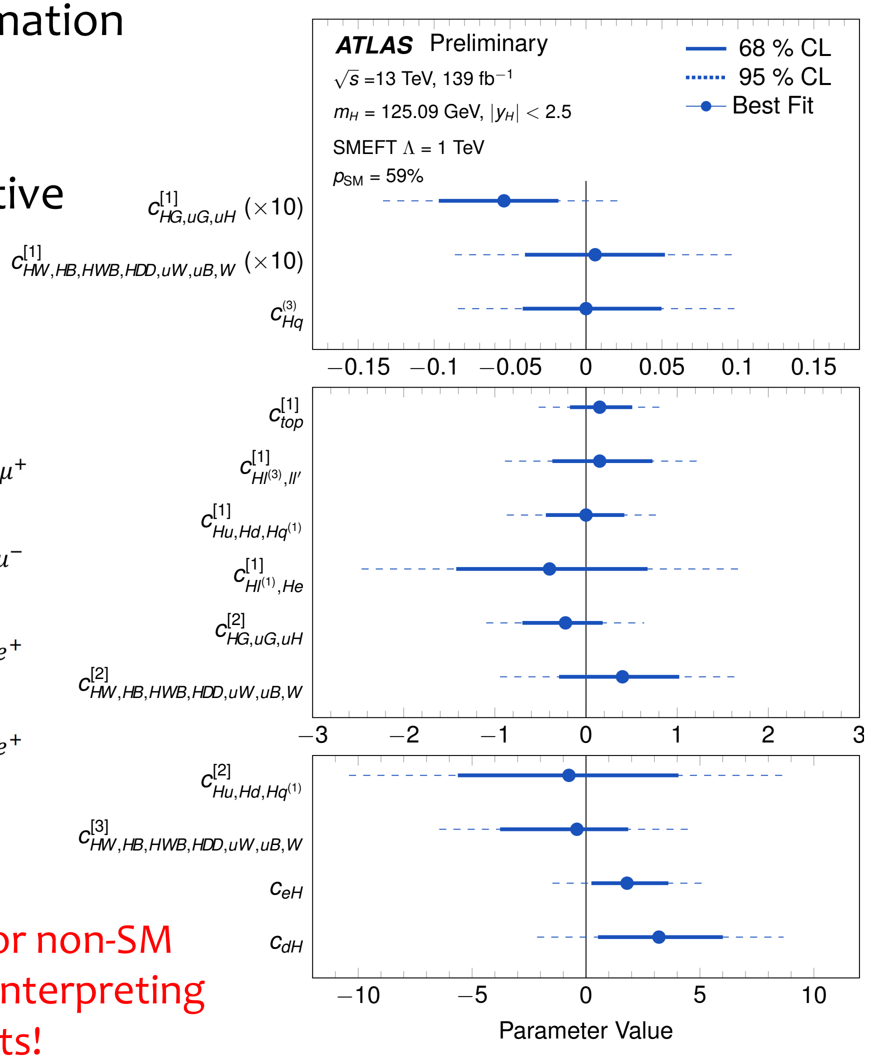
EPJC **80** 957 (2020)





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

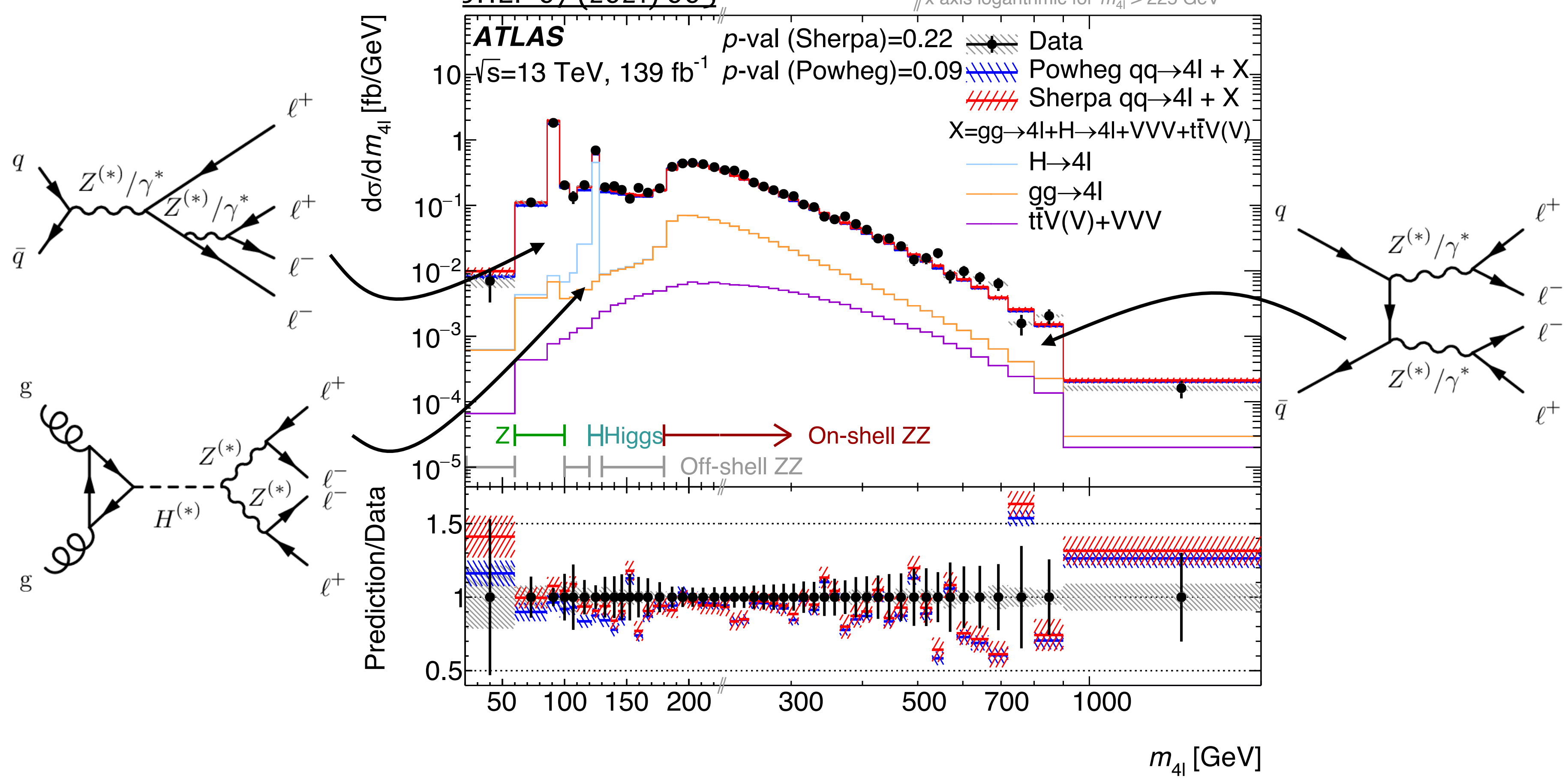
ATLAS-CONF-2021-053



EFT Interpretations – caveat 2.

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

JHEP 07 (2021) 005



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

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

Reccomendations for Re-interpretations

S. Kraml @Reinterp2021

Recommendations emphasise:

1. Prompt availability of numerical analysis data in digitised electronic form to enable re-use.
2. More complete publication of full-detail experimental data:
   - correlation information
   - public likelihoods
   - Open Data
   - forensic analysis code preservation
   - ....
3. Community-wide dialogue regarding re-use of unbinned fits and machine-learning algorithms.

Moreover, theorists should (start) to follow the same reproducibility requirements as we ask them from the experiments.

*"Re-use means a **longer legacy** for analyses, as well as compliance with ever stricter requirements of data-publication and reusability for publicly funded research."*

Sci|Post SciPost Phys. 9, 022 (2020)

Reinterpretation of LHC results for new physics: status and recommendations after run 2

The LHC BSM Reinterpretation Forum

SciPostPhys.9.2.022 (2020)

Abstract

We report on the status of efforts to improve the reinterpretation of searches and measurements at the LHC in terms of models for new physics, in the context of the LHC Reinterpretation Forum. We detail current experimental offerings in direct searches for new particles, measurements, technical implementations and Open Data, and provide a set of recommendations for further improving the presentation of LHC results in order to better enable reinterpretation in the future. We also provide a brief description of existing software reinterpretation frameworks and recent global analyses of new physics that make use of the current data.

Received 02-04-2020
Accepted 06-08-2020
Published 21-08-2020
doi:10.21468/SciPostPhys.9.2.022

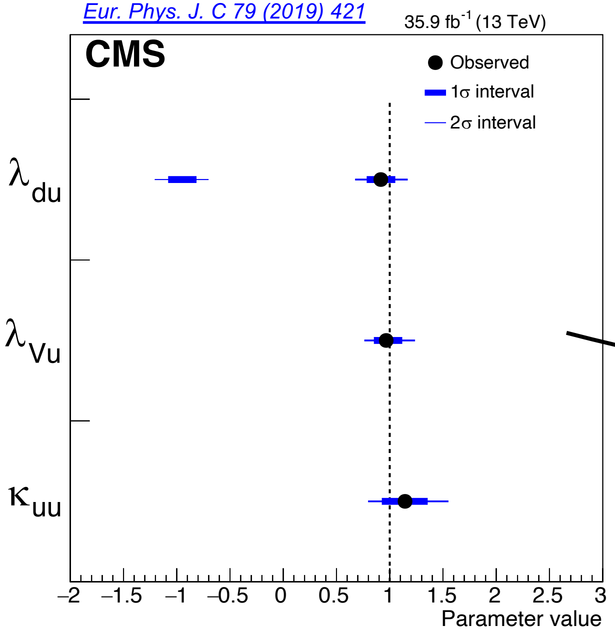
Check for updates

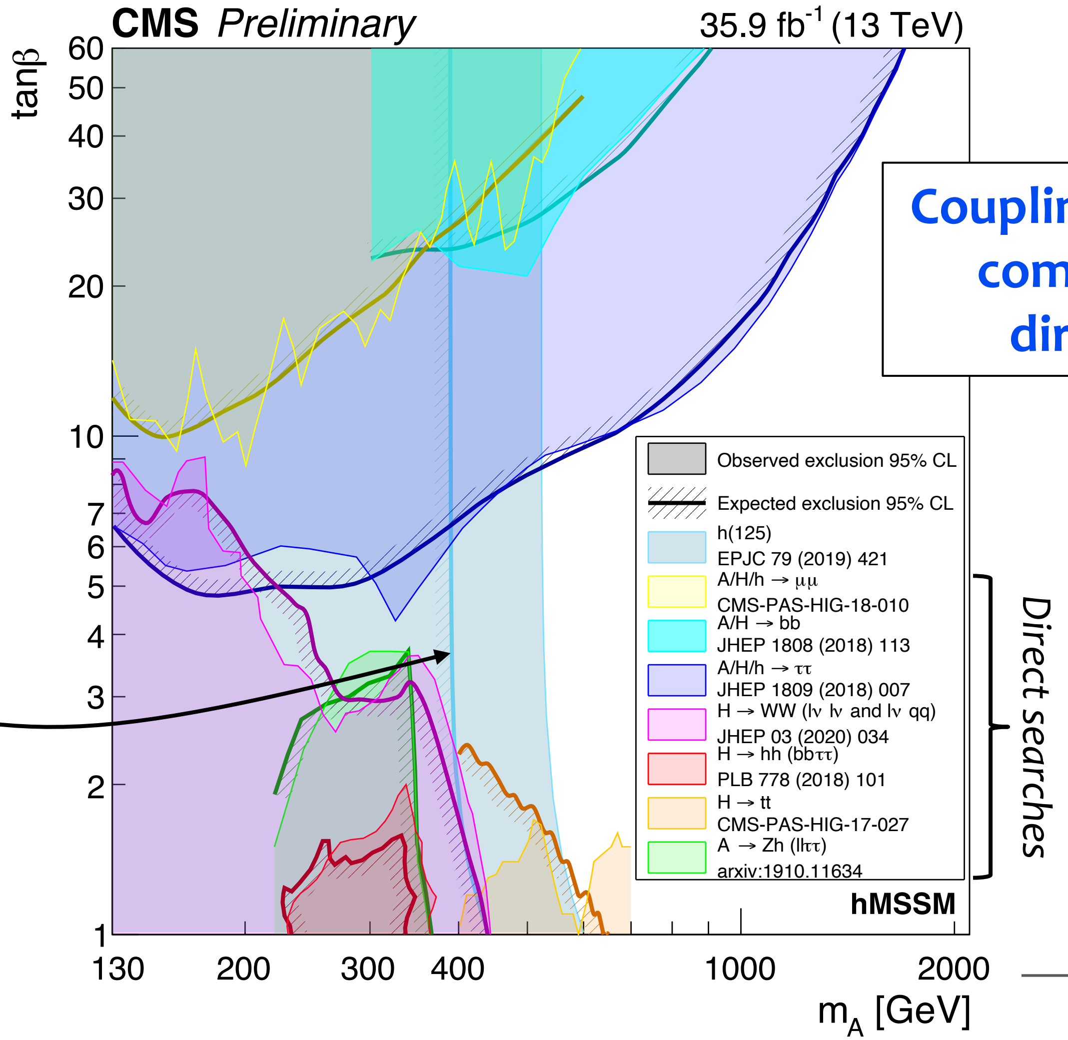
New whitepaper on open likelihoods!
https://arxiv.org/abs/2109.04981

Complementarity to BSM searches

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

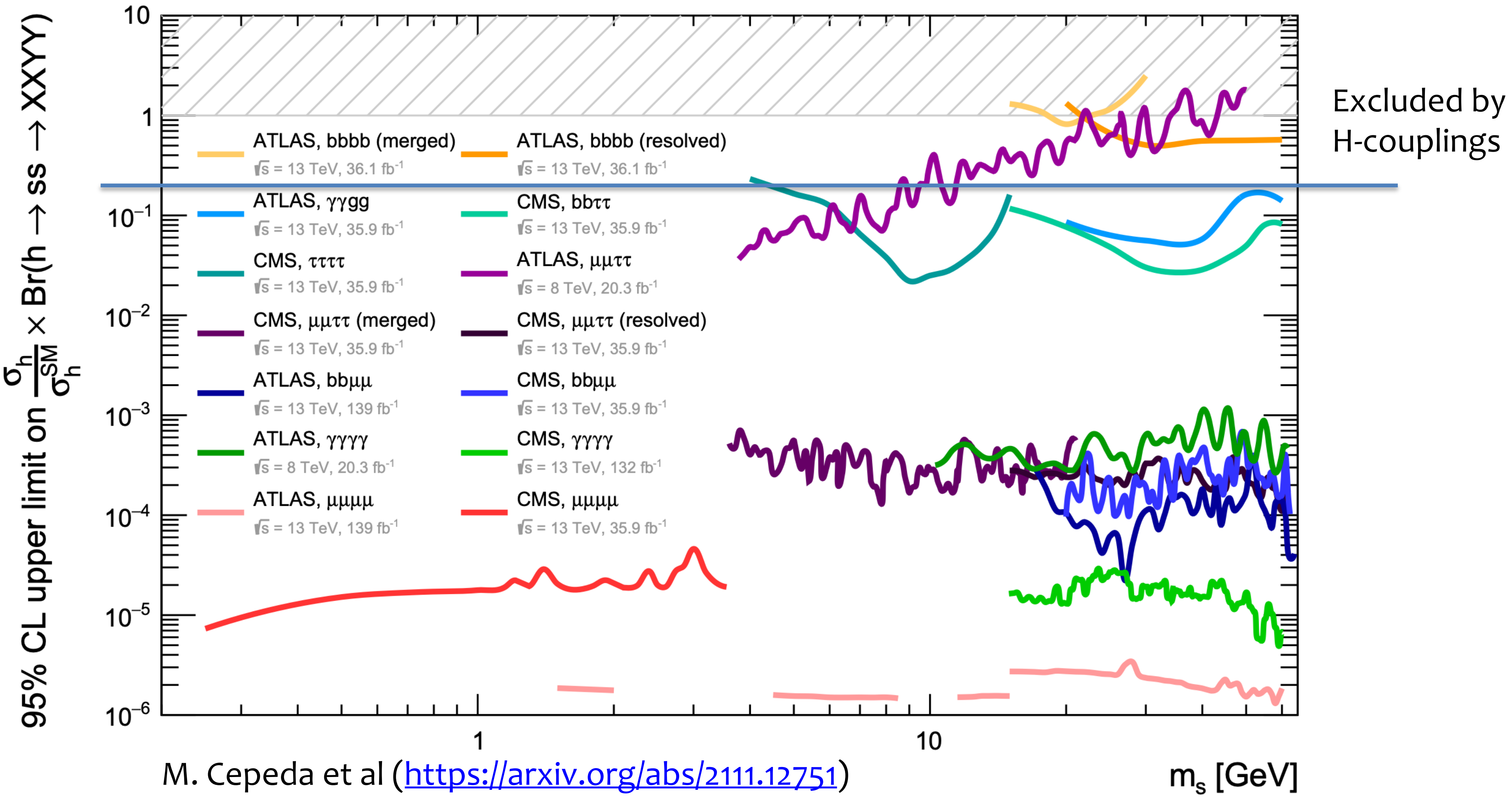
Supersymmetry (SUSY) is a popular extension of the SM…
→ Two Higgs doublets ϕ_u, ϕ_d
→ 5 Higgs bosons (A, H, h, $H^{+/-}$)





Coupling constraints are complementary to direct searches!

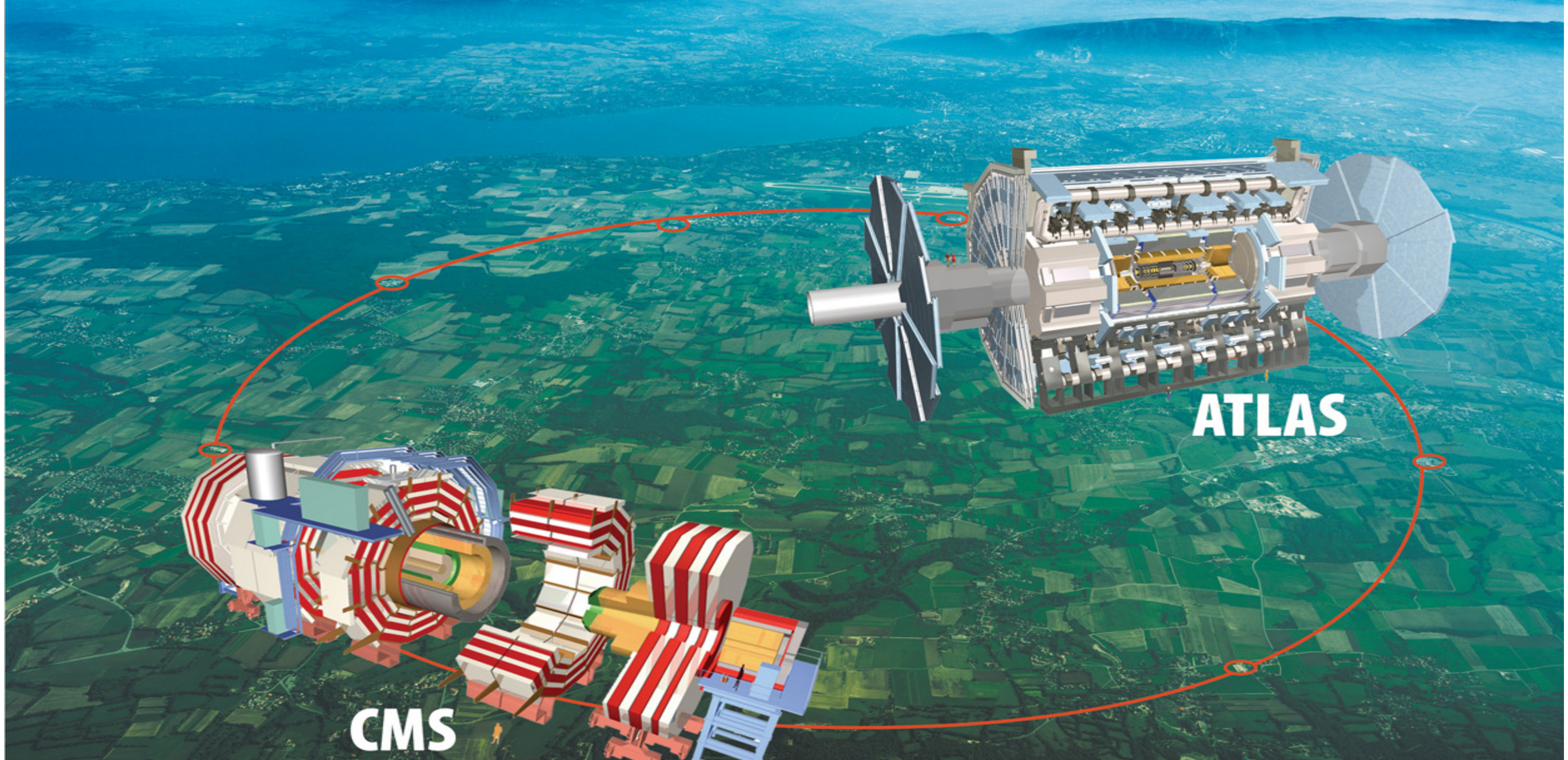
Complementarity to BSM searches



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

Higgs production at the LHC

- Run-1 discovery based on O(100) events at ATLAS and CMS
- To date LHC has produced ~8M Higgs bosons for each detector!



LHC Beam

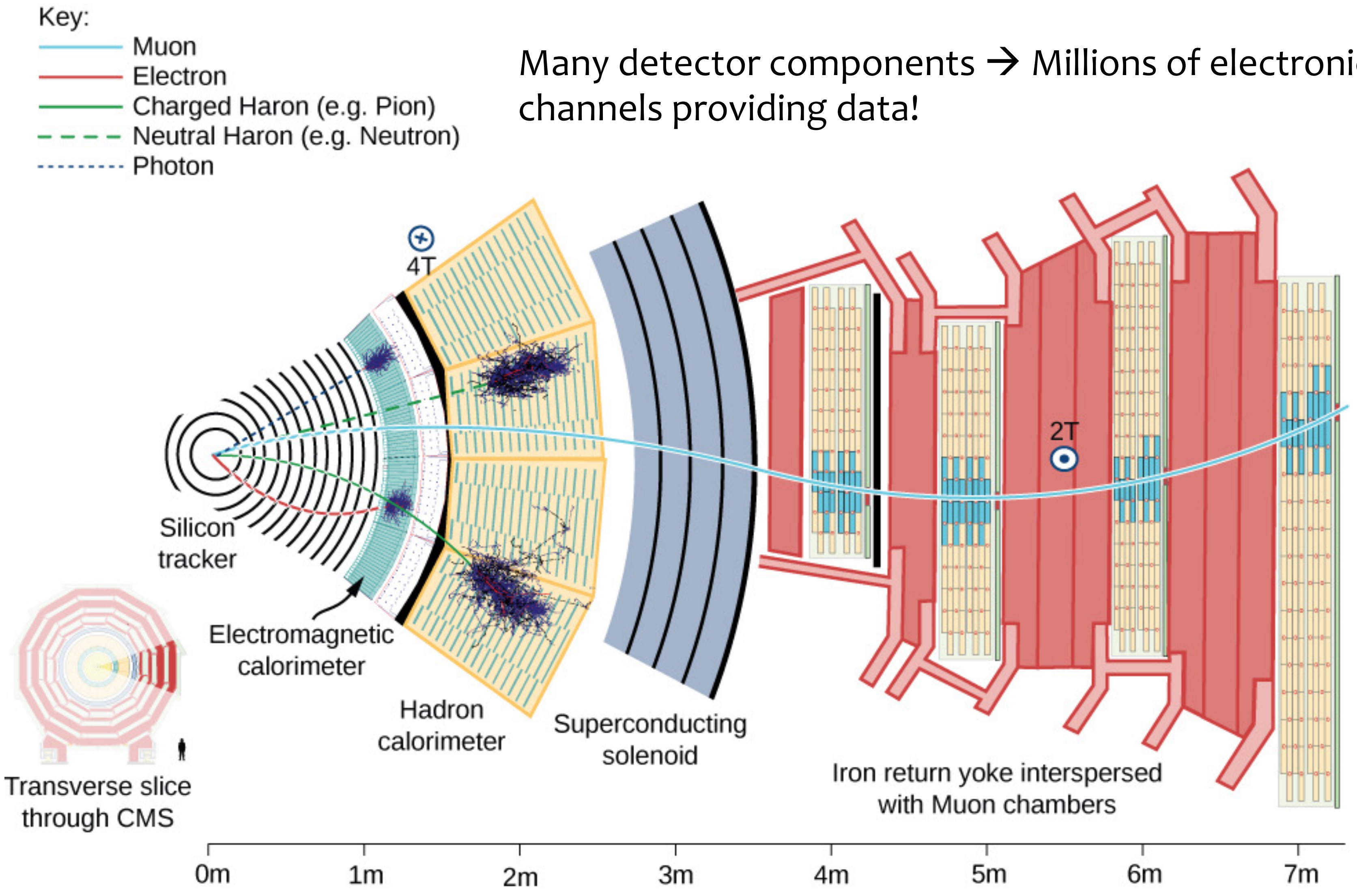
Run-1 – 7-8 TeV, L_{peak}~7 × 10^{33} cm^{-2} s^{-1}

Run-2 – 13 TeV, L_{peak}~2.06 x 10^{34} cm^{-2} s^{-1}

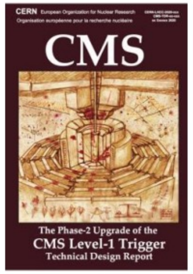
The CMS Detector

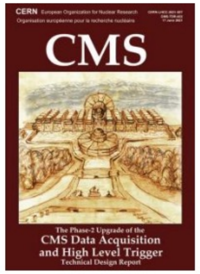
Different layers of the detector designed to reconstruct different stable particles.

Many detector components → Millions of electronic read-out channels providing data!



CMS Upgrades





L1-Trigger HLT/DAQ

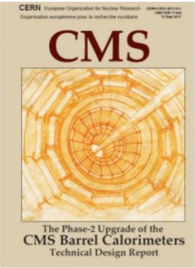
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072

- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Barrel Calorimeters

https://cds.cern.ch/record/2283187

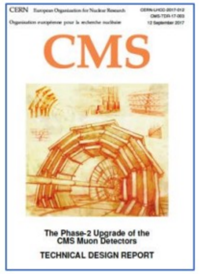
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

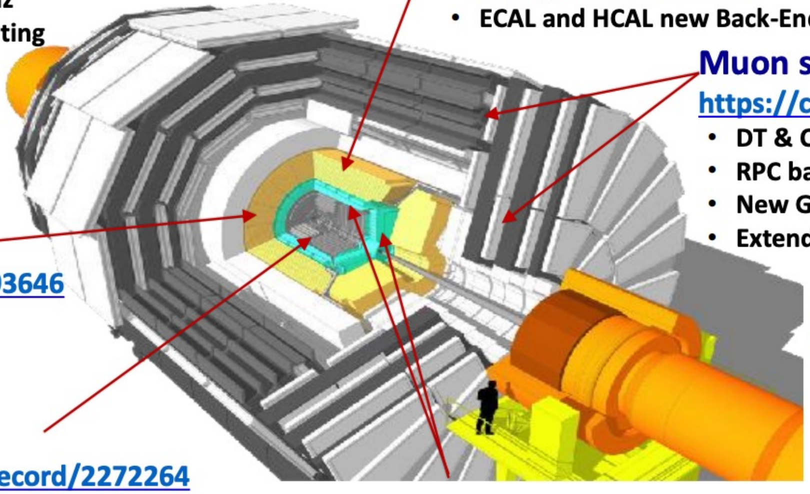


Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

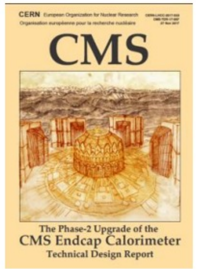




Calorimeter Endcap

https://cds.cern.ch/record/2293646

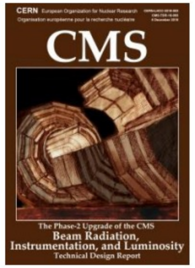
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Beam Radiation Instr. and Luminosity

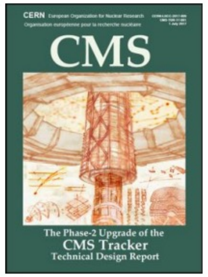
http://cds.cern.ch/record/2759074

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online



Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

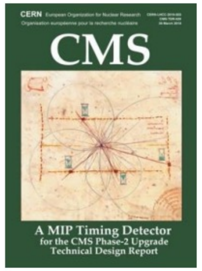


MIP Timing Detector

https://cds.cern.ch/record/2667167

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



Higgs Couplings @ HL-LHC

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

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

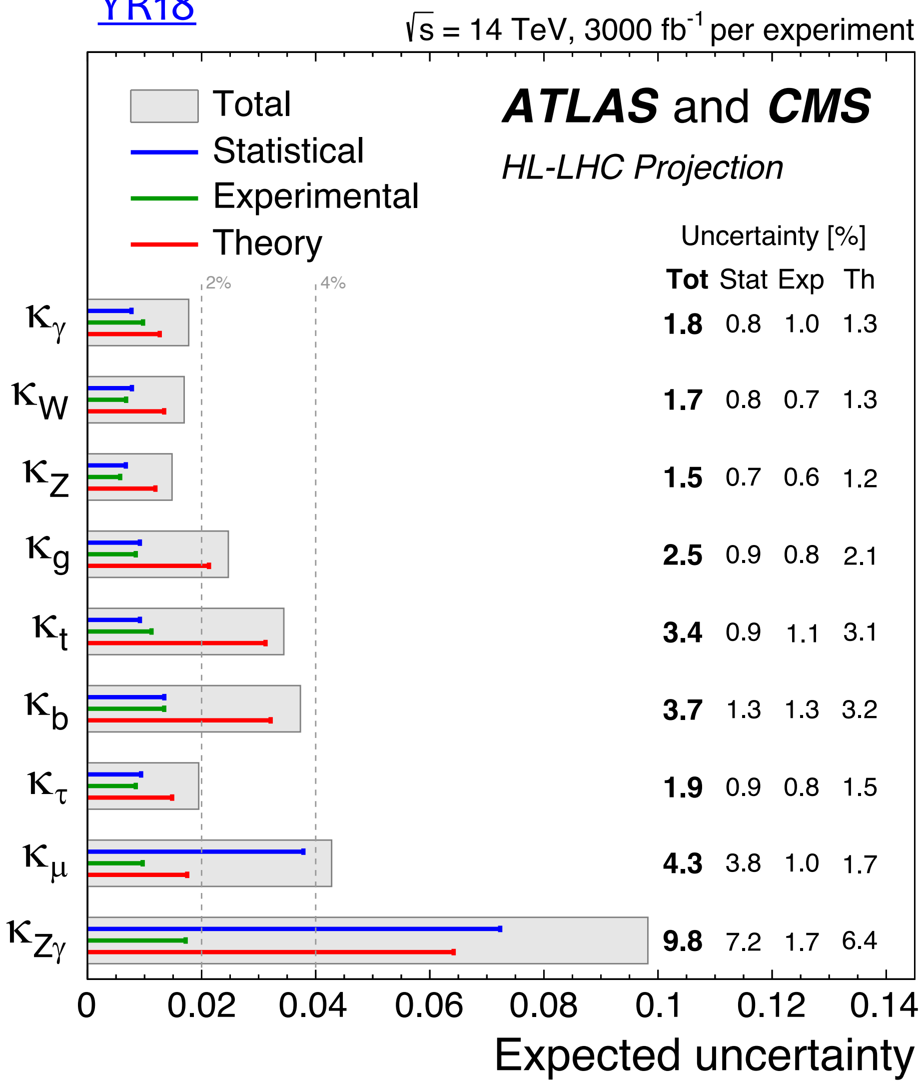
Uncertainty scaling:

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.

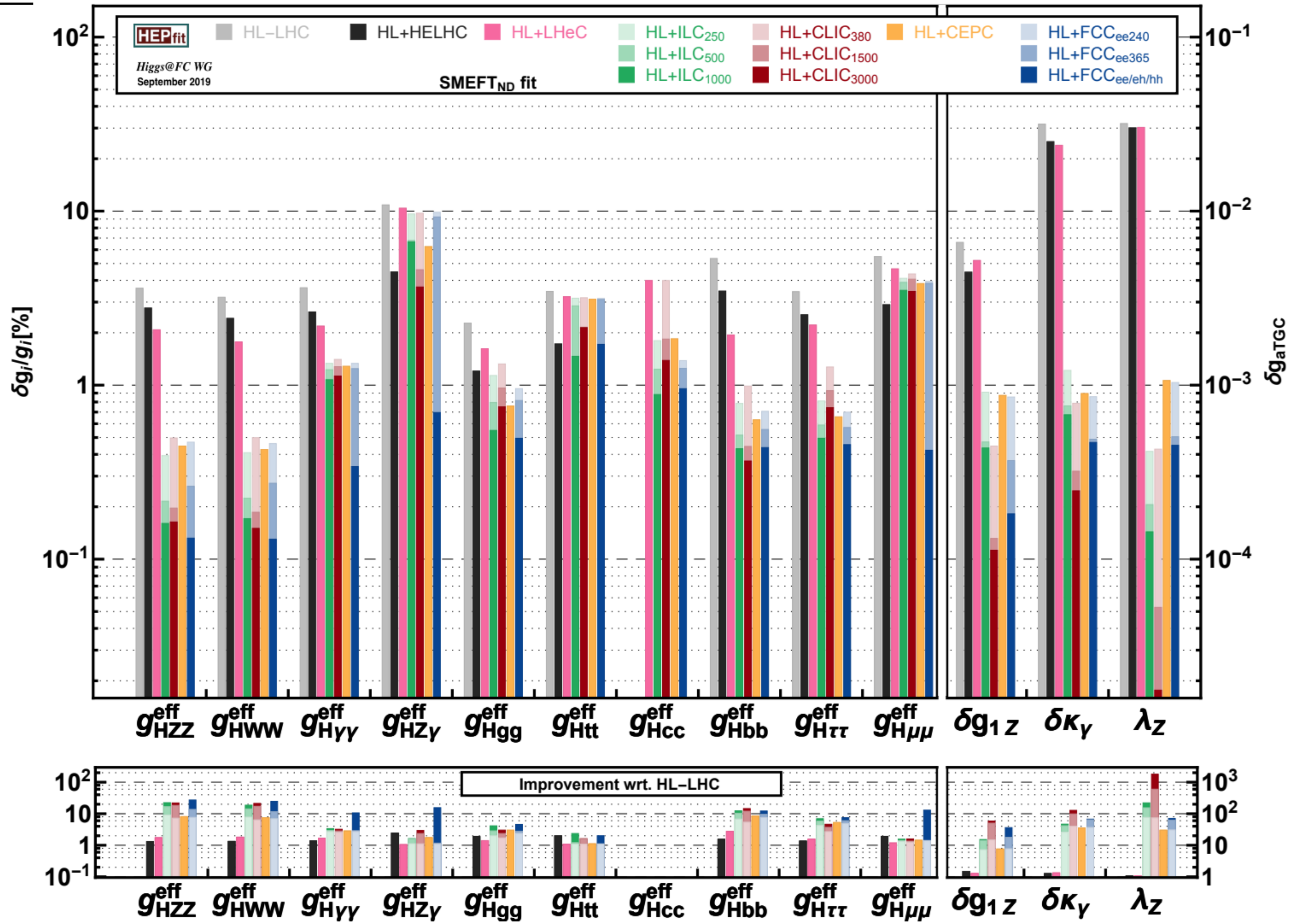
YR18



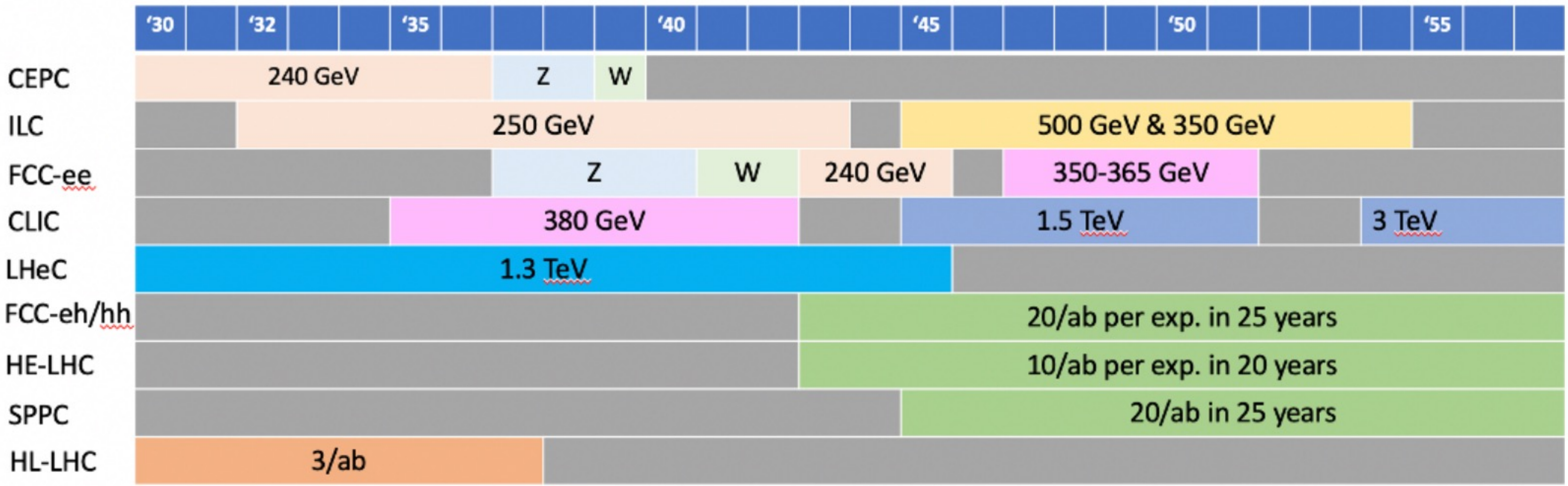
Future Colliders

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



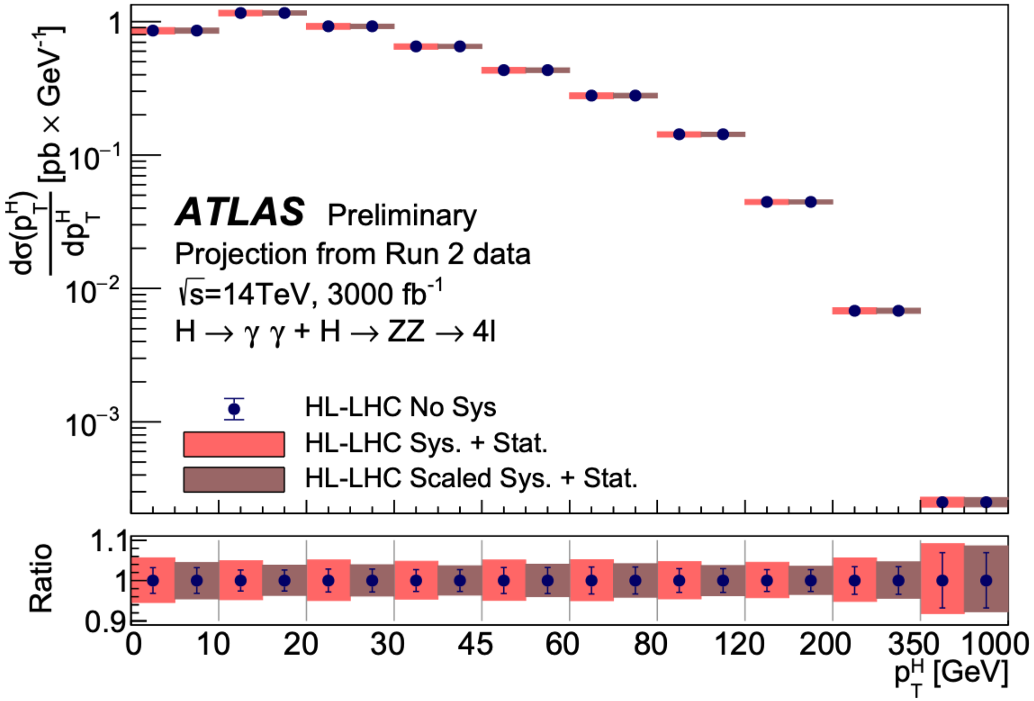
The future as of 2020

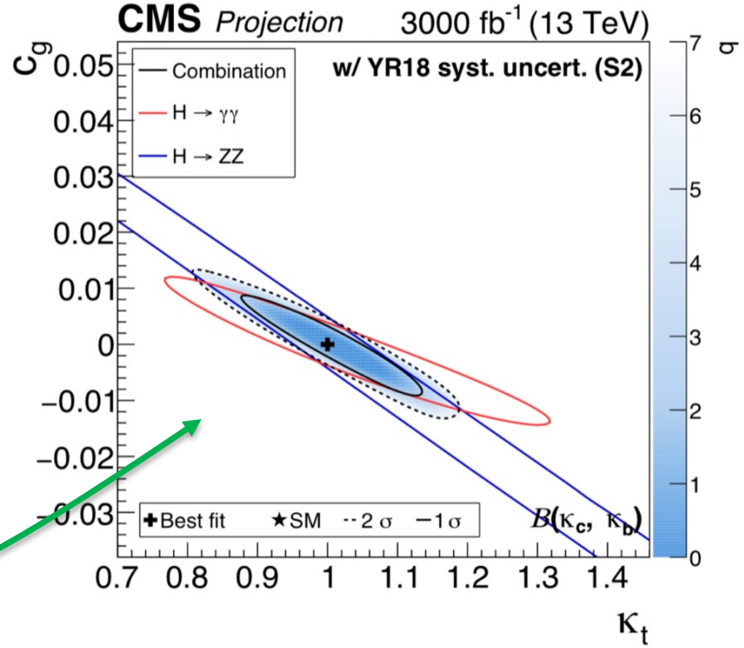


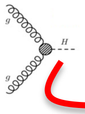
Top-Yukawa

Additional constraints on t-H coupling from differential measurements @HL-LHC [1] → complementary to direct measurements of κ_t

YR18







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

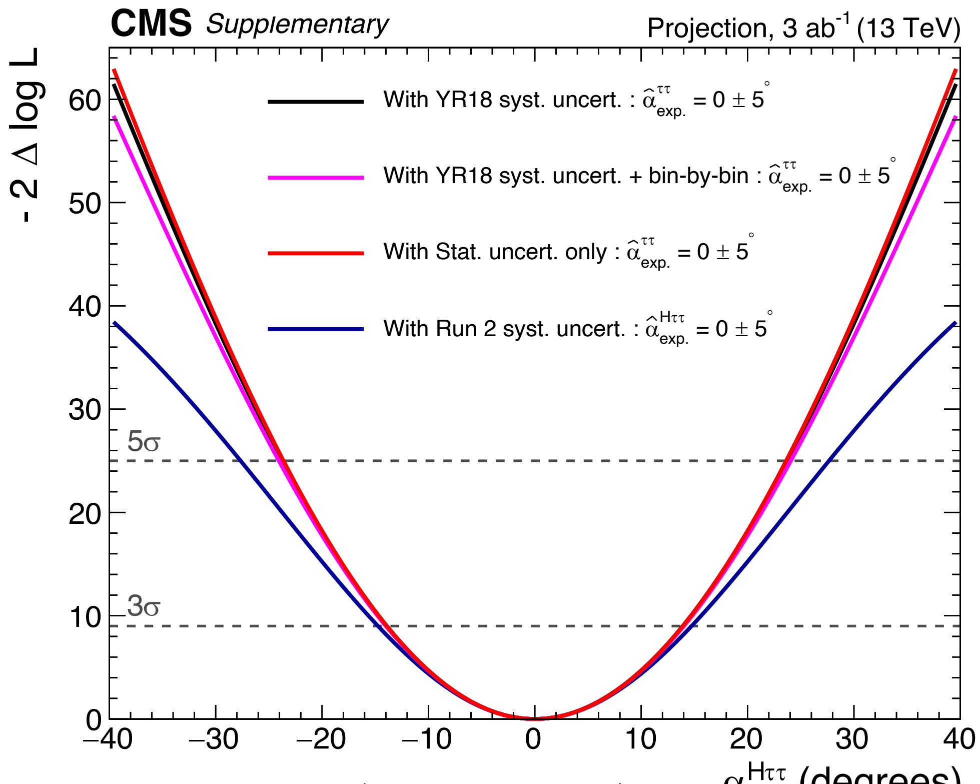
Yukawas

[1] https://arxiv.org/abs/1705.05143

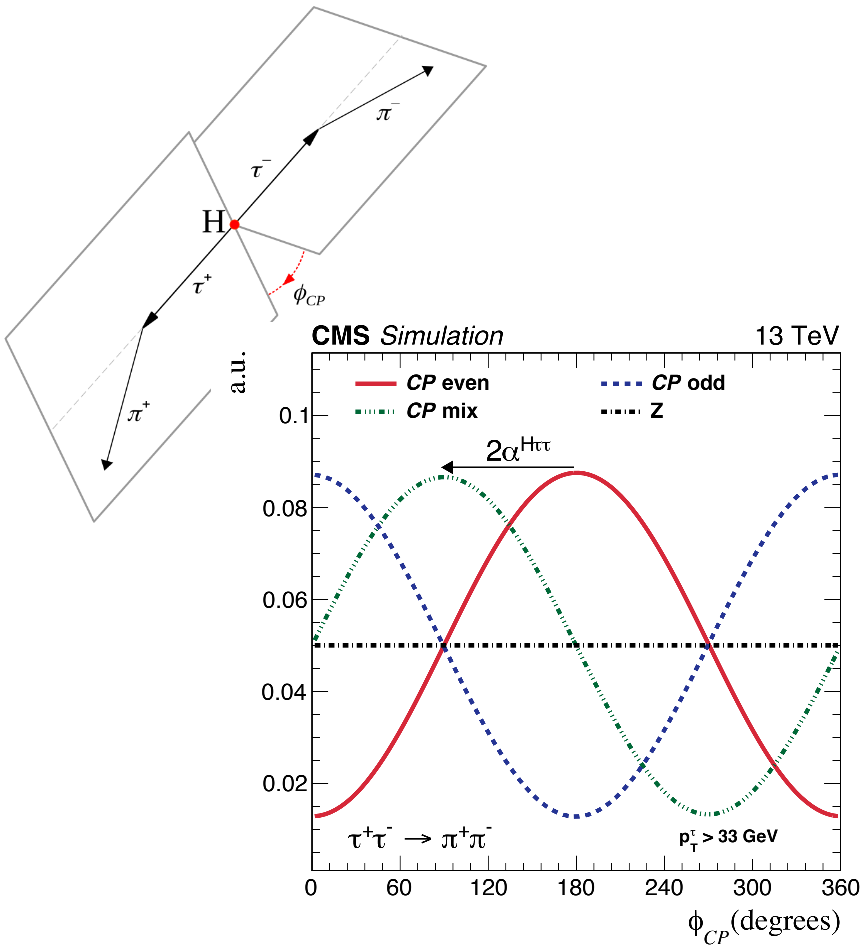
CP in H→ττ

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

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



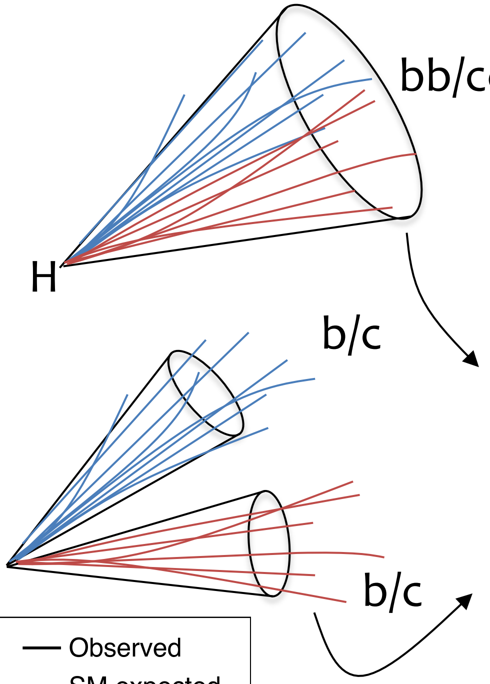
CMS-PAS-HIG-20-006 (submitted to JHEP)



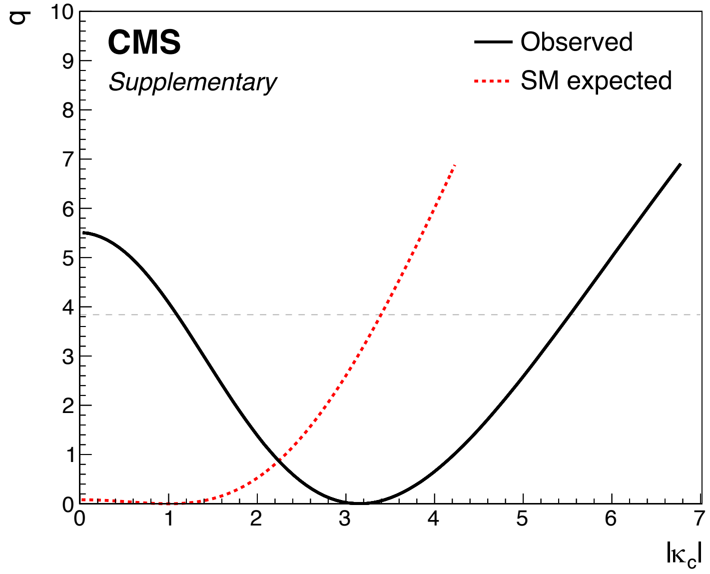
Projection of Run-2 analysis at CMS

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

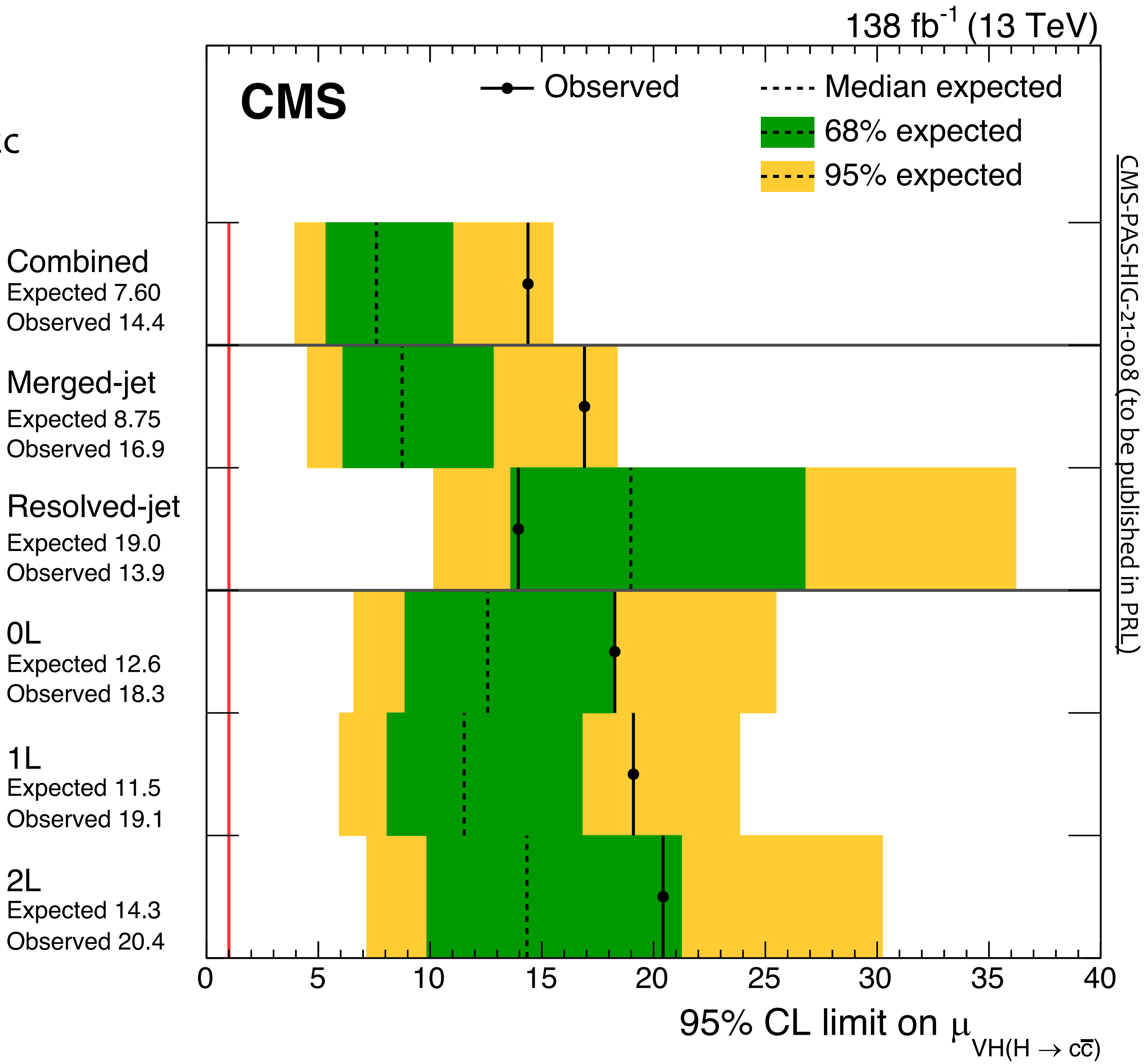
VH→cc



bb/cc
H
b/c
H
b/c

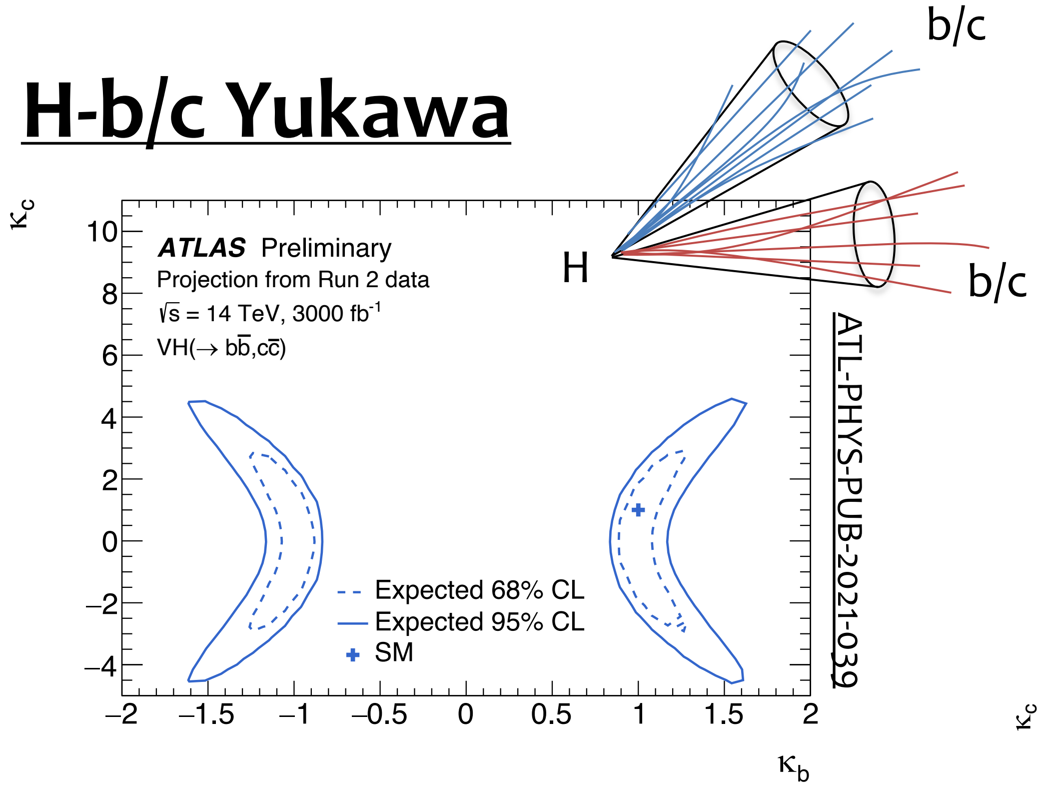


q
CMS
Supplementary
Observed
SM expected
$|\kappa_c|$



138 fb^{-1} (13 TeV)
CMS
Observed
Median expected
68% expected
95% expected
Combined
Expected 7.60
Observed 14.4
Merged-jet
Expected 8.75
Observed 16.9
Resolved-jet
Expected 19.0
Observed 13.9
0L
Expected 12.6
Observed 18.3
1L
Expected 11.5
Observed 19.1
2L
Expected 14.3
Observed 20.4
95% CL limit on $\mu_{VH(H \rightarrow c\bar{c})}$
CMS-PAS-HIG-21-008 (to be published in PRL)

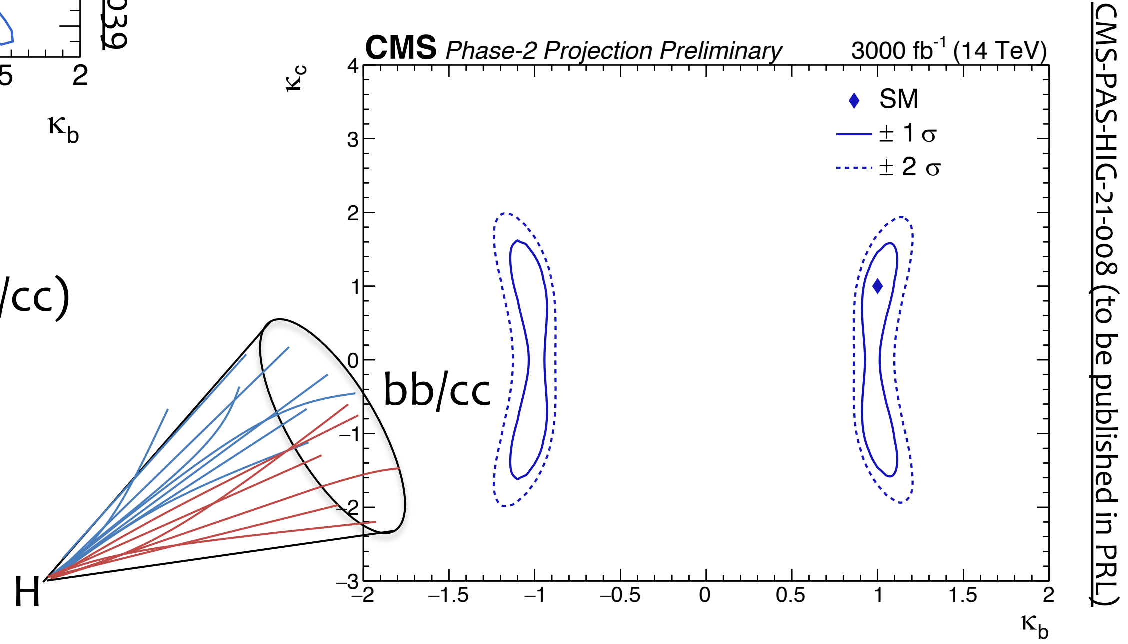
H-b/c Yukawa



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

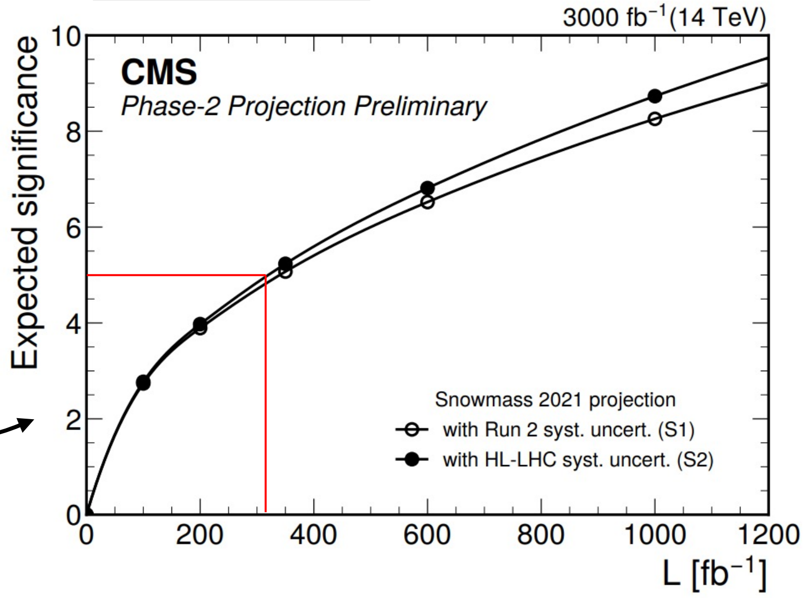
Second gen lepton couplings

Evidence for H→μμ decay in Run-2
- ATLAS: 2.0σ (1.7σ) obs (exp) Phys. Lett. B 812 (2021)
- CMS: 3.0σ (2.5σ) obs (exp) JHEP 01 (2021) 148

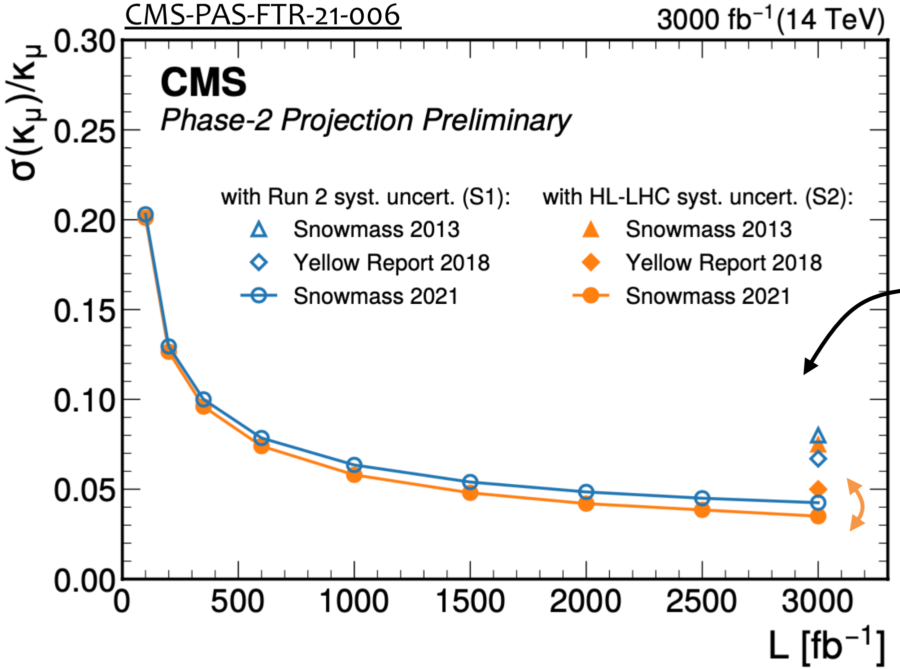
New projection from CMS based on Run-2 analysis

- Expect to reach 5σ @~300/fb – by the end of LHC Run-3
- Combination with ATLAS to reach 5σ sooner!

CMS-PAS-FTR-21-006



CMS-PAS-FTR-21-006



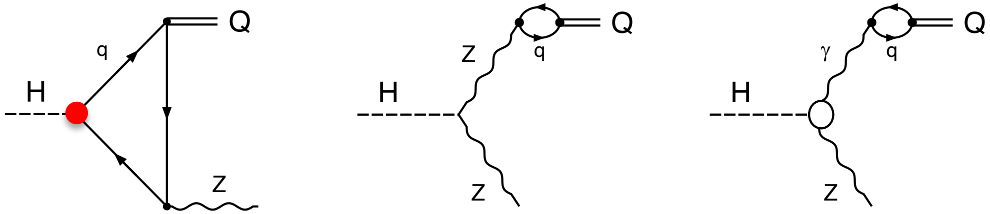
→ Expected improvement in mass resolution ~30% at HL-LHC brings sensitivity gain beyond sqrt(L)

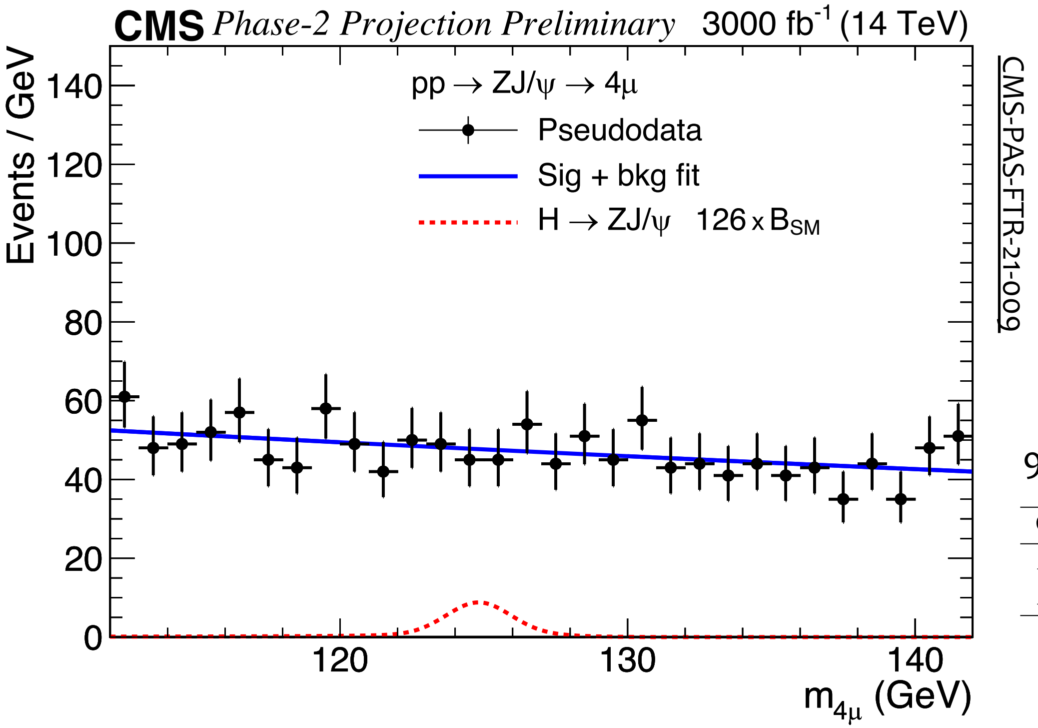
Uncertainty in coupling ~4-5% at HL-LHC

Improvement compared to 2016 analysis projection

Rare decays

Beyond SM physics can lead to large modifications of 1st generation quark Yukawas → possible enhancement in H→ZQ/QQ compared to SM





Projection of Run-2 search for H→Z J/ψ → 4μ and H→ YY → 4μ

Analysis still very statistics limited at HL-LHC → 3 events in H→YY Higgs peak would constitute discovery!

95% CL Upper limit on B(H→X) at (extended) HL-LHC

Channel	3000 fb^{-1}	(×SM)	4500 fb^{-1}	(×SM)
$H \to ZJ/\psi$	2.9×10^{-4}	(126)	2.7×10^{-4}	(117)
$H \to \Upsilon(mS)\Upsilon(nS)$	1.3×10^{-5}	(0.2)	8.5×10^{-6}	(0.14)

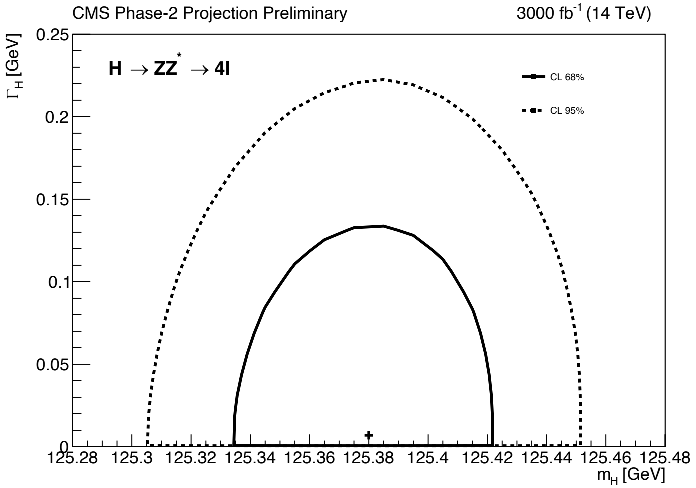
BSM in Higgs decays

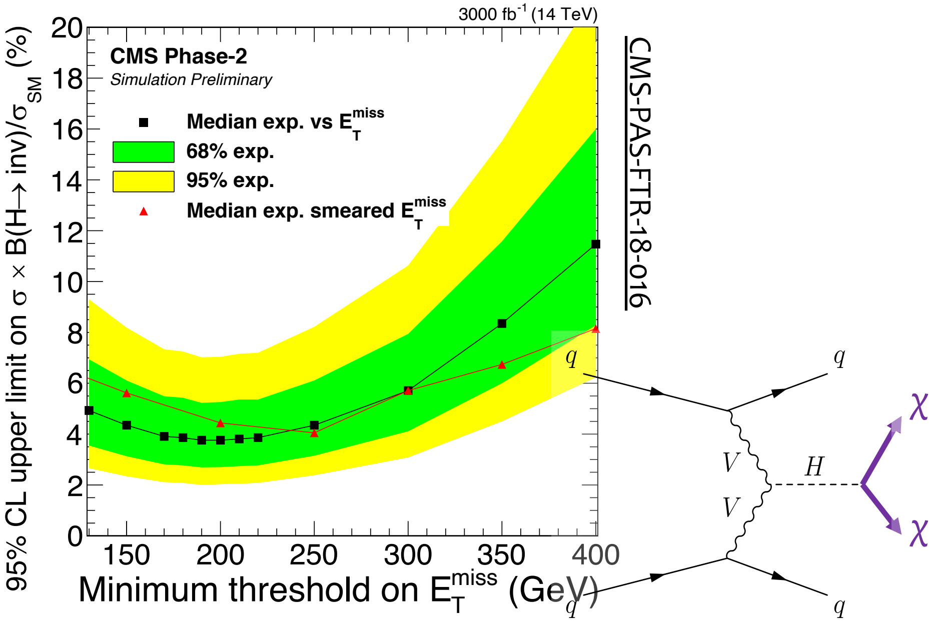
Additional (BSM) decays of the Higgs boson results in modified Higgs boson width

- 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		





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)!

STXS H→ττ

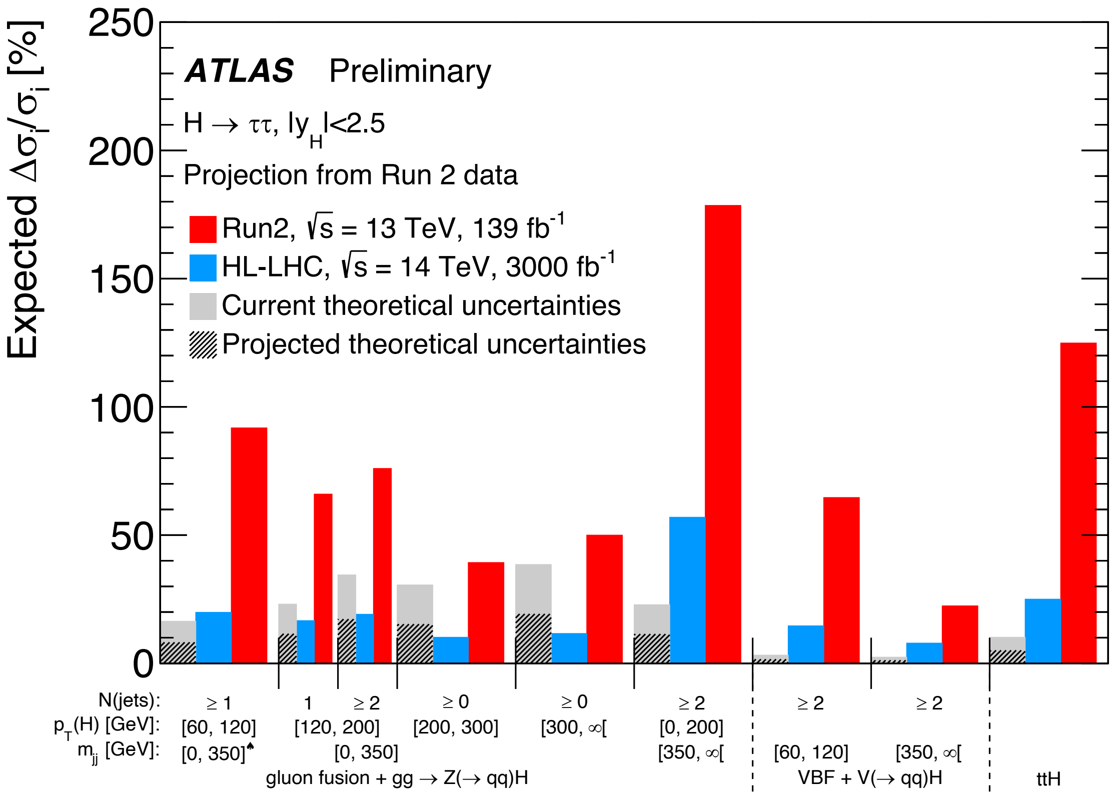
Simplified Template Cross Sections designed in stages as more data are collected

- Designed to be an evolution of the signal strength measurements with kinematic bins to reduce theoretical uncertainty

ATL-PHYS-PUB-2022-003

ATLAS STXS Stage 1.2 measurements in H→ττ projected to HL-LHC

- Several scenarios in which experimental precision will be greater than theoretical!
- With 3/ab of data, expect finer binning possible → greater sensitivity to EFT

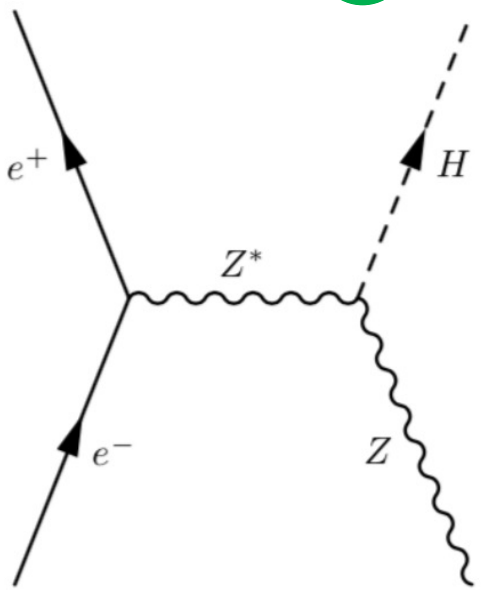


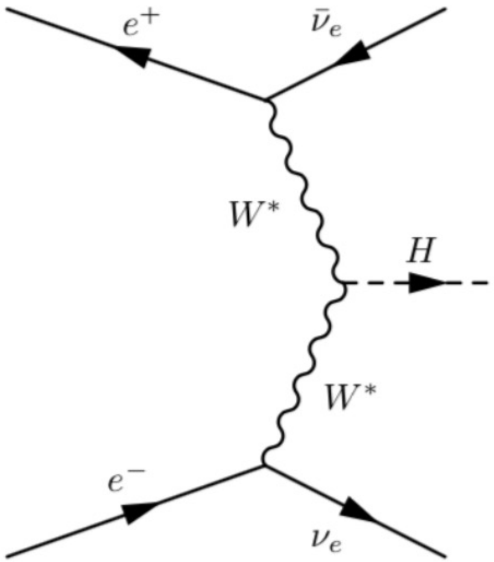
Next generation

Future e^+e^- colliders (eg FCC-ee) will provide ultimate precision in certain couplings

Total ZH cross-section measured from "missing mass" $m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{ll})^2 - |\vec{p}_{ll}|^2$
combined with total VBF cross-section
→ Access to **total width** and precision Higgs couplings

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}} \qquad \sigma_{\mathrm{H}\nu_e\bar{\nu}_e} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

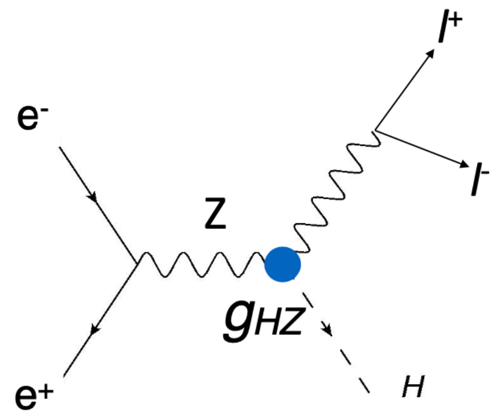


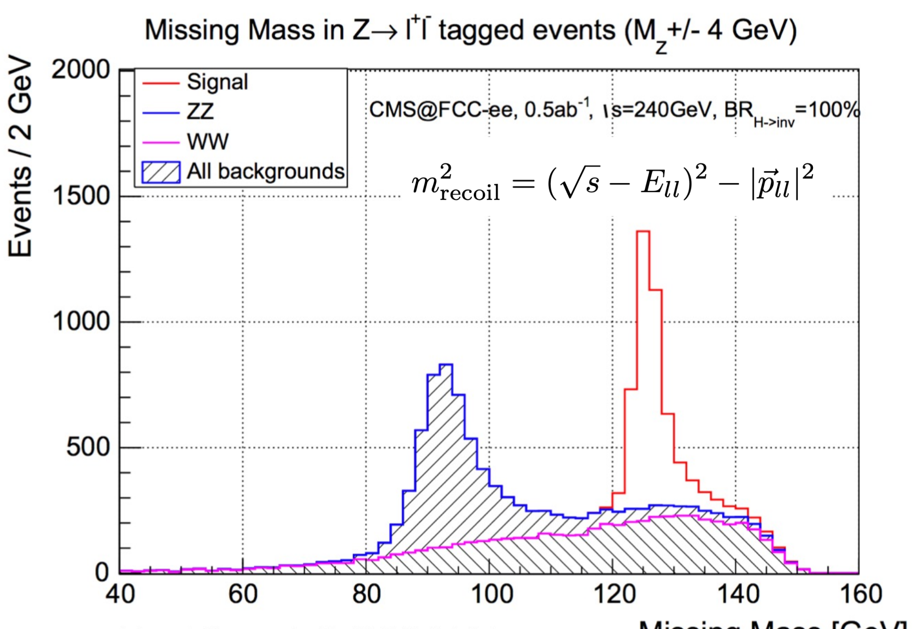


Next generation

Future e^+e^- colliders (eg FCC-ee) will provide ultimate precision in certain couplings

→ Access to **total width** and precision Higgs couplings
→ B(H→inv) as small as 2.4% observable at 5σ @FCC-ee





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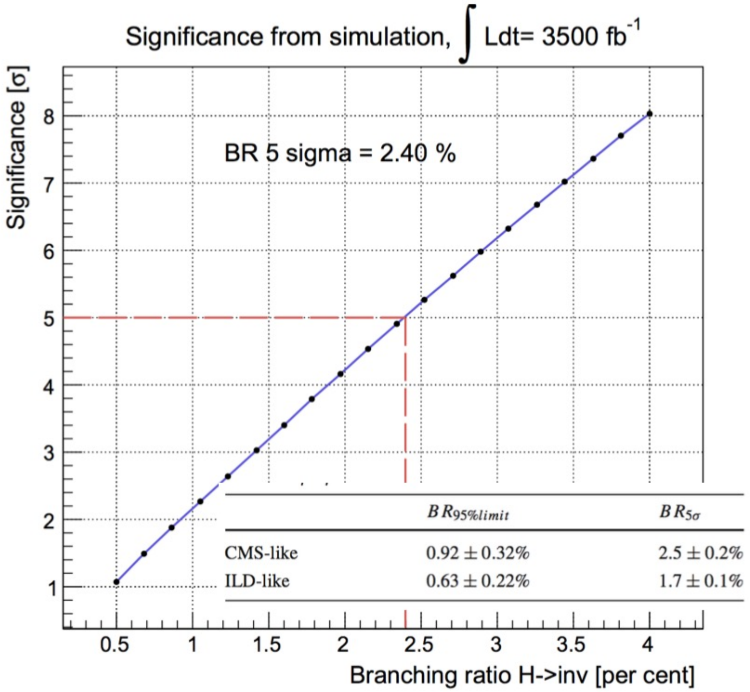

	$BR_{95\%limit}$	$BR_{5\sigma}$
CMS-like	$0.92 \pm 0.32\%$	$2.5 \pm 0.2\%$
ILD-like	$0.63 \pm 0.22\%$	$1.7 \pm 0.1\%$