Elastic and Total Cross-Section Measurements by TOTEM: Past and Future

Frigyes Nemes on behalf of the TOTEM experiment
CERN*

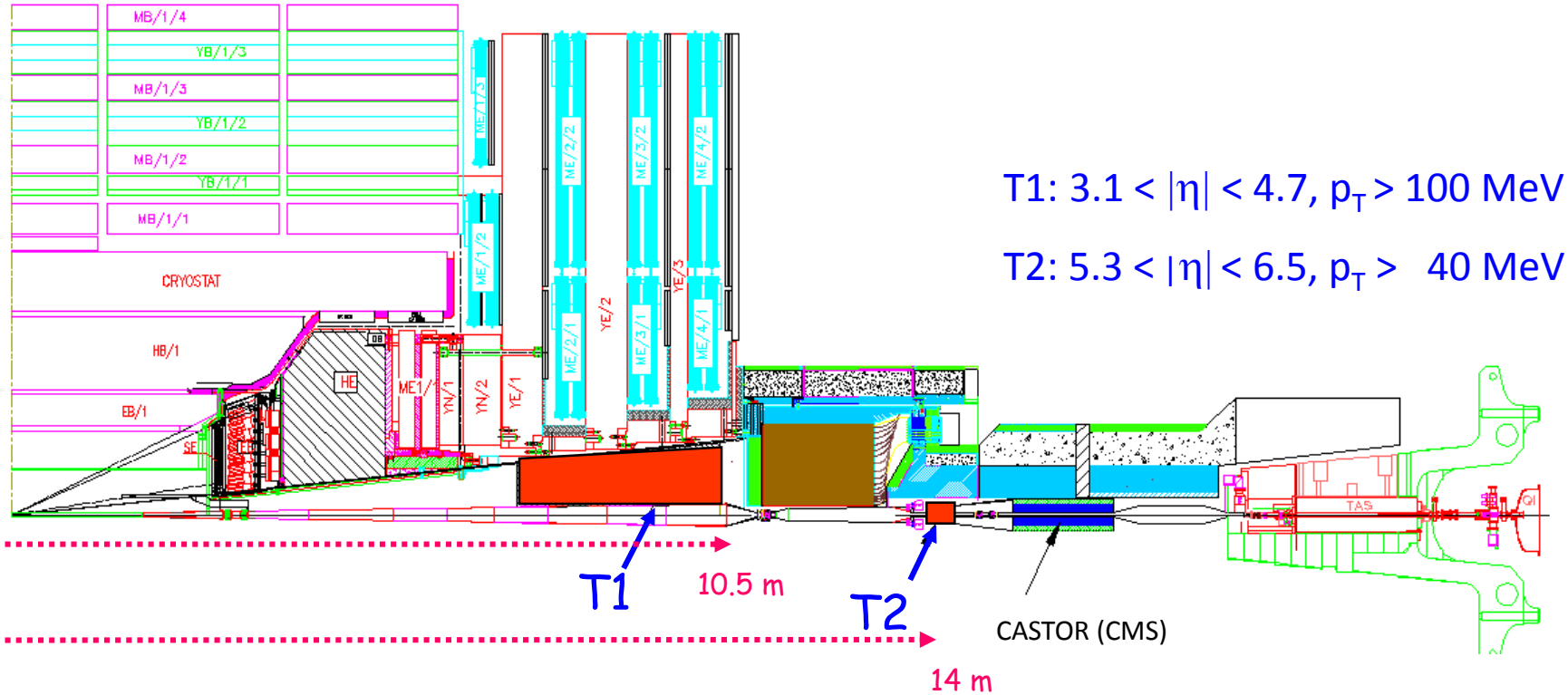
DIS 2017

Birmingham, England

2017, April 3. – 7.

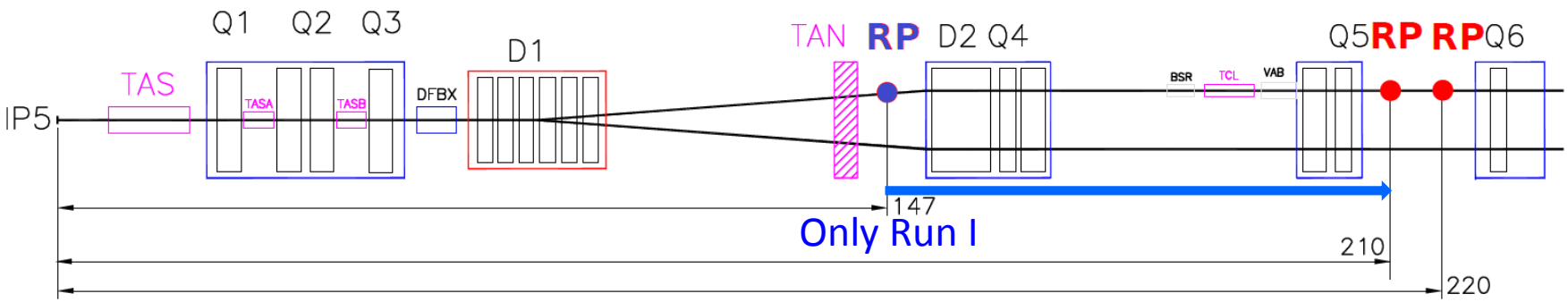
***Also at Wigner RCP, Budapest, Hungary**

Experimental layout of the TOTEM experiment (LHC Run II)



T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

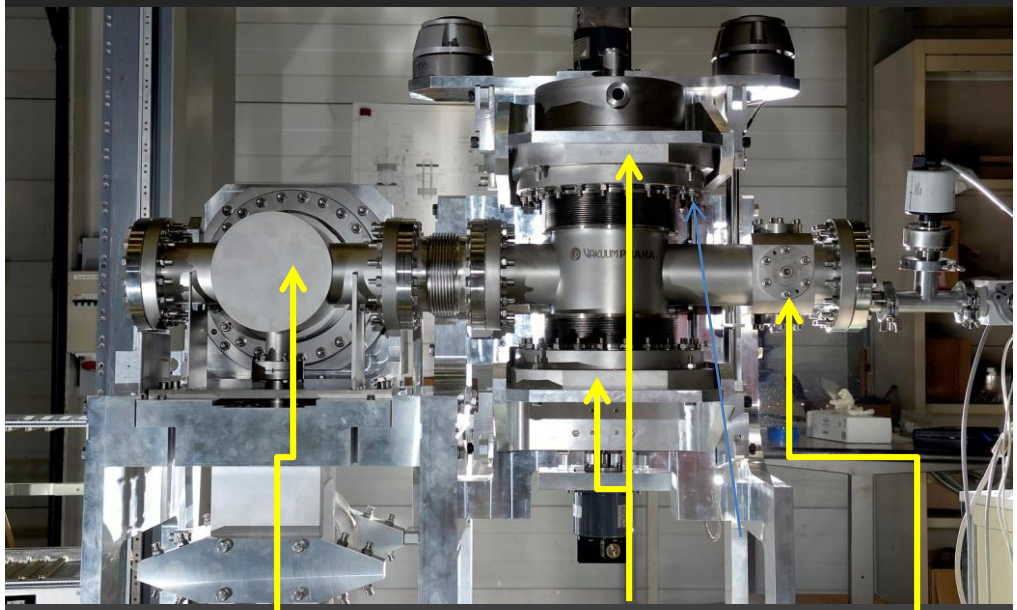


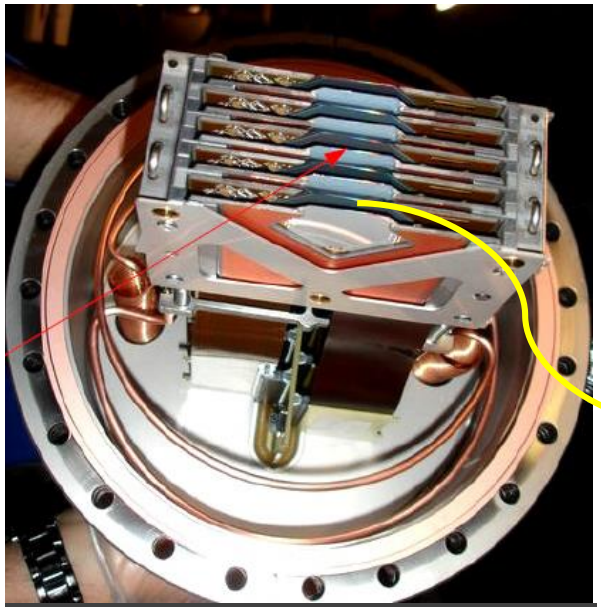
The Roman Pot (RP) stations of the TOTEM experiment

RP stations:

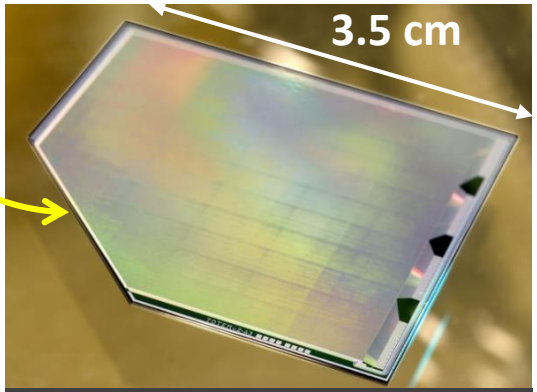
- 2 units (**N**ear, **F**ar) at about 5 m (RP220) and 10 m (RP210) distance
- Unit: 3 moveable RP to approach the beam and detect very small proton scattering angles (few µrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 µm inside unit among 3 RPs)

RP unit: 2 vertical, 1 horizontal pot + BPM

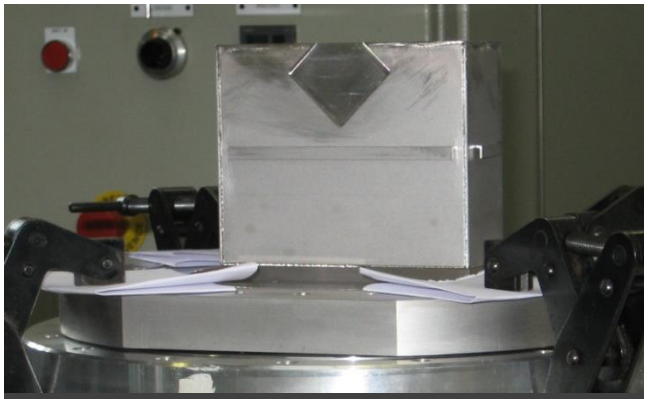




10 planes of edgeless detectors



Si edgeless detector



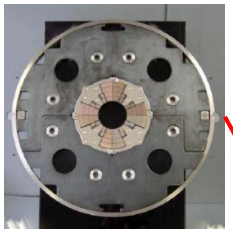
1 Roman Pot

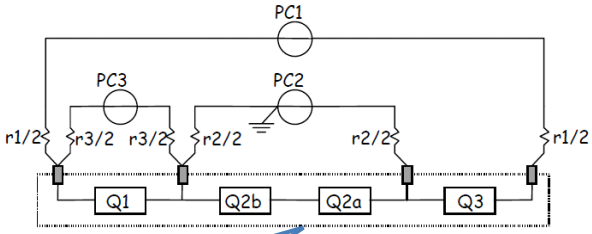
LHC optics at IP5 briefly

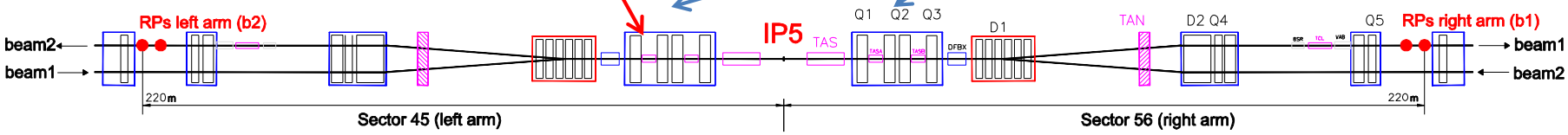
Sketch of the LHC magnet lattice at IP5:

$$k = \frac{1}{B\rho}\frac{dB_z}{dx}$$

MQXA quadrupole







s: distance from IP5 (*≡IP5)

Measured

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \xi \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ v'_x & L'_x & m_{23} & m_{24} & D'_x \\ m_{31} & m_{32} & v_y & L_y & D_y \\ m_{41} & m_{42} & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \\ \xi^* \end{pmatrix}$$

$$\sigma(\Theta) = \sqrt{\varepsilon / \beta_x(s)}$$

Determines angular resolution.

TOTEM cross-section measurements

√s = 7 TeV

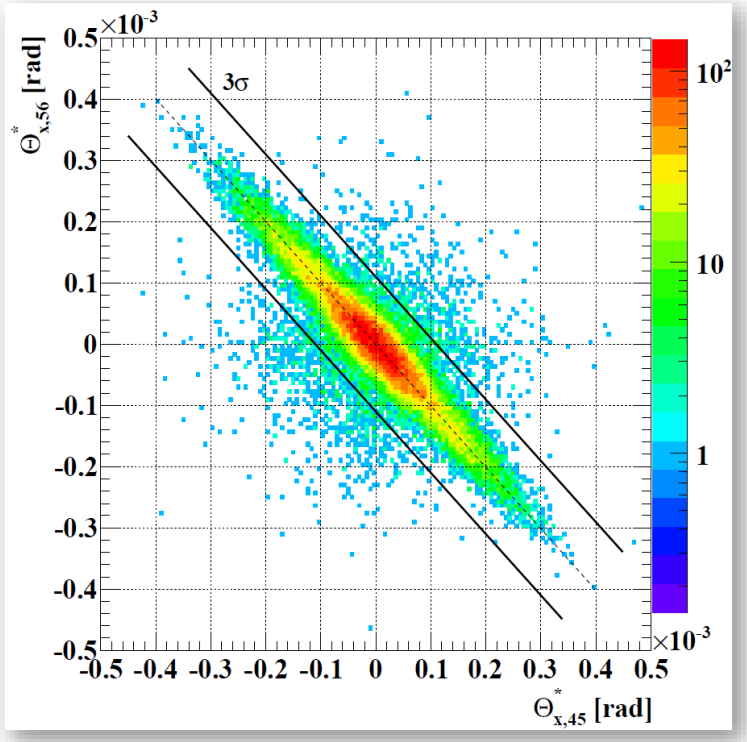
List of TOTEM publications

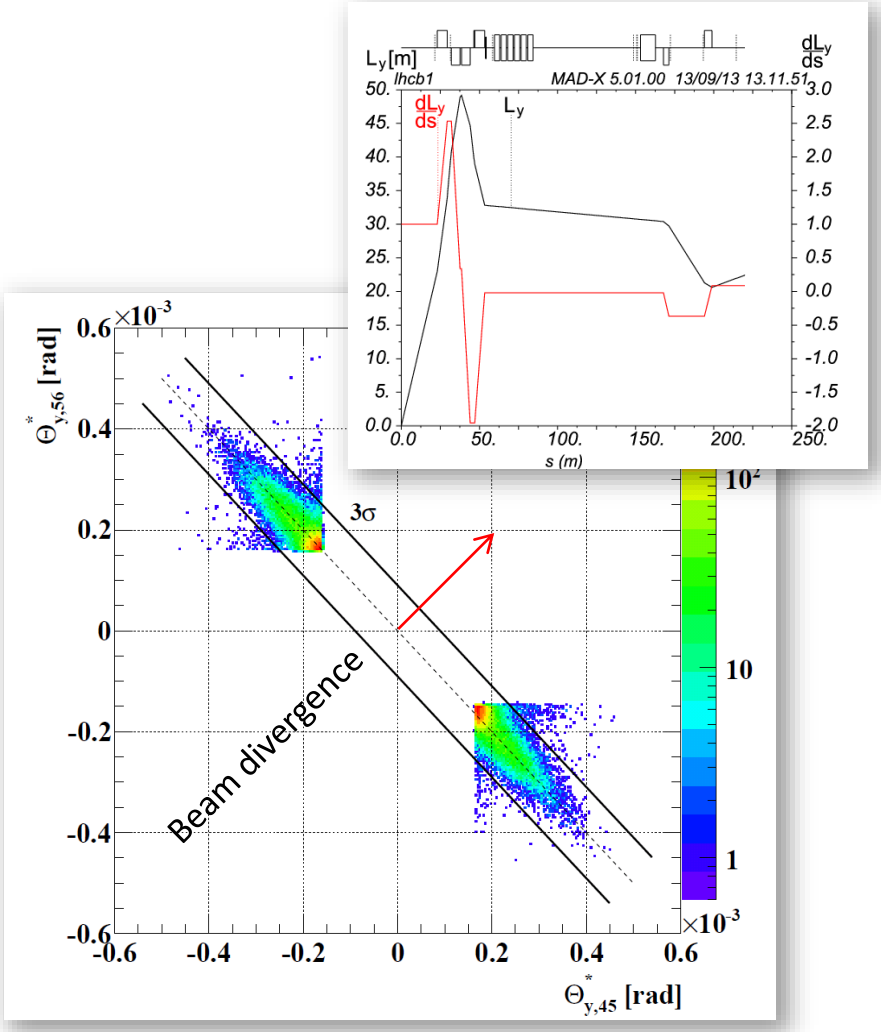
http://totem.web.cern.ch/Totem/publ_new.html

Reconstructed proton kinematics with β* = 3.5 m optics

Momentum conservation is required in elastic events:

- [Published in EPL **95** (2011) 41001]





Horizontally…

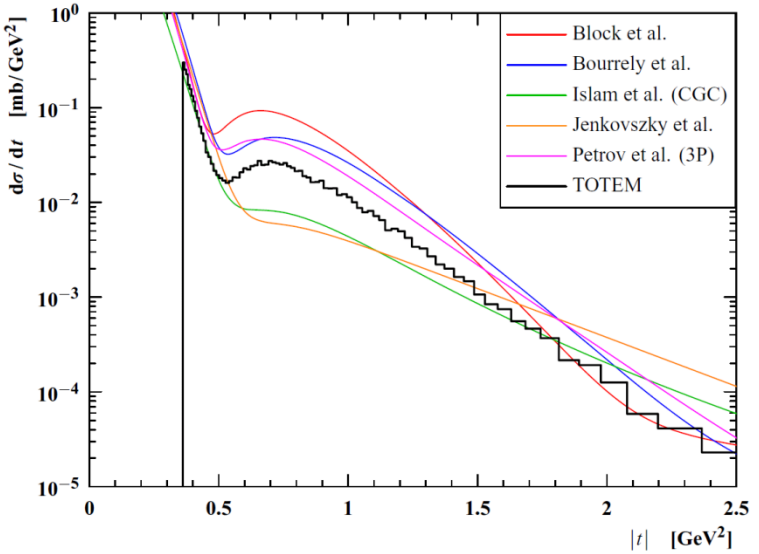
…and vertically

Spread agrees with beam divergence (17-18 μrad)

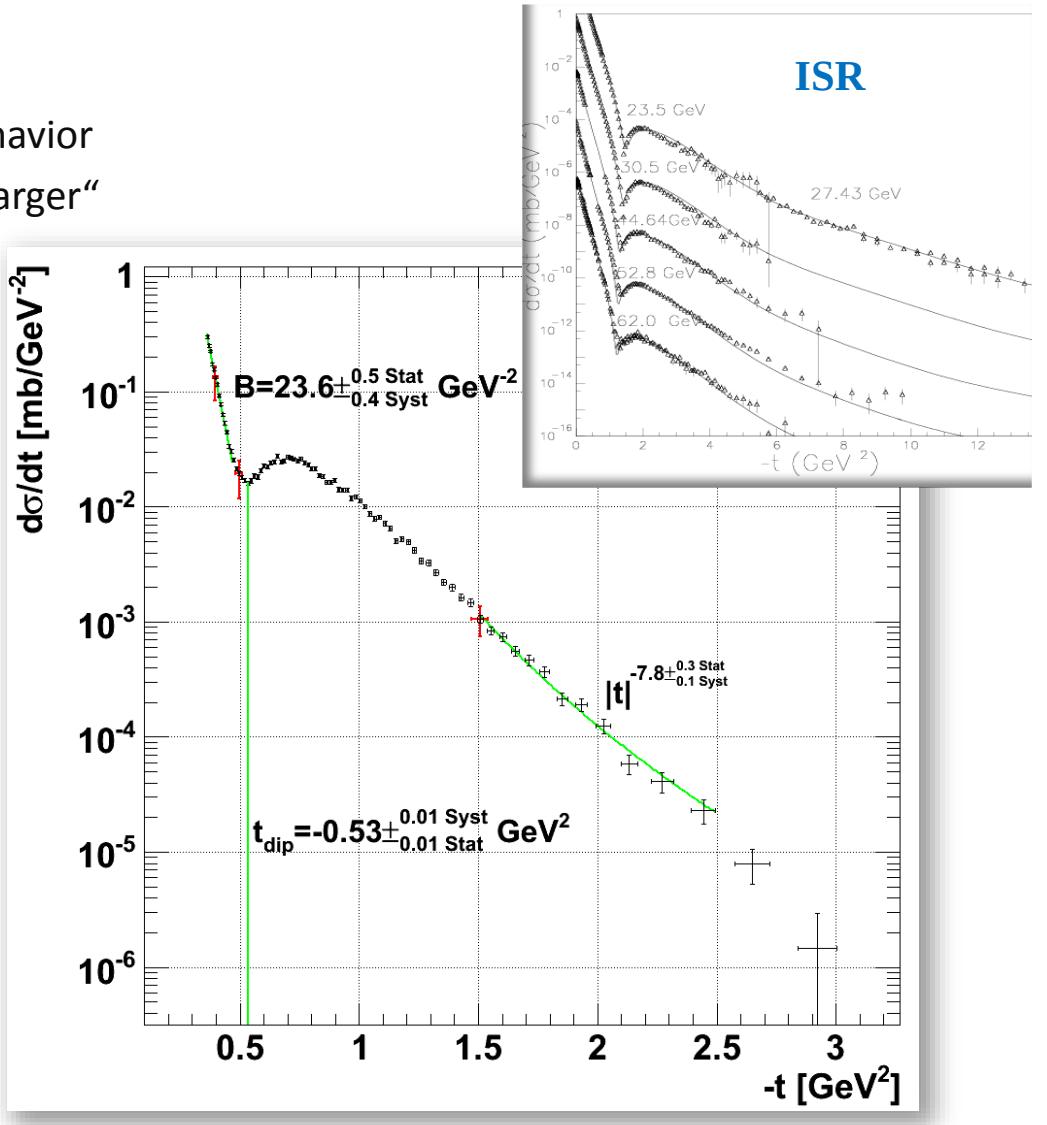
The elastic dσ/dt distribution at √s = 7 TeV (β* = 3.5 m)

Published in EPL **95** (2011) 41001:

- |t| range spans from 0.36 to 2.5 GeV^2
- Below |t| = 0.47 GeV^2 exponential $e^{-B|t|}$ behavior
- Dip moves to lower |t|, proton becomes "larger"
- 1.5 - 2.5 GeV^2 power low behavior $|t|^{-n}$



The measured dσ/dt compared with predictions of several models



Note on proton kinematics reconstruction & optics imperfections

Machine imperfections alter the optics:

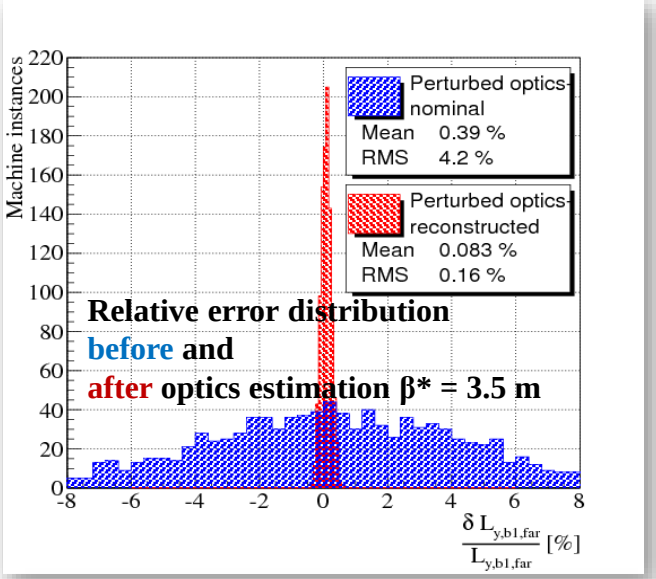
- **Strength conversion error, $\sigma(B)/B \approx 10^{-3}$**
- **Beam momentum offset, $\sigma(p)/p \approx 10^{-3}$**
- Magnet rotations, $\sigma(\phi) \approx 1$ mrad
- Magnetic field harmonics, $\sigma(B)/B \approx 10^{-4}$
- Power converter errors, $\sigma(I)/I \approx 10^{-4}$
- Magnet positions Δx, $\Delta y \approx 100$ µm

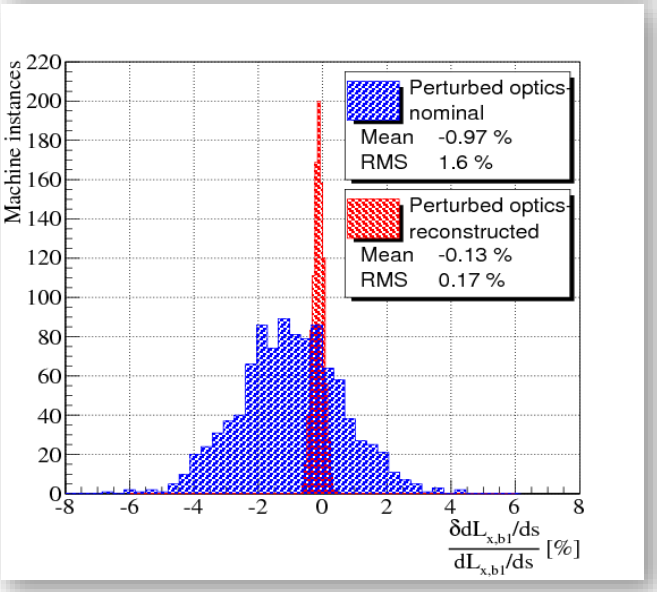
$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

→ **Precise model of the LHC optics is indispensable!**

Novel method from TOTEM:

- Use **measured** proton data from RPs
- Based on kinematics of elastic candidates
- Published in New Journal of Physics
- http://iopscience.iop.org/1367-2630/16/10/103041/





Low-t measurements with β* = 90 m at √s = 7 TeV

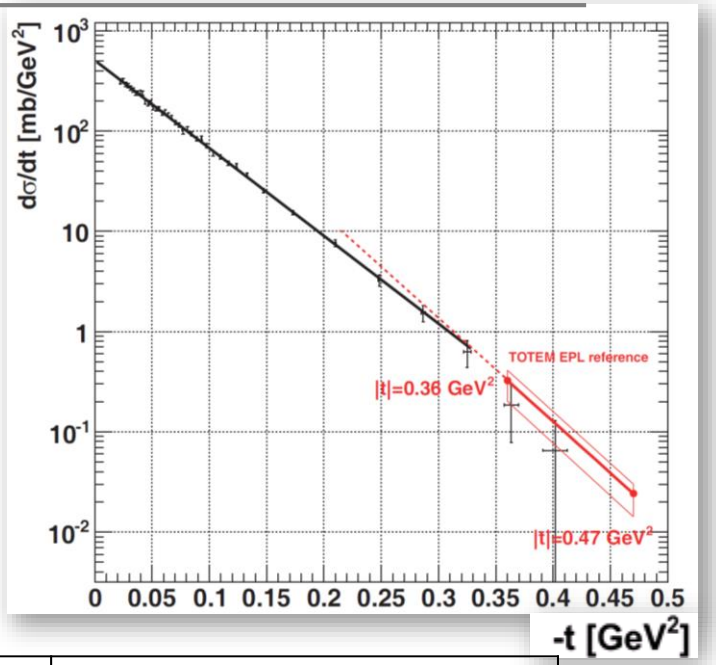
Properties:

- $L_{\gamma,b1}$ = 264.1 m
- Slope B confirms that it increases with √s
- Total cross-section with optical theorem
- ρ value from COMPETE:

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} \qquad \rho = \left.\frac{\mathrm{Re}\,A^H}{\mathrm{Im}\,A^H}\right|_{t=0}$$

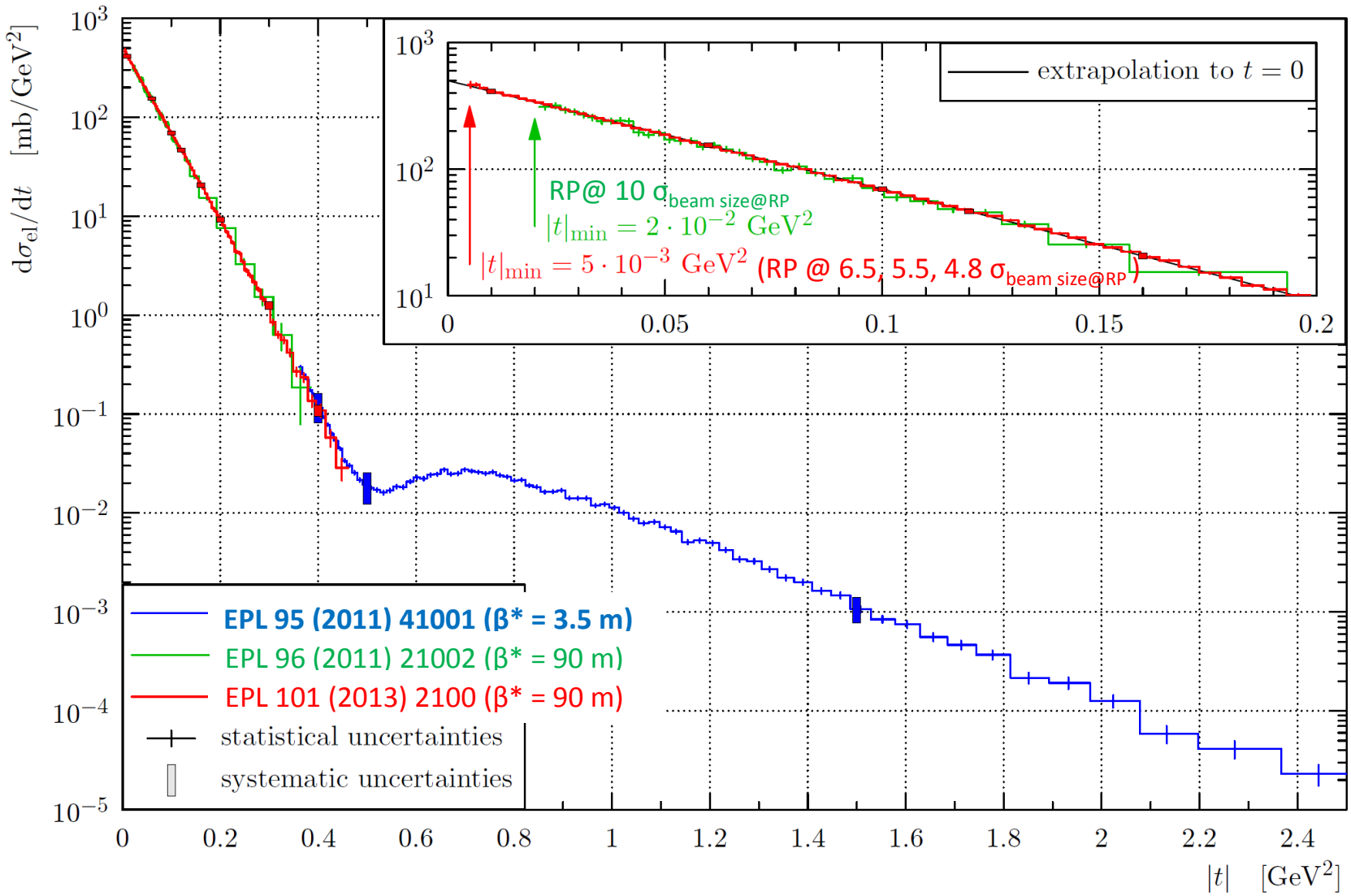
- Compatible results, published in:
  EPL **96** (2011) 21002
  EPL **101**(2013) 21002

$$\rho = 0.14^{+0.01}_{-0.08}$$



RP distance	σ_{beam}	10	5
B	GeV^{-2}	$20.1 \pm 0.2_{stat} \pm 0.3_{syst}$	$19.89 \pm 0.03_{stat} \pm 0.27_{syst}$
$\left.\frac{d\sigma}{dt}\right\|_{t=0}$	$\mathrm{mb\,GeV}^{-2}$	$503.7 \pm 1.5_{stat} \pm 26.7_{syst}$	$506.4 \pm 0.9_{stat} \pm 23_{syst}$
σ_{el}	mb	$24.8 \pm 0.2_{stat} \pm 1.2_{syst}$	$25.43 \pm 0.03_{stat} \pm 1.07_{syst}$
σ_{inel}	mb	$73.5 \pm 0.6_{stat} \begin{bmatrix} +1.8 \\ -1.3 \end{bmatrix}_{syst}$	$73.15 \pm 1.26_{full}$
σ_{tot}	mb	$98.3 \pm 0.2_{stat} \pm 2.8_{syst}$	$98.6 \pm 2.2_{full}$
t_{min}	GeV^2	2×10^{-2}	5×10^{-3}

√s = 7 TeV : combined elastic dσ/dt results



Inelastic cross-section measurement

Trigger: at least one track in T2

- 95 % of inelastic events

1. **Raw rate**: event counting with T2

   Experimental corrections: trigger and reconstruction inefficiencies, beam-gas event suppression, pile-up

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

   Estimation of events with no tracks in T2: T1-only events, events with gap over T2, low-mass diffraction

3. **Physics rate**: true rate of inelastic events
   - Only one major Monte-Carlo-based correction: low-mass diffraction (which can be constrained from data, 6.31 mb upper limit for $M_x < 3.4$ GeV)

4. **Cross-section**: uses CMS luminosity measurement


Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s} = 7$ TeV

EPL **101** (2013) 21003

$$\sigma_{inel} = 73.7 \pm 3.4 \text{ mb}$$

σ_{tot} with 4 methods at $\sqrt{s}$ = 7 TeV

Results:

1. Low luminosity (CMS) + Elastic dσ/dt + Optical th. (EPL 96(2011) 21002)
   - depends on CMS luminosity for low-L bunches, elastic efficiencies and on ρ

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{el}}{dt}\right|_{t=0}$$

σ_{tot} = 98.3 ± 2.8 mb

2. High luminosity (CMS) + Elastic + Optical theorem (EPL 101 (2013) 21002)

σ_{tot} = 98.6 ± 2.2 mb

3. High luminosity (CMS) + Elastic + Inelastic (**EPL, 101 (2013) 21004**)
   - minimizes dependence on elastic efficiencies and **no dependence on ρ**

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

σ_{tot} = 99.1 ± 4.3 mb

4. Elastic ratios + Inelastic ratios (T1, T2) + Optical theorem (**EPL, 101 (2013) 21004**)
   - Eliminates dependence **on luminosity**

$$\sigma_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\left.\frac{dN_{el}}{dt}\right|_{t=0}}{N_{el} + N_{inel}}$$

σ_{tot} = 98.0 ± 2.5 mb

TOTEM cross-section measurements at $\sqrt{s}$ = 8 TeV

Lumi. indep. cross-sections and non exponentiality (β* = 90 m optics)

Read more:

- EPL 101 (2013) 21004
- Phys. Rev. Lett. 111, 012001 (2013)
- Evidence for non-exponentiality

σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
101.7 ± 2.9	27.1 ± 1.4	74.7 ± 1.7

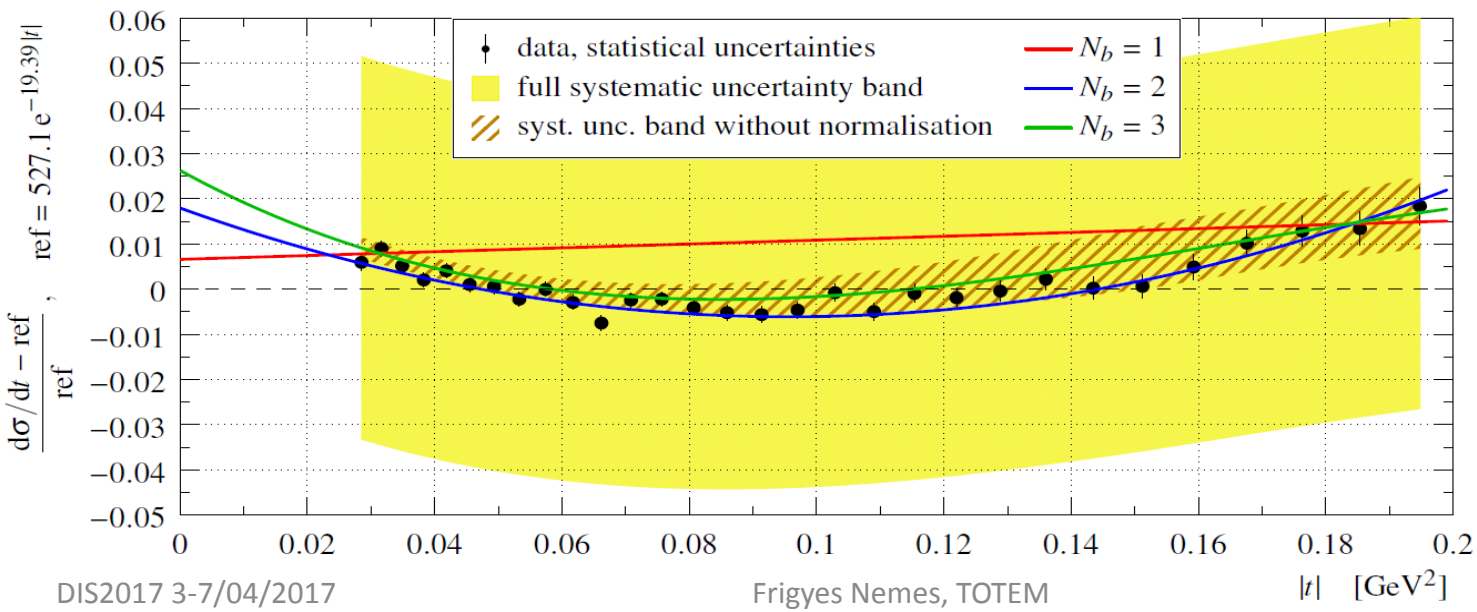
The observed differential cross-section w.r.t. reference exponential:

- Fits with different assumptions on hadronic component

$$\left|A^N\right| = a \cdot \exp(b_1 t) \quad \Rightarrow \quad \left|A^N\right| = a \cdot \exp(b_1 t + b_2 t^2 + b_3 t^3)$$

- Pure exponential **excluded** with more than 7σ significance !

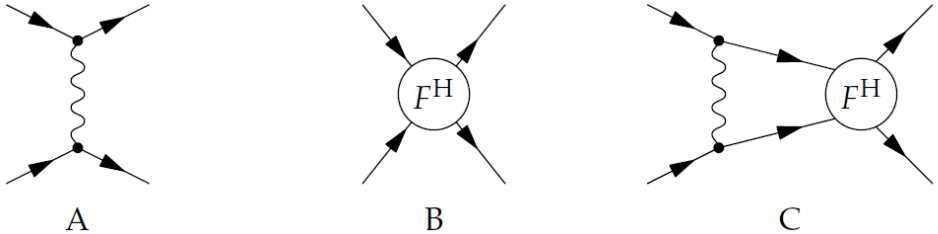
N_b	σ_{tot} [mb]
2	101.5 ± 2.1
3	101.9 ± 2.1



Hadronic-Coulomb interference with β* = 1000 m optics at 8 TeV

Basic properties of the data:

- RP detectors at about $3 \times \sigma_{beam}$
- $|t|_{min} = 6 \times 10^{-4}$ GeV^2



Analysis aims:

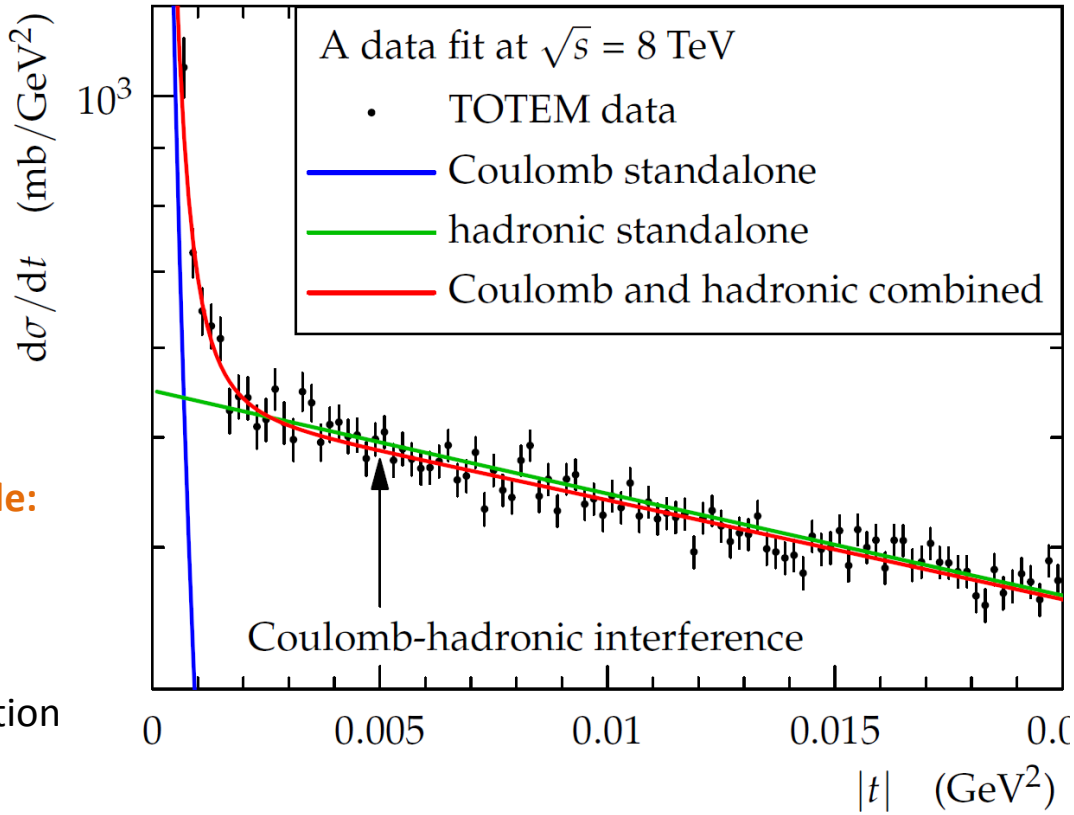
- Measure $d\sigma_{el}/dt$ at the smallest possible $|t|$
- A_{C+H}= Coulomb + Hadronic + Interference terms
- Interference: the **phase** of hadronic amplitude appears in

$$\frac{d\sigma}{dt} \propto \left|A_{C+H}\right|^2$$

- **Determination of ρ became possible:**

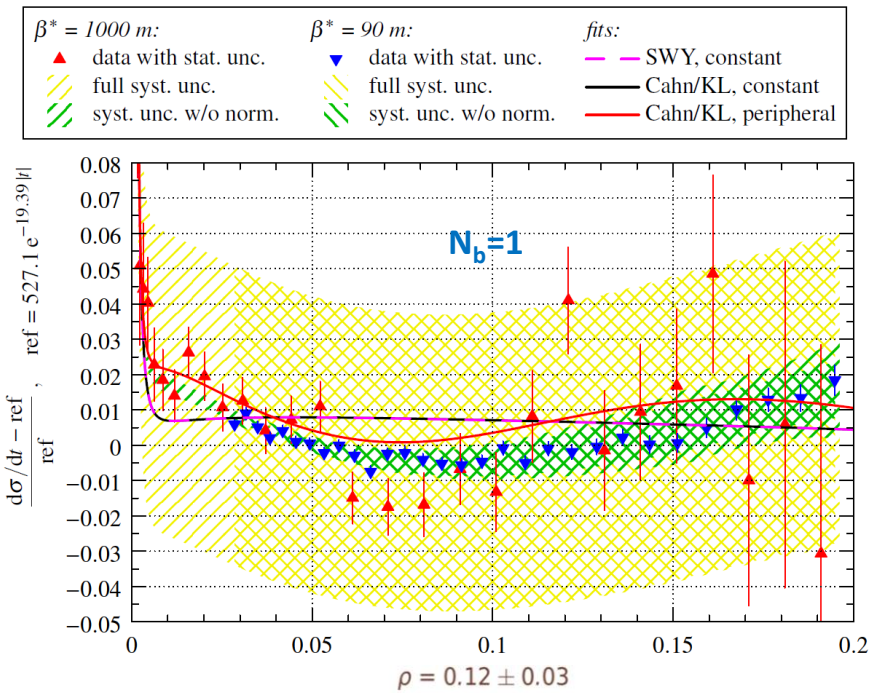
$$\rho = \left.\frac{\mathrm{Re}\,A^H}{\mathrm{Im}\,A^H}\right|_{t=0}$$

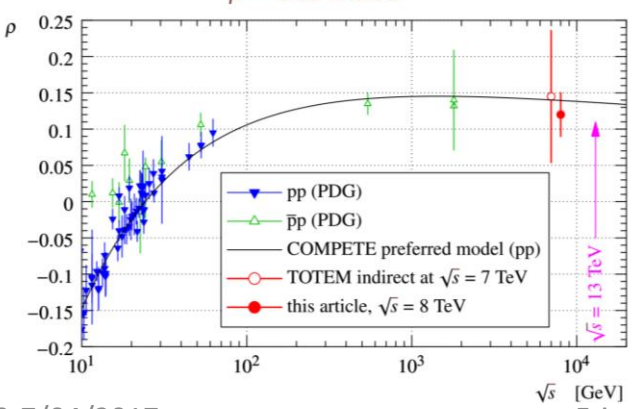
- Further improve the total cross-section σ_{tot} measurement



1st measurement of the ρ parameter at the LHC at 8 TeV

Publication



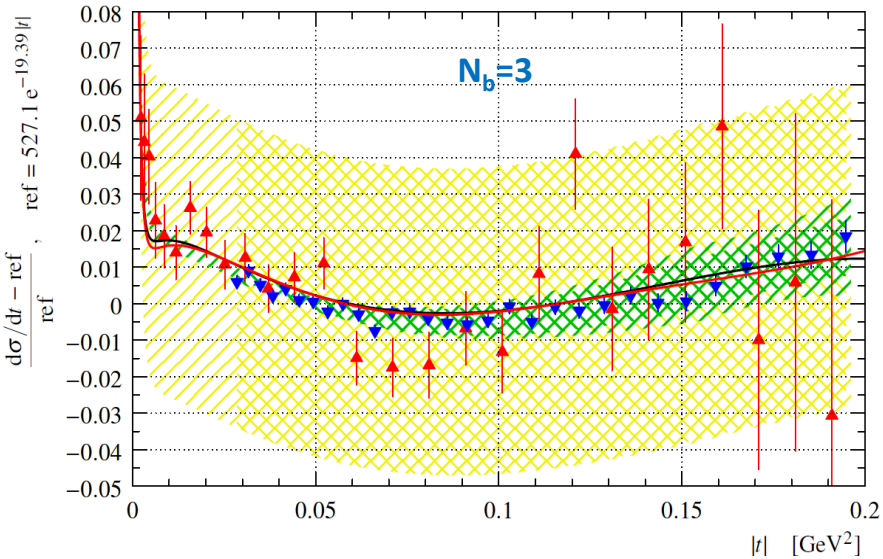


Purely exponential hadronic amplitude:

- Constant phase: excluded
- Peripheral phase: disfavored

Non-exponential hadronic amplitude:

- Both peripheral and constant phase compatible with data

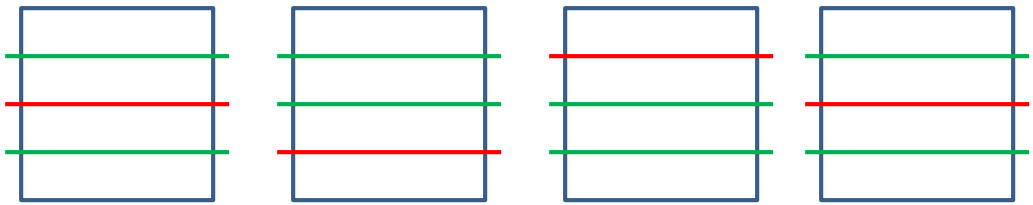


Hadronic phase	σ_{tot} [mb]
Central	102.9 ± 2.3
Peripheral	103.0 ± 2.3

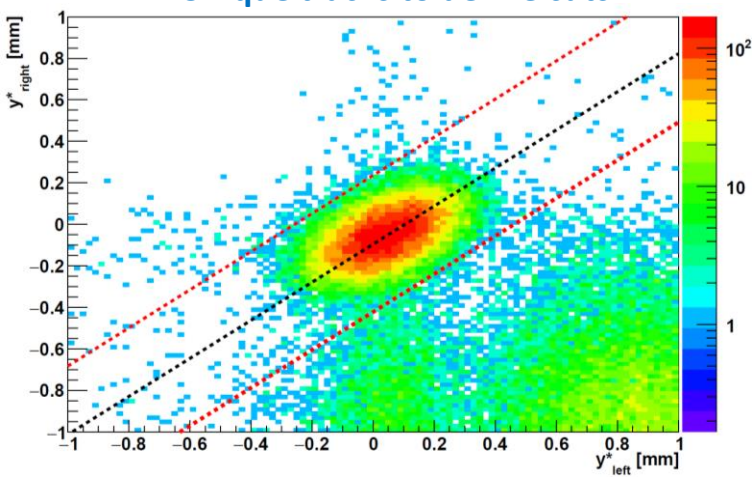
TOTEM elastic scattering measurement at √s = 2.76 TeV

Large background: elastic candidate selection from multitracks

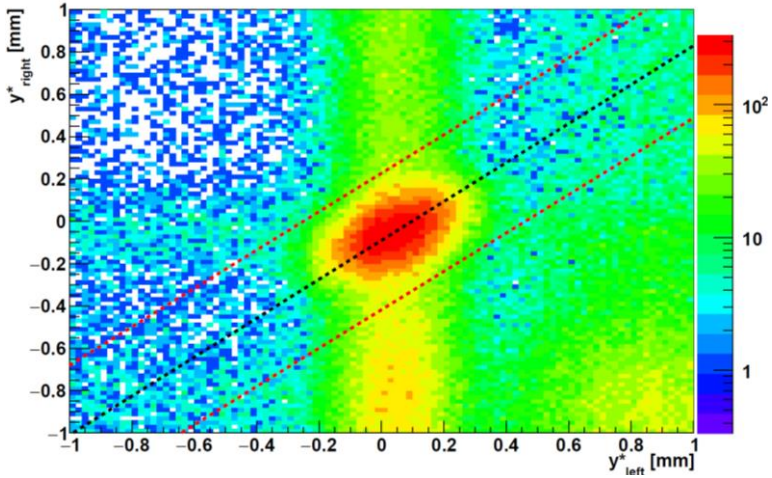
- RP can resolve uniquely single tracks
- If cannot be resolved: array of multitrack candidates per RP
- Elastic cuts defined with unique tracks
- **Every** combination of the 4 RPs of a diagonal
- **One** combination is selected with elastic cuts (+physics oriented topology studies)



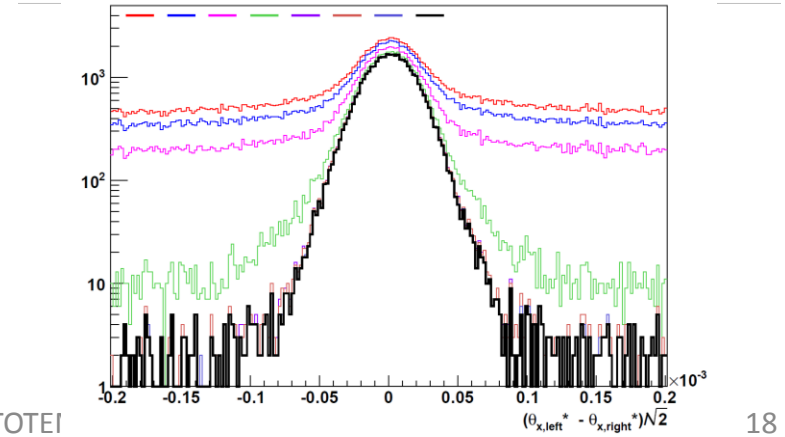
Unique tracks to define cuts



… to select elastic candidates from multitracks



- Progressive selection of elastic candidates cut by cut

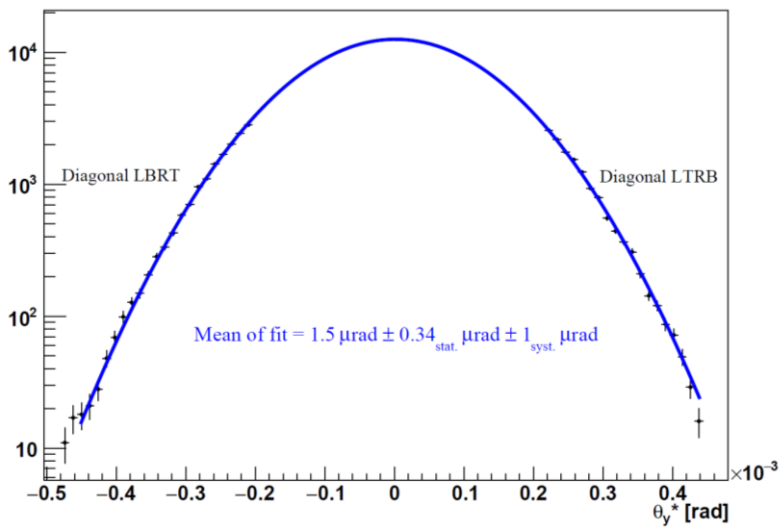


RP alignment and LHC optics calibration

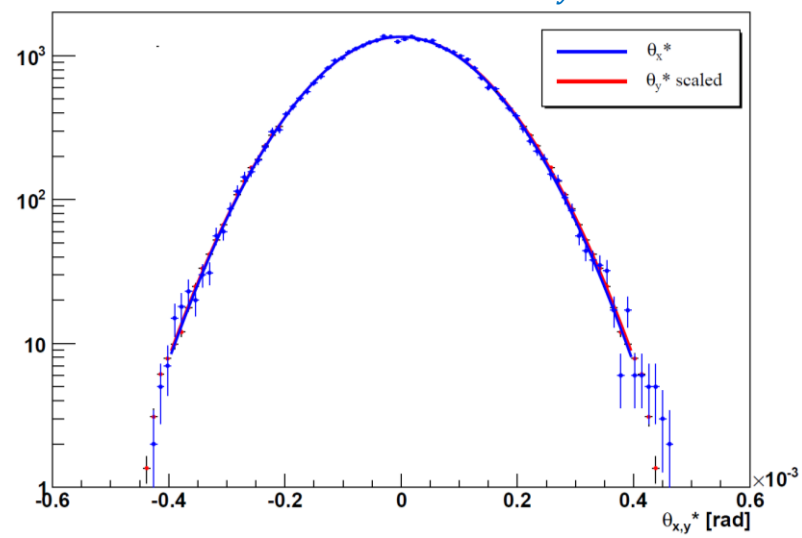
Horizontal RPs were not inserted:

- No track based **top - bottom** RP alignment
- Horizontal and relative near-far alignment is done
- New methods to find absolute y-alignment of the 2 diagonals
- 2 diagonals: 2 constraints from elastic scattering symmetries

1st constraint: alignment of θ_y^* barycenter to 0

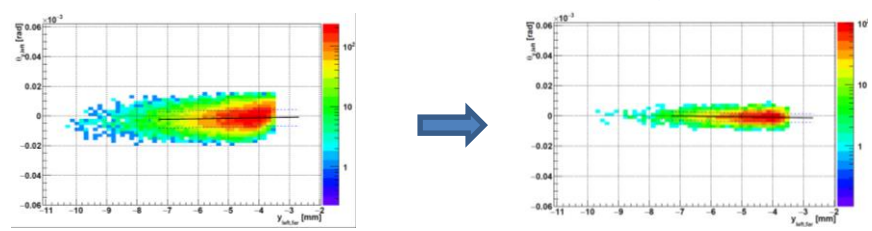


2nd constraint: alignment of θ_y^* to θ_x^*



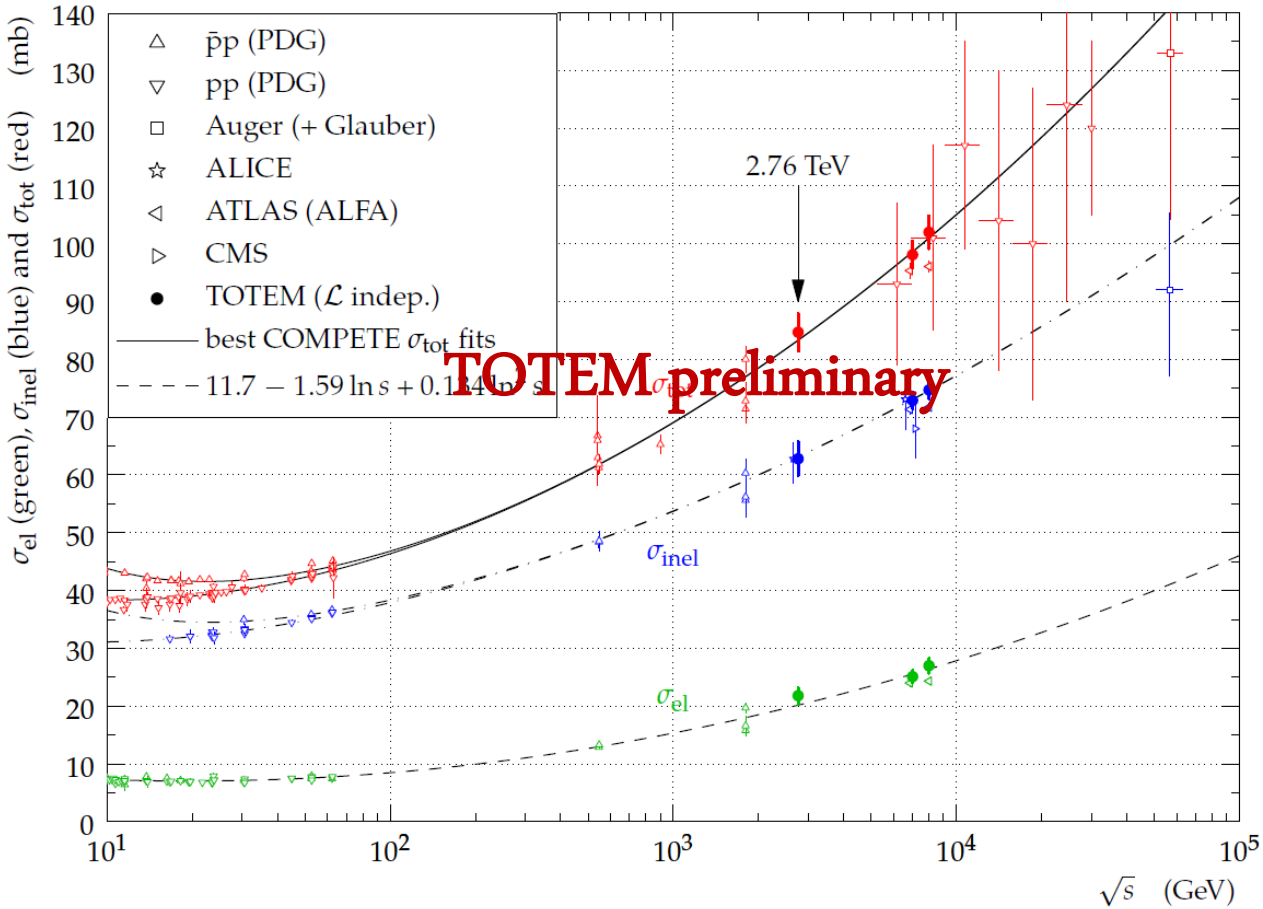
- Optics calibration done in the usual way (alignment independent procedure)
- Careful measurement of optics estimators:

After y* vertex cut

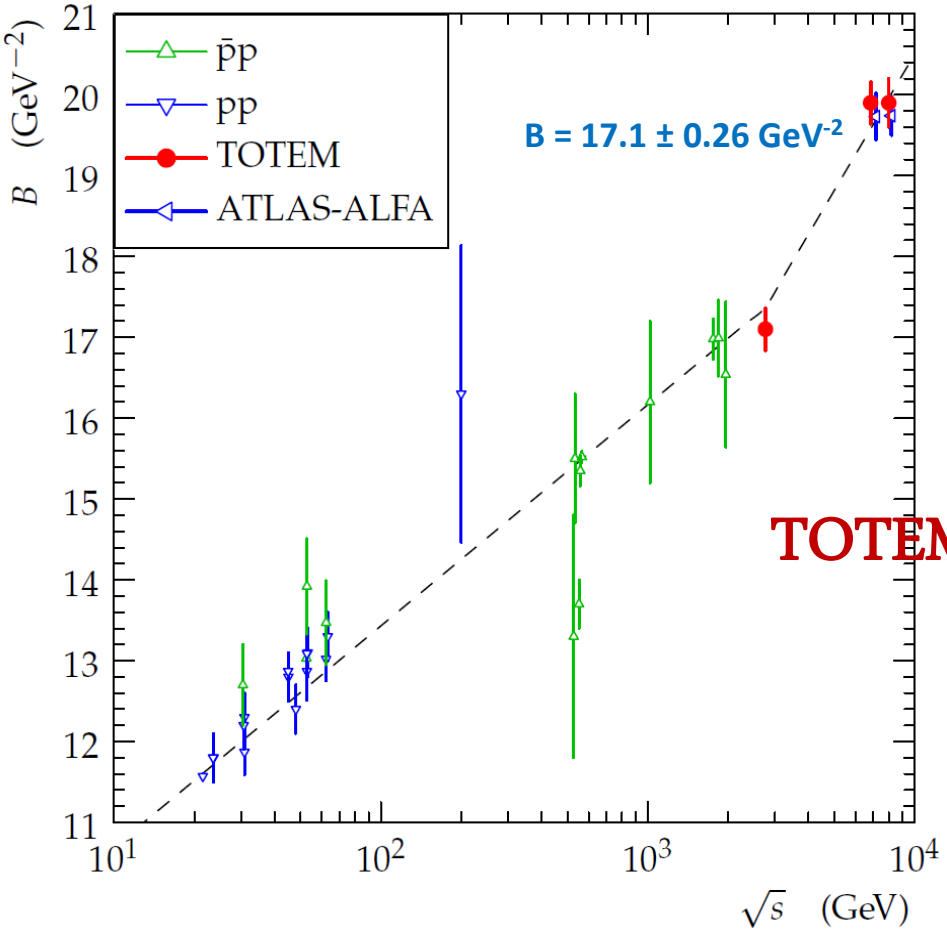


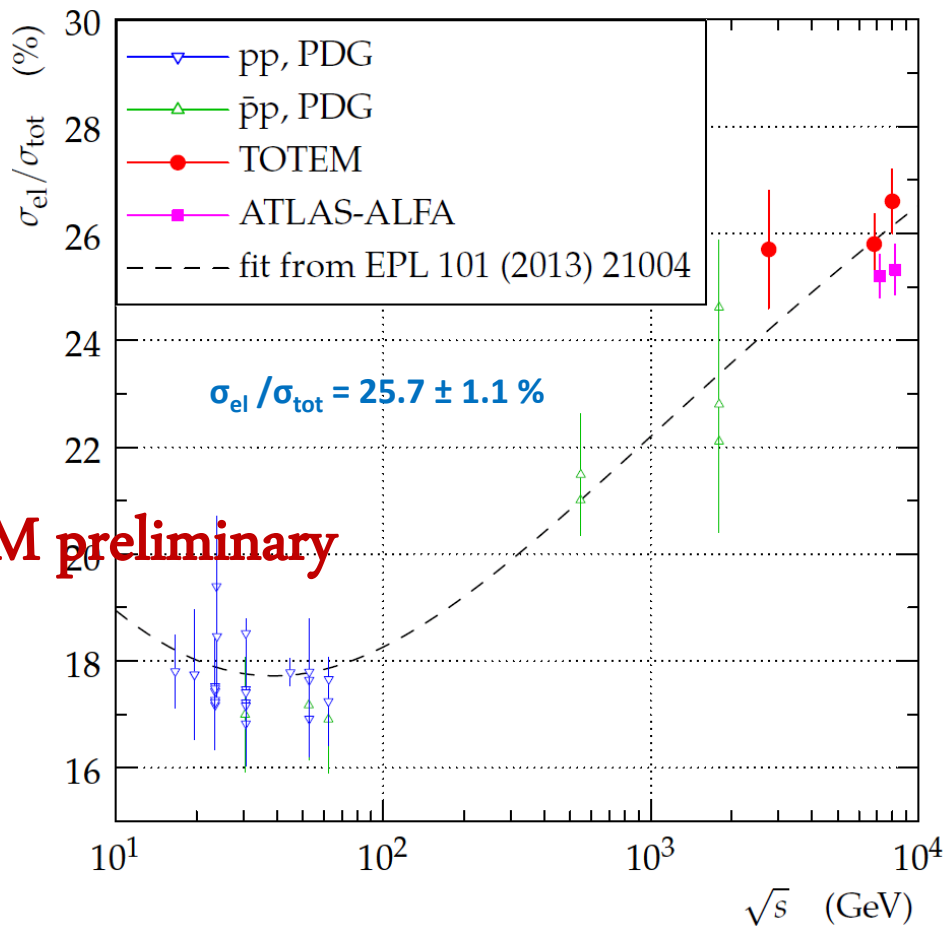
2.76 TeV luminosity independent cross-sections (β* = 11 m optics)

σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
84.7 ± 3.3	21.8 ± 1.4	62.8 ± 2.9



The nuclear slope B and the σ_{el}/σ_{tot} ratio at √s = 2.76 TeV





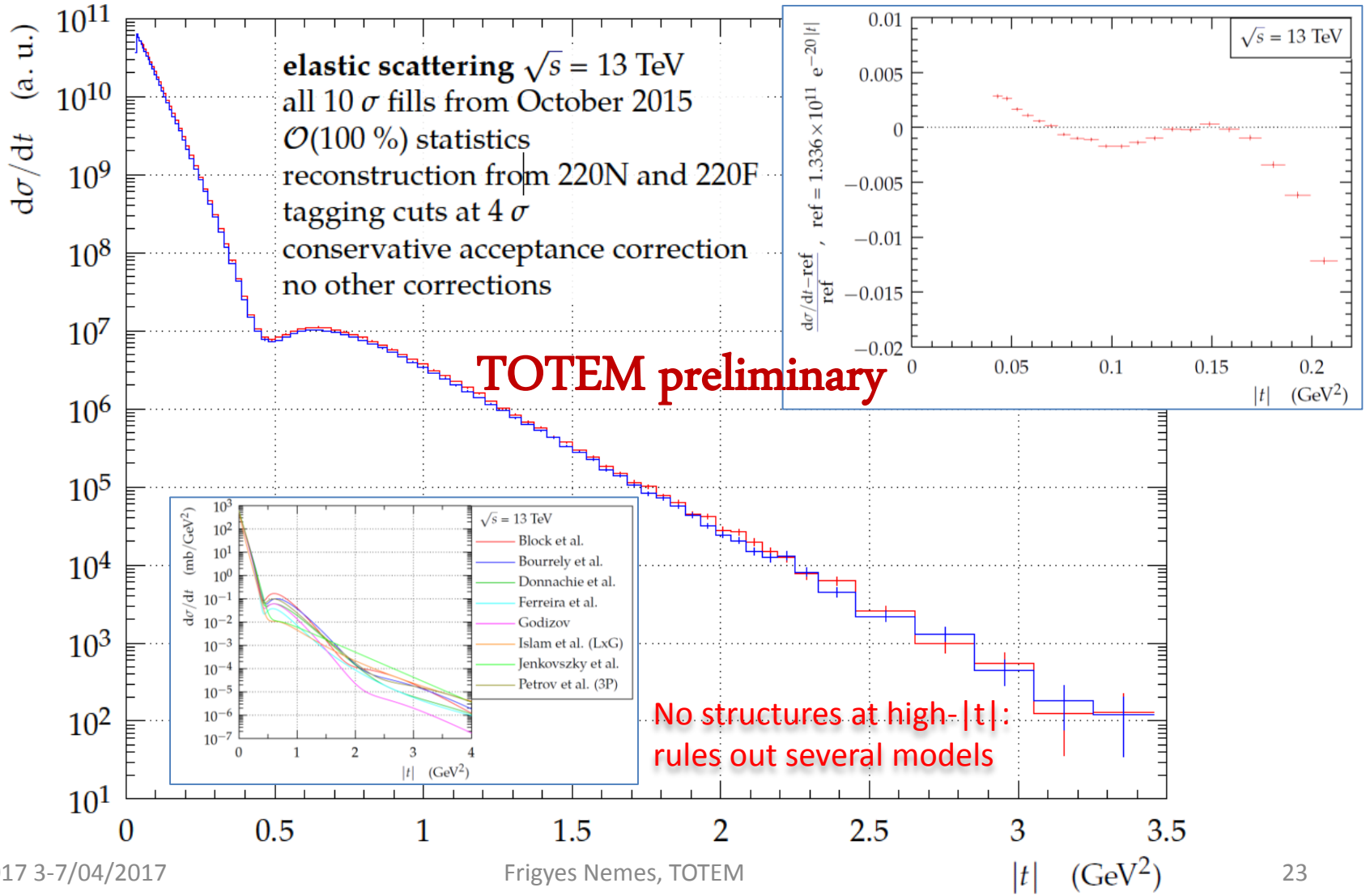
TOTEM preliminary

TOTEM elastic scattering measurement at √s = 13 TeV

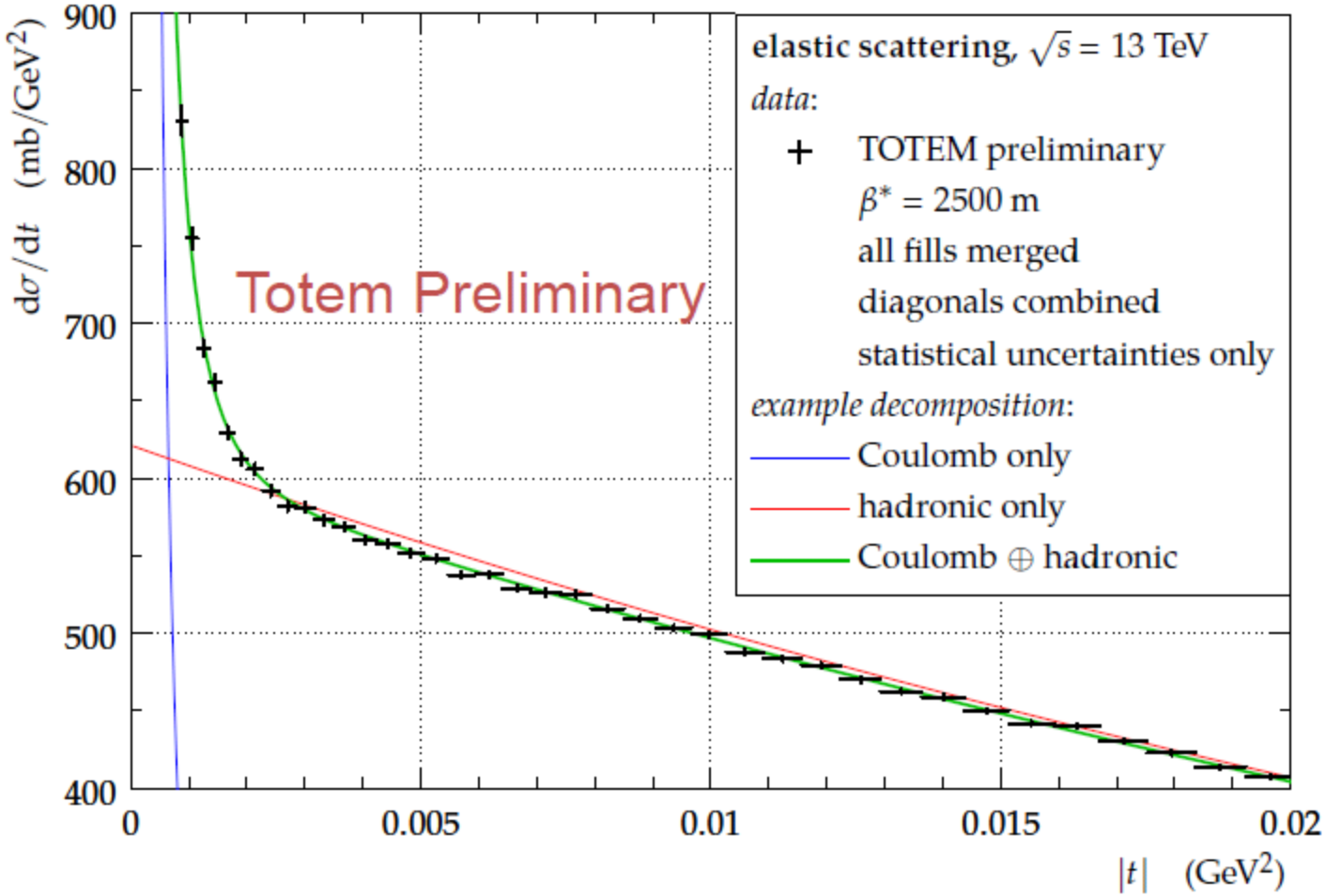
$\sqrt{s}$ = 13 TeV, β^* = 90 m optics: preliminary elastic dσ/dt

Note:

- Large amount of data (trigger rate **50×** w.r.t. Run I)



√s = 13 TeV, β* = 2500 m, first analysis cycle completed



Summary of elastic cross-sections

- Published proton-proton elastic analysis results at $\sqrt{s}$ = 7 TeV and 8 TeV
  - β^* = 3.5 m, 90 m, 1000 m
- Total cross-section measurements at $\sqrt{s}$ = 7 TeV, 8 TeV and 2.76 TeV
  - Luminosity independent method
- Non-exponentiality of the differential cross-section at low-|t| at 8 TeV and 13 TeV
  - β^* = 90 m, 1000 m
- Hadronic-Coulomb interference at 8 TeV with β^* = 1000 m optics
  - 1st determination of the ρ parameter at the LHC with CNI
- $\sqrt{s}$ = 2.76 TeV preprint in progress
- Ongoing analyses at $\sqrt{s}$ = 13 TeV (β^* = 90 m, 2500 m)

Thank you for your attention !

Backup slides

β* = 3.5 m optics estimation

On the basis of constraints R_1-R_{10} the optics can be estimated:

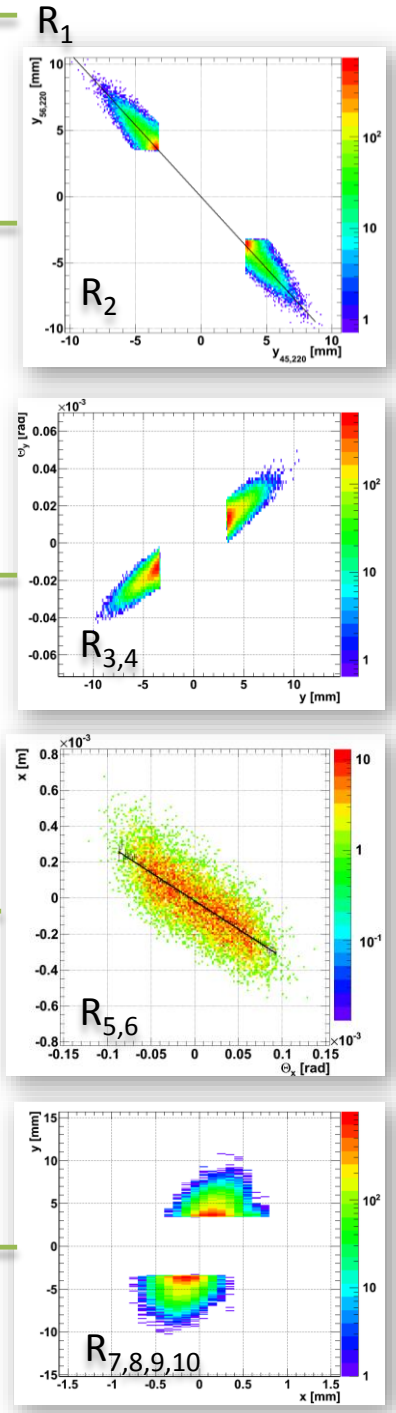
$$\chi^2 = \sum_{i=1}^{10} ((R_{i,\text{measured}} - R_{i,\text{calculated}}) / \sigma(R_i))^2 + \chi^2_{\text{LHC Design}}$$

Refine machine settings
- **2x6 quad. magnet strength**
- **2x6 quad. rotation**
- **Momentum of 2 beams**

MAD-X

Calculated ratios R_1-R_{10} → Comparison ← Measured ratios R_1-R_{10}

dL_x/ds, L_y



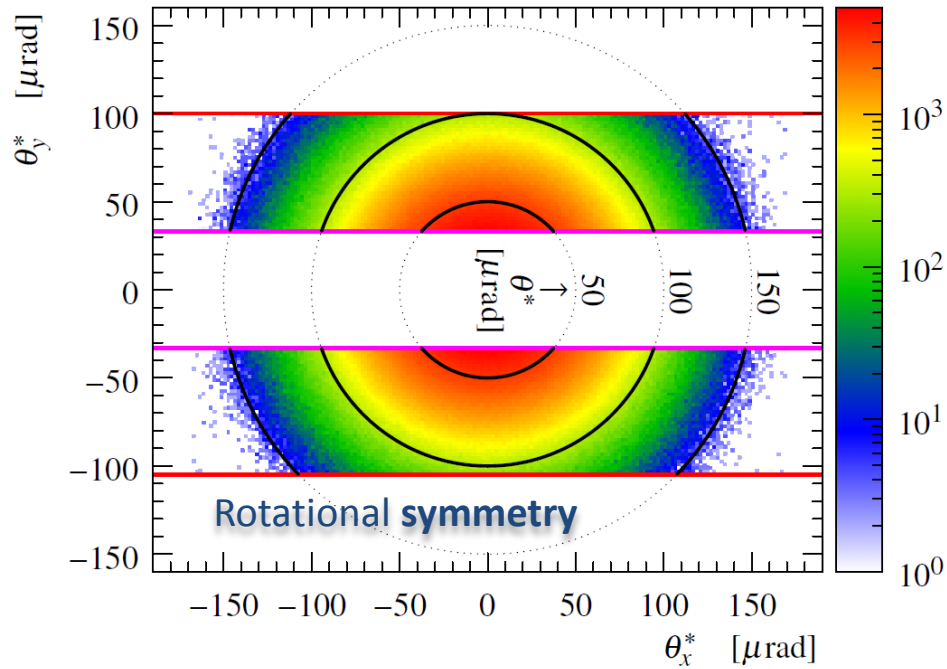
$$R_2 \equiv \frac{y_{b1,RP}}{y_{b2,RP}} \approx \frac{L_{y,b1,RP}}{L_{y,b2,RP}} \qquad R_3 \equiv \frac{\Theta_{y,b1,RP}}{y_{b1,RP}} \approx \frac{\frac{dL_{y,b1,RP}}{ds}}{L_{y,b1,RP}}$$

$$R_7 \equiv \frac{x_{b1,RP}}{y_{b1,RP}} \approx \frac{m_{14,b1,near\_pots}}{L_{y,b1,near\_pots}} \qquad R_5 \equiv \frac{x_{b1,RP}}{\Theta_{x,b1,RP}} \approx \frac{L_{x,b1,RP}}{dL_{x,b1,RP}/ds}$$

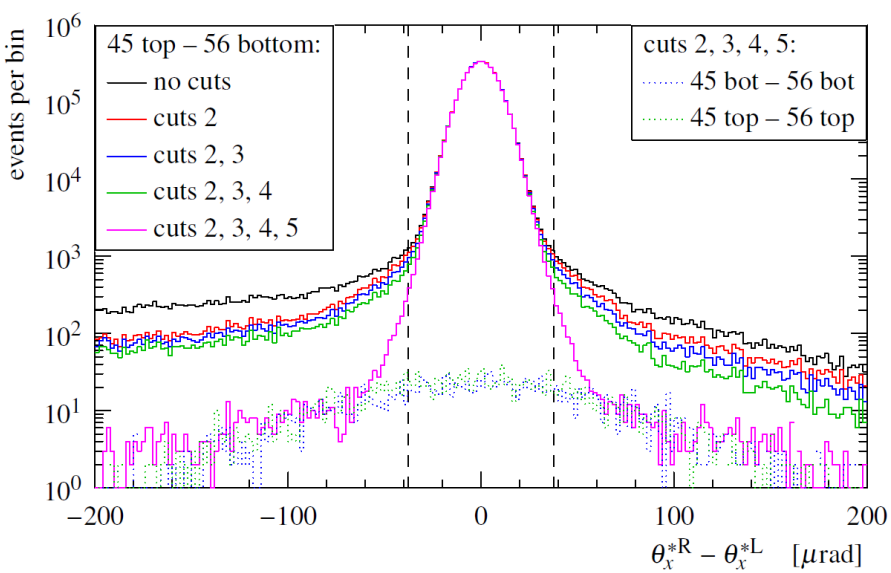
Reconstructed kinematics (β* = 90 m optics)

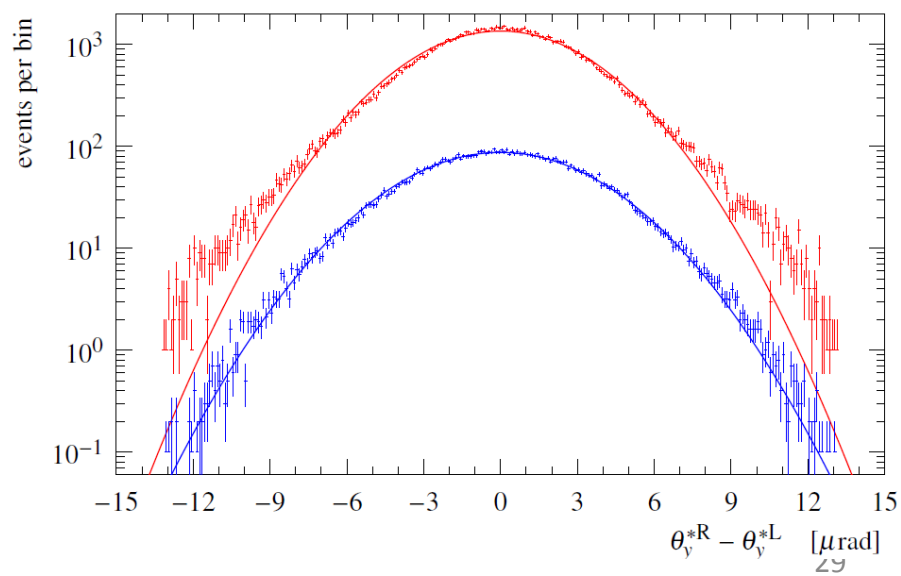
Symmetries of the tagged particles' reconstructed kinematics:

- High statistics
- Rotational symmetry
- Left-right arm symmetry



Left - right **symmetry** (in background estimation)



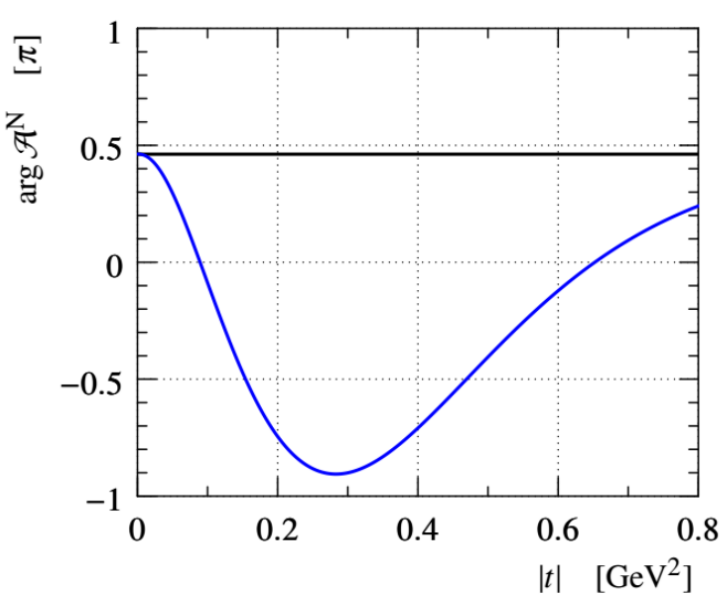


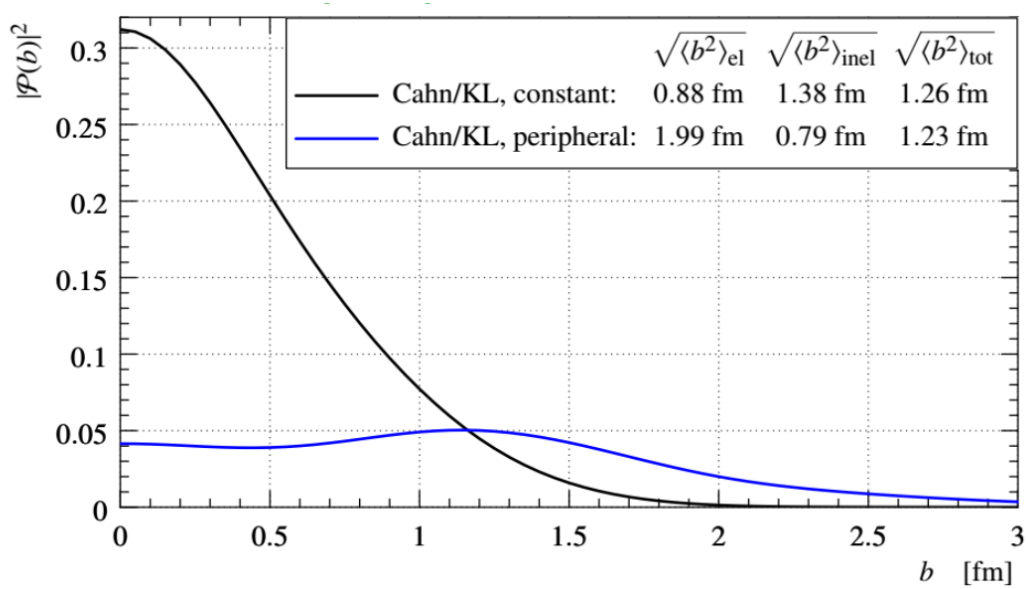
Central and peripheral phases

Different formulations of the interference phenomenon:

- Simplified West-Yennie (SWY)
  - Based on QFT
  - Simplifications: constant slope and constant hadronic phase
- Cahn or Kundrát-Lokajicek (KL) model
  - Eikonal framework
  - No explicit simplifications

The t-dependence of the two considered hadronic phase model families:



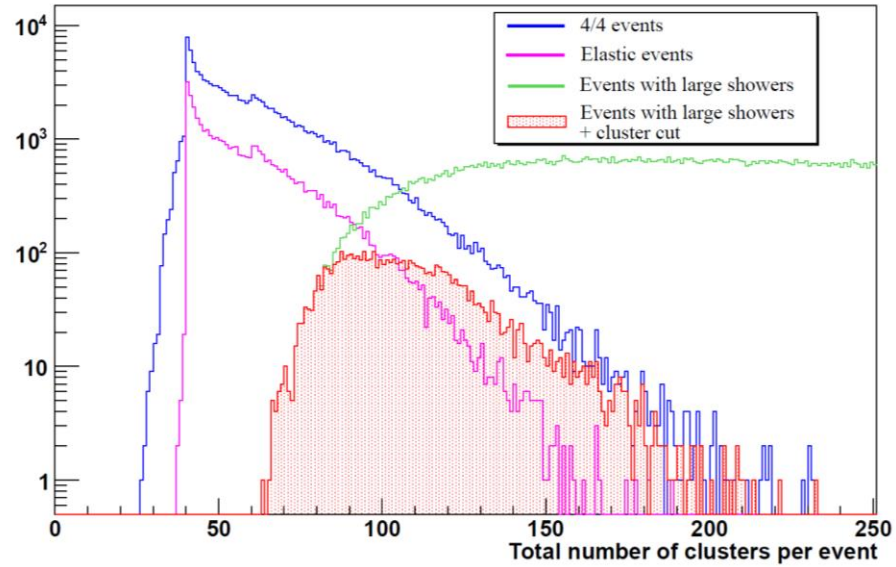


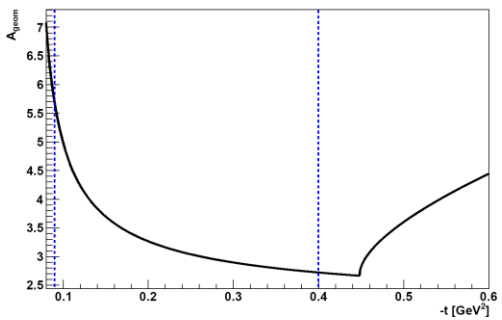
Physics corrections and dN/dt at 2.76 TeV

Physics corrections

- So-called 3 and 2/4 inefficiencies:
  - Several topology recovered by multitracking
  - Empty pot inefficiencies
  - Frequent showers (regulation)
  - Usual acceptance corrections (beam div., unfolding,. geometrical accep. corr.)

Regulation of showery events with cluster cut





- dN/dt histogram after physics corrections
- Fit for t=0 point measurement