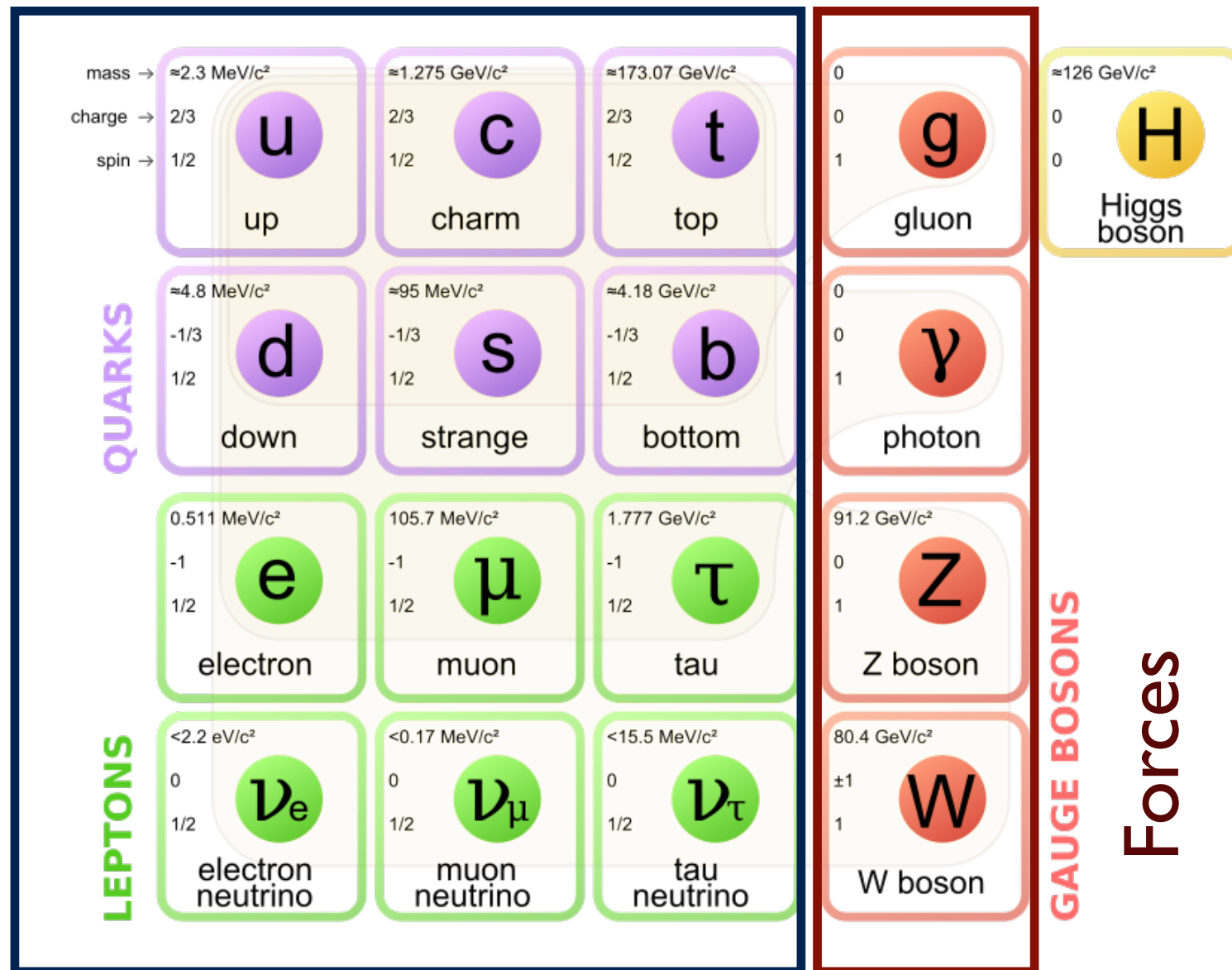# Characterising experimentally the Higgs Boson and the Electroweak processes as a portal to new phenomena

Gaetano Αθανάσιος Barone

Brookhaven National Laboratory

ATLAS
EXPERIMENT

July 2022

I

Matter

Fermions
$s=1/2$

Forces

Fields

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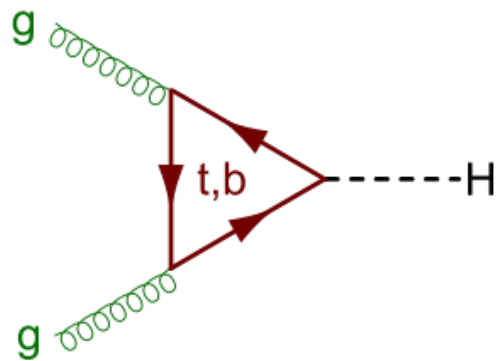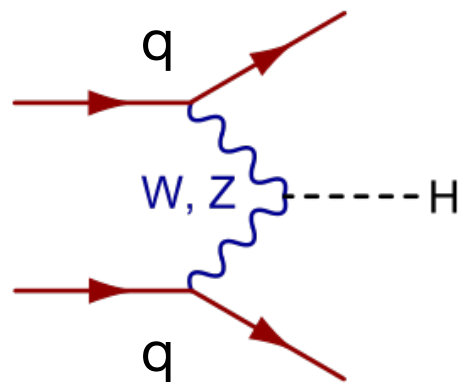
Introduction

- Higgs boson (*H*) main production in proton-proton collisions:
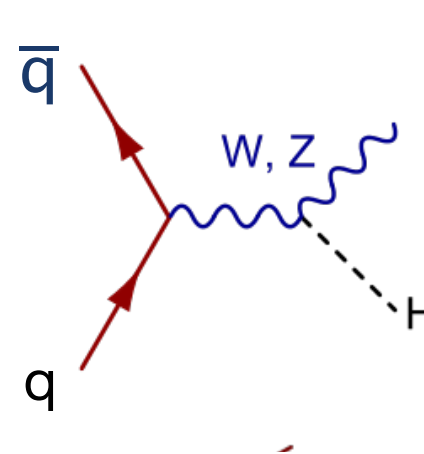
  ‣ Predominant production gluon-gluon fusion (87%) and VBF (6.8)

  ‣ W, Z associated production (4%) and $t\bar{t}H$ (<1%)

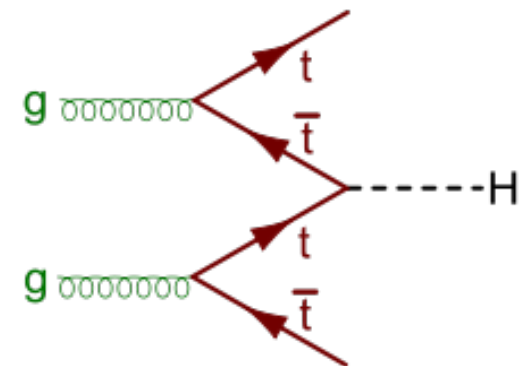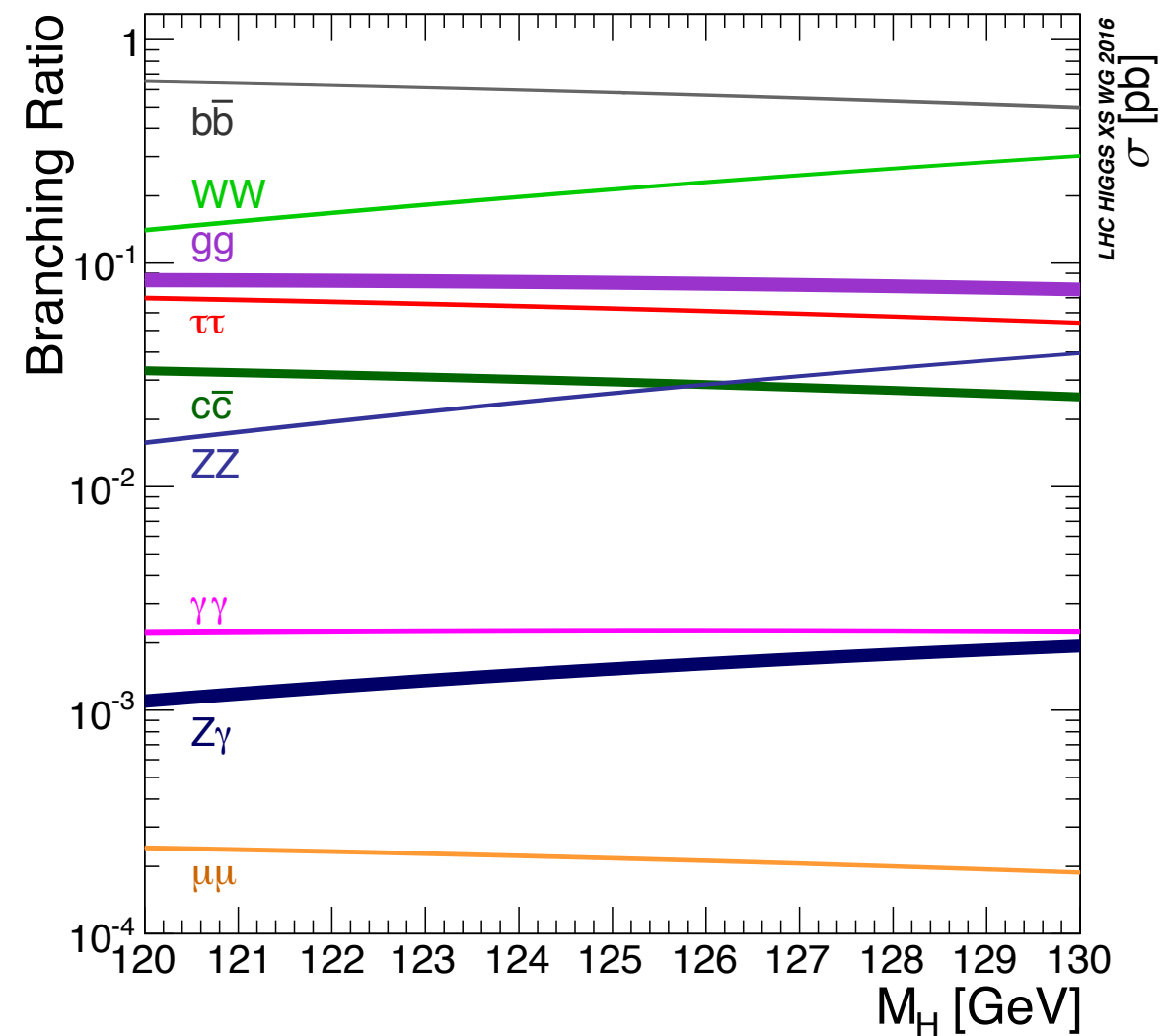$$gg\text{F} \qquad \text{VBF} \qquad WH,ZH \qquad t\bar{t}H$$
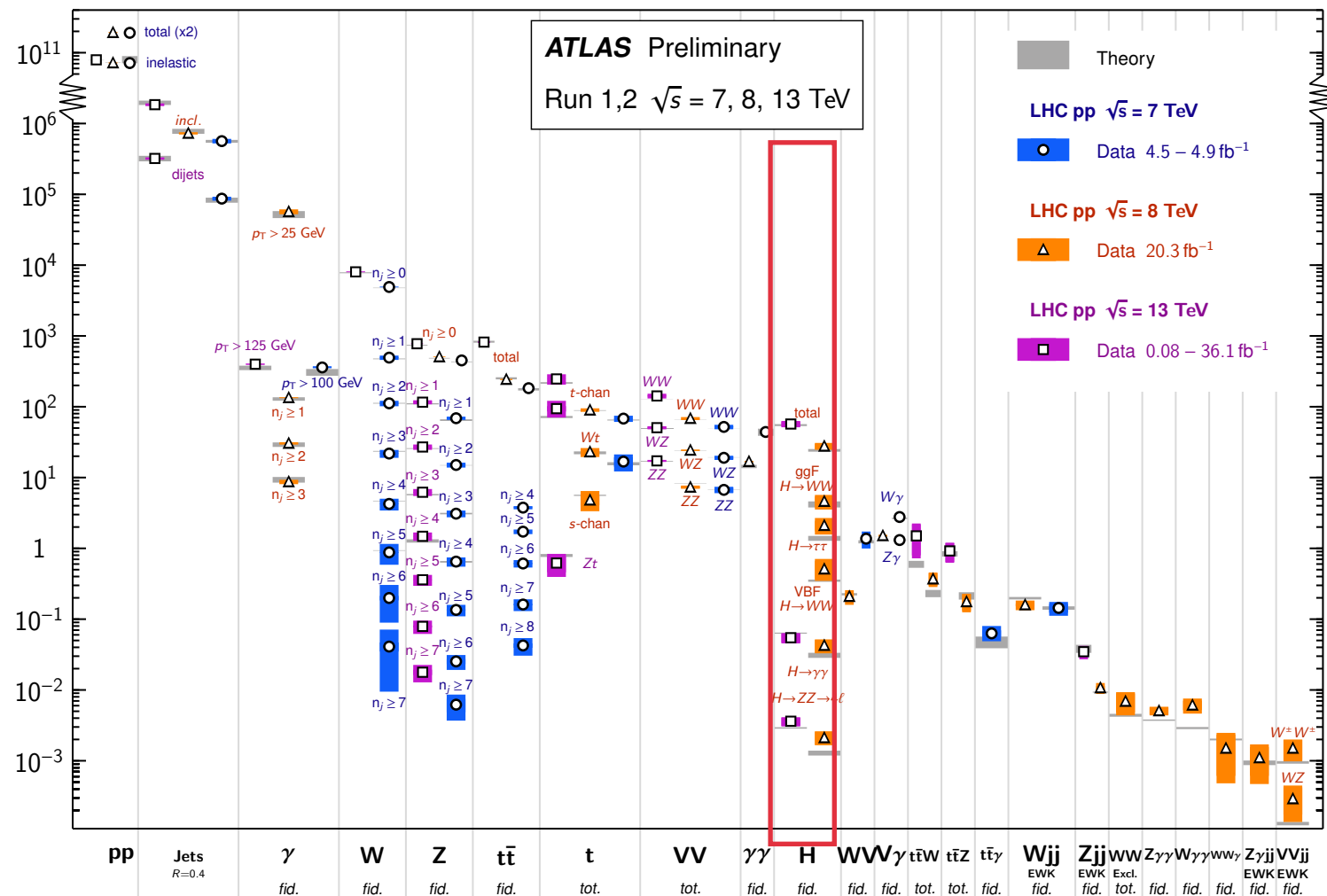
- **Experimentally challenging final states**

  ▸ In association with additional jets, same final state of many other processes

  ▸ forward jets with large rapidity gap, small rates

Run 1 Discovery

- Run-1 featured *in primis* the discovery in July 2012
  - First properties measurements
  - Programme largely limited by statistical accuracy.

  - Where do we stand with our understanding of the Higgs 10 years later ?

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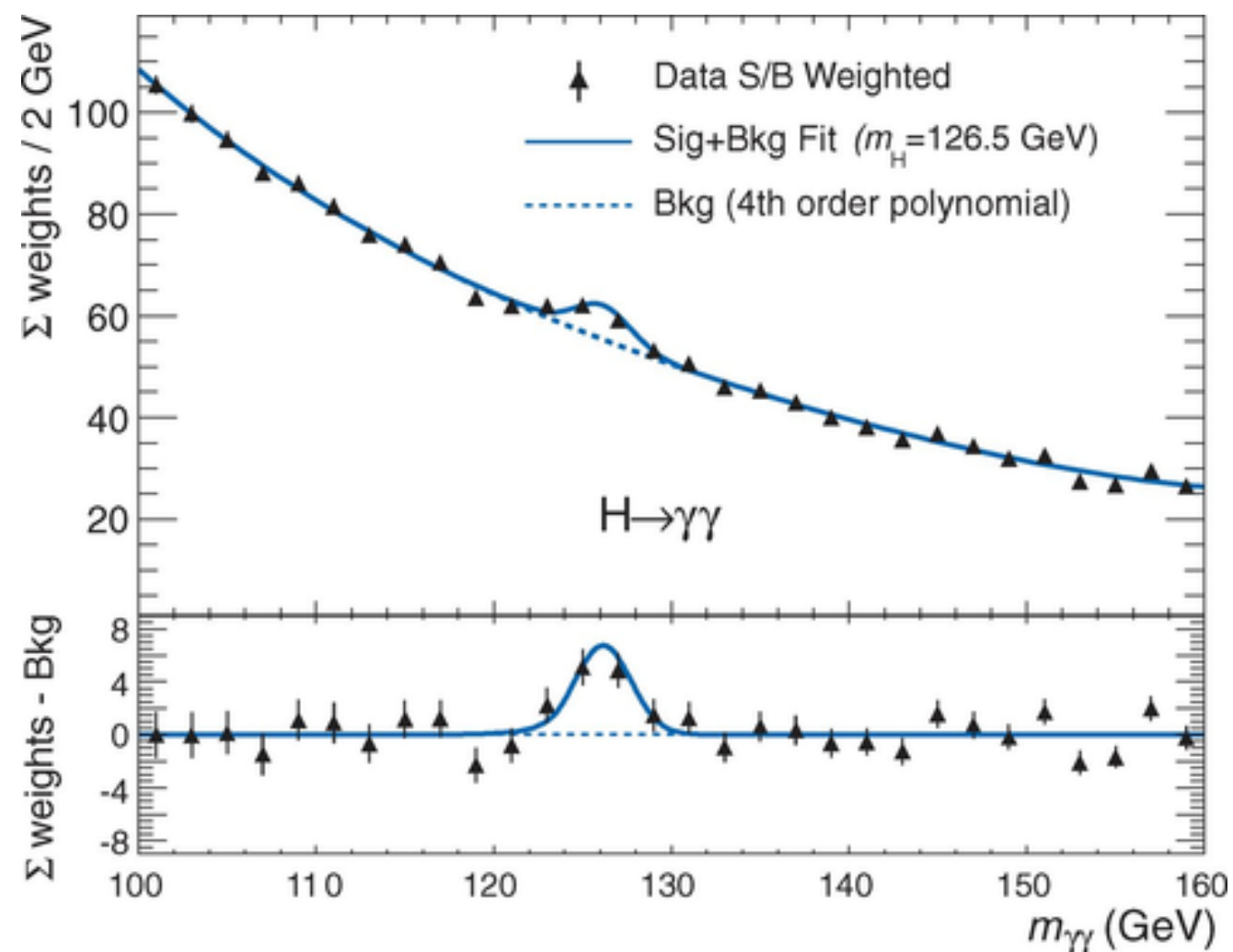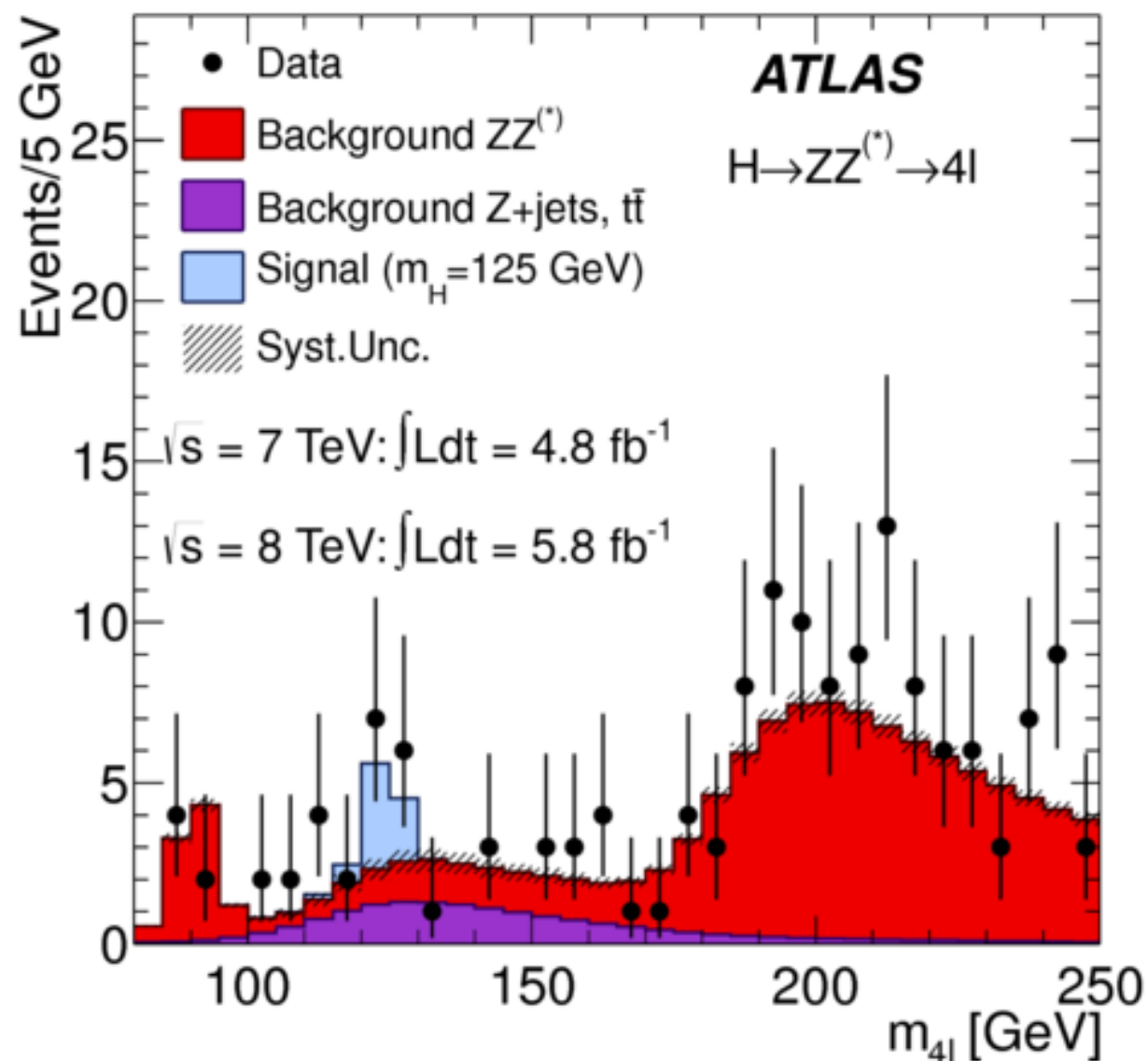
- Run-1 featured *in primis* the discovery
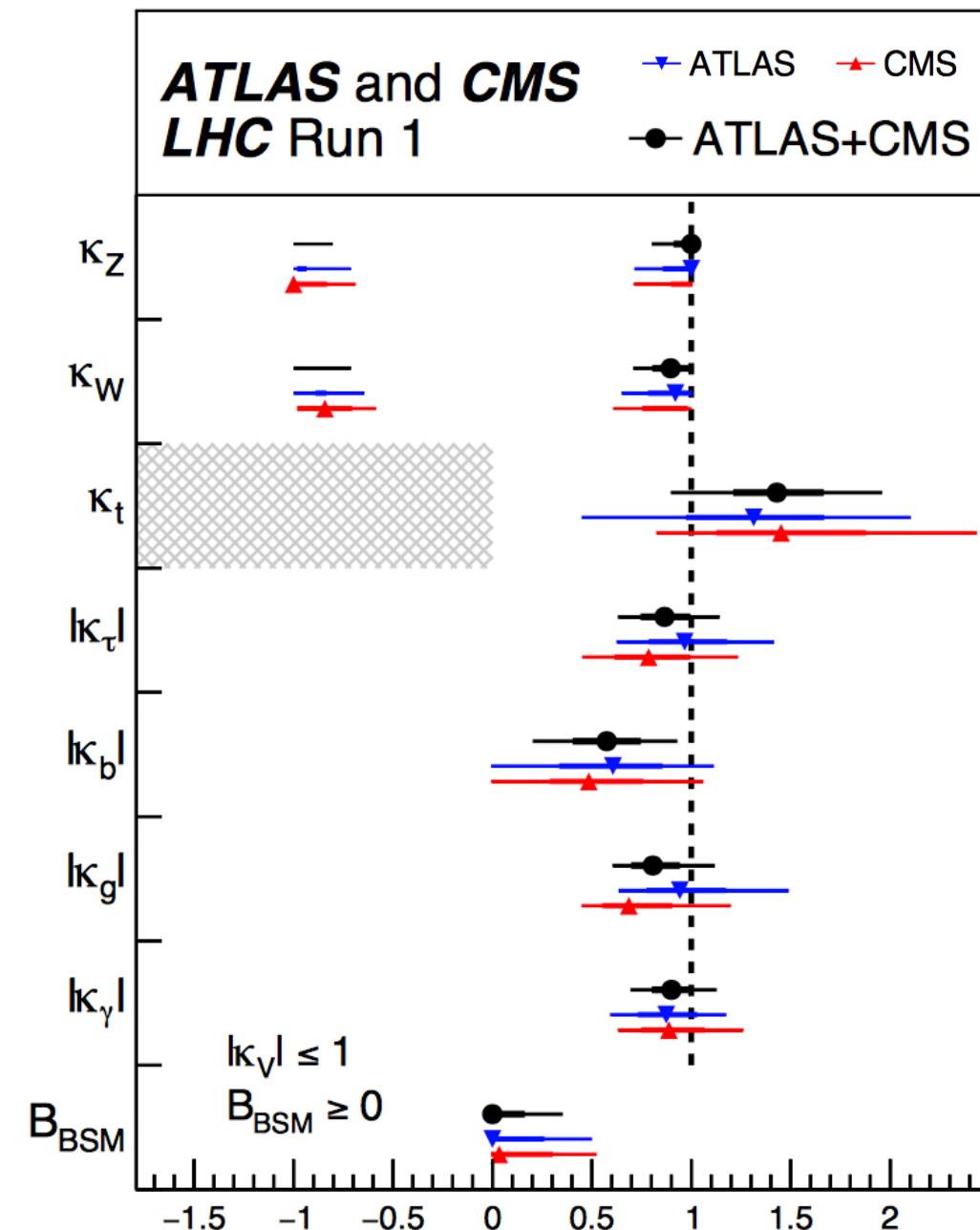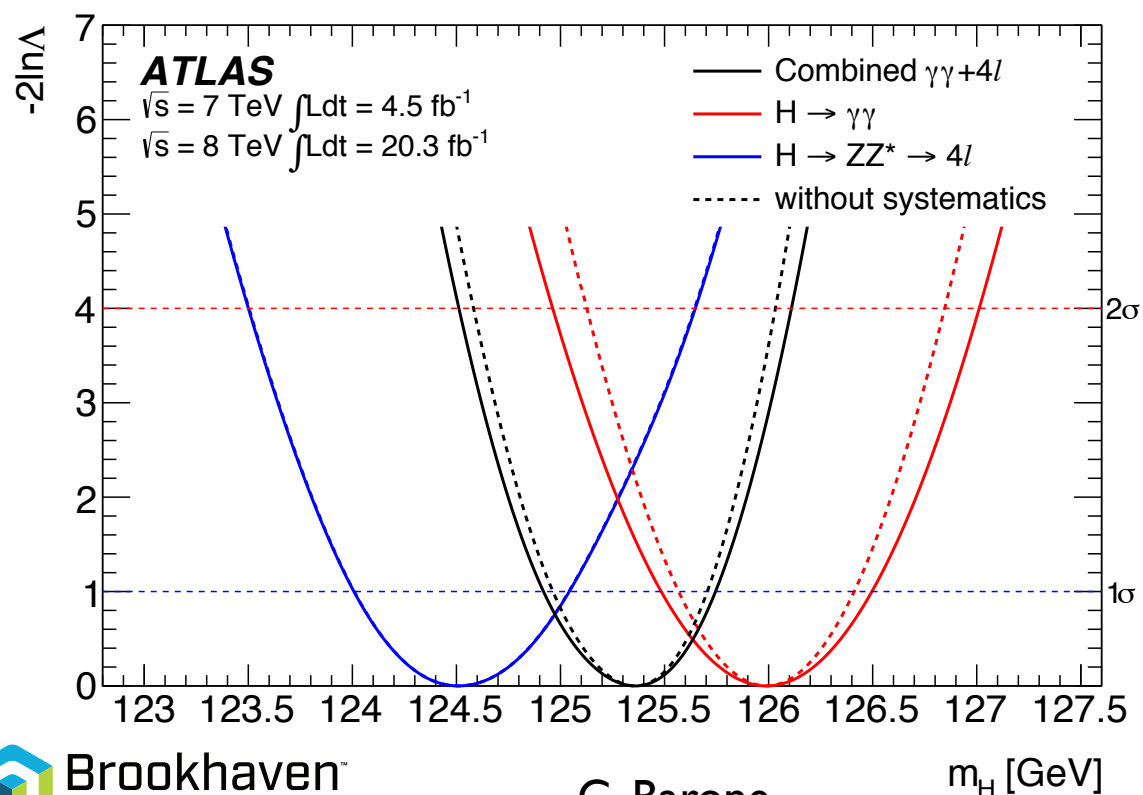 - First properties measurements
  - Programme largely limited by statistical accuracy.

- Properties:
  - ATLAS precision in m_H of 0.33%:
  - Couplings measured to 10% to 25% precision
  - $H \to$ inv. constrained to < 30%
  - First studies of $J^{PC} = 0^{++}$, (indirect) width $\Gamma_H < 14.4$ MeV (15.2 MeV)

Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	125.98 ± 0.42 (stat) ± 0.28 (syst) $= 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	124.51 ± 0.52 (stat) ± 0.06 (syst) $= 124.51 \pm 0.52$
Combined	125.36 ± 0.37 (stat) ± 0.18 (syst) $= 125.36 \pm 0.41$

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G. Barone

July-22

Overview

- **ATLAS collected 139 fb⁻¹ in Run 2**
  - Sufficient statistics for precision-level measurements.

  - Path open to exploration of SM Lagrangian in the Eelectro-Weak symmetry breaking sector.

  - Probe to couplings to bosons and fermions

  - Understand structure of its potential.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\Psi}\slashed{D}\psi$$
$$+ D_{\mu}\Phi^{\dagger}D^{\mu}\Phi - V(\Phi)$$
$$+ \bar{\Psi}_{L}\hat{Y}\Phi\Psi_{R} + h.c.$$

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Overview

- ATLAS collected 139 fb^{-1} in Run 2

  ‣ Sufficient statistics for precision-level measurements.

  ‣ Path open to exploration of SM Lagrangian in the Eelectro-Weak symmetry breaking sector.

  ‣ Probe to couplings to bosons and fermions

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$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\Psi}\slashed{D}\psi$$
$$+ \boxed{D_\mu\Phi^\dagger D^\mu\Phi} - \boxed{V(\Phi)}$$
$$+ \boxed{\bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.}$$

- In ten years from the discovery in July 2012:

  1. Understanding of the H potential structure, through the measurement of its mass.

  2. Advances in probes of Yukawa couplings to second and first generation fermions.

  3. Production mode cross sections.

  4. Differential cross sections.
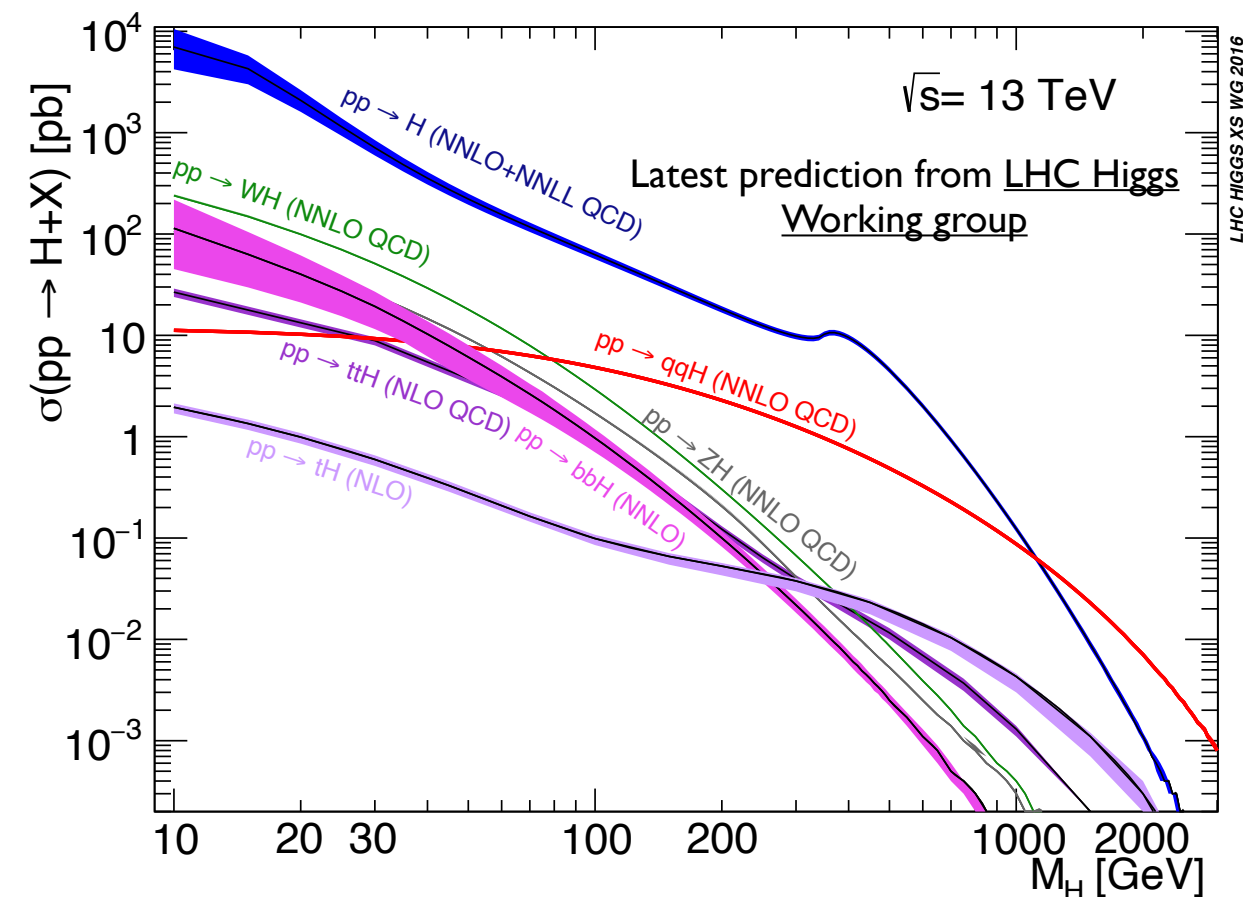
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2. Mass measurement

- Importance of m_H and Γ_H in several aspects of our understanding of fundamental physics.

Power law expansion of the potential

$$V(h) \;=\; \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\Psi}\slashed{D}\psi$$
$$+ D_\mu \Phi^\dagger D^\mu \Phi - \boxed{V(\Phi)}$$
$$+ \bar{\Psi}_L \hat{Y} \Phi \Psi_R + h.c.$$

‣ Understanding the perturbative expansion of its potential ($\lambda v^2 h^2$).

‣ Higgs couplings defined by the value of m_H.

‣ Input to precision global fit of the Standard Model.

Global Electroweak fits from the Gfitter Collaboration

Prediction and uncertainties of Higgs production processes as a function of the m_H
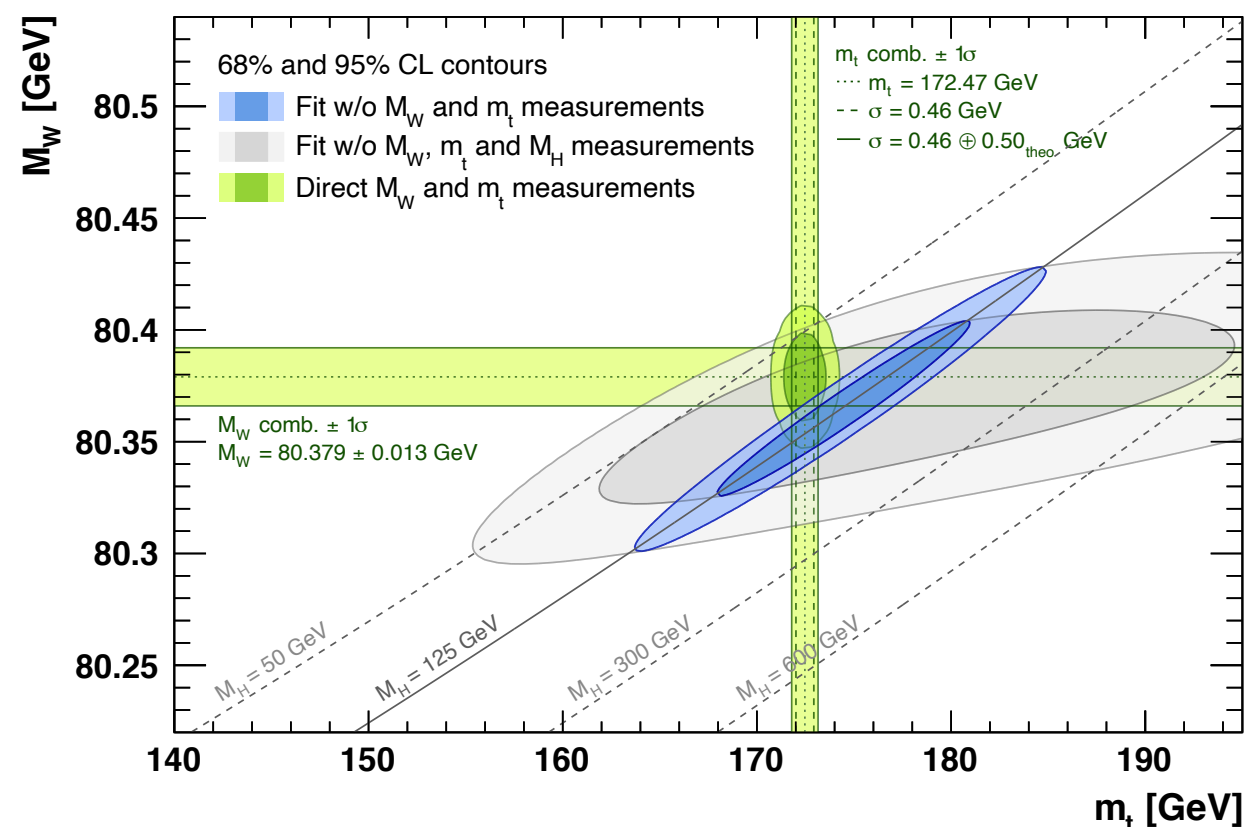
Run I status

- ATLAS run I precision on m_H of **0.33%**

 ▸ combined measurement from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$.

Channel	Mass measurement [GeV]
$H \rightarrow \gamma\gamma$	$125.98 \pm 0.42 \,(\text{stat}) \pm 0.28 \,(\text{syst}) = 125.98 \pm 0.50$
$H \rightarrow ZZ^* \rightarrow 4\ell$	$124.51 \pm 0.52 \,(\text{stat}) \pm 0.06 \,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37 \,(\text{stat}) \pm 0.18 \,(\text{syst}) = 125.36 \pm 0.41$

  ▸ Both channels dominated by statistical uncertainty

- At Run2 aim in improving significantly the precision:

  ▸ Expect 7 times more candidates, with 139 fb^{-1} at $\sqrt{s}$=13 TeV

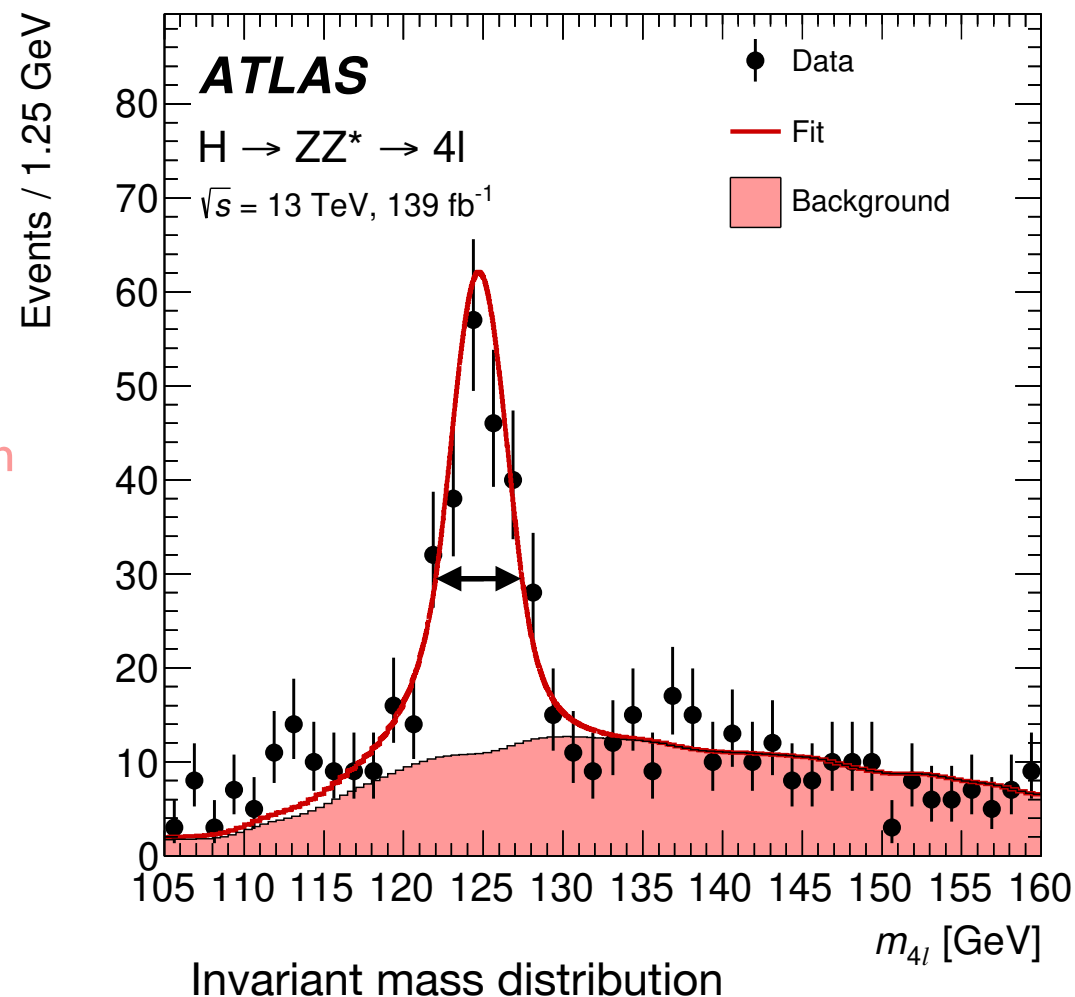 ▸ Improve on the detector calibration.

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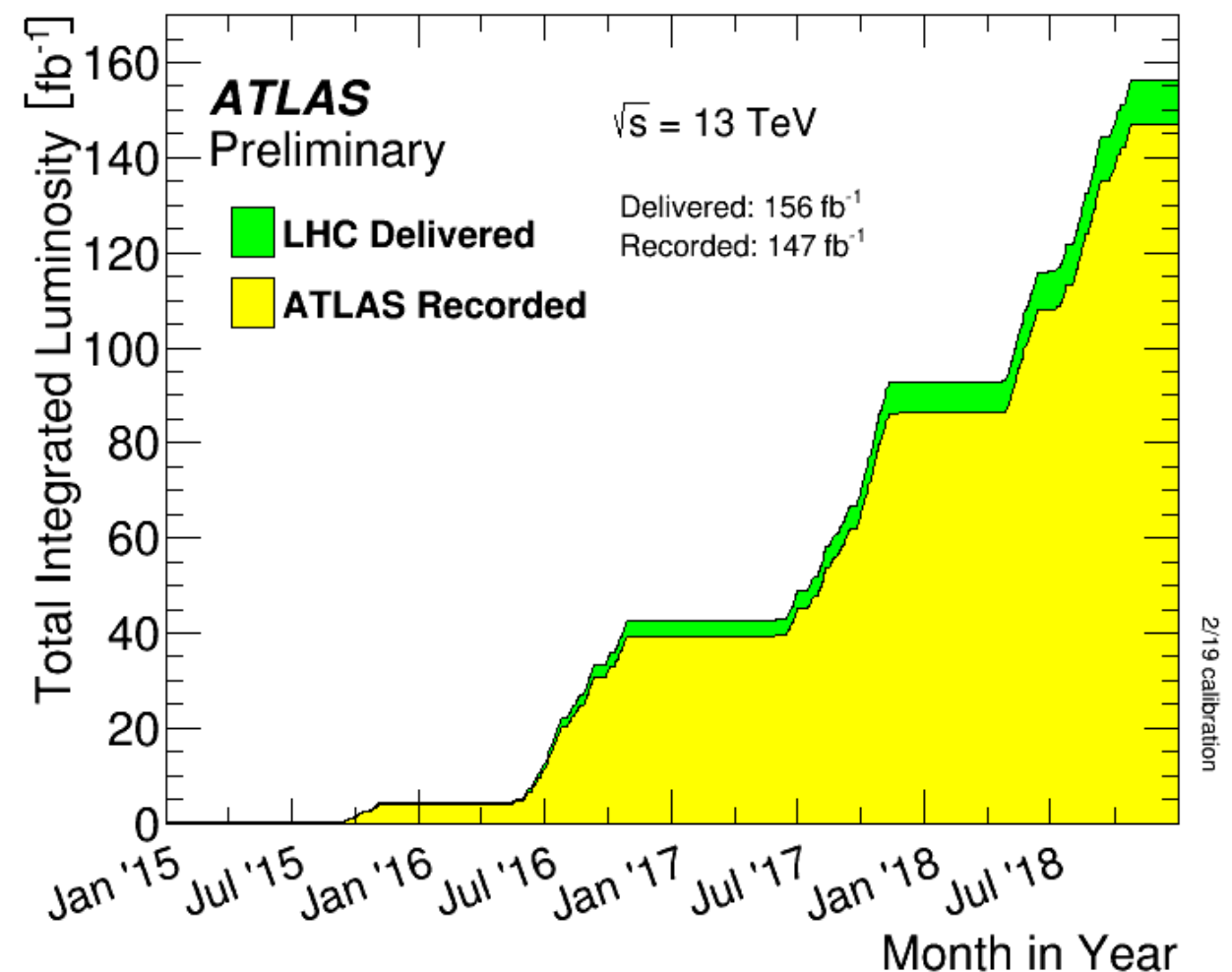
- In the $H \to ZZ \to 4\ell$ the signal is a narrow resonant peak above a background continuum.

ℓ = electron or muon

▸ 4ℓ final state forms 4μ, $4e$, $2\mu 2e$, and $2e2\mu$ channels.

Higgs signal, resonant at the value of m_H

Non resonant background from non H production

ATLAS

H → ZZ* → 4l

$\sqrt{s}$ = 13 TeV, 139 fb^{-1}

Data

Fit

Background

Events / 1.25 GeV

m_{4l} [GeV]

Invariant mass distribution

$$\delta m_H \simeq \frac{\sigma(m_{4\ell,\gamma\gamma})}{\sqrt{N - N_{\mathrm{b}}}}$$

Statistical uncertainty on m_H approximated by the uncertainty on the mean of the mass distribution

(I)   **Statistical** precision precision depends upon:

    ▸   resolution of the reconstructed final state and number of signal events.

(II)   **Systematic** uncertainty from understanding of detector performance.

    Addressing these from both improving the *detector performance* and novel *data analysis techniques*.

- Resolution in electron and muon reconstruction crucial for m_H uncertainty.

- We used well known processes to calibrate the detector response.
  - Resonant process of J/ψ, Υ and Z,
 - for modelling of calorimeters deposits, alignment precision, etc.
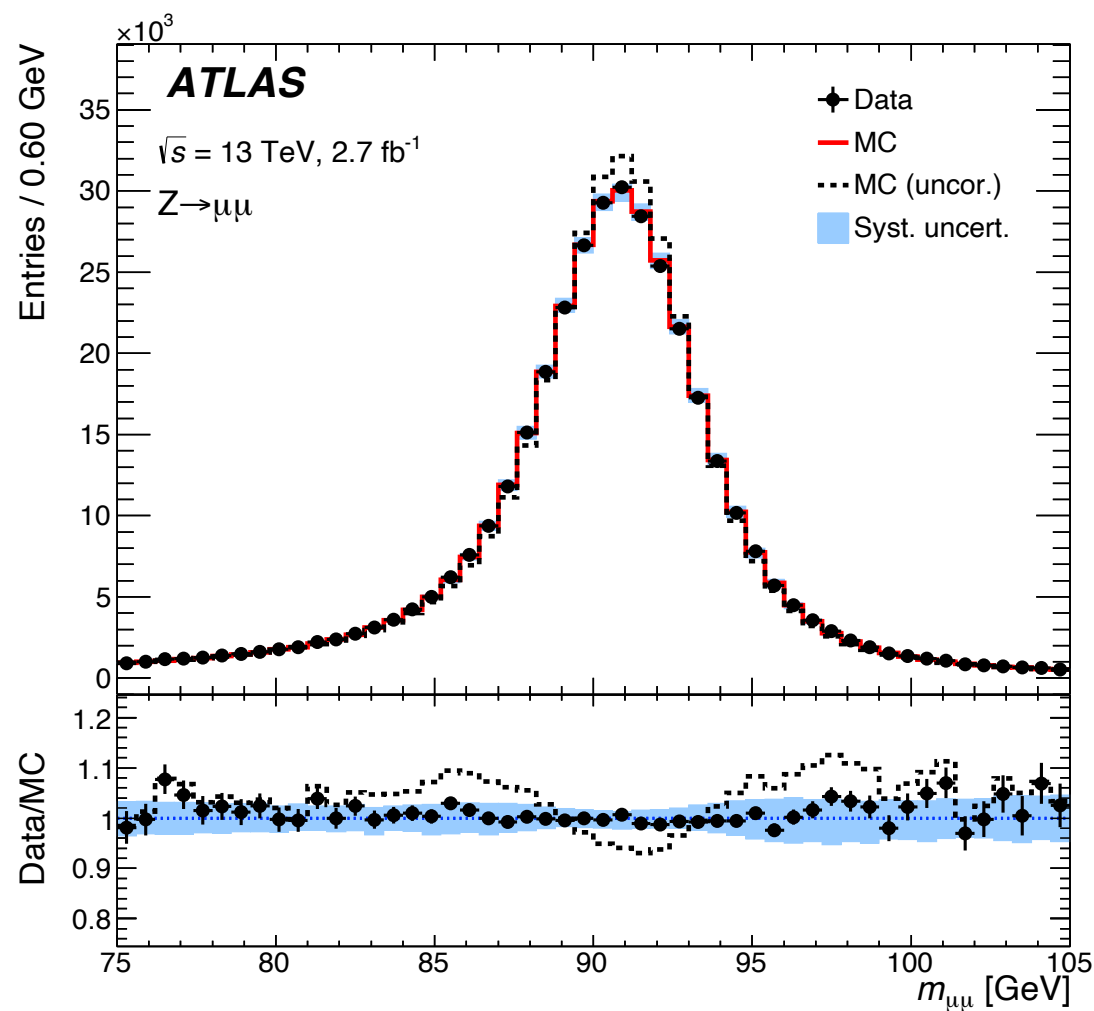
$Z \to \mu\mu$ resonant line shape for data and detector simulation

$Z \to ee$ resonant line shape for data and detector simulation

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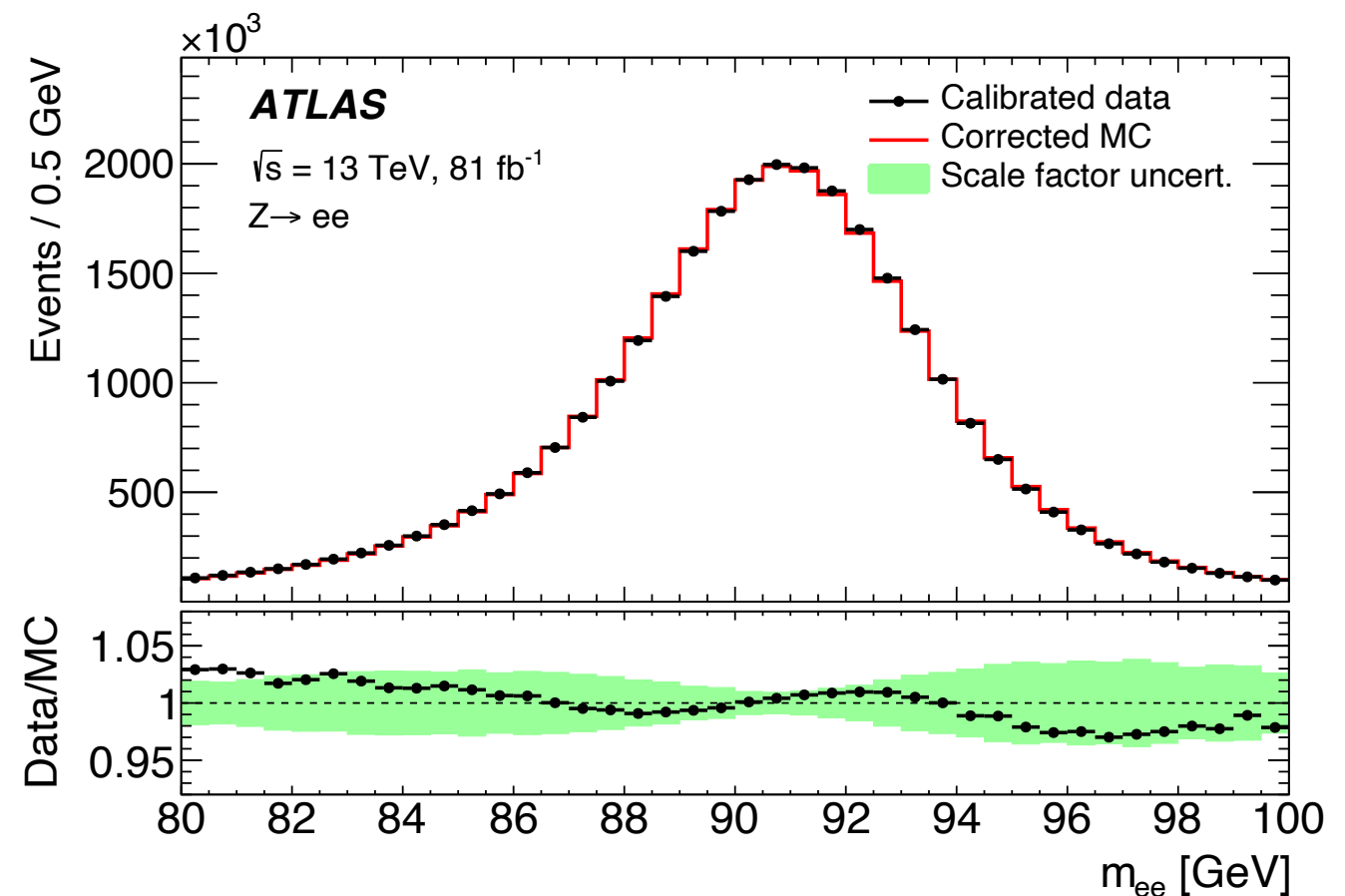
- High precision mandates for studying second order effects:

  ▸ charge-dependent bias because of detector movements.

  ▸ We created an innovative a*d-hoc* correction based on $Z \rightarrow \mu\mu$, recovering up to 5% in precision.

  ▸ Allows for per-mille level understating of detector's systematic uncertainties.
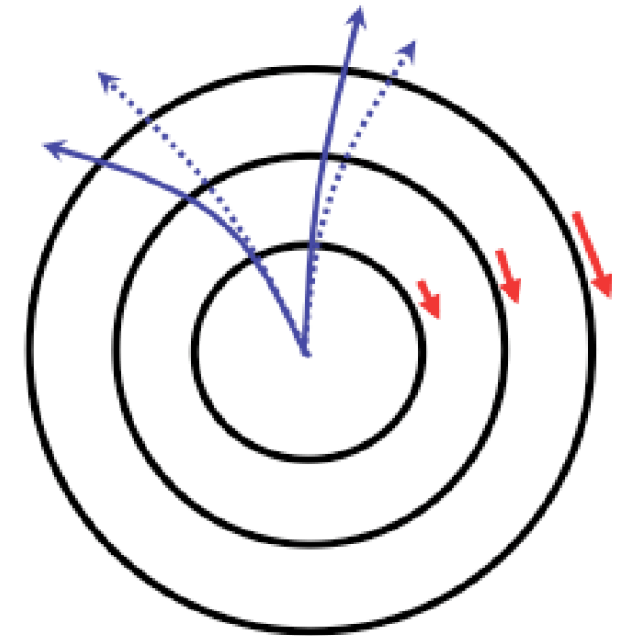
Detector layer movements biasing the measurement of the bending of the particle

⊕ Biased positive and negative tracks
✦ Corrected positive and negative tracks
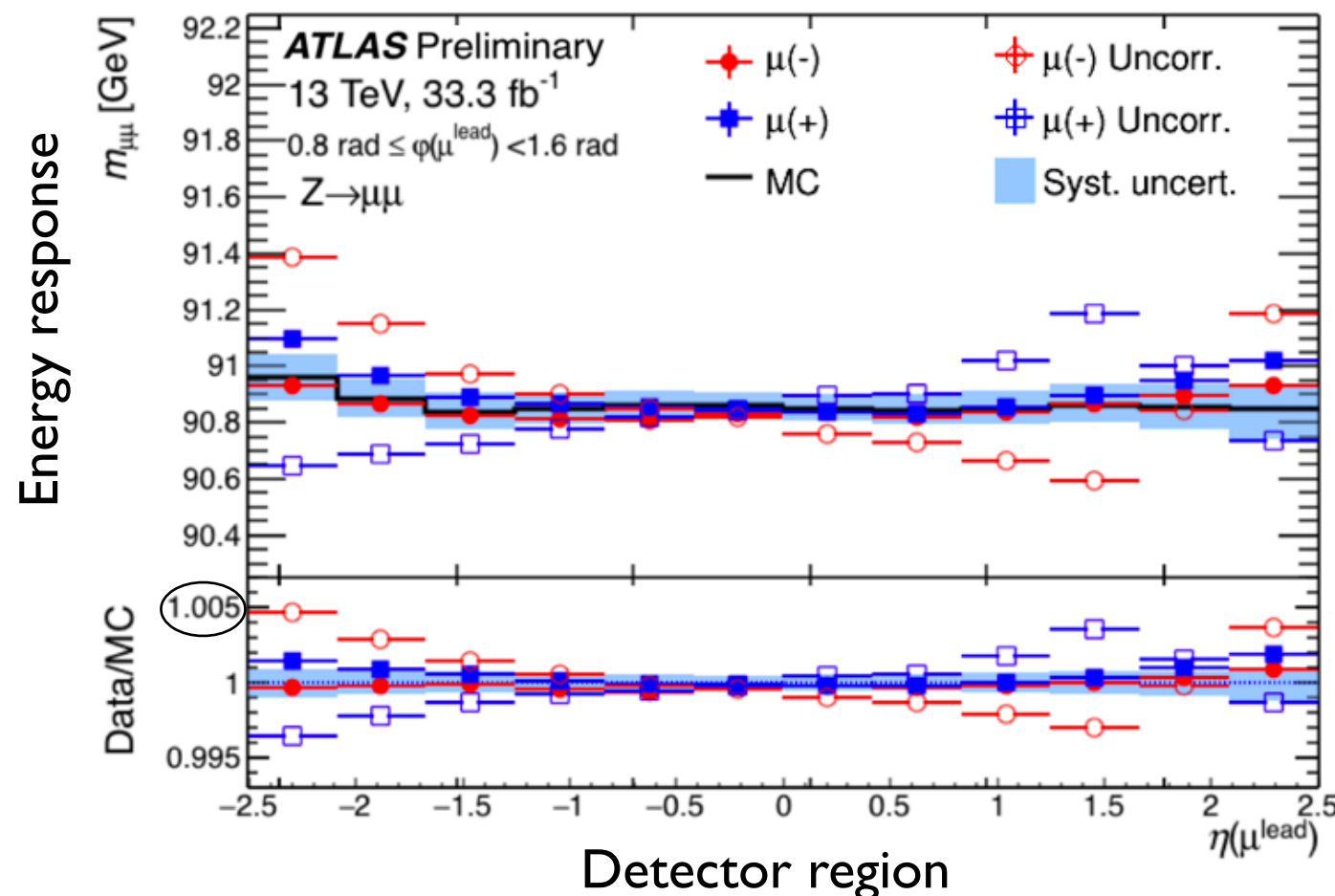
- Three-prong approach to reduce uncertainty at analysis level:

  (i)   constraint to m_Z with kinematic fit and second order detector effects.

  (ii)   machine-learning discriminant selecting signal and background events

  (iii)   Per-event resolution likelihood.

      ✦   Machine Learning to target each event's unique characteristics
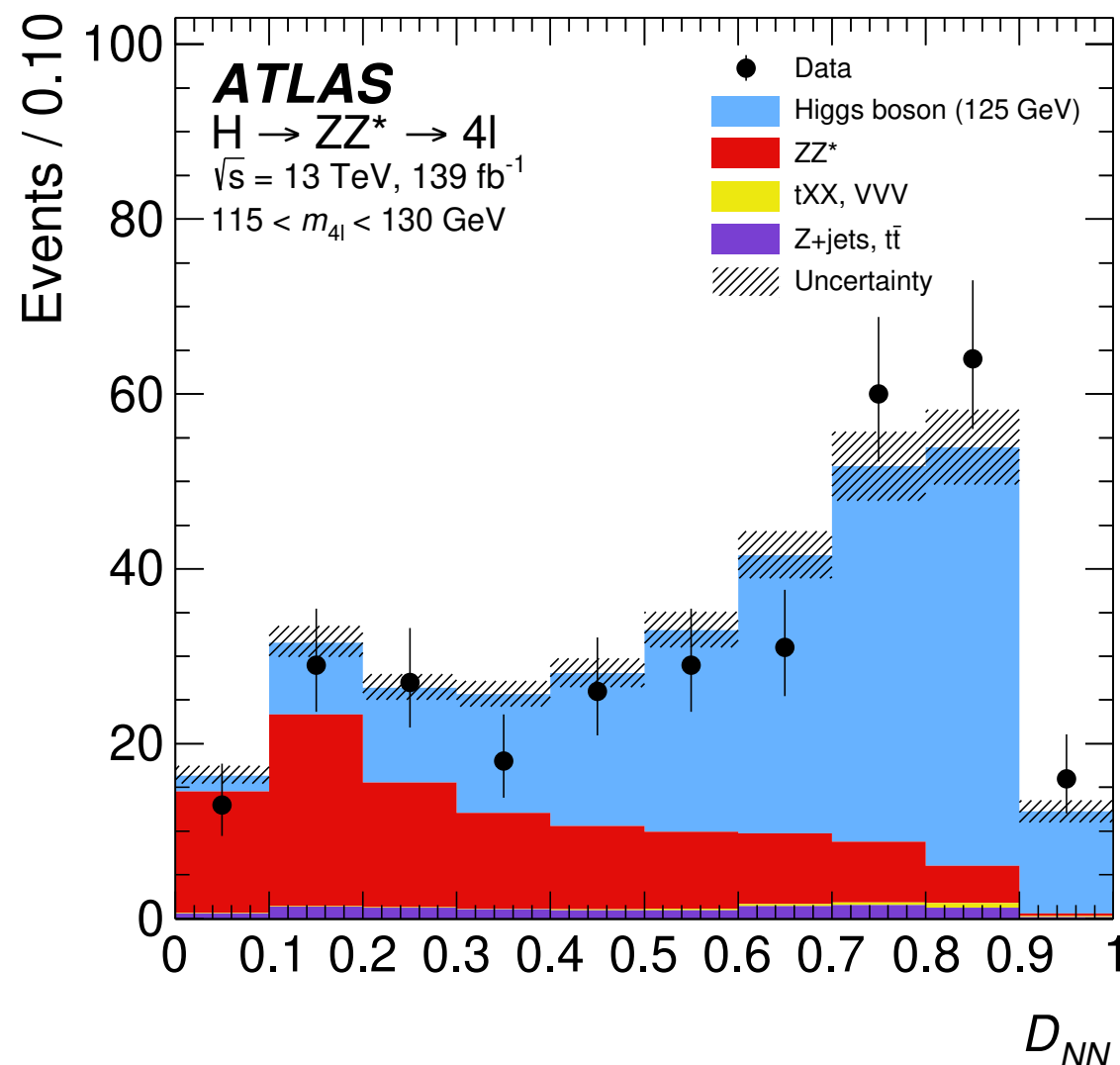
Neural network output of the event's resolution
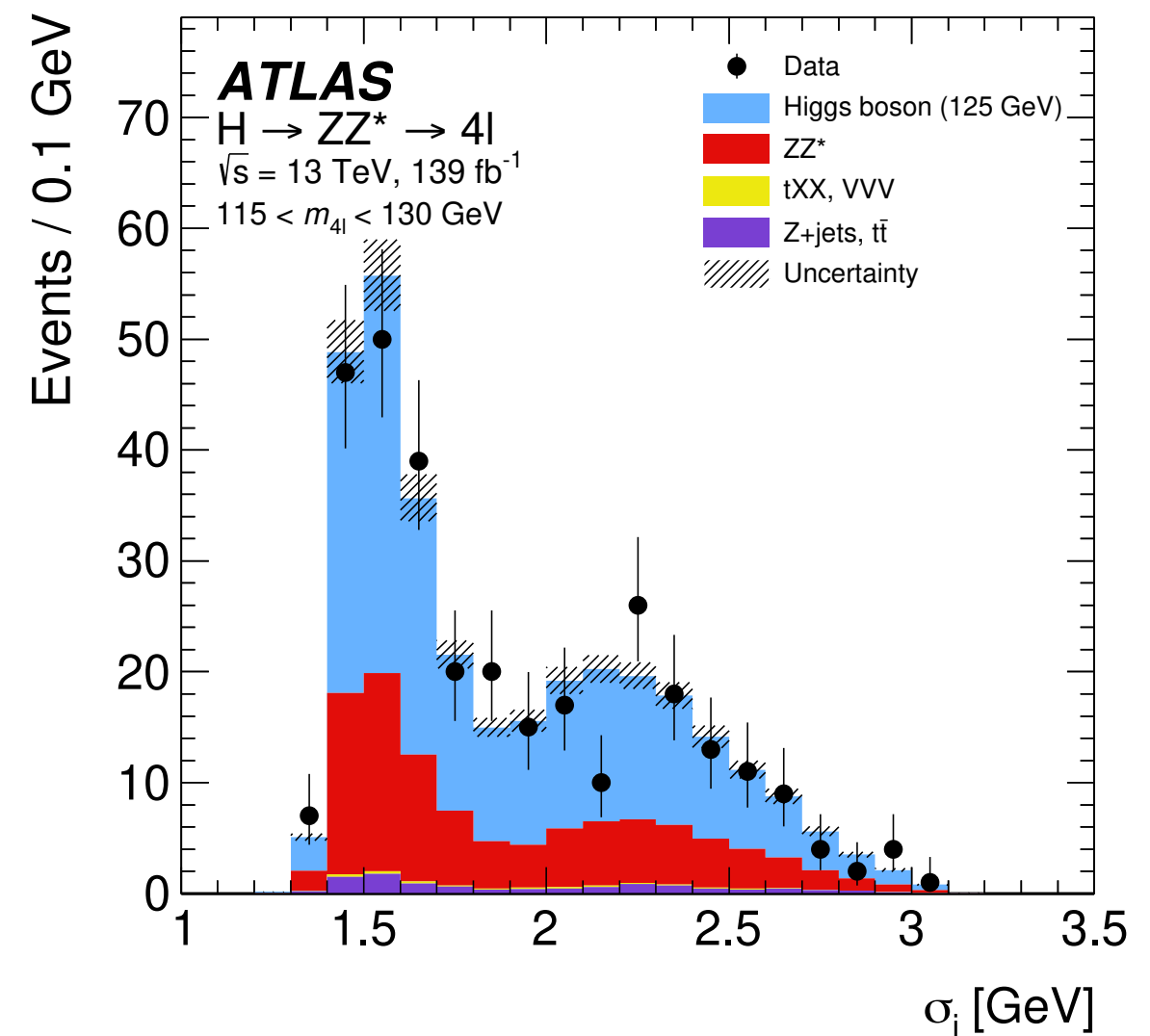
ML output for signal and background

- Output used in multidimensional fit, improving with respect to average detector response.
  - Fit dimensions: $m_{4\ell}$ x D_{NN} x σ_i
  - Tailored resolution to each event's characteristics.
  - One-sided p-value for compatibility between the observed and expected total uncertainties is 0.28.
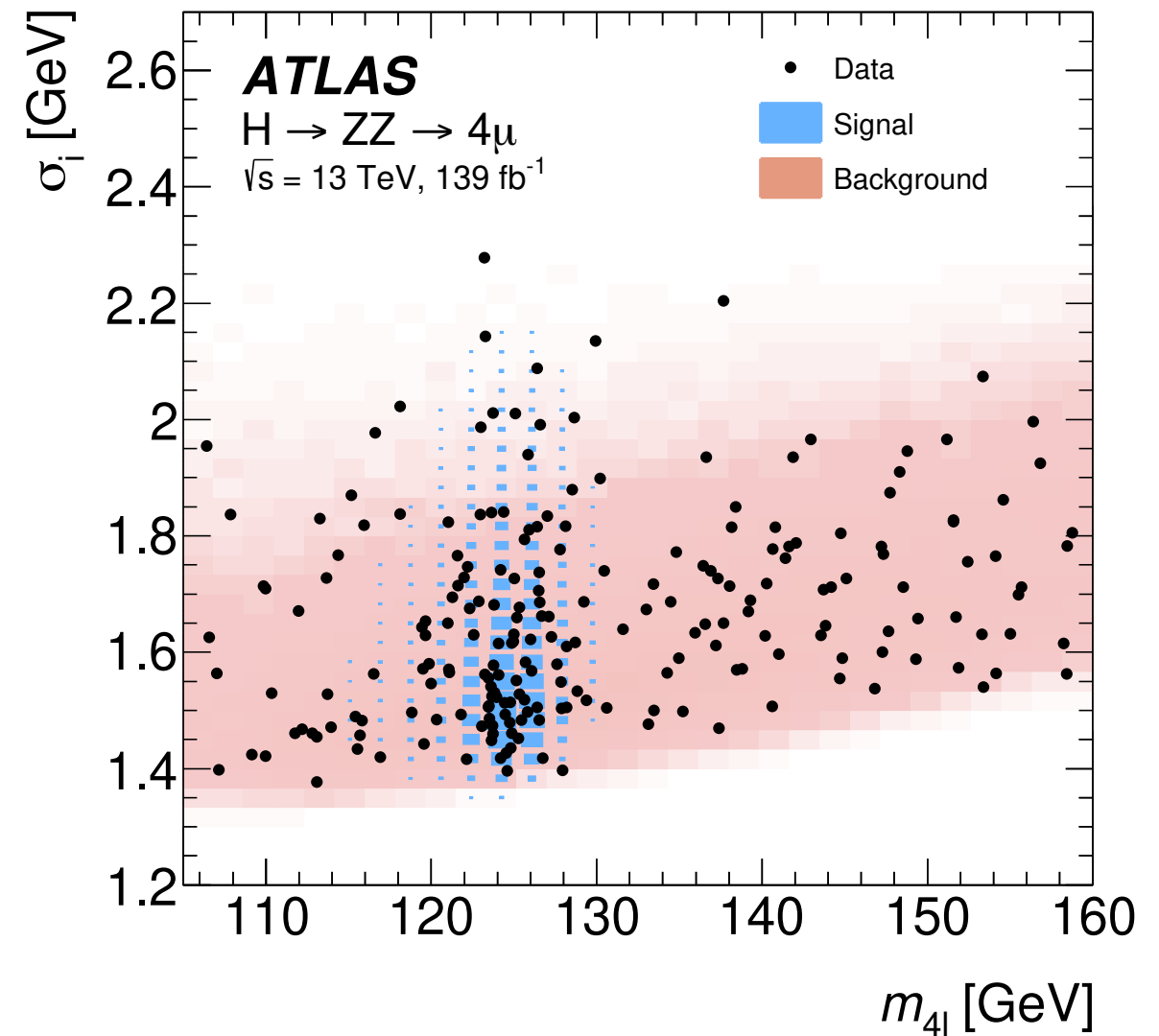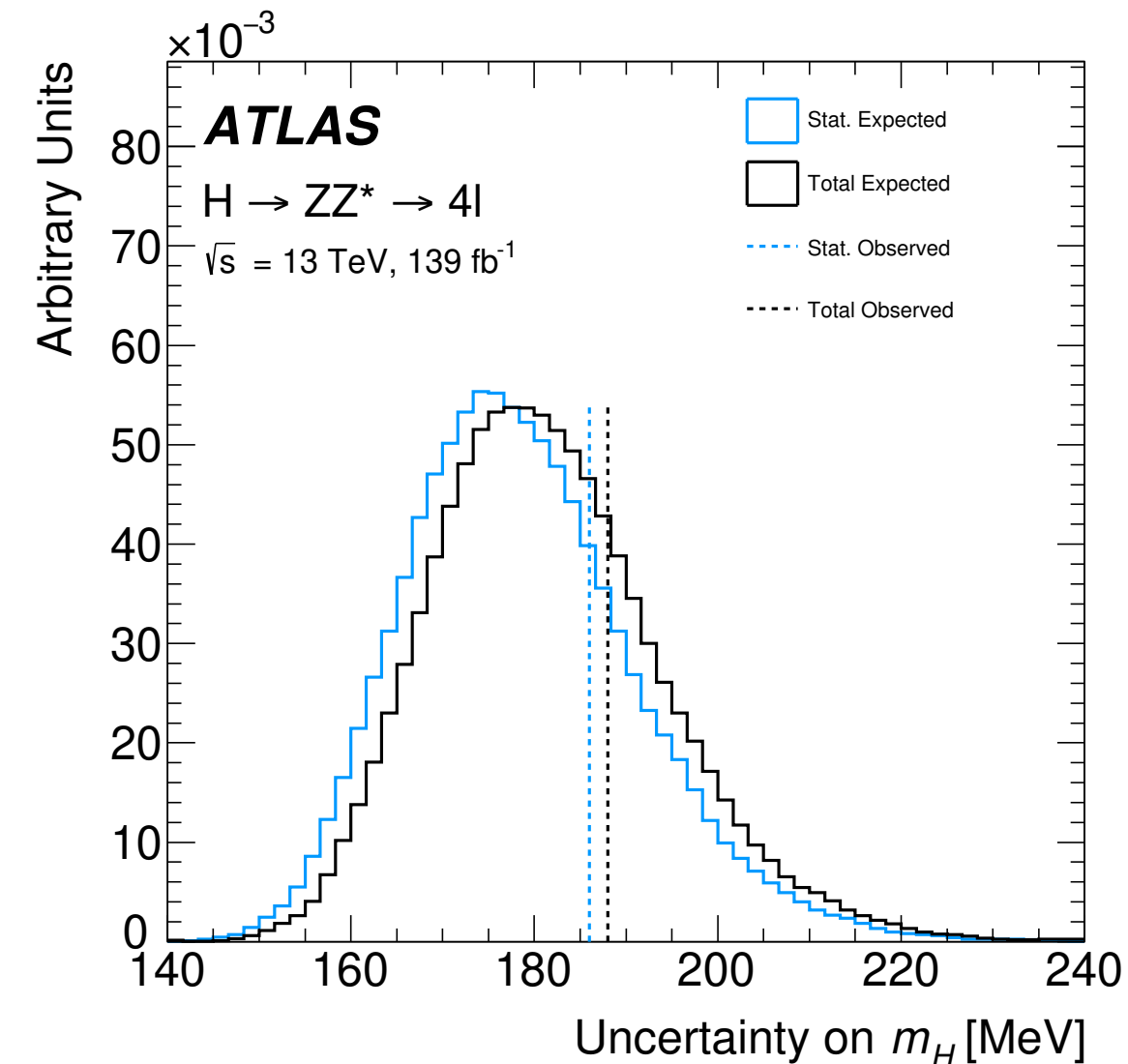
MC-based per-event pseudo experiments.

- **Simultaneous fit for all channels over the multidimensional model**

  ‣ Channel compatibility within a p-value of 0.8

- **Systematic uncertainty of 40 MeV**

- **Result:**

Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	± 28
Electron energy scale	± 19
Signal-process theory	± 14

ATLAS
$H \rightarrow ZZ^* \rightarrow 4l$
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}

Combined
Stat. Only
4μ
2e2μ
2μ2e
4e

1σ

m_H [GeV]
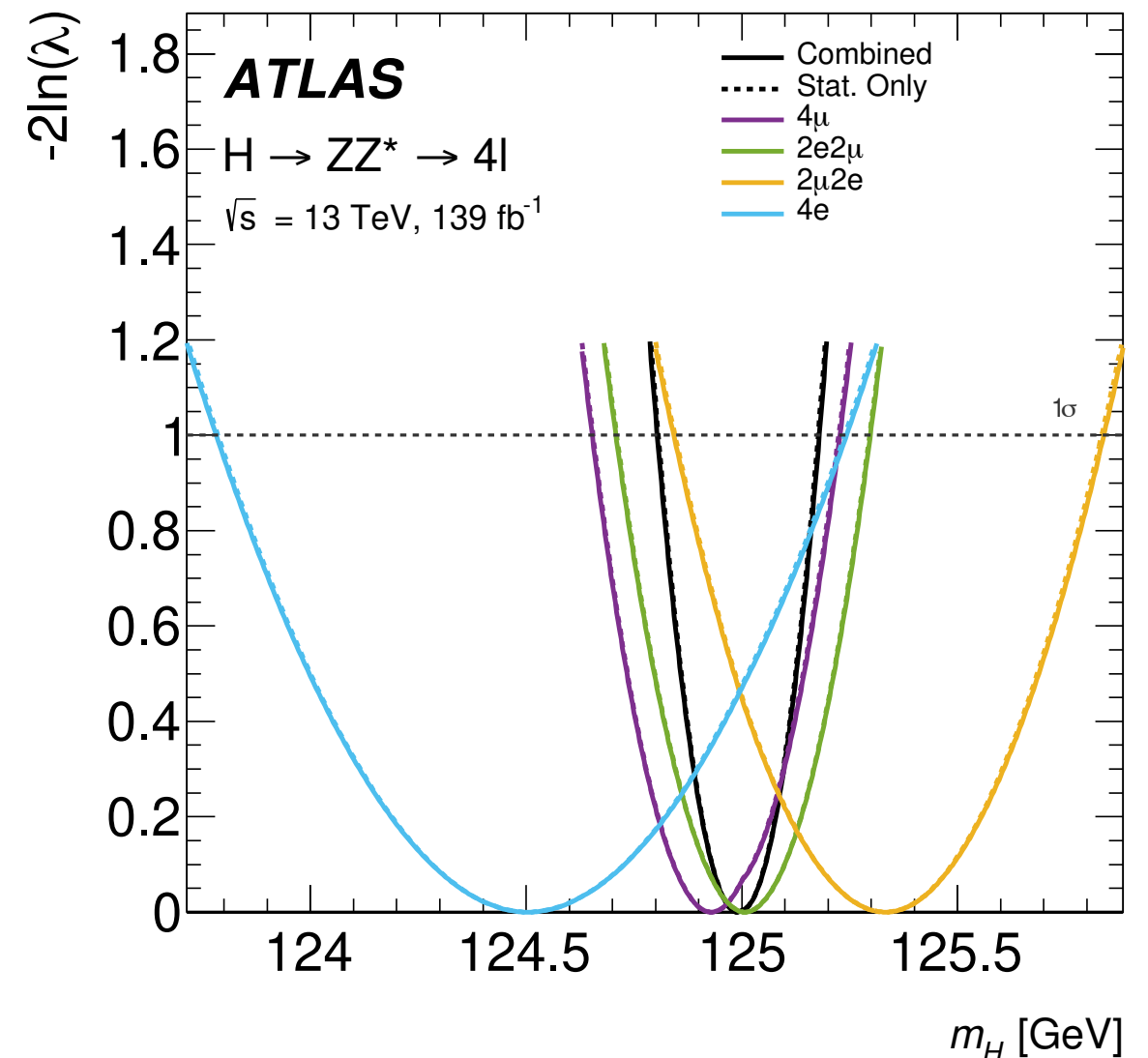
‣ 26% improved (total) precision with respect to Run I Combination.

$$m_H = 124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.}) \text{ GeV}$$

- Combination with $H \to ZZ \to 4\ell$ Run-1 measurement.
  - New p_T calibration techniques → uncorrelated $p_T(\mu)$ systematics between Run1 and Run2

- **Total uncertainty of 0.14%**

- Systematic uncertainty of 0.02%
  - **88% improvement** w.r.t $m_H^{H \to ZZ, Run1}$
  - Momentum scale uncertainties reduced by a factor 2.
  - 33% improved precision w.r.t previous $m_H^{ATLAS, Run1+2}$
  - Most precise measurement by ATLAS, so far.
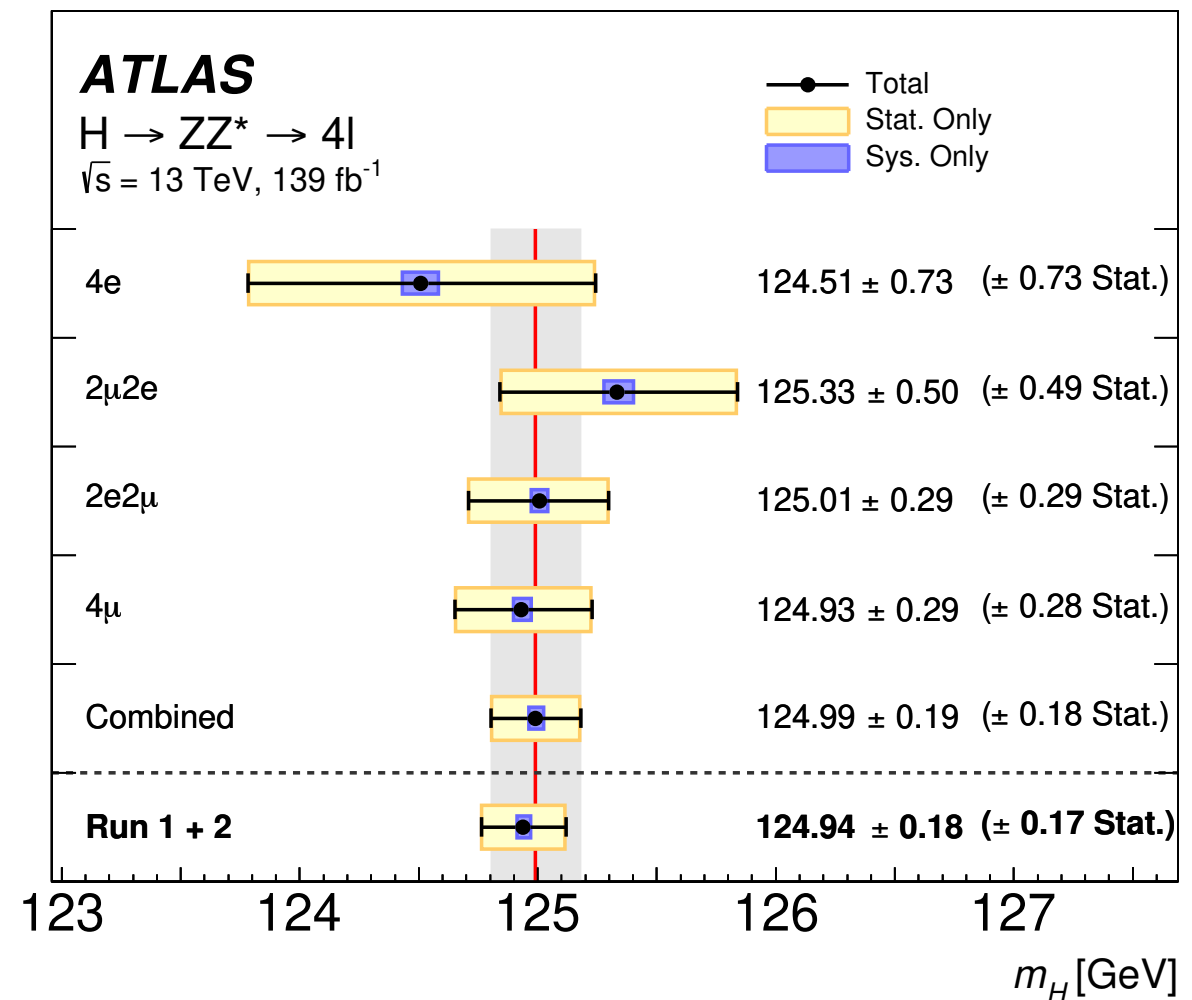
Measured m_H for all channels and combined.

$$m_H = 124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.}) \text{ GeV}$$

3.Elusive Yukawa couplings: light leptons

- Fermions acquire mass through Yukawa interactions with the Higgs field.

  ‣ Remains an elusive sector not probed by EWK precision tests.

  ‣ LHC successfully probed couplings to third generation fermions ($t\bar{t}H$, $H\to\tau\tau$)

- Next milestone, probe couplings to second and first generation fermions.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\Psi}\slashed{D}\psi$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi)$$
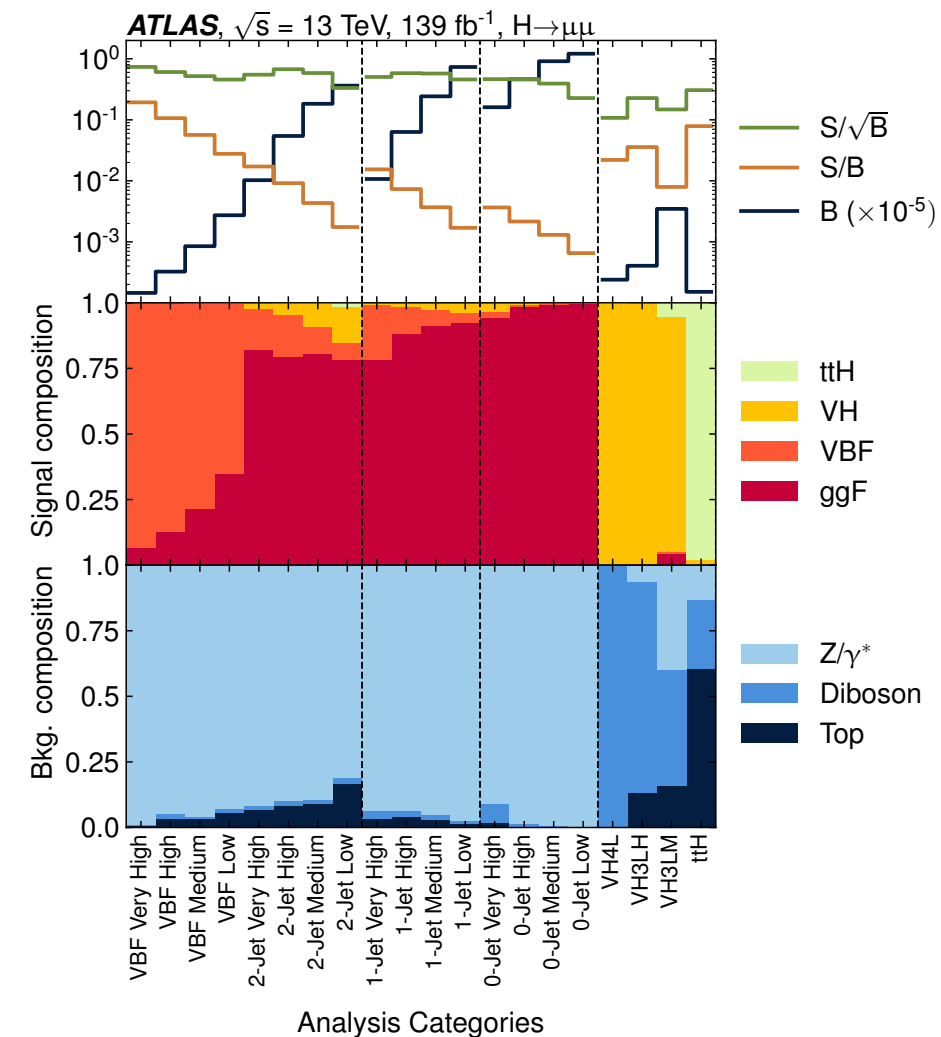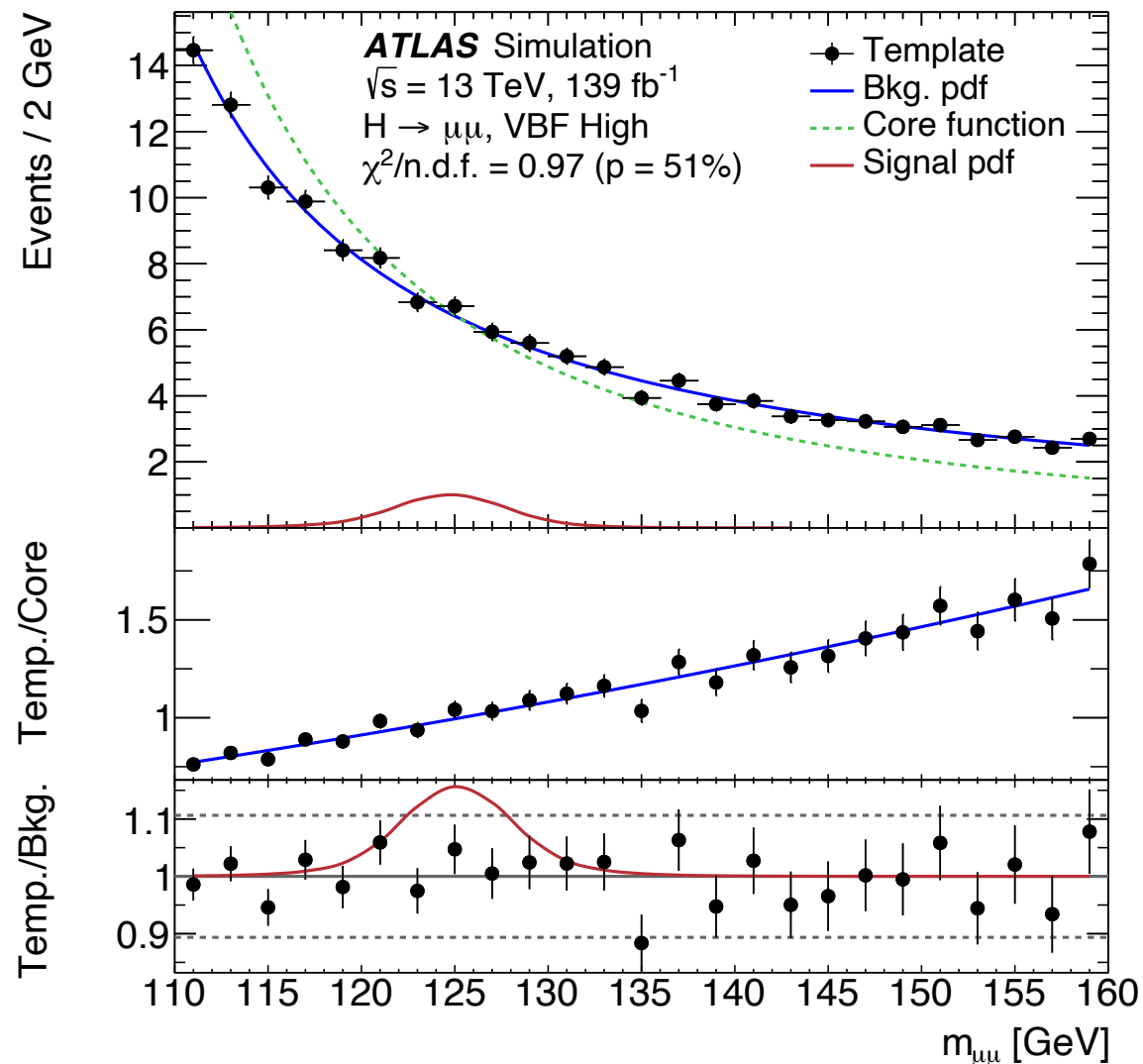$$+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

‣ $H\to\mu\mu$ and ee offer unique insight.

‣ Fully reconstructed final states with low hadronic activity.

‣ Very rare processes:

  ✦ $\mathcal{B}(H\to\mu\mu) \sim (2.17 \pm 0.04)\times10^{-4}$

  ✦ Large backgrounds from Drell-Yann production $Z\to \mu\mu$, ee

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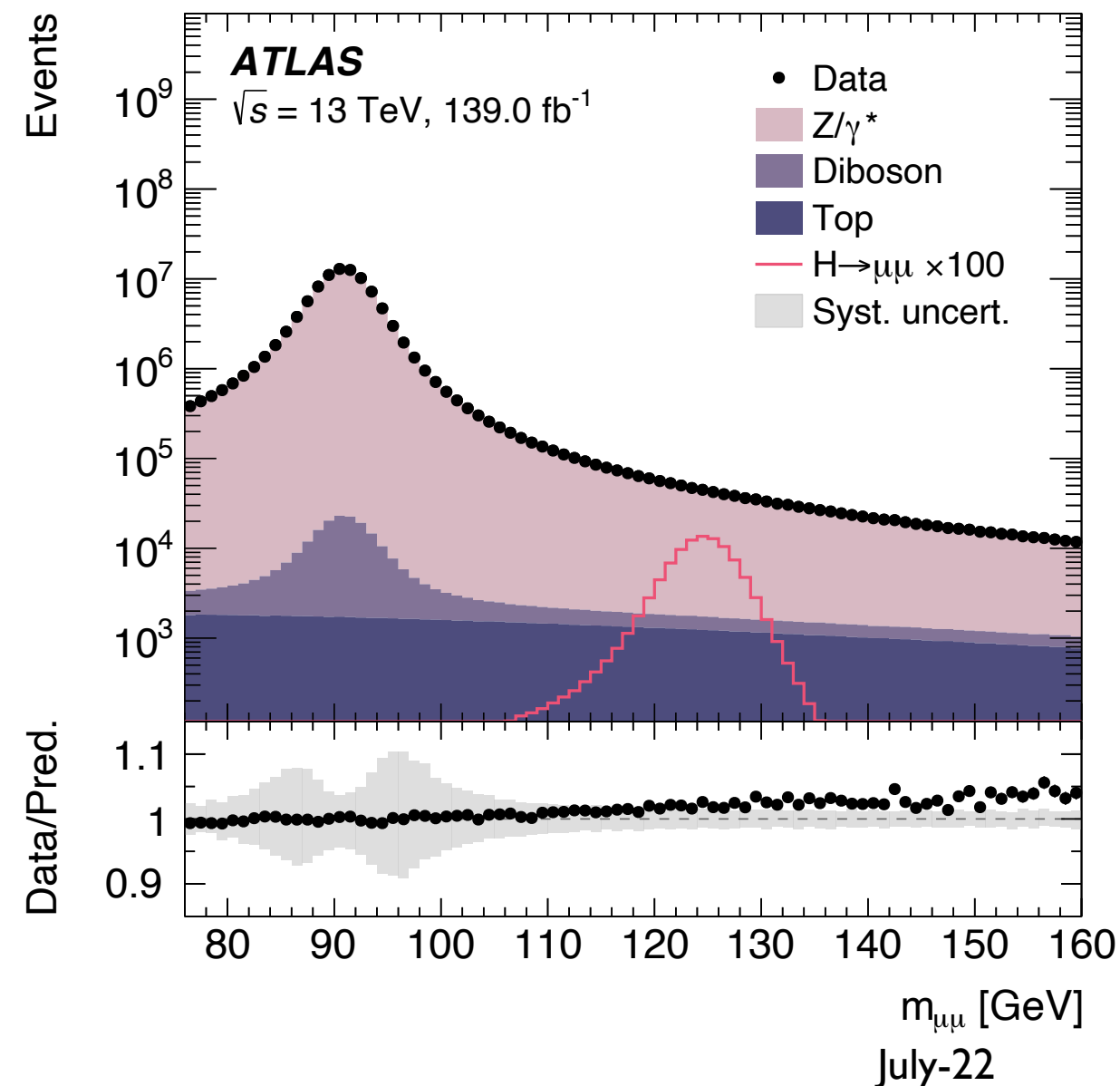
- **Mutually exclusive categories**

  ‣ Targeting the various Higgs production modes, to increase s/b.

  ‣ $H\to\mu\mu$, further splitting according process-specific multivariate boosted decision tree.

ATLAS, $\sqrt{s}$ = 13 TeV, 139 fb^{-1}, H→μμ

$S/\sqrt{B}$
S/B
B ($\times 10^{-5}$)

Signal composition

ttH
VH
VBF
ggF

Bkg. composition

Z/γ^*
Diboson
Top

Analysis Categories

ATLAS Simulation
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
H → μμ, VBF High
χ^2/n.d.f. = 0.97 (p = 51%)

Template
Bkg. pdf
Core function
Signal pdf

Events / 2 GeV

Temp./Core

Temp./Bkg.

$m_{\mu\mu}$ [GeV]

- **Empirical background modelling in both analyses.**

  ‣ $F(m_{\mu\mu})$ = Rigid core($m_{\mu\mu}$) × Flexible Empirical($m_{\mu\mu}$)

  ‣ Per-mille precision reached

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- $\mathcal{B}(H{\to}ee) < 3.6 \times 10^{-4}$ **at 95%CL.**

  ‣ Expected limit at 3.5×10^{-4}

  ‣ Improvement of a factor of 5 w.r.t previous.

- $H{\to}\mu\mu$: **observed significance** 2.0σ, $\mu = 1.2 \pm 0.5$.

  ‣ Expected 1.7σ.

  ‣ $\sigma(H{\to}\mu\mu) / \sigma^{SM}(H{\to}\mu\mu) < 2.2$ at 95%CL.

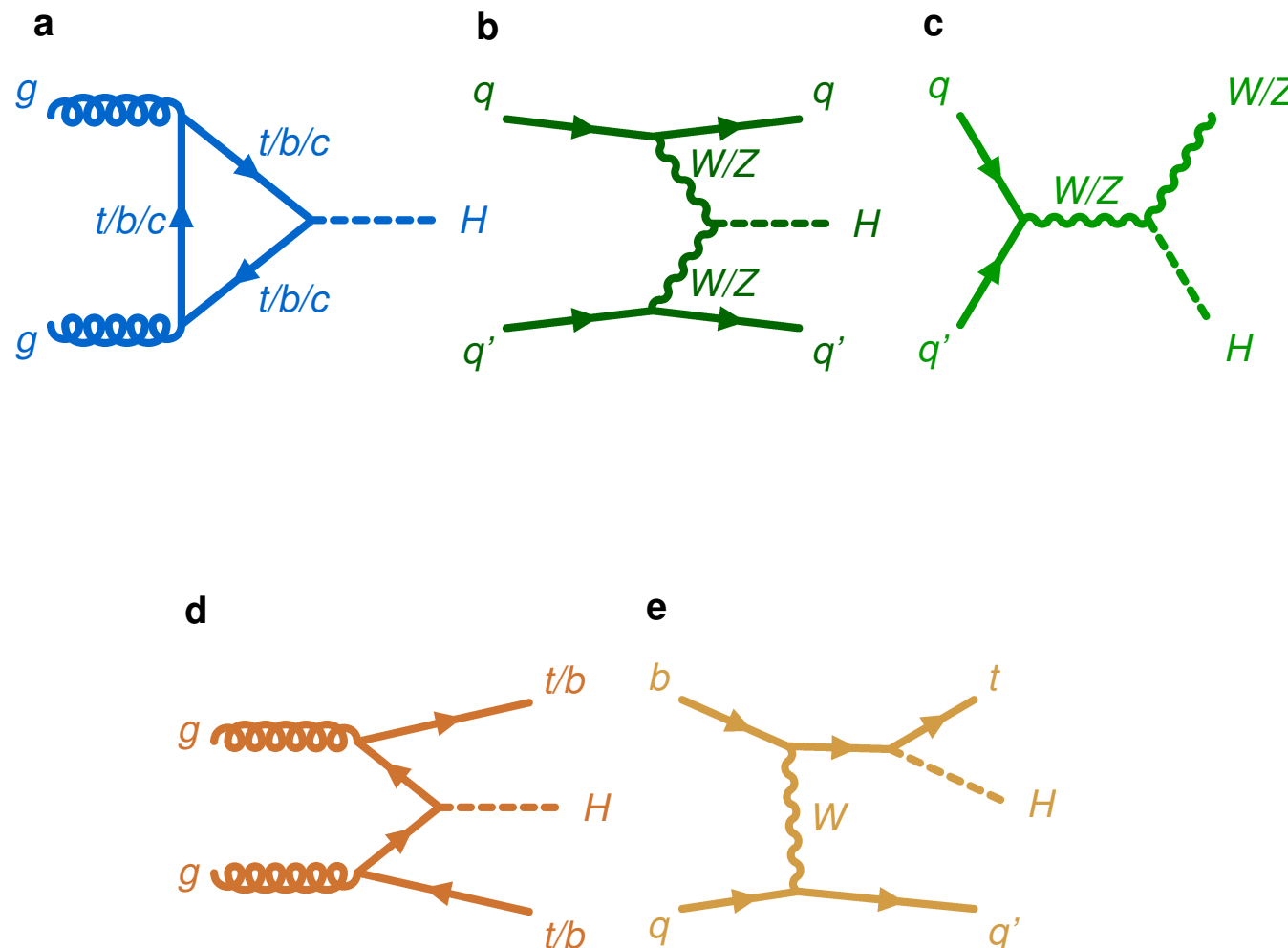 ‣ Improvement of a factor 2.5, with 25% from the methods used.
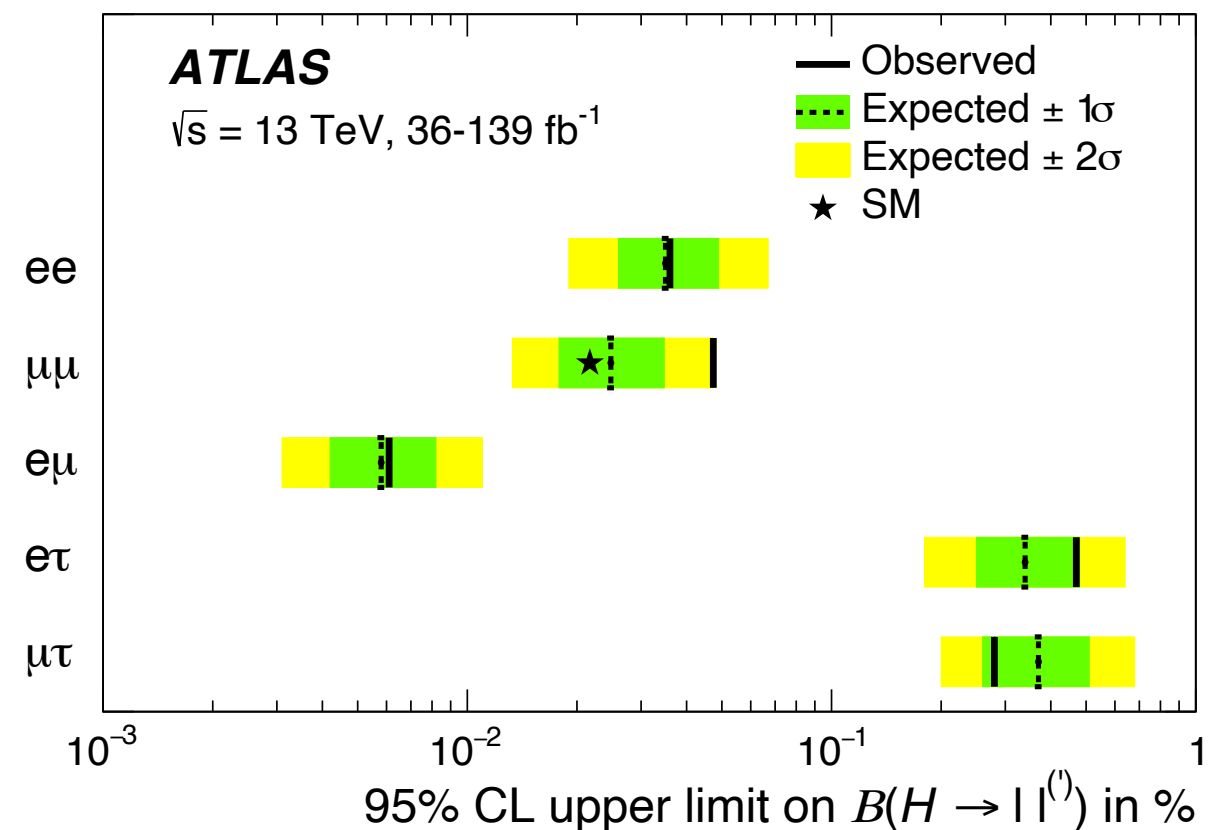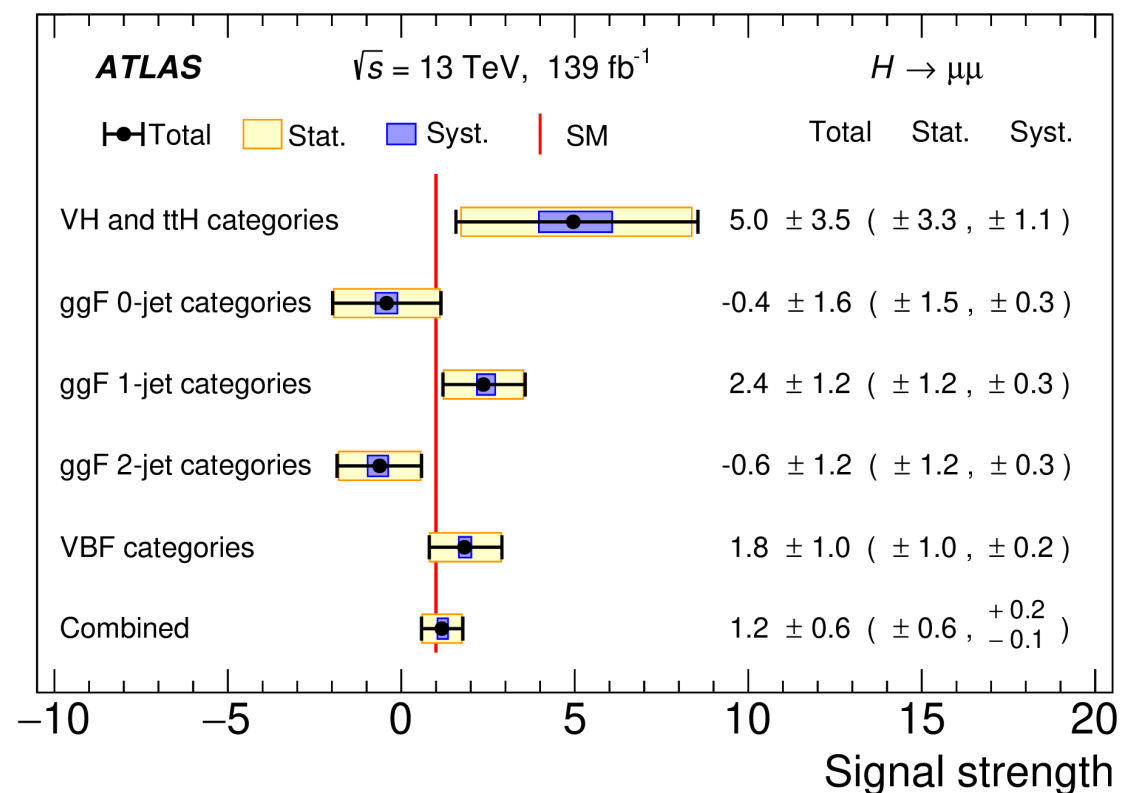
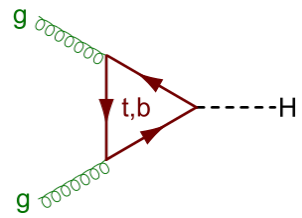# 4. Production mode measurements

- **ATLAS full Run-2 combination**
  ‣ Combined sensitivity of all channels to increase the precision of the Higgs productions.

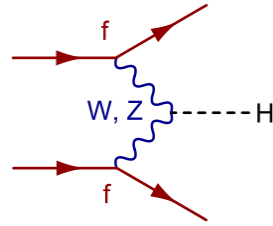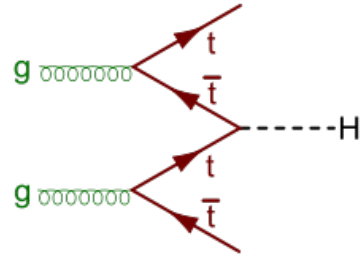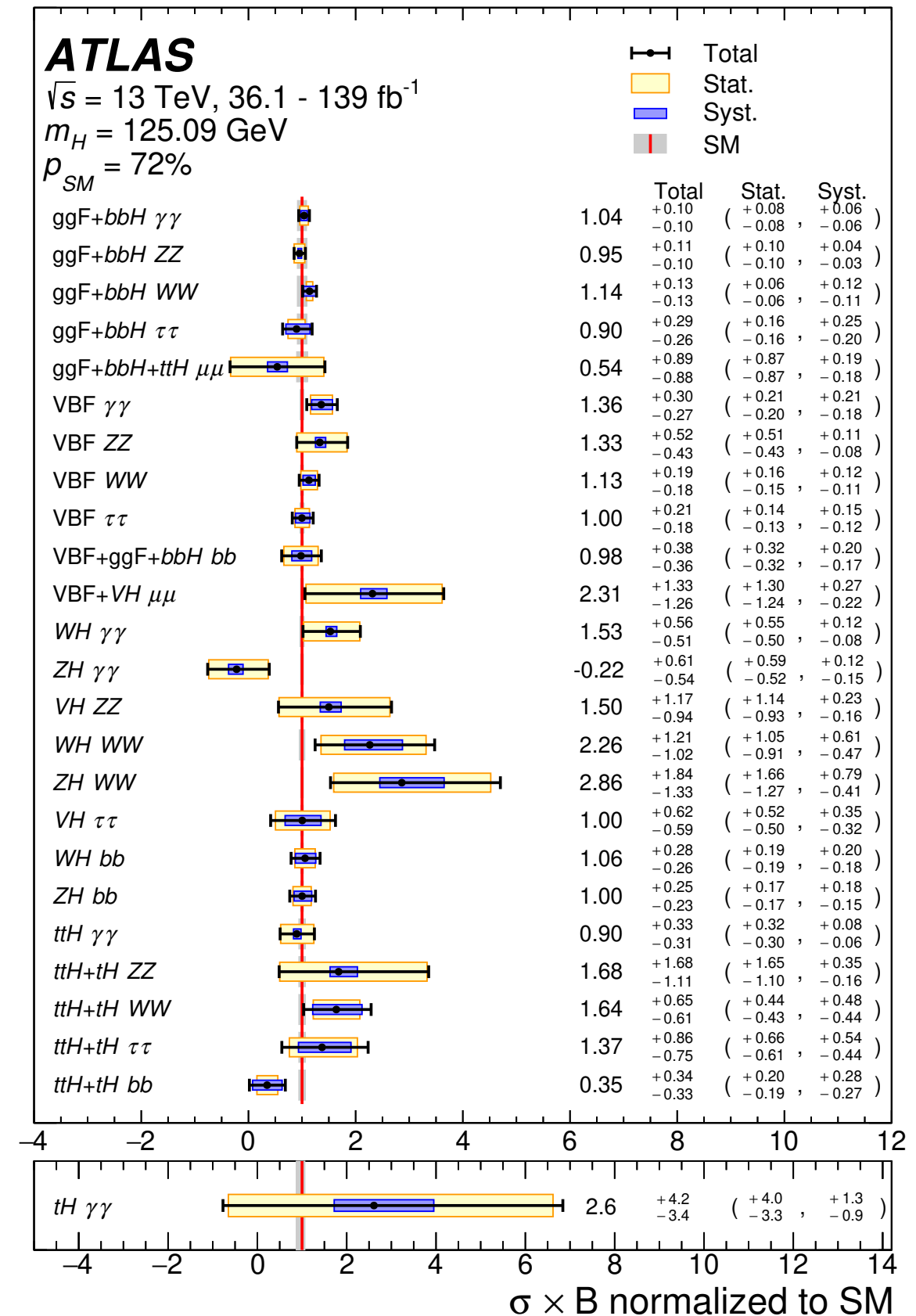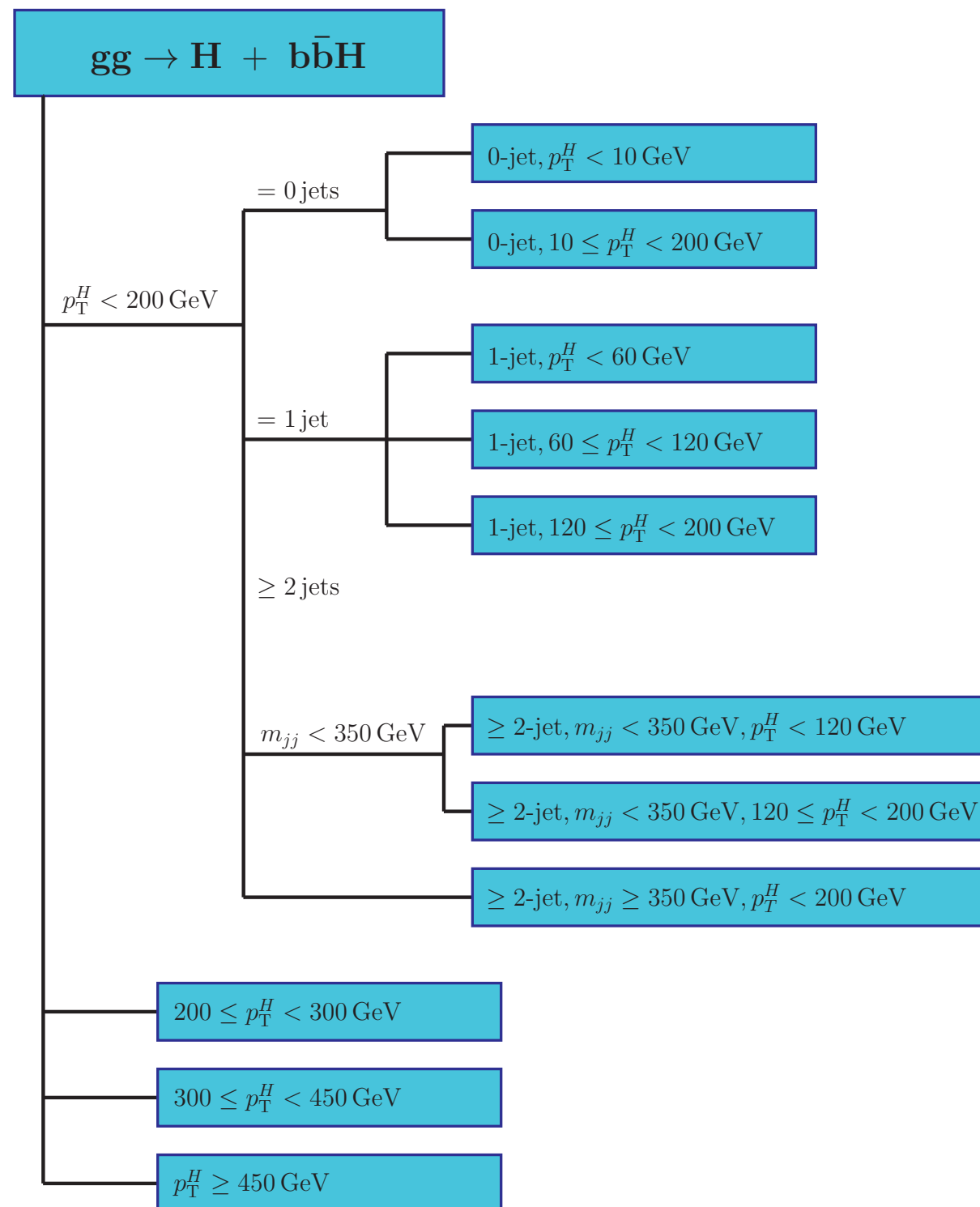| Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139
$H \to ZZ$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to WW$	ggF, VBF	139
	WH, ZH	36.1
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to Z\gamma$	inclusive	139
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H + tH$	139
	inclusive	139
$H \to \tau\tau$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to \mu\mu$	ggF $+ t\bar{t}H + tH$, VBF $+ WH + ZH$	139
$H \to c\bar{c}$	$WH + ZH$	139
$H \to$ invisible	VBF	139
	ZH	139

ggF   VBF: 6.5 σ
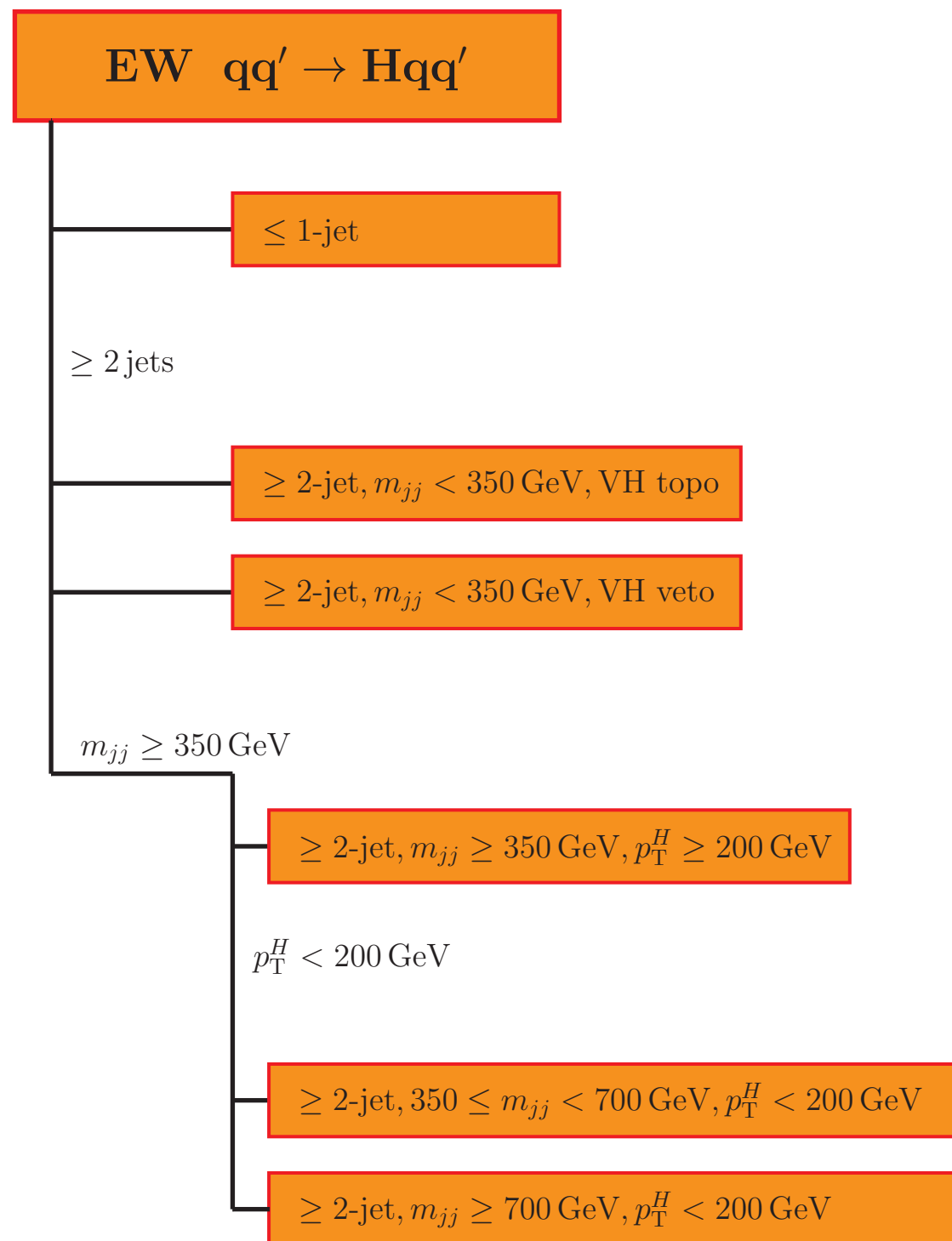
VH: 5.3 σ $t\bar{t}H$: 5.8 σ

- In the first Run-2 data observed all SM production modes at the LHC.

  ▸ With current precision uncertainties from 20% to 7% on production cross section.

 ▸ Sufficient for more in-depth investigations into the couplings

ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_H = 125.09 GeV
p_{SM} = 72%

	Total	Total	Stat.	Syst.
ggF+bbH $\gamma\gamma$	1.04	$^{+0.10}_{-0.10}$	($^{+0.08}_{-0.08}$,	$^{+0.06}_{-0.06}$)
ggF+bbH ZZ	0.95	$^{+0.11}_{-0.10}$	($^{+0.10}_{-0.10}$,	$^{+0.04}_{-0.03}$)
ggF+bbH WW	1.14	$^{+0.13}_{-0.13}$	($^{+0.06}_{-0.06}$,	$^{+0.12}_{-0.11}$)
ggF+bbH $\tau\tau$	0.90	$^{+0.29}_{-0.26}$	($^{+0.16}_{-0.16}$,	$^{+0.25}_{-0.20}$)
ggF+bbH+ttH $\mu\mu$	0.54	$^{+0.89}_{-0.88}$	($^{+0.87}_{-0.87}$,	$^{+0.19}_{-0.18}$)
VBF $\gamma\gamma$	1.36	$^{+0.30}_{-0.27}$	($^{+0.21}_{-0.20}$,	$^{+0.21}_{-0.18}$)
VBF ZZ	1.33	$^{+0.52}_{-0.43}$	($^{+0.51}_{-0.43}$,	$^{+0.11}_{-0.08}$)
VBF WW	1.13	$^{+0.19}_{-0.18}$	($^{+0.16}_{-0.15}$,	$^{+0.12}_{-0.11}$)
VBF $\tau\tau$	1.00	$^{+0.21}_{-0.18}$	($^{+0.14}_{-0.13}$,	$^{+0.15}_{-0.12}$)
VBF+ggF+bbH bb	0.98	$^{+0.38}_{-0.36}$	($^{+0.32}_{-0.32}$,	$^{+0.20}_{-0.17}$)
VBF+VH $\mu\mu$	2.31	$^{+1.33}_{-1.26}$	($^{+1.30}_{-1.24}$,	$^{+0.27}_{-0.22}$)
WH $\gamma\gamma$	1.53	$^{+0.56}_{-0.51}$	($^{+0.55}_{-0.50}$,	$^{+0.12}_{-0.08}$)
ZH $\gamma\gamma$	-0.22	$^{+0.61}_{-0.54}$	($^{+0.59}_{-0.52}$,	$^{+0.12}_{-0.15}$)
VH ZZ	1.50	$^{+1.17}_{-0.94}$	($^{+1.14}_{-0.93}$,	$^{+0.23}_{-0.16}$)
WH WW	2.26	$^{+1.21}_{-1.02}$	($^{+1.05}_{-0.91}$,	$^{+0.61}_{-0.47}$)
ZH WW	2.86	$^{+1.84}_{-1.33}$	($^{+1.66}_{-1.27}$,	$^{+0.79}_{-0.41}$)
VH $\tau\tau$	1.00	$^{+0.62}_{-0.59}$	($^{+0.52}_{-0.50}$,	$^{+0.35}_{-0.32}$)
WH bb	1.06	$^{+0.28}_{-0.26}$	($^{+0.19}_{-0.19}$,	$^{+0.20}_{-0.18}$)
ZH bb	1.00	$^{+0.25}_{-0.23}$	($^{+0.17}_{-0.17}$,	$^{+0.18}_{-0.15}$)
ttH $\gamma\gamma$	0.90	$^{+0.33}_{-0.31}$	($^{+0.32}_{-0.30}$,	$^{+0.08}_{-0.06}$)
ttH+tH ZZ	1.68	$^{+1.68}_{-1.11}$	($^{+1.65}_{-1.10}$,	$^{+0.35}_{-0.16}$)
ttH+tH WW	1.64	$^{+0.65}_{-0.61}$	($^{+0.44}_{-0.43}$,	$^{+0.48}_{-0.44}$)
ttH+tH $\tau\tau$	1.37	$^{+0.86}_{-0.75}$	($^{+0.66}_{-0.61}$,	$^{+0.54}_{-0.44}$)
ttH+tH bb	0.35	$^{+0.34}_{-0.33}$	($^{+0.20}_{-0.19}$,	$^{+0.28}_{-0.27}$)
tH $\gamma\gamma$	2.6	$^{+4.2}_{-3.4}$	($^{+4.0}_{-3.3}$,	$^{+1.3}_{-0.9}$)

Total / Stat. / Syst. / SM
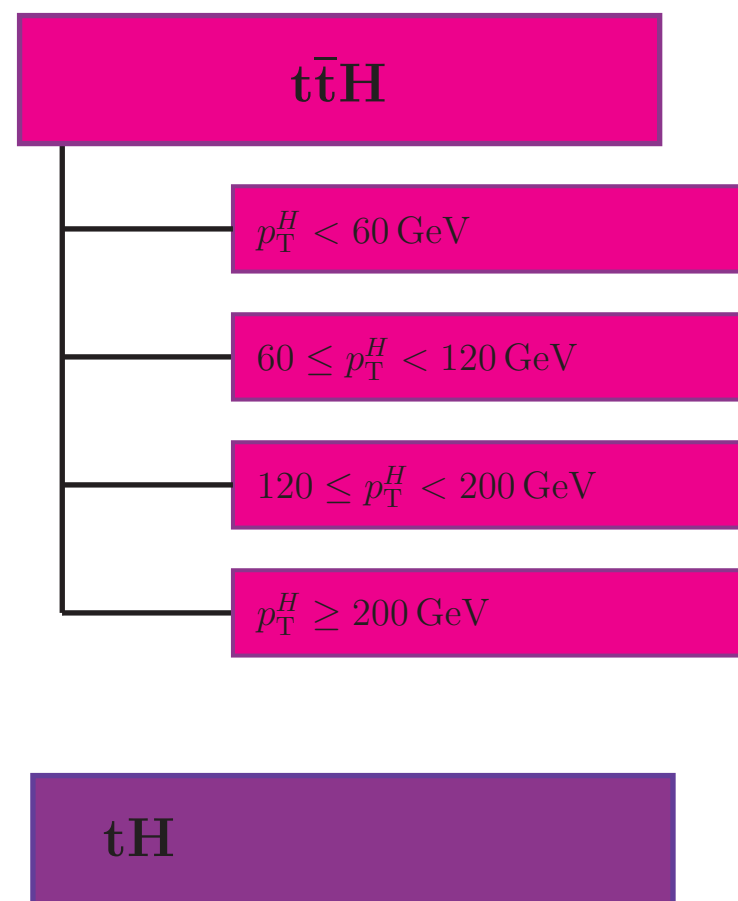
$\sigma \times$ B normalized to SM

- **Measure mutually exclusive phase-spaces**

  ▸ In terms of kinematics of the Higgs or associated objects in productions.

  ▸ Sensitivity to deviations from SM.

  ▸ Avoidance of large modelling uncertainties.

  ▸ Approximate experimental sensitivity.

- **Advantage of complementary sensitivity in production from different final states:**

  ▸ $m_{\mathrm{jj}} > 450$ GeV from $H \to WW^*$
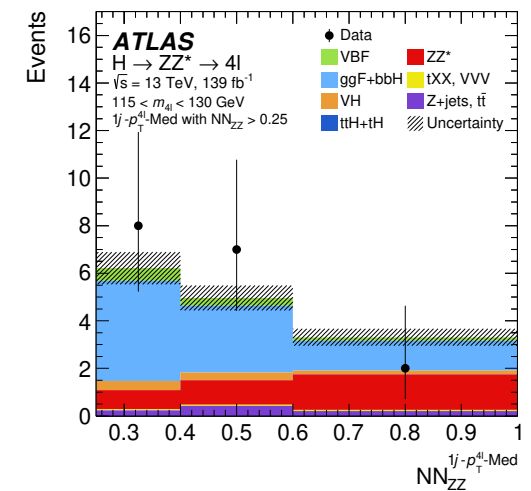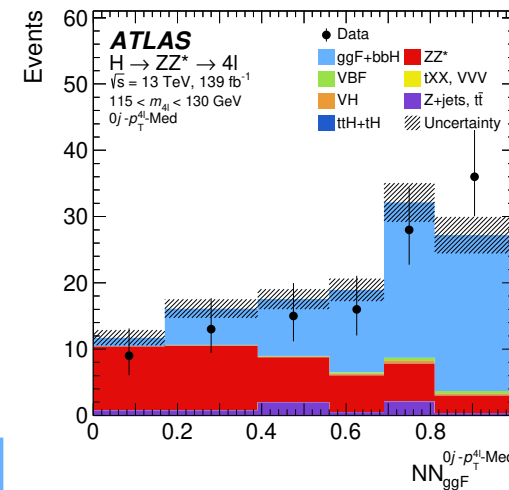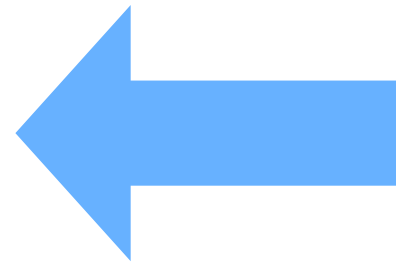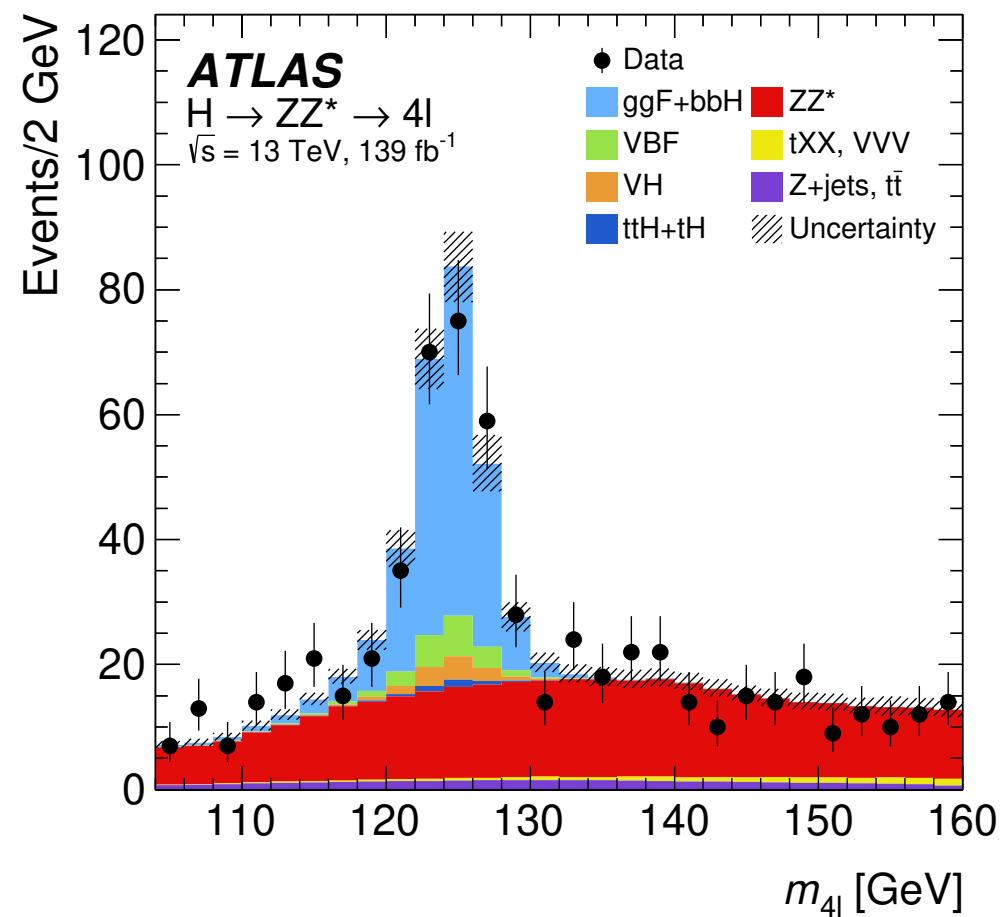
  ▸ High p_{T}^H from $H \to bb$

The diagram shows:

$gg \to H + b\bar{b}H$

$p_{\mathrm{T}}^H < 200\,\mathrm{GeV}$
- $= 0\,\mathrm{jets}$
  - 0-jet, $p_{\mathrm{T}}^H < 10\,\mathrm{GeV}$
  - 0-jet, $10 \leq p_{\mathrm{T}}^H < 200\,\mathrm{GeV}$
- $= 1\,\mathrm{jet}$
  - 1-jet, $p_{\mathrm{T}}^H < 60\,\mathrm{GeV}$
  - 1-jet, $60 \leq p_{\mathrm{T}}^H < 120\,\mathrm{GeV}$
  - 1-jet, $120 \leq p_{\mathrm{T}}^H < 200\,\mathrm{GeV}$
- $\geq 2\,\mathrm{jets}$
  - $m_{jj} < 350\,\mathrm{GeV}$
    - ≥ 2-jet, $m_{jj} < 350\,\mathrm{GeV}, p_{\mathrm{T}}^H < 120\,\mathrm{GeV}$
    - ≥ 2-jet, $m_{jj} < 350\,\mathrm{GeV}, 120 \leq p_{\mathrm{T}}^H < 200\,\mathrm{GeV}$
    - ≥ 2-jet, $m_{jj} \geq 350\,\mathrm{GeV}, p_T^H < 200\,\mathrm{GeV}$

$200 \leq p_{\mathrm{T}}^H < 300\,\mathrm{GeV}$

$300 \leq p_{\mathrm{T}}^H < 450\,\mathrm{GeV}$

$p_{\mathrm{T}}^H \geq 450\,\mathrm{GeV}$

$$\text{EW} \quad qq' \to Hqq'$$

$\leq 1\text{-jet}$

$\geq 2\,\text{jets}$

$\geq 2\text{-jet}, m_{jj} < 350\,\text{GeV}, \text{VH topo}$

$\geq 2\text{-jet}, m_{jj} < 350\,\text{GeV}, \text{VH veto}$

$m_{jj} \geq 350\,\text{GeV}$

$\geq 2\text{-jet}, m_{jj} \geq 350\,\text{GeV}, p_T^H \geq 200\,\text{GeV}$

$p_T^H < 200\,\text{GeV}$

$\geq 2\text{-jet}, 350 \leq m_{jj} < 700\,\text{GeV}, p_T^H < 200\,\text{GeV}$

$\geq 2\text{-jet}, m_{jj} \geq 700\,\text{GeV}, p_T^H < 200\,\text{GeV}$
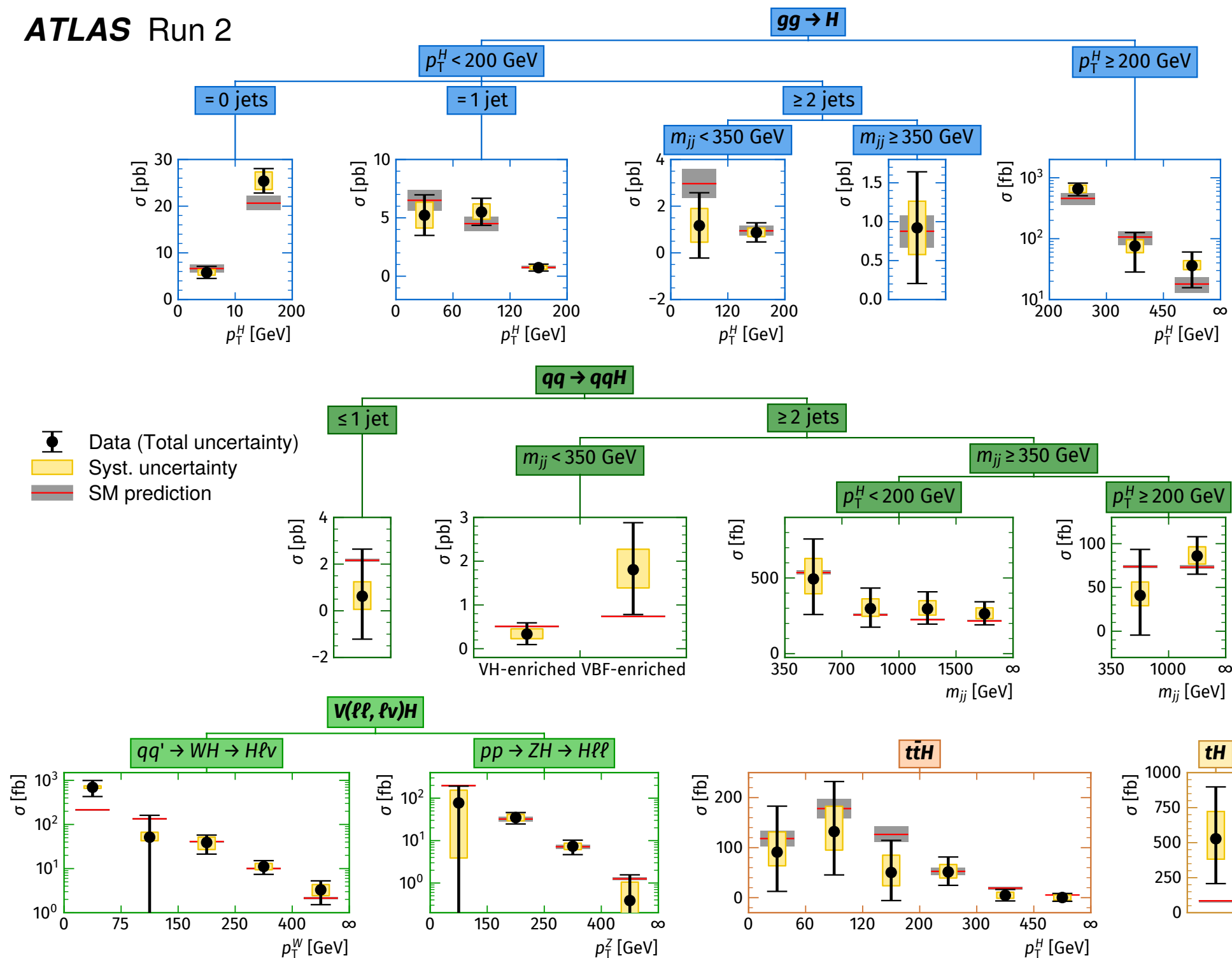
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  ‣ High p_T^H from $H \to bb$

V(lep)H

$qq' \to H\ell\nu$

$H\ell\nu,\ p_{\mathrm{T}}^{W} < 75\,\mathrm{GeV}$

$H\ell\nu,\ 75 \leq p_{\mathrm{T}}^{W} < 150\,\mathrm{GeV}$

$H\ell\nu,\ 150 \leq p_{\mathrm{T}}^{W} < 250\,\mathrm{GeV}$

$H\ell\nu,\ p_{\mathrm{T}}^{W} \geq 250\,\mathrm{GeV}$

$pp \to H\ell\ell$

$H\ell\ell,\ p_{\mathrm{T}}^{Z} < 150\,\mathrm{GeV}$

$H\ell\ell,\ 150 \leq p_{\mathrm{T}}^{Z} < 250\,\mathrm{GeV}$

$H\ell\ell,\ p_{\mathrm{T}}^{Z} \geq 250\,\mathrm{GeV}$

- Measure mutually exclusive phase-spaces

  ‣ In terms of kinematics of the Higgs or associated objects in productions.

  ‣ Sensitivity to deviations from SM.

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- Advantage of complementary sensitivity in production from different final states:

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- Measure mutually exclusive phase-spaces

  ‣ In terms of kinematics of the Higgs or associated objects in productions.

  ‣ Sensitivity to deviations from SM.

  ‣ Avoidance of large modelling uncertainties.

  ‣ Approximate experimental sensitivity.

t$\bar{\text{t}}$H

$p_{\text{T}}^{H} < 60\,\text{GeV}$

$60 \leq p_{\text{T}}^{H} < 120\,\text{GeV}$

$120 \leq p_{\text{T}}^{H} < 200\,\text{GeV}$

$p_{\text{T}}^{H} \geq 200\,\text{GeV}$

tH

- Advantage of complementary sensitivity in production from different final states:
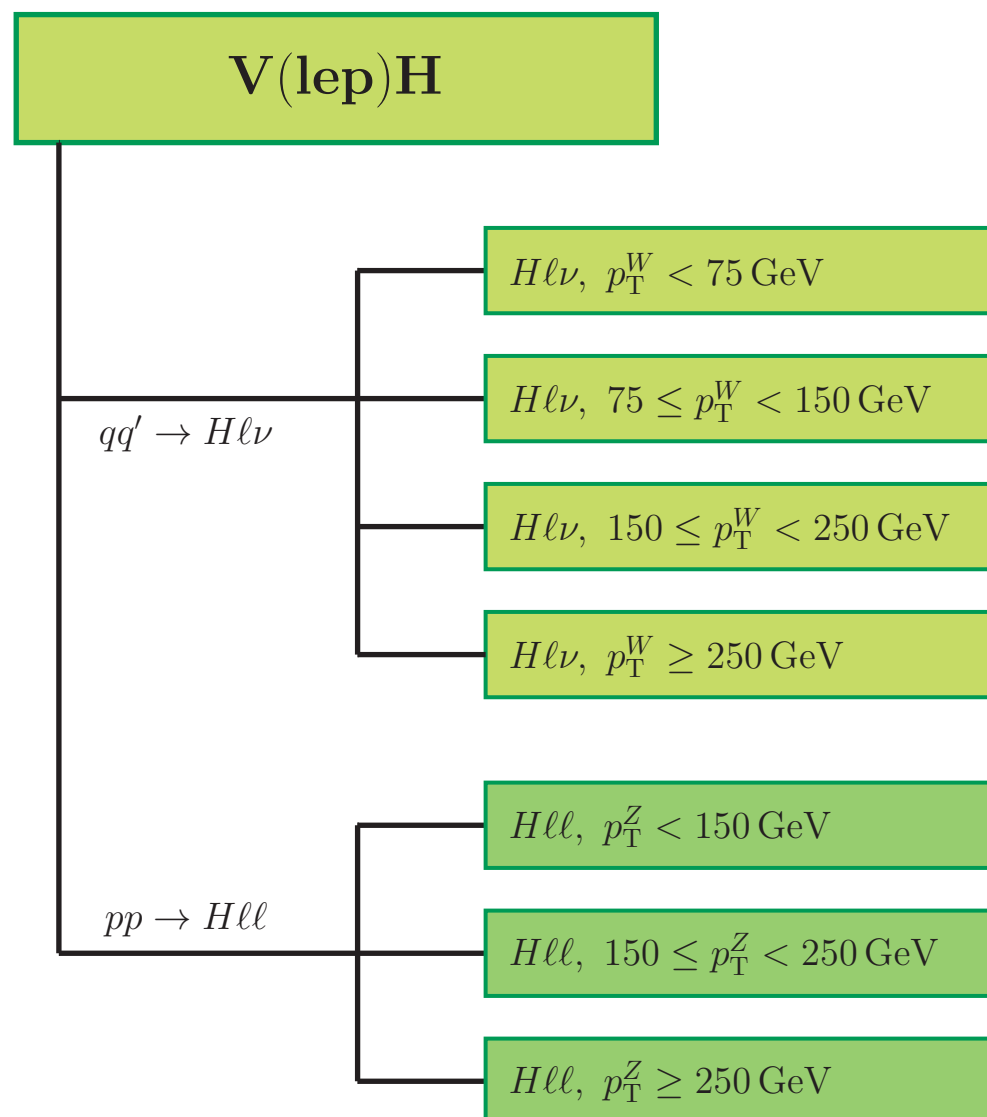
  ‣ $m_{\text{jj}} > 450\ \text{GeV}$ from $H{\rightarrow}WW^{*}$

  ‣ High p_{T}^{H} from $H{\rightarrow}bb$

- **Strategy in measuring the cross section in these exclusive categories**
  - Discussing here the example of the $H \rightarrow ZZ^*$

- **Cut-based reconstruction-level categories,**
  - maximising purity and minimising extrapolation to true phase-spaces.

- Multi-output-node neural network discriminants in detector category.
  - Multidimensional fits on n-1 dimensions on n output nodes per category.
- Backgrounds from data sidebands on resonant signal.
  - Performed as a function of the jet multiplicity to reduce higher order correction uncertainties.

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- Measure mutually exclusive phase-spaces

ATLAS Run 2

$gg \to H$

$qq \to qqH$

$V(\ell\ell, \ell\nu)H$

$qq' \to WH \to H\ell\nu$

$pp \to ZH \to H\ell\ell$

$t\bar{t}H$

tH

Data (Total uncertainty)
Syst. uncertainty
SM prediction

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- Simultaneous fit to all template cross sections

- ▸ Extraction of global signal strength ($\mu = \sigma^{obs} / \sigma^{exp}$).

- ▸ Experimental sensitivity of the same oder as of theory (up to N³LO for ggF)

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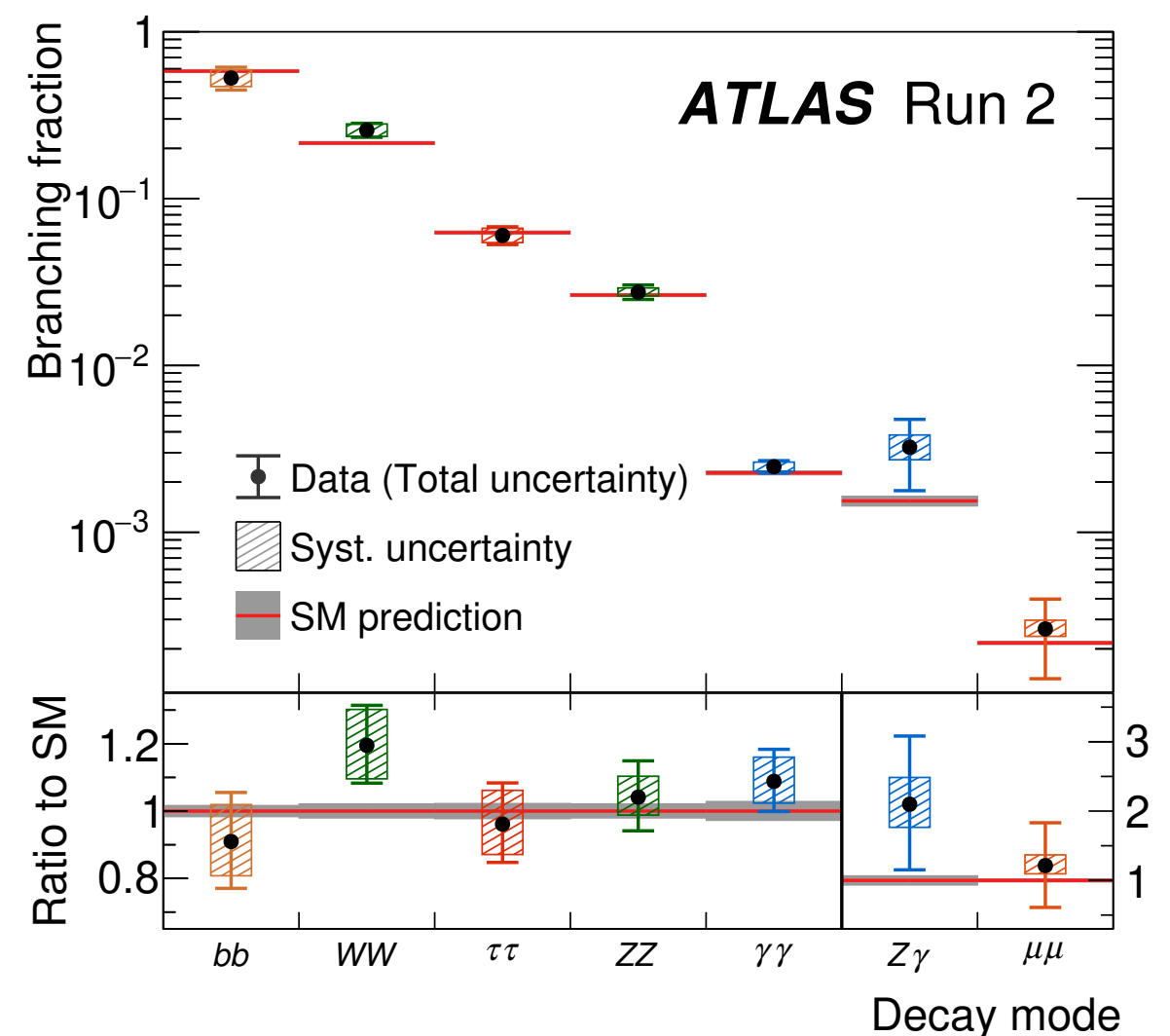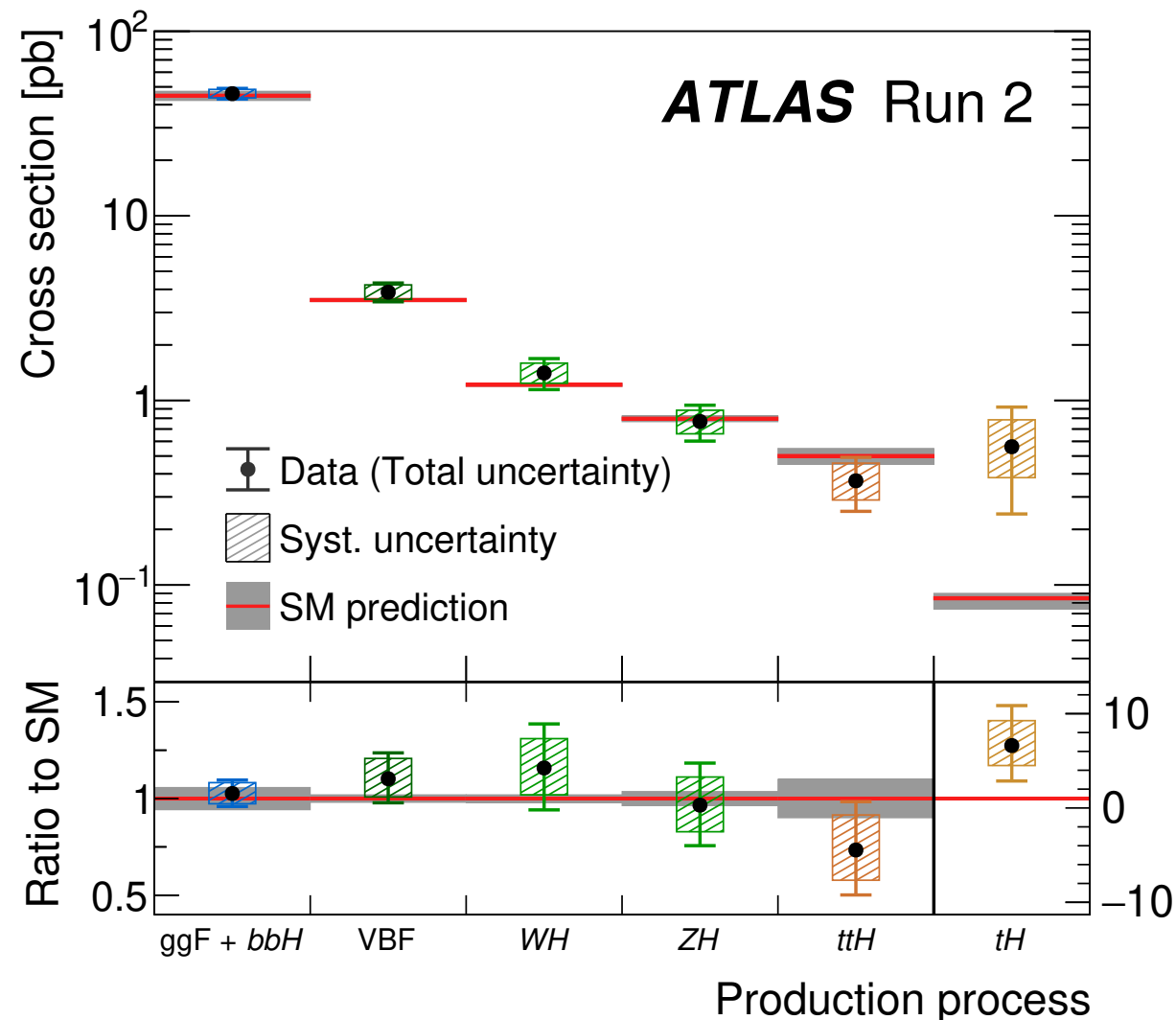
Running couplings

- Higgs boson couplings as a function of the particle mass
- Assuming production and decay are factorised...
- Coupling strength modifiers
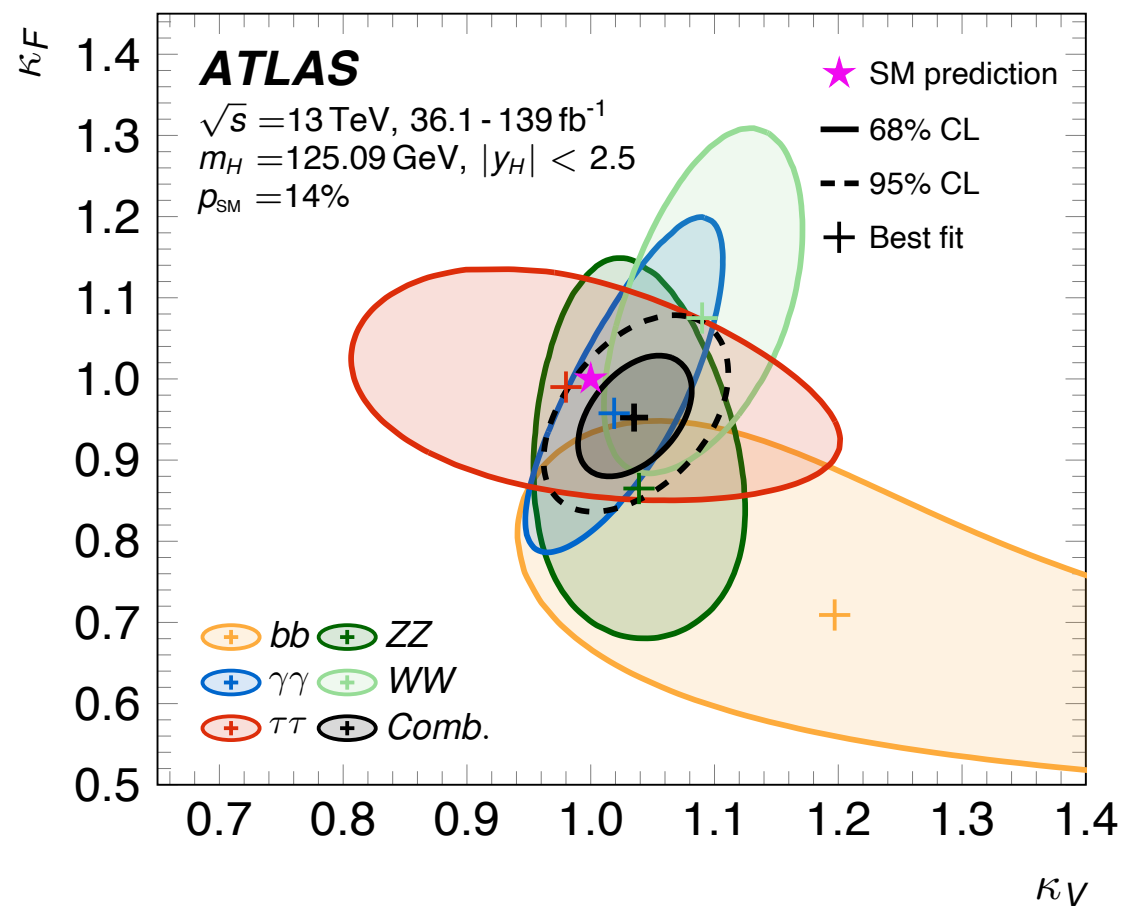
- Unprecedented agreement with SM Higgs.
- Yet, given λ_H's value, new phenomena might stabilise the vacuum expectation ?
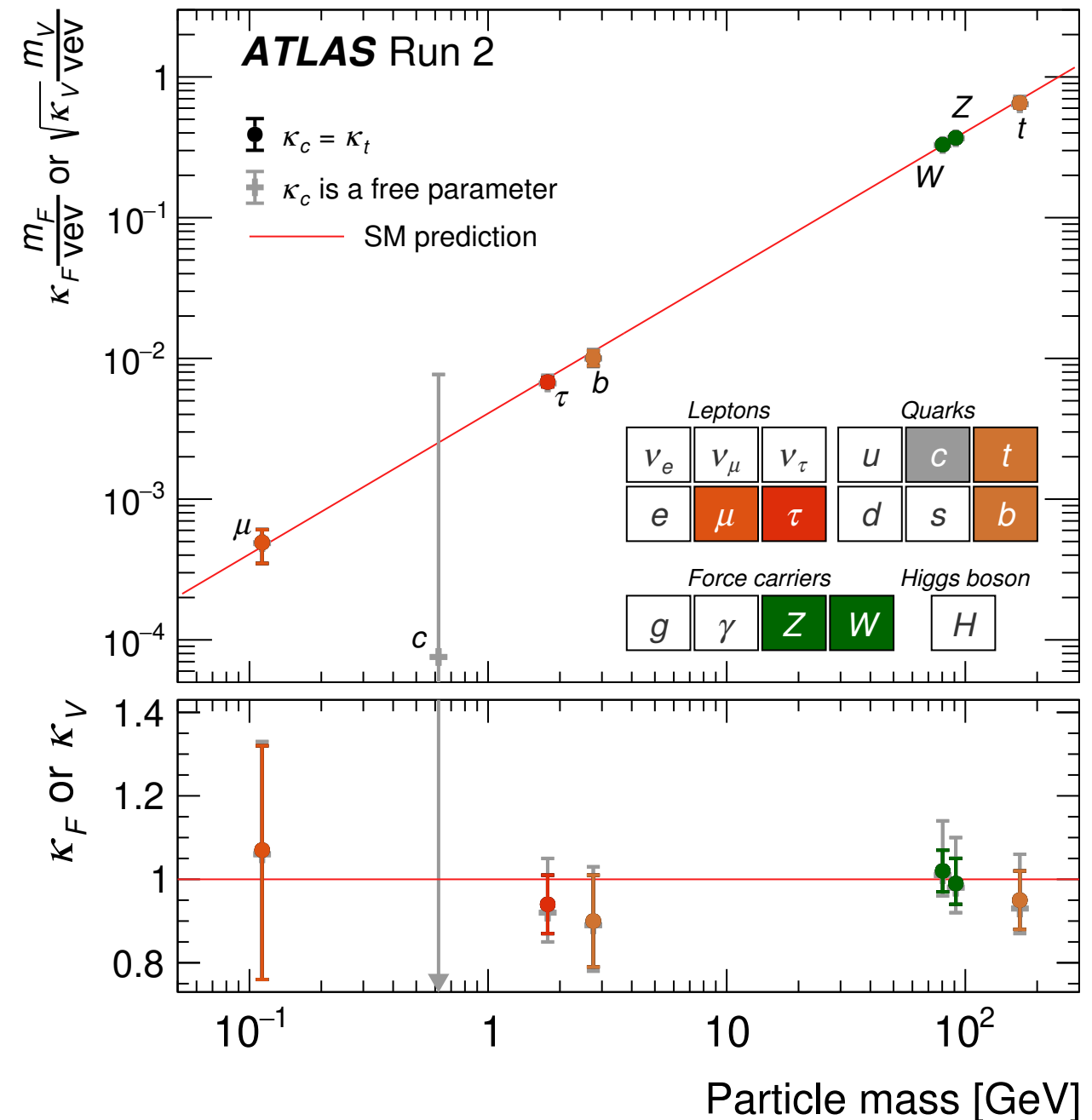
5. Differential cross section measurements

- At Run II sufficient statistics for constraining differential measurements

- Fiducial cross section definition
  - ▸ including detector efficiency (C) , detector acceptance (A) and branching $\mathcal{B}$

$$\sigma_{i,\text{fid}} = \sigma_i \times A_i \times \mathcal{B} = \frac{N_{i,\text{fit}}}{\mathcal{L} \times C_i}$$

  - ▸ Cuts mimicking reconstruction selection:

    (i) Model independent result.
    (ii) No extrapolation beyond measurable phase-space

- In diboson channels, resonant peak over smooth background

  - ▸ Good resolution on final-state particles,
    in particular in $H \to 4\ell$, $\gamma\gamma$

- *Unfolding* performed within the signal extraction fit

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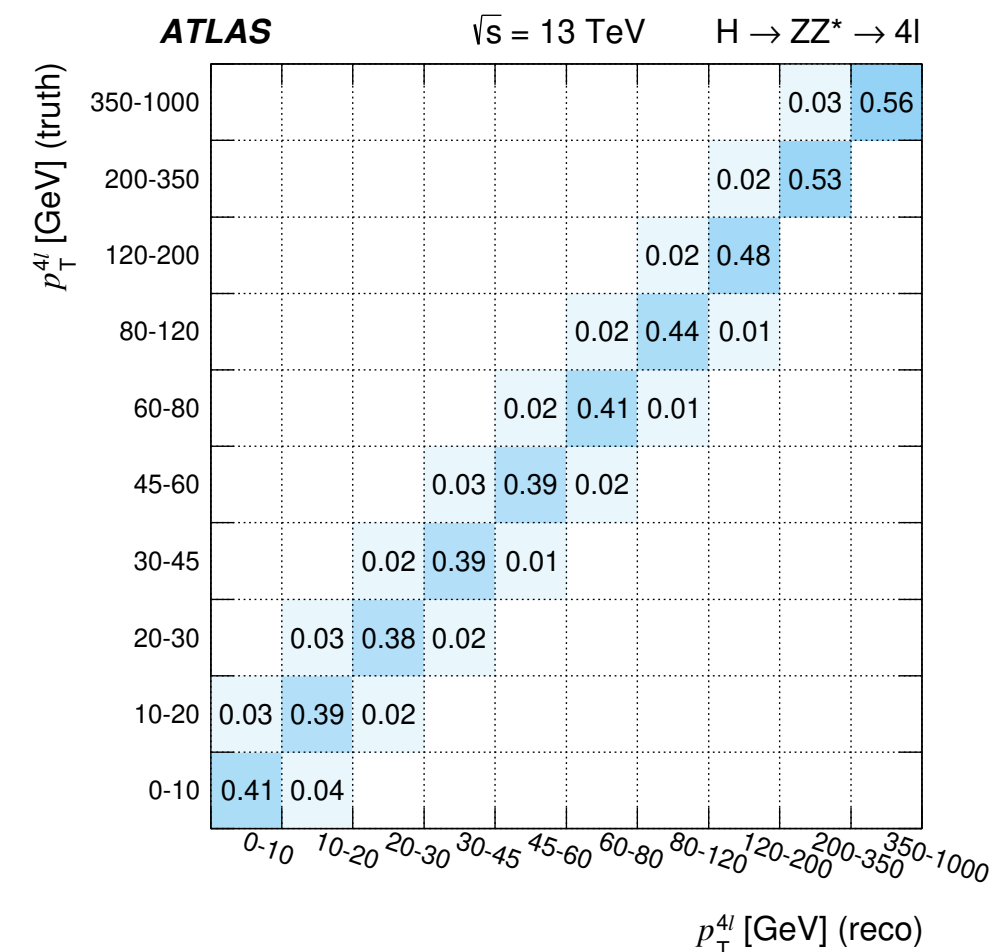
- **I**nclusive fiducial cross sections:

  ▸ SM predictions of 3.33 ± 0.15 fb ($H{\to}ZZ$) and 63.5 ± 3.3 fb ($H{\to}\gamma\gamma$)

- For ZZ also cross section per final state

  ▸ Eventually sensitivity to final state interference (10%) in same flavour quadruplets

- Study of the the $m_{4\ell}$ spectrum and off-shell H production

  ‣ Offshell Higgs production, enhanced at 350 GeV because of top-quark loops in ggF

  ‣ Measured upper limit on width combining 4ℓ and $\ell\bar{\ell}\nu\bar{\nu}$

  ‣ Limit Γ_H possibile from the off-shell to on-shell event yield ratio R_{gg}

  ✦ on-shell event yields ~ $k^2_{g,on\text{-}shell}$ / Γ_H, while off-shell ~ $k^2_{g,off\text{-}shell}$

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- 4ℓ: isolate signal under the Higgs resonant peak.

- γγ cross section extracted from resonant peak over the γγ continuum.

- Higgs boson $p_{T,4\ell(\gamma\gamma)}$ and rapidity ($y_{4\ell(\gamma\gamma)}$) probe.

  ‣ $p_{T,4\ell(\gamma\gamma)}$: Lagrangian structure of H interactions, Yukawa couplings
  ‣ $y_{4\ell(\gamma\gamma)}$: Sensitivity to proton's parton density functions.

- **Transition region**

  - Increased precision needed to disentangle effects from higher-order corrections from observables spectra:

    - Ex Higgs p_T as a function of jet vetos

Peak resummation

$N^3LL+NNLO_0(\infty)$

Fixed order dominates

Transition region

$NNLO_1(\infty)$

$NLO_1(m_t)$

m_t effects

$NNLL^*+NLO_0(m_b)$
m_b effects

$d\sigma/dp_T$

p_T

Depiction adapted from F. Tackmann

- Transition region

  ‣ Increased precision needed to disentangle effects from higher-order corrections from observables spectra:

    ‣ Ex Higgs p_T as a function of jet vetos

    ‣ State of the art predictions in these regions start being published.
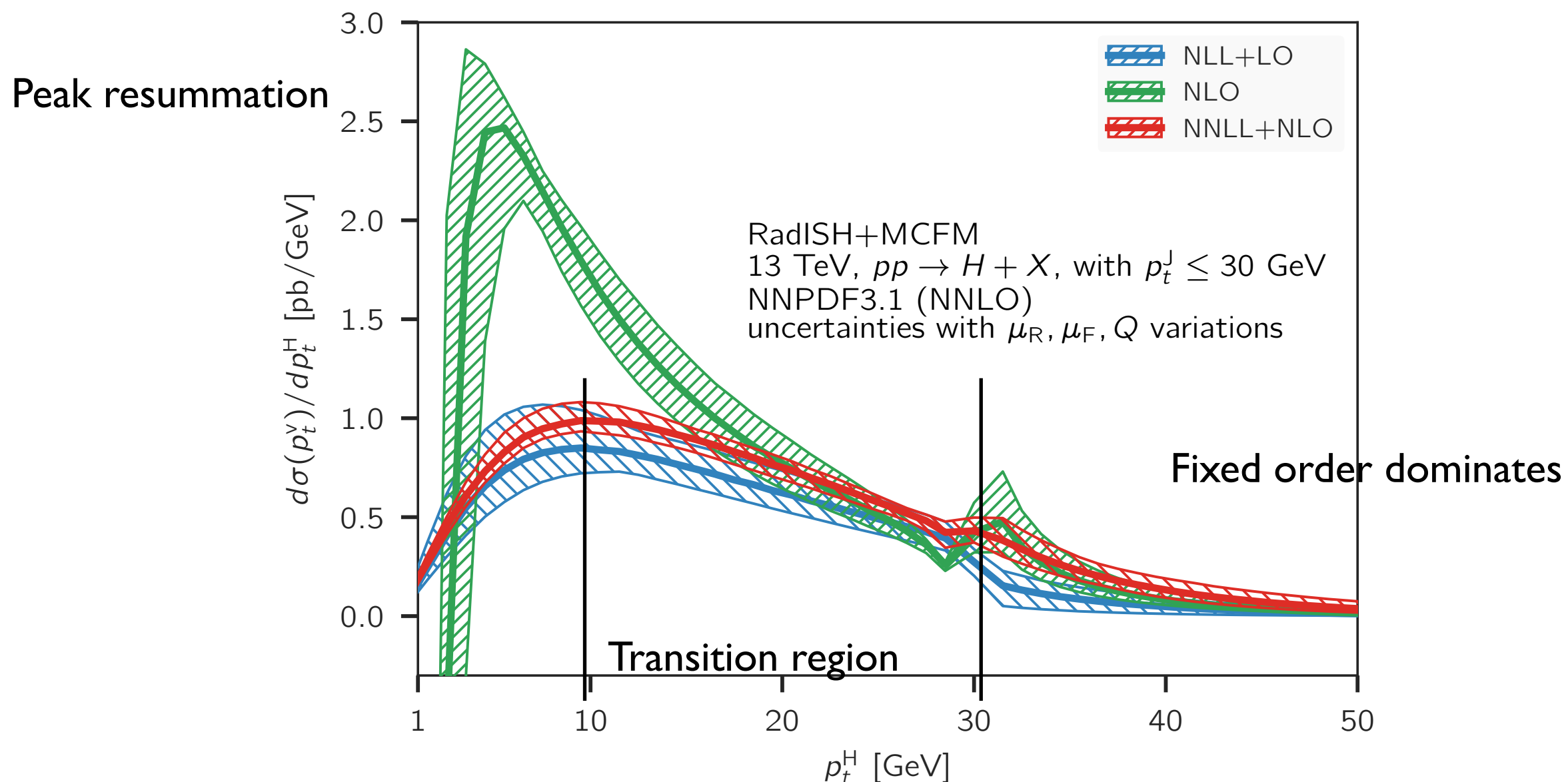
Peak resummation

RadISH+MCFM
13 TeV, $pp \rightarrow H + X$, with $p_t^J \leq 30$ GeV
NNPDF3.1 (NNLO)
uncertainties with μ_R, μ_F, Q variations

Fixed order dominates

Transition region

NLL+LO
NLO
NNLL+NLO

$d\sigma(p_t^Y)/dp_t^H$ [pb/GeV]

p_t^H [GeV]

▸ Increased precision needed to disentangle effects from higher-order corrections from observables spectra:

  ▸ Measurements at Run-2 competitive on these state-of-the art predictions

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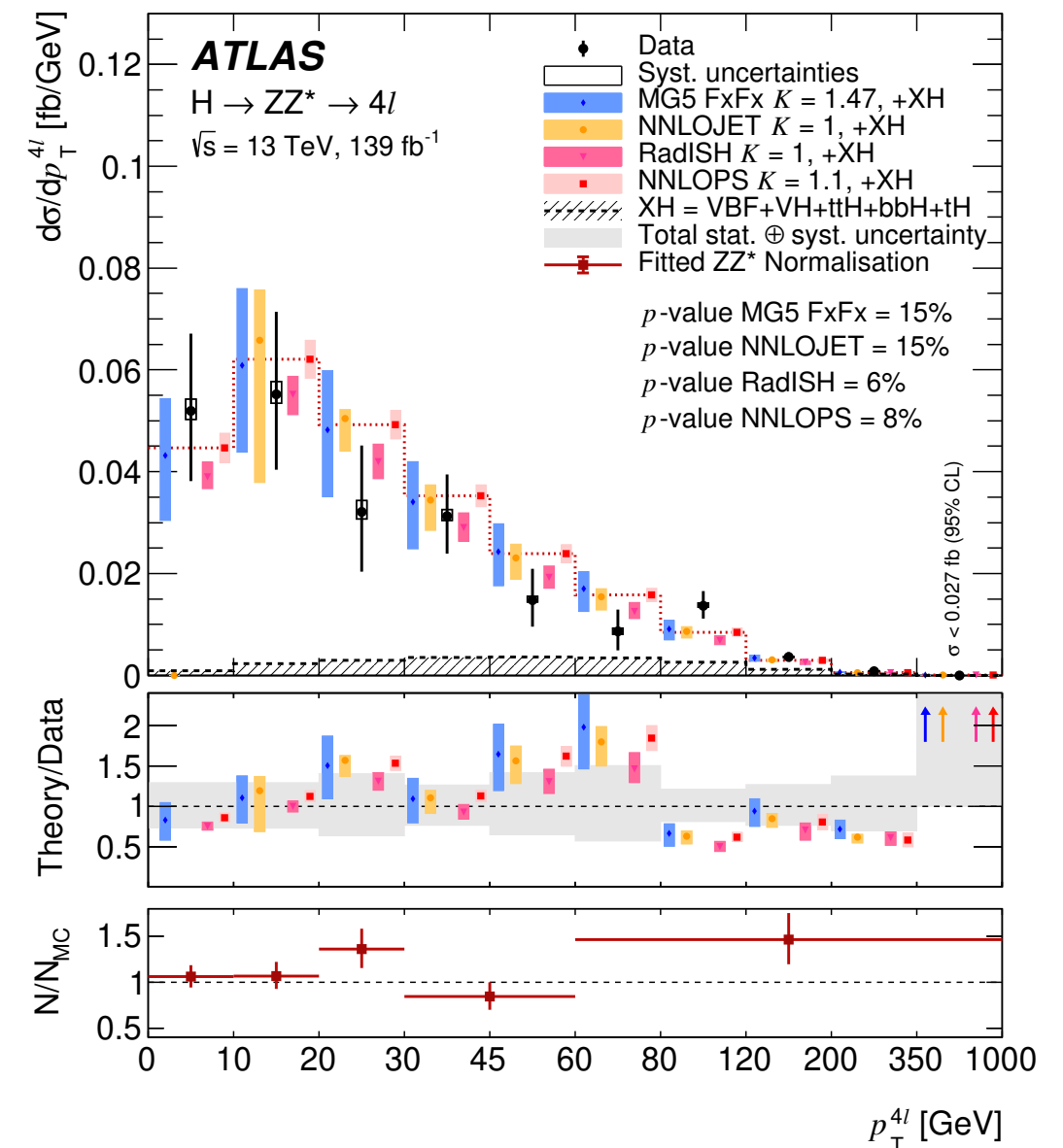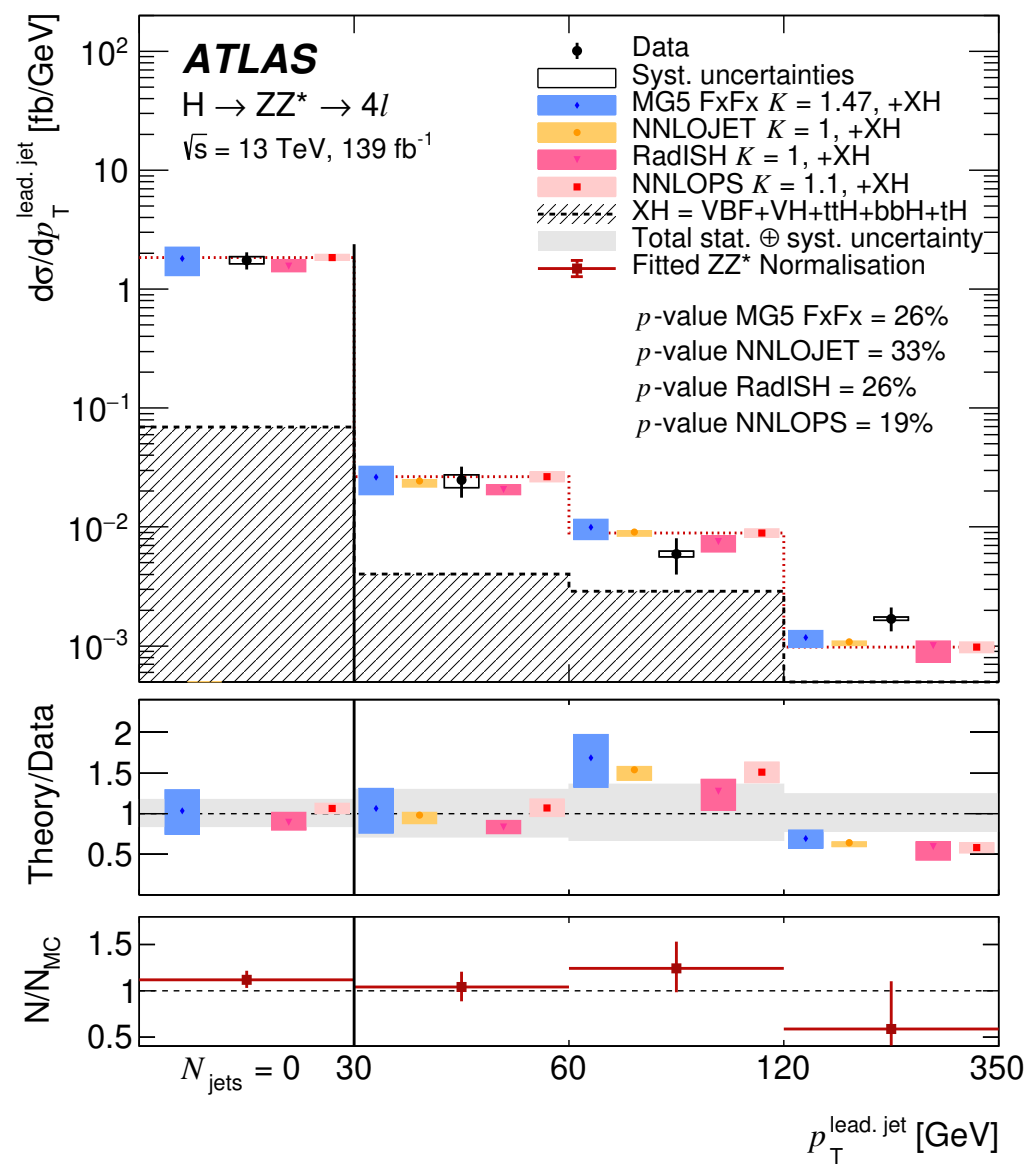
Where is the new physics ?

- The LHC search programme did not identify yet New Physics.

- Hints for new physics in HEP:

  ▸ Dark matter astronomy, g_μ-2, gravitational waves, lepton universality in $B^+ \to K^+ \ell\ell$, CP anomalies in B-physics…, For $m_H \sim 125$ GeV, vacuum metastable, mass unnatural $\Lambda > 550$ GeV.

- What if New Physics is resonant outside our direct experimental reach ?

Energy boundaries of the experiment

$N^3LL + NNLO_0(\infty)$

$NNLO_1(\infty)$

$NLO_1(m_t)$
m_t effects

$NNLL^* + NLO_0(m_b)$
m_b effects

$\dfrac{d\sigma}{dp_T}$

Energy

?

Z'

Depiction adapted from F. Tackmann

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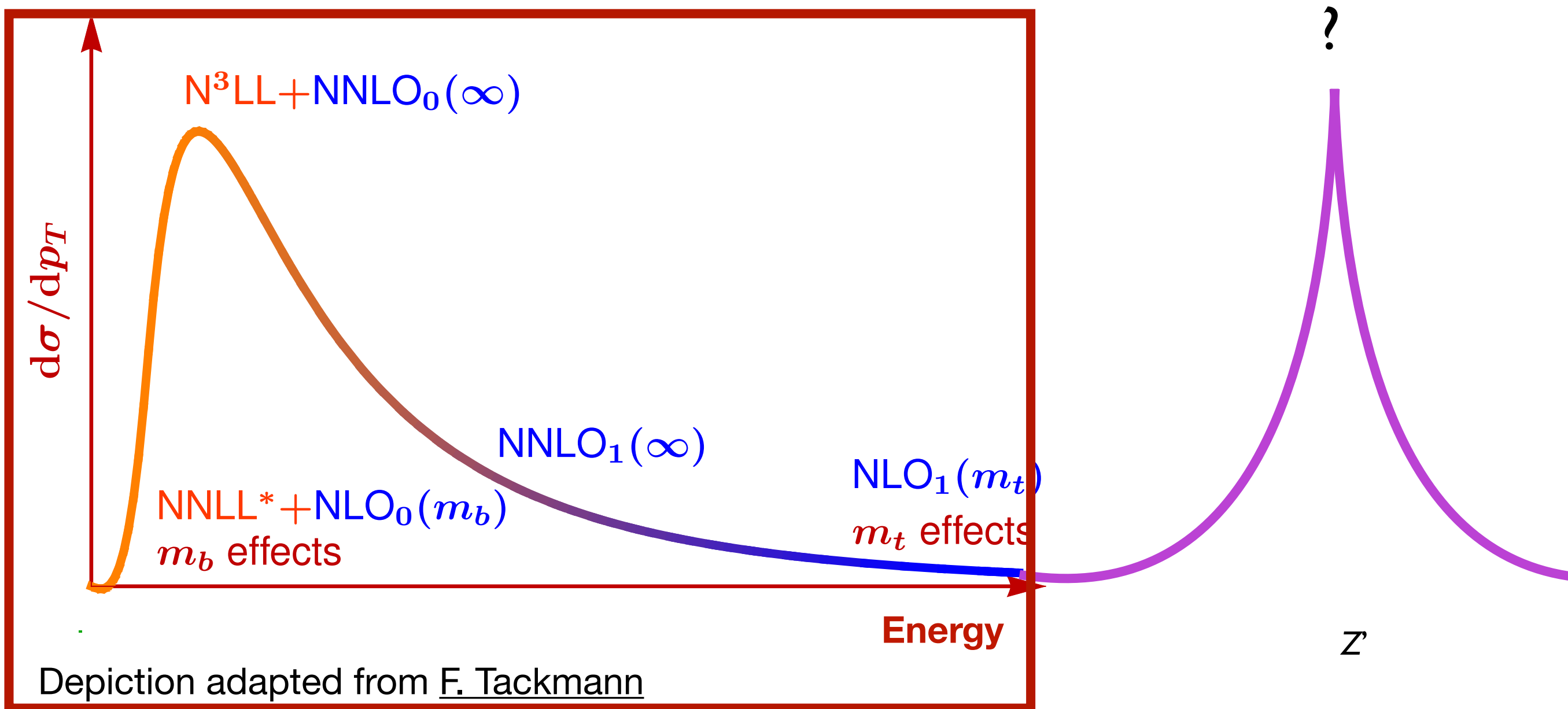
Pseudo observables

- In H→4ℓ m_{12} vs m_{34}: sensitivity to contact interactions:

  ▸ ε_R, ε_L and κ: flavour universal modifiers of the contact terms between H, Z and leptons (arXiv:1504.04018)

  ✦ Angular distributions unaffected: same Lorentz structure as SM term.

m_{12} vs. m_{34}

m_{12} vs. m_{34}

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- What if New Physics is resonant outside our direct experimental reach ?
- Systematic approach: Effective Field Theory

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

Energy boundaries of the experiment

N³LL+NNLO₀(∞)

NNLL*+NLO₀(m_b)
m_b effects

NNLO(∞)

NLO₁(m_t)
m_t effects

Energy

?

$d\sigma / dp_T$

Depiction adapted from F. Tackmann
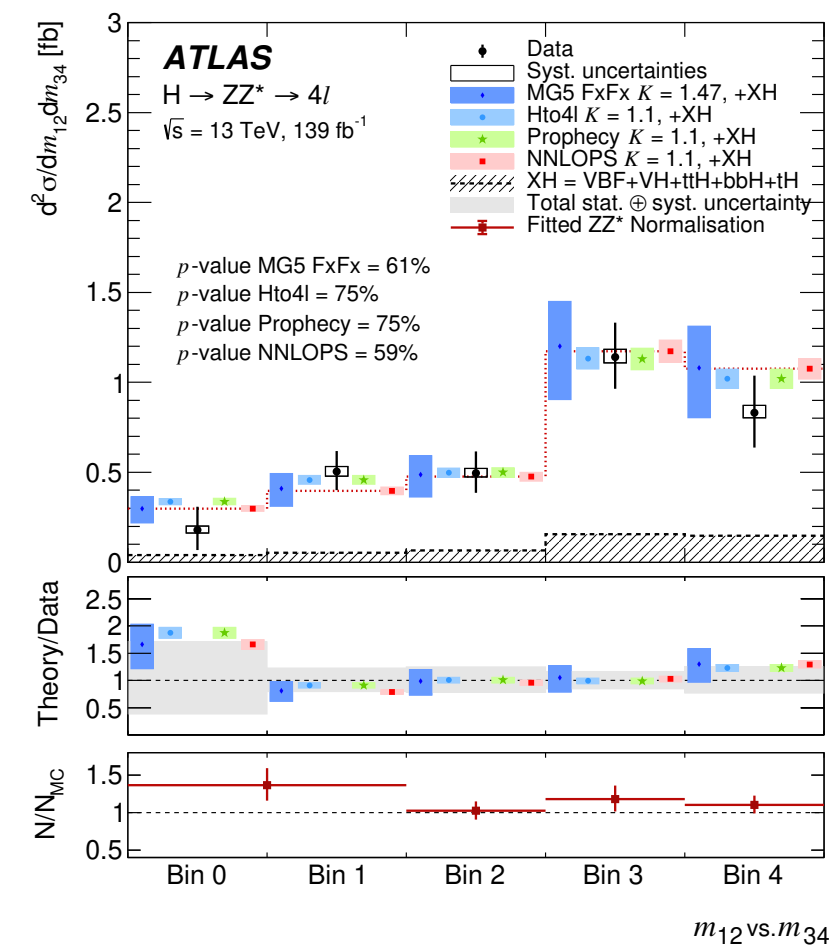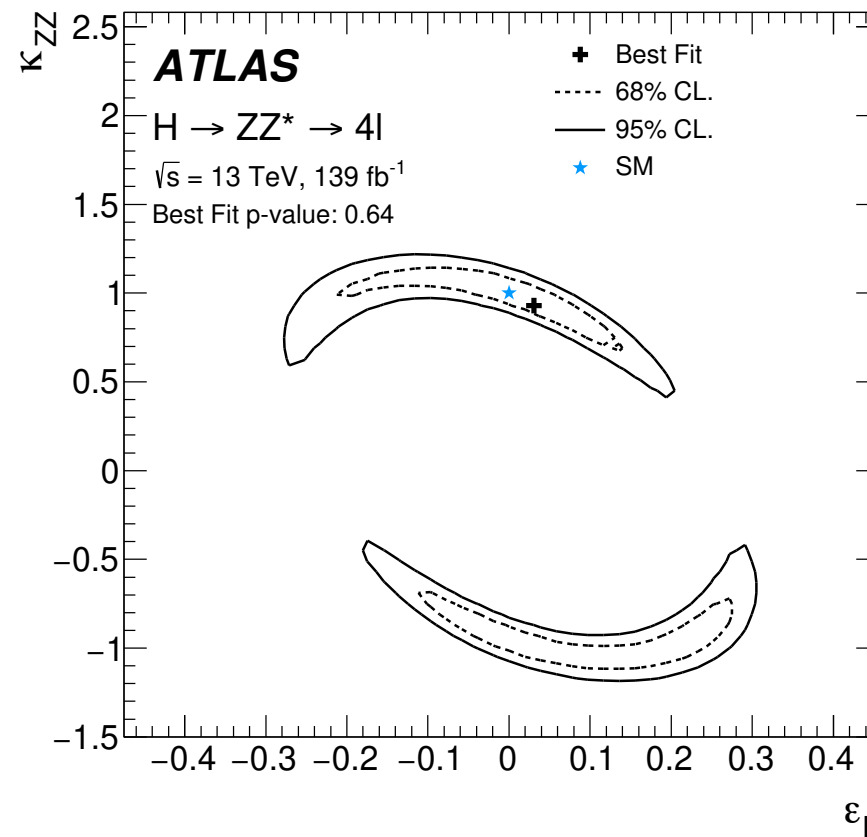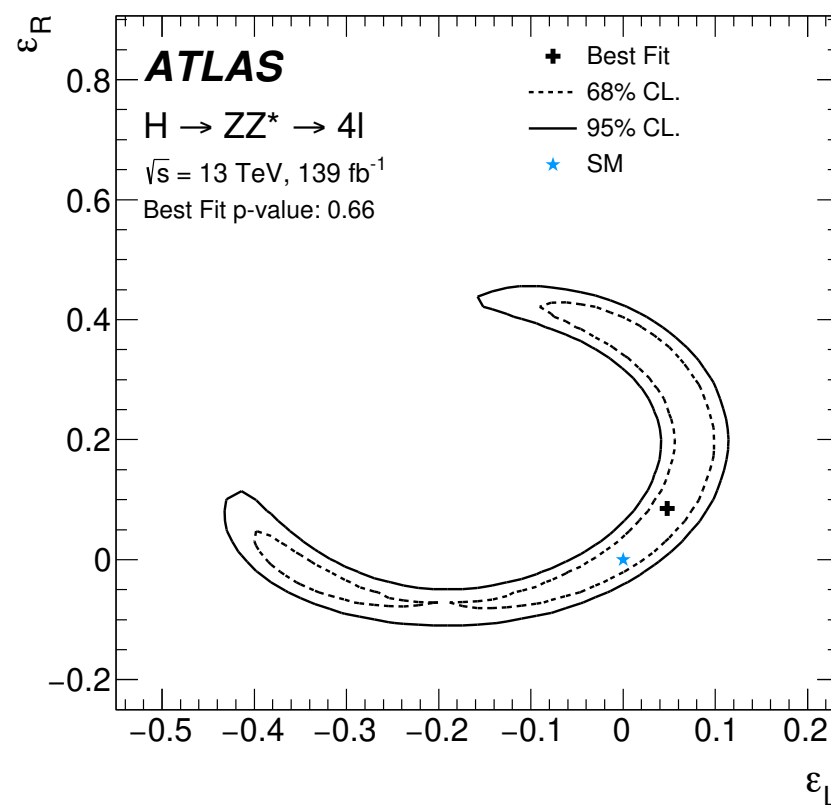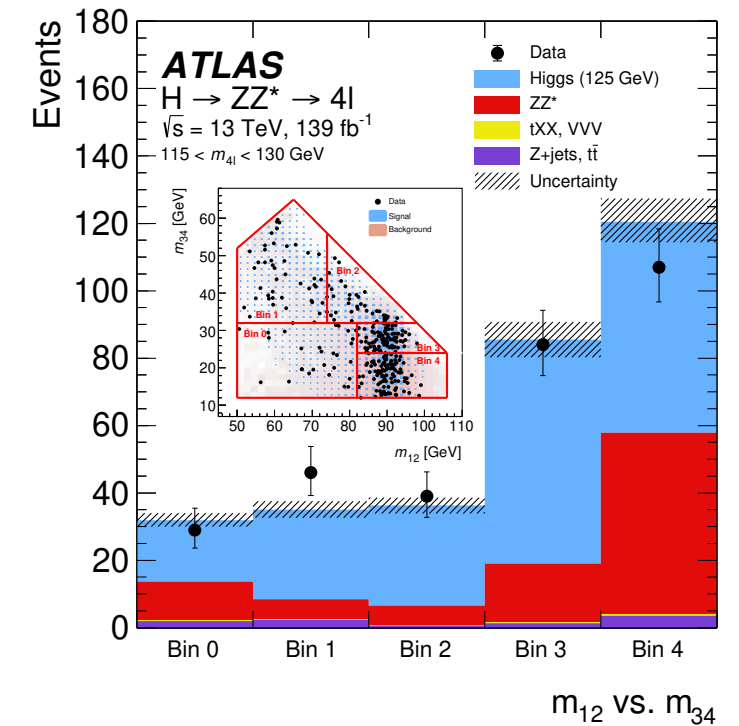
Where is the new physics ?

- What if New Physics is resonant outside our direct experimental reach ?

  ▸ Standard Model Effective Field Theory as the standard candle.

  ▸ Probe for non-SM contributions to the tensor structure of the Higgs boson.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

Energy boundaries of the experiment

$$\left.\begin{array}{l} \dfrac{c_1}{\Lambda^2} \mathcal{O}_1 \to \dfrac{\alpha_S}{\pi v} c_g h G_{\mu\nu}^a G^{a,\mu\nu} , \\[2em] \dfrac{c_2}{\Lambda^2} \mathcal{O}_2 \to \dfrac{m_t}{v} c_t h \bar{t}t , \\[2em] \dfrac{c_3}{\Lambda^2} \mathcal{O}_3 \to \dfrac{m_b}{v} c_b h \bar{b}b , \\[2em] \dfrac{c_4}{\Lambda^2} \mathcal{O}_4 \to c_{tg} \dfrac{g_S m_t}{2v^3}(v+h) G_{\mu\nu}^a (\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c) \end{array}\right.$$

c_g: ggH contact interaction

c_t: t and b Yukawa couplings

c_{tg}: dipole-moment, g-t interaction
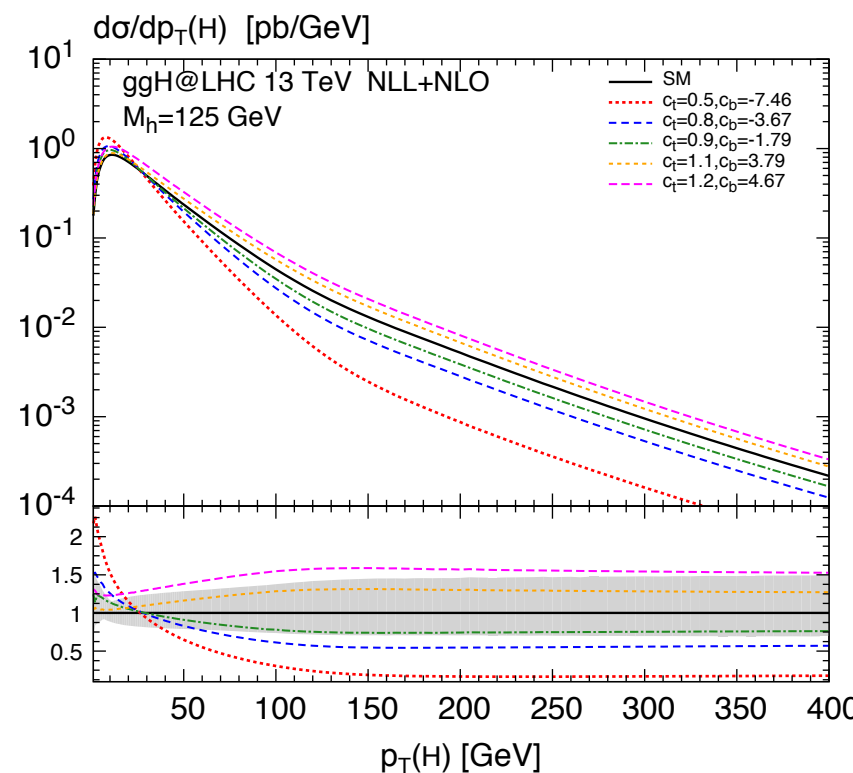
- Sensitivity from a multitude of couplings in each measured quantity
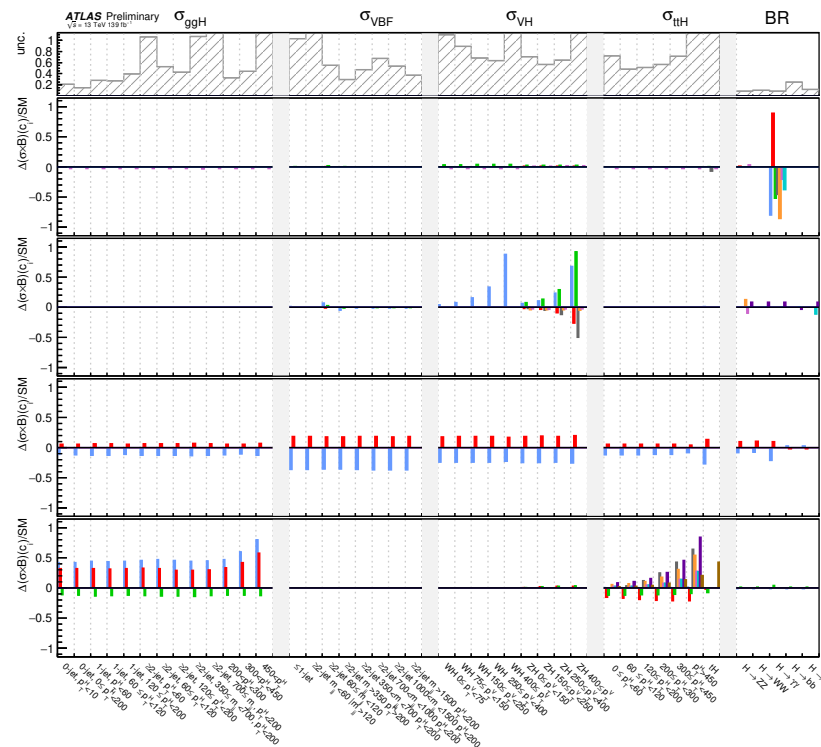
- Enhance sensitivity
  - by isolating dependencies in Wilson coefficients (c_i) allowing for simultaneous extraction through eigenvector decomposition of the dependencies.
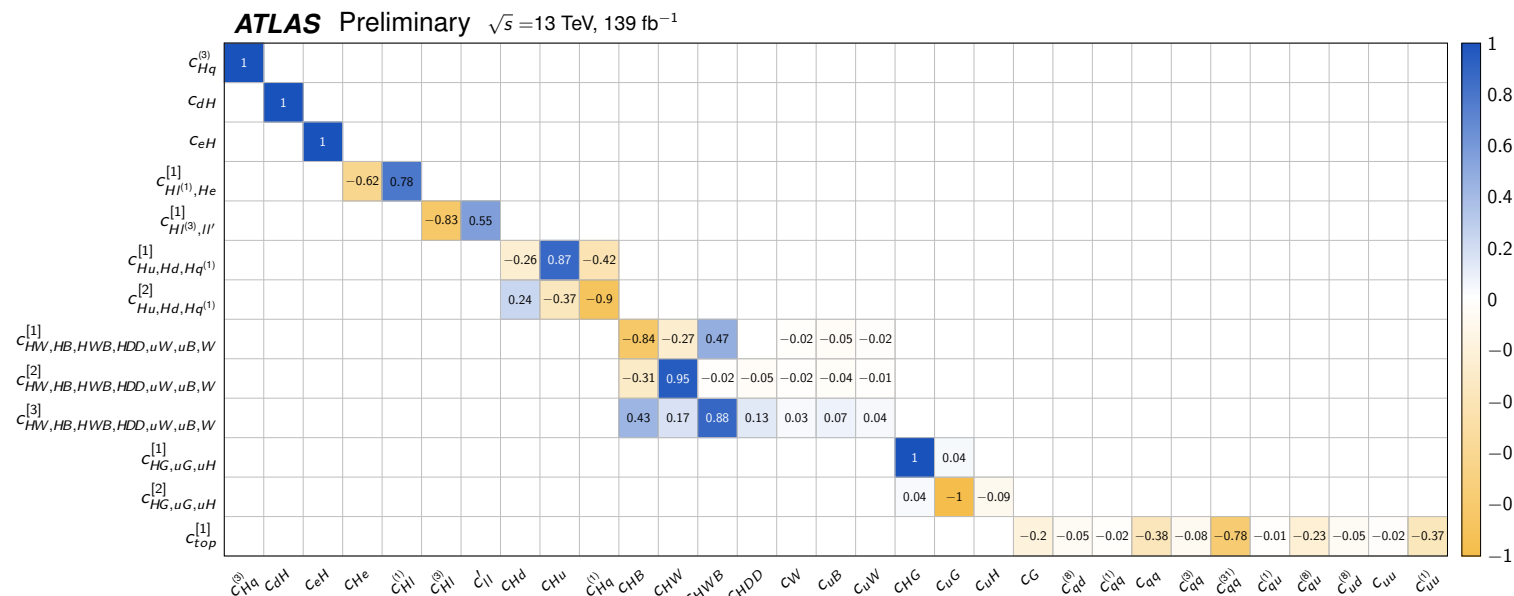
Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

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● Results interpreted in the context of new physics:

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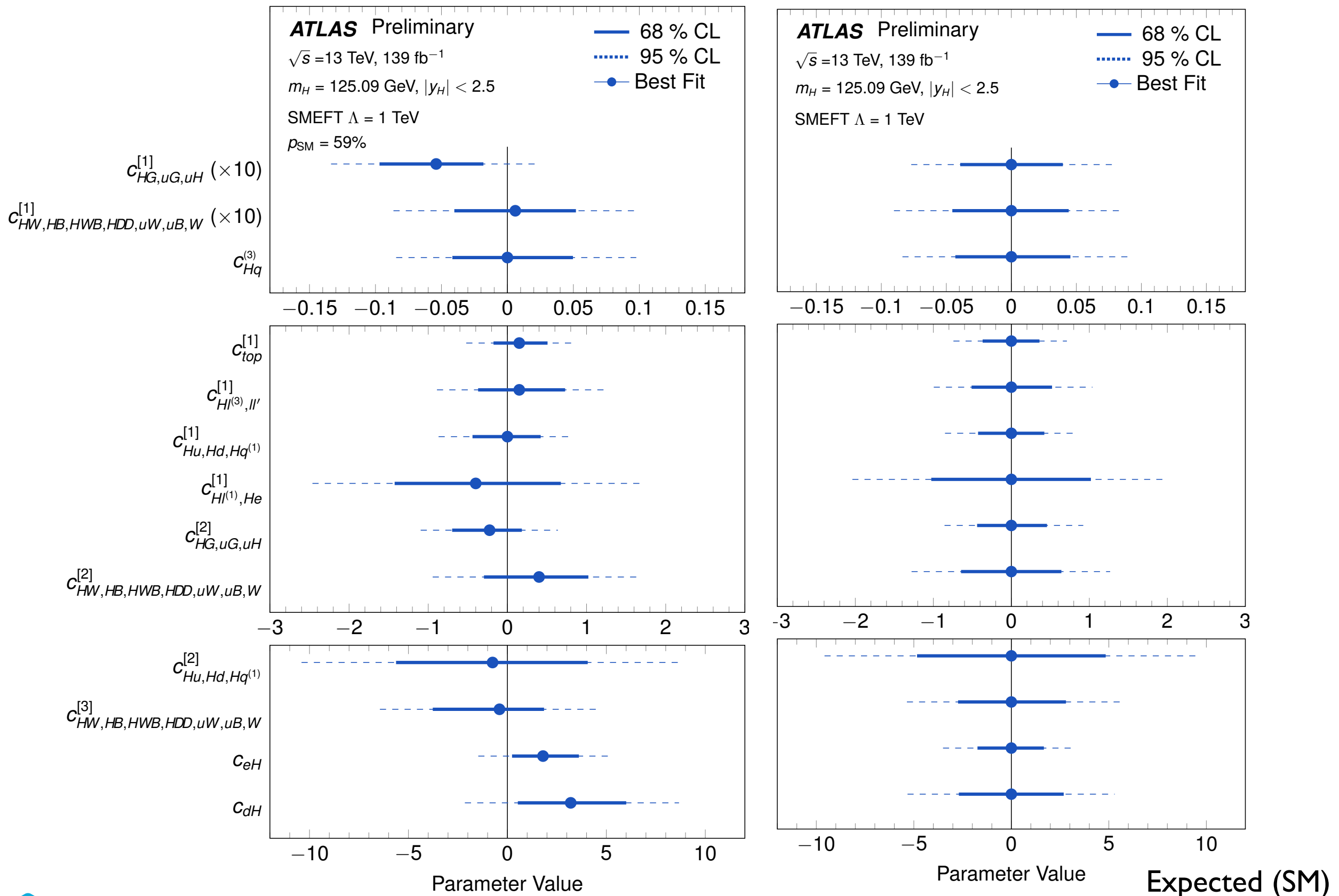
6. Conclusions

Conclusion

- Current reach same order of magnitude as that expected with 20 times the data.

  ‣ Inclusive measurements at percent level

  ‣ Double differential cross sections $O(20\%)$

- Path for higher luminosities at the LHC:

  ‣ Novel ideas in constraining (systematic) uncertainties at higher luminosities.

G. Barone

arXiv:1902.00134

July-22
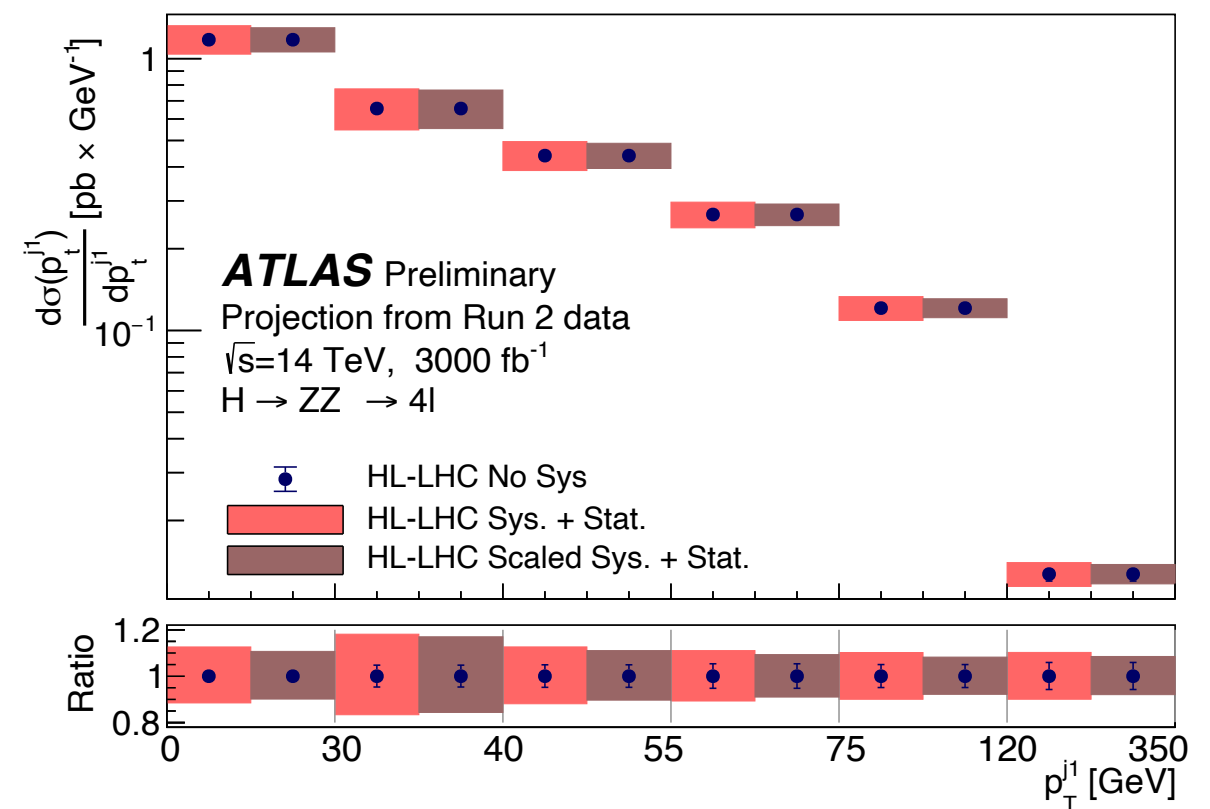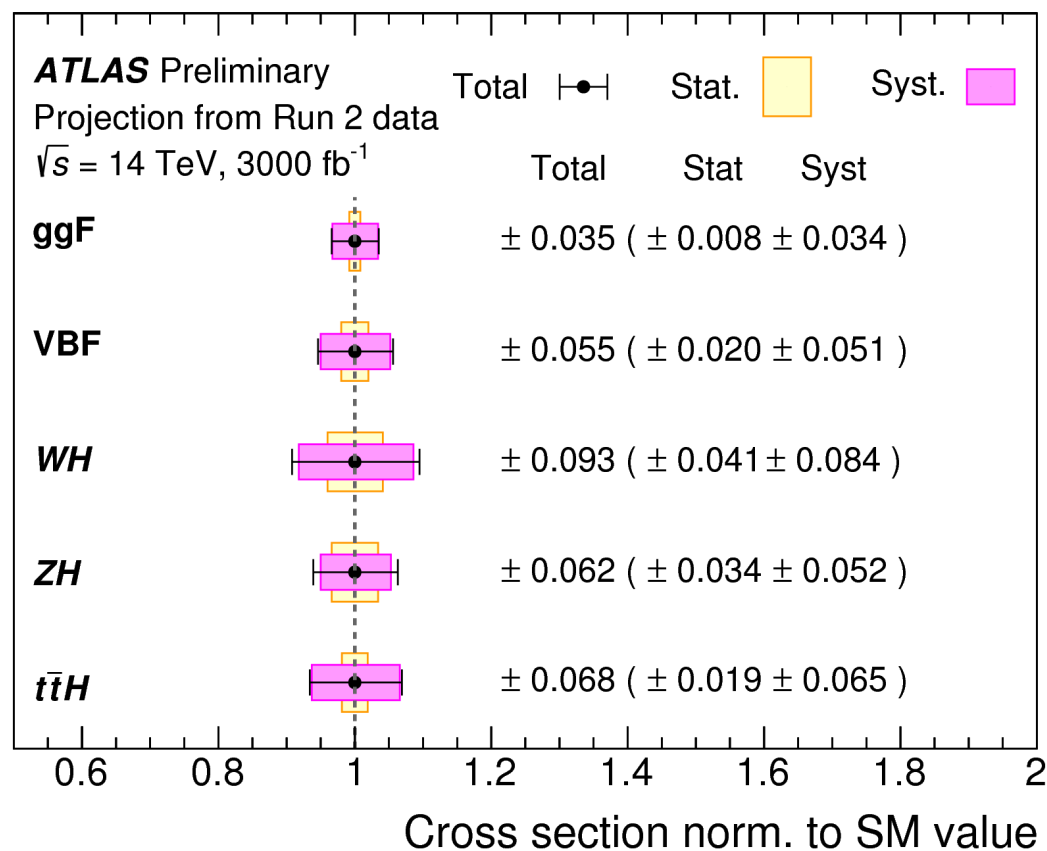
Conclusion

- The Standard Model (SM) is our current understanding of the microcosm.
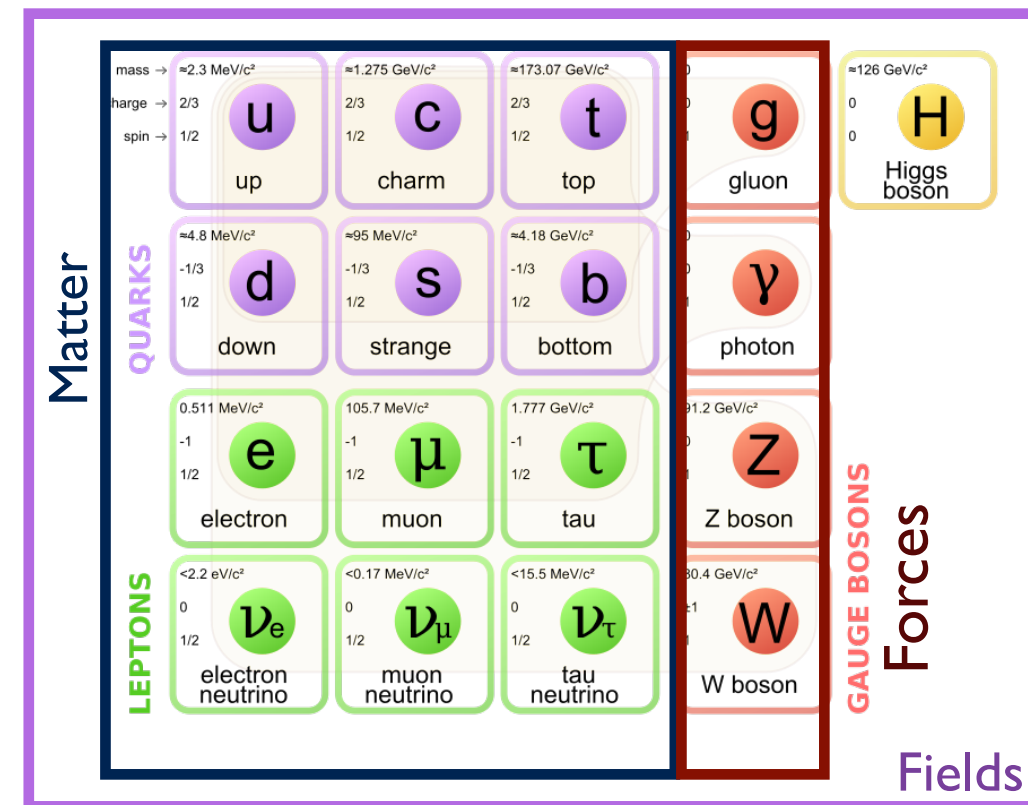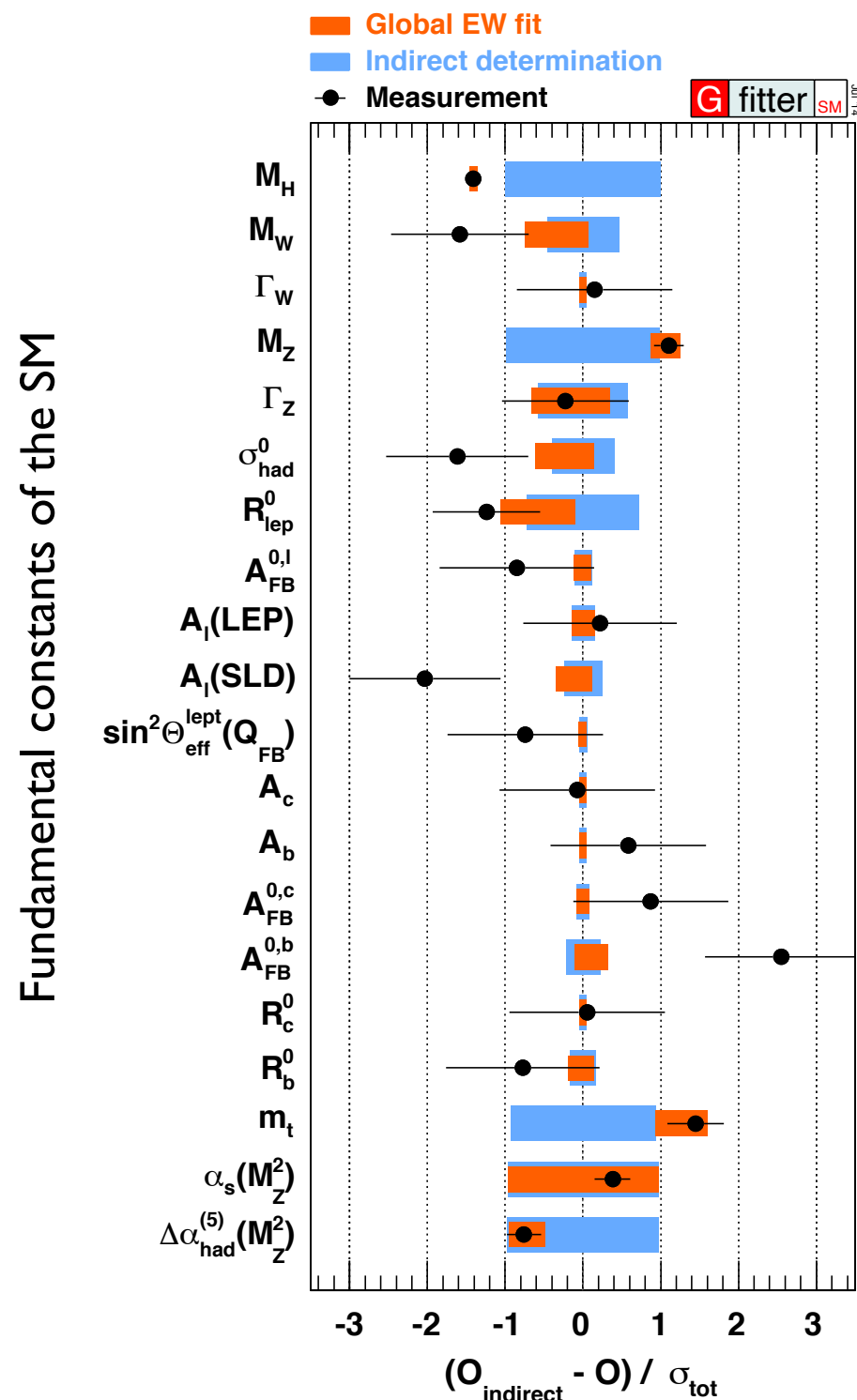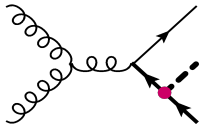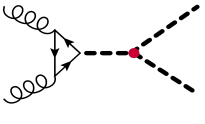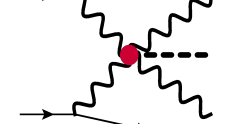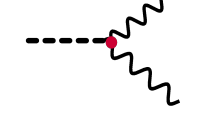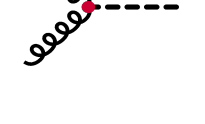
Global Electroweak fits from the Gfitter Collaboration

- Hints for new physics in HEP:
  - Dark matter astronomy, g_μ-2, gravitational waves, lepton universality in $B^+ \rightarrow K^+ \ell\ell$, CP anomalies in B-physics…

- New phenomena hide:
  - In unexplored corners of the phase-space.
  - At energies beyond what's accessible by our colliders.

- Methodical study from current experimental picture.

G. Barone

July-22

Conclusion

- Current reach sам... ...es the data.

  ▸ Inclusive measurem...

  ▸ Double differential...

- Path for higher lum...

  ▸ Novel ideas in cons...

  ▸ Combination of direct and indirect constraints on κ_λ.

  ▸ Combination of processes linked to H production.

Examples

Henning *et al* 10.1103/PhysRevLett.123.181801

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- Increase precision through novel techniques and analyses.

  ‣ VBF cross sections in $H \to ZZ/WW$ channels (ongoing)
  ‣ 2D measurements of $VV^*(+\mathrm{jj})$ and $H(+\mathrm{jj})$ productions.

  ‣ ….

- Increase sensitivity in offshell Higgs couplings.

- Direct measurements of HH production.

  ‣ High precision Higgs properties measurements.

- Precision measurements of $V_L V_L$

  ‣ e^+e^- (FCC-ee/ILC) colliders in VBS $VV \to gg$

time

now

LHC Run2 and Run3
~300 fb^{-1} pp collisions

High Luminosity LHC
~3000 fb^{-1} pp collisions

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Conclusion

- Higgs physics provide an excellent picture for

  ▸ Searches for new phenomena resonant at higher scales.

  ▸ Searches for deviations to theory within the scales of the experiment.

- After a decade of cracking the mass problem:

  1. Measurement of m_H at 2 per mille precision level.

  2. Fiducial cross section measurements, sensitivity to several distributions

  3. Production mode analysis and template cross section measurements.
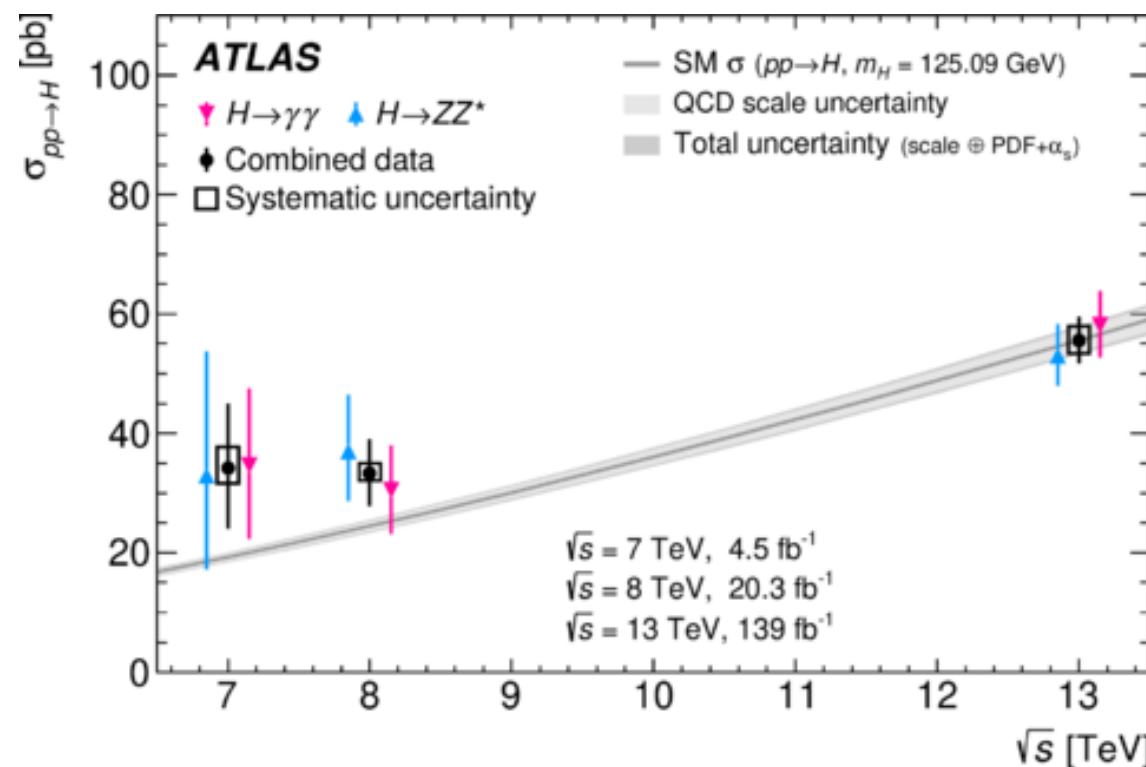
- Presented only a selection results full set

Additional material

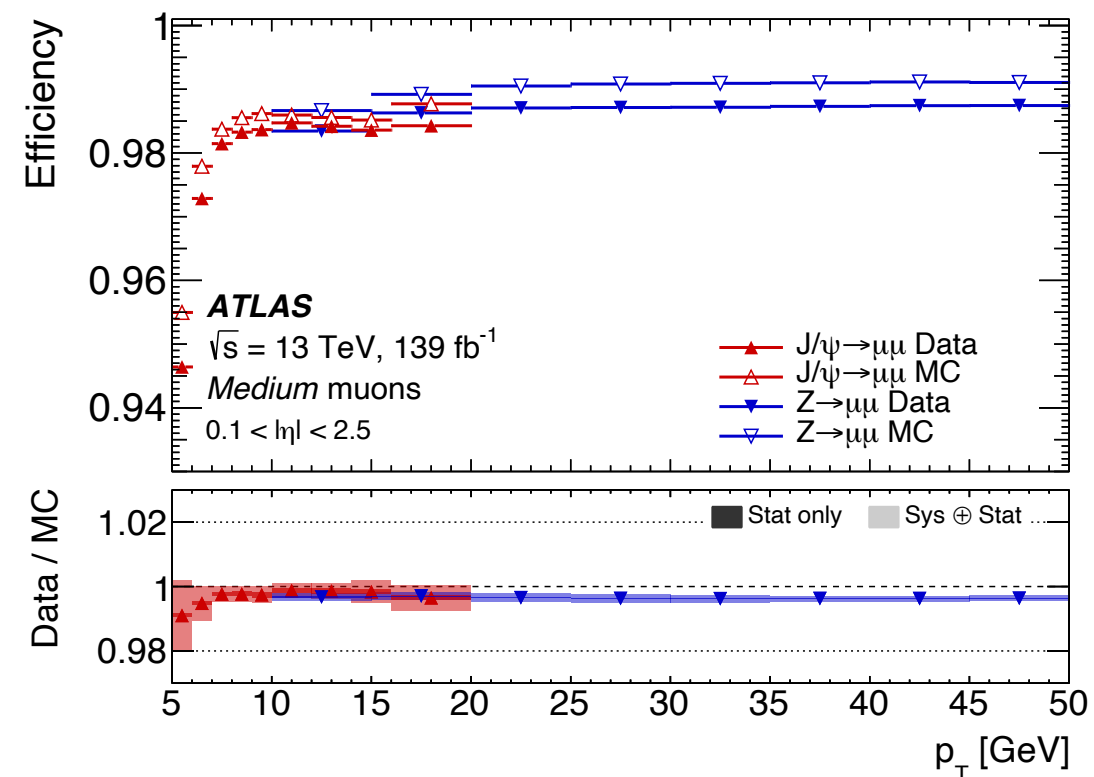# Object selection

- **Electrons (e).**
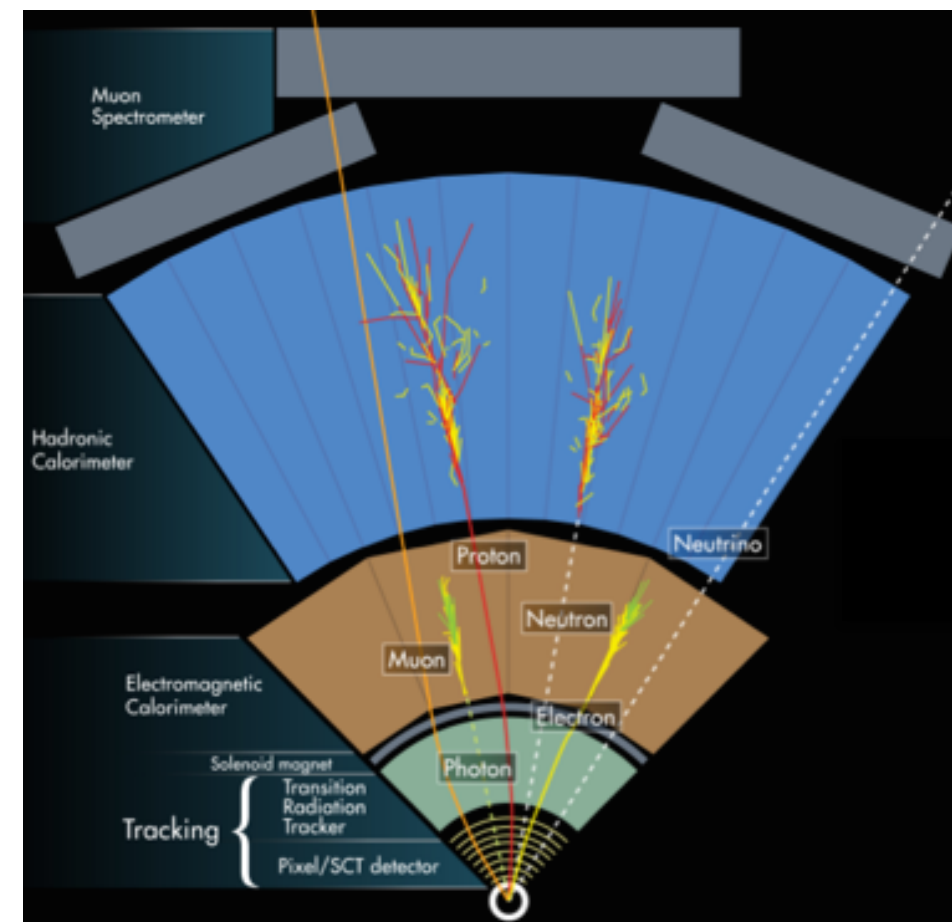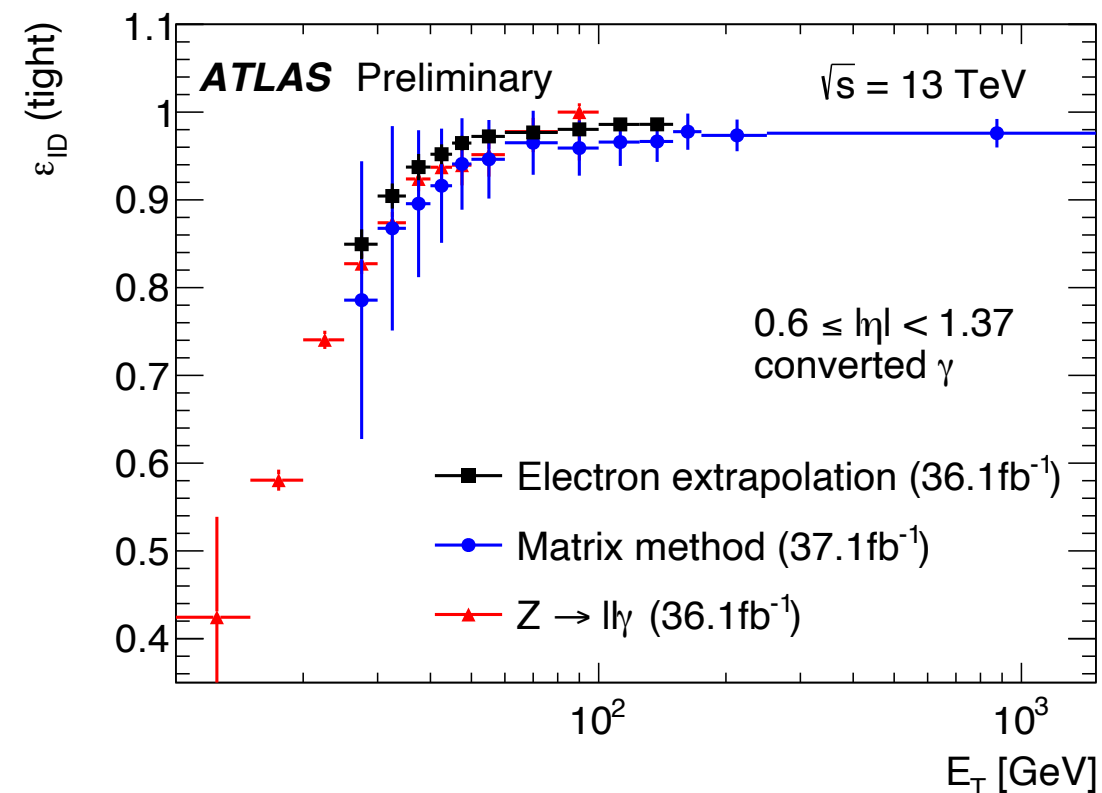 - ‣ Isolated objects clustered from calorimeter energy deposits with associated ID track.
  - ‣ E_T > 7 GeV, $|\eta|$ < 2.47 and $|z_0 \sin(\vartheta)|$ < 0.5 mm

- **Muons (μ).**
  - ‣ Combined track fit of Inner Detector and Muon Spectrometer hits,
  - ‣ p_T > 5 GeV, $|\eta|$ < 2.7 $|z_0 \sin(\vartheta)|$ < 0.5 mm of "loose or medium quality"
  - ‣ Isolated objects

- **Missing transverse energy (E_T^{miss}).**
  - ‣ Inferred from transverse momentum imbalance

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 43.8 fb^{-1}
-2.47<η<2.47
— Loose
— Medium
— Tight
Data: full, MC: open

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Object selection

- **Electrons (e).**

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  ‣ Isolated objects

- **Jets (j).**

  ‣ Energy deposit grouping with *infra*-red safe algorithm:

  ‣ p_T > 25 GeV and $|\eta|$ < 4.5
   - ✦ Clustering with anti-k_T, $R=0.4$

G. Barone

59

Object selection

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  - ‣ Isolated objects

- ● Photons (γ).
  - ‣ Clustering of calorimeter energy deposits.
  - ‣ Identified with rectangular cuts on shower shapes.

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Object selection

- **Electrons (e).**
  - Isolated objects clustered from calorimeter energy deposits with associated ID track.
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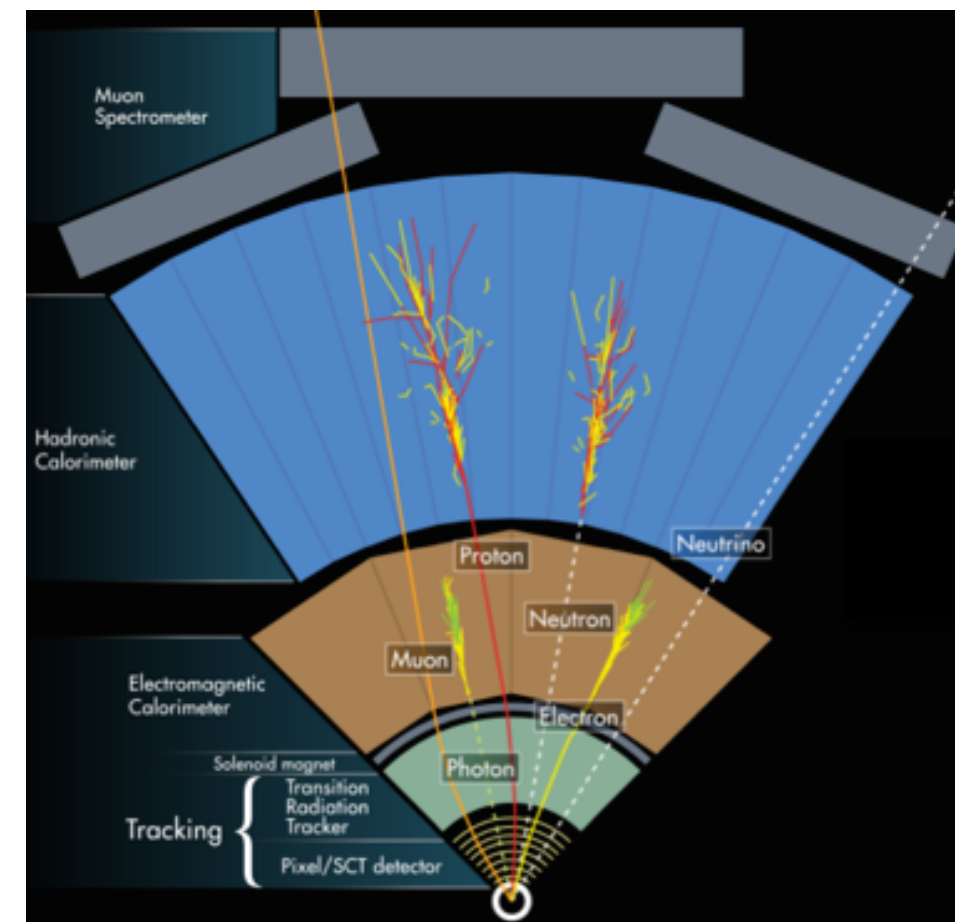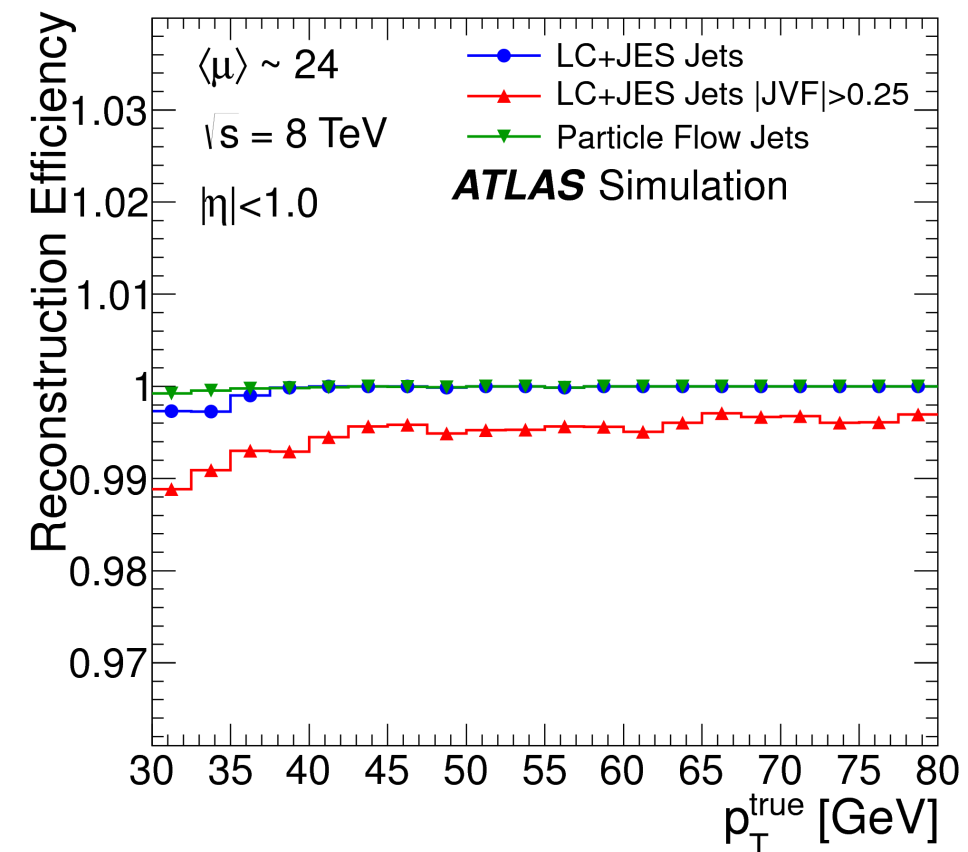
Di-Higgs production

- The Higgs boson can interact with itself through quadratic terms in the Higgs potential

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\Psi}\slashed{D}\psi$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - \boxed{V(\Phi)}$$
$$+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

$$V(\Phi) \sim -\mu^2(\Phi^\dagger\Phi) + \boxed{\lambda}(\Phi^\dagger\Phi)^2$$

‣ About 500 times suppression of $\sigma(gg\to H)$ (48.5 pb) / $\sigma(gg\to HH)$ (~33.4 fb)

‣ Destructive interference between the terms proportional to the κ_t^2 and the product of κ_t and κ_λ
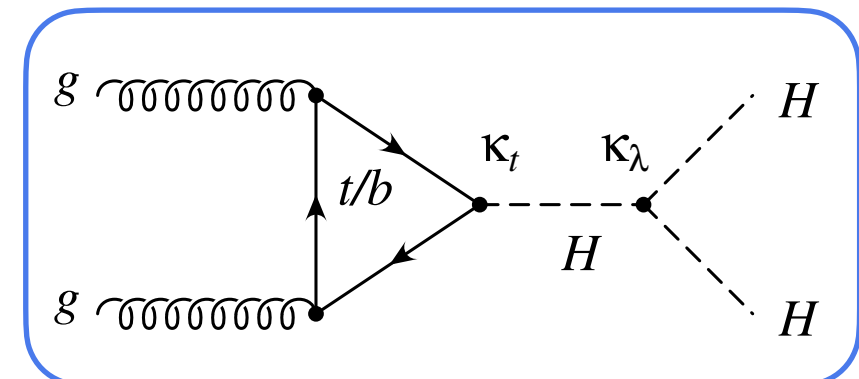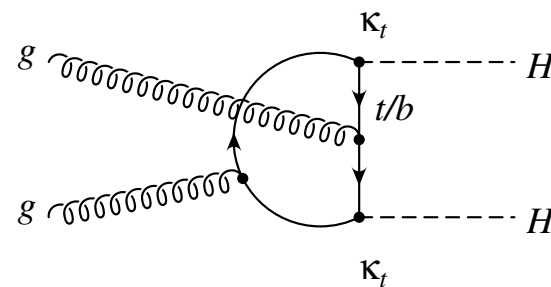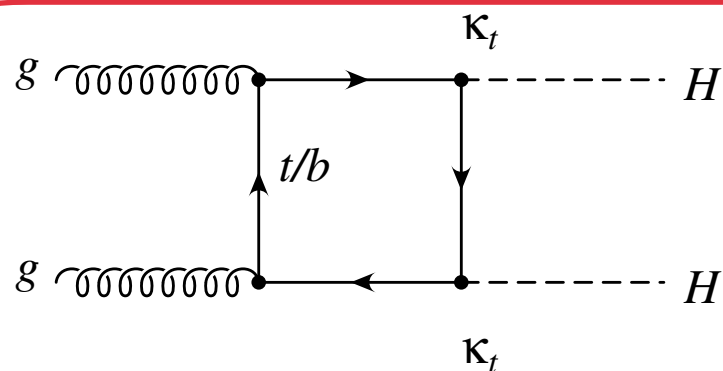
‣ Single Higgs process do not depend on the trilinear self (λ_{HHH}) coupling at LO but are needed for the NLO EW corrections.

- Indirect constraint with comparing NLO EW dependant λ_{HHH} *effects*

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62

July-22

Di-Higgs production

- Modified Higgs production cross section and branching rations to account for NLO EW corrections (K^i_{EW} and C^f)

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{BSM}}{\sigma^{SM}} = Z^{BSM}_H(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C^i_1}{K^i_{EW}}\right]$$
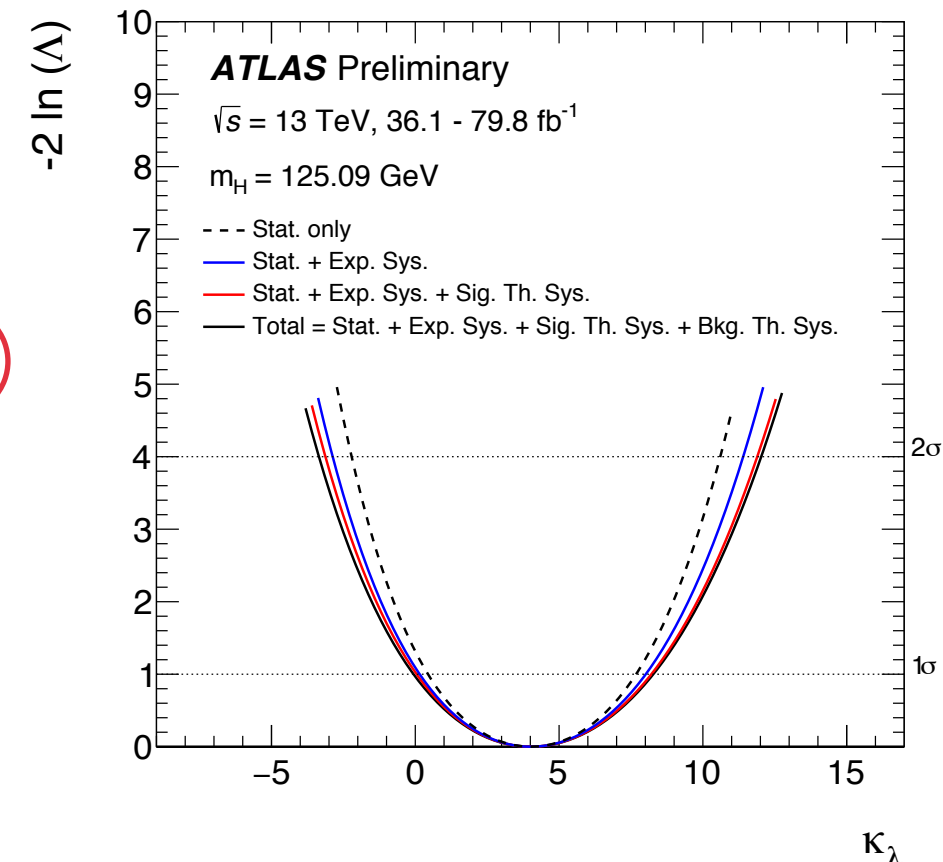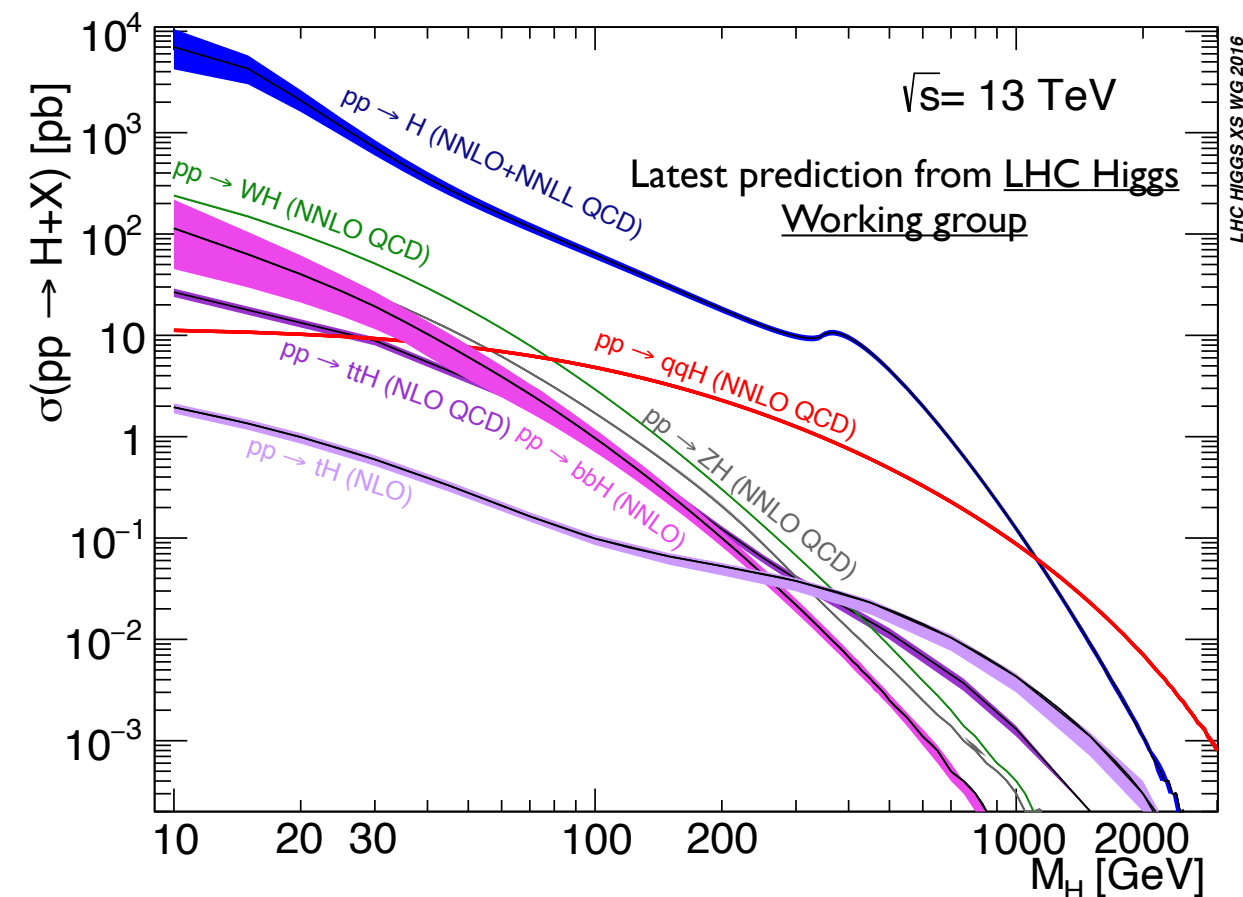
$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{BR^{BSM}_f}{BR^{SM}_f} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C^f_1}{\sum_j BR^{SM}_j\left[\kappa_j^2 + (\kappa_\lambda - 1)C^j_1\right]}$$
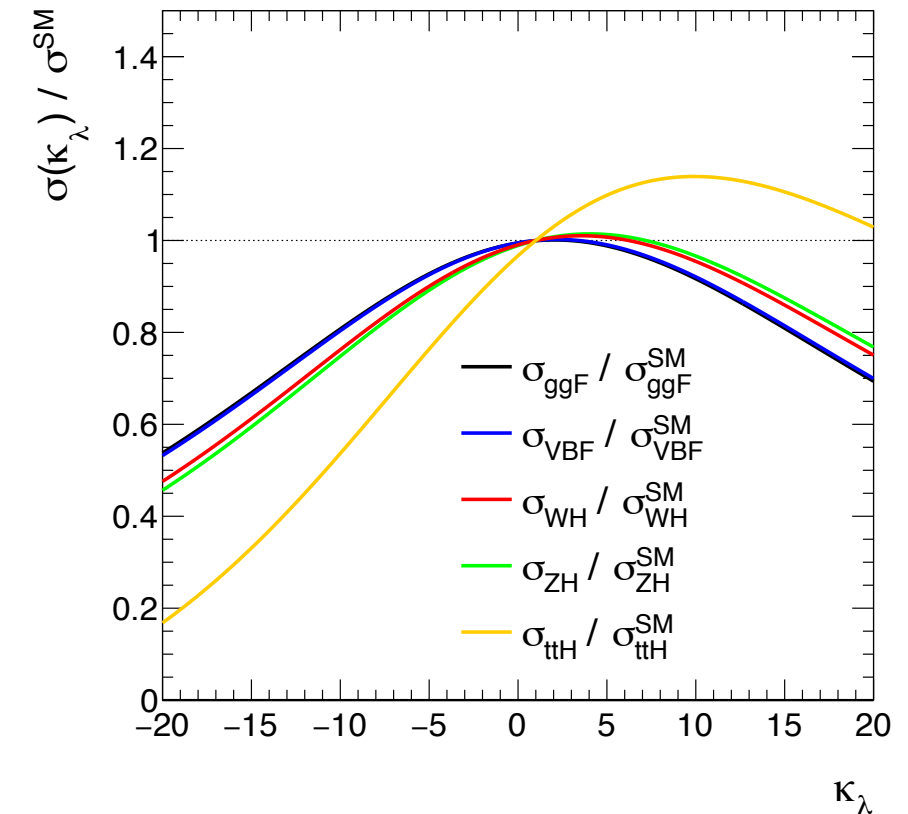
- Combined fit over Higgs combination

$$\kappa_\lambda = 4.0^{+4.3}_{-4.1} = 4.0^{+3.7}_{-3.6}\,(\text{stat.})^{+1.6}_{-1.5}\,(\text{exp.})^{+1.3}_{-0.9}\,(\text{sig. th.})^{+0.8}_{-0.9}\,(\text{bkg. th.})$$

▸ 95% C.L. -3.2 < κ_λ < 11.9 comparable over direct HH searches (-5.0 < κ_λ < 12.1)

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● Importance of m_H in several aspects of our understanding of fundamental physics.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+ i\bar{\Psi}\not{D}\psi$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - \boxed{V(\Phi)}$$
$$+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

Power law expansion of the potential

$$V(h) \quad = \quad \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$$

▸ Understanding the perturbative expansion of its potential ($\lambda v^2 h^2$).

▸ Precise higher order corrections to the theory predictions of the Higgs interactions depend on the value of m_H.

▸ Input to precision global fit of the Standard Model.

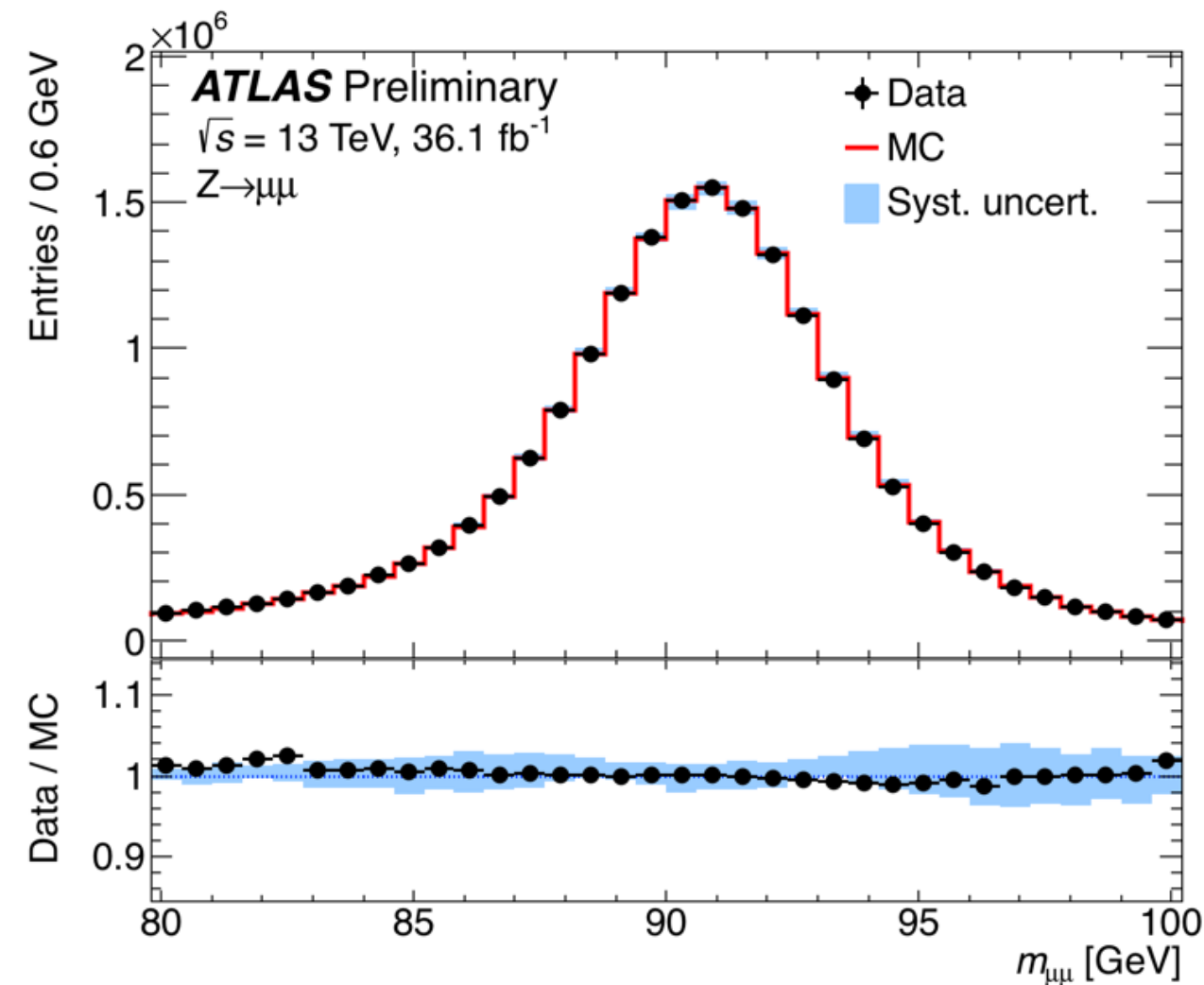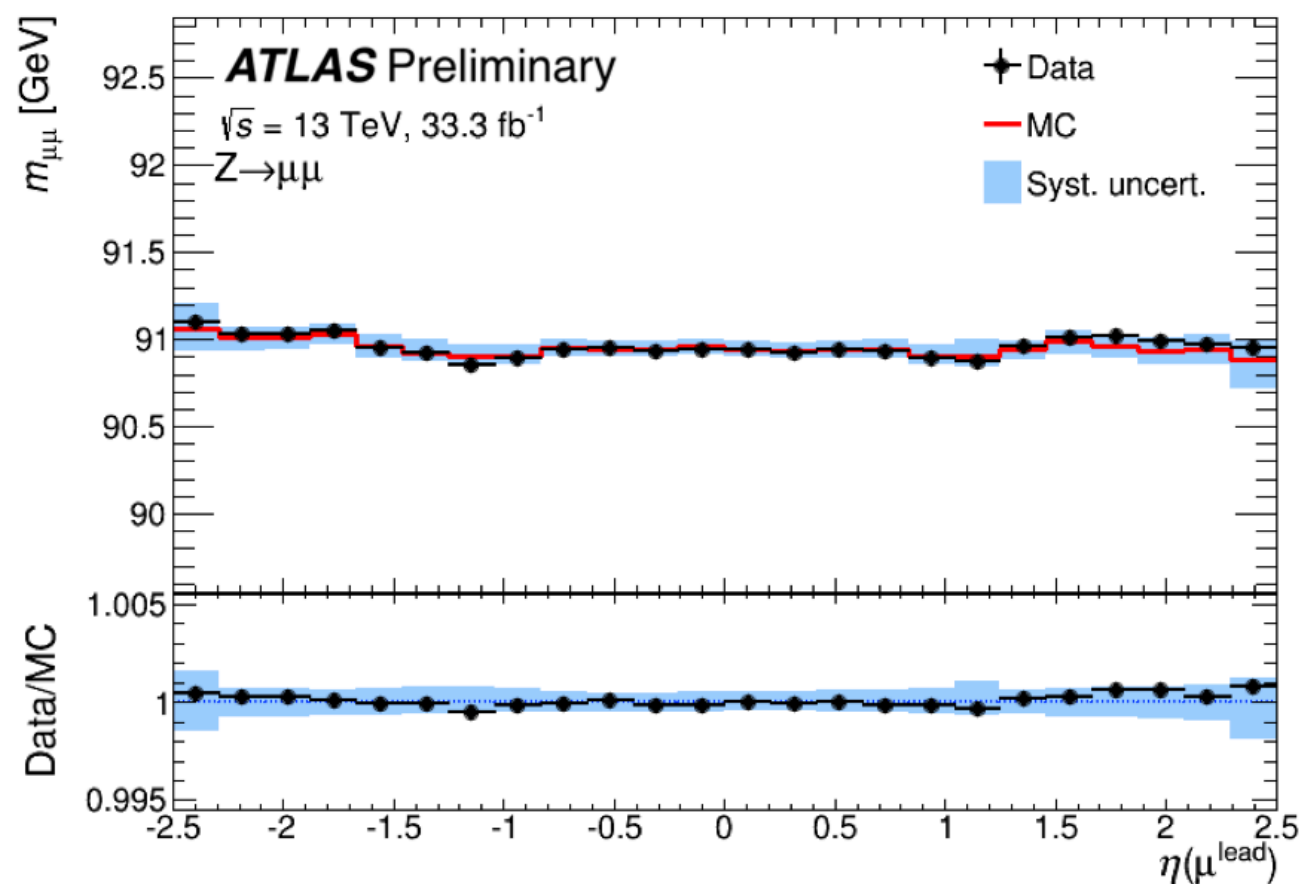Aim at improving significantly on the experimental precision on m_H

Prediction and uncertainties of Higgs production processes as a function of the m_H

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● Importance of m_H in several aspects of our understanding of fundamental physics.

Unbroken symmetry   Broken symmetry

Power law expansion of the potential

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Aim at improving significantly on the experimental precision on m_H

$\sqrt{s}$ = 13 TeV

Latest prediction from LHC Higgs Working group
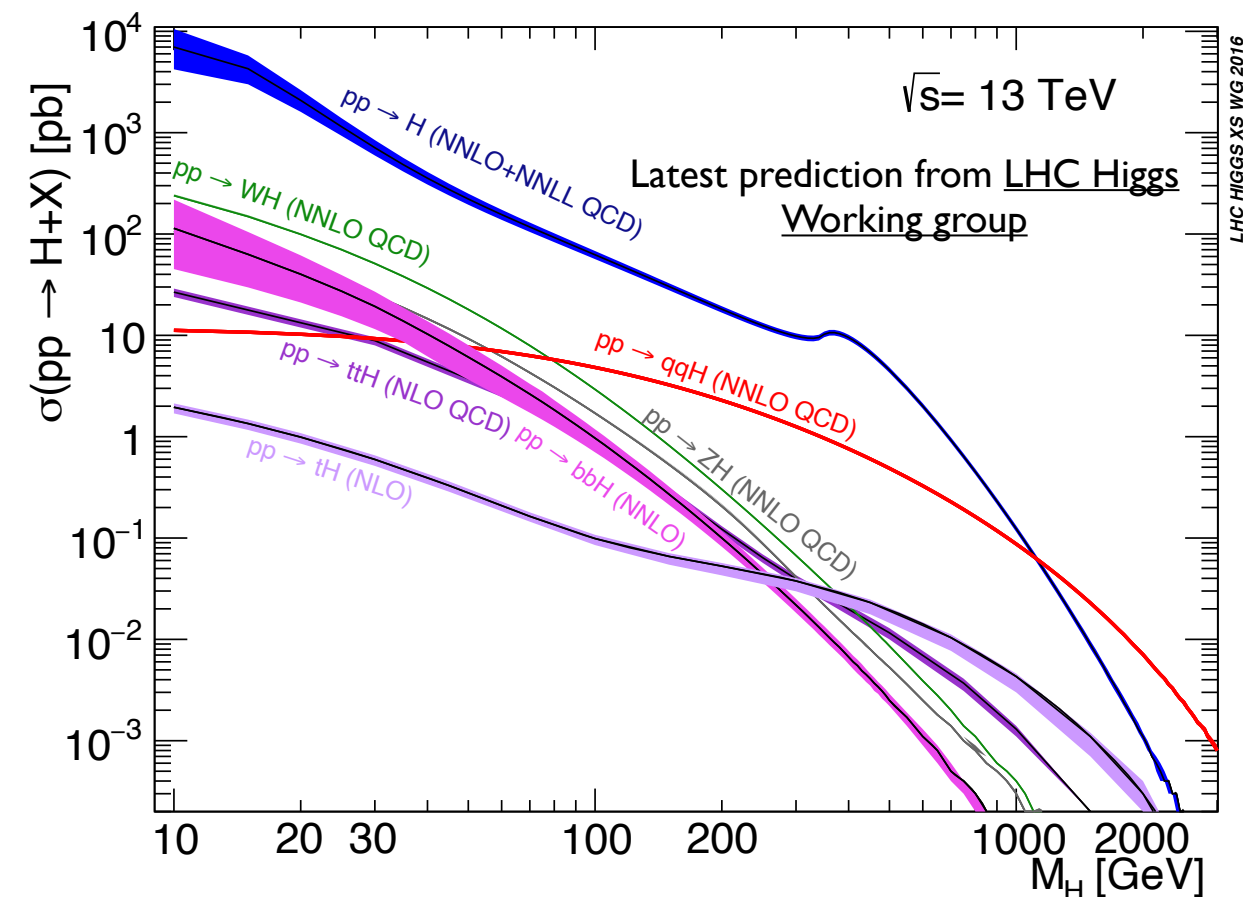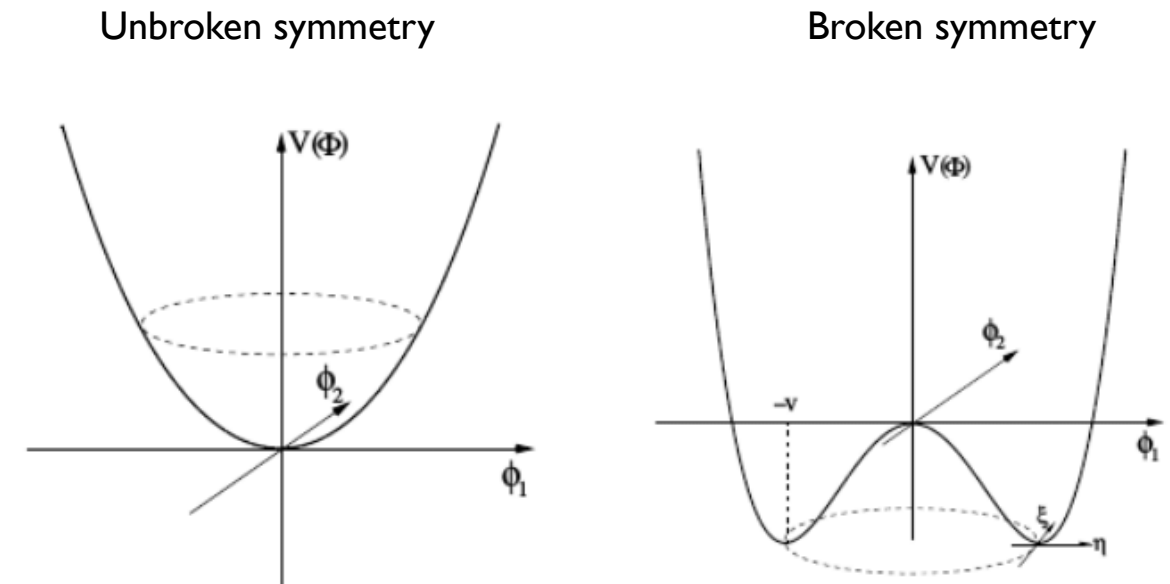
Prediction and uncertainties of Higgs production processes as a function of the m_H

- **Resolution muon channels (4μ, $2e2\mu$ and 4μ) crucial for m_H uncertainty:**

  ▸ Excellent momentum resolution of about 1% at about p_T 45 ~GeV.

- **Momenta calibrated to J/ψ and Z samples in data**

  ▸ for residual mis modelling of E^{loss} in calorimeters, alignment precision etc.

  ▸ Including corrections to data accounting for alignment weak modes.

  ▸ Precision down to 0.5 per mille for $|\eta|<1.0$
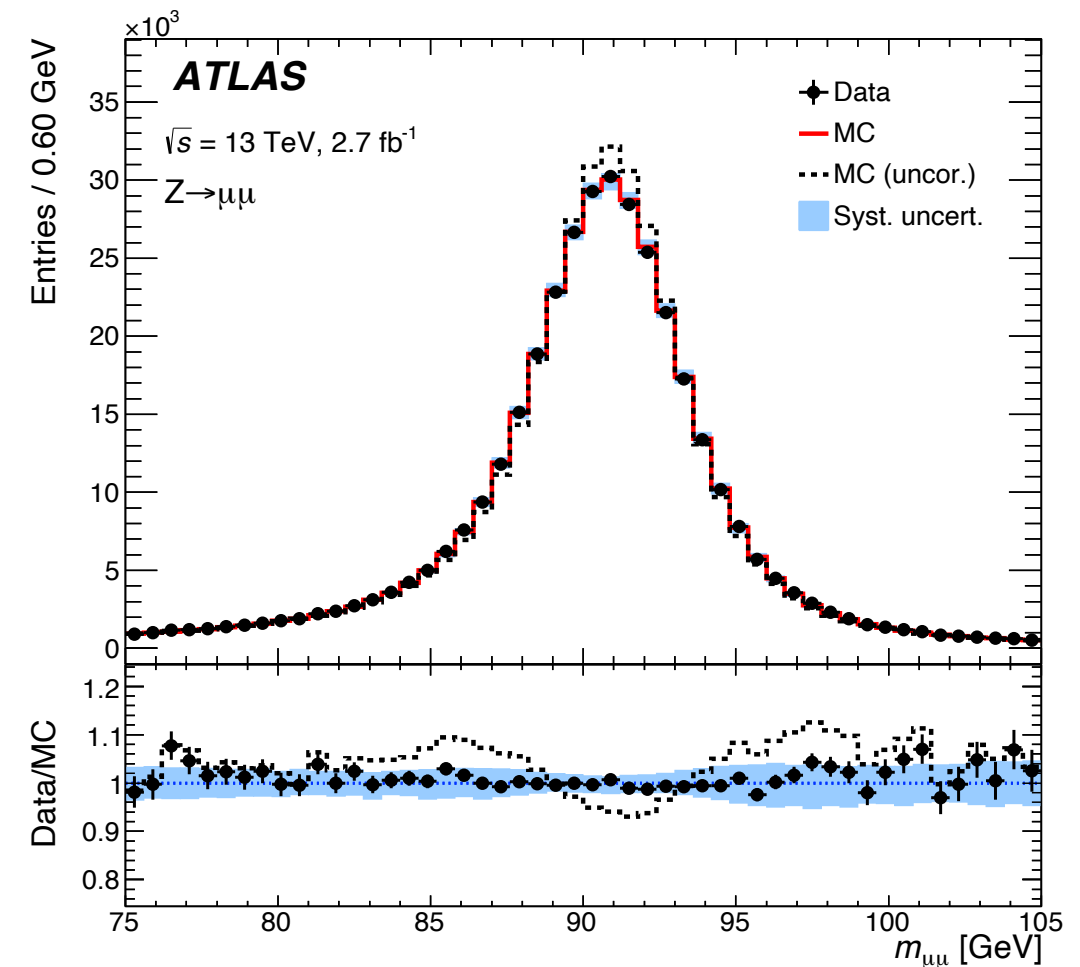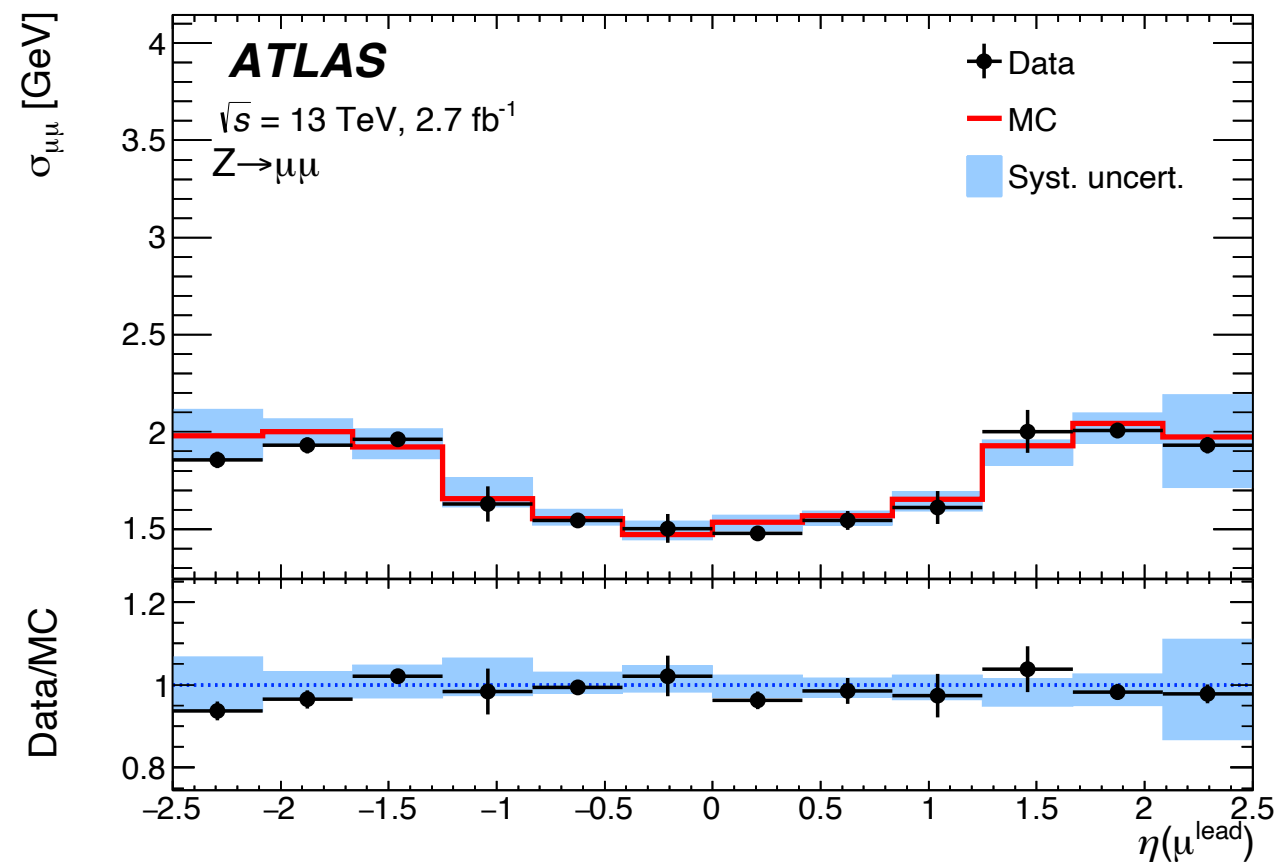
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- **Resolution muon channels (4μ, $2e2\mu$ and 4μ) crucial for m_H uncertainty:**

  ‣ Excellent momentum resolution of about 1% at about p_T 45 ~GeV.

- **Simulated momenta calibrated to J/ψ and Z samples in data**

  ‣ for residual mis modelling of E^{loss} in calorimeters, alignment precision etc.

 ‣ Uncertainty of about 10% on the resolution and 0.5% on the momentum scale.

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$$p_T^{reco} = p_T^{true}(1+q\,p_T^{true}\,\delta_{sagitta})$$

...and second order effects:

- ...arge dependent sagitta bias, with net effect of worsening resolution
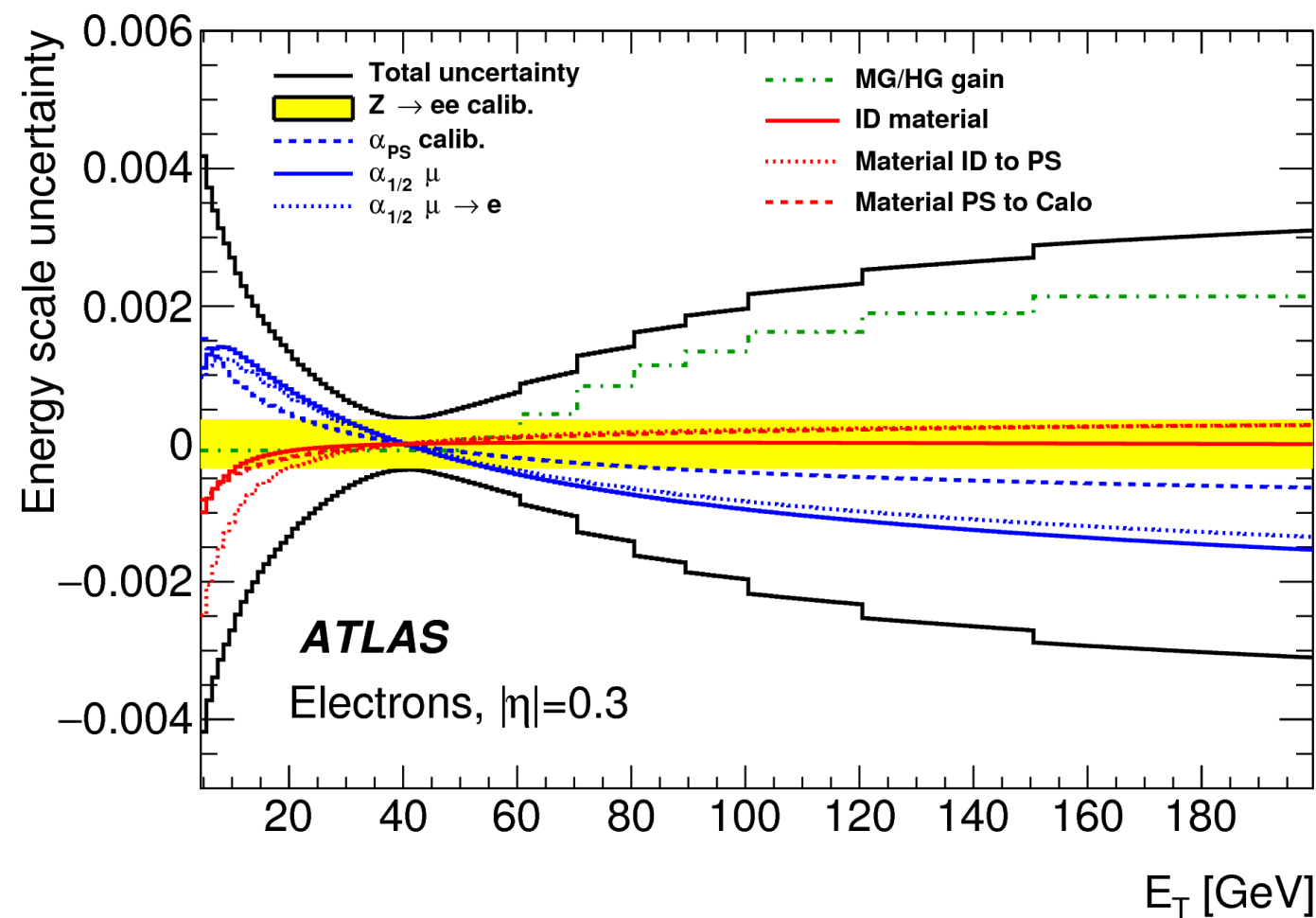 - In-situ correction based on Z→μμ data, recovers up to 5% in resolution.

● **Momentum scale understood down to the per mille level**

- Precision down to 0.5 per mille for |η|<1.0

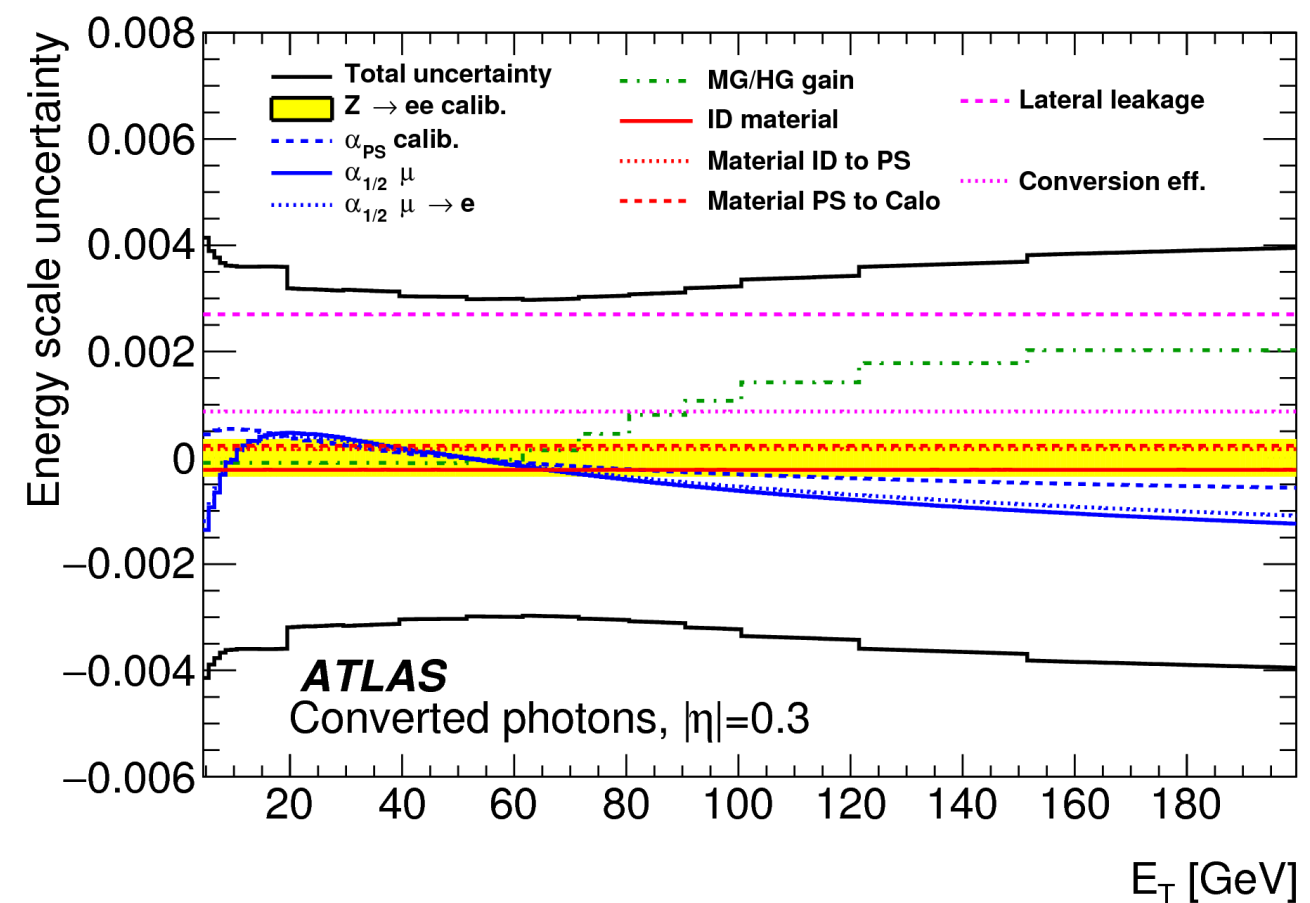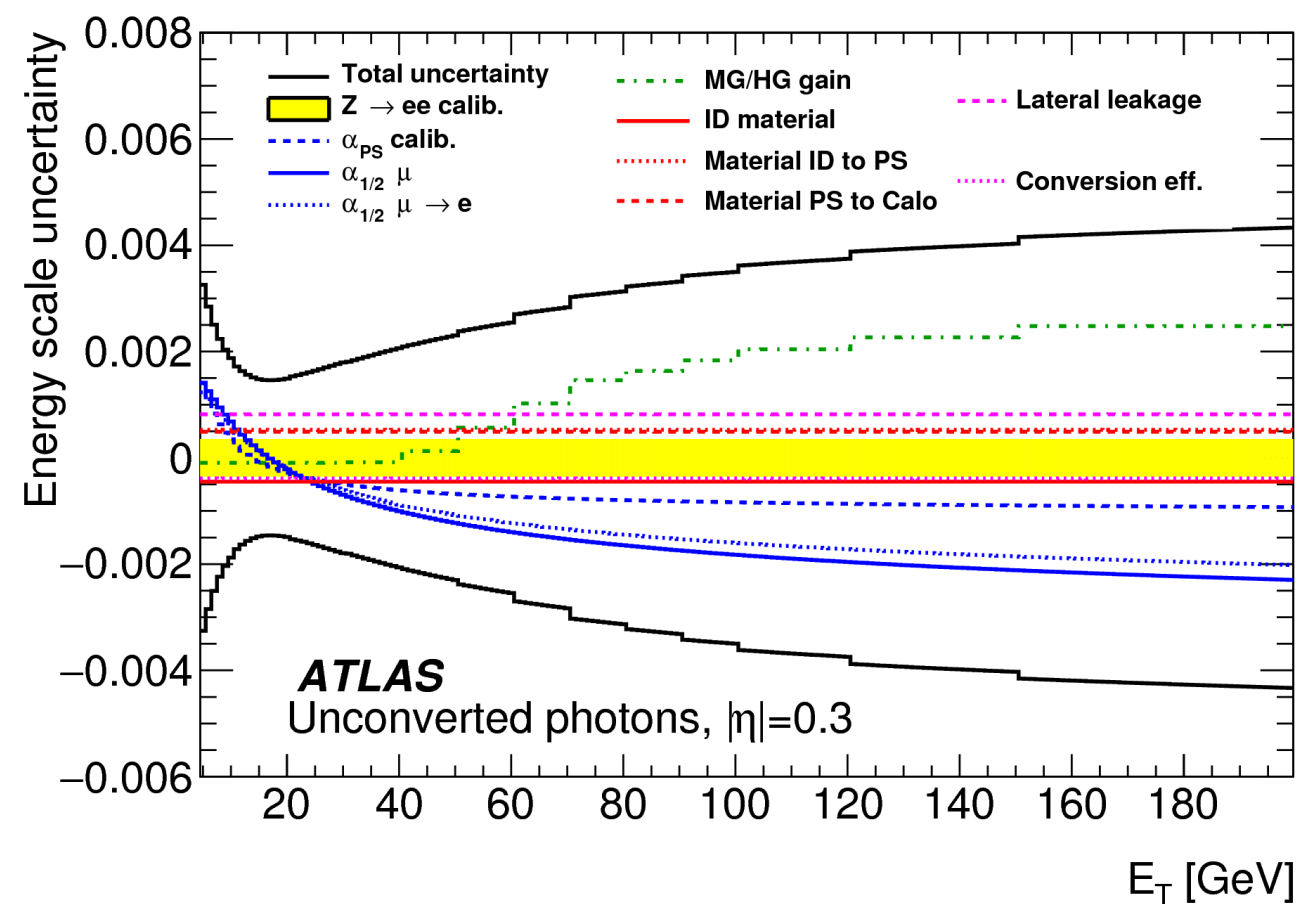ATLAS Preliminary
Data 2016, √s = 13 TeV


ATLAS Preliminary
Data 2015, √s = 13 TeV
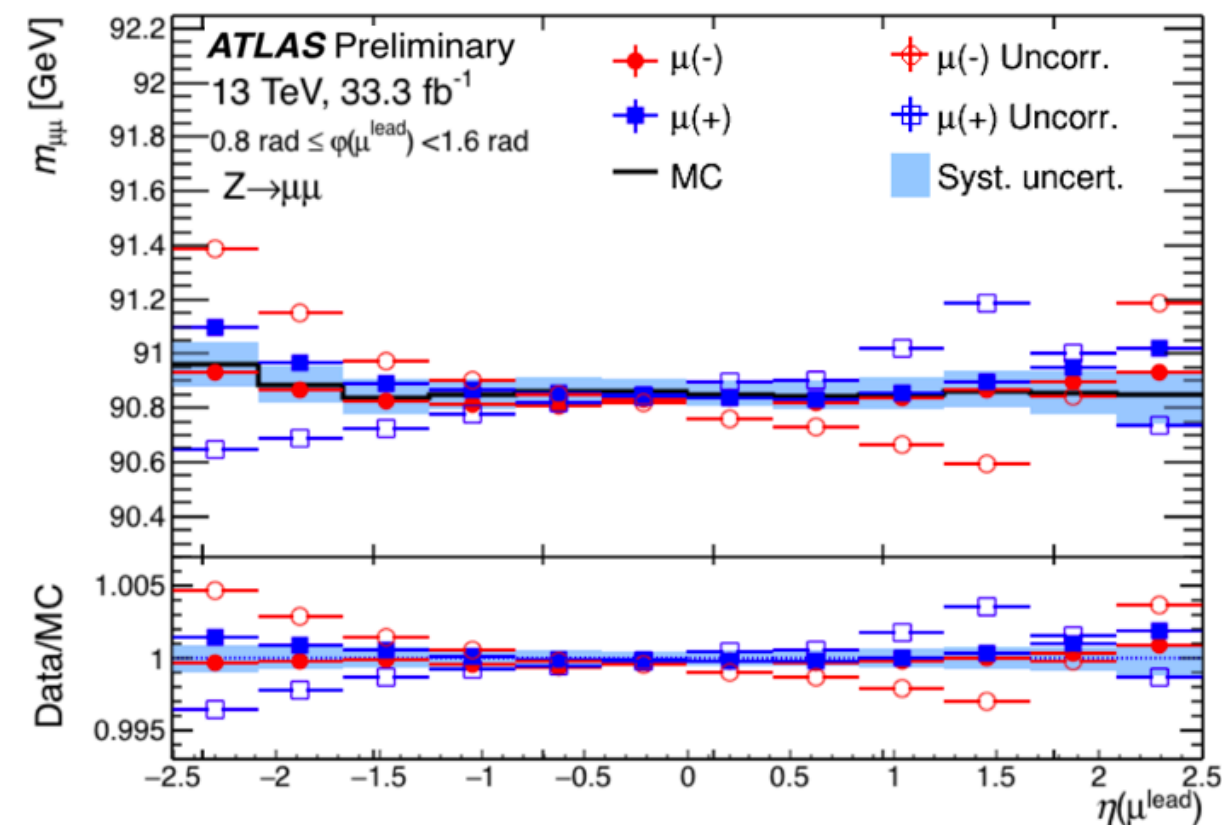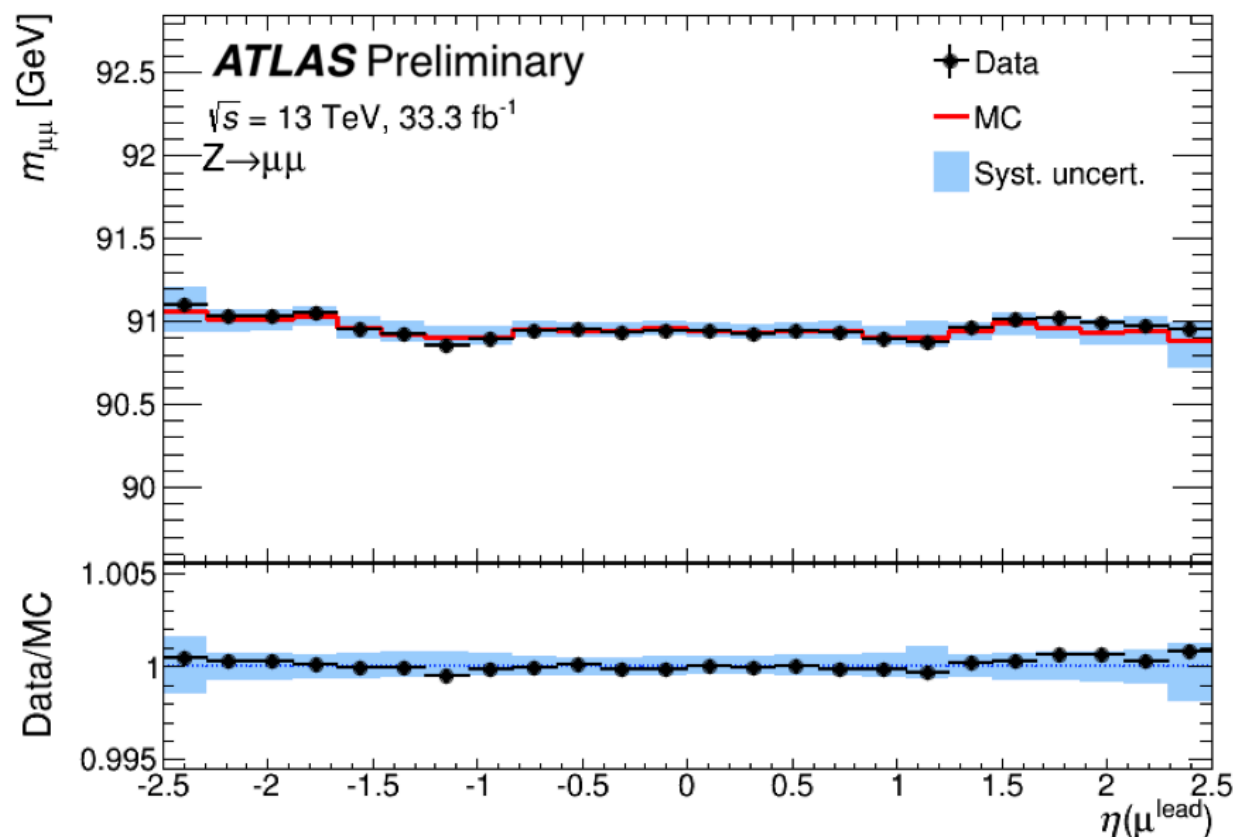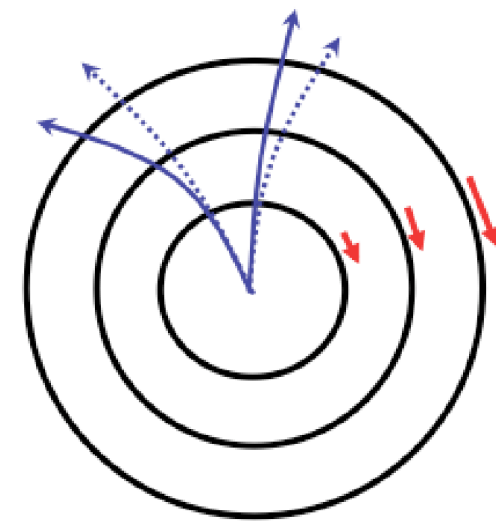
- **Good energy calibration necessary for increased precision on m_H**

  ‣ Two step approach: i) material energy loss and ii) global calorimetric scale from $Z \to ee$ data

- **Total scale uncertainty of at 40 GeV at the per-mille level.**

- Good energy calibration necessary for increased precision on m_H

  ‣ Two step approach: i) material energy loss and ii) global calorimetric scale from $Z \rightarrow ee$ data

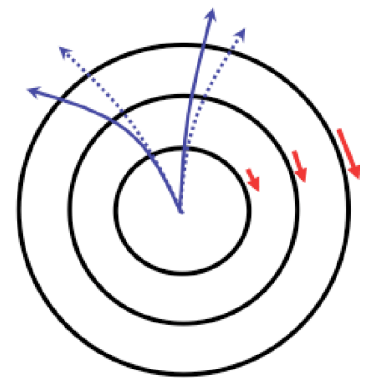- Total scale uncertainty of at 40 GeV at the per-mille level.

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$$p_T^{reco} = p_T^{true}(1 + q\, p_T^{true}\, \delta_{sagitta})^{-1}$$
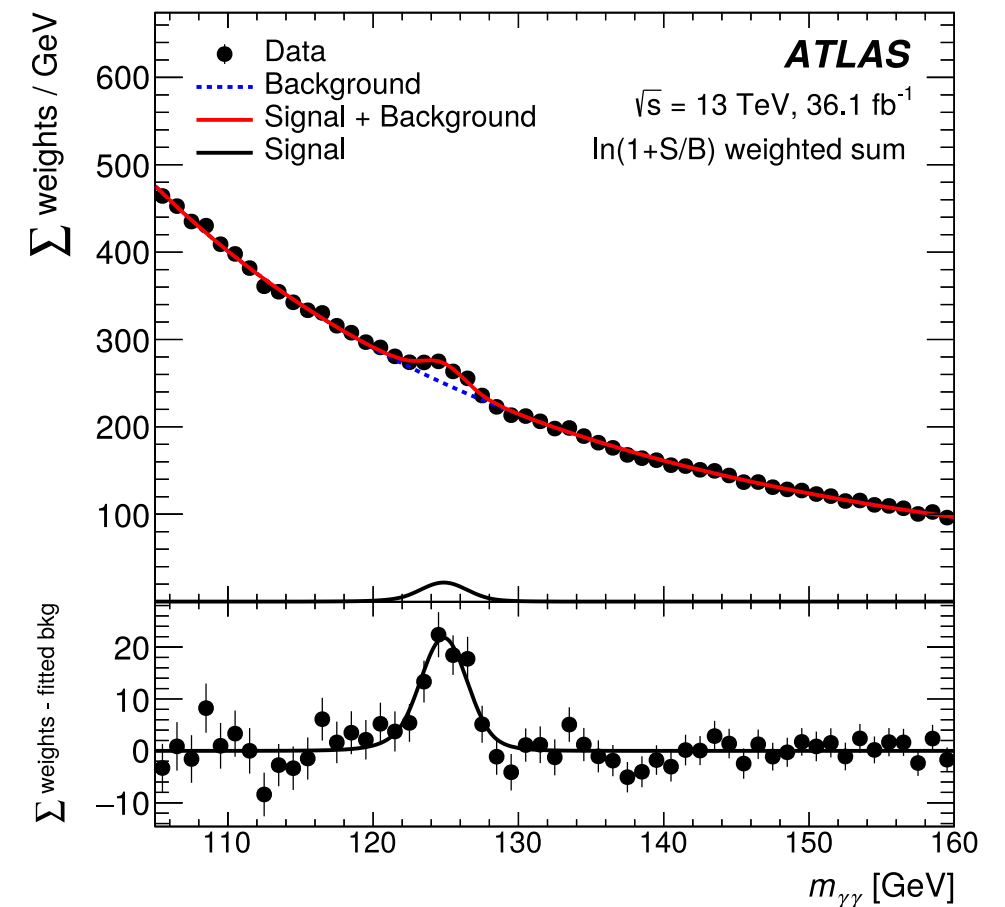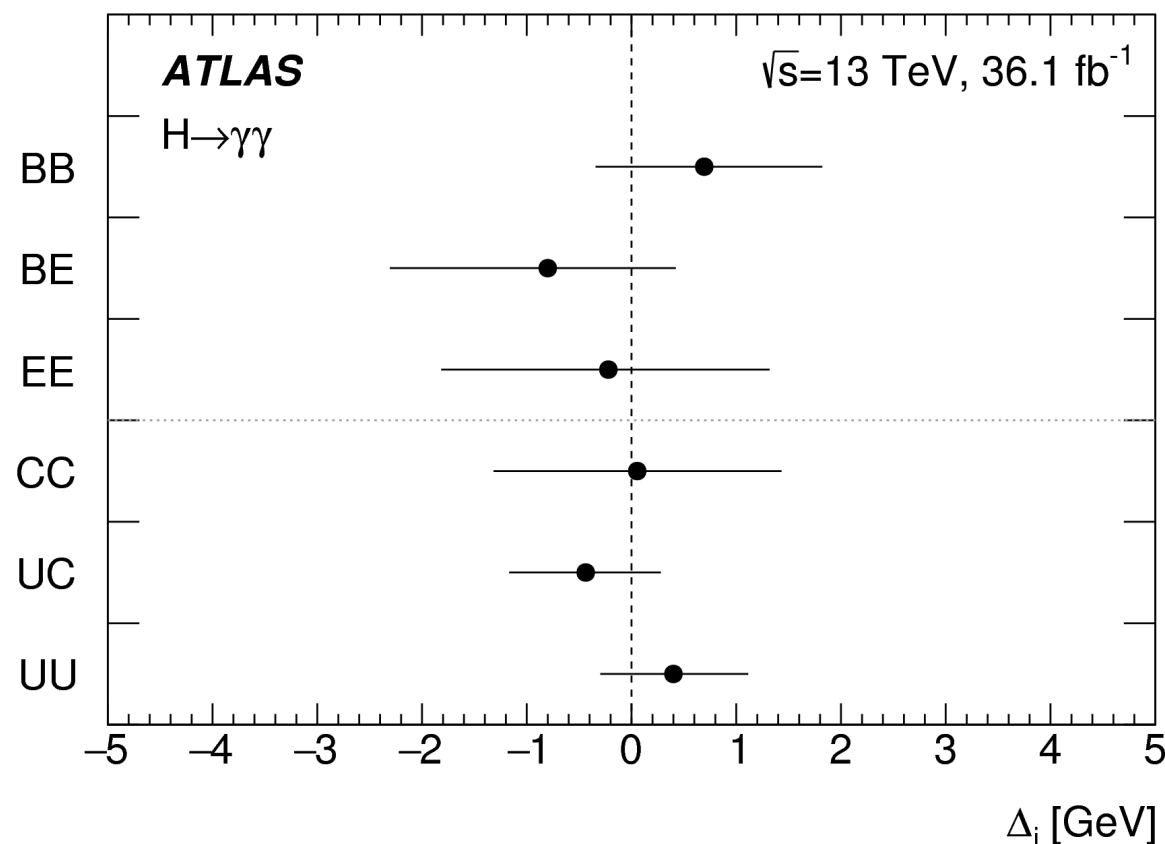
- ● Correction for local misalignments

  - ‣ Charge dependent bias, with net effect of worsening resolution

  - ‣ In-situ correction based on Z→μμ data, recovers up to 5% in resolution.
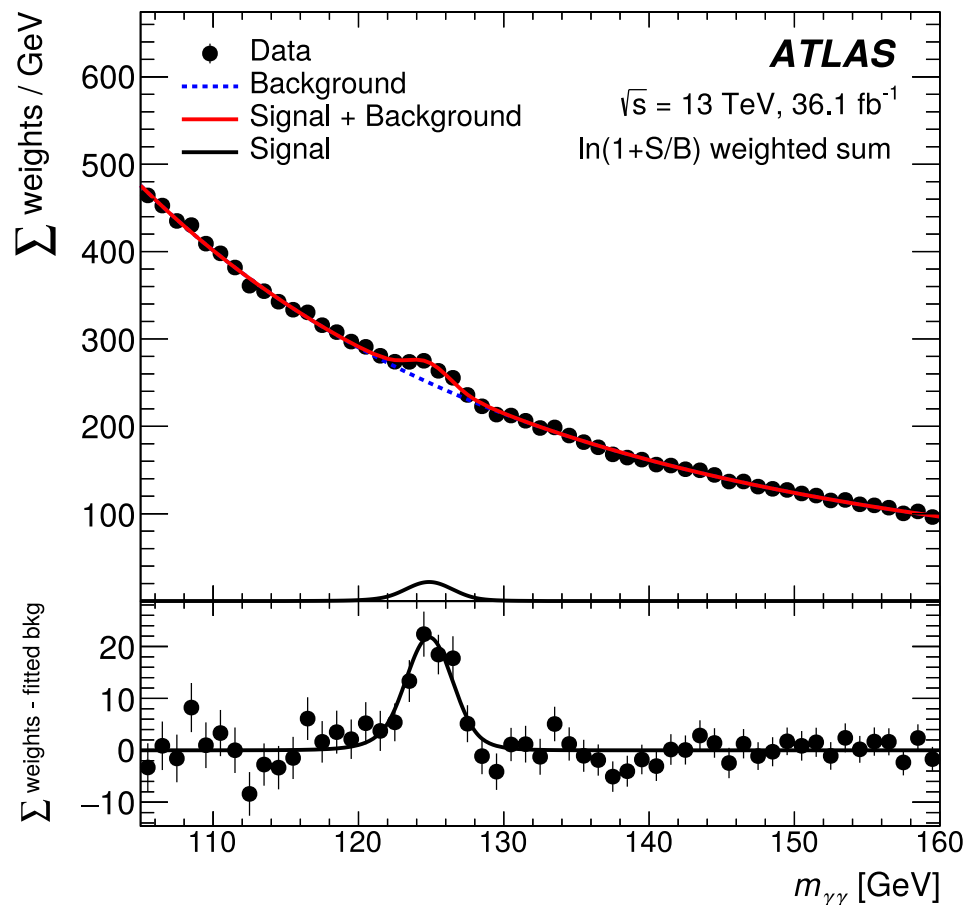
  - ‣ Iteratively removing the bias δ_s:
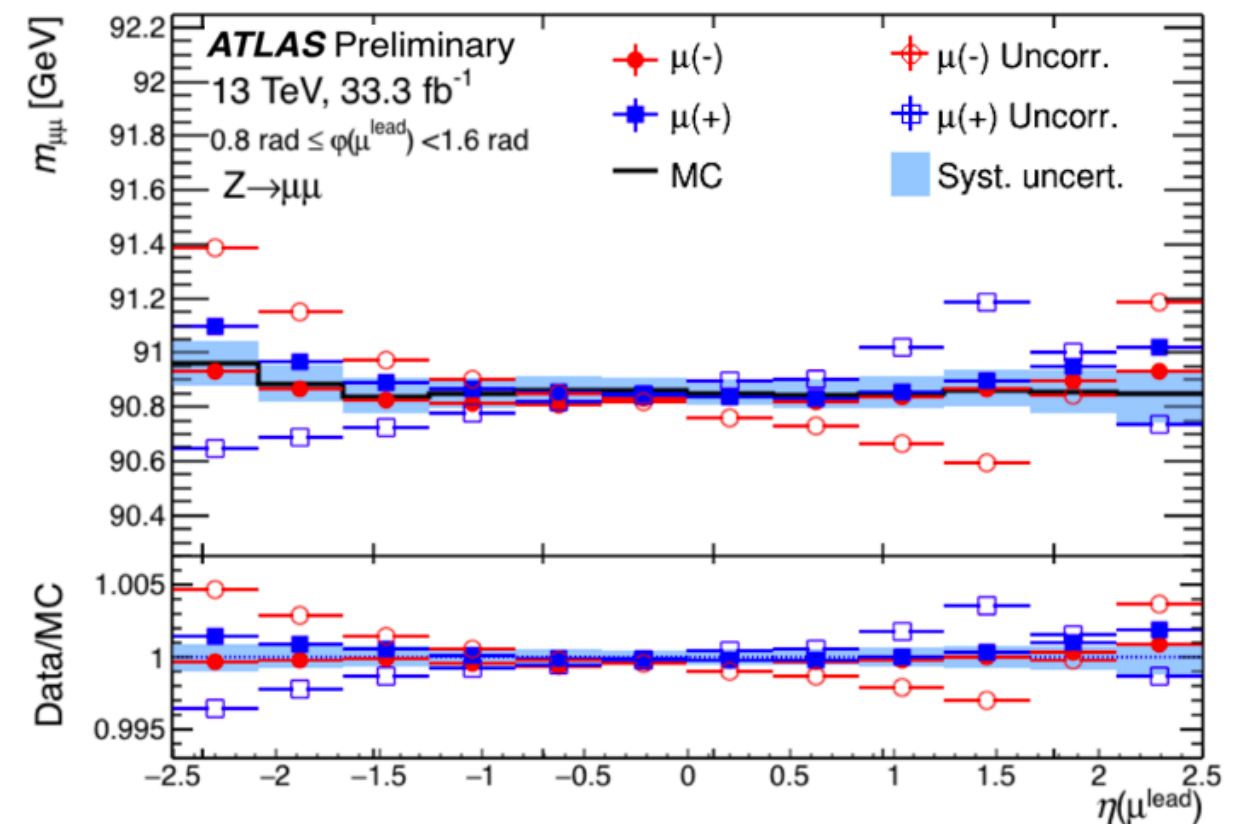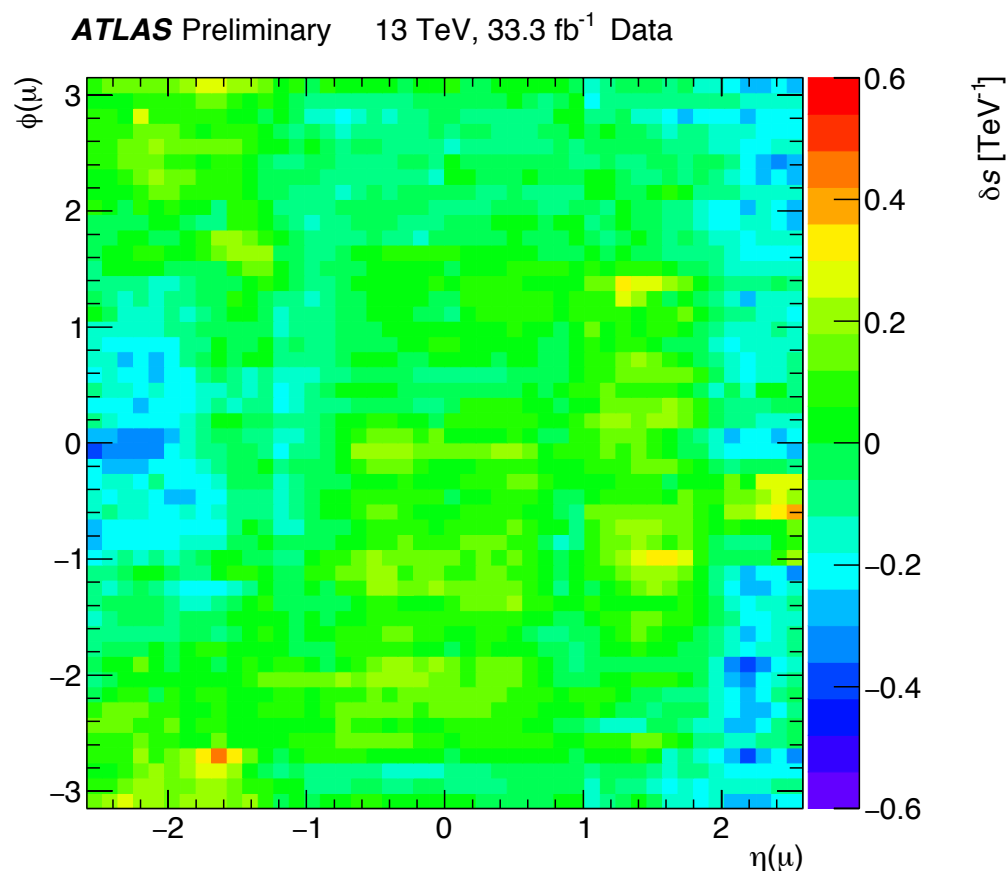
- $H \rightarrow \gamma\gamma$ updated result at Run II.

  ‣ Analytical function in kinematic and detector categories.

  ‣ Reduction of uncertainty through categorisation of events as a function of resolution and signal significance.

- Expected statistical uncertainty of 0.21 GeV and 0.34 GeV systematic uncertainty

$$m_H^{\gamma\gamma} = 124.93 \ \pm \ 0.40 \ (\pm 0.21 \text{ stat only}) \text{ GeV}$$

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- $H \to \gamma\gamma$ updated result at Run II.   <u>arXiv:1806.00242</u>

  ▸ Analytical function in kinematic and detector categories.

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- Expected statistical uncertainty of 0.21 GeV and 0.34 GeV systematic uncertainty

$$m_H^{\gamma\gamma} = 124.93 \ \pm \ 0.40 \ (\pm 0.21 \ \text{stat only}) \ \text{GeV}$$

Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

- **Three-prong approach to reduce uncertainty at analysis level:**

> (i)   ~15% from m_{12} constraint to m_Z with kinematic fit and m_Z constraints on alignment weak modes.
>
> (i)   ~2% from kinematic discriminant selecting signal and background events
>
>   ▹ Boosted Decision Tree on $p_T(4\ell)$, $y(4\ell)$ and $\log(|\mathcal{M}_H|^2/|\mathcal{M}_{ZZ*}|^2)$
>
> (ii)   ~5% from multivariate per-event resolution likelihood.
>
>   ▹ Neural network to solve uncertainty correlations induced by kinematic discriminant.
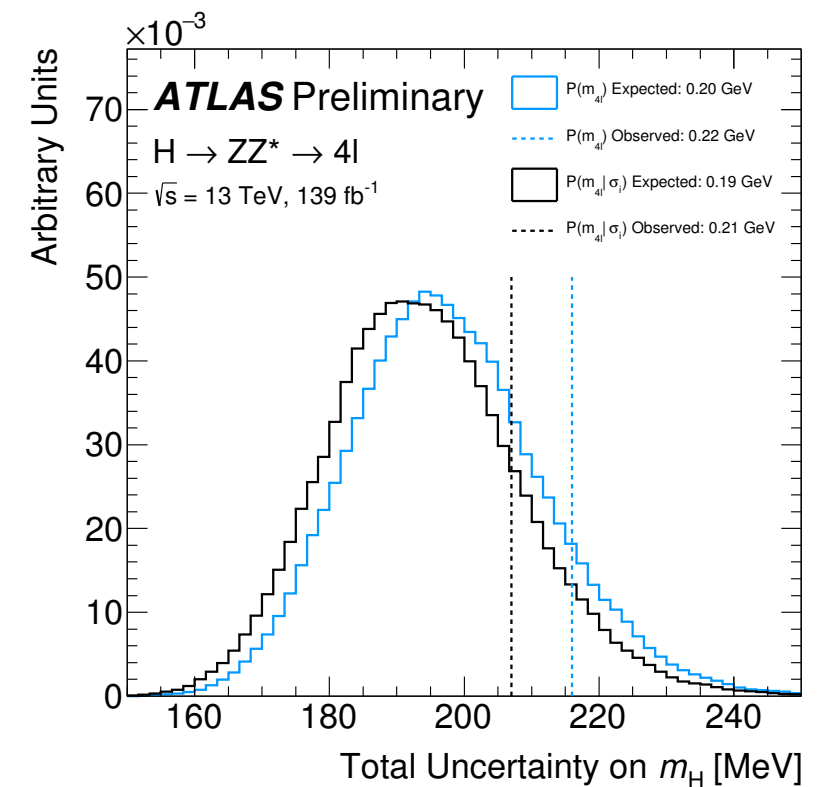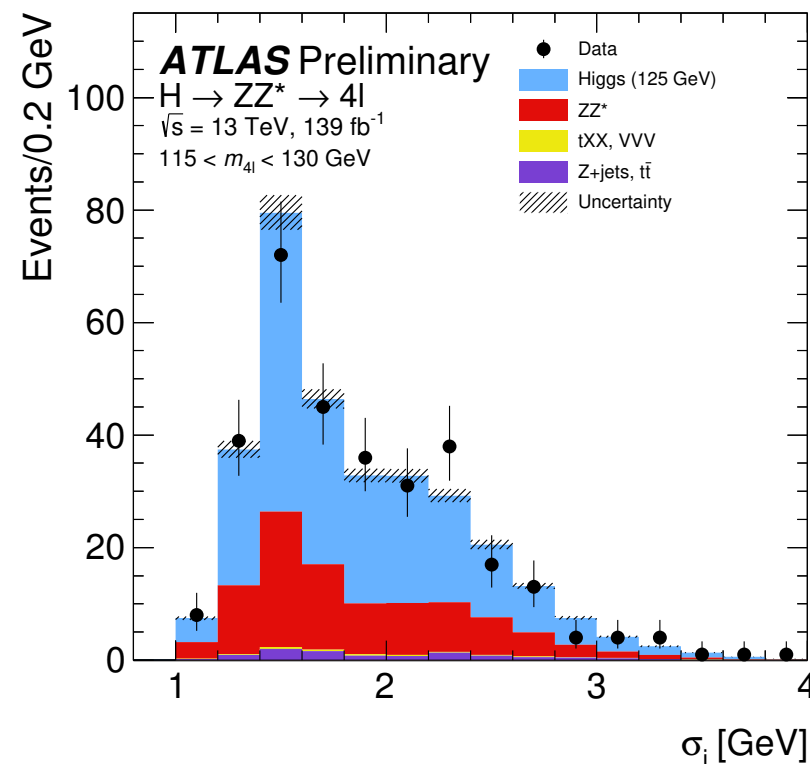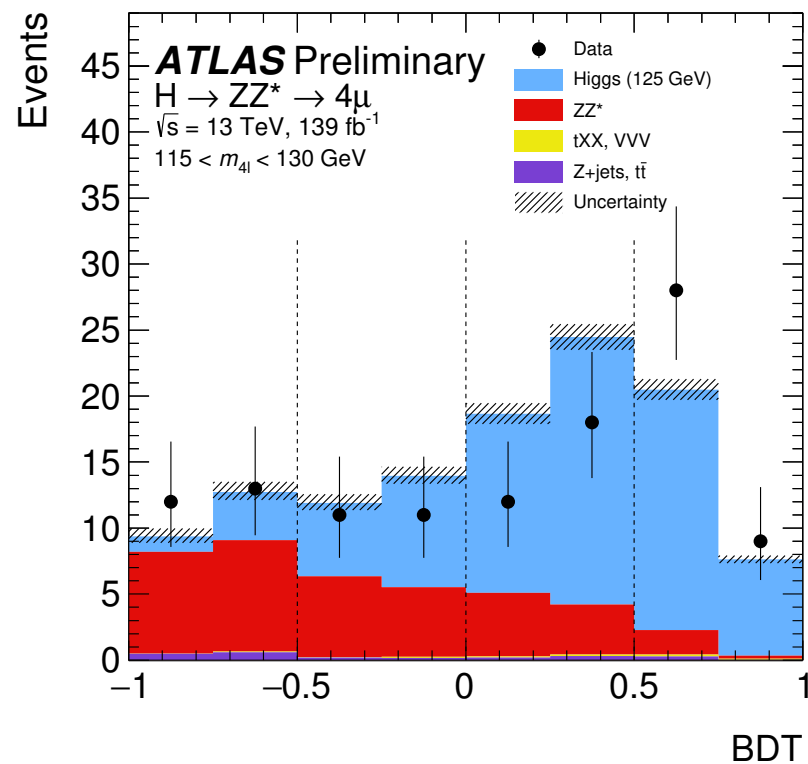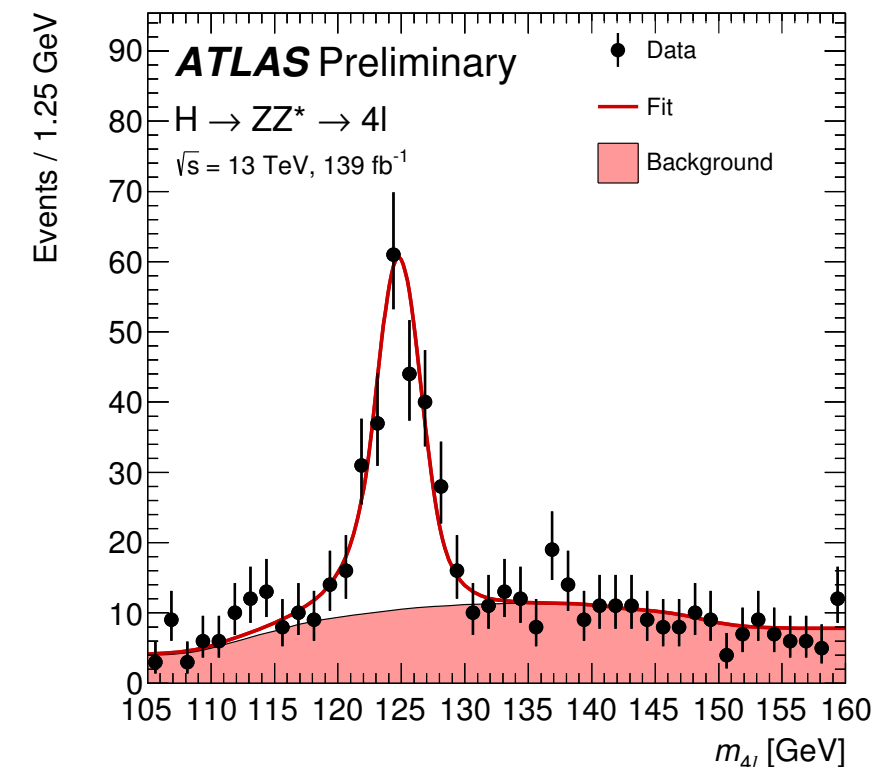
- Three-prong approach to reduce uncertainty at analysis level:

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>
> (ii) ~2% from multivariate **per-event resolution likelihood**.
> - Neural network to solve uncertainty correlations induced by kinematic discriminant.

- Systematic uncertainty of ~70 MeV

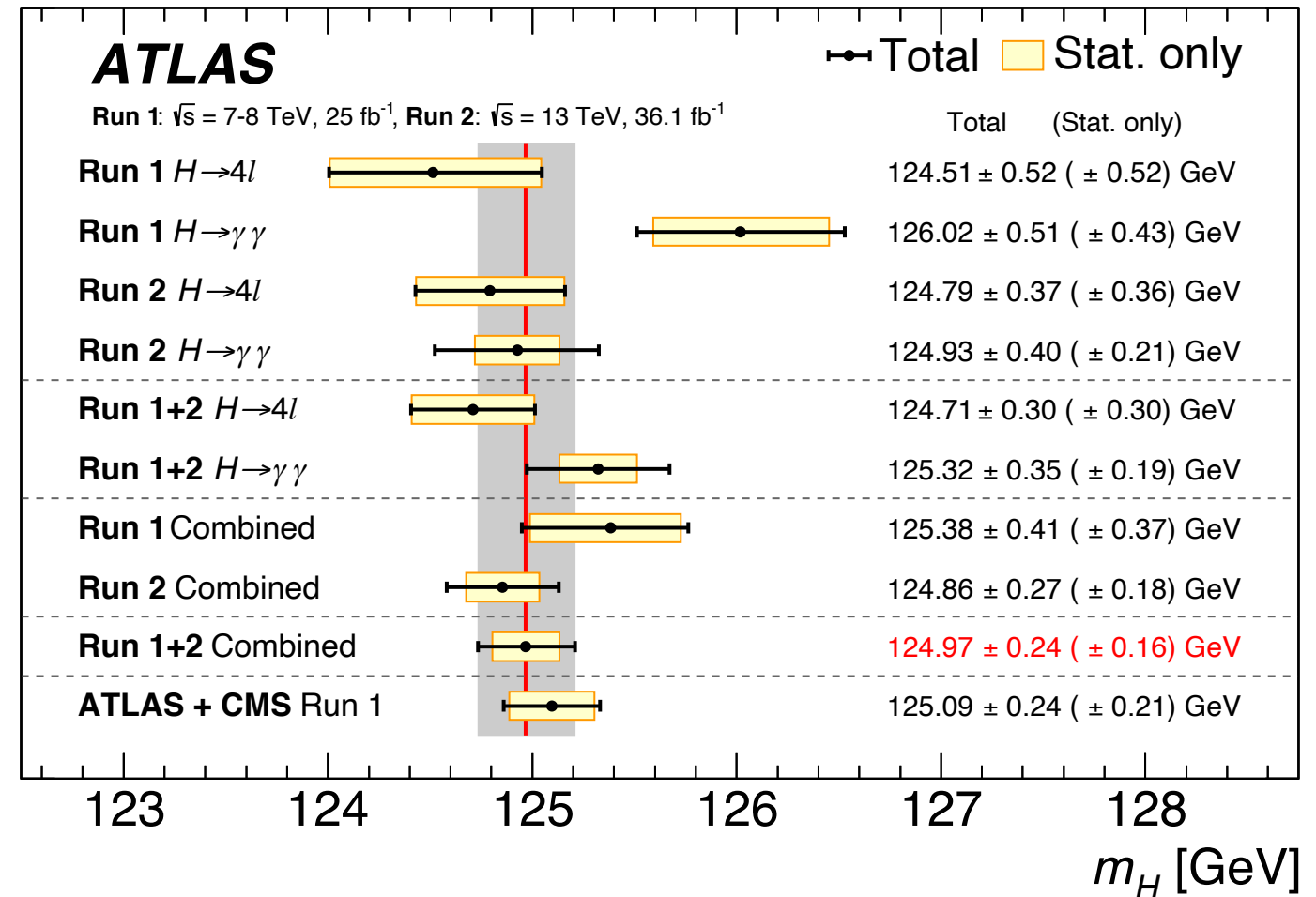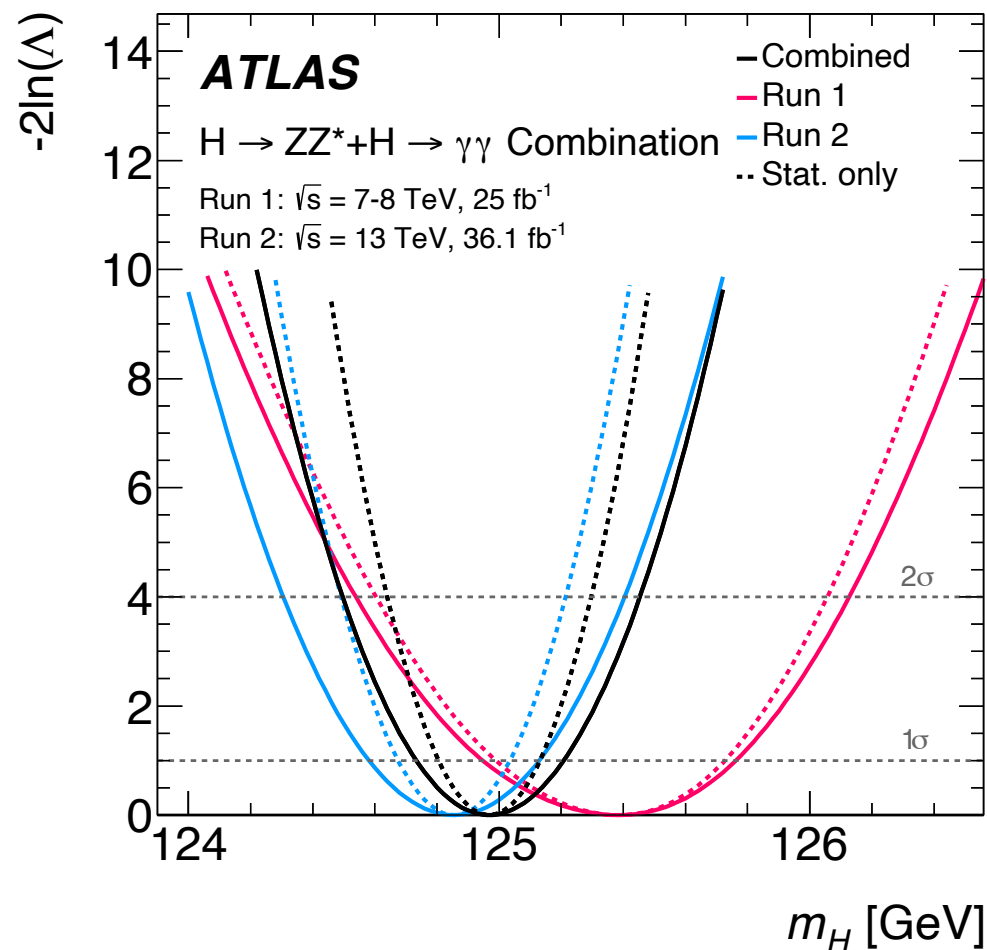| Systematic Uncertainty	Impact (GeV)
Muon momentum scale	$+0.08, -0.06$
Electron energy scale	± 0.02
Muon momentum resolution	± 0.01
Muon sagitta bias correction	± 0.01

- **61% improvement** w.r.t $m_H^{H \to ZZ, \text{Run1}}$
- **15% improved precision** w.r.t $m_H^{\text{ATLAS+CMS, Run1}}$

$$m_H = 124.92^{+0.21}_{-0.20} \text{ GeV}$$

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- 4ℓ and γγ measurements are combined with ATLAS Run 1 result
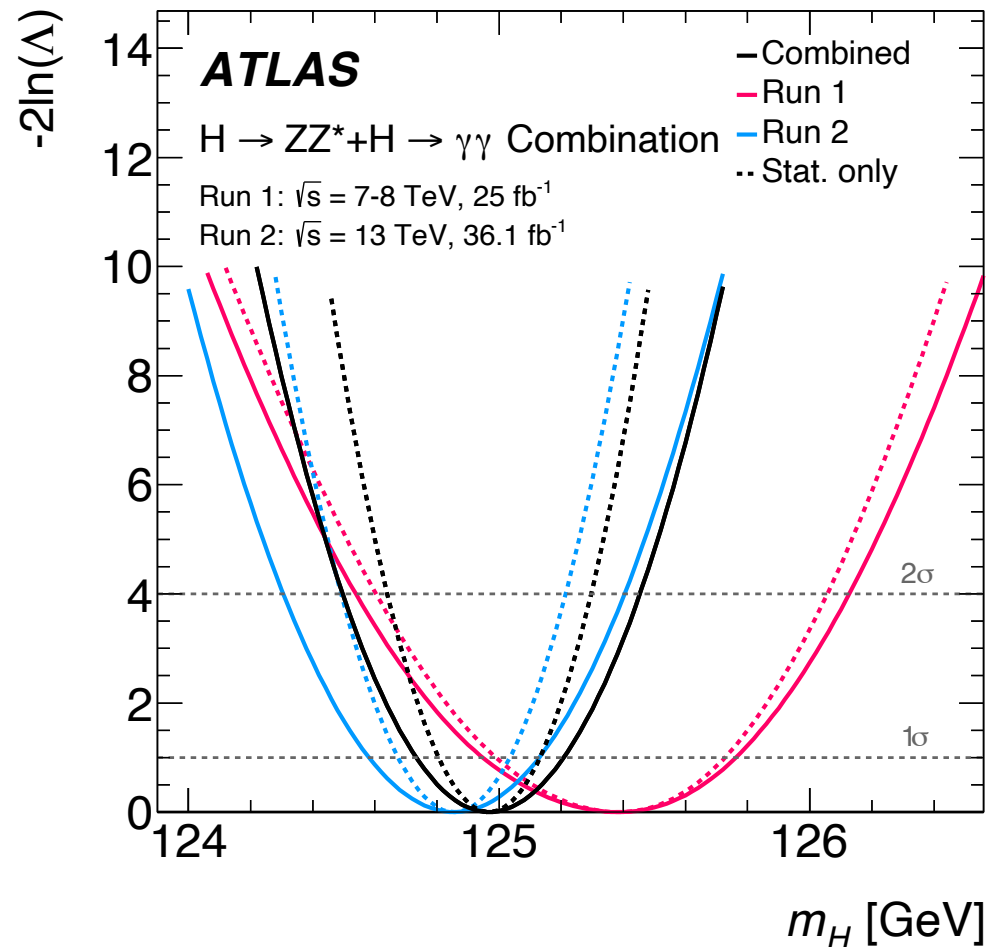

- Run 2 precision improved w.r.t Run 1.

$$m_H = 124.86 \pm 0.27(\pm0.18 \text{ stat only}) \text{ GeV}$$

- ATLAS Run 1 + 2 comparable precision to LHC Run 1 combination.

$$m_H = 124.97 \pm 0.24(\pm0.16 \text{ stat only}) \text{ GeV}$$

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- 4ℓ and γγ measurements are combined with ATLAS Run 1 result

Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
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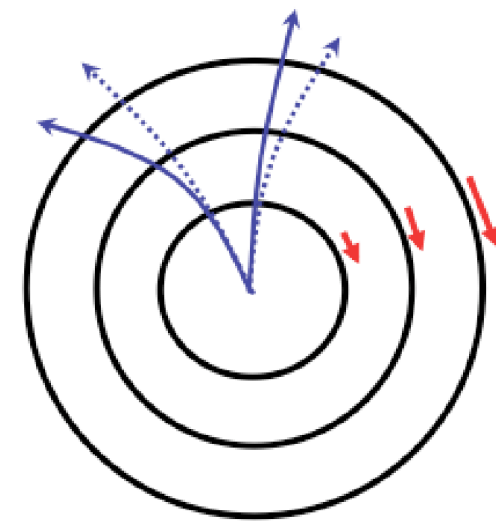$$m_H = 124.97 \ \pm \ 0.24(\pm 0.16 \text{ stat only}) \text{ GeV}$$

$$p_T^{reco} = p_T^{true}\left(1 + q\, p_T^{true}\, \delta_{sagitta}\right)^{-1}$$

...s and second order effects:

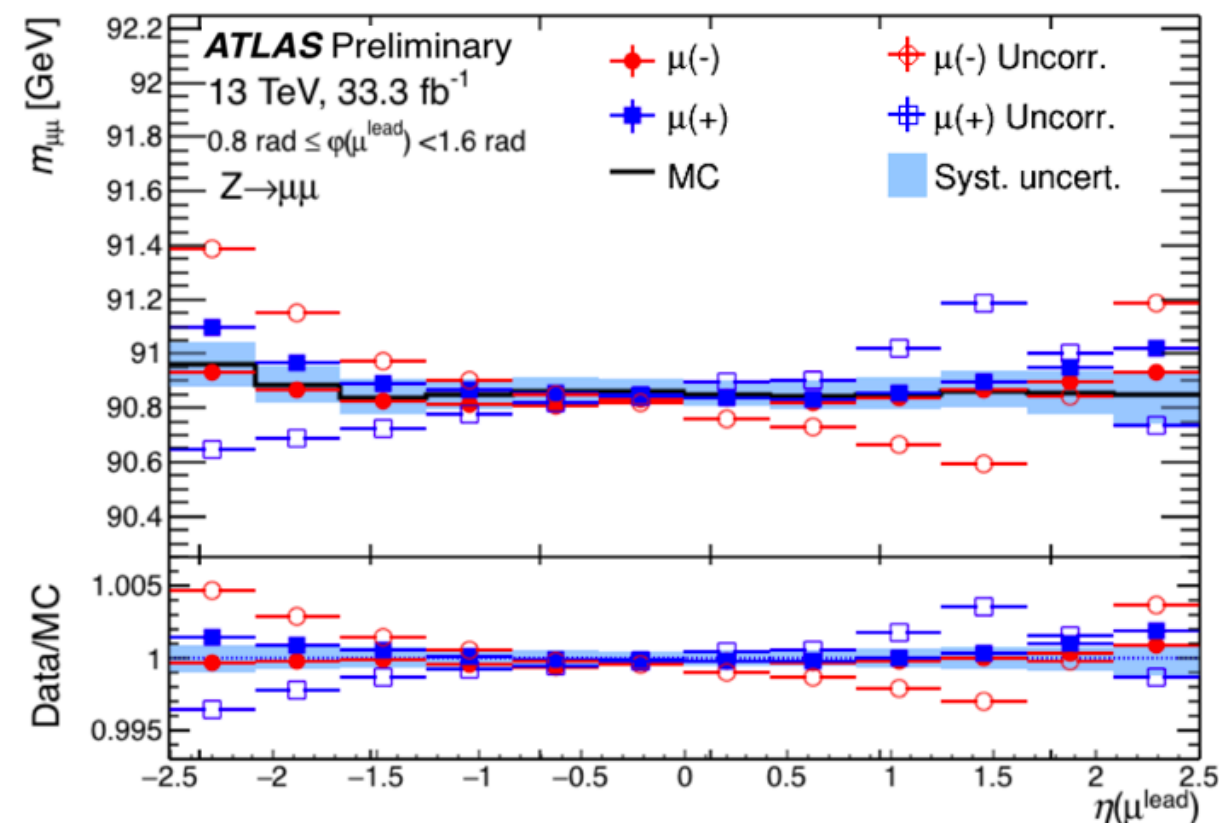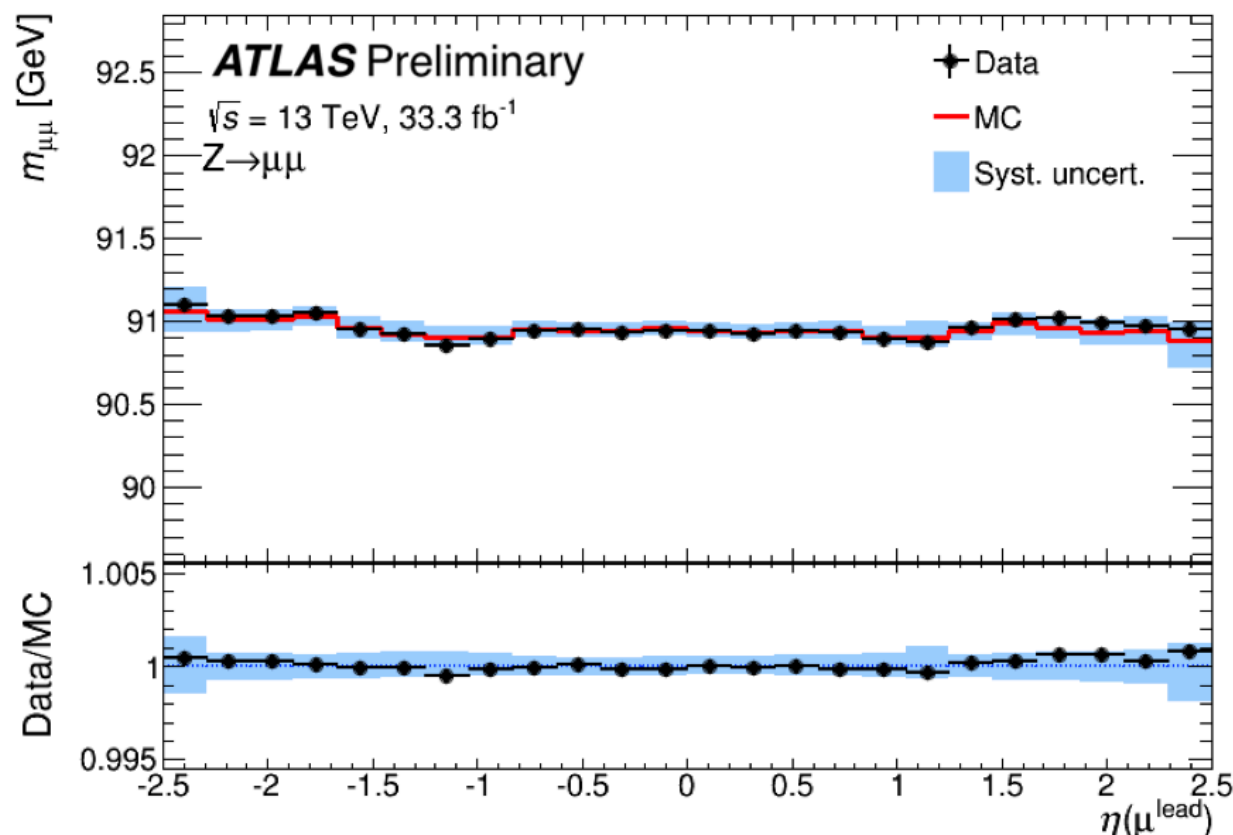- ...ge dependent sagitta bias, with net effect of worsening resolution
  - ▸ *In-situ* correction based on $Z \to \mu\mu$ data, recovers up to 5% in resolution.

- **Momentum scale understood down to the per mille level**

 - ▸ Precision down to 0.5 per mille for $|\eta| < 1.0$

Detector layer movements biasing the measurement of the bending of the particle

ATLAS Preliminary
Data 2016, √s = 13 TeV

$\delta_{sagitta}$ [TeV^{-1}]

η

ATLAS Preliminary
Data 2015, √s = 13 TeV

δ_{d_0} [μm]

η

) Uncorr.
) Uncorr.
st. uncert.

⊕ Biased positive and negative tracks
✦ Corrected positive and negative tracks

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- $H \rightarrow \gamma\gamma$ updated result at Run II with 36.1 fb⁻¹.

  ‣ Analytical $m_{\gamma\gamma}$ background functions in kinematic and detector related categories.

  ‣ Reduction of uncertainty through categorisation of events as a function of:

    ‣ resolution and signal significance.

    ‣ Systematic uncertainties.

- Expected statistical uncertainty of 0.21 GeV and 0.34 GeV systematic uncertainty

$$m_H^{\gamma\gamma} = 124.93 \ \pm \ 0.40 \ (\pm 0.21 \ \text{stat only}) \ \text{GeV}$$
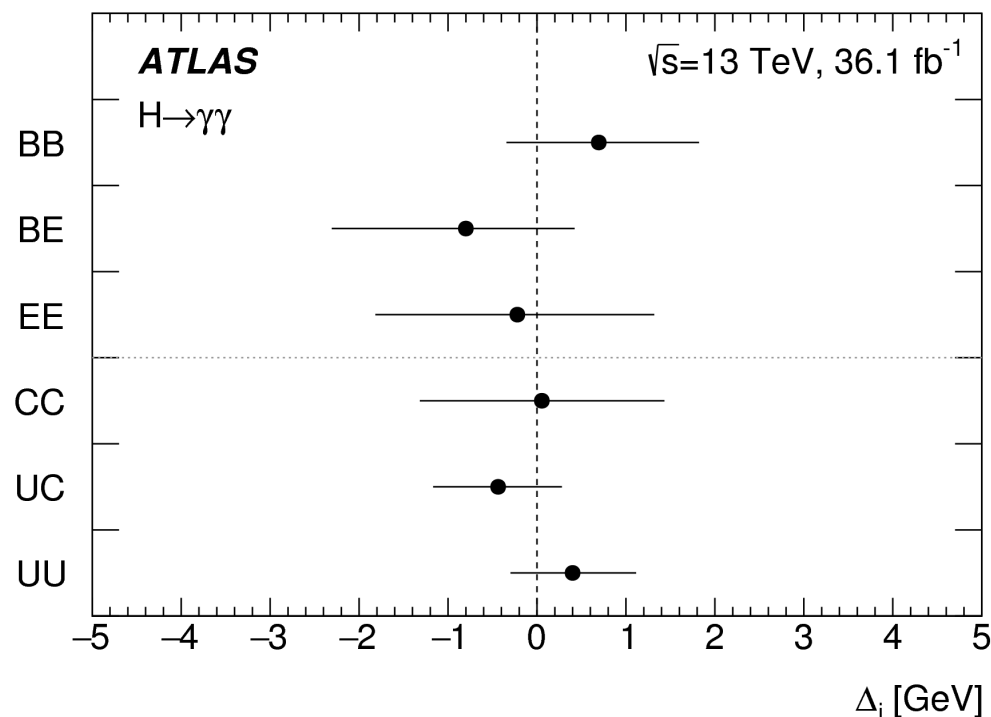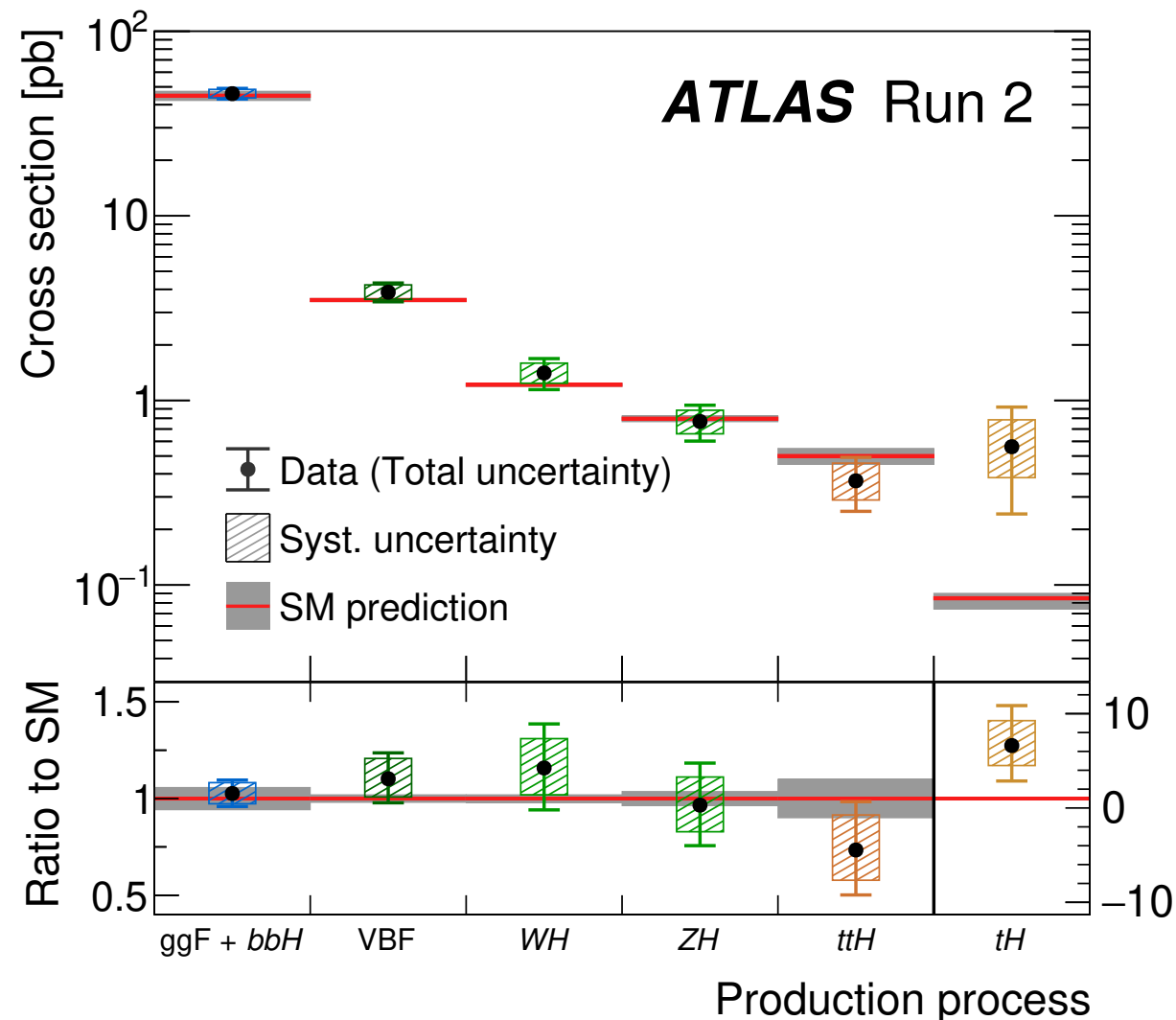

Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity	±180
EM calorimeter layer calibration	±170
Non-ID material	±120
ID material	±110
Lateral shower shape	±110
$Z \rightarrow ee$ calibration	±80
Conversion reconstruction	±50
Background model	±50
Selection of the diphoton production vertex	±40
Resolution	±20
Signal model	±20

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introduced in Section 4.

- Simultaneous fit to all template cross sections
  Nature 607, 52–59 (2022)
  - ▸ Extraction of global signal strength (μ=σ^{obs}/σ^{exp}).
  - ▸ Experimental sensitivity of the same oder as of theory (up to N^{3}LO for ggF)

all used in this section, all the μ_{if} are set to a global signal strength μ, describing the expected Higgs boson yield in all categories. Its combined measurement is

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

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

total uncertainty is decomposed into components for statistical uncertainties, e uncertainties, and theory uncertainties on signal and background modeling, fo

ory component includes uncertainties du orre   in t, the matching between the hard-scattering and branching ratio uncertainties. The me . $p_{\text{SM}} = 18\%$, computed using the procedu f $-2\ln\Lambda(\hat{\mu})$ as a function of μ is shown in sance parameters fixed to their best-fit val Section 4.

ties in the combined measurement of the g in Section 4. The dominant uncertainties a

eling of the signal and background processes in simulation. Further important u

ATLAS-CONF-2021-053

Uncertainty source	$\Delta\mu/\mu$ [%]
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavour tagging	1.2
Electrons, photons	2.2
Muons	0.2
τ-leptons	1.3
Other	1.6
MC statistical uncertainty	1.7

- **ATLAS full Run-2 combination**
  - ‣ Combined sensitivity of all channels to increase the precision of the Higgs productions.

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to WW$	ggF, VBF	139
	WH, ZH	36.1
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to Z\gamma$	inclusive	139
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H + tH$	139
	inclusive	139
$H \to \tau\tau$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139
	$t\bar{t}H + tH$ (multilepton)	36.1
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139
$H \to c\bar{c}$	$WH + ZH$	139
$H \to$ invisible	VBF	139
	ZH	139

Higgs width

- Study of the the $m_{4\ell}$ spectrum and off-shell H production

‣ Measured upper limit on width combining 4ℓ and $\ell\bar{\ell}\nu\bar{\nu}$

‣ Limit Γ_H possibile from the off-shell to on-shell event yield ratio R_{gg}

  ✦ on-shell event yields ~ $k^2_{g,\text{on-shell}}$ / Γ_H, while off-shell ~ $k^2_{g,\text{off-shell}}$

‣ Observed (expected) upper limit on Γ_H 14.4 (15.2) MeV
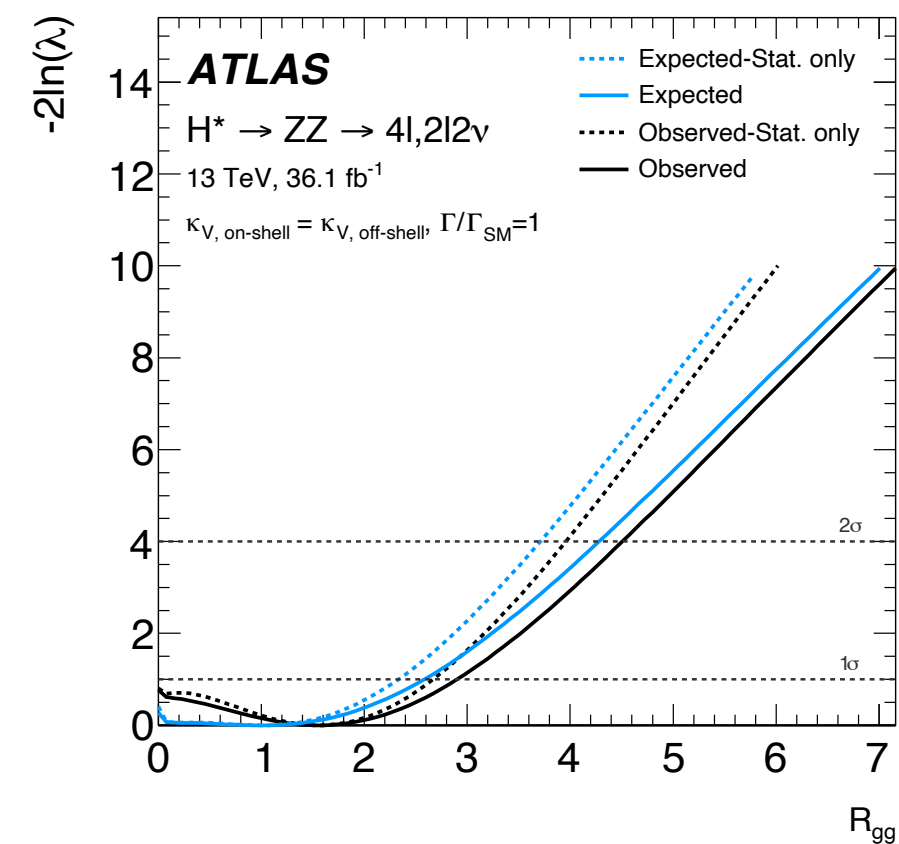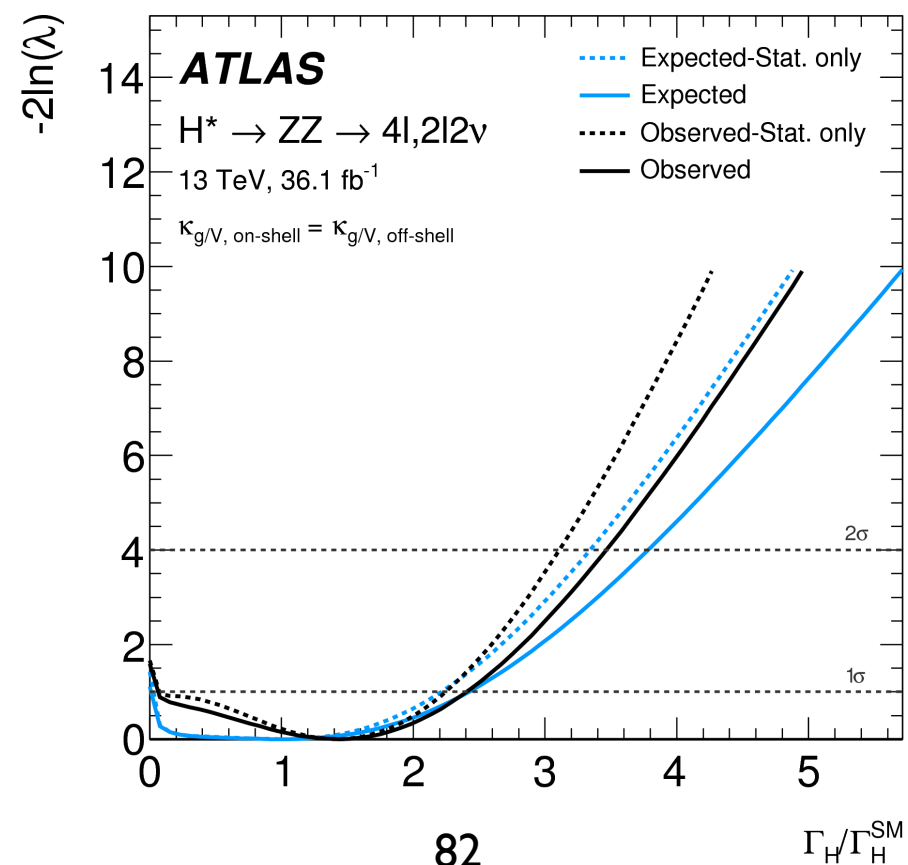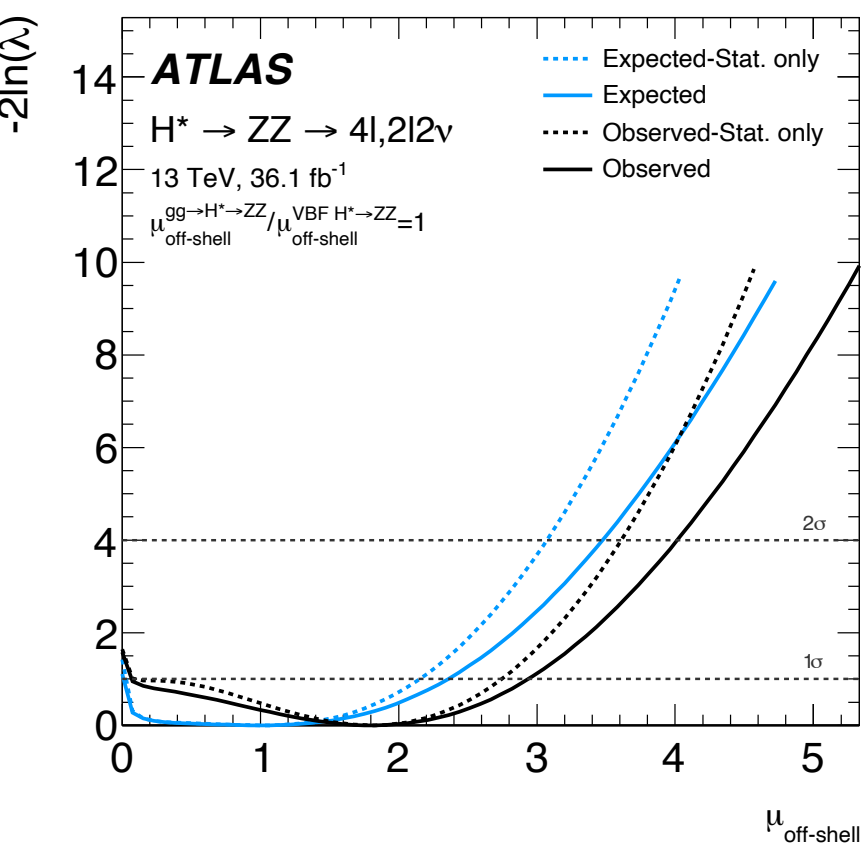
- **Higgs boson kinematics:**

  - $p_{T,4\ell}$: Lagrangian structure of H interactions.
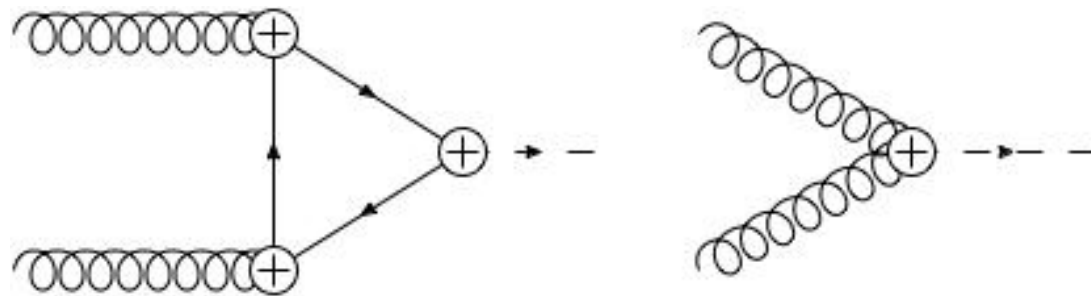
- Sensitivity to phenomena resonant at higher energies → changes in observables at lower energies.

$$\frac{c_1}{\Lambda^2}\, \mathcal{O}_1 \to \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}\,,\Big\}$$

c_g: ggH contact interaction

$$\frac{c_2}{\Lambda^2}\, \mathcal{O}_2 \to \frac{m_t}{v} c_t h \bar{t}t\,,$$

$$\frac{c_3}{\Lambda^2}\, \mathcal{O}_3 \to \frac{m_b}{v} c_b h \bar{b}b\,,$$

c_t: t and b Yukawa couplings
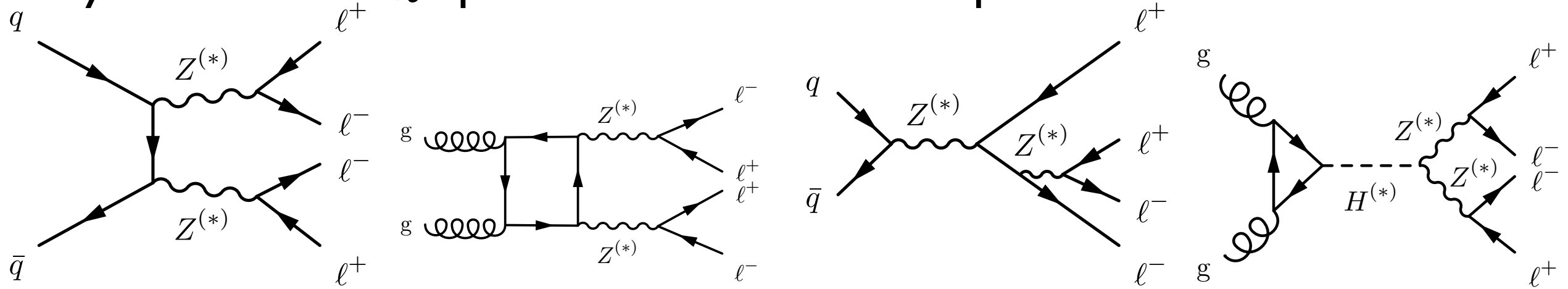
$$\frac{c_4}{\Lambda^2}\, \mathcal{O}_4 \to c_{tg} \frac{g_S m_t}{2v^3}(v+h) G^a_{\mu\nu}(\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c)$$

c_{tg}: dipole-moment, g-t interaction

4ℓ mass spectrum
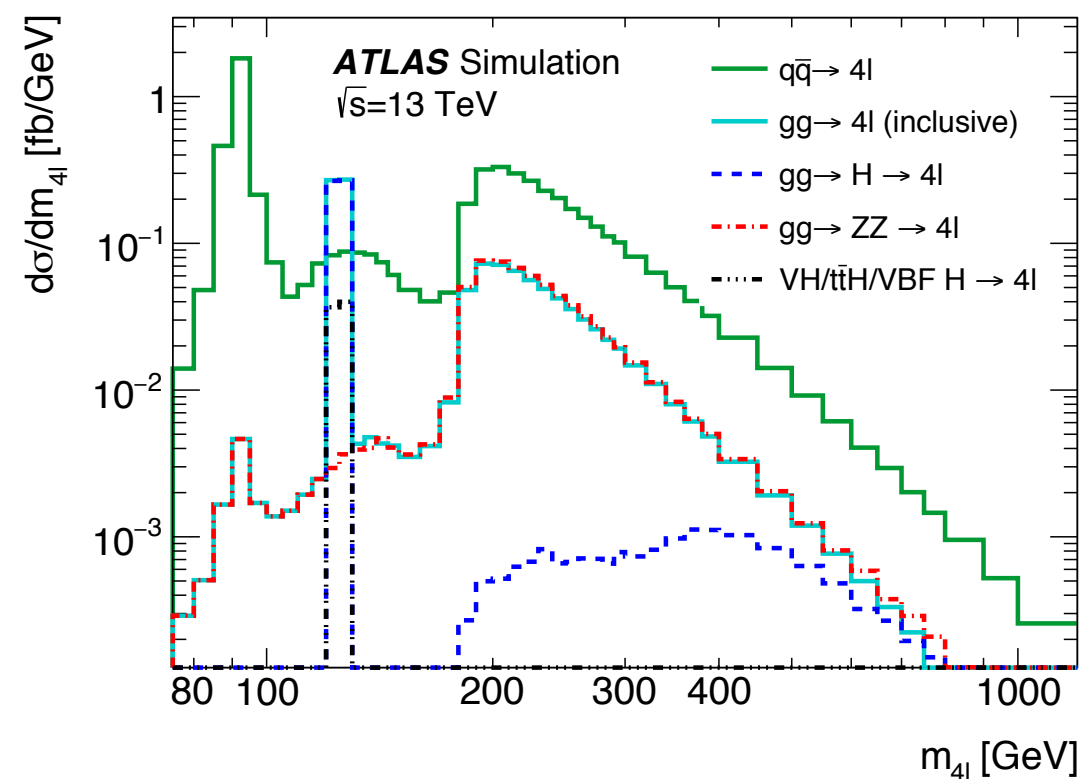
- **Study of the the $m_{4\ell}$ spectrum and**

‣ $m_{4\ell}$ ranges from single Z resonance, including *H* production up to *ZZ* production

‣ Extraction of the BR(Z→ 4ℓ)

Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s}$ = 7 TeV and 8 TeV [8]	4.31 ± 0.34(stat)±0.17(syst)
CMS, $\sqrt{s}$ = 13 TeV [6]	$4.83\ ^{+0.23}_{-0.22}$(stat) $^{+0.32}_{-0.29}$(syst)±0.08(theo)±0.12(lumi)
ATLAS, $\sqrt{s}$ = 13 TeV	**4.70 ± 0.32(stat) ± 0.21(syst) ± 0.14(lumi)**

‣ Offshell Higgs production, enhanced at 350 GeV because of top-quark loops in ggF

  ✦ Including interference between *H* and *ZZ* productions.

‣ Above ~ $2m_Z$ enhancements of qq→ZZ and gg→ZZ.

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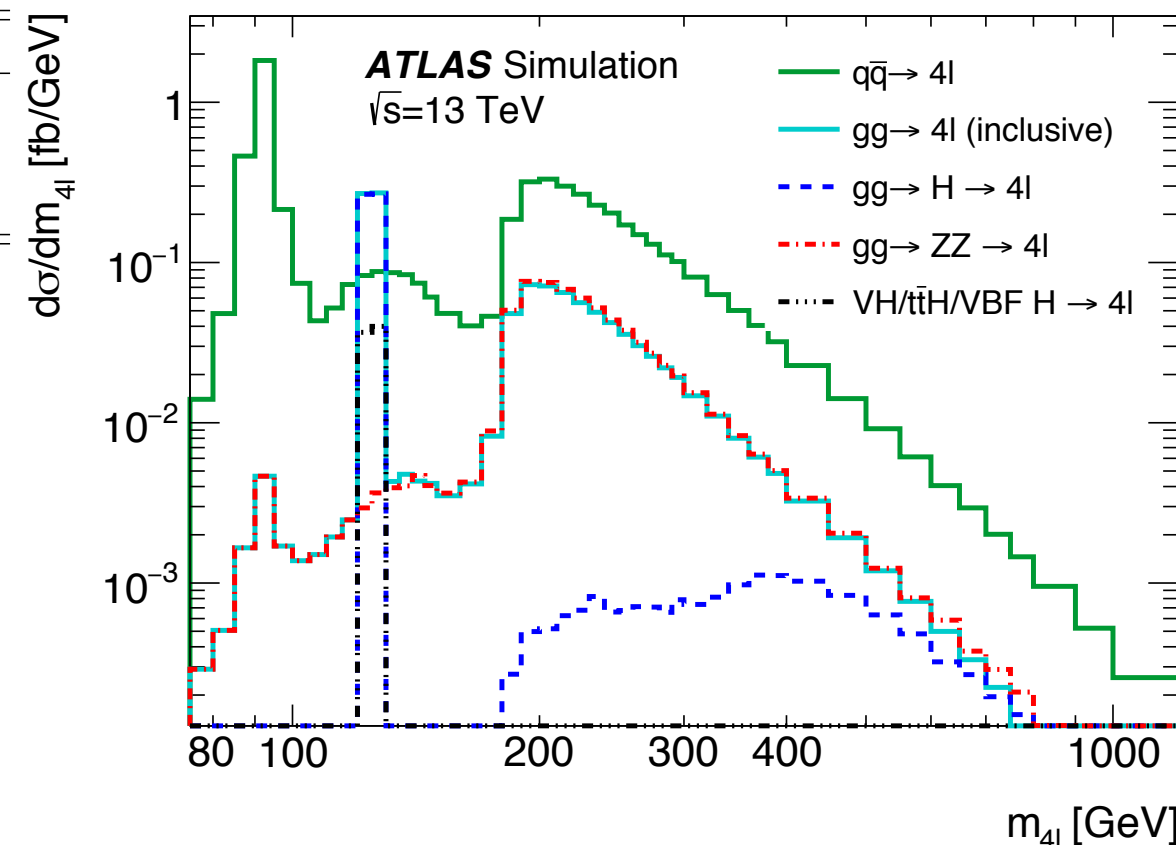
- Study of the the $m_{4\ell}$ spectrum and Offshell H production

  ‣ $m_{4\ell}$ ranges from single Z resonance, including H production up to ZZ production

  ‣ Offshell Higgs production, enhanced at 350 GeV because of top-quark loops in ggF

    ✦ Including interference between H and ZZ productions.

  ‣ Above ~ $2m_Z$ enhancements of $qq{\rightarrow}ZZ$ and $gg{\rightarrow}ZZ$.

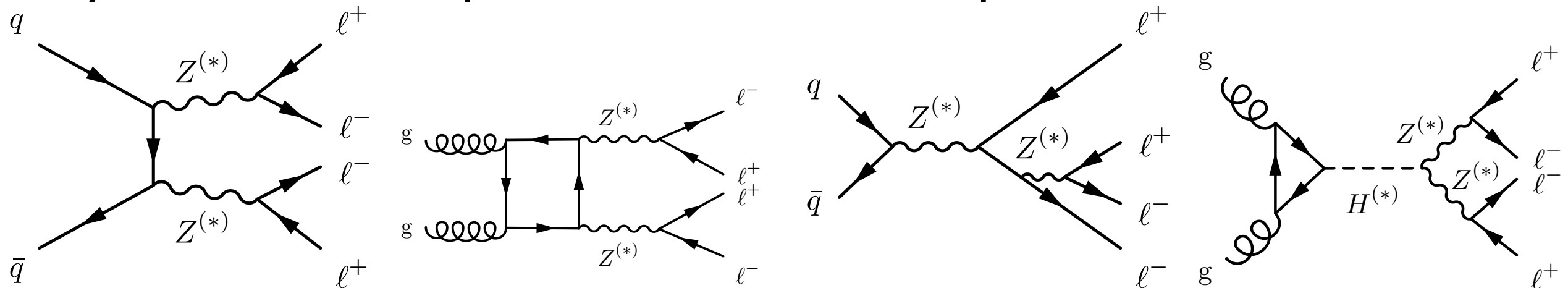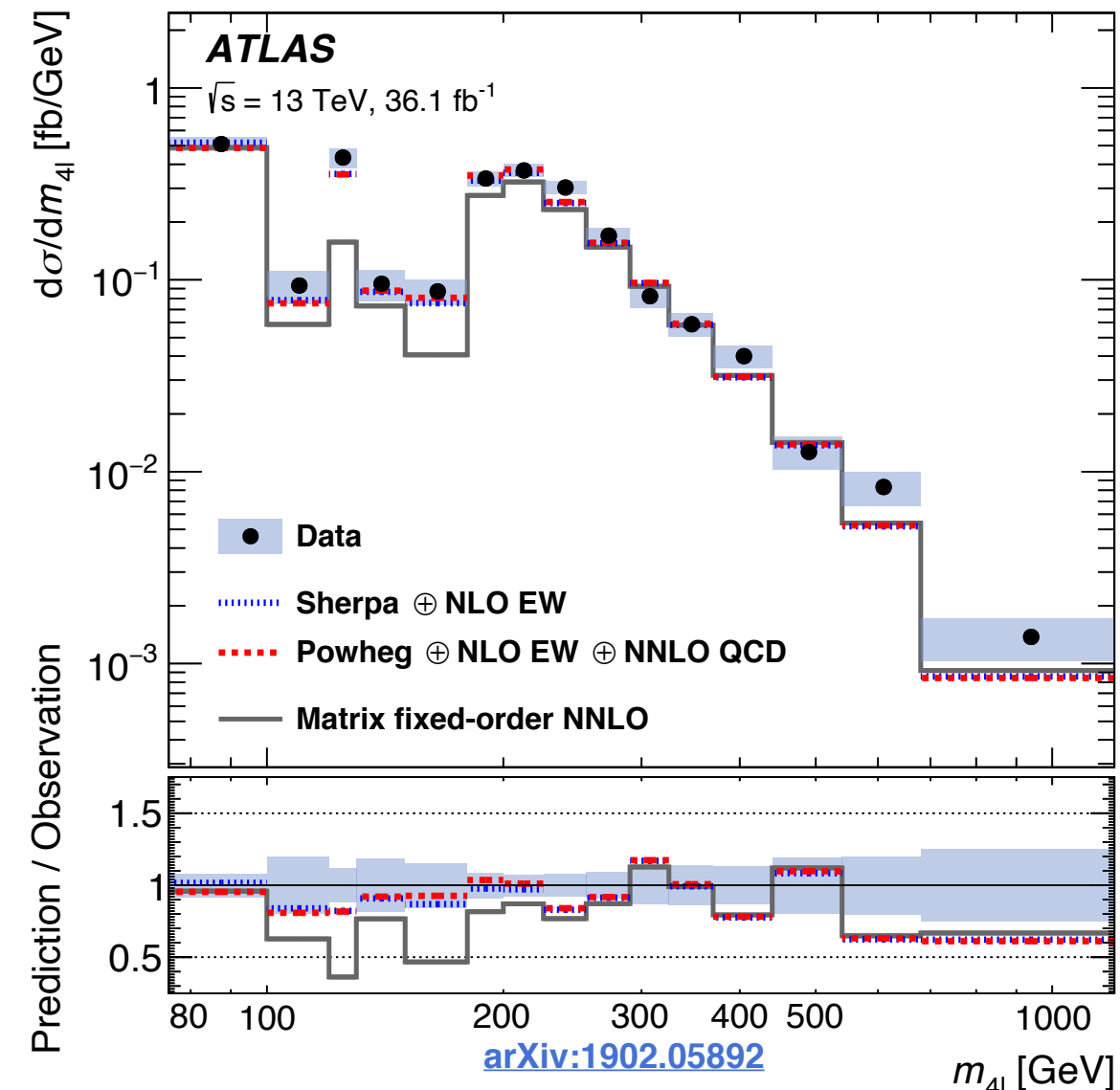- Study of the the $m_{4\ell}$ spectrum and Offshell H production

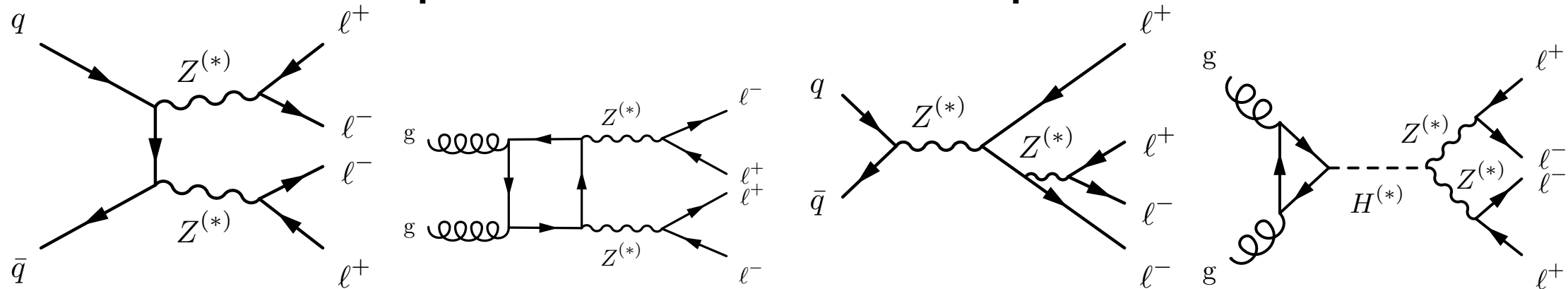▸ $m_{4\ell}$ ranges from single Z resonance, including H production up to ZZ production

▸ Extraction of the BR(Z→ 4ℓ)

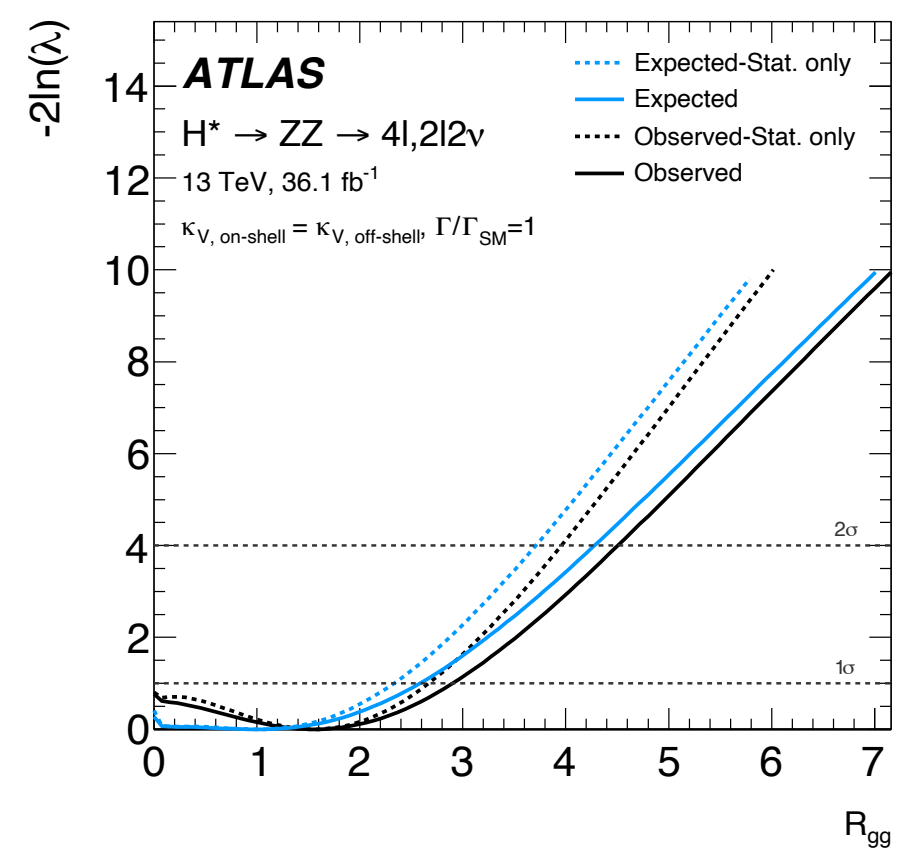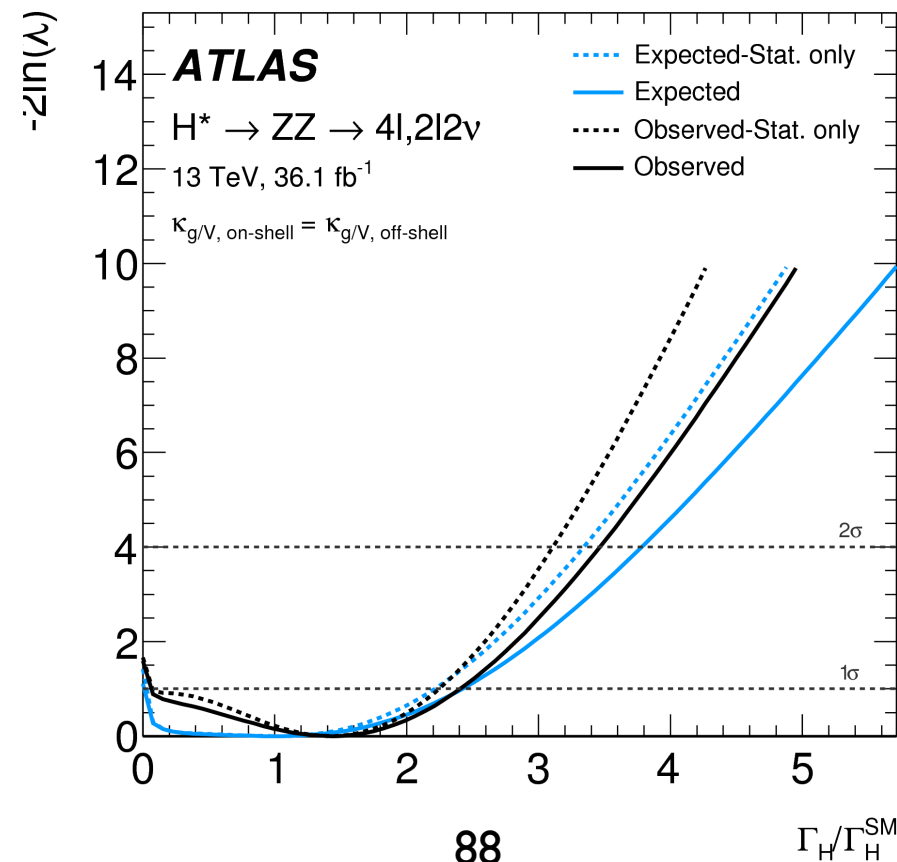| Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
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▸ $m_{4\ell}$ ranges from single Z resonance, including H production up to ZZ production

▸ Extraction of the BR(Z→ 4ℓ)

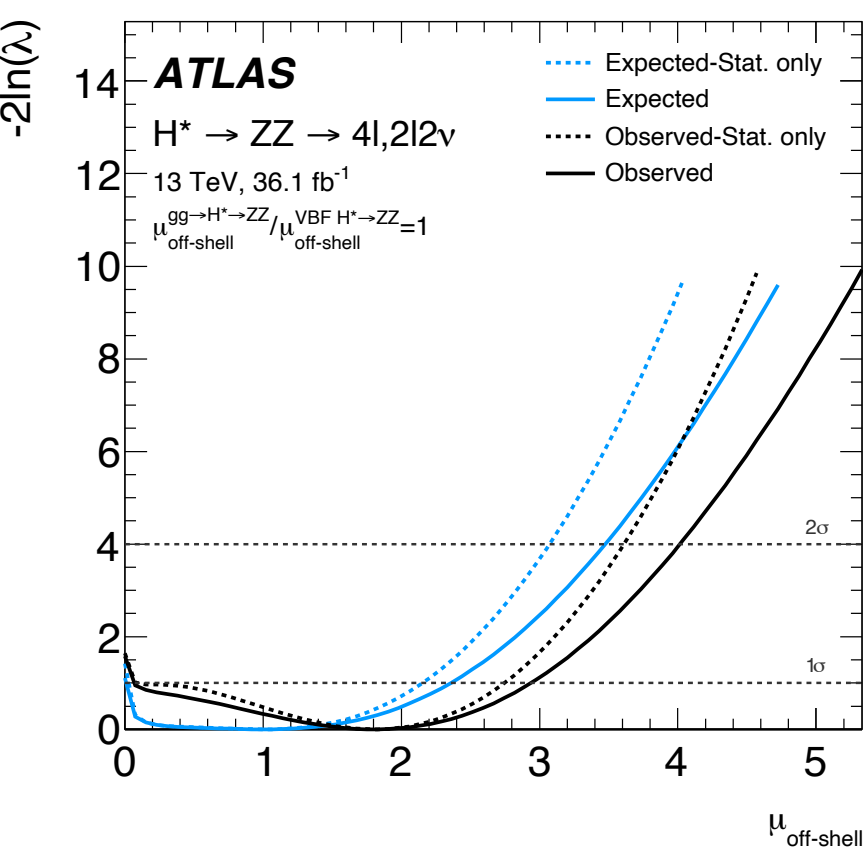| Measurement	$\mathcal{B}_{Z \to 4\ell}/10^{-6}$
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arXiv:1902.05892

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▸ Limit Γ_H possibile from the off-shell to on-shell event yield ratio R_{gg}

  ✦ on-shell event yields ~ $k^2_{\text{g,on-shell}} / \Gamma_H$, while off-shell ~ $k^2_{\text{g,off-shell}}$

- **Double differential $d^2\sigma/dp_Td N_J$:**
  - ‣ Probe the Higgs production mode
  - ‣ $N_j = 0$ dominated buy ggF production
  - ‣ $N_j > 1$ VBF enriched production
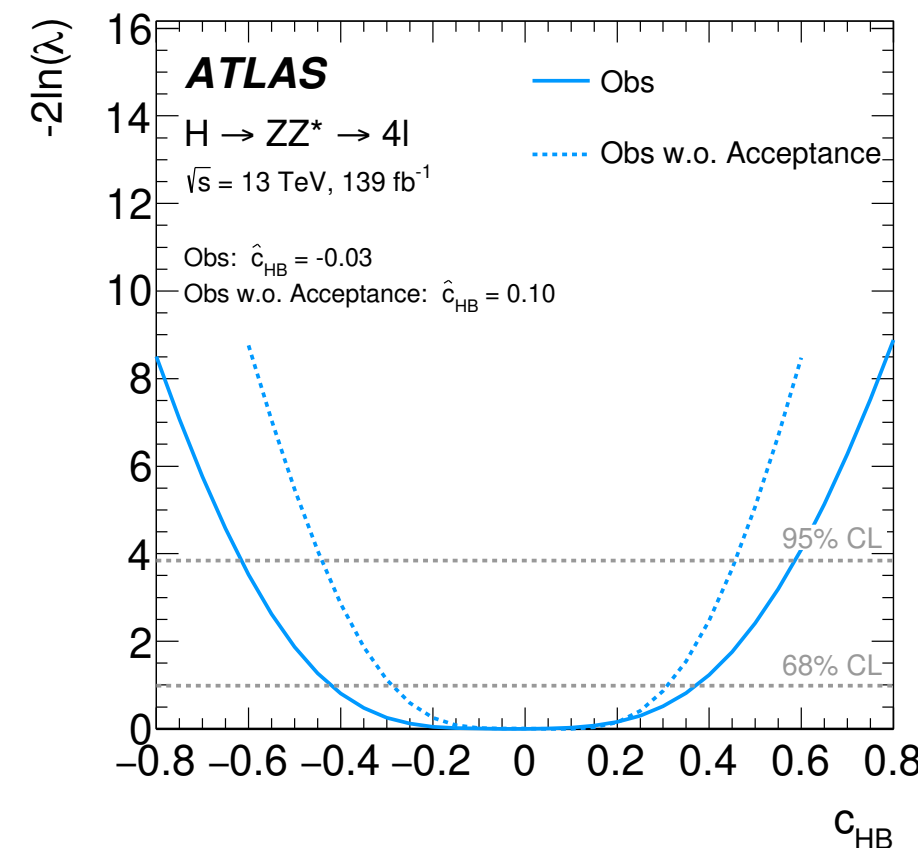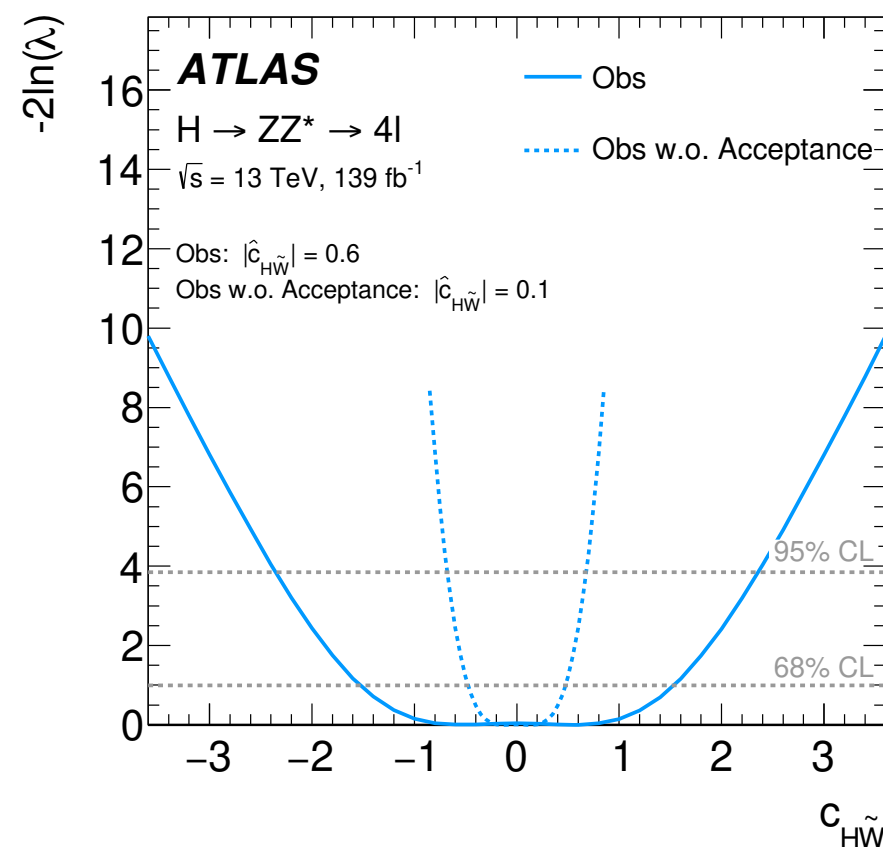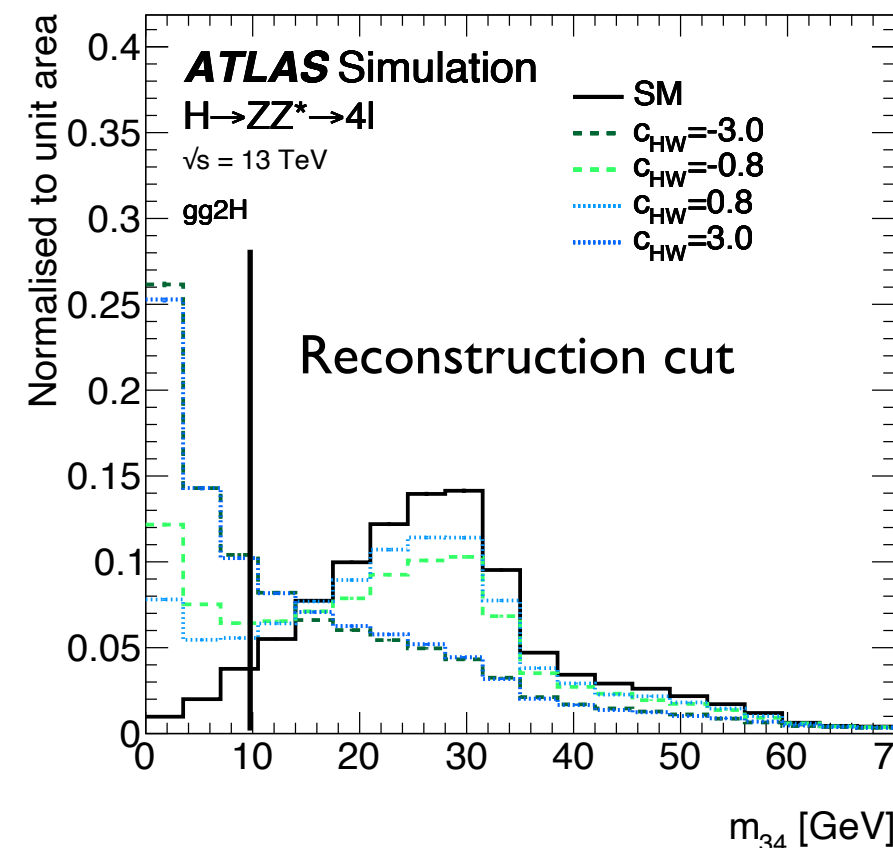
G. Barone

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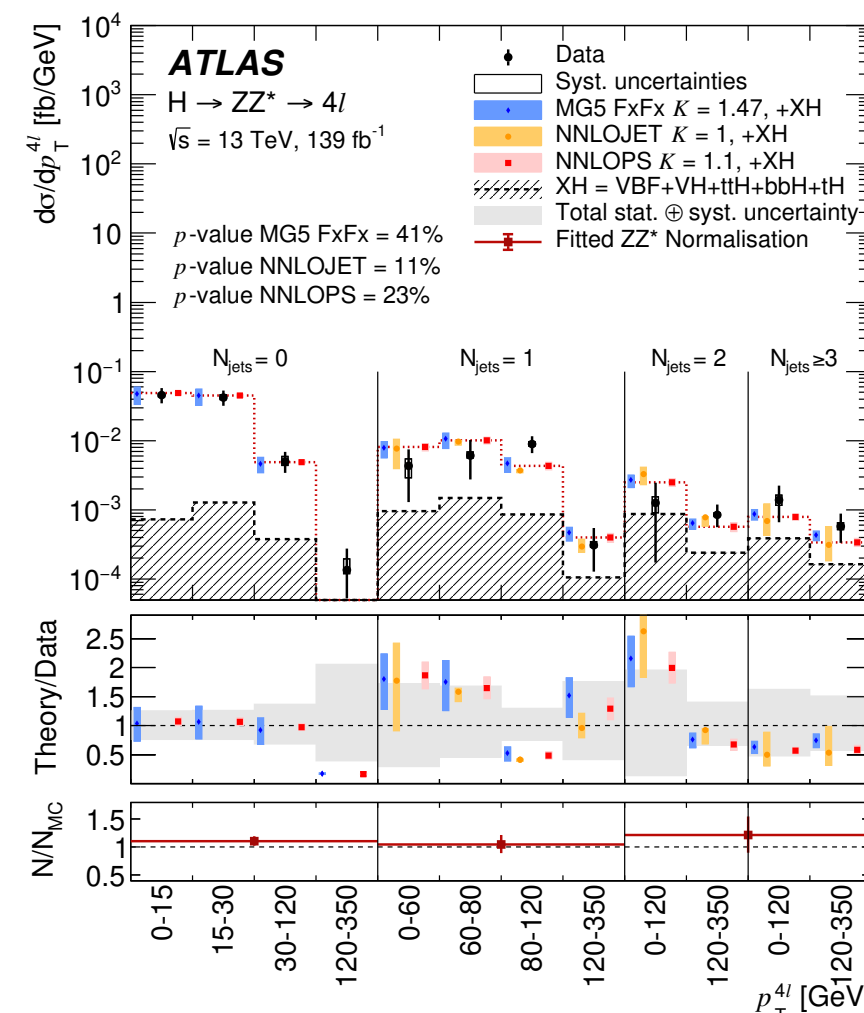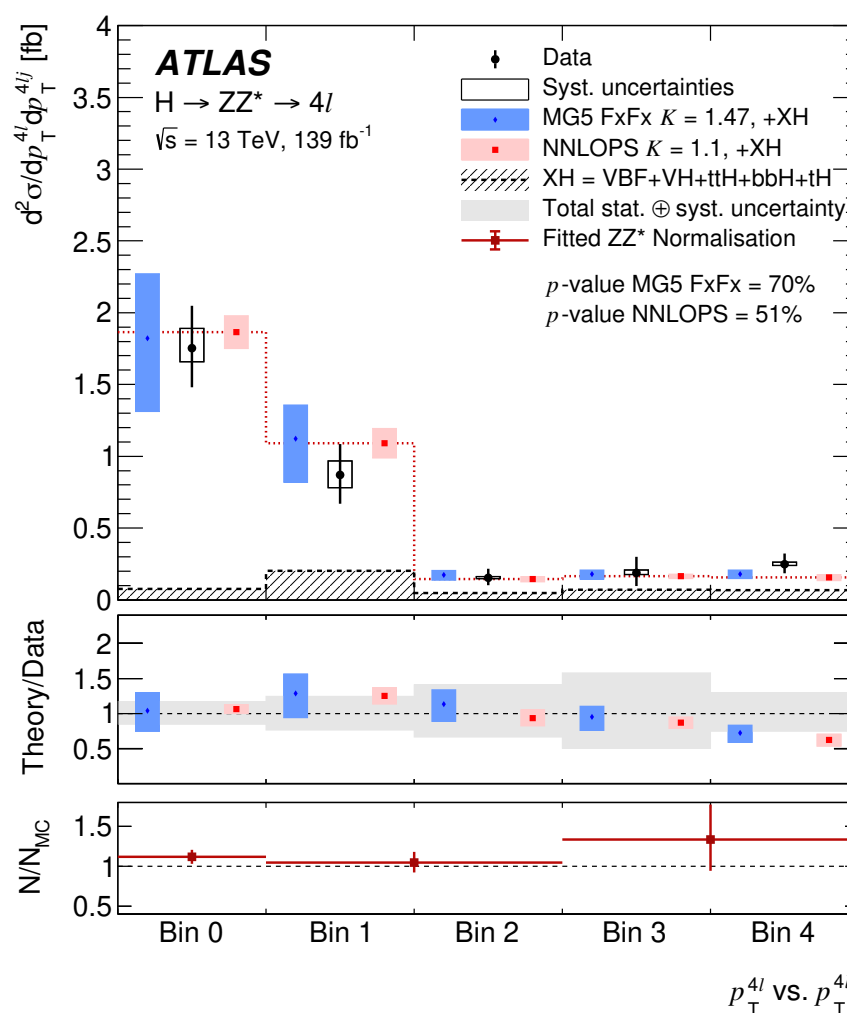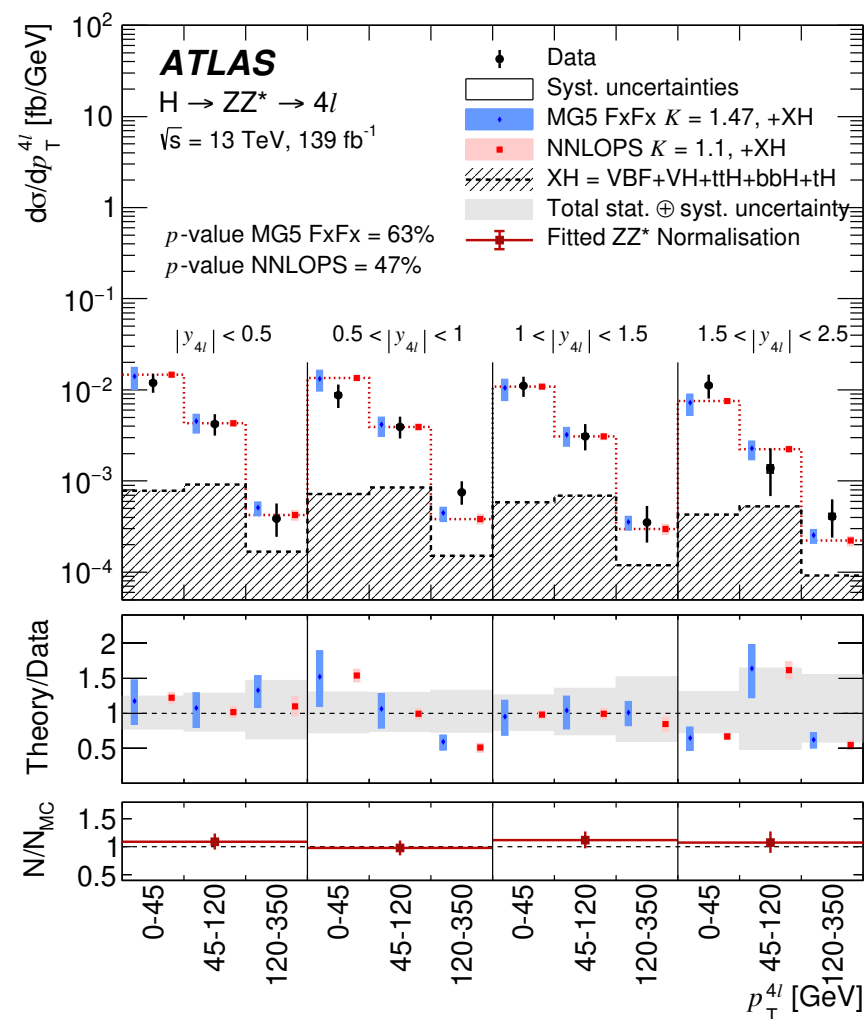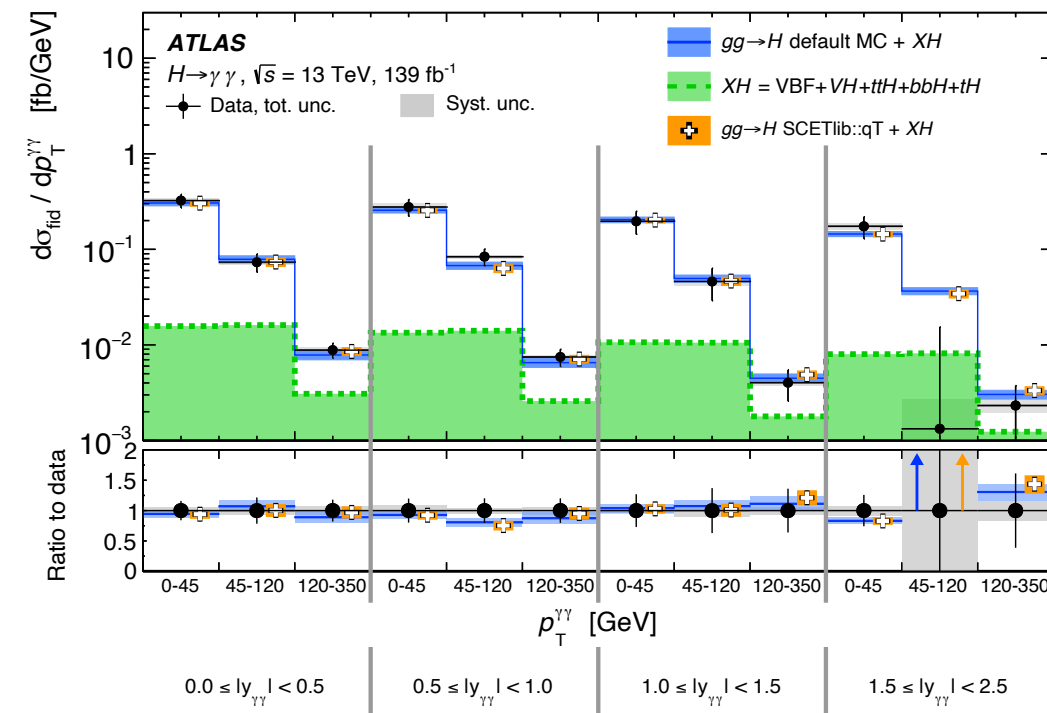
- Results interpreted in the context of new physics:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

SMEFT DRAFT

▶ Standard Model Effective Field Theory as the standard candle.

▶ Probe for non-SM contributions to the tensor structure of the Higgs boson.

- Account for BSM acceptance effects in kinematic observables of decay products

Figure 9: Summary of observed measurements of the parameters c_i' with the SMEFT linearized model (…) SMEFT model with additional quadratic terms.

Couplings interpretations

- **Interpretation...**
- **As...**
- **Coupling...**
- **BSM...**
- κ_g and κ_V measured with... modified...

$$\kappa_V = 1.03 \pm 0.03$$
$$\kappa_F = 0.97 \pm 0.07.$$

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV, 24.5 - 139 fb^{-1}

m_H = 125.09 GeV, $|y_H|$ < 2.5

68% CL

95% CL

κ_g

κ_γ

$B_{i.}$

$B_{u.}$

$B_{i.} = B_{u.} = 0$

p_{SM} = 51%

p_{SM} = 70%

0.9 1 1.1   0 0.5 1
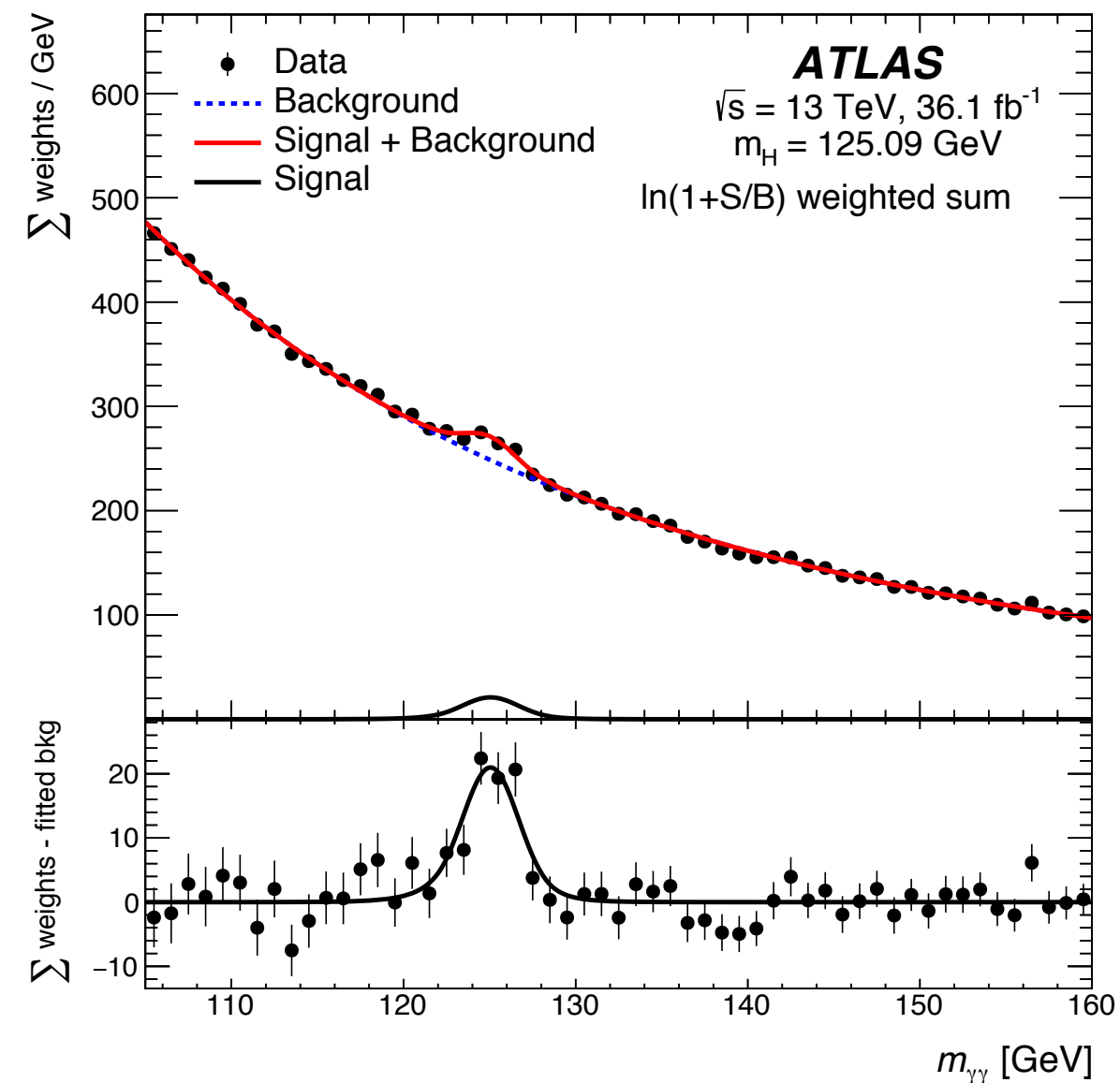
Diphoton event selection

- At least two photon with $E_T > 25$ GeV

- Highest E_T pair forms candidate.

- Vertex identification with Neural Network

  - Vertex within 0.3 mm for 79% of ggH events.

Background estimation

- Entirely estimated from data

- Prompt photons: maximum likelihood fit to $m_{\gamma\gamma}$ spectrum

- Jets misidentified as photons: from control sample

- 4ℓ: isolate signal under the Higgs resonant peak ($115 < m_{4\ell} < 130$).
- $\gamma\gamma$ cross section extracted from resonant peak over the $\gamma\gamma$ continuum.
- Higgs boson $p_{T,4\ell(\gamma\gamma)}$ and rapidity ($y_{4\ell(\gamma\gamma)}$) probe.
  - ‣ $p_{T,4\ell(\gamma\gamma)}$: Lagrangian structure of H interactions, Yukawa couplings
  - ‣ $y_{4\ell(\gamma\gamma)}$: Sensitivity to proton's parton density functions.

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