Total, elastic and inelastic p-p cross sections at the LHC

Tomáš Sýkora, Charles University in Prague

on behalf of the

ATLAS, CMS, LHCb and TOTEM collaborations

ICHEP 2016, August 3 - 10, 2016, Chicago
• total cross section $\sigma_{\text{tot}}$ of proton-proton interaction

• rising $\sigma_{\text{tot}}$, Regge model, pomeron

• measurements of $\sigma_{\text{tot}}$ by
  and
  • TOTEM - total cross-section, Elastic scattering and diffraction dissociation Measurement the LHC; dedicated experiment

  and their comparison

• inelastic cross section $\sigma_{\text{inel}}$ at LHC including measurements at 13 TeV by
  and
  • CMS

  and their comparison with results of ALICE, LHCb and TOTEM

• outlook
total cross section $\sigma_{\text{tot}}$ of proton-proton interaction

- $\sigma_{\text{tot}}$ of p-p interaction is a fundamental quantity giving the upper bound on probability (cross section) of any process in p-p collisions
- 1973 – Intersection Storage Rings (ISR): rising of $\sigma_{\text{tot}}$ value
- measurement of $\sigma_{\text{tot}}$ at LHC energies – TOTEM and ALFA
- at higher energies (57 TeV) – cosmic showers, Auger experiment
rising $\sigma_{\text{tot}}$, Regge model, pomeron

- using optical theorem and Regge theory we can write for a process

$$\sigma_{\text{tot}} \approx s^{\alpha(0)-1}$$

$$s = (p_1 + p_2)^2$$

$$\frac{d\sigma_{\text{el}}}{dt} \approx s^{2(\alpha(0)-1)} e^{-B|t|}$$

$$B = B_0 + 2\alpha' \ln s$$

where $\alpha(0)$ is so-called intercept of a Regge trajectory

$$\alpha(t) = \alpha(0) + \alpha't$$

$$t = (p_1 - p_2)^2 \approx -(p_0 \theta)^2, |p_1| = |p_2| = p_0$$

- if $\alpha(0) > 1$, $\sigma_{\text{tot}}$ will rise with rise of $s$

- trajectory with $\alpha(0) > 1$ has only one “particle” – pomeron $P$

- $\sigma_{\text{tot}}$ is not calculable in the framework of the perturbative QCD; Regge model is used in HEP generators to describe kinematic area where the QCD cannot be applied
measurement of total cross section $\sigma_{\text{tot}}$
ways of measurement of $\sigma_{\text{tot}}$

- **direct ($\rho$-independent) measurement** of $\sigma_{\text{tot}} = \frac{N_{\text{tot}}}{L}$, where $N_{\text{tot}}$ is total number of events with interaction, $L$ is luminosity, is nontrivial (due to limited acceptance, model dependence)

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$

$$\sigma_{\text{inel}} = \sigma_{\text{inel diffractive}} (\sigma_{\text{SD}} + \sigma_{\text{DD}} + \ldots) + \sigma_{\text{non diffractive}}$$

- **traditional way (ISR)** of $\sigma_{\text{tot}}$ measurement – via elastic cross section measurement and the use of optical theorem

$$\sigma_{\text{tot}} = 4\pi \text{ Im}[f_{\text{el}}(t = 0)]$$

where $f_{\text{el}}$ is elastic amplitude

$$\rho = \frac{\text{Re } f(0)}{\text{Im } f(0)}$$

luminosity dependent measurement,

$$N_X$$ - number of events of $X \in \{\text{el, tot, inel, \ldots}\}$ type

$$\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{\langle dN_{\text{el}}/dt \rangle_{t=0}}{N_{\text{tot}}}$$

luminosity independent measurement

---

3-August-16

Tom Sykora: Total, elastic and inelastic pp cross sections at the LHC
elastic differential rate

- to establish \( \left( \frac{dN_{el}}{dt} \right)_{t=0} \) we need to measure distribution covering very small angles
- appropriate accelerator optics: separation of elastically scattered protons from beam & beam halo, a small divergence of the beams at interaction point, monoenergetic beam, knowledge of the optics, knowledge of luminosity, …
ATLAS ALFA method

\[
\frac{d\sigma_{el}}{dt} = \frac{1}{16\pi} \left| f_N(t) + f_C(t)e^{i\alpha \phi(t)} \right|^2
\]

coulomb amplitude

\[ f_C(t) = -8\pi a_h c \frac{G^2(t)}{|t|} \]

nuclear amplitude

\[ f_N(t) = (\rho + i) \frac{\sigma_{tot}}{\hbar c} e^{-B|t|/2} \]

phase

\[ \phi(t) = -\ln \frac{B|t|}{2} - \phi_C \]

proton form factor

\[ G(t) = \left( \frac{\Lambda}{\Lambda + |t|} \right)^2 \]

Pythia 8 - values

| $\rho$ | 0.14 |
| $\Lambda$ | 0.71 GeV$^2$ |
| $\phi_C$ | 0.577 |

for an illustration, from ATLAS ALFA TDR, CERN/LHCC 2008-04

\[ B = 18 \text{ GeV}^2, \sigma_{tot} = 100 \text{ mb} \]

\[ \rho = 0.15 \]

\[ \rho = 0 \]

\[ \rho = 0, \alpha = 0 \]

ALFA fit $\in [0.014 - 0.1]$
ALFA fit result, 8 TeV, $\beta^* = 90$ m

\[ \sigma_{\text{tot}} = 96.07 \pm 0.18 \, \text{(stat.)} \pm 0.85 \, \text{(exp.)} \pm 0.31 \, \text{(extr.)} \, \text{mb} \]

\[ \sigma_{\text{el}} = 24.33 \pm 0.04 \, \text{(stat.)} \pm 0.39 \, \text{(syst.)} \, \text{mb} \]

Fit range set to 0.014-0.1 GeV^2 where acceptance > 10% and non-exponential terms expected to be negligible (<0.1)
Tom Sykora: Total, elastic and inelastic pp cross sections at the LHC

3-August-16

ATLAS ALFA vs earlier measurements

\[ \sigma_{\text{tot}} = (98.3 \pm 2.8) \text{ mb} \] (EPL 96 (2011) 21002)

\[ \sigma_{\text{tot}} = (98.6 \pm 2.2) \text{ mb} \] (EPL 101 (2011) 21004)

\[ \sigma_{\text{el}} = (95.35 \pm 0.6) \text{ mb} \] (Nuclear Physics, B (2014) 889)

\[ \sigma_{\text{tot}} = (101.7 \pm 2.9) \text{ mb} \] (Phys. Rev. Lett. 111, 012001 (2013))

\[ \sigma_{\text{el}} = (27.1 \pm 1.4) \text{ mb} \]
fitting ATLAS ALFA data with other models

<table>
<thead>
<tr>
<th>Model</th>
<th>( \sigma_{\text{tot}} \text{[mb]} )</th>
<th>( f_N(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>( 96.07 \pm 0.86 )</td>
<td>( f_N(t) = (\rho + i) \frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2} )</td>
</tr>
<tr>
<td>( Ct^2 )</td>
<td>( 96.16 \pm 0.80 )</td>
<td>( f_N(t) = (\rho + i) \frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2-Ct^2/2} )</td>
</tr>
<tr>
<td>( c\sqrt{-t} )</td>
<td>( 96.40 \pm 0.80 )</td>
<td>( f_N(t) = (\rho + i) \frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2-c/2(\sqrt{4\mu^2-t^2}-2\mu)} ), ( \mu = m_{\pi} )</td>
</tr>
<tr>
<td>SVM</td>
<td>( 96.16 \pm 0.80 )</td>
<td>( f_N(t) = \rho \frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_R t/2} + i \frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_1 t/2} )</td>
</tr>
<tr>
<td>BP</td>
<td>( 96.81 \pm 0.95 )</td>
<td>( f_{\text{el}}(t) = i \left[ G^2(t) \sqrt{A} e^{-Bt/2} + e^{i\phi} \sqrt{C} e^{-Dt/2} \right] )</td>
</tr>
<tr>
<td>BSW</td>
<td>( 96.67 \pm 0.99 )</td>
<td>( \text{Re} f_{\text{el}}(t) = c_1(t_1 + t)e^{-b_1 t/2} ), ( \text{Im} f_{\text{el}}(t) = c_2(t_2 + t)e^{-b_1 t/2} )</td>
</tr>
</tbody>
</table>

RMS of models 0.28 mb, simple model 0.31 mb -> all looks mutually consistent
non exp. fit for elastic differential cross section

\[ N_b = 2: \sigma_{\text{tot}} = (101.5 \pm 2.1) \text{ mb} \]
\[ N_b = 3: \sigma_{\text{tot}} = (101.9 \pm 2.1) \text{ mb} \]

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

Nuclear Physics B 899 (2015) 527–546

non exp. fit for elastic differential cross section & CNI effect

\[ N_b = 3 \text{ (central)}: \sigma_{\text{tot}} = (102.9 \pm 2.3) \text{ mb} \]
\[ N_b = 3 \text{ (peripheral)}: \sigma_{\text{tot}} = (103.0 \pm 2.3) \text{ mb} \]

8 TeV, \( \beta^* = 1 \text{ km} \)
central, peripheral – profile function shape in impact parameter space, depending on used nuclear phase model

measurement of inelastic cross section $\sigma_{\text{inel}}$
1) establish integrated luminosity $\int L \, dt$

2) in the same period measure a number of interactions $N$, e.g. via measuring a minimum energy deposition in a detector (Minimum Bias Trigger Scintillator for ATLAS, Hadron Forward CALorimeter & Centauro And STrange Object Research for CMS)

3) correct for detection efficiency – $\varepsilon$

4) correct for the possibility of having more than one interaction per bunch crossing, i.e. pileup, $F_{pu}$

$$\sigma_{\text{inel}} = \frac{N \, F_{pu}}{\varepsilon \int L \, dt}$$
situations before 13 TeV measurements

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ \sigma_{\text{inel}} = 66.9 - 73.7 \text{ mb} \]

\[ \sqrt{s} = 8 \text{ TeV} \]
\[ \sigma_{\text{inel}} = 74.7 \pm 1.7 \text{ mb} \]
\[ \sigma_{\text{inel}} = 71.78 \pm 0.71 \text{ mb} \]
ATLAS – $\sigma_{\text{inel}}$ at 13 TeV

arXiv:1606.02625

- MBTS – significantly upgraded for LHC RUN II
- 2 cm thick discs in front of forward calorimeters, made of highly efficient polystyrene scintillator
- trigger requires signal at least in one MBTS counter
- inclusive selection - at least 2 of 24 MBTS counters have to collect charge above the threshold
MBTS acceptance depends on $M_X$, required acceptance $> 50\% \rightarrow M_X > 13$ GeV & $\xi M_X = M_X^2/s > 10^{-6}$

uncertainty on extrapolation to full cross-section given by variations of model $\xi$-dependencies

try to minimize the impact of physics mismodeling within the fiducial range of the measurement by constraining the fraction of diffractive events

we get diffractive-enhanced sample by requiring hits in only one side of MBTS

$\alpha(t) = 1 + e + \alpha' t$

Regge trajectory
ATLAS – mc tuning and fiducial $\sigma_{\text{inel}}$

\[ R_{SS} \equiv \frac{\text{Number of events in single-sided sample}}{\text{Number of events in inclusive sample}} \]

- $R_{SS}$ depends on diffractive fraction $f_D \equiv (\sigma_{SD} + \sigma_{DD})/\sigma_{\text{inel}}$
- $R_{SS}$ in data = 10.4 ± 0.5%
- for each generator/tune, $f_D$ tuned to match $R_{SS}$ measured in data e.g. $f_D(\text{Pythia DL}) = 25\%$

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

\[ \sigma_{\text{inel}}^{\text{fid}} = 68.1 \pm 0.6 \text{ (exp.)} \pm 1.3 \text{ (lum.) mb} \]
\[ \sigma_{\text{inel}} = \sigma_{\text{inel}}^{\text{fid}} + \sigma_{7\text{ TeV}}^{\text{MC}}(\xi < 5 \times 10^{-6}) \times \frac{\sigma_{7\text{ TeV}}^{\text{MC}}(\xi < 5 \times 10^{-6})}{\sigma_{7\text{ TeV}}^{\text{MC}}(\xi < 5 \times 10^{-6})} \]

\[ \sigma_{\text{inel}} = 79.3 \pm 0.6 \text{ (exp.)} \pm 1.3 \text{ (lum.)} \pm 2.5 \text{ (extrap.) mb} \]
CMS – forward detectors and $\sigma_{\text{inel}}$ at 13 TeV

**Hadronic Forward CAL (CMS)**

- $3.152 < |\eta| < 5.205$

**TOTEM**

- T1 and T2 are used to detect charged particle in inelastic events

**CASTOR (CMS)**

- $3.1 < |\eta| < 4.7$
- $5.3 < |\eta| < 6.5$

- $-6.6 < \eta < -5.2$

Roman Pots detect elastic and diffractive protons close to outgoing beam

~ 10 m

~ 220 m

3-August-16

Tom Sykora: Total, elastic and inelastic pp cross sections at the LHC
CMS HFCAL and CASTOR

HFCAL

- 18 iron azimuthal wedges, with embedded quartz fibers running along the beam direction
- each wedge is subdivided into 13 pseudorapidity segments (towers)

CASTOR

- tungsten and quartz layers, 14.385 m from IP
- segmented in 16-sectors and 14 $z$-modules, in total 224 cells.
- CASTOR was only partially included in the detector setup during the run periods considered in this analysis
CMS – runs conditions and systematics

$$\eta_{\text{min}}$$

$$M_Y \left\{ \begin{array}{c}
\text{Largest Gap}
\end{array} \right\} M_X$$

$$\xi_X = \frac{M_X^2}{s}, \quad \xi_Y = \frac{M_Y^2}{s} \quad \xi = \max(\xi_X, \xi_Y)$$

- $$\epsilon_X$$ – fraction of selected stable-particle level events that fulfill the detector-level offline selection criteria
- $$b_X$$ – the contamination – fraction of detector-level offline selected events that are not part of the considered stable-particle level phase space domain

**Table:**

<table>
<thead>
<tr>
<th>Run</th>
<th>Purity (%)</th>
<th>Pileup (%)</th>
<th>Particle level cross section (mb) $\xi_X &gt; 10^{-6}$</th>
<th>Particle level cross section (mb) $\xi_X &gt; 10^{-7}$ or $\xi_Y &gt; 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>254989</td>
<td>98.54</td>
<td>52.29</td>
<td>$65.60 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>255019</td>
<td>99.18</td>
<td>53.72</td>
<td>$65.89 \pm 0.04$</td>
<td></td>
</tr>
<tr>
<td>255029</td>
<td>99.25</td>
<td>53.95</td>
<td>$65.74 \pm 0.04$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run</th>
<th>Purity (%)</th>
<th>Pileup (%)</th>
<th>Particle level cross section (mb) $\xi_X &gt; 10^{-7}$ or $\xi_Y &gt; 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>247324</td>
<td>98.53</td>
<td>5.14</td>
<td>$67.08 \pm 0.46$</td>
</tr>
<tr>
<td>247920</td>
<td>98.85</td>
<td>34.18</td>
<td>$66.84 \pm 0.07$</td>
</tr>
<tr>
<td>247934</td>
<td>98.78</td>
<td>31.99</td>
<td>$66.84 \pm 0.09$</td>
</tr>
</tbody>
</table>

$$\sigma = \frac{N_{\text{int}}(1-b_X)}{\epsilon_X \int \mathcal{L} \, dt}$$
The measured cross section is significantly lower than predicted by models for hadronic scattering and ATLAS.

\[
\sigma \left( \xi > 10^{-6} \right) = 65.8 \pm 0.8 \text{ (exp.)} \pm 1.8 \text{ (lum.) mb}
\]

\[
\sigma \left( \xi_x > 10^{-7} \text{ or } \xi_y > 10^{-6} \right) = 66.9 \pm 0.4 \text{ (exp.)} \pm 2.0 \text{ (lum.) mb}
\]

\[
\sigma_{\text{inel}} = 71.3 \pm 0.5 \text{ (exp.)} \pm 2.1 \text{ (lum.)} \pm 2.7 \text{ (ext.) mb}
\]
outlook

ATLAS ALFA

• ongoing analysis of 8 TeV data for $\beta^* = 1$ km – cross sections, B and rho parameters
• measurement covering CNI region for $\beta^* = 2500$ m at 13 TeV, fall of 2016 – planned 1 week of data taking

TOTEM

• ongoing cross sections analyses at 2.76 TeV for $\beta^* = 11$m and at 13 TeV for $\beta^* = 90$ m
• a new publication in preparation for $\beta^* = 1$ km, confirming the previously obtained results by TOTEM
• measurement covering CNI region for $\beta^* = 2500$ m at 13 TeV – cross sections, rho measurement, common week with ALFA
• search for oderon

LHCb

• inelastic cross section at 13 TeV, end of 2016
outlook

• understanding of differences: ALFA vs TOTEM, ATLAS vs CMS… and

• measurements at 14 TeV
optics

- no sextupoles between IP and RPs -> movement in $x$ and $y$ planes independent
- elastic proton (no dispersion), deflected in the IP from a vertex position $x$, under an angle $\theta_x$ arrives to detector

$$\begin{pmatrix} \chi \\ \theta_x \end{pmatrix}_{\text{RP}} = M_{\text{IP}\rightarrow\text{RP}} \begin{pmatrix} \chi \\ \theta_x \end{pmatrix}_{\text{IP}}, M_{\text{IP}\rightarrow\text{RP}} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

- in case of parallel to point optics

$$x_{\text{RP}} = L_x^{\text{eff}} \theta_{x_{\text{IP}}}$$

i.e. the scattering angle

$$\theta_{\text{IP}} = \sqrt{\theta_{x_{\text{IP}}}^2 + \theta_{y_{\text{IP}}}^2}$$

and

$$t = -p_0^2 \theta_{\text{IP}}^2$$

can be directly written as function of $x_{\text{RP}}$
event selection

both TOTEM and ALFA have the same event selection logic although technically differently realized

ALFA

- Lvl1 elastic trigger
- good LBs based on data quality
- geometrical cuts
- elastics selections
background

ways to estimate the irreducible background under the elastic peak:

• counting events in the anti-golden configuration, can also be used to get a $t$-spectrum for background events for subtraction – nominal method for ALFA

• reconstructing the vertex distribution in $x$ through the lattice, where background appears in non Gaussian tails, fraction estimated with background templates obtained from data – nominal for systematics ALFA, nominal TOTEM)

• TOTEM uses the non-colliding bunches to estimate the level of beam-gas background for the measurement of the inelastic rate
where $\Delta t_i$ is width of the $i$-th bin, $M^{-1}$ represents the unfolding procedure applied to the background-subtracted number of events $N_i-B_i$, $A_i$ is the acceptance, $\epsilon_{\text{reco}}$ is the event reconstruction efficiency, $\epsilon_{\text{trig}}$ is the trigger efficiency, $\epsilon_{\text{DAQ}}$ is the dead-time correction and $L_{\text{int}}$ is the integrated luminosity.
unfolding

Iterative dynamically stabilized unfolding used, cross-checked with bin-by-bin and singular value decomposition methods, unfolding impact for subtraction method is very small

Data/MC ratio at reconstruction level is parametrized to re-weight the simulation. The data-driven closure test consists of the comparison of the unfolded modified reconstruction level spectrum with the modified particle level spectrum.
reconstruction & reco efficiency

\[ \theta_w^* = \frac{w_A - w_C}{M_{12,A} + M_{12,C}} \]

\[ \theta_w^* = \frac{\theta_{w,A} - \theta_{w,C}}{M_{22,A} + M_{22,C}} \]

\[ \theta_w^* = M_{12}^{-1} \times w + M_{22}^{-1} \times \theta_w \]

reco eff: fully data-driven method, using a tag-and-probe approach exploiting elastic back-to-back topology and high trigger efficiency

\[ \varepsilon_{\text{rec}} = \frac{N_{\text{reco}}}{N_{\text{reco}} + N_{\text{fail}}} = \frac{N_{4/4}}{N_{4/4} + N_{3/4} + N_{2/4} + N_{1/4} + N_{0/4}} \]

\[ \varepsilon_{\text{arm1}} = 0.9050 \pm 0.0003_{\text{stat}} \pm 0.0034_{\text{syst}} \]

\[ \varepsilon_{\text{arm2}} = 0.8883 \pm 0.0003_{\text{stat}} \pm 0.0045_{\text{syst}} \]
• several constraints were recorded to fine-tune the transport matrix elements
• they are obtained from correlations in the positions/angles or by comparing the reconstructed scattering angle from different methods based on different transport matrix elements

the difference in reconstructed scattering angle in horizontal plane between subtraction and local angle method vs $\Theta^*_x$ from subtraction -> scaling factor $R(M12/M22)$
TOTEM further (preliminary) measurements

- New energies
- Higher statistics
- Movement of dip

\( \sqrt{s} = 2.76 \text{ TeV (arbitrary normalisation)} \)
- \( \beta^* = 11 \text{ m, VERY PRELIMINARY!} \)
- \( \sqrt{s} = 7 \text{ TeV} \)
- \( \beta^* = 3.5 \text{ m} \)
- \( \beta^* = 90 \text{ m} \)
- \( \sqrt{s} = 8 \text{ TeV (scaled 10x)} \)
- \( \beta^* = 90 \text{ m, PRELIMINARY!} \)
- \( \beta^* = 90 \text{ m} \)
- \( \beta^* = 1000 \text{ m} \)
- \( \sqrt{s} = 13 \text{ TeV (arbitrary normalisation)} \)
- \( \beta^* = 90 \text{ m, VERY PRELIMINARY!} \)