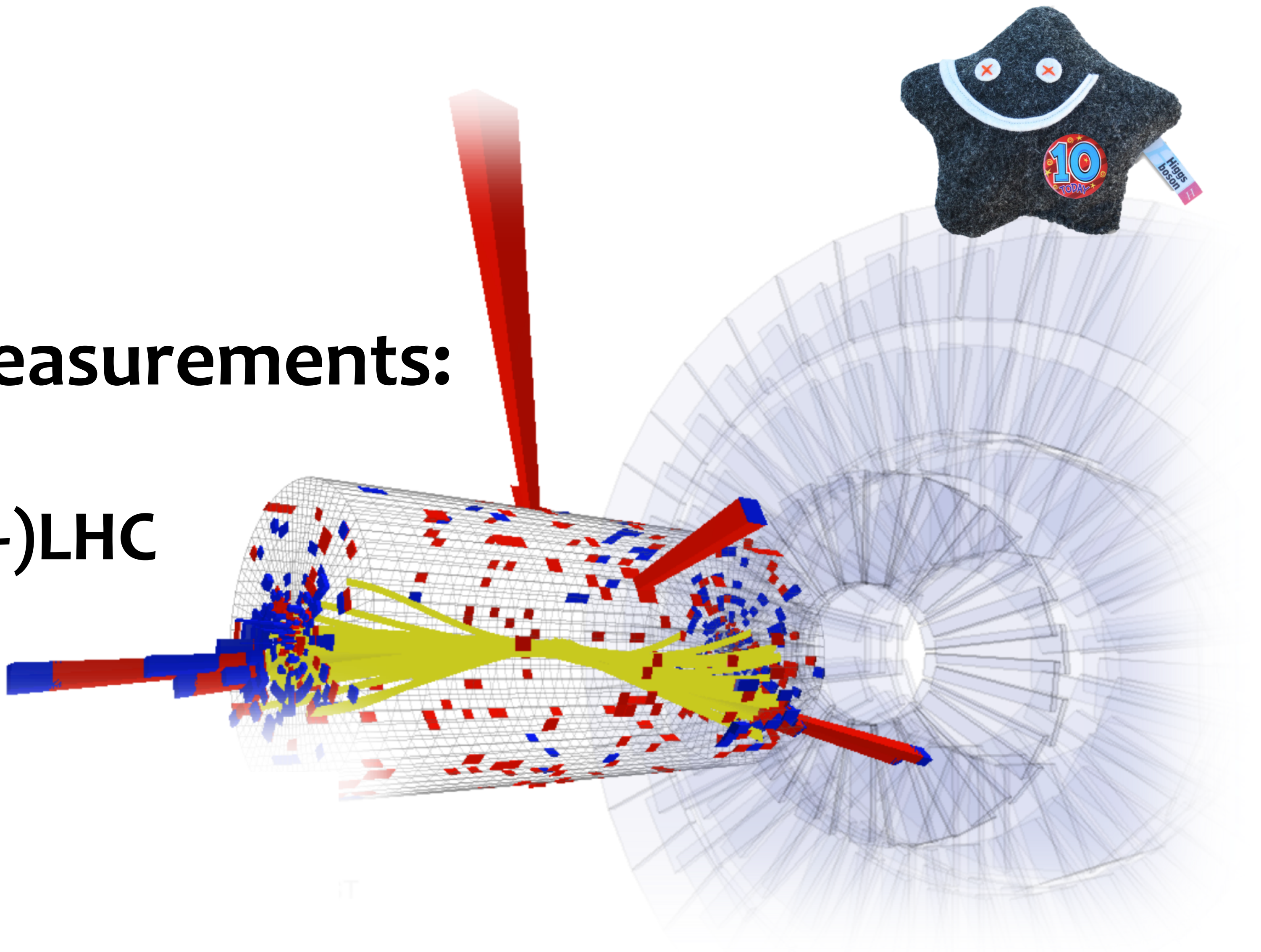
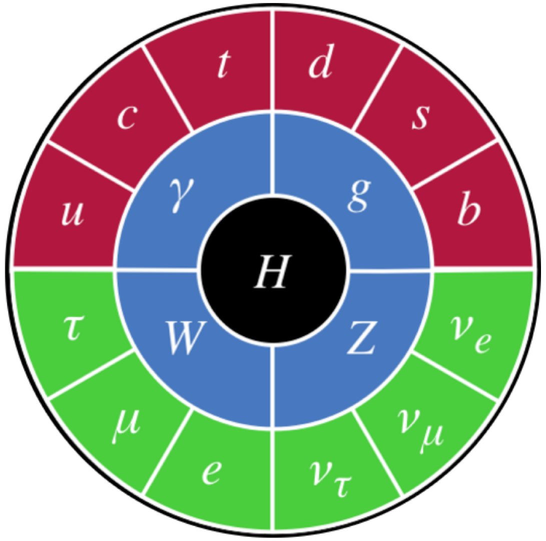


Discovery and Future Measurements:
25 years of measuring the Higgs boson @ the (HL-)LHC

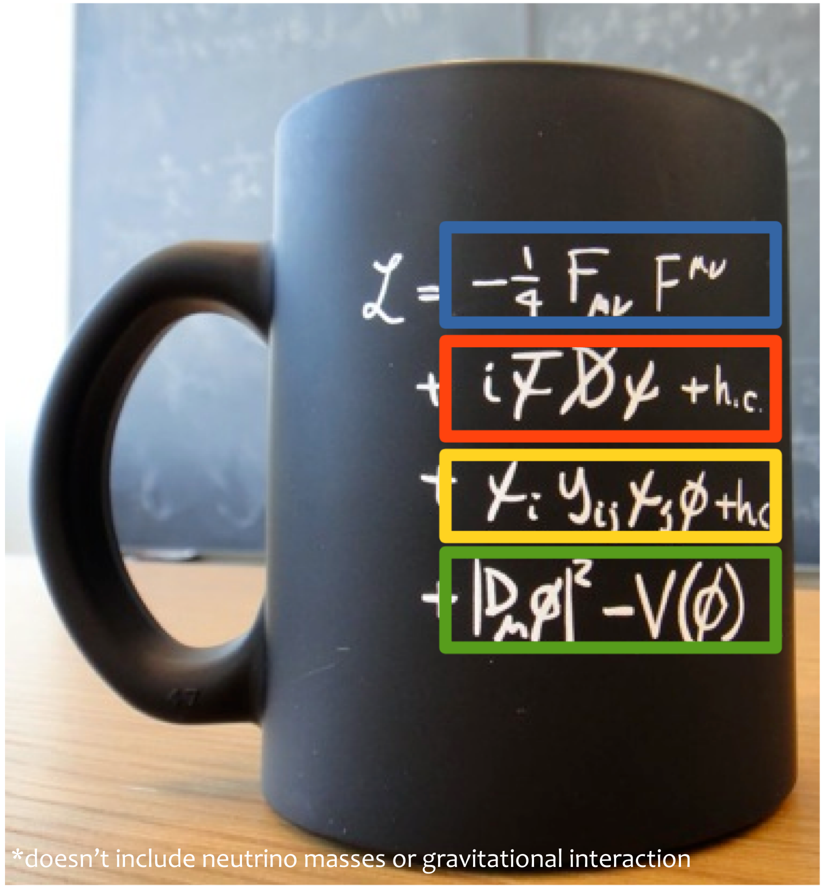
Nicholas Wardle

Higgs@10 Celebration – Imperial College London
12/10/2022

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

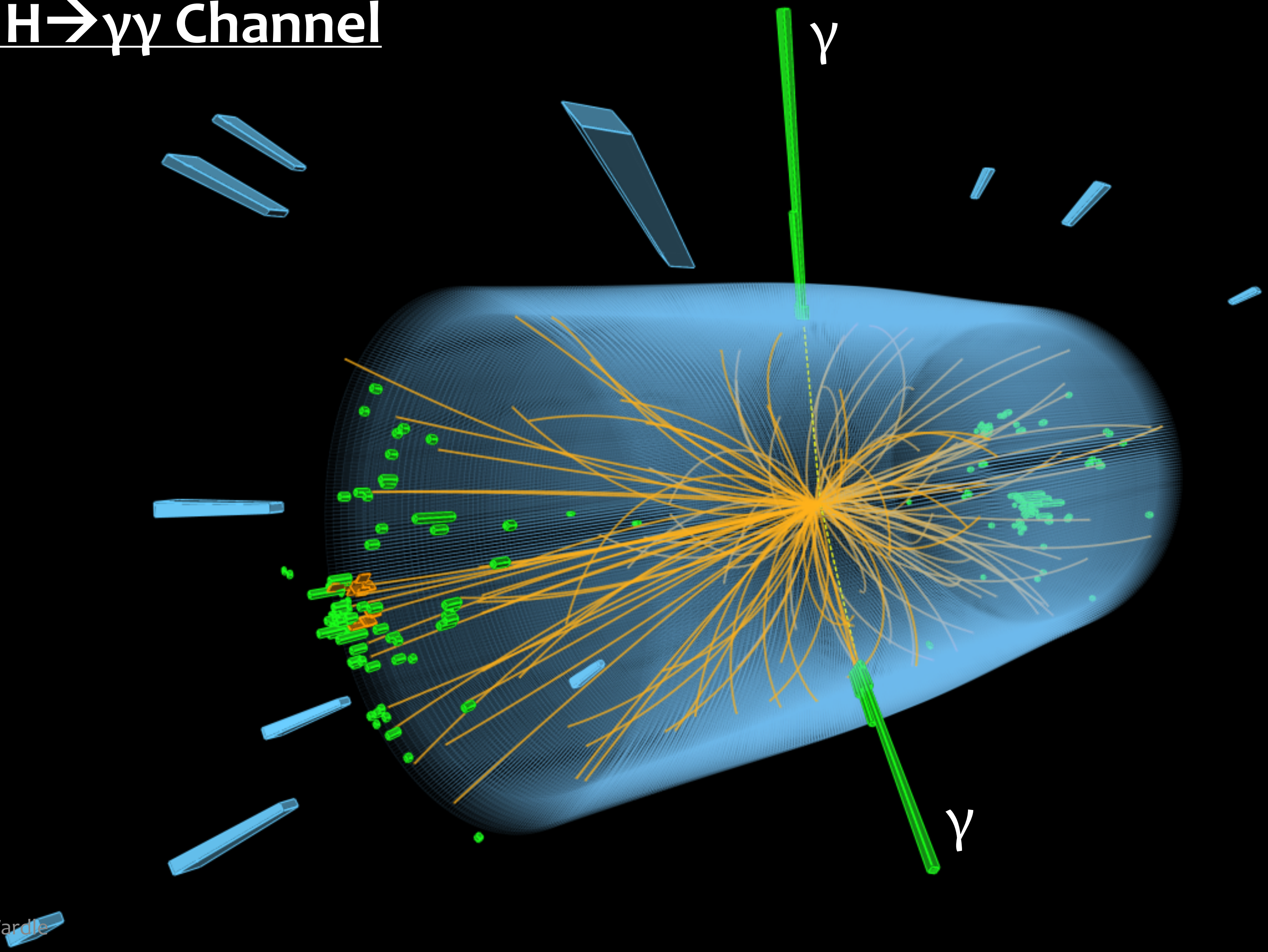
Propagation of force-carriers (spin-1 boson)

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

Masses of matter particles

Higgs interactions and mass of force carriers

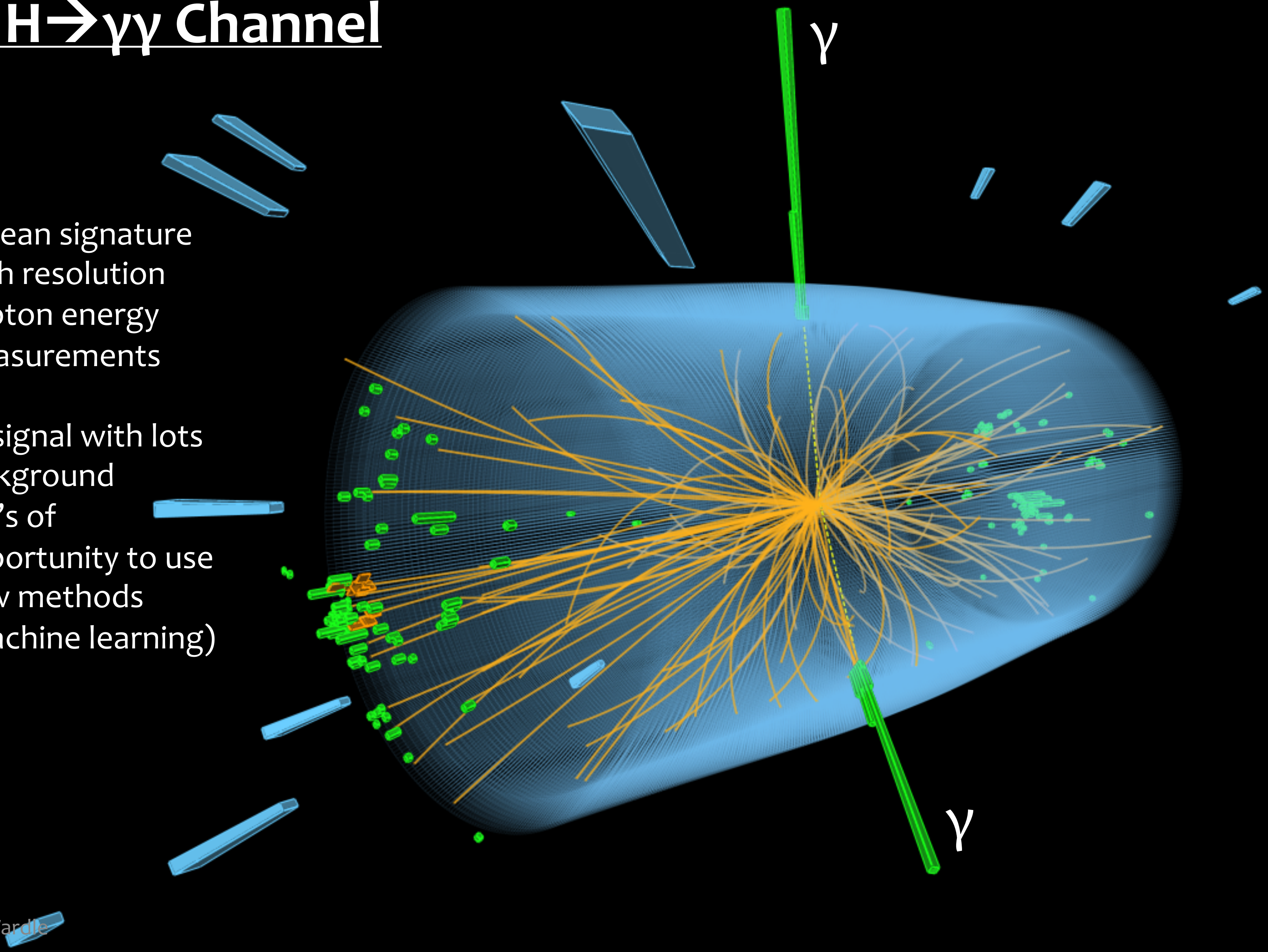
The H→γγ Channel



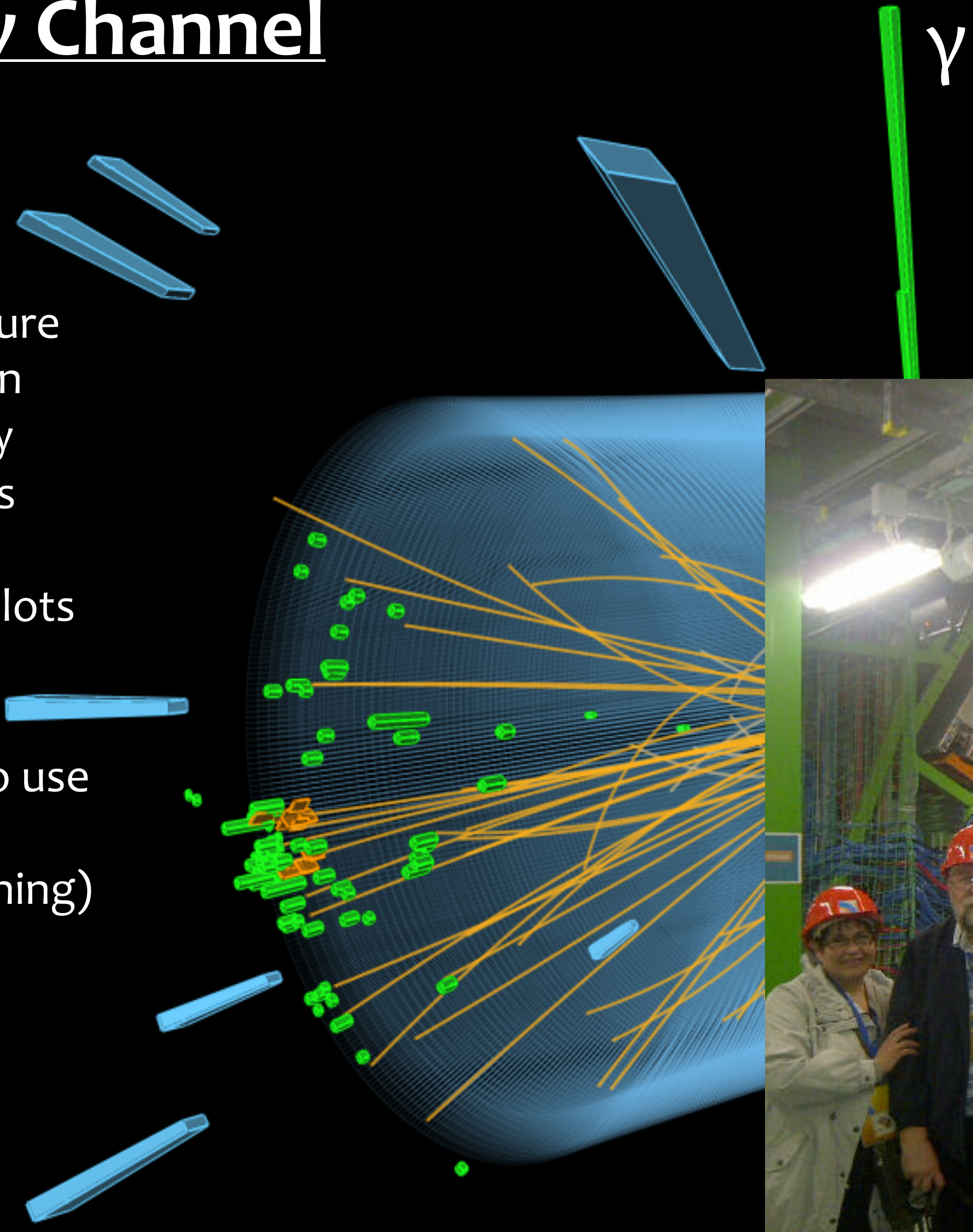
The H→γγ Channel

Very clean signature
- High resolution photon energy measurements

Small signal with lots of background
- Lot's of opportunity to use new methods (machine learning)



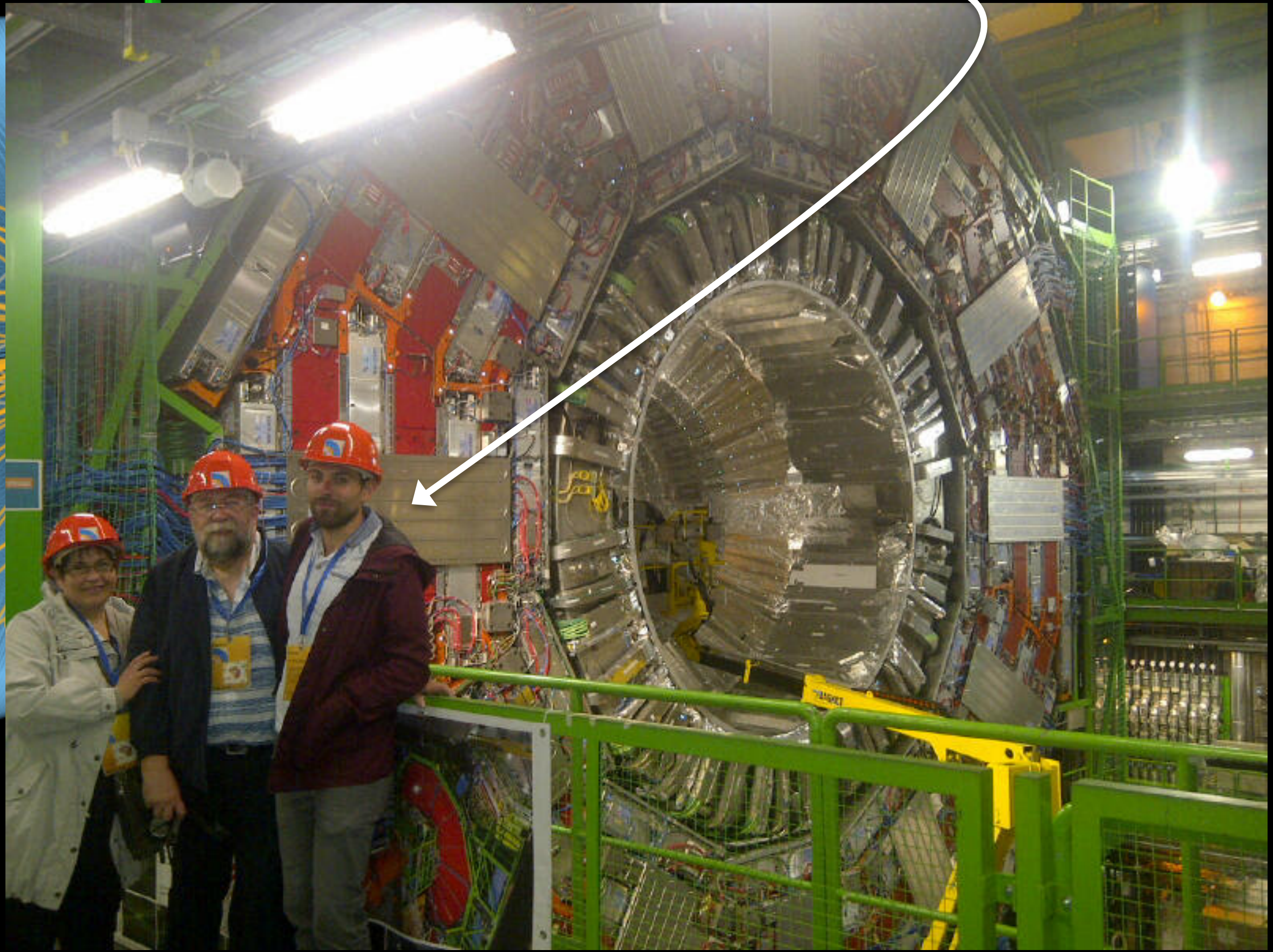
The H→γγ Channel



Very clean signature
- High resolution photon energy measurements

Small signal with lots of background
- Lot's of opportunity to use new methods (machine learning)

Exciting for a PhD student (me)
- Proud parents wanting to take photos in front of "which one is that again?"

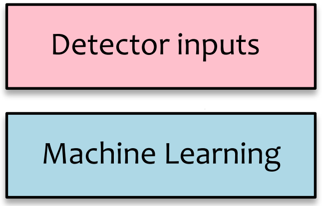


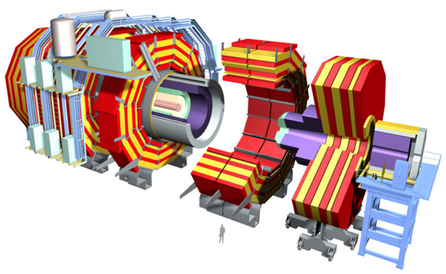
A daunting PhD student task

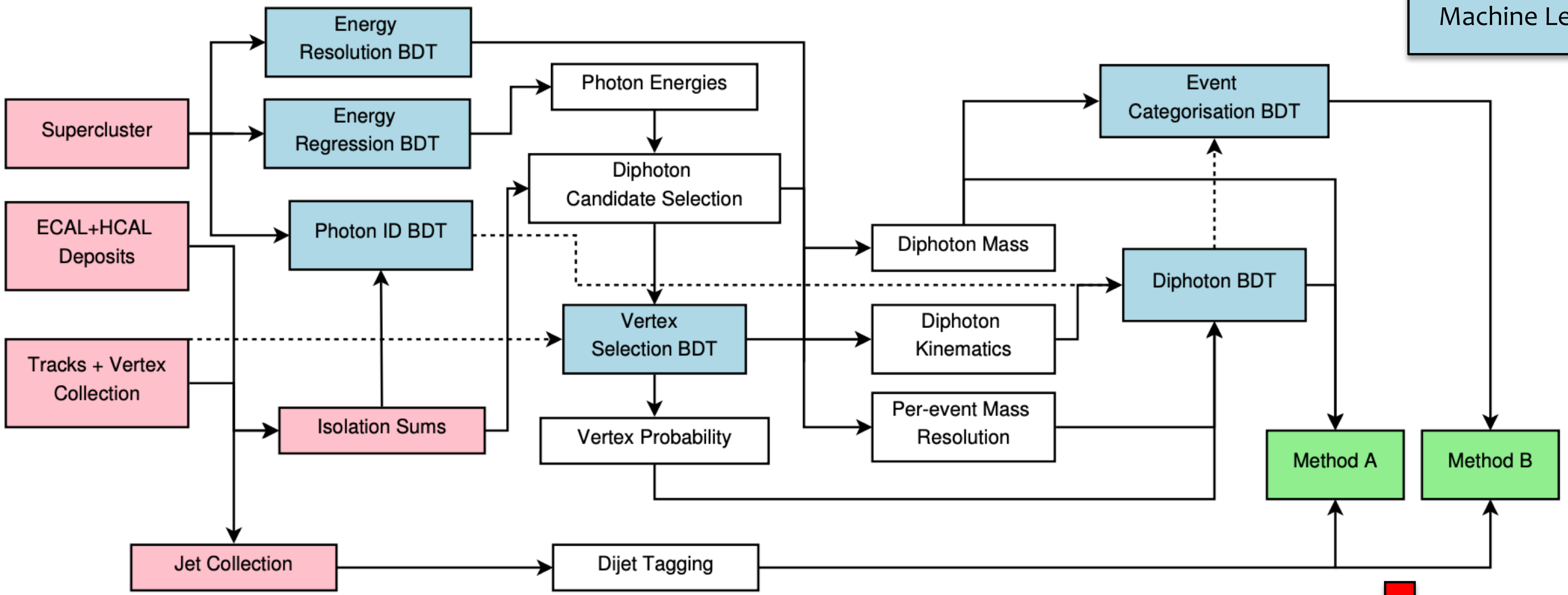
Gavin Davies : "Nick, we need a ***simple*** (baseline) analysis to search for $H \rightarrow \gamma\gamma$"

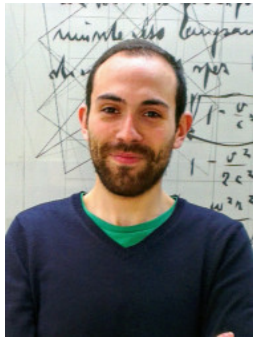
A daunting PhD student task

Gavin Davies : "Nick, we need a ***simple*** (baseline) analysis to search for H→γγ"









As a PhD student I didn't really know the meaning of the word ***"simple"***

Early days of searching: Keeping Prof. Virdee in the loop

Higgs Reference Analysis
Nick Wardle
15 March 2011 09:30
Jim's office (CERN)
...e » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Photon Purity
Nick Wardle
05 April 2011 09:50
Jim's office (CERN)
...e » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Progress towards the final Analysis
Nick Wardle
10 May 2011 09:30
Jim's office (CERN)
...e » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Limits
Nick Wardle
07 June 2011 09:30
Jim's office (CERN)
...e » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

a signal at 140
Nick Wardle
09 September 2011 10:20
Jim's office (CERN)
Home » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Signal+Background modeling
Nick Wardle
16 September 2011 10:00
Jim's Office (CERN)
Home » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Bump hunt
Nick Wardle
30 September 2011 10:40
Jim's office (CERN)
Home » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

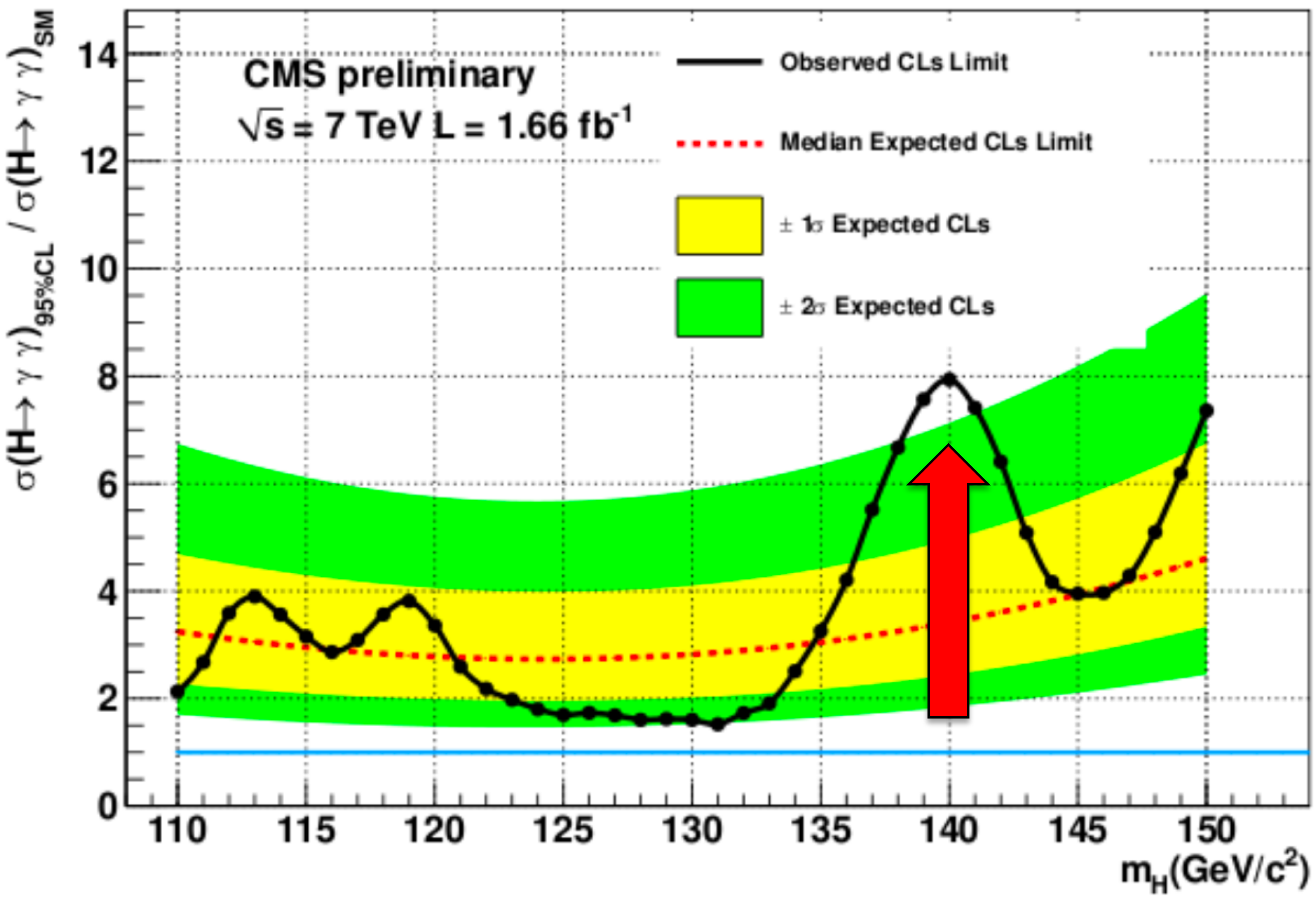
MVA Progress
Nick Wardle
07 October 2011 09:50
Jim's Office (CERN)
Home » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

Optimized Binning
Nick Wardle
20 October 2011 09:30
Jim's Office (CERN)
Home » Experin

Background model
Nick Wardle
20 October 2011 10:10
Jim's Office (CERN)
Home » Experiments » CMS meetings » National and Institute Meetings » UK » Imperial H-gg

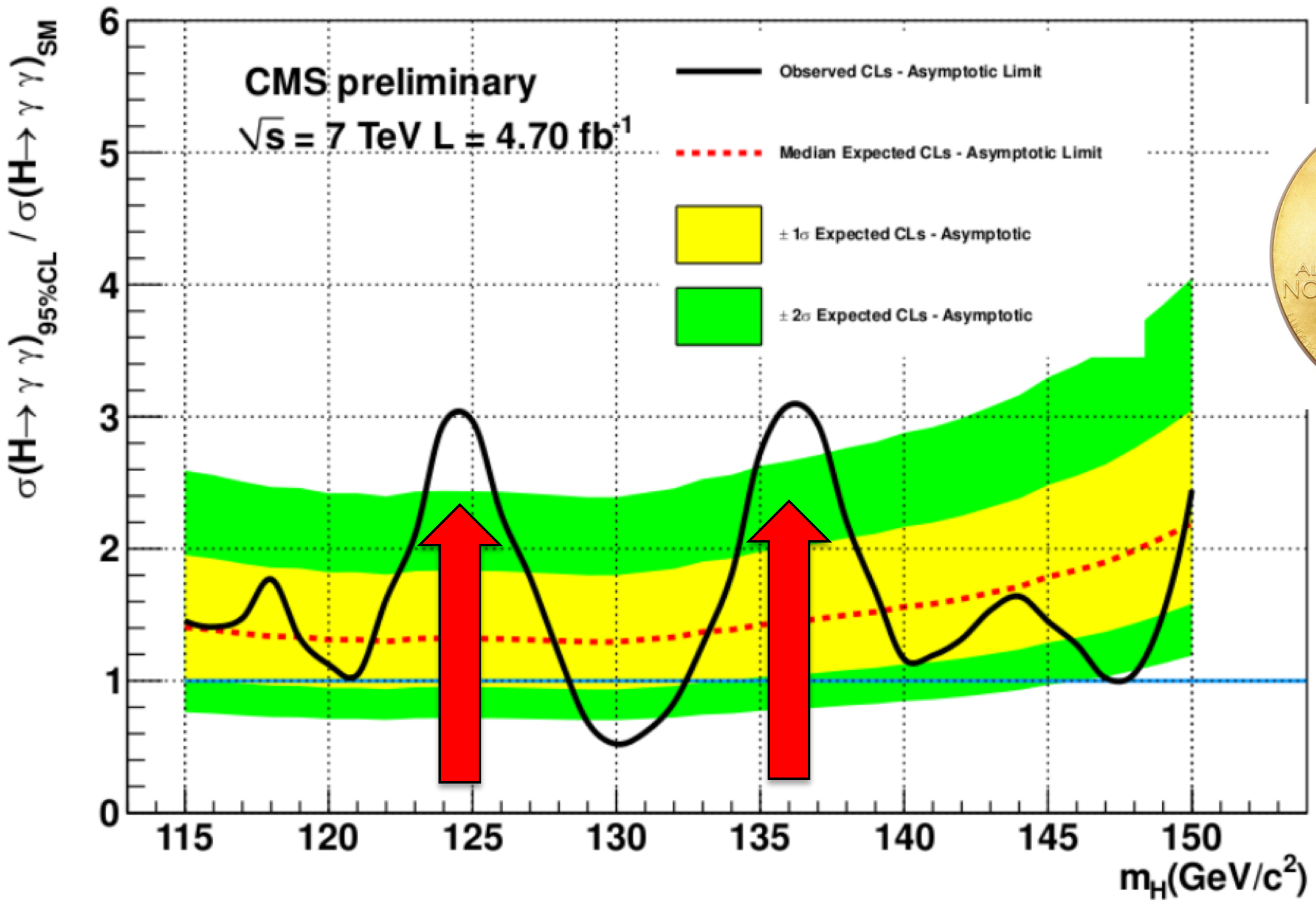
Still trying to model the backgrounds!

We found the Higgs! m_H=140 GeV



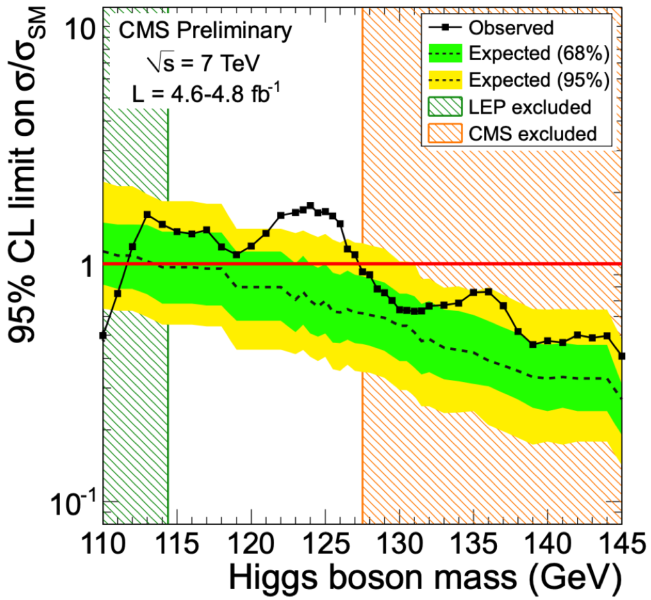
20th November 2011!

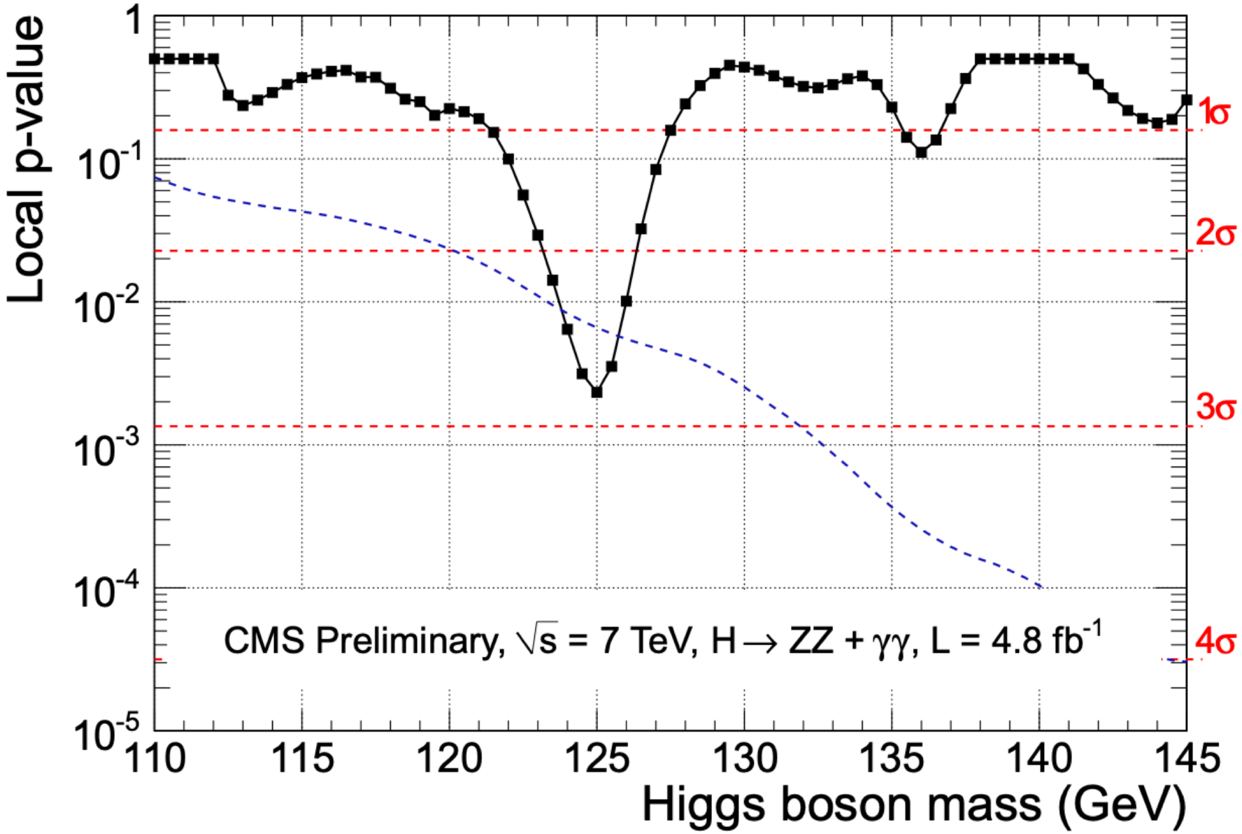
We found another Higgs!



1st December 2011!

Trying to keep our cool …





Status ~ today

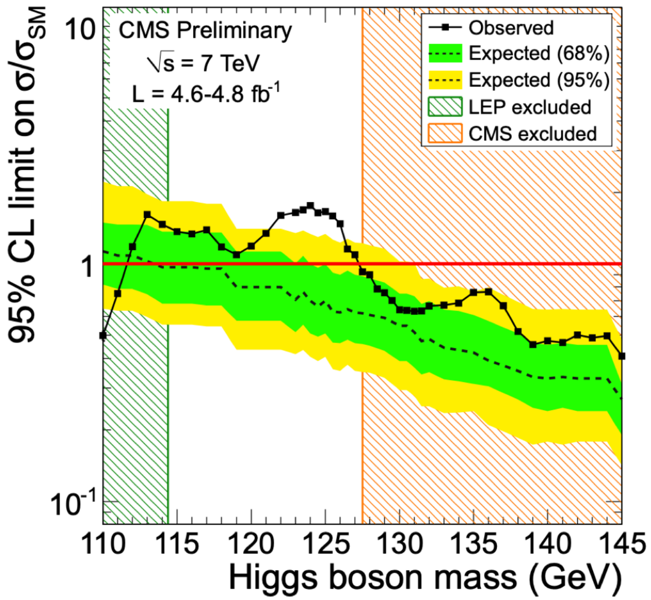
SM Higgs boson excluded with 95% cl up to a mass of 600 GeV except for the window **122.5 to 127.5** GeV

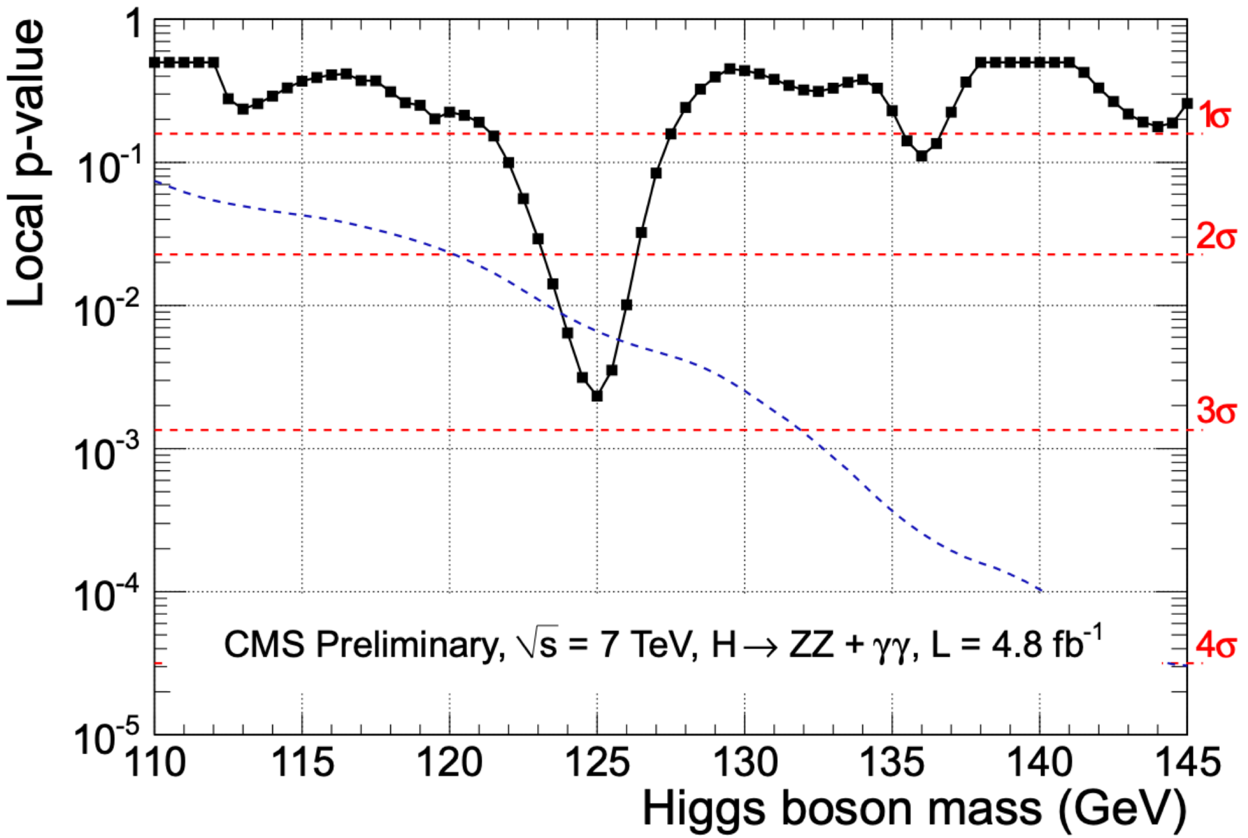
“interesting fluctuations” around masses of **124 to 126** GeV

- **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)
CERN Director General





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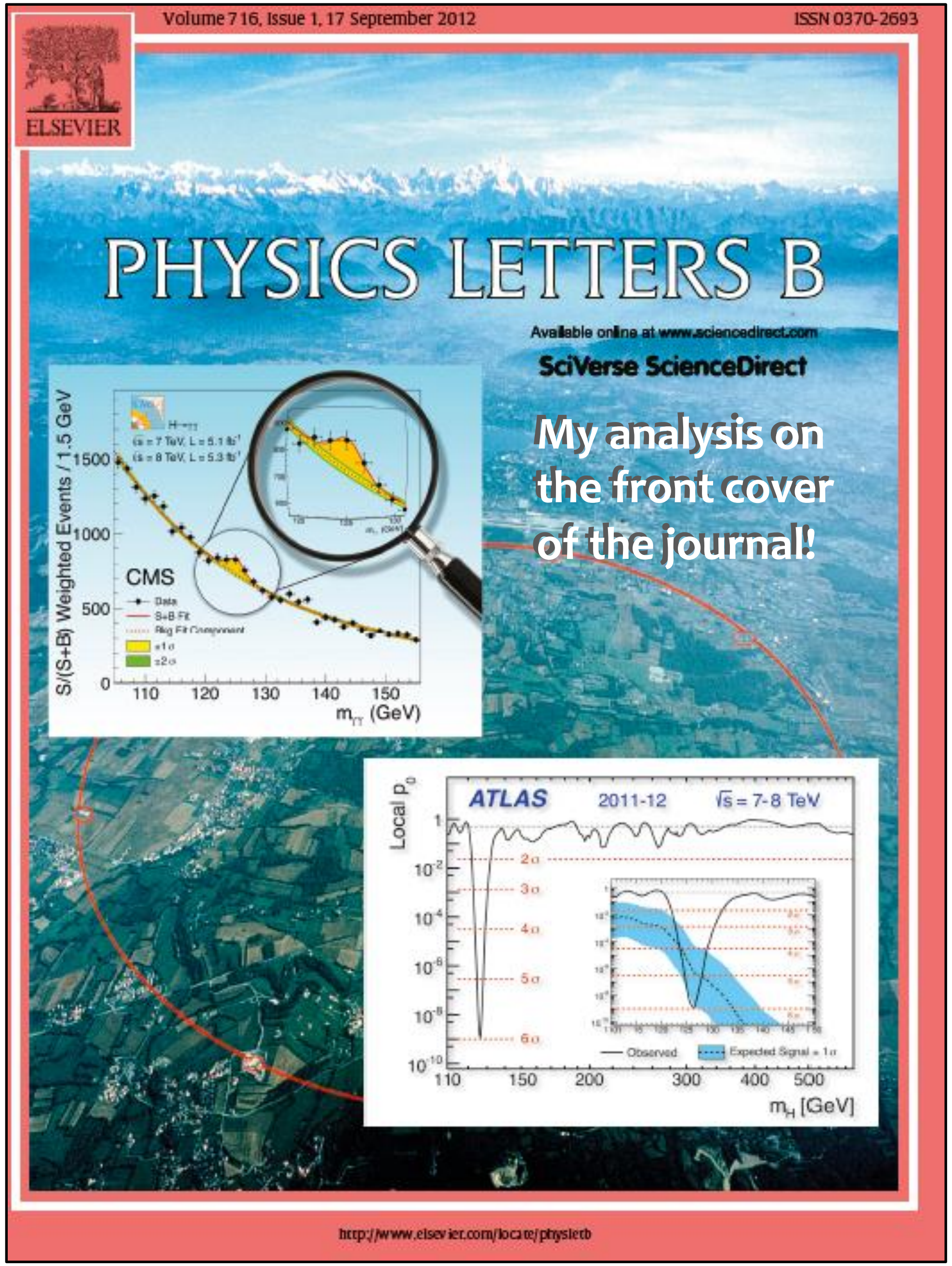
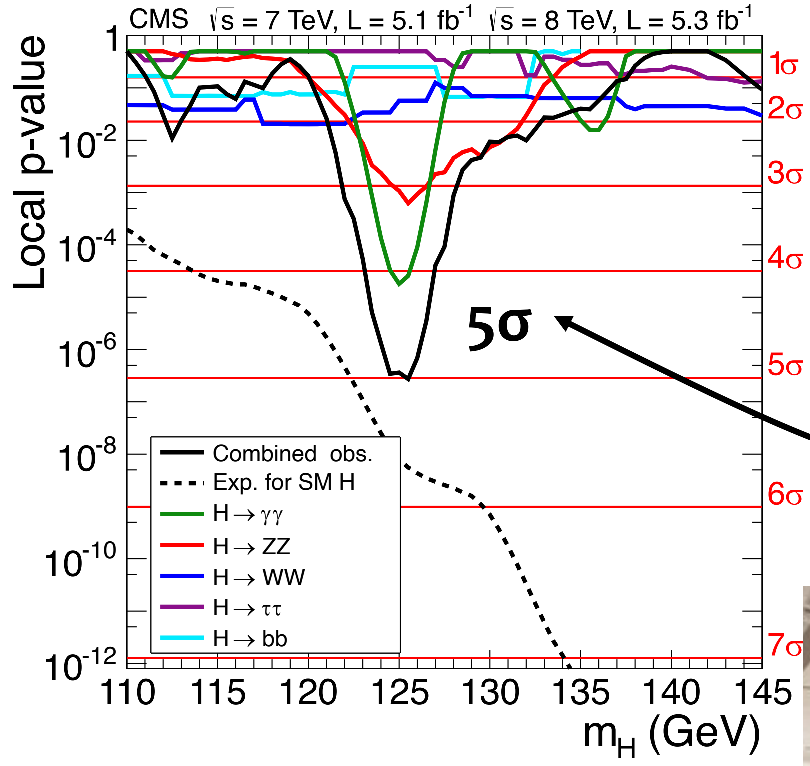
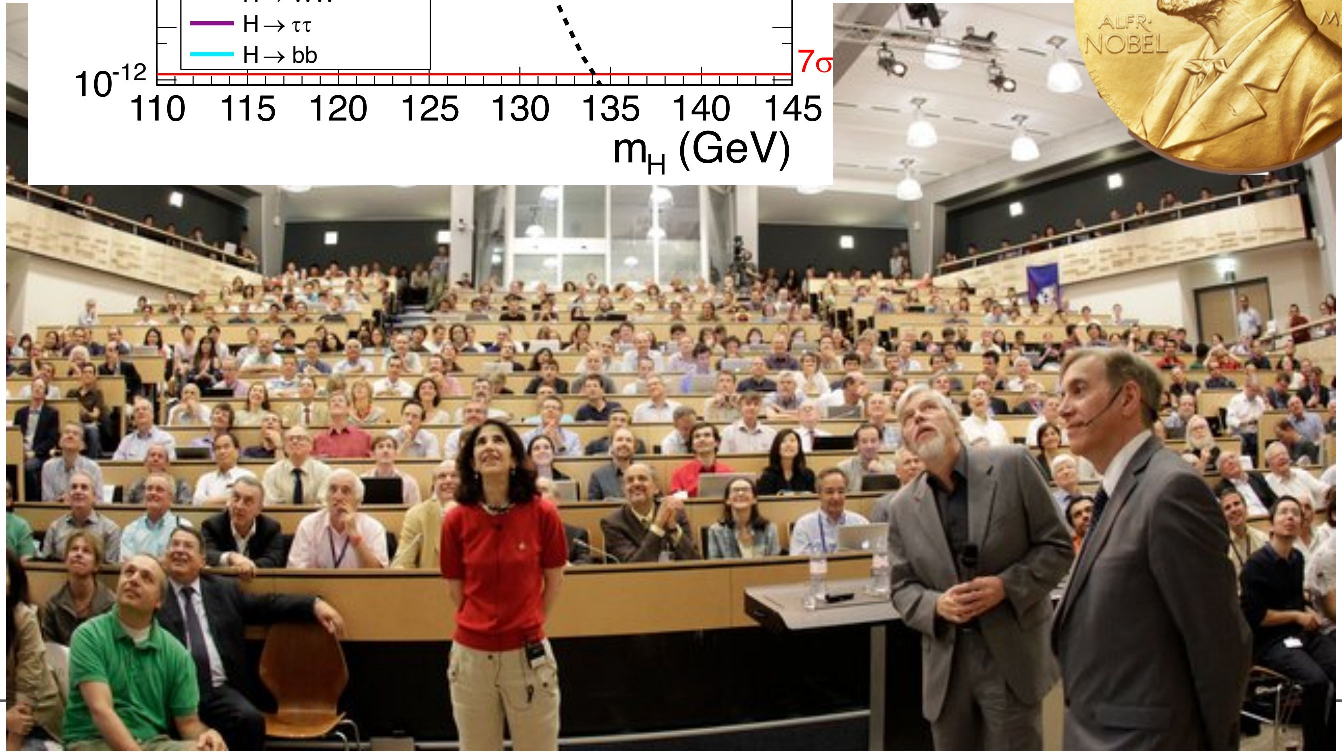
N. Wardle (8th June)
PhD Student



July 4th 2012

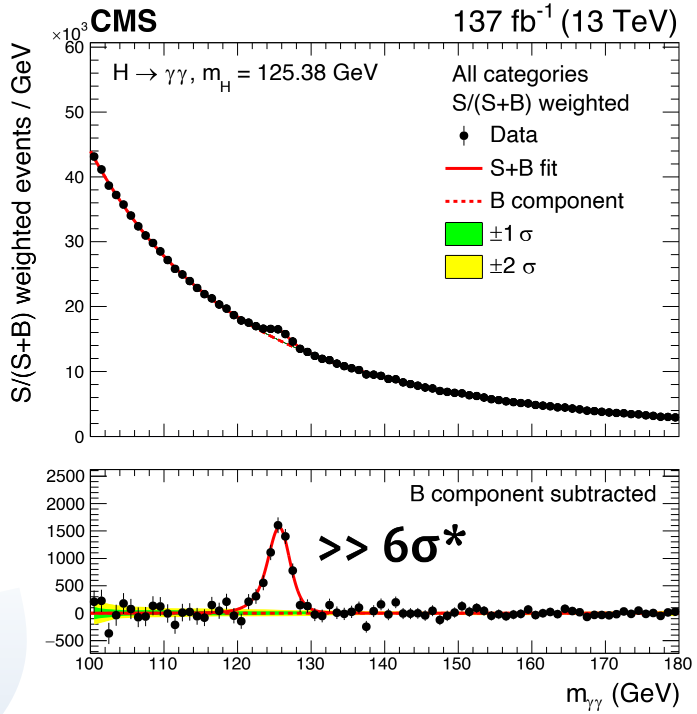


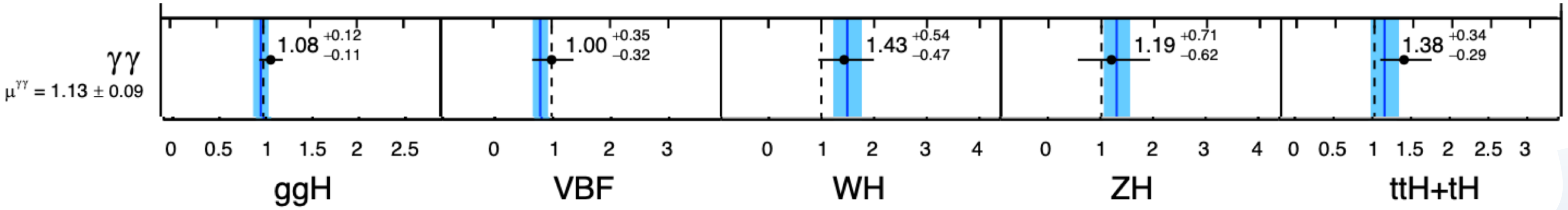


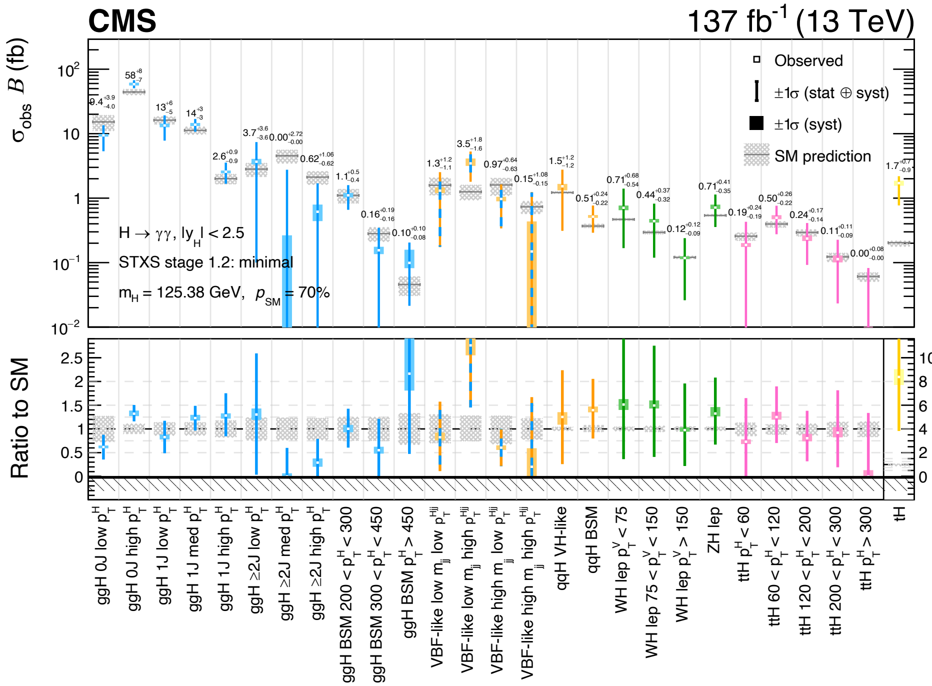
H→γγ channel a big factor in the discovery!

More data → more to study

10 years later and the H→γγ channel is still exciting to me!

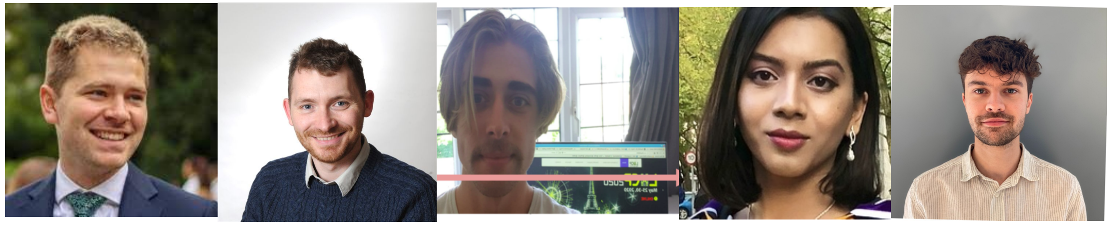






More data

...



...

Imperial HEPP PhD students still don't know the meaning of the word ***simple***

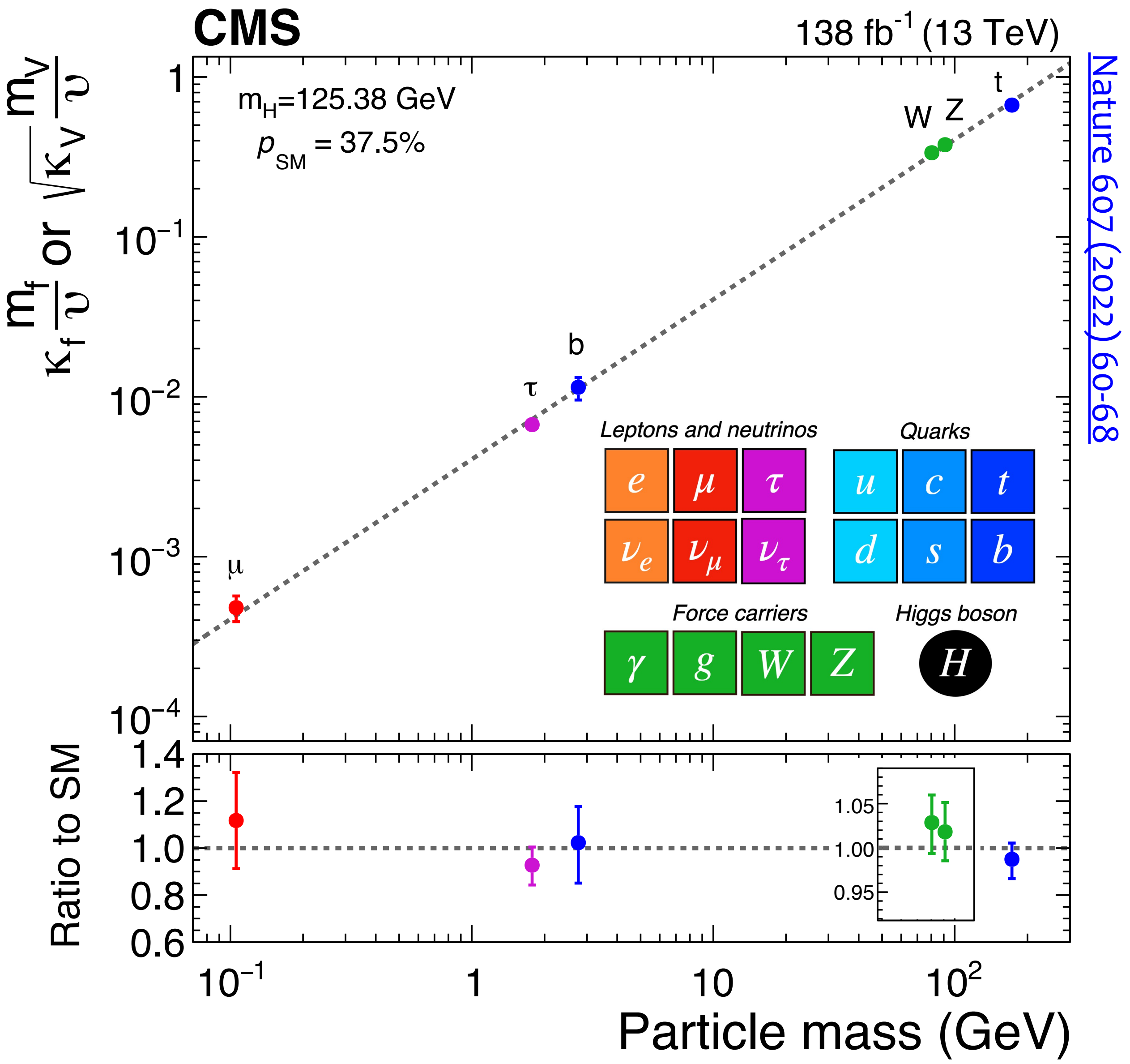
* By now you are more likely to dial a random UK mobile number and have Peter Higgs pick up than this signal being a background fluctuation

More than just H→γγ

Seeing the full picture of the Higgs boson is a huge computational challenge!

~850 channels (categories for data each with 100s-1000s of events) with varying signal-to-noise ratios

~9500 parameters in the model to fit



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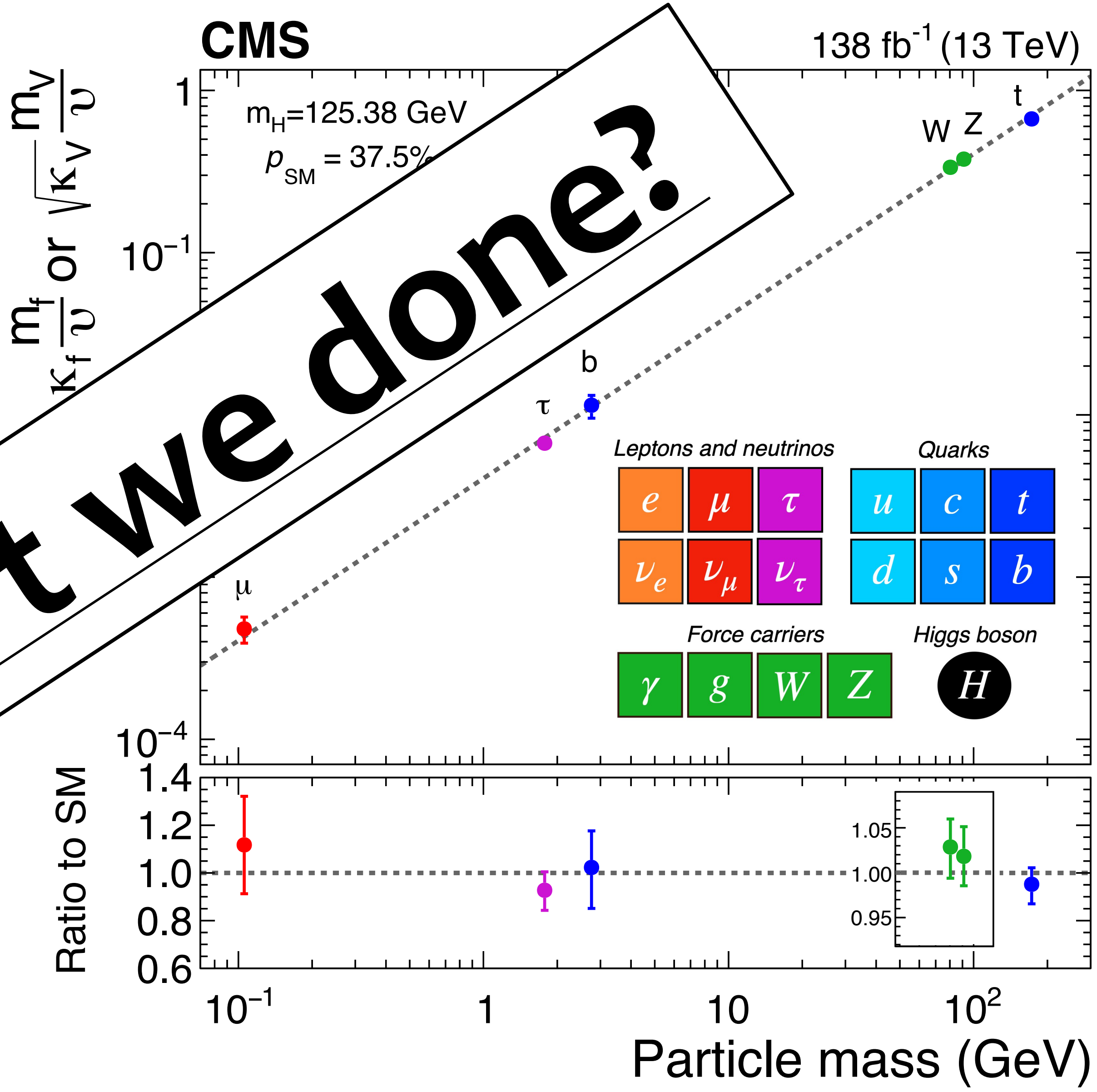
So, aren't we done?

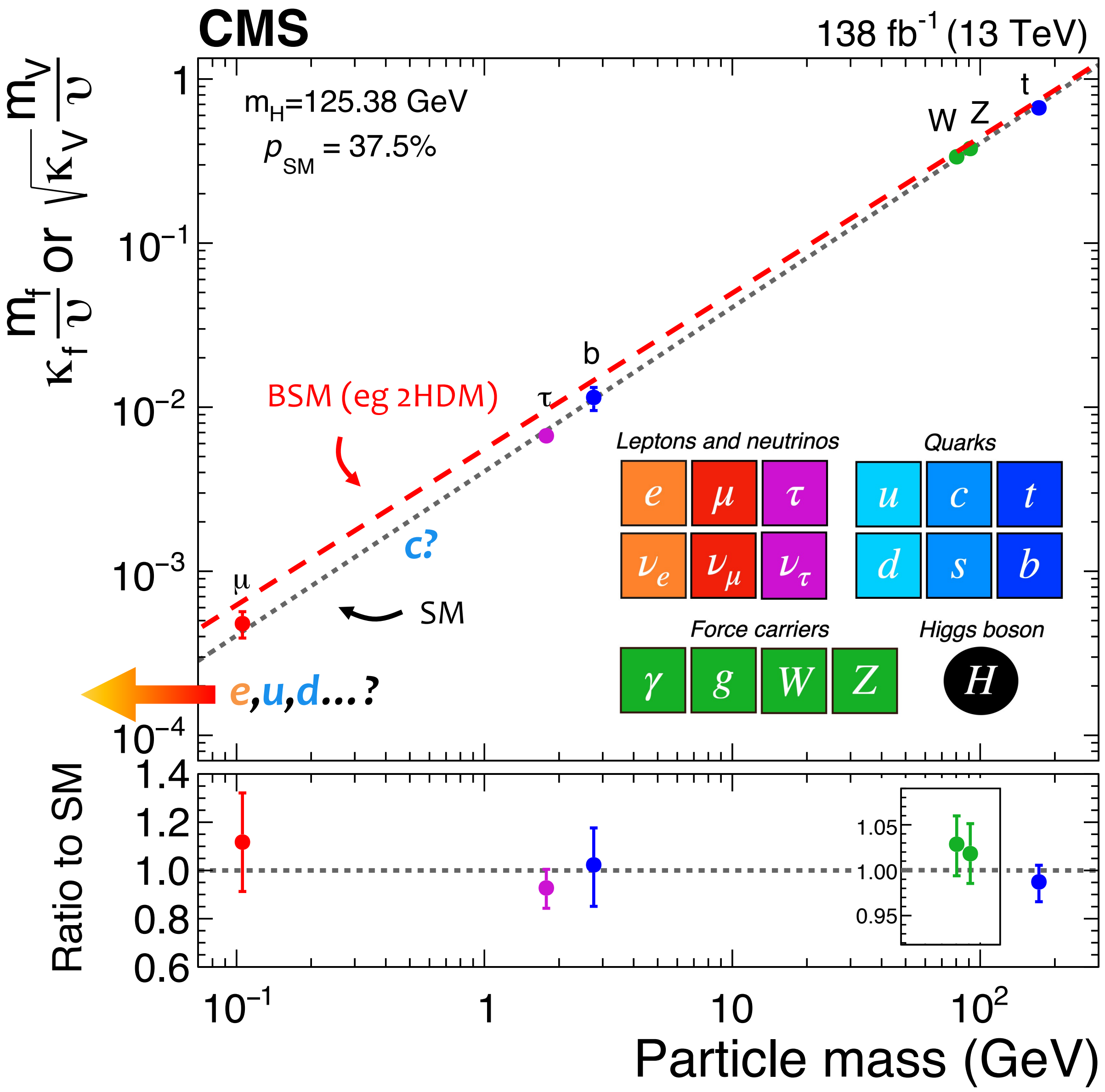


Nature 607 (2022) 60-68

So, we aren't 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 ?**



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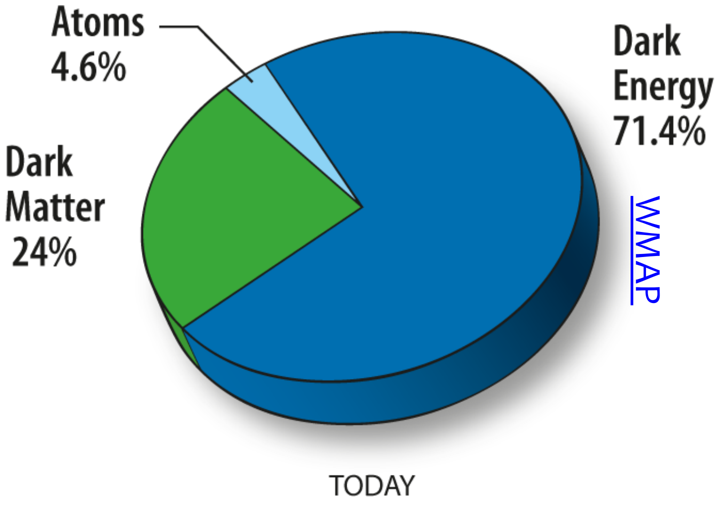
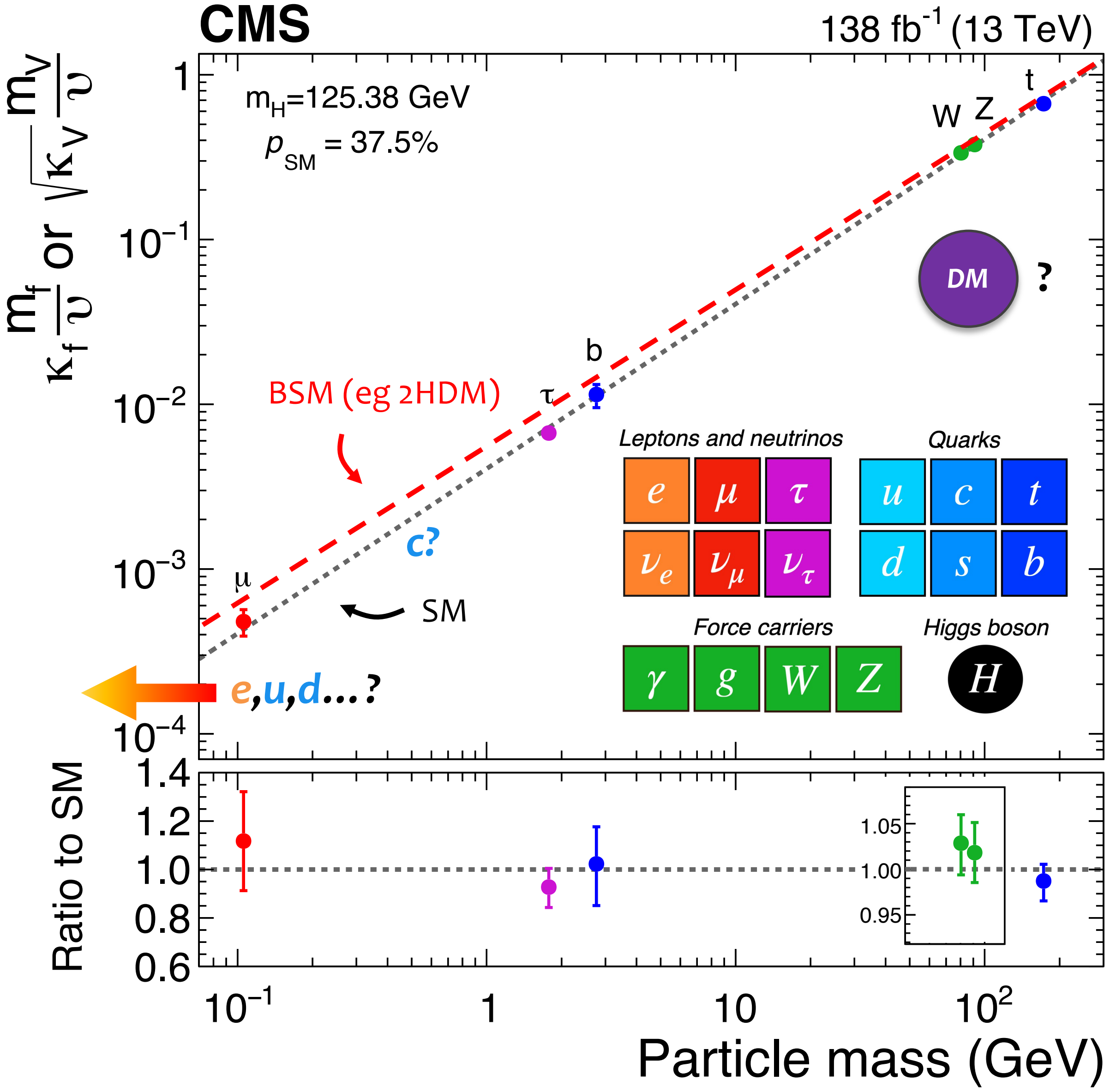
- **What does Dark Matter (DM) fit in ?**



[WMAP]



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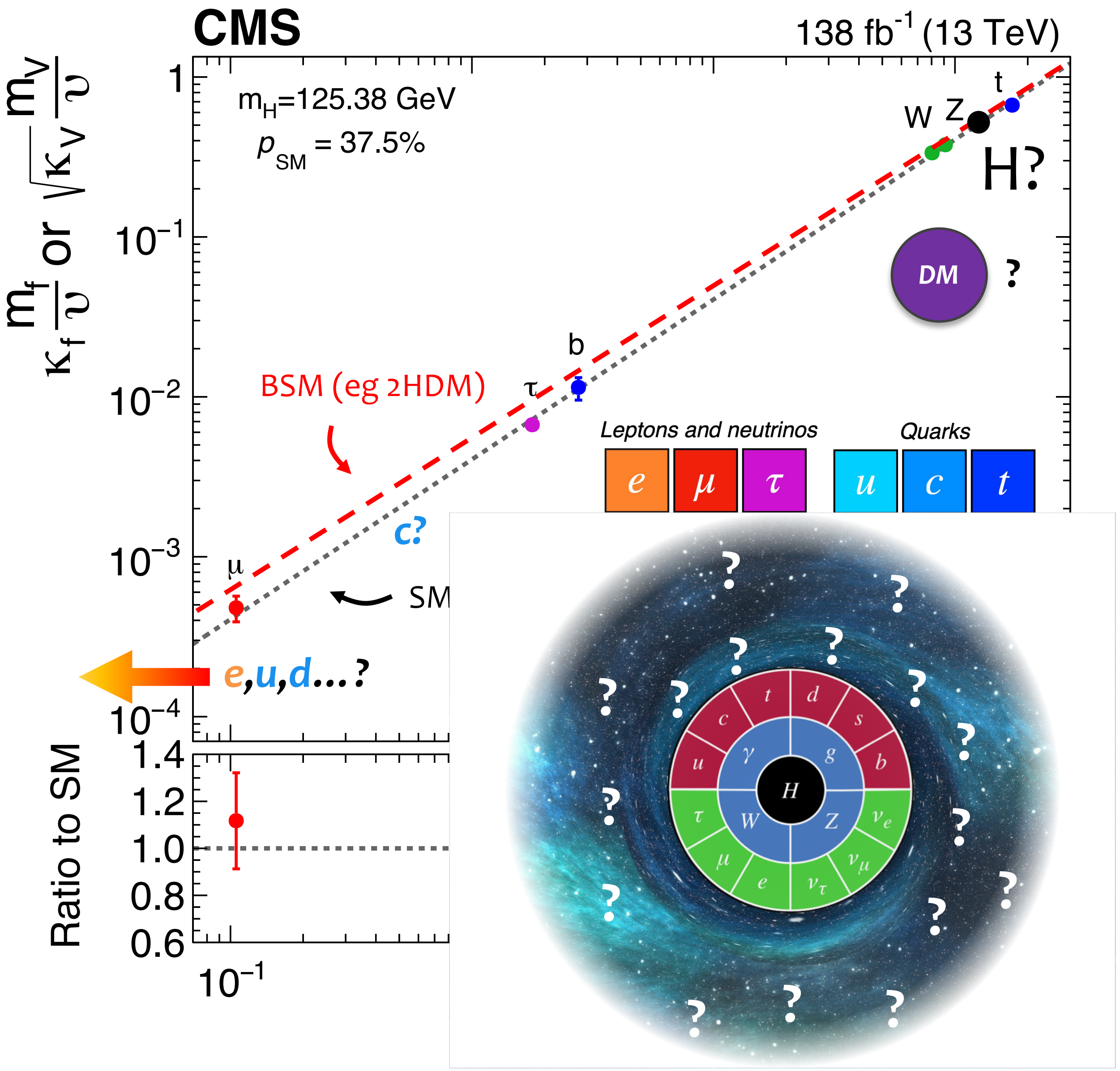
The **Higgs boson** was the **missing piece of the SM** and we've had it now for 10 years …

- **Is the Higgs sector SM-like ?**
- **What does Dark Matter (DM) fit in ?**
- **Why is there more matter in the universe? – can the Higgs potential explain it?**

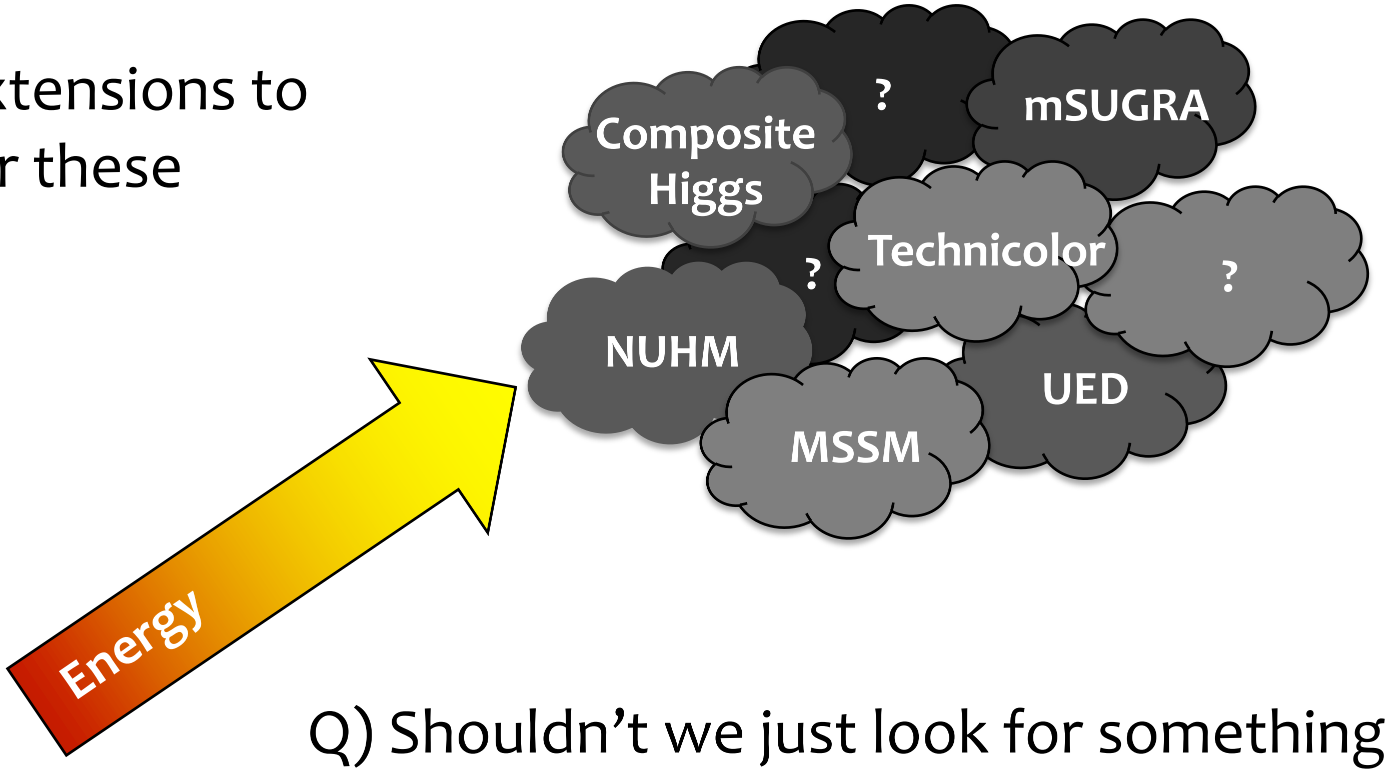


These are **fundamental questions** in physics

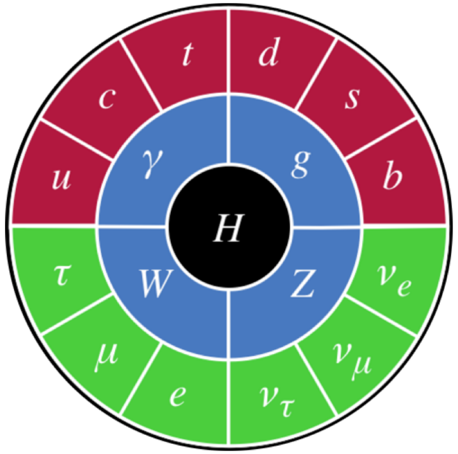
How can we solve them?

Many possible extensions to the SM to answer these questions

New Physics models



Standard Model

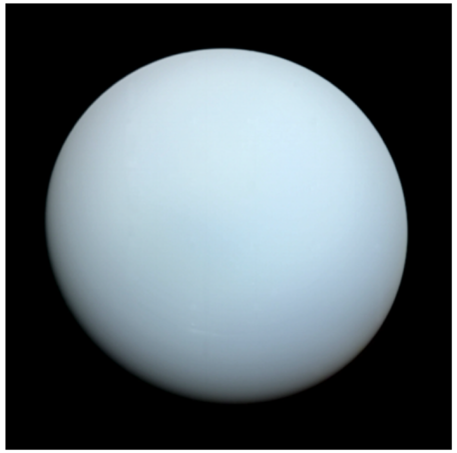


Q) Shouldn’t we just look for something else and move on from the Higgs boson?

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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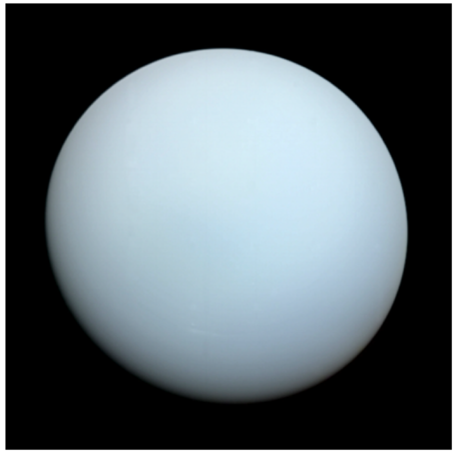

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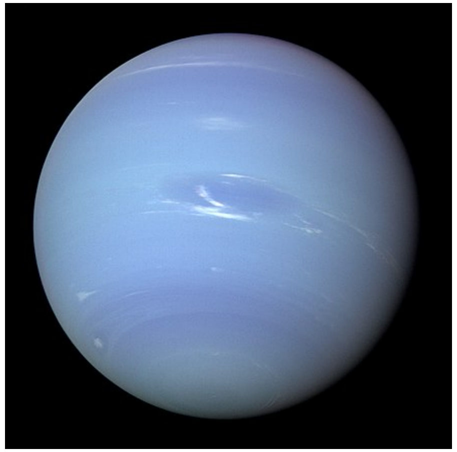
Le Verrier, Galle, d'Arrest 1846



Neptune discovered with 1°
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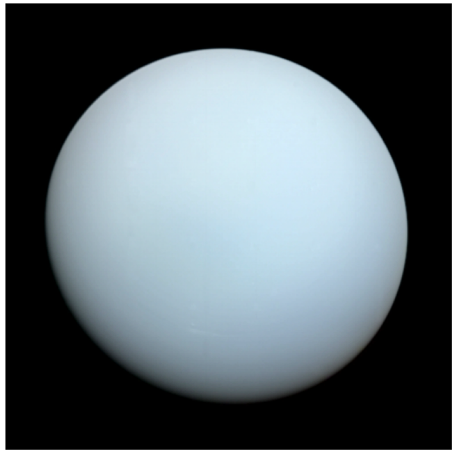

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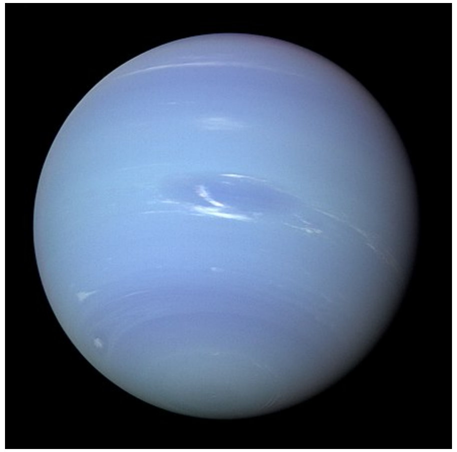

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Measurements of Mercury’s orbit reveals
43 arcseconds/century anomaly
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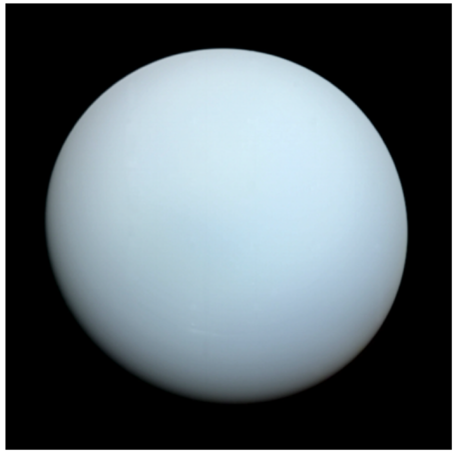

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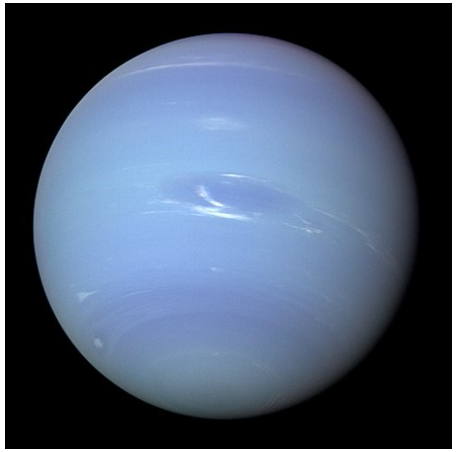
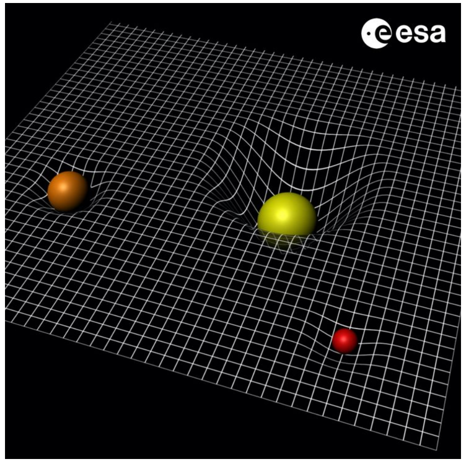


Le Verrier 1859, Einstein 1915



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**)

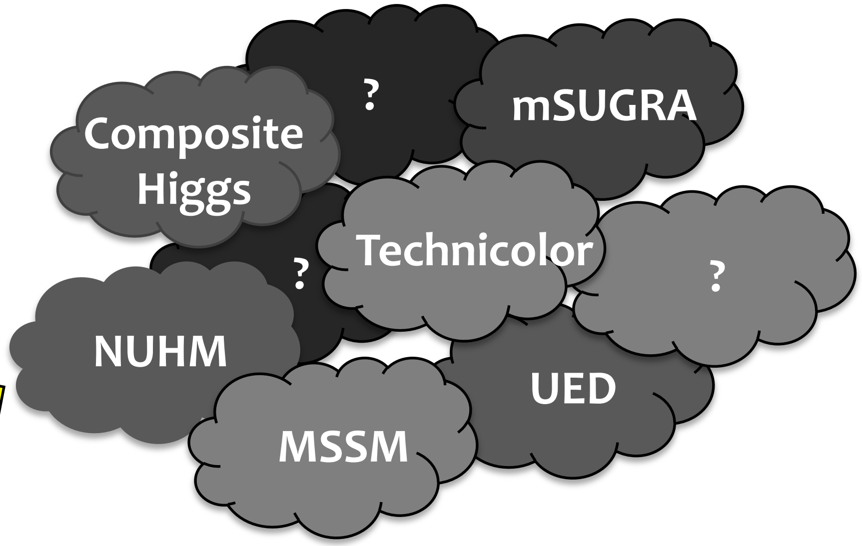
Slide heavily inspired by J. Liu (Cambridge)

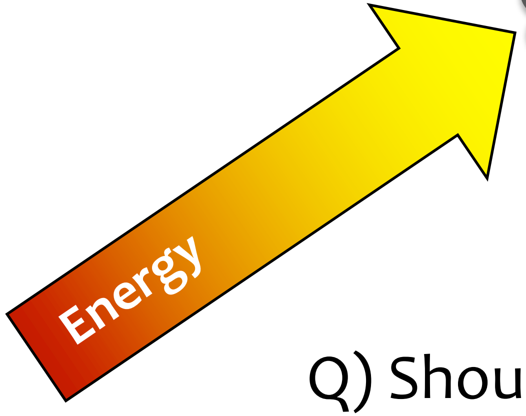
…History has a habit of repeating itself 🤞 …

How can we solve them?

Many possible extensions to the SM to answer these questions

New Physics models





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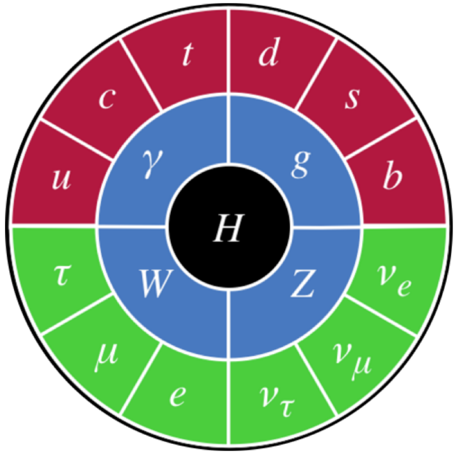


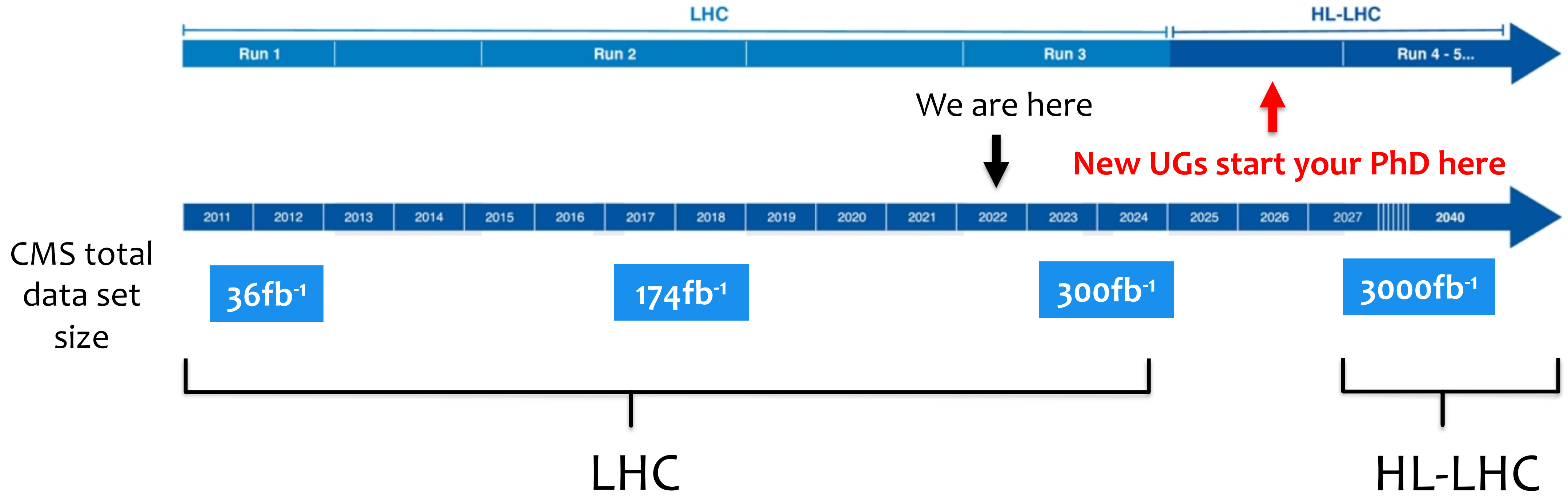
Q) Shouldn't we just look for something else and move on from the Higgs boson?

A) No! The **Higgs boson** is a unique tool to search for **physics Beyond the SM** (BSM). Precision measurements are a key to new discoveries!

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** !

Precision Higgs measurements for discovery

Higgs boson
discovery **(2012)**

Precision Higgs measurements for discovery

Higgs boson discovery **(2012)**

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

Time/precision

Precision Higgs measurements for discovery

Higgs boson discovery **(2012)**

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

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

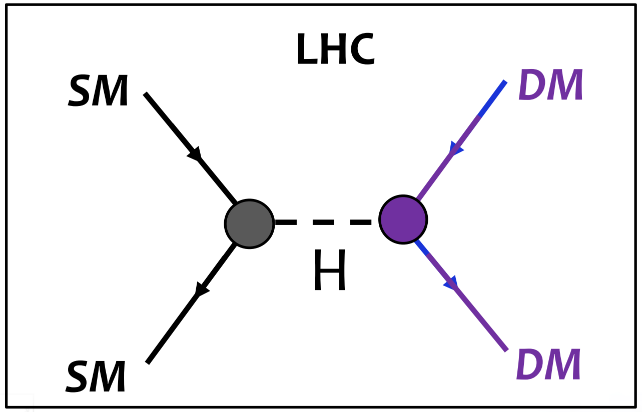
Time/precision

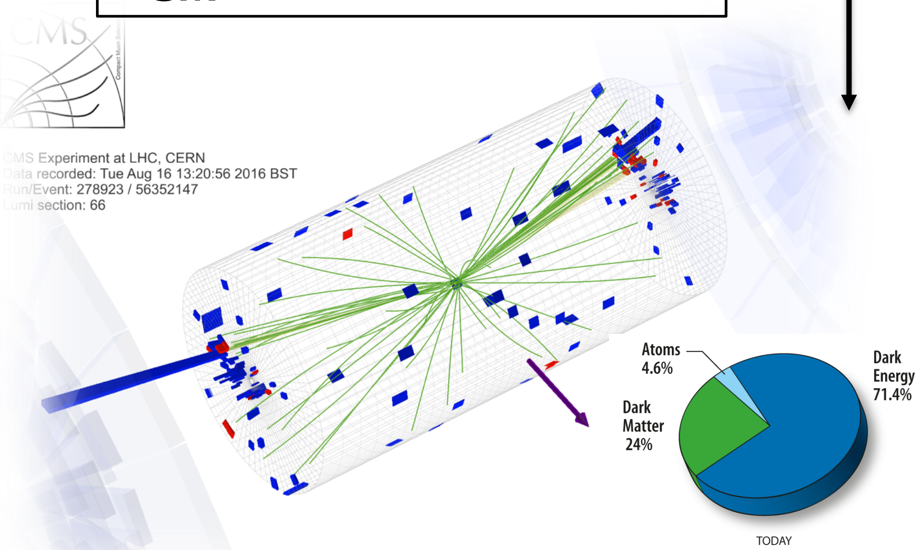
Thanks!

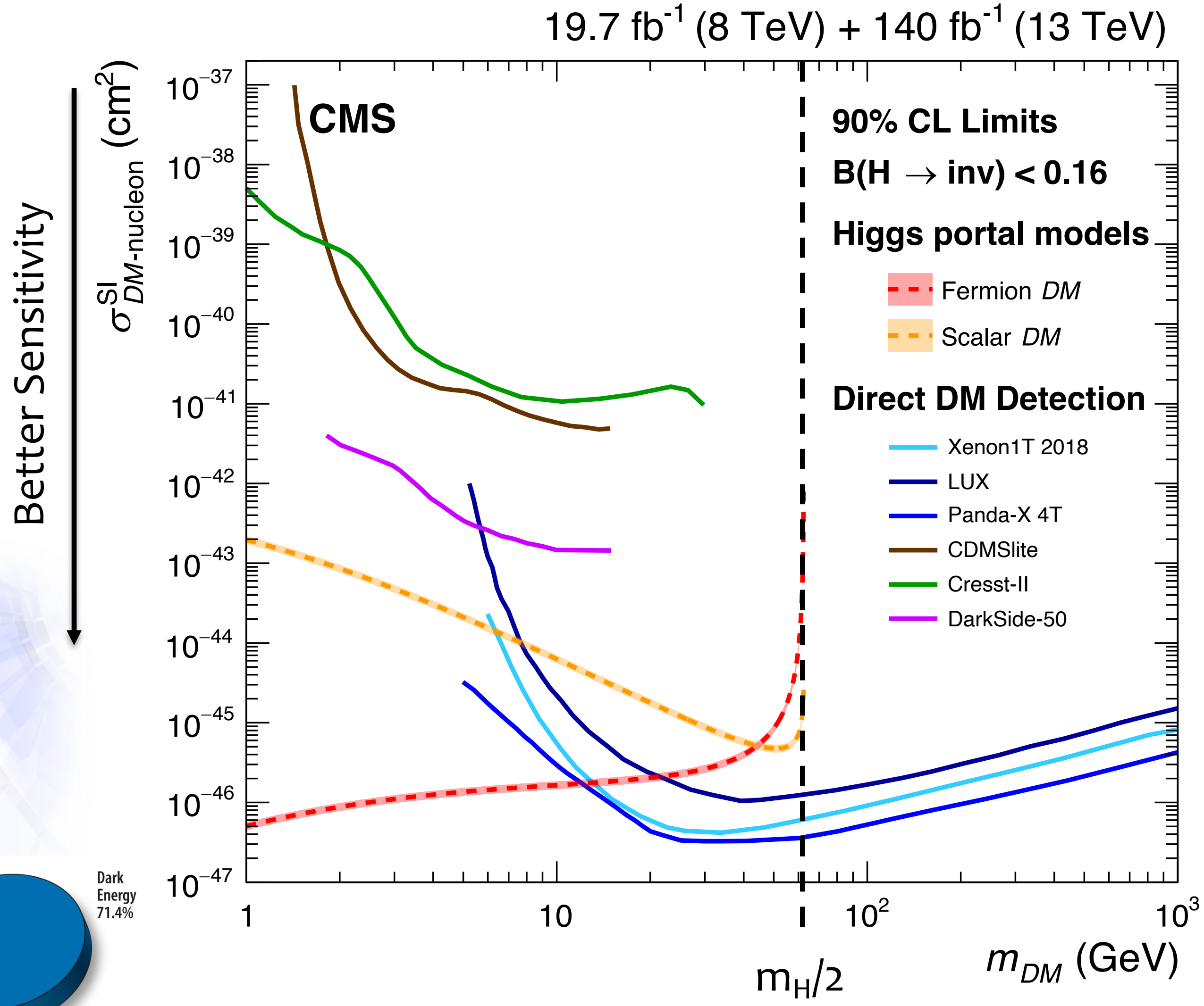
Backup Slides

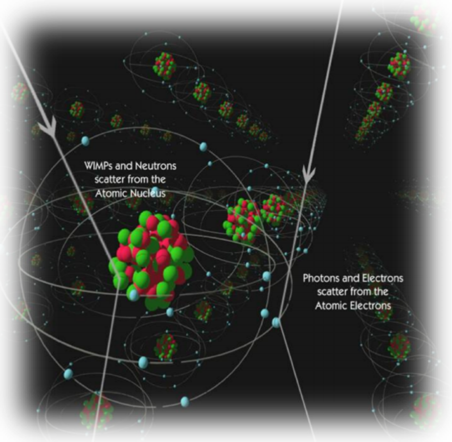
Higgs decays to new particles

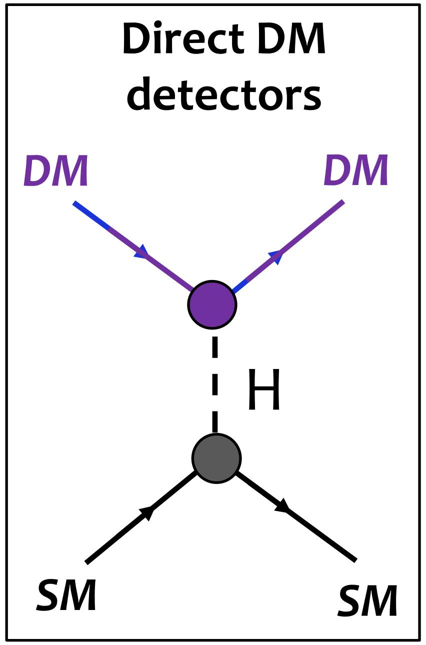
Invisible Higgs branching fraction measurements complementary to direct searches for Dark Matter!







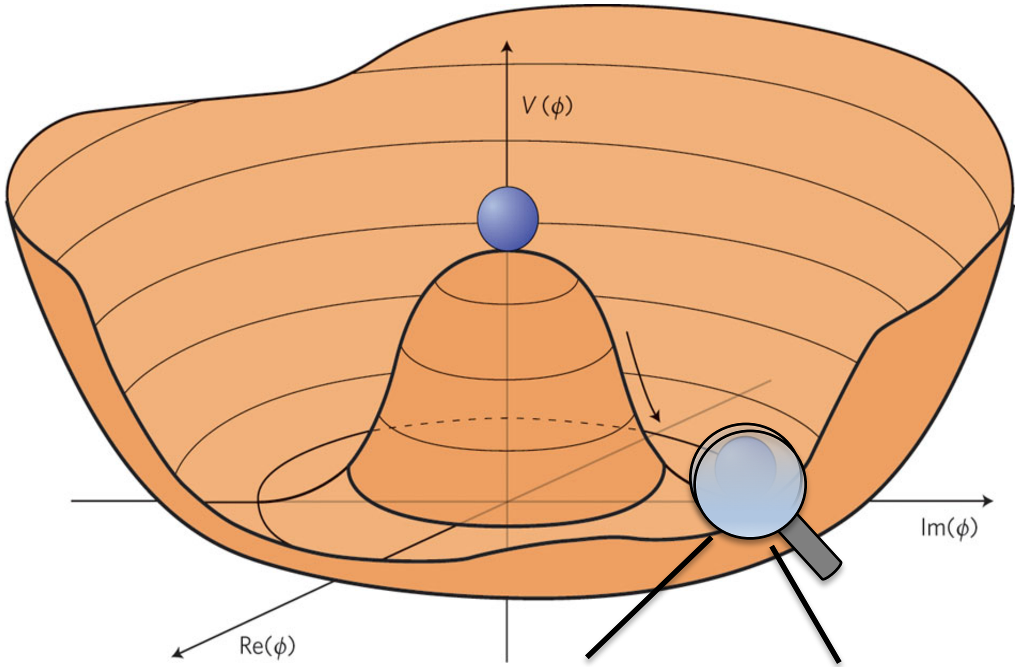




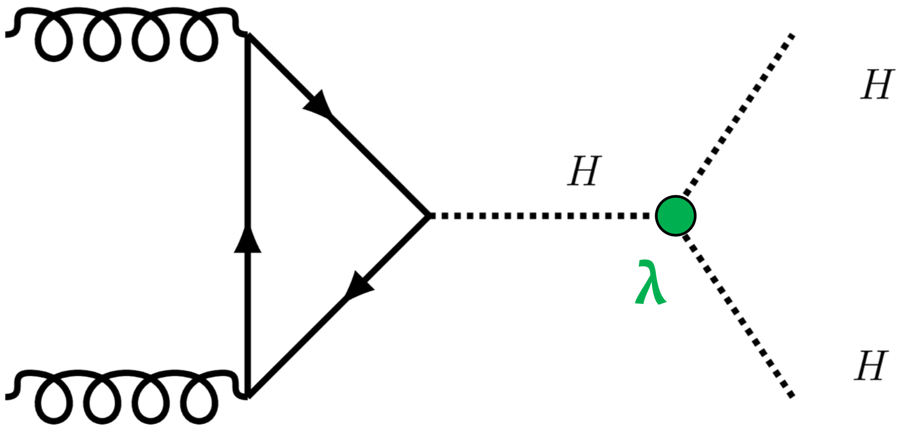
Higgs boson self-coupling

SM Higgs potential includes ***H*³** terms

"self-coupling" generates
Higgs-Higgs interactions



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



Search is underway for
production of events with
2 Higgs bosons at the LHC!

Higgs boson self-coupling

SM Higgs potential includes ***H*³** terms

"self-coupling" generates
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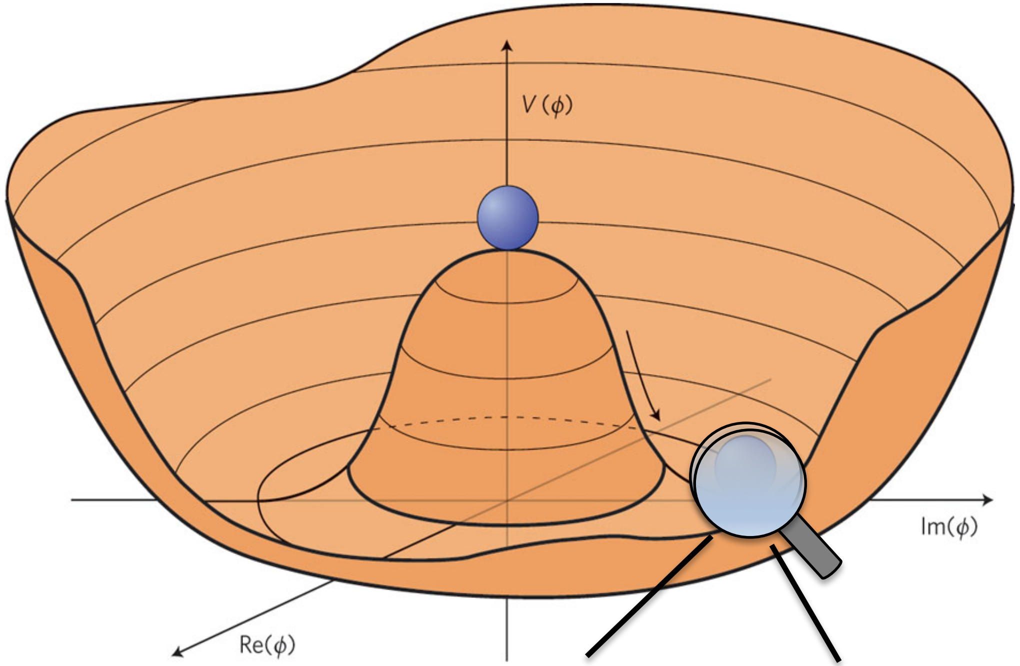
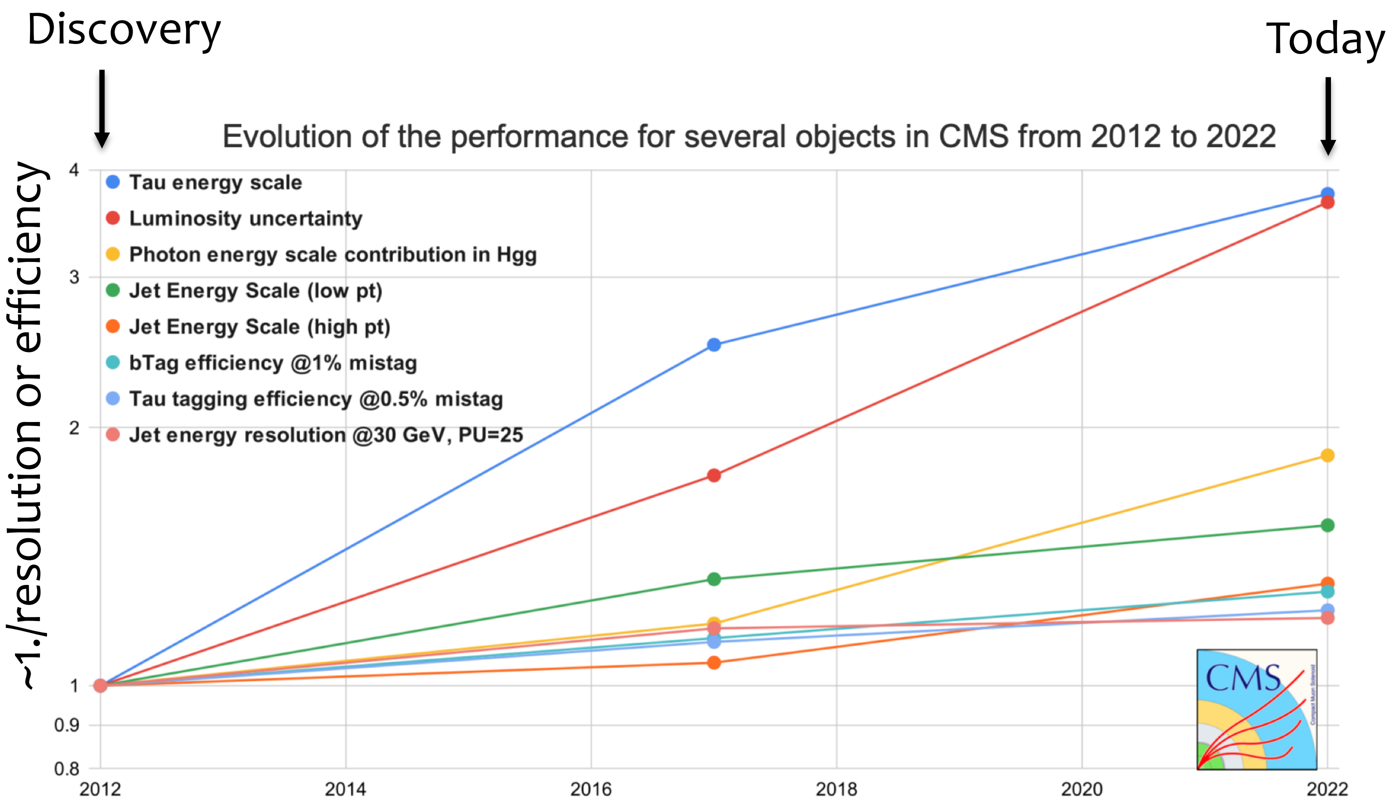
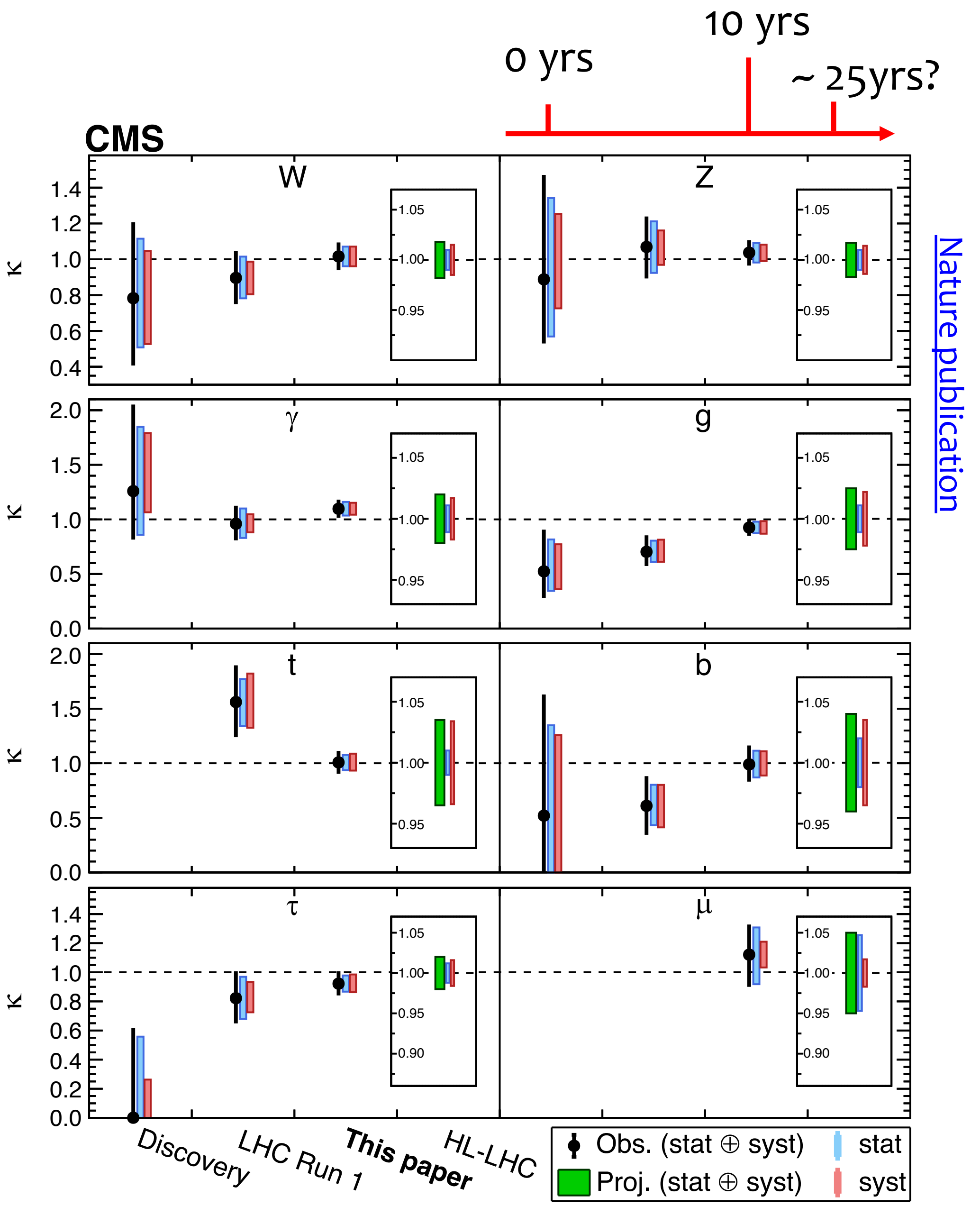


$$V(H) = \frac{m_H^2}{2} H^2 + \lambda v H^3 + \lambda H^4$$

Higgs couplings @ HL-LHC

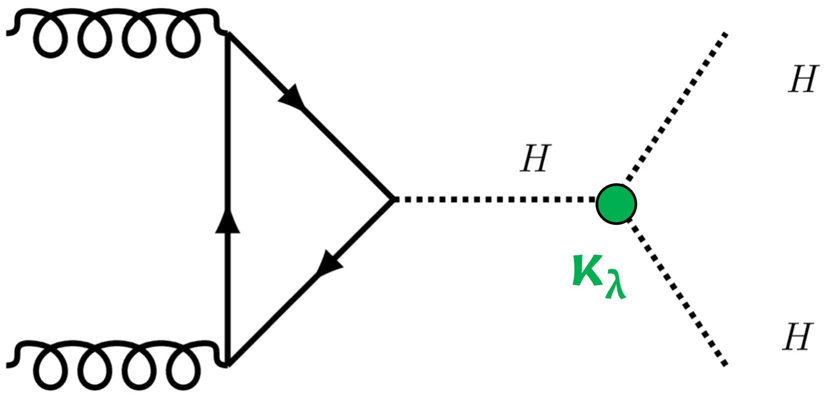
Precision measurements require more than just more data
→ Improvements in reconstruction techniques & calibrations will be needed for few % precision couplings @HL-LHC



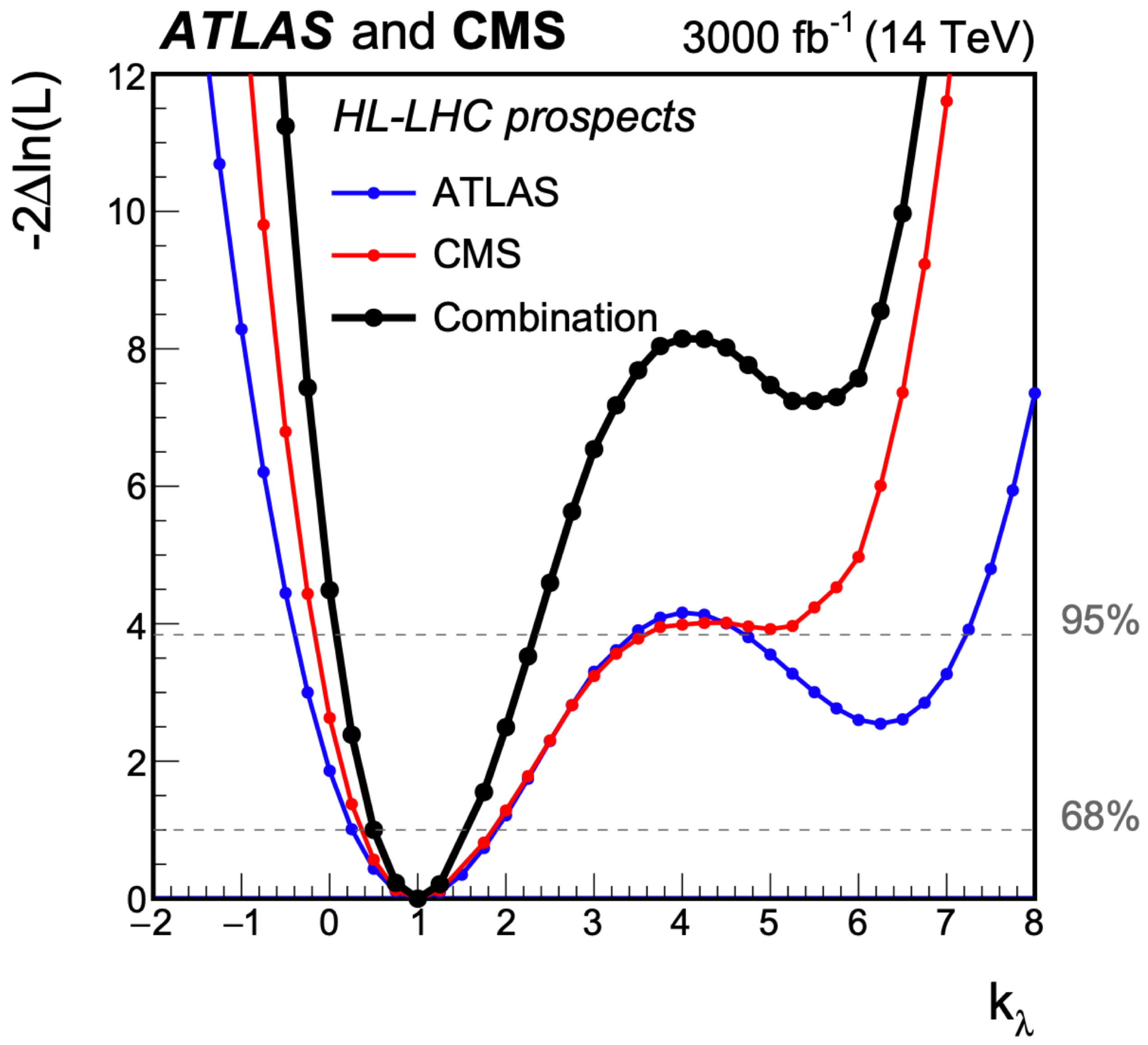


Higgs boson self-coupling @ HL-LHC

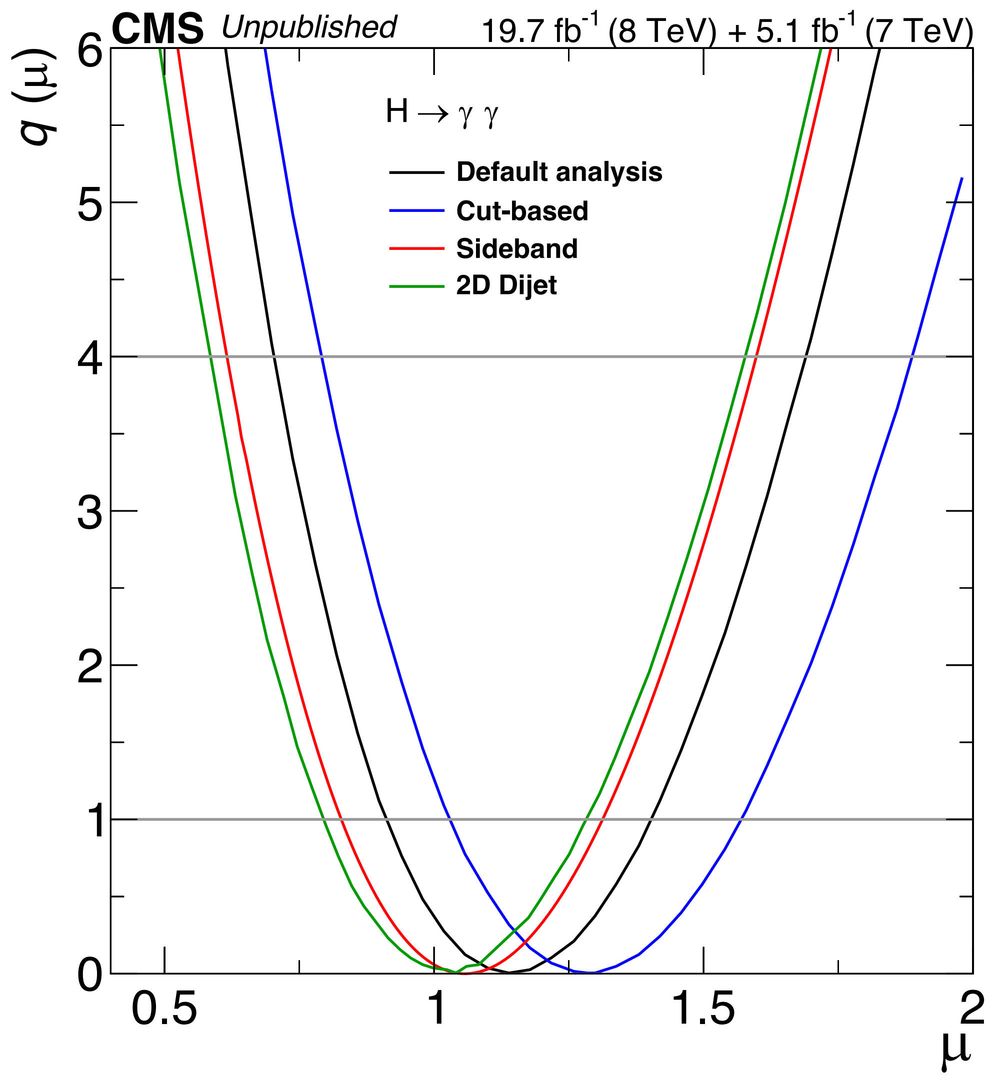
Observation of double-Higgs production is a major goal of the HL-LHC



→ Combined searches for HH production to expected approach **~50% uncertainty on self-coupling measurement**



A little obsessive about making sure …

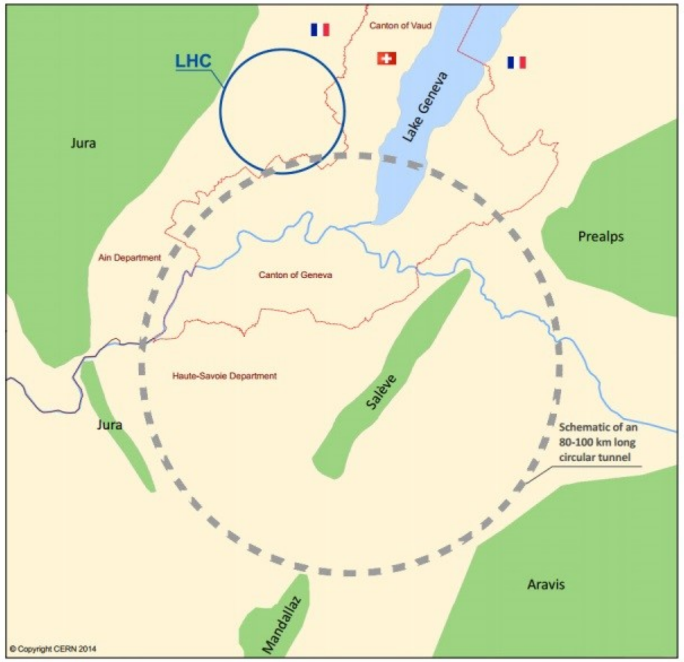


Just one method is not enough to convince us we had gotten it right!

- **4 different analyses** developed to cross-check various aspects of the discovery with H→γγ!

Higgs beyond the HL-LHC?

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

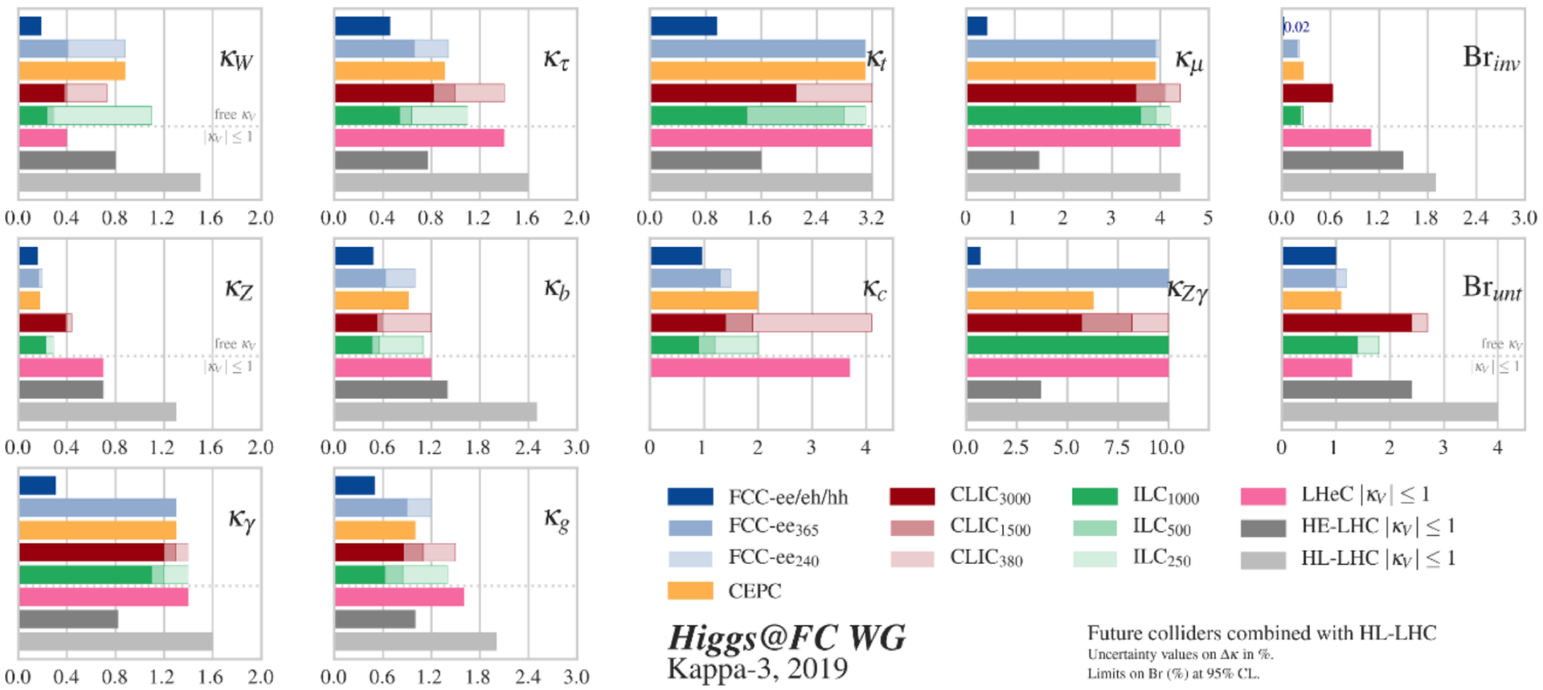


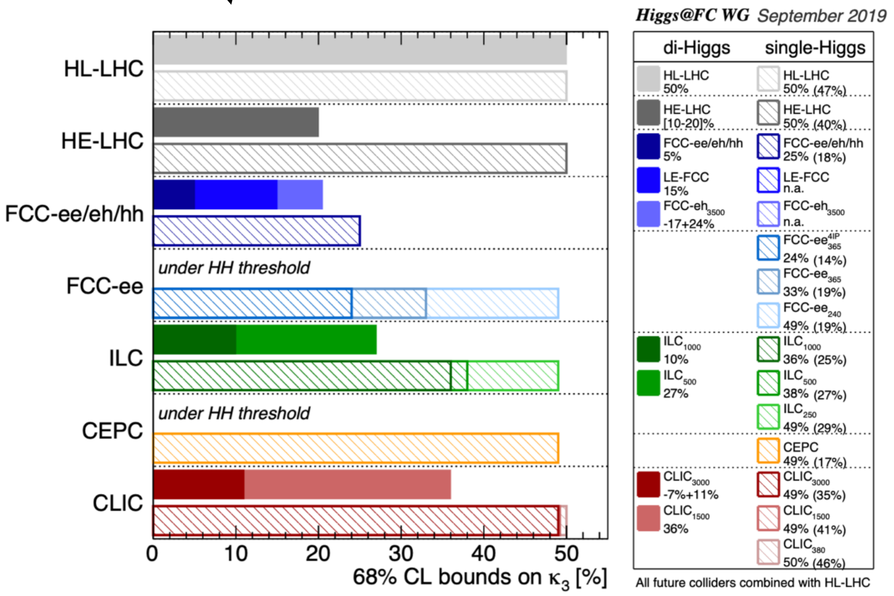
*"Europe, …, should **investigate the technical and financial feasibility** of a **future hadron collider** at CERN with a centre-of-mass energy of **at least 100 TeV** …*

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





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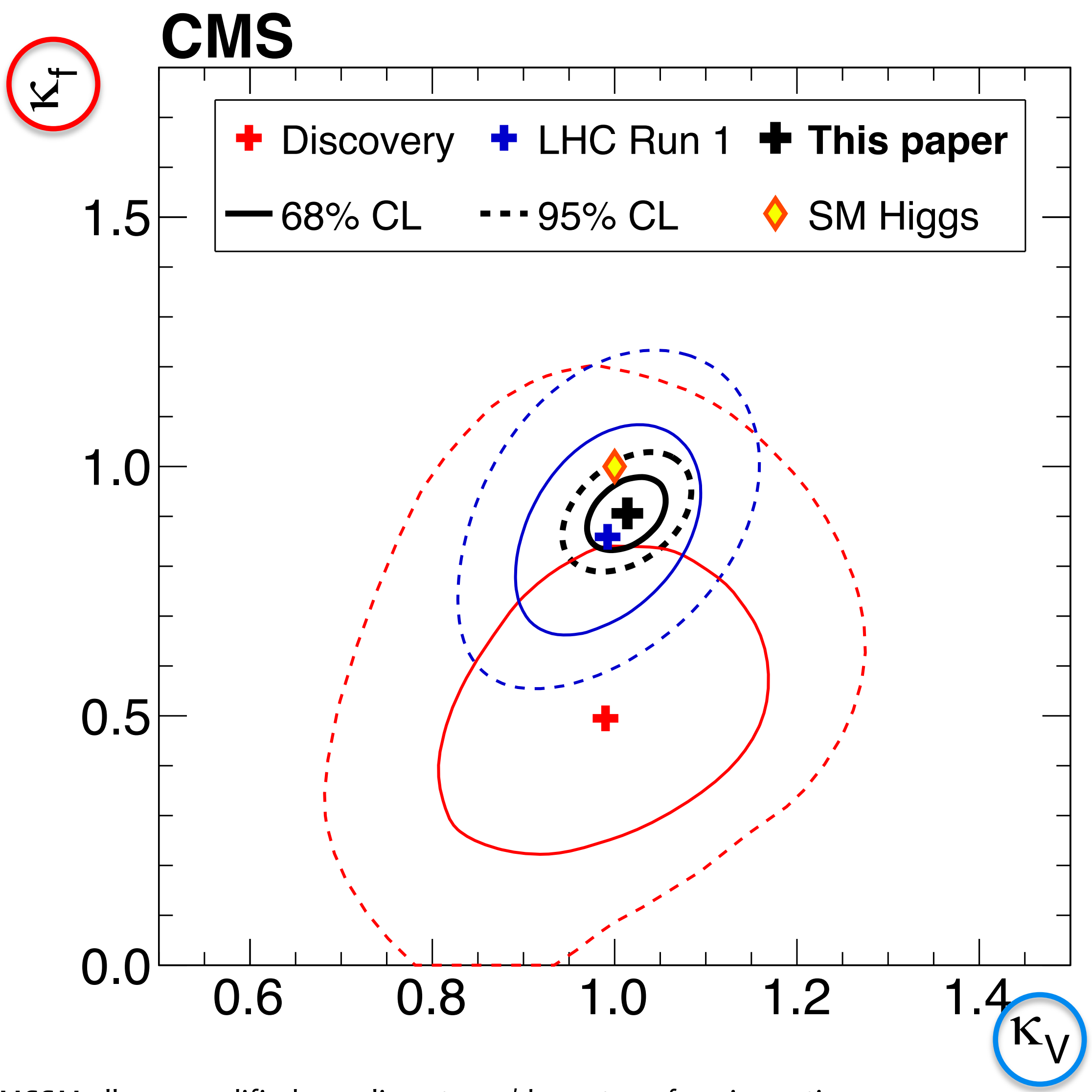
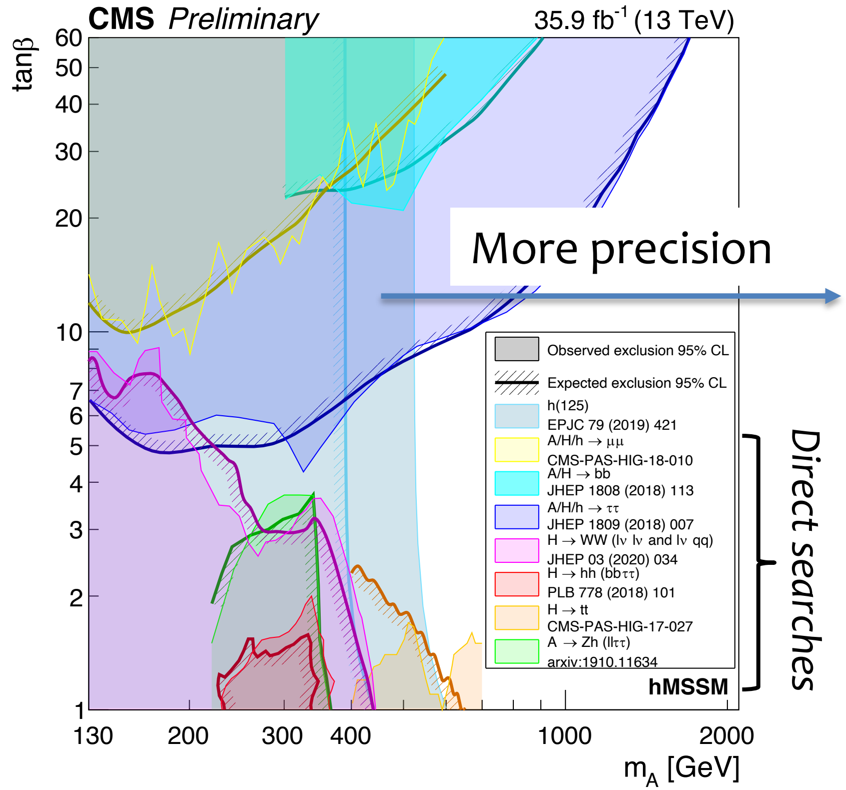
Higgs couplings for BSM physics



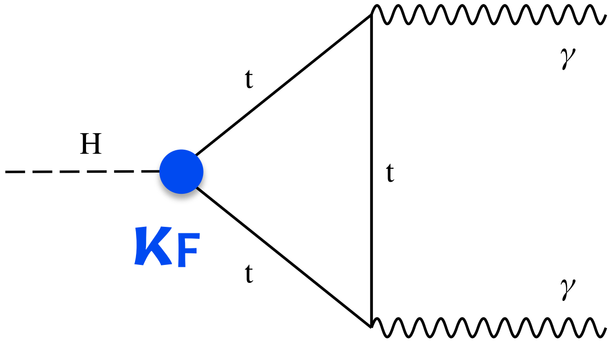
In extended Higgs sectors (e.g two 2HDM), couplings to vector bosons and fermions can be modified from SM

- → Measuring these couplings is a **direct probe of extended Higgs sector models**
- → **Complementary** approach **to direct searches*** for additional Higgs bosons

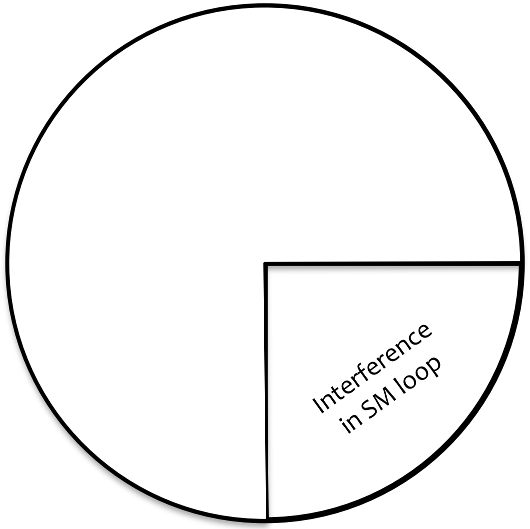


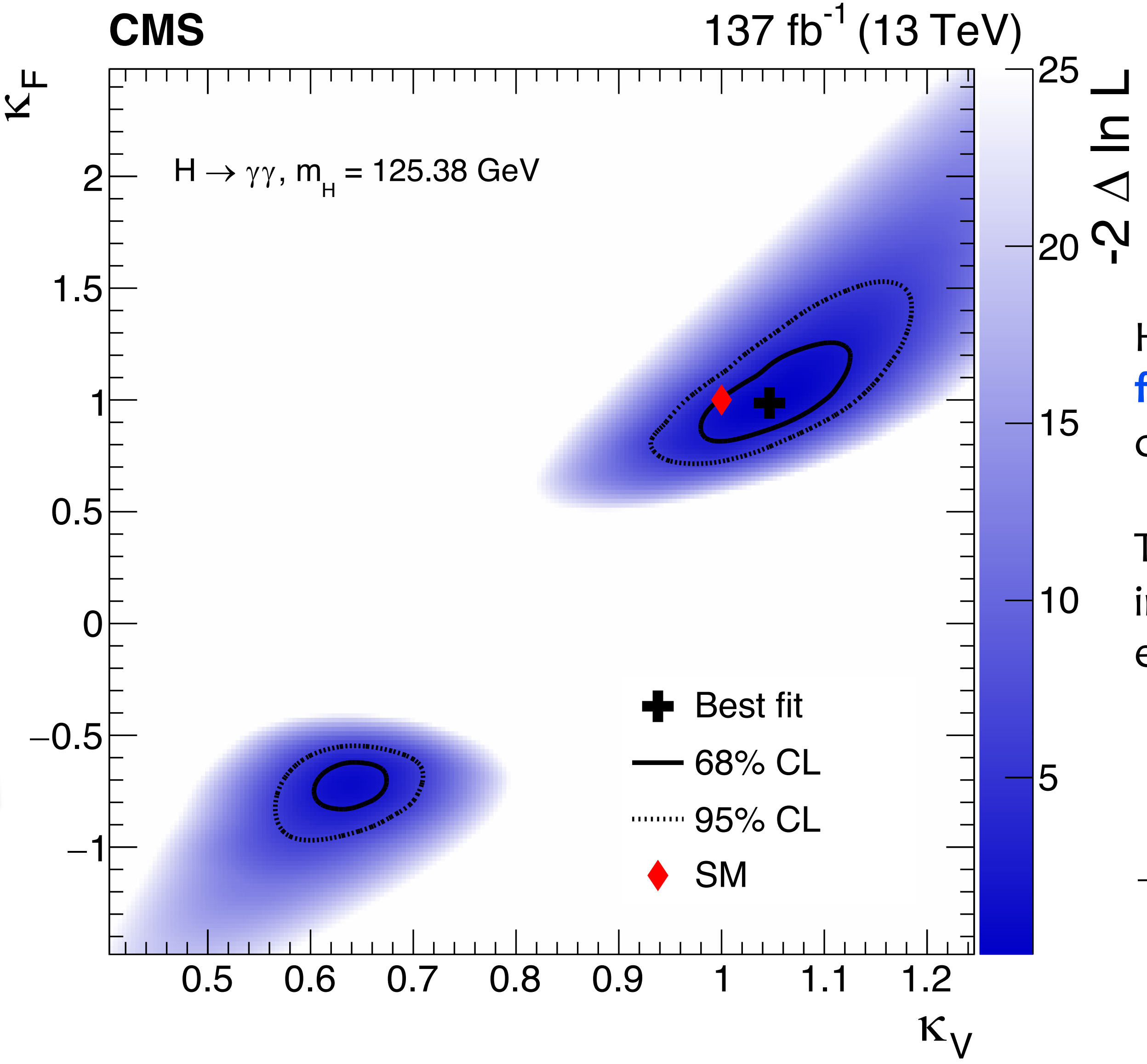
*hMSSM allows modified couplings to up/down type fermion ratio

H→γγ to probe BSM physics



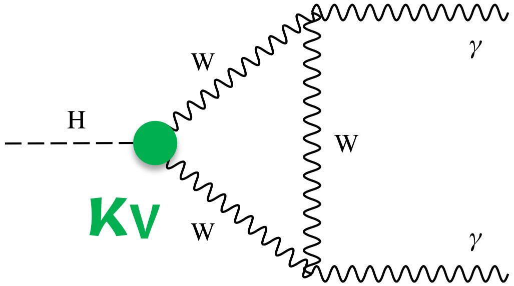
H→γγ useful features





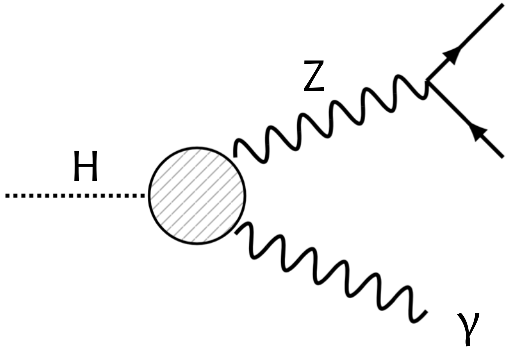
H→γγ decay sensitive to **fermion** and **vector boson** couplings

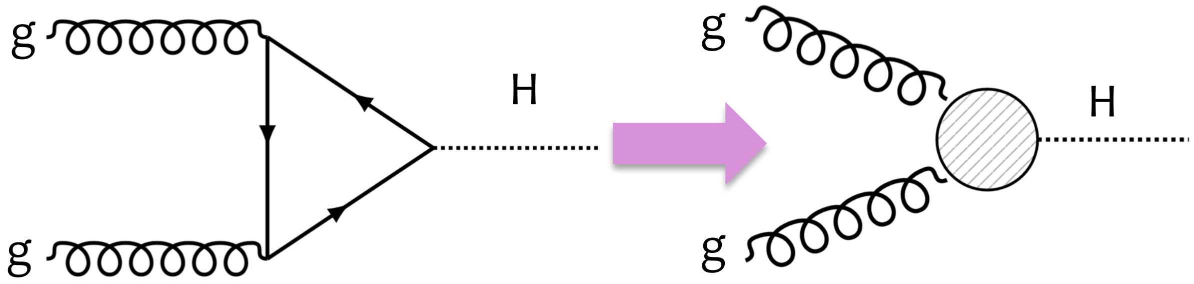
These couplings are modified in two-Higgs double model extensions to the SM



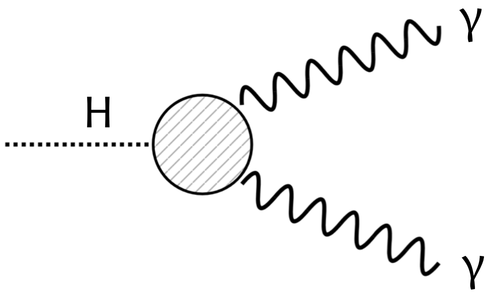
Effective couplings

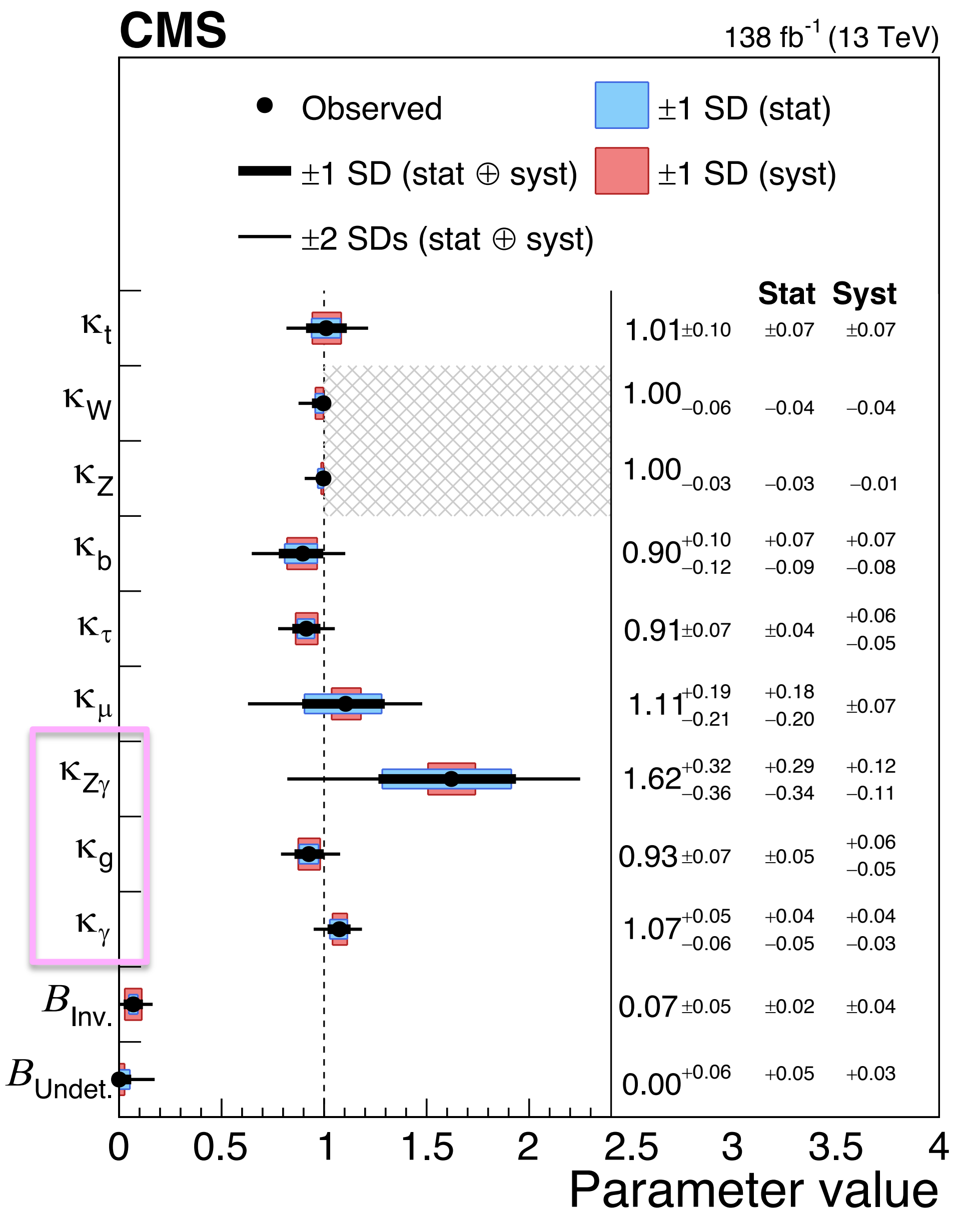
Higgs boson production and decay mechanisms that proceed by loops can be treated as effective couplings





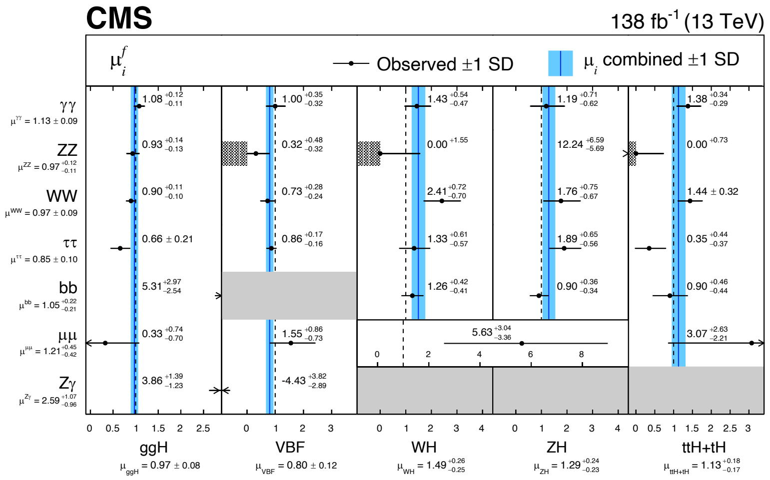
New heavy particles can appear in these loops leading to large deviation in the effective coupling:
H-Zγ, H-g, H-γ





Effective field theories

On-shell

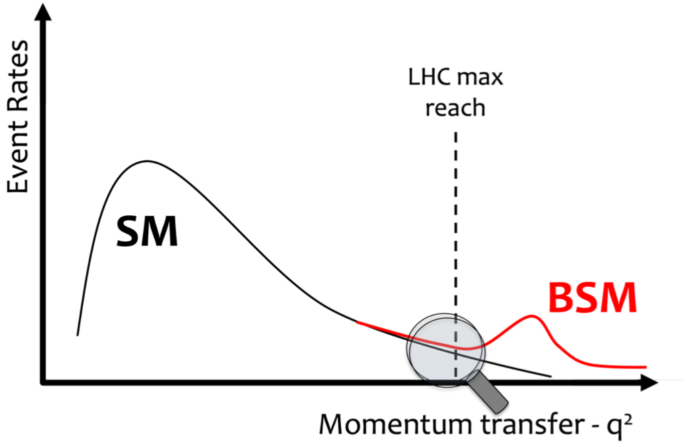


$$\delta \sim \left(\frac{v}{\Lambda}\right)^2$$

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

δ_μ = 1% → Λ ~ 2.5 TeV

Off-shell / large q^2



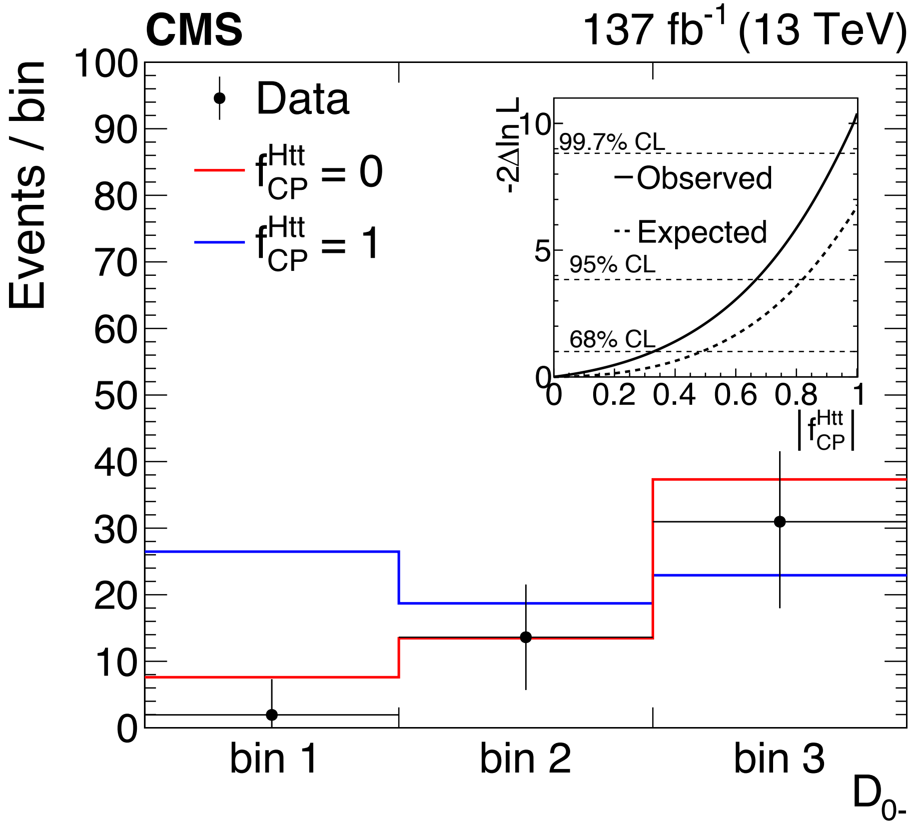
$$\delta \sim \left(\frac{q}{\Lambda}\right)^2$$

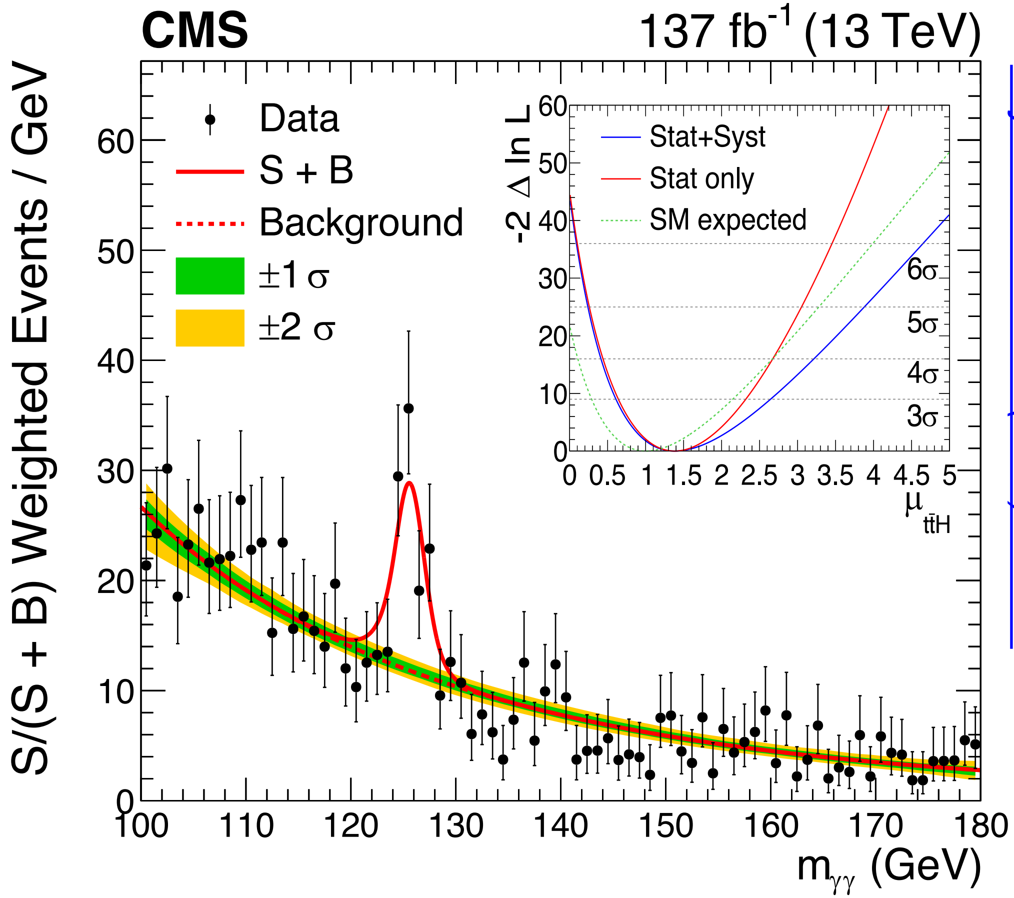
Differential: High momentum production sensitive to new physics

δ_σ = 15% (q=1TeV) → Λ ~ 2.5 TeV

Matter-vs-anti-matter

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

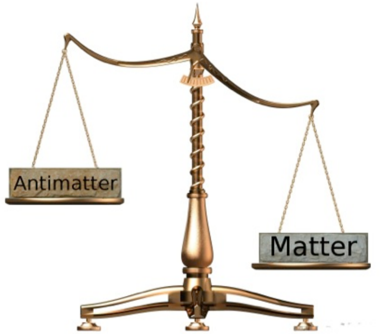




Phys. Rev. Lett. 125 (2020) 061801

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

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

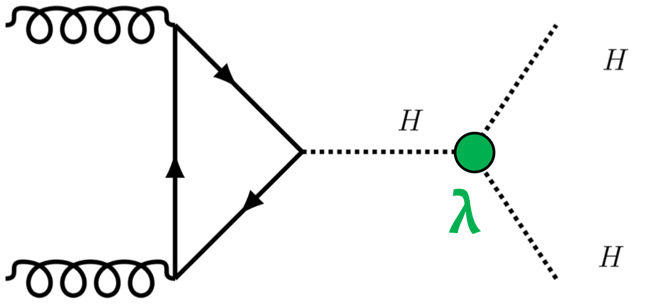


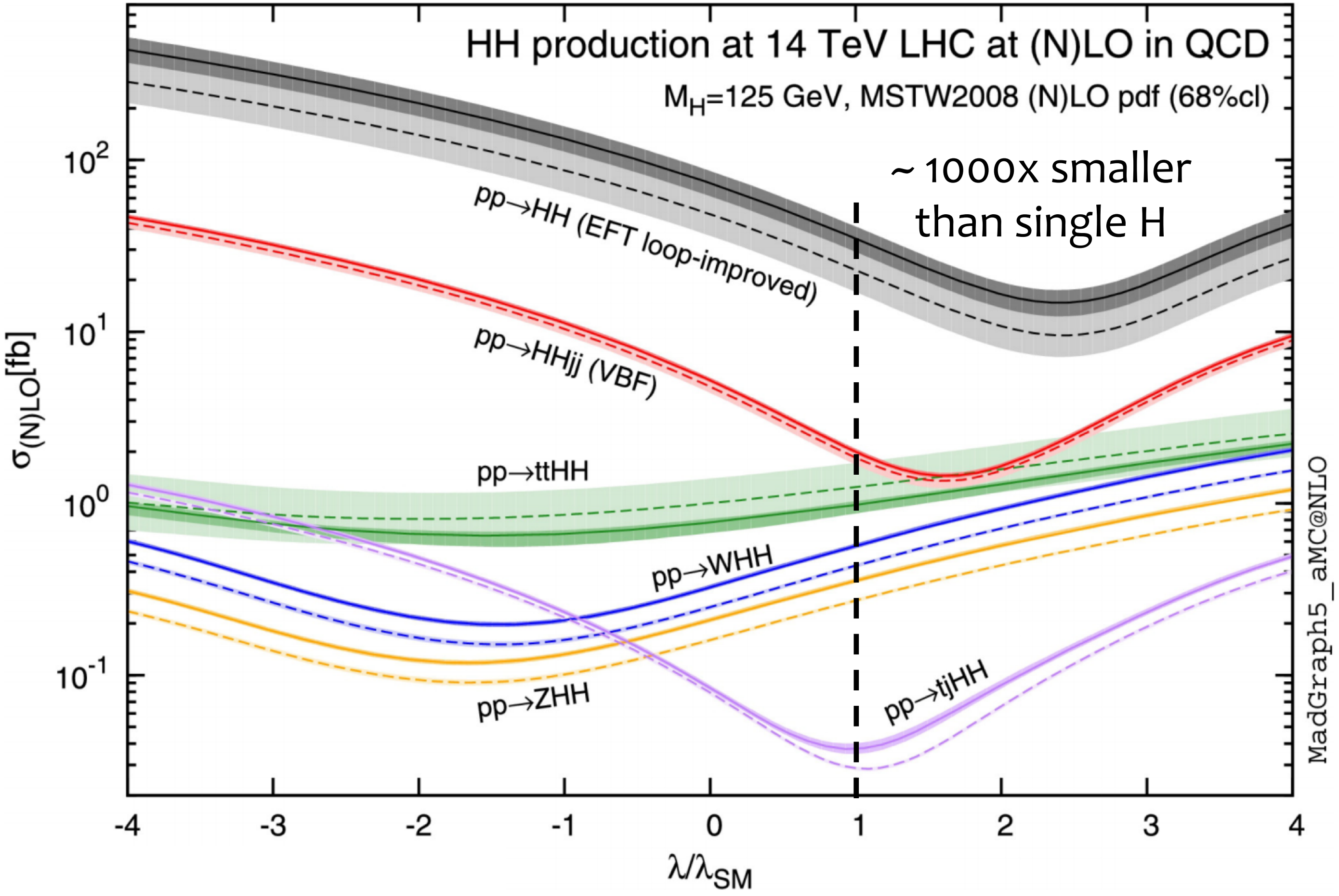
Higgs boson self-coupling

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

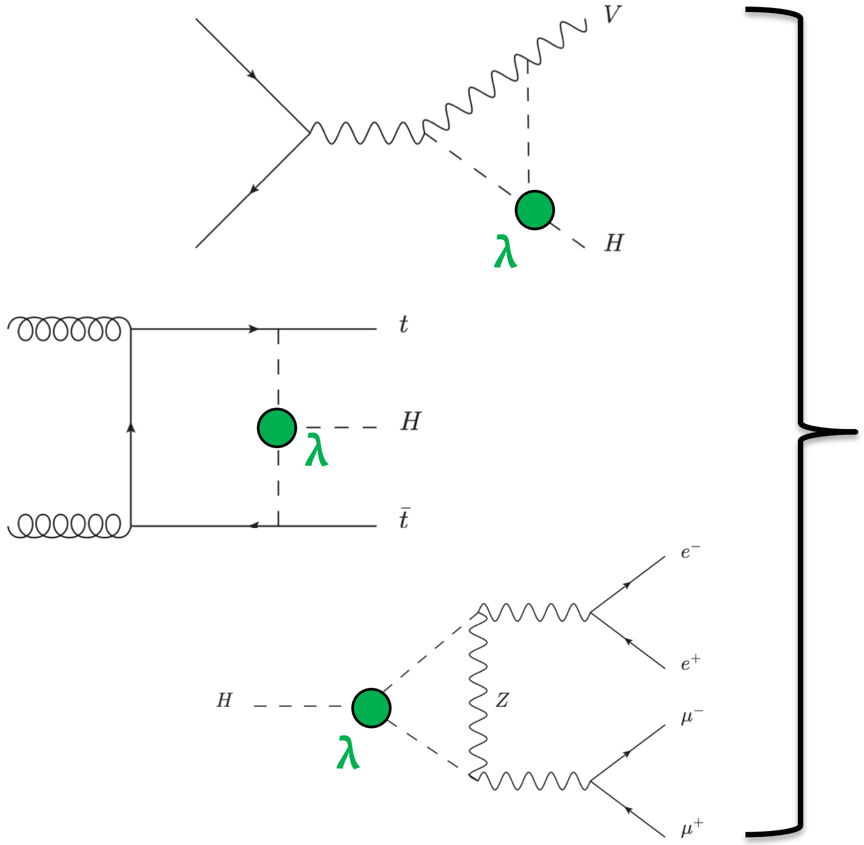




Direct searches for **Double Higgs (HH)** production one way to constrain the Higgs boson self-coupling!

Higgs boson self-coupling

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

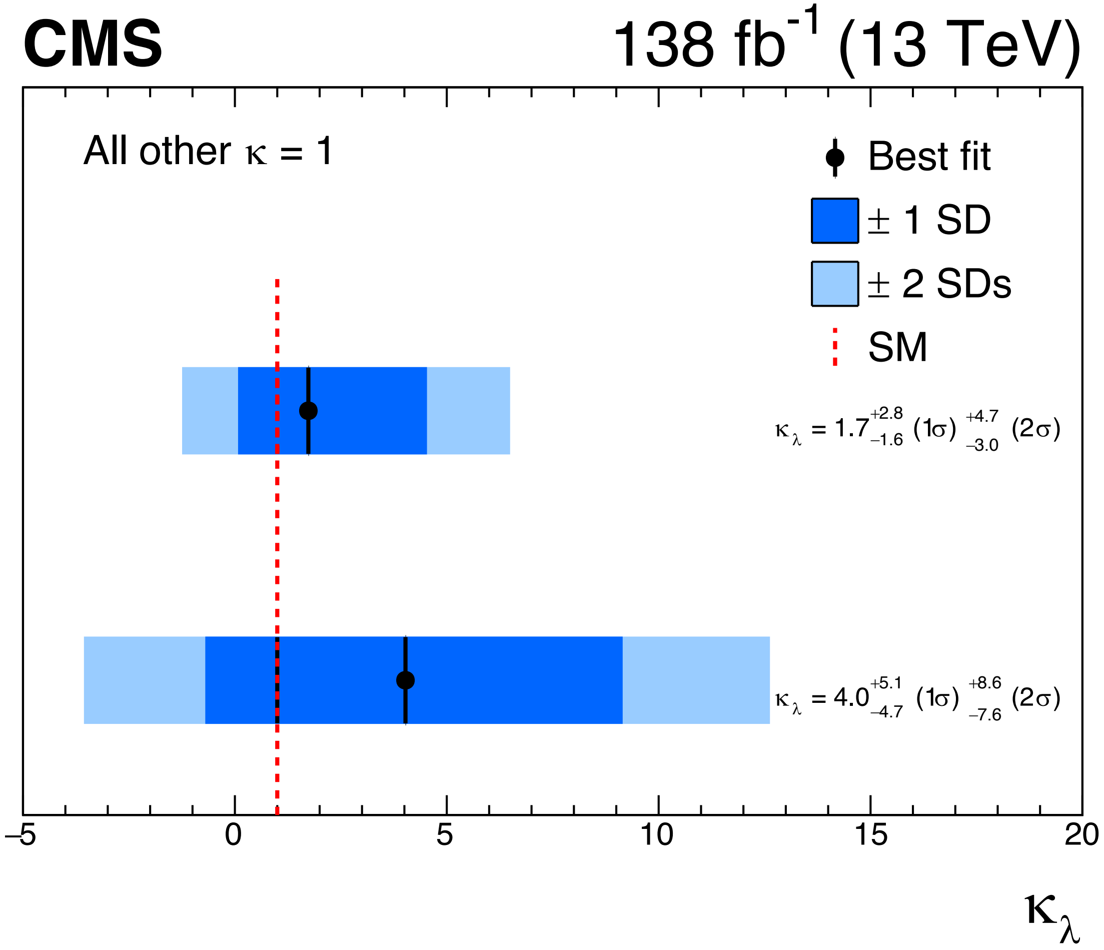


pp → HH

Direct search

pp → H

Indirect interpretation



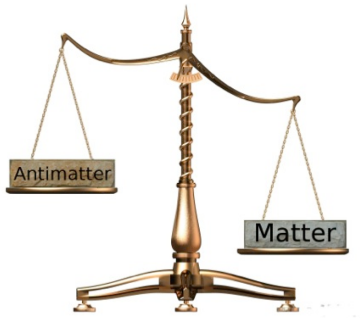
Precision (single) **Higgs boson measurements** also sensitive to **Higgs self-coupling**!

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

Why do we care?

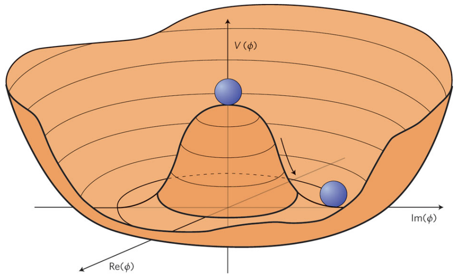
The universe today is **matter** (baryon)-**dominated,**

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



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

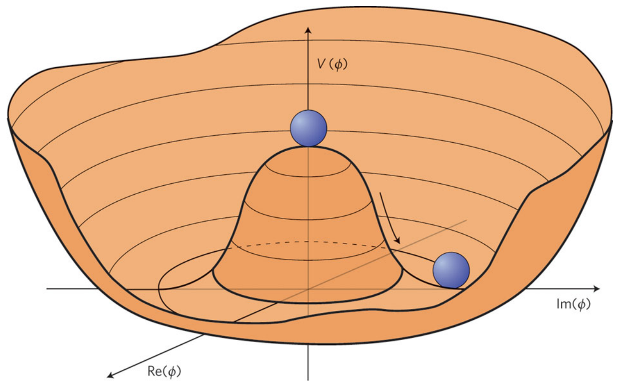
→ **First order phase transition** [1]



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

Modified Higgs potential and Baryogenesis

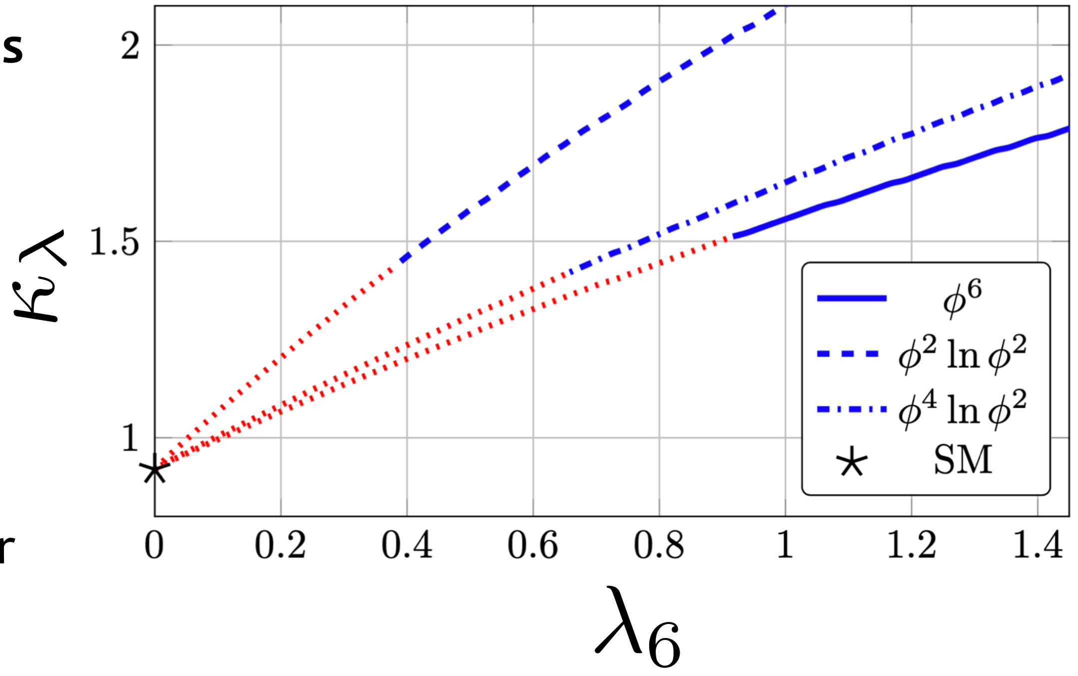
BSM physics in **Higgs potential** could be the solution!



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

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

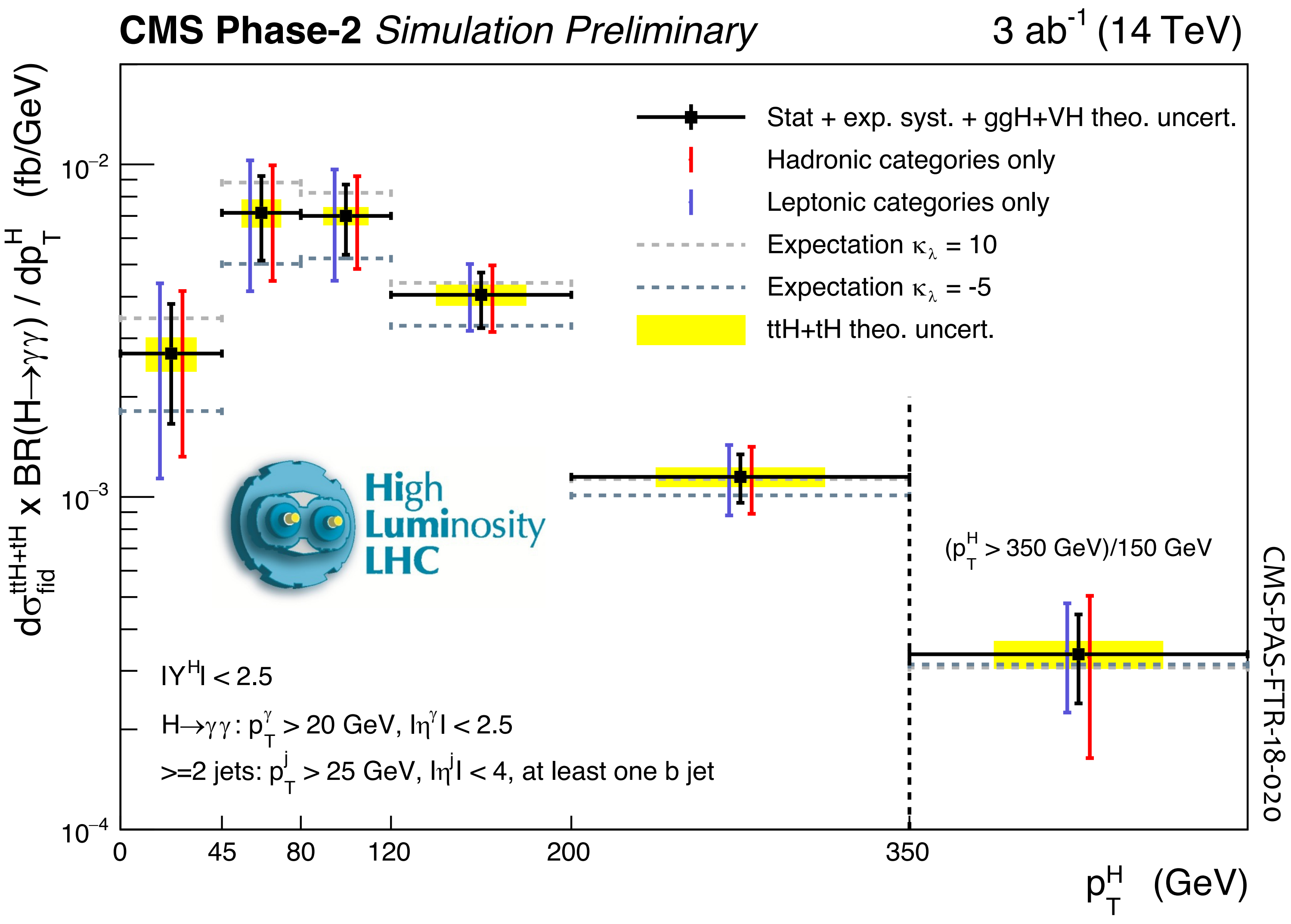
$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} = 1 + \frac{16\lambda_6 v^4}{m_H^2 \Lambda^2}$$

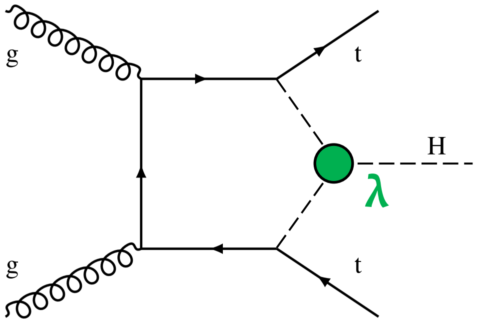


Phys. Rev. D 97, 075008 (2018)

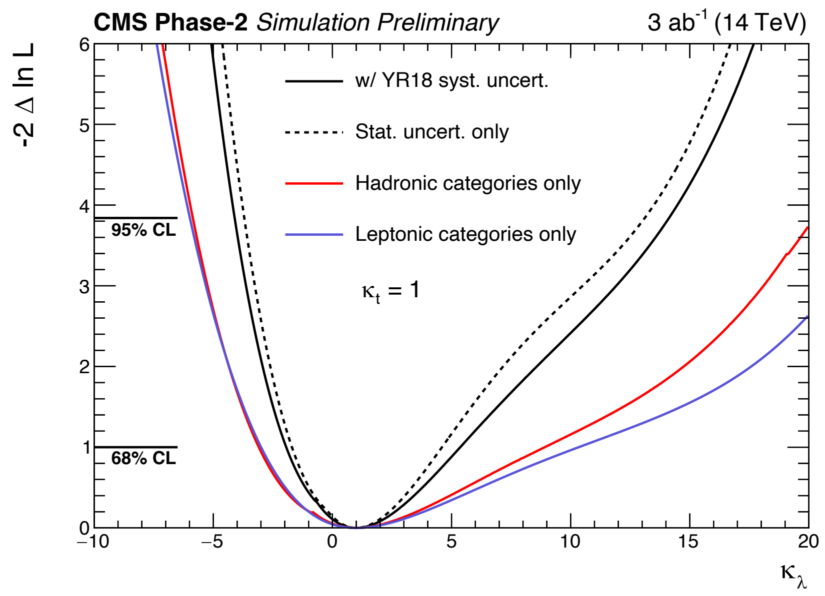
50% increase in self-coupling could hint at mechanism for 1st order EWK phase-transition accuracy crucial goal

Higgs boson self-coupling @ HL-LHC



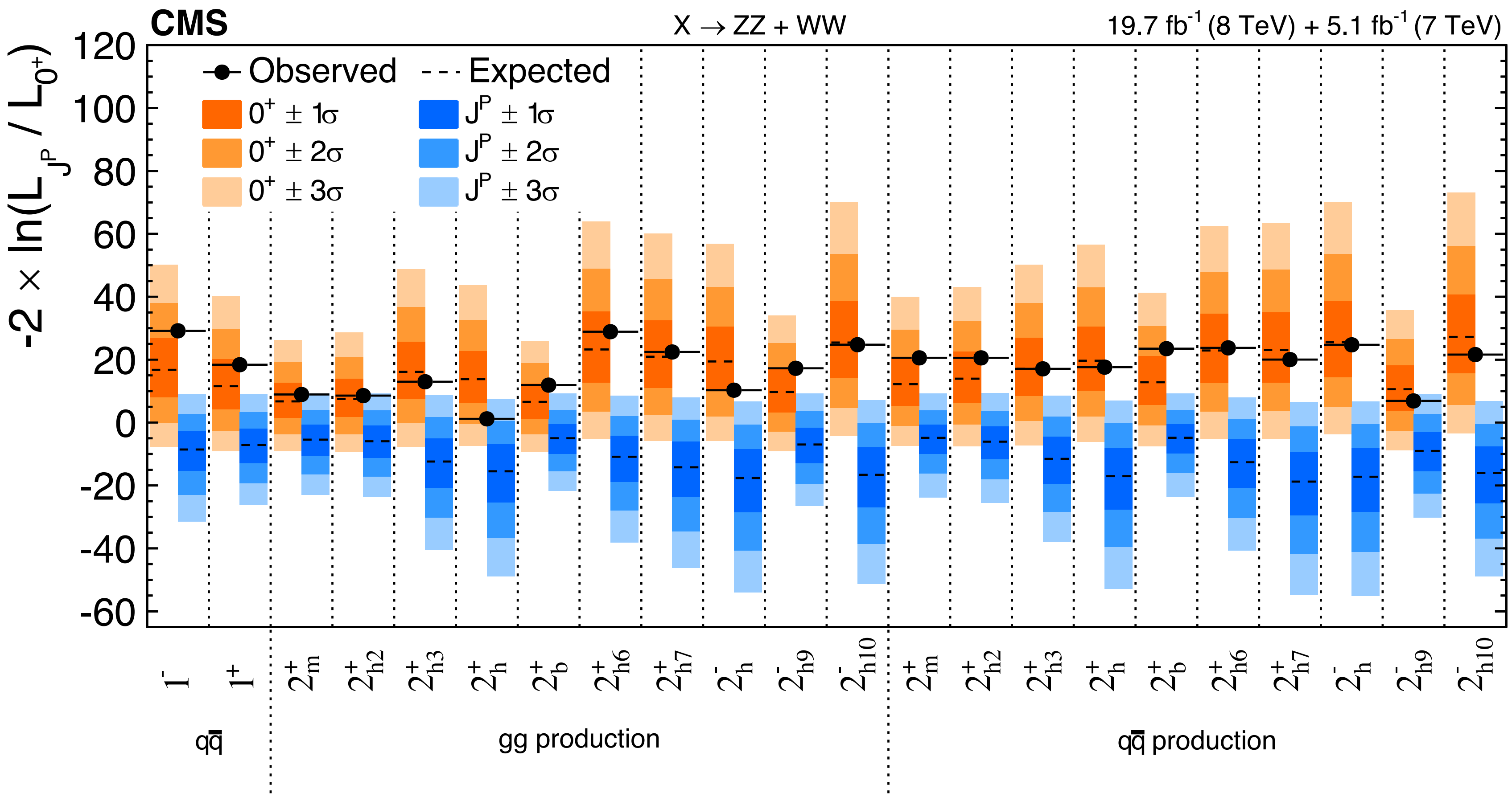


Combinations with **precision differential measurements** of **Higgs production** will push sensitivity even further!



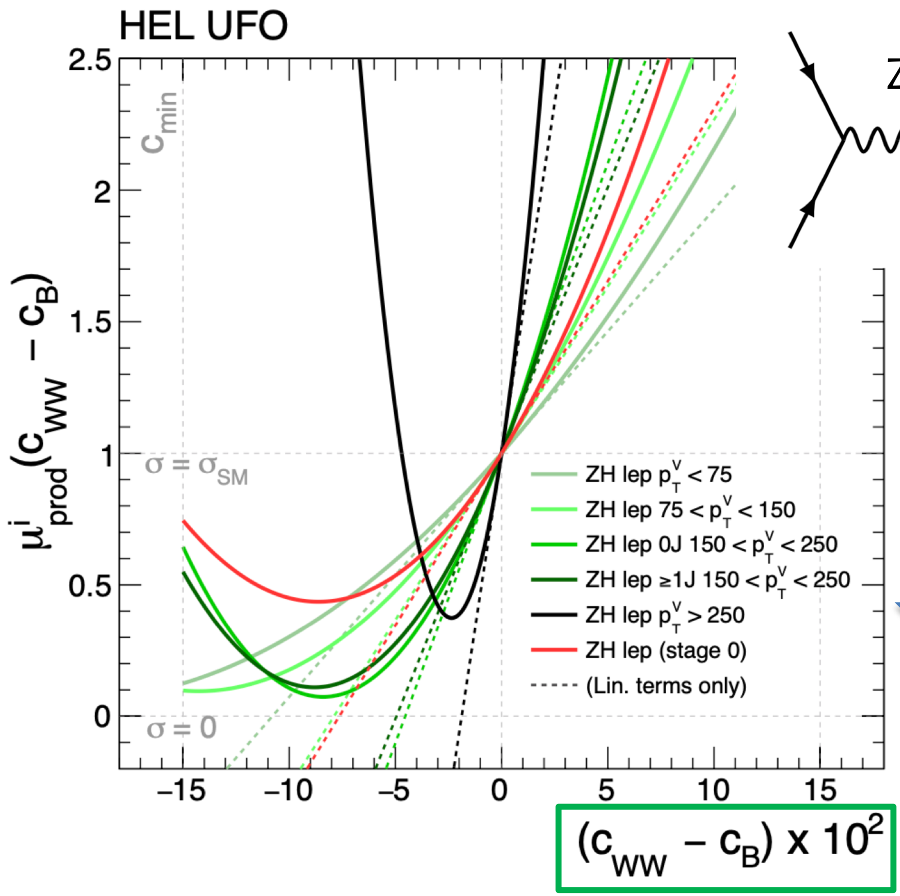
~~No~~ Zero - Spin zone

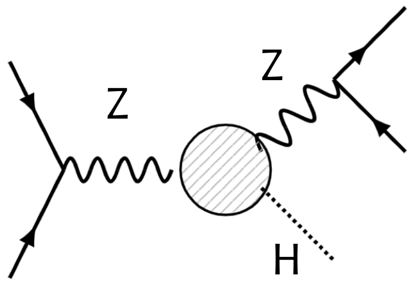
Hypothesis tests for ***non-nested models*** used to distinguish 0^+ from other J^{CP} states.

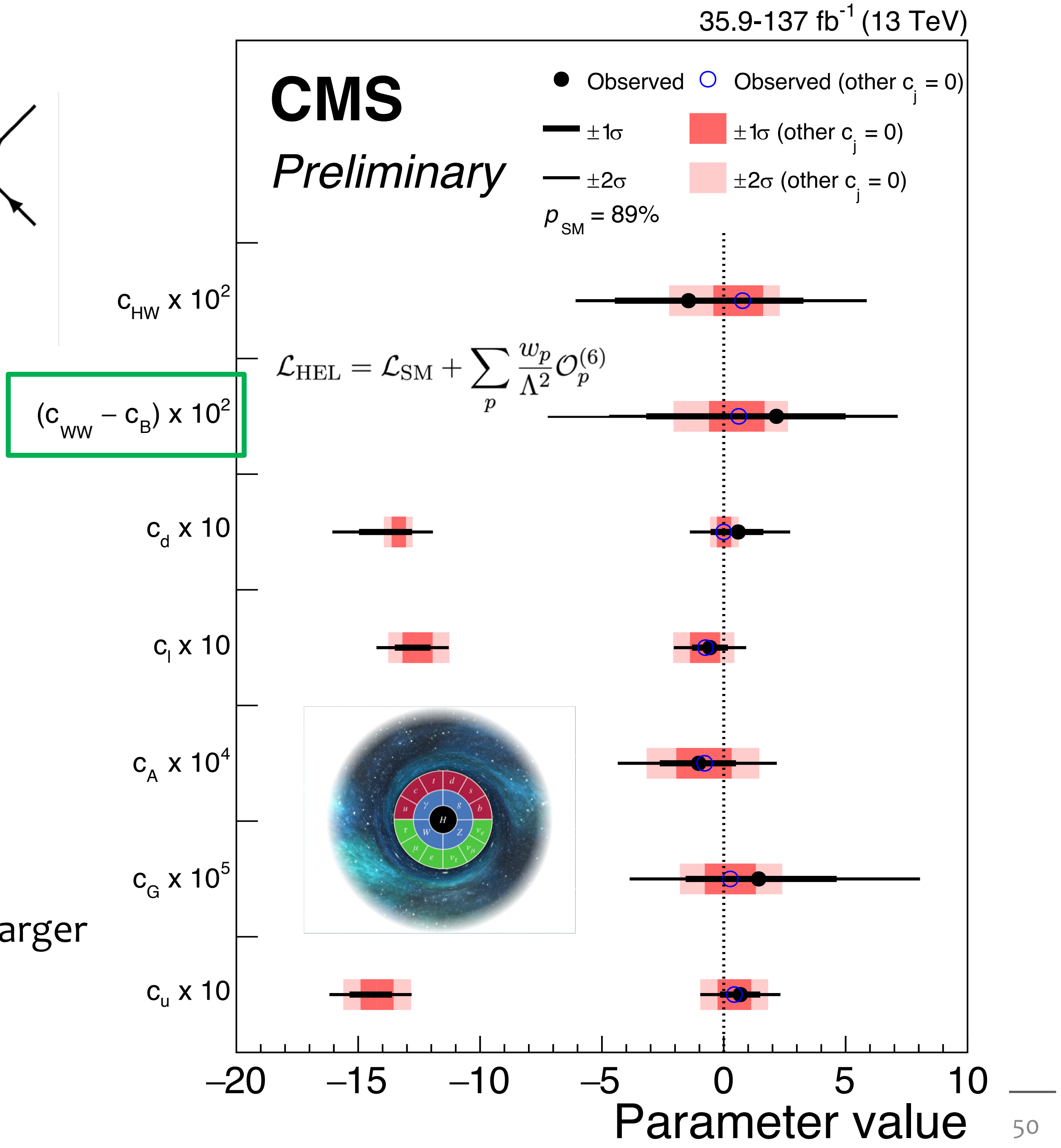


Run-1 data is already enough to rule out spin-2 (and many other J^P states) at > 99.9% confidence level

Effective field theories

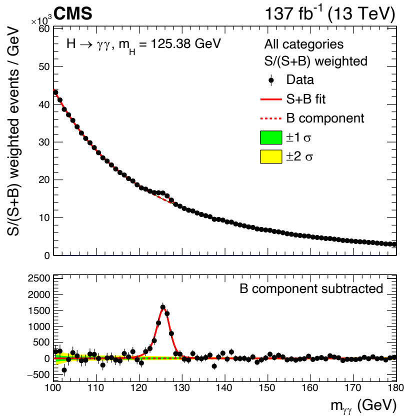


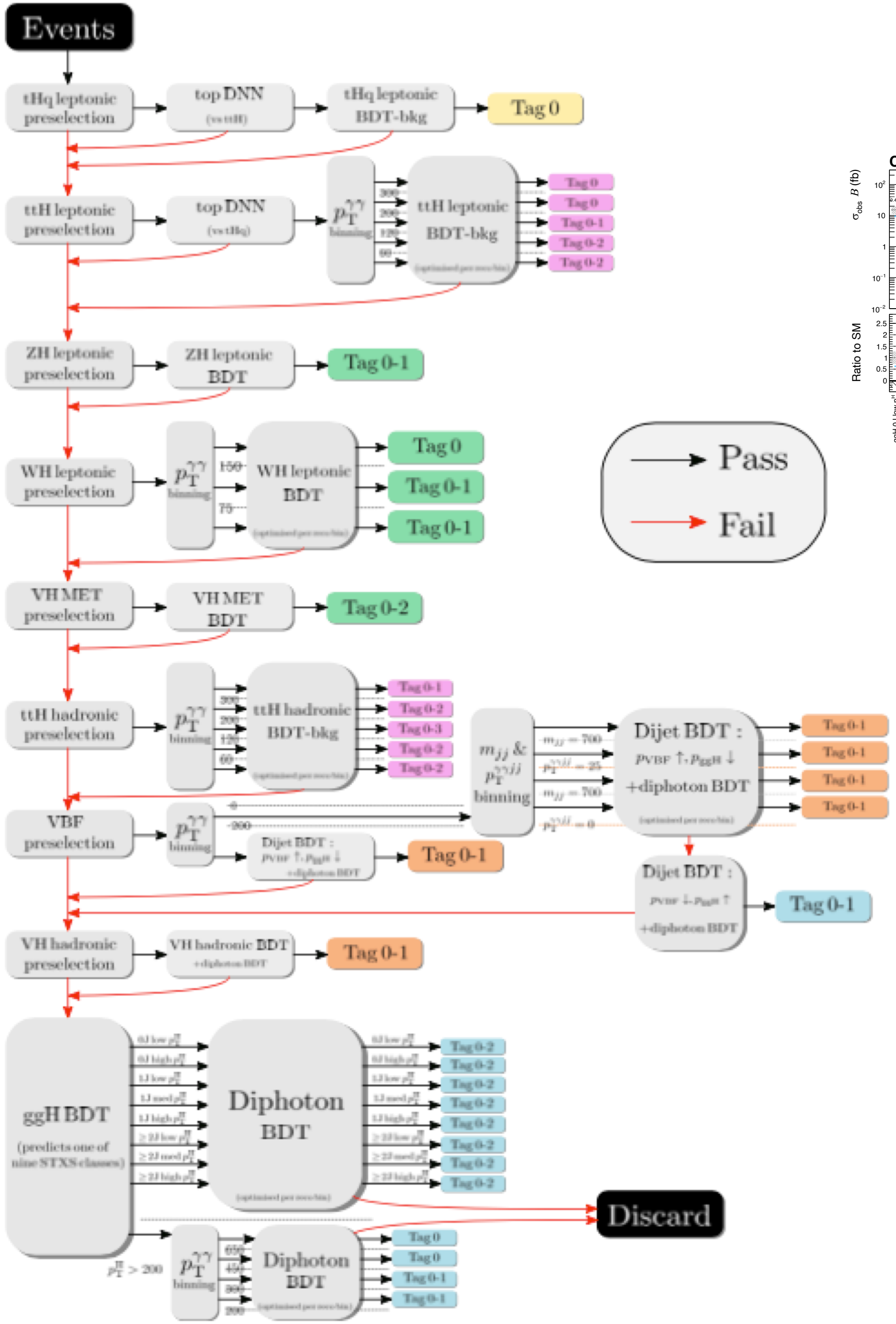




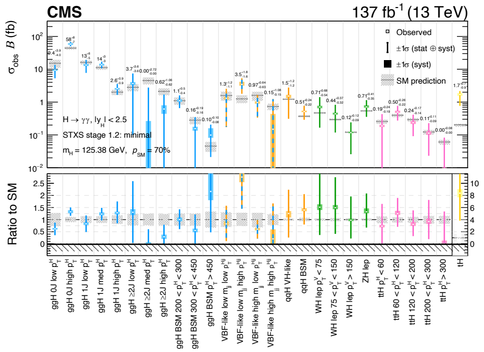
New physics effects are **typically larger** for processes with larger momentum transfer → Best sensitivity from **differential measurements of Higgs production**

Analysis workflow



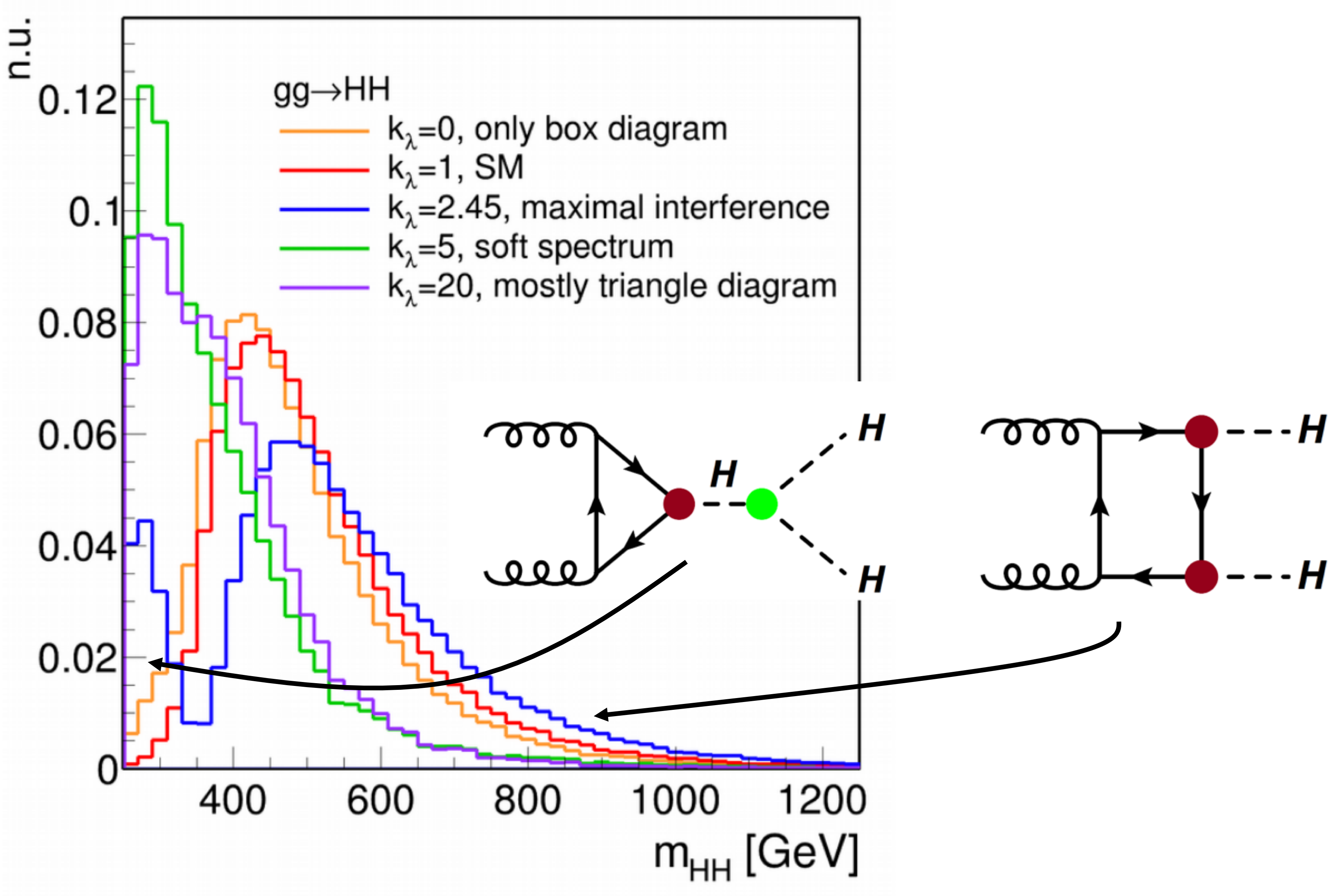


J. Langford thesis

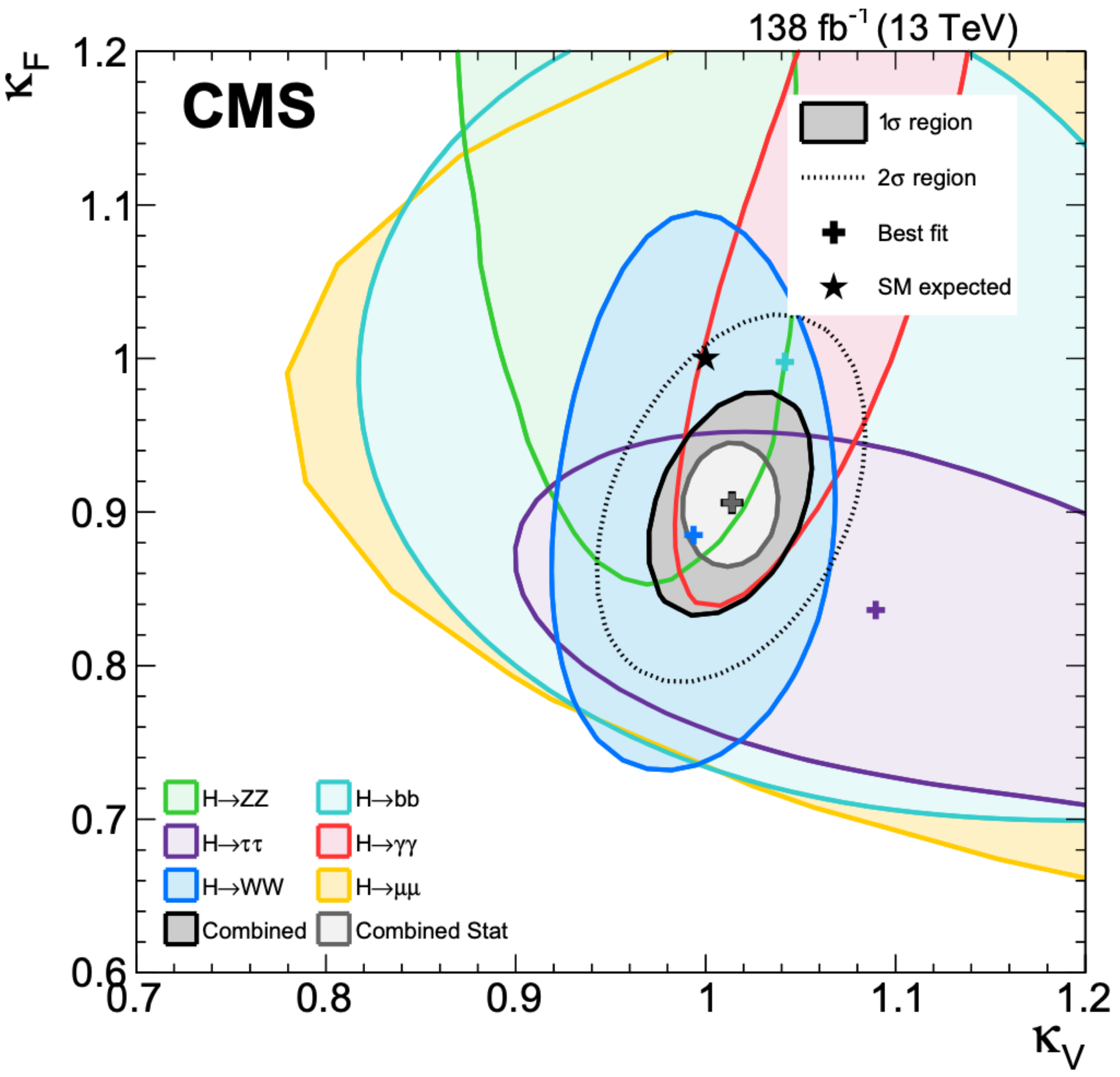


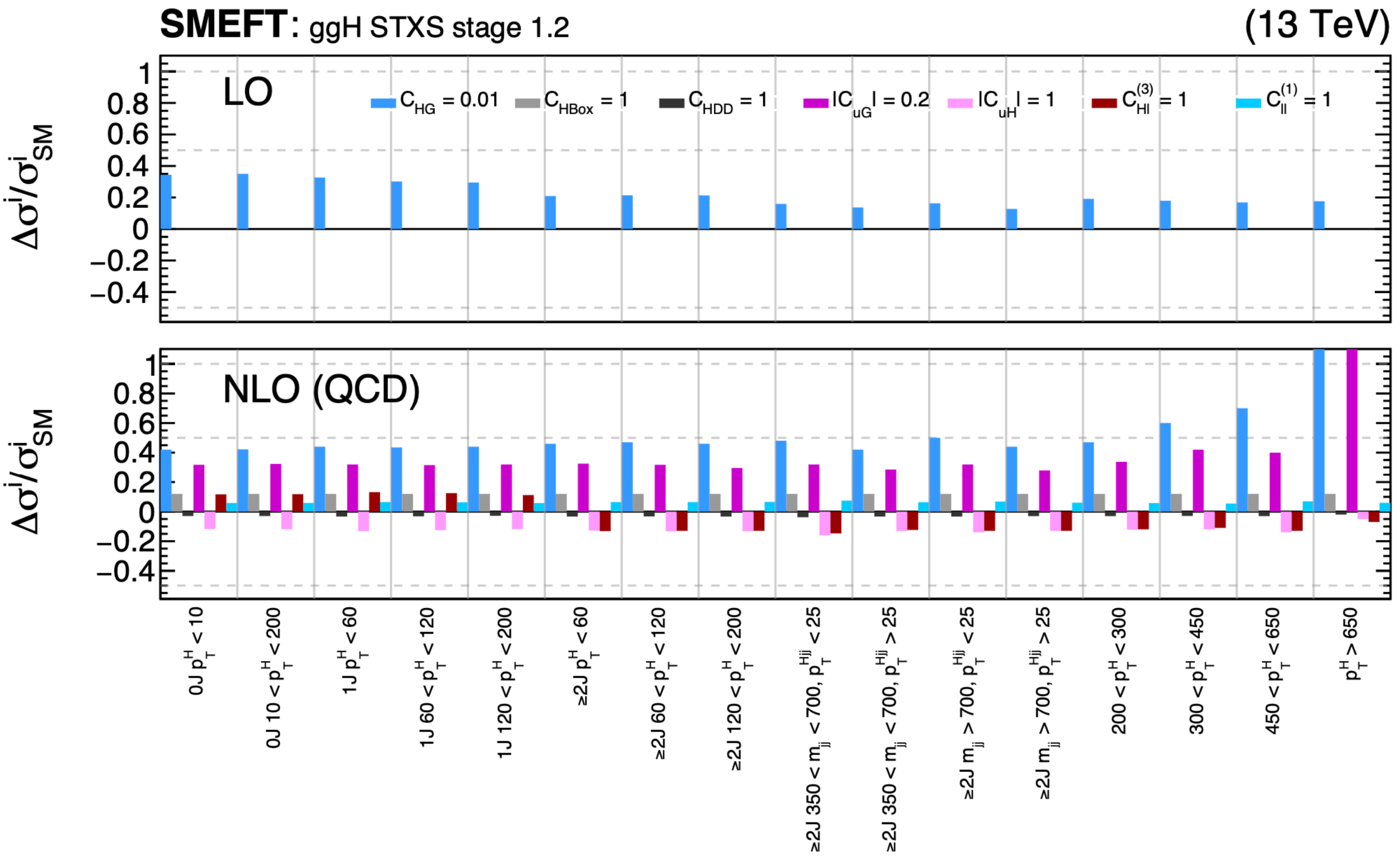
Large number of Higgs bosons available in Run-II → sophisticated analysis strategies to extract the most sensitivity out of the data we have

Sensitivity to self-coupling in HH



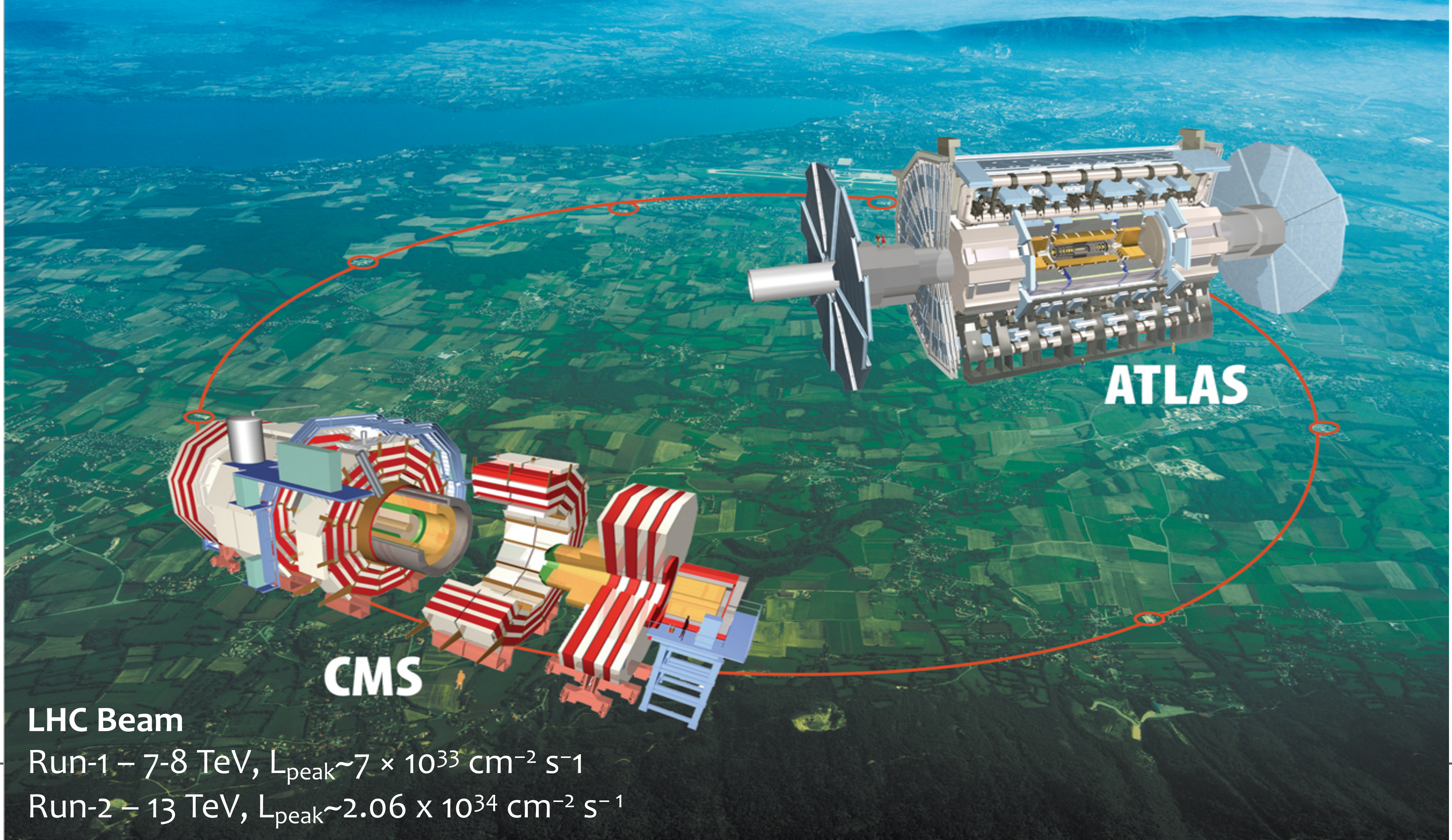
Couplings per decay




SMEFT: ggH STXS stage 1.2
(13 TeV)
LO
NLO (QCD)
C_{HG} = 0.01
C_{HBox} = 1
C_{HDD} = 1
$|C_{uG}|$ = 0.2
$|C_{uH}|$ = 1
$C_{Hl}^{(3)}$ = 1
$C_{ll}^{(1)}$ = 1
$\Delta\sigma^i/\sigma^i_{SM}$
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0J p_T^H < 10
0J 10 < p_T^H < 200
1J p_T^H < 60
1J 60 < p_T^H < 120
1J 120 < p_T^H < 200
≥2J p_T^H < 60
≥2J 60 < p_T^H < 120
≥2J 120 < p_T^H < 200
≥2J 350 < m_{jj} < 700, p_T^{Hjj} < 25
≥2J 350 < m_{jj} < 700, p_T^{Hjj} > 25
≥2J m_{jj} > 700, p_T^{Hjj} < 25
≥2J m_{jj} > 700, p_T^{Hjj} > 25
200 < p_T^H < 300
300 < p_T^H < 450
450 < p_T^H < 650
p_T^H > 650

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

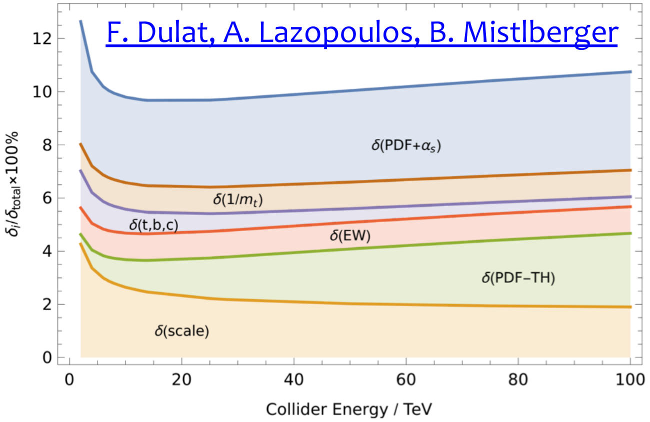
Run-1 – 7-8 TeV, L_{peak}~7 × 10^{33} cm^{-2} s^{-1}

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

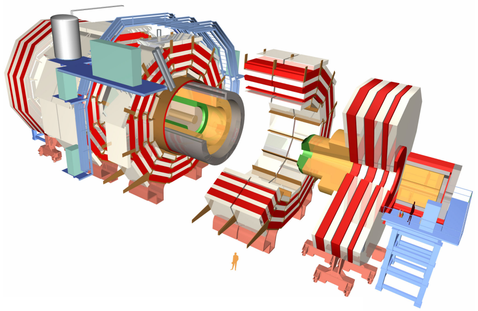
Breaking down the likelihood

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

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

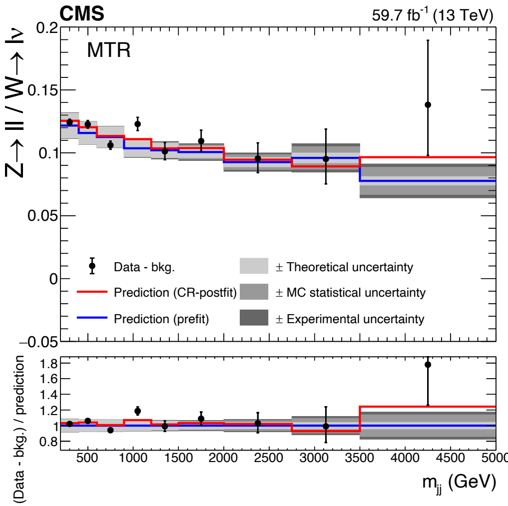


Experimental/Detector systematics:
- Object efficiencies, energy scales, luminosity



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

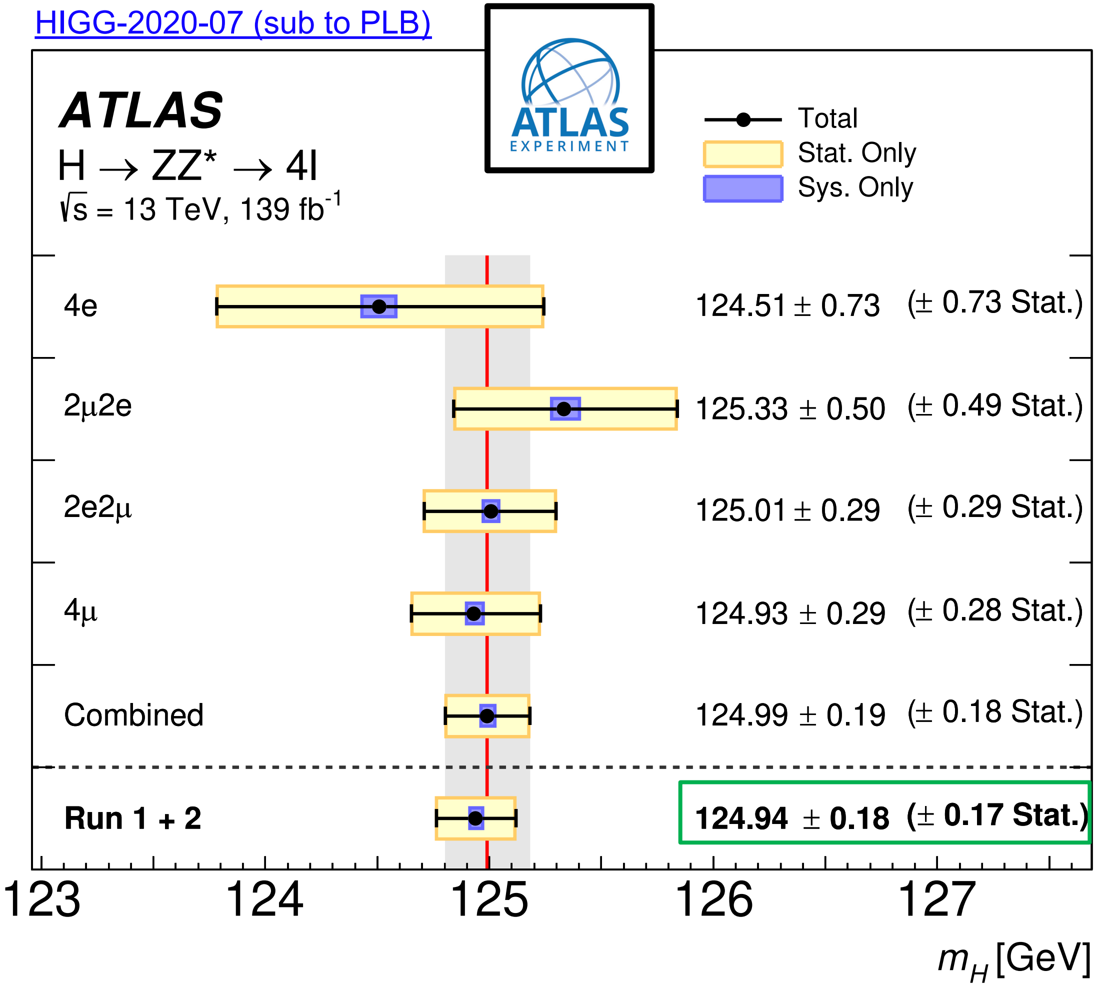
Background theory uncertainties:
- Often rather different phase-spaces considered for extrapolating from control regions for data-driven estimates



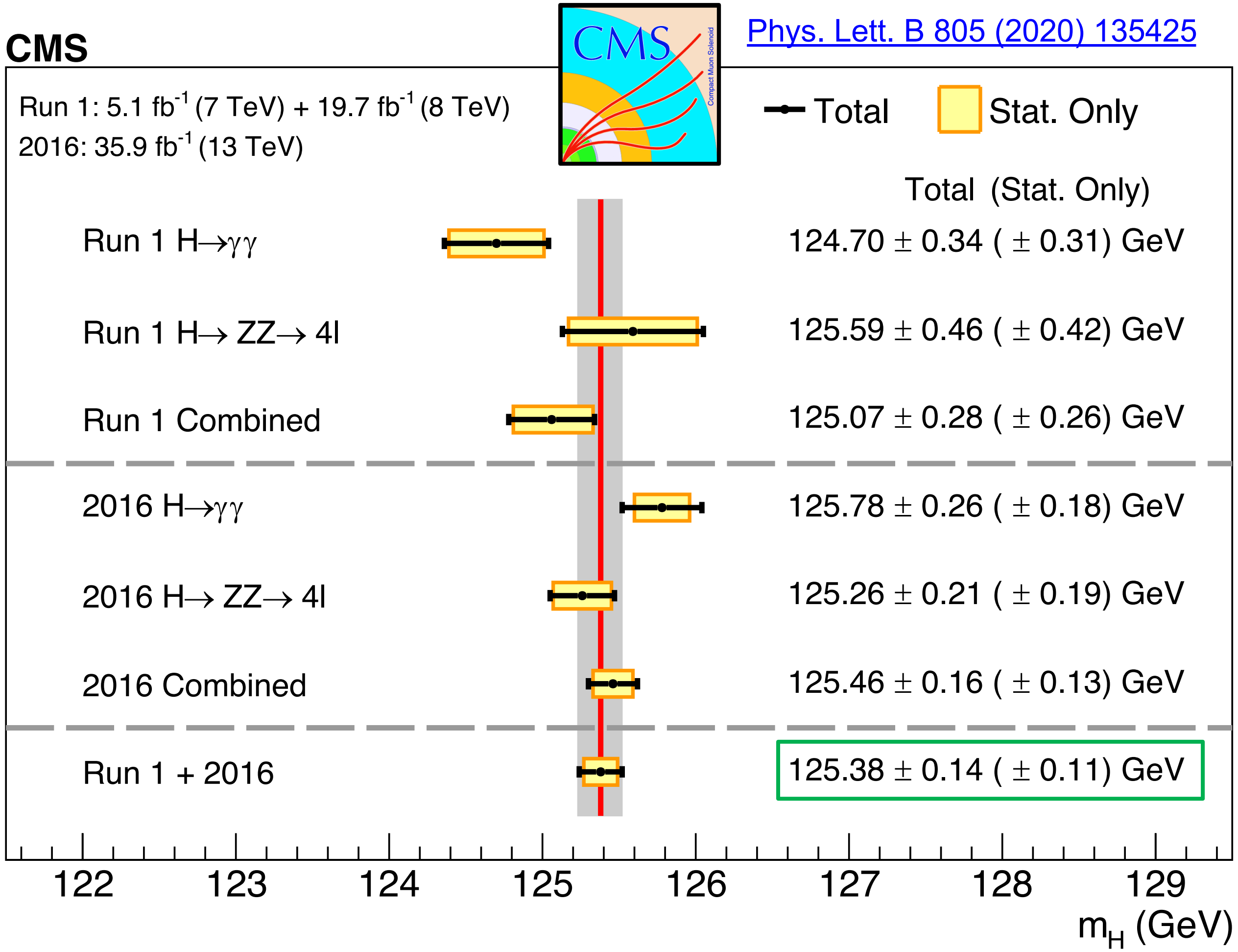
Combination has **O(1000)'s nuisance parameters** (sources of systematic uncertainty)

A *massive* achievement Take-II

HIGG-2020-07 (sub to PLB)



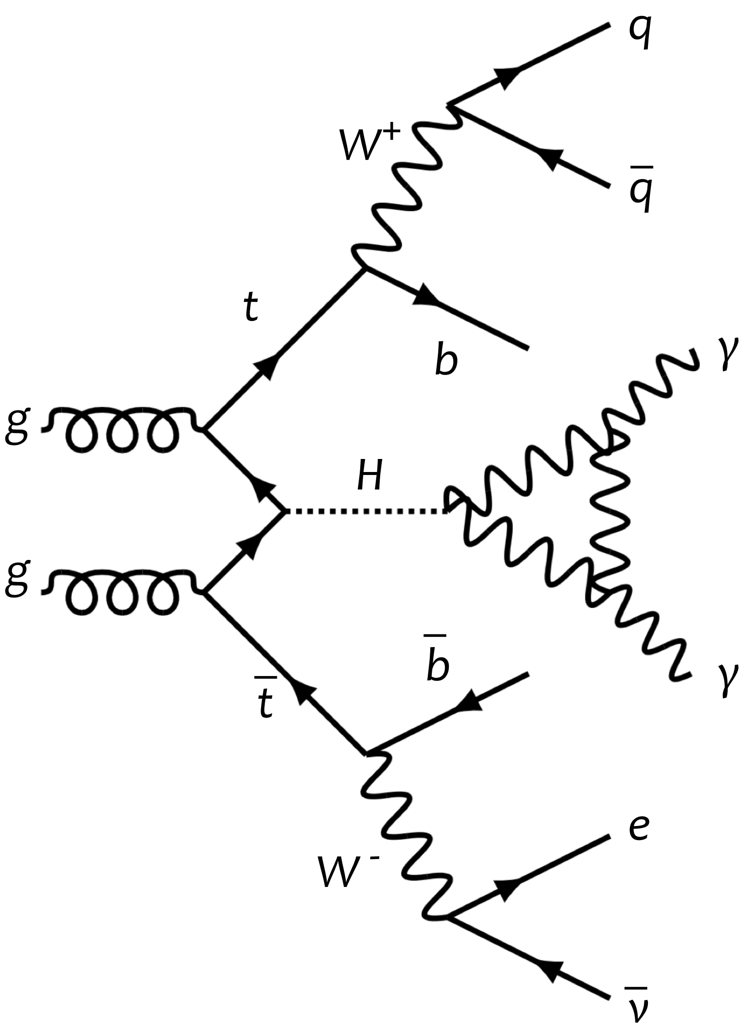
Phys. Lett. B 805 (2020) 135425



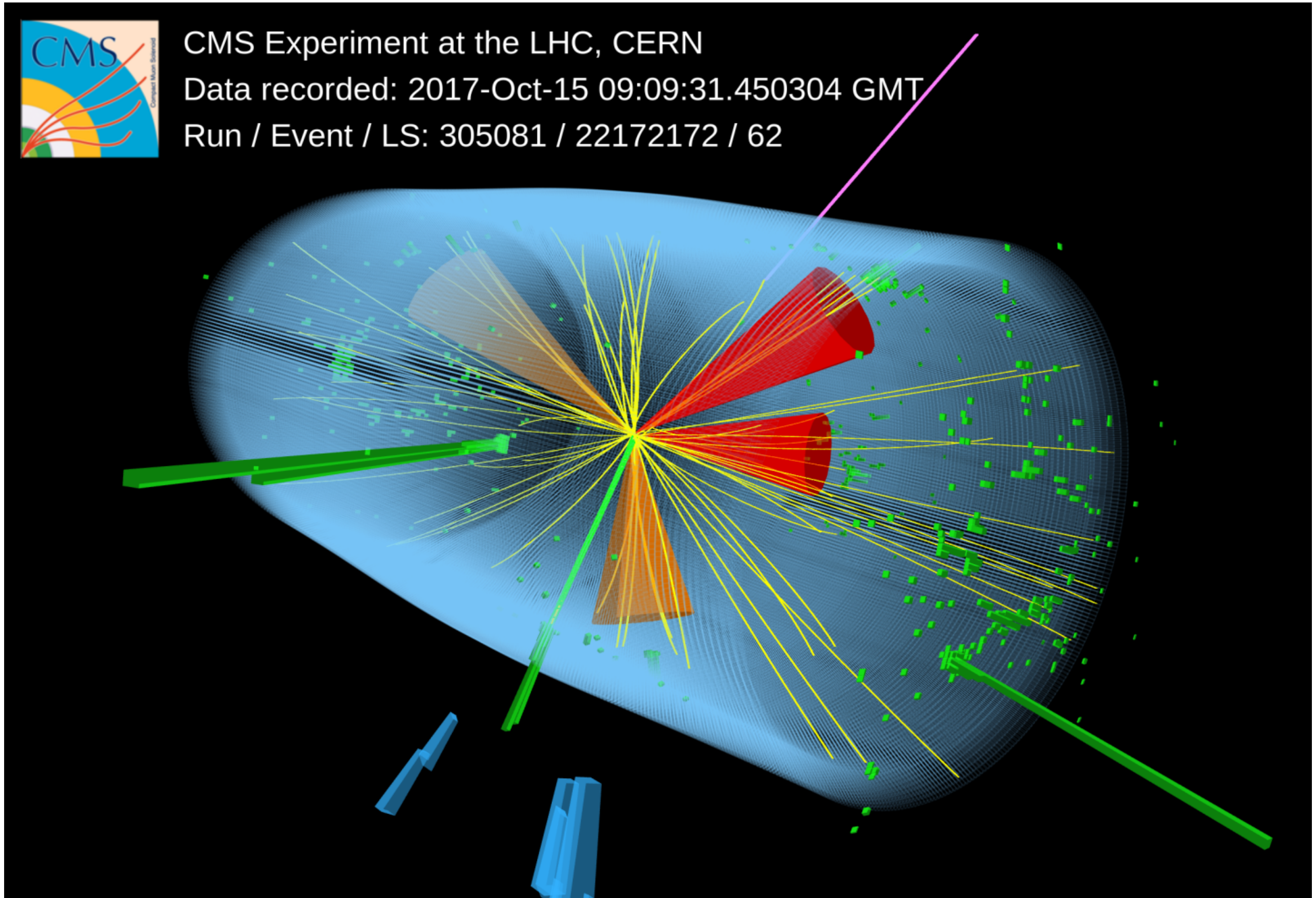
Precision in Higgs boson mass at the level of **11-14%** with the addition of Run-2 data!

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

From theory to measurement – A computational challenge



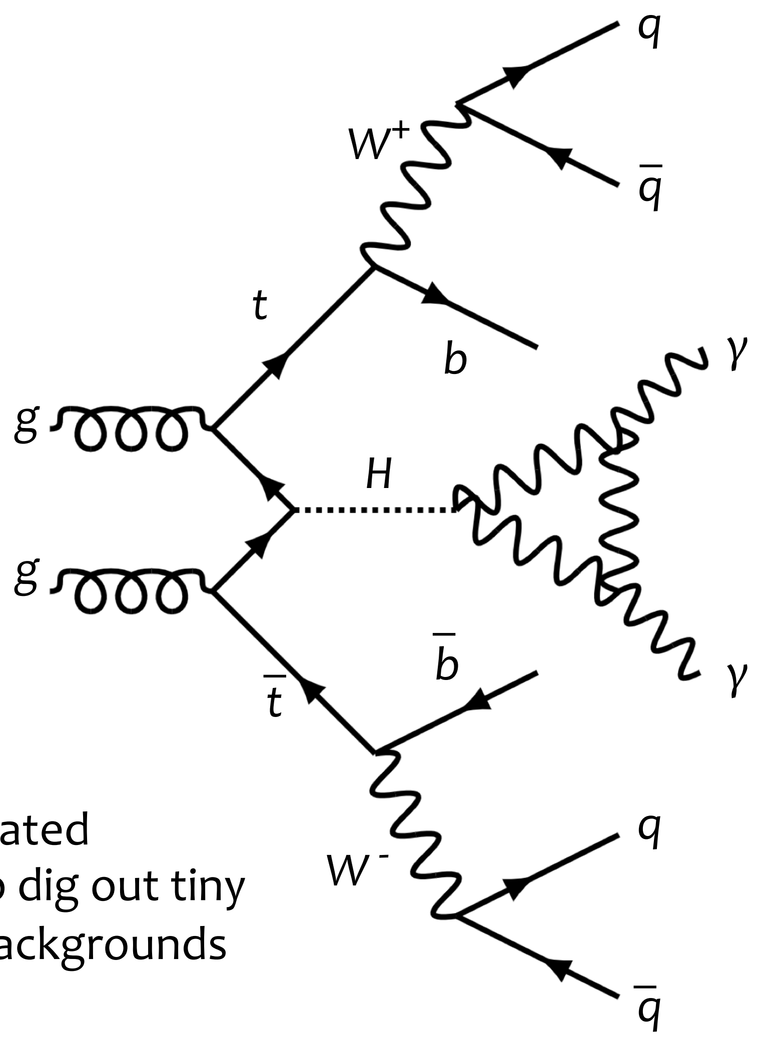
Theory calculation (hard process)

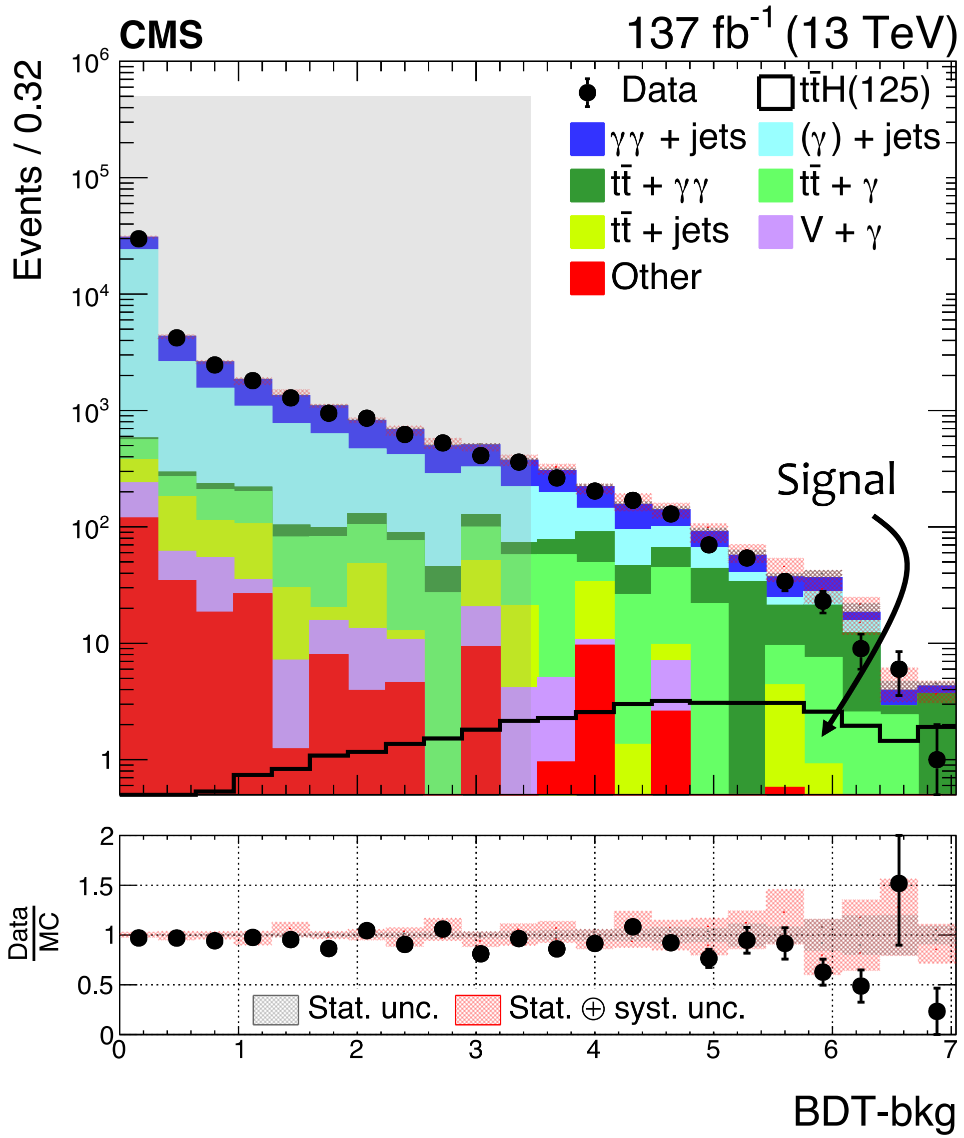


Experimental reality

From theory to measurement – An experimental challenge

The Higgs signal is not the only process we have to deal with

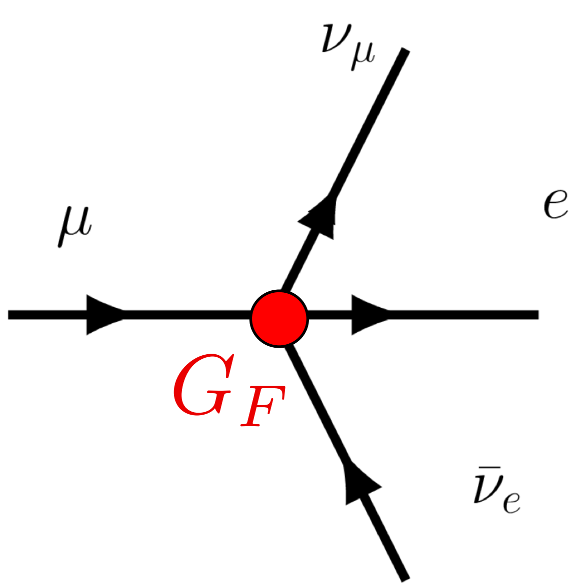




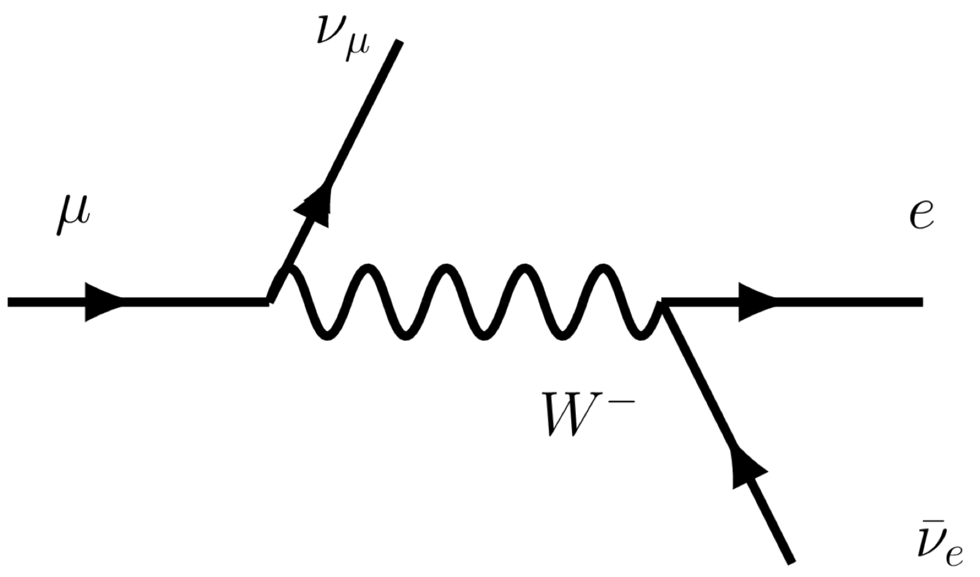
We rely on sophisticated **Machine-learning** to dig out tiny signals from huge backgrounds

Effective couplings

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



Effective field (Fermi) theory



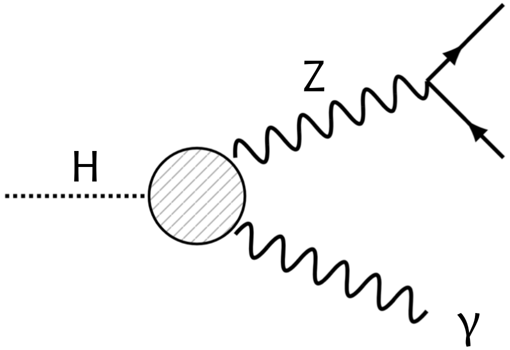
Standard Model

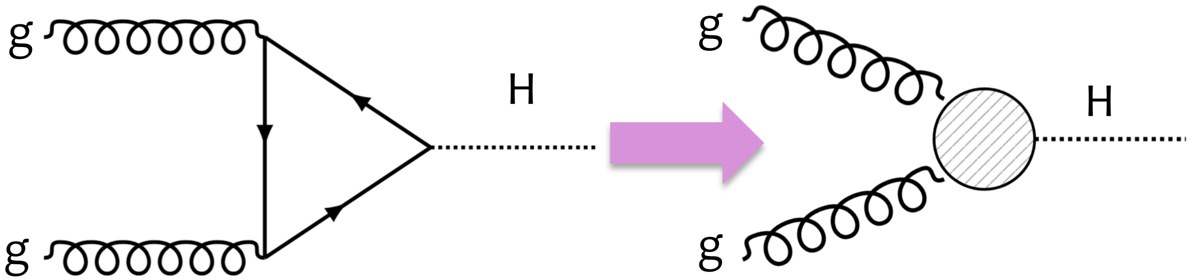
$E << m_W$ // $E > m_W$ → **E**

* At least for theory of weak interactions

Effective Couplings

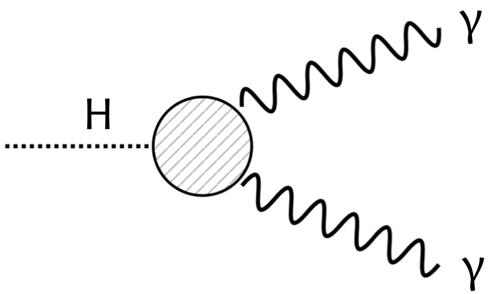
Higgs boson production and decay mechanisms that proceed by loops can be treated as effective couplings

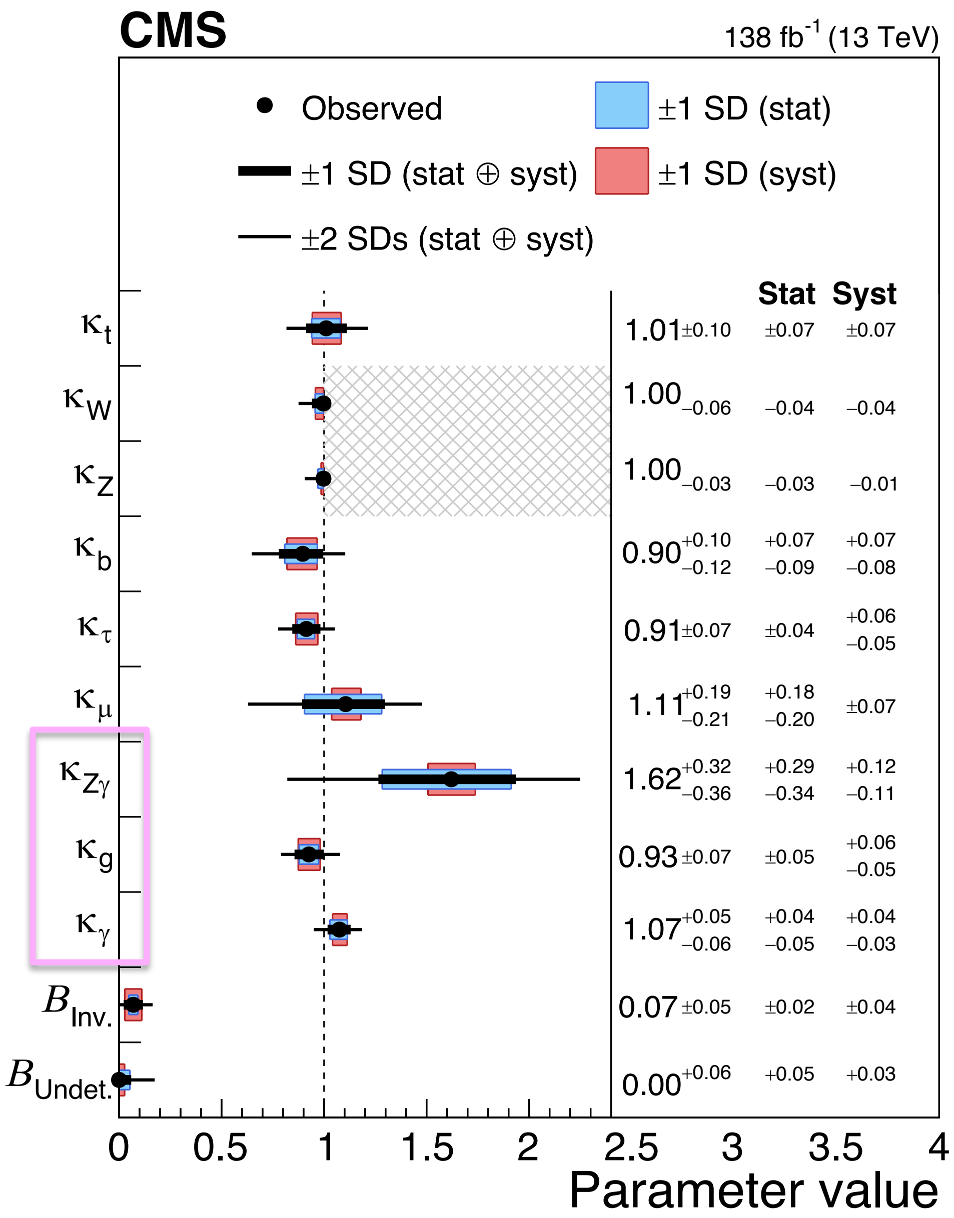




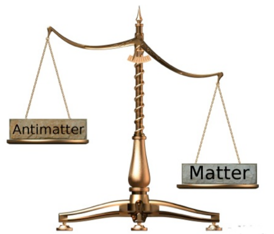
New heavy particles can appear in these loops leading to large deviation in the effective coupling:

H-Zγ, H-g, H-γ

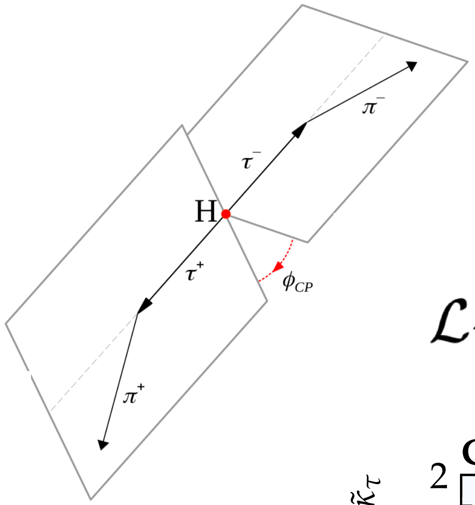




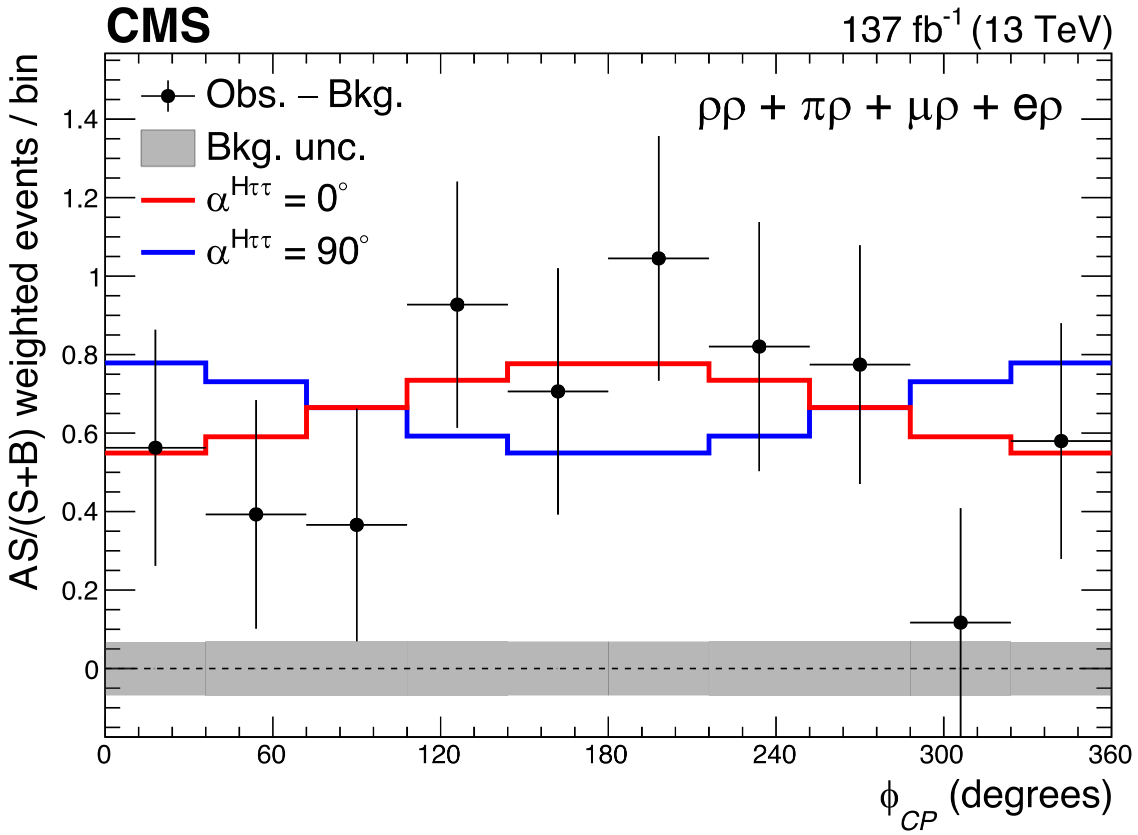
Matter-vs-anti-matter



Angular differential measurements of tau-decay products in H→ττ constrain **Charge Parity-odd contributions** to Higgs-tau effective coupling



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



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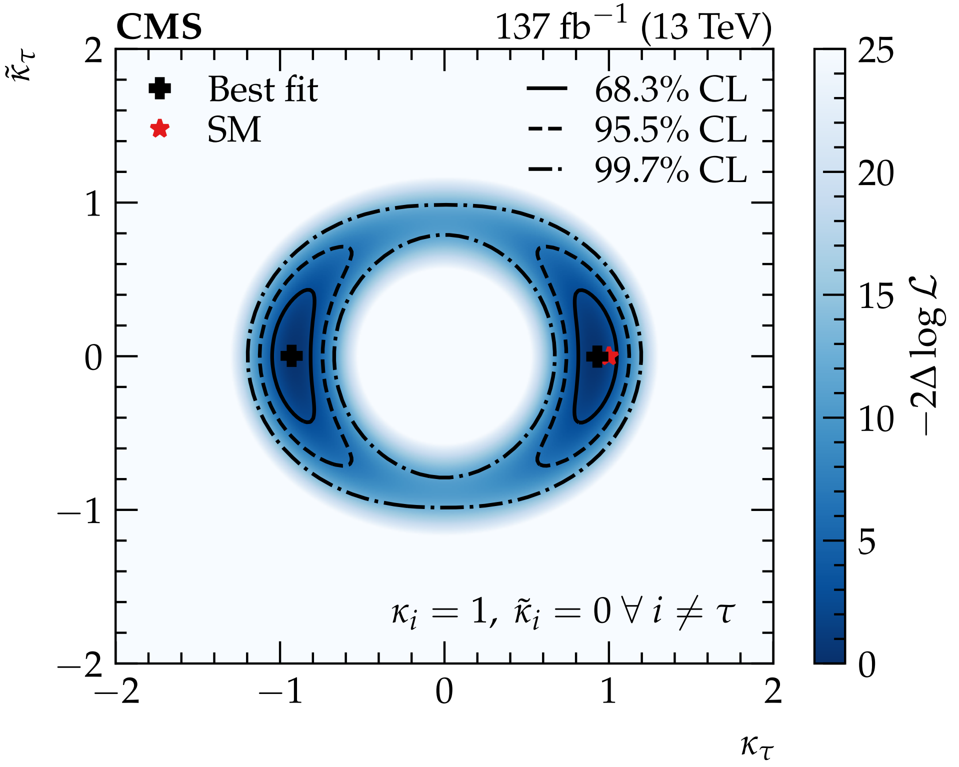
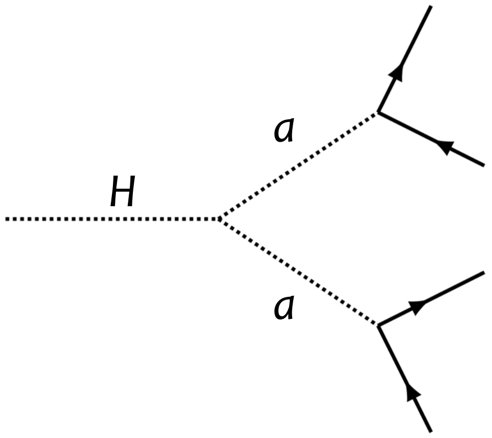


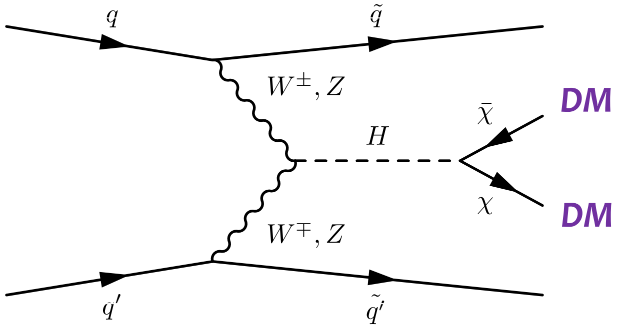
Higgs decays to new particles

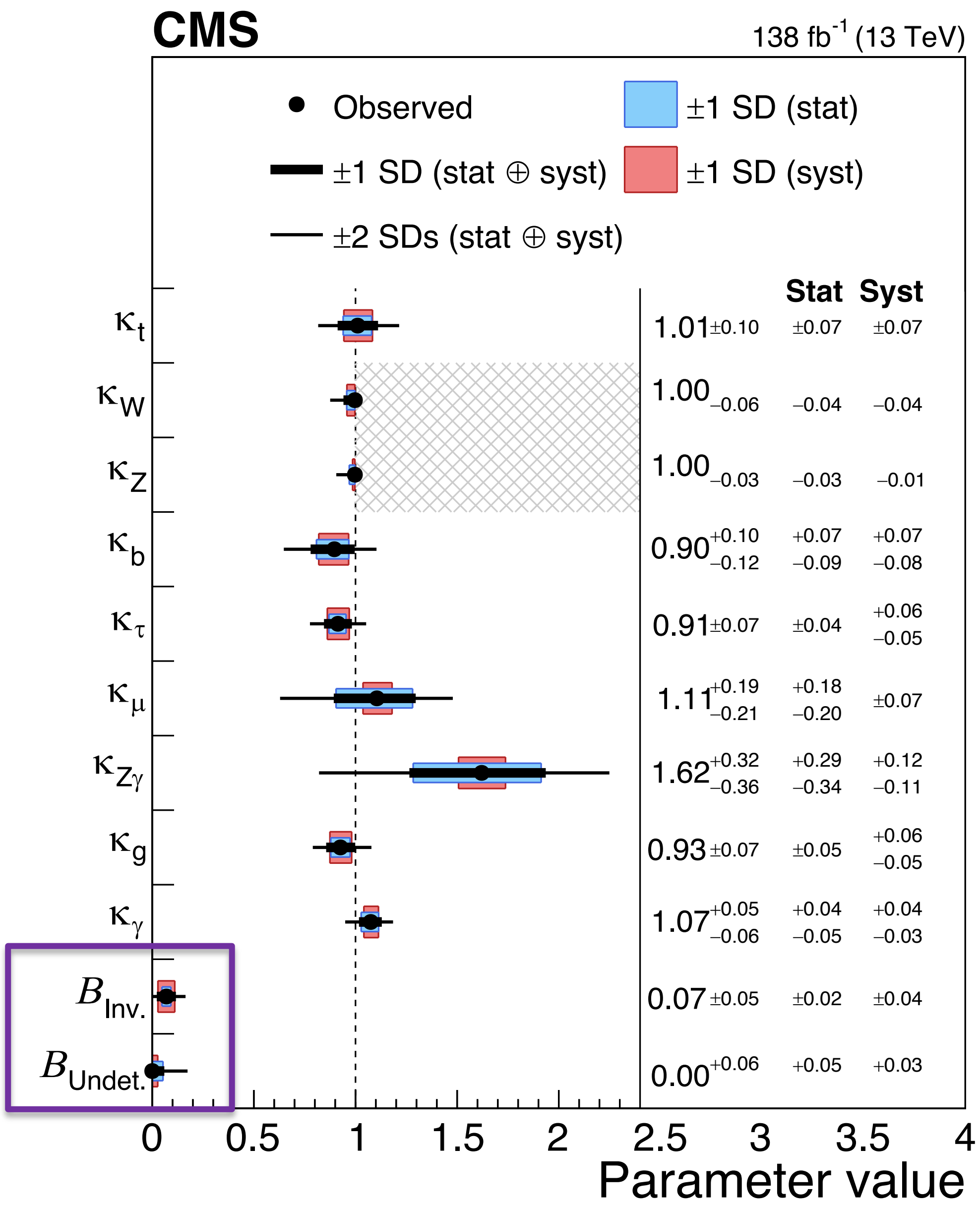
Current measurements of Higgs boson couplings allow for **"missing" decay modes to light particles**

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

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

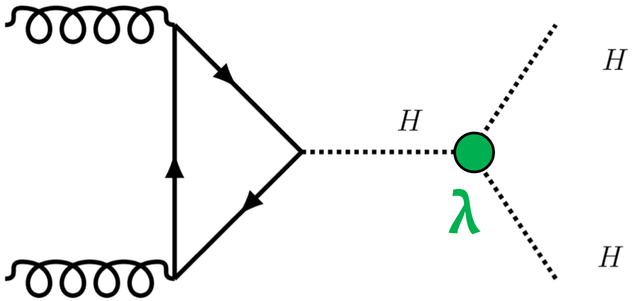






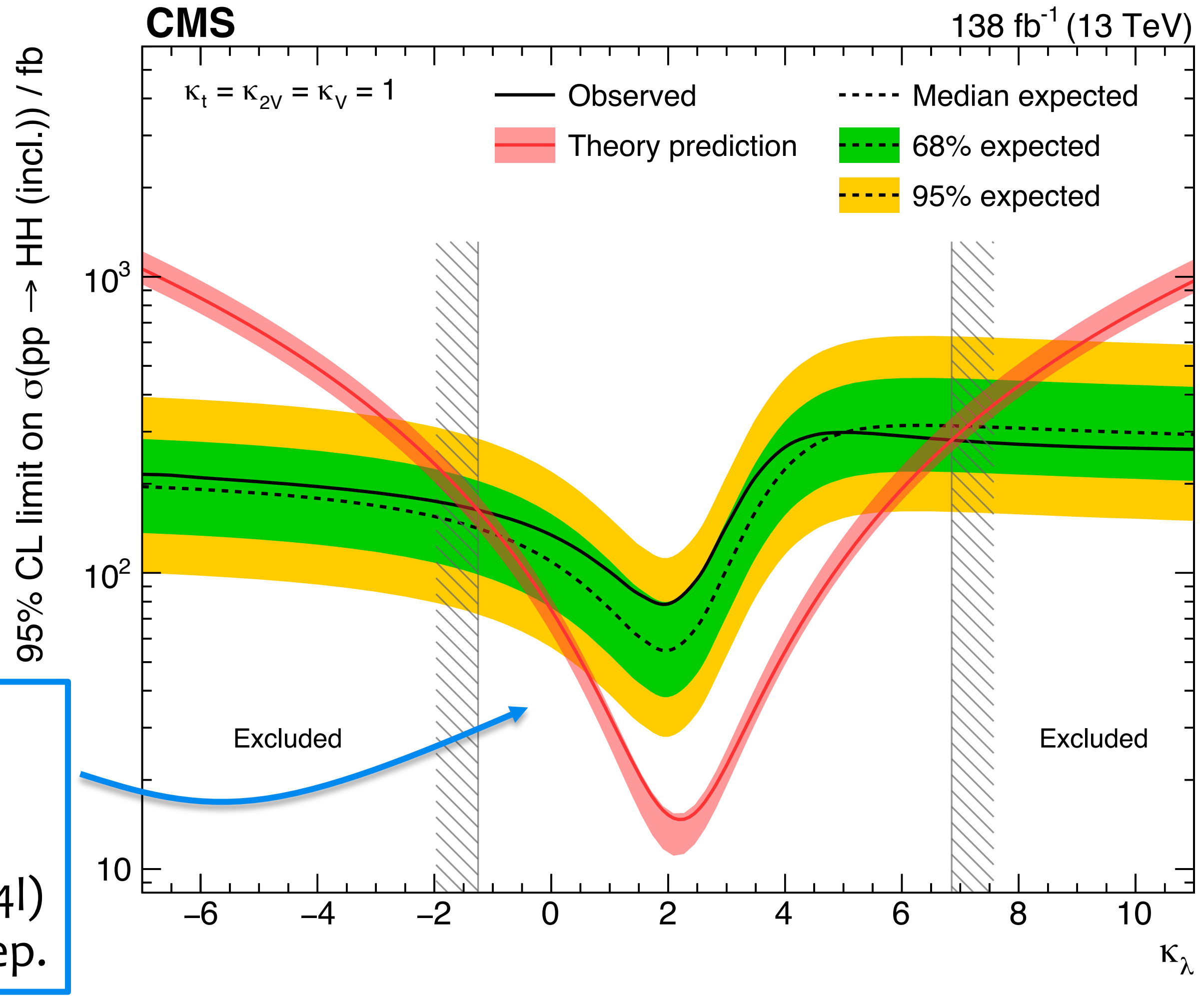
Higgs boson self-coupling

Production cross-section of **double-Higgs** is 1000x smaller than single-Higgs at the LHC!



Combinations of multiple searches for Higgs pair production vital for best sensitivity to **self-coupling**

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

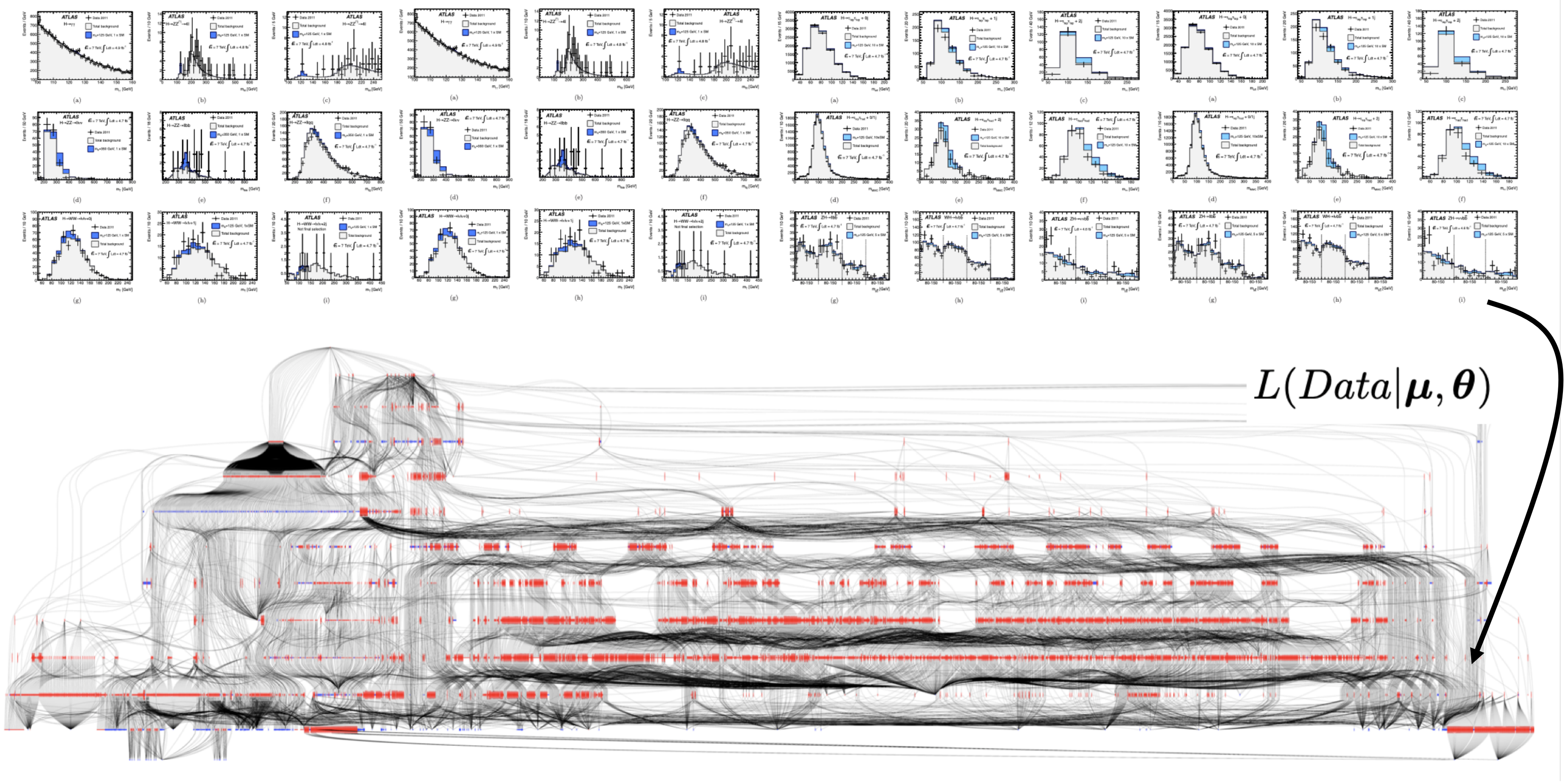


Nature publication

κ_λ [-1.25, 6.85] @ 95% CL

Putting things together

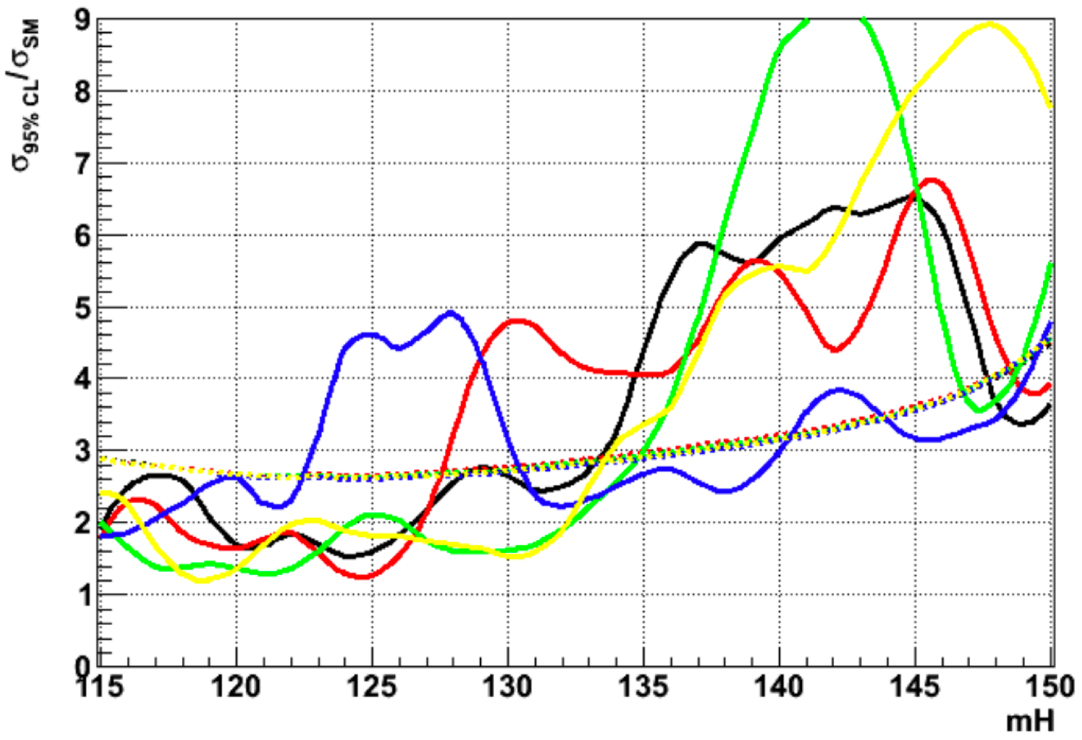
Combining multiple datasets (in this case targeting events with different Higgs production and decay) leads to extremely complicated likelihood functions



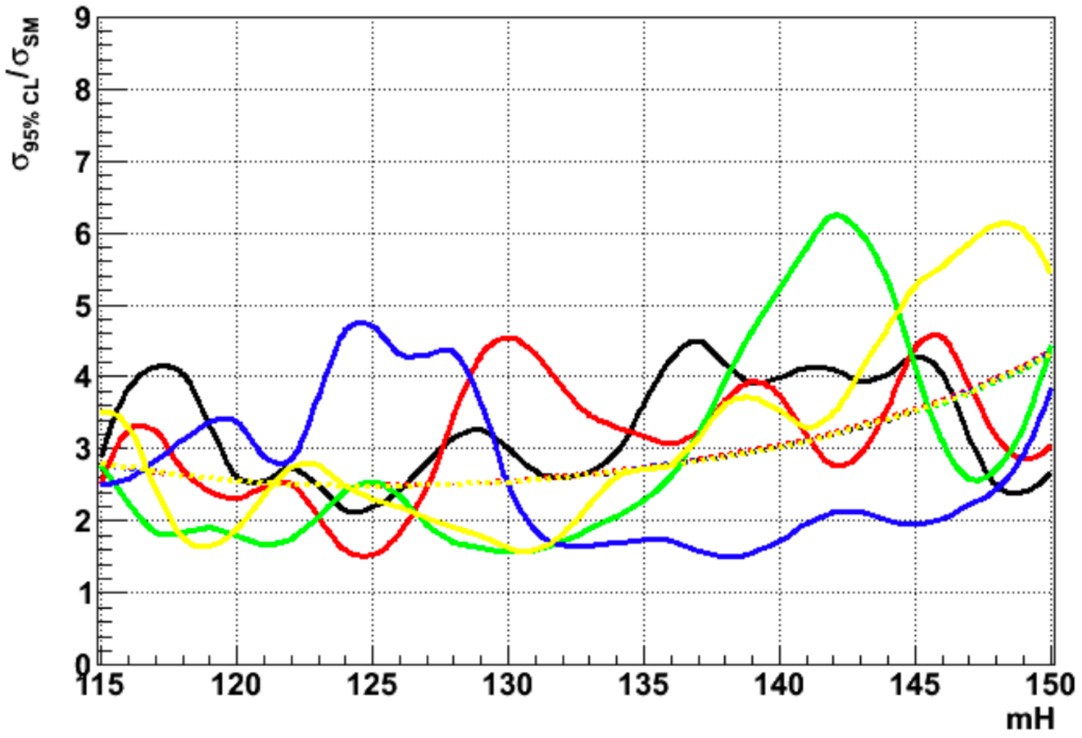
Which background function is right?

This is a figure from a study before the discovery that showed in toys how different the limits can be depending on whether you use the right function or not to fit the background

Gen Power, Fit Poly

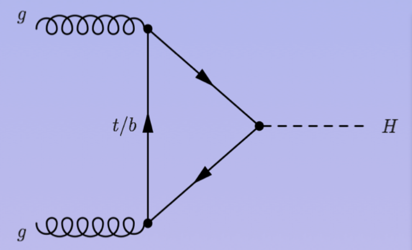


Gen Poly, Fit Power

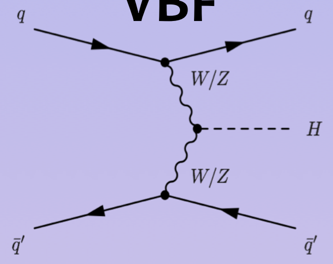


Many different ways to make and see a Higgs

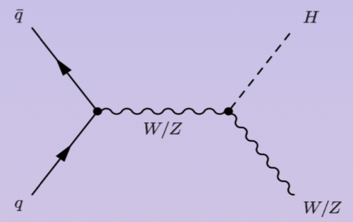
ggH

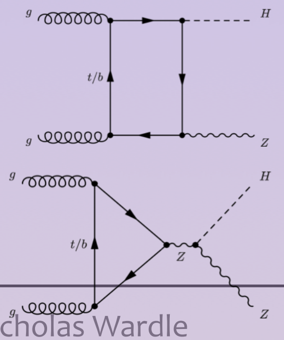


VBF



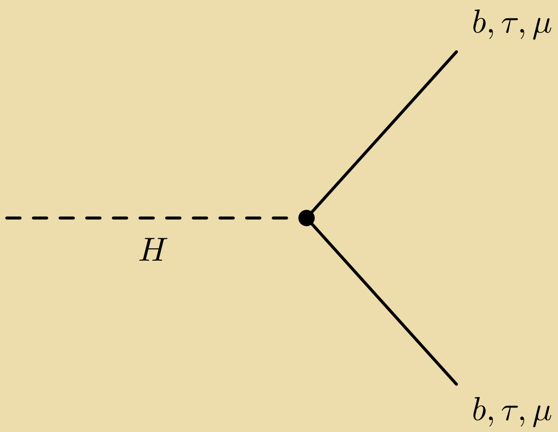
WH / ZH



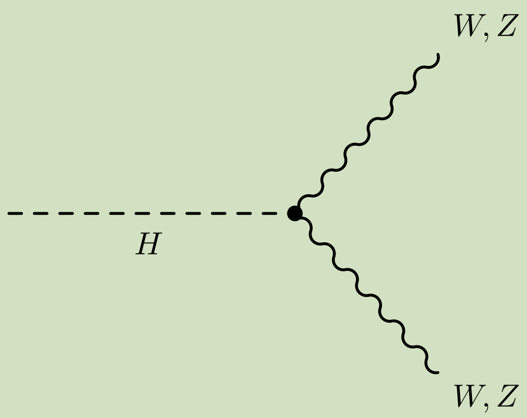


gg→ZH

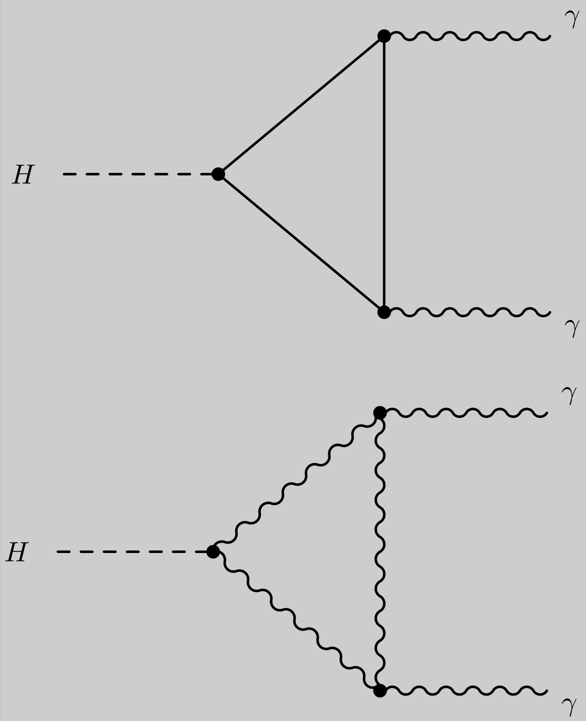
Decreasing cross-section



H→ff

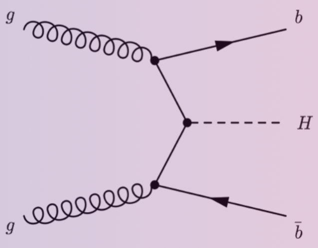


H→VV

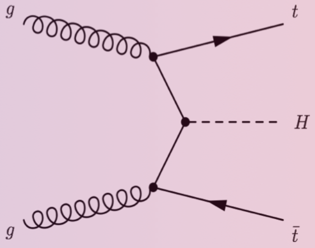


H→γγ

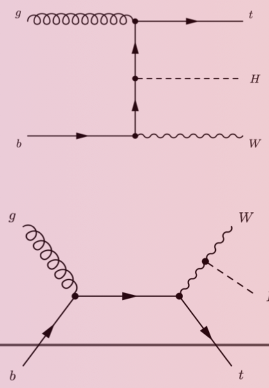
bbH



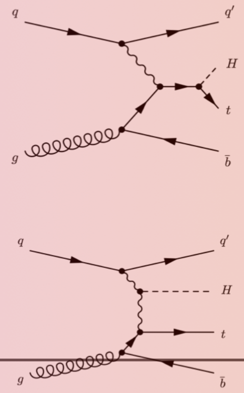
ttH



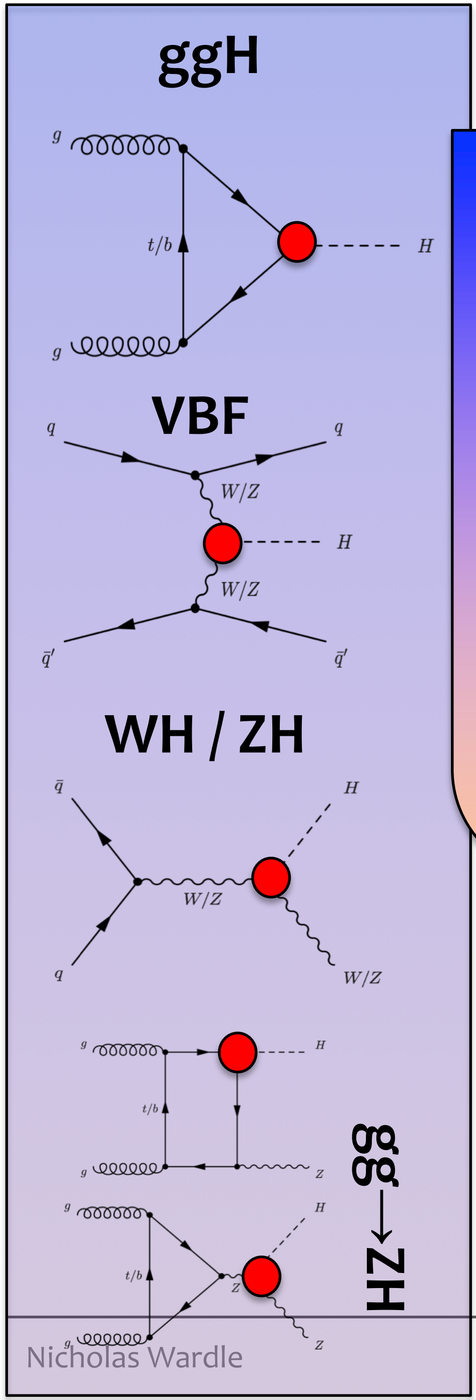
gb→tHW

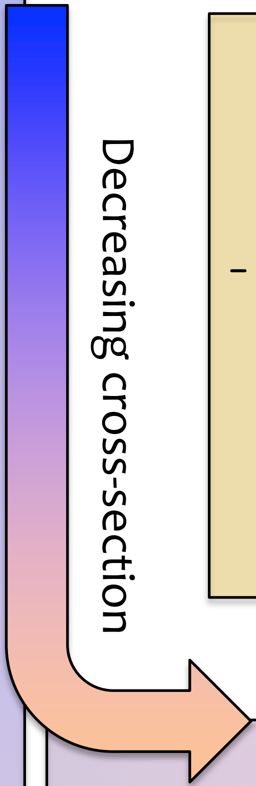


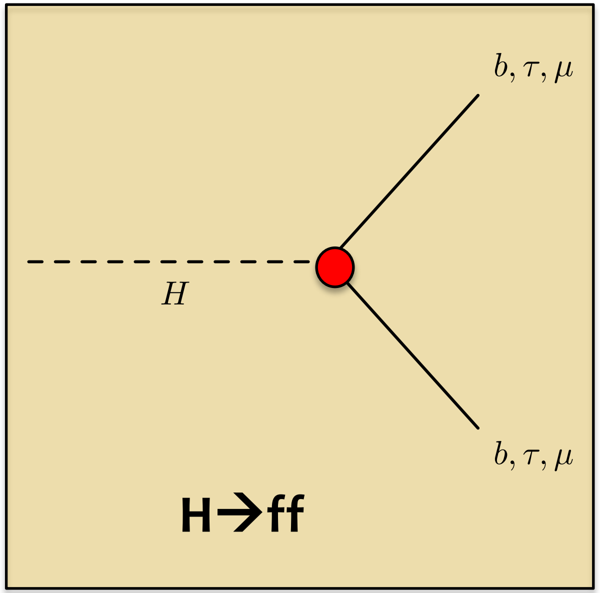
qg→tHq

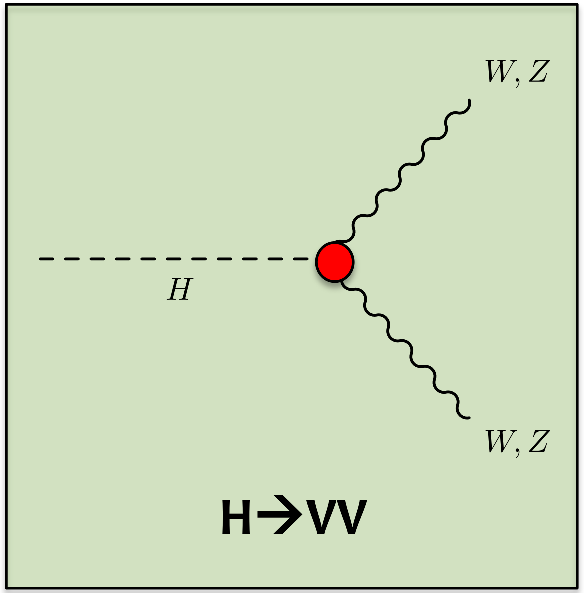


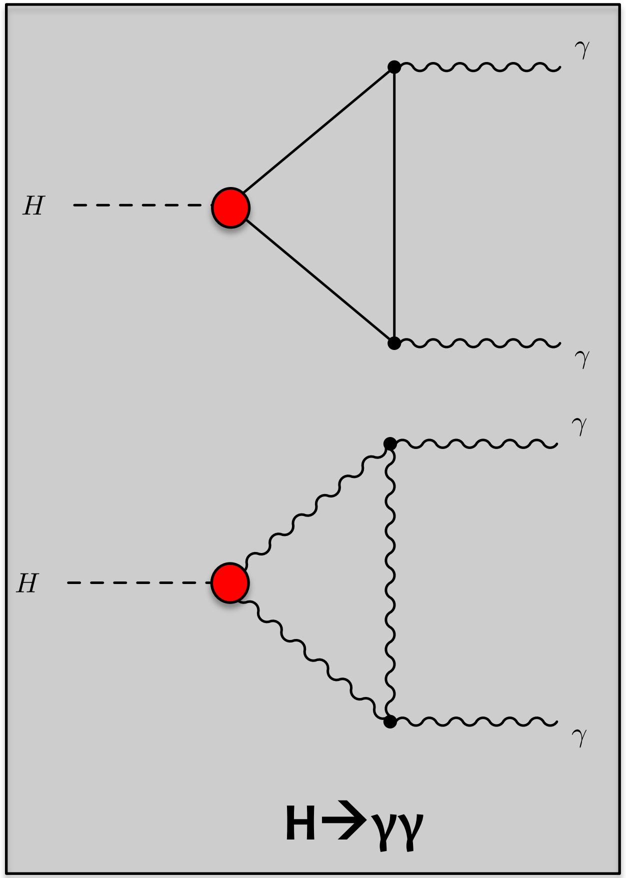
Many different ways to make and see a Higgs

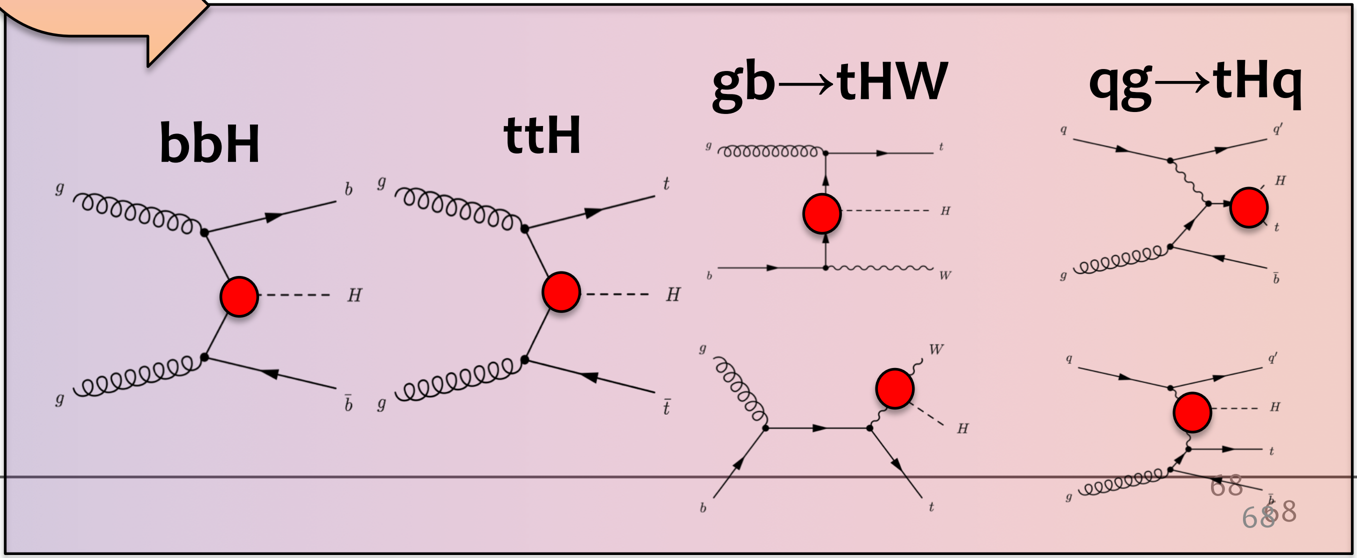






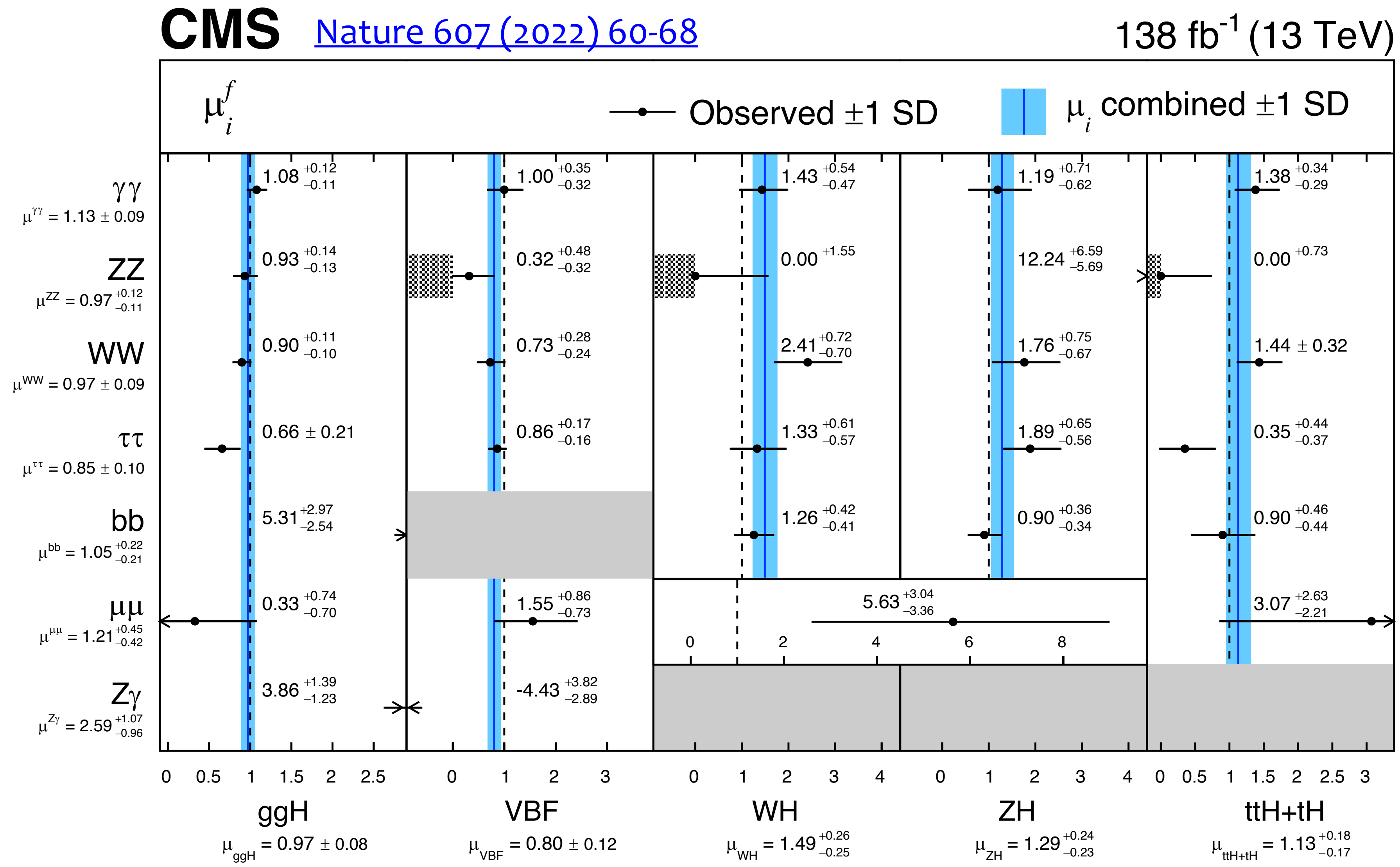






With the mass well measured we can test concrete predictions of **Higgs-SM couplings**

Detecting the different signals – An experimental challenge



Measuring the Higgs boson is a huge computational challenge!

~850 channels (categories for data each with 100s-1000s of events) with varying signal-to-noise ratios

~9500 parameters in the model to fit

Digging out the signals is only the first step …