ATLAS results on diffraction and forward physics

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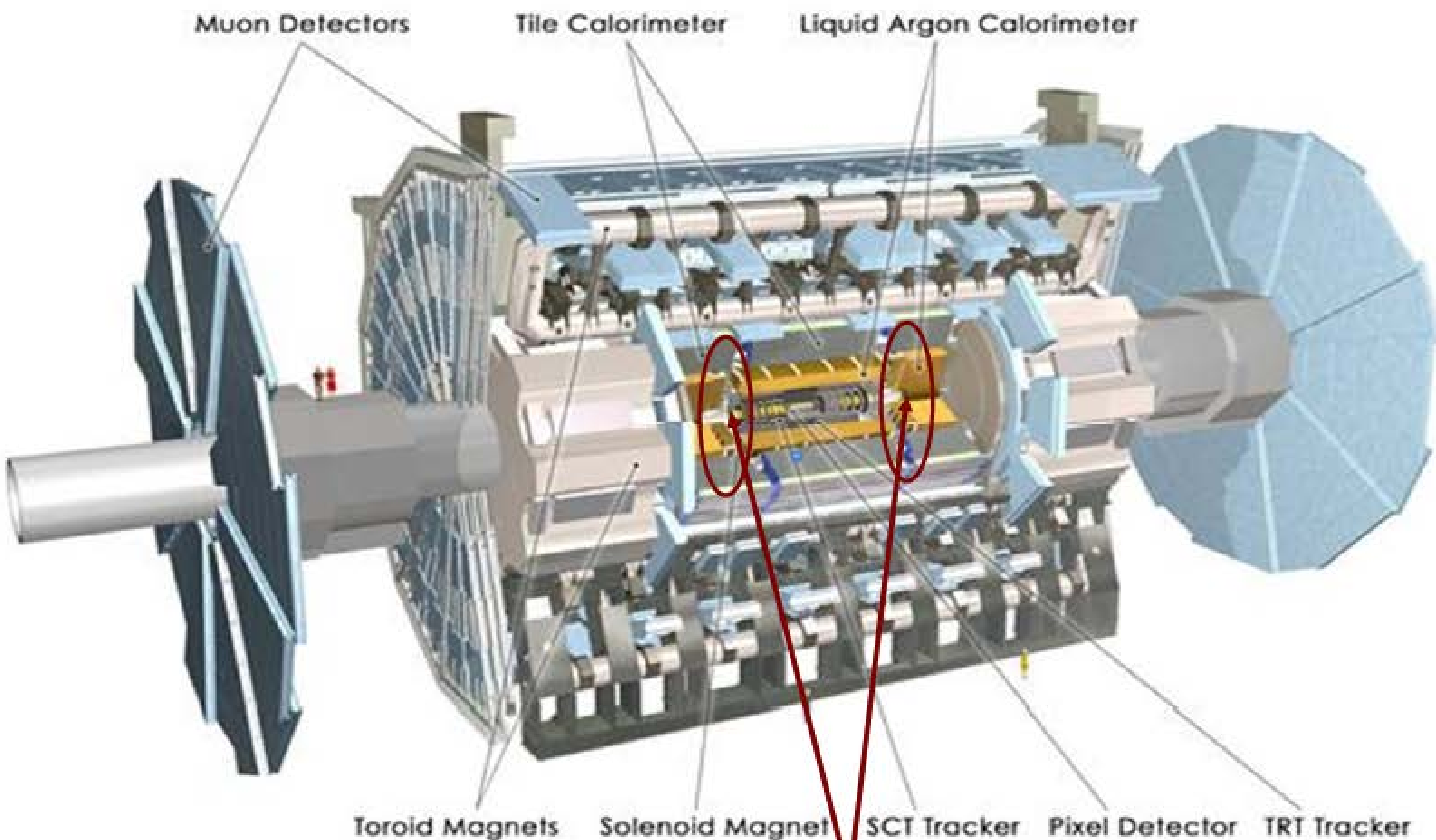
On behalf of the ATLAS collaboration

Diffraction 2014, Primošten, Croatia - Sept 10-16 2014

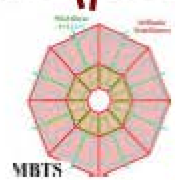
4 analyses:
1) **Vetoing one side of detector**
2) **Soft rapidity gaps**
3) **Jet veto**
4) $\sigma_{tot}, \sigma_{el}, \sigma_{inel}$ **with ALFA**

The ATLAS Detector



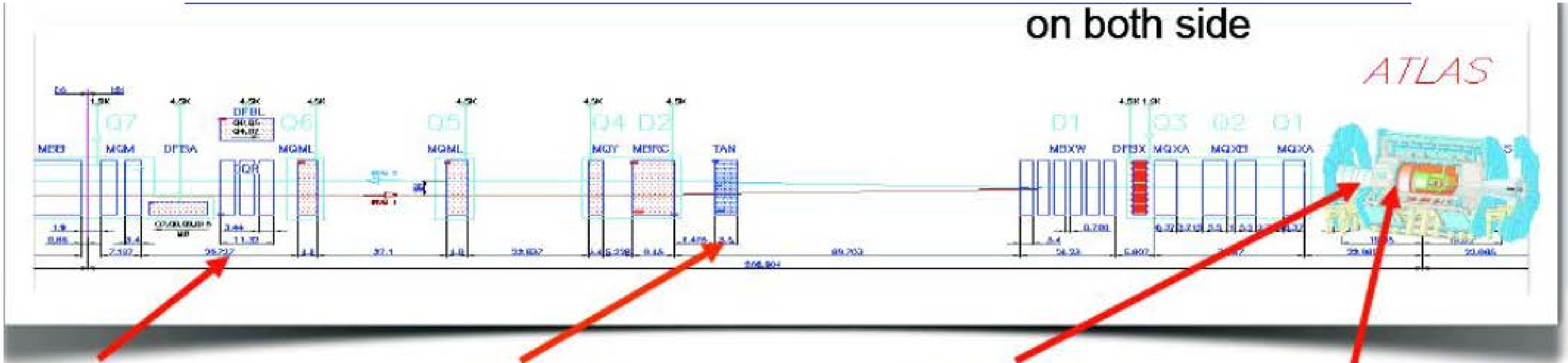
Trackers: $|\eta|<2.5$

Calorimeters: $|\eta|<4.9$



Minimum **B**ias
Trigger **S**cintillator
$2.1<|\eta|<3.8$

ATLAS Forward detectors

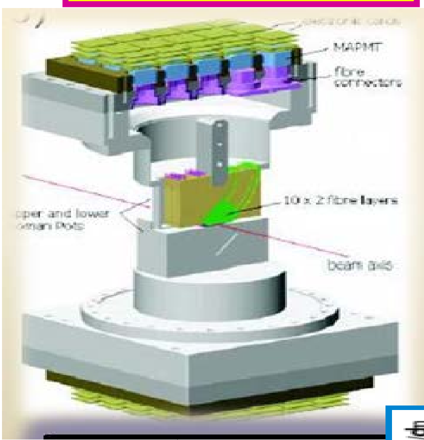


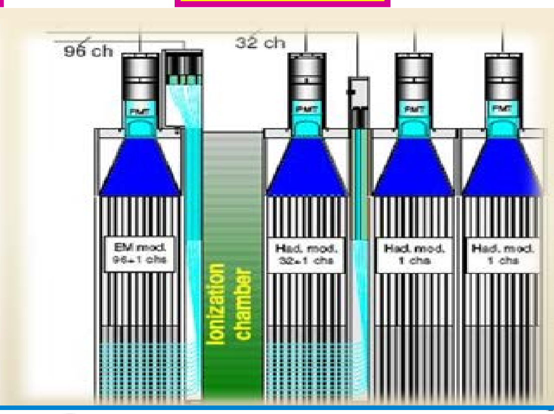
ALFA at 240 m — $10.6 < |\eta| < 13.5$

ZDC at 140 m — $|\eta| > 8.3$

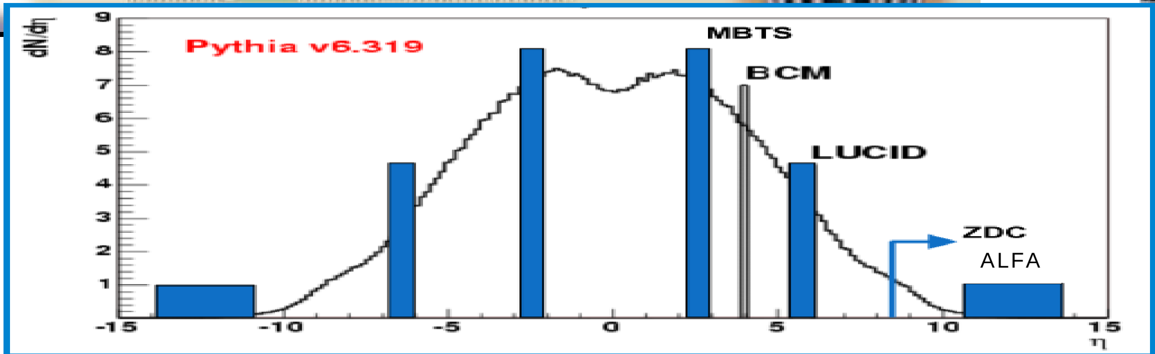
LUCID at 17 m — $5.6 < |\eta| < 5.9$

MBTS at 3.6 m — $2.1 < |\eta| < 3.8$



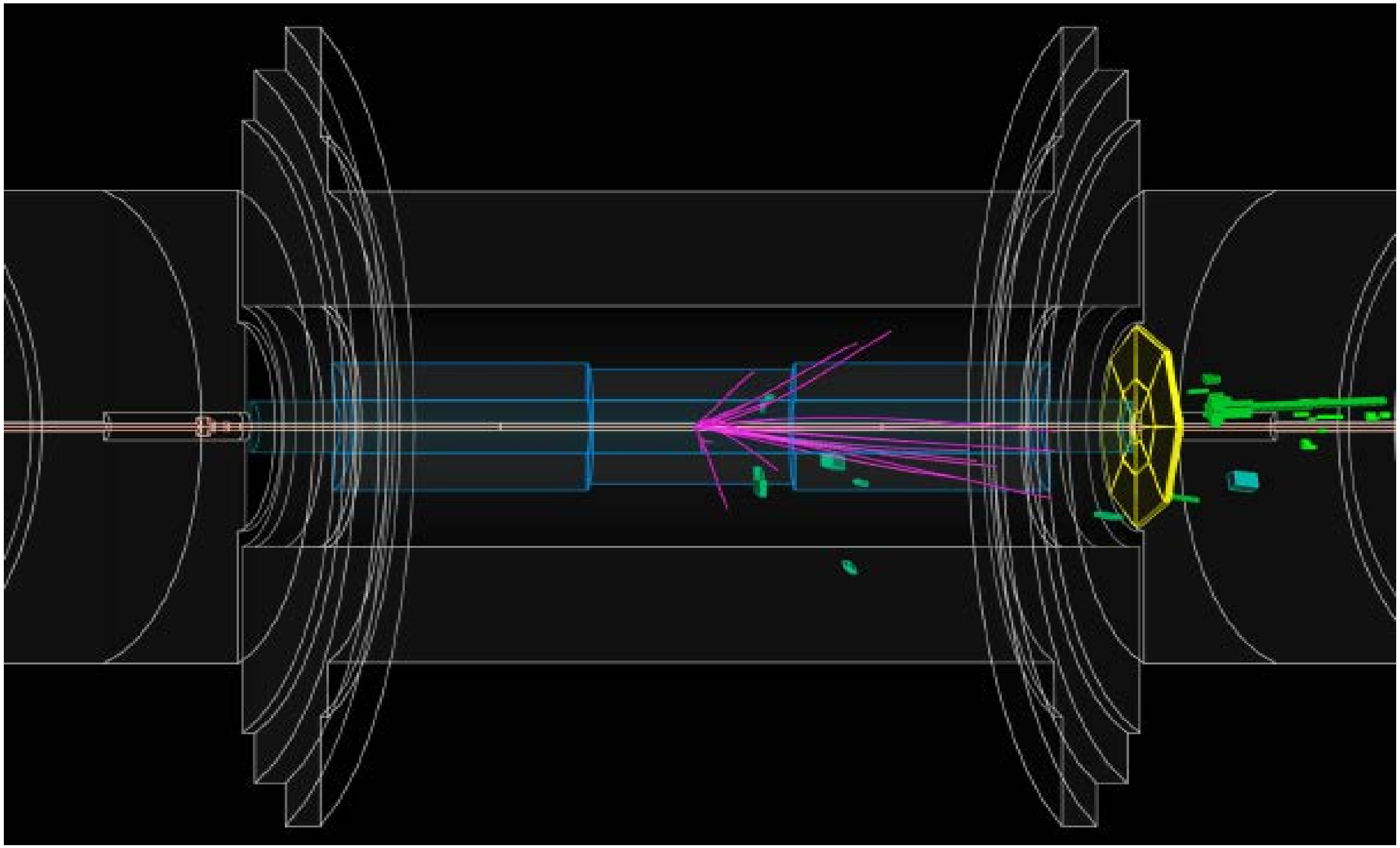


In operation since 2011



Gaps in the detector

Typical Single-Diffraction event: activity on one side (proton remnants + possibly hard scatter), the other part of detector empty.



Measure $\boldsymbol{R_{SS}} = \frac{\boldsymbol{N_{SS}}}{(\boldsymbol{N_{SS}+N_{DS}})}$, where N_{SS} = single-sided, N_{DS} = double-sided

Diffraction enhanced MinBias events

"Measurement of the inelastic pp cross section at √s = 7 TeV with the ATLAS detector"

Nature Comm 2 (2011) 1926

L= 20 μb^{-1}, single fill in March 2010, <μ> ~ 0.01

Event selection:

1) Veto activity in MBTS on one side of IP
2) N_{trk} ≥ 1 (p_T > 0.5 GeV, |η| < 2.5)

Study:

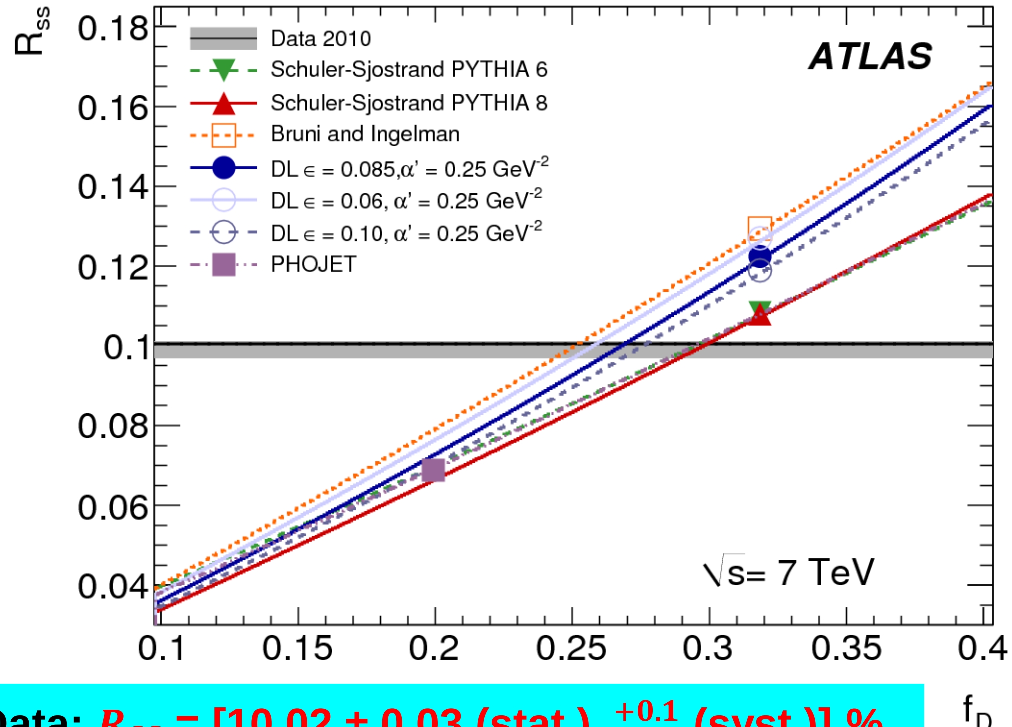
1) Ratio of diffraction enhanced to inclusive events
2) Inelastic cross section

Diffraction enhanced MinBias events

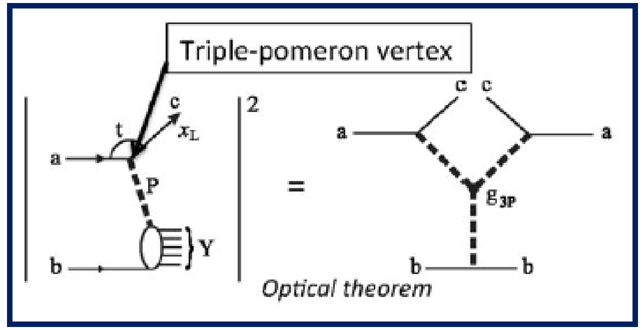
Measure $R_{SS} = \frac{N_{SS}}{(N_{SS}+N_{DS})}$, where N_{SS} = single-sided, N_{DS} = double-sided

R_{SS} as a function of f_D - fraction of diffractive to inelastic events

$$f_D = {(\sigma_{SD}+\sigma_{DD})}/{(\sigma_{SD}+\sigma_{DD}+\sigma_{ND})}$$



MC generators based on triple Pomeron exchange:



$\xi = M_Y^2/s$

Pythia 8 +DL with IP intercept $\alpha(t)=\alpha(0)+\alpha' t$

$\frac{d\sigma_{SD}}{d\xi} \sim \frac{(1+\xi)}{\xi^{1+\varepsilon}}$, $\varepsilon = \alpha(0)-1$

Data: R_{SS} = [10.02 ± 0.03 (stat.) $^{+0.1}_{-0.4}$ (syst.)] %

- syst.unc. from background, MBTS response, material

Measured σ_{inel} = 60.33±2.10 mb for $\xi > 5\times10^{-6}$.
Extrapolating to full ξ-range using DL MC gives
$\sigma_{inel}(\xi > m_p^2/s) = 69.4 \pm 2.4 \pm 6.9(\text{extr.})$ mb

f_D = 26.9 $^{+2.5}_{-1.0}$ - syst.unc. from varying DD/SD event ratio between 0.0 and 1.0 using default DL model and still consistent with data R_{SS} ± 1σ

Rapidity gaps in soft processes

"Rapidity gap cross section in pp interactions at $\sqrt{s}$ = 7 TeV"

Eur. Phys. J. C72 (2012) 1926

L= 7.1 μb^{-1}, taken in March 2010, μ < 0.005

Event selection:

1) Only good tracks with p_T > 200 MeV
2) Only calorimeter cells with E > noise (~5σ_{noise})
3) Look for empty η-rings starting from the edge of calorimeter ($|\eta|$ < 4.9)

Study:

1) Gap spectrum
2) Predictions of various MC models
3) Diffraction dynamics

Rapidity gaps in soft processes

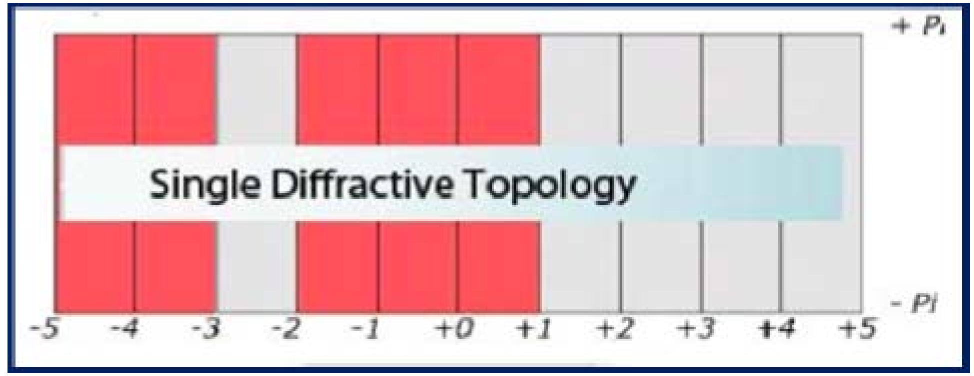
Definitions of gaps

Detector level:

Detector divided into η-rings of size 0.1
in the calorimeter (|η|<4.9)

Ring is considered empty if

- No track with p_T > 200 MeV (|η|<2.5)
- No calo cell with E > 4.5-5.5 σ_{noise}(η) (|η|<4.9)

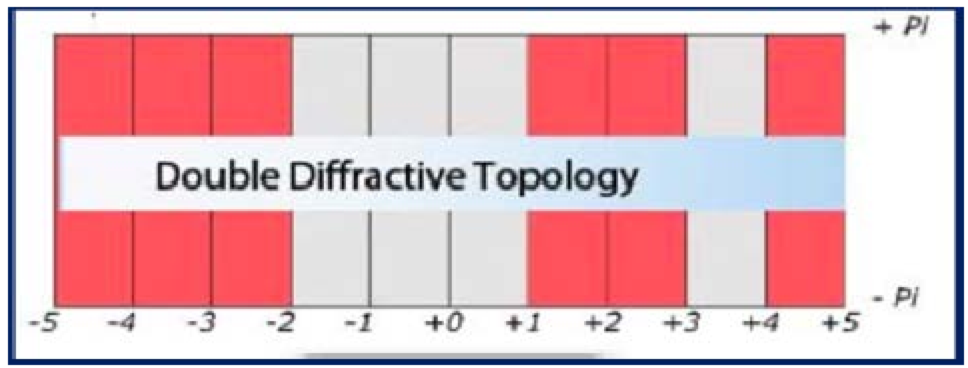


Hadron level:

Phase space divided into η-rings of size 0.1

Ring is considered empty if

- No stable particle with p_T > 200 MeV

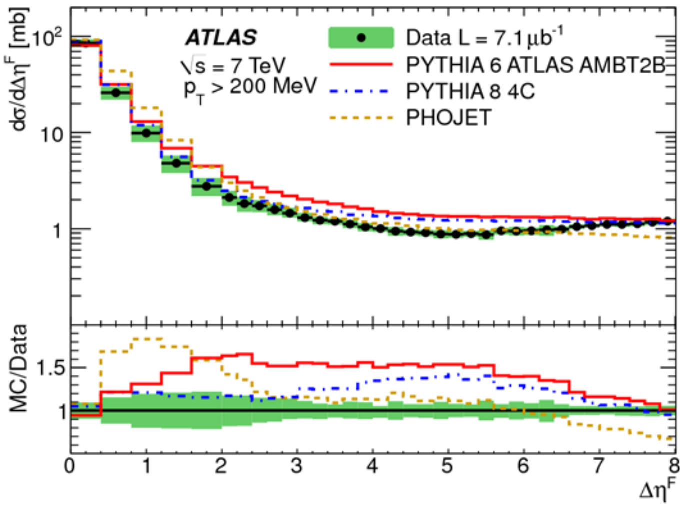


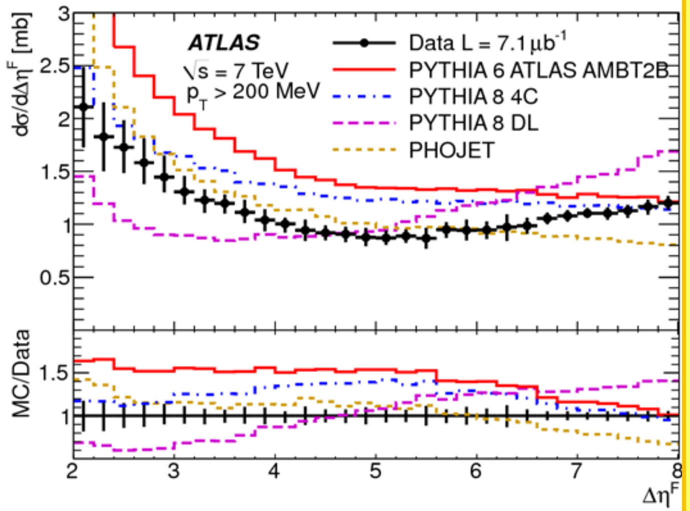
Observable: Forward gap $\Delta\eta_F$

- **The largest consecutive set of empty rings starting from the edge of the calorimeter**

Rapidity gaps in soft processes

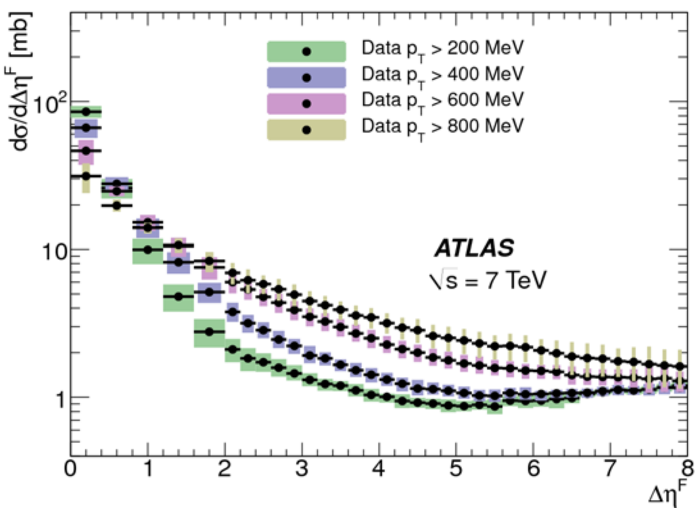
General properties of the gap spectrum





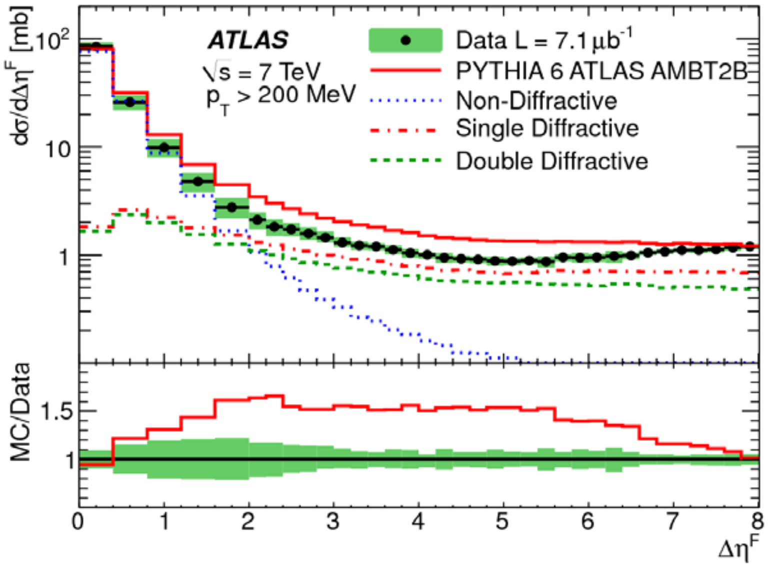
- ❑ Data show an exponential decrease at low $\Delta\eta_F$ (dominance of ND) and plateau at large $\Delta\eta_F$ (dominance of diffr. processes) – as expected from previous HERA and Tevatron results
- ❑ This general feature is followed by all MC models.
- ❑ Details are not described by any of the models.
- ❑ Data lie in between the DL slope and slope of the other models

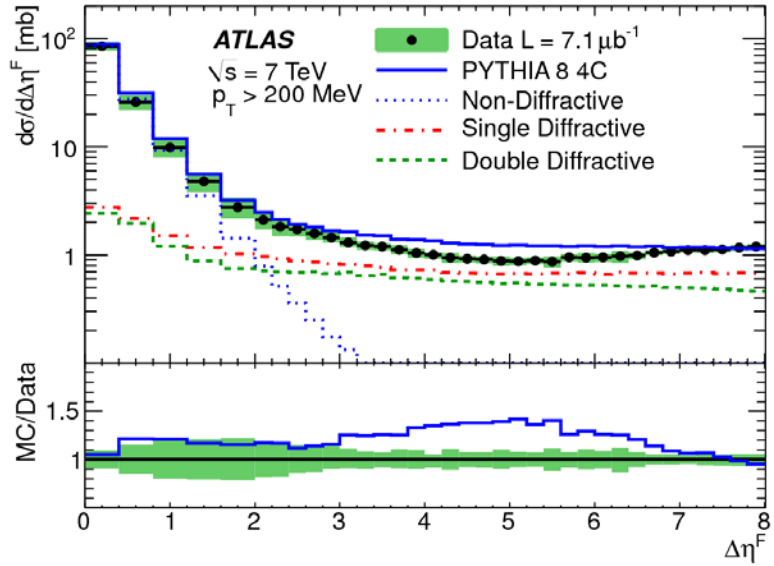
The effect of $p_{T,min}$ of clusters and tracks

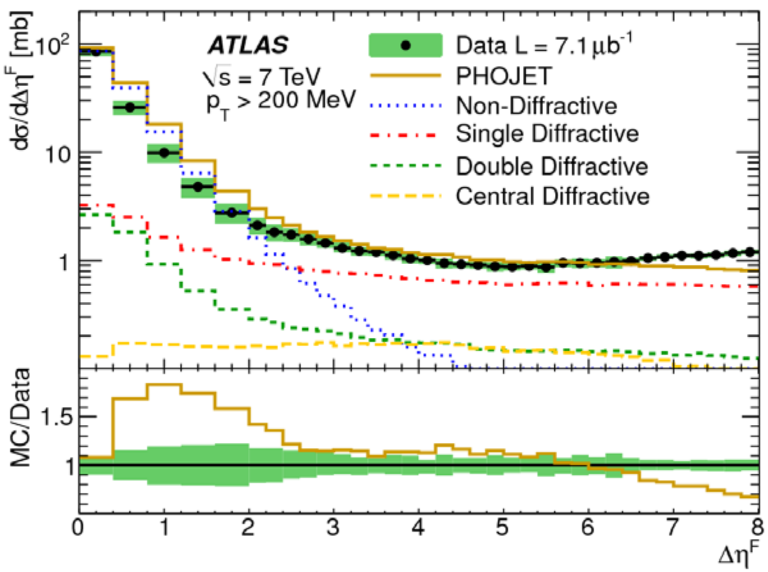


- ❑ Too large a $p_{T,min}$ produces artificial gaps
- ❑ $p_{T,min}$ = 200 MeV was found to be optimum:
  - Tracks are within the acceptance of inner tracker
  - Selection efficiency of calorimeter clusters > 50%
  - Above noise threshold in any part of calorimeter

Rapidity gaps in soft processes







Details about composition and components in PYTHIA 6, PYTHIA 8 and PHOJET

- ❑ All models overshoot the data (i.e. overshoot σ_{inel})
- ❑ PYTHIA 6, 8: unexpectedly large DD
- ❑ PHOJET: much smaller DD but contribution of CD

Jet veto

1) "Measurement of dijet production with a veto on additional central jet activity in pp collisions at √s = 7 TeV using the ATLAS detector" JHEP 1109 (2011) 053

L= 36 pb^{-1}, all 2010 data

A new study: 2) "Measurement of jet vetoes and azimuthal decorrelations in dijet events produced in pp collisions at √s = 7 TeV using the ATLAS detector" arXiv:1407.5756 [hep-ex]

L= 38 pb^{-1} (all 2010 data) + L= 4.5 fb^{-1} (all 2011 data)

i) optimised 2-jet trigger procedure to reach Δy of up to 8 on 2010 data (low pile-up)

ii) add 2011 data to extend the high-pt region up to 1.5 TeV

Event selection:

Jet anti-kt: R=0.6, $|\eta_{jet}|$ < **4.4,** $\boldsymbol{p_{T,jet1}}$ > 60 GeV, $p_{T,jet2}$ > 50 GeV

Veto scale $Q_0 = p_T$ > 20 (30) GeV for 2010 (2011) data

Define Gap fraction = $\sigma_{jj}(Q_0)/\sigma_{jj}$, σ_{jj} = inclusive dijet x-section,

$\sigma_{jj}(Q_0)$ = dijet cross section with no jets of $p_T > Q_0$ between η_{jet1} and η_{jet2}

Results:

1) Gap fraction vs. Δy for Q_0 = 20 GeV

2) Gap fraction vs. $\overline{p_T}$ for Q_0 = 30 GeV

3) Gap fraction vs. Q_0 for slices of y

4) $\langle N_{jets} \rangle$ vs. Δy and $\overline{p_T}$

5) Cross sections vs. Δy and Δφ

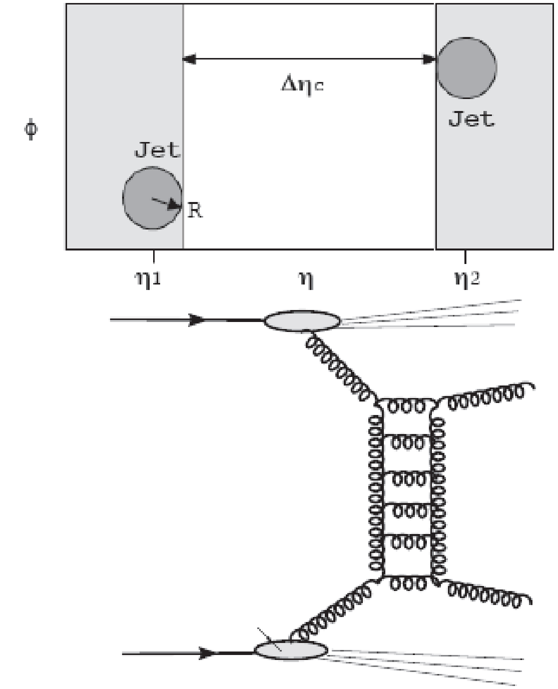
6) <cos Δφ> and <cos 2Δφ> vs. Δy and $\overline{p_T}$

Jet veto

Goal = study higher-order QCD effects in the dijet production

These are most visible when in the dijet system (2 highest Et jets):

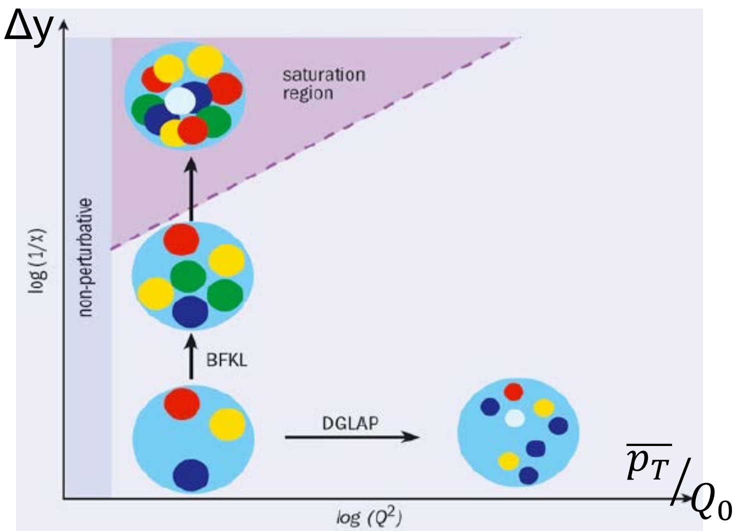
1) jet separation (**Δy**) is large
2) jet veto between jets (with scale $\boldsymbol{Q_0}$) is applied
3) azimuthal decorrelation between jets (**π-Δφ**) is large



Resummation of HO QCD effects: - in ln(Q^2) : DGLAP approach
- in ln(1/x) : BFKL approach

Gap fraction sensitive to
- **DGLAP effects if p_T/Q_0 large**
- **BFKL effects if Δy large**
- **Color-Singlet-Exchange if p_T/Q_0 & Δy large**

Azim. decorrelations sensitive to both DGLAP and BFKL effects



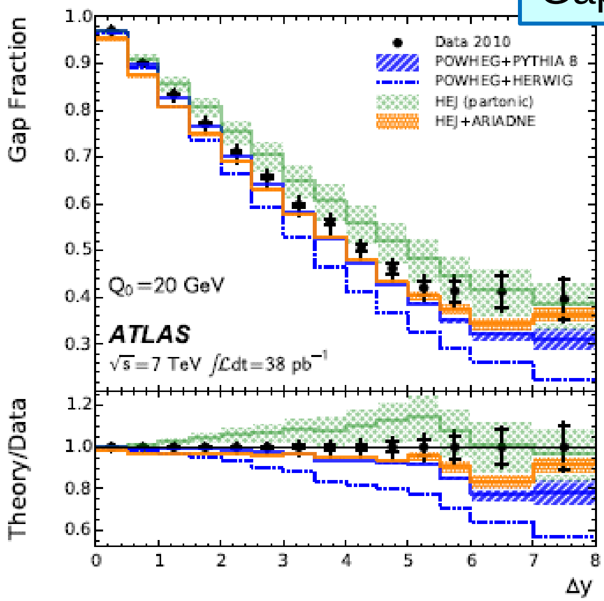
Theoretical predictions:

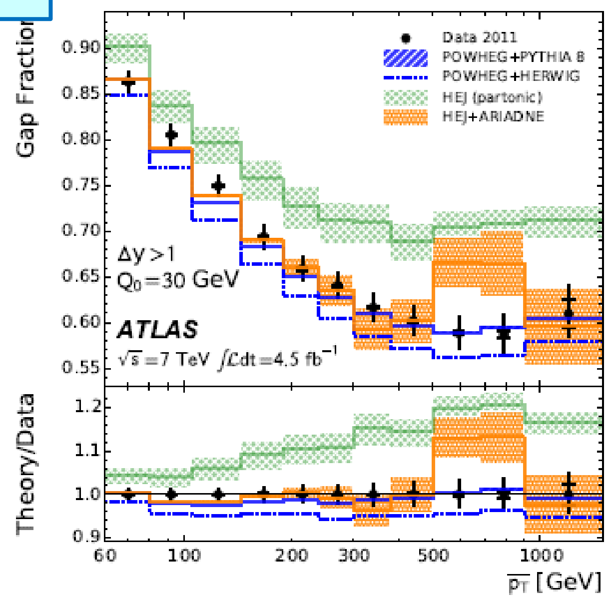
❑ **Powheg:** NLO dijet (DGLAP form.) interfaced with Pythia8 or Herwig to resum soft and collinear emissions using parton shower approximation

❑ **HEJ:** leading-log calc. of multi-jet (at least 2 hard jets) production in Mueller-Navelet limit – interfaced to ARIADNE (color-dipole cascades producing soft and collinear radiation in the gap between jets → contr. from low-x BFKL-like log. terms)

Jet veto

Gap fraction

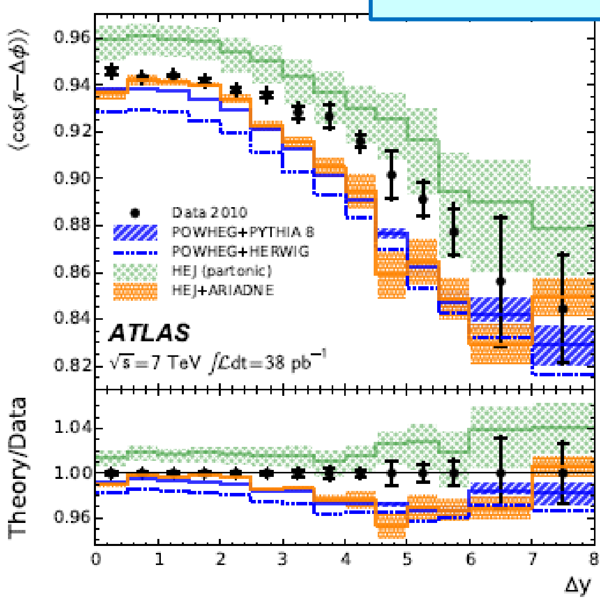




- ➢ Exponential decrease: exchange of color in the t-channel
- ➢ Plateau:
  a) steeply falling PDFs at large x disabling additional parton radiation
  [at extreme Δy or p_T gap fr. must reach unity]
  b) Contribution of color-singlet exchange (CSE) processes
  [cross section for CSE rises with Δy]
- ➢ All models fall at high Δy

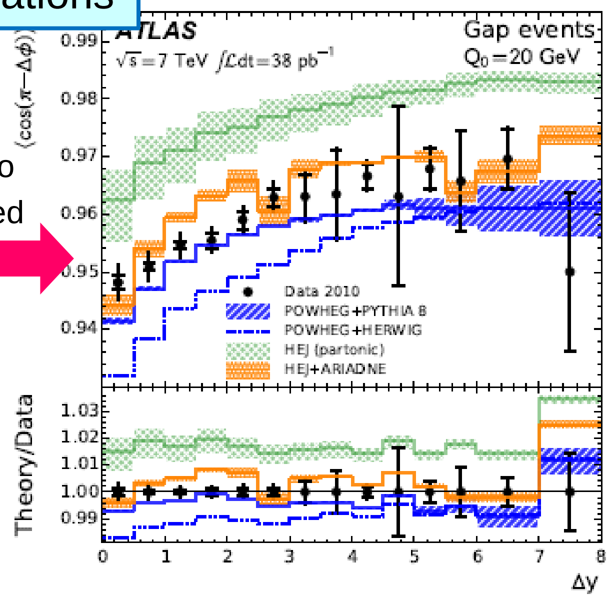
Azimuthal decorrelations

Inclusive sample



Jet veto imposed

Gap sample



- ➢ Powheg underestimates, HEJ overestimates azim. decorrelation
- ➢ With increasing Δy and p_T, the jet veto makes the dijet system more back-to-back

- o Best agreement with Powheg+Py8 except for low-p_T, high Δy region
- o Interfacing ARIADNE to HEJ improves significantly description of data

Total and elastic pp cross section

"Measurement of the total cross section from elastic scattering in pp **collisions at** $\sqrt{s}$ = 7 TeV **with the ATLAS detector"**

submitted to Nucl. Phys. B, arXiv: 1408.5778 [hep-ex]

L= 78.7 μb^{-1}, special run in 2011, <$\mu_{elastic}$> ~ 0.01

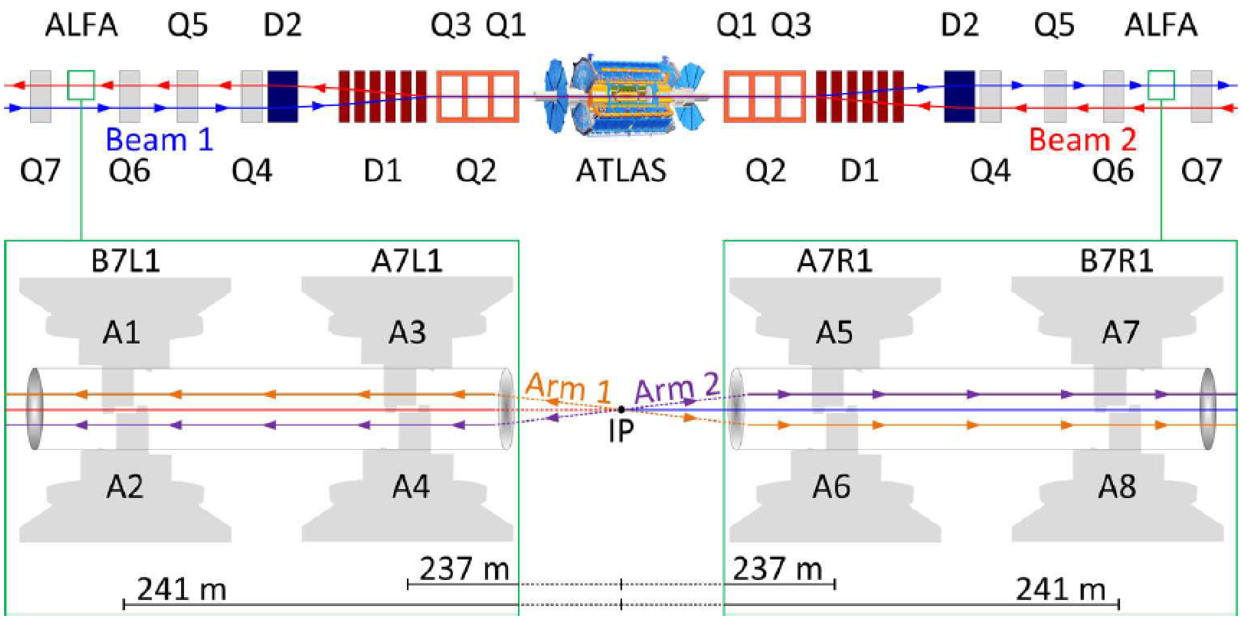
Event selection:

1) Dedicated run in 2011 (together with Totem), β^{*} = 90m
2) ATLAS subdetector: Forward Proton detector ALFA
3) Geometrical, fiducial and back-to-back signatures to select elastics & reduce background

Results:

1) Differential elastic cross section as a function of t
2) Total pp cross section via optical theorem: $\sigma_{tot} \propto 4\pi \cdot \mathrm{Im}\left(f_{el}\right)_{t\to 0}$
3) total elastic and total inelastic cross sections
4) Slope of the elastic cross section at small t

ALFA detector + Measurement principle



Vertical Roman Pots :

- Thin windows at bottom and front: 0.2mm and 0.5mm
- Main detectors (MD), Overlap detectors (for alignment), Trigger detectors
- MD = 10 staggered layers, 1 layer=64 single-cladded square (0.5mm) scintil. fibres in u- and v-directions
- Spatial resolution ~ 30 µm
- Reconstruction efficiency ~ 90%
- Distance of the closest approach in the run: 6.5σ_y ~ 5.8mm

To measure $d\sigma/dt$:

1) Measure track position **y**
2) Calculate scattering angle θ_y^*

using the beam optics, i.e. using transport matrix elements:

$$\begin{pmatrix} y \\ \theta_y \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} y^* \\ \theta_y^* \end{pmatrix}$$

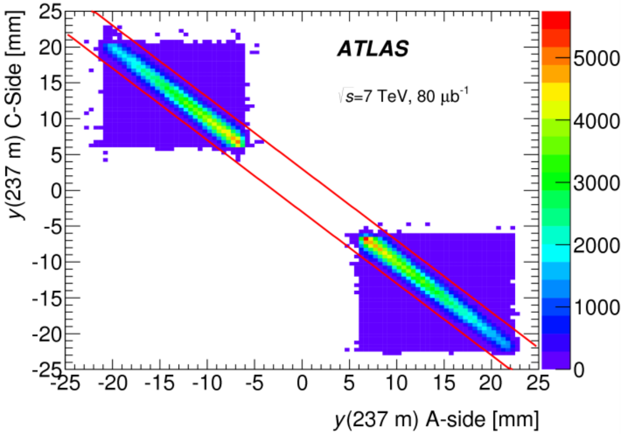
In the simple case (high beta*, phase advance 90 deg., parallel-to-point focusing):

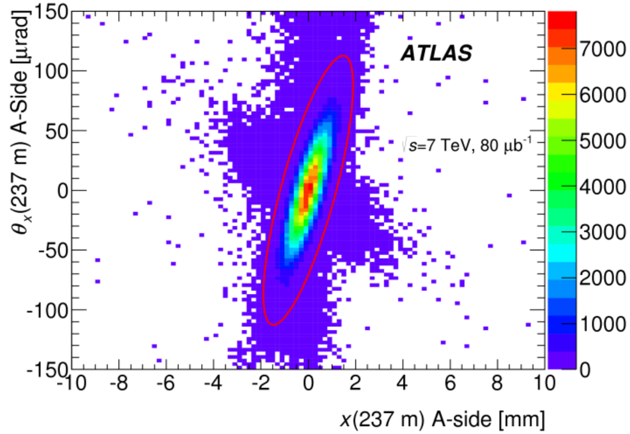
$$\theta_y^* = \frac{y}{M_{12}}$$

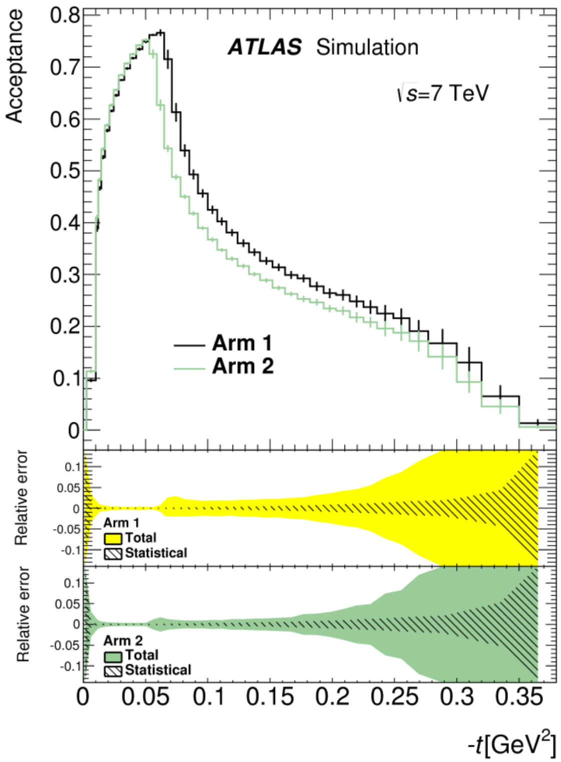
and $t = -(p\theta^*)^2$, p=beam mom.

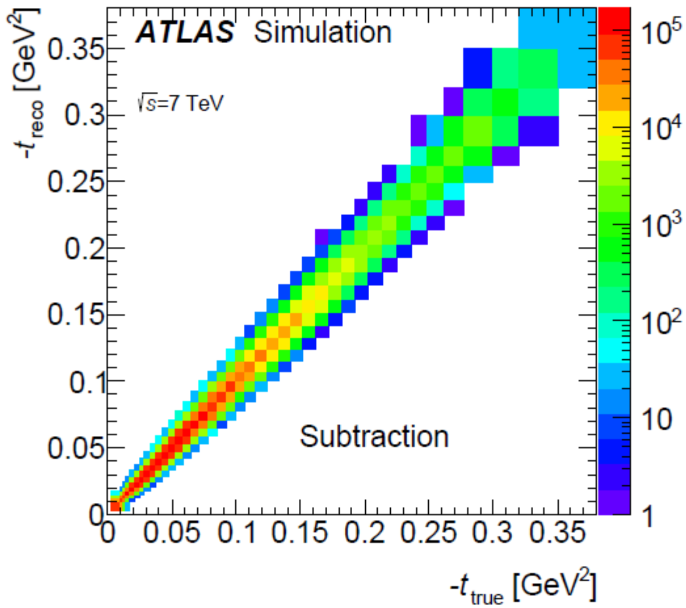
Experimental procedure (1)

Signal selection & Background rejection









- Beam transport using MadX
- Fast detector simulation tuned to data

Event selection:

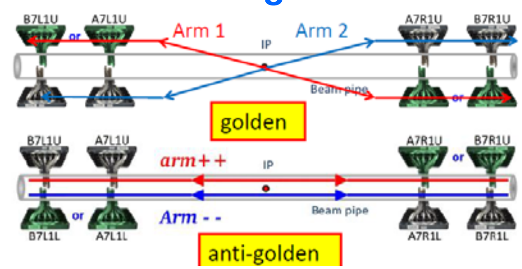
- L1 elastic trigger
- Data quality & track quality
- Geometrical & fiducial cuts: acceptance & signal selection & background rejection

Final sample: ~ 805k selected events

(~ 1k Pile-up events)

Data-driven Background estimates:

1)



2) Non-Gaussian tails in x_{vtx} distr.

~ 0.5% (dominantly beam halo)

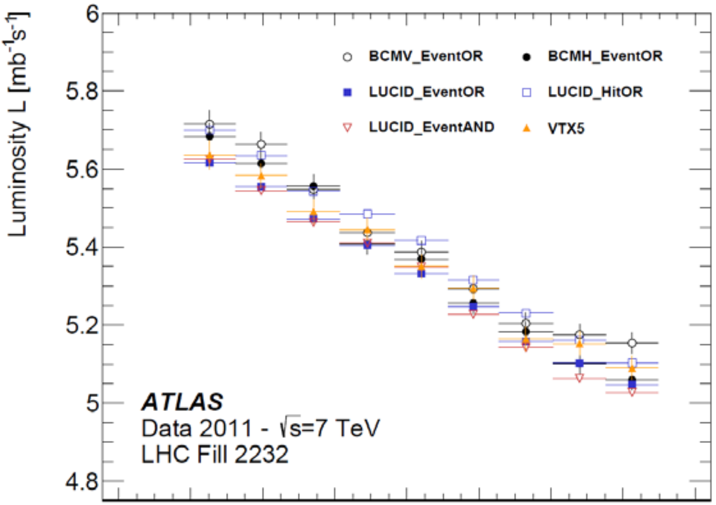
PYTHIA 8 for: 1) Acceptance

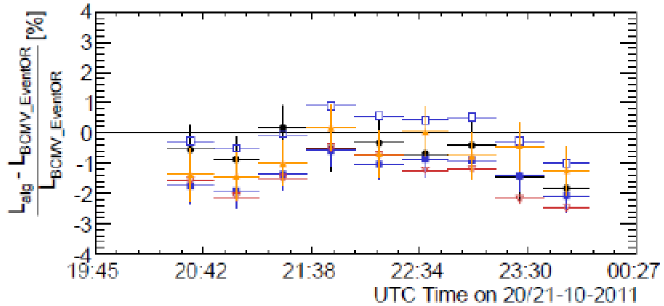
2) Smearing matrix (1D-unfolding):

a) **I**terative **D**ynamically **S**tabilized

b) checked with data-driven closure test and another unfolding method

Experimental procedure (2)



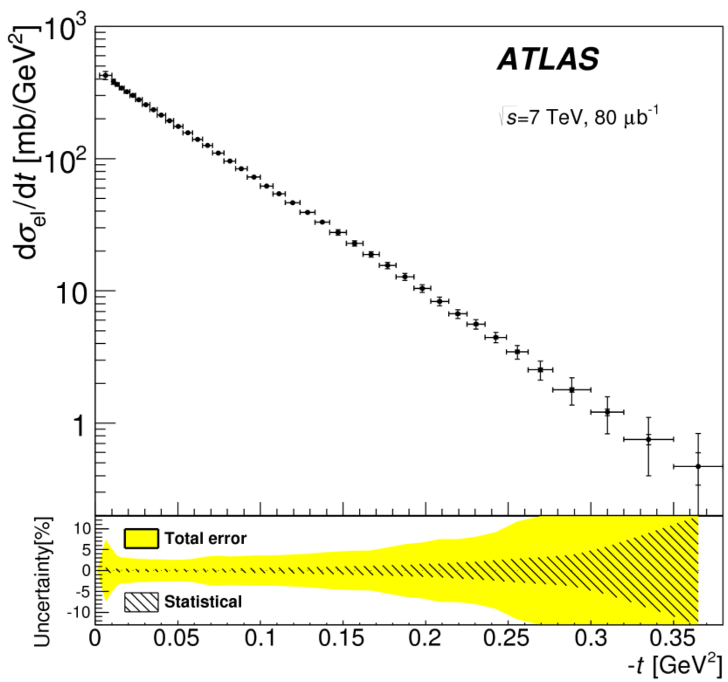


Independently measured Luminosity
(3 methods: BCM, LUCID and Inner Det.):
L = 78.7 ± 1.9 μb^{-1} (2.3% uncertainty)

Event reconstruction efficiency
(from data, separately for each arm):

$\epsilon_{reco,1}$ = **89.74 ± 0.04(stat) ± 0.61(syst) %**
$\epsilon_{reco,2}$ = **88.00 ± 0.05(stat) ± 0.92(syst) %**

[Trigger plates placed behind MD in arm1, but in front of MD in arm2]



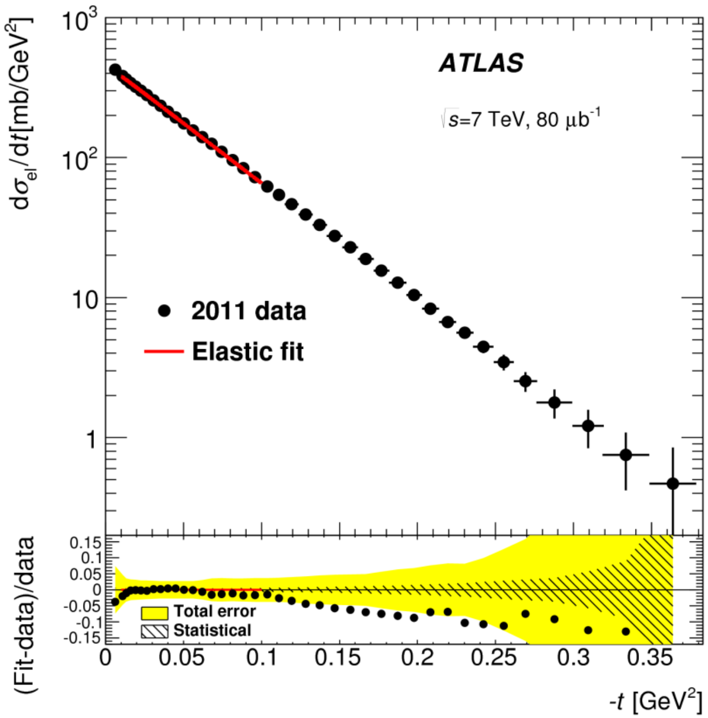
Correction procedure (separately for each arm):

$$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{t_i}\cdot\frac{\mathrm{M}^{-1}[N_i - B_i]}{A_i\cdot\varepsilon^{reco}\cdot\varepsilon^{trig}\cdot\varepsilon^{DAQ}\cdot\mathrm{L}_{\mathrm{int}}}$$

- A = Acceptance (t)
- M = Unfolding procedure (symbolic)
- N = Number of selected events
- B = Number of estimated background events
- ϵ^{reco} = reconstruction efficiency
- ϵ^{trig} = trigger efficiency
- ϵ^{DAQ} = dead-time correction
- L_{int} = integrated luminosity

Main system. uncertainties:
- **Luminosity**
- **Nominal beam energy**

Fitting elastic cr.section → $\sigma_{tot}, \sigma_{el}, \sigma_{inel}$, B-slope



Theoretical formula used to fit the data:

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2} \cdot G^4(t)$$ Coulomb interactions

$$- \sigma_{\rm tot} \cdot \frac{\alpha G^2(t)}{|t|} \left[\sin(\alpha\phi(t)) + \rho\cos(\alpha\phi(t))\right] \cdot \exp\frac{-B|t|}{2}$$ Coulomb-Nuclear interference

$$+ \sigma_{\rm tot}^2 \frac{1+\rho^2}{16\pi(\hbar c)^2} \cdot \exp(-B|t|)$$ Nuclear interactions

$$G(t) = \left(\frac{\Lambda}{\Lambda + |t|}\right)^2$$ Proton dipole form factor

$$\phi(t) = -\ln\frac{B|t|}{2} - \phi_C$$ Coulomb phase

$\rho = 0.14$

$\Lambda = 0.71$ GeV²

$\Phi_c = 0.577$

From COMPETE Global analysis

Conventional values. Other models in syst. uncert.

- **Fit result:** σ_{tot} = 95.35 ± 0.38 (stat.) ± 1.25 (syst.) ± 0.37 (extr.) mb

B = 19.73 ± 0.14 (stat.) ± 0.26 (syst.) GeV^{-2} {40%-correlation between σ_{tot} and B}

Fit quality good: χ^2/N_{dof} = 7.4/16, Fit range: -t ϵ <0.01, 0.1> GeV² - good Accept. & small deviations from exponential

Extrapolation uncertainty from changing the upper end **0.1** to **0.15** and **0.059**

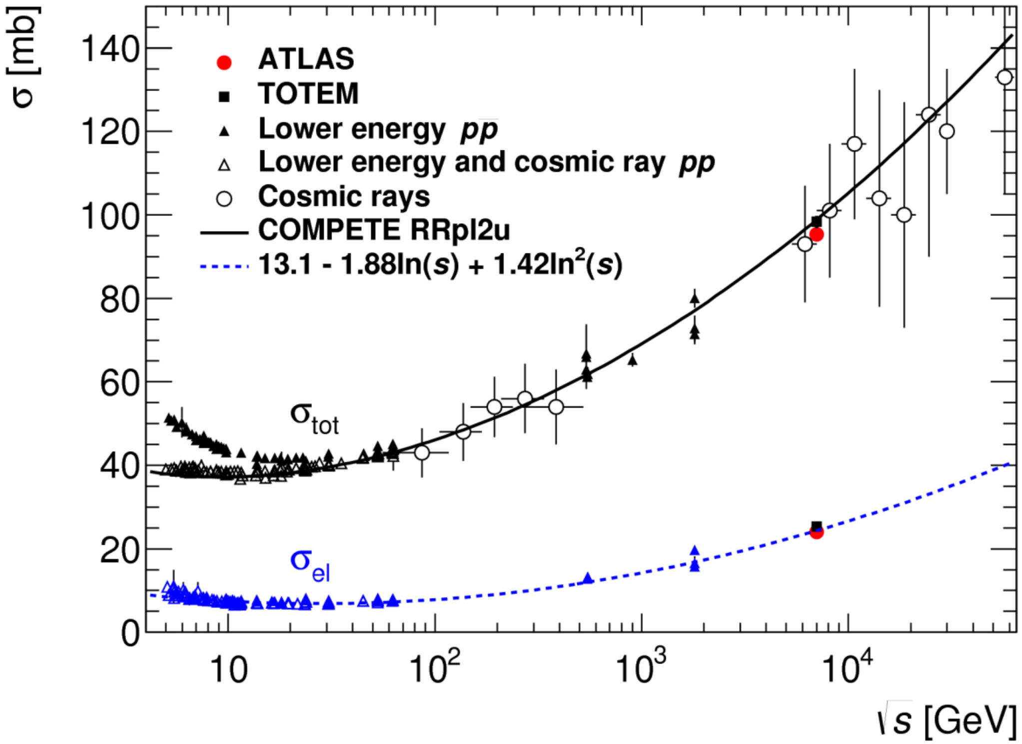
- Extraction of σ_{el}: assume Nuclear term only and B(t)=const:

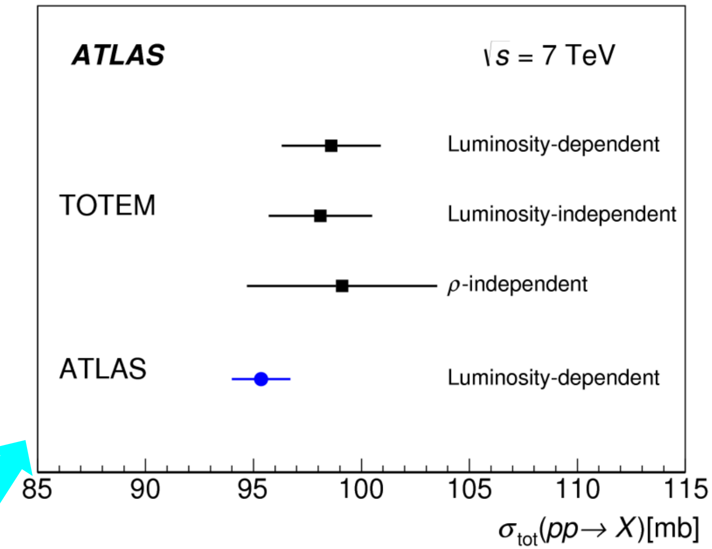
Integrating over full t-range σ_{el} = 24.00 ± 0.19 (stat.) ± 0.57 (syst.) mb

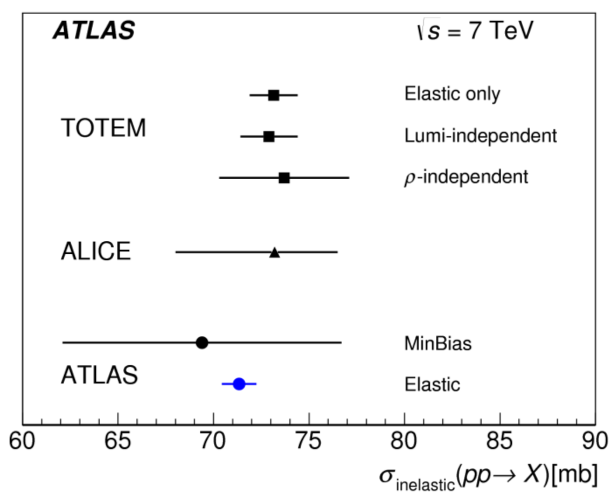
[Observed in -t ϵ <0.0025, 0.38> GeV²: σ_{el} = 21.66 ± 0.02 (stat.) ± 0.58 (syst.) mb (90% of the total σ_{el})]

- $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ ⟶ σ_{inel} = 71.34 ± 0.36 (stat.) ± 0.83 (syst.) mb

Comparison with previous measurements







σ_{inel}:
ALFA significantly improves precision of the previous ATLAS σ_{inel} measurement

The same run in 2011, Lumi-dependent method:

ATLAS: σ_{tot} = 95.4 ± 1.4 mb (Lumi unc=2.3%)
TOTEM: σ_{tot} = 98.6 ± 2.2 mb (Lumi unc=4%)
→ Difference = 1.3 σ
ATLAS value ~2σ below COMPETE fit, but closer to predictions by Block & Halzen, KMR, Soffer.

ATLAS: σ_{el} = 24.0 ± 0.6 mb (Lumi unc=2.3%)
Totem: σ_{el} = 25.4 ± 1.1 mb (Lumi unc=4%)
→ Difference = 1.1 σ

Summary

Four ATLAS analyses presented (two of them very fresh):

- ❑ 10%-fraction of diffraction-enhanced to inclusive events measured in minimum bias events with veto on one side of the detector.
- ❑ σ_{inel} = 69.4±2.4±6.9(extr.) measured by extrapolating to ξ<5x10^{-6} using DL model

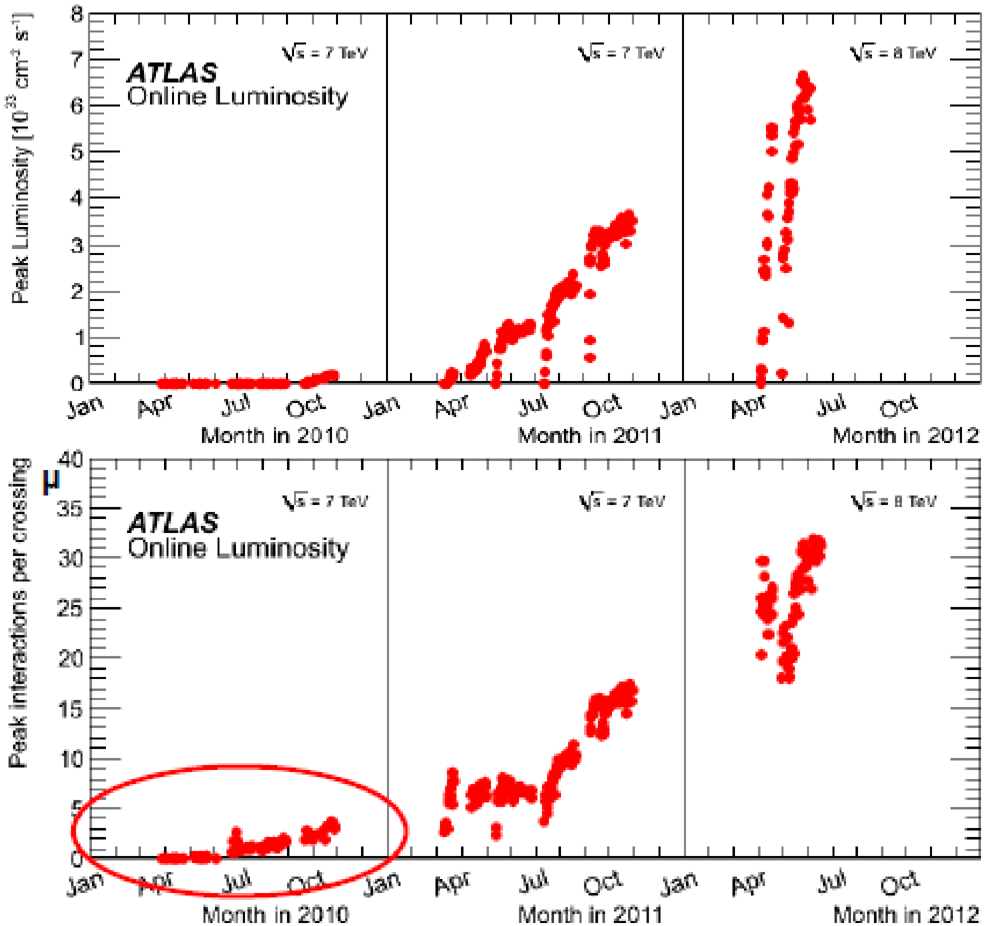
- ❖ Forward gap distribution measured for different $p_{T,min}$ cuts (200, 400, 600, 800 MeV)
- ❖ Plateau observed for large gaps suggests presence of diffractive processes
- ❖ None of the models able to describe the details of the gap spectrum
- ❖ σ_{inel} measured for various ξ values. Models not able to describe the ξ-evolution
- ❖ Pomeron intercept in DL model measured from fit to spectrum at large gaps. It is compatible with the default DL value (α_{IP}(0) = 1.085).

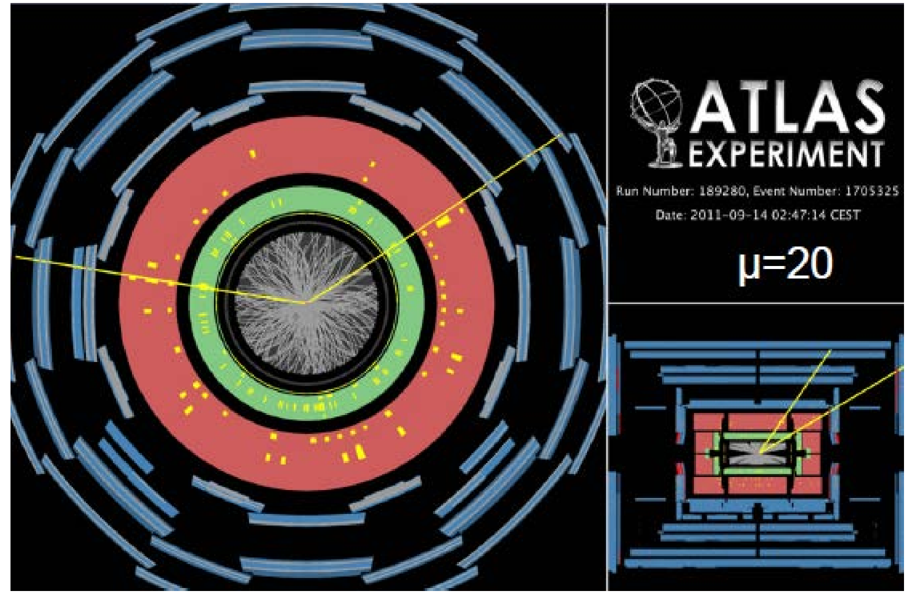
- ➢ Jet Gap fraction and azimuthal decorrelation measurements combined into a single analysis that extends the kinematic reach and tests models based on either DGLAP or BFKL dynamics.

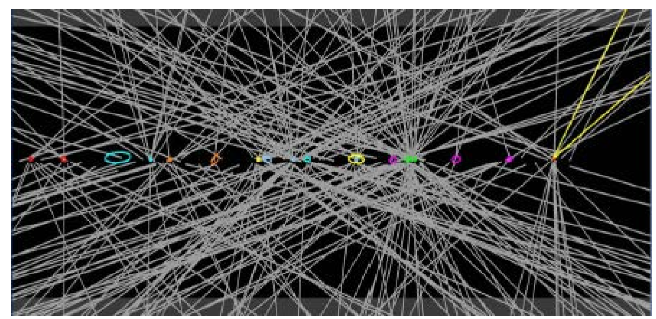
- First ATLAS measurement of σ_{tot} using fit to t-dependence of elastic cross section and independently measured luminosity. The value 95.4 ± 1.4 mb in agreement with Totem result.
- Measured total σ_{el} and σ_{inel}, and B-slope also agree with Totem.
- More data from 2012 data at √s=8 TeV (β^* = 90m and 1km) in the pipeline.

BACKUP SLIDES

Diffraction needs very low Pile-up





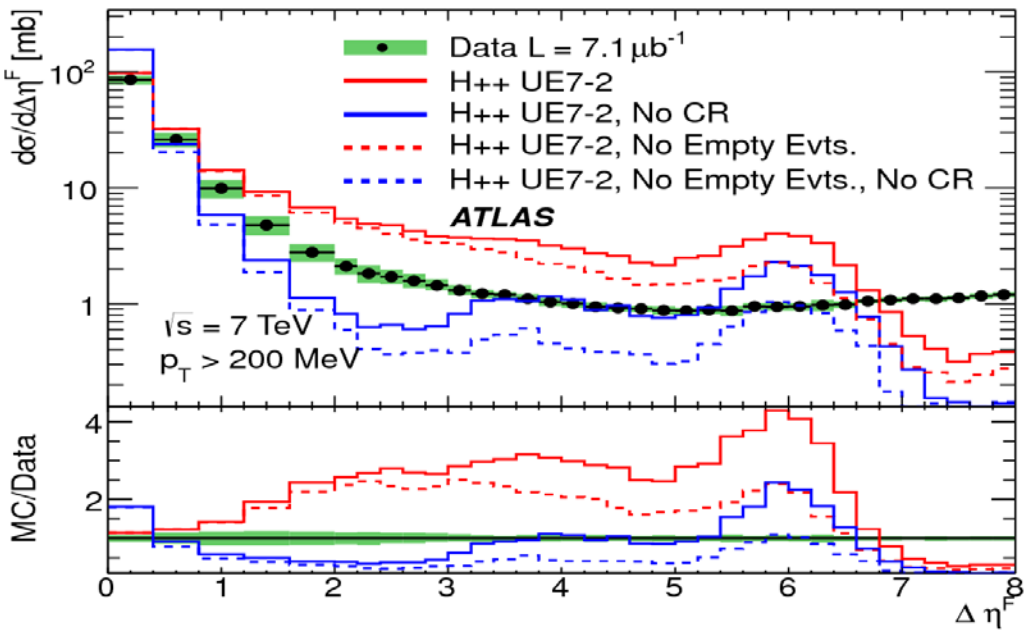


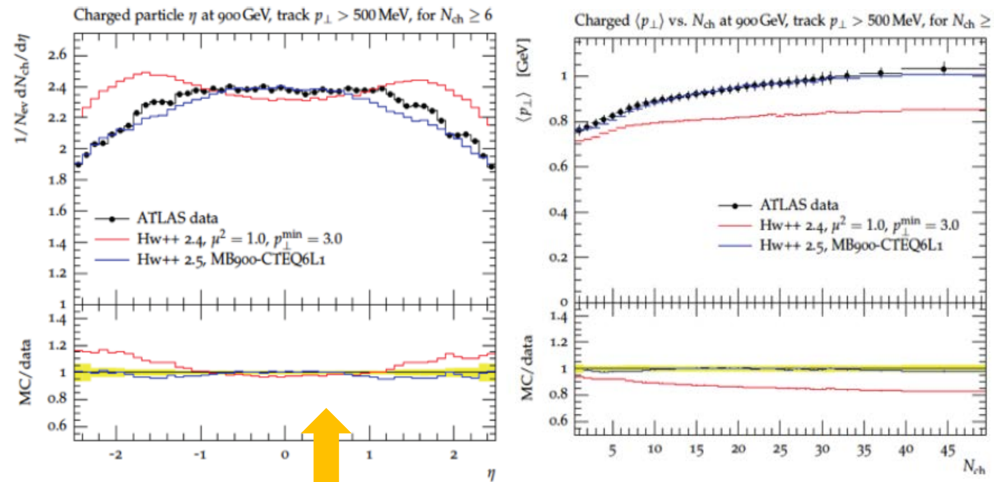
Pile-up = soft particles sitting on top of the hard-scale event, influencing efficiencies of various finding algorithms (Primary vertex, triggers, jets and other usual objects).

Diffractive signature: in the absence of forward proton detectors we have to rely on gaps. Gaps are easily seen only when Pile-up is low → concentrate on data 2010.

Rapidity gaps in soft processes

Special behaviour of HERWIG++ 2.5.1 UE7-2 which describes ATLAS MinBias data





ATLAS MinBias data [New J. Phys. 13 (2011) 053033]
Effect of CR studied by Gieseke et al., arXiv:1206.0041

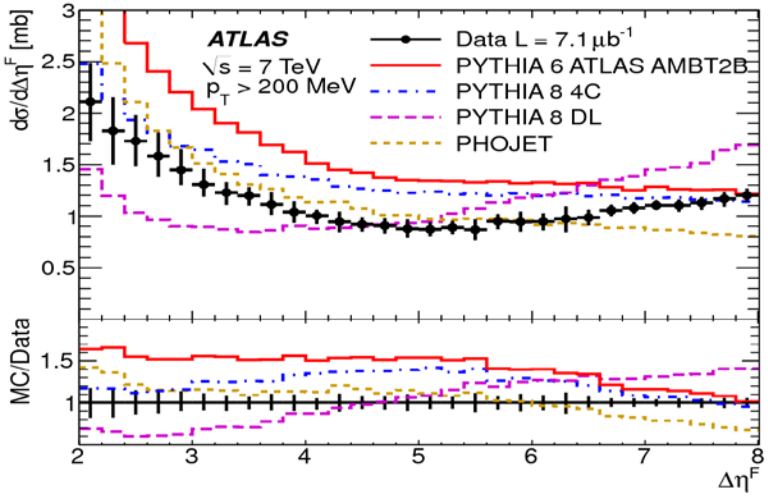
- ❑ HERWIG++ 2.5.1 MinBias UE7-2 does not contain diffractive processes, yet it produces very large gaps
- ❑ Different models of hadronization:

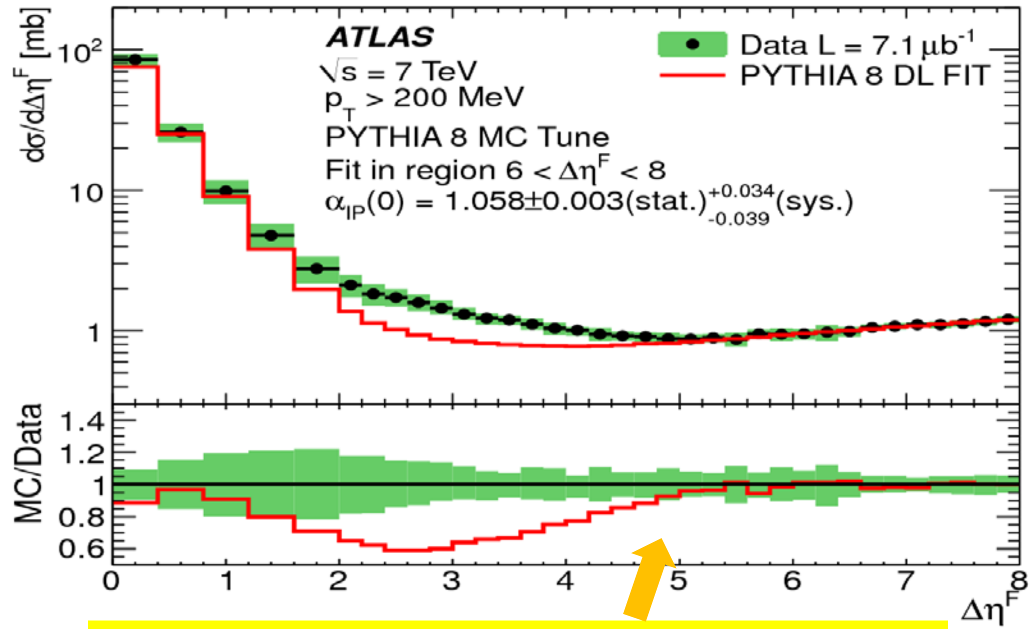
- No Empty Evts = excludes soft events
- No CR = excludes Color Reconnection

- ❑ HERWIG++ 2.5.1 MinBias UE7-2 fails to describe the shape for any of the tunings

Rapidity gaps in soft processes

Estimate of Pomeron intercept $\alpha_{IP}(0)$ in Donnachie-Landshoff model





Default DL:

$$\frac{d\sigma^{SD}}{d\xi dt} \propto \xi^{1-2\alpha_{IP}(t)} e^{bt} \qquad \begin{aligned} \alpha_{IP}(t) &= \alpha_{IP}(0) + \alpha_{IP}' t \\ \alpha_{IP}(0) &= 1.085 \\ \alpha_{IP}' &= 0.25 \end{aligned}$$

Improved description of the data by PYTHIA 8 DL with the fitted $\alpha_{IP}(0)$ = 1.058

- ❑ Implement DL model in PYTHIA 8
- ❑ Fit data in the region 6 < $\Delta\eta_F$ < 8 where ND is absent:

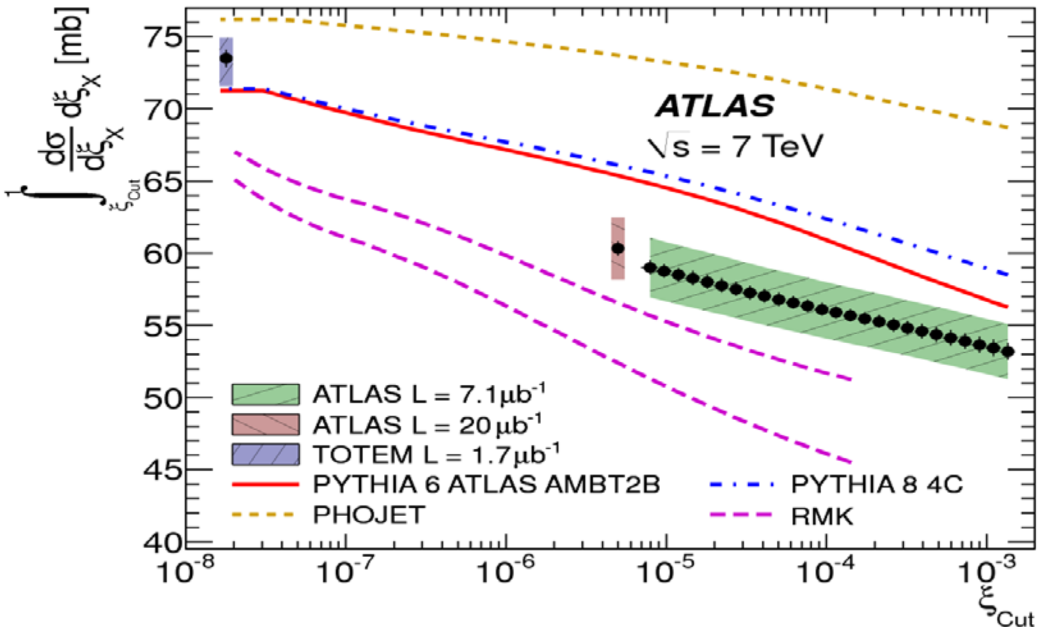
($\alpha_{IP}(0)$ governs the slope at large $\Delta\eta_F$: Flatness → $\alpha_{IP}(0)$ = 1, Increase → $\alpha_{IP}(0)$ > 1)

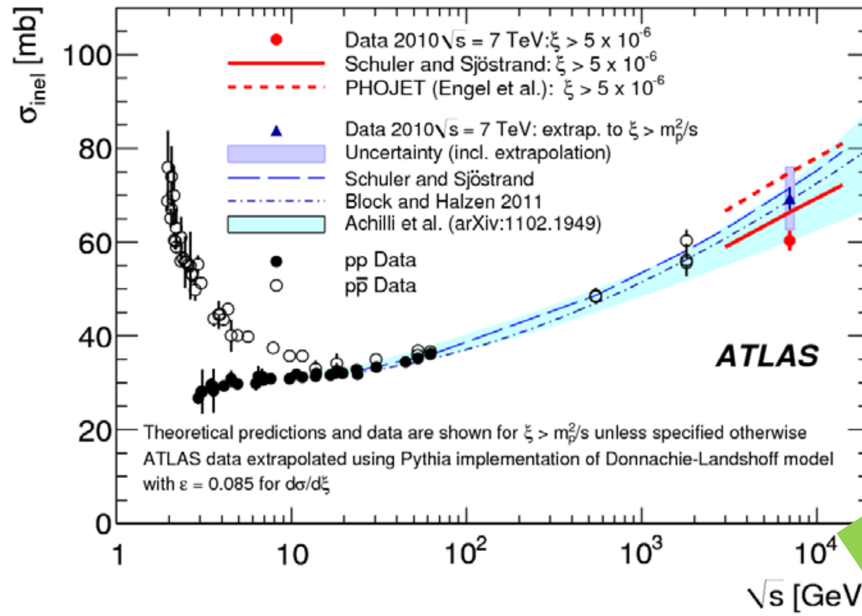
Best fit: $\alpha_{I\!P}(t=0) = 1.058 \pm 0.003(\mathrm{stat})^{+0.034}_{-0.039}(\mathrm{syst})$ ← due to large model uncert. still compatible with default DL $\alpha_{IP}(0)$

Cross section of ~ 1mb per unit of rapidity (see KMR, arXiv:1102.2844)

Rapidity gaps in soft processes

Estimate of the inelastic cross section





- Inelastic cross section obtained for $\xi > \xi_{cut}$ from MC thanks to strong correlation $\Delta\eta_F \sim -\ln \xi$
- Small corrections (~2%) applied to include particles with p_T < 200 MeV and to account for hadronization fluctuations
- Total uncertainty dominated by uncertainty on luminosity
- Comparison with Totem result and with previous ATLAS analysis ("Measurement of σ_{inel}(7 TeV)")
- Models fail to describe the evolution from low ξ (Totem) to large ξ (ATLAS) but RMK better in describing the slope (thanks to adding IP IP IR terms to IP IP IP terms)