

TOTEM Results on Elastic Scattering and Total Cross-Section

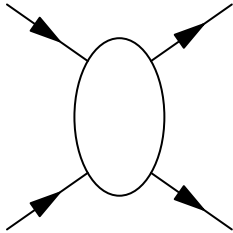
Jan Kašpar

on behalf of the TOTEM collaboration

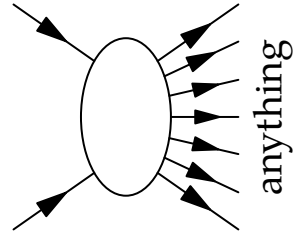


XXX-th International Workshop on High Energy Physics, Protvino
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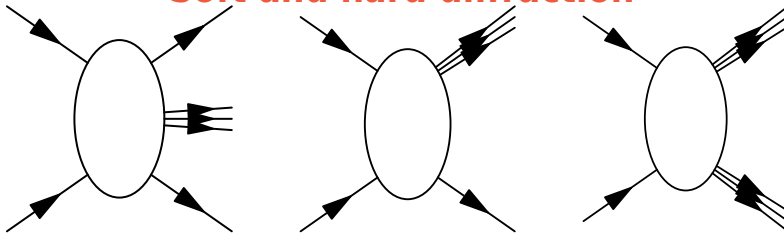
Elastic scattering



Total cross-section

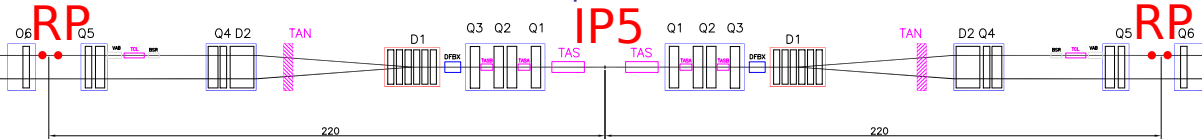


Soft and hard diffraction

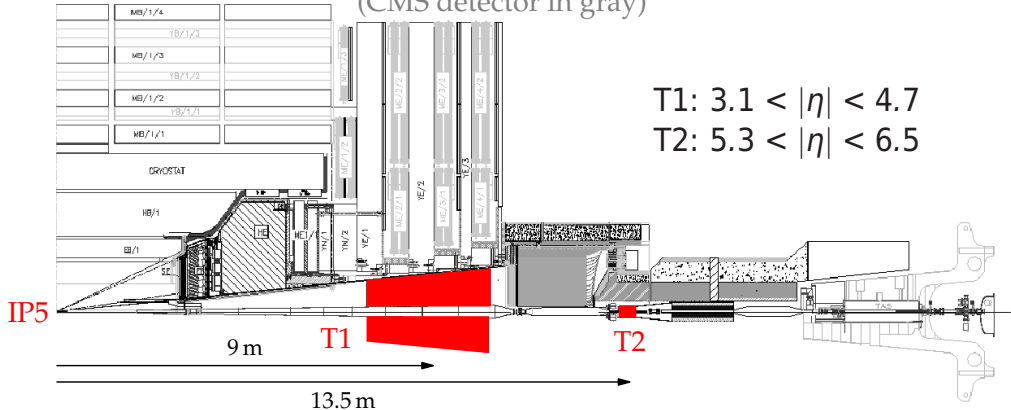


final state: rapidity gaps, very forward protons

- *Roman Pots*: elastic and diffractive protons

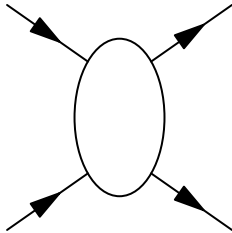


- *Telescopes T1 and T2*: charged particles from inelastic collisions
(CMS detector in gray)



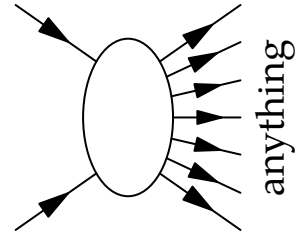
- all detectors symmetrically on both sides of IP5
- all detectors trigger-capable

Elastic scattering



optical theorem

Total cross-section

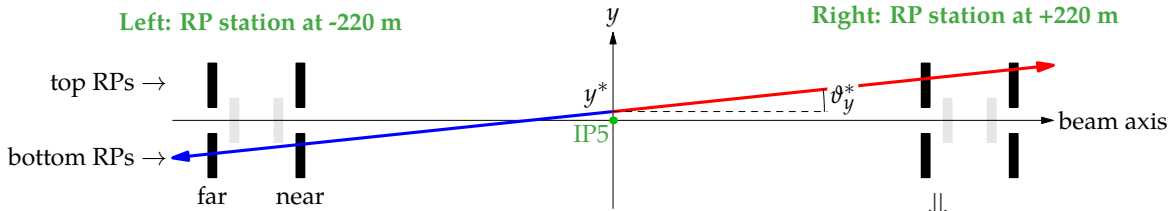


Outline

- 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:

Left: RP station at -220 m



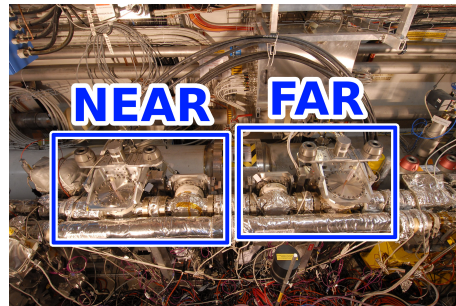
four-momentum transfer squared: t

scattering angle: $\vartheta^* \simeq \sqrt{t}/p$

azimuthal angle: φ^*

horizontal angle: $\vartheta_x^* = \vartheta^* \cos \varphi^*$

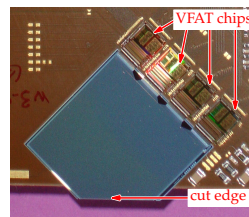
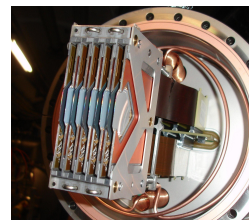
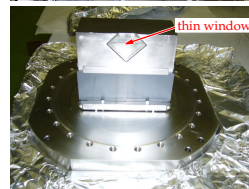
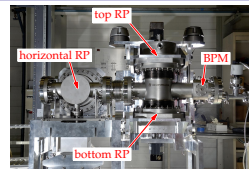
vertical angle: $\vartheta_y^* = \vartheta^* \sin \varphi^*$



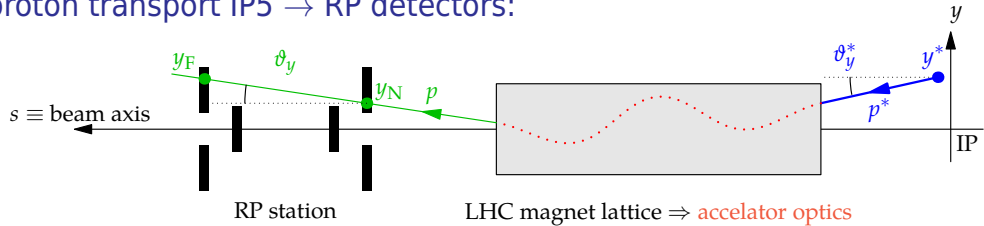
- 2 diagonals \Rightarrow control of systematics
 - left *bottom* - right *top*
 - left *top* - right *bottom*

- 2 units \Rightarrow 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): $\approx 50 \mu\text{m}$
 - strips with pitch $66 \mu\text{m}$ oriented at 45° wrt. active edge
- VFAT: trigger-capable read-out chip



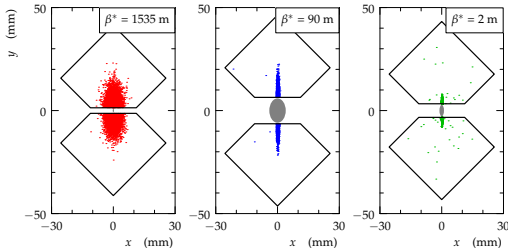
- proton transport IP5 → RP detectors:



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

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

- 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 \rightarrow kinematics at IP ($\xi = 0 \Rightarrow$ relatively easy)
- choice of formulae (using Near and Far RPs) \rightarrow minimisation of systematics, typically:

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

- optics can be refined with TOTEM data!

3. Elastic tagging

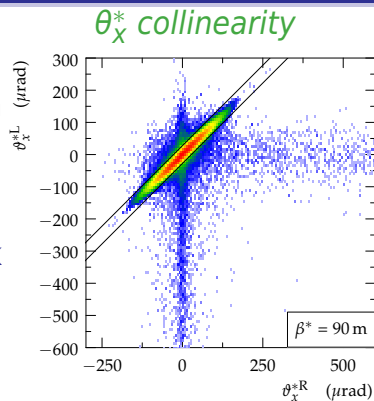
- angles left = angles right (tolerance set by beam divergence: higher β^* \Rightarrow more stringent cut)
- vertex left = vertex right
- protons $\xi \approx 0 \Rightarrow$ correlation hit position ξ vs. track angle at RP

4. Background subtraction

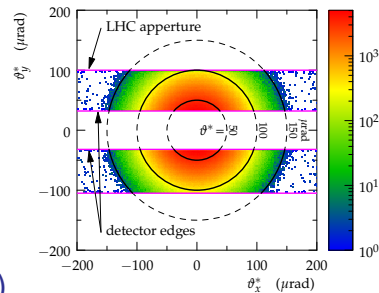
- typically needed only for low β^* optics
- interpolation of event distribution surrounding the signal (tagged) region

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)



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

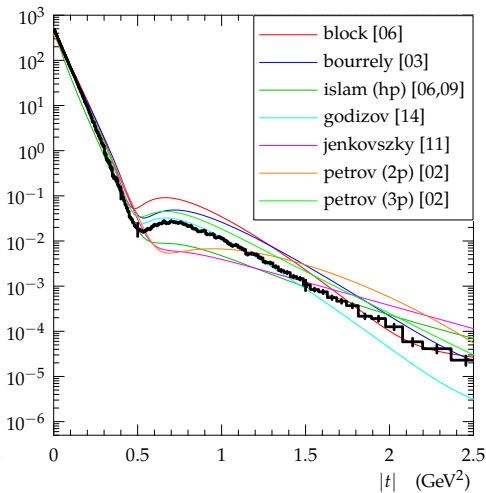
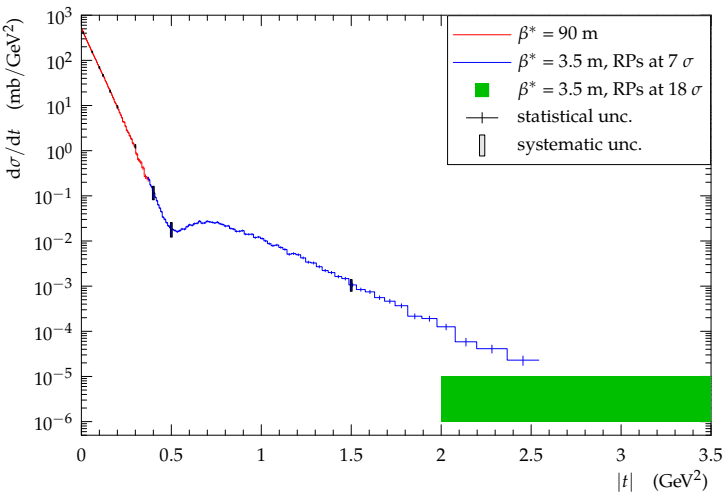
- from CMS (if available), uncertainty $\approx 4\%$
- from TOTEM (details later on)

9. Study of systematic uncertainties

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

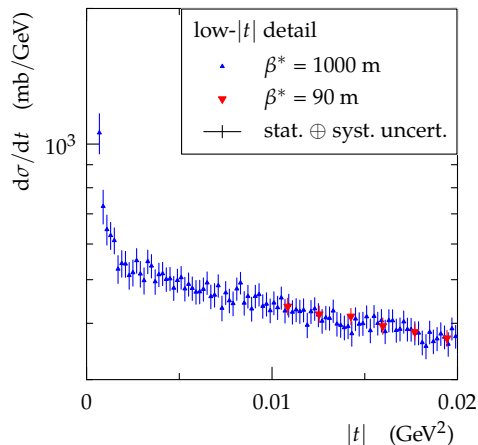
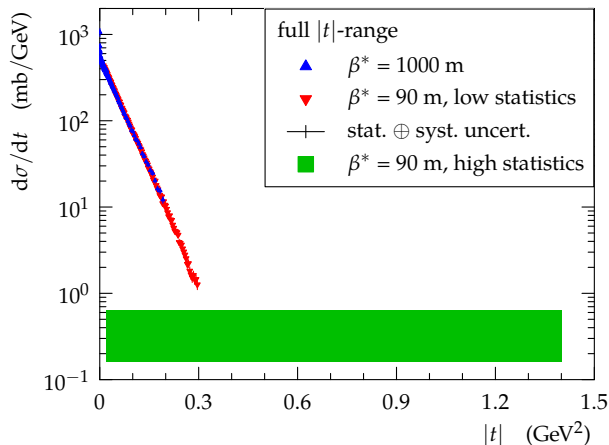
Elastic scattering results : $\sqrt{s} = 7 \text{ TeV}$

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	≈ 2 to 3.5 GeV^2	10 k	



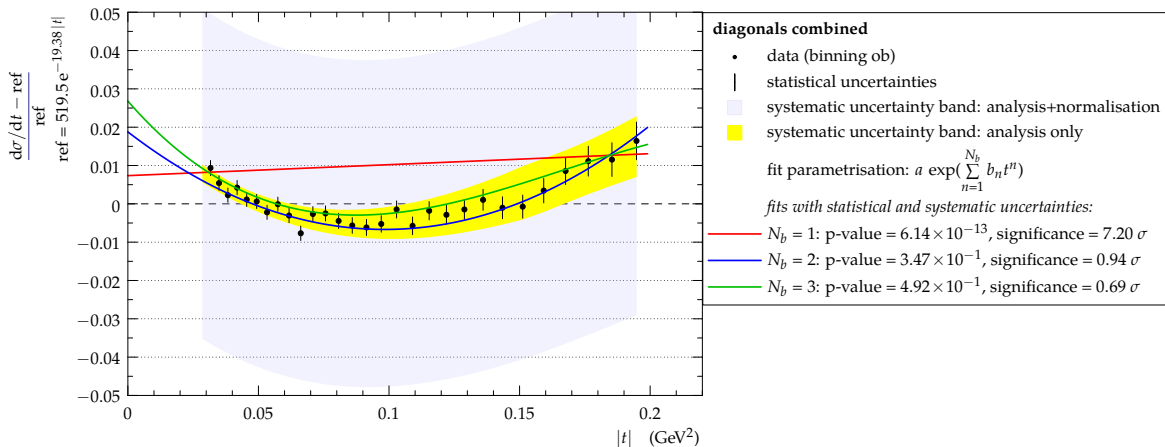
Elastic scattering results : $\sqrt{s} = 8 \text{ TeV}$

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	

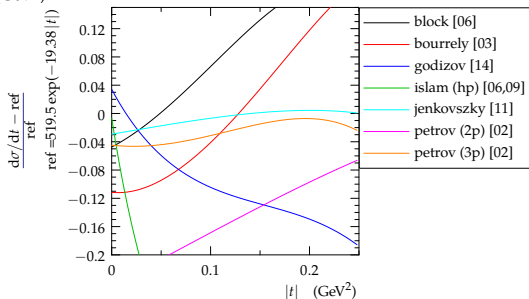


- dip+bump well visible in the high-statistics $\beta^* = 90 \text{ m}$ data

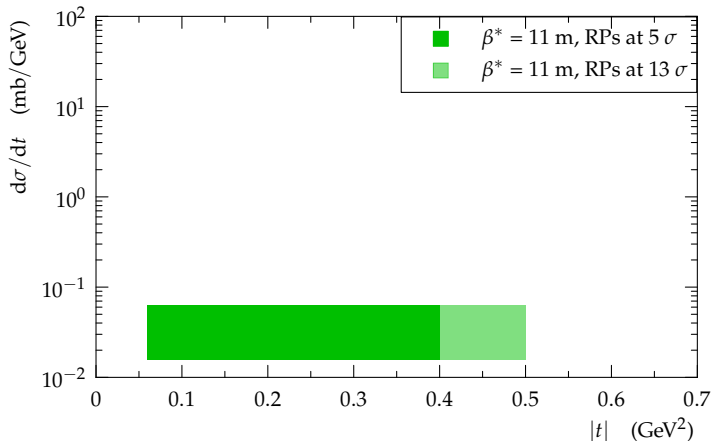
- high-statistics $\beta^* = 90 \text{ m}$ data:



pure exponential excluded with more than 7σ significance



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



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

3 complementary methods:

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

elastic observables only:

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

σ_{tot}

q independent:

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

luminosity independent:

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

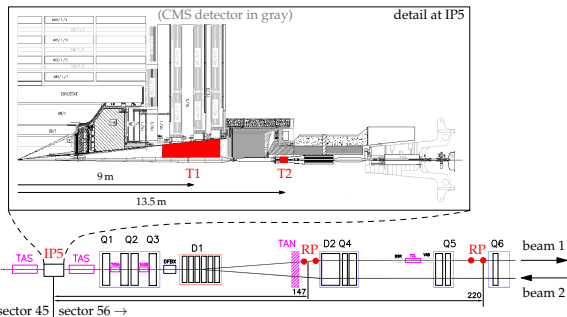
$$\mathcal{L} = \frac{1+q^2}{16\pi} \frac{(N_{el} + N_{inel})^2}{dN_{el}/dt|_0}$$

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*

⇒ but can be constrained from data ($\sigma_{\text{tot}}^{\text{RP}} - \sigma_{\text{el}}^{\text{RP}} - \sigma_{\text{visible}}^{\text{T2}}$)

$\sqrt{s} = 7$ TeV

elastic observables only:

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

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



σ_{tot}



q-independent:

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

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

luminosity-independent:

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

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

$\sqrt{s} = 8$ TeV

elastic observables only:

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



σ_{tot}



q-independent:

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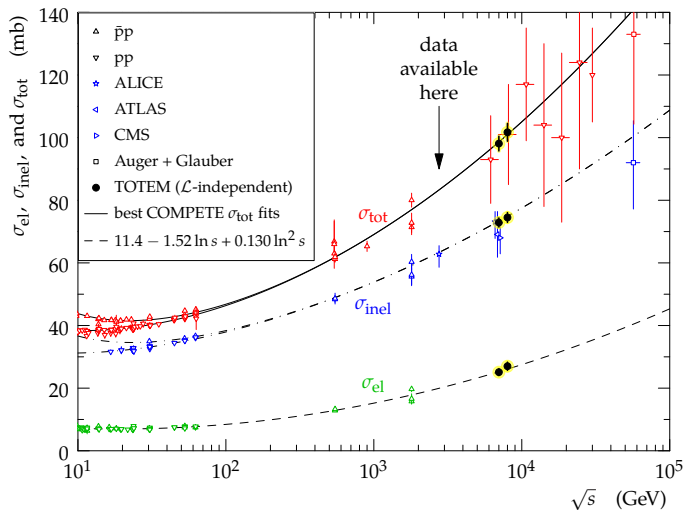
luminosity-independent:

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

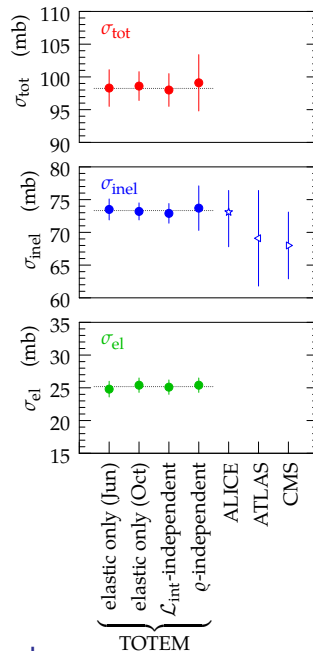
$$\sigma_{\text{tot}} = (101.7 \pm 2.9) \text{ mb}$$

- 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

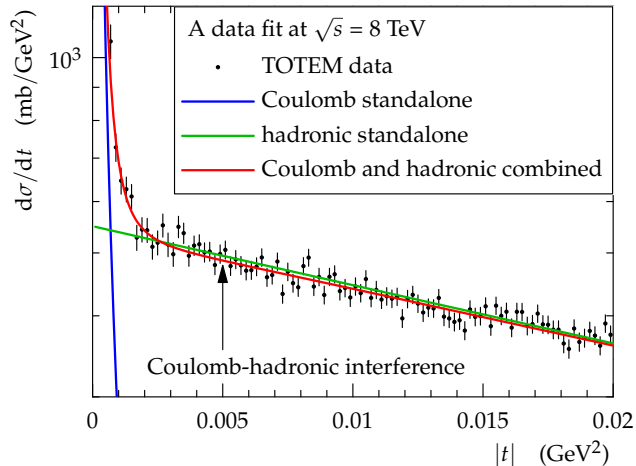


Measurements at $\sqrt{s} = 7$ TeV



- 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 $6 \cdot 10^{-4}$ GeV² \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}*

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

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

- **Coulomb amplitude** \mathcal{A}^C : well known (QED, form-factors measured)
- **Nuclear amplitude** \mathcal{A}^N
 - **modulus**: constrained by TOTEM data \Rightarrow parametrised:
 $\exp(b_1 t + b_2 t^2 + \dots)$ $N_b = \text{number of } b_i \text{ parameters} = 1 \text{ to } 3$
 - **phase**: weak guidance from data \Rightarrow 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

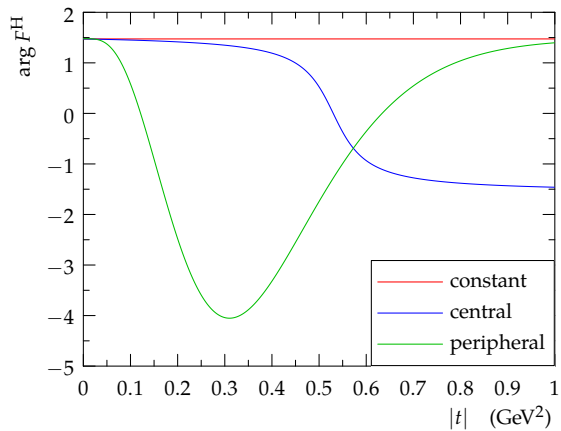
$$\arg \mathcal{A}^N = \frac{\pi}{2} - \text{atan} \frac{\rho_0}{1 - \frac{t}{t_d}}, \quad \rho_0 = \frac{1}{\tan p_0}$$

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

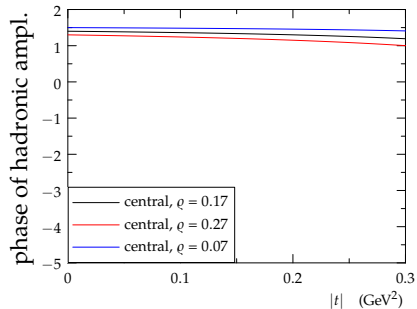
- peripheral phase [Z. Phys. C63 (1994) 619-630] – expected order in impact parameter space: elastic collisions more peripheral than inelastic $\langle b^2 \rangle^{\text{el}} > \langle b^2 \rangle^{\text{inel}}$

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

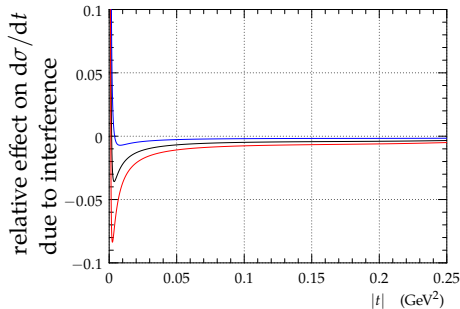
$$A \approx 5.53, \quad \kappa \approx 4.01, \quad t_m \approx -0.310 \text{ GeV}^2$$



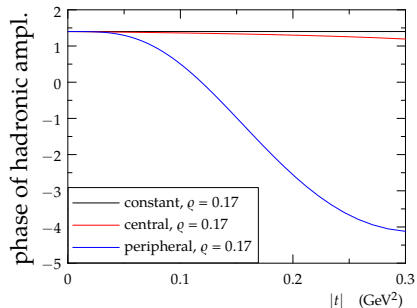
low- $|t|$ effect: sum of two complex amplitudes \Rightarrow sensitivity to relative phase
 \Rightarrow sensitivity to $\rho \equiv \Re \mathcal{A}^H / \Im \mathcal{A}^H (t=0)$



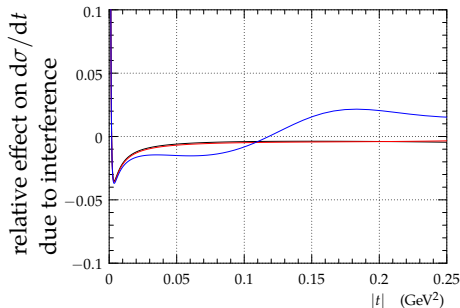
\Rightarrow



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

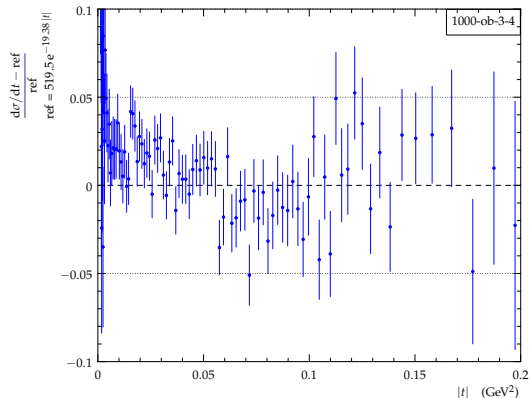


\Rightarrow



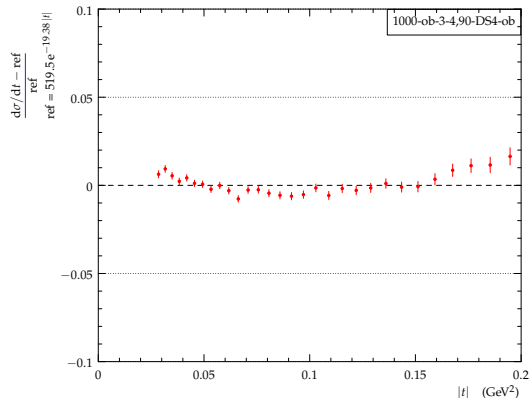
$$\beta^* = 1000 \text{ m}$$

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



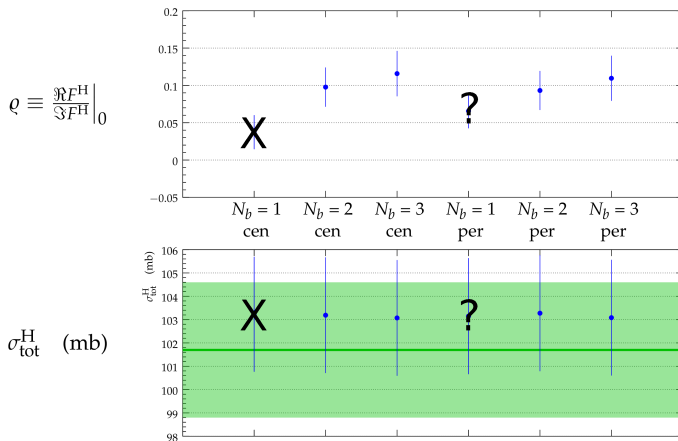
$$\beta^* = 90 \text{ m}$$

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



*goal: use both datasets to constrain the nuclear phase as much as possible
(in progress)*

- data fits \rightarrow 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 $\chi^2/\text{ndf} \approx 1$
 - 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



- σ_{tot} : very stable results
- green line and band: previous $\beta^* = 90$ m results [PRL 111 (2013) 012001]

- data taken so far

collision energy	optics (beta*)	data-set	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 statistics	published		x
	90 m	high statistics	in progress		
	1000 m		in progress		
2.76 TeV	11 m		in progress		x

- future data: repeat the same (and more)

- o elastic differential cross-section and phase (Coulomb-nuclear interference), total cross-section
- o every possible energy
- o widest $|t|$ range

Backup



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



- two types of alignment needed
 - alignment of mechanical RP edges \rightarrow for machine protection
 - alignment of RP sensors \rightarrow for physics

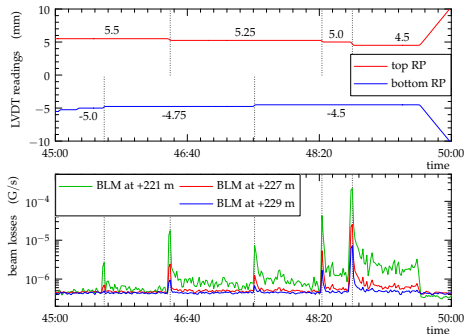
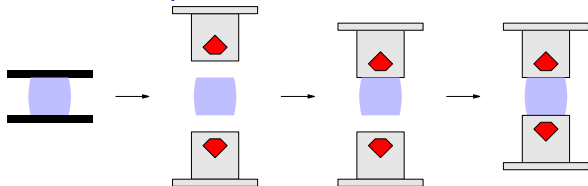
- need alignment *wrt. the beam*



3-step alignment procedure:

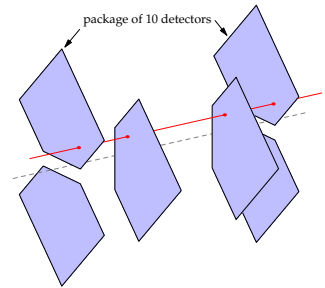
- 1) *Collimation alignment*: RP alignment wrt. beam, rough sensor alignment

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

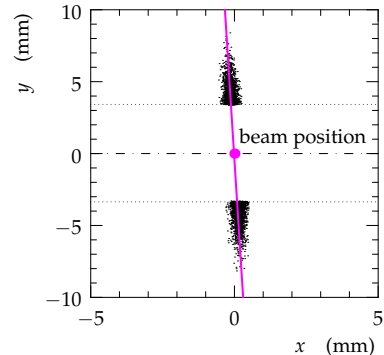
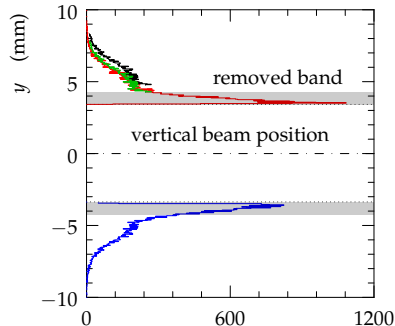
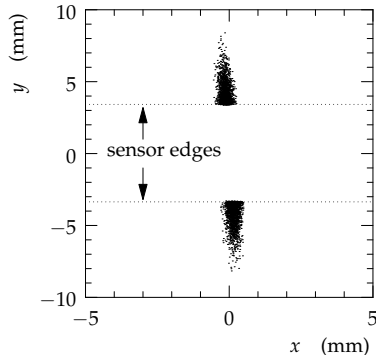


2) *Track-based alignment*: relative alignment among sensors

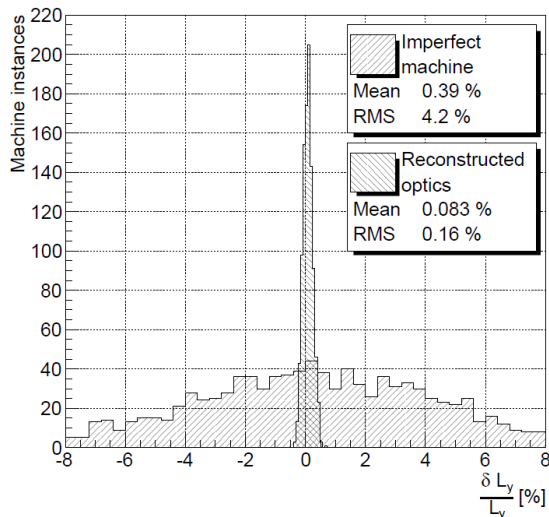
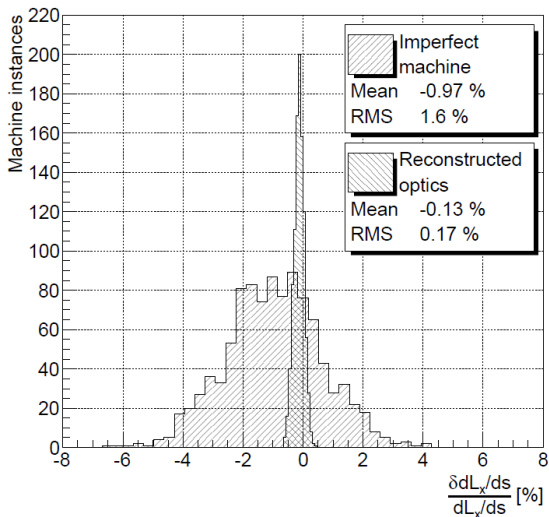
- RP station: no magnetic field → straight tracks
- misalignments → residuals
- residual analysis → alignment corrections
- overlap between horizontal and vertical RPs → relative alignment among all sensors
- singular/weak modes: e.g. overall shift/rotation
⇒ need further alignment step



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



- optics imperfection sources
 - power-converter error: $\Delta/I \approx 10^{-4}$
 - 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
 - $\frac{dL_y}{ds}/L_y$
 - $s(L_x = 0)$
 - xy coupling (tilts in xy plane)
 - ...

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

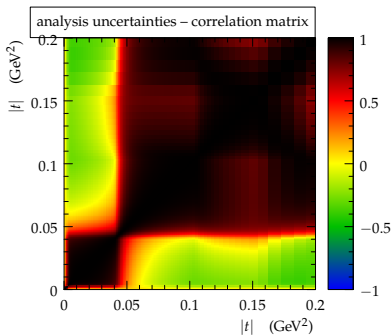
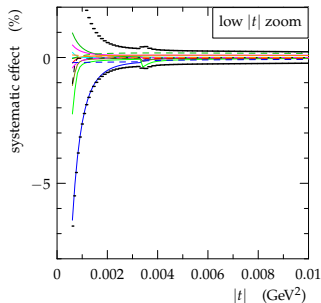
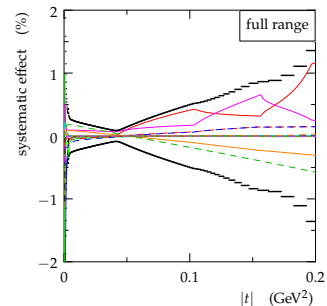
- optics uncertainty reduced:

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]

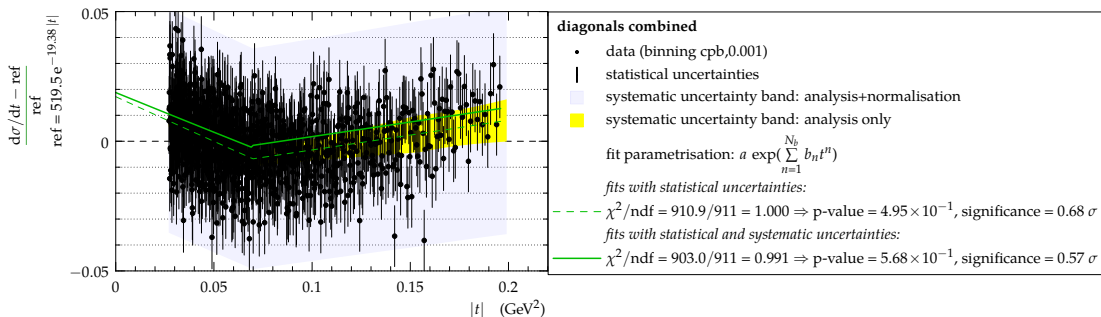
Backup : Systematic studies (1000 m)



- alignment: shift in θ_x^* (dgn. combination)
- alignment: shift in θ_y^* , R mode (dgn. combination)
- alignment: shift in θ_y^* , D mode (dgn. combination)
- alignment + optics: x-y tilt (dgn. combination)
- optics: $\theta_{x,y}^*$ scaling – mode 1 (dgn. combination)
- optics: $\theta_{x,y}^*$ scaling – mode 2 (dgn. combination)
- acceptance correction: unc. of beam divergence RMS (dgn. combination)
- acceptance correction: beam divergence L-R asymmetry (dgn. combination)
- acceptance correction: beam divergence non-gaussianity (dgn. combination)
- - - 3-out-of-4 efficiency: slope uncertainty (dgn. combination)
- - - 3-out-of-4 efficiency: slope uncertainty (2nd dgn. combination)
- - - beam momentum: offset (dgn. combination)
- - - unfolding: x smearing dependence (dgn. combination)
- - - unfolding: y smearing dependence (dgn. combination)
- - - unfolding: model dependence (dgn. combination)
- - - normalisation: luminosity and efficiencies (dgn. combination)
- $\pm 1 \sigma$ envelope of analysis uncertainties

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_j parameter only) and *constant nuclear phase*
 - acts as simple interference phase (i.e. Φ is real-valued)

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

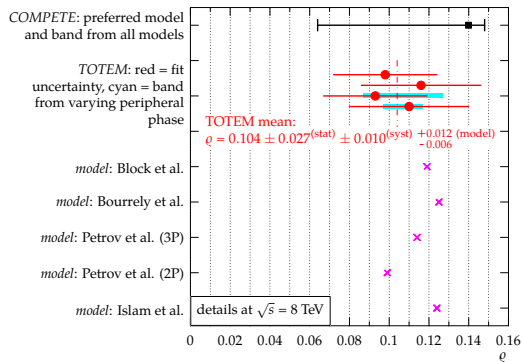
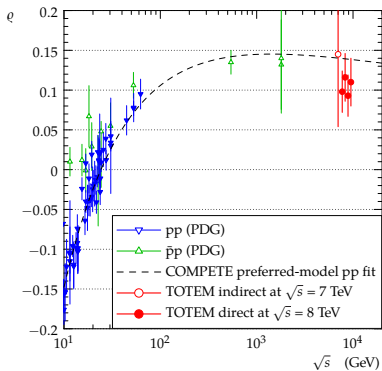
- Kandrát-Lokajíček formula (KL)
 - any slope B , any nuclear phase
 - more complicated effect (Ψ complex in general)

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

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

$$l(t, t') = \int_0^{2\pi} d\varphi \frac{\mathcal{F}^2(t'')}{t''}, \quad t'' = t + t' + 2\sqrt{tt'} \cos \varphi$$

Backup : Coulomb-nuclear interference - results



$\sigma_{\text{tot}} \rightarrow$

previous measurement
 ($\beta^* = 90 \text{ m}$)
 [PRL 111 (2013) 012001]

this analysis
 ($\beta^* = 1000 \text{ m}$)

