Recent results on soft QCD topics from ATLAS

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on behalf of the ATLAS collaboration

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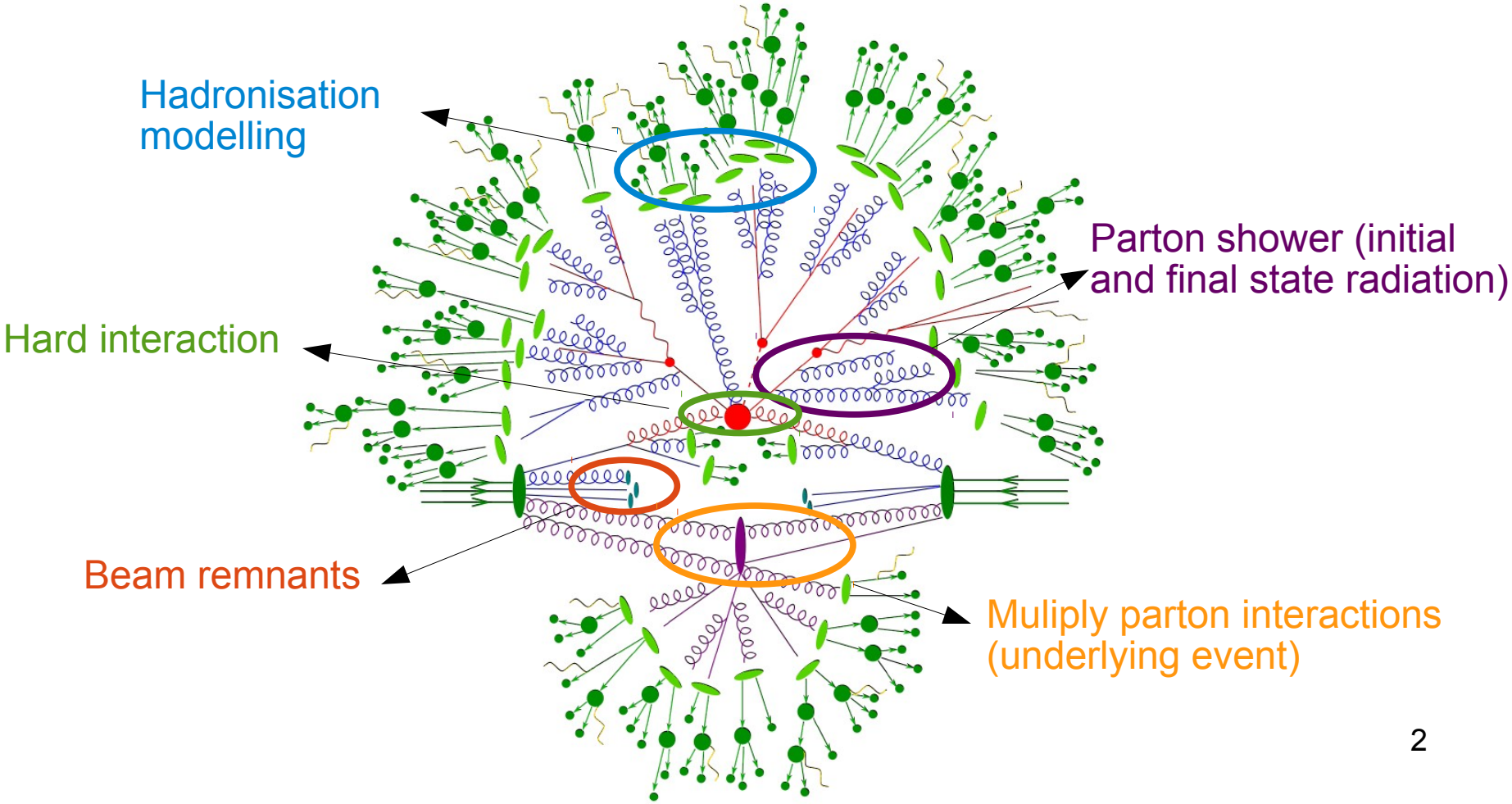
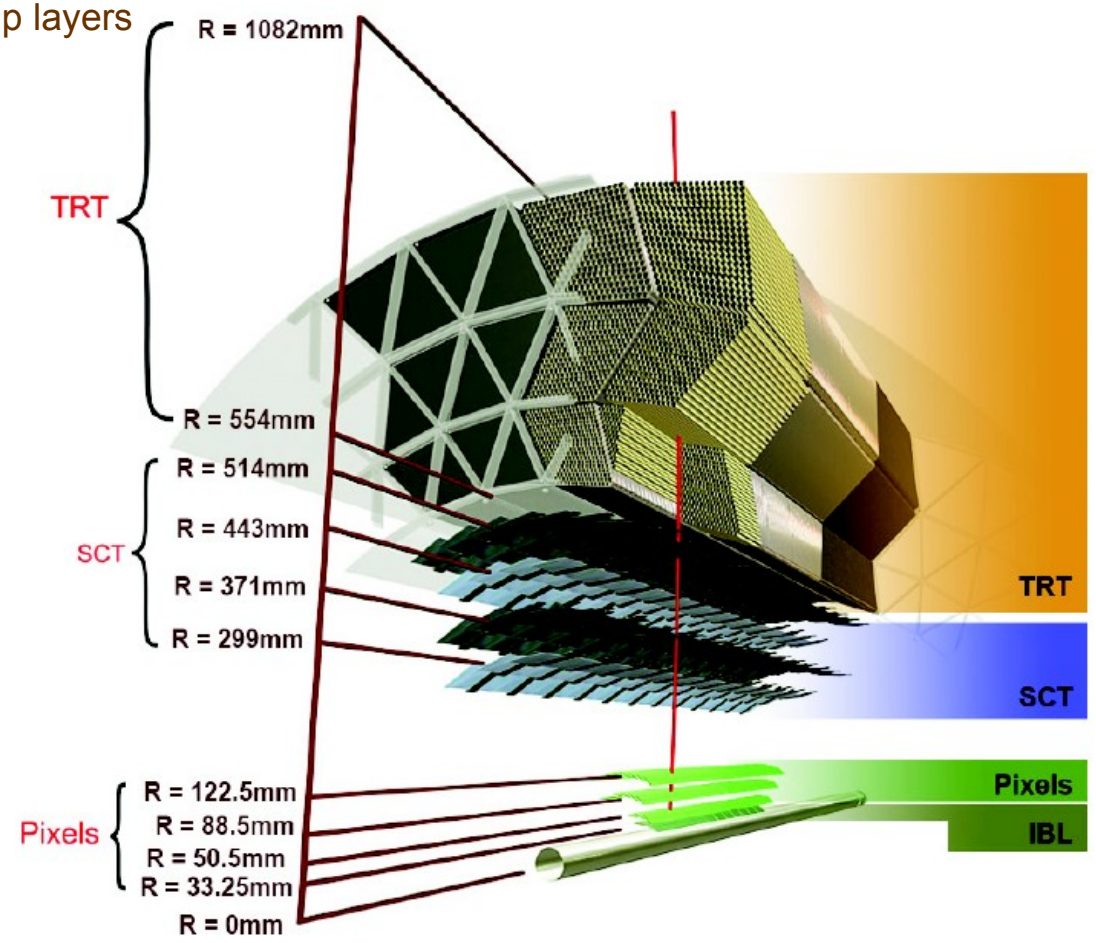
Overview

- Understanding of soft-QCD interactions has direct impact on precision measurements and searches for new physics
  - Soft QCD results used in Monte-Carlo generators tuning
  - Low energy QCD description essential for simulating multiple pp interactions

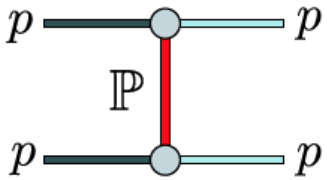
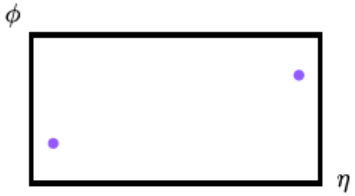
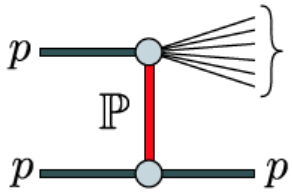
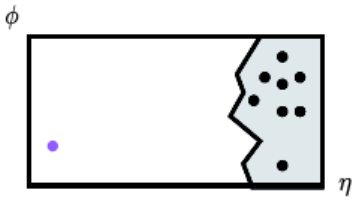
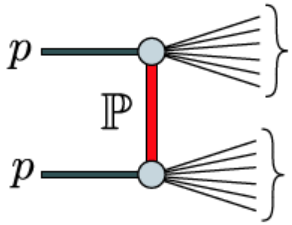
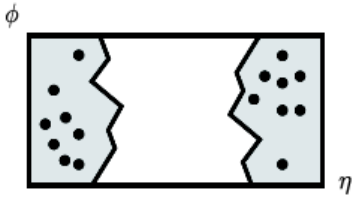
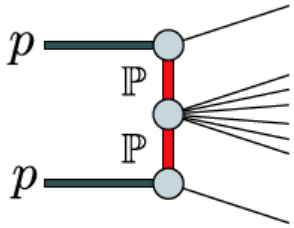
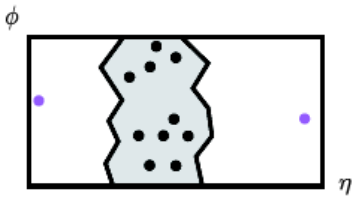


ATLAS @ LHC

- LHC Run 2 started last year at new energy frontier $\sqrt{s}$ = 13 TeV
  - Rebuilt Minimum Bias Trigger Scintillators (MBTS) in $2.07 < |\eta| < 3.86$
  - New Pixel Layer “IBL” at R = 33 mm
- For the following studies most important is Inner detector
  - Silicon Pixel: 3 Barrel + 3 Endcap layers
    - 1.7k modules 80Mpx
  - Silicon Strip (SCT): 4k modules
  - Transition Radiation Tracker
    - Drift Tube: 360k straws



Classifying of the events

Elastic			~25%
Inelastic	Single-Diffractive (SD)	 	~20%
	Double-Diffractive (DD)	 	~5%
	Central-Diffractive (CD)	 	~1%
	Non-Diffractive (ND)	Everything else (~ *t*-channel gluon exchange)	~50%

Total p-p cross-section at √s = 7 TeV

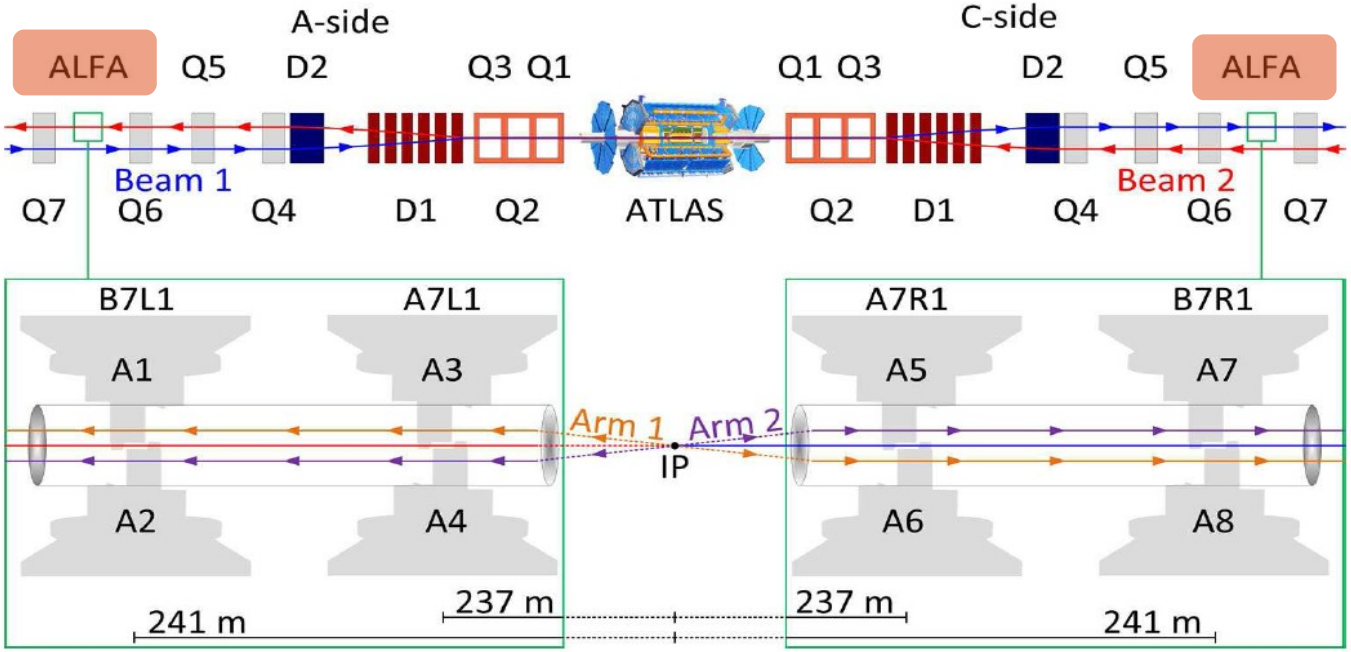
Nuclear Physics, B (2014) 486

- Total cross-section is a basic parameter of strong interactions
  - Can not be calculated from first principles in QCD
- We measure elastic cross-section (as a function of transfer momentum) and determine total x-sec via optical theorem:

$$\sigma_{\mathrm{tot}}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left.\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}t}\right|_{t\to 0}$$

t: Mandelstam variable

- Forward ALFA detectors: 2 pairs of Roman Pots tracking detectors on each side
  - Data collected in special run (beam optics with high β* = 90 m)

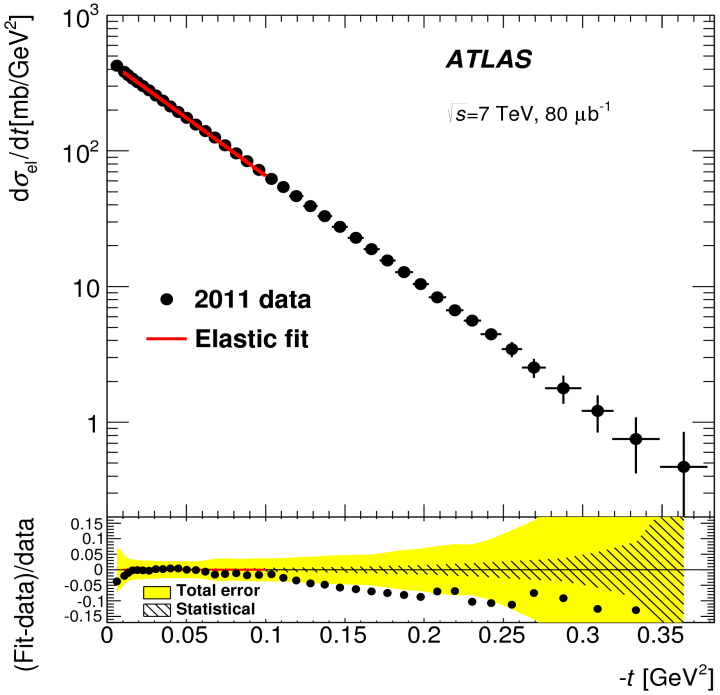


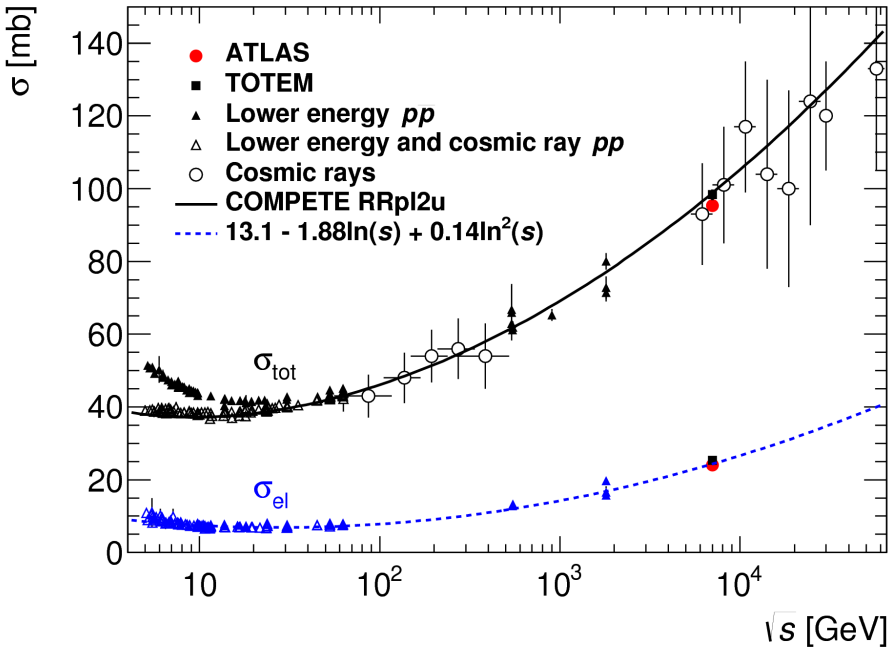
Total cross-section at √s = 7 TeV (cont.)

Nuclear Physics, B (2014) 486

- Measure scattering angle θ*

  → $-t = (\theta^\star \times p)^2$ for p (beam) = 3.5 TeV
- Luminosity precisely measured independently
  → δ = 2.3% → still dominant syst. uncertainty
- $d\sigma_{el}/dt$ fit to theoretical formula: including Coulomb interaction and interference
  - Measure also nuclear slope 'B'
- Elastic cross-section: $\frac{d\sigma_{el}}{dt} = \frac{d\sigma_{el}}{dt}\Big|_{t=0} \exp(-B|t|)$





σ_{tot} = 95.35 ± 0.38 (stat) ± 1.25 (exp) ± 0.37 (extr) mb

B = 19.73 ± 0.14 (stat) ± 0.26 (syst) GeV^{-2}

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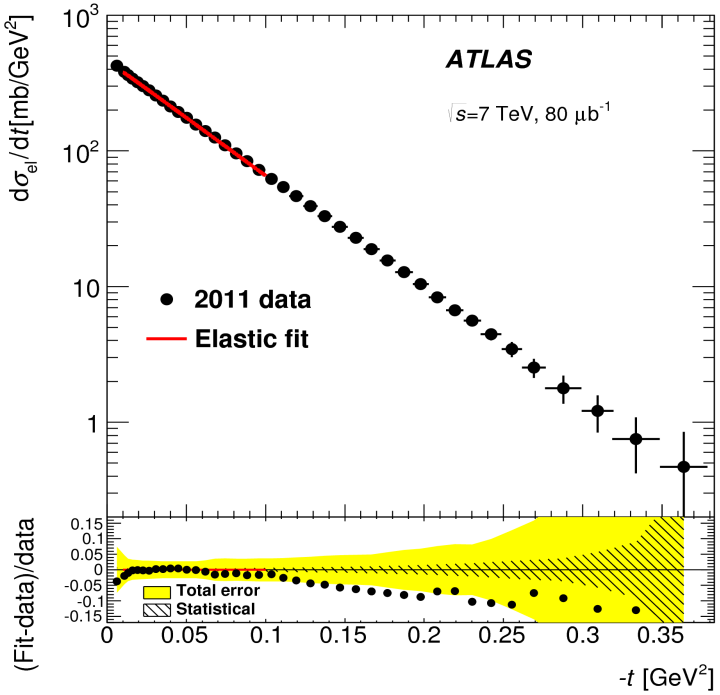
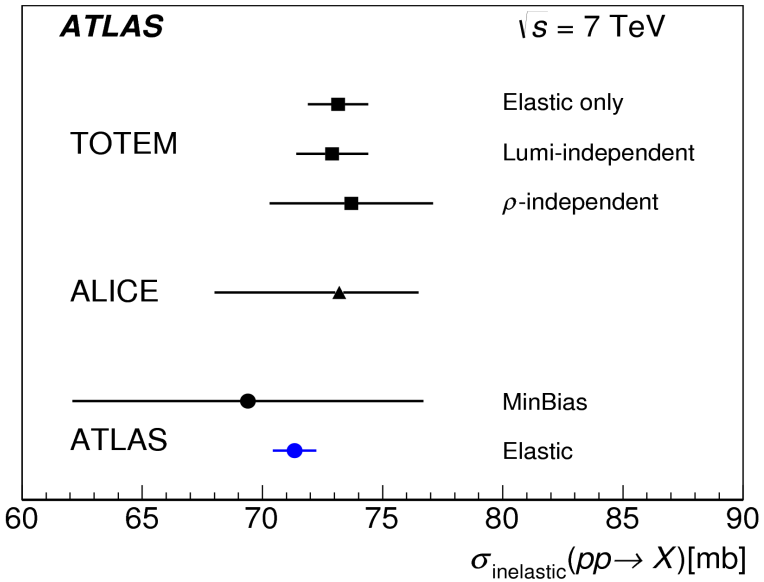




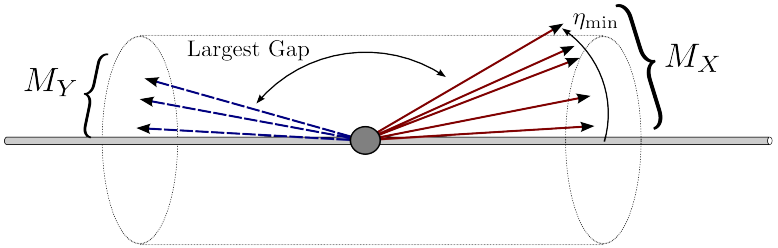
σ_{el} = 24.00 ± 0.19 (stat) ± 0.57 (syst) mb

σ_{inel} = 71.34 ± 0.36 (stat) ± 0.83 (syst) mb

Inelastic pp cross-section at √s = 13 TeV

ATLAS-CONF-2015-038

- Direct measurement using MBTS forward scintillators
  - Require ≥ 2 hits → 4M of events
  - Fiducial region: $M_X^2/s = \xi > 10^{-6}$



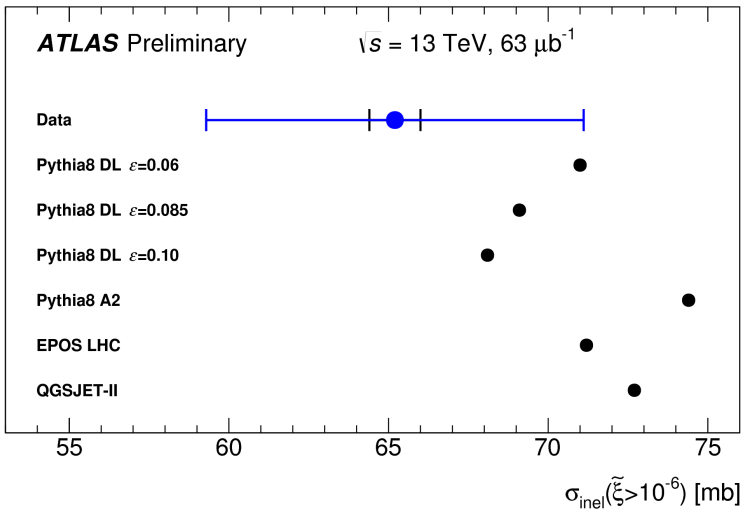
- Two different selections used to constrain the diffraction processes

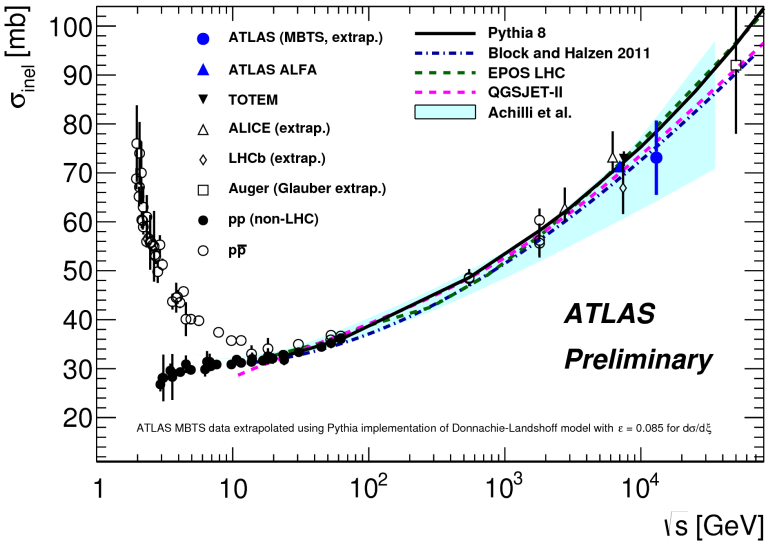
$$\sigma_{\text{inel}}(\tilde{\xi} > 10^{-6}) = \frac{N - N_{\text{BG}}}{\epsilon_{\text{trig}} \times L} \times \frac{1 - f_{\tilde{\xi}<10^{-6}}}{\epsilon_{\text{sel}}}$$

- ~1 sigma lower cross-section than MC predictions

σ_{inel} (ξ >10^{-6}) = 65.2 ± 0.8 (exp) ± 5.9 (lumi)

σ_{inel} = 73.1 ± 0.9 (exp) ± 6.6 (lumi) ± 3.8 (extr)

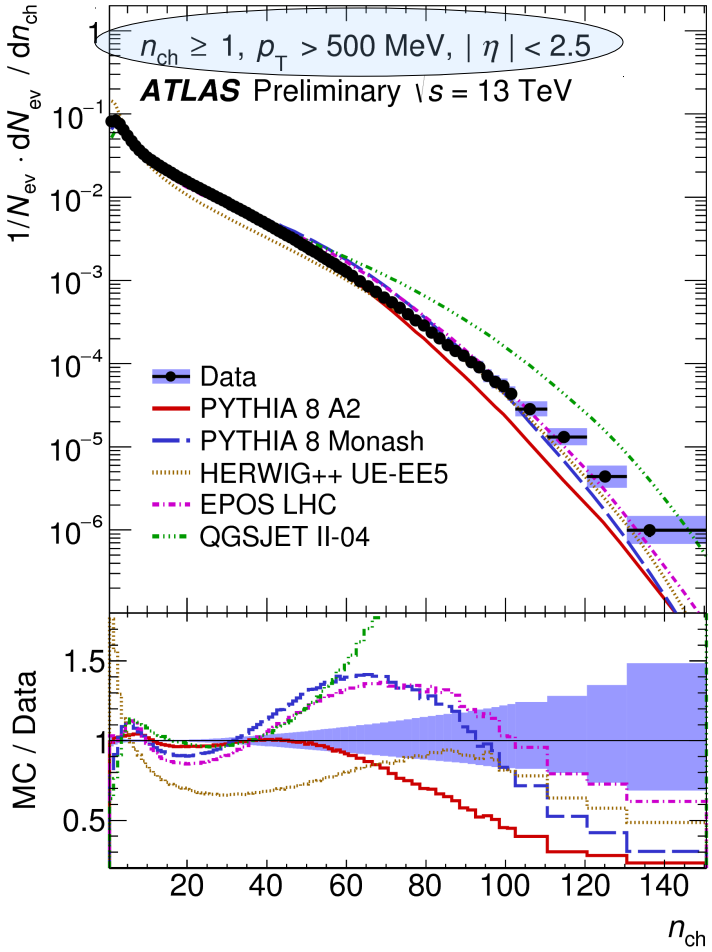




Minimum-bias measurement at √s = 13 TeV

ATLAS-CONF-2015-028

- Provides insight into strong interactions in non-perturbative QCD regime
  - Used in MC tuning, essential for simulating multiple pp interactions
- Measured charged particle multiplicities
  - Charged primary particles: $p_T > 500$ MeV, $\tau > 300$ps (excluding strange baryons)
  - 9M of events in special runs with low pile-up $\langle\mu\rangle = 0.005$ (expect. number of interactions)
  - Correct for trigger, vertex, tracking efficiencies + unfolding for detector effects
- Dominant systematics from track reconstruction efficiency



Pythia: separate diffraction (pomeron) and non-diffraction (ND)

Herwig: no diffractive model, apply MPI to events with no hard-scattering

Epos: parton based Gribov-Regge theory (EFT) (simultaneous hard+soft)

QGSJET-II: phenomenological Reggeon field theory, 'semi-hard Pomeron'

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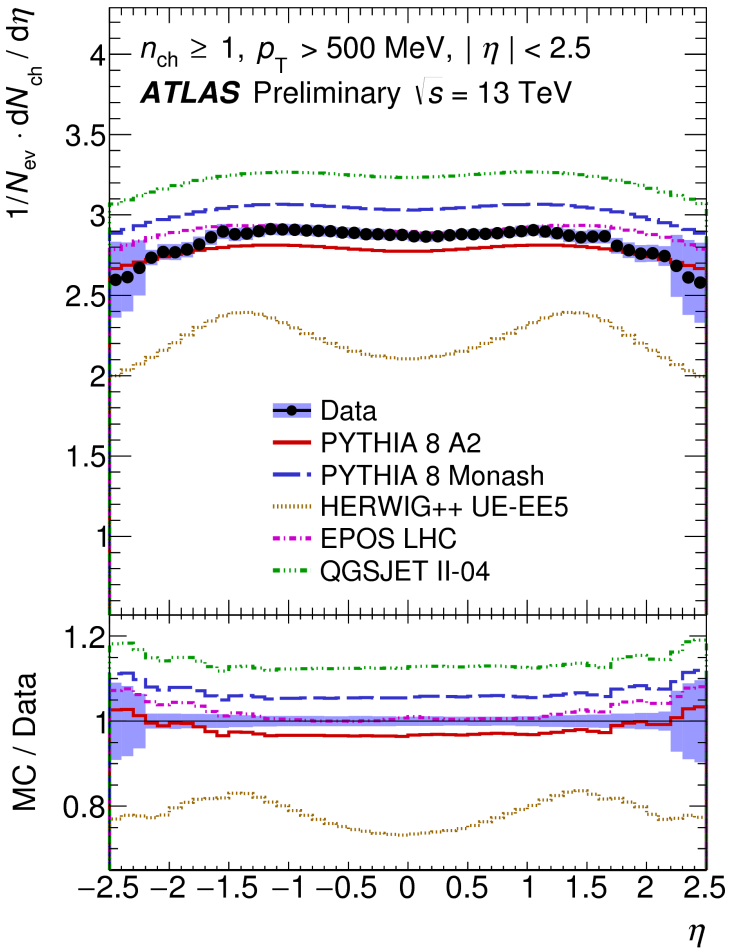

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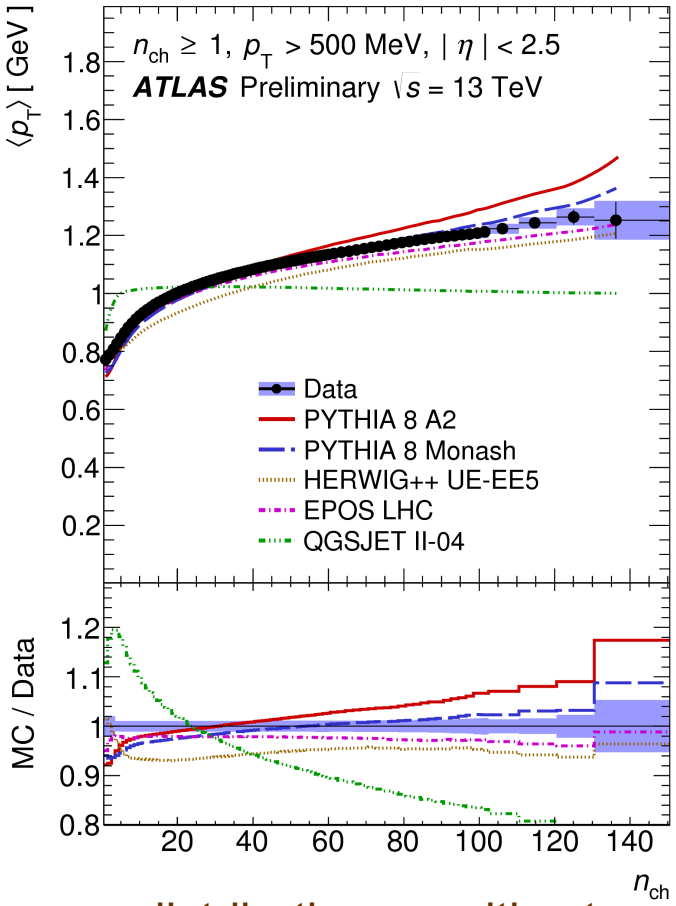
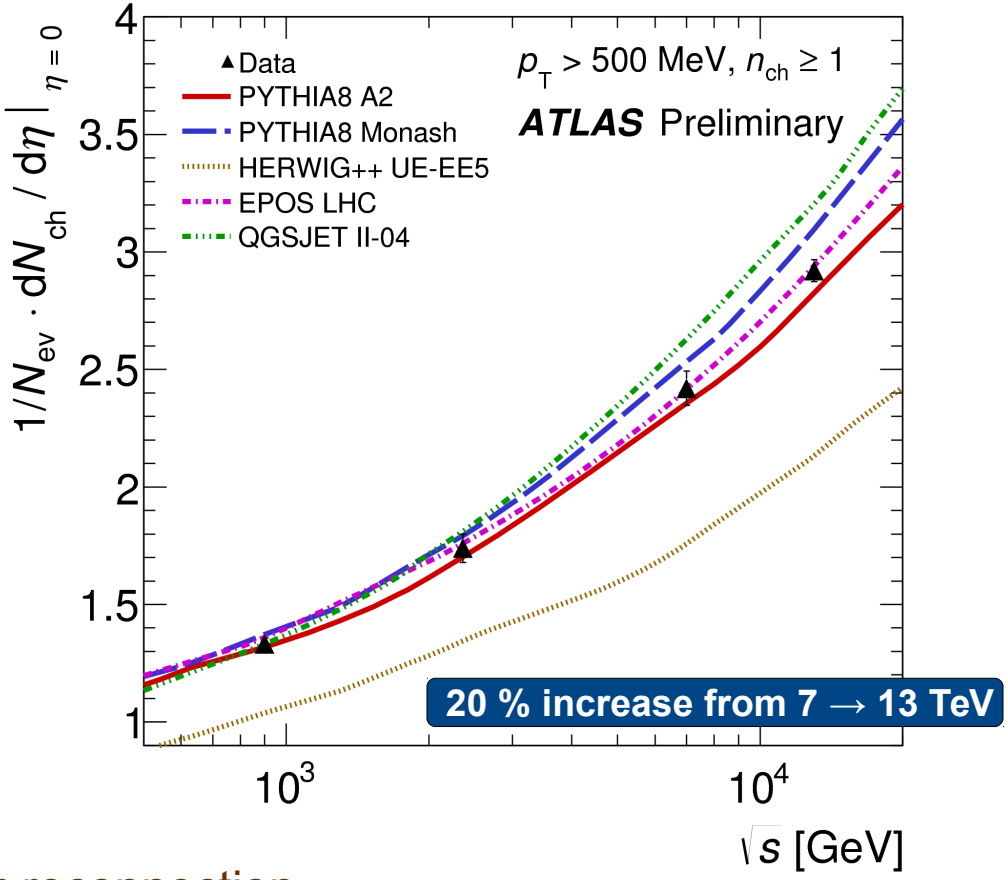
ATLAS-CONF-2015-028



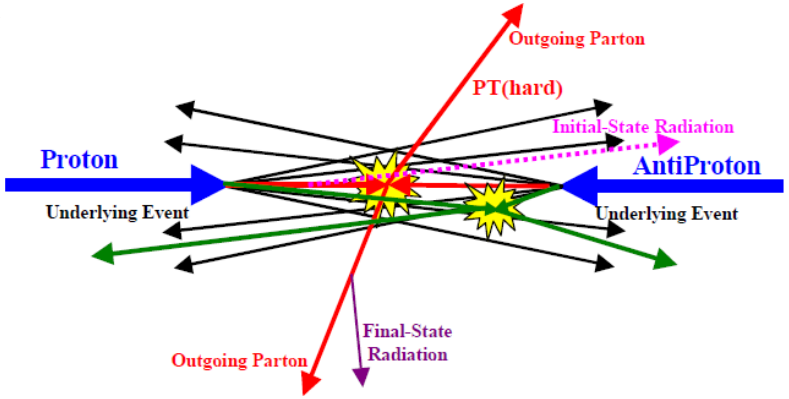


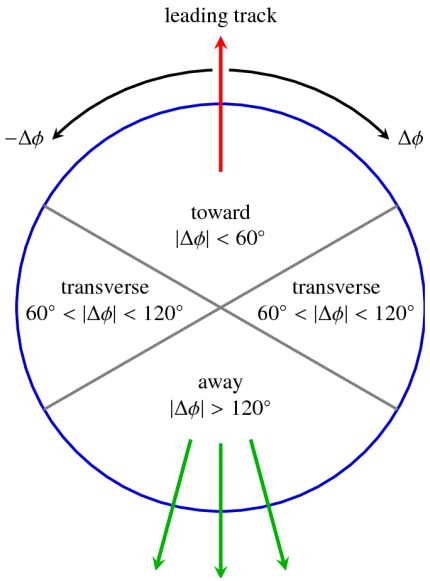
- <p_T> distribution sensitive to color-reconnection
- MC tunes have been already tuned with √s = 7 TeV LHC data
  - Herwig did not use min-bias data
- EPOS best (mainly η,p_T,<p_T>), Pythia 8 A2 (nch<50,η) /Monash (p_T,<p_T>) tunes provide reasonable description

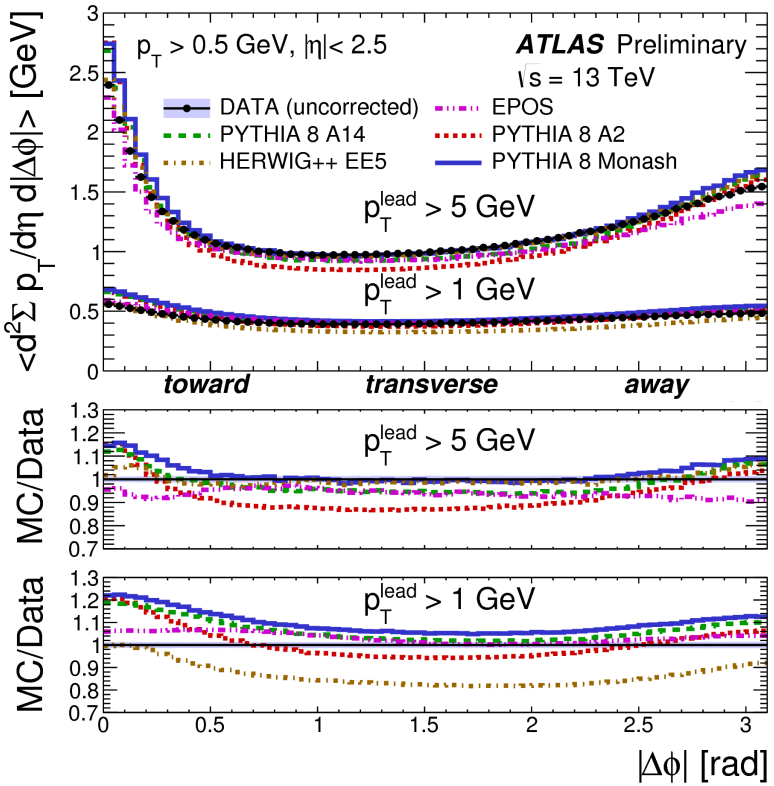
Underlying event (UE) at √s = 13 TeV

ATL-PHYS-PUB-2015-019

- UE: any activity accompanying hard scattering → help to constrain multi-parton interactions in MC





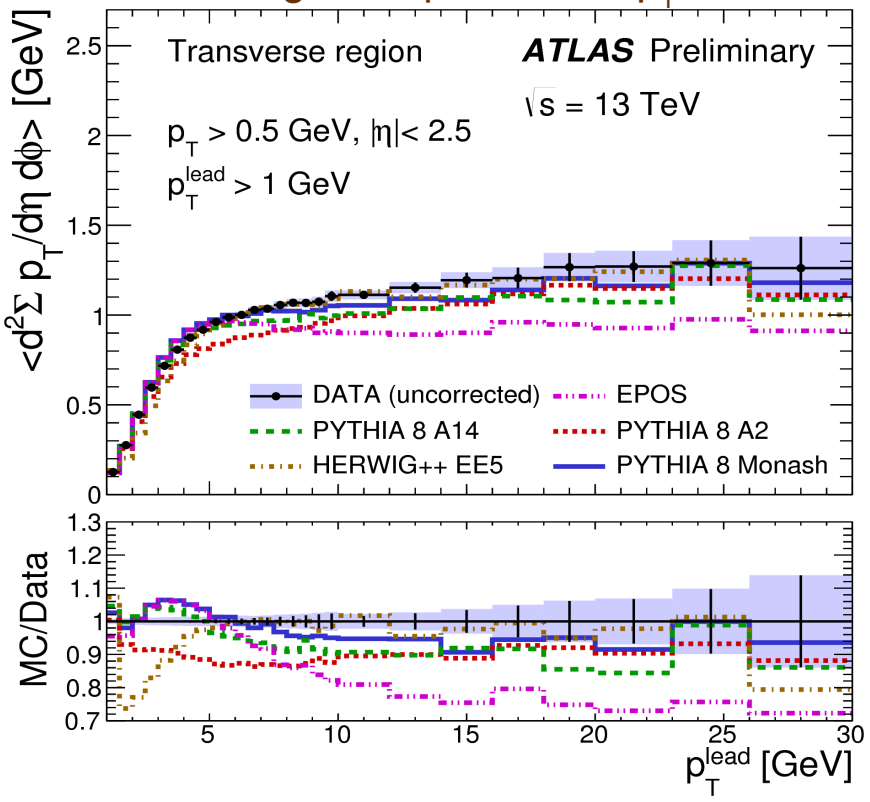


- Transverse region mostly sensitive to UE
- Same selection as for Minimum bias analysis + cut on $p_T^{lead} > 5$ (1) GeV
- Measure densities of N_{ch} and Σp_T of tracks
- Detector level distributions only
- $\Delta|\phi|$: better agreement for higher p_T^{lead}

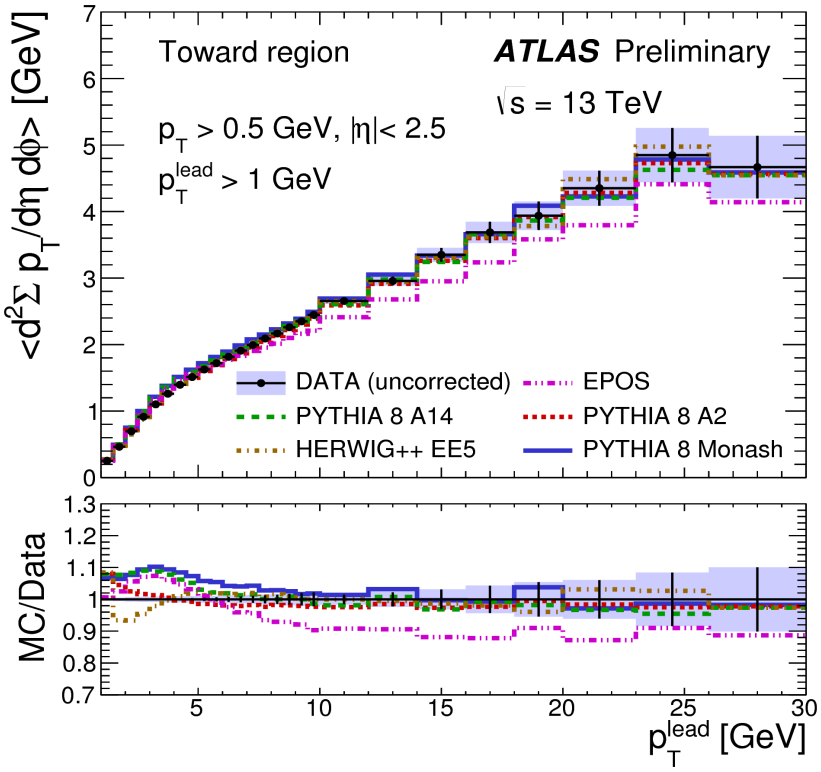
Underlying event at √s = 13 TeV (cont.)

ATL-PHYS-PUB-2015-019

Transverse region: ~ plateau for p_T > 6 GeV



Toward region: contribution from jet-like activity

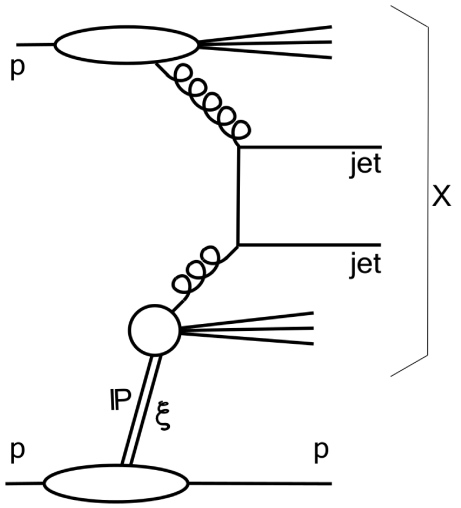


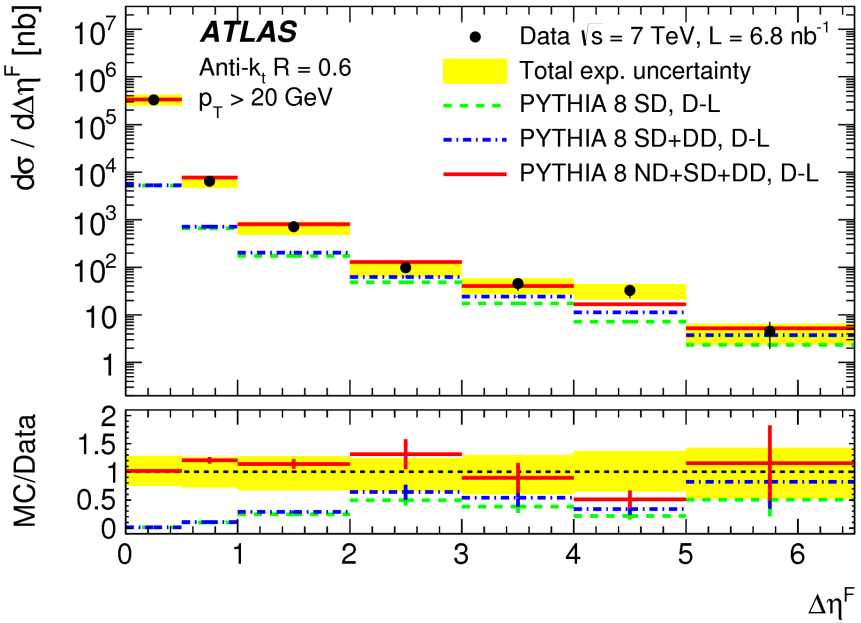
- 20% increase in UE activity comparing to √s = 7 TeV results in Run 1
- Most of the models agree reasonably with the data
  - Confidence in energy extrapolation of multi-parton interactions in MC

Diffractive dijet production at $\sqrt{s}$ = 7 TeV

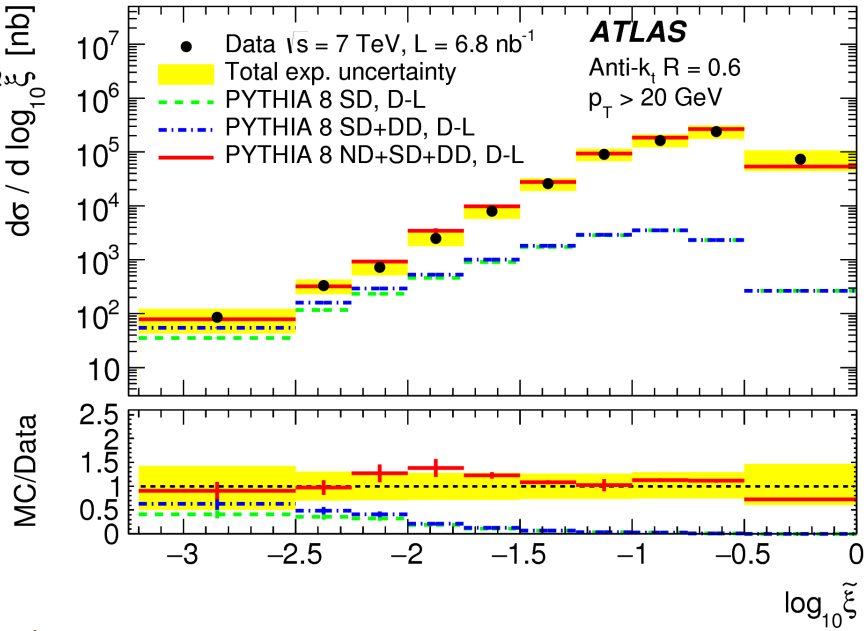
arXiv:1511.00502

- Diffraction is a large fraction of inelastic production
- Diffractive dijet events sensitive to underlying parton dynamics of diffraction and color-singlet exchange
- 2 high-p_T jets with p_T > 20 GeV
- Variables to separate diffractive and non-diffractive events: $\Delta|n_F|$, $\xi \sim M_X^2/s$





$\Delta|n_F|$: size of rapidity gap

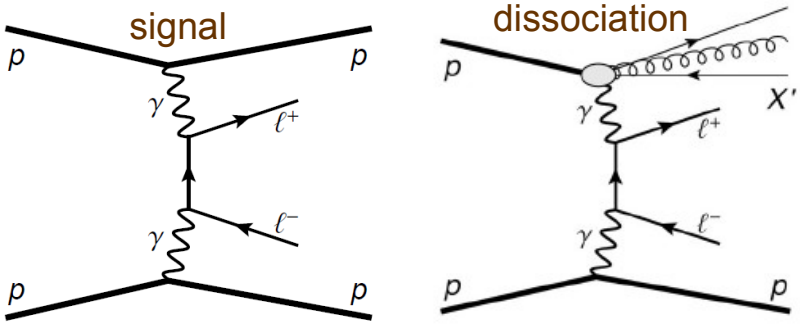


ξ: fractional momentum loss of the proton

Exclusive $\gamma\gamma \rightarrow ll$ (l=e,μ) at $\sqrt{s}$ = 7 TeV

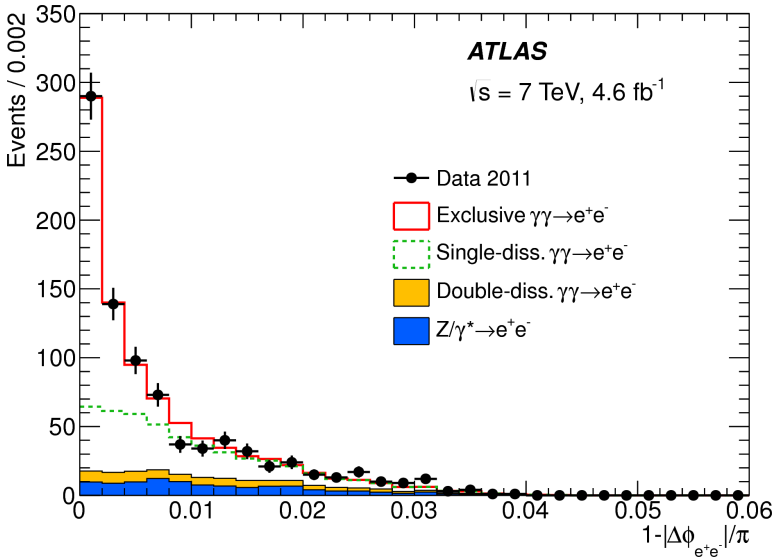
Physics Letters B 749 (2015) 242

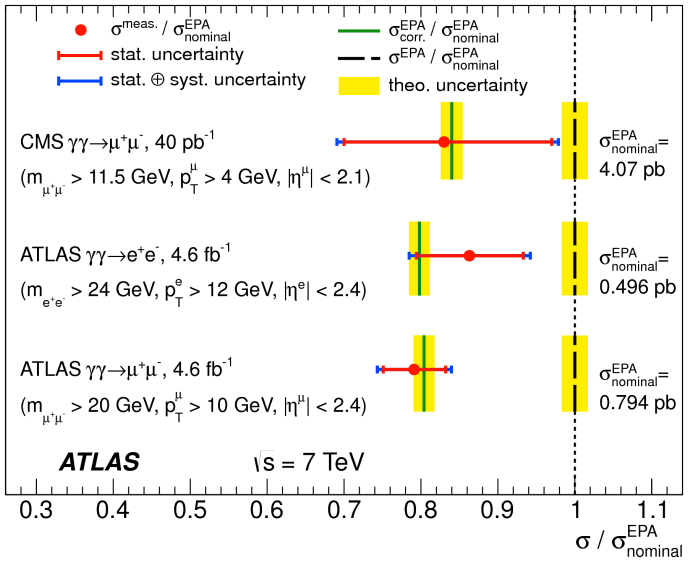
- Can be seen as γ-γ collision (QED)
  - predicted with high precision (2%)
- Simultaneous fit of signal + background to aplanarity: 1 - |Δϕ(ll)|
  - Discrimination between exclusive production and dissociation
- Have to correct for proton absorptive effects due to final proton size



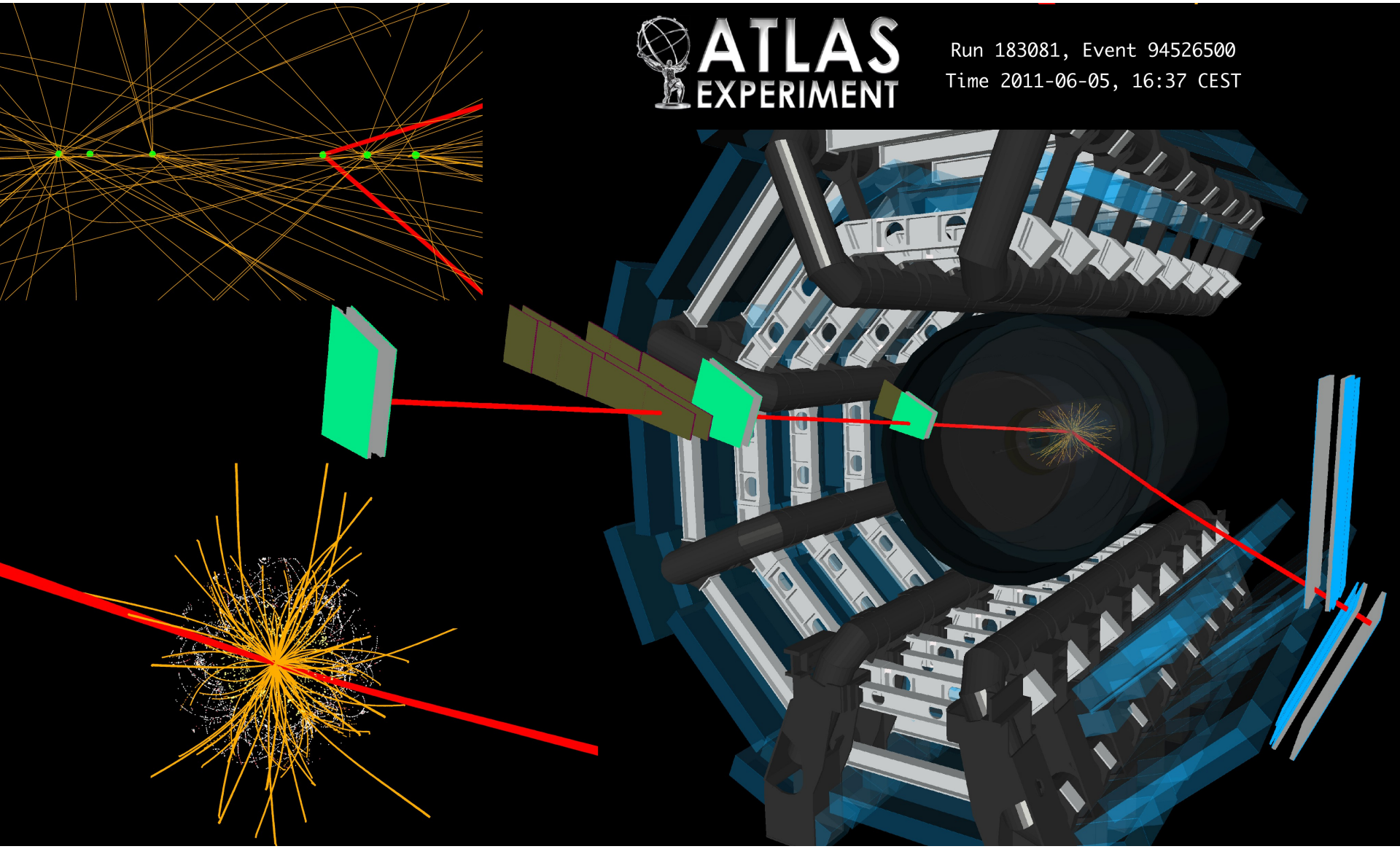
$\sigma_{\gamma\gamma\text{-->}ee}$ = 0.428 ± 0.035 (stat) ± 0.018 (syst) pb

$\sigma_{\gamma\gamma\text{-->}\mu\mu}$ = 0.628 ± 0.032 (stat) ± 0.021 (syst) pb





Example of exclusive $\gamma\gamma \rightarrow \mu\mu$ event



Conclusions

- First results from Run 2 at $\sqrt{s}$ = 13 TeV shown
- Inelastic cross-section lower (~1 sigma) than MC predictions
- MC generators tuned at $\sqrt{s}$ = 7 TeV describe 13 TeV min-bias data well
  - Epos & Pythia 8 preferred for inclusive min-bias data at $\sqrt{s}$ = 13 TeV
- Multi-parton interactions at $\sqrt{s}$ = 13 TeV well described by MC generators
- Studies of specific soft hadron processes performed at $\sqrt{s}$ = 7 TeV

All results on public web page:

- ATLAS: *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults*

BACKUP

Bose-Einstein correlations (BEC) at √s = 7 TeV

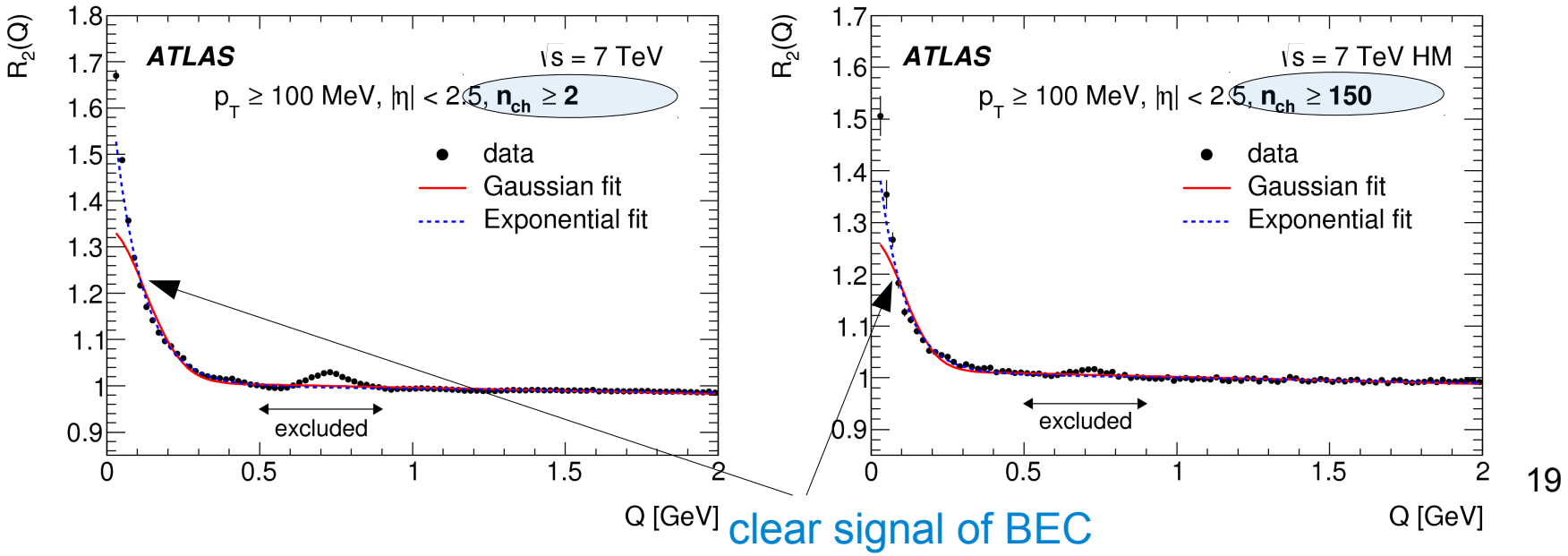
Eur. Phys. J. C75 (2015) 466

- BEC a sensitive probe of space-time geometry of the hadronization region
  - enhance the production of bosons close together in phase-space
- BEC experimentally studied in pairs of like-sign charged pions
  - Proximity in phase-space measured by: $Q = \sqrt{-(p_1 - p_2)^2}$
  - Effect observed as a low Q enhancement of Q distributions (ρ) ratio:

$$C_2(Q) = \frac{\rho(Q)}{\rho_0(Q)} = C_0[1 + \Omega(\lambda, QR)](1 + \varepsilon Q)$$

ρ_0 : reference sample(no BEC): unlike-charge pairs

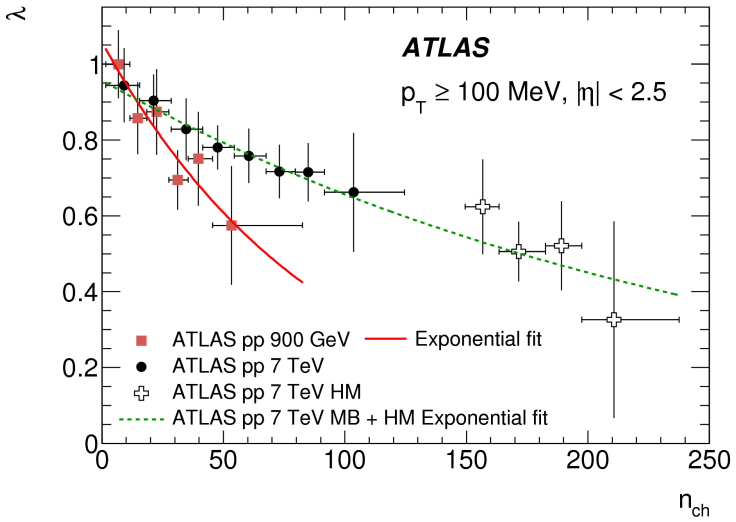
  - Parametrize BEC effect in terms of correlation strength (λ) and source size (R)
  - To account for the effects of resonances, take double-ratio $R_2(Q) = \frac{C_2(Q)}{C_2^{MC}(Q)}$

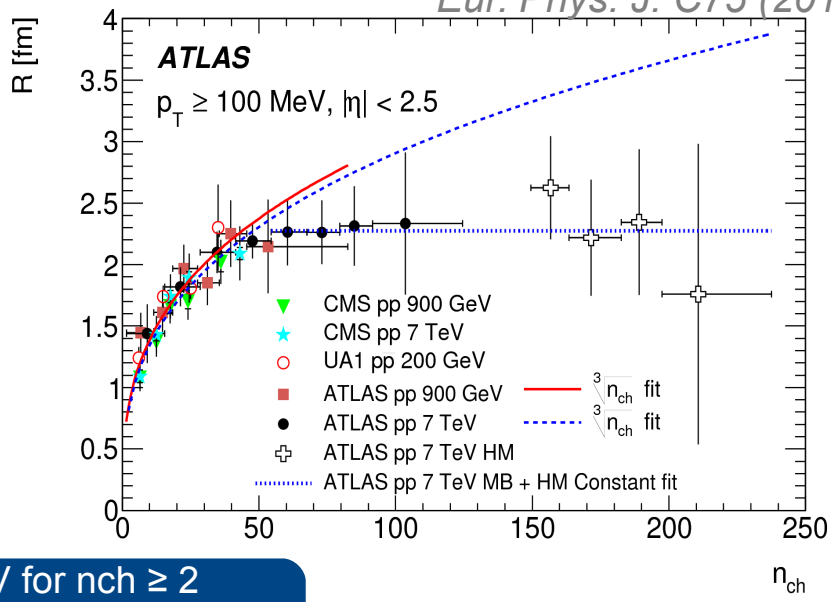


clear signal of BEC

Bose-Einstein correlations at √s = 7 TeV (cont.)

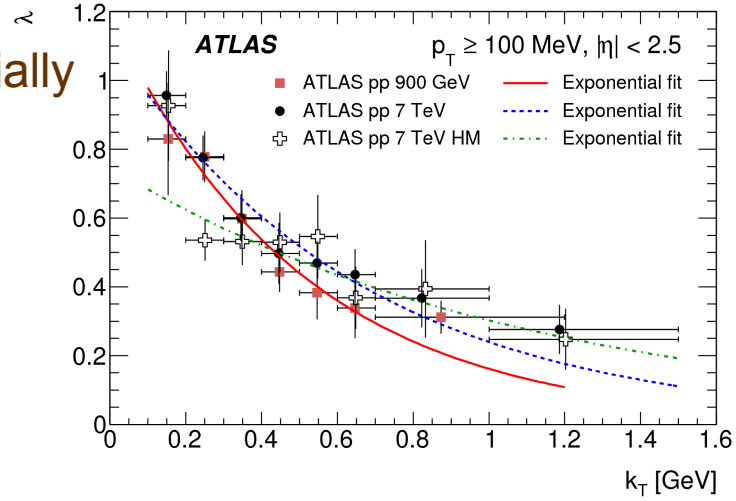
Eur. Phys. J. C75 (2015) 466





$\lambda = 0.74 \pm 0.11$, R= 1.83 ± 0.25 fm at $\sqrt{s} = 0.9$ TeV for nch ≥ 2
$\lambda = 0.71 \pm 0.07$, R= 2.06 ± 0.22 fm at $\sqrt{s} =$ 7 TeV for nch ≥ 2
$\lambda = 0.52 \pm 0.06$, R= 2.36 ± 0.30 fm at $\sqrt{s} =$ 7 TeV for nch ≥ 150

- Measure λ and R inclusively and differentially
- A saturation of R as function of n_{ch} → seen for the first time
- Decrease of both λ and R for increasing pair transverse momentum (k_T)



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ATLAS-CONF-2015-028

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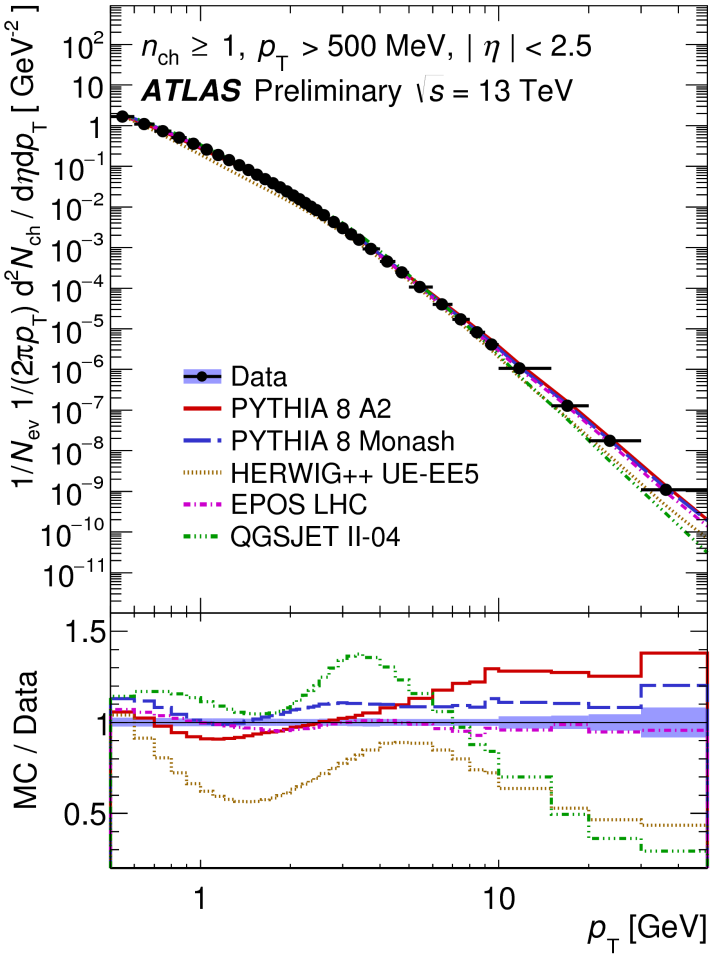
- Dominant systematics from track reconstruction efficiency



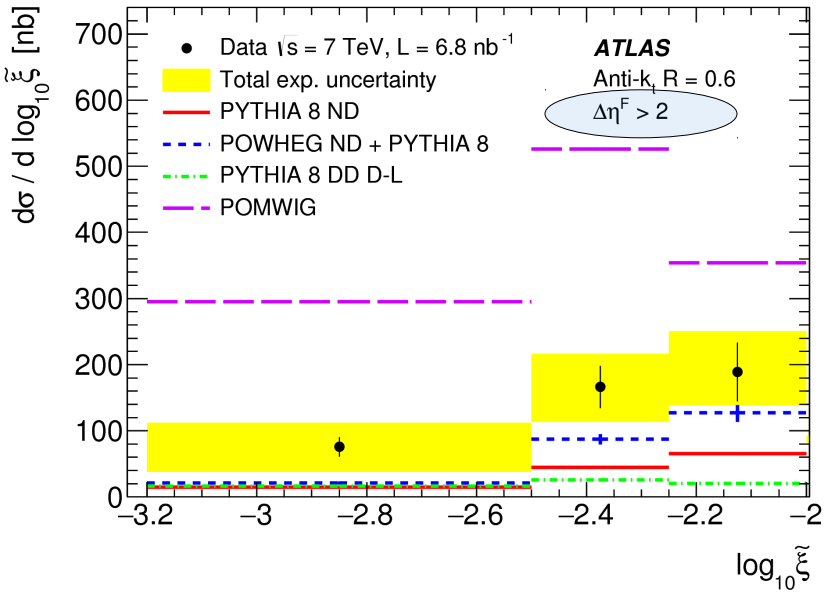
Pythia: separate diffraction (pomeron) and non-diffraction (ND)

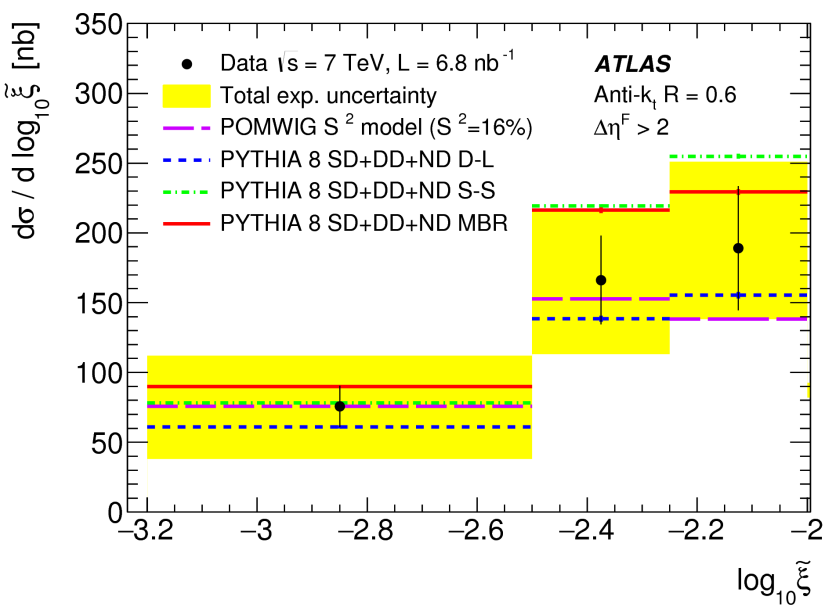
Herwig: no diffractive model, apply MPI to events with no hard-scattering

Epos: parton based Gribov-Regge theory (EFT) (simultaneous hard+soft)

QGSJET-II: phenomenological Reggeon field theory, 'semi-hard Pomeron'

Diffractive dijet production at √s = 7 TeV (cont.)





- Alternative MCs:
  - POMWIG: factorisable pomeron (DPDFs)
  - Pythia 8: soft/hard diffractive models interfaced
- Determine rapidity-gap survival probability to mixed POMWIG/Py8 model:
  - using ratio of data to SD in POMWIG after subtracted ND
  - $S^2 = 0.16 \pm 0.04\ (stat) \pm 0.08\ (syst)$