Recent Diffractive and Related Measurements with the ATLAS Detector

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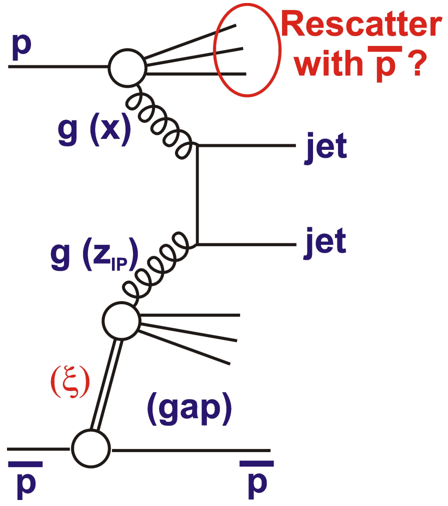
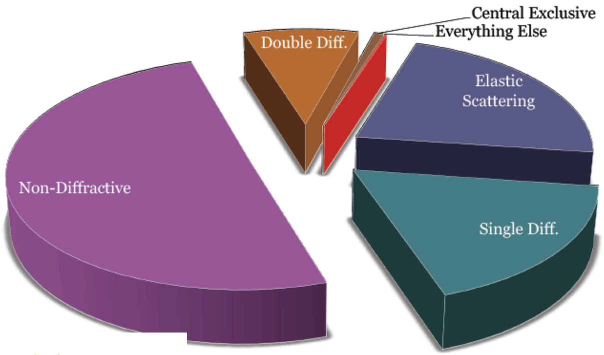
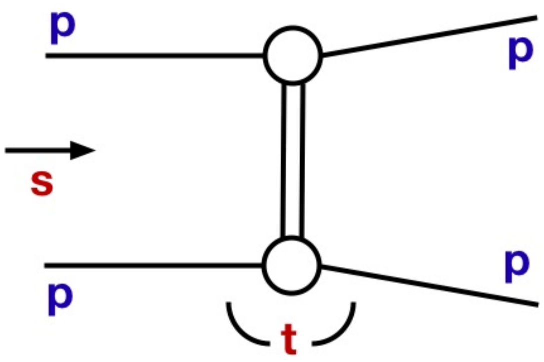




Low x Workshop, Gyongyos, Hungary
6-10 June 2016

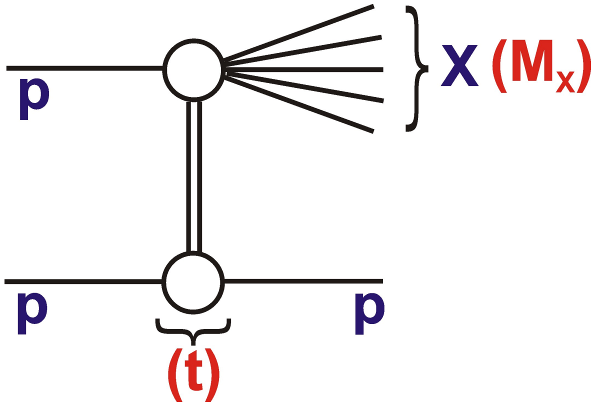
- → Total Inelastic Cross Section at 13 TeV NEW!
- → Diffractive Dijet Cross Sections
- → Via a bit of elastic and soft diffractive measurements

Decomposing the pp Cross Section



Elastic

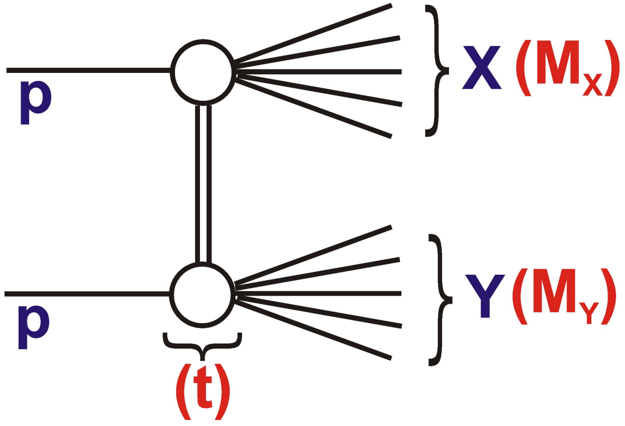
1 degree of freedom
→ scattering angle / t



Single diffractive dissociation

Also M_X

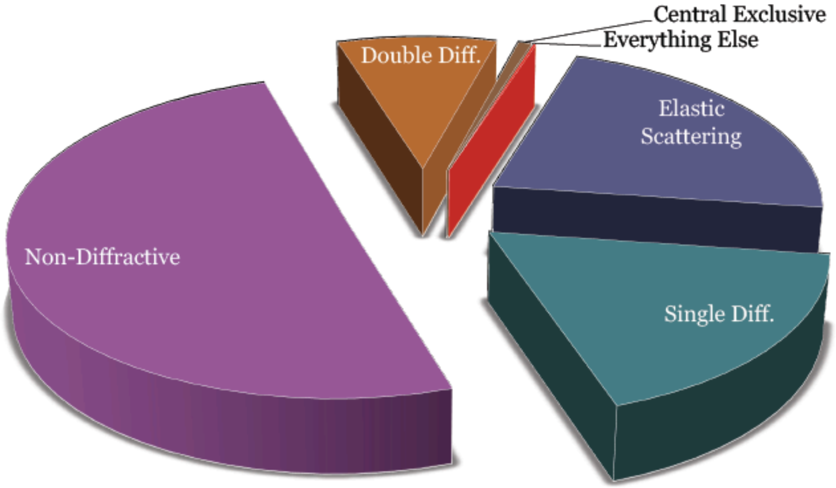
$$\xi = \frac{M_X^2}{s} = 1 - \frac{E_p^{/}}{E_p}$$



Double diffractive dissociation

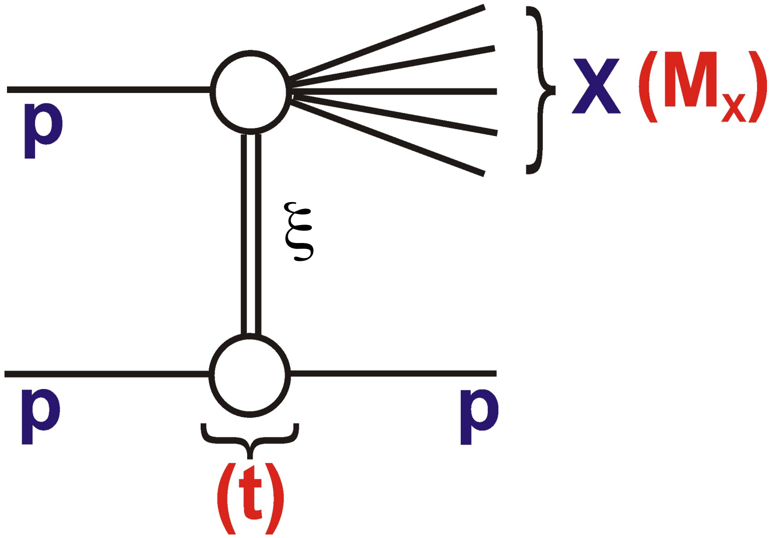
Also M_Y

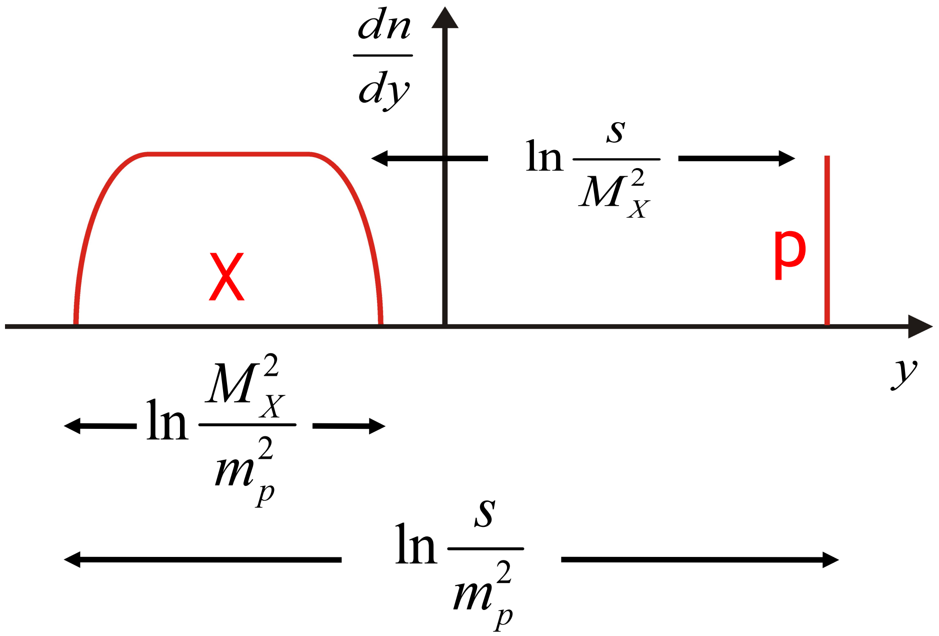
$$\xi_Y = \frac{M_Y^2}{s}$$



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

Diffractive Channels:
& Rapidity Gap Kinematics





- Protons not tagged directly

- ξ variable strongly correlated with empty rapidity regions

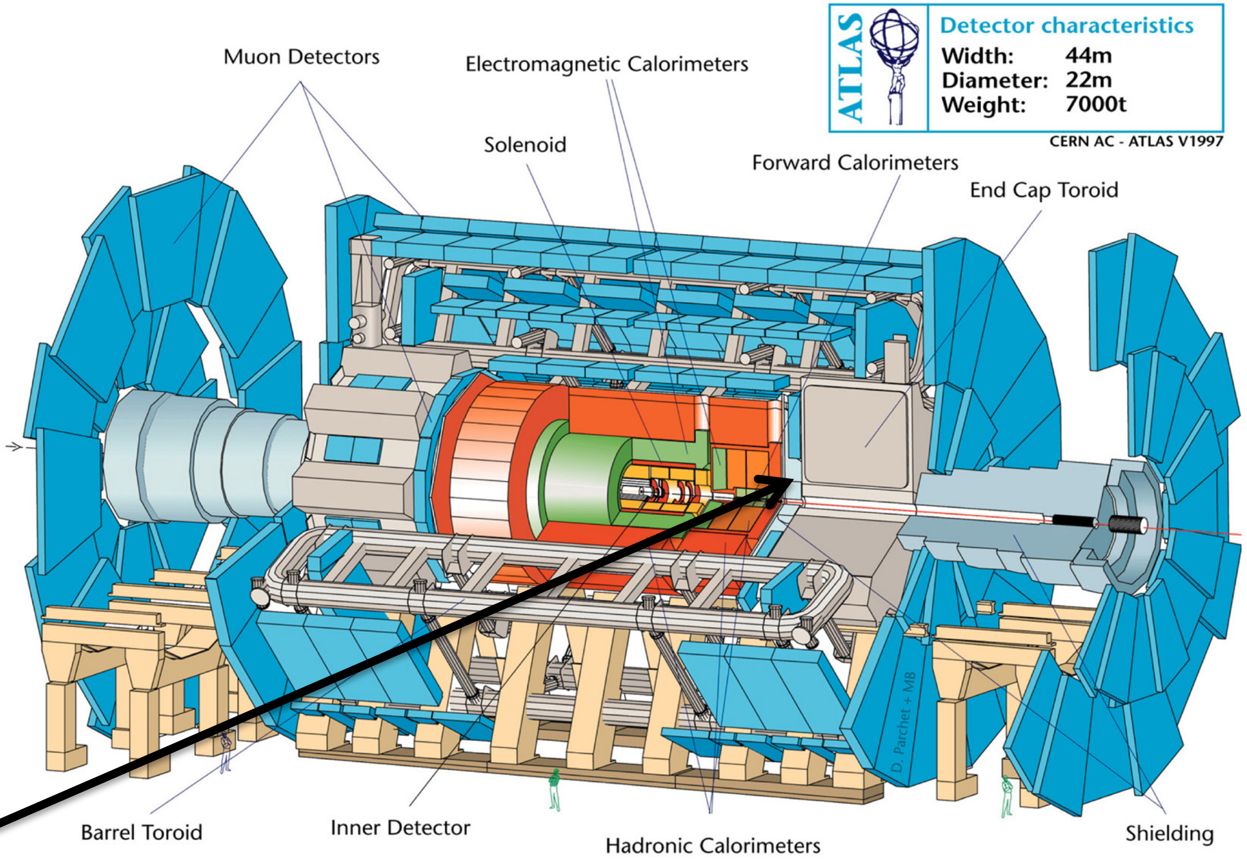
$$\Delta\eta \approx -\ln \xi$$

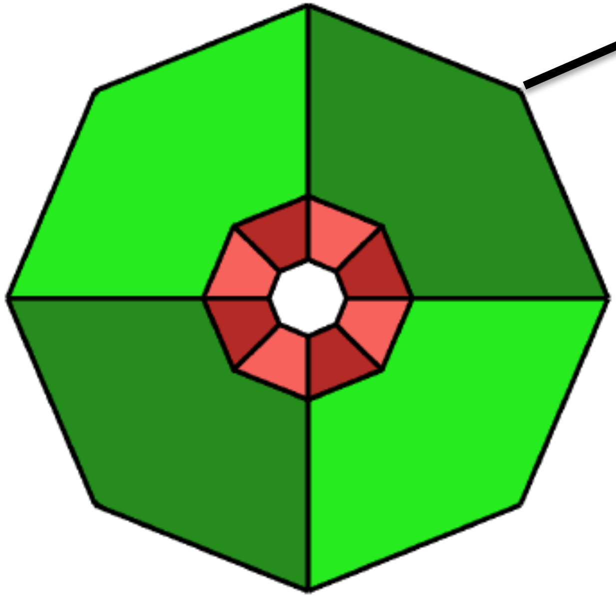
… exploited in both measurements to be shown

- Correlation limited by hadronisation fluctuations

ATLAS

Both measurements rely on minimum bias samples triggered using the MBTS scintillators





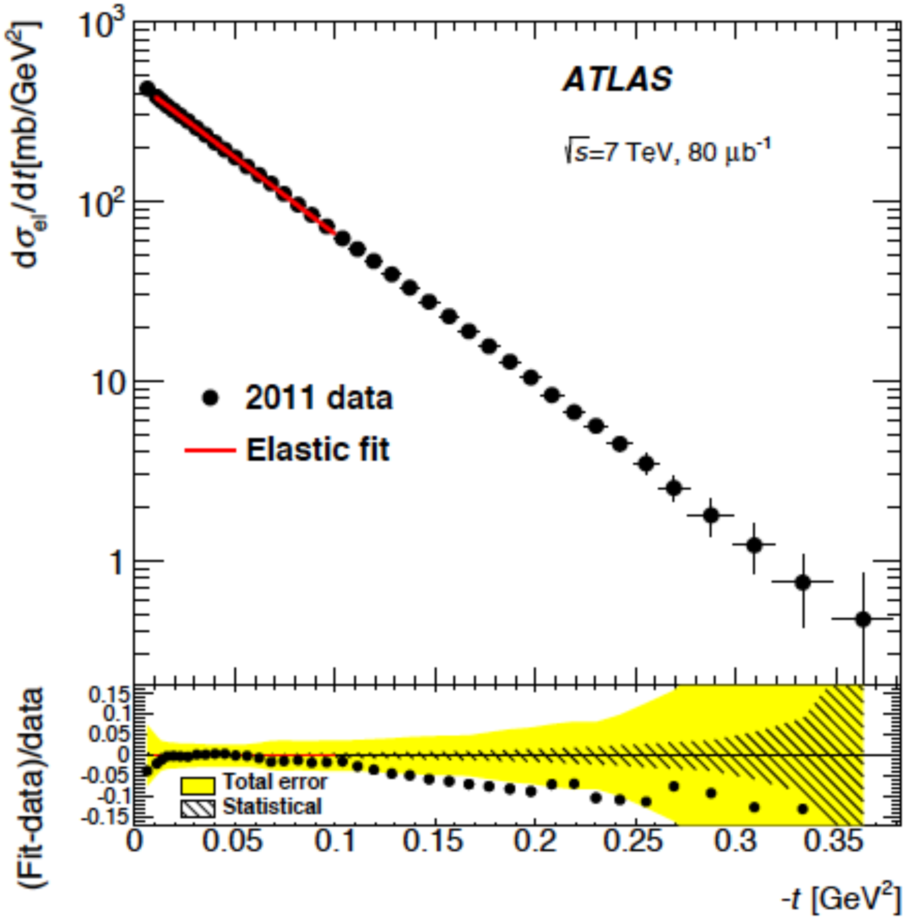
$z = \pm 3.6\text{m}, 2.1 < |\eta| < 3.8$

Run 1 version had 2 x 8-fold segmentation

Replaced for Run 2 – 8 fold segmentation nearest beam-pipe, 4-fold further out

Motivation:
Total and elastic cross sections

Measurements of the elastic cross section and its t-dependence (eg in ALFA) determine total cross section via optical theorem



Nucl Phys B889 (2014), 486

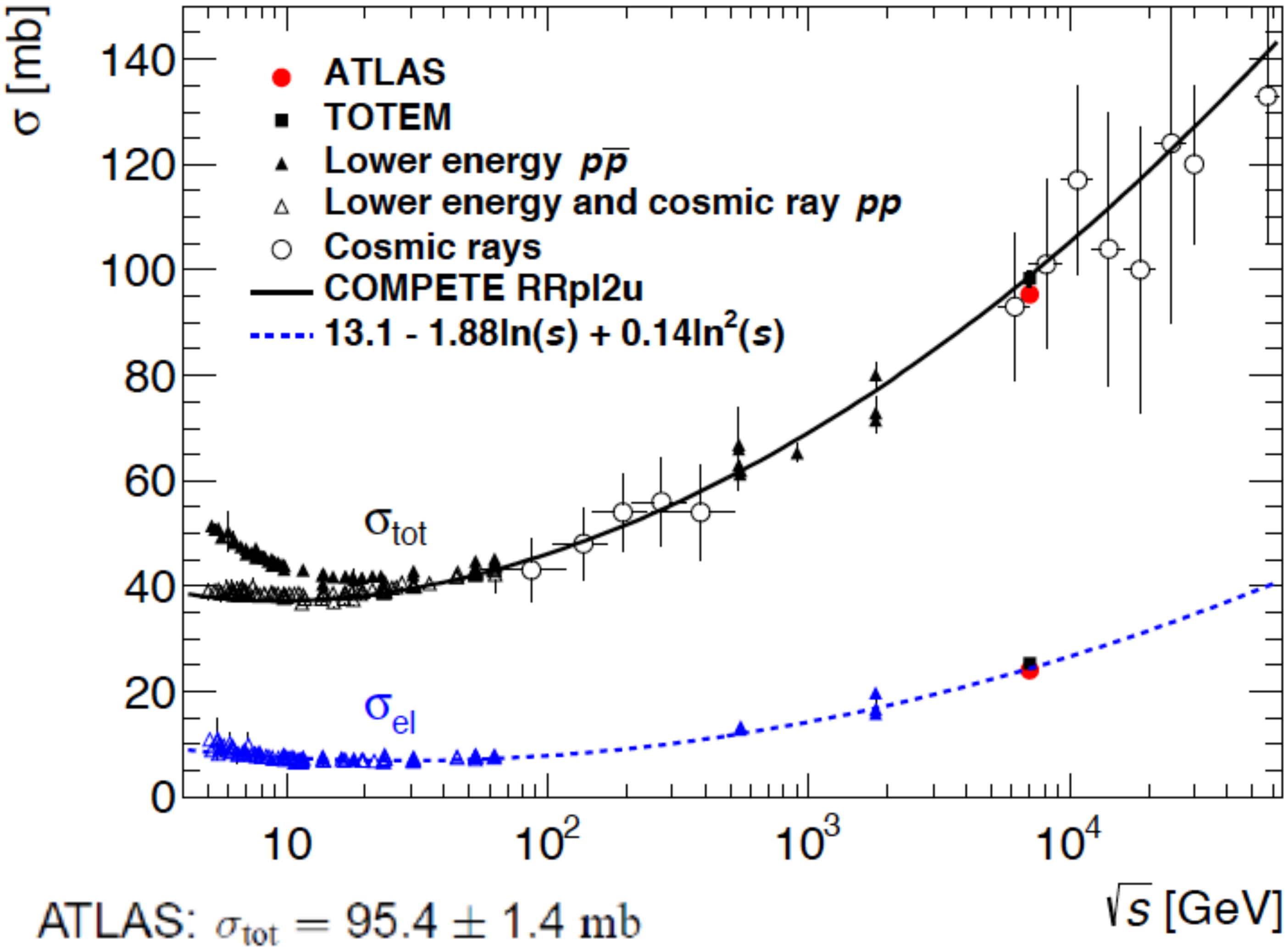
At fixed s: $$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

B=19.73±0.24 GeV^{-2} (ALFA)

$$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

[ρ~0.1 = phase of Coulomb-nuclear interference at t=0]

Total, Elastic and Inelastic Cross Sections



ATLAS: $\sigma_{\mathrm{tot}} = 95.4 \pm 1.4$ mb

Consistent with fits to previous data (with either a logarithmic or power law dependence).

[$\alpha_{IP}(0)$ ~ 1.08]

- σ_{tot} & σ_{el} indirectly determine total inelastic cross section σ_{inel}
- Direct σ_{inel} measurement tests self-consistency (expt & theory).

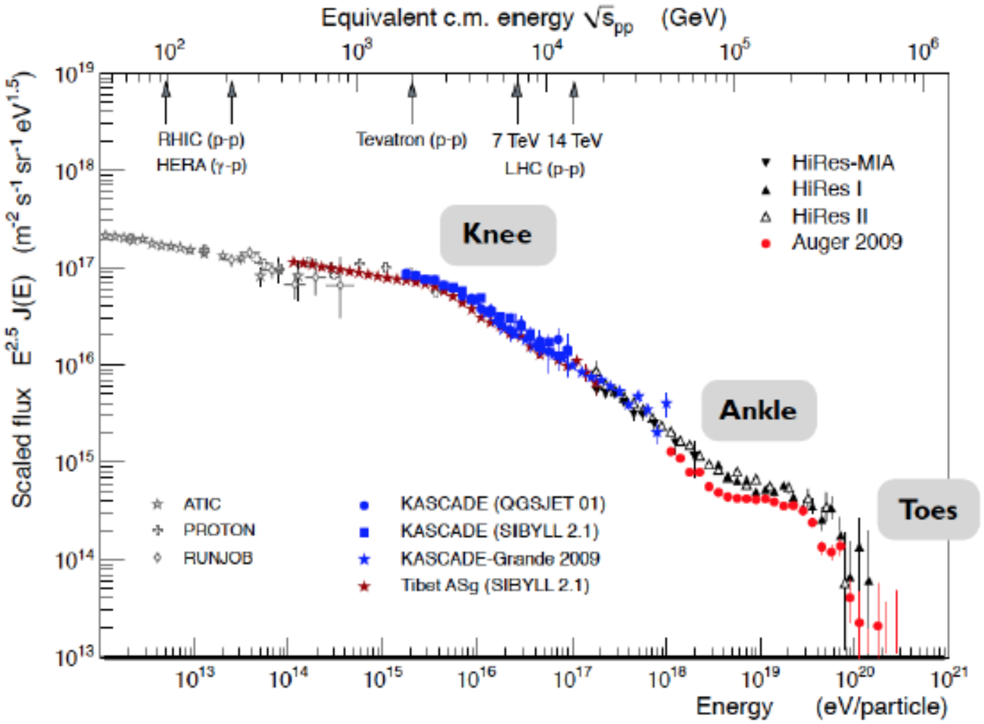
Total Inelastic Cross Section

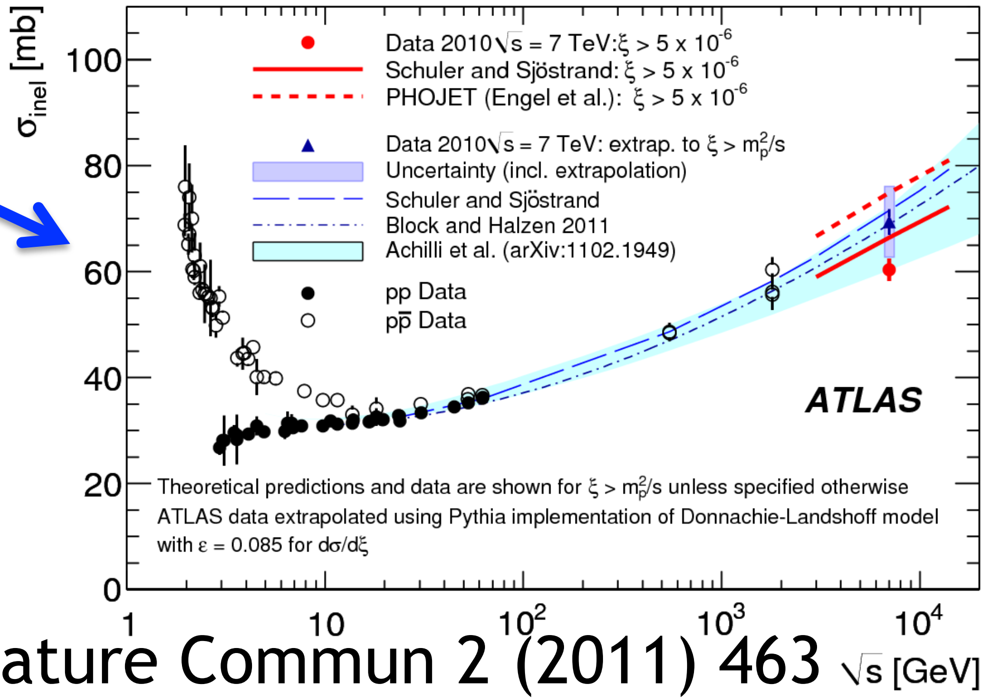
- Crucial quantity for understanding cosmic ray air showers

- Ingredient for modelling pile-up (and lumi) at LHC

Repeat and refine 7 TeV procedure using a short low pile-up run at 13 TeV taken in June 2015

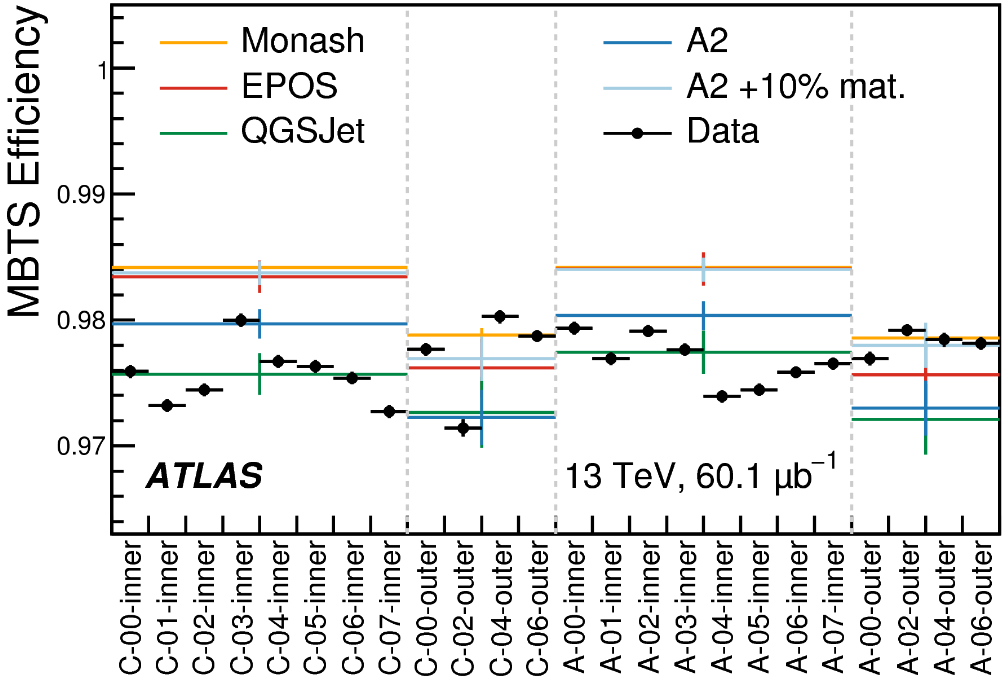
- MBTS sees 90-95% of all inelastic events → "simple" counting experiment.





Nature Commun 2 (2011) 463

Controlling MBTS Efficiency with Data

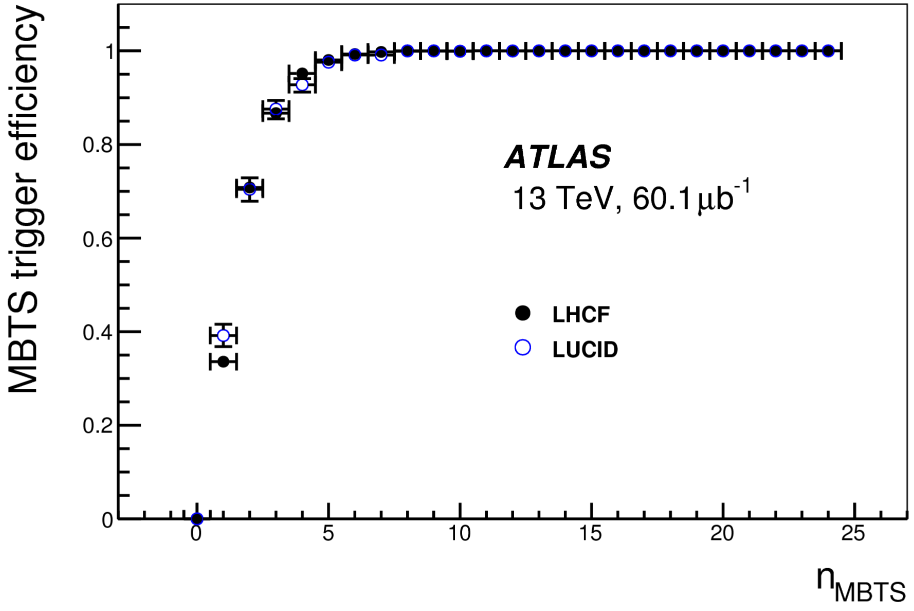


- Efficiencies for each MBTS counter measured relative to tracks in inner detector where possible and calorimeter clusters where not.
→MC efficiencies tuned accordingly

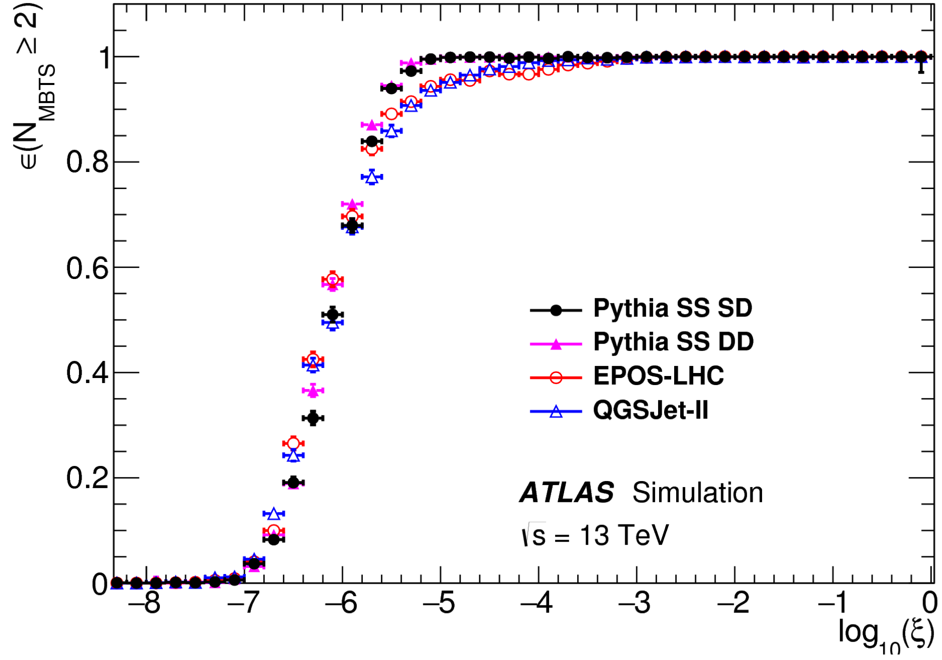
- Trigger efficiencies monitored relative to independent LUCID and LHCf triggers

- Efficiency / acceptance depends on MBTS segment multiplicity

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



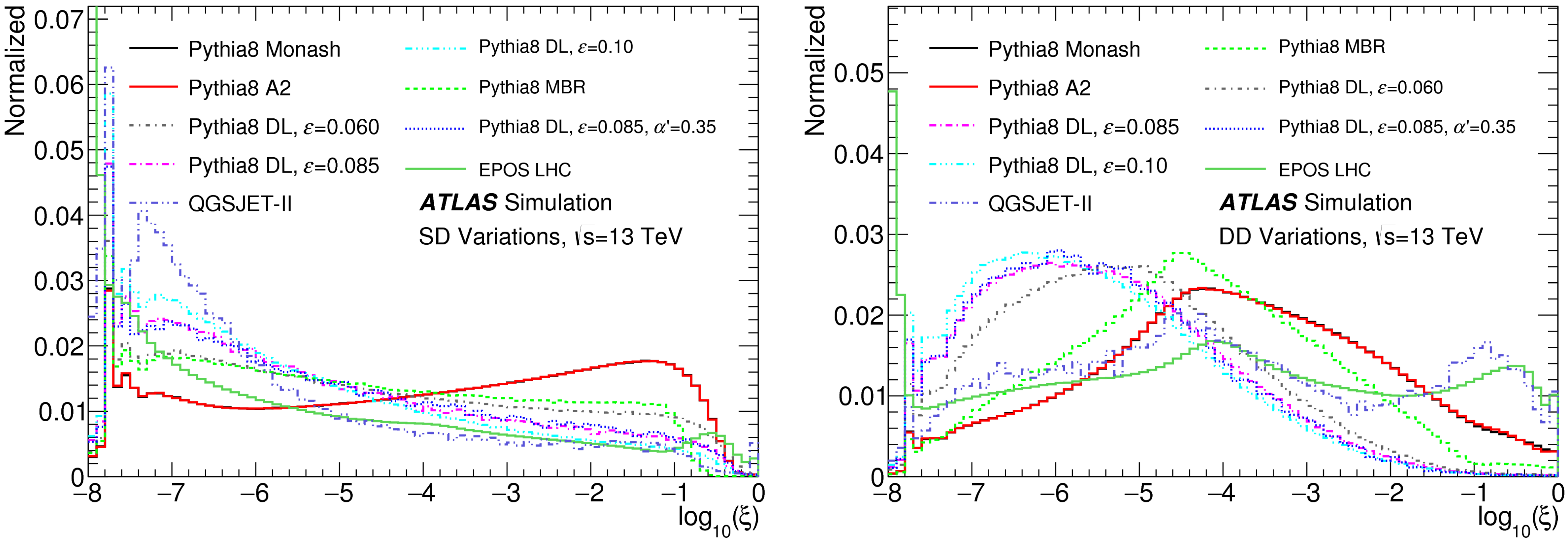
What we can't see: low mass diffraction



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

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

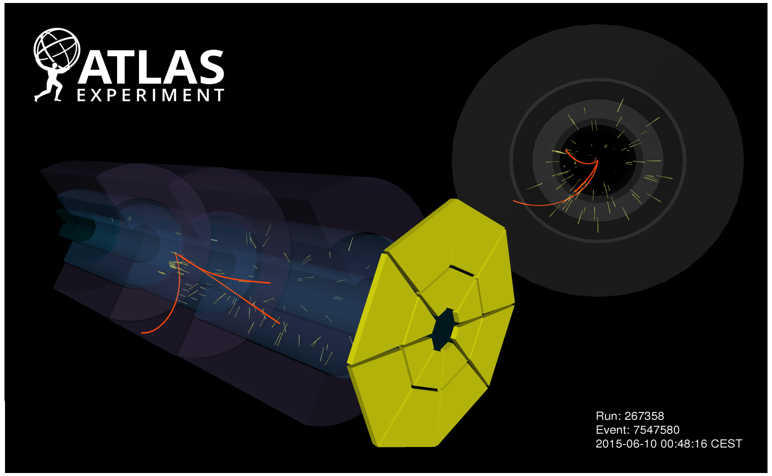
Cross section for $\xi < 10^{-6}$ poorly constrained

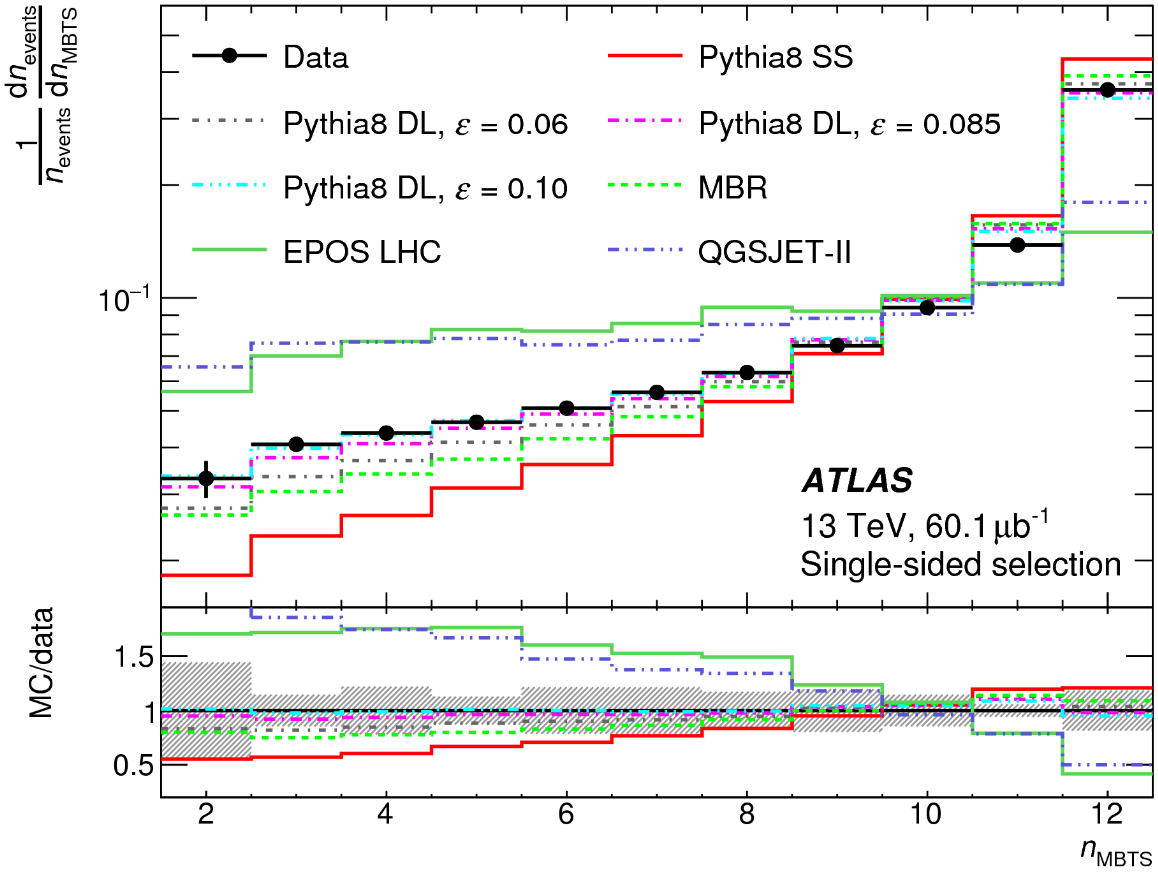


Benchmarking Diffractive MC models

“Single Sided” sample:

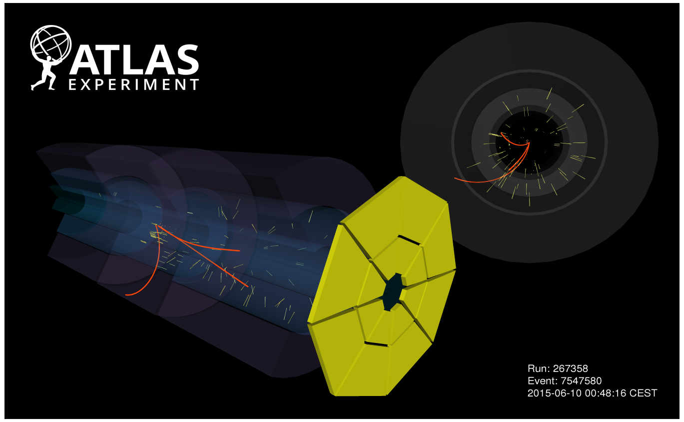
… activity on one side of MBTS, empty on other: enriched in SD events





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

Tuning Diffractive MC models



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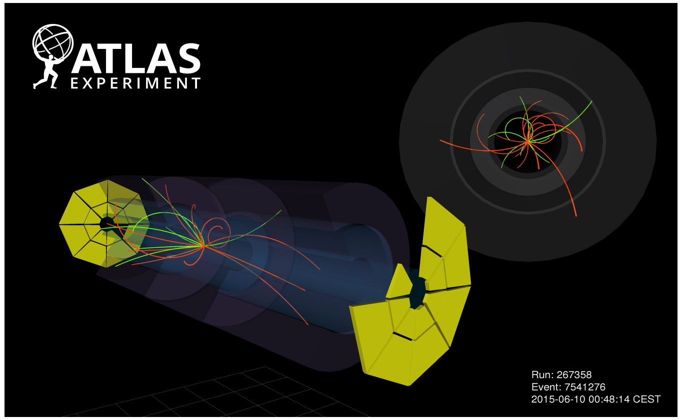
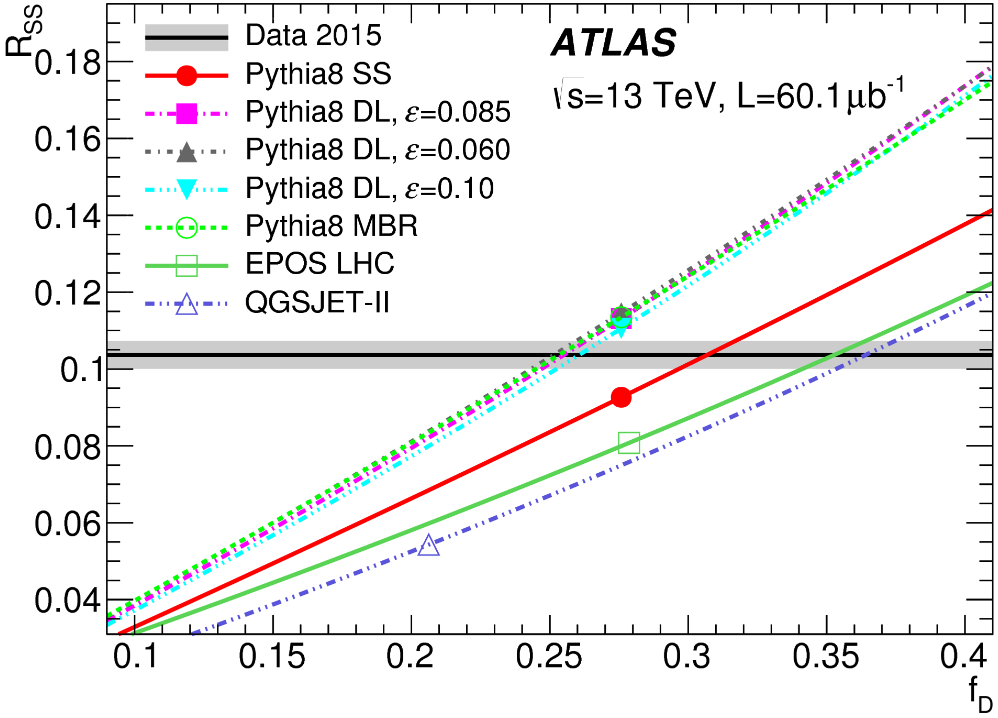


R_{SS} = Ratio of single sided to double sided MBTS samples … used to tune fractions of events considered diffractive in each MC model



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

Fiducial Cross Section Extraction

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

- 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

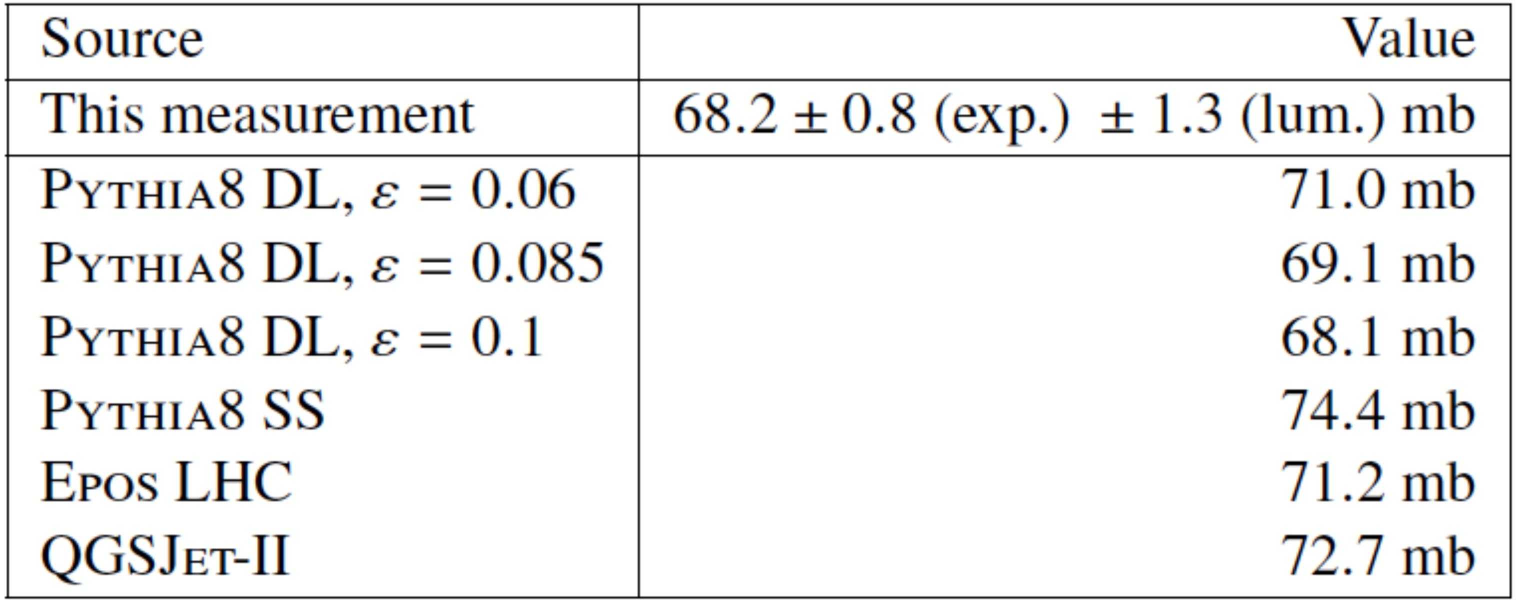
- Luminosity from final calibration of Van der Meer scan

  → 1.9% error … cf was 9% in preliminary result ☺

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%

Cross Section in Fiducial Range

For $\xi > 10^{-6}$ ...



Source	Value
This measurement	68.2 ± 0.8 (exp.) ± 1.3 (lum.) mb
Pythia8 DL, $\varepsilon = 0.06$	71.0 mb
Pythia8 DL, $\varepsilon = 0.085$	69.1 mb
Pythia8 DL, $\varepsilon = 0.1$	68.1 mb
Pythia8 SS	74.4 mb
Epos LHC	71.2 mb
QGSJet-II	72.7 mb

Due to final lumi calibration, cross section increased by 3mb relative to preliminary result and lumi uncertainty decreased from 5.9mb to 1.3mb

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

- 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:

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

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

from ALFA result

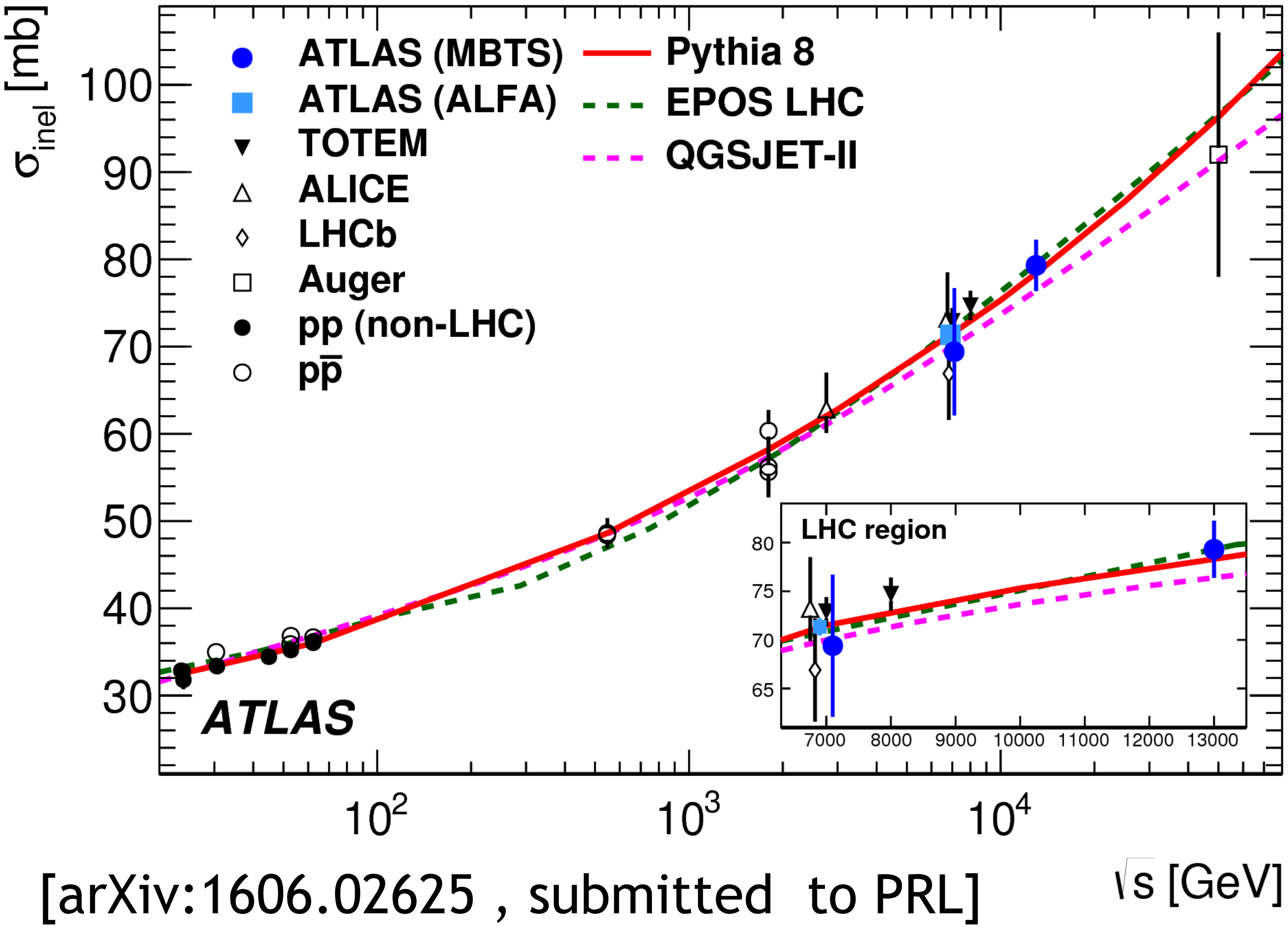
previous fiducial MBTS result

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

… extrapolation uncertainty reduced from 3.8 mb in prelim result to 2.5 mb in final

Extrapolation to Full Inelastic Cross Sec

$$\sigma_{\text{inel}} = 79.3 \pm 0.8\ (\text{exp.})\ \pm 1.3\ (\text{lum.})\ \pm 2.5\ (\text{extrap.})\ \text{mb}.$$

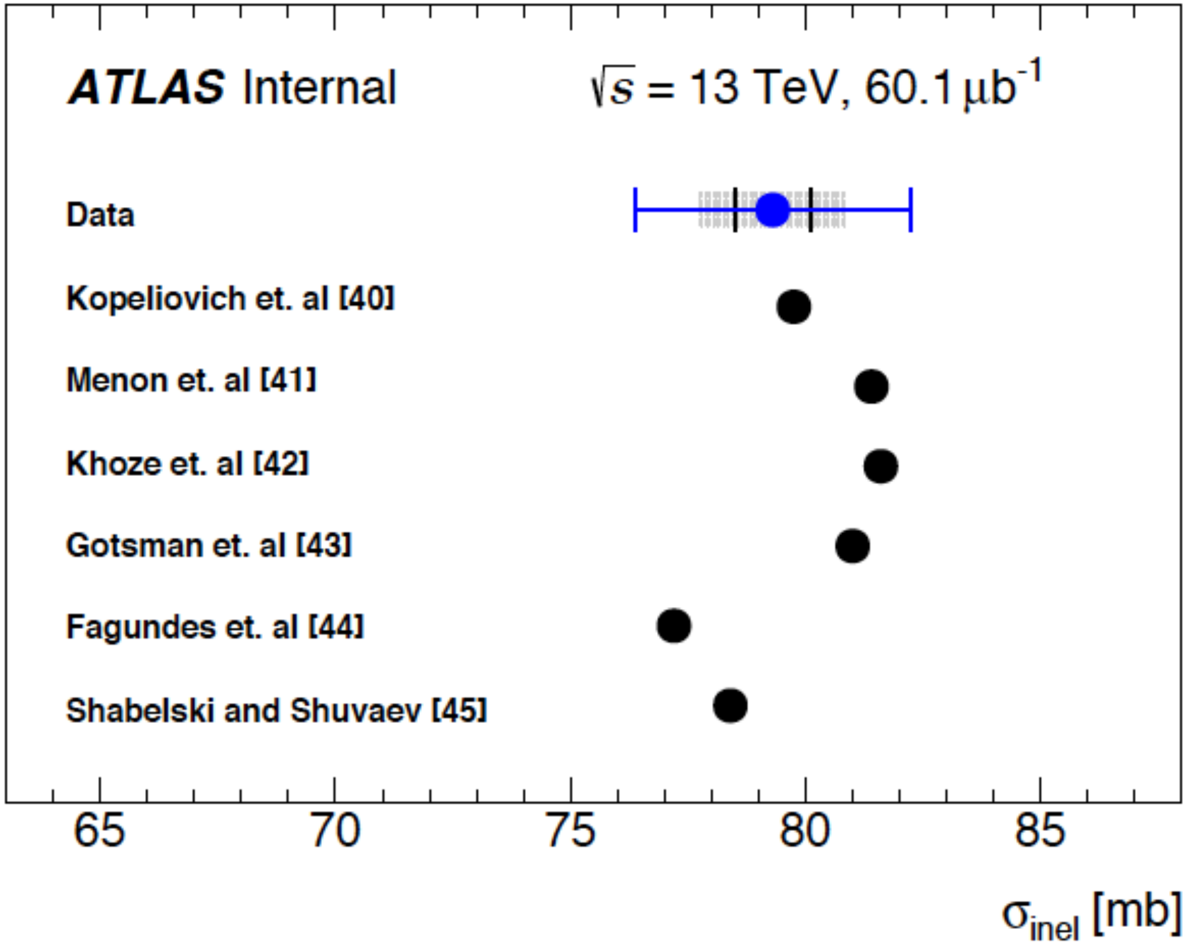


First LHC total cross-xec result at 13 TeV

Increase by 11±4% compared with 7 TeV ALFA point

[arXiv:1606.02625 , submitted to PRL]

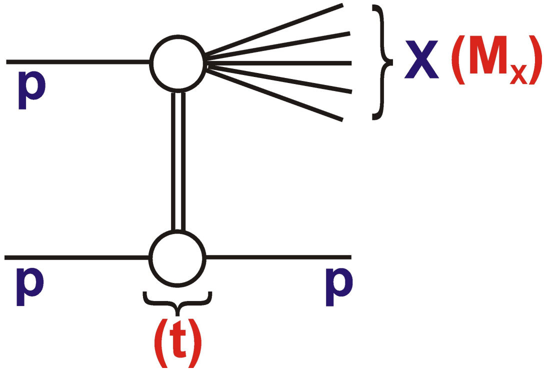
Total Inelastic Cross Section v Models



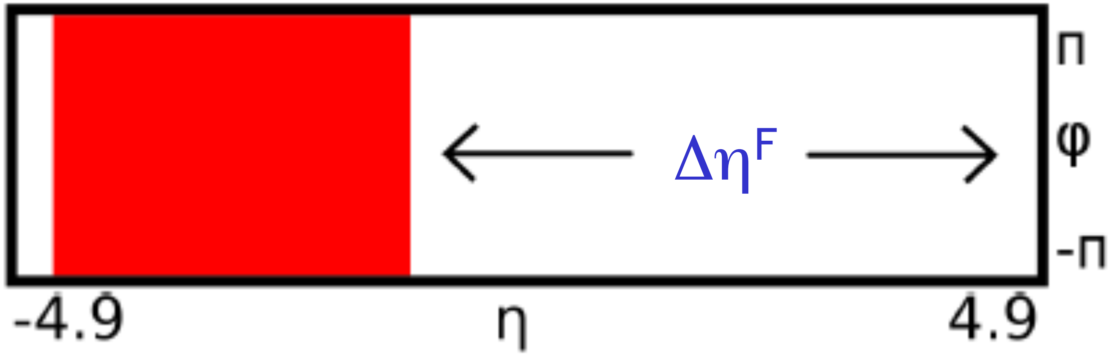
Within current uncertainties, result is consistent with indicative selection of models based on Regge phenomenology, eikonal approaches and other models of non-perturbative strong interactions

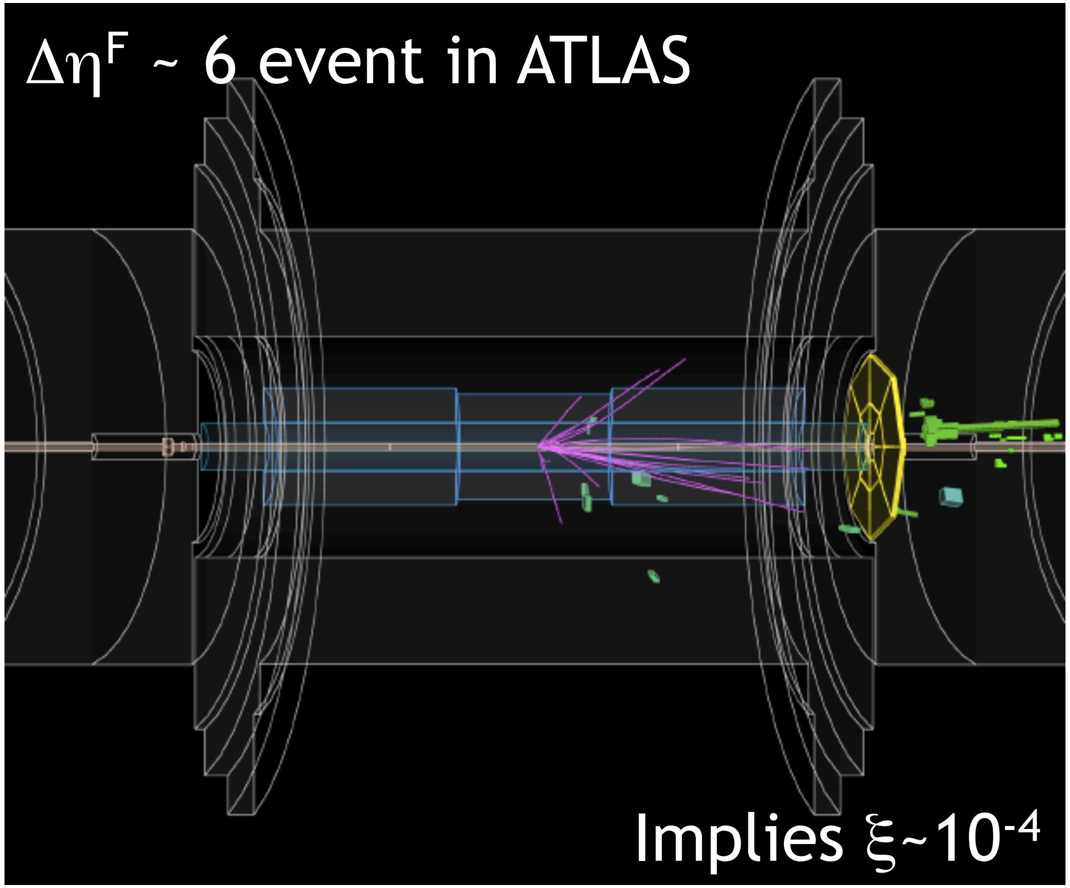
Rapidity gap cross-sections

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 η >~4.9
… large $\Delta\eta^F$ sensitive to
SD + low M_Y DD

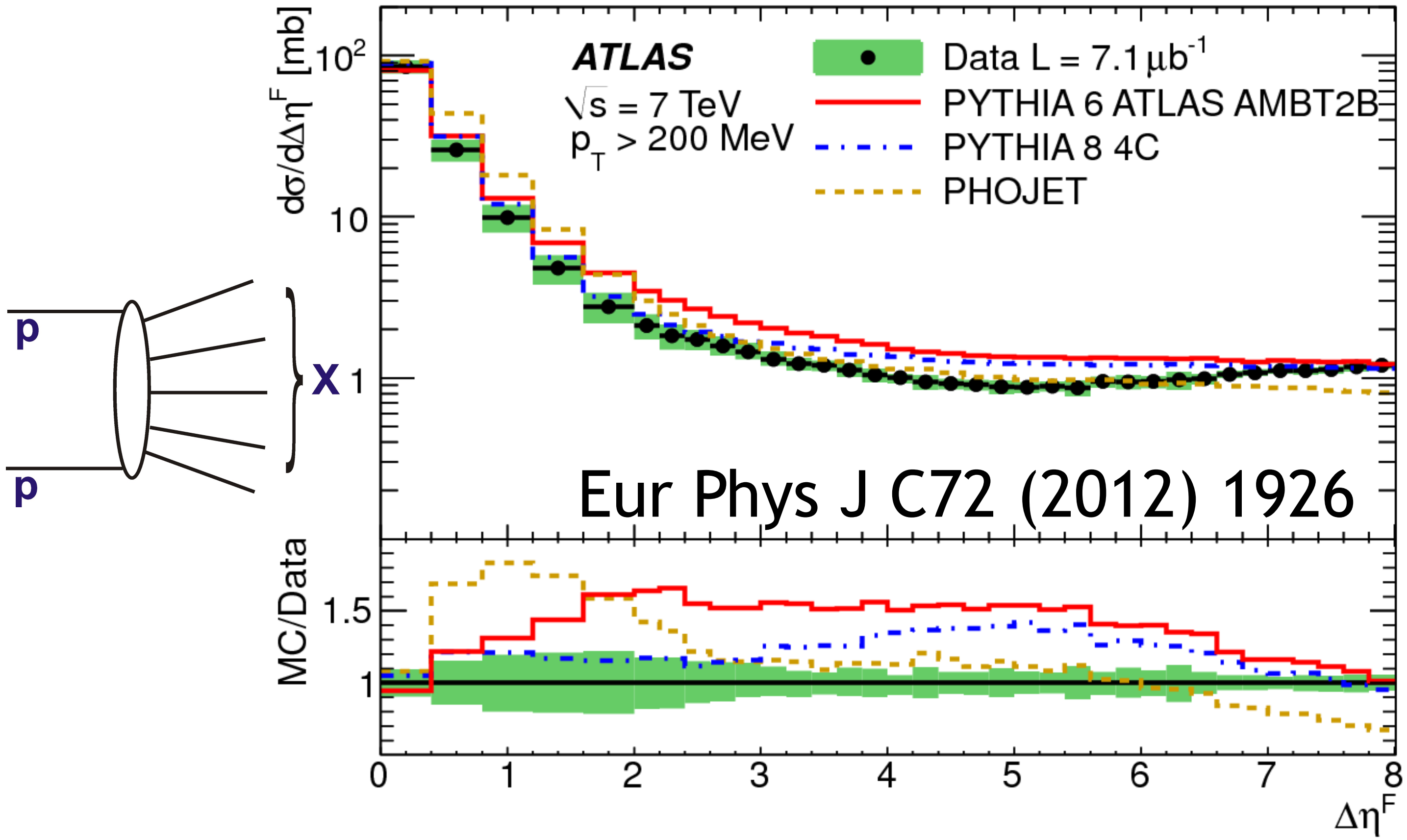




$\Delta\eta^F$ ~ 6 event in ATLAS

Implies ξ~10^{-4}

Inclusive Differential Gap Cross Section



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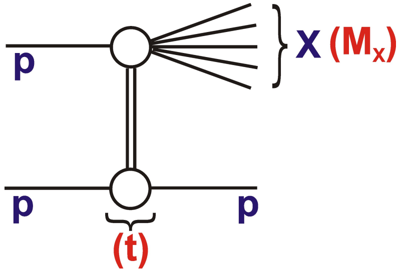
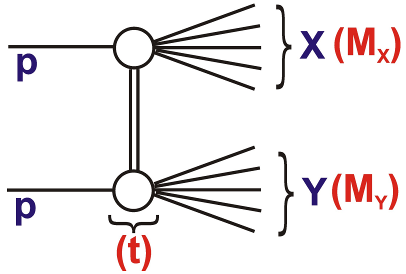
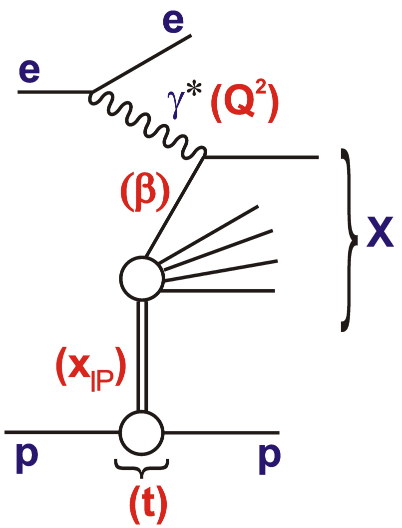




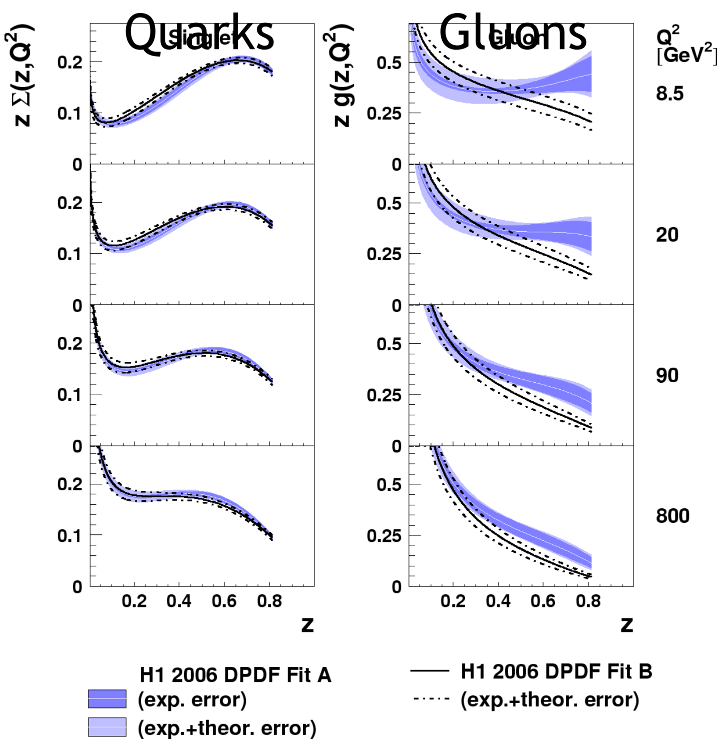
- Large Δη^F: Diffractive plateau with ~1mb per unit gap size, consistent with soft pomeron ($\alpha_{IP}(0)$ = 1.058 ± 0.036)
- Small Δη^F: sensitive to hadronisation fluctuations / MPI in ND

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

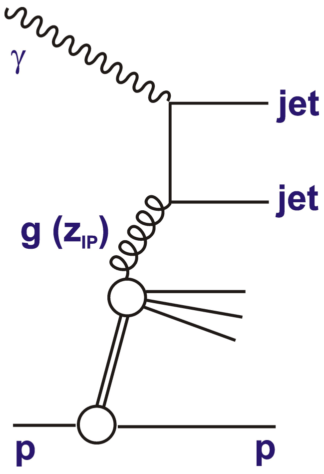
Hard Diffraction: Structure of Vacuum Exchange

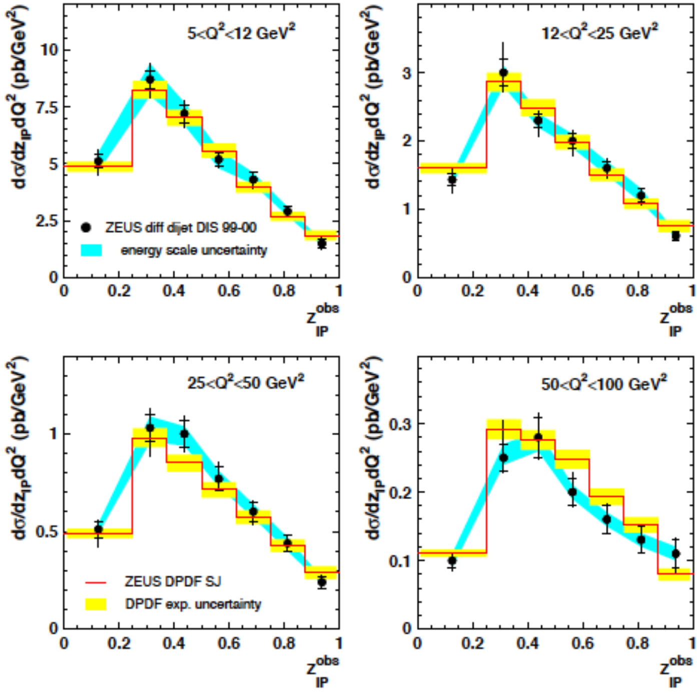


Diffractive DIS at HERA → Diffractive parton densities (DPDFs) dominated by gluon, which extends to large momentum fractions



… NLO predictions based on HERA DPDFs give impressive description of all HERA 'hard' diffractive data, eg jet production …

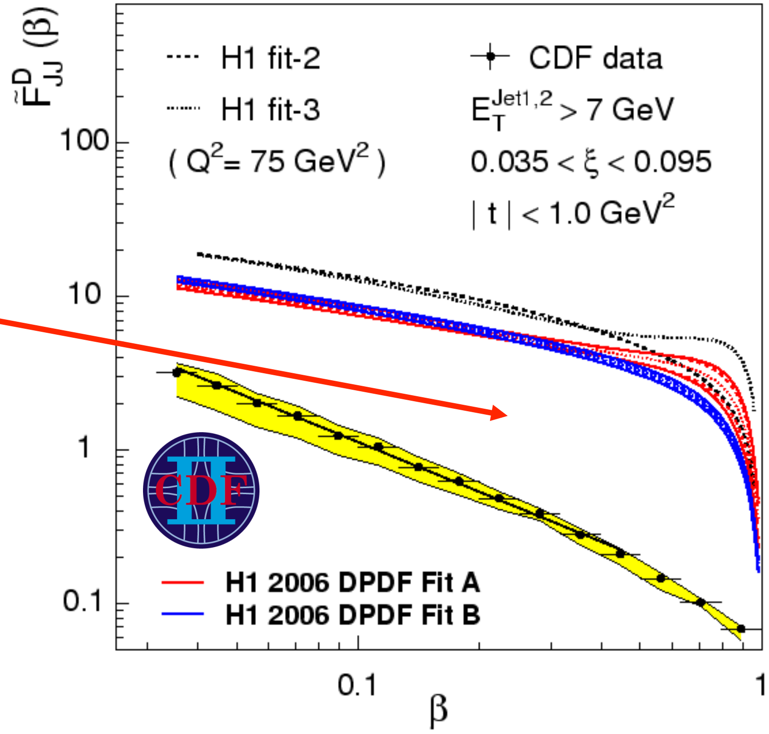




→ DPDFs used in many models in pp(bar)

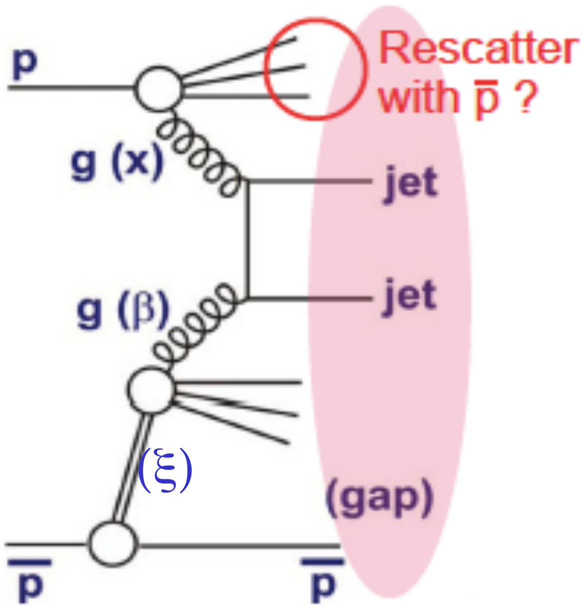
… but in pp(bar)

Spectacular failure in comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs [PRL 84 (2000) 5043]



CMS data suggest similar effect [Phys Rev D87 (2013) 012006]

… rescattering (absorptive corrections / related to MPI …) breaks factorisation … `rapidity gap survival probability' ~ 0.1

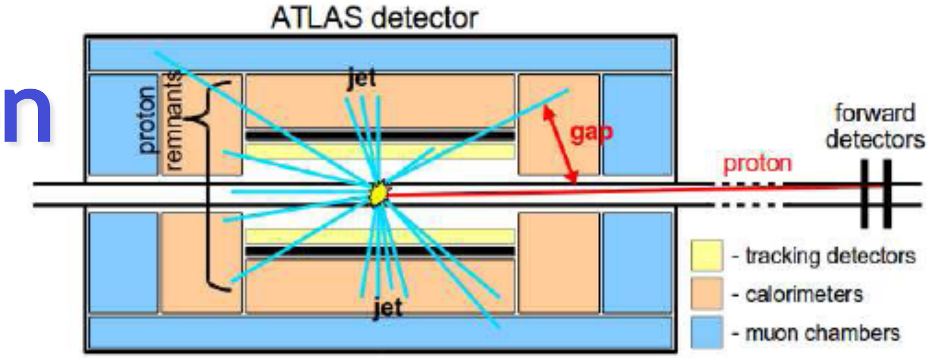


LHC hard diffraction sensitive to both DPDFs and gap survival probability →

Here: First results from ATLAS:

… dijets with large rapidity gaps …

Kinematics & Selection



- Low pile-up data sample from 2010 with $\sqrt{s} = 7$ TeV and integrated luminosity of 6.8 nb^{-1}.

- Triggered using either MBTS or calorimeter jet triggers

- Jets with anti-k_T algorithm, $p_T > 20$ GeV, $|\eta| < 4.4$, R=0.4, 0.6

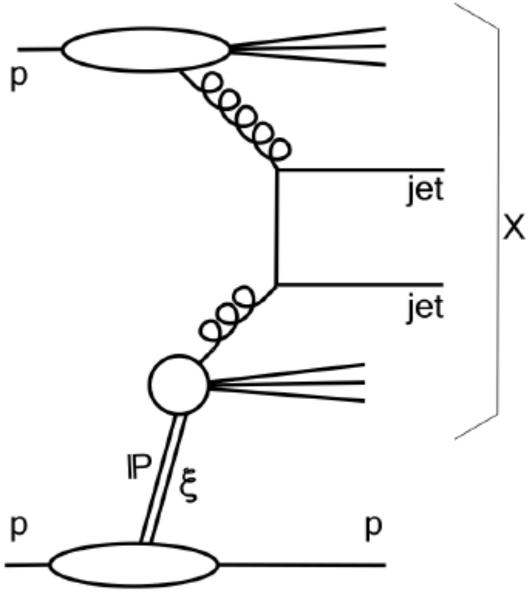
- Gaps characterised using $\Delta\eta^F$, based on tracks ($|\eta| < 2.5$) and calo cells ($|\eta| < 4.8$) that are $>5\sigma$ out of noise distribution.

- Corrected cross sections correspond to gaps with no neutral particle with $p > 200$ MeV and no charged particle with $p > 500$ MeV or $p_T > 200$ MeV.

- Uncertainty dominated by jet energy scale

Models

- POMWIG: Dedicated hard diffraction model with standard factorisable pomeron approach:
Cross section ingredients are proton PDFs, pomeron Flux and DPDFs



- PYTHIA8: Inclusive model with hard and soft ND, DD and SD contributions; smoothly interfaced.

- Both models use HERA DPDFs (H12006-FitB)

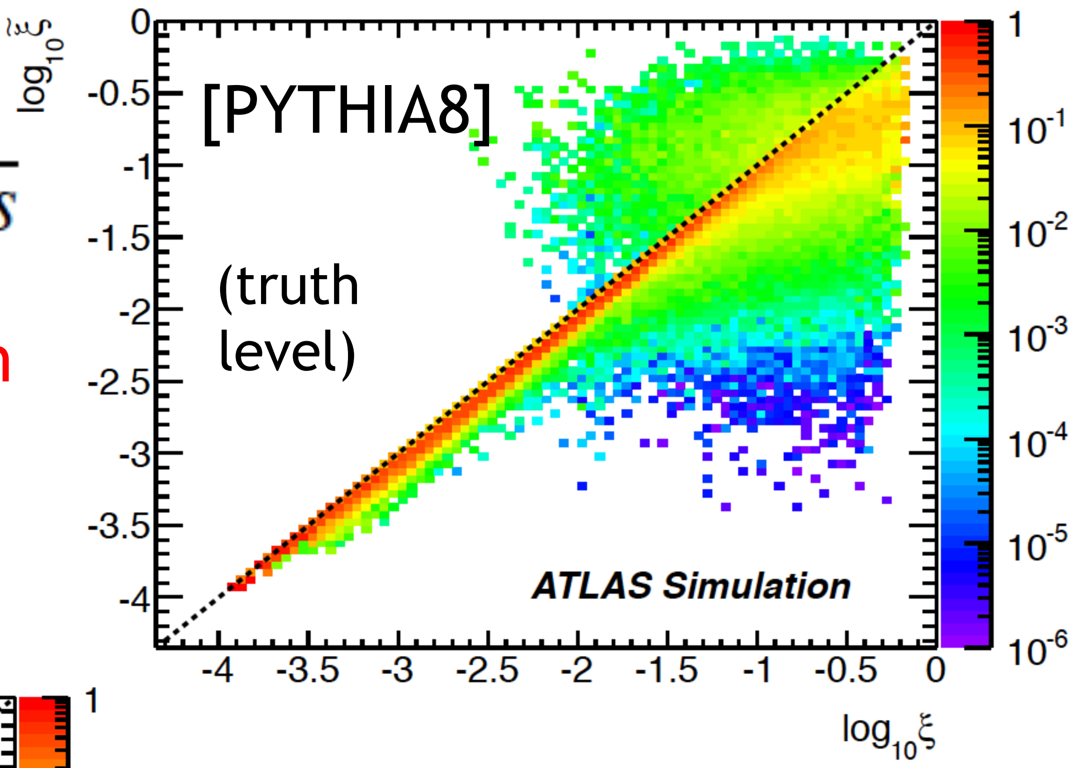
- Neither model includes rapidity gap destruction effects

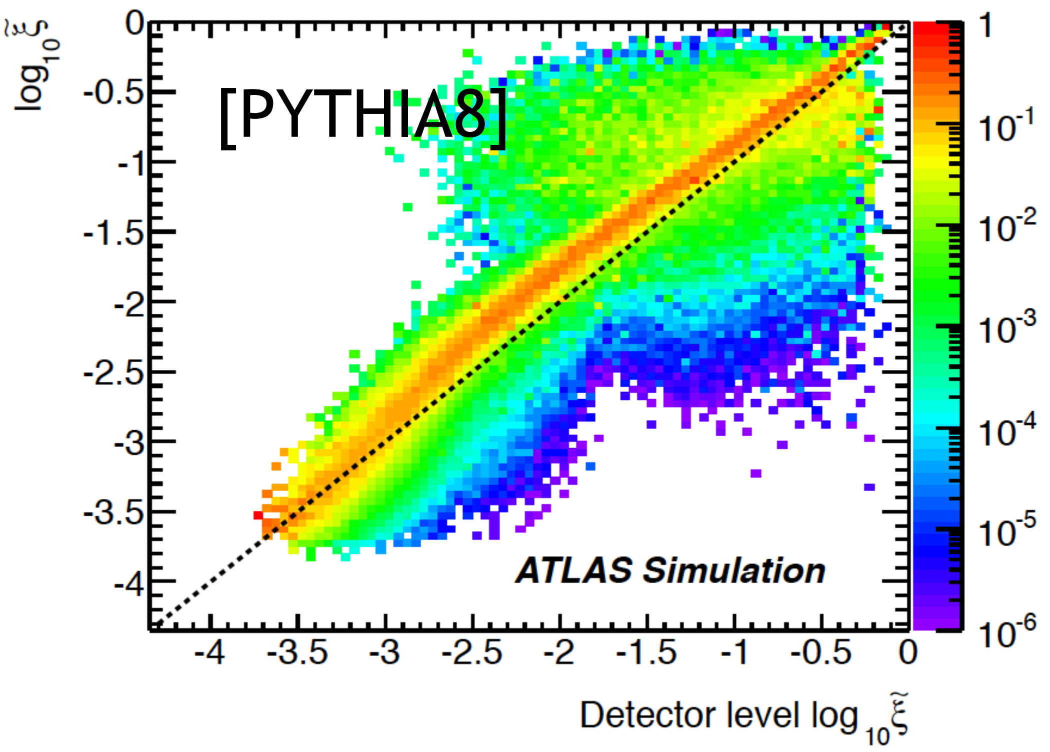
- Alternative ND model from POWHEG-NLO interfaced to PYTHIA

Constraining ξ

$$\tilde{\xi} \simeq M_X^2/s = \sum p_T e^{\pm\eta}/\sqrt{s}$$

… approximation to ξ which is relatively insensitive to losses of parts of X system into the beam-pipe

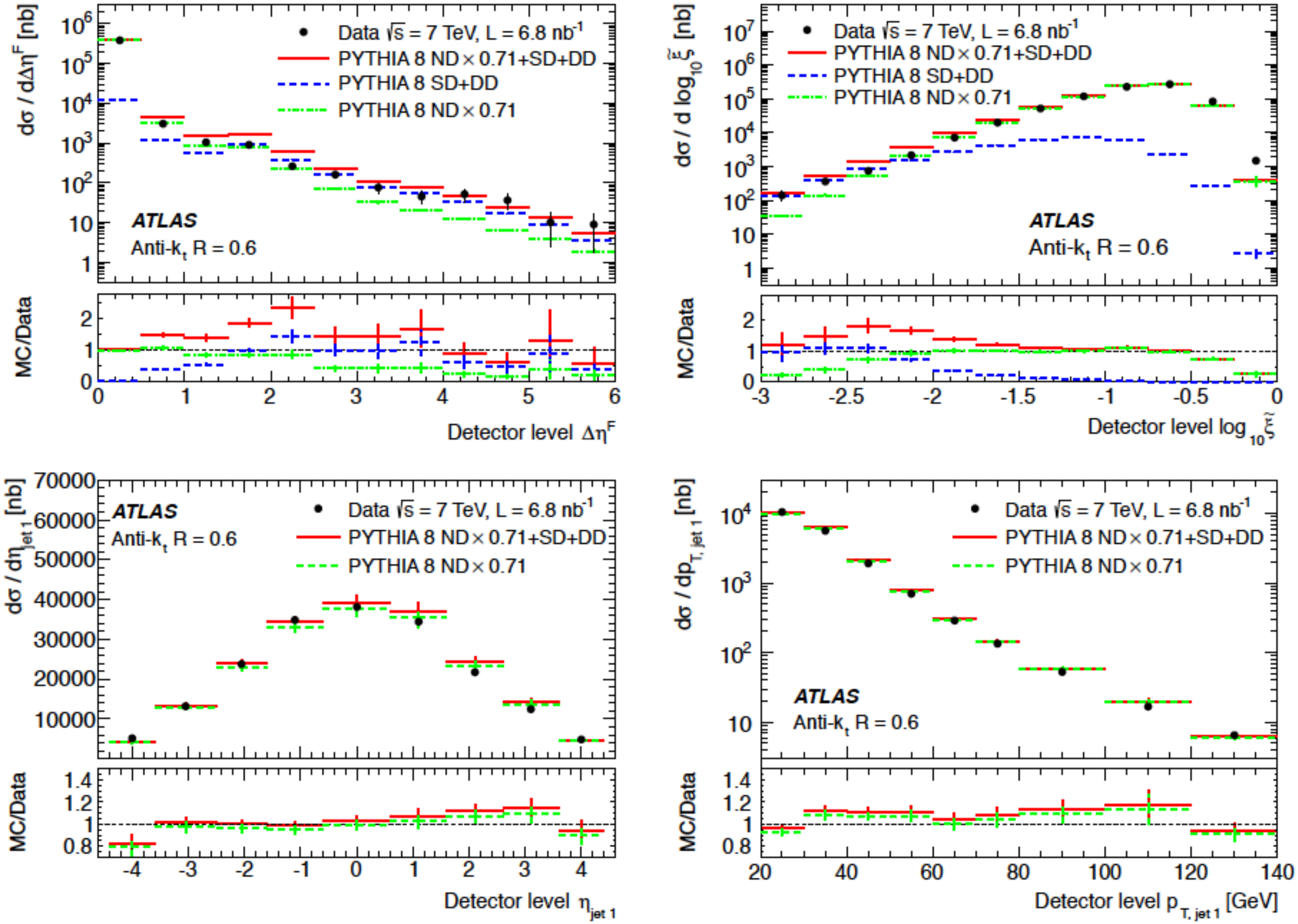




$\tilde{\xi}$ close to true ξ at truth level up to ~10^{-2} (slightly smaller, as only include particles in fiducial region).

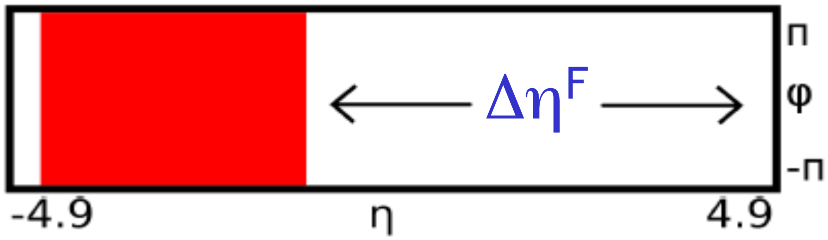
Experimental resolution on log $\tilde{\xi}$ approximately 10%.

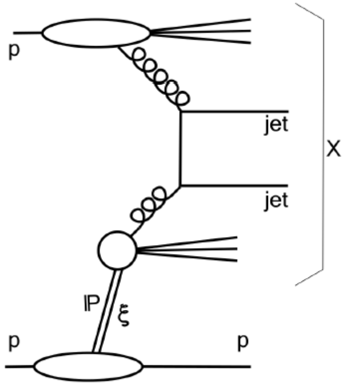
Unorrected Data (Control Distributions)



PYTHIA8 MC: ND scaled x 0.71 to match first bin of $\Delta\eta^F$, added to SD and DD 'out of the box' → Satisfactory descriptions of all relevant distributions; used for unfolding.

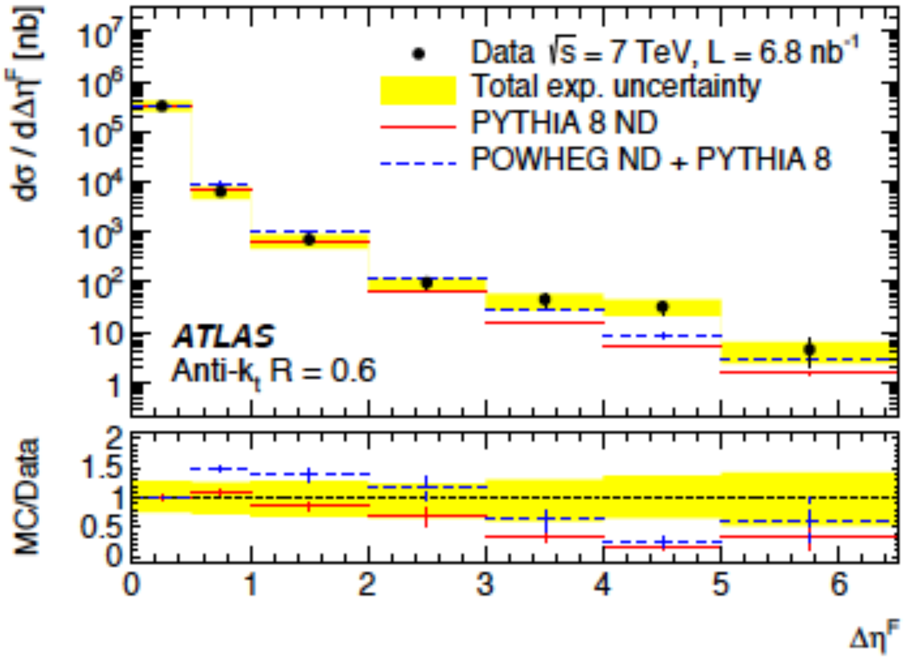
Corrected Data Compared with Non-Diffractive Models

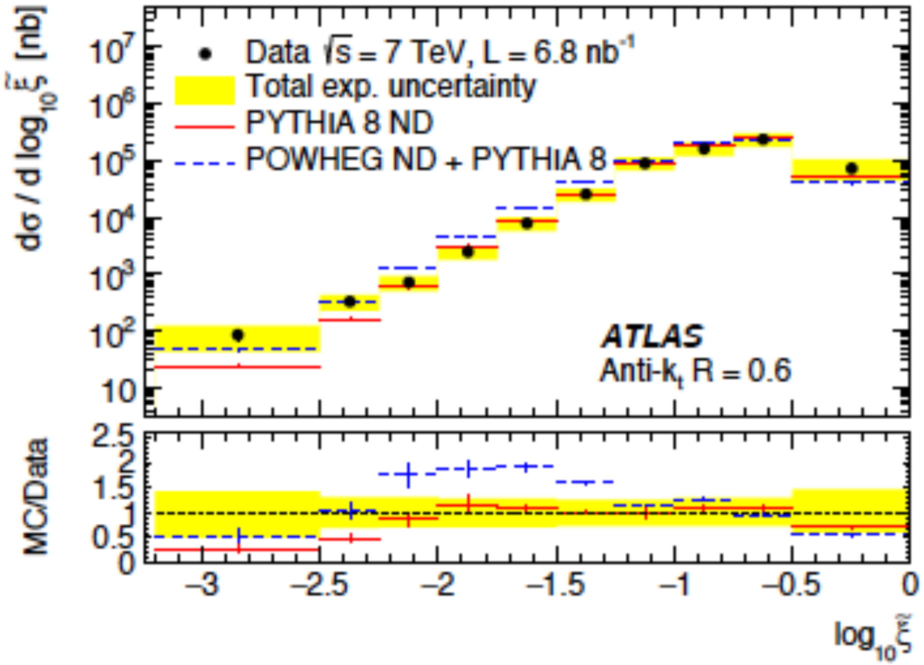




- Kinematic suppression of large gaps → no clear diffractive plateau (unlike minimum bias case)

- 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 …





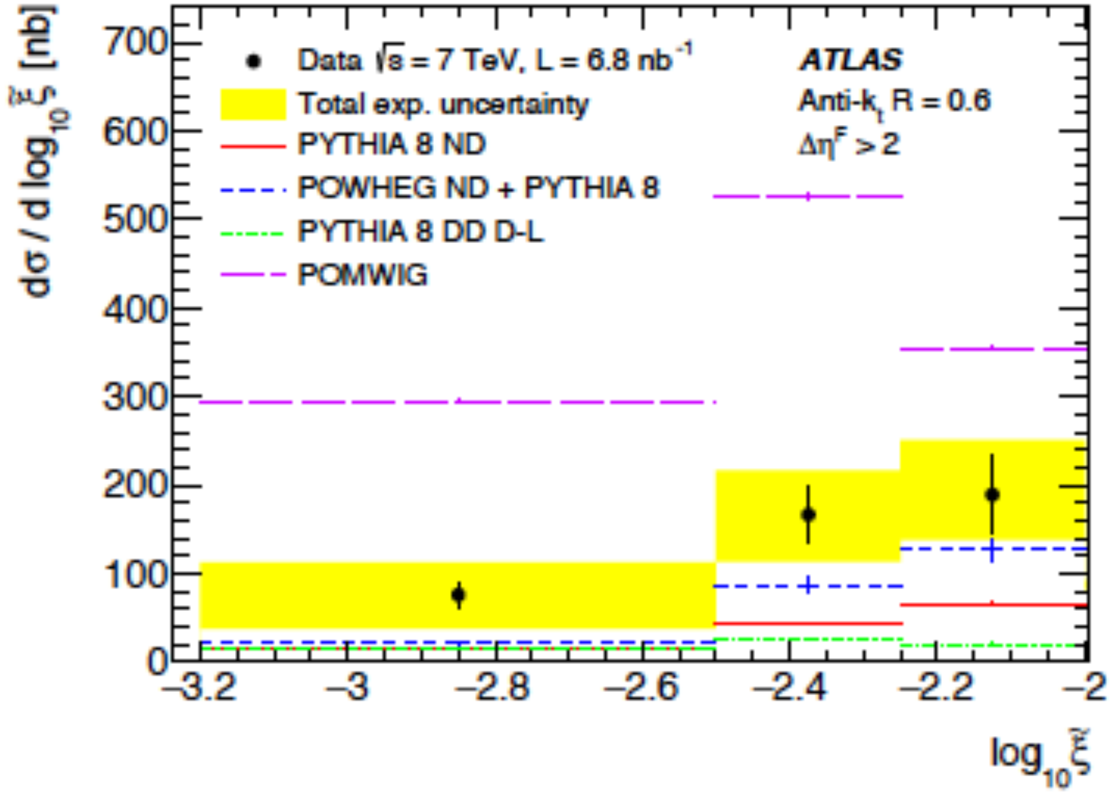
Evidence for Diffractive Contribution

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

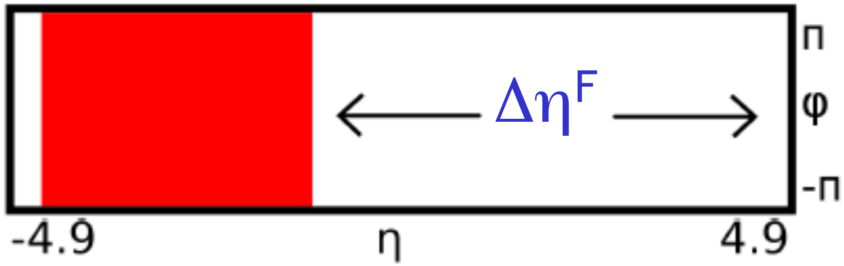
→ Comparison of smallest ξ with DPDF-based model (POMWIG) leads to rapidity gap survival probability estimate …

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

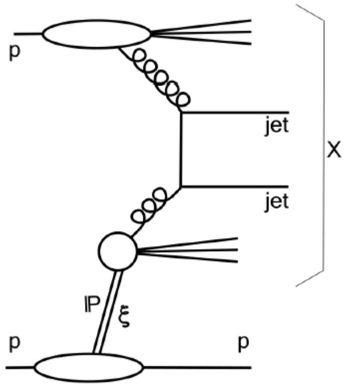


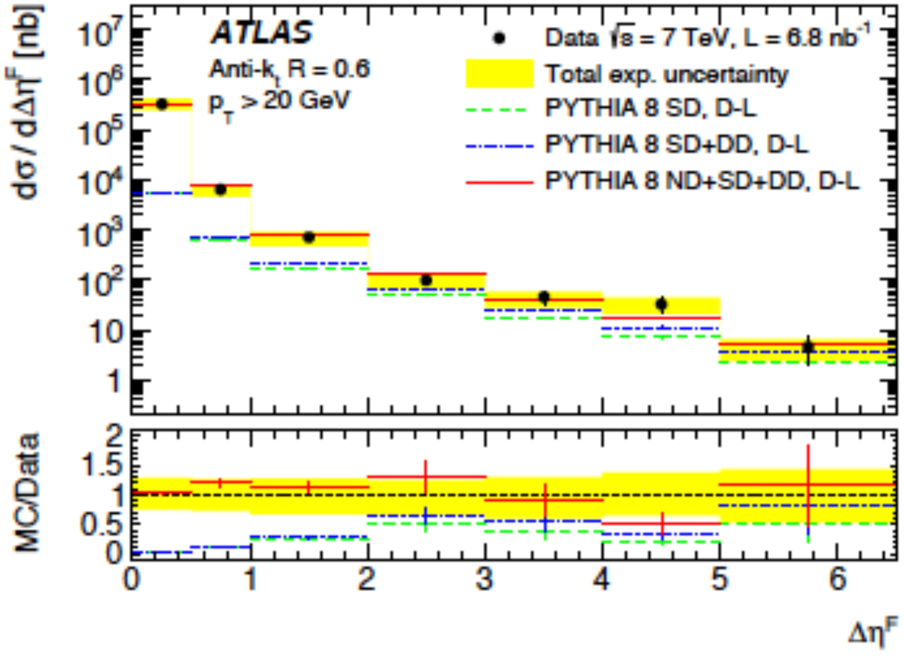
$$S^2 = 0.16 \pm 0.04\ (\text{stat.}) \pm 0.08\ (\text{exp. syst.})\ ,$$

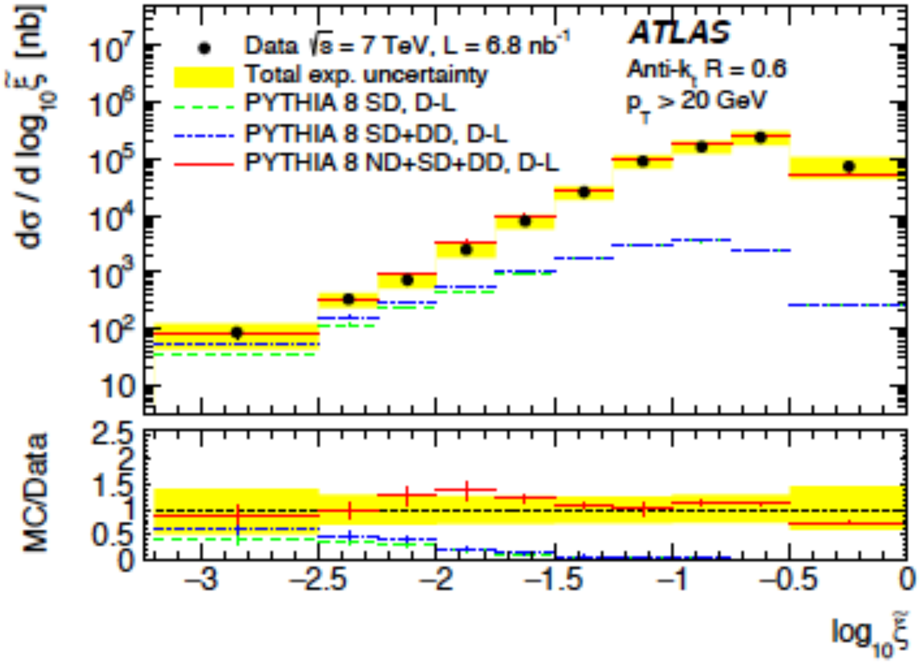
Comparison with Full PYTHIA8



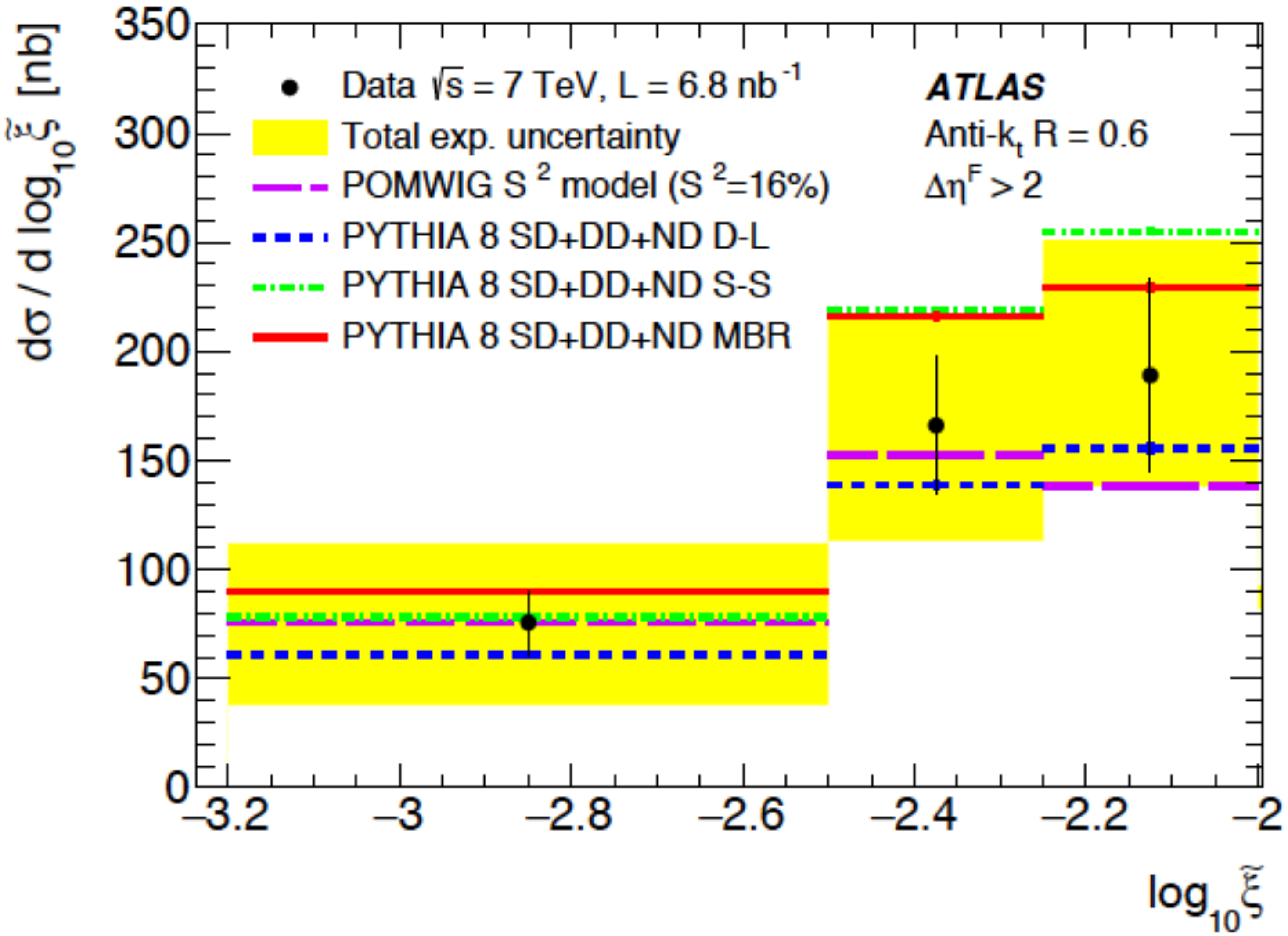
‘Off-the shelf’ PYTHIA8 ND*0.71 + SD + DD does a good job at all $\Delta\eta_F$ and ξ, with no need for a gap survival factor (though ND dominates, so compatible with a wide range of S^2 values).







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



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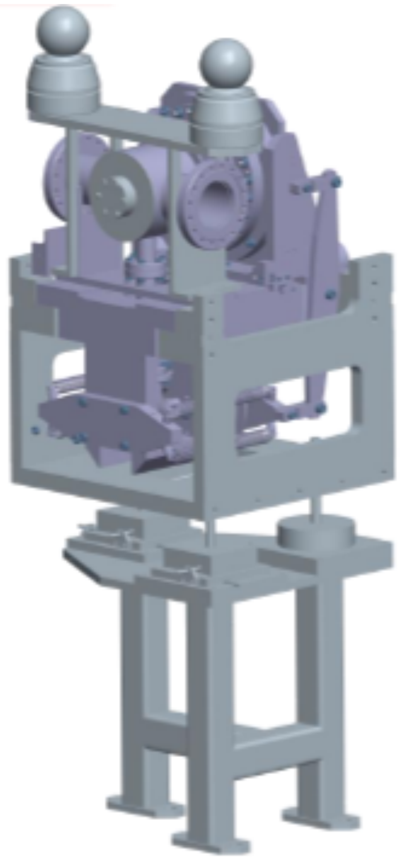
Future ATLAS Diffraction

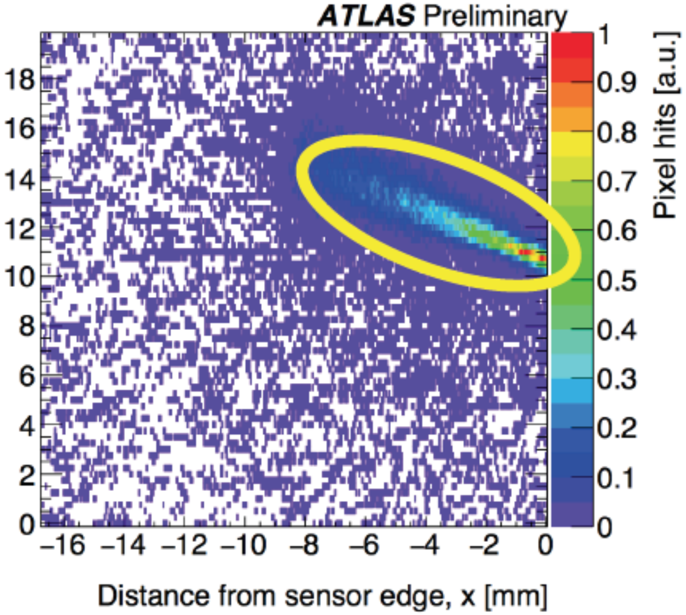
- Further progress will require proton tagging to unfold ND and DD from SD

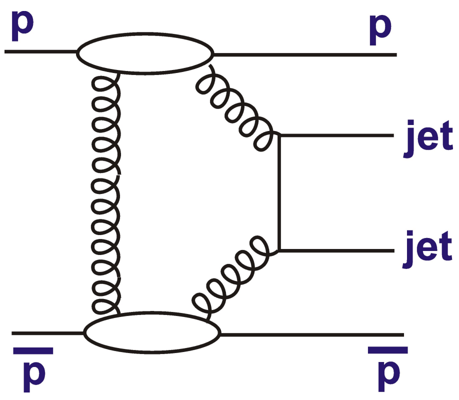
- Short term: ongoing ALFA analysis

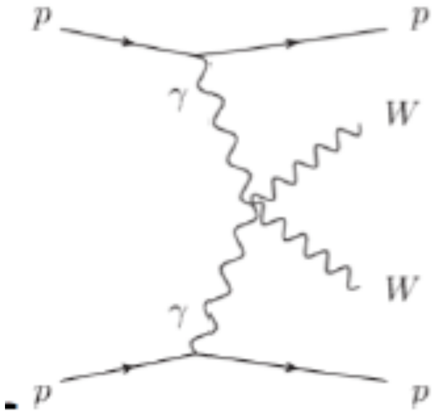
- Medium term = AFP, first arm commissioning underway → SD physics in 2016/17

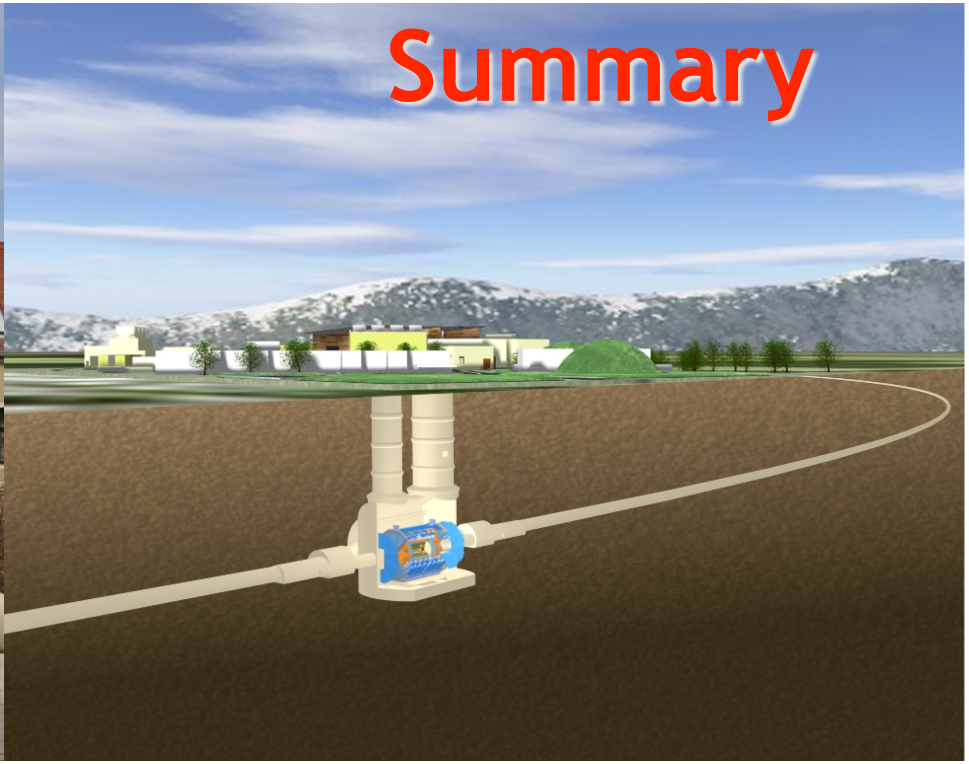
- Longer term: AFP with two arms & high lumi → ra exclusive (or exotic) processes …











Summary

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

- Significant improvement in precision (9% → 2%) over prelim.
- Some discrimination between models
- Consistent with indirect extractions using optical theorem

Dijet Cross Sections Differential in Gap Size at $\sqrt{s}$ = 7 TeV

- Evidence for diffractive contribution
- Understanding limited by poorly known non-diff contribution
- Future prospects with proton spectrometers (ALFA, AFP)