Exclusive, diffractive and beyond DGLAP jets at ATLAS

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Introduction

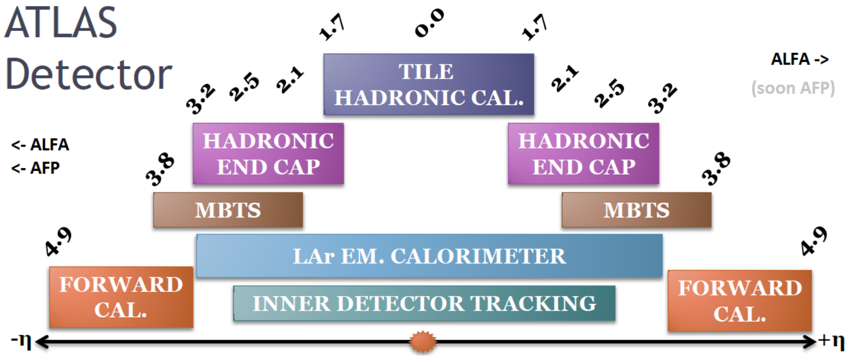
- Looking at analyses sensitive to higher order perturbative corrections & reabsorptive corrections.
- Will cover two published ATLAS analyses

Azimuthal decorrelation with di-jets.

Diffractive production of di-jets

- Plus one prospective study of exclusive jets using the new ATLAS Forward Physics proton tagging capability.

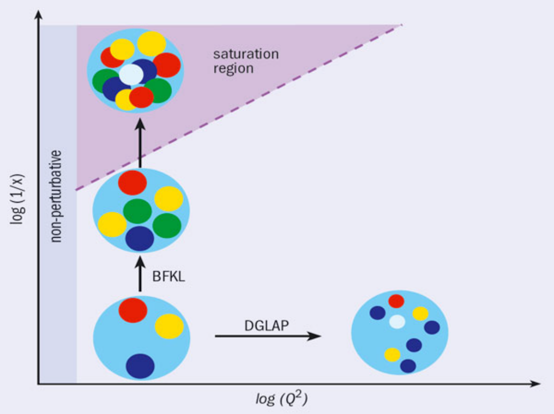
ATLAS



ATLAS
Detector
1.7
0.0
1.7
3.2
2.5
2.1
TILE
HADRONIC CAL.
2.1
2.5
3.2
ALFA ->
(soon AFP)
<- ALFA
<- AFP
3.8
HADRONIC
END CAP
HADRONIC
END CAP
3.8
MBTS
MBTS
4.9
LAr EM. CALORIMETER
4.9
FORWARD
CAL.
INNER DETECTOR TRACKING
FORWARD
CAL.
-η
+η

Parton Evolutions

Seek out regions where higher order terms become import and and require resummation. Typically in $\ln(1/x)$ (BFKL) or virtuality $\ln(Q^2)$ (DGLAP)



Azimuthal Decorrelation

& Jet Vetoes in 7 TeV Di-Jets

[Eur. Phys. J. C (2014) 74:3117][arXiv:1407.5756 [hep-ex]]

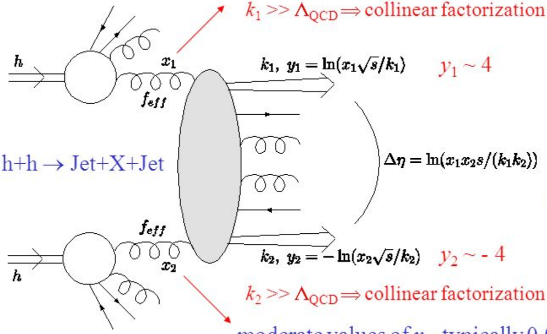
See also [Phys. Rev. Lett. 106 (2011) 172002] & [JHEP 1109 (2011) 053]

The observable: Mueller-Navelet jets

Mueller and Navelet (1994)

moderate values of x_1, typically 0.05

$k_1 >> \Lambda_{QCD} \Rightarrow$ collinear factorization of f_{eff}



$g + \frac{C_F}{N_C}(q+\bar{q})$

large rapidity interval $\Delta\eta \sim 8$

$k_2 >> \Lambda_{QCD} \Rightarrow$ collinear factorization of f_{eff}

moderate values of x_2, typically 0.05

pQCD: need ressumation of powers of $\alpha_S \Delta\eta \sim 1$ in the partonic cross-section $gg \rightarrow JXJ$

Dijet Gap Veto & ϕ Decorrelation

- Regions where fixed order pQCD fall short & re-summation of higher orders are needed.
  - Large rapidity separation (correction $\propto \Delta y$) $\rightarrow$ sensitive to BFKL evolution.
  - Jet-veto (correction $\propto \ln(\bar{p_T})$): wide-angle soft radiation

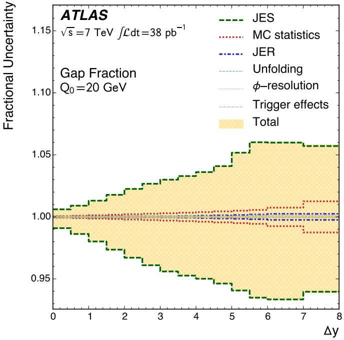
Define gap fraction $f(Q_0) = \sigma_{jj}(Q_0)/\sigma_{jj}$, $\sigma_{jj}(Q_0)$ the cross section for dijets with **no** additional jets $p_T > Q_0$ in the jj rapidity interval.

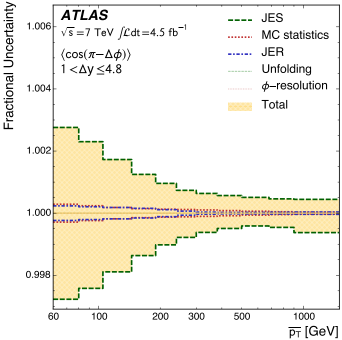
Azimuthal decorrelation: *i.e. non back-to-backness*, measurable via moment, n, of the azimuthal jet separation distribution $\langle \cos(n(\pi - \Delta\phi)) \rangle$. BFKL predicts increased decorrelation with increased Δy & sensitivity to the ratio of moments: $n = 2/n = 1$.

Using both 2010 data (down to $Q_0 = 20$ GeV, $|y| < 4.4$) and 2011 (up to $\bar{p_T} = 1.5$ TeV, but $Q_0 = 30$ GeV, $|y| < 2.4$, JVF cut)

Data Uncertainties

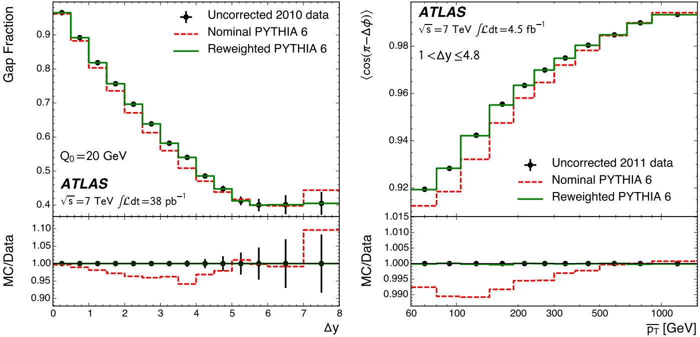
- Corrected via 2D or 3D Bayesian procedure with Pythia 6 migration matrices and 2 iterations & statistical propagation via pseudo-experiments.
- Largest systematic **Jet Energy Scale**: 13 (2010) / 64 (2011) independent components, varied individually by $\pm 1\sigma$





Unfolding Details

- Pythia 6 was re-weighted (Δy (2010) or $\bar{p}_{\mathrm{T}}$ (2011), $\Delta\phi$, $p_{\mathrm{T}}^{\mathrm{lead}}$) to better match the detector level data. This was unfolded with original matrix & deviation from weighted truth $\rightarrow$ systematic uncertainty.



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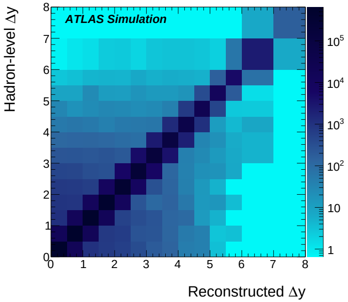
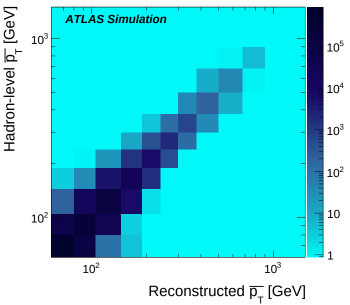
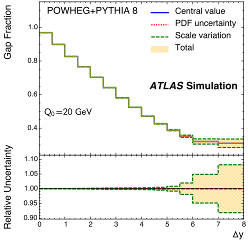


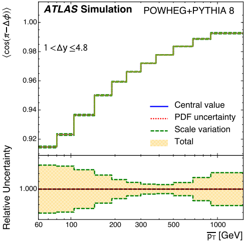


Theory & Uncertainties

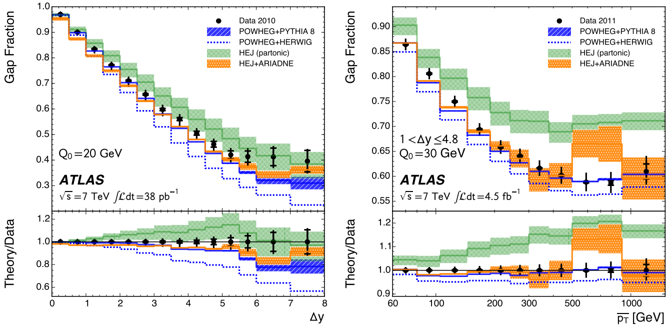
- High Energy Jets (HEJ), (BFKL formalism) approximating (leading log) the all-order perturbative corrections to multi-jet processes.
  - Interfaced to Ariadne colour-dipole cascade parton shower $\rightarrow$ soft and collinear radiation down to hadronic scale.
- POWHEG Box (DGLAP formalism). NLO di-jets interfaced with Pythia8 AU2 or HERWIG AUET1 parton showers

Both with CT10 PDF. HEJ $\mu_R = \mu_F = p_{\mathrm{T}}^{\mathrm{lead}}$. Scale uncertainty 0.5–2. No theory uncertainty show on HEJ+Ariadne.





Gap Fraction

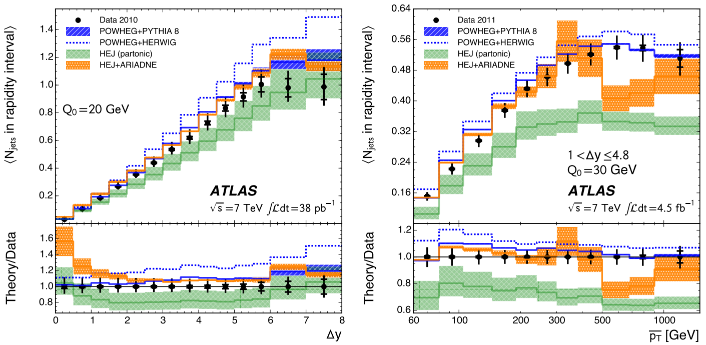


Expect exponential suppression in Δy & $\ln(\bar{p_T}/Q_0)$.

This should $\to 1$ (eventually): all $E(pp)$ going into jj $\to$ none left for additional radiation. Plus t channel QCD singlet contribution.

Plateau behaviour in Δy not well modelled, effects of singlet?

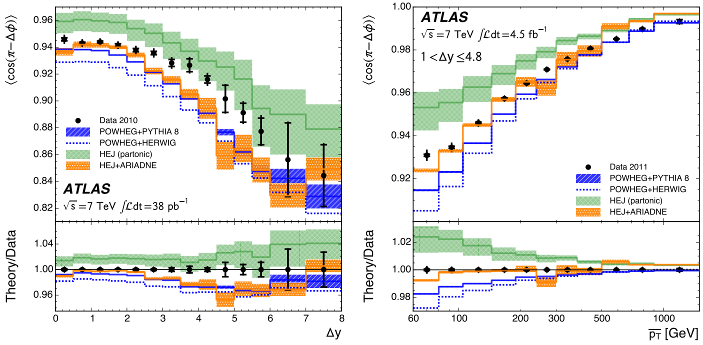
How Badly is the Gap Spoiled?



POWHEG overestimating $\langle N(j_{\text{in}-\text{gap}})\rangle$. HEJ uniformly better with addition of parton shower.

Soft & collinear POWHEG re-summation from Pythia 8 performing better than with HERWIG which yields too much jet activity.

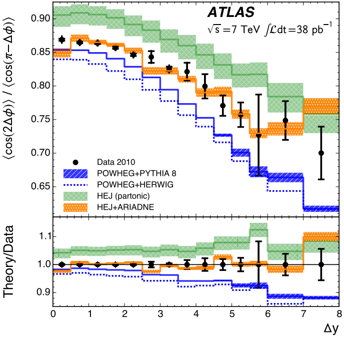
Mean Di-Jet ϕ Decorrelation

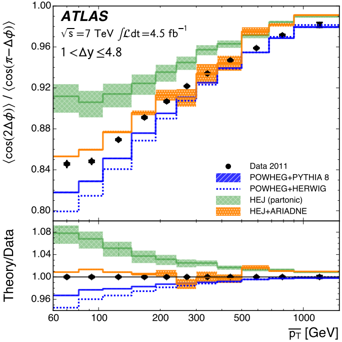


Azimuthal correlation $\downarrow$ = azimuthal moment $\downarrow$

HEJ on its own too back-to-back, with parton showers however - decorrelation is overestimated. POWHEG doing best for most massive systems.

Ratio of 1st and 2nd ϕ Decorrelation Moments

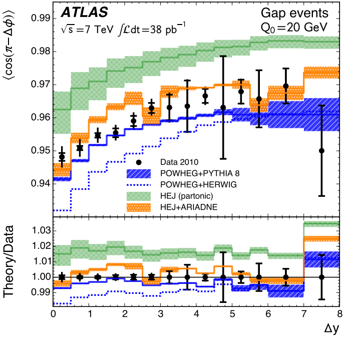


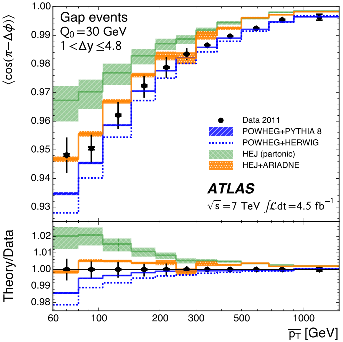


$n = 2$ falls faster than $n = 1$ for $\Delta\phi > \pi/2$.

Better theory discrimination. HEJ+ARIADNE doing well outside of extreme $\bar{p}_T$.

ϕ Decorrelation: but this time with a Gap



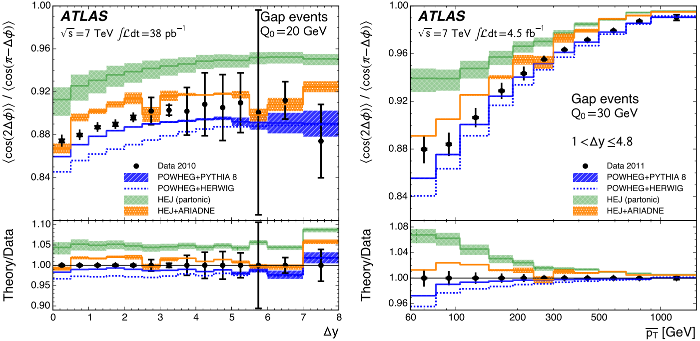


Bounding jet $p_T > Q_0$ veto preferentially selects back-to-back.

Similar spread of theory predictions.

ARIADNE not introducing enough decorrelation, doing worse than in the inclusive case.

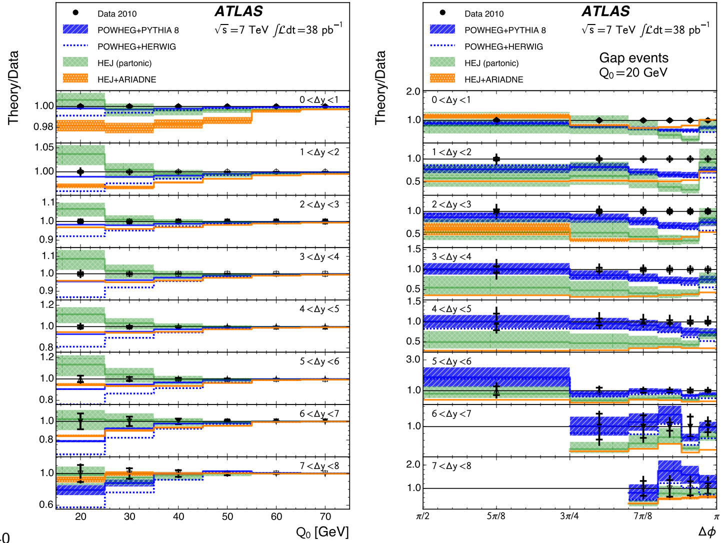
ϕ Decorrelation Ratio - with a Gap



POWHEG+PYTHIA8 again doing well at high $\bar{p}_T$.

Large separation hard jets with little radiation not well reproduced by HEJ.

Differential Data HEPMC + RIVET For Model Builders

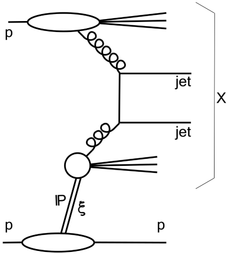


Hard Diffraction

Di-Jet Production with a Rapidity Gap

[Phys. Lett. B 754 (2016) 214][arXiv:1511.00502 [hep-ex]]

7 TeV Single Diffractive (SD) Di-Jet Production MCs

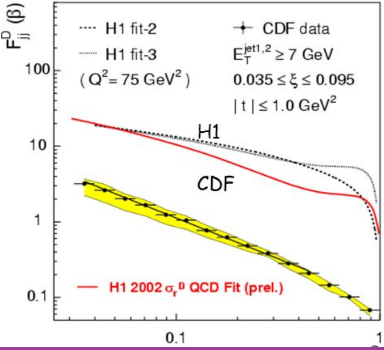


- POWHEG + PYTHIA (NLO DGLAP formalism, **Non Diff.**)
- Factorised models: Pomeron flux & partonic *p*-*IP* interaction.
  - POMWIG (HERWIG, so **cluster** hadronisation) **SD**: hard D(iffractive)PDFs & flux from HERA (H1 2006 DPDF B + CTEQ61)
  - Pythia 8 for **ND**, **SD** ($pp \to X(jj)\ p$), **DD** ($pp \to X(jj)\ Y$). Smooth **Soft**$\to$**Hard** based on diffractive system mass (M_X) (H1 2006 DPDF B + CT10). Different **choices** of Pomeron flux model.

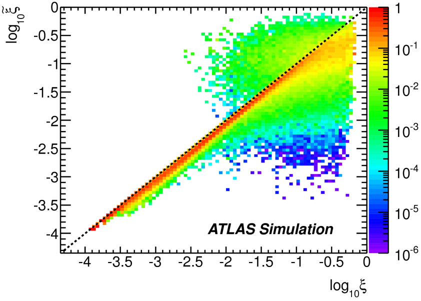
The Origin of S^2

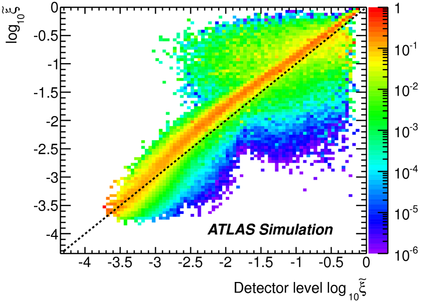
Neither of the factorised diffractive modes, Pythia 8 or POMWIG include a gap survival effects: $S^2 = 1$

Attributed to multiple scattering, beam remnant interactions: absorptive corrections. x10 suppression at Tevatron.



$\Delta\eta^F$ & Correlating ξ with $\widetilde{\xi}$

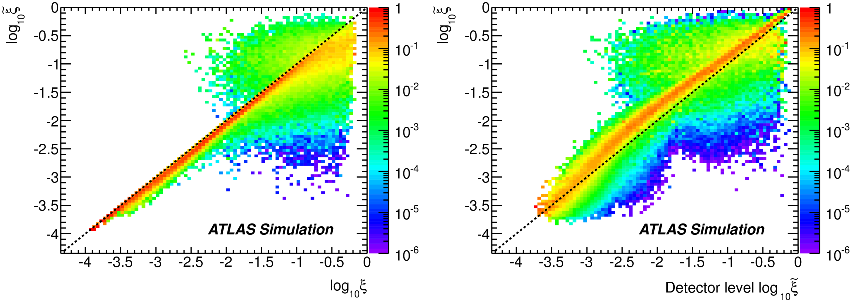




$$\xi = M_X^2/s = E_p - E_{\text{beam}}. \quad \widetilde{\xi} = \sum p_{\mathrm{T}} e^{\pm\eta}/\sqrt{s}$$

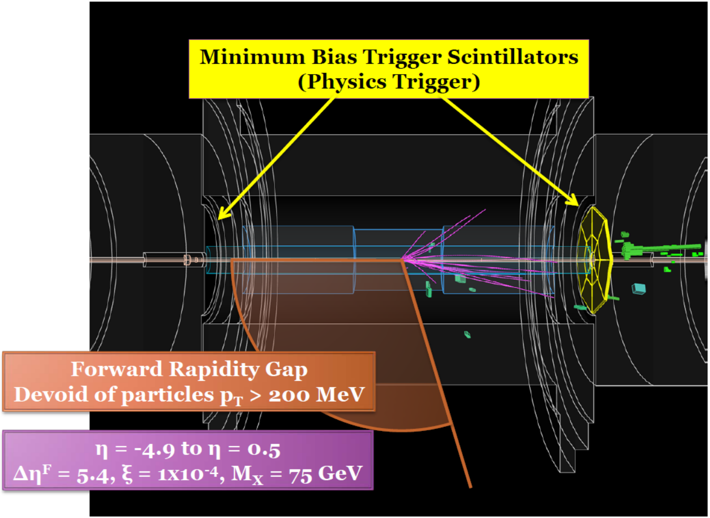
For Double. Diff., if mass $M_Y < 7$ GeV($\xi_Y < 10^{-6}$), system not observed (goes down the beamline).

$\Delta\eta^F$ & Correlating ξ with $\tilde{\xi}$



$\Delta\eta^F$: the *larger* of the two rapidity gaps stretching inward from $|\eta| = 4.8$ with no charged particles $p_T > 200$ MeV, $p > 500$ MeV or neutral particles $p > 200$ MeV. Based on tracks & calorimeter clusters. $\Delta\eta^F \propto ln(\xi)$.

Rapidy Gap Identification



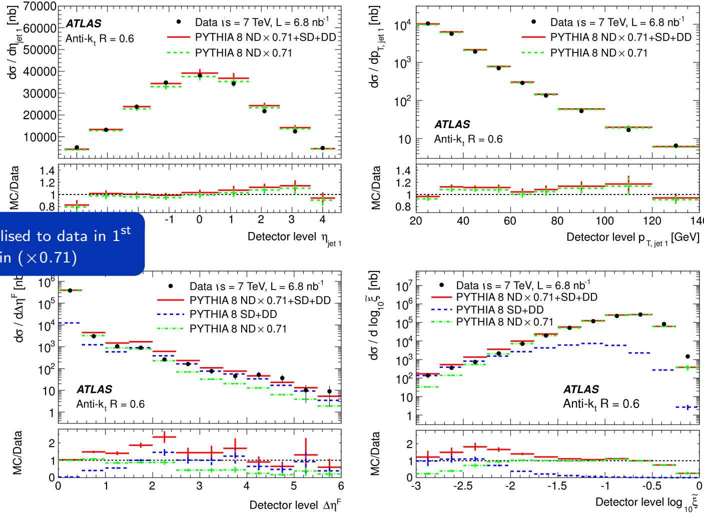
Selection & Correction

- Early 2010, $\langle\mu\rangle = 0.12$, $\mathcal{L} = 6.8\ \text{nb}^{-1}$ (of which MinBias trigger, $0.3\ \text{nb}^{-1}$, covers $20 < p_\text{T} < 34$ GeV). **[C.f: 2015 $\sqrt{s} = 13$ TeV 'low-μ' week: 1.6 nb^{-1}]**.
- anti-k_t, $R = 0.6$, 2+ jets, $|\eta| < 4.4$, $p_\text{T} > 20$ GeV.
- 2D Iterative Dynamically Stabilised unfolding in jet p_T^lead and $\Delta\eta^F$ or $\widetilde{\xi}$ with Pythia 8 (optimised `ND + (SD & DD)`) & 4 iterations.

Large uncertainties: Jet Energy Scale, **20–40%** for small–large gaps. Cluster energy scale on $\widetilde{\xi}$, **10%**. Cell significance threshold, **10–20%**. Unfolding, via MC-reweighting to data, **15–25%** for $\Delta\eta^F$ & **10%** for $\widetilde{\xi}$

Total uncertainty 25–45%

Detector Level

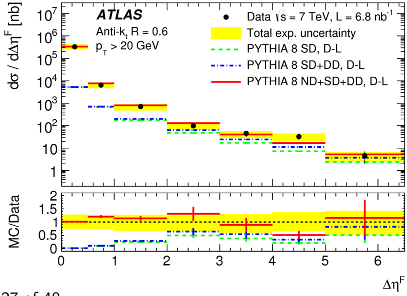


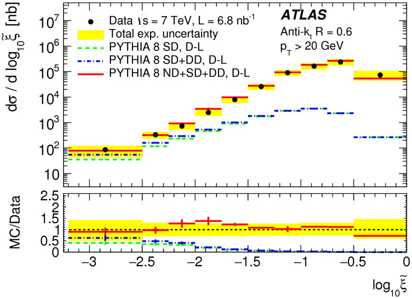
Py8 ND normalised to data in 1st $\Delta\eta^F$ bin ($\times 0.71$)

Corrected Cross Section vs. $\Delta\eta^F$ & $\tilde{\xi}$

No massively dominated diffractive region: kinematic in origin, small M_X (large gap) suppressed by di-jet requirement.

ND scaled to data in 1st $\Delta\eta^F$ bin ($\times 1.4$). SD & DD unscaled. At high $\Delta\eta^F$/low $\tilde{\xi}$ this implies diffractive component $\sim$twice that of ND.

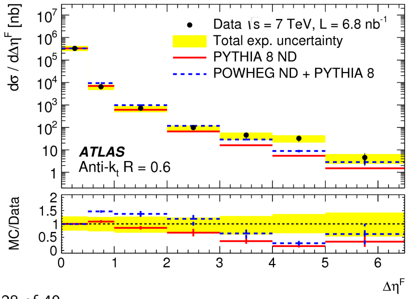


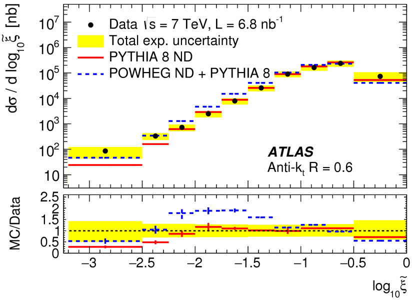


Corrected Cross Section Pythia vs. Powheg

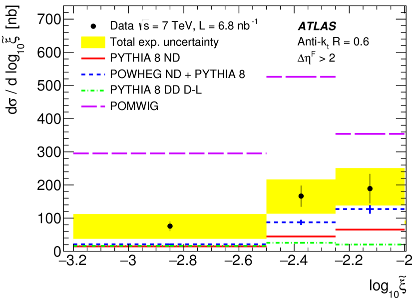
Non-diffractive modelling at large gap sizes is sensitive to hadronisation. *Are we sure we see a diffractive component?*

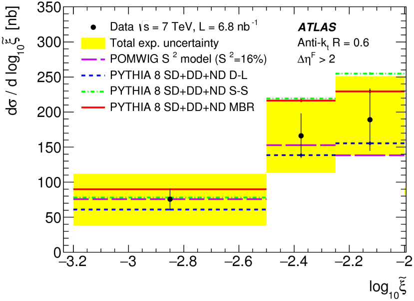
Large uncertainty across most of the distribution, **however** both Pythia 8 & POWHEG fall short for $\Delta\eta^F > 4$ or $\tilde{\xi} < 10^{-2.5}$: investigated for diffractive component.





Corrected Cross Section: $\Delta\eta^F > 2$

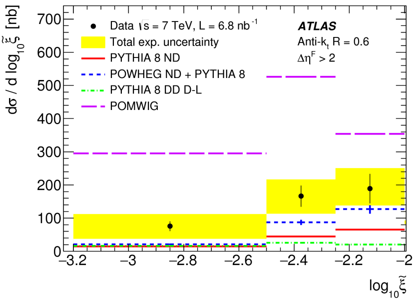


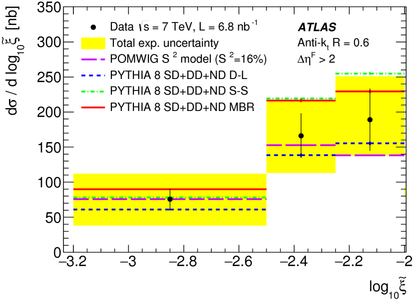


Focus on $\Delta\eta^F > 2$, $\tilde{\xi} < 0.01$. Note small expected ND & DD contributions at smallest $\tilde{\xi}$ on left ($< 25\%$).

POMWIG: Straight up hard diffraction, massively overshoots in absence of survival factor. Pythia: attempts inclusive soft & hard diffractive modelling, does not need additional survival factor.

Corrected Cross Section: $\Delta\eta^F > 2$

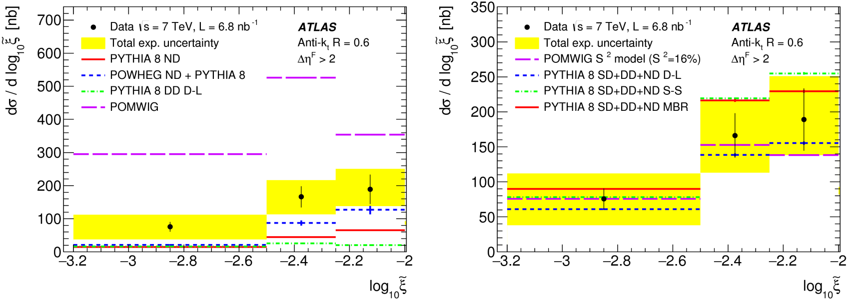




Extract S^2. Ratio of **(data - ND [Py8] - DD [Py8 assuming (SD/SD+DD) σ ratio])** to **POMWIG** in lowest bin. Plus additional 20% correction for HERA DPDFs containing DD component.

$S^2 = 0.16 \pm 0.04(\text{stat.}) \pm 0.08(\text{exp. syst.})$. (No full model uncertainty evaluation, indications S^2 is smaller with NLO models.)

Corrected Cross Section: $\Delta\eta^F > 2$



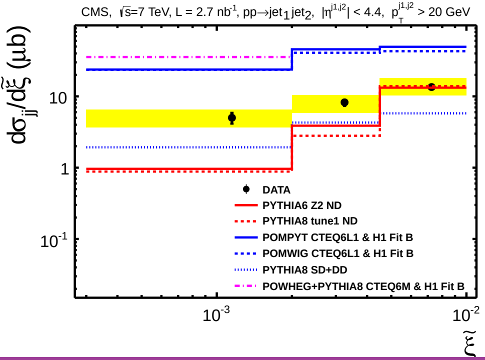
Effects of Pythia 8 Pomeron flux (right) visible, S-S (Schuler-Sjostrand), D-L (Donnachi-Landschoff), MBR (Minimum Bias Rockefeller). But within experimental uncertainty.

For comparison: CMS

[Phys. Rev. D 87 (2013) 012006]

Jet R, particle p_{T}, p & η differ a little to ATLAS.

C.f CMS: $S^2 = 0.12 \pm 0.05(0.08 \pm 0.04)$ for LO(NLO))



The Future

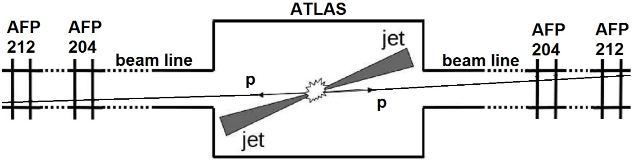
Central Exclusive Di-Jets

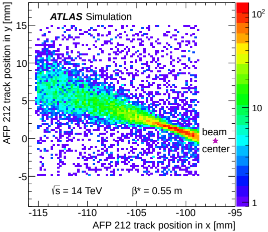
[ATL-PHYS-PUB-2015-003]

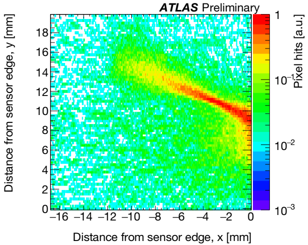
Atlas Forward Physics

AFP: Roman Pot based proton tagger at $z \sim \pm 210$ m from the IP.

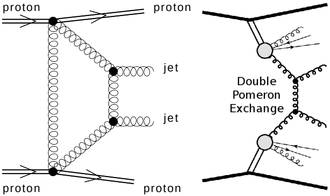
One arm of the detector is **installed** at ATLAS & has taken first data!





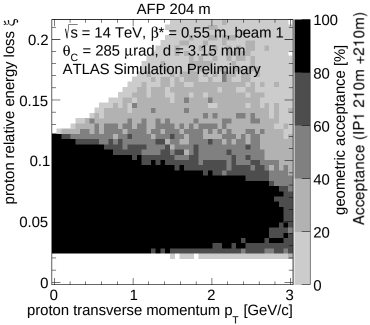


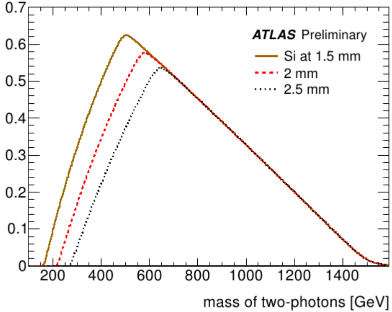
Central Exclusive Production



- Exclusive process modelled (**KMR**) perturbative + colour screening gluon. Exclusivity via **Sudakov** form factor. $\boldsymbol{J^{PC} = 0^{++}}$
- Implemented in **FPMC** (based on Herwig). Predicted $\boldsymbol{\sigma = 0.5}$ **pb** for $p_{\mathrm{T}}^{\mathrm{lead}} > 150$ GeV at $\sqrt{s} = 14$ TeV. $\boldsymbol{S^2}$ **set to 0.03**.
  - Background: Single diff. (**H++, no MPI,** $\boldsymbol{S^2 = 0.1}$) $\rightarrow$ **1 real** forward proton & **1 pileup** proton
  - Background: Double Pomeron Exchange (**H++, no MPI,** $\boldsymbol{S^2 = 0.03}$) $\rightarrow$ **2 real** forward protons
  - Background: Non-diffractive (**Py8**) $\rightarrow$ **2 pileup** forward protons, but **huge,** $\boldsymbol{> 10^6}$ **pb,** $\boldsymbol{\sigma}$

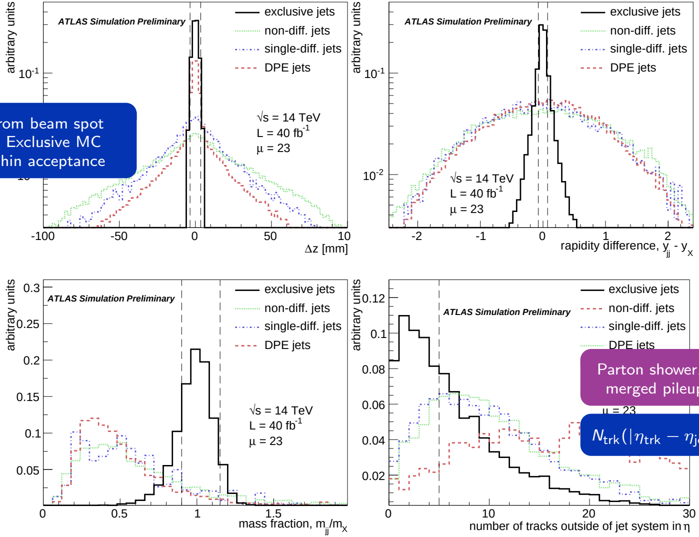
AFP Sensitivity





- Minimum $\xi \sim 0.02$ for AFP implies $E_{\text{jet}} > 150$ GeV
- AFP p energy resolution 5–10 GeV (much smaller than jet energy scale!).
- Timing detectors 10 ps $\rightarrow$ 2 mm vertex ID in z

Discriminating Variables



Broadening from beam spot $z \sim 10$ mm. Exclusive MC generated within acceptance

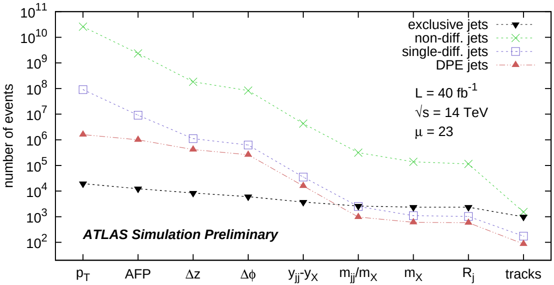
Parton shower, hadronisatio & merged pileup vertex effects

$N_{\text{trk}}(|\eta_{\text{trk}} - \eta_{\text{jet}}| > 0.7)$

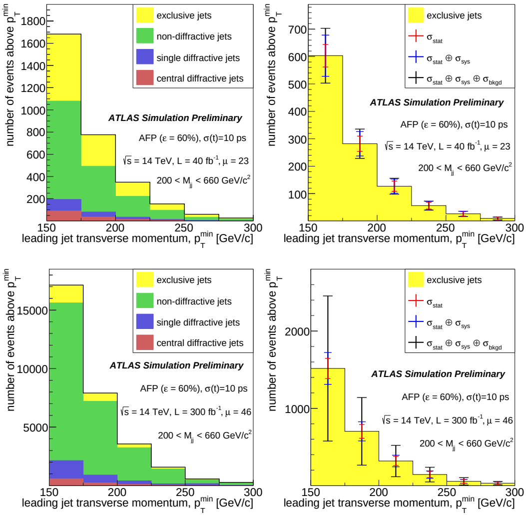
Isolating Exclusive Events

- Apply a L1 jet *and* double-sided AFP tag trigger $\rightarrow$ 400 Hz at $\mathcal{L} = 5 \times 10^{33}$ (x10 reduction from AFP coincidence)
- Correlate **AFP** and **Central** systems in the High Level Trigger $\rightarrow$ 12 Hz to disk.
- Event sample assumes a $\mathbf{40\ fb^{-1}}$ dataset.

Jets: a-k_t $R = 0.6$, $|\eta| < 2.6$, JVF > 0.85



Results for $\langle\mu\rangle = 23$ (Top) & $\langle\mu\rangle = 46$ (Bot.)



Conclusions

'Mueller-Navelet' Di-Jets probed up to $\Delta y = 8$, $\bar{p_{\mathrm{T}}} = 1.5$ TeV in 7 TeV data with and additional jet veto scale of $Q_0 = 20, 30$ GeV. *Large Δy will be challenging at 13 TeV due to the quickly obtained high-μ conditions.*

Evidence of hard diffraction observed in di-jets based on events with large rapidity gaps devoid of soft activity. Gap survival probabilities obtained comparable with Tevatron, whereas smaller were expected.

Large physics program with Atlas Forward Physics (AFP) to be explored in dedicated runs ($\langle\mu\rangle \sim 1$, O(100 pb^{-1})) and standard high-μ data taking. On the other side of the ring: CMS-TOTEM Precision Proton Spectrometer