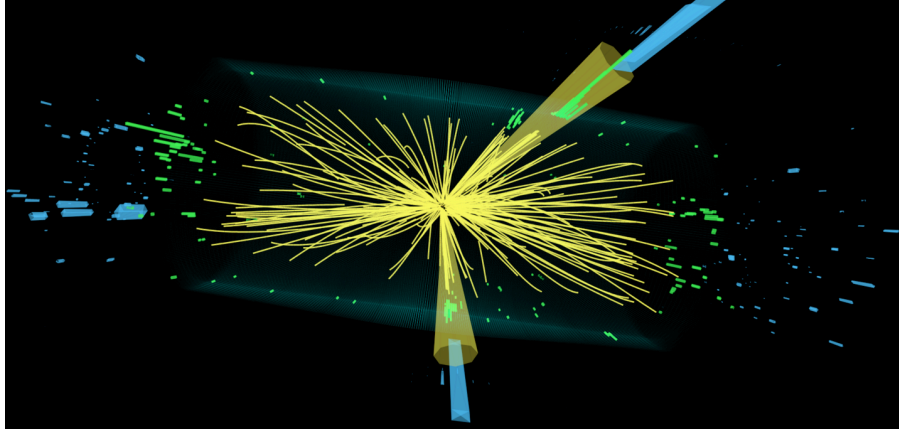


Higgs/EW physics: Experiment
Part 1

17th Hadron Collider Physics Summer School

August 17-18, 2022

Aram Apyan, Brandeis University

Introduction and goals

- Introductions: Prof. Aram Apyan
  - Email: arapyan@brandeis.edu
  - Experimental research in High-Energy Particle Physics
  - Member of CMS Collaboration 2011-2021
  - Member of ATLAS Collaboration 2021-present
- My goal is to focus on explanation of key points in context of experiment/ data analysis for Higgs/EW physics
  - I will cover personal selection of topics and results.
  - Impossible to talk about all the ATLAS/CMS/Tevatron results in this front.
  - I am also not too worried about showing the newest results.
  - I will not cover Higgs state of the art theory predictions, reconstruction and statistical techniques, etc. as these are covered in other lectures in this school.

While I am giving these lectures from Detroit area normally I can be found in one these places:

Brandeis
Abelson Building

CERN
Building 32

BNL
Building 510

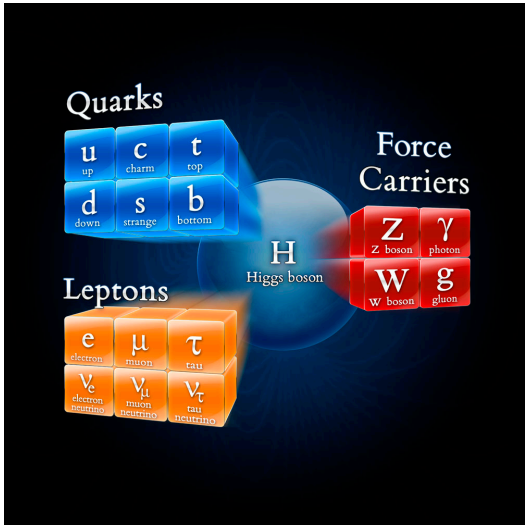
Overview

- Day-1: Higgs boson
  - What did we know before LHC?
  - How do we discover/study the Higgs boson?
  - Gauge and Yukawa couplings
  - From discovery to precision tests -> The portrait of the Higgs boson after 10 years
  - New couplings: Higgs boson self interactions

- Day-2: Electroweak physics
  - Quartic and triple gauge couplings
  - Higgs boson and Vector boson scattering
  - Precision electroweak observables
  - How do we measure the W mass?
  - How do we measure the Weinberg angle?

The Standard Model of Particles

- Building blocks: matter (fermions) and forces (bosons)



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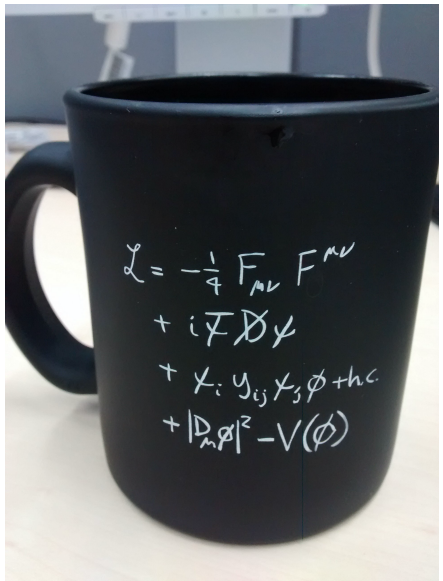
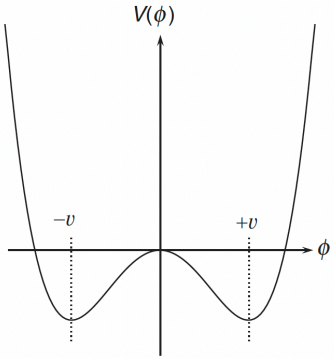
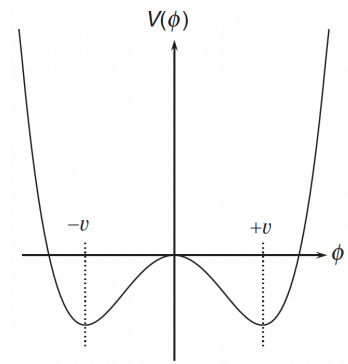


- Electroweak symmetry breaking: Responsible for generating mass of the W and Z gauge bosons
- The scalar potential: $$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$
- The scalar field is a complex $SU(2)_L$ doublet



The Standard Model Higgs boson

- CP-even scalar field: spin-0 (described by a number at every space point)
- Mass: $m_H = \sqrt{2\lambda}\, v$
- Vacuum expectation value fixed by Fermi coupling
  - $v = (\sqrt{2}G_F)^{-1/2} \approx$ 246 GeV
- λ is the self coupling parameter
  - Free parameter in the SM!
    - No a-priori prediction for the Higgs mass



$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- The SM Higgs boson couplings: 3 fundamental interactions

$$g_{Hf\bar{f}} \equiv y_f = \frac{m_f}{v}, \; g_{HVV} = \frac{2m_V^2}{v}, \; g_{HHVV} = \frac{2m_V^2}{v^2}, \; g_{HHH} = \frac{3m_H^2}{v}, \; g_{HHHH} = \frac{3m_H^2}{v^2},$$

Yukawa interactions (Fermions)

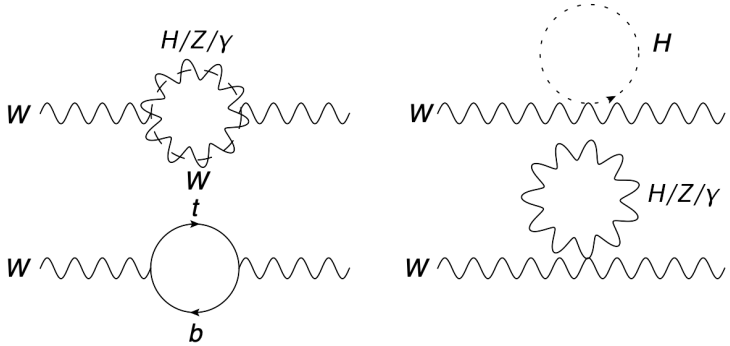
Gauge couplings (Massive bosons)

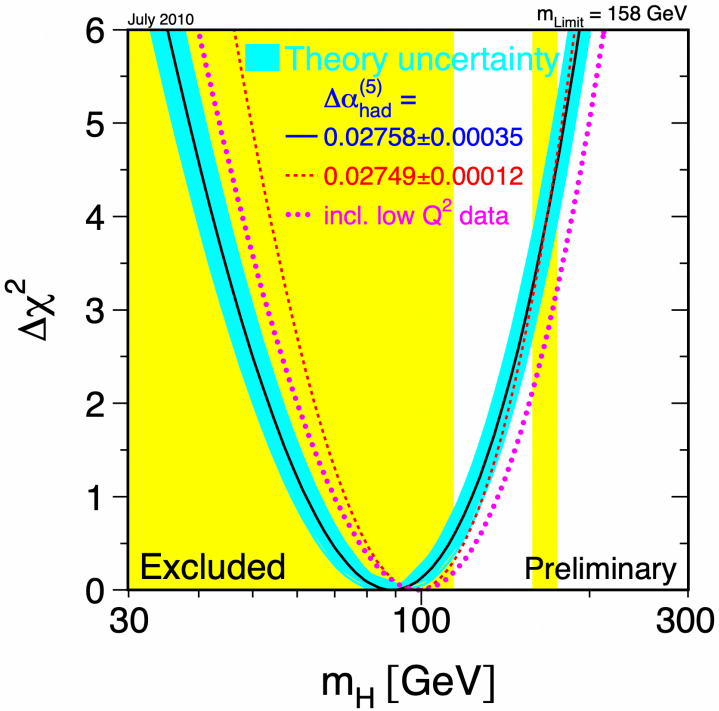
Self-interactions

- New type of interaction
  - Weak for light particles (up/down quarks, electrons)
  - Strong for heavy particles (W/Z bosons, top quark)

Clues about the Higgs mass before the discovery

- Constraints from precision measurements preferred light Higgs
  - Discovery of the top quark
  - Measurement of the W mass at LEP and Tevatron
  - Precise data from LEP and SLD





- Radiative corrections to the W mass
  - Quadratic dependence on top mass
  - Logarithmic dependence on Higgs mass

Final Electroweak Working Group Report 2010

Clues about the Higgs mass before the discovery

- Constraints from precision measurements
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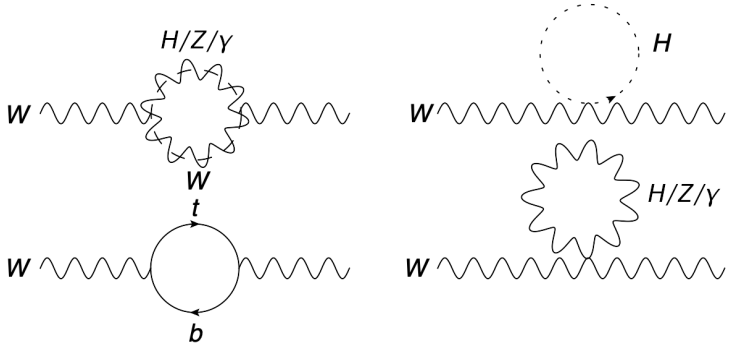
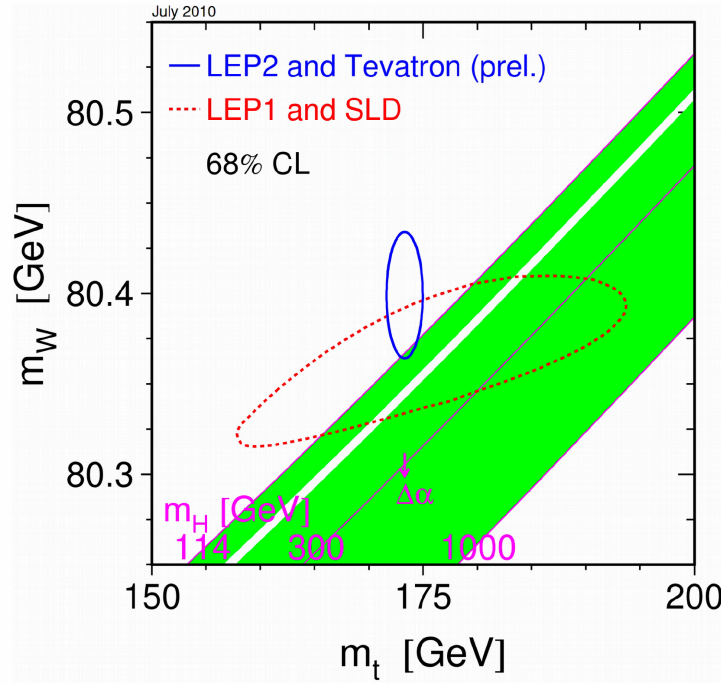


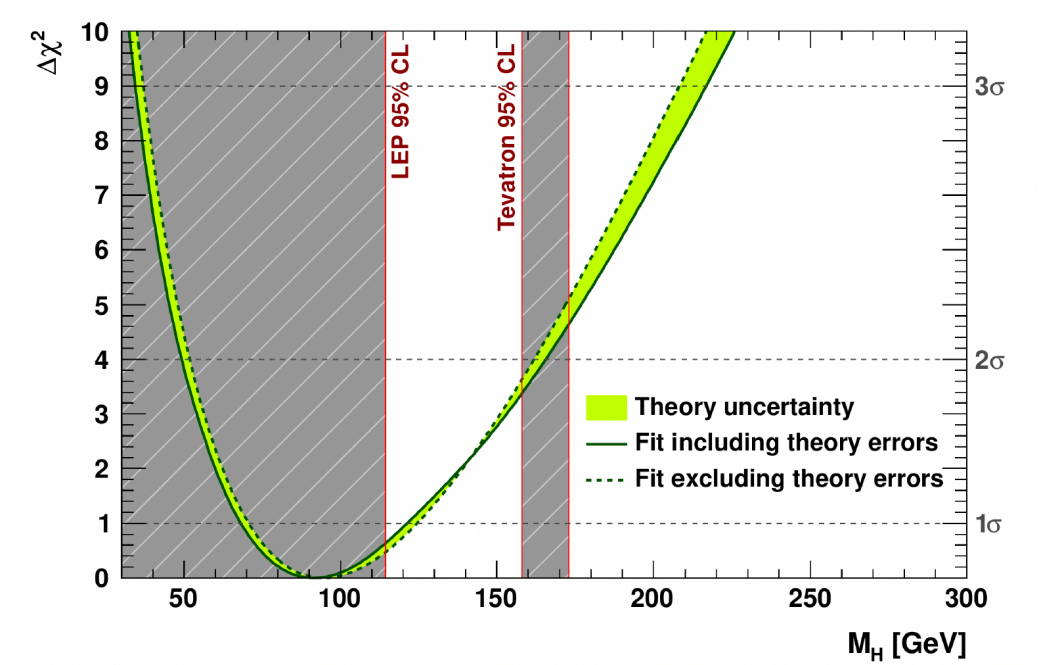


- Radiative corrections to the W mass
  - Quadratic dependence on top mass
  - Logarithmic dependence on Higgs mass

Final Electroweak Working Group Report 2010

Theoretical and experimental constraints

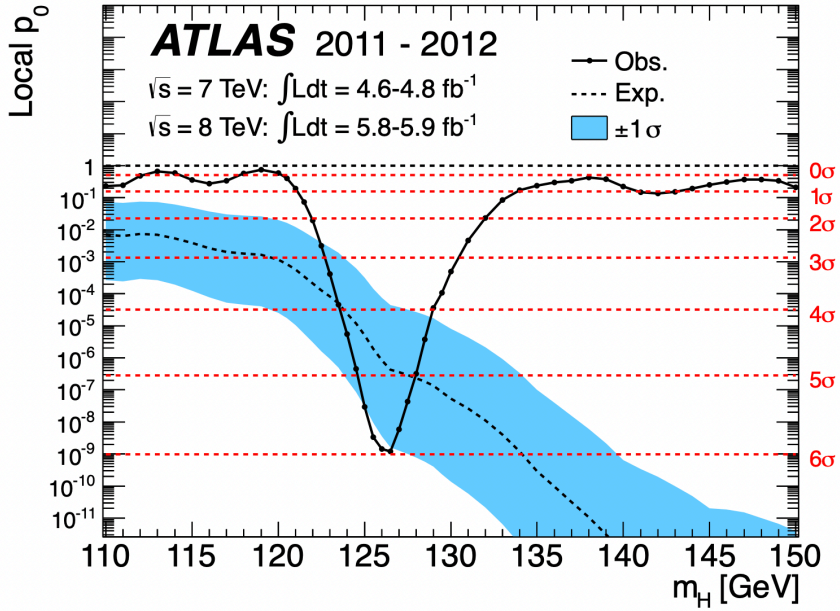
- Picture before the discovery:

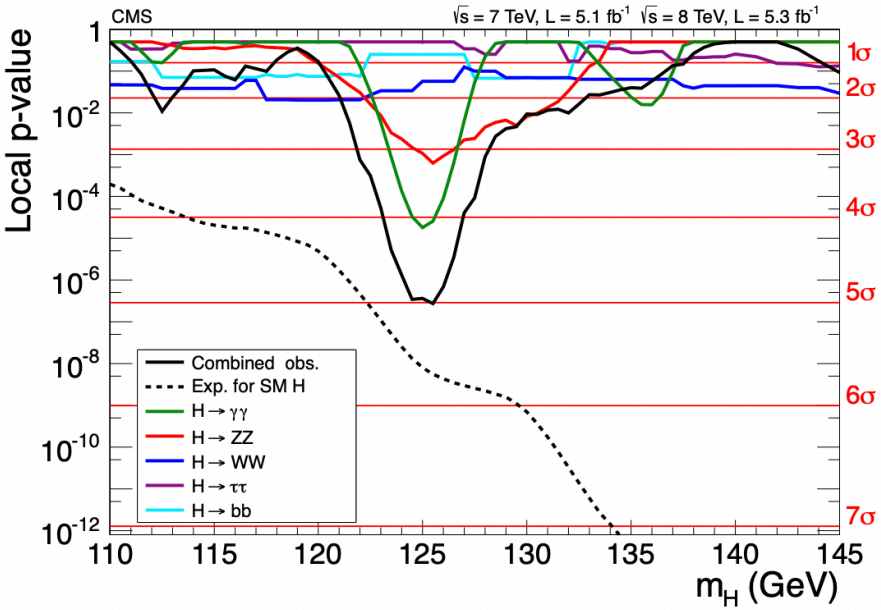


- Theoretical considerations (unitarity) require the mass to be < ~1 TeV
  - We will come back to this tomorrow
- Exclusions from direct searches at LEP experiments (limited by beam energy). Small intermediate region excluded by Tevatron.

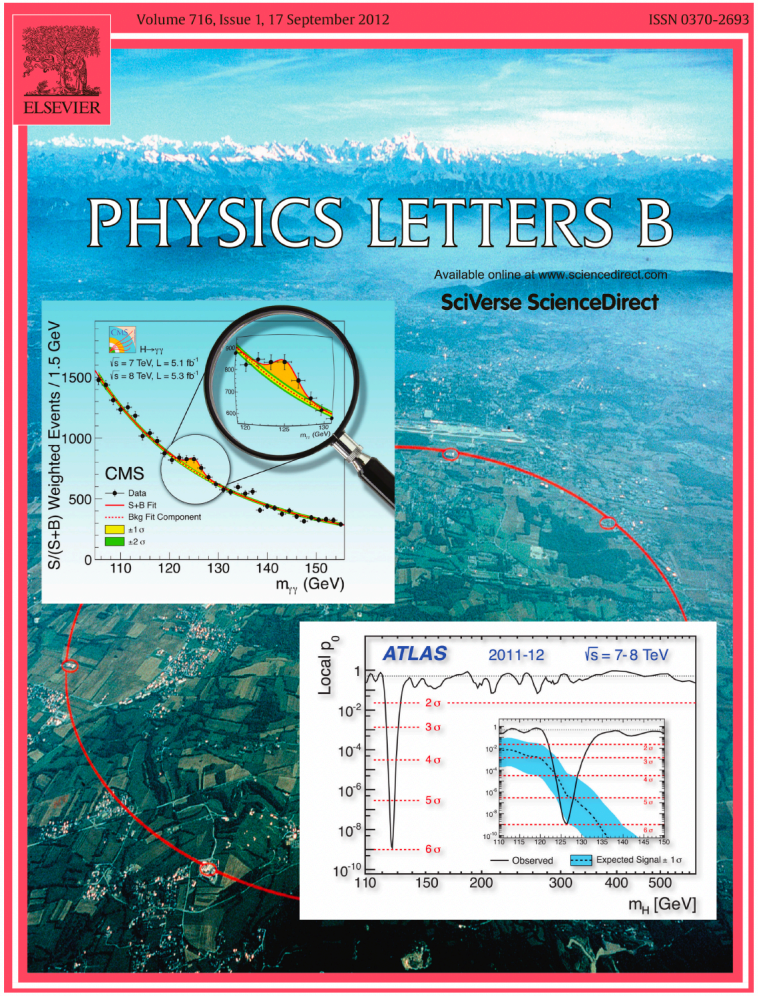
Discovery of a new particle at the LHC

- An excess of events around 125 GeV reported by ATLAS and CMS Collaborations on July 4th, 2012
  - New Higgs-like particle discovery





Higgs Discovery



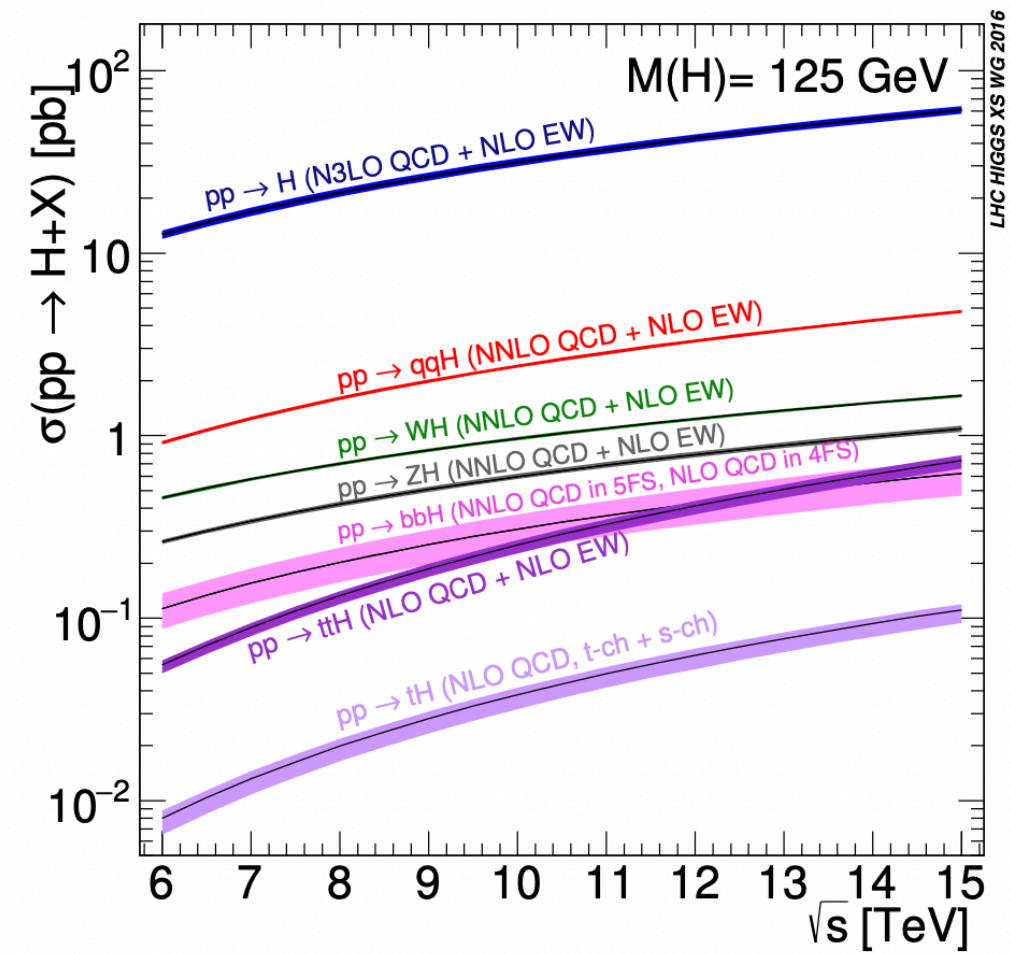
- Discovery of the Higgs announced July 4, 2012

Higgs Discovery

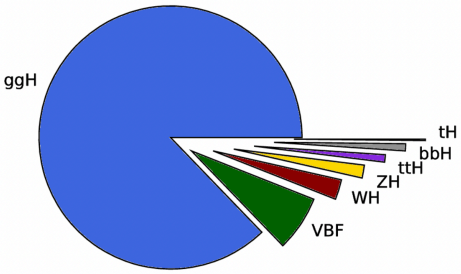
Nobel prize in physics 2013

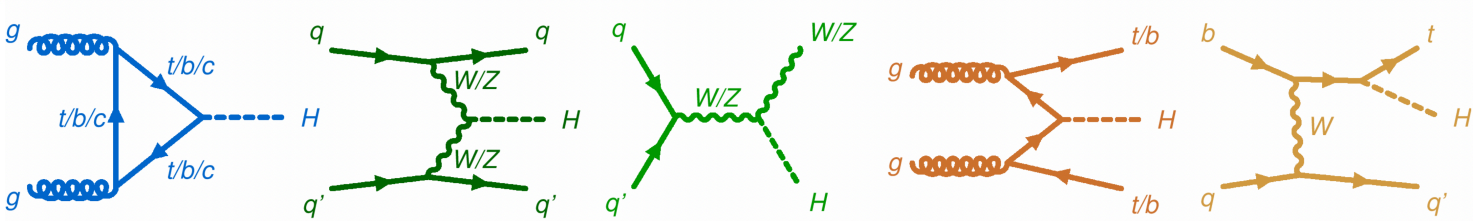
Two nobel theorists

Higgs Production at the LHC

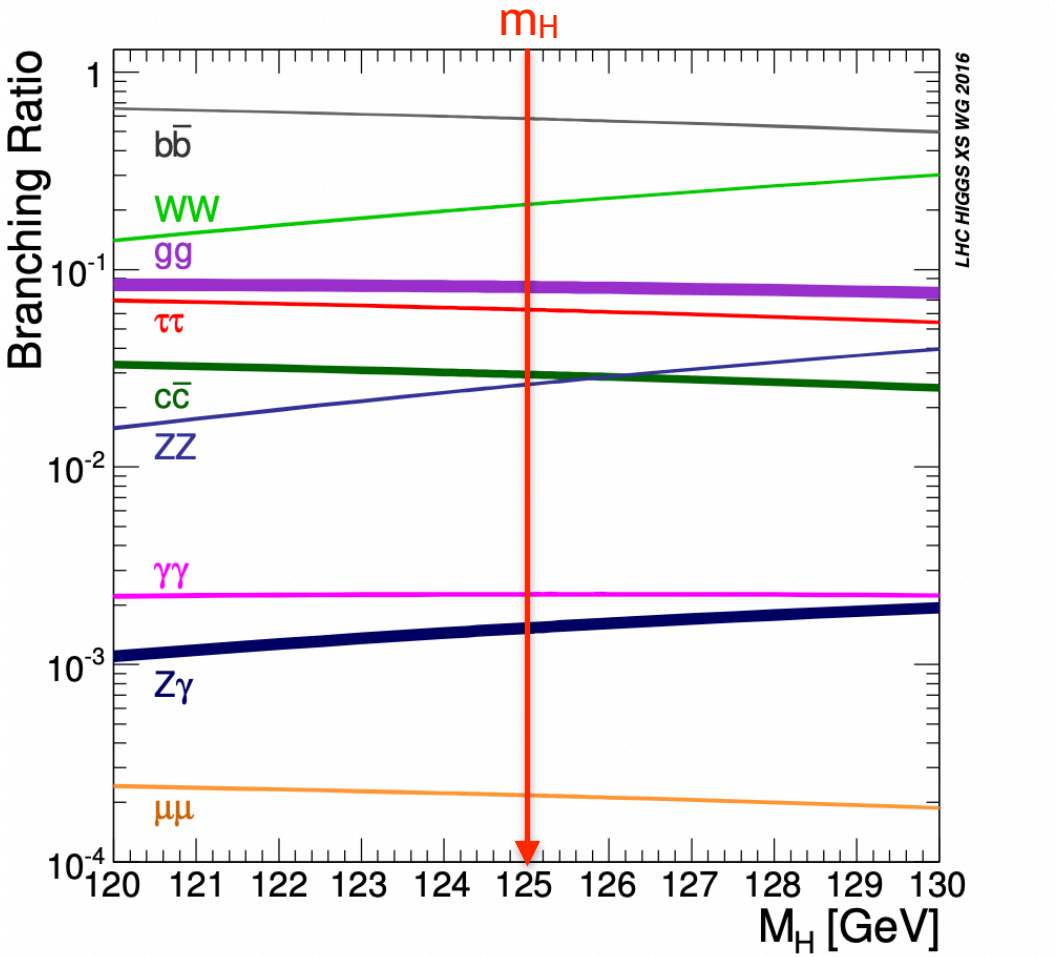


Production mode	Cross section (pb)
ggH	48.31 ± 2.44
VBF	3.771 ± 0.807
WH	1.359 ± 0.028
ZH	0.877 ± 0.036
ttH	0.503 ± 0.035
bbH	0.482 ± 0.097
tH	0.092 ± 0.008

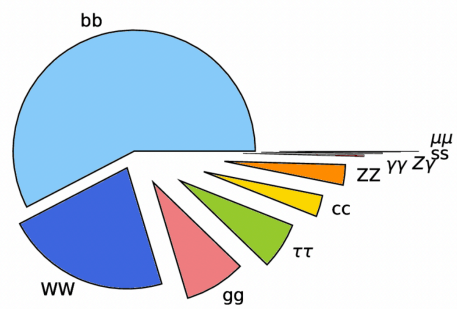


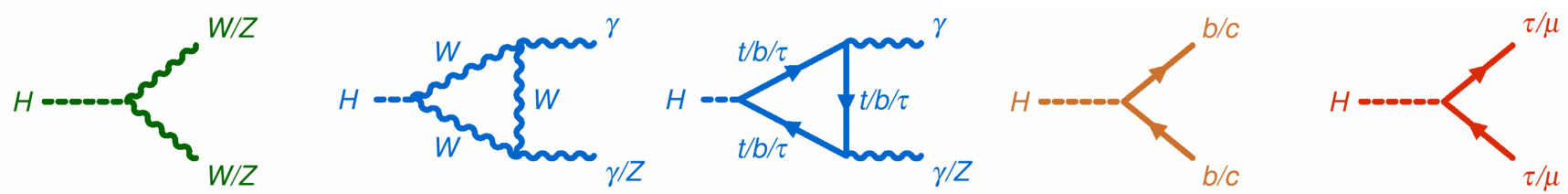


Higgs Branching Fractions



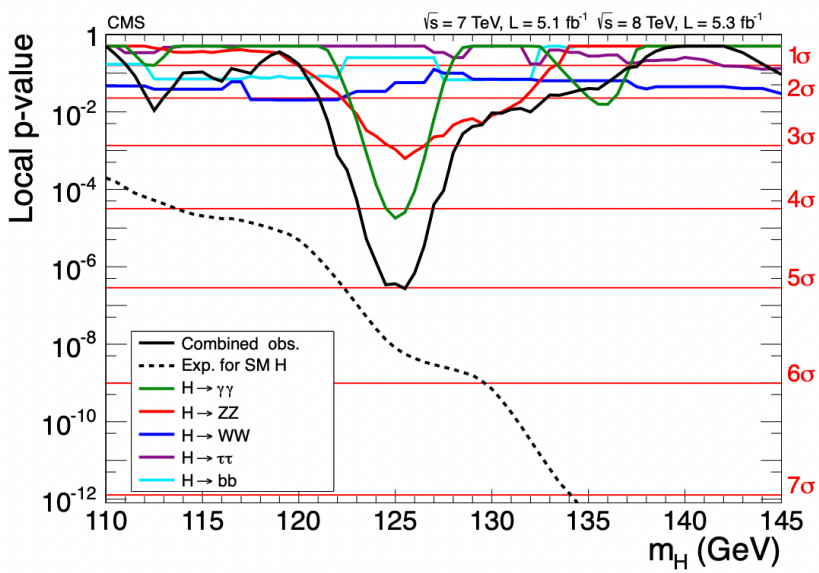
Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
$\tau\tau$	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
$\gamma\gamma$	0.227 ± 0.005
$Z\gamma$	0.157 ± 0.009
ss	0.025 ± 0.001
$\mu\mu$	0.0216 ± 0.0004





Discovery channels

- Higgs hunting with five channels
- But two channels played a special role in the search and discovery of the Higgs boson
  - H->ZZ->4l and H->$\gamma\gamma$
  - Fully reconstructed final states (no neutrinos)
  - Excellent energy/momentum resolution (inner tracking and electromagnetic calorimeters)



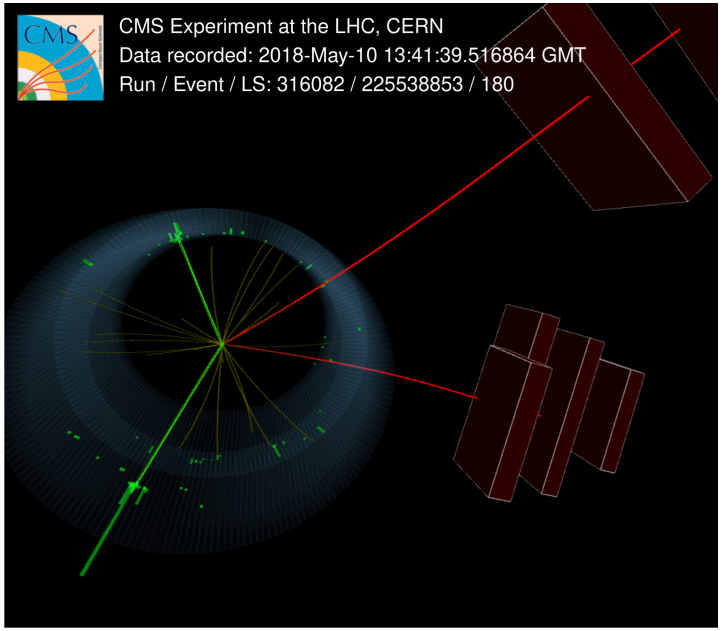
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$$

$$\sigma_{m_{\gamma\gamma}}/m_{\mathrm{H}} \approx 1\%$$

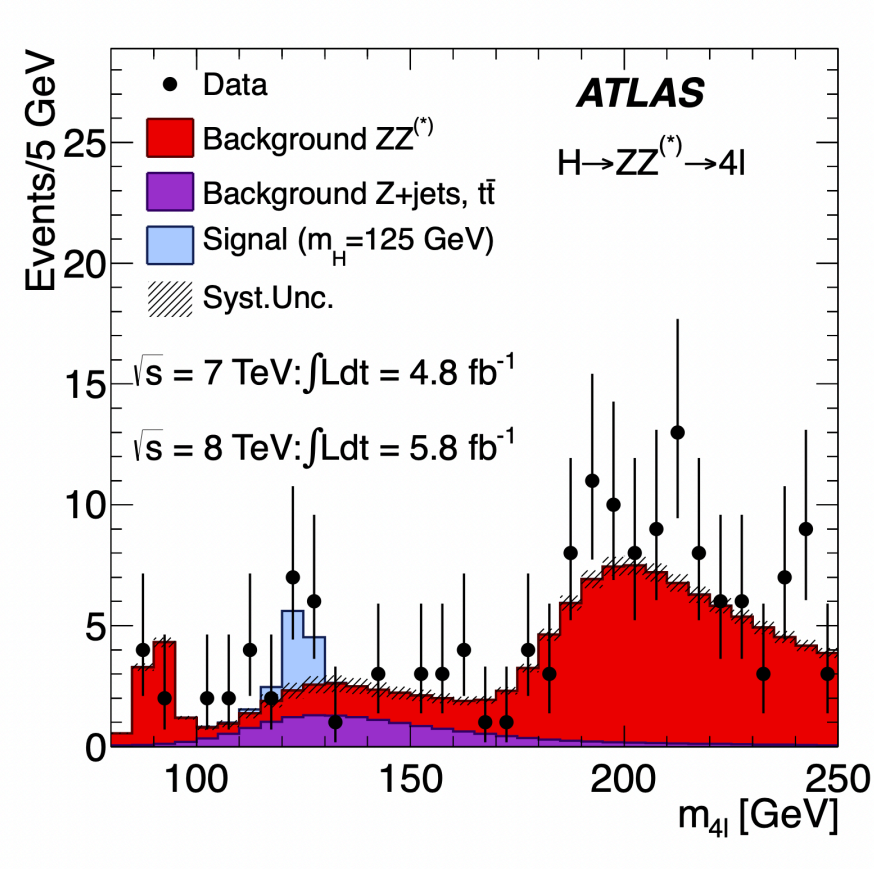
$$\sigma_{m_{4\ell}}/m_{\mathrm{H}} \approx 1\%$$

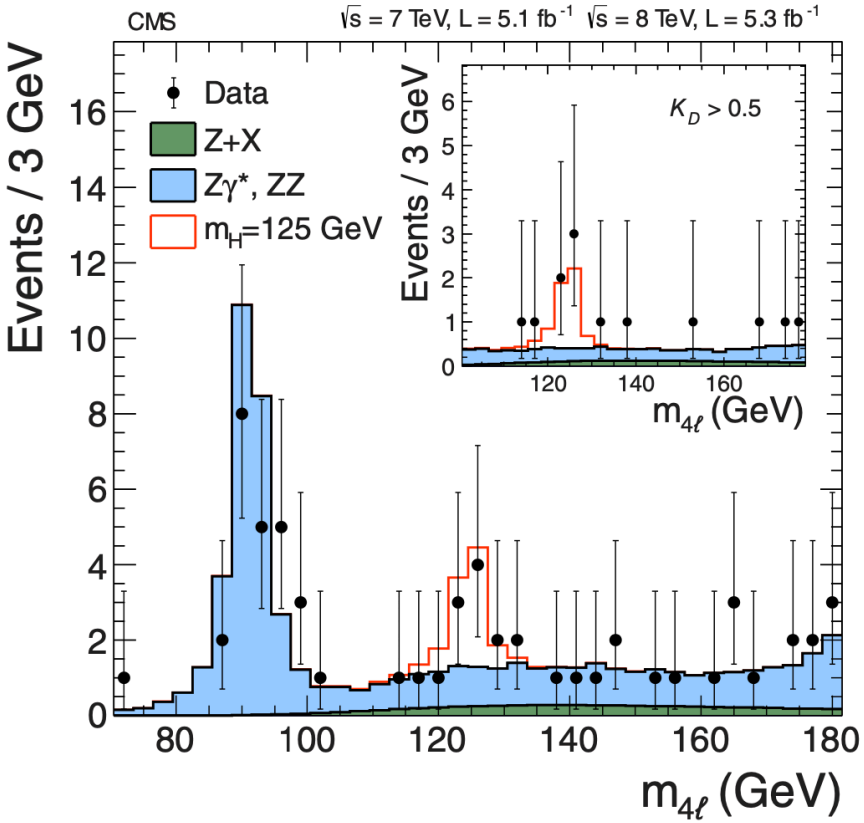
The golden channel, H->ZZ->4l

- Total branching fraction (including Z decays to electrons and muons) is small (~5×10^{-5})
- Select 4 isolated leptons (electrons/muons) consistent with Z decays
  - SM background contributions are very small (non-resonant ZZ production and 'reducible background' with mis-identified leptons (Zbb, tt->bb2l2nu)
    - Leptons from b-decays are non-isolated and displaced

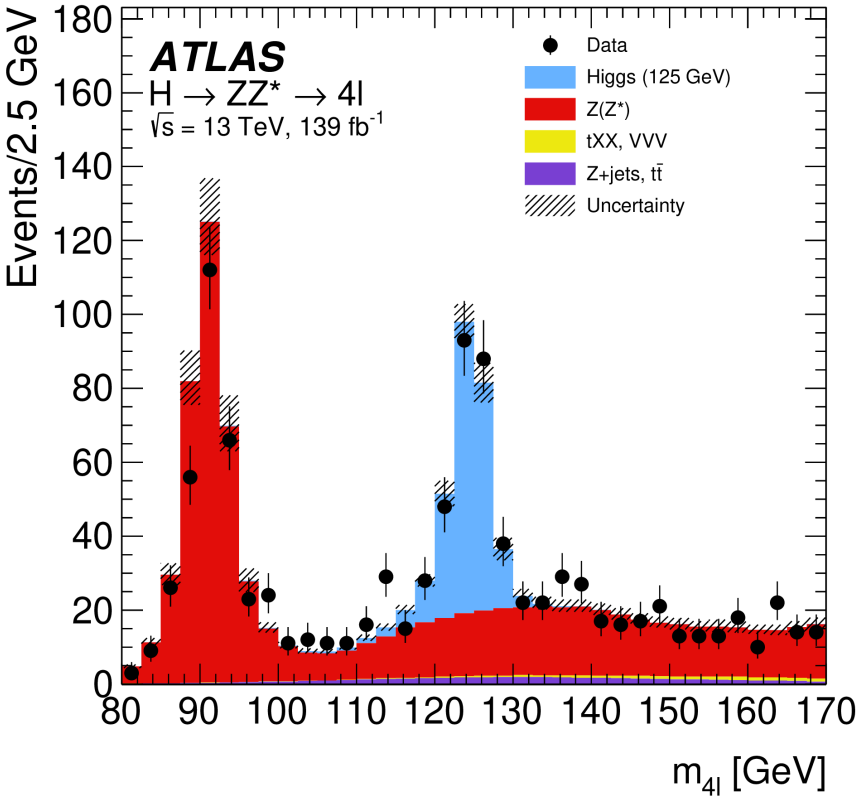


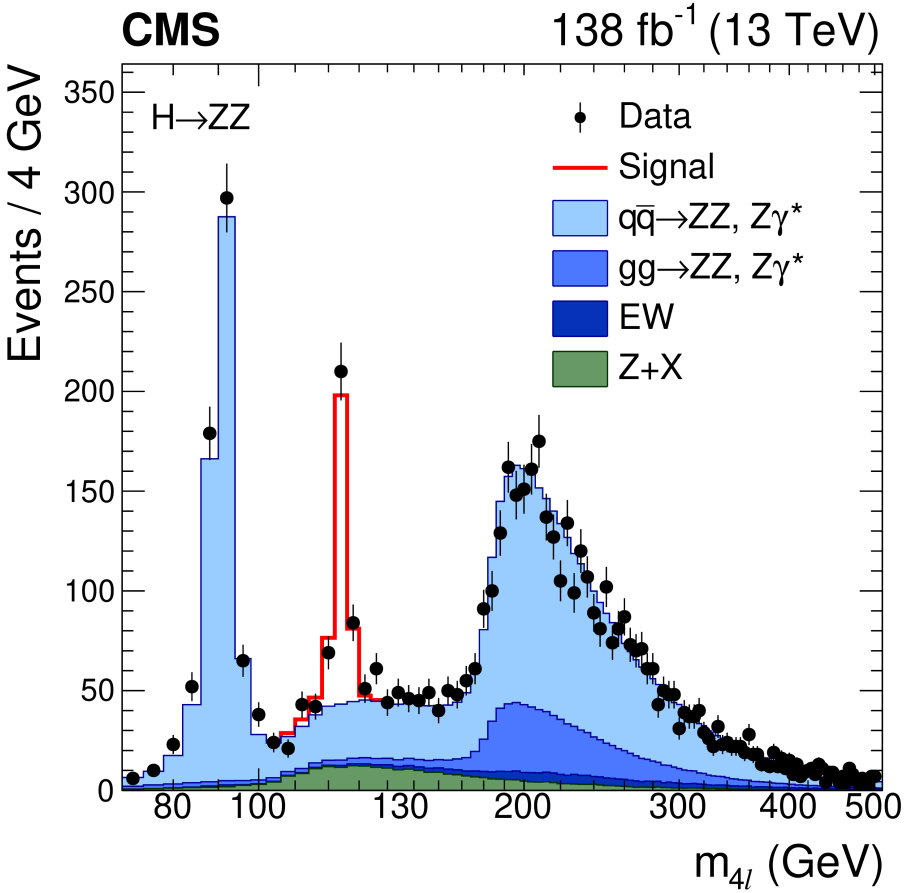
H->ZZ->4l: at the time of discovery



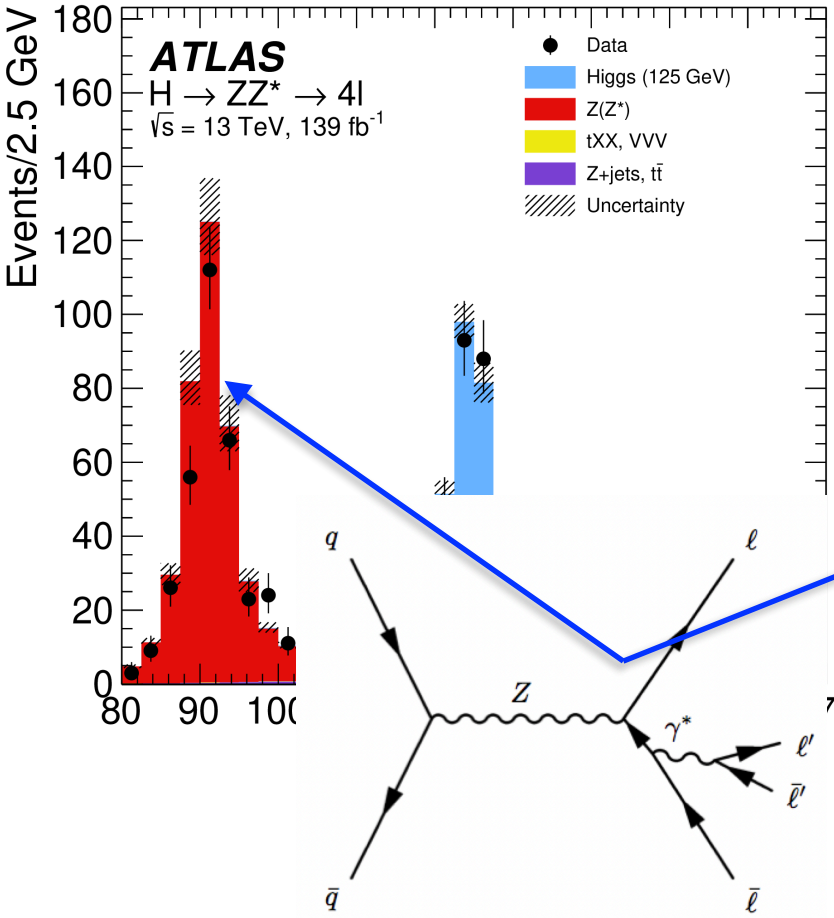


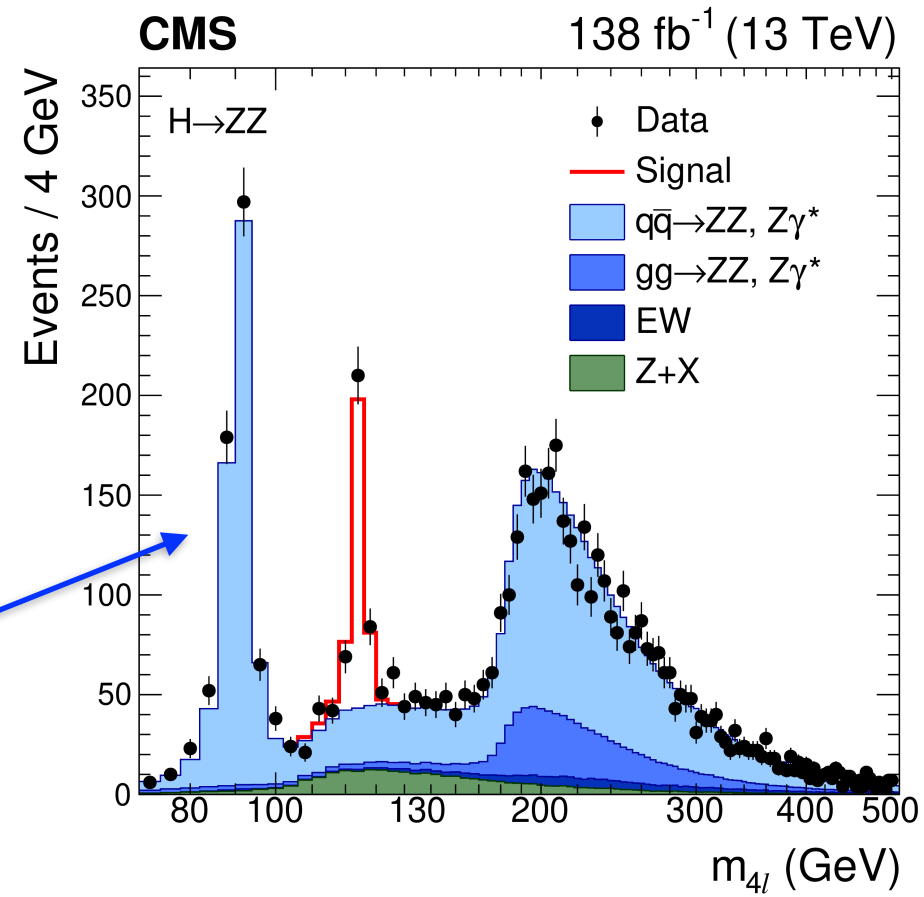
H->ZZ->4l: with full Run 2 data





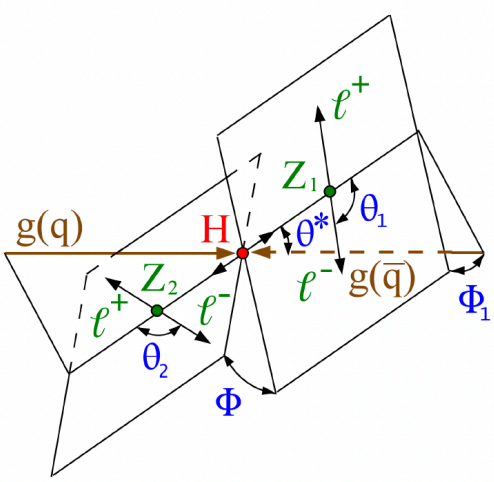
H->ZZ->4l: with full Run 2 data

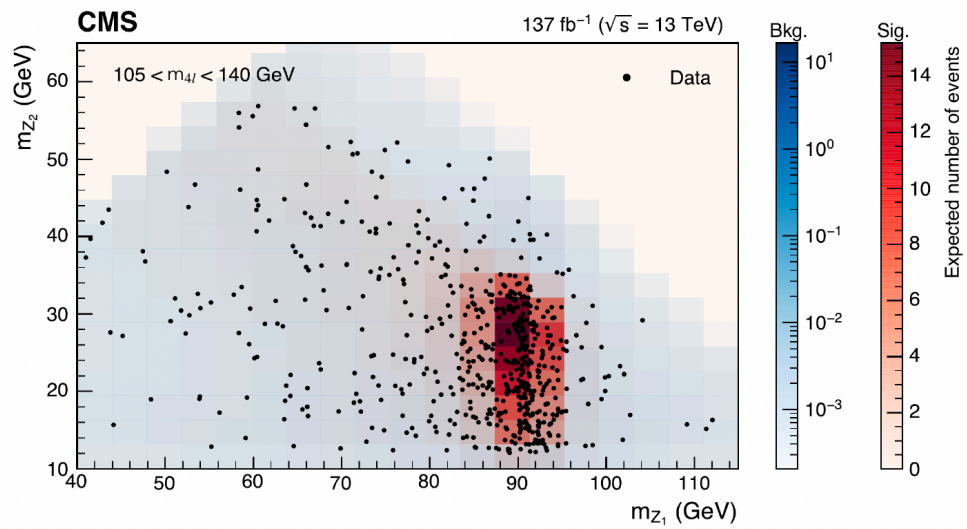




H->ZZ->4l

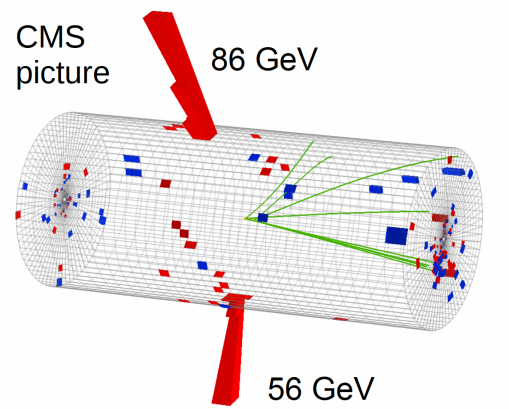
- Masses of the lepton pairs and decay angles contain additional information which can discriminate against the background
  - Can be used in Matrix element likelihood discriminators or machine learning classifiers
    - Sensitive to various spin/parity hypotheses. The data is compatible with spin-0, CP-even

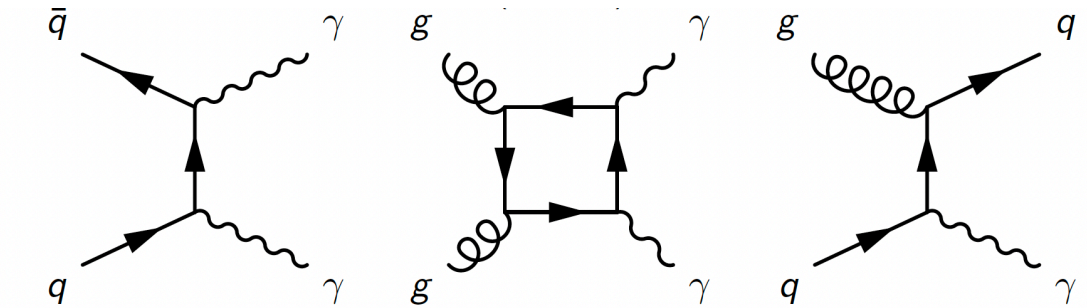




H->$\gamma\gamma$

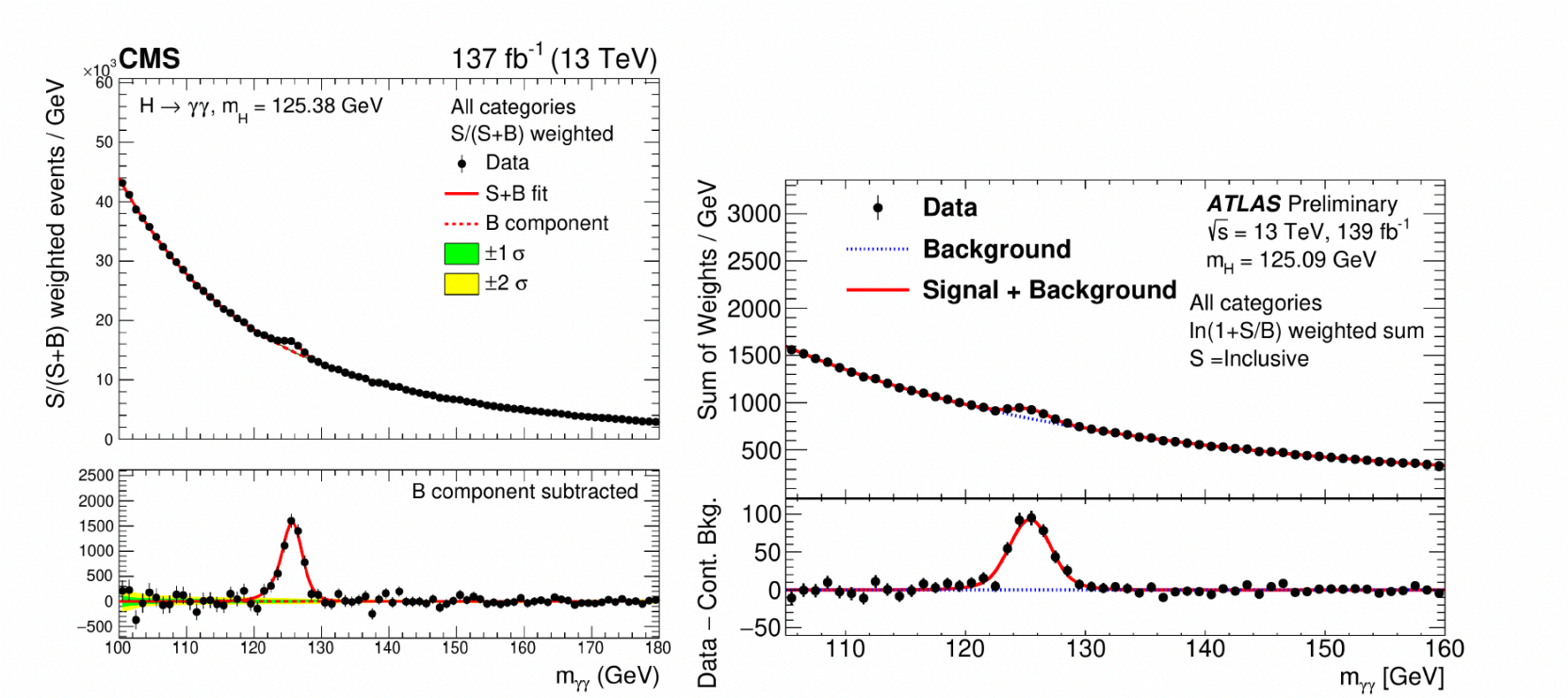
- Small branching fraction ~2 x10^{-3} but larger than H->ZZ->4l
  - Two high momentum photons. Looking for a narrow peak
  - Significant background contributions
    - Irreducible $\gamma\gamma$ and reducible γ + jet backgrounds
  - Primary vertex finding is challenging
- Key analysis features:
    - Machine learning techniques for photon identification and energy regression





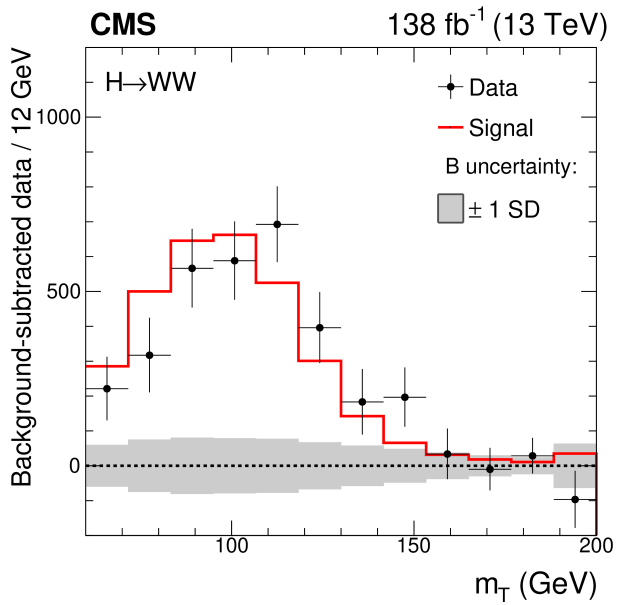
H->$\gamma\gamma$

- Peak appears over falling background
  - Multiple event classes are fitted for signal. The plot is weighted S/S+B to account for different quality of event classes



H->WW->2l2nu

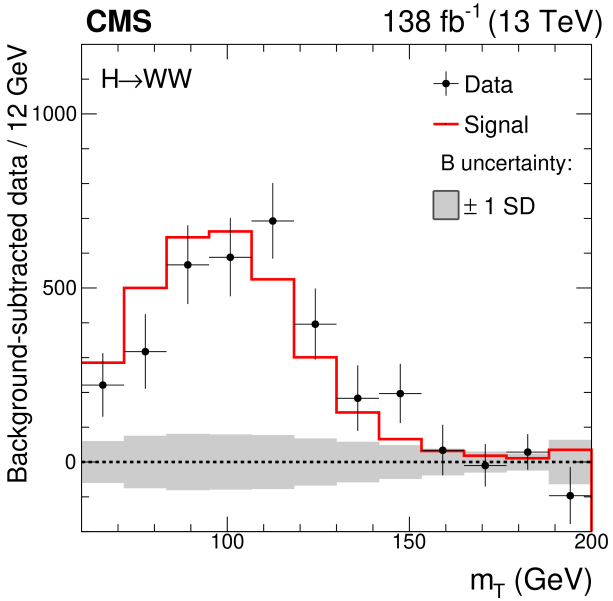
- Relatively large branching fraction
- Signature: 2 opposite charged leptons (electrons or muons)
  - Two neutrinos -> missing transverse momentum (MET)
    - No Higgs mass peak
- Significant backgrounds mainly from WW, top, W+jets with one misidentified lepton
  - Backgrounds estimated from dedicated control regions

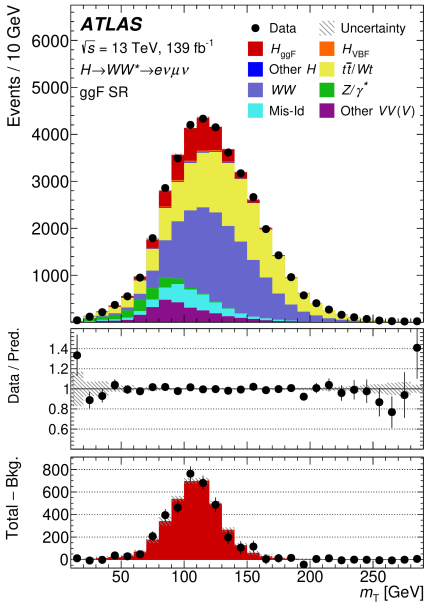


H->WW->2l2nu

- Relatively large branching fraction
- Signature: 2 opposite charged leptons (electrons or muons)
  - Two neutrinos -> missing transverse momentum (MET)
    - No Higgs mass peak but transverse mass can be computed
- Significant backgrounds mainly from WW, top, W+jets with one misidentified lepton
  - Backgrounds estimated from dedicated control regions

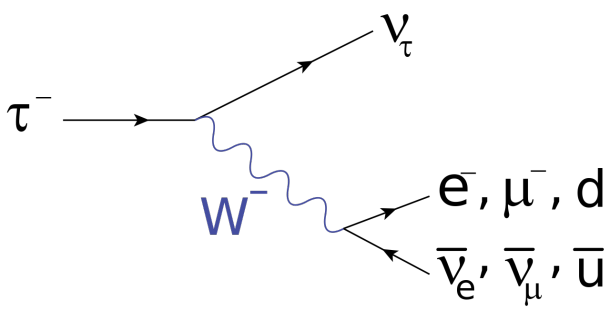
$$m_{\mathrm{T}}^2([P_i]) = (\sum|\vec{p}_{\mathrm{T},i}|)^2 - |\sum \vec{p}_{\mathrm{T},i}|^2$$

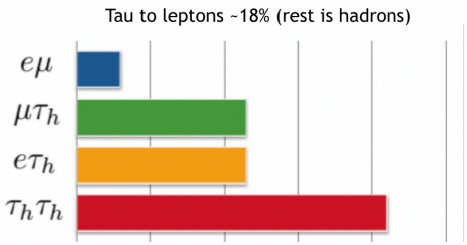


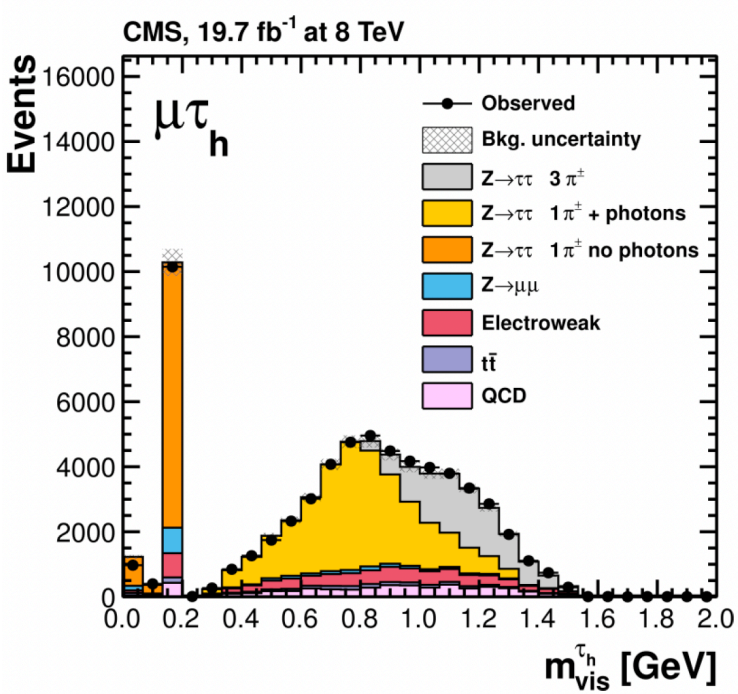


Yukawa couplings (part 1)

- Higgs couplings to leptons?
- Tau is the heaviest lepton. H->ττ branching fraction is about 6%
  - But tau also decays hadronically. Hadronically decaying tau identification is challenging (deep neural networks are now used)
  - Neutrinos in the final state complicate the di-tau reconstruction
    - Combine visible products with MET via kinematic fits, etc.

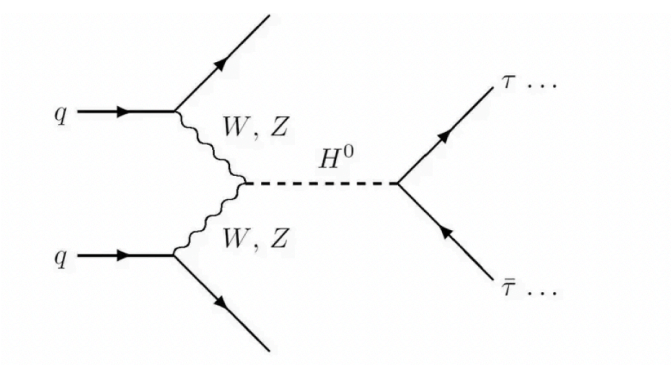


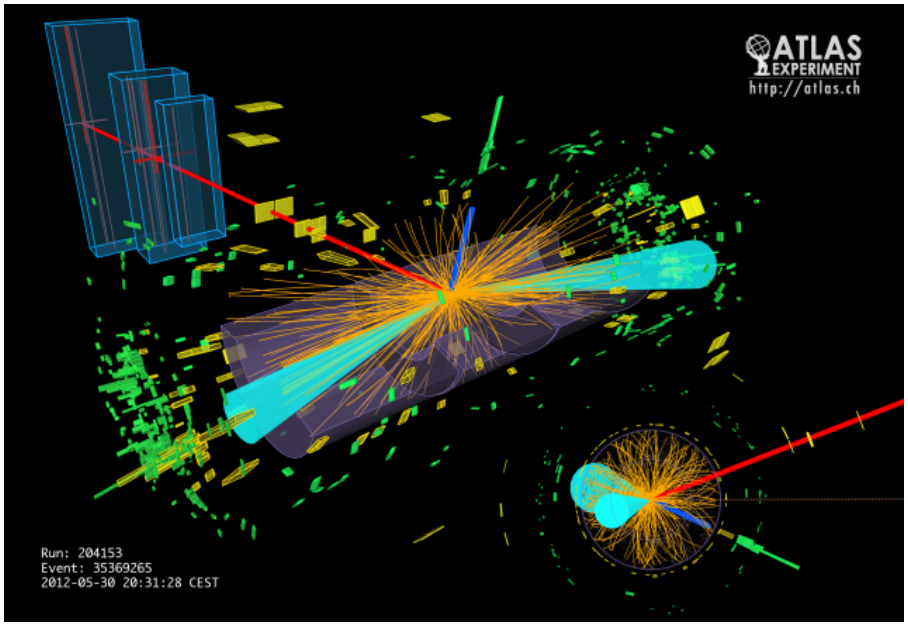




H->ττ analysis

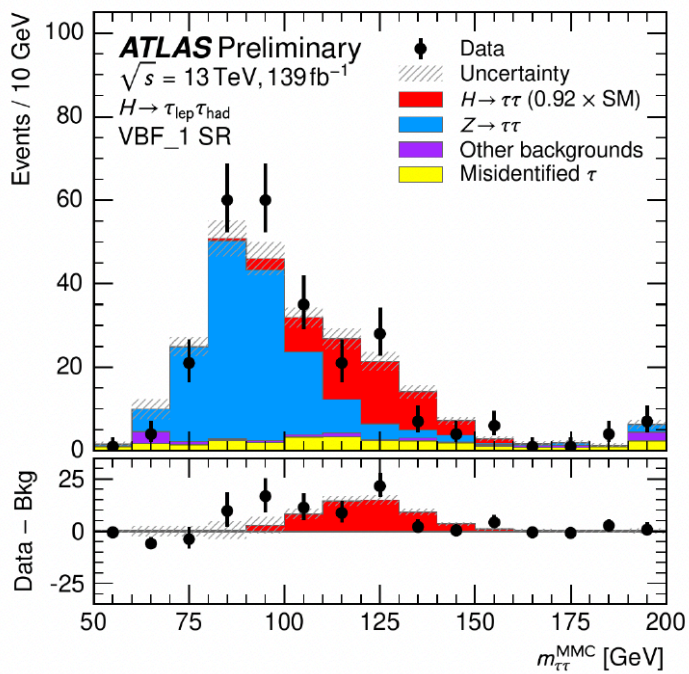
- Large background contribution and the mass resolution is not great
- Vector boson fusion (VBF) production provides additional constraints
  - Two forward jets with large rapidity gap (color singlet exchange)
- Events further categorized according to production
  - Additional leptons (VH production), additional jets in the event to target boosted topologies, etc.

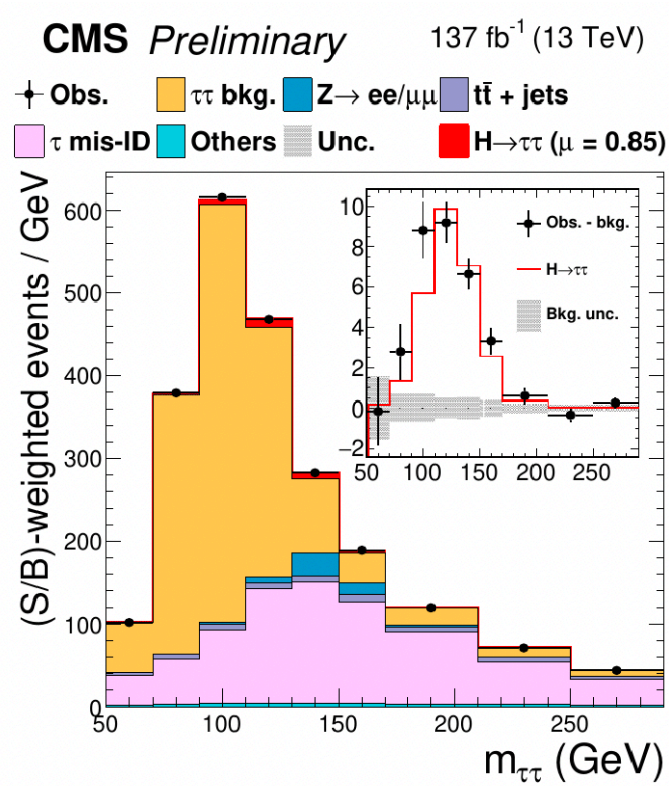




H->ττ results

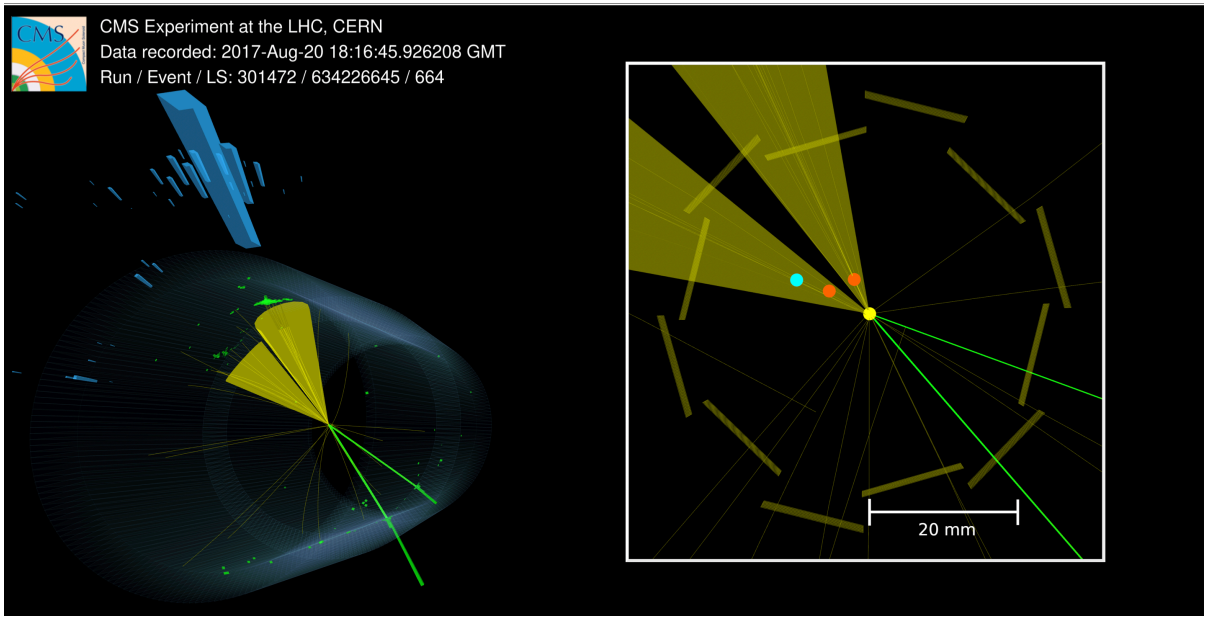
- Already at Run 1 evidence of Higgs coupling to taus with > 3 standard deviations
- Cross section measurements with full Run-2 data set





Yukawa couplings (part 2)

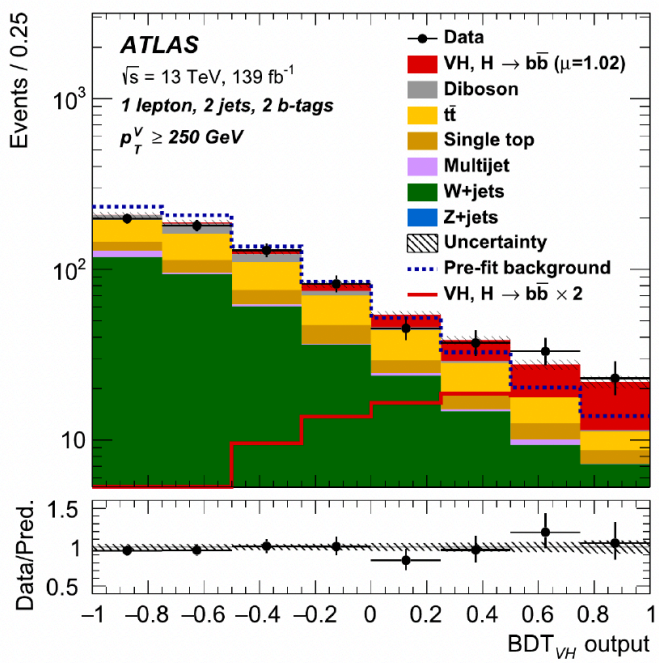
- Higgs boson decays to quarks?
  - H->bb decays account for ~60% of Higgs decays as b-quark is heavy
  - But it hadronizes into a jet and everything is a jet at the LHC
    - Huge QCD backgrounds
- The good news is that b-hadrons are long lived and often produce displaced particle tracks, secondary vertices, soft leptons
  - Use deep neural networks to tag the jets originating from b quarks

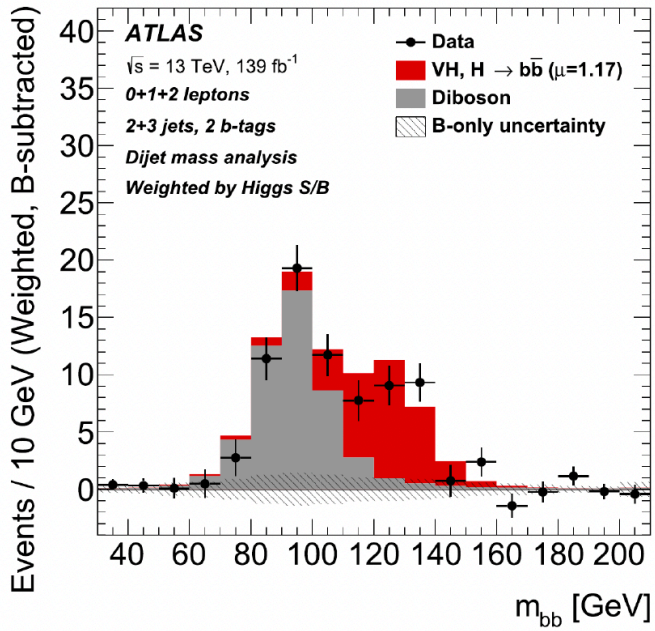


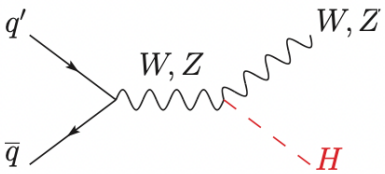
ZH->bb candidate
Green lines: electrons
Yellow cones: bjets
Red dots: displaced secondary vertices
Cyan dot: b->c->X

H->bb measurements

- Analysis key idea:
  - Use additional handles to reduce the huge QCD background
    - Associated production where W or Z boson decays to electrons, muons, neutrinos
    - 0-lepton, 1-lepton, and 2-lepton categories



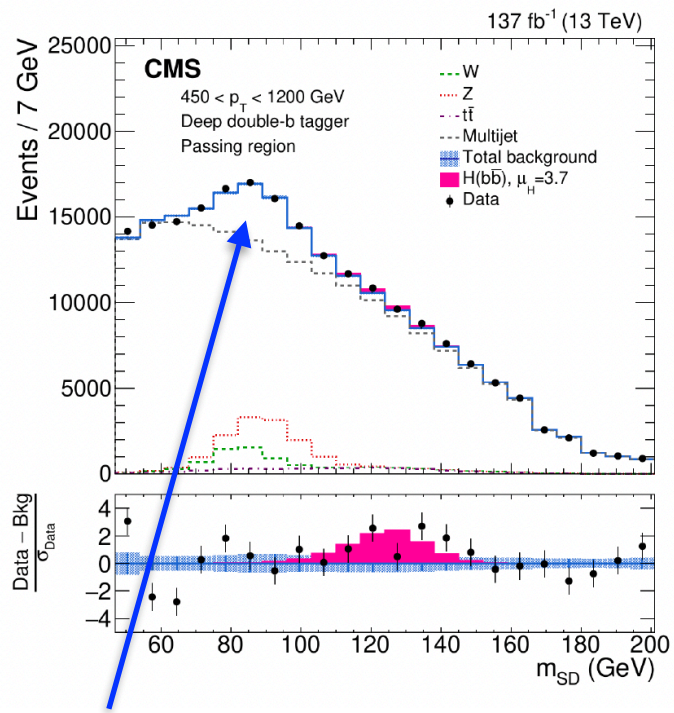


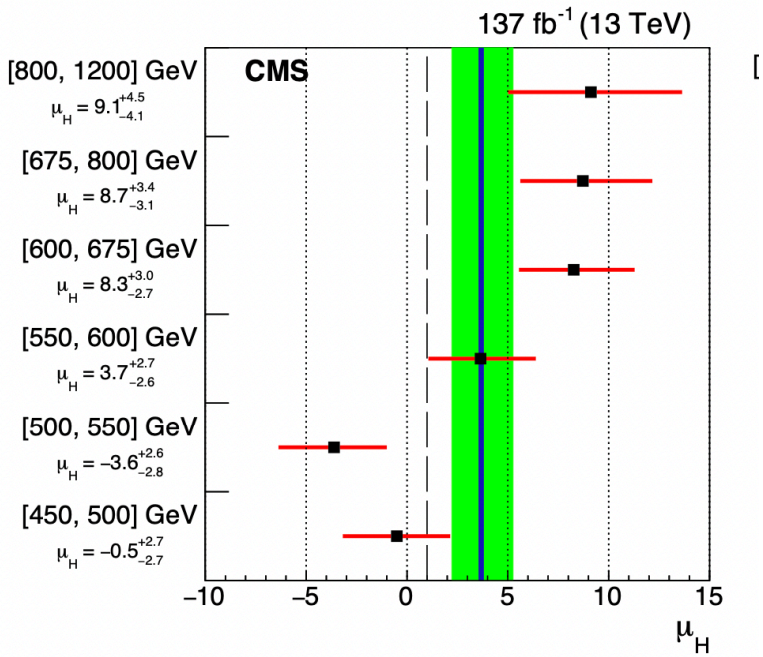


- VZ(bb) description is also quite good!

Gluon fusion H->bb?

- Can we access gluon fusion H->bb?
  - No longer have the additional handles from VH production but can consider boosted Higgs bosons to improve signal over background
    - The b-jets from the Higgs decay merge into a single large jet. Jet substructure techniques are needed



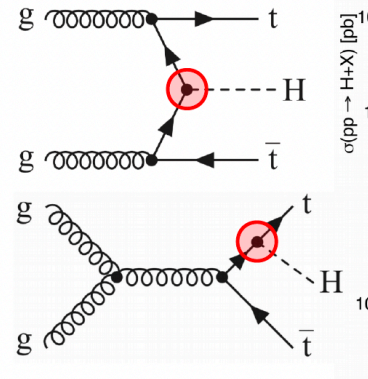


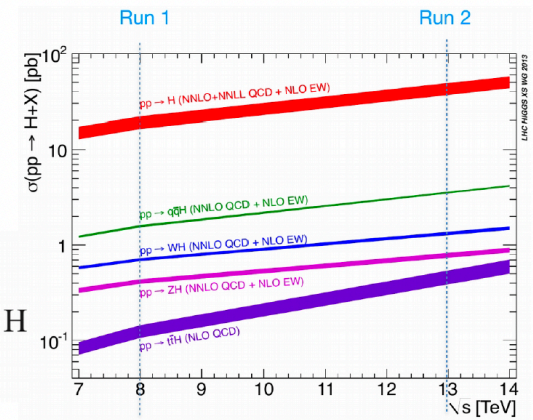
Validated by Z->bb events

$$\mu \equiv (\sigma \times \mathrm{BR})_{\mathrm{observed}} / (\sigma \times \mathrm{BR})_{\mathrm{expected}}$$

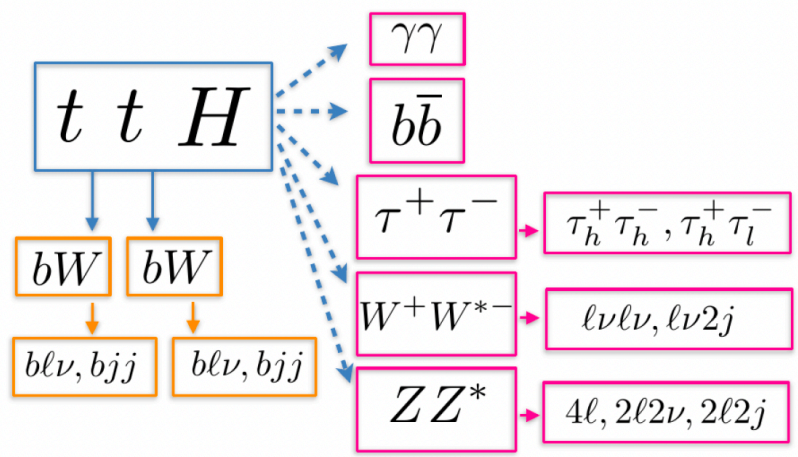
Higgs boson ttH production

- Direct probe of the top Higgs coupling
- Factor of ~4 larger cross section at Run 2 compared to Run 1
- The two tops provide additional handles
  - Very complex due to large number of objects in the final state

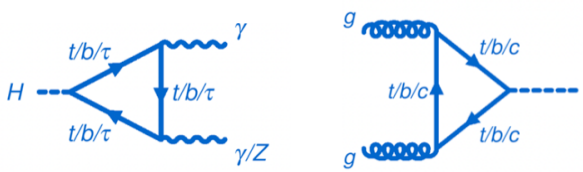




- ATLAS: 6.3 standard deviations (expected 5.1)
- CMS: 5.2 standard deviations (expected: 4.2)
- Consistent with SM expectation

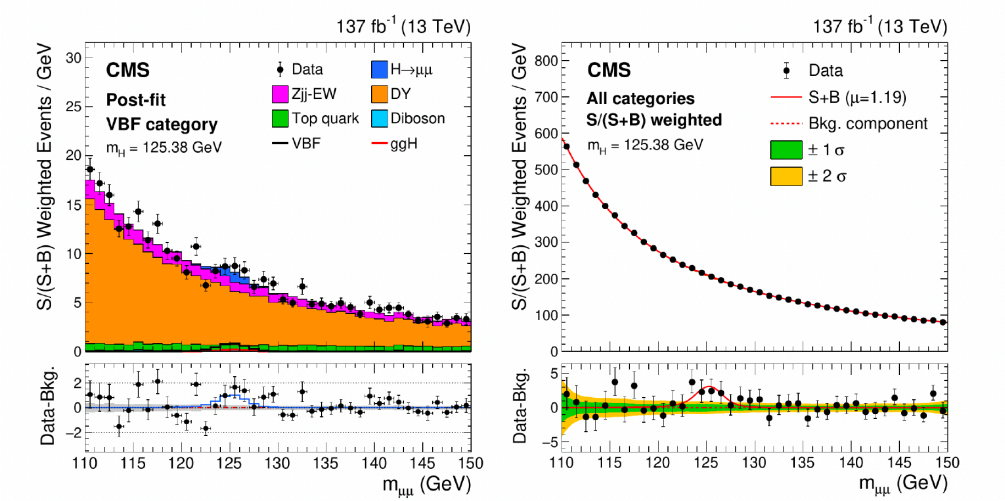


- Gluon fusion production and H->$\gamma\gamma$ are indirect probes of top to Higgs coupling



Second generation fermions

- Higgs boson couplings to second generation fermions?
  - How about H decay to muons?
    - Tiny branching fraction (~0.02%)
    - Muon mass: 105.6583755(23) MeV. Compare with tau mass: 1776.86(12) MeV
- Finding the di-muon pair is straightforward but very few events and a continuous irreducible Drell-Yan
    - VBF category is the main contributor
    - Evidence: >3 standard deviation excess seen



The SM-like Higgs boson

- ATLAS and CMS have observed the Higgs boson in numerous fermionic and bosonic decay channels
  - From previous slides we know Higgs couples to bosons, to leptons, to quarks of the 3rd generation
  - First evidence that Higgs also couples to 2nd generation
  - Impossible to cover all the Higgs results -> Higgs invisible decays, H->cc, spin/parity tests, mass measurement, width determination, search for additional Higgs bosons and exotic decays, etc.

- Many open questions and opportunities
  - Are observations fully consistent with the SM picture?
  - Interactions with new particles (including Higgs as portal to Dark Matter)
  - Higgs self interactions
  - Extended Higgs sector

- Ultimate goal is to find disagreement with predictions and learn something new!

Higgs boson precision measurements

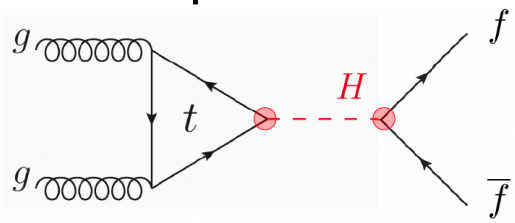
- Thirty times more Higgs bosons have been recorded at the end of Run-2 since the discovery by ATLAS and CMS
  - Established the spin-parity quantum numbers and determined its mass with ~0.10% precision. Which channels should we consider for the mass measurement?
  - Measured the production cross sections in various modes

- ATLAS and CMS released the latest combination results
  - Extract the global picture of the Higgs couplings to SM particles
    - ATLAS nature paper
    - CMS nature paper

- Let's look at the global picture that has emerged 10 years after the discovery!

Combination of Higgs results

- Combine the measurements to determine strengths of Higgs interactions
  - Measurements always almost involve several Higgs couplings
    - Production and decay
- The number of events in any category is split into different production and decay modes



$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma_i B_f)(A\epsilon)_{if}^k$$

ggF, VBF, $WH, ZH, t\bar{t}H, tH$ $\quad$ $ZZ, WW, \gamma\gamma, Z\gamma, b\bar{b}, c\bar{c}, \tau^+\tau^-, \mu^+\mu^-$ $\quad$ Acceptance x Efficiency

- Construct combined likelihood function (profile likelihood ratio for tests)

$$L(\boldsymbol{\alpha}, \boldsymbol{\theta}, \text{data}) = \prod_{k \in \text{cat}} \prod_{b \in \text{bins}} P(n_{k,b} | n_{k,b}^{\text{signal}}(\boldsymbol{\alpha}, \boldsymbol{\theta}) + n_{k,b}^{\text{bkg}}(\boldsymbol{\theta})) \prod_{\theta \in \boldsymbol{\theta}} G(\theta)$$

Observed $\quad$ Expected $\quad$ Gaussian constraint

Higgs combined measurements

- Production cross section and branching fraction for a specific production process and decay mode can't be measured separately
- Signal strength modified where 'expected' is the SM prediction

$$\mu \equiv (\sigma \times \mathrm{BR})_{\mathrm{observed}} / (\sigma \times \mathrm{BR})_{\mathrm{expected}}$$

- First test: Assume all production and decay modes scale by the same global signal strength

CMS

$\mu = 1.002 \pm 0.057$ 0.029 (stat.), 0.033 (syst.), 0.046 (sig. th.)

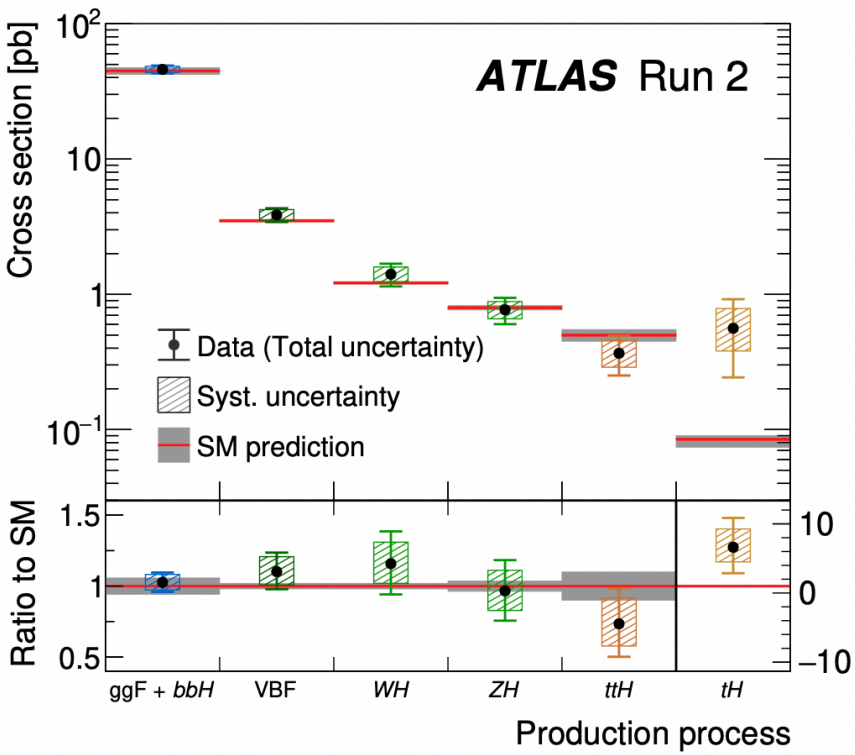
ATLAS

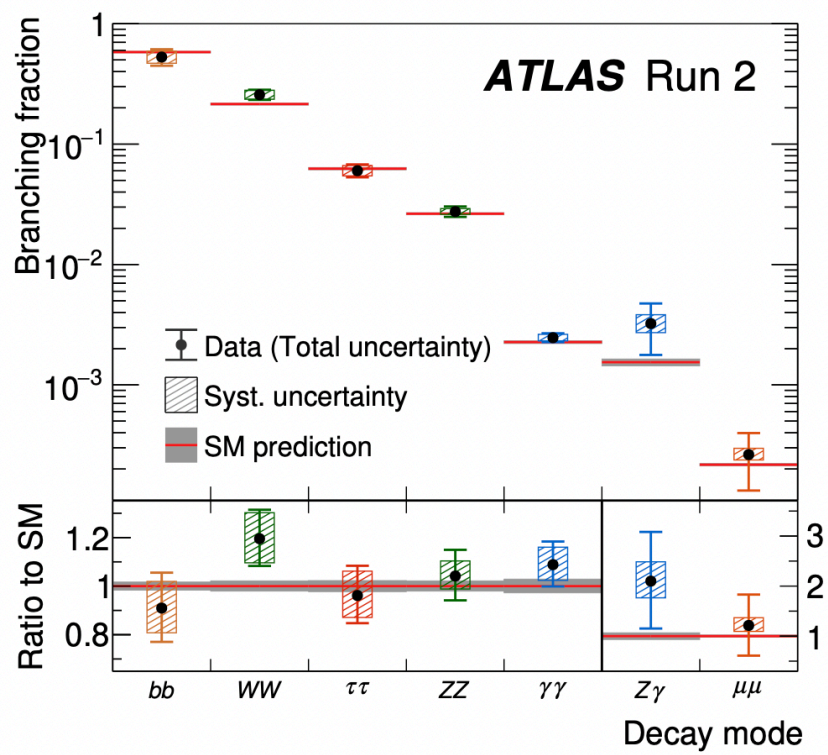
$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{exp.}) \pm 0.04\,(\mathrm{sig.\ th.}) \pm 0.02\,(\mathrm{bkg.\ th.})$

- Looks like measurements agree with the SM! Experimental and theoretical uncertainties are ~2 lower with respect to Run 1

Higgs cross sections and branching fractions

- Cross sections are measured assuming SM values for branching fractions
- Branching fractions are measured assuming SM values for the production cross sections





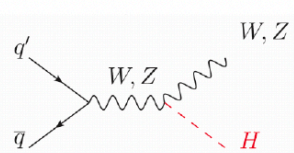
Higgs couplings modifiers

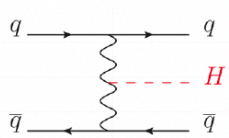
- Introduce coupling modifiers
  - Modify each coupling strength with specific kappa factor
    - Without altering any kinematic distributions of a given process
    - Kappa = 1 is SM

$$\mathcal{L} \supset \kappa_Z \frac{\mathrm{m_Z^2}}{v} Z_\mu Z^\mu + \kappa_W \frac{\mathrm{m_W^2}}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{\mathrm{m}_f}{v} f\overline{f}$$

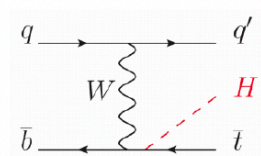
- Loop induced couplings can be decomposed (one can also introduce effective couplings)

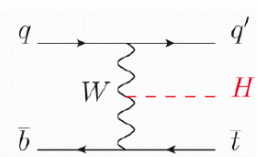
$$\propto 3.3 \times \kappa_W^2 - 5.1\kappa_W\kappa_t + 2.8\kappa_t^2$$

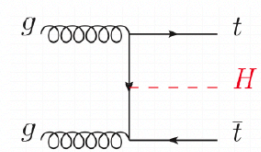




$\propto \kappa_V^2$



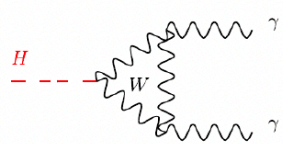


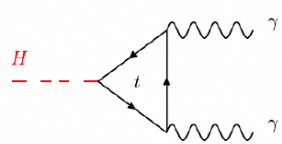


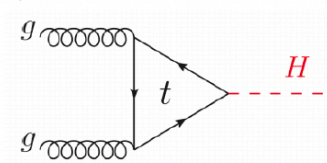
$\propto \kappa_t^2$

$$\propto 1.6 \times \kappa_W^2 - 0.7\kappa_W\kappa_t + 0.1\kappa_t^2$$

$$\propto 1.06 \times \kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$







Higgs couplings modifiers

- How to measure the coupling modifiers?
  - Express the various signal strengths in terms of the kappas

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu_f = \frac{\Gamma_f}{\Gamma_H} \quad \text{where} \quad \Gamma_H = \sum_f \Gamma_f \qquad \mu_f = \frac{\kappa_f^2}{\kappa_H^2}$$

$$\kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_H^{SM}}$$

$$\begin{aligned}\kappa_H^2 \sim\ & 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 \\ & +0.06\kappa_\tau^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2 \\ & +0.0023\kappa_\gamma^2 + 0.0016\kappa_{Z\gamma}^2 + 0.00022\kappa_\mu^2\end{aligned}$$

- Different scenarios can be considered
  - No new physics in loops (resolved loops with SM content)
  - Join some kappas together (for example vector bosons and fermions)
  - Allow for invisible or undetected Higgs boson decays to modify the total decay width
    - SM total width: Γ_{SM} = 4.14 ± 0.02 MeV (lifetime is ~1.6 x 10^{-22}s)

$$\Gamma_{\mathrm{H}} = \sum \Gamma_f(\kappa) / (1 - \mathcal{B}_{\mathrm{Inv.}} - \mathcal{B}_{\mathrm{Undet.}})$$

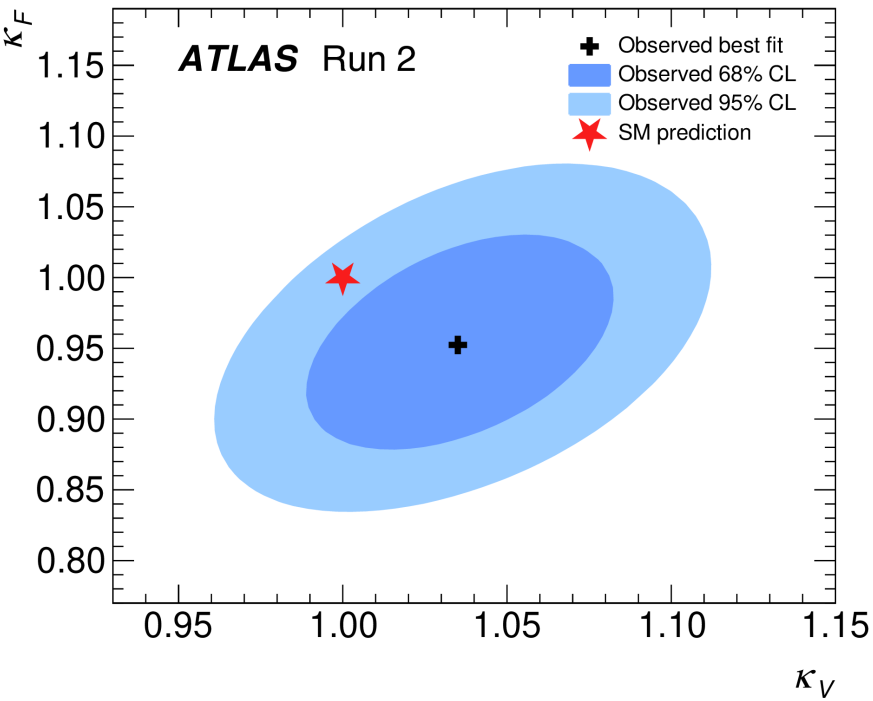
Higgs couplings modifiers

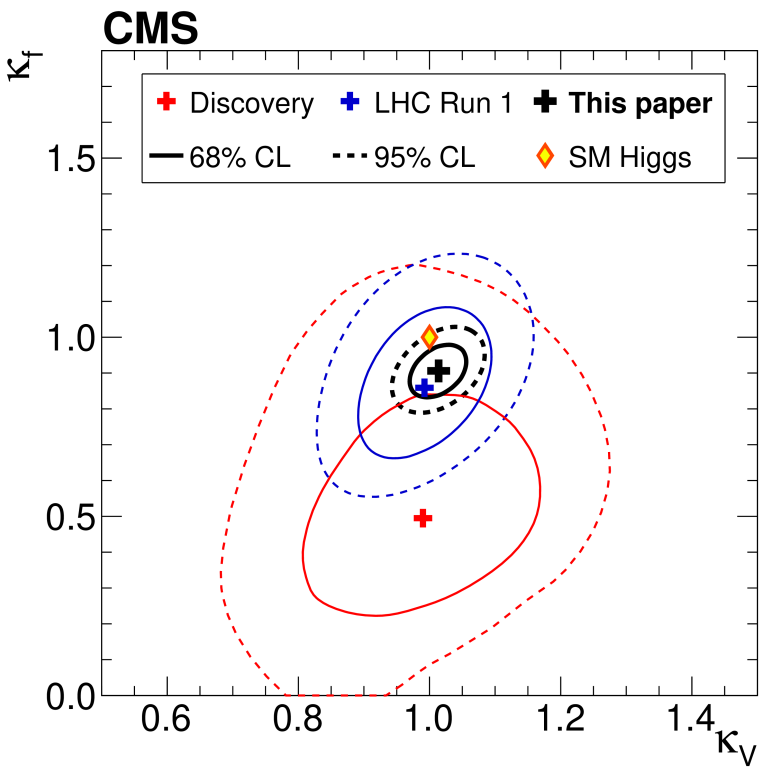
- More details on the coupling fits and assumptions can be found here:
  - Arxiv:1809.10733

	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\mathrm{ggH})$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(\mathrm{WH})$	—	—		κ_W^2
$\sigma(\mathrm{qq/qg} \to \mathrm{ZH})$	—	—		κ_Z^2
$\sigma(\mathrm{gg} \to \mathrm{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	—	—		κ_t^2
$\sigma(\mathrm{gb} \to \mathrm{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(\mathrm{qb} \to \mathrm{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{BSM} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 + 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 + 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$

Higgs coupling results

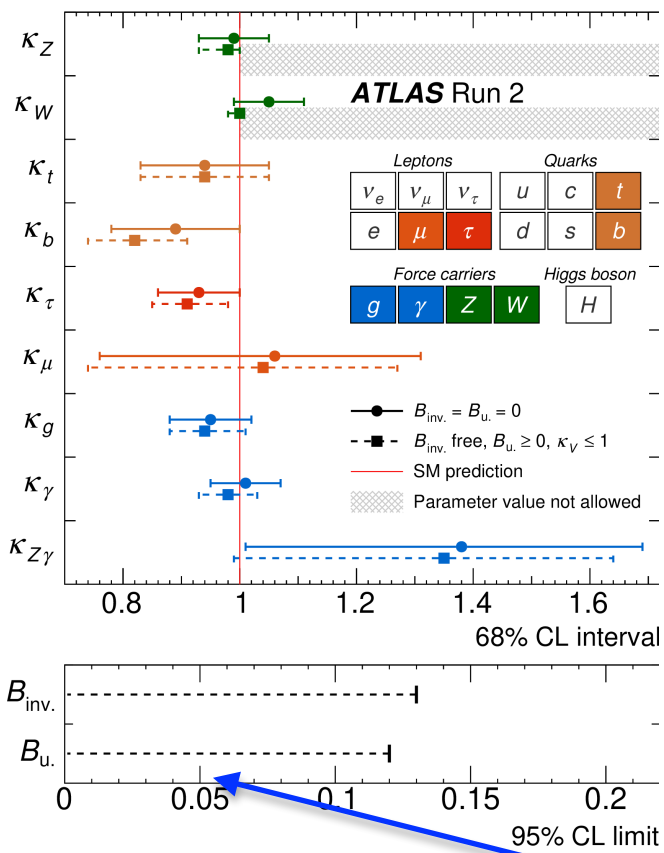
- Only two parameters in the fit: kappa for fermions and kappa for bosons
  - Loops are resolved with no new physics in the decays

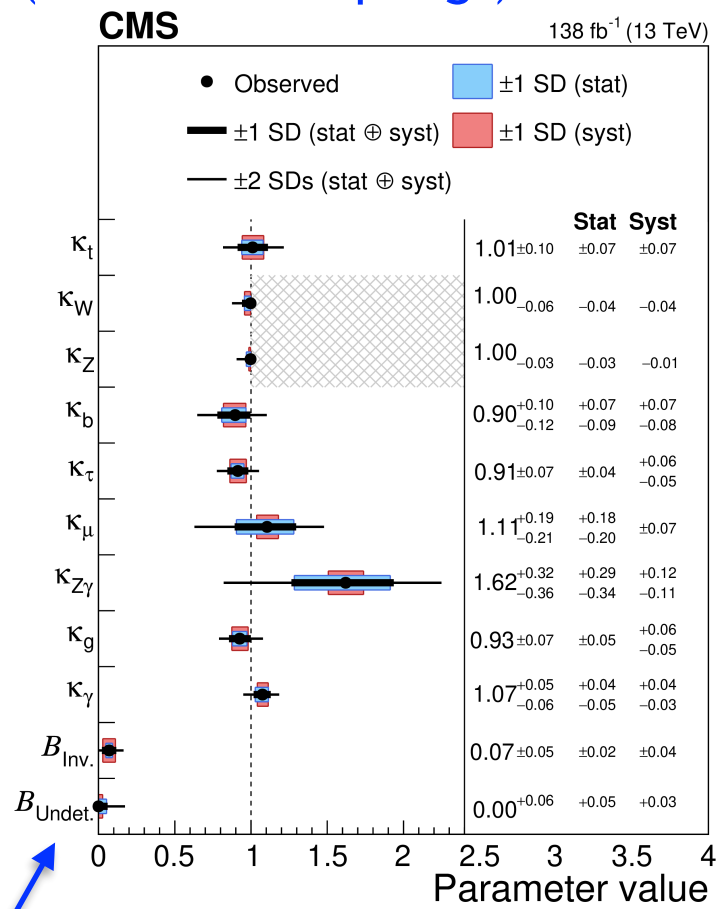




Higgs coupling results

- Fit for all the kappas
  - New physics allowed in the loops (effective couplings)



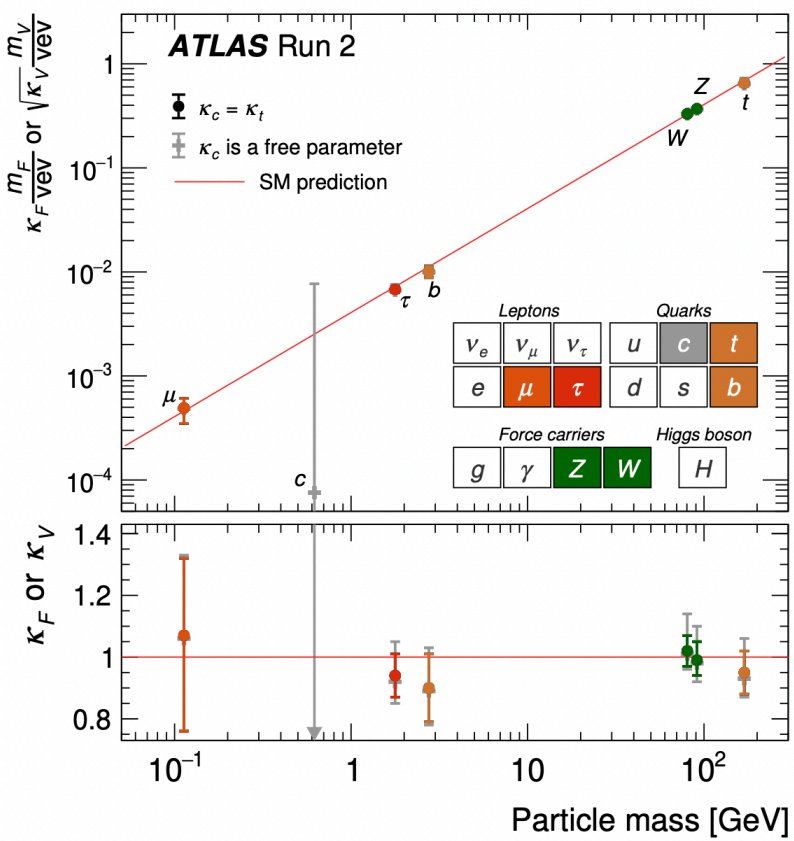


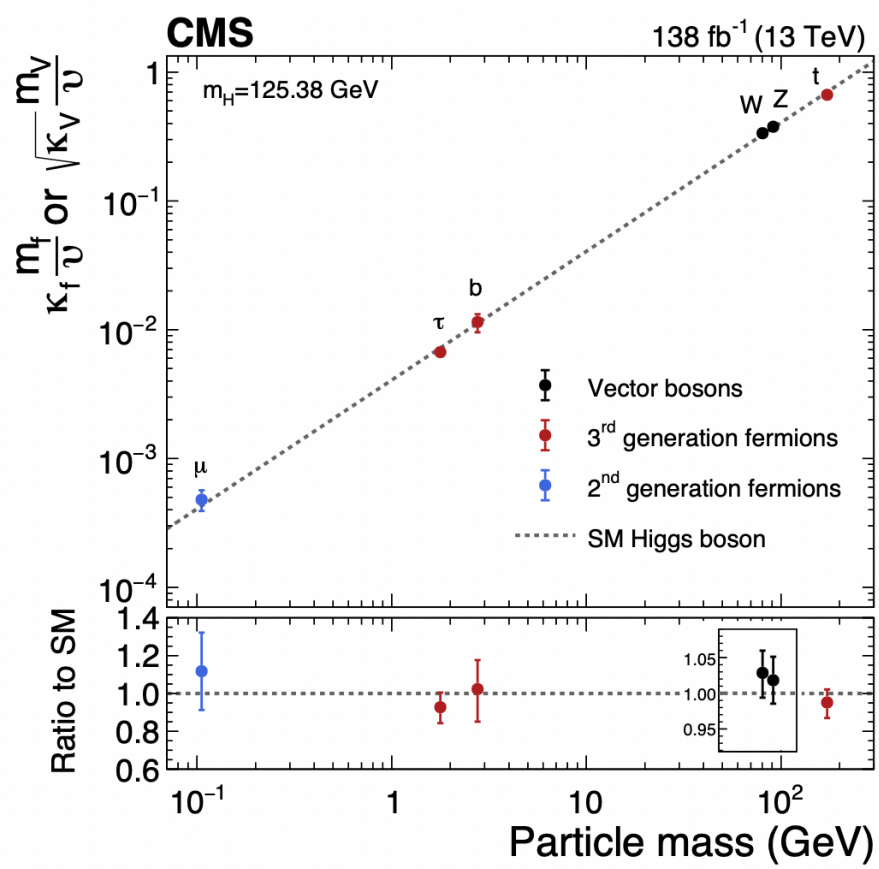
- Also allow for BSM invisible/undetected decays

Higgs couplings

- Higgs coupling parameters vs mass
  - We know that the coupling dependence is different for fermions and bosons but we can correct for that

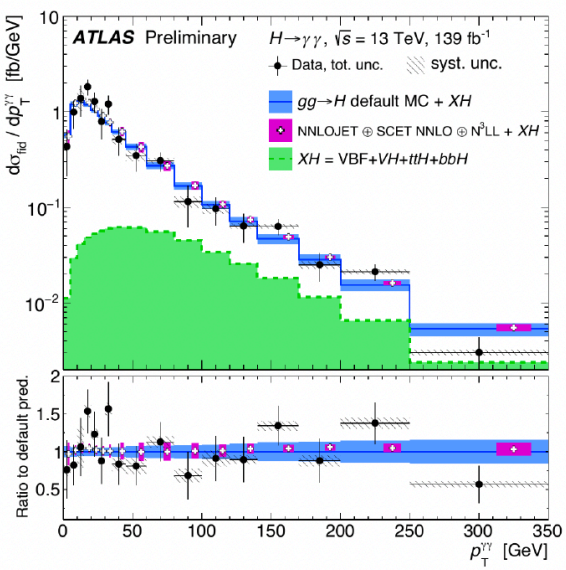
$$g_{Hf\bar{f}} \equiv y_f = \frac{m_f}{v}, \; g_{HVV} = \frac{2m_V^2}{v}$$

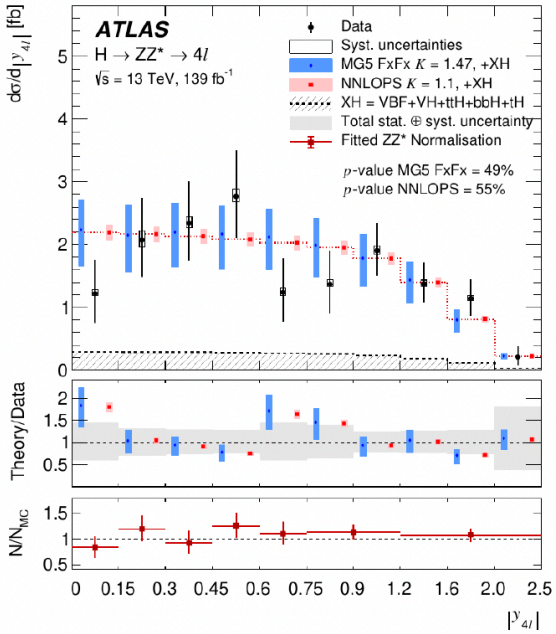




Higgs kinematics

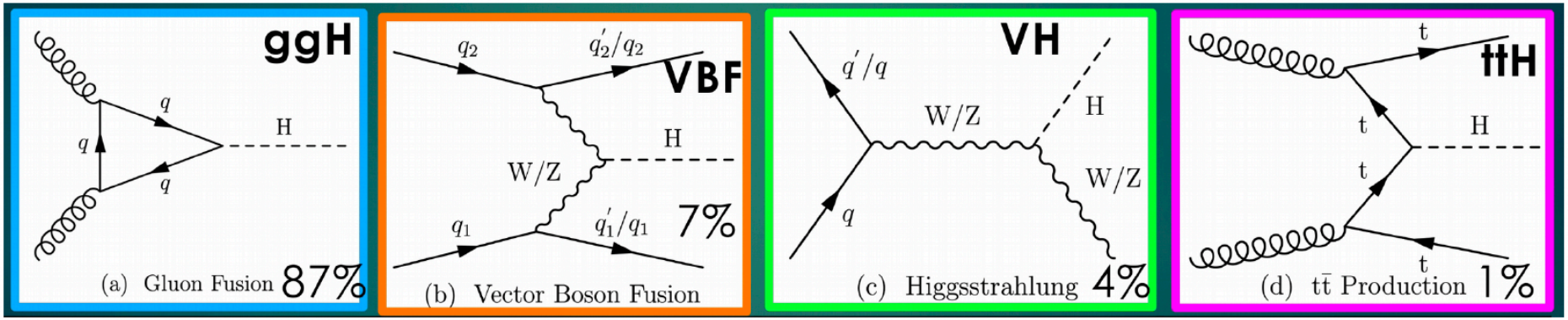
- So far we have seen that couplings appear to agree with SM
  - We can also probe the Higgs boson production kinematics!
  - Unfolded differential fiducial cross sections can be measured
    - Most straightforward in H->ZZ->4l and H->$\gamma\gamma$ where Higgs kinematics can be fully reconstructed





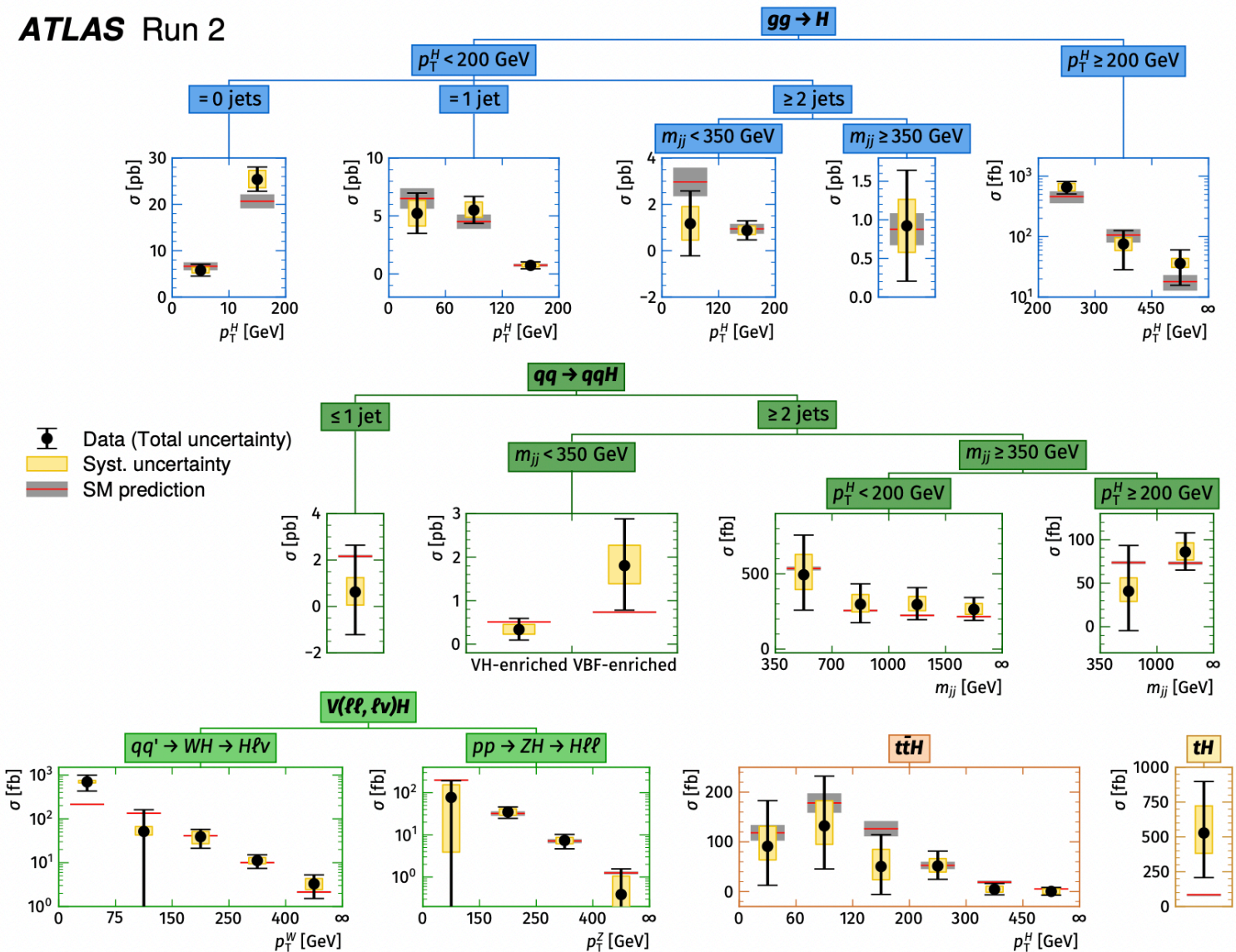
Simplified template cross sections

- To facilitate reinterpretation of the results in BSM simplified template cross sections can be provided
  - Different production processes are further separated in different kinematic regions (extra jets, etc.)



$p_T(H)$	N_{jets}	$p_T(V)$	$p_T(H)$
N_{jets}	M_{jj}, $p_T(H+jj)$ (if $N_{jets}>1$)	N_{jets}	
M_{jj}, $p_T(H+jj)$ (if $N_{jets}>1$, VBF-like)	$p_T(H)$		

Simplified template cross sections

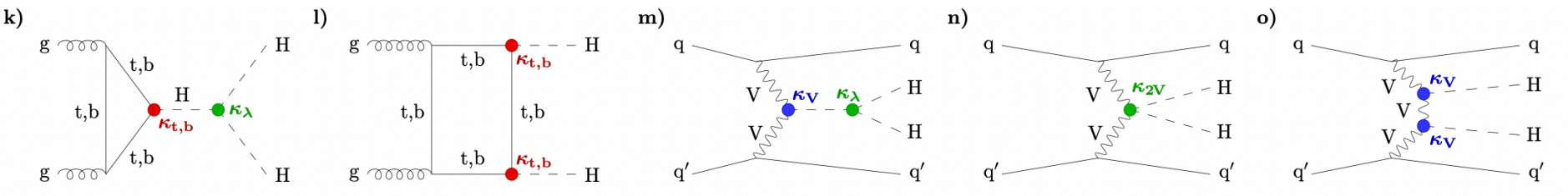


Higgs potential

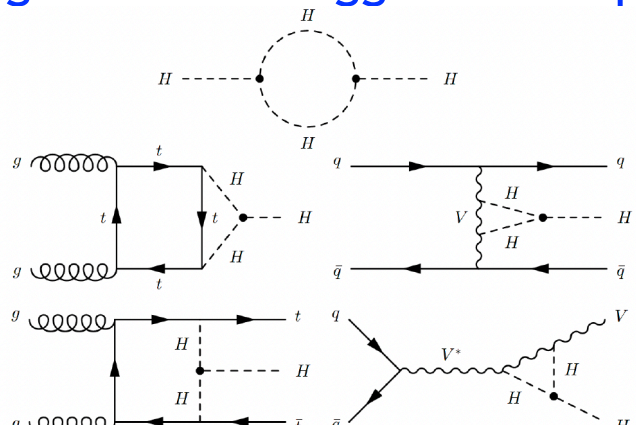
- Back to the Higgs boson potential -> Higgs self couplings

$$V(\phi) = \frac{1}{2}m_{\mathrm{H}}^2\phi^2 + \sqrt{\lambda/2}m_{\mathrm{H}}\phi^3 + \frac{1}{4}\lambda\phi^4$$

- Direct approach is to study Higgs boson pair production

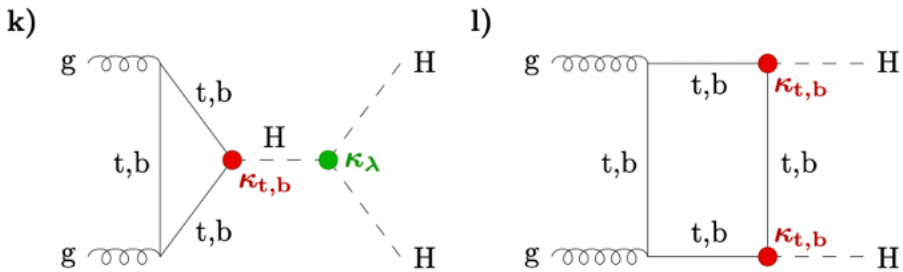


- Indirect information can be extracted by studying the single Higgs production
  - Higher order diagrams with Higgs self-coupling



Higgs boson pair production

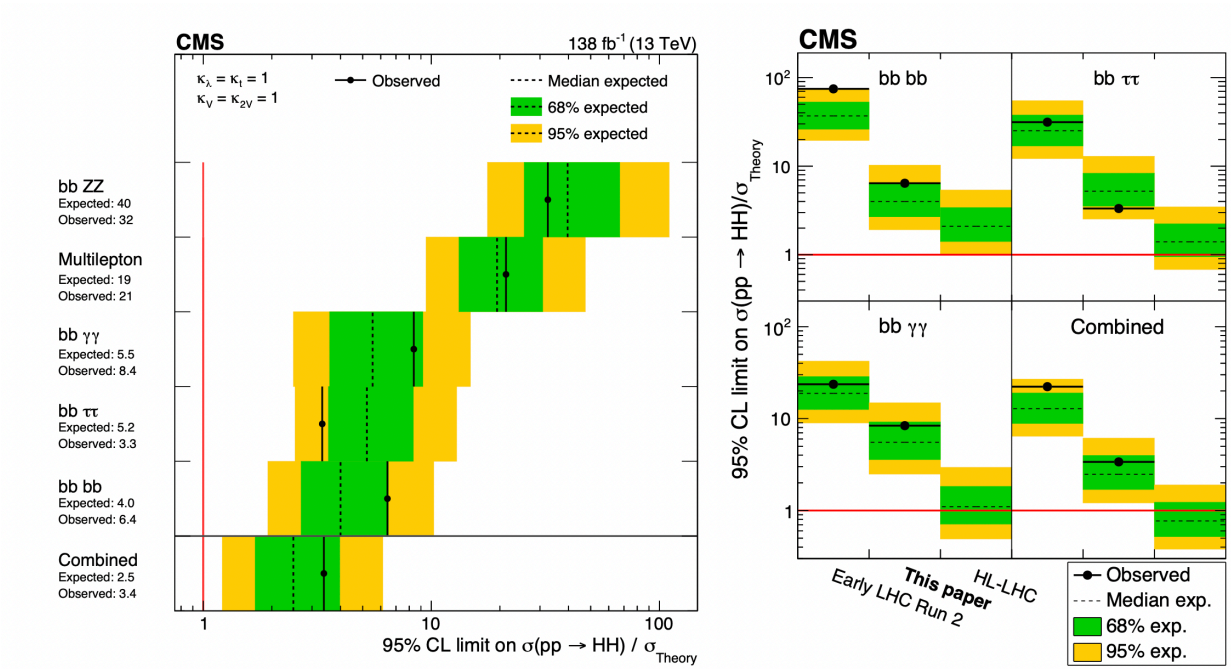
- The SM cross section for HH production is three orders of magnitude smaller than the Single Higgs boson cross section!



  - Huge destructive interference in SM between the loop diagram and the self-coupling diagram
- Strategy is to study events with two candidate Higgs bosons decaying to most promising channels that we are already familiar
  - Typically we do want for at least one of the Higgs bosons to decay to bb to benefit from large branching fraction
  - The channels where one of the Higgs bosons decays to H->ZZ->4l and H->$\gamma\gamma$ benefit from the presence of a narrow peak

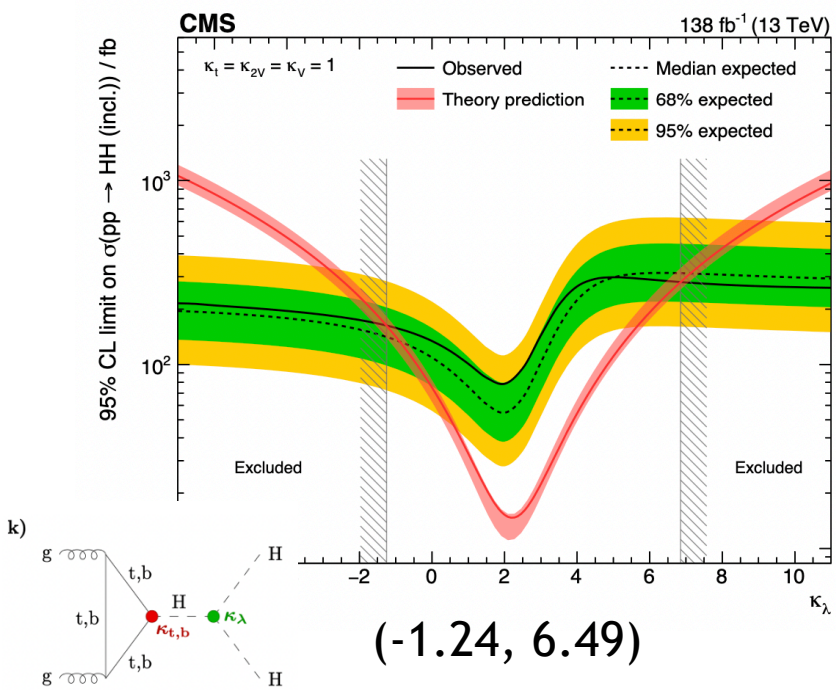
Higgs boson pair production

- Expected and observed 95% CL limits
  - Left plot: the search modes are ordered from the least sensitive to most sensitive. The overall limit is less than 3.4xSM prediction!
  - Right plot: The evolution of the limits including High-Luminosity LHC projections. Sufficient expected sensitivity at HL-LHC to establish existence of HH production.

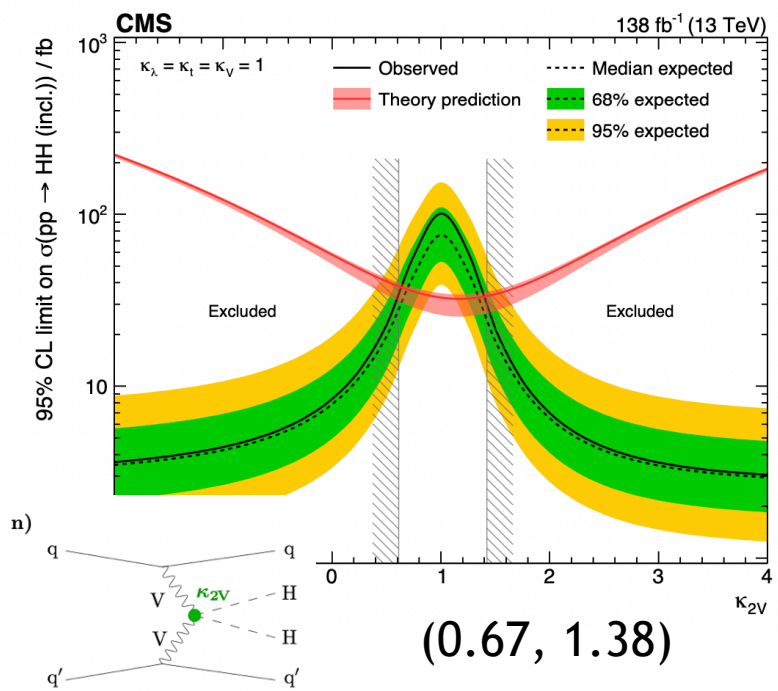


Di-Higgs couplings

- Back to coupling modifiers (kappas)
  - Characteristic dip at kappas of about 1 in predicted cross sections due to the destructive interference.
  - The experimental limits also show strong dependence on kappas as the interferences between different subprocesses also changes the differential kinematic properties of the two Higgs bosons
  - Existence of quartic coupling VVHH with a significance of 6.6 s.d.



(-1.24, 6.49)



(0.67, 1.38)

Conclusions (Day 1)

- The Higgs boson 10 years after the discovery
  - It looks like the SM Higgs boson, also walks and talks like it
  - Yukawa coupling is established and consistent with expectations
  - Completing 2nd (and 1st) generation couplings is important. First evidence that Higgs also couples to 2nd generation
  - Need to wait for the self-coupling until HL-LHC but could be found earlier if non-SM

- Exciting times ahead with many open questions and opportunities with Run 3 and HL-LHC data
  - Are observations fully consistent with the SM picture?
  - Higgs boson as a tool to find new physics (example: portal to dark matter)
  - Role of the Higgs boson in vector boson scattering processes
    - To be discussed tomorrow
  - More complex Higgs models, extended Higgs sectors…

References

- All publications from ATLAS and CMS
  - ATLAS publicatons on Higgs (196)
  - CMS publications on Higgs (168)