Diffraction at the LHC

Results from TOTEM, CMS and ATLAS

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• Summary
Events in p+p collisions at the LHC

- Elastic + diffractive (colorless interaction) + non-diffractive (color exchange)
- Single diffr.: pp→pX/Xp
- Double diffr.: pp→XY
- Classification: rapidity gap
- Need well-placed detectors
- Also with jets: hard diffraction
- Soft diffraction:
  - Regge theory & the Pomeron
- Kinematic variables:
  - Invariant mass of dissociated particles: \( M \)
  - Mom. loss of the proton:
    \[ \xi = \frac{\Delta p}{p} = \frac{M^2}{s} \]
  - Rapidity gap: \( \Delta \eta = \ln(\xi) \)
Forward detectors at TOTEM & CMS

- Roman Pot detects deflected protons
  - Edgeless silicon detector
  - Placed 147 and 220 m from IP
  - Few $\mu$rad scattering angle (|\(\eta\)| around 10)
  - Momentum-transfer: $10^{-4} < |t/GeV^2| < 10$

- Other forward detectors
  - tracks in SD & DD events
  - HF: $3 < |\eta| < 5$
  - T1: $3.1 < |\eta| < 4.7$
  - T2: $5.3 < |\eta| < 6.5$
  - CASTOR: $5.2 < |\eta| < 6.6$
  - FSC: $6 < |\eta| < 8$
Forward detectors at ATLAS

- LUCID (luminosity): $5.6 < |\eta| < 6$
- ALFA (Roman Pots): $10.6 < |\eta| < 13.5$
  - four RP stations at 237.4 and 241.5 m
- Geometric acceptance:
- AFP (ATLAS Forward Proton): in approval
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LHC optics for elastic events

• An elastic event at LHC

• In reality

• \( \left( x, \Theta_x, y, \Theta_y, \frac{\Delta p}{p} \right) \to \left( x, \Theta_x, y, \Theta_y, \frac{\Delta p}{p} \right) \) via the transport matrix, based on betatron amplitude \( \beta(s) \); magnification & effective length calculated from it

• Optics errors induced by LHC imperfections need to be under control

• See arXiv:1206.3058 (F. Nemes & H. Niewiadomski) for details
TOTEM: Differential elastic cross-sections

- Based on event numbers & luminosity: $\mathcal{L} \frac{d\sigma}{dt} = \frac{dN}{dt}$
- Measurements at several optics ($\beta^*$) setups
- Small $|t|$ (mom. transfer): exponential; diffractive minimum; power-law tail
- Special $\beta^* = 1000$ m run, down to $6 \cdot 10^{-4}$ GeV$^2$
- Sensitive to Coulomb-nuclear interference

\[ \rho = \mathcal{R}F^H / \mathcal{S}F^H \]

measured:
\[ 0.110 \pm 0.027 \text{(stat)} \pm 0.010 \text{(syst)}^{+0.013}_{-0.012} \text{(model)} \]
**TOTEM: Total cross-section measurements**

- „Elastic only” method via optical theorem: 
  \[ \sigma_{tot}^2 = \frac{16\pi(hc)^2}{1+q^2} \left( \frac{dN_{el}}{L} \right) \]

- Luminosity-independent method: 
  \[ \sigma_{tot} = \frac{16\pi(hc)^2}{1+q^2} \frac{dN_{el}/dt}{N_{el}+N_{inel}} \]

- \( q \)-independent method: 
  \[ \sigma_{tot} = \frac{N_{el} + N_{inel}}{L} \]

- Total inelastic rate via T2 trigger, corrections from T1 & MC

- Ongoing analyses for 2.76 and 8 TeV with different optics
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Soft single diffraction at TOTEM

- Rapidity gap ($\Delta \eta = -\ln \xi$) determines diffractive mass ($M_X^2 = \xi s$)

- Event classification based on tracks in T1 & T2, proton in RP

<table>
<thead>
<tr>
<th>SD class</th>
<th>Configuration</th>
<th>$M_X$ [GeV]</th>
<th>$\xi = \Delta p/p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low mass</td>
<td>1 RP + opp. T2</td>
<td>3.4 – 7.0</td>
<td>$2 \times 10^{-7}$ – $10^{-6}$</td>
</tr>
<tr>
<td>Medium mass</td>
<td>1 RP + opp. T2 + opp. T1</td>
<td>7.0 – 350</td>
<td>$10^{-6}$ – 0.0025</td>
</tr>
<tr>
<td>High mass</td>
<td>1 RP + opp. T2 + same T1</td>
<td>350 – 1100</td>
<td>0.0025 – 0.025</td>
</tr>
<tr>
<td>Very high mass</td>
<td>1 RP + both T2</td>
<td>1100 – …</td>
<td>0.025 – …</td>
</tr>
</tbody>
</table>
TOTEM results on soft single diffraction

- Exponential shape fitted $(e^{-B|t|})$
- Corrections:
  - Trigger efficiency
  - Reco. efficiency
  - Proton acceptance
  - Background
  - Extrapolation
- Estimated $\sigma$ uncertainty: 20%
- Quite preliminary result
  $$\sigma_{3.4-1100\, \text{GeV}} = 6.5 \pm 1.3 \, \text{mb}$$
  - To be understood!
- Very high mass: ongoing
- ALICE result for $M_X < 200\, \text{GeV}$
  $$\sigma_{<200\, \text{GeV}} = 14.9^{+3.4}_{-5.9} \, \text{mb}$$
Diffractive dijets at CMS

- Diffraction with a hard scale set by a dijet system
- Described by dPDF (P flux × PDF) + pQCD σ
- Diffractive selection described by mix of diffr. (POMPYT) & non-diffractive (PYTHIA) samples

- Inclusive cross-section in 3 bins
- ND MCs underestimate the data at low ξ: evidence for hard diffraction
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Soft double diffraction at TOTEM

- Particle in both T2 arms, no T1 tracks
  - $0 \times T1 + 2 \times T2$ topology
  - Pseudorapidity range: $4.7 - 6.5$, i.e. $3.4 < M < 8$ GeV

- Background estimation:
  - Single diffractive: $0 \times T1 + 1 \times T2 +$ proton in RP
  - Non-diffractive: MC prediction based on $2 \times T1 + 2 \times T2$

- Validation of backgr. estimates:

TOTEM results on double diffraction

• Cross-section result: $\sigma_{DD} (4.7<\eta<6.5) = 116 \pm 25 \, \mu b$
• PYTHIA 8: 159 $\mu b$, PHOJET: 101 $\mu b$
• Two $\eta_{\text{min}}$ regions: 4.7-5.9 (a) and 5.9-6.5 (b)
• „Differential” result:

|                  | (a|b)+(a|b) | a+a | b+b | a+b | b+a |
|------------------|-----------|-----|-----|-----|-----|
| TOTEM result [$\mu b$] | 116 $\pm$ 25 | 65 $\pm$ 20 | 12 $\pm$ 5 | 26 $\pm$ 5 | 27 $\pm$ 5 |
| PYTHIA [$\mu b$]     | 159       | 70  | 17  | 36  | 36  |
| PHOJET [$\mu b$]     | 101       | 44  | 12  | 23  | 23  |

• PYTHIA total: 8.1 mb, PHOJET total: 3.9 mb
• Largest source of uncertainty: tracking, $\eta_{\text{min}}$ reco. to generator transformation
• Improvement expected with 8 TeV data (with CMS)
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Central diffraction with TOTEM+CMS

- Diffractive mass determined by TOTEM \( M_X = \sqrt{s} \xi_1 \xi_2 \) & CMS (directly)

- Unprecedented rapidity coverage
- M & p from CMS & TOTEM consistent
- Pile-up removal crucial
  - Elastic + SD or elastic + beam halo
  - Cut on CMS FSC: QCD background
  - CMS and TOTEM masses equal
- High \( p_t \) jets with leading protons:
  - Signature: \( \geq 2 \) tracks with \( p_t > 20 \) GeV
  - Proton in RP
  - FSC & T2 empty
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Pseudorapidity distribution results

- TOTEM: based on T2 trigger, at least 1 particle with $p_t > 40$ MeV/$c$
- More than 99% of ND
- Diffractive as well (if $M > 3.4$ GeV/$c^2$)
- LHC dataset compiled

More results

Pseudorapidity density

- TOTEM to LHCb: gap covered via displaced vtx. collisions:
Pseudorapidity distributions with TOTEM+CMS

- CMS & TOTEM also triggered with T2, same reconstruction (at least 1 track)
- Corrections and correlated systematics under study

CMS & TOTEM Preliminary

Inclusive pp, $\sqrt{s} = 8$ TeV

- Pythia6 Z2*
- Pythia8 4C
- Herwig++ EE3C
- EPOS LHC
- QGSJetII-04

- NSD & SD enhanced measurement also ongoing

$\frac{dN_{ch}}{d|\eta|}$

$N_{ch} (p_T > 40\text{ MeV}) \geq 1 \text{ in } 5.3 < \eta < 6.5 \text{ or } -6.5 < \eta < -5.3$
Forward rapidity gap cross-sections, ATLAS

- Rapidity gap measured from calorimeter edge ($\eta = \pm 4.9$)
- Systematic uncertainties: $\sim 8\%$ at large gaps, $\sim 20\%$ at small gaps
- Large gaps: contribution of SD and DD
- Small gaps: dominated by hadronization fluctuations in ND
- HERWIG++ (does not contain diffraction): bumps around $\eta \sim 6$, fails
  - Next version handles heavy mass clusters better, fixes rapidity gap modelling
- PYTHIA generally too high; PHOJET works best.
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![Graphs of different diffraction processes](image_url)
Summary

• TOTEM, CMS and ATLAS provide unprecedented measurement possibilities
  • Very forward detectors, especially Roman Pots

• Cross-section measurements
  • Differential cross-section results hardly describable by models
  • Total elastic & inelastic cross-sections measured via independent methods
  • ATLAS measurement: integrated to $\xi_{\text{cut}}$

• Single diffraction
  • TOTEM measurement done in three mass ranges
  • Diffractive dijets measured at CMS

• Double diffraction
  • TOTEM: final result in a limited rapidity region

• Central diffraction
  • Preliminary result at TOTEM & CMS
  • High $p_t$ jets with leading protons seen

• Other results
  • TOTEM+CMS: single diffractive enhanced pseudorapidity distributions
  • Forward rapidity gap cross-section at ATLAS & CMS
Thank you for your attention

Recent talks for further reading:

- ATLAS Results on Soft Diffraction, Simone Monzani, EDS Blois 2013
- Diffraction and rapidity gap measurements with ATLAS, Vlastimil Kus, Photon 2013
- CMS results on soft diffraction, Konstantin Goulianos, EDS Blois 2013
- Diffraction at CMS, Sercan Sen, Forward Physics at the LHC 2013
- CMS results on Hard Diffraction, Christina Mesropian, EDS Blois 2013
- TOTEM Results on Elastic Scattering and Total Cross-Section, Jan Kaspar, EDS Blois 2013
- Review of TOTEM Results, Mario Deile, WE-Heraeus-Summerschool 2013
- Elastic and Inelastic Diffraction at the LHC, Risto Orava, LHCp 2013
- Soft diffraction and forward multiplicity meas. with TOTEM, F. Oljemark, EDS Blois 2013
Differential elastic cross-section vs. models

- Block et al.
- Bourrely et al.
- Islam et al. (CGC)
- Jenkovszky et al.
- Petrov et al. (3P)

TOTEM

\[ \frac{d\sigma}{dt} \quad \text{(mb/GeV}^2) \]
Pseudorapidity distributions: SD/NSD enhanced

- Analysis ongoing in both CMS & TOTEM

NSD-enhanced

SD-enhanced
Different optics conditions as seen by TOTEM

Regular $\beta^* = 3.5$ m optics

$\beta^* = 90$ m optics

- RP structure reflects possibilities in various optics conditions
- Low cross-section processes studied with regular optics (continuous running)
- High cross-section processes: dedicated short runs with optimized conditions
Cross-section measurements TOTEM

• Elastic differential cross-section
  • 7 TeV
    • $\beta^* = 90$ m and medium $|t|$ at $\beta^* = 3.5$ m: published
    • high $|t|$ at $\beta^* = 3.5$ m: advanced analysis
  • 8 TeV
    • $\beta^* = 1000$ m: publication ongoing
    • $\beta^* = 90$ m: advanced analysis
  • 2.76 TeV
    • $\beta^* = 11$ m: analysis ongoing

• Total cross-section
  • 7 TeV
    • $\beta^* = 90$ m: published
  • 8 TeV
    • $\beta^* = 90$ m: published
    • $\beta^* = 1000$ m: publication ongoing (+ separation Coulomb/nuclear effects)
  • 2.76 TeV
    • $\beta^* = 11$ m: elastic analysis started, inelastic ready

• Coulomb-nuclear interference studies
  • 8 TeV
    • $\beta^* = 1000$ m: publication ongoing
TOTEM upgrade plans

• RP system will consist of 4 RP units/arm, each with 2 vertical + 1 horizontal pots equipped with 10 planes Si-strip detectors, with full trigger capability

• Improving RP multi-track capability
  • Tilt far RP station for ghost track suppression
  • Replace strip detectors with pixel detectors

• Reducing RP-beam coupling
  • Optimized RP impedance (reduce heating & feedback) needed
  • Cylindrical RP with Ferrites shown a reduced beam power-loss
  • For 210m far-horizontal RP a cylindrical copper shield is studied for impedance reduction

• Improving proton left-right correlation capability
  • Timing sensors with few times 10 ps timing resolution
LHC setup

- IP1: ATLAS, LHCf
- IP2: ALICE
- IP3: Momentum Cleaning
- IP4: RF (Acceleration)
- IP5: CMS, TOTEM
- IP6: Beam Dump
- IP7: Betatron Cleaning
- IP8: LHCb
ATLAS: Integrated cross-section for $\xi > \xi_{\text{cut}}$

- The inelastic cross-section obtained by integration from $\xi_{\text{cut}}$ to 1
- Same as integrating from 0 to $\Delta\eta_f^{\max}$
- RMK model (Ryskin, Martin, Khoze), PYTHIA and PHOJET used
- Small $\xi$ region underestimated
- 14.5 mb for $\xi < 8 \cdot 10^{-6}$ compared to 6 mb (3 mb) by PYTHIA (PHOJET)
- RMK model lies below data generally
- Low $\xi$ enhancement in agreement
- Total inelastic cross-section:
  $\sigma_{\text{inel}} = 69.4 \pm 2.4(\text{exp}) \pm 6.9(\text{extr})$ mb
- In agreement with TOTEM (large uncert.)
SD & DD cross-sections at CMS

- Measure event counts with gap on + or - side

\[ \sigma_{SD} = 4.7 \pm 0.04 \text{(stat)}^{+0.65}_{-0.58} \text{(syst)} \text{ mb, int. over } 2.5 < -\log \xi < 5.5 \]

- Multiplied by 2 to account for both side processes

\[ \sigma_{DD} = 0.93 \pm 0.01 \text{(stat)}^{+0.26}_{-0.22} \text{(syst)} \text{ mb, for } \Delta \eta > 3, M_X, M_Y > 10 \text{ GeV} \]

- Pythia8-MBR: describes SD, DD partially

- Pythia6/8: fails with SD
Forward rapidity gap cross-sections, CMS

- Exponentially falling non-diffractive contribution at small gap size
- Diffractive plateau and slowly rising cross-section with increasing gap size
- Hard to separate SD and DD events at central region using forward rapidity gap observable
- CMS & ATLAS result compared (slightly different rapidity region)
Central diffraction at TOTEM

- Event topology (2RP+T2):

  \[ \xi_1 = \Delta p_1/p_1 \quad \text{low } \xi \]
  \[ \xi_2 = \Delta p_2/p_2 \quad \text{high } \xi \]

- Two rapidity gaps \( \Delta \eta_1 = \xi_1 \) and \( \Delta \eta_2 = \xi_2 \), thus \( M_X^2 = \xi_1 \xi_2 s \)

- Background: elastic, inelastic with beam-halo (pile-up)

- Beam halo negligible: \( y > 11 \sigma_{\text{beam}} \)

- Elastic rejected via anti-elastic cuts, non-elastic topologies (e.g. top-top)

- Single-arm event rate in RP (corrected):

  \[ \text{Only } t \text{ distribution is exponential (Jac.)} \]
  \[ \text{MC based fit on } t_y \text{ distribution} \]

- Cross-section estimate: \( \sigma_{CD} \approx 1 \text{ mb} \)

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