# Recent results on soft QCD topics, and jet and photon production from ATLAS

## HEP2016
### Valparaiso, Chile

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on behalf of the ATLAS Collaboration

January 9, 2016

# Outlook

ATLAS has performed several measurements of phenomena connected to QCD at soft scales or at the transition to the hard regime

- Sensitive to non-perturbative models of soft QCD
  - elastic, inelastic and total cross sections in pp collisions (ATLAS: Nucl. Phys. B (2014) 486-548)
    - inelastic cross section in pp collisions (ATLAS-CONF-2015-038) 13 TeV
  - properties of the underlying event interactions (ATL-PHYS-PUB-2015-019) 13 TeV
  - properties of minimum bias (ATLAS-CONF-2015-028) 13 TeV
  - particle production and their correlations, as well as diffractive and exclusive events

    PRD 91 (2015) 032004, PLB 749 (2015) 242-61, CERN-PH-EP-2015-227

- Sensitive to hard QCD, parton densities of the proton, as well as fragmentation models
  - inclusive jet production differential cross section (ATLAS-CONF-2015-034) 13 TeV
  - inclusive photon and diphoton distributions (ATL-PHYS-PUB-2015-016, ATL-PHYS-PUB-2015-020) 13 TeV
  - jet production properties and determination of the strong coupling constant alpha_s

    JHEP02(2015)153, Eur. Phys. J. C75 (2015) 228, Physics Letters B 750 (2015) 427-447, arXiv:1509.05190, arXiv:1509.07335

Due to time constraints, this presentation will focus on most recent results!

A complete list of ATLAS Standard Model results can be found here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

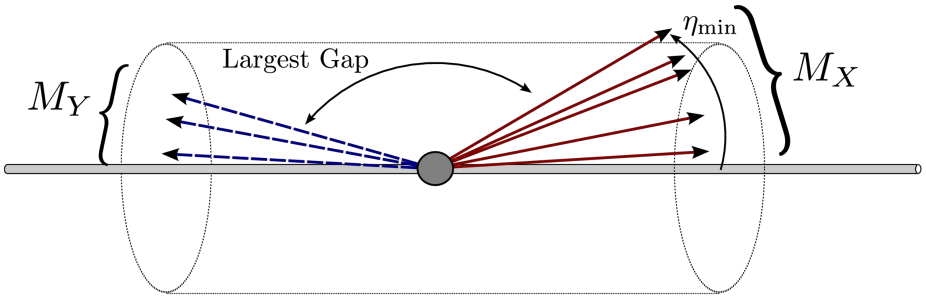
# pp inelastic cross section at 13 TeV

## ATLAS-CONF-2015-038

- June 2015: 13 TeV but mean number of pp interactions per bunch crossing was $\mu=2.3\times10^{-3}$ (integrated luminosity $63\pm6\ \mu b^{-1}$)

- Using Minimum Bias Trigger Scintillators (MBTS) mounted in front of the forward calorimeters:
  - at ±3.6 m from IP, covering $2.07 < |\eta| < 3.86$

- Inelastic interaction: at least one of the two protons dissociates




- Fiducial measurement limited by the phase space where the larger of the invariant masses $M_x$ is within the detector acceptance: $\tilde{\xi} = M_X^2 / s > 10^{-6}$

# pp inelastic cross section at 13 TeV

## ATLAS-CONF-2015-038

- Fiducial measurement limited by the phase space where the larger of the invariant masses $M_x$ is within the detector acceptance

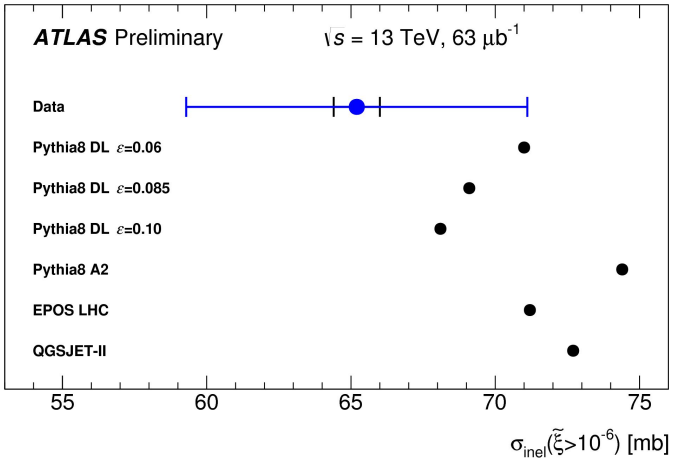
$$\sigma_{\text{inel}}(\tilde{\xi} > 10^{-6}) = \frac{N - N_{\text{BG}}}{\epsilon_{\text{trig}} \times L} \times \frac{1 - f_{\tilde{\xi}<10^{-6}}}{\epsilon_{\text{sel}}}$$

- Values used in the calculation:

| Factor | Value | Rel. unc. |
|---|---|---|
| Number of selected events ($N$) | 4159074 | – |
| Number of background events ($N_{\text{BG}}$) | 43512 | ±100 % |
| Luminosity [$\mu\text{b}^{-1}$] ($L$) | 62.9 | ±9 % |
| Trigger efficiency ($\epsilon_{\text{trig}}$) | 99.7% | ±0.1 % |
| MC Correction factor ($(1 - f_{\tilde{\xi}<10^{-6}})/\epsilon_{\text{sel}}$) | 0.993 | ±0.5 % |

- Measurement compared to MC predictions

| Source | Value |
|---|---|
| This measurement | $65.2 \pm 0.8$ (exp.) $\pm 5.9$ (lum.) mb |
| Pythia8 DL, $\epsilon = 0.06$ | 71.0 mb |
| Pythia8 DL, $\epsilon = 0.085$ | 69.1 mb |
| Pythia8 DL, $\epsilon = 0.1$ | 68.1 mb |
| Pythia8 A2 | 74.4 mb |
| EPOS LHC | 71.2 mb |
| QGSJET-II | 72.7 mb |



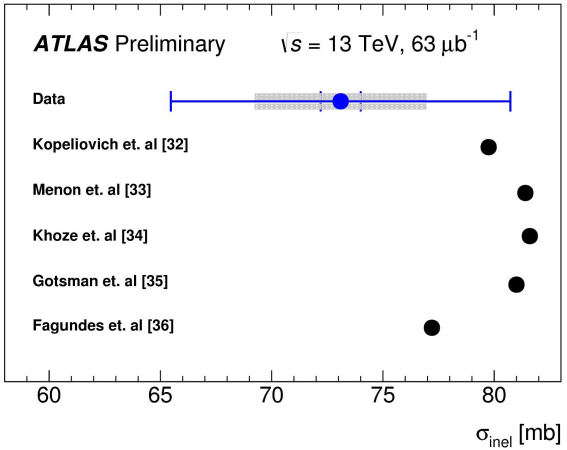
# pp inelastic cross section at 13 TeV

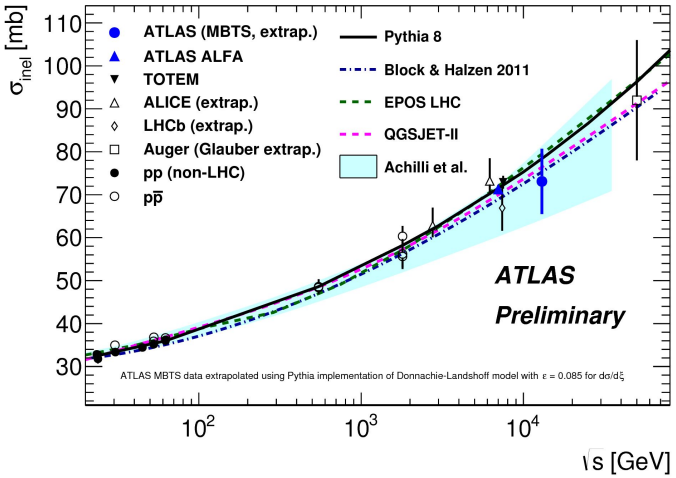
## ATLAS-CONF-2015-038

- Extrapolation to full inelastic cross section using models of inelastic interactions
- Depending on models, acceptance ranges from 87.6% to 93.7%
- Final value is

$$73.1 \pm 0.9\,(\text{exp.}) \pm 6.6\,(\text{lum.}) \pm 3.8\,(\text{extr.})\ \text{mb}.$$

- About 1-1.5 standard deviations below theoretical predictions currently available

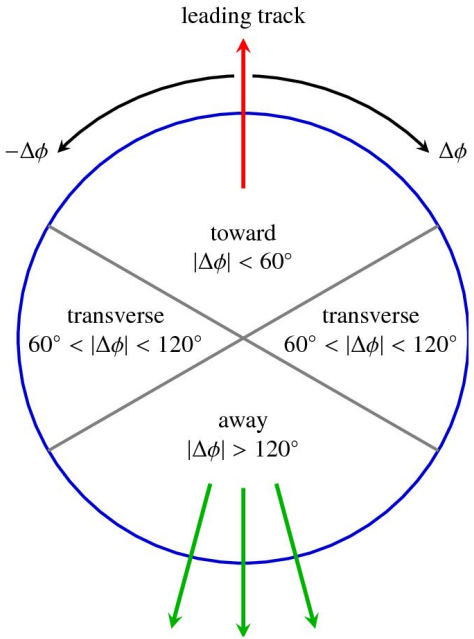


# Detector-level underlying event distributions at 13 TeV

## ATLAS-PHYS-PUB-2015-019

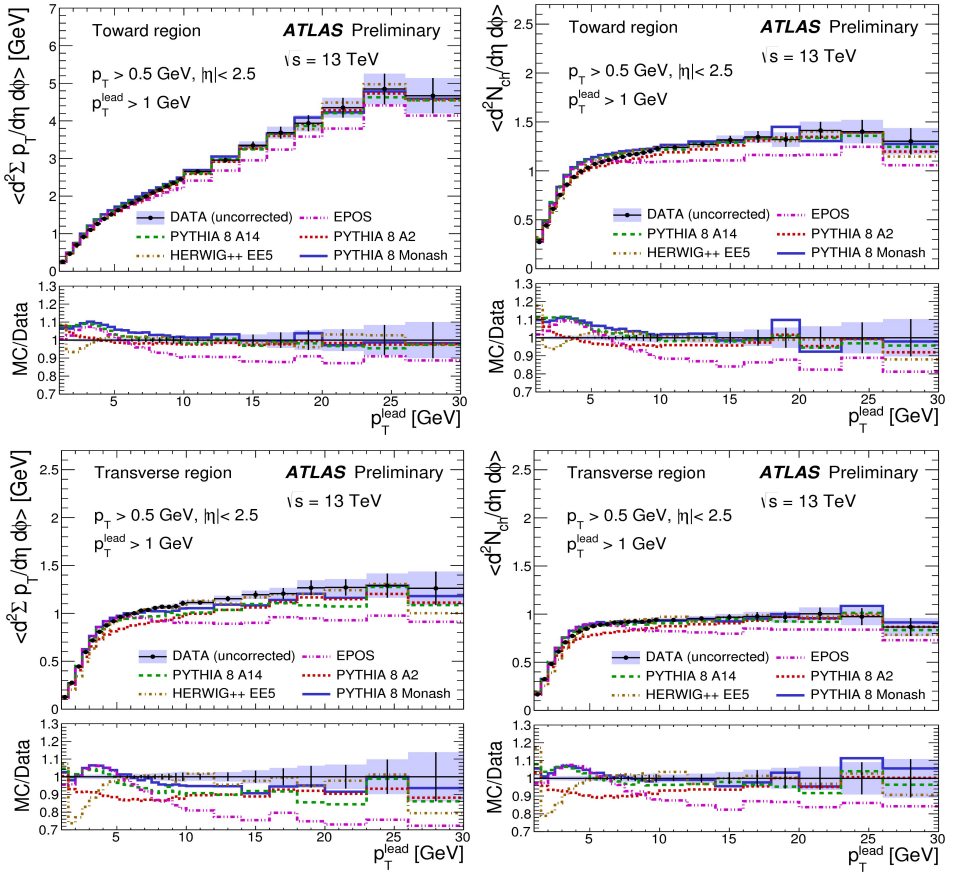
- UE: any hadronic activity not associated with hard scattering process
- Typically modelled with
  - multiple parton interactions
  - initial/final-state radiation
  - colour reconnection with beam remnants
- Strategy:
  - Identify a “hard scatter” using a reference object (eg. jet/Z/track)
  - Define azimuthal regions with respect to this leading object
    - Toward and transverse regions most sensitive to the underlying event
    - High $p_T$ recoil important in away region → perturbative QCD
  - Reconstruct kinematics from charged tracks



# Detector-level underlying event distributions at 13 TeV

**ATLAS-PHYS-PUB-2015-019**

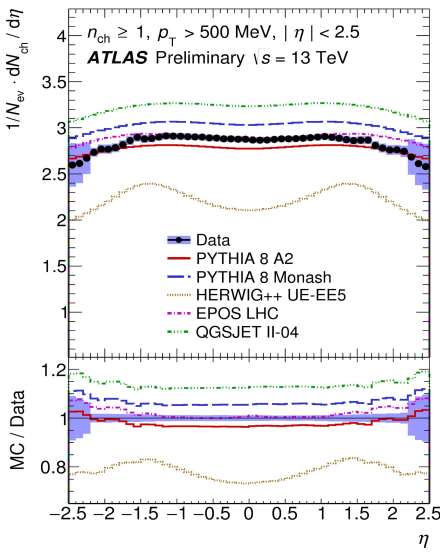
- Preliminary result: detector-level distributions
- Predictions show good agreement with data in toward region
- Greater discriminating power in transverse region
  - Still only minor discrepancies from the data
  - MPI energy extrapolation working well

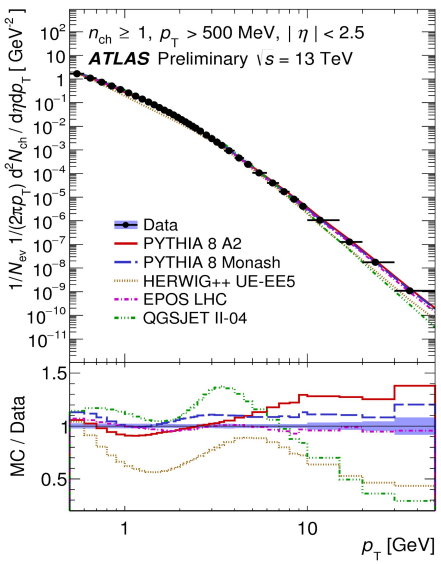


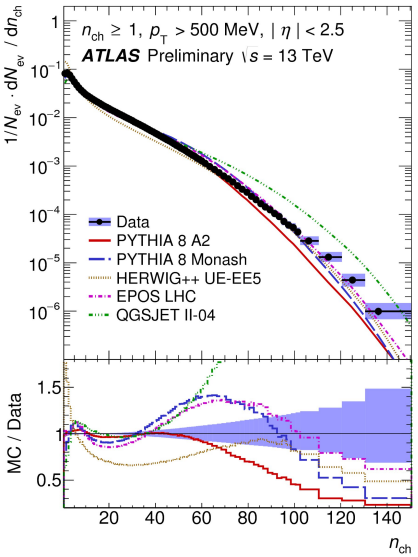
# Track-based minimum bias at 13 TeV

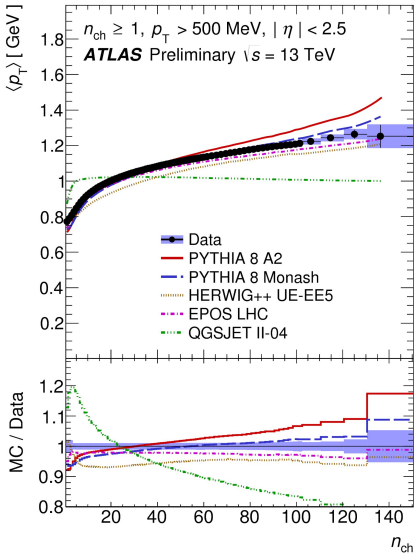
## ATLAS-CONF-2015-028

- Inclusive charged-particle measurements in pp collisions provide insight into the strong interaction in the low energy, non-perturbative QCD region



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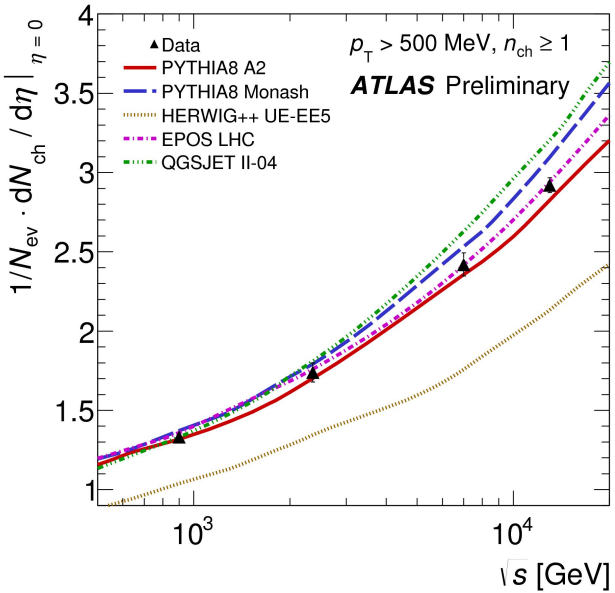
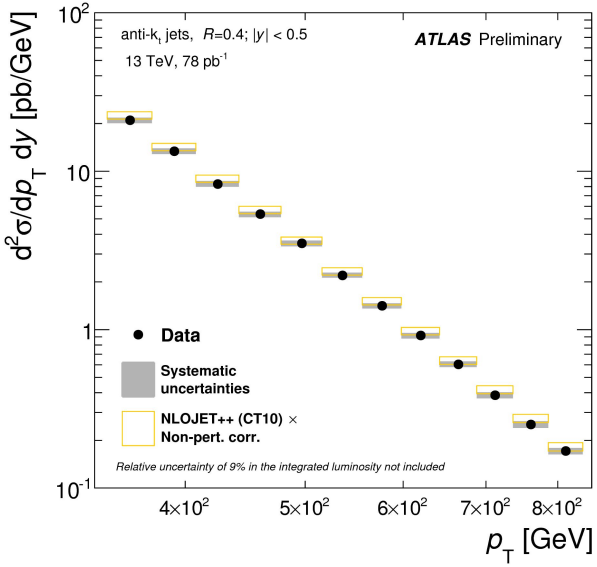


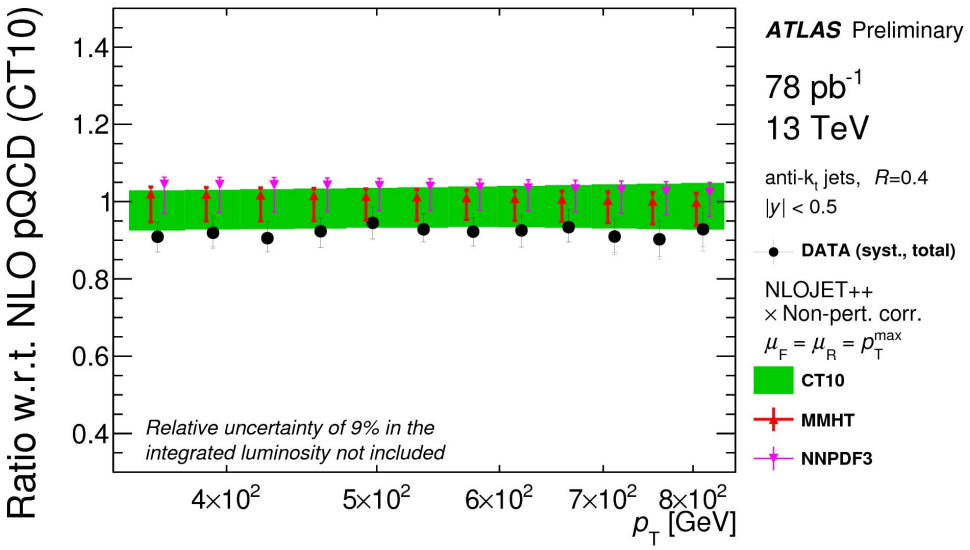

- MC tunes describe the data reasonably well at this new centre-of-mass energy

# Inclusive jet cross section at 13 TeV

## ATLAS-CONF-2015-034

- 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, in the jet rapidity range of $|y^{jet}| < 0.5$
- Data unfolded to particle-level using modified Bayesian technique



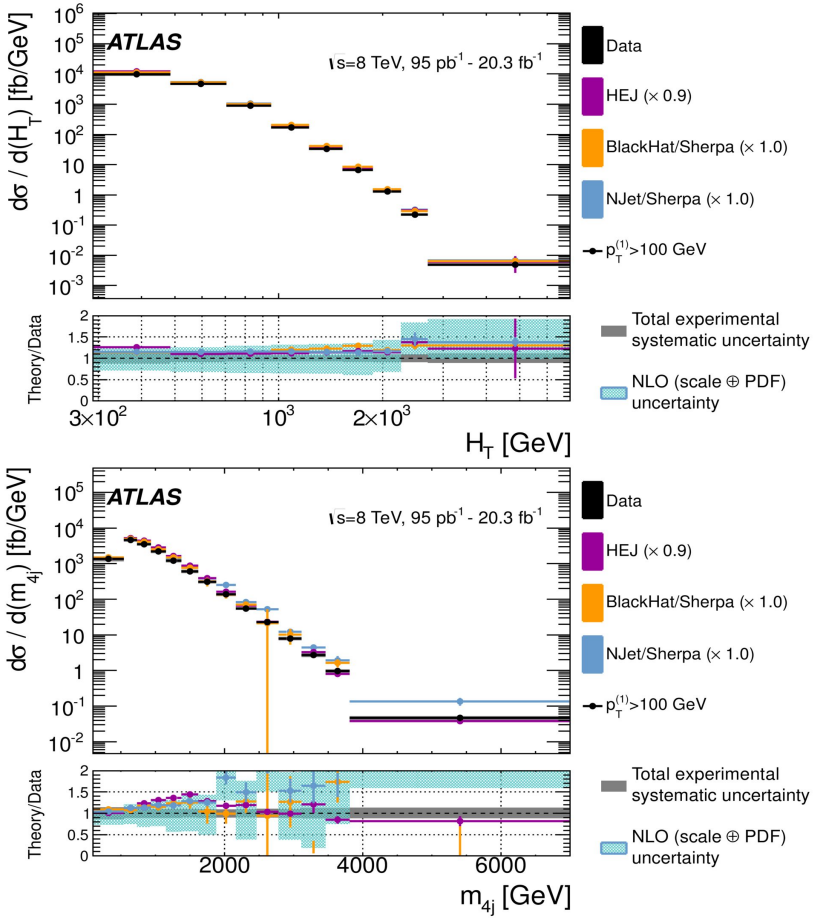




- NLO pQCD predictions, corrected for non-perturbative effects, are consistent with the data

# Four-jet cross section at 8 TeV

**CERN-PH-EP-2015-181**

- Measurement of differential cross sections for events with at least four jets
- 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 both NLO up to 3 TeV and HEJ at high masses
- NLO uncertainties are relatively large O(30%) at low momenta



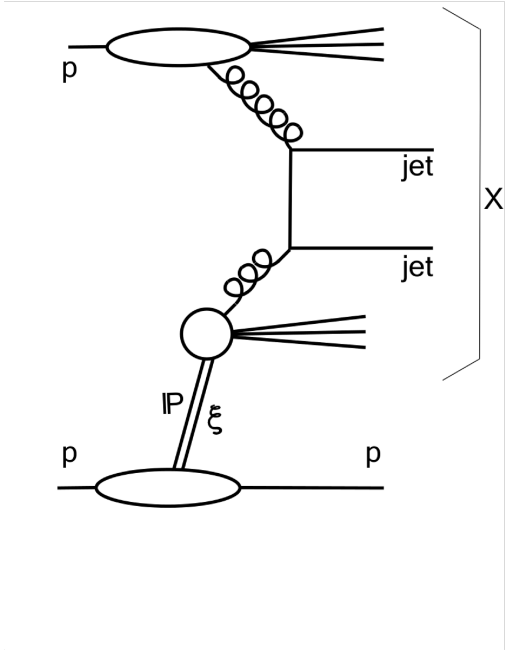
# Diffractive di-jet production at 7 TeV

## CERN-PH-EP-2015-227

- A 6.8 $nb^{-1}$ low pile-up sample of pp collision data (peak $<\mu>$ ~ 0.04–0.14)
- Events with at least two jets with $p_T > 20$ GeV and $|\eta^{jet}| < 4.4$
- Quantum numbers of respective initial and final states are the same in diffractive interaction
- Diffractive processes can be identified by
  - the presence of a space devoid of particles, rapidity gap
  - detecting intact forward protons

$$M_X^2 = \sqrt{s} \sum p_T e^{-|\eta|}$$

$$\tilde{\xi} \simeq M_X^2/s = \sum p_T e^{-|\eta|}/\sqrt{s}$$



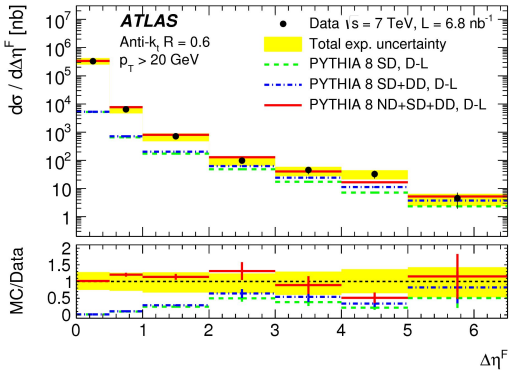

- Diffractive process with hard scale for pQCD calculations
- Sensitivity to underlying parton dynamics and colour singlet exchange
- Sensitivity to soft survival probability, $S^2$

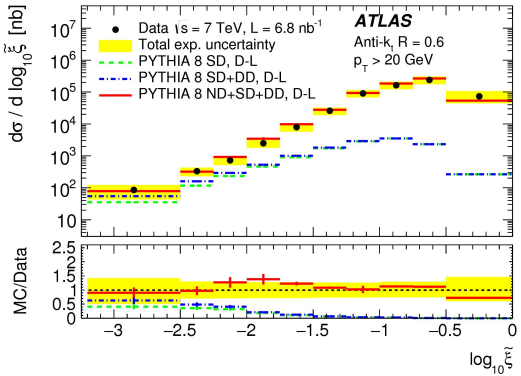
# Diffractive di-jet production at 7 TeV

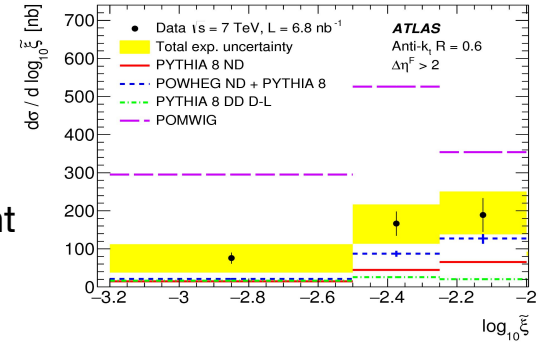
## CERN-PH-EP-2015-227

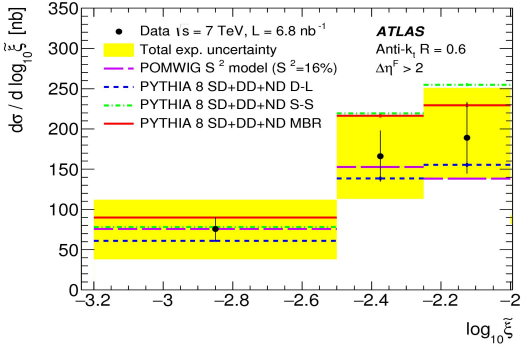
- Non-diffractive MC describe the data over a wide kinematic range
- Diffractive component required for a more complete description
  - particularly when both large $\Delta\eta^F$ and small $\tilde{\xi}$ are required
- PYTHIA8 gives the best description of the shape and normalisation
- Application of a cut $\Delta\eta^F > 2$ significantly reduces non-diffractive background
- The lowest log $\tilde{\xi}$ bin gives model-dependent estimate of the rapidity-gap survival probability

$S^2 = 0.16 \pm 0.04\ (\text{stat.}) \pm 0.08\ (\text{exp. syst.})$



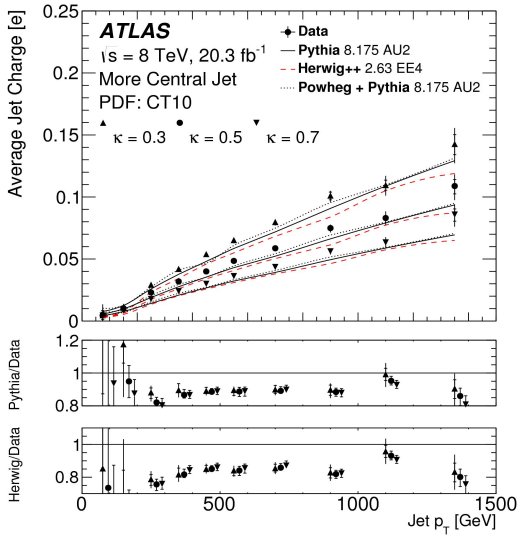



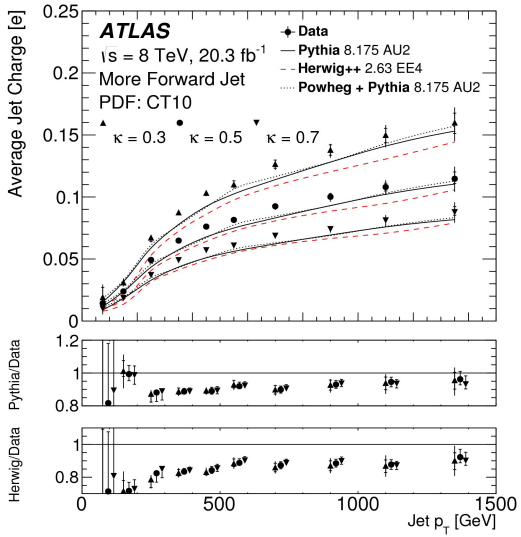



# Jet charge in di-jet events at 8 TeV

**CERN-PH-EP-2015-207**

- Jet charge: momentum-weighted sum of the charges of tracks associated to a jet: $Q_J = \frac{1}{(p_{\mathrm{T}J})^\kappa} \sum_{i \in Tracks} q_i \times (p_{\mathrm{T},i})^\kappa$
  - sensitive to charge of initiating quark or gluon
  - depends on jet flavor, driven by x-dependence of PDFs, and energy-dependence of fragmentation functions
  - can provide constraint on models of jet formation
- Average charge expected to increase with jet $p_T$ due to increased contribution from up-quark initiated jets
- Dijet events:
  - Jet $p_T > 50$ GeV
  - $p_{T1}/p_{T2} < 1.5$
  - $|\eta_{jet}| < 2.1$
  - Tracks for reco-jet + charged particles for particle-jets
  - Track multiplicity and JES are the major systematics



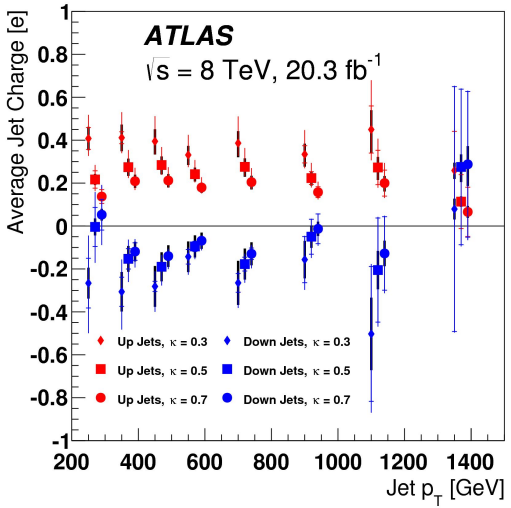




- Comparison with NLO/LO MCs for more central (left) and forward (right) jets.
- Data consistently above predictions, possibly due to fragmentation modelling (not PDFs alone).

# Jet charge in di-jet events at 8 TeV

## CERN-PH-EP-2015-207

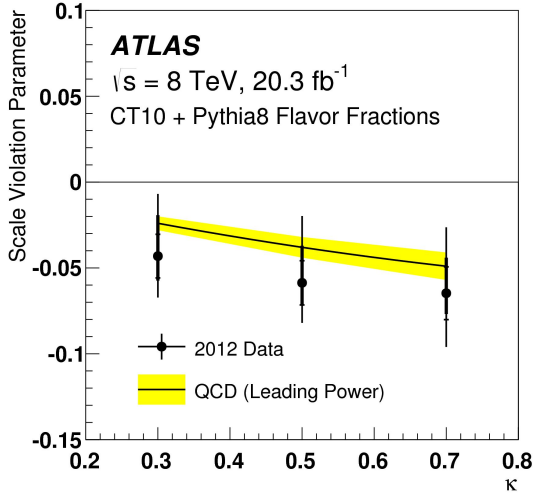
- The charge of up/down quark-initiated jets can be extracted from data using the fraction of such quarks computed in the MC (Pythia with CT10 PDF and AU2 tune)




- Scale violation parameter can be defined as a function of k and then extracted from data using

$$\langle Q_i \rangle \approx \sum_f \alpha_{f,i} \bar{Q}_f (1 + c_\kappa \log(p_{T,i}/\bar{p}_T))$$

$\alpha_{f,i}$: flavour fraction in the i-th $p_T$ bin
$Q_f$ : mean charge at fixed $p_T$ = 700 GeV




- Data supports prediction: $c_k < 0$ and $\partial c_k/\partial k < 0$

# TEEC in multi-jet events at 7 TeV

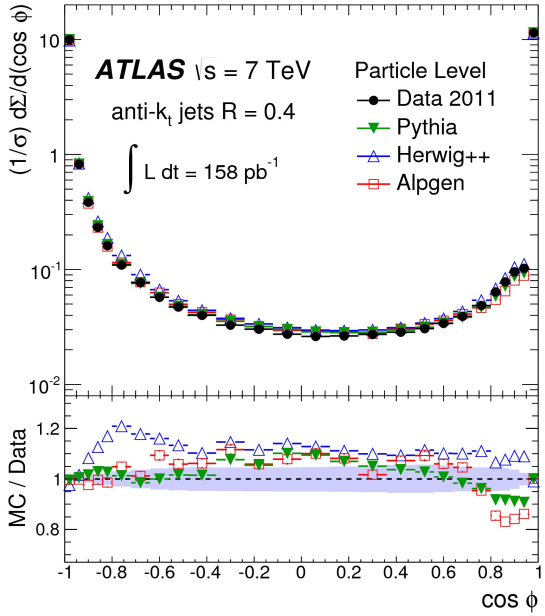
**Physics Letters B 750 (2015) 427-447**

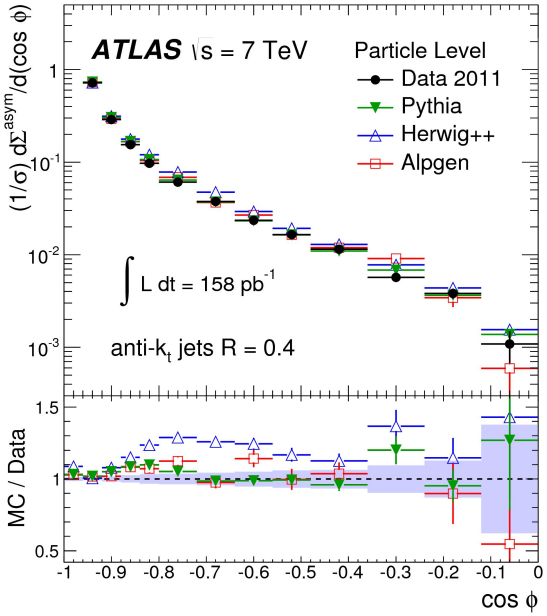
$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj}$$

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

- Transverse energy-energy correlation (TEEC):
  - Event shape used in $e^+e^-$, adapted to pp
  - Exhibits quadratic dependence on $\alpha_s$
  - Measures angular distributions of jet pairs weighted by $w_{ij} = x_{Ti}x_{Tj} = \dfrac{E_{Ti}E_{Tj}}{(\sum_k E_{Tk})^2}$

- Analysis strategy:
  - 158 $pb^{-1}$ of data at 7 TeV
  - at least two jets with $p_T > 50$ GeV
  - $p_{T1} + p_{T2} > 500$ GeV;
  - $|y^{jet}| < 2.5$
  - Total uncertainty is about 5%
    - dominated by the JES
    - pileup
    - MC parton-shower modeling



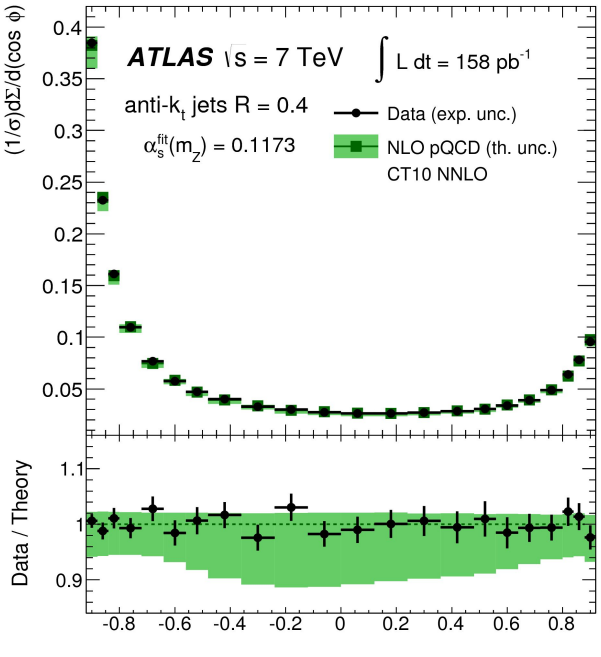

- Pythia/Alpgen predictions agree reasonably well with data, Herwig++ deviates from data by up to 20%

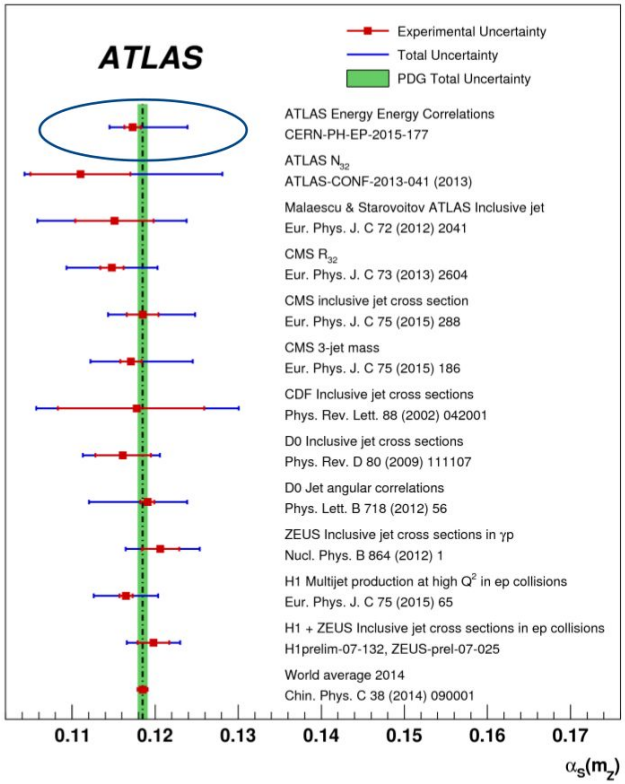
# TEEC in multi-jet events at 7 TeV: $\alpha_s(m_Z)$ measurement

**Physics Letters B 750 (2015) 427-447**

TEEC measurement:

- good agreement with NLO pQCD calculations
- small sensitivity to non-perturbative effects
- theoretical scale unc. dominate over experimental uncertainties




- $\alpha_s(m_Z)$ extraction from $\chi^2$ fit of NLO predictions to data

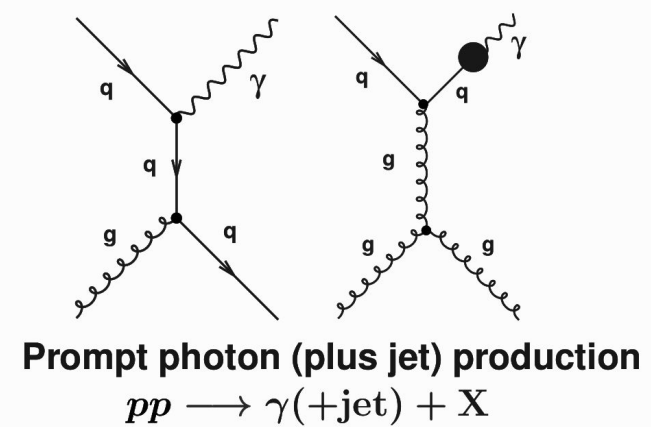
$$\alpha_s(m_Z) = 0.1173 \pm 0.0010\,(\text{exp.})\ ^{+0.0063}_{-0.0020}\,(\text{scale})\ \pm 0.0017\,(\text{PDF})\ \pm 0.0002\,(\text{NPC})$$

- Excellent compatibility between World Average and ATLAS jet-based measurements
- Very good experimental precision. Uncertainty dominated by the unc. in theory predictions

# Prompt photons in pp collisions at 13 TeV

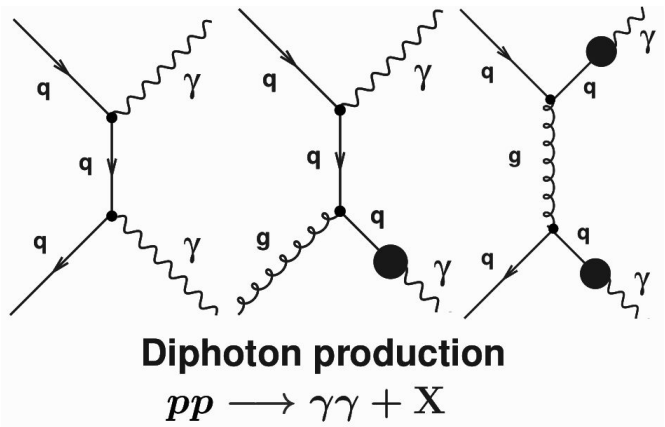
- Measurements of the production of high $p_T$ prompt photons (in association with jets) and pairs of photons in hadron colliders provide
  - tests of pQCD predictions
  - constraints on the proton PDFs
  - input to understand QCD background to Higgs production and BSM searches

- Prompt photons in pp collisions are produced via two mechanisms: direct-photon and fragmentation processes




**Prompt photon (plus jet) production**

$pp \longrightarrow \gamma(+\text{jet}) + \text{X}$




**Diphoton production**

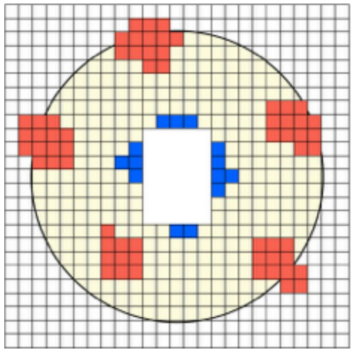
$pp \longrightarrow \gamma\gamma + \text{X}$

# Prompt photon in pp collisions at 13 TeV

- In addition to prompt photons, photons are produced copiously inside jets (eg, $\pi^0$ decays)
  - it is essential to require isolation to study prompt photons in hadron colliders

- The isolation requirement is based on the energy deposited inside a circle of radius R centered on the photon in the η−ϕ plane (not counting energy depositions coming from the photon itself)

$$E_{\mathrm{T}}^{\mathrm{iso}} \equiv \sum_i E_T^i < E_T^{\mathrm{max}}$$

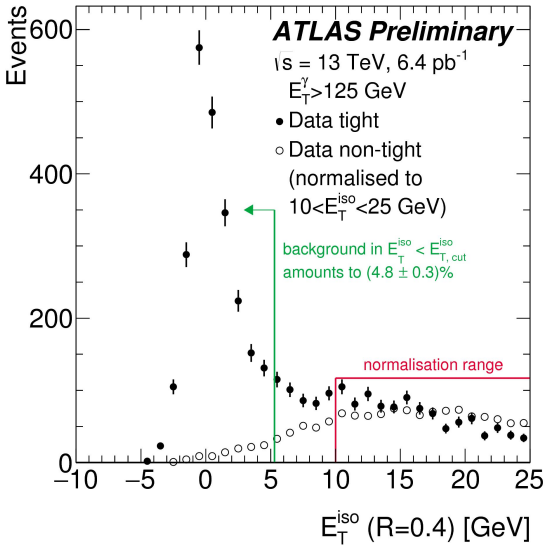


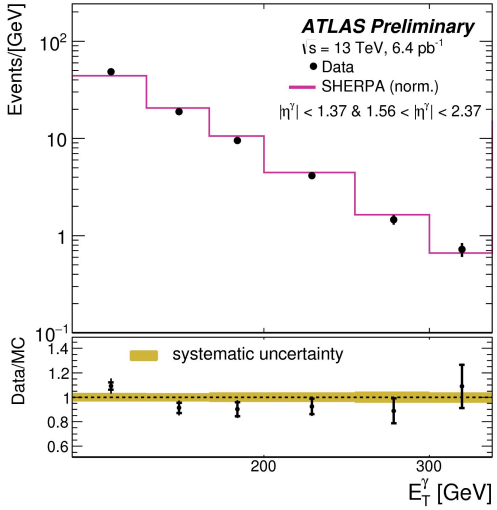
- Is able to suppress most of the contribution of photons inside jets (from $\pi^0$'s and other neutral mesons decays) and the fragmentation contribution

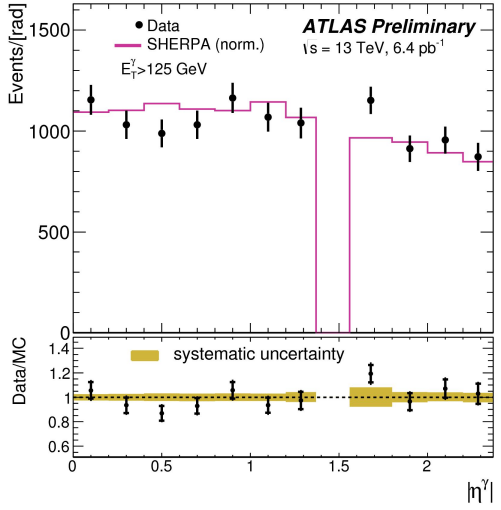
# Inclusive isolated photon distributions at 13 TeV

## ATLAS-PHYS-PUB-2015-016

- Inclusive isolated-photon distributions using 6.4 $pb^{-1}$ ($pp \rightarrow \gamma + X$)
- Photon selection:
  - $E_T^{\gamma} > 125$ GeV and $|\eta^{\gamma}| < 2.37$, excluding the region $1.37 < |\eta^{\gamma}| < 1.56$
  - photon isolation: $E_T^{iso}$ ($R = 0.4$) $< 4.8$ GeV $+ 4.2 \cdot 10^{-3} \times E_T^{\gamma}$



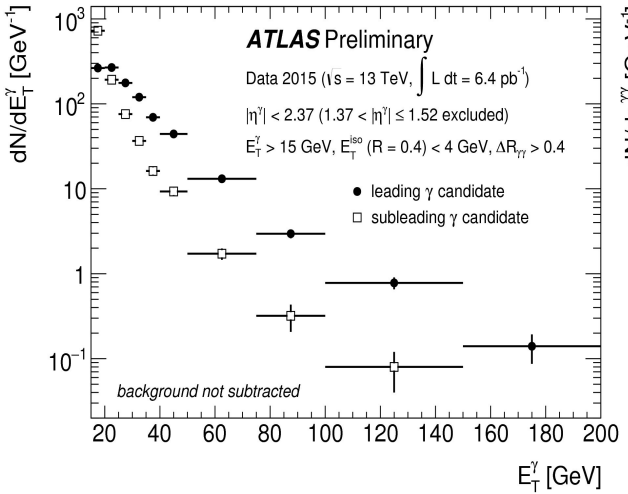



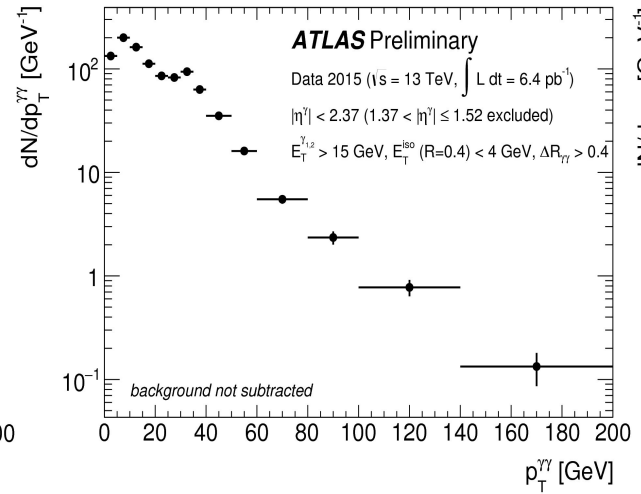

- Clear observation of isolated photon signal at 13 TeV
- Comparison to normalised LO MC predictions. Good description of data by SHERPA 2.1

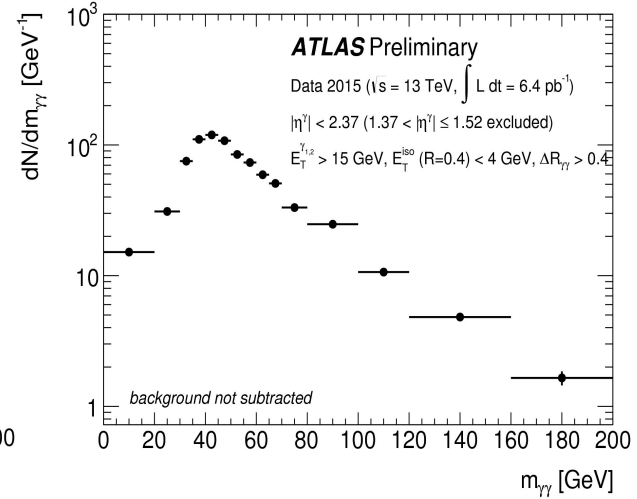
# Diphoton distributions at 13 TeV

## ATLAS-PHYS-PUB-2015-020

- Isolated photon-pair distributions using 6.4 $pb^{-1}$ ($pp \rightarrow \gamma\gamma + X$)
- Photon pair selection:
  - $E_T^{\gamma} > 15$ GeV and $|\eta^{\gamma}| < 2.37$, excluding the region $1.37 < |\eta^{\gamma}| < 1.52$
  - photon isolation: $E_T^{iso}$ ($R = 0.4$) $< 4$ GeV
  - $\Delta R^{\gamma\gamma} > 0.4$




- Clear observation of isolated photon-pair signal at 13 TeV

# Summary

- ATLAS performed a wide range of measurements covering a variety of SM physics aspects

- Soft QCD
  - Inelastic proton-proton cross section at 13 TeV
  - Underlying event at 13 TeV
  - Charged particle multiplicities at 13 TeV

- Jet production and properties
  - Inclusive jet cross section at 13 TeV
  - Four-jet cross section at 8 TeV
  - Diffractive di-jet production at 7 TeV
  - Jet charge in di-jet events at 8 TeV
  - Extraction of QCD coupling constant from TEEC in multi-jet events at 7 TeV

- Photon production
  - First measurements of isolated photon and di-photon distributions at 13 TeV

- … and much more

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

# Thanks