QCD Studies at ATLAS

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on behalf of the ATLAS collaboration

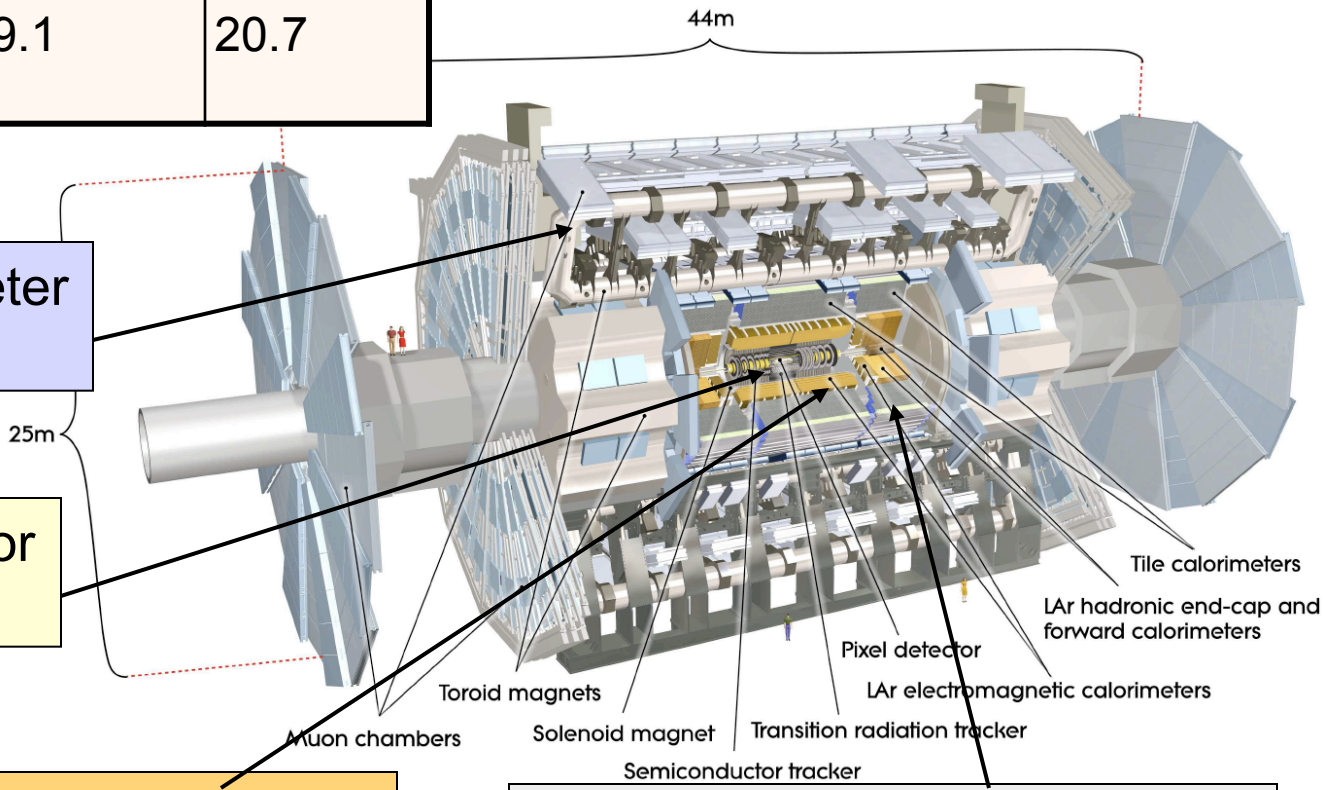
Outline

- ATLAS and Run 1 operation
- QCD Physics Results
  - Soft QCD
  - Jets
  - W/Z+jets
  - Photons
- Summary

- Disclaimer: I can only show some select recent examples but not the full wealth of the ATLAS QCD results
- All public results can be found here
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

The ATLAS Detector and Run 1 operation

Run 1	2010	2011	2012
cms energy	7 TeV	7 TeV	8 TeV
ATLAS record-ed int. lumi	45 pb^{-1}	5.25 fb^{-1}	21.3 fb^{-1}
<interactions> / bunch cross.	~2	9.1	20.7



Muon Spectrometer ($|\eta|<2.7$)

Tracking Detector ($|\eta| < 2.5$)

Electro-magnetic calorimeter ($|\eta|<3.2$ with fine granularity in $|\eta| < 2.5$)

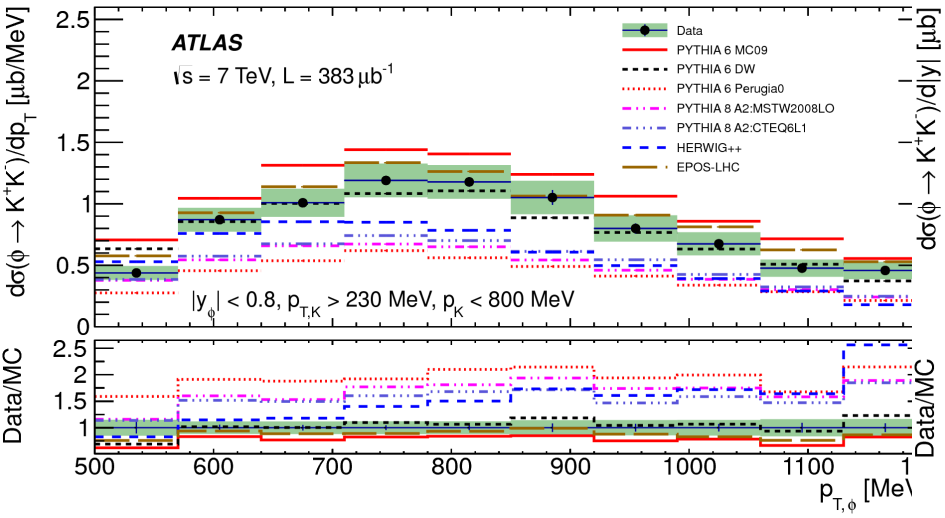
Hadronic calorimeter ($|\eta|<4.9$)

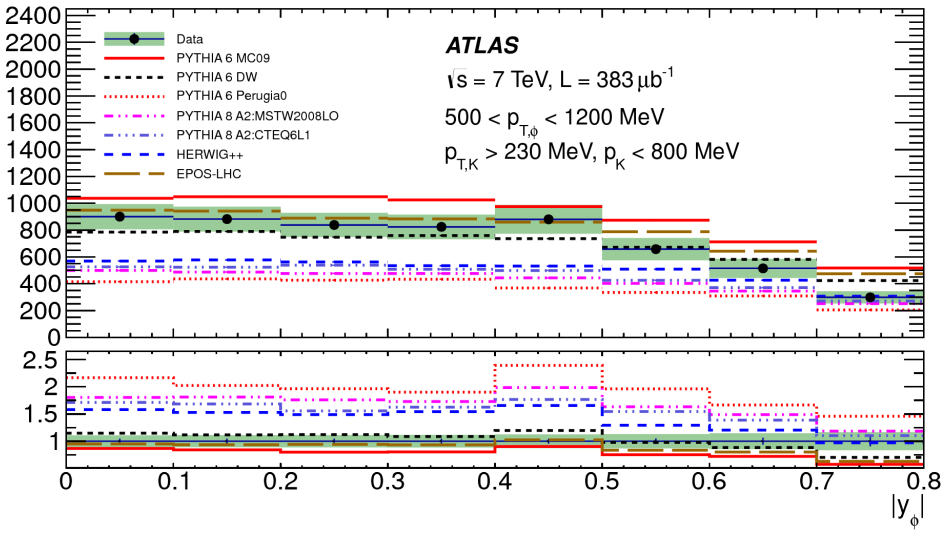
Soft QCD

- Cross section of Φ(1020) (2010 data)

Cross section of Φ(1020)

- Measure cross section of $\Phi \rightarrow K^+K^-$ in minimum bias events
  - Select tracks with p_T > 150 MeV, p < 800 MeV in |η| < 2.0
  - Identify K's via dE/dx in pixel detector





- Discriminating power among MC models
  - Data best described by Pythia6 tune DW and EPOS-LHC
- More details in
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2011-47/

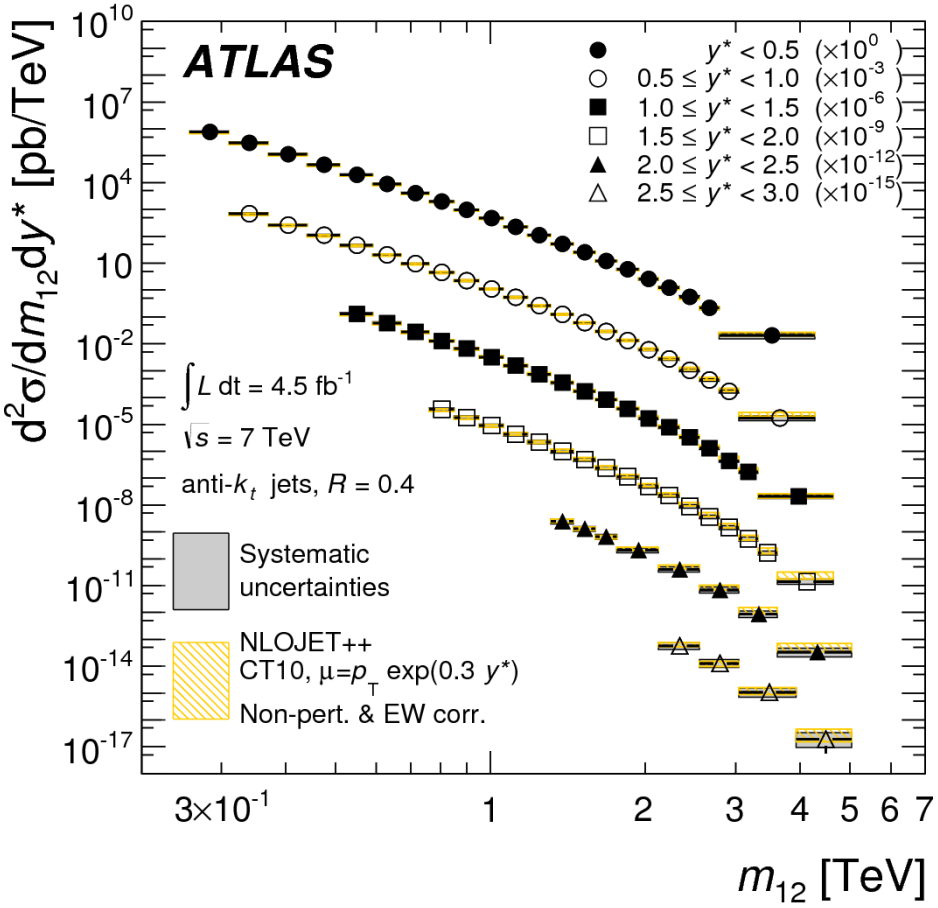
Jet Physics

- Dijet cross section (2011 data)
- Multijet cross section (2010 data)

Dijet cross section

Submitted to JHEP
arXiv:1312.3524

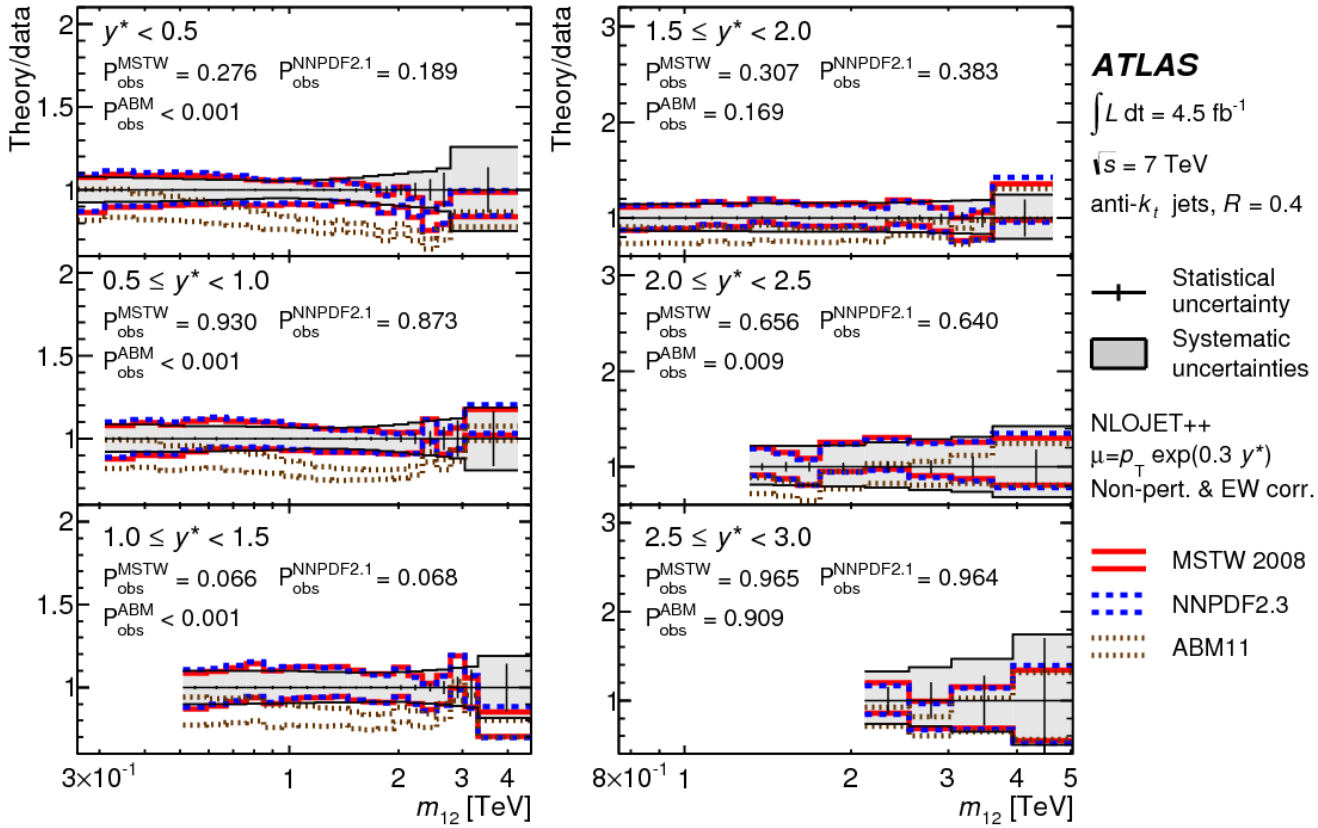
- Update of 2010 analysis using 4.5 fb^{-1} (2011 data)
  - ⊕ >100 times the 2010 statistics (Eur. Phys. C71)
  - ⊕ Better jet energy calibration
  - ⊖ More pileup
  - → Smaller syst uncertainty
- Default jet algorithm: anti-k_T with R=0.4, 0.6
- Measure cross section as a function of dijet mass and $y^*=|y_1-y_2|/2$
- biggest uncertainty from JES



Dijet cross section

Submitted to JHEP
arXiv:1312.3524

- Ratio NLO QCD / data



- Agreement with NLO prediction within uncertainties for MSTW 2008, NNPDF2.3 but not for ABM11
- Improved measurement of high mass region can be used to constrain PDF at high momentum fraction

Multi-jet cross sections and α_s

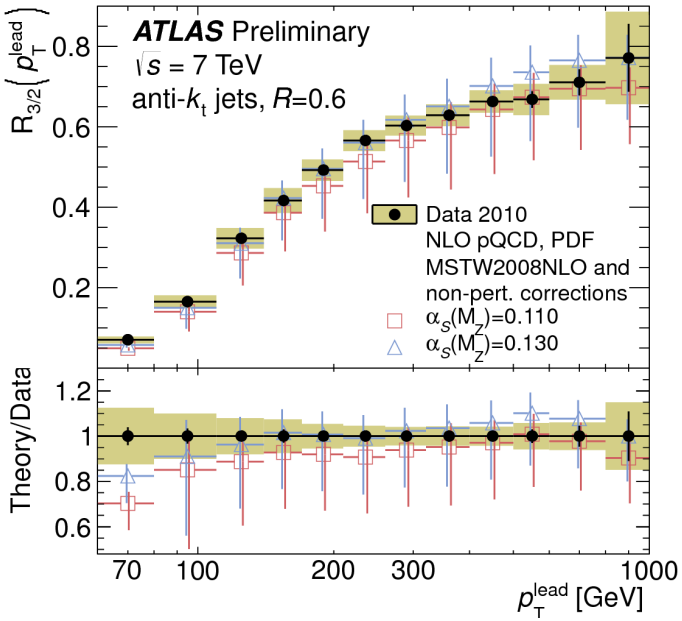
ATLAS-CONF-2013-041
Data 2010

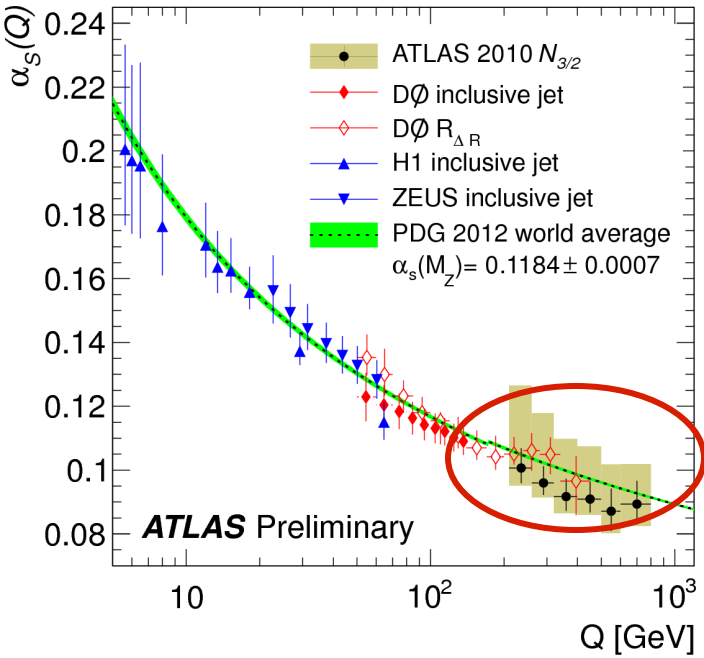
- Select jets with anti-k_T with R=0.6
  - p_T>40GeV, |y|<2.8, p_T^{lead} > 60 GeV
- Measure

$$R_{3/2}(p_T^{lead}) = \frac{d\sigma_{N_{jet}\geq 3}/dp_T^{lead}}{d\sigma_{N_{jet}\geq 2}/dp_T^{lead}}$$

$$N_{3/2}(p_T^{(all\ jets)}) = \frac{\sum_i^{N_{jet}} \left(d\sigma_{N_{jet}\geq 3}/dp_{T,i}\right)}{\sum_i^{N_{jet}} \left(d\sigma_{N_{jet}\geq 2}/dp_{T,i}\right)}$$

- NLO pQCD description good for p_T^{lead}>140GeV
- $R_{3/2}$, $N_{3/2}$ proportional to α_s
  - Extract using $N_{3/2}$ as less sensitive to choice of renormalisation and factorisation scale
  - Use 210 < $p_T^{(all\ jets)}$ < 800 GeV
  - $\alpha_s(M_Z) = 0.111 \pm 0.006\ (\text{exp.})^{+0.016}_{-0.003}\ (\text{th.})$
  - Consistent with world average and renormalisation group equation (RGE)

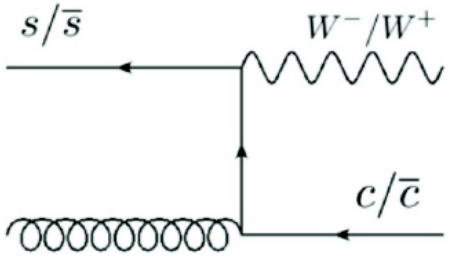




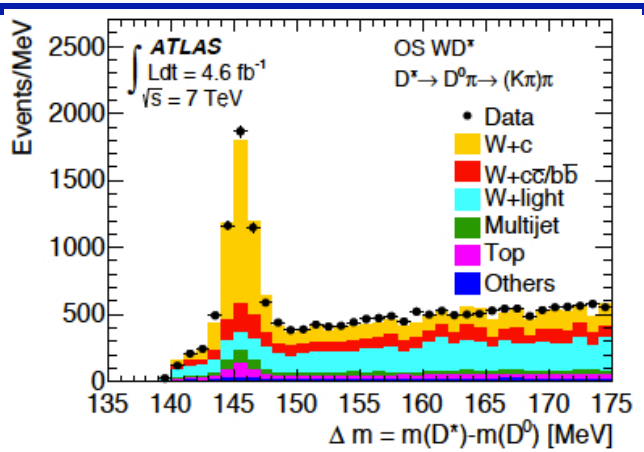
W/Z + jets Physics

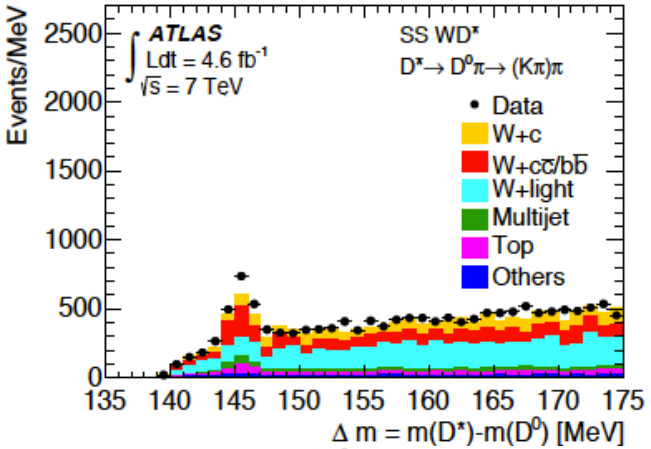
- W+charm production (2011 data)

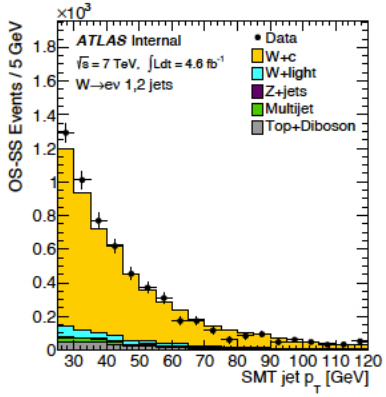
W+charm production



- Sensitive to strange PDF and $s/\bar{s}$ asymmetry
  - Mixed results from other experiments
- Selection
  - W identified via $W \to e\nu$, $W \to \mu\nu$
  - Charm tagged by
    - full reconstruction of $D^{(*)}$ decays
      - $D^+ \to K^- \pi^+ \pi^+$
      - $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi$ $D^0 \to K^-\pi^+\pi^-\pi^+$
    - Soft muon from semileptonic decay inside jet
- Use charge correlation between W and $c/D^{(*)}$
  - opposite – same sign events (OS-SS)

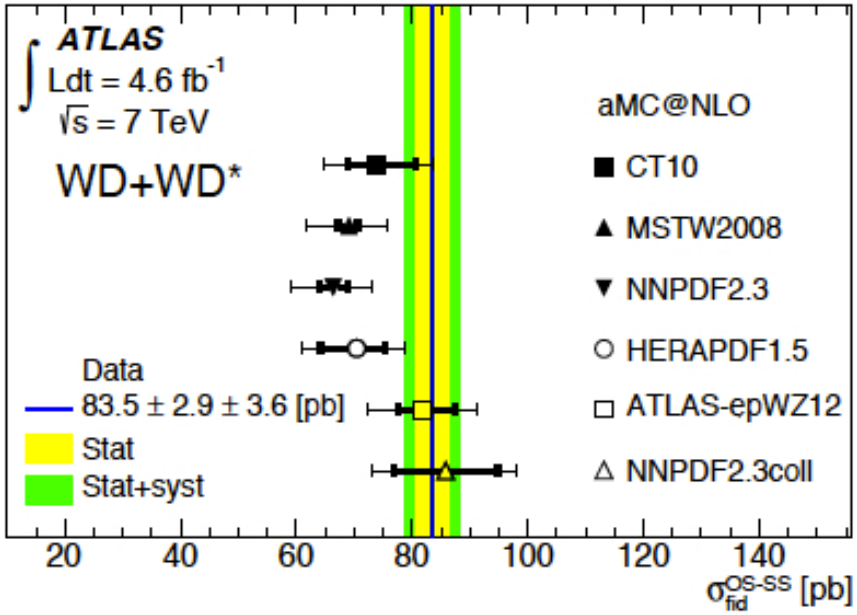




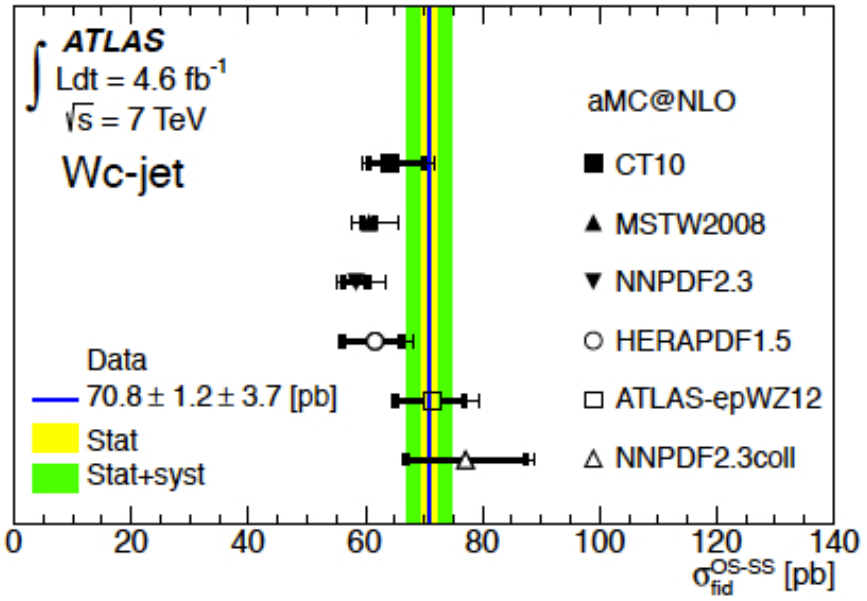


W+charm production

Error ~2x smaller than previous results in conference note



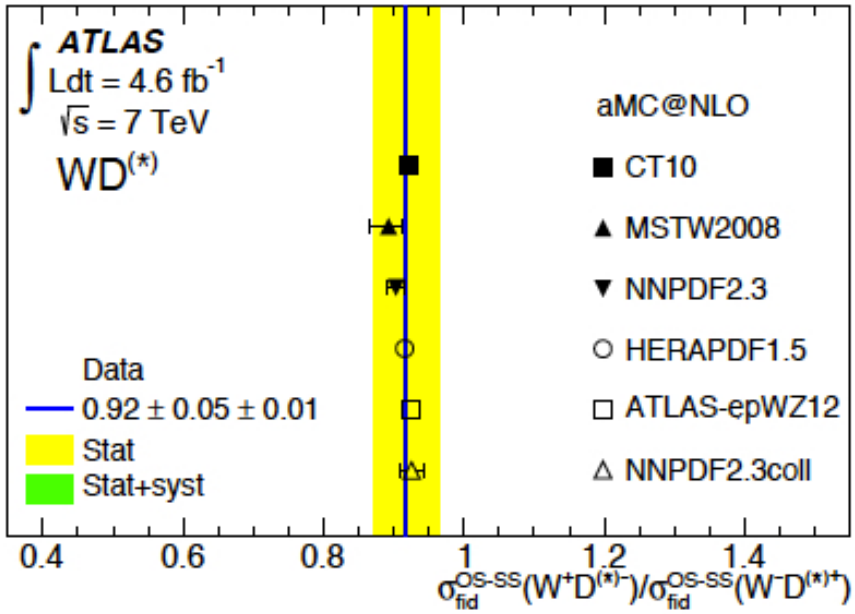
New Result

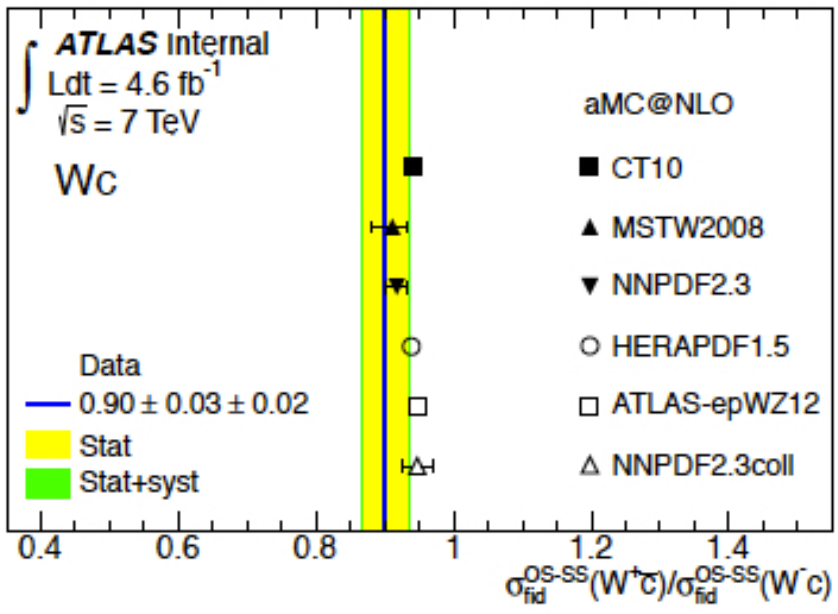


- Cross section depends on PDF
  - s-quark enhanced PDF are favoured (as in NNPDF2.3coll)
  - Corroborate preference for SU(3) symmetric sea (as in epWZ which includes ATLAS 2010 W and Z cross section data)

W+charm production

- Measure ratio W^++c/W^-+c
  - <1 due to d-valence quarks
- Deviation of predicted value might be due to strange sea asymmetry

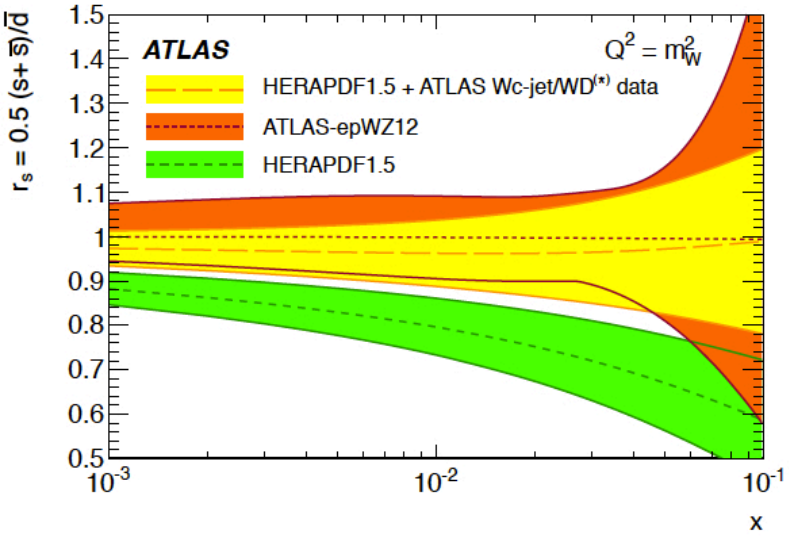




- Take CT10 prediction (no asymmetry) and get estimate of sensitivity
  - $A_{s\bar{s}} = \frac{< s(x,Q^2) > - < \bar{s}(x,Q^2) >}{< s(x,Q^2) >} \approx R_c^{\pm}(\mathrm{CT10}) - R_c^{\pm}(\mathrm{Data})$ = (3±2)%

W+charm production

- Vary strange quark density in HERA PDF
  - Just one single parameter
- Free fit of strange to down sea content of proton
  - $r_s \equiv 0.5(s+\bar{s})/\bar{d} = f_s/(1-f_s) = 0.96\,^{+0.16\,+0.21}_{-0.18\,-0.24}$ at $Q^2 = 1.9$ GeV^2



- Light quark sea symmetric over whole x range
- Consistent with ATLAS-epWZ
- More details in
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-14/

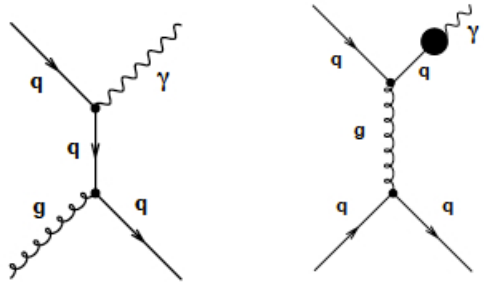
Photon Physics

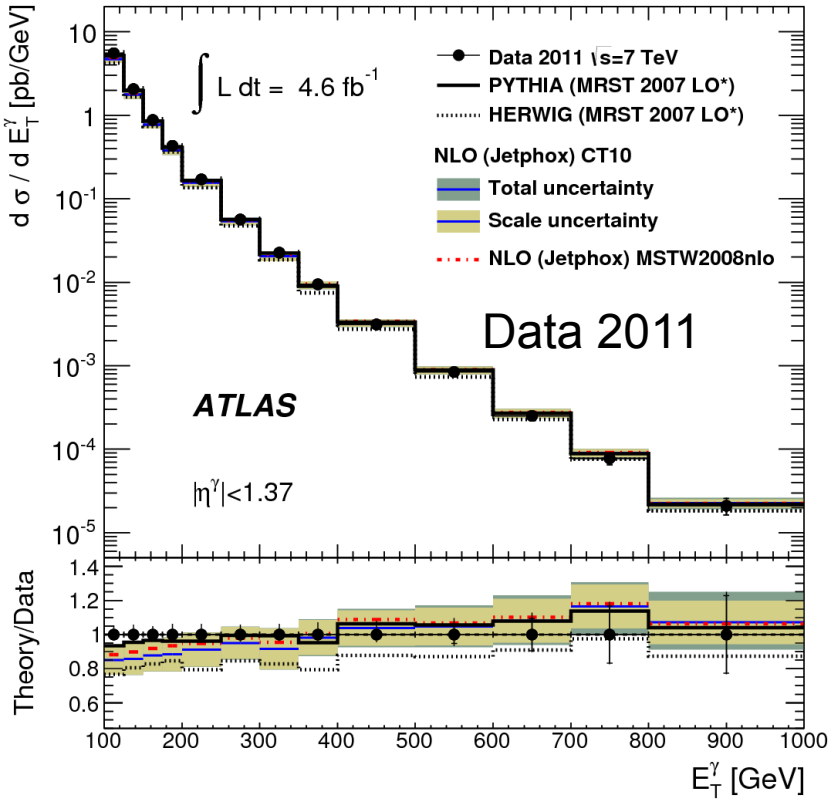
- Inclusive isolated prompt photon cross section (2011 data)
- Dynamics of Photon + Jet production (2010 data)

Incl. isolated prompt photon cross section

Accepted by PRD
arXiv:1311.1440

- Prompt γ = direct γ + γ from fragmentation
- Analysis updated using 2011 data
  - > 100 × 2010 statistics
  - Select events with γ's with E_T > 100 GeV and $E_T^{iso}(R=0.4)$ < 7 GeV
- Comparison with predictions
  - Good agreement for NLO predictions
    - Data a bit higher for E_T<200 GeV but within uncertainties
    - Fragmentation contributes to the shape of $d\sigma/dE_T^{\gamma}$ at lower E_T
  - LO parton shower MCs
    - Pythia describes data well
    - Herwig σ 10-20% lower than data
  - Potential to constrain shape and uncertainty of gluon PDF in 0.03 < x < 0.3 (ATL-PHYS-PUB-2013-018)

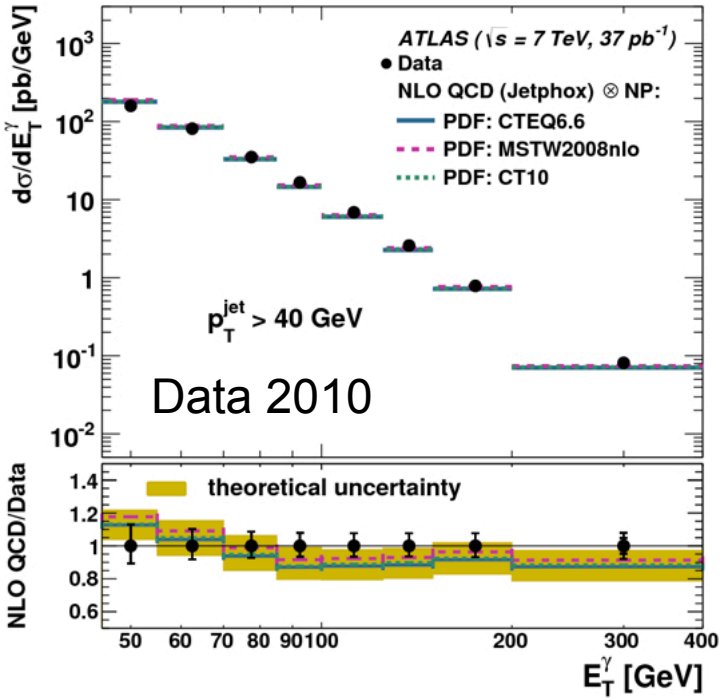




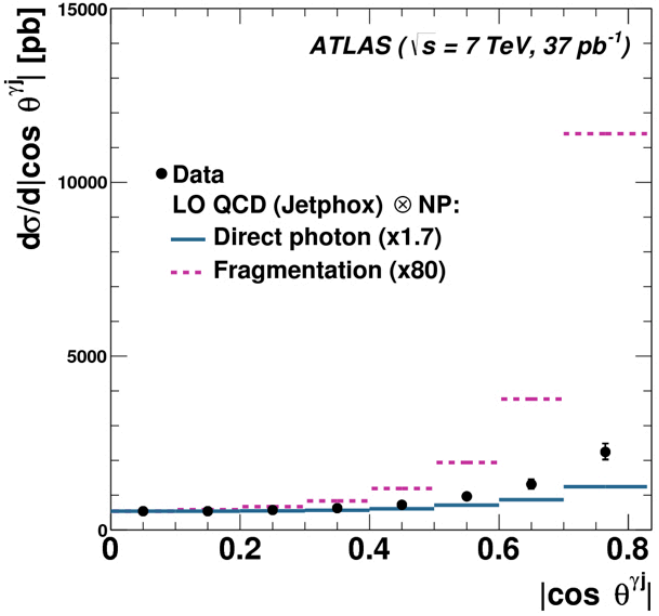
Dynamics of Photon + Jet production

Nucl. Phys. B875 (2013) 483-535

- Good test of pQCD (cleaner environment than jets)
  - Measure cross section as functions of E_T^{γ}, p_T^{j}, $|y^{j}|$, $\Delta\Phi^{\gamma j}$, $m^{\gamma j}$, $\cos\Theta^{\gamma j}$
  - Good agreement with Jetphox NLO predictions



- Excellent probe of dynamics of hard scattering process
  - $\cos\Theta^{\gamma j} = \tanh(dy^{\gamma j}/2)$ sensitive to quark or gluon exchange in $2 \rightarrow 2$ process
  - Quark exchange dominant
  - Good sensitivity to fragmentation contribution



Summary and Outlook

- Significant ongoing effort to better understand QCD effects
- Results show
  - Data and pQCD predictions in general show good agreement
  - Some MC tunes and PDFs are now disfavoured
  - Lots of new input for PDF tunes from jet, photon and W/Z measurements
  - Better understanding of QCD effects and backgrounds to new physics

- 8 TeV analyses ongoing, so expect new results soon!

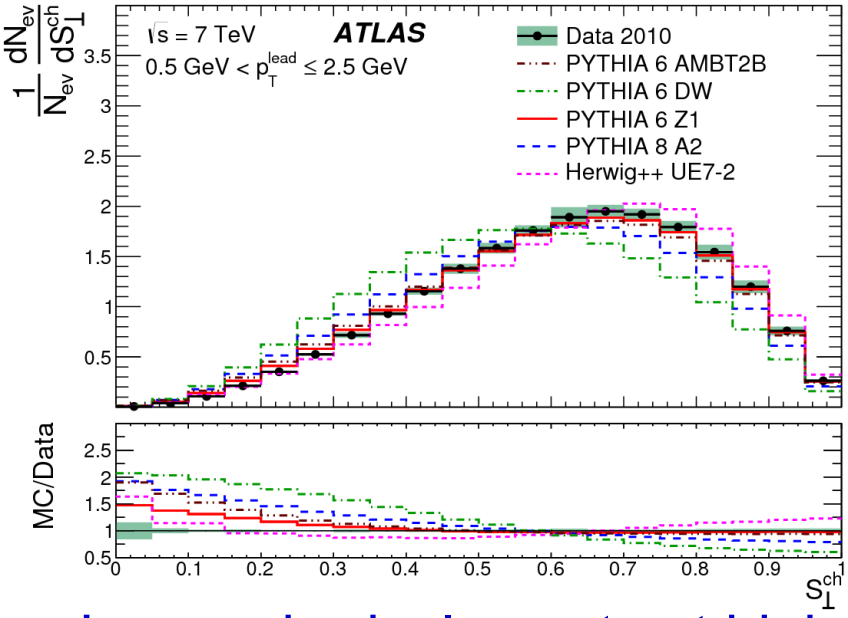
Backup

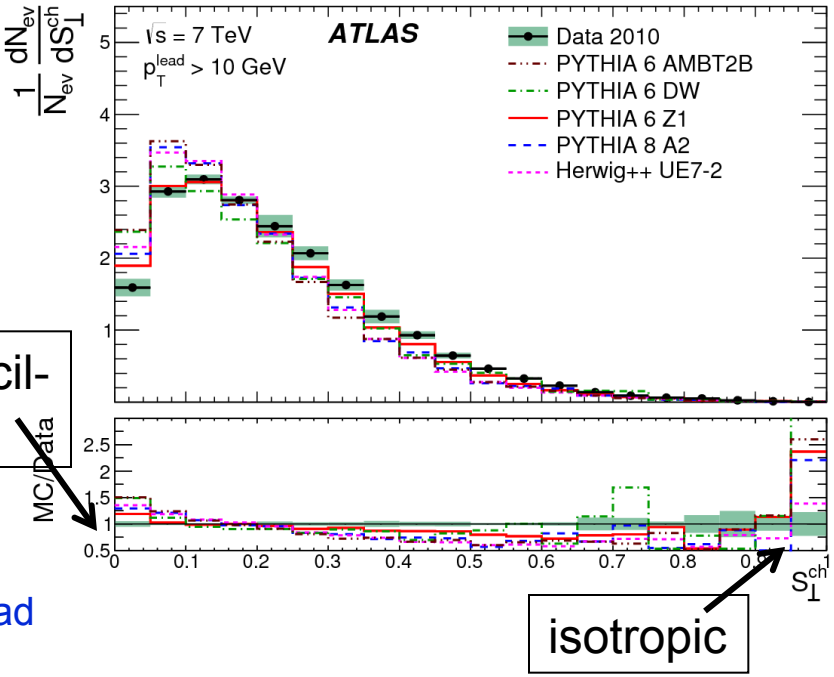
Event shapes in underlying event

Phys. Rev. D88 (2013) 032004
2010 data

- Motivation
  - More accurate phenomenological modeling of soft and semi-hard multi parton interactions
- Select min bias events: ≥ 6 ch. particles with p_T>0.5 GeV, |η|<2.5
- Look at thrust and sphericity:
  - $1/N_{ev}\ dN_{ev}/dT_{\perp}^{ch}$, $1/N_{ev}\ dN_{ev}/dT_{M}^{ch}$, $1/N_{ev}\ dN_{ev}/dS_{\perp}^{ch}$

$$S^{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{x,i}p_{y,i} & p_{y,i}^2 \end{bmatrix}$$



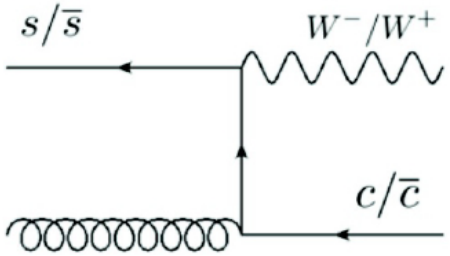


"pencil-like"

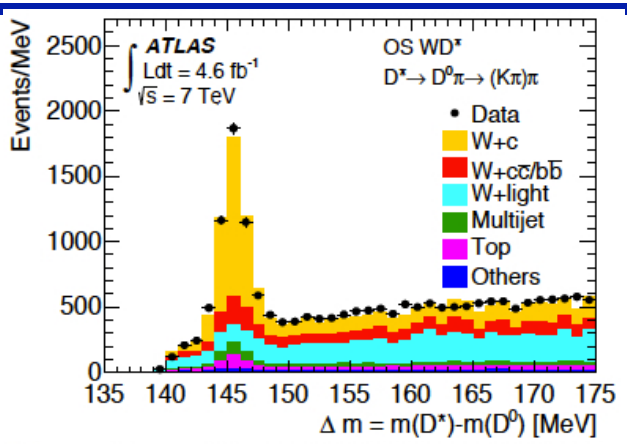
isotropic

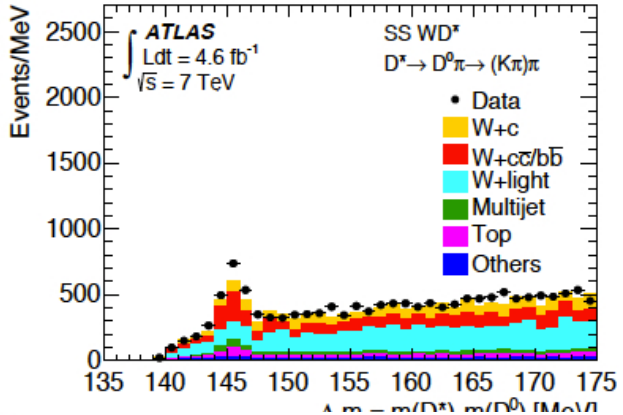
- Less spherical events at higher p_T^{lead}
- PYTHIA6 tune Z1 (tuned to the LHC's UE distributions) closest to data

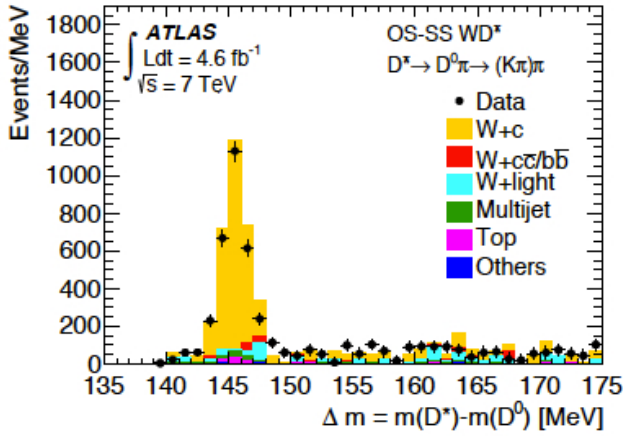
W+charm production



- Selection
  - W via semileptonic decays
  - Charm tagged by
    - full reconstruction of $D^{(*)}$ decays
      - $D^+ \rightarrow K^- \pi^+ \pi^+$
      - $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^0$, $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
      - $D^{*+} \rightarrow D^0\pi^+$
- Use charge correlation between W and $c/D^{(*)}$
  - opp. – same sign events (OS-SS)

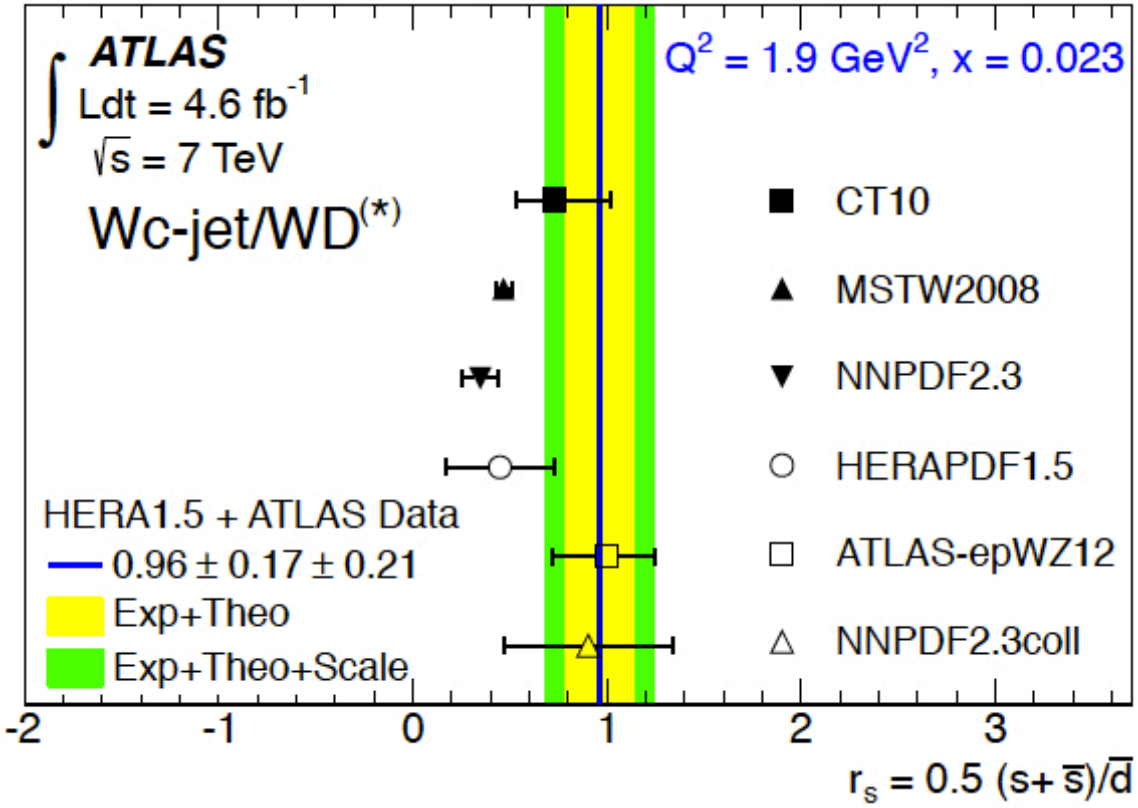






W+charm production

Sea strange quark asymmetry

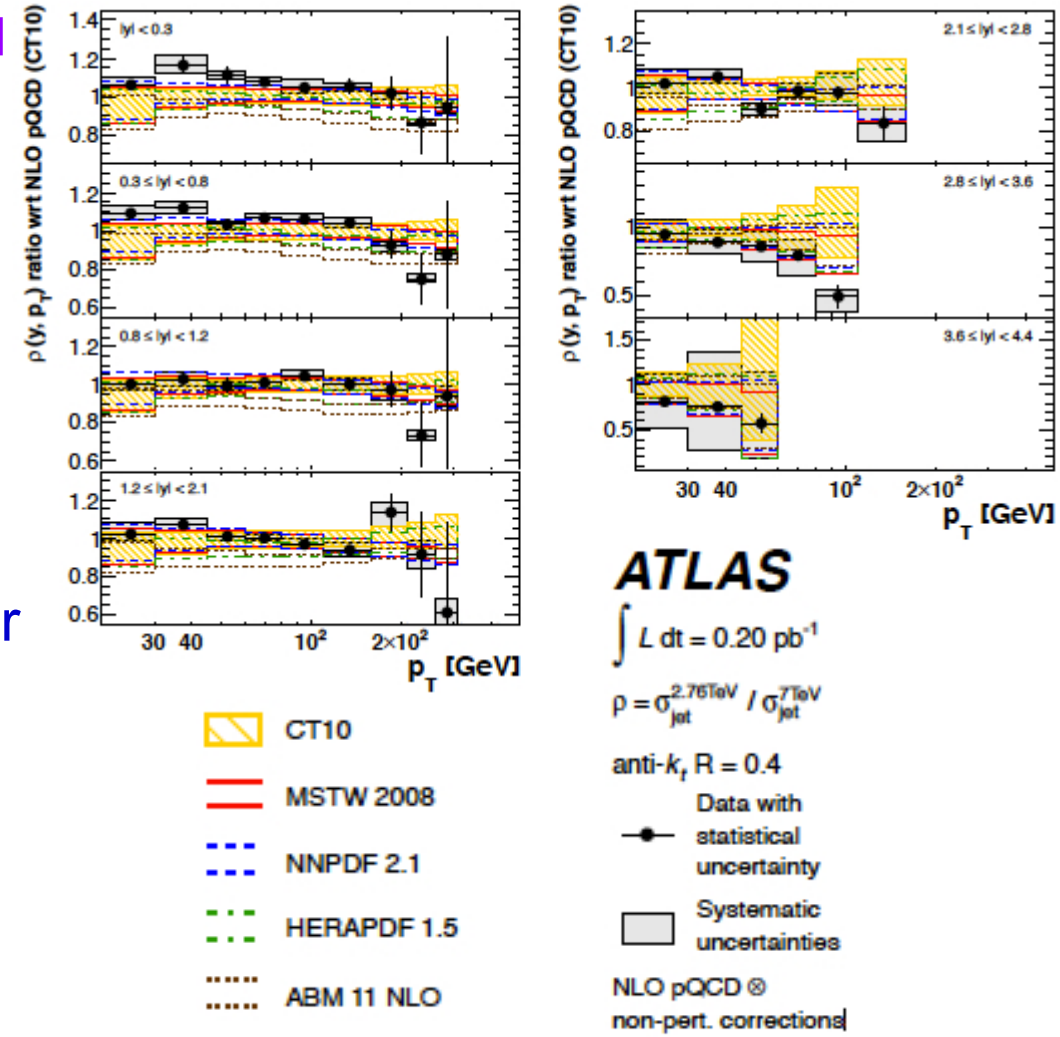


Eur. Phys. J. C 73 (2013) 2509

Inclusive jet production at √s=7 TeV and 2.76 TeV

- Use cross section ratio at 2.76 and 7TeV (2011/2010 data)
  - Advantage: many correlated systematics cancel!
- Compare with pQCD predictions using NLOjet++
  - Data above predictions in central region
  - Data below predictions in forward region
- Syst. uncert generally smaller than theory uncertainties
  - Means to constrain PDFs

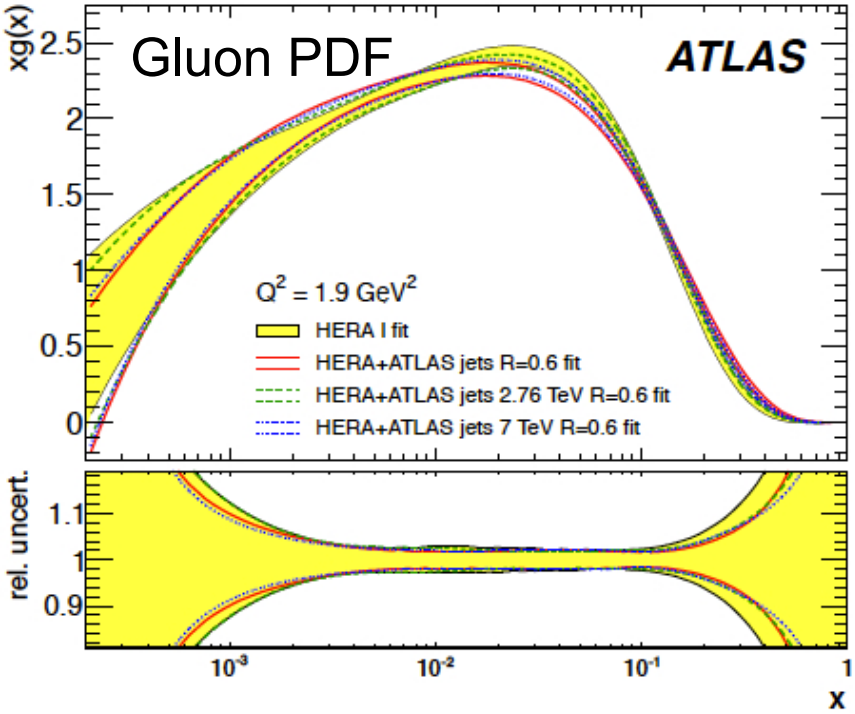
Ratio σ(2.76 TeV)/σ(7TeV) divided by NLOjet++ using CT10

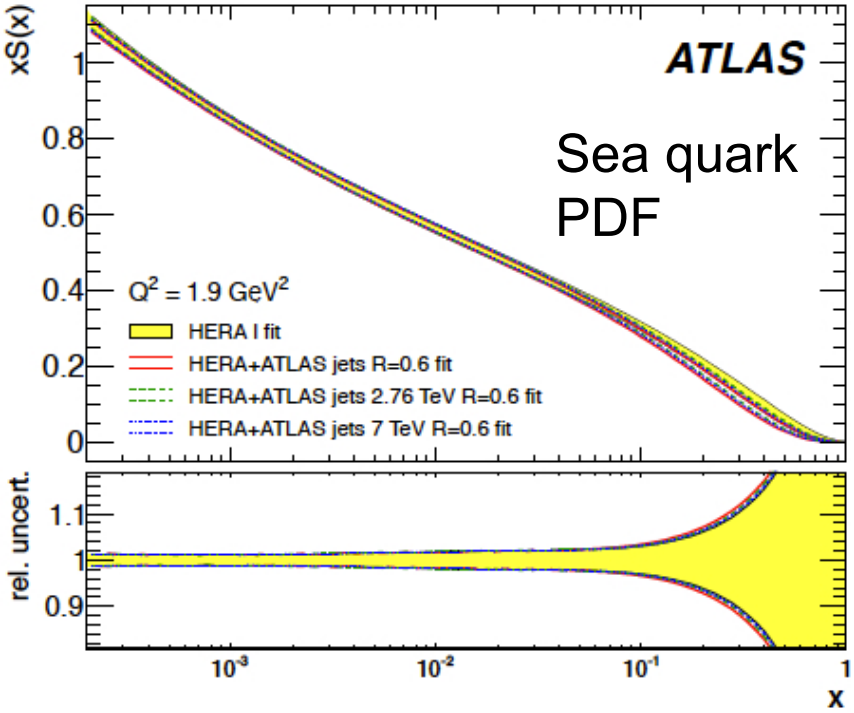


Eur. Phys. J. C 73 (2013) 2509

Inclusive jet production at √s=7 TeV and 2.76 TeV

- HERA data constrains well distributions for x<0.01





- Combined fit using HERA-1 and ATLAS data lead to improved shape constraints
  - Gluon PDF tends to be harder
  - Sea-quark PDF tends to be softer