ATLAS results on diffraction

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Diffraction and Low-x 2024
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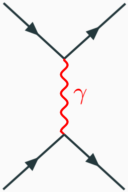
THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

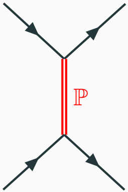
ATLAS
EXPERIMENT

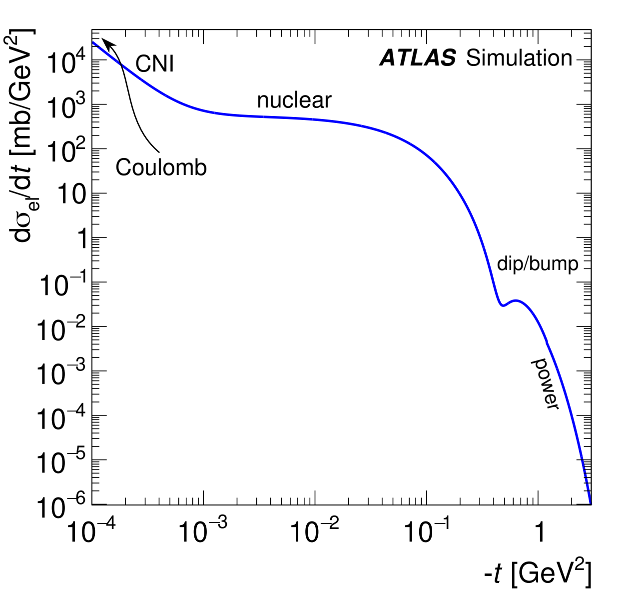
Diffraction in elastic pp interactions

Coulomb (electromagnetic)

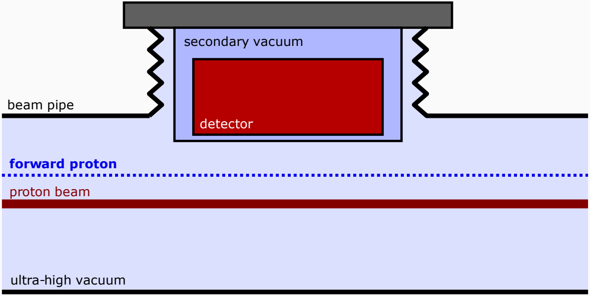


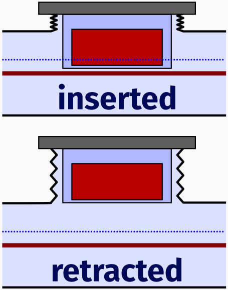
Nuclear (strong)



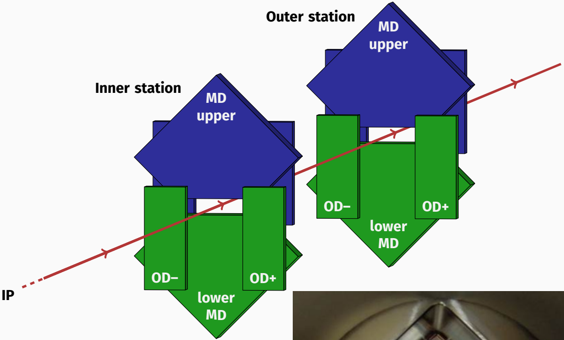


atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-08/


secondary vacuum
detector
beam pipe
forward proton
proton beam
ultra-high vacuum


inserted
retracted

ALFA detectors

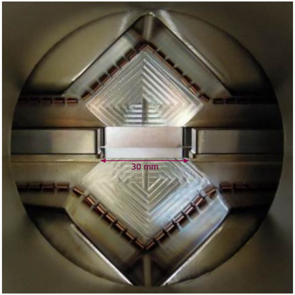


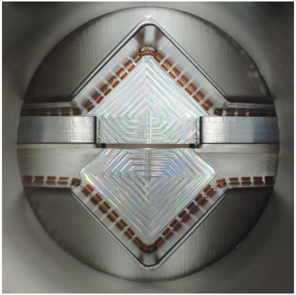
Main detectors (MDs)
for physics

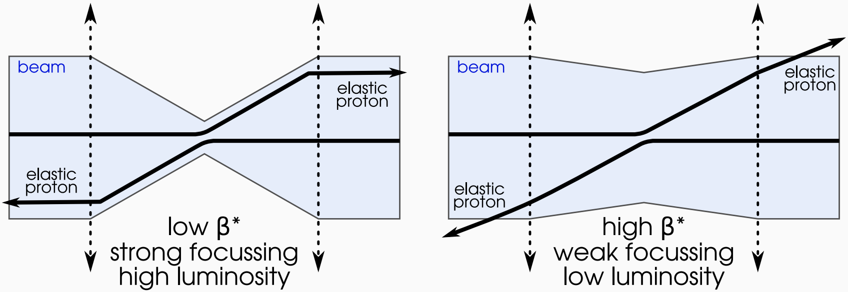
Overlap detectors (ODs)
for alignment

Detectors operate very close to the beam

Distance to the beam determines the lowest scattering angles (lowest t)





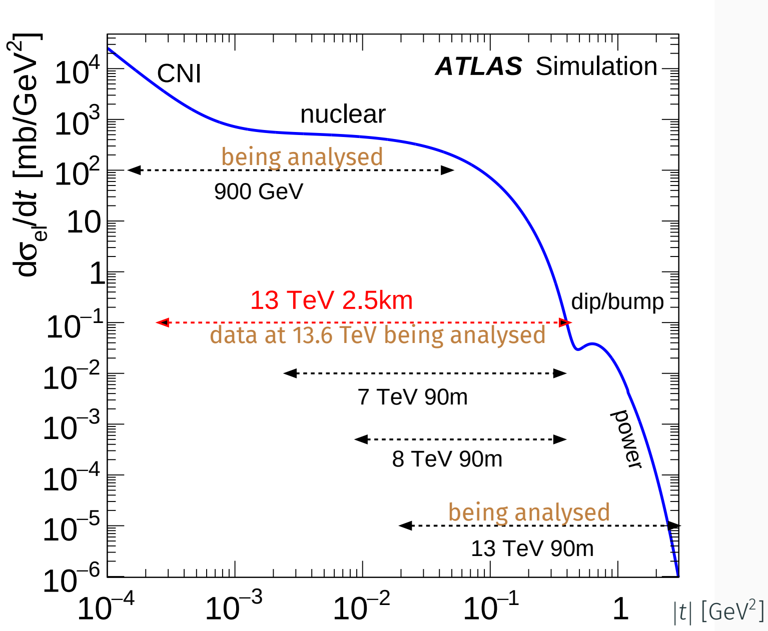


Typical values at LHC:

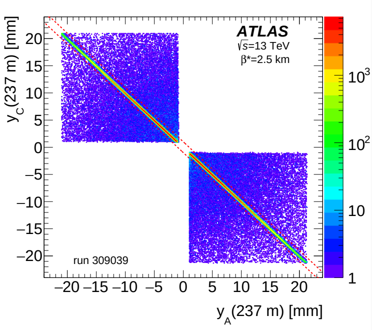
$\beta^* < 1$ m

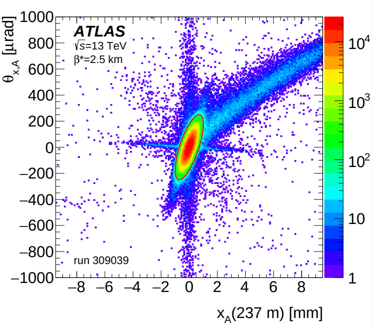
$\beta^* \geq 90$ m

ATLAS measurements of elastic scattering



Elastic event selection



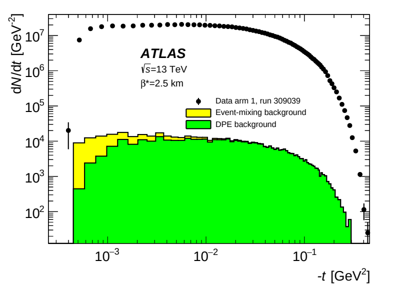


Event selection based on strong correlations present in elastic events

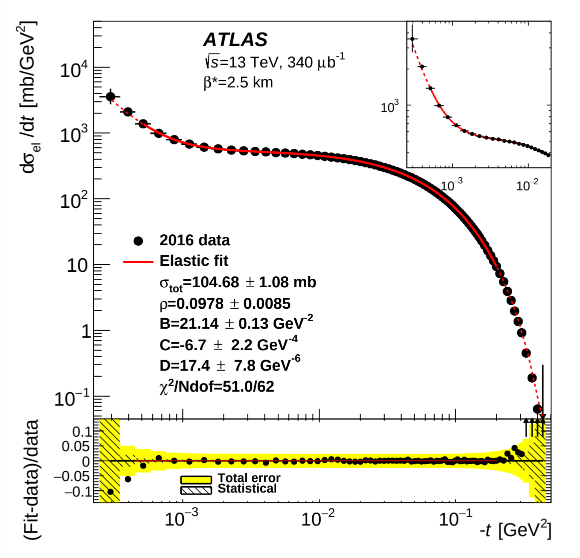
Background (normalized in control regions):

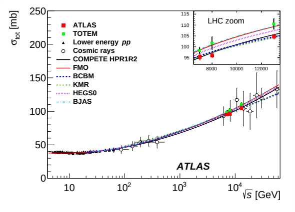
- accidental halo+halo and halo+SD coincidences (data-driven templates)
- central diffraction (MC simulation)

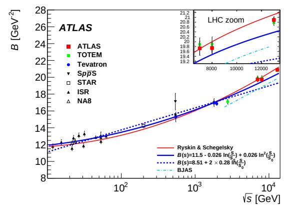
Relative uncertainty of 10 – 15%.

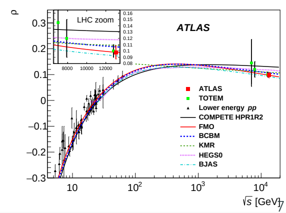


Differential cross section and fit results



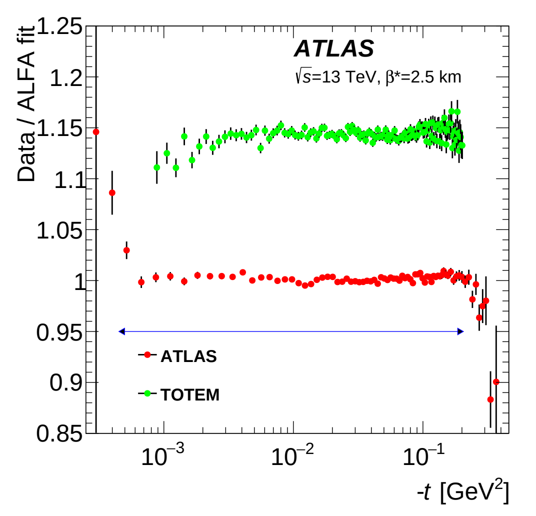






Not possible to describe both σ_{tot} and ρ without either the Odderon or a slowdown of σ_{tot} growth

Tension between ATLAS and TOTEM σ_{tot} (2.2σ for σ_{tot})



Luminosity-independent (TOTEM)

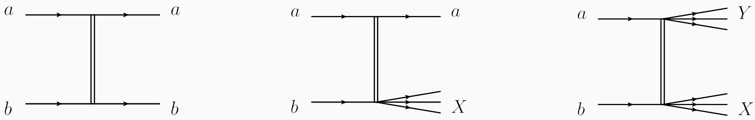
$$\sigma_{\text{tot}} = \frac{16\pi}{1+\rho^2} \frac{1}{N_{\text{el}} + N_{\text{inel}}} \left.\frac{dN_{\text{el}}}{dt}\right|_{t\to 0}$$

Requires correction for low-mass diffraction

Luminosity-dependent (ATLAS)

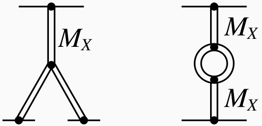
$$\sigma^2_{\text{tot}} = \frac{16\pi}{1+\rho^2} \frac{1}{L} \left.\frac{dN_{\text{el}}}{dt}\right|_{t\to 0}$$

Requires a dedicated luminosity measurement



Regge theory

Triple pomeron vertex



Good-Walker

Ψ_k – mass eigenstates

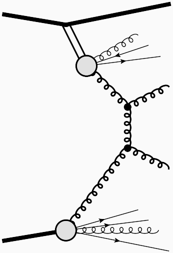
Φ_n – diffractive eigenstates

$$\Psi_k = \sum c_{kn}\Phi_n$$

$$d\sigma_{\text{diss}}/d^2b = \langle T^2 \rangle - \langle T \rangle^2$$

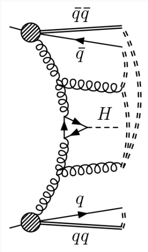
Resolved pomeron

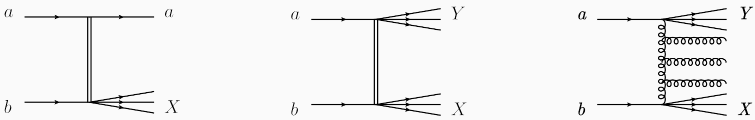
- Ingelman-Schlein model
- pomeron has partonic structure
- absorptive corrections (survival probability)

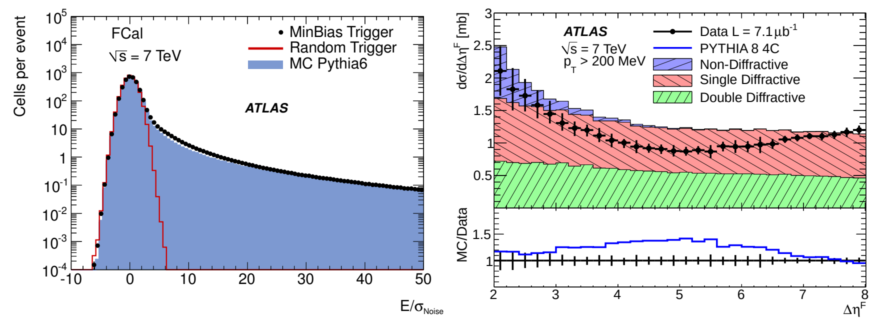


Soft colour interactions

- QCD-inspired model
- additional gluon exchanges screen the color flow

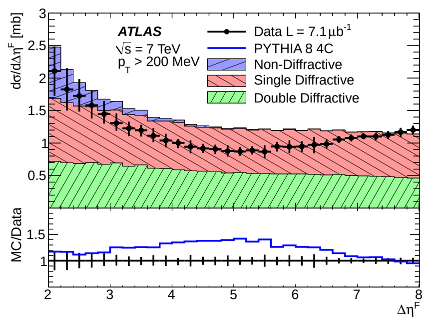


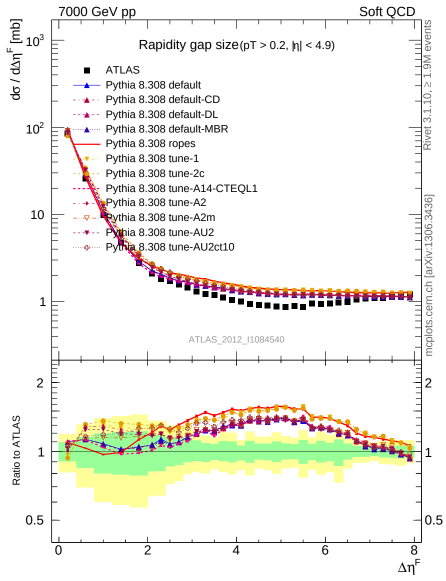




- Calorimeter used to measure rapidity gaps
- Separation of diffractive processes from non-diffractive processes
- Full separation of single and double diffraction not possible

Measurement of rapidity gap size distribution





- Result from 2012, but still relevant
- Recent Pythia versions continue to overestimate number of events with rapidity gaps of 4–5 units

Generated using `mcplot.cern.ch`

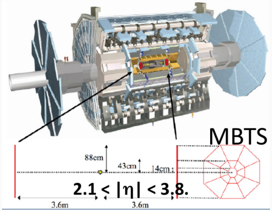
Measurement of SD using proton tag

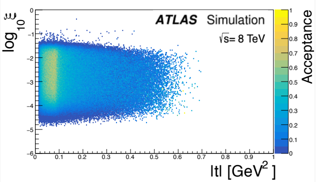
- Data from special run: $\sqrt{s}$ = 8 TeV, β^* = 90 m, L = 1.67/nb, μ < 0.08
- Intact proton measured in ALFA
- Dissociated proton measured using ATLAS tracking detector
- Trigger: opposite side coincidence of the signal in ALFA and Minimum Bias Trigger Scintilator (MBTS)
- Acceptance
  - tracker: charged particles with
    - p_T > 0.2 GeV
    - |η| < 2.5
  - MBTS: charged particles with 2.1 < |η| < 3.8
  - Fiducial region for the proton

$$0.016 < |t| < 0.43 \text{ GeV}^2$$

$$4.0 < \log_{10} \xi < 1.6$$

$$(\text{i.e. } 80 < M_X < 1270 \text{ GeV})$$

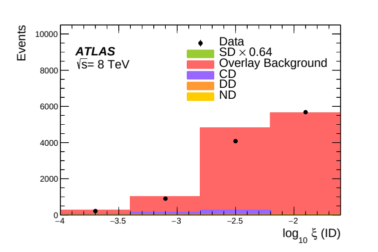




Background

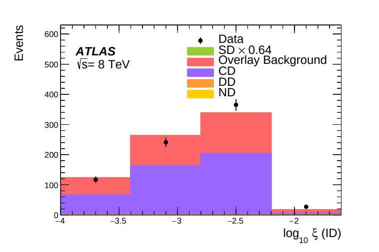
Overlay background

- Coincidence between a proton in ALFA (elastic, halo) and activity in central ATLAS (minimum bias interaction)
- Largest background
- Data-driven estimate using strongly ND-enriched events
- Control region: nominal selection, but with protons in two armlets (dominated by elastics + ND)

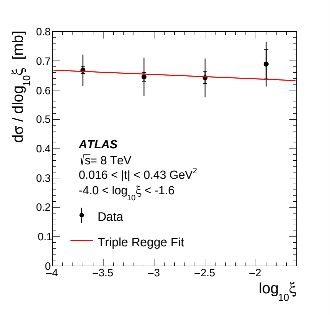


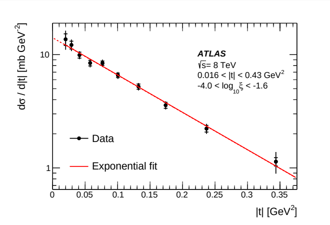
Central diffraction

- Dominant physics background
- Estimated from simulations
- Good description of normalizations and shapes
- Reweighting ξ distributions to match the data, preserving normalization
- Control region: protons in two armlets and 2–10 MBTS segments fired

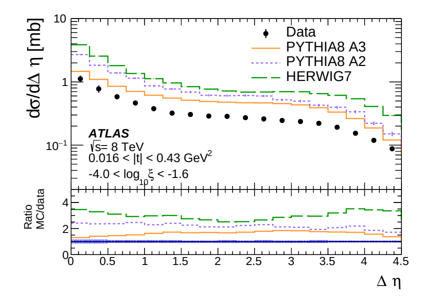


Proton kinematics distribution





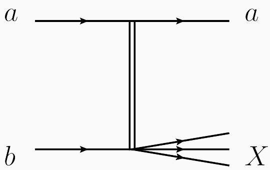
- Distribution fitted with:
  $$\frac{d\sigma}{d\log_{10}\xi} = \left(\frac{1}{\xi}\right)^{\alpha(0)-1} \frac{\exp(Bt_{high}) - \exp(Bt_{low})}{B},$$
- Measured Pomeron intercept
  $\alpha(0) = 1.07 \pm 0.02\,(stat.) \pm 0.06\,(\text{syst.}) \pm 0.06\,(\alpha')$
- Main systematic uncertainty from
  $\alpha' = 0.25 \pm 0.25$ GeV^{-2}
- PYTHIA 8 A3 (Donnachie-Landshoff): α(0) = 1.14
  PYTHIA 8 A2 (Schuler-Sjostrand): α(0) = 1.00
- Measured exponential slope:
  $B = 7.60 \pm 0.23$ (stat.) $\pm$ 0.22 (syst.) GeV^{-2}
- In agreement with Pythia 8 prediction:
  PYTHIA8 A2: 7.82 GeV^{-2}, PYTHIA8 A3: 7.10 GeV^{-2}
- Main systematic uncertainty from overlay background subtraction

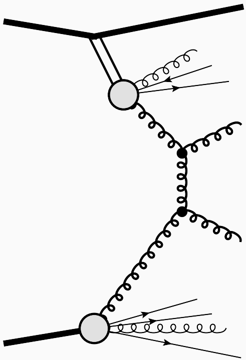


- Unfolded hadron level cross sections after background subtraction
- Diffractive plateau is visible
- Increase at small rapidity gaps: limited acceptance of ATLAS tracker
- Decrease at large rapidity gaps: loss of small-ξ events close to the ξ-edge (10^{-4})

MCs describe the shape but not the overall cross section:

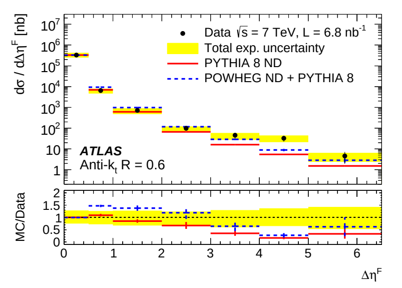
Distribution	$\sigma_{SD}^{\text{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t\text{-extrap}}$ [mb]
Data	1.59 ± 0.13	1.88 ± 0.15
Pythia8 A2 (Schuler–Sjöstrand)	3.69	4.35
Pythia8 A3 (Donnachie–Landshoff)	2.52	2.98
Herwig7	4.96	6.11

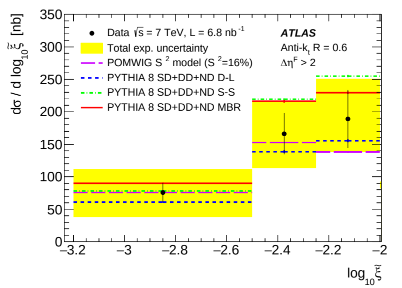




- ξ – momentum fraction of the proton carried by the pomeron
- t – squared four-momentum transferred from the proton
- β – momentum fraction of the pomeron carried by the interacting parton
- M_X – mass of the dissociated system ($M_X^2 = s\xi$)

Measurement of diffractive jet production

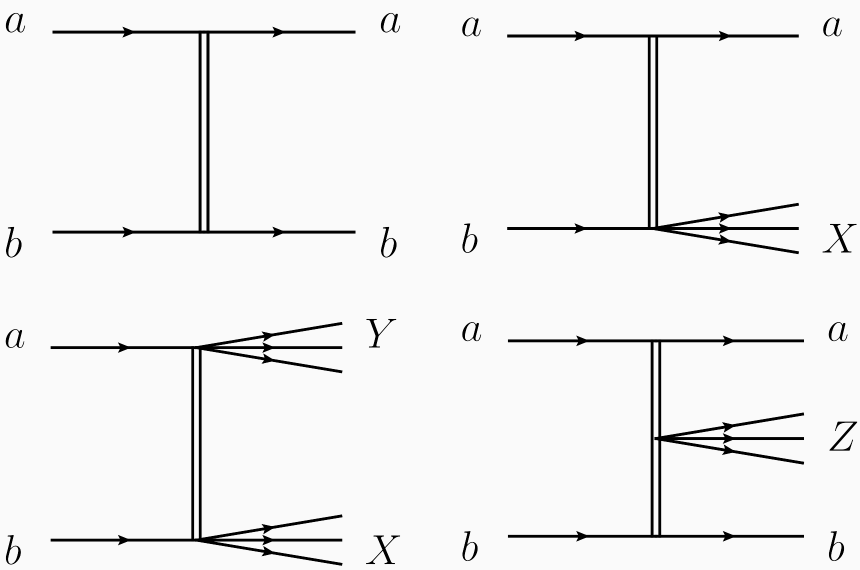




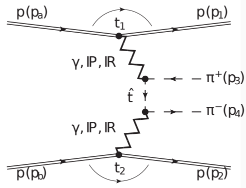
- Enhancement of data over ND producion for event with large rapidity gaps
- Evidence of diffractive component
- Good description by Pythia8
- Gap survival probability extracted:
  $0.16 \pm 0.04\,(\text{stat}) \pm 0.08\,(\text{exp. syst.})$

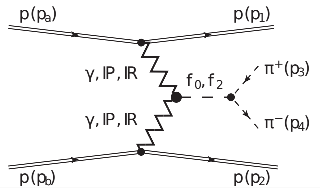
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-04/

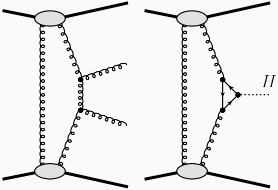
Central diffraction

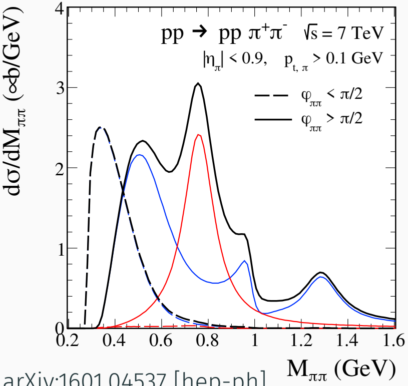


Exclusive diffraction (central exclusive production)









arXiv:1601.04537 [hep-ph]

Soft exclusive diffraction

– interesting and complex mechanism

– non-trivial interplay of continuous and resonant production

– important absorptive corrections

Hard exclusive diffraction

– interesting pQCD mechanism

– constraints on spin of the produced system

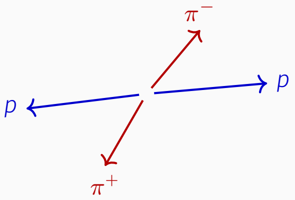
– important absorptive corrections

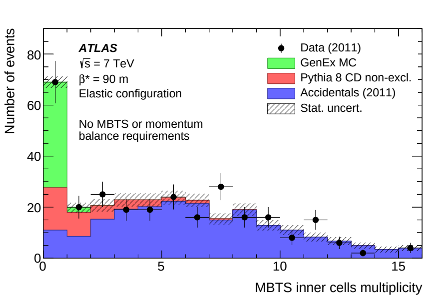
– difficulty with triggering

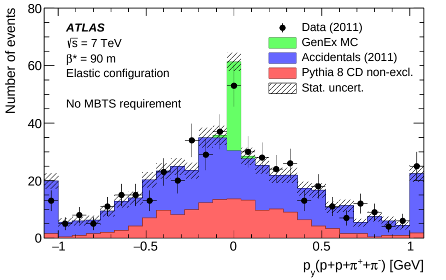
Exclusive pion pair production

Selection of $pp \to p\pi^+\pi^- p$ events:

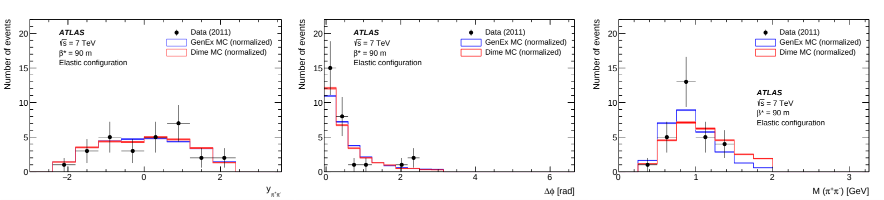
- forward protons detected in ALFA
- opposite-charged pions detected in the central ATLAS detector
- vetoing activity in Minimum Bias Trigger Scintillator (MBTS)
- Exclusivity enforced by looking at p_T balance in the event







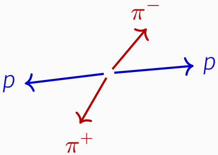
Results: Eur. Phys. J. C 83 (2023) 627



First exclusive $\pi^+\pi^-$ measurement with proton tagging at LHC!

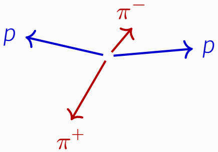
– elastic *pp* configuration

$$\sigma = 4.8 \pm 1.0(\text{stat})^{+0.3}_{-0.2}(\text{syst}) \pm 0.1(\text{lumi}) \pm 0.1(\text{model})\ \mu\text{b}$$

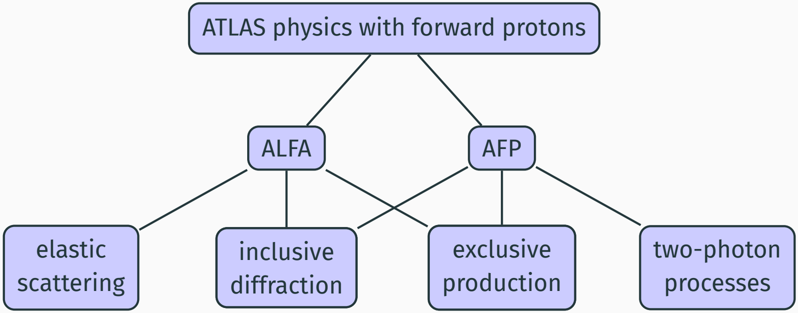


– anti-elastic *pp* configuration

$$\sigma = 9 \pm 6(\text{stat}) \pm 1(\text{syst}) \pm 1(\text{lumi}) \pm 1(\text{model})\ \mu\text{b}$$



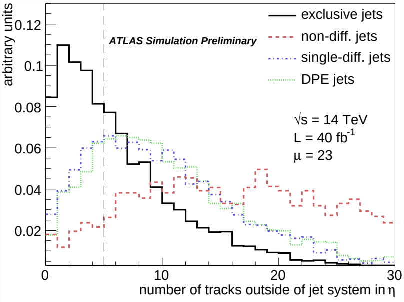
- ATLAS is well capable of measuring diffractive processes
- Forward proton tagging significantly enhances these possibilities
- ALFA detectors – high-β^* optics, precise t measurement
- AFP detectors – standard optics, precise ξ measurement
  (see Maciej's talk about detectors and André's talk about photon-induced processes)

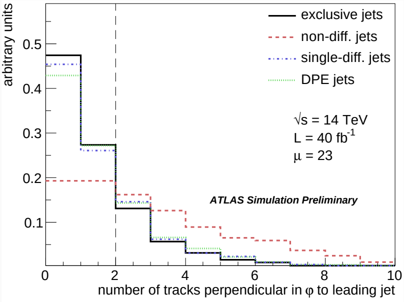


BACKUP

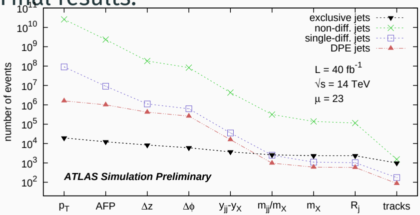
Exclusive jets

Selection based on event activity:





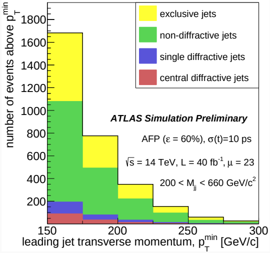
Final results:

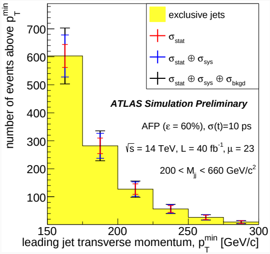


- Low cross section ⟶ high pile-up conditions ⟶ large backgrounds
- Many selection criteria: ToF, kinematic correlations, event activity
- Data-driven background estimation needed for precise measurement

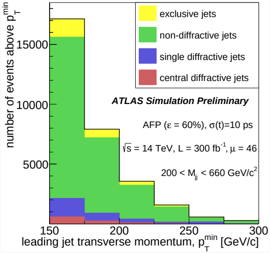
Exclusive jets

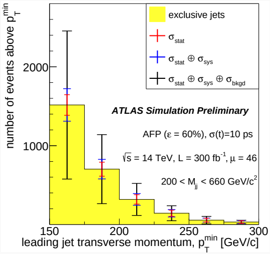
μ = 23, L = 40/fb





μ = 46, L = 40/fb





Assumed:

- 6% uncertainty on non-diff. jets
- 20% uncertainty on single-diff. jets
- 20% uncertainty on central-diff. jets
- 10 ps ToF resolution

Dominant uncertainty due to non-diff. jets. Should be possible to constrain it much better from control regions (e.g. using ToF).