Elastic and Inelastic Diffraction at the LHC

- Risto Orava
WHY DIFFRACTION?

• SPACE-TIME EVOLUTION OF HADRON-HADRON SCATTERING

• PARTON CONFIGURATIONS WITHIN HADRONS

• ASYMPTOPIA - QUARK-GLUON CONFINEMENT
**TOTEM ⊗ CMS running scenarios**

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>β (m)</td>
<td>L (cm⁻² s⁻¹)</td>
</tr>
<tr>
<td>1540</td>
<td>10²⁹</td>
</tr>
<tr>
<td>90</td>
<td>10³⁰</td>
</tr>
<tr>
<td>2</td>
<td>10³²</td>
</tr>
<tr>
<td>0.5</td>
<td>10³⁴</td>
</tr>
</tbody>
</table>

**TOTEM LHC runs**

**Standard LHC runs**

- pp->pX
- pp->pXp
- soft diffraction

- pp->pjjX
- pp->pjjXp
- (semi)-hard diffraction

- pp->pjj (bosons, heavy quarks, Higgs...)
- pp->pjjp
- hard diffraction
Leading protons: RP’s at (±147 m), ±220 m
Rap gaps & Fwd particle flows: T1 & T2 spectrometers
Fwd energy flows: Castor & ZDC
Fwd counters at: ±60 m to ±100 (140) m - FSCs
T1, T2 and CASTOR help in rejecting the backgrounds from SD and ND events. Have good acceptance in $p_T$: $T2 > 40\text{MeV}$, $T1 > 100\text{MeV}$
ATLAS detector properties – summary

- single cladded 0.5 mm x 0.5 mm (square) fibers
- 10 layers in U, 10 in V; staggering
- ~30 µm position resolution
- efficiency ~ 90% per plane → ~ 100% efficiency of the detector
TOTEM DETECTORS

Package of 10 “edgeless” Si-detectors

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Leading forward protons at ±220 meters: Low & High $\beta^*$ ($\beta^* \approx 0.55\text{m, 90m}$)

**At low $\beta^*$** (nominal LHC beam optics) the protons are measured through their **horizontal** deviation from the beam axis.

The proton fractional longitudinal momentum loss, $\xi$, is proportional to the (horizontal) distance from the beam axis:

$$\xi = \frac{\Delta p}{p} \propto x$$

- measurement sensitive to the transverse $(x^*, y^*)$ position of the interaction vertex

**At high $\beta^*$** ($\beta^* \approx 90\text{m custom optics}$) the protons are measured through their scattering angle in **vertical** direction.

$$\Theta_y \propto p_T \approx \sqrt{|t_y|}$$

- measurement sensitive to the horizontal $x^*$ position of the interaction vertex in diffractive events
- horizontal vertex position obtained by measuring elastic events (if beams assumed to be symmetric in the transverse plane)
ELASTIC CROSS SECTION

\( \frac{d\sigma_{el}}{dt} \) yields:

- **pp interaction radius** (slope of the \( \frac{d\sigma_{el}}{dt} \) distribution)

  with the measurement of the total inelastic rate - the *total pp cross section*,

- A test of the Coulomb-nuclear interference (expected to have an effect over large interval in \(-t\)).

- A measurement of the ratio of the real and imaginary parts of the forward pp scattering amplitude, \( \rho = \frac{\text{Re}A(s,t)}{\text{Im}A(s,t)} \)

  Through dispersion relations, a precise measurement of \( \rho \) will constrain \( \sigma_{tot} \) at substantially higher energies

  > “Shadow scattering”
ELASTIC CROSS SECTION - TOTEM

$B = 19.89 \pm 0.03 \text{(stat)} \pm 0.27 \text{(syst)} \text{ GeV}^{-2}$

$\sqrt{s} = 7 \text{ TeV}$

Data can be fitted with a single exponential slope in the range:
$0.005 < |t| < 0.2 \text{ GeV}^2$

Region around and after the dip: very sensitive for model discrimination.

Shrinkage of the forward peak:
- minimum moves to lower $|t|$ with increasing CM energy
- exponential slope grows with the CM energy

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CROSS SECTION MEASUREMENTS - TOTEM

- Dedicated fill with $t_{\text{min}} = 0.01 \text{ GeV}^2$, 90% of the nuclear elastic scattering events detected

- With the same analysis performed at 7 TeV, the luminosity independent cross sections are found:

$$\sigma_{\text{TOT}} = 101.7 \pm 2.9 \text{ mb} \quad \sigma_{\text{EL}} = 27.1 \pm 1.4 \text{ mb} \quad \sigma_{\text{INEL}} = 74.7 \pm 1.7 \text{ mb}$$

Comparison of 7 and 8 TeV measurements:

- consistent in terms of detectors performance.
- comparable systematics uncertainties.
- both in good agreement with the extrapolation of the lower energy measurements.

EFFICIENCY OF DETECTING SD EVENTS

WITH FSC, DETECT SD EVENTS DOWN TO $M_{\text{diff}} \geq 1.1$ GeV

THE FWD DETECTORS AS DIFFRACTIVE MASS SELECTORS – CLASSIFICATION
$dN_{ch}/d\eta$ measured in T2, $\sqrt{s} = 7$ TeV

**EPL, 98 (2012) 31002**
COMBINED CMS-TOTEM CHARGED PARTICLE DENSITIES
Probability of finding a rap gap (in inclusive QCD events) depends on the $p_T$ cut-off.

**Fig. 4.** Probability for finding a rapidity gap (definition 'all') larger than $\Delta \eta$ in an inclusive QCD event for different threshold $p_\perp$. From top to bottom the thresholds are $p_\perp, \text{cut} = 1.0, 0.5, 0.1 \text{ GeV}$. Note that the lines for cluster and string hadronisation lie on top of each other for $p_\perp, \text{cut} = 1.0 \text{ GeV}$. No trigger condition was required, $\sqrt{s} = 7 \text{ TeV}$. 

**KKMRZ:**
Single diffraction low x

Correlation between leading proton and forward detector T2

Rapidity Gap
\[ \Delta \eta = -\ln \xi \]

\[ M^2 = \xi \, s \]

Run: 37280003, event: 3000

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Single diffraction large x

correlation between leading proton and forward detector T2

\[ \Delta \eta = -\ln \xi \]

\[ M_{x^2} = \xi s \]

run: 37280006, event: 9522
Single diffraction: $d\sigma/dt$ vs. $\xi$

**TOTEM Preliminary**

$d\sigma/dt \sim e^{-Bt}$

- $B = 9.6 \pm 1.5 \text{ GeV}^{-2}$
- $2 \times 10^{-7} < \xi < 1 \times 10^{-6}$

- $B = 8.0 \pm 1.5 \text{ GeV}^{-2}$
- $1 \times 10^{-6} < \xi < 0.25\%$

- $B = 6.6 \pm 1.5 \text{ GeV}^{-2}$
- $0.25\% < \xi < 2.5\%$

$t$-distributions still to be corrected for beam divergence \\& effect of $\xi$ on proton $\phi$-acceptance correction

\[
\frac{d\sigma_{SD}^{\text{class } i}}{dt} = e^{-Bt} - \text{backgr.}
\]

\[
\sigma_{SD}(\xi > 2 \times 10^{-7}) = \sum_{i} \int_{0}^{\infty} dt \frac{d\sigma_{SD}^{\text{class } i}}{dt}
\]
Diffractive cross section at the ISR (0.95 < x_F < 1.0)

Diffraction due to peripheral interactions; fluctuations in:

- impact parameter 45%
- number of 45%
- rapidities 10%

of the wee partons.

Miettinen & Pumplin, PRD 1978
Diffractive cross section at the ISR (0.95 < $x_F$ < 1.0)

At small $-t$ fluctuations in the no. of wee parton states dominate?

only this chain interacts!

Miettinen & Pumplin, PRD 1978

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At small diffractive masses (small $\xi$ values), fluctuations in number of wee states grows in relative importance vs. b- or y- fluctuations?
Central diffraction

\[ \beta^* = 2m, 6m, 18m?? \]
\[ \frac{d\sigma^{CD}}{dM_X dt} \] (hard CD?)

\[ \beta^* = 90m \]
\[ \frac{d\sigma^{CD}}{dM_X dt} \] (soft & semihard CD)

\[ \beta^* = 0.55m \]
\[ \frac{d\sigma^{CD}}{dM_X dt} \] (hard CD, discoveries)

\[ \beta^* = 1540m \]
\[ \frac{d\sigma^{CD}}{dt} \] (soft CD, \(\xi\)-t coverage!)
Central Exclusive Diffraction (CED)
correlation between leading protons and forward detector T2

Run: 37220007, event: 9904

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DI-JET CANDIDATE EVENT

- $E_T$ of 3 GeV, 27 GeV
- $M(pp, TOTEM) = 244$ GeV
- $M(CMS) = 219$ GeV
- Proton $\Delta p/p = 0.01$ (+z)
- Proton $\Delta p/p = 0.1$ (-z)
- $\Sigma(pT, CMS) = 3.4$ GeV

- CMS thresholds for event display
  - ECAL and HCAL $E_T > 200$ MeV
  - Track $p_T > 1$ GeV
Soft Central Diffraction Exchange

TOTEM alone, 20.10.2011 data

$\beta^* = 90\text{m optics runs, } \sqrt{s} = 7\text{ TeV}$:

- $y < 11\sigma$ removed: protection against pile-up

\begin{itemize}
  \item beam halo $\times$ beam halo
  \item beam halo $\times$ elastic proton
\end{itemize}

- DPE protons of $-t > 0.02\text{GeV}^2$ detected by RP

- nearly complete $\xi$-acceptance

$\sigma_{DPE}$ estimation:

$$\frac{d^2\sigma_{DPE}}{dt_1 dt_2} = C(\Delta \phi_{1,2}) e^{-B_1} e^{-B_2} - \text{b a c k g r.}$$

$$\sigma_{DPE} = \int_0^\infty \int_0^\infty \frac{d^2\sigma_{DPE}}{dt_1 dt_2} \approx 1\text{mb}$$

Single arm DPE event rate in RP

integrated $\xi$, acceptance corrected

$\sigma_{DPE} = \int \frac{d^4\sigma_{DPE}}{dt_1 dt_2 d\xi_1 d\xi_2}$

$B = 7.8 \pm 1.4\text{ GeV}^{-2}$
Soft Central Diffraction – dN/dM

TOTEM alone, 20.10.2011 data

Uncorrected dN/dM

\[ M = \sqrt{s} \cdot \sqrt{\frac{\xi_1 \xi_2}{\xi_3 \xi_4}} \] [GeV]
Event Classification by the T2s

Tracks in both T2s: dd & nd

Tracks in ±T2: mostly sd (M* > 3.5 GeV)
Event Classification by the T1s&T2s

Tracks in both $\pm$T2s
No Tracks in $\pm$T1s : Clean dd!
- A study being completed

Tracks in either +T2 or −T2
No Tracks in T1s:
Mostly sd ($M^* > 3.5$ GeV),
- But not so clean
Small Mass Diffractive States
SMALL MASS REGION DOMINATED BY N* RESONANCES

\( N^*(1680\text{MeV}) \)

Fig. 1 Compilation of low-mass SD data from Fermilab experiments \( p + d \rightarrow X + d, P_{\text{lab}} = 275\text{GeV/c} \), see [2]. The first peak has the mean value of \( M_{X,1} = 1400\text{MeV} \) and the second bump has \( M_{X,1} = 1688\text{MeV} \), which correspond to the masses of \( N^* \) resonances, see Sec. 4.2.
Single Diffraction at $M_X < 10$ GeV

For $\sigma_{\text{tot}}^{pp}$ via Optical Theorem need to measure the inelastic rate.

$\sigma_{SD}(M_X < 3 \text{ GeV}) = ?$

FSCs will solve the problem.

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WHAT NEXT...

- Analysis of Castor and ZDC data: N*, neutral leading states
- Soft SD, CDE, Double Diffraction, (Soft) Evt Classification
- CMS + TOTEM data:
  - Homework: beam halo pile-up, optics, resolutions, acceptance, reconstruction ...
  - Soft and Hard CDE (differential) cross-sections
  - Further studies of particular events (common visualisation soon)
- Upgrade of TOTEM Roman Pot detectors to profit from low-β* optics after LHC shut-down
- More data welcome:
  - Data taking : 1000 bunches + x-angles @ β*=90m
Roman Pot detector system

study of combination: Si strip- Si pixel- timing (schematic)