New Results on Elastic, Diffractive and Exclusive Processes

K. Österberg,
Department of Physics & Helsinki Institute of Physics, University of Helsinki
on behalf of
the LHC collaborations

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Elastic pp scattering, total and inelastic pp cross-section
Central Exclusive Production
Photon-photon collisions

Concentrate on recent LHC results and trends with some personal preferences!

Apologies to all producing interesting theoretical work & experimental results not being covered!
Elastic scattering, total and inelastic cross-section

Physics motivation:
- Proton structure
- Non-perturbative QCD phenomena
- Soft diffraction
- Input to cosmic airshower modelling
- ....
Elastic pp scattering @ $\sqrt{s} = 13$ TeV

- Photon exchange
- "Diffractive cone"
- "Coulomb-nuclear interference" (CNI) region
- $\beta^* = 2.5$ km, RPs @ 3σ
- $\beta^* = 90$ m, RPs @ 10σ

"Pomeron" exchange
"Perturbative QCD" (pQCD) region

Elastic pp scattering: trends

|t|-value of dip position decreases with increasing \( \sqrt{s} \)

diffractive slope parameter \( B = \frac{d}{dt} \ln \left( \left| \frac{d\sigma}{dt} \right|_{t=0} \right) \) increase with \( \sqrt{s} \)

TOTEM measurement @ \( \sqrt{s} = 2.76 \) TeV:

\[ B = 17.10 \pm 0.26 \text{ GeV}^{-2} \ (d\sigma_{el}/dt \propto e^{-B|t|}) \]

For details ⇒ see F. Nemes talk on Tuesday

B \propto \ln \sqrt{s} \rightarrow \ln \sqrt{s^2} @ LHC: larger impact from contribution of multi-Pomeron exchanges

A. Donnachie and P. V. Landshoff, arXiv1112.2485;
V. A. Schegelsky and M. G. Ryskin, PRD 85 (2012) 094024
Elastic pp scattering: non-exponentiality

- Diffractive cone looks almost "perfectly exponential" magnify deviations \( \Rightarrow (d\sigma_{el}/dt - \text{ref. exp.})/\text{ref. exp.} \).

Pure (constant B) exponential slope excluded with > 7\( \sigma \) @ \( \sqrt{s} = 8 \text{ TeV} \)

\[ \text{TOTEM collaboration, NPB 899 (2015) 527} \]

Can only be due to hadronic amplitude having a non-purely exponential slope

\[ \text{TOTEM collaboration, EPJC 76 (2016) 661} \]

Not only one single hadronic elastic pp scattering diagram \( \Rightarrow \) multiple exchange channels exists

\[ \text{A.D. Martin, V.A. Khoze, M.G. Ryskin, JPG 42 (2015) 025003; D.A. Fagundes et al., IJMPA 31'(2016) 1645022} \]

Similar effect observed at \( \sqrt{s} = 13 \text{ TeV} \)
Study elastic pp scattering in CNI region at very low $|t|$ able to measure:

$$\rho \equiv \Re A^{\text{had}} / \Im A^{\text{had}}|_{t=0}$$

**TOTEM measurement @ $\sqrt{s} = 8$ TeV:** $\rho = 0.12 \pm 0.03$

*$\alpha^*$ $= 2.5$ km $@ \sqrt{s} = 13$ TeV $\Rightarrow \sigma(\rho) = 0.01$

LHC high $\beta^*$ run @ low $\sqrt{s}$ (0.65 – 0.9 TeV) in 2018?
Elastic pp CNI study: implications

CNI with constant B and constant hadronic phase (labelled ”SWY”) excluded by TOTEM 8 TeV data ⇒ usage of most common CNI formula, simplified West-Yennie (SWY) not valid (since above conditions required)

|t|-dependence of hadronic phase: controls behaviour in impact parameter space (b)

considered 2 options:
+ central: black
+ peripheral: blue

TOTEM 8 TeV data compatible with both ⇒ elastic pp scattering not necessarily central

Most common description:

$\langle |b| \rangle_{el} < \langle |b| \rangle_{inel}$
$\sigma_{\text{tot}}, \sigma_{\text{inel}}, \sigma_{\text{el}} \text{ vs } \sqrt{s}$

**Luminosity independent method:**

$$\sigma_{\text{tot}} = \frac{16\pi}{(1 + \rho^2)} \frac{(dN_{\text{el}}/dt)_{t=0}}{(N_{\text{el}} + N_{\text{inel}})}$$

**TOTEM @ \( \sqrt{s} = 2.76 \) TeV \((\rho = 0.145)\):**

- $\sigma_{\text{tot}} = 84.7 \pm 3.3$ mb
- $\sigma_{\text{inel}} = 62.8 \pm 2.9$ mb
- $\sigma_{\text{el}} = 21.8 \pm 1.4$ mb

For details ⇒ see F. Nemes talk on Tuesday

**ALICE @ \( \sqrt{s} = 2.76 \) TeV:**

- $\sigma_{\text{inel}} = 62.8 \pm 2.4 \pm 1.2$ mb

*ALICE coll., EPJC 73 (2013) 2456*
$\sigma_{\text{tot}}$ @ LHC energies

**ATLAS @ $\sqrt{s} = 8$ TeV:** $\sigma_{\text{tot}} = 96.07 \pm 0.18$ (stat.) $\pm 0.85$ (exp.) $\pm 0.31$ (ext.) mb

*ATLAS collaboration, PLB 761 (2016) 158*

Luminosity dependent method:

$$\sigma_{\text{tot}}^2 = \frac{16\pi}{(1 + \rho^2)} \frac{1}{\mathcal{L}} \left( \frac{dN_{\text{el}}}{dt} \right)_{t=0}$$

$|t| > 0.014$; B constant, CNI taken into account, $\mathcal{L}$ and $\rho$ external input

**TOTEM @ $\sqrt{s} = 8$ TeV:**

$\sigma_{\text{tot}} = 101.7 \pm 2.9$ mb

*TOTEM coll., PRL 111 (2013) 012001*

Luminosity independent method, $|t| > 0.01$; B constant, CNI negligible, $\rho$ external input

**TOTEM @ $\sqrt{s} = 8$ TeV:**

$\sigma_{\text{tot}} = 102.9 \pm 2.3$ mb

*TOTEM coll., EPJC 76 (2016) 661*

Normalisation from previous analysis, $|t| > 6 \cdot 10^{-4}$; B polynomial, CNI taken into account, $\rho$ determined from data

ATLAS & TOTEM B-slopes agree
⇒ difference normalisation

Next: $\sigma_{\text{tot}}$ @ $\sqrt{s} = 13$ TeV
$\sigma_{\text{inel}} \oplus LHC$ energies

Low mass diffraction ($M_{\text{diff}}$) contribution? (i) resonances (ii) low mass continuum

@ $\sqrt{s} = 7$ TeV: $\sigma_{\text{inelastic}}$, $|\eta| > 6.5 < 6.3$ mb @ 95 % CL  \text{ TOTEM coll., EPL 101 (2013) 21003}

From elastic pp scattering using optical theorem

Visible inelastic rate + extrapolation using "average" of several MCs (not necessarily with good low $M_{\text{diff}}$ model)

Shouldn't cosmic ray shower MCs with multi-Pomeron exchange be used for extrapolation?

Shouldn't we try to measure low $M_{\text{diff}}$ using very forward shower counters?

Visible inelastic rate measurements @ $\sqrt{s} = 7$ TeV:

LHCb coll., JHEP 02 (2015) 129

$\sigma_{\text{inel}}$ measurements @ $\sqrt{s} = 7$ TeV:

ATLAS: $\sigma_{\text{inel}} = 78.1 \pm 2.9$ mb
\textit{ATLAS coll., PRL 117 (2016) 182002}

CMS: $\sigma_{\text{inel}} = 71.3 \pm 0.5$ (exp.) $\pm 2.1$ (lum.) $\pm 2.7$ (ext.) mb
Central exclusive production

Physics motivations:
- study glueball candidates
- measure non-perturbative QCD effects: rapidity gap survival probability…
- study perturbative QCD: unintegrated gluon parton distributions…
- search for signs of new physics
Central Exclusive Production (CEP)

- CEP exclusivity verified by rapidity gaps or intact forward protons ($p$)
- Rapidity gap method: $p$ dissociation contamination (giving only particles outside instrumented $\eta$ regions) however no inefficiency due to $p$ acceptance
- Intact proton method: require forward vs central system compatibility
  $M(pp) =? M(\text{central}), \quad p_{T,z}(pp) =? p_{T,z}(\text{central}), \quad \text{vertex}(pp) =? \text{vertex}(\text{central})$
  but limited $p$ acceptance: high $\beta^*$: $|t| > 0.01 \text{ GeV}^2$, low $\beta^*$: $M_X > 300-400 \text{ GeV}/c^2$

Selection rules for system $X$:
$$J^{PC} = 0^{++}, 2^{++}, \ldots \ (\text{PP, gg})$$
$$J^{PC} = 1^{--} (\gamma P)$$

CMS-PAS-FSQ 12-004 (2015)
CMS Preliminary pp at $\sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 450 \mu\text{b}^{-1}$

STAR coll., arXiv:1611.0723

Low mass exclusive $\pi^+\pi^-$ production

Invariant mass of $\pi\pi$, $p_T^{[\pi\pi]} < 0.1 \text{ GeV}/c$, not acceptance-corrected, statistical errors only
Low mass resonance & glueball CEP

At $x \sim 10^{-3} - 10^{-4}$ gluon overwhelms $\Rightarrow$ CEP@LHC ideal for glueball production since @ LHC: CEP with $M_{\chi} \sim 1 - 4$ GeV produced very purely from gg

$0^{++}(2^{++})$ glueball candidates: $f_0 (f_2)$ resonances in 1.3 -1.8 GeV($> 2$ GeV) mass range

Determine $\sigma_{\text{CEP}}$ of glueball candidates & characterize their decays: $\pi^+\pi^-$, $K^+K^-$, $\rho^0\rho^0$...

CMS+TOTEM advantages:
- Good reconstruction of charged-particle-only events using dedicated low $p_T$ tracking
- Good particle ID & mass resolution ($\sigma(M) \sim 30$ MeV) using CMS tracker
- RP protons from TOTEM to assure exclusivity ($p_{T,\text{RP}} \sim p_{T,\text{tracker}}$, $vtx_{\text{RP}} \sim vtx_{\text{tracker}}$)

CMS+TOTEM 2015: $\mathcal{L} = 0.4$ pb$^{-1}$ of high $\beta^*$ with dedicated low mass CEP trigger

Low mass CEP trigger: double arm RP & T2 Veto & at least 1 track in CMS tracker
Low mass resonance CEP

$pp \rightarrow p + \pi^+\pi^- + p$ candidates

Transverse momentum sum of protons $(p_{x,y}^{\text{TOTEM}})$ vs transverse momentum sum of charged particles in tracker $(p_{x,y}^{\text{CMS}})$

Different proton configurations

Top-top, diagonal, bottom-bottom

Very pure exclusive sample selected!!
Low mass resonance CEP

$pp \rightarrow p + \pi^+\pi^- + p$ candidates

Horizontal vertex position from tracks ($x_{VTX}^{CMS}$), proton left ($x_{VTX}^{p\text{ left}}$), right ($x_{VTX}^{p\text{ right}}$) and both protons ($x_{VTX}^{TOTEM}$).

no sensitivity to proton $y_{VTX}$ due to LHC optics

Results coming!
Stay tuned!

Offset due to different CMS & TOTEM reference frames
Charmonium CEP

LHCb@ $\sqrt{s} = 13$ TeV:

$pp \rightarrow p + J/\Psi (\rightarrow \mu^+\mu^-) + pp$

$pp \rightarrow p + \Psi(2s) (\rightarrow \mu^+\mu^-) + p$

Repeat of 7 TeV analysis with an increased veto $\eta$-coverage (Herschel: $\sim 5 < |\eta| < \sim 10$)

For details ⇒ see B. Rachwals talk on Tuesday

2015 dataset @13 TeV(200pb$^{-1}$)

LHCb preliminary

LHCb-CONF-2016-007 (2016)
Charmonium CEP

LHCb@13 TeV:

\[ \sigma_{J/\psi \rightarrow \mu^+ \mu^-} (2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \text{ (stat)} \pm 24 \text{ (syst)} \pm 16 \text{ (lumi)} \text{ pb} \]

\[ \sigma_{\psi(2S) \rightarrow \mu^+ \mu^-} (2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

LHCb-CONF-2016-007 (2016)

Observed deviation from pure power law for J/\(\Psi\) CEP reproduced well by NLO calculation.
Photon-photon collisions

Physics motivations:
- luminosity
- anomalous gauge couplings
- searches for new physics
**Photon-photon collisions**

cross section for $\text{AA} (\gamma\gamma) \rightarrow \text{AA} \ X$ process:

**(i)** Number of equivalent photons (EPA) by integration of relevant EM form factors:

$$n(b, \omega) = \frac{Z^2 \alpha_{em}}{\pi^2 \omega} \left| \int dq_1 q_2^2 \frac{F(Q^2)}{Q^2} J_1(bq_\perp) \right|^2$$

$$Q^2 < 1/R^2 \quad \omega_{\text{max}} \approx \gamma/R$$

**(ii)** $\text{EW} \ \gamma\gamma \rightarrow X$ (elementary) cross section

$$\sigma^{\text{EPA}}_{A_1 A_2 (\gamma\gamma) \rightarrow A_1 A_2 X} = \int \int d\omega_1 \ d\omega_2 \ n_1(\omega_1) \ n_2(\omega_2) \ \sigma_{\gamma\gamma \rightarrow X (W\gamma\gamma)}$$

**pp collisions**

+ harder spectrum ($\omega_{\text{max}} \sim \text{TeV}$)
- large pile-up
- harder to trigger on low pT objects
+ large datasets, O(40 fb$^{-1}$)

Timely with first LHC high-lumi forward proton detector (CT-PPS & AFP) data

**PbPb collisions**

- softer spectrum ($\omega_{\text{max}} \sim 100 \text{ GeV}$)
+ AA ($\gamma\gamma$) cross-sections $\propto Z^4$
+ gluonic cross-sections $\propto \sim A^2$
  (lower CEP background wrt pp)
+ lower pile-up (<1%)
- smaller data set
Exclusive (UPC) dimuons

ATLAS @ $\sqrt{s_{\text{NN}}} = 5.02$ TeV:

$\sigma = 32.2 \pm 0.3$ (stat) $\pm 4.0$ (syst) $\mu$b

STARLIGHT1.1: 31.6 $\mu$b

($p_{T,\mu} > 4$ GeV, $|\eta_{\mu}| < 2.4$ and $M_{\mu^+\mu^-} > 10$ GeV)

M. Guzik's talk on Tuesday

For details ⇒ see M. Guzik's talk on Tuesday
Exclusive (UPC) diphotons

**ATLAS @ $\sqrt{s_{NN}} = 5.02$ TeV:**

Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering:

- Indirectly in measurements of electron & muon anomalous magnetic moment
- At lower energies measured in both Delbrück scattering and photon splitting
- Not observed previously in HEP

Proposed as possible channel to study

- Anomalous gauge couplings
- Contributions from BSM particles (axions etc.)

Main backgrounds:

- CEP $gg \rightarrow \gamma\gamma$
- Misidentified electron from $\gamma\gamma \rightarrow e^+e^-$

Signal significance:
**Light-by-light scattering**

**ATLAS @ $\sqrt{s_{NN}} = 5.02$ TeV:**

13 events (bkgd 2.6) $\Rightarrow 4.4\sigma$ evidence

$\sigma = 70 \pm 20$ (stat) $\pm 17$ (syst) nb

($p_{T,\gamma} > 3$ GeV, $|\eta_\gamma| < 2.4$, $M_{\mu^+\mu^-} > 6$ GeV, $p_T(\gamma\gamma) < 2$ GeV, $A_{\text{co}} < 0.01$)


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**SM predictions:**

- $45 \pm 9$ nb
  
  *D. d'Enterria et al., PRL 111 (2013) 080405*

- $49 \pm 10$ nb
  
  *A. Szczurek et al., PRC 93 (2016) 044907*  

For details $\Rightarrow$ see M. Guzik's talk on Tuesday

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**Graphical Content:**

- Plot showing signal selection for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
- Legend indicating data, MC, and model predictions.
- Highlighted region for $\gamma\gamma$ acoplanarity.

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**Diagram:**

- ATLAS experiment setup.
- Event selection criteria visualized.
- Run: 287931
- Event: 461251458
- Date: 2015-12-13 09:51:07 CEST
High-lumi proton detector physics

Exclusive Production:
- photon-photon fusion
- gluon-gluon fusion in colour-singlet state \((J^{PC} = 0^{++}, 2^{++} \ldots)\)

Strategy: require correlation central system & forward protons

Early analyses (not requiring timing):
Proton kinematic reconstruction:
- cross-checked using \(pp \rightarrow p + \mu^+\mu^- + X/p\) events (with only one \(p\) detected in Roman Pots)

With timing detectors:
- Exclusive WW
- Exclusive dijets
- Inclusive missing mass/missing energy..

CT-PPS (CMS-TOTEM) & AFP (ATLAS) ⇒

for details see L. Forthomme’s and G. Gachs talks on Tuesday
CT-PPS 2016

- Beam pockets: horizontal RPs (with RF shields or new cylindrical design)
- Tracking detectors: TOTEM Si strips (red) (2017: added Si Pixels)
- Timing detectors: TOTEM diamonds (2017: added UFSD)

RPs at 15\(\sigma\) regularly in all high-lumi fills

2016 luminosity with CT-PPS:
- Strip detectors \(~15\) fb\(^{-1}\)
- Diamond detectors \(~2.5\) fb\(^{-1}\)

Si strips suffered radiation damage
- e.g. in 56 210-far:

AFP 2016: one arm \(~500\) nb\(^{-1}\)
AFP 2017: both arms
CT-PPS mass acceptance
(e.g. 2016 before TS2)

$\beta^* = 0.4 \, \text{m, } \alpha_X = 370 \, \mu\text{rad, mild orbit bump, RPs @ } 15\sigma$

Using asymmetric dispersion as measured in data

$\frac{y}{2} = \ln \frac{\xi_1}{\xi_2}$

$M^2 = \xi_1 \xi_2 \alpha$
Conclusions

- Elastic scattering: contains rich physics (not theoretically and experimentally well understood)
- Central Exclusive Production: high potential in glueball studies, (non-)perturbative QCD, new physics searches
- Photon-photon physics: new physics searches
- CT-PPS (& AFP) pave way for high mass & low cross-section CEP & photon-photon physics
- Exclusive UPC production: rich physics opening up

Examples of topics covered in parallel sessions but not here:
- AQGC from $\gamma\gamma \rightarrow WW$ (CMS)
- Exclusive $Y$ in pPb(CMS)
- Low $x$: $J/\Psi$ and $\rho$ photoproduction in UPC (ALICE), inclusive $E$ spectrum in pp (CMS), underlying event with DY (CMS)
Backup
Roman Pot system 2015

Movable beam pipe section allowing insertion of detector to \(O(\text{mm})\) distance from the beam

High luminosity standard running:
- 2-3 horizontal RPs (+ 4 vertical for RP alignment runs)

Special high \(\beta^*\) runs (90 m, 1 km, 2.5 km):
- 4-6 vertical RPs & 2-3 horizontal RPs

2010-13 data: only RP220
Elastic pp scattering: selection & data sets

Selected based on topology, low $|\xi|$, anti-collinearity & vertex

Data sets at different conditions to measure over as wide $|t|$-range as possible

Key issues:
- RP alignment
- Optics

Data published
- Analysis finished
- Analysis on-going

- $\beta^* = 1\ km$, 3$\sigma$, 8 TeV
- $\beta^* = 90\ m$, 10$\sigma$, 7 TeV
- $\beta^* = 90\ m$, 5$\sigma$, 7 TeV
- $\beta^* = 90\ m$, 6-9$\sigma$, 8 TeV
- $\beta^* = 3.5\ m$, 7$\sigma$, 7 TeV
- $\beta^* = 3.5\ m$, 18$\sigma$, 7 TeV
- $\beta^* = 11\ m$, 5-13$\sigma$, 2.76 TeV

<table>
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<tr>
<th>$E$ (TeV)</th>
<th>$\beta^*$ (m)</th>
<th>RP approach</th>
<th>$L_{int}$ ($\mu$b$^{-1}$)</th>
<th>$t$ range (GeV$^2$)</th>
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Total pp cross-section: methods & results

Excellent agreement between 7 TeV $\sigma$ measurements:

Based on elastic scattering $\Rightarrow$ low mass diffraction independent

$$\sigma_{tot}^2 = \frac{16\pi}{(1 + \rho^2)} \frac{1}{L} \left( \frac{dN_{el}}{dt} \right)_{t=0}$$

Testing validity of optical theorem at ~3.5% level

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

Optical theorem & $\rho$ independent

$\sigma_{total} = 98.3 \text{ mb} \pm 2.0 \text{ mb}$  
*EPL 96 (2011) 21002*

$\sigma_{total} = 98.6 \text{ mb} \pm 2.3 \text{ mb}$  
*EPL 101 (2013) 21002*

$\sigma_{total} = 99.1 \text{ mb} \pm 4.3 \text{ mb}$  
*EPL 101 (2013) 21004*

$\sigma_{total} = 98.1 \text{ mb} \pm 2.4 \text{ mb}$  
*EPL 101 (2013) 21004*

Combining 8 TeV $\beta^* = 90 \text{ m} \& 1 \text{ km}$ data: Improved extrapolation of hadronic amplitude to $t = 0$ (Coulomb interference measured) & simultaneous $\rho$ determination

$\sigma_{total} = 101.7 \text{ mb} \pm 2.9 \text{ mb}$  
*PRL 111(2013) 012001*

$\sigma_{total} = 102.9 \text{ mb} \pm 2.3 \text{ mb}$ (central hadronic phase)

$\sigma_{total} = 103.0 \text{ mb} \pm 2.3 \text{ mb}$ (peripheral hadronic phase)

*CERN-PH-EP-2015-235, accepted by EPJC*

8 TeV
Coulomb-hadronic interference – analysis strategy

**Central question:**
Observed non-exponentiality due to hadronic Coulomb or both

- fits with 2 different assumptions on hadronic amplitude
  - purely-exponential – non-exponentiality due to Coulomb (& interference)
    \[ |F^H| = a \exp(b_1 t) \]
  - flexible enough to describe non-exponentiality even without Coulomb
    \[ |F^H| = a \exp(b_1 t + b_2 t^2 + b_3 t^3) \]

- role of \(|t|\)-dependence of hadronic phase?
  - large impact at low \(|t|\)
  - controls behaviour in impact parameter space (b)

- consider 2 options:
  + central: black
  + peripheral: blue
Coulomb-hadronic interference – fits

\[ \beta^* = 1000 \text{ m}; \quad \beta^* = 90 \text{ m}; \]

- **Purely-exponential hadronic amplitude**
  - Central phase excluded (with SWY, Cahn & KL) \( \Rightarrow \) application of SWY formula excluded too
  - Peripheral phase not explicitly excluded by data but disfavoured
    - \( \rho \) value outside a consistent pattern of other fits & theoretical predictions
    - several theoretical reasons for non-exponential hadronic amplitude

\[ N_b = 1 \]

\[ \text{TOTEM collaboration, EPJC 76 (2016) 661} \]

- **Non-exponential hadronic amplitude**
  - Both central & peripheral phase compatible with data \( \Rightarrow \) centrality not a necessary description for elastic scattering

\[ N_b = 3 \]

Not one single hadronic scattering amplitude \( \Rightarrow \) multiple exchange channels for elastic scattering