Recent results on associated vector boson production with the ATLAS & CMS experiments

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On behalf of the ATLAS & CMS Collaborations

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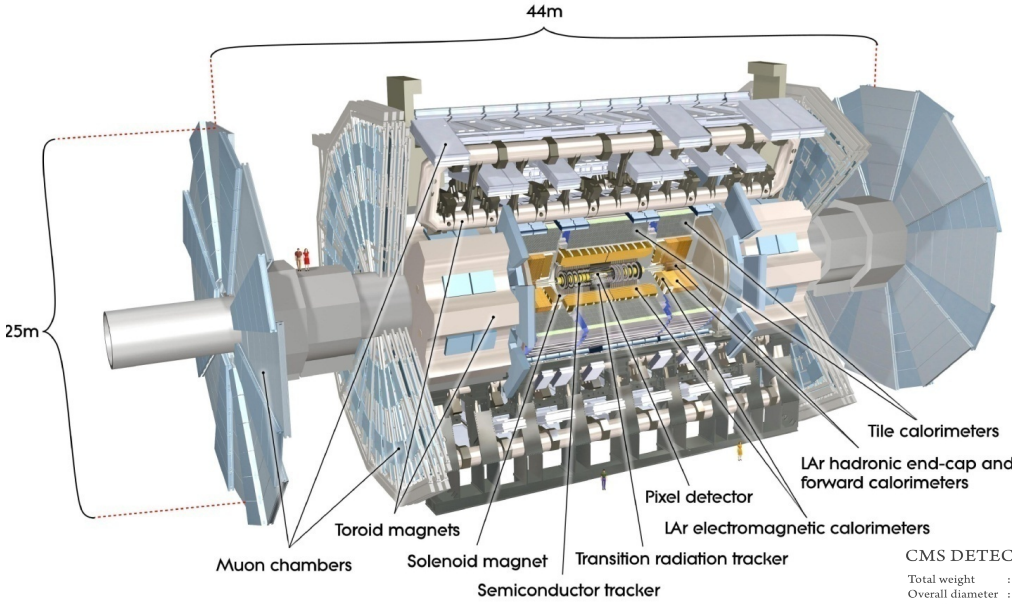
Outline - References

- ATLAS and CMS Detectors

Results at √s = 7 TeV and √s = 8 TeV

- **W + jets NEW!**
  - **ATLAS:** ATLAS-CONF-2014-035, **CMS:** arXiv:1406.7533
- **Z + jets**
  - **ATLAS:** JHEP07 (2013) 032
  - **CMS NEW!:** arXiv:1408.3104 , CMS-PAS-SMP-13-007, CMS-PAS-SMP-14-009, CMS-PAS-SMP-14-005
- **Rjets = (W + jets) / (Z + jets)**
  - **ATLAS NEW!:** arXiv:1408.6510, **CMS:** JHEP01 (2012) 010
- **Zb, Zbb NEW!**
  - **ATLAS:** arXiv:1407.3643, **CMS:** JHEP06 (2014) 120, JHEP12(2013)039
- **Wb, Wbb**
  - **ATLAS:** JHEP06 (2013) 084, **CMS NEW!:** arXiv:1312.6608
- **Wc**
  - **ATLAS:** JHEP05 (2014) 068, **CMS:** JHEP02 (2014) 013
- **ttbarW, ttbarZ NEW!**
  - **ATLAS:** ATLAS-CONF-2014-038, **CMS:** arXiv:1406.7830
- Summary and Outlook

A Toroidal LHC ApparatuS & Compact Muon Solenoid

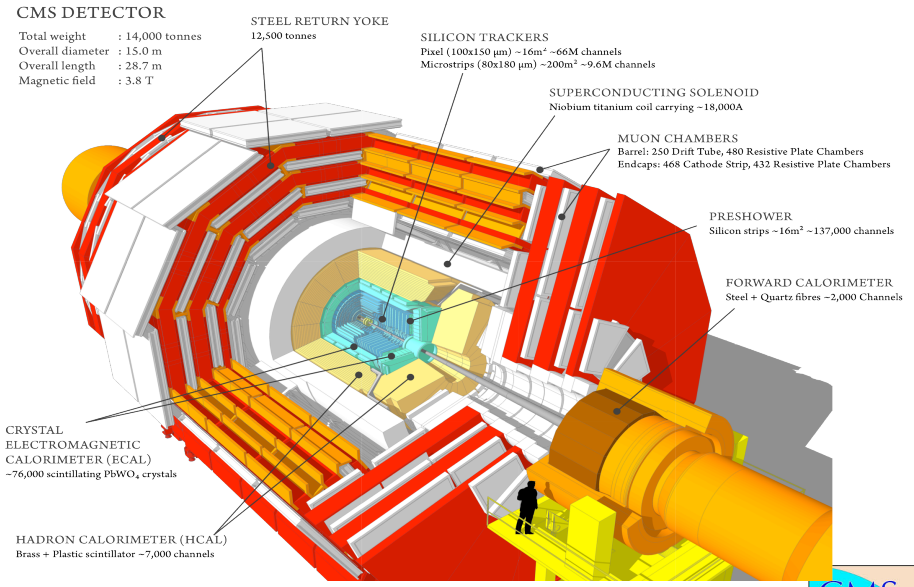


ATLAS:

- Total weight: **7000 tons** (same as the Eiffel Tower)
- Superconducting solenoid (**2 T**) surrounding three kinds of trackers
- Three superconducting toroids (muon spectrometer)

CMS:

- Total weight: **14000 tons**
- Superconducting solenoid (**3.8 T**) surrounding two kinds of trackers and both calorimeters



Motivation

- Precision measurements of **associated vector boson production** at the LHC are crucial
  - Vector boson leptonic decays (**electrons, muons**) are studied (**clean signatures**)
- **Test and validate** the perturbative QCD (**pQCD**) calculations
- Constrain the parton proton structure (**PDFs**)
- Provide important experimental constraints **to improve the theoretical uncertainties** on existing predictions
- Important background for numerous **Standard Model (SM) processes**
  - ttbar, single top
  - Higgs boson production

  and for **physics beyond SM**
  - Supersymmetry

W + jets (7 TeV)

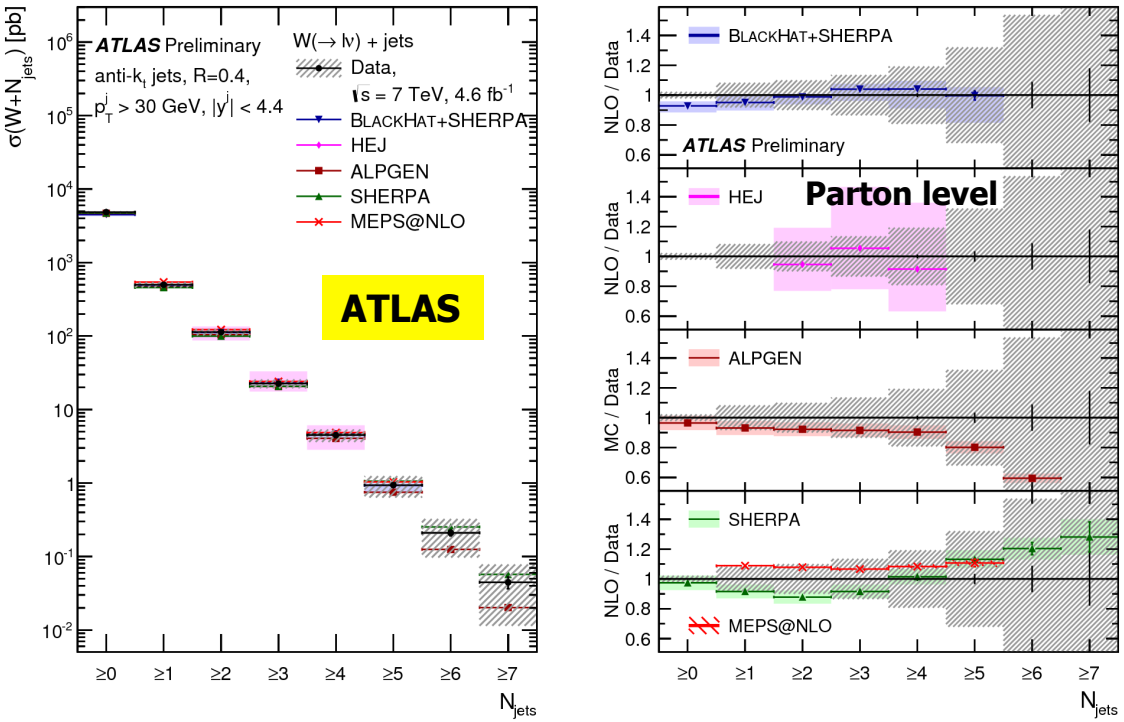
ATLAS
- $p_{T\,\mu}$, $p_{T\,e}$ > 25 GeV
- $|\eta|$ < 2.47 (e), 2.4 (μ)
- AntikT4, Jet p_T > 30 GeV, **|y| < 4.4**
- E_{Tmiss} **> 40 GeV**, m_T **> 40 GeV**

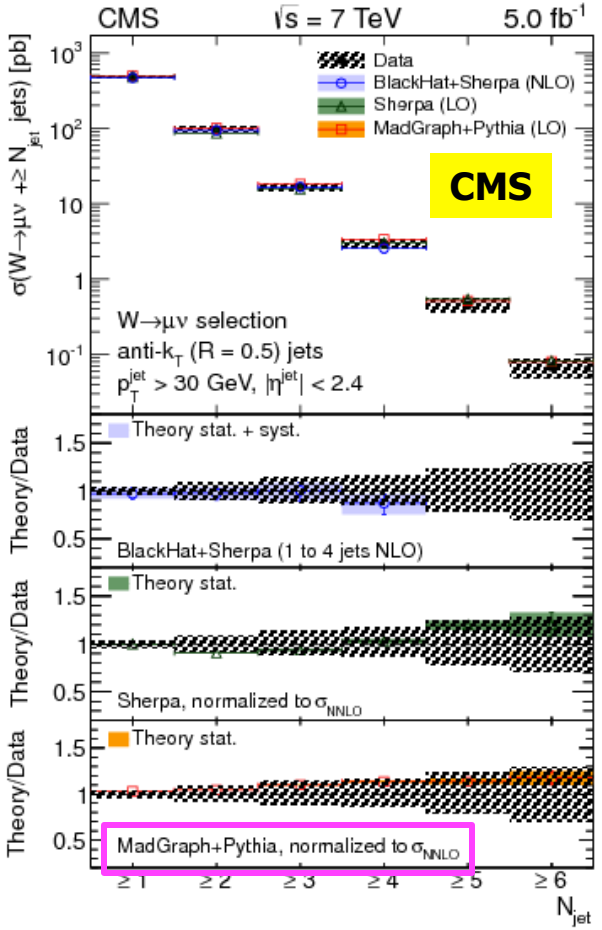
CMS – muon channel only
- $p_{T\,\mu}$ > 25 GeV
- $|\eta_\mu|$ < 2.1
- AntikT5, Jet p_T > 30 GeV, **| η | < 2.4**, **b-jet veto**
- m_T **> 50 GeV**

- **Unfolded** results compared at **particle level** with **LO** and **NLO** theory predictions
  - Bayesian Iterative Unfolding (ATLAS)
  - Singular Value Decomposition (SVD) unfolding (CMS)
- **Parton-level predictions (BLACKHAT+SHERPA)** corrected for hadronisation, UE, QED FSR
- Theory systematic uncertainties: PDF, scale(μ_R, μ_F), α_s
- Dominant systematic uncertainties
  - ATLAS: Jet energy scale (JES), data driven ttbar background estimation (high jet multiplicities)
  - CMS: JES and Jet energy resolution (JER)
    - ttbar background is modelled with simulation

W + jets (7 TeV)

- **Inclusive jet multiplicity** for up to **7** (ATLAS) and **6** (CMS) jets

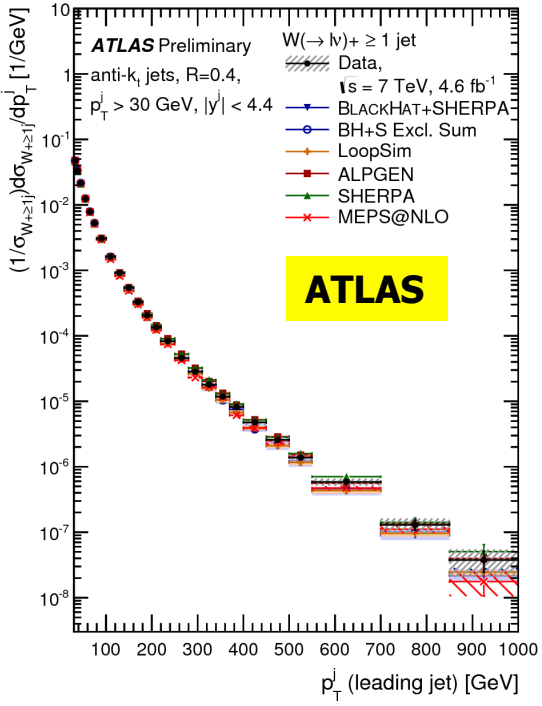


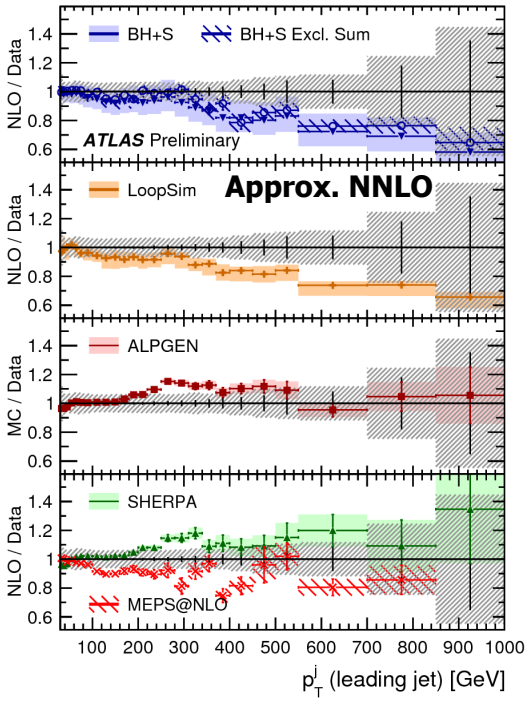


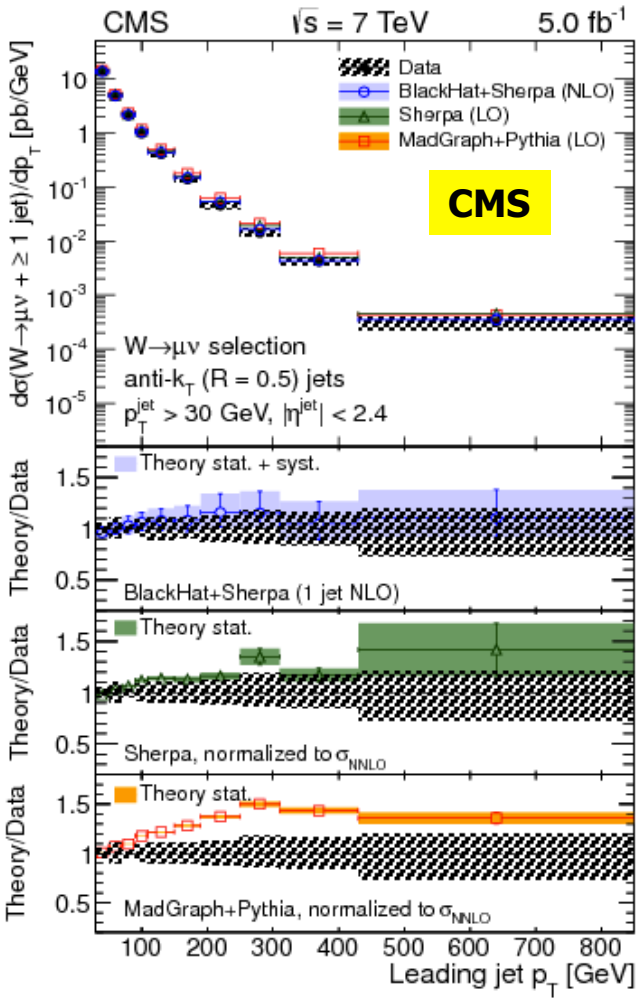
Measurements in agreement within uncertainties with theoretical predictions

W + jets (7 TeV)

- **Leading jet p_T** up to **850 GeV** and **1 TeV**!
  - Up to 5th (ATLAS) and 4th leading jet (CMS)



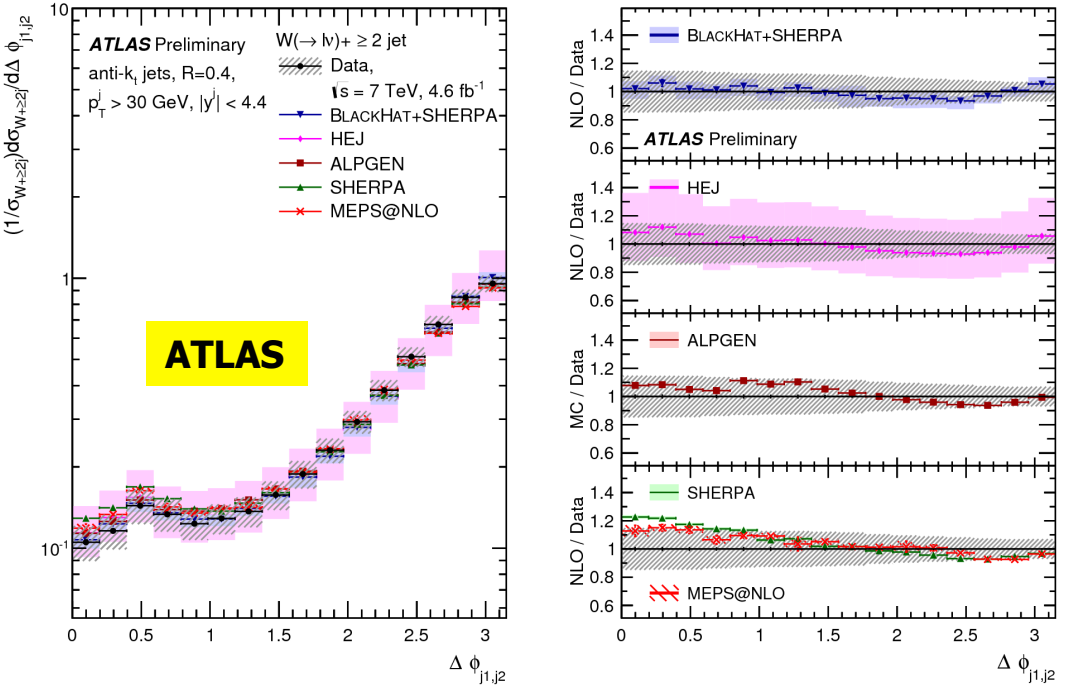


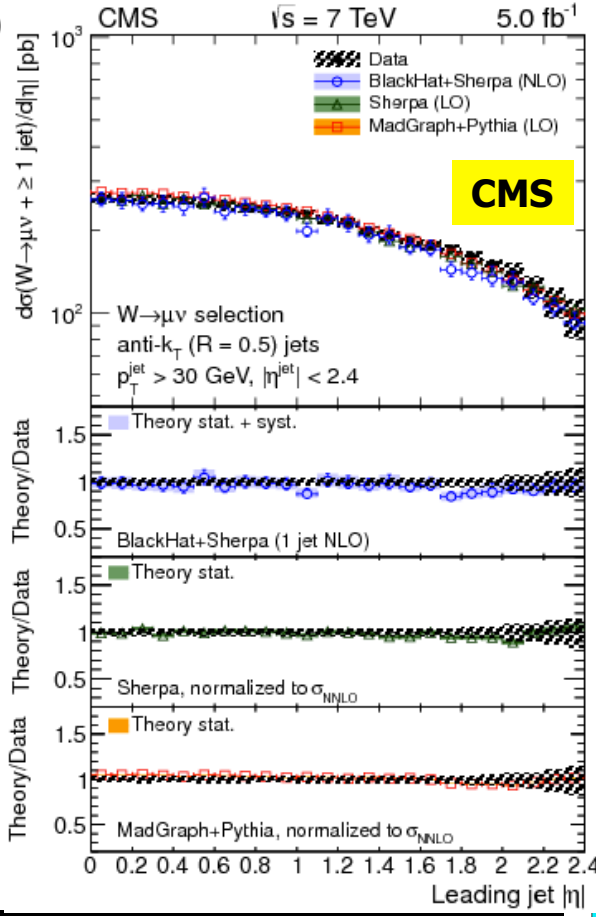


- **BLACKHAT+SHERPA, LoopSim** underestimate the data at high p_T (ATLAS)
- **MADGRAPH+PYTHIA** overestimates the yields up to ~50% (CMS)

W + jets (7 TeV)

- **Δ Φ(j1,j2) and leading jet | η |**
- Many other variables measured
  - **Exclusive jet multiplicity** up to 7 (ATLAS) and 6 (CMS) jets
  - **jets y** (ATLAS), **jets** η (CMS)
  - **H_T**: scalar sum of jets p_Ts (CMS), scalar sum of jets p_Ts, lepton p_Ts, E_{Tmiss} (ATLAS)
  - Δ Φ(j1,j2), Δ Y(j1,j2), Δ R(j1,j2), m(j1,j2) (ATLAS)
  - Δ Φ(j, μ) (CMS)





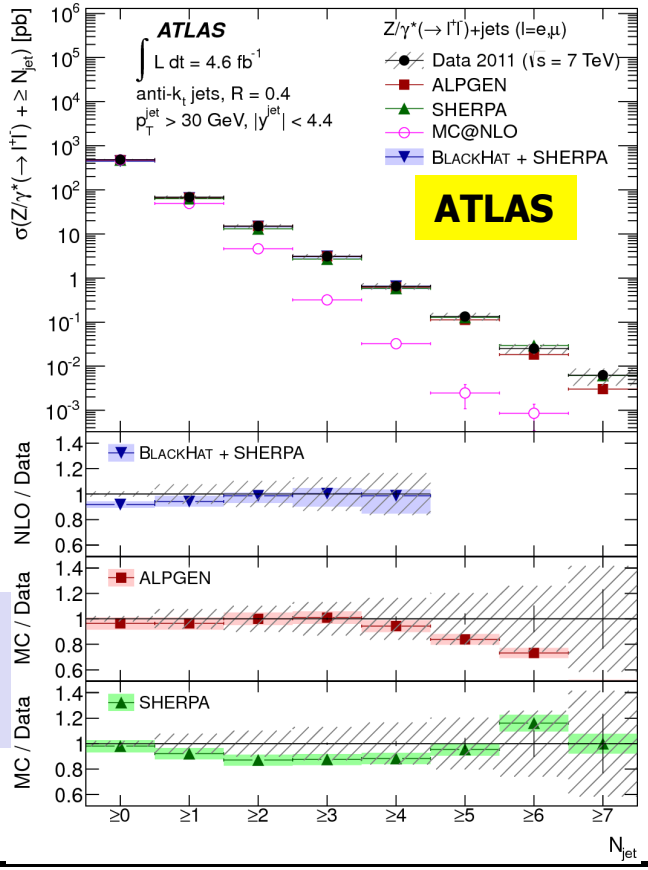
- **Δ Φ(j1,j2) :** Small shape differences with **SHERPA**

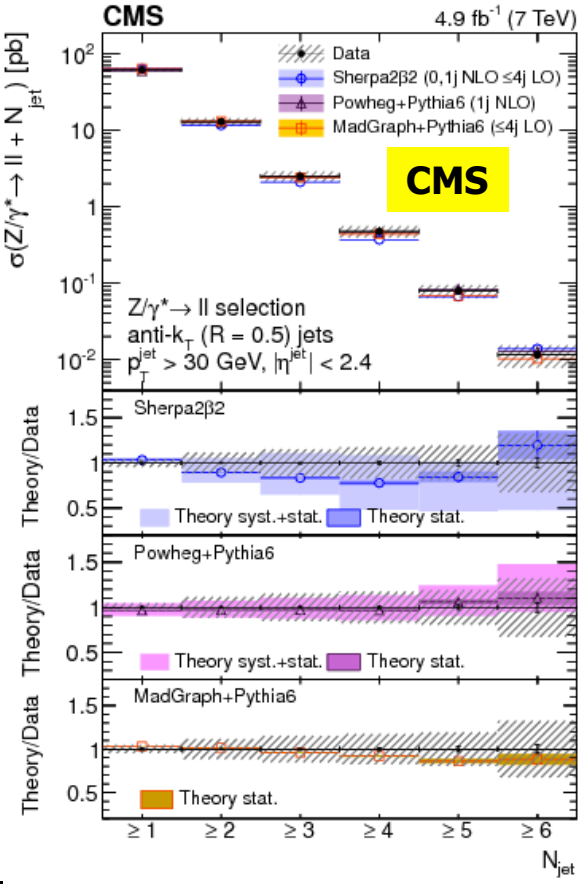
Z + jets (7 TeV)

ATLAS
- $p_{T\,\mu}$, p_{Te} > 20 GeV
- $|\eta|$ < 2.47 (e), 2.4 (μ)
- AntikT4, Jet p_T > 30 GeV, **$|y|$ < 4.4**
- Two OSSF **66 < m_{ll} < 116 GeV**

CMS
- $p_{T\,\mu}$, p_{Te} > 20 GeV
- $|\eta_\mu|$ < 2.4
- AntikT5, Jet p_T > 30 GeV, **$|\eta|$ < 2.4**
- Two OSSF **71 < m_{ll} < 111 GeV**

- **Inclusive jet multiplicity** up to **7** (ATLAS) and **6** (CMS) jets





MC@NLO parton shower underestimates the observed rate

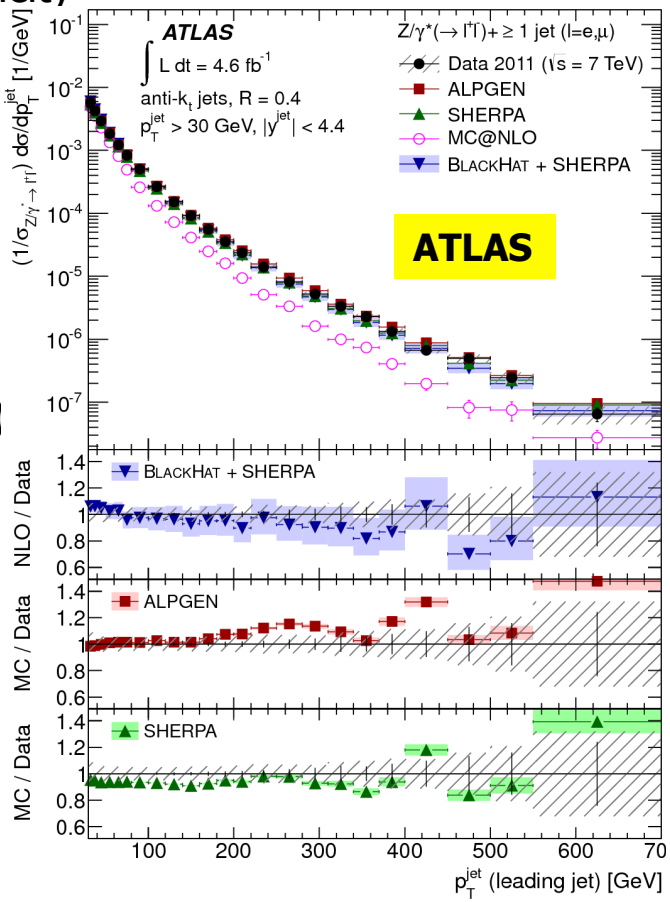
Z + jets (7 TeV)

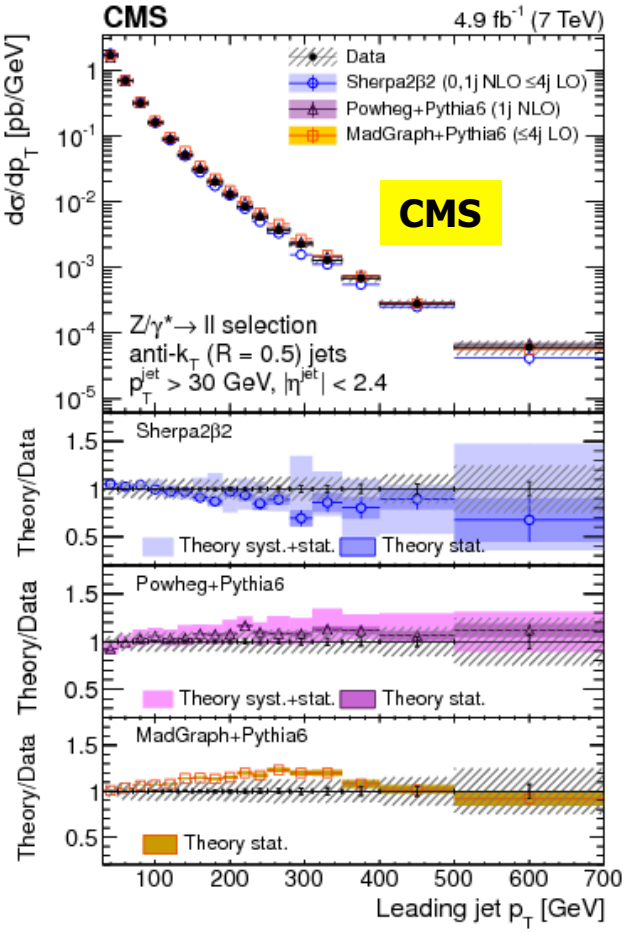
- **Leading jet p_T** up to 700 GeV
  - Up to 4th leading jet
- Also measured:
  - Exclusive jet multiplicity
  - **jets y** (ATLAS)
  - **jets η** (CMS)
  - **H_T, S_T** (ATLAS)
  - **H_T (CMS)**

ATLAS:

- $N_{jet}+1/ N_{jet}$
- $\Delta\Phi, \Delta Y, \Delta R(j1,j2)$
- m(j1,j2)

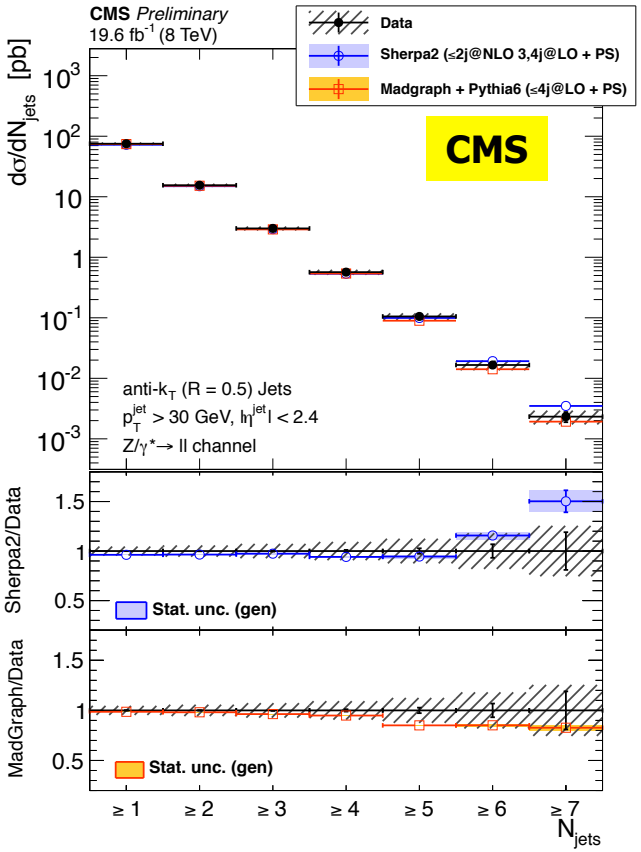
ALPGEN spectrum harder at higher p_T
SHERPA small offset to data

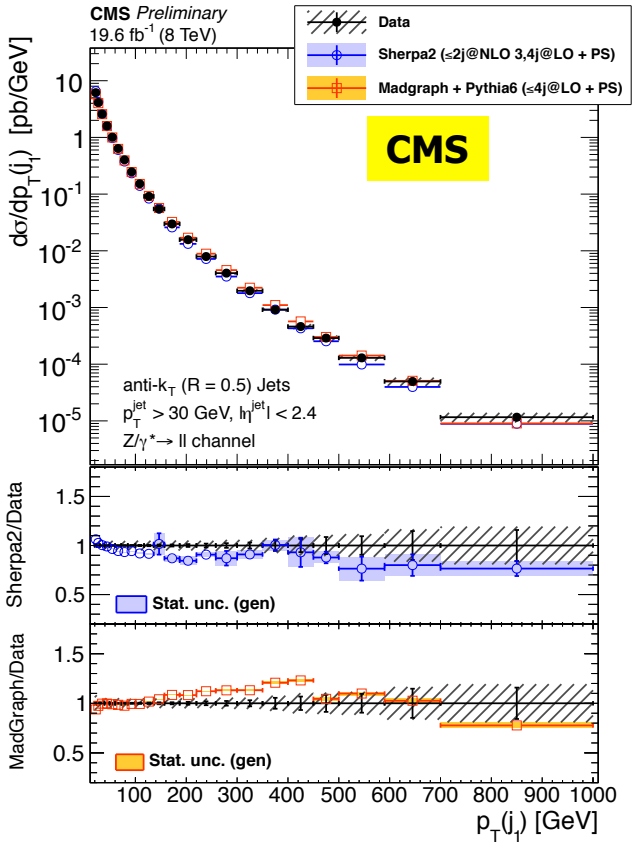




Z + jets (8 TeV, CMS)

- **Same event selection** as for 7 TeV CMS analysis
- Unfolding performed with D' Agostini Method (**Bayesian iterative unfolding**)
- Also measured **up to 5 jets**:
  - Exclusive jet multiplicity (7 jets)
  - jets p_T , $|\eta|$
  - H_T
- Also measured 8 TeV:
  - **Z+jets / γ +jets** (Matthias Weber talk)



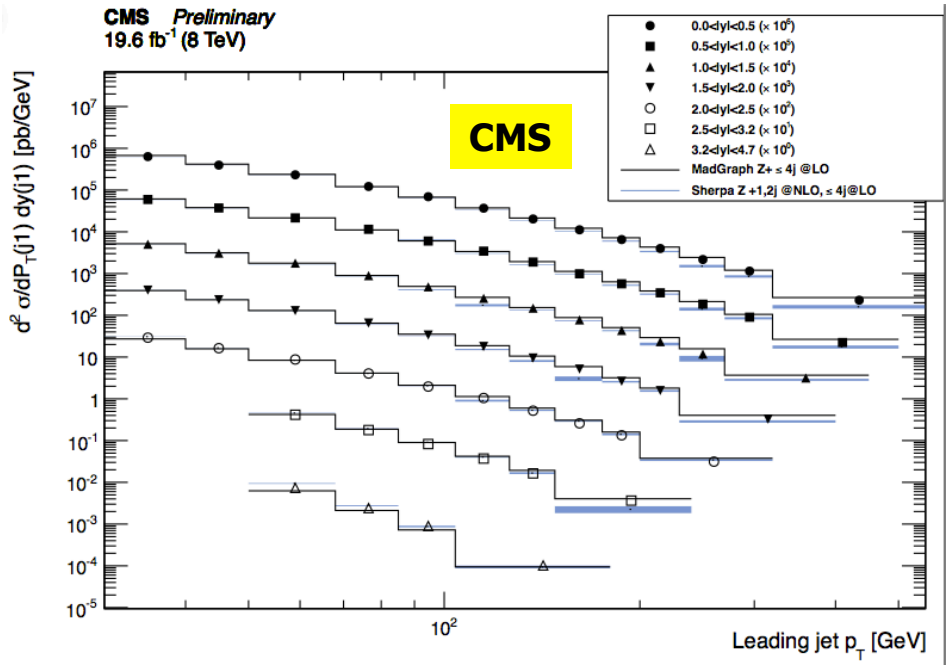


SHERPA2 spectrum slightly underestimates the data
MADGRAPH: discrepancies from ~150 – 450 GeV

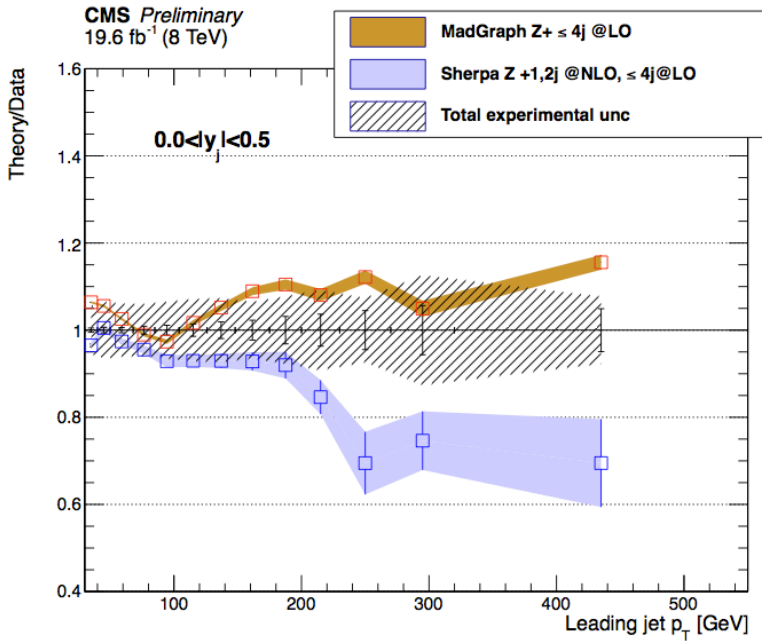
Double Differential cross section (8 TeV, CMS)

- **First study** of the double differential cross section in the Z + jets final state
  - Versus the **leading jet p_T and jet rapidity y** (seven y bins)

- Similar analysis to the previous CMS ones
  - Jet p_T > 30 GeV for $|\eta| < 2.5$
  - Jet p_T > 50 GeV for $2.5 < |\eta| < 4.7$



Theory/Data ratio, 0.0 < |y| <0.5



- Disagreement of ~ 10% between **MADGRAPH** and data for jet p_T > 100 GeV
- Some discrepancies also with **SHERPA 2** (need more investigation)

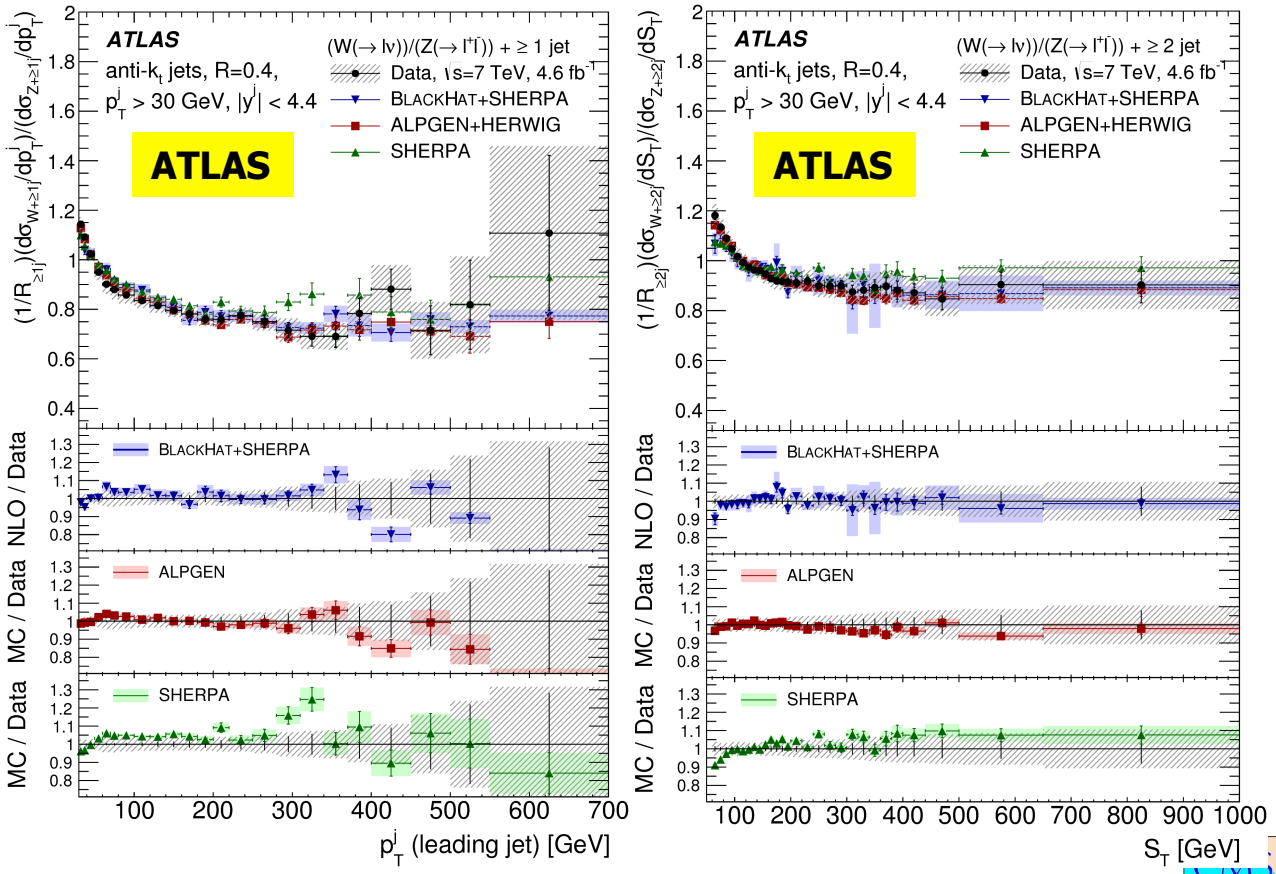
Rjets (7 TeV, ATLAS)

- Some experimental uncertainties and non-perturbative effects are greatly reduced
- **Sensitive to new physics** at high energies
- Measured versus many more variables

- $p_{T\,\mu}$, $p_{T\,e}$ > 25 GeV
- $|\eta|$ < 2.47 (e), 2.4 (μ)
- AntikT4, Jet p_T > 30 GeV, $|y|$ < 4.4
- **W:** E_{Tmiss} > 25 GeV, m_T > 40 GeV
- **Z:** Two OSSF 66 < m_{ll} < 116 GeV

S_T = scalar sum of all jets p_T
SHERPA: discrepancies at the lowest values

CMS Rjets measurement: jet multiplicity up to four jets, with 36 pb^{-1} at √7 TeV (JHEP01 (2012) 010)



Zb, Zbb (7 TeV)

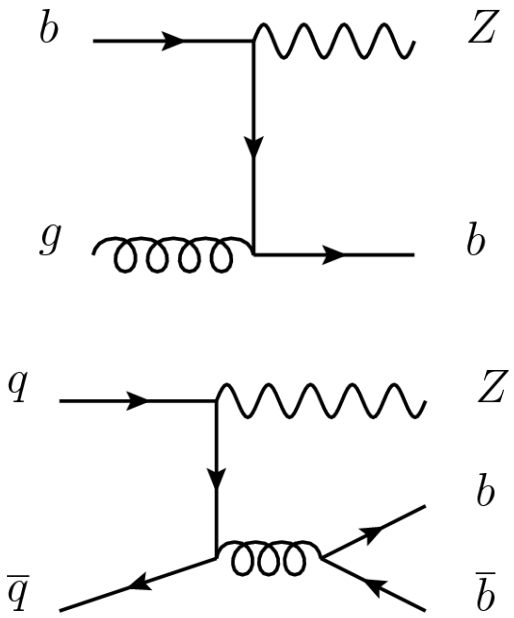
ATLAS
- $p_{T\,\mu}$, $p_{T\,e}$ > 20 GeV
- $|\eta|$ < 2.47 (e), 2.4 (μ)
- AntikT4, **Jet p_T > 20 GeV, $|y|$ < 2.4**
- Two OSSF 76 < m_{ll} < 106 GeV
- **At least one or two b-jets**

CMS
- $p_{T\,\mu}$, $p_{T\,e}$ > 20 GeV
- $|\eta_\mu|$ < 2.4
- AntikT5, **Jet p_T > 25 GeV, $|\eta|$ < 2.1**
- Two OSSF 76 < m_{ll} < 106 GeV
- **Exactly one or at least two b-jets**

- Jets originating from b quarks are tagged by
  - **MV1** algorithm (ATLAS)
  - **Simple Secondary Vertex (SSV)** algorithm (CMS)

- **CMS measurements:**
  - Z + 1 b-jet, **Z + ≥ 1 b-jet, Z + ≥ 2 b-jet**
  - Ratio: Z + ≥ 1 b-jet / Z + any flavour jet
  - **Angular correlations of b hadrons** probing the collinear gluon splitting to bb (JHEP12(2013)039)

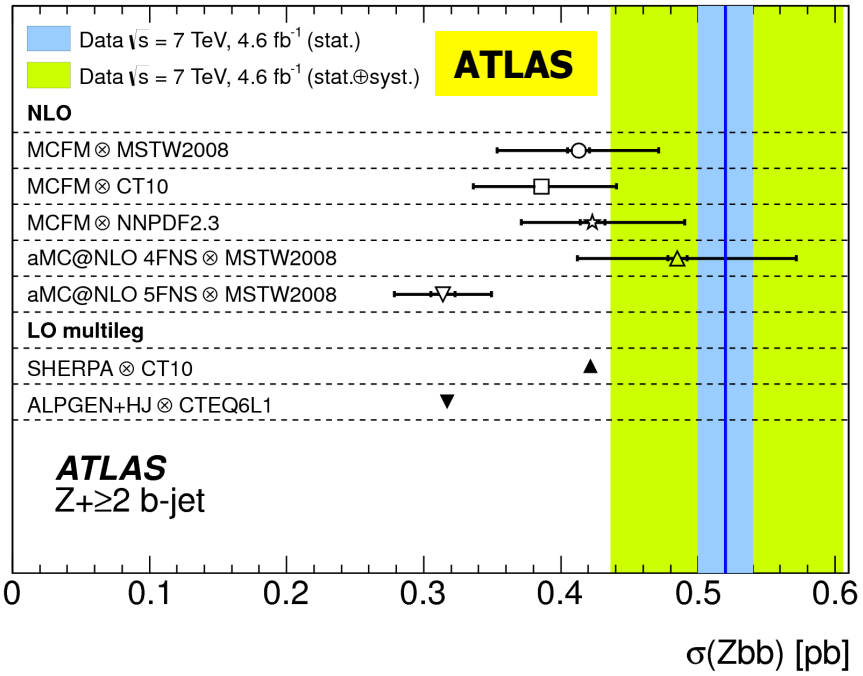
- **ATLAS measurements:**
  - **Z + ≥ 1 b-jet, Z + ≥ 2 b-jet**
  - b-jet p_T and rapidity, Zp_T and rapidity
  - $\Delta\Phi$(Z,b), Δ Y (Z,b), ΔR(Z,b)
  - m(b,b), ΔR(b,b)

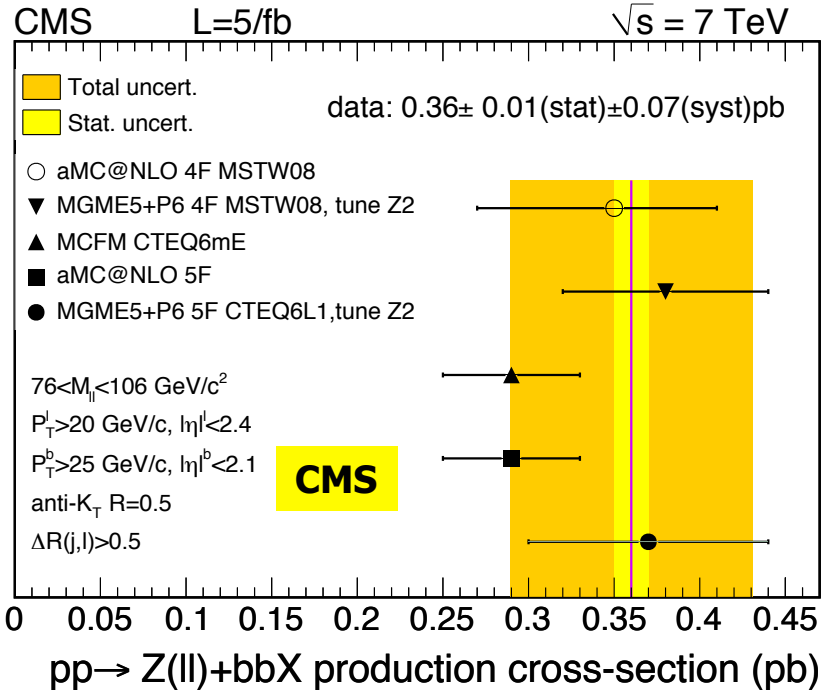


Zb, Zbb (7 TeV)

- Z production with **at least two b-jets**

- Two schemes in pQCD calculations containing heavy flavour quarks
  - **4FNS**: no b quarks at initial state
  - **5FNS**: b quarks considered at initial state



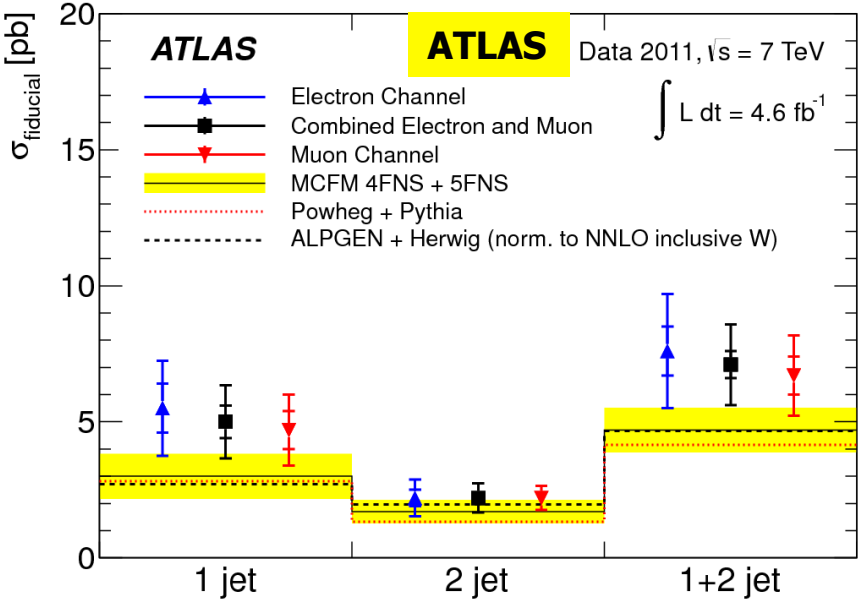


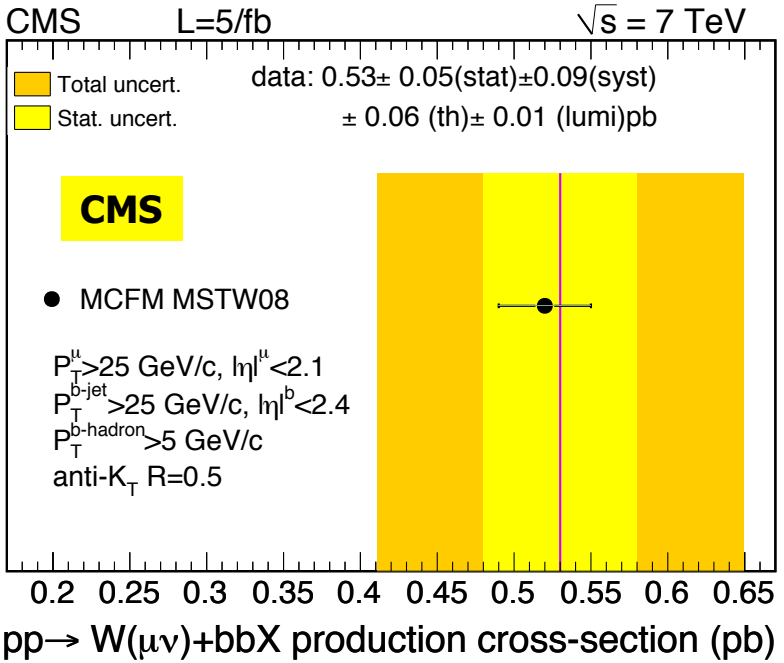
aMC@NLO 5FNS, ALPGEN (4FNS), SHERPA (5FNS): largest discrepancies (ATLAS)

Wb, Wbb (7 TeV)

ATLAS
- $p_{T\,\mu}$, $p_{T\,e}$ > 25 GeV, |η| < 2.47 (e), 2.4 (μ)
- AntikT4, Jet p_T > 25 GeV, |y| < 2.1
- E_{Tmiss} > 25 GeV, m_T > 60 GeV
- **Only one b-jet**

CMS – muon channel only
- $p_{T\,\mu}$ > 25 GeV, $|\eta_\mu|$ < 2.1
- AntikT5, Jet p_T > 25 GeV, | η | < 2.4
- m_T > 45 GeV
- **Exactly two b-jets**

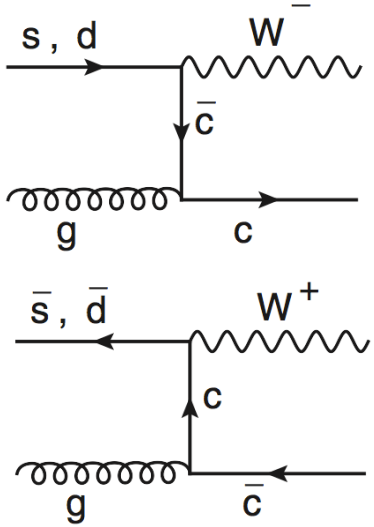


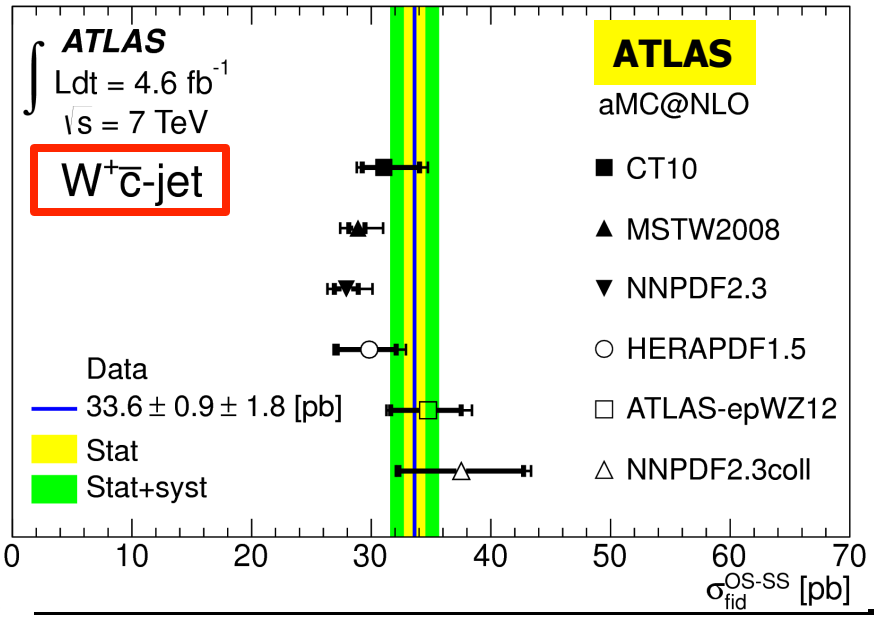


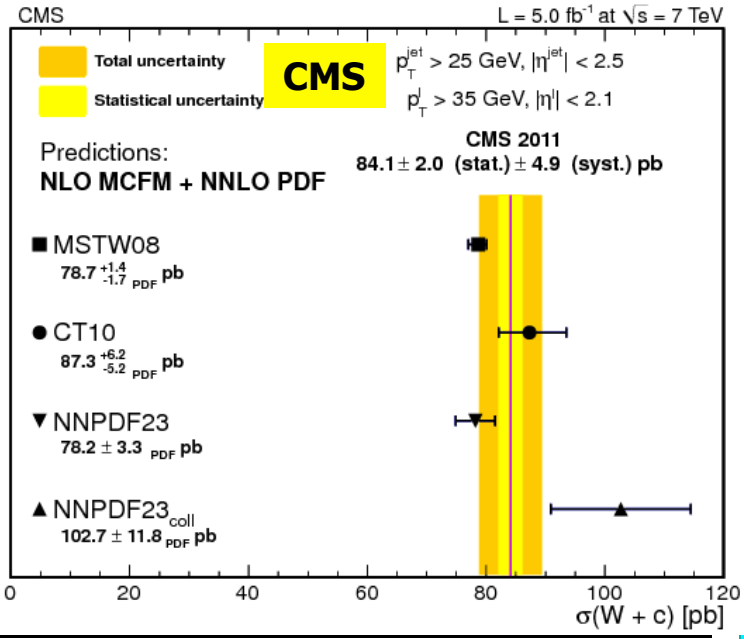
Measurements in agreement with theoretical predictions
- ATLAS: consistent with NLO within 1.5 σ

Wc (7 TeV)

- Sensitive to the **s-quark PDF** at momentum transfer ~M_W
- Six measurements:
  - **$W^{\pm}$ + c-jet, $W^{\pm}$ + D, $W^{\pm}$ + D***
  - CMS presents also results of their combination
- **Important strategy:**
  - Charge correlation between W and c => μ in c-jet and D/D* have a charge opposite (OS) to the W boson
  - **W + c yields = OS events — SS events (backgrounds)**

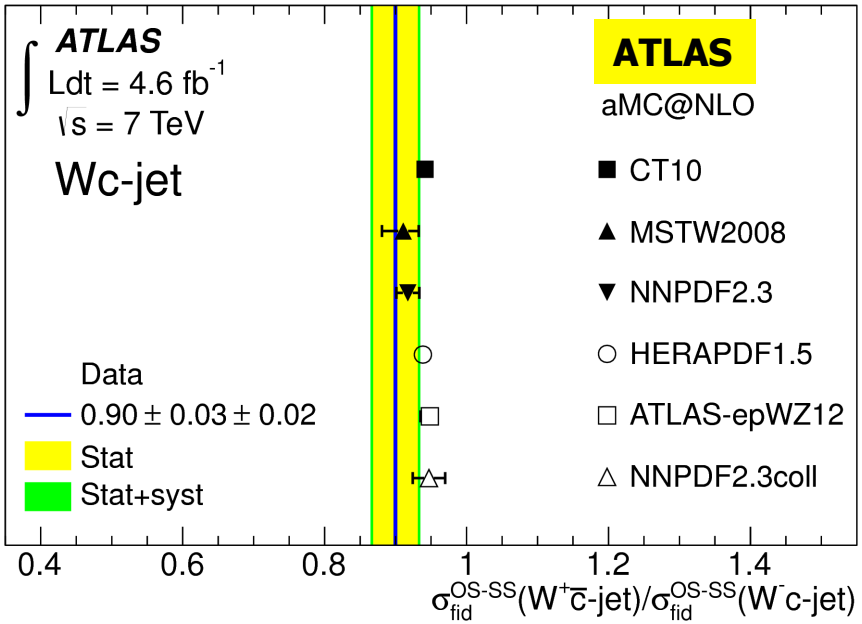


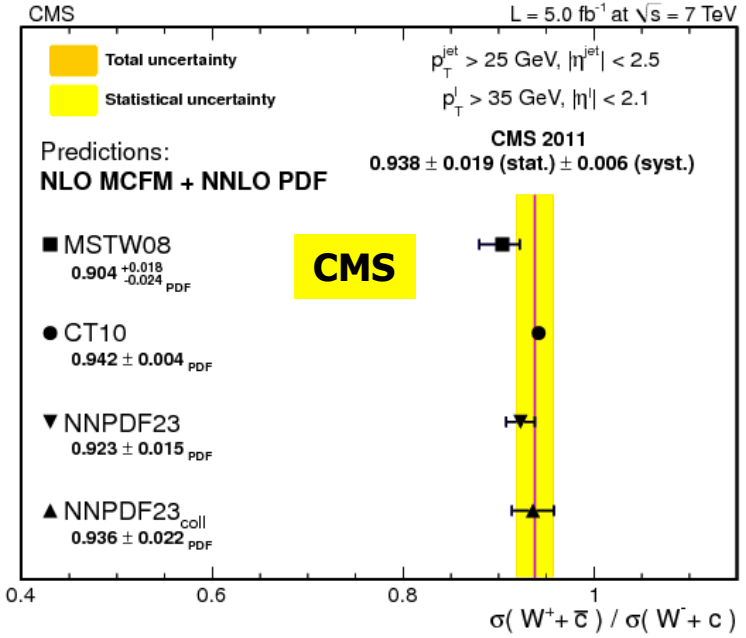




Wc (7 TeV)

- **Cross section ratio (W^+ + cbar) / (W^- + c)**
- The observed **W^- + c** yield slightly larger than the **W^+ + cbar**
  - dominance of the d-quark over the d-antiquark in the proton (as expected)





- Also measured:
  - Differential cross sections (W + c) vs. lepton | η |
  - The ratio (r_s) of the strange-to-down sea-quark distributions (symmetric light-quark sea) (ATLAS)

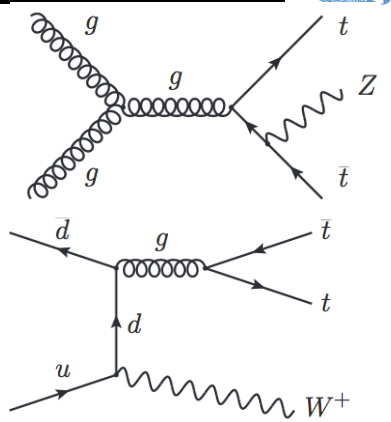
$$r_s \equiv 0.5(s+\bar{s})/\bar{d} = 0.96^{+0.26}_{-0.30}$$

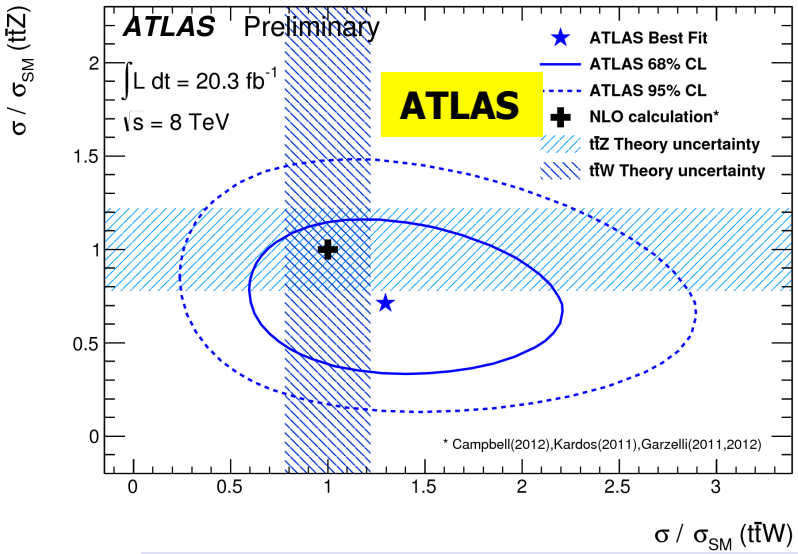
ttbarW, ttbarZ (8 TeV)

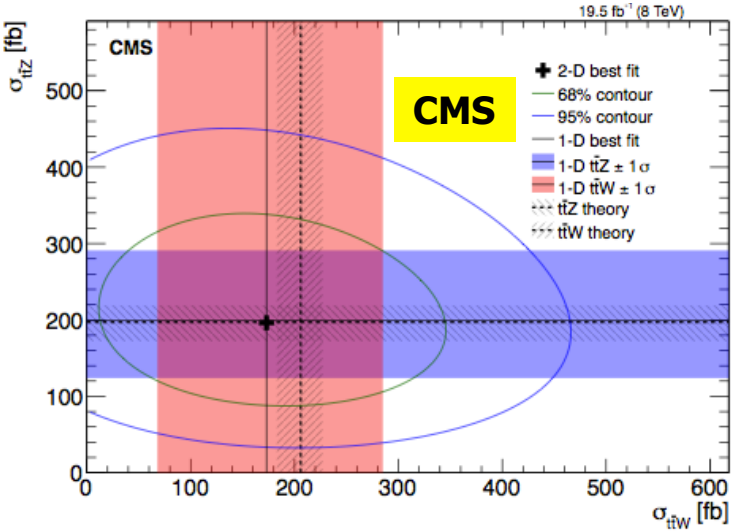
- **Three channels** considered:

ATLAS
- Same-sign **dimuon** (ttbarW)
- Trilepton (ttbarZ)
- Opp. Sign dilepton (ttbarW, ttbarZ)

CMS
- Same-sign dilepton (ttbarW)
- Trilepton (ttbarZ)
- Four-lepton (ttbarZ)







Results of the **combined simultaneous fit** for ttbarW and ttbarZ cross sections are **in agreement** with **NLO QCD predictions**:
- Campbell (2012), Kardos (2011) and Garzelli (2011,2012) for ATLAS
- MADGRAPH5_aMC@NLO for CMS (in agreement with those used by ATLAS)

Summary and Outlook

- **ATLAS and CMS excellent performance** allow the precise study of associated vector boson production
- A **hot topic** for theoretical studies for several years can be finally exploited with high precision experimental measurements!
- Several results for **7 TeV (2011)** and **8 TeV (2012)** were presented
  - Overall good agreement with theory predictions; some discrepancies exist
- Many **8 TeV (2012)** measurements are in progress
- **Important feedback** to theorists and our understanding of QCD and electroweak processes in the high energy LHC regime

Looking forward for more precise measurements next year at 13 TeV!

BACKUP

Total Integrated Luminosity in 2011 and 2012

- Excellent performance by both detectors
- Utilize most of the LHC delivered luminosity