TOTEM Results on Elastic Scattering and Total Cross-Section

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on behalf of the TOTEM collaboration

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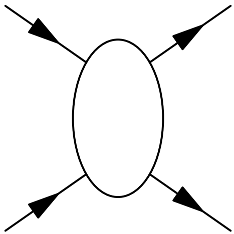
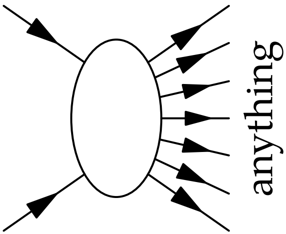
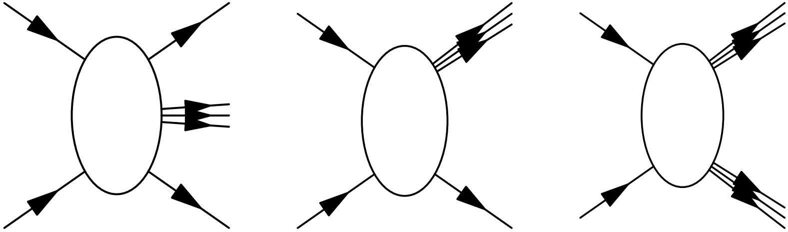
Elastic scattering



Total cross-section

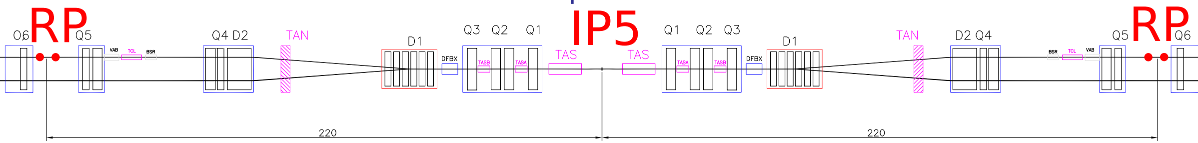


Soft and hard diffraction

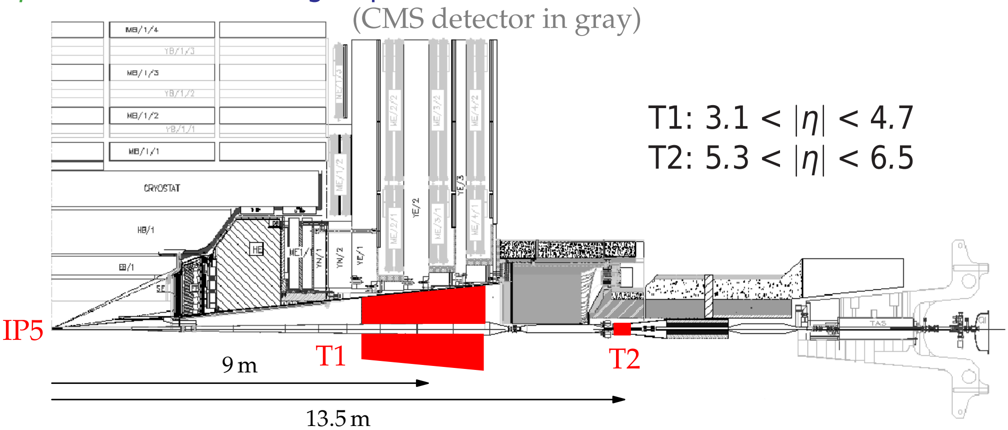


final state: rapidity gaps, very forward protons

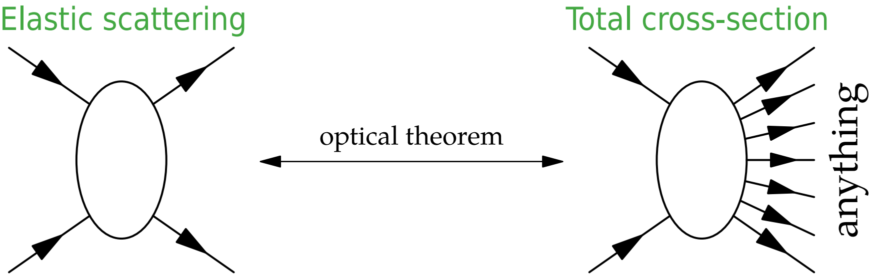
- *Roman Pots*: elastic and diffractive protons



- *Telescopes T1 and T2*: charged particles from inelastic collisions



- all detectors symmetrically on both sides of IP5
- all detectors trigger-capable



Outline

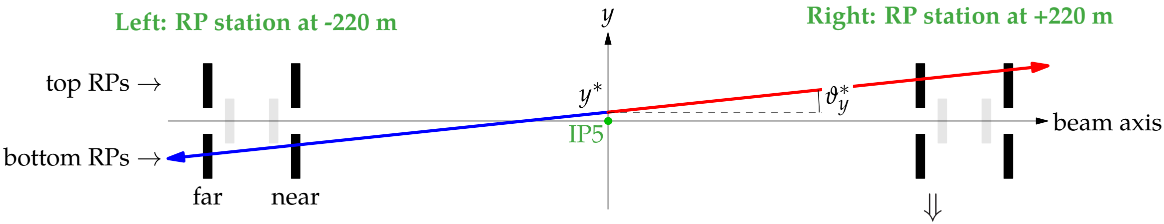
1) Experimental method: *Roman Pot detectors, optics ...*

2) Elastic scattering: *analysis method and results*

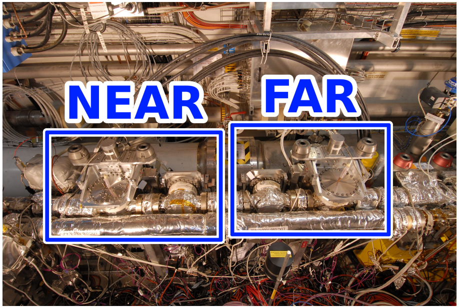
3) Total cross-section: *analysis method and results*

4) Study of Coulomb-nuclear interference

- elastic scattering = 2 anti-collinear protons from the same vertex:

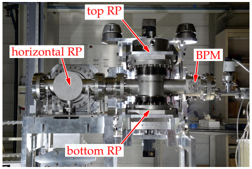


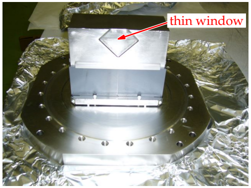
four-momentum transfer squared: t
scattering angle: $\vartheta^* \simeq \sqrt{t}/p$
azimuthal angle: φ^*
horizontal angle: $\vartheta^*_x = \vartheta^* \cos\varphi^*$
vertical angle: $\vartheta^*_y = \vartheta^* \sin\varphi^*$

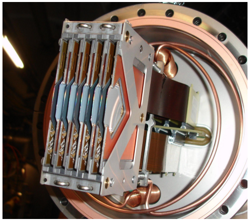


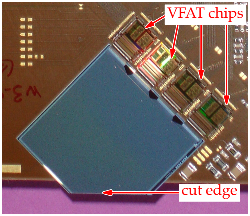
- 2 diagonals ⇒ control of systematics
  - left *bottom* – right *top*
  - left *top* – right *bottom*
- 2 units ⇒ improved:
  - event selection
  - kinematics reconstruction

- 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

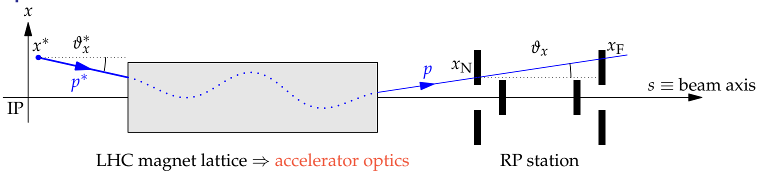








- proton transport IP5 → RP detectors:

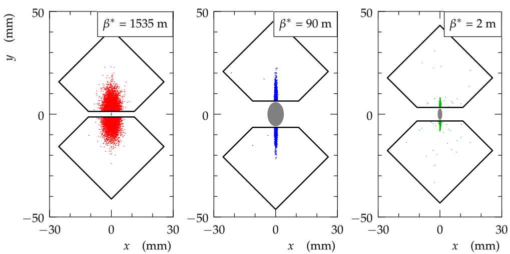


- optics

hit position at RP → optical functions → proton kinematics at IP

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

- example: elastic sample seen with 3 different optics:



⇒ *optics knowledge essential*

⇓

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

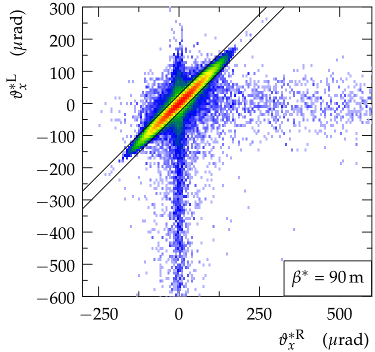
4. Background subtraction

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

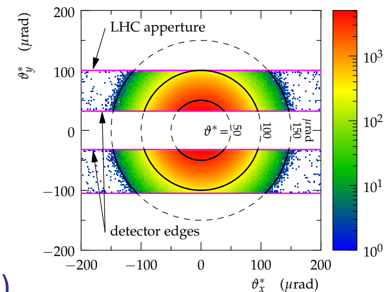
5. Acceptance corrections

- 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)

θ_x^* collinearity



acceptance correction



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

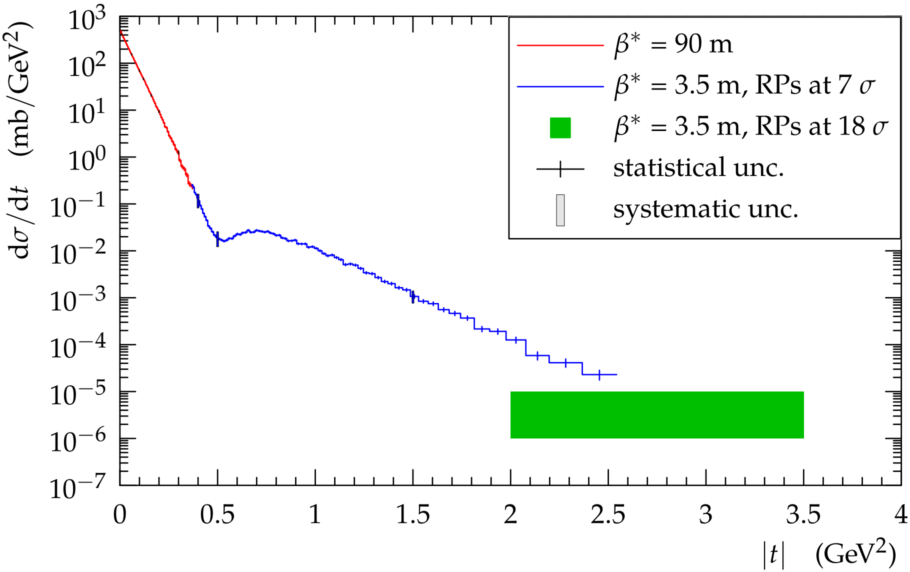
- from CMS (if available), uncertainty $\approx 4\%$
- from TOTEM (details later on)

9. Study of systematic uncertainties

- final $\mathrm{d}\sigma/\mathrm{d}t$ $\Rightarrow$ input to Monte-Carlo simulation or numerical integration
- any analysis parameter: discrepancy simulation vs. reconstruction $\Rightarrow$ study impact on t-distribution

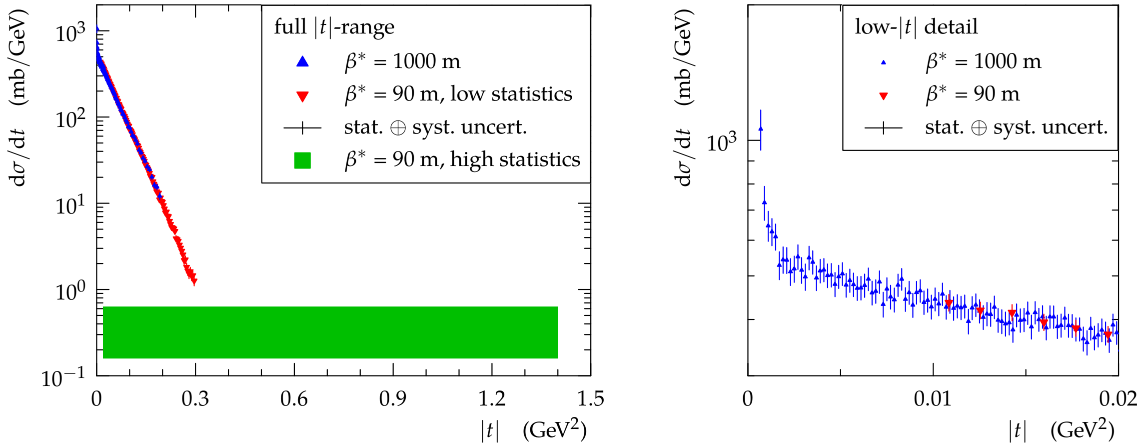
Elastic scattering results : $\sqrt{s}$ = 7 TeV

β^*	RP approach	$\|t\|$ range	el. events	publication
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	

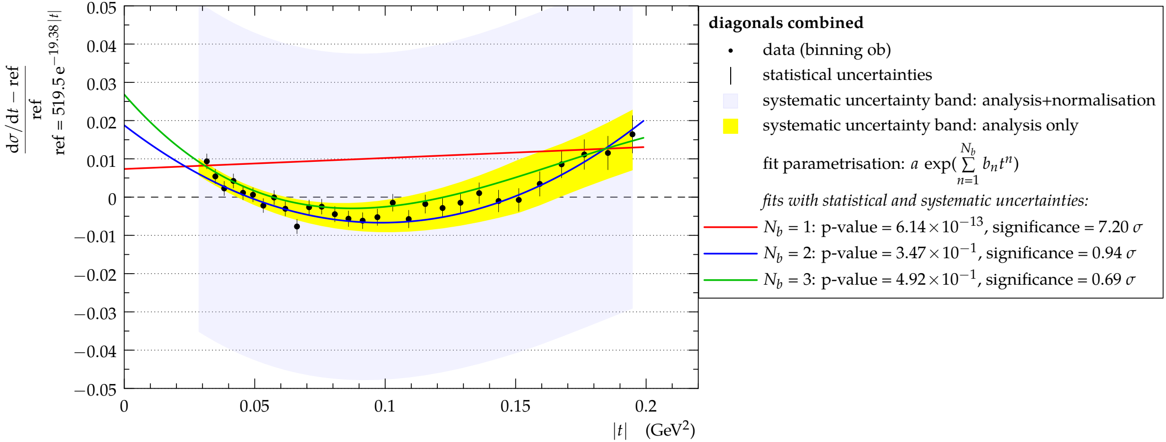


Elastic scattering results : $\sqrt{s} = 8$ TeV

β^*	RP approach	$|t|$ range	el. events	publication
1000 m	3 or 10 σ	0.0006 to 0.2 GeV^2	352 k	
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	

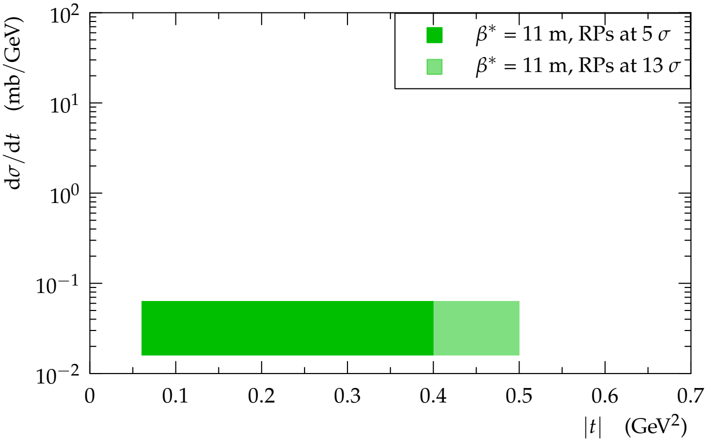


- dip+bump well visible in the high-statistics $\beta^* = 90$ m data high-statistics β^* = 90 m data:



pure exponential excluded with more than 7 σ significance

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



- 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

3 complementary methods:

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

elastic observables only:

$$\sigma_{tot}^2 = \frac{16\pi}{1 + \varrho^2} \frac{1}{\mathcal{L}} \left. \frac{dN_{el}}{dt} \right|_0$$

$$\sigma_{tot}$$

ϱ-independent:

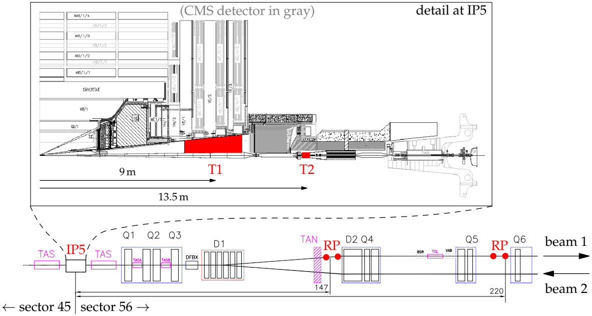
$$\sigma_{tot} = \frac{1}{\mathcal{L}} (N_{el} + N_{inel})$$

luminosity-independent:

$$\sigma_{tot} = \frac{16\pi}{1 + \varrho^2} \frac{dN_{el}/dt|_0}{N_{el} + N_{inel}}$$

$$\mathcal{L} = \frac{1 + \varrho^2}{16\pi} \frac{(N_{el} + N_{inel})^2}{dN_{el}/dt|_0}$$

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



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

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

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

↓ 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 ($\sigma_{\mathrm{tot}}^{RP} - \sigma_{\mathrm{el}}^{RP} - \sigma_{\mathrm{visible}}^{T2}$)

$\sqrt{s}$ = 7 TeV

elastic observables only:

$$\sigma^2_{tot} = \frac{16\pi}{1+\varrho^2} \frac{1}{\mathcal{L}} \left.\frac{dN_{el}}{dt}\right|_0$$

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

σ_{tot}

ϱ-independent:

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

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

luminosity-independent:

$$\sigma_{tot} = \frac{16\pi}{1+\varrho^2} \frac{dN_{el}/dt|_0}{N_{el} + N_{inel}}$$

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

$\sqrt{s}$ = 8 TeV

elastic observables only:

$$\sigma^2_{tot} = \frac{16\pi}{1+\varrho^2} \frac{1}{\mathcal{L}} \left.\frac{dN_{el}}{dt}\right|_0$$

σ_{tot}

ϱ-independent:

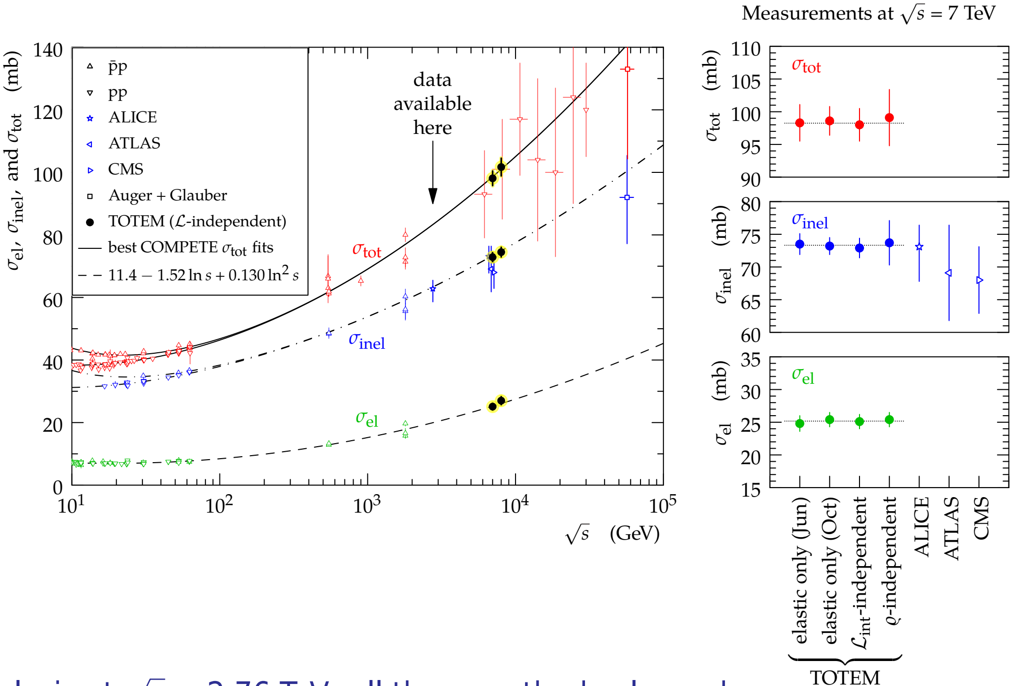
$$\sigma_{tot} = \frac{1}{\mathcal{L}} (N_{el} + N_{inel})$$

luminosity-independent:

$$\sigma_{tot} = \frac{16\pi}{1+\varrho^2} \frac{dN_{el}/dt|_0}{N_{el} + N_{inel}}$$

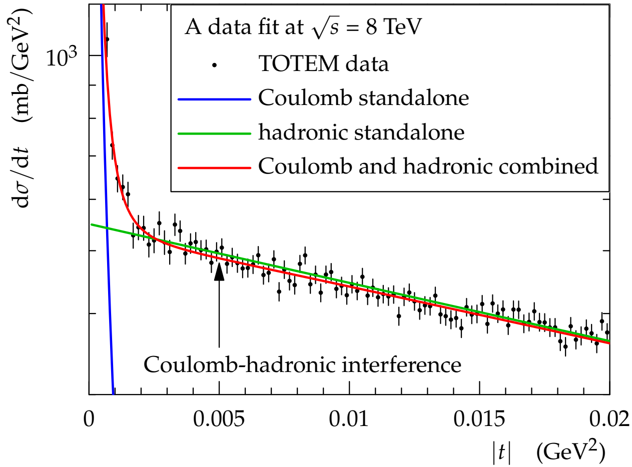
$\sigma_{tot} = (101.7 \pm 2.9)$ mb

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



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

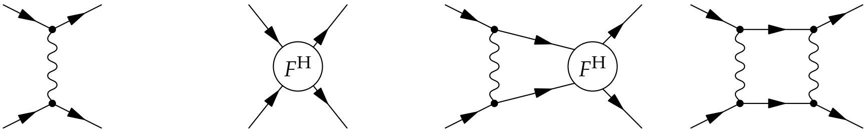
- $\beta^* = 1000$ m : $|t|$ as low as $6 \cdot 10^{-4}$ GeV^2 $\Rightarrow$ *observed Coulomb-nuclear interference* (between Coulomb/electromagnetic and nuclear/strong interactions):



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

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

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



- *Coulomb amplitude* $\mathcal{A}^{C}$: well known (QED, form-factors measured)
- *Nuclear amplitude* $\mathcal{A}^{N}$
  - *modulus*: constrained by TOTEM data ⇒ parametrised:
    $\exp(b_1 t + b_2 t^2 + \ldots)$ 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

- constant phase – the simplest choice

$$\arg \mathcal{A}^{N} = p_0$$

- central phase – similar shape as in many phenomenological models

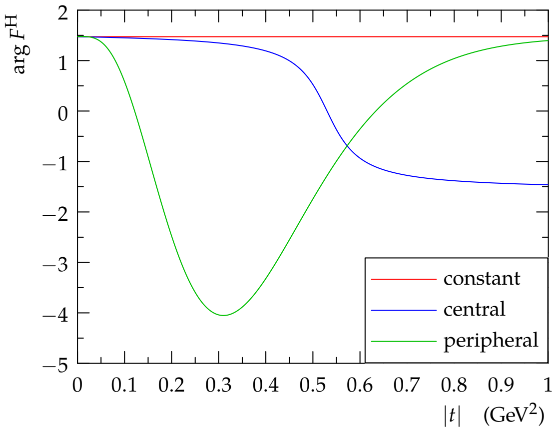
$$\arg \mathcal{A}^{N} = \frac{\pi}{2} - \operatorname{atan} \frac{\rho_0}{1 - \frac{t}{t_d}}, \quad \rho_0 = \frac{1}{\tan p_0}$$

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

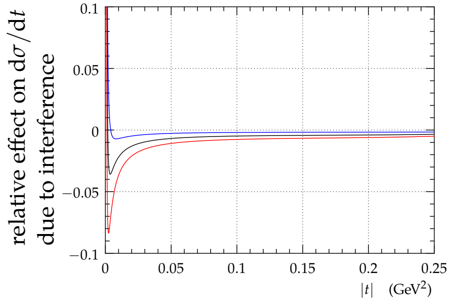
- peripheral phase [Z. Phys. C63 (1994) 619-630] – expected order in impact parameter space: elastic collisions more peripheral than inelastic $\langle b^2 \rangle^{el} > \langle b^2 \rangle^{inel}$

$$\arg \mathcal{A}^{N} = p_0 + A \exp\left[\kappa \left(\ln \frac{t}{t_m} - \frac{t}{t_m} + 1\right)\right]$$

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



low-$|t|$ effect: sum of two complex amplitudes ⇒ sensitivity to relative phase ⇒ sensitivity to $\rho \equiv \Re\mathcal{A}^{\mathrm{H}} / \Im\mathcal{A}^{\mathrm{H}}(t = 0)$



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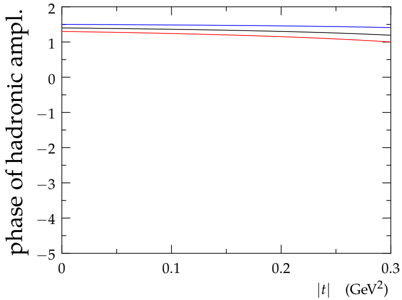
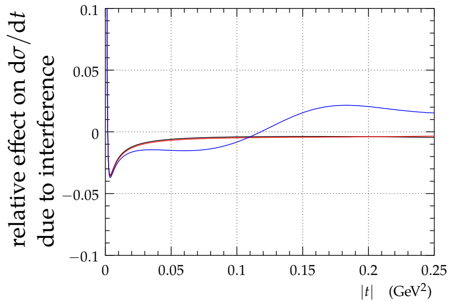


higher-$|t|$ effect: additional amplitude contributions (combining both forces) ⇒ (some) sensitivity to nuclear phase t-behaviour



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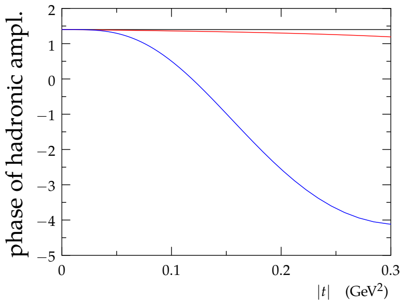
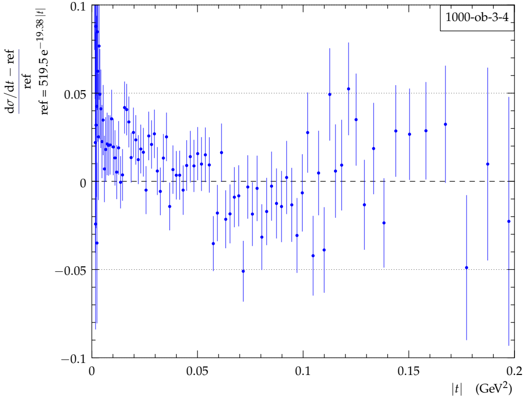


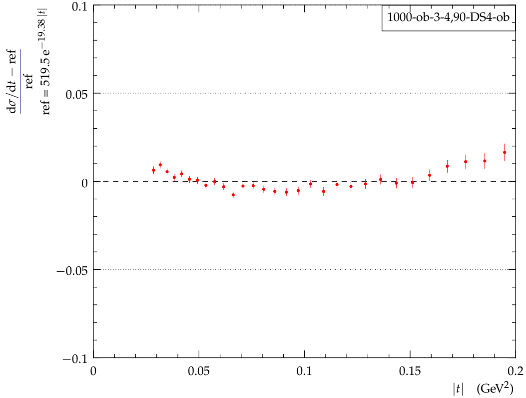
$\beta^* = 1000$ m

- $|t|_{\min} \simeq 6 \cdot 10^{-4}$ GeV^2
- statistics: 0.3 M el. events



$\beta^* = 90$ m

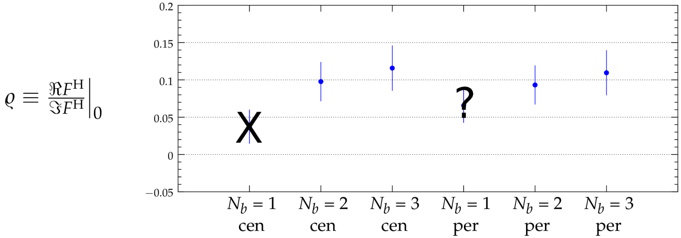
- $|t|_{\min} \simeq 2 \cdot 10^{-2}$ GeV^2
- statistics: 7 M el. events



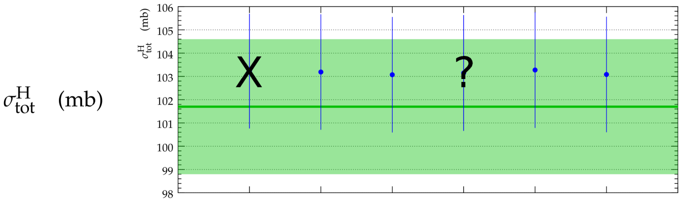
goal: use both datasets to constrain the nuclear phase as much as possible

(in progress)

- 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 β^* = 90 m results [PRL 111 (2013) 012001]

		elastic differential cross-section	total cross-section	Coulomb-nuclear interference
7 TeV	90 m	published		x
	3.5 m, medium |t|	published	x	x
	3.5 m, high |t|	in progress	x	x
8 TeV	90 m, low stat.	published		x
	90 m, high stat.	in progress		
	1000 m			
2.76 TeV	11 m	in progress		x

Backup

↓

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

⇓

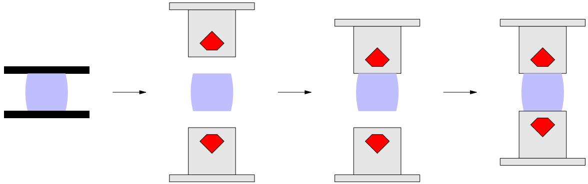
- two types of alignment needed
  - alignment of mechanical RP edges → for machine protection
  - alignment of RP sensors → for physics
- need alignment *wrt. the beam*

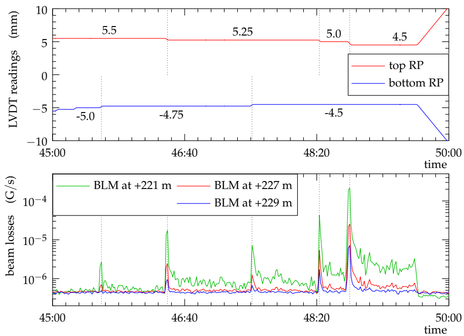
⇓

3-step alignment procedure:

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

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

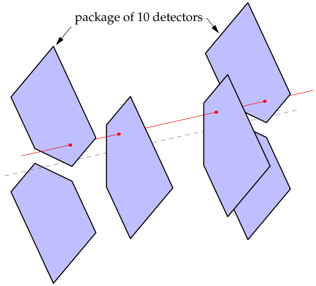




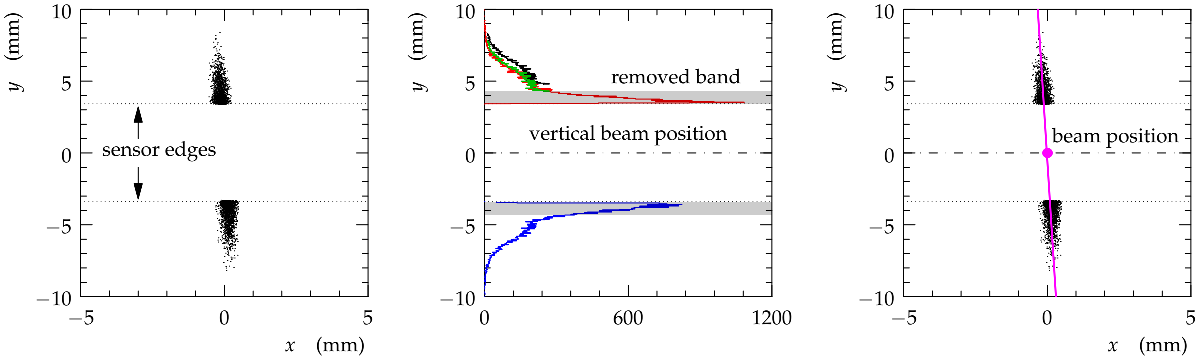
2) *Track-based alignment*: relative alignment among sensors

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

⇒ need further alignment step



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

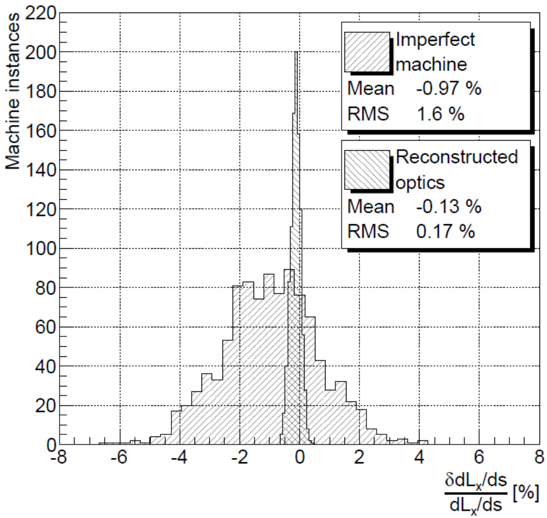


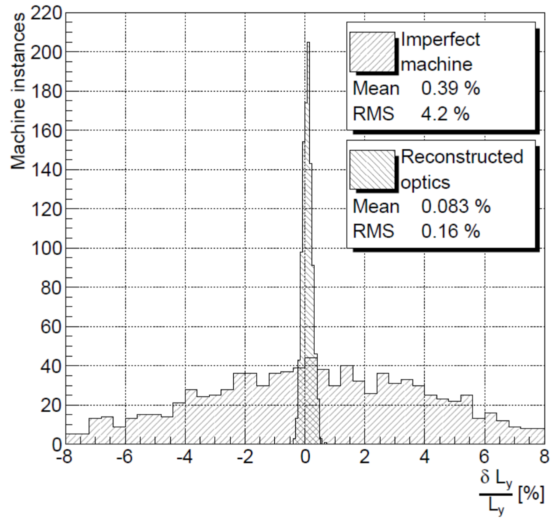
- optics imperfection sources
  - power-converter error: $\Delta I/I \approx 10^{-4}$
  - magnet transfer function: $\Delta B/B \approx 10^{-3}$
  - magnet rotation (< 1 mrad) and displacements (< 0.5 mm)
  - magnet harmonics ($\Delta B/B \approx 10^{-4}$)
  - beam momentum offset: $\Delta p/p \approx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





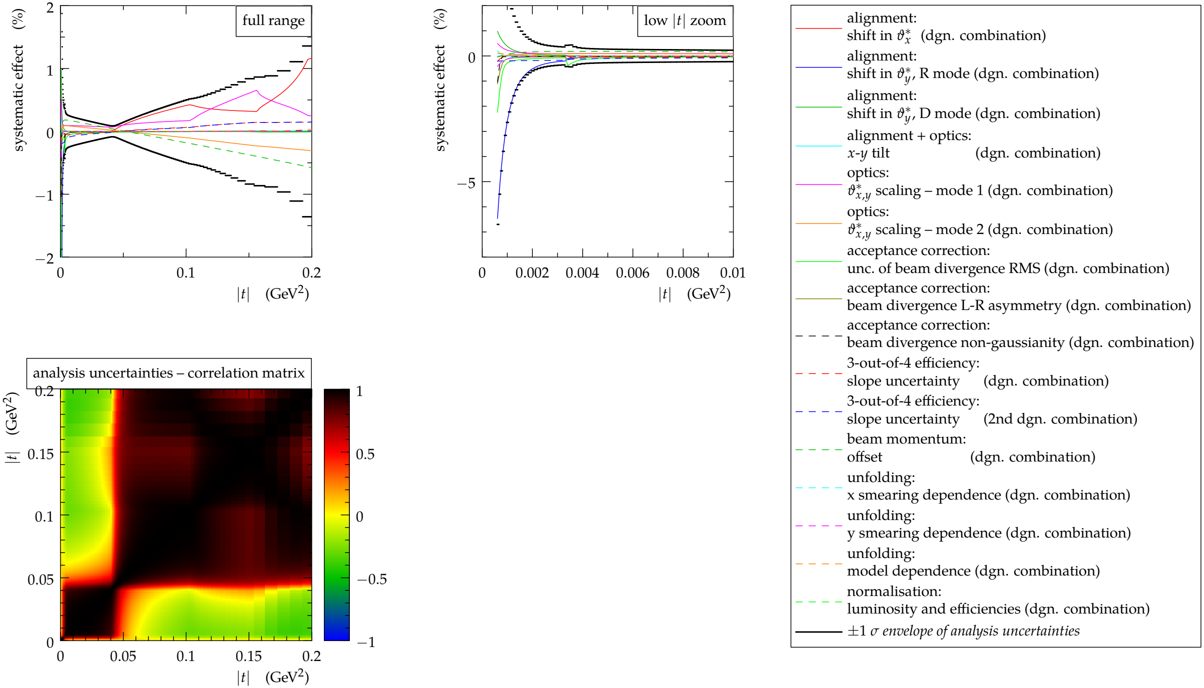
- optics uncertainty reduced:

  x projection: from 1.6% to 0.17%

  y projection: from 4.2% to 0.16%

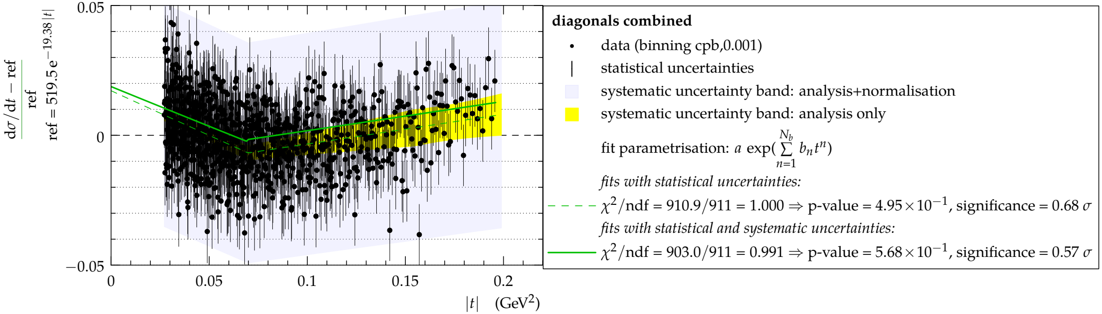
→ LHC Optics Measurement with Proton Tracks Detected by the Roman Pots of the TOTEM Experiment [arXiv:1406.0546]

Backup : *Systematic studies (1000 m)*



fit parametrisation: $A_1 \exp(B_1 t)$ for $t < 0.07$, $A_2 \exp(B_2 t)$ for $t > 0.07$

DS4



- tried split points $t = 0.05$ up to 0.10 GeV^2; 0.07 gives best significance
- fits with systematics
  - $A_1 = 529.30 \pm 22.33, B_1 = -19.678 \pm 0.074, A_2 = 514.68 \pm 22.33, B_2 = -19.264 \pm 0.057$
  - important correlation between segments 1 and 2
  - $A_1 - A_2 = 14.617 \pm 1.789 \Rightarrow 8.2\ \sigma$
  - $B_1 - B_2 = -0.414 \pm 0.056 \Rightarrow 7.4\ \sigma$

combined significance: 7.7 σ

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

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

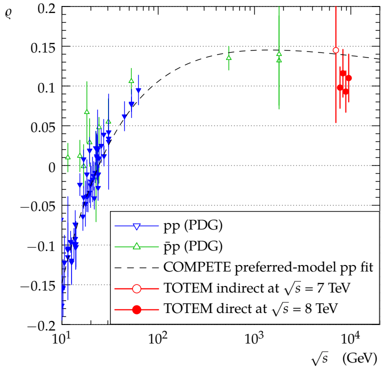
- Kundrát-Lokajíček formula (KL)
  - any slope B, any nuclear phase
  - more complicated effect (Ψ complex in general)

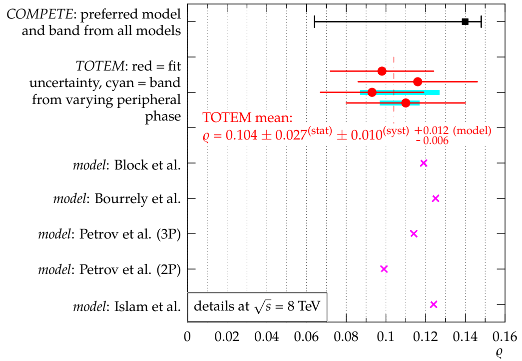
$$F^{C+H} = F^{C} + F^{H} e^{i\alpha\Psi}$$

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

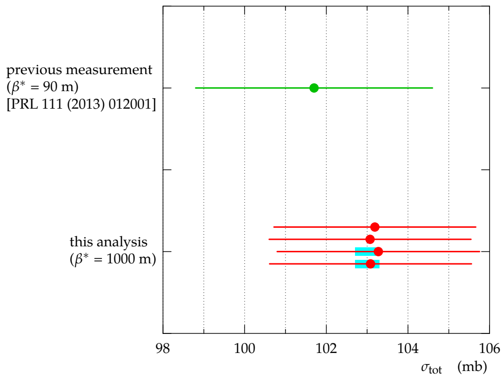
$$I(t,t') = \int_{0}^{2\pi} d\varphi \, \frac{\mathcal{F}^2(t'')}{t''} , \qquad t'' = t + t' + 2\sqrt{tt'}\cos\varphi$$

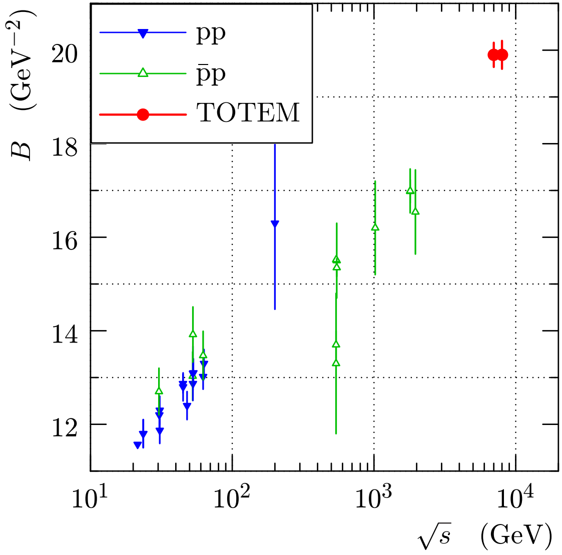
$\rho \rightarrow$

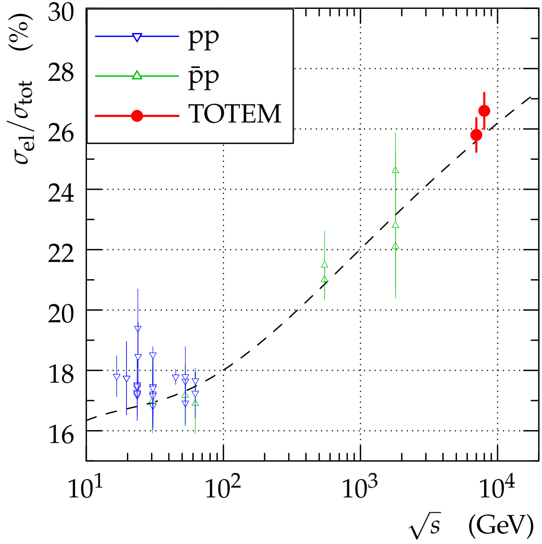




$\sigma_{tot} \rightarrow$




pp
p̄p
TOTEM
B (GeV⁻²)
20
18
16
14
12
10¹
10²
10³
10⁴
√s (GeV)


pp
p̄p
TOTEM
σel/σtot (%)
30
28
26
24
22
20
18
16
10¹
10²
10³
10⁴
√s (GeV)