Higgs couplings and properties from run 1 and run 2 measurements and their combination

Rainer Mankel (DESY)

on behalf of the ATLAS and CMS collaborations

29th Rencontres de Blois –
Particle Physics and Cosmology
29 May 2017

Outline

- Introduction

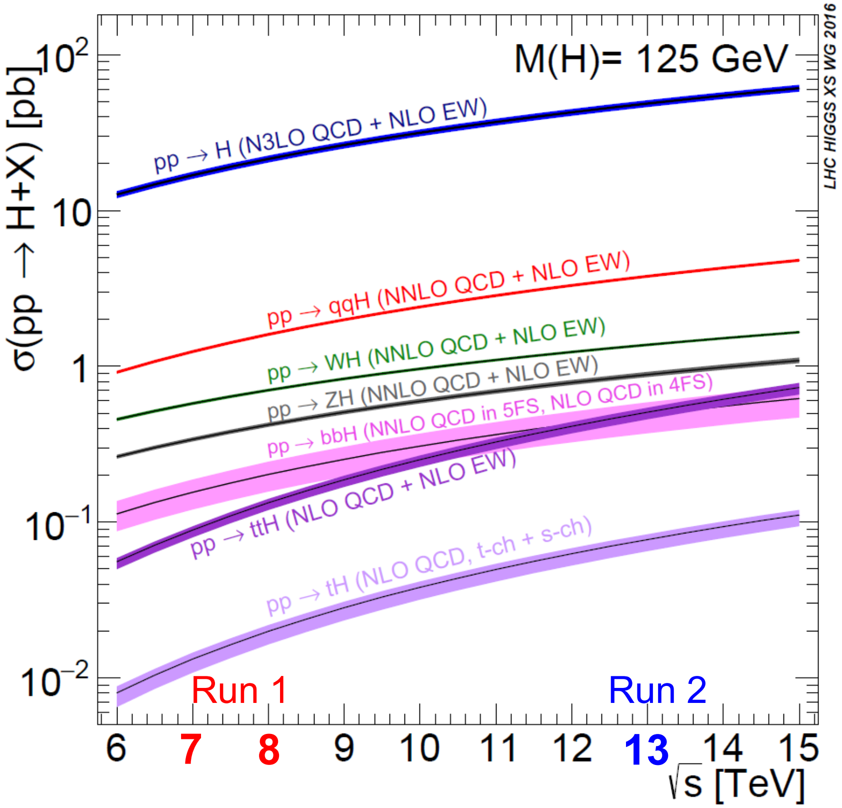
- The Higgs boson according to Run 1

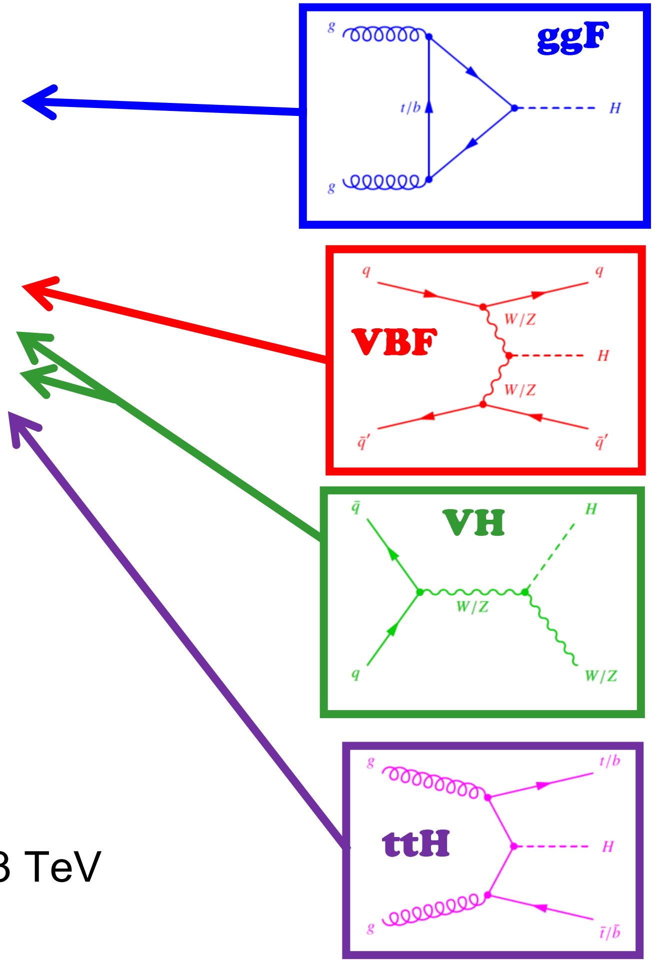
- Run 2: a new level
  - bosonic couplings
  - fermionic couplings

- Summary

The Higgs boson in the SM: production & decay

Higgs boson production mechanisms





- ➔ Sizable increase in cross sections in transition 8 → 13 TeV
  - factors of ~2.3 (ggF), ~4 (ttH)
- ➔ Significant improvements in theory
  - e.g. uncertainty of ggF cross sections reduced to ~½ (N^3LO)

Higgs boson decay modes

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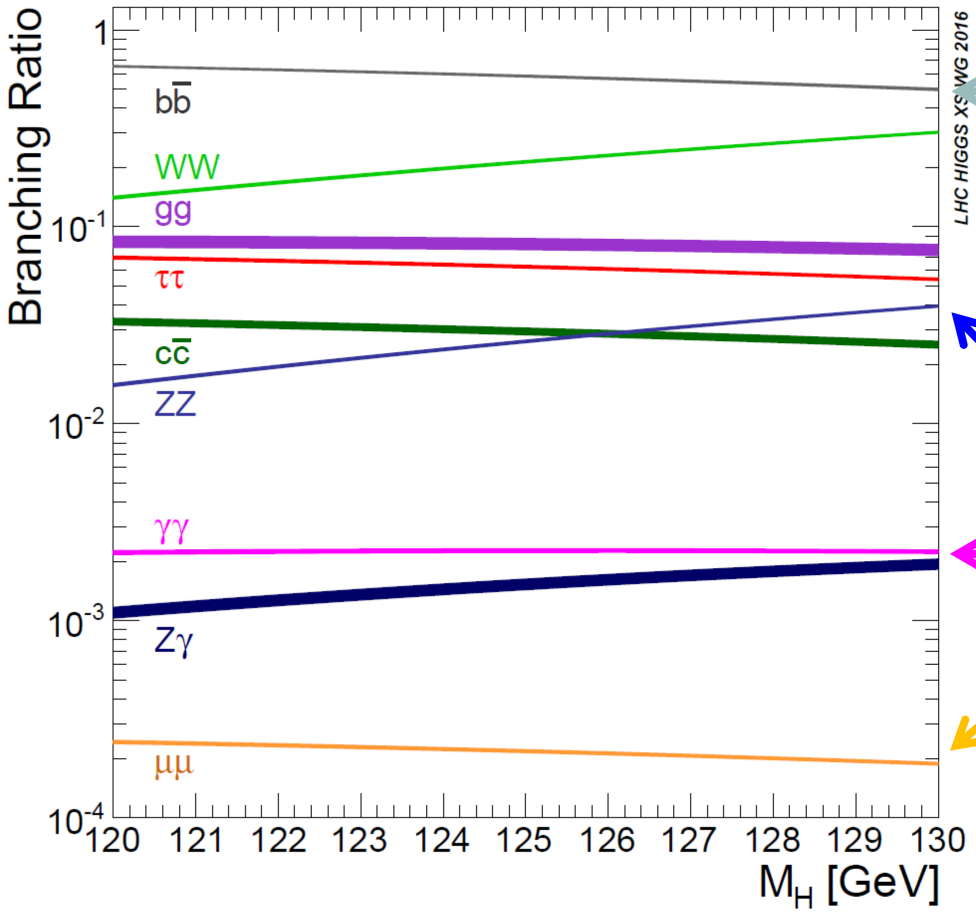
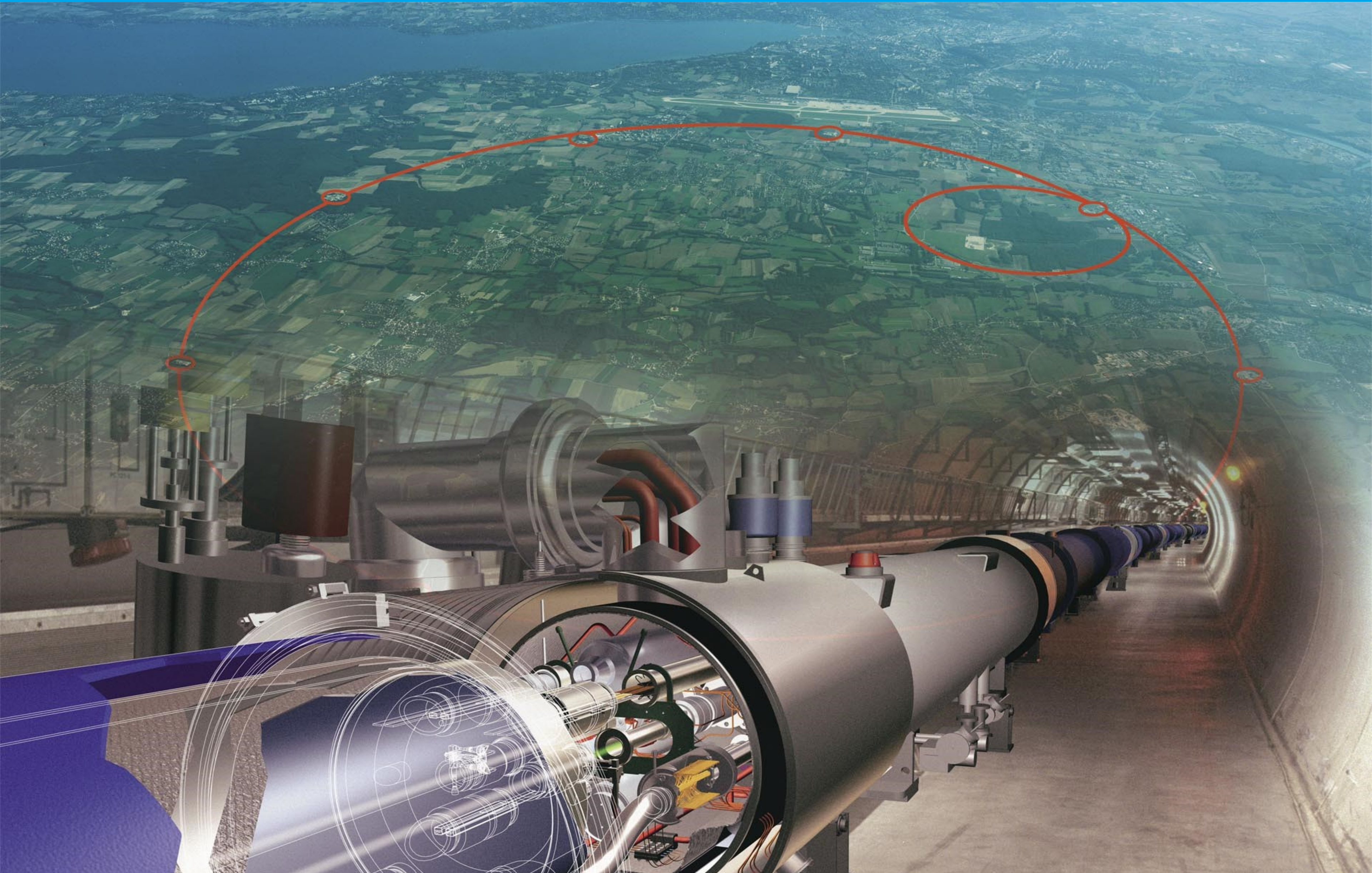


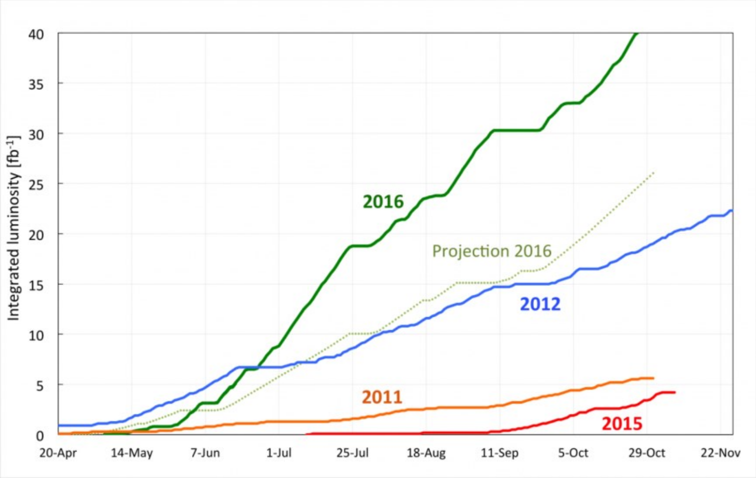
largest BR, but huge backgrounds

cleanest in terms of mass resolution & backgrounds

The Large Hadron Collider



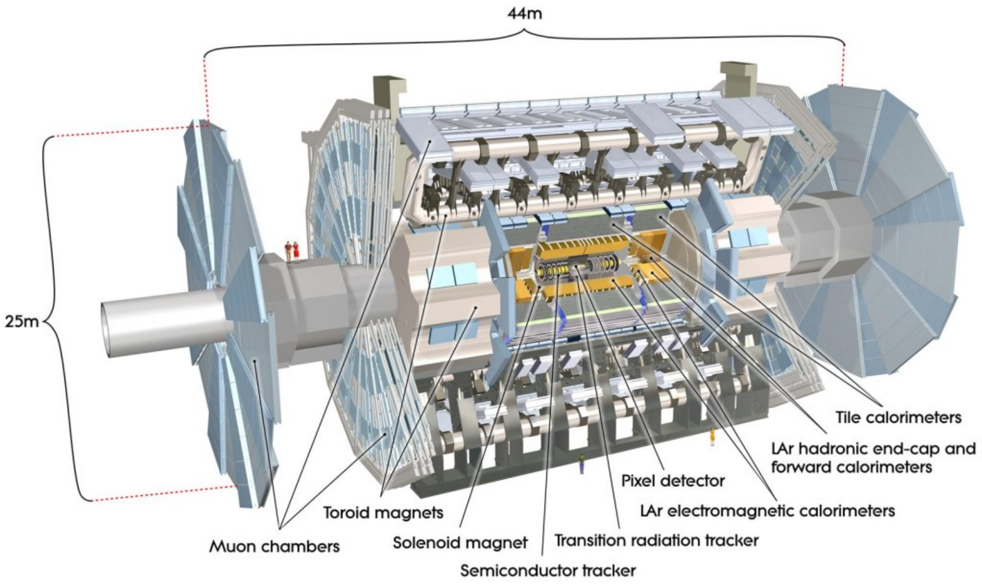
The Large Hadron Collider

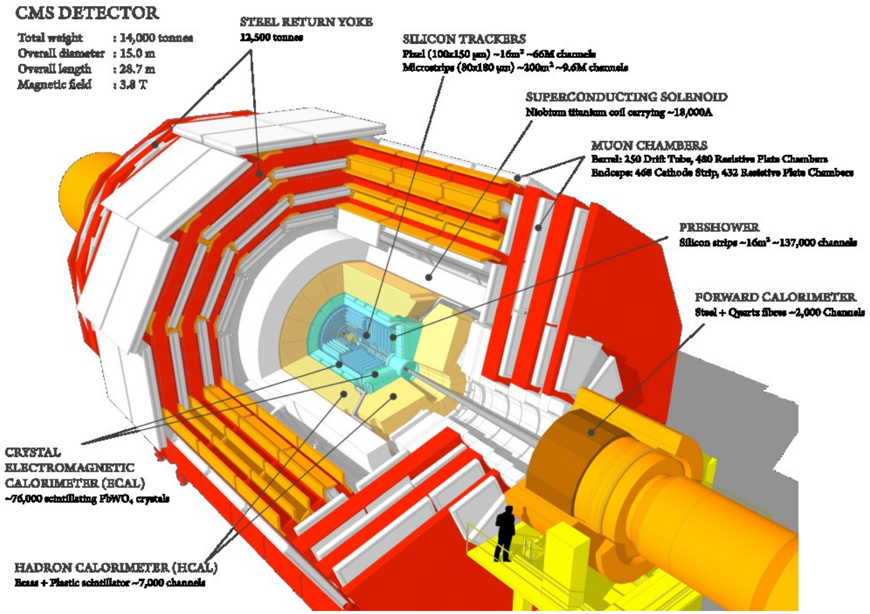


- LHC performance exceeded by far the expectations for 2016
- ~40 fb^{-1} of pp integrated luminosity delivered to ATLAS + CMS
  - ➔ excellent availability, peak luminosity > 1.4 x 10^{34} cm^{-2} s^{-1}
  - ➔ >6.5 x 10^{15} collisions recorded per experiment at 13 TeV

ATLAS & CMS experiments

- The two multi-purpose detectors at the LHC





44 m x 25 m, 7,000 tons

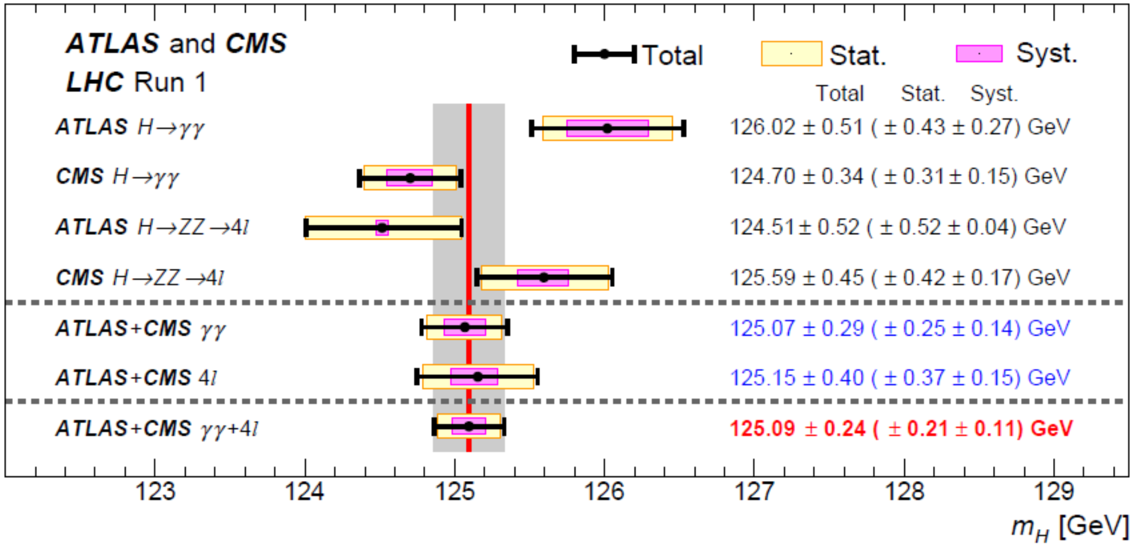
29 m x 15 m, 14,000 tons

The Higgs boson according to LHC Run I

Higgs Mass (Run 1)

ATLAS+CMS PRL 114 (2015) 191803

- m_H is a free parameter of the SM → crucial also for extraction of couplings
- Run 1 combination: based on the best-resolution decay modes, $\gamma\gamma$ and 4ℓ



- Combined results from ATLAS + CMS:

$$m_H = 125.09 \ \pm 0.21\ (stat.) \pm 0.11\ (syst.)\ \ \mathrm{GeV}$$

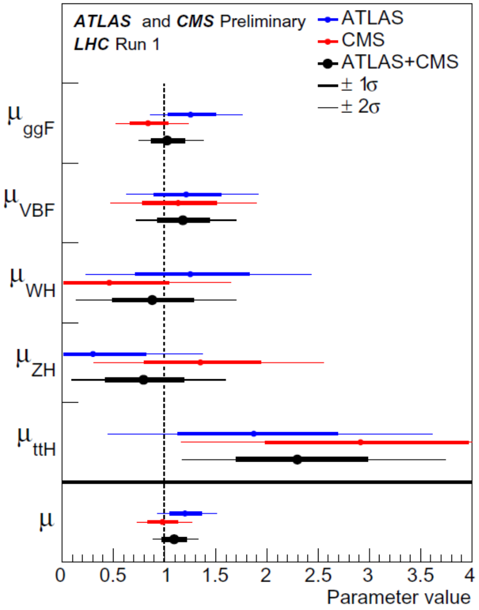
➔ → already very remarkable precision of ~0.2 %

Production & decay (Run 1)

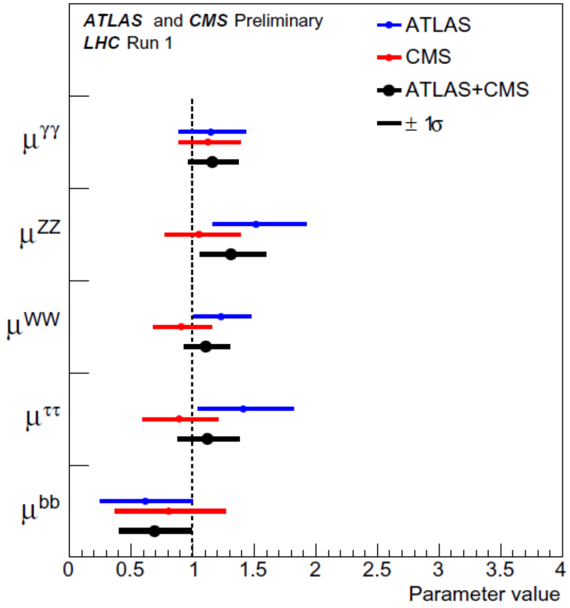
ATLAS+CMS JHEP 08 (2016) 045

- Global fits of either production (μ_i) or decay (μ^f) signal strengths

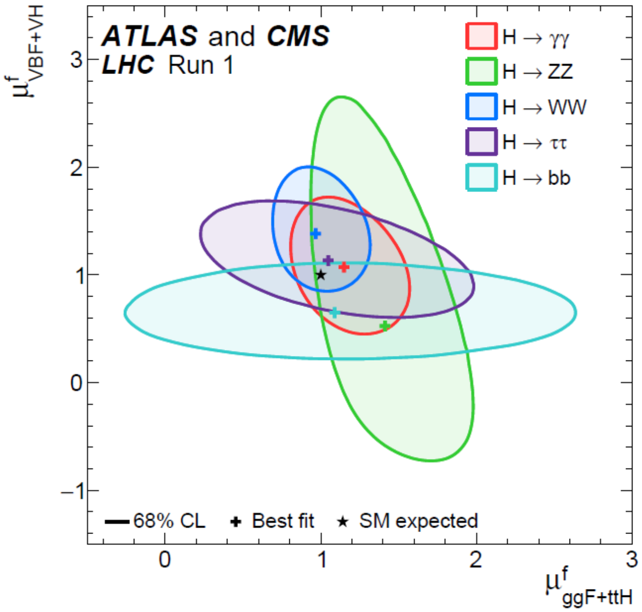
Production modes



Decay modes



Boson vs fermion mediation



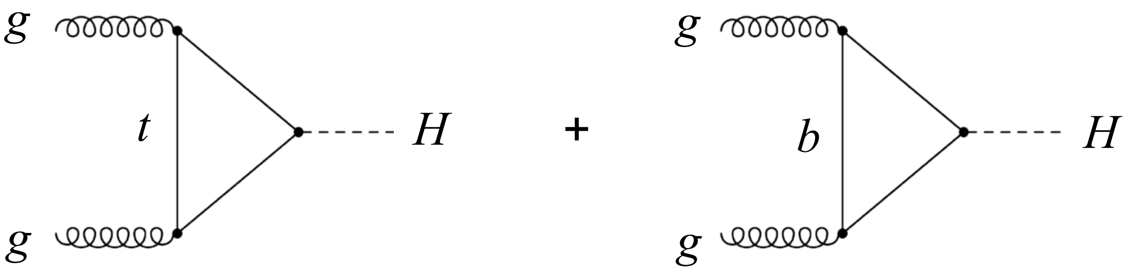
→ Clear evidence for VBF. ttH production somewhat high, bb decay slightly low.

→ Good consistency across experiments. Overall good agreement with SM.

Couplings (Run 1)

ATLAS+CMS JHEP 08 (2016) 045

- Leading-order motivated κ framework
  - For each coupling, introduce a modifier κ, where κ =+1 corresponds to SM value
  - Express all cross sections and decay widths in terms of coupling modifiers
  - Example: gg → H

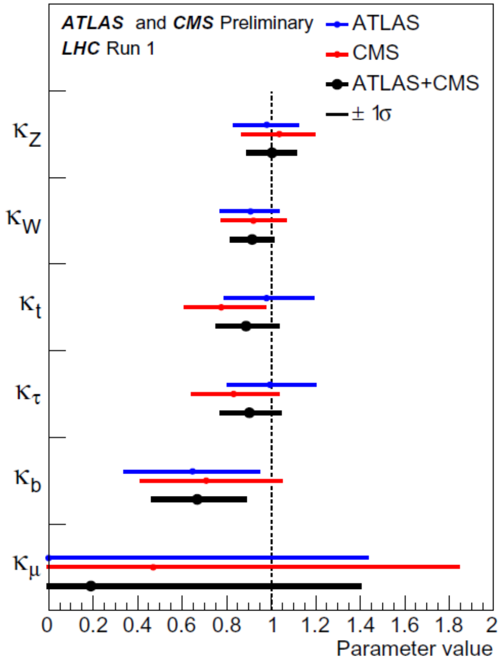


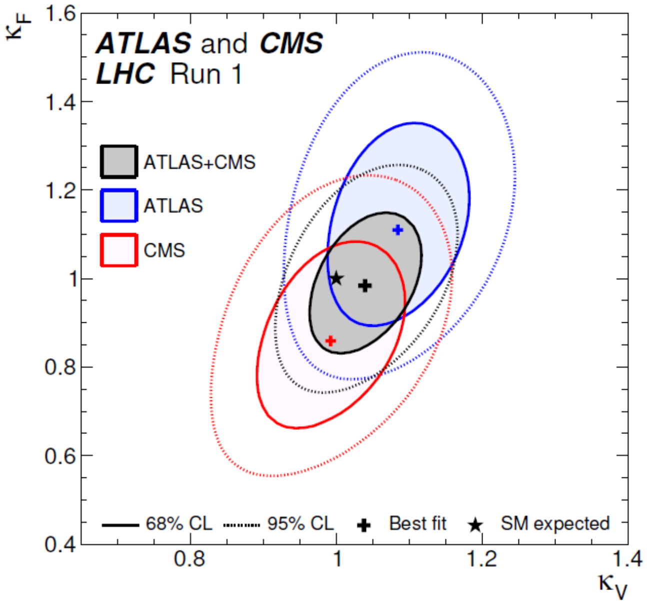
$$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\, \kappa_b$$

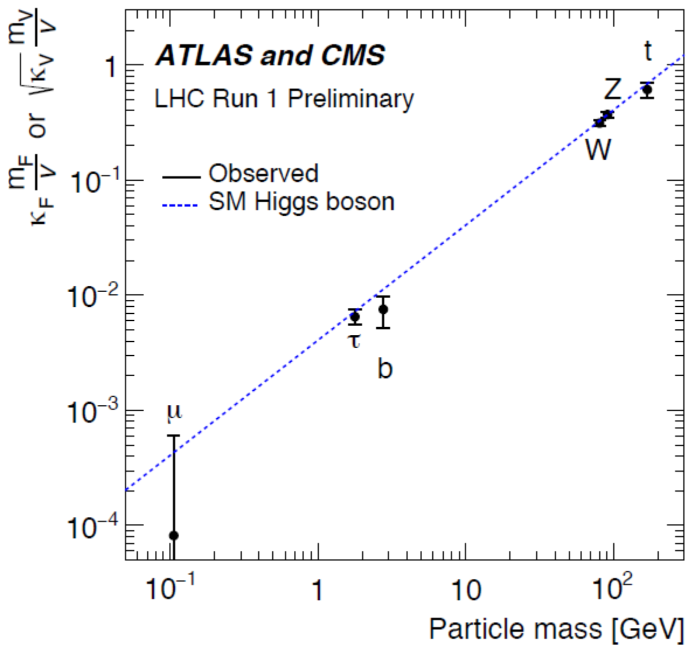
- With σ×BR measurements of all relevant channels, compute likelihood functions and profile the various coupling modifiers
- Also contributions of BSM decay modes to the total Higgs boson width Γ_H can be considered

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

Individual couplings







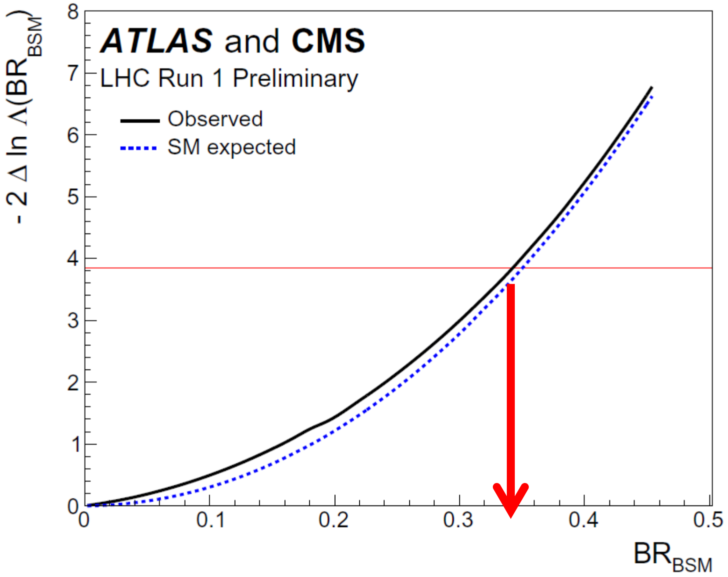
- Individual coupling study includes H→μμ analysis (upper limit only)
- κ_V and κ_F are global modifiers for vector (W, Z) and fermion couplings (t, τ, b)
  - ➔ agreement with $\kappa_V = \kappa_F = 1$ (SM couplings)

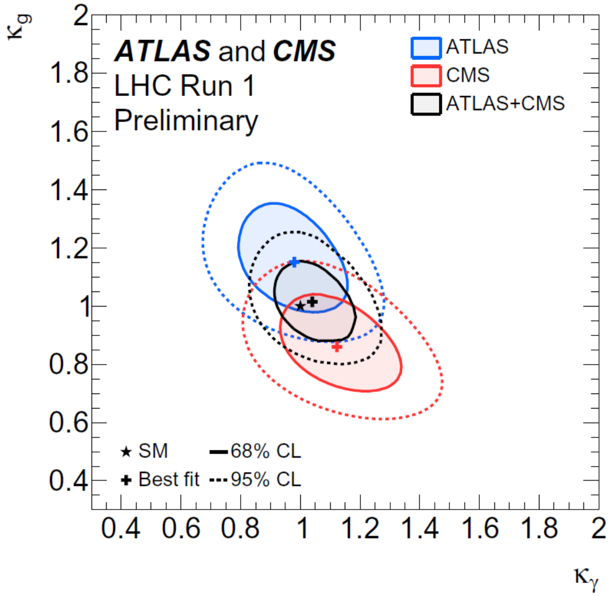
➔ Mass dependence of Higgs couplings clearly shown

  - finger print of a SM Higgs boson

Indications for BSM effects?

- New physics could manifest itself in
  - decay modes to invisible particles
  - BSM particles in loops: (gg fusion, $\gamma\gamma$ decay mode) →fit κ_g, κ_γ as autonomous parameters





- ➔ $BR_{BSM} < 0.34$ (95% CL) → up to $^1/_3$ of decay width may yet be unaccounted for
- ➔ No indication for modification of loops
- ➔ In summary: Run 1 results confirm properties as expected for a SM Higgs boson

Run 2: a new level of Higgs boson research

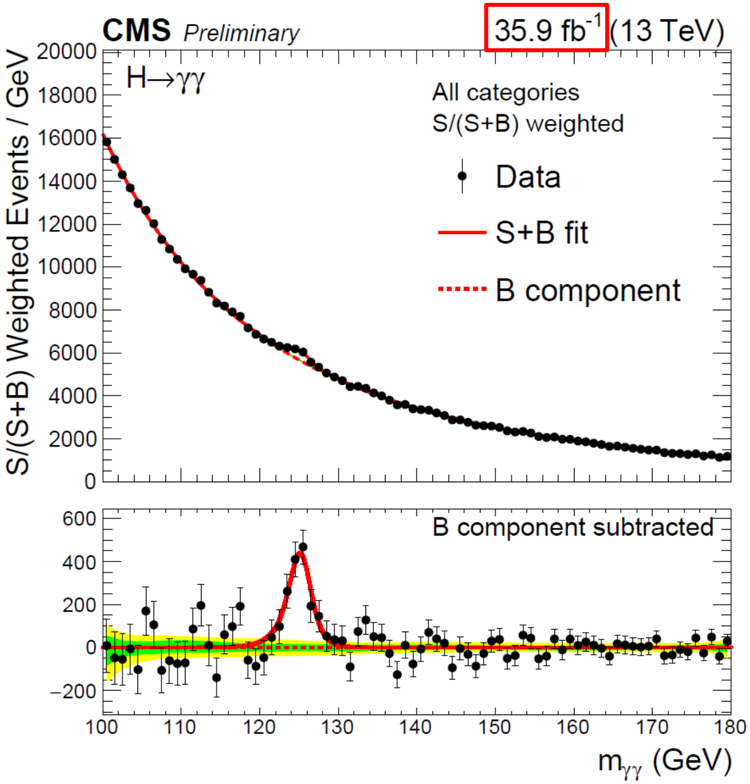
Bosonic couplings

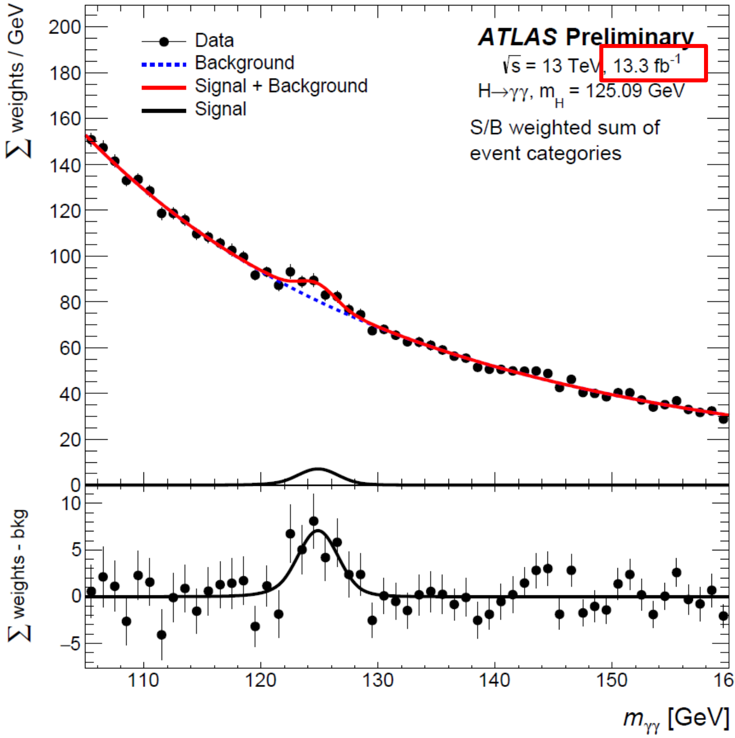
H→γγ @ 13 TeV

CMS PAS HIG-17-015

ATLAS-CONF-2016-067

- The Higgs signal in the di-photon channel has been clearly re-discovered in the 2016 data

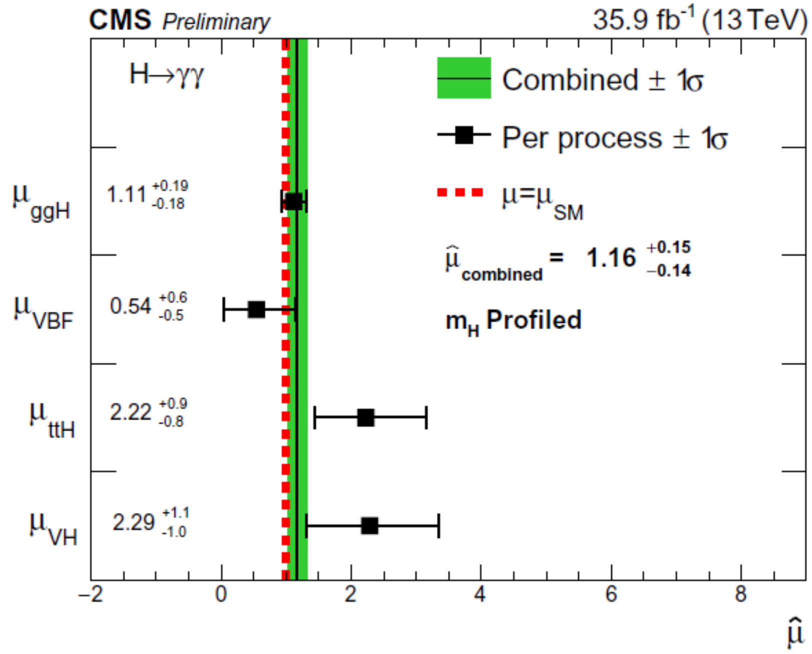


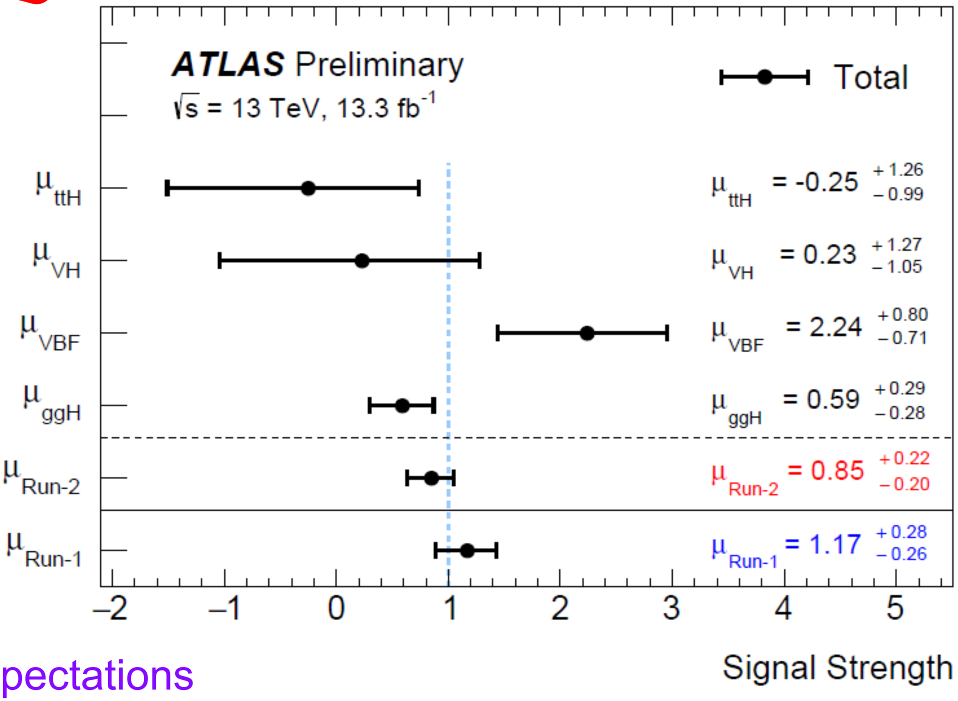


H→γγ: Signal strength

CMS PAS HIG-16-040

NEW!





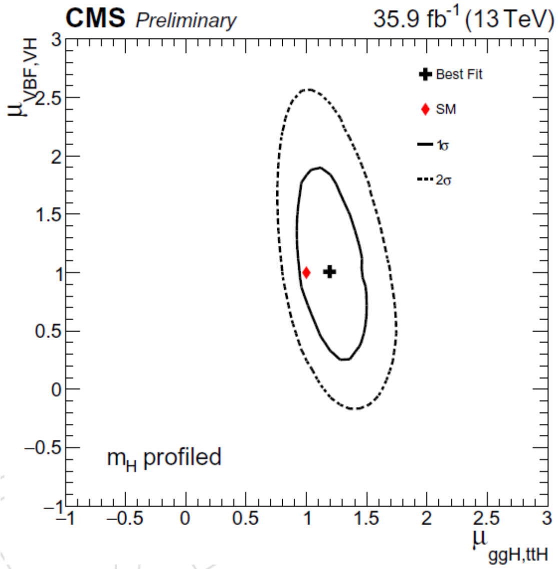
- ➔ Signal strength agrees well with SM expectations
- ➔ Good agreement between ATLAS and CMS
- Fiducial, differential and Simplified Template cross sections:
  - see next presentation by Stefan Gadatsch

ATLAS: $\mu = 0.85^{+0.22}_{-0.20}$
CMS: $\mu = 1.16^{+0.15}_{-0.14}$

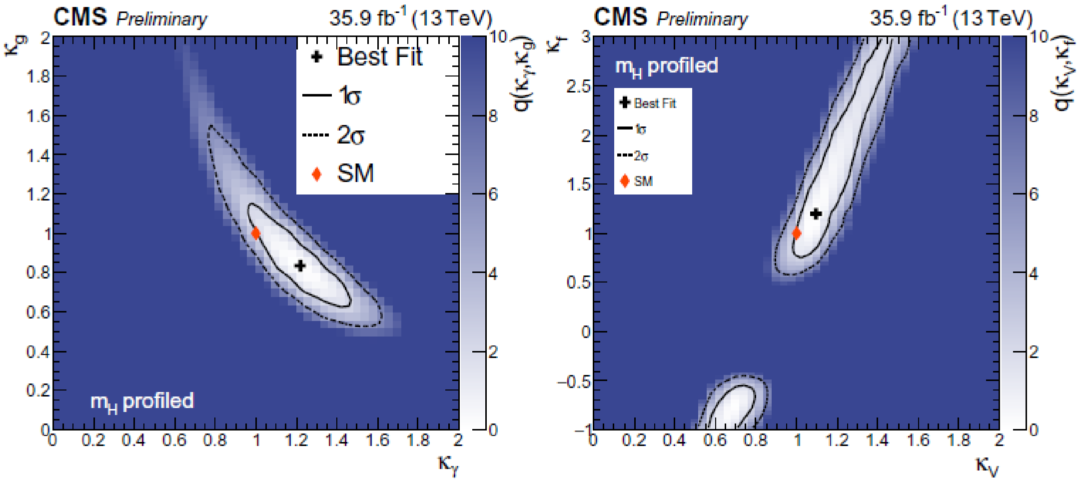
H→γγ properties

NEW!

- Signal strengths for fermionic (ggH, ttH) vs bosonic (VBF, VH) production modes (2D likelihood scan)



- Coupling modifiers in 2D likelihood scans
    - γ vs. g
    - fermion vs. vector boson



➔ In all cases, no deviations from SM couplings observed

H→ZZ*→4 ℓ (full 2016 statistics)

CMS PAS HIG-16-041 | ATLAS-CONF-2017-032

- Improve sensitivity by introducing mutually exclusive categories

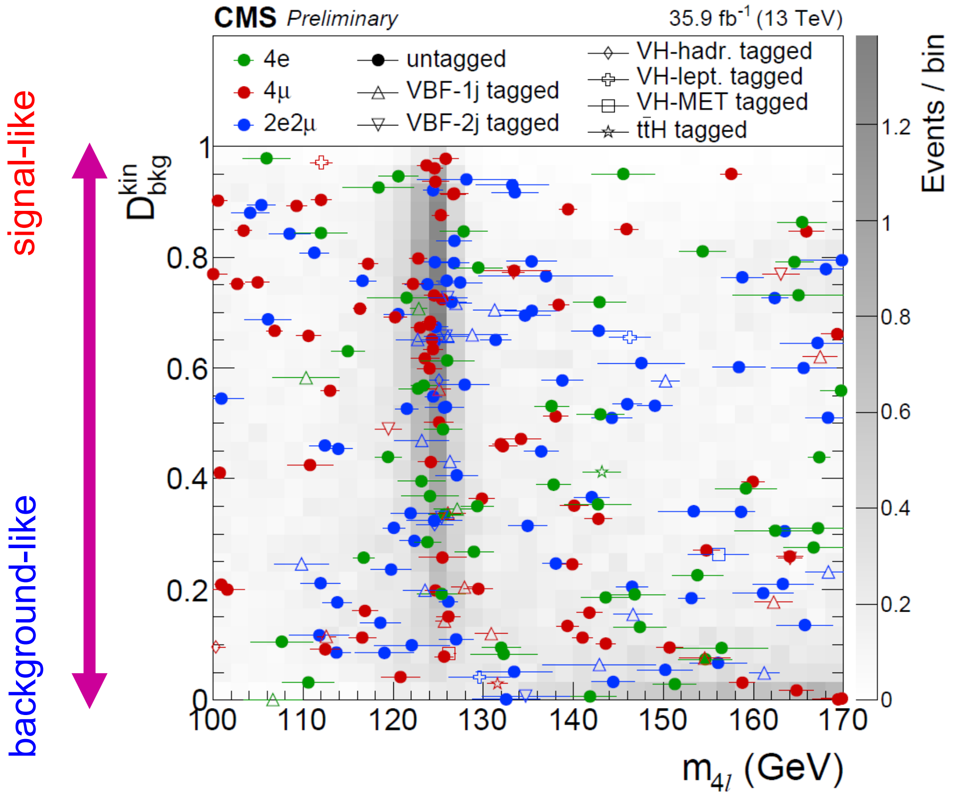
- Signal / background discrimination performed based on matrix elements

background process

$$\mathcal{D}^{\text{kin}}_{\text{bkg}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\text{bkg}}(\vec{\Omega}^{\text{H}\to4\ell}|m_{4\ell})}{\mathcal{P}^{gg}_{\text{sig}}(\vec{\Omega}^{\text{H}\to4\ell}|m_{4\ell})}\right]^{-1}$$

signal process

- Signal extraction performed in 2D variable space $(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$
- Simultaneous fit to all categories

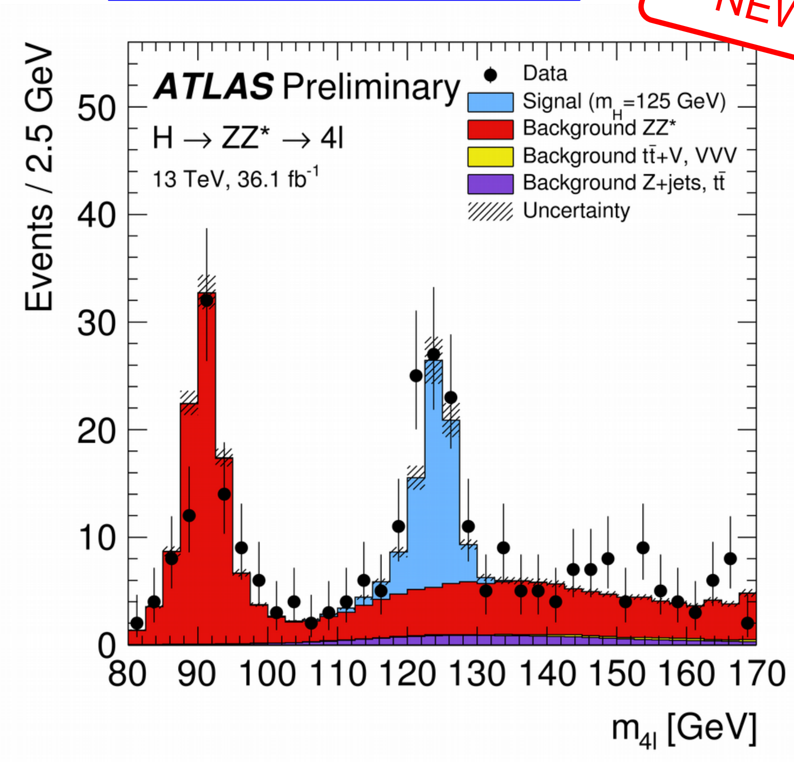


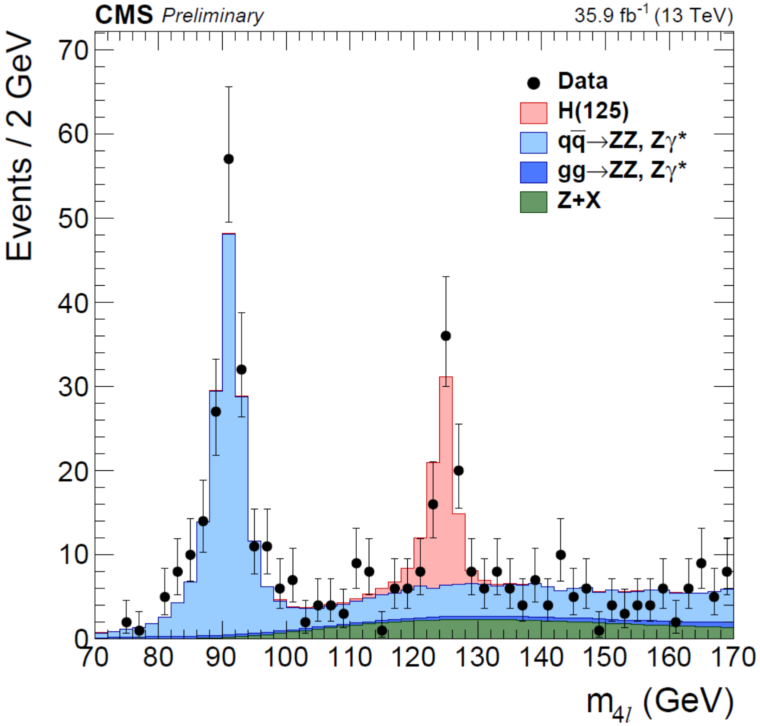
$H \rightarrow ZZ^* \rightarrow 4\ell$

ATLAS-CONF-2017-032

NEW!

CMS PAS HIG-16-041





- ➔ Excellent mass resolution. Signal strength in perfect agreement with SM
- Fiducial and differential cross sections: see next talk

ATLAS: $\sigma_{tot} = 69^{+10}_{-9} \pm 5\, pb$

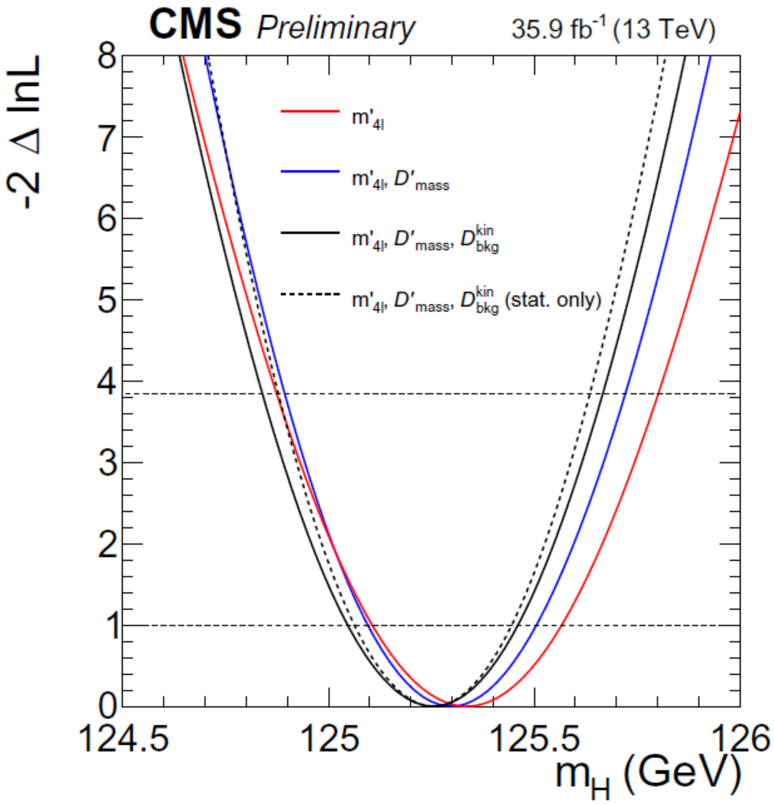
$\sigma_{SM} = 55.6 \pm 2.5\, pb,\ p = 0.19$

CMS: $\mu = 1.05^{+0.19}_{-0.17}$

Run 2 mass (4ℓ)

CMS PAS HIG-16-041

- Significant methodical improvements compared to the Run I analysis
- 3D fit, $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$
- Kinematic fit: higher mass Z is usually on-shell
  → apply mass constraint
- Likelihood scan of Higgs mass, combining the different 4l decay channels
- Result:
  - $m_H = 125.26 \pm 0.20\,(stat.) \pm 0.08\,(syst.)\ GeV$
  - observed uncertainty is smaller than expected by ~ 49 MeV (p-value ~18%)



➔ This single channel, single experiment Run 2 measurement is already more precise than the full ATLAS+CMS Run 1 combination:

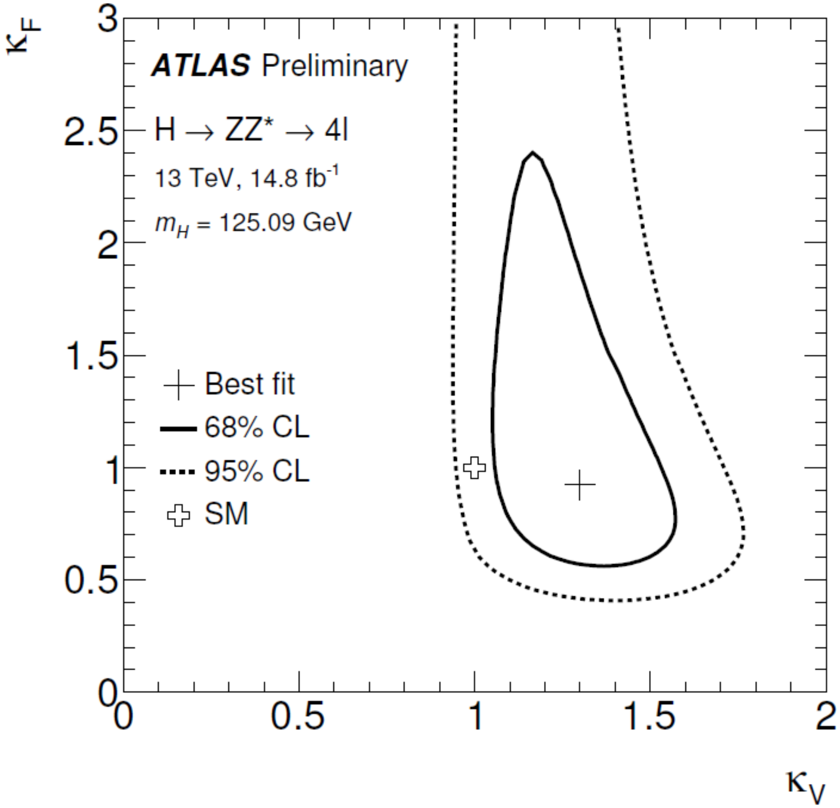
  - $m_H = 125.09 \pm 0.21\,(stat.) \pm 0.11\,(syst.)\ GeV$
  - still statistics-limited

Run 2 couplings

ATLAS-CONF-2016-079

- Vector vs fermion coupling (assume no new particles in the loops)

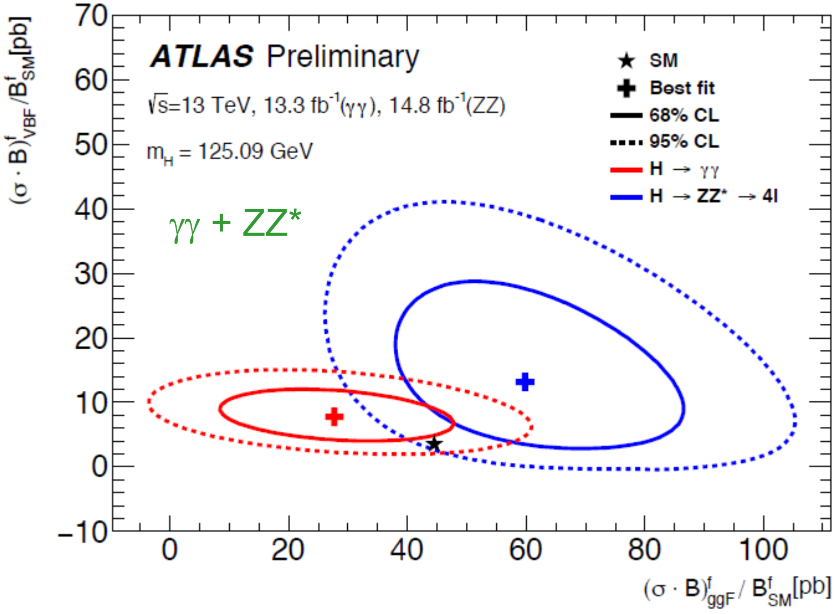
Run 2 (ZZ* only)



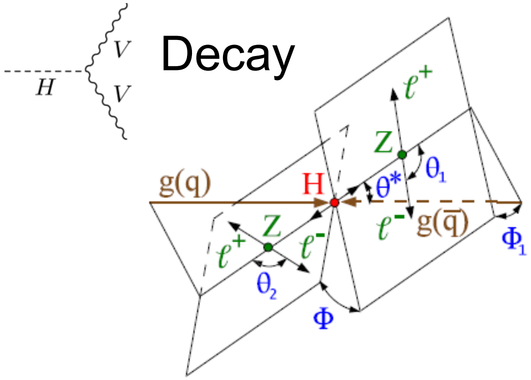
ATLAS-CONF-2016-081

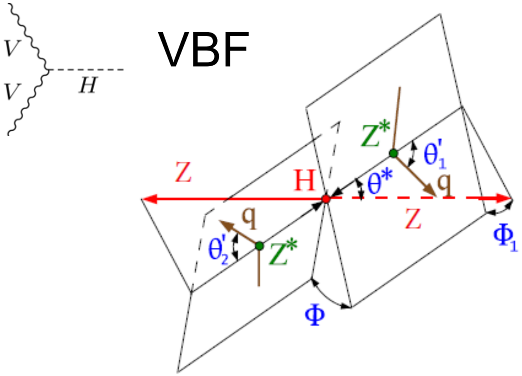
- Measurements of ($\sigma\cdot$ BR) in ggF and VBF are generally correlated, since they contribute jointly to event categories → contours are shown

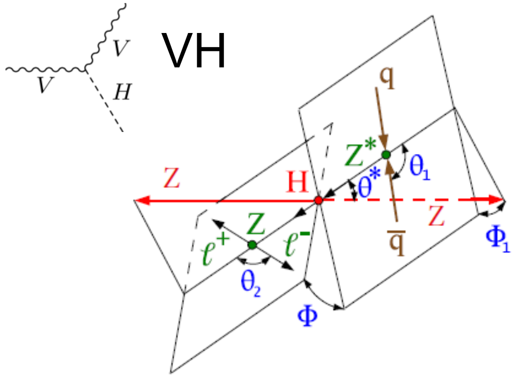
→ Compatible with SM (p-value 11%)



Anomalous VVH couplings?







- Anomalous HVV couplings (→ BSM) can show both in production (VBF, VH) and decay (H→ZZ) → investigate in final states with 4ℓ
- Use full angular information from production & decay modes, compare with matrix element computations (JHUGen+MCFM, MELA package)
- Discriminants to separate/isolate
  - signal from background
  - anomalous from SM couplings
  - interference contribution

$$\mathcal{D}_{\mathrm{bkg}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{bkg}}(\vec{\Omega})}.$$

$$\mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}. \quad \mathcal{D}_{\mathrm{int}} = \frac{\mathcal{P}^{\mathrm{int}}_{\mathrm{SM-BSM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})},$$

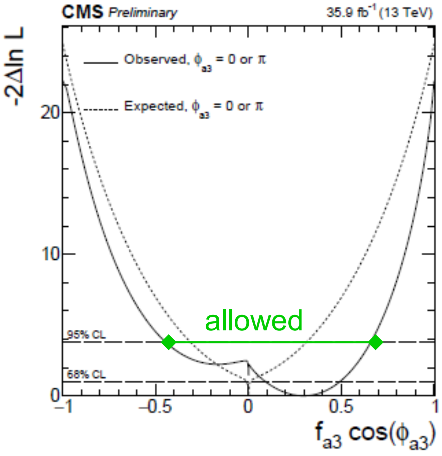
Anomalous VVH couplings (cont'd)

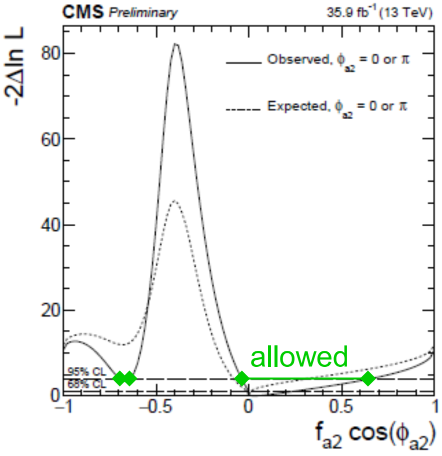
CMS PAS HIG-17-011

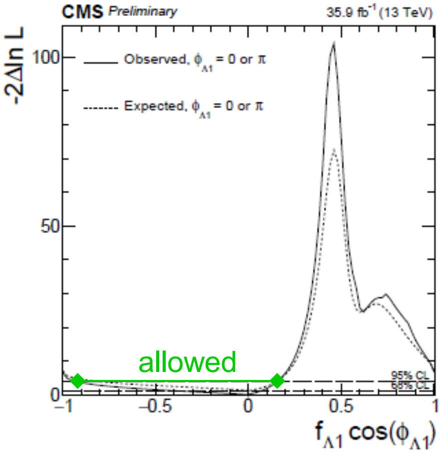
- With an overall likelihood fit, determine coefficients of general tensor structures in scattering amplitudes as allowed by Lorentz symmetry, beyond the SM case
  - including lowest-order terms in form factor expansion
  - assume couplings for WW and ZZ are identical

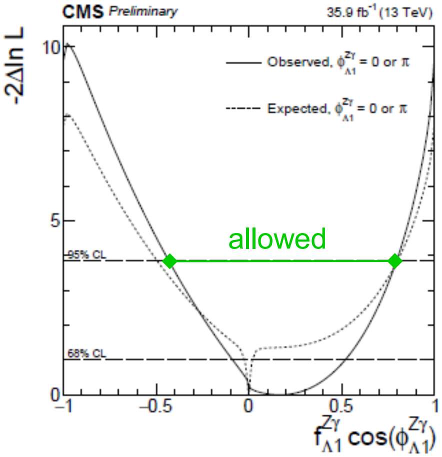
➔ All BSM-related coefficients are found to be compatible with zero (=SM)

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$







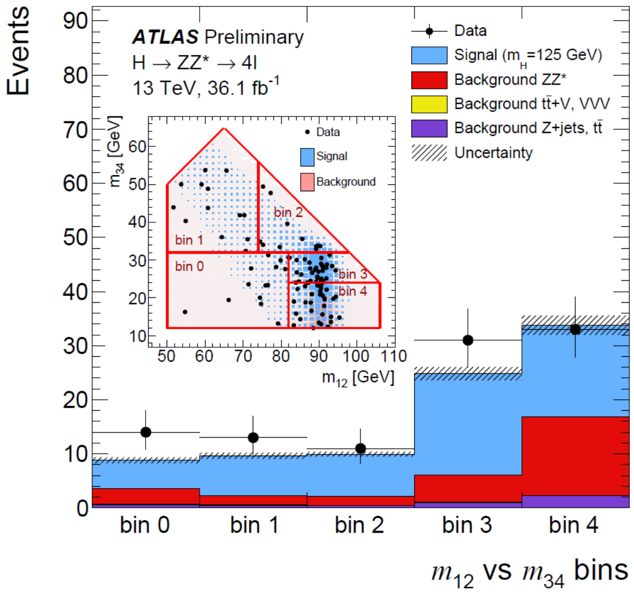


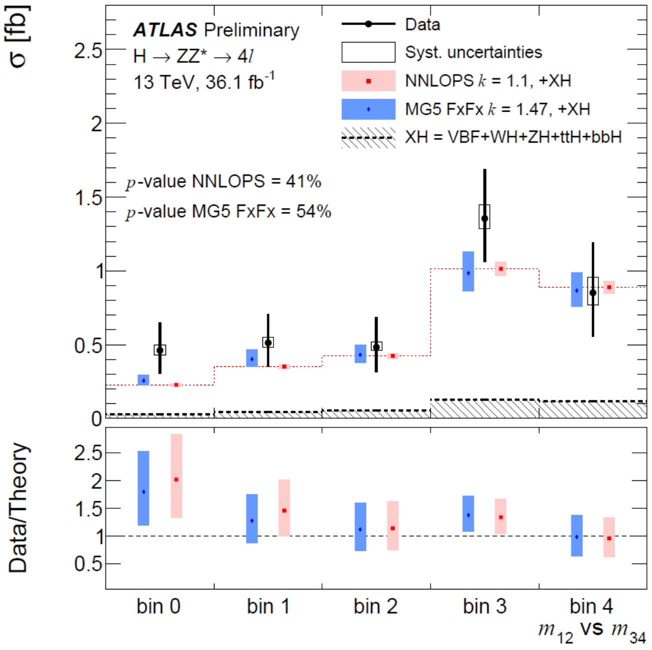
Anomalous couplings (cont'd)

ATLAS-CONF-2017-032

NEW!

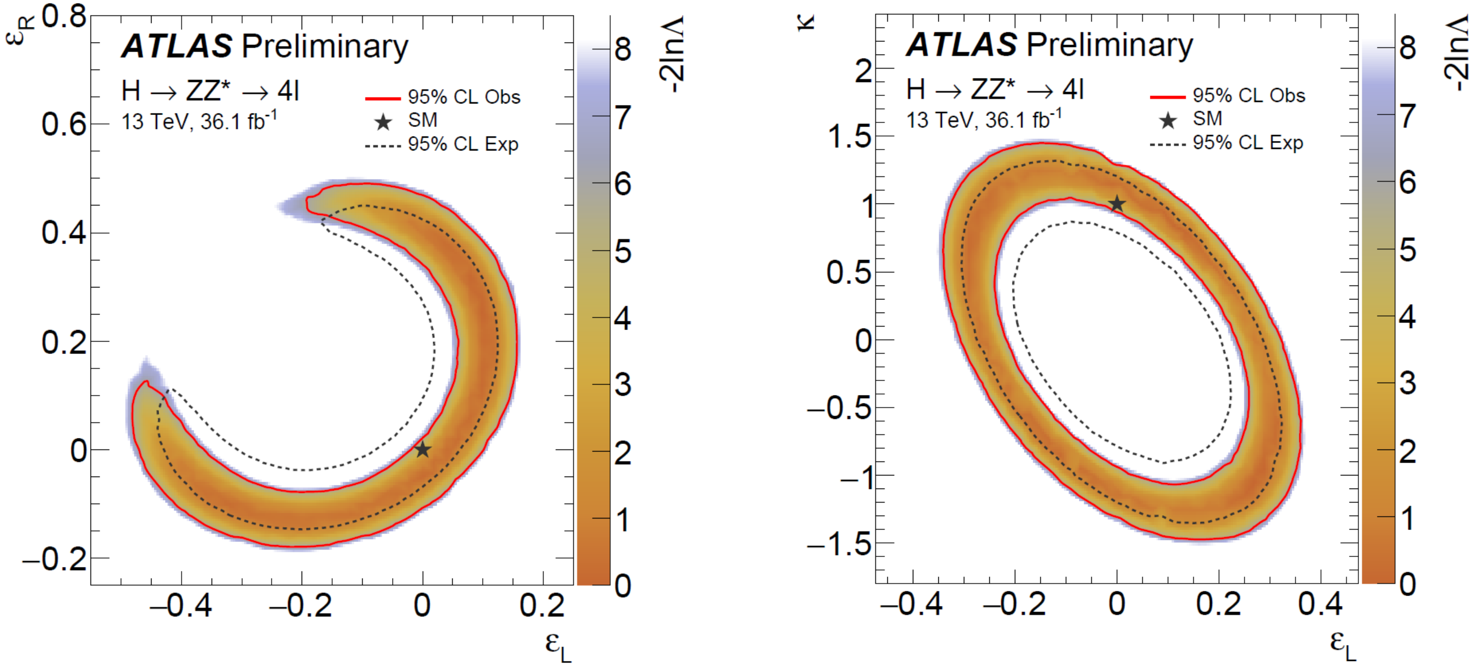
- Distribution of m_{12} vs m_{34} (where $m_{12} > m_{34}$) is sensitive to modified Higgs couplings
  - studied in the context of pseudo-observables (Eur.Phys.J. C75 (2015) 128 + 341)
  - e.g. modified contact terms → ϵ_L and ϵ_R
- (m_{12}, m_{34}) distribution mapped to 5 bins
  - good data / MC agreement





Anomalous couplings (cont'd)

ATLAS-CONF-2017-032



- Assuming lepton flavor universality. Also considering modification of Higgs-to-Z coupling (κ)

➔ SM parameters ($\epsilon_L = \epsilon_R = 0;\ \kappa = 1$) are included within allowed region

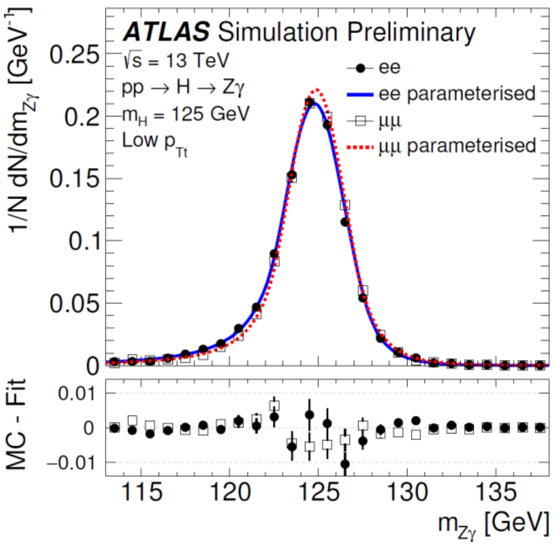
  ➔ no indication for anomalous couplings

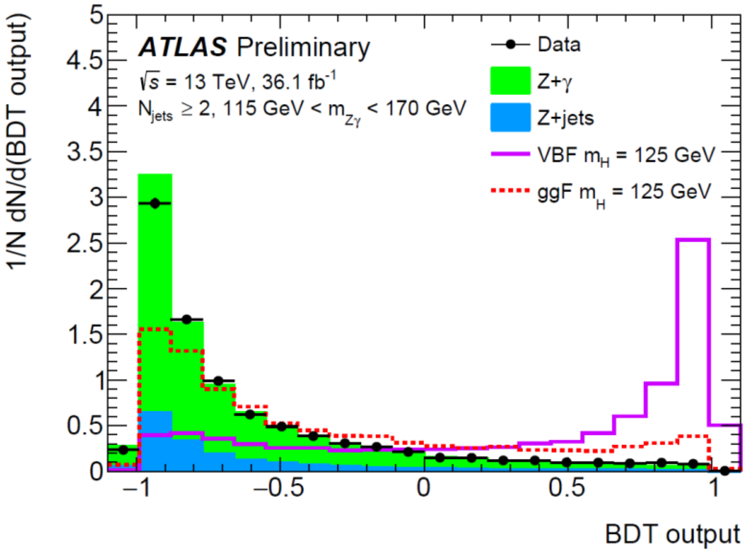
H→Zγ

NEW!

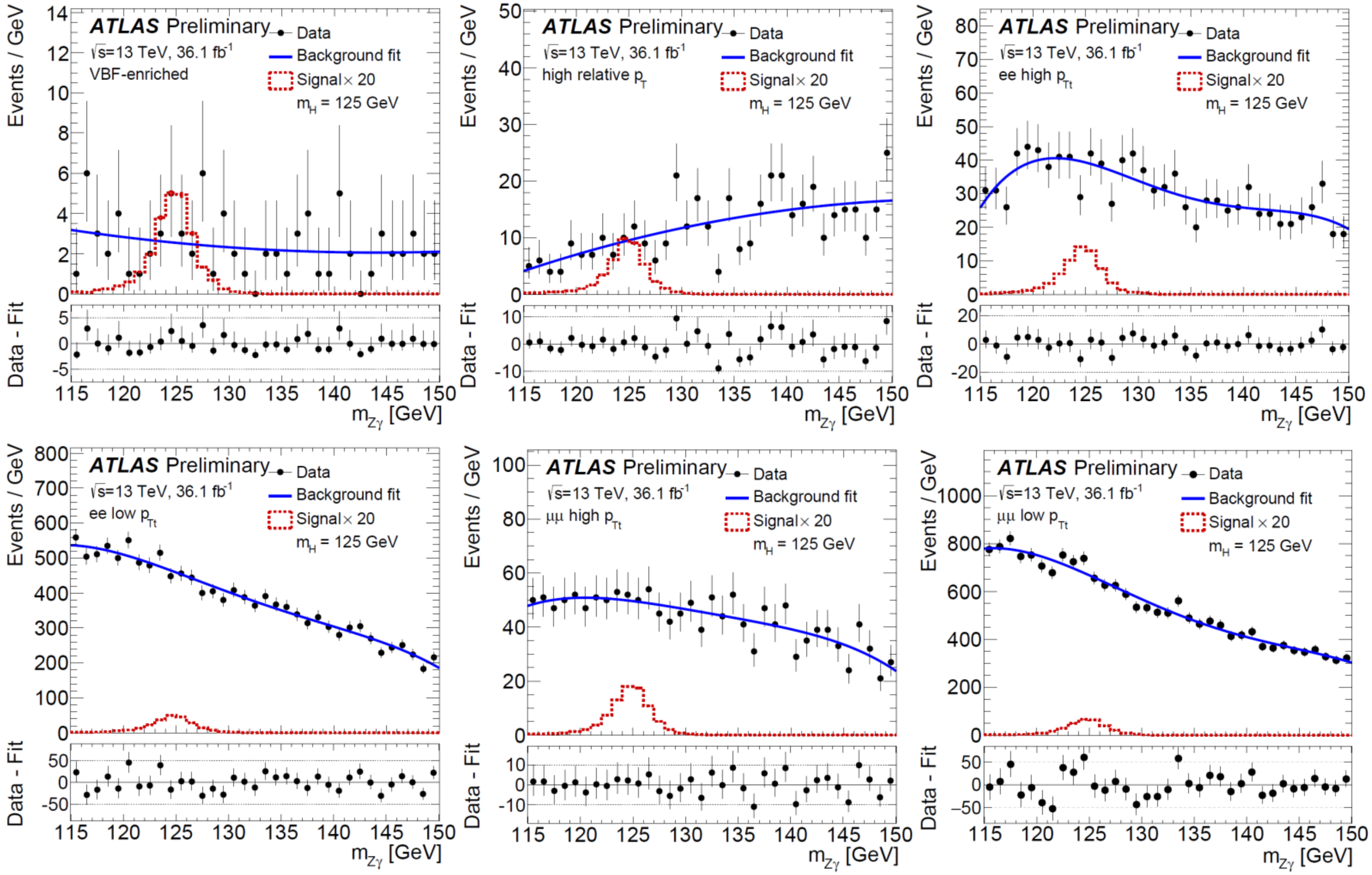
CERN-EP-2017-095

- In the SM, H→Zγ proceeds through loop diagrams similar to H→ γγ
  - with BR of similar magnitude (1.54×10^{-3})
- Various BSM scenarios could lead to a deviating BR
  - e.g. composite scalars, new particles in the loop
- Main backgrounds: non-resonant Z + γ, Z + jet (fake photon)
- ATLAS uses BDT to separate signal from backgrounds
  - six categories





H→Zγ (cont'd)



- ➔ No signal observed (yet). $\sigma \cdot BR(H \to Z\gamma) < 6.6\ (\sigma \cdot BR)_{SM}\quad (5.2\ exp.)\ @\ 95\%\ CL$
- ➔ Assuming SM Higgs cross section: $BR(H \to Z\gamma) < 0.01$

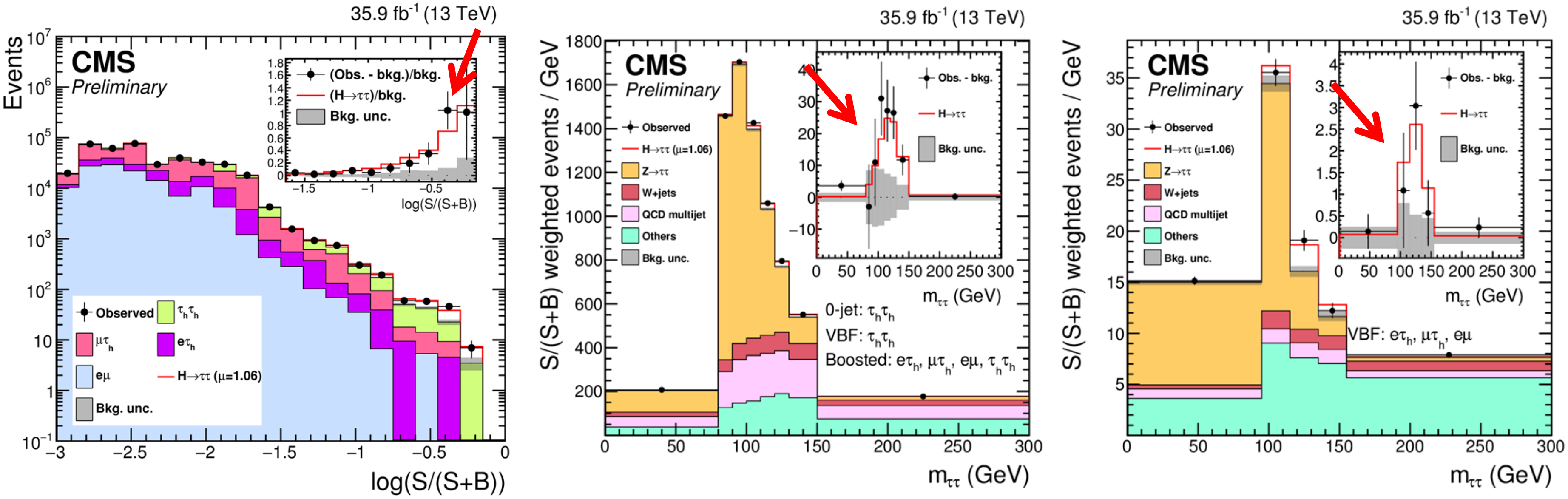
Fermionic couplings

H→ττ

CMS PAS HIG-16-043

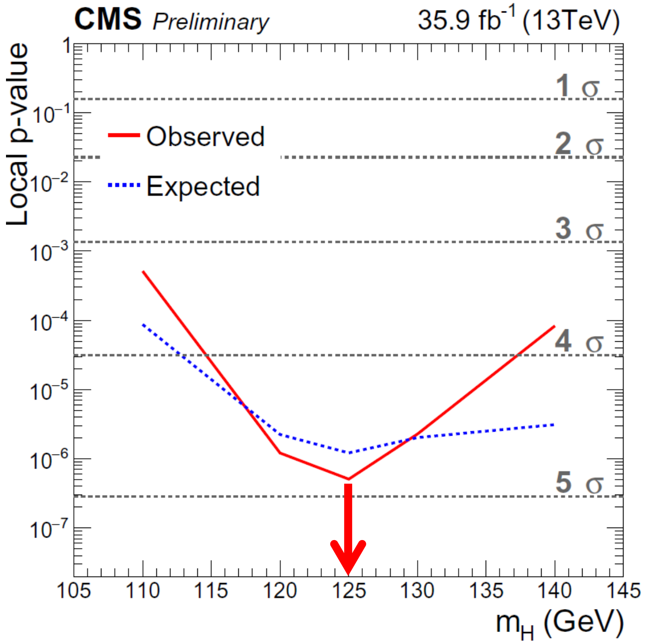
NEW!

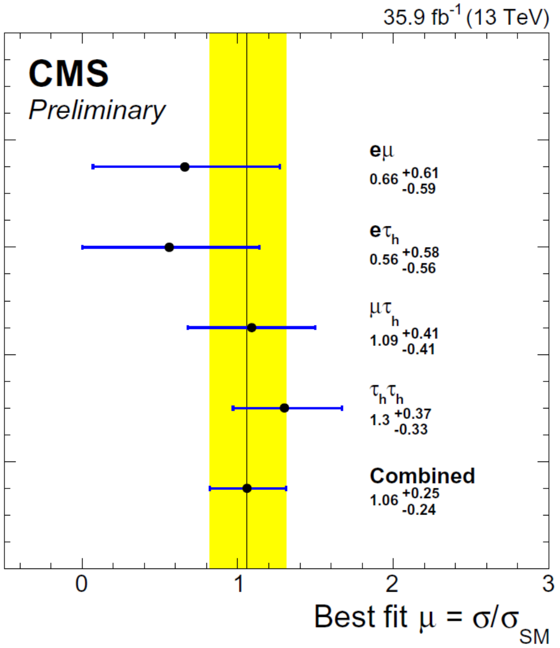
- Four decay mode combinations used: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, $e\mu$
- Categories: 0 jet, VBF, boosted
- Main backgrounds: Drell-Yan, W/Z+jets, $t\bar{t}$, QCD
- Global likelihood fit in 2D distributions of discriminating variables in all channels
  - m_{vis}, p_T^{μ}, $m_{\tau\tau}$, m_{jj}, $p_T^{\tau\tau}$, τ_h decay mode



➔ Clear excess at m_H=125 GeV

H→ττ [cont'd]





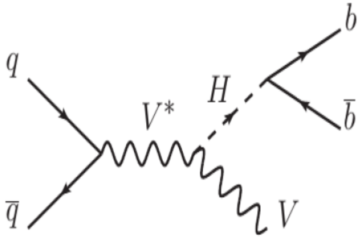
- ➔ Minimum of p-value at m_H=125 GeV

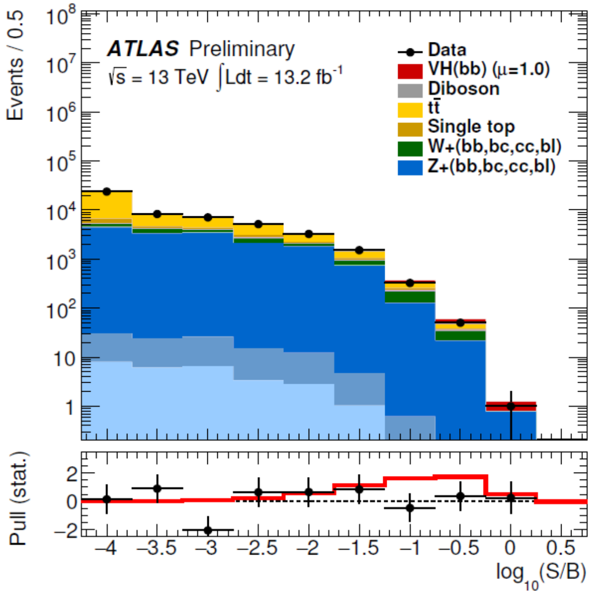
CMS (Run 2):	$\mu =$	1.06 ± 0.25	(4.9σ obs., 4.7σ exp.)
[ATLAS + CMS (Run 1):	$\mu =$	$1.12^{+0.25}_{-0.23}$	(5.5 σ)]

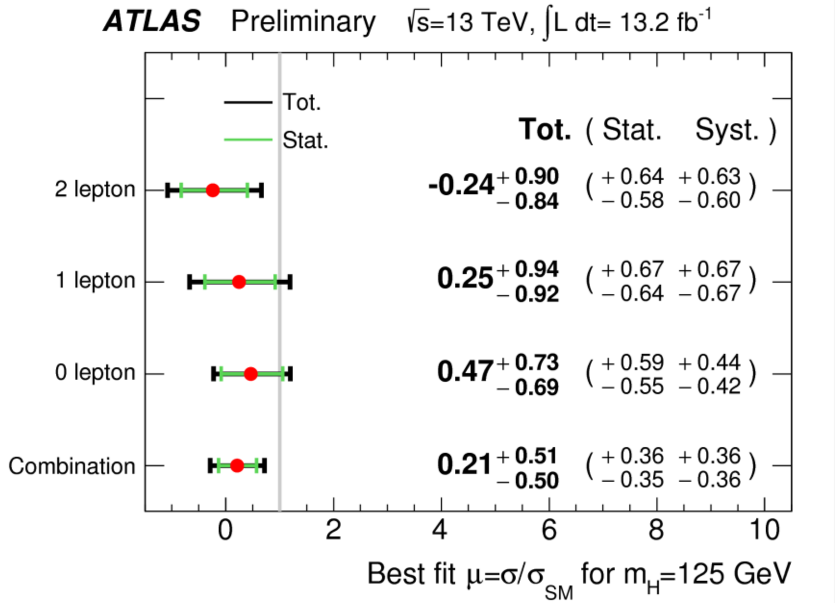
➔ For the first time, single-experiment sensitivity for a fermionic decay channel touches 5σ level

H→bb

- H→bb dominant decay mode in SM, but not yet discovered
  - golden channel: associated production with vector boson (W or Z)
  - three main categories: no lepton (Z→νν), one lepton (W→ℓν), two leptons (Z→ ℓℓ). Cross check with VZ production.







- ➔ Not yet exceeding Run 1 sensitivity
- ➔ Wait for analysis of full 2016 dataset

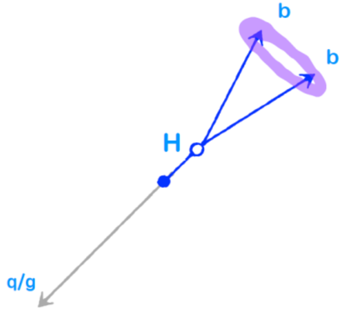
ATLAS Run 2: $\mu = 0.21^{+0.51}_{-0.50}$ (0.42σ)
[ATLAS + CMS (Run 1): $\mu = 0.69^{+0.29}_{-0.27}$ (2.6 σ)]

H→bb in boosted topology

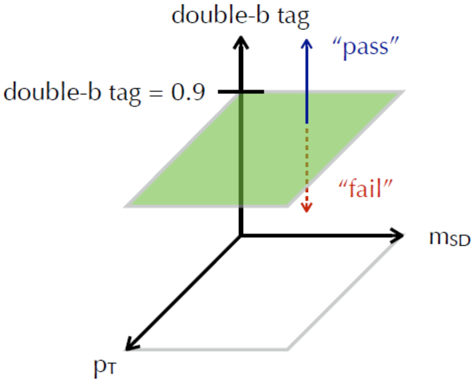
CMS PAS HIG-17-010

NEW for Blois2017!

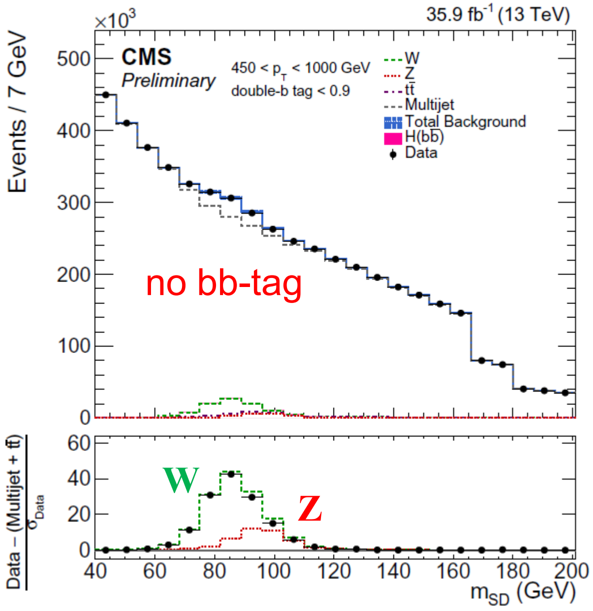
- Inclusive search for H→bb in gluon fusion traditionally considered hopeless
  - overwhelming multi-jet background
- New idea: inclusive Higgs search at very high p_T [e.g. JHEP05 (2014) 022]
  - "boosted topology"
  - both b's in a single jet → substructure
  - recoiling quark or gluon jet

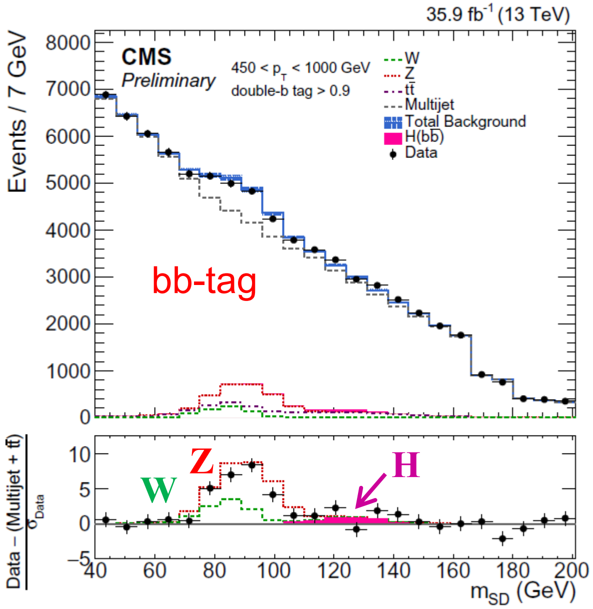


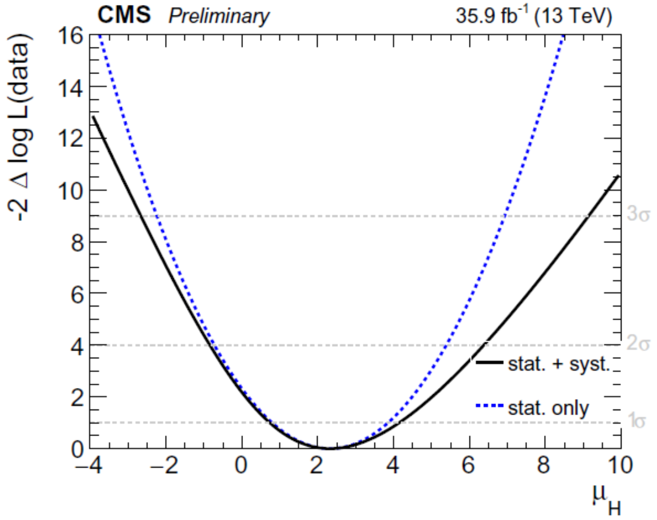
- Methodology:
  - reconstruct H decay products as one AK8 jet
    - $p_T > 450$ GeV
  - double b-tag within jet
  - soft drop algorithm to reconstruct mass
- Background estimation using control region of events with jets failing double b-tag



H→bb boosted (cont'd)







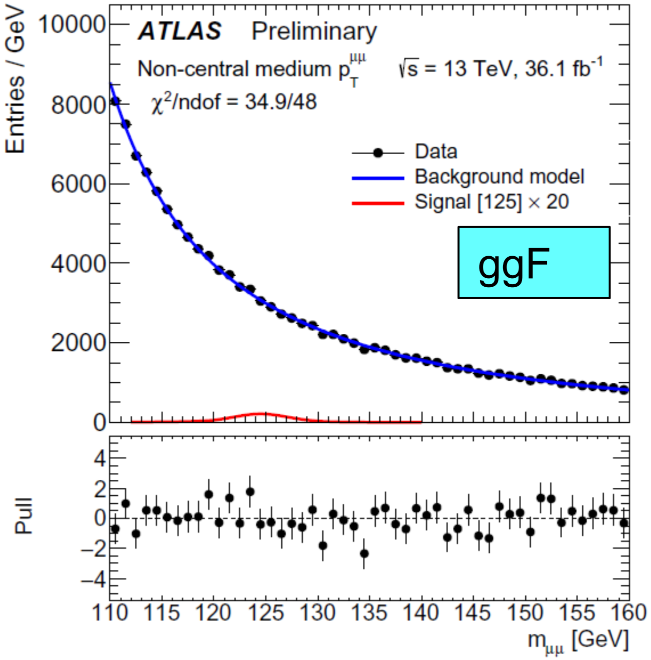
- Clear observation of resonant Z signal (standard candle)
  - $\mu_Z = 0.78^{+0.23}_{-0.19}$, 5.1σ (5.8σ expected)
  - ➔ proof of principle
- Higgs boson searched in the same distribution
  - $\mu_H = 2.32^{+1.80}_{-1.57}$, 1.5σ (0.7σ expected)

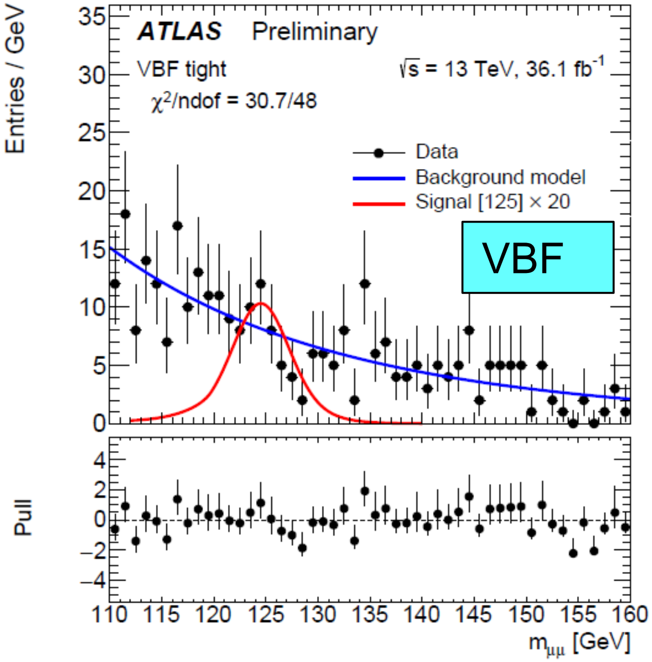
➔ Novel analysis. Very promising technique

H→μμ

ATLAS-CONF-2017-014

- Yukawa coupling of 2nd generation fermion. SM predicts very small BR (2.18×10^{-4}).
- Clean experimental signature. Main background: Drell-Yan
- Six categories for gluon fusion, two for VBF





$$\mu = \quad -0.1 \pm 1.5$$
$$\mu < 3.0\, obs.\, (3.1\, exp.)$$

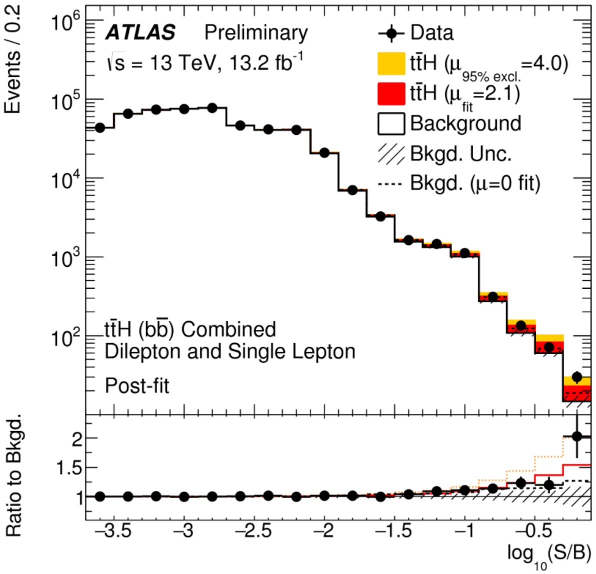
→ Channel gradually comes into reach → hope for 3σ sensitivity before HL-LHC

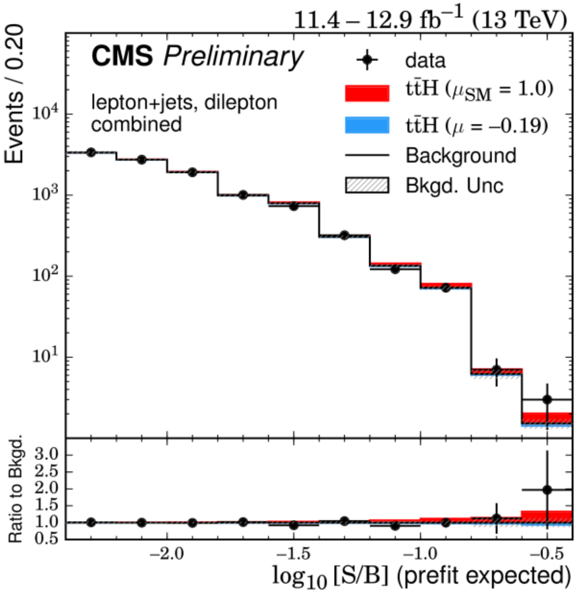
ttH: bb channel

ATLAS-CONF-2016-080

CMS PAS HIG-16-038

- Allows direct measurement of top quark Yukawa coupling. Very challenging.
- ttH(→bb) analysis:
  - two-stage multivariate approach (ATLAS), BDT + matrix element (CMS)





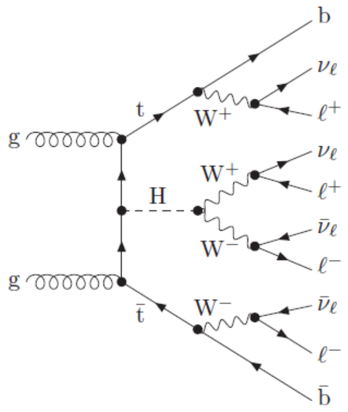
- ATLAS: $\mu = 2.1^{+0.5}_{-0.5}(stat.)^{+0.9}_{-0.7}(syst.)$; CMS: $\mu = -0.19^{+0.45}_{-0.44}(stat.)^{+0.66}_{-0.68}(syst.)$
- Increasing role of systematic uncertainties
- No clear evidence for ttH(→bb) yet → wait for results from full 2016 dataset

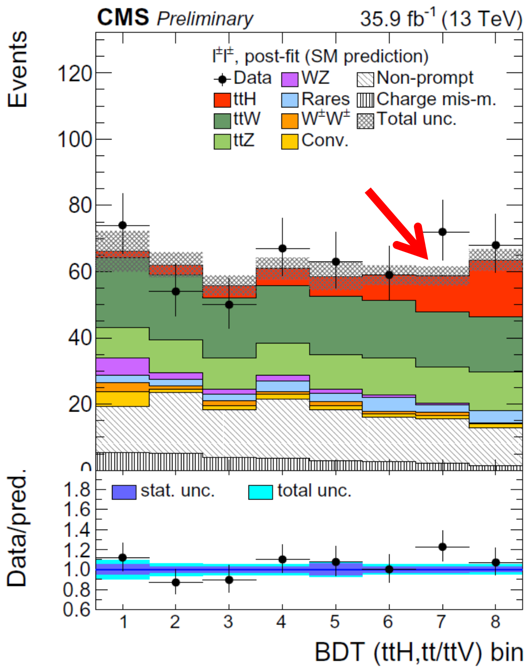
ttH: multi-lepton channel

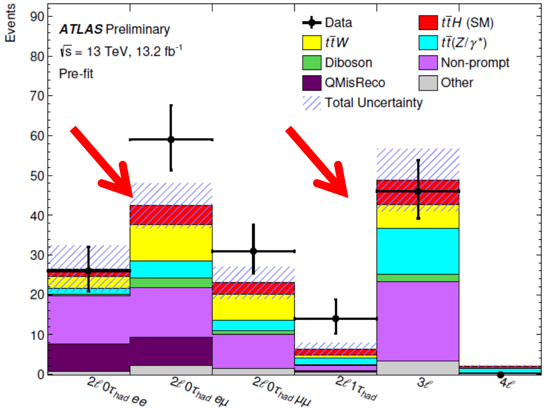
ATLAS-CONF-2016-058

CMS PAS HIG-17-004

- ttH with mainly H→WW, ZZ, ττ
    - for CMS, events with ≥1 τ_h go into separate analysis (CMS PAS HIG-17-003)
- Select events with $\ell^\pm\ell^\pm$ or ≥3ℓ, plus jets and btags
- Main backgrounds:
    - tt + W / Z / γ^* production
    - tt + jets
- Signal extraction strategies:
    - ATLAS: counting experiment
    - CMS: BDT approach for 2ℓ and 3ℓ





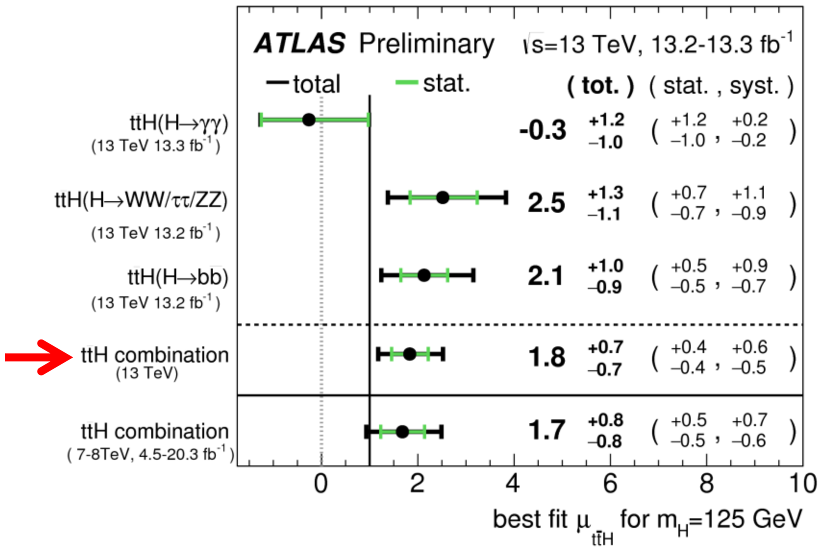


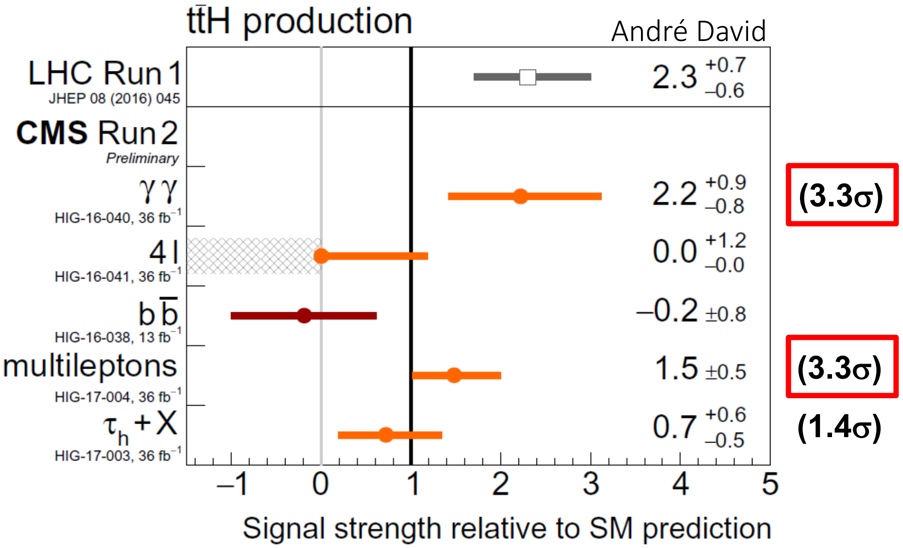
ATLAS (13.2 fb^{-1}) $\mu = 2.5\,^{+1.3}_{-1.1}$ (2.2σ)

CMS (35.9 fb^{-1}): $\mu = 1.5 \pm 0.5$ (3.3σ)

➔ "Evidence" for ttH production from a single channel

ttH: combination





- ATLAS performed combination of all channels at level of ~13 fb^{-1}
  - ➔ Run 1 + Run 2 results are in good agreement, similar sensitivity
- CMS also measured ttH in additional channels
  - ➔ also ttH(➔γγ) gives >3σ
- Looking forward to full 2016 ttH combination

ATLAS-CONF-2016-068

CMS PAS HIG-17-003

CMS PAS HIG-16-040

CMS PAS HIG-16-041

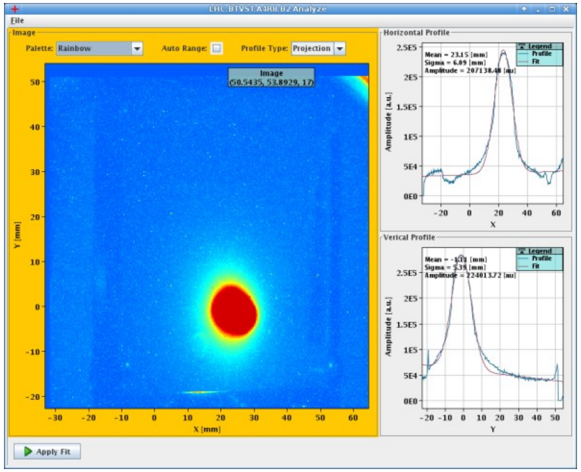
CMS PAS HIG-16-038

Summary

- Run 1 has established the essential finger print of the Higgs boson
  - agrees with SM, although BSM Higgs sector or couplings not excluded
- The first ~40 fb^{-1} of Run 2 @ 13 TeV have already effected big impact
- Improved sensitivity to couplings & other properties already visible
  - many new ideas & methods
  - not all analyses yet at full 2016 statistics → much more to come

- Since end of April, beams are back circulating in the LHC
- First stable beams last Tuesday
- Scrubbing planned for next week
- Physics run planned to start very soon (2nd week of June)

- **Target: 90 fb^{-1} (2017+2018)**



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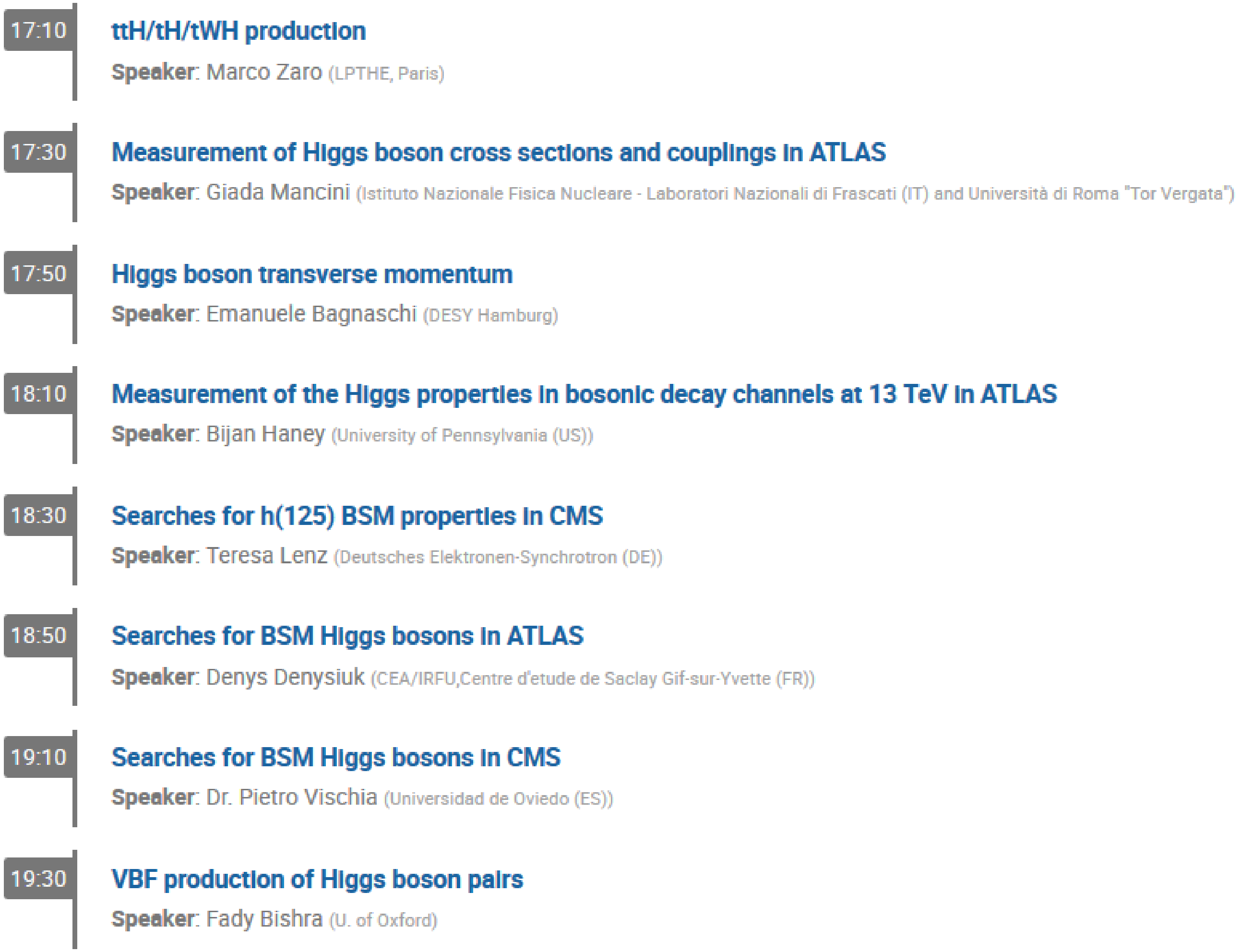
Auto Range: ☐
Profile Type: Projection

Mean = 23.15 [mm]
Sigma = 6.09 [mm]
Amplitude = 207138.48 [au]

Mean = -1.11 [mm]
Sigma = 5.39 [mm]
Amplitude = 224013.72 [au]

from: M. Solfaroli, LHCC Open Session Report, 10-May

Higgs properties in the parallel session (Wed 31 May)



17:10 ttH/tH/tWH production

Speaker: Marco Zaro (LPTHE, Paris)

17:30 Measurement of Higgs boson cross sections and couplings in ATLAS

Speaker: Giada Mancini (Istituto Nazionale Fisica Nucleare - Laboratori Nazionali di Frascati (IT) and Università di Roma "Tor Vergata")

17:50 Higgs boson transverse momentum

Speaker: Emanuele Bagnaschi (DESY Hamburg)

18:10 Measurement of the Higgs properties in bosonic decay channels at 13 TeV in ATLAS

Speaker: Bijan Haney (University of Pennsylvania (US))

18:30 Searches for h(125) BSM properties in CMS

Speaker: Teresa Lenz (Deutsches Elektronen-Synchrotron (DE))

18:50 Searches for BSM Higgs bosons in ATLAS

Speaker: Denys Denysiuk (CEA/IRFU,Centre d'etude de Saclay Gif-sur-Yvette (FR))

19:10 Searches for BSM Higgs bosons in CMS

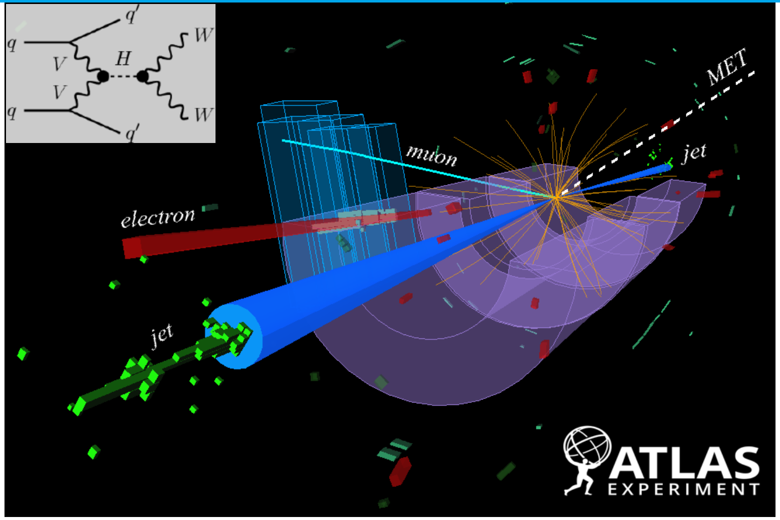
Speaker: Dr. Pietro Vischia (Universidad de Oviedo (ES))

19:30 VBF production of Higgs boson pairs

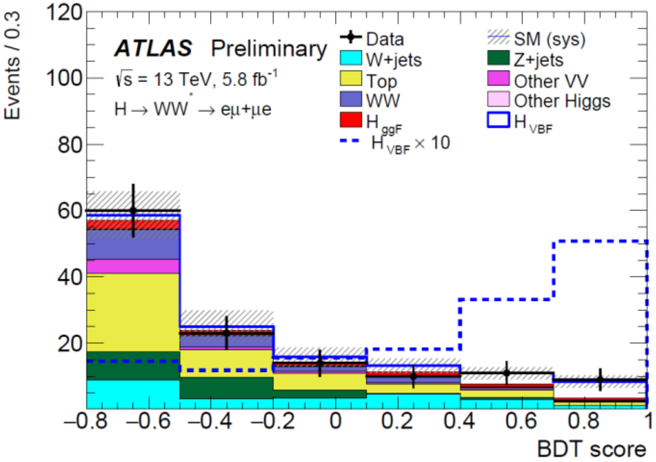
Speaker: Fady Bishra (U. of Oxford)

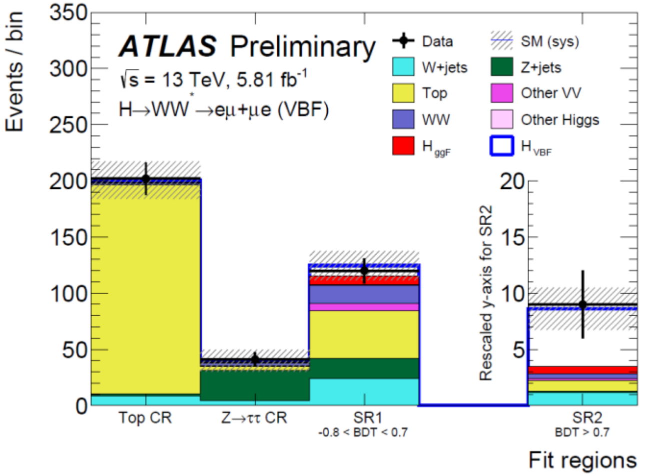
Backup

H→WW



ATLAS-CONF-2016-112





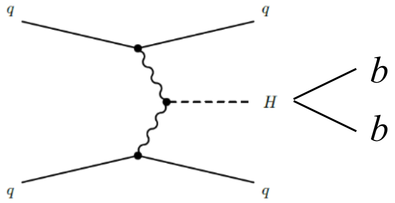
- Strong backgrounds from Drell-Yan and di-boson processes
  - search in $e^+\mu^-$ and $e^-\mu^+$ final states
  - VBF and VH processes
  - Signal extraction from BDT, backgrounds estimated in CR

ATLAS: $\mu_{VBF} = 1.7^{+1.1}_{-0.9}$, 5.8 fb^{-1}

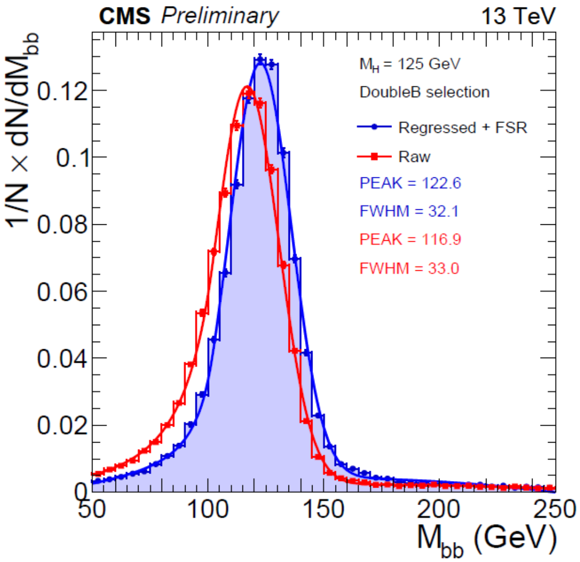
$\mu_{VH} = 3.2^{+4.4}_{-4.2}$, “

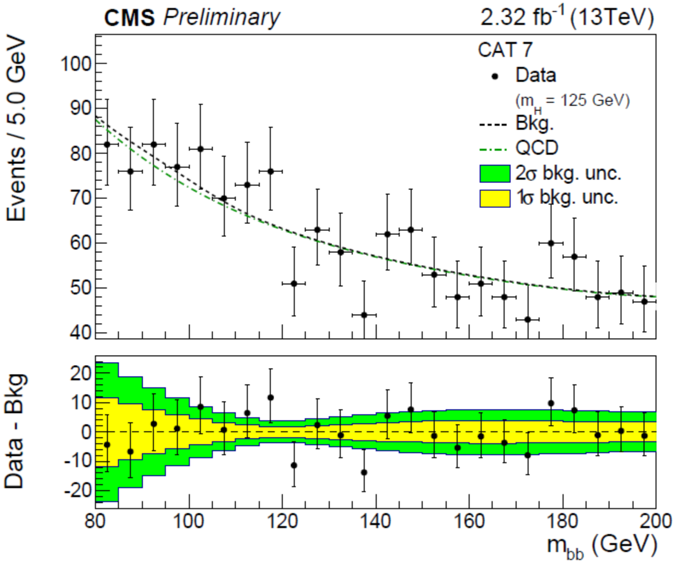
VBF H→bb

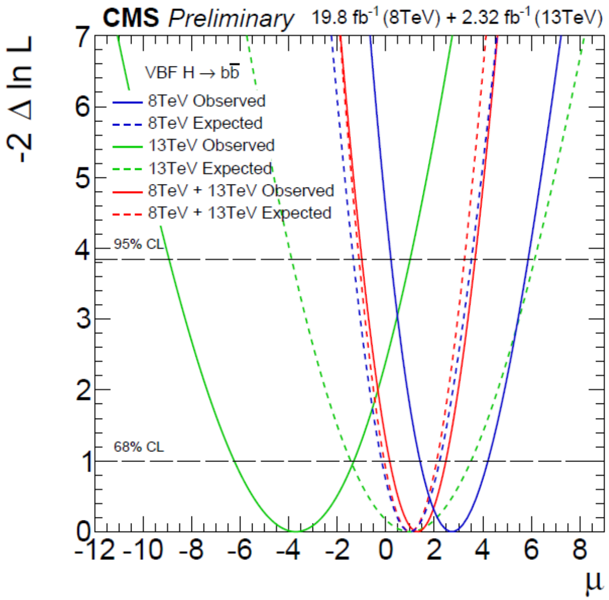
CMS PAS HIG-16-003



- Search for SM Higgs boson in a fully hadronic final state!
  - challenging trigger + backgrounds







- Regression of jet p_T → improves mass resolution
- Event classification with BDT
- Combination of 2012 + 2015 data
- Further improvement expected with 2016 data

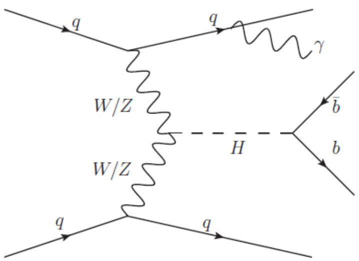
Run 1: $\mu = 2.8^{+1.6}_{-1.4}$

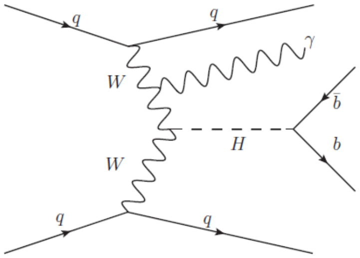
Run 2 (2015): $\mu = -3.7^{+2.4}_{-2.5}$

Combined: $\mu = 1.3^{+1.2}_{-1.1}$

VBF H→bb with photon

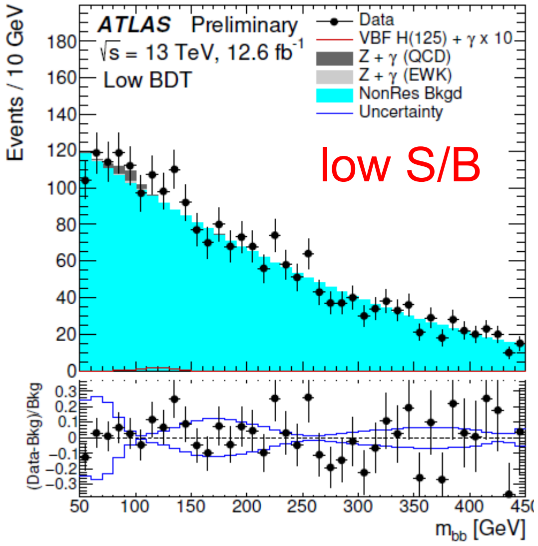
ATLAS-CONF-2016-063



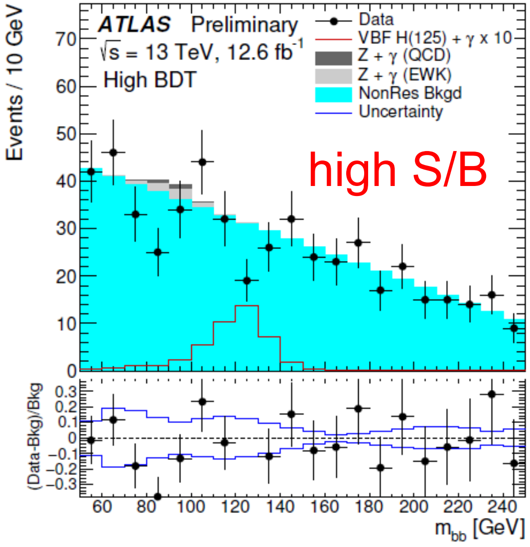


- Dramatic enhancement of signal / background ratio through requirement of additional hard photon
- Destructive interference in central photon background processes
- Easy triggering: γ (p_T>25 GeV) + 4 jets
- Simultaneous fit of m_{bb} in three BDT intervals (two are shown)

$$\boxed{\begin{array}{l} \mathrm{H} + \gamma : \ \mu = -3.9^{+2.8}_{-2.7} \\ \mathrm{Z} + \gamma : \ \mu = \ \ 0.3 \pm 0.8 \end{array}}$$



low S/B



high S/B

→ Very promising sensitivity

→ Complementary to inclusive analysis

LHC Schedule 2017

-

LHC schedule 2017

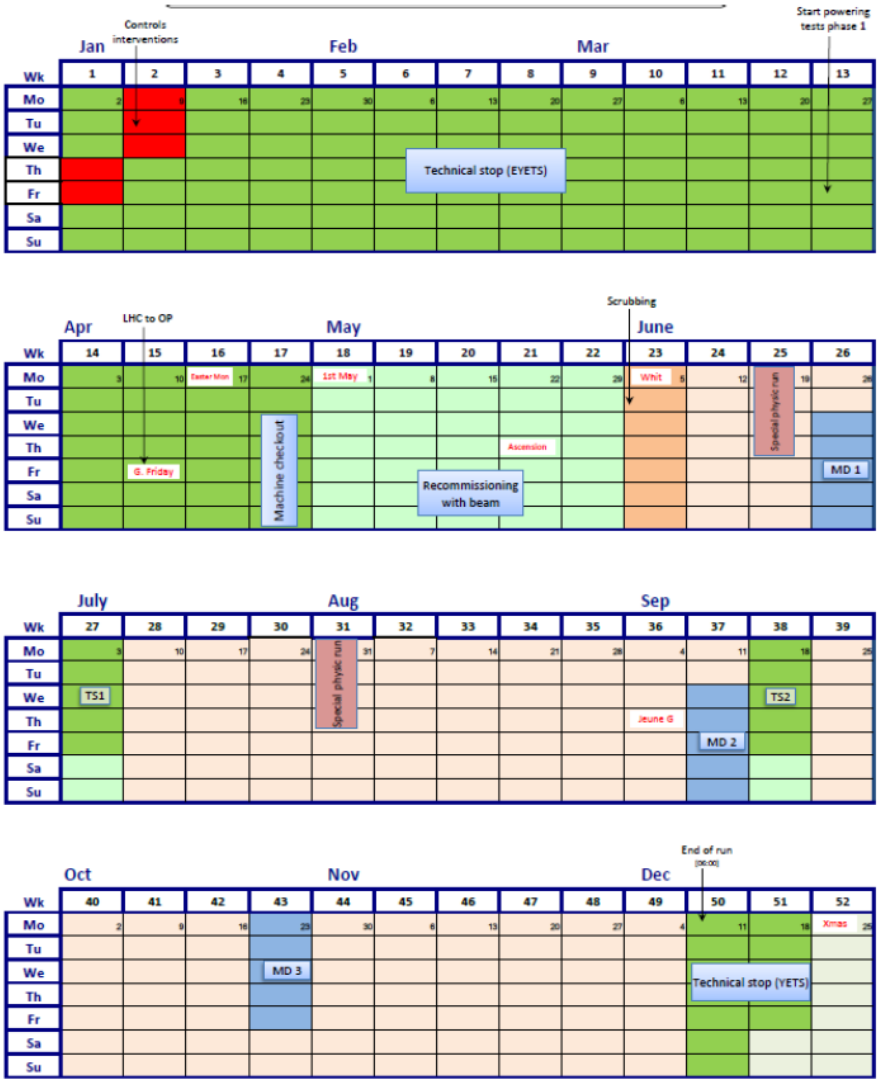
a new production year

~45fb^{-1} (final goal on March 1st)

keeping the LHC availability close to 50% (stable beams)

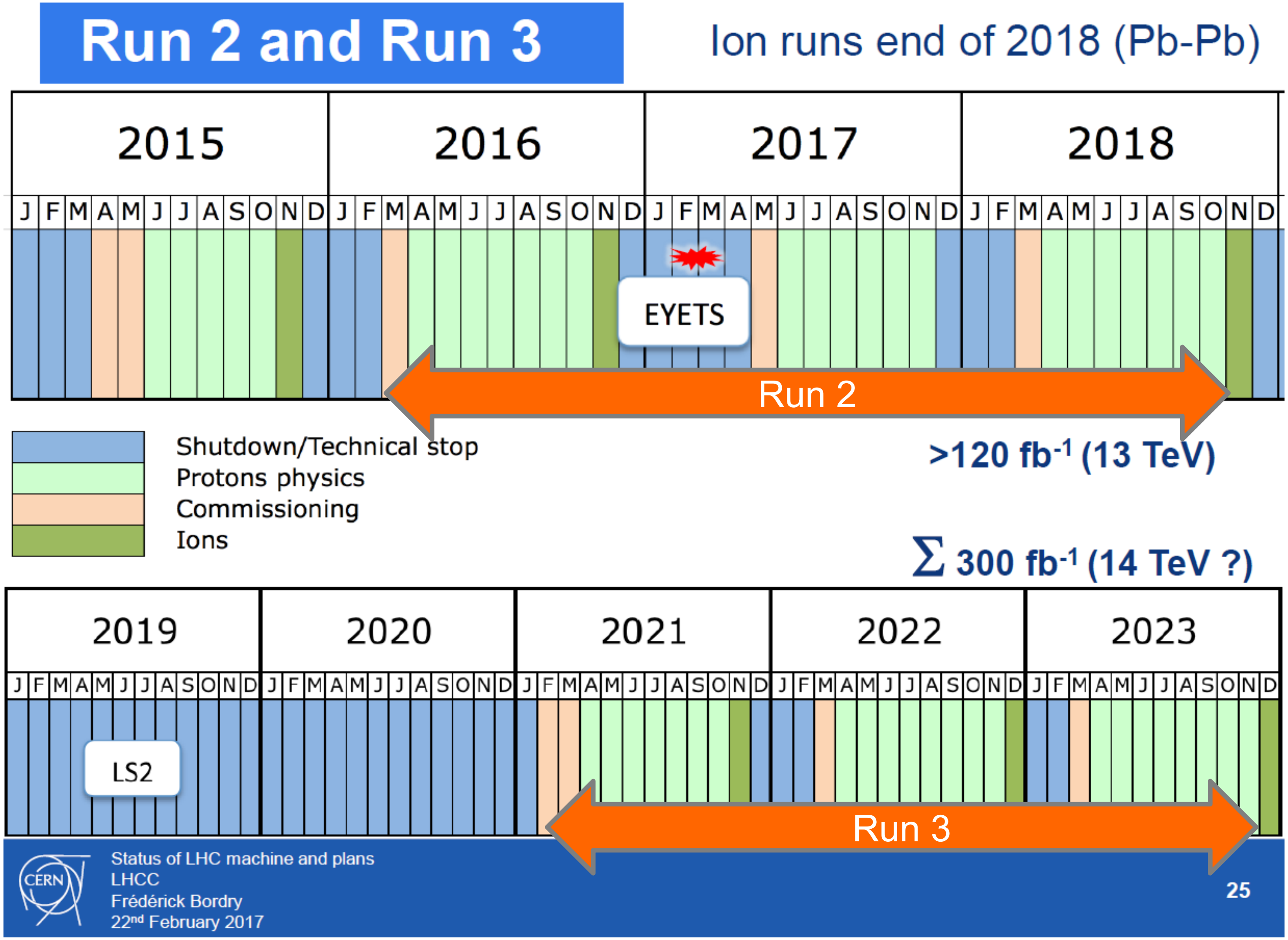
Initially 15 days of MD; later during 2017 according integrated luminosity : + 3 days ?

Special runs: VdM scans,… and see slide 24



Status of LHC machine and plans
LHCC
Frédérick Bordry
22nd February 2017

LHC schedule long-term



- **Run 2 and Run 3**

Ion runs end of 2018 (Pb-Pb)

2015	2016	2017	2018
J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D

EYETS

Run 2

🟦	Shutdown/Technical stop
🟩	Protons physics
🟧	Commissioning
▨	Ions

>120 fb^{-1} (13 TeV)

Σ 300 fb^{-1} (14 TeV ?)

2019	2020	2021	2022	2023
J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D

LS2

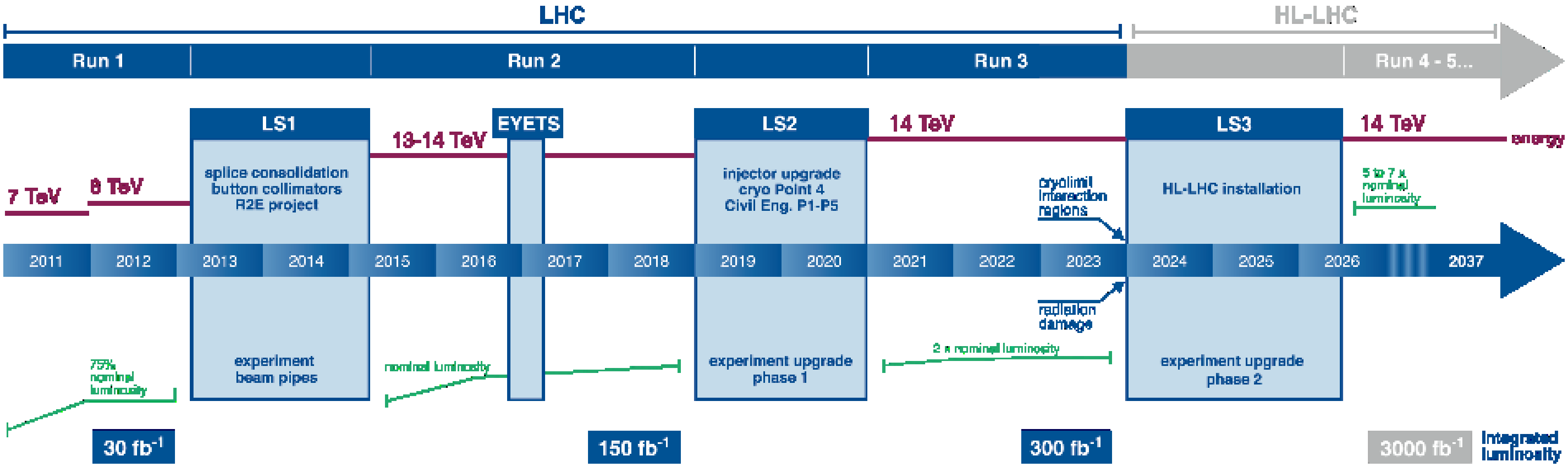
Run 3

Status of LHC machine and plans
LHCC
Frédérick Bordry
22nd February 2017

25

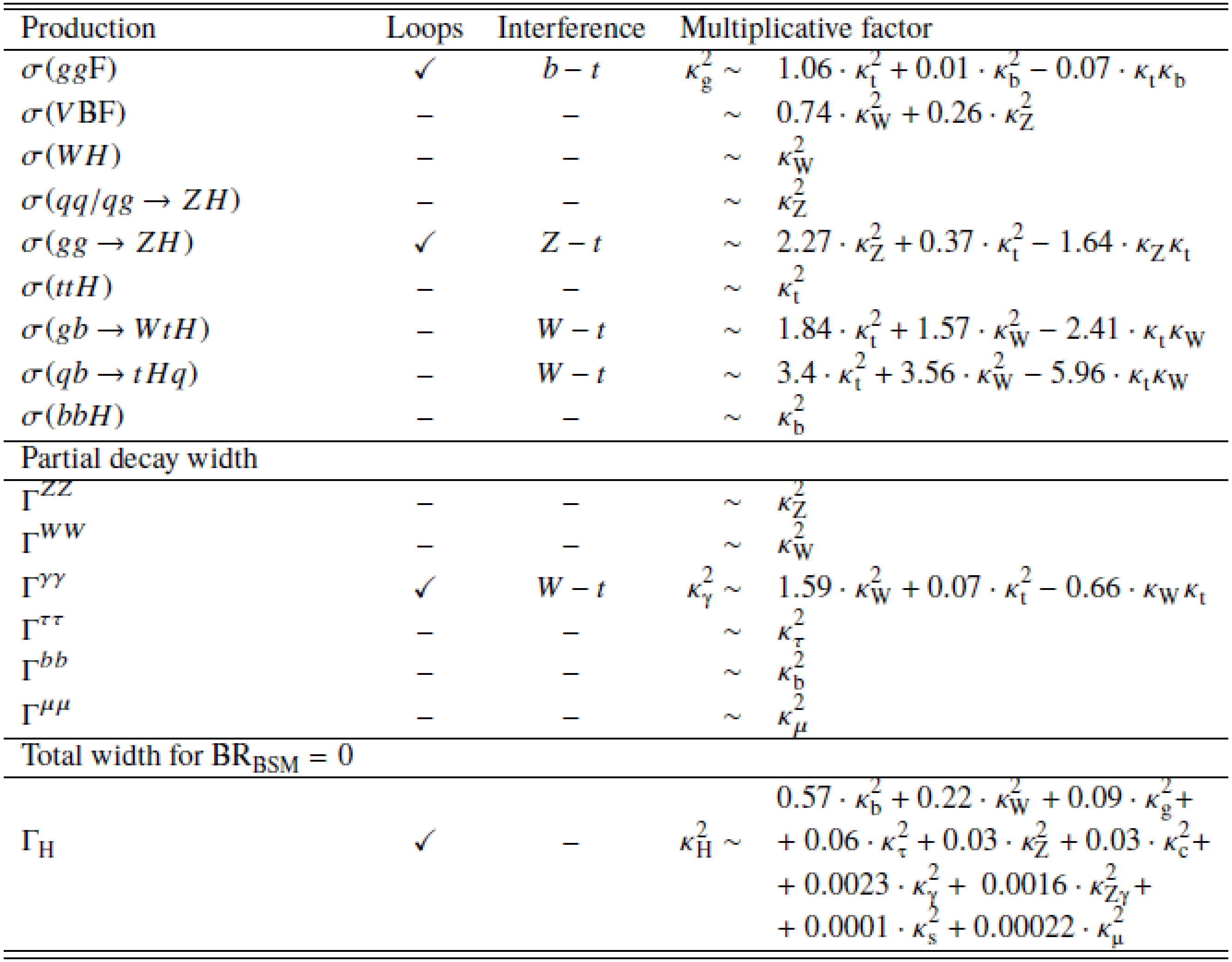
LHC full schedule

-



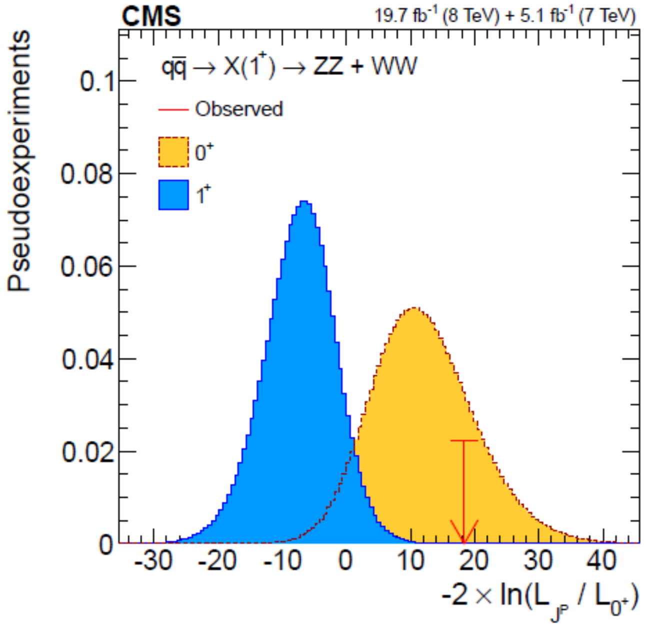
κ parameters

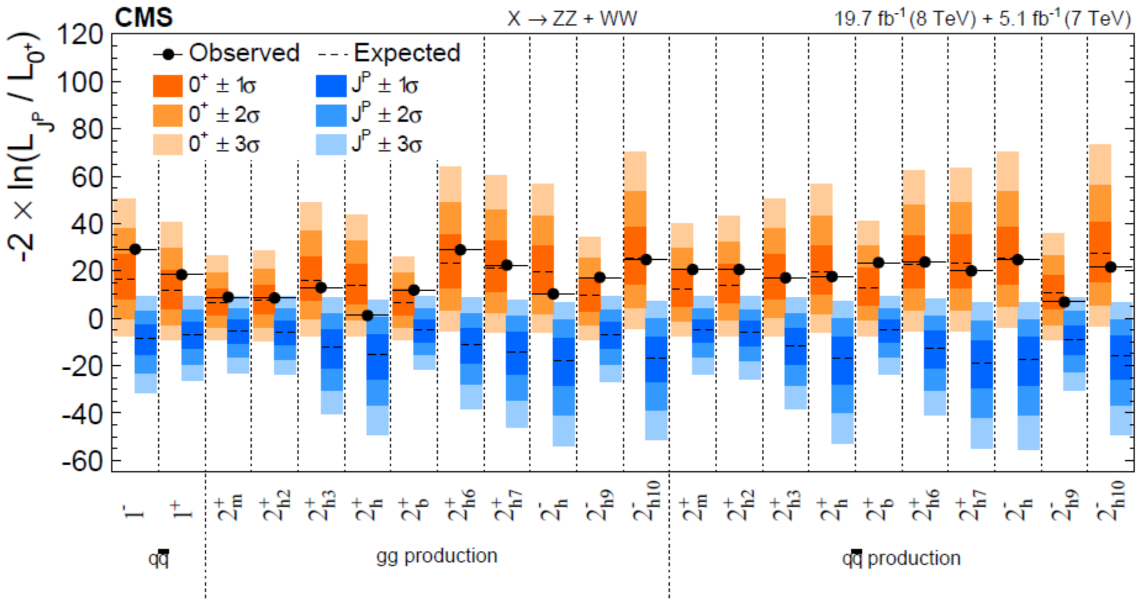
-



Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $\mathrm{BR_{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Spin and parity





ATLAS arXiv:1506.05669v2,
Eur.Phys.J. C75 (2015) 476

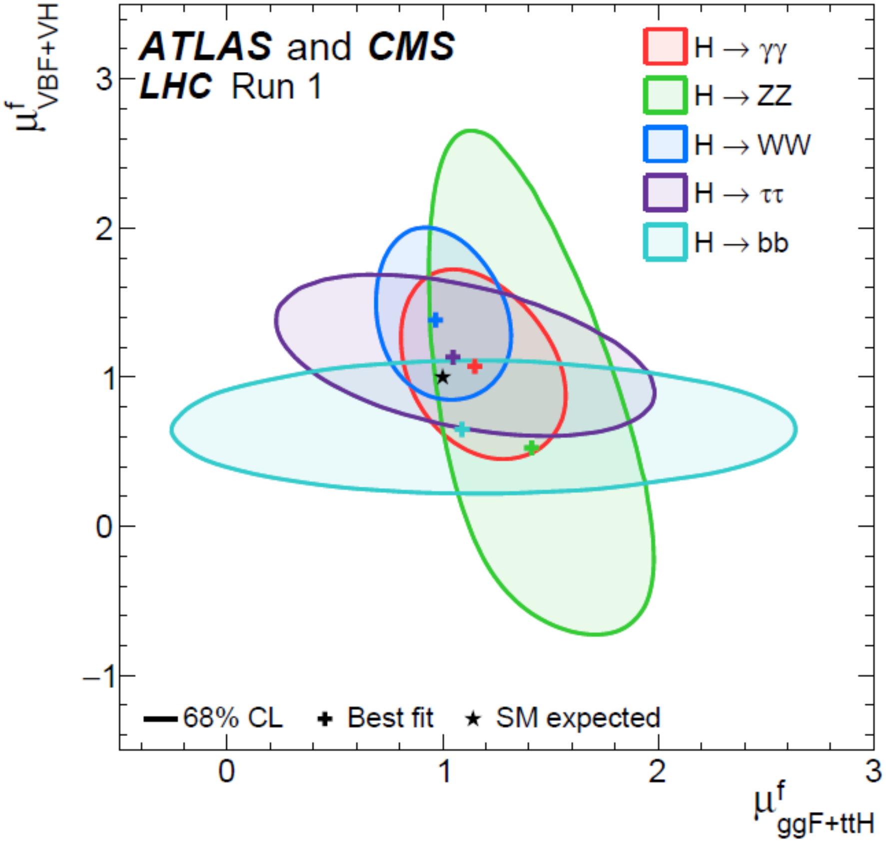
CMS PAS HIG-14-018, Phys.Rev.
D92 (2015) 012004

Boson- vs fermion-mediation

- Compare production processes associated with Higgs couplings to
  - vector bosons (VBF, VH)
  - fermions (ggF, ttH)

$$\mu^f = \frac{\mathrm{BR}^f}{(\mathrm{BR}^f)_{\mathrm{SM}}}.$$

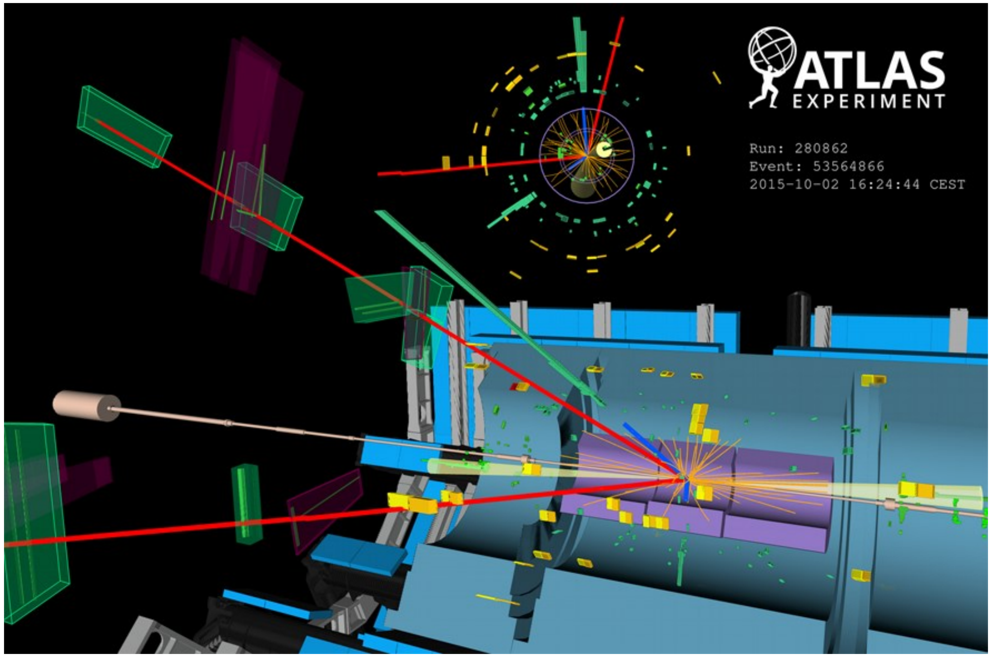
- 10 parameter fit of μ^f_{VBF+VH} and $\mu^f_{ggF+ttH}$ in the 5 decay modes
- Good agreement with SM ($\mu^f_{VBF+VH} = \mu^f_{ggF+ttH} = 1$)



H→ZZ*→4 ℓ (cont'd)

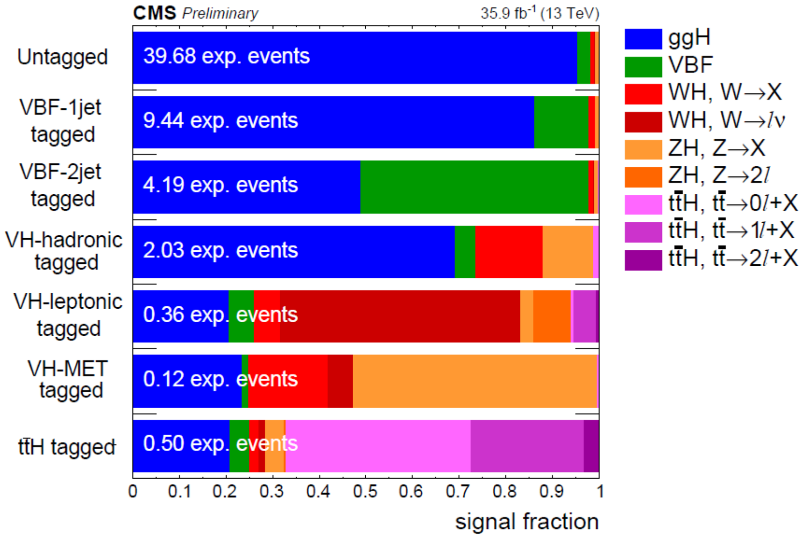
NEW!

- Varying purity and production profiles in categories



ATLAS-CONF-2017-032

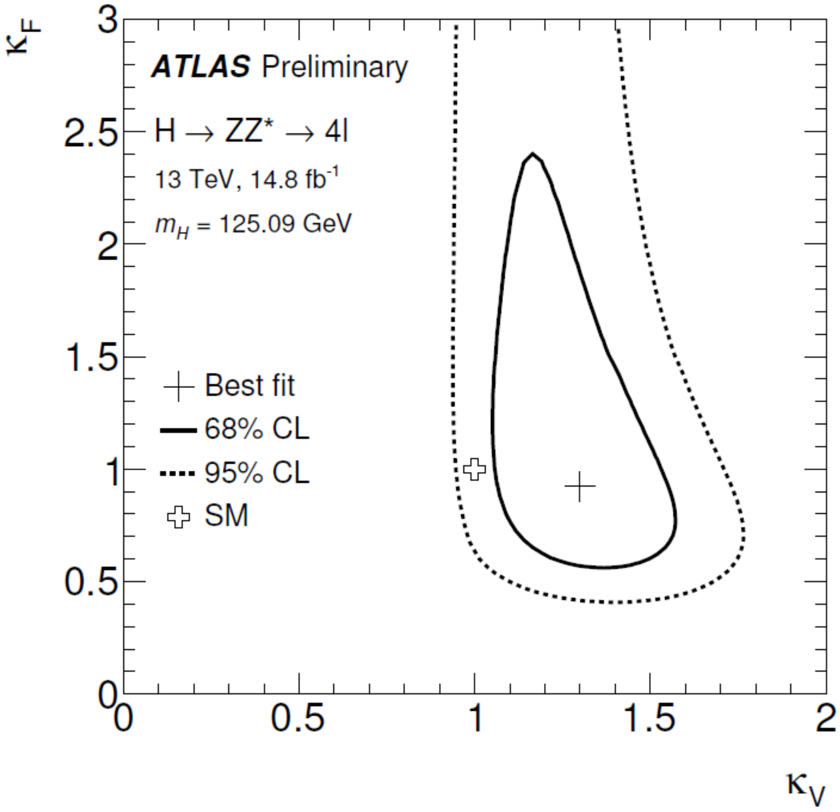
Final state	SM Higgs	ZZ^*	Z + jets, $t\bar{t}$ WZ, ttV, VVV	Expected	Observed
4μ	20.1 ± 2.1	9.8 ± 0.5	1.3 ± 0.3	31.2 ± 2.2	33
$4e$	10.6 ± 1.2	4.4 ± 0.4	1.3 ± 0.2	16.3 ± 1.3	16
$2e2\mu$	14.2 ± 1.4	7.1 ± 0.4	1.0 ± 0.2	22.3 ± 1.5	32
$2\mu 2e$	10.8 ± 1.2	4.6 ± 0.4	1.4 ± 0.2	16.8 ± 1.3	21
Total	56 ± 6	25.9 ± 1.5	5.0 ± 0.6	87 ± 6	102



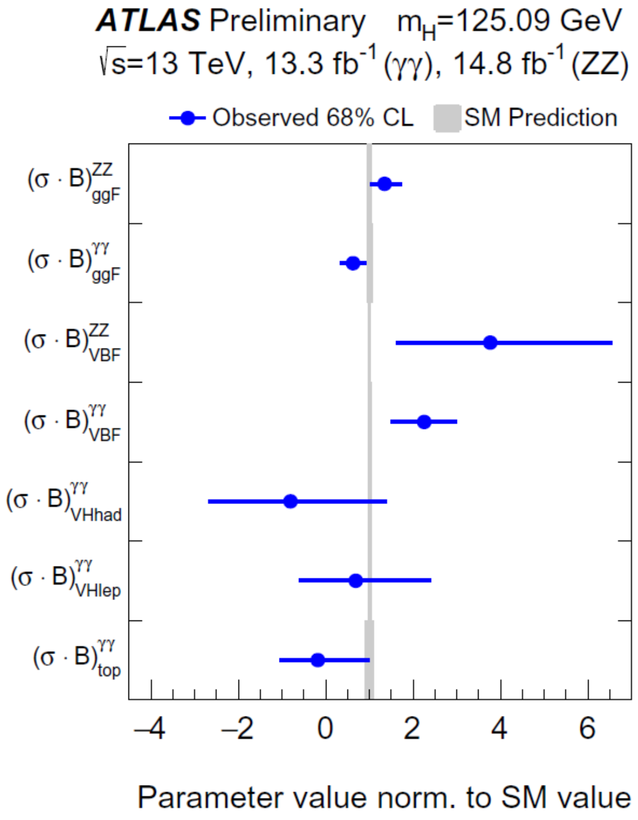
Vector vs fermion coupling

- Vector vs fermion coupling (assume no new particles in the loops)

Run 2 (ZZ* only)

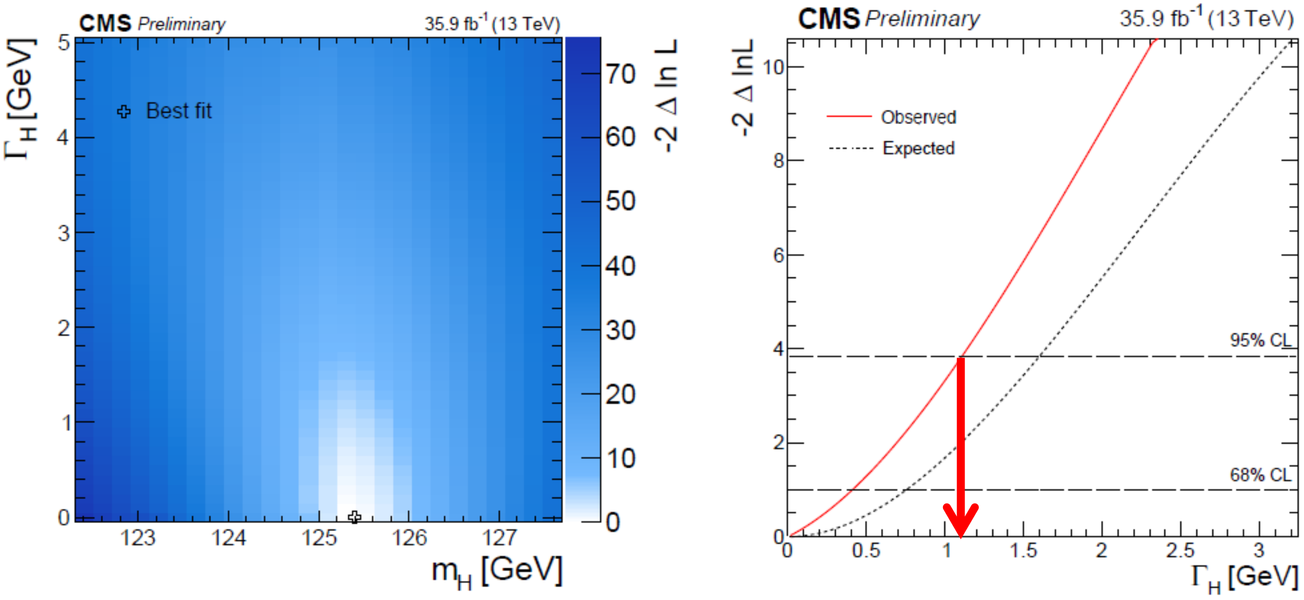


- Cross sections in H→γγ and ZZ



Run 2 width measurement

- Using on-shell production → no assumptions needed regarding BSM particles or interactions
- Mass resolution ~GeV → allow for signal/background interference



- Γ_H< 1.10 GeV (SM: Γ_H ~4 MeV)
  - less stringent than indirect limit from off-shell production (17.4 MeV) [PLB736 (2014) 64]

Anomalous VVH couplings

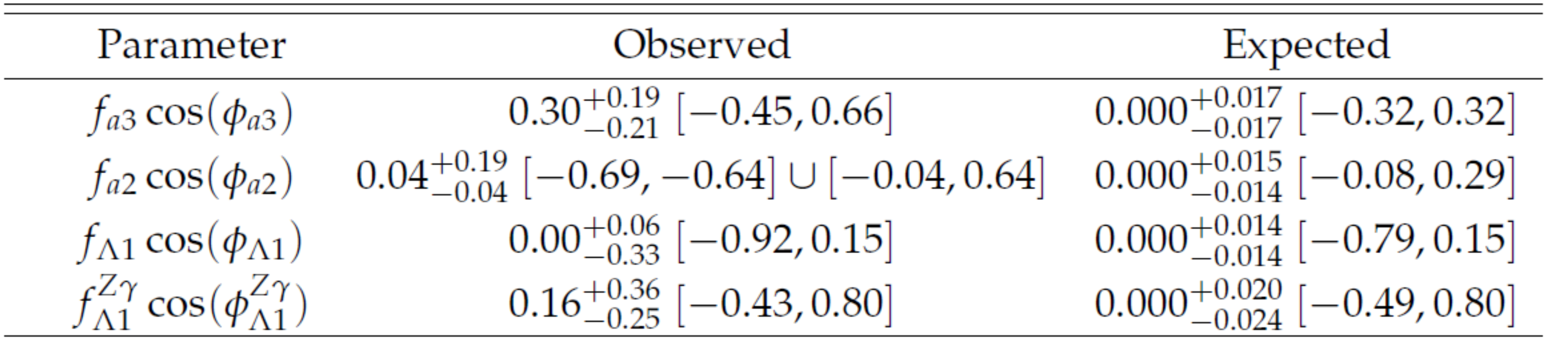
- HVV scattering amplitude: three tensor structures
  - including a form factor expansion within the first structure

$$\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_1 + q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- Translation between couplings in different formulations

couplings in PO formulation	couplings in AC or EFT formulation
κ_{ZZ}	$\frac{v}{2}\left(a_1 - 2\frac{m_Z^2}{(\Lambda_1)^2}\cos\phi_{\Lambda 1}\right)$
ϵ_{ZZ}	va_2
ϵ_{ZZ}^{CP}	va_3
ϵ_{ZfR}	$-g_Z^{fR}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda 1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda 1}^{Z\gamma}$
ϵ_{ZfL}	$-g_Z^{fL}\frac{vm_Z^2}{2(\Lambda_1)^2}\cos\phi_{\Lambda 1} + e\frac{vm_Z^2}{2(\Lambda_1^{Z\gamma})^2}\cos\phi_{\Lambda 1}^{Z\gamma}$

Anomalous VVH couplings



Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$

Anomalous couplings (cont'd)

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- Effective field theory approach: Higgs characterization model (P. Artoisenet et al., JHEP 11 (2013) 043)
  - determine BSM couplings κ_{HVV} (0^+) and κ_{AVV} (0^-), from H decay variables
  - assume $\kappa_{HVV} = \kappa_{HWW} = \kappa_{HZZ}$ and $\kappa_{AVV} = \kappa_{AWW} = \kappa_{AZZ}$

➔ Mild tension of κ_{HVV} with SM (agreement within 2.1 σ)

➔ No significant deviation from SM observed

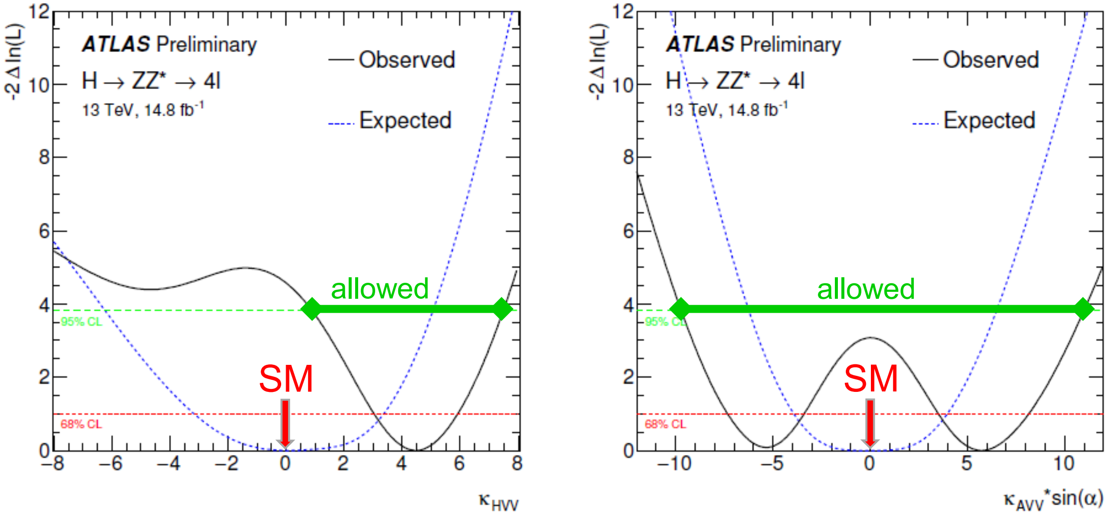
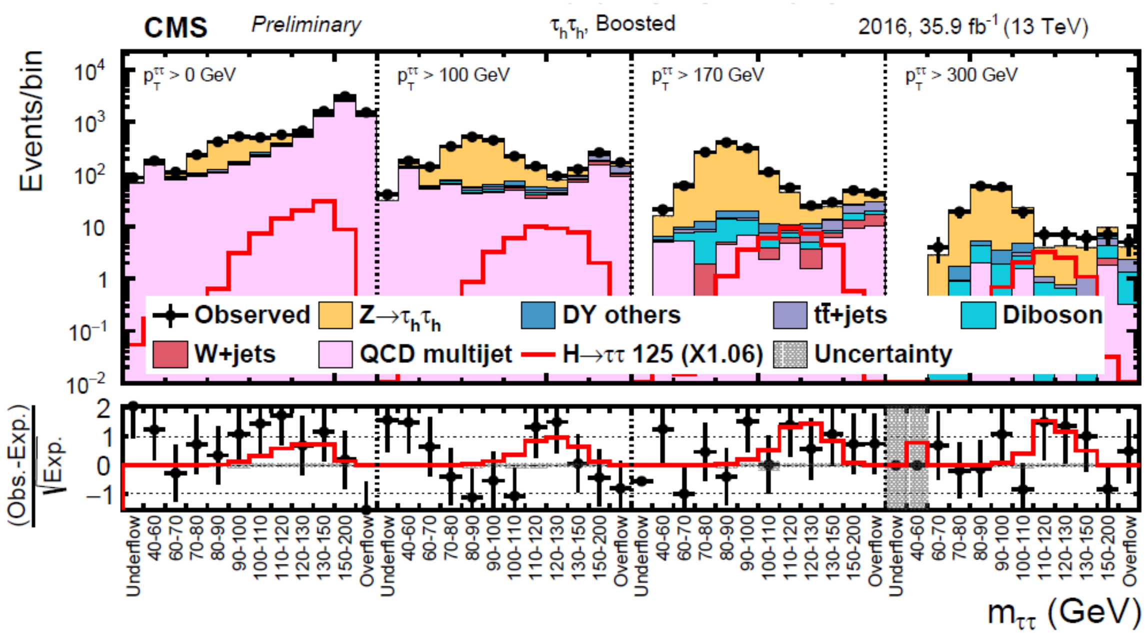


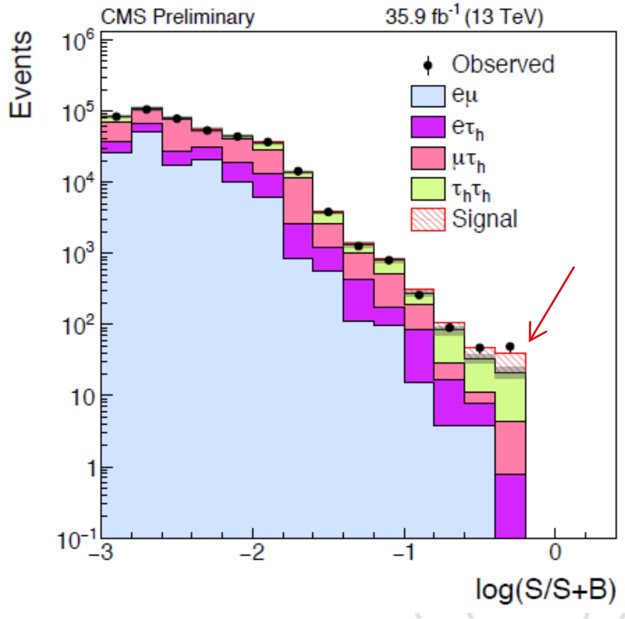
Table 13: Observed and expected limits at 95% CL on κ_{HVV} and $\kappa_{AVV} \cdot \sin\alpha$.

Not excluded range at 95% CL	κ_{HVV} expected	κ_{HVV} observed	$\kappa_{AVV} \cdot \sin\alpha$ expected	$\kappa_{AVV} \cdot \sin\alpha$ observed
	$[-6.3, 5.1]$	$[0.9, 7.5]$	$[-6.3, 6.5]$	$[-9.7, 11.0]$

H→ττ

- Four decay mode combinations used: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, $e\mu$
- Categories: 0 jet, VBF, boosted
- Main backgrounds: Drell-Yan, W/Z+jets, $t\bar{t}$, QCD
- Discriminating variables: m_{vis}, $m_{\tau\tau}$





H→ττ: categories & variables

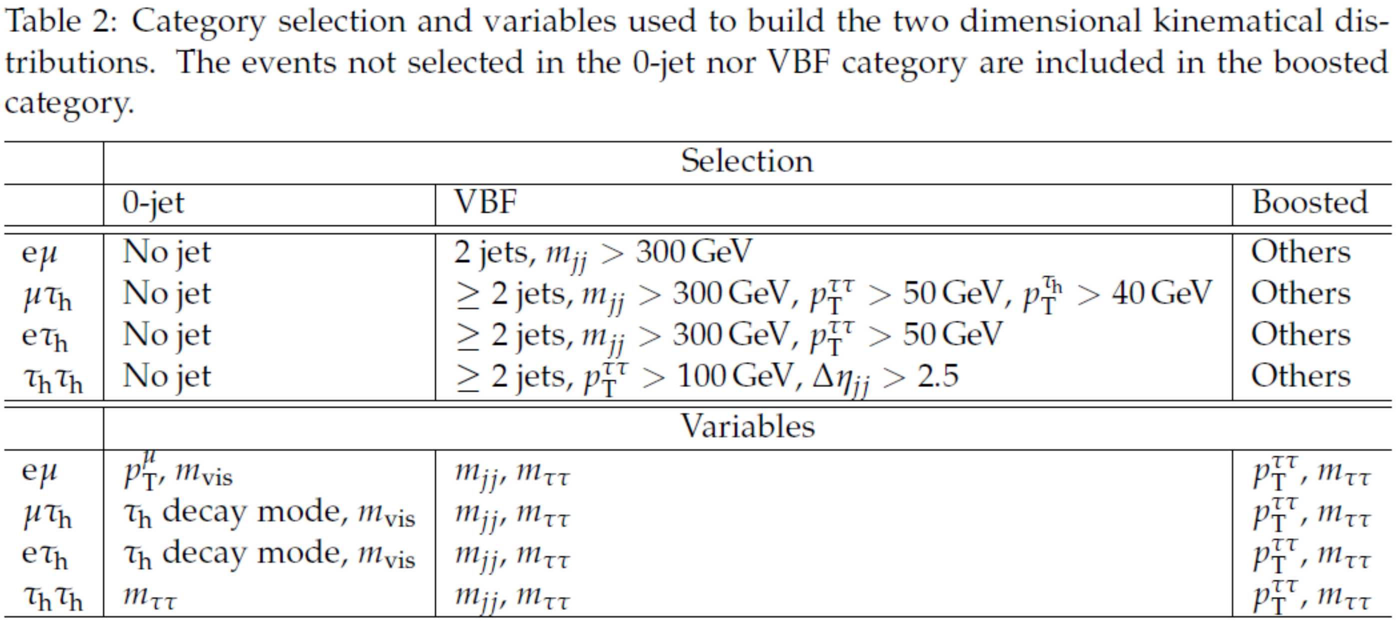
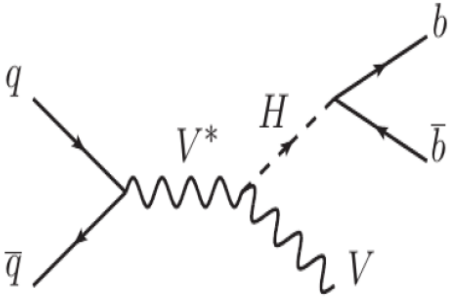


Table 2: Category selection and variables used to build the two dimensional kinematical distributions. The events not selected in the 0-jet nor VBF category are included in the boosted category.

	Selection		
	0-jet	VBF	Boosted
$e\mu$	No jet	2 jets, $m_{jj} > 300\,\mathrm{GeV}$	Others
$\mu\tau_h$	No jet	≥ 2 jets, $m_{jj} > 300\,\mathrm{GeV}$, $p_T^{\tau\tau} > 50\,\mathrm{GeV}$, $p_T^{\tau_h} > 40\,\mathrm{GeV}$	Others
$e\tau_h$	No jet	≥ 2 jets, $m_{jj} > 300\,\mathrm{GeV}$, $p_T^{\tau\tau} > 50\,\mathrm{GeV}$	Others
$\tau_h\tau_h$	No jet	≥ 2 jets, $p_T^{\tau\tau} > 100\,\mathrm{GeV}$, $\Delta\eta_{jj} > 2.5$	Others
	Variables		
$e\mu$	p_T^{μ}, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\mu\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$e\tau_h$	τ_h decay mode, m_{vis}	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$
$\tau_h\tau_h$	$m_{\tau\tau}$	m_{jj}, $m_{\tau\tau}$	$p_T^{\tau\tau}$, $m_{\tau\tau}$

VHbb

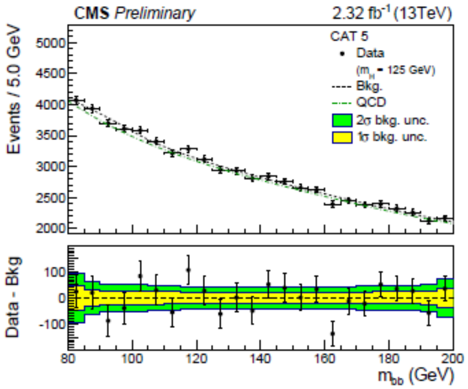


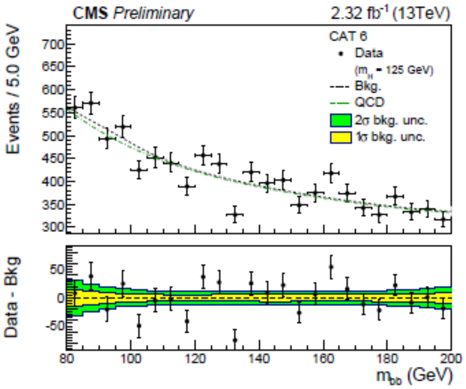
- Cross check with standard candle (ATLAS):
  - VZ production
  - $\mu_{VZ} = 0.91 \pm 0.17\ (stat.)^{+0.32}_{-0.27}(syst.)$
  - VZ signal observed with 3.0σ significance

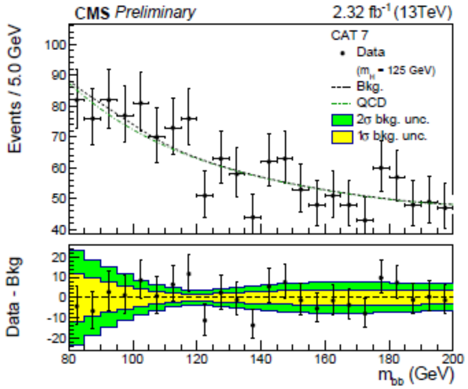
- VHbb production:
  - ATLAS: $\mu = 0.21^{+0.51}_{-0.50}$ (0.42σ)
  - CMS (Run 1): $\mu = 1.0 \pm 0.5$ (2.1σ)
  - " (+VBF,ttH) : $\mu = 1.03^{+0.44}_{-0.42}$ (2.6σ)
- Sensitivity still significantly below 3σ

VBF Hbb

- m_{bb} in different Categories







ttH(→ττ)

- ttH(→ττ):
  - at least 1 hadronic τ decay
  - significance 1.4σ (1.8σ exp.)

CMS PAS HIG-17-003