TOTEM Results on Elastic Scattering and Total Cross-Section

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on behalf of the TOTEM collaboration

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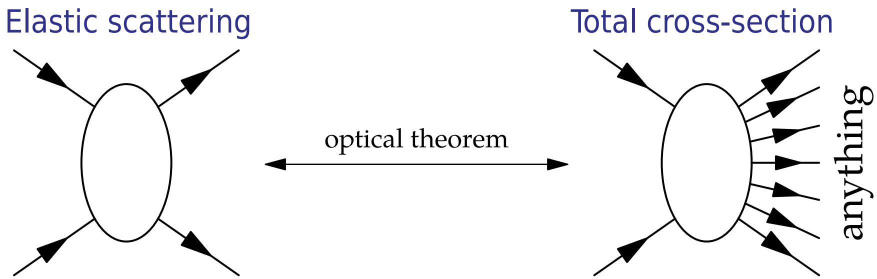


Outline

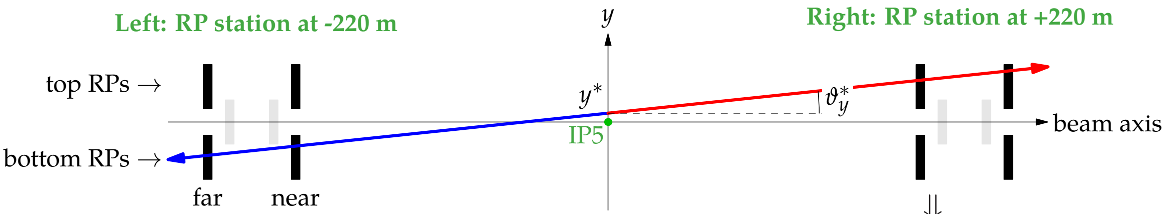
1) Introduction: *Roman Pot detectors, ...*

2) Elastic scattering: *analysis method and results*

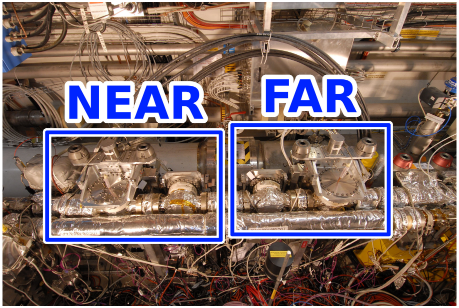
3) Total cross-section: *analysis method and results*

4) Study of Coulomb-nuclear interference

- TOTEM shares the LHC interaction point (IP5) with CMS
- elastic scattering = 2 anti-collinear protons from the same vertex:

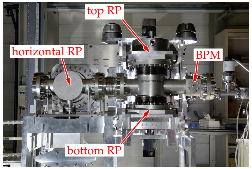


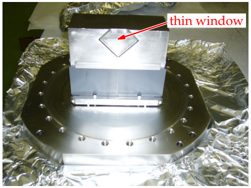
four-momentum transfer squared: t
scattering angle: $\vartheta^* \simeq \sqrt{t}/p$
azimuthal angle: φ^*
horizontal angle: $\vartheta^*_x = \vartheta^* \cos\varphi^*$
vertical angle: $\vartheta^*_y = \vartheta^* \sin\varphi^*$

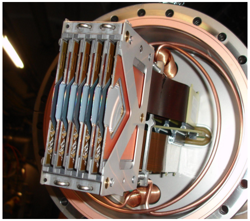


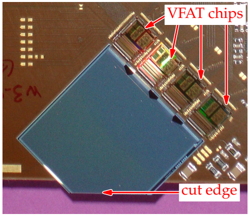
- 2 diagonals ⇒ control of systematics
  - left *bottom* – right *top*
  - left *top* – right *bottom*
- 2 units ⇒ improved:
  - event selection
  - kinematics reconstruction

- each station: near and far units
- each unit: top, bottom and horizontal Roman Pots
- Roman Pot
  - movable beam-pipe insertion
    - retracted when beam unstable
    - close to beam for data taking
  - contains: 5×2 back-to-back mounted silicon sensors
- edge-less silicon sensors
  - insensitive edge (facing beam): $\approx 50\ \mu$m
  - strips with pitch 66 μm oriented at 45° wrt. active edge
- VFAT: trigger-capable read-out chip

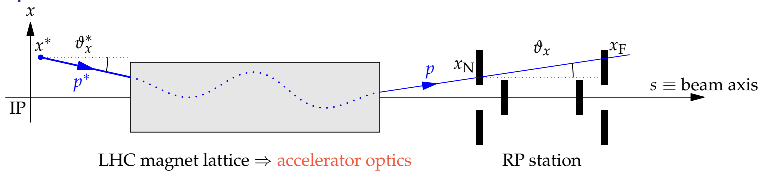








- proton transport IP5 $\rightarrow$ RP detectors:

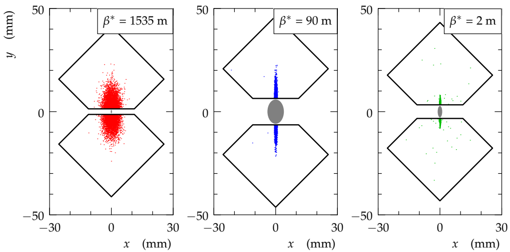


- optics

hit position at RP → $x(\mathrm{RP})$; optical functions → L_x, v_x, D_x; proton kinematics at IP → ϑ_x^*, x^*, ξ

$$
\begin{aligned}
x(\mathrm{RP}) = \; & (\text{effective length } L_x) \cdot (\text{scattering angle } \vartheta_x^*) \\
& + (\text{magnification } v_x) \cdot (\text{vertex } x^*) \\
& + (\text{dispersion } D_x) \cdot \left(\text{rel. momentum loss } \xi \equiv \frac{\Delta p}{p}\right)
\end{aligned}
$$

- example: elastic sample seen with 3 different optics:



$\Rightarrow$ *optics knowledge essential*

$\Downarrow$

TOTEM can improve optics accuracy

- entirely data-driven
- two diagonals, several LHC fills $\simeq$ different experiments $\Rightarrow$ control of systematics

1. Alignment

- prior to data-taking: collimator-like beam-based alignment
- offline alignment: *relative* (analysis of track fit residuals) and *absolute wrt. beam* (symmetries of elastic scattering)

2. Kinematics reconstruction

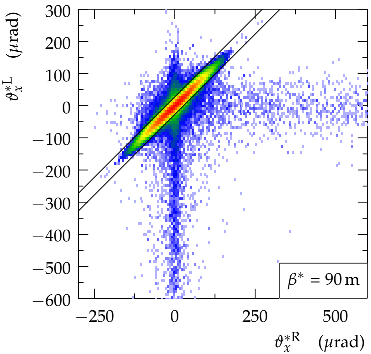
- tracks in RPs $\longrightarrow$ kinematics at IP ($\xi = 0 \Rightarrow$ relatively easy)
- choice of formulae (using *N*ear and *F*ar RPs) $\rightarrow$ minimisation of systematics, typically:

$$\theta_x^* = \frac{x^{\mathrm{F}} - x^{\mathrm{N}}}{L_x^{\mathrm{F}} - L_x^{\mathrm{N}}}, \qquad \theta_y^* = \frac{1}{2}\left(\frac{y^{\mathrm{N}}}{L_y^{\mathrm{N}}} + \frac{y^{\mathrm{F}}}{L_y^{\mathrm{F}}}\right)$$

3. Elastic tagging

- angles left = angles right (tolerance set by beam divergence: higher β^* $\Rightarrow$ more stringent cut)
- vertex left = vertex right
- protons $\xi \approx 0$ $\Rightarrow$ correlation hit position vs. track angle at RP

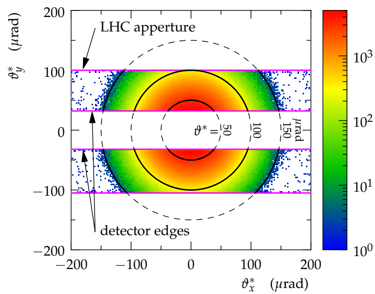
θ_x^* collinearity



4. Background subtraction

- typically needed only for low β^* optics
- interpolation of event distribution surrounding the signal (tagged) region

acceptance correction



5. Acceptance corrections

- RP sensors have finite size $\Rightarrow$ low $|\theta_y^*|$ cut
- LHC apertures $\Rightarrow$ high $|\theta_y^*|$ cut
- azimuthal symmetry (verified) $\Rightarrow$ geometrical correction (+ smearing around edges)

6. Unfolding of resolution effects

- angular resolution (better for high β^*): left-right proton comparison
- Monte Carlo calculation $\Rightarrow$ impact on t-distribution

7. Inefficiency corrections

- uncorrelated 1-RP inefficiencies: repeat tagging with 3 RPs only and check the signal in 4th RP
- near-far correlated RP inefficiencies (showers from near to far RP)
- "pile-up" = elastic event + another track in a RP (prob. from zero-bias stream)

8. Luminosity

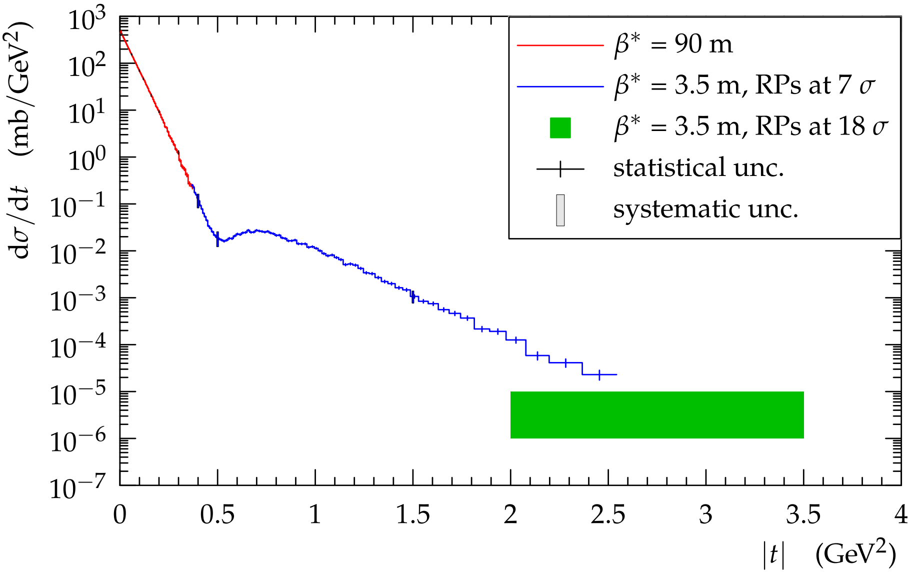
- from CMS (if available), uncertainty $\approx 4\%$
- from TOTEM (details later on)

9. Study of systematic uncertainties

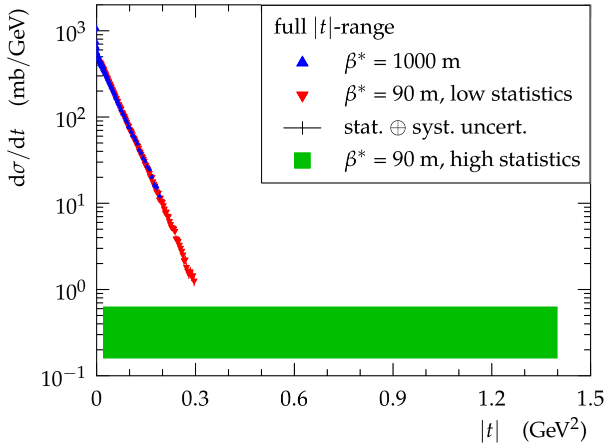
- final $d\sigma/dt$ $\Rightarrow$ input to Monte-Carlo simulation
- any analysis parameter: discrepancy simulation vs. reconstruction $\Rightarrow$ study impact on t-distribution

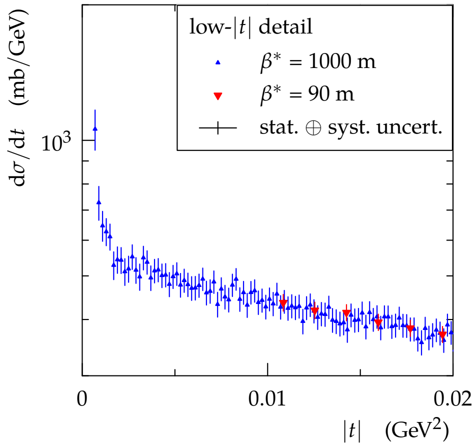
Elastic scattering results : $\sqrt{s} = 7\ TeV$

β^*	RP approach	$\|t\|$ range	el. events	status
90 m	4.8 to 6.5 σ	0.005 to 0.4 GeV^2	1 M	[EPL 101 (2013) 2100]
3.5 m	7 σ	0.4 to 2.5 GeV^2	66 k	[EPL 95 (2011) 41001]
3.5 m	18 σ	$\approx$ 2 to 3.5 GeV^2	10 k	anal. advanced



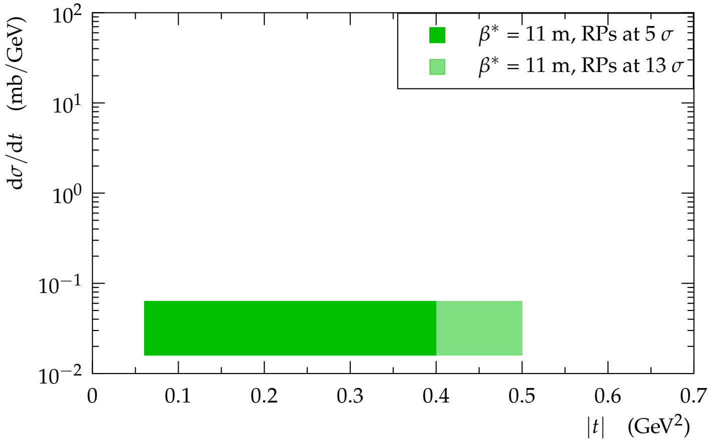
β^*	RP approach	$\|t\|$ range	el. events	status
1000 m	3 or 10 σ	0.0006 to 0.2 GeV^2	352 k	publ. in prep.
90 m	6 to 9.5 σ	0.01 to 0.3 GeV^2	0.68 M	[PRL 111 (2013)]
90 m	9.5 σ	0.02 to 1.4 GeV^2	7.2 M	anal. advanced





- dip well visible in the combined $\beta^* = 90$ m data

β^*	RP approach	$|t|$ range	el. events	status
11 m	5 σ	0.06 to 0.4 GeV^2	45 k	anal. started
11 m	13 σ	0.4 to 0.5 GeV^2	2 k	anal. started



- β^* = 11 m optics tuning in progress ($\rightarrow$ t values preliminary)
- LHC aperture(s) at $\approx$ 14 σ
- dip (expected at $|t| \approx 0.6$ GeV^2) unlikely to be visible

Total cross-section

3 complementary methods:

$$\rho \equiv \left.\frac{\Re \mathcal{A}_{\rm el}}{\Im \mathcal{A}_{\rm el}}\right|_{t=0}$$

elastic observables only:

$$\sigma_{\rm tot}^2 = \frac{16\pi}{1+\rho^2} \frac{1}{\mathcal{L}} \left.\frac{{\rm d}N_{\rm el}}{{\rm d}t}\right|_0$$

$$\sigma_{\rm tot}$$

ρ-independent:

$$\sigma_{\rm tot} = \frac{1}{\mathcal{L}} \left(N_{\rm el} + N_{\rm inel}\right)$$

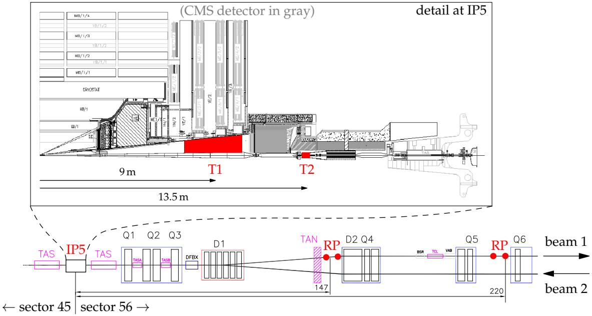
luminosity-independent:

$$\sigma_{\rm tot} = \frac{16\pi}{1+\rho^2} \frac{{\rm d}N_{\rm el}/{\rm d}t|_0}{N_{\rm el} + N_{\rm inel}}$$

$$\mathcal{L} = \frac{1+\rho^2}{16\pi} \frac{(N_{\rm el} + N_{\rm inel})^2}{{\rm d}N_{\rm el}/{\rm d}t|_0}$$

$N_{\rm el}$ from RPs $\quad$ $N_{\rm inel}$ from T2 $\quad$ $\mathcal{L}$ from CMS $\quad$ ρ from COMPETE or TOTEM

Inelastic cross-section



Forward inelastic telescope T2

- detects charged particles at $5.3 < |\eta| < 6.5$
- $\approx$ 95 % of inelastic events seen (enough to detect 1 track!)

Inelastic cross-section analysis

1) *Raw rate*: event counting with T2

$\downarrow$ experimental corrections: *trigger and reconstruction inefficiencies, beam-gas event suppression, pile-up consideration*

2) *Visible rate*: visible with T2 in perfect conditions

$\downarrow$ recovery of events with no tracks in T2: *T1-only events, events with gap over T2, low-mass diffraction, cen. diff. without tracks in T1 and T2*

3) *Physics rate*: true rate of inelastic events

- only one major Monte-Carlo-based correction: *low-mass diffraction*
  $\Rightarrow$ but can be constrained from data ($\sigma_{\text{tot}}^{RP} - \sigma_{\text{el}}^{RP} - \sigma_{\text{visible}}^{T2}$)

Total cross-section : $\sqrt{s}$ = 7 and 8 TeV results

$\sqrt{s}$ = 7 TeV

elastic observables only:

$$\sigma^2_{\rm tot} = \frac{16\pi}{1+\varrho^2}\,\frac{1}{\mathcal{L}}\,\frac{{\rm d}N_{\rm el}}{{\rm d}t}\bigg|_0$$

$\sigma_{\rm tot} = (98.6 \pm 2.3)$ mb

$\sigma_{\rm tot}$

ϱ-independent:

$$\sigma_{\rm tot} = \frac{1}{\mathcal{L}}\,(N_{\rm el} + N_{\rm inel})$$

$\sigma_{\rm tot} = (99.1 \pm 4.4)$ mb

luminosity-independent:

$$\sigma_{\rm tot} = \frac{16\pi}{1+\varrho^2}\,\frac{{\rm d}N_{\rm el}/{\rm d}t|_0}{N_{\rm el} + N_{\rm inel}}$$

$\sigma_{\rm tot} = (98.1 \pm 2.4)$ mb

$\sqrt{s}$ = 8 TeV

elastic observables only:

$$\sigma^2_{\rm tot} = \frac{16\pi}{1+\varrho^2}\,\frac{1}{\mathcal{L}}\,\frac{{\rm d}N_{\rm el}}{{\rm d}t}\bigg|_0$$

$\sigma_{\rm tot}$

ϱ-independent:

$$\sigma_{\rm tot} = \frac{1}{\mathcal{L}}\,(N_{\rm el} + N_{\rm inel})$$

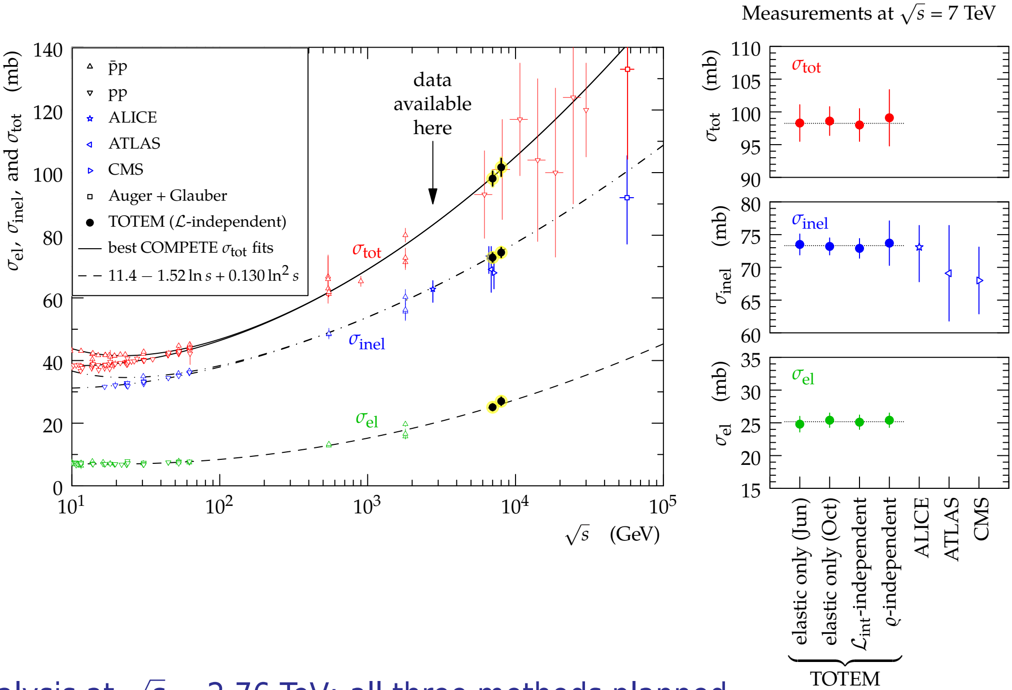
luminosity-independent:

$$\sigma_{\rm tot} = \frac{16\pi}{1+\varrho^2}\,\frac{{\rm d}N_{\rm el}/{\rm d}t|_0}{N_{\rm el} + N_{\rm inel}}$$

$\sigma_{\rm tot} = (101.7 \pm 2.9)$ mb

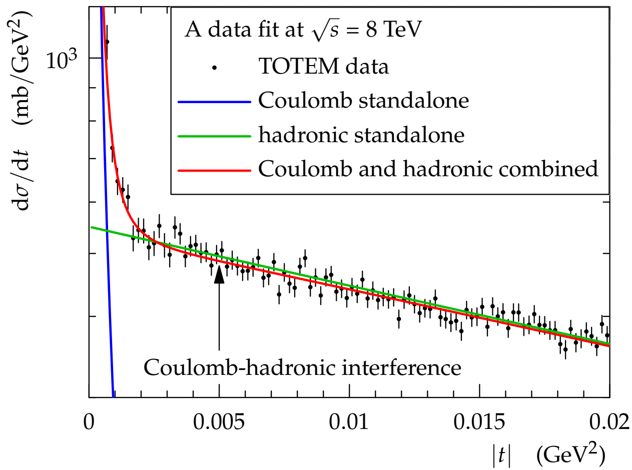
- CMS luminosity unavailable
- $\mathcal{L}$ from luminosity-independent method
  $\Rightarrow$ normalisation of $d\sigma/dt$ both at $\beta^* = 90$ and 1000 m

Total cross-section : *Results in context*



- analysis at $\sqrt{s}$ = 2.76 TeV: all three methods planned
  - elastic analysis: ongoing
  - inelastic analysis: almost finished

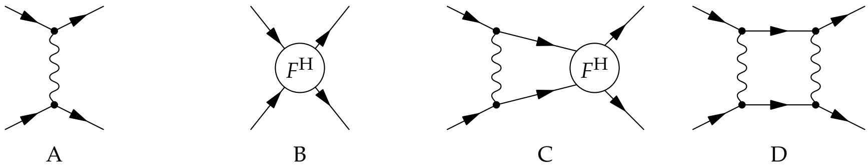
- $\beta^* = 1000$ m : $|t|$ as low as $6 \cdot 10^{-4}$ GeV^2 $\Rightarrow$ *observed Coulomb-nuclear interference* (between Coulomb/electromagnetic and nuclear/strong interactions):



- interesting aspects
  - interference $\Rightarrow$ *determination of phase* of nuclear amplitude
  - separation of Coulomb/nuclear effects $\Rightarrow$ *methodically better determination of $\sigma_{\rm tot}$*

$$\sigma_{\rm tot}^{\rm (nuclear)} \propto \Im \mathcal{A}_{\rm el}^{\rm nuclear}(t=0)$$

$$\frac{d\sigma}{dt} \propto |\mathcal{A}^{C+N}|^2, \qquad \mathcal{A}^{C+N} = \text{interference formula}(\mathcal{A}^{C}, \mathcal{A}^{N})$$



- *Coulomb amplitude* $\mathcal{A}^{C}$: well known (QED, form-factors measured)
- *Nuclear amplitude* $\mathcal{A}^{N}$
  - *modulus*: constrained by TOTEM data ⇒ parametrised:
    $\exp(b_1 t + b_2 t^2 + \ldots)$ $\quad N_b$ = number of b_i parameters = 1 to 3
  - *phase*: weak guidance from data ⇒ test a range of theoretical alternatives
- *interference formula*
  - simplified West-Yennie (SWY) [Phys. Rev. 172 (1968) 1413-1422]
    - traditional but
    - only compatible with constant phase and purely exponential modulus
  - Kundrát-Lokajíček (KL) [Z. Phys. C63 (1994) 619-630]
    - no $\mathcal{A}^{N}$ limitations

general approach: exploration

Coulomb-nuclear interference : *Phase of nuclear amplitude*

- constant phase – the simplest choice

$$\arg \mathcal{A}^{\mathrm{N}} = \mathrm{p}_0$$

- central phase – similar shape as in many phenomenological models

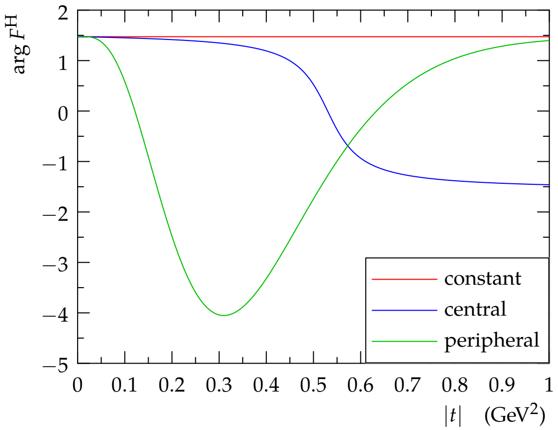
$$\arg \mathcal{A}^{\mathrm{N}} = \frac{\pi}{2} - \operatorname{atan} \frac{\rho_0}{1 - \frac{t}{t_d}}, \quad \rho_0 = \frac{1}{\tan \mathrm{p}_0}$$

$$t_d \approx -0.53\ \mathrm{GeV}^2$$

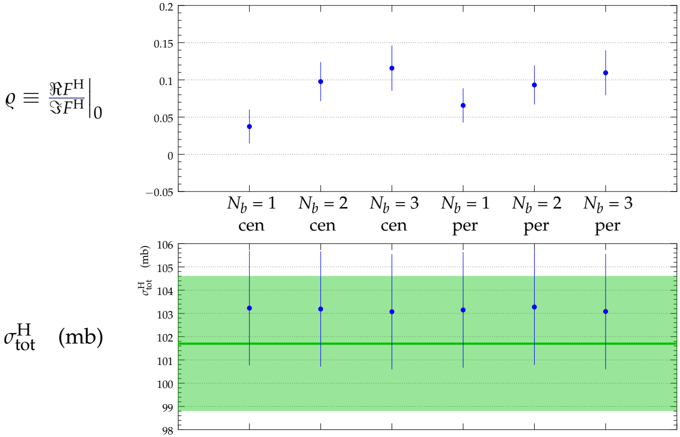
- peripheral phase [Z. Phys. C63 (1994) 619-630] – expected order in impact parameter space: elastic collisions more peripheral than inelastic $\langle b^2 \rangle^{\mathrm{el}} > \langle b^2 \rangle^{\mathrm{inel}}$

$$\arg \mathcal{A}^{\mathrm{N}} = \mathrm{p}_0 + A \exp\left[\kappa \left(\ln \frac{t}{t_m} - \frac{t}{t_m} + 1\right)\right]$$

$$A \approx 5.53,\ \kappa \approx 4.01,\ t_m \approx -0.310\ \mathrm{GeV}^2$$

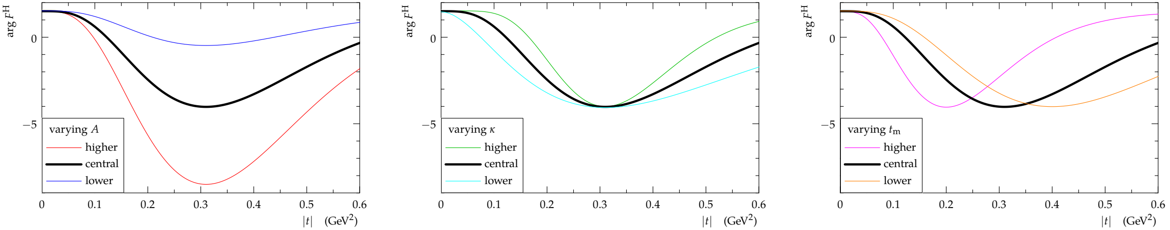


- data fits → for every parameter: value and uncertainty
  - full $|t|$-range: $6 \cdot 10^{-4}$ to 0.2 GeV^2
  - generalised χ^2 (full covariance matrix)
  - typical χ^2/"ndf" ≈ 1
  - nuclear phase: only p_0 (value at $t = 0$) free parameter
- fits with constant and central phase: undistinguishable
- fits with $N_b = 1$ and KL or SWY interference formula: undistinguishable



- indications that $N_b = 1$ insufficient to describe data
- σ_{tot}: very stable results
- green line and band: previous $\beta^* = 90$ m results [PRL 111 (2013) 012001]

- data fits: only p_0 is free
- probe influence of phase shape: vary peak amplitude, width and position:



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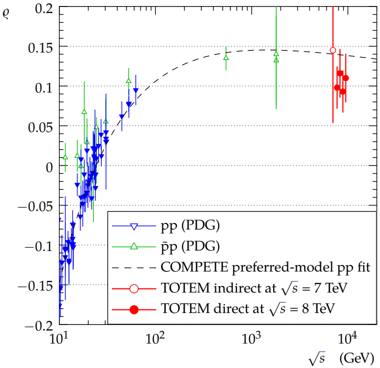
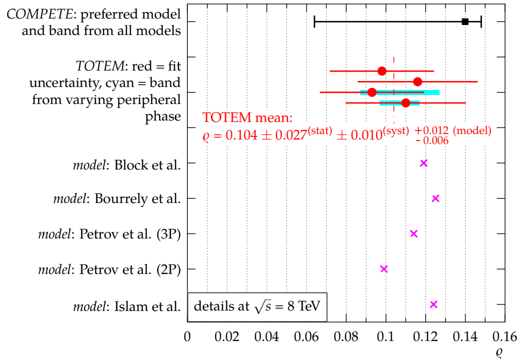
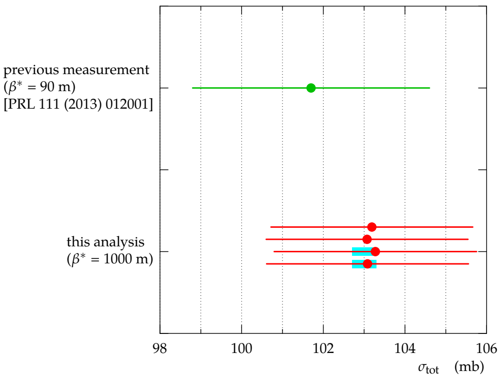
range of fit results

$\rho \rightarrow$





$\sigma_{tot} \rightarrow$



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

Backup

↓

- RPs = movable insertions ⇒ each run at different positions
- required angular precision μrad ⇒ μm alignment precision needed

⇓

- two types of alignment needed
  - alignment of mechanical RP edges → for machine protection
  - alignment of RP sensors → for physics
- need alignment *wrt. the beam*

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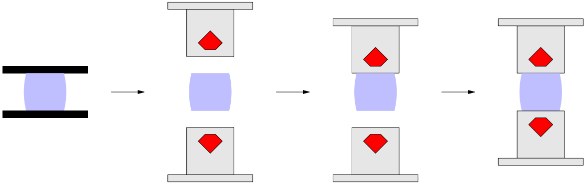
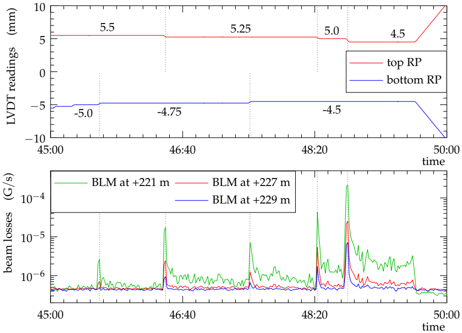
3-step alignment procedure:

1) *Collimation alignment*: RP alignment wrt. beam, rough sensor alignment

- procedure prior to data taking
- standard procedure for LHC collimators

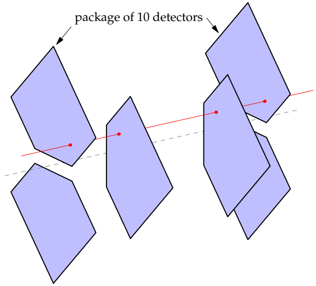




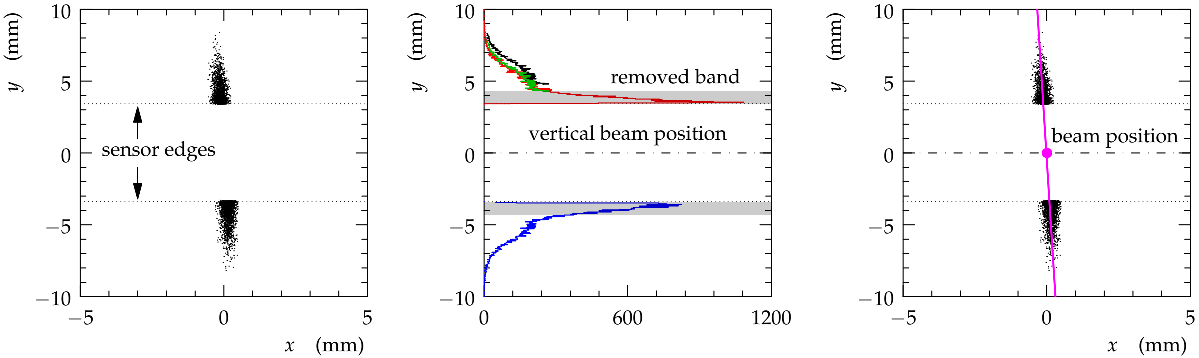
2) *Track-based alignment*: relative alignment among sensors

- RP station: no magnetic field $\rightarrow$ straight tracks
- misalignments $\rightarrow$ residuals
- residual analysis $\rightarrow$ alignment corrections
- overlap between horizontal and vertical RPs $\rightarrow$ relative alignment among all sensors
- singular/weak modes: e.g. overall shift/rotation

$\Rightarrow$ need further alignment step



3) *Alignment with elastic scattering*: sensor alignment wrt. beam

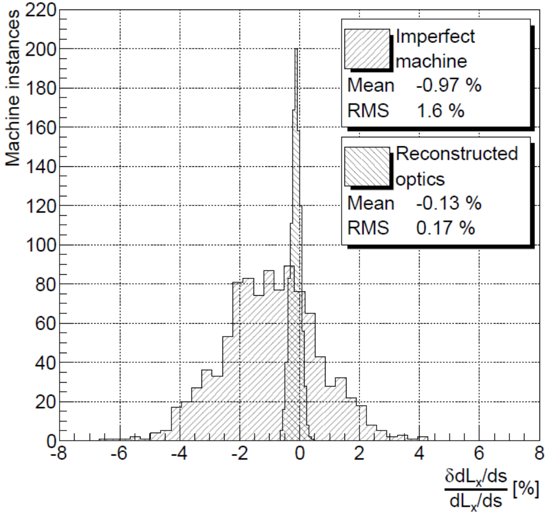


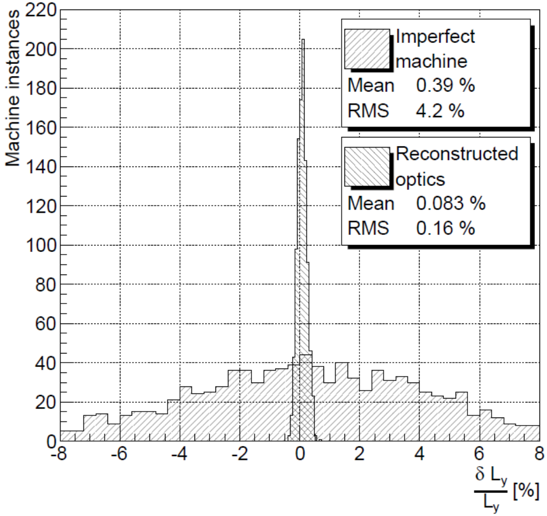
- optics imperfection sources
  - power-converter error: $\Delta I/I \approx 10^{-4}$
  - magnet transfer function: $\Delta B/B \approx 10^{-3}$
  - magnet rotation (< 1 mrad) and displacements (< 0.5 mm)
  - magnet harmonics ($\Delta B/B \approx 10^{-4}$)
  - beam momentum offset: $\Delta p/p \approx 10^{-3}$
  - beam crossing-angle uncertainty

- optics determination
  - direct measurement – difficult
  - indirect from TOTEM observables

- TOTEM optics determination – variation of magnet/beam parameters (within tolerances) to match TOTEM observables:
  - L_y^L/L_y^R
  - $\frac{\mathrm{d}L_y}{\mathrm{d}s}/L_y$
  - $s(L_x = 0)$
  - xy coupling (tilts in xy plane)
  - ...

example for $\beta^* = 3.5$ m optics





- optics uncertainty reduced:

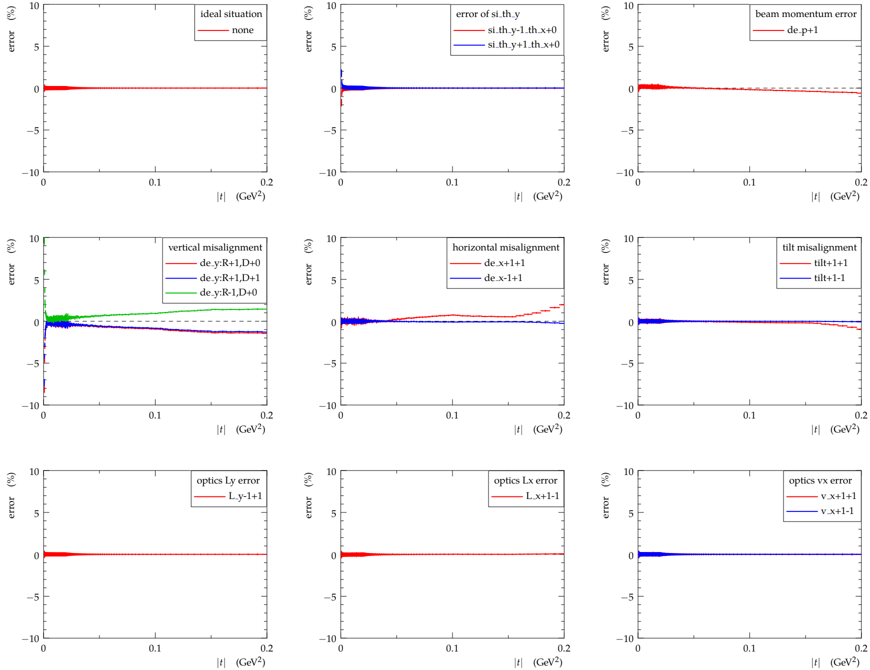
x projection: from 1.6% to 0.17%
y projection: from 4.2% to 0.16%

[H. Niewiadomski, Roman Pots for beam diagnostic, OMCM, CERN, 20-23.06.2011]

[H. Niewiadomski, F. Nemes, LHC Optics Determination with Proton Tracks, IPAC’12, Louisiana, USA, 20-25.05.2012]

- Monte-Carlo: offset in 1 parameter $\Rightarrow$ impact on t-distribution

example for $\beta^* = 1000$ m optics



- simplified West-Yennie formula (SWY)
  - *limitation*: derived for *constant slope B* (1 b_i parameter only) and *constant hadronic phase*
  - acts as simple interference phase (i.e. Φ is real-valued)

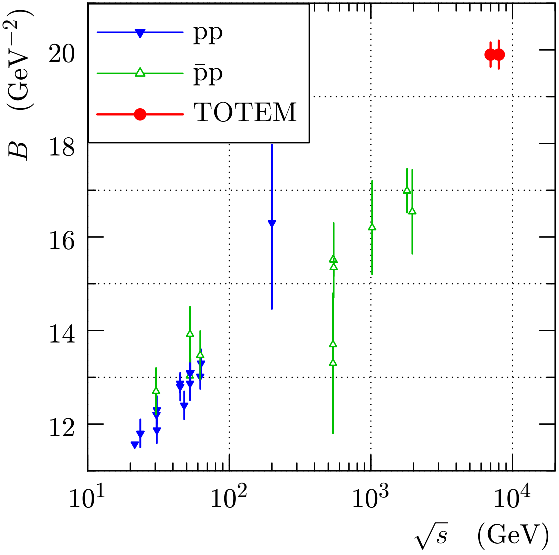
$$F^{C+H} = F^{C} e^{i\alpha\Phi} + F^{H}\,, \qquad \Phi = -\left(\frac{B|t|}{2} + \gamma\right)$$

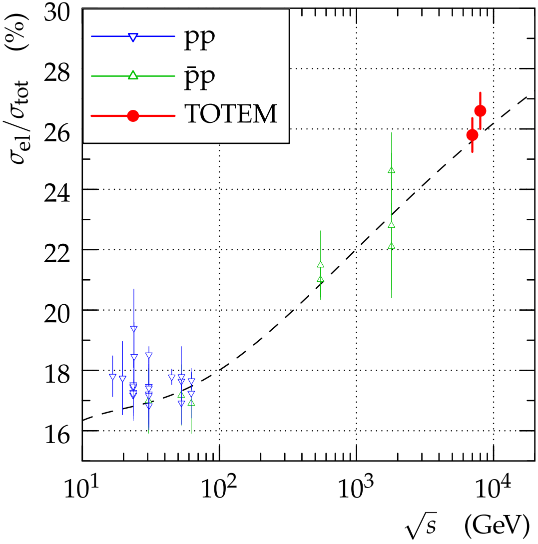
- Kundrát-Lokajíček formula (KL)
  - any slope B, any hadronic phase
  - more complicated effect (Ψ complex in general)

$$F^{C+H} = F^{C} + F^{H} e^{i\alpha\Psi}$$

$$\Psi(t) = \mp \int\limits_{t_{\min}}^{0} dt' \ln\frac{t'}{t}\,\frac{d}{dt'}\mathcal{F}^2(t') \pm \int\limits_{t_{\min}}^{0} dt' \left(\frac{F^{H}(t')}{F^{H}(t)} - 1\right) \frac{I(t,t')}{2\pi}$$

$$I(t,t') = \int\limits_{0}^{2\pi} d\varphi\,\frac{\mathcal{F}^2(t'')}{t''}\,, \qquad t'' = t + t' + 2\sqrt{tt'}\cos\varphi$$


pp
p̄p
TOTEM
$B \quad (\text{GeV}^{-2})$
20
18
16
14
12
10^1
10^2
10^3
10^4
$\sqrt{s} \quad (\text{GeV})$


pp
p̄p
TOTEM
$\sigma_{el}/\sigma_{tot} \quad (\%)$
30
28
26
24
22
20
18
16
10^1
10^2
10^3
10^4
$\sqrt{s} \quad (\text{GeV})$