Measurements of the Total Proton-Proton Cross Section with the ATLAS Detector

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for the ATLAS Collaboration

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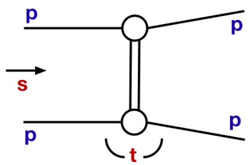
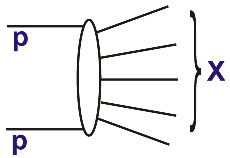
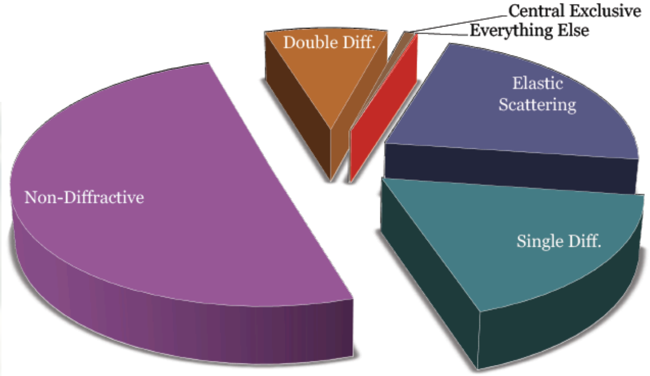


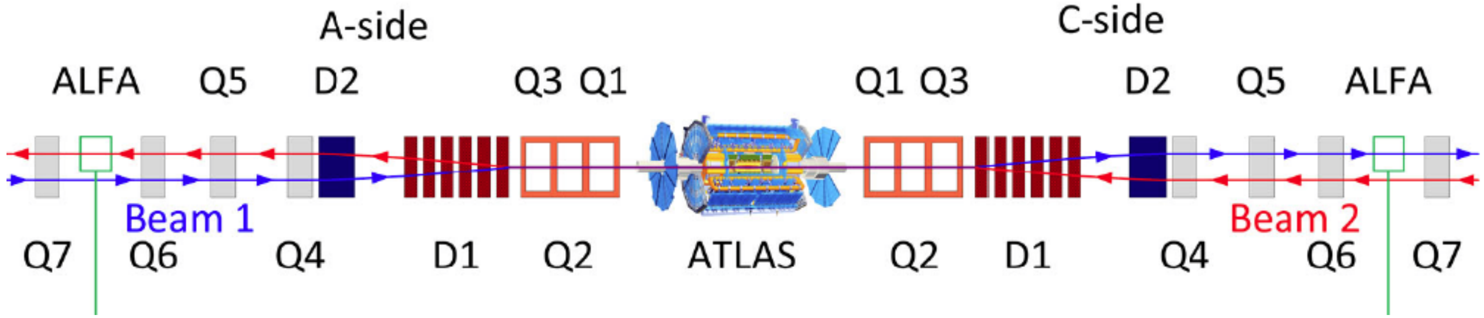




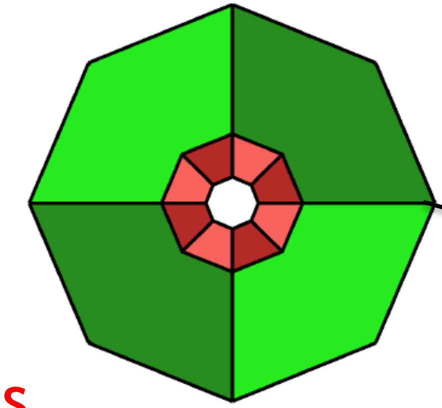
→ Elastic & total cross sections with ALFA Roman pots

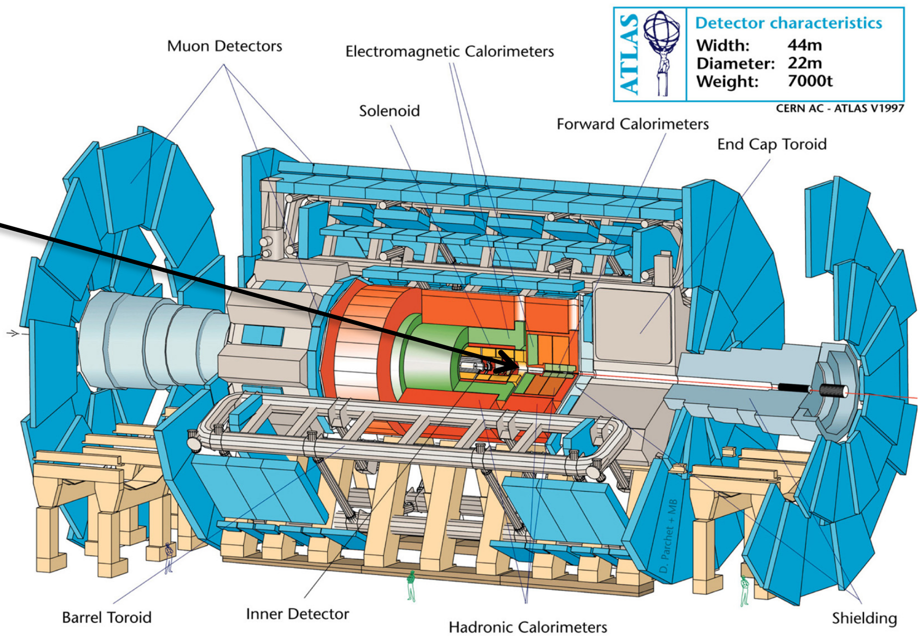
→ Total inelastic cross section from minimum bias data

Methods



1) Directly tag outgoing protons in ALFA Roman pot spectrometer
[4 stations at ~240m from interaction point].
… obtain σ_{el} directly and apply optical theorem for σ_{tot}.



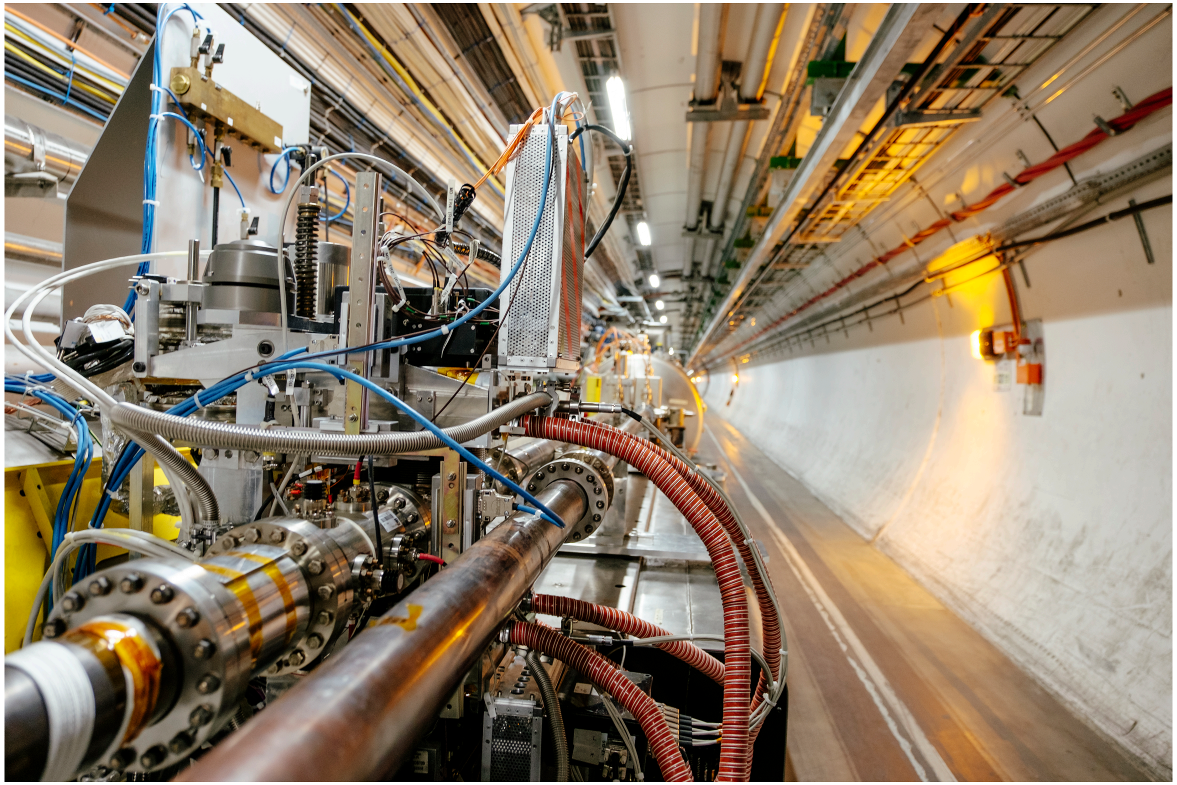


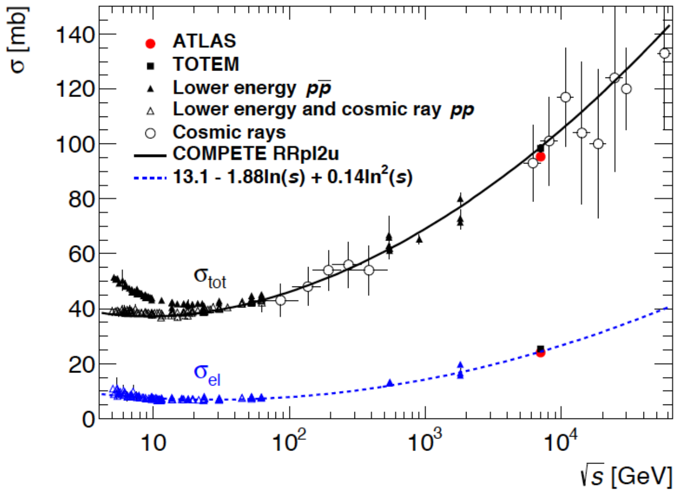
2) Obtain minimally biased samples triggered by any charged particle in the Minimum Bias Trigger Scintillator (MBTS) detectors

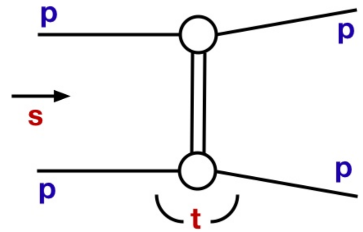
[z = ± 3.6m, 2.1 < |η| < 3.9, rebuilt in long shutdown]

1) Proton Tagging Method

- Earlier result at $\sqrt{s}$=7 TeV: Nucl Phys B889 (2014) 486
- Presented here, $\sqrt{s}$=8 TeV result: Phys Lett B761 (2016) 158





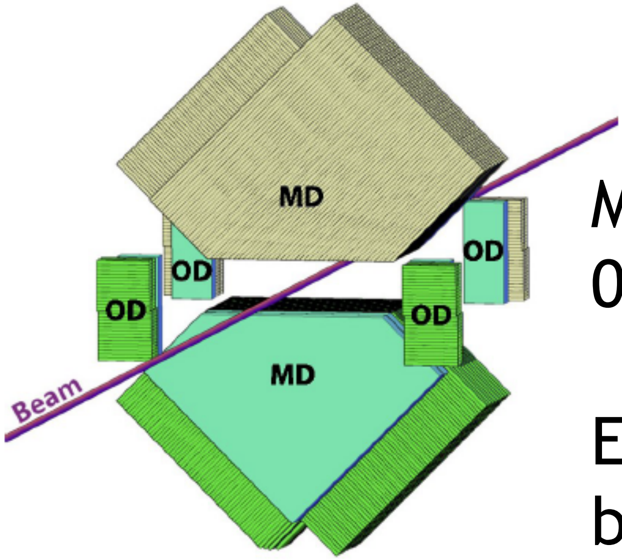


2012 β^* = 90m run low lumi run (μ=0.1) with

pots at 7.5mm (9.5σ) from beam, allowing access to small t

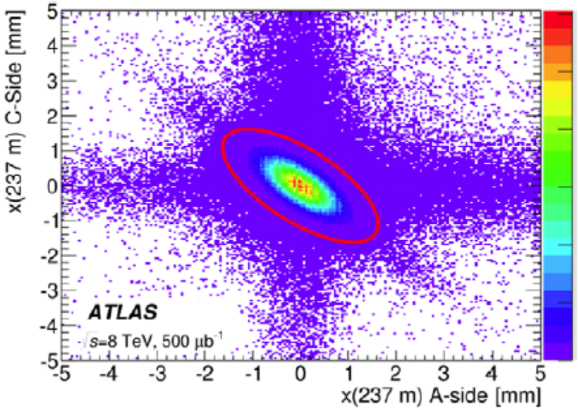
→3.8M events after selection, background ~0.1%

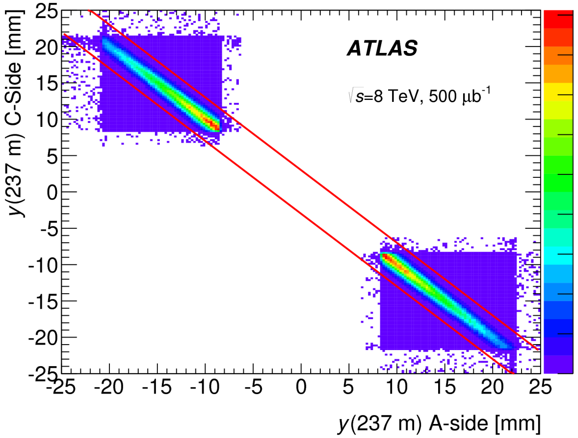
Measurement Principle



Main detectors (MD) are 2x10 layers of 0.5mm^2 square scintillating fibres per pot.

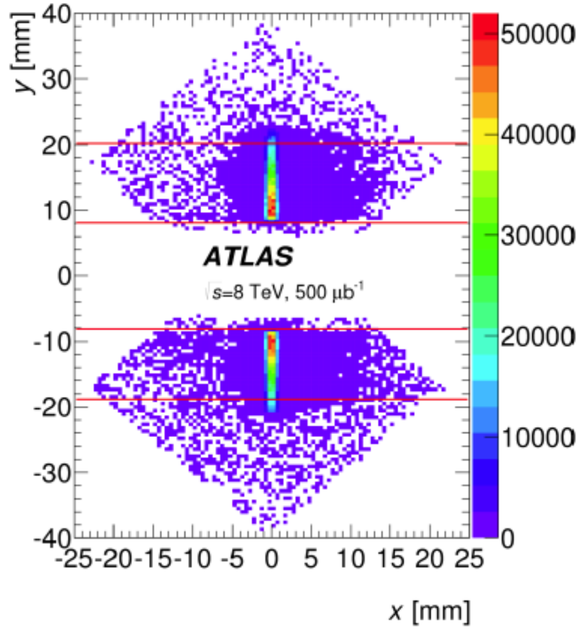
Elastically scattered protons characterised by back-to-back topology (anti-correlation in x and y between A and C sides of ATLAS)





At high β^*, parallel-to-point focusing in vertical plane…

$$t = -\left(p\theta^*\right)^2$$

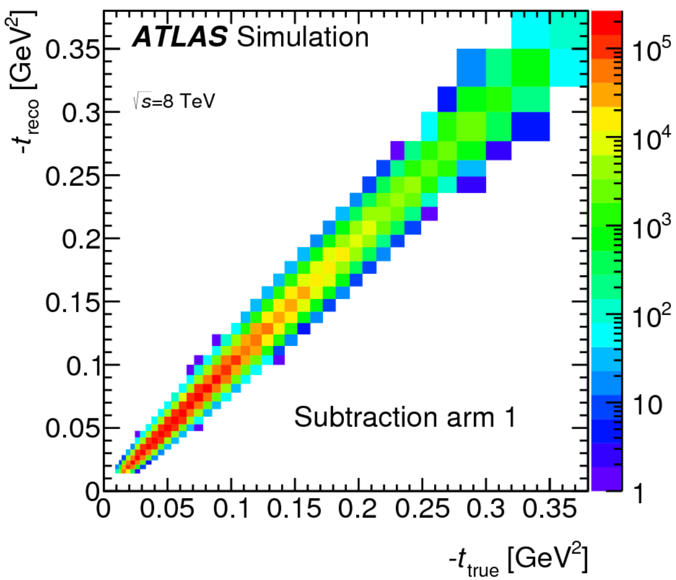


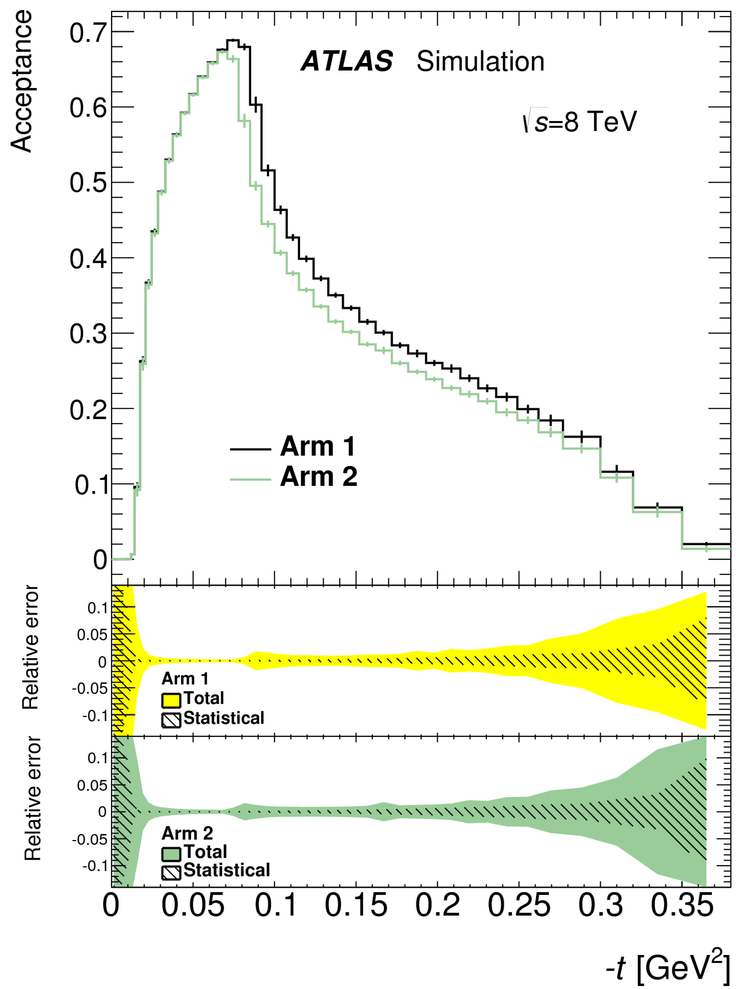
- Beam: p=3988±26 GeV

- θ^* from y coordinate and knowledge of beam optics

Correcting for Instrumental Effects

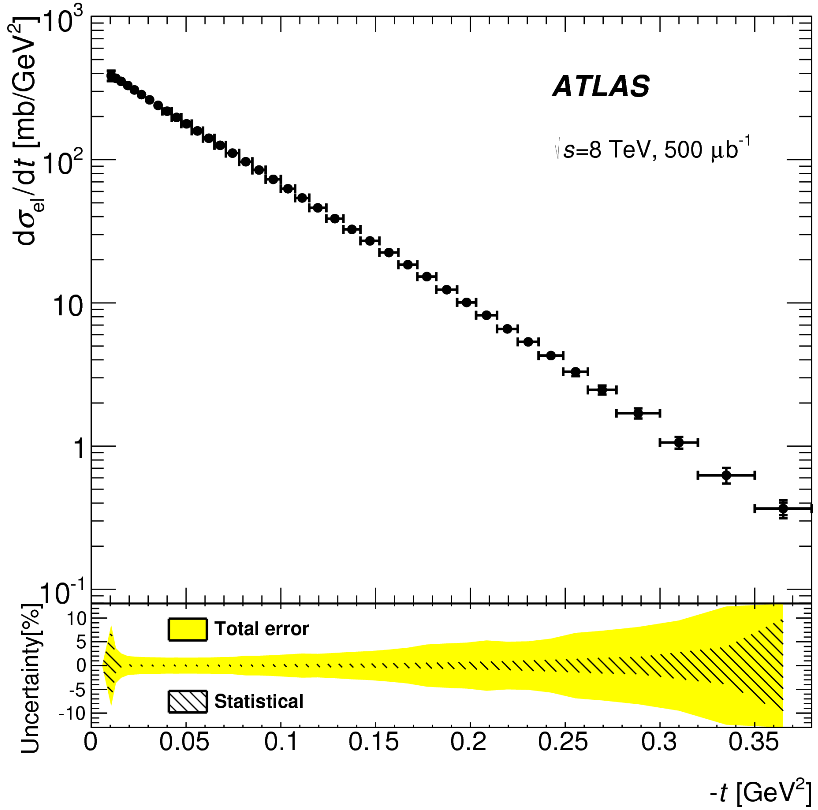
- Reconstruction (~90%), trigger (>99.9%) efficiencies from data.
- Beam optics model tuned with ALFA constraints and applied via PYTHIA8:





- Unfolding corrections usually < 2%
- Acceptance limitations due to fiducial volume cuts well controlled
- Dedicated lumi determination: Beam Condition Monitors (& vertices, LUCID, van der Meer) → 1.5% uncertainty

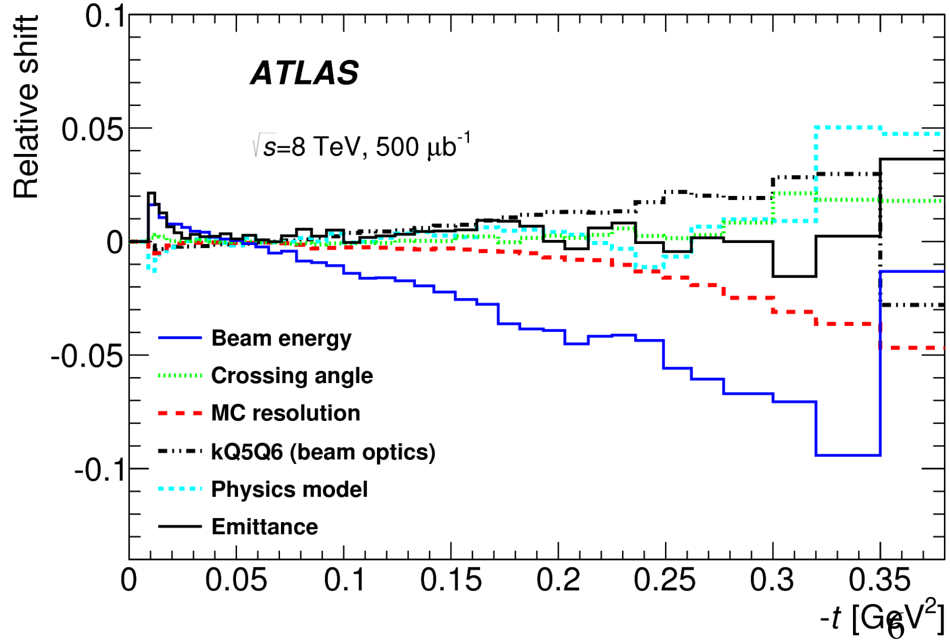
Unfolded Data



- Data cover the region 0.01 < |t| < 0.36 GeV², systemtaics limited throughout

- Dominant systematic at small |t| is luminosity (1.5% normalisation)

- 0.65% uncertainty on beam energy generates largest systematic at high |t|



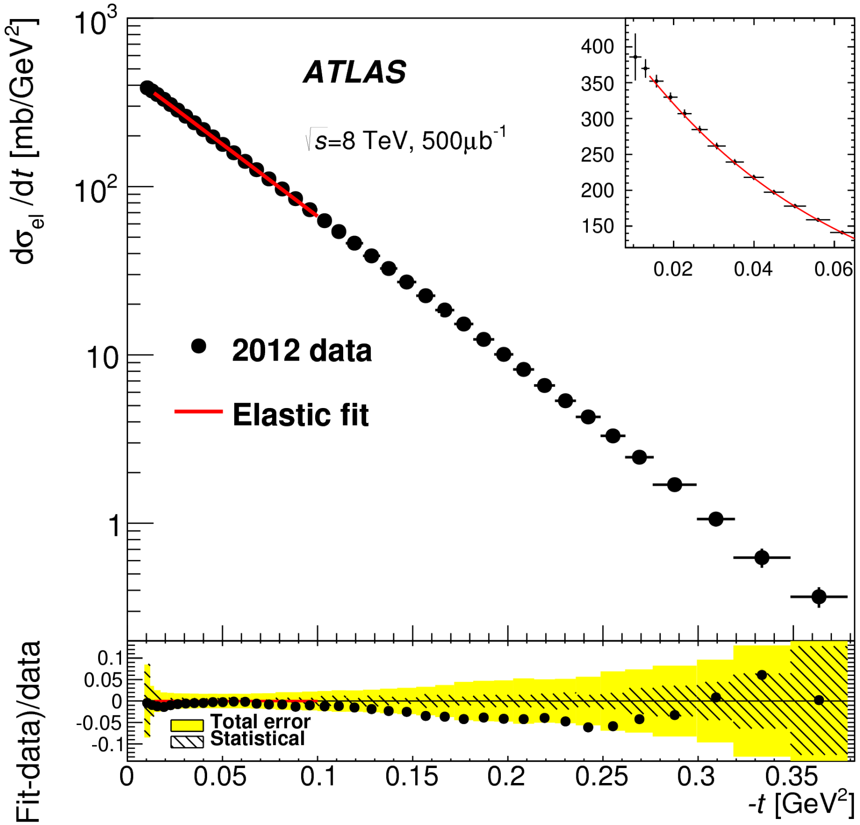
(a)

Fitting the Data

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2 ,$$

$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|} ,$$

$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c}e^{-B|t|/2} ,$$



(b)

Fixed parameters:
- ρ (~0.14) = ratio of Re/Im amplitudes at t=0
- G = proton electric form factor
- ϕ = phase of Coulomb-nuclear interference at t=0

- Fit $0.014 < |t| < 0.1$ GeV^2, where acceptance is large and theory uncertainty is small

- Influence of interference small.

- Hadronic region compatible with pure exponential: ~ e^{Bt}

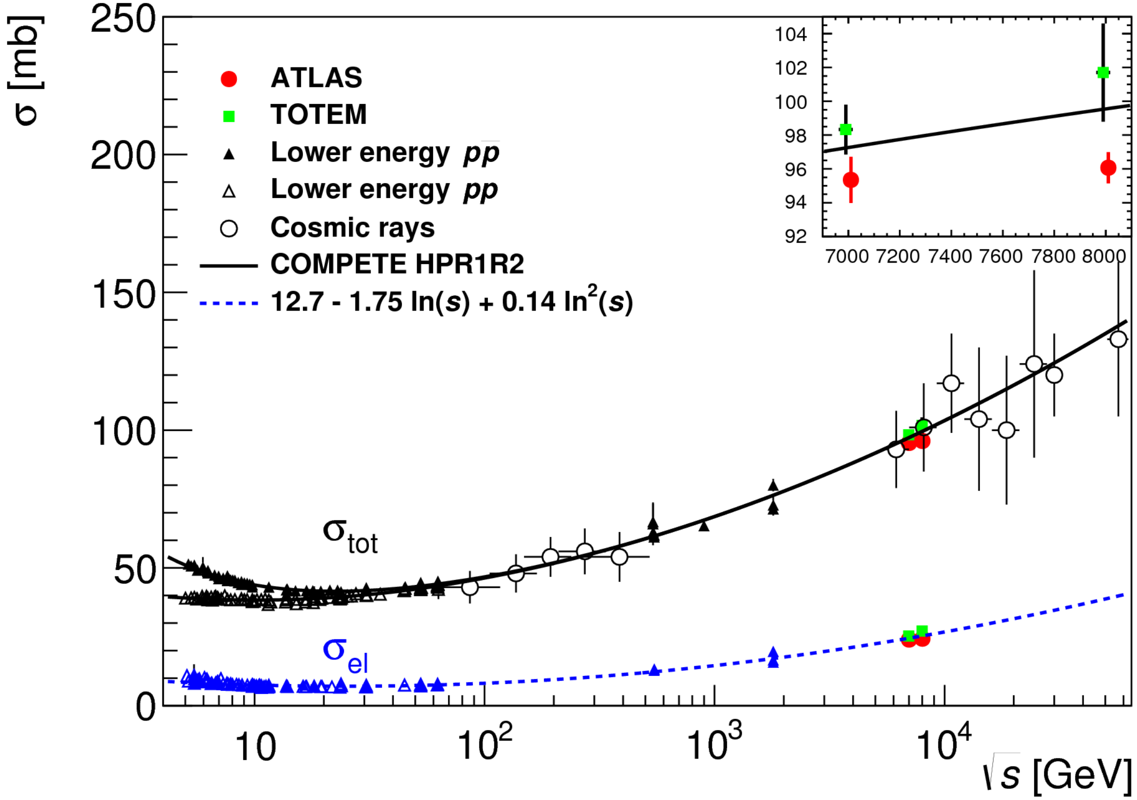
- Total hadronic cross section emerges via fit normalisation

Results and Energy Dependence: σ_{tot}

$$\sigma_{tot}(8\ \text{TeV}) = 96.07 \pm 0.18(\text{stat.}) \pm 0.85(\text{exp.}) \pm 0.31(\text{extr.})\ \text{mb}$$

$$\sigma_{el}(8\ \text{TeV}) = 24.33 \pm 0.04(\text{stat}) \pm 0.39(\text{syst})\ \text{mb}$$

$$\sigma_{inel}(8\ \text{TeV}) = 71.73 \pm 0.15(\text{stat}) \pm 0.69(\text{syst})\ \text{mb}$$



- Luminosity uncertainty dominates

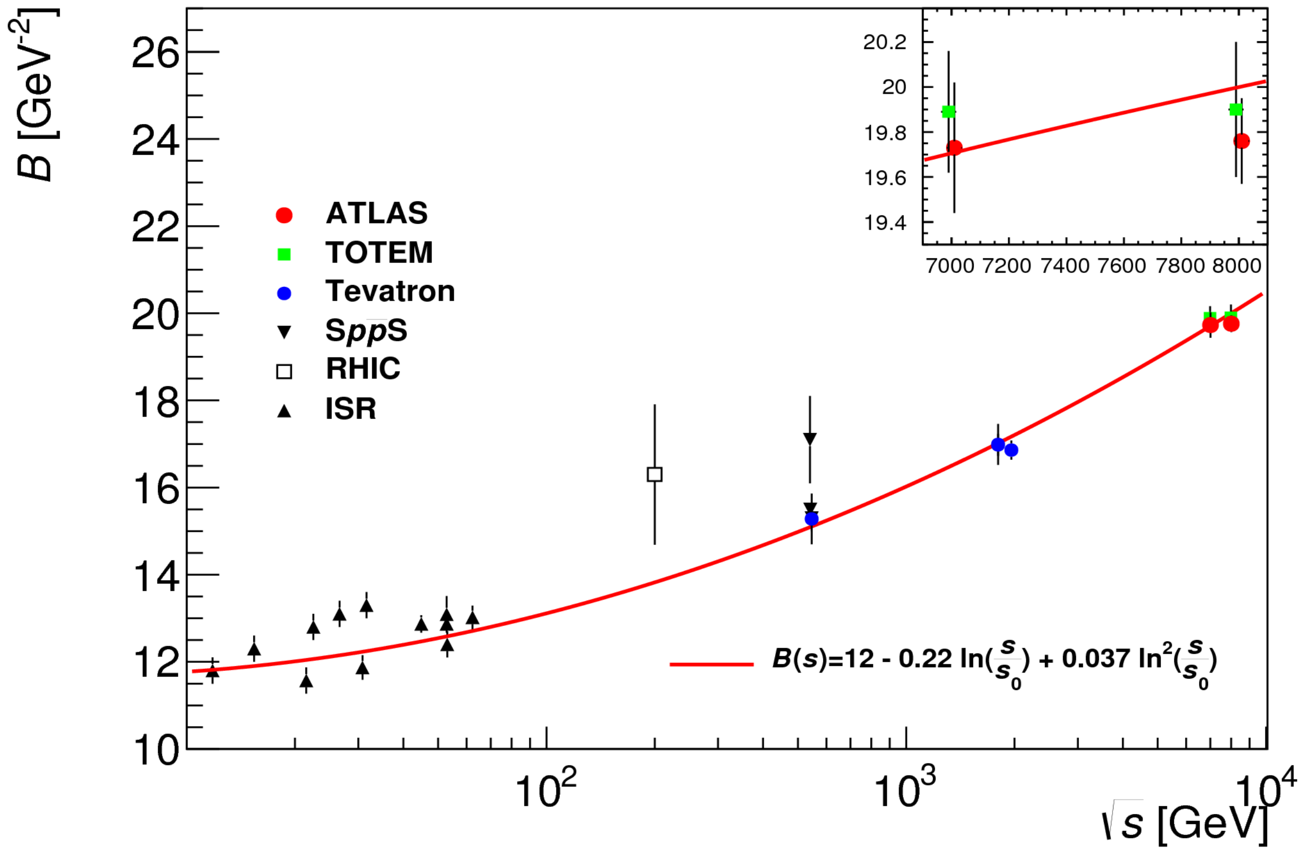
- Extrapolation error from varying fit range & theory assumptions

- ATLAS 1.9σ lower than TOTEM lumi-independent result (cf 1.3σ at 7TeV)

Data remain compatible with slow growth with √s (logarithmic or power law?...)

Results and Energy Dependence: B

$$B(8\ \text{TeV}) = 19.74 \pm 0.05(\text{stat.}) \pm 0.16(\text{exp.}) \pm 0.15(\text{extr.})\ \text{GeV}^{-2}$$

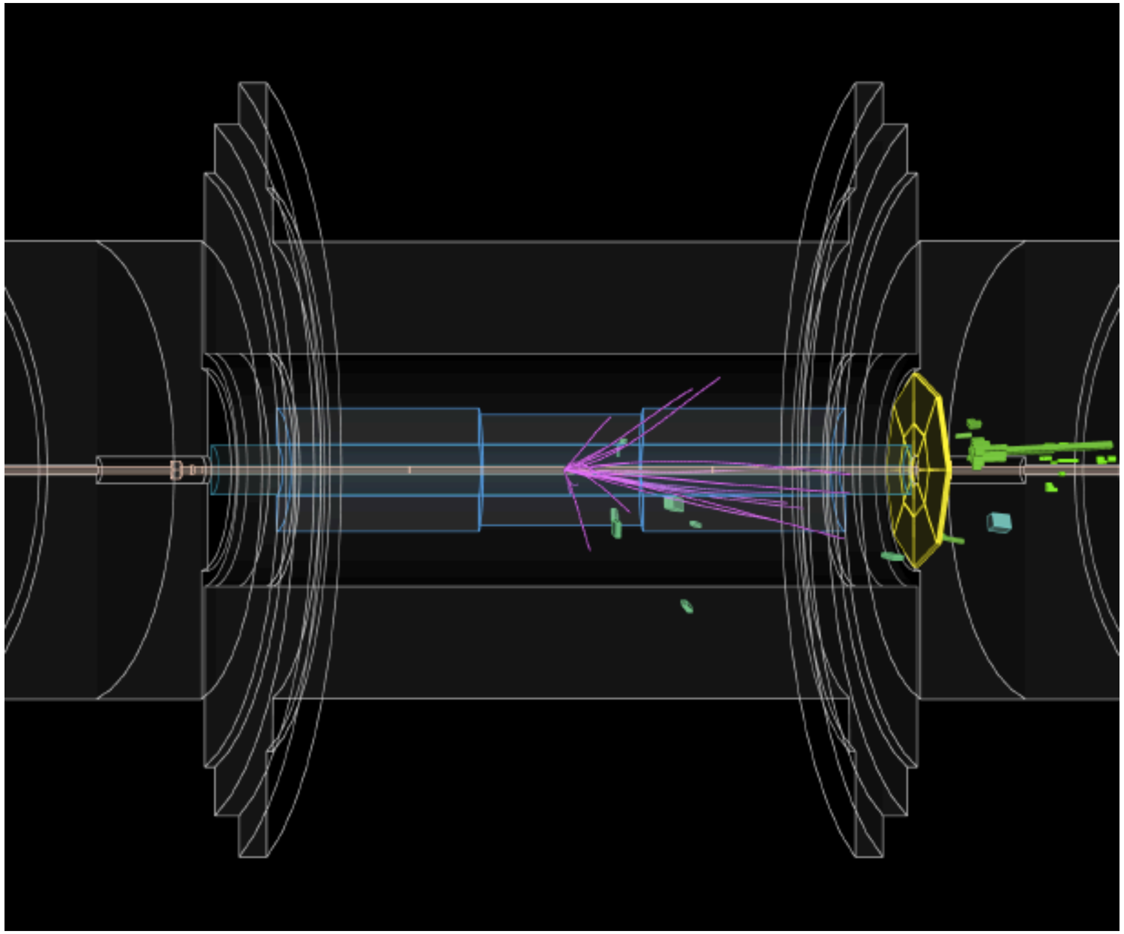


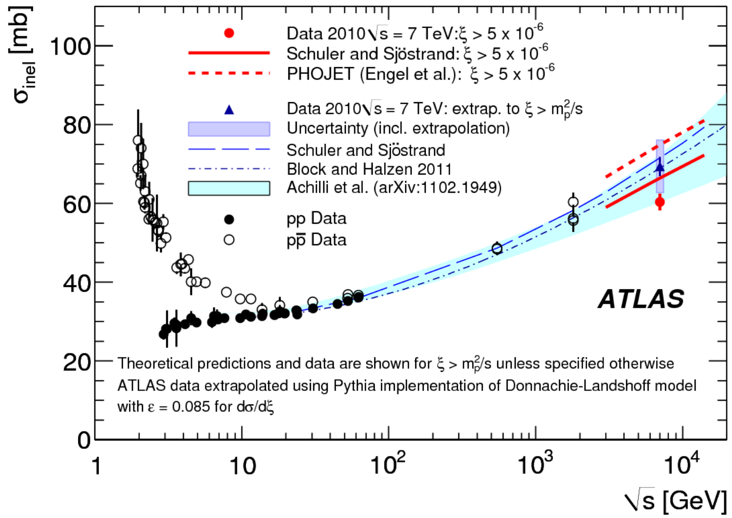
- Dominant uncertainties are beam energy (exp), fit range (extr)
- ALFA and TOTEM in good agreement
- Data remain compatible with shrinkage of forward elastic peak with √s [Schegelsky & Ryskin model shown, α'~0.11 GeV^{-2}]

2) Minimum Bias Method

- Earlier result at $\sqrt{s}$=7 TeV: Nature Commun 2 (2011) 463
- Presented here, 13TeV result: PRL 117 (2016) 182002

(from short low pile-up (μ<0.1) run taken in June 2015)





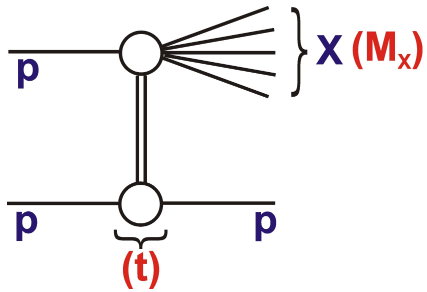
MBTS = plastic scintillator, $2.1 < |\eta| < 3.9$ with 8-fold segmentation nearest beam-pipe and 4-fold further out.

… obtain almost all of σ_{inel} directly.

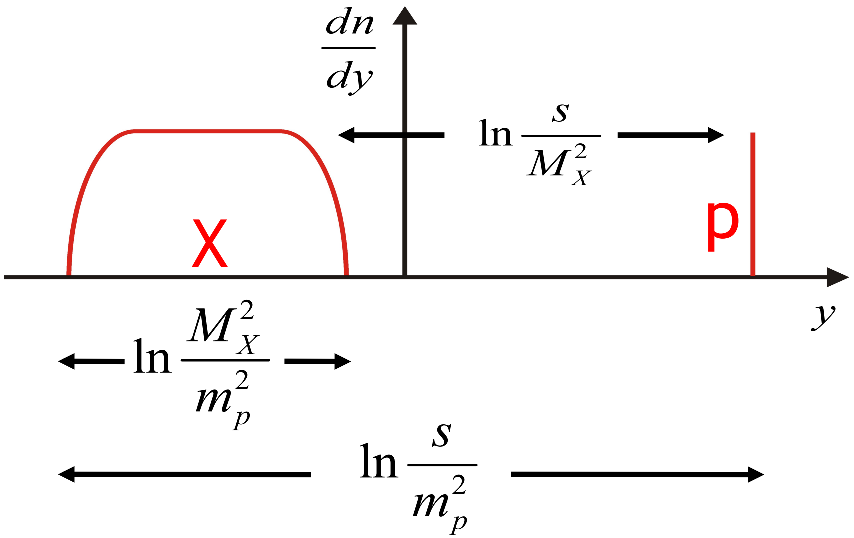
Total Inelastic Cross Section

- MBTS sees 90-95% of all inelastic events → "simple" counting experiment.

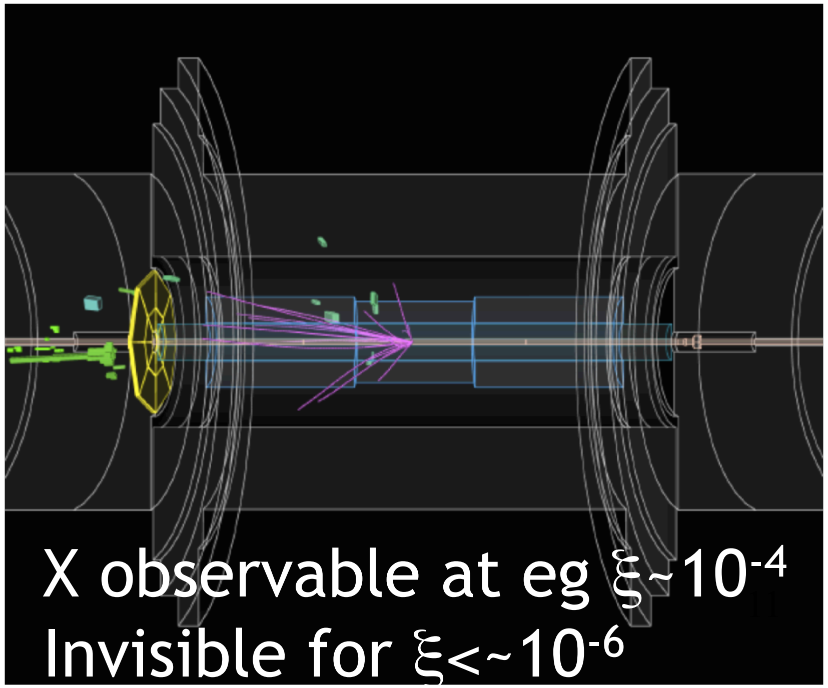
$$\xi = M_X^2 / s$$



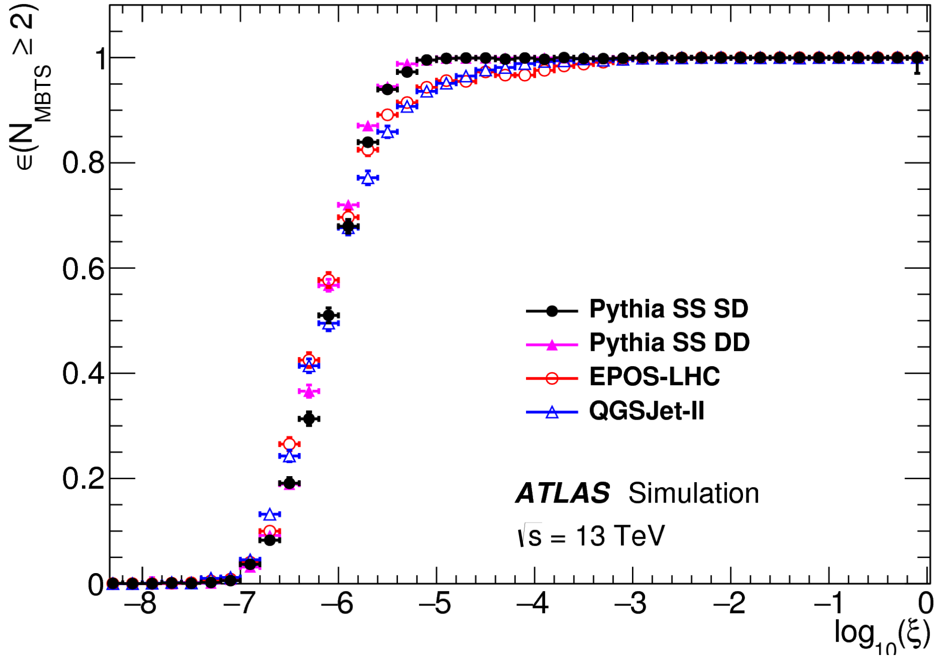
- Complication: controlling low mass diffractive dissociation that leaves no signal in MBTS (M_X <~ 13 GeV)



$$\Delta\eta \approx -\ln \xi$$



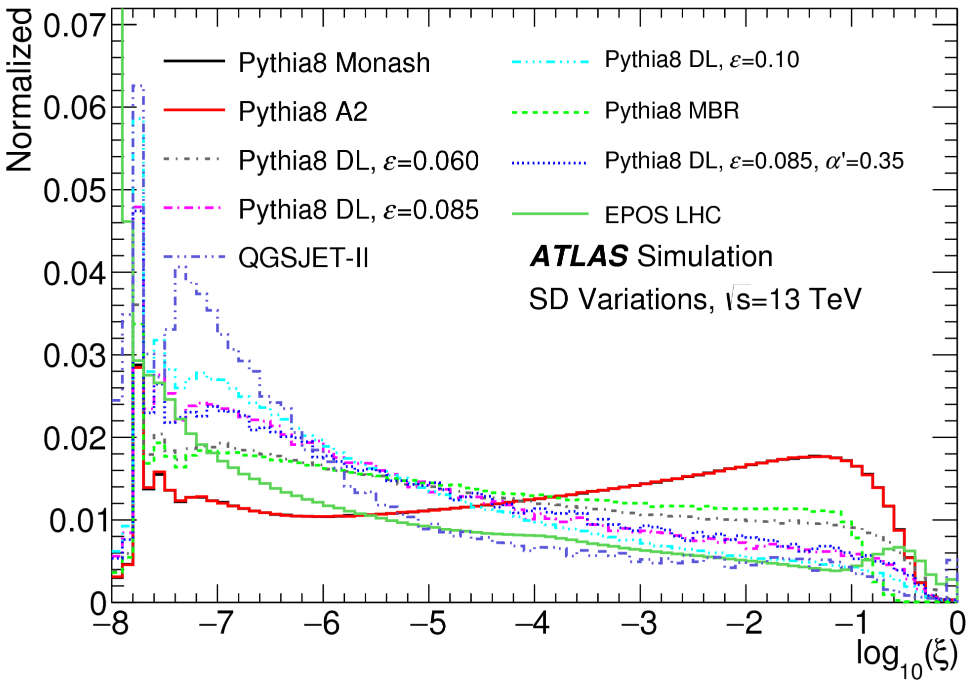
Why low mass diffraction is a problem

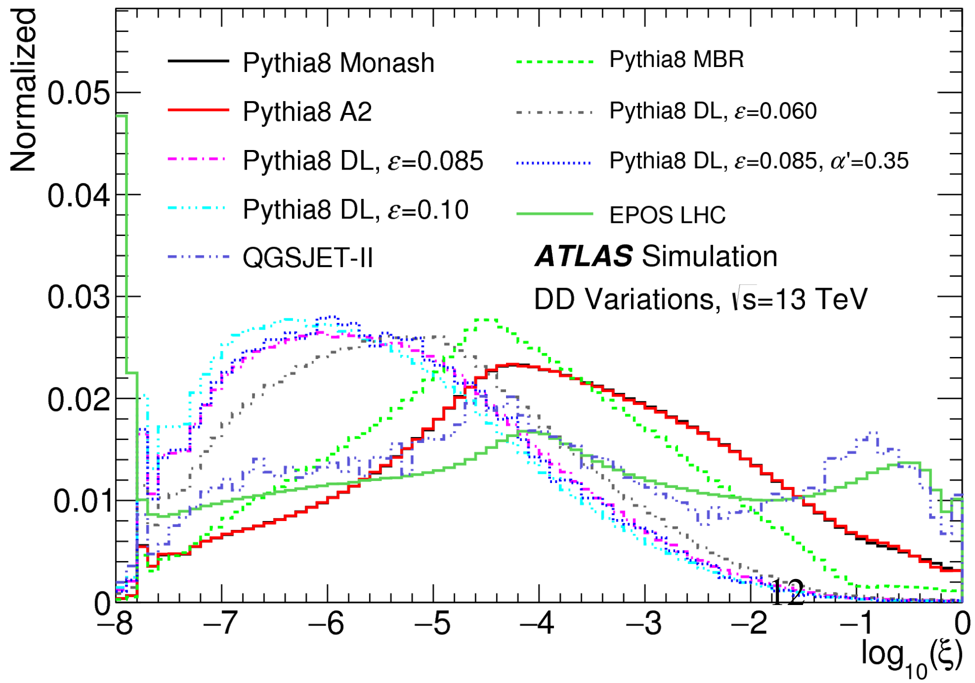


$$\Delta\eta \approx -\ln\xi$$

Acceptance limit of MBTS ($|\eta|$~ 4) corresponds to ξ ~ 10^{-6}

Cross section for $\xi < 10^{-6}$ poorly constrained → fiducial region defined as $\xi > 10^{-6}$

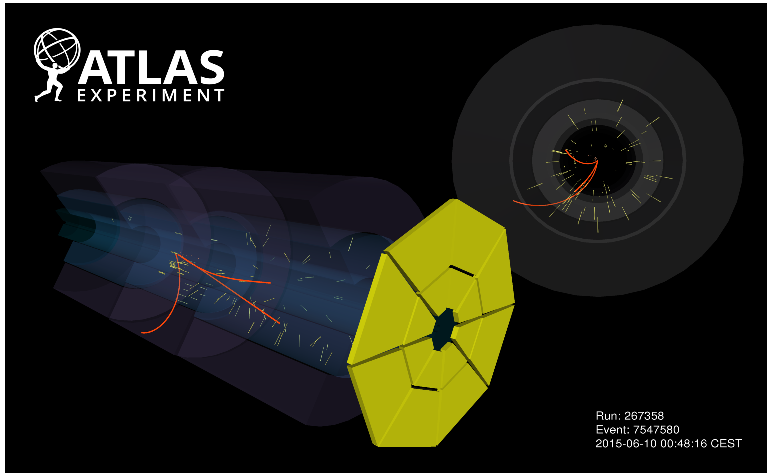


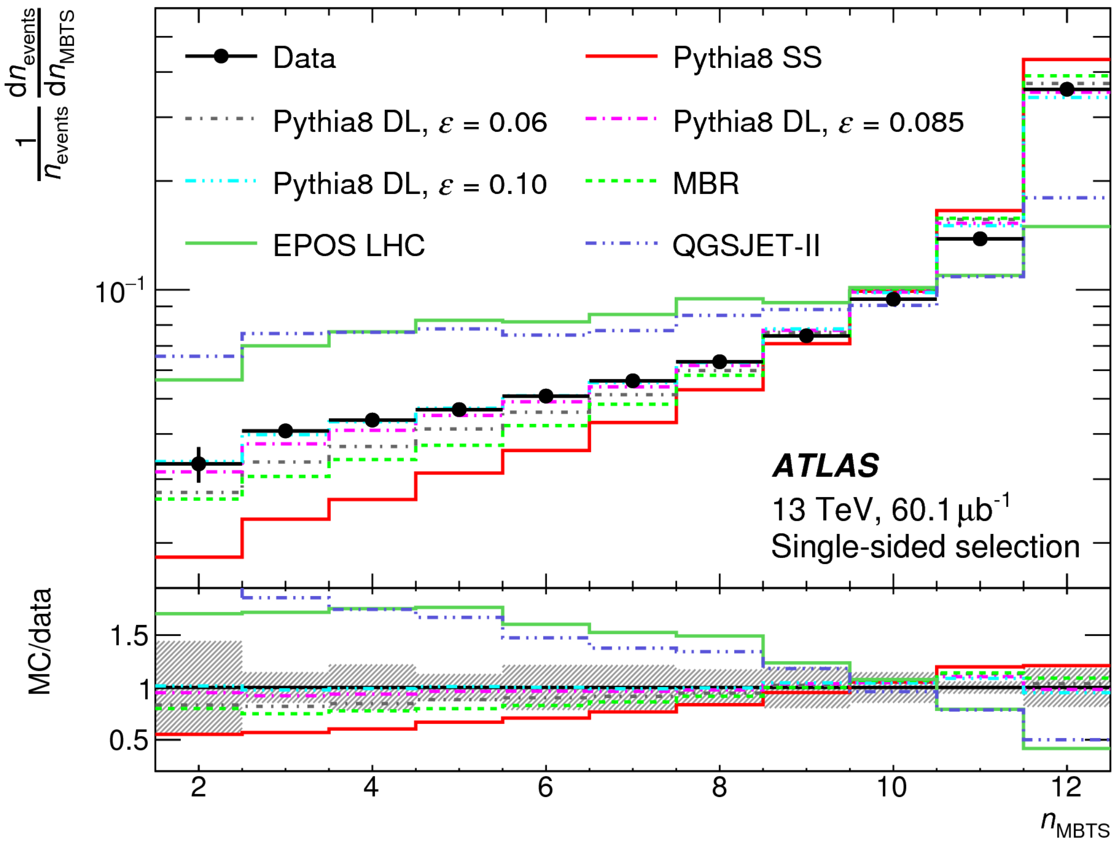


Benchmarking Diffractive MC models

"Single Sided" sample:

… activity on one side of MBTS, empty on other: enriched in SD events



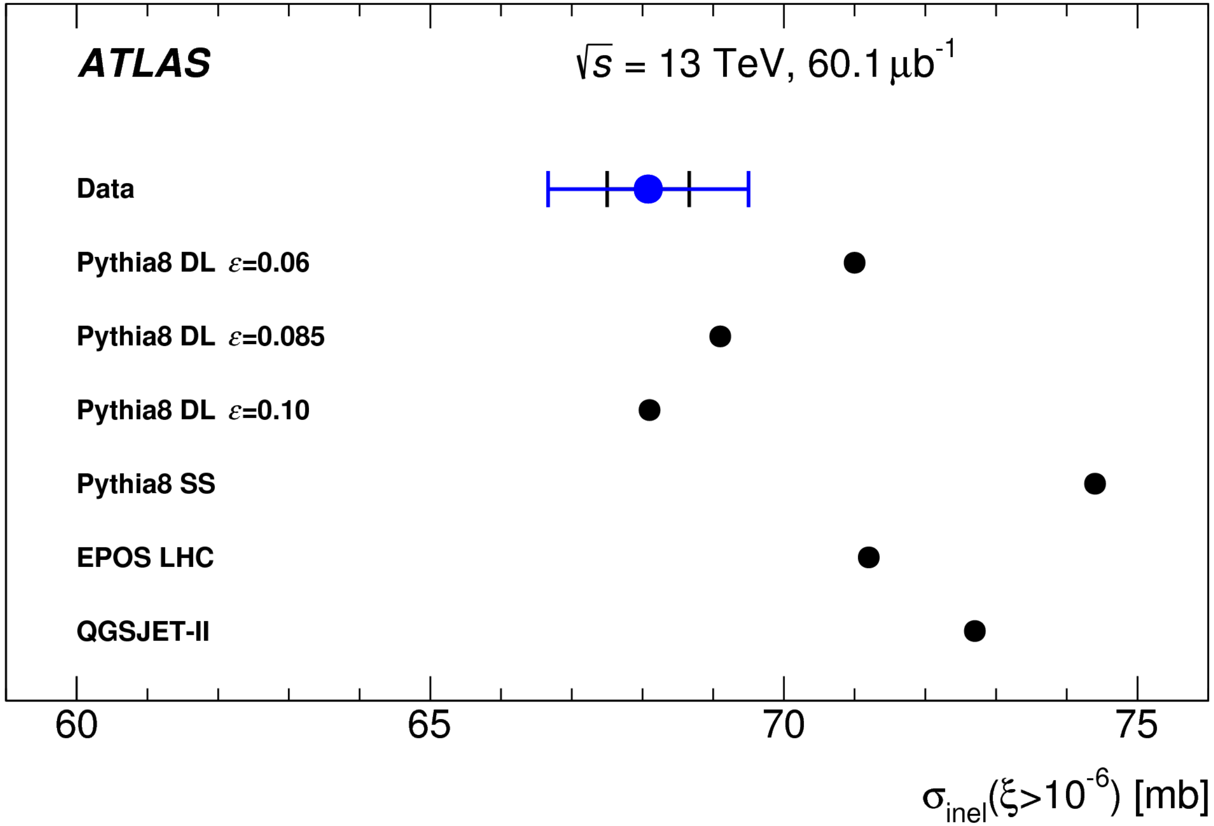


→ MBTS multiplicity in single sided sample distinguishes between MC diffraction models

… Baseline MC is PYTHIA8 with DL pomeron flux and $\alpha_{IP}(0) = 1.085$

Cross Section in Fiducial Range

$$\sigma_{\text{inel}}^{\text{fid}}(13\,\text{TeV}) = 68.1 \pm 0.6\,(\text{exp.}) \pm 1.3\,(\text{lumi})\,\text{mb}$$



- Correction factor to reach fiducial region ξ<10-6 is 0.7%

- 1.9% luminosity uncertainty (from Van der Meer scans)

- Donnachie-Landshoff implmentation in PYTHIA8 consistent with data within ~2σ for $\alpha_{IP}(0)$ = 1.06 … 1.14

- EPOS, QGSJET, PYTHIA8 S&S ($\alpha_{IP}(0)$ = 1) exceed result by >2σ

Extrapolation to Full Inelastic Cross Sec

Data-driven extrapolation into region with ξ < 10^{-6}, with minimal dependence on MC models:

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{inel}}^{\mathrm{fid}} + \sigma^{7\ \mathrm{TeV}}(\xi < 5\times10^{-6}) \times \frac{\sigma^{\mathrm{MC}}(\xi < 10^{-6})}{\sigma^{7\ \mathrm{TeV,\,MC}}(\xi < 5\times10^{-6})}$$

$$\sigma^{7\ \mathrm{TeV}}(\xi < 5\times10^{-6}) = \sigma_{\mathrm{inel}}^{7\ \mathrm{TeV}} - \sigma^{7\ \mathrm{TeV}}(\xi > 5\times10^{-6})$$
$$= 11.0 \pm 2.3\ \mathrm{mb}$$

from ALFA result

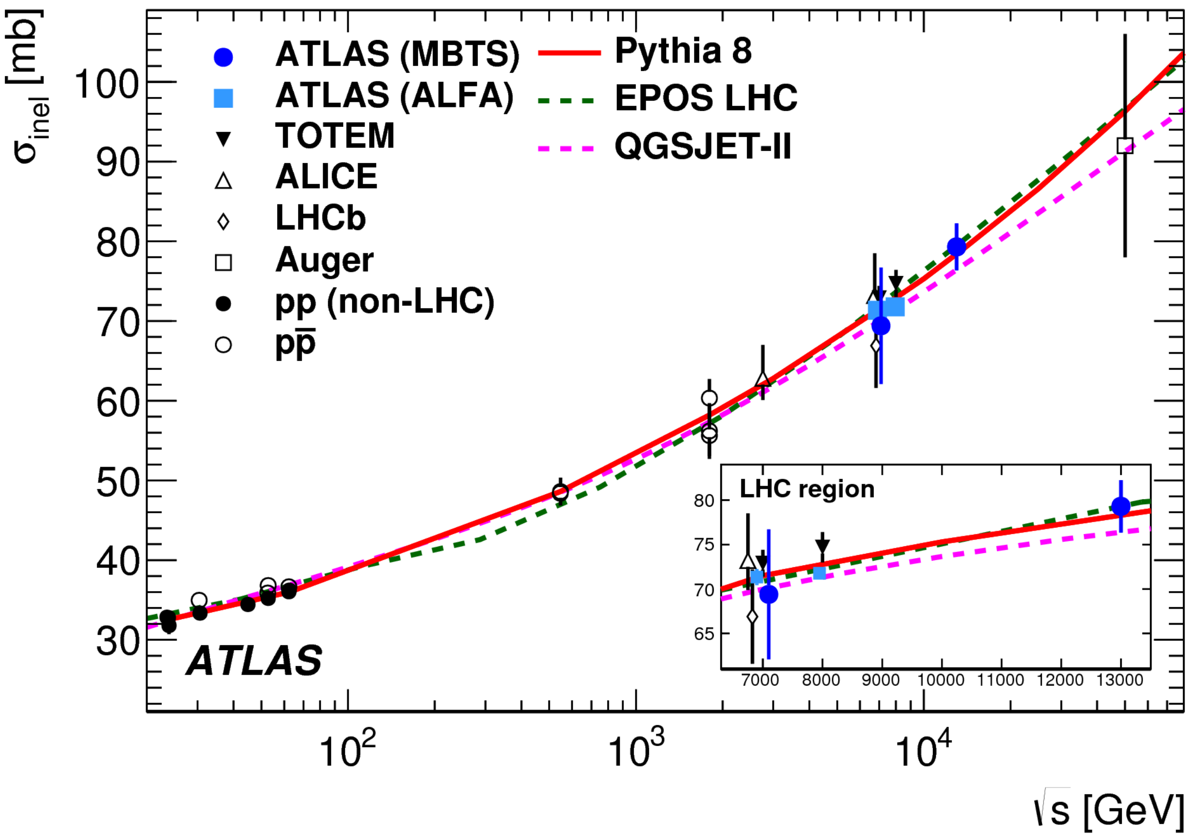
previous fiducial MBTS result

$$\frac{\sigma^{\mathrm{MC}}(\xi < 10^{-6})}{\sigma^{7\ \mathrm{TeV,\,MC}}(\xi < 5\times10^{-6})} = 1.015 \pm 0.081$$

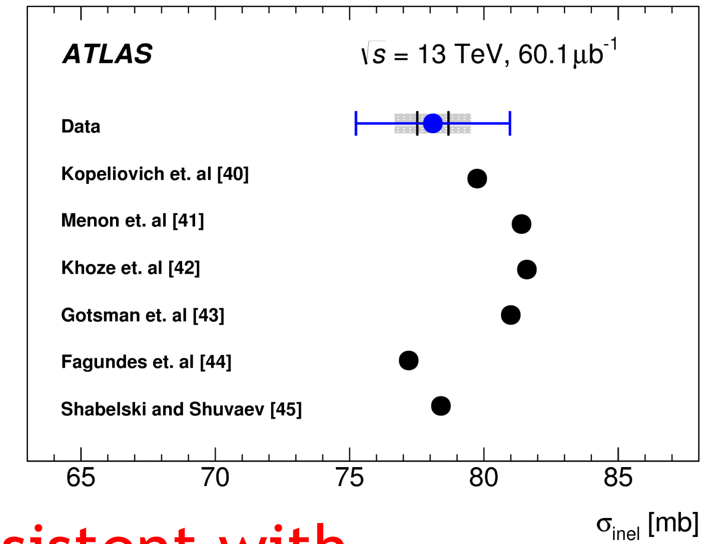
… extrapolation uncertainty is 2.5 mb, dominates in total inelastic cross section measurement

Extrapolation to Full Inelastic Cross Sec

$$\sigma_{inel} = 79.3 \pm 0.6(\mathrm{exp}) \pm 1.3(\mathrm{lum}) \pm 2.5(\mathrm{extr})\ \mathrm{mb}$$



Continued growth with centre of mass energy (9±4% above ALFA 7 TeV)



- Within current uncertainties, result consistent with indicative selection of models based on Regge phenomenology, eikonal approaches and other models of non-perturbative strong interactions

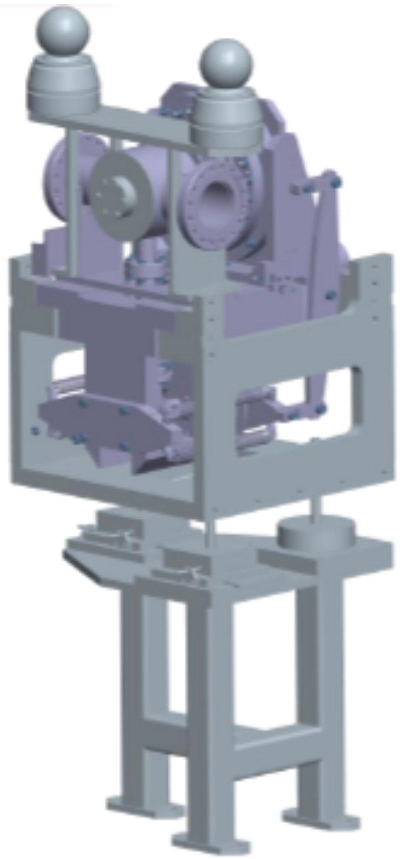
Future at ATLAS

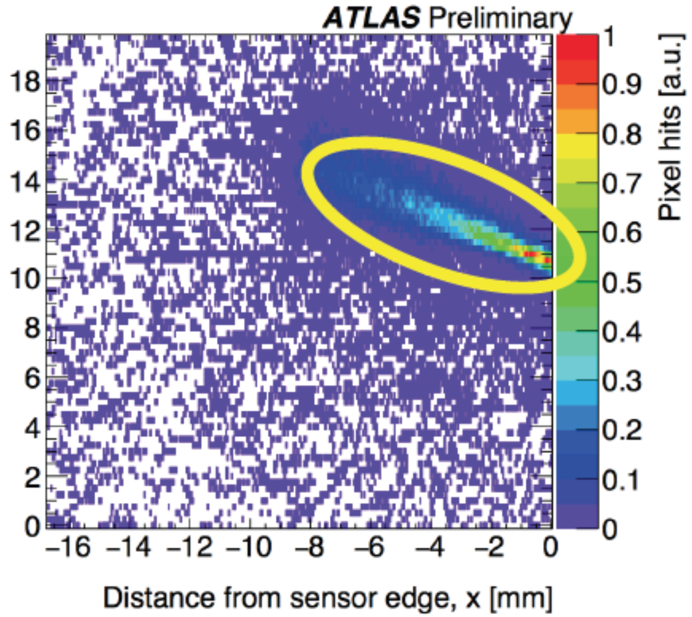
- 13 TeV σ_{tot} ALFA measurement still ongoing

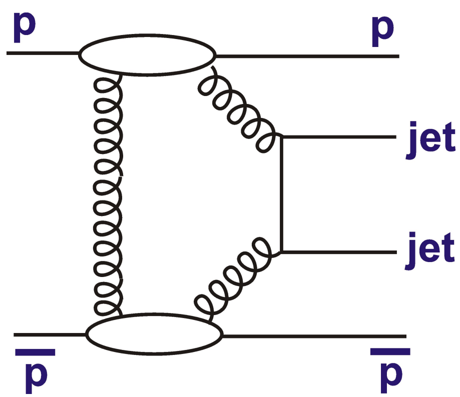
- Diffactive studies still ongoing

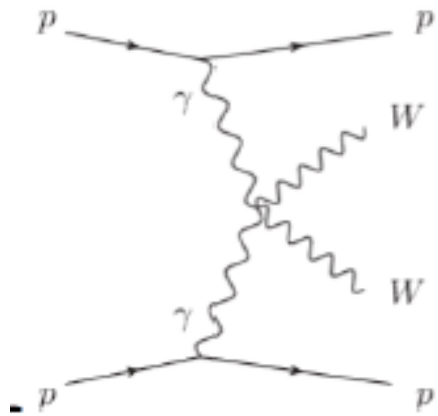
- ALFA being preserved for 14 TeV running

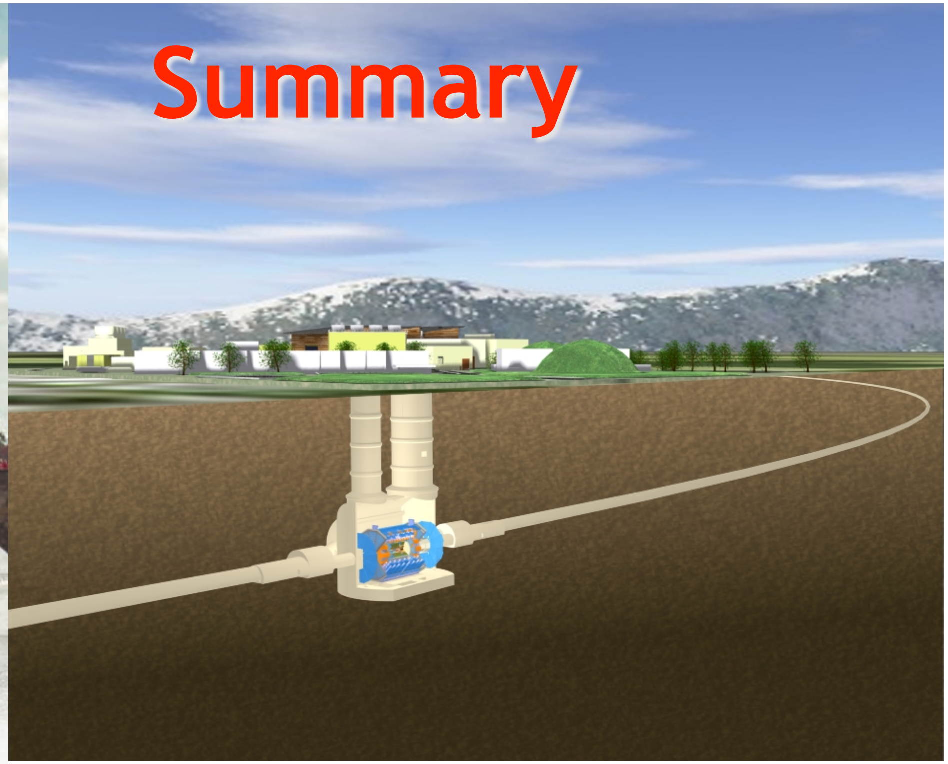
- Meanwhile, focus of Roman pots in ATLAS switches towards AFP & high lumi → rare exclusive (or exotic) processes …











Summary

Proton-tagged elastic and total cross sections at $\sqrt{s}$ = 8 TeV

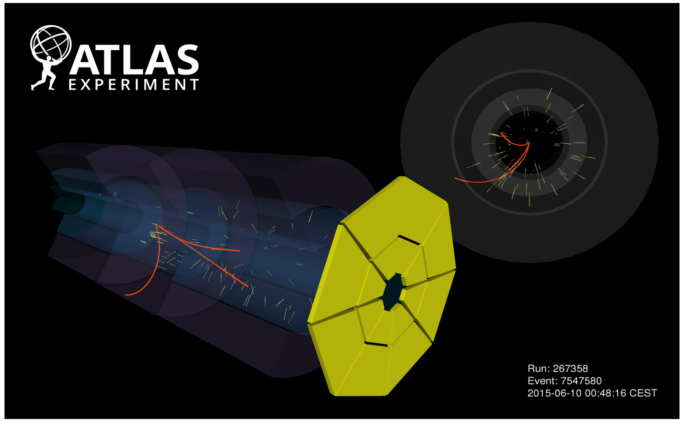
- Highly precise measurements of σ_{tot} (→ <1%), σ_{el}, σ_{inel}, B_{el}
- Continued cross sec growth and elastic peak shrinkage with $\sqrt{s}$
- Compatibility with TOTEM at 2σ level

Direct Inelastic Cross Section Measurement at $\sqrt{s}$ = 13 TeV

- Improvement in precision (→ 2%) over previous data.
- Some discrimination between models
- Consistent with ATLAS-ALFA extractions using optical theorem

Back-ups / Working material

Tuning Diffractive MC models



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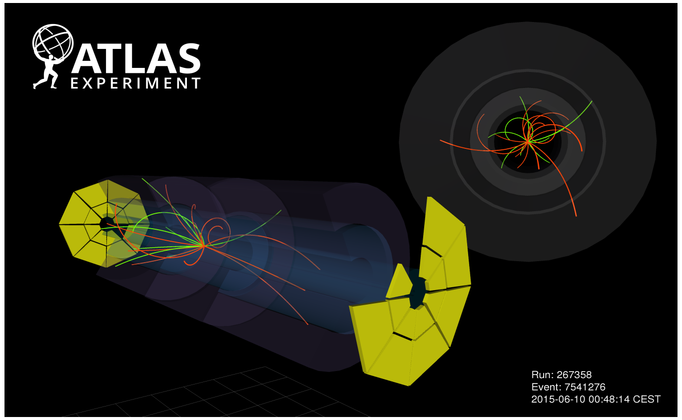
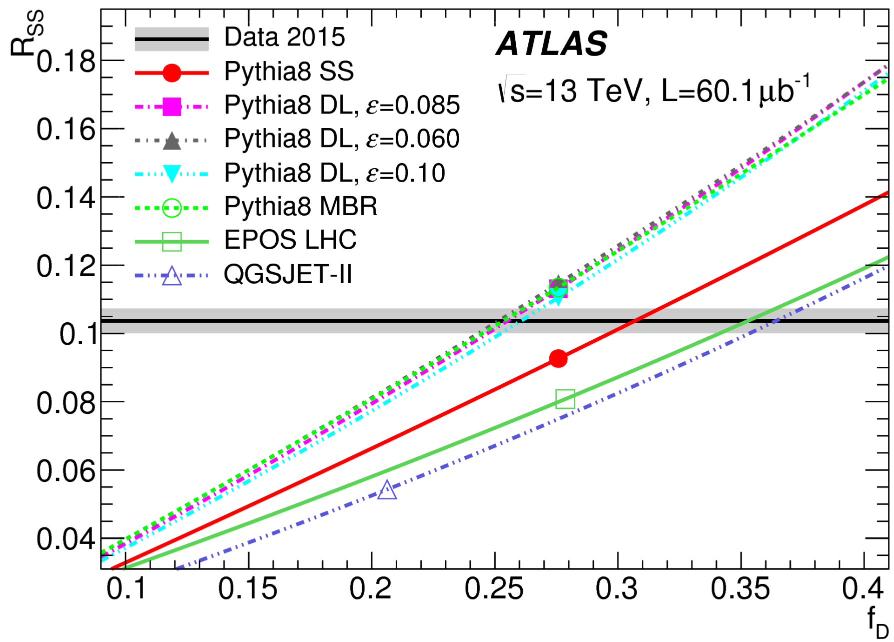


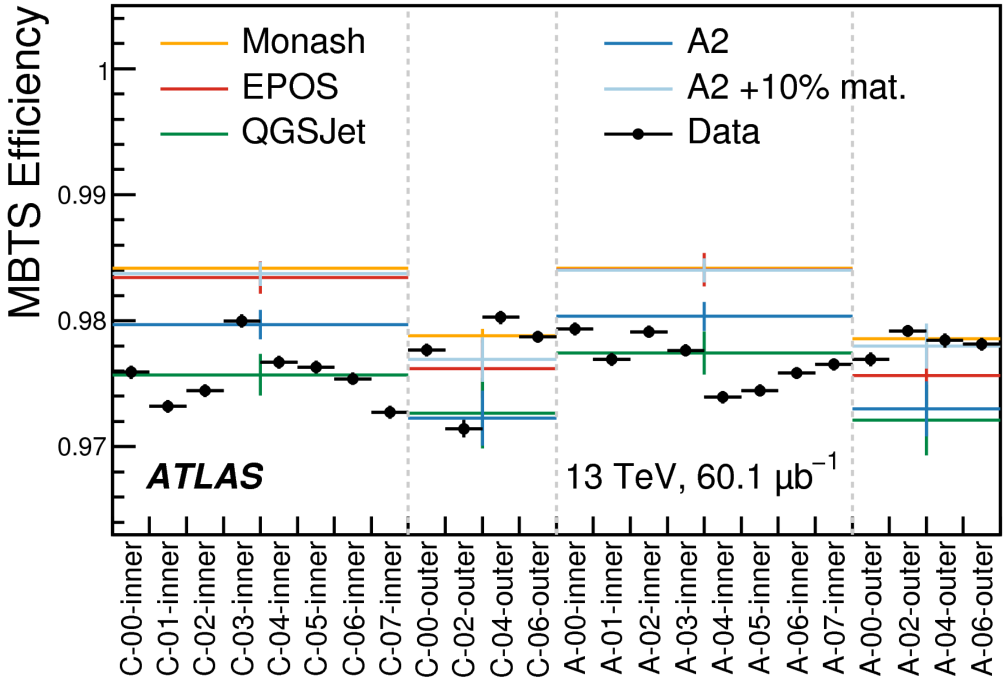
R_{SS} = Ratio of single sided to double sided MBTS samples … used to tune fractions of events considered diffractive in each MC model



Baseline MC is PYTHIA8 with DL pomeron flux and $\alpha_{IP}(0) = 1.085$

- Uncertainty in $\xi > 10^{-6}$ fiducial region dominated by luminosity
- After extrapolation to full σ_{inel}, model uncertainty dominates

Controlling MBTS Efficiency with Data

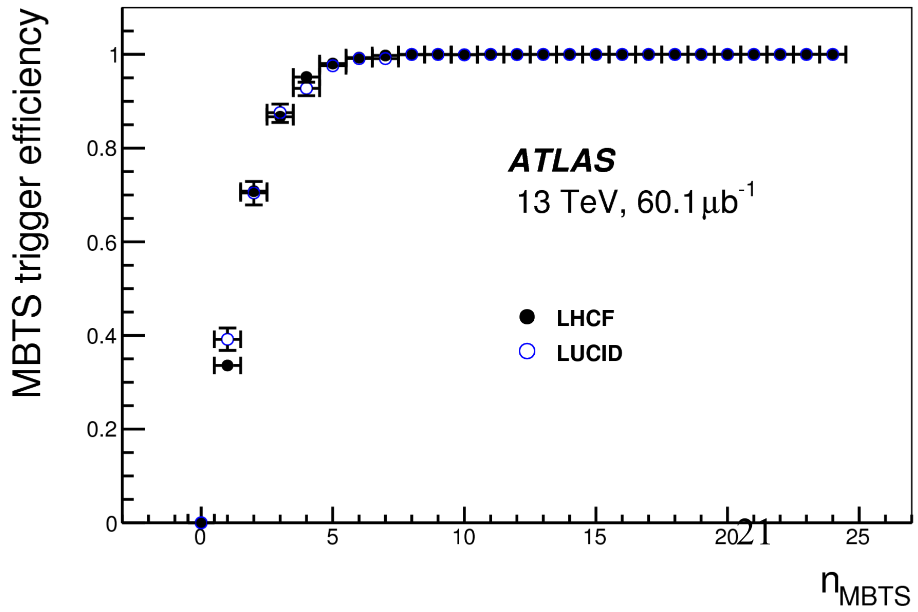


- Efficiencies for each MBTS counter measured relative to tracks in inner detector where possible and calorimeter clusters where not.
→MC efficiencies tuned accordingly

- Trigger efficiencies monitored relative to independent LUCID and LHCf triggers

- Efficiency / acceptance depends on MBTS segment multiplicity

- Analysis selection is $N_{MBTS} \geq 2$



Fiducial Cross Section Extraction

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

DROP???

- N_{BG}: Small background from beam-gas, radiation & activation, determined using triggers in non-colliding bunches

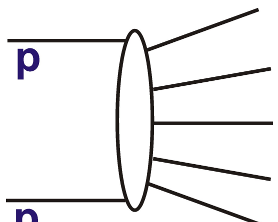
- $(1-f_{\xi<10\text{-}6})/\varepsilon_{sel} = C_{MC}$ = MC acceptance and migration correction

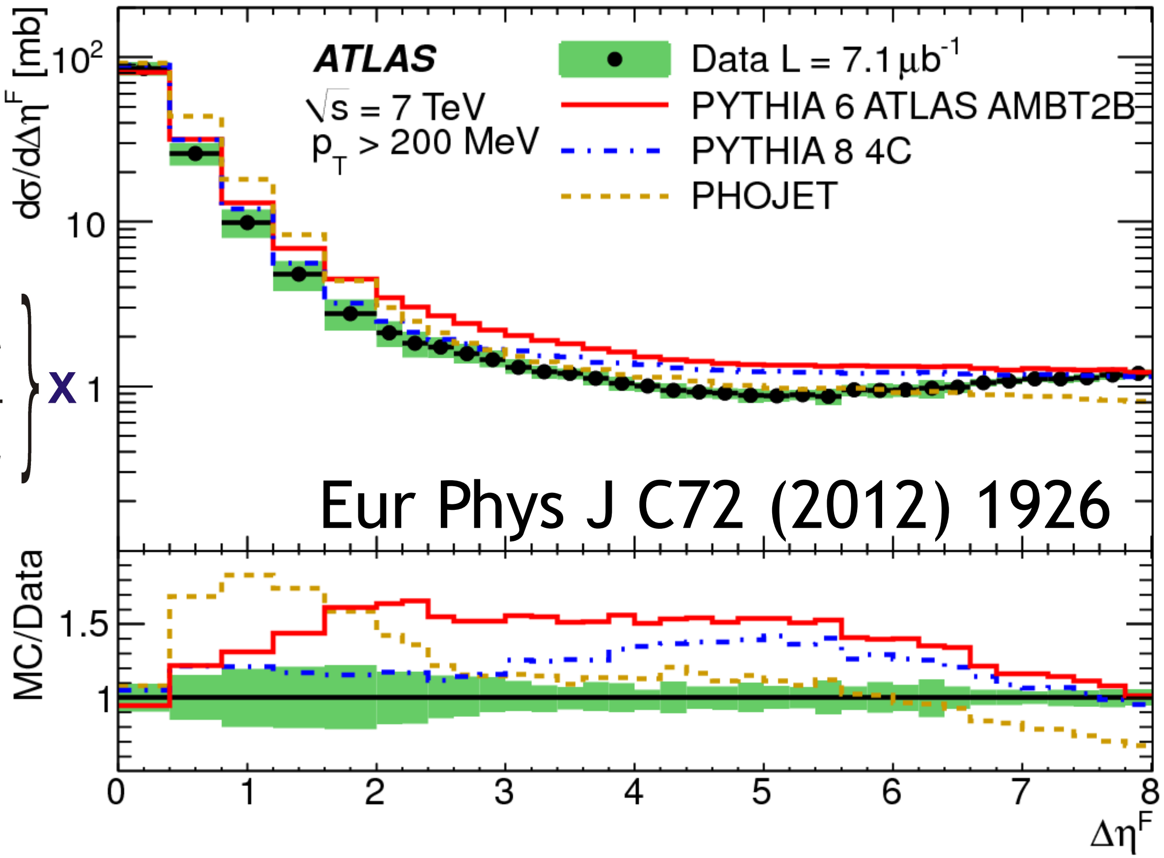
- Luminosity from final calibration of Van der Meer scan
  → 1.9% error

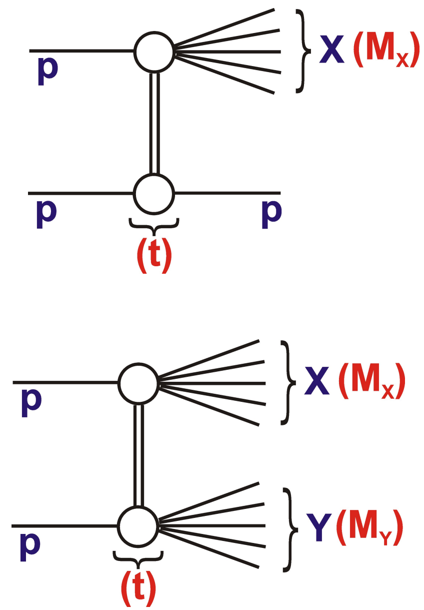
Factor	Value	Rel. uncertainty
Number of events passing the inclusive selection (N)	4159074	–
Number of background events (N_{BG})	51187	±50%
Integrated luminosity [μb^{-1}] ($\mathcal{L}$)	60.1	±1.9%
Trigger efficiency (ϵ_{trig})	99.7%	±0.3%
MC correction factor (C_{MC})	99.3%	±0.5%

$$\sigma_{\text{inel}}^{\text{fid}}(13\text{ TeV}) = 68.1 \pm 0.6\,(\text{exp.}) \pm 1.3\,(\text{lumi})\text{ mb}$$

Inclusive Differential Gap Cross Section



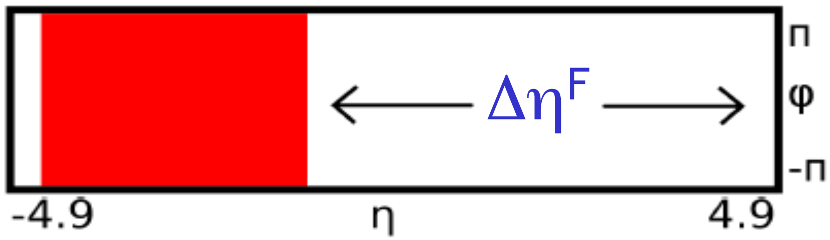


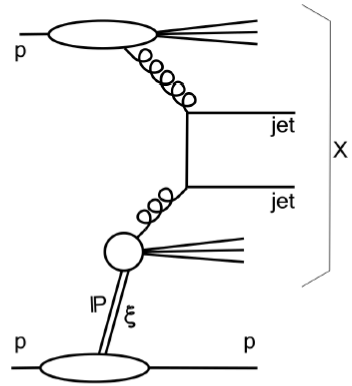


- Large $\Delta\eta^F$: Diffractive plateau with ~1mb per unit gap size, consistent with soft pomeron ($\alpha_{IP}(0) = 1.058 \pm 0.036$)
- Small $\Delta\eta^F$: sensitive to hadronisation fluctuations / MPI in ND

Can the same method be applied to hard diffractive processes?...

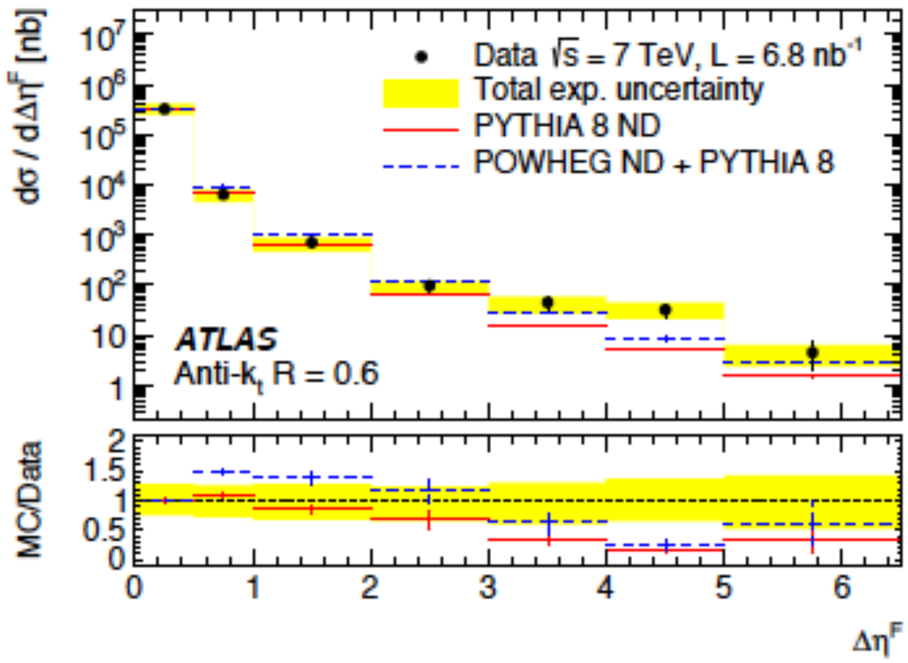
Corrected Diffractive Jet Data v Non-Diffractive Models

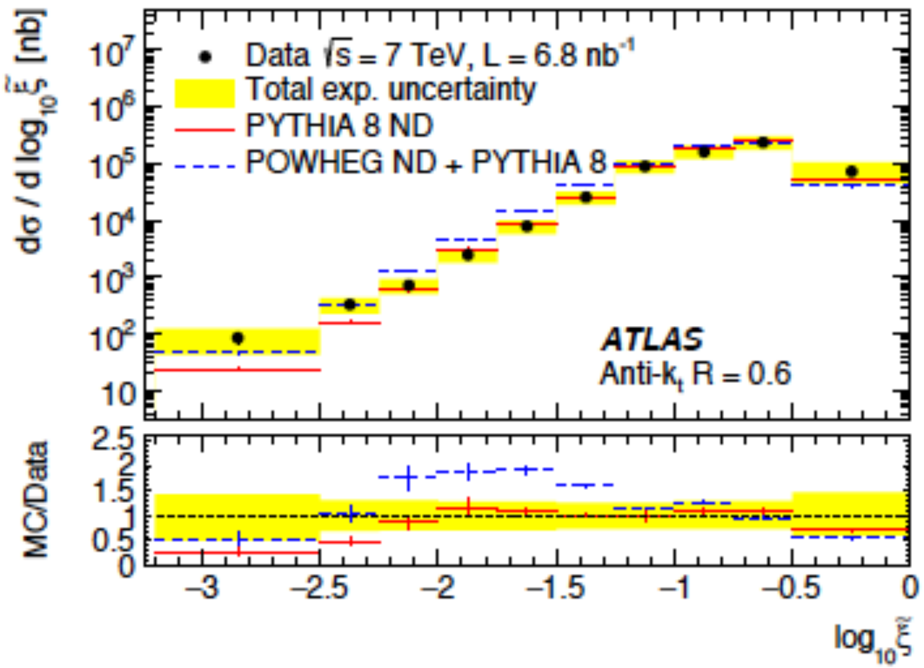




- Kinematic suppression of large gaps → no clear diffractive plateau (unlike minimum bias case)

- ND models matched to data at small gap sizes give contributions compatible with data up to largest $\Delta\eta_F$ and smallest ξ … no clear diffractive signal …





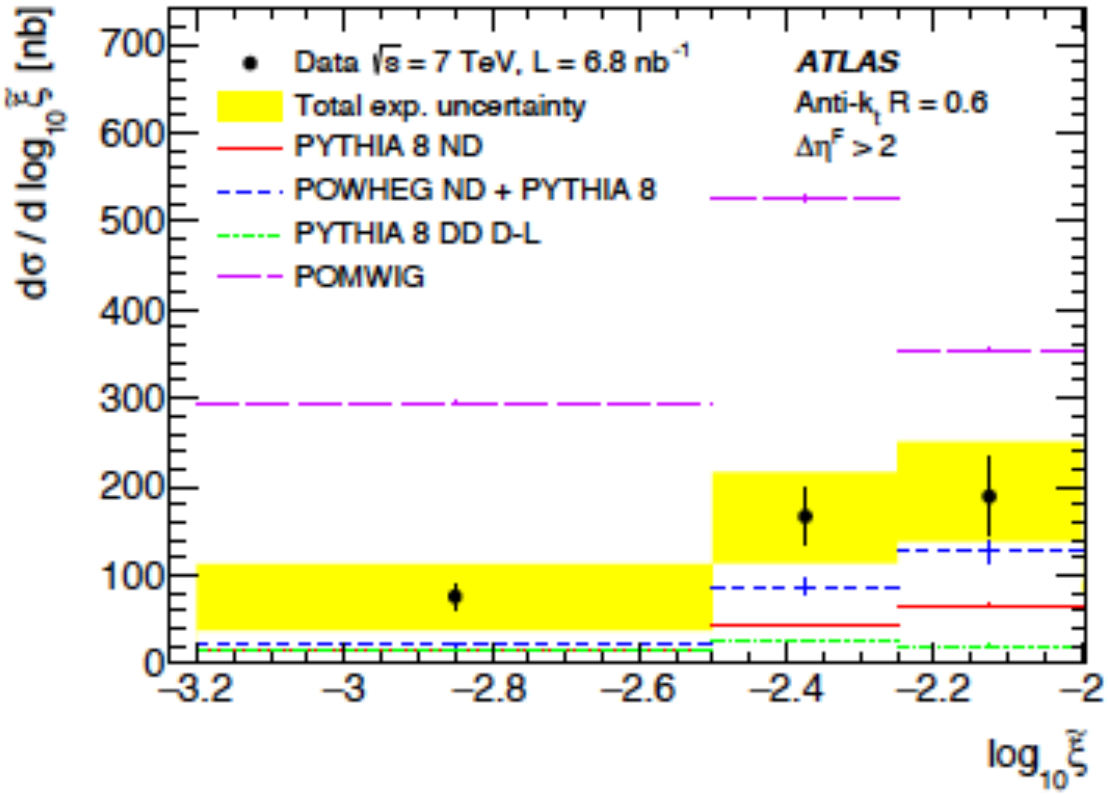
Evidence for Diffractive Contribution

Focusing on small ξ, whist simultaneously requiring large gap size ($\Delta\eta_F$ > 2) gives best sensitivity to diffractive component

→ Models with no SD jets are below data by factor >~3

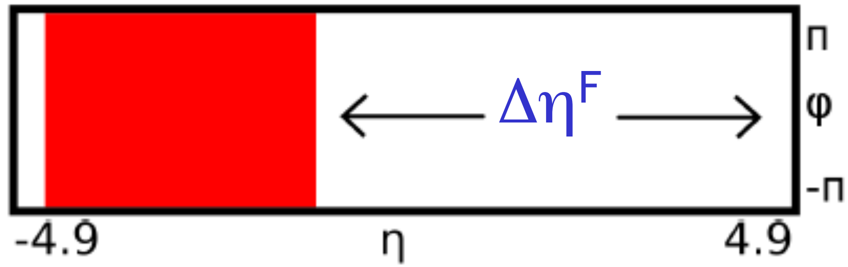
→ Comparison of smallest ξ with DPDF-based model (POMWIG) leads to rapidity gap survival probability estimate …

- Model dependence not investigated in detail
- In context of POMWIG, using anti-k_T with R=0.6:

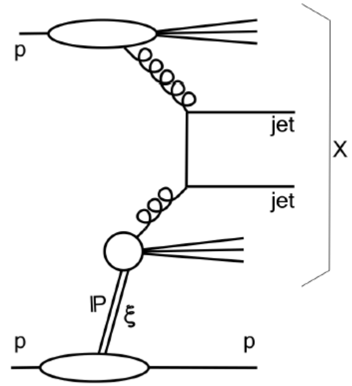


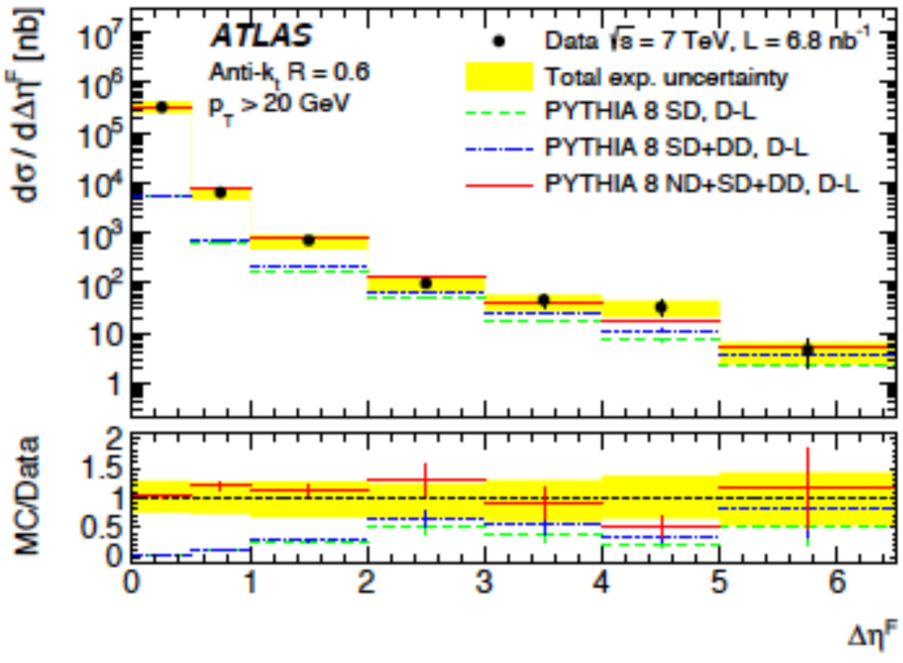
$$S^2 = 0.16 \pm 0.04\ (\text{stat.}) \pm 0.08\ (\text{exp. syst.})\ ,$$

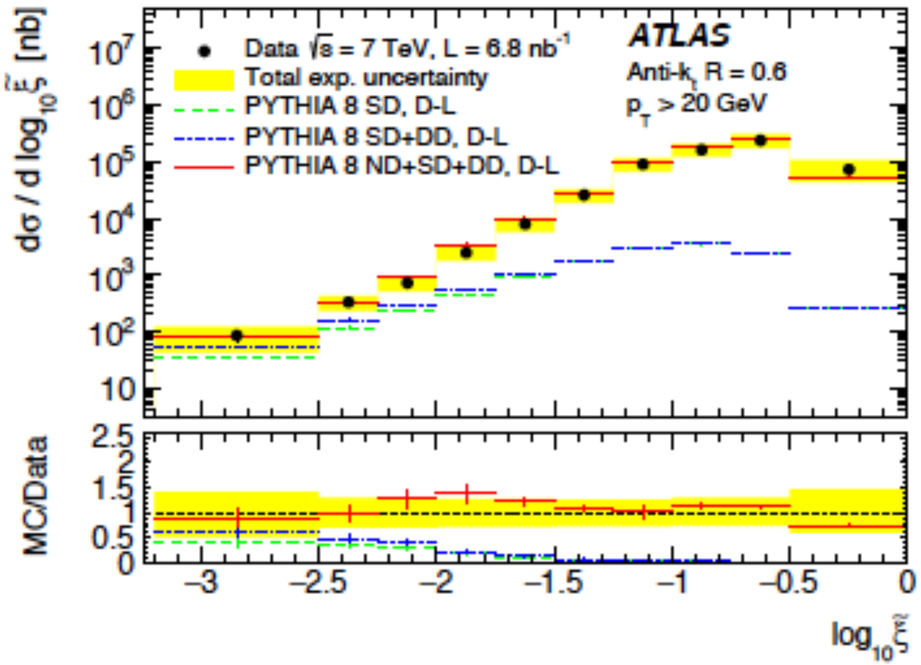
Comparison with Full PYTHIA8



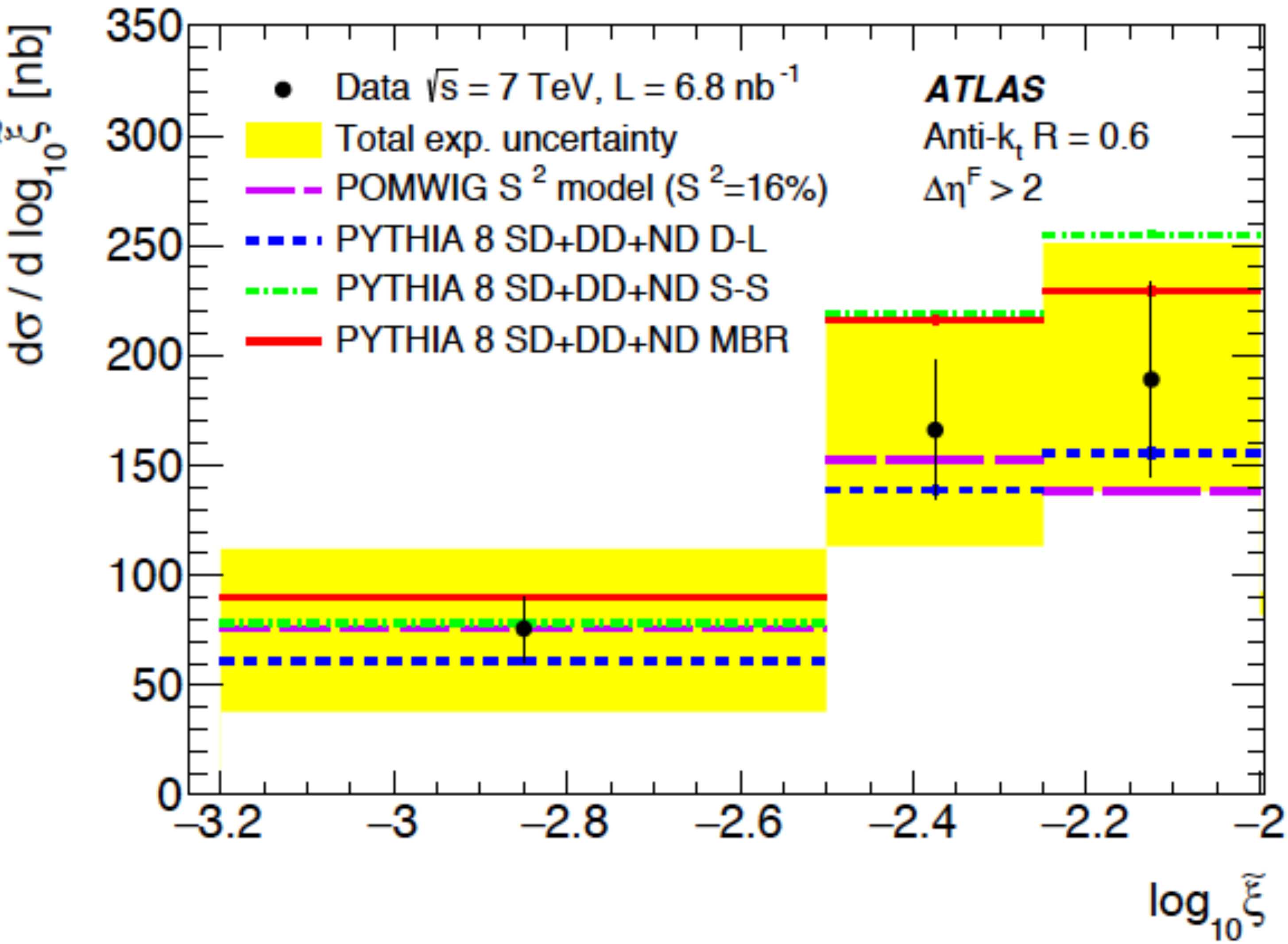
‘Off-the shelf’ PYTHIA8 ND*0.71 + SD + DD does a good job at all $\Delta\eta_F$ and ξ, with no need for a gap survival factor (though ND dominates, so compatible with a wide range of S^2 values).







Diffractive Models Focusing on $\Delta\eta^F > 2$



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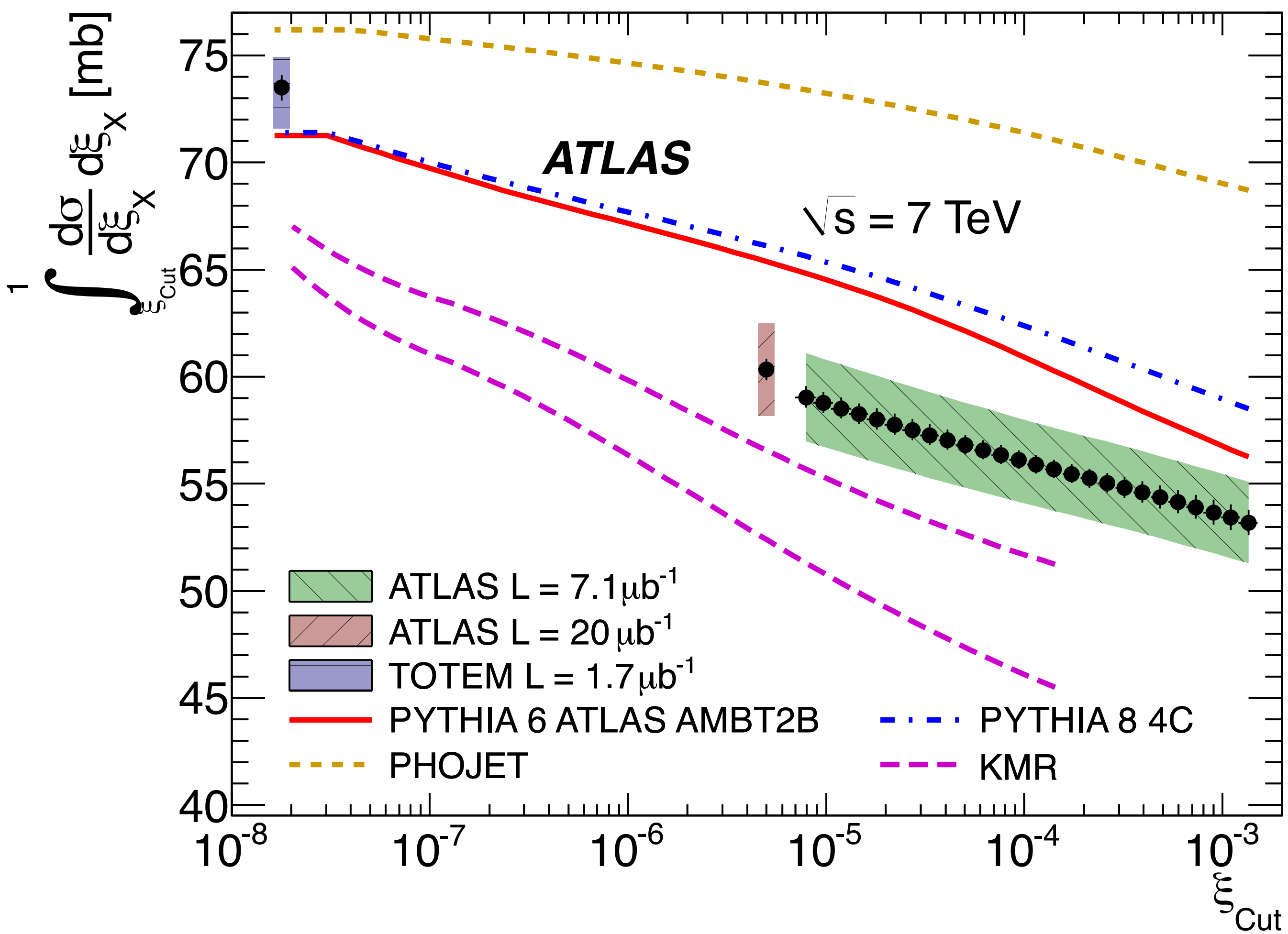
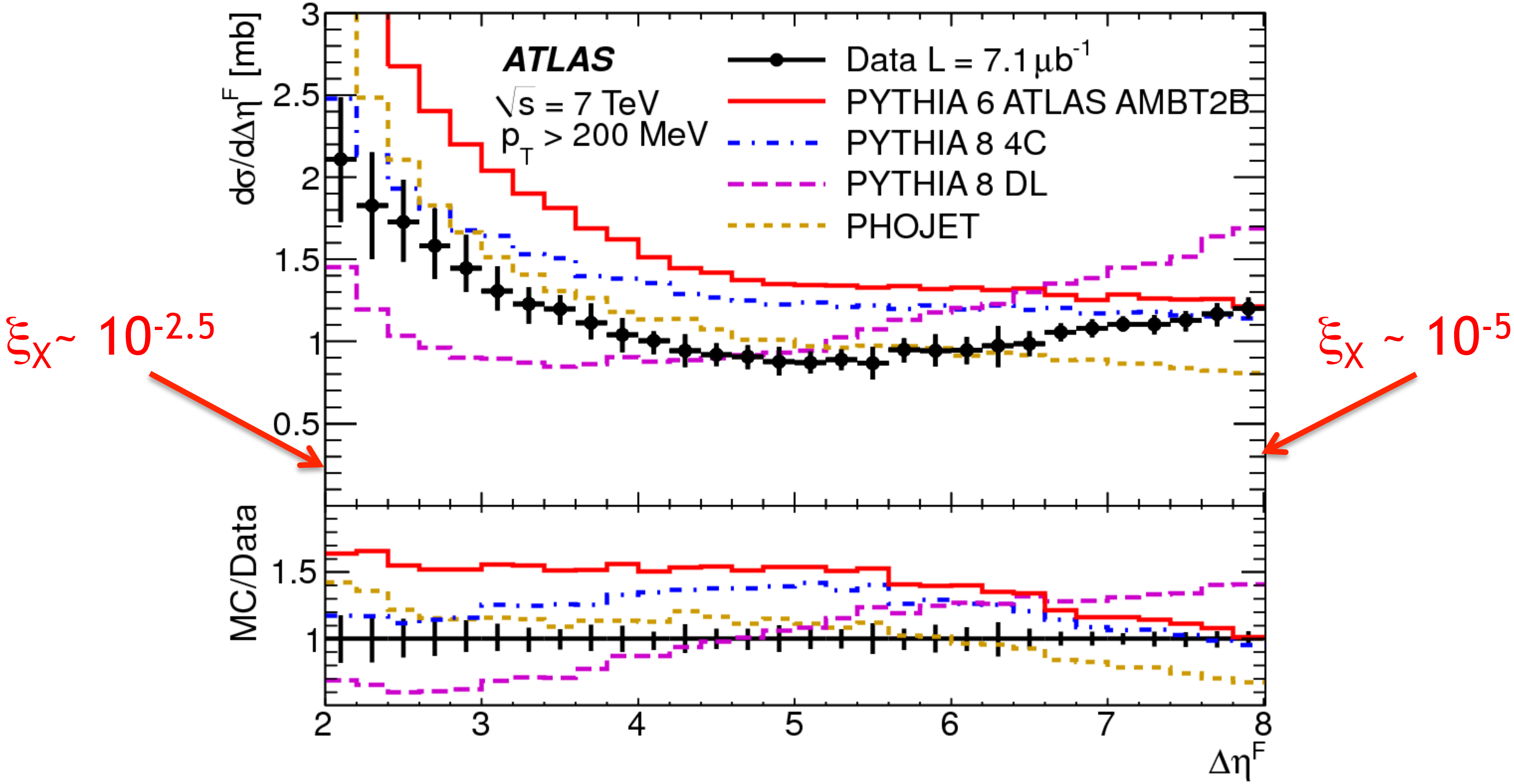
Investigating Low Mass Extrapolations



[Inelastic cross section excluding diffractive channels with $\xi < \xi_{cut}$]

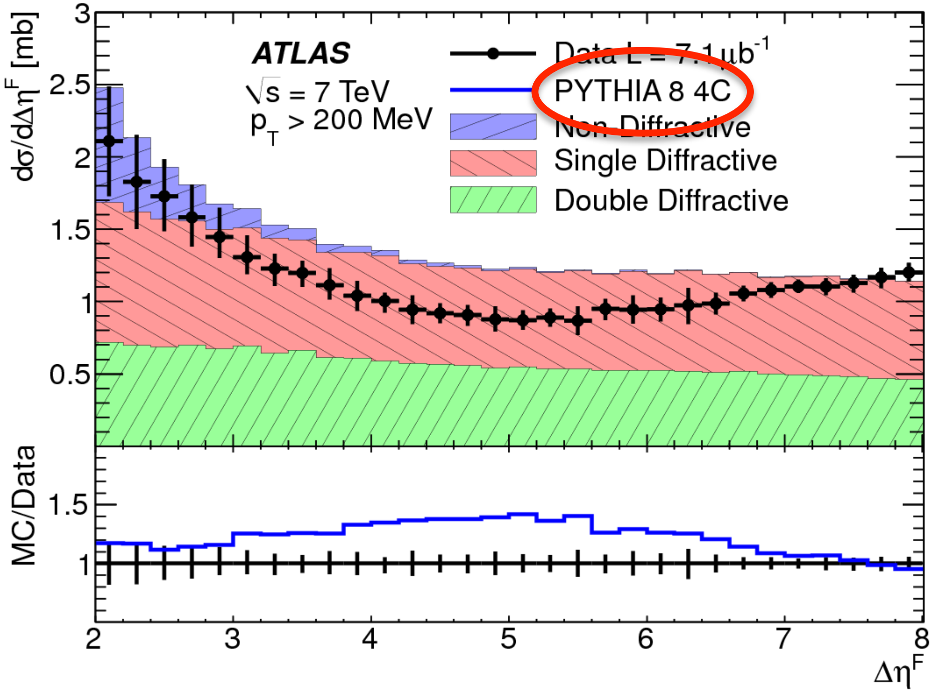
- Integrating ATLAS gap cross section up to some max $\Delta\eta^F$ (equivalently min ξ_X) and comparing with TOTEM indicates that small ξ_X region underestimated in PHOJET and PYTHIA:
- 14 mb with $\xi < 10^{-5}$, compared to 6 (3) mb in PYTHIA (PHOJET)

Large Gaps and Diffractive Dynamics



- Default PHOJET, PYTHIA have $\alpha_{IP}(0)$ = 1; DL has $\alpha_{IP}(0)$ = 1.085
- Fit to large $\Delta\eta^F$ data: $\alpha_{IP}(0)$ = 1.058 ± 0.003 (stat) ± 0.036 (syst)
- CMS also favour intermediate value of $\alpha_{IP}(0)$

Large Gaps and Diffractive Dynamics



- Diffractive plateau with ~ 1 mb per unit of gap size for $\Delta\eta^F > 3$
- Broadly described by models
- $\alpha_{IP}(0) = 1.058 \pm 0.036$ (ATLAS)
- Further significant progress will require proton tagging to unfold SD from DD and ND