Measurements of the Higgs boson mass and width at the LHC

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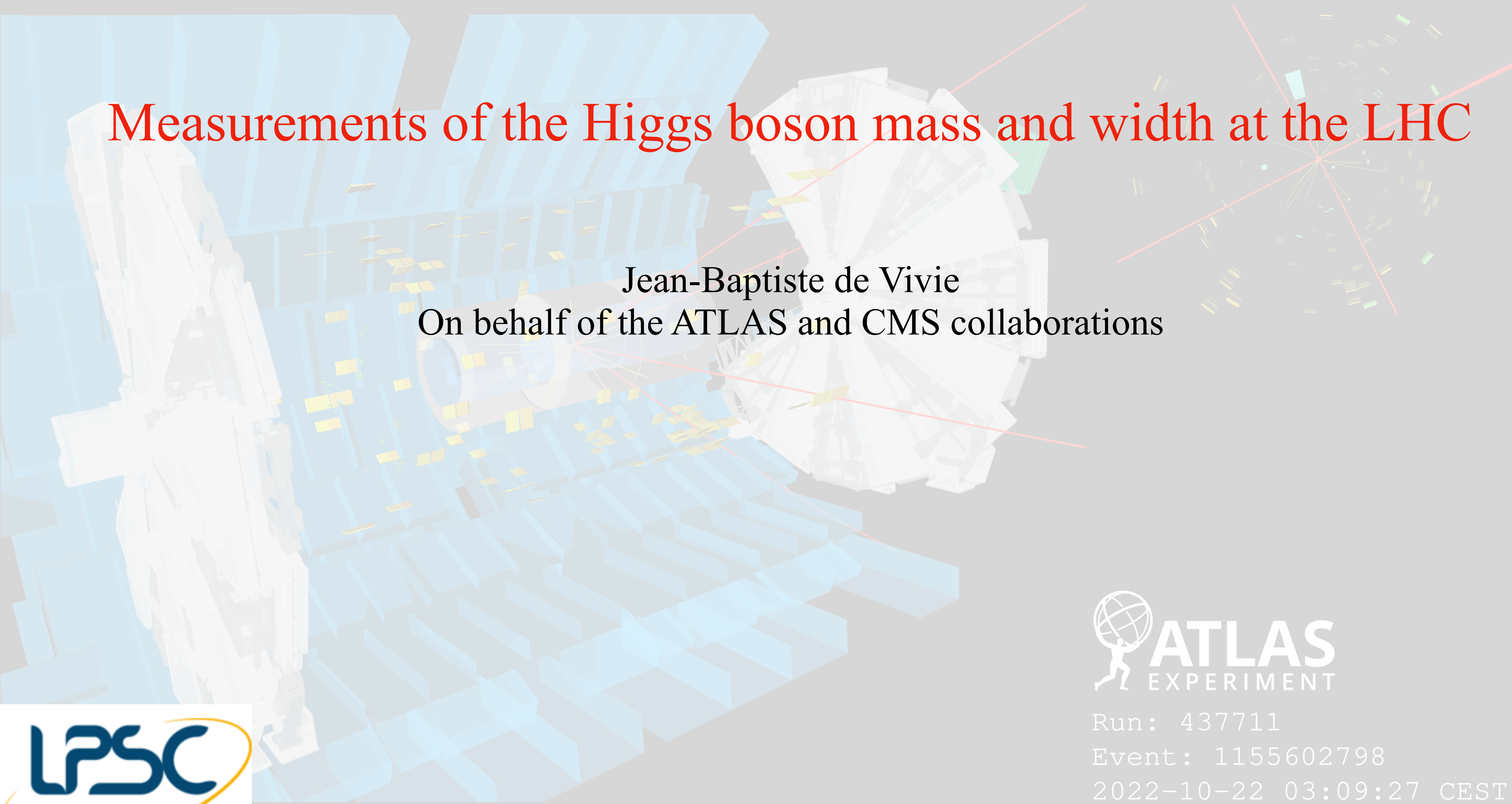
On behalf of the ATLAS and CMS collaborations



Higgs boson mass measurements

One of the fundamental parameters of the standard model (SM)
Knowing its value with good precision is paramount

→ Fixes phenomenology : production cross-sections and decay branching ratios
→ Fate of the SM vacuum
→ Consistency tests of the SM at quantum level

Also important for BSM model selection, e.g. m_H = 150 GeV would have killed the MSSM

The mass measurement : Run I legacy and Run II expectation

$m_H = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}$ GeV

precision better than 2‰

⇒ Parametric uncertainty on Higgs boson branching ratios and production cross-sections in general smaller than other theory uncertainties

⇒ not limiting EW fit

Yet, m_H is a fundamental quantity in the SM

⇒ try to measure it the best as possible in Run II

Uncertainties : lepton and photon energy scales, obviously !

Expectation for Run II :

~ lumi × 5.6,

~ signal cross-section × 2.4

~ Background × 2

⇒ stat. uncertainty expected to be divided by ~ 4 : smaller than Run I syst.

⇒ Hard work needed to decrease systematic uncertainties, especially for $H \rightarrow \gamma\gamma$ where they would become dominant

Mass measurements with $H \to ZZ^* \to 4\ell$

Tiny yield, large S/B, very good mass resolution

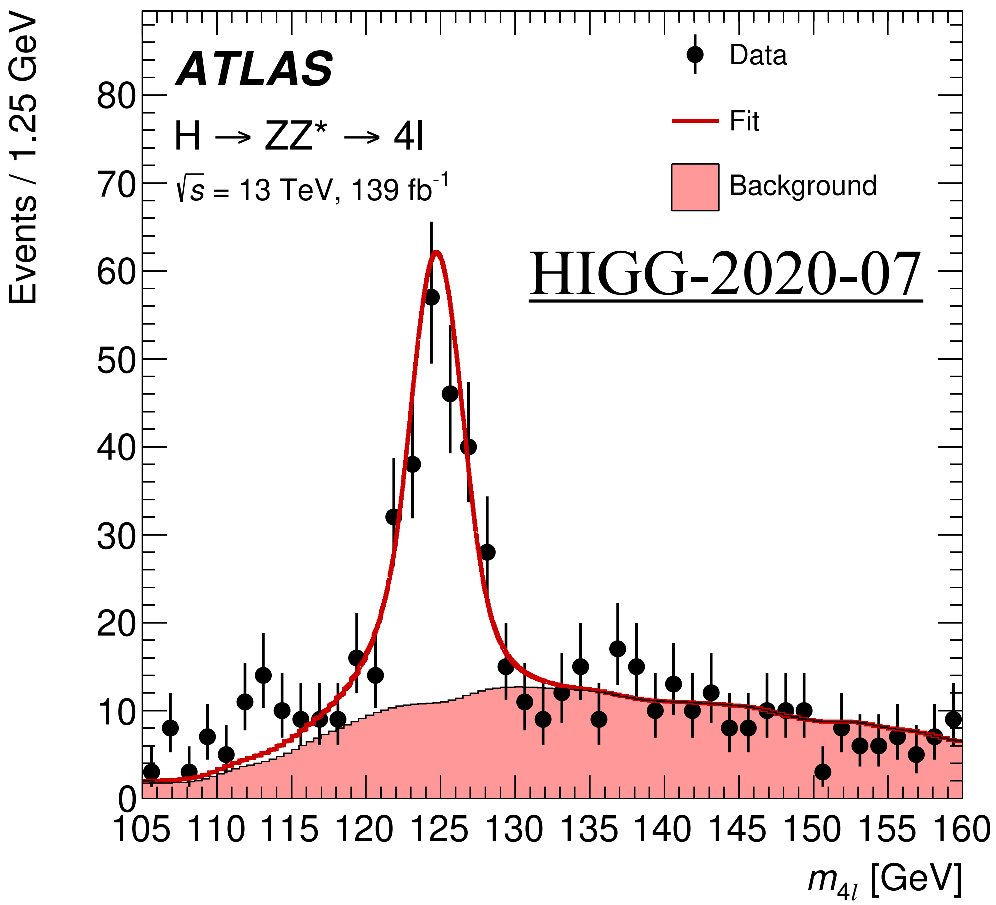
Main observable : 4-lepton mass $m_{4\ell}$ with

- FSR recovery (at most one)
- Refit of momenta of lepton pair making the « on-shell » Z (Z_1, $m_{\ell\ell}$ closest to m_Z) using a Z-mass constraint

ATLAS (2022) : quick reminder

Simultaneous fit to data in 4 categories 4μ/2e2μ/2μ2e/4e depending on the flavor of the leptons forming the « on-shell » and « off-shell » Zs.

- In addition to $m_{4\ell}$ include S/B discriminant and per-event $m_{4\ell}$ uncertainty estimated via quantile regression network in the likelihood
- Free-floating normalisations of signal and dominant ZZ* background (≳ 85%) in each category



$m_H = 124.99 \pm 0.18_{stat} \pm 0.04_{syst}$ GeV

syst ≪ stat , yet important to show that the momentum / energy scales are understood

Uncertainty (MeV)	Previous measurement ($36\ fb^{-1}$)	This measurement (Legacy)
Muon momentum scale	40	28
Electron energy scale	26	19
Signal modeling	na	14

Several improvements with respect to previous analysis (using 2016 data) :

- Beam spot constraint :

  adjust muon momenta by requiring the four lepton tracks to originate from a common vertex compatible with the beam spot $\Rightarrow \sigma(m_{4\ell})$ improves by 3-8%

- Introduction of per-event $m_{4\ell}$ uncertainty $\delta_{4\ell}$:

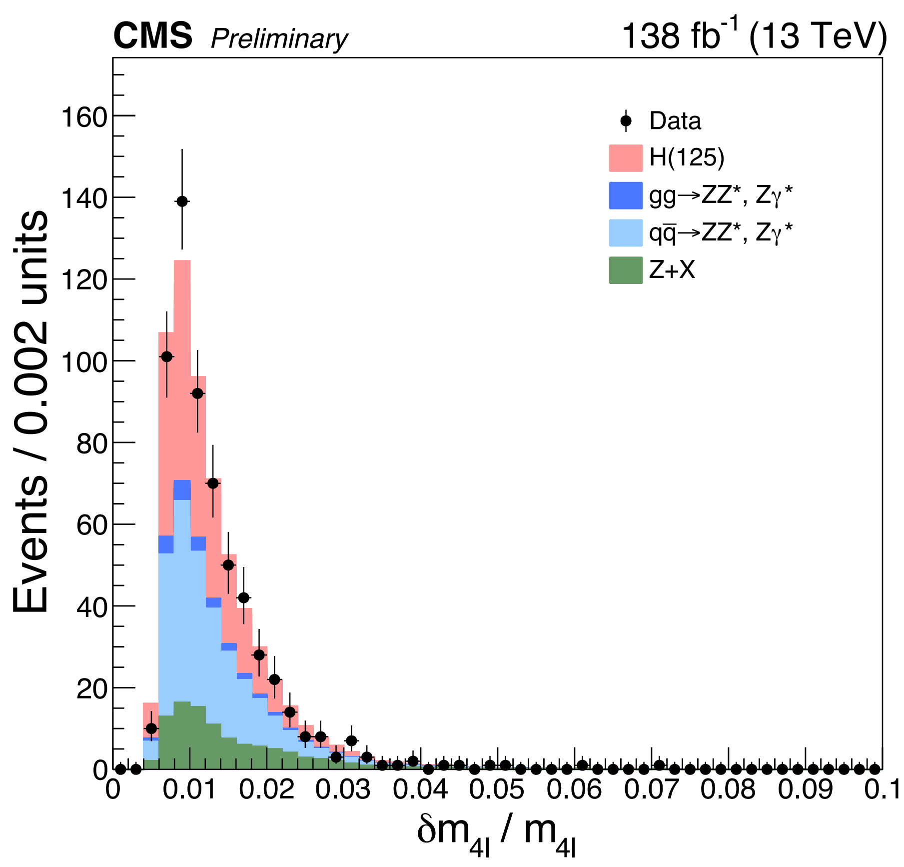
  Estimated from per-lepton momentum uncertainty with error propagation

  From track-fit covariance matrix (muons) or combination of ECAL energy and track momentum (electron)

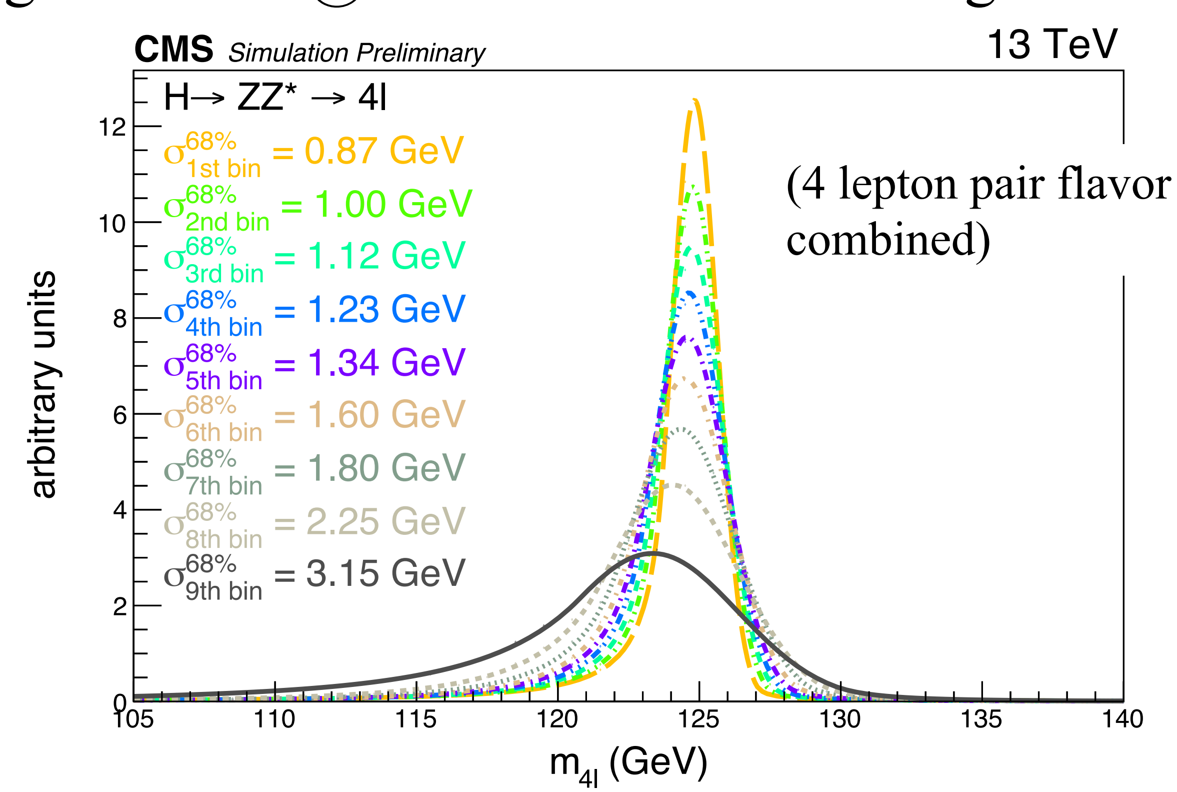
  Corrected using $Z \rightarrow \ell\ell$ data

  Used to categorize the events : 9 $\delta_{4\ell}/m_{4\ell}$ categories, equal share for signal

  $\Rightarrow$ isolate events with better resolution and improve the lineshape description



Signal model @ 125 GeV for the 9 categories



Mass measurements with $H \to 4\ell$ CMS (2023) cont'd

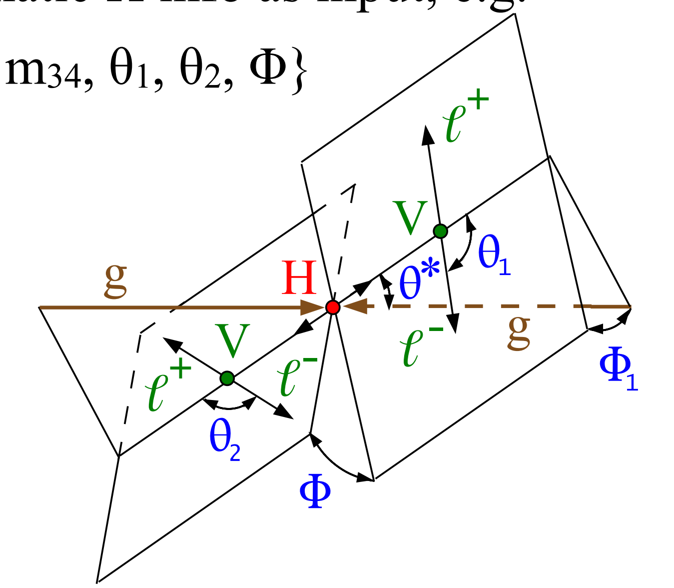
Two observables used to build the signal and background pdf used in the likelihood fit

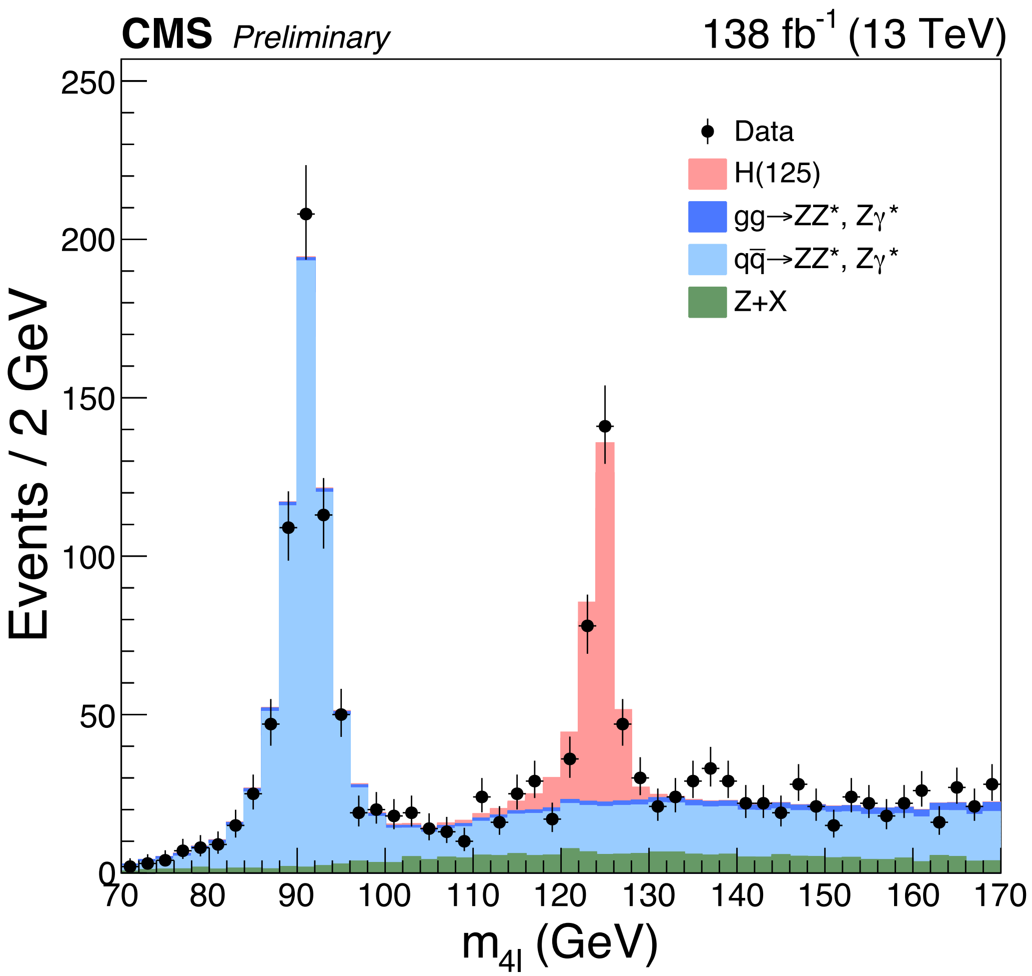
$$m_{4\ell} \text{ and } \mathcal{D}^{\text{kin}}_{\text{bkg}} = \frac{\mathcal{P}_{H\to 4\ell}}{\mathcal{P}_{H\to 4\ell} + \mathcal{P}_{q\bar{q}\to 4\ell}}$$

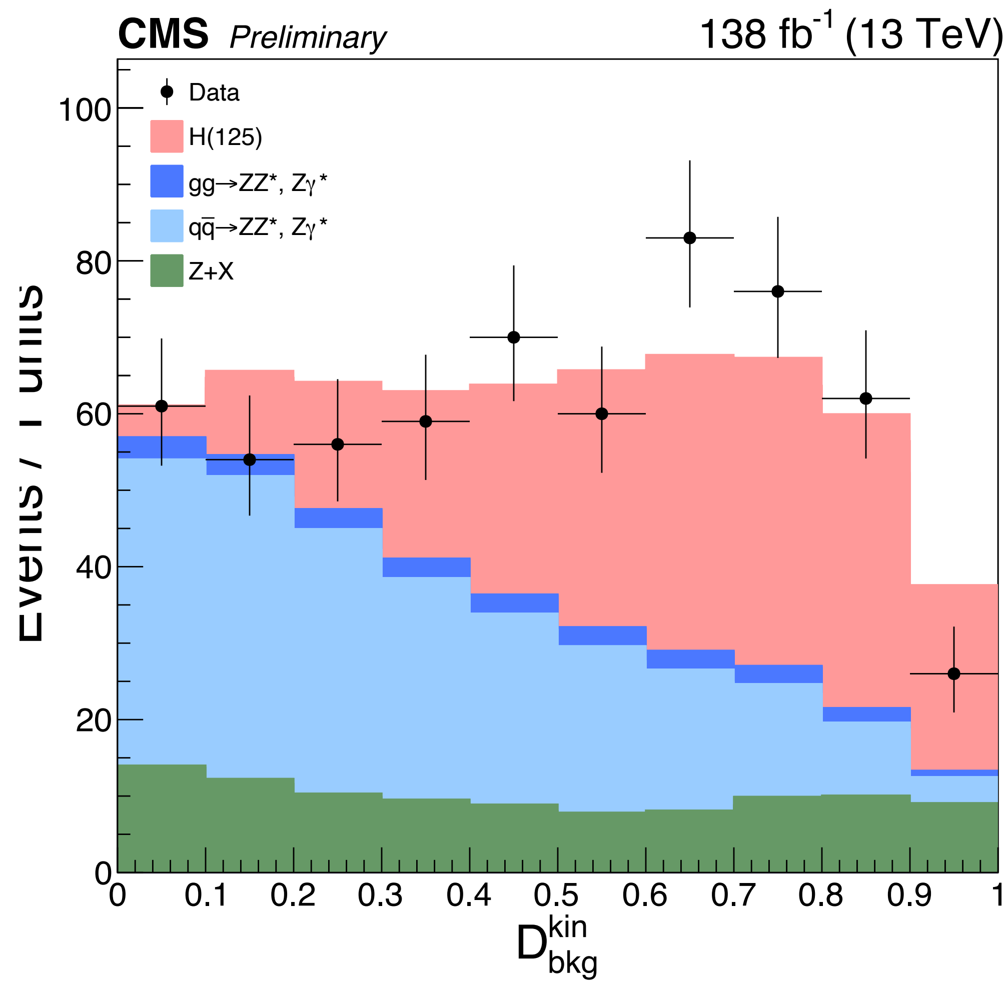
in each $\delta_{4\ell}/m_{4\ell} \times [4\mu/2e2\mu/2\mu2e/4e] \times$(data-taking period) category

$\mathcal{P}$: « probability » calculated from Matrix Elements (MELA) using kinematic Ω info as input, e.g.

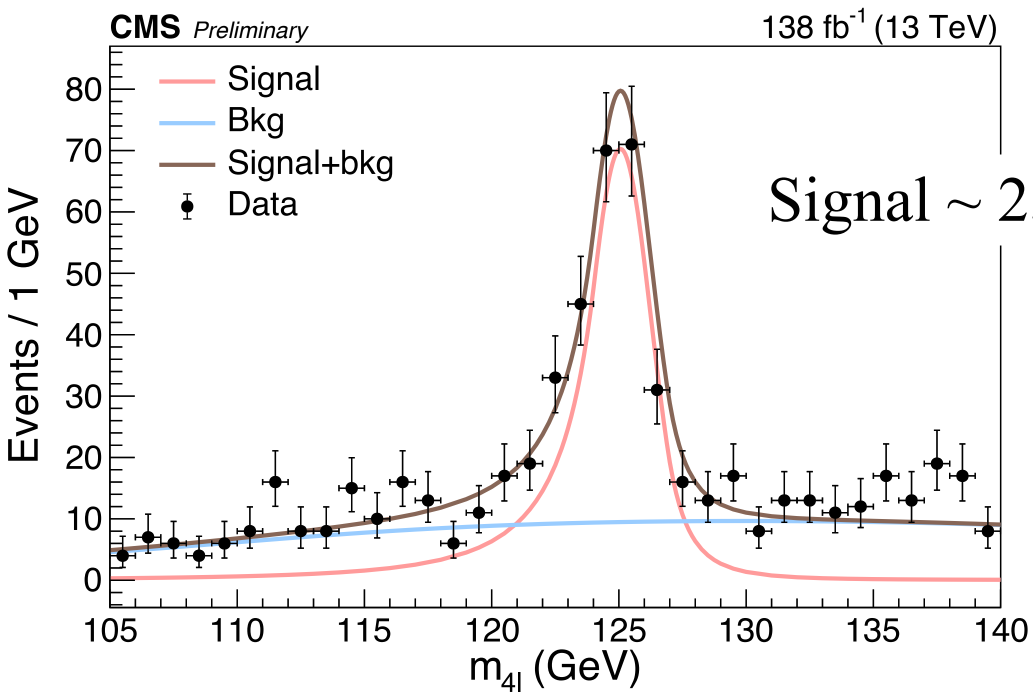
$\Omega^{\text{dec}} \supseteq \{m_{12}, m_{34}, \theta_1, \theta_2, \Phi\}$







Fit result, all categories combined

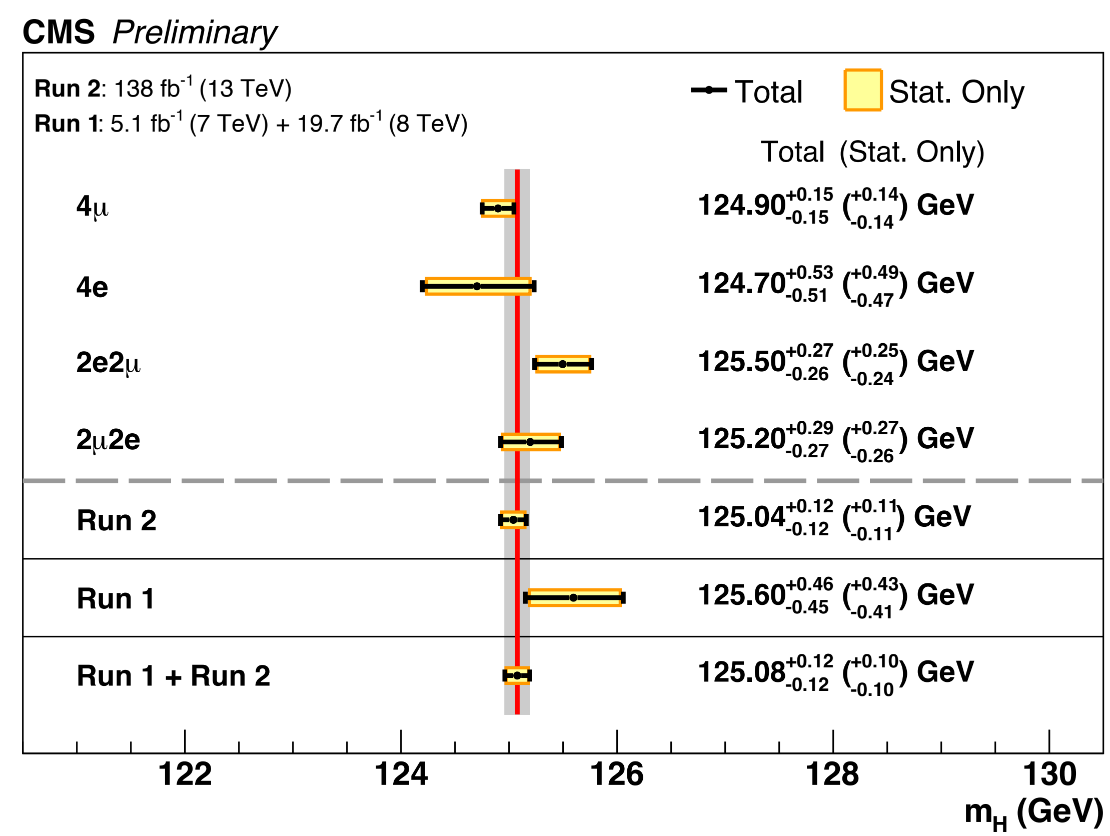


Signal ~ 258 events

$m_H = 125.04 \pm 0.11_{stat} \pm 0.05_{syst}$ GeV

Most precise single measurement

Uncertainties from lepton energy scale
~ 30 / 40 MeV for μ / e



Fit cross-checked with 1D model

Z_1-mass + beam spot constraint : 15% improvement

+ Per-event error categorization : 10%

+ $\mathscr{D}^{kin}_{bkg}$ in fit model : 4%

Very similar methods between ATLAS and CMS (FSR, Z-mass constraint, …)

- Variations on how to incorporate per-lepton $m_{4\ell}$ uncertainty in fit model
- CMS stat. uncertainty ~ ATLAS / 1.6 thanks to higher magnetic field

Mass measurements with $H \to \gamma\gamma$

Small yield, small S/B, very good mass resolution

Given the more difficult environment and harder to control systematic uncertainties than $H \to 4\ell$, Run II might be the last LHC run where an absolute m_H measurement in $H \to \gamma\gamma$ is worthwhile…

ATLAS (2023) :

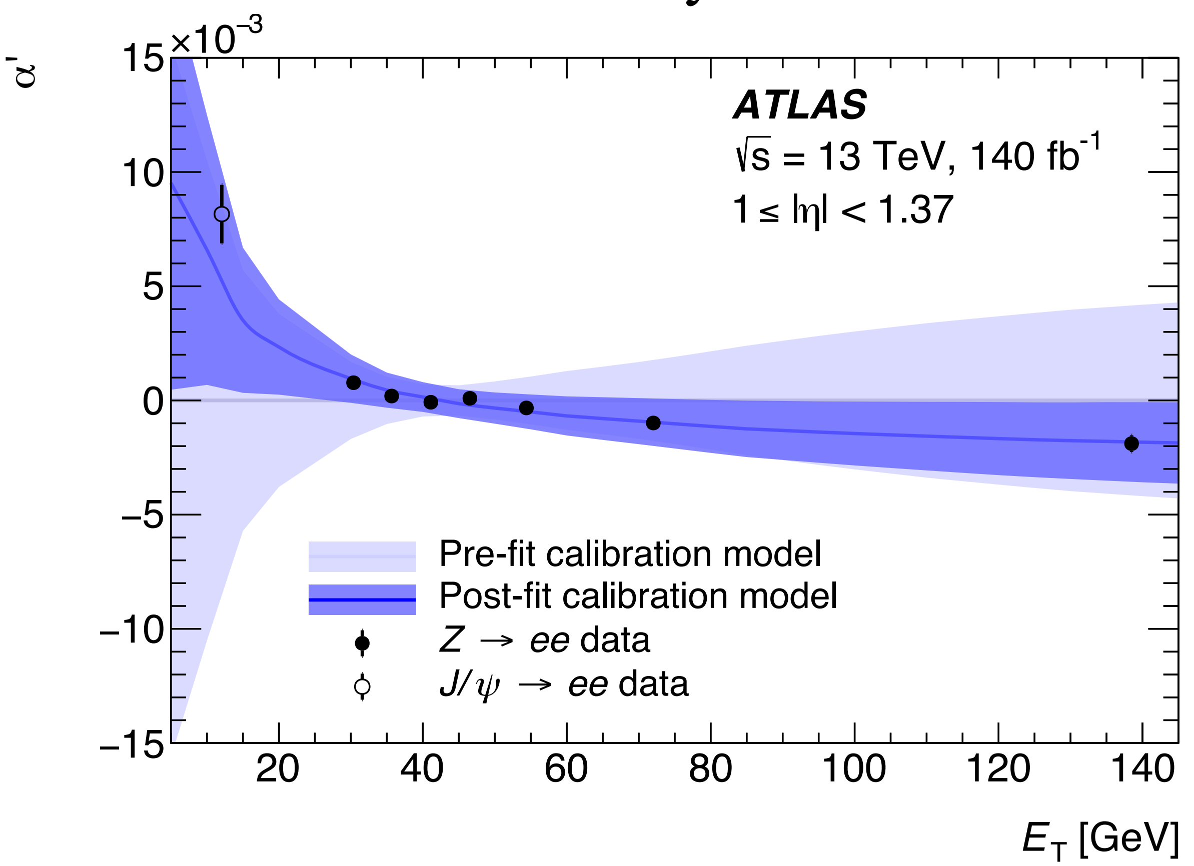
Large part of the work is about the photon energy scale calibration and its uncertainty ESU
Reconstruction/calibration changes w.r.t. previous measurement, among others

- better energy collection (especially for converted photons)
- refined ECAL layer inter-calibration $\Rightarrow$ linearity and electron $\to$ photon extrapolation
- better understanding on electronics non-linearity
- dedicated correction for photon out-of-cluster energy leakage mis-modeling by simulation

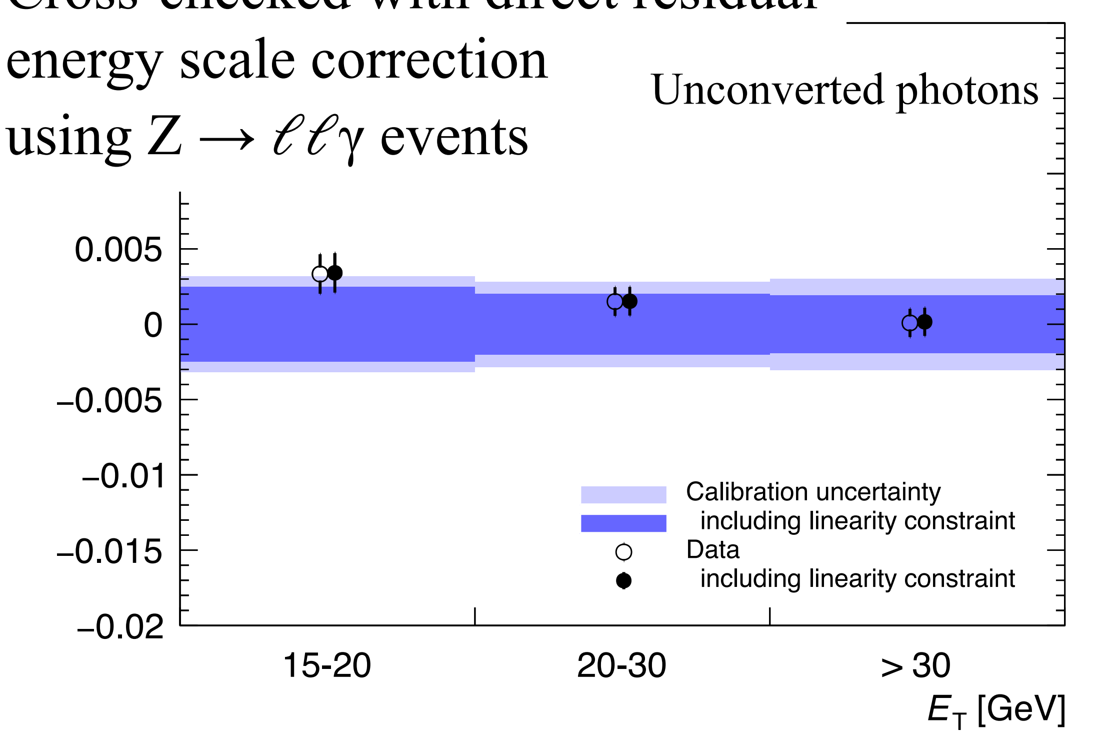
$\Rightarrow$ e.g. ~ 40% reduction in ESU for E_T = 60 GeV photon at η = 0.3

In addition measure the energy response linearity with the huge $Z \to ee$ sample available
$\Rightarrow$ use it to constrain the systematic uncertainties

~ 30% / ~ 50% *further* reduction of ESU for E_T = 60 GeV unconverted photon in barrel / endcap



Cross-checked with direct residual energy scale correction using $Z \to \ell\ell\gamma$ events

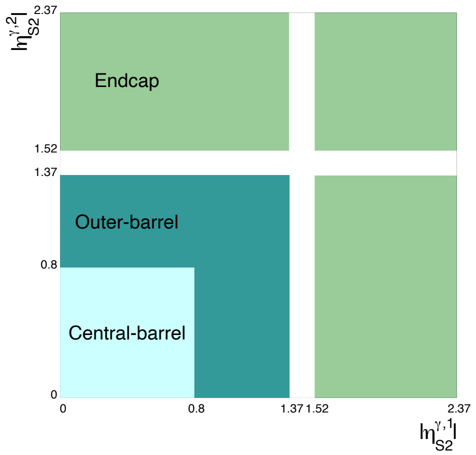


Mass measurements with $H \to \gamma\gamma$ ATLAS (2023) cont'd

- Standard event selection : 2 high-E_T isolated photons ($E_T/m_{\gamma\gamma} > 0.35, 0.25$)
  - ~ 6300 signal events,
  - ~ 130k background events (mostly irreducible) in a di-photon mass $m_{\gamma\gamma}$ window containing 90% of the signal

- Categorization dedicated to the mass measurement : 14 categories

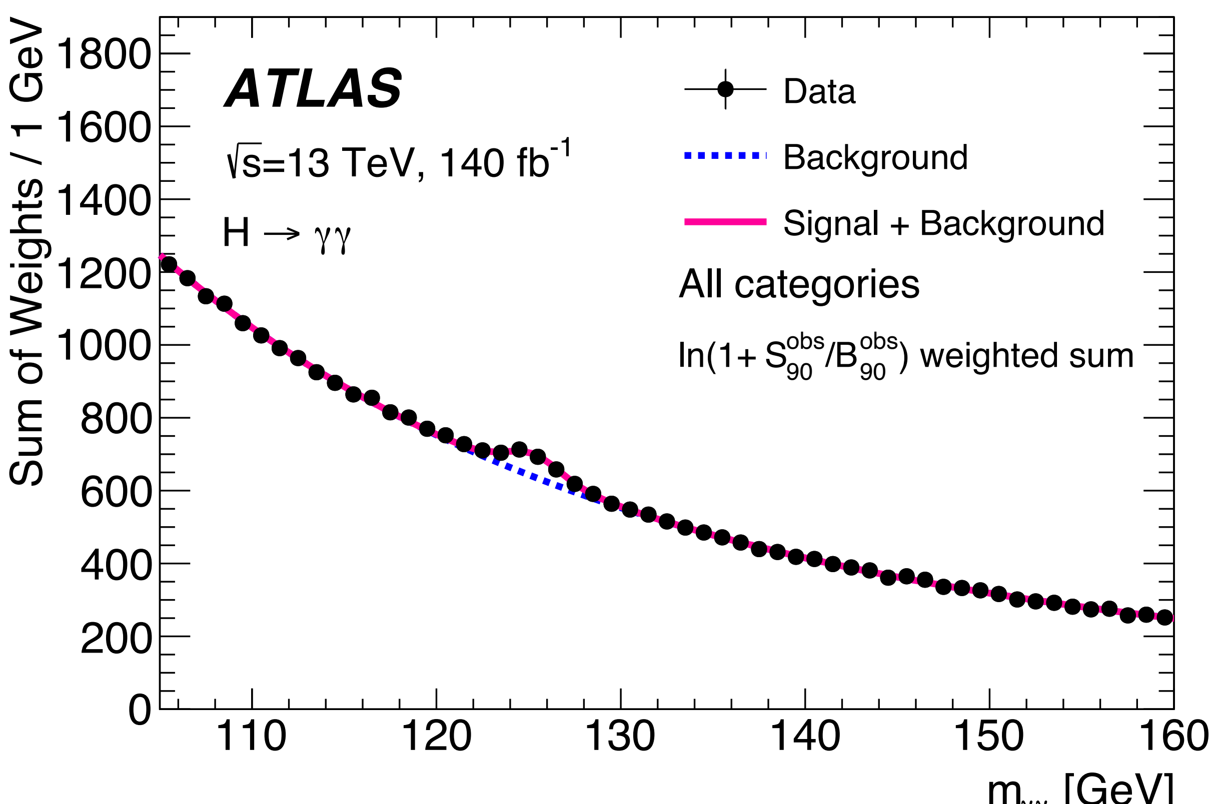
  Using p_{Tt} (linked to diphoton system transverse momentum : $p_{Tt} = |\mathbf{p}_T(\gamma\gamma)\times\mathbf{t}(\gamma\gamma)|$, $\mathbf{t}$ = thrust axis in transverse plane)



$\times$ (0, $\geq$ 1 conversion) $\times$ p_{Tt} ($<$ 70, [70,140[, $\geq$ 140 GeV)
(No p_{Tt} for « endcap » category)

$\Rightarrow$ 6% improvement w.r.t. previous iteration

- Mass extraction from simultaneous fit of S+B model to the 14 diphoton mass $m_{\gamma\gamma}$ distributions

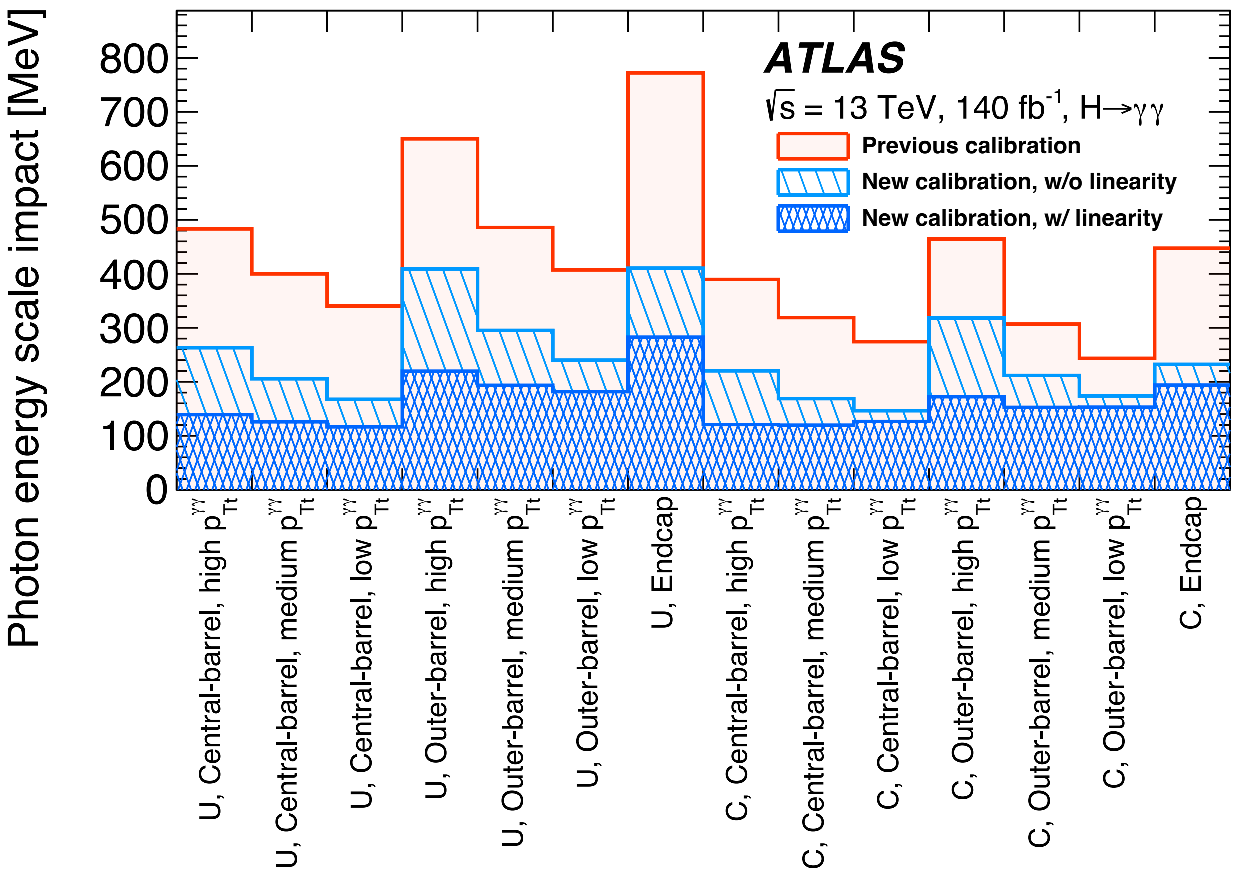


Normalisations (signal and bkg) uncorrelated between categories, and free-floating

Mass measurements with $H \to \gamma\gamma$ ATLAS (2023) cont'd

HIGG-2019-16

Impact of photon energy scale PES uncertainties :



⇒ Large improvements
- refined calibration model
- linearity fit, especially for no-conversion and high p_{Tt}

⇒ Uncertainty due to PES decreased by a factor of 4
320 MeV → 80 MeV

$m_H = 125.17 \pm 0.11_{stat} \pm 0.09_{syst}$ GeV
Managed to keep systematic uncertainty below stat !

Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

CMS : 36 fb^{-1}, $m_H = 125.78 \pm 0.18_{stat} \pm 0.18_{syst}$ GeV
HIG-19-004

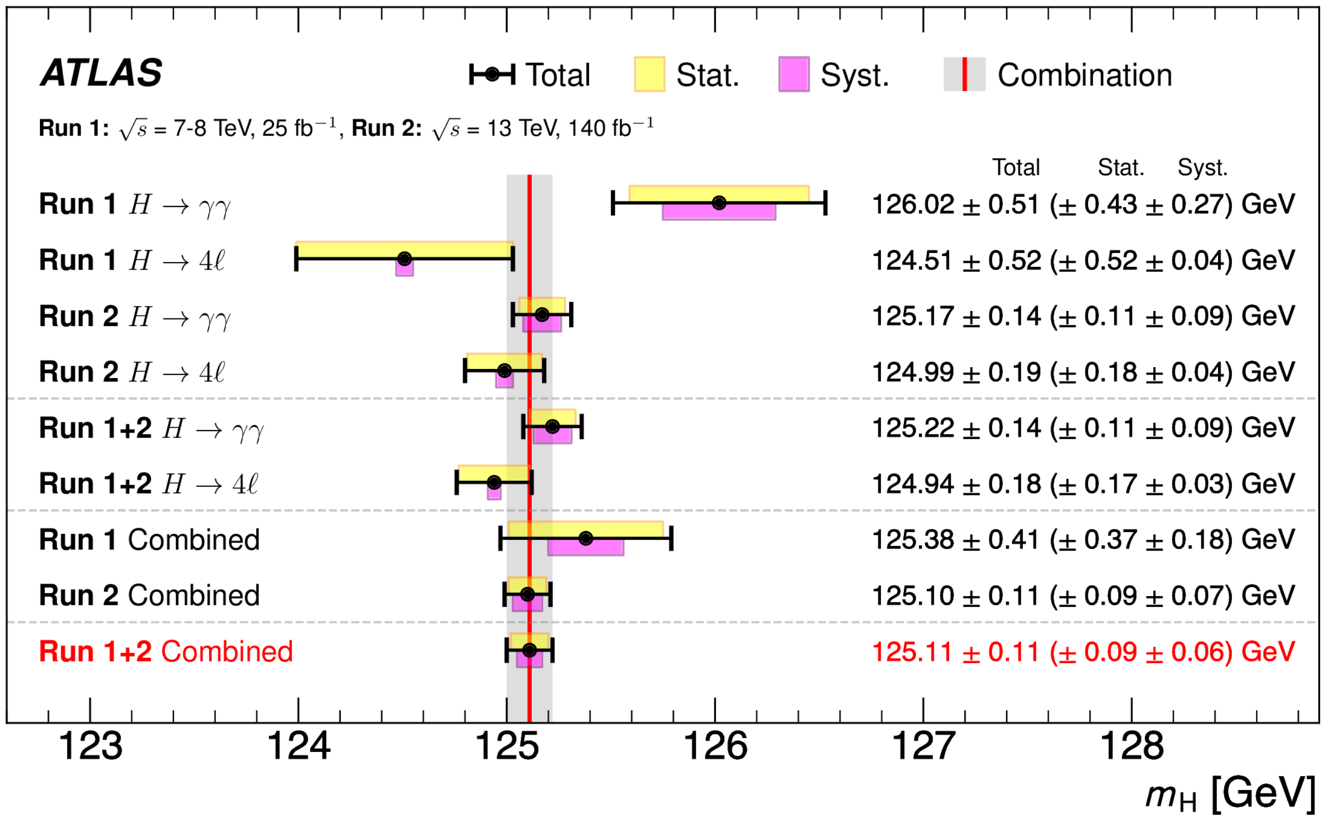
finalizing the measurement with the full Run II dataset
Stay tuned…

HIGG-2022-20

ATLAS Legacy : combination of Run I and Run II measurements in $H \to \gamma\gamma$ and $H \to 4\ell$

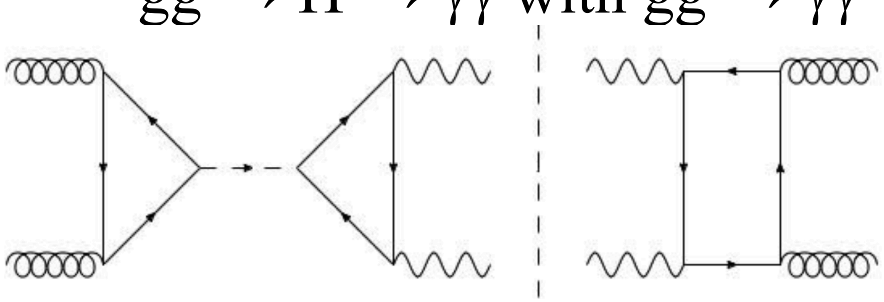
Yields uncorrelated between Run I and Run II, $H \to \gamma\gamma$ and $H \to 4\ell$ to reduce model-dependence

$m_H = 125.11 \pm 0.09_{stat} \pm 0.06_{syst}$ GeV : precision $\mathcal{O}(0.09\%)$



Main systematic uncertainties :
experimental from PES especially

From theory :
Interference between (mainly)
$gg \to H \to \gamma\gamma$ with $gg \to \gamma\gamma$



not taken into account

Effectively distorts the lineshape ⇒ mass shift
Δm_H = -26 MeV for $H \to \gamma\gamma$ Run II measurement

In the combination : → 17 MeV uncertainty
The only sizable theory uncertainty

(Turning around this : constrain width from mass shift, need
→ reference for « mass »
e.g. $H \to 4\ell$, or $H \to \gamma\gamma$ at high p_T where $\Delta m_H \sim 0$
→ very precise theory description)

Constraints on the total Higgs boson width

The Higgs boson width

- Coupling to SM particles through mass : only tiny couplings to « accessible » SM decay final states

  ⇒ tiny width predicted in SM : $\Gamma_{SM} = 4.1$ MeV

  BSM contributions could bring a huge enhancement (e.g. Higgs portal to DM)

- Far smaller than experimental $m_{\gamma\gamma}$ or $m_{4\ell}$ mass resolution $\mathcal{O}$(1-2 GeV)

  ⇒ only loose constraint from *naïve* study of the on-shell line shape

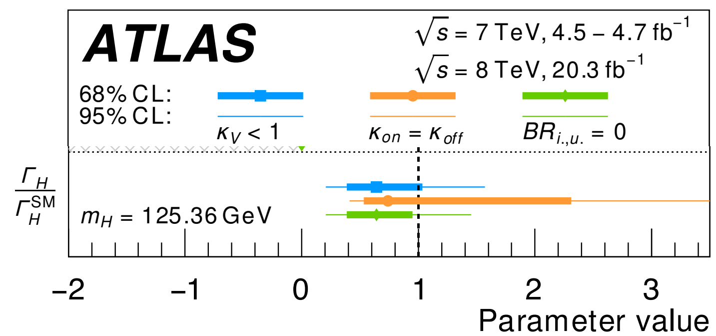
  CMS : $\Gamma < 330$ MeV @ 95% CL (~ $80\times\Gamma_{SM}$)

  (A lower limit from lifetime (displaced 4-lepton vertex) has also been set by CMS : $\Gamma > 3.5$ meV)

- Indirect from off-shell regime : $\sigma(i \to H^{(*)} \to f) \sim \dfrac{g_i^2 g_f^2}{(\hat{s} - m_H^2)^2 + m_H^2\Gamma^2}$

On-shell ⟶ $\sim \dfrac{g_i^2 g_f^2}{m_H \Gamma}$: degeneracy couplings ↔ width $\Gamma = \dfrac{\sum_i \kappa_i^2 \mathcal{B}_i^{\rm SM}}{1 - \mathcal{B}_{\rm u} - \mathcal{B}_{\rm inv}} \times \Gamma^{\rm SM}$

Invisible decay $\mathcal{B}_{\rm inv}$ can be searched for, undetectable cannot ! ⇒ needs assumptions



e.g. all modifiers floating **but $\kappa_V \leq 1$** : $\Gamma/\Gamma^{\rm SM} = 0.64^{+0.40}_{-0.25}$ (ATLAS, Run I)

Off-shell

⟶ $\sim \dfrac{g_i^2 g_f^2}{\hat{s}}$: no width dependence ⇒ in conjunction with on-shell,

and assuming $[g_i g_f]_{\text{off-shell}} = [g_i g_f]_{\text{on-shell}}$: $\Gamma/\Gamma^{\rm SM} = \dfrac{\mu_{\rm off-shell}}{\mu_{\rm on-shell}}$

$$\mu_{\rm on(off)} = \frac{\sigma(i \to H^{(*)} \to f)}{\sigma(i \to H^{(*)} \to f)_{\rm SM}}$$

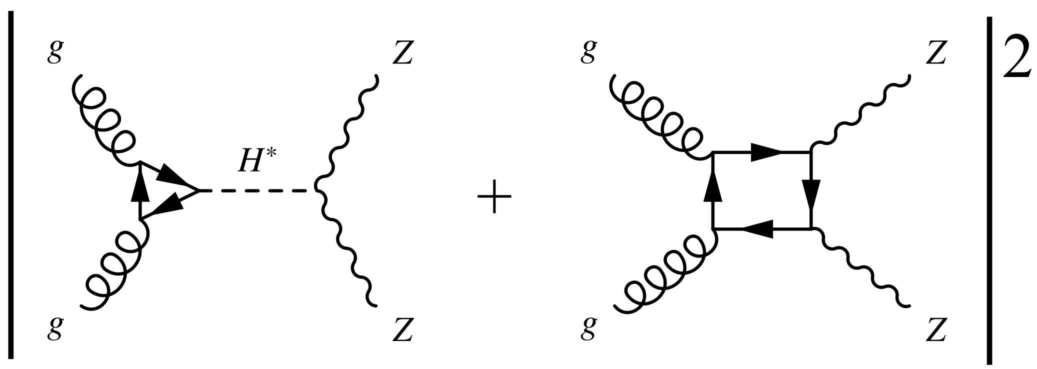
Width from off-shell measurement using $H^{(*)} \to ZZ, WW$

1st step : measure Higgs boson signal strength in the off-shell region

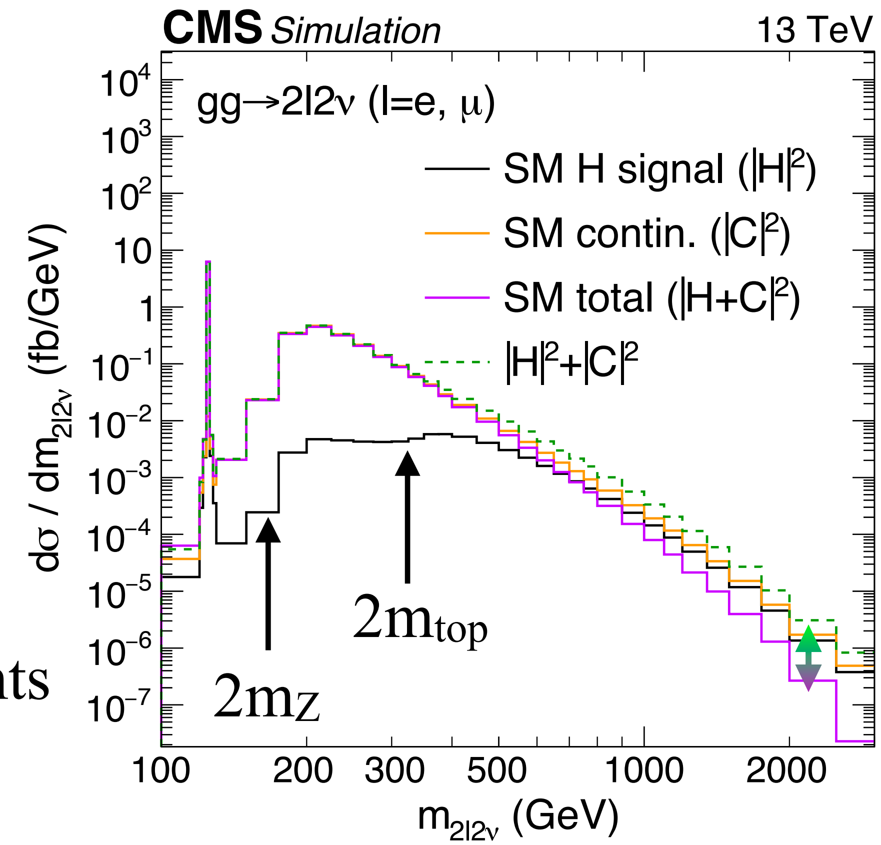
Despite propagator suppression, non-negligible contribution from Higgs thanks to enhanced coupling to longitudinal polarisation of V = W/Z at high energy

$$\frac{\sigma(pp \to H^* \to ZZ, m_{ZZ} > 2m_Z)}{\sigma(pp \to H^{(*)} \to ZZ)} \sim 8\%$$

Large interference with continuum background (mainly gg → VV)



In SM, negative ⇒ off-shell Higgs manifestation = *deficit* of events w.r.t. background only expectation



Among other key ingredients :

- state-of-the-art estimation of the very large (non-interfering) background qq → VV
- Very good modeling of signal and interfering background :

$$N_{gg\to(H^*)\to VV} = \mu_{\mathrm{off-shell}} N_{gg\to H^*\to VV} + \sqrt{\mu_{\mathrm{off-shell}}} N_{\mathrm{int}} + N_{gg\to VV}$$

Also add EW (VBF + VH) production and different signal strength modifiers $\mu_{\mathrm{F}}^{\mathrm{off-shell}}$ (ggF) and $\mu_{\mathrm{V}}^{\mathrm{off-shell}}$ (EW)

2nd step : combine with on-shell measurement to infer total width Γ

Latest results from CMS (2023) : H → 4ℓ, 138 fb^{-1}

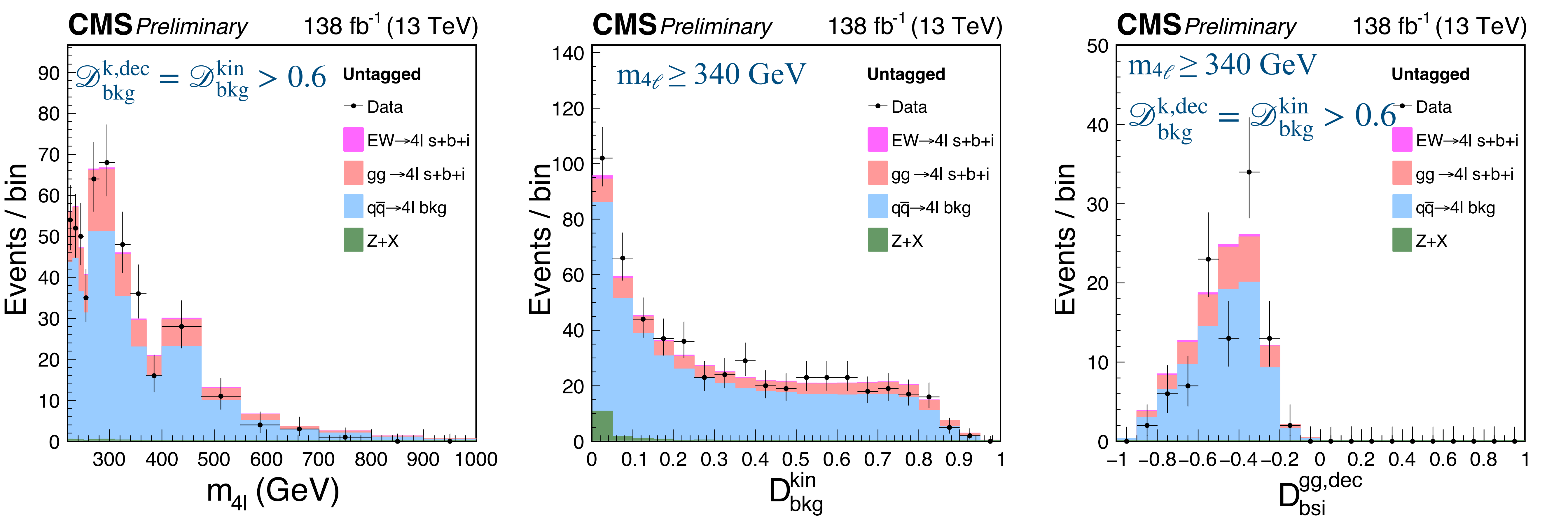
- 3 categories : VBF-tagged, VH-tagged (W/Z → qq), untagged (mostly ggF)
  (Categorization using discriminants $\mathfrak{D}_k = \mathscr{P}_{target} / (\mathscr{P}_{target} + \mathscr{P}_{ggF+2jets})$ with target = VBF or VH)
- 3D discriminant distribution : 3 observables $m_{4\ell}$ (> 220 GeV), $\mathscr{D}^{k,dec}_{bkg}$ (signal vs bkg separation) and

$$\mathscr{D}^{k,dec}_{bsi} = \frac{\mathscr{P}_{int}}{2\sqrt{\mathscr{P}_{i\to H^*+X\to ZZ+X} \times \mathscr{P}_{i\to ZZ+X}}} \in [-1,1]$$

dedicated to interference w.r.t. pure (signal, bkg) separation [(I, X) = qq for (VBF, VH)-tagged, (gg, -) for untagged],

Different « normalized probability » $\mathscr{P}$ (estimated from ME) definitions in different categories k

Example in the untagged category :

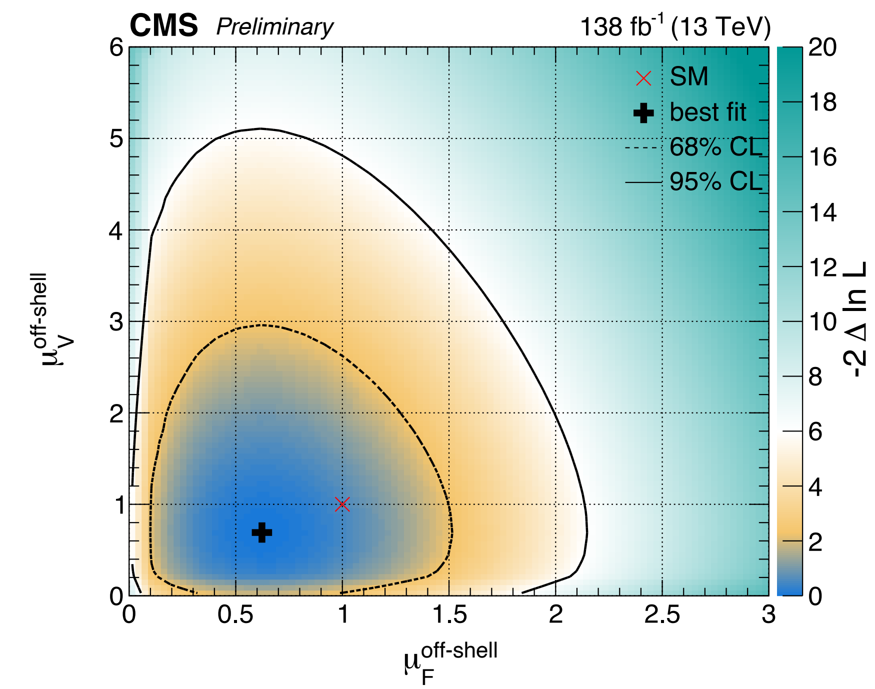


Statistically limited

Main uncertainty from qq → $(Z/\gamma^*)(Z/\gamma^*) \to 4\ell$ background modeling

$$\mu_{\text{off-shell}} = 0.64^{+0.50}_{-0.37},\ < 1.69\,@\,95\,\%\,\text{CL (expected : } 1^{+0.99}_{-0.97})$$

Also 2D (μ_V,μ_F) measurement ☛



combining with $2\ell 2\upsilon$ off-shell analysis ***(New)***

+ on-shell (assuming $[g_i g_f]_{\text{off-shell}} = [g_i g_f]_{\text{on-shell}}$) :

$$\Gamma = 2.9^{+1.9}_{-1.4}\ \text{MeV},\ \in [0.6,7.0]\ \text{MeV}\,@\,95\,\%\,\text{CL}$$

$$(\text{Expected : }\Gamma = 4.1 \pm 3.5\ \text{MeV},\ \in [0.1,10.5]\ \text{MeV}\,@\,95\,\%\,\text{CL})$$

Impact of anomalous couplings, from e.g. higher dimensional operators $HZ^{\mu\nu}Z_{\mu\nu},\ H\tilde{Z}^{\mu\nu}Z_{\mu\nu}\ \ or\ \ HZ_\mu\partial_\nu Z^{\mu\nu}$

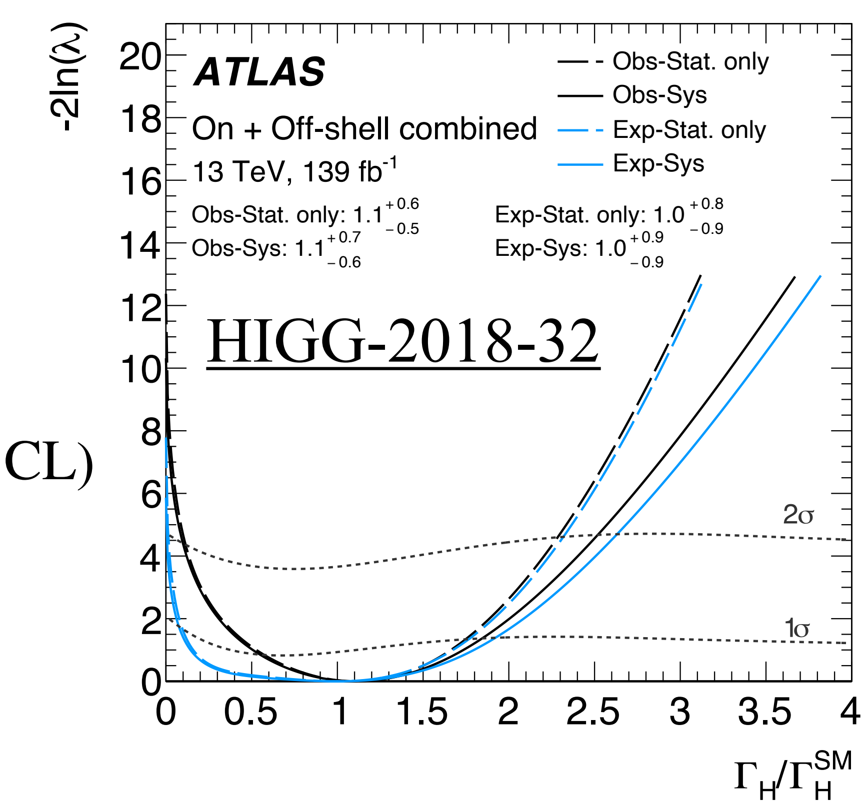
⇒ very small (almost identical expected 95% CL intervals)

ATLAS measurement

(using $2\ell 2\upsilon$ and 4ℓ @ 140 fb-1 and similar techniques) ,

$$\Gamma = 4.5^{+3.0}_{-2.5}\ \text{MeV},\ < 10.2\ \text{MeV}\,@\,95\,\%\,\text{CL}$$

$$(\text{Expected : }\Gamma = 4.1 \pm 3.8\ \text{MeV},\ < 10.6\ \text{MeV}\,@\,95\,\%\,\text{CL})$$



Rough expectations for HL-LHC (3 ab^{-1}/exp)

- Mass measurements : mainly from $H \to 4\mu$, $2e2\mu$

  Naive stat. uncertainty extrapolation for a CMS-like experiment ~ 24 MeV
  Run II syst. uncertainty from muon energy scale ~ 30 MeV
  Might expect improvements from the huge calibration sample
  + decrease of stat. uncertainty from increased acceptance

  $\Rightarrow$ target $\mathcal{O}$(20 MeV) ? [target e^+e^- Higgs factory < 10 MeV]

- Width measurements : from off-shell measurement (+ on-shell/off-shell couplings as in SM)

  CMS extrapolation from Run II, 78 fb^{-1} $H \to 4\ell$ analysis $\Rightarrow \Gamma = 4.1^{+1.0}_{-1.1}$ MeV
  assuming theory uncertainties halved w.r.t. Run II

  $\Rightarrow$ ATLAS + CMS : $\Gamma = 4.1^{+0.7}_{-0.8}$ MeV : a $\mathcal{O}$(20%) measurement ? 1902.00134
  [target e^+e^- Higgs factory 2-3%]

  Could even try to improve using more information and more channels

  Other ideas, *a priori* leading to worse precision / constraints,
  but with different techniques and hypotheses will also be explored
  (using e.g. interference in $gg \to H \to \gamma\gamma$ (on-shell) and mass/signal-strength shifts vs reference)

Conclusions

- ATLAS and CMS made huge progress in understanding the detectors during Run II

  $\Rightarrow$ Very precise lepton and photon energy scale determinations
  allowing improvement in the Higgs boson mass determination

  Final Run II legacy measurement combining ATLAS and CMS under preparation
  Achieved precision already better than 1‰ in each experiment

- The determination of the Higgs boson width is very hard at a hadron collider
  However, with *reasonable* assumptions, can be constrained to less than 3 times the SM width

- Other ideas are being explored already using the full Run II dataset

References

Mass measurements

Run I :

- ATLAS : HIGG-2013-12 , Phys. Rev. D. 90 (2014) 052004
- CMS : HIG-13-001 , Eur. Phys. J. C 74 (2014) 3076 ($H \to \gamma\gamma$)
  HIG-13-002 , Phys. Rev. D 89 (2014) 092007 ($H \to 4\ell$)
  HIG-14-009 , EPJC 75 (2015) 212 (Combination)
- ATLAS + CMS : HIGG-2014-14 , HIG-14-042, Phys. Rev. Lett. 114 (2015) 191803

Run II :

- ATLAS 36 fb^{-1} : HIGG-2016-33 , Phys. Lett. B 784 (2018) 345
- ATLAS Legacy : HIGG-2020-07 , Phys. Lett. B 843 (2023) 137880 ($H \to 4\ell$)
  HIGG-2019-16 , Phys. Lett. B 847 (2023) 138315 ($H \to \gamma\gamma$)
  HIGG-2022-20 , Phys. Rev. Lett. 131 (2023) 251802 (Combination)

- CMS 36 fb-1 : HIG-16-041 , JHEP 11 (2017) 047 ($H \to 4\ell$)
  HIG-19-004 , PLB 805 (2020) 135425 ($H \to \gamma\gamma$)
- CMS Legacy : HIG-21-019 preliminary ($H \to 4\ell$)

HL-LHC :

- CMS : FTR-21-007 ($H \to 4\ell$)
  FTR-21-008 ($H \to \gamma\gamma$)

Width estimation

For CMS, limits from line shape measurements in the « mass » papers

Run I :

- ATLAS : HIGG-2014-10 , Eur. Phys. J. C (2015) 75:335
  HIGG-2014-06 , Eur. Phys. J. C (2016) 76:6 (on-shell couplings)
- CMS : HIG-14-002 , PLB 736 (2014) 64
  HIG-14-036 , PRD 92 (2015) 072010 (lifetime)
  HIG-14-032 , JHEP 09 (2016) 051

Run II :

- ATLAS 36 fb^{-1} : HIGG-2017-06 , Phys. Lett. B 786 (2018) 223
- ATLAS 140 fb^{-1} : HIGG-2018-32 , Phys. Lett. B 846 (2023) 138223
- CMS 80 fb^{-1} : HIG-18-002 , PRD 99 (2019) 112003
- CMS 140 fb^{-1} : HIG-21-013 , Nat. Phys. 18 (2022) 1329
- CMS 140 fb^{-1} : HIG-21-019 preliminary

HL-LHC :

- Yellow Report Higgs Physics at the HL-LHC and HE-LHC 1902.00134
- ATLAS : ATL-PHYS-PUB-2015-024
- CMS : FTR-18-011

Lepton / photon performances (Run II, among others)

- ATLAS : ElectronGammaPublicCollisionResults , MuonPublicResults
    - e/γ energy scale, 36 fb^{-1} : PERF-2017-03 , JINST 14 (2019) P03017
    - e/γ reconstruction, energy scale : EGAM-2018-01 , JINST 14 (2019) P12006
    - e/γ energy scale, Legacy : EGAM-2021-02 , JINST 19 (2024) P02009
    - μ momentum scale, 3 fb^{-1} : PERF-2015-10 , Eur. Phys. J. C 76 (2016) 292
    - μ momentum scale, legacy : MUON-2022-01 , Eur. Phys. J. C 83 (2023) 686

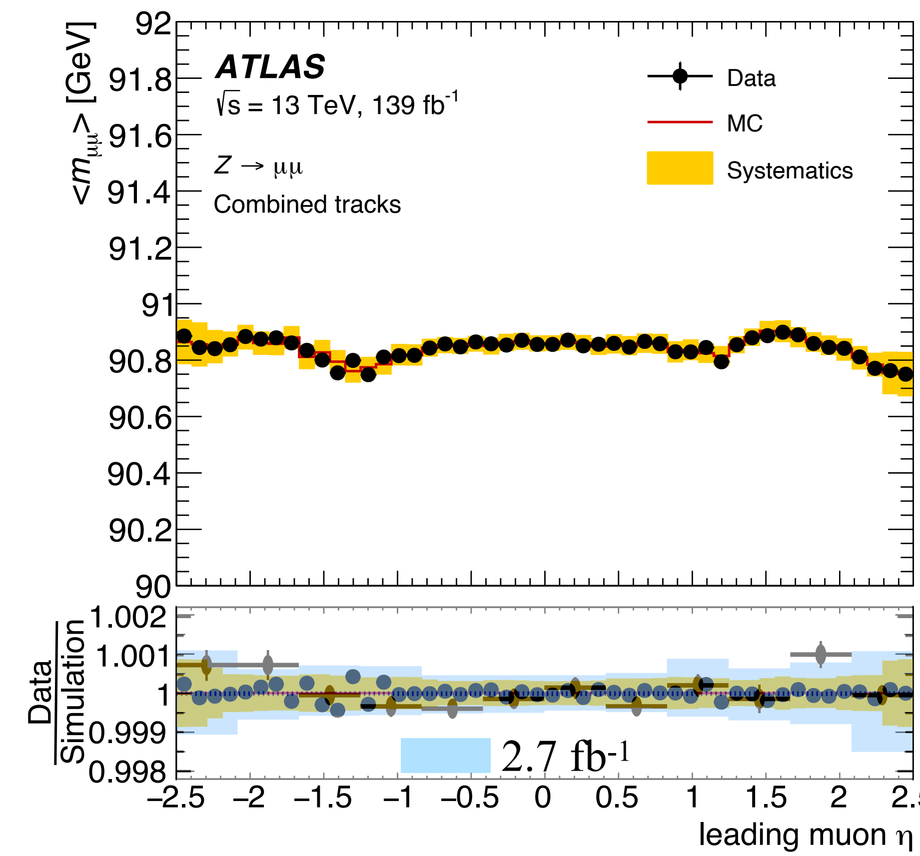
- CMS : PhysicsResultsEGM , PhysicsResultsMUO
    - electron / photon : EGM-17-001 , JINST 16 (2021) P05014
    - electron / photon : DP2020_021
    - Muon (2015-2016) : MUO-16-001 , JINST 13 (2018) P06015
    - Muon (2017) : DP2020_040

More information

ATLAS muon momentum scale uncertainty

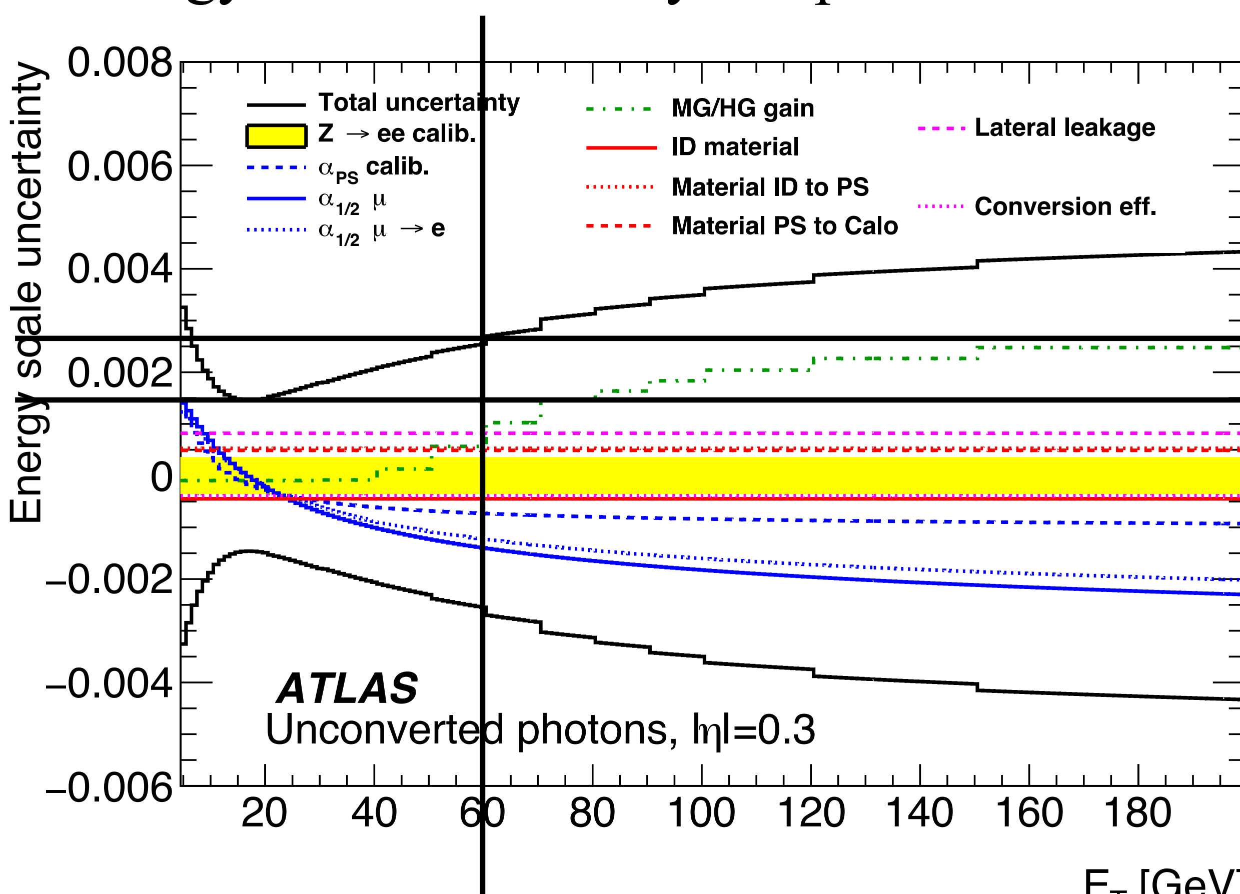
Better corrections to scale for both data / simulation
(Larger stat., better methodology ⇒ decrease
of associated uncertainty by factor of ~ 4)

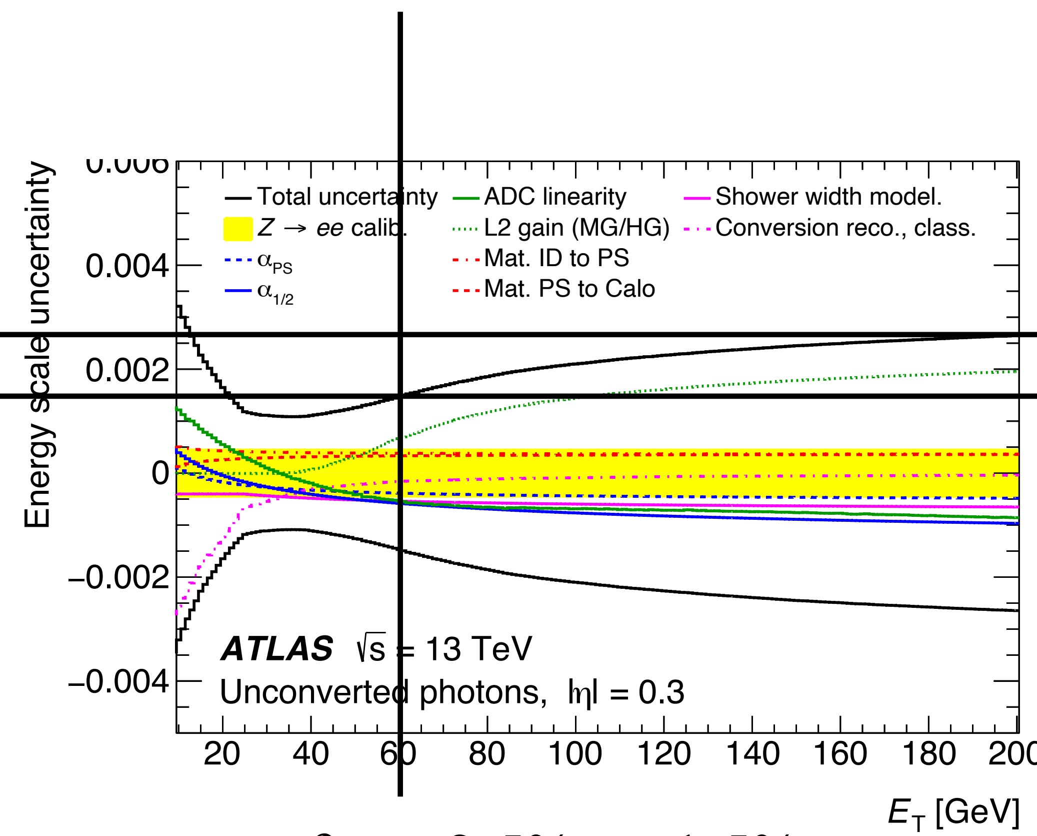
Improvement on total uncertainty up to a factor 2 vs 2.7 fb^{-1}



Photon energy scale uncertainty : improvement 36 fb^{-1} → 140 fb^{-1}

2.5‰

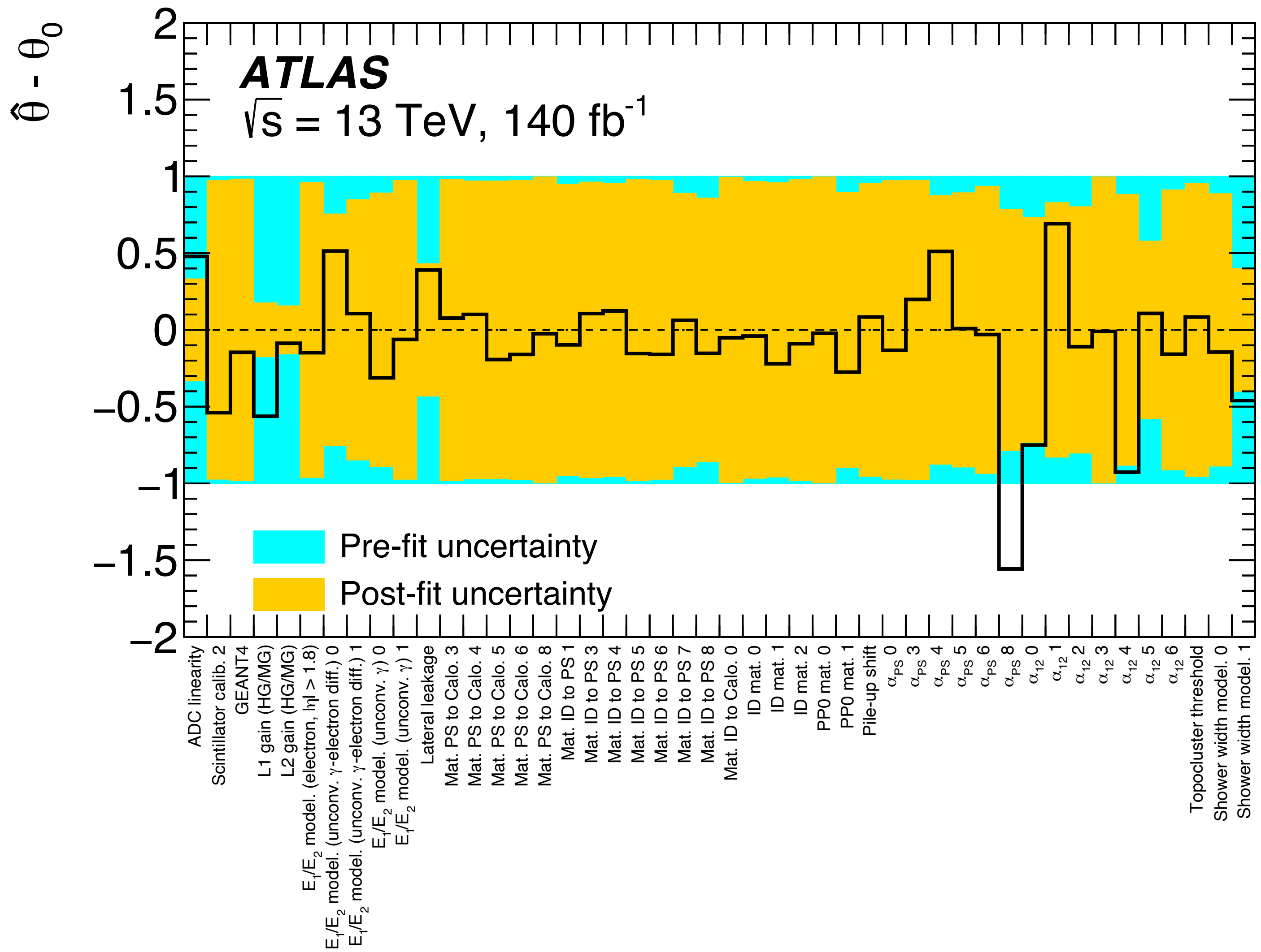




1.5‰

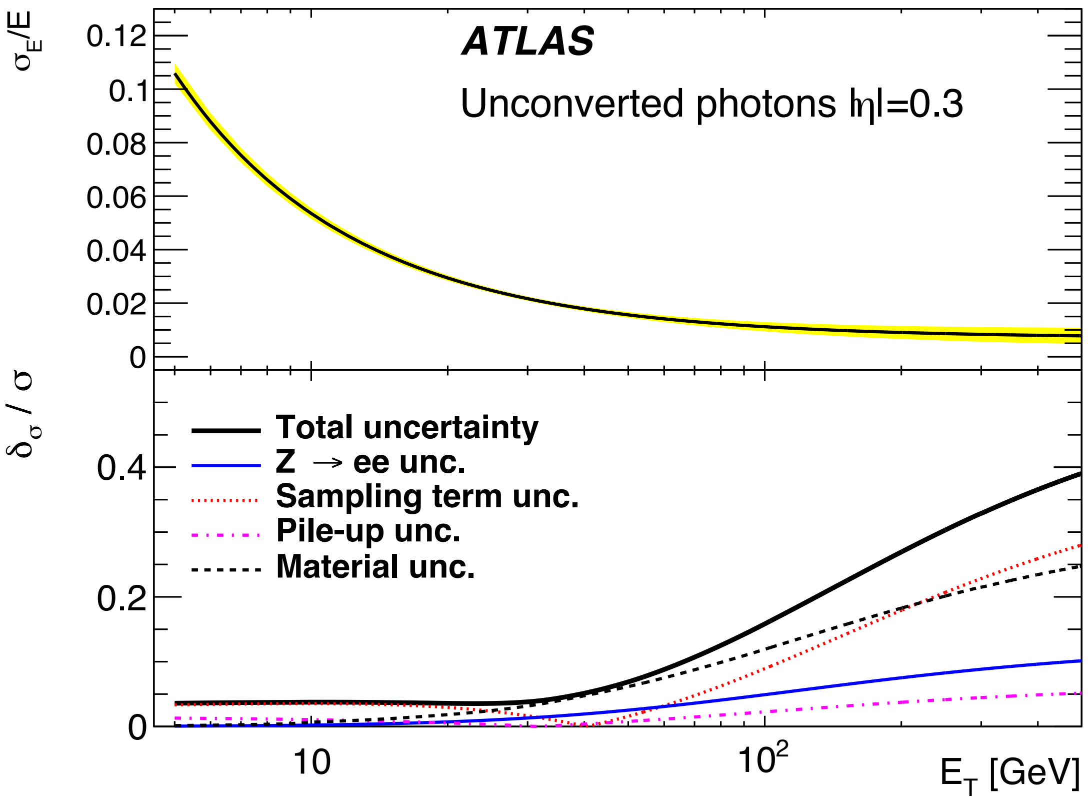
e.g. from 2.5‰ to 1.5‰
for 60 GeV E_T unconverted photon
in the central barrel

Uncertainty reduction from linearity fit



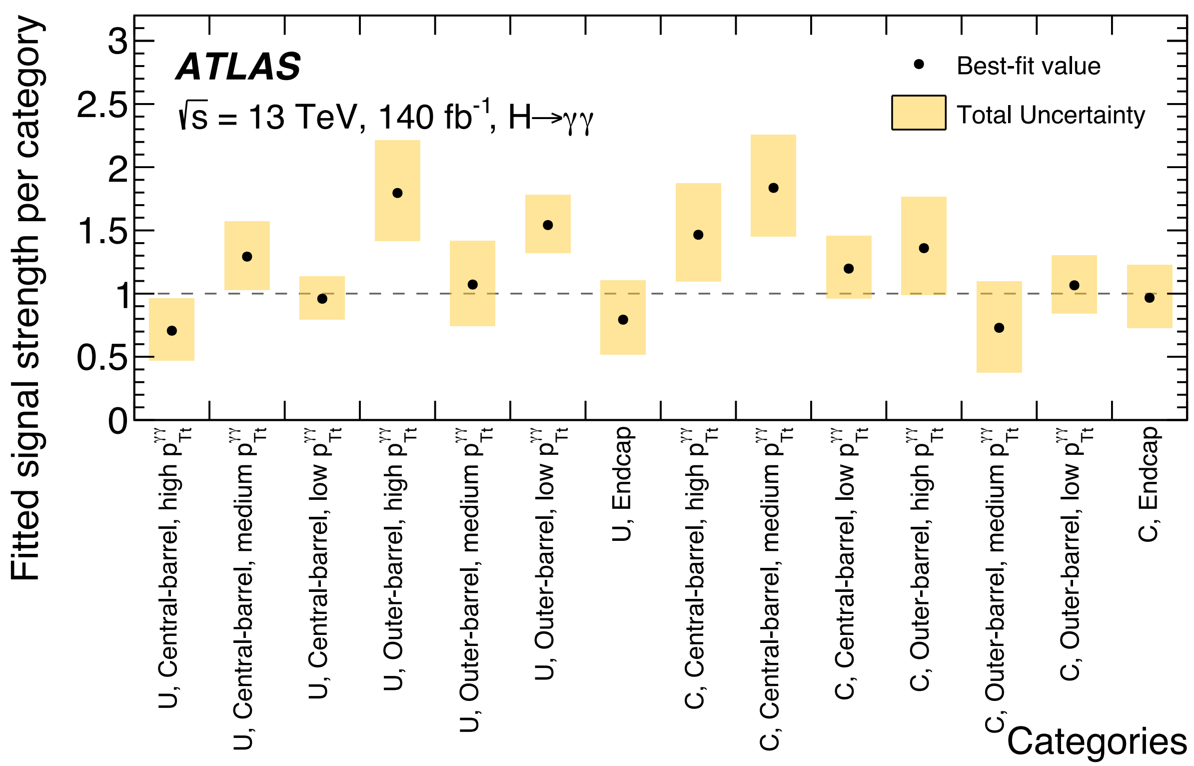
ATLAS m_H with $H \to \gamma\gamma$: $m_{\gamma\gamma}$ resolution in the 14 categories

Single photon energy resolution + uncertainty

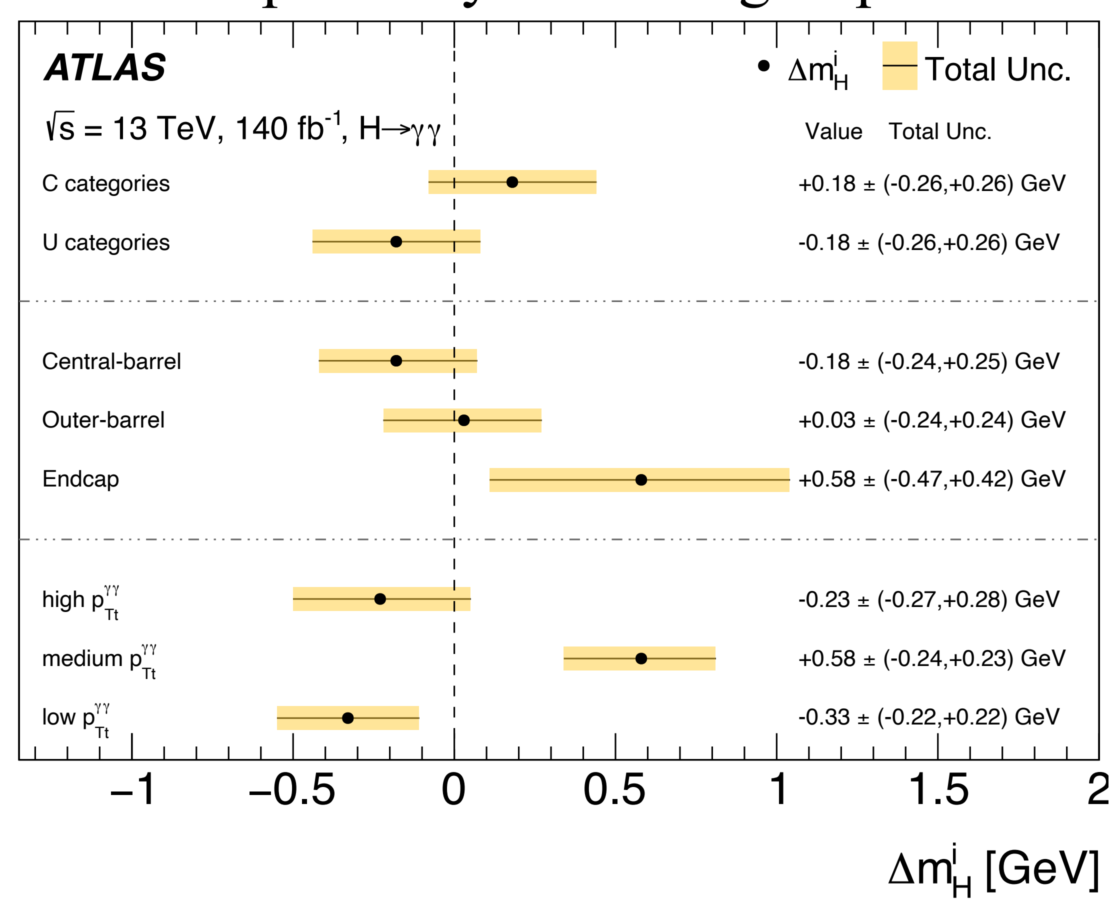


Category	$\sigma_{68}^{\gamma\gamma}$ [GeV]
U, Central-barrel, high $p_{Tt}^{\gamma\gamma}$	1.10
U, Central-barrel, medium $p_{Tt}^{\gamma\gamma}$	1.38
U, Central-barrel, low $p_{Tt}^{\gamma\gamma}$	1.47
U, Outer-barrel, high $p_{Tt}^{\gamma\gamma}$	1.24
U, Outer-barrel, medium $p_{Tt}^{\gamma\gamma}$	1.52
U, Outer-barrel, low $p_{Tt}^{\gamma\gamma}$	1.75
U, Endcap	1.90
C, Central-barrel, high $p_{Tt}^{\gamma\gamma}$	1.17
C, Central-barrel, medium $p_{Tt}^{\gamma\gamma}$	1.51
C, Central-barrel, low $p_{Tt}^{\gamma\gamma}$	1.68
C, Outer-barrel, high $p_{Tt}^{\gamma\gamma}$	1.44
C, Outer-barrel, medium $p_{Tt}^{\gamma\gamma}$	1.82
C, Outer-barrel, low $p_{Tt}^{\gamma\gamma}$	2.10
C, Endcap	2.23
Inclusive	1.82

Signal strength per category : p-value ≲ 1σ



Compatibility between groups



Mass measurements with $H \to ZZ^* \to 4\ell$

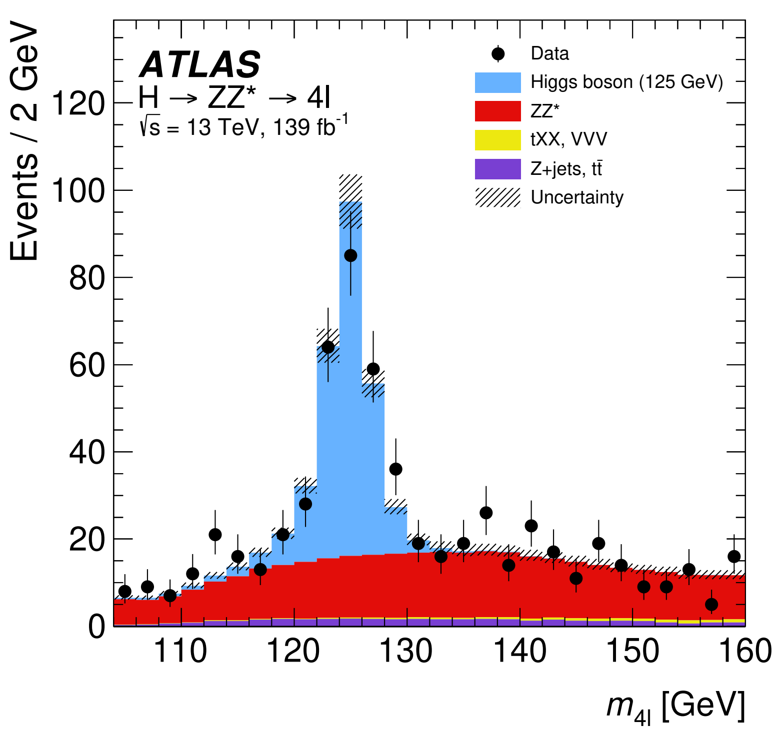
Tiny yield, large S/B, very good mass resolution

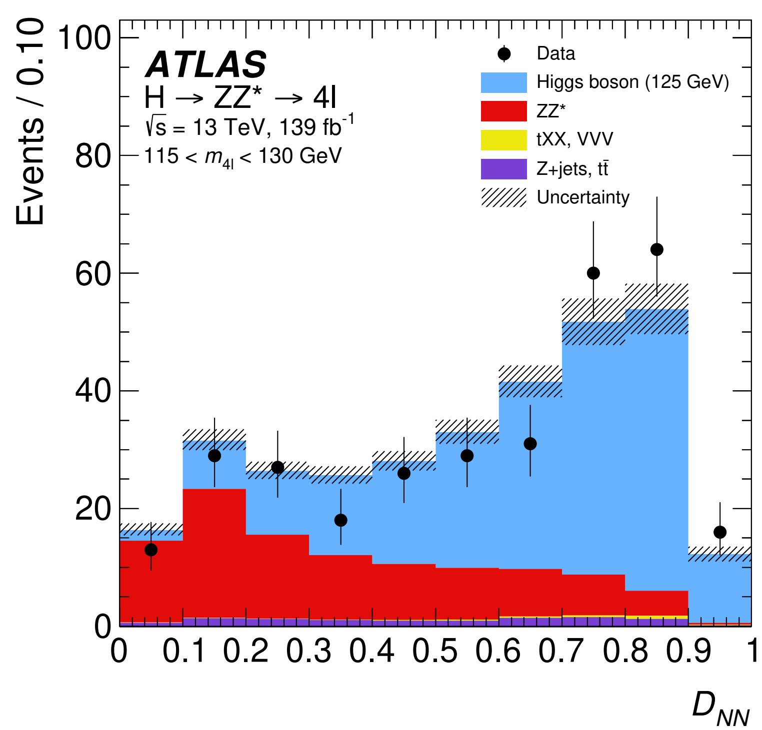
Main observable : 4-lepton mass $m_{4\ell}$ with

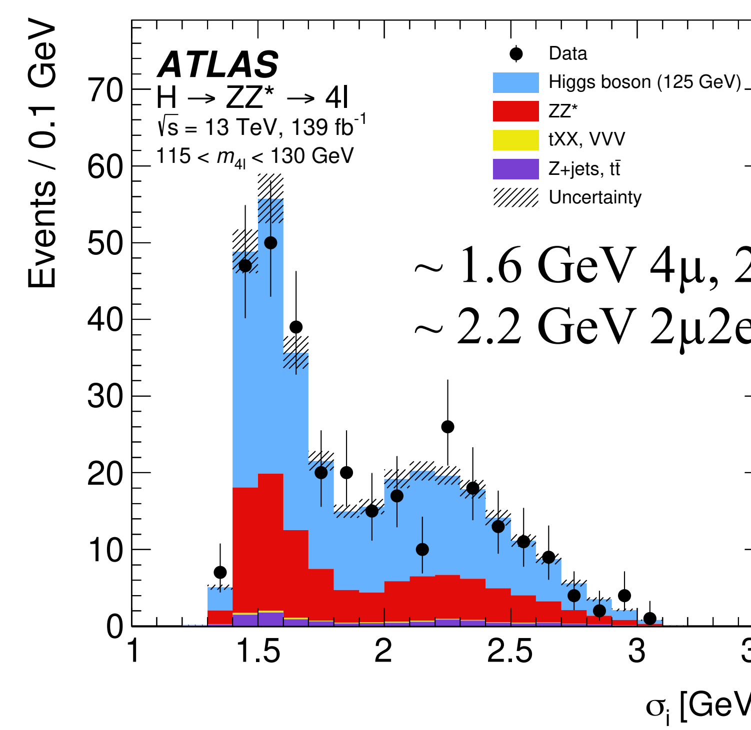
- FSR recovery (at most one)
- Refit of momenta of lepton pair making the « on-shell » Z (Z_1, $m_{\ell\ell}$ closest to m_Z) using a Z-mass constraint

<u>ATLAS (2022) :</u>

- Improved muon momentum scale determination (up to factor of 2 reduction in systematic uncertainty)
- Improved methods :
  - Better signal / background separation using a Deep Neural Network (DNN instead of BDT)
    (Inputs : $p_T(4\ell)$, $\eta_{4\ell}$, and LO matrix elements via $\log[|ME(H \to 4\ell)|^2/(|ME(gg \to 4\ell)|^2 + |ME(qq \to 4\ell)|^2)]$)
  - Per-event $m_{4\ell}$ resolution σ_i estimated with a Quantile Regression NN (QRNN)
  - Three observables used to build the full likelihood : ($m_{4\ell}$, DNN, σ_i)







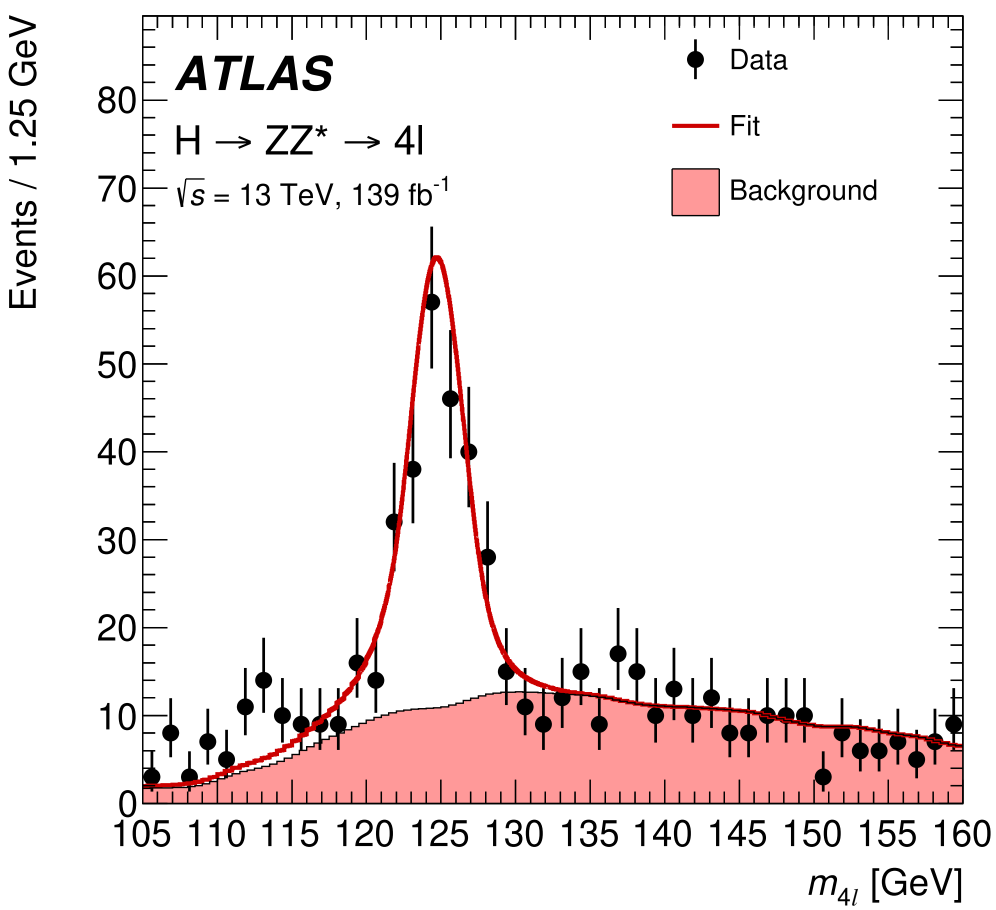
~ 1.6 GeV 4μ, 2e2μ
~ 2.2 GeV 2μ2e, 4e

 ATLAS (2022) cont'd HIGG-2020-07

Simultaneous fit to data in 4 categories 4μ/2e2μ/2μ2e/4e depending on the flavor of the leptons forming the « on-shell » (Z_1) and « off-shell » (Z_2) Zs

Free-floating normalisations of signal and dominant ZZ* background (≳ 85%) in each category

S = 209±13 signal events for this measurement ($m_{4\ell} \in [115,130]$ GeV)



$m_H = 124.99 \pm 0.18_{stat} \pm 0.04_{syst}$ GeV

syst ≪ stat , yet important to show that the momentum / energy scales are understood

Uncertainty (MeV)	Previous measurement (36 fb^{-1})	This measurement (Legacy)
Muon momentum scale	40	28
Electron energy scale	26	19
Signal modeling	na	14

ATLAS m_H combination : uncertainty impact

Source	Systematic uncertainty on m_H [MeV]
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

$H \to 4\ell$ selection

ATLAS : $p_T > 20 / 15 / 10 / 7{,}5$ (e,μ) GeV

$\Delta R(\ell,\ell') \geq 0.1$

$50 < m_{12} < 106$ GeV, $m_{min} < m_{34} < 115$ GeV

($m_{min} = 12$ ($m_{4\ell} < 140$), 50 ($m_{4\ell} > 190$), linear in $m_{4\ell}$ ($140 < m_{4\ell} < 190$))

4μ / 4e : alternative pairing $m_{\ell\ell} > 5$ GeV

Efficiency : 33% / 25% / 19% / 16% for 4μ / 2e2μ / 2μ2e / 4e and $|y_H| < 2.5$

CMS : $p_T > 20 / 10 / 7{,}5 / 7{,}5$ (e,μ) GeV

$12 < m_{34}, m_{12} < 120$ GeV, $m_{4\ell} > 70$ GeV

For 36 fb^{-1}, $m_{12} > 40$ GeV , $\Delta R(\ell,\ell') \geq 0.02$,

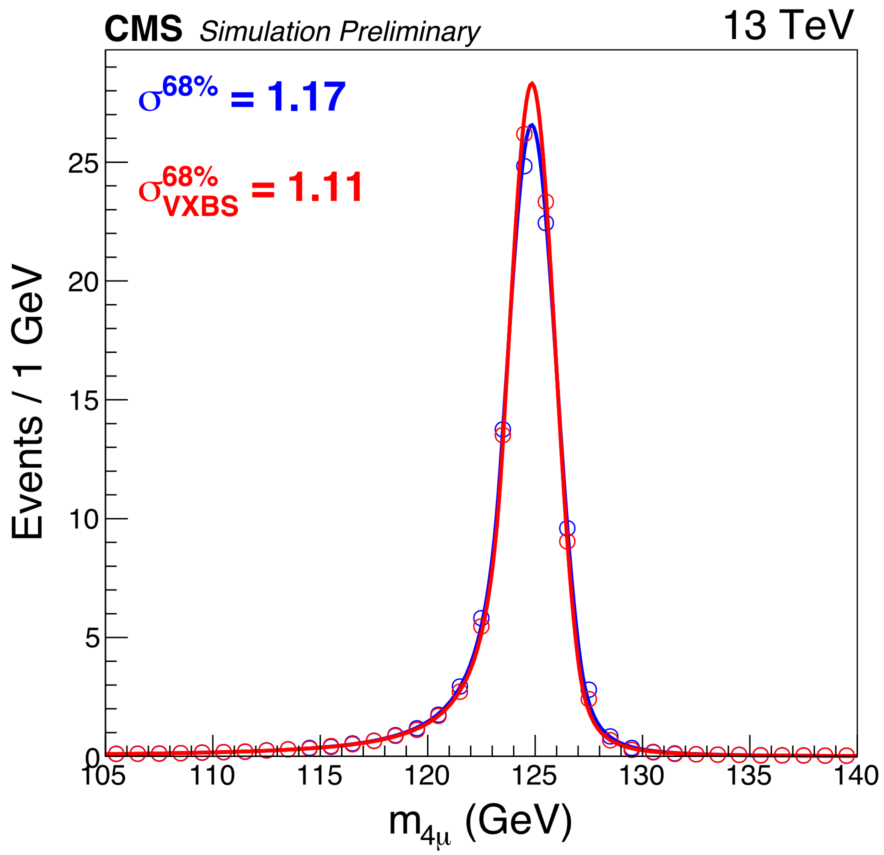
$m_{\ell^+\ell^-} > 4$ GeV (also different flavors; against (B-) hadron decays)

Uncertainty on muon momentum / electron energy scale ~ 0.03% / 0.15%

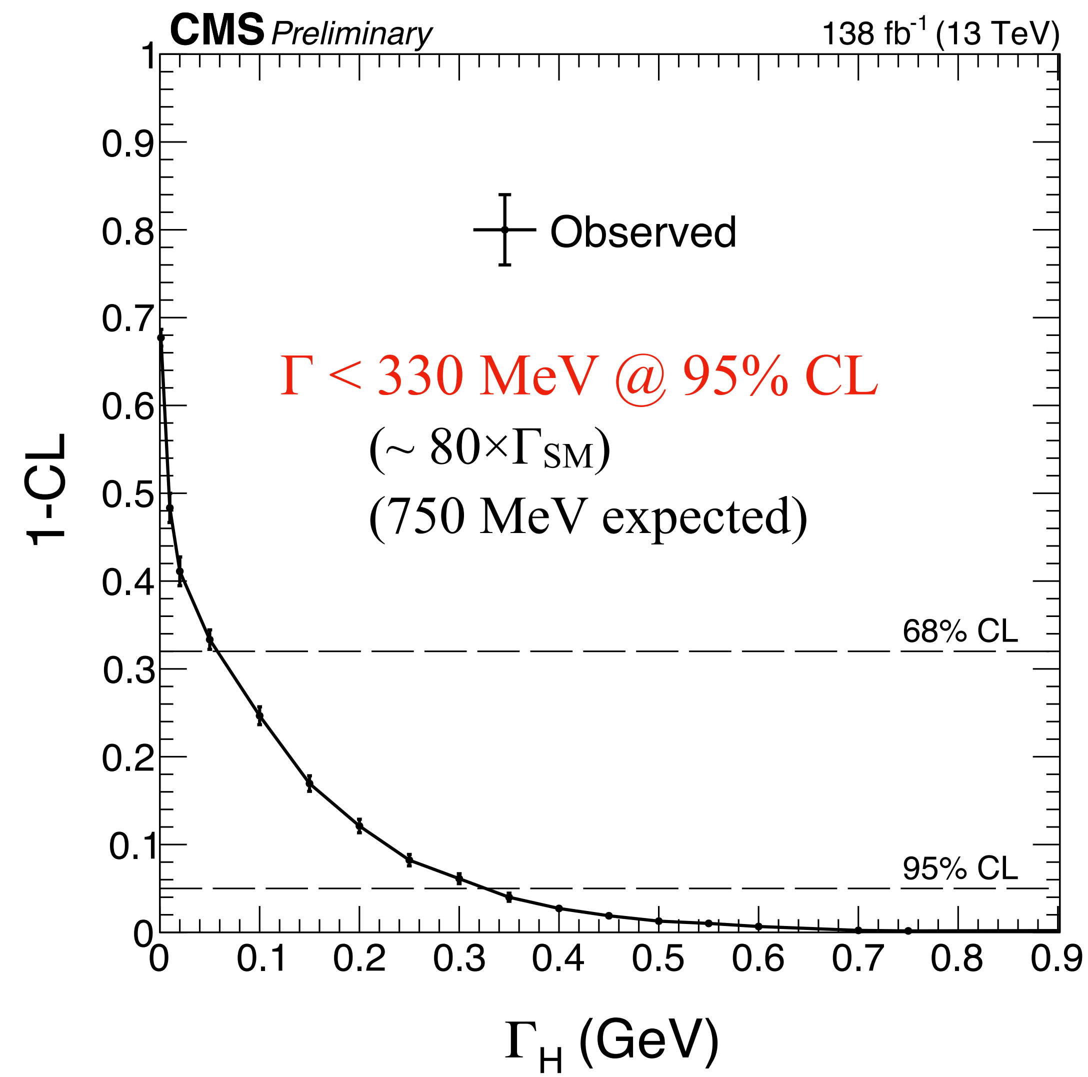
($H \to 4\ell$ (p_T,η) spectrum)

Uncertainty on muon momentum / electron energy resolution ⇒ 3% / 10% on $\sigma(m_{4\ell})$

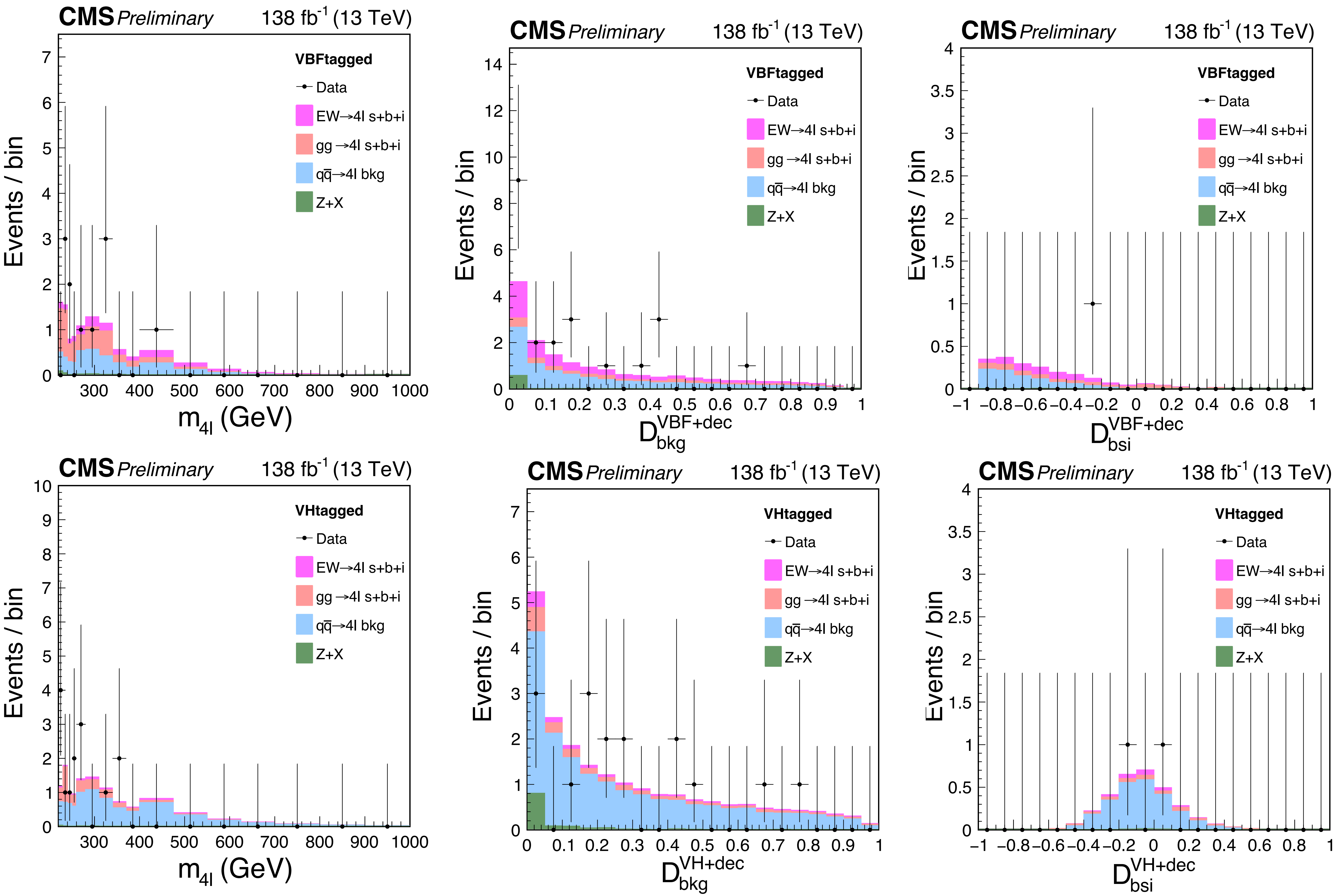
Impact of beam spot constraint on 4 muon mass



Width upper limit from on-shell line shape



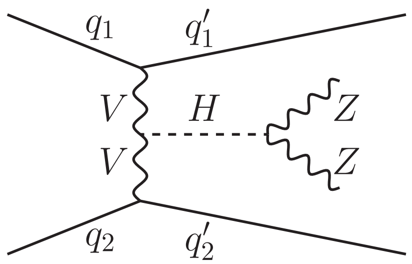
CMS width from off-shell : observables in the VBF/VH tagged categories



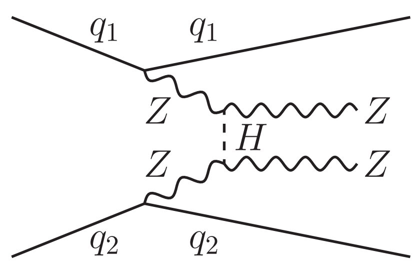
t-channel off-shell Higgs in VBF

→ included in off-shell signal contribution, with scaling as $\mu_V^{\mathrm{off-shell}}$

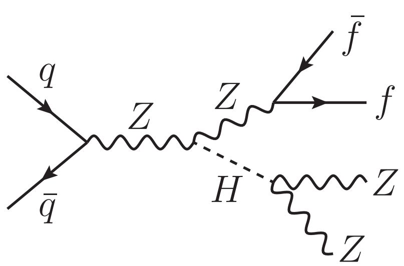
VBF (s-channel):



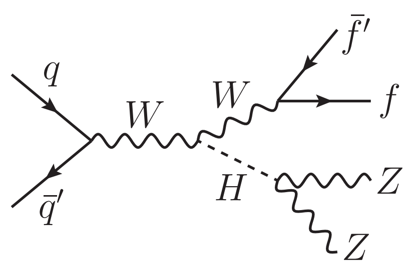
VBF (t-channel):



ZH (s-, t-, u-channels):

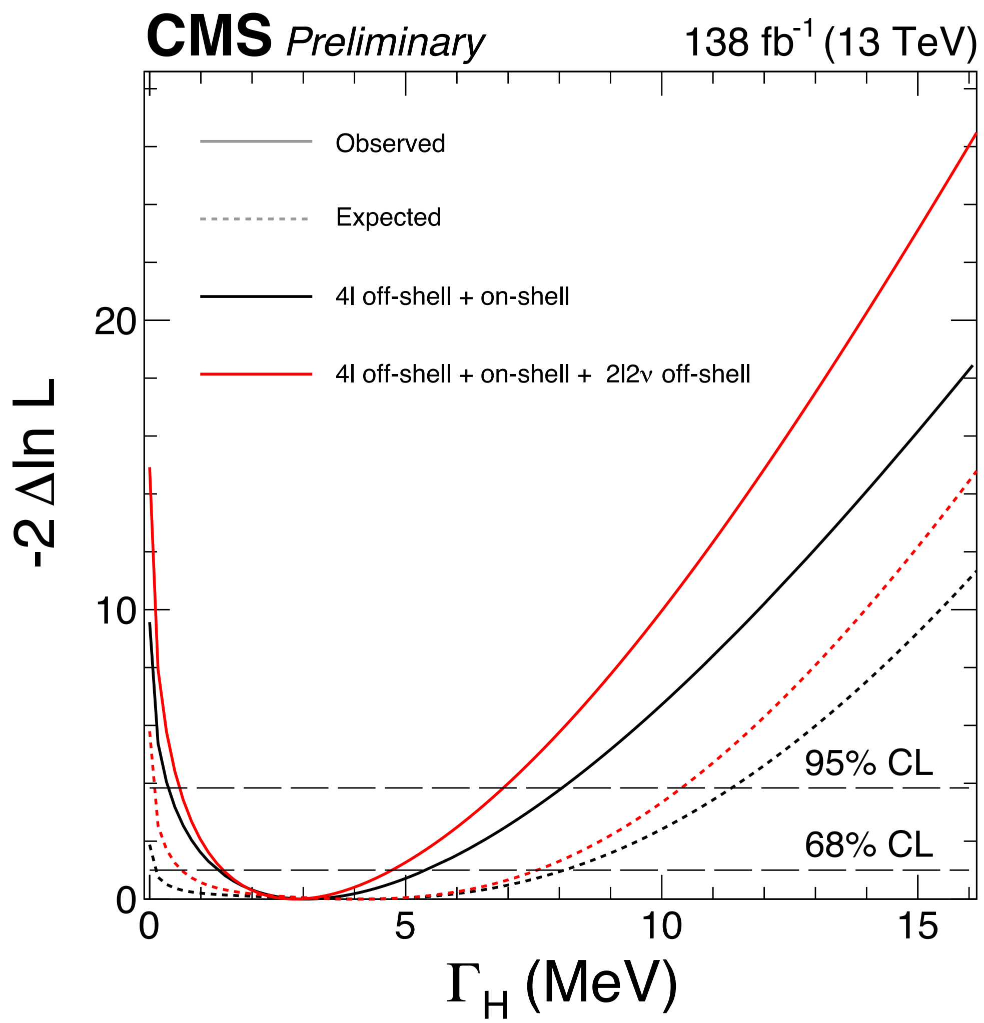


WH:



Width from off-shell : Likelihood scans

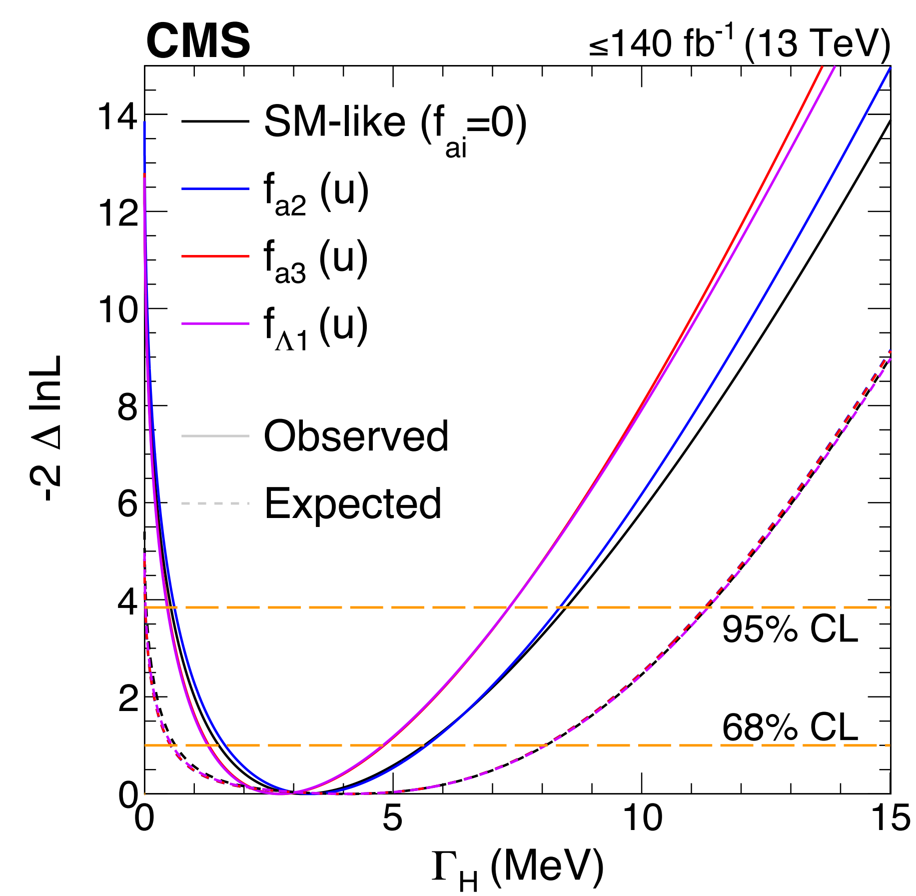
$H \rightarrow 4\ell + 2\ell 2\nu$ 138 fb^{-1}



Impact of anomalous couplings

(78 fb^{-1} $H \rightarrow 4\ell$ off-shell

+ 140 fb^{-1} $H \rightarrow 4\ell$ on-shell + $H \rightarrow 2\ell 2\nu$ on-shell)



EW fit (old) status (GFitter 2018)

$m_H = 90^{+21}_{-18}$ GeV

$$m_W = 80.3535 \pm 0.0027_{m_{top}} \pm 0.0030_{\delta_{theo} m_{top}} \pm 0.0026_{m_Z}$$
$$\pm 0.0024_{\Delta\alpha_{had}} \pm 0.0026_{\alpha_s} \pm 0.0001_{m_H} \pm 0.0040_{theo} \text{ GeV}$$
$$= 80.354 \pm 0.007 \text{ GeV}$$

$$\sin^2\theta^{\ell}_{eff} = 0.231532 \pm 0.000011_{m_{top}} \pm 0.00016_{\delta_{theo} m_{top}} \pm 0.000012_{m_Z}$$
$$\pm 0.000035_{\Delta\alpha_{had}} \pm 0.000021_{\alpha_s} \pm 0.000001_{m_H} \pm 0.000040_{theo}$$
$$= 0.23153 \pm 0.00006$$

$\Rightarrow$ improving m_H determination not useful