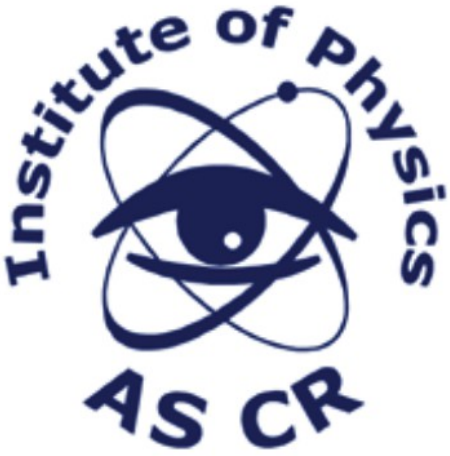
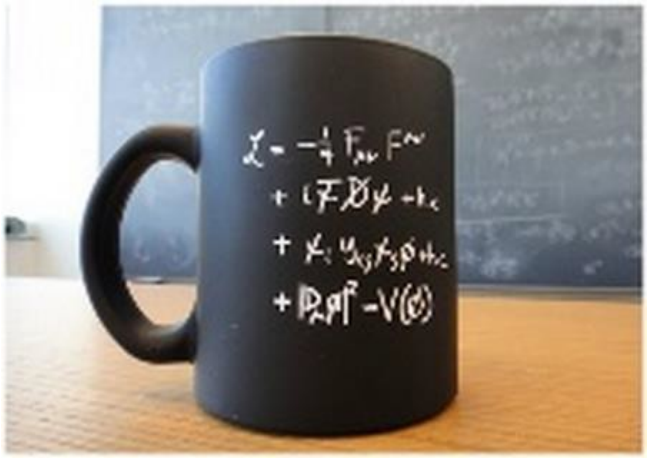


Recent SM measurements with the ATLAS detector

Jiri Hejbal
on behalf of the ATLAS Collaboration

ICPPA 2015, Moscow, Russia

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 γγ →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

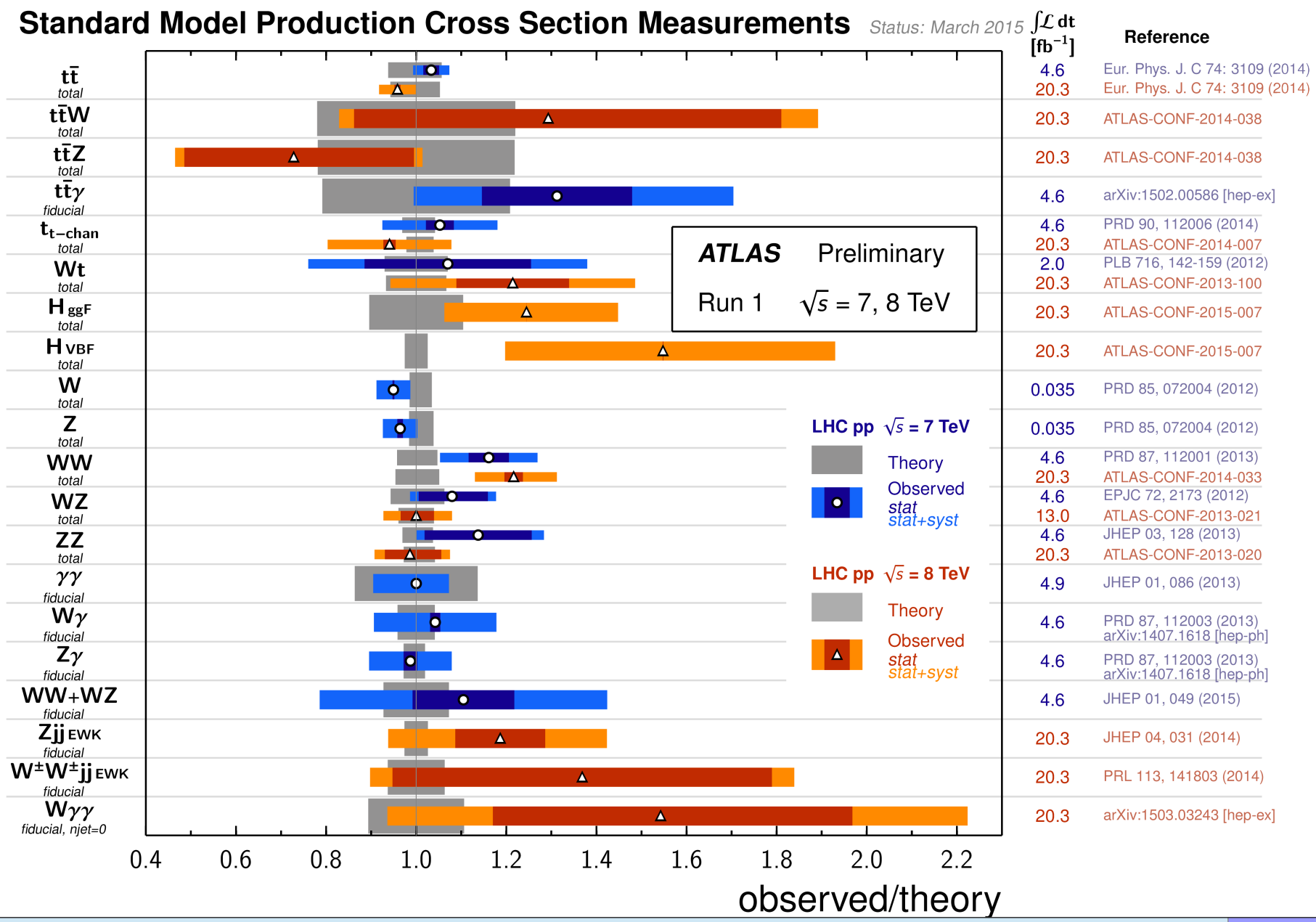
W/Z/gamma production

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

EWK measurements

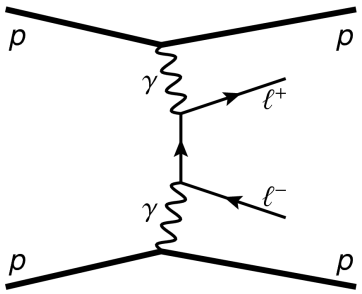
- WW, 4-lepton, Vector boson fusion, Vector Boson Scattering, Wγγ production

Standard model measurements

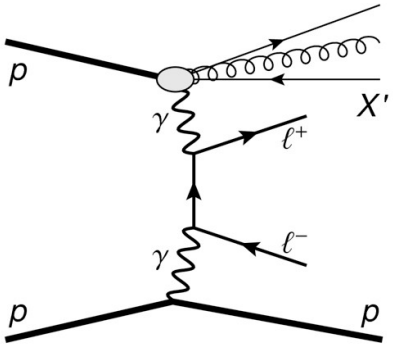


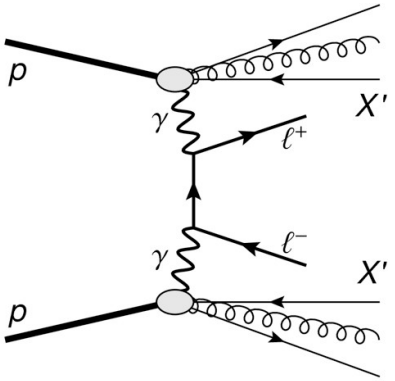
Two photon scatering – $\gamma\gamma \rightarrow ll$

elastic signal



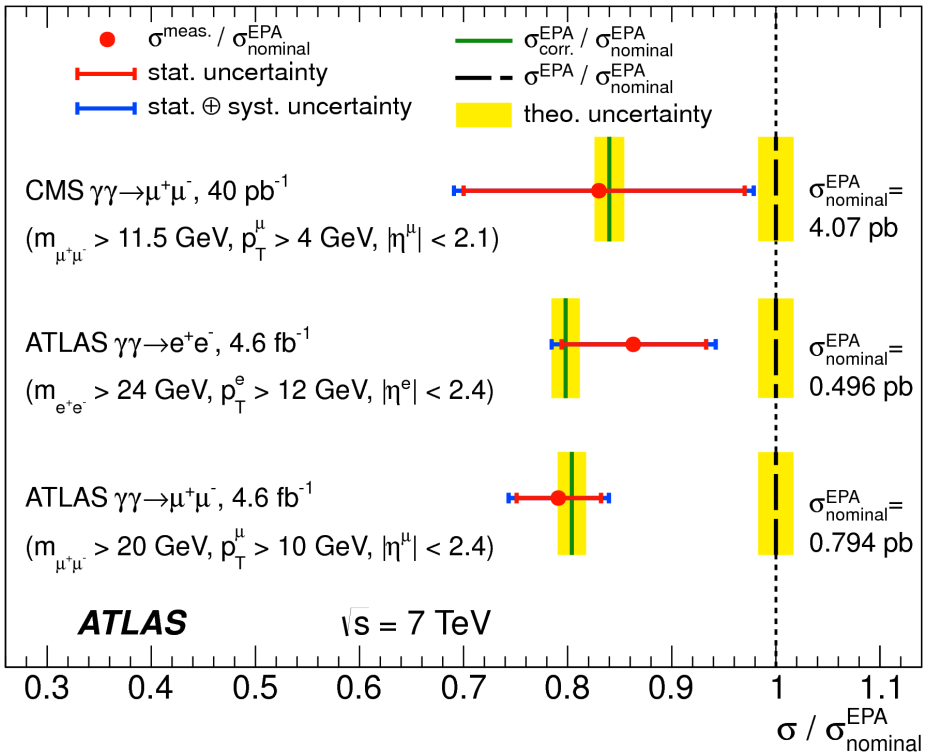
dissociative backgrounds





- use LHC as a two-photon collider
- use Equivalent Photon Approximation (EPA) (with absorbtive corrections for finite proton size)
- other background: Z/γ*, 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

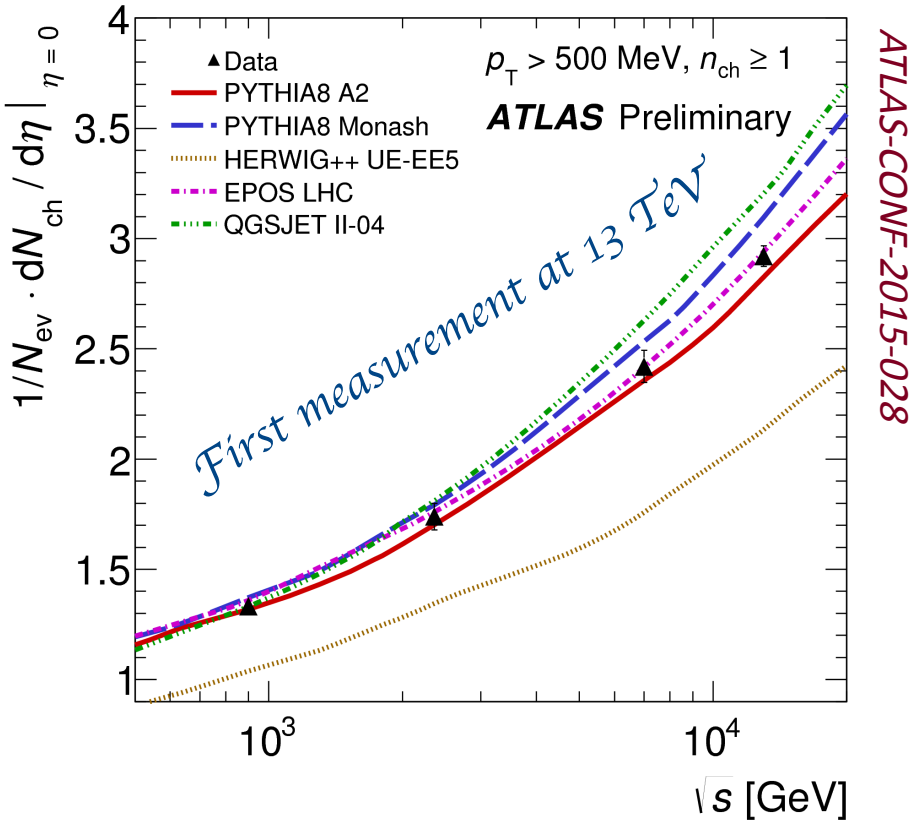


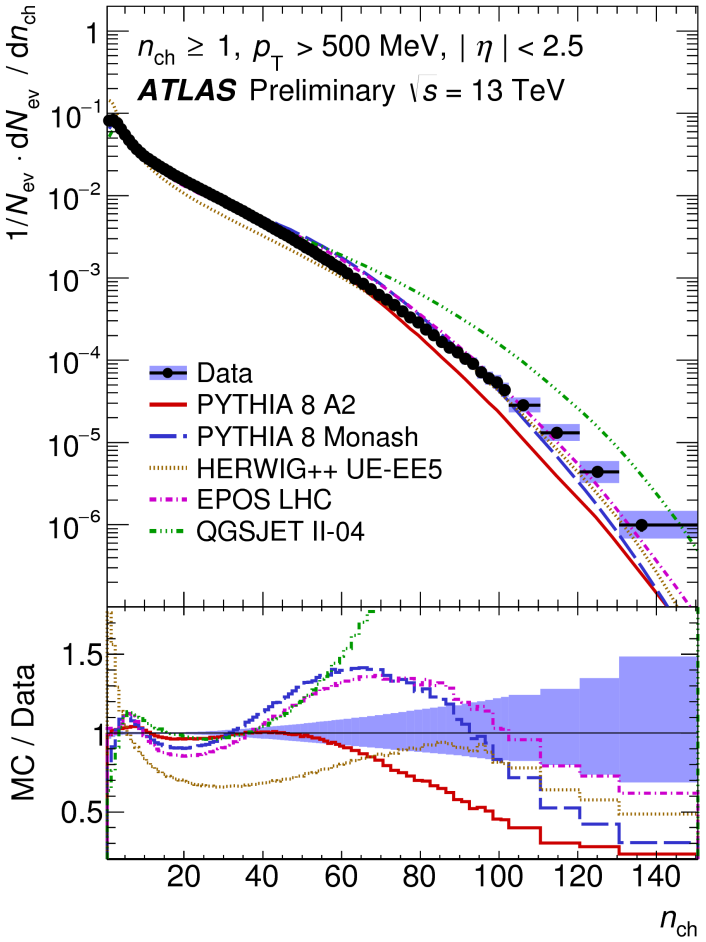
Charged particle multiplicities

- 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 μb^{-1}

~ 10M events

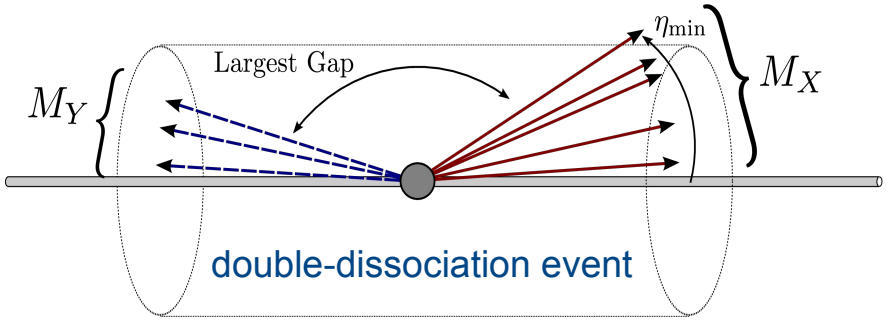




Inelastic pp cross section at 13 TeV

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

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



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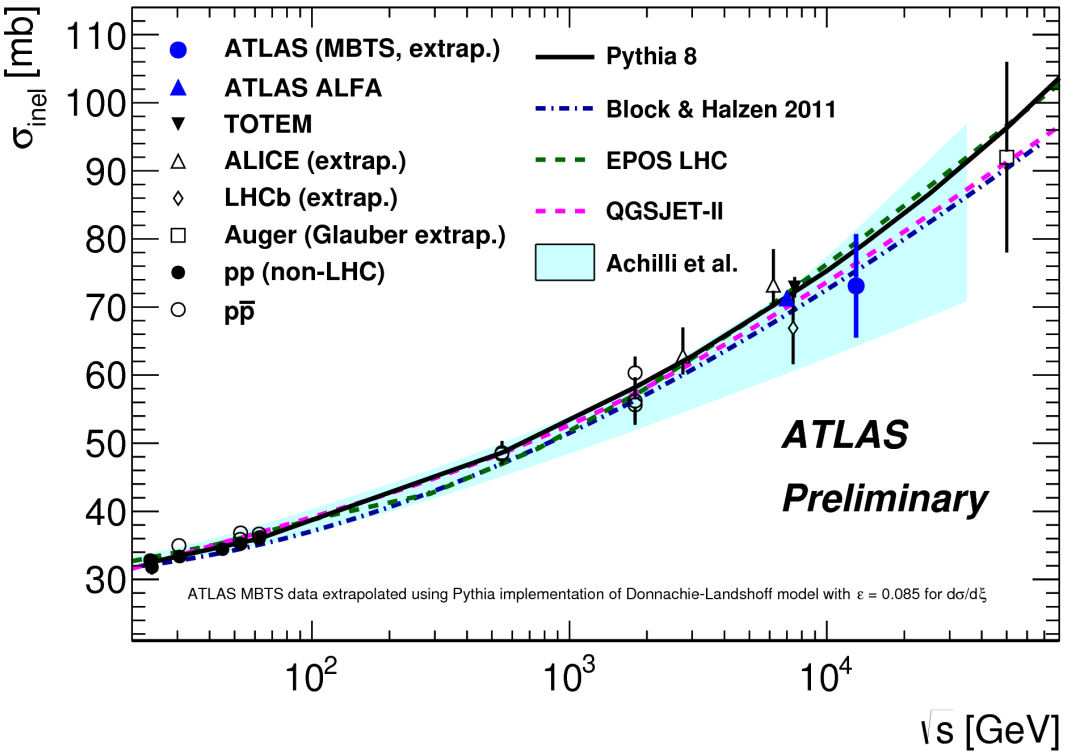

Fiducial cross section:

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

(uncertainty of the luminosity is 9%)

Total cross section:

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

Extrapolation from fid. to full $\tilde{\xi}$ phase space

Results are about 1σ – 1.5σ below the theoretical predictions currently available

Jet production at 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

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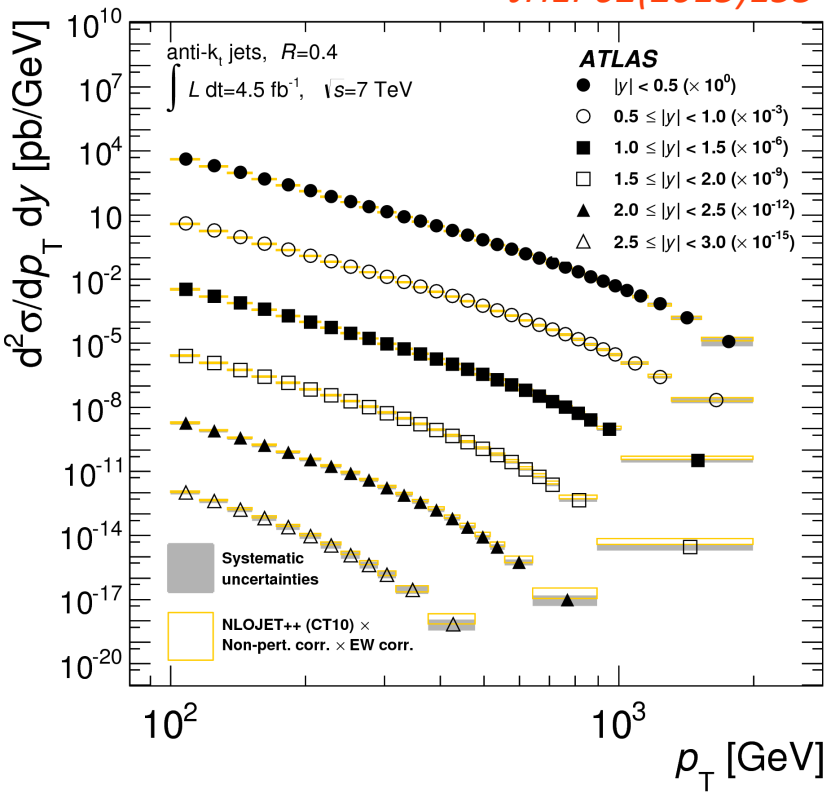
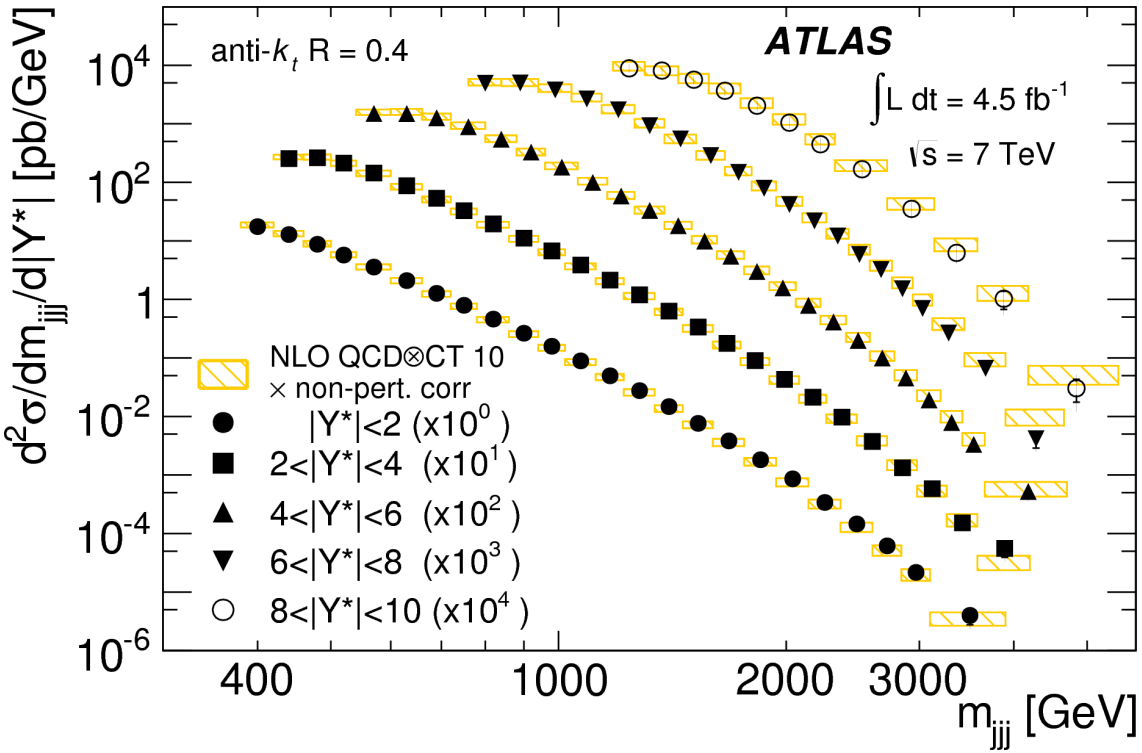


Three-jet production

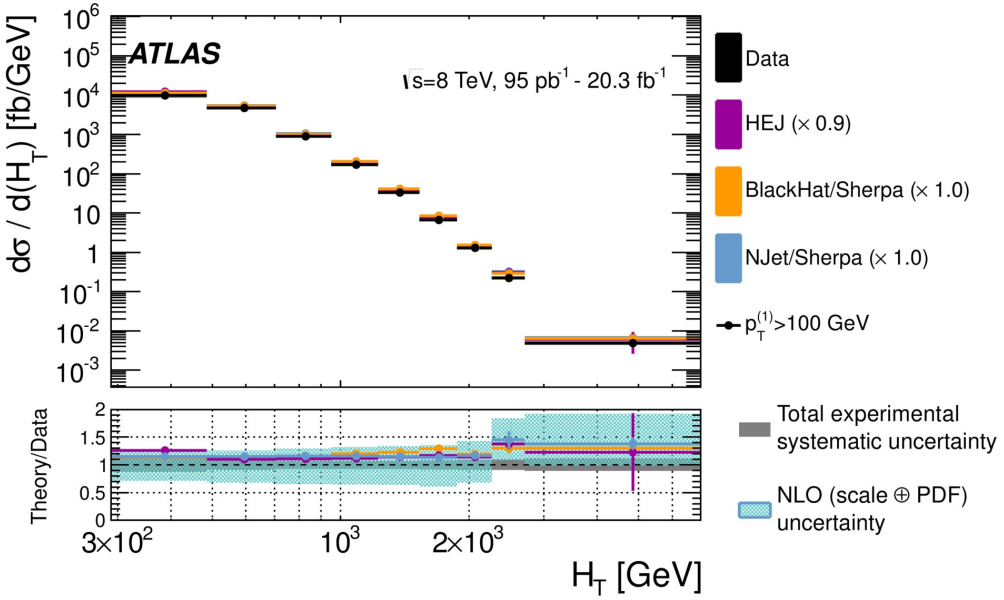
- Jets with 3-j mass up to 5 TeV
- Probed (m_{jjj}, $|Y^*|$) plane with a variety of PDFs
- Data are well described by pQCD at NLO (corrected for non perturbative effects)

Eur. Phys. J. C75 (2015) 228

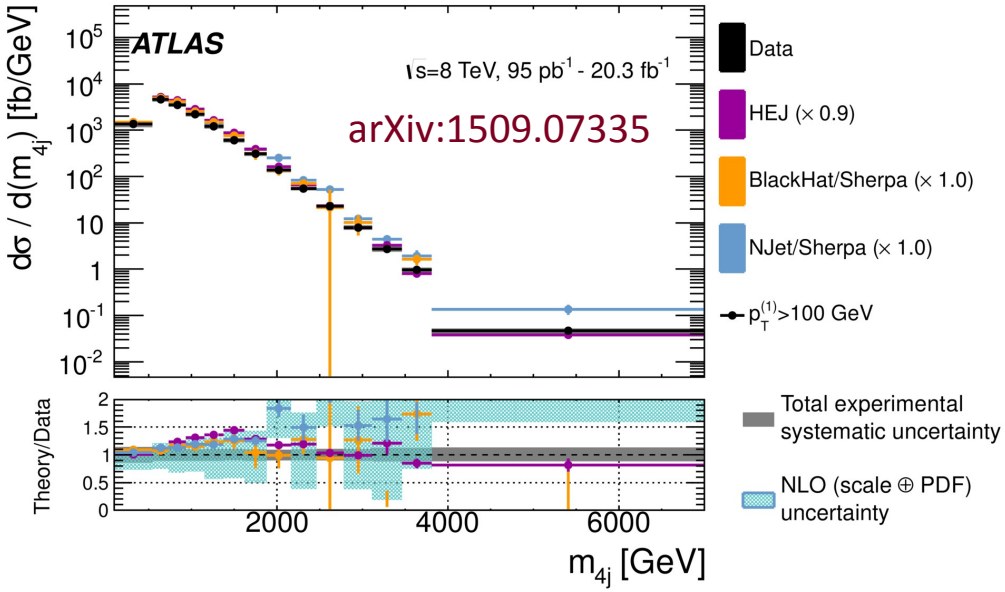


Four jets production at 8 TeV

- 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 $n_{jet} \geq 2$)



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

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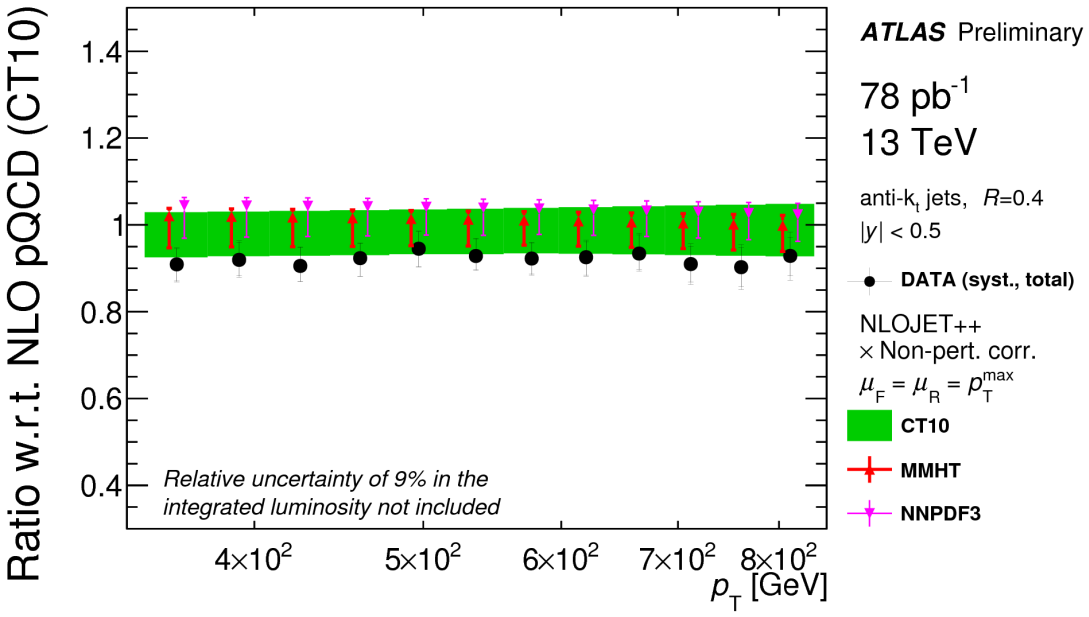
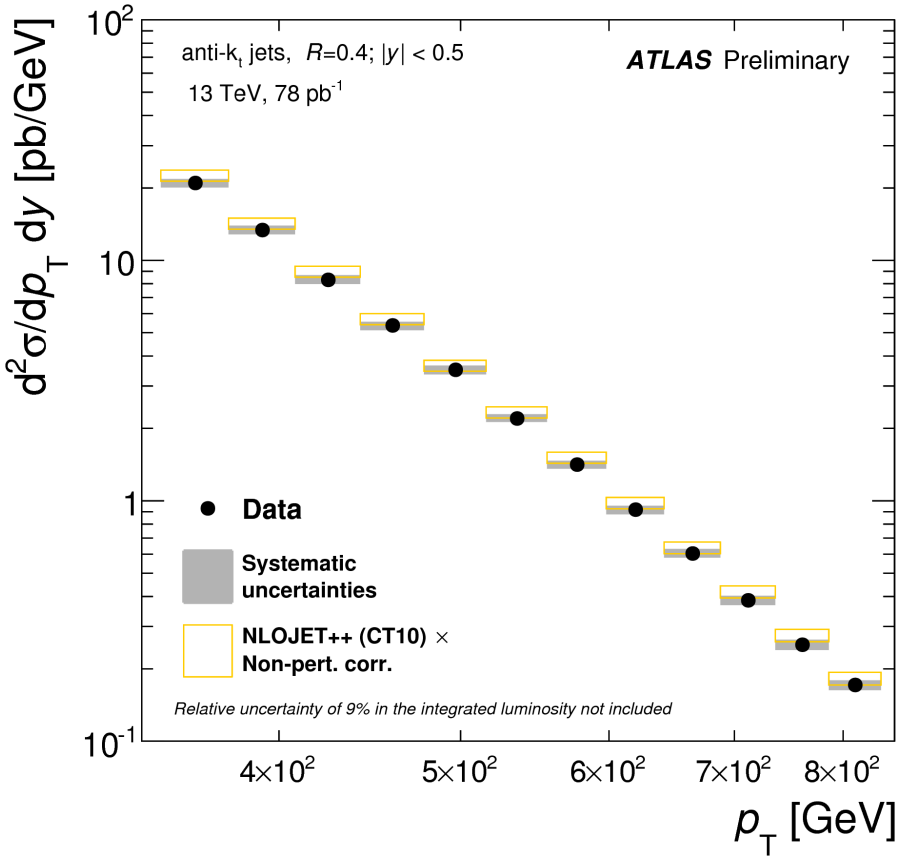




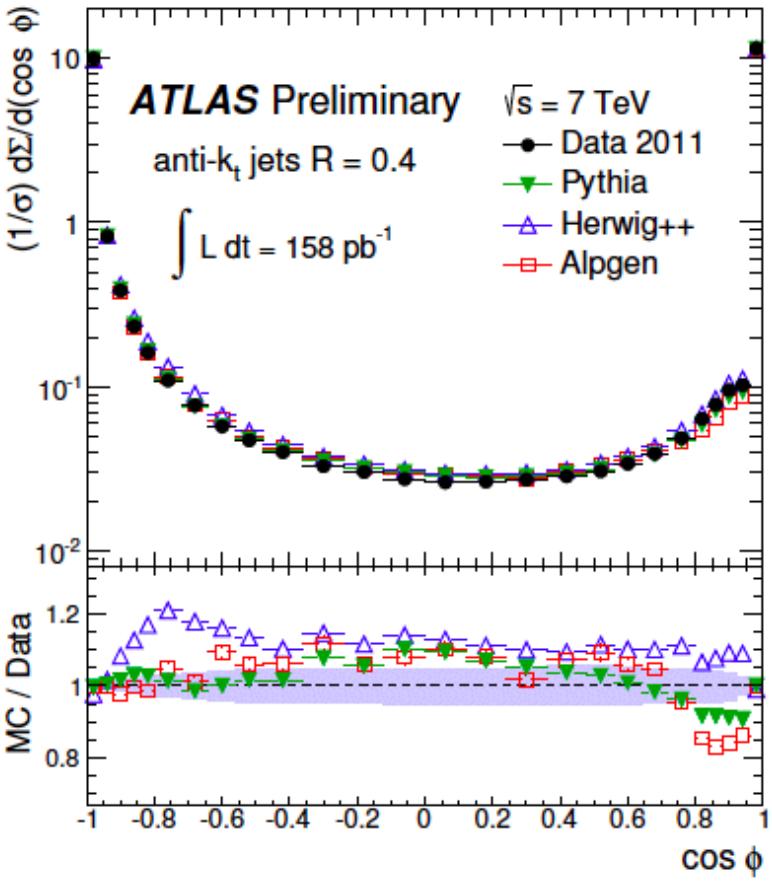
Jet physics – α_s measurement

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

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

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

arxiv:1508.01579

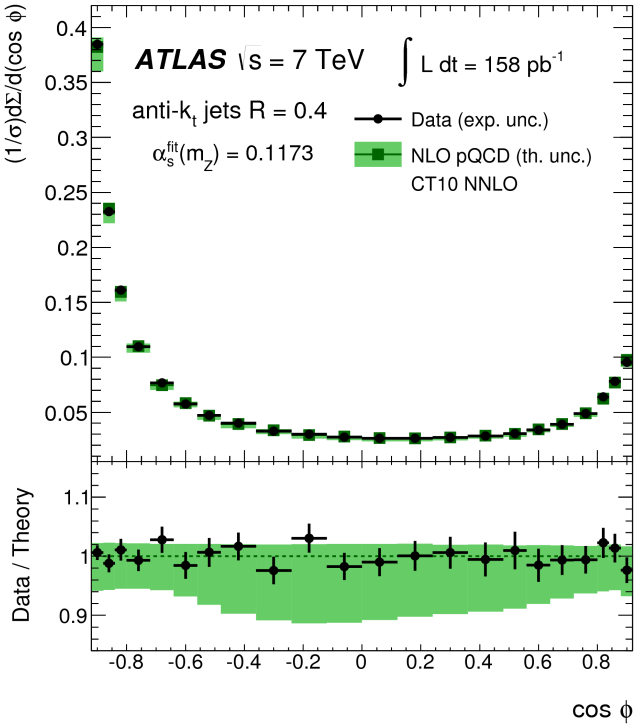


Analysis strategy:

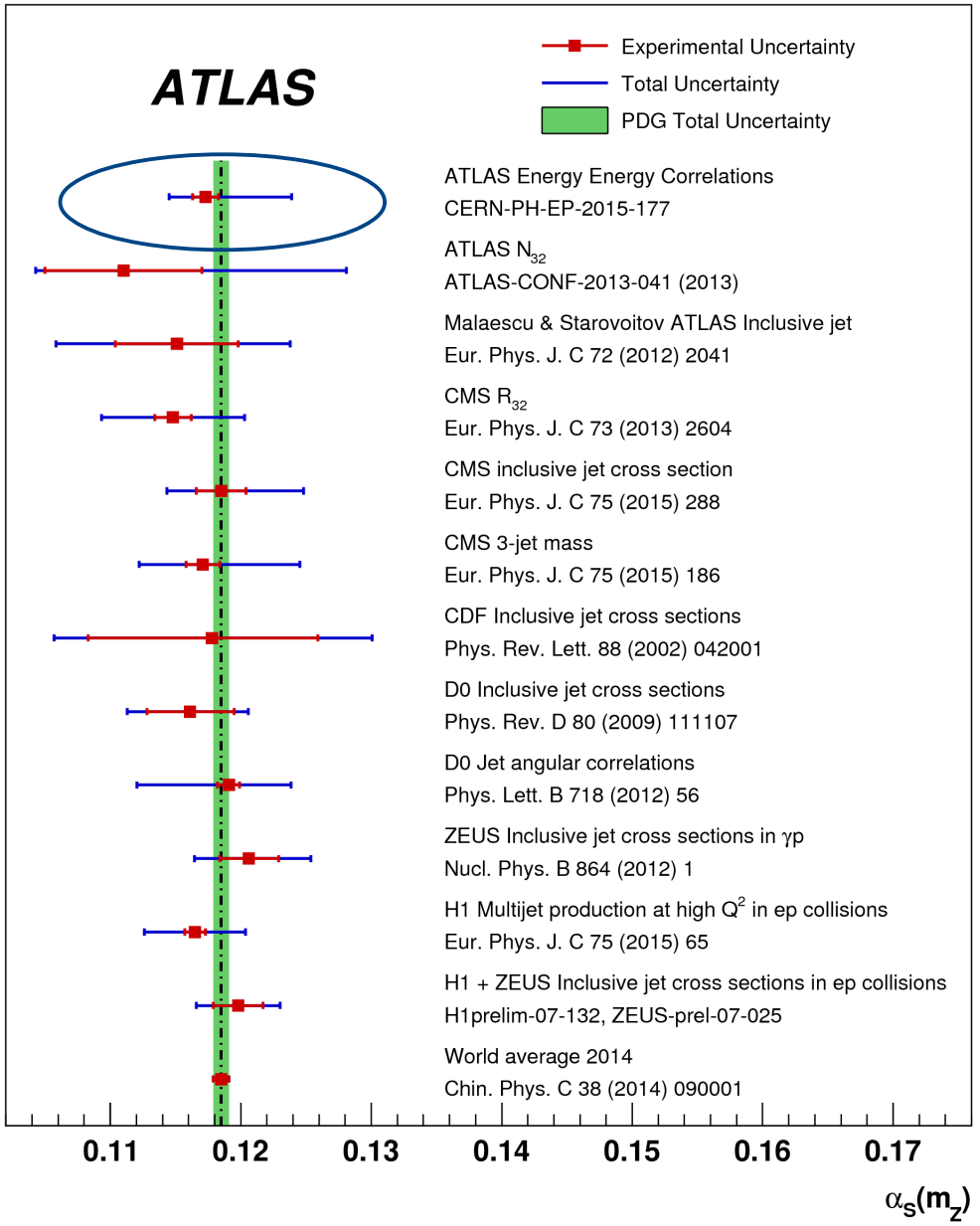
- 158 pb^{-1} of data @ 7 TeV
- $p^1_T + p^2_T > 500$ GeV; $p^{(all)}_T > 50$ GeV; $|y(jet)| < 2.5$
- Total uncertainty is about 5%, dominated by the jet energy scale, pileup and MC parton-shower modeling.
- Pythia/Alpgen predictions agree reasonably well with data, Herwig++ deviates from data by up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

Jet physics – α_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



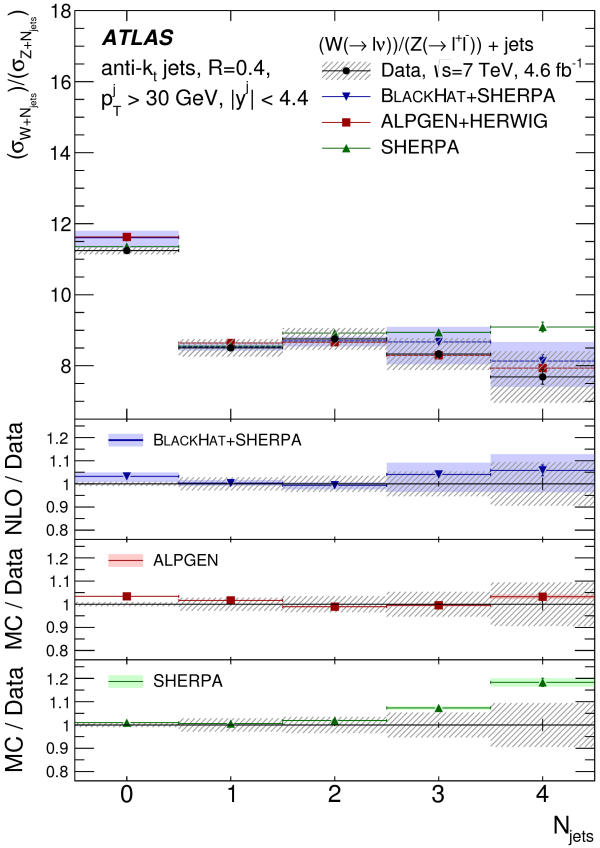
arXiv:1508.01579



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

W+jets / Z+jets at 7 TeV

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



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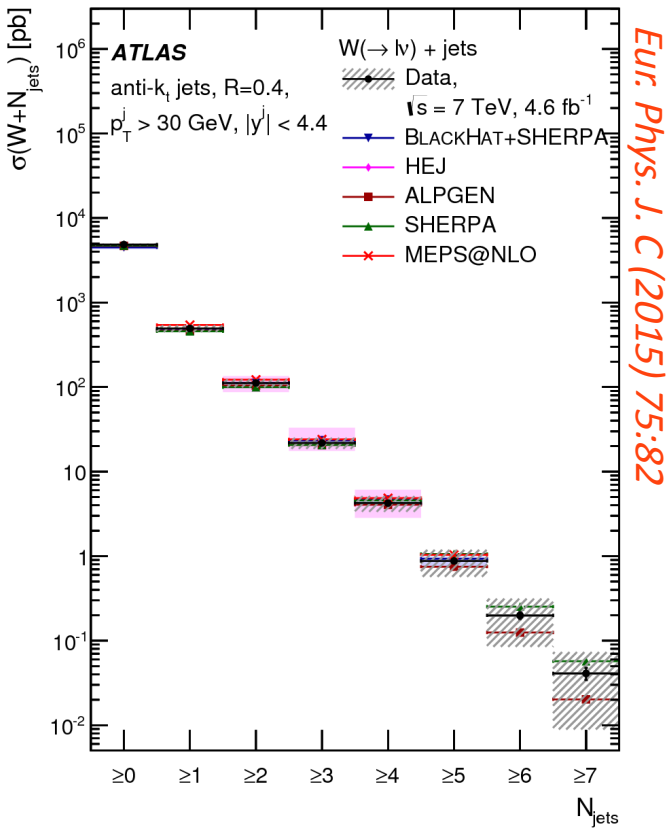
W+jets production



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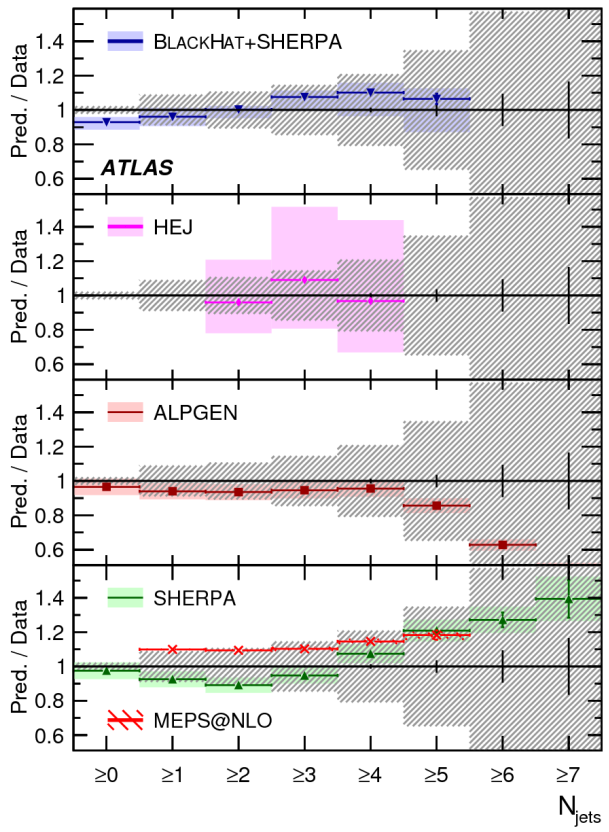
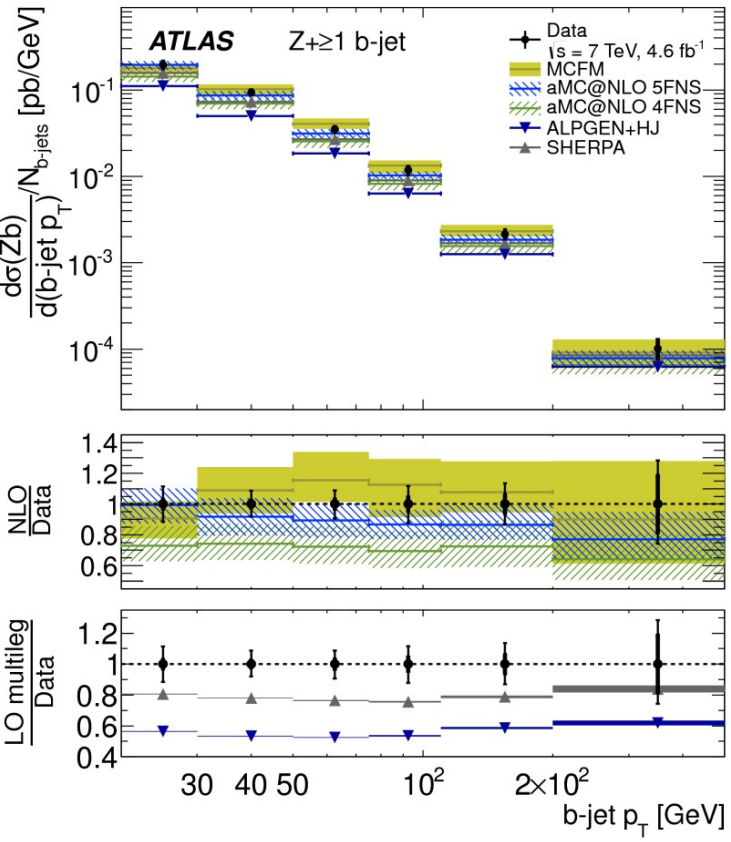


- Differential measurement for the first time up to four jets
- Observed discrepancy of 1.5σ at high jet multiplicities with SHERPA
- BlackHat+SHERPA is 1σ above data at high inclusive jet multiplicities

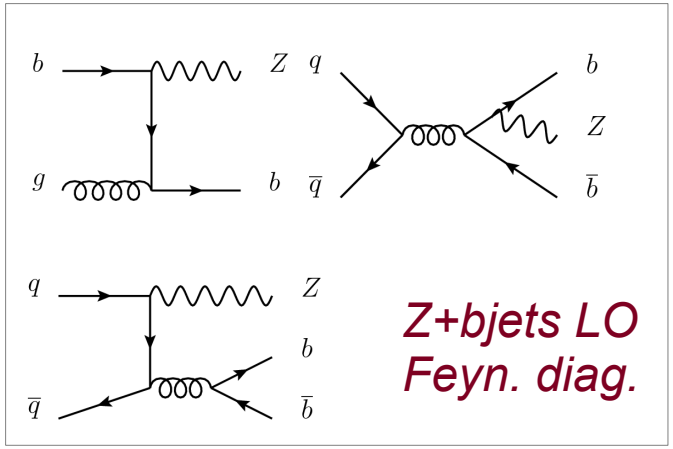
- Measurement with multiplicities up to seven associated jets and p_T of jets up 1 TeV
- Fixed-order predictions provide good description (BlackHat+SHERPA)
- Overall reasonable agreement with predictions is observed

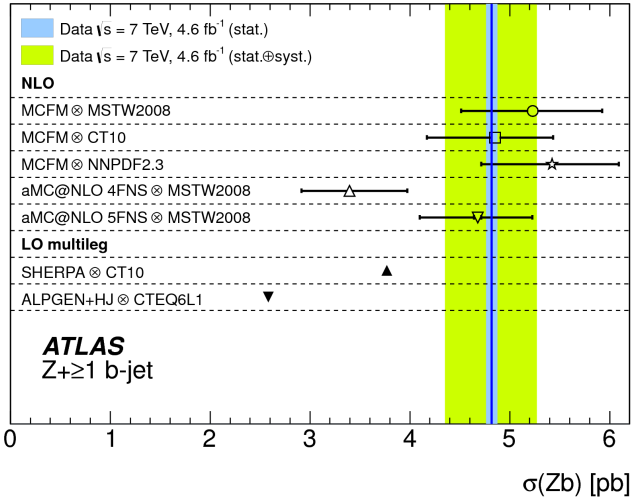
Z+bjets at 7TeV

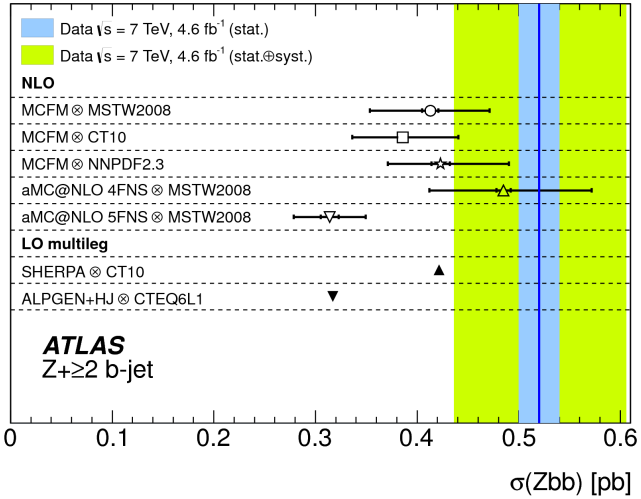


- Important background to ZH with H -> bb and BSM signatures
- Two schemes considered 4-flavour (4FNS) vs. 5FNS
- MCFM in five-flavour number scheme agrees with data within uncertainties
- aMC@NLO 4FNS describes better Z+2 b-jets, while 5FNS describes better Z+1 b-jet
- Shape of differential cross sections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

JHEP10(2014)141

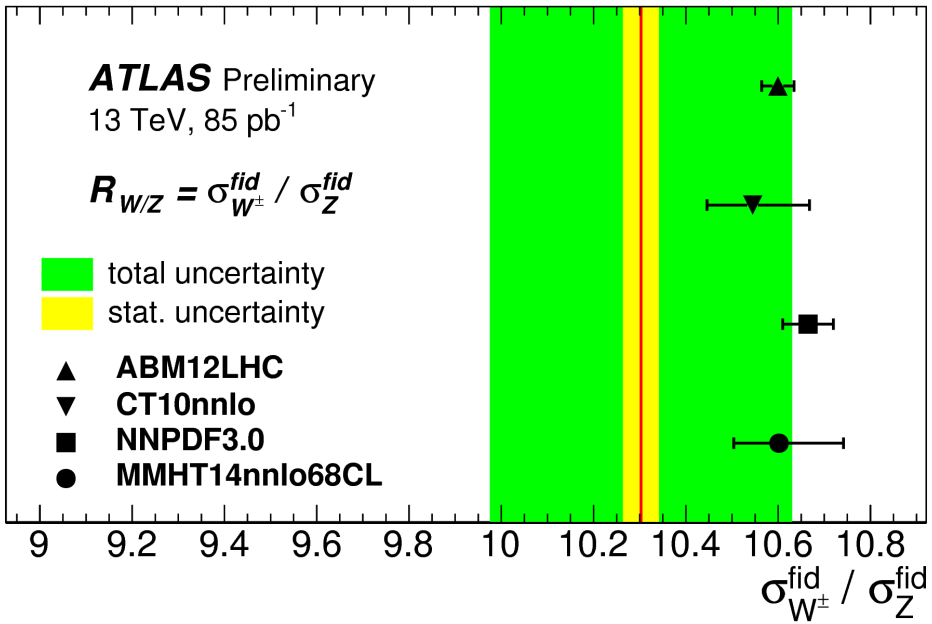


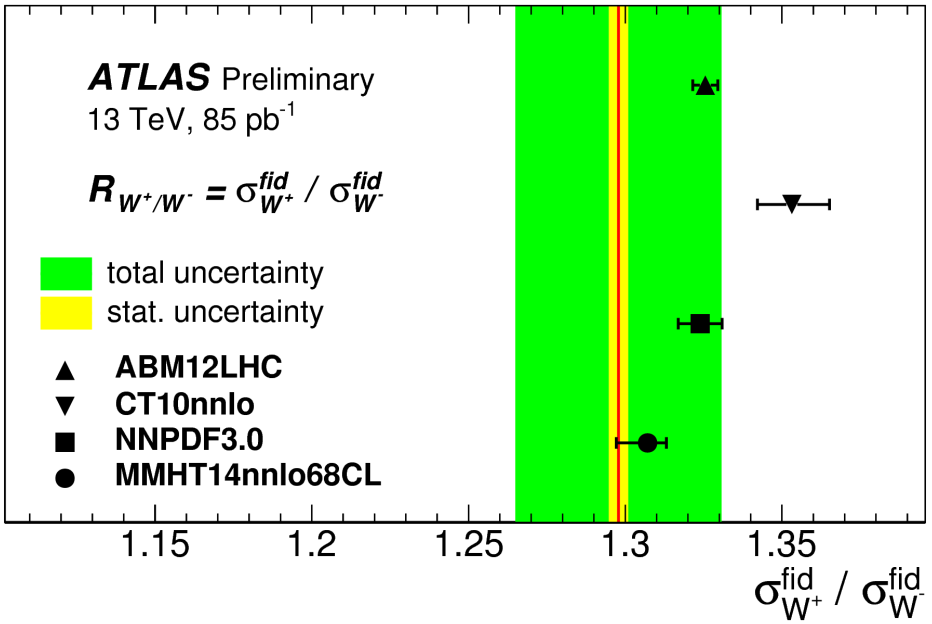




W and Z production at 13 TeV

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



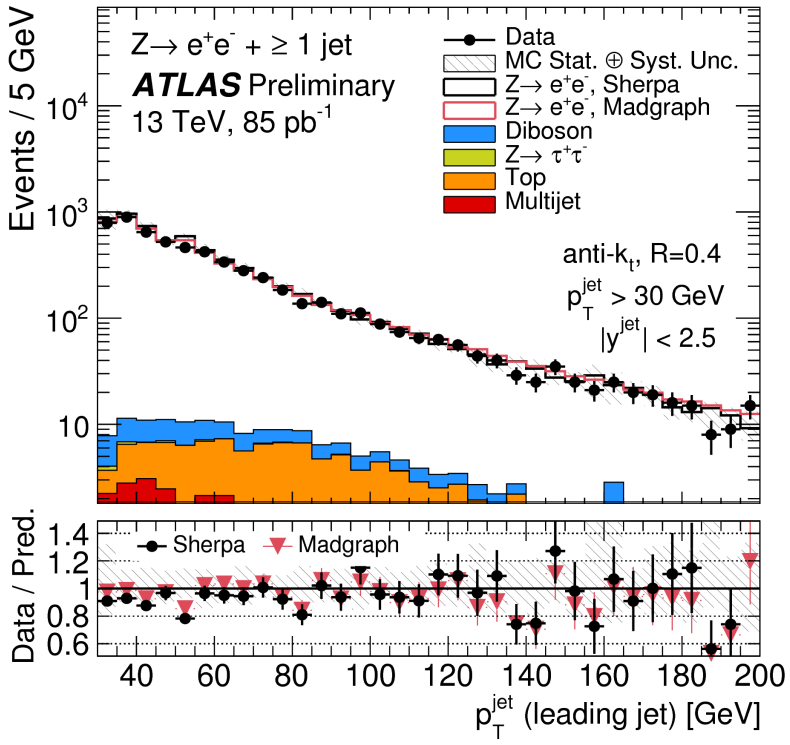


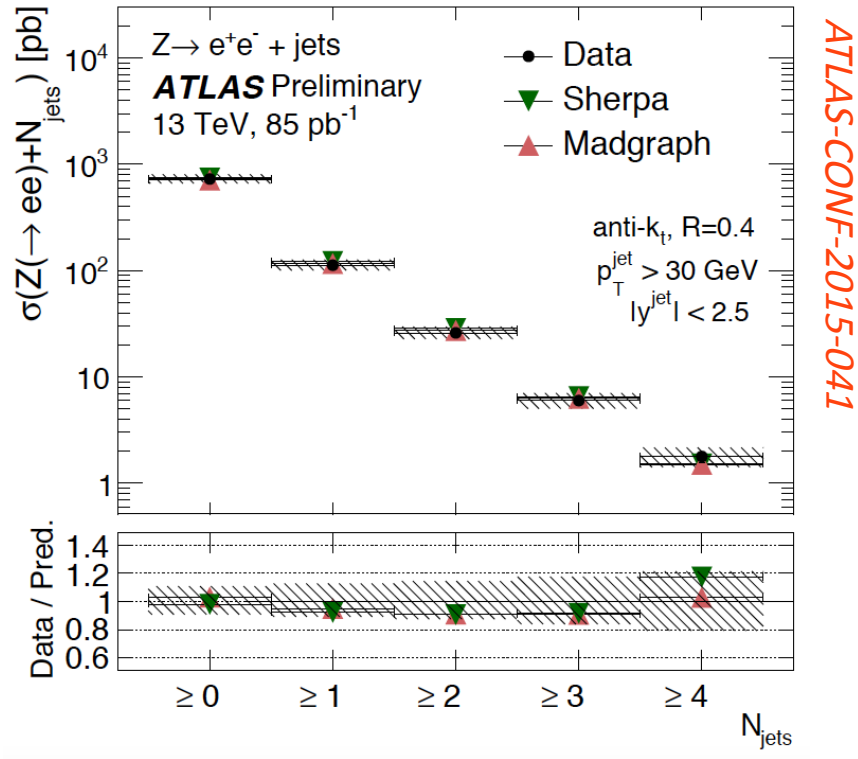
ATLAS-CONF-2015-039

- Ratio of measured cross sections benefits from the cancellation of some experimental uncertainties
- Ratio $R_{W/Z}$ constraints 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^{-1} of data
- Z bosons is decaying to electron or muon pairs: $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$
- Jets are definied by anti-k_T, R=0.4: $p_T > 30$ GeV, $|y|<2.5$
- Measurement of fiducial cross sections and their ratios for successive jet multiplicities





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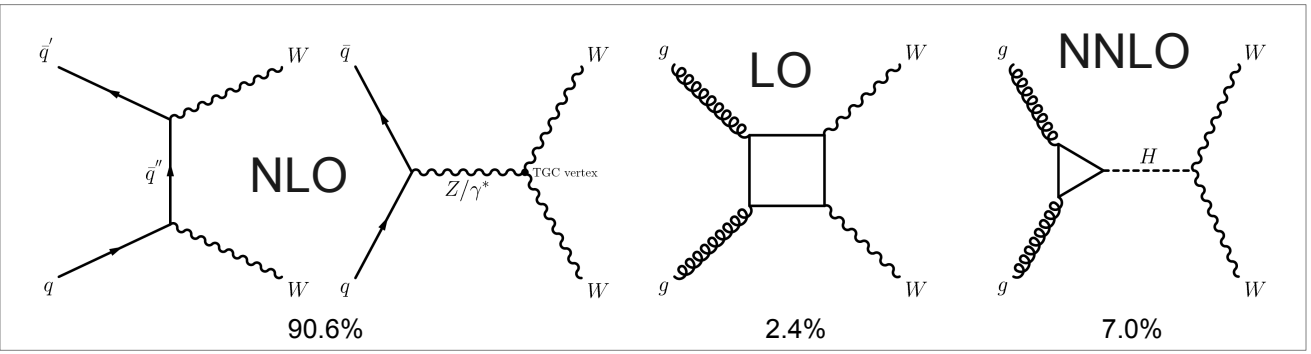
Reasonable agreement between observed cross sections and predictions from Sherpa and MadGraph

WW->lvlv cross section at 8 TeV



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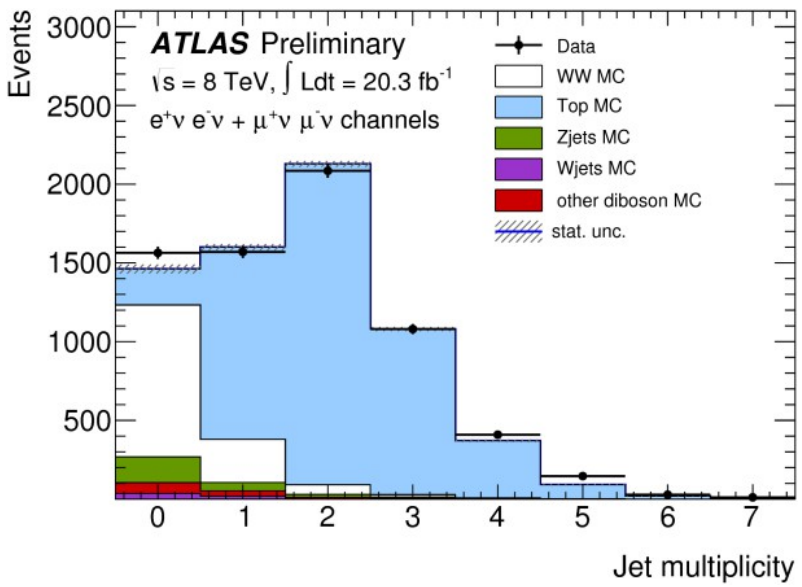
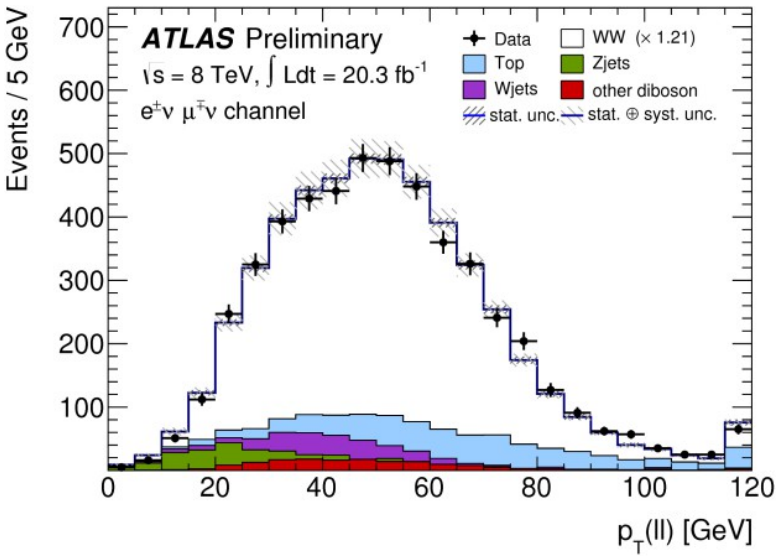


- Total and fiducial WW production cross section measurements
- Important test of the non-Abelian structure of SM
- Cross section measurements are sensitive to anomalous triple gauge couplings (aTGC)
- Non-resonant WW production is an irreducible background process to Higgs boson studies



Backgrounds:

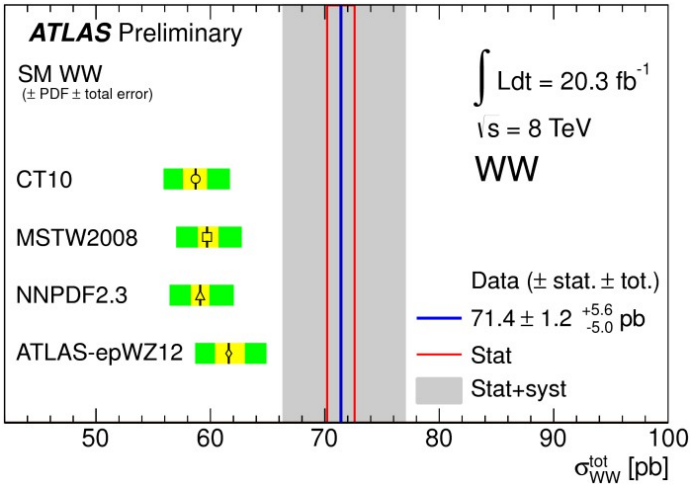
- Top, Drell-Yan, W+jets (all data-driven), other dibosons (MC based)
- Very hard selection-criteria on E_T^{miss} and jet-veto to suppress $t\bar{t}$ background

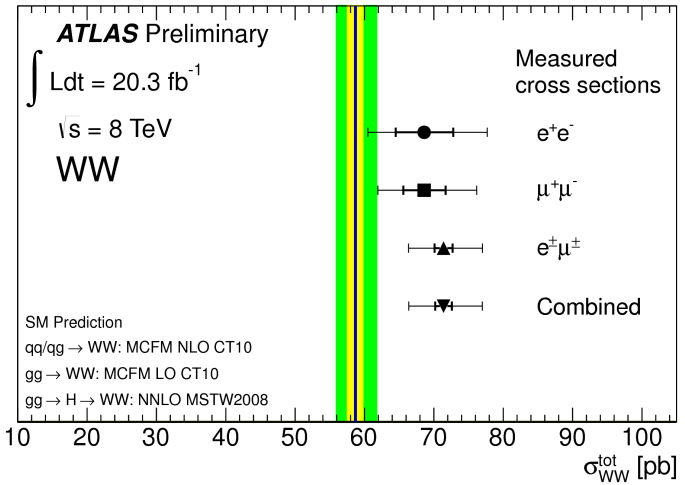
WW->lvlv cross section at 8 TeV

- 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

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

- Compatible with full NNLO prediction at about 1σ

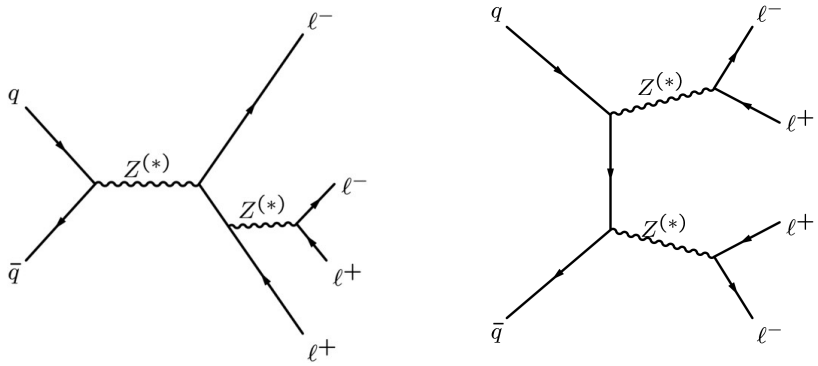




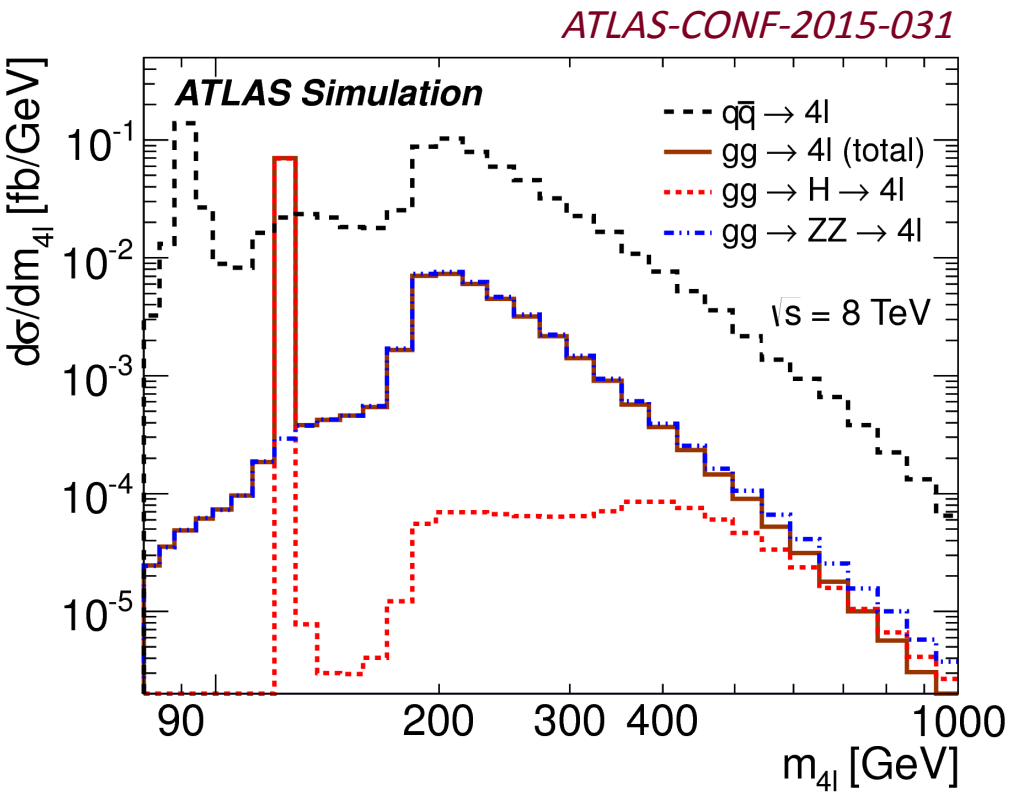
- New result from CMS (arXiv:1507.03268): measured total σ agree well with NNLO prediction
- Major difference: 1) H → WW process is subtracted as background
  2) pTWW-resummed calculation reweighting

→ Otherwise fairly comparable

4-lepton production at 8 TeV



- Measurement of integrated and differencial 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 (~5%)



Selection:

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

Background:

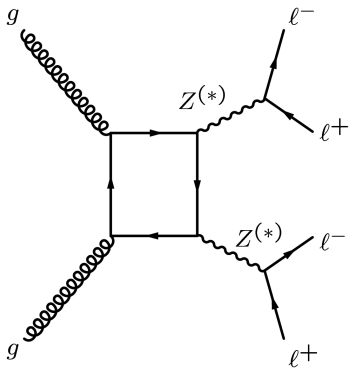
- Z+jets and tt (data driven)
- ZW, Zγ, Z+top, VVV, ZH and
- double Drell Yan (MC)

4-lepton production at 8 TeV

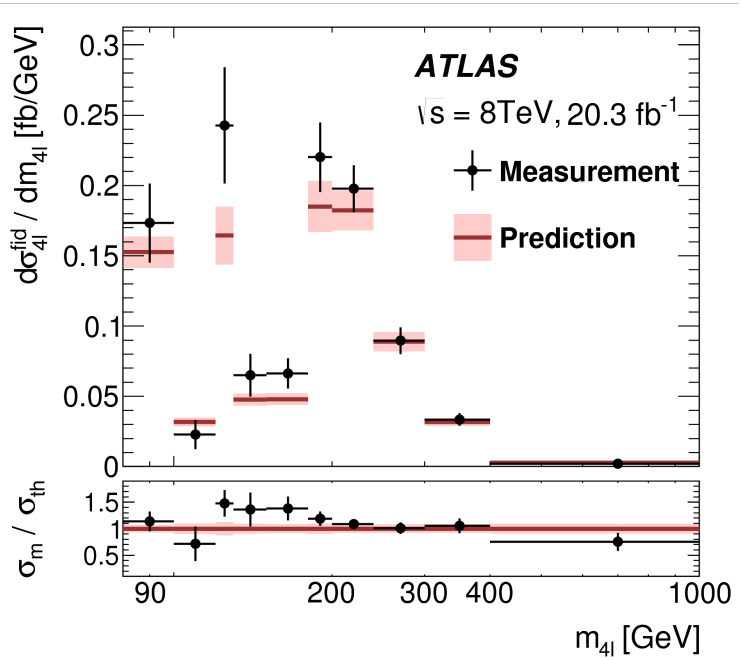
- Measurement of signal strength of non-resonant gg→4l production:

$$\frac{\sigma(data)}{\sigma(g\,g \to 4l; LO)}$$

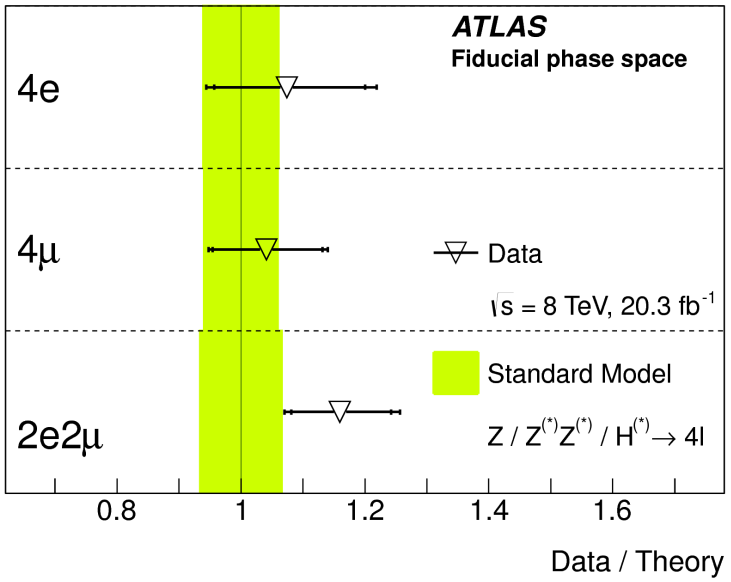
μ_{gg} = 2.4 ± 1.0(stat.) ± 0.5(syst.) ± 0.8(theory)



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

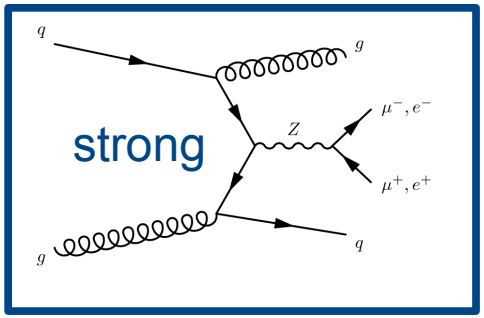


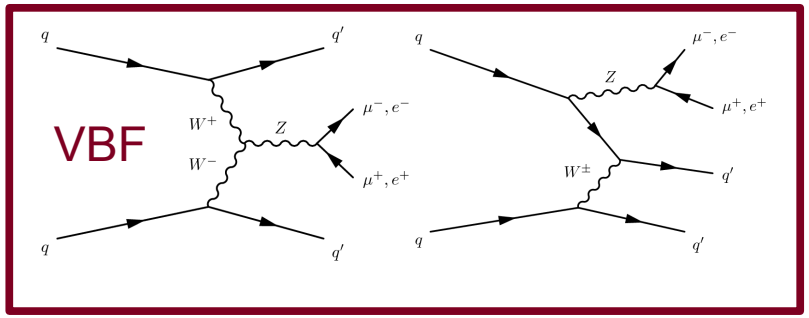
Overall good agreement between theory prediction and measurement of differential cross-section distributions of $m_{4\ell}$



Measured channel specific cross sections in fiducial phase space

Z+2 jets production (VBF)



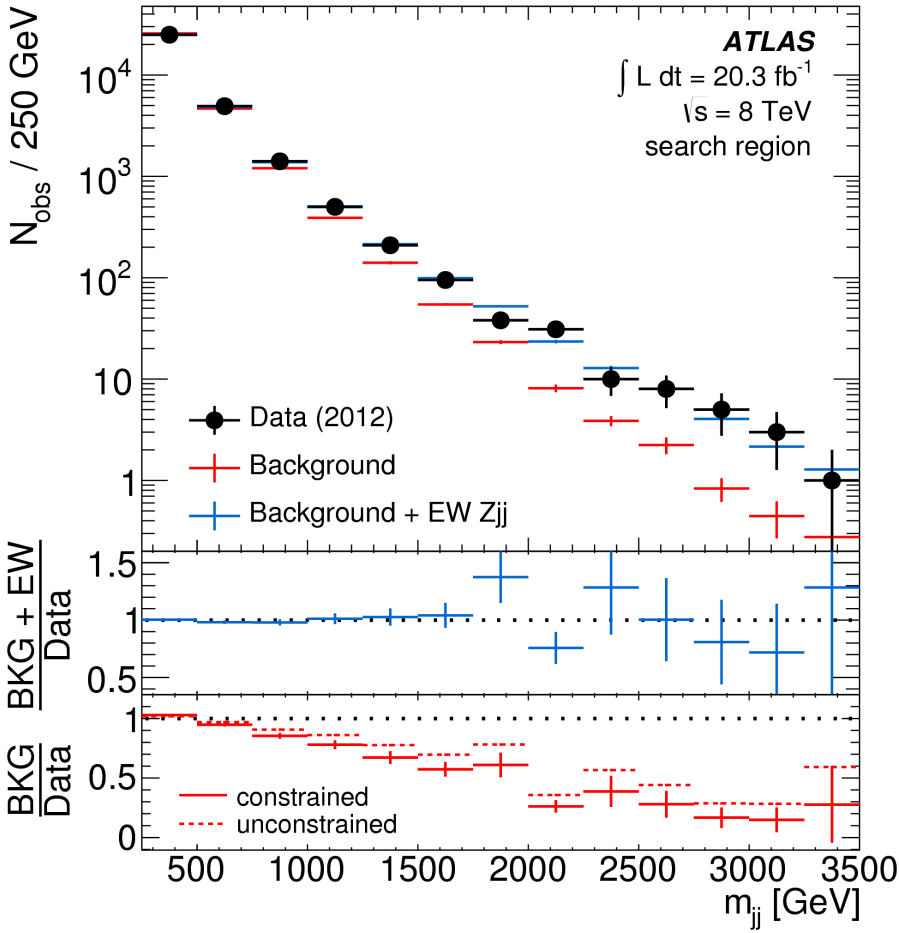


JHEP04(2014)031

- 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 > 5σ

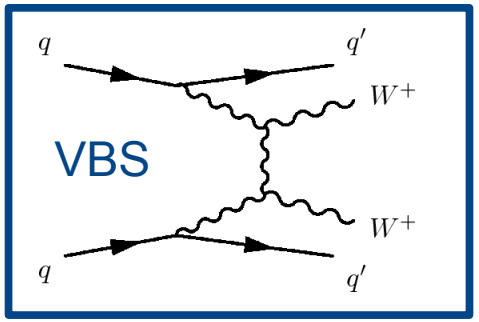
$$\sigma_{\mathrm{EW}} = 54.7 \pm 4.6\ (\mathrm{stat})^{+9.8}_{-10.4}\ (\mathrm{syst}) \pm 1.5\ (\mathrm{lumi})\ \mathrm{fb}$$

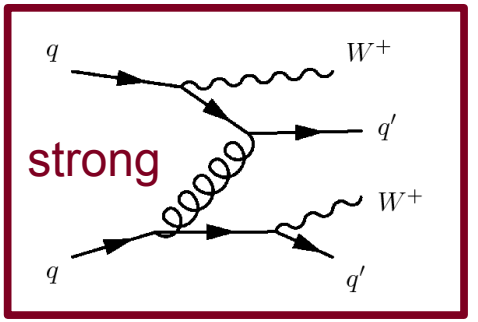
$$\sigma^{\mathrm{Powheg}}_{\mathrm{EW}} = 46.1 \pm 0.2(\mathrm{stat})^{+0.3}_{-0.2}(\mathrm{scale}) \pm 0.8(\mathrm{PDF}) \pm 0.5(\mathrm{model})\ \mathrm{fb}$$



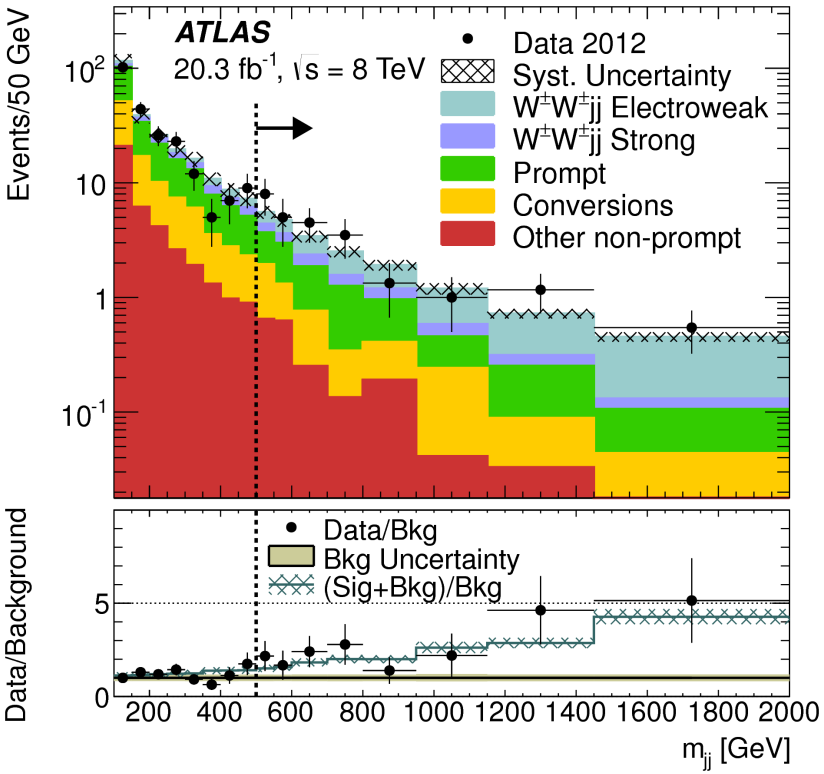
Electroweak WWjj production (VBS)

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

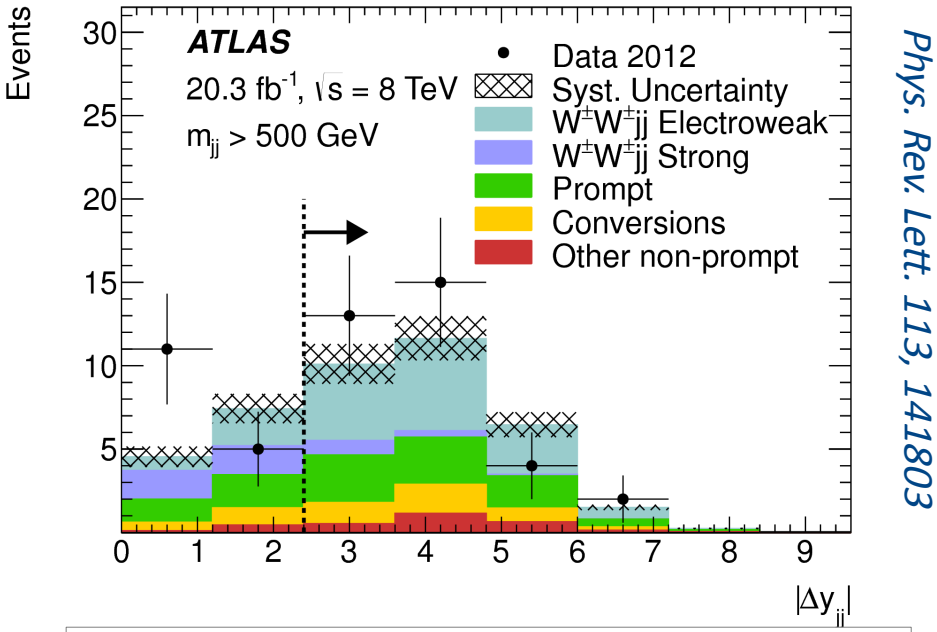




measurement of EW + strong production in m_{jj} > 500 GeV region



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

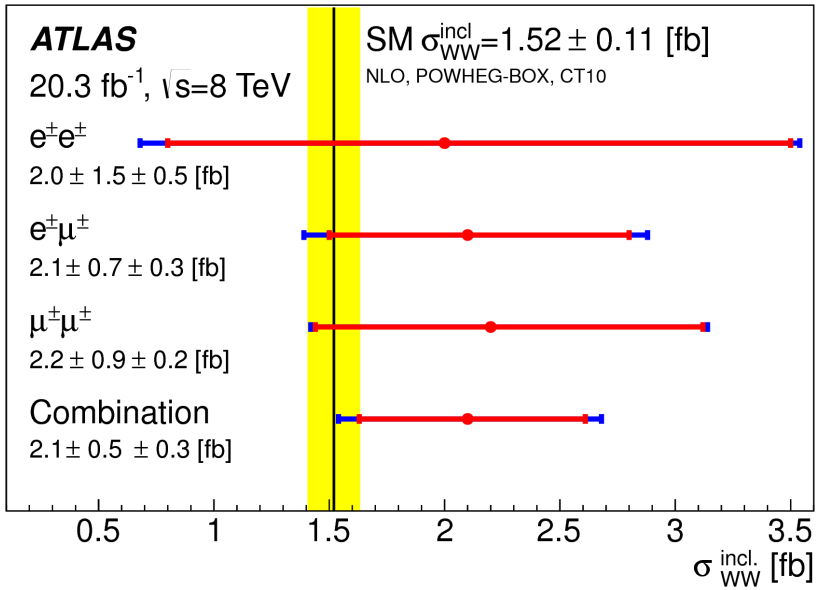


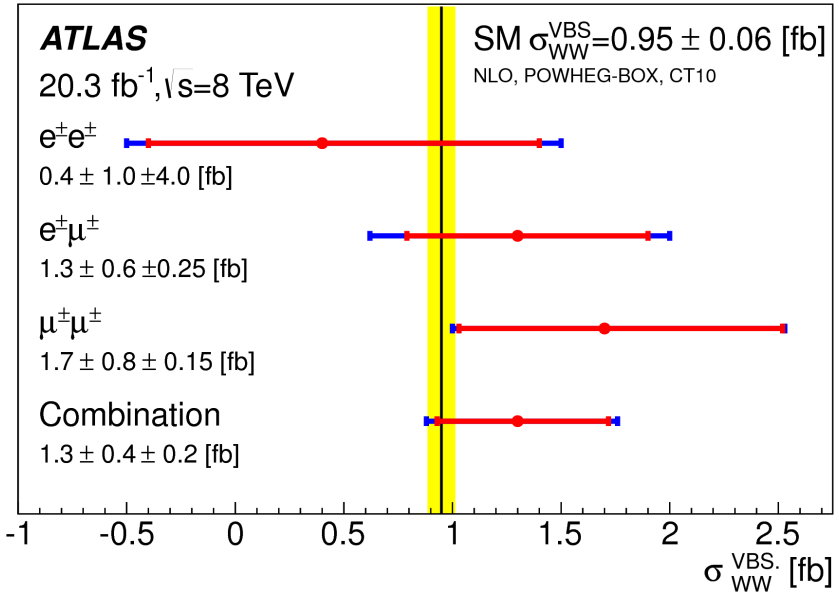
Phys. Rev. Lett. 113, 141803

prompt: prompt leptons from multilepton processes

conversions: photon conversions and charge mis-ID

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:

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

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

significance: 4.5σ (exp. 3.4σ)

VBS measurements:

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

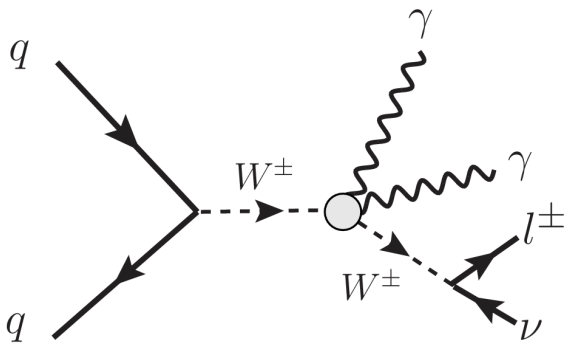
$\sigma^{\text{Powheg}} = 0.95 \pm 0.06$ fb

significance: 3.6σ (exp. 2.8σ)

Wγγ production

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

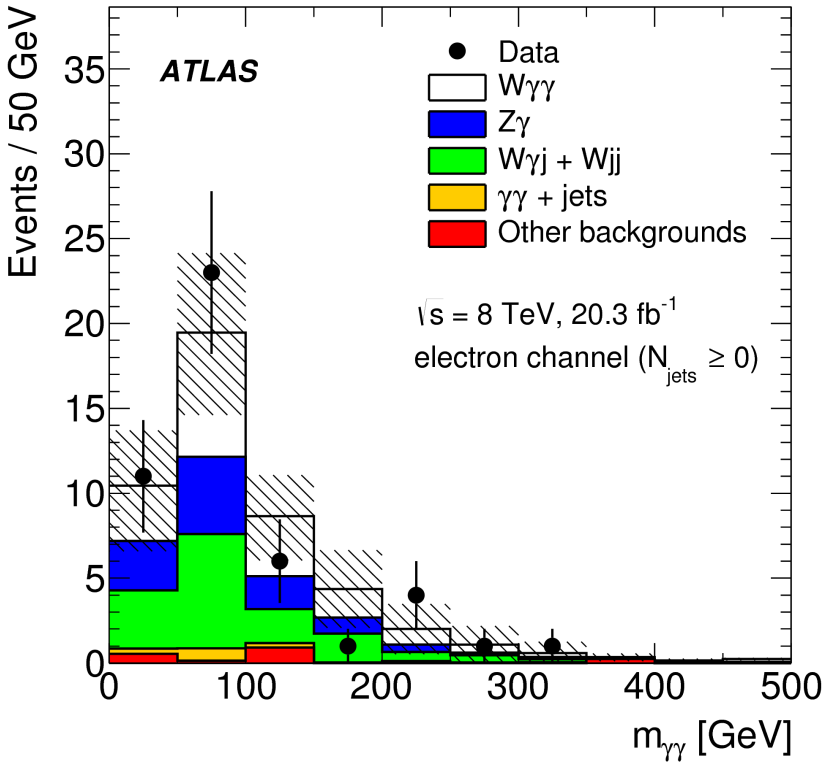
- First evidence of triboson production
- Sensitive to (anomalous) quartic coupling



- Signature:
  - Isolated lepton + MET and 2 isolated photons
- Background:
  - Multijet background (data driven); e.g. Wγ + jets
  - Prompt leptons (MC based); e.g. Zγ
- Results:
  - Measurements in inclusive ($N_{jet} \geq 0$) and exclusive region($N_{jet} = 0$)
  - Combined significance over background only > 3σ

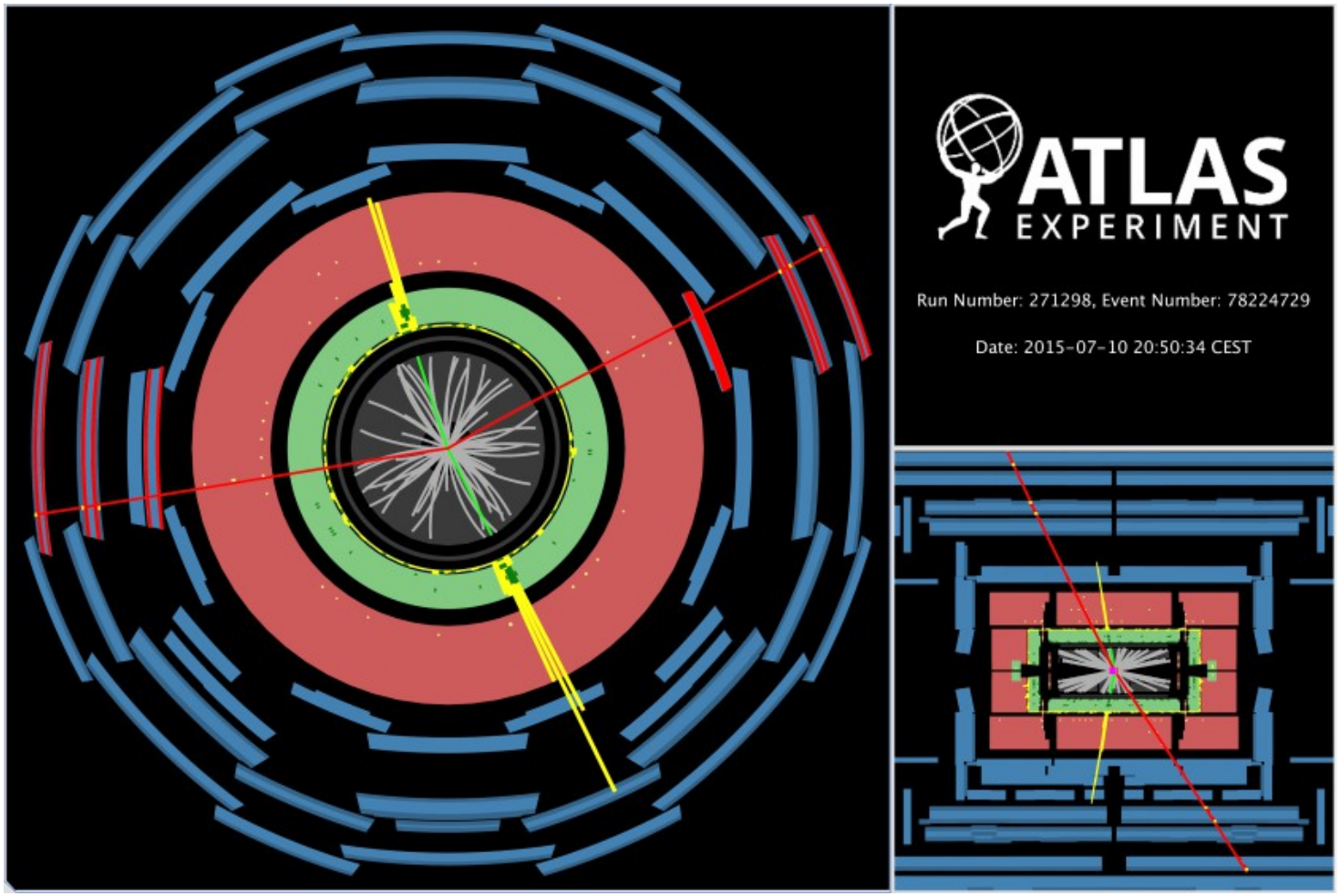
$\sigma^{\text{fid}} = 6.1^{+1.1}_{-1.0}\ (\text{stat.}) \pm 1.2\ (\text{syst.}) \pm 0.2\ (\text{lumi.})\ \text{fb}$
$\sigma^{\text{MCFM}} = 2.90 \pm 0.16\ \text{fb}$
Inclusive region

$\sigma^{\text{fid}} = 2.9^{+0.8}_{-0.7}\ (\text{stat.})^{+1.0}_{-0.9}\ (\text{syst.}) \pm 0.1\ (\text{lumi.})\ \text{fb}$
$\sigma^{\text{MCFM}} = 1.88 \pm 0.20\ \text{fb}$
Exclusive region



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



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

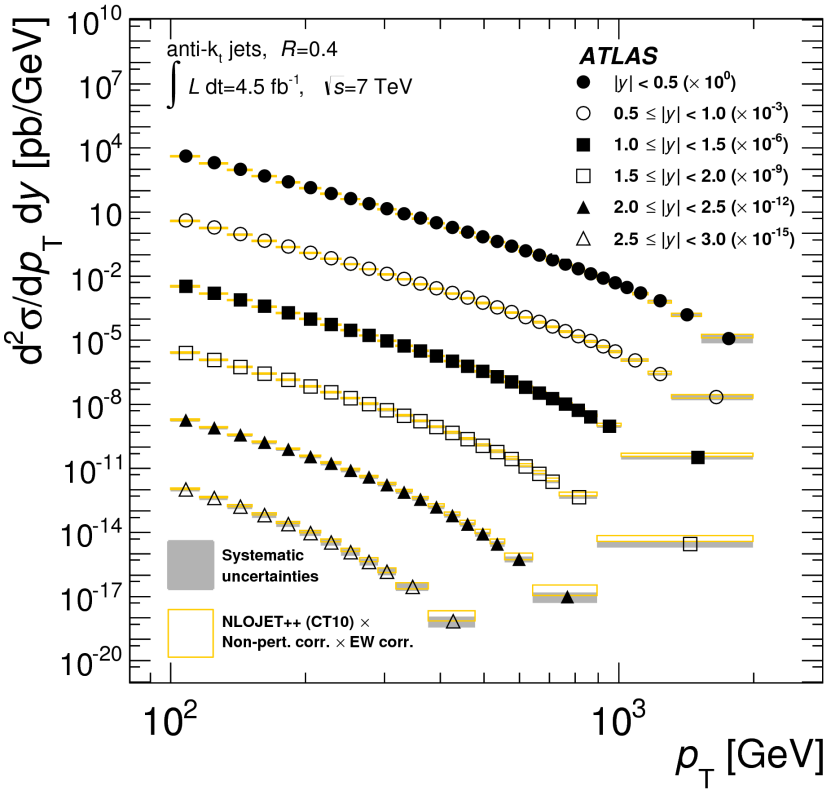
Summary

- ATLAS successfully recorded ~ 5 fb^{-1} 7TeV and ~21 fb^{-1} 8 TeV pp collision data delivered by LHC during Run-I period
- ATLAS performed a wide range of SM physics measurements covering a variety of SM physics aspects: QCD, Electroweak, V+X, multibosons, jets physics:
  - Charged particle multiplicities – first measurement at 13 TeV
  - Two photon scatering: γγ -> ll
  - 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 – preliminary results at 13 TeV
  - Electroweak production of Zjj, sensitive to vector boson fusion
  - First evidence of vector boson scattering
  - First measurement of triboson (Wγγ) production in ATLAS
  - ...and much more not shown in this presentation
- Measurements at 13TeV already underway!

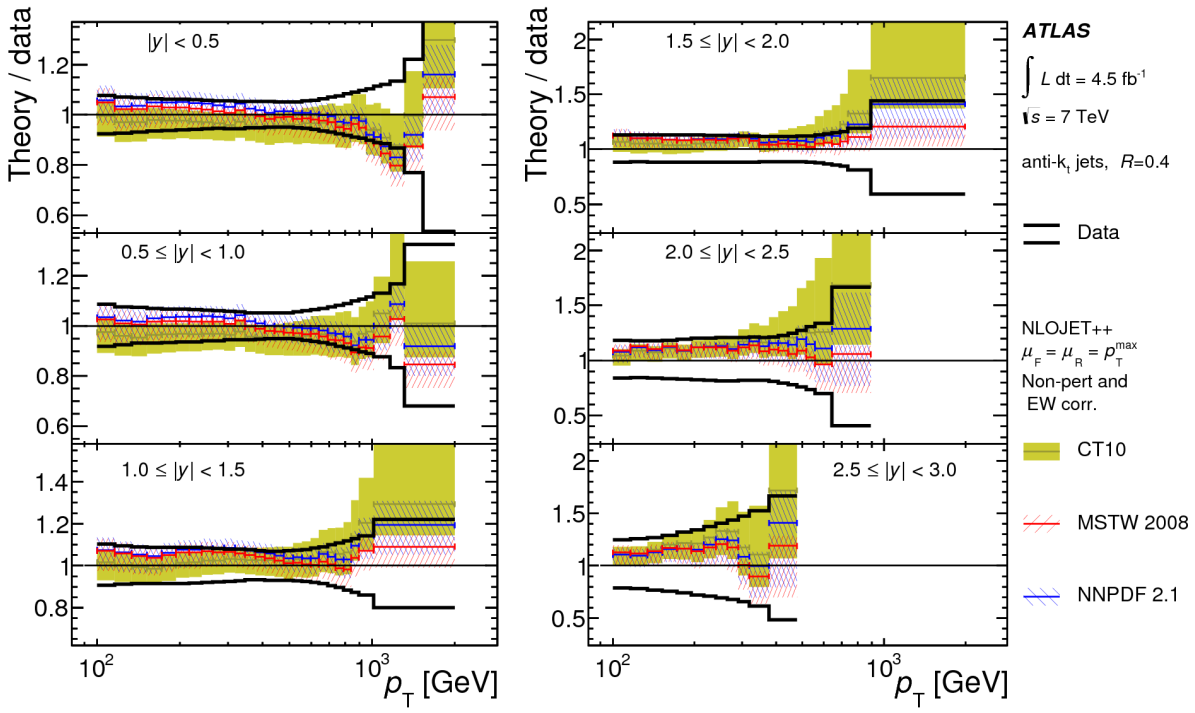
BACKUP

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



JHEP02(2015)153



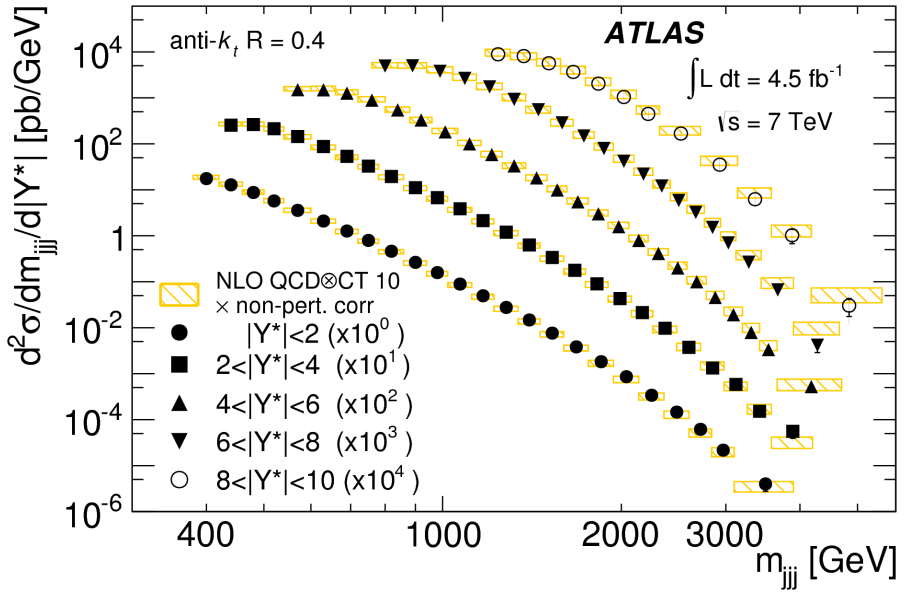
Three jet production at 7 TeV

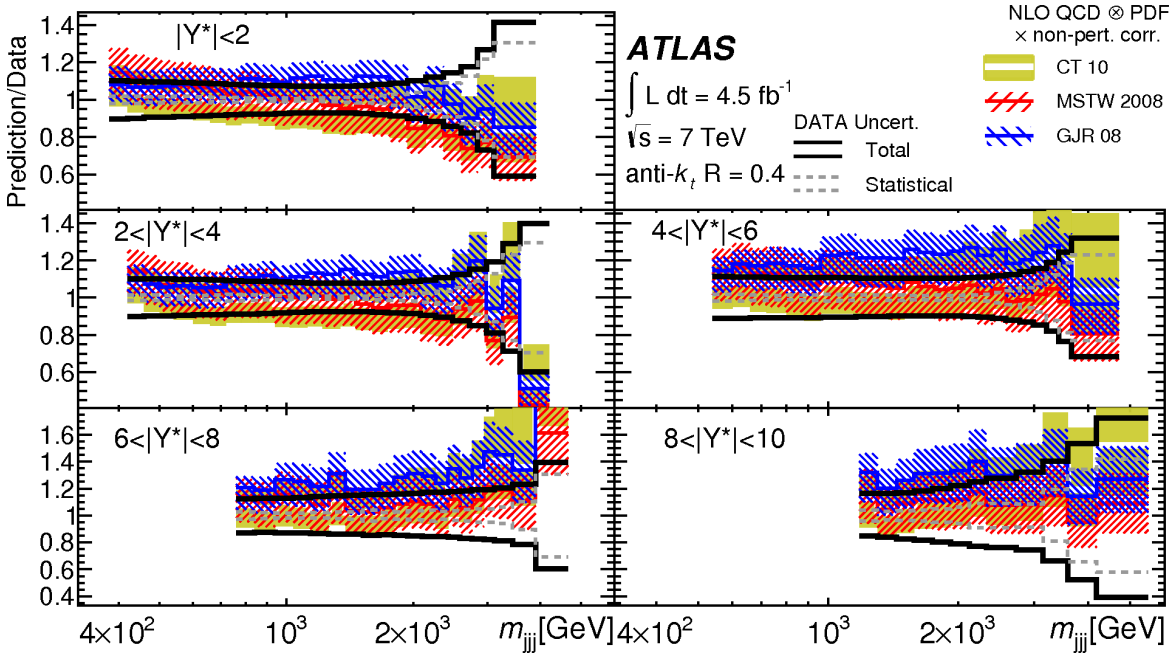
Eur. Phys. J. C75 (2015) 228

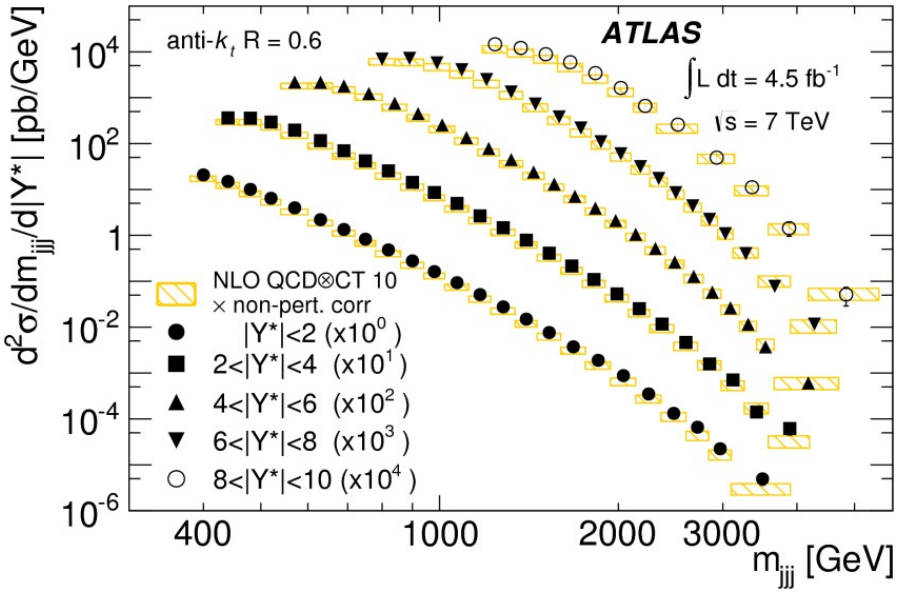
- Jet of anti-k_T 0.4 and 0.6 with 3-j mass up to 5 TeV
- Probed and well described by pQCD at NLO on full (m_{jjj}, $|Y^*|$) plane with a variety of PDFs

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

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



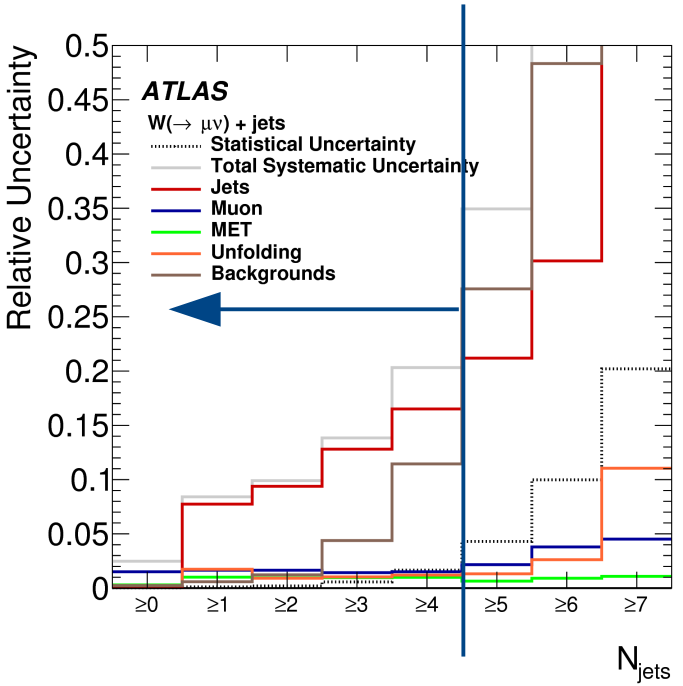




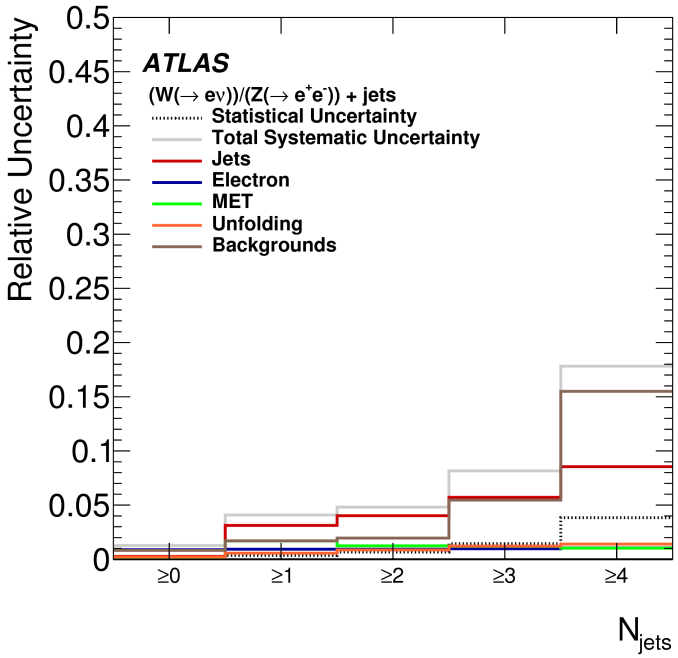
W+jets / Z+jets at 7 TeV

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^{-1} full dataset
- Differential measurement for the first time up to four jets
- Comparison with NLO pQCD calculation, LO ME Monte Carlo generators done

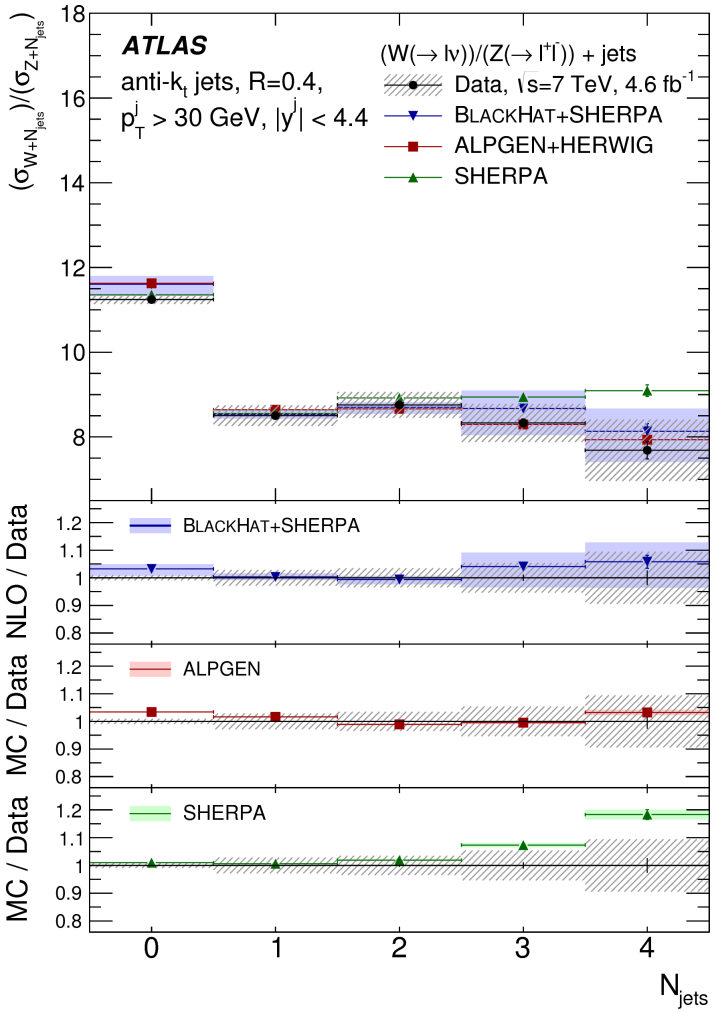


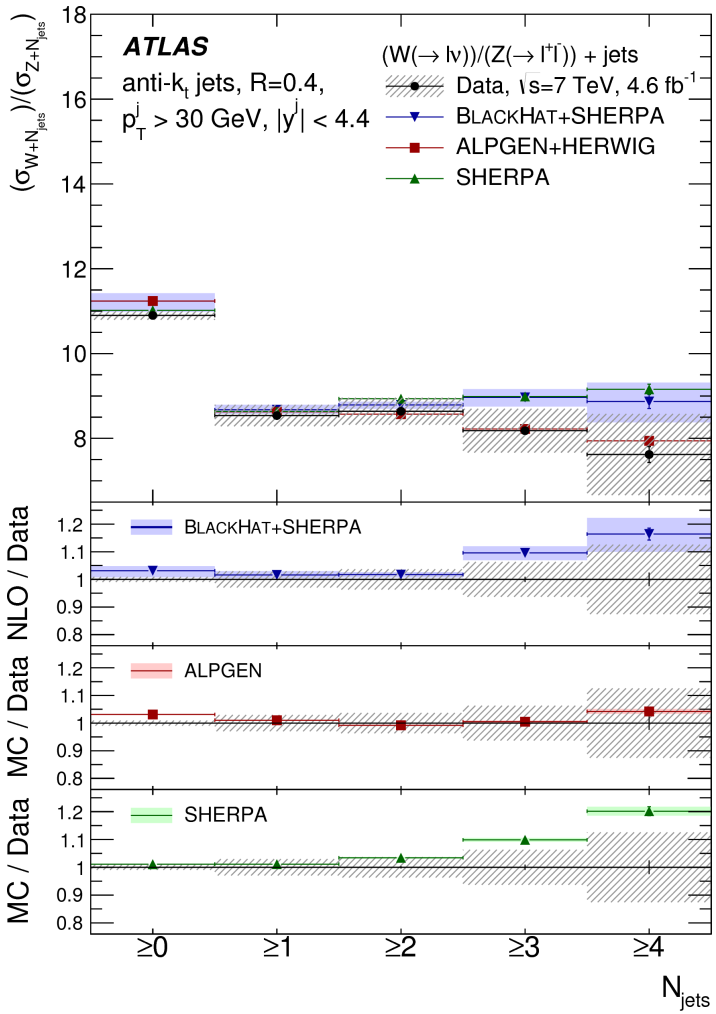
Eur. Phys. J. C (2015) 75:82



W+jets / Z+jets at 7 TeV

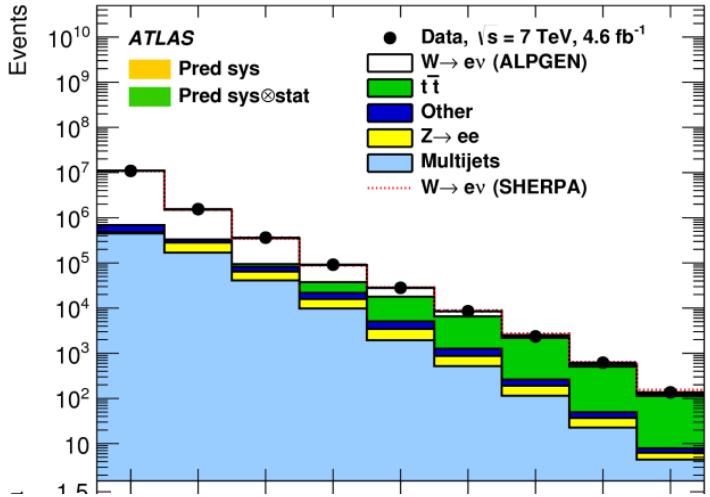
Eur. Phys. J. C (2014) 74: 3168





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

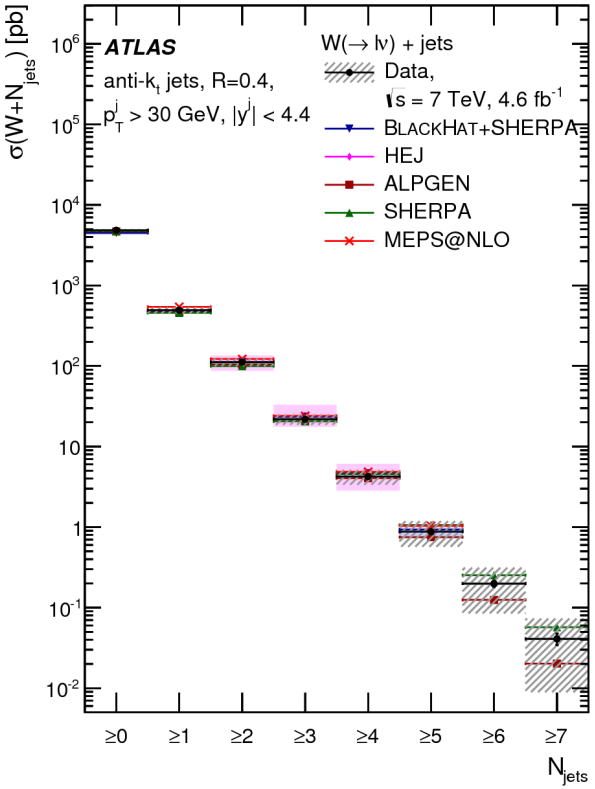
W+jets production at 7 TeV

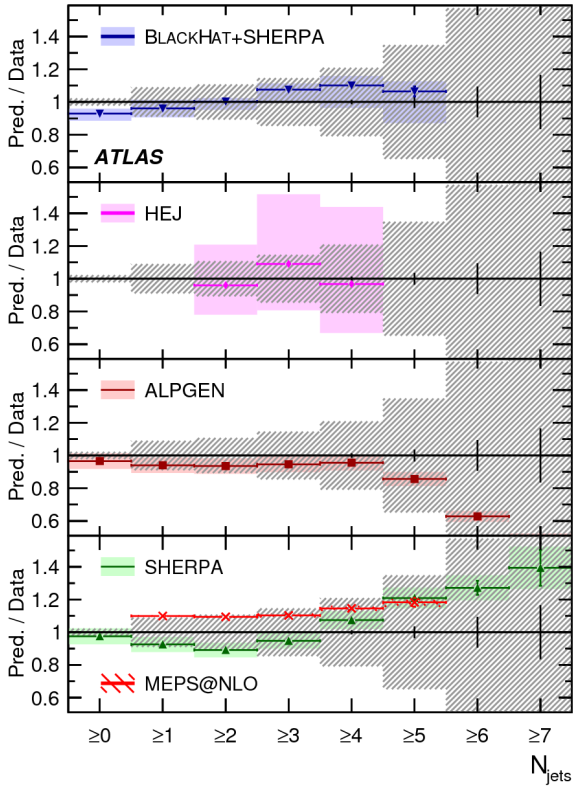


- Test of pQCD calculation in large kinematic range
- Background for many SM processes and BSM searches
- Fully leptonic final states (e/μ) at √s= 7 TeV with 4.6fb^{-1}

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

- 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





W and Z production at 13 TeV

ATLAS-CONF-2015-039

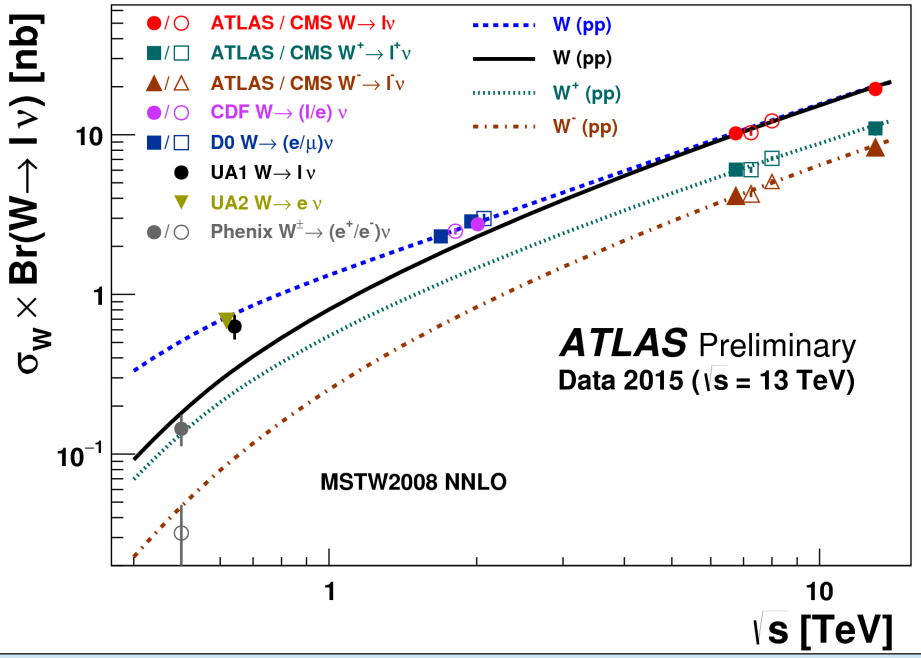
Measurement:

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

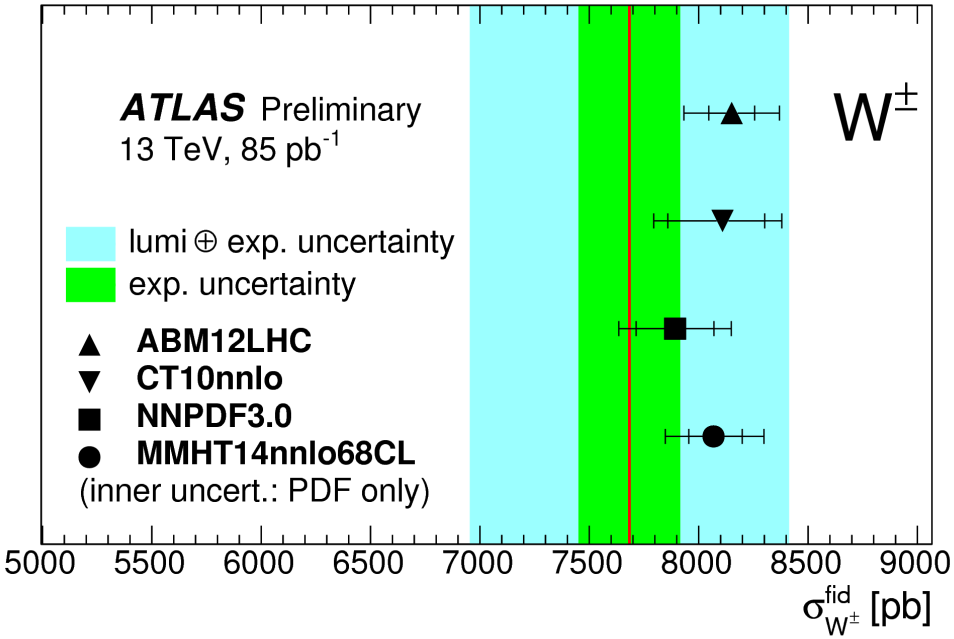
Backgrounds:

- 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)



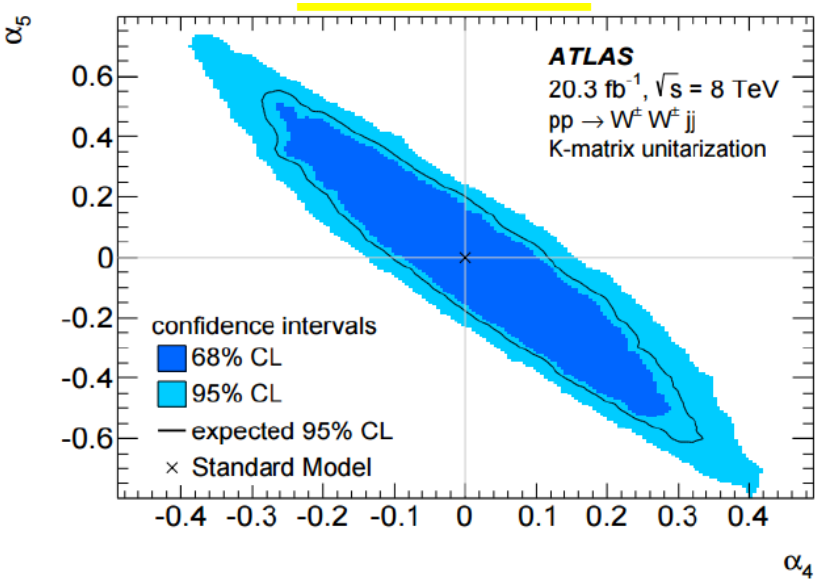
Combined fiducial cross section with different PDFs
The experimental precision is already comparable to PDF

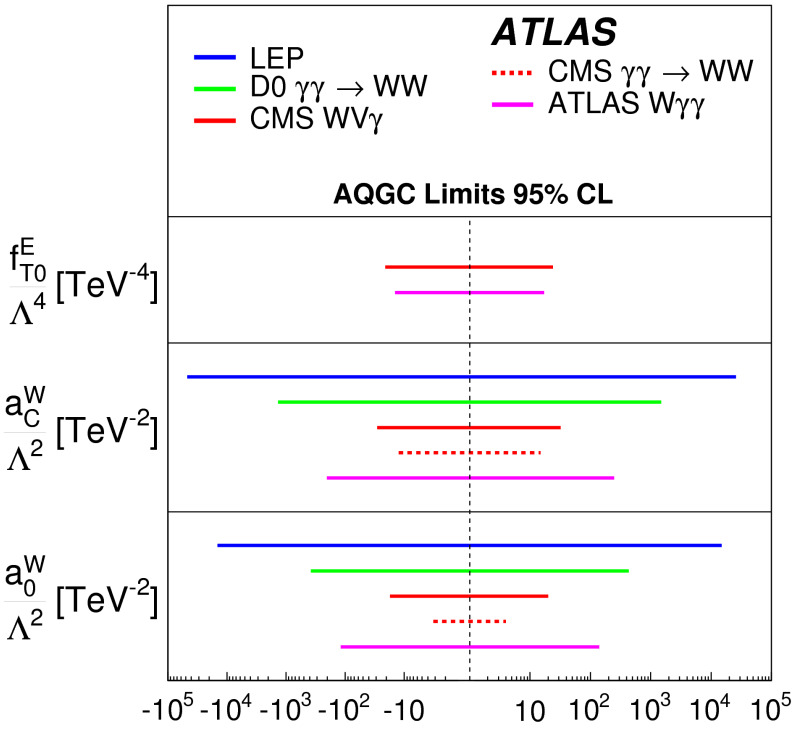


Lumi unc. of 9%

Wγγ / WWjj aQGC

- First aQGC limits on α4, α5 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