Measuring Diffraction at the LHC
Measuring Diffraction at the LHC - Recent Results & Plans from TOTEM

- Elastic Scattering and Total Cross Section
- Single, Double and Central diffraction
- Bremsstrahlung from Elastic Events
- Classification of Diffractive Events
Leading protons: RP’s at ±147m, ±220m (and ±420m!)
Rap gaps & Fwd particle flows: T1 & T2 spectrometers
Fwd energy flows: Castor & ZDC
Fwd counters at: ±60m to ±140m - FSC’s
Roman Pots: measure elastic & diffractive protons close to outgoing beam

Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$
1. Total pp cross section with a precision of $\approx 1\%$ (5%) 

2. Elastic pp scattering:
   $10^{-3}(10^{-2}) < t = (p\theta)^2 < 10$ GeV$^2$

3. Leading particles:
   $2 \times 10^{-3} < \xi < 2 \times 10^{-1}$

Particle flows, rap gaps:
...$3.1 < \eta < 4.7$ and $5.3 < \eta < 6.5$...

$\Rightarrow$ Investigate diffractive & forward phenomena together with CMS$^+$
($= CMS+Castor+FCS+ZDC+fp420m$)
TOTEM Collaboration

- Countries: 7
- Institutes: 15
- Collaborators: ~ 100
- Authors: ~ 80
- Construction: ~ 7 MCHF

Spokesman: Simone Giani
Packag of 10 “edgeless” Si-detectors

TOTEM DETECTORS
Leading Proton Measurements

Measure the deviation of the leading proton location from the nominal beam axis ($\Rightarrow \xi$) and the angle between the two measurement locations ($\Rightarrow -t$) within a doublet.

Acceptance is limited by the distance of a detector to the beam. Resolution is limited by the transverse vx location (small $\xi$) and by beam energy spread (large $\xi$).
Correlation with the CMS Signatures.

- **e, γ, μ, τ, and b-jets:**
  - tracking: $|\eta| < 2.5$
  - calorimetry with fine granularity: $|\eta| < 2.5$
  - muon: $|\eta| < 2.5$

- **Jets, $E_T^{\text{miss}}$**
  - calorimetry extension: $|\eta| < 5$

- **High $p_T$ Objects**
  - Higgs, SUSY, ...

- **Precision physics (cross sections...)**
  - energy scale: $e$ & $μ$ 0.1%, jets 1%
  - absolute luminosity vs. parton-parton luminosity via "well known" processes such as $W/Z$ production?
Leading forward protons at ±220 meters: Low & High $\beta^*$ ($\beta^* \approx 0.55m, 90m$)

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:

$$\xi = \Delta p/p \propto x$$

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

At high $\beta^*$ ($\beta^* \approx 90m$ 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)
Dispersion – transversal deviation from the beam axis - has to be large enough for the measurement of leading protons with small fractional momentum losses.
Elastic Scattering
Elastic cross section

dσ_{el}/dt yields:

- **pp interaction radius** (slope of the dσ_{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, \( \rho = \text{Re}A(s,t)/\text{Im}A(s,t) \)

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

\( (x^*, y^*) \): vertex position

\( (\theta_x^*, \theta_y^*) \): emission angle: \( t \approx -p^2 (\theta_x^*^2 + \theta_y^*^2) \)

\( \xi = \Delta p/p \): momentum loss (diffraction)

\[ y_{\text{det}} = L_y \theta_y^* + v_y y^* \]

\( \beta^* = 90 \text{ m}: L_y = 263 \text{ m}, v_y \approx 0 \)

\( \beta^* = 3.5 \text{ m}: L_y \approx 20 \text{ m}, v_y = 4.3 \)

\( \rightarrow \) Reconstruct via track positions

\[ x_{\text{det}} = L_x \theta_x^* + v_x x^* + D\xi \]

\( \beta^* = 90 \text{ m}: L_x \approx 0, v_x = -1.9 \)

\( \beta^* = 3.5 \text{ m}: L_x \approx 0, v_x = 3.1 \)

\( \rightarrow \) Use derivative (reconstruct via local track angles):

\[ \frac{dx_{\text{det}}}{ds} = \frac{dL_x}{ds} \theta_x^* + \frac{dv_x}{ds} x^* \]

| Beam width @ vertex | Angular beam divergence | Min. reachable \(|t|\) |
|---------------------|-------------------------|---------------------------|
| \( \sigma_{x,y}^* \) | \( \sigma_{x,y}^* \) | \( |t_{\text{min}}| \) |
| \( \sqrt{\frac{\varepsilon^* \beta^*}{\gamma}} \) | \( \sqrt{\frac{\varepsilon^*}{\beta^* \gamma}} \) | \( \frac{n_s p \varepsilon^* m_p}{\beta^*} \) |

Standard optics \( \beta^* \approx 1\text{–}3.5 \text{ m} \)

\( \sigma_{x,y}^* \) small \( \sigma(\theta_{x,y}^*) \) large \( |t_{\text{min}}| \approx 0.3\text{–}1 \text{ GeV}^2 \)

Special optics \( \beta^* = 90 \text{ m} \)

\( \sigma_{x,y}^* \) large \( \sigma(\theta_{x,y}^*) \) small \( |t_{\text{min}}| \approx 10^{-2} \text{ GeV}^2 \)
2010 Data from Runs with RPs at 25σ (1.5nb⁻¹)
First p-p Elastic Scattering Event Candidates [LPCC July 2010]

Event scanning and constraining analysis procedure

S. Giani

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \beta^* = 3.5 \text{ m} \]
Proton tracks of a single diagonal – left-right coincidences

\[ \beta^* = 3.5 \, \text{m, big bunches (7 x10^{10} \, \text{p/b})} \]
RPs at 7 \( \sigma \) from beam centre

\[ \beta^* = 90 \, \text{m, small bunches (1.5 x10^{10} \, \text{p/b})} \]
RPs at 10 \( \sigma \) from beam centre

\[ t = -p^2 \theta^2 \]
\[ \xi = \Delta p / p \]

Integrated luminosity: 6.2 nbarn\(^{-1}\)
Inelastic pile-up \( \approx 0.8 \, \text{ev / bx} \)

Integrated luminosity: 1.65 \( \mu \)barn\(^{-1}\)
Inelastic pile-up \( \approx 0.005 \, \text{ev / bx} \)
after resolution unfolding:

\[ \text{top 45 - bottom 56 ; bottom 45 - top 56} \]

2 diagonals:

2 different experiments, but not 2 independent experiments

\( \rightarrow \) verification of alignment
<table>
<thead>
<tr>
<th>Correction</th>
<th>Effect on</th>
<th>Functional form</th>
<th>Total values or integral</th>
<th>Details</th>
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<tr>
<td>Recorded Luminosity</td>
<td>$d\sigma/dt$</td>
<td>const($t$)</td>
<td>Efficiency-corrected int. Luminosity</td>
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<td>$(6.03 \pm 0.36)\text{nb}^{-1}$</td>
<td>Trigger eff. $(99 \pm 1)%$</td>
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<td>Ineff. = const($t$)</td>
<td>Tot. ineff. $(30 \pm 10)%$</td>
<td>DAQ eff. $(99 \pm 1)%$</td>
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<td>mult. corr. factor = $1 + \text{ineff.}$</td>
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<td>Event reconstruction $(29 \pm 10)%$</td>
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<td>Hyperbola function:</td>
<td>$f_{A} = \left{ \begin{array}{ll} 4.96 \pm 0.05 &amp; \text{if }</td>
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<td>$d\sigma/dt$</td>
<td>Parameterisation</td>
<td>$\frac{\text{bkg.}}{\text{total}} = (8 \pm 1)%$</td>
<td>$\phi : 4.5</td>
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<td>bkg. = $1.16e^{-6.0</td>
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<td>Resolution</td>
<td>$\rightarrow d\sigma/dt$</td>
<td>$f_{\theta}(\Theta^{\ast}) = \frac{\text{measured}}{\text{unmeasured}}$</td>
<td>$f_{\theta} = \left{ \begin{array}{ll} 0.55 \pm 0.02 &amp; \text{if }</td>
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<td>Unfolding</td>
<td>$t \rightarrow d\sigma/dt$</td>
<td>mult. corr. factor</td>
<td>$\delta t/t = 0.6%</td>
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<td>$t$</td>
<td>$\delta t_{x} = \frac{2p}{(\Delta s \cdot dL_{x}/ds)\sqrt{</td>
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<td>$t$</td>
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<td>Optics</td>
<td>$t$</td>
<td>$t_{x} = f(k, \psi, p); t_{y} = f(k, \psi, p)$</td>
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<td>$\delta k = 0.1%$</td>
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<td>$k$: magnet strength</td>
<td>$\frac{\delta \psi}{dt} = 1.5%$</td>
<td>$\delta \psi = 1\text{mrad}$</td>
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<td>$\psi$: magnet rotation</td>
<td>$\frac{\delta t_{y}}{dt} = 2%$</td>
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<td>$p$: LHC beam momentum</td>
<td></td>
<td>$\delta \frac{\delta p}{p} = 10^{-3}$</td>
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TOTEM Result

\[ B = 23.6 \pm 0.5 \text{ stat} \mp 0.4 \text{ syst } \text{GeV}^{-2} \]

\[ t_{\text{dip}} = -0.53 \pm 0.01 \text{ stat} \mp 0.01 \text{ syst } \text{GeV}^2 \]
At 8 TeV the pots have to move by \( \sim 1\sigma \) closer to reach the same \( t \) as at 7 TeV.

\[ \implies \text{Challenging but possible} \]

Need to move the RPs \( 1\sigma \) closer per 1 TeV to retain the same acceptance in \( -t \).
Further analysis ongoing:

\( \beta^* = 3.5 \text{ m}: \)
Elastic scattering extended to larger t-values - up to 3.5 GeV\(^2\)

\( \beta^* = 90 \text{ m}: \)
Elastic scattering extended to smaller t-values - down to \(6 \times 10^{-3}\) GeV\(^2\)
Include inelastic triggers (T1, T2, zero bias)

→ Total cross section with the luminosity independent method
Extended low-t limit

Raw distribution
(to be corrected for acceptance, ...)

$6 \times 10^{-3}$
ELASTIC AND
TOTAL CROSS SECTION
Cross-Section Formulae

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

Using luminosity from CMS: \[ \frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt} \]

and \( \rho \) from COMPETE fit: \( \rho = 0.14^{+0.01}_{-0.08} \)

\[ \sigma_{TOT} = \sqrt{19.20 \text{ mb GeV}^2} \cdot \left. \frac{d\sigma_{EL}}{dt} \right|_{t=0} \]

\[ \sigma_{TOT} = \sigma_{EL} + \sigma_{INEL} \]
“Raw Data” Jun’11 – Vertical RPs@10σ

\( \beta^* = 90 \text{ m} \)

\( L_y \sim 260 \text{ m} \)
\( L_x \sim 0-3 \text{ m} \)

Integrated luminosity : 1.65 \( \mu \text{barn}^{-1} \)

Inel. pile-up \( \sim 0.005 \) ev/bx
TOTEM: pp Elastic Cross-Section

Exponential slope:
\[ B \bigg|_{t=0} = 20.1 \text{GeV}^{-2} \]

Extrapolation to \( t = 0 \):
\[ \left. \frac{d\sigma}{dt} \right|_{t=0} = 5.037 \times 10^2 \text{mb/GeV}^2 \]

Integral Elastic Cross-Section
\[ \sigma_{\text{EL}} = 8.3 \text{mb}^{(extrapol) \, + 16.5 \text{mb}^{(measured)} = 24.8 \text{mb} \]
TOTEM: pp Total Cross-Section

Elastic exponential slope:

\[ B_{t=0} = (20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}}) \text{ GeV}^{-2} \]

Elastic diff. cross-section at optical point:

\[ \left. \frac{d\sigma_{el}}{dt} \right|_{t=0} = (503.7 \pm 1.5^{\text{stat}} \pm 26.7^{\text{syst}}) \text{ mb / GeV}^2 \]

Optical Theorem, \( \rho = 0.14^{+0.01}_{-0.08} \)

Total Cross-Section

\[ \sigma_T = \left( 98.3 \pm 0.2^{\text{stat}} \pm 2.7^{\text{syst}} \begin{bmatrix} +0.8 \\ -0.2 \end{bmatrix}^{\text{syst from } \rho} \right) \text{ mb} \]
TOTEM: pp Inelastic Cross-Section

\[ \sigma_{el} = \left( 24.8 \pm 0.2^{(\text{stat})} \pm 1.2^{(\text{syst})} \right) \text{mb} \]

\[ \sigma_T = \left( 98.3 \pm 0.2^{(\text{stat})} \pm 2.7^{(\text{syst})} \right) \text{mb} \left[ \begin{array}{c} +0.8 \\ -0.2 \end{array} \right]^{(\text{syst from } \rho)} \]

Inelastic Cross-Section

\[ \sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left( 73.5 \pm 0.6^{(\text{stat})} \right) \left[ \begin{array}{c} +1.8 \\ -1.3 \end{array} \right]^{(\text{syst})} \text{mb} \]

\[ \sigma_{inel} (\text{CMS}) = (68.0 \pm 2.0^{(\text{syst})} \pm 2.4^{(\text{lumi})} \pm 4.0^{(\text{extrap})}) \text{mb} \]

\[ \sigma_{inel} (\text{ATLAS}) = (69.4 \pm 2.4^{(\text{exp})} \pm 6.9^{(\text{extrap})}) \text{mb} \]

\[ \sigma_{inel} (\text{ALICE}) = (72.7 \pm 1.1^{(\text{mod})} \pm 5.1^{(\text{lumi})}) \text{mb} \]
PLANS for 2012:

Optics with $\beta^* \sim 800 - 1000$ m

$\Rightarrow$ Elastic scattering down to the Coulomb region ($|t| \sim 5 \times 10^{-4}$ GeV$^2$)

$\Rightarrow$ Measurement of $\rho$

At $\sqrt{s} = 8$ TeV, measure large-t elastic scattering

Common triggering/data taking with CMS commisioned
Single Diffraction (SD)

Central Exclusive Diffraction (CDE):

Forward multiplicities
Forward Detectors – Mass Selectors

Calculate using the rap gap:

\[ \ln M_x^2 = \Delta \eta \]

Access to small \( M_x \) iff forward detectors at \( |\eta| > 5 \).

T1, T2 and the FSCs see diffractive systems with decreasing masses – a natural way to select.
EFFICIENCY OF DETECTING SD EVENTS

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

J.W. Lämsä & RO
Diffractive forward protons @ RPs

\[ y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^* \]
\[ x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s) \]

Dispersion shifts diffractive protons in the horizontal direction

For low-\( \beta^* \) optics \( L_x, L_y \) are low
\( v_x, v_y \) are not critical because of small IP beam size

\( L_x=0, L_y \) is large
beam \( \sigma = 212 \mu \text{m} \) → \( v_x, v_y \) important (deterioration of rec. resolution)
Single diffraction low $\xi$

Correlation between leading proton and forward detector $T_2$

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

\[ M_x^2 = \xi s \]

run: 37280003, event: 3000
Single diffraction large $\xi$

correlation between leading proton and forward detector T2

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

\[ M_x^2 = \xi s \]
**Raw distribution** (to be corrected for acceptance, ...)

---

Single proton with T2 tracks on opposite side

$\beta^* = 90$ m, RP@6.5$\sigma$ – Oct 11

$B \sim 10$ GeV$^{-2}$
Central Exclusive Diffraction (CED)
correlation between leading protons and forward detector T2

run: 37220007, event: 9904
Data Oct’11: Elastic + CDE
Angular correlations

Preliminary
Data Oct’11: CDE (as logic complement to the elastic tag)

DPE RP candidates
Data Oct’11: CDE Cross-Section

DPE RP candidates t-distribution
B=10 GeV$^{-2}$

Raw distribution
(to be corrected for acceptance, ...)

$\sim 8 \times 10^{-3}$ GeV$^2$
Example of CDE Mass Reconstruction

\[ \xi_1 < 1.5\%; \quad \xi_2 > 5.0\% \]

Low-\(\beta\)
RP vertical
RP horizontal
T2
CED Mass Measurement at 420m…

Mass resolution vs. central mass assuming $\Delta x_F/x_F = 10^{-4}$

$\Delta M = (1.5 - 3.0)$ GeV ($\Delta x_F/x_F = (1-2)\times10^{-4}$)

Stable result since 2001.

A historical note....

J.W. Lämsä, R.O.

| 20 GeV < $M_X$ < 160 GeV |

$M_{X_{\text{max}}}$ determined by the aperture of the last dipole, B11,
$M_{X_{\text{min}}}$ by the minimum deflection = 5mm

Workshop on Diffractive Physics
4. – 8. February 2002
Rio de Janeiro, Brazil
Double Diffraction

• Event Selection Scenarios
  – use T1 veto on both sides
  – if FSCs (ZDCs) in use: use T1 veto on the opposite side and/or T2 veto on both sides
  – event classification schemes
CED Extended
- Use T1, T2 & FSCs as Diffractive Mass Selectors to Tag CED Processes:

- $pp \rightarrow p + X + p^*$
- $pp \rightarrow p^* + X + p$
- $pp \rightarrow p^* + X + p^*$
Small Mass Diffractive States
Single Diffraction at $M_X < 10$ GeV

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

$\sigma_{\text{SD}}(M_X<10$ GeV) =?

L. Jenkovzsky, O. Kuprash, J.W. Lämsä, V. Magas, RO
Forward Multiplicities
$dN/d\eta$ from ALICE, ATLAS, CMS, LHCb & TOTEM-T2

- ALICE Data. Inelastic, $N_{ch} > 0$ in $|\eta| < 1$
- ATLAS Data. Inelastic, $N_{ch} \geq 2$ in $|\eta| < 2.5$, $p_{T} > 0.1$ GeV/c
- CMS Data (NSD)
- TOTEM-T2 Data. Inelastic, at least 1 Track in $5.3 < |\eta| < 6.5$, $p_{T} > 30$ MeV/c

T1 coming soon
The experimental points (black squares) represent the average of the 4 T2 quarters, with the error bars including both statistical and systematic error.

Red triangles, blue circles, green circles and orange diamonds show the Phojet, Pythia8, Pythia6 and Sherpa predictions for charged particles with $P_T > 40\text{MeV/c}$ in events where at least one charged particle is generated in the $5.3 < |\eta| < 6.5$ range.
Bremsstrahlung in Elastic pp Events
Due to very small momentum transfer in forward radiation, theoretical uncertainties are minimized → direct relation between the photon spectra and $\sigma_{el}$

- Bremsstrahlung cross section is large enough $\sim 0.18 \times 10^{-3}$ of $\sigma_{el}$

Work in progress: Forward Physics at the LHC, Detecting Elastic pp Scattering by Radiative Photons.

Road map

• Use Totem measured $\sigma_{el}$ and have independent measure of the elastic slope (or vice versa)

• The ZeroDegreeCalorimeter (ZDC) for detecting the bremsstrahlung gammas - the Forward Shower Counters (FSC) to veto backgrounds.

• The set-up of the proposed measurement with $k=50-500$ GeV and for 3.5 x 3.5 TeV and/or 4 x 4 TeV.
ND BACKGROUND vs. BREMSSTRAHLUNG PHOTONS

ND background

pp → ppγ
Classifying Diffractive Events
Figures: Left: Charged particle multiplicity distribution for double diffractive (DD) events. Right: Distributions after subtraction of MC truth. Comparison of soft classification (soft kNN) and hard classification (hard kNN & neural network).
TOTEM ⊕ CMS RUN SCENARIOS
TOTEM + CMS run scenarios

- **Soft diffraction**: \( \text{pp} \to \text{pX} \), \( \text{pp} \to \text{pXp} \)
- **(semi)-hard diffraction**: \( \text{pp} \to \text{pjjX} \), \( \text{pp} \to \text{pjjXp} \)
- **Hard diffraction**: \( \text{pp} \to \text{pjj} \) (bosons, heavy quarks, Higgs...)

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<th>( \beta^* (\text{m}) )</th>
<th>TOTEM LHC runs</th>
<th>Standard LHC runs</th>
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<td>1540</td>
<td>( 10^{29} )</td>
<td>( 10^{30} )</td>
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<tr>
<td>90</td>
<td>( 10^{30} )</td>
<td>( 10^{32} )</td>
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<td>2</td>
<td>( 10^{32} )</td>
<td>( 10^{34} )</td>
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**Luminosity**

- **TOTEM LHC runs**
- **Standard LHC runs**

S. Giani
TOTEM Analysis Plans

- **Full** *t*-range pp elastic differential cross-section
- **Total** cross-section from elastic differential cross-section at extended lower *t* limit (using CMS lumi)
- **Total** cross-section with lumi-independent method (using inelastic rate T1+T2)
- **SD, DD, CDE,**... differential cross-sections in *t*
- **SD, DD, CDE,**... channels: ξ, mass, rapidity gaps, event classification!
- **Forward multiplicities -** dN/dη
- **HI** runs (in future pA) jointly with CMS