What we learned experimentally about Higgs ?

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Disclaimer:
Lecture is meant to be pedagogical, not a comprehensive review of all experimental results. Usually results of one experiment (CMS or ATLAS) are discussed, conclusions from both experiments are ~ the same

This lecture is limited to Higgs -125 Gev.

Higgs particle properties from the Standard Model (SM) theory

Higgs boson

A very special particle of SM (it is not just yet another SM particle)

- **As discussed in previous lectures: Higgs mechanism is the most simple and elegant way to generate masses of all other SM particles** (in SM, one cannot introduce particle masses by hand without breaking everything)
- **Higgs potential is very unusual - minimum of energy is achieved in presence of Higgs field** (and, hence, vacuum must be literally packed with Higgs field)
- **Higgs boson is the only fundamental scalar in SM**

Higgs boson experimental studies

Establish existence of a Higgs boson – achieved in 2012. The mass turned out to be ~ 125 Gev

Measure its mass and width with with the ultimate achievable precision.

Measure its spin-parity properties, and compare with prediction by the Standard Model (SM).

Measure its other couplings from studying various production and decay modes

Deviations of these measurements from the Standard Model (SM) theory would be an experimental signal for Beyond the Standard Model (BSM) physics

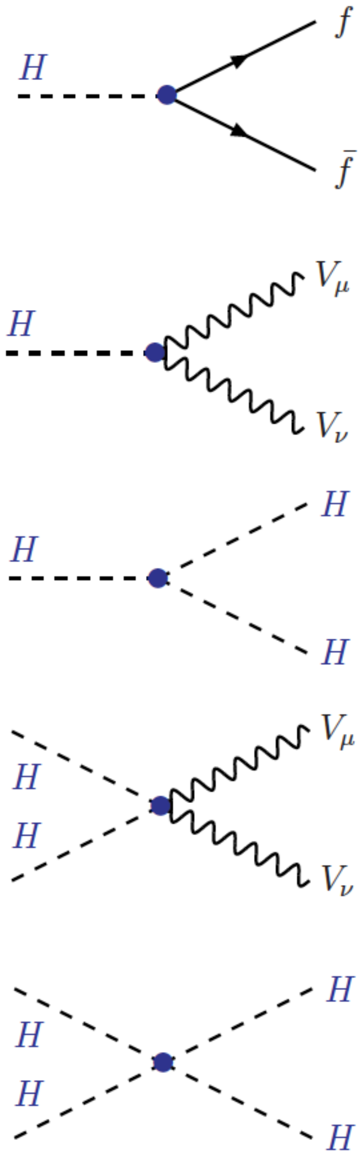
Look for exotic (forbidden by SM) Higgs production and decay modes – BSM physics – covered in this lecture.

Look for more Higgs bosons, additional to discovered Higgs~125 . Such particles may be predicted by extensions of the SM, e.g. Supersymmetry. This is not discussed in this lecture for the lack of time.

SM Higgs boson phenomenology

In Standard Model, there is only one Higgs boson:

- it is elementary (not composite)
- spin – zero
- parity – even
- mass – free parameter
- Higgs tree-level couplings to fermions (f), W and Z bosons ("vector" bosons, or V - bosons), are defined by particles masses: the heavier the particles, the larger the couplings



$$g_{Hff} = m_f/v$$

$$g_{HVV} = 2M_V^2/v$$

$$g_{HHH} = 3M_H^2/v$$

$$g_{HHVV} = 2M_V^2/v^2$$

$$g_{HHHH} = 3M_H^2/v^2$$

As a result Higgs is the only "Yukawa" particle in SM which couplings depend on masses of other particles, violating universality of generations:

- Higgs boson "prefers" to decay to the heaviest particles
- Decays of Higgs to zero-mass particles ($\gamma\gamma$, Zγ, gg, etc.) are also possible via loops of heavy particles

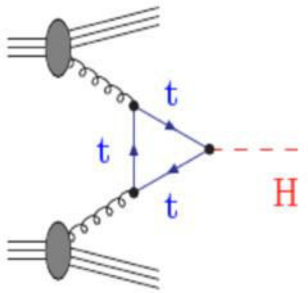
Couplings also define the dominant productions mechanisms:

- one needs to produce a heavy particle first, to which Higgs boson couples willingly
- again heavy particle can actually be virtual and not present in the final state

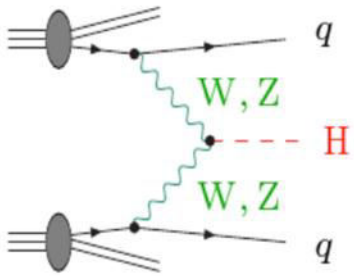
Higgs boson production in SM

Couplings define the dominant productions mechanisms:

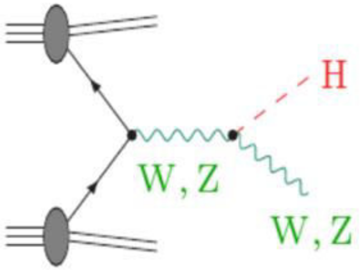
- one needs to produce a heavy particle first, to which Higgs boson couples willingly
- that heavy particle can actually be virtual (in loops) and not present in the final state



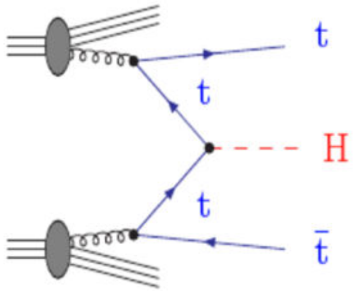
gluon fusion into Higgs (ggF). It is loop induced



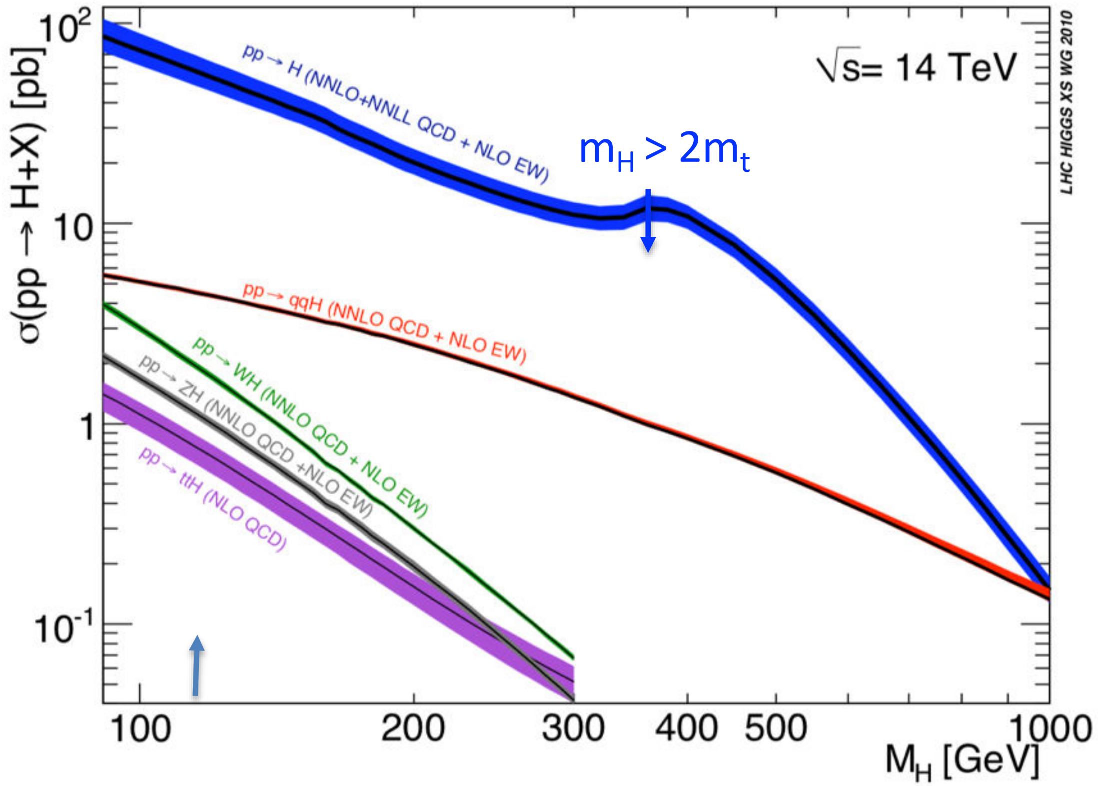
vector boson W, Z fusion (VBF) into Higgs



associate Higgs production with Z/W (VH)



associate Higgs production with tt (ttH)

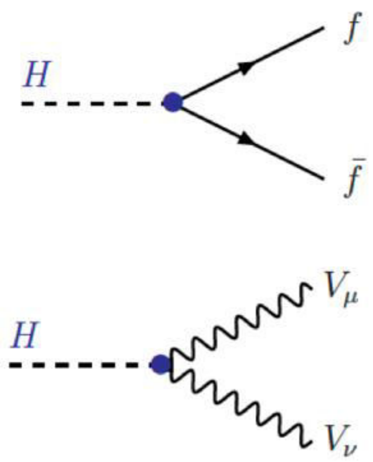


Higgs production mechanisms
as predicted by SM, as a function of Higgs mass

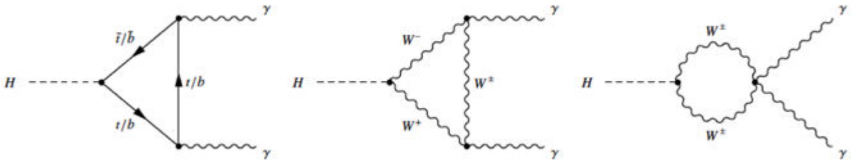
SM Higgs boson decays

Higgs boson decay modes and branching fractions are set by its mass and couplings:

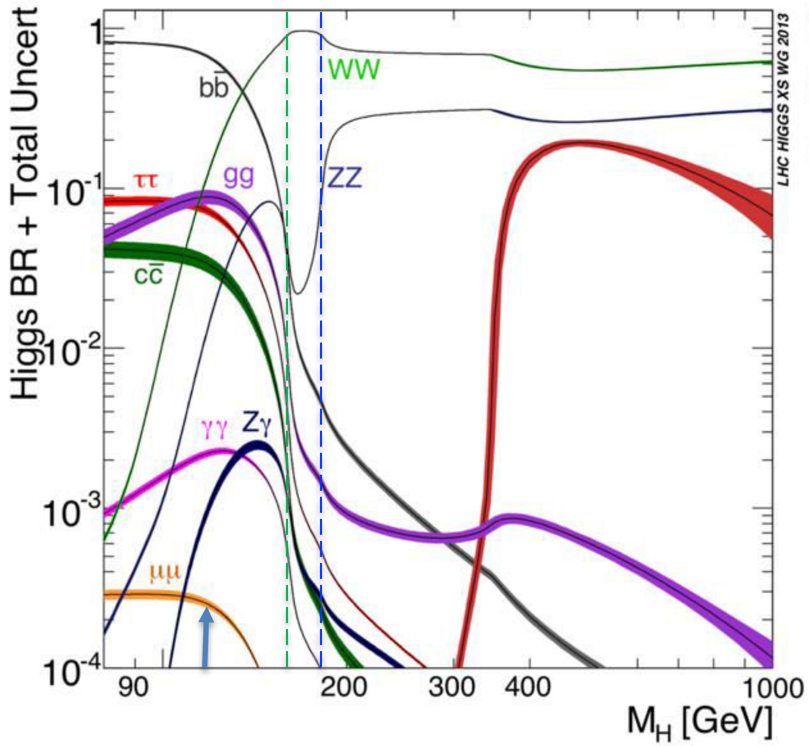
- **Higgs boson "prefers" to decay to the heaviest particles it kinematically can decay to**
- **Decays to zero-mass particles ($\gamma\gamma$, Zγ, gg, etc.) are also possible via loops**



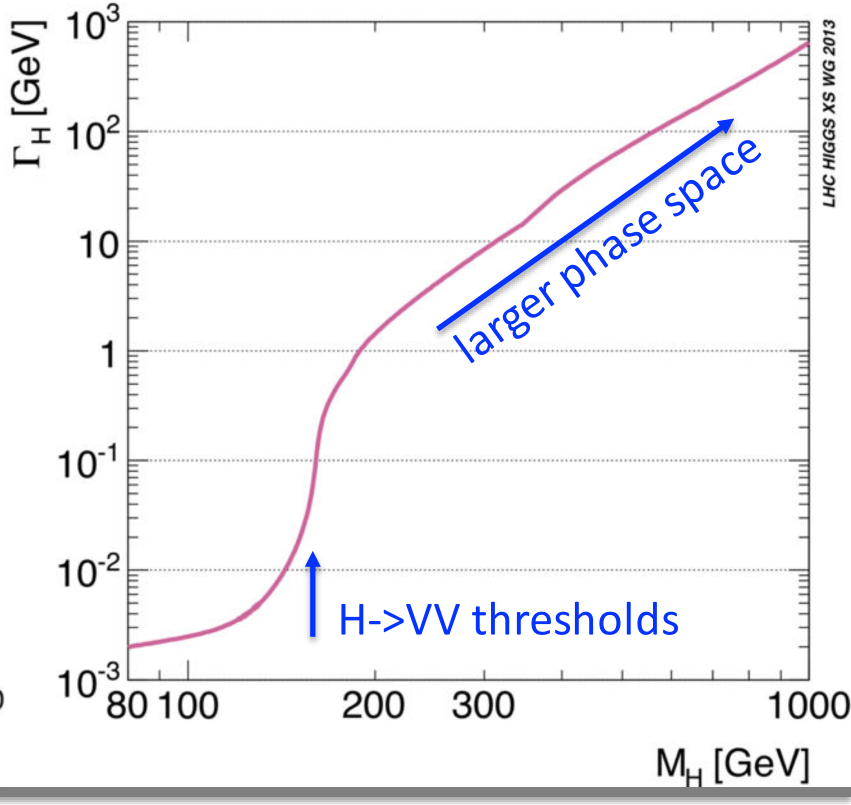
loop induced H → $\gamma\gamma$



Branching fractions



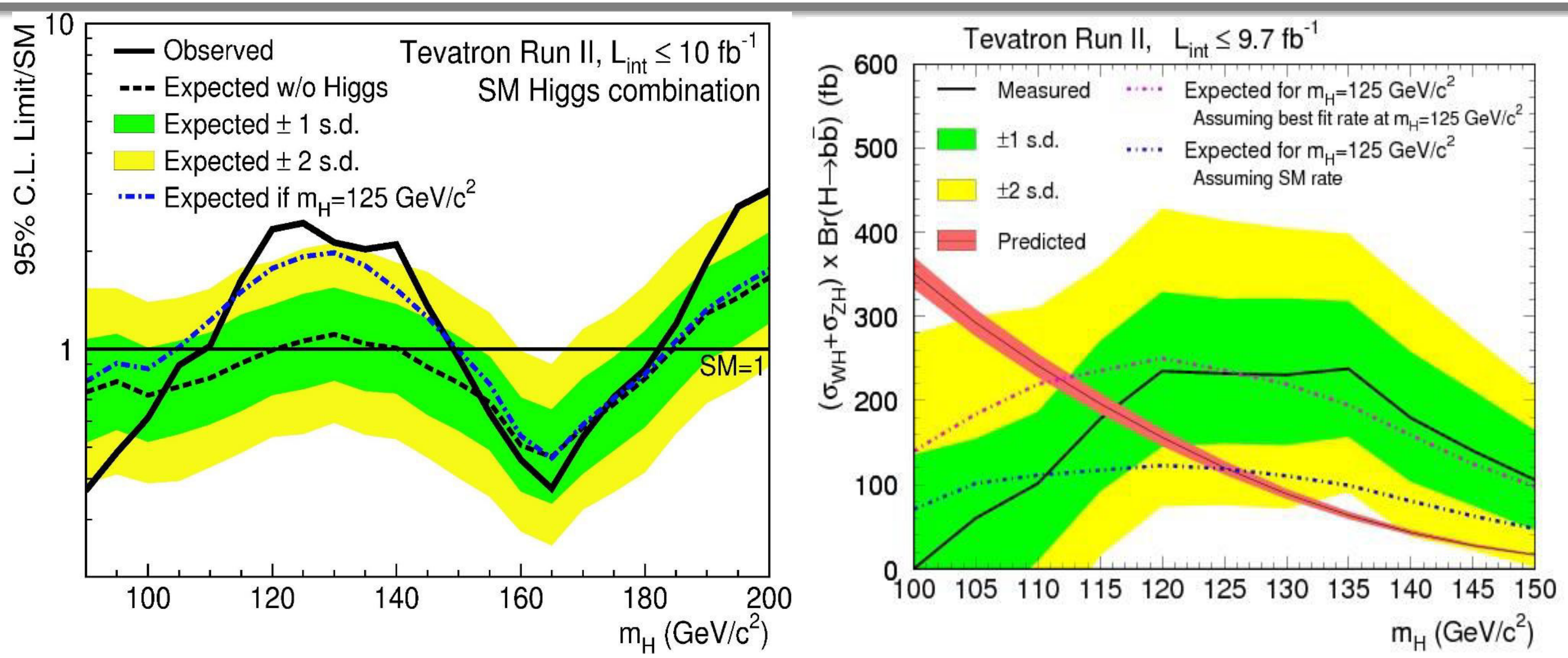
Higgs width



Tevatron past Higgs searches

The Tevatron hunt for the Higgs boson

CDF and D0 combined
Phys. Rev. Lett. 109 (2012) 071804

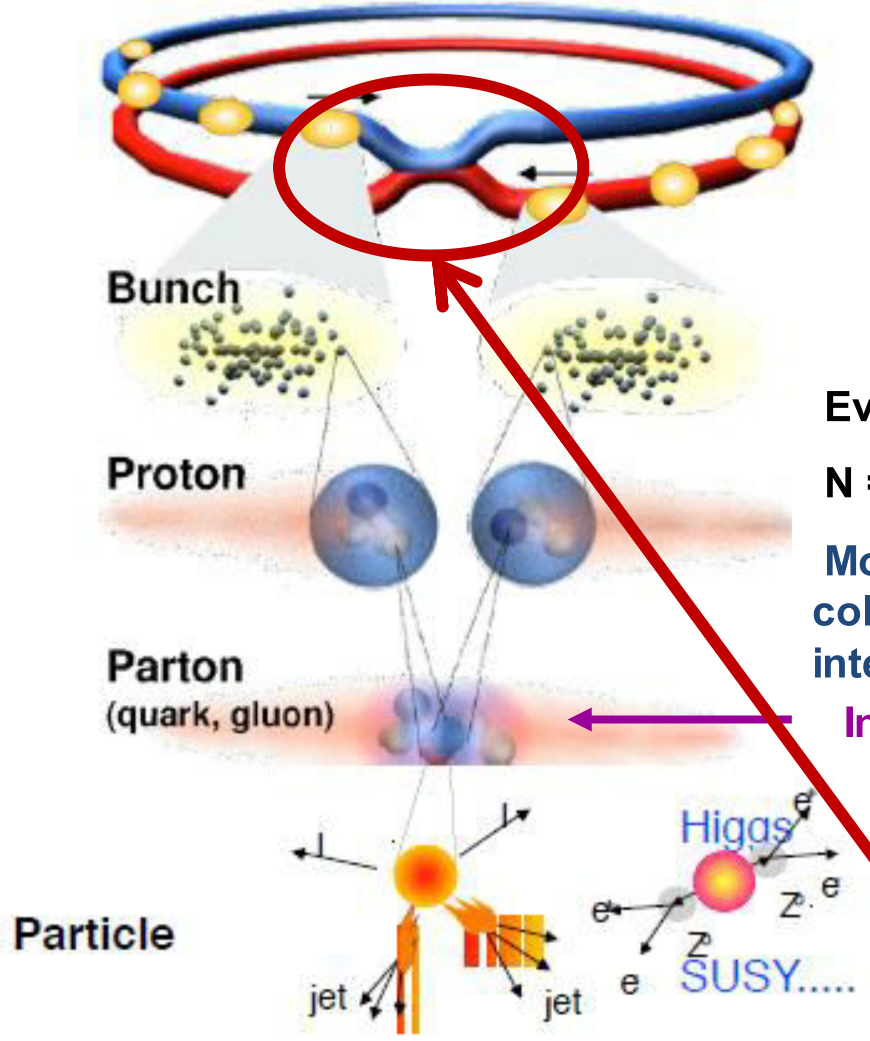


From Paul Grannis, D0 founding spokesperson (June 2018 Fermilab Users Meeting, 'Tevatron Highlights' talk):

'The Higgs was discovered in 2012 at LHC in the $\gamma\gamma$ & ZZ decays. Simultaneously, CDF & DØ obtained the first 3σ evidence for H→bb decays, using the combined W(lν)H, Z(ll)H and Z($\nu\nu$)H channels. This preceded the LHC evidence for fermionic Higgs decays by 4 years and was the first direct evidence for the Higgs Yukawa coupling.'

LHC (collider) and universal detectors: ATLAS and CMS

Collisions at the LHC



Proton - Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	$10^{34}cm^{-2}s^{-1}$
Crossing rate	40 MHz

Event rate:

N = L x σ (pp) ≈ 10^9 interactions/s

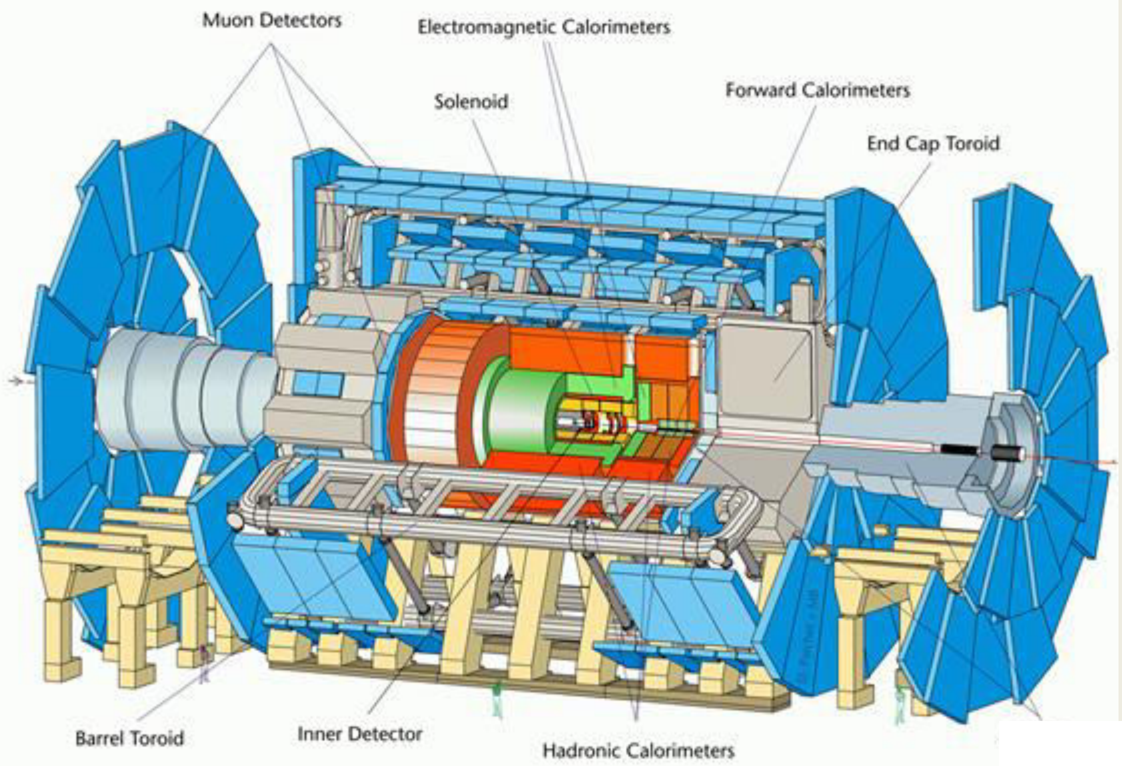
Mostly background for interesting "hard" collisions: soft (low p_T) proton- proton interactions

Interesting hard (high-p_T) events are rare

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

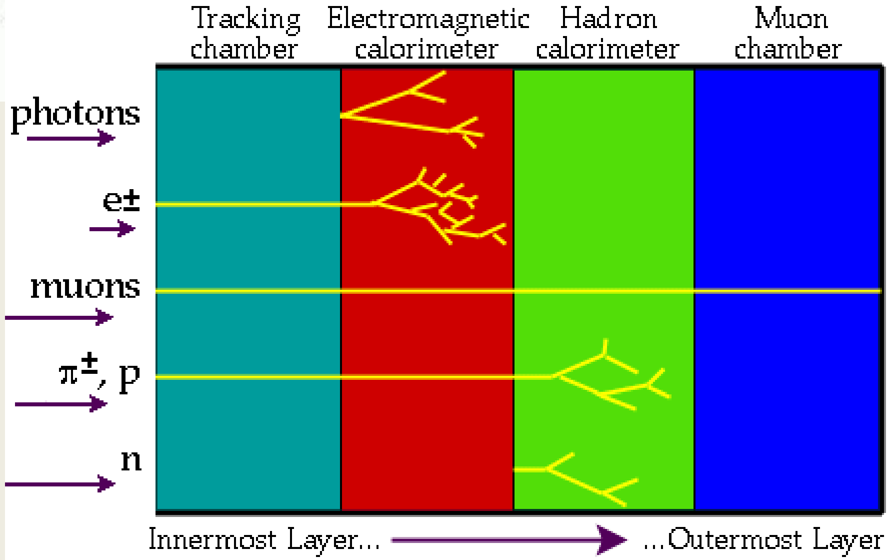
→ Interesting events are very, very rare
→ One needs highly sophisticated instruments to find them



ATLAS

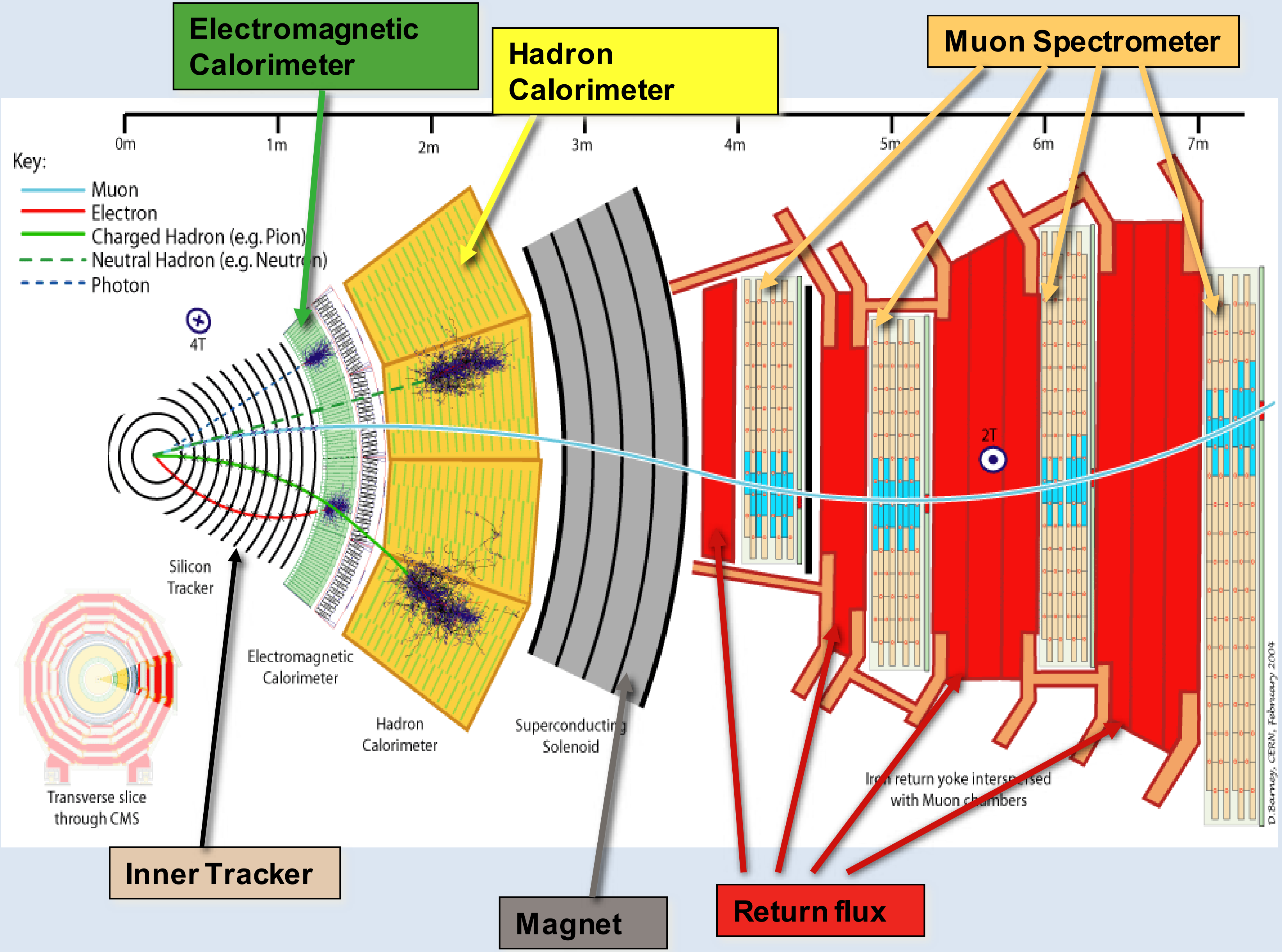
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

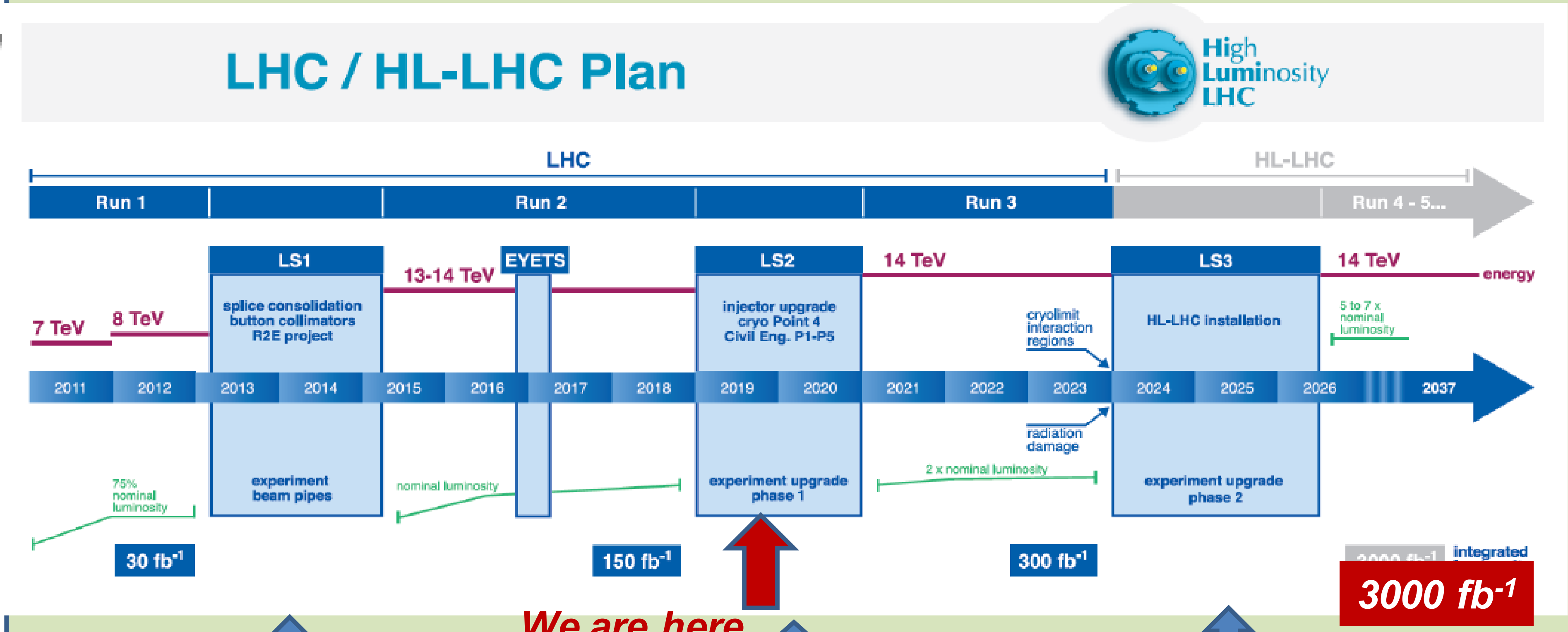
- **Tracking (|η|<2.5, B=2T) :**
  - -- Si pixels and strips
  - -- Transition Radiation Detector (provided e/π separation)
- **Calorimetry (|η|<5) :**
  - -- ElectroMagnetic (EM) : Pb-LAr
  - -- Hadronic (HAD): Fe/scintillator (central), Cu/W-LAr (fwd)
- **Muon Spectrometer (|η|<2.7) :**
  - -- air-core magnetic toroids with muon chambers



Principle of detection of particles

Principle of detection of various particles in the sector of CMS





We are here

Phase-0 upgrades

Phase-1 upgrades

Phase-2 detector and machine upgrades

Accumulated datasets in Ran 2 (CMS, ATLAS similar)

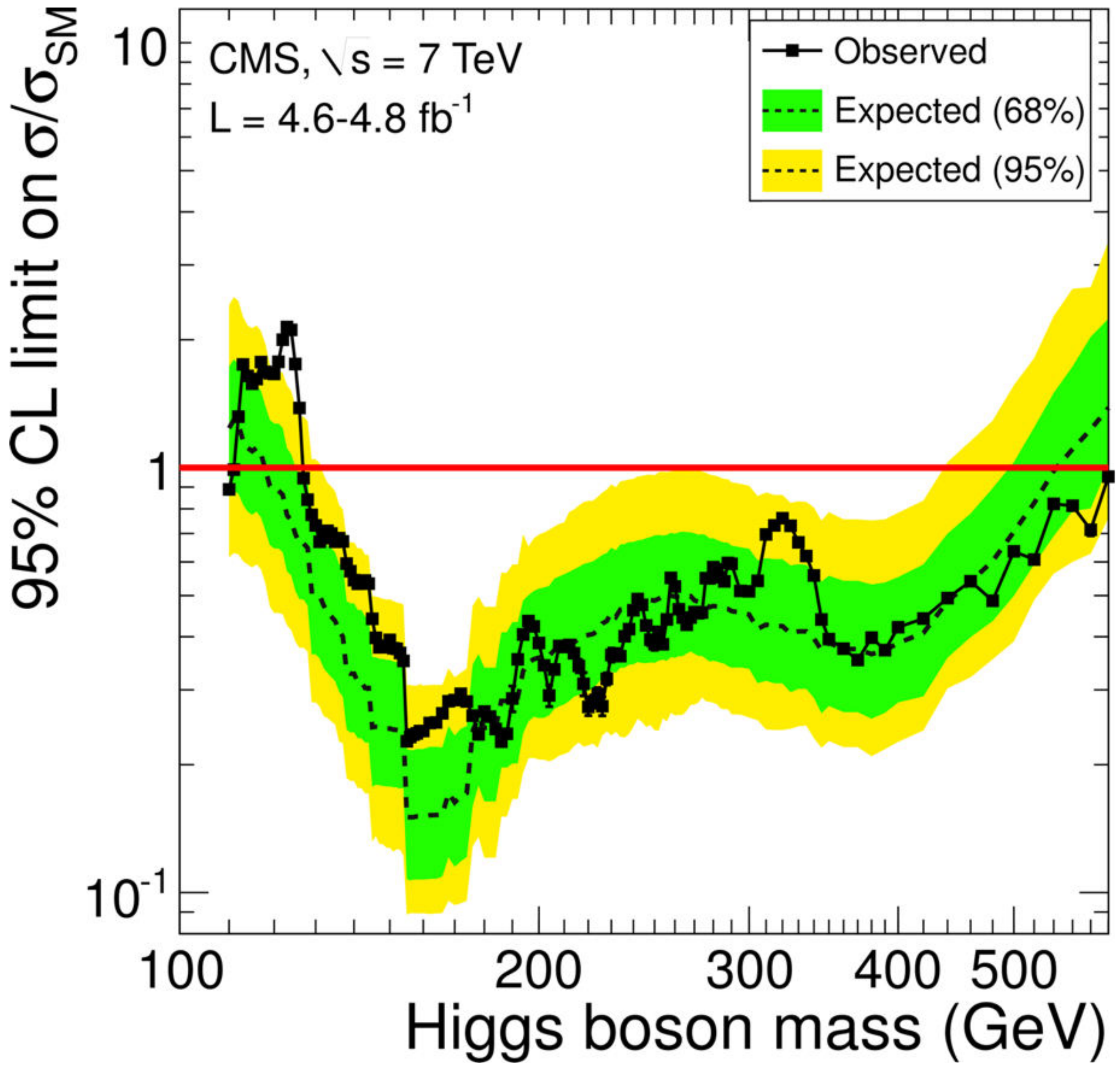
~35 fb^{-1}: 2016

~80 fb^{-1}: 2016+2017

~140 fb^{-1}: 2016+2017+2018 (full Run 2)

Higgs searches at LHC

Physics implications of not seeing Higgs boson early
(LHC Higgs experimenal limits in 2011, a year before discovery)



Not seeing a Higgs boson

in the entire meaningful mass range

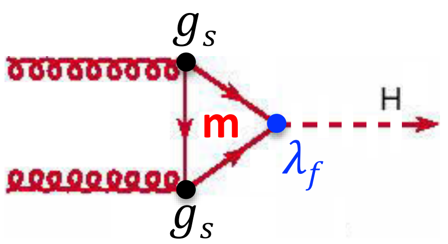
with production cross section < 2 x σ_{SM} implies that

there are only 3 SM-like fermion generations

(assuming that 4th generation would have heavier quarks)

2011: Implications of not seeing Higgs boson early

Gluon fusion with the top quark in the loop is the dominant Higgs boson production mechanism



$$A \sim \frac{g_s^2 \quad {}_f}{m}$$

BACK OF ENVELOPE:

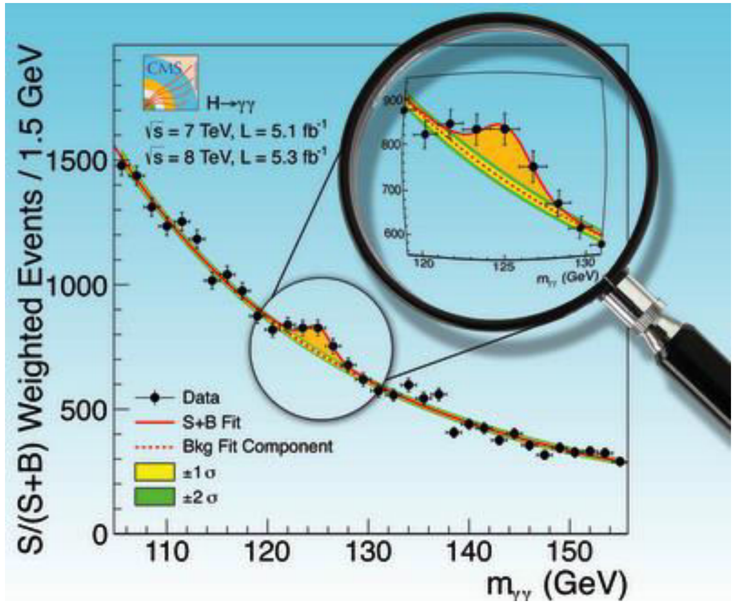
- For heavy quark of mass m ($m>m_H$), the amplitude is suppressed as 1/m
- Higgs coupling to the quark is proportional to m, $\lambda_f \sim m$
- So, for a heavy quark loop, *the amplitude is approximately independent of the quark's mass m*

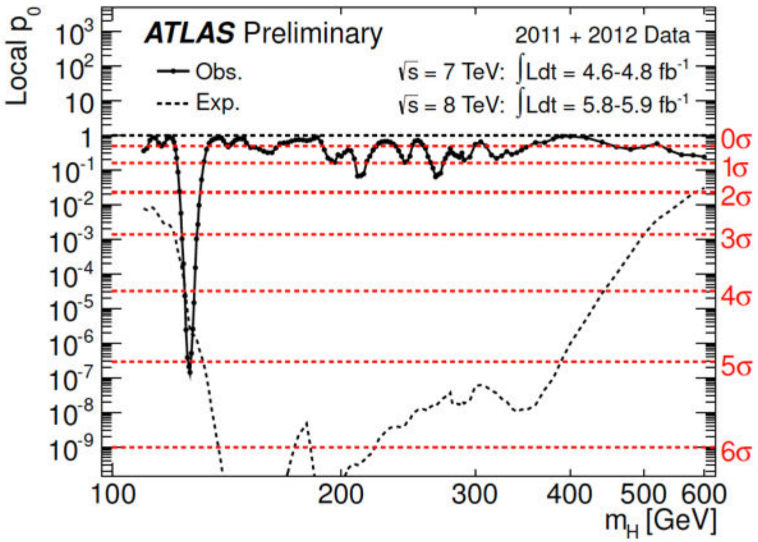
Should there be a fourth generation of SM-like fermions,

- In addition to the top quark ***t*** there would be two more heavy quarks, ***T*** and ***B***.
- *However heavy **T** and **B** might be (and hence not seen directly),* each of them would give its own contribution to the production amplitude similar in magnitude to that due to the top quark.
- The production amplitude then becomes 3 times larger.
- **The production cross section then becomes 9 times larger (wow!)**

2012: Discovery of the Higgs boson with mass near 125 GeV

(Announced at seminar at CERN, with a live translation to major HEP conference in Melbourne)

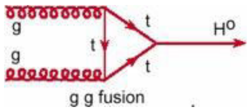




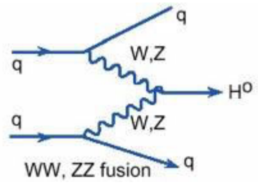
Reminder of some theoretical SM predictions: Higgs production and decays in SM

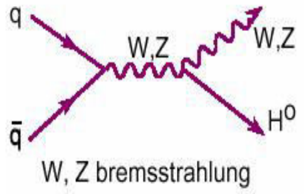
SM Theory: H(125) production modes in (pb)

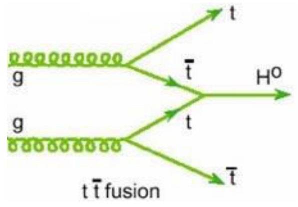
	ggF	VBF	WH	ZH	bbH	ttH	tHq	tHW
8 TeV	19.5	1.60	0.70	0.42	0.20	0.13	0.019	0.0012
13 TeV	44.1	3.78	1.37	0.88	0.49	0.51	0.074	0.0029
ratio	2.3	2.4	2.0	2.1	2.5	3.9	3.9	2.4

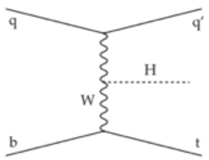


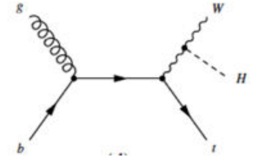
ggF - loop induced

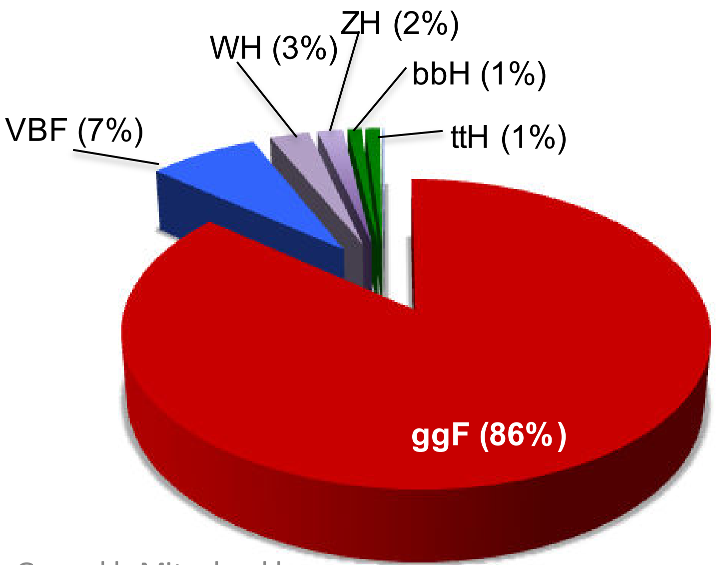












How accurate are these predictions?

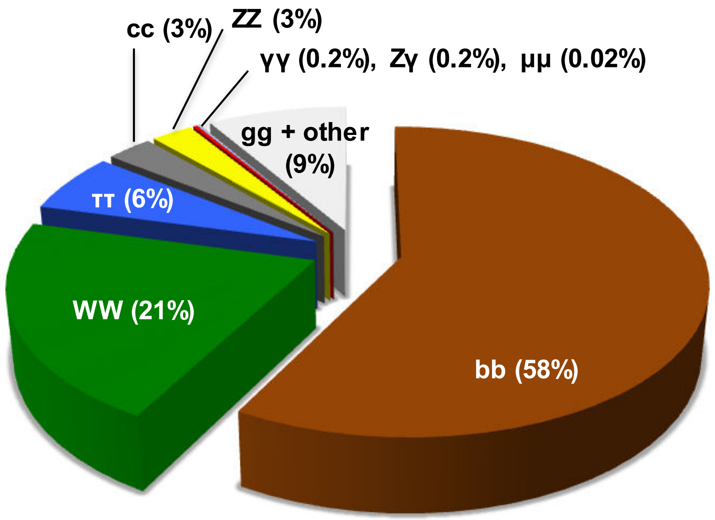
[LHC Higgs Cross Section Working Group]

Process	Perturbative calc. order	Theory	Parametric (α_s)	PDF
ggF	N^{3}LO QCD + NLO EW	~5%	~3%	~2%
VBF	NNLO QCD + NLO EWK	~0.4%	~2%	
WH	NNLO QCD + NLO EWK	~0.5%	~1%	
ZH	NNLO QCD + NLO EWK	~3%	~2%	
ttH	NLO QCD + NLO EWK	~8%	~2%	~3%

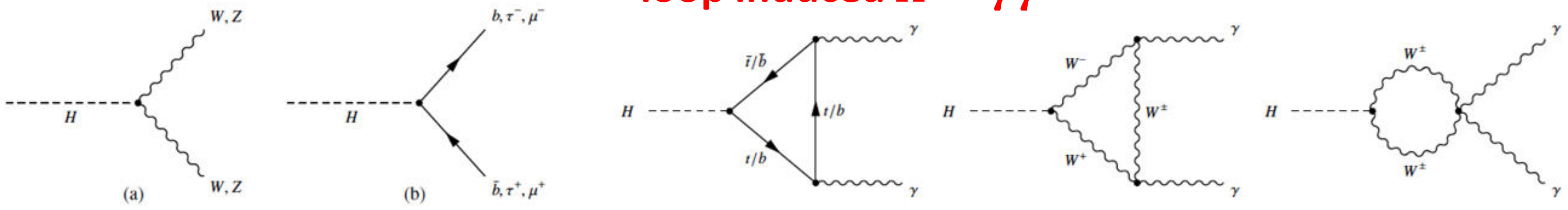
SM Theory: H(125) prediction for production and decay modes

	bb	WW	ττ	cc	ZZ	γγ	Zγ	μμ	gg + …
all	58%	21%	6.3%	2.9%	2.6%	0.23%	0.15%	0.022%	9%
leptonic		1.0%			0.012%		0.010%		

Highlighted in red are experimentally established decays



loop induced $\mathrm{H} \rightarrow \gamma\gamma$



The most prolific decay is $\mathrm{H} \rightarrow bb$ (about 60%), also very hard to observe

The most sensitive channels for observation are $\mathrm{H} \rightarrow ZZ \rightarrow 4l$ and $\mathrm{H} \rightarrow \gamma\gamma$

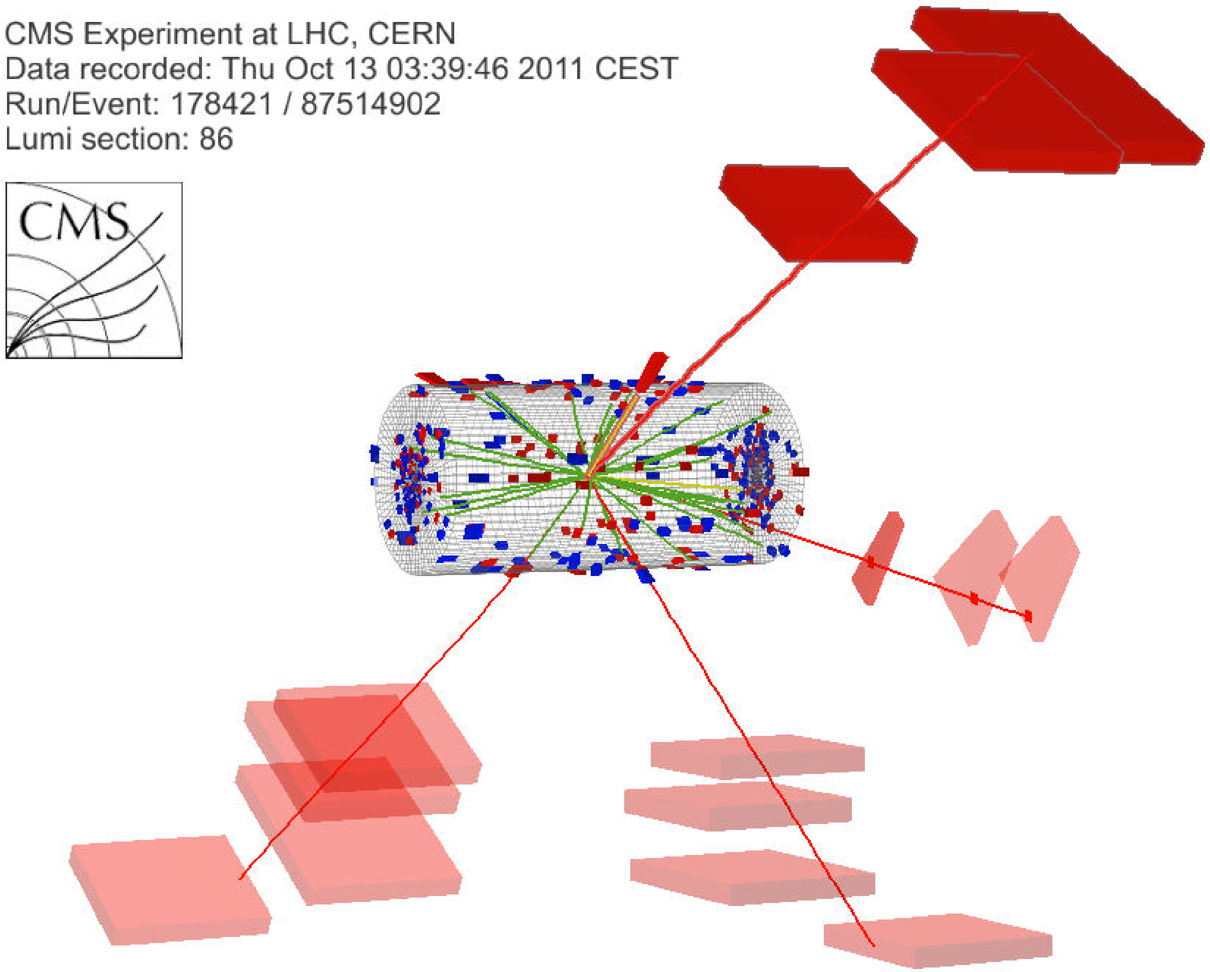
How accurate are these predictions? [LHC Higgs Cross Section Working Group]

Typically 1-2%, more accurate than production cross sections

Experimental Analyses targeting specific Higgs boson decay modes (specific channels)

$H \to ZZ^* \to 4\ell$

Run 2: σ×B×L = 850 events



Experimental analysis features to note:

- **Relatively low event yield: 850**
- **best final Signal/Background (S/B) -ratio in this mode, better than 2:1**
- **Excellent Higgs mass resolution = 1-2%**
- **As a result: the best channel to observe Higgs at 125 GeV** (due to excellent S/B ratio, despite of low yield)
- **Best for the Higgs mass measurement** (very small systematics, particularly for muons)
- **Best for studying Higgs spin-parity J^P properties** (fully reconstructed four-body final state)
- **Best for studying Higgs width, particularly** via ratio of off-shell to on-shell production rates
- **Second-best for measuring cross sections** (after the diphoton channel)

$H \to ZZ^* \to 4\ell$: analysis strategy
(experimental selections to reduce backgrounds)

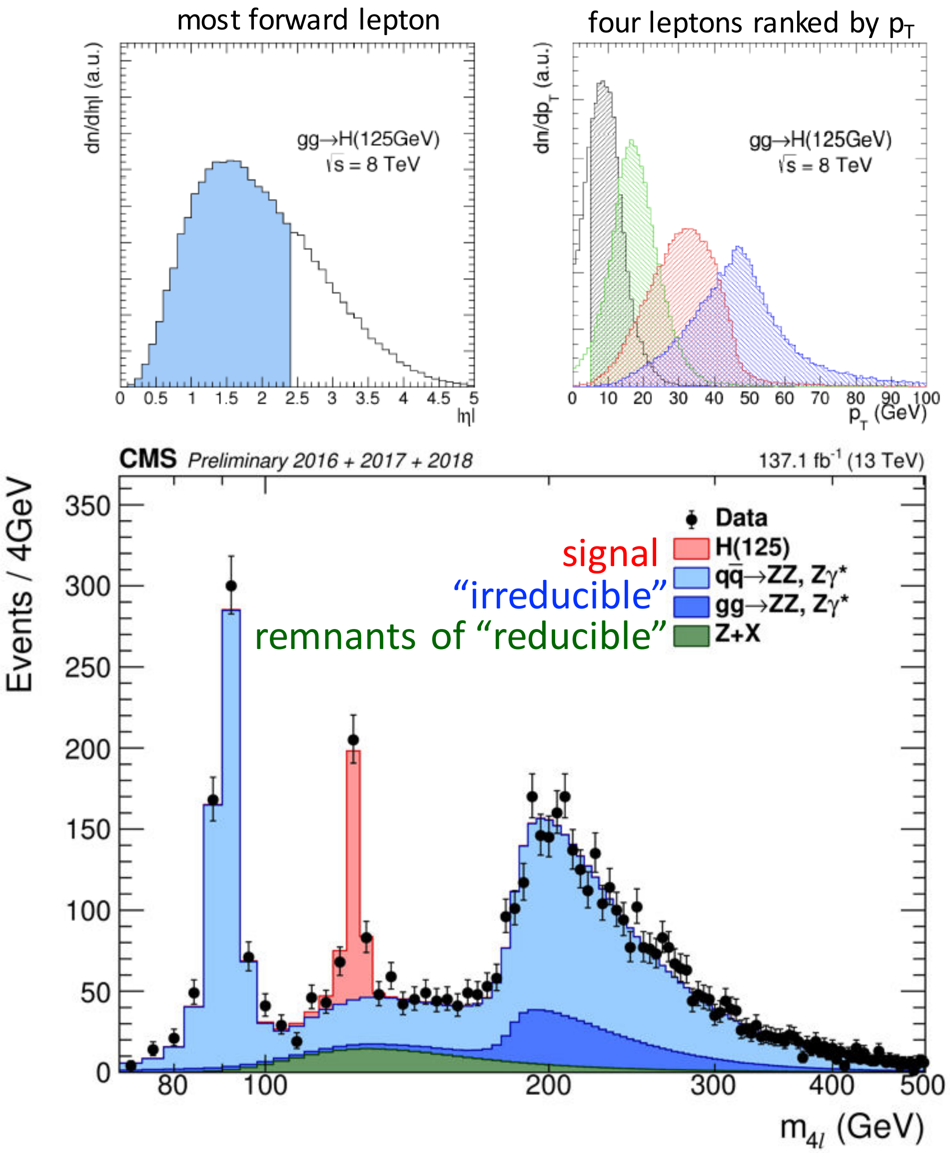
Selection: four "stable" (directly detected) leptons, e and/or μ (relatively low p_T and forward leptons important for high efficiency of detected events! See pictures)

pp-collisions have plenty of leptons, produced in jets

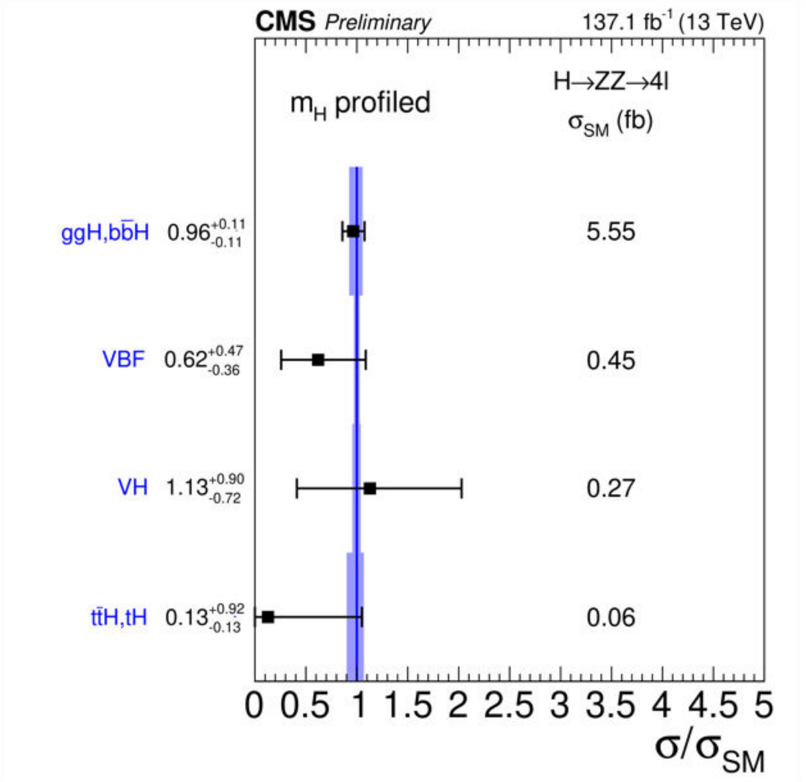
Selection: require all four photons to be **isolated and not displaced wrt Interaction Point (IP)**. This will kill most of leptons produced in jets background; it is hence called **"reducible" background**

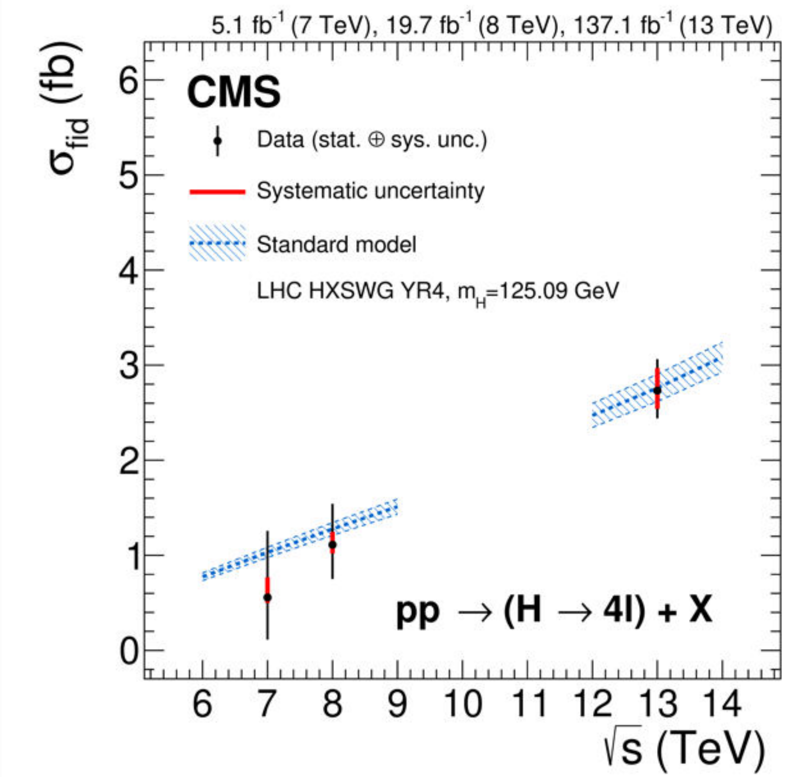
BUT: there is still large "irreducible" background, e.g. pp->ZZ->4l
Invariant mass of such four leptons will be all over the place

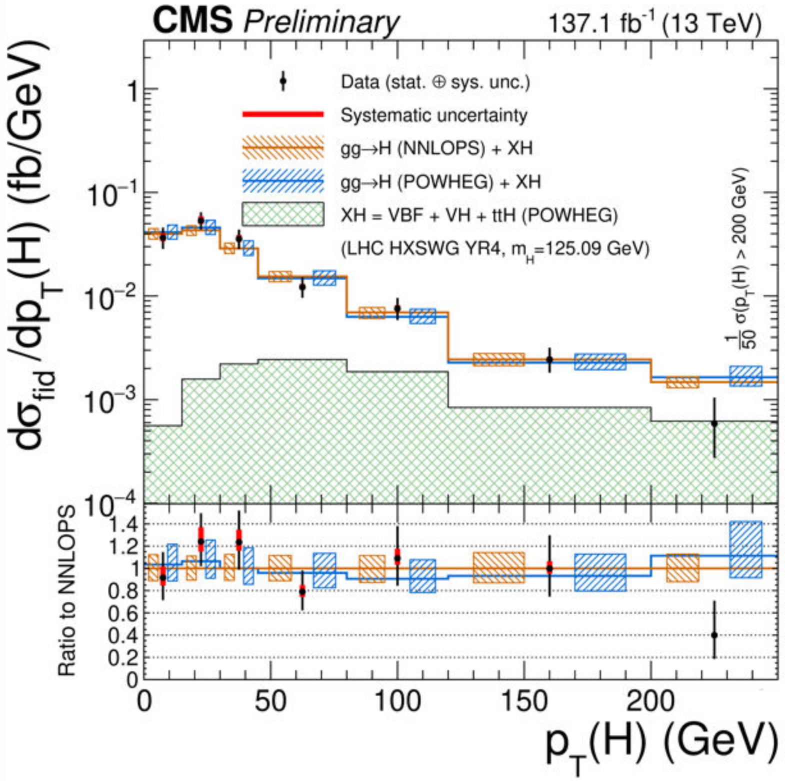
Selection: look for a narrow peak (dm/m = 1%) in four-lepton mass distribution



$H \to ZZ^* \to 4\ell$ differential production rates
a subset of results







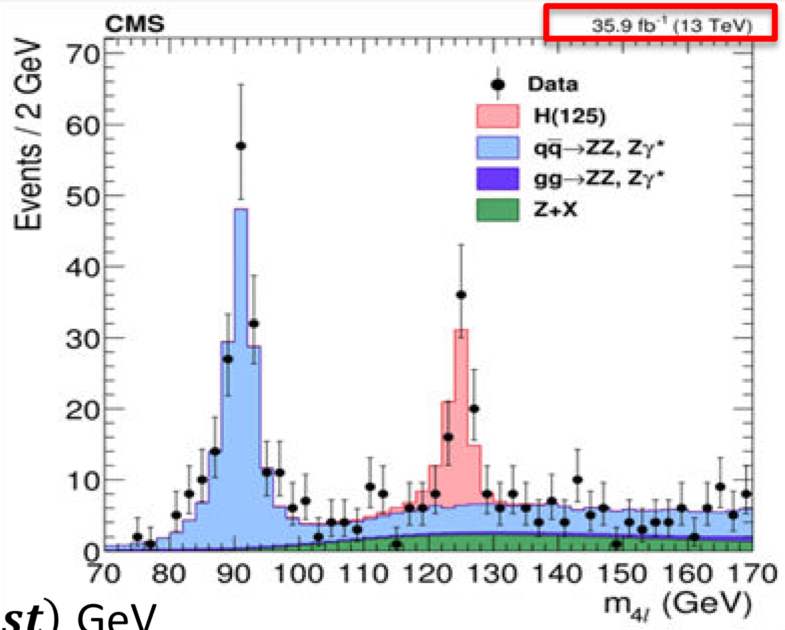
$$\mu = 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

All event rates measurements agree with the SM predictions

$H \to ZZ^* \to 4\ell$: Higgs mass measurement

Mass measurement:

- Three event categories: $4\mu, 2e2\mu, 4e$
- Momenta of two leptons forming Z_1 are refit using $\boldsymbol{pdf_{Z1}(m_{ll})}$
- Fit is performed for m_H in 3D space: $\boldsymbol{pdf\left(m_{4l}, D_{bkg}^{kin}, \sigma_{m_{4l}} \middle| m_H\right)}$
- With respect to using just mass distribution
  - Z_1-refit improves m_H measurement by **10%**
  - per-event four-lepton uncertainties -- by **8%**
  - ME-based discriminant (signal-vs-background) -- by **3%**



Run 2, 2016 CMS result: $\boldsymbol{m_H = 125.26 \pm 0.21 = 125.26 \pm 0.20(stat) \pm 0.08(syst)}$ GeV

This is the best Higgs boson mass measurement at the moment

Run 1
ATLAS+CMS ZZ+$\gamma\gamma$ combination
125.09 ± 0.24 GeV

2016 dataset	**H->ZZ->4l**	**H->$\gamma\gamma$**	**Combination**
ATLAS	124.79 ± 0.37	124.93 ± 0.40	124.97 ± 0.24
CMS	**125.26 ± 0.21**	125.4 ± 0.3	

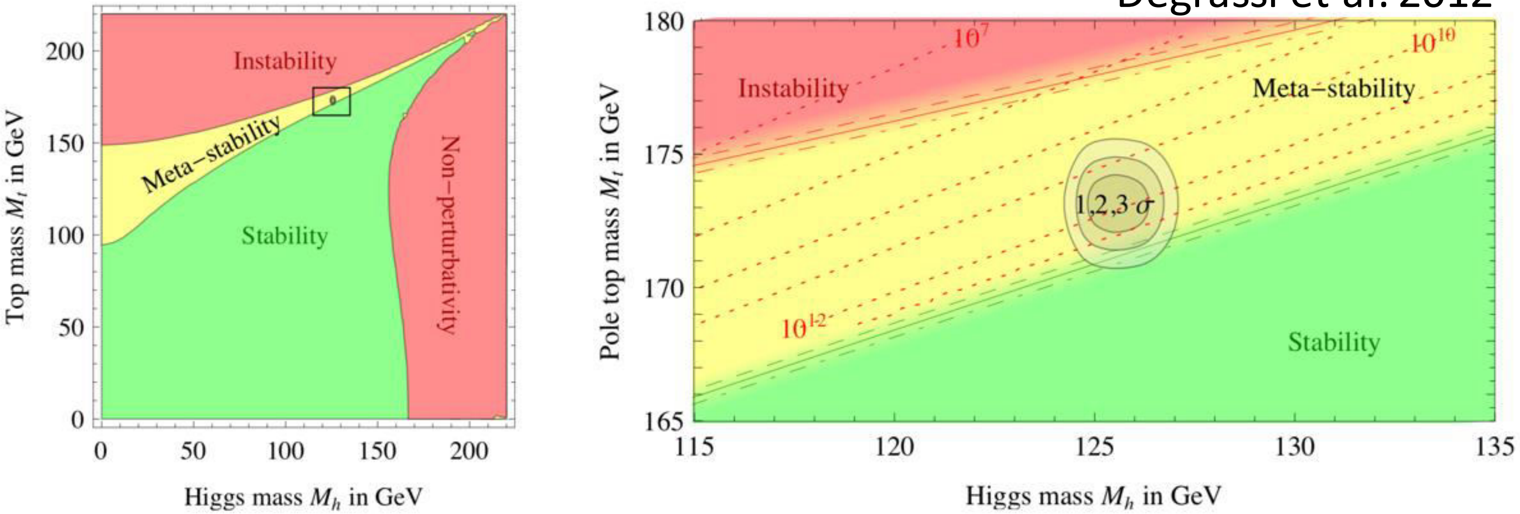
Awaiting updates with full Run 2 dataset, stat errors are expected to improve by a factor of 2 (systematic errors smaller!)
With HL-LHC results: stat error will improve by a factor of 10: ~20 MeV
One needs to improve systematics proportionally to about 10 MeV, or 0.01% – huge challenge!

$H \to ZZ^* \to 4\ell$: Higgs boson mass implications (fun stuff)

Vacuum stability:

- **If no BSM will be found up to the Planck scale, the experimental top quark and Higgs boson masses seem to imply that we may be living in a metastable universe – what?!**
- *If you about to get scared, you can relax a bit:* with m_t = 173 GeV and m_H = 126 GeV, **$\tau_{transition}$ ~ 10^{588} $T_{Universe}$**

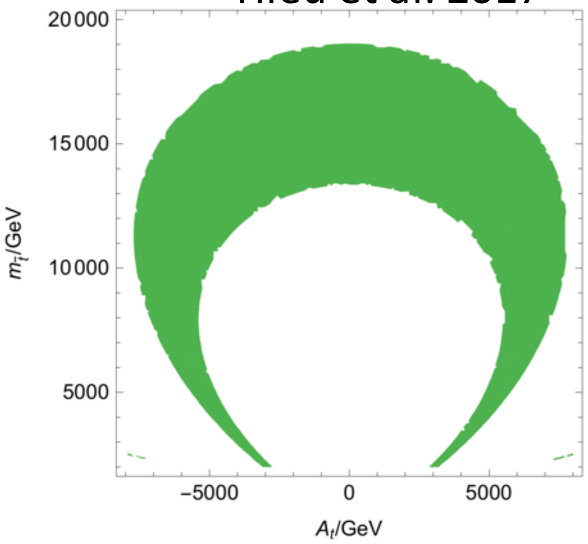
Degrassi et al. 2012



MSSM constraints:

- In MSSM, at tree level, Higgs mass m_H<m_Z.
- One can boost it somewhat higher (up to as much as 130 GeV or so) via loop corrections
- Mass m_H=125 is fairly large and sets interesting constraints on the average mass of two stop quarks (SUSY partners of the top quark).

Hieu et al. 2017



$m_H = 125.1 \pm 5(0.24)$ GeV (very generous!)
$tan\beta = 10$ (very weak dependence)
$\mu = 500\ GeV$ (Higgsino masses, not yet excluded)

Spin-parity (J^P) properties

SPIN (J)

Spin – internal quantum number of a particle; its internal angular momentum. It is quantized, $J = \frac{1}{2}\hbar \cdot n$

Experimentally, we see $H \rightarrow \gamma\gamma$ decays:

- **Spin must be integer** (it is a boson)
- **Spin cannot be 1** by the Landau-Yang theorem (a massive spin-1 particle cannot decay to two photons)

Can spin be 0?

- Yes. **In fact, for SM Higgs boson, J=0.**

Can spin be 2?

- Many theorists say don't bother; a massive spin-2 particle cannot be elementary (QFT is a mess otherwise)
- Experimentalists say… we must check

PARITY (P)

Parity -- internal quantum number of a particle, like its spin]

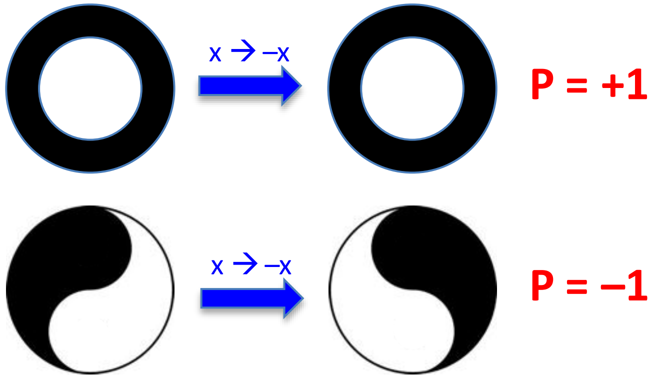
Allowed values: $P = \pm 1\ (or\ even/odd)$

Symmetry upon reflection in a mirror ($x \rightarrow -x$)

$$\hat{P} \quad = P$$

$$\hat{P}\left(\hat{P} \quad \right) = P^2 \quad = (\text{must be}) =$$

Allowed $P = \pm 1$



The Higgs boson in SM is scalar P=+1 (as opposed to pseudo-scalar P=-1)

$H \to ZZ^* \to 4\ell$: Spin-Parity and more (1)

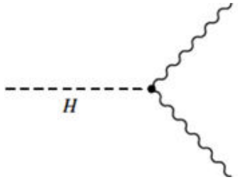
For a spin-0 boson, the most general amplitude describing its on-shell decay to two vector bosons (V) of mass m_V can be translated into the following effective Lagrangian:

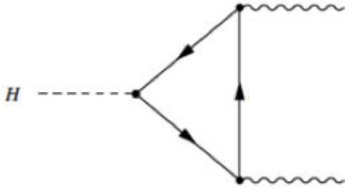
$$\mathcal{L}_{HVV} \sim \kappa_V \frac{m_V^2}{v} H V^\mu V_\mu + \frac{\alpha_V}{v} H V^\mu \Box V_\mu + \frac{\beta_V}{v} H V^{\mu\nu} V_{\mu\nu} + \frac{\gamma_V}{v} H V^{\mu\nu} \tilde{V}_{\mu\nu}$$

SM Higgs 0^+ ($\kappa = 1$)
[tree level decays]

scalar 0^+, decays via loop,
In SM, $\alpha \sim \beta \sim O(10^{-2})$

pseudo-scalar 0^-, decays via loops,
In SM, appear only at 3-loop level, $\gamma \sim O(10^{-11})$





If exists (larger than SM), this term would provide an additional source of CP violation

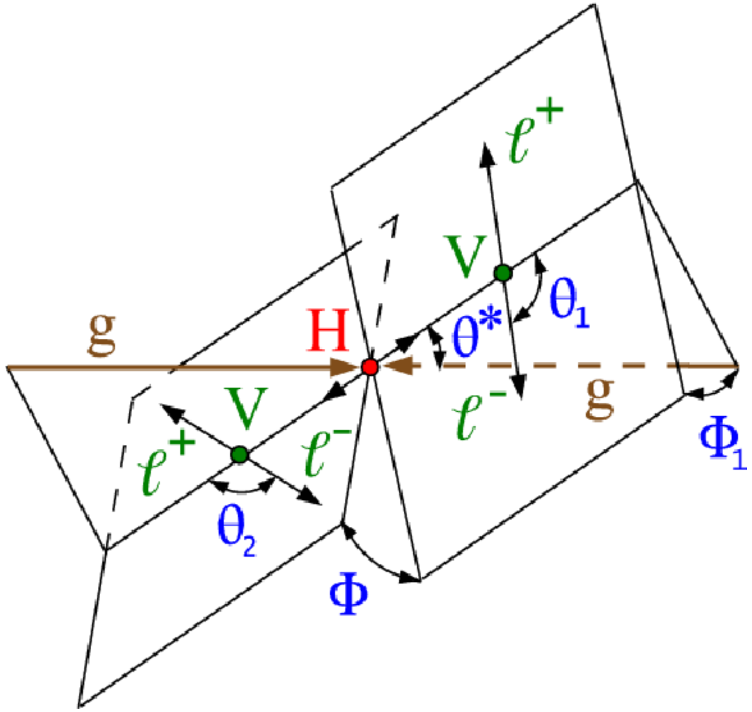
For a spin2 boson, the number of distinct terms is more than twice larger…

$H \to ZZ^* \to 4\ell$: Spin-Parity and more (2)

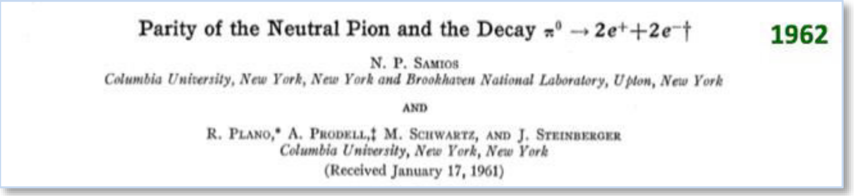
- **Essential kinematics of a four-lepton final state can be fully described by 7 observables.**
- Distributions and correlations of these observables are sensitive to the presence of all underlying decay amplitude terms.
- With all four leptons reconstructed, one can identify which distinct terms are responsible for decays – **this goes beyond just spin-parity study**

4 leptons x (p_x, p_y, p_z) = 12
COM frame: P_x=0, P_y=0, P_z=0 (-3)
Phi rotation of the entire system is not essential: (-1)
E in COM frame = m_H: (-1)
----
12 - 3 - 1 - 1 = 7

Usually, these observables are:
5 angles shown in the figure +
invariant mass of dileptons associated with each V.



Overall, this is reminiscent of the classic $\pi^0 \to \gamma^*\gamma^* \to$ 4e studies


1962

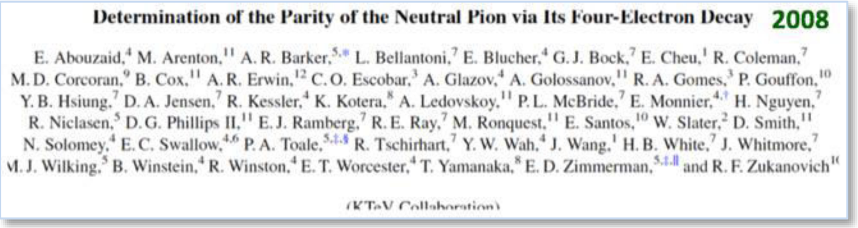
Parity of the Neutral Pion and the Decay $\pi^0 \to 2e^+ + 2e^-$†

N. P. Samios
Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

AND

R. Plano,* A. Prodell,‡ M. Schwartz, and J. Steinberger
Columbia University, New York, New York
(Received January 17, 1961)

data agree with pseudoscalar hypothesis, scalar excluded at 3.6σ


2008

Determination of the Parity of the Neutral Pion via Its Four-Electron Decay

E. Abouzaid,[4] M. Arenton,[11] A. R. Barker,[5,*] L. Bellantoni,[7] E. Blucher,[4] G. J. Bock,[7] E. Cheu,[1] R. Coleman,[7] M. D. Corcoran,[9] B. Cox,[11] A. R. Erwin,[12] C. O. Escobar,[3] A. Glazov,[4] A. Golossanov,[11] R. A. Gomes,[3] P. Gouffon,[10] Y. B. Hsiung,[7] D. A. Jensen,[7] R. Kessler,[4] K. Kotera,[8] A. Ledovskoy,[11] P. L. McBride,[7] E. Monnier,[4,†] H. Nguyen,[7] R. Niclasen,[5] D. G. Phillips II,[11] E. J. Ramberg,[7] R. E. Ray,[7] M. Ronquest,[11] E. Santos,[10] W. Slater,[2] D. Smith,[11] N. Solomey,[4] E. C. Swallow,[4,6] P. A. Toale,[5,‡,§] R. Tschirhart,[7] Y. W. Wah,[4] J. Wang,[1] H. B. White,[7] J. Whitmore,[7] M. J. Wilking,[5] B. Winstein,[4] R. Winston,[4] E. T. Worcester,[4] T. Yamanaka,[8] E. D. Zimmerman,[5,‡,‖] and R. F. Zukanovich[10]

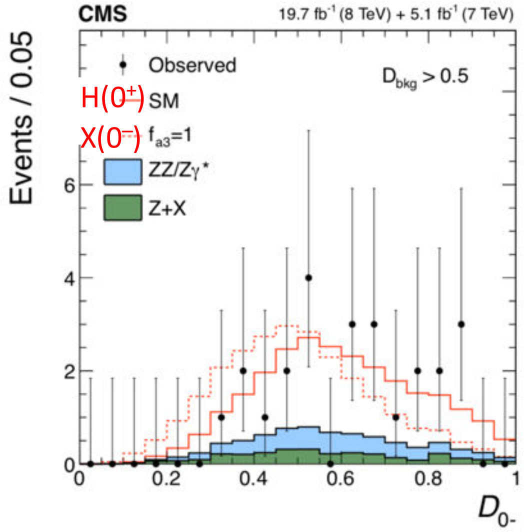
(KTeV Collaboration)

fractional scalar amplitude admixture < 0.033

$H \rightarrow ZZ^* \rightarrow 4\ell$: Spin-Parity results

In nut shell:

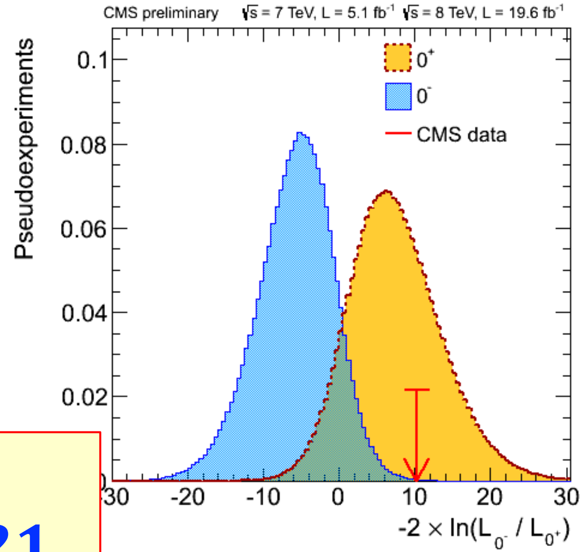
- Construct a **LO ME-based discriminant D** of, e.g., pseudoscalar vs scalar. It is an observable calculated using momenta of four leptons
  (one can use CompHEP, JHGen, MadGraph – all the same, of course)
- Simulation of Higgs H(0⁺) or X(0⁻) gives one **pdf(D|H)** and **pdf(D|X)**



- For all events from the signal peak, **build a test statistics** (one number for the entire set of observed events)

$$q = 2ln\prod\frac{pdf\,(D_i|H)}{pdf\,(D_i|X)}$$

- The larger observed q, the more likely the decaying particle is H(0⁺)
- **Simulation of H and X events can be used to quantify the consistency of the observed q with one or another hypothesis**



PLOT: Test of X(0⁻) vs H(0⁺) in Run 1:
Observed q agrees with H(0⁺)
Pure X(0⁻) is excluded with 99.9% CL

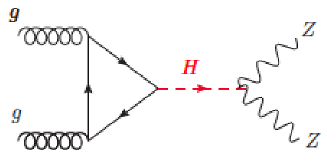
By now,
all other pure J=0 and J=2 decay amplitudes are excluded as well in one by one test against H(0⁺)

Using CMS datasets of Run 1 and 2017 + 2018 Run 2 in combination

Possible wrong parity 0⁻ addition to 0⁺ $\sim 20\%$, or: $-0.19 < \gamma_V/\kappa_V < 0.21$

$H \to ZZ$: Γ_H from off-shell to on-shell production

Breit-Wigner production pp $\to H \to ZZ$

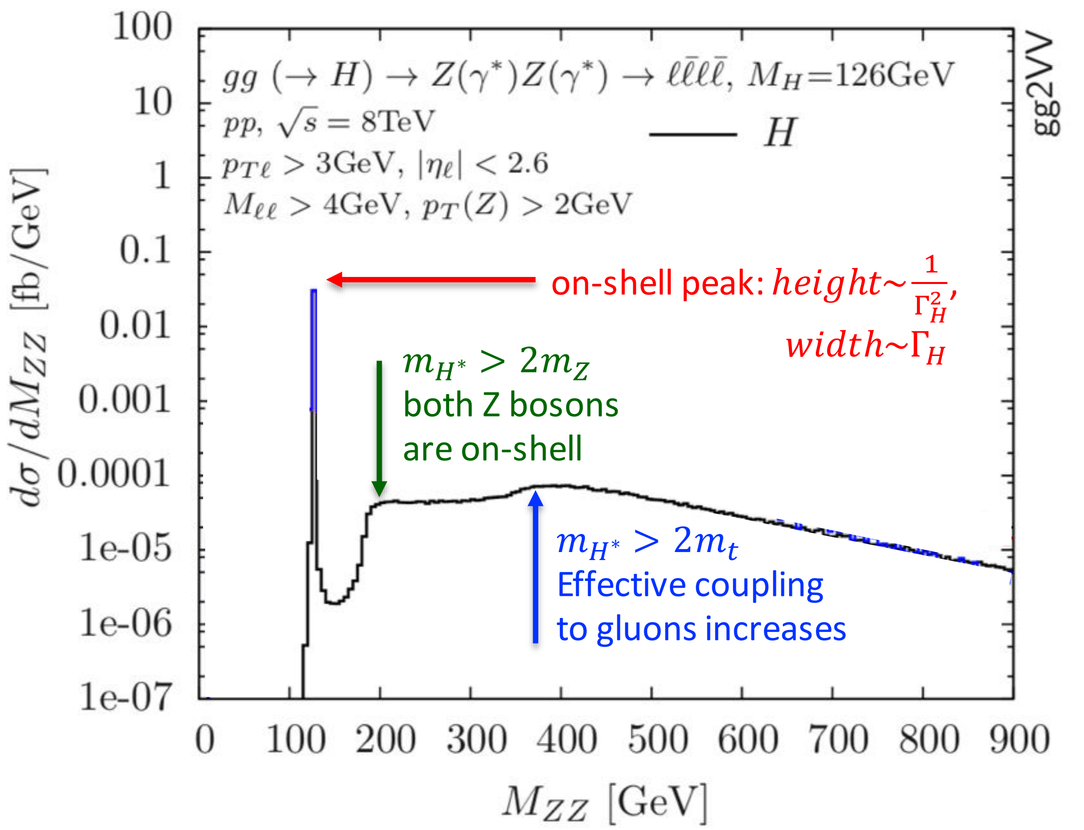


$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

On-peak cross sections: $\sigma^{\text{on-shell}} = \int_{|m-m_H| \le n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}$

Off-peak cross sections: $\sigma^{\text{off-shell}} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2$

Off-peak to on-peak ratio $\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H$



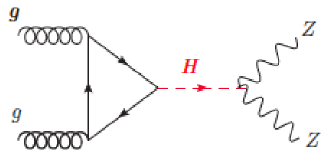
F(m) depends on:

- **huge boost for $m_{H^*} > 2m_Z$ (both Z bosons are now on-shell)**
- Hgg coupling g_g^2 evolution (notice the bump for $m_{H^*} > 2m_t$)
- partonic gg-luminosity drives F(m) down
- tensor structure Hgg coupling (non-SM couplings tend to give a large boost to off-shell production)

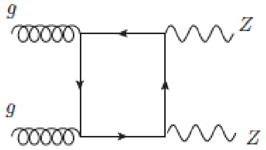
$H \to ZZ$: Γ_H from off-shell to on-shell production (results)

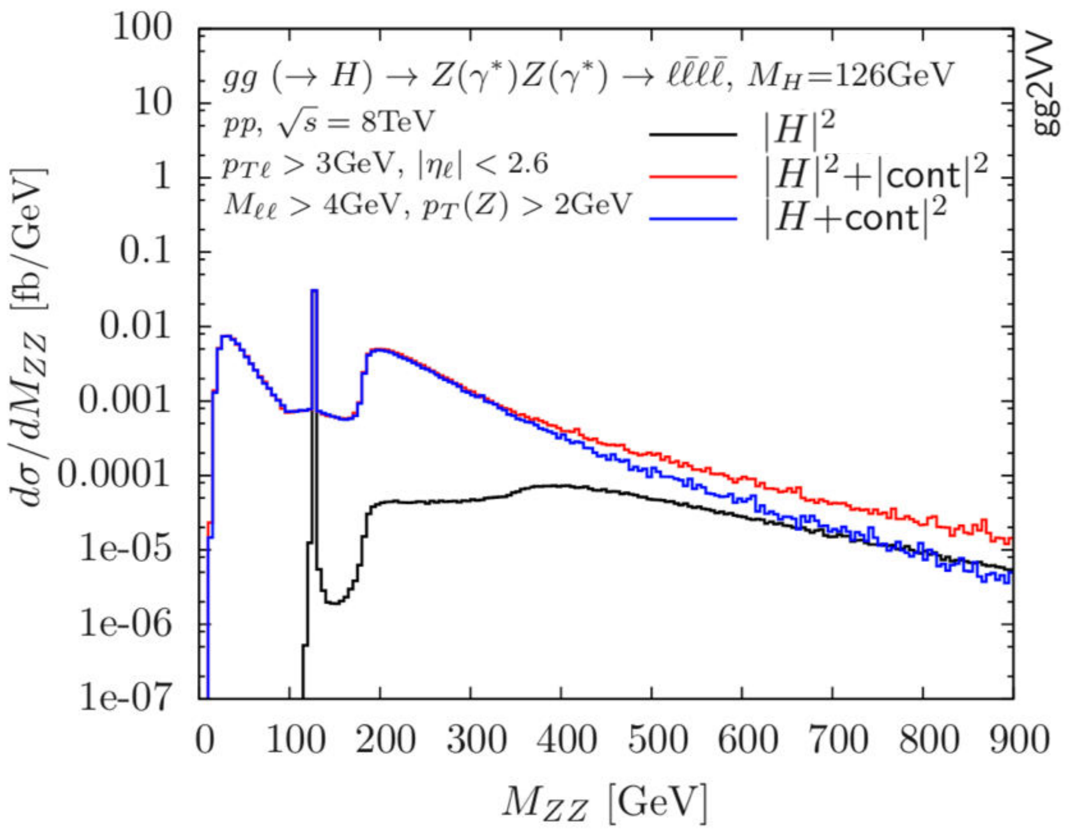
The picture gets more complicated due to interference with non-resonant gg→ZZ

Signal gg $\to H \to ZZ$



Non-resonant gg $\to ZZ$





The two amplitudes have negative interference

Assuming constant yield for on-shell events, the event yield in the tail changes with Higgs width as

$$N \sim 1 - 2\alpha\sqrt{\Gamma} + \alpha^2\Gamma$$

CMS RESULTS (ZZ→4l/2l2v; Run 1 + 2017+2018):

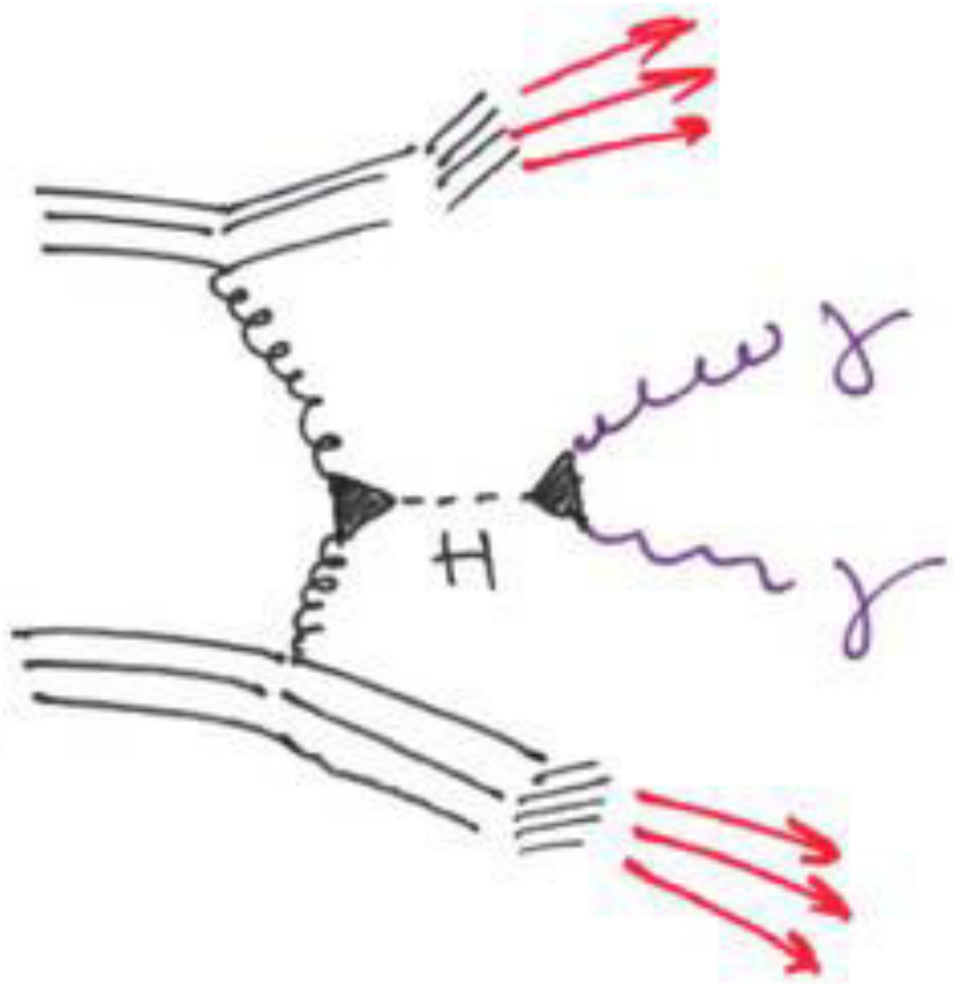
$$\Gamma_H\ (\text{MeV}) = 3.2^{+2.8}_{-2.2}\ [0.08, 9.16]$$

[95% Conf. Interval]

Result comparable with the SM Higgs width Γ_H = 4.0 MeV,
Much better precision than results of direct Γ_H Measurements

$H \to \gamma\gamma$

Run 2: σ×B×L = 16K events

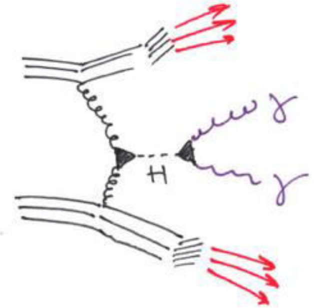


Analysis features to note:

- **fairly high event yield:**
  $20 \times (H \to ZZ^* \to 4\ell)$
- **Excellent Higgs mass resolution: 1-2%**
- **fair final S/B-ratio: 1:20**
- **Excludes J=1** (Landau-Yan theorem)
- **Best for measuring cross sections**
  (comb. of high yield and fair S/B ratio)
- **Good for Higgs mass measurement**
  but not the best due to systematics
- **Decay is via loop:** look for BSM contributions!

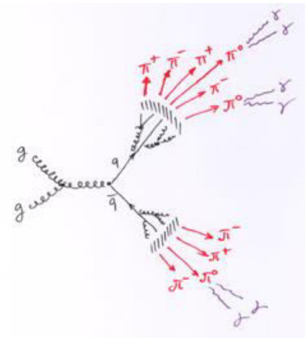
$H \rightarrow \gamma\gamma$: analysis strategy

Selection: **two photons**

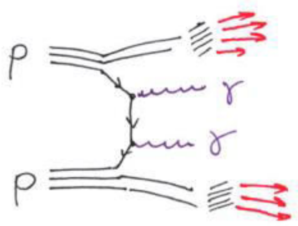


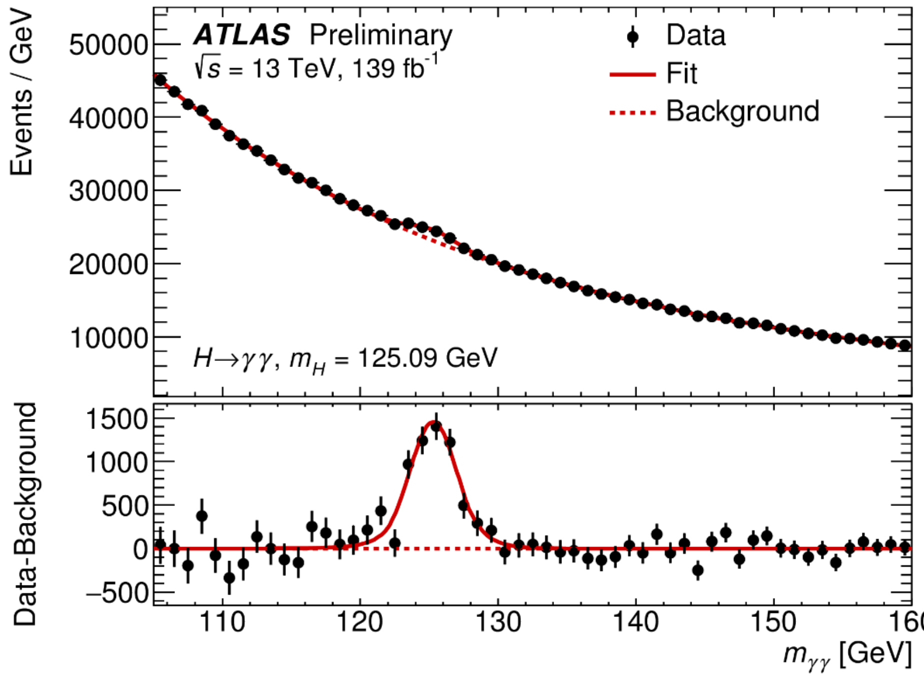
BUT: pp-collisions have plenty of photons produced in jets!

Selection: **require two photons to be isolated**



BUT: there is still large "irreducible" background. Invariant mass of such photon pairs will be all over the place, i.e it should gave a broad distribution





Selection: **look for a narrow peak** $\left(\frac{\delta m}{m} \sim 1\%\right)$

In di-photon mass distribution

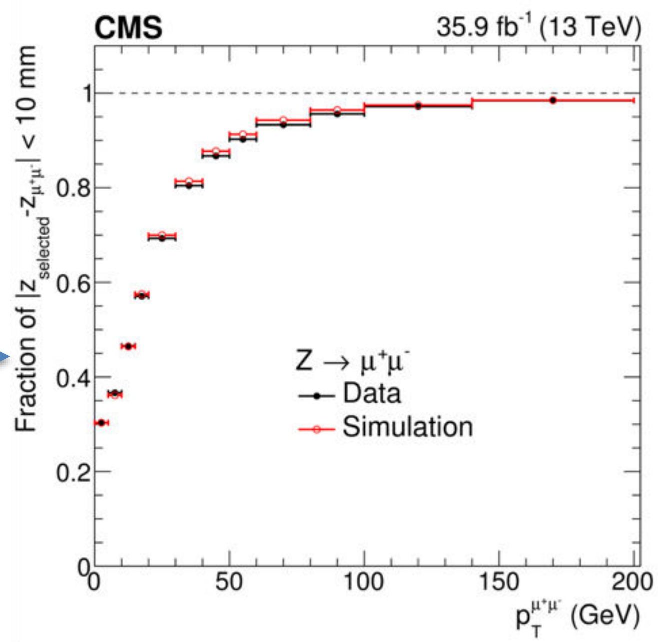
$H \to \gamma\gamma$: analysis strategy (cont'd)

BUT: To form an invariant mass, one must know the origin (primary vertex) from which photons come from, and there are many vertices in the PU spread over about $\pm$10 cm (bunch size)

Selection: Take the vertex with the largest energy flow of charged particles.

Validation: Can one validate how well we do it? Yes, use Drell-Yan $pp \to \mu\mu$ events. Muons unambiguously identify collision from which they come from. Remove muons from the list of reconstructed particles and select a vertex as you would do for a di-photon event. Probability to get it right is indeed high.

Selection: ATLAS EM calorimeter is capable of providing good photon directionality – this is used for vertex unique determination too.



Validation of correct vertex finding using Drell-Yan events

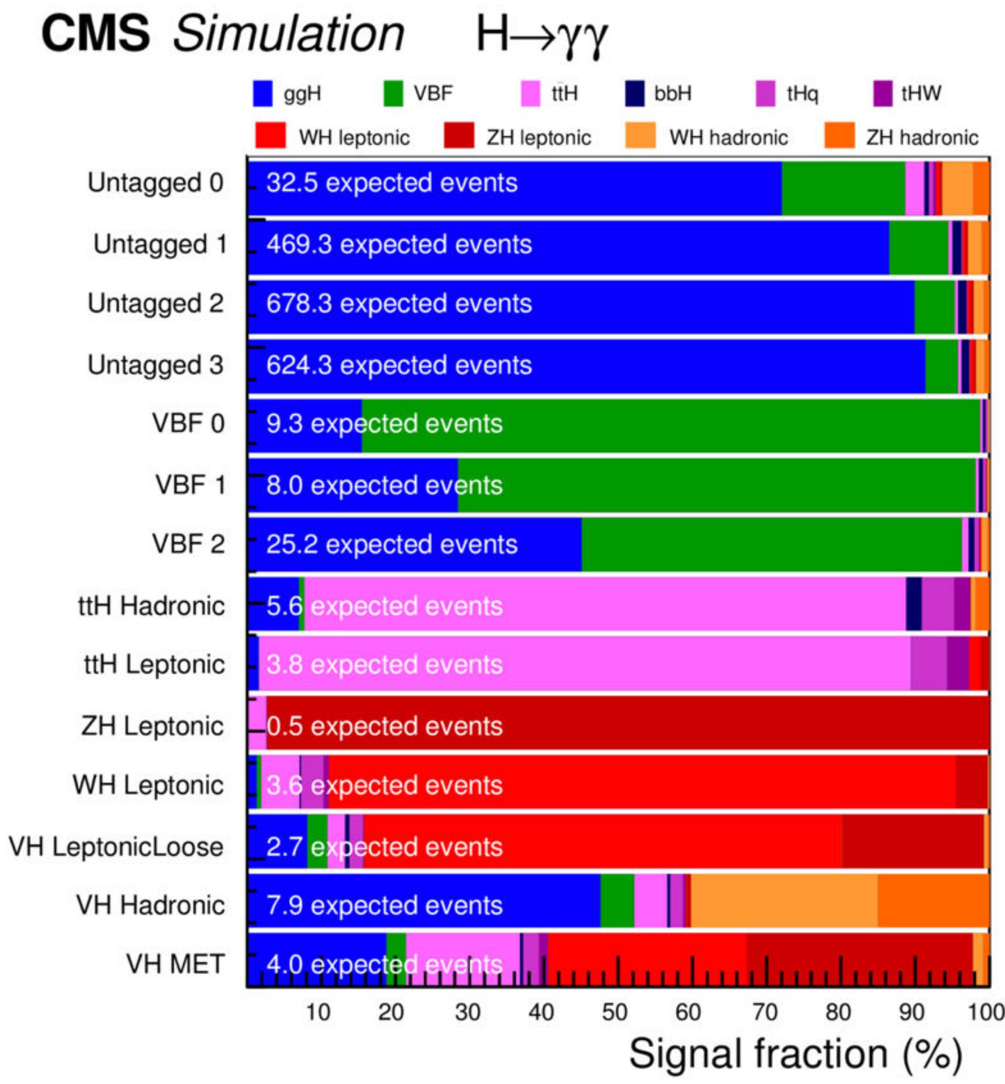
$H \rightarrow \gamma\gamma$: analysis strategy (cont'd 1)

Categorization (1): Categorize events (i.e. put them in different buckets), based on presence of "production mechanism tags": VBF, WH, ZH, ttH, untagged (more on the next slide).

1) Categorization helps to separate events with different S/B ratios and improves the total precision (As we get more and more data, we always find more ways to slice the data.)

2) This is also obviously necessary for studying relative contributions of different production mechanisms

Beware: Experimental "tags" are never pure, i.e. X-tagged events do not necessarily come from production mechanism X. (Of course, the fraction of X-produced events is enhanced by construction.)



$H \rightarrow \gamma\gamma$: analysis strategy (cont'd 2)

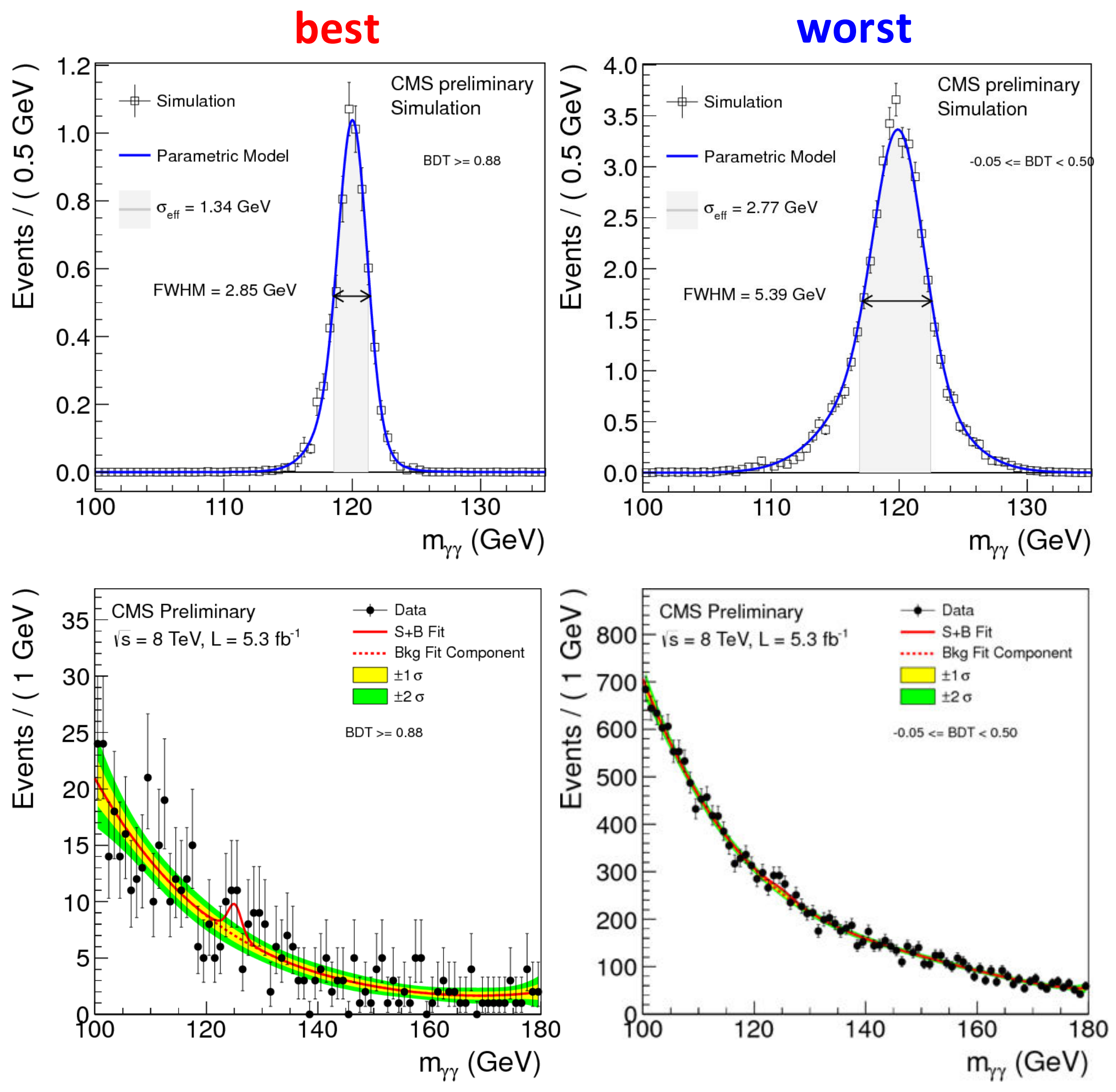
Categorization (2): *not all photons are equal!*
The untagged category (the largest) is always sub-divided further based on the expected diphoton mass resolution:

A photon's energy measurement resolution depends strongly on whether the photon is measured in the **central or forward parts of the detector**.

A photon's energy measurement resolution also depends on whether the photon is **converted on not** to e+e- pair in the tracker on the way to ECAL.

Events with **PV deemed to be reconstructed unreliably** have a worse diphoton mass resolution as well

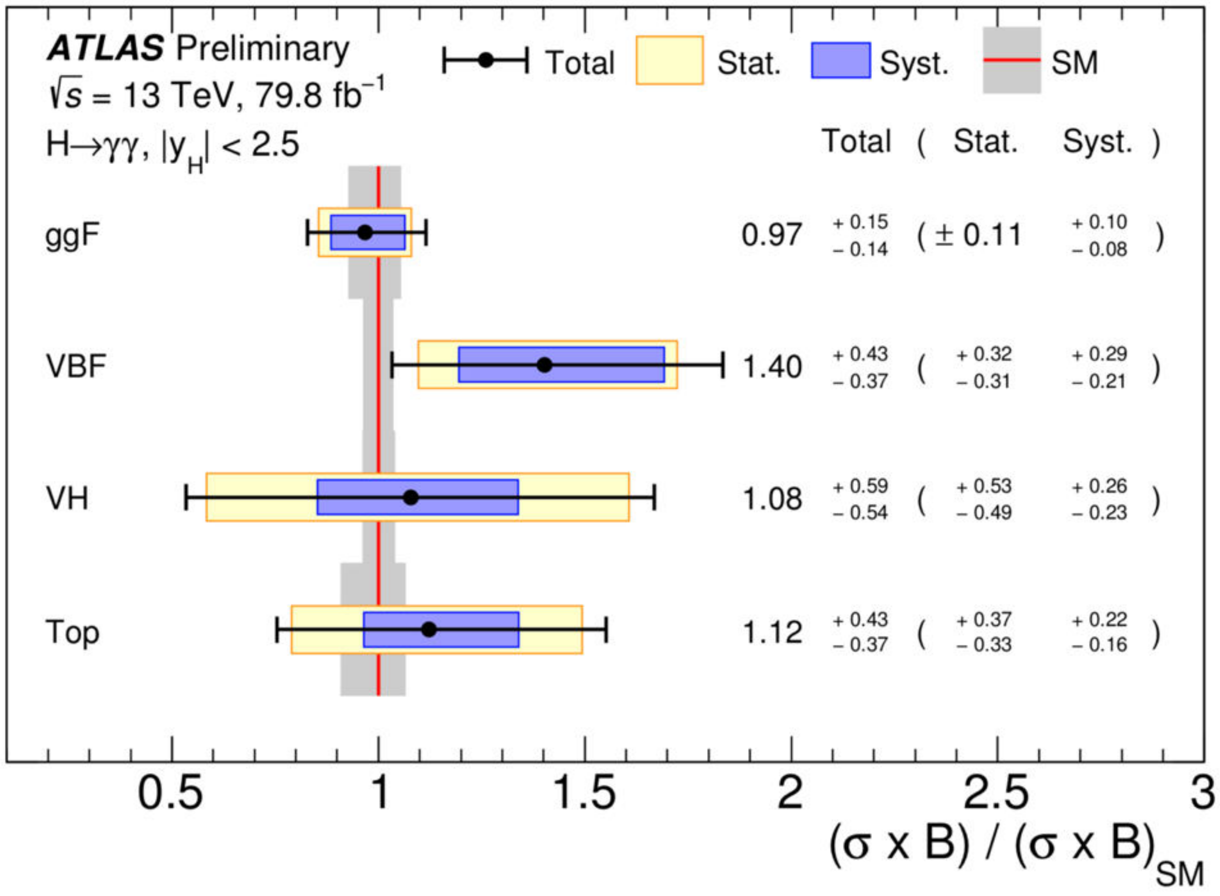
…



Observe the differences in $m_{\gamma\gamma}$ resolutions, S/B ratios

H → γγ results: signal strength

(Run 2, 2016+2017 = 60% of all Run 2)



- All four main production modes are probed with reasonable sensitivities. Observations agree with the expectations for SM Higgs boson.

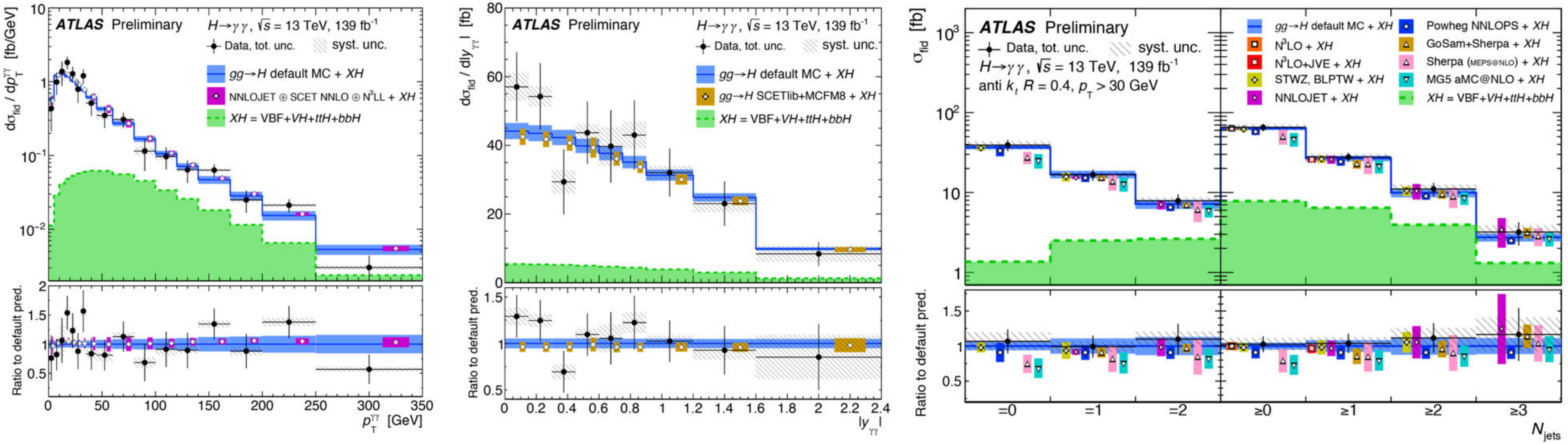
- **Overall signal strength [ATLAS, 80 fb^{-1}]:**

$$\mu = 1.06 \,^{+0.14}_{-0.12} = 1.06 \pm 0.08\,(\text{stat.}) \,^{+0.08}_{-0.07}\,(\text{exp.}) \,^{+0.07}_{-0.06}\,(\text{theo.})$$

- **stat errors ≈ exp. syst. ≈ theory uncertainties in ggF**
Looking ahead, a very hard life awaits both experimentalists and theorists

$H \rightarrow \gamma\gamma$ results: differential cross sections

(Full Run 2)



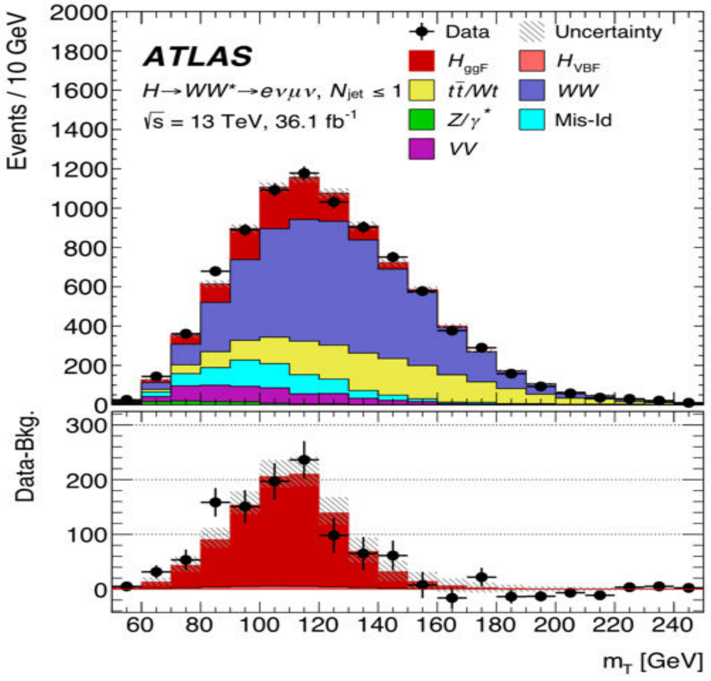
- There are already many different results: **very detailed studies of Higgs production are beginning to unfold**
- Experiment massively confronts theory (Recall that ggF calculations are notoriously challenging!)
- BSM physics may reveal itself in the tails of distributions (e.g., Higgs high pT tail)

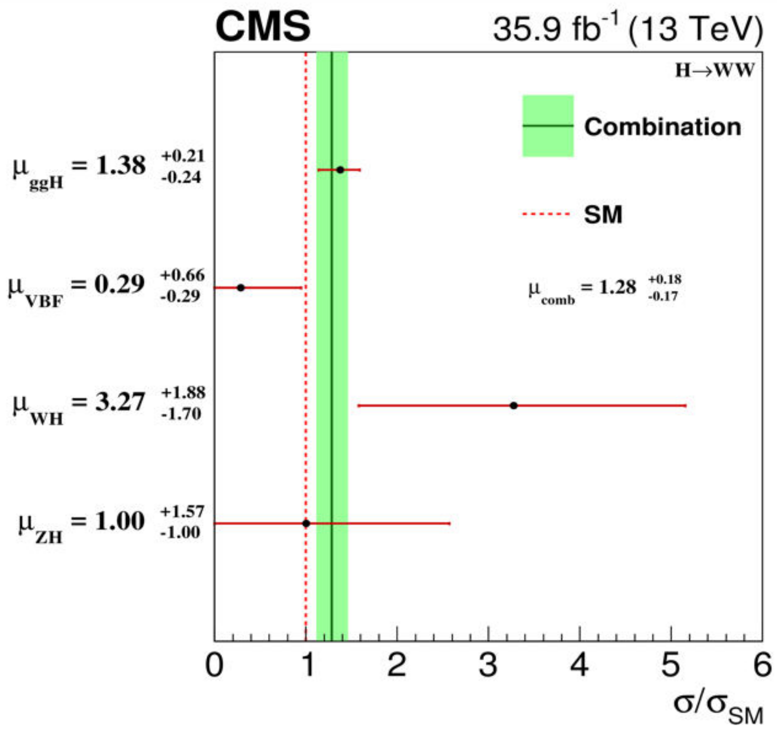
Run 2: σ×B×L = 70K events

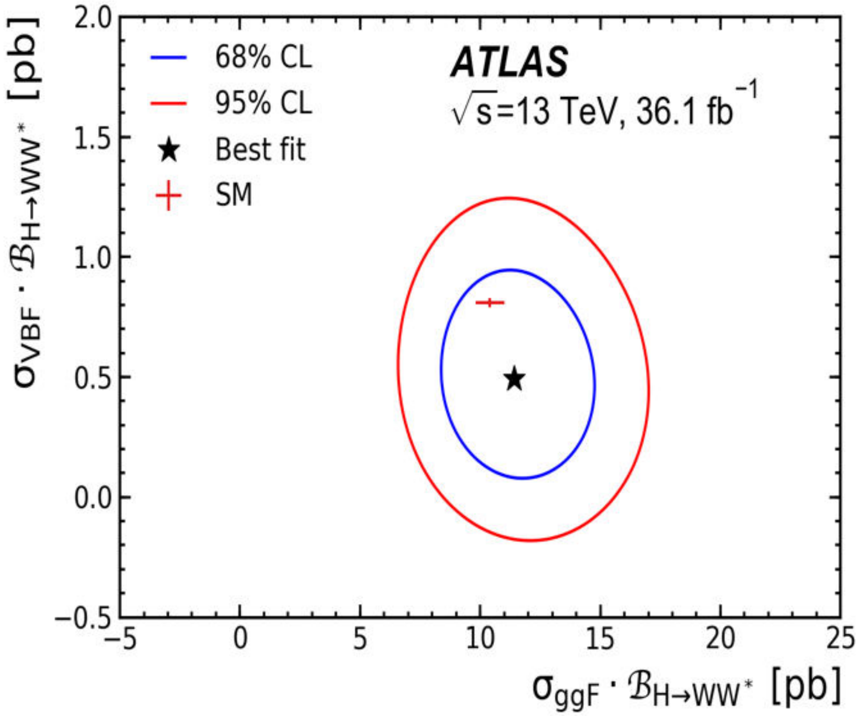
Analysis features to note:

- **high event yield: $5 \times (\mathrm{H} \to \gamma\gamma)$**
- **Neutrinos in each event: loss of energy (loss of information)**
- **Many backgrounds: WW, tt, Drell-Yan, W+jets, afer removal large systematic errors remain**
- **bad mass resolution ~15%**
- **fair final S/B-ratio: 1:5**
- **Reasonable sensitivity to Higgs at 125 GeV** (high yield with fair S/B)

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$: results (Run 2, 2016)







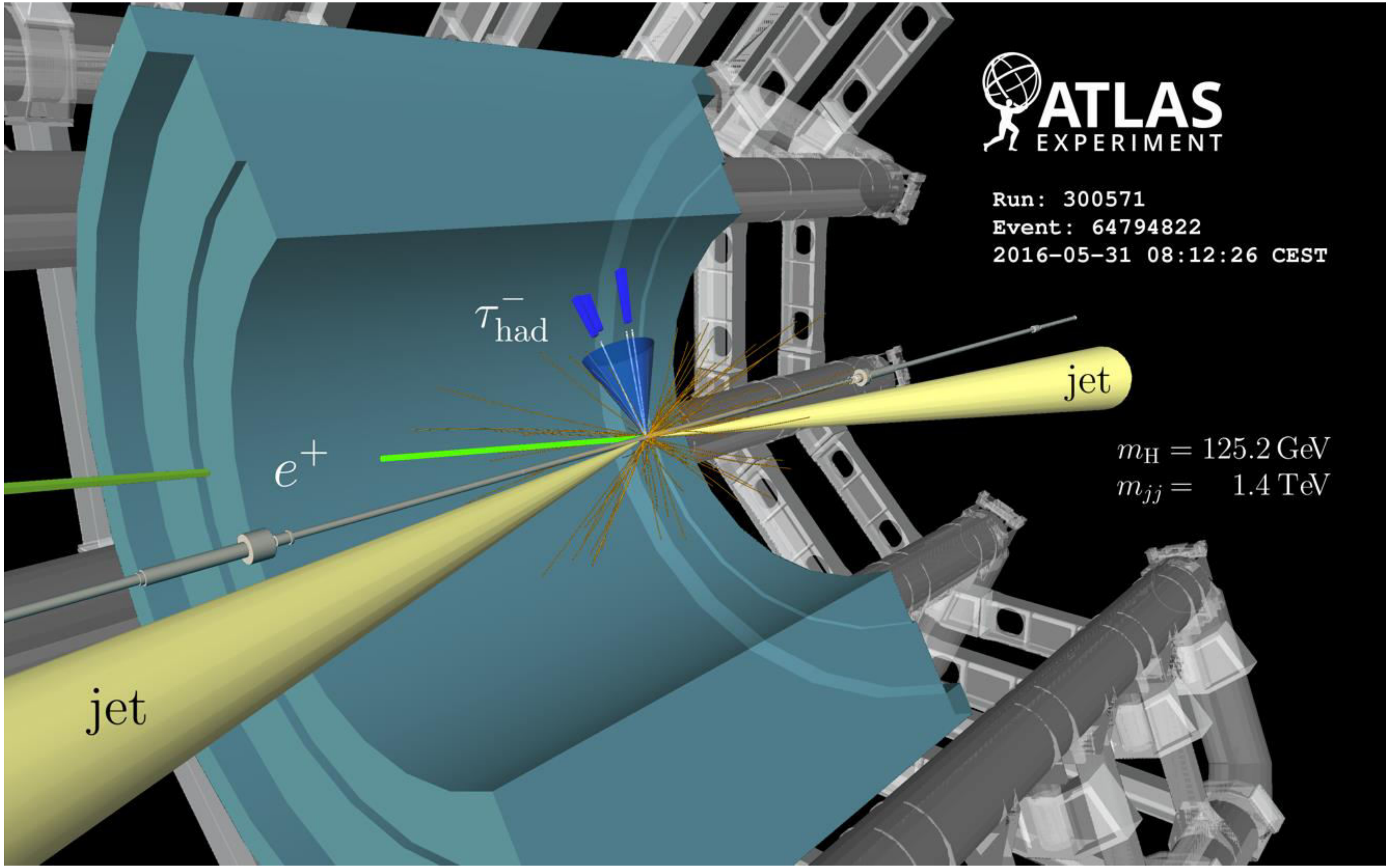
$$\mu_{ggF} = 1.10^{+0.10}_{-0.09}(\text{stat.})^{+0.13}_{-0.11}(\text{theo syst.})^{+0.14}_{-0.13}(\text{exp syst.}) = 1.10^{+0.21}_{-0.20}$$

$$\mu_{VBF} = 0.62^{+0.29}_{-0.27}(\text{stat.})^{+0.12}_{-0.13}(\text{theo syst.}) \pm 0.15(\text{exp syst.}) = 0.62^{+0.36}_{-0.35}$$

After several selections suppressing backgrounds, Higgs signal is clearly seen on the left plot (top red)
With the full Run 2 dataset, the stat errors will be reduced by a factor of two, but systematic errors are very significant. Improving systematic uncertainties is a challenge for both the experimentalists and theorists

$H \to \tau\tau$

Run 2: σ×B×L = 450K events



Analysis features to note:

- **Very high event yield:**
  $6 \times (H \to WW \to \ell\nu\ell\nu)$
- **Taus decays**
  - with one/two neutrinos each: loss of energy information
  - 2/3 of decays are hadronic: expect large background
- **bad mass resolution: ~15%**
- **Bad final S/B-ratio: 1:50**
- **The best channel to probe Higgs boson couplings to leptons since Tau mass is large**

$H \rightarrow \tau\tau$: analysis strategy (1)

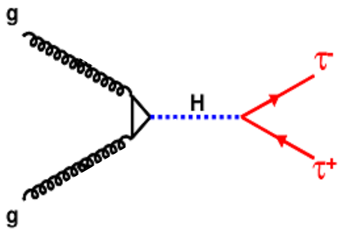
Strategy:

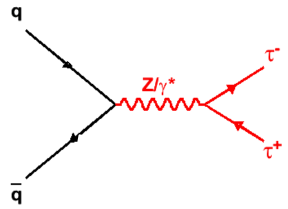
- **Selection:** di-tau pairs ($e\tau_h$, $\mu\tau_h$, $e\mu$, ee, $\mu\mu$, $\tau_h\tau_h$) + MET

  DiTau mass (including MET): key observable

Main background is Drell-Yan

It is huge and "irreducible" – it is very difficult to compete with

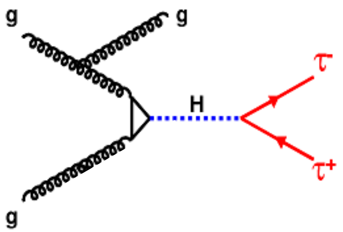


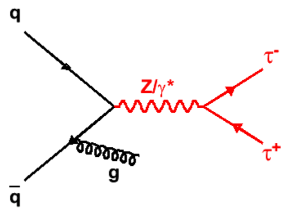


Introduce a category with a high p_T jet (boosted Higgs, suppressing Drell-Yan)

ISR off quarks in DY is $\sim c_F \alpha_s$,

ISR off gluons for ggF is $\sim c_V \alpha_s$ (twice more intense than for quarks)

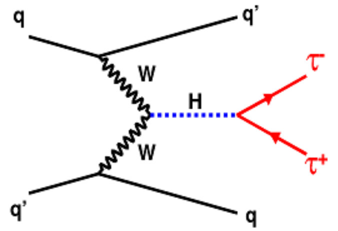


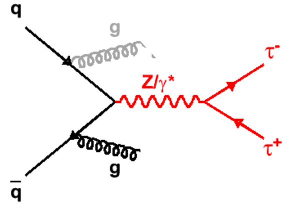


Introduce a VBF di-jet category, also suppressing Drell-Yan

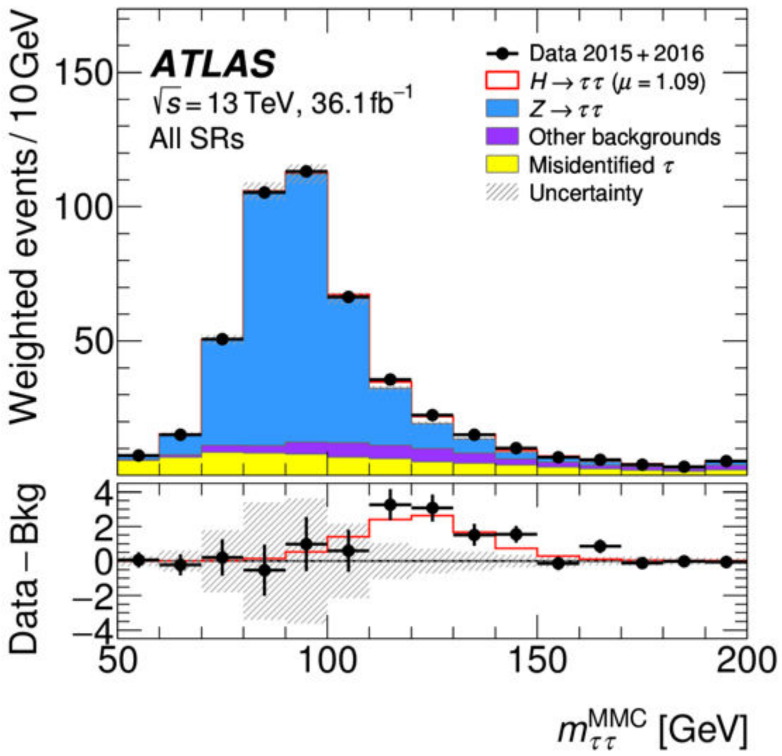
VBF/ggF ~ 0.1

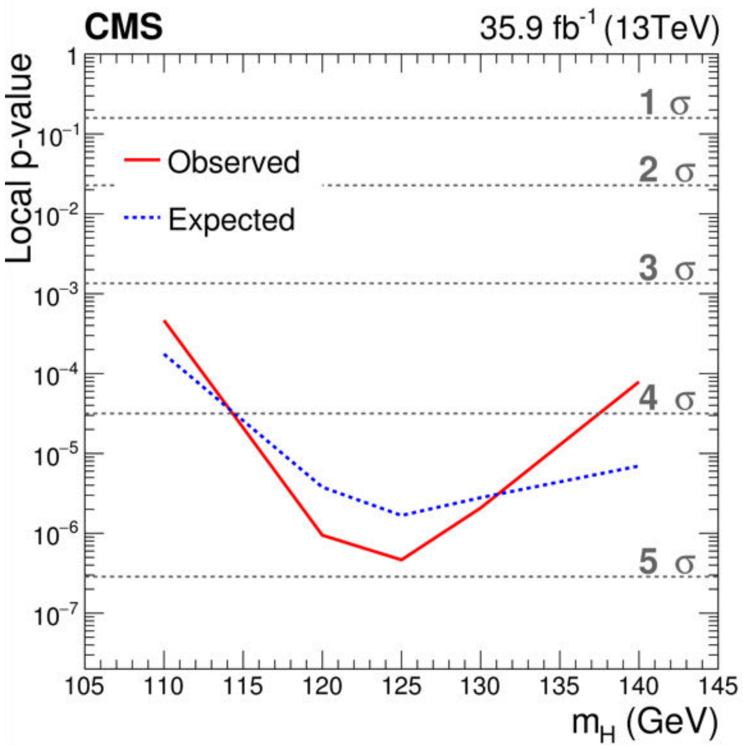
(DY+2 jets)/DY $\sim \alpha_s^2 \sim 0.01$. VBF dijet selection – bkg more suppression

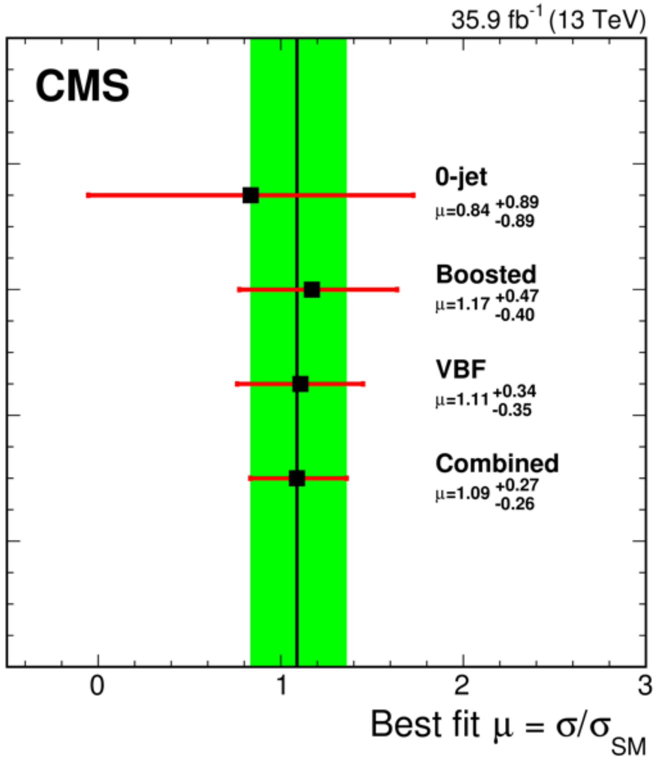




$H \to \tau\tau$: observed! (at the right place, with the right strength)







ATLAS Run 1 + Run 2 (2016)

Significance = 6.4σ

$$\mu = 1.09\,^{+0.18}_{-0.17}\,(\text{stat.})\,^{+0.26}_{-0.22}\,(\text{syst.})\,^{+0.16}_{-0.11}\,(\text{theory syst.})$$

CMS Run 1 + Run 2 (2016)

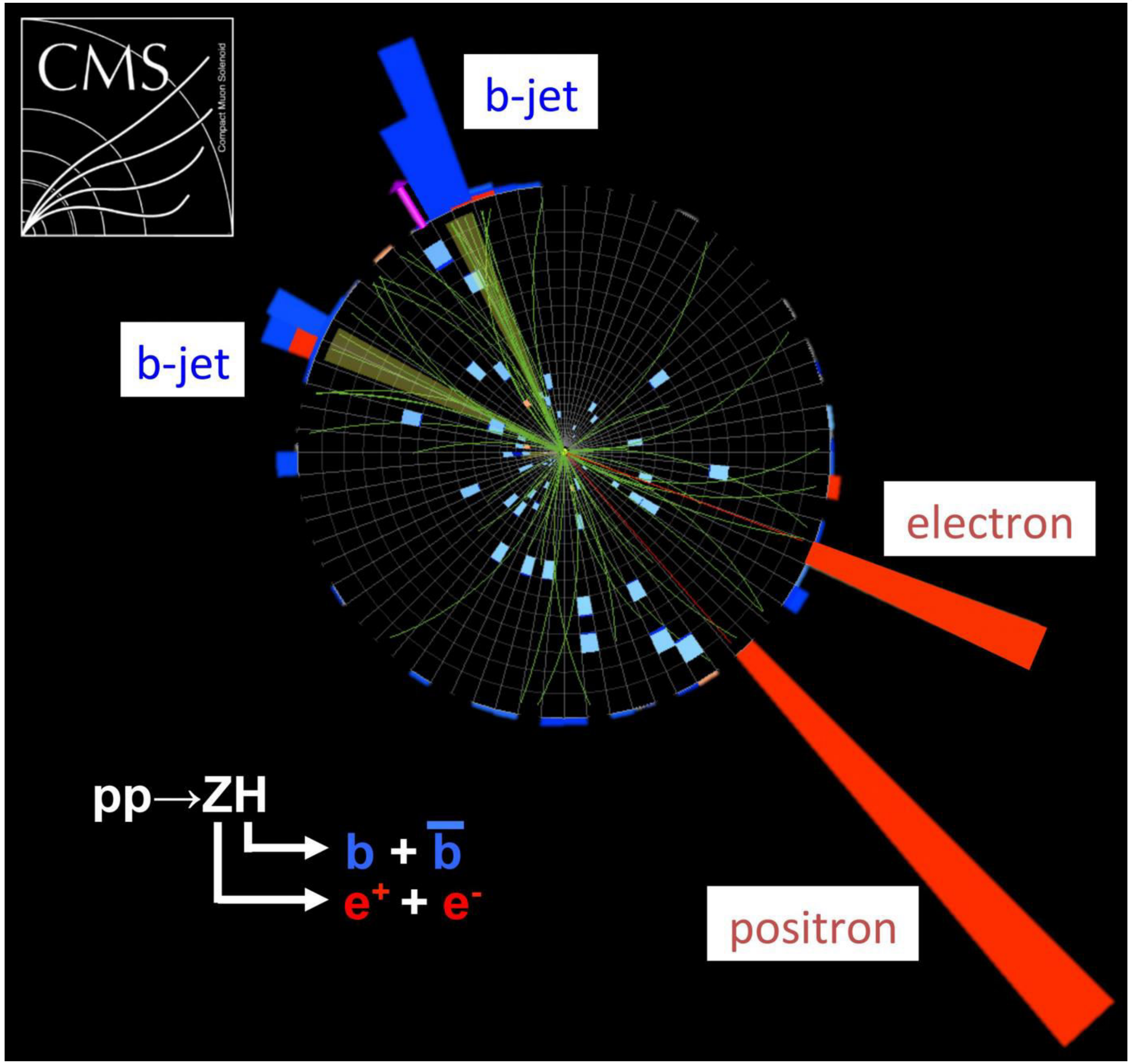
Significance = 5.9σ

$$\mu = 1.09^{+0.15}_{-0.15}\,(\text{stat})^{+0.16}_{-0.15}\,(\text{syst})^{+0.10}_{-0.08}\,(\text{theo})^{+0.13}_{-0.12}\,(\text{bin-by-bin})$$

* Signal strength is for the 2016 data alone

$H \rightarrow bb$

Run 2: σ×B×L = 4M events



Analysis features to note:

- The **highest** event yield: 9 $\times$ $(H \rightarrow \tau\tau)$
- b-quarks make jets
- **bad** mass resolution: $\sim$10%
- **Huge** QCD background

  At the time before the LHC startup, an observation of this decay at LHC was widely thought to be impossible due to overwhelmingly large QCD bkg…

- After selections: much better acceptable final S/B-ratio: 1:20

$H \to bb$: analysis strategy (1)

Selection: two b-jets

BUT: QCD $pp \to bb$ background is $\mathbf{10^7}$ times larger than signal

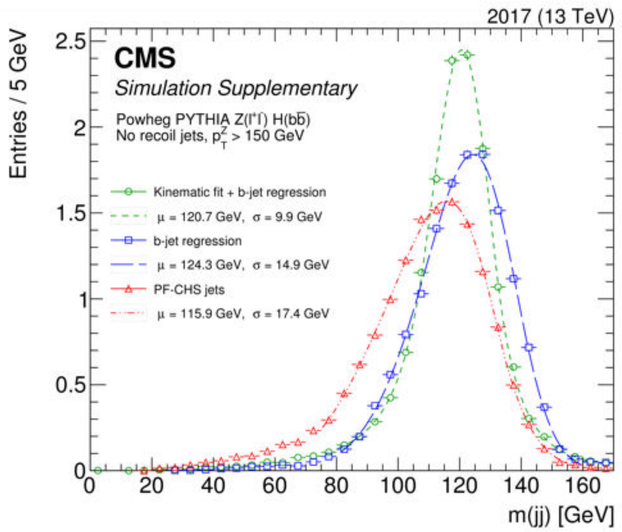
Categorization: Use the full suite of production tags enhancing S/B in the sum

the order of the best-to-worst S/B sensitivities in the categories:

- **VH: Z(ll), Z(vv), W(lv) - most sensitive;**
- ttH:
- VBF
- ggF+jet (boosted Higgs)

Use in the above recently Improved di-jet mass resolution:

- Apply b-jet specific corrections dependent on the jet substructure (e.g., presence of soft muons).
- For Z(ll)H(bb) candidates, refit jet energies with a constraint that MET=0 (within uncertainties).



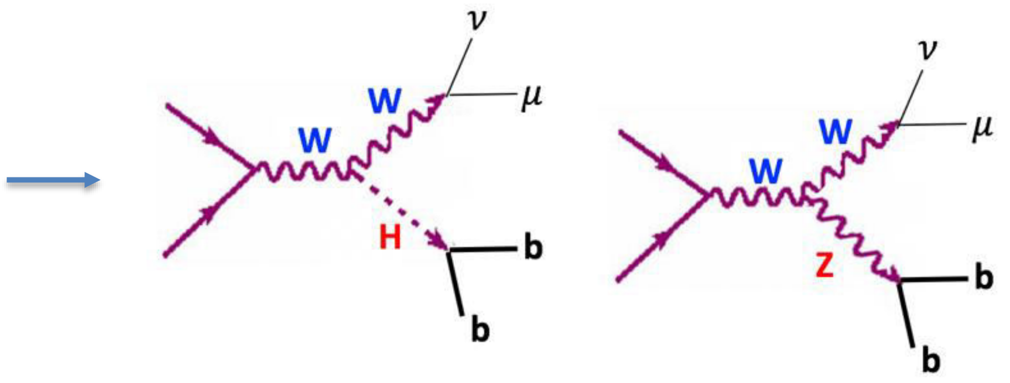
$H \rightarrow bb$: analysis strategy (2)

Main remaining backgrounds

- **Vbb, Vcc, V+jets, ttbar, single-top:** *all assessed from control regions*
- **VV:** *from simulation*

VZ(bb) is a standard candle in this analysis:

- *Experimentally, VZ(bb) is nearly identical to VH(bb), except for the mass of the $j_b j_b$-system.*
- *The expected VZ(bb) event rate is somewhat larger than that of VH(bb).*

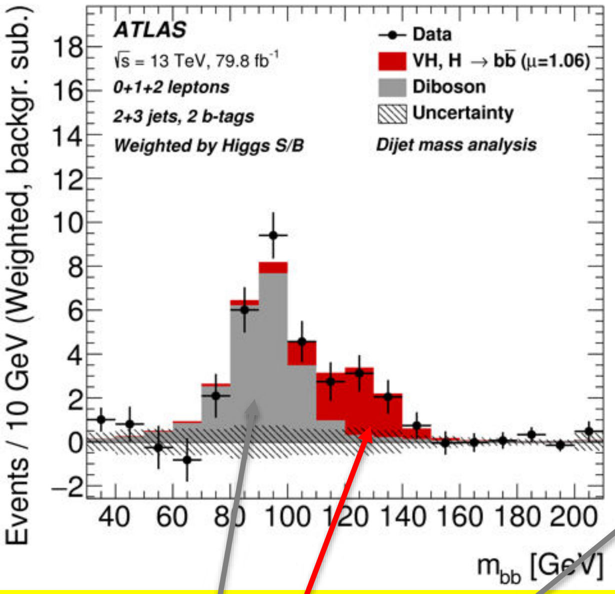


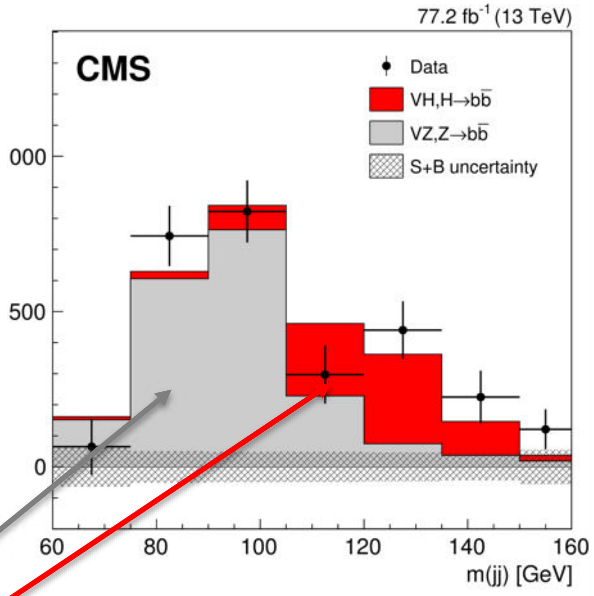
For finding final observable MVA-discriminant is used. It is trained on MC samples (signal vs bkg soup). The most important input observables used in the training:

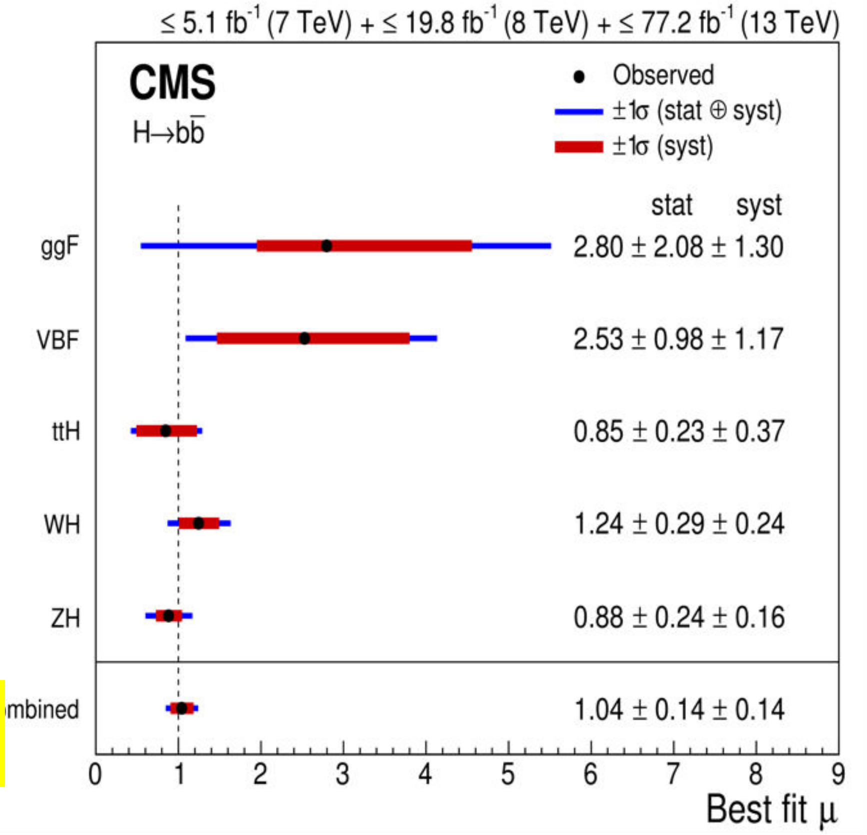
- $m(j_b j_b)$
- $p_T(V)$
- b-tag quality (score) of two b-jets
- angular separation of two b-jets
- number of additional jets (top events tend to have more jets)
- …

$H \to bb$: observed! (at the right place, with the right strength)

Run 2 (2016+2017)







Dijet mass distribution with all backgrounds subtracted except for VZ (bb).

Higgs contribution to two b-tagged jets

- **The standard candle process pp->VZ->V(bb) at right place with right strength nicely validates the analysis**

Final results with Run 1 data included:

ATLAS: Significance = 5.4σ

$\mu = 1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$

CMS: Significance = 5.6σ

$\mu = 1.04^{+0.20}_{-0.19}$

Note: the analysis becomes systematic-error dominant: more hard work ahead

Higgs (125) coupling with 2^{nd} generation particles

Probing Higgs couplings to the 2nd gen. fermions ?

All production/decay modes observed are associated with Higgs boson couplings to the 3rd generation fermions only (and W/Z bosons).

Fermions in the other generations are much lighter and their couplings to the Higgs boson are expected to be much smaller (~m), and hence the expected decay rates are much smaller (~m^2).

Can we possibly probe Higgs couplings to fermions in at least second generation: μ, c, s?

Muon:

- Muon is 17 times lighter than tau lepton (BR(H->$\tau\tau$)=6%)
- BR(H->$\mu\mu$)=0.02% - tiny, 10^x smaller than BR(H->$\gamma\gamma$) – **BAD**
- Muons are well identifiable particles at LHC - **GOOD**
- Signal dimuon mass will form a narrow peak – **GOOD**
- There is huge Drell-Yan production of muon pairs -- **BAD**

Charm:

- Charm is >3 times lighter than b-quark (BR(H→bb)=60%)
- BR(H→cc)=3% - much smaller than H→bb – **BAD**
- Charm jets are hard to tag, their properties are somewhere between ”light-flavor” jets and b-jets. One needs to fight overwhelming “light-flavor” jet background on one side and b-jet background on the other side (including H→bb!) – **TERRIBLE**

Search for H → μμ (1)

Run 2: σ×B×L = 1500 events

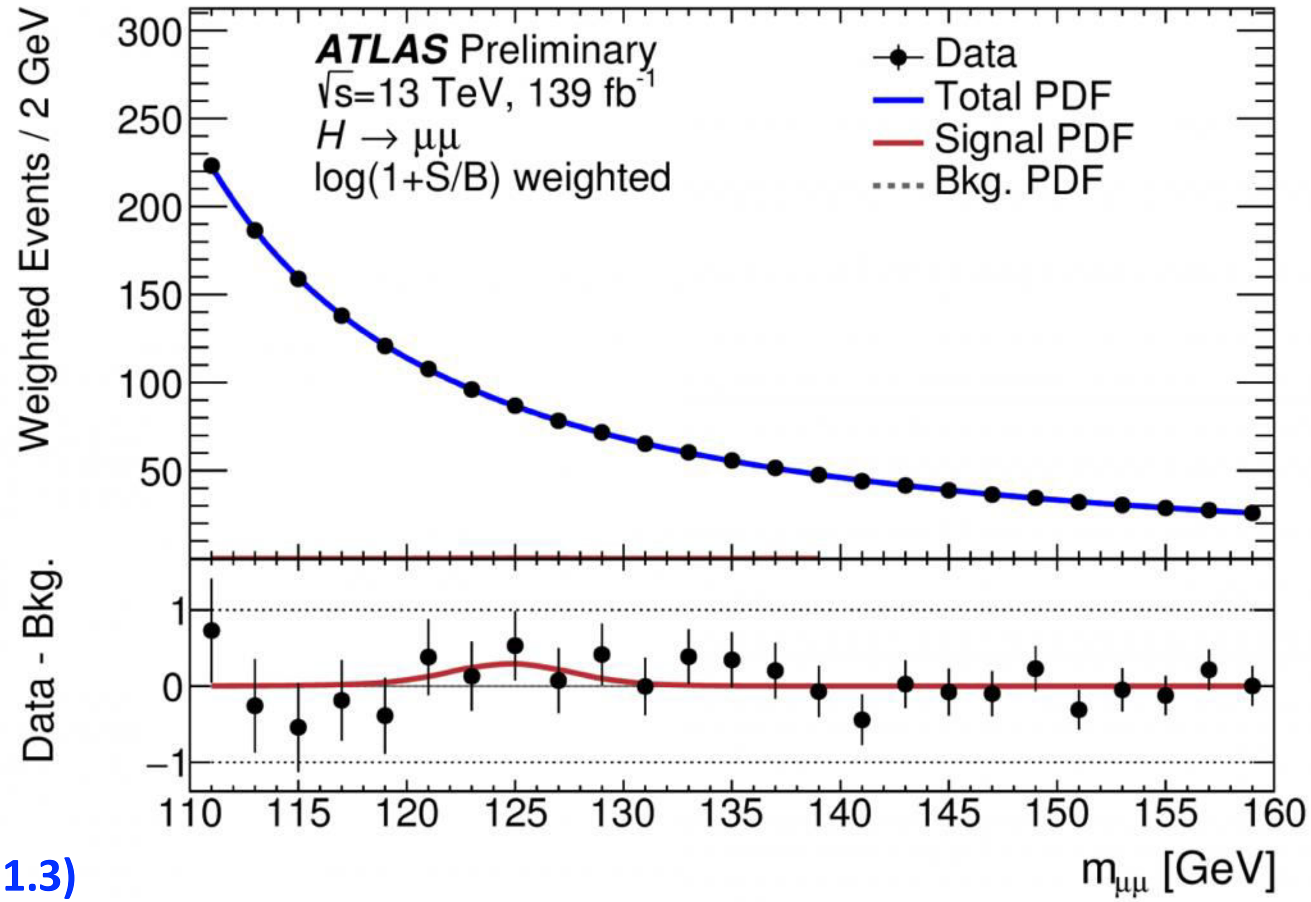
Analysis features to note

Very small signal
very bad "effective" S/B-ratio: **~1:400 (!)**
good mass resolution: **1-2%**

Backgrounds: *mostly DY, some tt*

Event Selection Strategy

- SELECTION: 2 high-p_T muons, isolated, not displaced
  key observable: **di-muon mass**



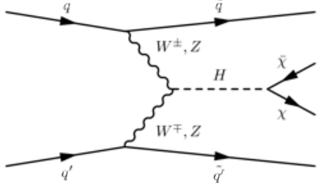
RESULT: Upper limit on signal strength 1.7 (expected 1.3)
Signal strength $\mu = 0.5 \pm 0.7$

Probing Higgs (125) → invisible decays (BSM level?)

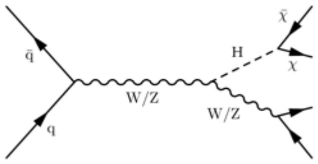
Search for H(125) → invisible (BSM?)

- In SM, $BR(H \rightarrow invisible) = 0.1\%$ (due to H→ZZ→4ν)
- Searches for H→invisible probe BSM possibilities, e.g., Higgs boson decaying to DM particles

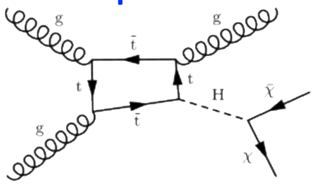
- **Direct search:** production modes exploited



mono-VBF



W/Z



mono-jet

- **Main backgrounds:** Z(νν)+jets, W(lν)+jets, Z(νν)+V, tt

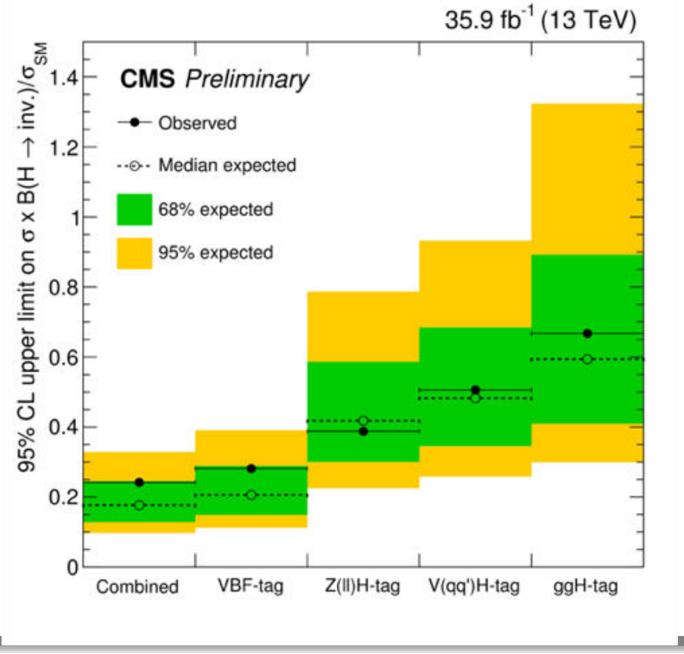
- **RESULT: Direct search upper limits:**

Run 2, 2016: $BR(H \rightarrow inv) < 0.26$ at 95% CL

Combined with Run 1: $BR(H \rightarrow inv) < 0.19$ at 95% CL

Side note: Combination of all visible decays is also sensitive to invisible decays.

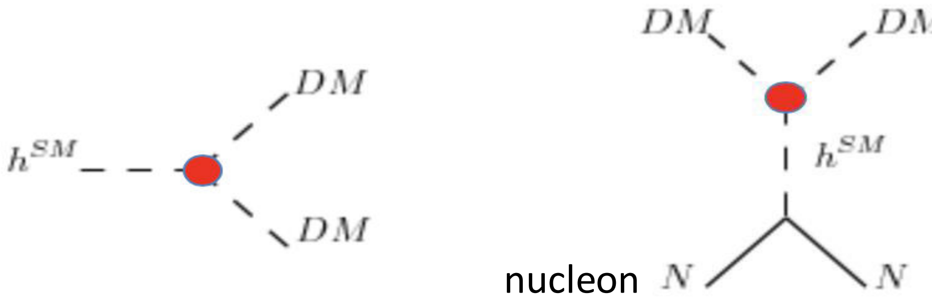
More on that later



Interpreting experimental limits of H (125) -> invisible as dark matter searches

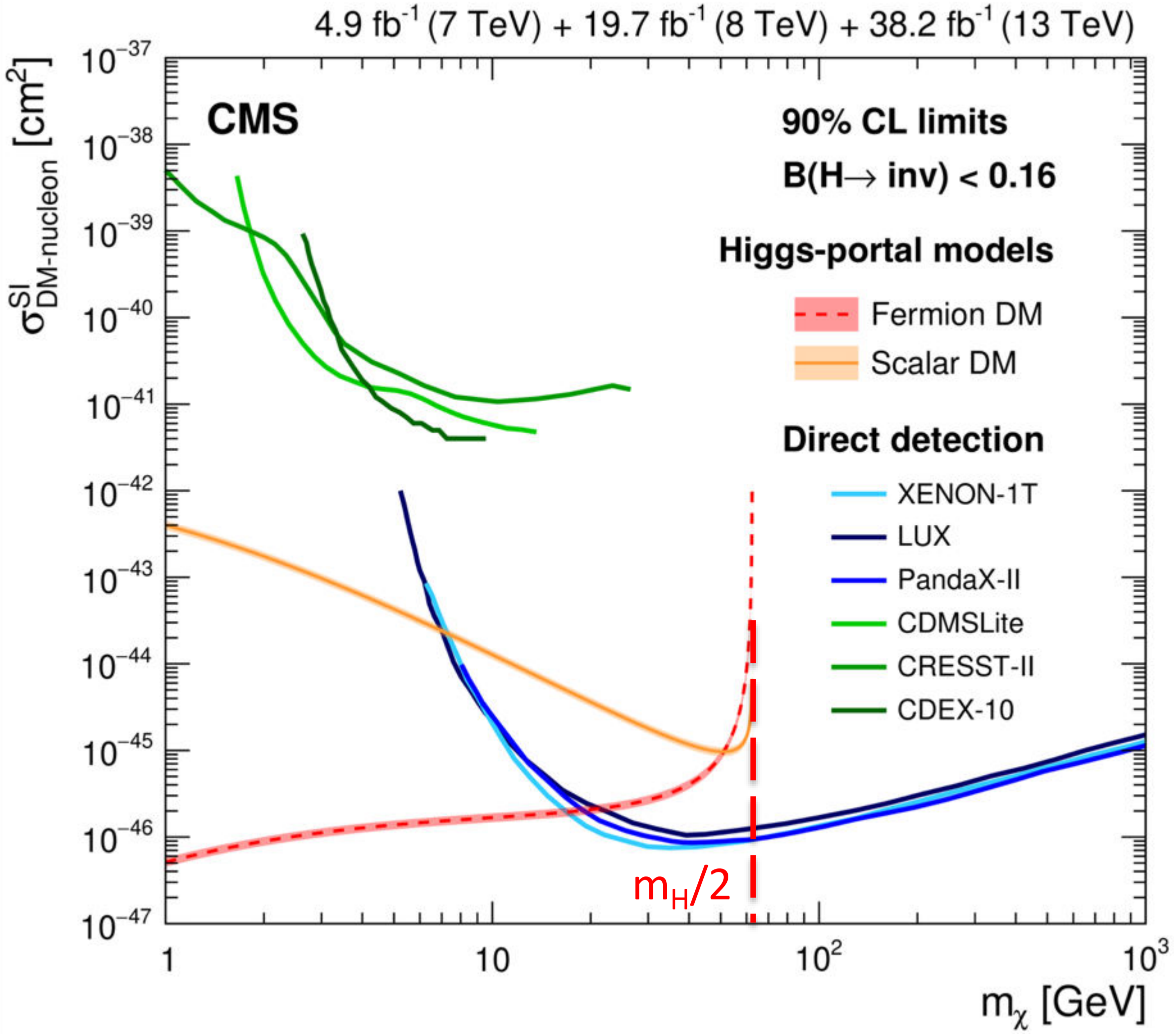
Limit on BR(H→inv) can be recast in the context of direct dark matter searches assuming Higgs is the mediator of interaction between DM and SM particles

Direct DM searches look for scattering **rate of DM+N -> DM+N.**
Rate = (cross section DM+N -> DM+N) x (DM flux) x (Target size),
where the flux is know from the local DM density,
assumed dark matter mass, m_{MD},
and the sun's velocity in our galaxy



H->invisible search **Dark Matter search**

- BR(H->inv) limits sets max coupling (m_{DM}<m_H/2, of course)
- This coupling sets a limit on cross section DM+N -> DM+N



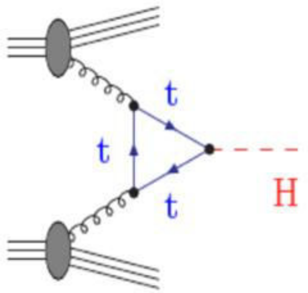
Note the complementarity of LHC results and the results of the direct DM searches

Experimental Analyses targeting specific Higgs boson production modes

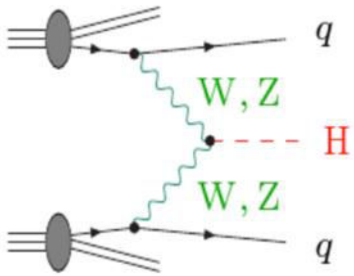
Higgs boson production in SM

Couplings define the dominant productions mechanisms:

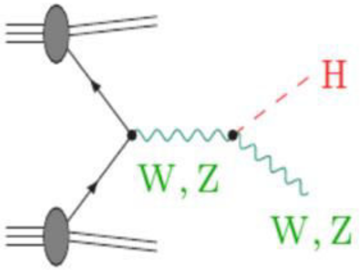
- **one needs to produce a heavy particle first, to which Higgs boson couples willingly**
- **that heavy particle can actually be virtual (in loops) and not present in the final state**



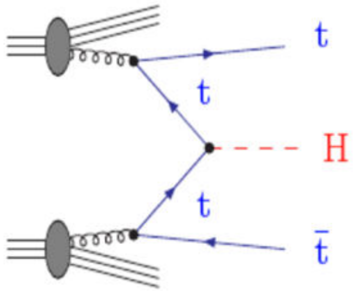
gluon fusion into Higgs (ggF). It is loop induced



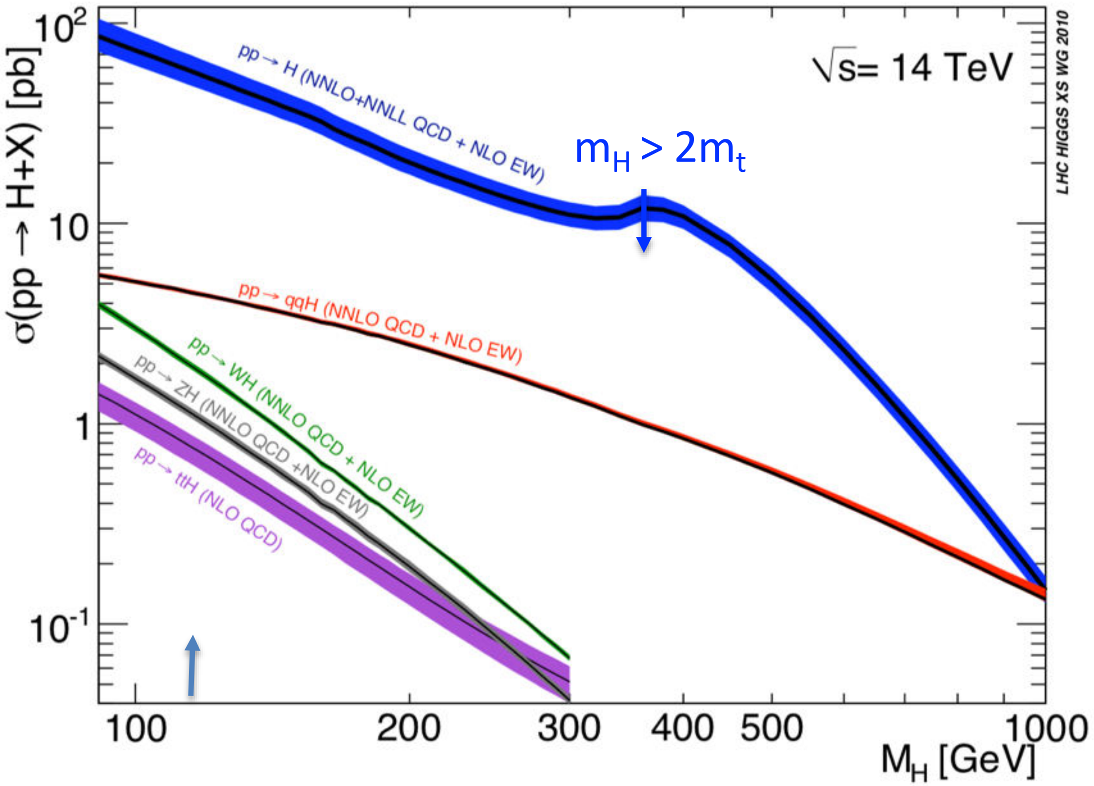
vector boson W, Z fusion (VBF) into Higgs



associate Higgs production with Z/W (VH)

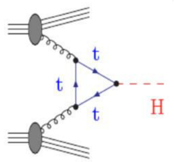


associate Higgs production with tt (ttH)

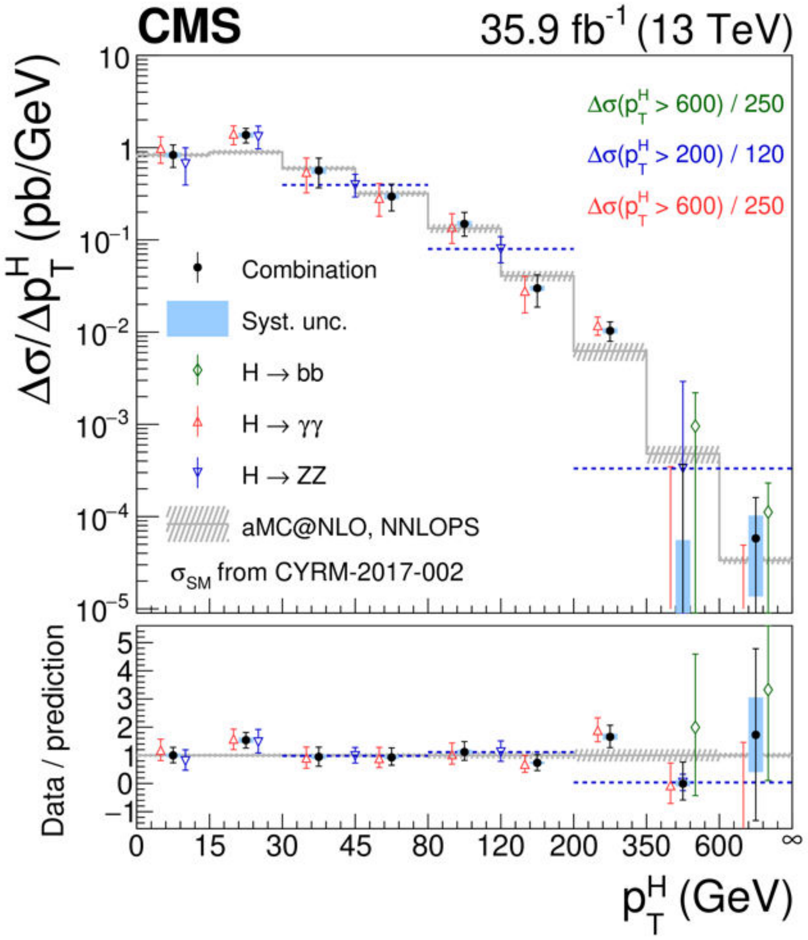


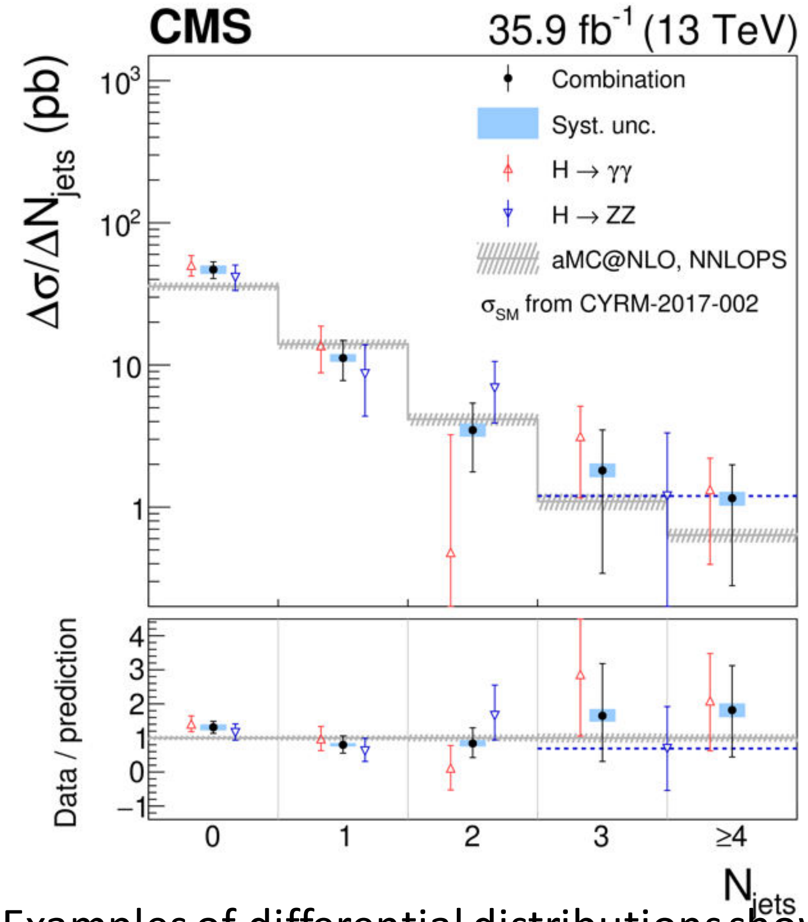
Higgs production mechanisms as predicted by SM, as a function of Higgs mass

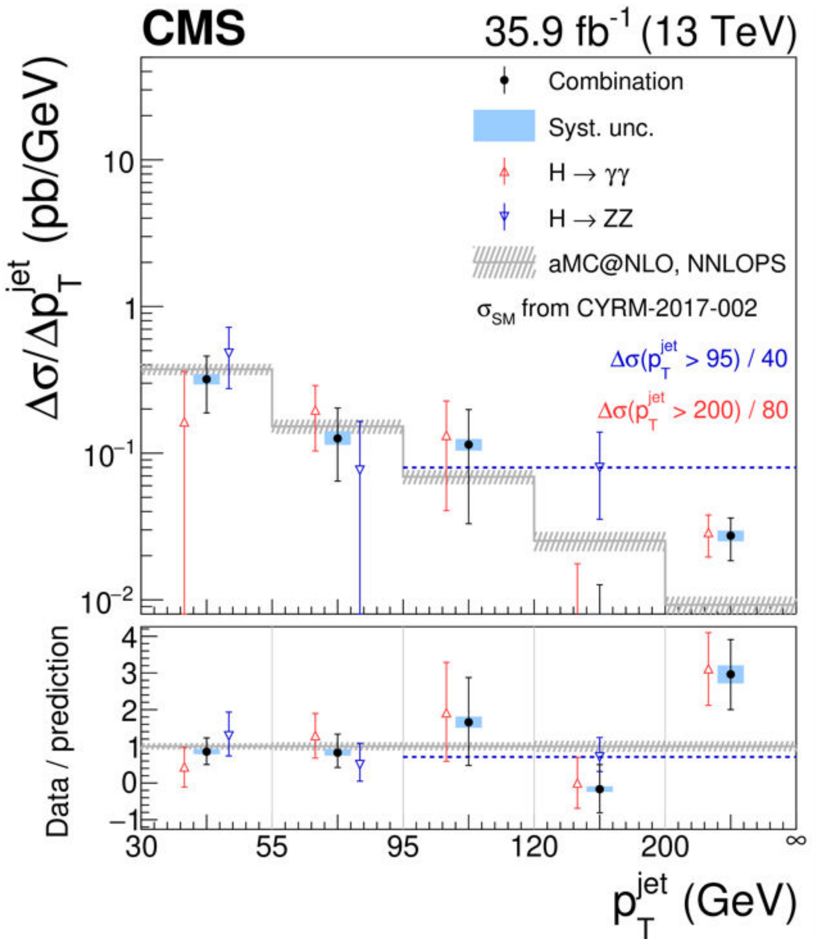
Higgs: ggF production mode



ggF is well established. Program of detailed studies is underway using $H \to \gamma\gamma,\ H \to ZZ \to 4\ell,\ H \to bb$

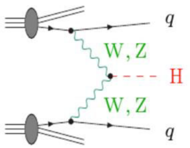






Examples of differential distributions shown

Higgs: VBF production mode

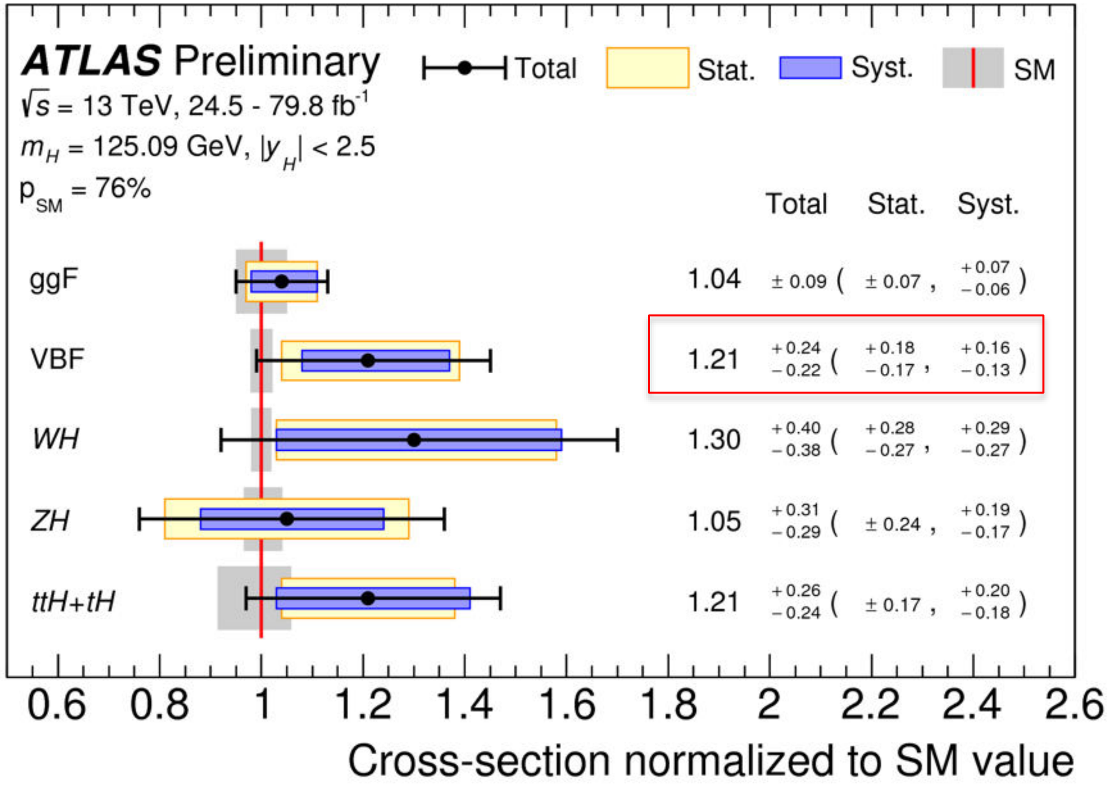


Analyses in all decay modes include categories targeting VBF production:

- VBF is about 8% of total H production
- VBF-tag is fairly efficient for VBF Higgs production
- VBF-tag has a large suppression for background

However, experimentally VBF-tagged events tend to have a substantial contamination of ggF

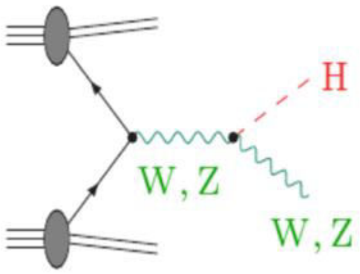
To ascertain an observation of VBF production, one needs to analyze the VBF-tagged and untagged (ggF) categories simultaneously.



Bringing all decay modes together (assuming SM BRs) gives a large boost in sensitivity

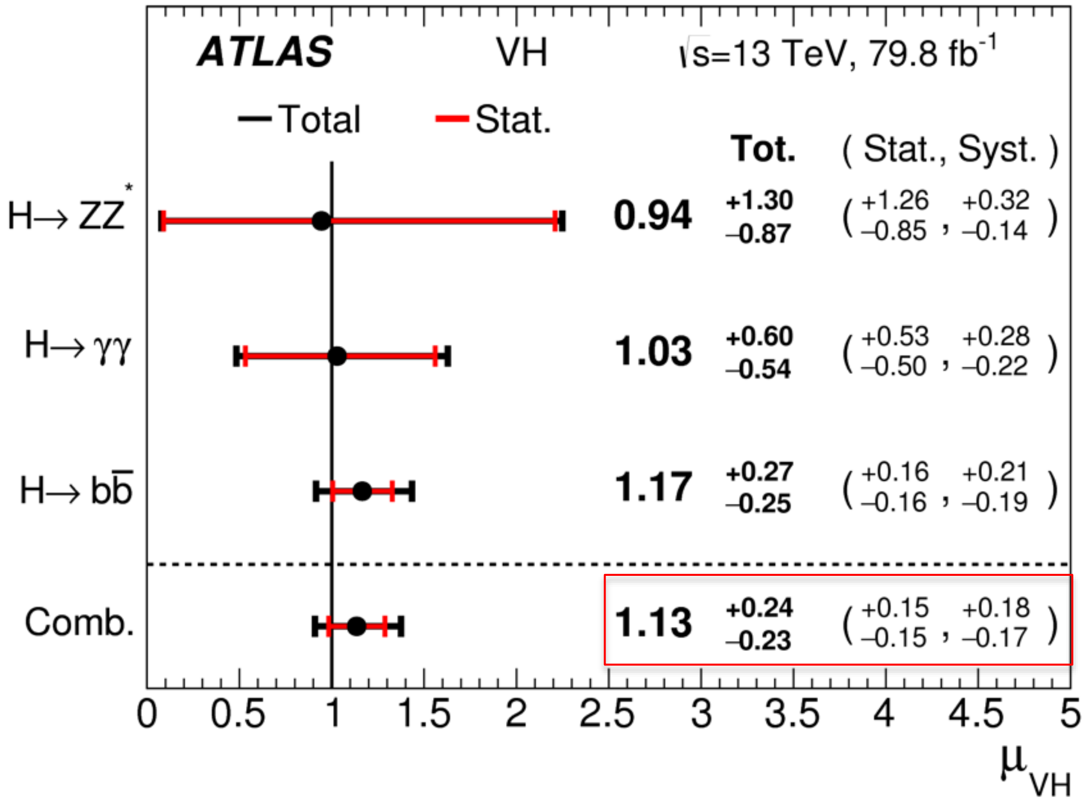
VBF observed experimentally with significance $>5\sigma$

Higgs: V(W,Z) H production mode



VH production rate, once practical decay modes for the associated W(lν) and Z(ll,νν) are considered, is only 1.5% of the total Higgs boson production cross section

Unlike VBF, VH-tagged events have very high purity

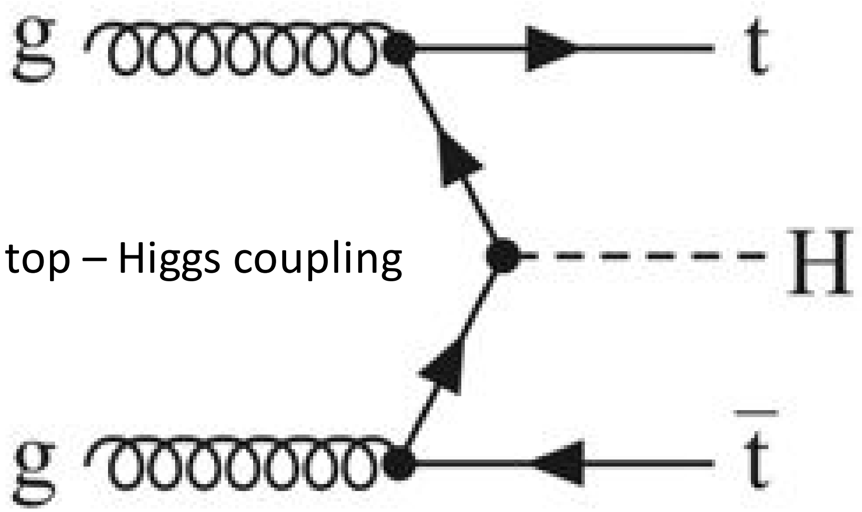


VH production observed expertmentally with significance $\sim 5\sigma$

ttH mode

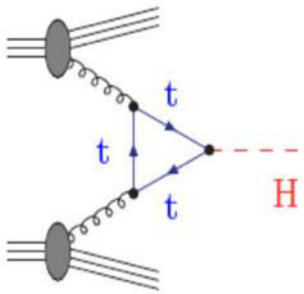
Run 2, 2016: σ×L = 700K events

probing "direct" coupling of H with top (not in top loops as in ggF!)



Direct top – Higgs coupling

Not in top loops
(as in ggF),
Where additional (e.g. BSM) backround in loops possible

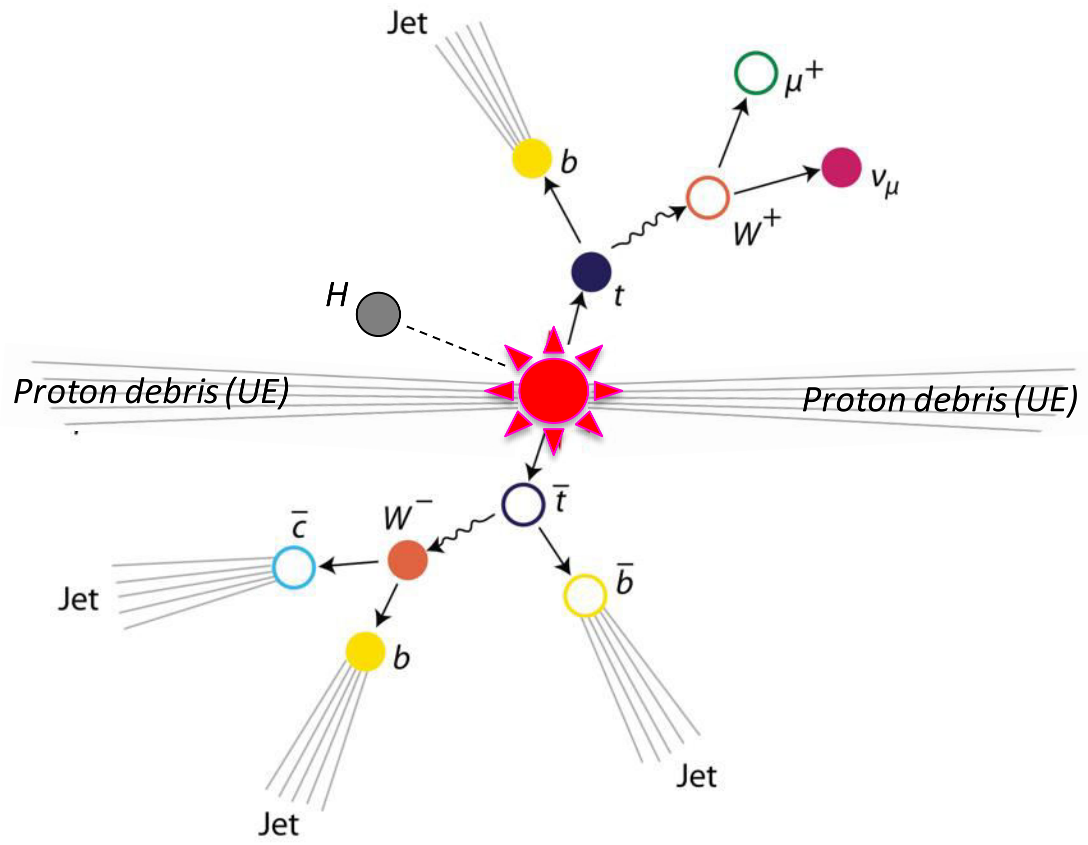


Analysis features to note:

- **The only way to prove directly Higgs couplings to the top quark**
- **Rare production rate:** 1% of all
- **Main background is tt+X:** tt : ttH=2000
- **One also must fight "huge" non-ttH Higgs background**: non-ttH : ttH = 100
- **Need a coordinated search in as many decay modes as possible; all five most-sensitive decays are exploited:** $\gamma\gamma,\ bb,\ \tau\tau\ /WW\ /ZZ \rightarrow leptons$

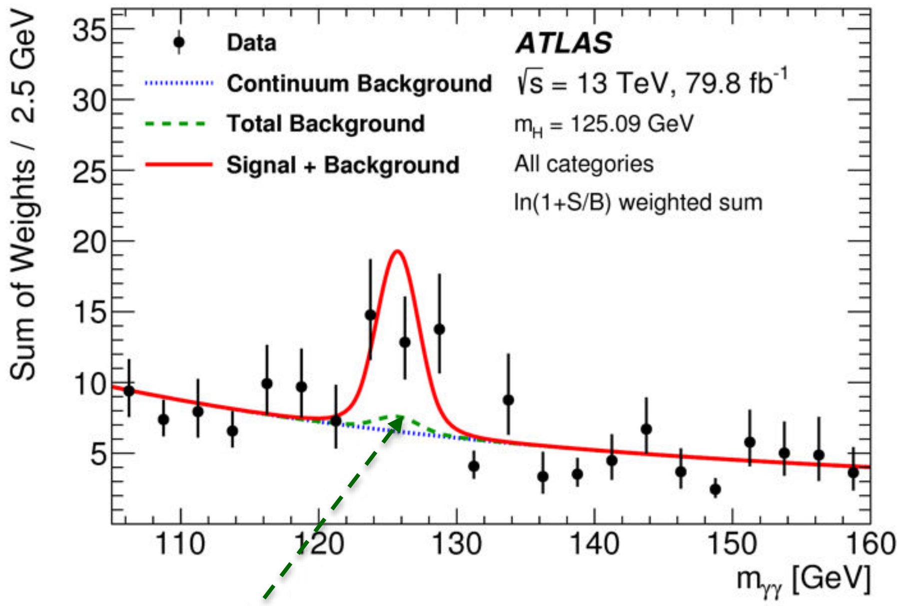
$pp \to ttH$: analysis strategy

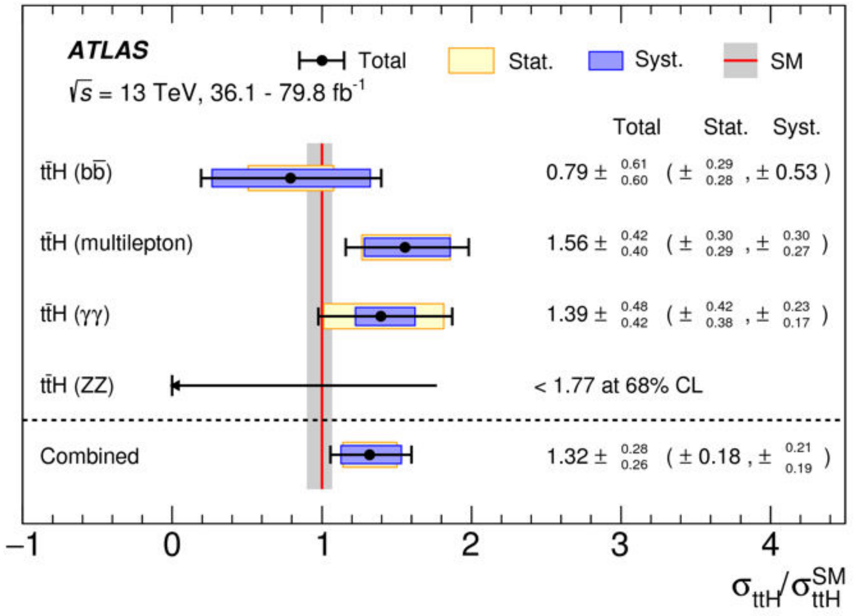
- **Use all five most-sensitive decays**
  - $\gamma\gamma$
  - bb
  - $\tau\tau\ /WW/ZZ \to \ell, \tau_h$
- **Consider distinct tt final states**
  - 64%: 2 b-jets + 4 jets
  - 32%: b-jets + 1 jet + lepton + MET
  - 4%: 2 b-jets + 2 leptons + MET

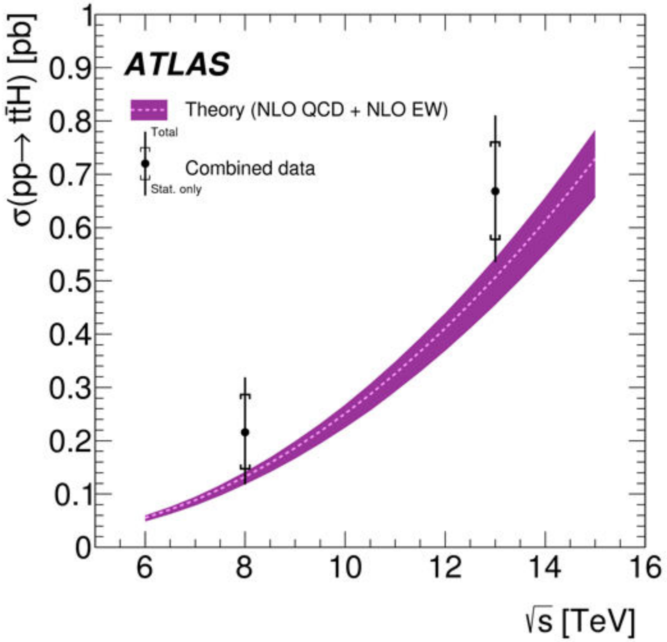


- **Event categories:**
  - $\boldsymbol{H \to bb}$ **(3):** $\geq 3\ b\text{–}jets\ with\ \ 0\ell,\ \ 1\ell,\ \ \ell^+\ell^-$
  - $\boldsymbol{H \to \gamma\gamma}$ **(2):** $\gamma\gamma + 0\ell + 3jets\ (\geq 2\ b\text{–}tag), \gamma\gamma + \ell + 2jets\ (\geq 1\ b\text{–}tag),$
  - $\boldsymbol{\tau\tau\ /WW/ZZ \to \ell, \tau_h}$ **(6):** defined by the multiplicity of ℓ and τ_h
    Note: Leptons from Higgs ($\tau\tau\ /WW/ZZ$) and from tt cannot be easily resolved
- Use kinematics of top quark decays, including **top** and **W** mass constraints

pp → ttH: observed with significance > 5!







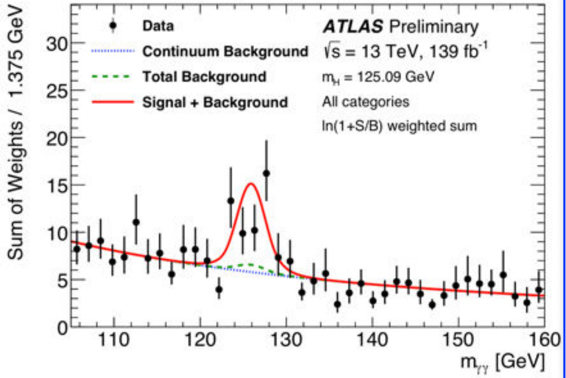
non-ttH Higgs background

Run 1 + Run 2 (2016)

CMS: Significance = 5.2σ
Signal strength = $1.26^{+0.31}_{-0.26}$

ATLAS: 6.3σ and $1.32 \pm ^{0.28}_{0.26}$

Fresh out of press:
ATLAS, full Run 2 dataset
ttH, H→ $\gamma\gamma$
Significance 4.9σ
Signal strength $1.38\ ^{+0.41}_{-0.36}$

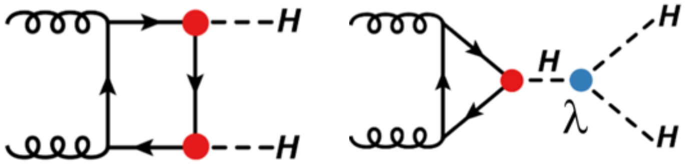


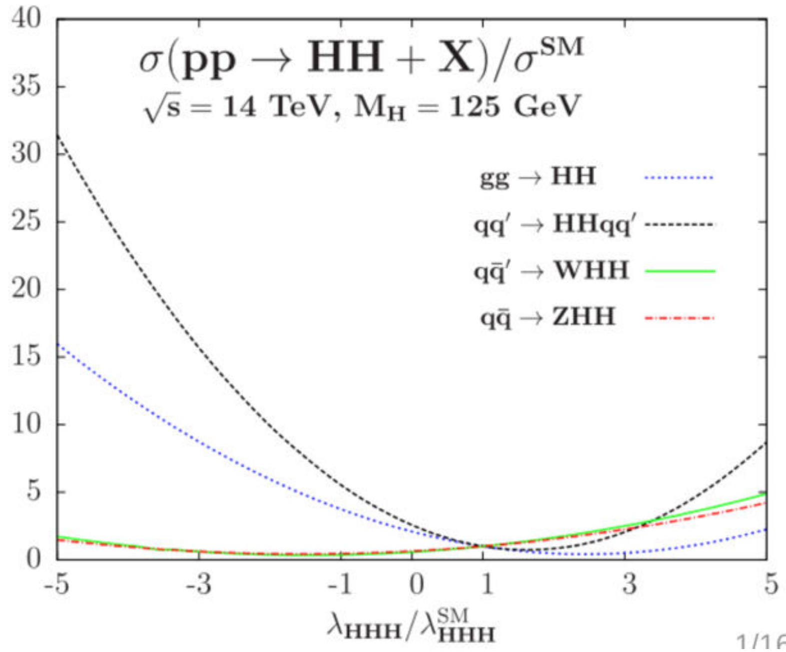
Experimental studies of the double Higgs (125) production, probing e.g. Higgs self coupling

Search for double Higgs production, $pp \to HH$ includes Higgs self coupling, predicted by the SM

Two main HH production modes:

- associated with the Higgs-top Yukawa coupling
- associated with Higgs self-coupling (λ)





Each, by itself, would give a fairly small cross section

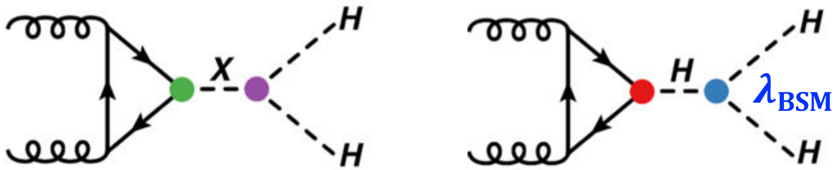
Worse, they interfere negatively, and almost completely kill each other

- $\sigma_{HH} \sim 0.001 \times \sigma_H$

Why do we need to measure it?

- If H(125) is the SM Higgs boson, we need to measure its mass and nothing else
- However, all "standard models" are temporary… As is, the Higgs field is already weird and fascinating – all aspects of this new phenomenon must be subject to detailed scrutiny…
- There is not a lack of BSMs that may readily reveal themselves in the di-Higgs production, in particular:
  - **New heavy particles decaying to two Higgs bosons [look for a resonance!]**
  - **Modifications of the self-coupling λ [non-resonant]**

Possible BSM?



Double Higgs production $pp \to HH$: analysis strategy

- **Pursue searches for both non-resonant and resonant HH productions**

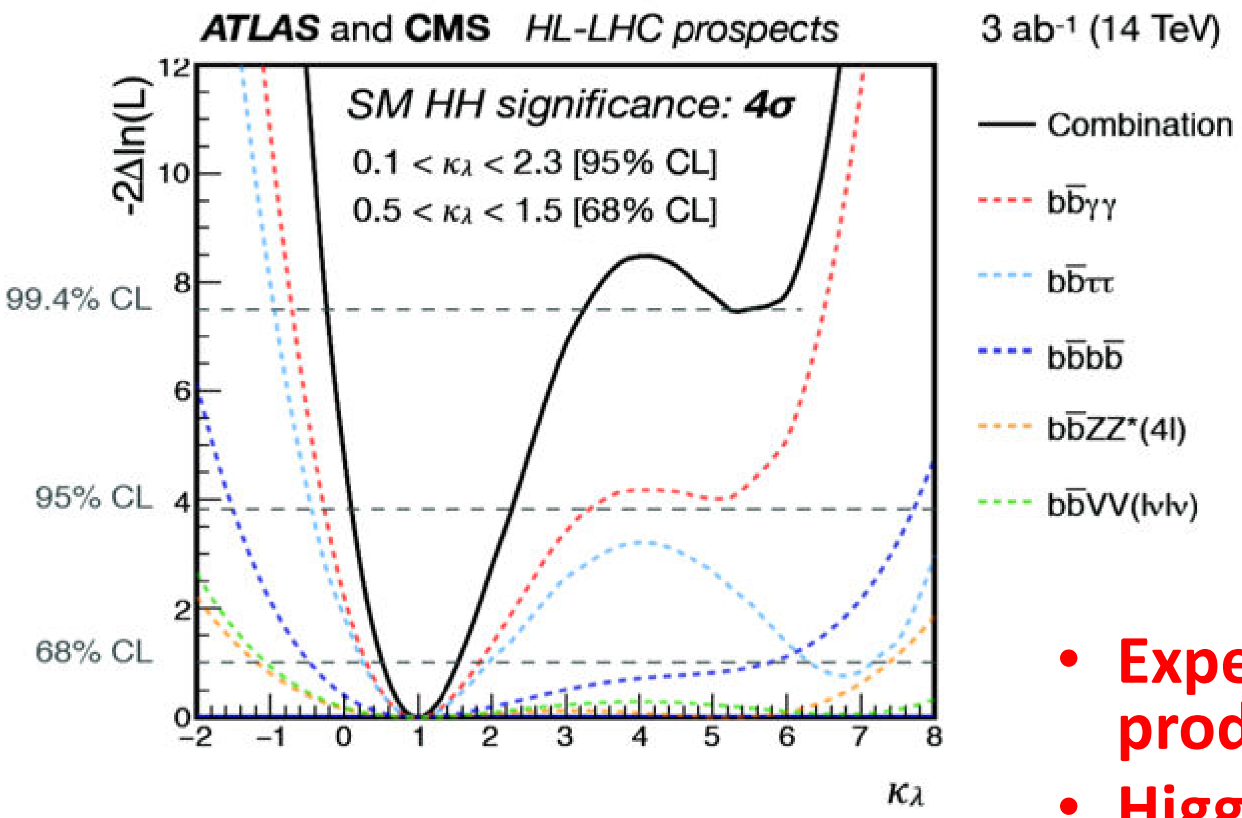
- **Final states explored:**
  - $(\boldsymbol{bb})(\boldsymbol{bb})$ – go after the largest BR(bb), but suffer larger background: 33% of all HH decays
  - $(\boldsymbol{bb})(\boldsymbol{\tau\tau})$ – di-tau signature is much cleaner (less QCD background), but smaller BR($\tau\tau$): 7% of all HH decays
  - $(\boldsymbol{bb})(\boldsymbol{\gamma\gamma})$ – VERY clean di-photon signature (narrow peak, low QCD bkg), but also very small BR($\gamma\gamma$): 0.3% all HH decays
  - more final states are being added recently… E.g., $(W_{qq}W_{lv})(\gamma\gamma)$ – 10 times smaller rate than $(bb)(\gamma\gamma)$, but cleaner

  Recall mass resolutions:
  - $m(bb)$: ~10%
  - $m(\tau\tau)$: ~15%
  - $m(\gamma\gamma)$: ~1–2%

- **Combine all final state searches to get the maximum sensitivity**

double Higgs production $pp \to HH$: future prospects

HL-LHC projections (arXiv:1902.00134)



- **Expected significance for observing HH production at HL-LHC: 4σ (ATLAS + CMS)**
- **Higgs self coupling is going to be measured with 50% accuracy**

Combination of the Higgs (125) boson experimental analyses

Combination of all Higgs boson analyses

	gg->H	VBF	VH	ttH
WW	✔	✔	✔	✔
ZZ	✔	✔	✔	✔
bb	✔	✔	✔	✔
ττ	✔	✔	✔	✔
γγ	✔	✔	✔	✔
μμ	✔	✔		
invisible		✔	✔	

$$(xx \to H) \cdot BR(H \to yy) \propto \frac{xx \cdot yy}{TOT}$$

One needs **11 independent parameters** to describe all currently relevant production & decay mechanisms:

Γ_{gg} **(loop induced: t and some b)**

Γ_{WW}

Γ_{ZZ}

Γ_{tt}

Γ_{bb}

$\Gamma_{\tau\tau}$

$\Gamma_{\gamma\gamma}$ **(loop induced: W and t)**

$\Gamma_{\mu\mu}$

$\Gamma_{invisible}$

Γ_{TOT} = (sum of all Γ listed above) + (sum of all other SM Γ) + Γ_{BSM}

decay modes not studied or, perhaps, studied, but not included in combination

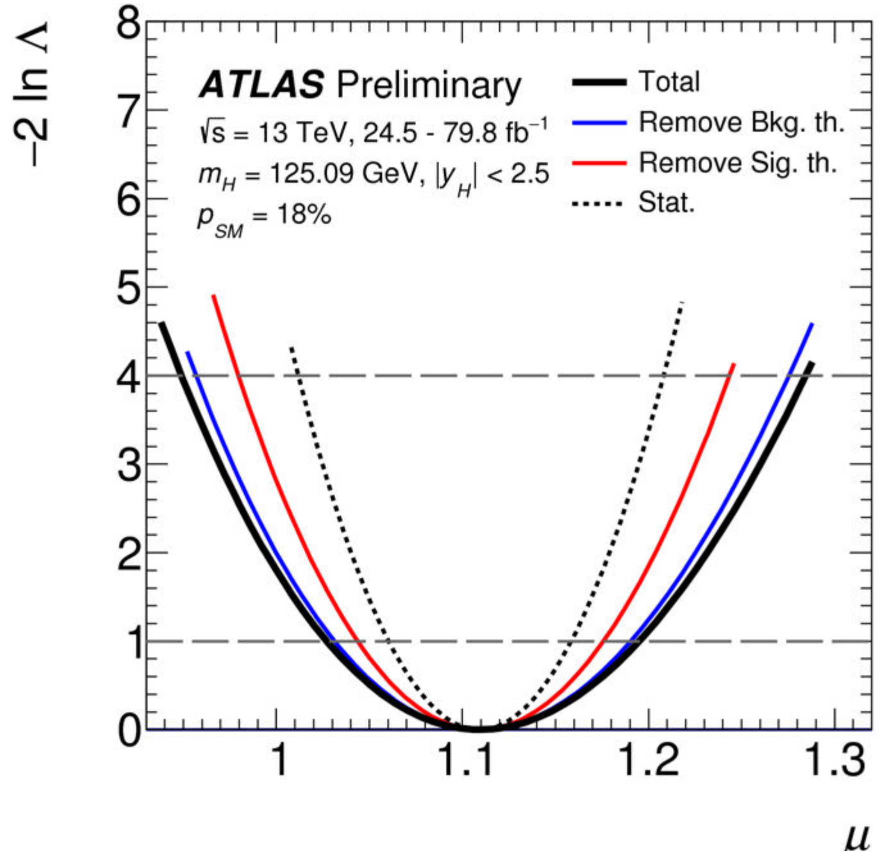
One parameter fit: μ

$$(xx \to H)\cdot BR(H \to yy) \propto \mu \frac{xx \cdot yy}{\mathrm{TOT}}$$

SM values are in blue

- $\mu\,\Gamma_{gg}$ **(loop induced: t and some b)**
- $\mu\,\Gamma_{WW}$
- $\mu\,\Gamma_{ZZ}$
- $\mu\,\Gamma_{tt}$
- $\mu\,\Gamma_{bb}$
- $\mu\,\Gamma_{\tau\tau}$
- $\mu\,\Gamma_{\gamma\gamma}$ **(loop induced: W and t)**
- $\mu\,\Gamma_{\mu\mu}$
- $\mu\,\Gamma_{invisible}$

Γ_{TOT} = (sum of all $\mu\Gamma$ listed above) + μ(sum of all other SM Γ) ~~+ Γ_{BSM}~~



$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$$

Note the relative scale of stat and systematic uncertainties, including theory uncertainties

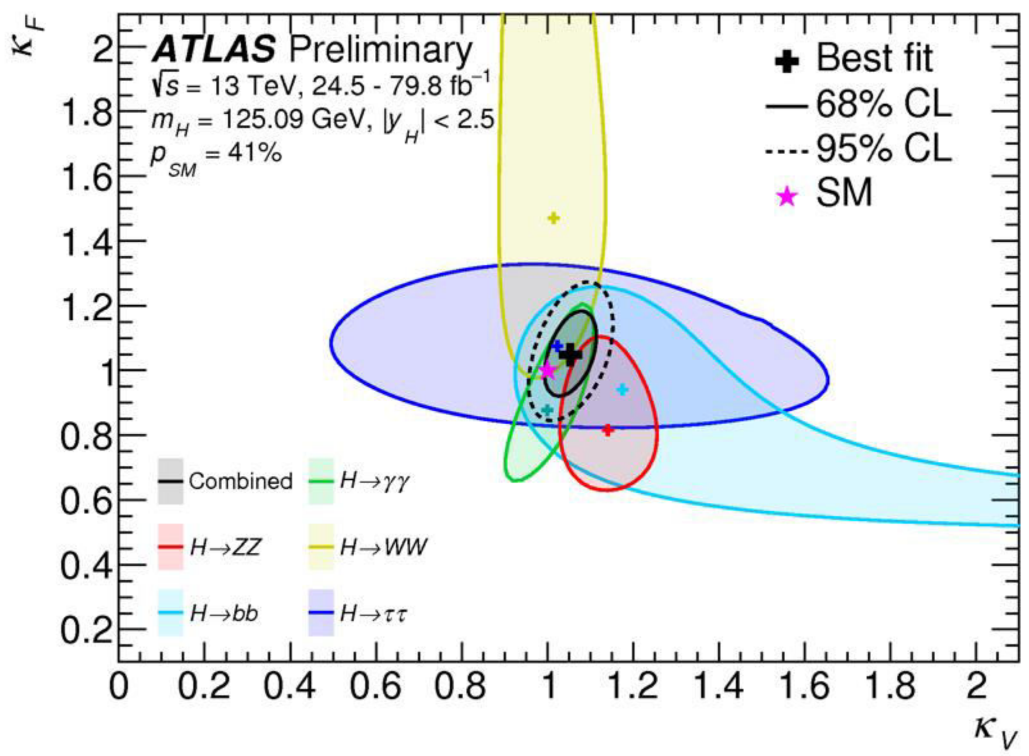
Two-parameter fit: (κ_V, κ_F)

Consider one modifying factor for vector bosons (κ_V) and another common modifying factor for all fermions (κ_F).
Couplings to gluons and photons are loop induced via t/b and W, and are not independent

SM values are in blue

Γ_{gg} (modified as loop induced: t and some b)
$\kappa_V \Gamma_{WW}$
$\kappa_V \Gamma_{ZZ}$
$\kappa_F \Gamma_{tt}$
$\kappa_F \Gamma_{bb}$
$\kappa_F \Gamma_{\tau\tau}$
$\Gamma_{\gamma\gamma}$ (modified as loop induced: W and t)
$\kappa_F \Gamma_{\mu\mu}$
$\kappa_V \Gamma_{invisible}$
Γ_{TOT} = (sum of all Γ listed above) + κ_F(sum of all other SM Γ) + ~~Γ_{BSM}~~

All other Γ are for light fermions



Two-parameter fit (different parameters): $(\kappa_g, \kappa_\gamma)$

Consider one modifying factor for loop induced couplings, for gluons (κ_g) and photons fermions (κ_γ).

All other couplings are set to the SM values.

I.e., search for new physics contributing to the loop induced couplings

SM values are in blue

κ_g Γ_{gg} **(loop induced: t and some b)**

Γ_{WW}

Γ_{ZZ}

Γ_{tt}

Γ_{bb}

$\Gamma_{\tau\tau}$

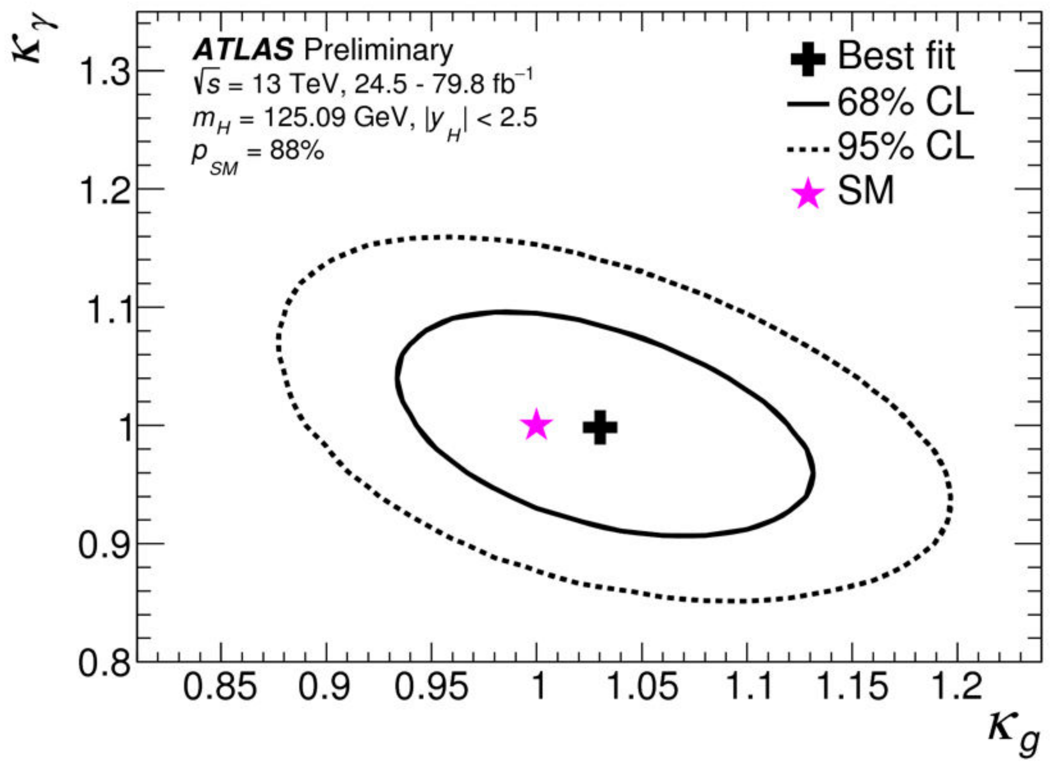
κ_γ $\Gamma_{\gamma\gamma}$ **(loop induced: W and t)**

$\Gamma_{\mu\mu}$

$\Gamma_{invisible}$

Γ_{TOT} = (sum of all Γ listed above) + (sum of all other SM Γ) + ~~Γ_{BSM}~~

All other Γ are for light fermions



Six-parameter fit: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$

Fit for couplings to W, Z, and fermions relevant in the current measurements/searches

Assume no new physics contributing to the loop-induced processes or to invisible/undetected decay modes

SM values are in blue

Γ_{gg} (modified as loop induced: t and some b)

κ_W Γ_{WW}

κ_Z Γ_{ZZ}

κ_t Γ_{tt}

κ_b Γ_{bb}

κ_τ $\Gamma_{\tau\tau}$

$\Gamma_{\gamma\gamma}$ (modified as loop induced: W and t)

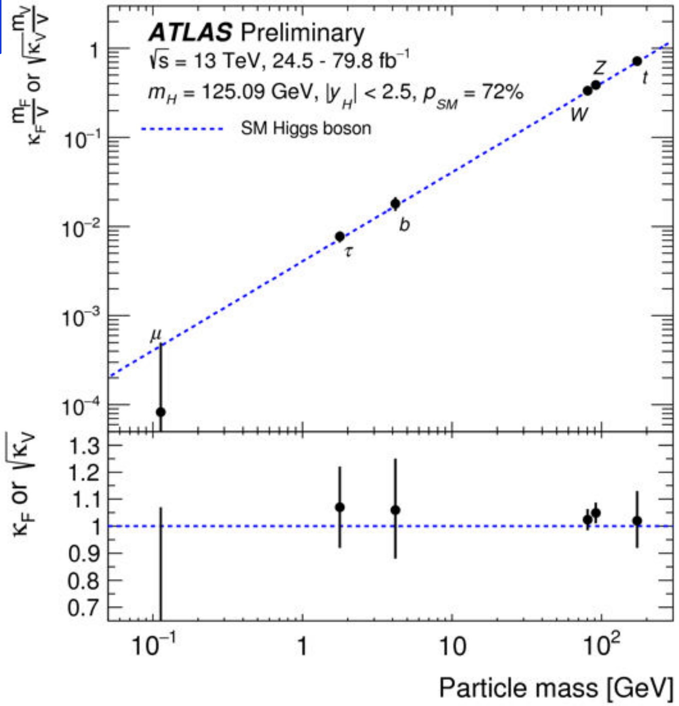
κ_μ $\Gamma_{\mu\mu}$

$\Gamma_{invisible}$

Γ_{TOT} = (sum of all Γ listed above) + (sum of all other SM Γ) + ~~Γ_{BSM}~~

$\kappa_t \Gamma_{cc} + \kappa_b \Gamma_{ss}$ +(the rest is negligible)

The uncertainties from the fits for each of the six parameters, while treating the others as nuisance parameters



Parameter	Result
κ_Z	1.10 ± 0.08
κ_W	1.05 ± 0.08
κ_b	$1.06^{+0.19}_{-0.18}$
κ_t	$1.02^{+0.11}_{-0.10}$
κ_τ	1.07 ± 0.15
κ_μ	< 1.51 at 95% CL.

Clear SM-like dependence on particles' masses
Precision on W/Z/t/b/τ coupling measurements is 10-20%

Eight-parameter fit: $(\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu), BR(H \to inv), BR(H \to undected)$ (1)

- **Open a possibility for new physics contributing to invisible/undetected decay modes**
- This leads to a degeneracy predicted rates on the fit parameters (if something depends on the ratio of a/b, one cannot constrain a and b as independent parameters)
- To break the degeneracy, assume $\kappa_W, \kappa_Z \leq 1$ (from the theory side, it is virtually impossible to pushthese coupling above 1)

SM values are in blue

Γ_{gg} (modified as loop induced: t and some b)

$\kappa_W \Gamma_{WW}$ $(\kappa_W \leq 1)$

$\kappa_Z \Gamma_{ZZ}$ $(\kappa_Z \leq 1)$

$\kappa_t \Gamma_{tt}$

$\kappa_b \Gamma_{bb}$

$\kappa_\tau \Gamma_{\tau\tau}$

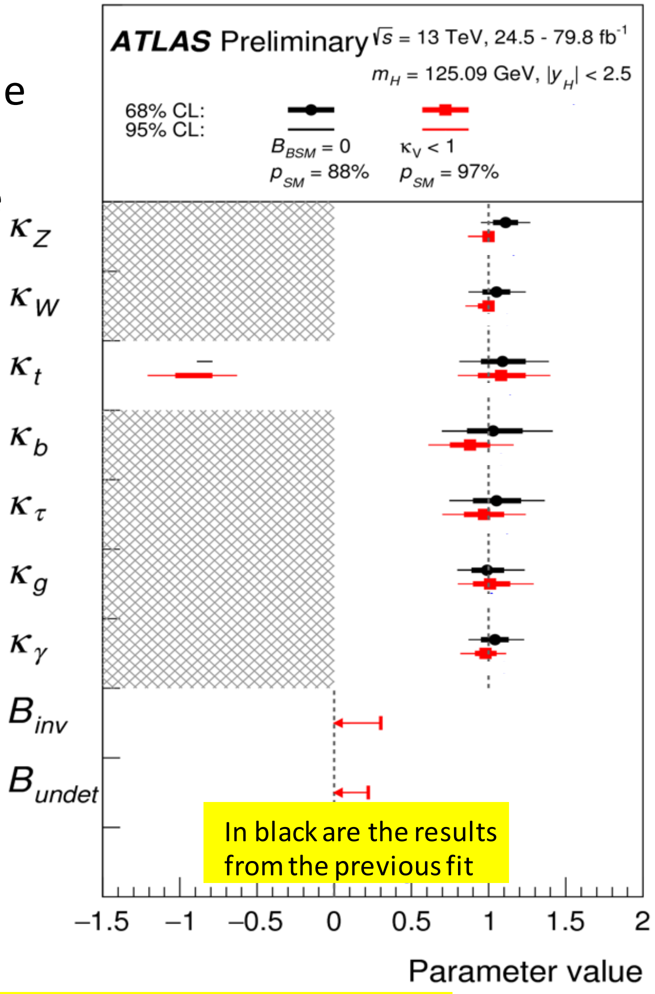
$\Gamma_{\gamma\gamma}$ (modified as loop induced: W and t)

$\kappa_\mu \Gamma_{\mu\mu}$

$\Gamma_{invisible}$

Γ_{TOT} = (sum of all Γ listed above) + (sum of all other SM Γ) + Γ_{BSM}

$\kappa_t \Gamma_{cc} + \kappa_b \Gamma_{ss}$ +(the rest is irrelevant)

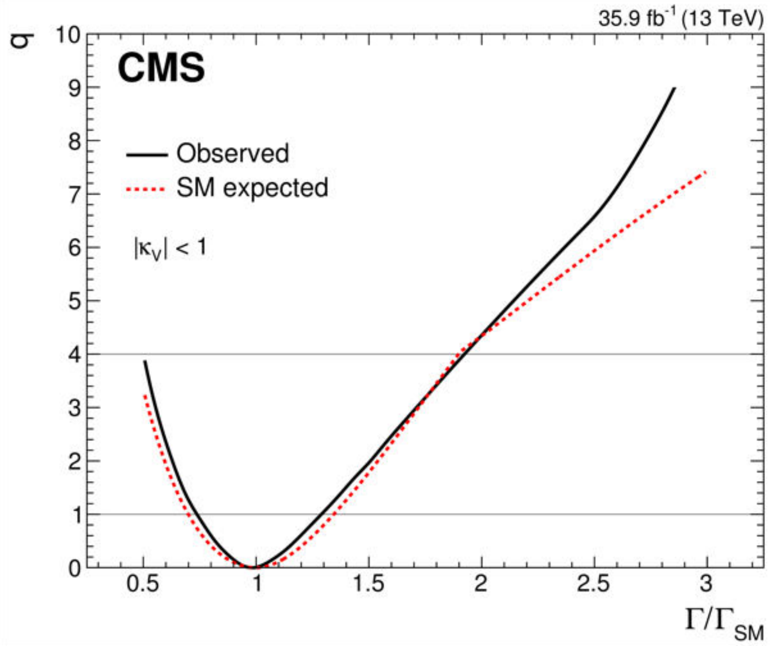


The uncertainties from the fits for each of the six parameters, while treating the others as nuisance parameters

At 95% CL	CMS	ATLAS
BR(H → invisible)	< 0.22	<0.30
BR(H → undetected)	< 0.38	<0.22

Eight-parameter fit: $(\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu), BR(H \rightarrow inv), BR(H \rightarrow undected)$(2)

- **Open a possibility for new physics contributing to invisible/undetected decay modes**
- This leads to a degeneracy predicted rates on the fit parameters (if something depends on the ratio of a/b, one cannot constrain a and b as independent parameters)
- To break the degeneracy, assume $\kappa_W, \kappa_Z \leq 1$ (fro theory side, it is virtually impossible to push these coupling above 1)



SM values are in blue

Γ_{gg} (loop induced: t and some b)

$\kappa_W \Gamma_{WW}$ $(\kappa_W \leq 1)$

$\kappa_Z \Gamma_{ZZ}$ $(\kappa_Z \leq 1)$

$\kappa_t \Gamma_{tt}$

$\kappa_b \Gamma_{bb}$

$\kappa_\tau \Gamma_{\tau\tau}$

$\Gamma_{\gamma\gamma}$ (loop induced: W and t)

$\kappa_\mu \Gamma_{\mu\mu}$

$\Gamma_{invisible}$

Γ_{TOT} = (sum of all Γ listed above) + (sum of all other SM Γ) + Γ_{BSM}

$\kappa_t \Gamma_{cc} + \kappa_b \Gamma_{ss}$+(the rest is irrelevant)

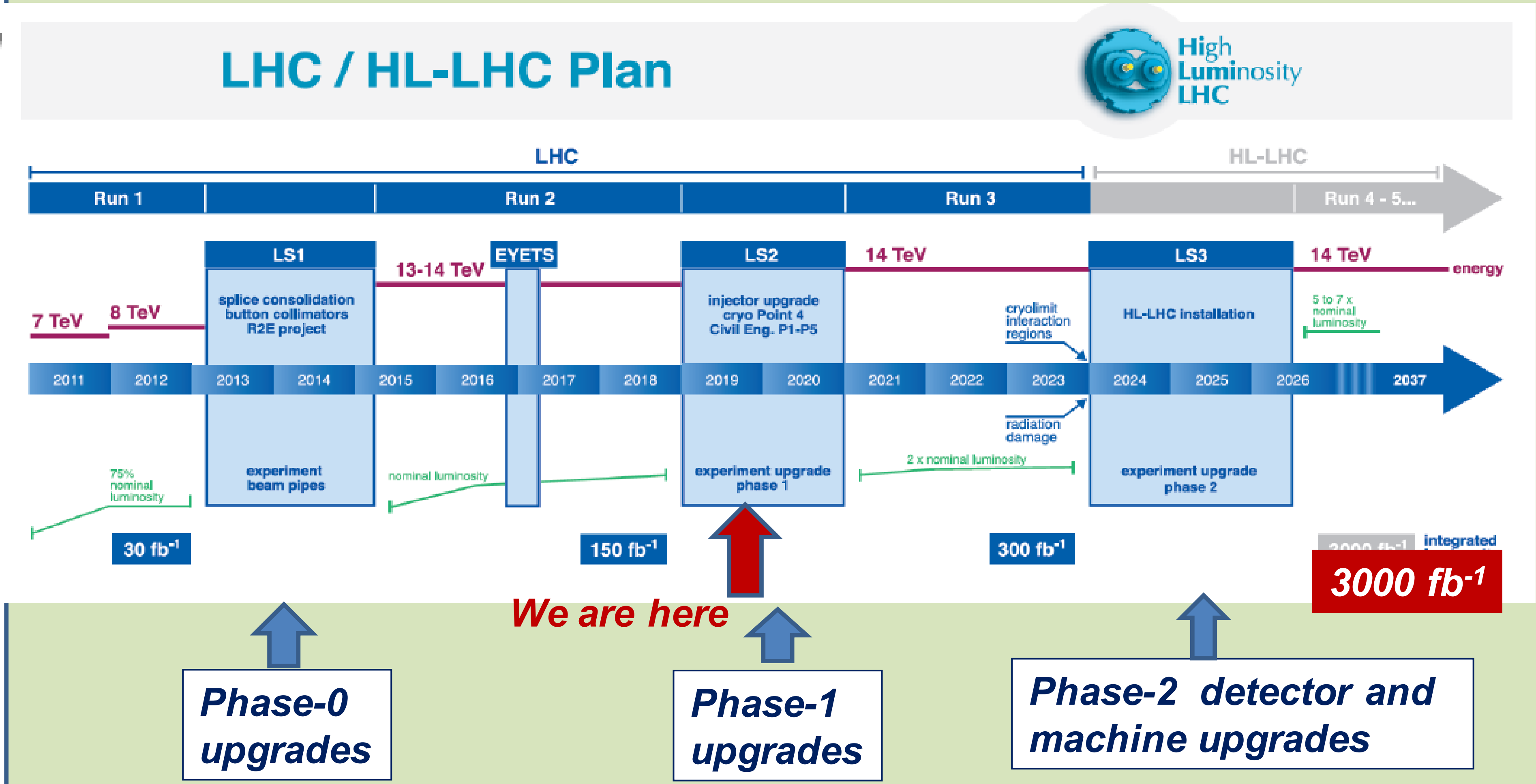
The fit results can be recast as a limit on the total Higgs boson width:

$$\Gamma_{tot}/\Gamma_{SM} = 0.98^{+0.31}_{-0.25}$$

Cf. results form off-shell/on-shell H->ZZ analysis (with twice larger dataset): $\Gamma_{tot}/\Gamma_{SM} = 0.80^{+0.70}_{-0.55}$

Upcoming LHC upgrade.

HL-LHC (3000 fb^{-1} integrated luminosity) projections for Higgs



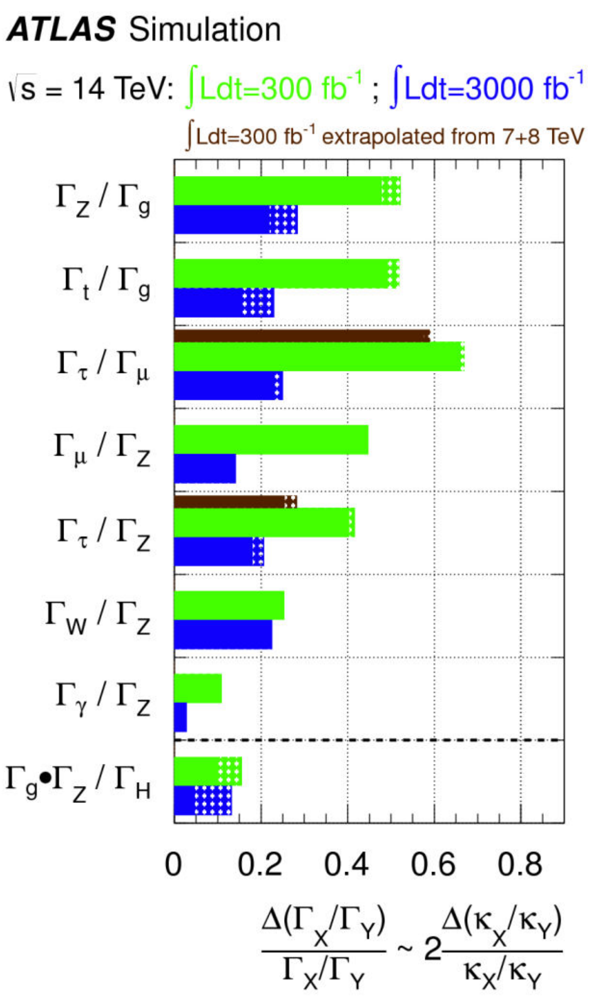
Accumulated datasets in Ran 2 (CMS, ATLAS similar)

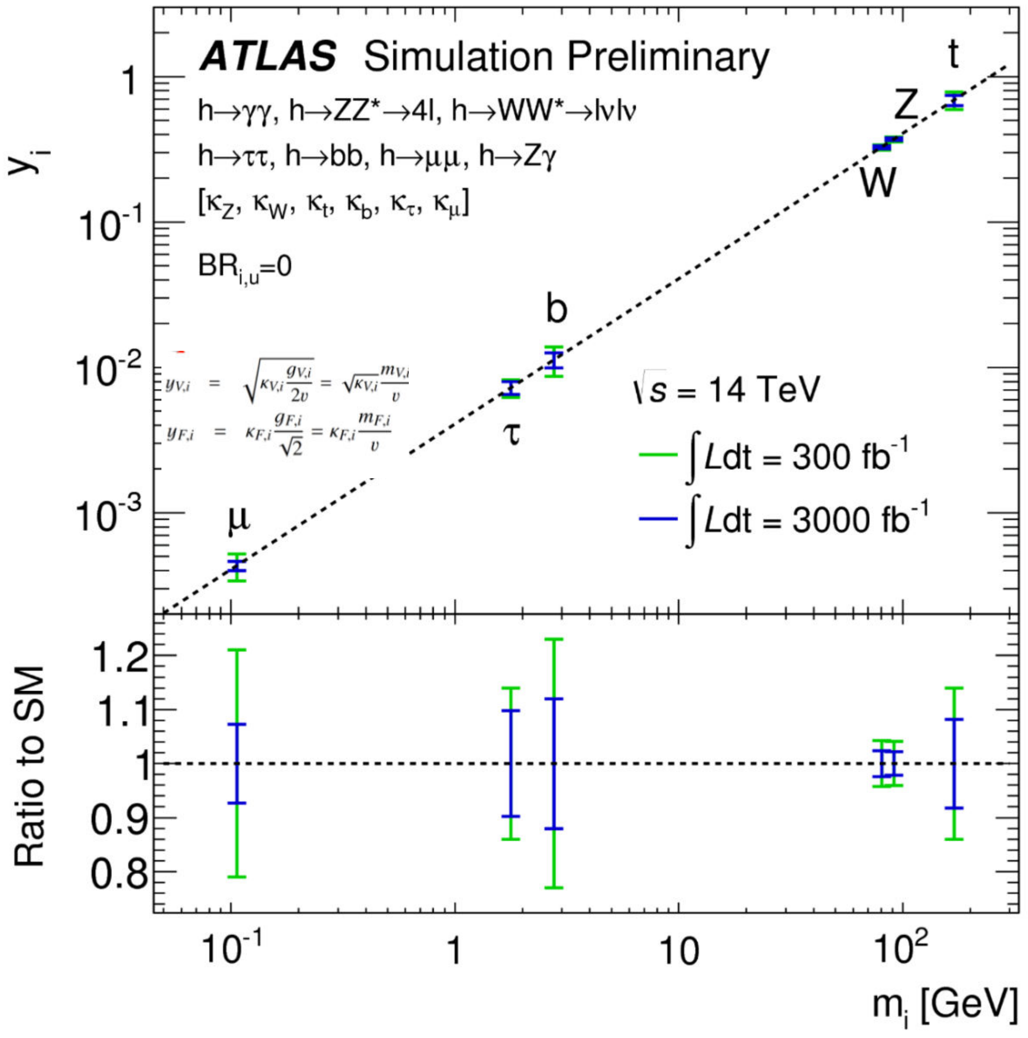
~35 fb^{-1}: 2016

~80 fb^{-1}: 2016+2017

~140 fb^{-1}: 2016+2017+2018 (full Run 2)

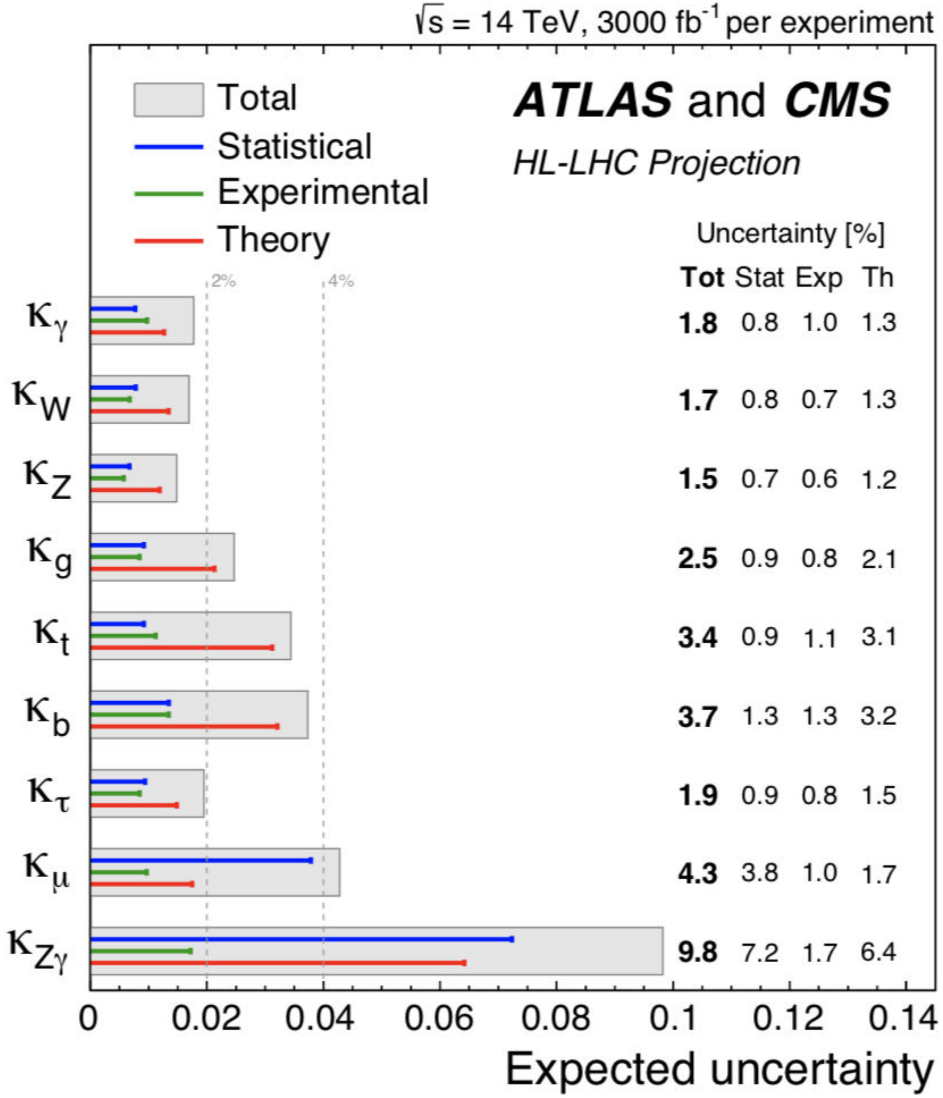
HL-LHC Outlook (compared to final LHC statistics) for Higgs (ATLAS, CMS similar)





ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

HL-LHC projections (without comparing to LHC): couplings



With cautious optimism, summary for 3000 fb^{-1}:

δκ ~ 2-4%

BR(H→BSM) < 0.07 at 95% CL

Extrapolation scenarios:

Theoretical uncertainties: halved

Experimental stat. uncertainties scaled as 1/sqrt(L)

Limited MC statistics – ignored

Instrumental uncertainties: same as now or specifically revised

Luminosity uncertainty: 1% (halved)

Many experimental searches for additional to Higgs (125) neutral and charged Higgs bosons have been also conducted at LHC, they are not covered in this talk

See e.g. some BSM motivations for searches of additional Higgs bosons in the next slide

Slide on searches for additional Higgs bosons: many searches in ATLAS and CMS, why? (some reasons)

Model	What is it good for?	Higgs bosons
SM: one doublet of complex scalar fields (HD)	3 d.o.f. give mass to $W^{\pm}$ and Z bosons Yukawa couplings generate fermion masses	**h**
HD + real singlet	attractive in the context of DM, EWK baryogenesis, …	**h, H**
HD + 2nd doublet (2HDM: 2 Higgs Doublets Model)	Prerequisite for SUSY Natural in Grand Unifying Theories Additional to SM source of CP violation: needed for observed matter-antimatter asymmetry. Helps DM originating directly from 2HDM	**h, H, A, $H^{\pm}$**
2HDM + complex singlet	Used in so-called nMSSM, next-to-minimal Super Symmetry resolves the μ-problem MSSM h(125) is unnaturally heavy in MSSM – not in nMSSM	**h_1, h_2, h_3, a_1, a_2, $H^{\pm}$**
HD + triplet	can provide Majorana neutrino masses	**h, H, A, $H^{\pm}$, $H^{\pm\pm}$**

Conclusions

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- Higgs particle is unusual, studying it may be a good way to look for deviations from the SM predictions
- Many Higgs particle properties have been measured with high accuracy,
  more to come at LHC, HL-LHC and other future accelerators
- No deviations from SM so far have been observed, but the search is on

I expess my gratitude to Prof Korytov for helping with preparation of this talk