Recent Diffractive and Related Measurements with the ATLAS Detector

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→ 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

Double diffractive dissociation

Also $M_X$

Also $M_Y$

Also $M_X$

Also $M_Y$

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

- $\xi$ variable strongly correlated with empty rapidity regions
  
  ... exploited in both measurements to be shown

- Correlation limited by hadronisation fluctuations

$\Delta \eta \approx -\ln \xi$
Both measurements rely on minimum bias samples triggered using the MBTS scintillators

\[ z = \pm 3.6\text{m}, \quad 2.1 < |\eta| < 3.8 \]

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

\[ \frac{d\sigma}{dt} = \frac{d\sigma}{dt} \mid_{t=0} e^{Bt} \]

\[ B = 19.73 \pm 0.24 \text{ GeV}^{-2} \text{ (ALFA)} \]

\[ \sigma_{TOT}^2 = \frac{16\pi(hc)^2}{1 + \rho^2} \frac{d\sigma_{EL}}{dt} \mid_{t=0} \]

\[ [\rho \sim 0.1 = \text{phase of Coulomb-nuclear interference at } t=0] \]

Nucl Phys B889 (2014), 486
Consistent with fits to previous data (with either a logarithmic or power law dependence).

\[ \alpha_{IP}(0) \sim 1.08 \]

ATLAS: \( \sigma_{\text{tot}} = 95.4 \pm 1.4 \text{ mb} \)

- \( \sigma_{\text{tot}} \) & \( \sigma_{\text{el}} \) indirectly determine total inelastic cross section \( \sigma_{\text{inel}} \)
- Direct \( \sigma_{\text{inel}} \) 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 \( \sqrt{s} \) [GeV]
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

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

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

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

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

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

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

- Luminosity from final calibration of Van der Meer scan
  → 1.9\% error ... cf was 9\% in preliminary result 😊

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
<th>Rel. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events passing the inclusive selection ((N))</td>
<td>4159074</td>
<td>—</td>
</tr>
<tr>
<td>Number of background events ((N_{\text{BG}}))</td>
<td>51187</td>
<td>±50%</td>
</tr>
<tr>
<td>Integrated luminosity ([\mu\text{b}^{-1}] (\mathcal{L}))</td>
<td>60.1</td>
<td>±1.9%</td>
</tr>
<tr>
<td>Trigger efficiency ((\epsilon_{\text{trig}}))</td>
<td>99.7%</td>
<td>±0.3%</td>
</tr>
<tr>
<td>MC correction factor ((C_{\text{MC}}))</td>
<td>99.3%</td>
<td>±0.5%</td>
</tr>
</tbody>
</table>
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 implementation 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
Data-driven extrapolation into region with $\xi < 10^{-6}$, with minimal dependence on MC models:

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

$$\sigma^{7 \text{ TeV}} (\xi < 5 \times 10^{-6}) = \sigma_{\text{inel}}^{\text{fid}} - \sigma^{7 \text{ TeV}} (\xi > 5 \times 10^{-6}) = 11.0 \pm 2.3 \text{ mb}$$

from ALFA result

previous fiducial MBTS result

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

... 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\(\pm\)4\% compared with 7 TeV ALFA point
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.
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 $M_\gamma$ DD

Implies $\xi \sim 10^{-4}$
- Large $\Delta \eta^F$: Diffractive plateau with $\sim 1 \text{mb}$ 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...
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 ...
- 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
- **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 $\xi$

\[ \tilde{\xi} \approx \frac{M_X^2}{s} = \sum p_T e^{\pm \eta} / \sqrt{s} \]

... approximation to $\xi$ which is relatively insensitive to losses of parts of X system into the beam-pipe

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

Experimental resolution on log $\tilde{\xi}$ approximately $10\%$. 
Uncorrected 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 $\xi$ … no clear diffractive signal …
Focusing on small $\xi$, whist simultaneously requiring large gap size ($\Delta \eta_F > 2$) gives best sensitivity to diffractive component

$\rightarrow$ Models with no SD jets are below data by factor $>\sim 3$

$\rightarrow$ Comparison of smallest $\xi$ 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 $\xi$, 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
**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 ...
Direct Inelastic Cross Section Measurement at $\sqrt{s} = 13$ TeV
- Significant improvement in precision (9% $\to$ 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)