

# Recent SM measurements with the ATLAS detector

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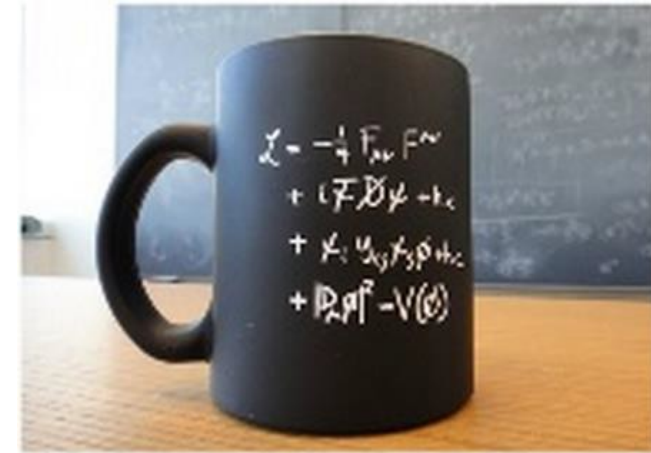
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November 12, 2015, FZÚ Seminar

# Introduction

## Standard Model measurements performed to:

- ▶ validate SM in new energy regime
- ▶ constrain parton distribution functions (PDFs)
- ▶ understand processes which are backgrounds for other studies
- ▶ improve precision of known SM parameters
- ▶ constrain new physics contributions (like anomalous couplings)



## Selection of recent SM results, based on the categories:

### Soft QCD

- ▶ Exclusive  $\gamma\gamma \rightarrow ll$  production, charged-particle multiplicities, Inelastic pp cross section at 13 TeV

### Jet physics

- ▶ Inclusive jet, three and four-jet production, QCD coupling constant measurement

### W/Z/gamma production

- ▶ W and Z Boson production, W+jets / Z+jets cross section ratio, W+jets and Z+bjets production

### EWK measurements

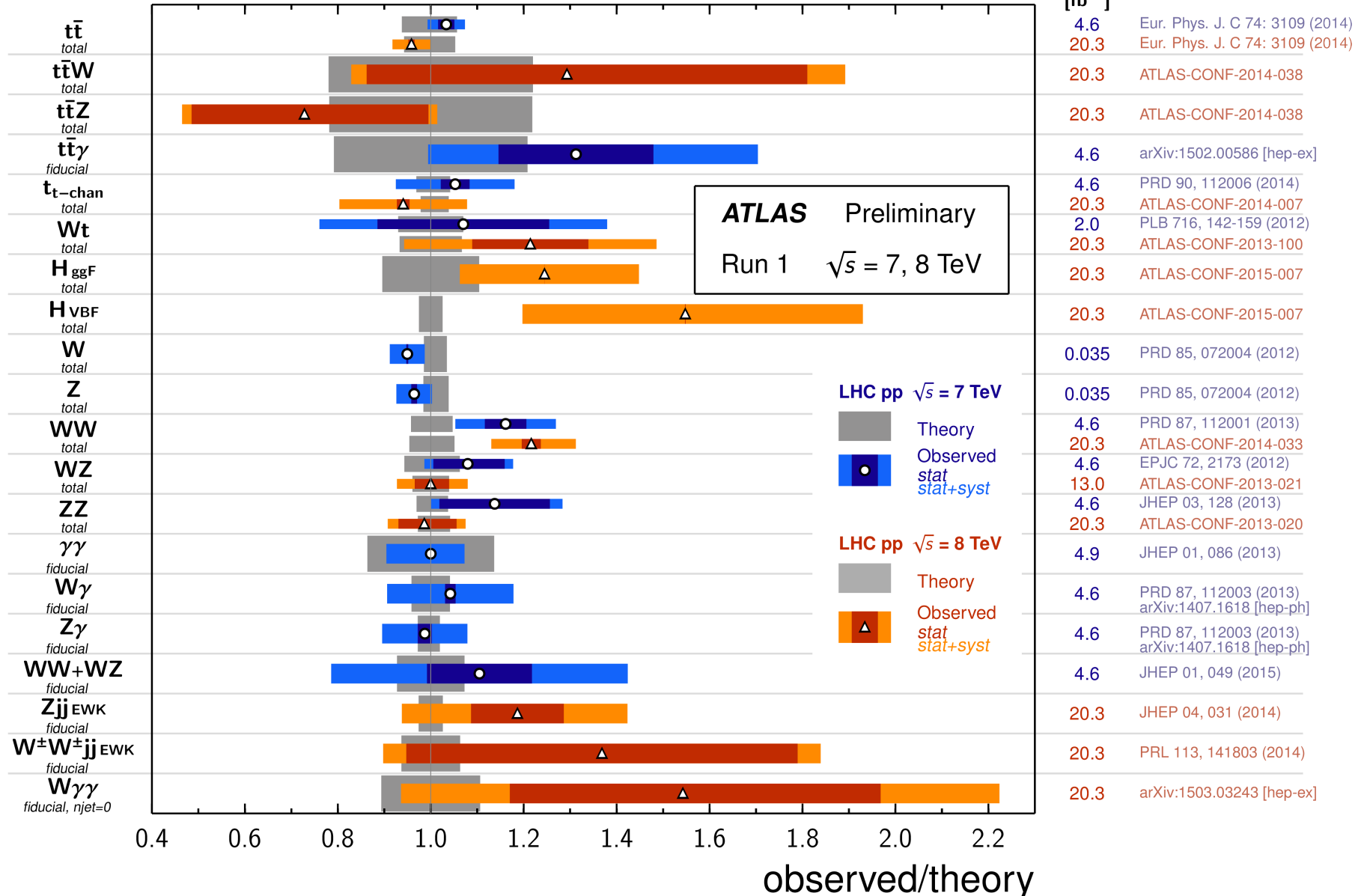
- ▶ WW, 4-lepton, Vector boson fusion, Vector Boson Scattering, W $\gamma\gamma$  production

# Standard model measurements

## Standard Model Production Cross Section Measurements

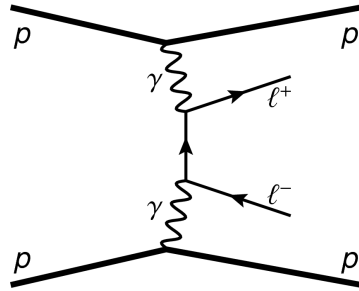
Status: March 2015  $\int \mathcal{L} dt$   
[fb<sup>-1</sup>]

Reference

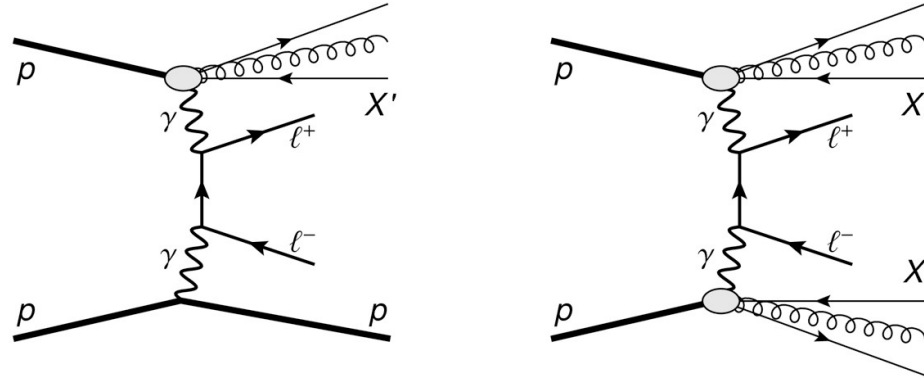


# Two photon scattering - $\gamma\gamma \rightarrow l\bar{l}$

elastic signal

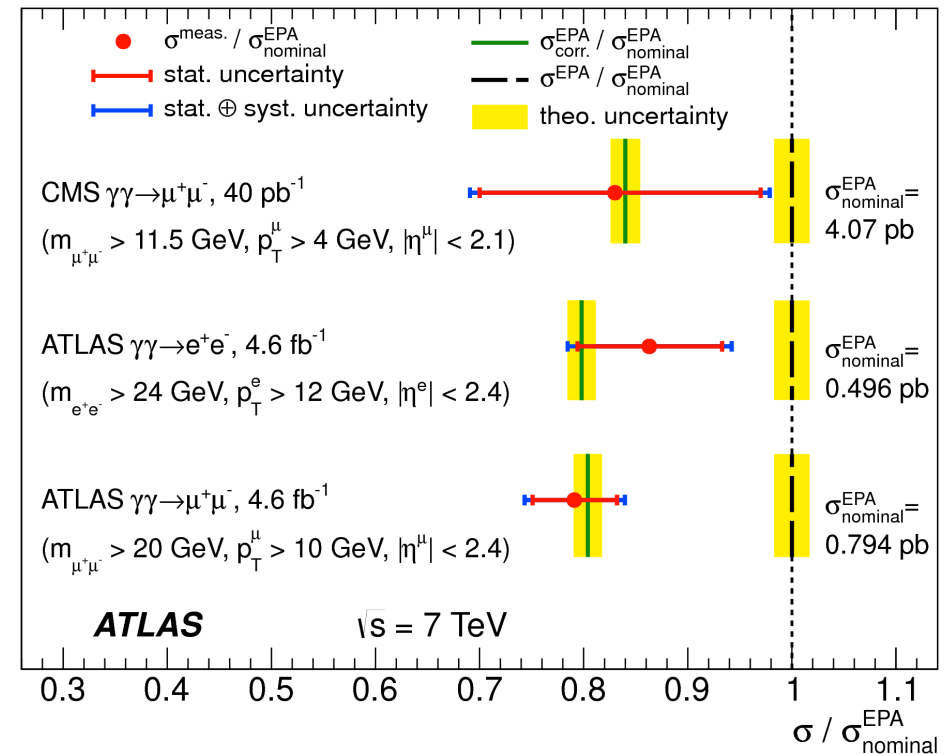


dissociative backgrounds



- ▶ use LHC as a two-photon collider
- ▶ use **Equivalent Photon Approximation (EPA)** (with absorptive corrections for finite proton size)
- ▶ **other background:**  $Z/\gamma^*$ , diboson,  $t\bar{t}$  and multi-jet production
- ▶ observed cross-sections are about 20% below the nominal EPA prediction
- ▶ consistent with the suppression due to reabsorption of photon into proton

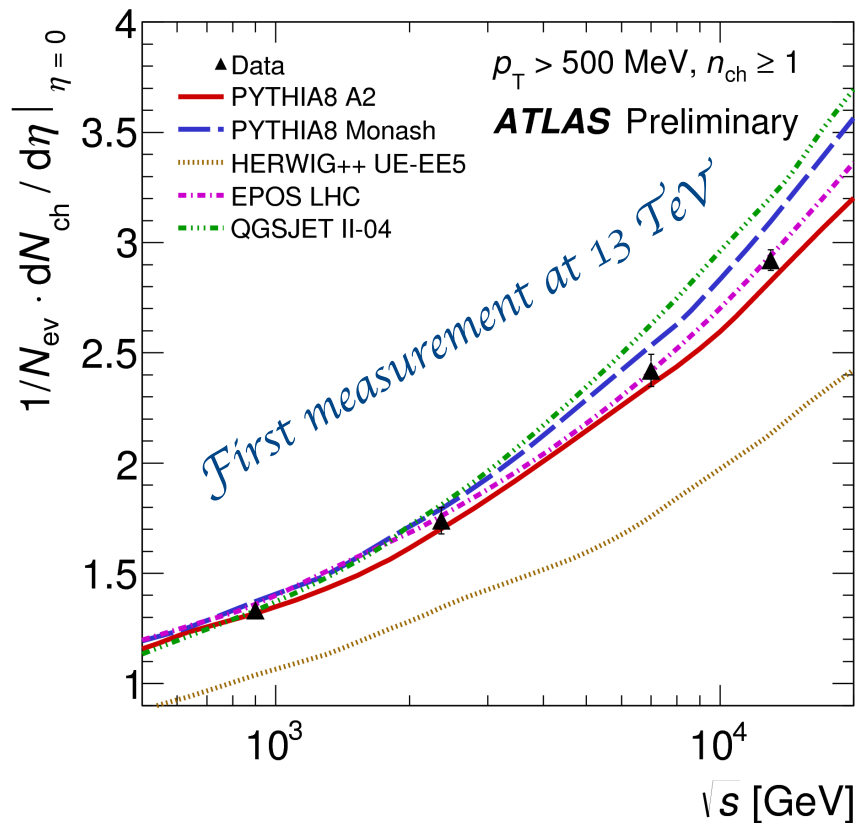
*Physics Letters B 749 (2015) 242-261*



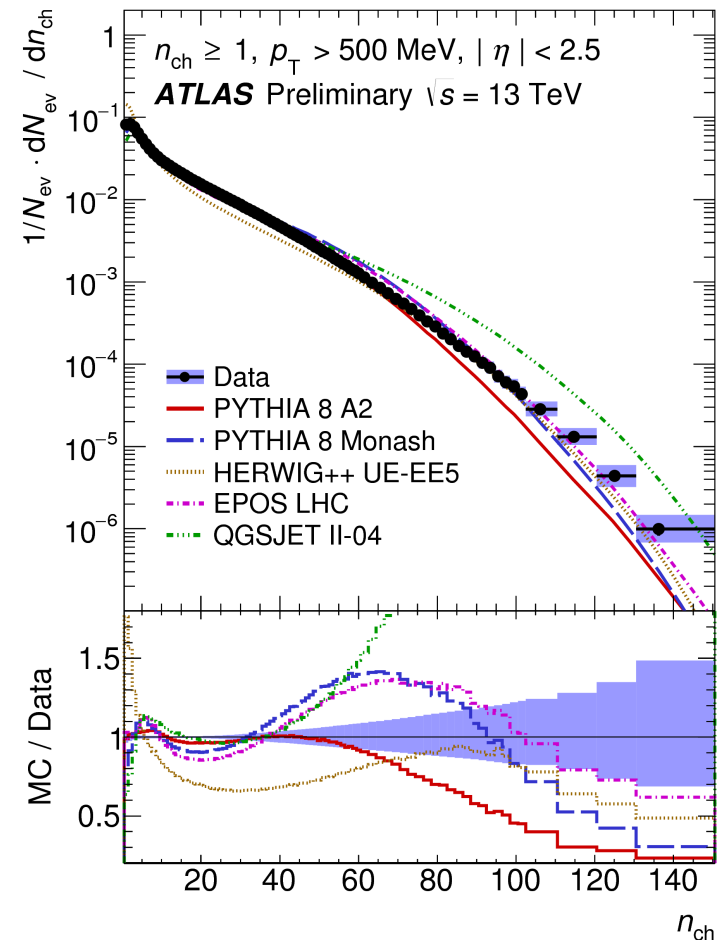
# Charged particle multiplicities

- ▶ Inclusive charged-particle measurements in pp collisions provide insight into the strong interaction in the low energy, non-perturbative QCD region
- ▶ Compare different generators (with different parton showers) and different tunes
- ▶ MC tunes describe the data reasonably well at this new centre-of-mass energy

169  $\mu\text{b}^{-1}$   
 $\sim 10\text{M}$  events



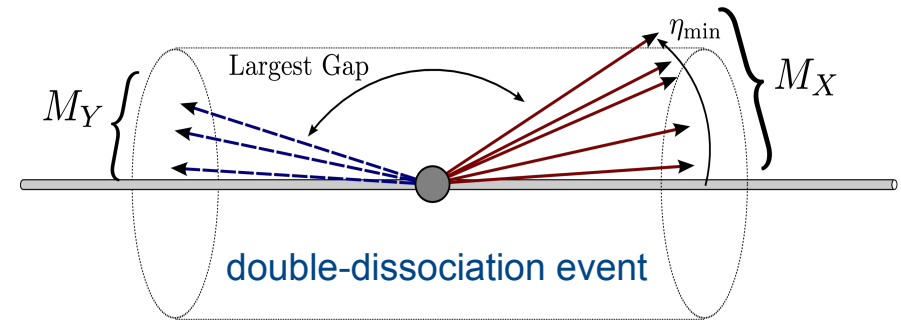
ATLAS-CONF-2015-028



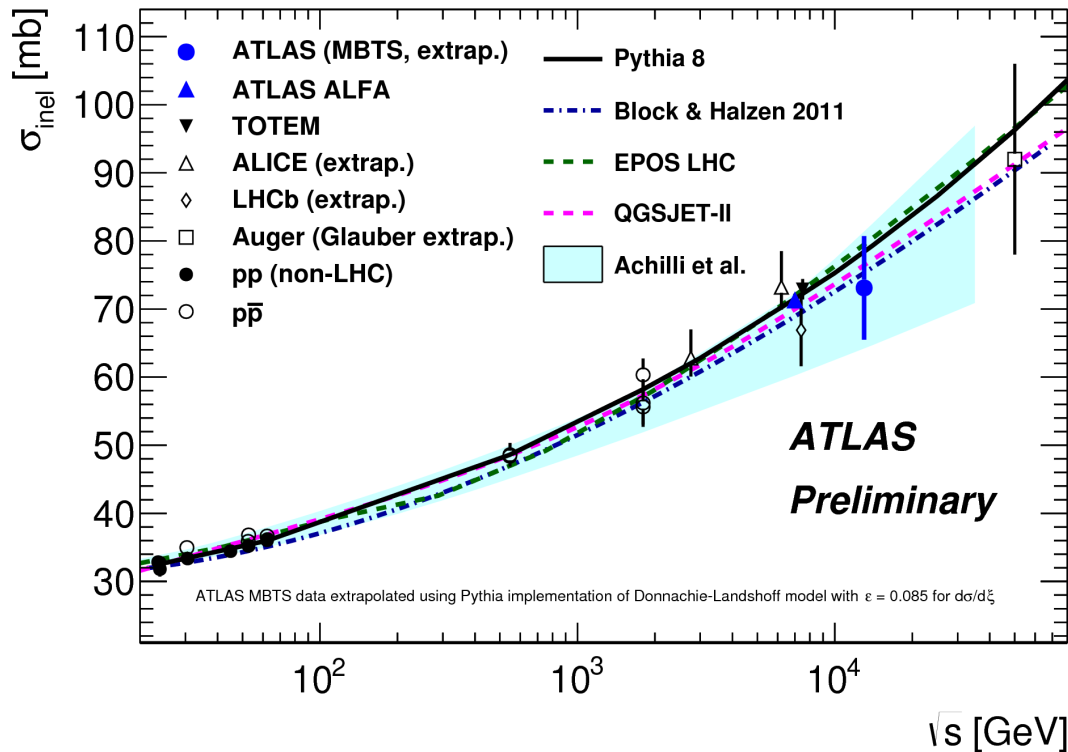
# Inelastic pp cross section at 13 TeV

The measurement is performed using scintillators mounted in front of the forward calorimeters:  
**Minimum Bias Trigger Scintillators (MBTS)**

- Measurement performed in fiducial region:  
 $\xi \approx M_X^2 / s > 10^{-6}$  (MBTS efficiency is above 50%)
- $M_X$  = larger of the dissociation masses



ATLAS-CONF-2015-038



**Fiducial cross section:**

$$\sigma^{\text{fid}} = 65.2 \pm 0.8(\text{exp.}) \pm 5.9(\text{lumi}) \text{ mb}$$

(uncertainty of the luminosity is 9%)

**Total cross section:**

$$\sigma^{\text{total}} = 73.1 \pm 0.9(\text{exp.}) \pm 6.6(\text{lumi}) \pm 3.8(\text{extr.}) \text{ mb}$$

Extrapolation from fid. to full  $\xi$  phase space

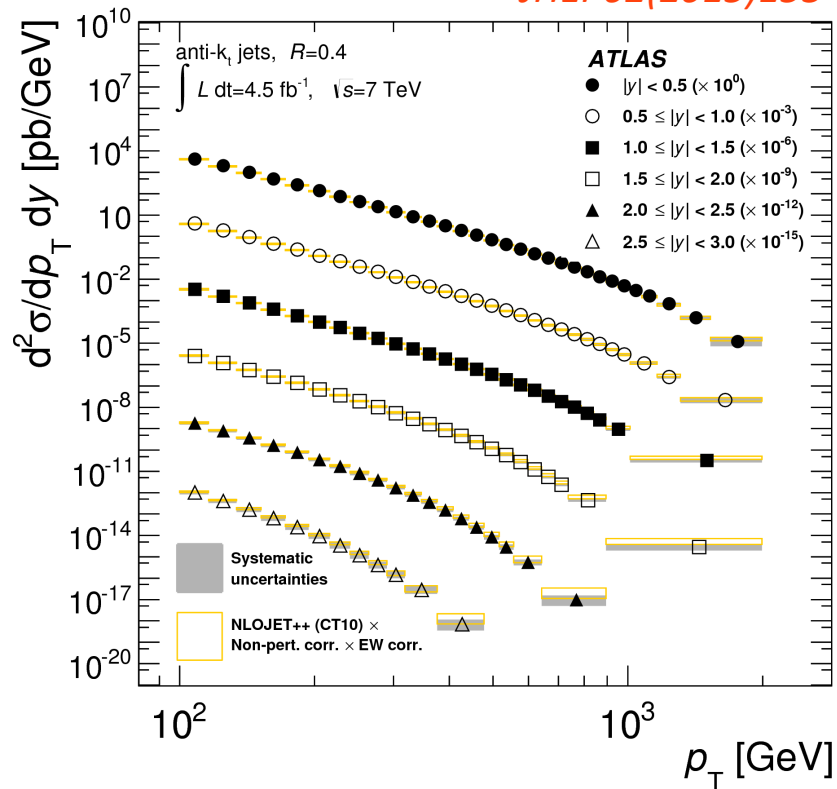
Results are about  $1\sigma - 1.5\sigma$  below the theoretical predictions currently available

# Jet production at $\sqrt{s} = 7$ TeV

## Inclusive production

- ▶ Jets are defined by anti- $k_T$  algorithm (R=0.4, 0.6):  $0.1 < p_T < 2$  TeV
- ▶ Data are compared to fixed-order NLO pQCD (corrected for both perturbative effect and electroweak effect) as well as NLO ME+PS

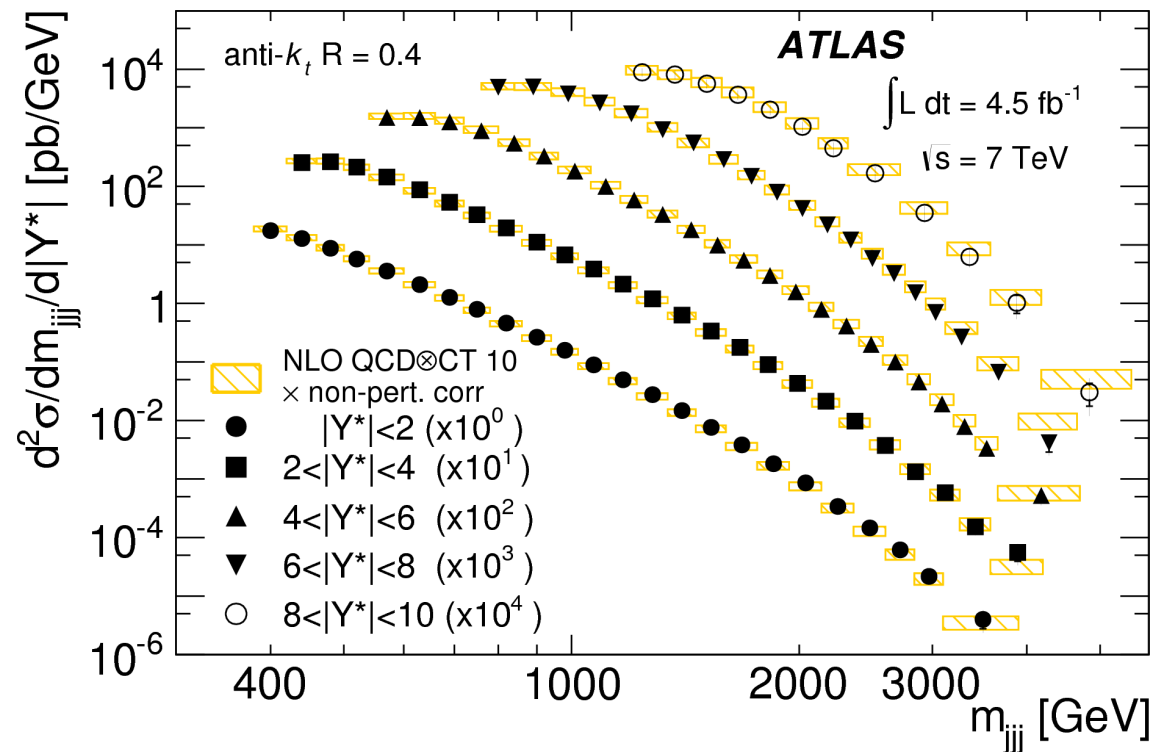
*JHEP02(2015)153*



## Three-jet production

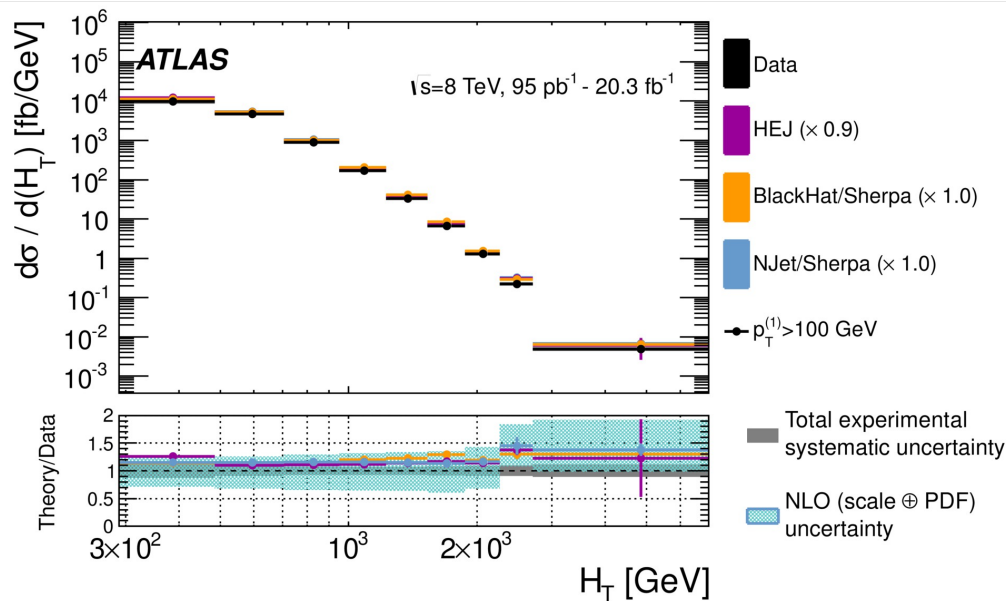
- ▶ Jets with 3-j mass up to 5 TeV
- ▶ Probed ( $m_{jij}$ ,  $|Y^*|$ ) plane with a variety of PDFs
- ▶ Data are well described by pQCD at NLO (corrected for non perturbative effects)

*Eur. Phys. J. C75 (2015) 228*

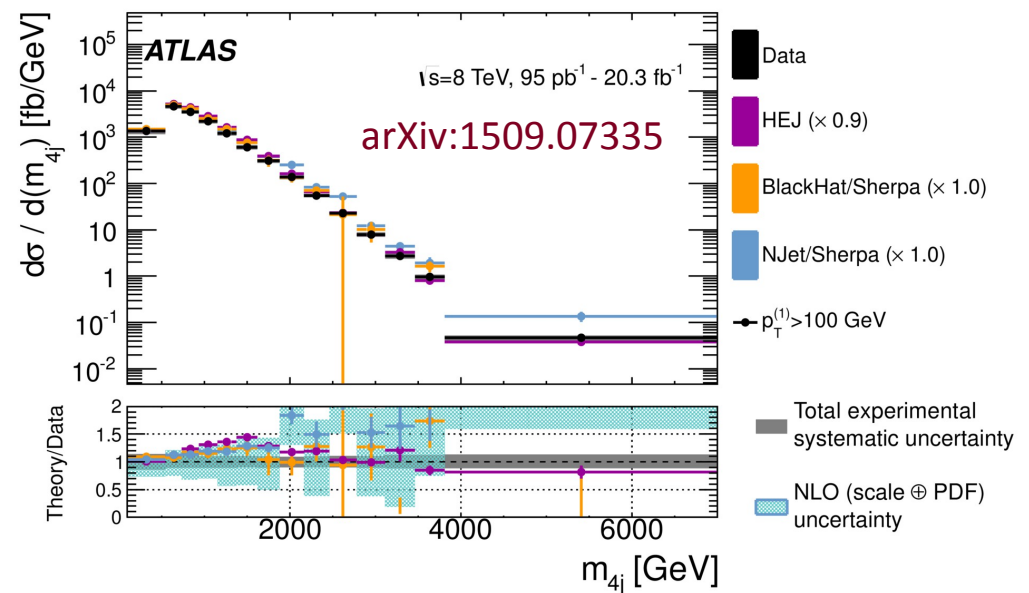


# Four jets production at 8 TeV

- ▶ Measurement of differential cross sections for events with at least four jets (as a function of the jet momenta, invariant masses and various angular variables)
- ▶ Test of prediction at
  - LO: PYTHIA, HERWIG and MADGRAPH+PYTHIA
  - NLO pQCD: Blackhat/Sherpa and Njet/Sherpa
  - HEJ: exclusive MC generator, based on approximate all-orders calculations (for  $n_{\text{jet}} \geq 2$ )



$H_T$  (scalar sum of jet  $p_T$ ) is well described by both NLO and HEJ

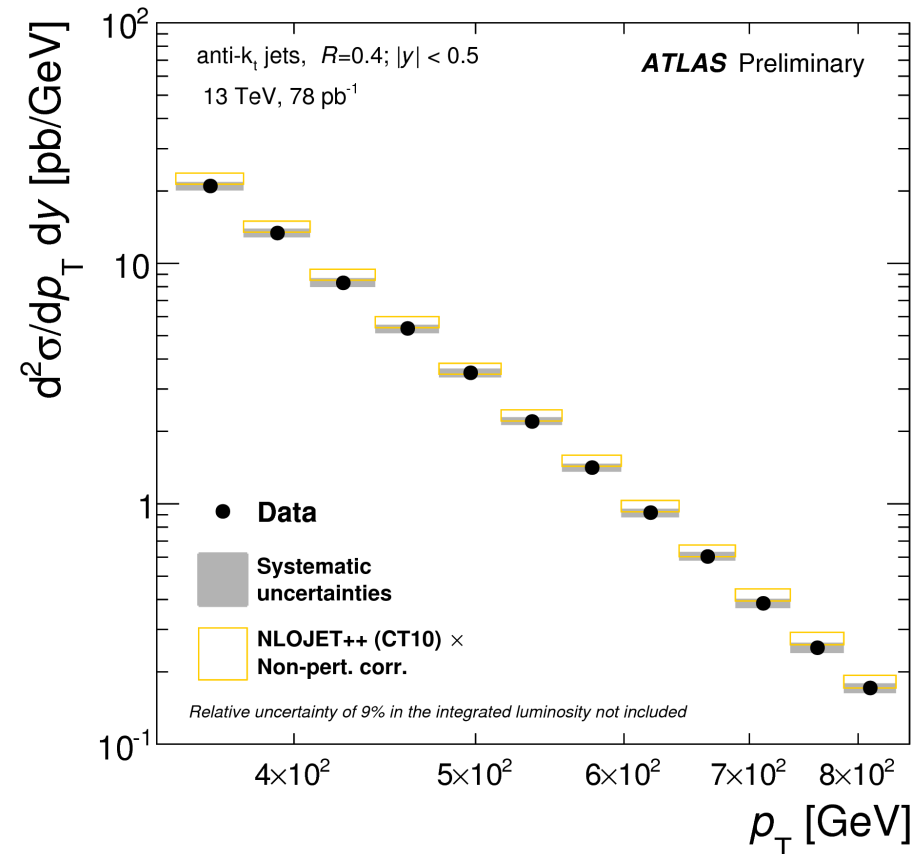
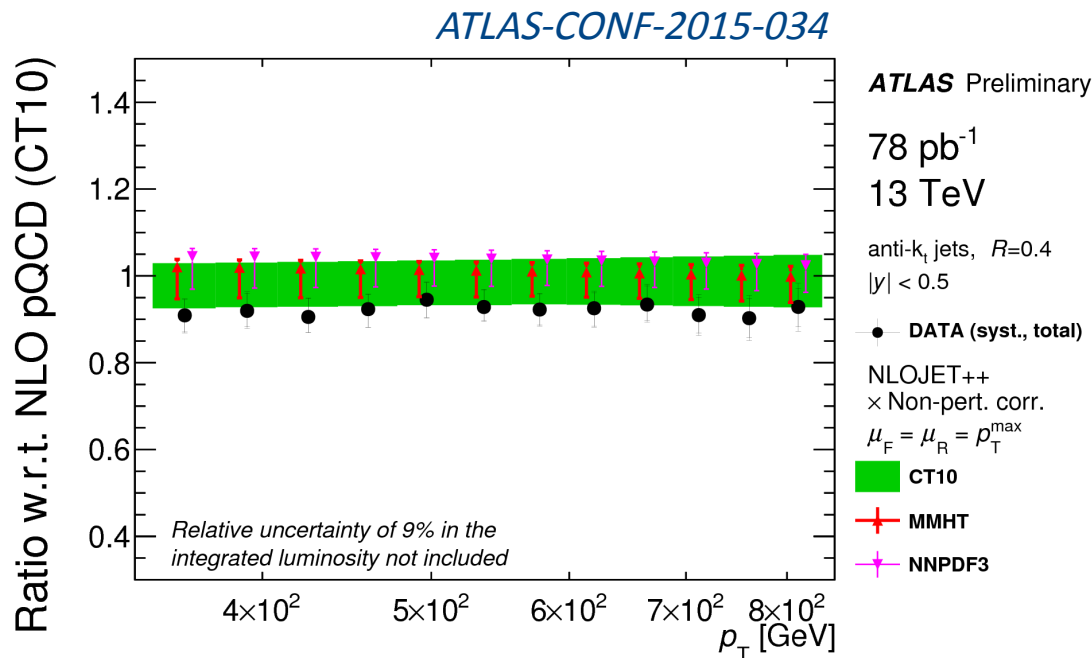


$m_{4j}$  is well described by NLO up to 3 TeV and by HEJ at high masses. NLO uncertainties are relatively large,  $O(30\%)$  at low momenta



# Inclusive Jets cross-section at 13 TeV

- ▶ Preliminary results on the inclusive-jet cross section using  $78 \text{ pb}^{-1}$  of data at 13 TeV
- ▶ Differential measurement as a function of
  - jet transverse momentum:  $346 < p_T^{\text{jet}} < 838 \text{ GeV}$
  - jet rapidity range of  $|y^{\text{jet}}| < 0.5$
- ▶ Data unfolded to particle-level using modified Bayesian technique
- ▶ NLO pQCD predictions are consistent with the data



# Jet physics – $\alpha_s$ measurement

- ▶ Transverse energy-energy correlation (TEEC) exhibit a quadratic dependence on the strong coupling constant
- ▶ Measurements of the angular distributions of jet pairs weighted by  $E_T^1 E_T^2 / (\sum E_T)^2$ :

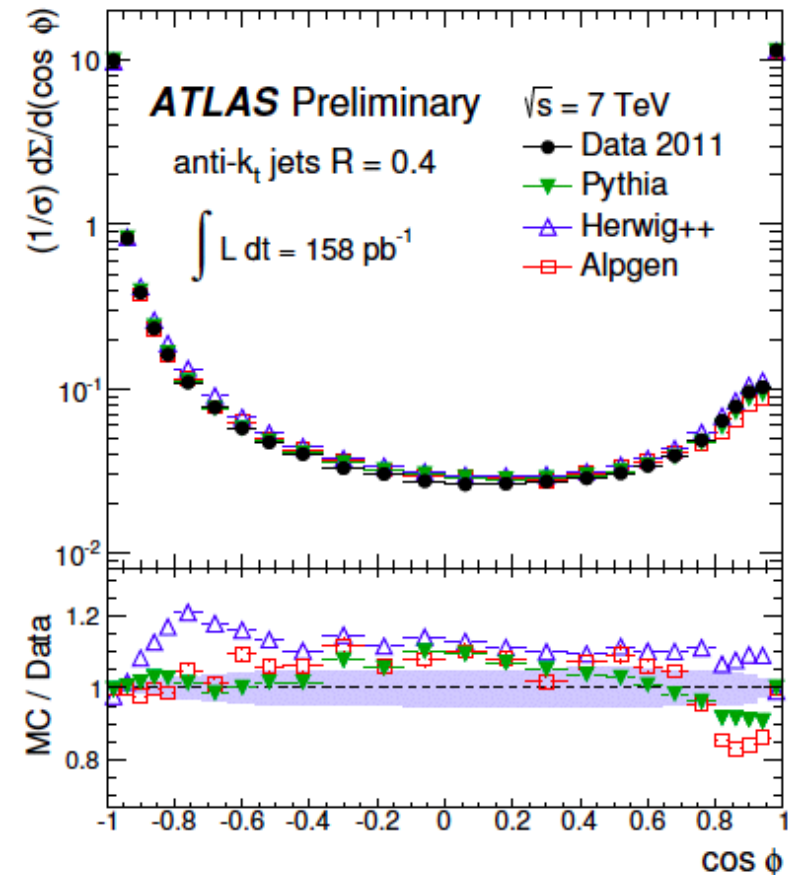
$$\frac{1}{\sigma} \frac{d\Sigma}{d(\cos \phi)} = \frac{1}{\sigma} \sum_{ij} \int \frac{d\sigma}{dx_{Ti} dx_{Tj} d(\cos \phi)} x_{Ti} x_{Tj} dx_{Ti} dx_{Tj}$$

where  $x_{Ti} = E_{Ti}/E_T$  and  $E_T = \sum_i E_{Ti}$

## Analysis strategy:

- ▶ 158 pb<sup>-1</sup> of data @ 7 TeV
- ▶  $p_T^1 + p_T^2 > 500$  GeV;  $p_T^{(all)} > 50$  GeV;  $|\eta(\text{jet})| < 2.5$
- ▶ Total uncertainty is about 5%, dominated by the jet energy scale, pileup and MC parton-shower modeling.
- ▶ **Pythia/Alpgen** predictions agree reasonably well with data, Herwig++ deviates from data by up to 20%

*arxiv:1508.01579*

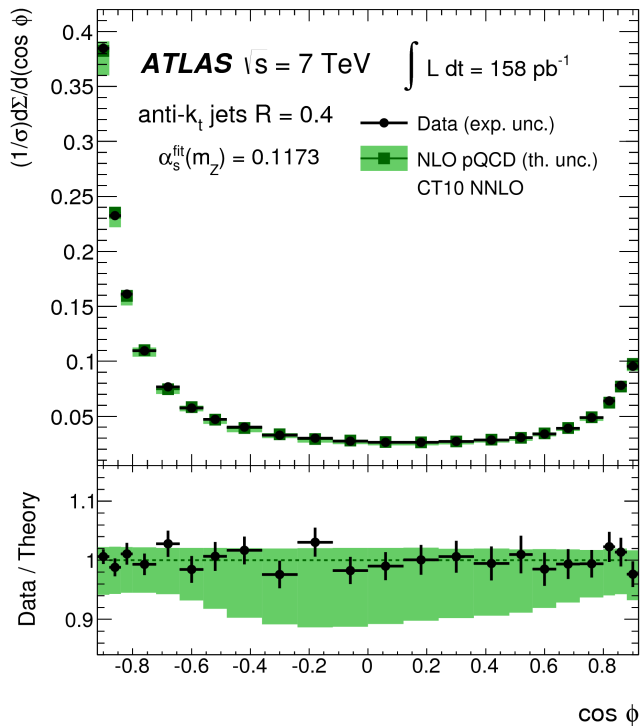


# Jet physics – $\alpha_s$ measurement

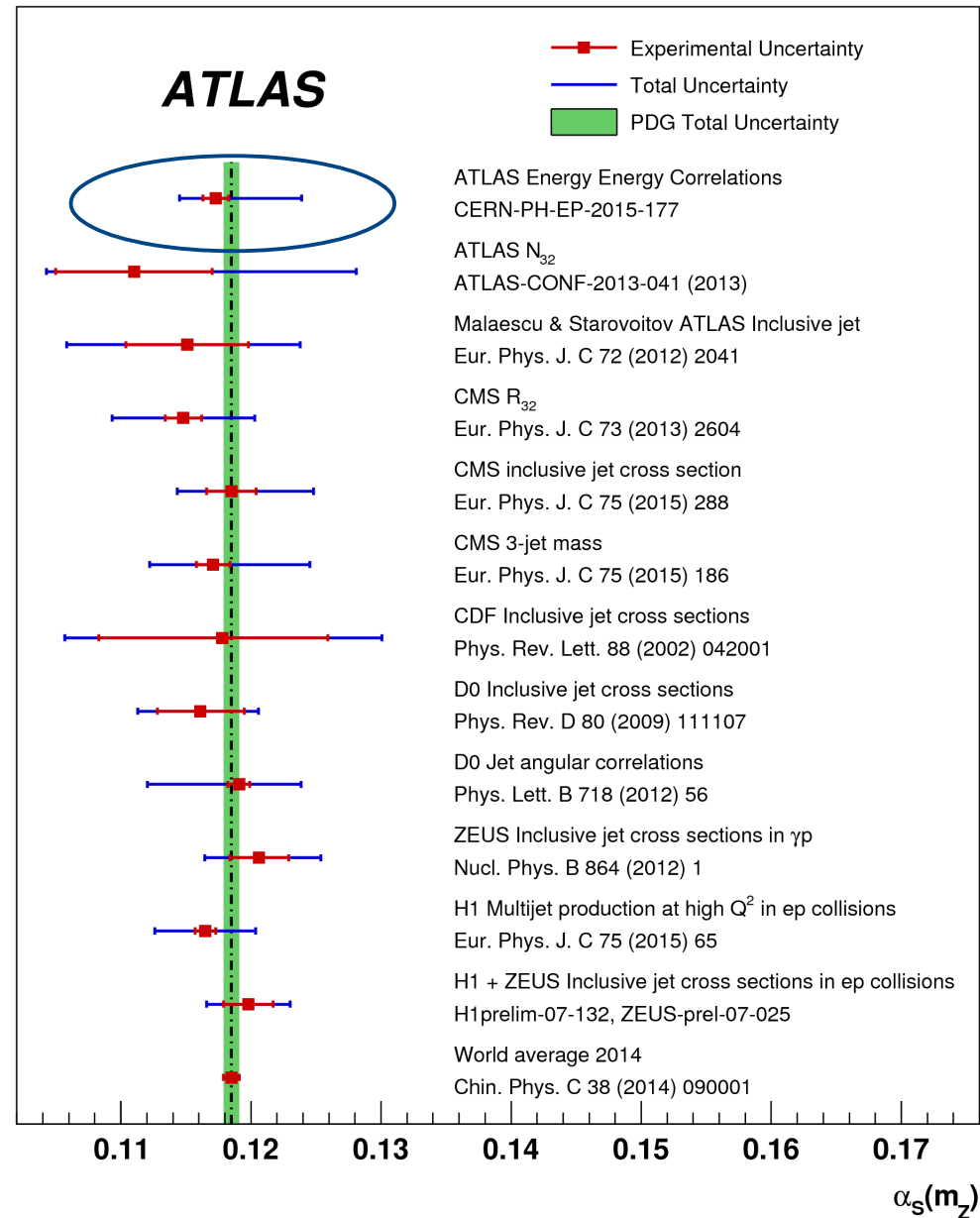
## ▶ TEEC measurement:

- In a good agreement with NLO pQCD
- Theoretical scale uncertainty dominate over experimental uncertainties

## ▶ Excellent compatibility between World Average and ATLAS jet-based measurements



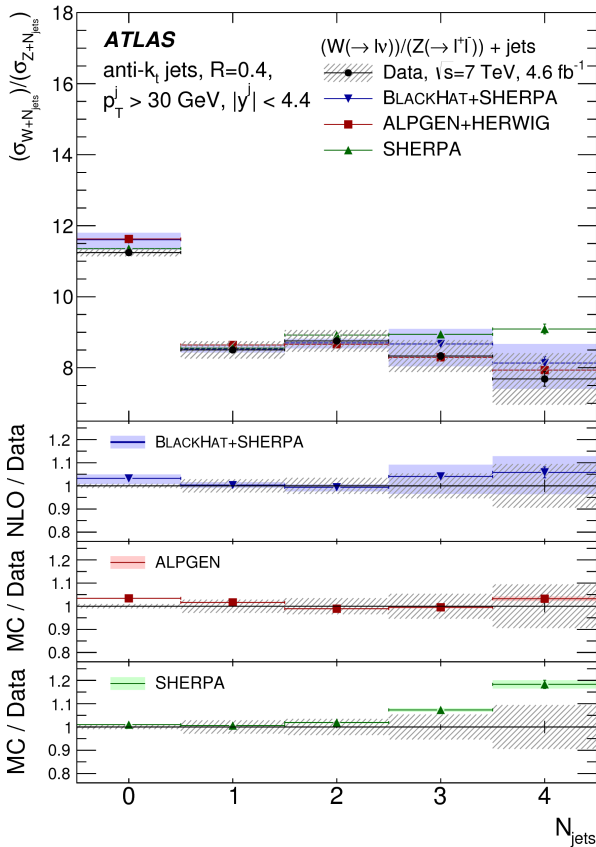
arXiv:1508.01579



$$\alpha_s(m_Z) = 0.1173 \pm 0.0010(\text{exp.}) \begin{matrix} +0.0063 \\ -0.0020 \end{matrix} (\text{scale}) \pm 0.0017(\text{PDF}) \pm 0.0002 (\text{NPC})$$

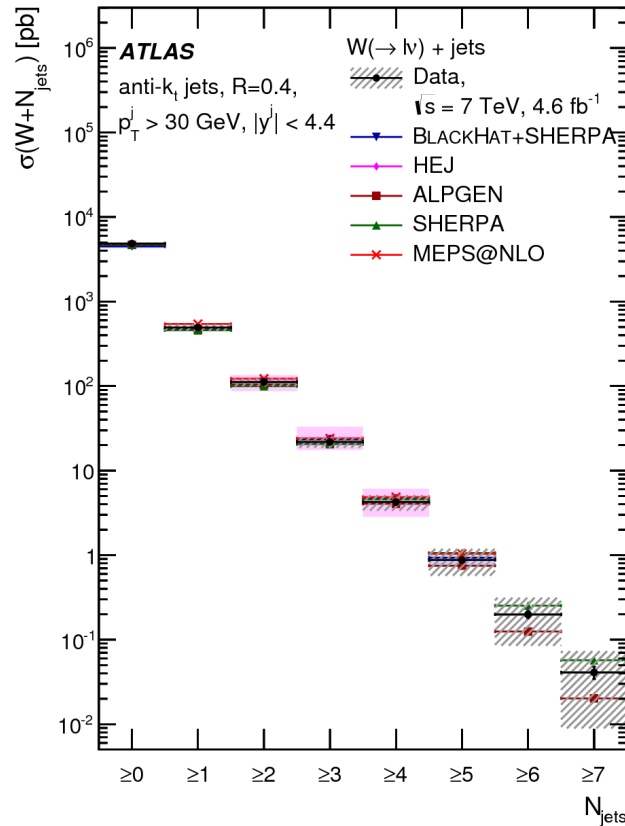
# W+jets / Z+jets at 7 TeV

## R-jets: ratio of W+jets and Z+jets

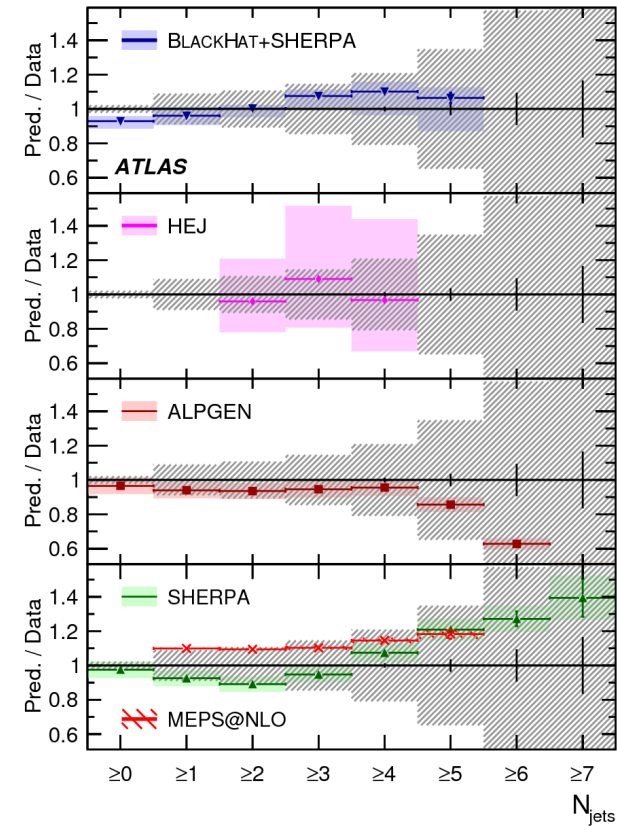


*Eur. Phys. J. C (2014) 74: 3168*

## W+jets production



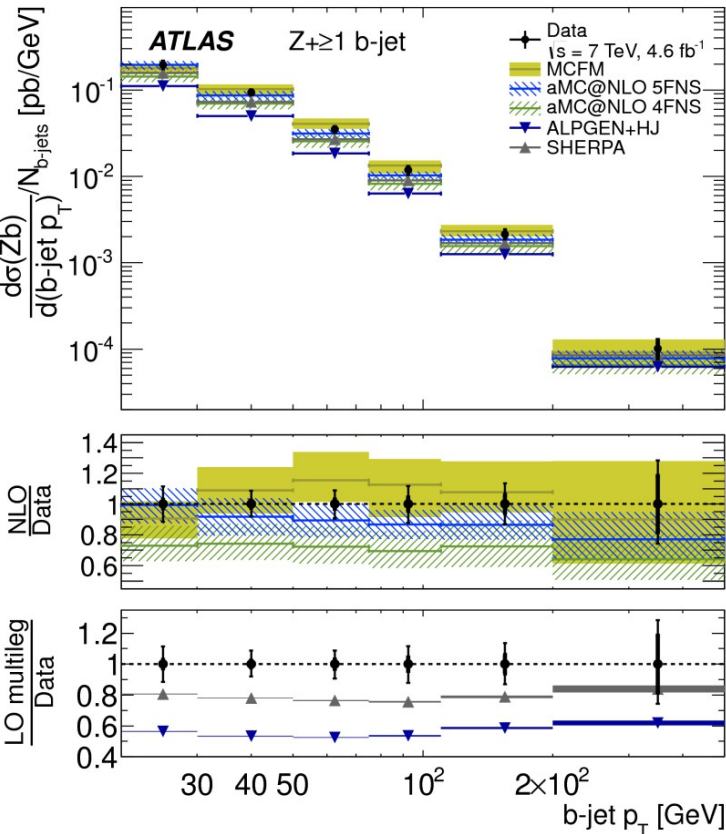
*Eur. Phys. J. C (2015) 75:82*



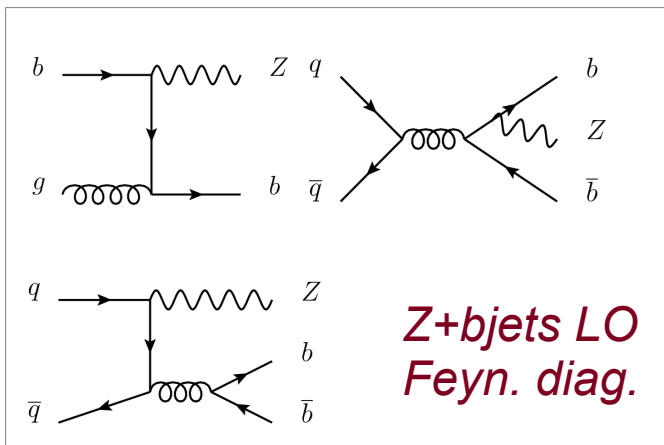
- ▶ Differential measurement for the first time **up to four jets**
- ▶ Observed discrepancy of  $1.5\sigma$  at high jet multiplicities with **SHERPA**
- ▶ **BlackHat+SHERPA** is  $1\sigma$  above data at high inclusive jet multiplicities

- ▶ Measurement with multiplicities **up to seven associated jets** and  $p_T$  of jets up 1 TeV
- ▶ Fixed-order predictions provide good description (**BlackHat+SHERPA**)
- ▶ Overall reasonable agreement with predictions is observed

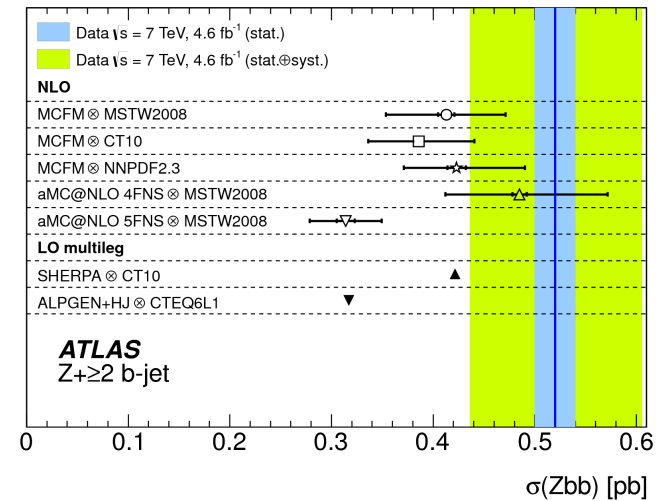
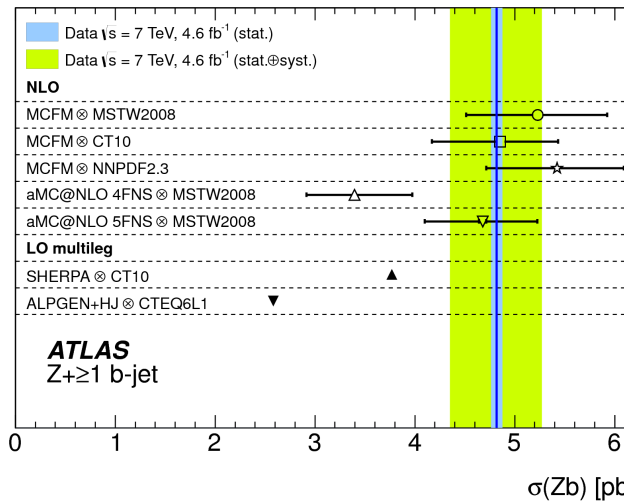
# Z+bjets at 7TeV



- ▶ Important background to ZH with  $H \rightarrow bb$  and BSM signatures
- ▶ Two schemes considered 4-flavour (4FNS) vs. 5FNS
- ▶ MCFM in five-flavour number scheme agrees with data within uncertainties
- ▶ aMC@NLO 4FNS describes better Z+2 b-jets, while 5FNS describes better Z+1 b-jet
- ▶ Shape of differential cross sections are in general well modeled with LO and NLO prediction

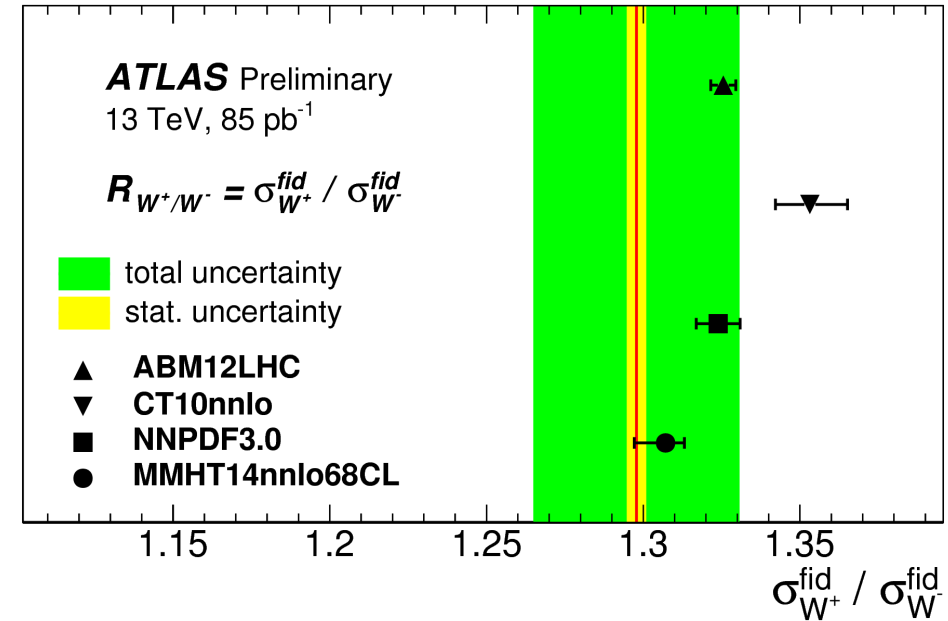
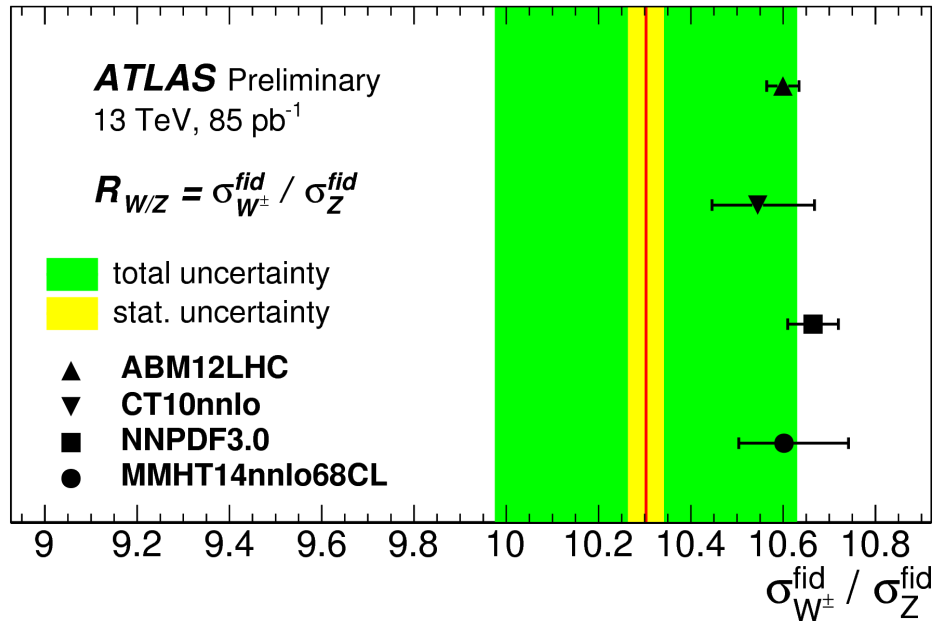


*JHEP10(2014)141*



# W and Z production at 13 TeV

**Measurement:** total inclusive and charge-specific cross sections and  $W^+ / W^-$  and of  $W^\pm / Z$  cross section ratio in leptonic channels  $e, \mu$

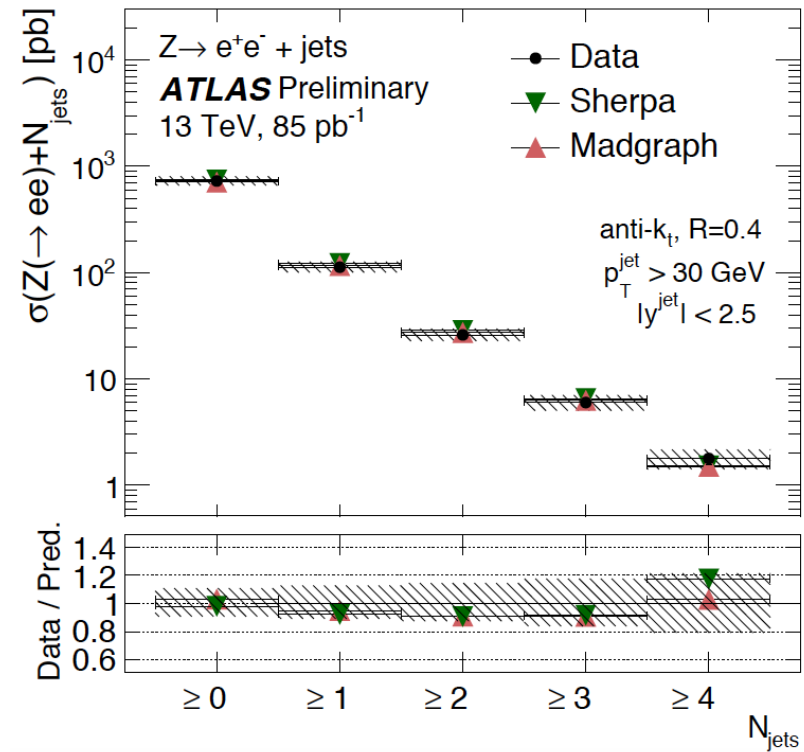
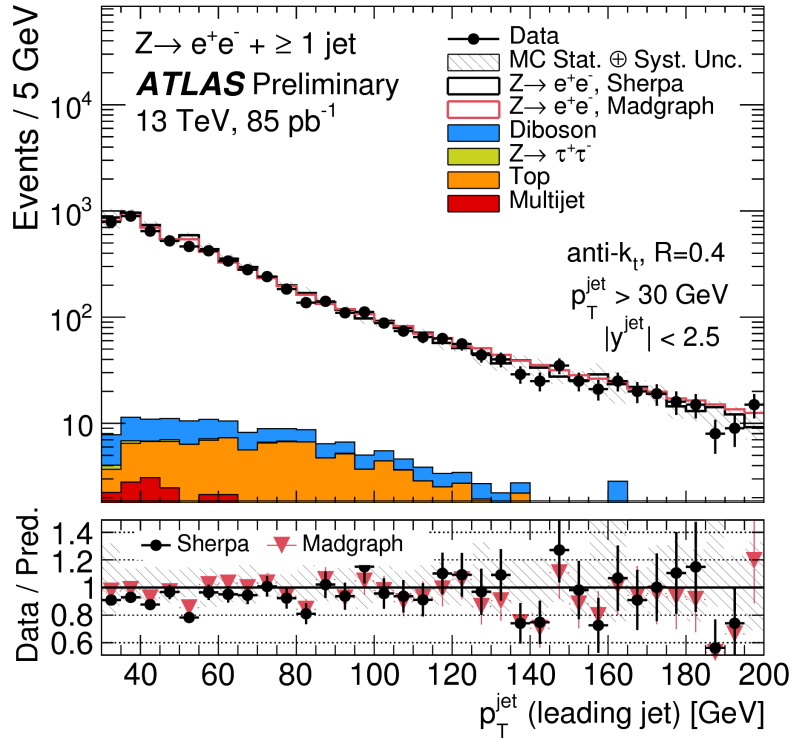


ATLAS-CONF-2015-039

- ▶ Ratio of measured cross sections benefits from the cancellation of some experimental uncertainties
- ▶ Ratio  $R_{W/Z}$  constrains strange-quark distribution
  - measurement agrees with different PDF predictions within uncertainties
- ▶ Ratio  $R_{W^+/W^-}$  sensitive to  $u_v - d_v$  valence-quark distribution at low x
  - significant scatter of different PDF predictions observed, the measurement agrees with PDFs which include LHC measurements from Run I

# Z+jets at 13 TeV

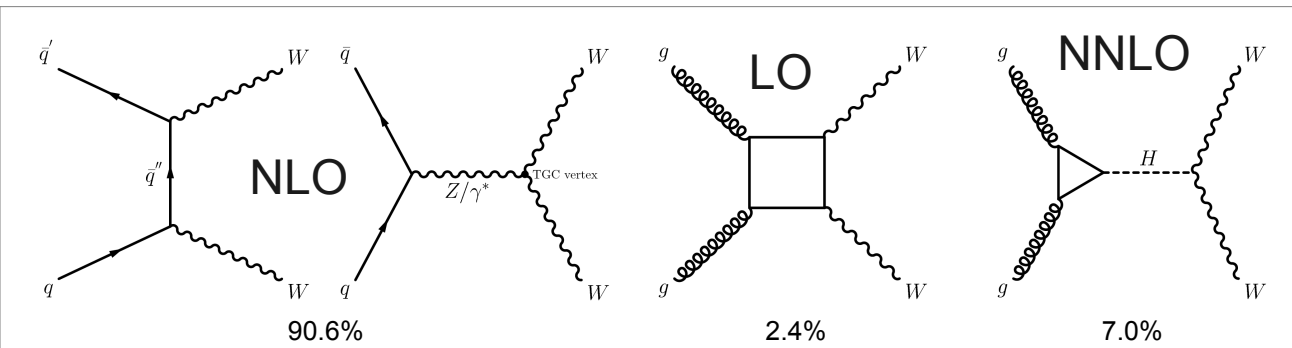
- ▶ Preliminary measurement of the Z boson in association with up to four jets using 85 pb<sup>-1</sup> of data
- ▶ Z bosons is decaying to electron or muon pairs:  $Z \rightarrow e^+ e^-$  and  $Z \rightarrow \mu^+ \mu^-$
- ▶ Jets are defined by anti-k<sub>T</sub>, R=0.4:  $p_T > 30$  GeV,  $|y| < 2.5$
- ▶ Measurement of fiducial cross sections and their ratios for successive jet multiplicities



ATLAS-CONF-2015-041

Reasonable agreement between observed cross sections and predictions from Sherpa and MadGraph

# WW->lvlv cross section at 8 TeV

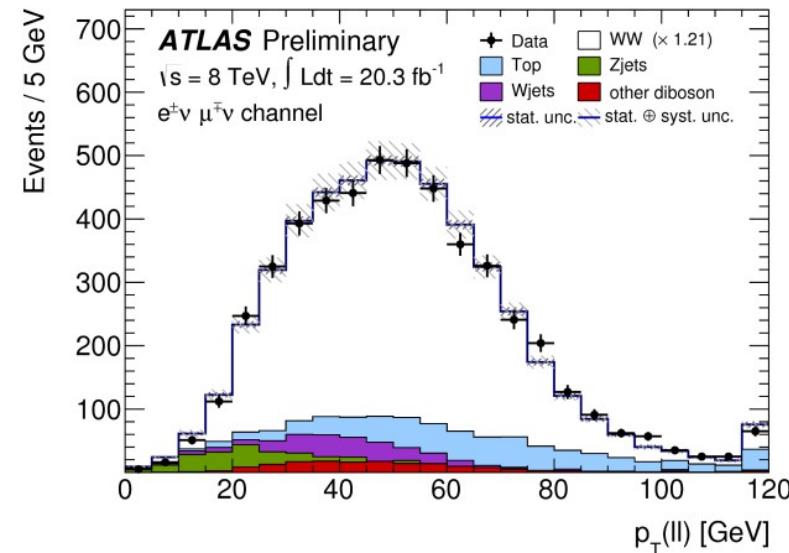
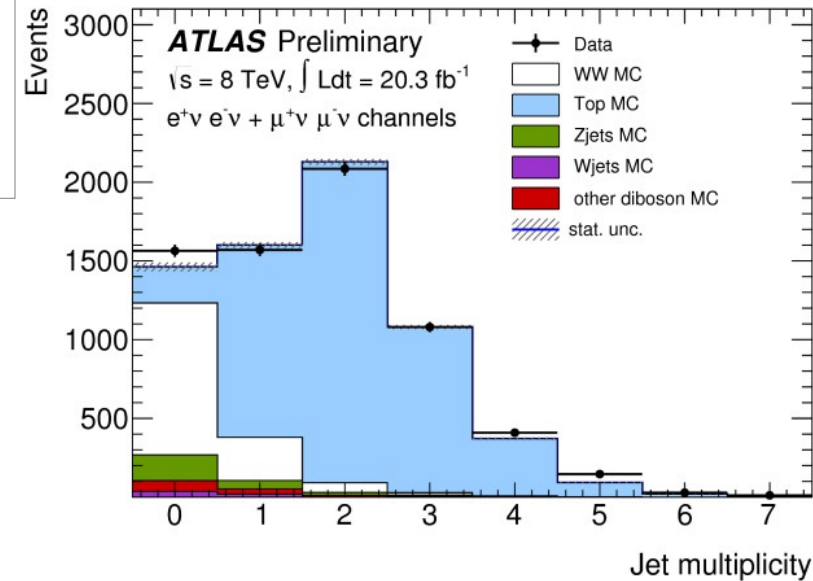


- ▶ Total and fiducial WW production cross section measurements
- ▶ Important test of the non-Abelian structure of SM
- ▶ Cross section measurements are sensitive to anomalous triple gauge couplings (aTGC)
- ▶ Non-resonant WW production is an irreducible background process to Higgs boson studies

## Backgrounds:

- ▶ Top, Drell-Yan, W+jets (all data-driven), other dibosons (MC based)
- ▶ Very hard selection-criteria on  $E_T^{\text{miss}}$  and jet-veto to suppress  $t\bar{t}$  background

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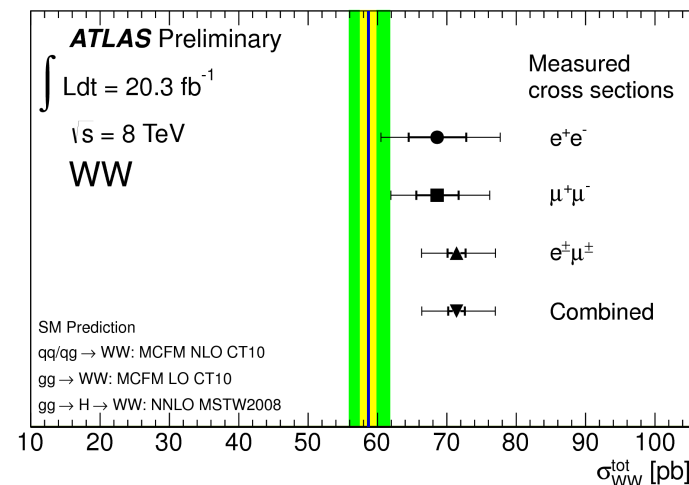
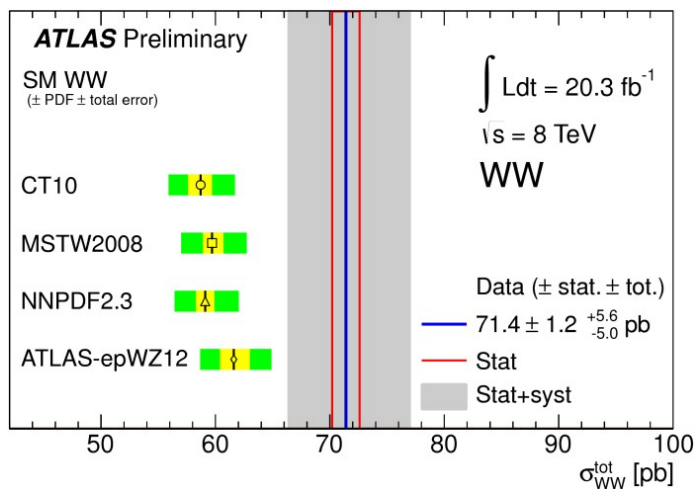


# WW → lνlν cross section at 8 TeV

- ▶ The individual channels are compatible within their uncertainties.
- ▶ The measured combined cross section **differs by +2.1σ** from the partial NNLO SM prediction computed using CT10 PDF using the standard PDF and scale uncertainties

$$\sigma_{\text{WW}}^{\text{tot}} = 71.4_{-1.2}^{+1.2}(\text{stat})_{-4.4}^{+5.0}(\text{syst})_{-2.1}^{+2.2}(\text{lumi}) \text{ pb} \quad \sigma_{\text{WW}}^{\text{predicted}} = 58.7_{-2.7}^{+3.0} \text{ pb}$$

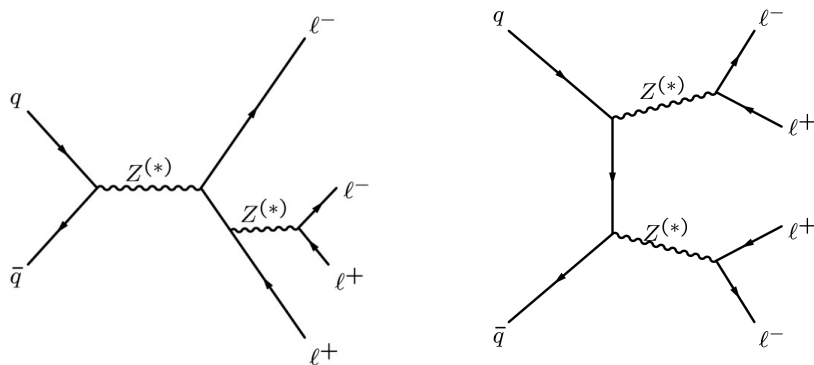
- ▶ Compatible with full NNLO prediction at about 1σ



- ▶ New result from CMS (arXiv:1507.03268): measured total σ agree well with NNLO prediction
- ▶ Major difference: 1) H → WW process is subtracted as background  
2) pTWW-resummed calculation reweighting

→ **Otherwise fairly comparable**

# 4-lepton production at 8 TeV



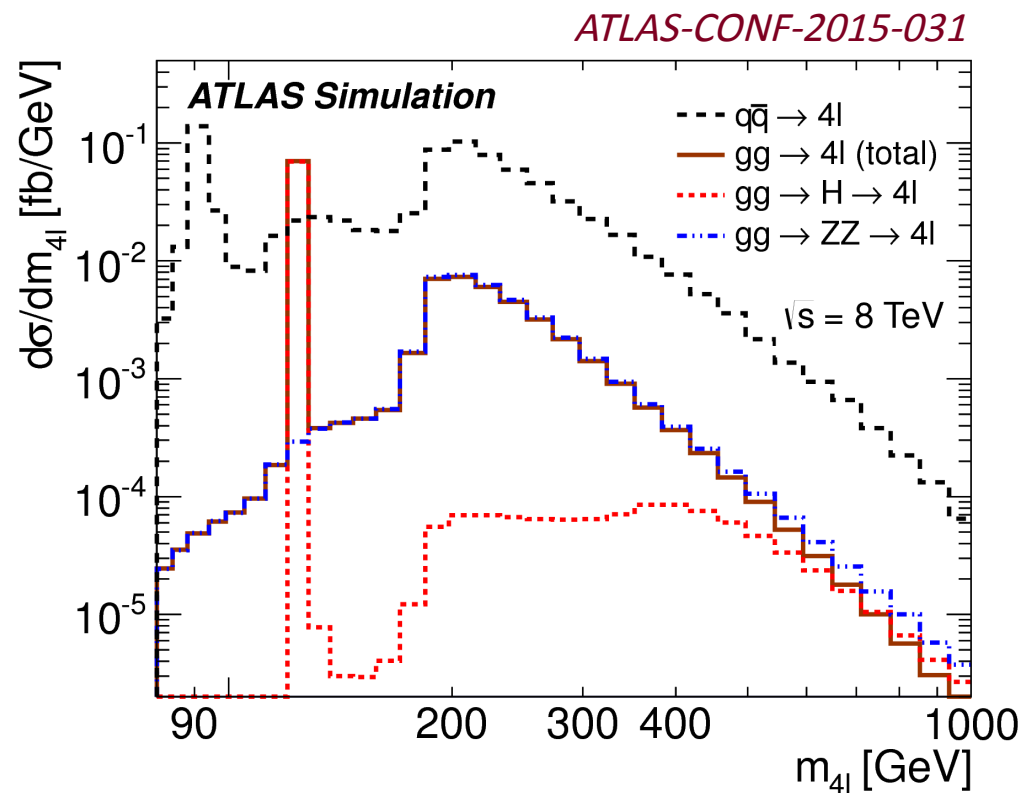
- ▶ Measurement of integrated and differential cross sections in  $m(4l)$  and  $p_T(4l)$
- ▶ Test of SM through interplay of QCD and EW effects for different production mechanisms
- ▶ Background very small ( $\sim 5\%$ )

## Selection:

- 4 high  $p_T$  isolated leptons
- Build same flavor, opp. charge pairs
- $50 \text{ GeV} < m_{12} < 120 \text{ GeV}$ ;  $12 \text{ GeV} < m_{34} < 120 \text{ GeV}$

## Background:

- Z+jets and  $t\bar{t}$  (data driven)
- ZW,  $Z\gamma$ , Z+top, VVV, ZH and
- double Drell Yan (MC)

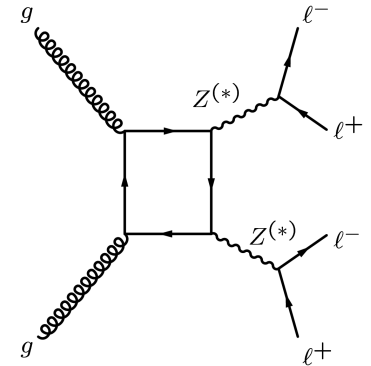


# 4-lepton production at 8 TeV

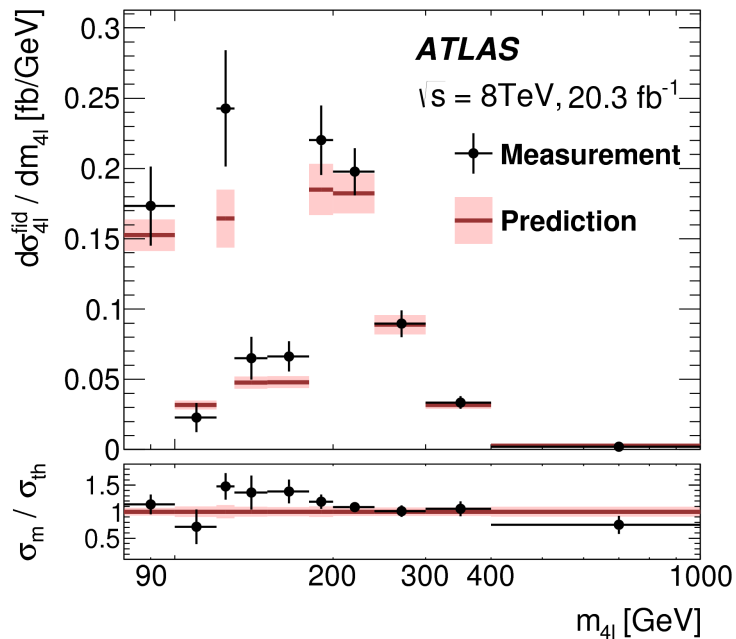
- ▶ Measurement of signal strength of **non-resonant**  $gg \rightarrow 4l$  production:

$$\frac{\sigma(data)}{\sigma(gg \rightarrow 4l; LO)}$$

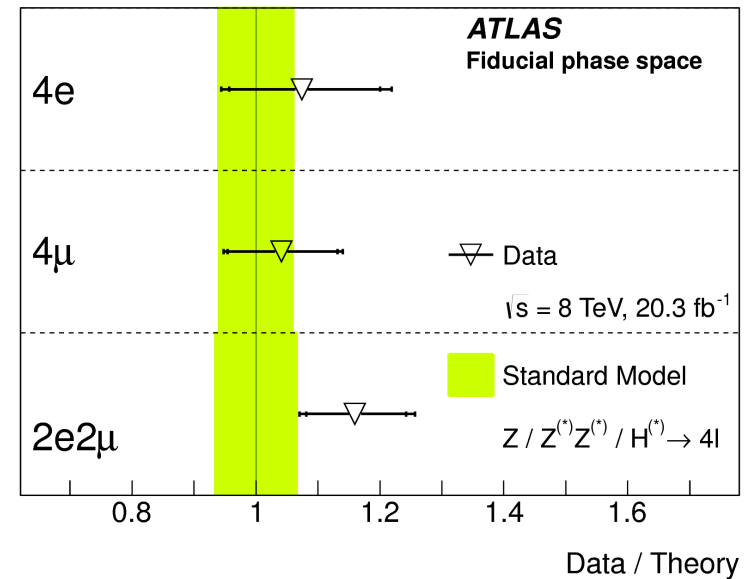
$$\mu_{gg} = 2.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.8(\text{theory})$$



- ▶ We require:  $m_{4l} > 180$  GeV region ( $gg \rightarrow 4l$  is dominated by continuum  $gg \rightarrow ZZ$ )
- ▶ LH fit to data including non- $ggZZ$  contribution (QCD NNLO and EW NLO) and background

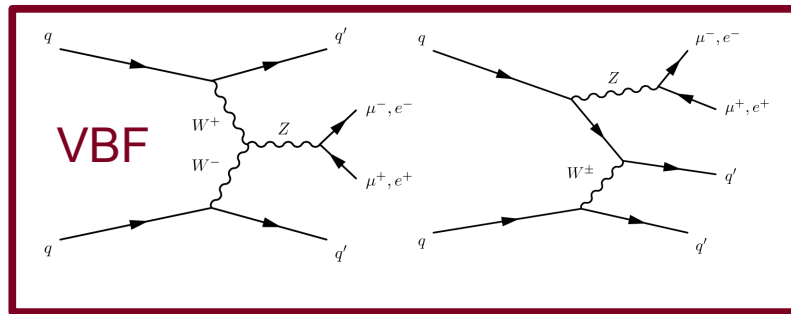
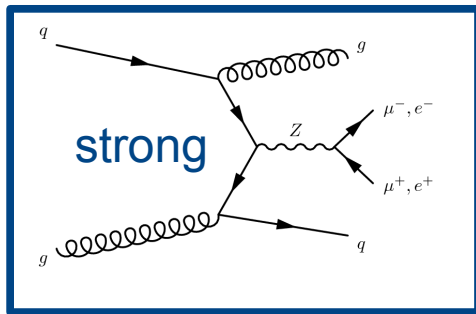


Overall good agreement between theory prediction and measurement of differential cross-section distributions of  $m_{4e}$



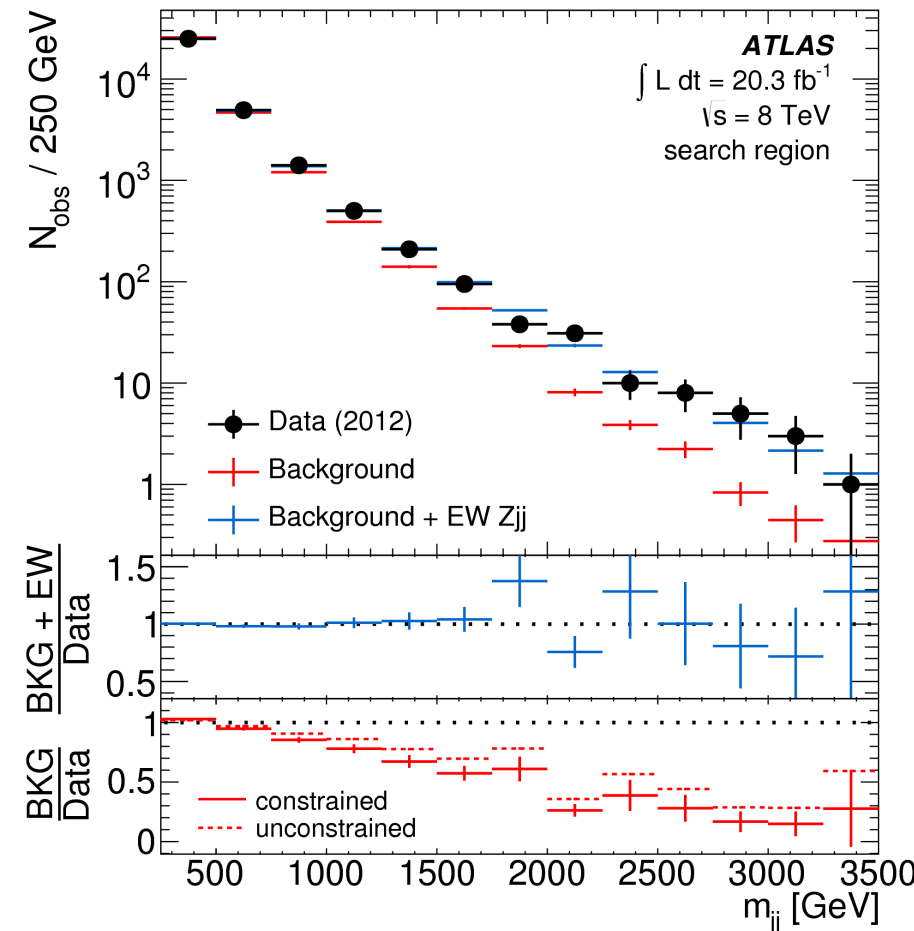
Measured channel specific cross sections in fiducial phase space

# Z+2 jets production (VBF)



JHEP04(2014)031

- ▶ Inclusive Zjj production is dominated by the strong production process
- ▶ VBF process is of particular interest because of the similarity to the VBF production of a Higgs boson
- ▶ (strong) background template constrained by data-driven technique, electroweak production extracted in EW enriched region
- ▶ strong-production-only hypothesis rejected at  $> 5\sigma$

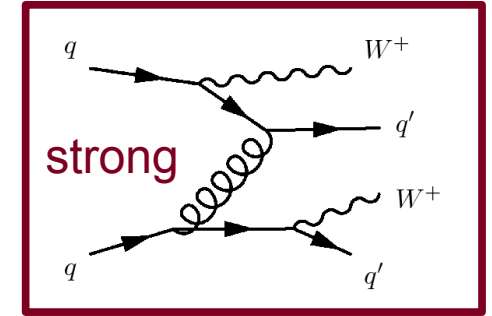
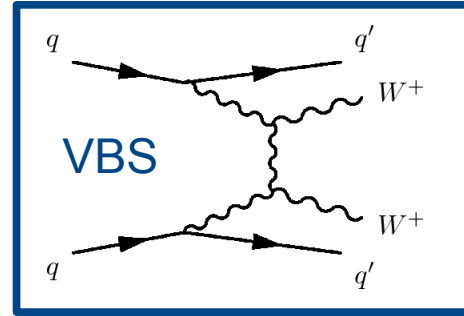


$$\sigma_{EW} = 54.7 \pm 4.6 \text{ (stat)}_{-10.4}^{+9.8} \text{ (syst)} \pm 1.5 \text{ (lumi)} \text{ fb}$$

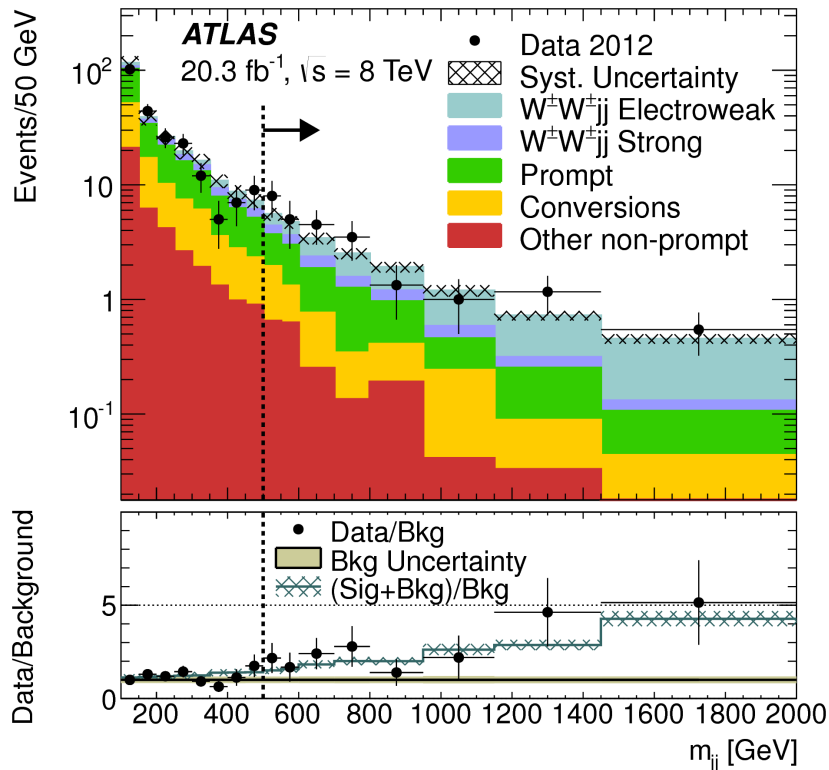
$$\sigma_{EW}^{\text{Powheg}} = 46.1 \pm 0.2 \text{ (stat)}_{-0.2}^{+0.3} \text{ (scale)} \pm 0.8 \text{ (PDF)} \pm 0.5 \text{ (model)} \text{ fb}$$

# Electroweak $WWjj$ production (VBS)

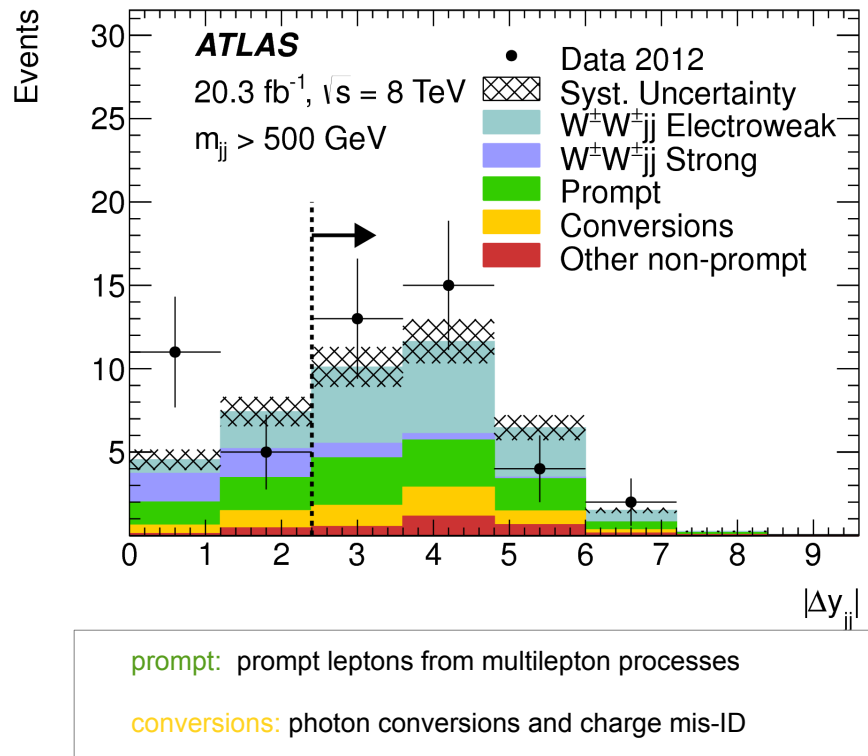
- ▶ Key process to probe EW symmetry breaking
- ▶ VBS amplitude increases with  $\sqrt{s}$ ; without Higgs this would violate unitarity at  $\sim 1$  TeV



measurement of EW + strong production  
in  $m_{jj} > 500$  GeV region

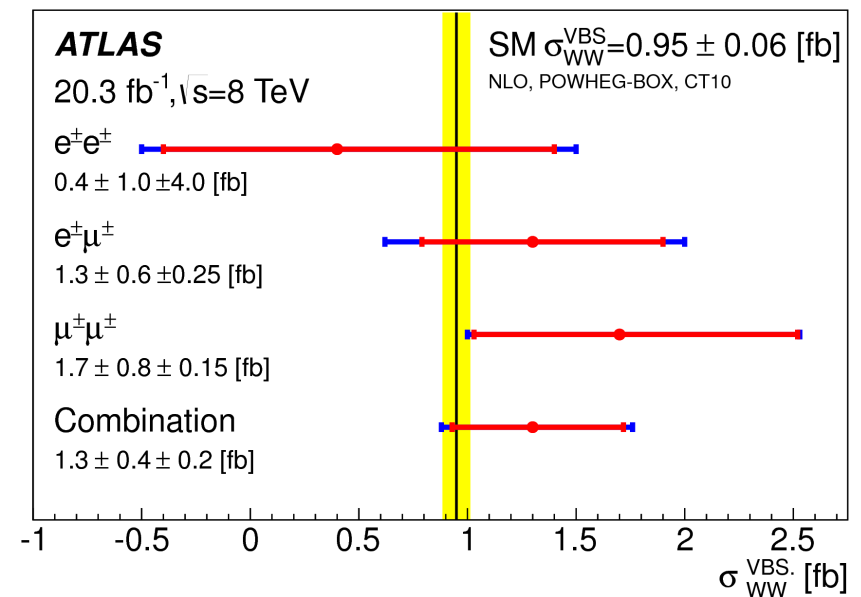
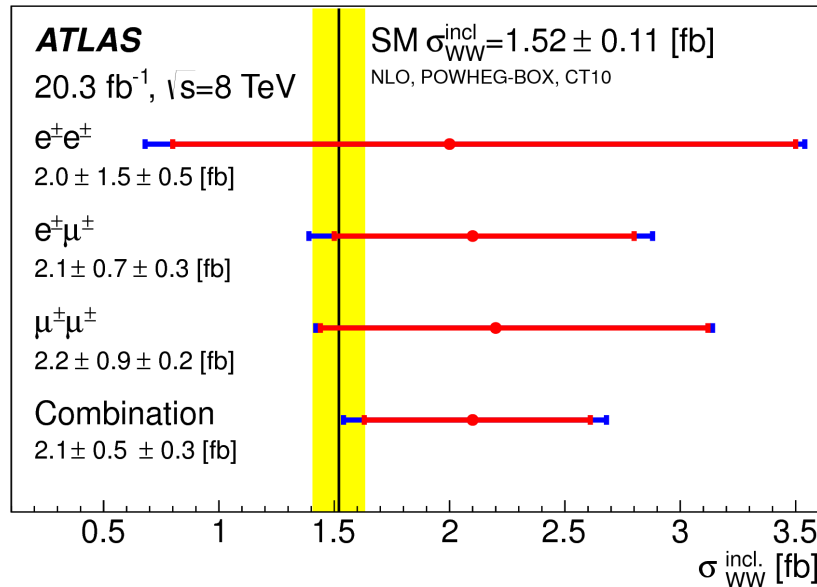


Sensitivity to EWK increases by cutting  
on  $|\Delta y_{jj}|$  in addition



Phys. Rev. Lett. 113, 141803

# Electroweak WWjj production (VBS)



- ▶ measured cross-sections slightly higher but in agreement with theory prediction
- ▶ a total of 34 candidate events in VBS region
- ▶ **first evidence for a VVVV vertex**

Inclusive measurements:

$$\sigma^{\text{fid}} = 2.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst}) \text{ fb}$$

$$\sigma^{\text{Powheg}} = 1.52 \pm 0.11 \text{ fb}$$

significance:  $4.5\sigma$  (exp.  $3.4\sigma$ )

VBS measurements:

$$\sigma^{\text{fid}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst}) \text{ fb}$$

$$\sigma^{\text{Powheg}} = 0.95 \pm 0.06 \text{ fb}$$

significance:  $3.6\sigma$  (exp.  $2.8\sigma$ )

# $W\gamma\gamma$ production

- ▶ First evidence of triboson production
- ▶ Sensitive to (anomalous) quartic coupling
- ▶ **Signature:**
  - Isolated lepton + MET and 2 isolated photons
- ▶ **Background:**
  - **Multijet background** (data driven); e.g.  $W\gamma$  + jets
  - **Prompt leptons** (MC based); e.g.  $Z\gamma$
- ▶ **Results:**
  - Measurements in inclusive ( $N_{\text{jet}} \geq 0$ ) and exclusive region ( $N_{\text{jet}} = 0$ )
  - Combined significance over background only  $> 3\sigma$

$$\sigma^{\text{fid}} = 6.1^{+1.1}_{-1.0} \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.2 \text{ (lumi.) fb}$$

$$\sigma^{\text{MCFM}} = 2.90 \pm 0.16 \text{ fb}$$

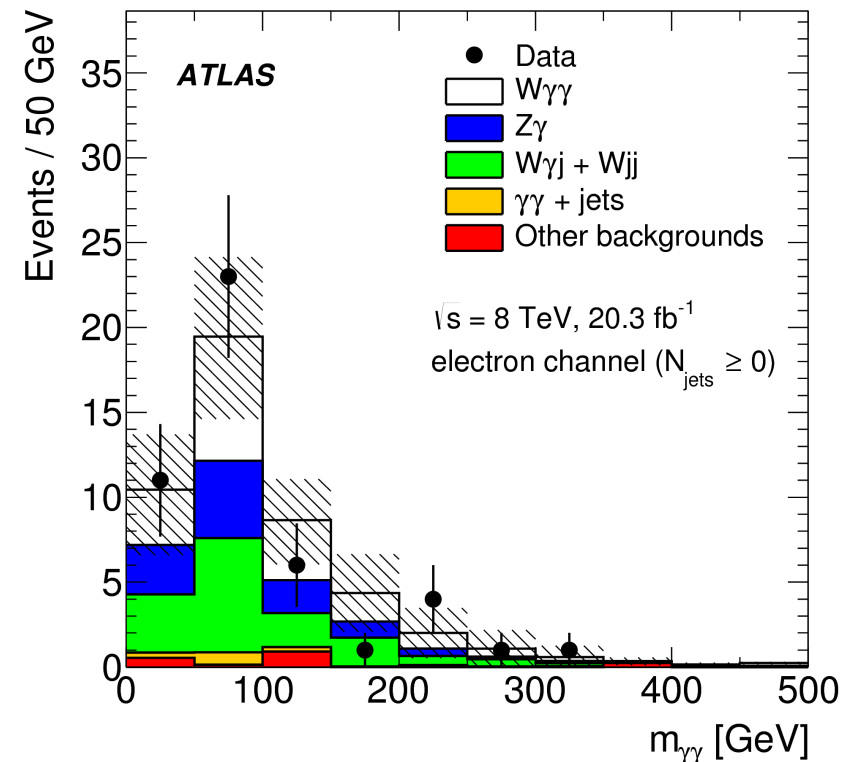
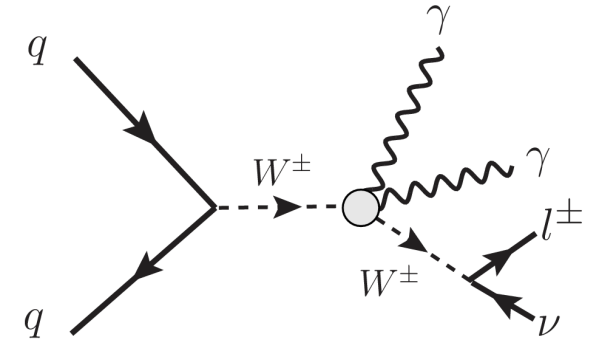
Inclusive region

$$\sigma^{\text{fid}} = 2.9^{+0.8}_{-0.7} \text{ (stat.)}^{+1.0}_{-0.9} \text{ (syst.)} \pm 0.1 \text{ (lumi.) fb}$$

$$\sigma^{\text{MCFM}} = 1.88 \pm 0.20 \text{ fb}$$

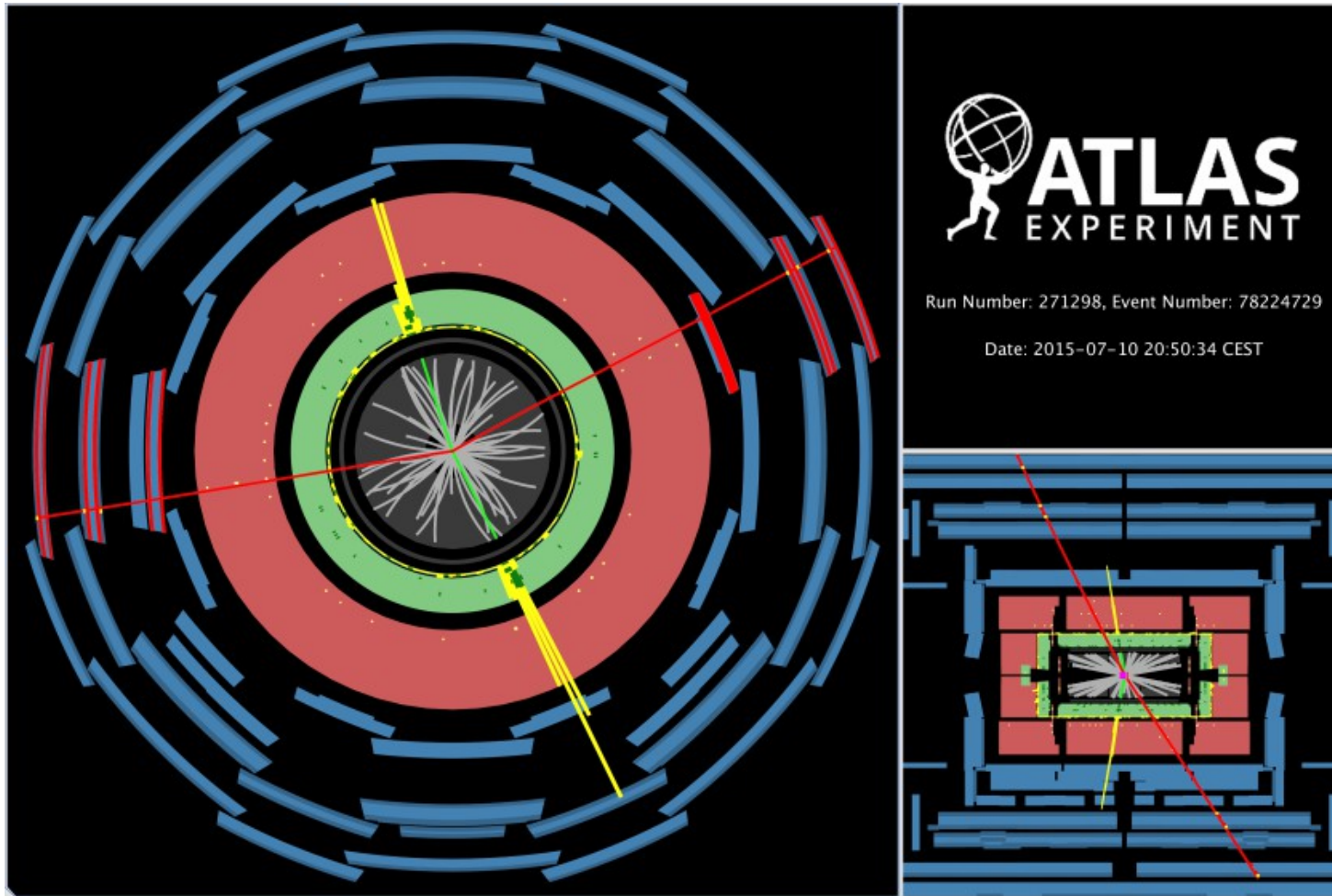
Exclusive region

*Phys. Rev. Lett. 115, 031802 (2015)*



# First ZZ events @ 13 TeV

- ▶ Display of a ZZ candidate event from proton-proton collisions with LHC beams at a collision energy of 13 TeV.
- ▶ The first Z boson candidate has a mass of 94 GeV and  $p_T$  of 35 GeV (two oppositely charged muons)
- ▶ The other candidate has a mass of 86 GeV and  $p_T$  of 19 GeV (two oppositely charged electrons)



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions>



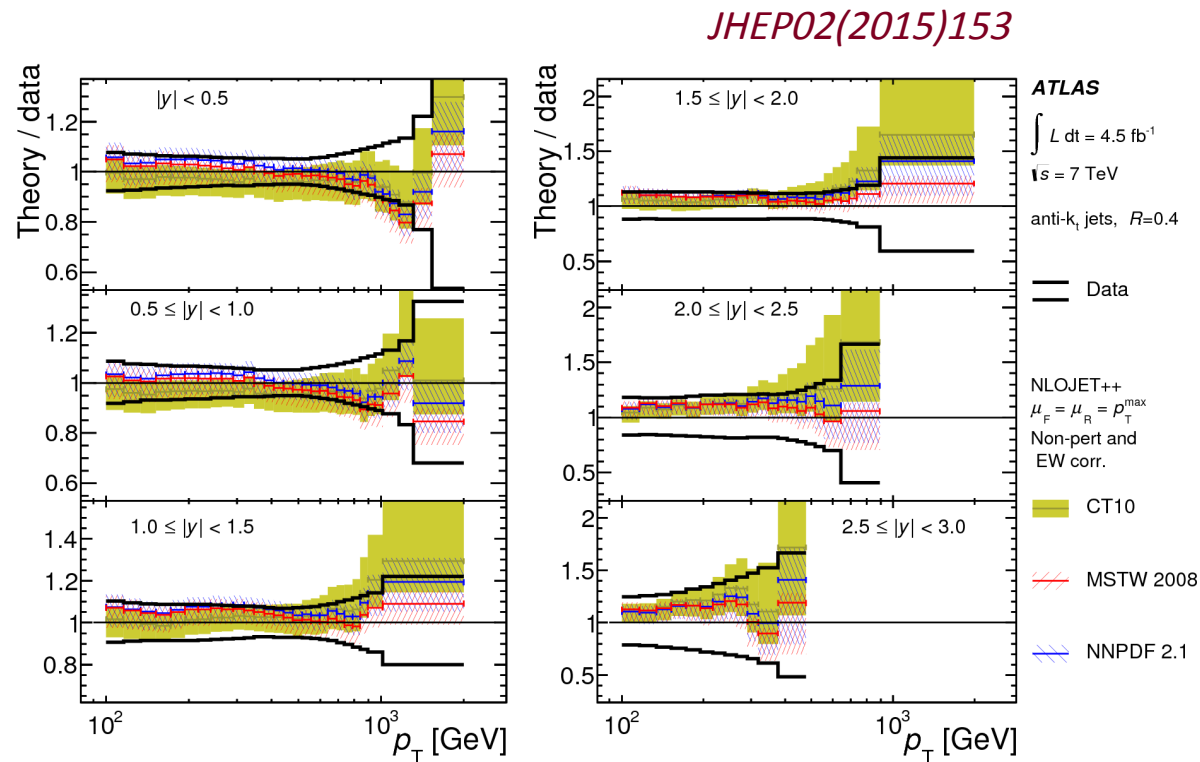
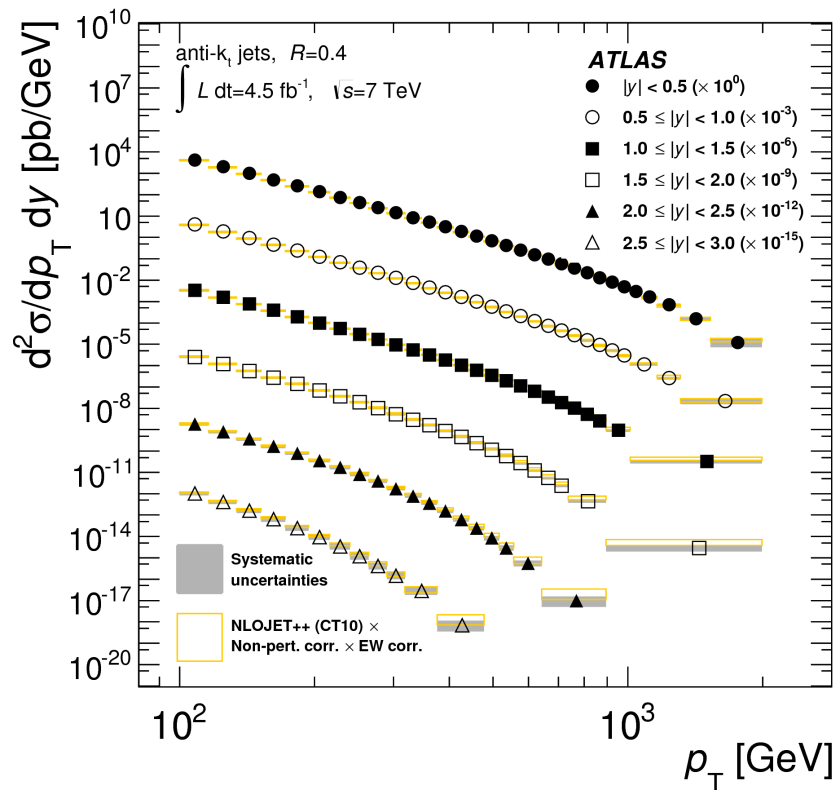
# Summary

- ▶ ATLAS performed a wide range of SM physics measurements covering a variety of SM physics aspects: QCD, Electroweak, V+X, multibosons, jets physics:
  - ▶ Two photon scattering:  $\gamma\gamma \rightarrow ll$
  - ▶ Charged particle multiplicities – first measurement at 13 TeV
  - ▶ Inelastic proton-proton cross section at 13 TeV
  - ▶ Inclusive, three-jet and four-jet cross section measurements
  - ▶ Extraction of QCD coupling constant from transverse energy-energy correlation
  - ▶ W a Z production in association with jets – also preliminary results at 13 TeV
  - ▶ WW $\rightarrow ll$  and 4-lepton production at 8 TeV
  - ▶ Electroweak production of Zjj, sensitive to vector boson fusion
  - ▶ First evidence of vector boson scattering
  - ▶ First measurement of triboson (W $\gamma\gamma$ ) production
  - ▶ ...and much more not shown in this presentation
  
- ▶ Measurements at 13TeV already underway!

**BACKUP**

# Inclusive jet production at 7 TeV

- ▶ Jets defined by anti- $k_T$  algorithm ( $R=0.4, 0.6$ ):  $0.1 < p_T < 2$  TeV
- ▶ Double-differential cross-sections as a function of transverse momentum and jet rapidity
- ▶ Data compared to fixed-order NLO pQCD (corrected for both perturbative effect and electroweak effect) as well as NLO ME+PS



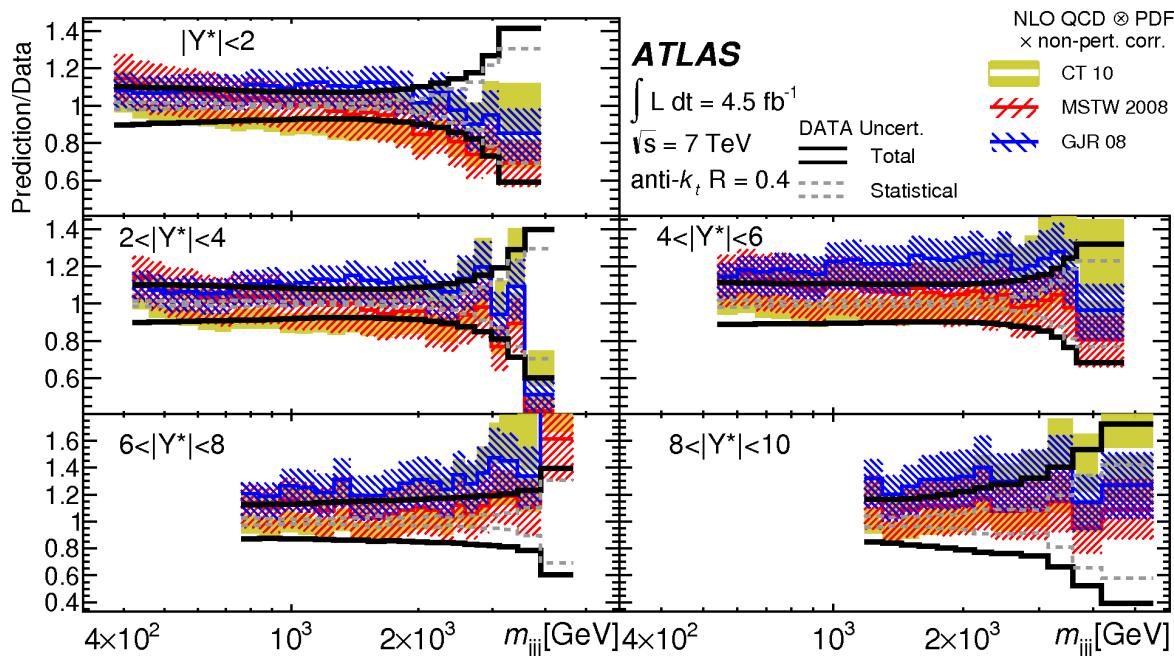
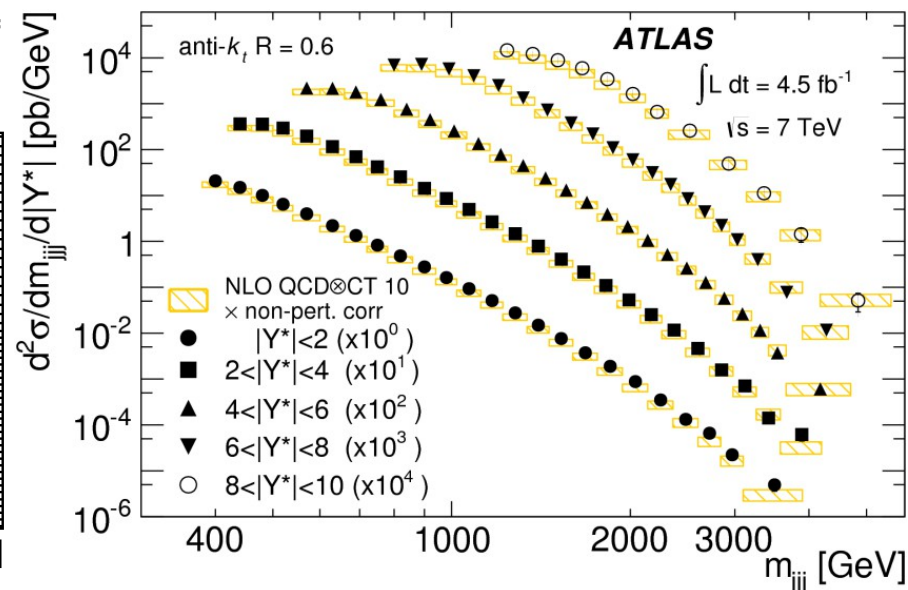
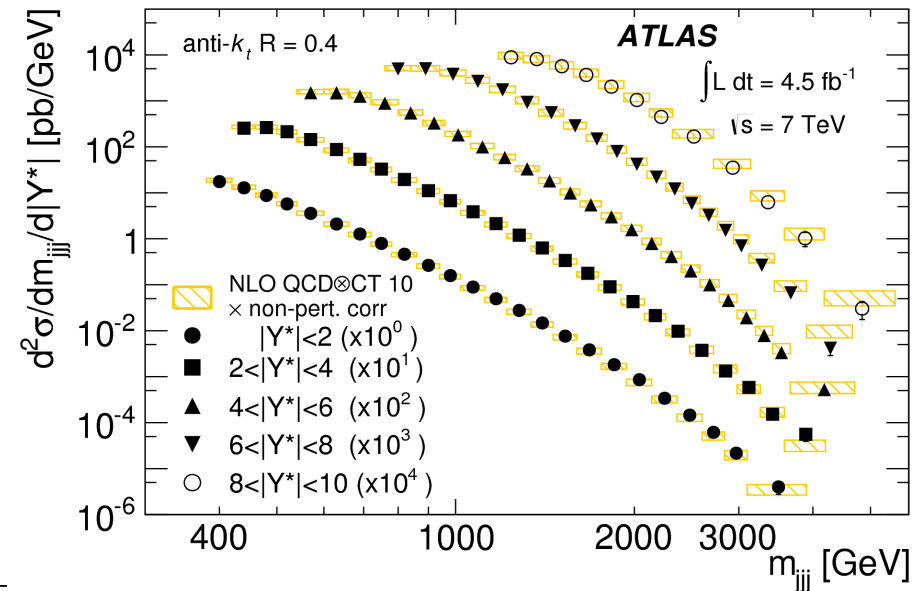
# Three jet production at 7 TeV

- ▶ Jet of anti- $k_T$  0.4 and 0.6 with 3-j mass up to 5 TeV
- ▶ Probed and well described by pQCD at NLO on full  $(m_{jjj}, |Y^*|)$  plane with a variety of PDFs

$$m_{jjj} = \sqrt{(p_1 + p_2 + p_3)^2}$$

$$|Y^*| = |y_1 - y_2| + |y_2 - y_3| + |y_1 - y_3|$$

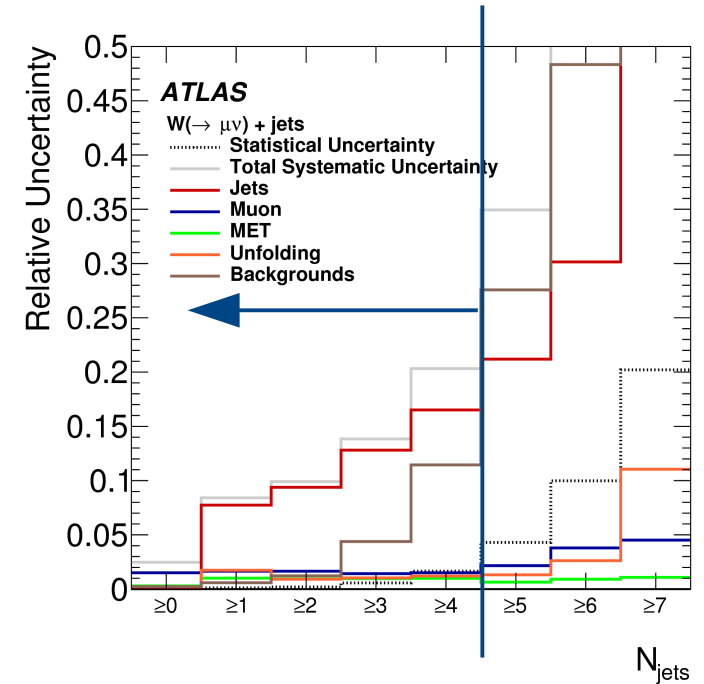
*Eur. Phys. J. C75 (2015) 228*



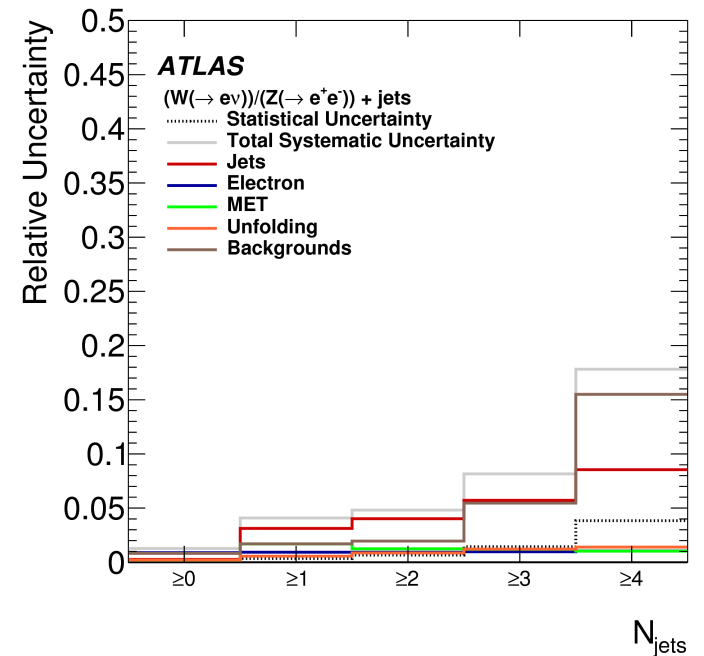
# W+jets / Z+jets at 7 TeV

*Eur. Phys. J. C (2014) 74: 3168*

- ▶ Calculated “R-jets”: ratio of W+jets to Z+jets production cross – sections
- ▶ More precise test of pQCD than individual V+jets
- ▶ Experimental uncertainties and non-pQCD effects are significantly canceled in the ratio
- ▶ Leptonic channels (e/μ) of W/Z
- ▶ 7 TeV 4.6 fb<sup>-1</sup> full dataset
- ▶ Differential measurement for the first time up to four jets
- ▶ Comparison with NLO pQCD calculation, LO ME Monte Carlo generators done

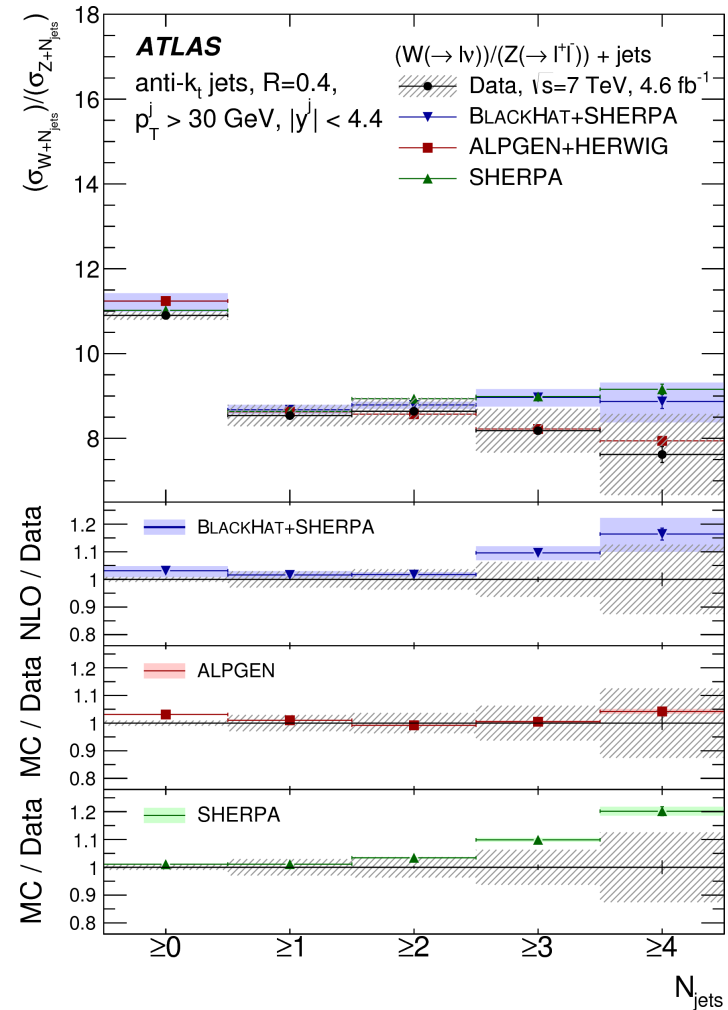
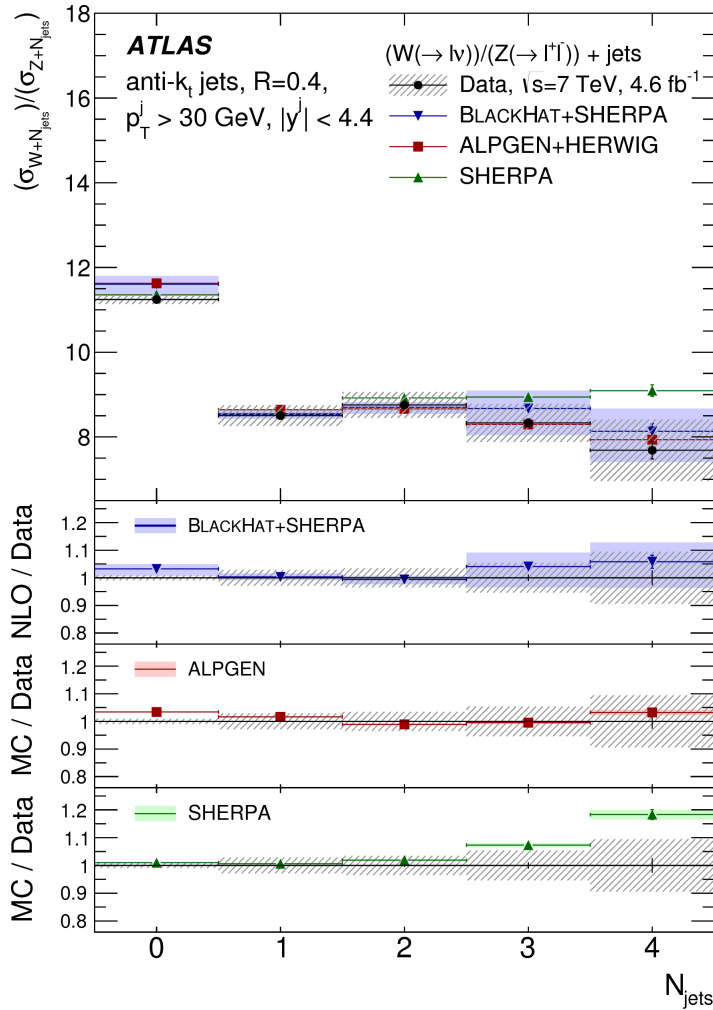


*Eur. Phys. J. C (2015) 75:82*



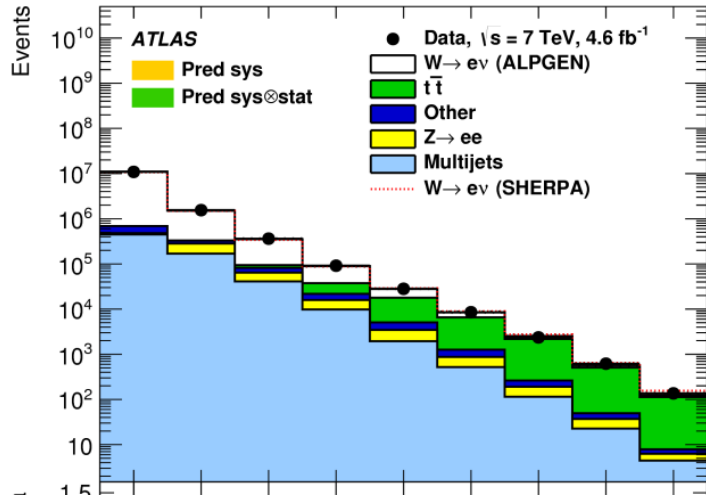
# W+jets / Z+jets at 7 TeV

Eur. Phys. J. C (2014) 74: 3168



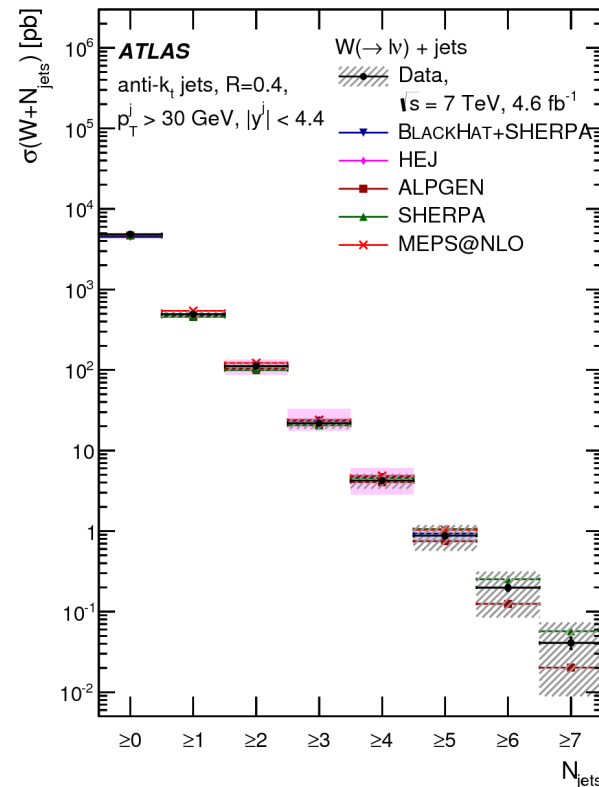
- ▶ The theoretical predictions describe the data fairly well within experimental uncertainties
- ▶ Observed discrepancy of  $1.5\sigma$  at high jet multiplicities with **SHERPA**
- ▶ **BlackHat+SHERPA** is  $1\sigma$  above data at high inclusive jet multiplicities (it is expected -> not all contributions for events with at least four jets are included)

# W+jets production at 7 TeV

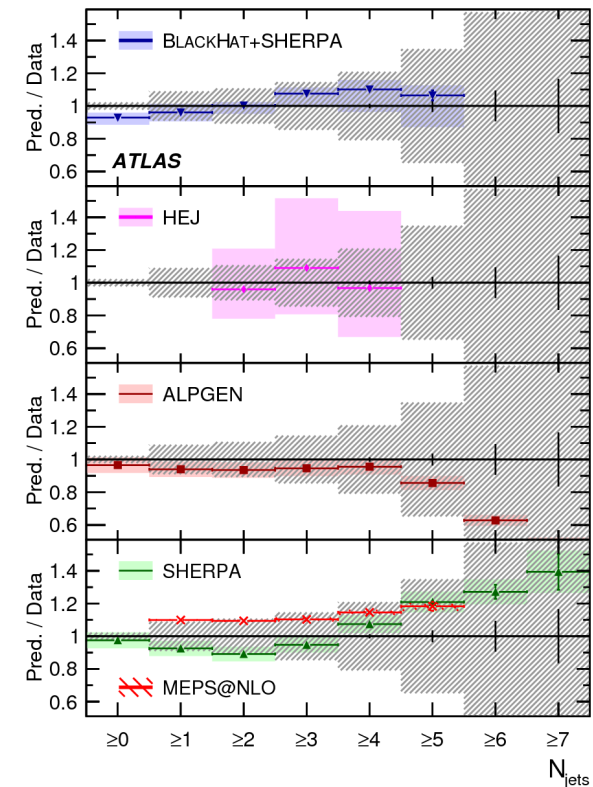


- ▶ Test of pQCD calculation in large kinematic range
- ▶ Background for many SM processes and BSM searches
- ▶ Fully leptonic final states ( $e/\mu$ ) at  $\sqrt{s}=7\text{ TeV}$  with  $4.6\text{ fb}^{-1}$

- ▶ Many exclusive and inclusive differential distributions compared to a variety of theory predictions at LO/NLO
- ▶ Measurement with multiplicities up to seven associated jets and  $p_T$  of jets up 1 TeV
- ▶ Fixed-order predictions provide good description (BlackHat+SHERPA)
- ▶ Overall reasonable agreement with predictions is observed



*Eur. Phys. J. C (2015) 75:82*



# W and Z production at 13 TeV

ATLAS-CONF-2015-039

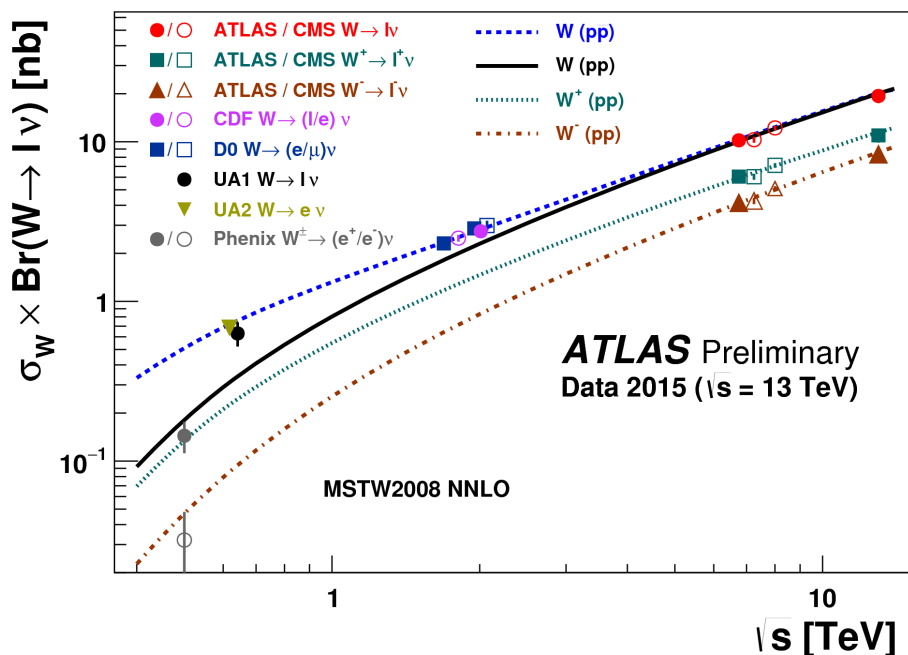
## Measurement:

- ▶  $W \rightarrow e\nu$ ,  $W \rightarrow \mu\nu$ ,  $Z \rightarrow e^+e^-$ , and  $Z \rightarrow \mu^+\mu^-$  processes with int. lum. of  $\sim 85 \text{ pb}^{-1}$
- ▶ Total inclusive and charge-specific production cross sections
- ▶ Evaluation of  $W^+ / W^-$  production and of  $W^\pm / Z$  production cross-section ratios

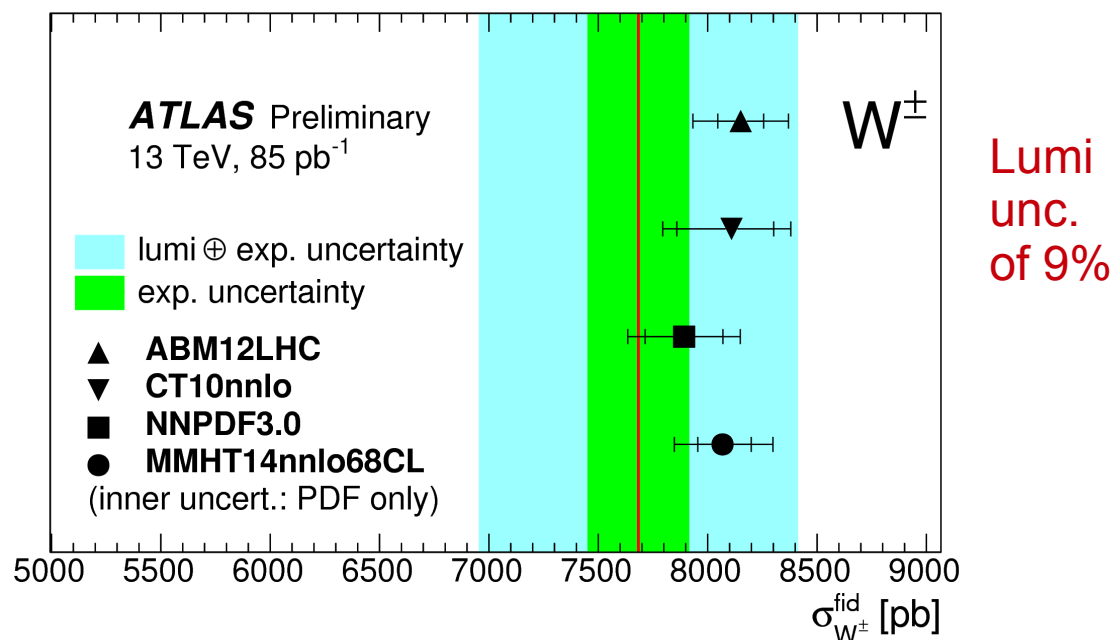
## Backgrounds:

- ▶ Single and double bosons, top (from MC) and multijets (template fit on  $m_T$  spectrum)

Cross-sections as a function of centre of mass energy well described by NNLO (QCD)



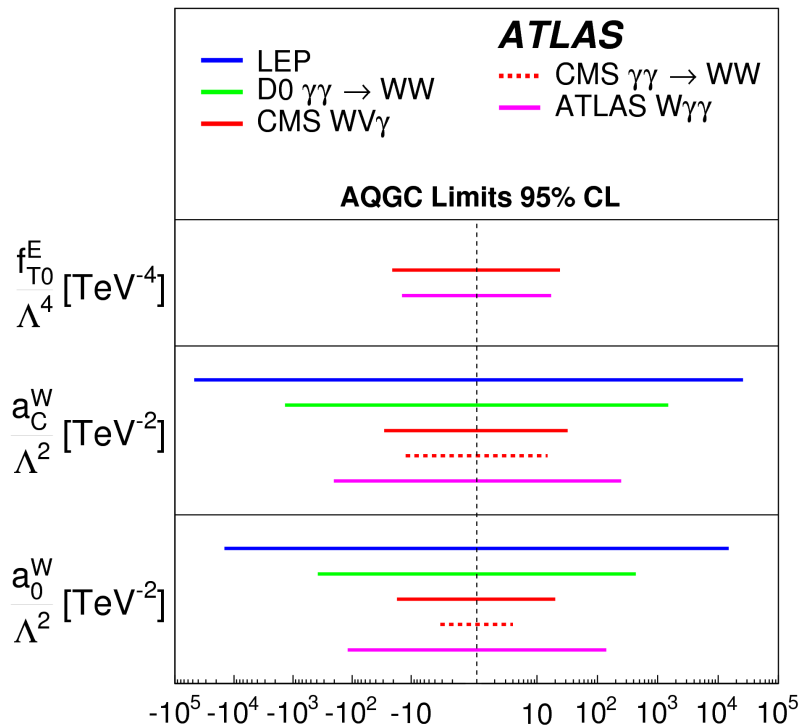
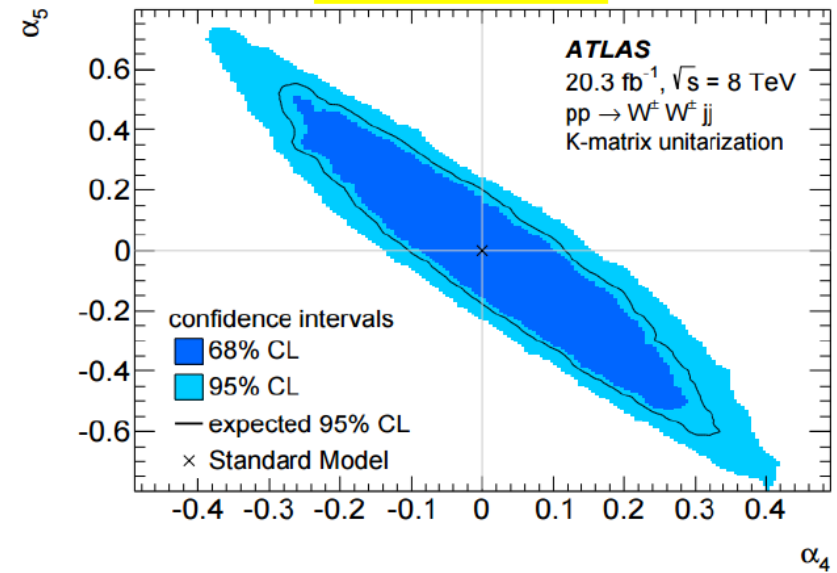
Combined fiducial cross section with different PDFs  
The experimental precision is already comparable to PDF





# $W\gamma\gamma / WWjj$ aQGC

- ▶ First aQGC limits on  $\alpha_4, \alpha_5$  parameters using measured cross-section in a VBS fiducial region (for notation see *Phys.Rev. D22 (1980) 200*)
- ▶ k-matrix unitarized



- ▶ First triboson aQGC limits of high dimension operators  $f_{T0}$ ,  $a_C^W$  and  $a_0^W$  determined in jet-exclusive region with  $M_{\gamma\gamma} > 300$  GeV
- ▶ dipole-FF unitarized

# Summary plot

## Standard Model Production Cross Section Measurements

Status: March 2015

