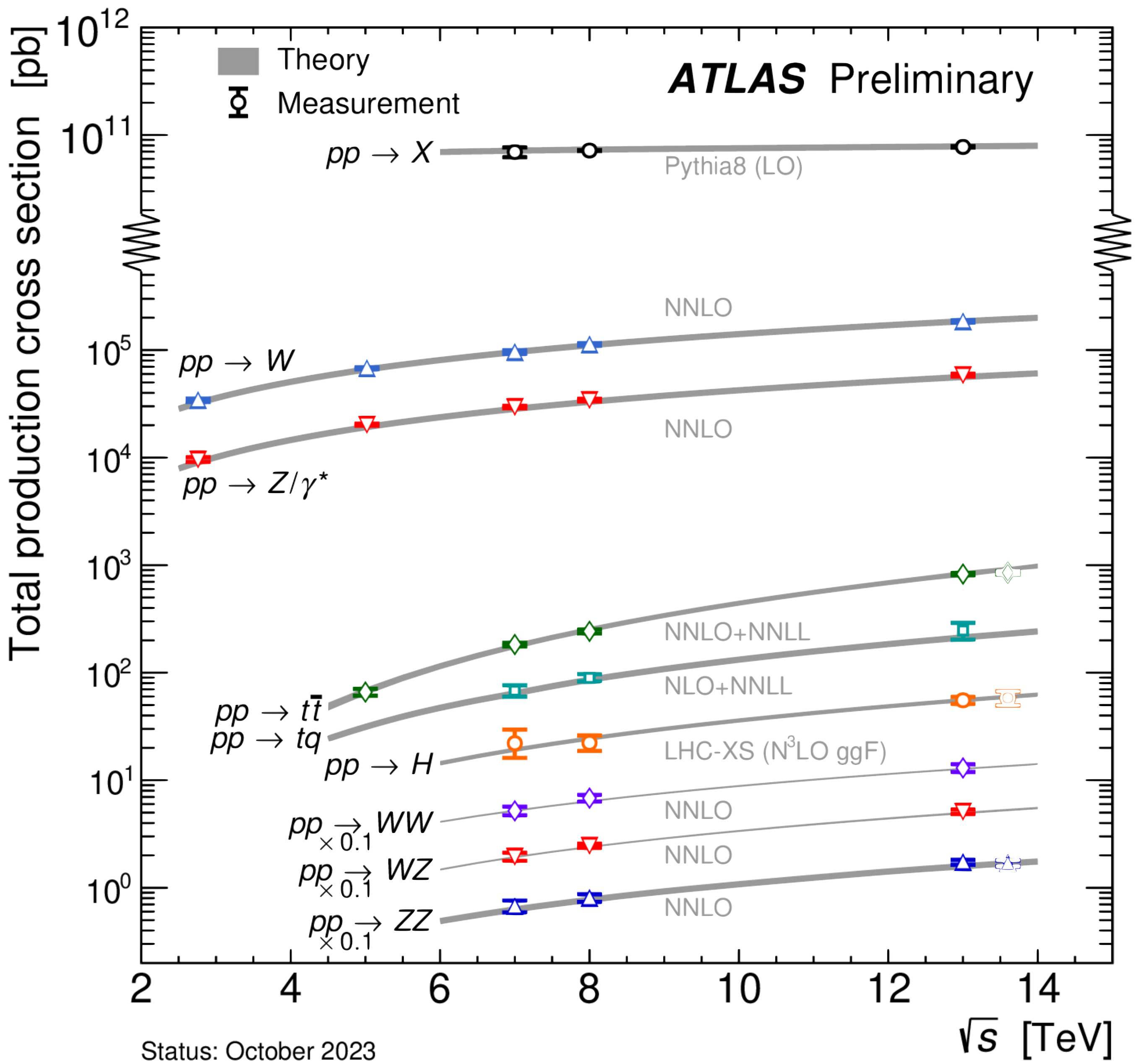
Electroweak measurements using *Run 3* data with ATLAS

SM@LHC Rome 7-10/5/2024

Ludovica Aperio Bella (DESY) on behalf of ATLAS collaboration

LHC Run-2 data taking

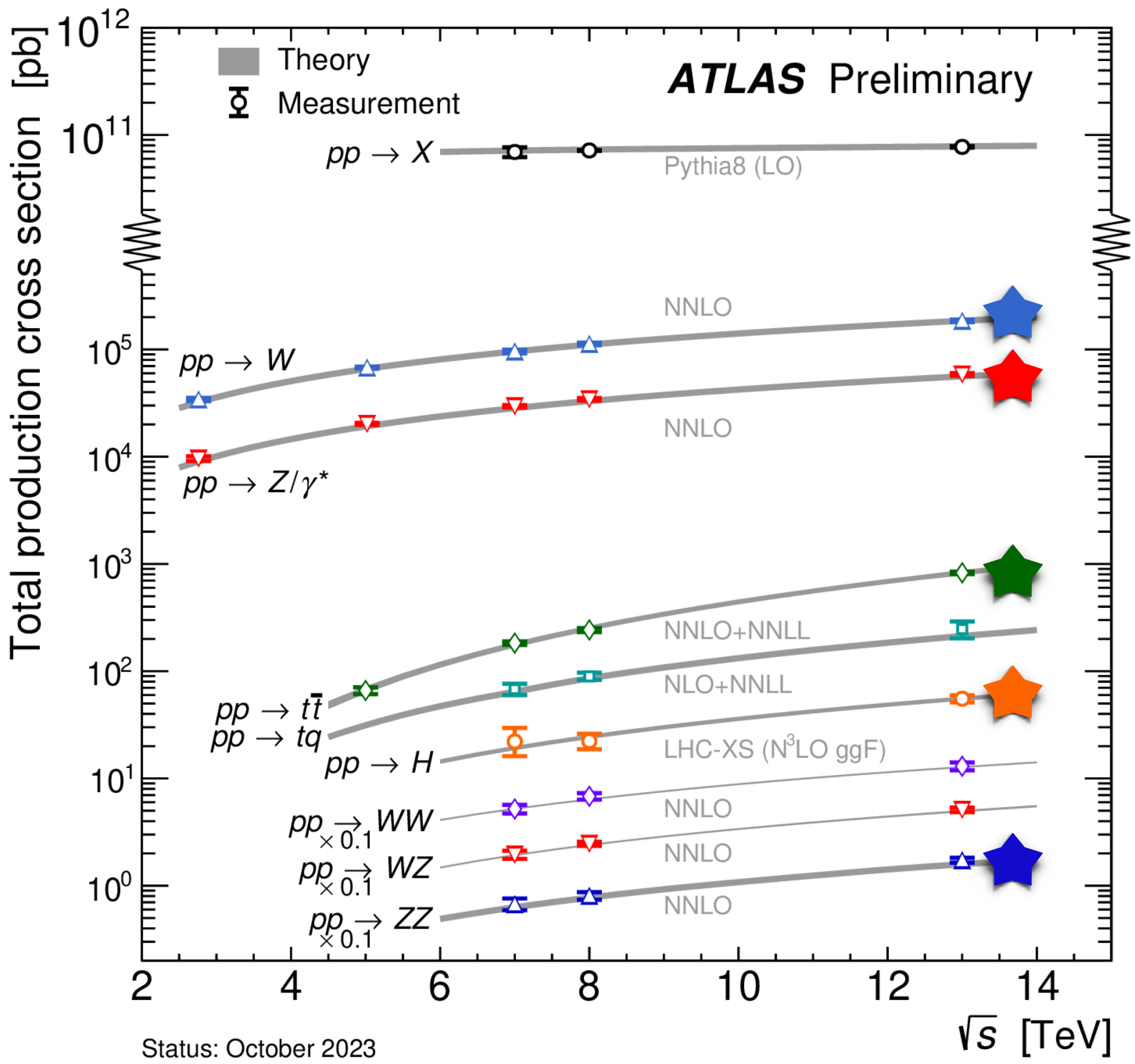


LHC Run-2 data-taking offered a **unprecedented physics potential**: probing high-precision Higgs and other Standard Model processes, detecting very rare processes, and exploring new physics via direct and indirect measurements

The LHC is an **everything** factory

Particle	Produced in 140 fb^{-1} pp at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.8 million	
Top quark	275 million	(115 million $t\bar{t}$)
Z boson	8 billion	($\to \ell\ell$, 270 million per flavour)
W boson	26 billion	($\to \ell\nu$, 2.8 billion per flavour)
Bottom quark	~160 trillion	(significantly reduced by acceptance)

LHC Run3



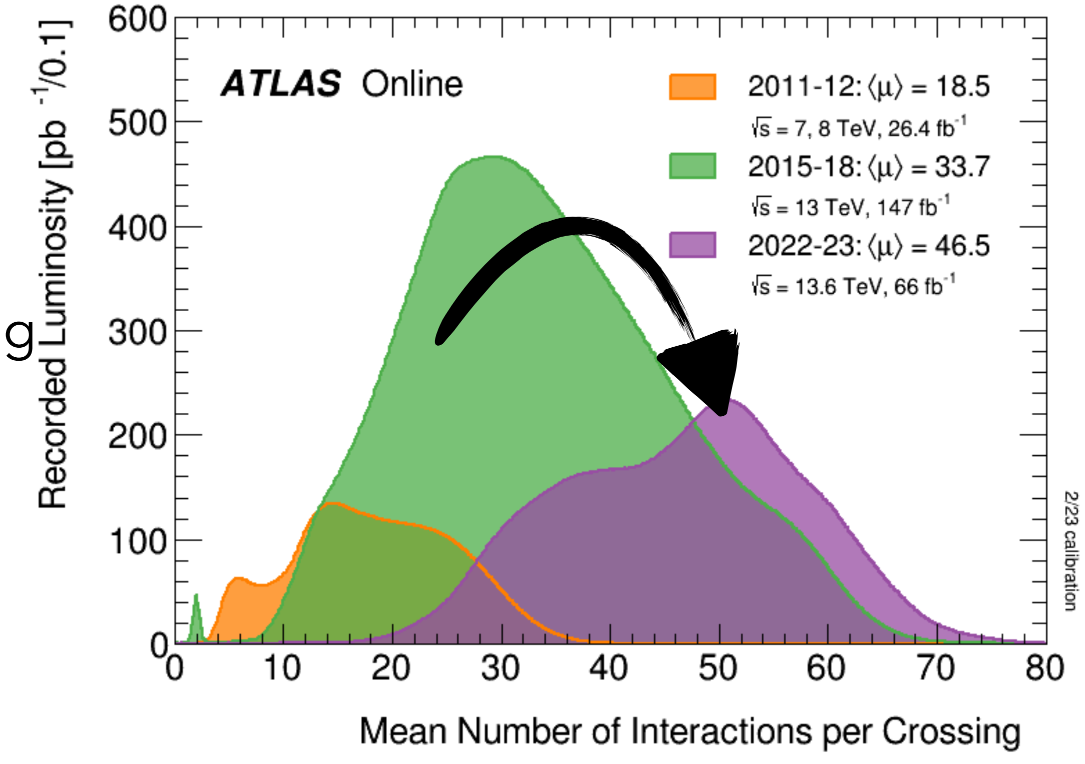
After over three years of upgrade and maintenance work, the Large Hadron Collider in July 2022 started its third period of operation *Run 3*.
@record-breaking energy of *13.6 TeV* and peak $\mathcal{L}$ $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$

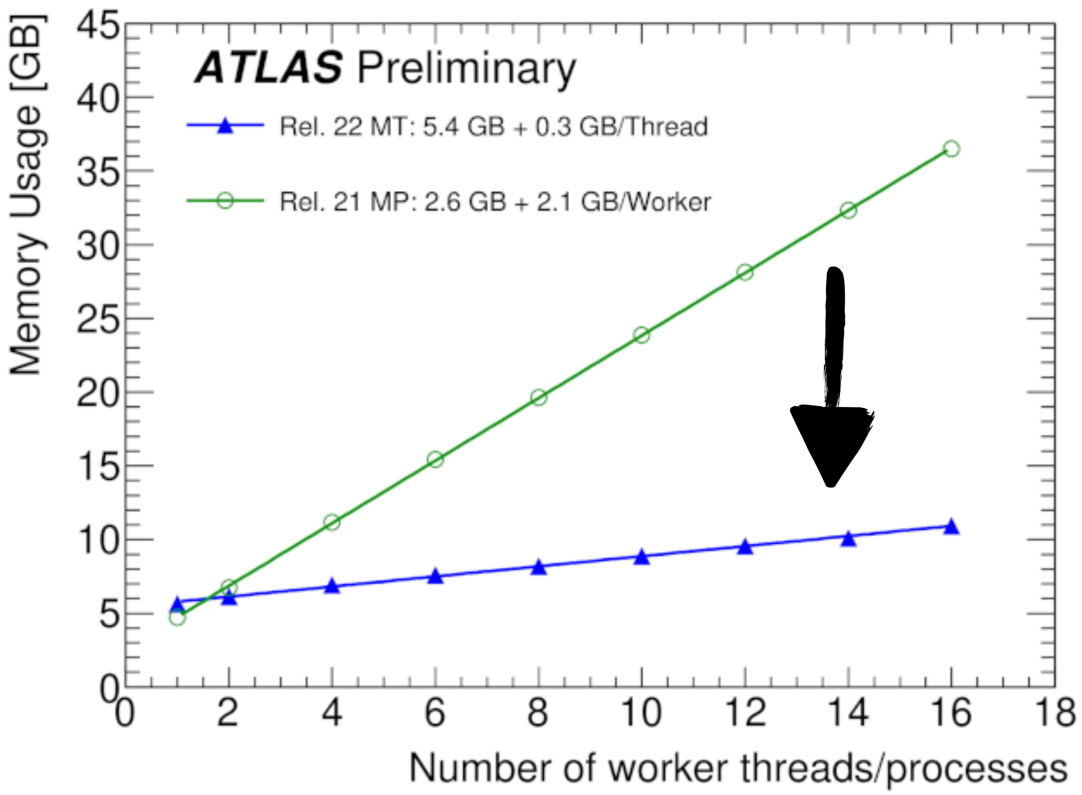
TODAY focus on early Run-3 SM measurements

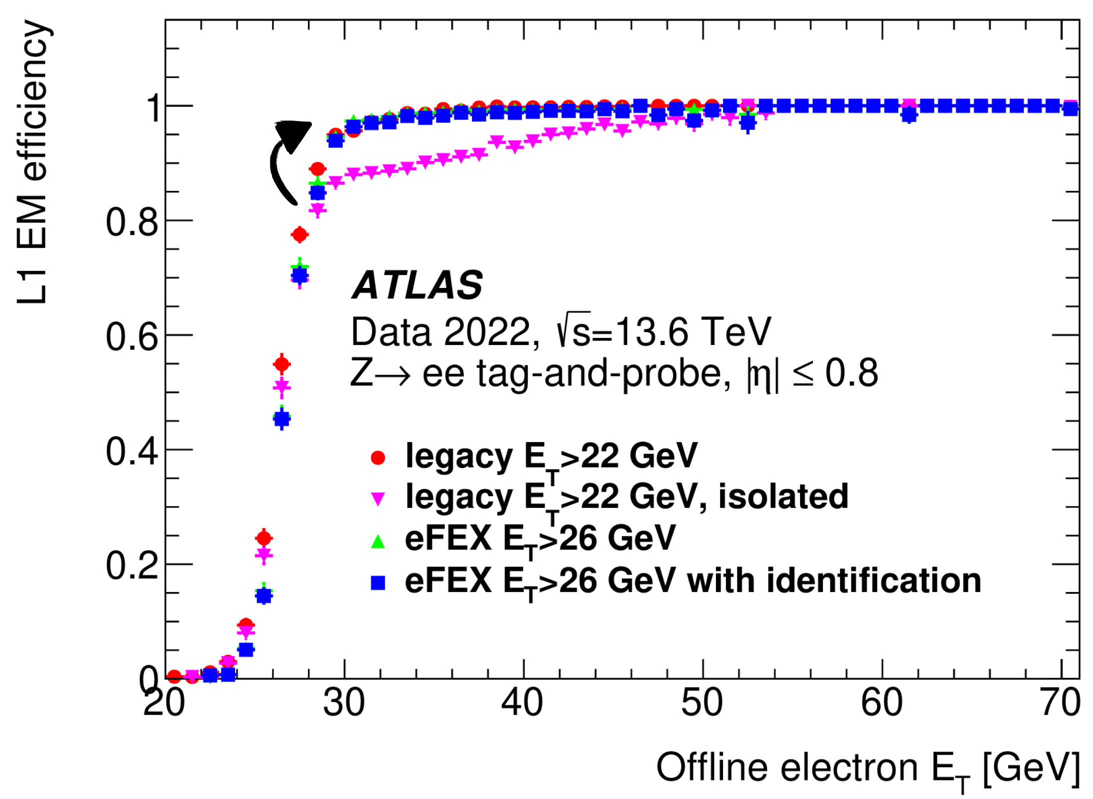
LHC Run3: The challenges at the new frontier

The functionality of the ATLAS detector and its reconstruction software underwent many improvements **to cope with Run 3 increase instantaneous luminosity and pileup:**

- Upgraded Detector performances, Trigger & computing
  - more sophisticated algorithms to identify physics objects
  - multi-threaded software framework AthenaMT
- **All this improvement affect physics object performances**



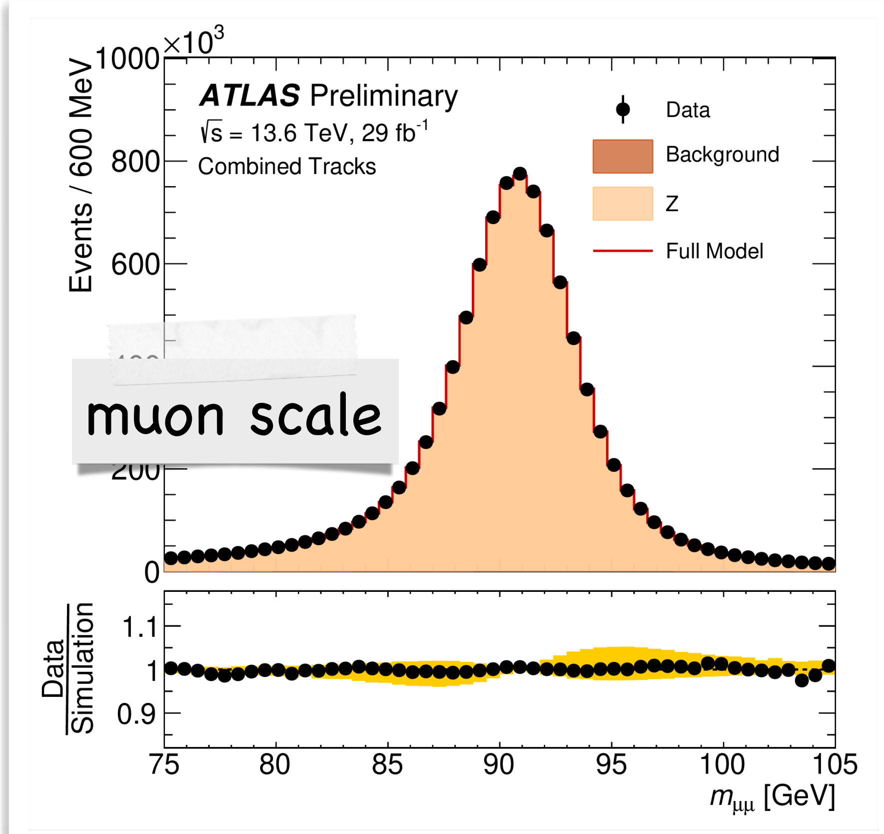


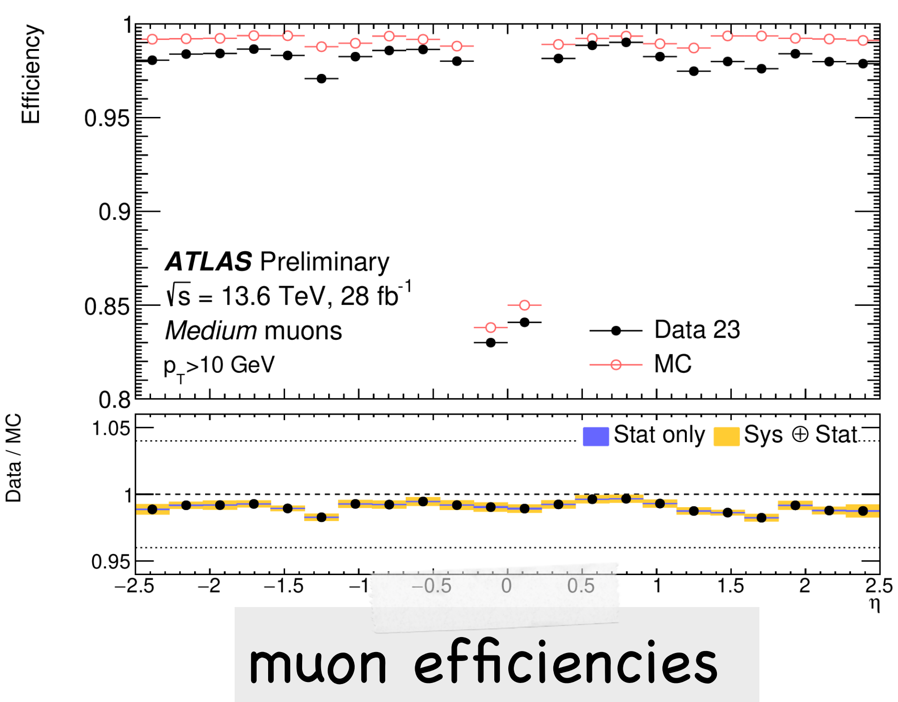


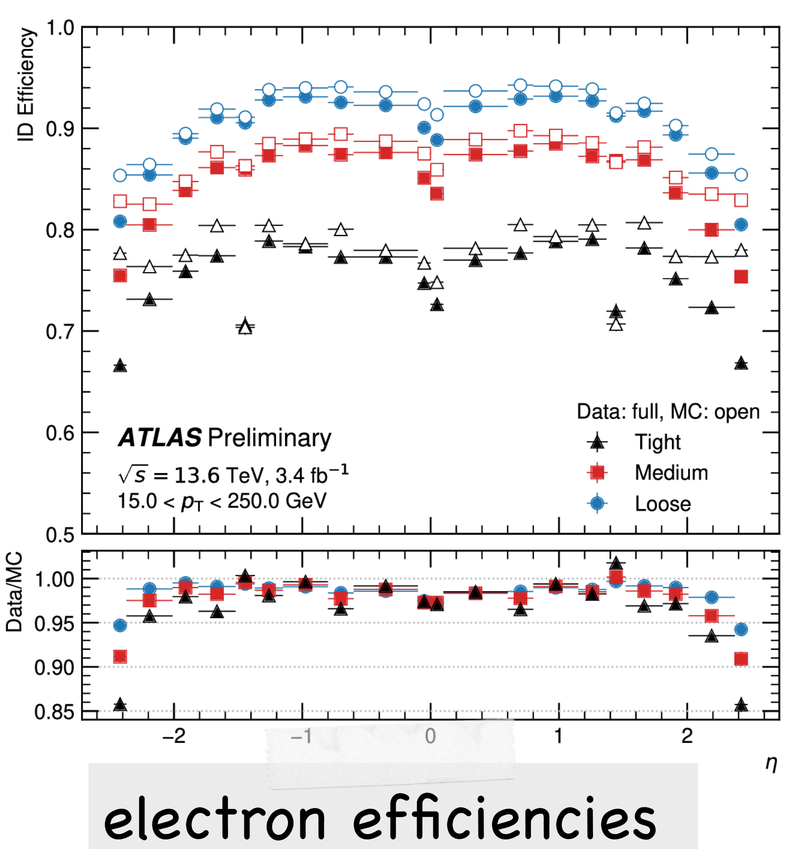
Early Run3 combined performance

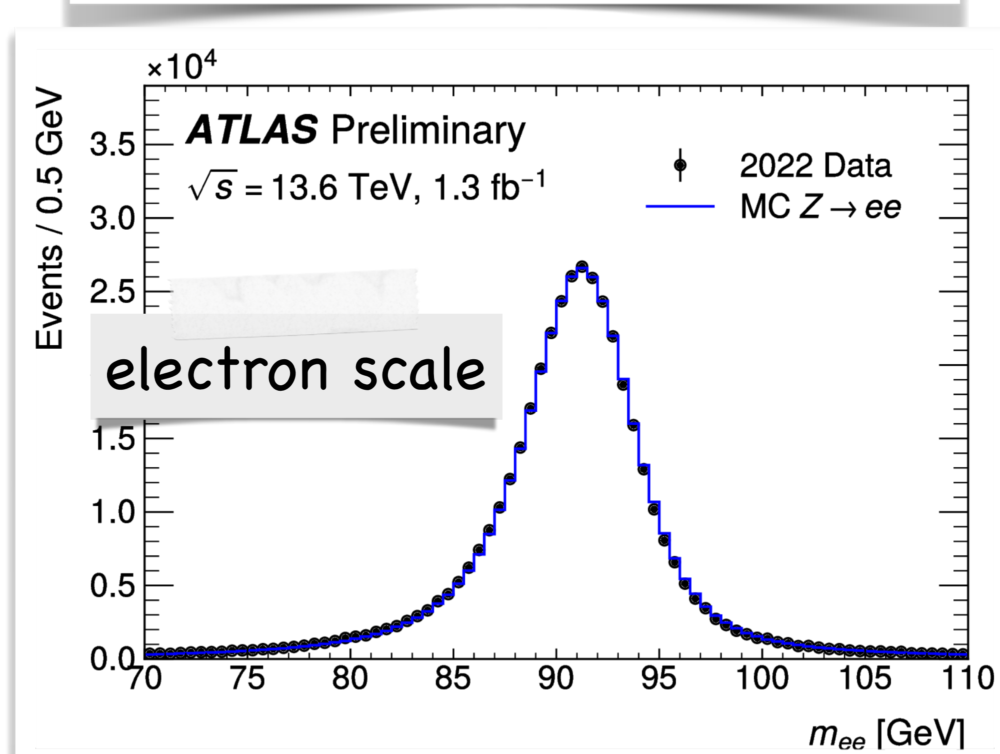
The functionality of the ATLAS detector and its reconstruction software underwent many improvements **to cope with Run 3 increase instantaneous luminosity and pileup:**

- Upgraded Detector performances, Trigger & computing
  - more sophisticated algorithms to identify physics objects
  - multi-threaded software framework AthenaMT
- **Excellent object performances for the early Run3**

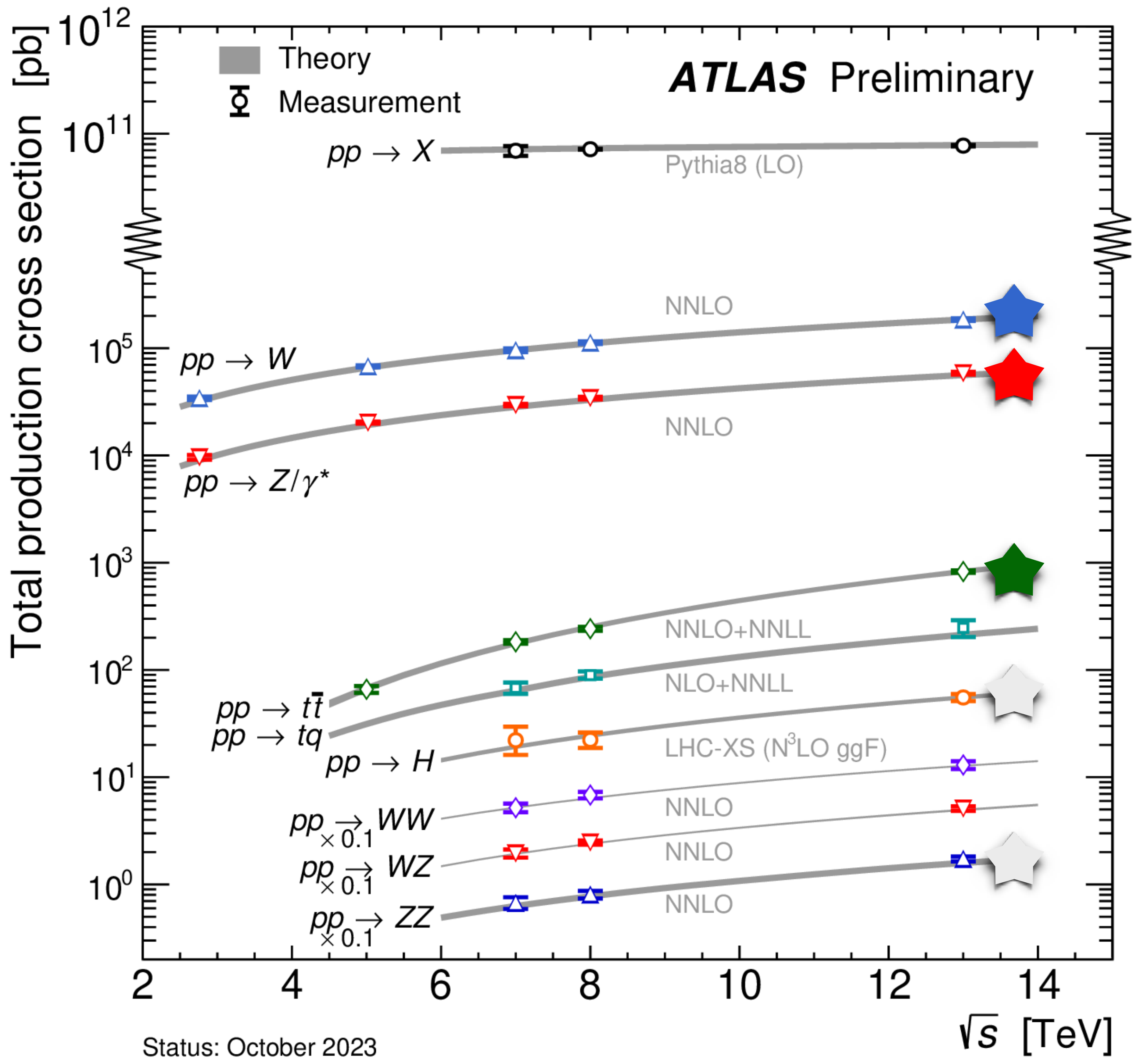








Single boson and $t\bar{t}$ x-section



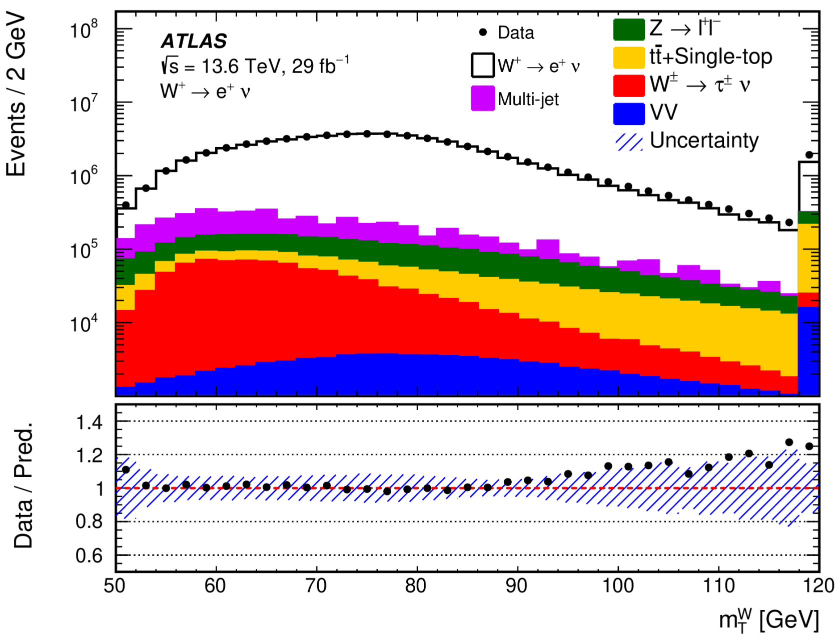
- W,Z measurements "**standard candle**" :
  - Large cross sections
  - clean experimental signature
    - used to check performance of detectors
  - check validity of the SM at the energy frontier
  - Important for early validation of detector performance and software
- Test theoretical predictions at a new centre-of-mass energy of 13.6 TeV
  - Cross section Ratios with $t\bar{t}$ **process** allow test PDF

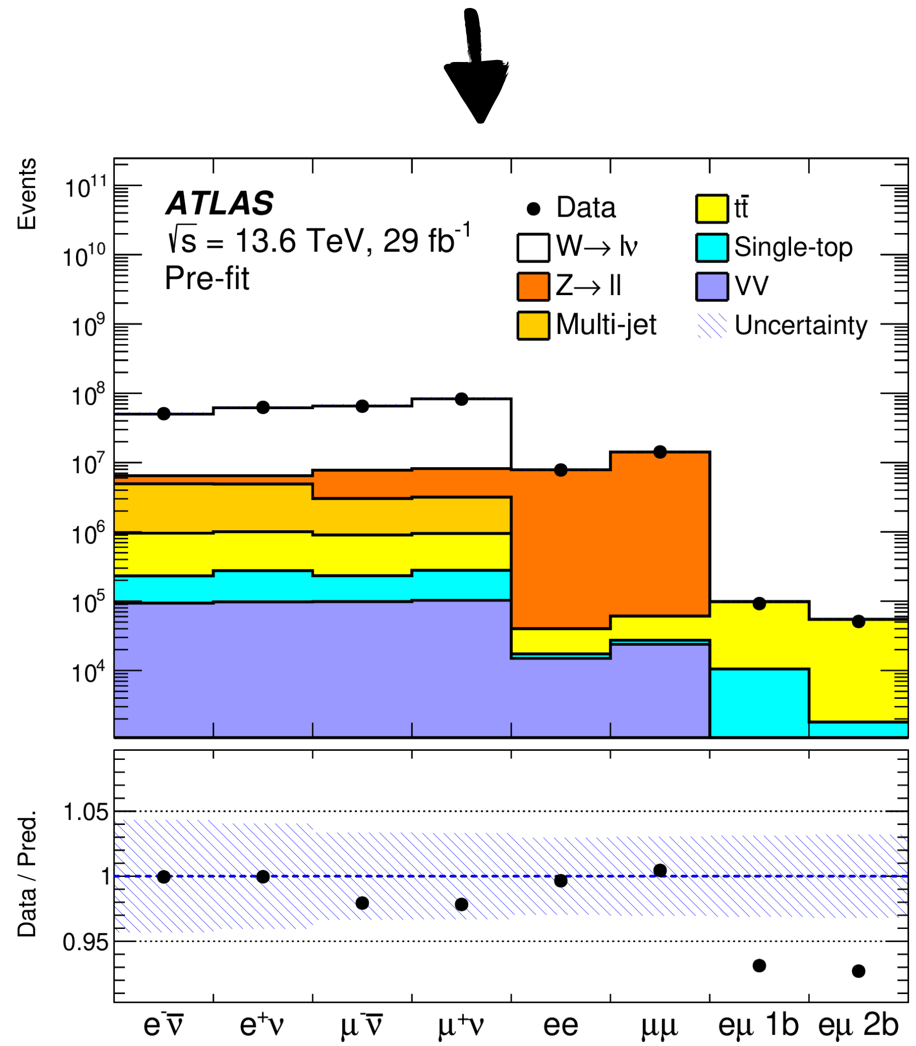
2403.12902 [hep-ex]

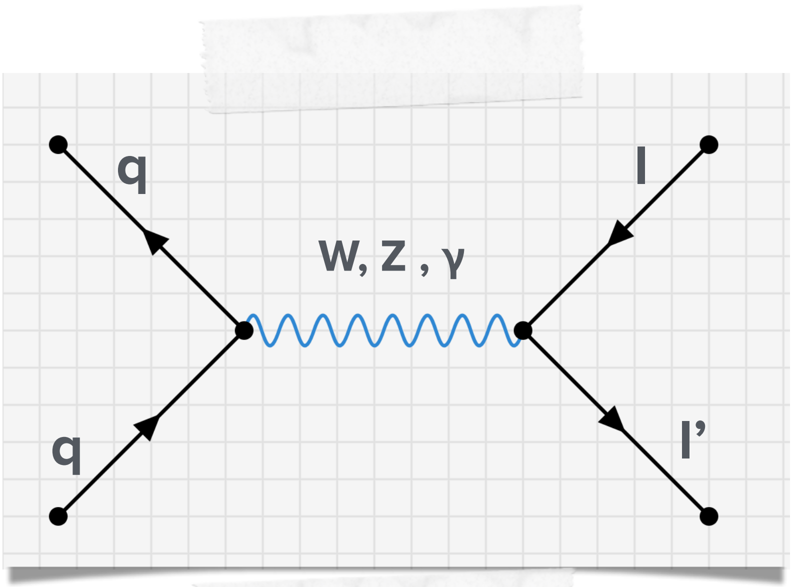
PLB 848 (2024) 138376

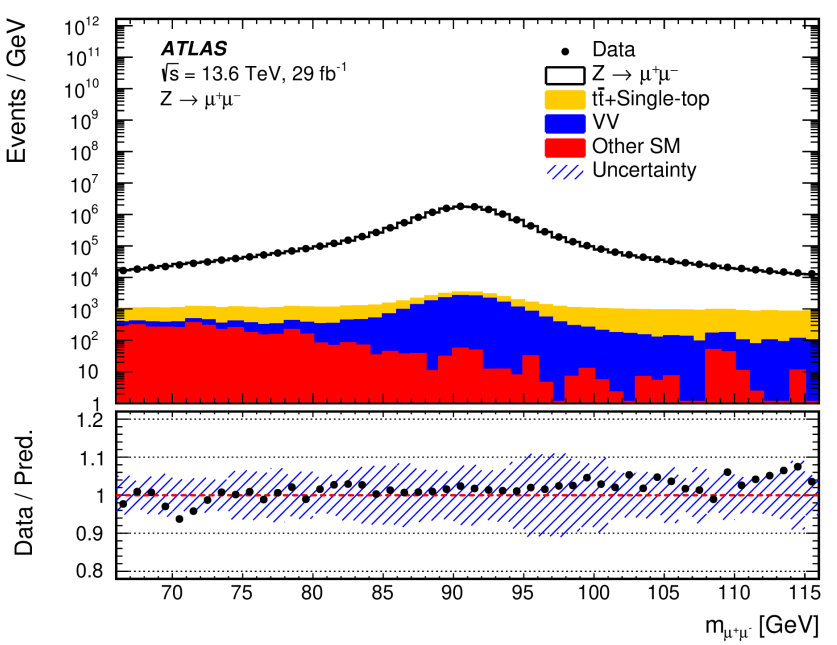
Inclusive Drell-Yan Cross-section measurement

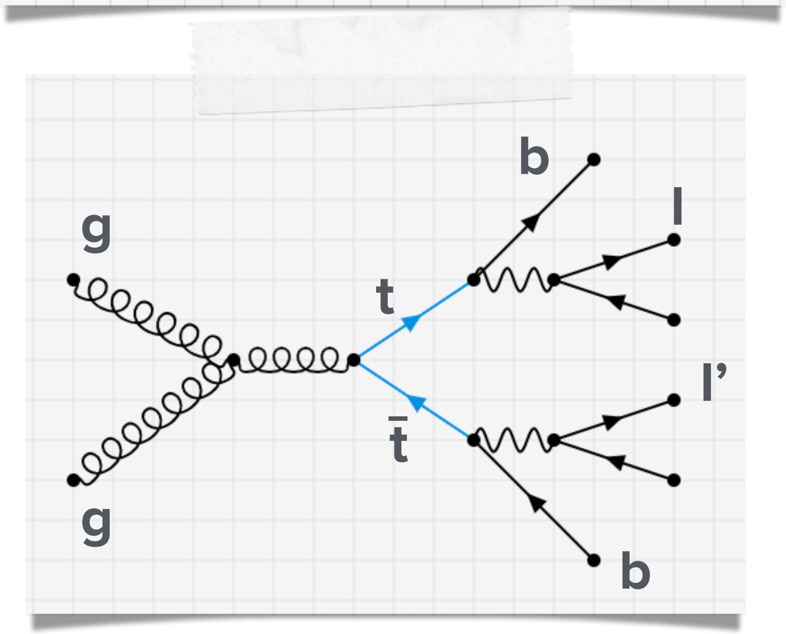
- Measurement of vector boson production cross-sections and their ratios at **13.6 TeV**
- Using **29 fb**$^{-1}$ of data collected in 2022
- Cross section obtained from Profile likelihood fit of 8 channels:
  - Leptonic final states used for reconstruction and signal identification (also for $t\bar{t}$)









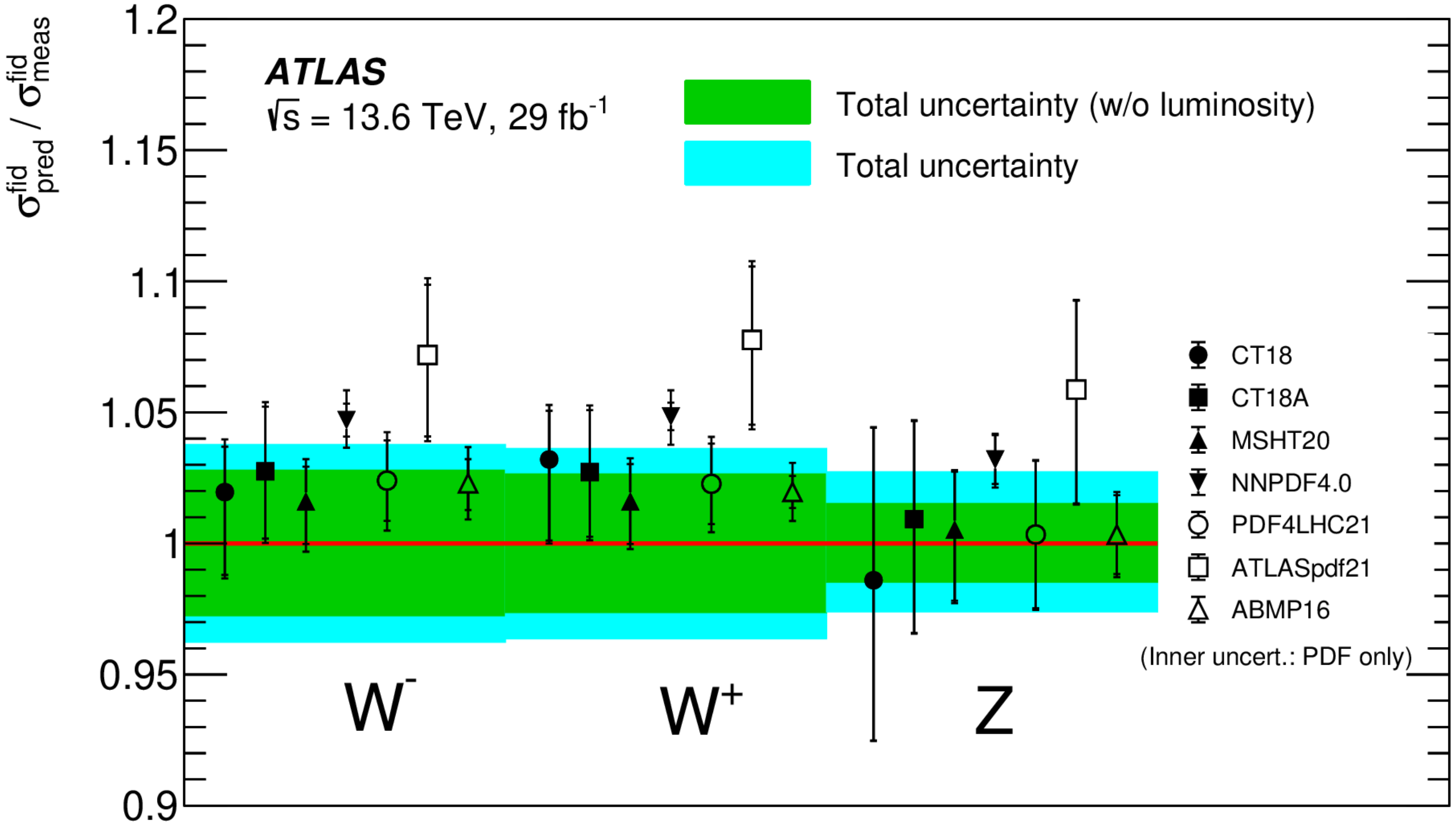


x-section measurements

Fiducial Volume:

	$pp \to \ell^+\ell^-$	$pp \to \ell^-\bar{\nu}_\ell$ / $pp \to \ell^+\nu_\ell$
Lepton p_T cuts	$p_T > 27$ GeV	$p_T > 27$ GeV
Lepton η cuts	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
Mass cuts	$66 < m_{\ell\ell} < 116$ GeV	$m_T^W > 50$ GeV
Neutrino cuts	–	$E_T^{miss} > 25$ GeV

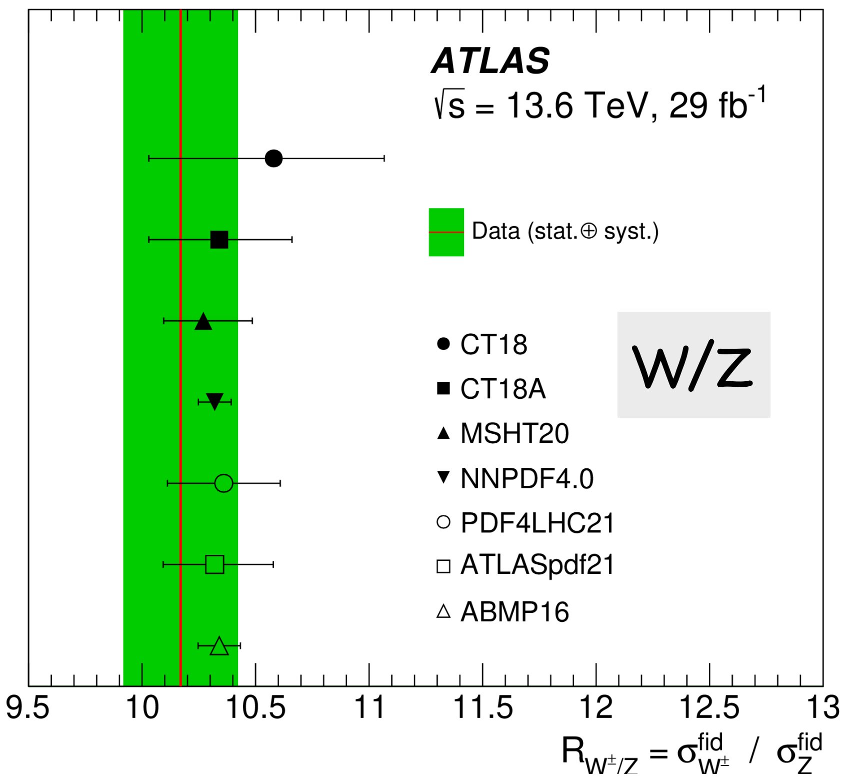
- Fiducial cross sections compared to theoretical predictions calculated with **different PDFs**
- Benchmark for our understanding of QCD and EW processes
- Measurement compared to the state-of-the-art MC and analytical NNLO+NNLL (QCD) + NLO (EWK)]
- Good agreement between results and SM prediction

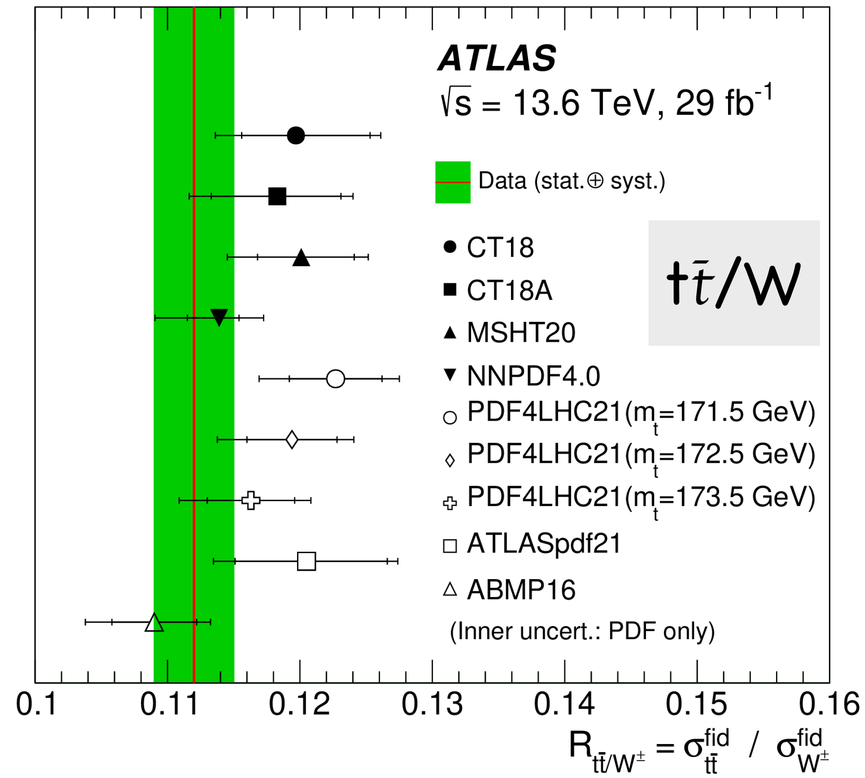


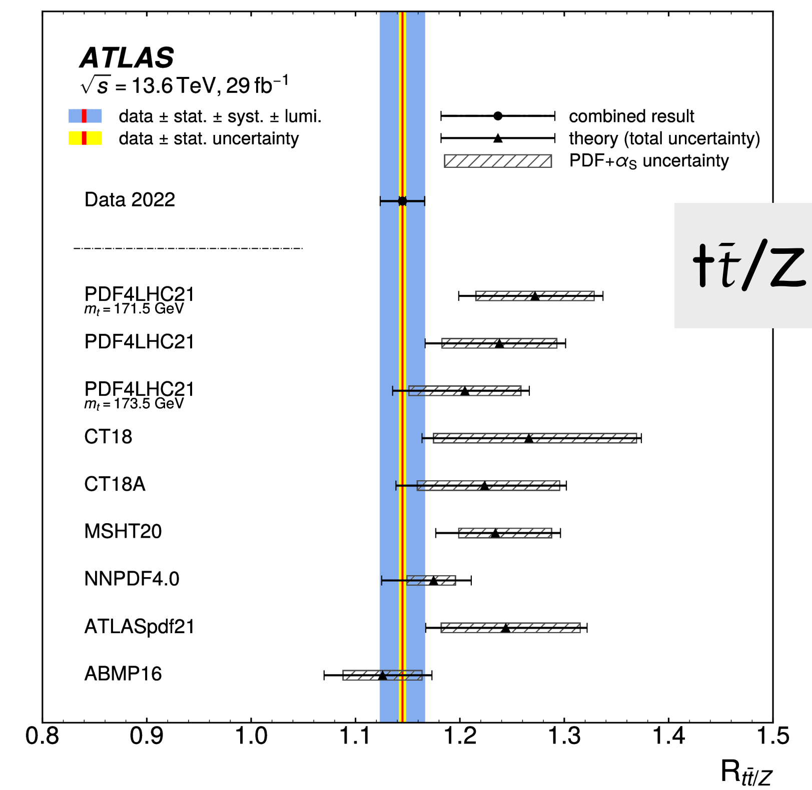
Z-boson cross sections limited by the luminosity and lepton uncertainties.

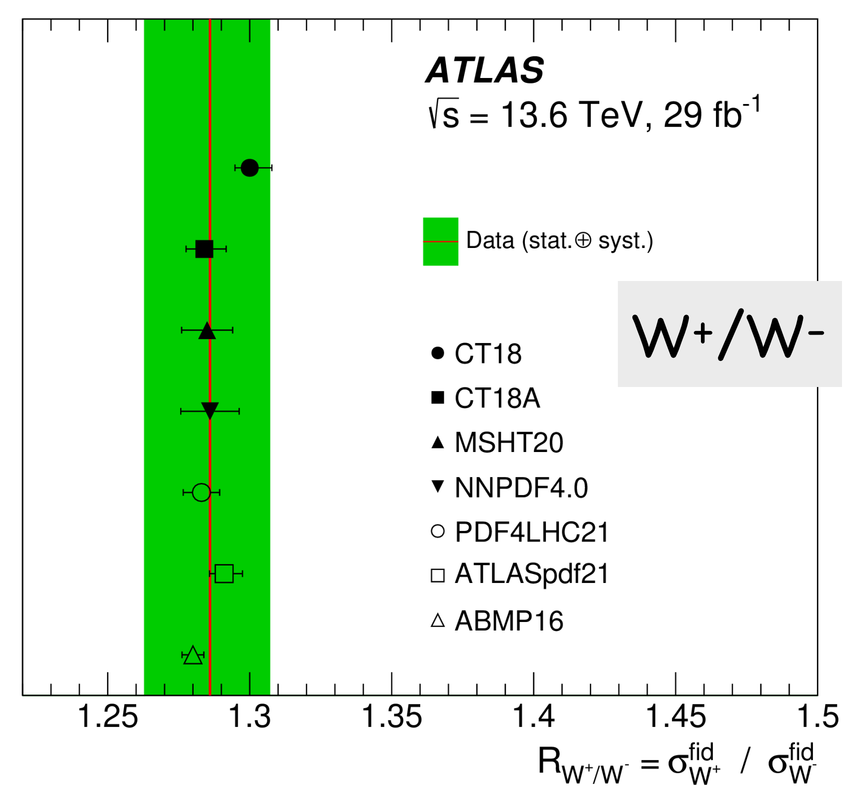
W-boson cross sections, the multi-jet background and jet-related uncertainties are dominant

x-section ratio







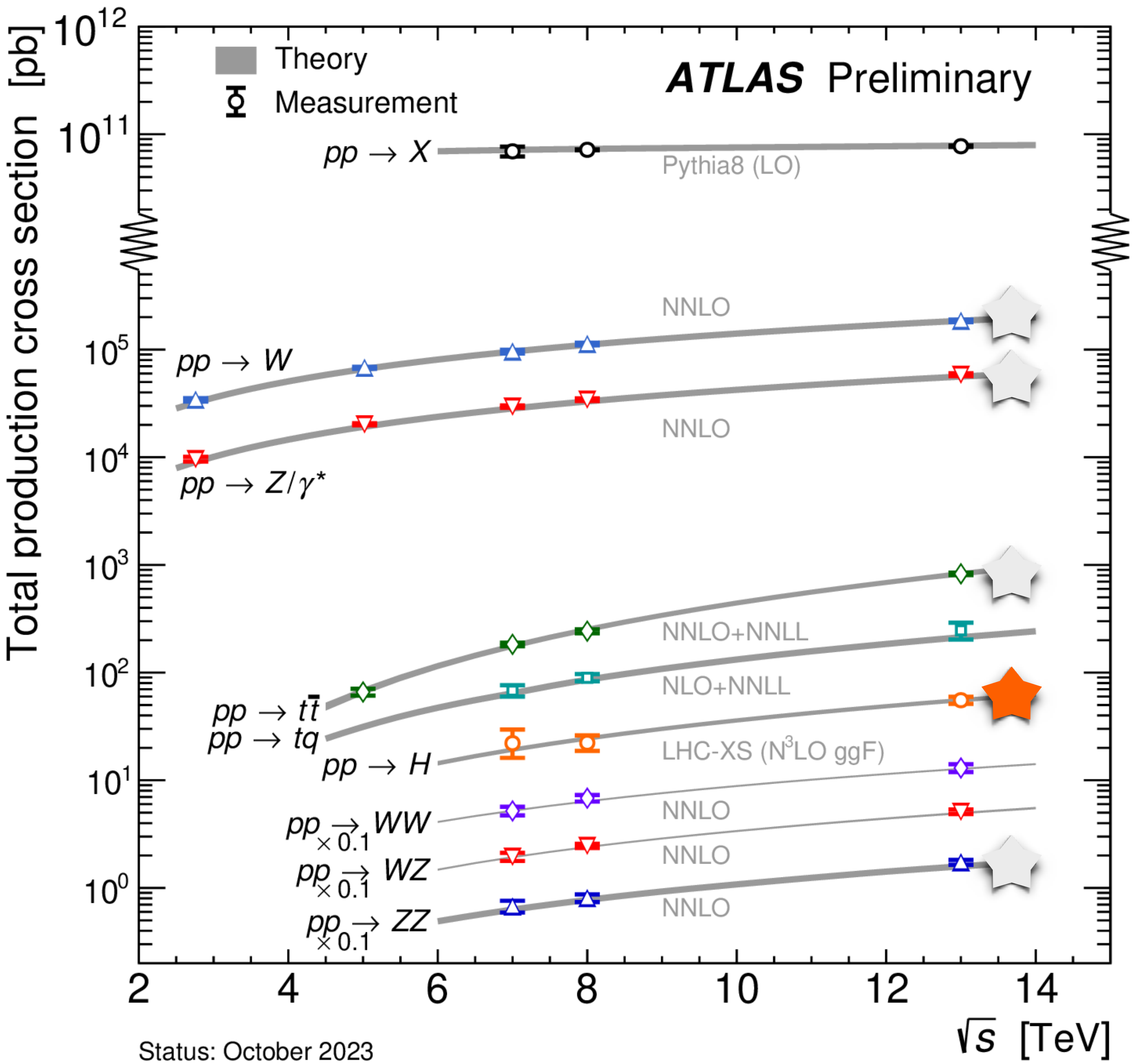


In the x-section ratio some uncertainties are reduce/increase because of correlation between process:

- lepton experimental uncertainty cancel between processes
- $t\bar{t}$/W,Z theory uncertainty (in particular PDF) do not cancel in ratio
    - $t\bar{t}$/W,Z cross section ratio ⇒ **data precision better then theory**

  slightly lower than **PDF4LHC21** prediction, but consistent with $t\bar{t}$ x-section measurement PLB 848 (2024) 138376

Higgs boson production cross-section



Check the X-section of the Higgs boson at new energy frontier :

- **H→γγ and H→ZZ^{*}→4ℓ** "golden channels"
- Experimental measurement are compared with **N³LO [ggF] theoretical accuracy**

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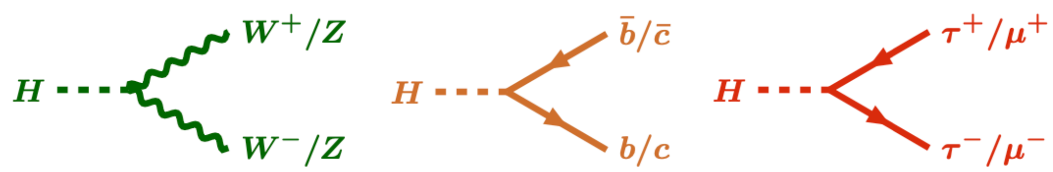
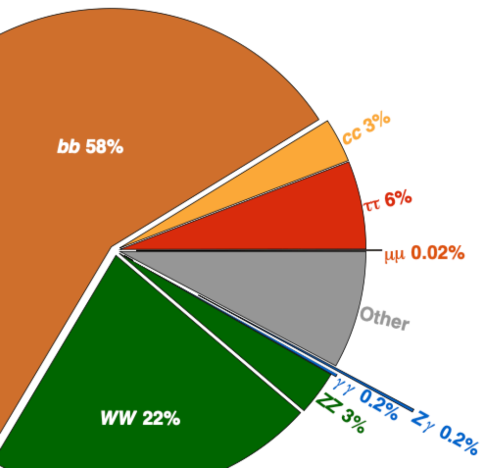
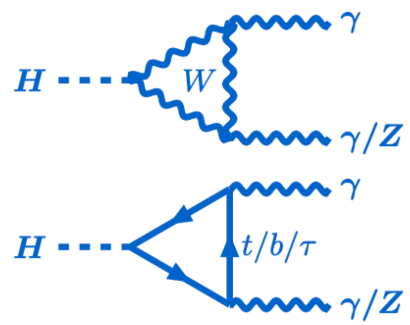
Inclusive Higgs boson production x-section @13.6 TeV

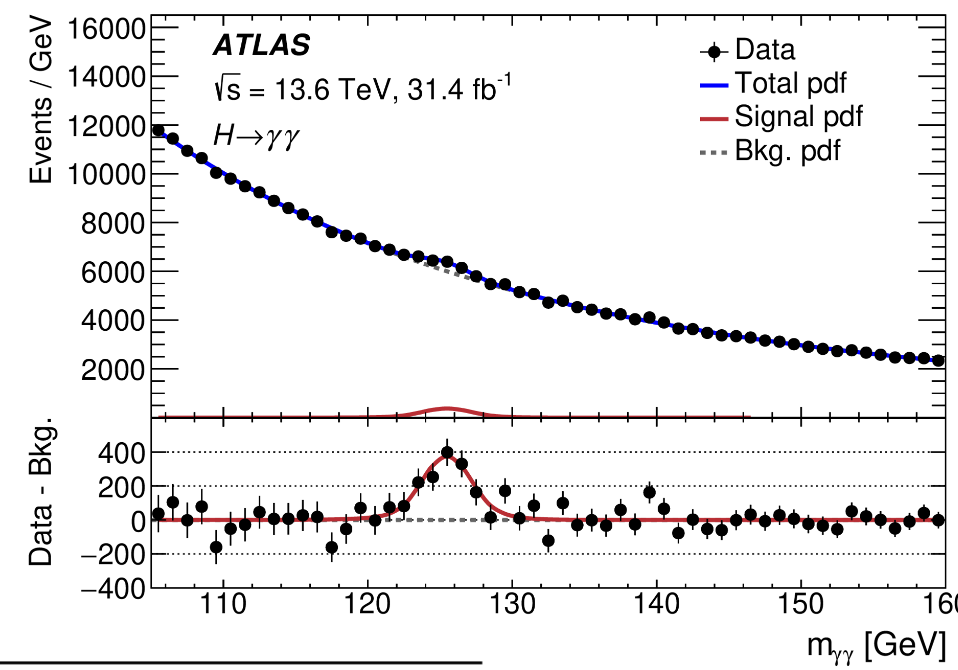


Higgs boson decays directly into massive particles (except into t quarks)

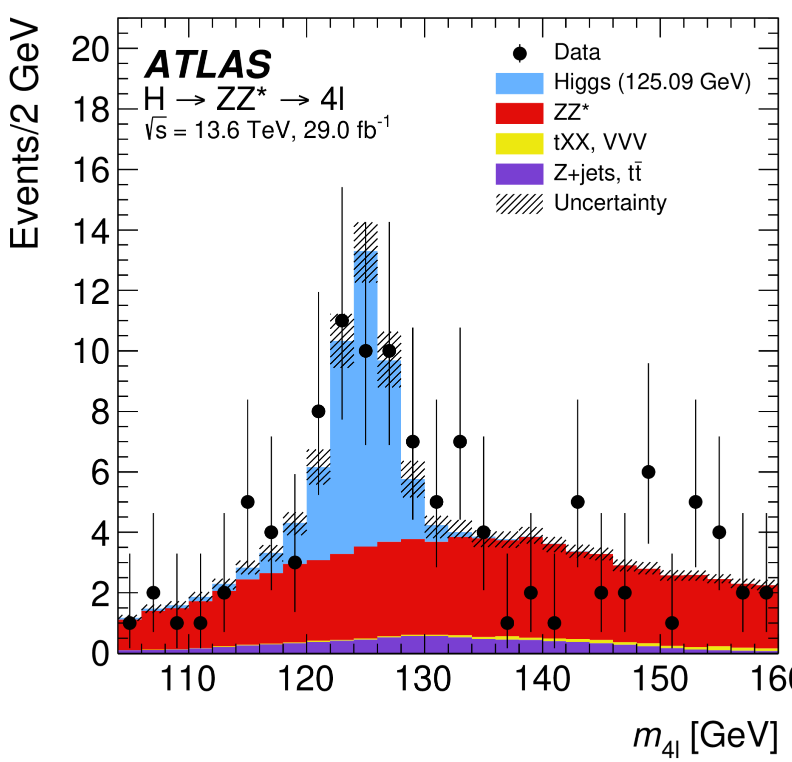




- H→γγ and H→ZZ^*→4ℓ "golden channels"
  - **small** branching rations
  - **excellent** mass reconstruction.
- First data measurement at √s =13.6TeV with 29 fb[-1]
- Signal yield extracted from a likelihood fit on the H mass pick

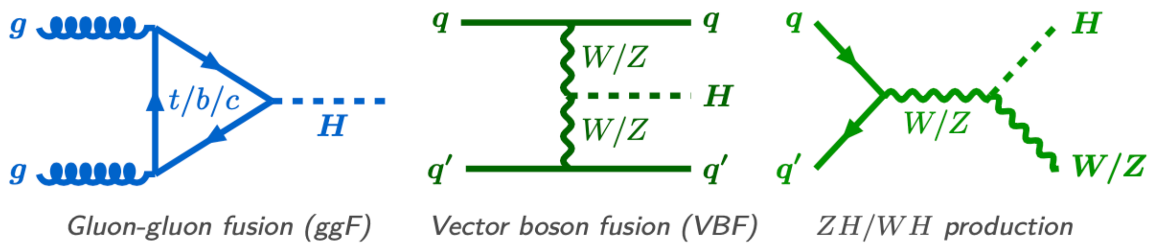


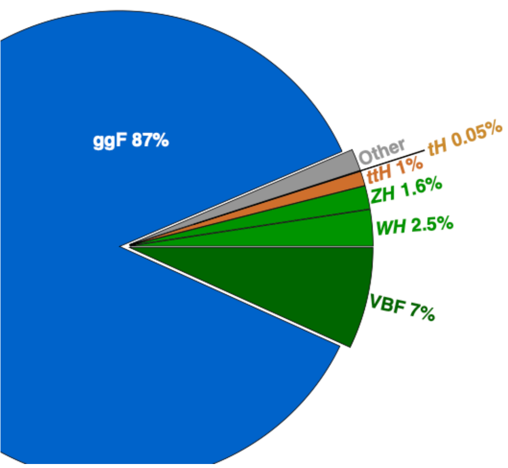
Photons	
Leading (sub-leading) p_T^γ	$p_T^\gamma/m_{\gamma\gamma} > 0.35(0.25)$
Pseudorapidity	$\lvert\eta\rvert < 2.47$ and outside $1.37 < \lvert\eta\rvert < 1.52$
Isolation	$E_T^{iso}/E_T^\gamma < 0.05$
Di-photon system	
	105 GeV $< m_{\gamma\gamma} <$ 160 GeV

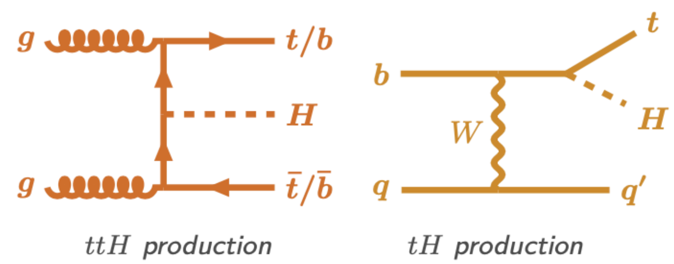


Leptons	
Leptons	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	quadruplet with largest matrix element value

Inclusive Higgs boson production x-section @13.6 TeV







H→γγ H→ZZ^*→4ℓ cross-sections are measured inclusively in the production modes within fiducial volume.

- The MC samples are normalised to the **state-of-the-art cross-section predictions:**
  - **compared with N³LO accuracy prediction (ggF)** + NLO EW corrections
  - **VBF/VH** to an approximate NNLO QCD + NLO EW corrections

H→γγ

$$\sigma_{\text{fid}} = 76 \pm 11\,(\text{stat.})\,{}^{+9}_{-7}\,(\text{syst.})$$

$$\sigma_{\text{fid,SM}} = 67.6 \pm 3.7\text{ fb.}$$

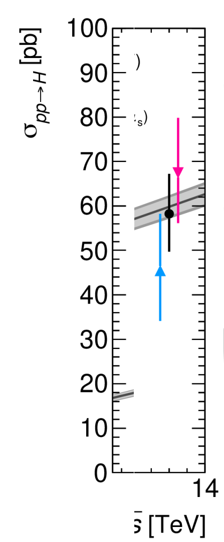
H→ZZ^*→4ℓ

$$\sigma_{\text{fid}} = 2.80 \pm 0.70\,(\text{stat.}) \pm 0.21\,(\text{syst.})$$

$$\sigma_{\text{fid,SM}} = 3.67 \pm 0.19\text{ fb.}$$

Measurements statistically limited

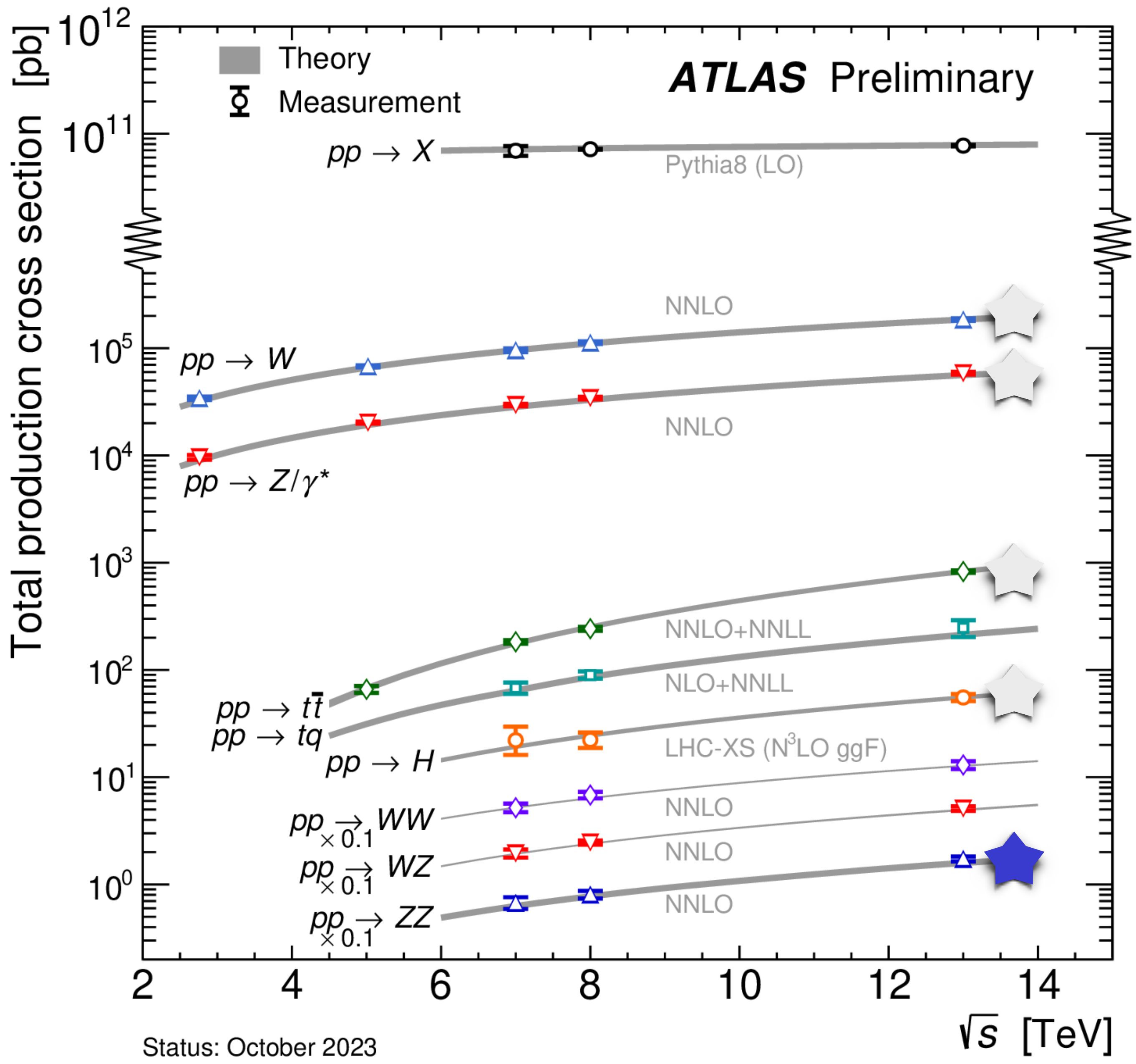
Fiducial cross-sections are extrapolated to the full phase space corrected for the predicted SM decay BR [assuming SM values] (p-value 20%) and combined.



$$\sigma(pp \to H) = 58.2 \pm 8.7\text{ pb,}$$

$$\sigma(pp \to H)_{\text{SM}} = 59.9 \pm 2.6\text{ pb.}$$

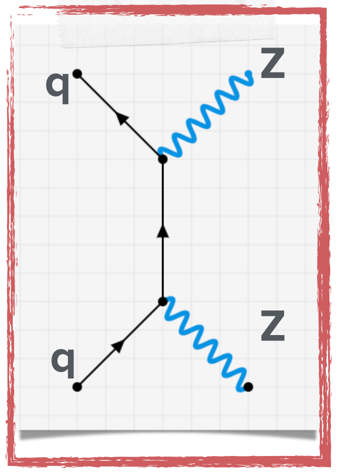
Diboson production

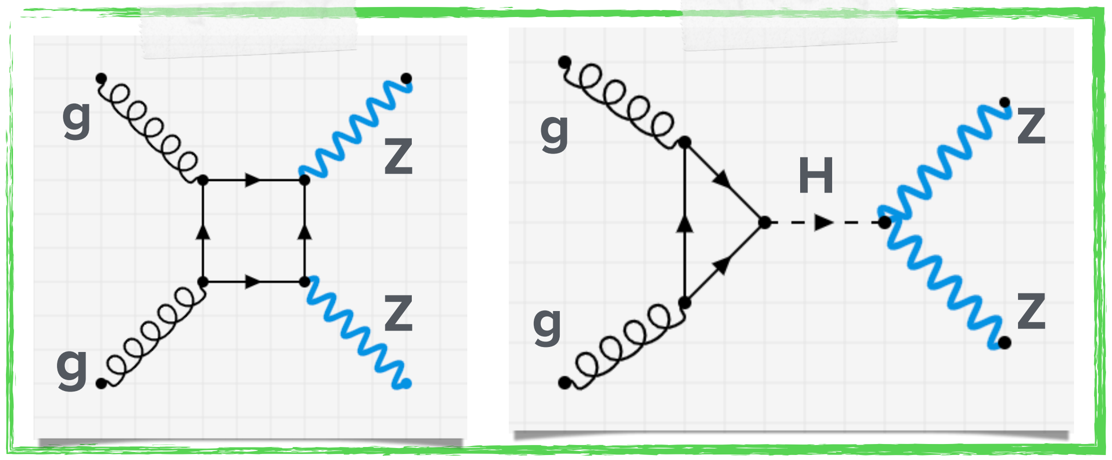


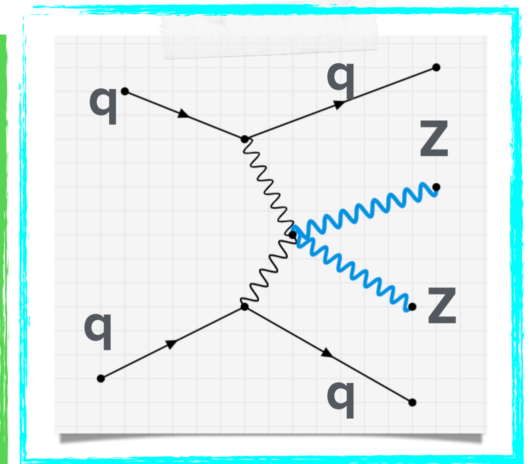
Rare SM processes key ingredients for the current and future LHC physics program direct connections with two fundamental features of the SM EW theory *[non-Abelian gauge group structure and spontaneous EW symmetry breaking]*

arXiv:2311.09715 [hep-ex]

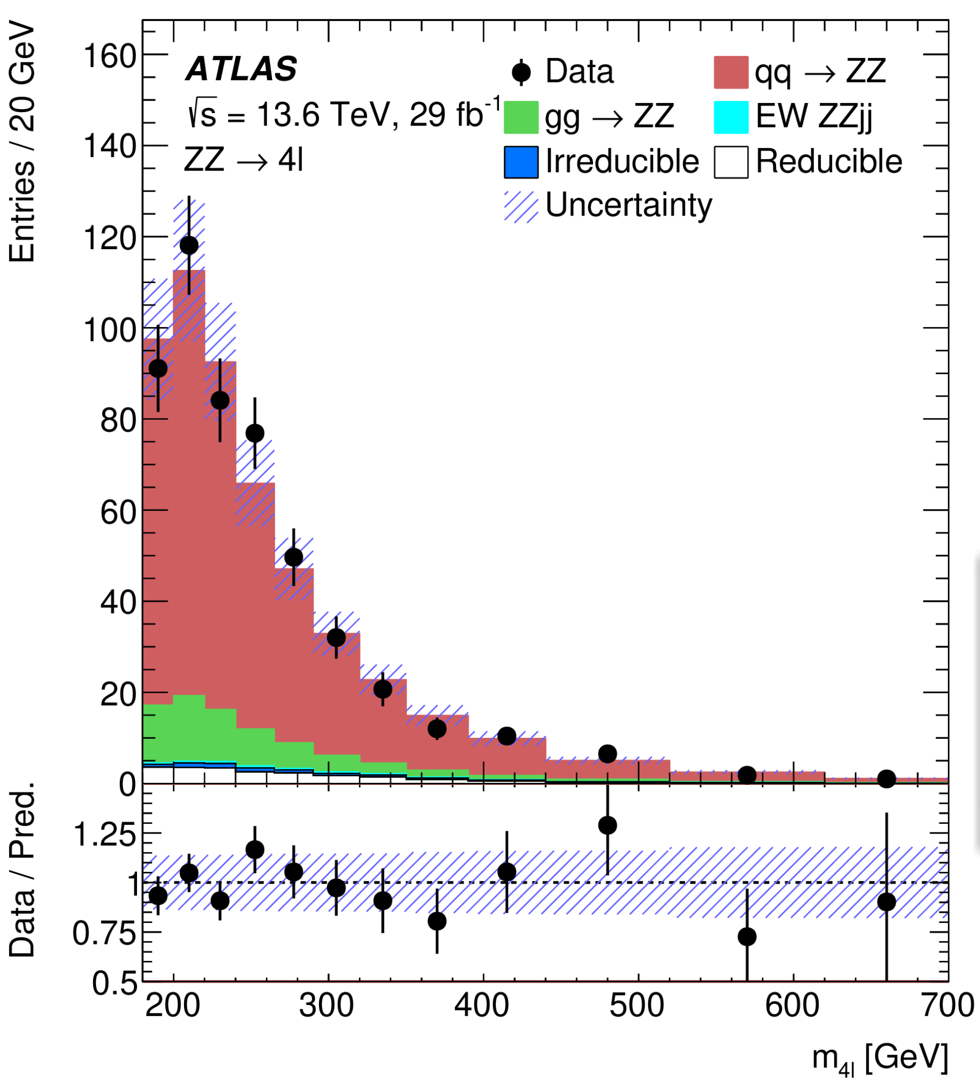
ZZ productions







$ZZ \to 4\ell$ fiducial/total cross-section is measured inclusively in the production modes at $\sqrt{s}$ =13.6TeV with 29fb^{-1}



	Fiducial phase space	Total lepton phase space
Muon selection	Bare, $p_T > 5$ GeV, $\lvert\eta\rvert < 2.5$	Born
Electron selection	Dressed, $p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$	Born
Four-lepton signature	≥ 2 SFOC pairs	≥ 2 SFOC pairs
Lepton kinematics	$p_T > 27/10$ GeV	
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$	
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180$ GeV	

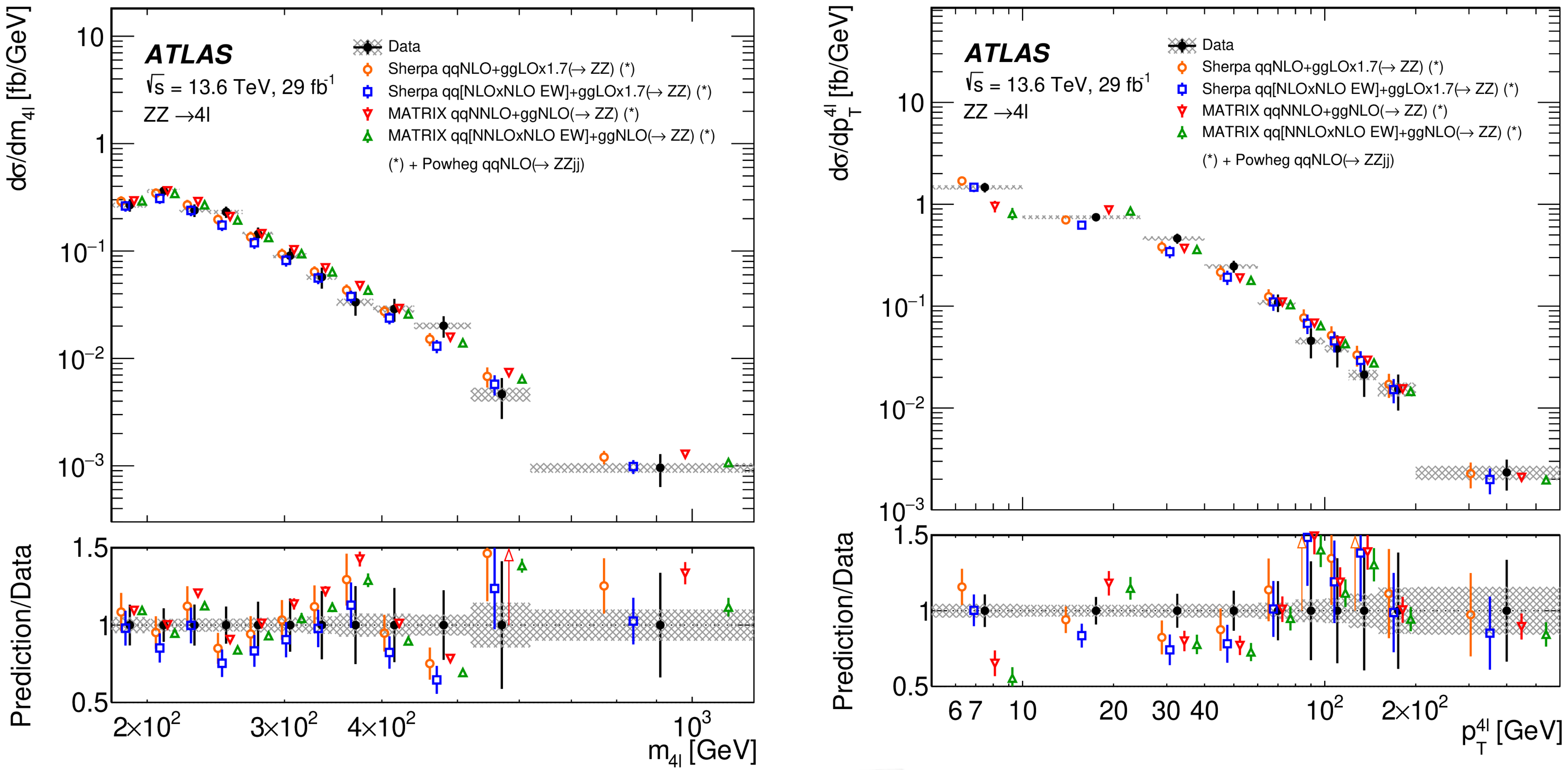
- $\sigma_{fid} = N_{Sig.evs} / C \times BR \times \mathcal{L}$ where C is the detector eff
- $\sigma_{tot} = \sigma_{fid}/A$, where A is the detector acceptance

	Measurement	MC prediction	MATRIX prediction
Fiducial	$36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})$ fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	$16.8 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

Main sys uncertainty coming from Luminosity and Lepton sys
⇒ Better calibration is foreseen for the full run-3 dataset

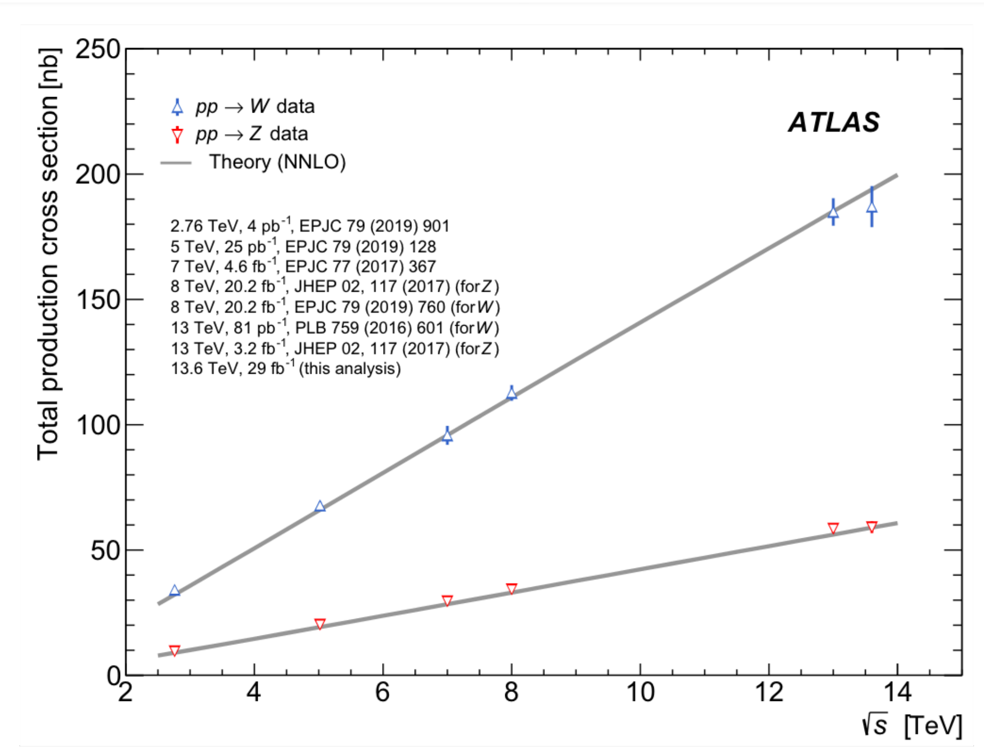
differential cross-sections

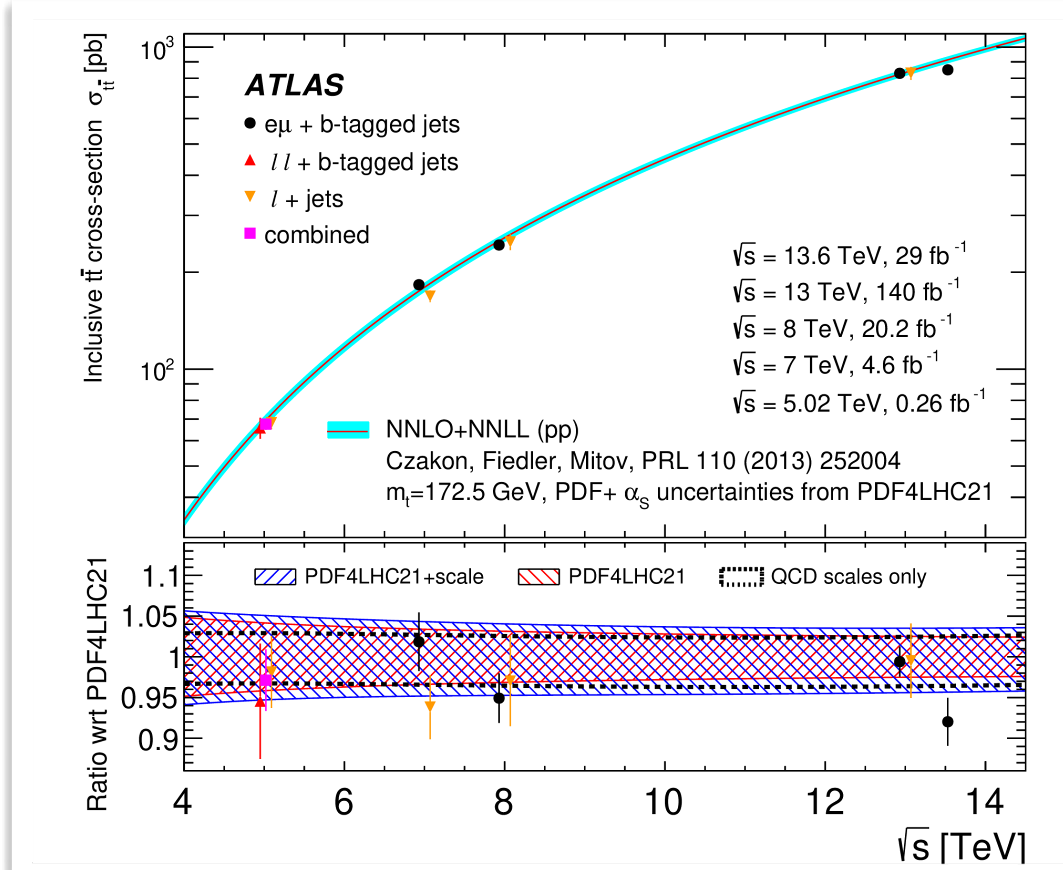
Bayesian unfolding use to extract differential measurement:

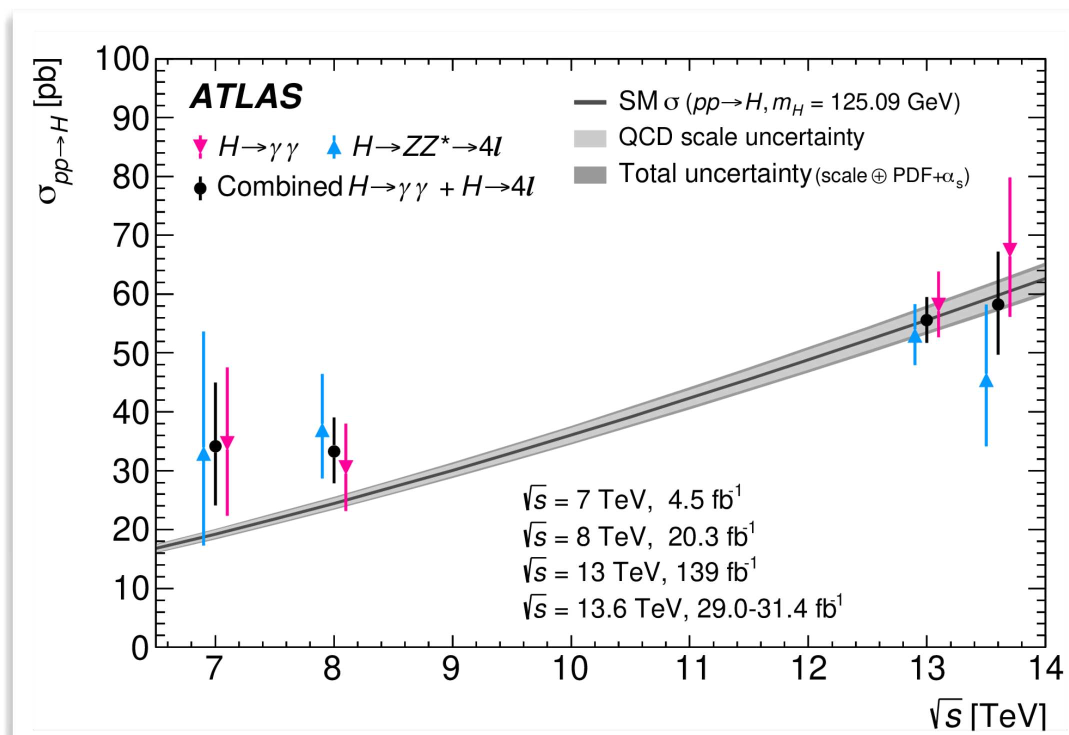


Compare with state-of-the-art MC simulation & fixed-order MATRIX calculations up to NNLO QCD + NLO EW

Conclusion



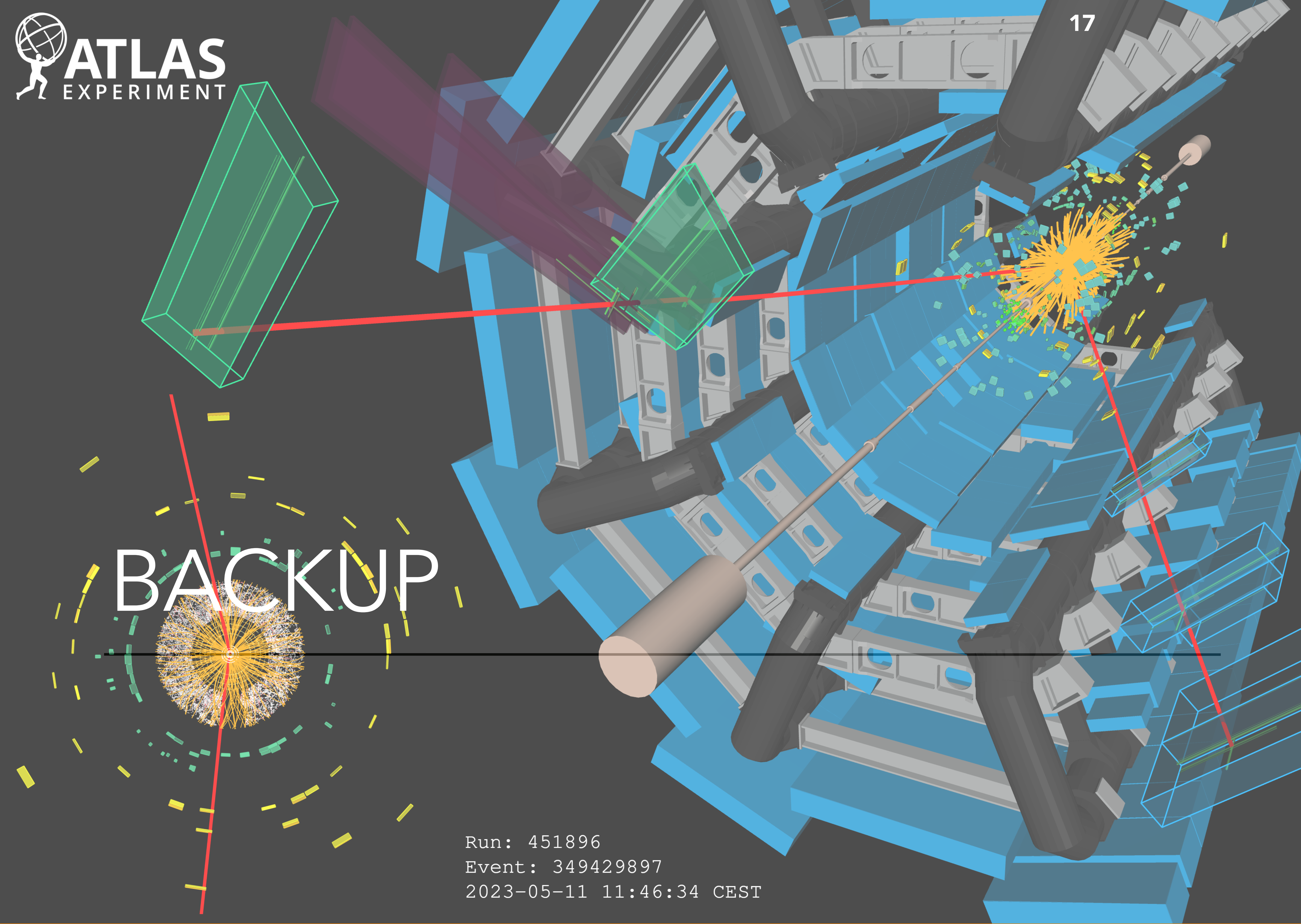




LHC Run-3 has started in July 2022, with collisions at the unprecedented center of mass energy of 13.6 TeV

This is only the beginning of the exciting run-3 LHC physics program with the ATLAS experiment!

BACKUP

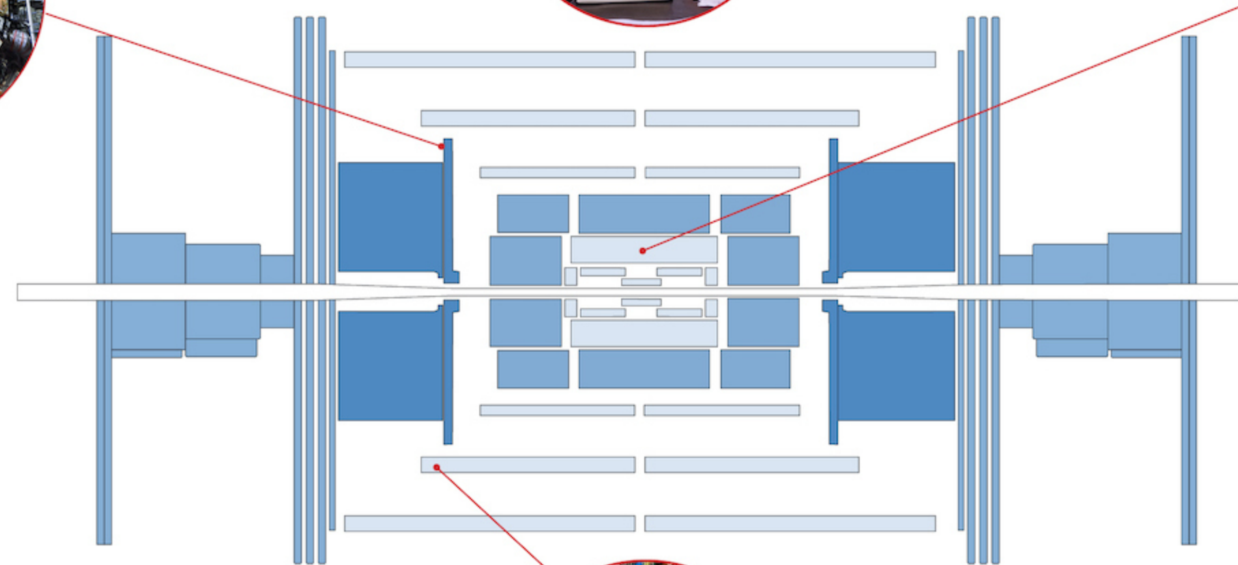

ATLAS
EXPERIMENT
Run: 451896
Event: 349429897
2023-05-11 11:46:34 CEST

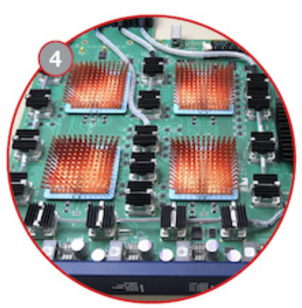
ATLAS detector LS2 Upgrades

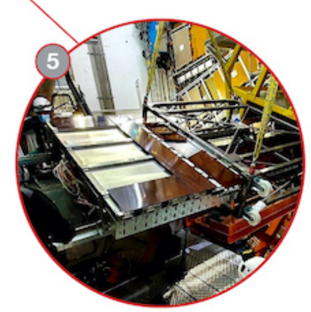
MUON NEW SMALL WHEELS (NSW)
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

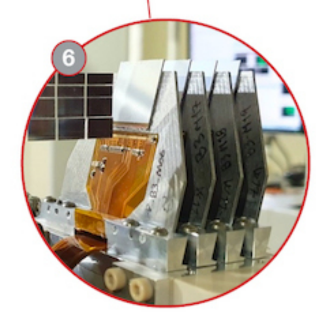
NEW READOUT SYSTEM FOR THE NSWs
The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

LIQUID ARGON CALORIMETER
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.









TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)
Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

NEW MUON CHAMBERS IN THE CENTRE OF ATLAS
Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

ATLAS FORWARD PROTON (AFP)
Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.

Breakdown of uncertainty (W,Z measurement)

Category	$\sigma(Z \to ee)$	$\sigma(Z \to \mu\mu)$	$\sigma(Z \to \ell\ell)$	$\sigma(W^- \to e^-\bar{\nu})$	$\sigma(W^+ \to e^+\nu)$	$\sigma(W^- \to \mu^-\bar{\nu})$	$\sigma(W^+ \to \mu^+\nu)$
Luminosity	2.2	2.2	2.2	2.5	2.5	2.5	2.4
Pile-up	1.2	0.3	0.8	1.1	1.1	0.3	0.4
MC statistics	< 0.2	< 0.2	< 0.2	< 0.2	0.4	< 0.2	0.4
Lepton trigger	0.2	0.4	0.2	1.2	1.3	1.0	1.0
Electron reconstruction	1.4	–	0.9	0.7	0.8	–	–
Muon reconstruction	–	2.1	1.4	–	–	1.0	1.0
Multi-jet	–	–	–	2.9	2.4	1.3	1.1
Other background modelling	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.5	0.4
Jet energy scale	–	–	–	1.4	1.4	1.3	1.4
Jet energy resolution	–	–	–	< 0.2	0.3	0.2	0.2
NNJVT	–	–	–	1.6	1.5	1.3	1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ track soft term	–	–	–	< 0.2	0.4	< 0.2	< 0.2
PDF	0.2	0.2	< 0.2	0.8	0.8	0.6	0.5
QCD scale (ME and PS)	0.6	< 0.2	0.3	1.3	1.2	0.6	0.6
Flavour tagging	–	–	–	–	–	–	–
$t\bar{t}$ modelling	–	–	–	–	–	–	–
Total systematic impact [%]	3.0	3.1	2.7	5.0	4.5	3.8	3.6
Statistical impact [%]	0.04	0.03	0.02	0.02	0.01	0.01	0.01

Category	$\sigma(W^- \to \ell^-\bar{\nu})$	$\sigma(W^+ \to \ell^+\nu)$	$\sigma(W^\pm \to \ell\nu)$	R_{W^+/W^-}	$R_{W^\pm/Z}$	$R_{t\bar{t}/W^\pm}$
Luminosity	2.5	2.4	2.4	< 0.2	0.3	< 0.2
Pile-up	0.5	0.7	0.6	< 0.2	< 0.2	< 0.2
MC statistics	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
Lepton trigger	1.0	0.9	0.9	< 0.2	0.7	0.8
Electron reconstruction	0.4	0.5	0.4	< 0.2	0.5	0.4
Muon reconstruction	0.6	0.6	0.6	0.2	0.8	0.6
Multi-jet	1.2	1.2	1.2	1.6	1.1	1.0
Other background modelling	0.4	0.4	0.4	< 0.2	0.3	0.9
Jet energy scale	1.3	1.3	1.3	< 0.2	1.3	1.3
Jet energy resolution	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
NNJVT	1.4	1.3	1.3	< 0.2	1.3	< 0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ track soft term	< 0.2	0.3	0.3	< 0.2	0.3	0.3
PDF	0.5	0.5	0.3	0.5	0.2	0.4
QCD scale (ME and PS)	0.8	0.7	0.6	< 0.2	0.7	0.7
Flavour tagging	–	–	–	–	–	< 0.2
$t\bar{t}$ modelling	–	–	–	–	–	1.1
Total systematic impact [%]	3.7	3.5	3.5	1.7	2.4	2.5
Statistical impact [%]	0.01	0.01	0.01	0.01	0.02	0.32

Breakdown of uncertainty (H, ZZ measurement)

Breakdown of relative unc, ZZ

Source	Relative uncertainty(%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3

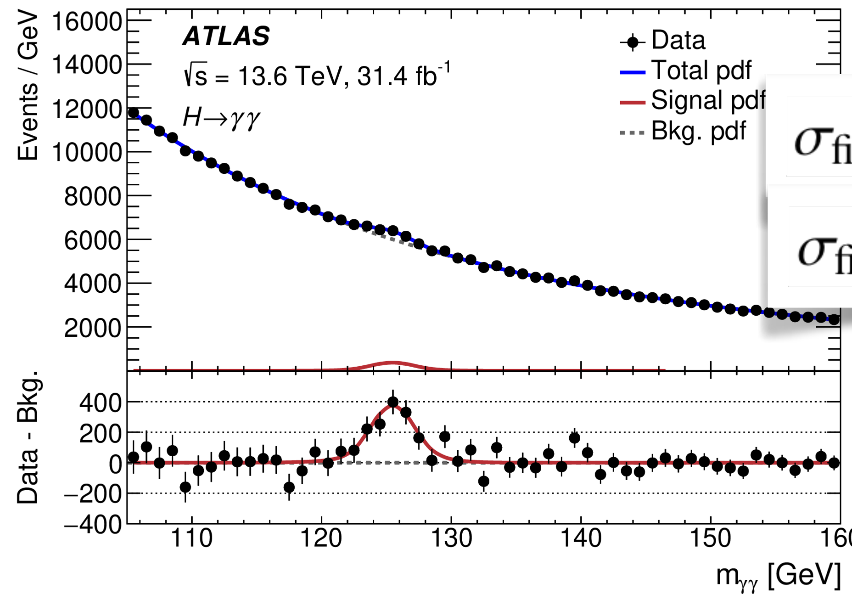
Table 7: Breakdown of the relative uncertainties in the fiducial $H \to ZZ^* \to 4\ell$ cross-section measurement.

Source	Uncertainty [%]
Statistical uncertainty	25.1
Systematic uncertainty	7.9
Electron uncertainties	6.3
Muon uncertainties	3.8
Luminosity	2.2
ZZ^* theoretical uncertainties	0.7
Reducible background estimation	0.6
Other uncertainties	<1.0
Total	26.4

Table 3: Breakdown of the relative uncertainties in the inclusive di-photon fiducial cross-section measurement.

Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

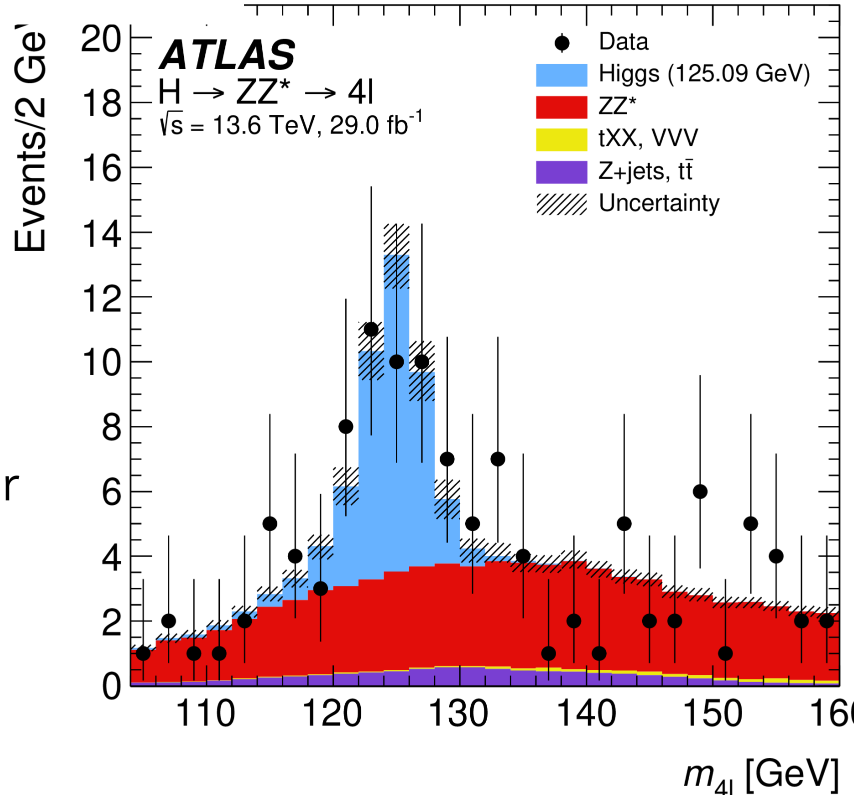
Photons	
Leading (sub-leading) p_{T}^{γ}	$p_{\mathrm{T}}^{\gamma}/m_{\gamma\gamma} > 0.35(0.25)$
Pseudorapidity	$\lvert\eta\rvert < 2.47$ and outside $1.37 < \lvert\eta\rvert < 1.52$
Isolation	$E_{\mathrm{T}}^{\mathrm{iso}}/E_{\mathrm{T}}^{\gamma} < 0.05$
Di-photon system	
Mass window	$105\ \mathrm{GeV} < m_{\gamma\gamma} < 160\ \mathrm{GeV}$



$$\sigma_{\mathrm{fid}} = 76 \pm 11\ (\mathrm{stat.})\ ^{+9}_{-7}\ (\mathrm{syst.})$$

$$\sigma_{\mathrm{fid,SM}} = 67.6 \pm 3.7\ \mathrm{fb.}$$

Leptons	
Leptons	$p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Lepton selection and pairing	
Lepton kinematics	$p_{\mathrm{T}} > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements	$50\ \mathrm{GeV} < m_{12} < 106$ GeV and $12\ \mathrm{GeV} < m_{34} < 115$ GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	$105\ \mathrm{GeV} < m_{4\ell} < 160$ GeV
If extra lepton with $p_{\mathrm{T}} > 12$ GeV	quadruplet with largest matrix element value



$$\sigma_{\mathrm{fid}} = 2.80 \pm 0.70\ (\mathrm{stat.}) \pm 0.21\ (\mathrm{syst.})$$

$$\sigma_{\mathrm{fid,SM}} = 3.67 \pm 0.19\ \mathrm{fb.}$$

H→γγ H→ZZ^*→4ℓ cross-sections are measured inclusively in the production modes within fiducial volume.

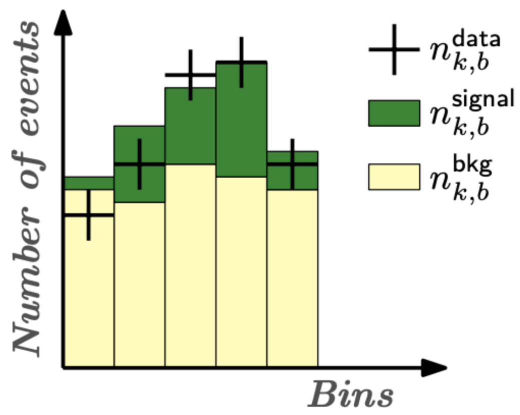
- Fiducial cross-sections are extrapolated to the full phase space corrected for the predicted SM decay BR [assuming SM values] and combined.
- The MC samples are normalised to the **state-of-the-art cross-section predictions:**
  - **ggF** up to N3LO QCD calculation + NLO EW corrections
  - **VBF/VH** to an approximate NNLO QCD + NLO EW corrections
- **Measurements statistically limited** (p-value 20%)

- **Profiled likelihood ratios used to obtain the results**
- **Combined likelihood** = products of likelihoods from individual channels/categories (k)

$$L(\boldsymbol{\alpha}, \boldsymbol{\theta}, \text{data}) = \prod_{k} \prod_{b \in \text{bins}} \underbrace{P(n_{k,b}^{\text{data}} \mid n_{k,b}^{\text{signal}}(\boldsymbol{\alpha}, \boldsymbol{\theta}) + n_{k,b}^{\text{bkg}}(\boldsymbol{\theta}))}_{\text{Poisson distribution}} \underbrace{\prod_{\theta \in \boldsymbol{\theta}} G(\theta)}_{\text{Constraints}}$$

$\boldsymbol{\alpha}$: parameters of interest

$\boldsymbol{\theta}$: nuisance parameters (uncertainties)



- **Profiled likelihood ratios used to obtain the results**
- **Combined likelihood** = products of likelihoods from individual channels/categories (k)

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$\boldsymbol{\alpha}$: parameters of interest

$\boldsymbol{\theta}$: nuisance parameters (uncertainties)

- **Number of signal events** in category k:

$$n_{k,b}^{\text{signal}} = \mathcal{L} \underbrace{\sum_{i} \sum_{f}}_{\text{Production and decay}} \underbrace{(\sigma \times B)_{if}}_{\text{Cross-section} \times \text{branching ratio}} \underbrace{(A \times \epsilon)_{if,k,b}}_{\text{Acceptance} \times \text{efficiency}}$$

- No or negligible overlap between categories
- Systematic uncertainties correlated