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

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for the ATLAS Collaboration

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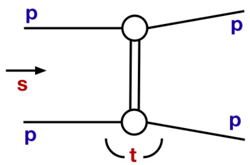
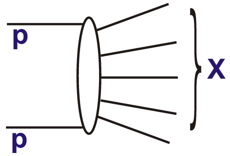
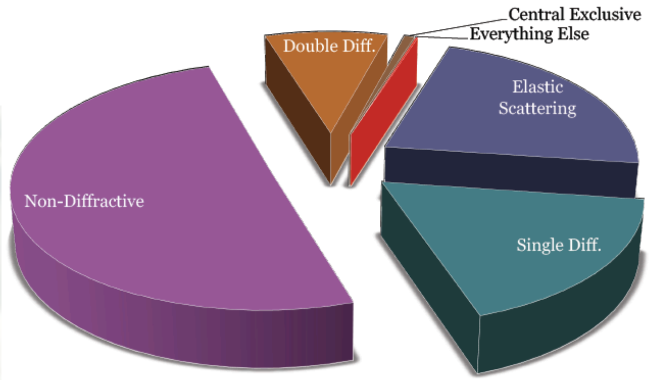
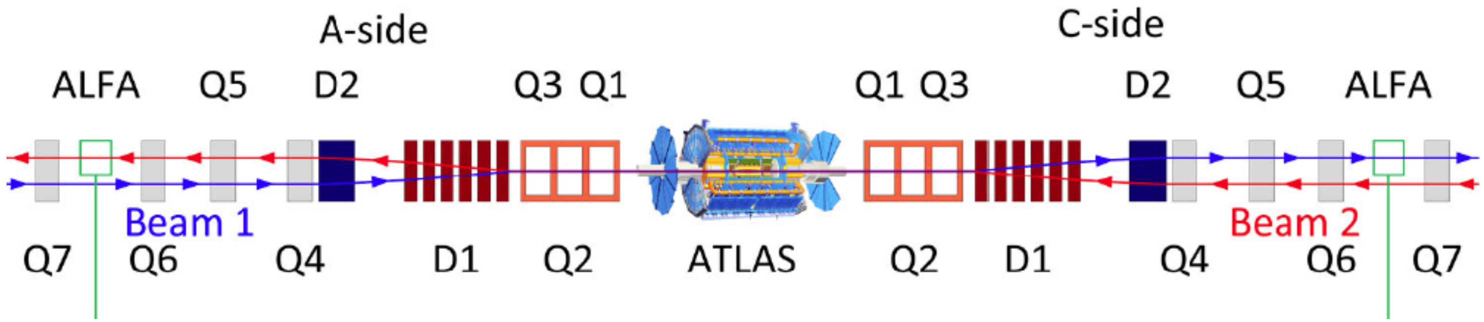






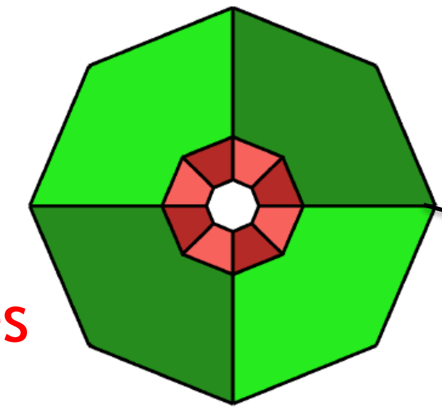
→ Elastic & total cross sections with ALFA Roman pots
→ Total inelastic cross section from minimum bias data
→ Including a bit on soft low mass diffraction

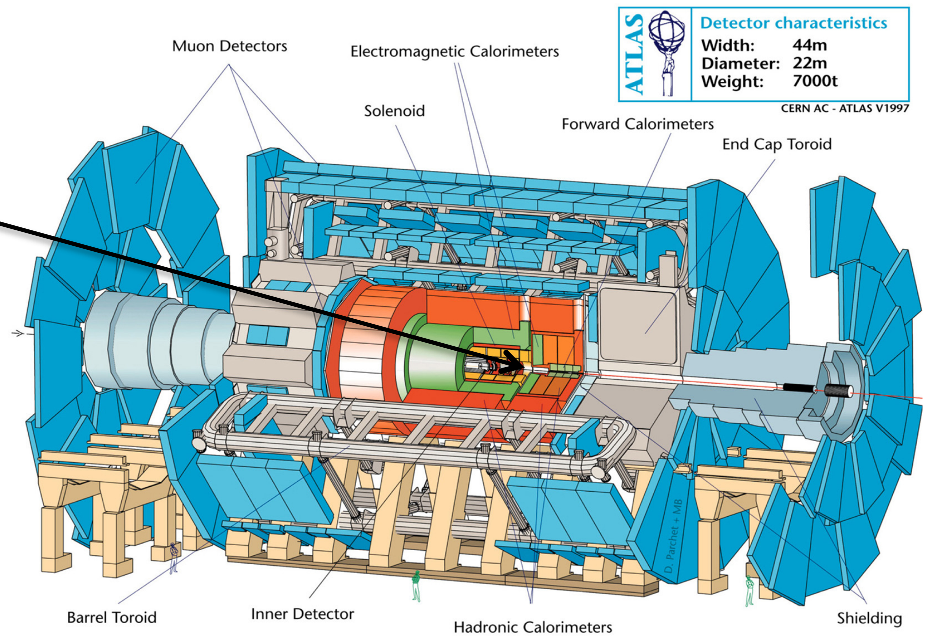
Methods



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 using the Minimum Bias Trigger Scintillator (MBTS) detectors

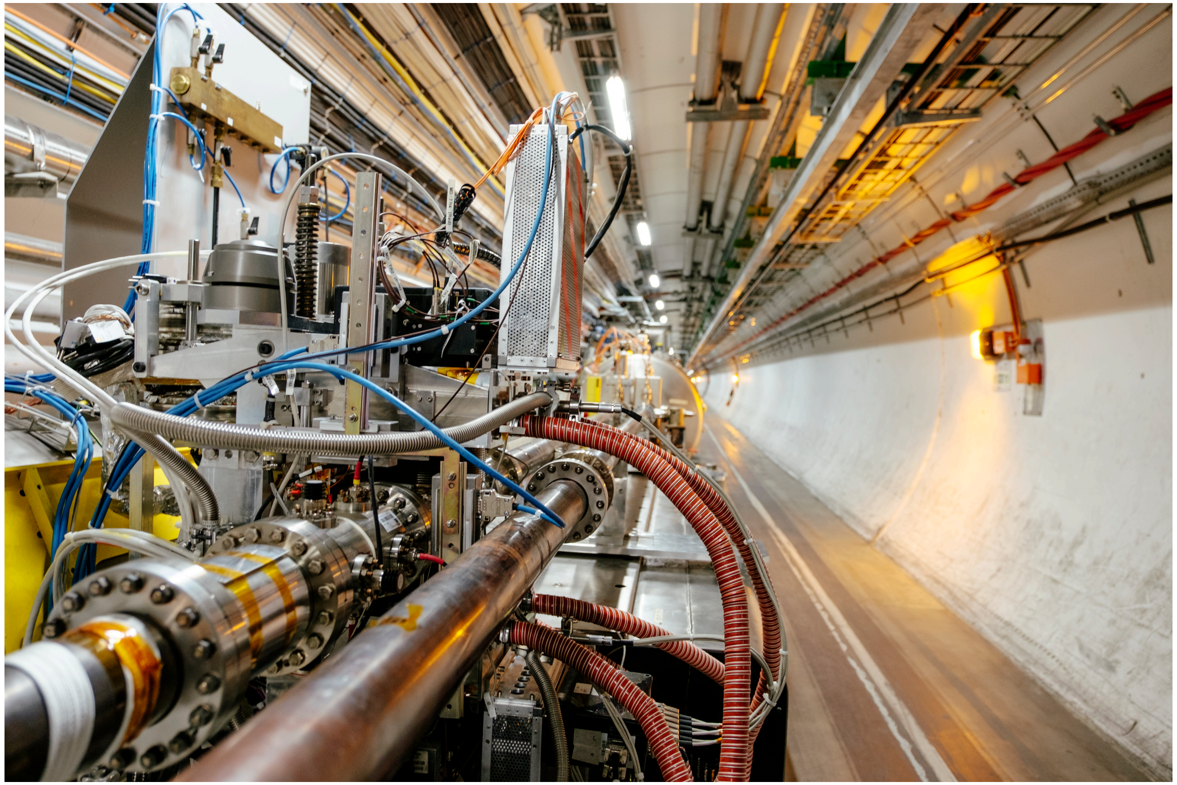


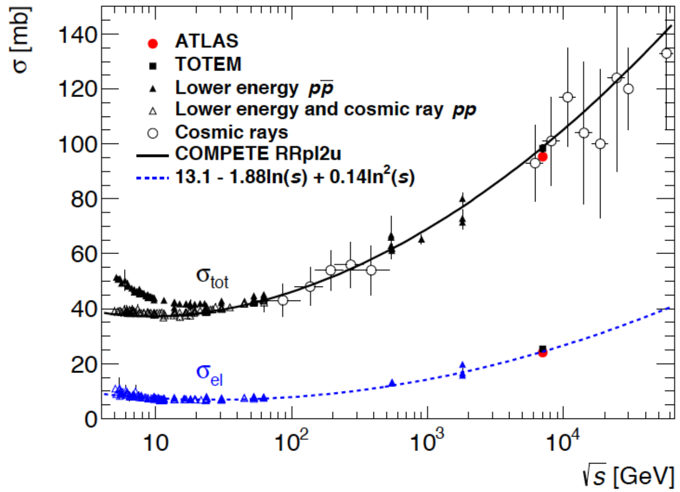


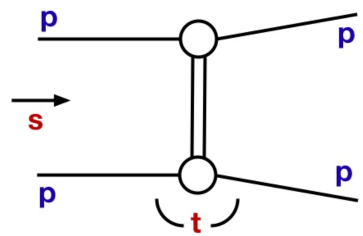
[z = ± 3.6m, 2.1 < |η| < 3.8, 8-fold Segmentation nearest beam-pipe, 4-fold further out].
… obtain almost all of σ_{inel} directly.

1) Proton Tagging Method

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



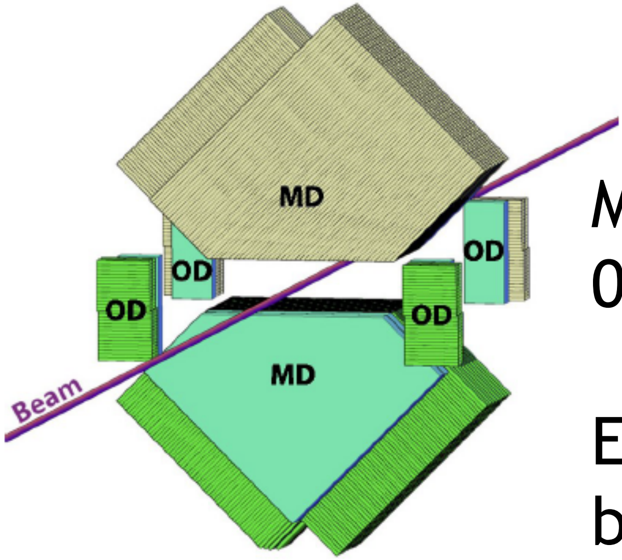




2012 β* = 90m run, allowing access to small t

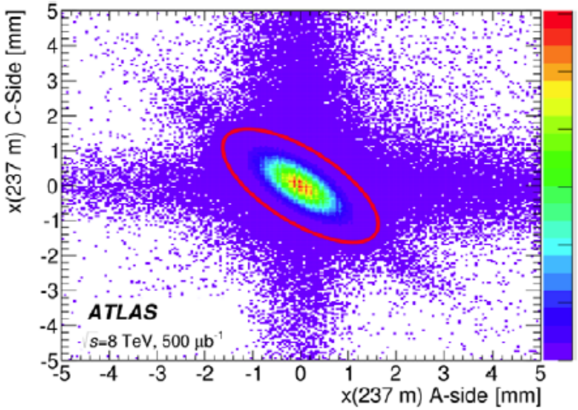
→3.8 million events after selection, background ~0.1%

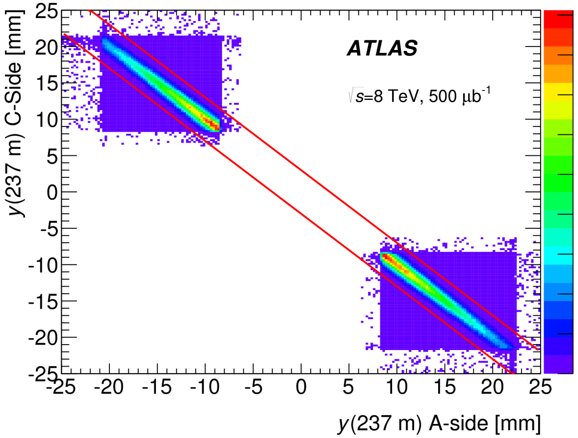
Measurement Principle



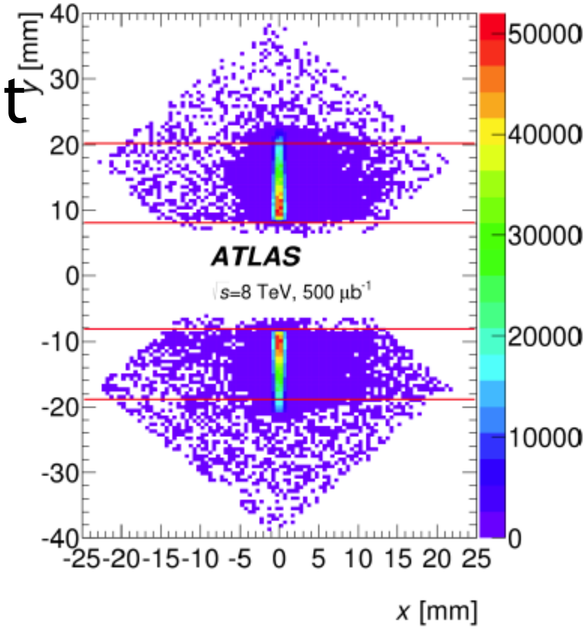
Main detectors (MD) are 2x10 layers of 0.5mm^2 square fibres per pot.

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 such that y coordinate maps linearly onto proton p_T; hence quadratically onto t:

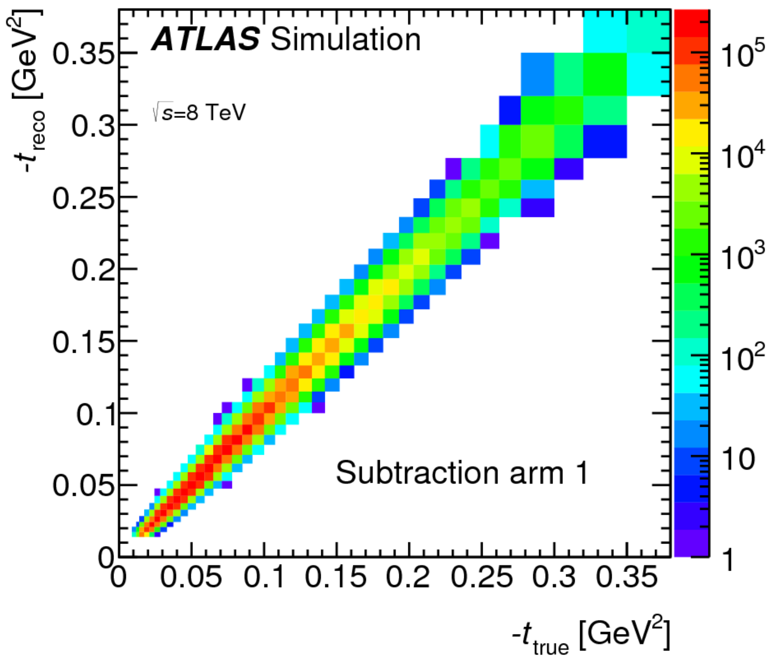


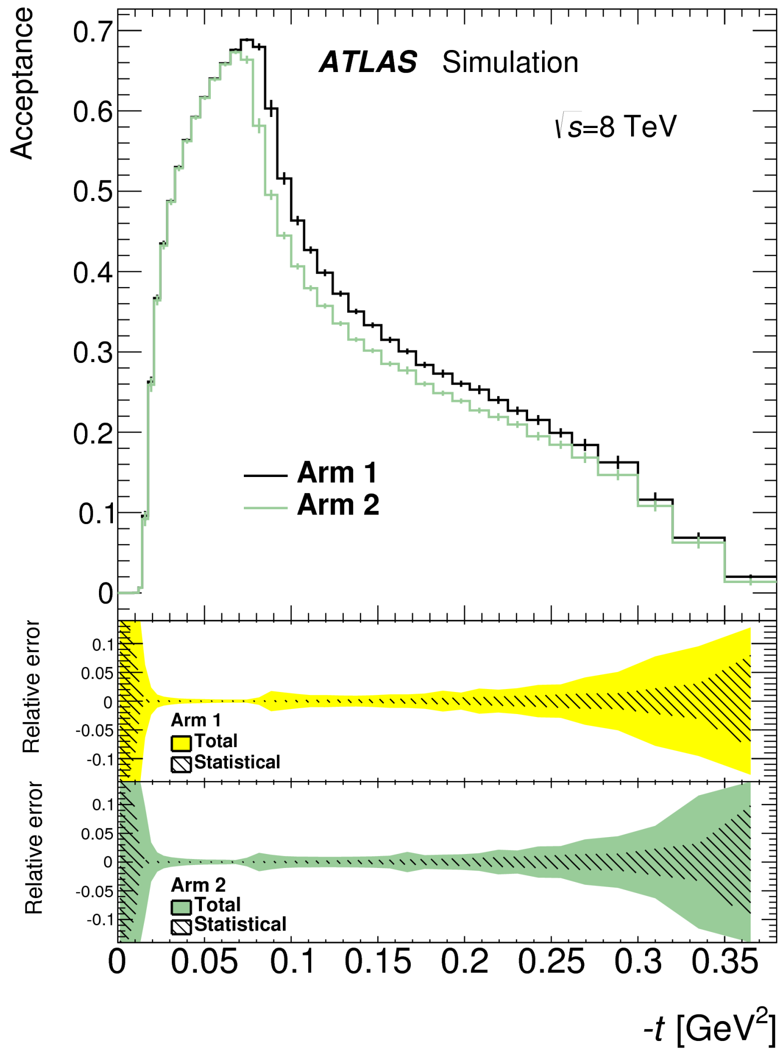
$$\begin{pmatrix} y \\ \theta_y \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} y^* \\ \theta_y^* \end{pmatrix}$$

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

Correcting for Instrumental Effects

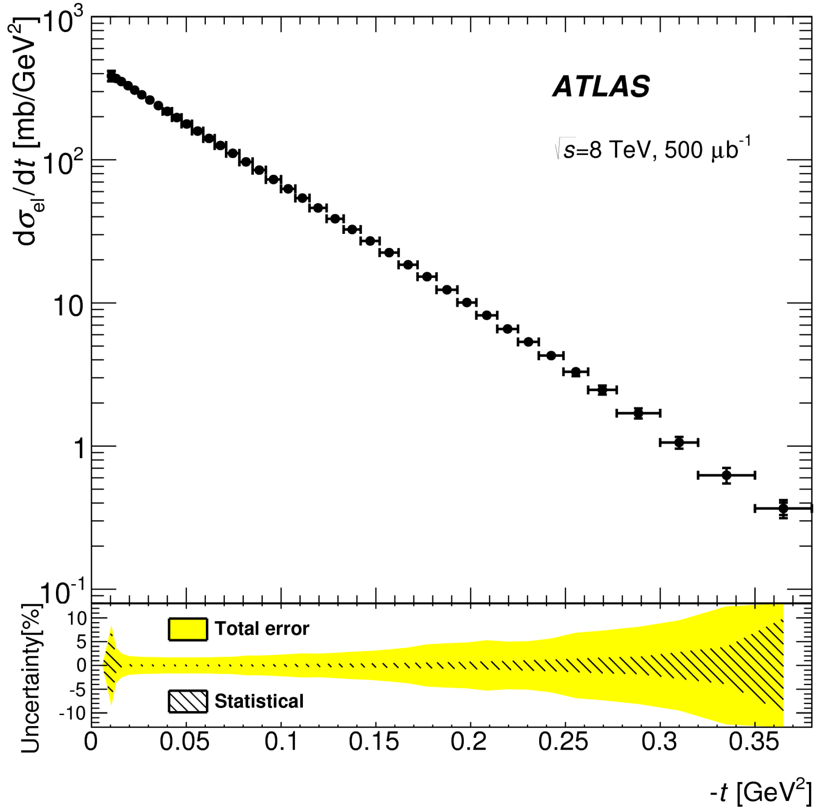
- Reconstruction (~90%) and trigger (>99.9%) efficiencies determined from data.
- Beam optics model tuned with ALFA constraints and applied to resolution and acceptance considerations via PYTHIA8





Dedicated lumi determination → 1.5% uncertainty

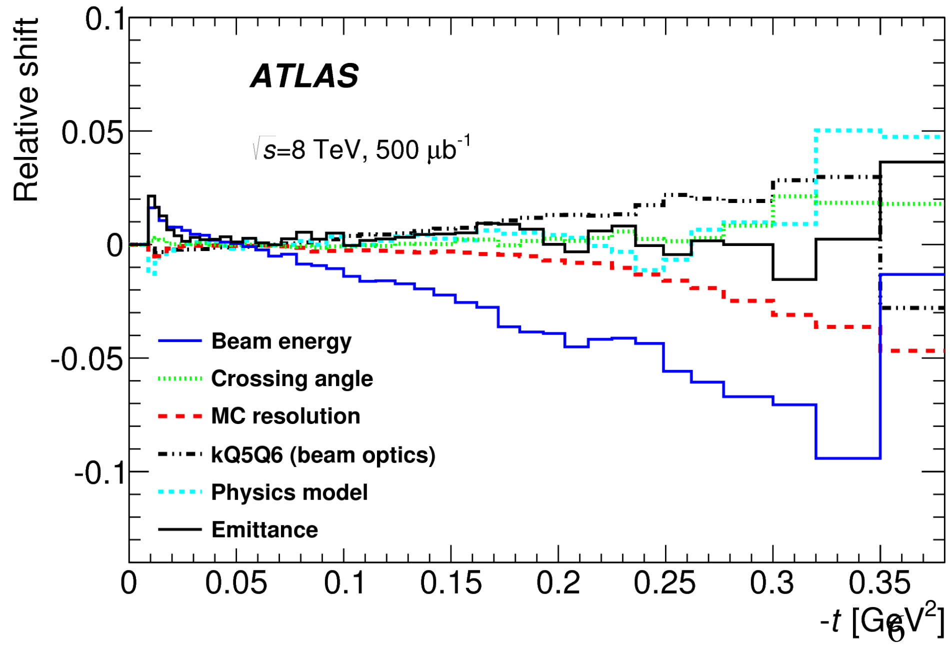
Unfolded Data



- Data cover the region 0.01 < |t| < 0.36 GeV^2, 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)

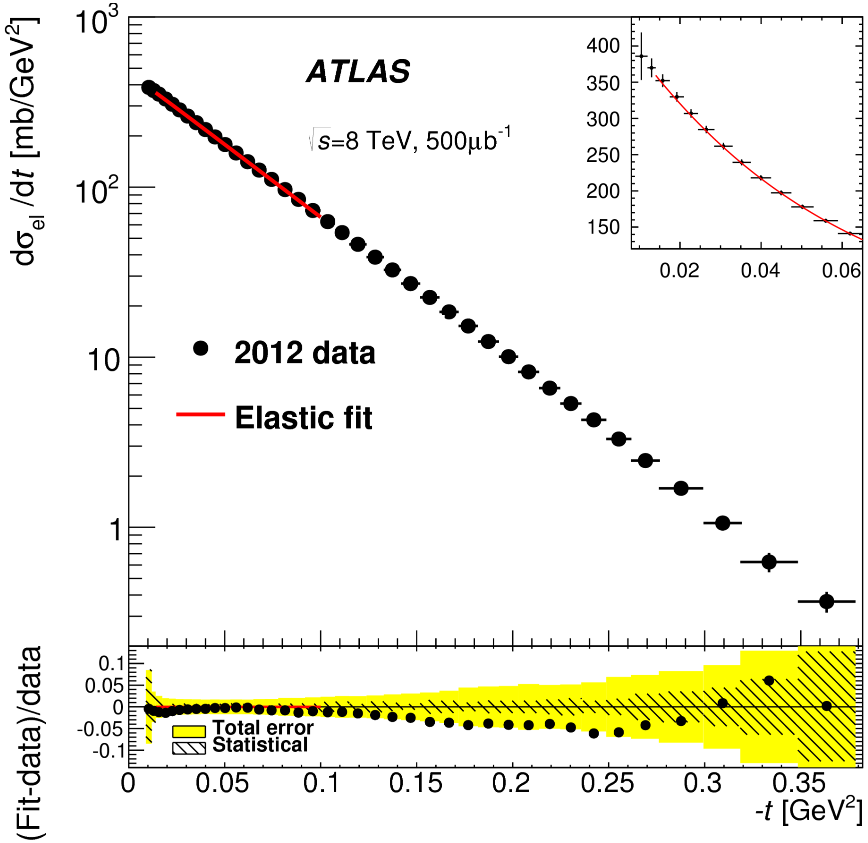
Fitting the Data

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

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

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

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



(b)

Influence of interference term small.

Data in hadronic region compatible with pure exponential: ~ e^{Bt}

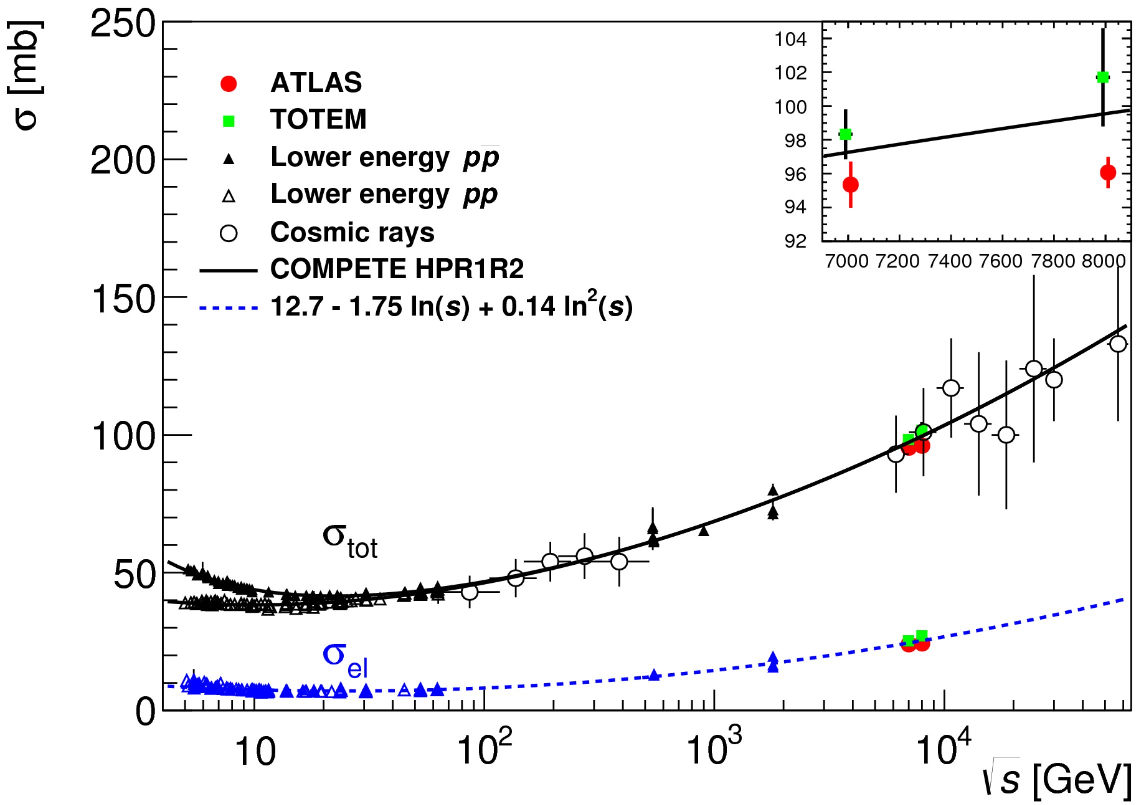
Total hadronic cross section emerges via fit normalisation

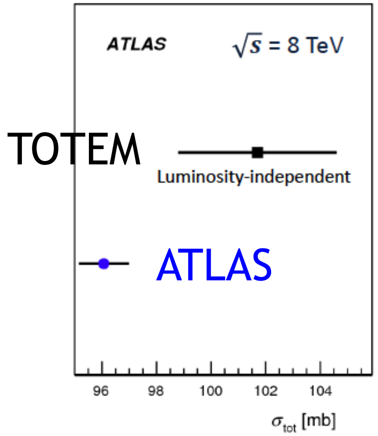
Results and Energy Dependence: σ_{tot}

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

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

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



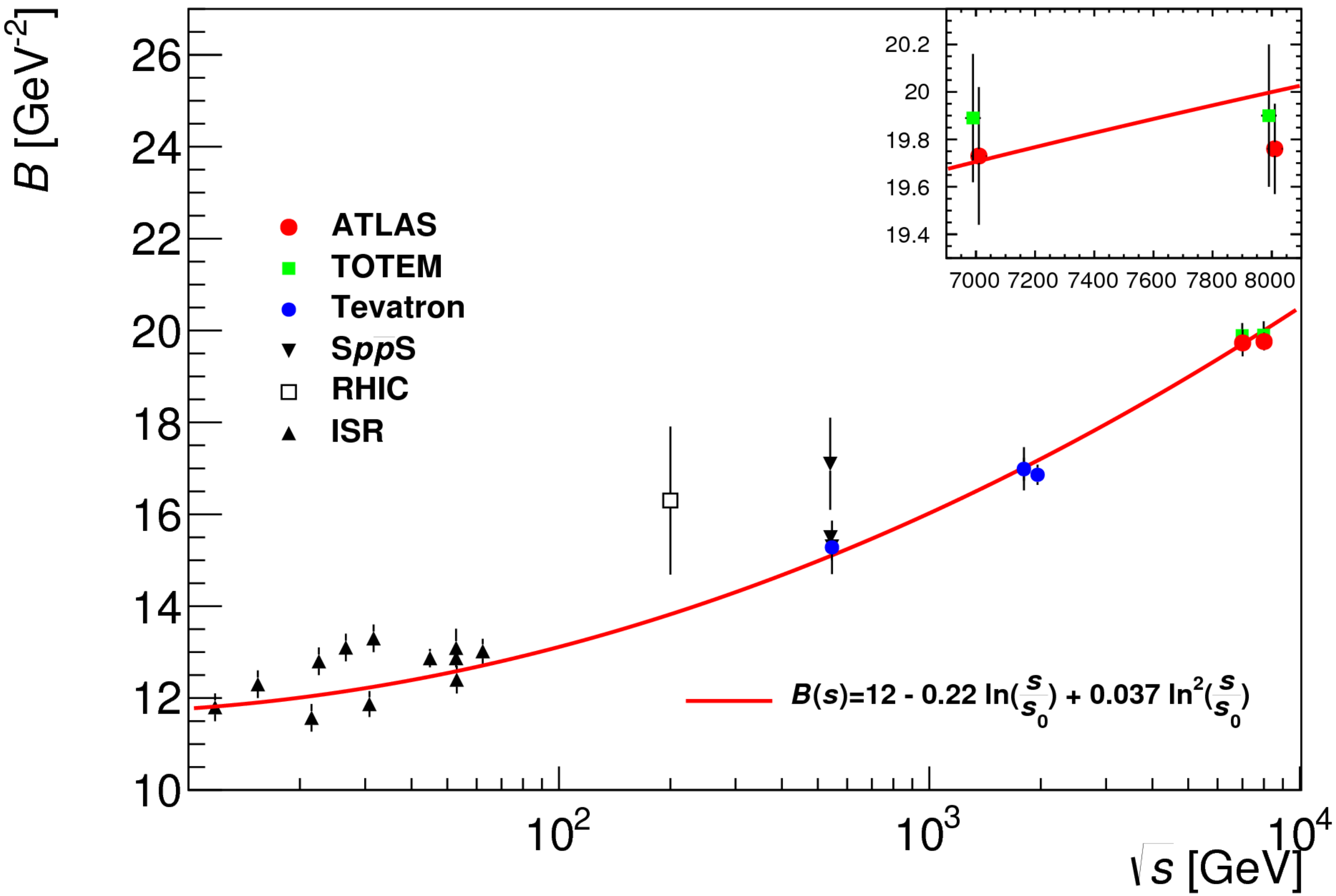


- ATLAS 1.9σ lower than TOTEM lumi-independent result (cf 1.3σ at 7TeV)
- Both uncertainties dominated by luminosity

Data remain compatible with slow (log / power) growth with √s

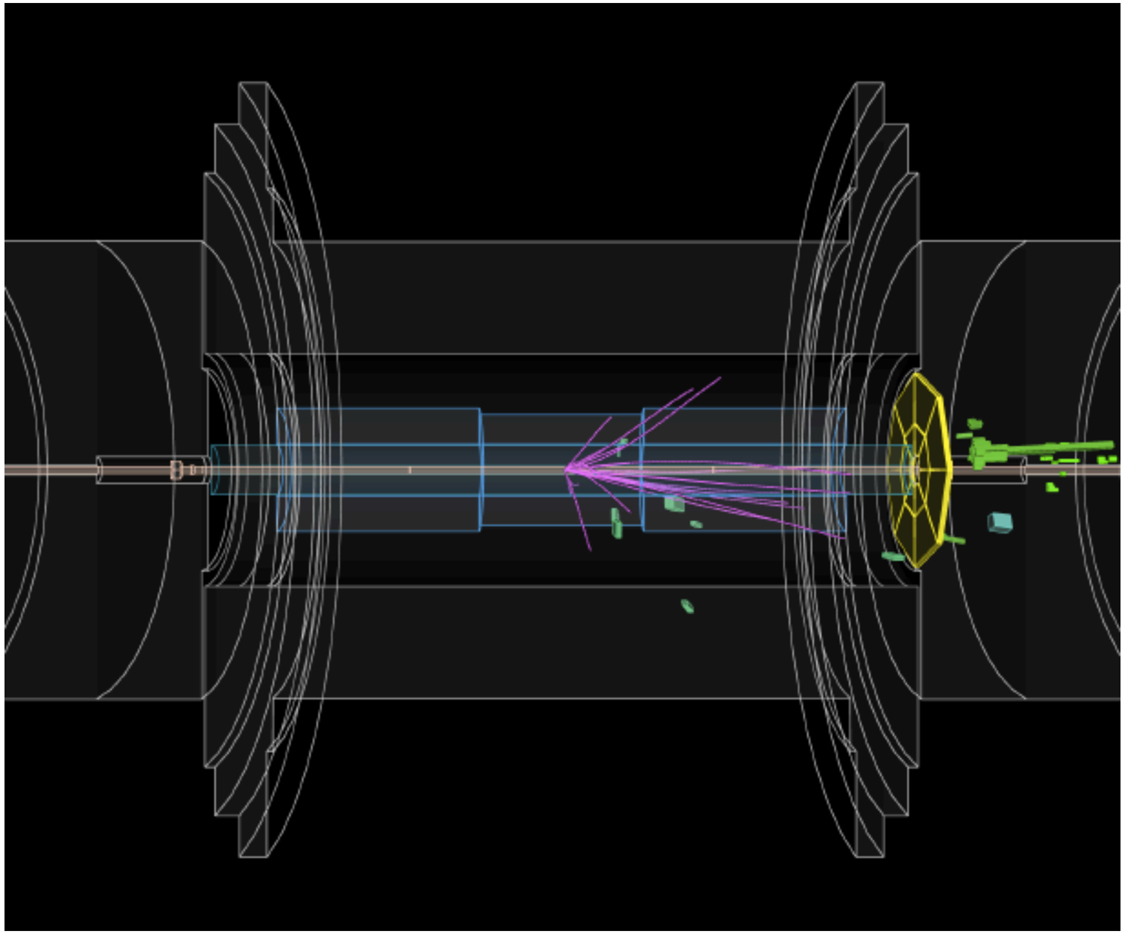
Results and Energy Dependence: B

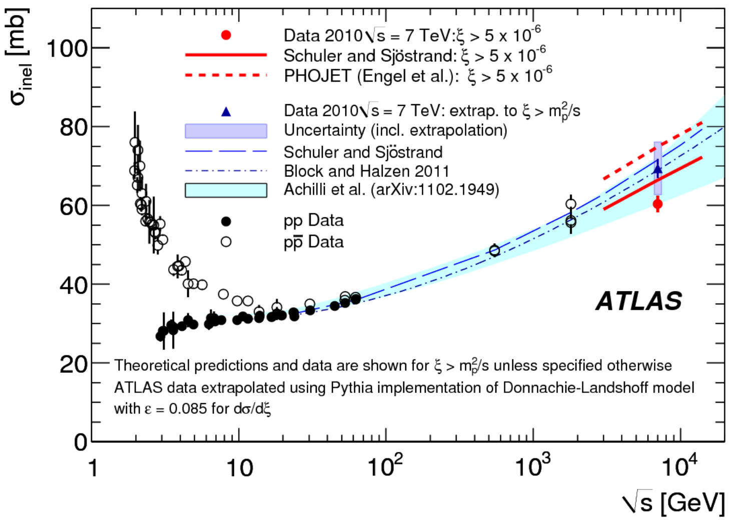
$$B(8\ \text{TeV}) = 19.74 \pm 0.05(\text{stat.}) \pm 0.16(\text{exp.}) \pm 0.15(\text{extr.})\ \text{GeV}^{-2}$$



Data remain compatible with shrinkage of forward elastic peak with √s. Logarithmic model shown is Schegelsky & Ryskin

2) Minimum Bias Method





- Earlier result at √s=7 TeV: Nature Commun 2 (2011) 463

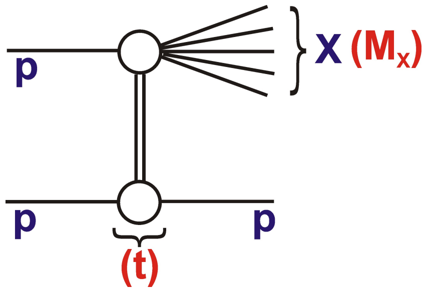
-bPresented here, 13TeV result: PRL 117 (2016) 182002 (from short low pile-up run taken in June 2015)

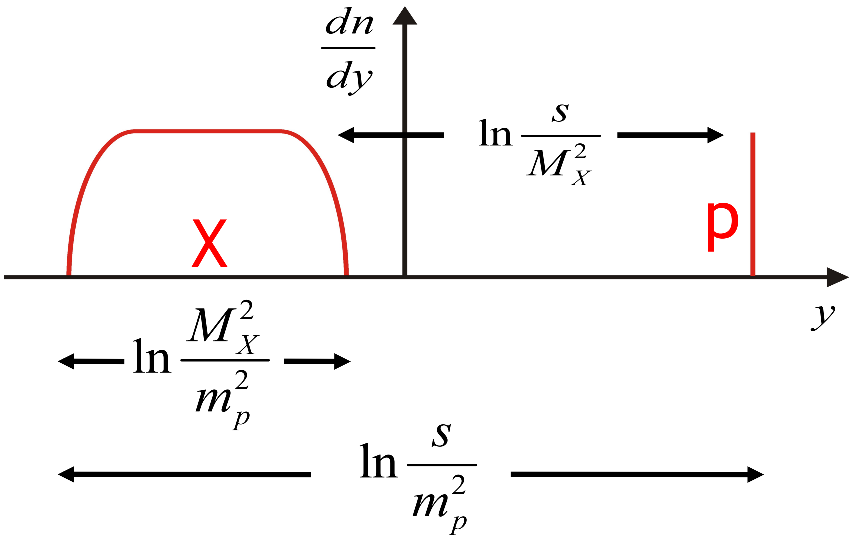
Total Inelastic Cross Section

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

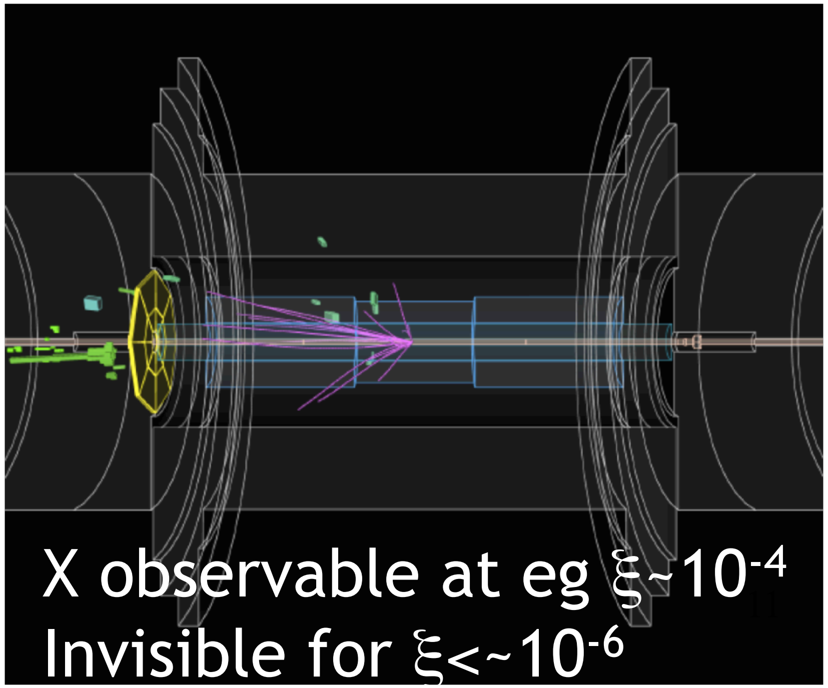
- Complication: controlling low mass diffractive dissociation that leaves no signal in MBTS

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

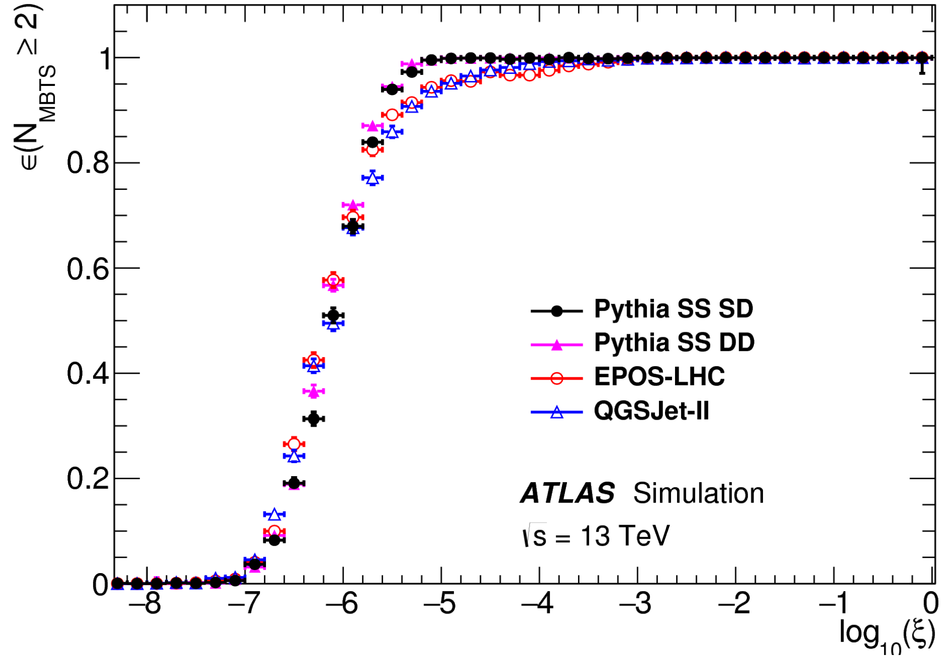




$$\Delta\eta \approx -\ln \xi$$



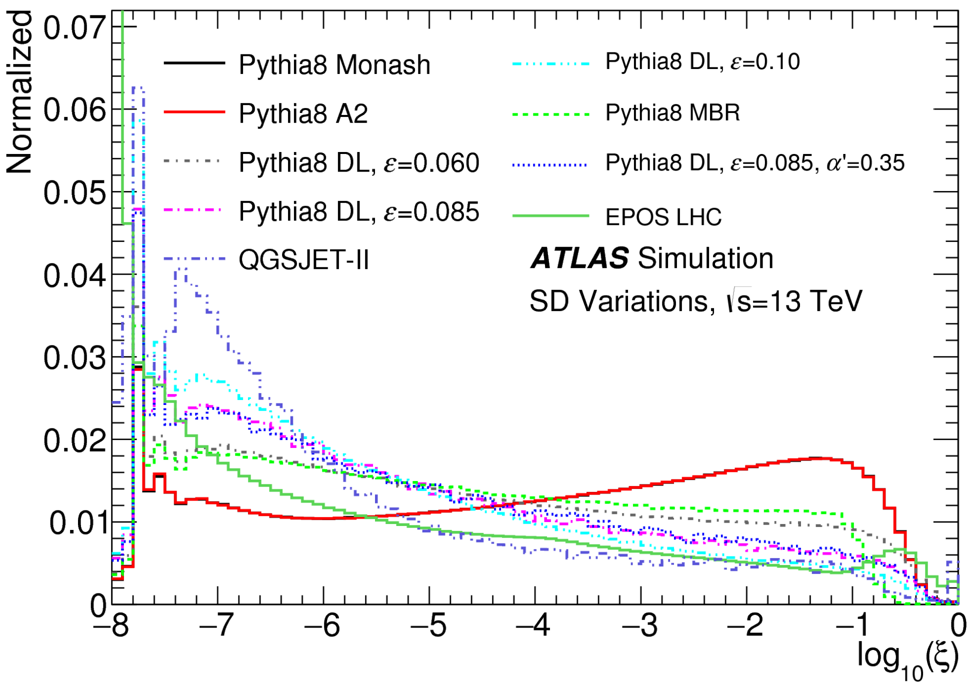
Why low mass diffraction is a problem

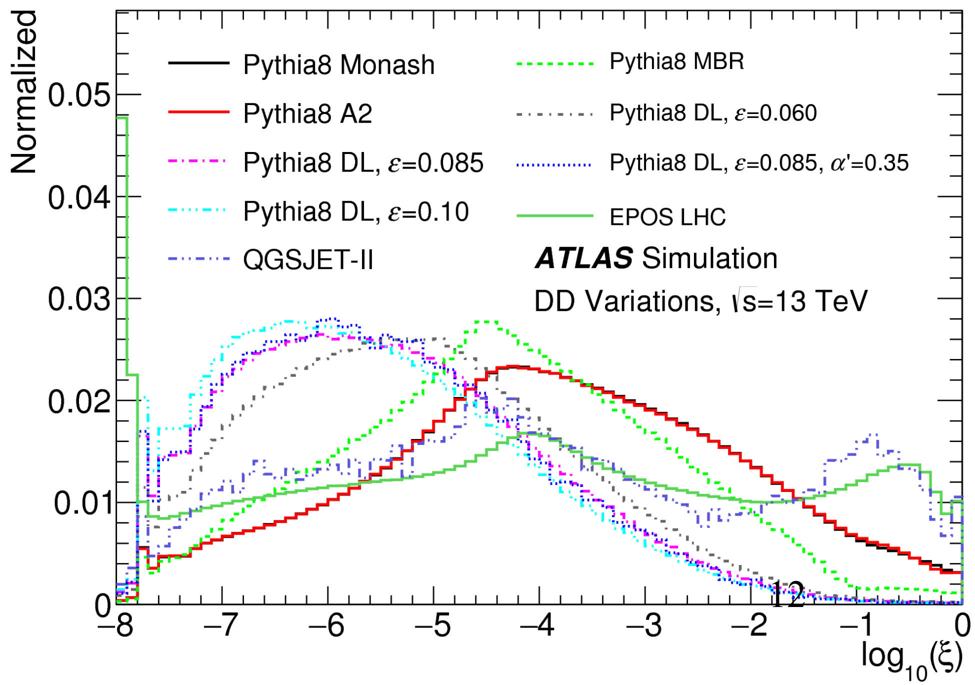


$$\Delta\eta \approx -\ln\xi$$

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

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

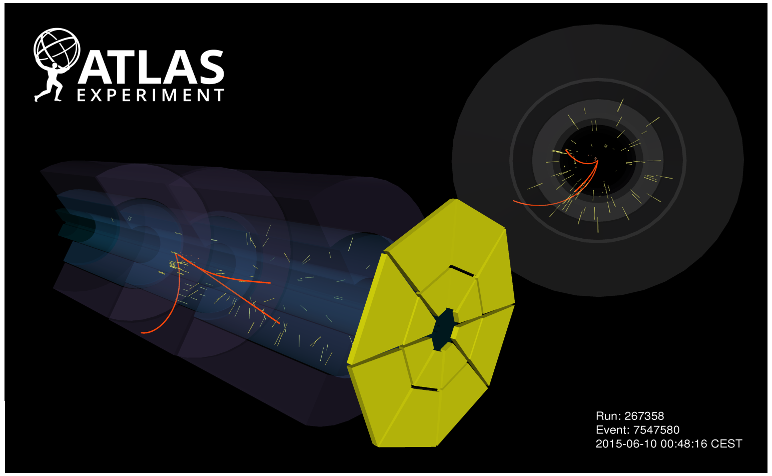


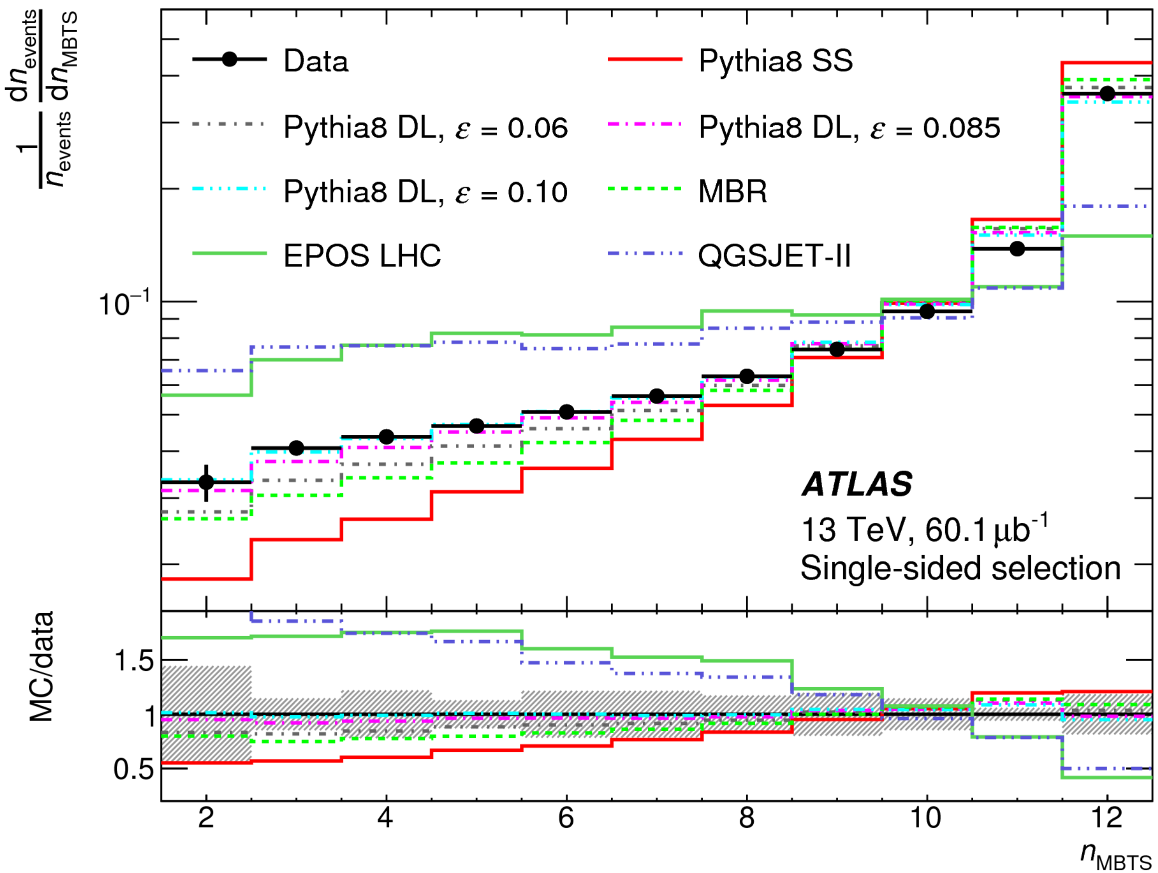


Benchmarking Diffractive MC models

"Single Sided" sample:

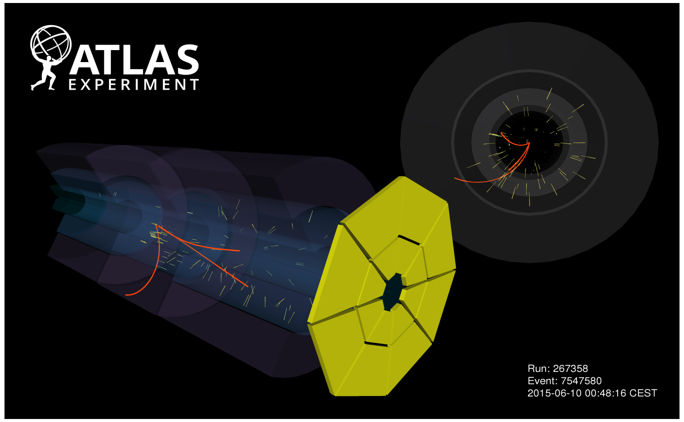
… activity on one side of MBTS, empty on other: enriched in SD events





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

Tuning Diffractive MC models



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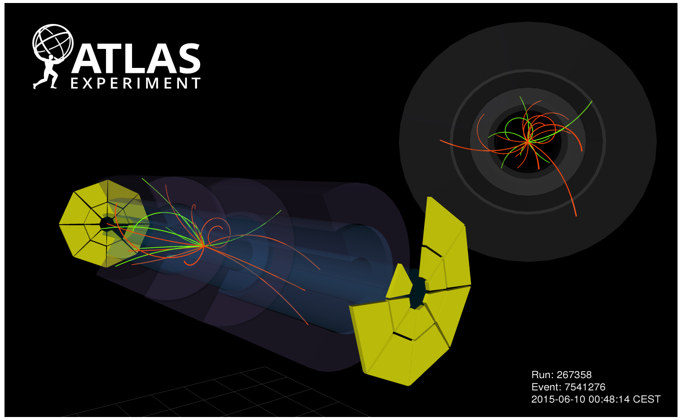
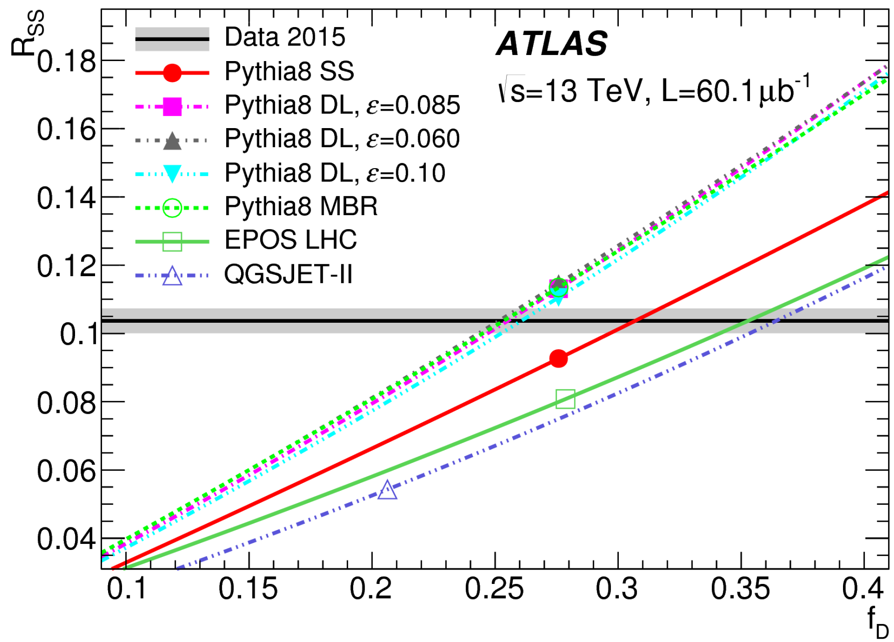


R_{SS} = Ratio of single sided to double sided MBTS samples … used to tune fractions of events considered diffractive in each MC model

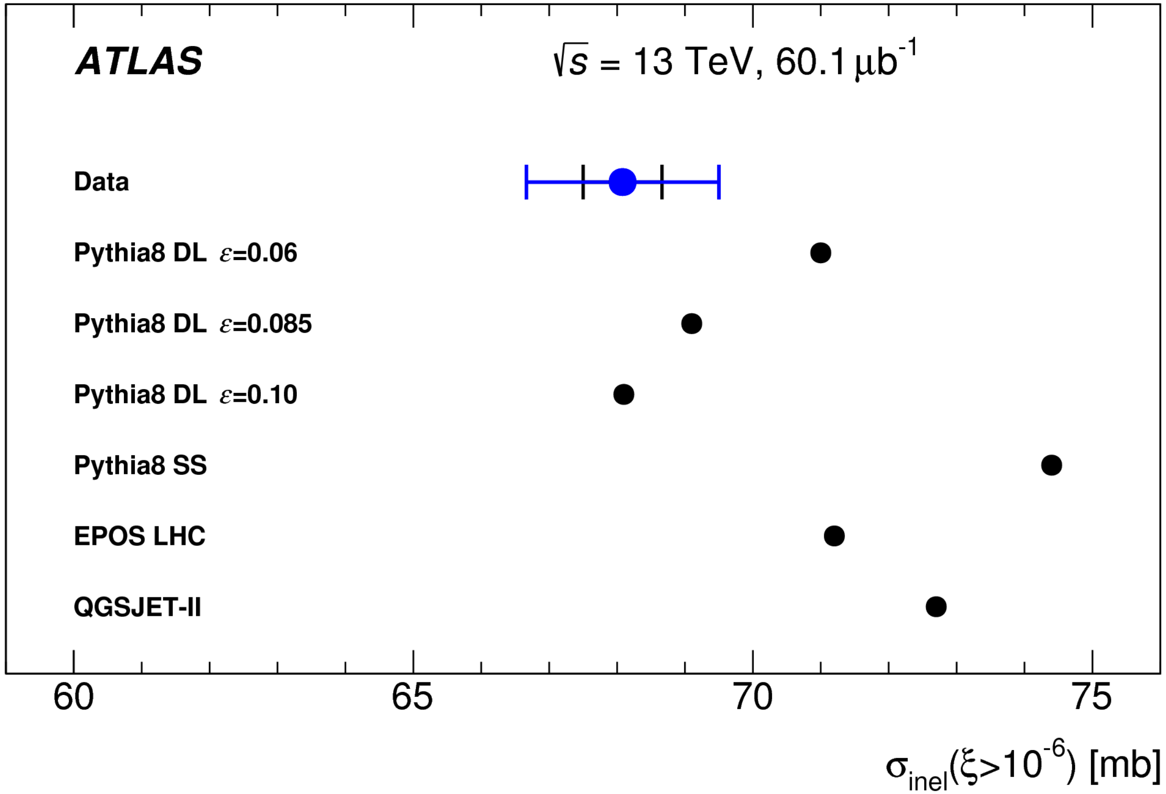


Baseline MC is PYTHIA8 with DL pomeron flux and $\alpha_{IP}(0)$ = 1.085

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

Cross Section in Fiducial Range

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



- 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 $\xi < 10^{-6}$, with minimal dependence on MC models:

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

$$\sigma^{7\ {\rm TeV}}(\xi < 5\times10^{-6}) = \sigma_{\rm inel}^{7\ {\rm TeV}} - \sigma^{7\ {\rm TeV}}(\xi > 5\times10^{-6})$$

$$= 11.0 \pm 2.3\ {\rm mb}$$

from ALFA result

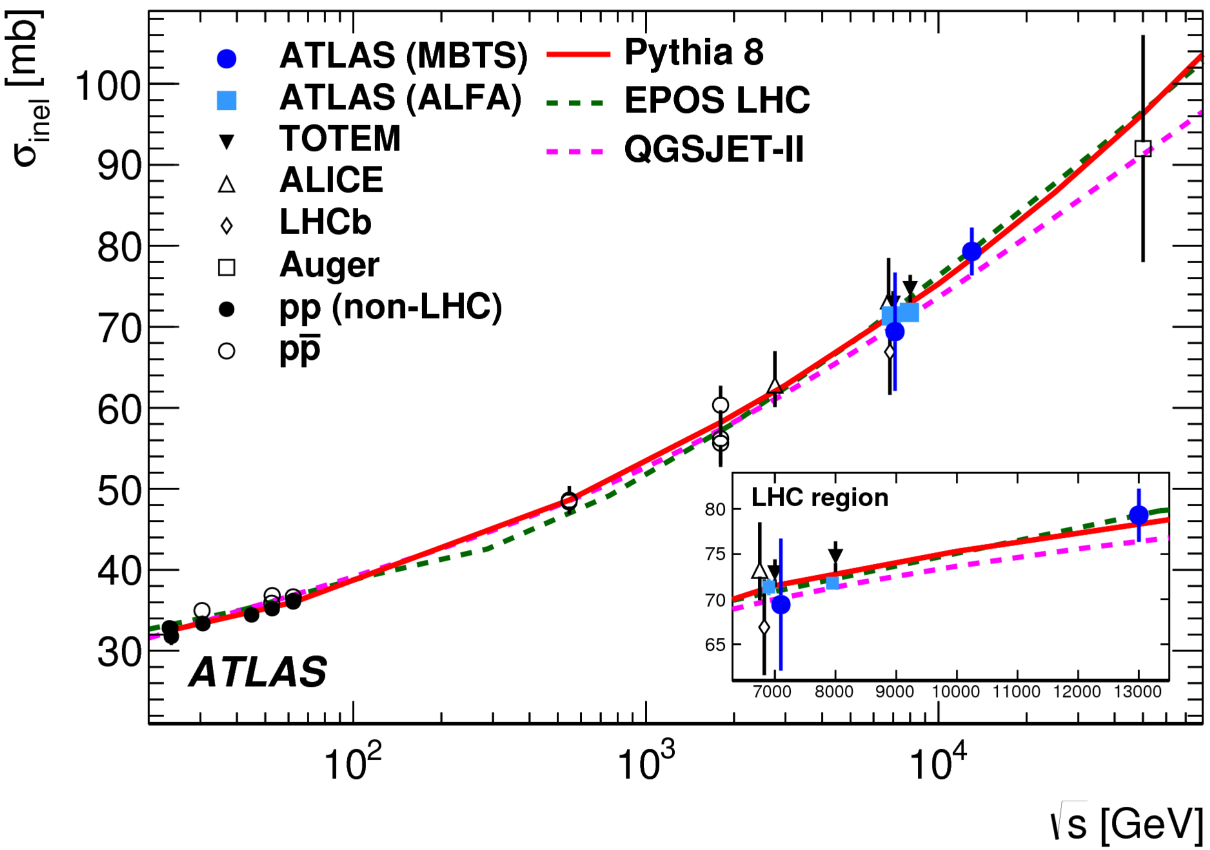
previous fiducial MBTS result

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

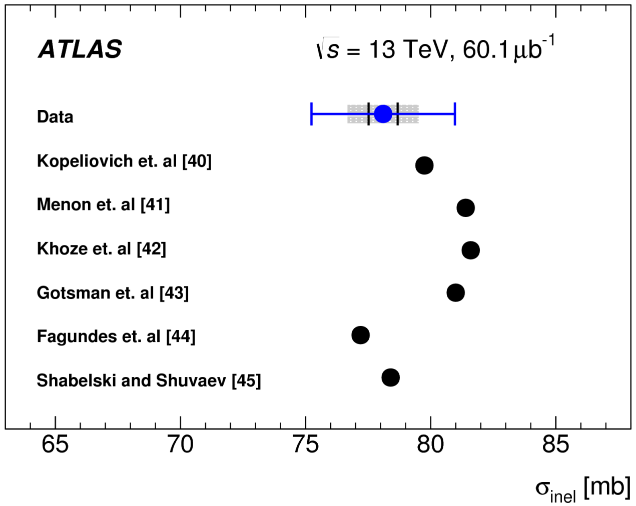
… extrapolation uncertainty is 2.5 mb

Extrapolation to Full Inelastic Cross Sec

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

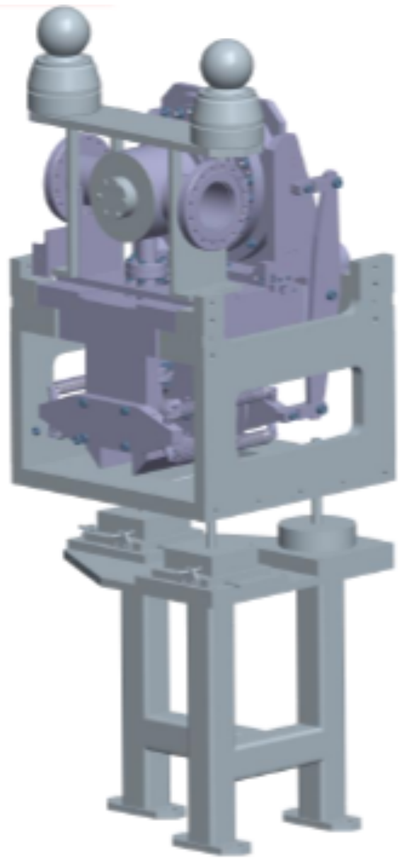


Consistent with continued growth with √s



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

Future at ATLAS

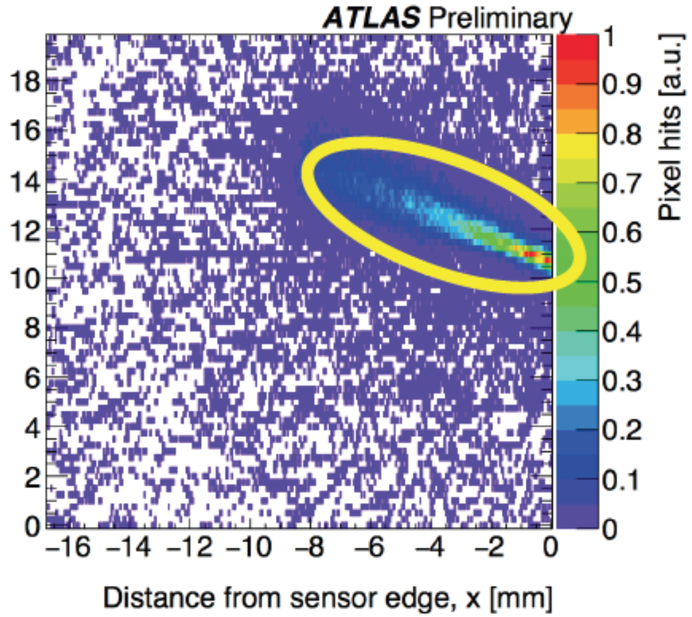


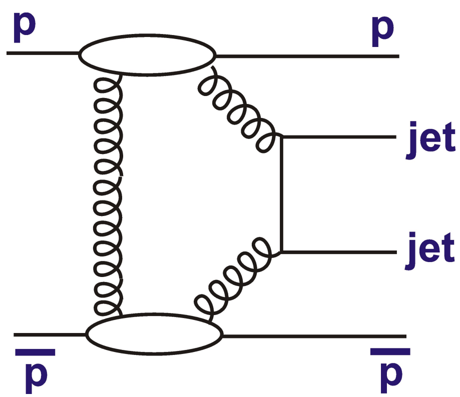
- 13 TeV σ_{tot} ALFA measurement still ongoing

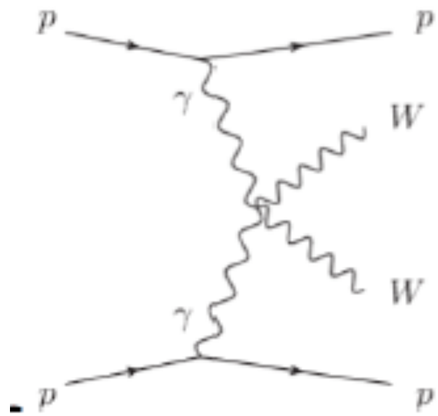
- Diffactive studies still ongoing

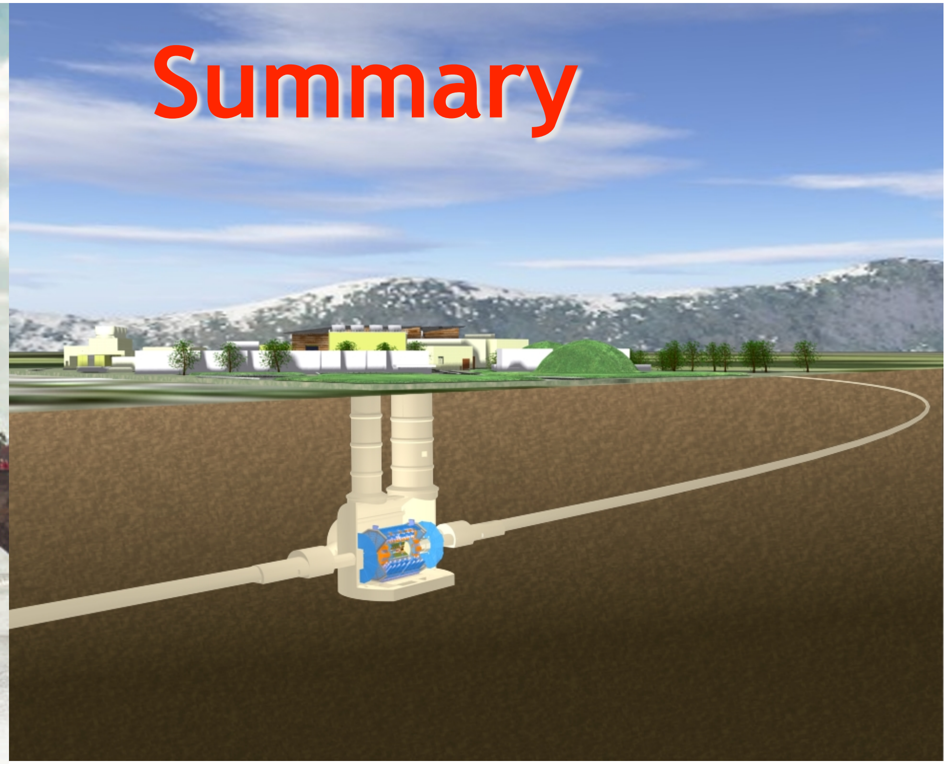
- ALFA being preserved for 14 TeV running

- 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

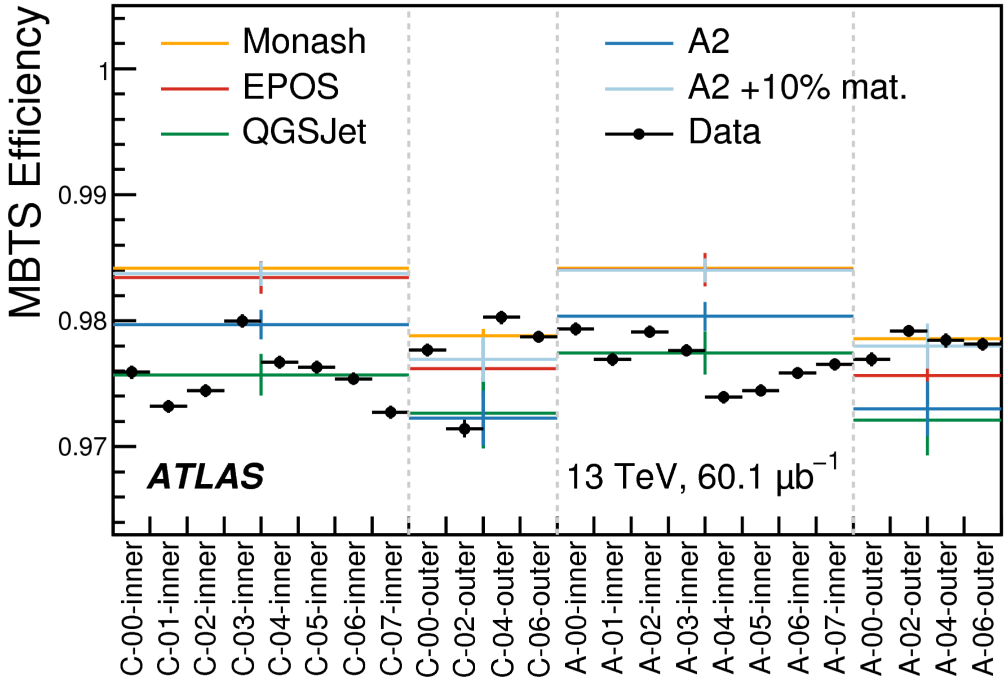
- Highly precise measurements of σ_{tot} (±1%), σ_{el}, σ_{inel}, B_{el}
- Continued cross sec growth and elastic peak shrinkage with $\sqrt{s}$
- Compatibility with TOTEM at 2σ level

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

Controlling MBTS Efficiency with Data

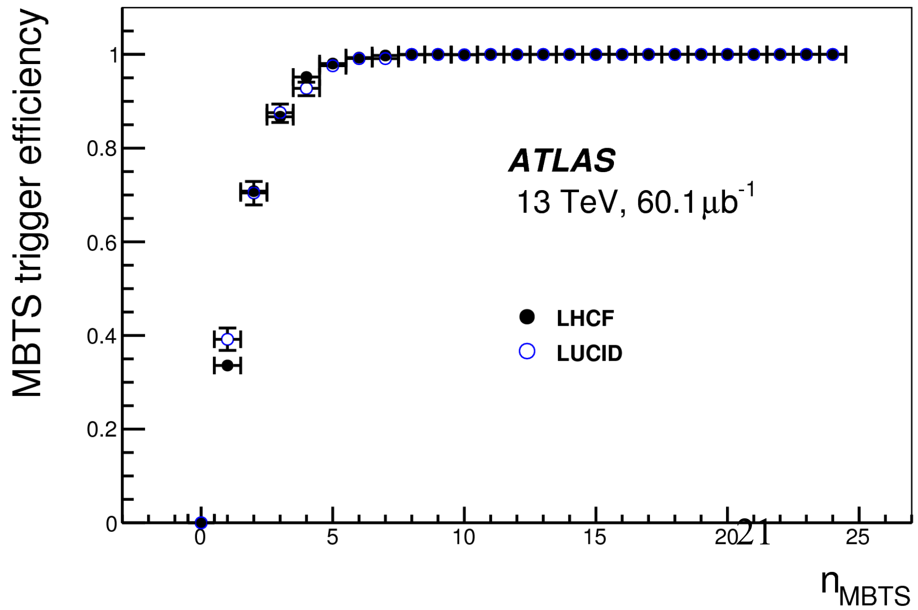


- Efficiencies for each MBTS counter measured relative to tracks in inner detector where possible and calorimeter clusters where not.
→MC efficiencies tuned accordingly

- 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

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

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

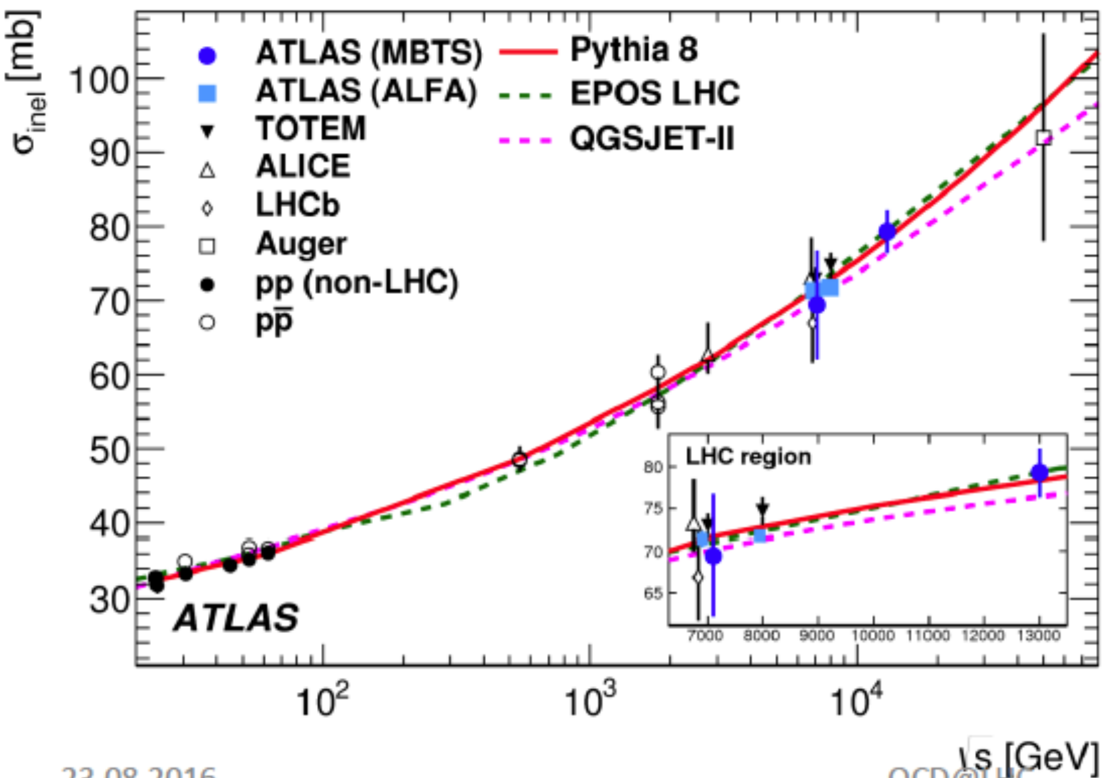
- Luminosity from final calibration of Van der Meer scan → 1.9% error

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%

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

Summary of Total Inelastic Cross Sections

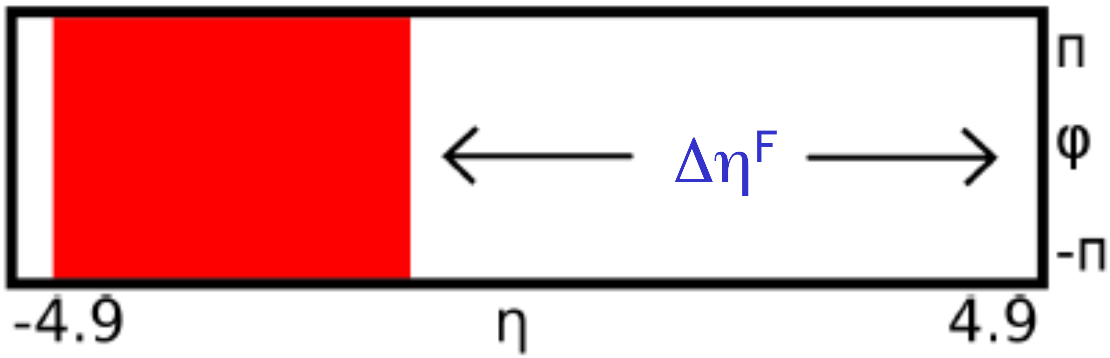
	7 TeV	8 TeV	13 TeV	Comments
MBTS	69.1 ± 7.3 mb		79.3 ± 2.9 mb	Main error contribution extrapolation
ALFA	71.3 ± 0.9 mb	71.7 ±0.7mb		Small errors due to precise lumin.
TOTEM	72.9 ± 1.5 mb	74.7± 1.7 mb		Based on elastic & inelastic rates
CMS			71.3 ± 3.5 mb	Preliminary, based on HF calorimeters

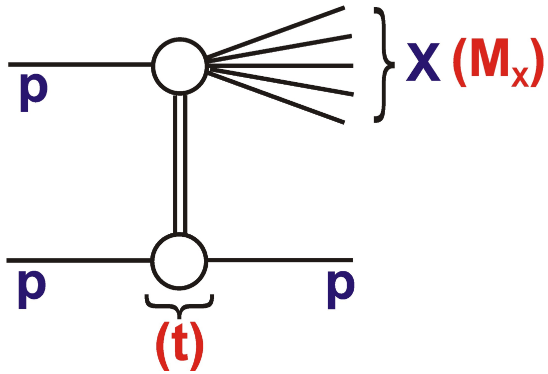


- In general increase with $\sqrt{s}$ visible as expected.
- Values at 7 TeV and 8 TeV agree within errors.
- At 13 TeV some discrepancy, but large errors.

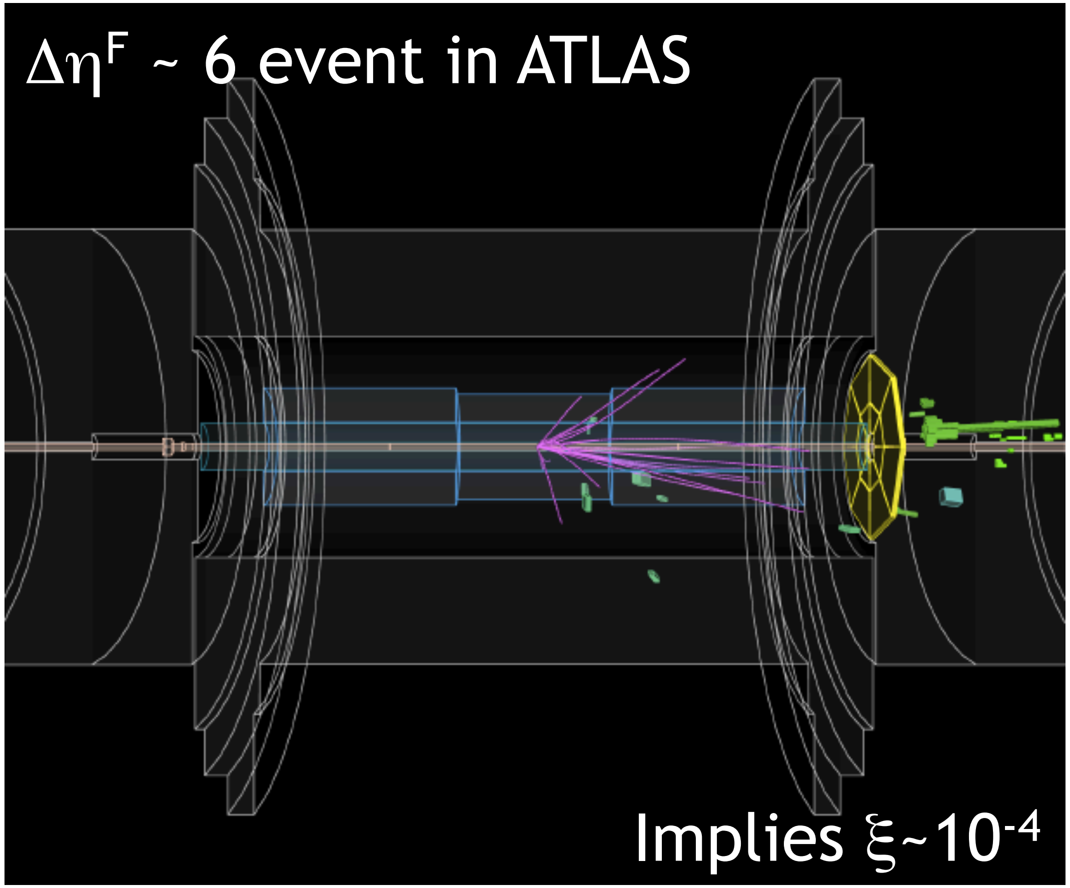
Rapidity gap cross-sections

Method developed by ATLAS to measure hadron Level cross section as a function of $\Delta\eta^F$: forward or backward rapidity gap extending to limit of instrumented range:
i.e. including $\eta = \pm 4.9$

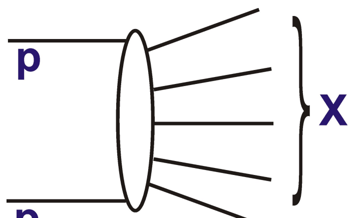


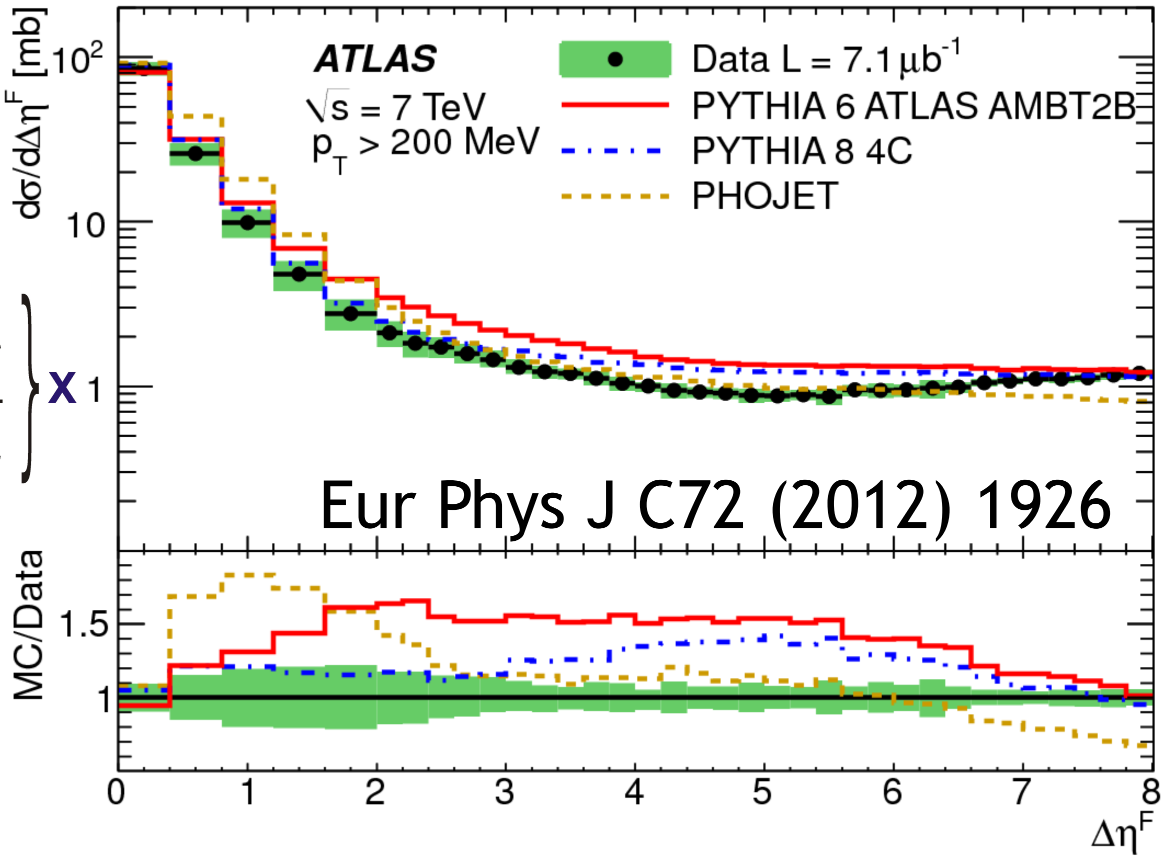


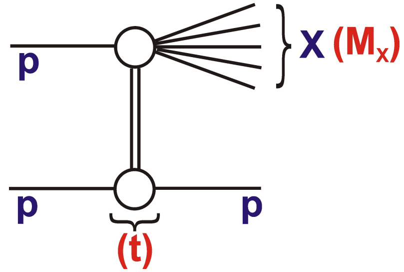
… no statement on $\eta >\sim 4.9$
… large $\Delta\eta^F$ sensitive to SD + low M_Y DD

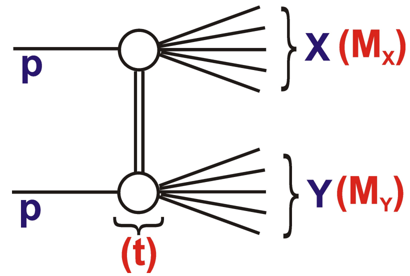


Inclusive Differential Gap Cross Section





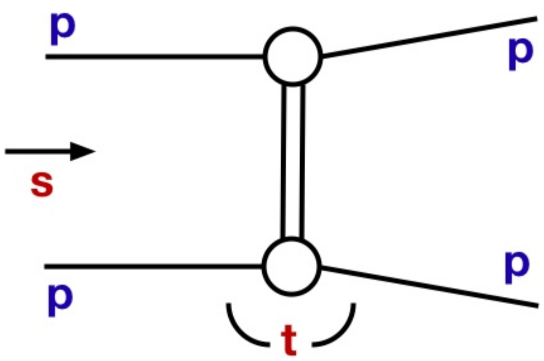




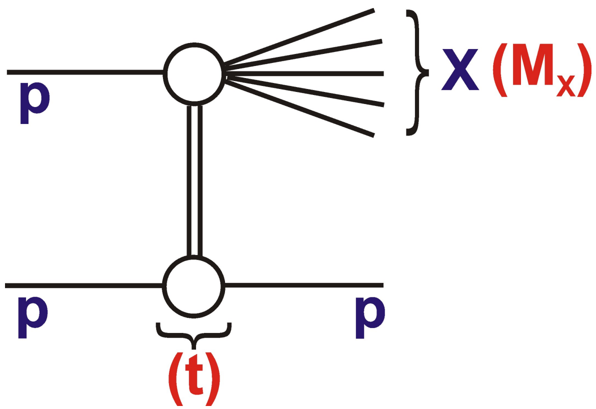
- Large $\Delta\eta^F$: Diffractive plateau with ~1mb per unit gap size, consistent with soft pomeron ($\alpha_{IP}(0) = 1.058 \pm 0.036$)
- Small $\Delta\eta^F$: sensitive to hadronisation fluctuations / MPI in ND

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

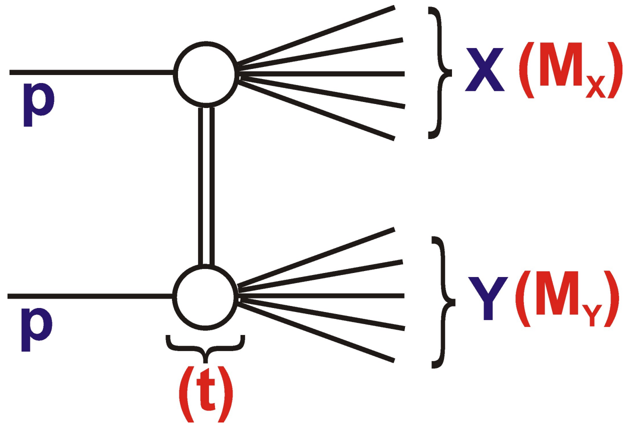
Decomposing the pp Cross Section



Elastic



Single diffractive dissociation



Double diffractive dissociation

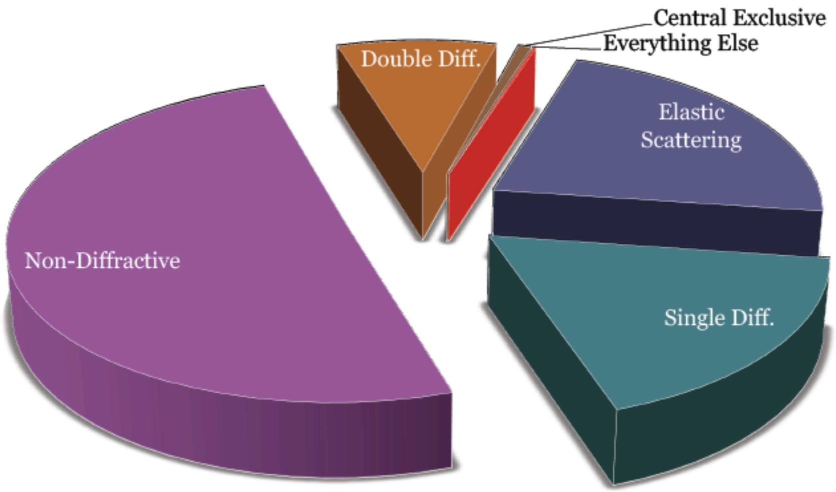
1 degree of freedom
→ scattering angle / t

Also M_X

$$\xi = \frac{M_X^2}{s} = 1 - \frac{E_p^{/}}{E_p}$$

Also M_Y

$$\xi_Y = \frac{M_Y^2}{s}$$



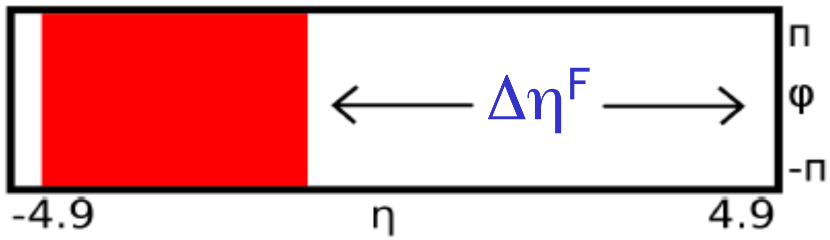
At LHC, M_X, M_Y can be as large as 1 TeV → plenty of phase space to produce jets and other hard probes

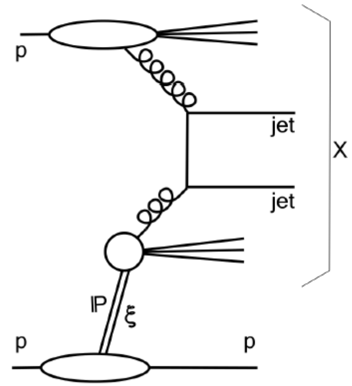
Probably for the back-up

$$\frac{d\sigma_{el}}{dt_i} = \frac{1}{\Delta t_i} \times \frac{\mathcal{M}^{-1}[N_i - B_i]}{A_i \times \epsilon^{reco} \times \epsilon^{trig} \times \epsilon^{DAQ} \times L_{int}}$$

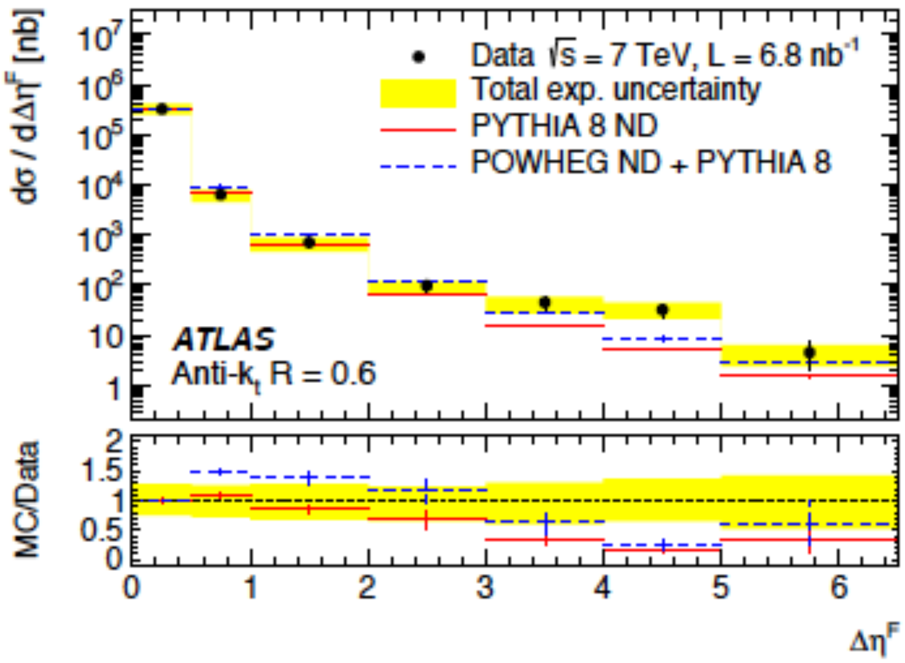
- Unfolding procedure
- Events per bin
- Background (0.12%)
- Acceptance (fit range > 10%)
- Reconstruction efficiency (≈ 90%)
- Trigger efficiency (> 99.9%)
- Dead-time fraction (0.44%)
- Luminosity 1.5% errror

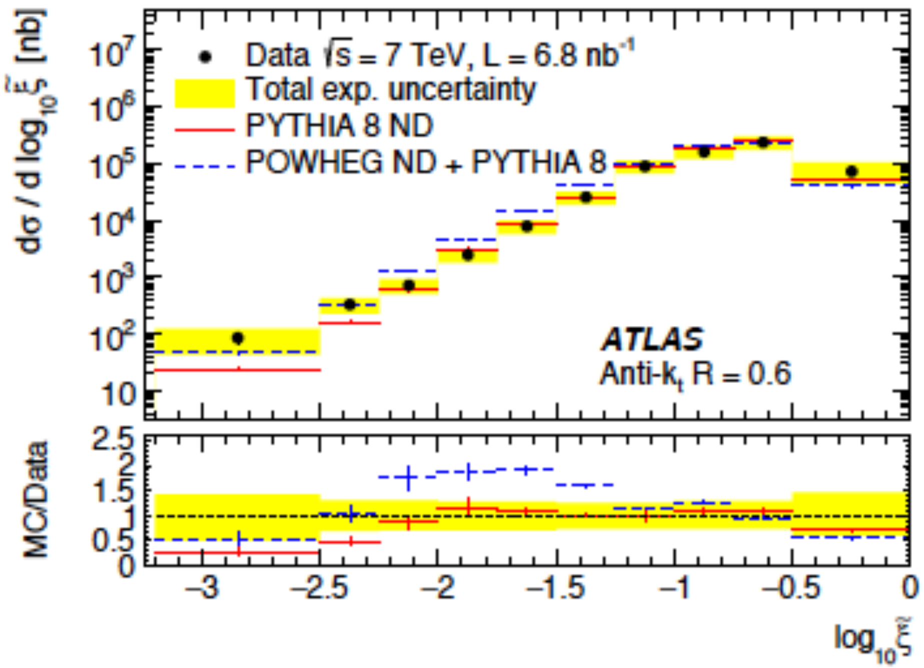
Corrected Diffractive Jet Data v Non-Diffractive Models





- 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 …





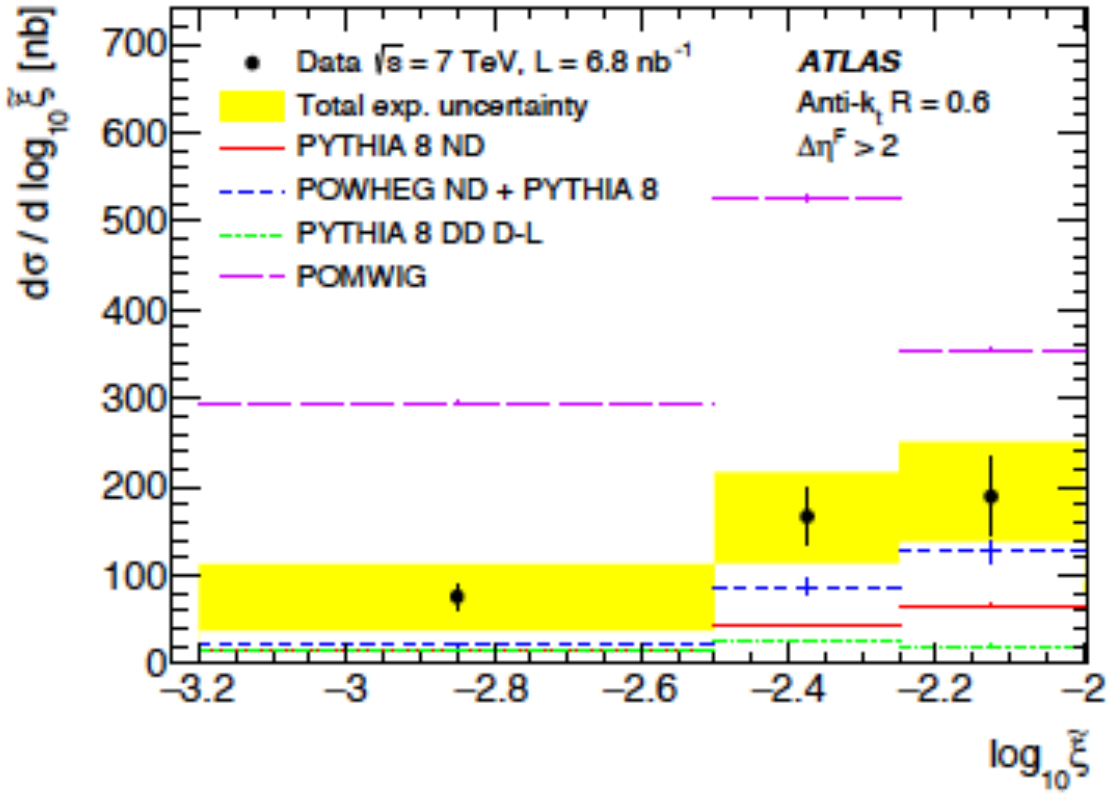
Evidence for Diffractive Contribution

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

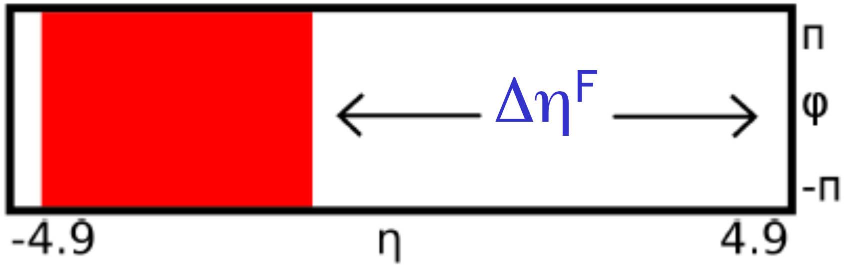
→ Comparison of smallest ξ with DPDF-based model (POMWIG) leads to rapidity gap survival probability estimate …

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

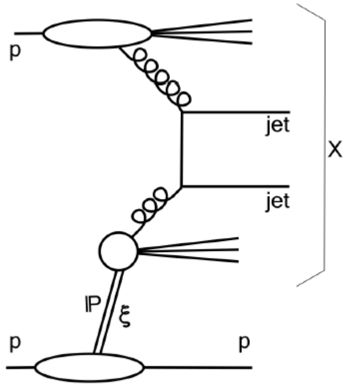


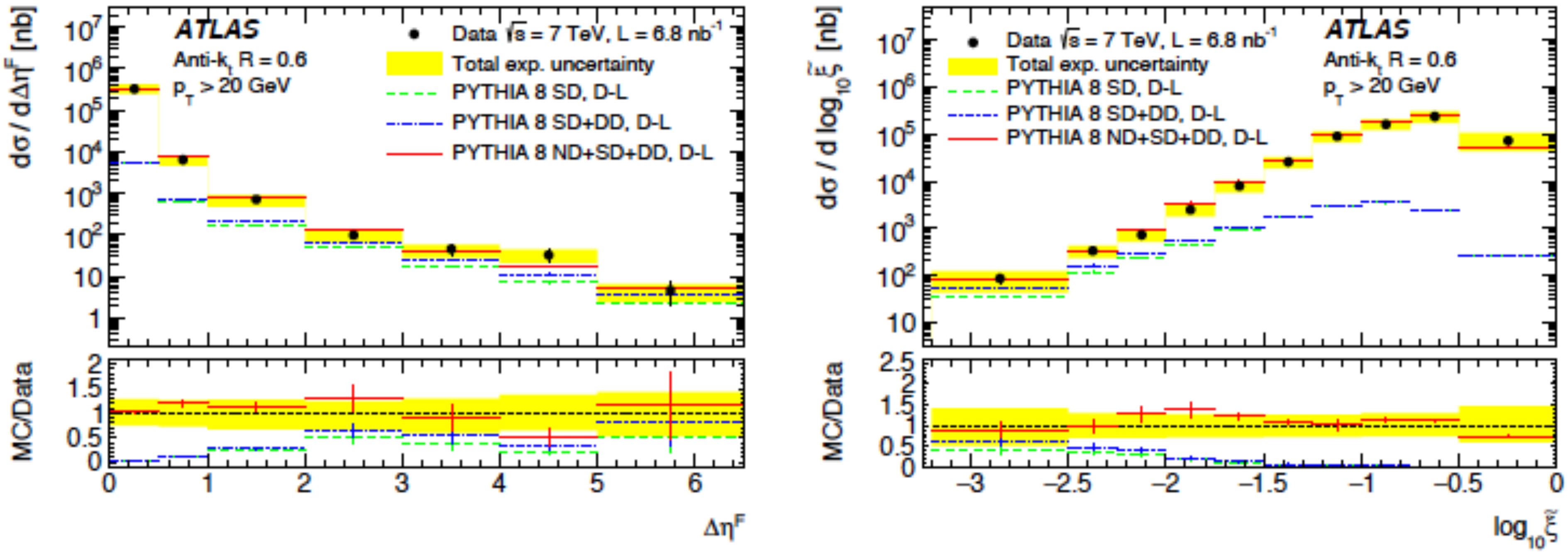
$$S^2 = 0.16 \pm 0.04\ (\text{stat.}) \pm 0.08\ (\text{exp. syst.})\ ,$$

Comparison with Full PYTHIA8

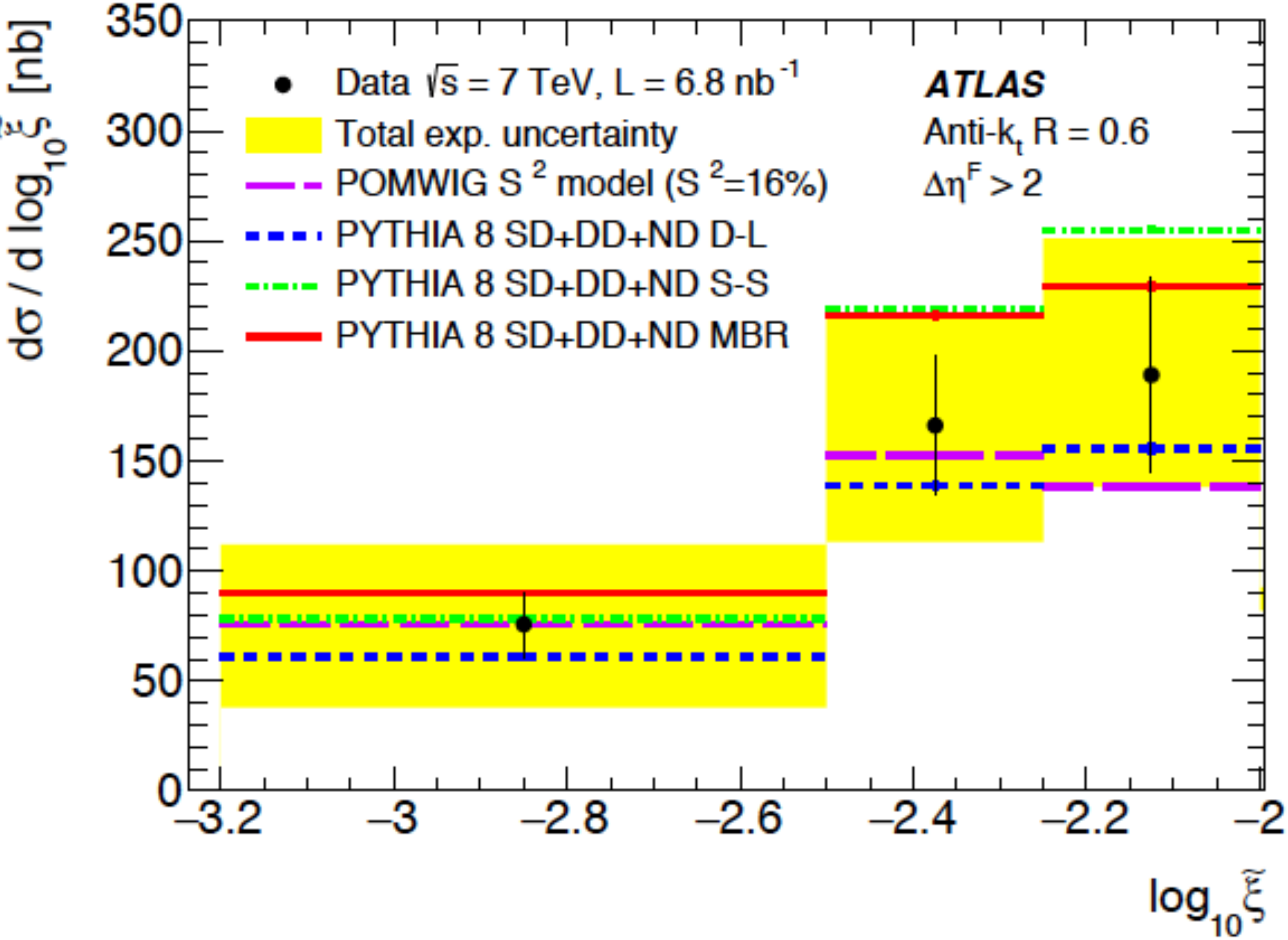


'Off-the shelf' PYTHIA8 ND*0.71 + SD + DD does a good job at all $\Delta\eta_F$ and ξ, with no need for a gap survival factor (though ND dominates, so compatible with a wide range of S^2 values).



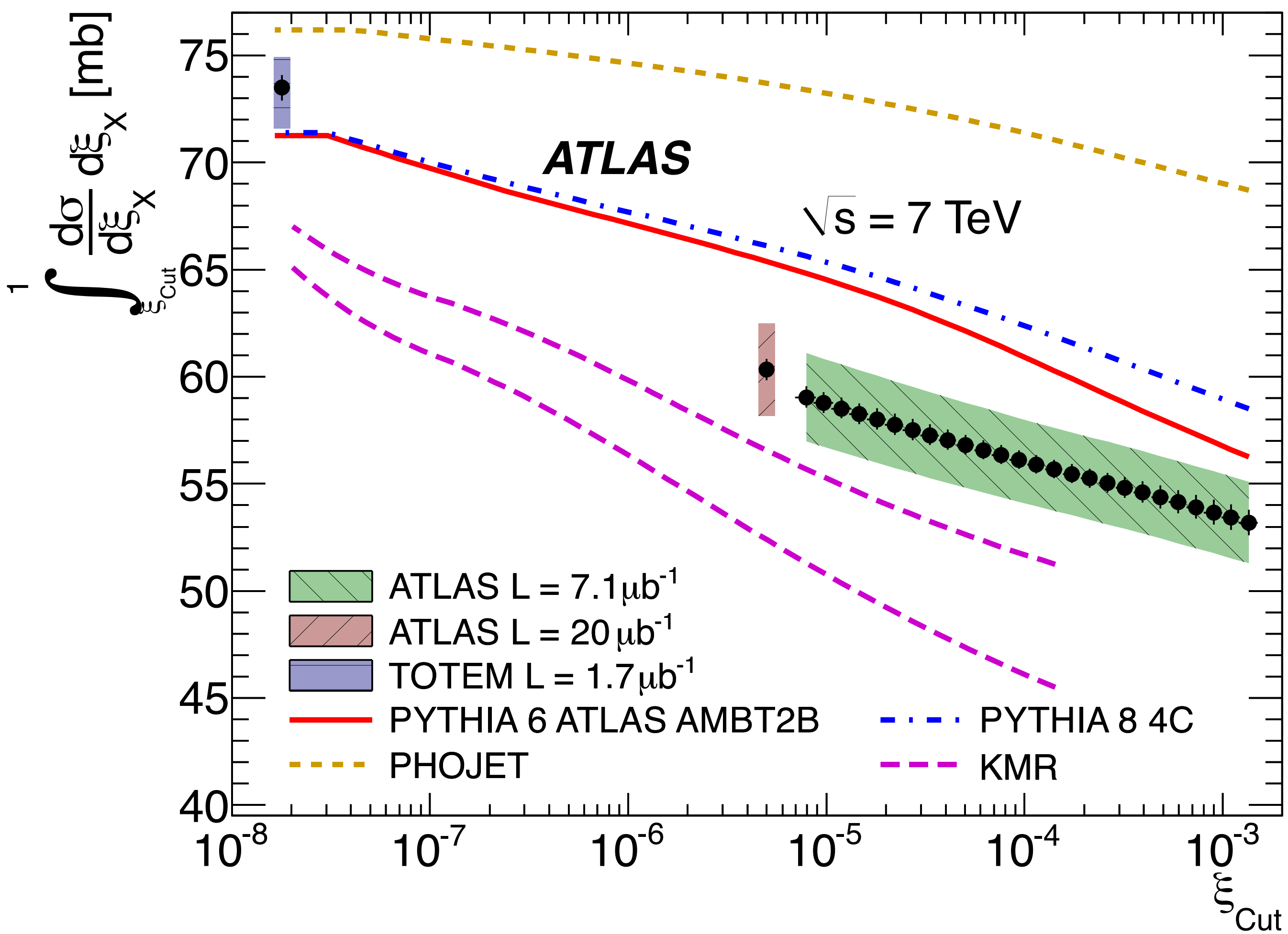


Diffractive Models Focusing on $\Delta\eta^F > 2$



Phys Lett B754 (2016), 214

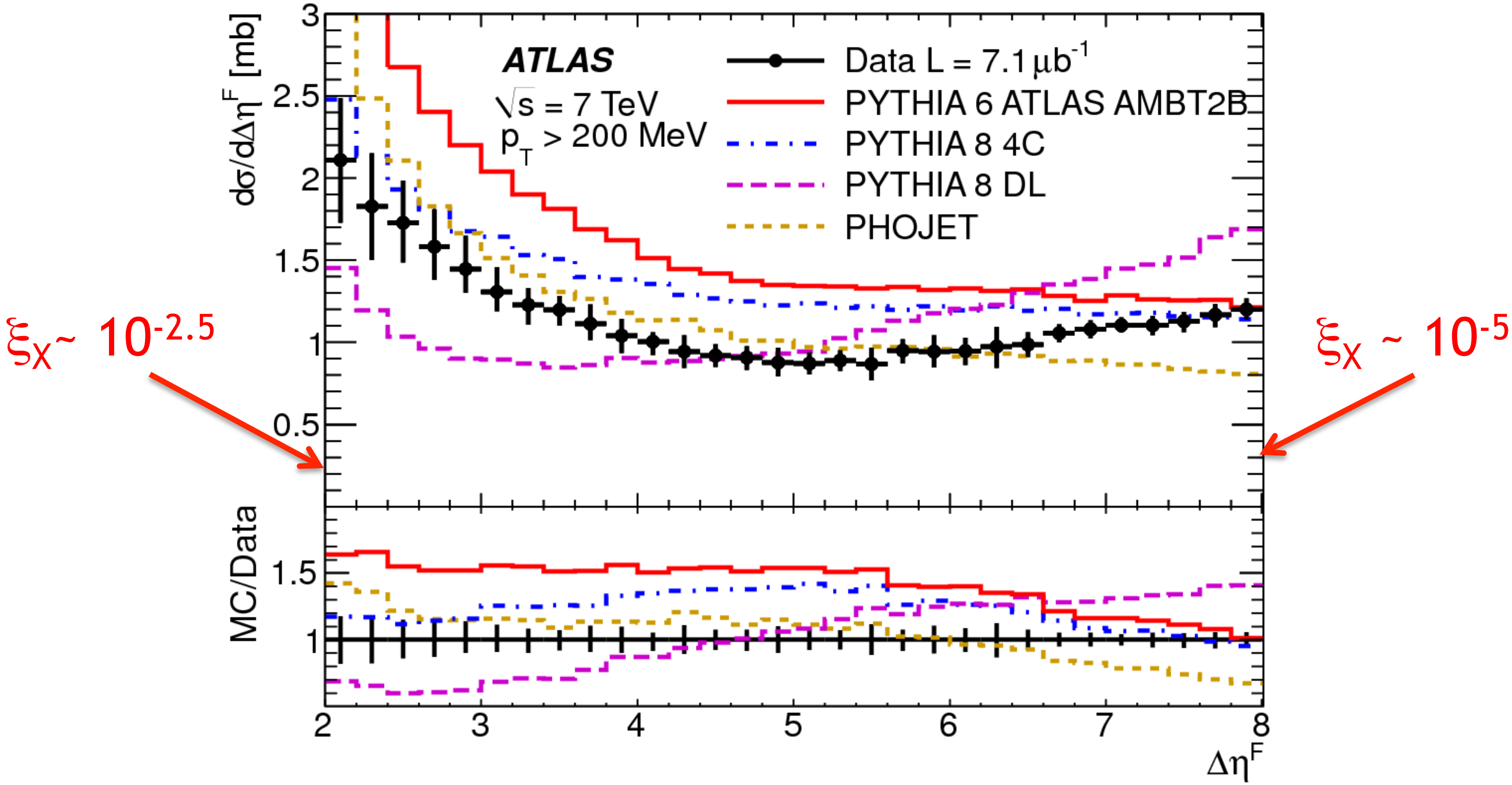
Investigating Low Mass Extrapolations



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

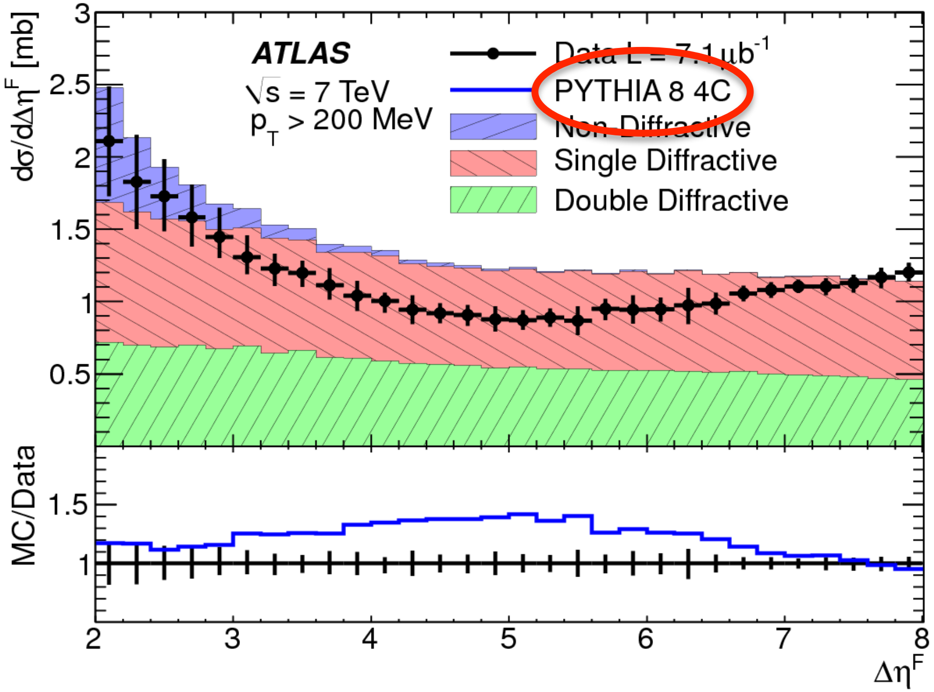
- Integrating ATLAS gap cross section up to some max $\Delta\eta^F$ (equivalently min ξ_X) and comparing with TOTEM indicates that small ξ_X region underestimated in PHOJET and PYTHIA:
- 14 mb with $\xi < 10^{-5}$, compared to 6 (3) mb in PYTHIA (PHOJET)

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: $\alpha_{IP}(0) = 1.058 \pm 0.003$ (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