Recent QCD results from ATLAS

PASCOS 2013

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On behalf of the ATLAS collaboration

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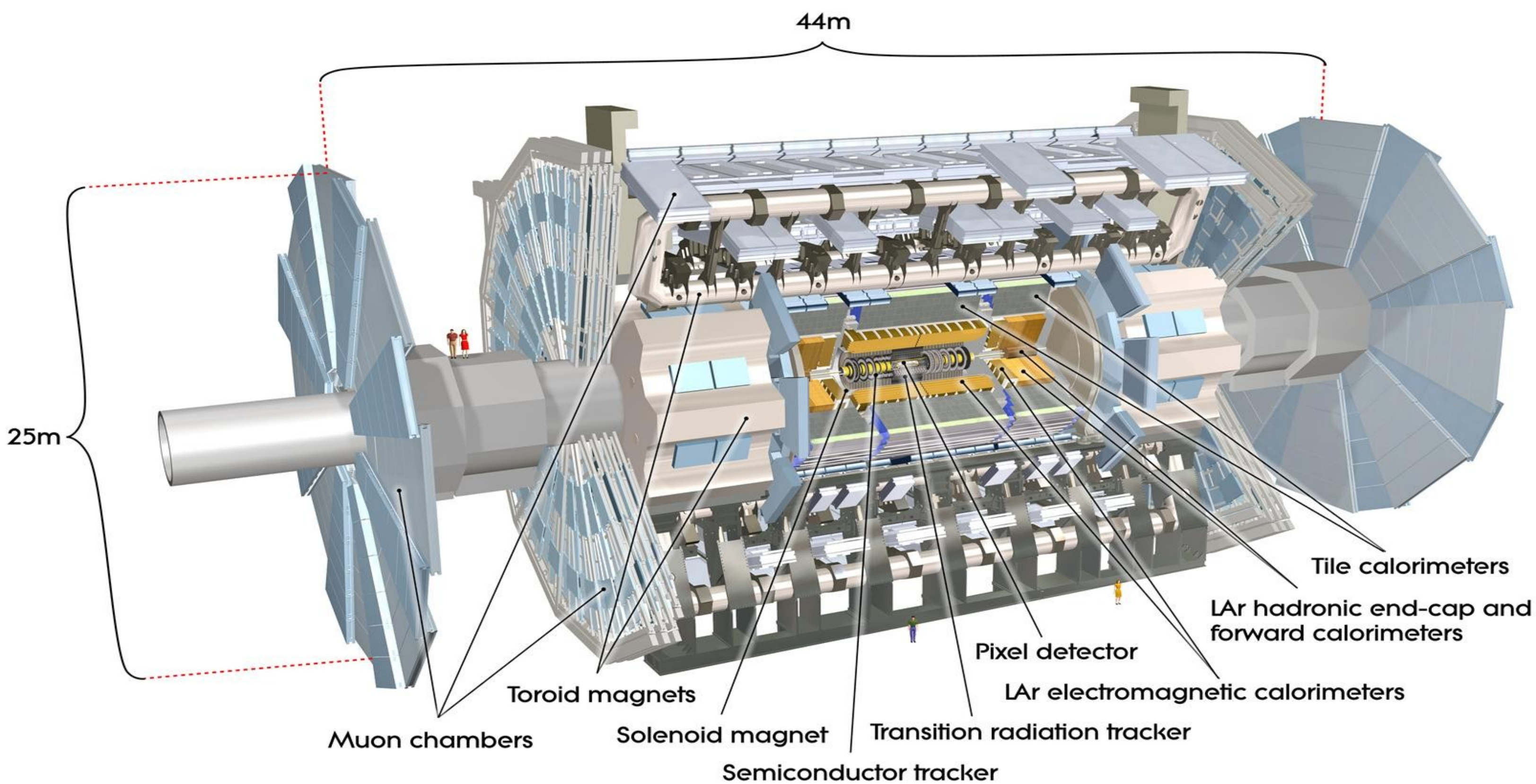
Introduction / Outline

- Soft QCD:
  - Underlying event in jet events @7TeV (2010 data)
  - Hard double parton interactions in $W \rightarrow l\nu + 2$ jets events @7TeV (2010 data)
- Jet cross sections:
  - Inclusive jet cross section @7TeV (2010 data) and @2.76TeV (2011 data) with their ratio
  - Dijet cross section @7TeV (2011 data)
- Photon cross sections:
  - Inclusive prompt isolated photon cross section @7TeV (2011 data)
  - Dynamics of isolated-photon plus jet production @7TeV (2010 data)
  - Photon pair production cross section @7TeV (2011 data)

The ATLAS detector



- Inner detector: $|\eta|<2.5$
- Calorimeters: $|\eta|<4.9$
- Muon tracker: $|\eta|<2.7$

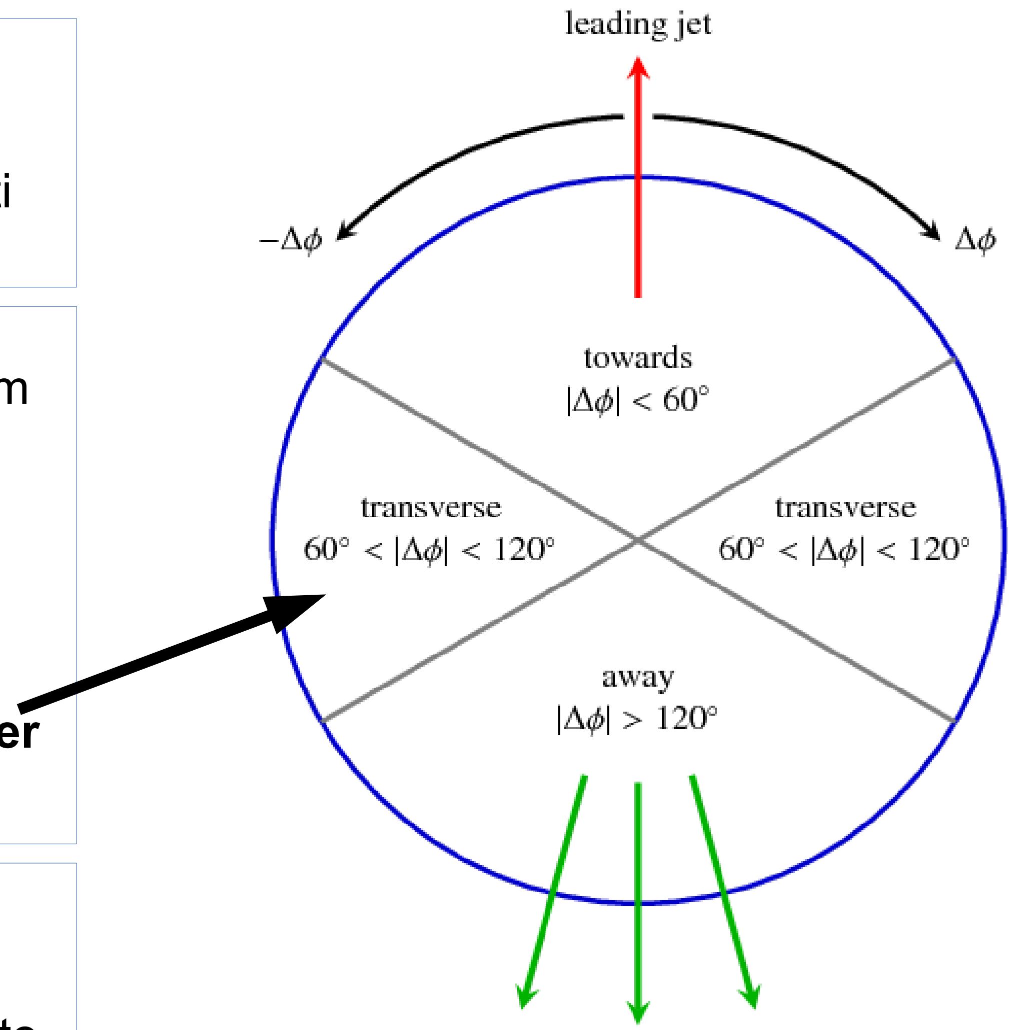
Soft QCD

- Measured on ATLAS:
  - Underlying event (2010 data), ATLAS-CONF-2012-164
  - Double parton interaction (2010 data), New J. Phys. 15 (2013) 033038
  - And much more, see ATLAS public results - soft QCD

Underlying event - introduction

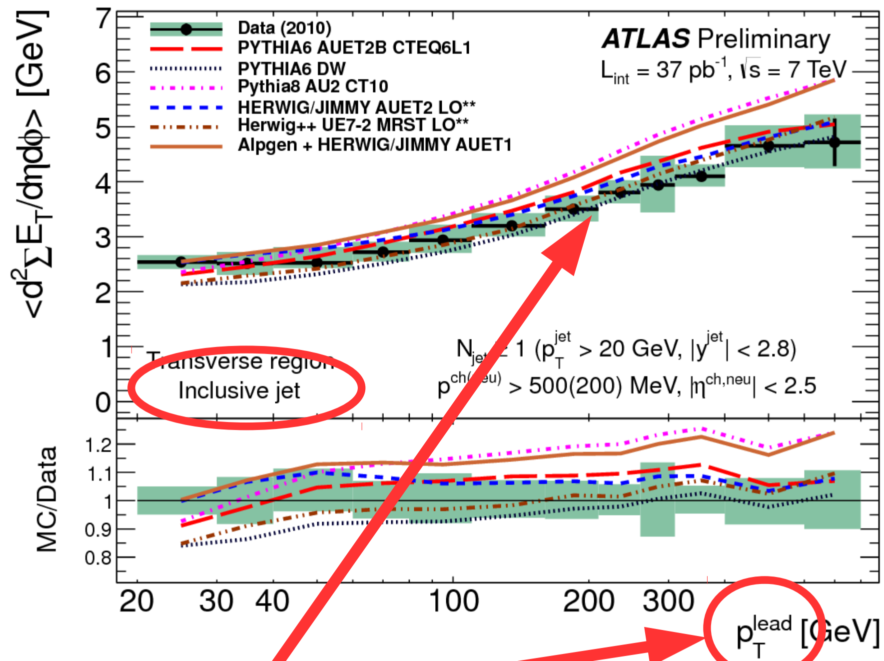
- Motivation:
  - More accurate phenomenological modeling of soft and semi-hard multi parton interactions

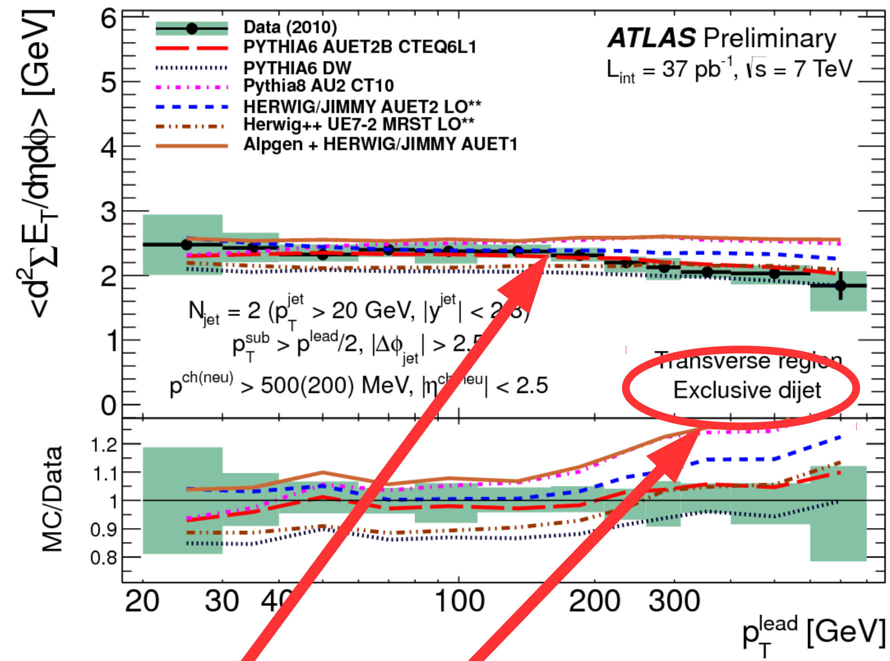
- Observables studied: Sum of transverse energy, number of charged particles, sum of transverse momentum of charged particles
- studied as function of the hard scale ~ leading jet pT
- **in regions less affected by hard scatter process**



- Azimuthal segmentation of events:
  - the two regions transverse to the leading jet in Δφ are most sensitive to the UE

Underlying event - results





Correlated with impact parameter: the higher p_T^{lead} the lower impact parameter

Idea is to veto wide-angle emissions

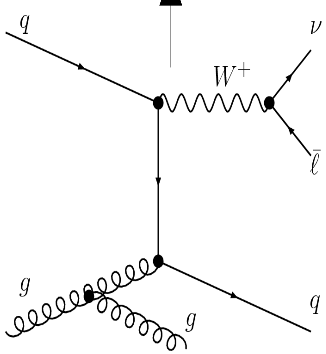
Increase indicates contribution from the wide-angle emissions from the hard scattering

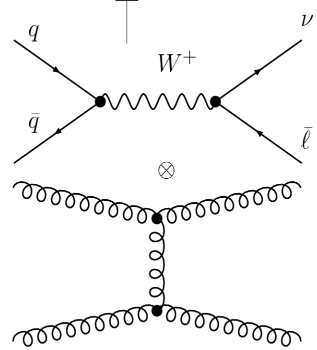
Flat or slightly decreasing with p_T^{lead}: rate of multiparton interactions reaches plateau when the proton-proton collision is head-on (small impact parameter)

Double parton interactions

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

Production of final state Y+Z





Regulates the contribution of DPI
To the production of the Y+Z final state

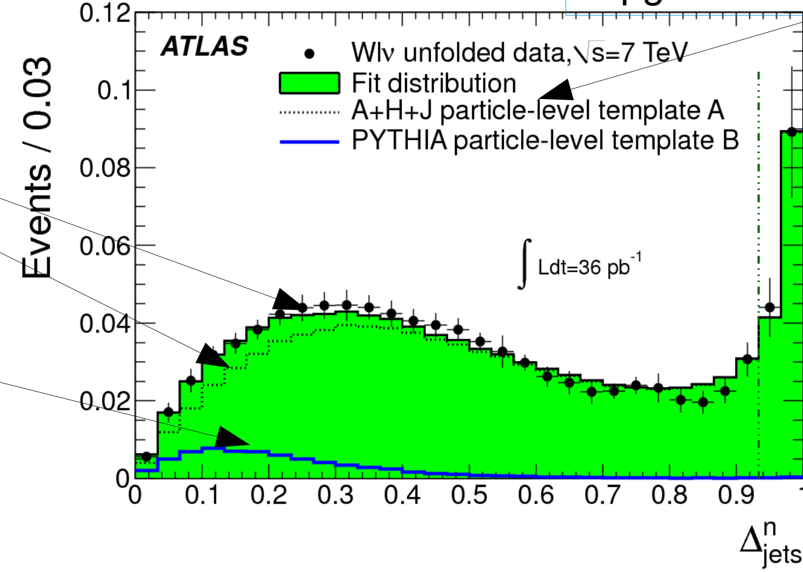
Note: the DPI produced jets are expected to be back to back;
but not in SPI production where they are kinematicaly correlated to the W

$f^{(\mathrm{D})}_{\mathrm{DP}}$ ← Fraction of DPI events in all the $W \to l\nu + 2j$ events;
Theoretical input needed for its derivation;
Measured by a template fit

Double parton interactions

- $f_{DP}^{(D)}$ extracted from fit of combination of two templates to the Δ_{jets}^{n} distribution in $W \to l\nu + 2$ jets events
  - Template A: DPI-off ($W \to l\nu + 2j$ SPI events) … derived from MC
  - Template B: DPI-only (exclusive dijet sample used as an approximation)
  - $\Delta_{\text{jets}}^{\text{n}} = \frac{|\vec{p}_{\text{T}}^{J_1} + \vec{p}_{\text{T}}^{J_2}|}{|\vec{p}_{\text{T}}^{J_1}| + |\vec{p}_{\text{T}}^{J_2}|}$
  - Fit: $(1 - f_{DP}^{(D)}) \cdot A + f_{DP}^{(D)} \cdot B$

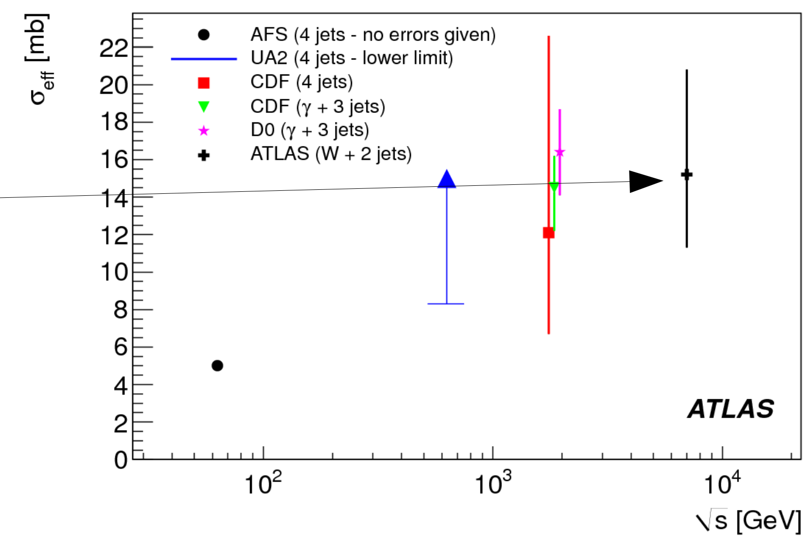
Alpgen+Herwig+Jimmy



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

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

Compatible with previous results



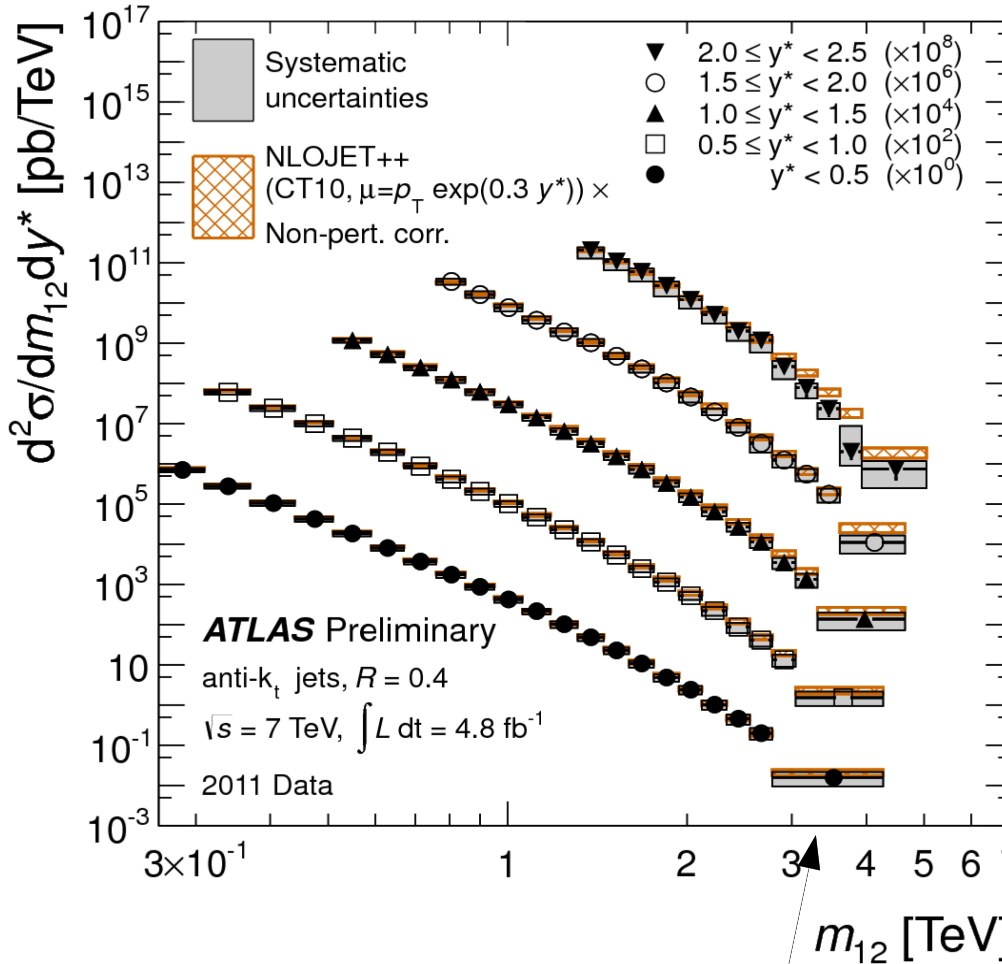
Jet cross sections

- Measured by ATLAS:
  - Inclusive jet and dijet XS @ 7TeV (2010 data), Phys.Rev. D86 (2012) 014022
  - Dijet XS @ 7TeV (2011 data), ATLAS-CONF-2012-021
  - Inclusive jet XS @ 2.76TeV (2011 data) and its ratio to the inclusive jet XS @ 7TeV (2010 data), Eur. Phys. J. C 73 (2013) 2509
  - Multi-jet XS @ 7TeV (2010 data), Eur.Phys.J. C71 (2011) 1763
  - For more jet XS measurements see ATLAS public results - jet physics

Jet cross sections – motivation and technique

- General motivation for the measurements:
  - Test of perturbative QCD (pQCD)
  - Constrain proton parton distribution functions (PDFs)
  - Strong coupling measurement
  - Constraints on physics beyond the SM

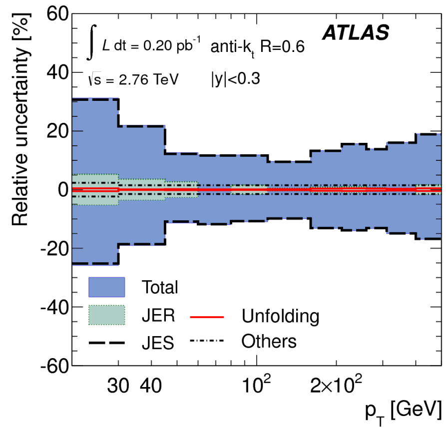
- Basic strategy:
  - anti-kt jets R=0.4, 0.6 of topological calorimeter clusters
  - Unfolded to particle level
  - Compared with NLO prediction of NLOjet++ with non-perturbative corrections
  - Dominant systematic uncertainty: due to the jet energy scale



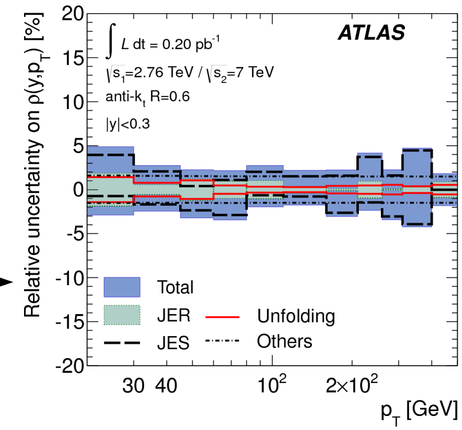
High kinematic reach

Inclusive jet cross section @2.76TeV and @7TeV

- The same jet calibration strategy as for the JIXS @ 7TeV in 2010
  - Many correlated uncertainties cancel in the cross section ratio to 7TeV
  - Strong constraint on the PDFs

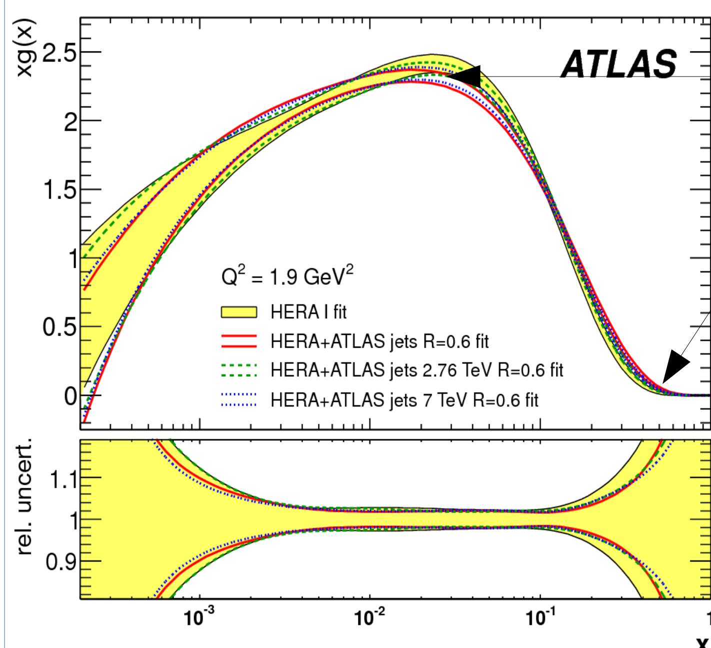


Significant reduction of the experimental systematic uncertainty



PDF fit using the two measurements

- Precise proton PDFs measurement at HERA
- The understanding of correlations of uncertainties provides more sensitivity
- Constraint of the gluon PDF at low and moderate transverse momentum possible
- Initial parametrisation inspired by HERAPDF
- Fit performed using both HERA-I and ATLAS jet results

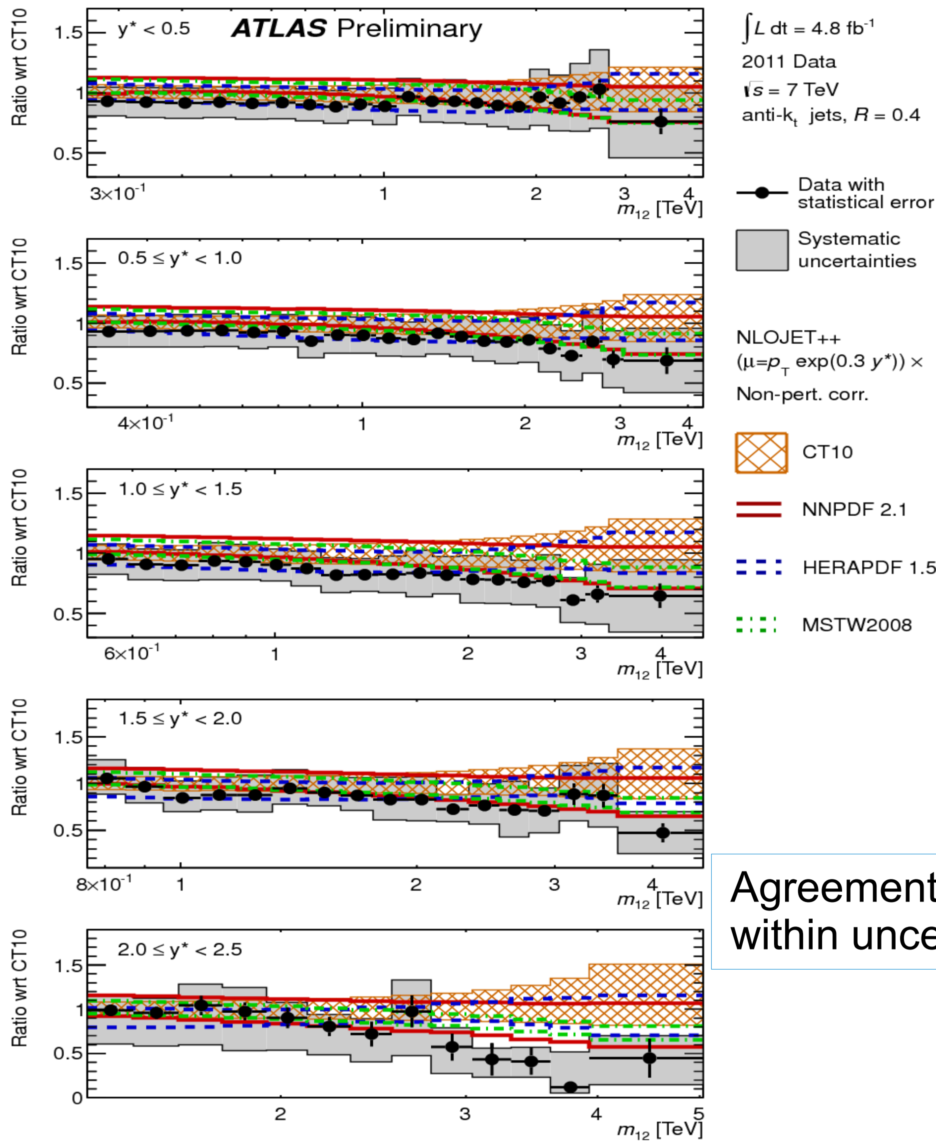


Shape constraint: ATLAS data lead to harder gluons

Dijet cross section @7TeV

- Double differential:
  - As a function of invariant mass and $y^* = |y_1 - y_2|/2$
- Sensitive to new resonances and interactions beyond the Standard Model
- Region of high dijet masses sensitive to the gluon PDF at high momentum fraction

- Data taken in 2011 used:
  - Larger statistics than in 2010
  - Price to pay: pileup
- Despite pileup, the systematic uncertainty is smaller than in 2010



Agreement with NLO prediction within uncertainties

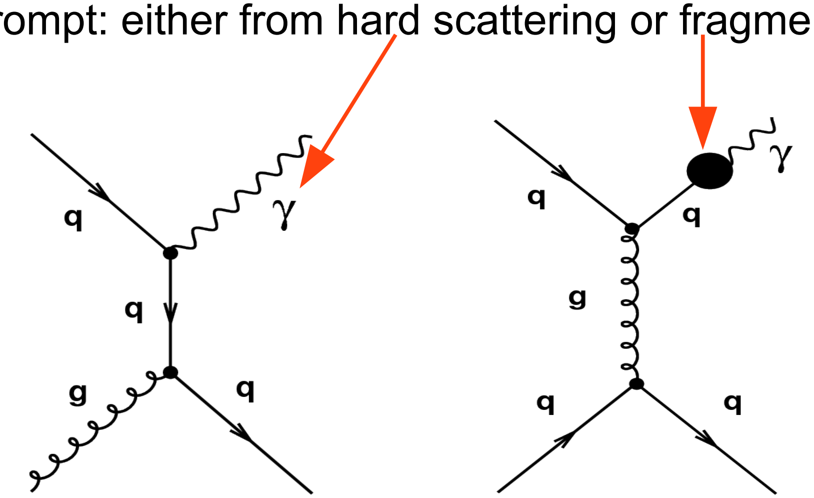
Photon cross sections

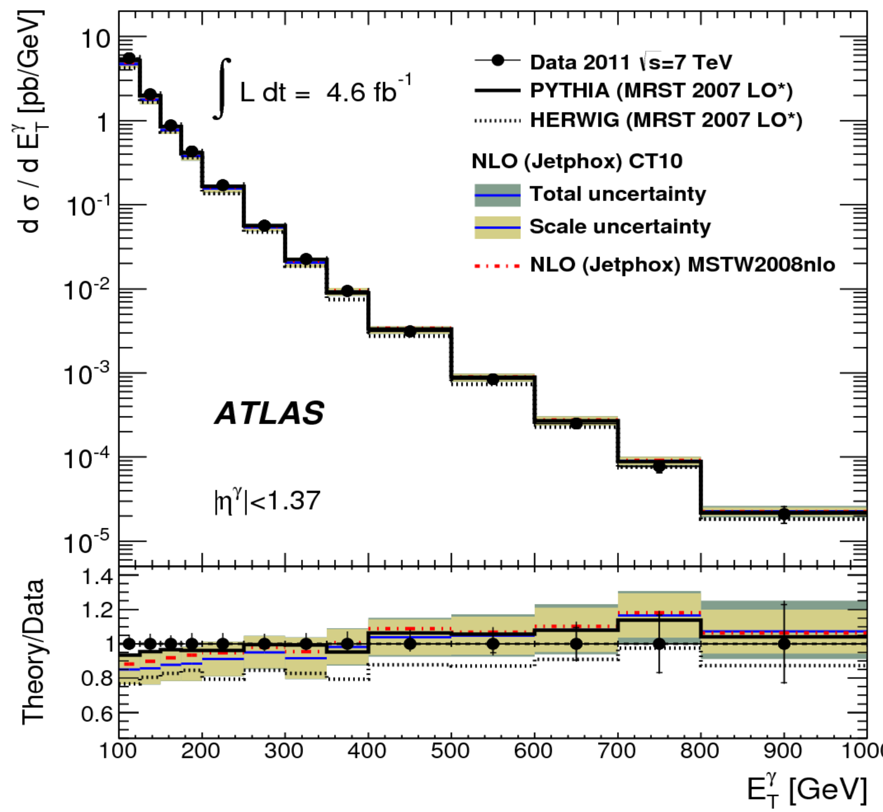
- Measured on ATLAS:
  - Inclusive isolated prompt photon XS @ 7TeV (2011 data), arXiv:1311.1440 (submitted to PRD)
  - Production isolated-photon + jet XS @ 7TeV (2010 data), Phys. Rev. D 85, 092014 (2012)
  - Dynamics of the isolated-photon + jet production @ 7TeV (2010 data), Nucl. Phys, B 875 (2013) 483-535
  - Isolated-photon pair production XS @ 7TeV (2011 data), JHEP01(2013)086
  - For more photon XS measurements see ATLAS public results - direct photons

Inclusive isolated prompt photon XS

- Motivation:
  - Precise test of pQCD
  - Sensitive to gluons: dominant process is qg → qγ

- Prompt: either from hard scattering or fragmentation





- Isolated: to get rid of background that is usually more surrounded by hadrons
  - Isolation energy (in the cone ΔR < 0.4 around photon) E_T^{iso} < 7GeV

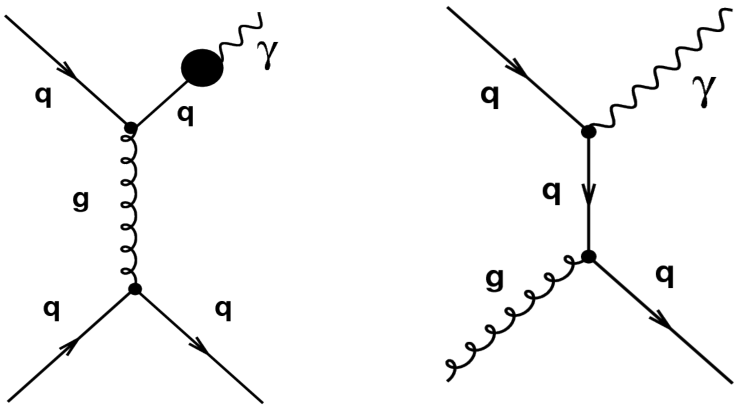
- Agreement with the NLO calculation (Jetphox) within uncertainties
- LO parton-shower MC generators describe the shape of the spectrum

Isolated-photon + jet XS

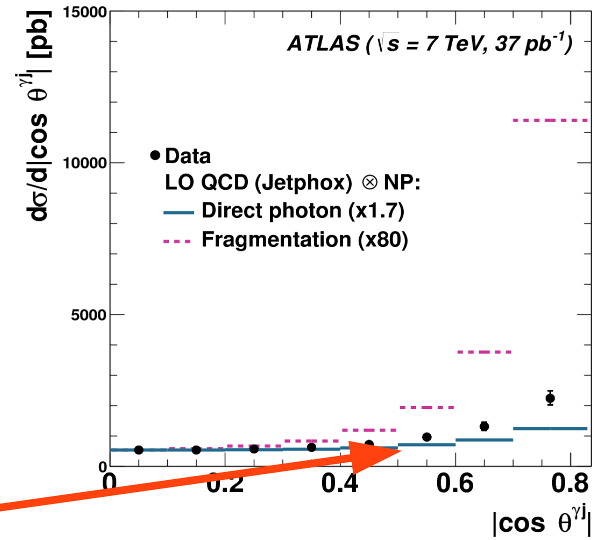
- Additional motivation:
  - Background to Higgs decay
- Measured as a function of several variables
  - $|\cos\theta^{\gamma j}|$ ... polar angle between photon and jet in their rest frame … sensitive to spin of the exchanged particle

For $|\cos\theta^{*}| \rightarrow 1$:

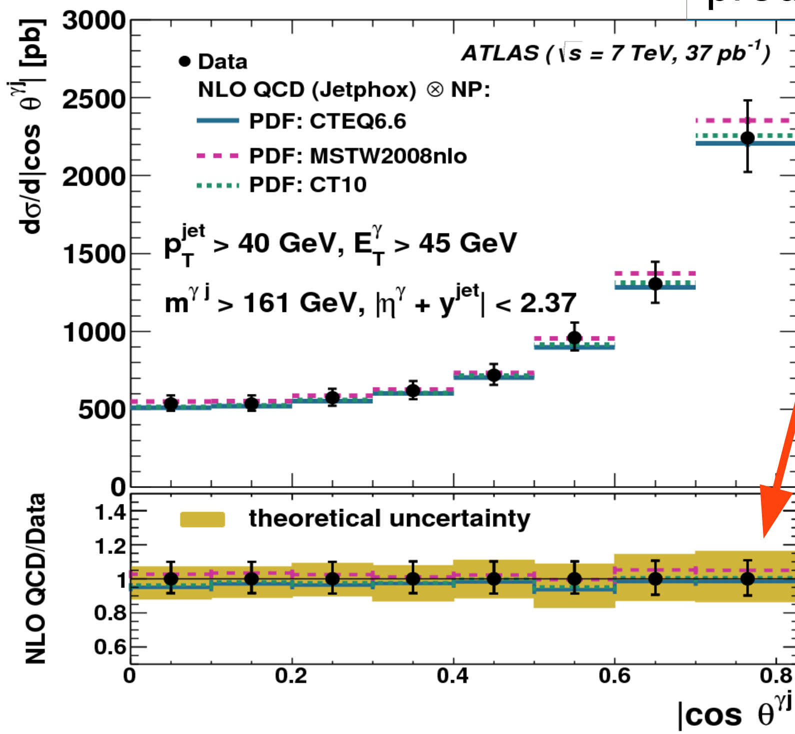
$(1-|\cos\theta^{*}|)^{-2}$ $\quad$ $(1-|\cos\theta^{*}|)^{-1}$



Good test of dominance of the quark exchange channel (and of direct photons)

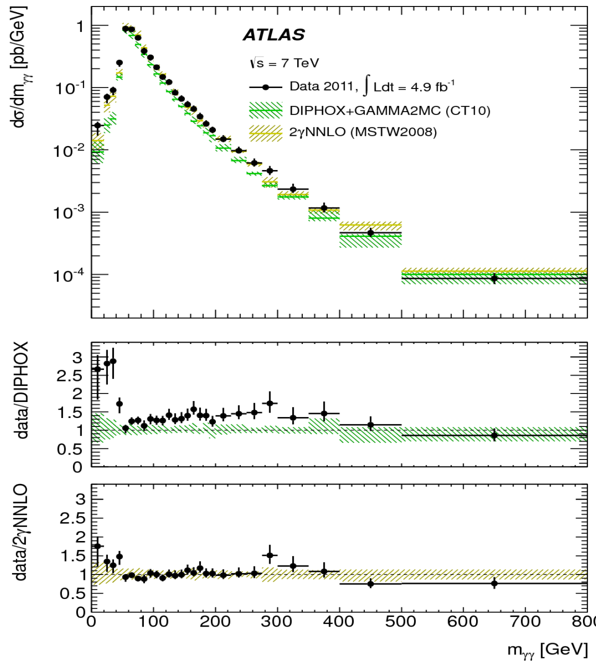


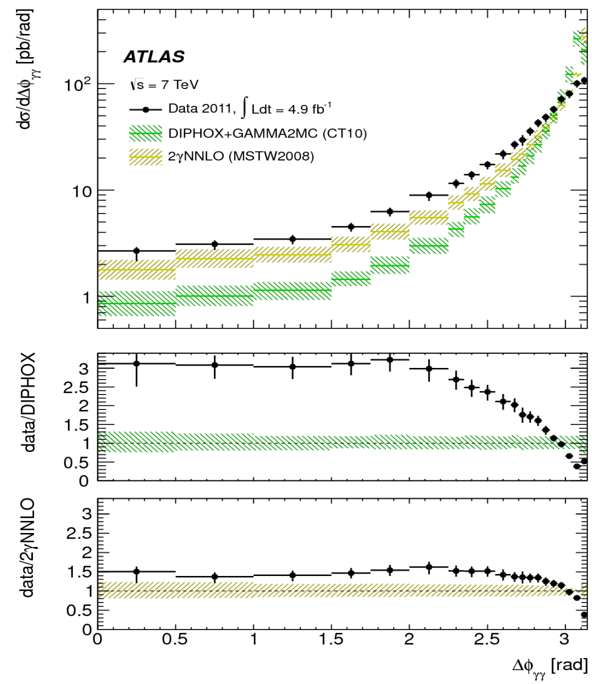
Good agreement with Jetphox NLO prediction



Isolated-photon pair cross section

- Additional motivation:
  - Background to some new physics processes (e.g. Higgs)
- Measured as a function of:
  - $m_{\gamma\gamma}$… sensitive to resonant searches
  - $p_{\mathrm{T},\gamma\gamma}$and $\Delta\phi_{\gamma\gamma}$ … sensitive to higher-order pQCD effects and fragmentation
  - $\cos\theta^{*}_{\gamma\gamma}$ … sensitive to spin of the exchanged particle





- DIPHOX+GAMMA2MC: NLO calculation of both the direct and fragmentation part of the XS
  - Poor description of $\Delta\phi_{\gamma\gamma}$ at π because soft gluon emission is divergent at NLO
  - Underestimation of data (missing NNLO contribution)
- 2γNNLO: NNLO calculation of the direct part of the XS
  - Better description of data (mostly matches within uncertainties)
  - Discrepancy where the soft gluon radiation or fragmentation important (low $m_{\gamma\gamma}$, $p_{\mathrm{T},\gamma\gamma}$,$\Delta\phi_{\gamma\gamma}$ at π)

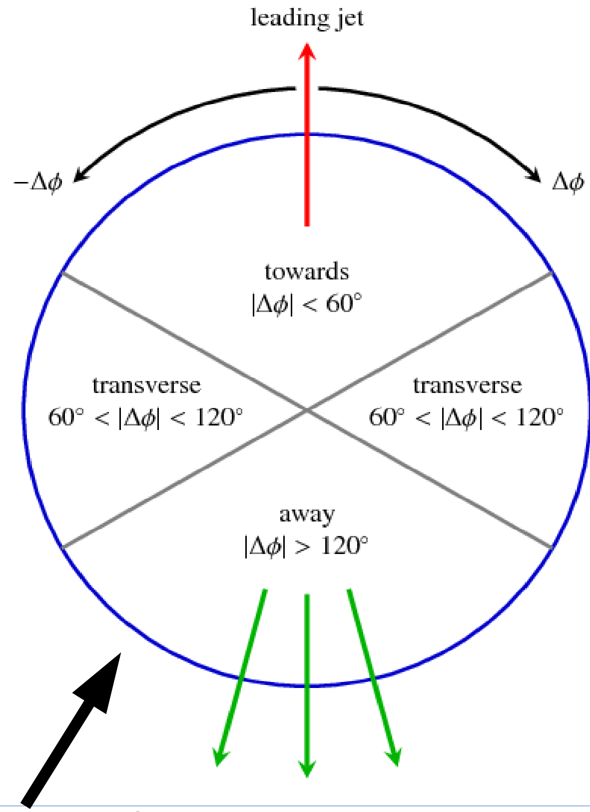
Conclusions

- Many precise QCD measurements performed by the ATLAS collaboration
  - The most recent ones shown here
- Soft QCD results help us to better understand the underlying event processes in pp collisions
- Jet and photon cross sections are in general in agreement with theoretical predictions
- Constraint of PDFs possible
- A better understanding of backgrounds to new physics can be achieved

BACKUP

Underlying event – motivation and technique

- Processes:
  - Initial and final state radiation, interactions of partons not entering the hard scattering and of beam-beam remnants, additional hard scatters
- Motivation:
  - Good understanding needed to perform precise new physics measurements at hadron colliders (LHC)
    - adequate modeling of background to rare physics processes
  - UE contribution to the jet energy scale (UE activity must be subtracted from the jet energy)
  - Simulation of pileup
  - UE cannot be calculated with pQCD: tune of phenomenological MC models to experimental data



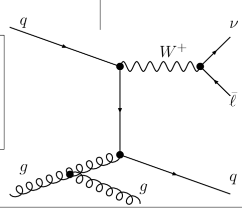
- Typical observables:
  - Sum of transverse energy, number of charged particles, sum of transverse momentum of charged particles in regions not affected by hard scatter process

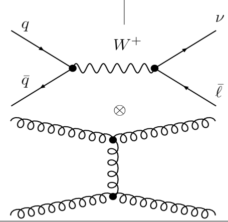
- Azimuthal segmentation of events:
  - Introduced by Rick Field at Tevatron
  - Interesting are the two regions transverse to the leading jet φ-coordinate
  - TR with higher (lower) activity: “trans-max” (min)

Double parton interactions

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

Production of final state Y+Z





Regulates the contribution of DPI To the production of the Y+Z final state

Note: the DPI produced jets are expected to be back to back; but not in SPI production where they are kinematically correlated to the W

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

Can be measured

Theoretical input needed

3) In our case:

$$\sigma_{\text{eff}} = \frac{N_{W_{0j}}\, N_{2j}}{f^{(D)}_{DP}\cdot N_{W+2j}}\cdot\frac{1}{\varepsilon_{2j}}\cdot\frac{1}{\mathscr{L}_{2j}}$$

W boson yield with no associated jets

Exclusive 2 jet yield

Efficiency and luminosity factors

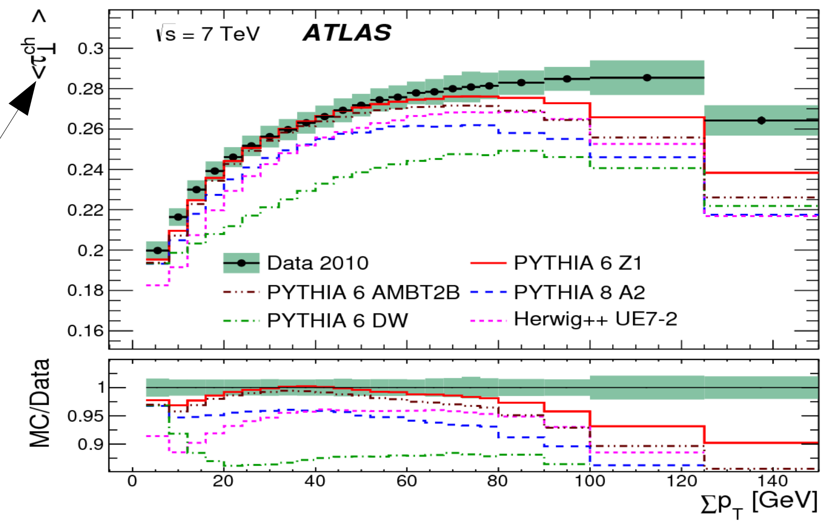
Needs to be estimated, see next slide

W+2jet events yield

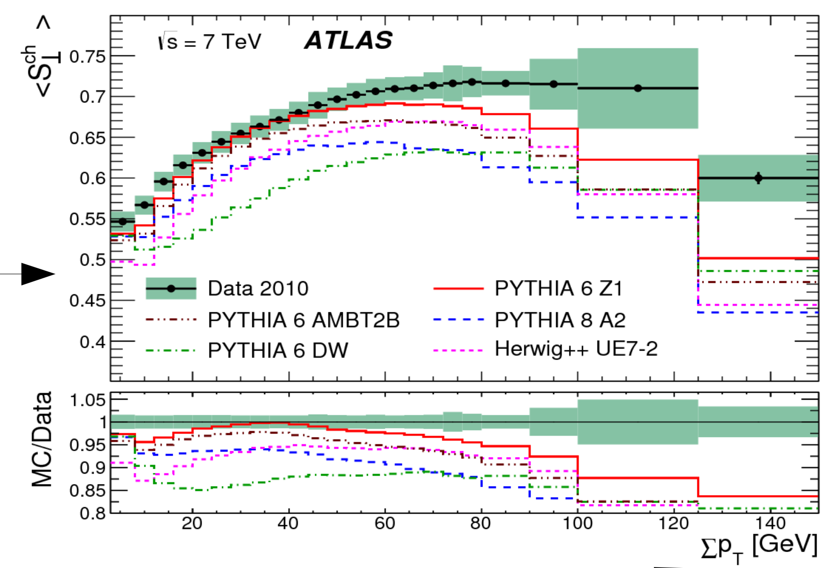
Charged-particle event shapes

2010 data, Phys. Rev. D 88, 032004 (2013)

- Description of the geometric properties of the energy flow in the event
- (Continuous) discrimination between events with flow along single axis and uniform distribution in space angle
- Helps to fine tune MC description of the UE

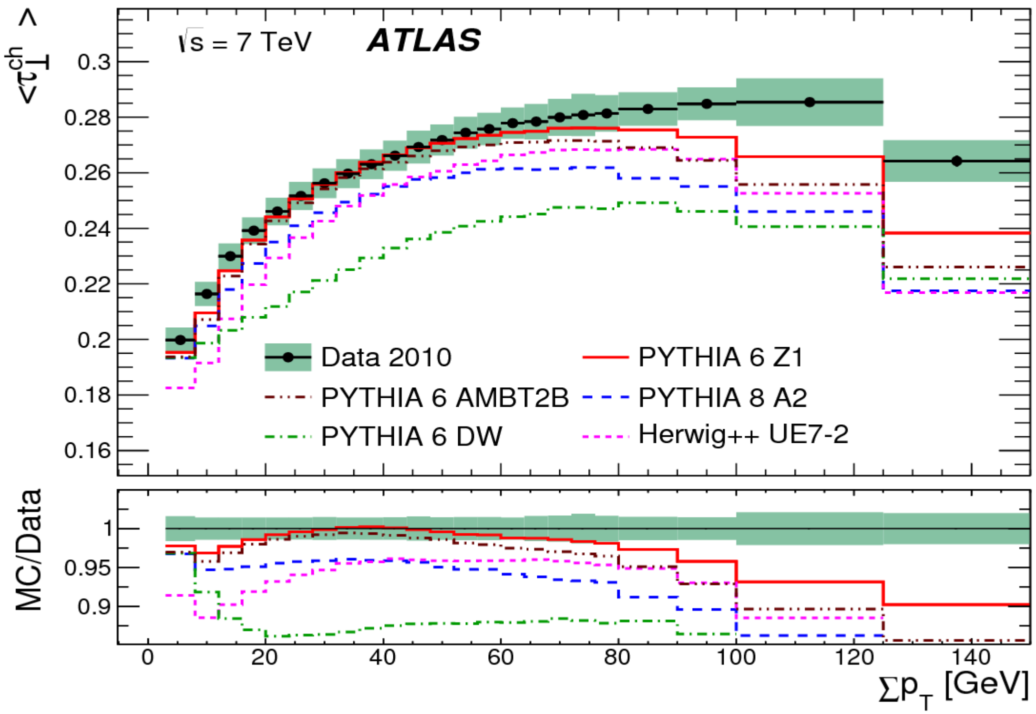


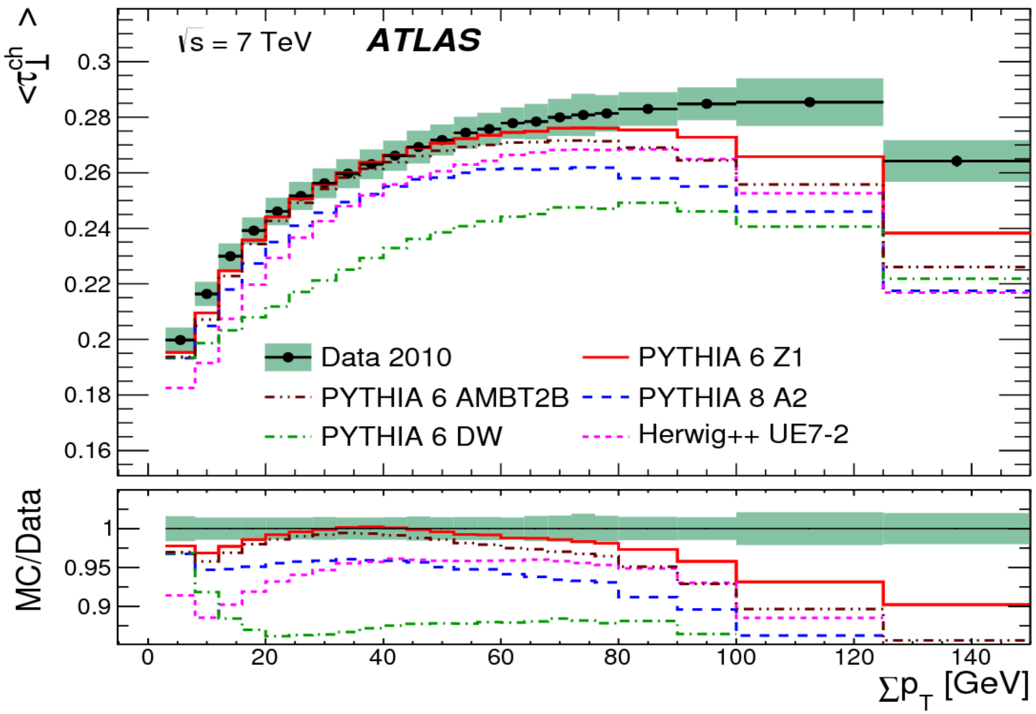
- Measured: transverse thrust, thrust minor and sphericity as a function of the highest transverse momentum of a charged particle in the event
- Complement of the transverse thrust: $\tau_{\perp} = 1 - T_{\perp}$
  - is 0 for perfectly balanced dijet topology and $1 - \frac{2}{\pi}$ for spherical symmetric topology
- Transverse sphericity
  - is 0 for perfectly balanced dijet topology and 1 for spherical symetric topology
- Increasing trend of both graphs except for highest bins



Sum of charged particle transvers momenta

Charged-particle event shapes





- Complement of the transverse thrust: $\tau_\perp = 1 - T_\perp$

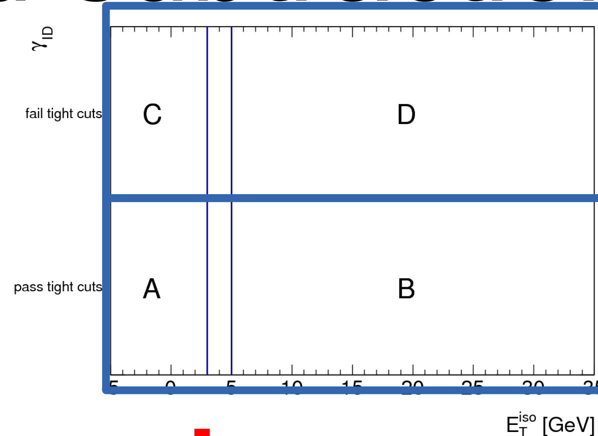
$$T_\perp = \max_{\hat{n}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}$$

- Transverse sphericity: $S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}$

$\lambda_2^{xy} < \lambda_1^{xy}$ are eigenvalues of: $S^{xy} = \sum_i \frac{1}{|\vec{p}_{\mathrm{T},i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}\,p_{y,i} \\ p_{x,i}\,p_{y,i} & p_{y,i}^2 \end{bmatrix}$

Inclusive isolated prompt photon XS background subtraction

- Main background: decay of neutral hadrons (π0, η0)
- Subtracted by data-driven technique: two dimensional side bands
- Photons from π0, η0 decays expected to be less isolated than the prompt ones
  - Due to the activity of other particles in the jet
  - E_T^{iso} is therefore the discriminating variable
- Subtraction:
  - Need of another variable (or set of variables) that:
    - discriminates between background and signal candidates
    - is uncorrelated to E_T^{iso}
  - subset of the tight photon selection criterium based on the shower shape in the first calorimeter layer chosen
  - Sample of candidates split into 4 regions: A=(tight, isolated), B=(tight, non-isolated), C=(non-tight, isolated), D=(non-tight, non-isolated)
  - N^i is the number of entries in region i

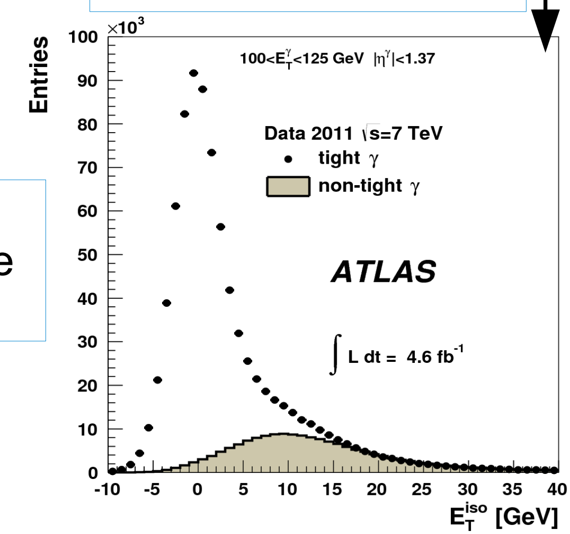


The two samples are assumed to have the same E_T^{iso} distribution (by construction)

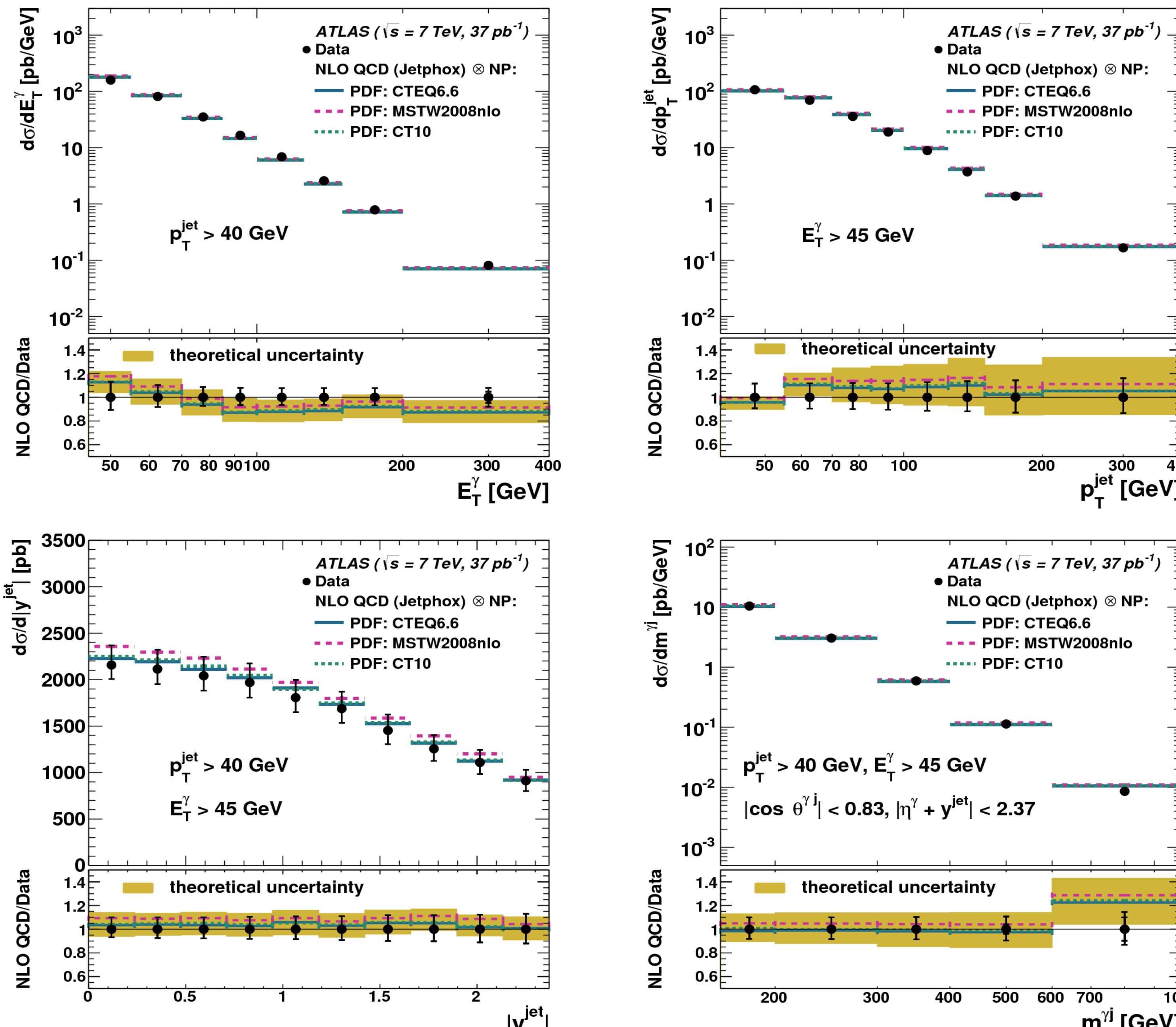
$$N_S^A = N^A - N^C \frac{N^B}{N^D}$$

The exact formula used is slightly modified; but the main idea is this one

Indication of that due to the same shape of E_T^{iso} distribution for E_T^{iso}> 15GeV



Isolated-photon + jet XS



Good agreement with Jetphox NLO prediction for all the variables

Isolated-photon pair cross section

- Pythia: LO MC generator with parton shower
- SHERPA: similar and includes NLO higher-order real-emission matrix elements
- Pythia and SHERPA describe data reasonably
  - Parton showers used take care of the resummation the soft gluon leading logarithms (good $\Delta\phi_{\gamma\gamma}$ description at π)
  - Good description of low $p_{\mathrm{T},\gamma\gamma}$ and $\Delta\phi_{\gamma\gamma}$ region in SHERPA (due to NLO contribution and different parton shower)
  - Both underestimate the total XS (in the figures scaled by 1.2)
- Large $\cos\theta^{*}_{\gamma\gamma}$ sensitive to fragmentation and therefore fixed-order predictions fail to describe it; however SHERPA does a good job