# Recent QCD Results from ATLAS at the LHC

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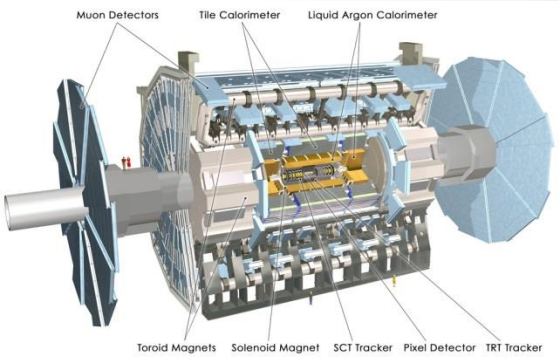
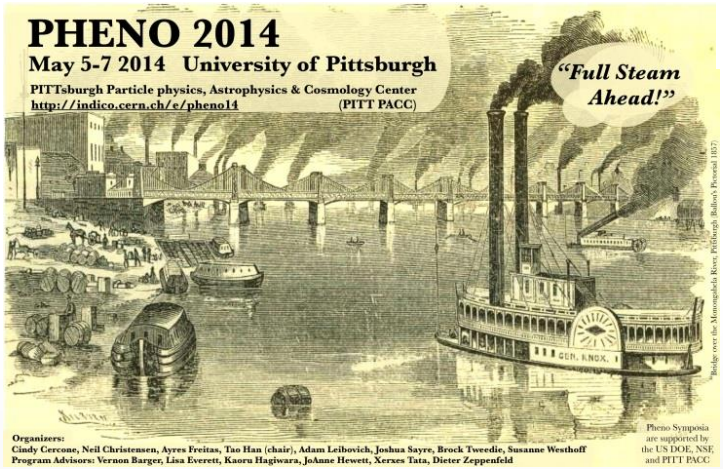
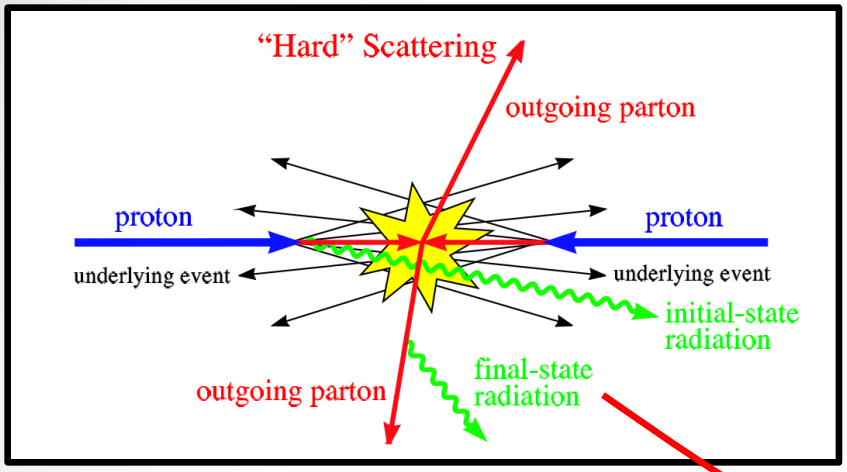
for the ATLAS Collaboration



# QCD in p-p collisions

***A proton-proton collision is:***




I. Soft processes
- Underlying Event (UE)
  - Spectator partons fragments
  - Initial/Final State Radiation(ISR/FSR)
  - MultiPartonInteraction(MPI)

II. Hard processes

$$\sigma_{pp\to X} = \sum_{ijk} \underbrace{f_i(\mu^2) \otimes f_j(\mu^2)}_{\text{PDFs}} \otimes \underbrace{\hat{\sigma}_{ij\to k}\left(\alpha_s(\mu^2), Q^2, \mu^2\right)}_{\text{Matrix element}}$$

I. Non perturbative effects of QCD
- Experimental measurements used to improve the phenomenological modeling of soft QCD (jets measurements, vector meson production)

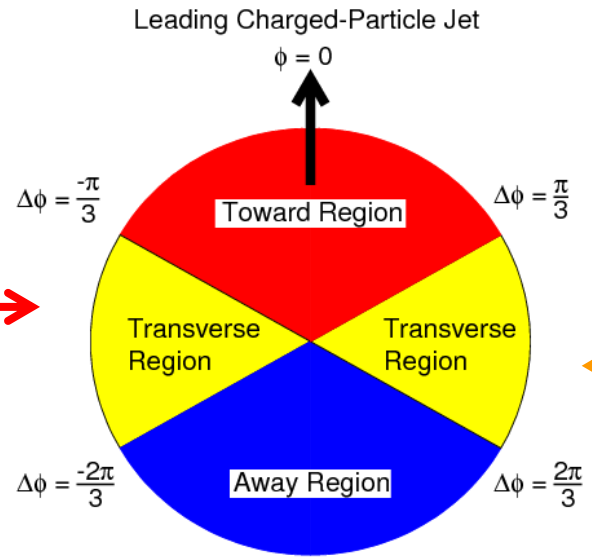
II. Predicted through perturbative calculations
- Experimental measurements test the higher order theoretical predictions
- Additional constraints on Parton Distribution Functions (PDF)s (jets and photons cross section measurements)

# Soft QCD

# Underlying Event

**UE is irreducible background for precision and new physics measurements**

**Looking to the particles energy densities in the azimuth plane**



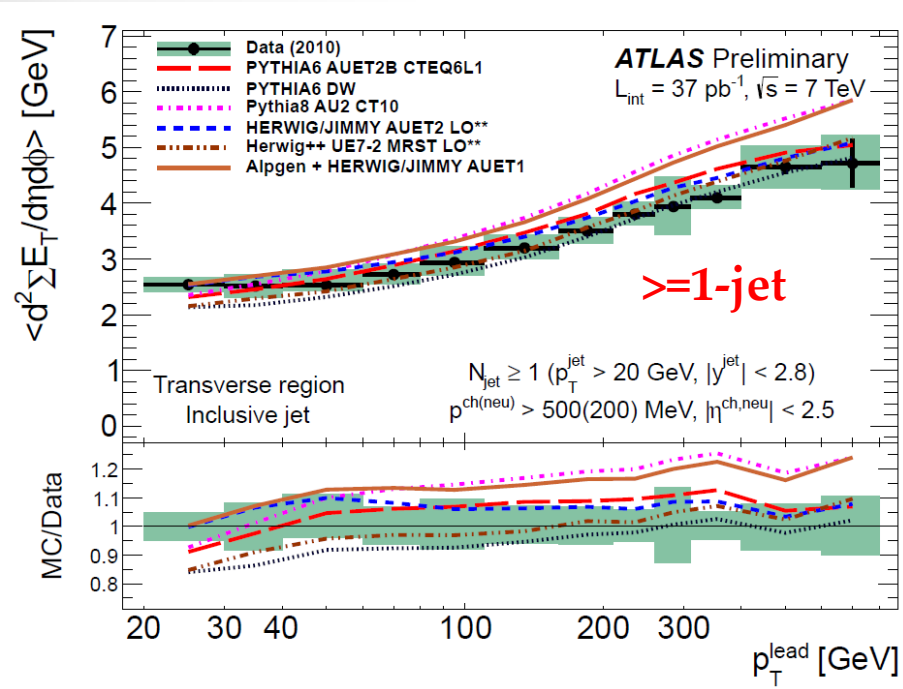

- Study performed in the transverse region that is most sensitive to the UE
- Studying for ex. $\sum E_T, N_{p^{\pm}}, \sum p_T$ as a function of leading object $p_T$
  - Trans(max/min) observables : max/min $\sum E_T$, on event by event basis

# Underlying Event

ATLAS-CONF-2012-164

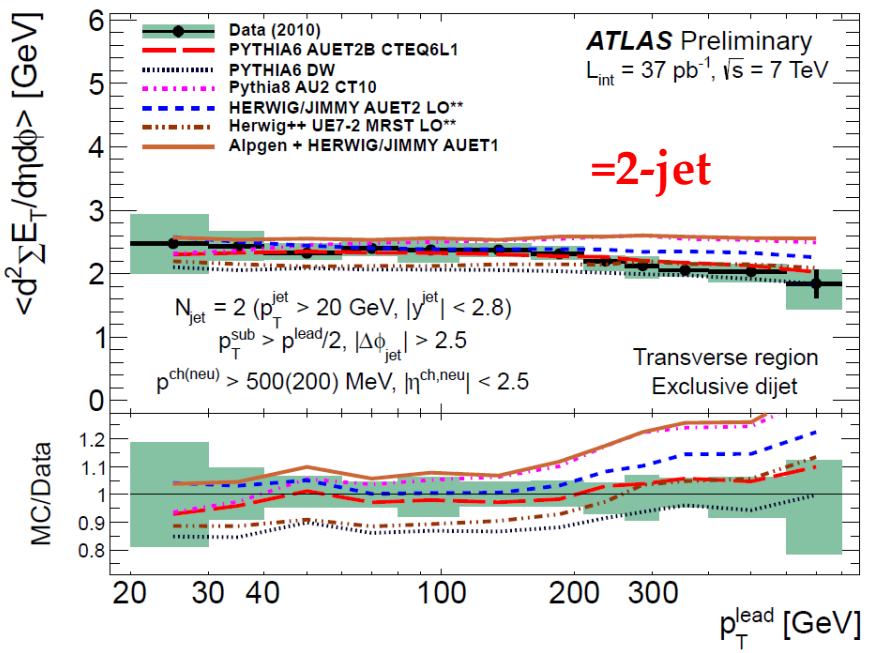
Selections:

- 1-jet: $p_T$>20 GeV, |y|<2.8 or 2-jet: $p_T^{sub}/p_T^{lead}$ > 0.5 and |Δφ|> 2.5 (back-to-back jets)
- leading jet $p_T$: inversely proportional to impact parameter




high $p_T^{lead}$: increase from wide-angle emission of the hard scatter

**best description: Herwig++**




Remove the wide-angle emissions

- Flat or falling with ↗ $p_T^{lead}$
- MPI modeling independent of hard process scale (central collisions)

**best description: Pythia6 AUET2B**

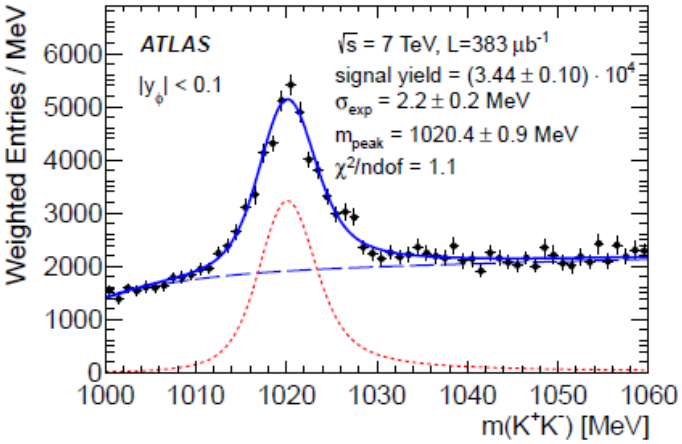
- Measurement going to larger η: larger deviations from MC ➔ tune

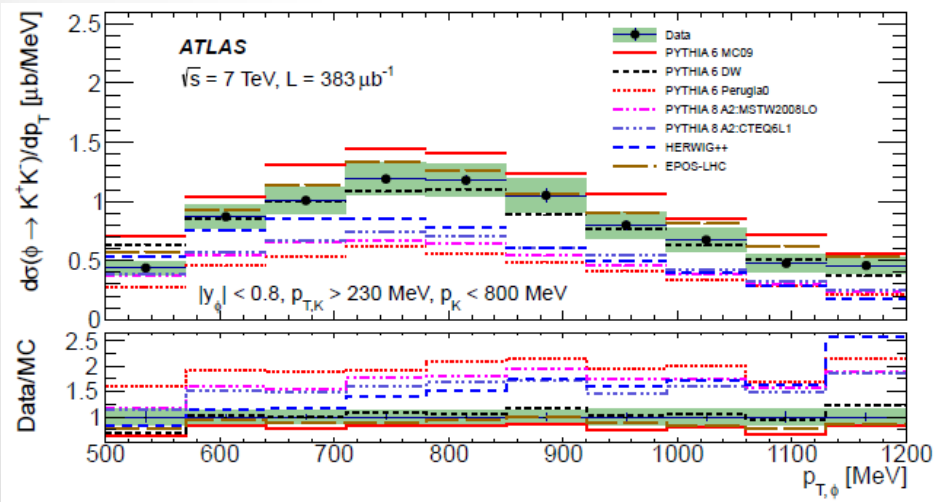
# Φ(1020)-meson production cross section

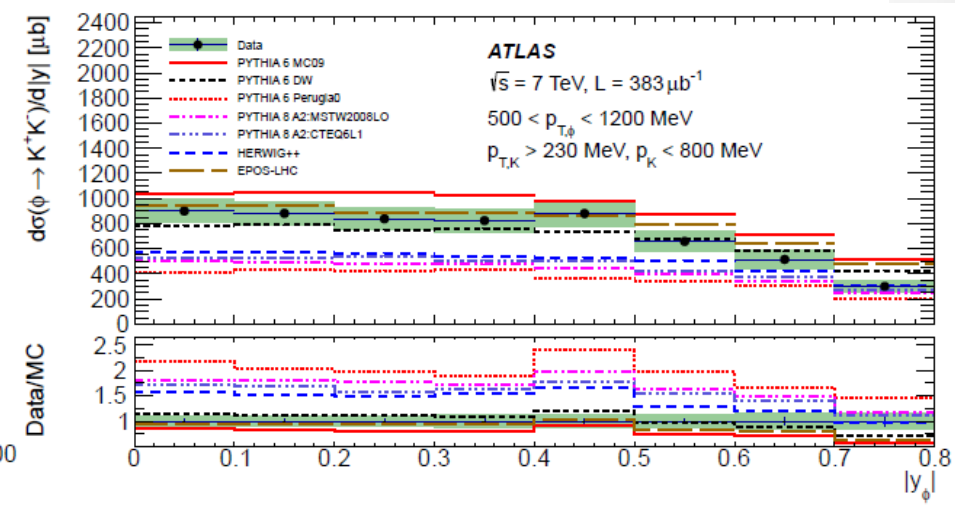
Cross section measured in $\Phi \rightarrow K^+K^-$ minimum bias events

submitted to EPJC
arXiv:1402.6162

- Probe the strangeness production and hadronization models at a scale of ~ 1GeV
- Kaons identification: energy deposited in the pixel




- Pythia 6 DW &EPOS-LHC tunes closer to data
  - Discriminating power between generator tunes
    - ➢ Inputs for tuning MC generators

# Hard QCD

# Inclusive Jets cross section

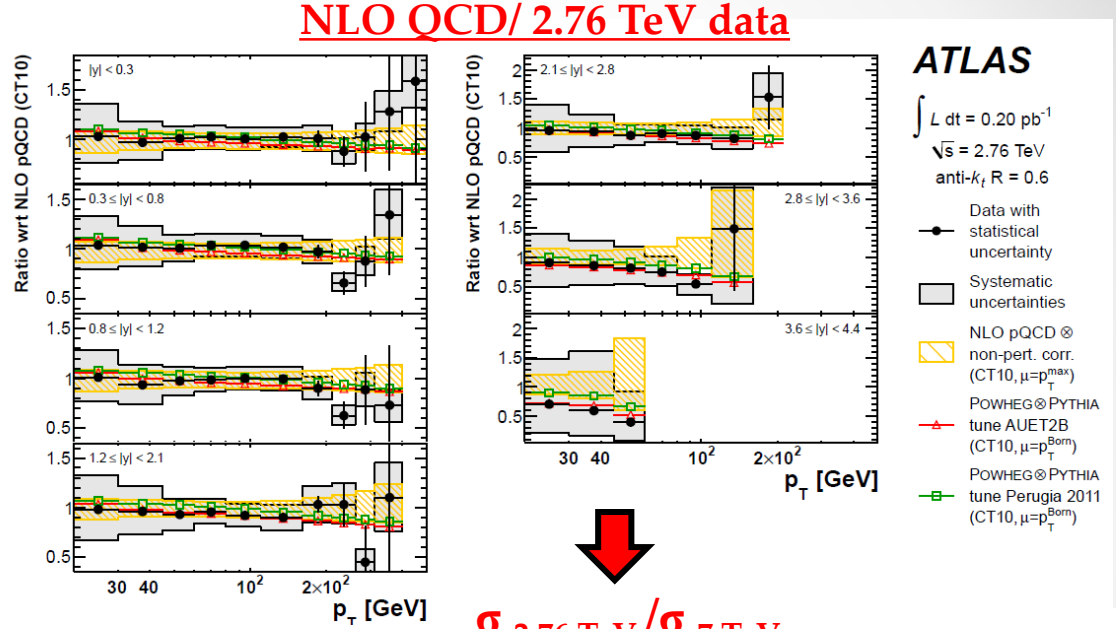
EPJ C73 (2013) 2509

New measurement at 2.76 TeV with 0.20 $pb^{-1}$

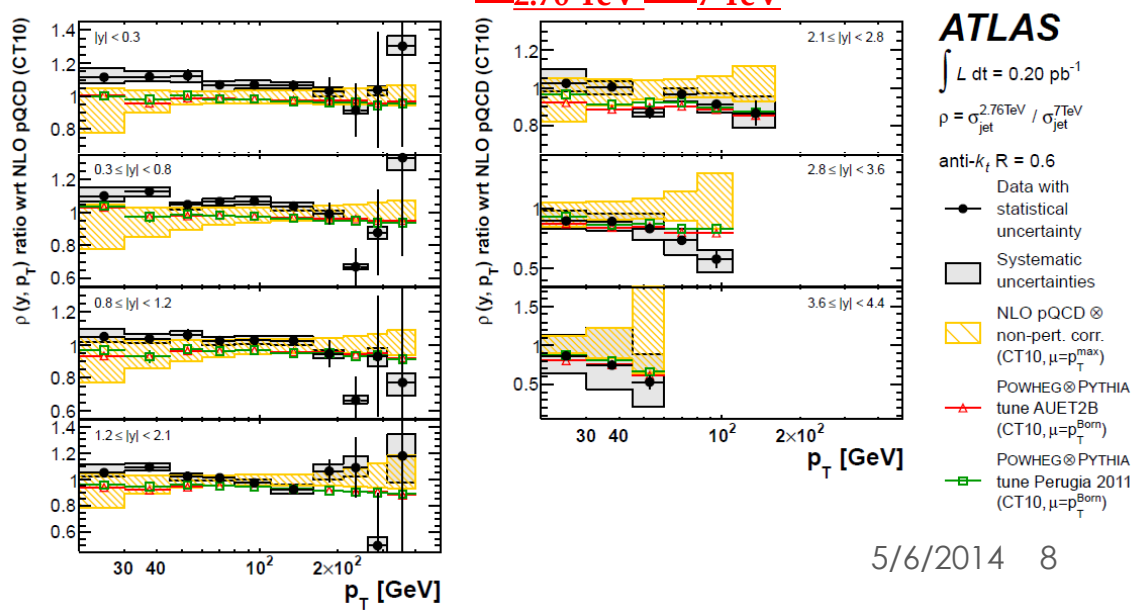
- Main experimental systematic uncertainty is JES
- NLOjet++ describes the data well
  - Corrected for non perturbative effects

**Reduction of correlated uncertainties in the ratio with 7 TeV data**

NLO QCD/ 2.76 TeV data




$\sigma_{2.76\ TeV} / \sigma_{7\ TeV}$



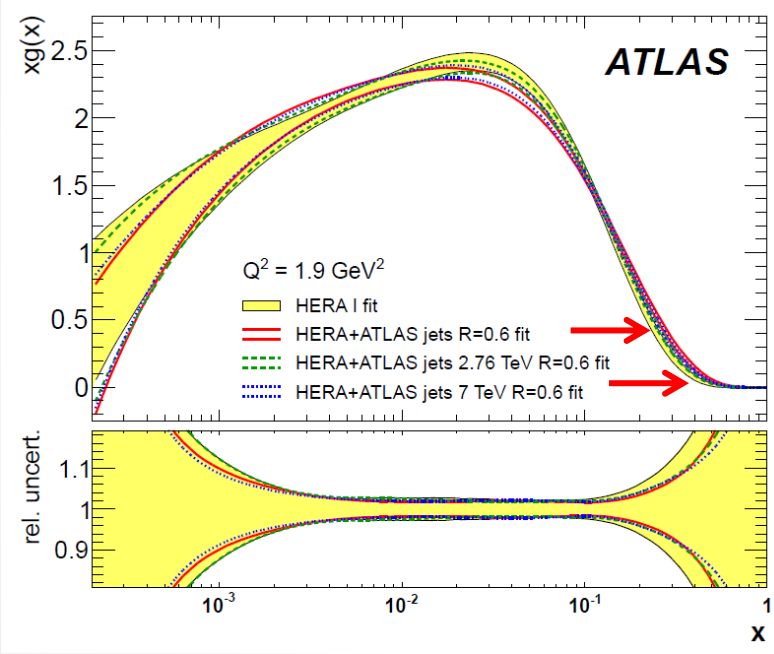
# Inclusive Jets cross section PDF constraints

EPJ C 73 (2013) 2509

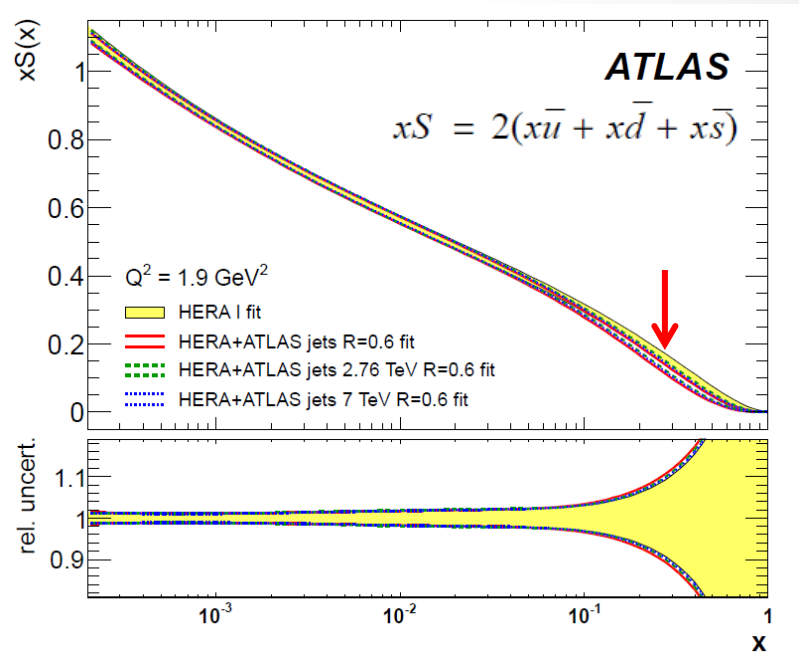
HERA I + 2.76 and 7 TeV ATLAS data included in NLO PDF fit

Correlated uncertainties are taken into account in PDF fit: more sensitivity

**Gluon momentum distribution**




**Sea quark momentum distribution**



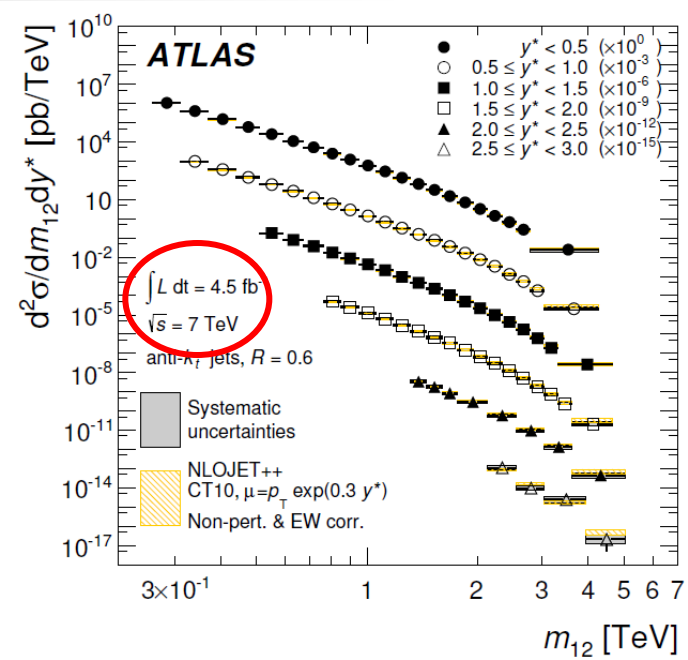

Changes at high x due to ATLAS data:

- Gluon momentum distribution: Harder
  - Uncertainty on xg reduced after including ATLAS jet data
- Sea quark momentum distribution: Softer
  - Larger relative uncertainty on xS

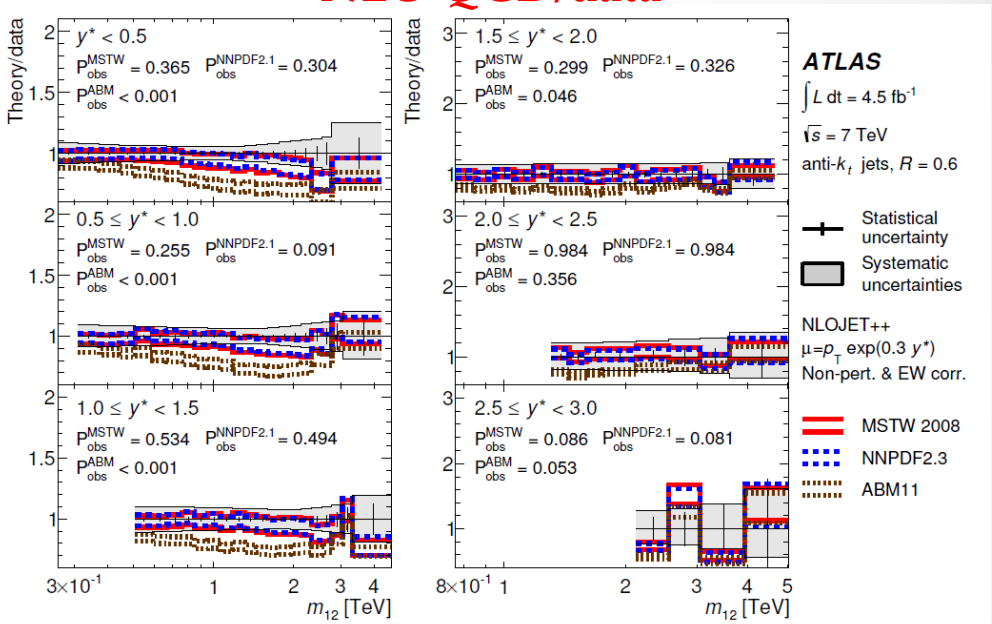
# Dijet cross section with 7 TeV data

accepted by JHEP: arXiv:1312.3524

- Increased statistics: > 100 × 2010 statistics
- Improved JES calibration (Still largest systematics)




NLO QCD/data



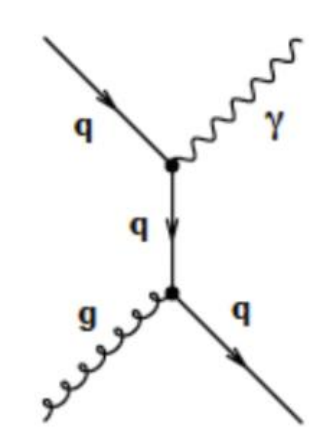

- Double differential cross section as a function of m-dijet and $y^* = |y_1 - y_2|/2$
  - Improved precision at high $m_{12}$
    $\Rightarrow$ Constrain proton PDFs at high $x_{bjorken}$
  - Agreement with **MSTW08**, **NNPDF2.3**, but not for **ABM11**
- Unfolded cross section sensitive to new physics models

# Prompt photons production

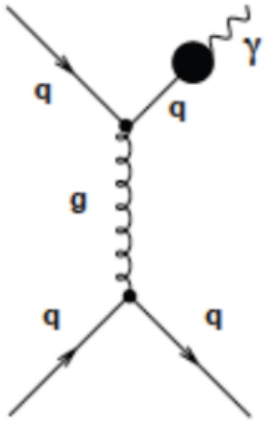
- Photons provide a cleaner environment than jets
  - Precise tests of perturbative QCD (pQCD)

Prompt photons produced from:

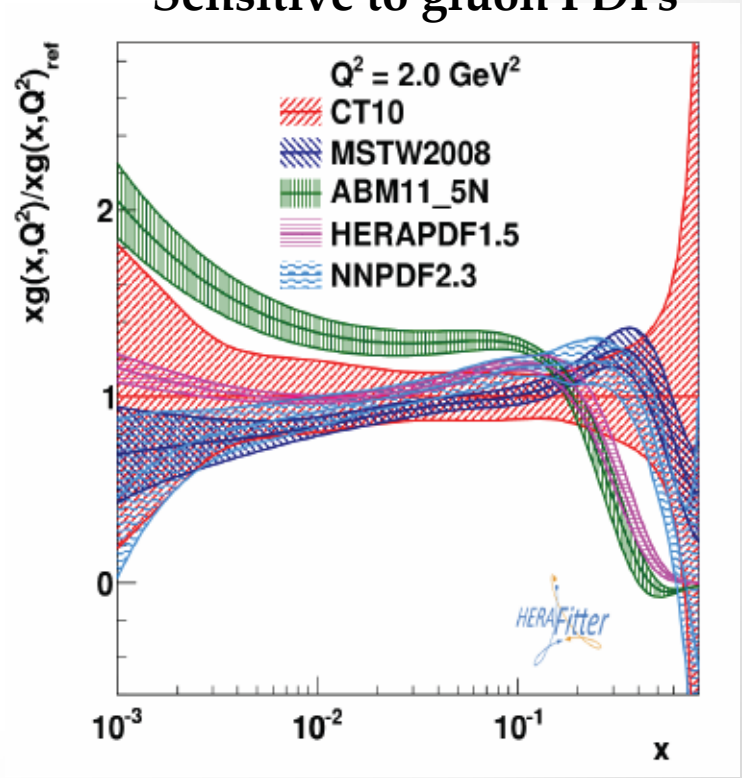
Hard scattering




Fragmentation




**Among the hard scattering processes: Dominant process qg->qγ => Sensitive to gluon PDFs**



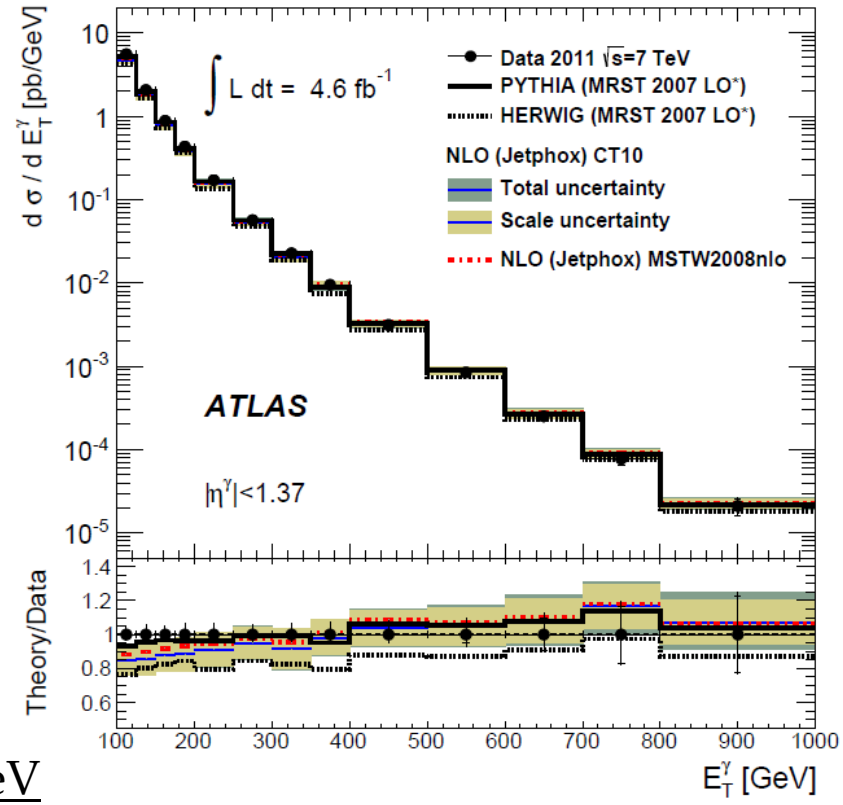
# Inclusive isolated prompt γ cross section

Phys. Rev. D 89, 052004 (2014)

- $E_T^{\gamma}$>100 GeV and $|\eta^{\gamma}|$<1.37 ($0.03<x_{bjorken}<0.3$)
- Isolation: ΔR<0.4, $E_T^{iso}$ < 7 GeV
  - Avoid photons from hadron decays

- Pythia: describes well the data
- Herwig: ~ 15 % lower cross section
- Shape description: Both

- NLO Jetphox : Good agreement up to highest photon energies




<u>In the kinematic regime: for 200 <$E_T^{\gamma}$ <600 GeV</u>

Scale uncertainties most important

<u>For $E_T^{\gamma}$ >600 GeV</u>

Measurement more sensitive to constrain PDFs

A study of PDF sensitivity of this measurement can be found in **ATL-PHYS-PUB-2013-018**

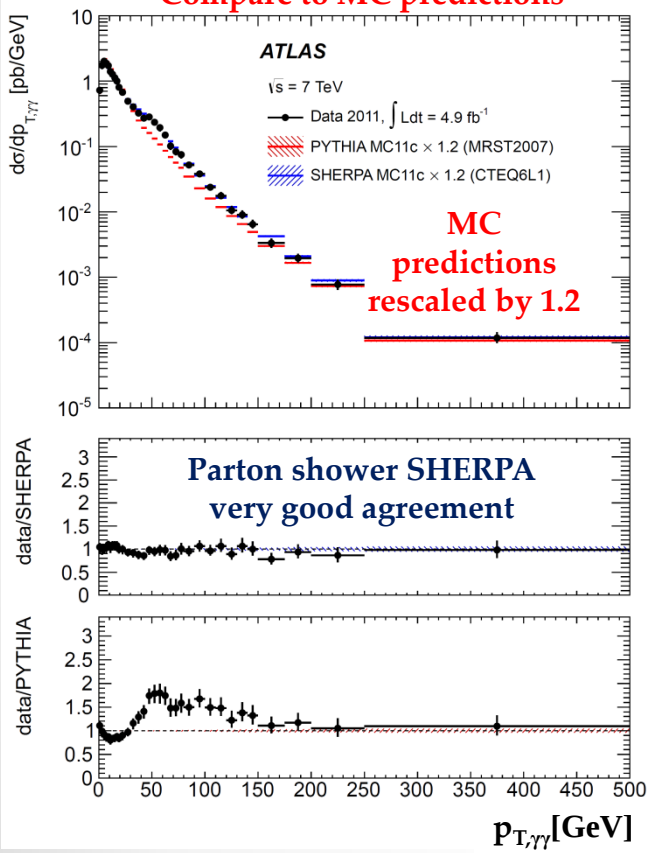
# Isolated di-photon cross section

JHEP 1301 (2013) 086

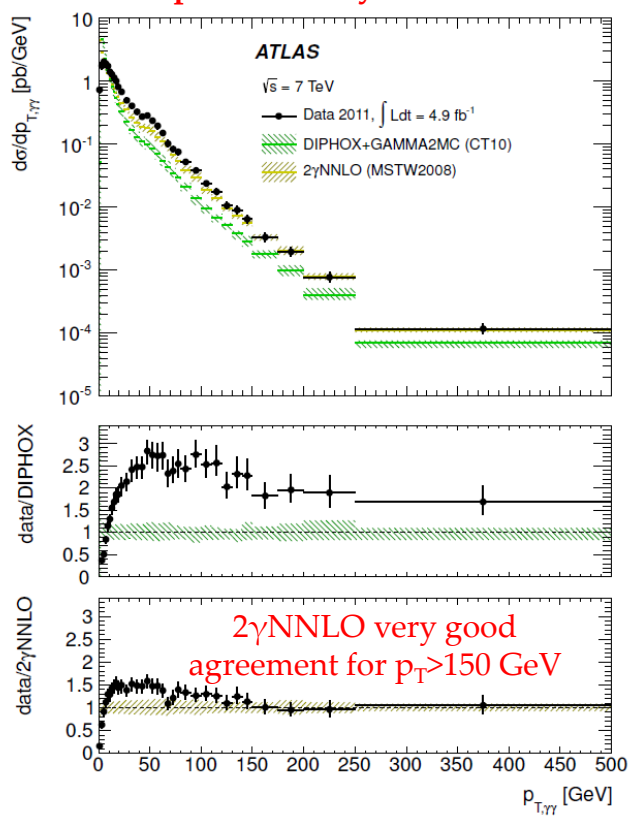
Di-photon pair's differential cross section

- $m_{\gamma\gamma}$ sensitive to new resonances
- $p_{T\gamma\gamma}$ senstive to pQCD and fragmentation

**Compare to MC predictions**




**Compare to theory calculation**




- Good description by the 2γNNLO for $p_T$>150 GeV.
- 20-150 GeV range: fragmentation component significant
- Divergence at low $p_T$: needs soft gluon resummation

- **Sherpa, Pythia: global under-estimation of $\sigma_{tot}$ by 20%**
- **Shape well reproduced by parton showers**

- DIPHOX + γ2MC is NLO: global normalisation problem
- 2γNNLO: divergence at low $p_T$< 20 GeV and missing fragmentation at $p_T$ in[20, 150] GeV

# Conclusion

- QCD measurements at ATLAS are more and more precise
- Unfolded measurements available for any further phenomenology studies

<u>Soft QCD results</u>

- Underlying event measurements can be used to further improve the MC modeling ("tuning")

<u>Hard QCD results</u>

- Jets and photons cross section measurements show a good agreement with the NLO predictions except for low energies where soft processes are dominant
- Potential for new PDF constraints at high x from jet and γ+jet data
- Different $\sqrt{s}$ cross section ratios strongly reduce the experimental systematic uncertainties
- NNLO calculations would be desirable to reduce the scale uncertainties

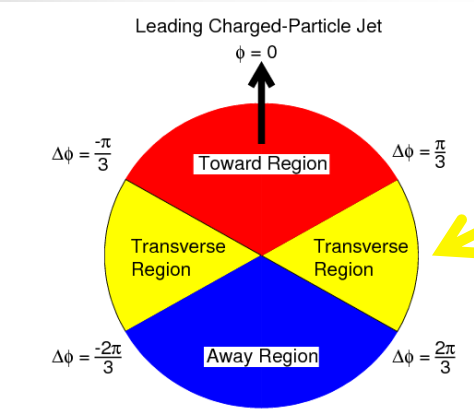
**Ongoing effort to improve results using 8 TeV data**

# Thank You For Your Attention

# Backup

# Soft QCD Introduction

**Underlying Event** →




- Studying for ex. $\sum E_T, N_{p^{\pm}}, \sum p_T$ as a function of leading jet $p_T$
- Study performed in the transverse region that is less affected by the hard scatter
- **UE is irreducible background for precision and new physics measurements**

- Y+Z final state production [W(->lν)+2jets]

$$d\hat{\sigma}^{(tot)}_{Y+Z}(s) = d\hat{\sigma}^{(SPI)}_{Y+Z}(s) + d\hat{\sigma}^{(DPI)}_{Y+Z}(s) = d\hat{\sigma}^{(SPI)}_{Y+Z}(s) + \frac{d\hat{\sigma}_Y(s)\cdot d\hat{\sigma}_Z(s)}{\sigma_{eff}(s)}$$

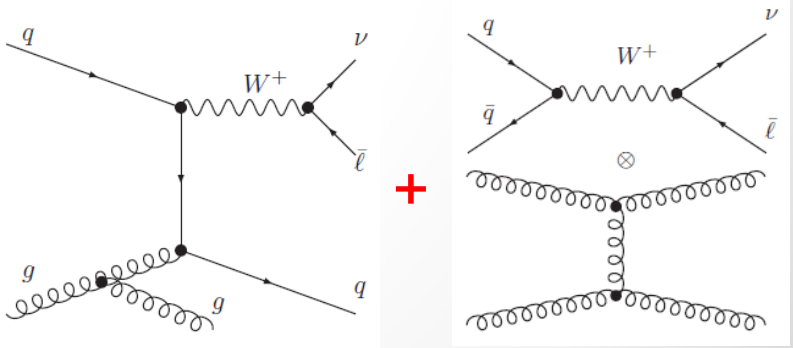
- Measured quantities → Effective area
  → Fraction of DPI used to compute $\sigma_{eff}(s)$

$$f^{(D)}_{DP} = \frac{N_{W_{0j}+2j_{DPI}}}{N_{W+2j}} = \frac{N_{W_{0j}+2j_{DPI}}}{N_{W_{2j}} + N_{W_{0j}+2j_{DPI}}}$$

**$\sigma_{eff}(s)$ regulator parameter of the DPI contribution to $d\sigma_{Y+Z}$**

← **Double parton scattering**

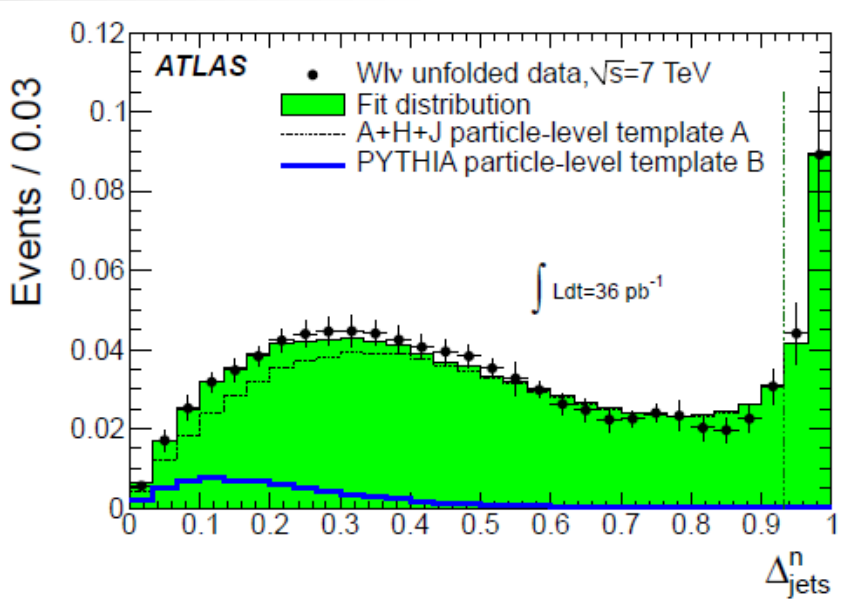
**Single Parton Int. (SPI)** **Double Parton Int. (DPI)**

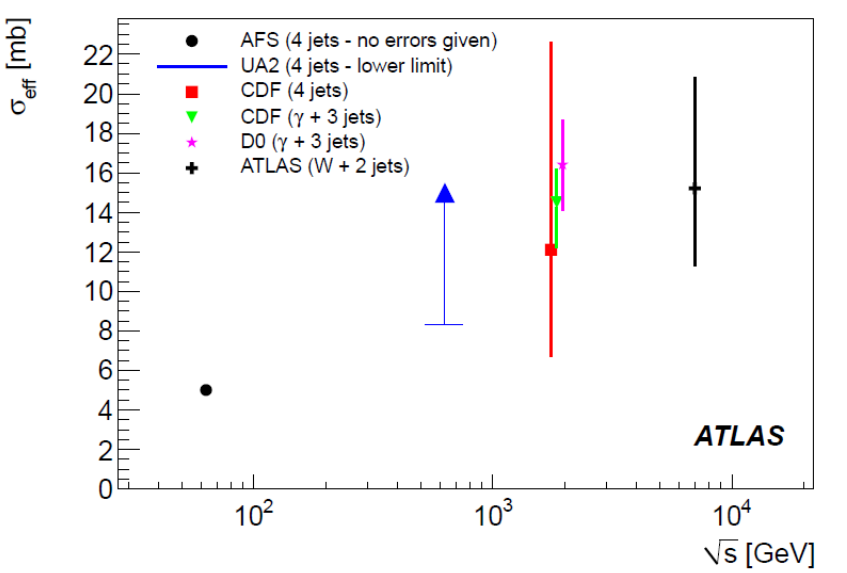



**Non back-to-back jets** **Back-to-back jets**

# Double Parton Interaction

arXiv:1301.6872




$$f_{\mathrm{DP}}^{(\mathrm{D})} = 0.08 \pm 0.01\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{sys.})$$

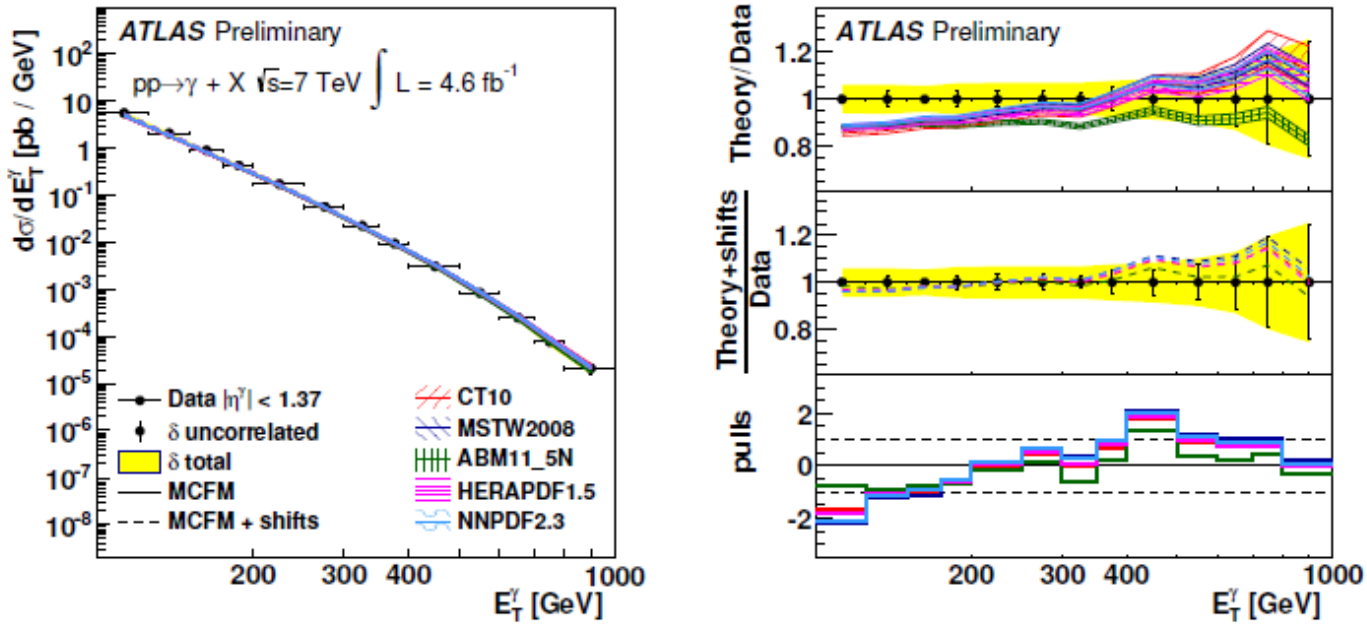
$$\sigma_{\mathrm{eff}}(7\ \mathrm{TeV}) = 15 \pm 3\ (\mathrm{stat.})\ ^{+5}_{-3}\ (\mathrm{sys.})\ \mathrm{mb}.$$

# PDF Data

Glazov, ICHEP2012

| | MSTW08 | CTEQ6.6/CT10 | NNPDF2.1/2.3 | HERAPDF1.0/1.5 | ABKM09/ABM11 | GJR08/JR09 |
|---|---|---|---|---|---|---|
| Evolution | LO | LO | LO | — | — | — |
| Order | NLO | NLO | NLO | NLO | NLO | NLO |
| | NNLO | NNLO | NNLO | NNLO | NNLO | NNLO |
| HF Scheme | RT-GMVF | ACOT-GMVF | FONLL-GMVF | RT-GMVF (*) | BMSN-FFNS | FFNS |
| $\alpha_S$ NLO | 0.120 | 0.118(f) | 0.1191(b) | 0.1176(f) | 0.118 | 0.1135 |
| $\alpha_S$ NNLO | 0.1171 | 0.118(f) | 0.1174(b) | 0.1176(f) | 0.1135 | 0.1124 |
| HERA DIS | not up-to-date | + | + | +/prelim. | partial | + |
| Fixed target DIS | + | + | + | - | + | + |
| DY | + | + | + | - | + | + |
| Tevatron W,Z | some | some | some | - | some | some |
| Tevatron jets | some | + | + | - | some | some |
| LHC | - | - | $W, Z$+jets (NNPDF2.3) | - | - | - |

# Study of the PDF sensitivity of Inclusive isolated prompt γ cross section measurement




In the present study the potential of the inclusive photon production cross section to constrain the gluon PDF has been considered using NLO theoretical predictions from the MCFM and JetPhox calculations. Studies using both calculations and current PDF sets indicate that the inclusive photon data from ATLAS displays sensitivity to the gluon distribution, arising from the large contribution from *u-g* scattering in the initial state. The data have potential to constrain both the shape and uncertainty of the gluon distribution. However, at intermediate $E_T^\gamma$ where the data are most precise, the scale uncertainty is dominant. Therefore NNLO calculations, which are currently unavailable, may be necessary to fully exploit the measurement.

# Study of the PDF sensitivity of Inclusive isolated prompt γ cross section measurement

| | Excluding PDF uncertainties | | Including PDF uncertainties | |
|---|---|---|---|---|
| | $\mu_r = \mu_f = E_T^\gamma$ | Envelope | $\mu_r = \mu_f = E_T^\gamma$ | Envelope |
| CT10 | 49.1 | 34.7 - 63.1 | 29.8 | 20.0 - 38.4 |
| MSTW2008 | 39.9 | 27.2 - 52.7 | 32.0 | 21.3 - 42.3 |
| ABM11_5N | 16.2 | 9.2 - 25.5 | 15.7 | 8.9 - 24.9 |
| HERAPDF1.5 | 28.7 | 19.0 - 38.9 | 23.6 | 15.7 - 32.0 |
| NNPDF2.3 | 33.5 | 22.6 - 44.7 | 27.6 | 18.7 - 36.9 |

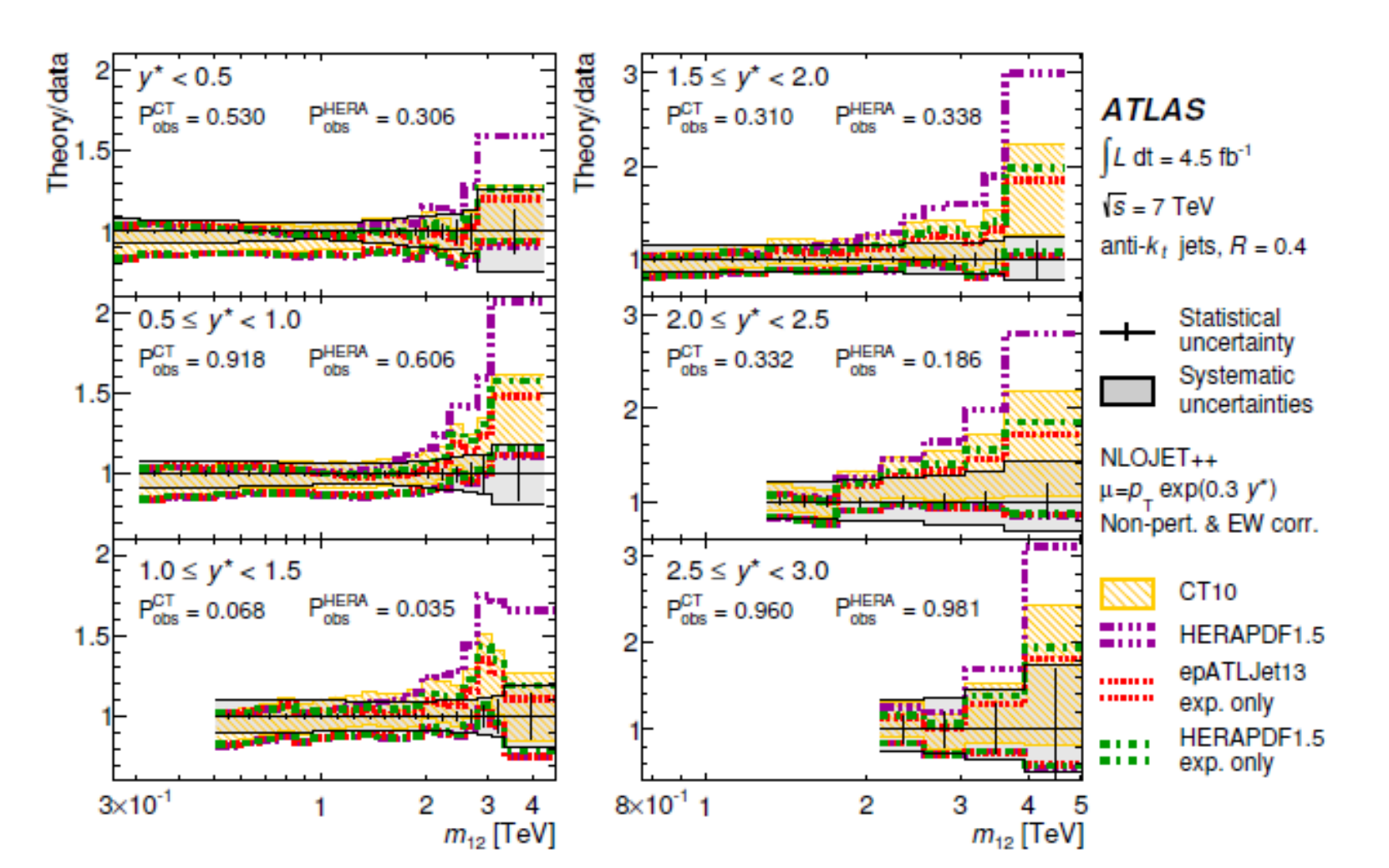
Table 1: The $\chi^2$ values evaluated between the measured cross section and the NLO predictions from MCFM using different PDF sets. Shown are the central values using the nominal scales, $\mu_r = \mu_f = E_T^\gamma$ together with the envelope of the maximum and minimum $\chi^2$ values found by varying both $\mu_r$ and $\mu_f$ between $E_T^\gamma/2$ and $2E_T^\gamma$ independently. For each PDF the $\chi^2$ values for the central scale, and the envelope are shown separately for the cases both including, and excluding the PDF uncertainties. The number of degrees of freedom is 23.

| | $\alpha_{EM} = 1/137$ | 1-loop running $\alpha_{EM}$ |
|---|---|---|
| CT10 | 52.6 (33.4) | 44.9 (26.5) |
| MSTW2008 | 39.3 (32.3) | 33.2 (25.9) |
| ABM11_5N | 20.5 (20.2) | 11.2 (11.1) |
| HERAPDF1.5 | 37.7 (32.6) | 33.1 (27.5) |
| NNPDF2.3 | 39.5 (33.1) | 37.3 (30.7) |

Table 2: The $\chi^2$ values evaluated between the measured cross section and JetPhox NLO predictions using different PDF sets with different choices for $\alpha_{EM}$; fixed and 1-loop running. Shown are values using the nominal scales, $\mu_r = \mu_f = E_T^\gamma$. The fragmentation scale was also set to $E_T^\gamma$. The $\chi^2$ values including PDF uncertainties are shown in parentheses. The number of degrees of freedom is 23.

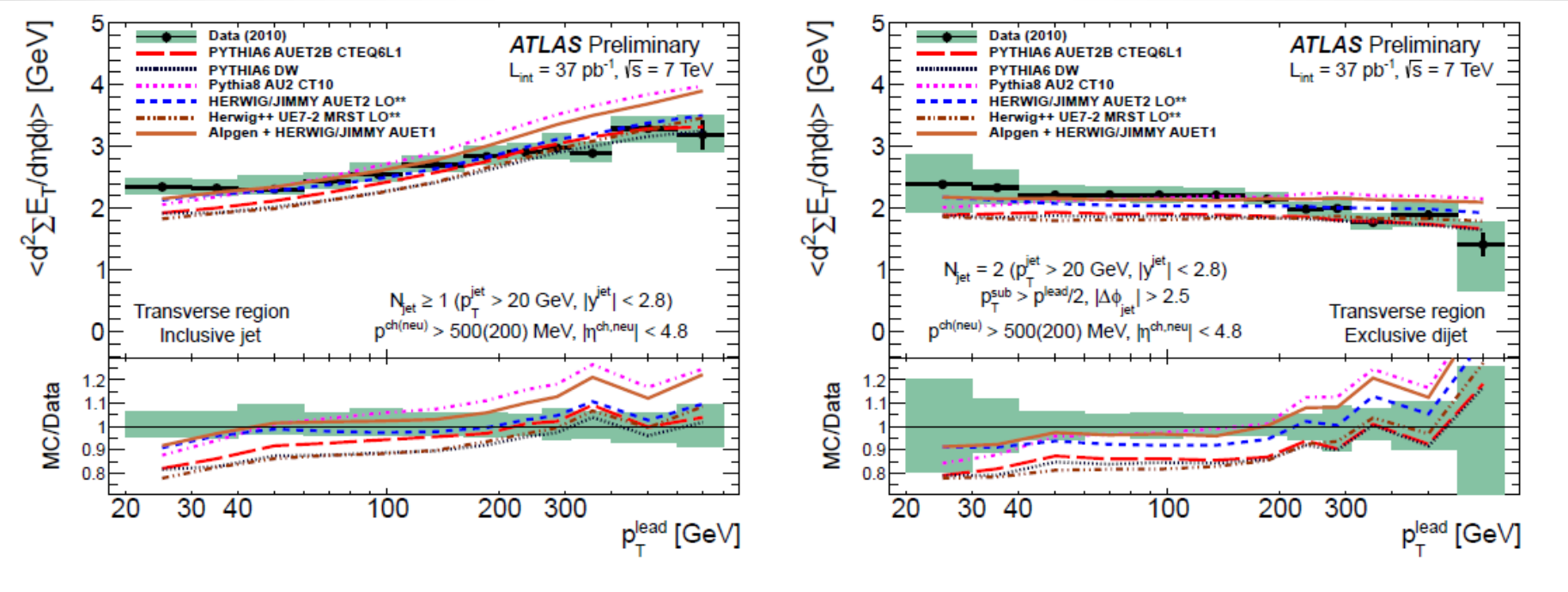
The results of the $\chi^2$ tests indicate that there is a tension between the measured data and the predictions for many of the current PDF sets for the central choice of renormalisation and factorisation scales which is reduced when including the PDF uncertainties, however some tension remains. Thus the data have great potential to constrain both the shape and uncertainty of the gluon distribution. However, in the region where the data are most precise, $200 < E_T^\gamma < 600$ GeV, the scale uncertainty is dominant. Just as in the case of jet production, next-to-next-to-leading order (NNLO) calculations may be necessary to fully exploit this potential.

# Dijet cross section with 7 TeV data




**Good agreement also with CT10**

# Underlying Event

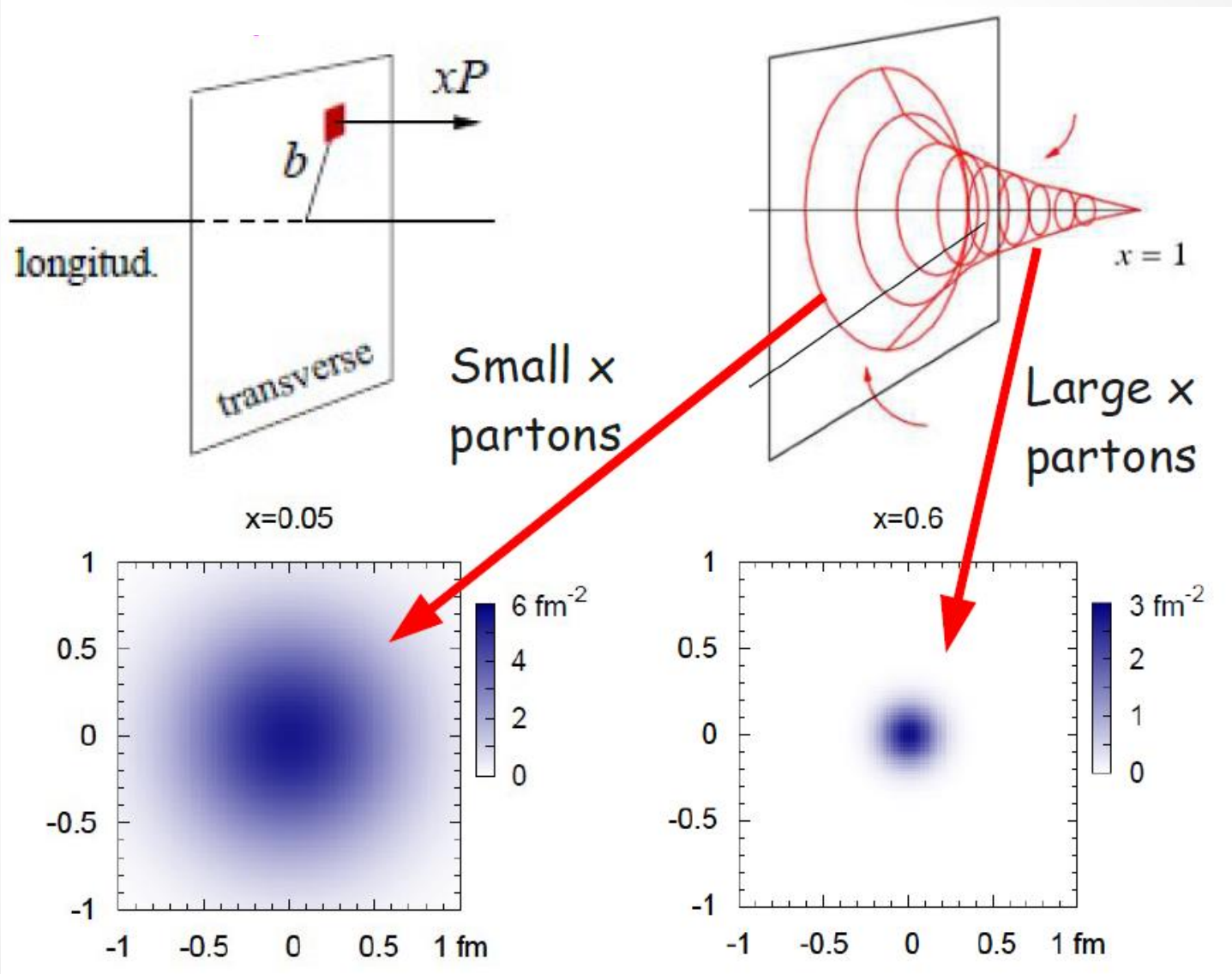



Energy densities spectra for a wider range

For the exclusive measurement the depletion of the spectrum at high $p_T^{lead}$ ~300 GeV more accentuated

# Underlying Event: The most violent collisions are central

Ann.Rev.Nucl.Part.Sci. 55 (2005) 403-465

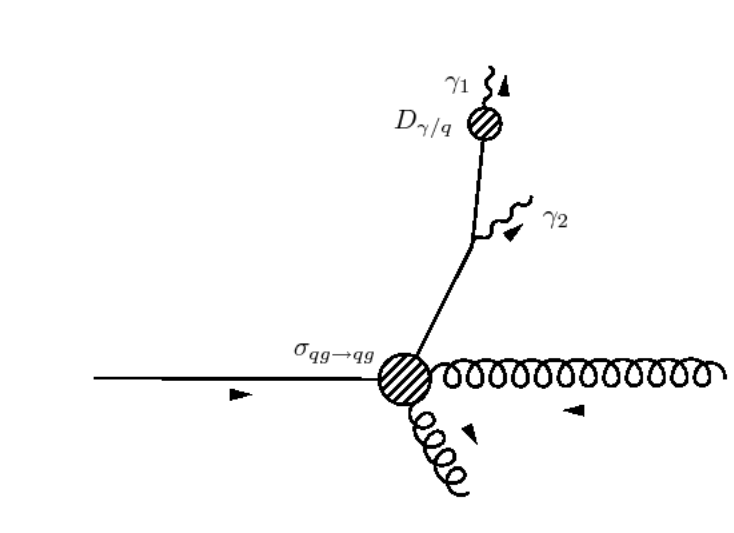


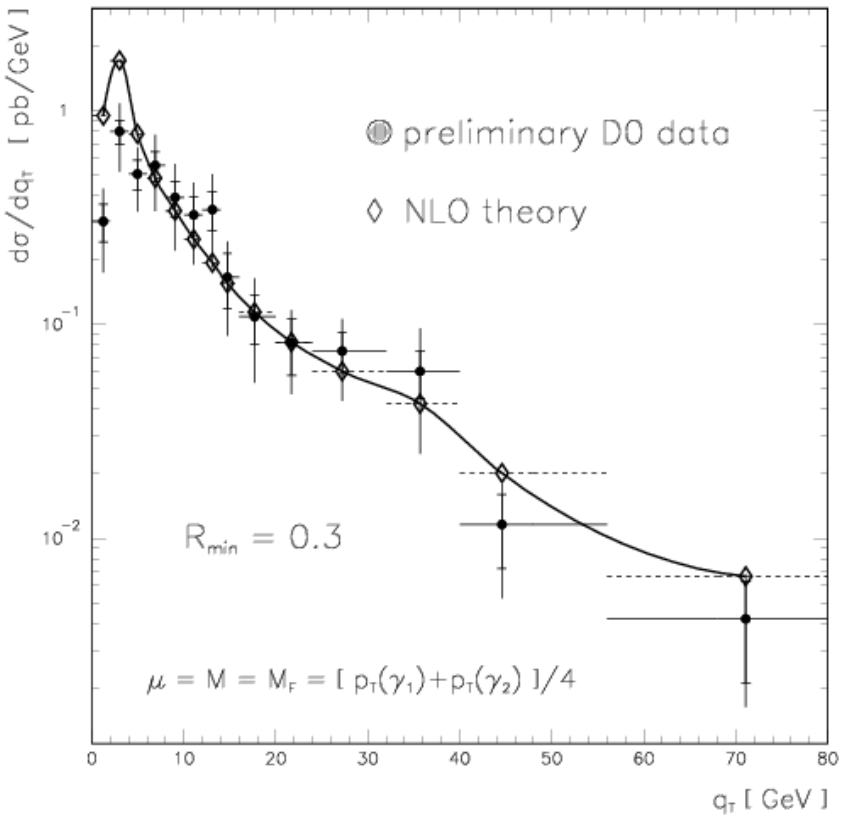
# Isolated di-photon cross section

Phys Rev D 63 (2001)

**Guillet Showlder**

Extra particles in the final state generate kinematical configuration which is forbidden at LO




Enhancement due to NLO effects of fragmentation
When two photons are produced close to each other

# y* variable use in dijet cross section measurement

Phys. Rev. Lett. 103:191803,2009

Rapidity (y) is related to the polar scattering angle θ with respect to the beam axis

(y*) is related to the polar scattering angle θ* in the partonic center of mass frame for massless 2→2 scattering

(y*) more suitable than (y) for constraining the PDFs

# Main sources of background

| Analysis | Dominant Background |
|---|---|
| Underlying Event | Cosmic ray muons, non-collision backgrounds |
| Phi (1020) meson | Pairs containing one or two charged particles that are not kaons (mostly pions, discriminated using the energy loss in the pixel) |
| Inclusive jet | Non collision signals: beam related background, cosmic rays, detector noise |
| Dijet | SM, QCD |
| Inclusive prompt photon | Photons from decays of light neutral mesons like pi0 or eta |
| Di-photon | Hadronic jets and isolated electrons |

# Main sources of Systematics

| Analysis | Dominant Systematics |
|---|---|
| Underlying Event | Track and cluster reconstruction efficiency (10-15 %) |
| Phi (1020) meson | MC material description (5 % per track pair) |
| Inclusive jet | JER (10%) JES (2.5→14%) |
| Dijet | JEC (5 %) JER (10%) |
| Inclusive prompt photon | Photon energy measurement (2→ 6%) |
| Di-photon | Choice of the background control region (9 % ) |