

# Standard Model measurements with ATLAS

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on behalf of the ATLAS Collaboration

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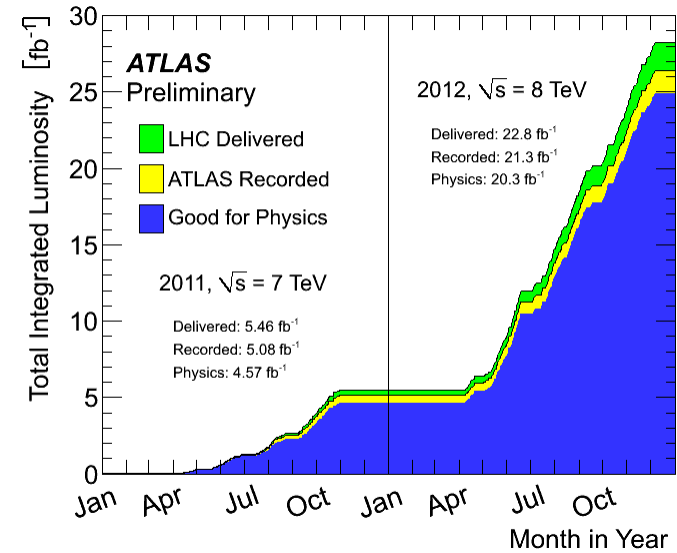
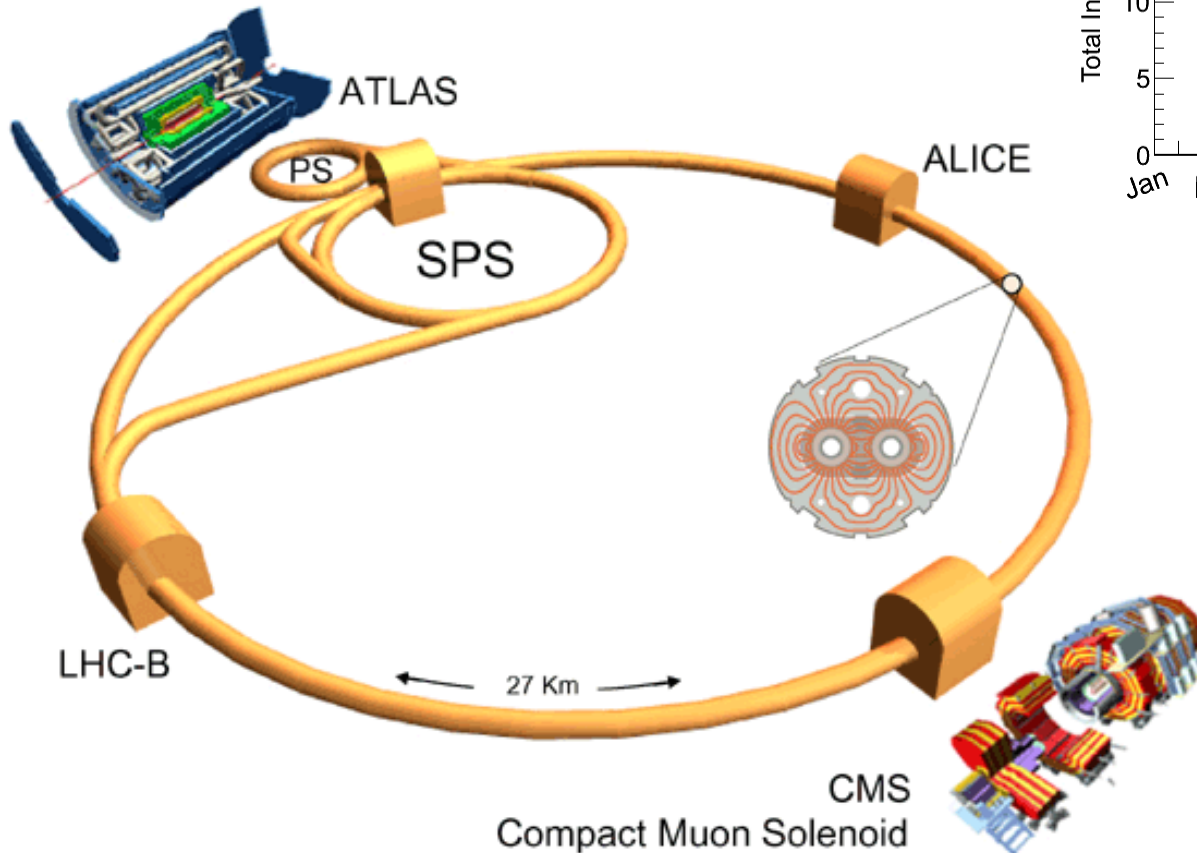


- Standard Model measurements performed to:
  - validate SM in **new energy** regime
  - understand processes which are **backgrounds** for other studies / searches
  - improve **precision** of known SM parameters
  - constrain **new physics** contributions (like anomalous couplings)
- $\approx 100$  SM ATLAS papers since LHC started; only few analyses presented here, more available at <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults>
- Selection of **recent results**, based on the categories:
  - Soft QCD, Diffraction and Forward Physics
  - Electroweak Physics: W and Z bosons, Dibosons, ....
  - Jet Physics
  - Direct Photons

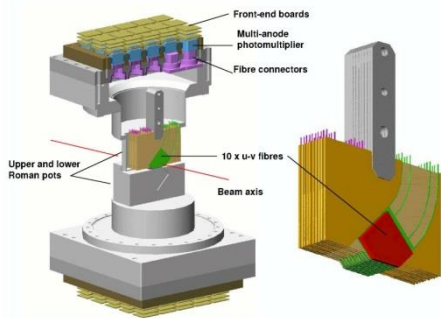
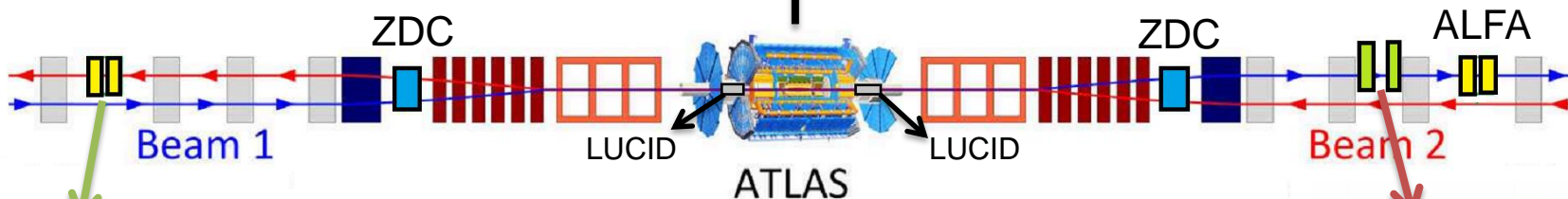
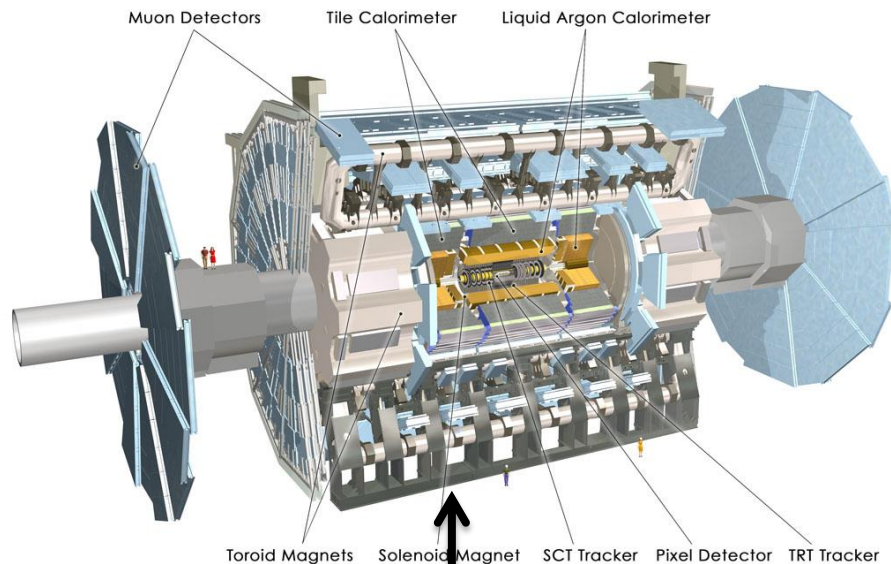
# Run-1 data collection with ATLAS detector



- Run-1 data for analysis:  $\approx 25 \text{ fb}^{-1}$
- $\sqrt{s} = 7 \text{ TeV}$ :  $4.6 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}$ :  $20.3 \text{ fb}^{-1}$

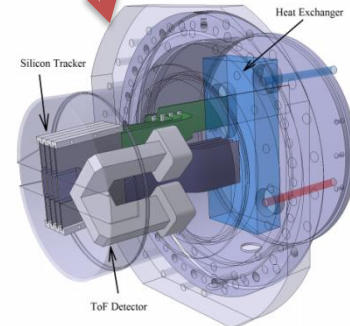


# The ATLAS sub-detectors



**ALFA:**  
elastic protons  
measurement

**AFP:**  
diffractive protons  
measurement.  
A first-phase installation  
in 2016.

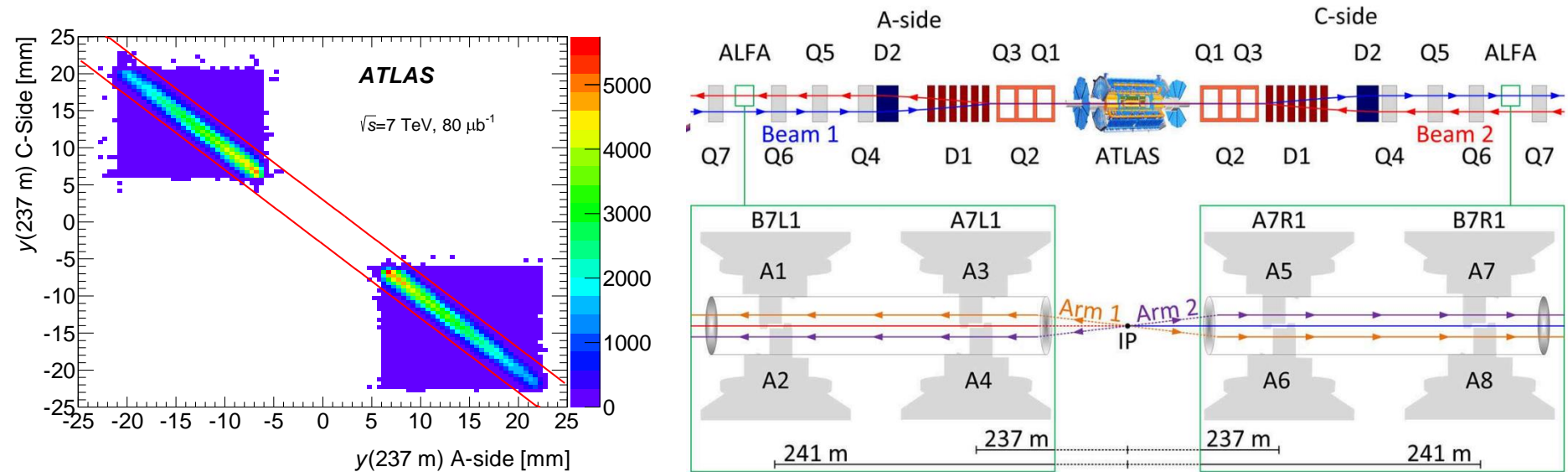


[CERN-LHCC-2015-009](https://cds.cern.ch/record/1370000/files/CERN-LHCC-2015-009.pdf); [ATLAS-TDR-024](https://cds.cern.ch/record/1370000/files/ATLAS-TDR-024.pdf)

# Soft QCD, Diffraction and Forward Physics



- **Total  $pp$  cross-section at 7 TeV with ALFA** [Nuc. Phys B \(2014\), 486-548](#)



- ALFA - dedicated tracking detectors in the beam line at  $z = \pm 238$  &  $\pm 241$  m
- Data taking in **special runs** (high- $\beta^*$ )
- **Elastic scattering** angle at ATLAS IP maps to a  $y$  displacement in ALFA
- Allows the reconstruction of the **4-momentum transfer**:  $-t = (p \times \theta)^2$

# Soft QCD, Diffraction and Forward Physics

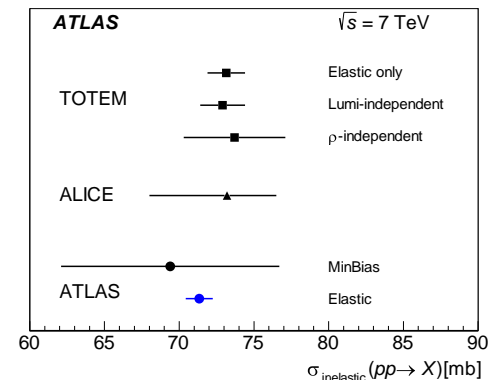
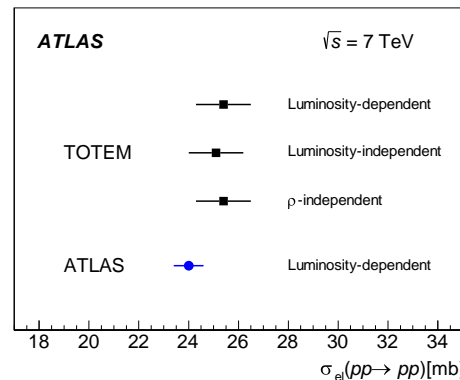
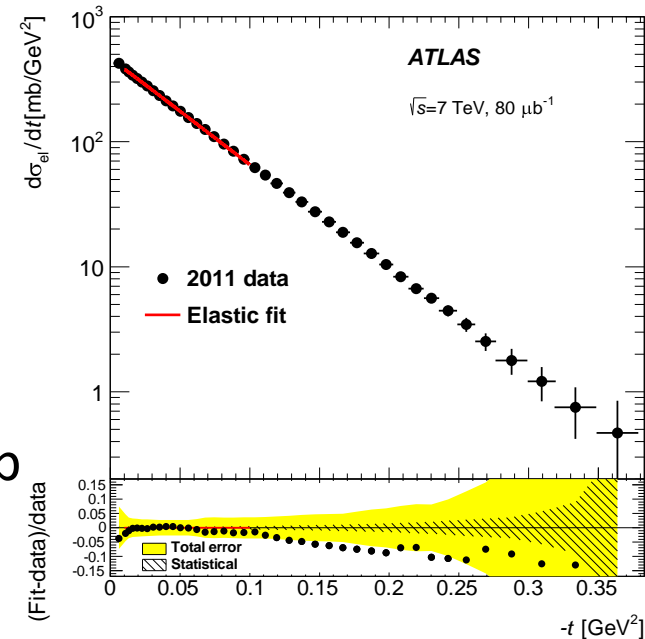
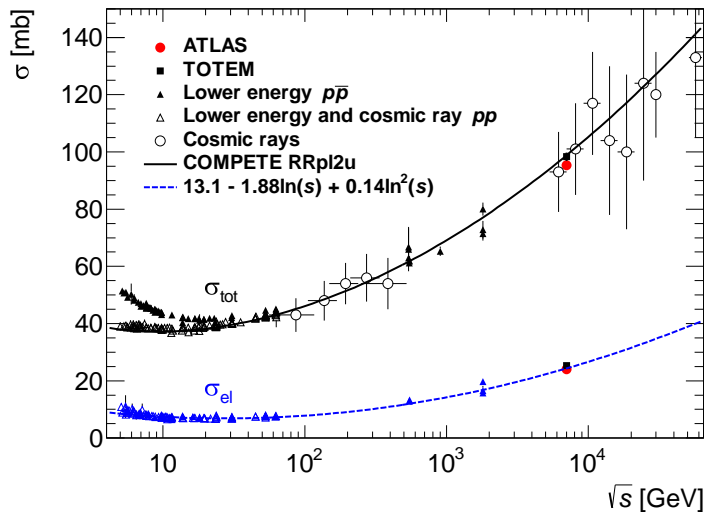


- **Total  $pp$  cross-section at 7 TeV with ALFA** [Nuc. Phys B \(2014\), 486-548](#)

- The exponential  $-t$  slope is fitted in the region of high ALFA acceptance ( $> 10\%$ ) yielding nuclear slope parameter:

$$B = 19.73 \pm 0.14(\text{stat.}) \pm 0.26(\text{syst.}) \text{ GeV}^{-2}$$

- **Total cross-section** (obtained via the **optical theorem** from elastic events):  
 $\sigma_{\text{tot}}(pp \rightarrow X) = 95.35 \pm 0.38(\text{stat.}) \pm 1.30(\text{syst.}) \text{ mb}$

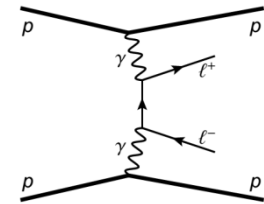


# Soft QCD, Diffraction and Forward Physics



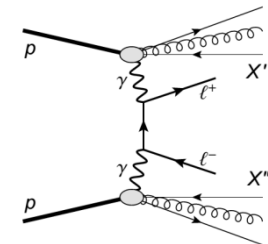
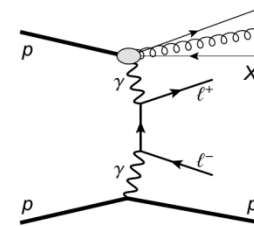
- Exclusive  $pp(\gamma\gamma) \rightarrow pp\ell^+\ell^-$  production at 7 TeV [CERN-PH-EP-2015-134](#)

- Photon-induced (PI) processes: cross-section dominated by so-called **single-** and **double-proton dissociative** reactions. Non-negligible background for many analyses (low, high-mass DY,  $\phi^*/p_T(Z)$  measurement, ...)



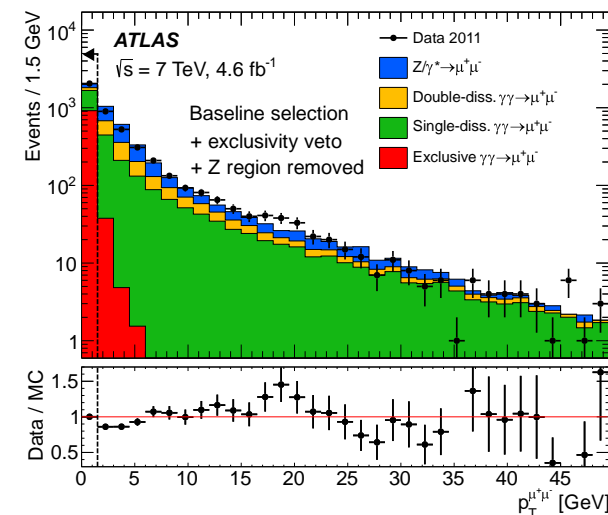
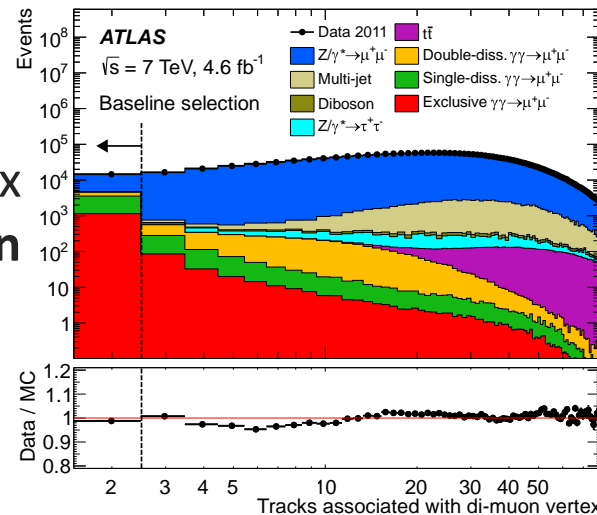
- Preselection:

- $p_T^\mu > 10$  GeV,  $|\eta_\mu| < 2.4$ ,  $M_{\mu^+\mu^-} > 20$  GeV
- $p_T^e > 12$  GeV,  $|\eta_e| < 2.4$ ,  $M_{e^+e^-} > 24$  GeV



- **Exclusive selection:**

- 3 mm dilepton-vertex longitudinal isolation
- $p_T$  of the dilepton system  $< 1.5$  GeV





- Exclusive  $pp(\gamma\gamma) \rightarrow pp\ell^+\ell^-$  production at 7 TeV [CERN-PH-EP-2015-134](#)

- **Signal extraction:** binned maximum-likelihood fit to the measured dilepton acoplanarity distribution

- Corresponding fiducial cross-sections:

- $\sigma_{\gamma\gamma \rightarrow e^+e^-}^{excl.} = 0.428 \pm 0.035(\text{stat.}) \pm 0.018(\text{syst.}) \text{ pb}$

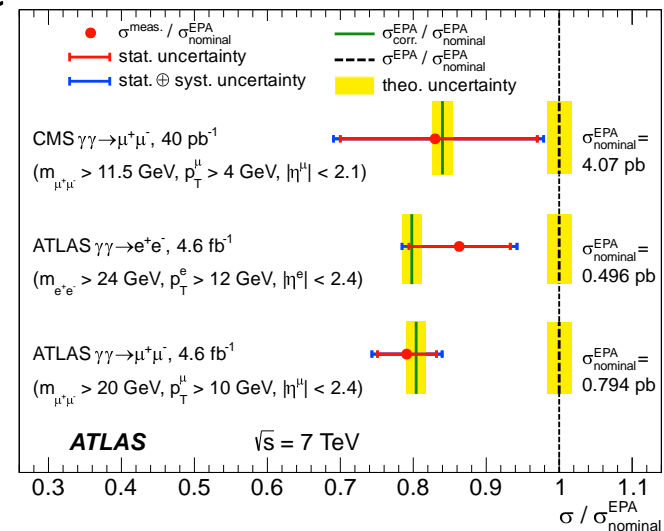
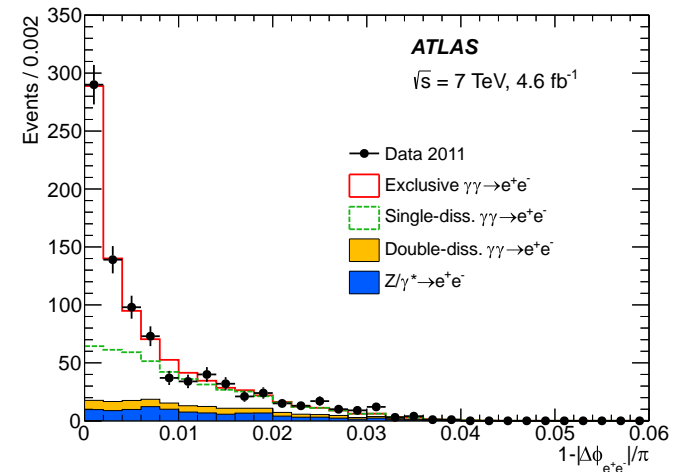
- $\sigma_{\gamma\gamma \rightarrow \mu^+\mu^-}^{excl.} = 0.628 \pm 0.032(\text{stat.}) \pm 0.021(\text{syst.}) \text{ pb}$

- Theory predictions (QED-EPA), with absorptive corrections from [Phys. Lett. B741 \(2015\) 66-70](#) (**20% effect**)

- $\sigma_{\gamma\gamma \rightarrow e^+e^-}^{EPA, corr.} = 0.398 \pm 0.007(\text{theo.}) \text{ pb}$

- $\sigma_{\gamma\gamma \rightarrow \mu^+\mu^-}^{EPA, corr.} = 0.638 \pm 0.011(\text{theo.}) \text{ pb}$

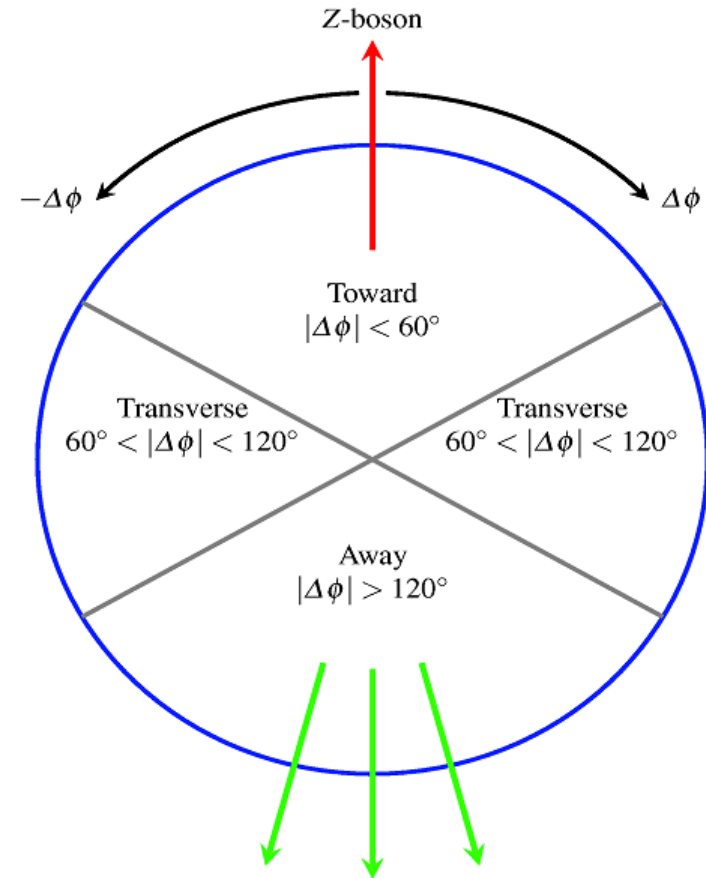
- **Agreement** also with similar CMS measurement





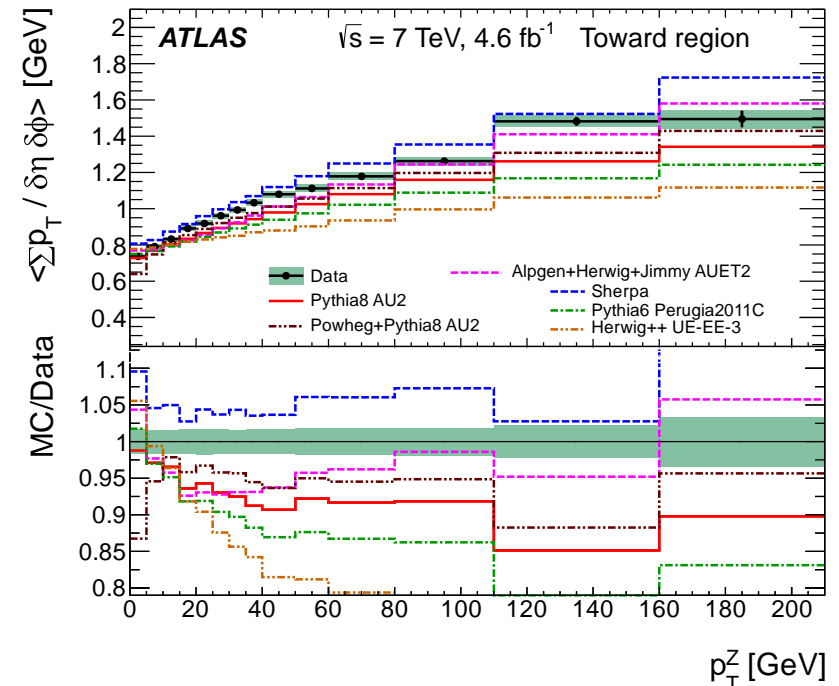
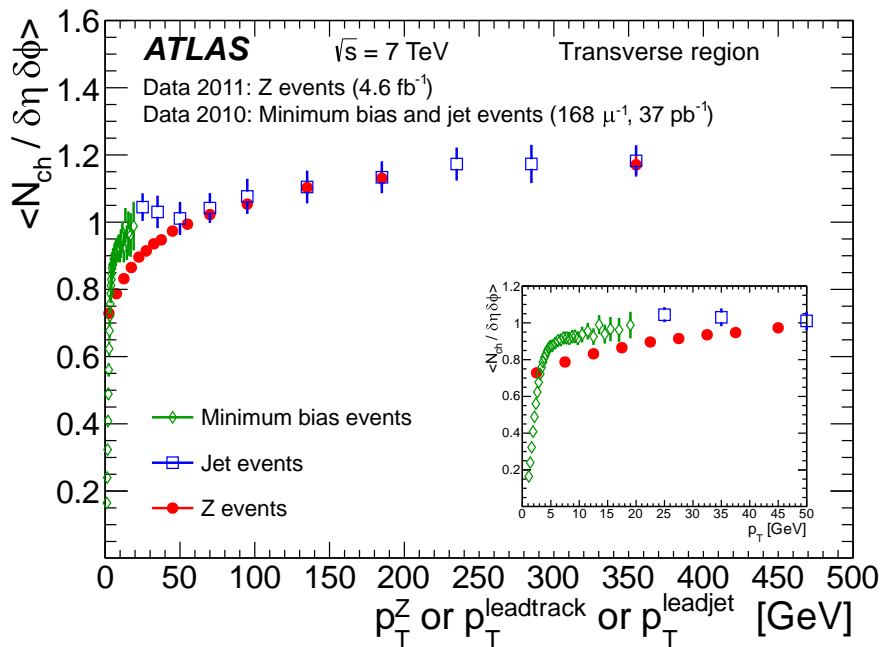


- **Underlying event in Z boson events** [Eur. Phys. J. C 74, 3195 \(2014\)](#)
- UE probe everything *but* the hard scatter:  
multi-parton interactions,  
colour reconnection etc.
- Measured **charged-particle track** observables:  
 $\Sigma p_T$  and  $N_{ch}$  per  $\delta\eta \cdot \delta\phi$  unit,  
average mean  $p_T$
- **Three regions** considered,  
depending on  $\Delta\phi$  to the  
direction of the Z boson:  
**toward, away, transverse**





- **Underlying event in Z boson events** [Eur. Phys. J. C 74, 3195 \(2014\)](#)
- At high- $p_T$  the  $\langle N_{ch} \rangle$  UE looks to be a **universal quantity**
- Disagreement at low- $p_T$  due to the hard scale ( $m_Z$ ) in Z events
- MC model predictions **qualitatively describe** the data well



# Electroweak Physics (W, Z bosons)



- **W+jets cross-sections at 7 TeV** [Eur. Phys. J. C \(2015\) 75:82](#)

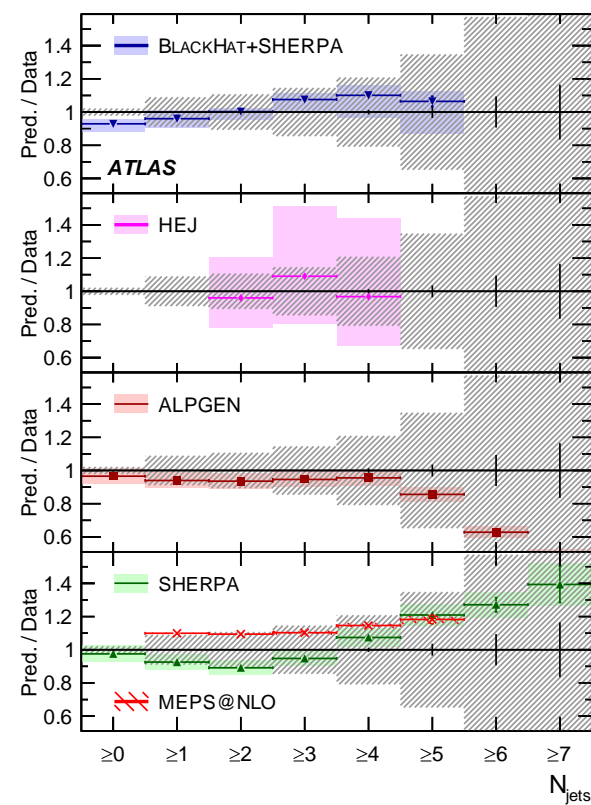
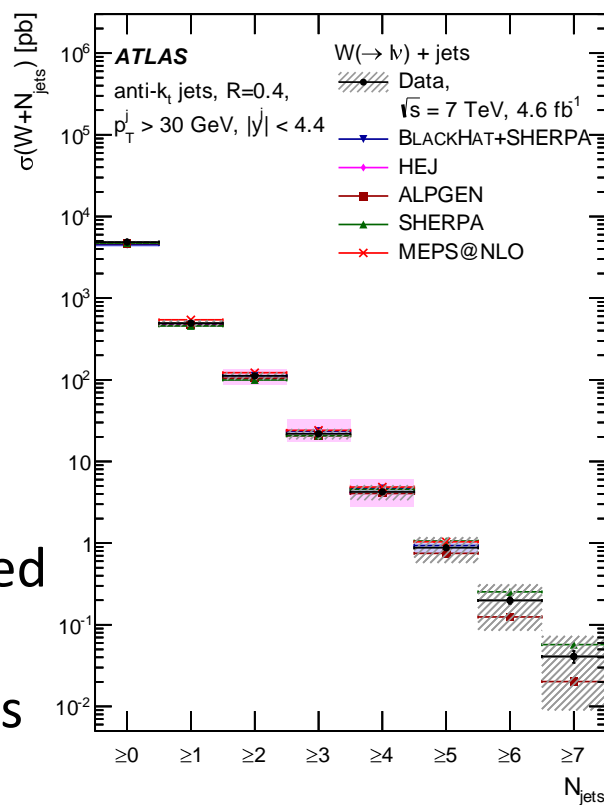
- Tests of perturbative QCD over **5 orders of magnitude**

- **Electroweak effects**

become important  
at large W boson  $p_T$   
( $> 1$  TeV)

- not included in  
predictions used here

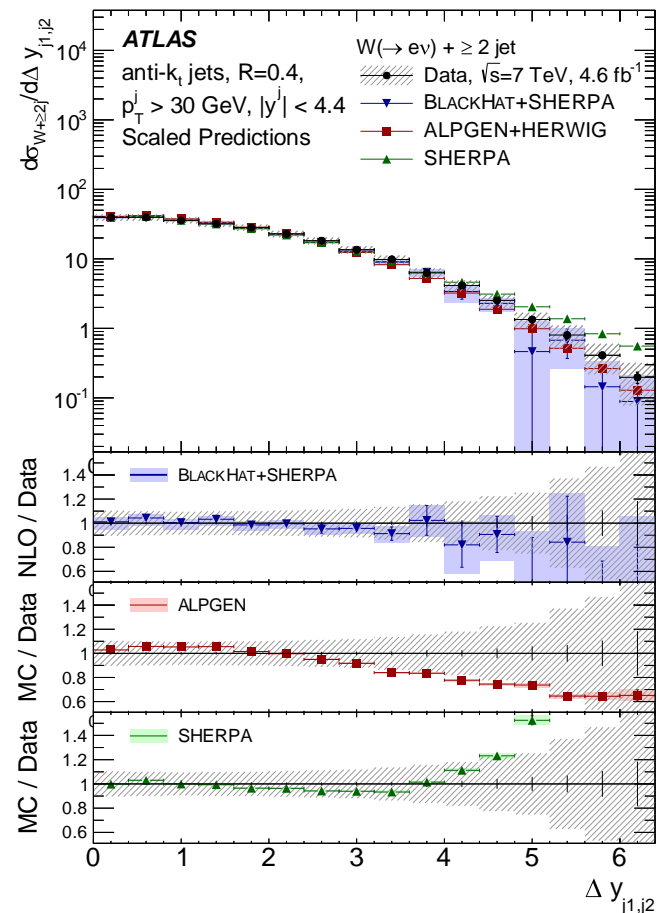
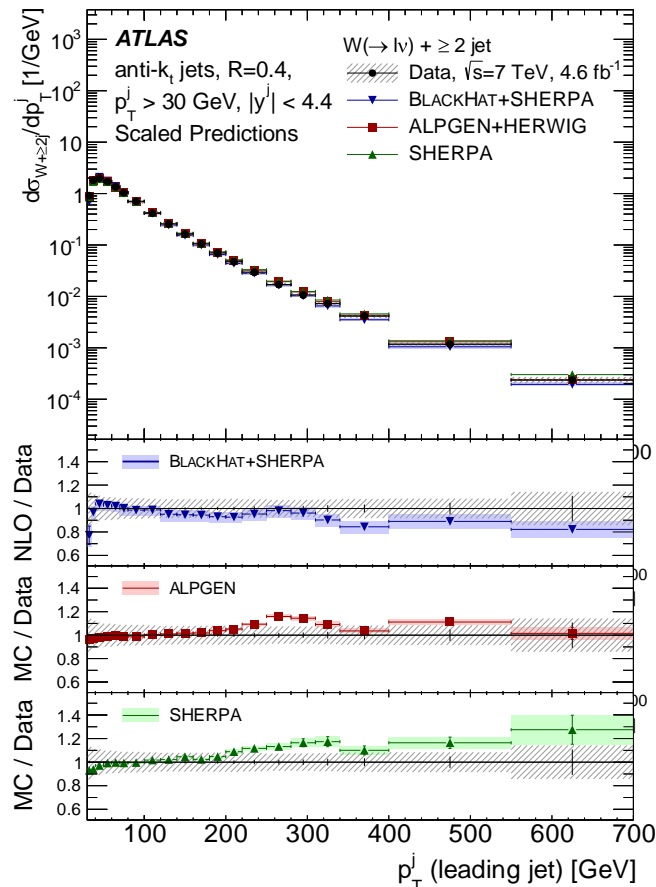
- Many exclusive +  
inclusive **differential  
distributions** compared  
to a variety of  
theoretical predictions



# Electroweak Physics (W, Z bosons)



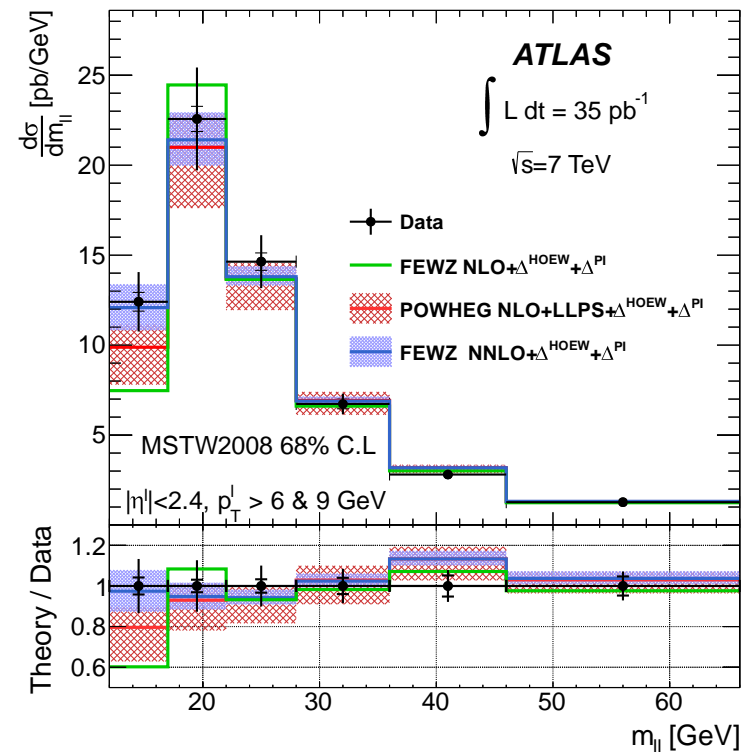
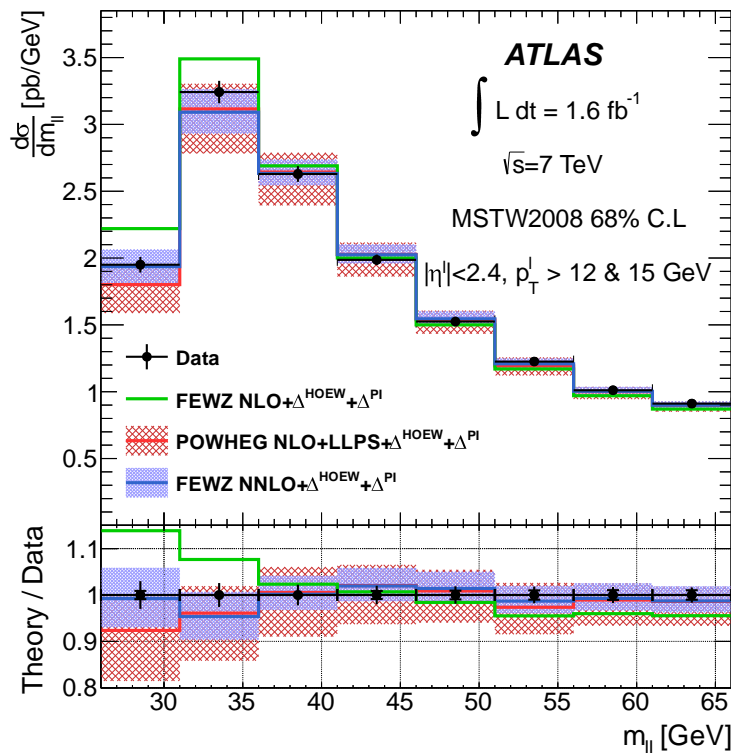
- **W+jets cross-sections at 7 TeV** [Eur. Phys. J. C \(2015\) 75:82](#)
- Overall **good agreement** with predictions is found (but in some regions of phase-space significant disagreement observed)



# Electroweak Physics (W, Z bosons)



- **Low-mass DY differential cross-section at 7 TeV** [JHEP 06 \(2014\) 112](#)
- Access to dilepton invariant mass down to 12 GeV (**low-x region**)
- Fixed-order **NNLO QCD + NLO EW + PI** (photon-induced dilepton pair production) calculations describe the data well



# Electroweak Physics (W, Z bosons)

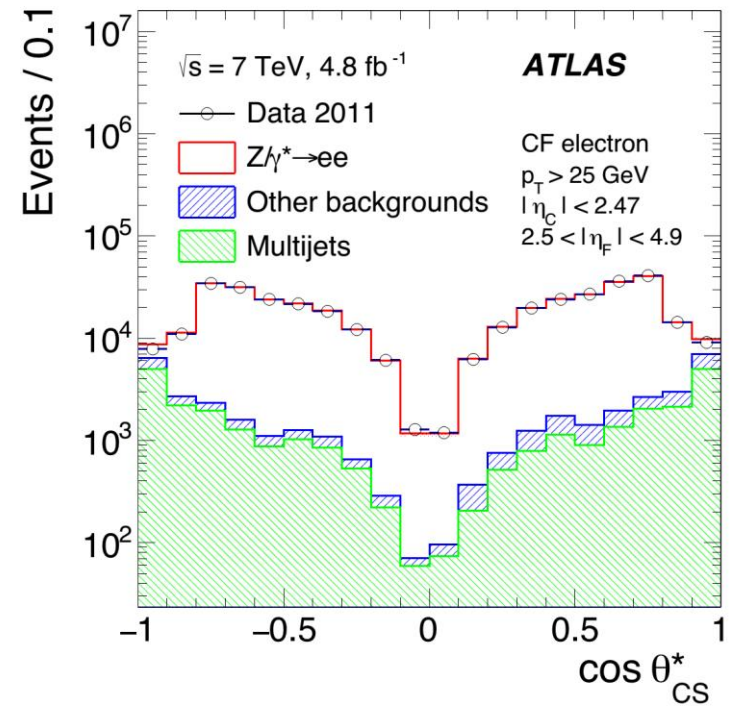
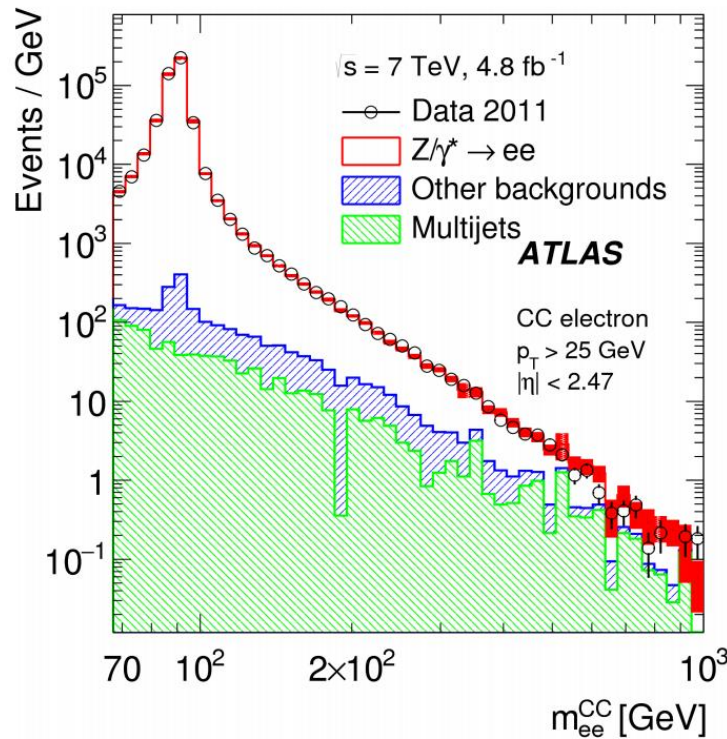
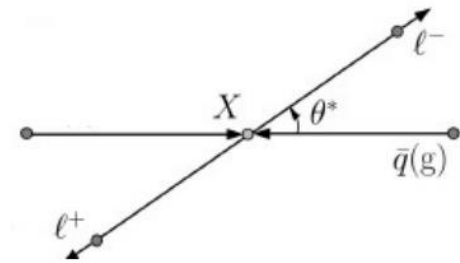


- **FB asymmetry in lepton pair production (7 TeV)** [CERN-PH-EP-2014-259](https://arxiv.org/abs/1405.3026)

- Measurement of **asymmetry** defined as

$$A_{FB} = \frac{N_{\cos \theta_{CS}^* \geq 0} - N_{\cos \theta_{CS}^* < 0}}{N_{\cos \theta_{CS}^* \geq 0} + N_{\cos \theta_{CS}^* < 0}}$$

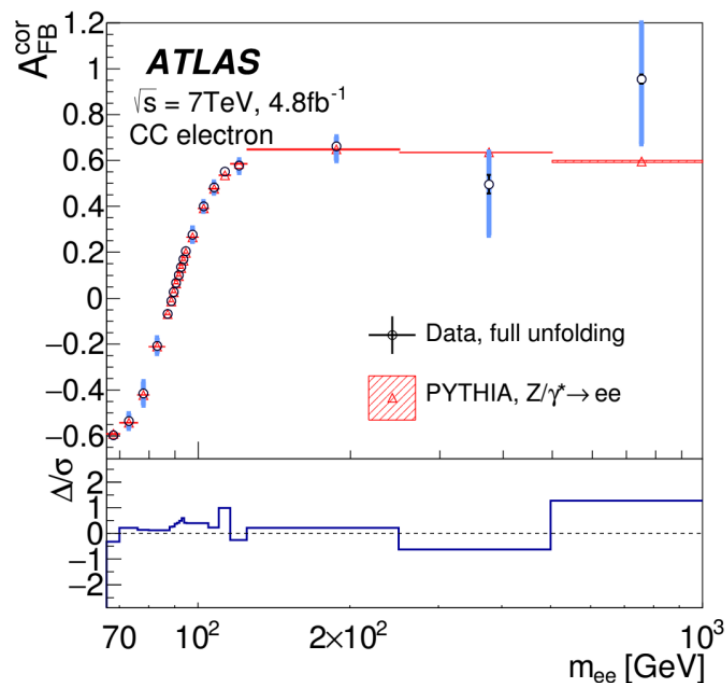
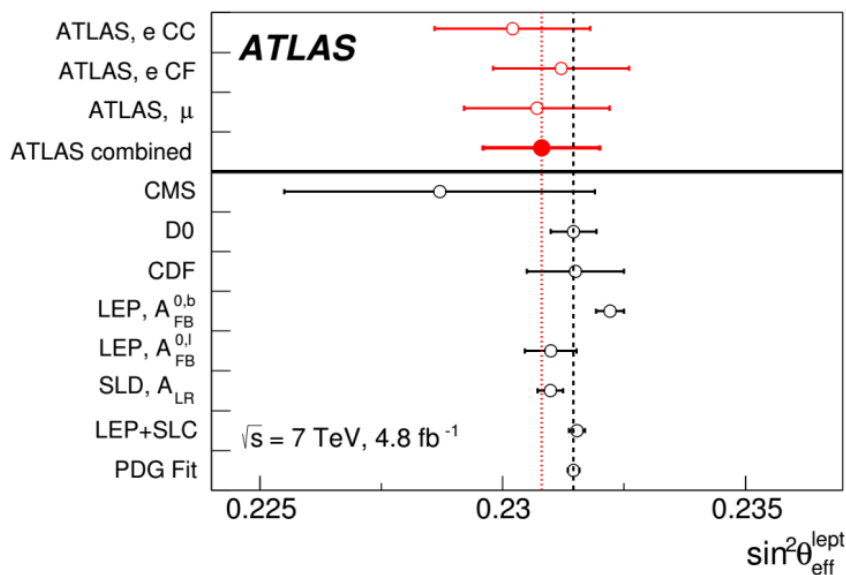
as a function of the **dilepton invariant mass**



# Electroweak Physics (W, Z bosons)



- **FB asymmetry in lepton pair production (7 TeV)** [CERN-PH-EP-2014-259](https://arxiv.org/abs/1405.3001)
- Effective **weak mixing angle** ( $\sin^2 \theta_{eff}^{lept}$ ) is also extracted - from the detector-level  $A_{FB}$  values
- $\sin^2 \theta_{eff}^{lept} = 0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF})$
- **Agreement** with the current world average



# Electroweak Physics (Multi-bosons)



- WW/WZ  $\rightarrow \ell v j j$  cross-section at 7 TeV [JHEP 01 \(2015\) 049](#)

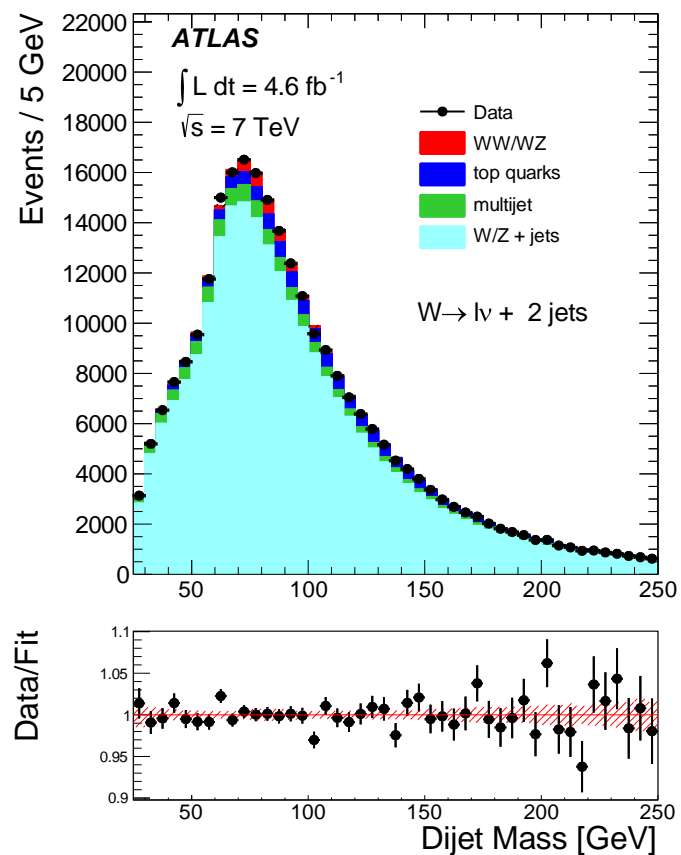
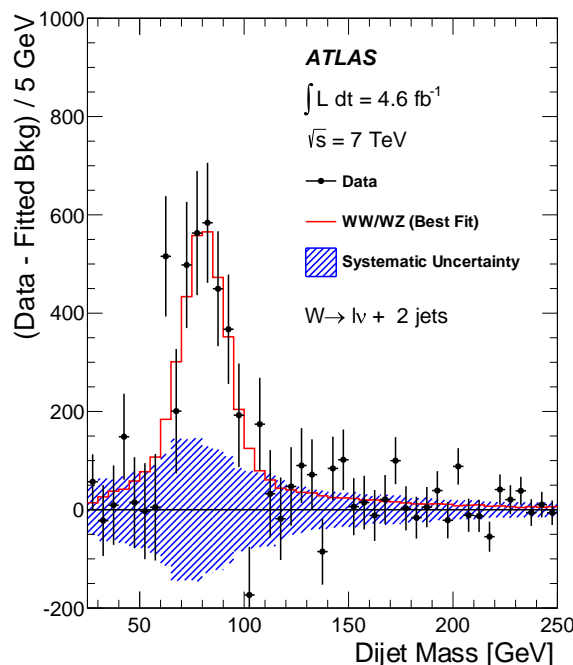
- Measurement of combined WW/WZ cross-section in **semi-leptonic** final state

- Background composition:

- W/Z+jets ( $\approx 89\%$ ), multi-jet ( $\approx 5\%$ ) - data driven
- Top ( $\approx 4\%$ ) - MC estimate

- Signal yield extracted from a fit to  $m_{jj}$  distribution ( $3.4\sigma$  significance)

- $\sigma_{tot.} = 68 \pm 7(\text{stat.}) \pm 18(\text{syst.}) \text{ pb}$ , compared with  $\sigma_{tot.}^{theo.} = 61.1 \pm 2.2 \text{ pb}$

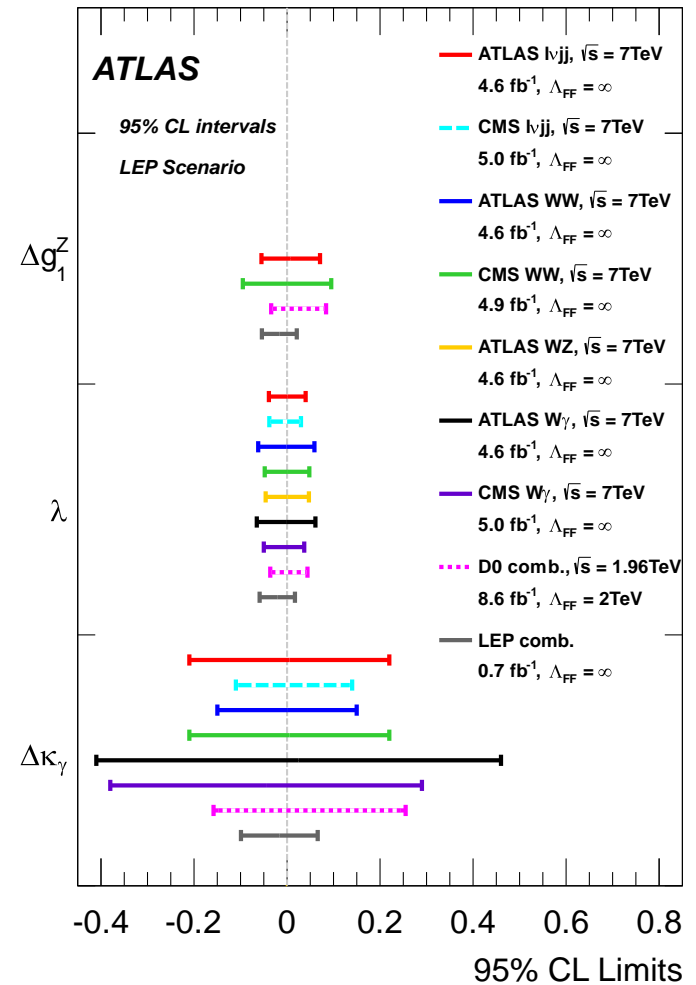
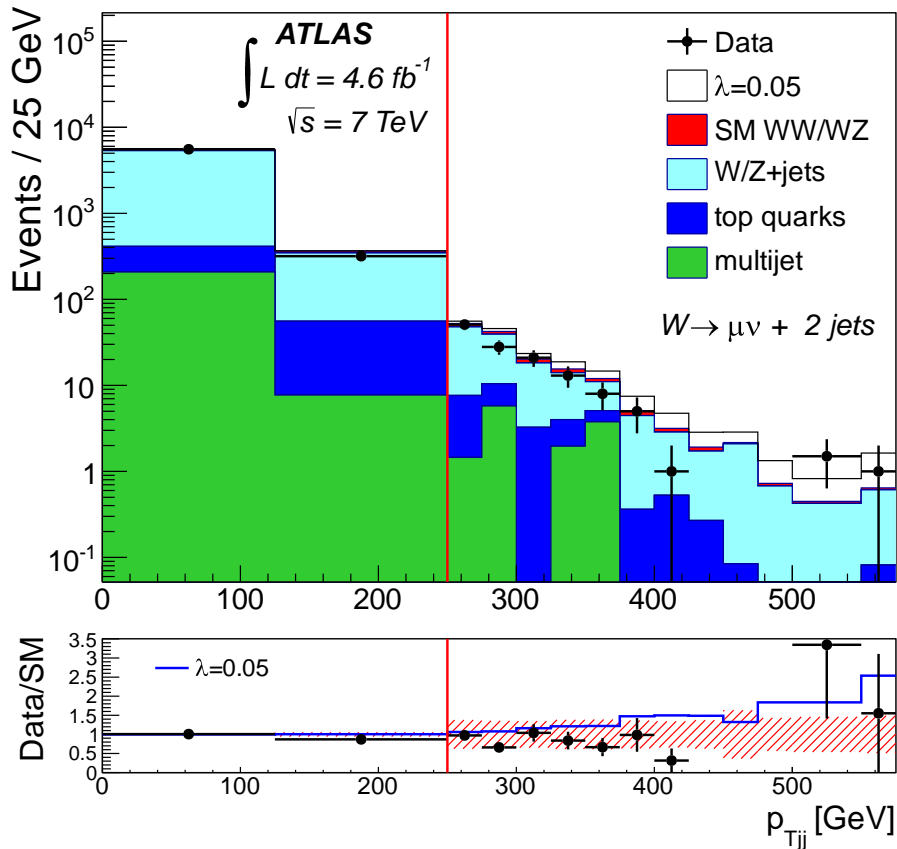




# Electroweak Physics (Multi-bosons)



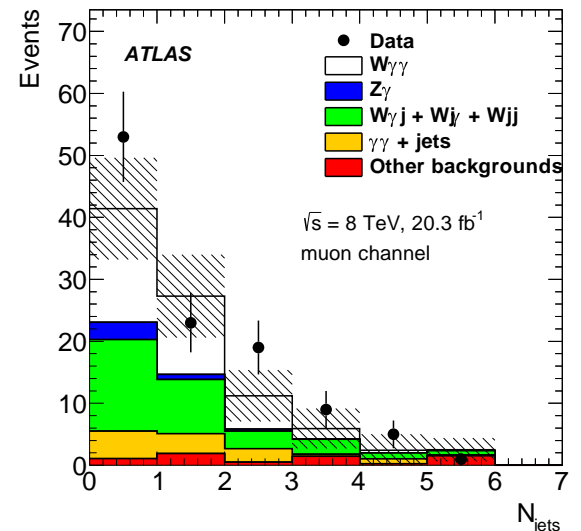
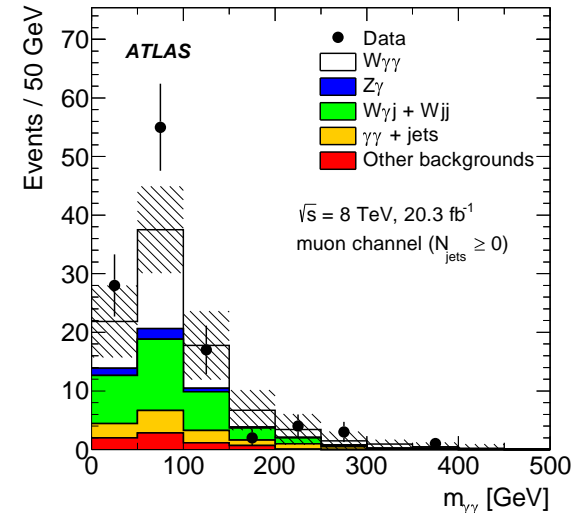
- **WW/WZ  $\rightarrow \ell v jj$  cross-section at 7 TeV** [JHEP 01 \(2015\) 049](#)
- **Limits on aTGC:** binned maximum-likelihood fit of a chosen observable ( $p_{T,jj}$ )



# Electroweak Physics (Multi-bosons)



- **Evidence of  $W\gamma\gamma$  production at 8 TeV** [CERN-PH-EP-2015-009](#)
- **First evidence of  $W\gamma\gamma$  production with  $> 3\sigma$  significance** (  $20.3 \text{ fb}^{-1}$ , inclusive selection:  $N_{\text{jets}} \geq 0$ )
- **Largest background:** jets faking photon or lepton (data-driven estimate)
- **Fiducial cross-section** obtained using a maximum-likelihood fit:

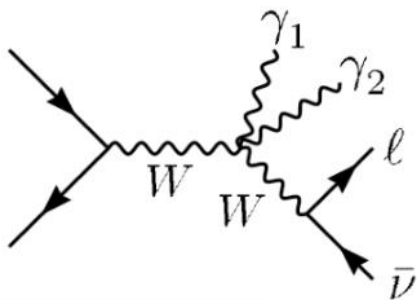


	$\sigma^{\text{fid}}$ [fb]	$\sigma^{\text{MCFM}}$ [fb]
Inclusive ( $N_{\text{jet}} \geq 0$ )		
$\mu\nu\gamma\gamma$	$7.1^{+1.3}_{-1.2}$ (stat.) $\pm 1.5$ (syst.) $\pm 0.2$ (lumi.)	$2.90 \pm 0.16$
$e\nu\gamma\gamma$	$4.3^{+1.8}_{-1.6}$ (stat.) $\pm 1.9$ (syst.) $\pm 0.2$ (lumi.)	
$l\nu\gamma\gamma$	$6.1^{+1.1}_{-1.0}$ (stat.) $\pm 1.2$ (syst.) $\pm 0.2$ (lumi.)	
Exclusive ( $N_{\text{jet}} = 0$ )		
$\mu\nu\gamma\gamma$	$3.5 \pm 0.9$ (stat.) $\pm 1.1^{+1.1}_{-1.0}$ (syst.) $\pm 0.1$ (lumi.)	$1.88 \pm 0.20$
$e\nu\gamma\gamma$	$1.9^{+1.4}_{-1.1}$ (stat.) $\pm 1.1^{+1.1}_{-1.2}$ (syst.) $\pm 0.1$ (lumi.)	
$l\nu\gamma\gamma$	$2.9^{+0.8}_{-0.7}$ (stat.) $\pm 1.0^{+1.0}_{-0.9}$ (syst.) $\pm 0.1$ (lumi.)	

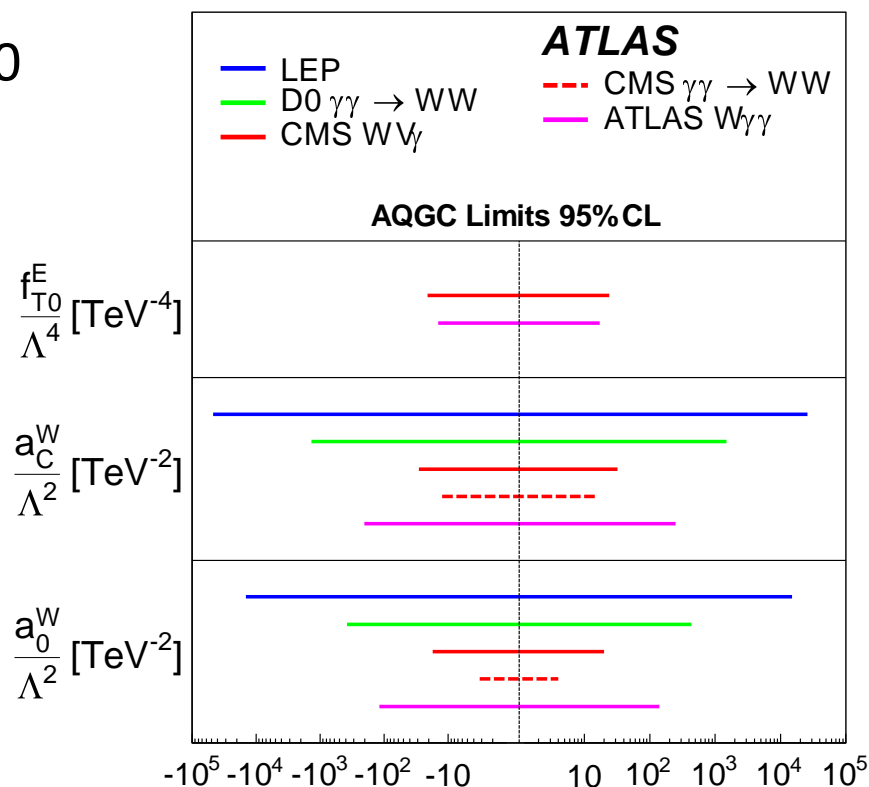
# Electroweak Physics (Multi-bosons)



- **Evidence of  $W\gamma\gamma$  production at 8 TeV** [CERN-PH-EP-2015-009](#)
- **aQGC limits** set for  $N_{\text{jets}} = 0$  (exclusive selection) and  $m_{\gamma\gamma} > 300$  GeV
- Limits better or similar to LEP and D0
- CMS is more sensitive in  $a_C^W$  and  $a_0^W$  ( $\gamma\gamma \rightarrow WW$  measurement)



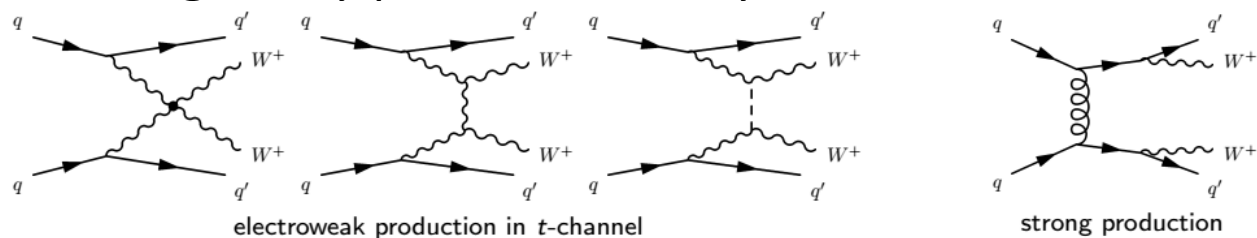
$\Lambda$  - scale at which new physics appears,  
 $a, f$  - coupling of the respective operator.



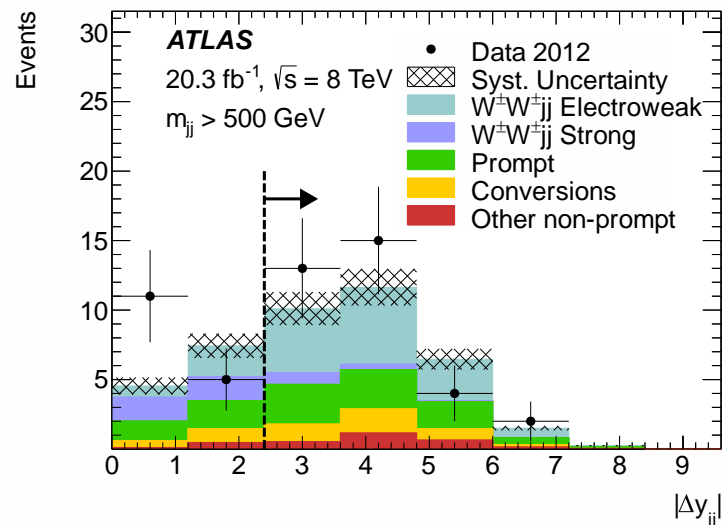
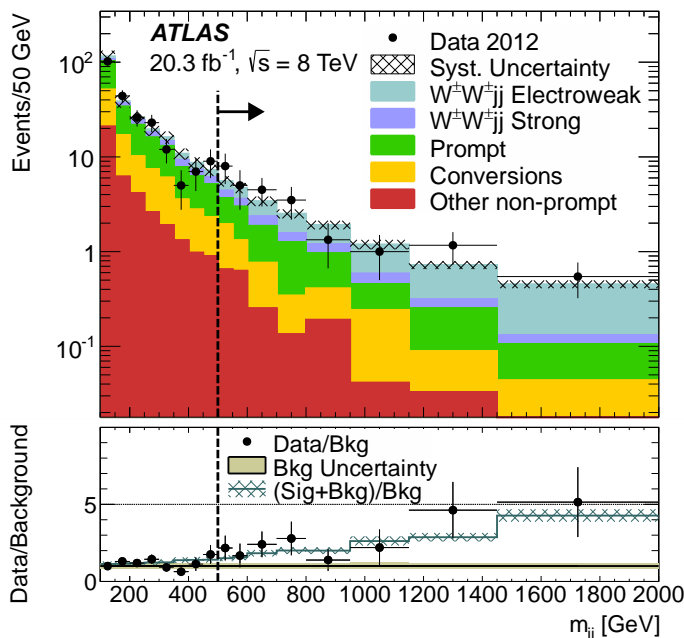
# Electroweak Physics (Multi-bosons)



- EW  $WWjj$  production at 8 TeV [Phys. Rev. Lett. 113, 141803](#)
- Same-sign  $W^\pm W^\pm$  scattering: a key process to study the SM nature of EWSB at the LHC



- Measurement of EW  $WWjj$ : selection at high  $m_{jj}$  and cutting on  $|\Delta y_{jj}|$  (VBS region)

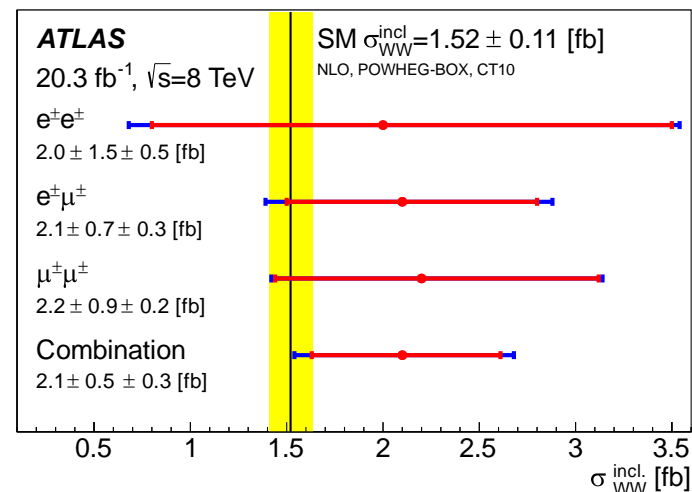
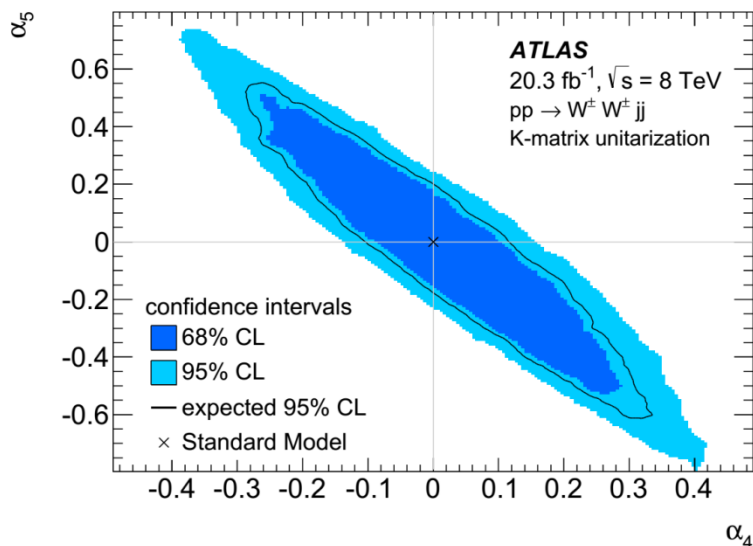
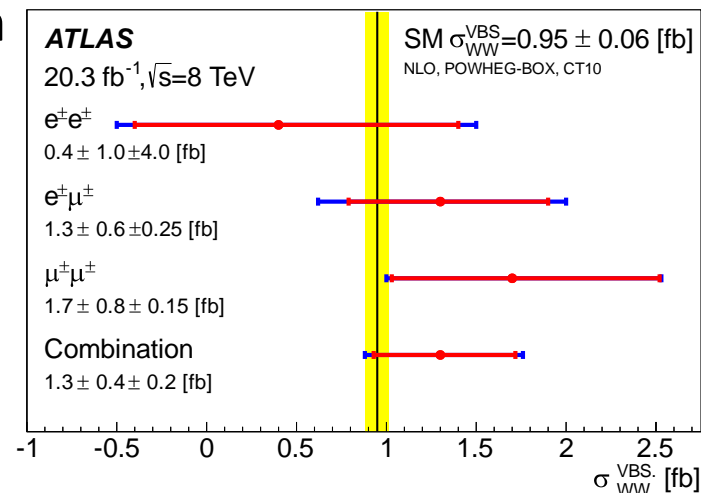


Prompt - prompt leptons from multilepton processes  
Conversions - photon conversions and charge mis-ID

# Electroweak Physics (Multi-bosons)

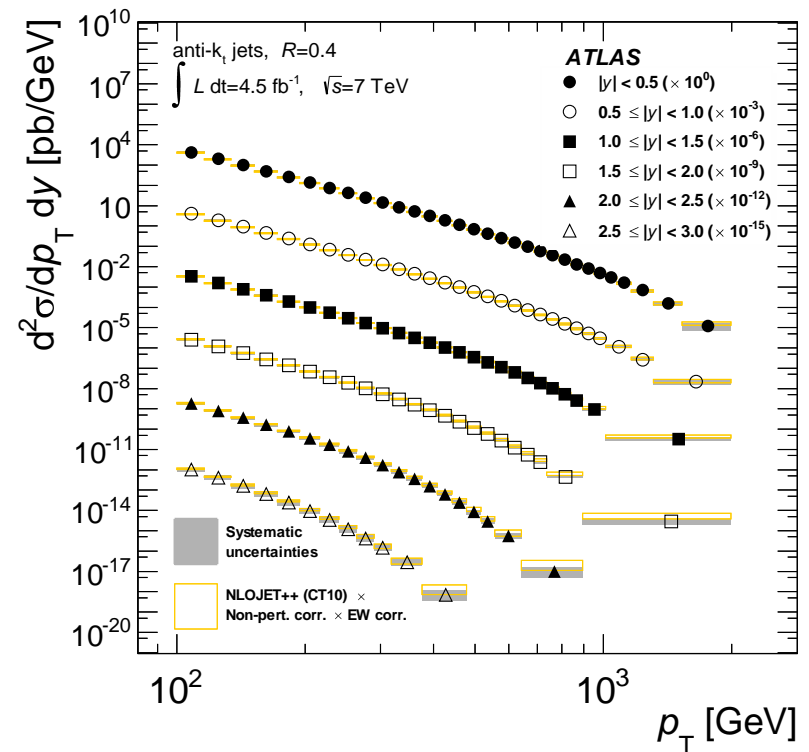
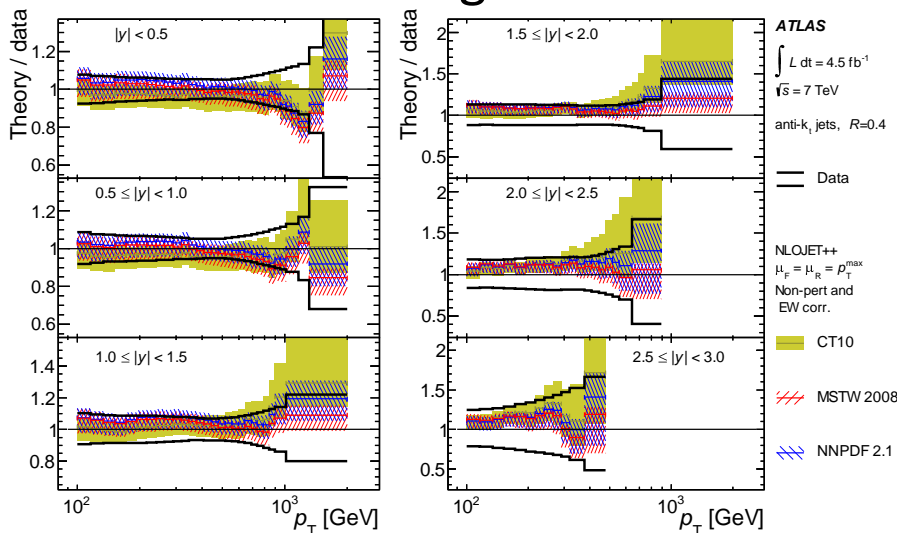


- **EW WWjj production at 8 TeV** [Phys. Rev. Lett. 113, 141803](#)
- A total of **34 candidate events** in VBS region
- Measured cross-sections **in agreement** with theory prediction
- First **aQGC limits** on  $\alpha_4$ ,  $\alpha_5$  parameters are also set (for notation see [Phys.Rev. D22 \(1980\) 200](#))



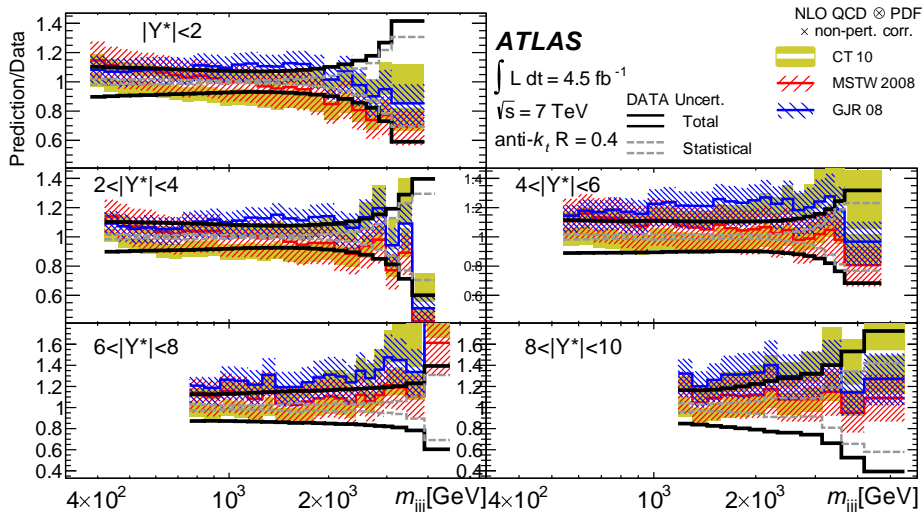


- **Inclusive jet cross-section at 7 TeV** [JHEP 02 \(2015\) 153](#)
- **Double-differential** cross-section measurement as a function of jet  $p_T$  and rapidity
- Two jet radii are used:  $R = 0.4$  and  $R = 0.6$ . Jets with  $p_T > 100$  GeV and  $|y| < 3$  considered.
- Comparison with **NLO predictions** corrected for **EW** and **NP** effects. Several PDF investigated.

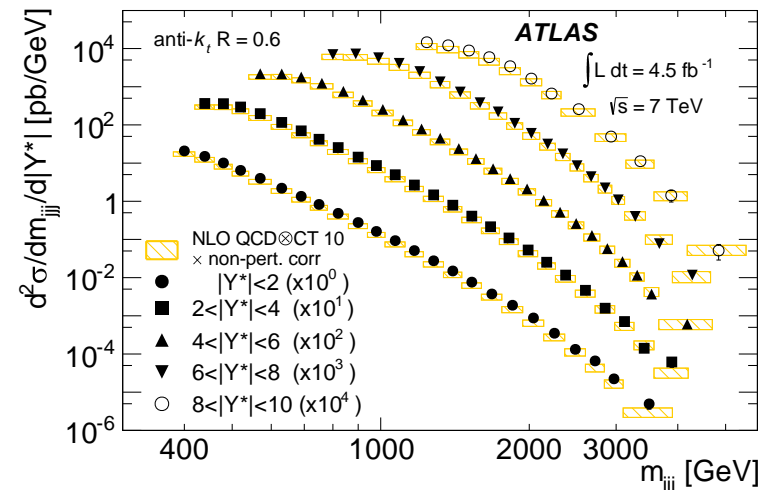
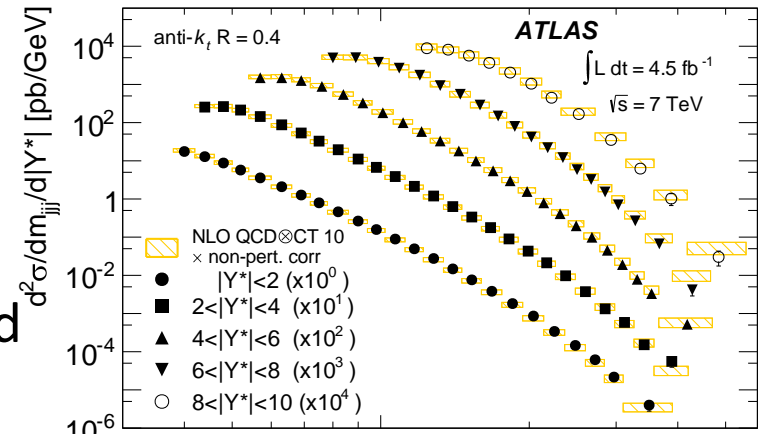




- **Three-jet production cross-section at 7 TeV** [Eur. Phys. J. C \(2015\) 75](#)
- **Double-differential** cross-section measurement as a function of  $m_{jij}$  and  $Y^* = |y_{j1} - y_{j2}| + |y_{j2} - y_{j3}| + |y_{j1} - y_{j3}|$
- Asymmetric kinematic cuts:  $p_{Tj1} > 150$  GeV,  $p_{Tj2} > 100$  GeV and  $p_{Tj3} > 50$  GeV
- Comparison with **NLO predictions** corrected for **NP** effects. Several PDF investigated.



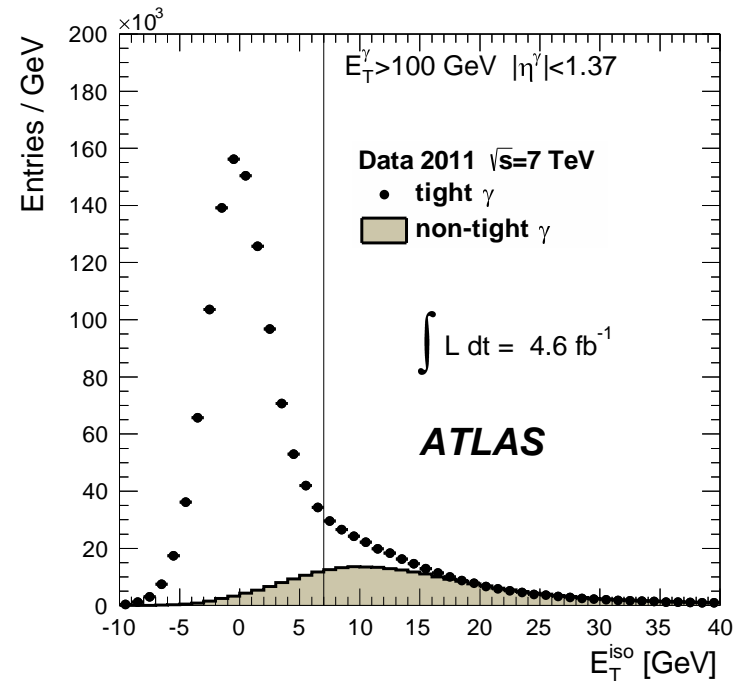
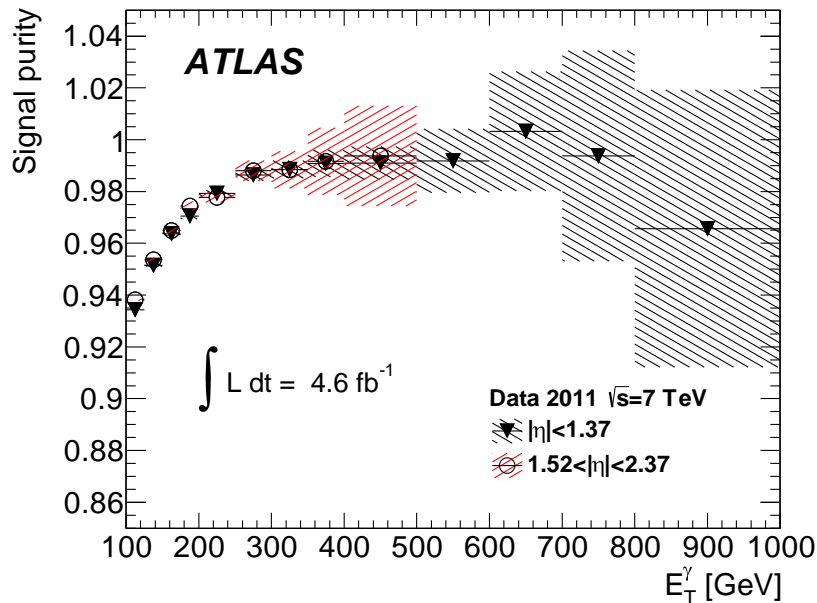
## Dijet: [JHEP 05 \(2014\) 059](#)



# Direct Photons



- **Inclusive photon cross-section at 7 TeV** [Phys. Rev. D 89, 052004 \(2014\)](#)
- Cross-section for isolated, high- $p_T$  photons (with  $E_{T,\gamma} > 100$  GeV,  $E_{T,iso} < 7$  GeV)
- Isolation requirement reduces **jet background**
- EM shower shape variables provide tight / loose photon identification

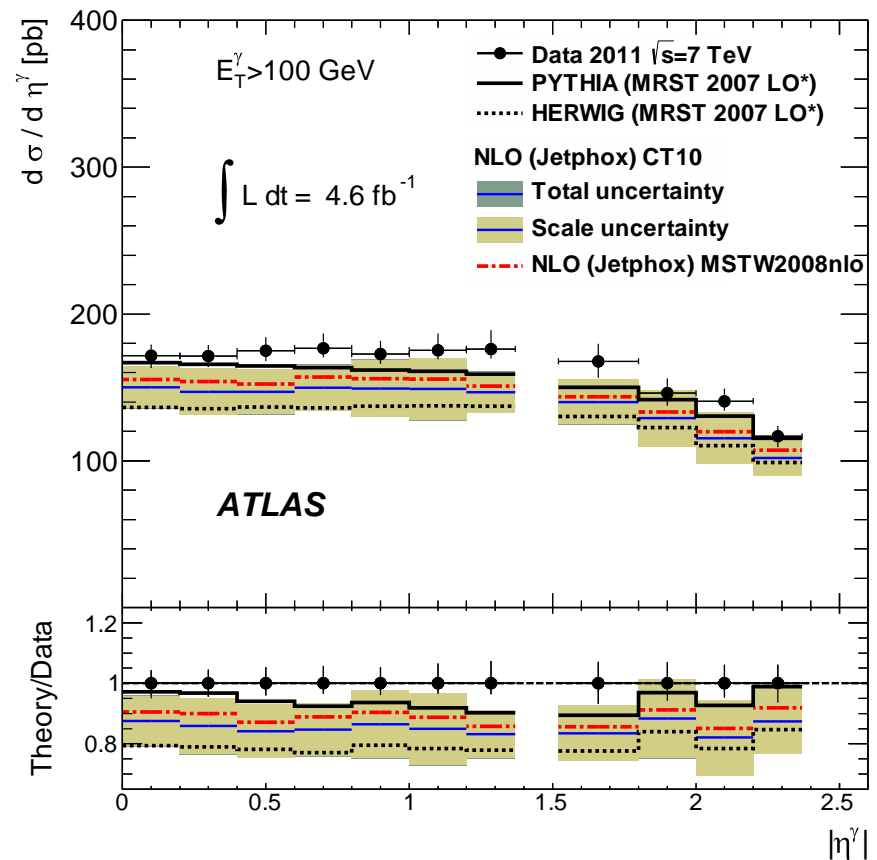
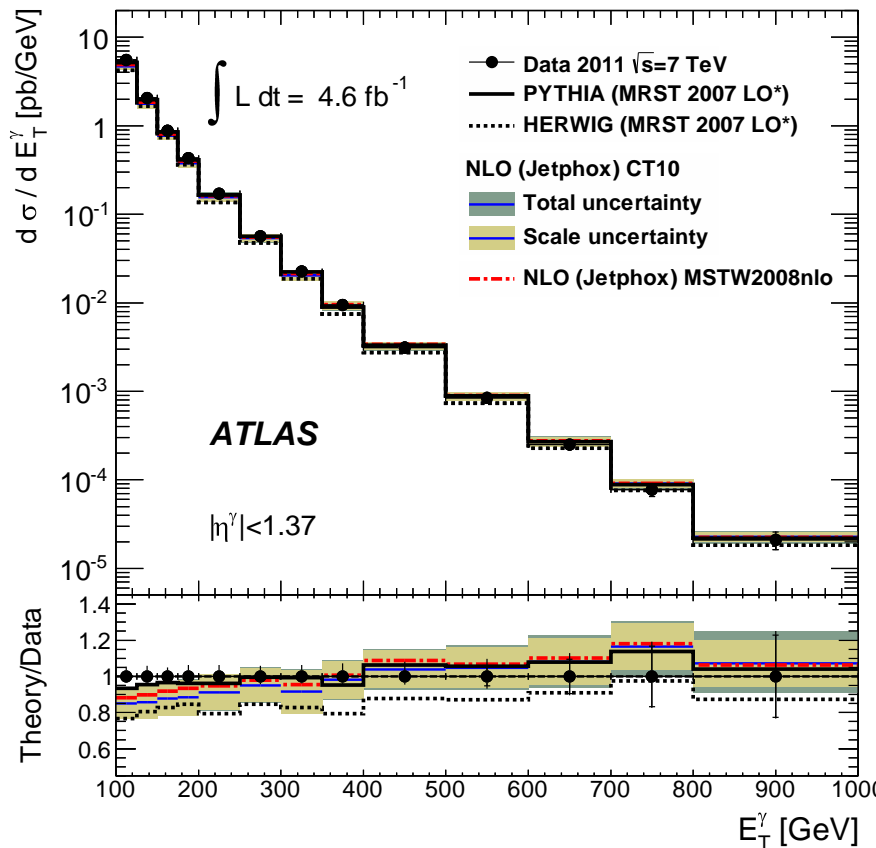




# Direct Photons



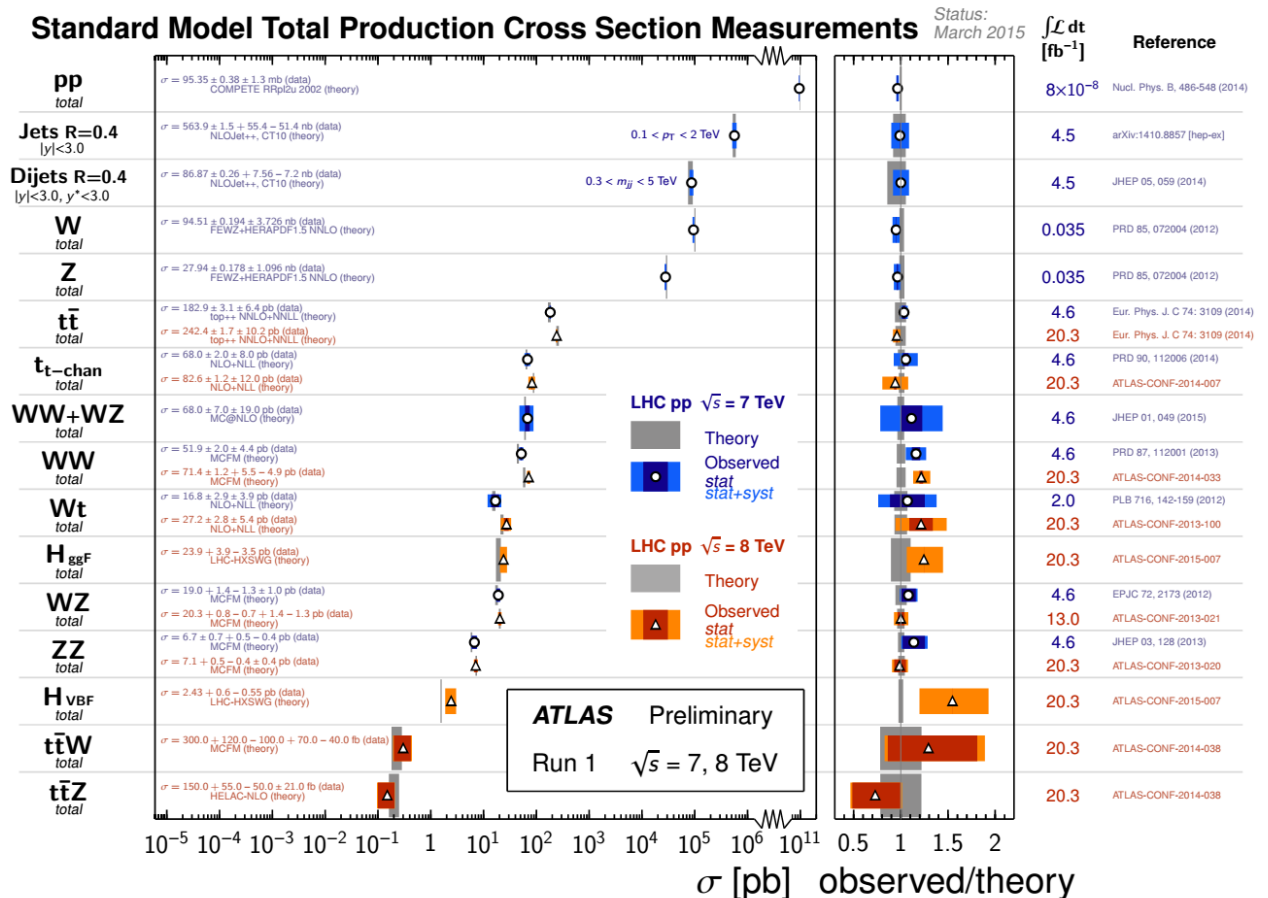
- **Inclusive photon cross-section at 7 TeV** [Phys. Rev. D 89, 052004 \(2014\)](#)
- Production is sensitive to the **gluon content** of the proton ( $qg \rightarrow q\gamma$ )
- Comparison with **LO** and **NLO** predictions corrected for NP effects



# Summary



- SM measurements are important to **explore** new kinematic regimes, to **test** theoretical predictions and to **improve** precision of the SM parameters



# Summary



- **New measurements** for soft QCD / Diffraction / Forward Physics, Electroweak studies, Jet Physics and Direct Photons are presented

## Vector Boson + X Cross Section Measurements

Status: March 2015

$$\sigma^{\text{fid}}(\gamma+X) [|\eta^\gamma| < 1.37]$$

$$- [1.52 < |\eta^\gamma| < 2.37]$$

$$\sigma^{\text{fid}}(Z \rightarrow ee, \mu\mu)$$

$$- [n_{\text{jet}} \geq 1]$$

$$- [n_{\text{jet}} \geq 2]$$

$$- [n_{\text{jet}} \geq 3]$$

$$- [n_{\text{jet}} \geq 4]$$

$$- [n_{\text{b-jet}} \geq 1]$$

$$- [n_{\text{b-jet}} \geq 2]$$

$$- \sigma^{\text{fid}}(Z_{\text{jj}}^{\text{EWK}})$$

$$\sigma^{\text{fid}}(Z \rightarrow \tau\tau)$$

$$\sigma^{\text{fid}}(Z \rightarrow \text{bb})$$

$$\sigma^{\text{fid}}(W \rightarrow e\nu, \mu\nu)$$

$$- [n_{\text{jet}} \geq 1]$$

$$- [n_{\text{jet}} \geq 2]$$

$$- [n_{\text{jet}} \geq 3]$$

$$- [n_{\text{jet}} \geq 4]$$

$$- [n_{\text{jet}} \geq 5]$$

$$- [n_{\text{jet}}=1, n_{\text{b-jet}}=1]$$

$$- [n_{\text{jet}}=2, n_{\text{b-jet}}=1]$$

$$\sigma^{\text{fid}}(W \rightarrow e\nu, \mu\nu) / \sigma^{\text{fid}}(Z \rightarrow ee, \mu\mu)$$

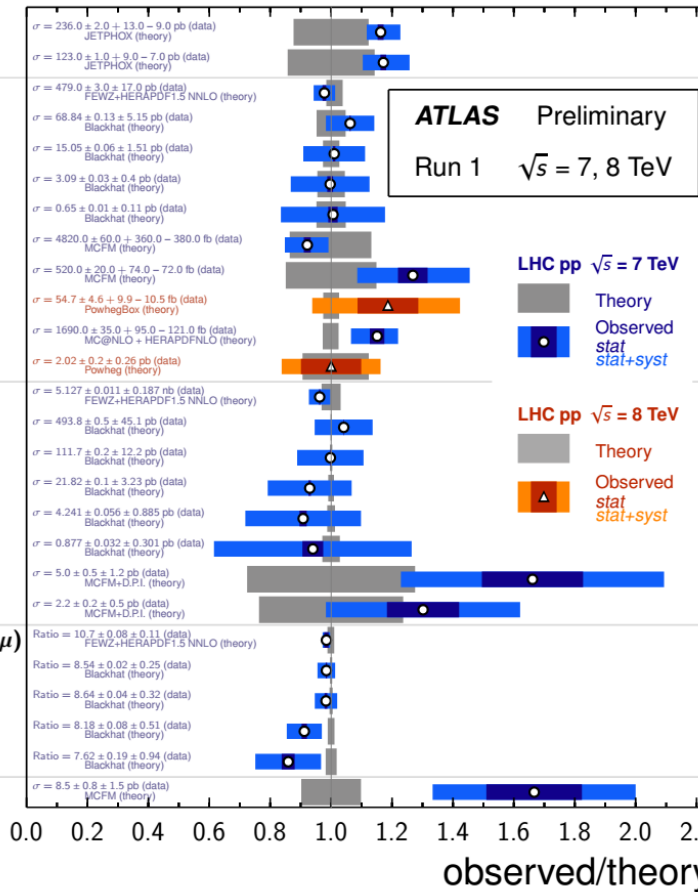
$$- [n_{\text{jet}} \geq 1]$$

$$- [n_{\text{jet}} \geq 2]$$

$$- [n_{\text{jet}} \geq 3]$$

$$- [n_{\text{jet}} \geq 4]$$

$$\sigma^{\text{fid}}(W+Z \rightarrow \text{qq})$$



$\int \mathcal{L} dt$   
[fb<sup>-1</sup>]

Reference

4.6	PRD 89, 052004 (2014)
4.6	PRD 89, 052004 (2014)
0.035	PRD 85, 072004 (2012)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 10, 141, (2014)
4.6	JHEP 10, 141, (2014)
20.3	JHEP 04, 031 (2014)
19.5	PLB 738, 25-43, (2014)
0.035	PRD 85, 072004 (2012)
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	JHEP 06, 084 (2013)
4.6	JHEP 06, 084 (2013)
0.035	PRD 85, 072004 (2012)
4.6	Eur. Phys. J. C 74: 3168 (2014)
4.6	Eur. Phys. J. C 74: 3168 (2014)
4.6	Eur. Phys. J. C 74: 3168 (2014)
4.6	Eur. Phys. J. C 74: 3168 (2014)
4.6	New J. Phys. 16, 113013 (2014)

# Summary



- **New data at  $\sqrt{s} = 13$  TeV being collected!**

13 TeV collisions

Run: 265573

Event: 970468

2015-05-21 11:10:20 CEST