HIGGS PHYSICS FOR RUN 2, HL-LHC AND FUTURE COLLIDERS

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On behalf of the ATLAS and CMS collaborations

7th ENHEP School on High Energy Physics
26-31 January 2019
Ain Shams University

Outline

- SM Higgs production and decay
- Higgs era at Run 1
- Run 2 @LHC
- Highlights for Higgs physics @ Run 2
  - H→bb observation
  - H→ZZ and $\gamma\gamma$
  - H→$\tau\tau$
  - ttH
- HL-LHC and Higgs prospects

STANDARD MODEL OF ELEMENTARY PARTICLES

04/07/2012

the Higgs boson has been found !

THE HIGGS MECHANISM

IMAGES COURTESY OF CERN

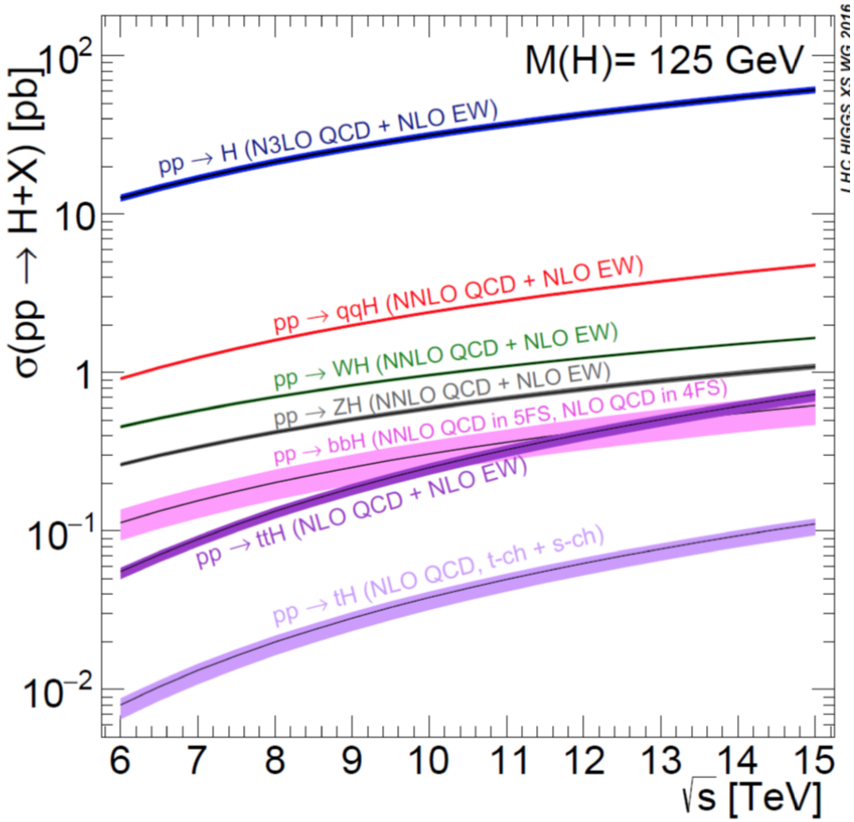
A WELL KNOWN SCIENTIST, ALBERT EINSTEIN, WALKS IN, CREATING A DISTURBANCE AS HE MOVES ACROSS THE ROOM, AND ATTRACTING A CLUSTER OF ADMIRERS WITH EACH STEP.

THIS INCREASES HIS RESISTANCE TO MOVEMENT – IN OTHER WORDS, HE ACQUIRES MASS, JUST LIKE A PARTICLE MOVING THROUGH THE HIGGS FIELD.

IF A RUMOUR CROSSES THE ROOM ...

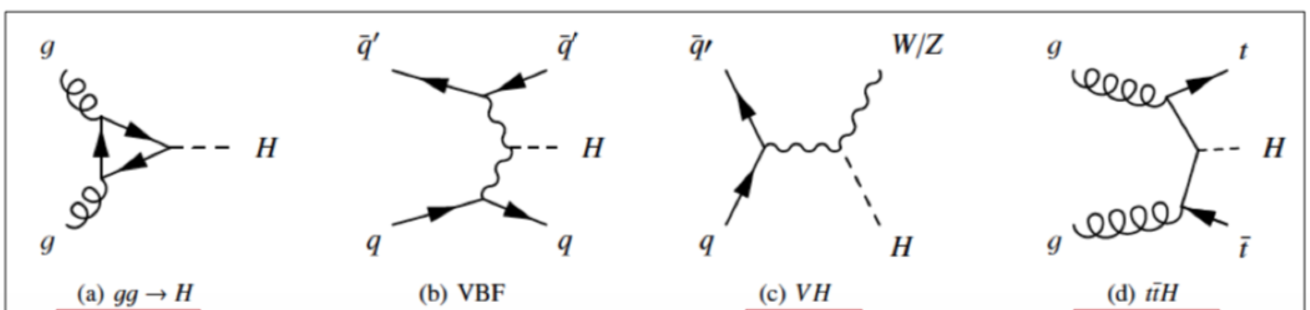
IT CREATES THE SAME KIND OF CLUSTERING, BUT THIS TIME AMONG THE SCIENTISTS THEMSELVES. IN THIS ANALOGY, THESE CLUSTERS ARE THE HIGGS PARTICLES.

SM Higgs production at the LHC



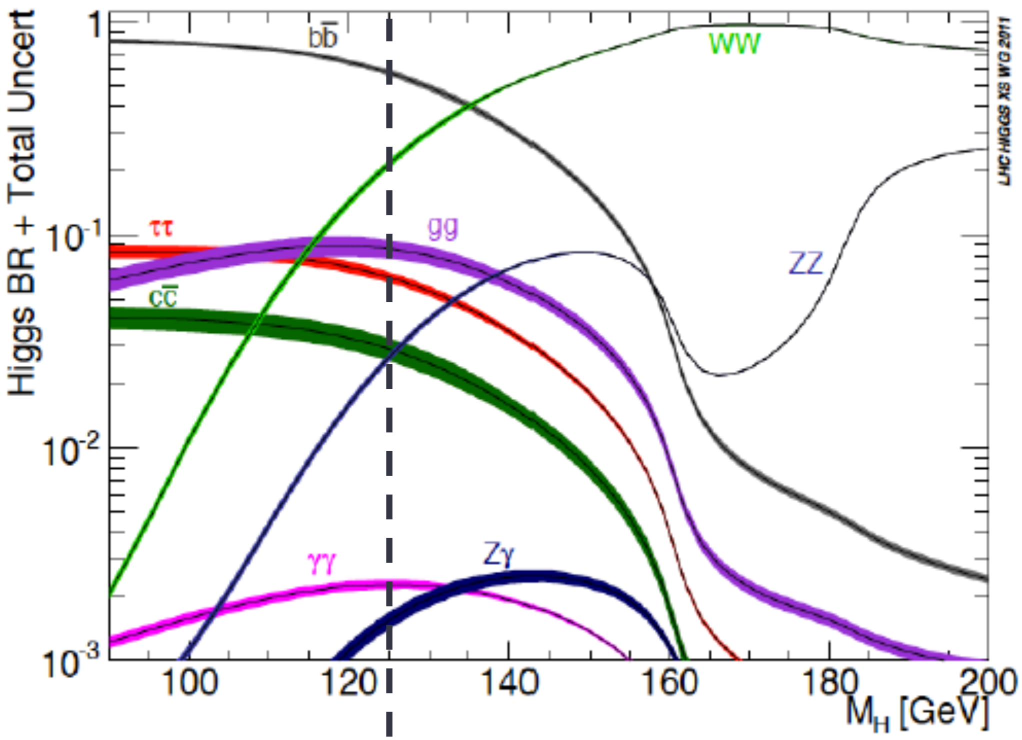
- ggF: dominant, larger initial state radiation from gluons
- VBF: two forward jets with high mass and large rapidity gap
- VH: vector boson (lν, ll', qq')
- ttH: many b-jets, leptons, E_T^{miss}

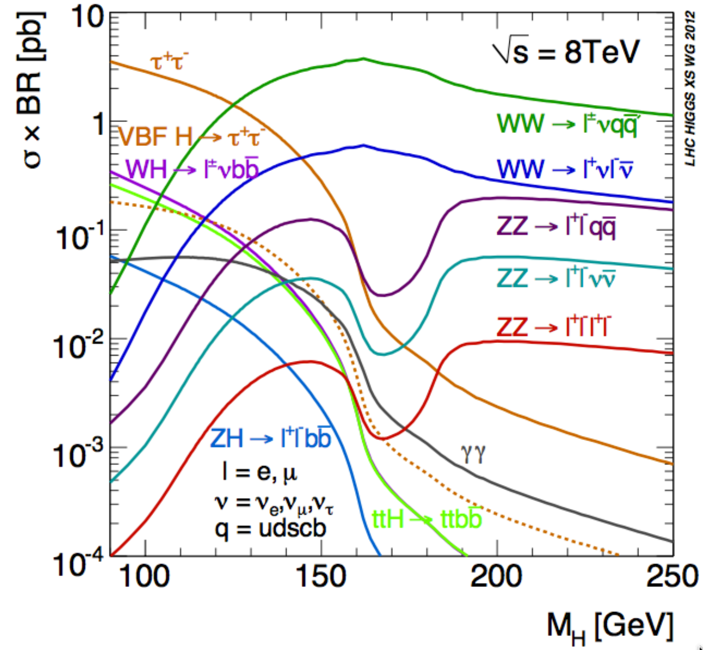
Total cross-section = 56 pb at 13 TeV



87%	7%	5%	<1%

Higgs decay channels





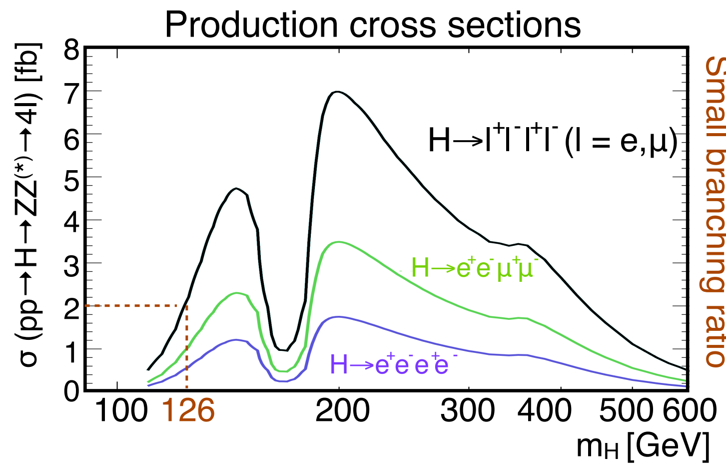
At m_H =125 GeV:

- H(bb) = 57.8%
- H(WW) = 21.4%
- H(gg) = 8.19%
- H(ττ) = 6.27%
- H(ZZ) = 2.62%
- H(cc) = 2.89%
- H(γγ) = 0.23%
- H(Zγ) = 0.15 %
- H(μμ) = 0.02%

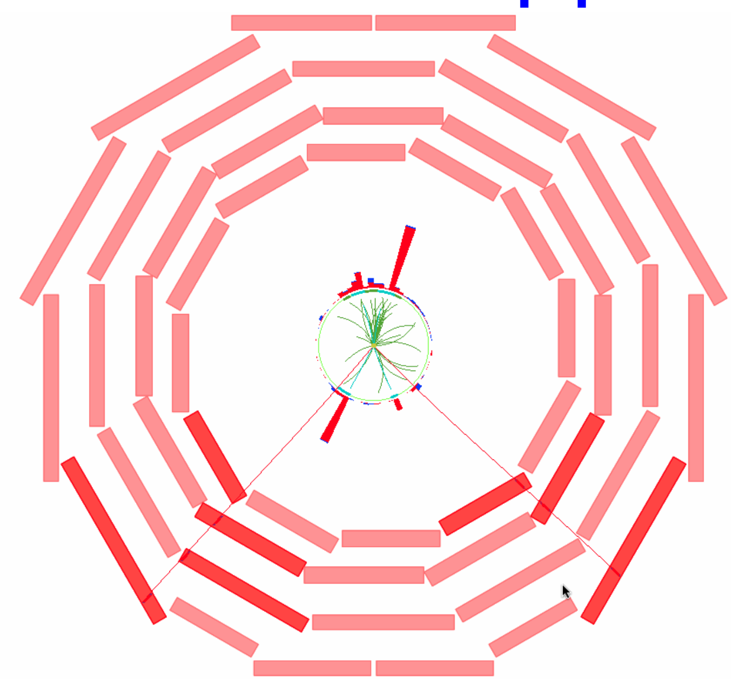
Channel	m_H resolution
$H \to \gamma\gamma$	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	20%
$H \to \tau\tau \to \mu\mu + X$	20%
$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu's$	20%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu$	10%
$H \to WW^* \to 2\ell 2\nu$	20%
$WH \to W(WW^*) \to 3\ell 3\nu$	20%
$H \to ZZ^{(*)} \to 4\ell$	1–2%
$H \to ZZ^{(*)} \to 2\ell 2q$	3% 3%
$H \to ZZ \to 2\ell 2\tau$	10–15%
$H \to ZZ \to 2\ell 2\nu$	7%

H→ZZ→4l in a nutshell

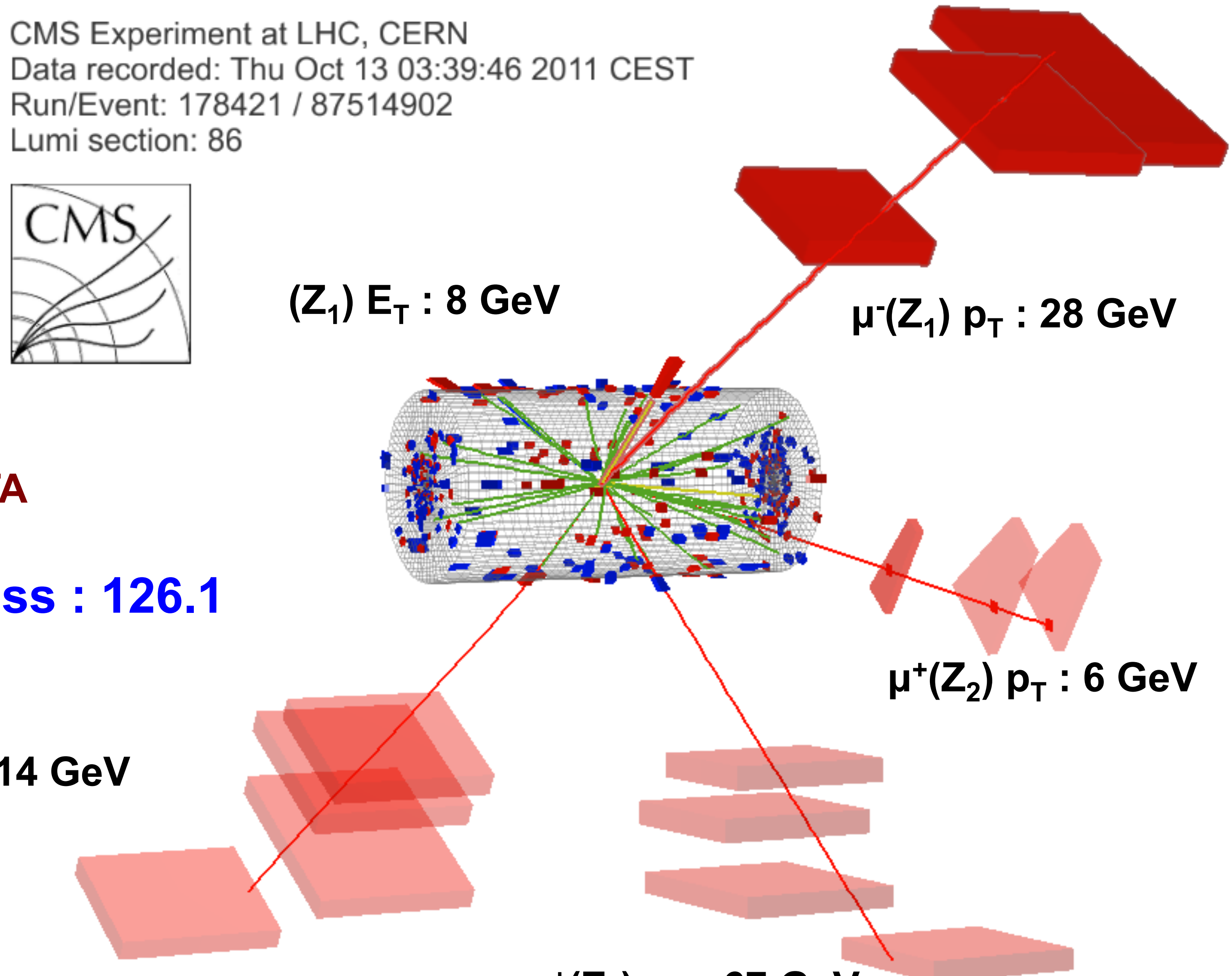
- Signatures: **4e, 4μ and 2e2μ** final state
  - clean but extremely demanding channel for requiring the **highest possible efficiencies (lepton Reco/ID/Isolation)**.
  - s x BR small ≈ few fb
- Backgrounds:
  - Irreducible: ZZ*
  - Reducible: Zbb, tt+jets, Z+light jets, WZ+jets
- Sensitivity: 115 < m_H < **1000** GeV
- Selection strategy:
  - triggering on double leptons
  - applying reco, id and isolation of leptons
  - recovery of FSR photons
  - use of impact parameter
  - m_Z and m_{Z*} constraint
  - kinematical discriminant / scalarity of the Higg



H → ZZ* → e+e-μ+μ-



Candidates



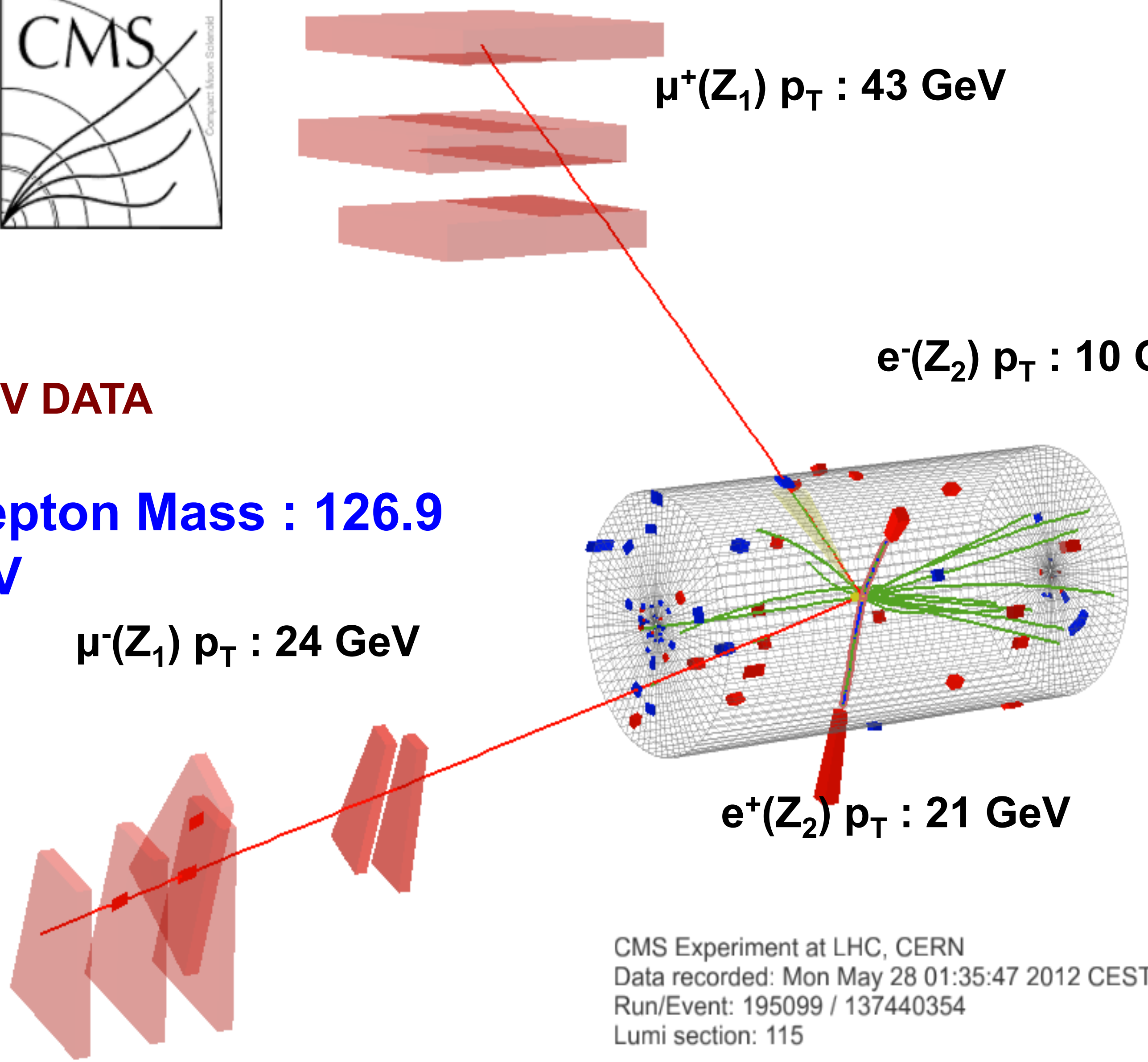
7 TeV DATA

4μ+γ Mass : 126.1 GeV

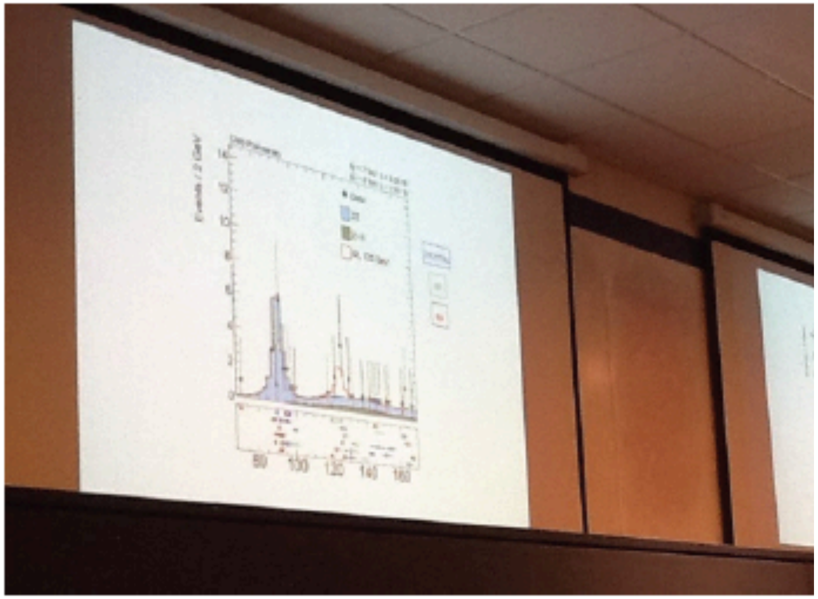
Candidates

8 TeV DATA

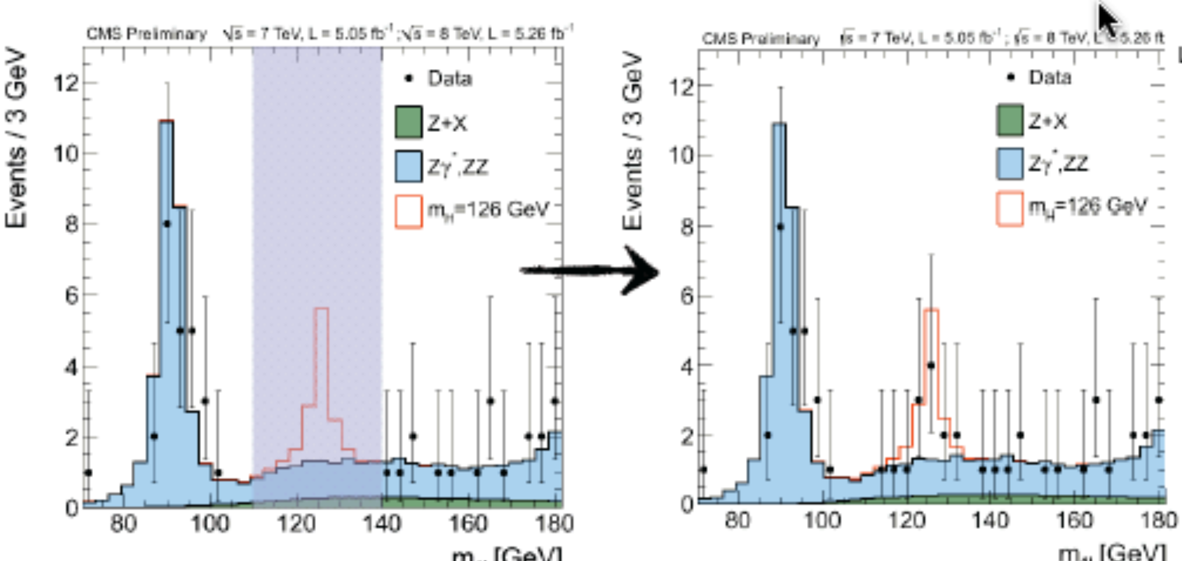
4-lepton Mass : 126.9 GeV

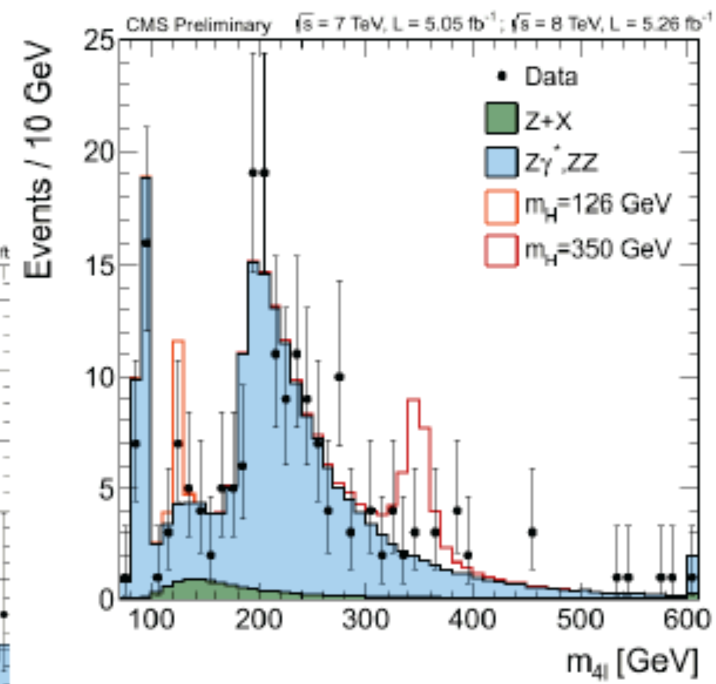


June 2012:

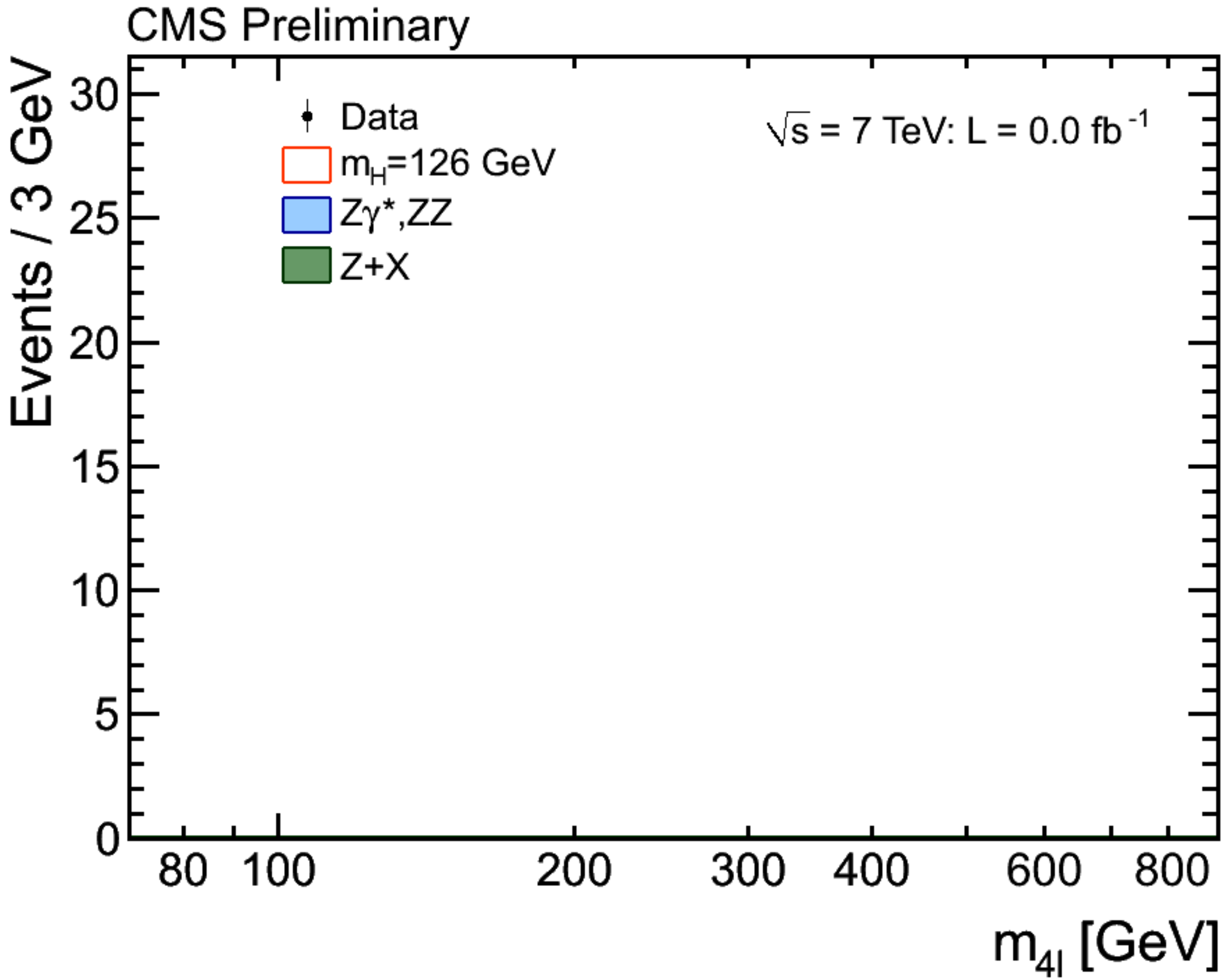


14/6/2012: Approval of **H→ZZ→4l** analysis

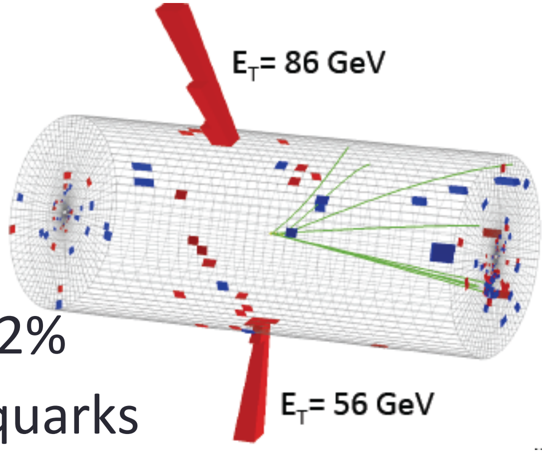




4-lepton mass: H→ZZ→4l, July 4 2012



$H \rightarrow \gamma\gamma$ in a nutshell



Important channel for Higgs with $110 < m_H < 140$ GeV

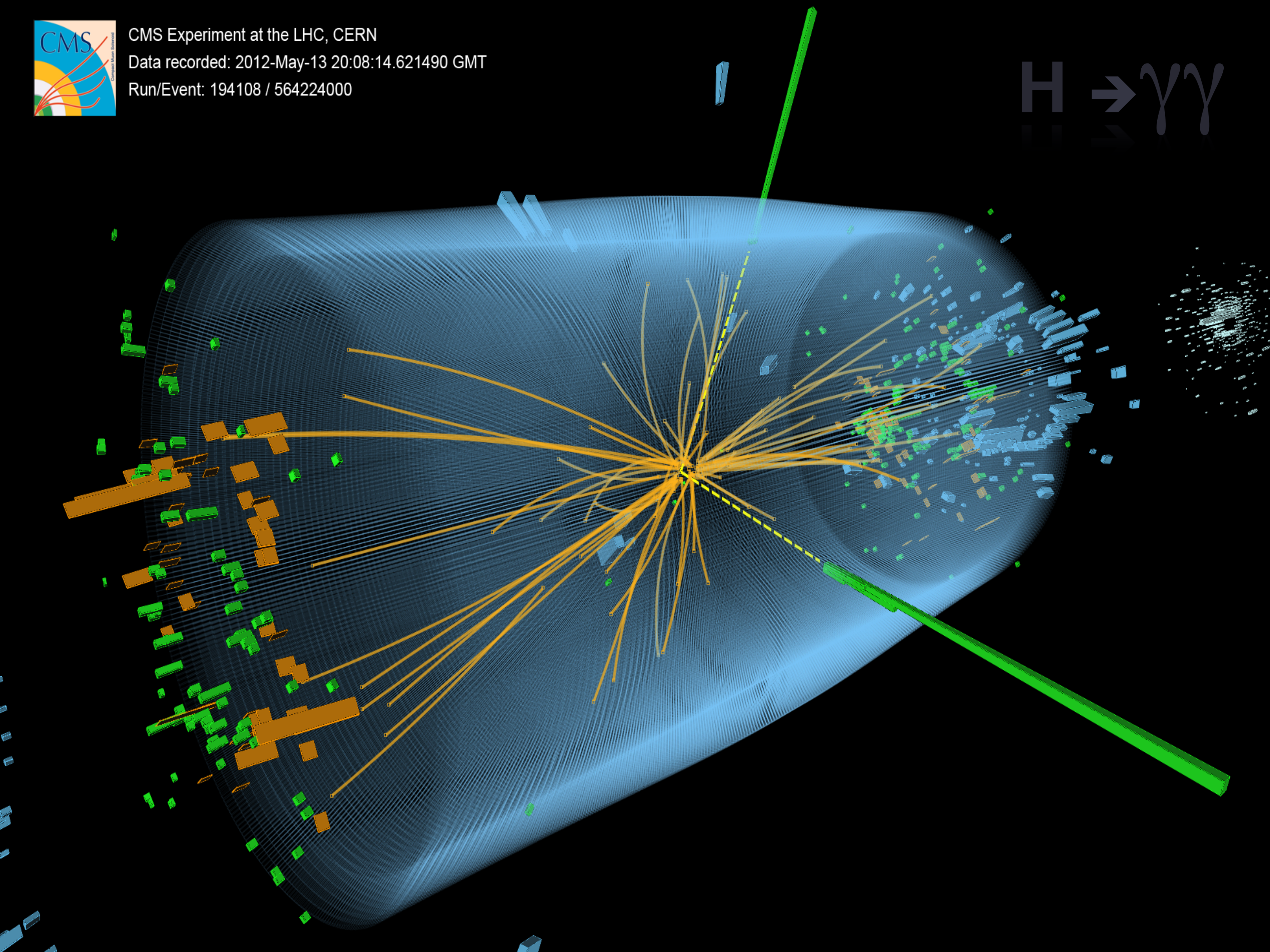
- clear signature of two isolated high E_T photons
- small B.R. (0.2%)
- narrow mass peak with very good mass resolution 1-2%
- **VBF** channels has two additional jets from outgoing quarks
- Associate production: WH with $W \rightarrow l\nu$

Background:

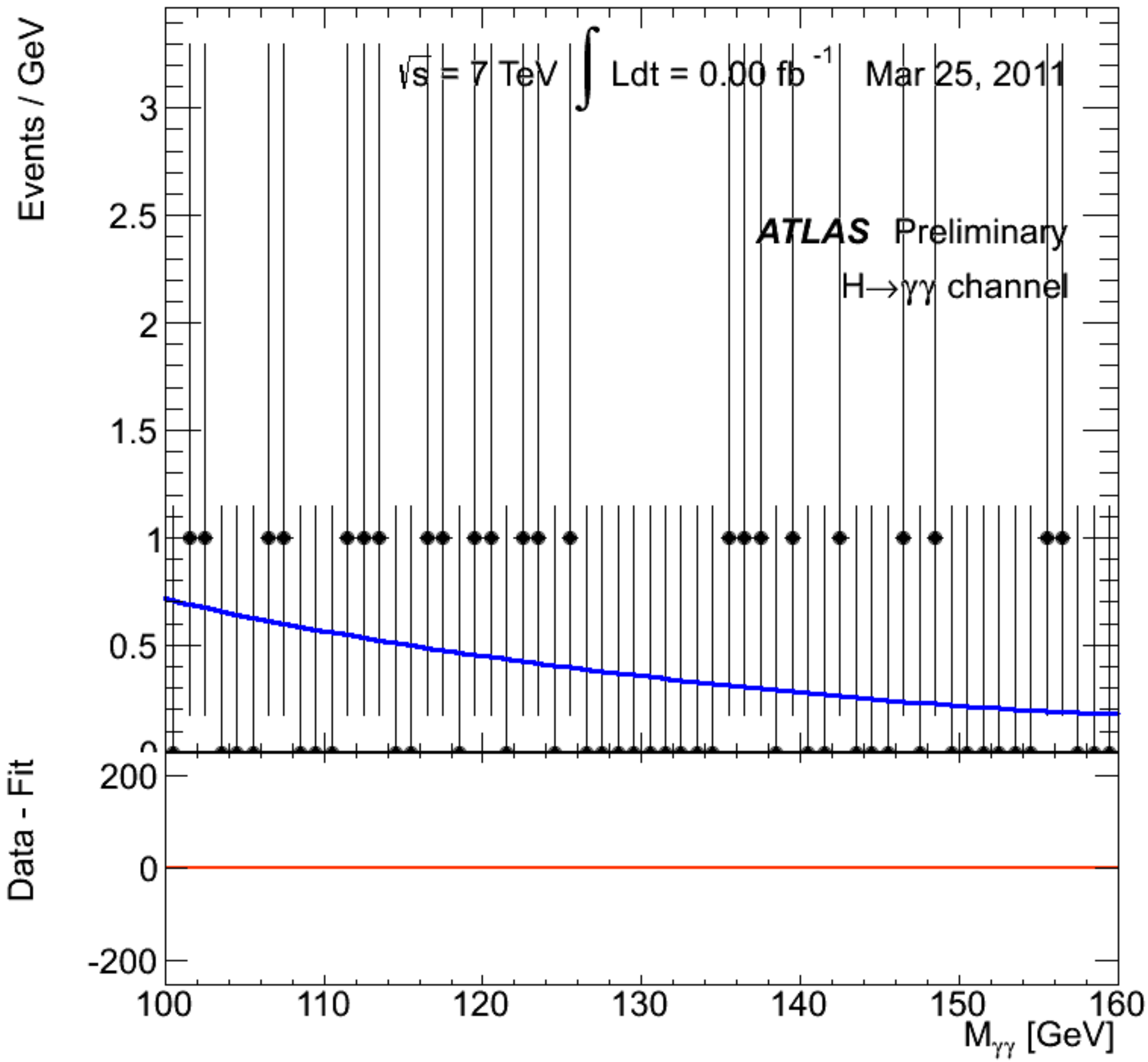
- irreducible : $\gamma\gamma \rightarrow \gamma\gamma$, qqbar, $qg \rightarrow \gamma\gamma$ from QCD
- reducible: pp $\rightarrow$ γ+jets (1 prompt γ + 1 fake γ)
  pp $\rightarrow$ jets (2 fake γ), fake γ from $\pi^0 \rightarrow \gamma\gamma$

Analysis strategy based on:

- trigger (double photon HLT)
- vertex ID via MVA, photon reconstruction, ID and isolation via MVA
- categories of events based on the γ shower shape (R_9) to optimize s/b
- look for a peak with MVA techniques and cut-based


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ

Di-photon mass: H→γγ, July 4 2012



Statistical interpretation of results

Test of hypotheses

H_0: null hypothesis / no Higgs
H_1: existence of the Higgs

Quantify the level for which the hypotheses are accepted or rejected

- Identify the experimental observables
- Define a statistical test and the parameters of the model
- Define intervals for the variable to say that H_0 is confirmed or rejected

- Confedence level for the exclusion
- Significance of the discovery

Statistical test variable

likelihood function

$$\mathcal{L}(data \mid \mu,\theta) = Poisson(data \mid \mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta} \mid \theta)$$

$Poisson(data \mid \mu \cdot s(\theta) + b(\theta))$: Poisson probability di Poisson of observing data

can be written

Product of poissonian distribution for observing n_i events in bin i

$$\prod_i \frac{(\mu \cdot s_i + b_i)^{n_i}}{n_i} e^{-\mu s_i - b_i}$$

Unbinned Likelihood function for k events in data

$$k^{-1} \prod_i \frac{(\mu S f_s(x_i) + B f_b(x_i))}{n_i} e^{-(\mu S - B)}$$

$f_s(x)$ e $f_b(x) \rightarrow$ p.d.f. of signal and background for x observable

S e $B \rightarrow$ rate of tot events expected for signal and background

$$\mu(\text{"}signal\ strenght\ modifier\text{"}) = \frac{\#\, observed\ \ events}{\#\, events\ \text{expected}\ \ by\ \ SM}$$

Exclusion and discovery

$$CL_S(\mu) = \frac{P\left(q_\mu \geq q_\mu^{obs} \mid \mu s\left(\hat{\theta}_\mu^{obs}\right) + b\left(\hat{\theta}_\mu^{obs}\right)\right)}{P\left(q_\mu \geq q_\mu^{obs} \mid b\left(\hat{\theta}_0^{obs}\right)\right)}$$

$CL_S \leq \alpha$ for $\mu = 1$ → the existence of Higgs is excluded at confidence level $(1-\alpha)$

→ Exclusion at 95% confidence level means $\alpha = 0.05$ → μ

Signicance for discovery: background **ONLY** hypothesis

$$q_0 = -2\ln\frac{\mathcal{L}\left(data \mid 0, \hat{\theta}_0\right)}{\mathcal{L}\left(data \mid \hat{\mu}, \hat{\theta}\right)} \quad con\ \hat{\mu} \geq 0$$

(q_μ computed for $\mu = 0$)

the significance of a signal is quantified by the *p-value*

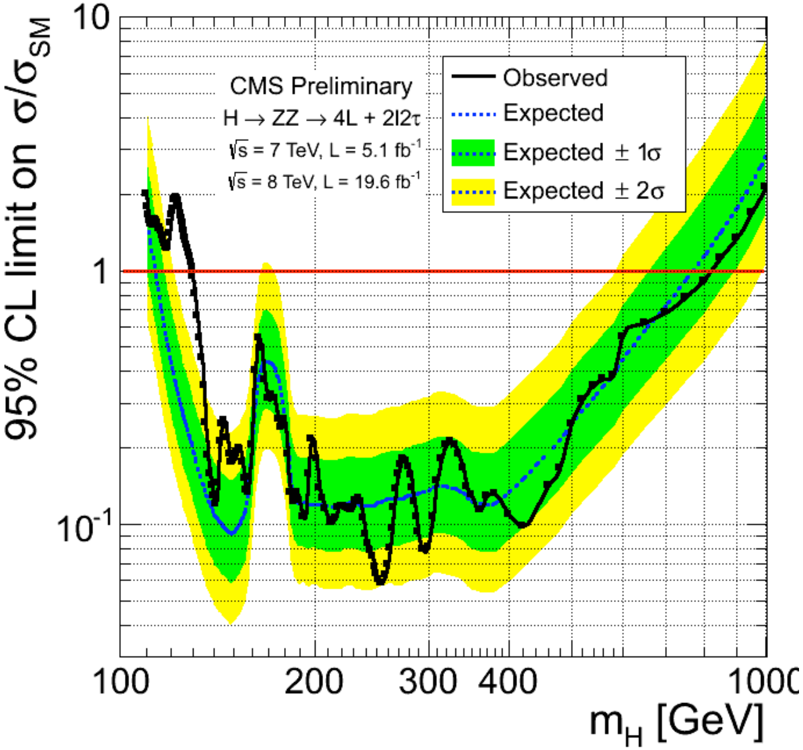
probability that the backgroud can fluctuate to give an excess of events equal or larger than what observed

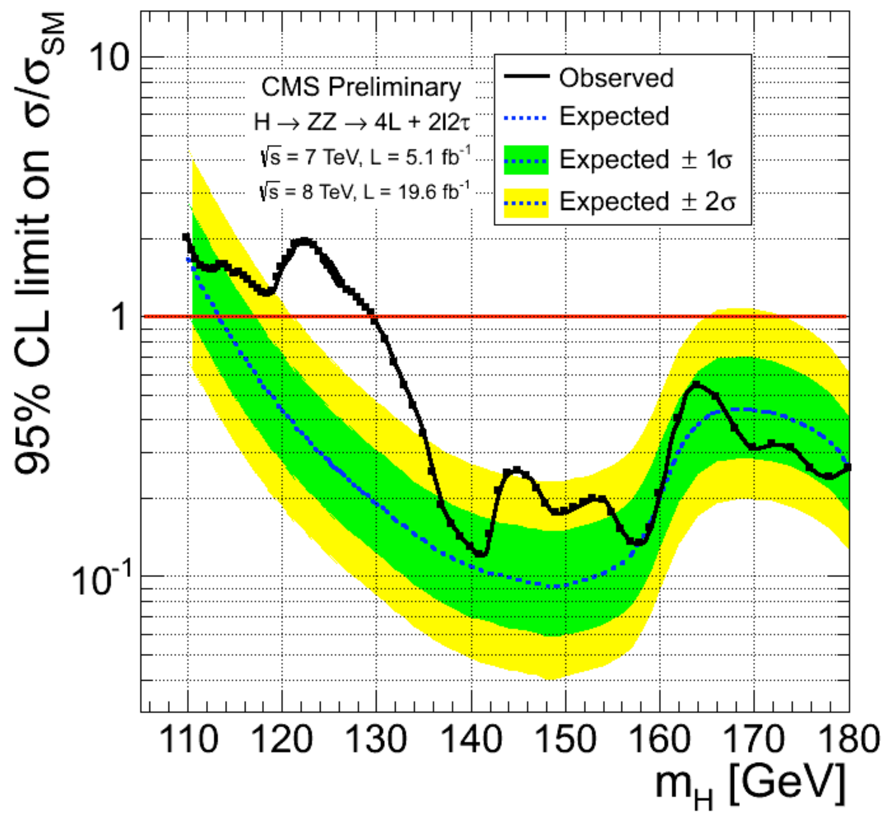
Statistical treat. : exclusion limits

2D pdf built (KD,m4l):

$$\mathcal{P}_{\rm sig}(m_{4\ell},{\rm KD}) = \mathcal{P}^{\rm 1D}_{\rm sig}(m_{4\ell}) \times \mathcal{P}_{\rm sig}(KD|m_{4\ell})$$

- ✓ Test statistic: profile likelihood ratio
- ✓ nuisance parameters included
- ✓

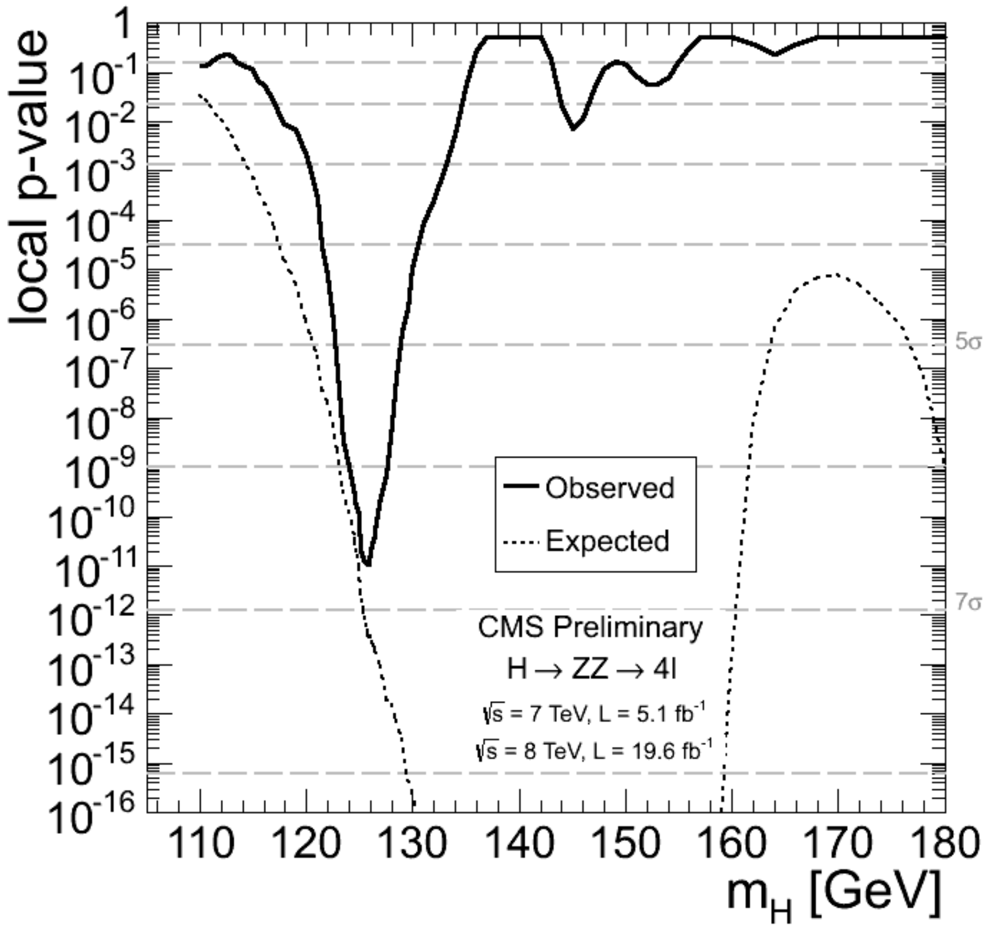




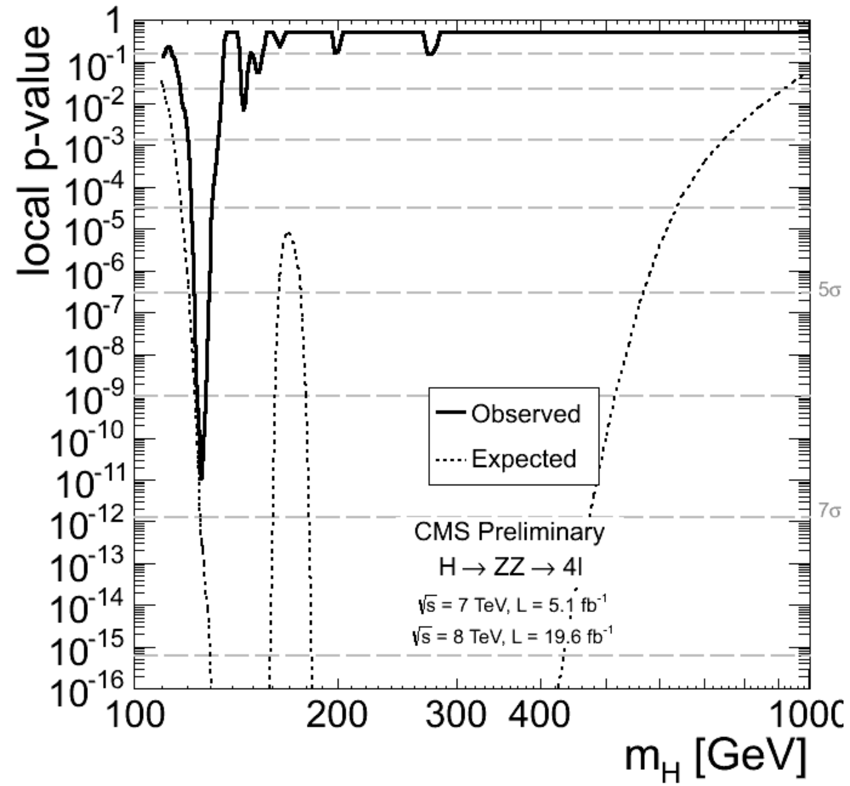
Observed limit:

95% CL exclusion in ranges 114.5-119 and 129–800 GeV

Statistical treat. : local significance

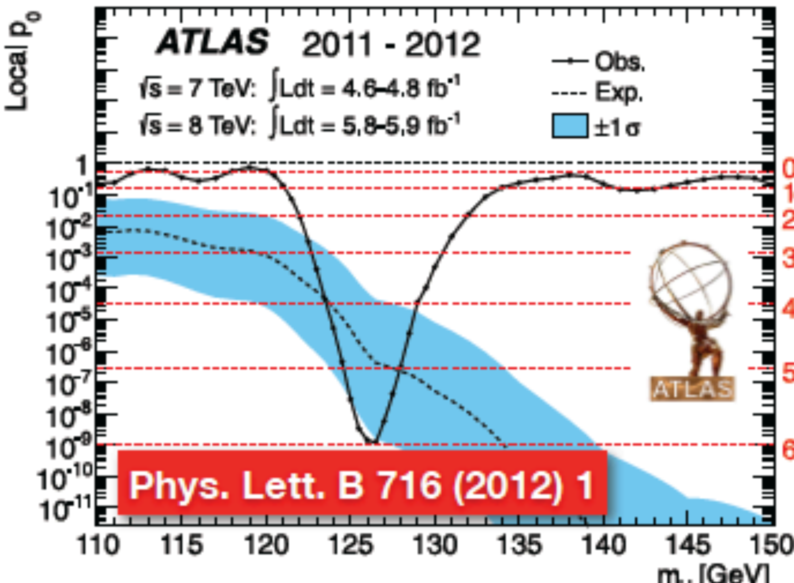


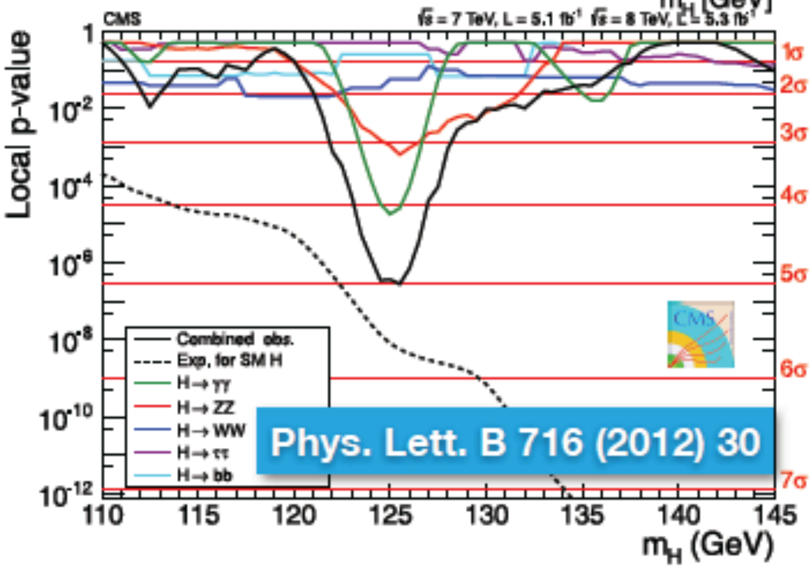
p-value: probability that the background can fluctuate to give an excess of events equal or larger than what observed

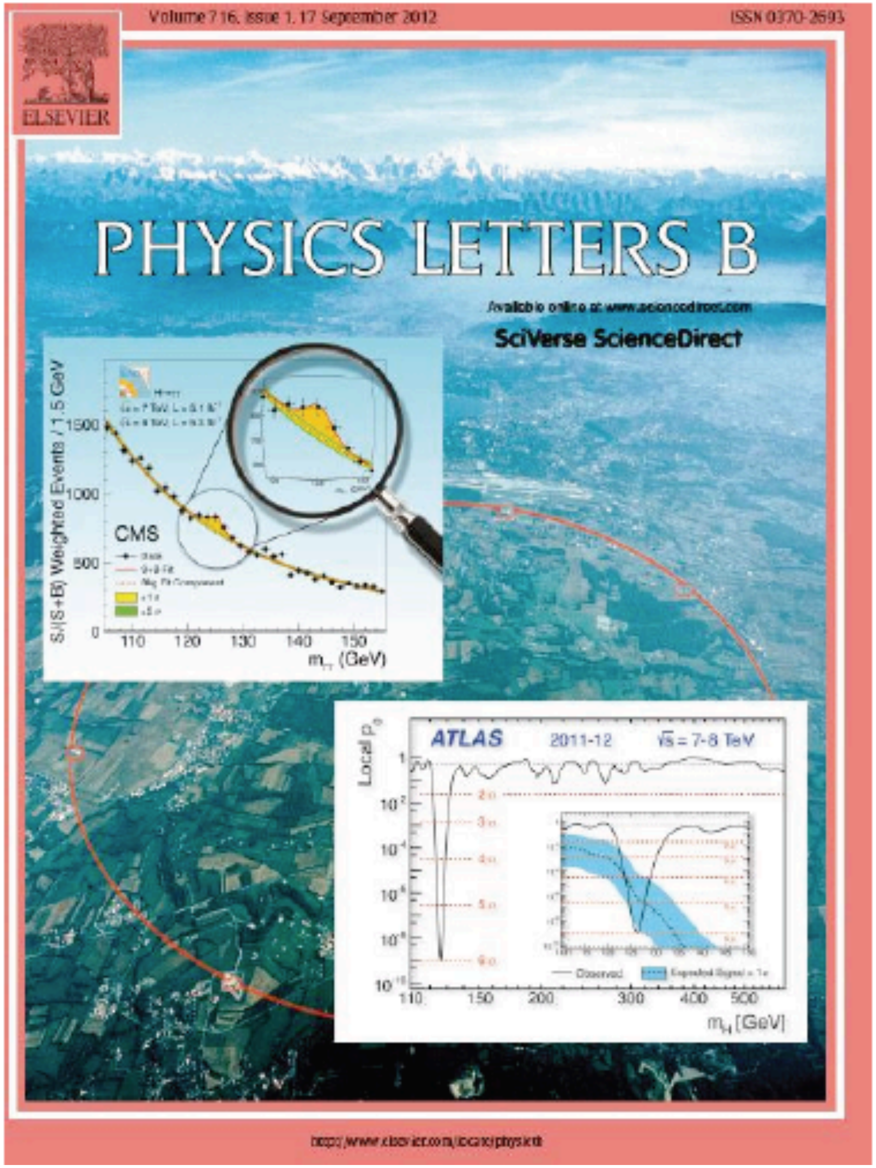


Minimum observed p-value ≈ 6.8σ (6.7σ expected)

The Higgs boson discovery: July 4 2012



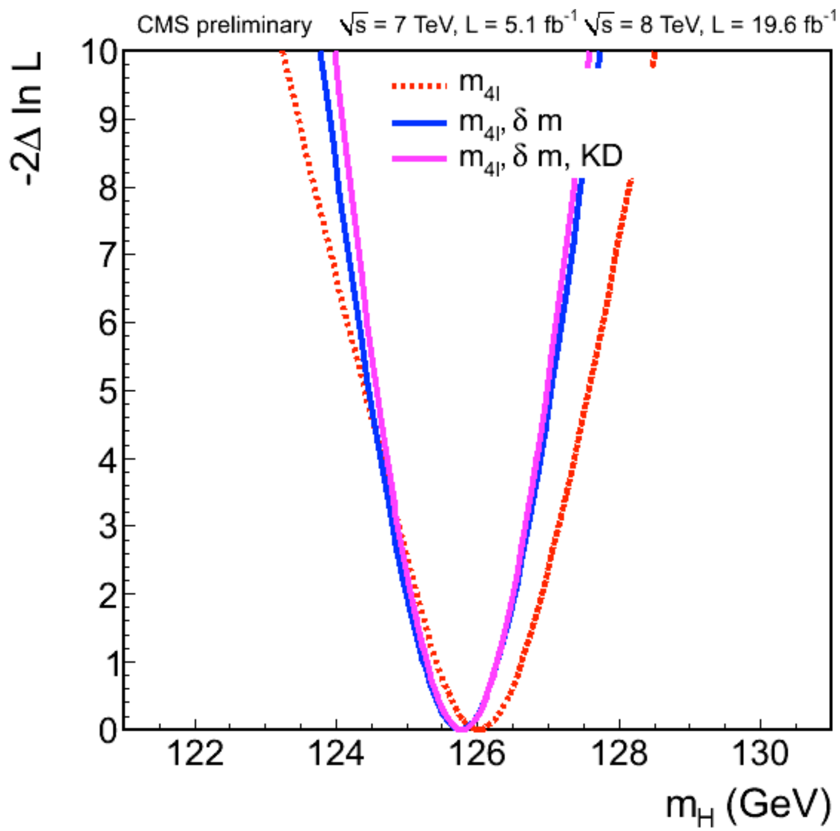




Mass measurement

3D pdf built (KD,m4l, EBE):

$$\mathcal{P}_{\rm sig}(m_{4\ell}, EBE, KD) = \mathcal{P}^{\rm 1D}_{\rm sig}(m_{4\ell}) \times \mathcal{P}_{\rm sig}(EBE|m_{4\ell}) \times \mathcal{P}_{\rm sig}(KD|m_{4\ell})$$



- Event by Event mass error (EBE) included
  - from muon track fit error matrix
  - from electron momentum error
- 3% of better significance by using the EBE
- 10% improvement on error on m_X

The combined best-fit mass is

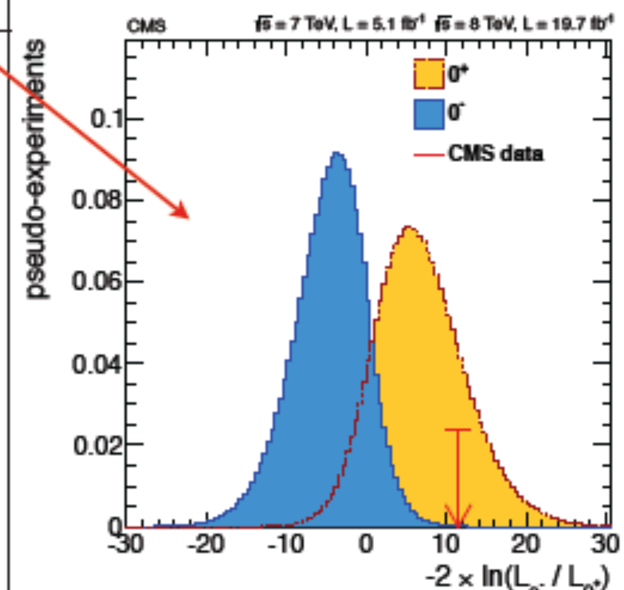
$$m_X = 125.6\ ^{+0.5}_{-0.4}\ \text{(stat)}\ ^{+0.1}_{-0.4}\ \text{(syst) GeV}$$

Statistical analysis: J^{CP}

- Strong exclusion of a spin-1 resonance (could not decay to $H\rightarrow\gamma\gamma$)
- pseudo-scalar excluded at >3σ level
- graviton-like resonances excluded at >~3σ level

J^P model	J^P production	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-0.9σ	$+3.6\sigma$	0.09%
0^+_h	any	1.7σ (1.9σ)	0.0σ	$+1.8\sigma$	7.1%
1^-	$q\bar{q} \to X$	2.6σ (3.1σ)	-1.4σ	$+4.8\sigma$	0.001%
1^-	any	2.6σ (3.0σ)	-1.7σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \to X$	2.1σ (2.5σ)	-1.5σ	$+4.1\sigma$	0.03%
1^+	any	2.0σ (2.3σ)	-1.9σ	$+4.5\sigma$	0.01%
2^+_m	$gg \to X$	1.7σ (1.9σ)	-1.6σ	$+3.5\sigma$	0.04%
2^+_m	$q\bar{q} \to X$	1.6σ (1.9σ)	-1.6σ	$+3.6\sigma$	0.03%
2^+_{m}	any	1.5σ (1.6σ)	-1.0σ	$+2.6\sigma$	3.0%
2^+_b	$gg \to X$	1.6σ (1.9σ)	-1.2σ	$+3.1\sigma$	0.9%
2^+_h	$gg \to X$	3.7σ (4.3σ)	$+1.8\sigma$	$+1.9\sigma$	3.1%
2^-_h	$gg \to X$	4.0σ (4.9σ)	$+1.0\sigma$	$+3.0\sigma$	1.7%

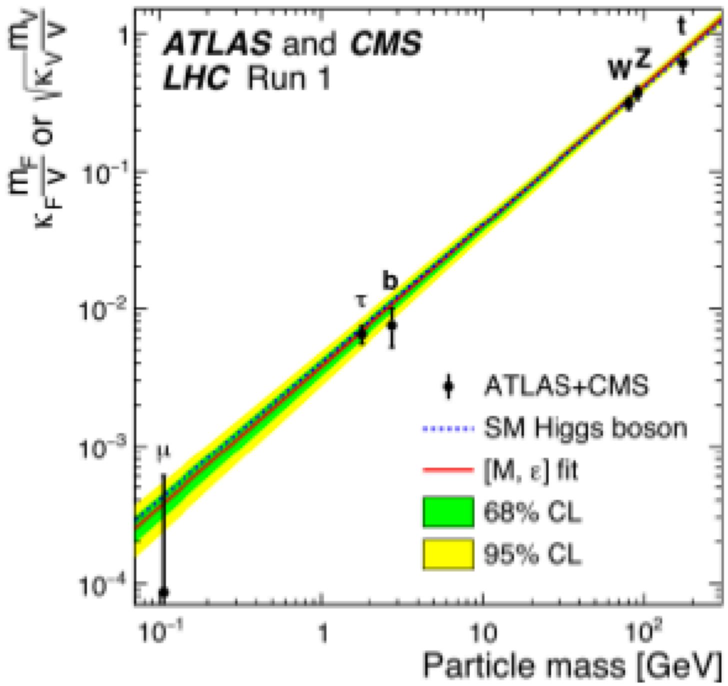
0^+ vs 0^-



Higgs properties @ LHC Run 1

- **Mass:** $125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$ ATLAS+CMS: PRL 114 (2015) 191803
- **Spin/Parity:** 0^+ ATLAS: EPJC 75 (2015) 476 CMS: PRD 92 (2015) 012004
- **Width:** < 1 GeV (direct) CMS: JHEP 11 (2017) 047

  < 0.015 GeV (indirect) ATLAS: arXiv:1808.01191 submitted to PLB
- **Observed direct coupling to:**
  - Vector bosons ATLAS: PLB 716 (2012) 1-29 CMS: PLB 716 (2012) 30
  - τ leptons ATLAS: ATLAS-CONF-2018-021 CMS: PLB 779 (2018) 283
  - top quarks ATLAS: PLB 784 (2018) 173 CMS: PRL 120 (2018) 231801



All measurements compatible with SM predictions

October 8 2013: Nobel prize

Nobel Prizes and Laureates

Physics Prizes ‹ 2013 ›

▼ About the Nobel Prize in Physics 2013

- Summary
- Prize Announcement
- Press Release
- Advanced Information
- Popular Information
- Greetings

▶ François Englert

▶ Peter Higgs

All Nobel Prizes in Physics

All Nobel Prizes in 2013

The Nobel Prize in Physics 2013

François Englert, Peter Higgs

The Nobel Prize in Physics 2013

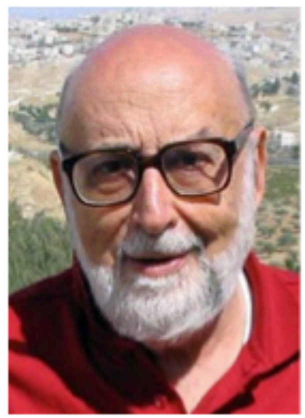


Photo: Pnicolet via Wikimedia Commons

François Englert

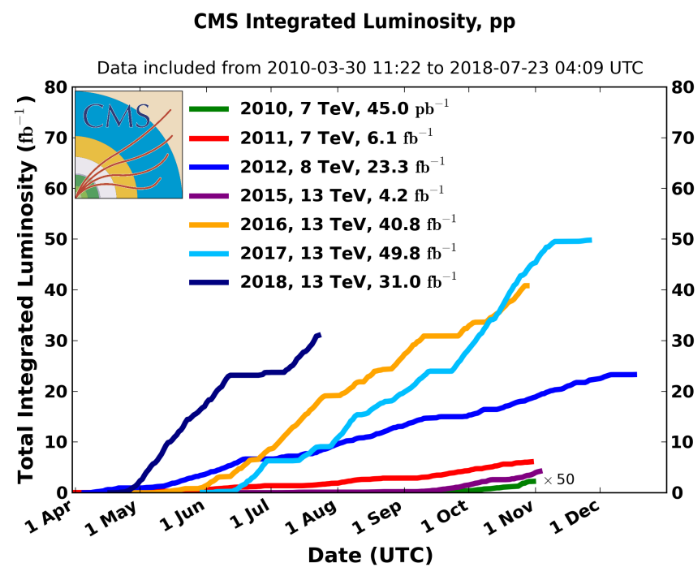
Photo: G-M Greuel via Wikimedia Commons

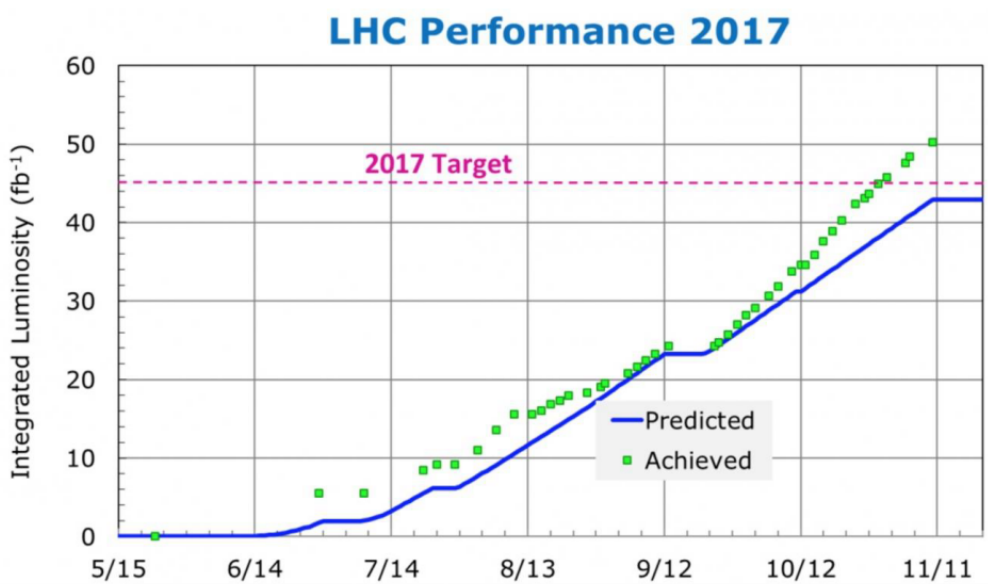
Peter W. Higgs

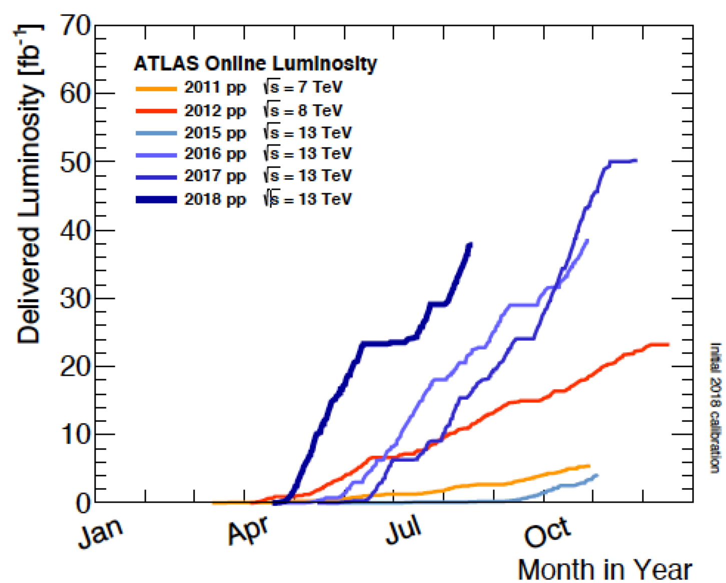
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

LHC Run 2

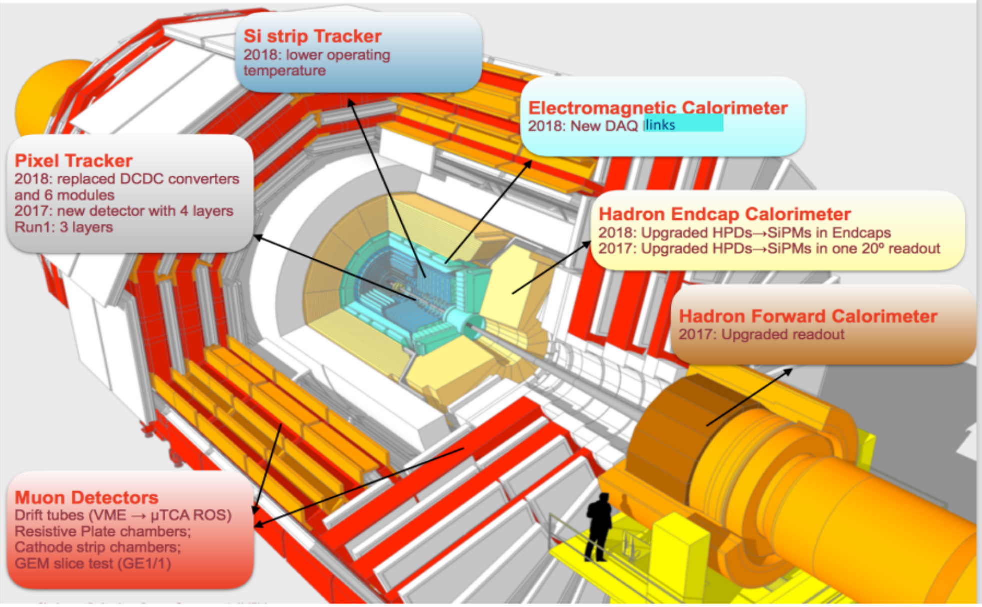
- LHC has produced **> 3 years of 13 TeV** data with fantastic performance
  - expected to result in **>150 fb^{-1}** by the end of the 2018 run
  - Maximum peak luminosity ~2x10^{34} cm^{-2}s^{-1} with mean pileup ~33 in 2017, ~38 in 2018
  - DESIGN peak luminosity exceeded by a factor of 2!

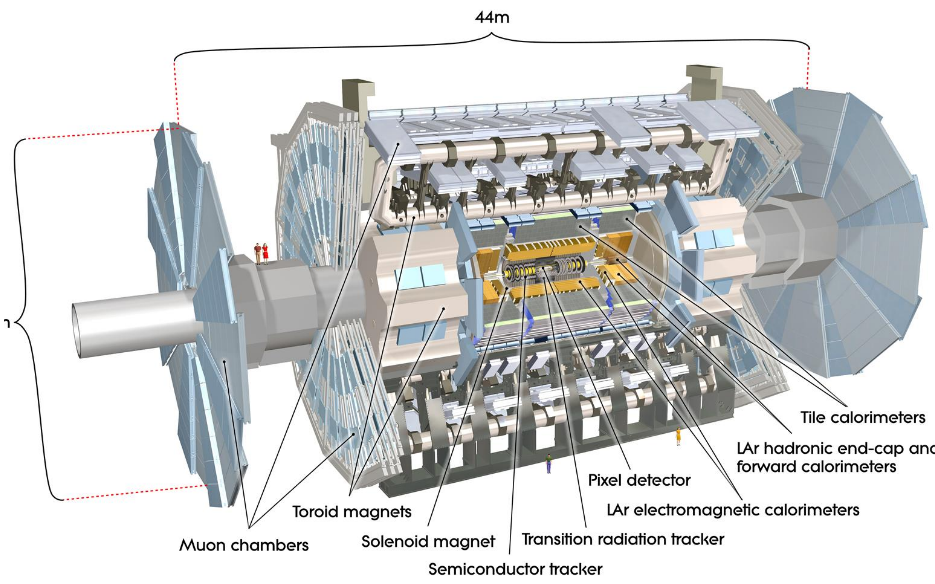


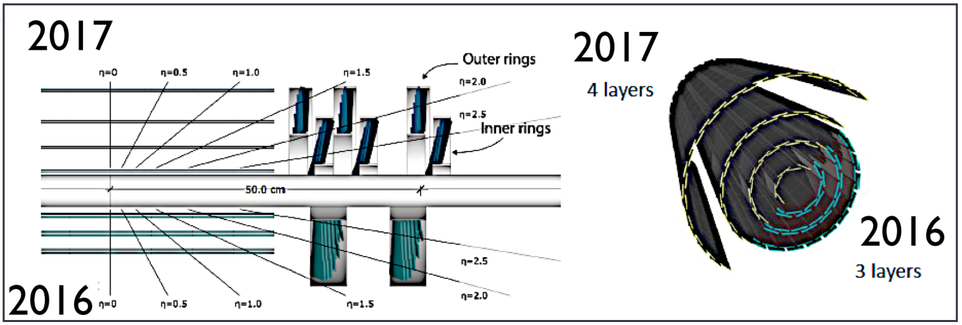




CMS/ATLAS in 2017/2018 (after LS1)

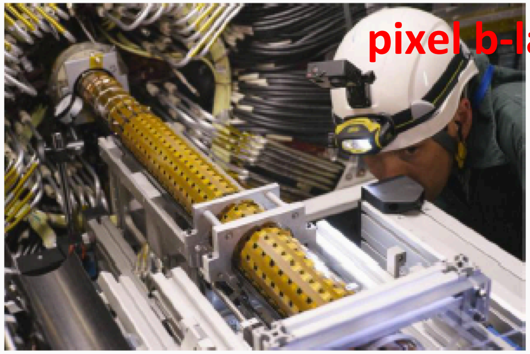






- New IBL detector installed in LS1 (2013-2014)
- Tracking optimized for high-PU and high-p_T environments
- Better ML algorithms

4th insertable pixel b-layer (IBL)



Large impact on b-tagging performance

Highlights for Higgs physics @ Run 2

- It is matter of 6 months (Aug. 28 2018) the announcement of the **observation of H→bb**

Precise measurements with:

- **H→γγ**
- **H→ZZ**

Evidence/observation of:

- **H→ ττ**
- **ttH**
- **…**

H→bb

Motivation:

- H→ bb has the largest BR (58%) for m_H=125 GeV
- Unique final state to measure coupling with down-type quarks
- Drives the uncertainty of the total Higgs boson width
- Primary decay mode for searches at LEP and Tevatron
  → a long history or searches

First H→bb searches started at LEP...

Physics Letters B 565 (2003) 61–75

ELSEVIER

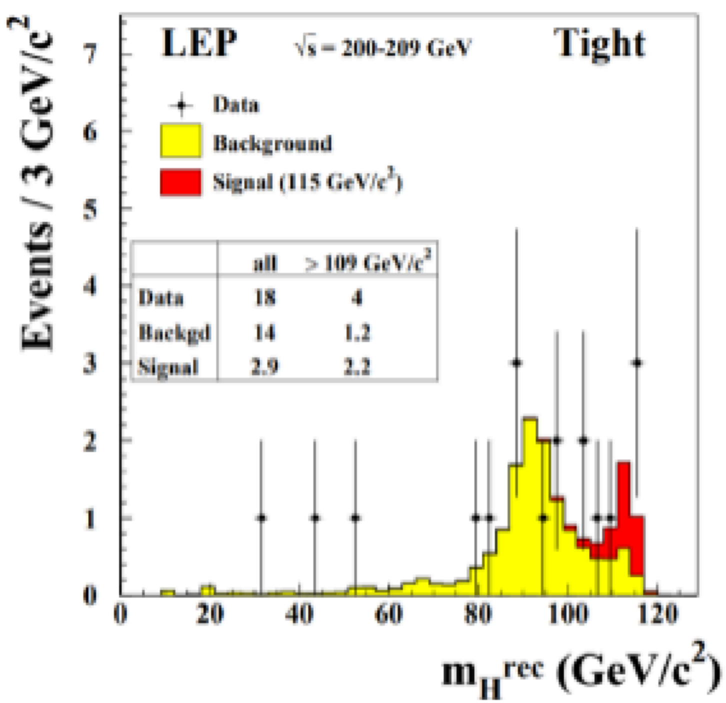
Search for the Standard Model Higgs boson at LEP

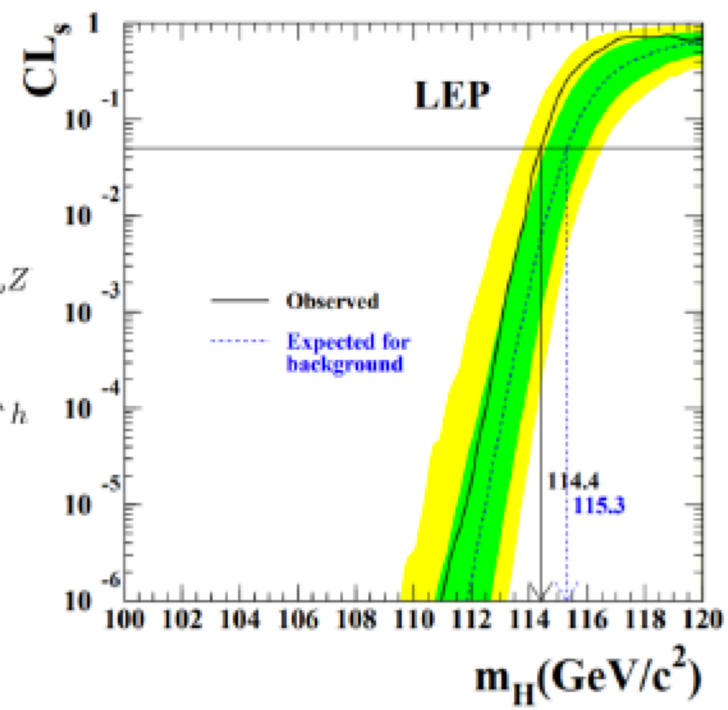
ALEPH Collaboration [1] DELPHI Collaboration [2] L3 Collaboration [3] OPAL Collaboration [4]

The LEP Working Group for Higgs Boson Searches [5]

PHYSICS LETTERS B

$m_H > 114.4$ GeV @ 95%CL



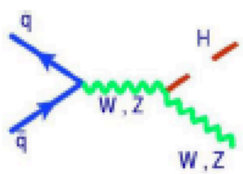


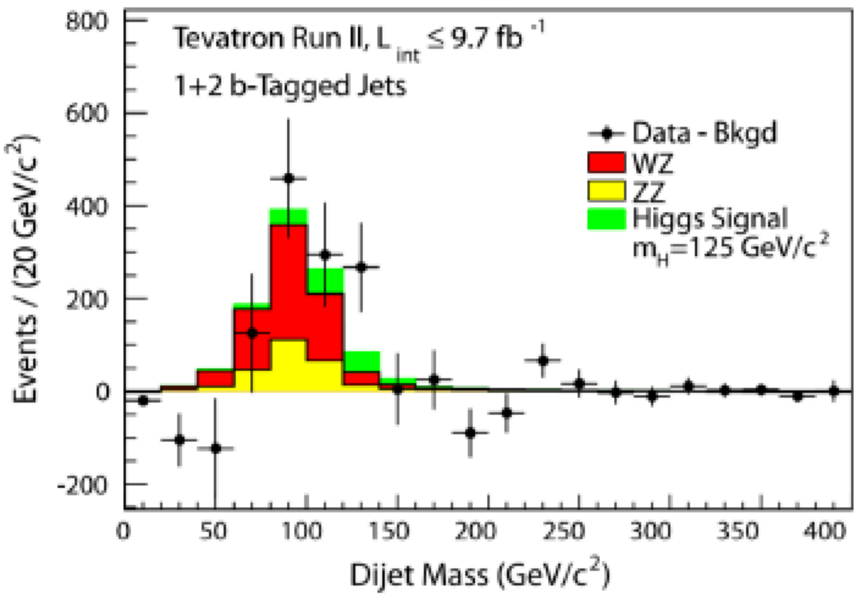
... and continued at Tevatron

PRL 109, 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

(*CDF Collaboration)
(†D0 Collaboration)



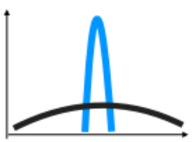


Significance

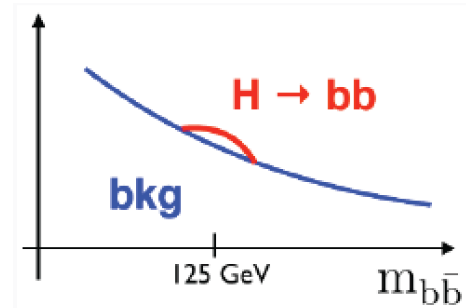
2.8σ observed @ 125 GeV

H→bb search challenge:

- **Needs:**
  - Good **b-jets identification** performance:
    70% efficiency with < 1% q/g mis-identification probability
  - Best possible **resolution on m(bb)**
  - Capability to exploit all possible information from the event to **improve S/B**
- **H(bb) compared with discovery channel**



	$H \to 4\ell$	$H \to b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	1%	10%
S/B	2	0.05



- **Higgs-strahlung - VH (4%) is the most sensitive channel**
  - leptons, E_T^{miss} to trigger and high p_T V to suppress backgrounds

@CMS so far
Evidence established last year
Phys. Lett. B 780 (2018) 501

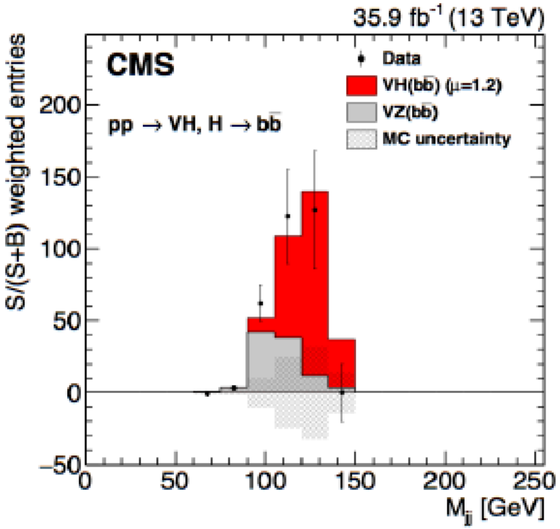
Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

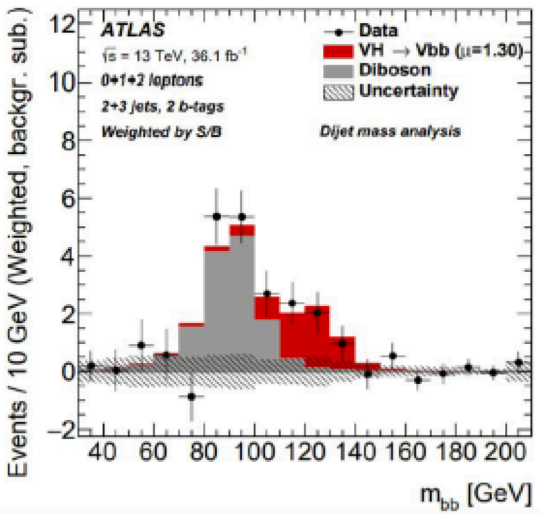
VH, H→bb results at LHC

- **VH(bb) evidence at LHC established with 2016 data by both ATLAS and CMS**
  - Detectors clearly demonstrated ability to deal with very high pile-up for such complex analysis
- **Signal strength uncertainty ~40%**

	signal strength	significance (exp)	significance (obs)
ATLAS Run 1 [1]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run 1 [2]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run 1 [3]	$0.79^{+0.29}_{-0.27}$	3.7σ	2.6σ
ATLAS 2015+2016 [4]	$1.20^{+0.42}_{-0.36}$	3.0σ	**3.5σ**
CMS 2016 [5]	$1.19^{+0.40}_{-0.38}$	2.8σ	**3.3σ**

[1] JHEP 01 (2015) 069
[2] JHEP 08 (2016) 045
[3] JHEP 08 (2016) 045
[4] JHEP 12 (2017) 024
[5] PLB 780 (2018) 501

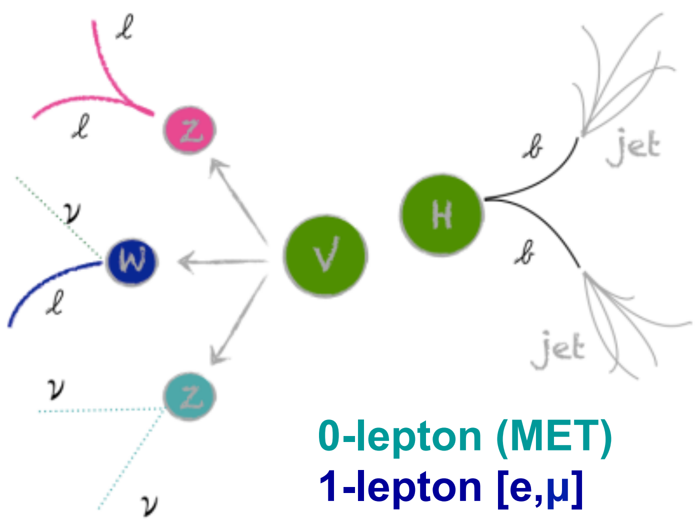




VH(H→bb): analysis strategy

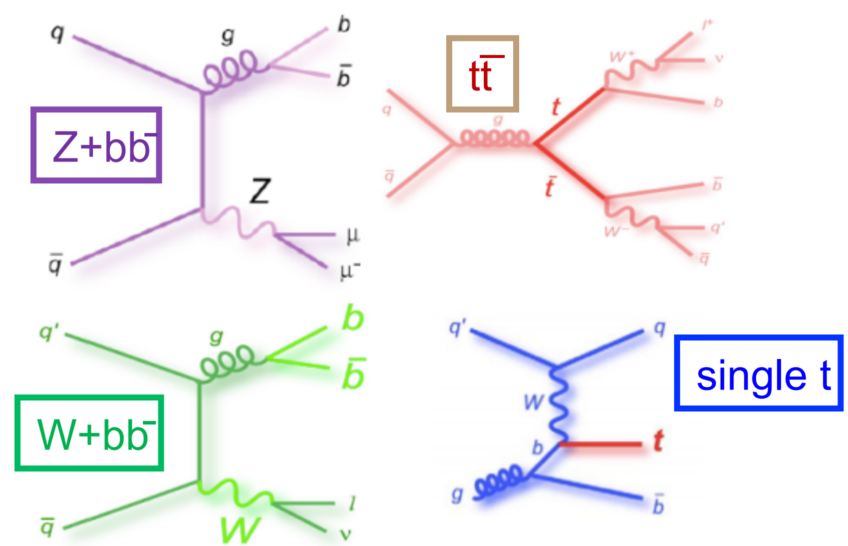
- **Analysis strategy:**
  - **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
    - To target Z(νν)H(bb), W(lν)H(bb) and Z(ll)H(bb) processes
  - **Signal region designed to increase S/B**
    - **Large boost** for vector boson
    - **Multivariate analysis** exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tagging)
  - **Control regions**: to validate background samples and control/constrain background normalization and systematics

signal



0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

irreducible backgrounds



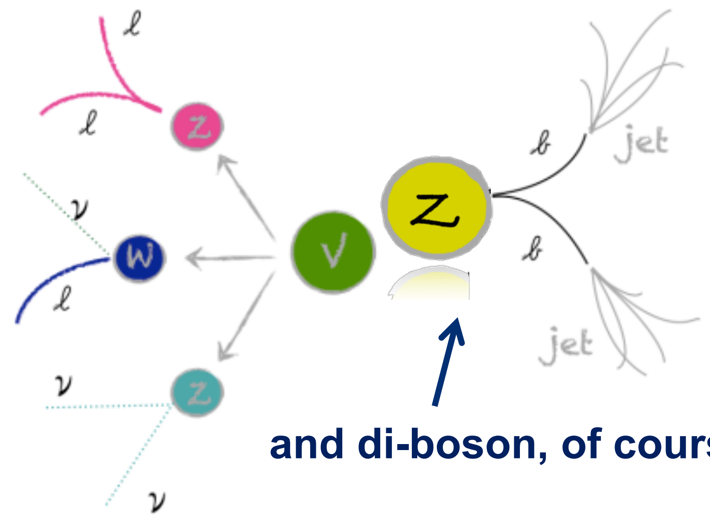
normalization from data, shapes from MC

N. De Filippis

VH(H→bb): event selection (CMS)

- Jet/lepton p_T **selection** and b-tagging discriminator working points **optimized separately by channel**
  - Boosted Vector Boson
    - 2-lepton: two p_T categories
      - Low: 50 GeV < $p_T(Z)$ < 150 GeV
      - High: $p_T(Z)$ > 150 GeV
    - 1-lepton: $p_T(W)$ > 150 GeV
    - 0-lepton: $p_T(Z)$ > 170 GeV

VZ background



and di-boson, of course

used to validate the analysis strategy

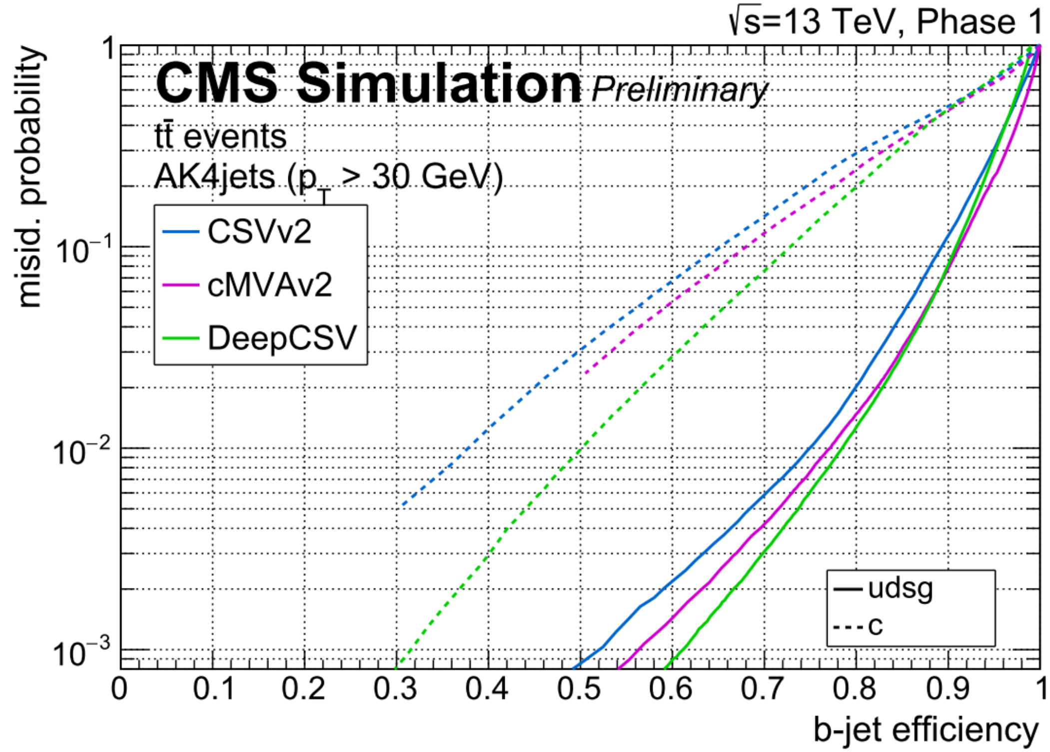
- **Control regions** designed to map closely signal region, with inverted selections to **enhance purity in targeted backgrounds**

- **Separate** $t\bar{t}$, V+light flavor jets, and V+heavy flavor jets **control regions per channel**

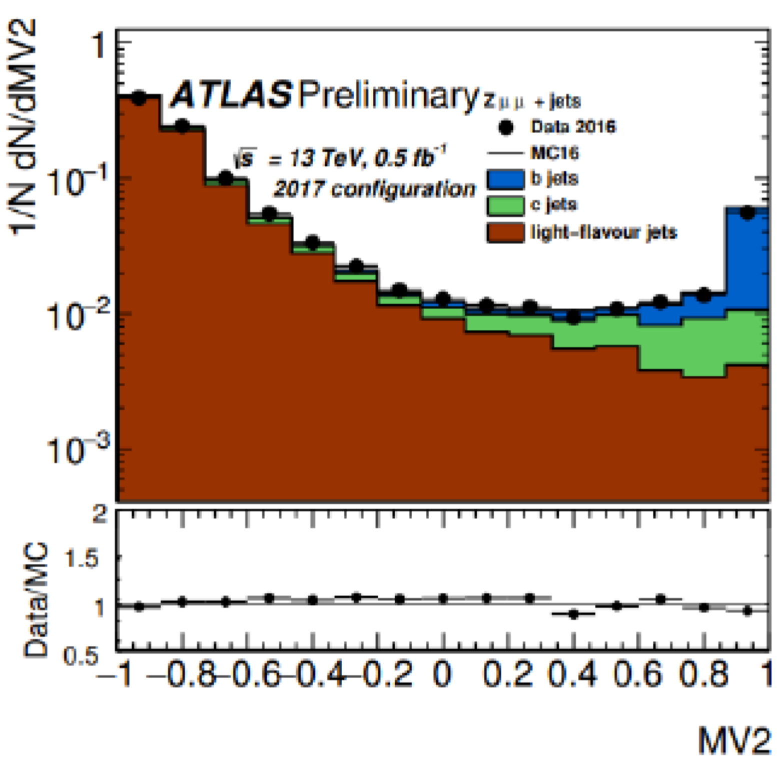
Improvement of b-tagging

CMS: better mis-identification rate and data/MC agreement with Phase 1 pixel detector and DeepCSV algorithm

- Efficiency ~70% per fake rate at < 1%

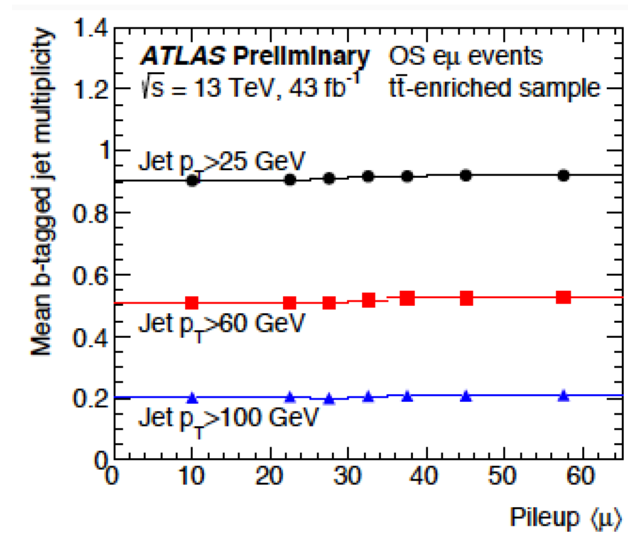


b-tagging discriminant

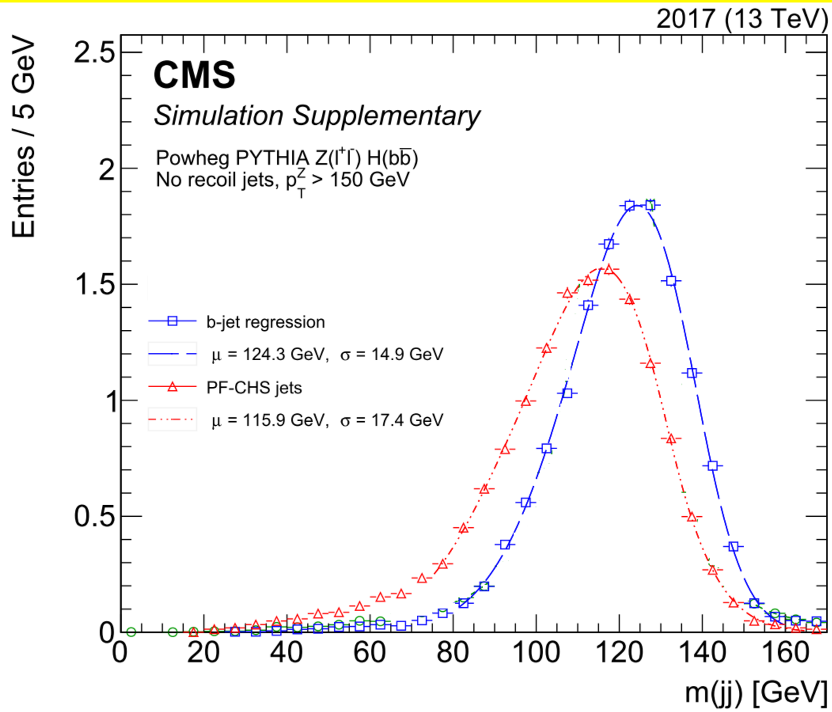


ATLAS:

- rejection of light/c jets 300/8 at 70% b-jet efficiency
- Good performance even at high PU



Improvement of di-jet mass resolution



CMS:

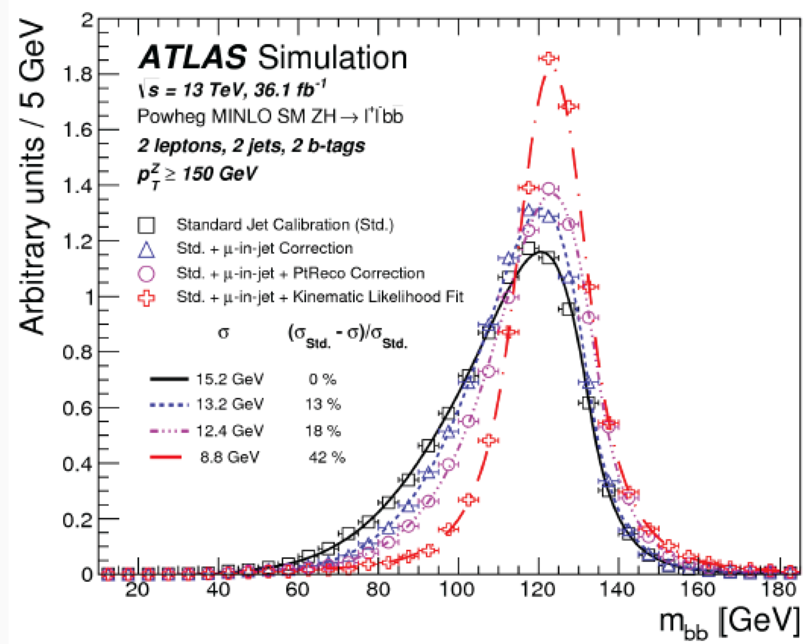
- Regression mainly recovers missing energy in the jet due to neutrino
- Extended set of input variables now including lepton flavour (μ/e), jet mass, p_T wrt to lepton axis, energy fractions in ΔR rings
- Significant m(bb) resolution improvement → σ/peak down to 11.9% in 2017 wrt 13.2% in 2016

ATLAS

Mass resolution improvements

Higgs boson candidate from a pair of *b*-jets

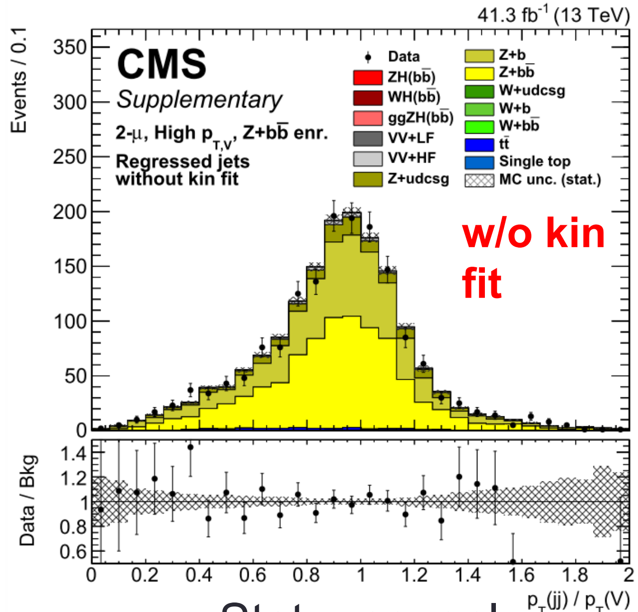
- Add muons in the vicinity (semi-lep. decays)
- Simple average jet p_T correction
  - Accounts for neutrinos, and interplay of resolution and p_T spectrum effects.
- Mass resolution improvement: ∼ 18%



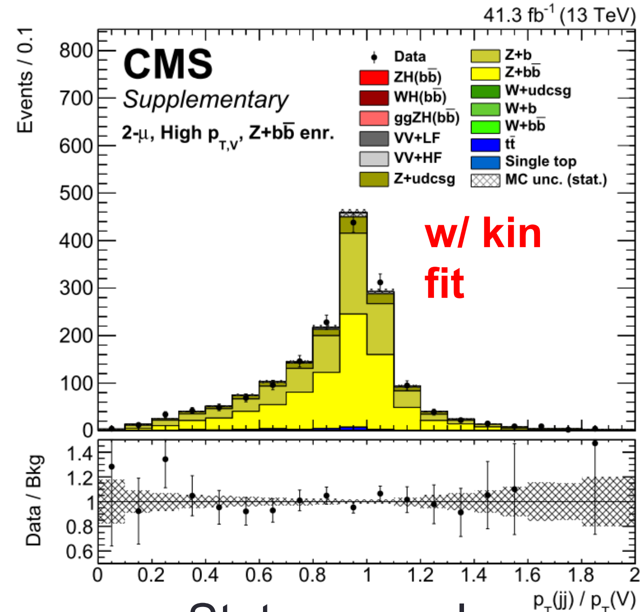
Kinematic fit in 2-lepton channel

CMS:

- No intrinsic missing energy in the Z(ll)H(b$\bar{b}$) process
- Improve jet p_T measurement through kinematic fit procedure
    - Constrain dilepton system to Z mass
    - Balance the ll+bb system in the (p_x,p_y) plane
- Improvement of up to 36% on m(b$\bar{b}$) resolution



Stat. unc. only

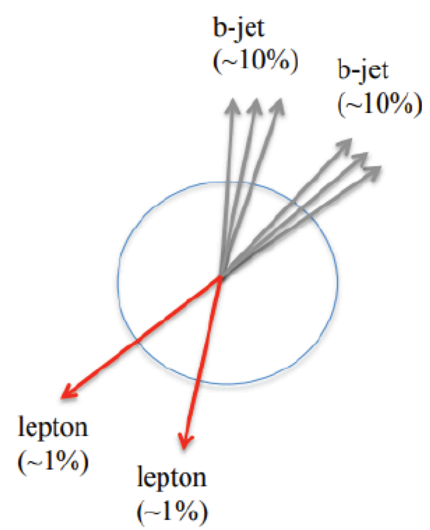


Stat. unc. only

ATLAS:

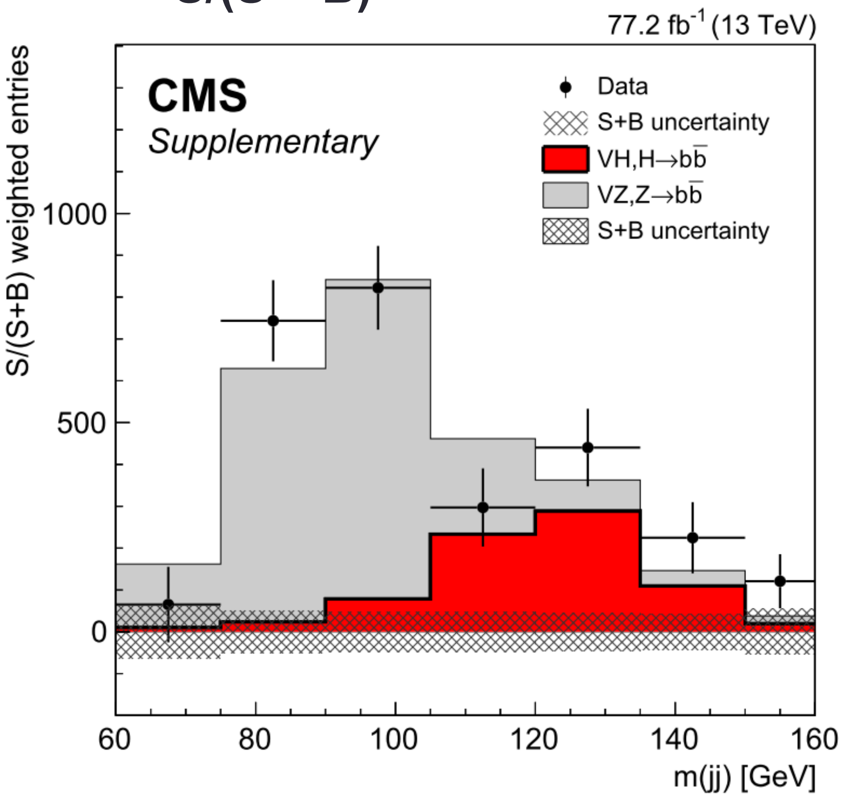
Kinematic Fit in 2-lepton channel

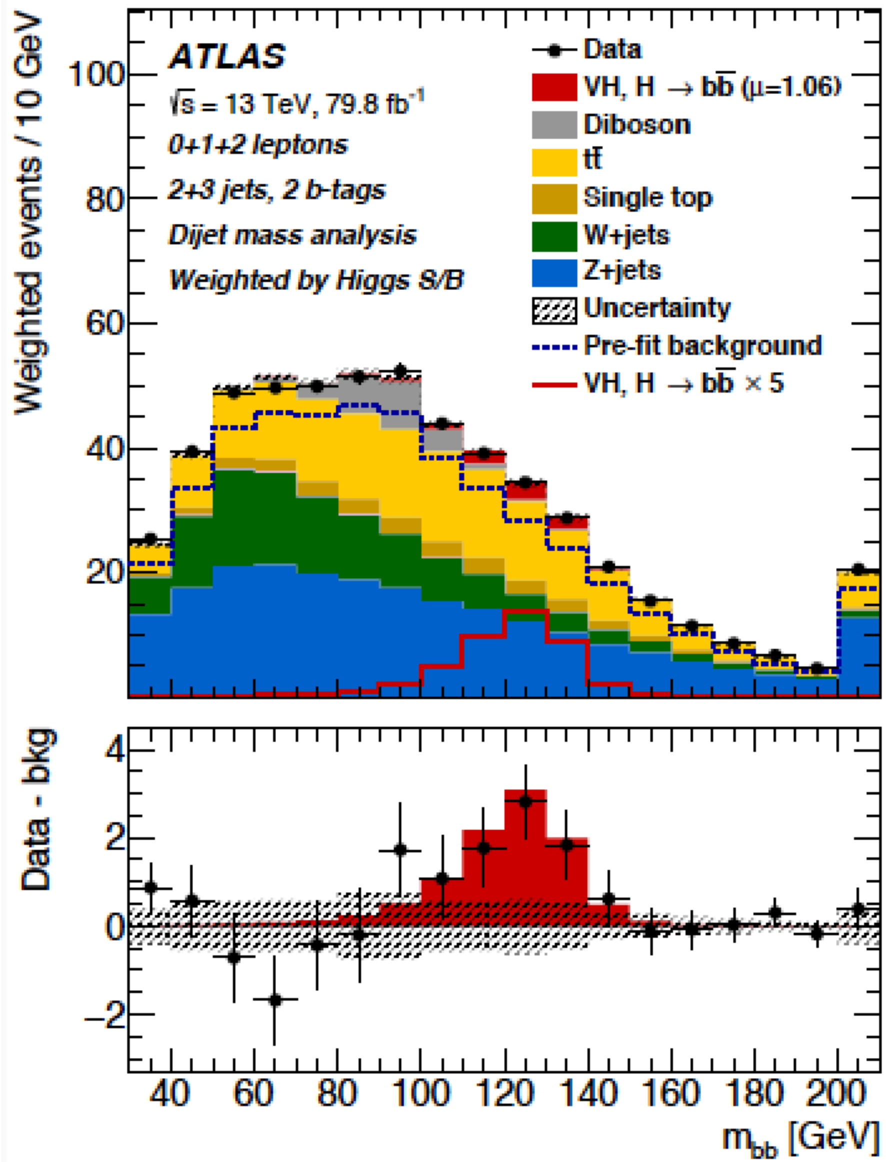
- Final state fully reconstructed
- High resolution on leptons
- Constrain jet kinematics better:
  $\sum \vec{p_T}(\ell) = -\vec{p_T}(bb)$ modulo soft radiation
- Mass resolution improvement: $\sim$ 40%



VH(H→bb): m(bb)

- **Fit to the m(bb)**: lower sensitivity but direct visualization of the Higgs boson signal.
- The fitted **m(bb) distributions are combined and weighted by S/(S + B)**

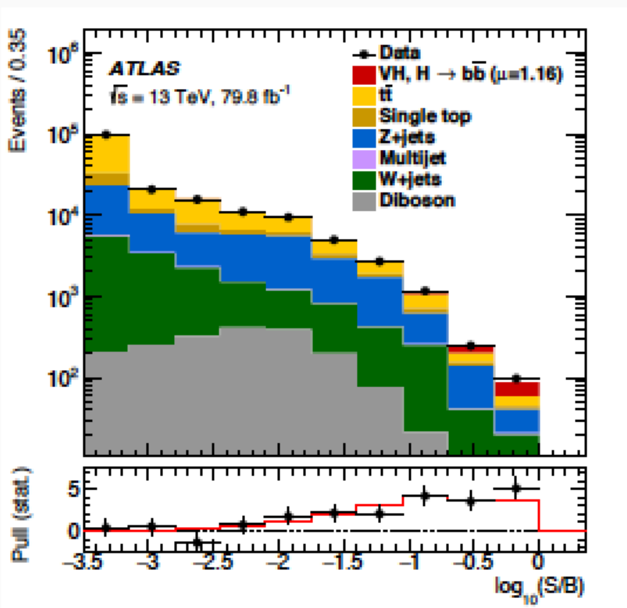


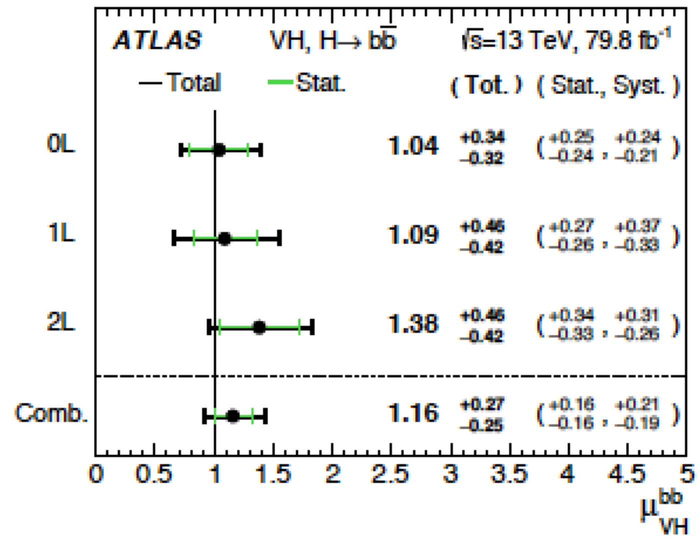


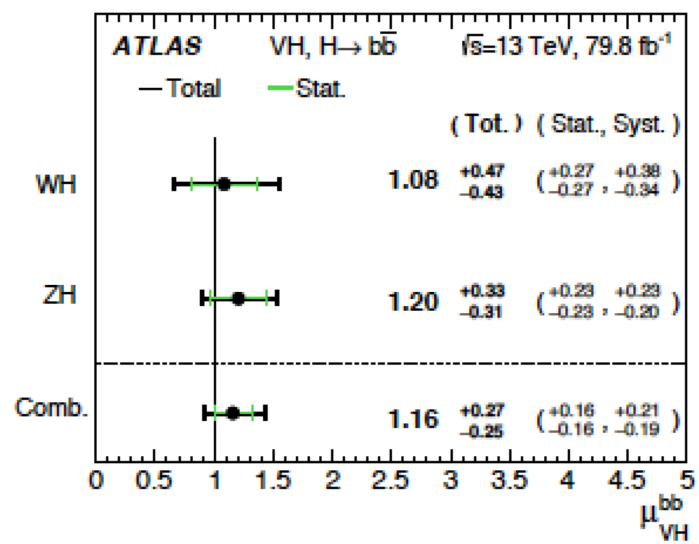
VH(H→bb): significance (ATLAS)

Results

- Significance of $VH(bb)$ signal at 4.9σ (4.3σ exp.)
  - Signal strength compatible with SM
  - Lepton channels compatible at 80% level
- Individual production modes significances:
  - 2.5σ (2.3σ exp.) for WH
  - 4.0σ (3.5σ exp.) for ZH

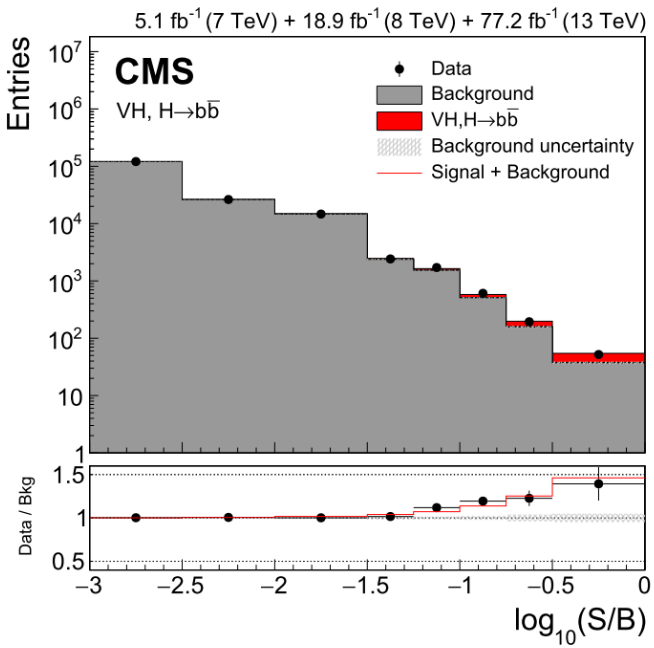


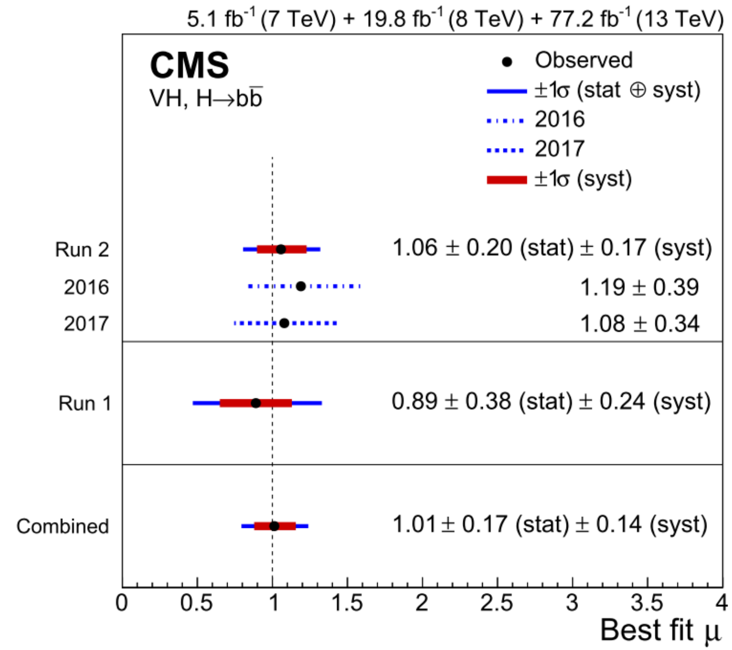




VH(H→bb): Run 1 + Run 2 results (CMS)

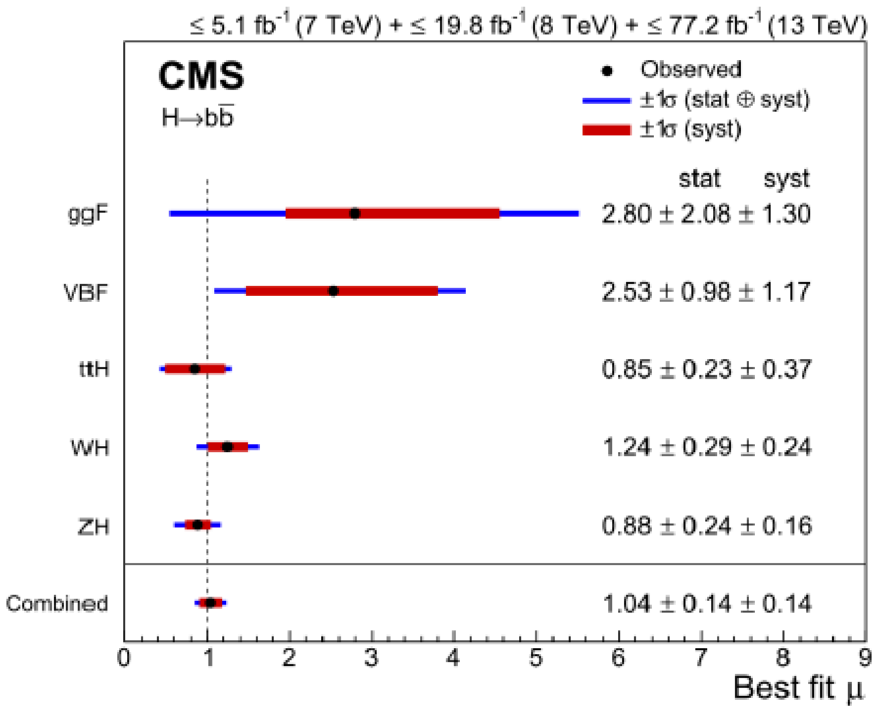
	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23





Combination of H→bb searches by CMS

- **Combination of CMS H→bb measurements : VH, boosted ggH, VBF, ttH**
- **Most sources of systematic uncertainty are treated as uncorrelated**
  - Theory uncertainties are correlated between all processes and data sets
- **Measured signal strength is μ = 1.04 ± 0.20**



Significance

5.5σ expected

5.6σ observed

Observation of the H→bb decay by the CMS Collaboration

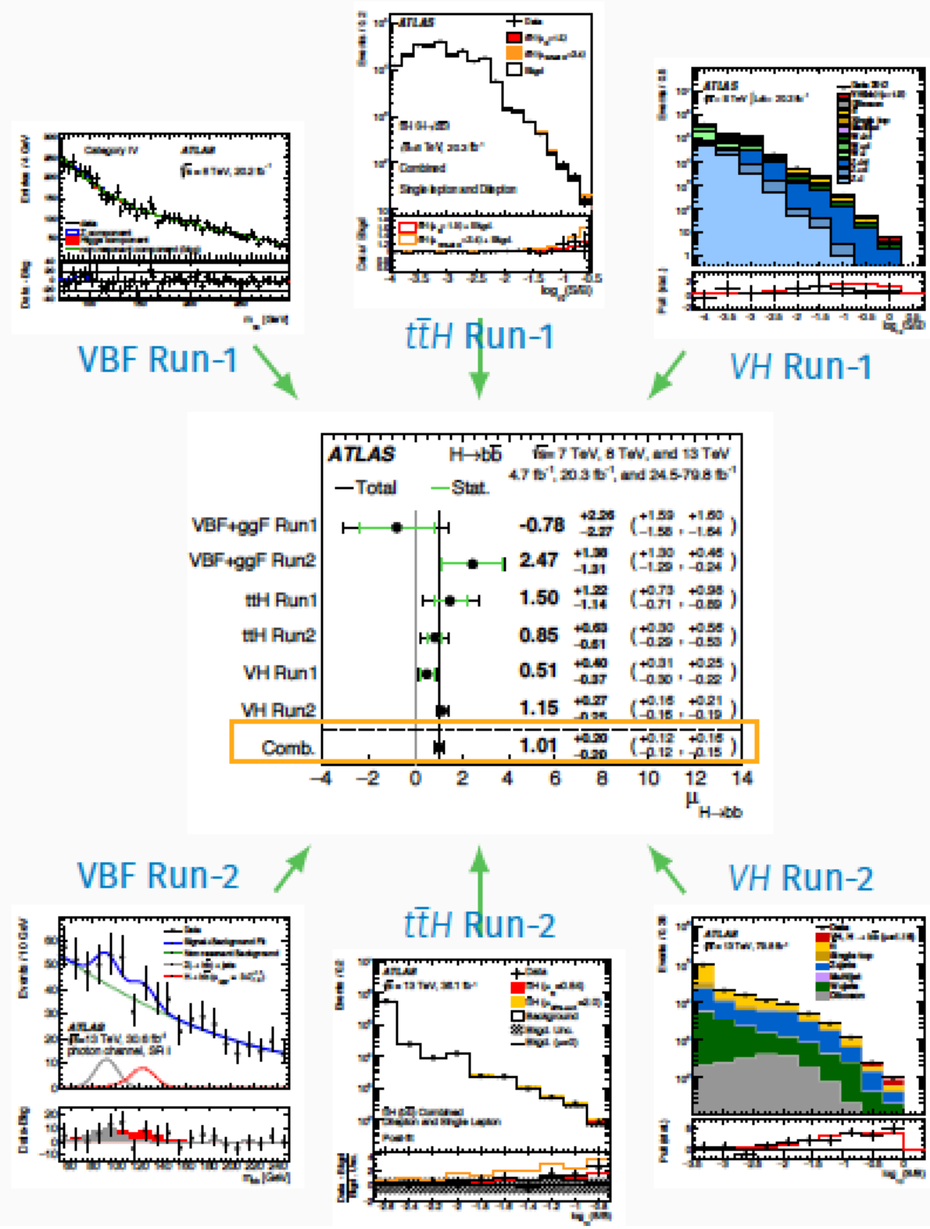
Combination of H→bb searches by ATLAS

$H \to b\bar{b}$ combination

- Combine Run-1 and Run-2 analyses in *VH*, VBF, $t\bar{t}H$ production modes
  - 2015+2016 Run-2 data for VBF and $t\bar{t}H$
- Uncertainty model from previous Run-1 and Run-2 combinations
- Results assume SM Higgs boson production cross-sections

Results

- Observation of $H \to b\bar{b}$ decays at 5.4σ (5.5σ exp.)
- $\mu_{H\to bb} = 1.01 \pm 0.20$
- Contributions of VBF and $t\bar{t}H$ channels 1.5σ and 1.9σ
- Compatibility of the 6 measurements 54%



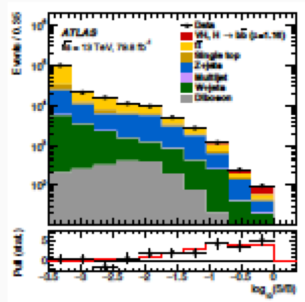
Combination of VH searches by ATLAS

VH combination

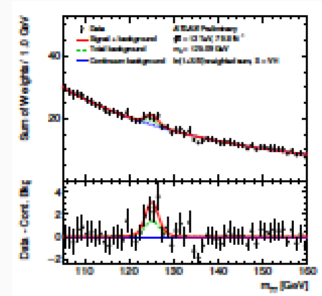
- Combine Run-2 analyses in $b\bar{b}$, $\gamma\gamma$ and 4ℓ decays
  - Updated analyses with 2015-2017 Run-2 data in all channels
- Results assume SM Higgs boson branching fractions

Results

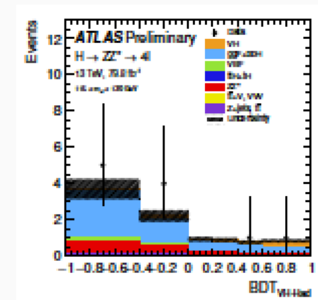
- Observation of *VH* production at 5.3σ (4.8σ exp.)
- $\mu_{VH} = 1.13 \pm 0.24$
- Contributions of 4ℓ and $\gamma\gamma$ channels 1.1σ and 1.9σ
- Compatibility of the 3 measurements 96%



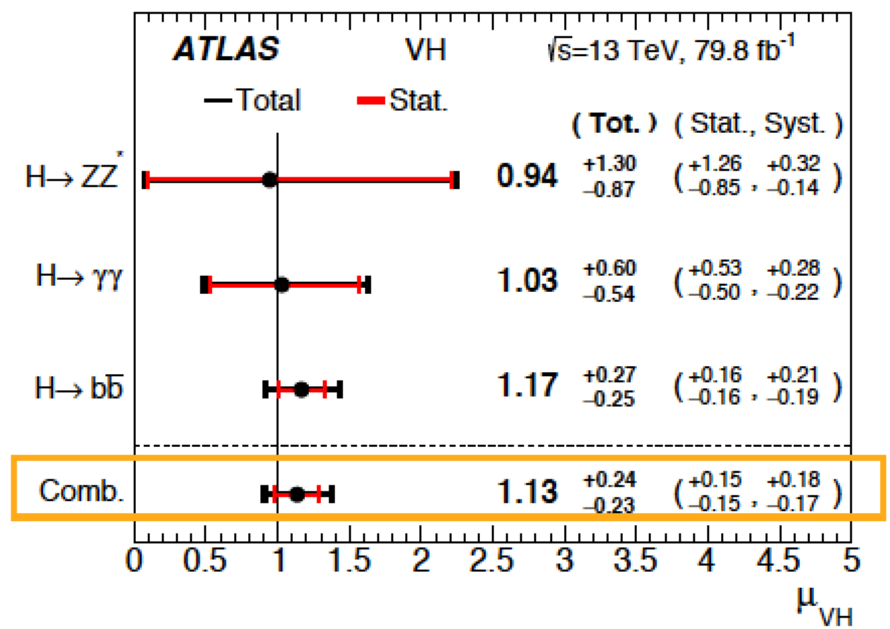
$H \rightarrow b\bar{b}$



$H \rightarrow \gamma\gamma$



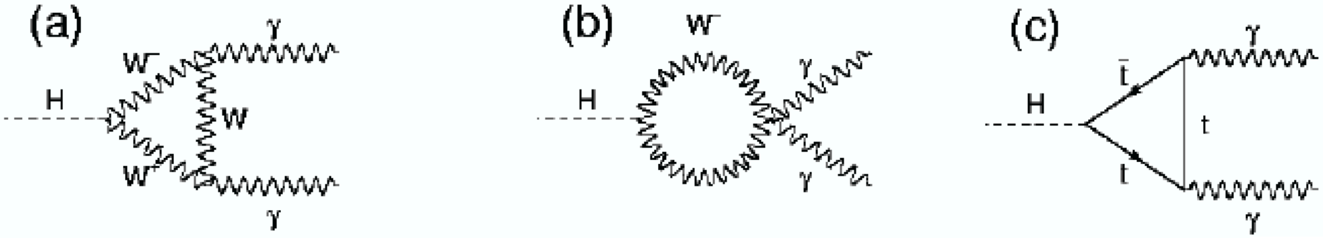
$H \rightarrow 4\ell$



$H \rightarrow \gamma\gamma$

H→γγ

CMS-HIG-16-040 (arXiv:1804.02716)
CMS-PAS-HIG-17-015
ATLAS-2016-21 (arXiv:1802.04146)



Indirect probe of coupling through production loops

- Sensitive to vector/fermion couplings (k_V, k_F)
- Can test NP in the loops

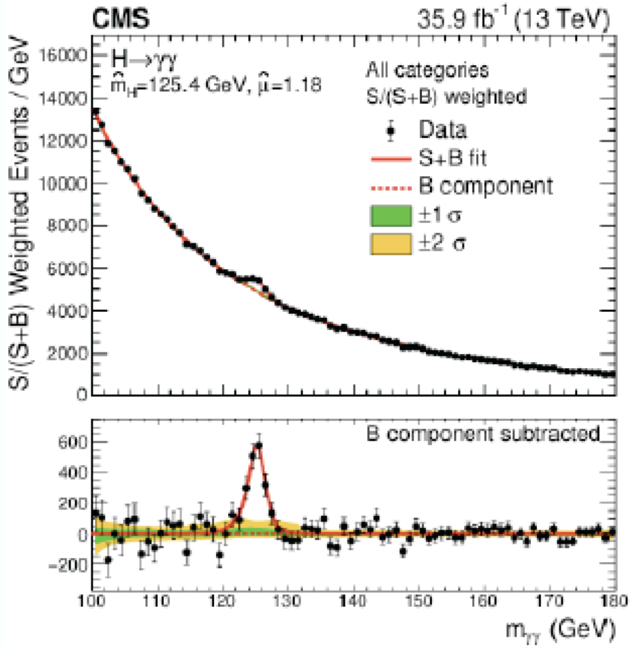
Search strategy: peak over (abundant) and regular background

Observed width dominated by detector resolution

Efficient selection (40%)

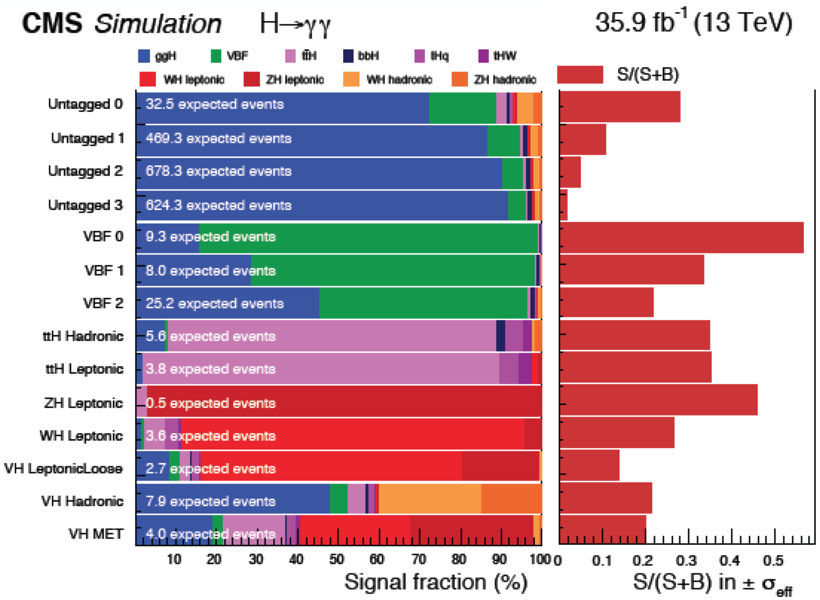
- Trigger, photon ID, E_T, isolation,…
- Abundant number of selected events allows for a large number of categories→sensitivity to different production/decay modes

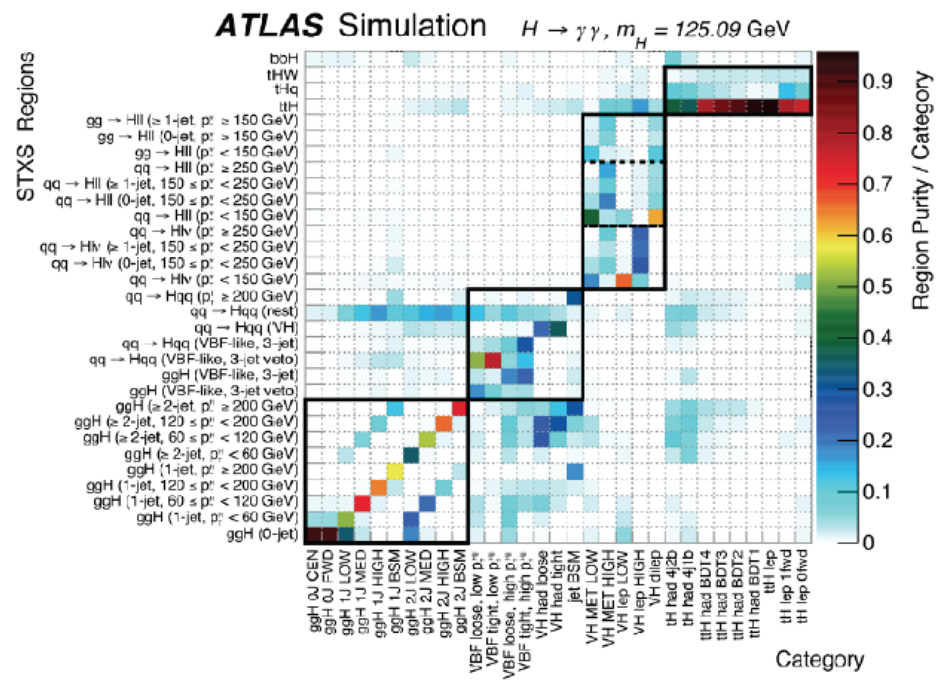
Main uncertainties: photon ID/resolution, luminosity, statistical uncertainty still the largest factor



H→γγ: categorization

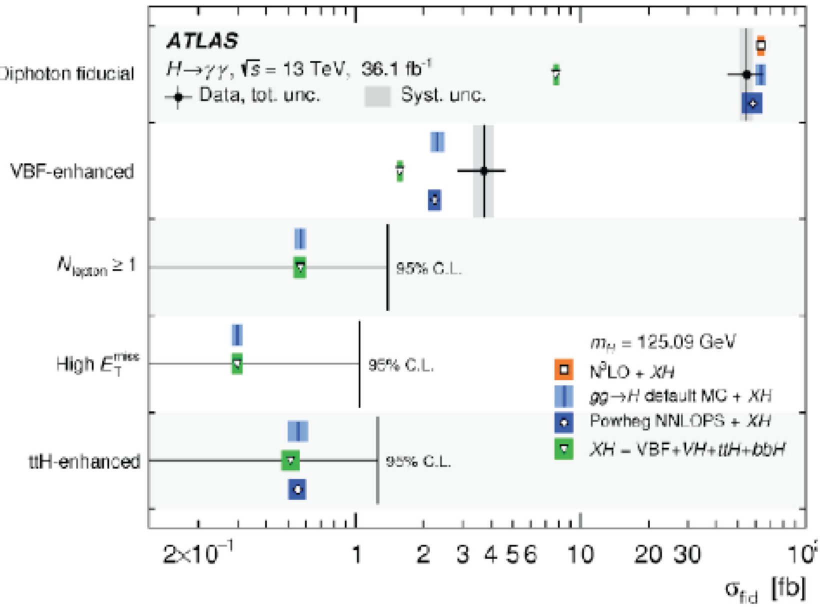
Vertex+photonID+kinematic BDT to select and classify the events
Large number of categories, with different S/B ratios and sensitive to different production modes
- Can be tuned to increase sensitivity to the STXS scheme (ATLAS)

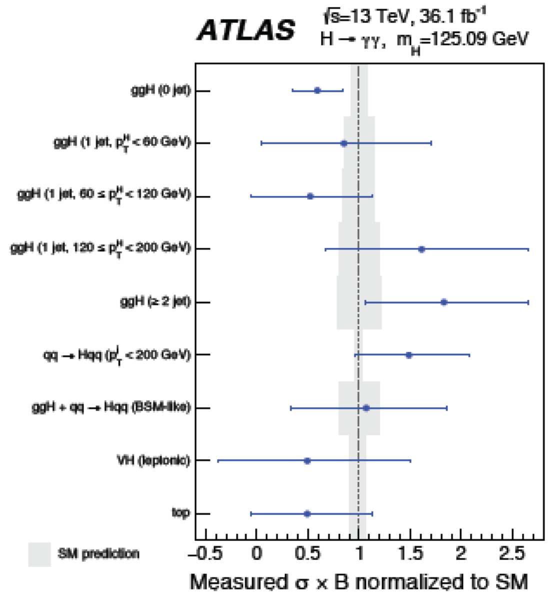


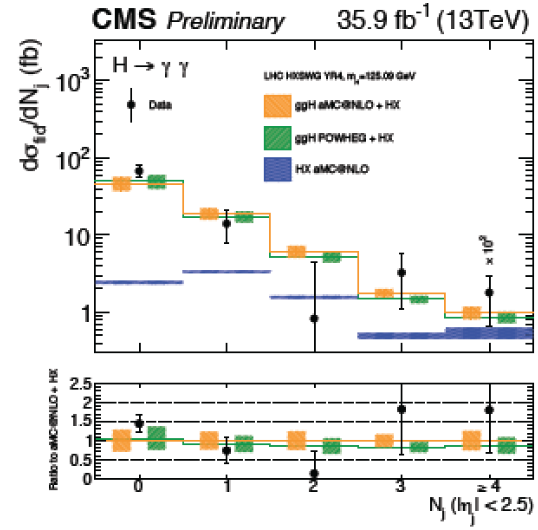


H→γγ: cross section

CMS-PAS-HIG-17-015
ATLAS-2016-21 (arXiv:1802.04146)







Both fiducial (inclusive) cross section, STXS, and differential distributions show good agreement with theoretical predictions

Experimental uncertainties are comparable to theoretical ones in the most populated bins (low p_T, low N_{jets})

Differential cross-section as a function of $p_T(H)$, N_{jet}, y_H, $\cos\vartheta^*$ (see backup)

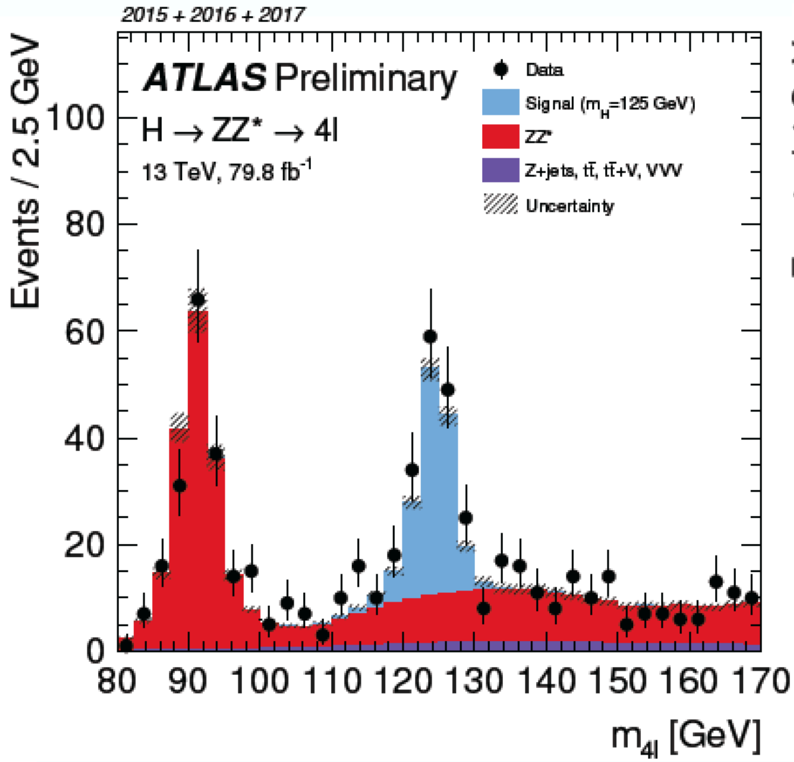
ATLAS: EFT reinterpretation to probe anomalous couplings

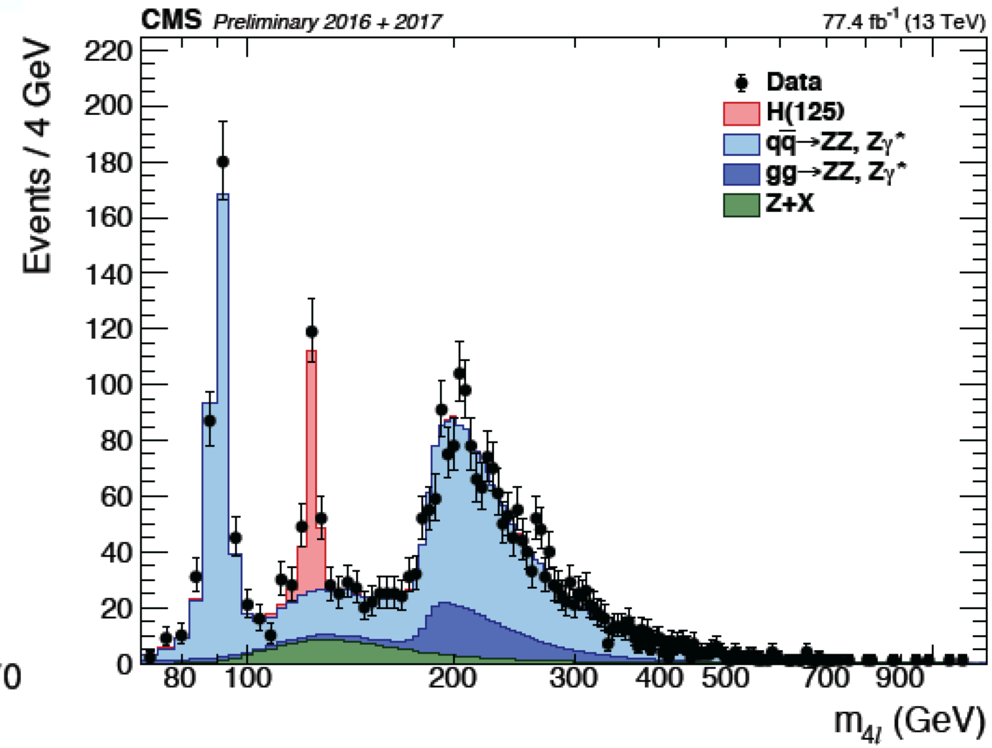
$H \to ZZ$

H→ZZ→4l

CMS-PAS-HIG-18-001 JHEP 03 (2018) 095
Phys. Lett. B 775 (2017) 1 ATLAS-CONF-2018-018

Low signal rate, but very clear signal topology over a small, flat background (mainly qqZZ, Z+jets)
- 4 isolated leptons in final state combined in 2 Z pairs
- Kinematical information (matrix element KD discriminants) or BDT techniques to separate signal and background and categorise events





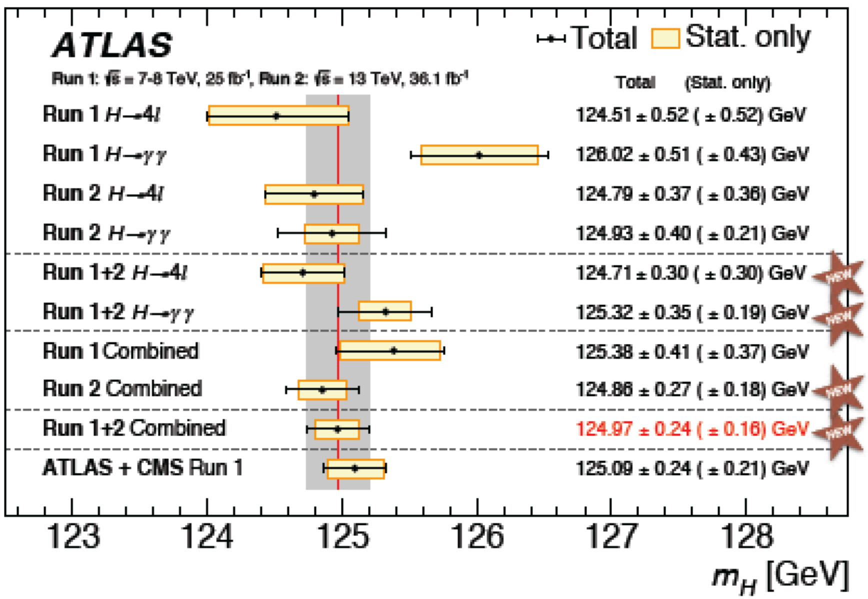
Analysis is still being improved:
- Improved event categorisation to target VH and ttH productions
- CMS: dedicated discriminants to target different production modes (ggH, VBF, VH)

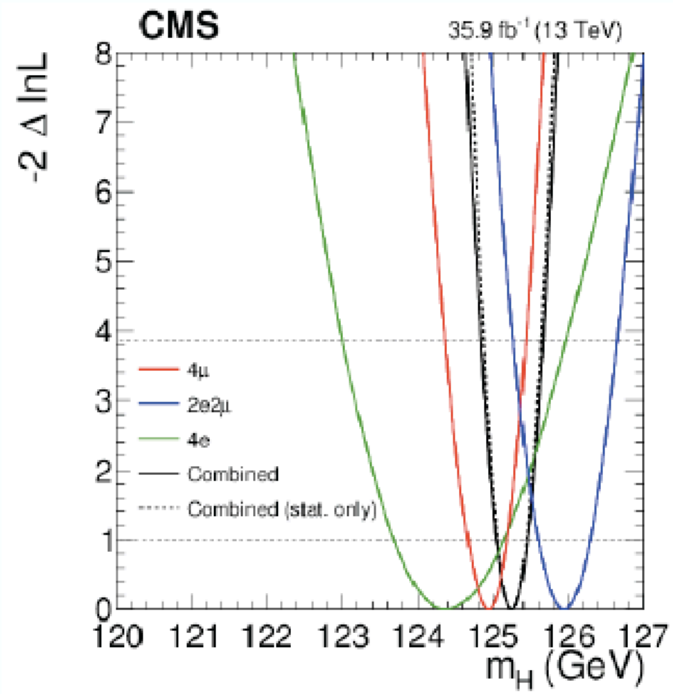
H→ZZ→4l + H→γγ: mass measurement

CMS-PAS-HIG-16-041
arXiv:1806.00242

H→ZZ→4l and H→**γγ** are the final states with the highest precision for the mass measurement

ATLAS performed the combined measurement of the Run1 and Run2 (2015+2016) H→ZZ→4l and H→**γγ** mass measurements, m_H = 124.97±0.24 GeV



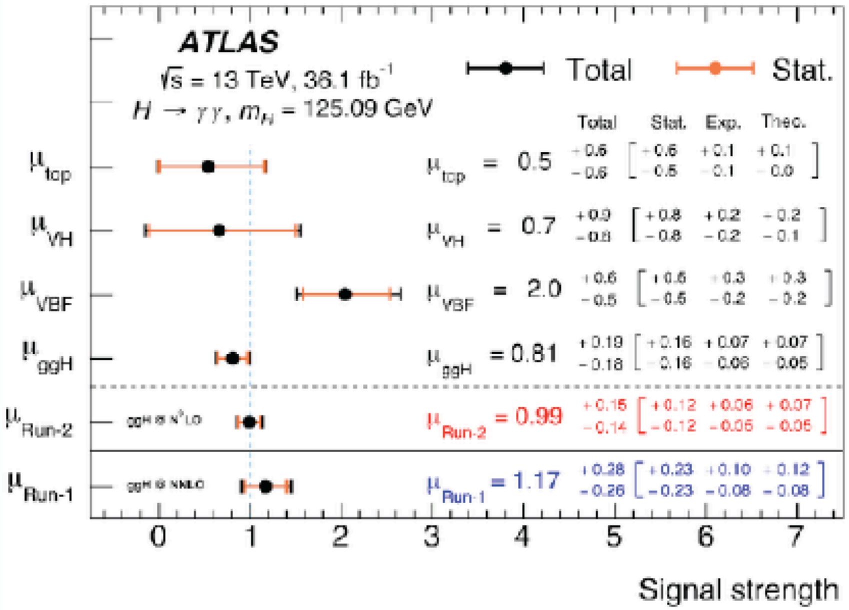


Most precise measurement at the moment comes from CMS H→ZZ→4l mass measurement with 2016 data m_H = 125.26±0.21 GeV

H→ZZ→4l + H→γγ: signal strength

H→γγ

$\widehat{\mu}_{CMS} = 1.18^{+0.17}_{-0.14} = 1.18\ ^{+0.12}_{-0.11}\,(\text{stat})^{+0.09}_{-0.07}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{theo})$



Very good agreement between measurements and with expectations.
Run1: ATLAS excess, CMS deficit

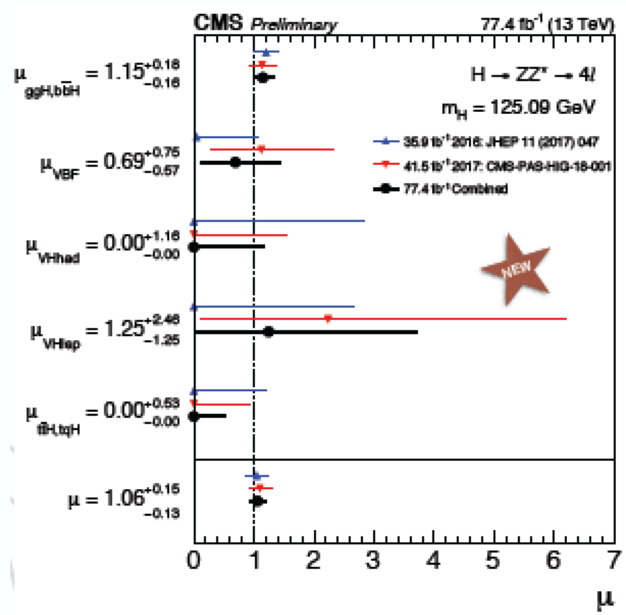
25% improvement on Run1 combination

H→ZZ→4l

ATLAS 2015+2016+2017:

$\mu = 1.20 \pm 0.12(\text{stat.}) \pm 0.06(\text{exp.})^{+0.08}_{-0.07}(\text{th.})$
$= 1.20^{+0.16}_{-0.15}.$

NEW



$H \rightarrow \tau^+\tau^-$

$H \rightarrow \tau^+\tau^-$

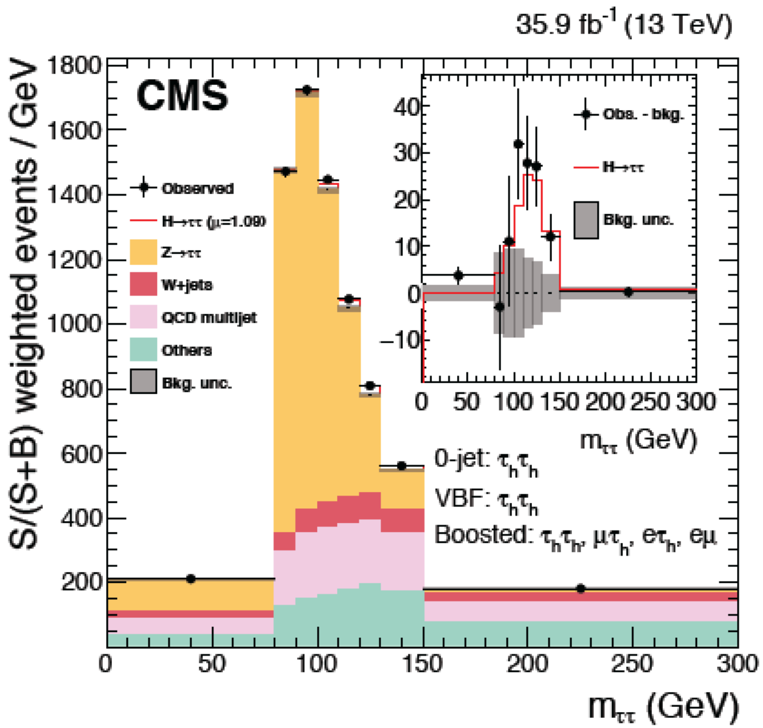
- Higgs boson in ττ decay mode is the most promising channel to explore the Higgs Yukawa coupling to fermions (decay rate to ττ is less than bb, but this channel has much less background)
- Analyzing Run1 data, in 4 production modes led to the first evidence of Higgs coupling to fermions

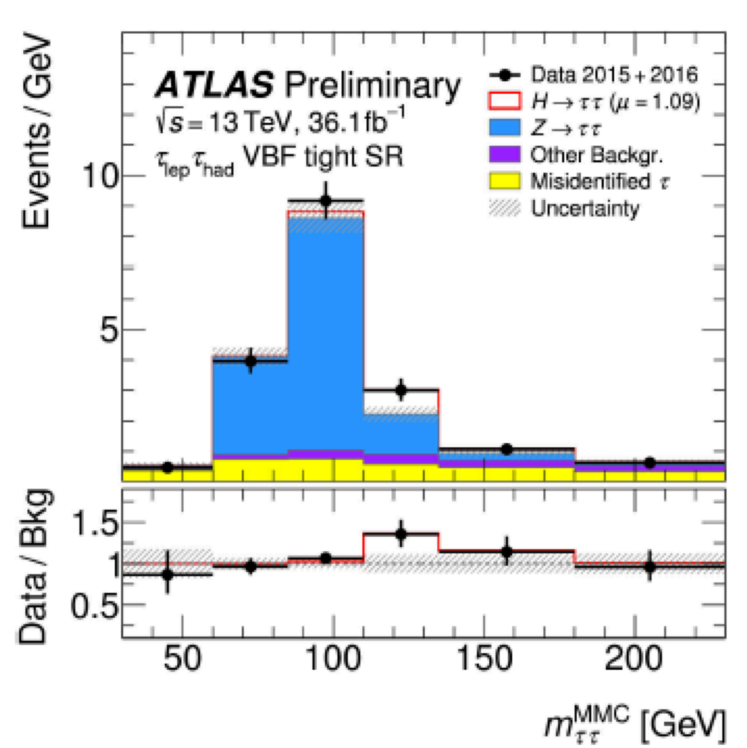
Date	Experiment	Result	Significance Obs. (Exp.) [σ]	Reference
May 2014	CMS	evidence	3.2 (3.7)	JHEP05(2014)104
April 2015	ATLAS	evidence	4.5 (3.4)	JHEP04(2015)117
August 2016	ATLAS+CMS	observation	5.5 (5.0)	JHEP08(2016)045
April 2018	CMS	observation	5.9 (5.9)	Phys.Lett. B779 (2018) 283-316
June 2018	ATLAS	observation	6.4 (5.4)	ATLAS-CONF-2018-021

$H \rightarrow \tau^+\tau^-$

CMS: Event categorization changed in Run2

- 4 different final states (based on tau decays)
- 3 main categories (mainly) based on the n. jet
- events split depending on tau decay modes/muon p_T (in 0jet), p_T of the Higgs boson(in boosted) and mass of the two forward jets(in VBF mode)





$\tau_{lep}\tau_{had}$ VBF

√s (TeV)	7, 8	13	Combined
Observed (σ)	4.5	4.4	6.4
Expected (σ)	3.4	4.1	5.4

Combining 2016 data with Run1 → 5.9 σ

PLB 779 (2018) 283

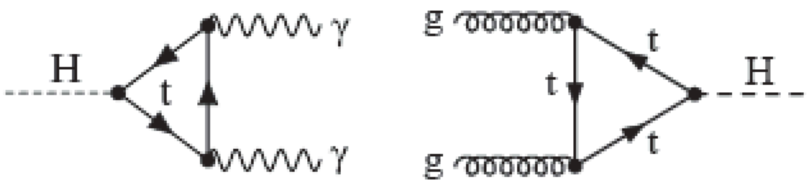
The first observation of the Higgs coupling to tau leptons in a single experiment

ttH

ttH

Motivation

- Provides a **direct probe** of the important top–Higgs coupling
  - Yukawa coupling $y_t \sim 1$
  - Indirect loop measurements can be influenced by BSM physics



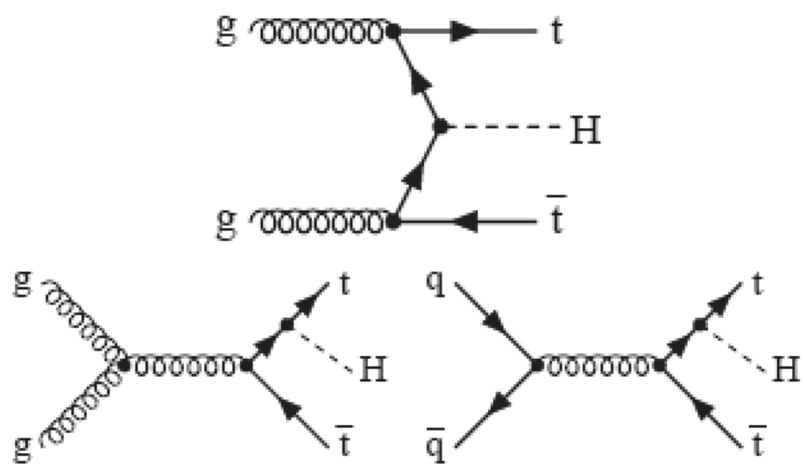
- First measurement of Higgs coupling to up-type fermion
- Non-SM ttH rate could indicate presence of new physics

Properties

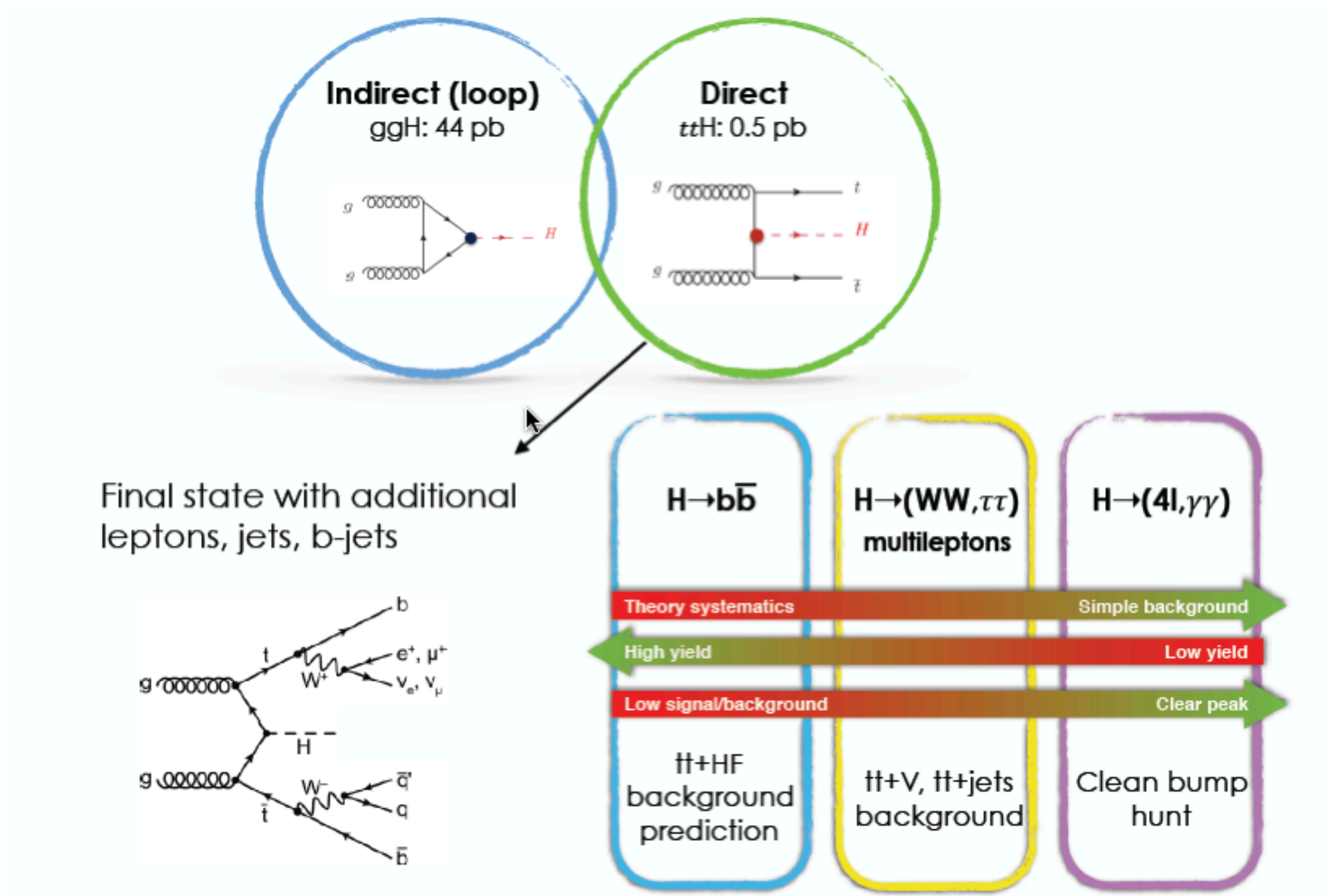
CERN-2017-002-M

LHC Higgs Cross Section WG Report 4

- Xsec: 0.5071 pb +6.8/−9.9%
  - NLO QCD and NLO EW accuracy
- **Expect ~18,000 SM ttH events** in 2016 data at CMS
  - ~ 36 fb^{-1}
- LO Feynman diagrams:



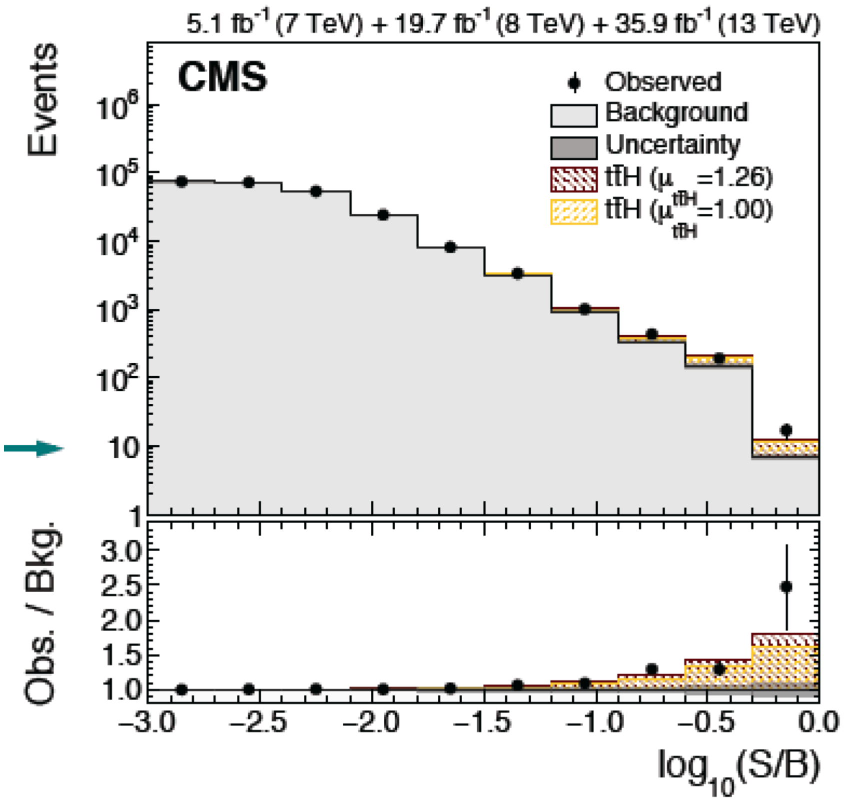
ttH observation

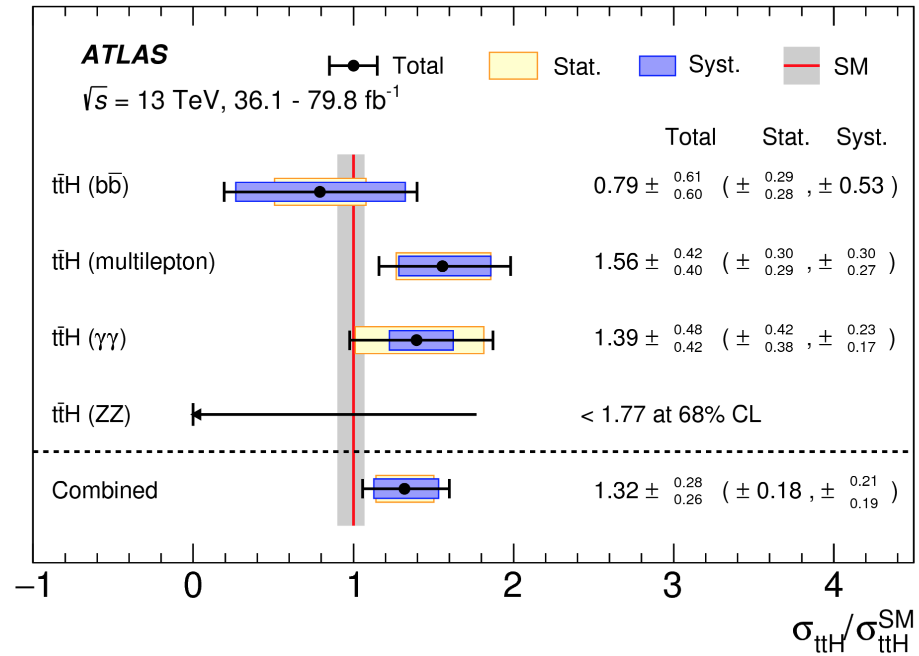


ttH

Decay channels analysed:
Fermions: H→bb H→ττ
Bosons: H→WW H→ZZ H→γγ

CMS Phys. Rev. Lett. 120, 231801 (2018)
ATLAS arxiv:1806.00425



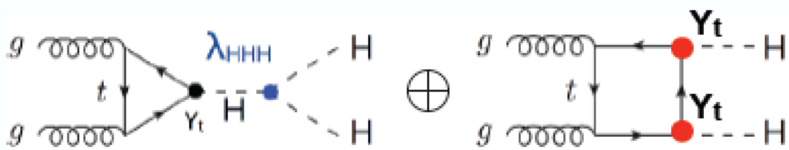


CMS Run 2 (2016)	**4.5σ obs.** (4.1σ exp.)
ATLAS Run 2 (2015-2016)	**4.2σ obs.** (3.8σ exp.)
ATLAS Run 2 (2015-2017)	**5.8σ obs.** (4.9σ exp.)
CMS Run 1 + Run 2 (2016)	**5.2σ obs.** (4.2σ exp.)
ATLAS Run 1 + Run 2 (2015-2017)	**6.3σ obs.** (5.1σ exp.)

- First observation of tree-level Higgs–top coupling
- Consistent with standard model Higgs within 1 sigma

Double Higgs production

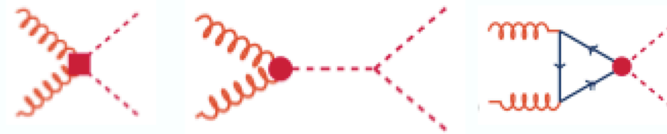
Main probe for trilinear Higgs coupling λ_{HHH}. Diagrams interfere destructively in SM



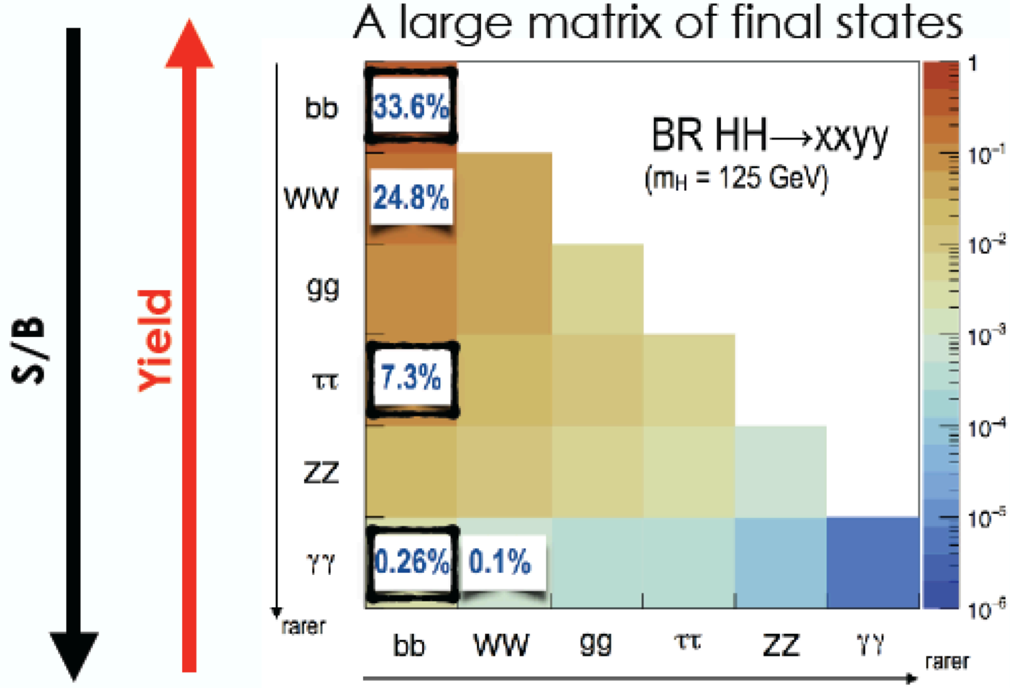
$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, HXSWG, arXiv:1610.07922]

sensitive to possible BSM contributions



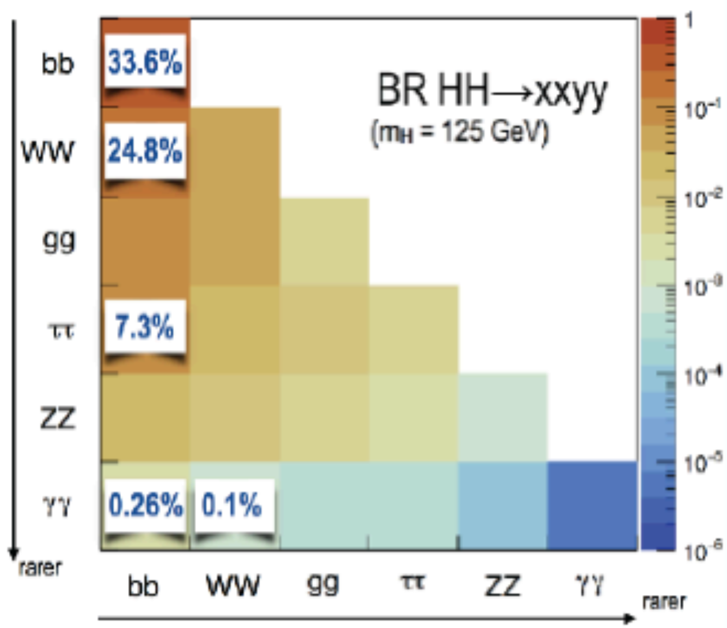
A large matrix of final states



bbbb largest statistics

bb(γγ,ττ) good compromise between statistics and S/B

Double Higgs production



σ/σ_{SM} 95% CL (exp)

	ATLAS	CMS
bbbb	<29 (38)	<342 (308)
bbWW		<79 (89)
bbττ		<28 (25)
bbγγ	<117 (161)	<19 (17)
WWγγ	<747 (386)	

Run2 | 3 fb^{-1} | 13 fb^{-1} | 36 fb^{-1}

NEW

Reaching ~ O(10) xSM sensitivity

Will require full HL-LHC statistics to approach SM sensitivity

Conclusions – lecture 1

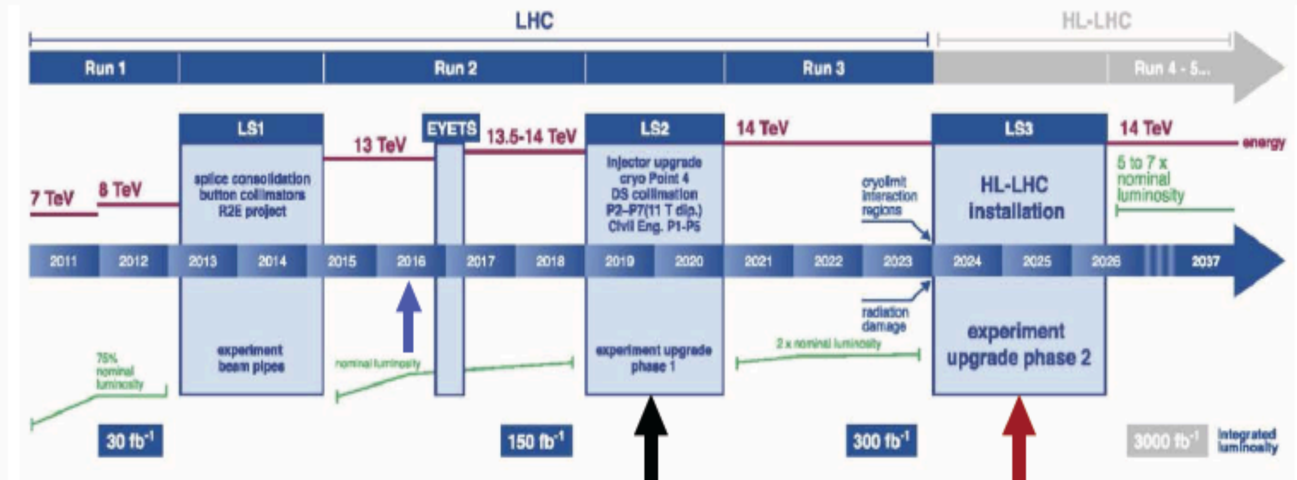
- Highlights:
  - CMS/ATLAS reached **> 5σ** observation of the **H→bb** decays
  - New mass measurement combining H→ZZ→4l and H→γγ in both Run1 and Run2 →towards the measurement of **differential distributions** and crosssections
  - First observation of tree-level Higgs–top coupling with **ttH** events (Run1 + Run2 data)
  - The first observation of the Higgs coupling to **tau** leptons in a single experiment using 2016 and Run1 data

Exiting Higgs Physics so far and in the future

Lecture 2

LHC and HL-LHC

- LHC
  - 300 fb^{-1} by 2023
    - 30 fb^{-1} Run 1
    - >100 fb^{-1} so far
    - ...
- HL-LHC
  - ~3000 fb^{-1} by ~2035



LS2 (2019-2020):
- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment @ P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

ATLAS, CMS Upgrade plan

8×10^{33} Hz/cm^2
30 fb^{-1}
PU ~40

LS1

2×10^{34} Hz/cm^2
300 fb^{-1}
PU ~50

Phase 1 Upgrade

5×10^{34} Hz/cm^2
3000 fb^{-1}
PU ~140

LS3

Phase 2 Upgrade

Phase II upgrades and Higgs @ HL-LHC

Phase II Detector Upgrades:

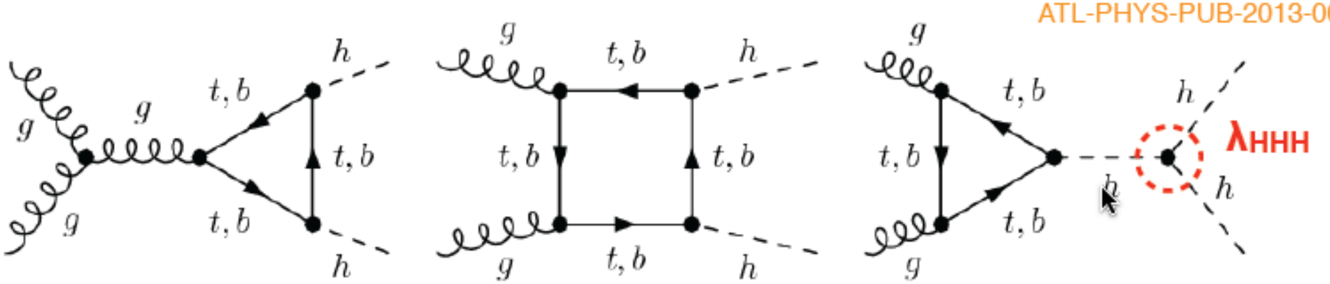
Significant upgrades of ATLAS and CMS for HL-LHC conditions

- Radiation hardness
- Mitigate physics impact of high pileup

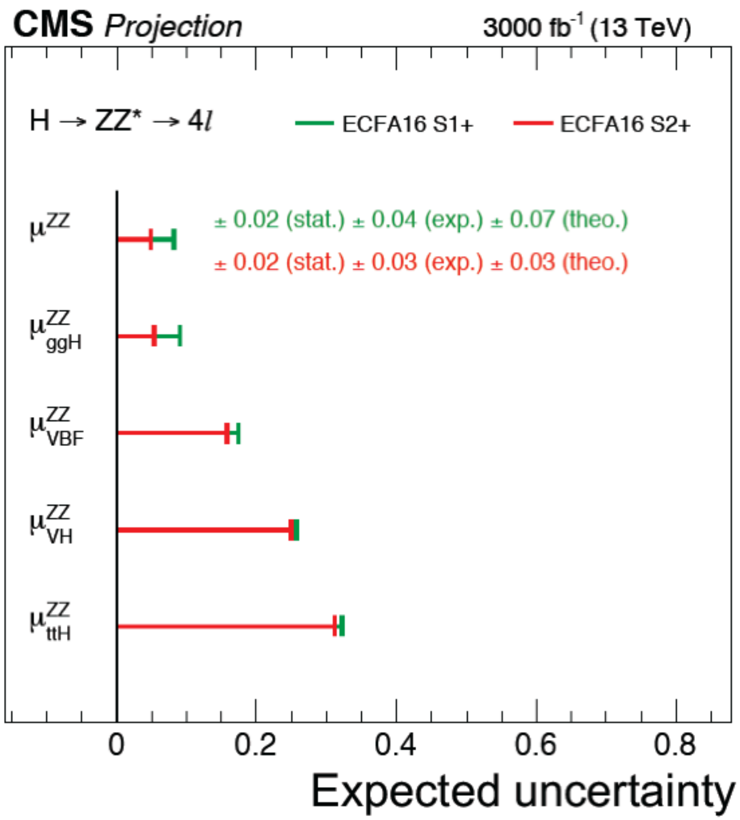
Higgs@HL-LHC:

- Precision Measurements (Couplings, Cross Sections, Width, Differential Distributions,…)
- Rare decays and couplings
- BSM Higgs searches: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings
- VV scattering
- Di-Higgs production ➜ self coupling

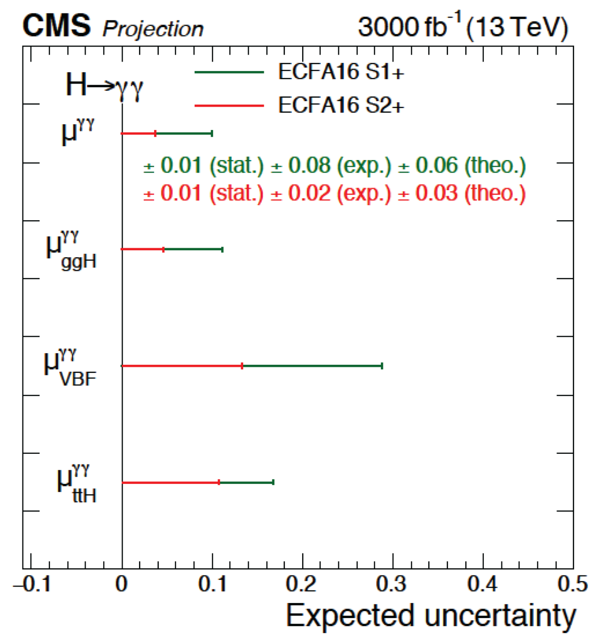
ATL-PHYS-PUB-2013-007

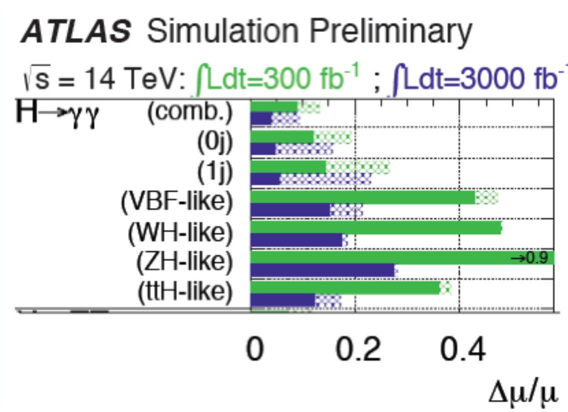


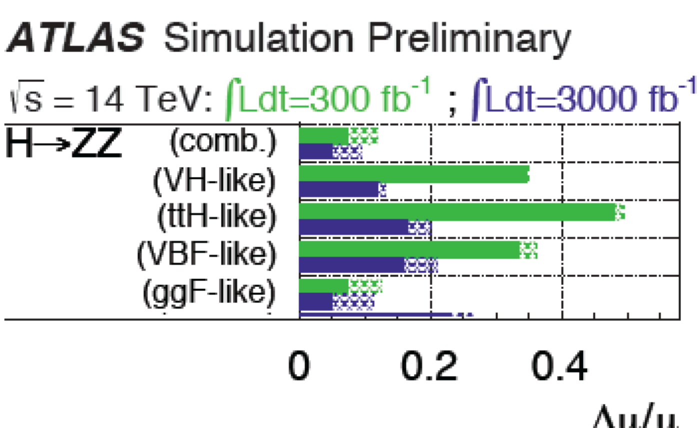
Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ – 3000 fb^{-1}



ECFA 16







- Similar expected sensitivities between the two experiments
- Precision larger than 5-10%

CMS Phase 2 upgrade

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

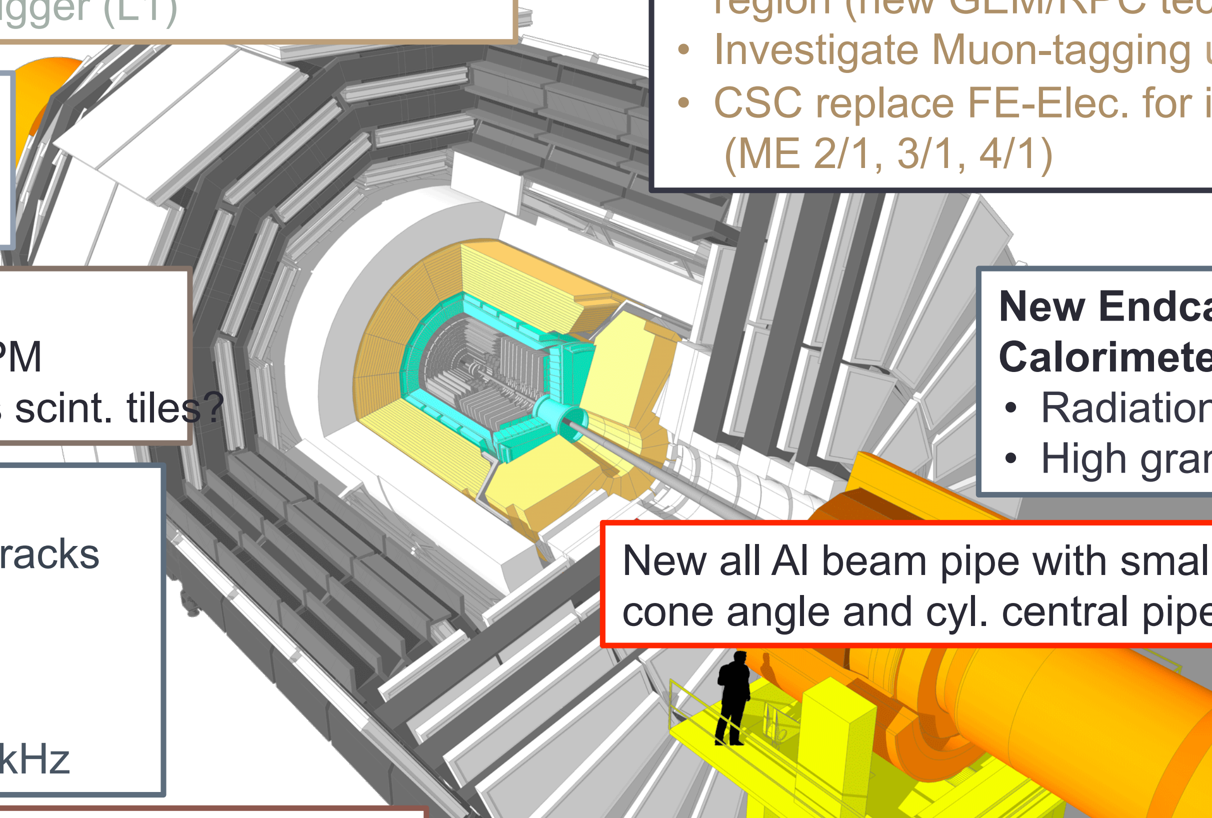
Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

Barrel HCAL
- Replace HPD by SiPM
- Replace inner layers scint. tiles?

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

Other R&D
- Fast-timing for in-time pileup suppression

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3
- CSC replace FE-Elec. for inner rings (ME 2/1, 3/1, 4/1)



New Endcap Calorimeters
- Radiation tolerant
- High granularity

New all Al beam pipe with smaller cone angle and cyl. central pipe

Modeling the projections for HL-LHC: ECFA 16

Snowmass '13, ECFA '13, ECFA '16

Goal to **keep** the current performance with the detector and software upgrades

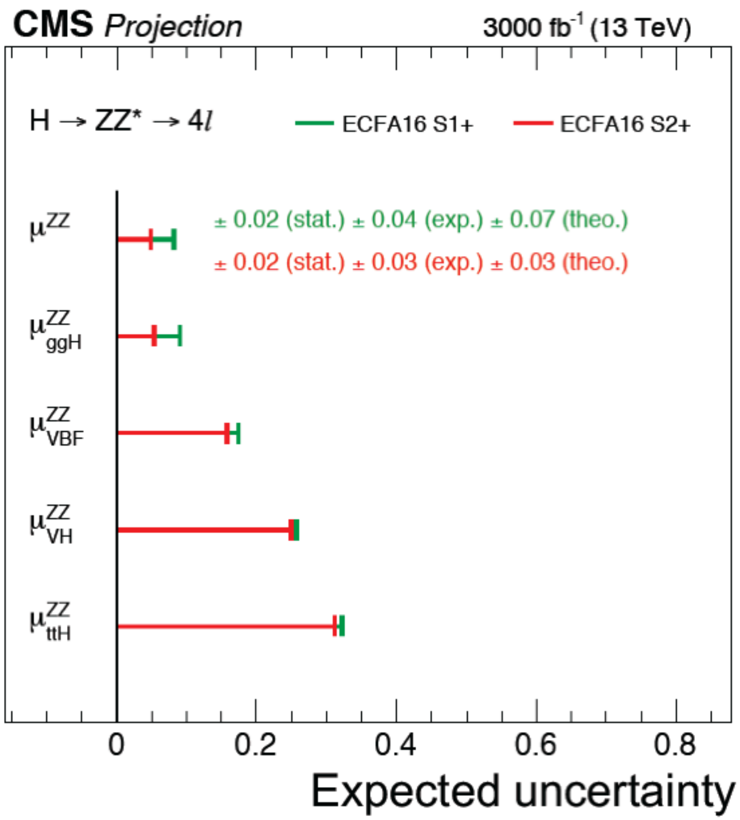
ATLAS:

- parametrisation of the detector response (**FAST SIMULATION**) to mimic the effects on selection efficiency and resolution, derived from:
  - full Run 2 detector simulation with pile-up up to $\langle\mu\rangle = 69$
  - full Phase II detector options for $\langle\mu\rangle = 140, 200$ for HL-LHC
- 2 scenarios for uncertainties:
  - systematics based on Run 2, improvements from stat.
  - theory systematics scaled by 1, 0.5 or 0 factor
  - PU and detector upgrades taken into account

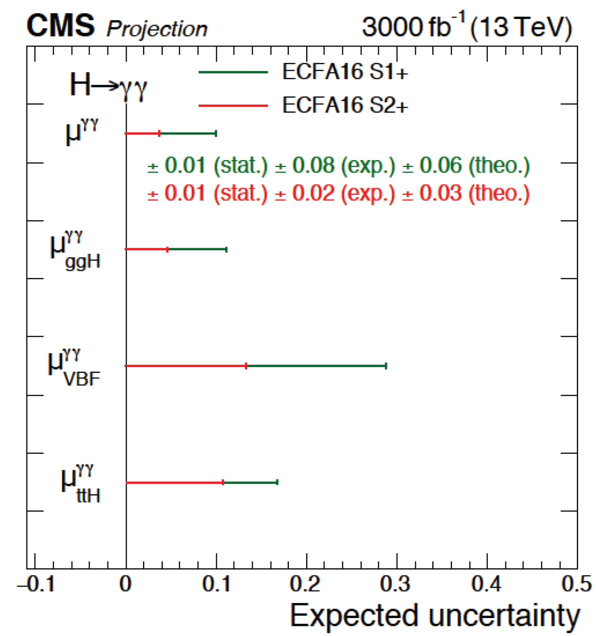
CMS:

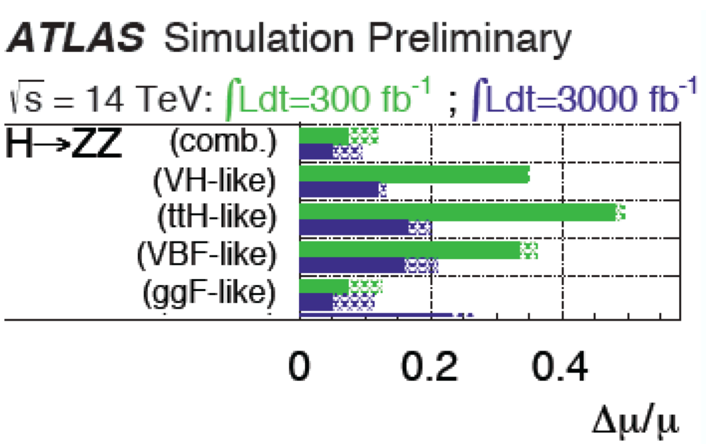
- rescaling of run 2 signal and background yields for 14 TeV with the assumption that current detector performance kept after upgrades.
- 2scenarios for uncertainties:
  - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses + PU/detector upgrades (S1+)
  - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by $1/\sqrt{L}$ + PU/detector upgrades (S2+)

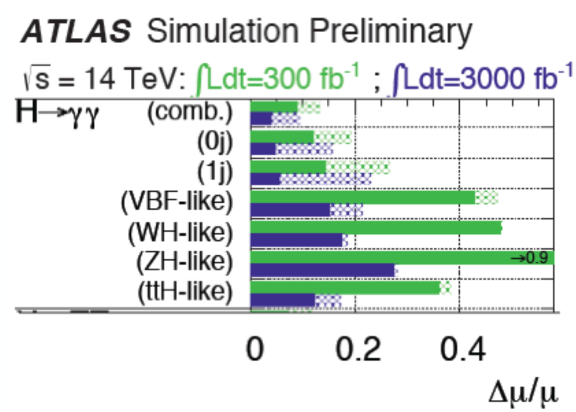
Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ - 3000 fb^{-1}



ECFA 16



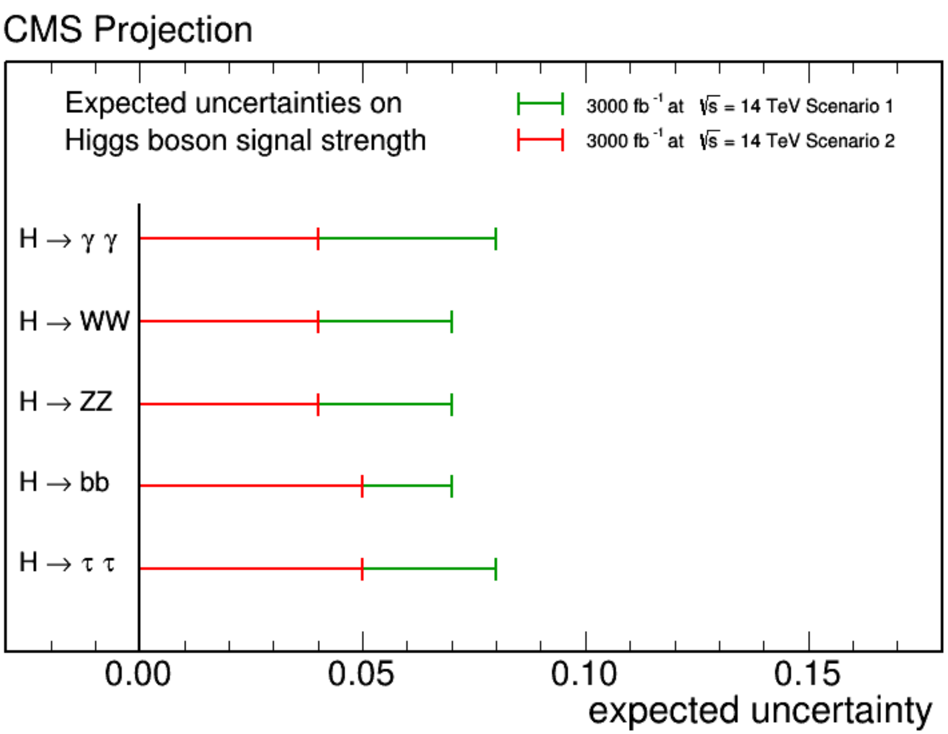


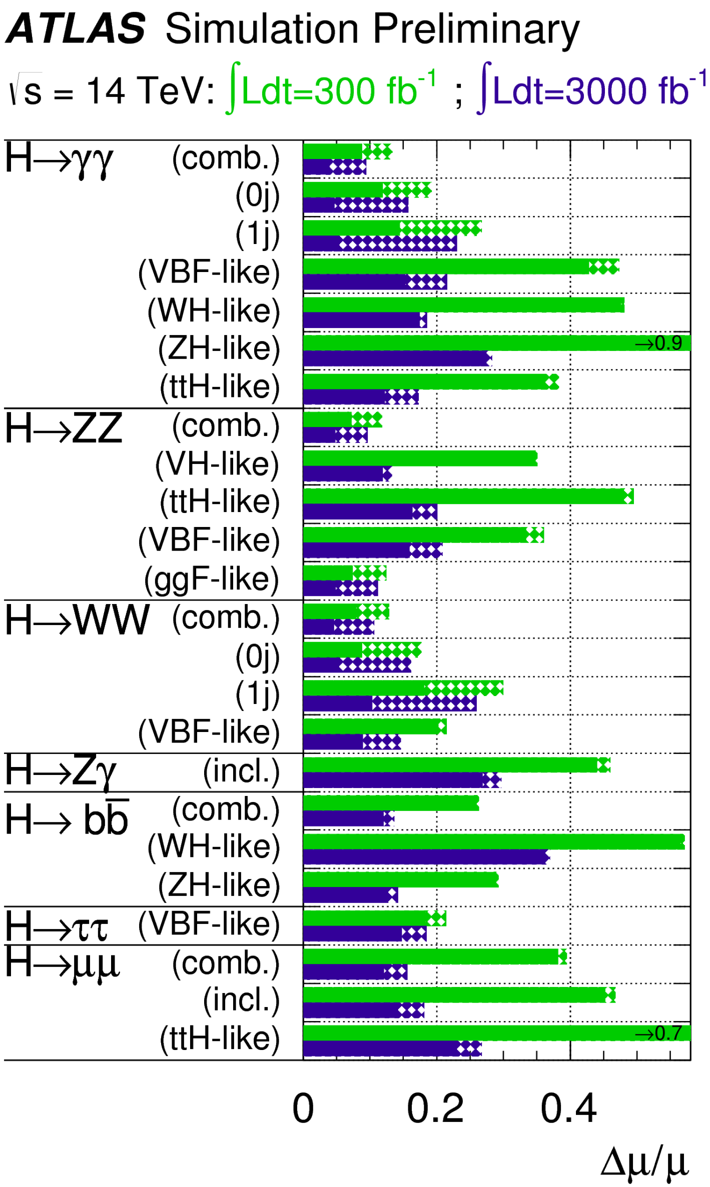


- Similar expected sensitivities between the two experiments
- Precision larger than 5-10%

Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ - 3000 fb^{-1}

Snowmass13 arXiv:1307.7135v2





- Similar expected sensitivities between the two experiments

Higgs couplings formalism

LHC Higgs Xsection WG - arXiv: 1307.1347v2

- Single resonance with mass of 125 GeV.
- Zero-width approximation

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- the tensor structure of the lagr. is the SM one → observed 0^+
- coupling scale factors K_i are defined in such a way that:
  - the cross sections σ_i and the partial decay widths Γ_i scale with K^2_i compared to the SM prediction
- deviations of K_i from unity → new physics BSM
- Results from fits to the data using the profile likelihood ratio with κ_i couplings
  - as parameters of interest or
  - as nuisance parameters, according to the measurement

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa^2_W$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa^2_Z$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa^2_b$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa^2_\tau$$

Higgs couplings formalism

arXiv:1307.1347v2

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_{(Z\gamma)} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}}$$

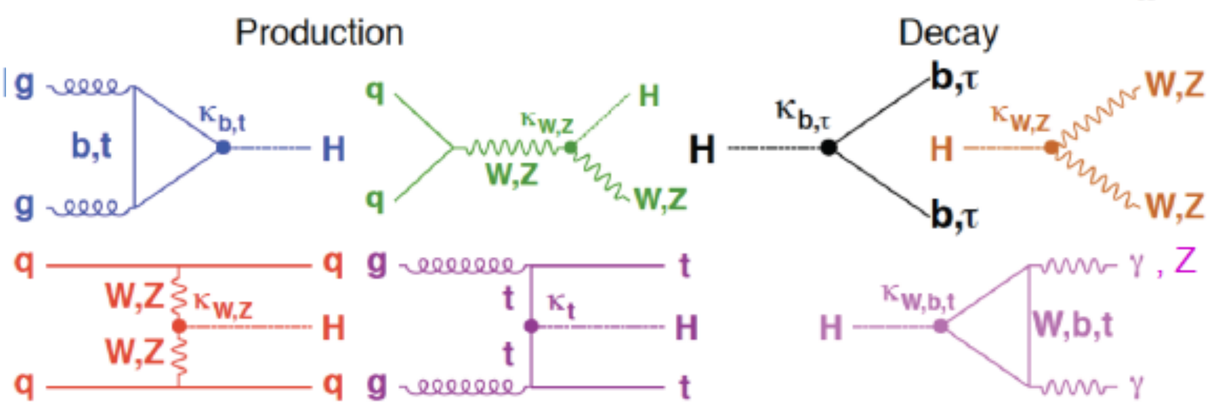
$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$



$$\Gamma_H = \Sigma_{SM}\,\Gamma_Y \quad (+\,\Gamma_{BSM})$$

Contributions from **new physics** through Γ_{BSM} and loop processes

Higgs couplings scale factors – 3000 fb^{-1}

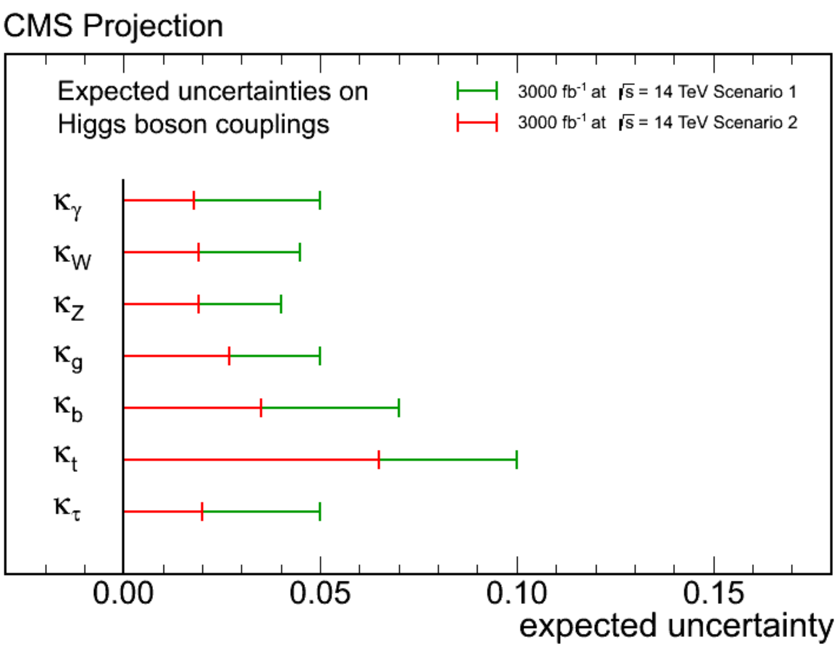
Assump. : No extra BSM Higgs decays → absolute couplings can be extracted

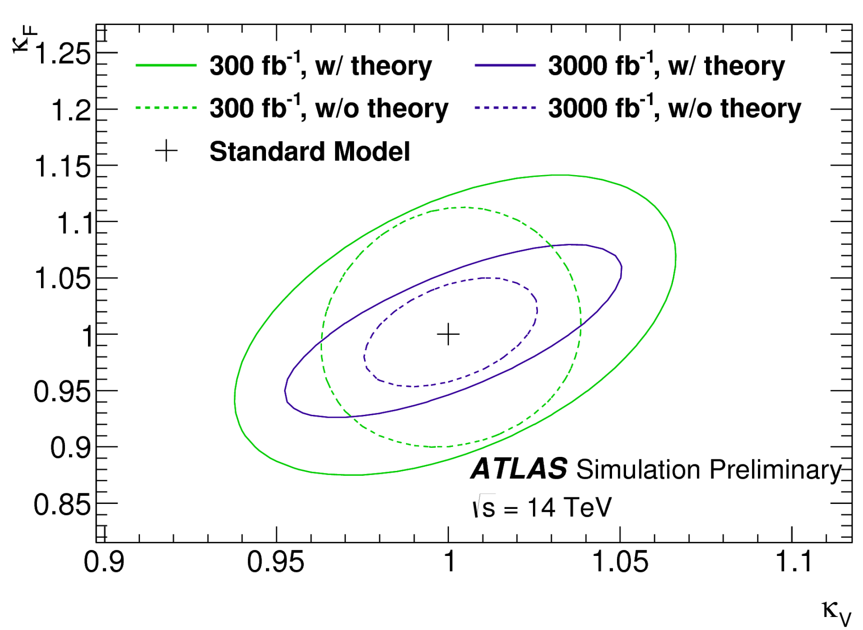
Snowmass13 arXiv:1307.7135v2

Minimal coupling fit:

$$\kappa_V = \kappa_Z = \kappa_W$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$

Full line: Scenario 1
Dotted line: Scenario 3





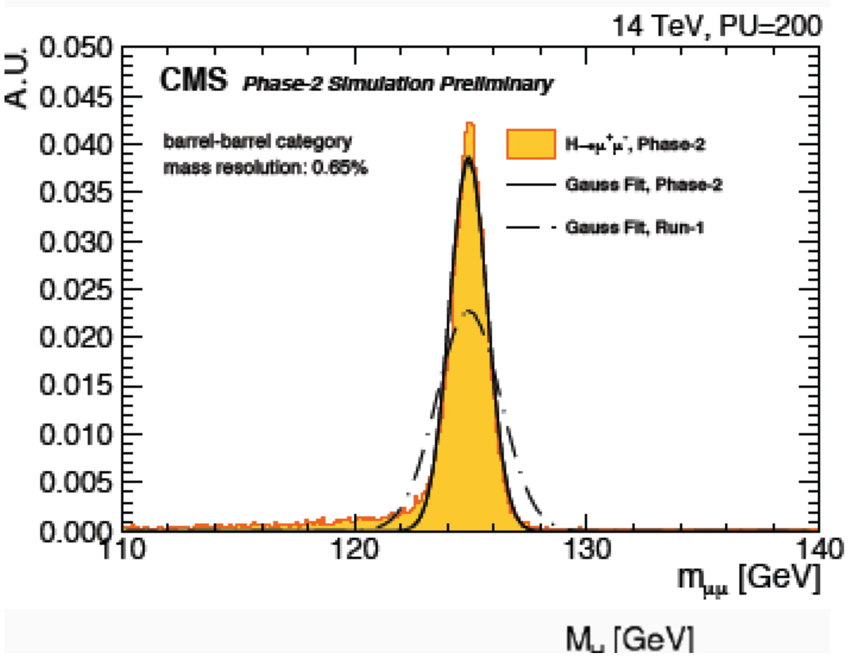
CMS: uncertainties on K_i limited by theoretical uncertainties on production and decay rates

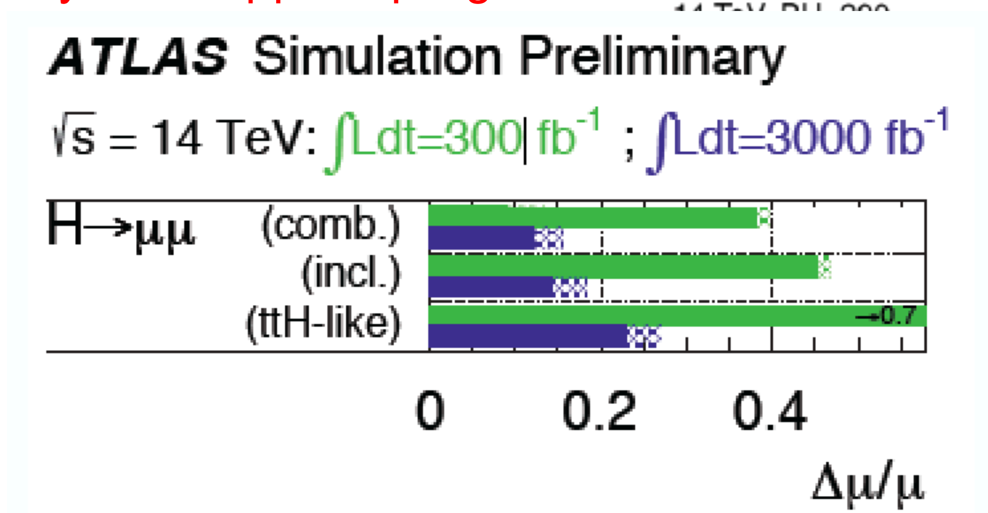
$\sigma(\kappa_V) \approx$ 3-5% $\sigma(\kappa_F) \approx$ 5-10%

ATLAS: Couplings can be determined with **5 %** precision at 3000 fb^{-1}

Rare decays: H→μμ

- **High statistics: rare decays become accessible**
  - 2 OS sign isolated muons, resonant peak at the Higgs mass, very clear signature
  - BR(H→μμ)=0.022. Only visible at HL-LHC
  - CMS projections from Run1: 16% precision on signal strength at 3000 fb^{-1}
  - With improved Phase2 detector:
    mass resolution <1%, uncertainty on H→μμ coupling <5%





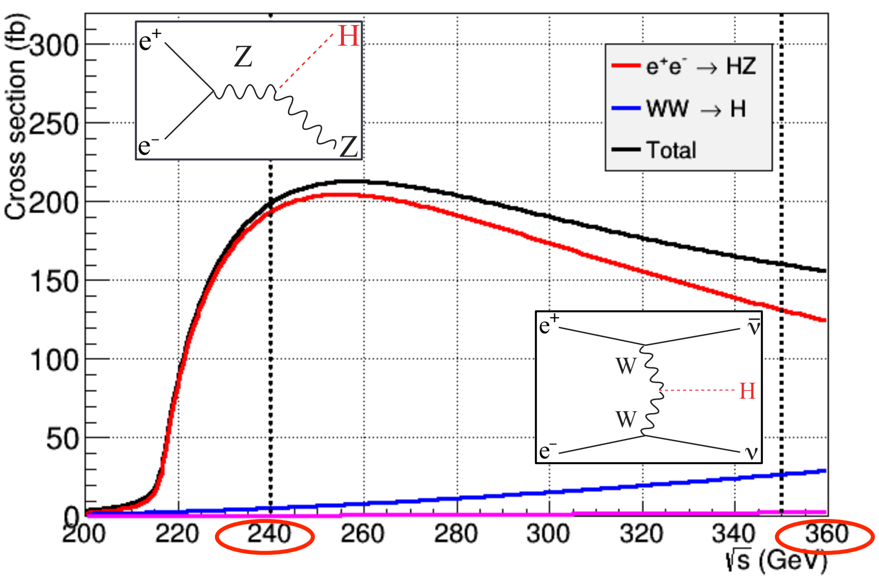
Higgs studies for FCC-ee/CepC

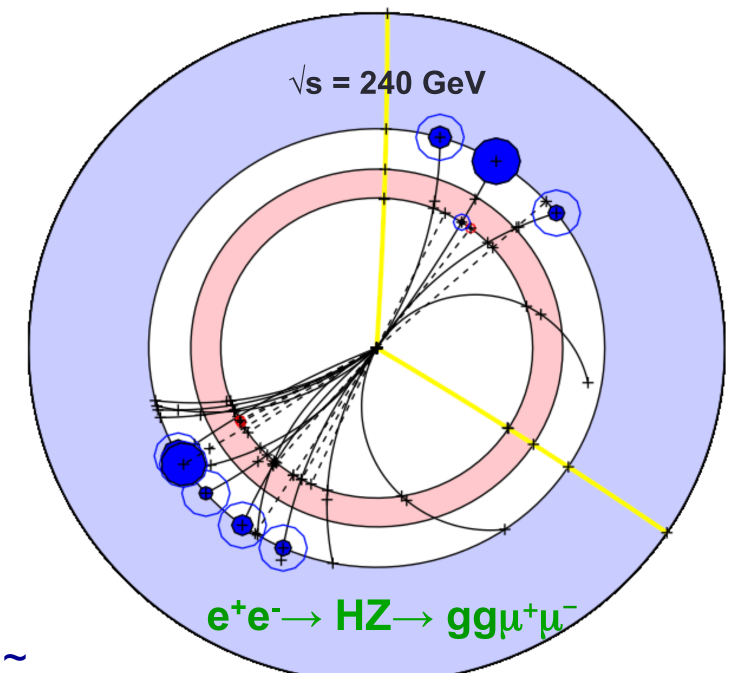
FCC-ee/CepC motivation

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be

FCC-ee/CepC: focus on a 90-250 GeV e^+e^- machine (100 km circumf.)
5 ab^{-1} integrated luminosity to two detectors over 10 years → 10^6 clean Higgs events → FCC-ee/CEPC measure the Higgs boson production cross sections and most of its properties with precisions far beyond achievable at the LHC

- Higgs-strahlung (m_H = 125 GeV)



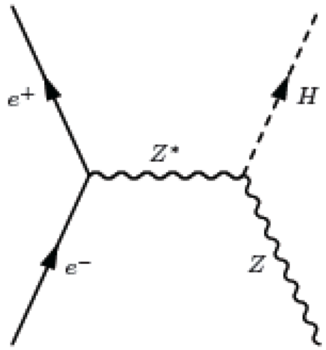


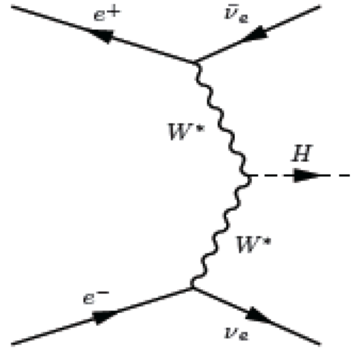
- The gluon can be studied with Higgs decays (BR ~ 10%)

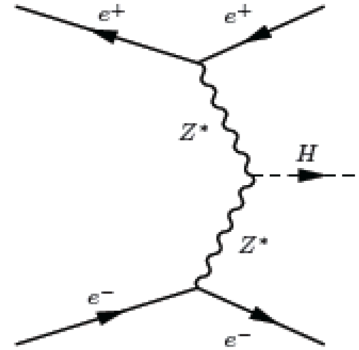
Higgs production at CepC

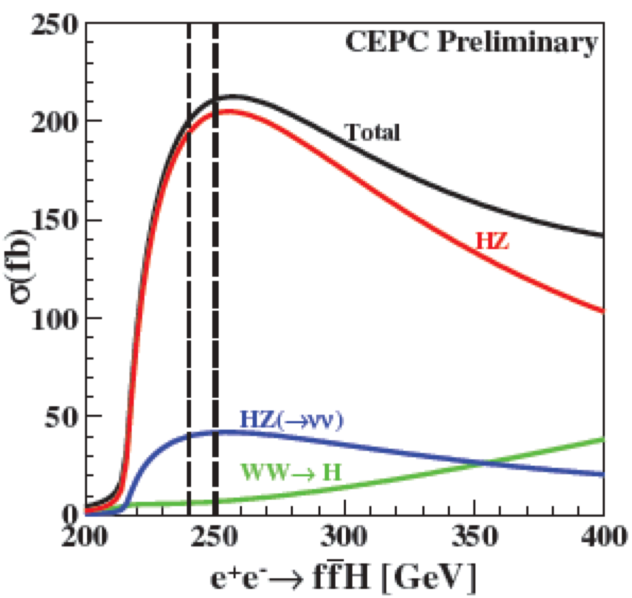
Higgs-strahlung or $e^+e^- \rightarrow ZH$

VBF production: $e^+e^- \rightarrow \nu\nu H$ (WW fus.), $e^+e^- \rightarrow He^+e^-$ (ZZ fus.)

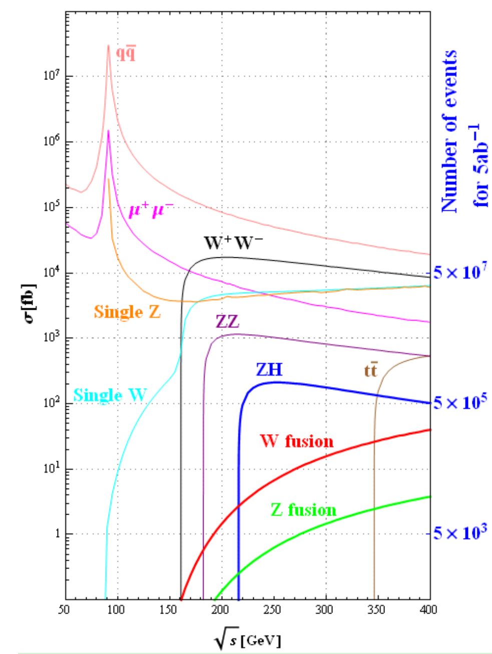




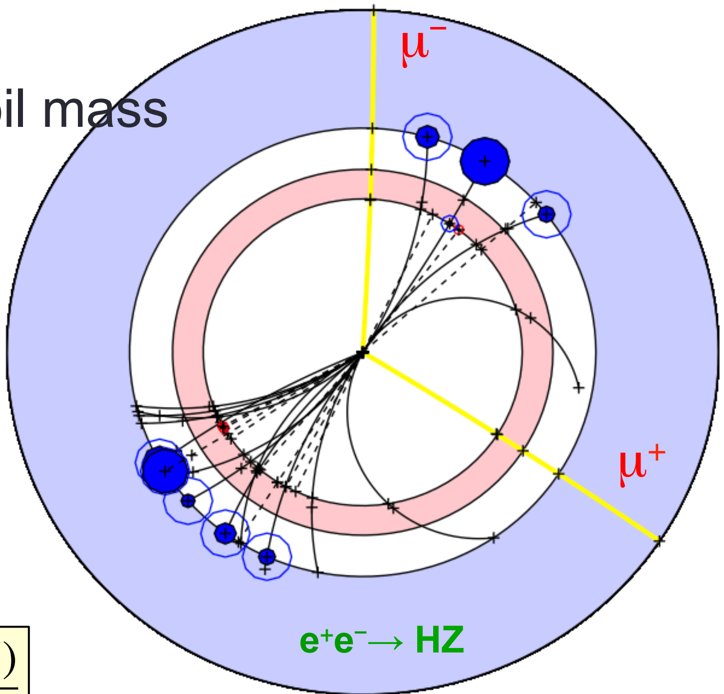




Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \rightarrow ZH$	212	1.06×10^6
$e^+e^- \rightarrow \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \rightarrow e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \rightarrow e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \rightarrow q\bar{q}$	50.2	2.5×10^8
$e^+e^- \rightarrow \mu\mu$ (or $\tau\tau$)	4.40	2.2×10^7
$e^+e^- \rightarrow WW$	15.4	7.7×10^7
$e^+e^- \rightarrow ZZ$	1.03	5.2×10^6
$e^+e^- \rightarrow eeZ$	4.73	2.4×10^7
$e^+e^- \rightarrow e\nu W$	5.14	2.6×10^7



FCC-ee/CepC Higgs factory: √s = 240 GeV



Model-independent precision measurements

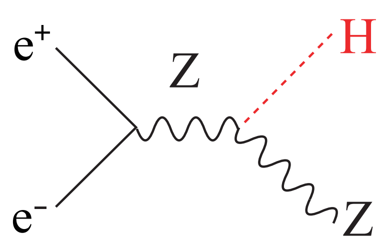
- A Higgs boson is tagged by a Z and the recoil mass

$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

  - Measure $\sigma(e^+e^- \to HZ)$
  - Deduce g_{HZZ} coupling
  - Infer $\Gamma(H \to ZZ)$
  - Select events with $H \to ZZ^*$
  - Measure $\sigma(e^+e^- \to HZ$, with $H \to ZZ^*)$

$$\sigma(e^+e^- \to HZ \to ZZZ) = \sigma(e^+e^- \to HZ) \times \frac{\Gamma(H \to ZZ)}{\Gamma_H}$$

  - Deduce the total Higgs boson width Γ_H
  - Select events with H → bb, cc, gg, WW, ττ, γγ, μμ, Zγ, …
  - Deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , $g_{H\tau\tau}$, $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …
  - Select events with H → "nothing"
  - Deduce $\Gamma(H \to \text{invisible})$



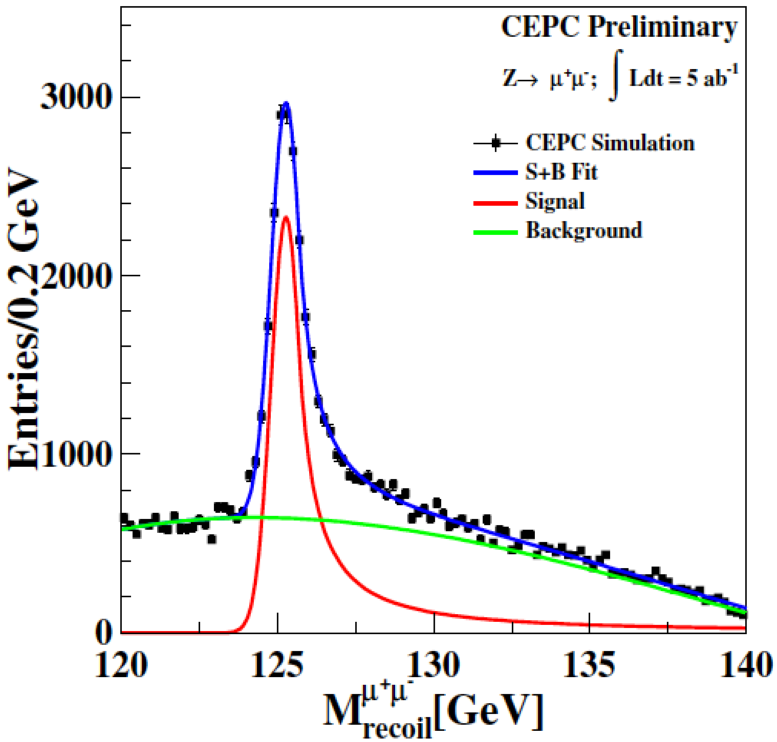
Higgs from recoil mass method

$$m_{\mathrm{recoil}}^2 = (\sqrt{s} - E_{f\bar{f}})^2 - p_{f\bar{f}}^2 = s - 2E_{f\bar{f}}\sqrt{s} + m_{f\bar{f}}^2$$

- Best mass precision can be achieved with the Z→ll (ee,μμ) decays
- Cross section, ZH and the Higgs-Z boson coupling g(HZZ), can be derived in a model-independent way
- g(HZZ) and Higgs decay branching ratios can be used to derive the total Higgs boson decay width.
- A relative precision of 0.9% for the inclusive cross section has been achieved with CepC.
- The Higgs mass can be measured with a precision of 6.5 MeV; the precision is limited by the beam energy spread, radiation effect and detector resolution
- A relative precision of 0.51% on σ(ZH) by combining ee,μμ and qq channels
- g(HZZ) can be extracted from σ(ZH) with a relative precision of 0.25%

Z decay mode	ΔM_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$	$\Delta g(HZZ)/g(HZZ)$
ee	14	2.1%	
$\mu\mu$	6.5	0.9%	
$ee+\mu\mu$	5.9	0.8%	0.4%
$q\bar{q}$		0.65%	0.32%
$ee+\mu\mu+q\bar{q}$		0.51%	0.25%

CepC CDR

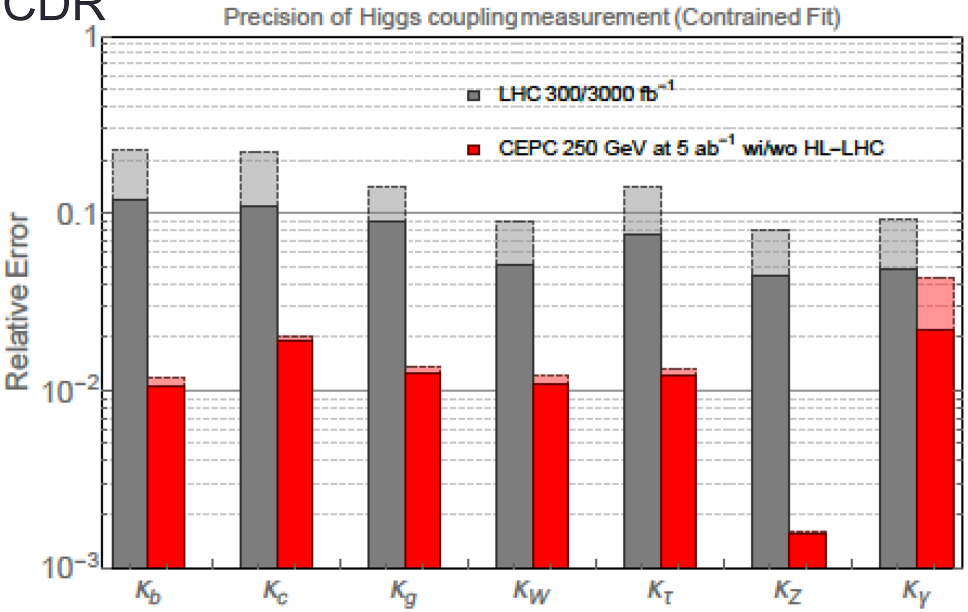


Higgs coupling measurements

- 10 parameters $\kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu, \kappa_Z, \kappa_W, \kappa_\gamma, \kappa_g, BR_{inv}, \Gamma_h$
- assuming lepton universality → 9 paramete $\kappa_b, \kappa_c, \kappa_\tau = \kappa_\mu, \kappa_Z, \kappa_W, \kappa_\gamma, \kappa_g, BR_{inv}, \Gamma_h$
- assuming the absence of exotic and invisible decays →7 parameters:

$$\kappa_b, \kappa_c, \kappa_\tau = \kappa_\mu, \kappa_Z, \kappa_W, \kappa_\gamma, \kappa_g$$

CepC CDR



Projections for CEPC at 250 GeV with 5 ab^{-1} integrated luminosity and 7 parameters fit

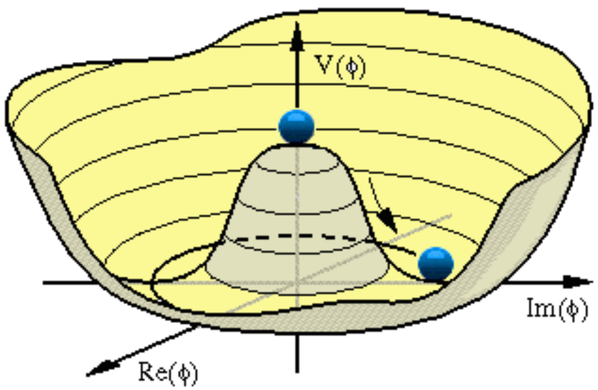
	CEPC				CEPC+HL-LHC			
Luminosity (ab^{-1})	0.5	2	5	10	0.5	2	5	10
κ_b	3.7	1.9	1.2	0.83	2.3	1.5	1.1	0.78
κ_c	5.1	3.2	1.6	1.2	4.0	2.3	1.5	1.1
κ_g	4.7	2.3	1.5	1.0	2.9	1.9	1.3	0.99
κ_W	3.8	1.9	1.2	0.84	2.3	1.6	1.1	0.80
κ_τ	4.2	2.1	1.3	0.94	2.9	1.8	1.2	0.90
κ_Z	0.51	0.25	0.16	0.11	0.49	0.25	0.16	0.11
κ_γ	15	7.4	4.7	3.3	2.6	2.5	2.3	2.0

Concerning BR_{inv} a high accuracy of 0.25%, while the HL-LHC can only manage a much lower accuracy of 6-17%.

Higgs studies for FCC-hh/SppS

THE HIGGS POTENTIAL

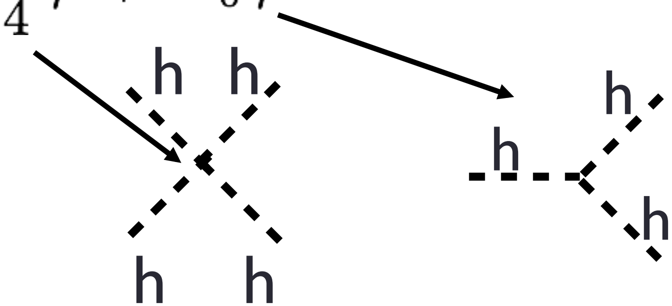
$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



After spontaneous symmetry breaking:

$$\lambda h_0^2 \eta^2 + \frac{\lambda}{4} \eta^4 + \lambda h_0 \eta^3$$

$$m_h^2 = 2\lambda h_0^2$$



The strength of the triple and quartic couplings is fully fixed by the potential shape.

Why is it relevant?

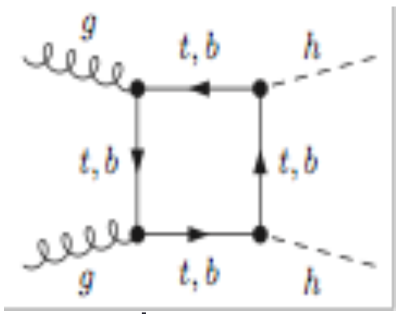
1) it is the last missing ingredient of the SM, like the Higgs boson was the last missing particle, we need to prove that things really behave like we expect;

2) It has implications on the stability of the Vacuum;

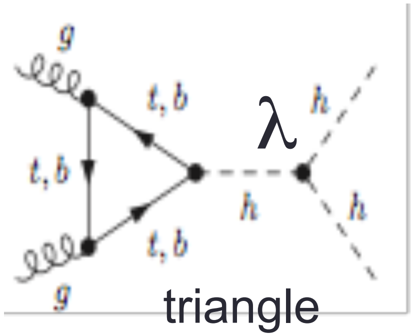
3) It could make the Higgs boson a good inflation field

HH PRODUCTION AND DECAY

Standard Model



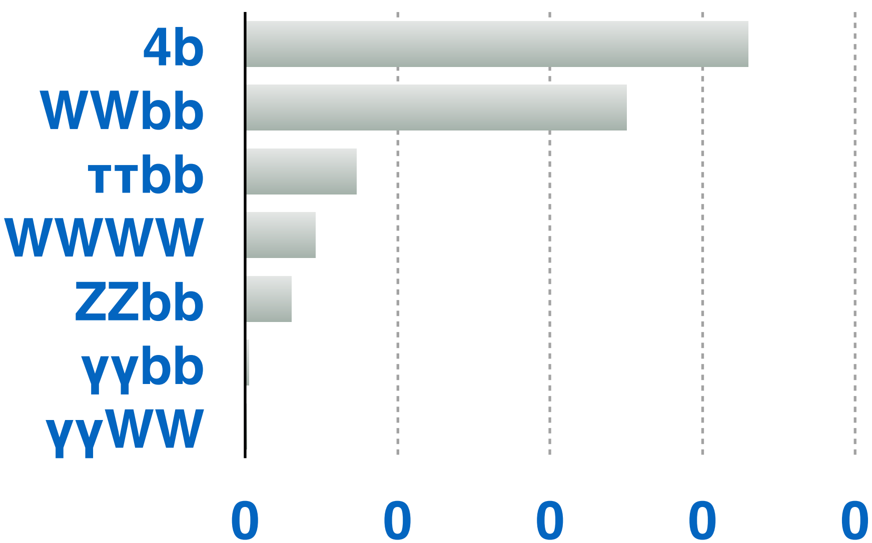
box

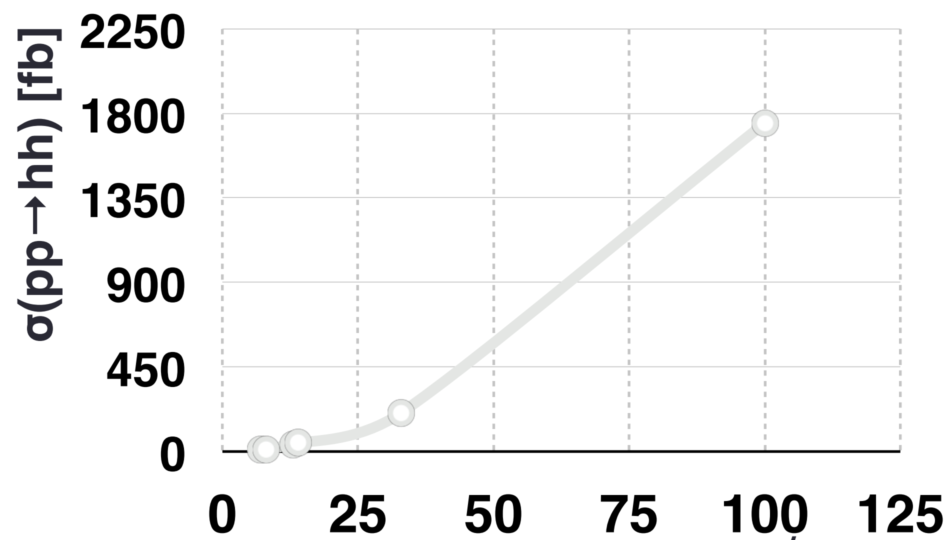


NNLO with full top mass *NLO $m_t \rightarrow \infty$

m_h = 125.09 GeV	σ(fb)	scale unc. (%)	PDF unc. (%)	α_s unc.
√s = 7 TeV	7,71	+4.0/-5.7	± 3.4	± 2.8
√s = 8 TeV	11,17	+4.1/- 5.7	± 3.1	± 2.6
√s = 13 TeV	37,91	+4.3/-6.0	± 2.1	± 2.3
√s = 14 TeV	45,00	+4.4-6.0	± 2.1	± 2.2
√s = 33 TeV*	206,6	+15.1 - 12.5	+5.8/-5.0	
√s = 100 TeV	1748	+5.1/-6.5	± 1.7	± 2.0

Higgs decay branching fraction





Highest possible energy pays

CURRENT STATUS @LHC

	$\sqrt{s}$ **[TeV]**	L (fb^{-1})	**σ(fb) 95% C.L.**	σ/σ_{SM} 95%C.L.
ATLAS: 4b, bbττ, bbγγ, WWγγ WWWW	8	20,3	< 470	< 48
ATLAS: 4b	13	13,3	< 1000	< 29
CMS: 4b	13	2,32	< 11760	< 310
ATLAS: WWγγ	13	13,3	< 12900	< 340
ATLAS: bbγγ	13	3,2	< 5400	< 142
CMS: bbττ	13	39,5	< 950	< 25
CMS: WWbb	13	36	< 3270	< 86

HL-LHC $\sqrt{s}$ = 14 TeV, L = 3000 fb^{-1}	**Exp. sign**	λ/λ_{SM} 95% C.L.	exp σ/σ_{SM}
ATLAS: bbγγ	1.05 σ	[-0.8, 7.7]	< 1.7 [recalc.]
CMS: bbγγ	1.6 σ		< 1.3
ATLAS: 4b	?	$[0.2, 7.0]_{stat.}$, [-3.5, 11]	< $1.5_{stat.}$, 5.2
CMS: 4b	0,67		< $2.9_{stat.}$, 7
ATLAS: bbττ	0.6 σ	[-4, 12]	< 4.3
CMS: bbττ	0,39		<$3.9_{stat.}$, 5.2
CMS: VVbb	0,45		< $4.6_{stat.}$, 4.9

Present best channel 4b, situation will change with higher statistics when syst. dominated channels will saturate their sensitivity.

HL-LHC doesn't seem able to provide a useful constraint on λ, it could probably provide an observation of the whole process.

But advanced analysis techniques can improve the results…

FCC STUDIES

- Main references
  - Physics at a 100 TeV pp collider [arXiv:1606.09408]
  - 1st FCC-hh Physics Workshop - 16-20 January 2017 CERN
  - FCC-hh physics analysis meetings
  - FCC week 2017 @ Berlin
  - studies performed with different level of details, in particular trigger, eff. simulation and pile-up studies need to be implemented in many of them, but first bulk of phys. potentiality ready.

Physics at a 100 TeV *pp* collider: Higgs and EW symmetry breaking studies

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FCC studies: HH→bbγγ

Selection:

1. 2γ, 2 b-jet |η| < 4.5, p_T^{sub} > 35, p_T^{lead} > 60 GeV
2. $|m_{\gamma\gamma} - m_h|$ < 2.0 , 100 < m_{bb} < 150 GeV
3. p_T^{bb}, $p_T^{\gamma\gamma}$ > 100 GeV, ΔR_{bb}, $\Delta R_{\gamma\gamma}$ < 3.5

Simulation: 6T magnetic field

Signal LO samples, Pythia6 showering, no pile-up simulation

Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.73	0.40	12061
$bbj\gamma$	132	0.467	13996
$jj\gamma\gamma$	30.1	0.164	4909
$t\bar{t}h(\gamma\gamma)$	1.85	0.163	4883
$b\bar{b}\gamma\gamma$	47.6	0.098	2947
$b\bar{b}h(\gamma\gamma)$	0.098	7.6×10^{-3}	227
$bj\gamma\gamma$	3.14	5.2×10^{-3}	155
Total background	212	1.30	27118

S/√B 23 [3 ab^{-1}] 73 [30 ab^{-1}]

$\Delta\sigma/\sigma$ = 1.6% [30 ab^{-1}] $\Delta\lambda/\lambda$ = 6% [2.5% sig. syst.]

Updates:

4T magnetic field

Pythia8 showering

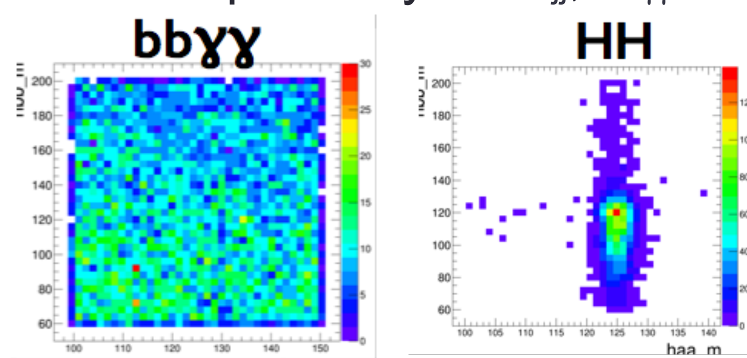
Process	Events
hh→bbγγ	12300
bbjγ	16700
jjγγ	14272
tth(γγ)	14213
bbγγ	7078
bjγγ	1873
Total bkg.	66436

2x Total background

$\Delta\sigma/\sigma$ = 2.1% [30 ab^{-1}]

$\Delta\lambda/\lambda$ = 7% [2.5% sig. syst.]

Shape analysis m_{jj}, $m_{\gamma\gamma}$



$\Delta\sigma/\sigma$ = 1.6%

$\Delta\lambda/\lambda$ = 4.2% [0% sig. syst.]

FCC studies: HH→bbbb

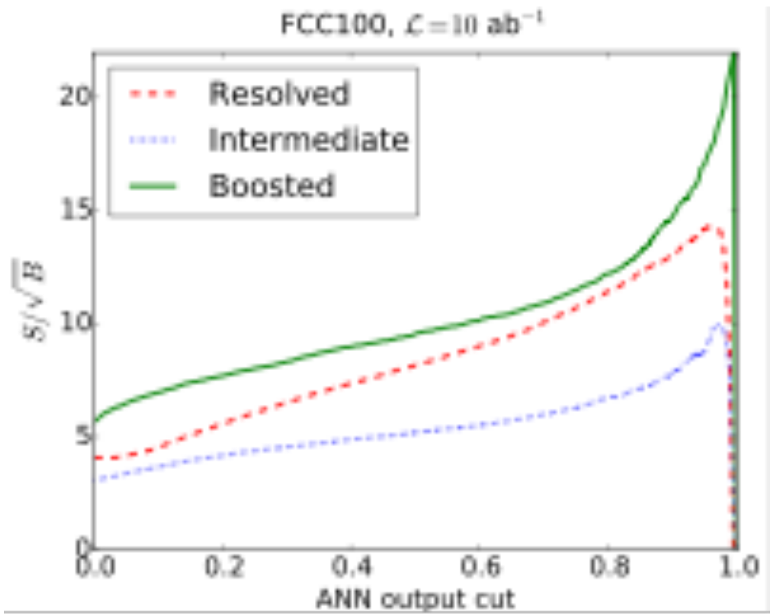
Main background: multi-jet 4b
Strategy: truth level study, resolved + boosted analysis (Neural Network used as signal discriminator)

1. R 0.4 jets p_T > 40 GeV, |η| < 2.5
2. R 1.0 jets p_T > 200 GeV, |η| < 2.0
3. R 0.3 jets ghost ass. to R 1.0 p_T > 50 |η| < 2.5

10 ab^{-1}

Category		N_{ev} signal	N_{ev} back	$S/\sqrt{B}$	S/B
Boosted	$y_{cut} = 0$	$5 \cdot 10^4$	$8 \cdot 10^7$	6	$6 \cdot 10^{-4}$
	$y_{cut} = 0.99$	$2 \cdot 10^4$	$1 \cdot 10^6$	22	$2 \cdot 10^{-2}$
Intermediate	$y_{cut} = 0$	$3 \cdot 10^4$	$1 \cdot 10^8$	3	$3 \cdot 10^{-4}$
	$y_{cut} = 0.98$	$2 \cdot 10^4$	$2 \cdot 10^6$	10	$7 \cdot 10^{-3}$
Resolved	$y_{cut} = 0$	$1 \cdot 10^5$	$8 \cdot 10^8$	4	$1 \cdot 10^{-4}$
	$y_{cut} = 0.95$	$6 \cdot 10^4$	$2 \cdot 10^7$	15	$4 \cdot 10^{-3}$

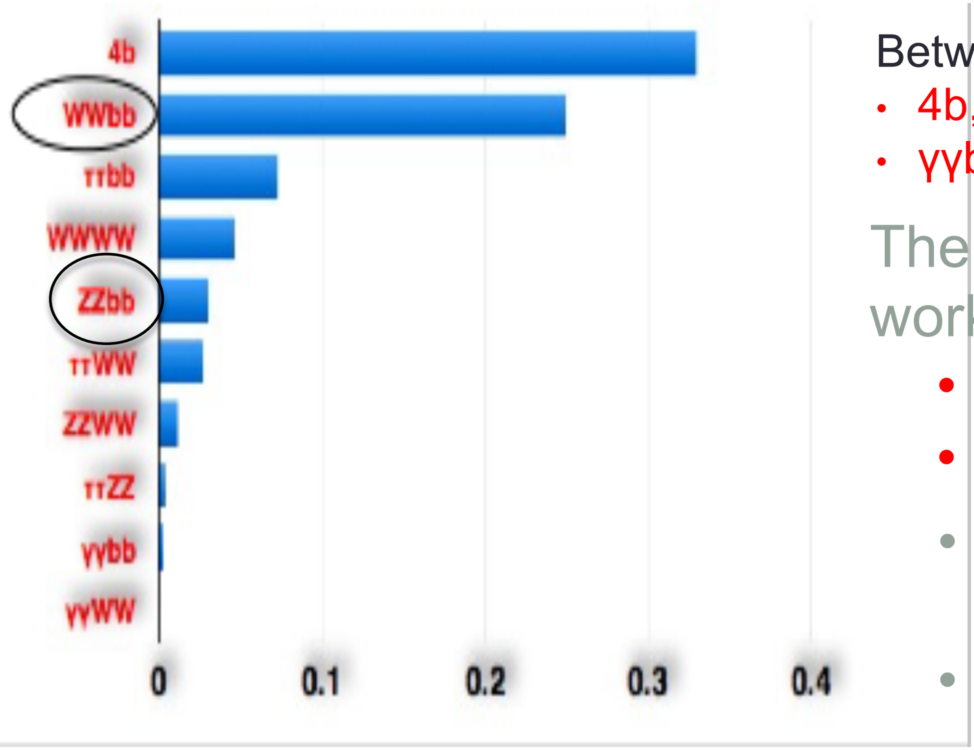
	$\delta_{sys}\sigma = 25\%$	$\delta_{sys}\sigma = 100\%$
Boosted	$\lambda_3 \in [-0.1, 2.2]$	$\lambda_3 \in [-1.5, > 9]$
Intermediate	$\lambda_3 \in [0.7, 1.6]$	$\lambda_3 \in [-0.4, > 9]$
Resolved	$\lambda_3 \in [0.9, 1.5]$	$\lambda_3 \in [-0.1, 7]$



Sensitivity to λ from unboosted objects, λ diagram contributes mainly at low m_{hh}

25% on σ with S/B ~4 · 10^{-3}, ΔB/B ~ 10^{-3} (very challenging)

Current FCC studies in Italy



Between the final state from the HH decay:
- 4b, WWbb are dominant
- γγbb, ZZbb are the cleanest

The **Italian community** started to work in 2016 on:
- WWbb, lnuqqbb
- ZZbb, 4lbb
- We used a fast simulation tool (Delphes)
- Pileup simulation with 50, 200, 900 events

L=30 ab^{-1}	**Δσ/σ**	**Δλ/λ**
γγbb	1.3%	2.5%
4b	25% (S/B ~2%)	200%
ZZbb, 4l	~30%	~40%

Last contributions to conferences:
- B. Di Micco, IFAE – Trieste – April 19-21 2017
- B. Di Micco, FCC Week – Berlin – May 29 – June 1 2017

What will we know by 2018/2019 ?

P. Janot (CERN)

- If new physics is found by the end of LHC Run2
  - It will – hopefully – point to the best new accelerator to build
    - Will in turn make it easier to get financial/political/societal support
  - This hypothesis is, unfortunately, getting less and less likely

- Much greater challenge if no new physics is convincingly found
  - Cannot continue indefinitely with R&D towards all possible future facilities
    - A choice will have to be made in 2019-2020

- Physics absolutely need an e^+e^- EW factory with $90 < \sqrt{s} < 400$ GeV
  - Four e^+e^- collider studies on the planet (ILC, CLIC, CEPC, FCC) in the energy range !
  - Exploration of the energy frontier best done with a hadron collider (e.g., FCC-hh/CppS)

Conclusions

HL-LHC: potential for new physics discoveries and precision measurements:

- Higgs couplings modifiers and signal strenghts with precision between 5-15% level
- Measurement on mass, width, CP properties
- Search for additional bosons, dark matter, rare decays, VV scattering
- Similar conclusions from ATLAS and CMS projections in spite of the differences in the assumptions and detector upgrades

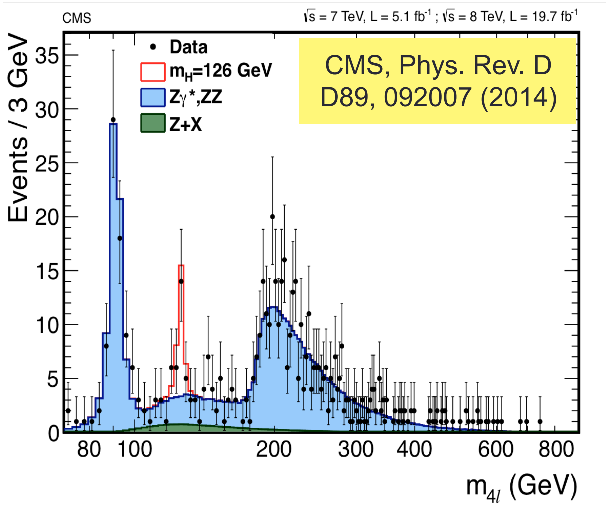
FCC-ee/CepC: large potential beyond the HL-LHC

- Measurement of the Higgs mass at few MeV level
- Sub-percent measurement of the higgs couplings
- Model-independent measurement of the Higgs width
- deduce $\Gamma(H \rightarrow \text{invisible})$
- show evidence of BSM Higgs

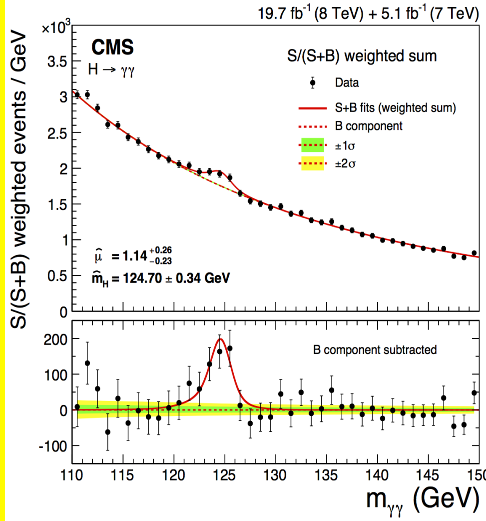
FCC-hh/SppS:

Large potential on Higgs physics and more… if realized it will be the future of the field

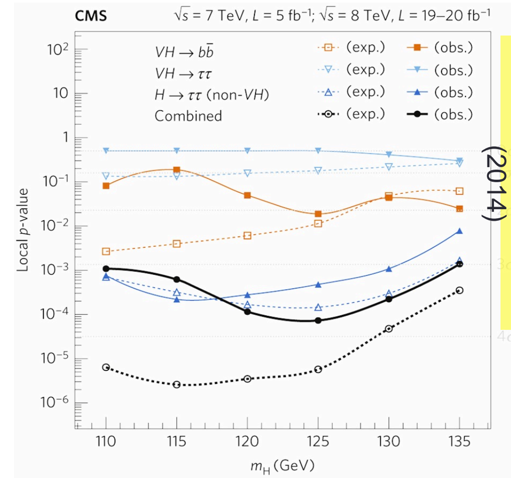
The LHC/Higgs era at Run 1



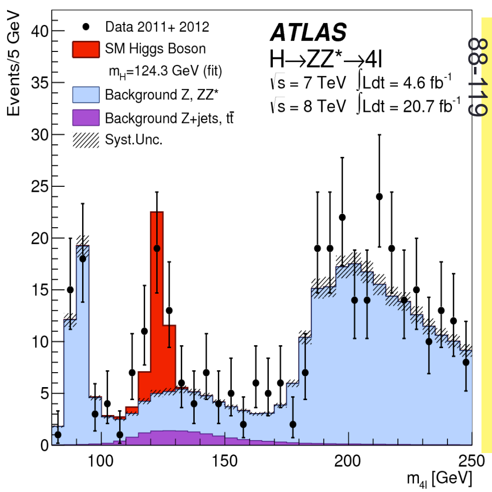
CMS, Phys. Rev. D D89, 092007 (2014)



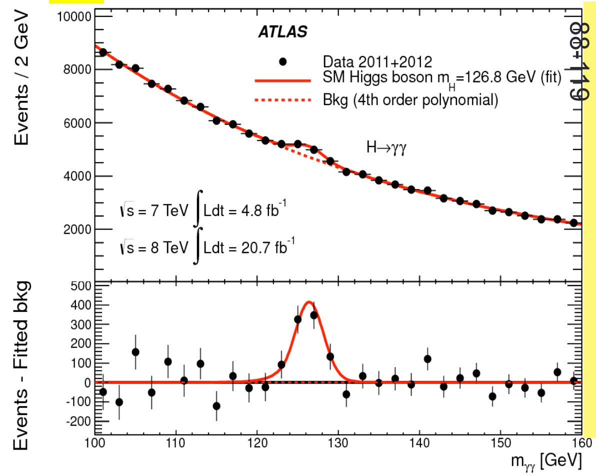
arXiv: 1407.0558, submitted to Eur. Phys. J. C



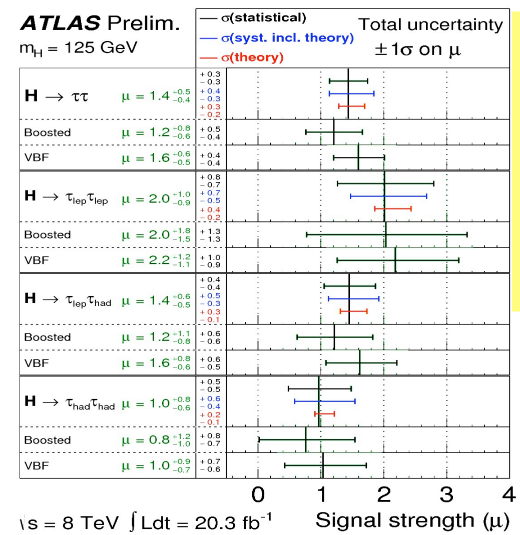
Nature Physics (2014)



Phys. Lett. B 726 (2013), pp. 88-119



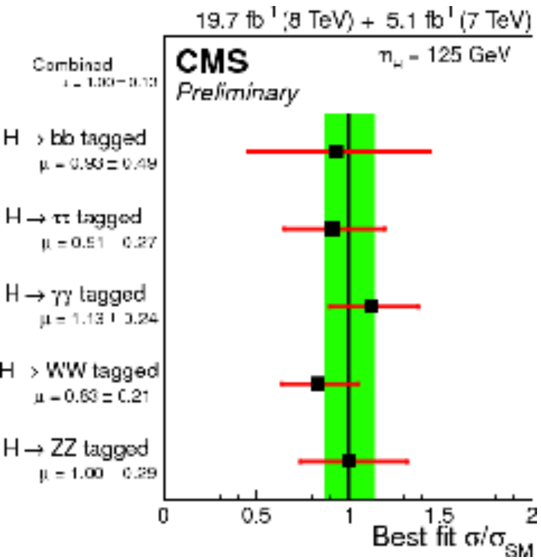
Phys. Lett. B 726 (2013), pp. 88-119

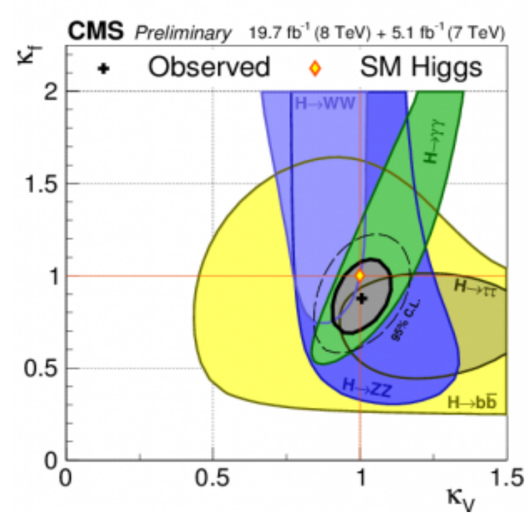


ATLAS-CONF-2013-108/

4l/γγ	CMS	ATLAS
Measured mass	**125.03 $^{+0.26}_{-0.27}$(stat) $^{+0.13}_{-0.15}$(syst) GeV**	**125.36+-0.37(stat)+-0.18(syst) GeV**
Syst. Uncert.	Electron e/p-scale ≈ 0.1-0.3%	Electron e/p-scale ≈ 0.2-0.4%
	Muon p-scale ≈ 0.1%	Muon p-scale ≈ 0.1-0.2%

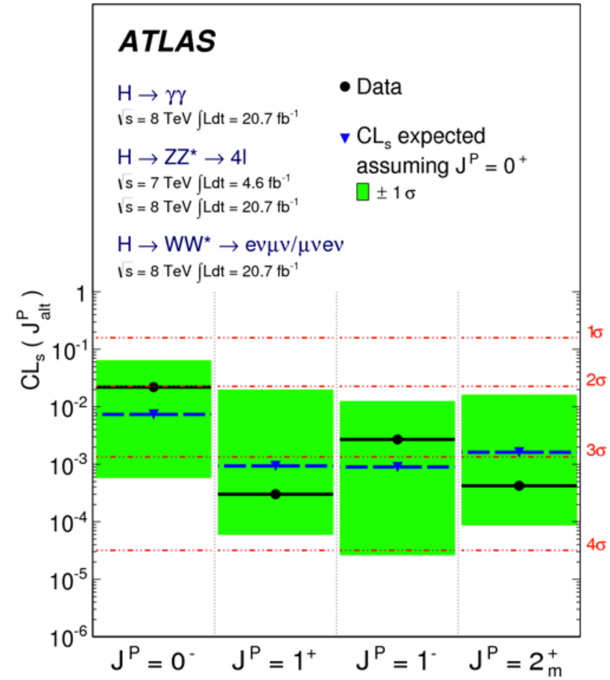
The LHC/Higgs era at Run 1

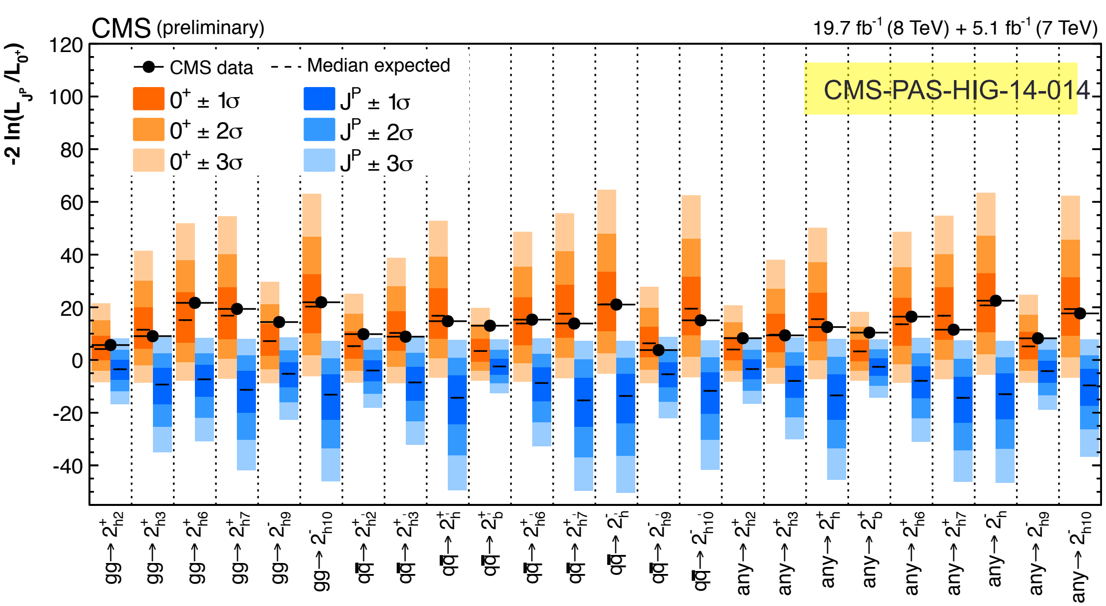


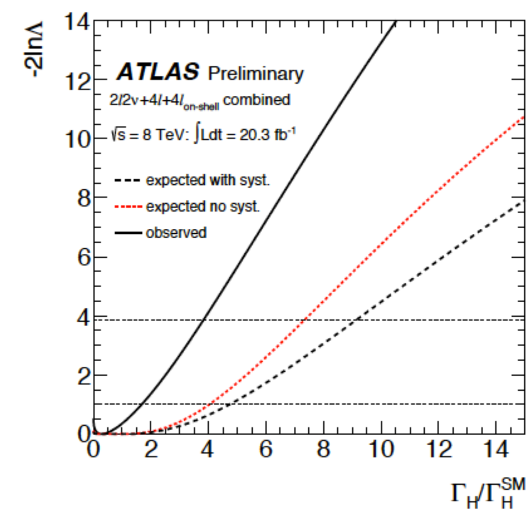


CMS-PAS-HIG-14-009

Phys. Lett. B 726 (2013), pp.



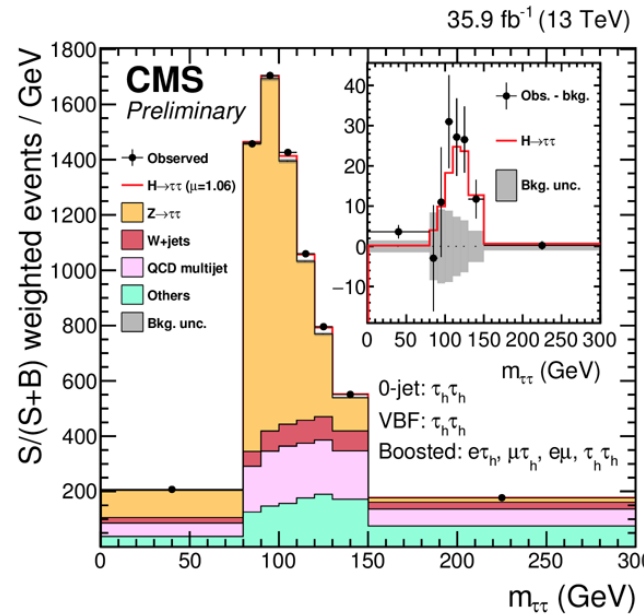




ATL-COM-CONF-2014-052

The LHC/Higgs era at Run 2

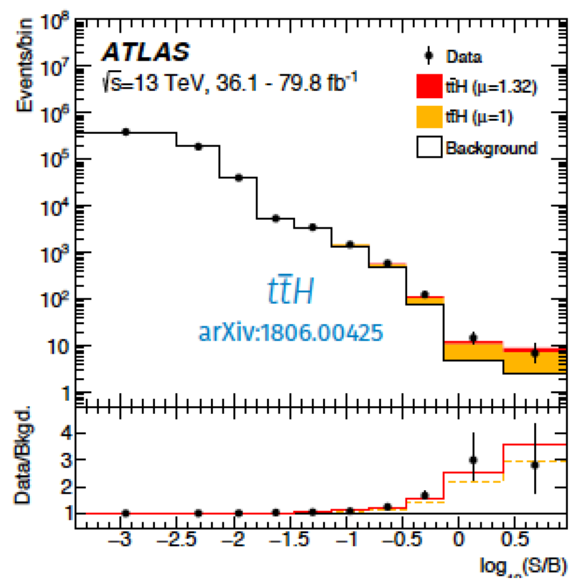
H→ ττ :
Observation of the SM scalar boson decaying to a pair of τ leptons with the CMS experiment at the LHC (**4.9σ** *vs* 4.7σ expected) → HIG-16-043

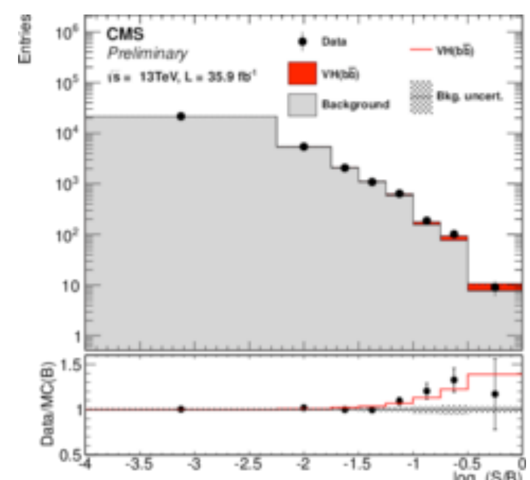


H→bb :
CMS has **3.8σ** evidence (3.8σ expected) for Higgs boson decays to b-quarks and for its production in association with a vector boson → HIG-16-044, arXiv:1709.07497

ttH→ZZ,WW,ττ → multi-leptons: evidence observed (expected) significance of **3.3σ** (2.5σ), by the combination of the 2016 results with 2015 → HIG-17-004

* Similar results from ATLAS





H→bb

VH(H→bb): improvement wrt 2016

CMS

- Extensive use of **deep neural network (DNN)**
  - To **identify b-jet** candidates
  - To **regress the energy** of reconstructed b-jet
  - To **discriminate among the background components** in some Vector boson + heavy flavor jets control regions
  - To **discriminate signal from background**
- **Kinematic fit** in 2-lepton channel
- **FSR jet recovery**
- New **Pythia8 Underlying Event Tune**

- **Improved mass resolution (~10%) leads to 10% increase of the analysis sensitivity**

Systematic uncertainties

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Analysis dominated by systematic uncertainties

Measured by impact on signal strength (μ)

Many important sources !

b-tagging both b and c jet tagging calibration

- Resp. ∼3% and ∼10% per jet

Background modelling Z+hf, W+hf, $t\bar{t}$

- Mainly shape and extrapolation uncertainties

Signal modelling little impact on significance

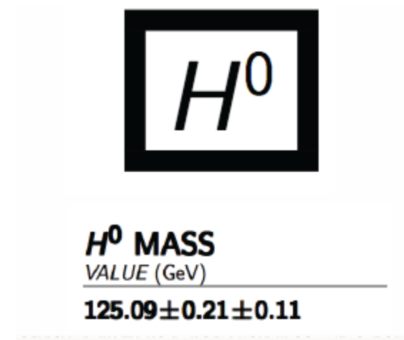
- Dominated by systematic uncertainties on the acceptance

MC stats never-ending race between data stat and MC stat

- Use of dedicated MC filters
- Not easy in all cases, e.g $t\bar{t}$ phase space in 0/1-lepton

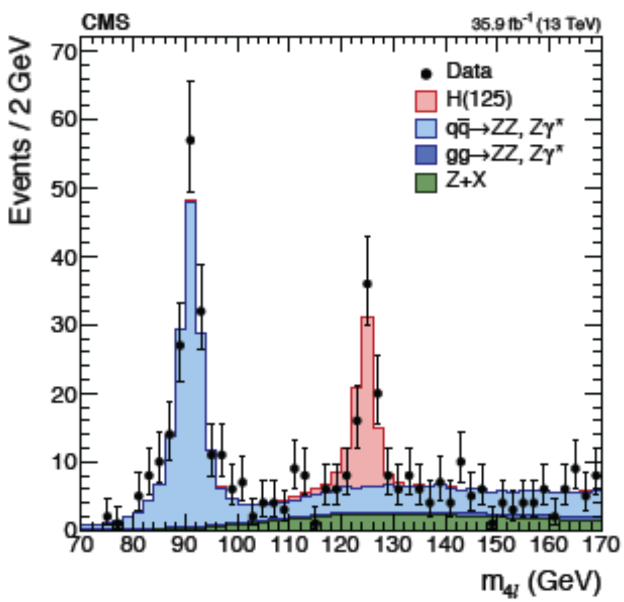
The LHC/Higgs era at Run 2

- Re-discovery of the Higgs
- measur. Higgs properties
  - cross section (also differential)
  - mass & width
  - couplings:
    - to gauge bosons, to fermions
    - tensor structure and effective couplings in the lagrangian
    - ttH couplings
  - Searches for BSM Higgs



- Mass measured to 0.2%
- Main couplings to ~10%

HIG-16-041



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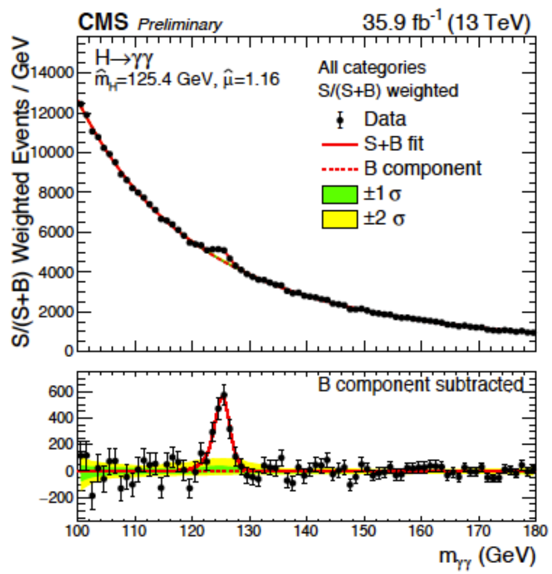
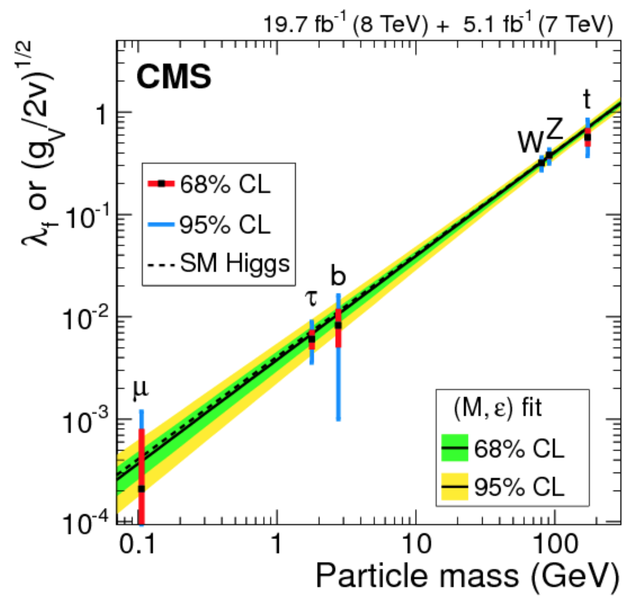
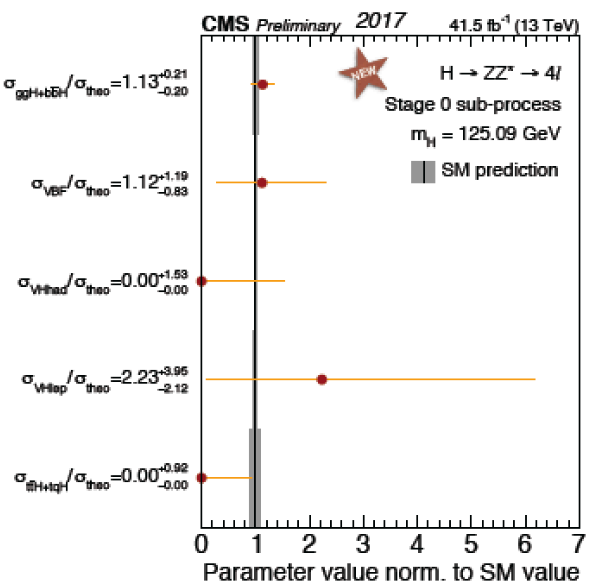
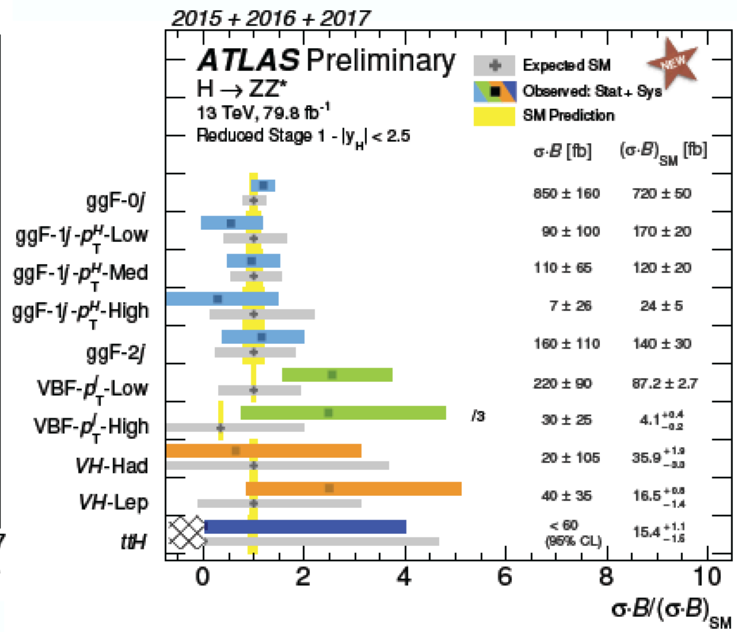
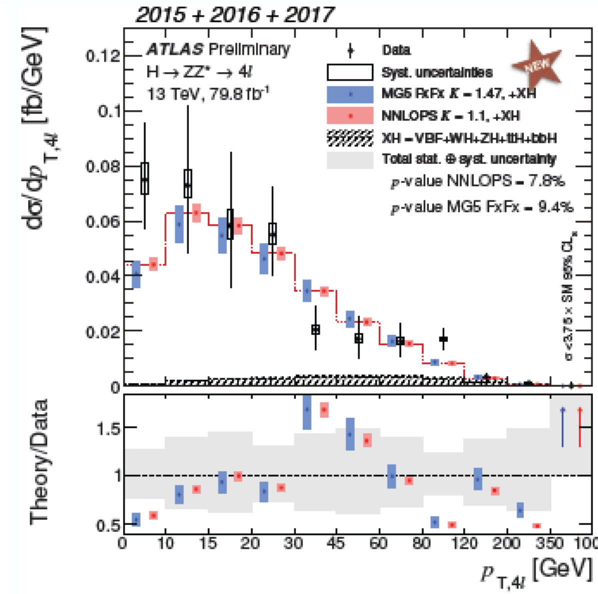




H→ZZ→4l: cross section







ATLAS already attempting at (simplified) stage-1 STXS subprocesses.

CMS show a small excess (mostly driven by excess in 2e2μ)

no ttH event observed yet in either of the experiments