The TOTEM experiment at the LHC and its physics results

F. Nemes (CERN)*

on behalf of the

TOTEM collaboration

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

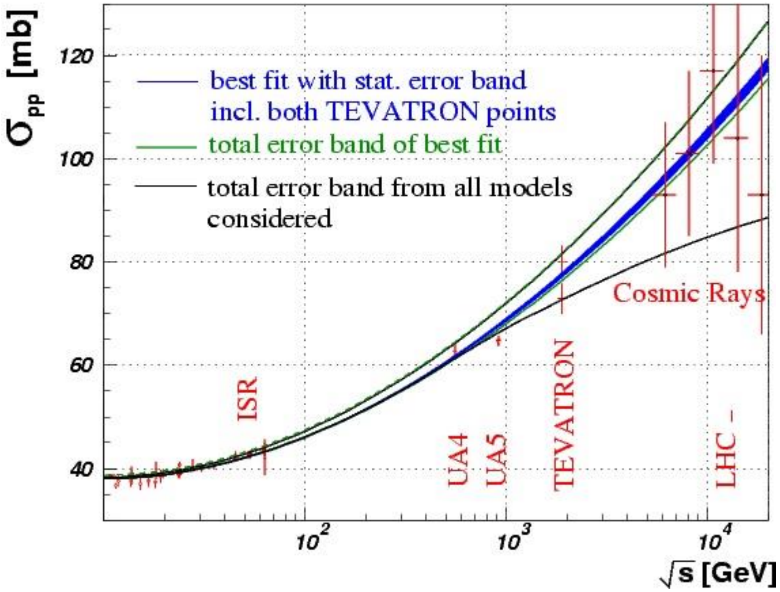
ZIMÁNYI WINTER SCHOOL'15

2015, Dec 7 – 11, Budapest, Hungary

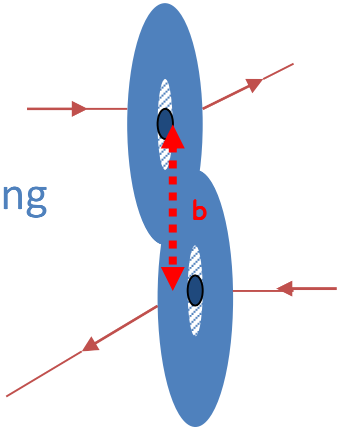
*** Also at Wigner RCP**

The TOTEM physics spectrum

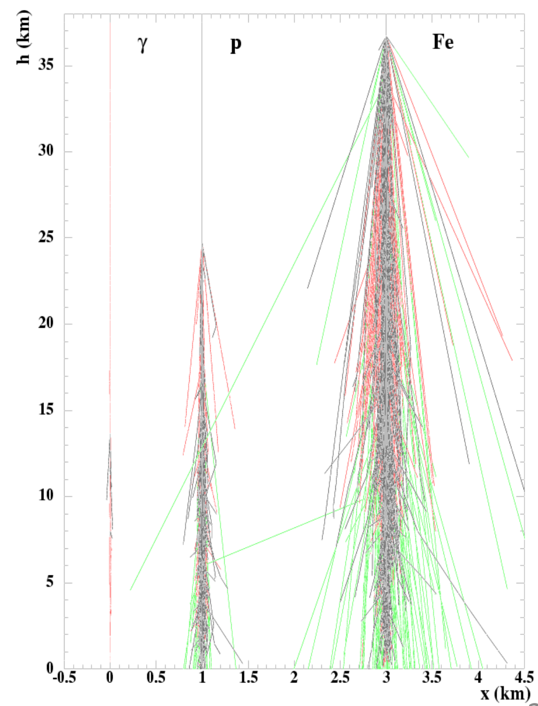
Total cross-section



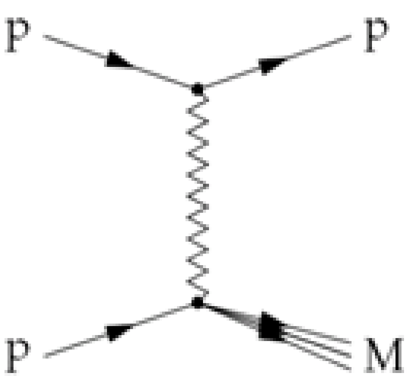
Elastic scattering

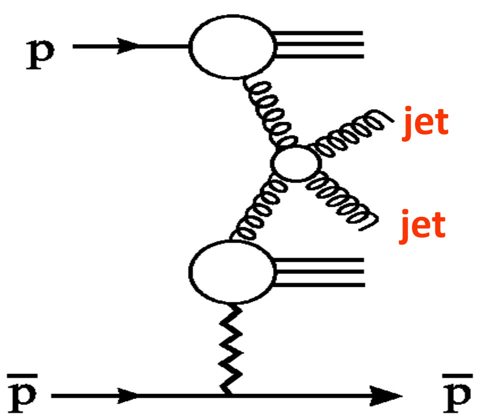


Forward physics



Diffraction: soft (and hard with CMS)

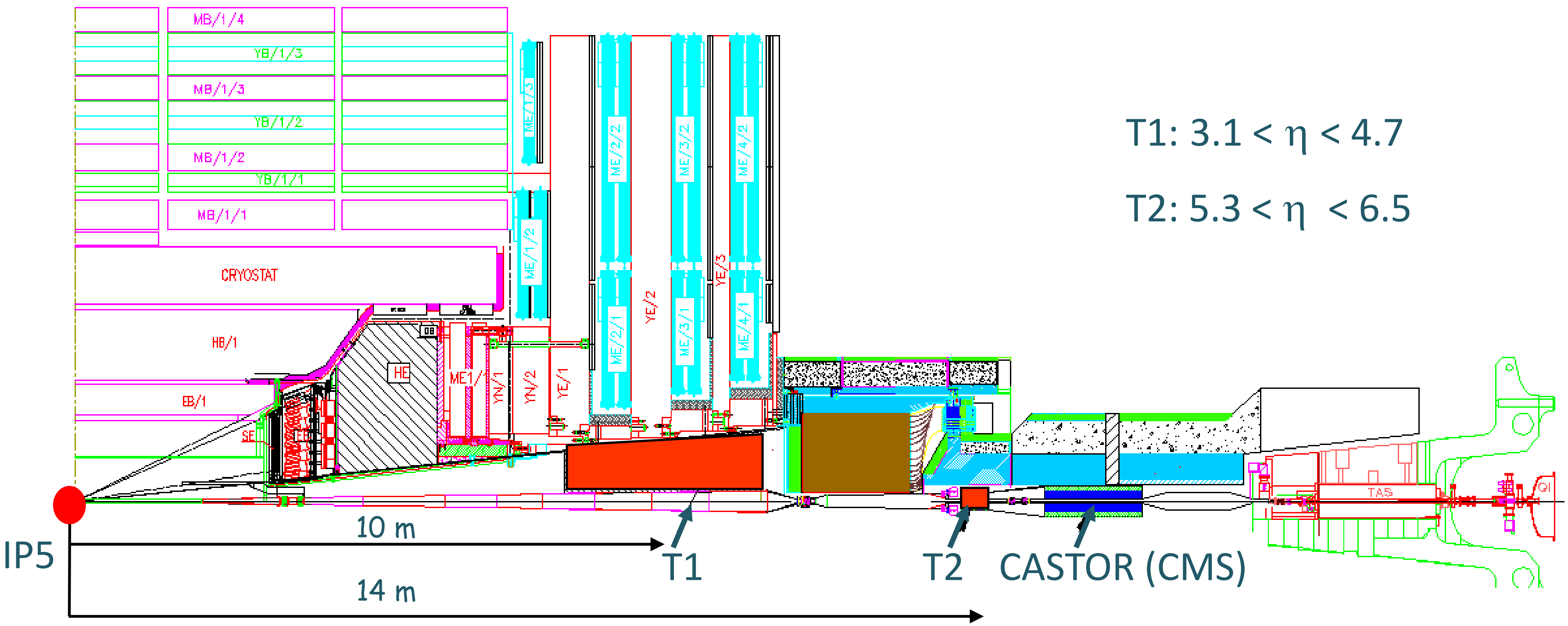


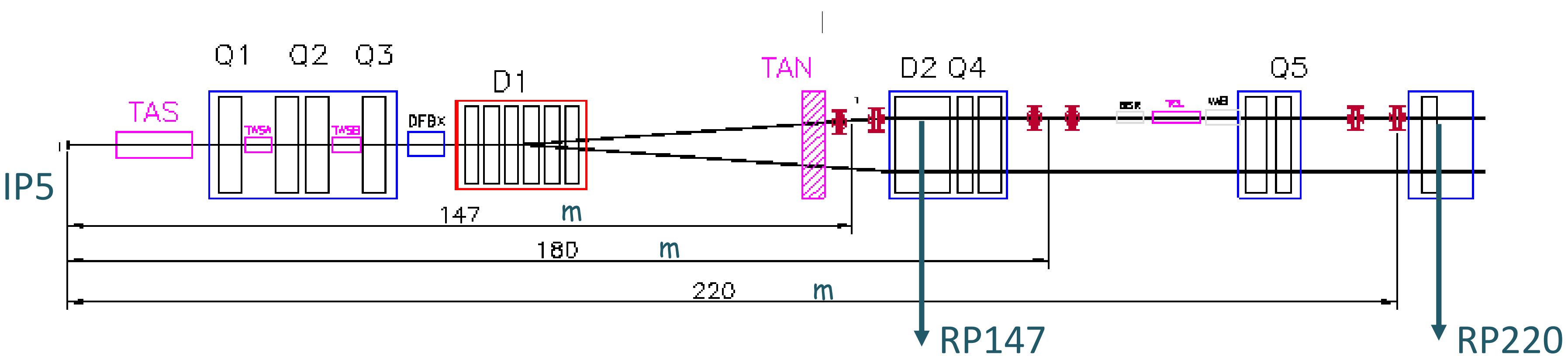


Experimental layout before LS1

T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

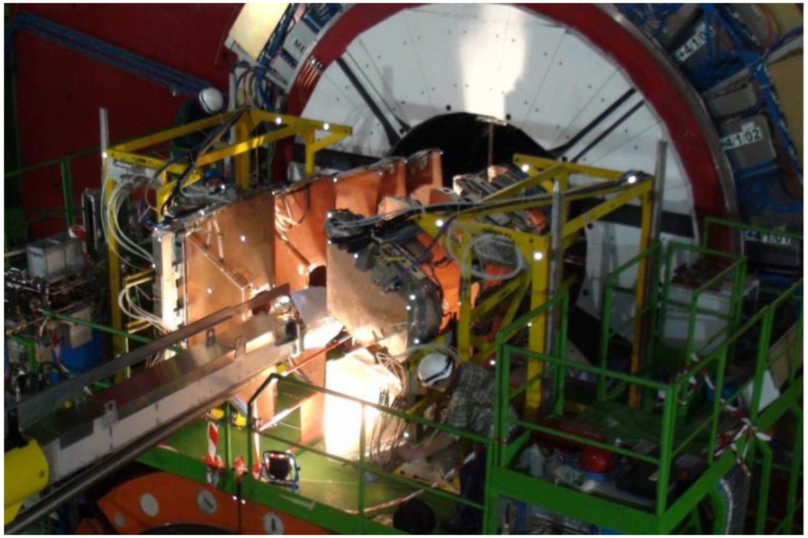




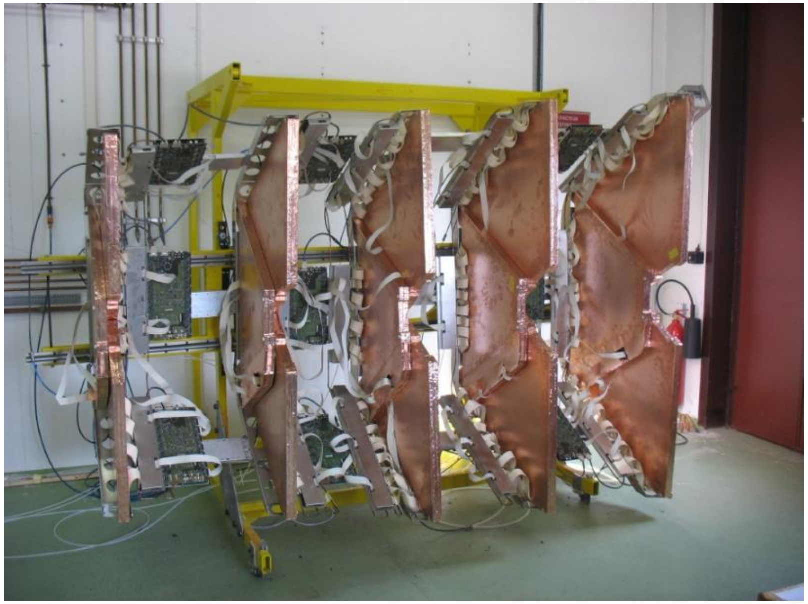
The inelastic telescope T1

Properties:

- Inside CMS 7.5 - 10.5 m from IP5
- One telescope on each side of IP5
- Two quarters per telescope



- Quarters: 5 equally spaced planes
- Planes: 3 trapezoidal CSC detectors, 60˚ in azimuth
- Cathode Strip Chamber: gaseous detector with 3 read-out coordinates (at 60˚ w.r.t. each other)

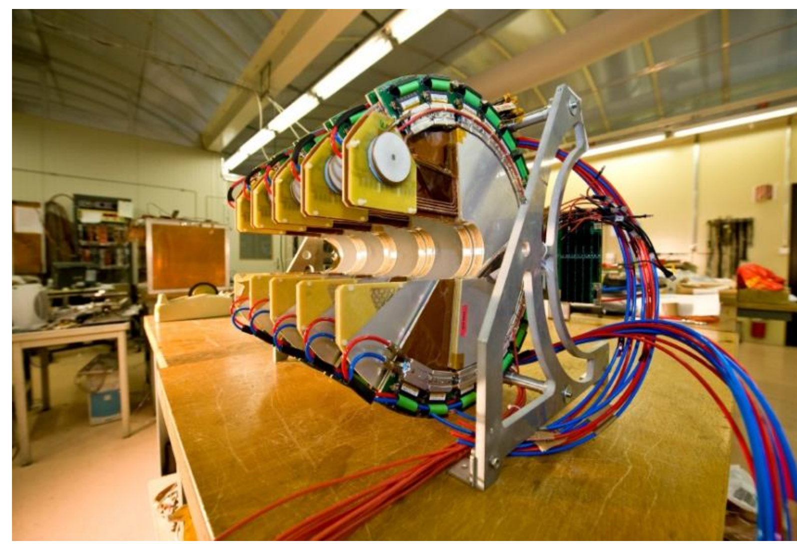


The T2 inelastic telescope

Properties:

- Installed inside CMS shielding between HF and Castor calorimeters
- Centered around 13.5 m from IP5
- One telescope on each side of IP5
- Two quarters per telescope

- Each quarter formed by 10 semi-circular planes, assembled in 5 back-to-back mounted pairs
- Each plane equipped with a Gas Electron Multiplier detector
- Gaseous detector, electron multiplication by 3 perforated foils (2 mm separation)
- Radial segmentation: strips (resolution ≈ 0.15 mm)

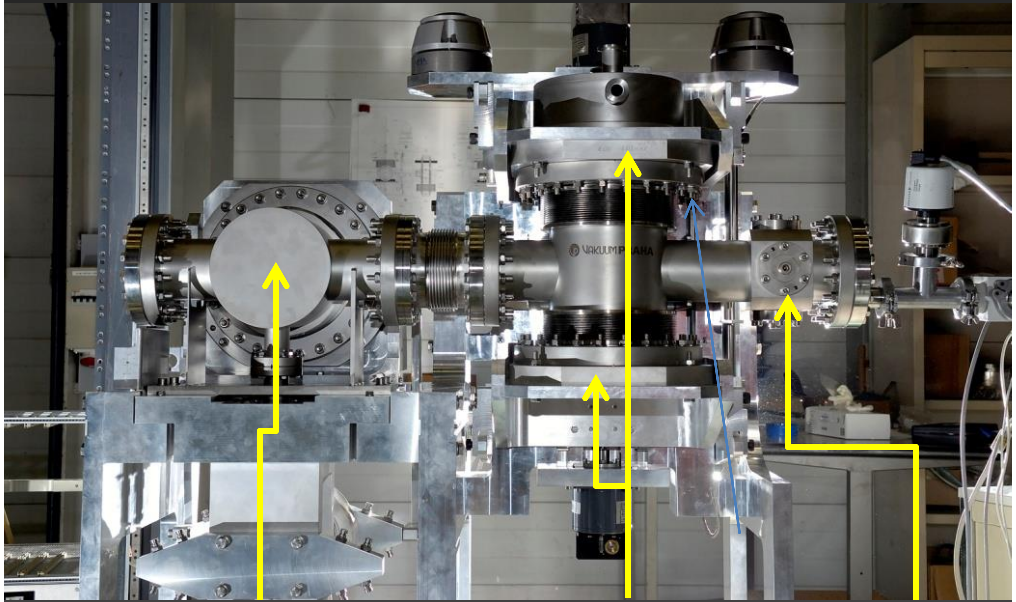


Roman Pot stations

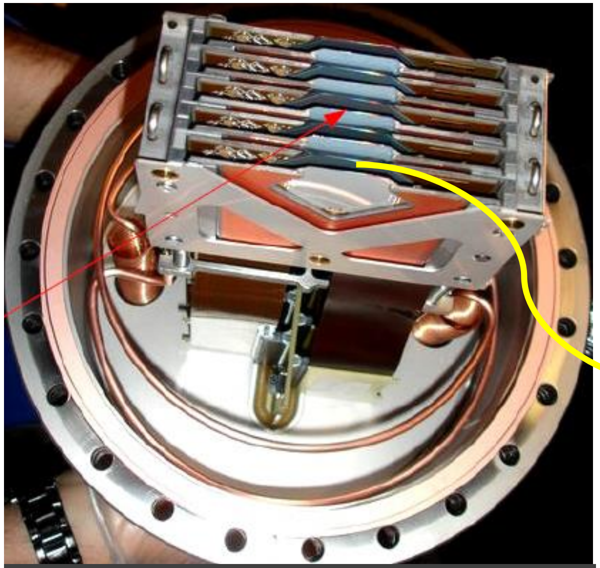
1 RP station:

- 2 units at about 5 m distance
- Measurement of very small proton scattering angles (few μrad)
- Vertical and horizontal pots mounted as close as possible to the beam
- BPM fixed to the structure gives precise position relative to the beam
- Overlapping detectors: relative alignment (10 μm inside unit between 3 RPs)

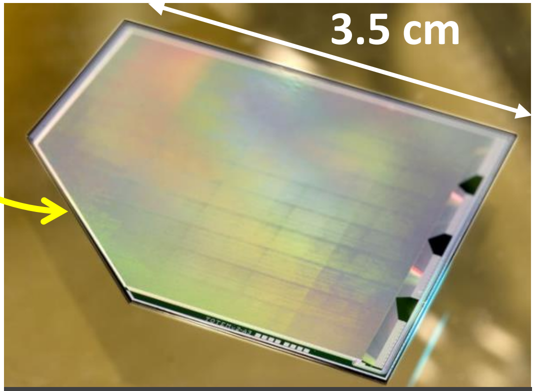
RP unit: 2 vertical, 1 horizontal pot + BPM



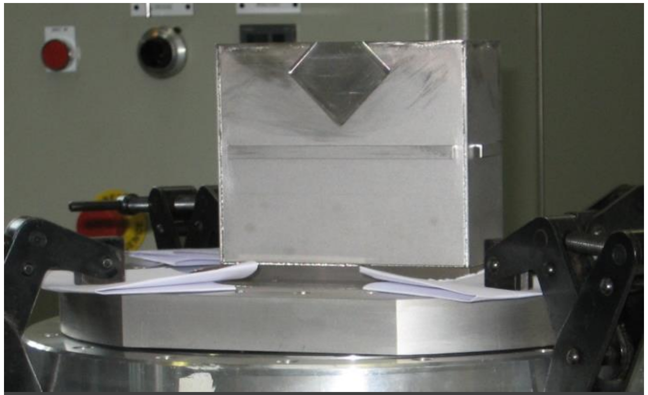
Horizontal RP Vertical RPs BPM



10 planes of edgeless detectors



Si edgeless detector



1 Roman Pot

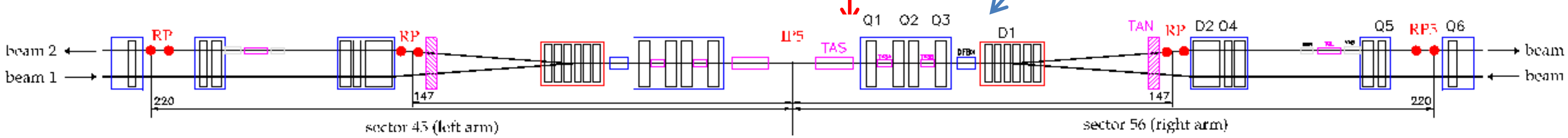
LHC Optics

Essential for TOTEM physics !

- The relevant magnet lattice:

MQXA quadrupole

MBXW separation dipoles normal conducting



$$\frac{d^2x}{ds^2} - k(s)x = 0, \qquad x = \sqrt{\varepsilon\beta(s)}\cos[\phi(s)+\phi_0] \to x', \qquad (\ )' \equiv \frac{d}{ds}$$

Measured RP

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \\ \Delta p/p \end{pmatrix}_{IP5}$$

and **reconstructed** IP5 proton kinematics

$$\Theta^*_y = \frac{y}{L_y} \qquad \Theta^*_x = \left(\frac{dL_x}{ds}\right)^{-1}\left(\Theta_x - \frac{dv_x}{ds}x^*\right)$$

Machine imperfections alter the optics:

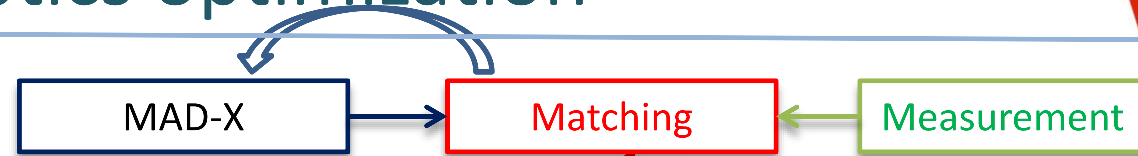
- Strength conversion error, $\sigma(B)/B \approx 10^{-3}$
- Beam momentum offset, $\sigma(p)/p \approx 10^{-3}$
- Magnet rotations, beam harmonics, …

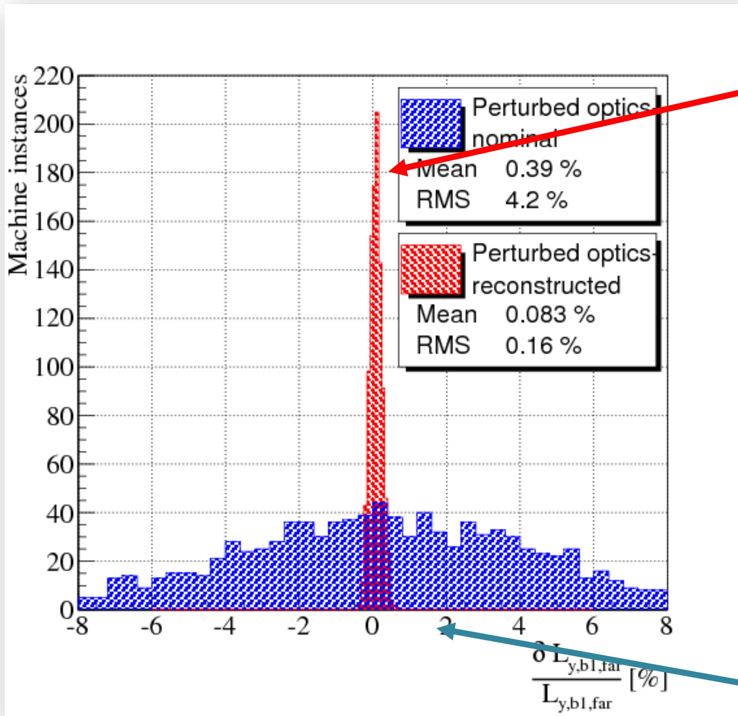
Perturbed element	$\delta L_{y,b1}/L_{y,b1}$ [%]
MQXA.1R5	0.98
MQXB.A2R5	−2.24

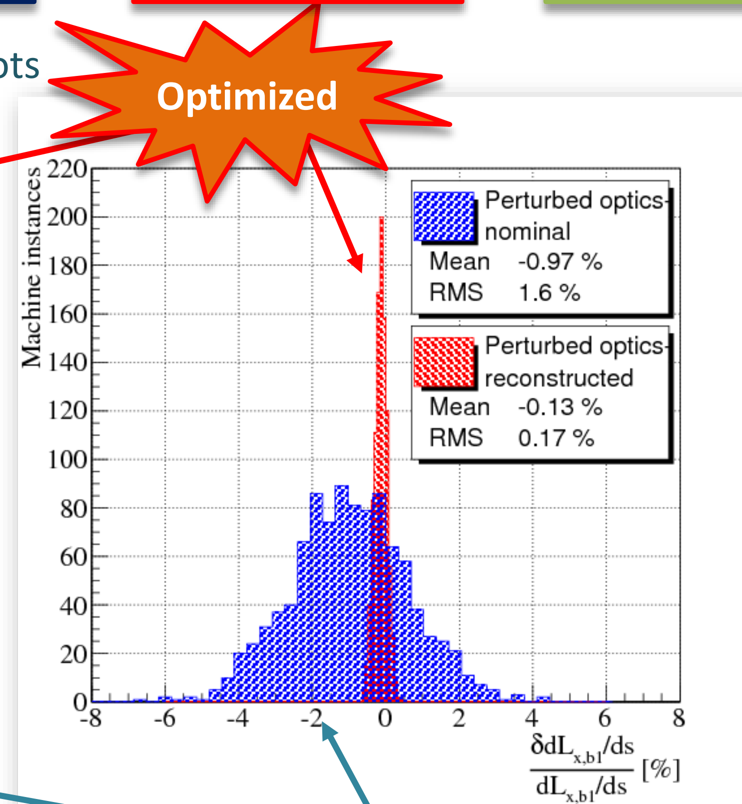
Optics optimization

Optics estimation based on:

- MAD-X based Monte-Carlo
- **Measured** optical function ratios from Roman Pots







Spread due to LHC imperfections

Novel method from TOTEM:

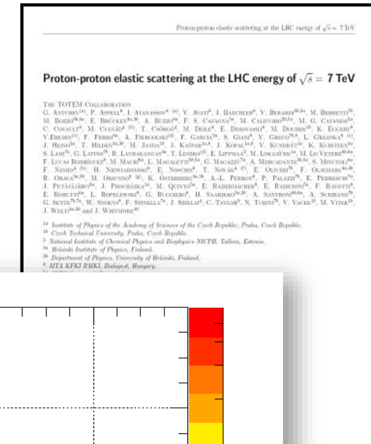
- Uses **measured** proton data from RPs
- http://iopscience.iop.org/1367-2630/16/10/103041/

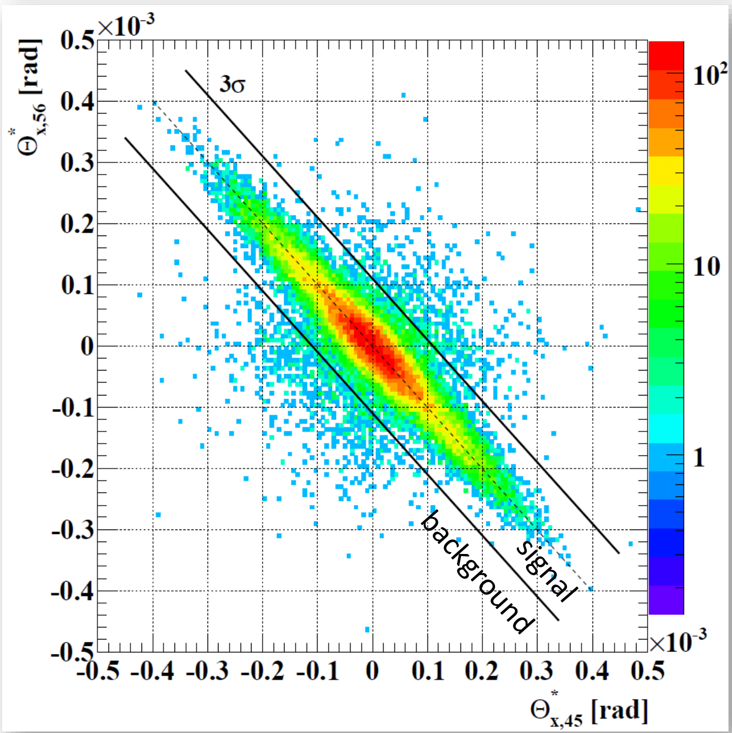
Elastic scattering at √s = 7 TeV

Elastic tagging:

- $\beta^* = 3.5$ m
- Topology, collinearity cuts

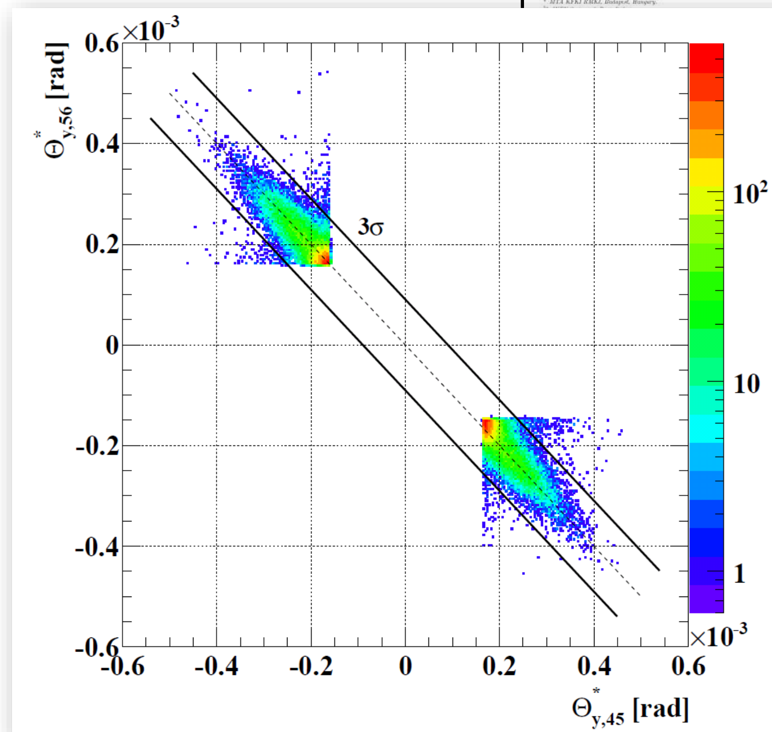
[EPL 95 (2011) 41001]


Proton-proton elastic scattering at the LHC energy of $\sqrt{s}$ = 7 TeV



Collinearity Θ_x

Spread in agreement with beam divergence (17-18 μrad)

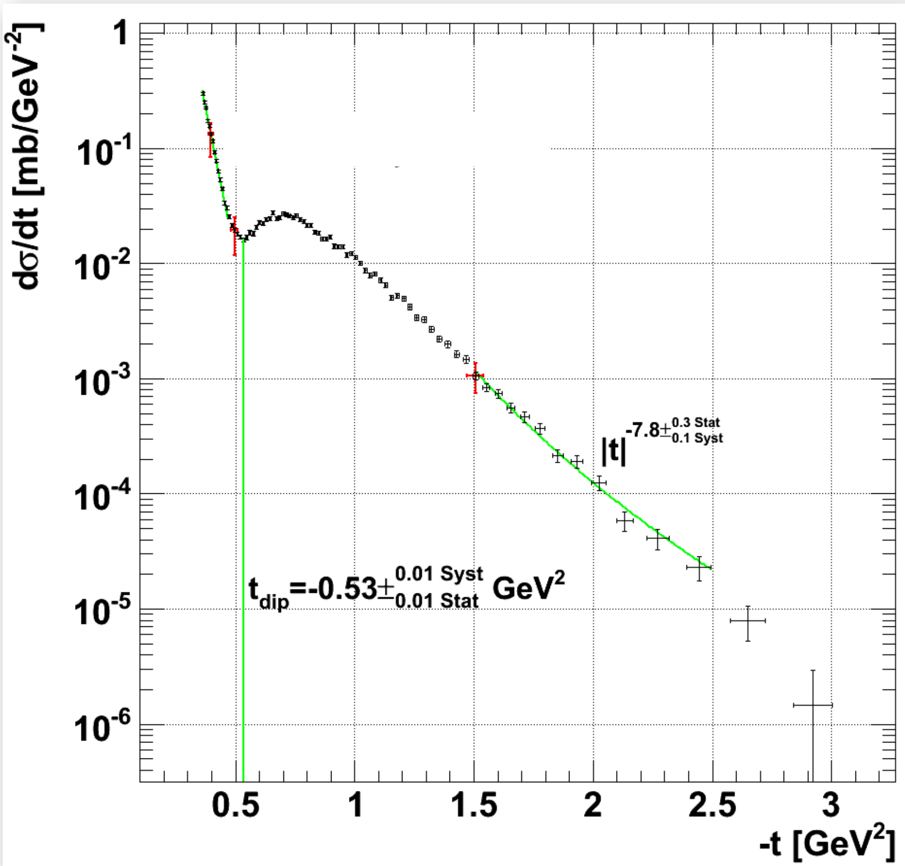


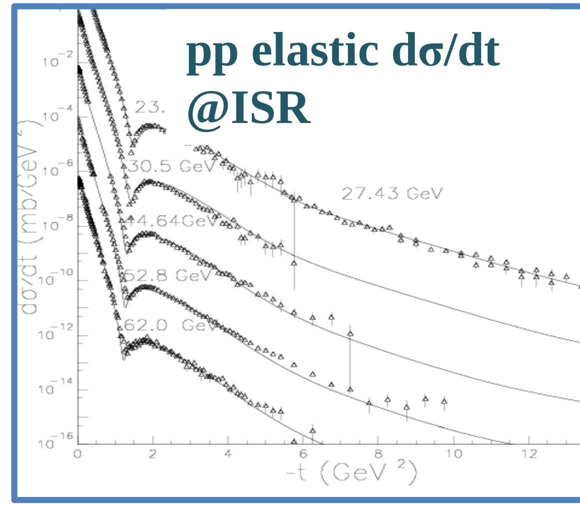
Collinearity Θ_y

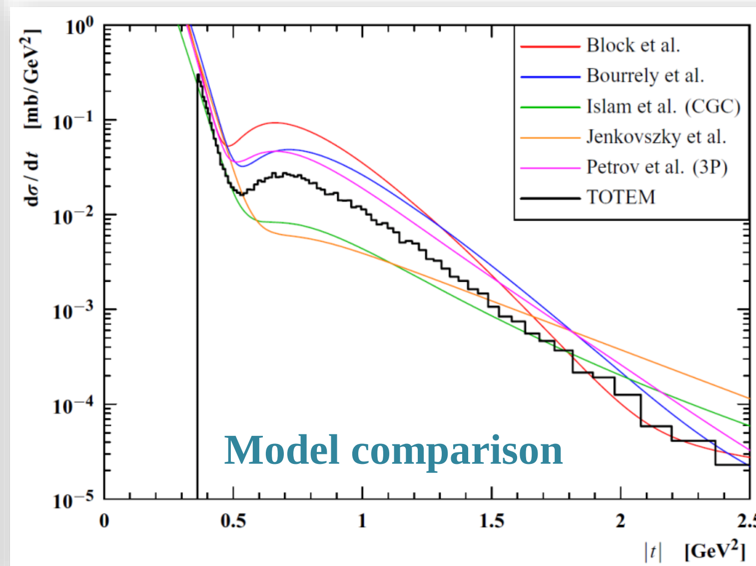
TOTEM first elastic dσ/dt result at √s = 7 TeV

After acceptance corrections, unfolding, inefficiency corrections, luminosity:

- |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 - 2.0 GeV^2 : power low behavior $|t|^{-n}$







Low-t measurement, cross-sections at √s = 7 TeV

Properties:

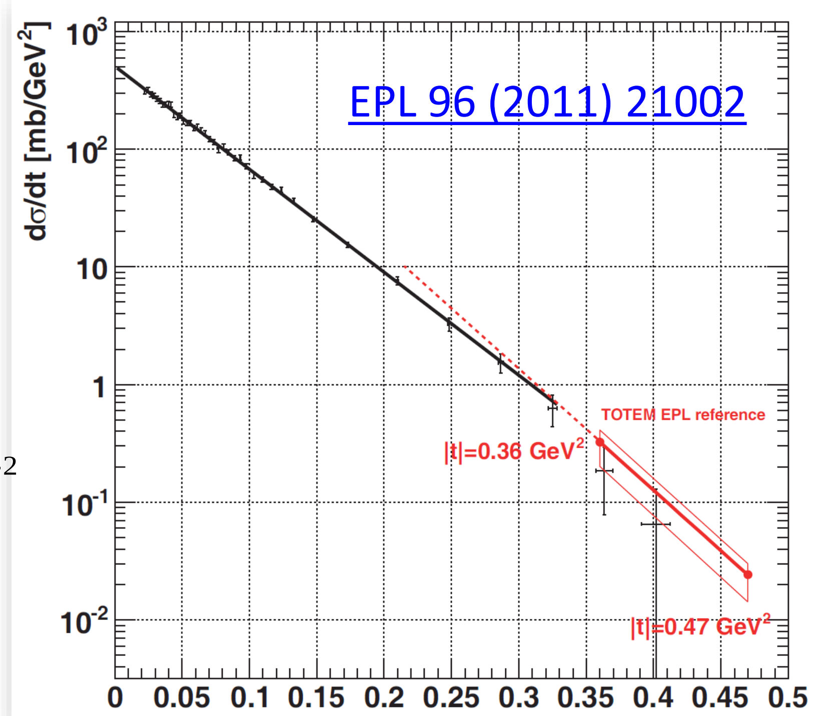
- β* = 90 m

  The exponential slope B confirms that it increases with √s:

$$B = (20.1 \pm 0.2_{stat} \pm 0.3_{syst})\ \mathrm{GeV}^{-2}$$

- Extrapolation to t = 0:

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = (503.7 \pm 1.5_{\mathrm{stat}} \pm 26.7_{\mathrm{syst}})\ \mathrm{mb\ GeV}^{-2}$$



- Integral elastic cross-section:

$$\sigma_{el} = 8.3\,\mathrm{mb}^{\mathrm{extrapol.}} + 16.5\,\mathrm{mb}^{\mathrm{measured}} = 24.8 \pm 0.2_{stat} \pm 1.2_{syst}\ \mathrm{mb}$$

- Total cross-section (with optical theorem):

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} \qquad \rho_{COMPETE} = 0.14^{+0.01}_{-0.08} \quad \Rightarrow \quad \sigma_{tot} = (98.3 \pm 0.2_{stat} \pm 2.8_{syst})\,\mathrm{mb}$$

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left(73.5 \pm 0.6_{stat} \begin{bmatrix} +1.8 \\ -1.3 \end{bmatrix}_{syst}\right)\mathrm{mb}$$

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

$|t_{min}| = 5 \cdot 10^{-3}$ GeV^2 reach at 7 TeV

- **Slope parameter:**

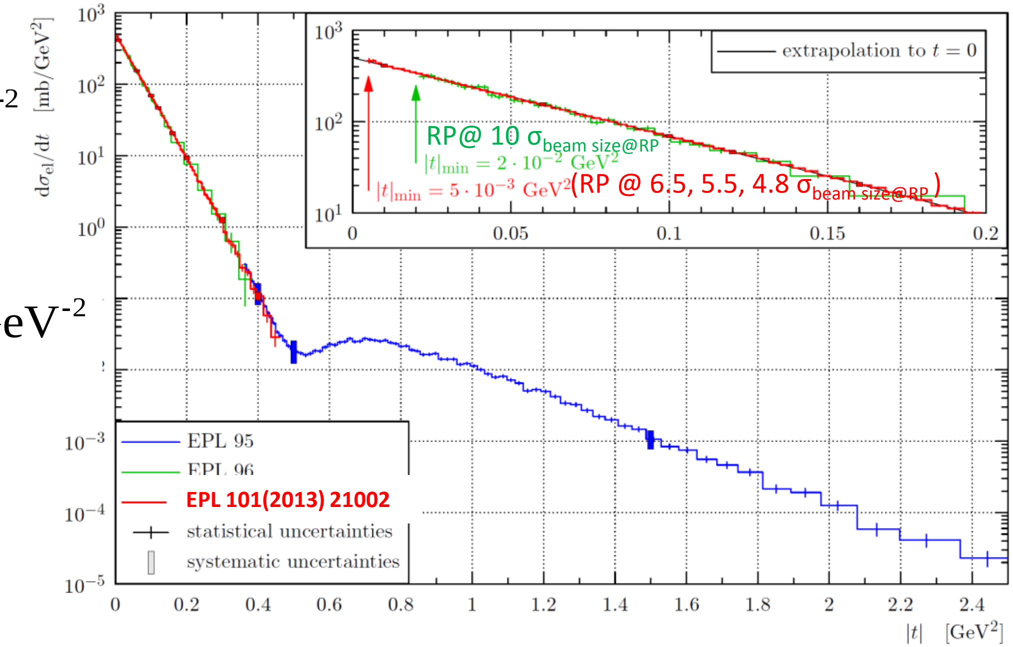
$$B = \left(19.89 \pm 0.03_{stat} \pm 0.27_{syst}\right)\ \mathrm{GeV}^{-2}$$

- **Extrapolation:**

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = (506.4 \pm 0.9_{\mathrm{stat}} \pm 23_{\mathrm{syst}})\ \mathrm{mb\ GeV}^{-2}$$

- **Elastic cross section:**

$$\sigma_{el} = 25.43 \pm 0.03_{stat} \pm 1.07_{syst}\ \mathrm{mb}$$



- **91 % is measured**
- EPL 101(2013) 21002
- Inelastic cross-section measurement

σ_{inel} = 73.7 ± 3.4 mb


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

EPL 101 (2013) 21003

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

At $\sqrt{s}$=7 TeV:

1. Low luminosity (CMS) + Elastic $d\sigma/dt$ + 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 + Optical theorem (EPL, 101 (2013) 21004)
   - Eliminates dependence **on luminosity**

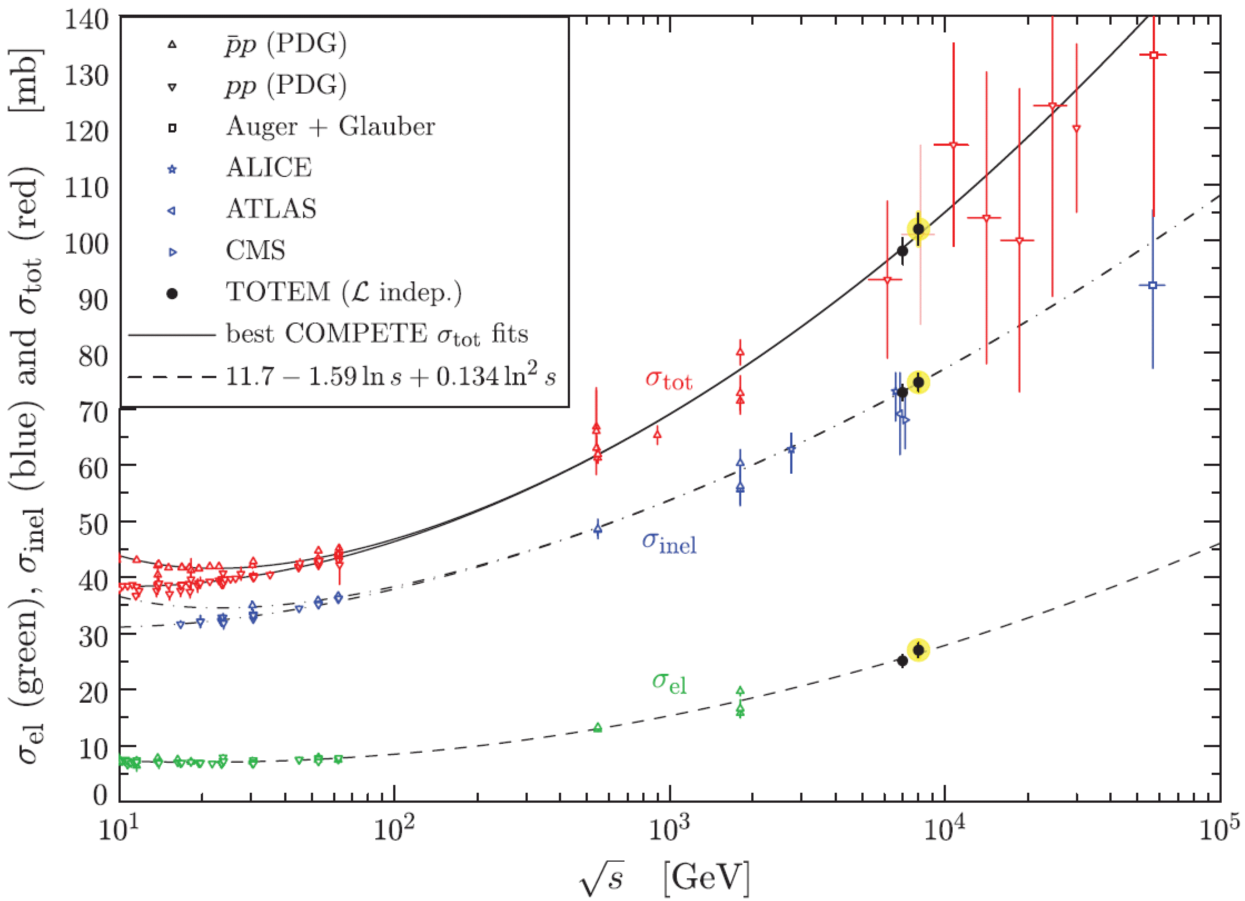
$$\sigma_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\left.\frac{dN_{EL}}{dt}\right|_{t=0}}{N_{EL} + N_{INEL}}$$

σ_{tot} = 98.0 ± 2.5 mb

Luminosity independent cross-sections √s = 8 TeV

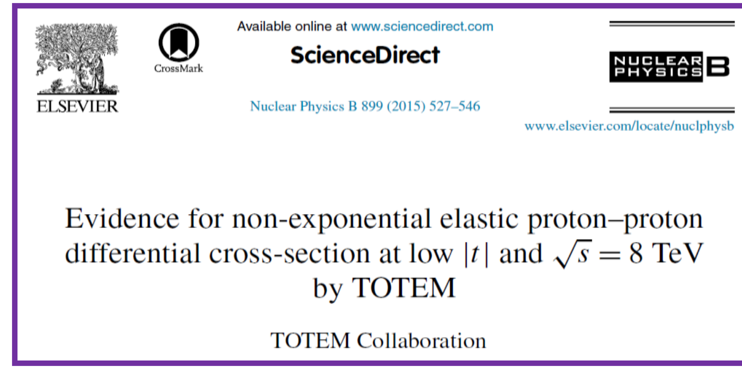
- β* = 90 m
- **Phys. Rev. Lett. 111, 012001 (2013)**
- Elastic, inelastic, total cross-sections →

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



Evidence for non-exponential elastic $d\sigma/dt$ $\sqrt{s}$ = 8 TeV

- High statistics data set (β* = 90 m, 2012)
- 7 M elastic events
- 0.027 GeV^2 < |t| < 0.2 GeV^2 dominated by hadronic interaction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ScienceDirect
Nuclear Physics B 899 (2015) 527–546
ELSEVIER
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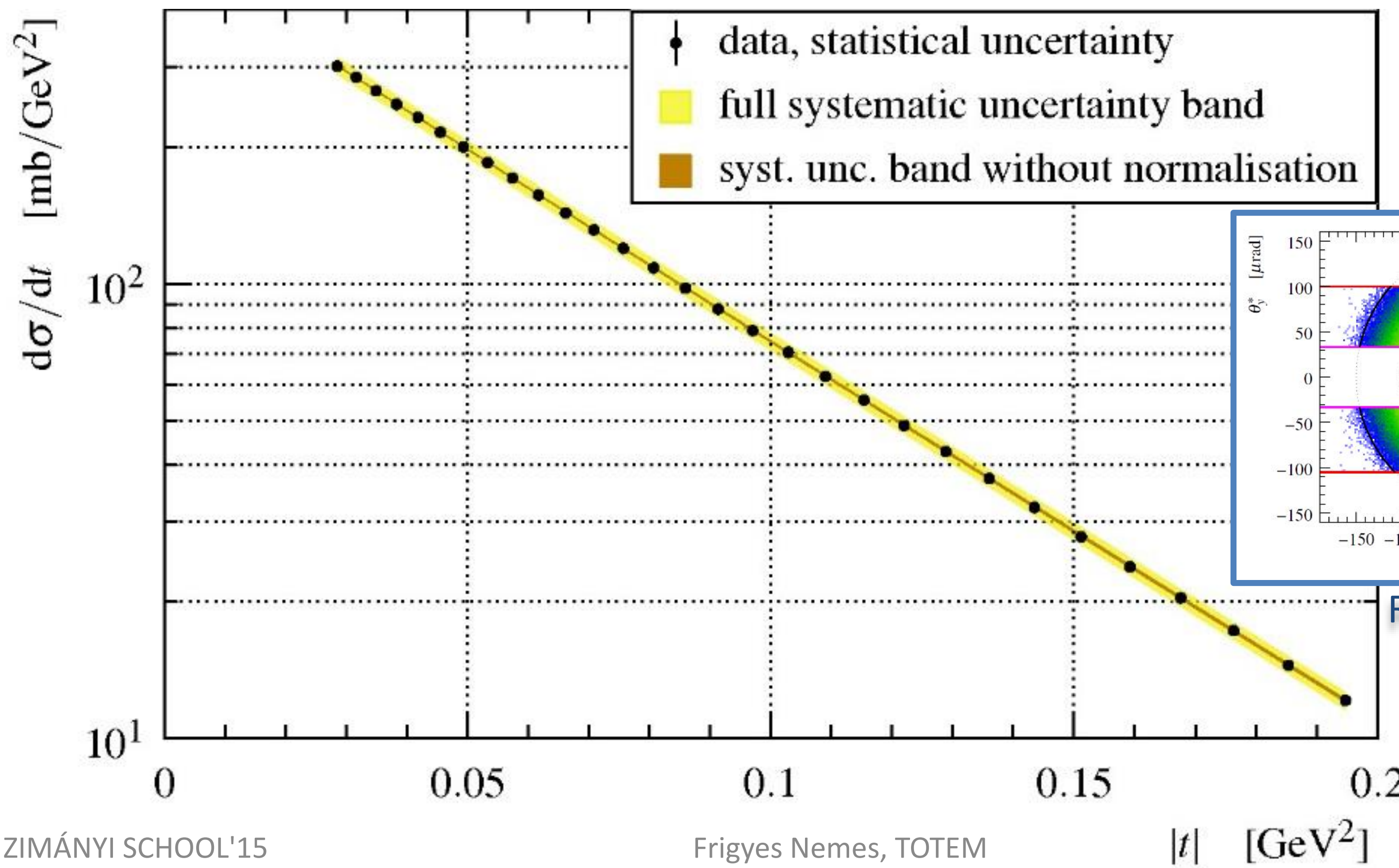
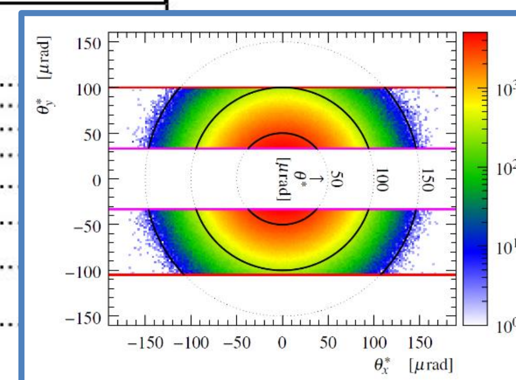
Evidence for non-exponential elastic proton–proton differential cross-section at low $|t|$ and $\sqrt{s} = 8$ TeV by TOTEM

TOTEM Collaboration

Nucl. Phys. B899 (2015) 527





Rotational **symmetry**

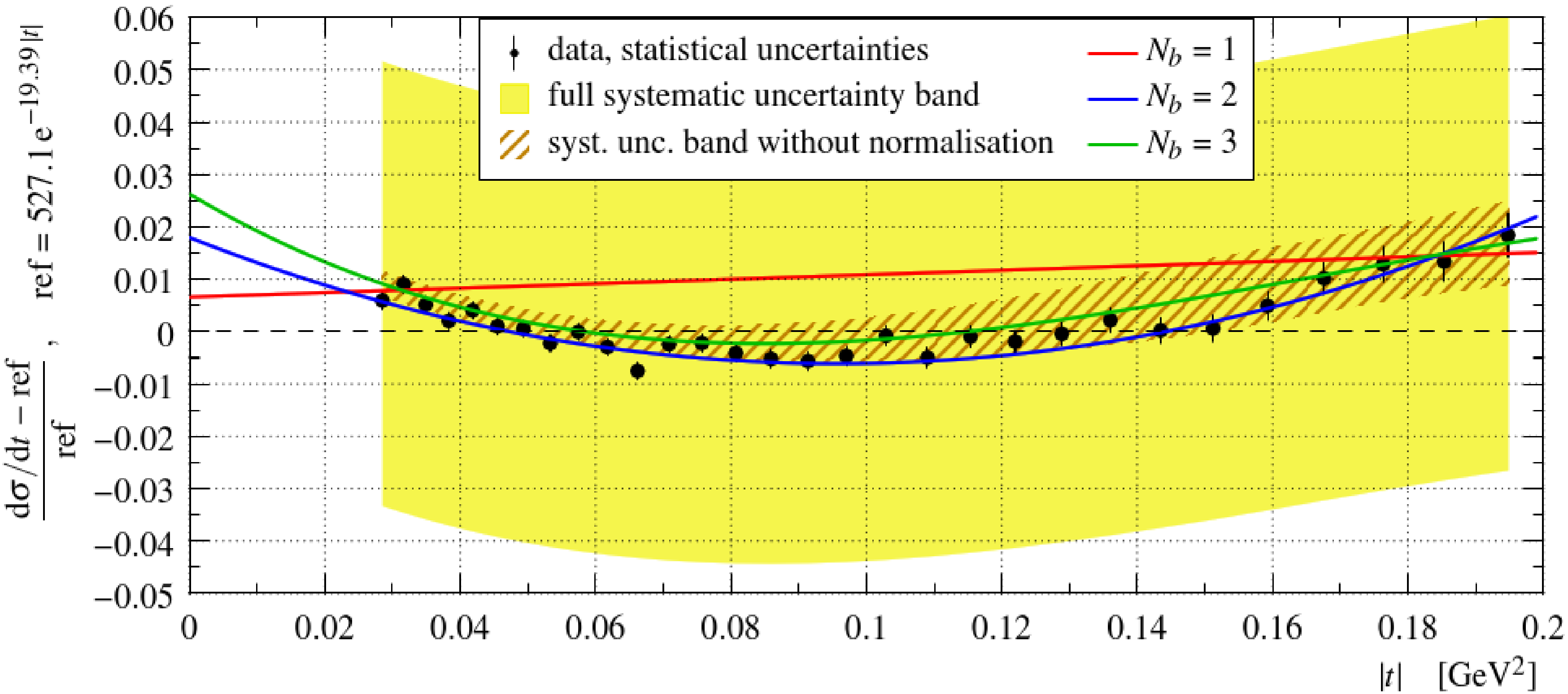
Evidence for non-exponential elastic dσ/dt

$$B \to \sum_{i=1}^{N_b} b_i t^i$$

$N_b = 2$: σ_{tot} = 101.5 ± 2.1 mb

$N_b = 3$: σ_{tot} = 101.9 ± 2.1 mb

Relative deviation of dσ/dt from exponential

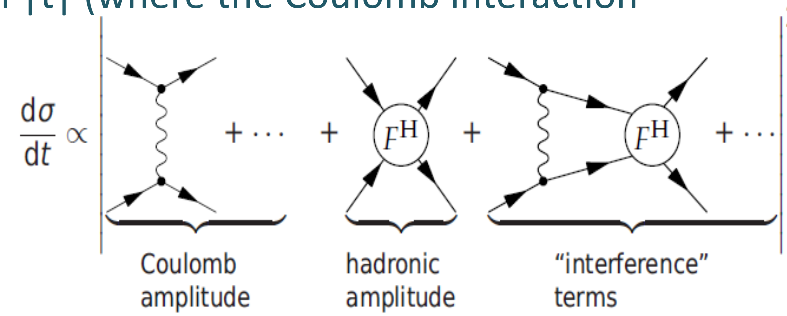


Pure exponential form **excluded** at 7.2 σ significance.

Coulomb-hadronic interference at $\sqrt{s}$ = 8 TeV

Analysis aims:

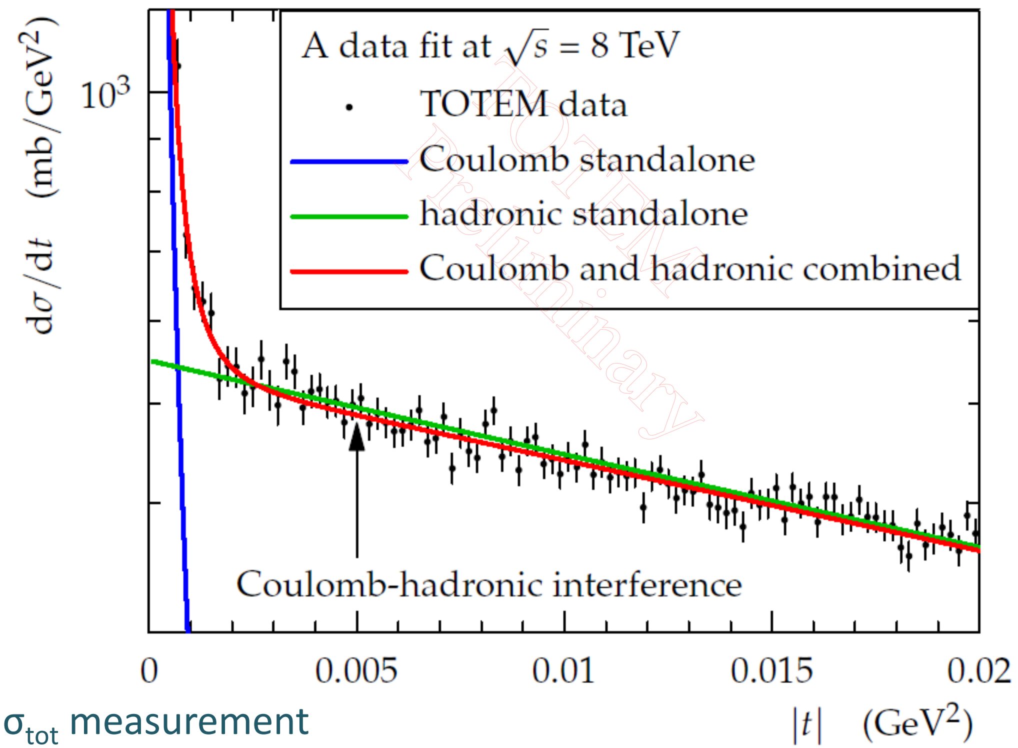
- Measure $d\sigma_{el}/dt$ at the smallest possible proton |t| (where the Coulomb interaction can be probed)
- β^* = 1000 m, RP at **3** σ_{beam}
- $\Rightarrow |t|_{min} = 6 \times 10^{-4}$ GeV^2
- $\Rightarrow$ Coulomb-hadronic interference



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

$$|F^H| \quad \arg(F^H)$$

$$A \cdot e^{-B(t)\cdot|t|} \qquad \text{Hadronic phase}$$



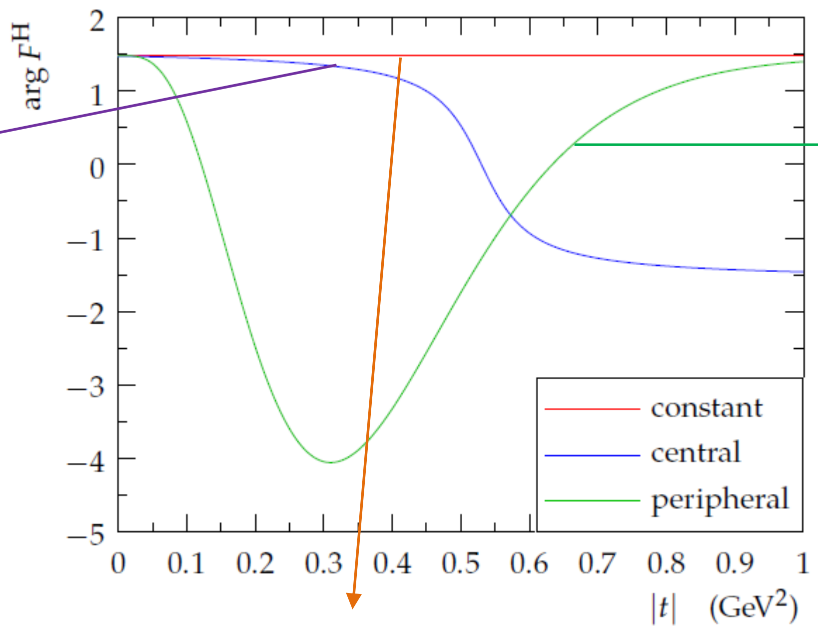
- **Determination of ρ:**

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

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

Nuclear phase parametrizations

"central phase": profile function in impact parameter picture: Elastic scattering preferentially central (Bailly et al.)



"peripheral phase": profile function in impact parameter picture: Elastic scattering preferentially peripheral

$$\arg F^H(t) = \frac{\pi}{2} - \operatorname{atan} \frac{\cot p_0}{1 - \frac{t}{t_d}}$$

Constant phase: also central behavior

$$\arg F^H(t) = p_0$$

$$\arg F^H(t) = p_0 + \zeta_1 \left| \frac{t}{t_0} \right|^{\kappa} \exp(\nu t), \quad t_0 = 1\,\mathrm{GeV}^2$$

Result for

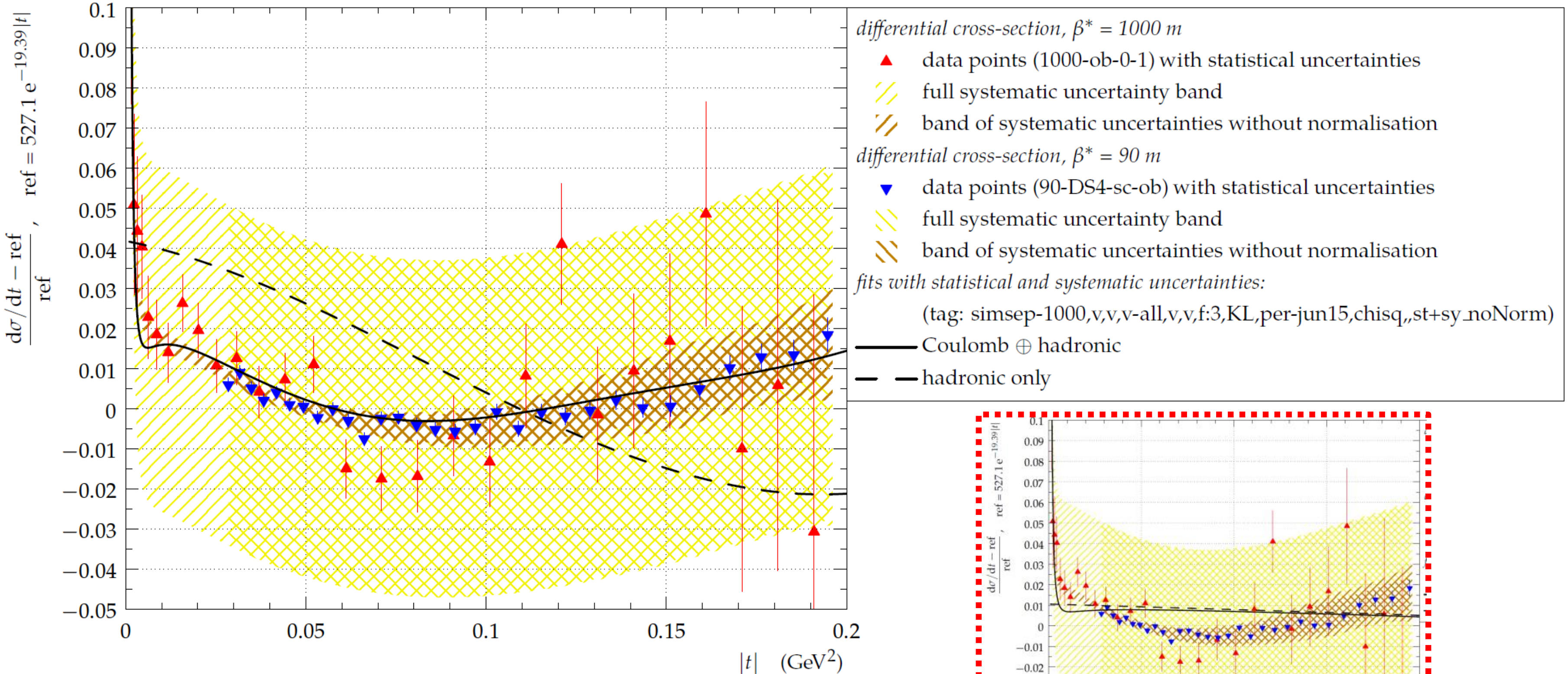
$$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0) = \cot p_0$$

is model dependent

Coulomb-hadronic interference: results

Model descriptions:

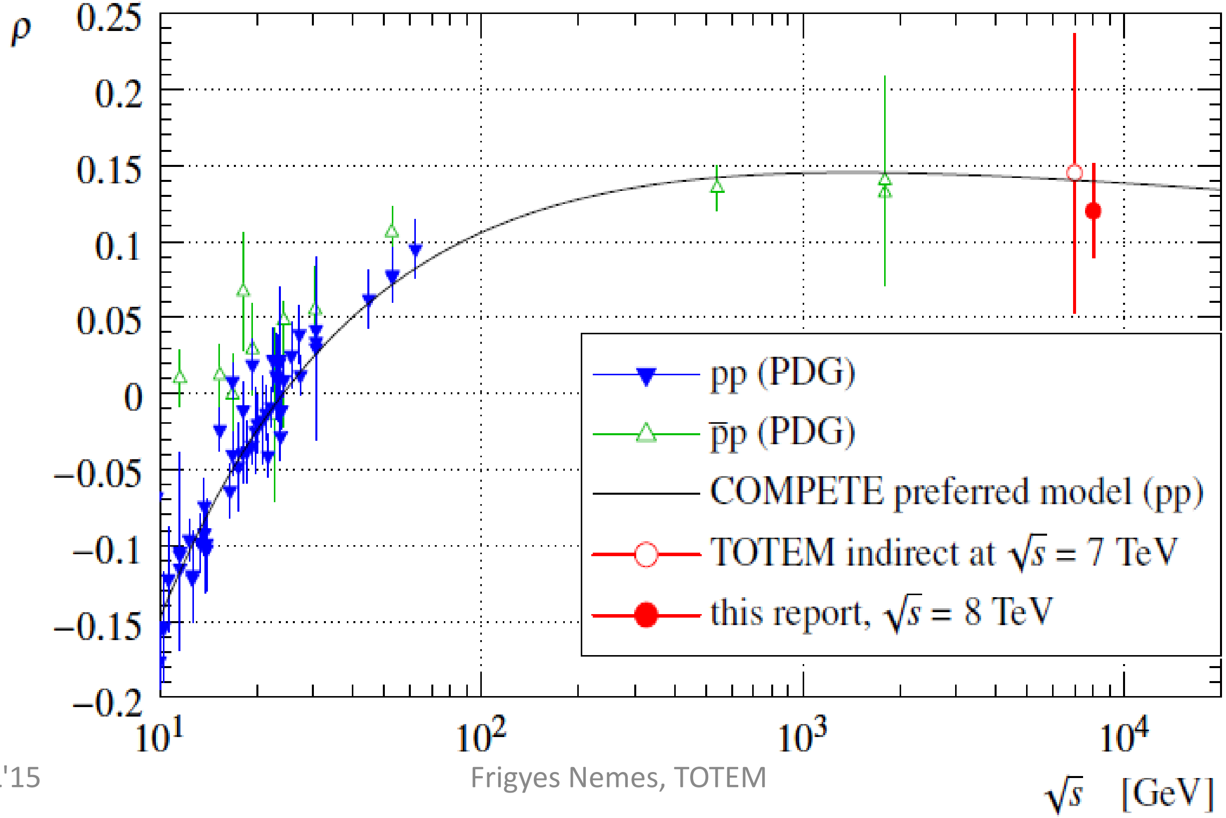
- **Polynomial** exponential hadronic slope
- **Both *central*** and ***peripheral*** hadronic phase compatible with data
- Central (peripheral) had. phase + purely exponential hadronic slope excluded (disfavoured)
- In agreement with TOTEM non-exponential dσ/dt



Measurement of ρ at the LHC

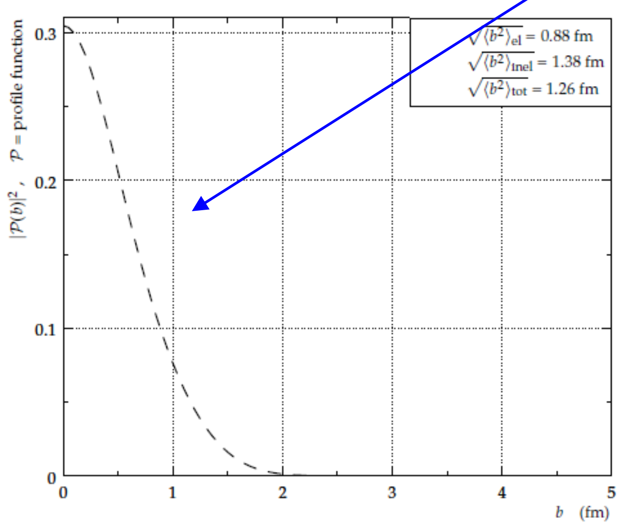
Results:

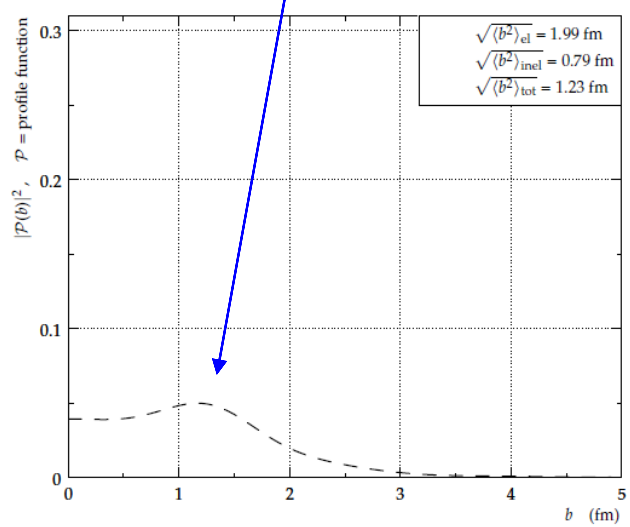
	KL, constant	KL, peripheral
step 1: χ^2/ndf	25.7/25 = 1.03	25.0/25 = 1.00
step 2: χ^2/ndf	57.5/56 = 1.03	57.6/56 = 1.03
a [mb/GeV^2]	549 ± 24	549 ± 24
b_1 [GeV^{-2}]	20.47 ± 0.14	19.56 ± 0.13
b_2 [GeV^{-4}]	8.8 ± 1.6	−3.3 ± 1.5
b_3 [GeV^{-6}]	20 ± 6	−13 ± 5
ρ	0.12 ± 0.03	0.12 ± 0.03
σ_{tot} [mb]	102.9 ± 2.3	103.0 ± 2.3



Coulomb-hadronic interference

Hadronic Slope	Constant Phase (representative for all central phases)	Peripheral Phase
$N_B = 1$ (pure exponential)	Excluded	Disfavoured
$N_B = 3$ (parabolic exp. slope)	Possible	Possible





Impact parameter picture: profile functions

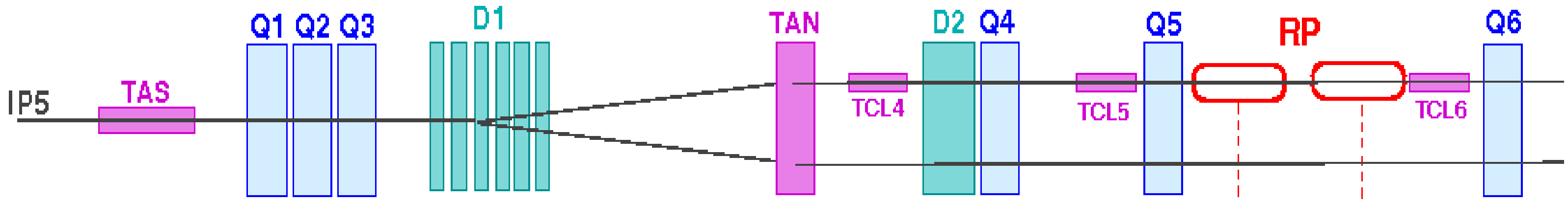
2015: special $\beta^* = 90$ m run at 13 TeV

Integrated Luminosity

• LHC delivered:	0.74 pb^{-1}
• CMS recorded:	~ 0.68 pb^{-1}
• TOTEM Trigger & CMS data:	0.55 pb^{-1}
• CMS + TOTEM **data:**	**~ 0.4 pb^{-1}**

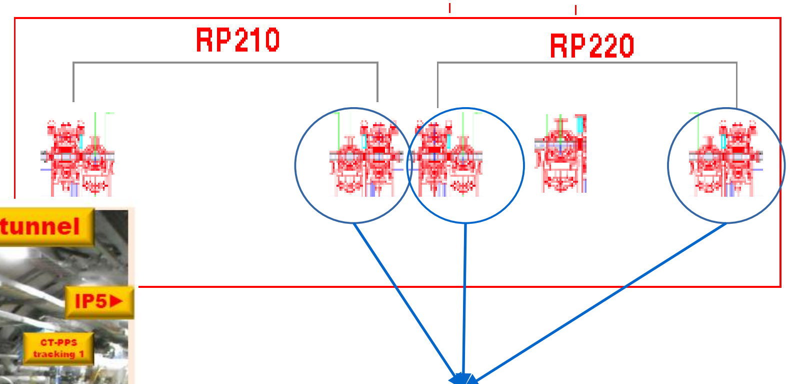
- **Details: TOTEM Status report 2015**

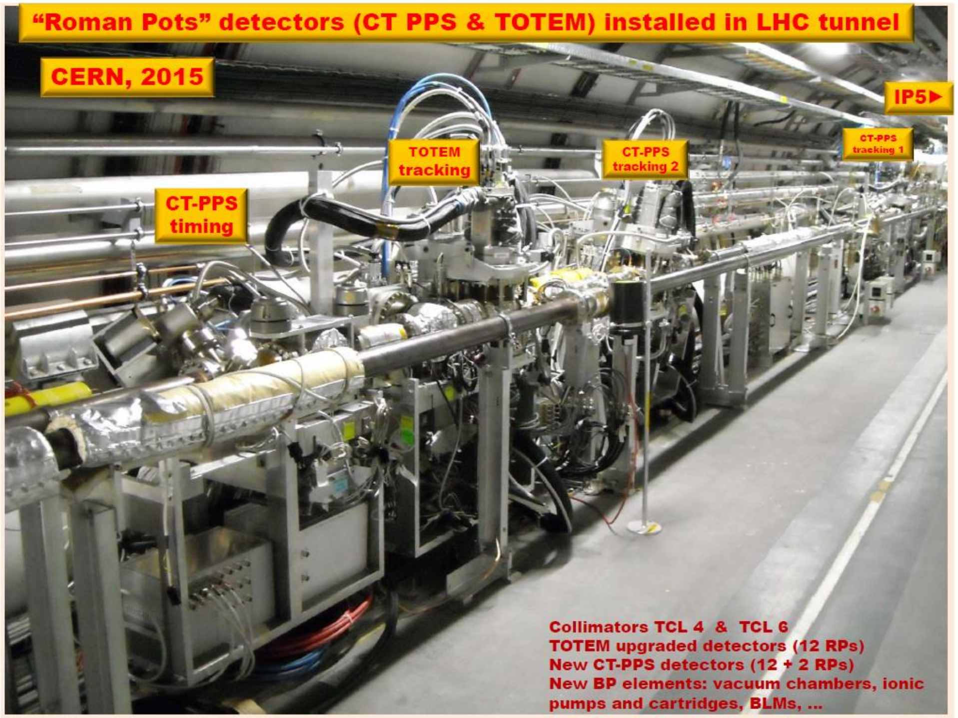
2015 special run @13TeV : detector setup



After LS1:

Roman Pot stations in the LHC tunnel

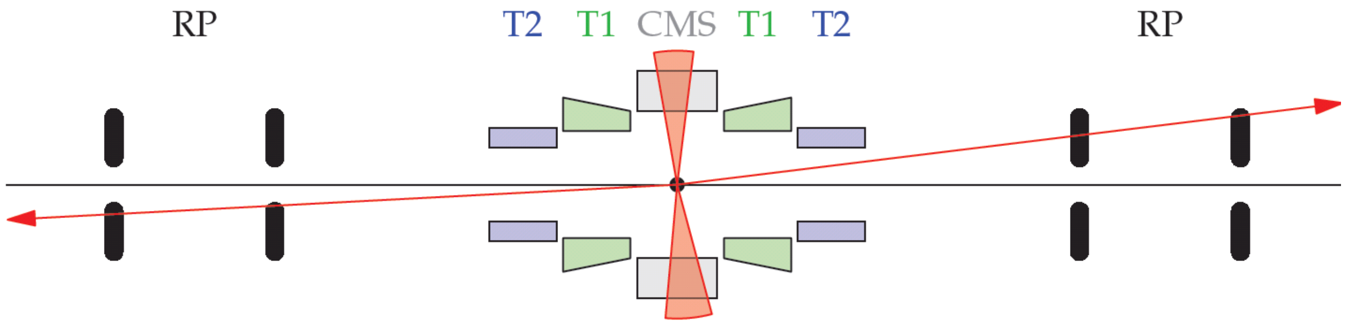




Inserted RPs at β*=90m

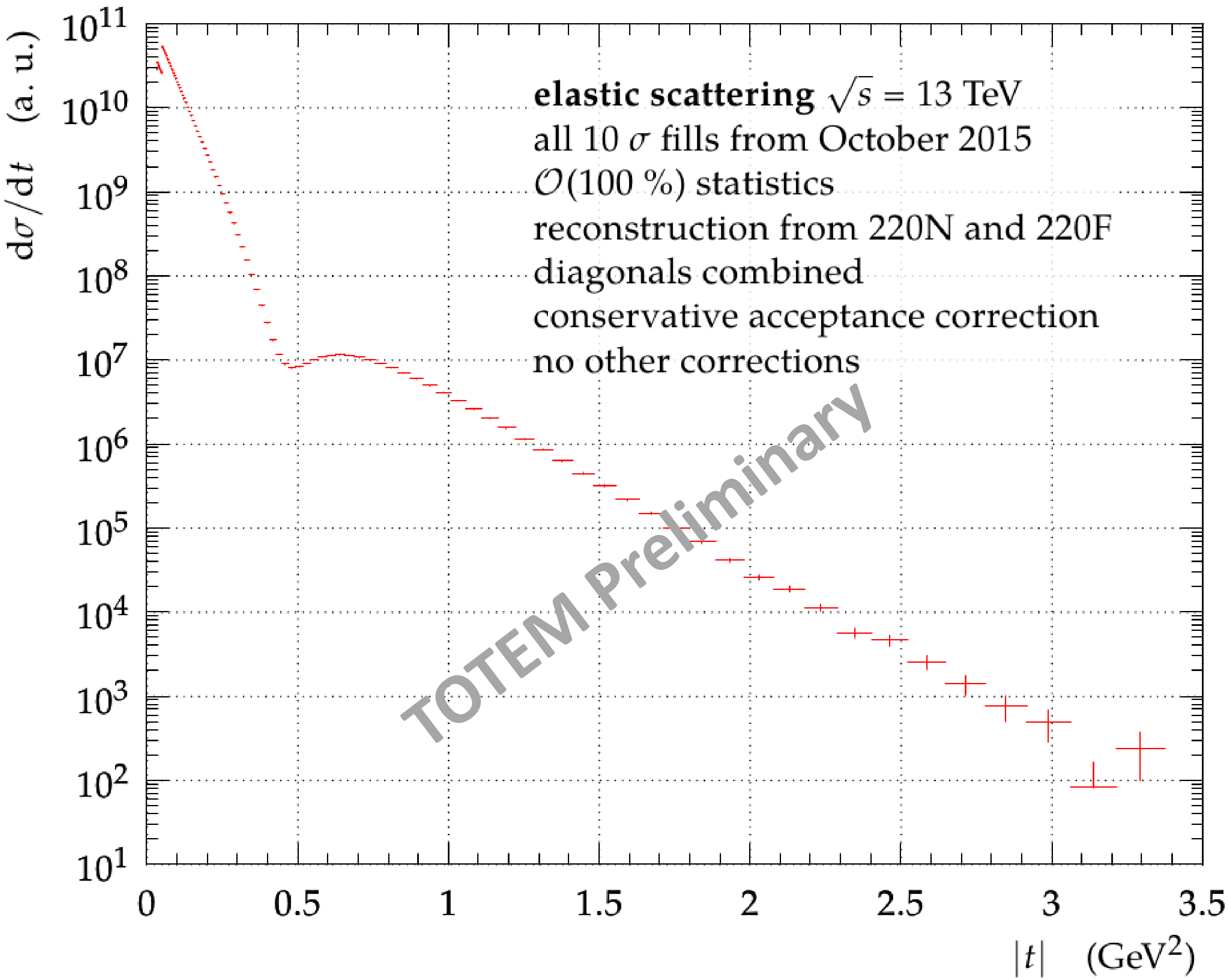
2015 special run @13TeV : trigger settings

- **TOTEM Triggers → CMS**
  - Roman Pots Double Arm & T2 Veto
  - Roman Pots Double Arm (TopTop/BottomBottom)
  - T2 Min Bias
  - Zero Bias
- **CMS Triggers → TOTEM**
  - Dijets (p_T threshold 20, 32 GeV)
  - Dimuon
  - Single mu & HF Veto



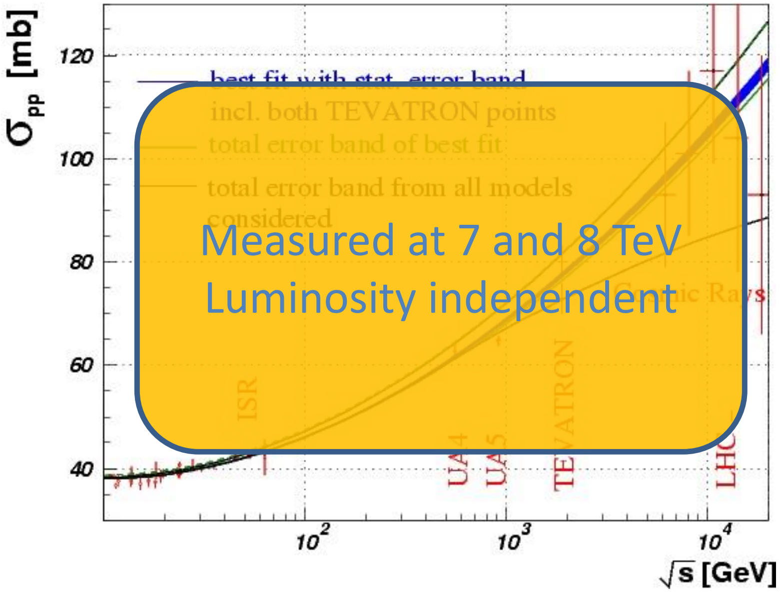
- **CMS + TOTEM**
  - Independent DAQ
  - Level 1 Trigger exchange
  - TOTEM offline merging
  - LV1 Rate ~ **50 kHz !** → recorded
    (x 50 wrt. Run-I, thanks to zero suppression)
  - ~ **$3 \cdot 10^9$** events collected!
  - CMS HLT Rate ~ 10 kHz → recorded

TOTEM : (large-t) Elastic Scattering @13TeV



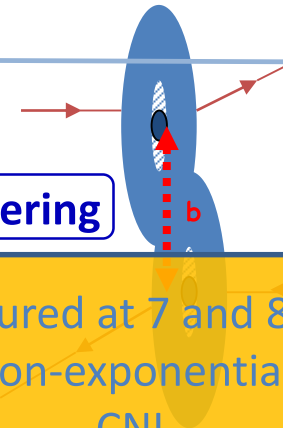
Summary

Total cross-section



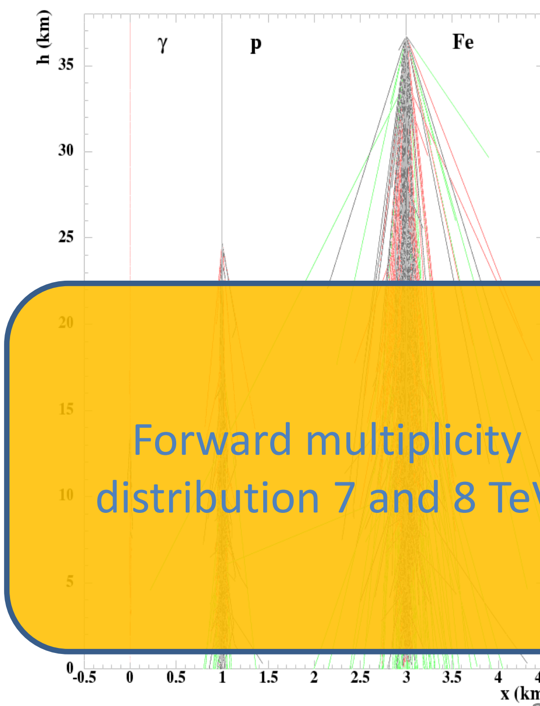
Measured at 7 and 8 TeV
Luminosity independent

Elastic Scattering



Measured at 7 and 8 TeV
Non-exponential
CNI

Forward physics



Forward multiplicity distribution 7 and 8 TeV

Diffraction: soft (and hard with CMS)

Preliminary results
DD, CD, SD
Many analysis in progress !

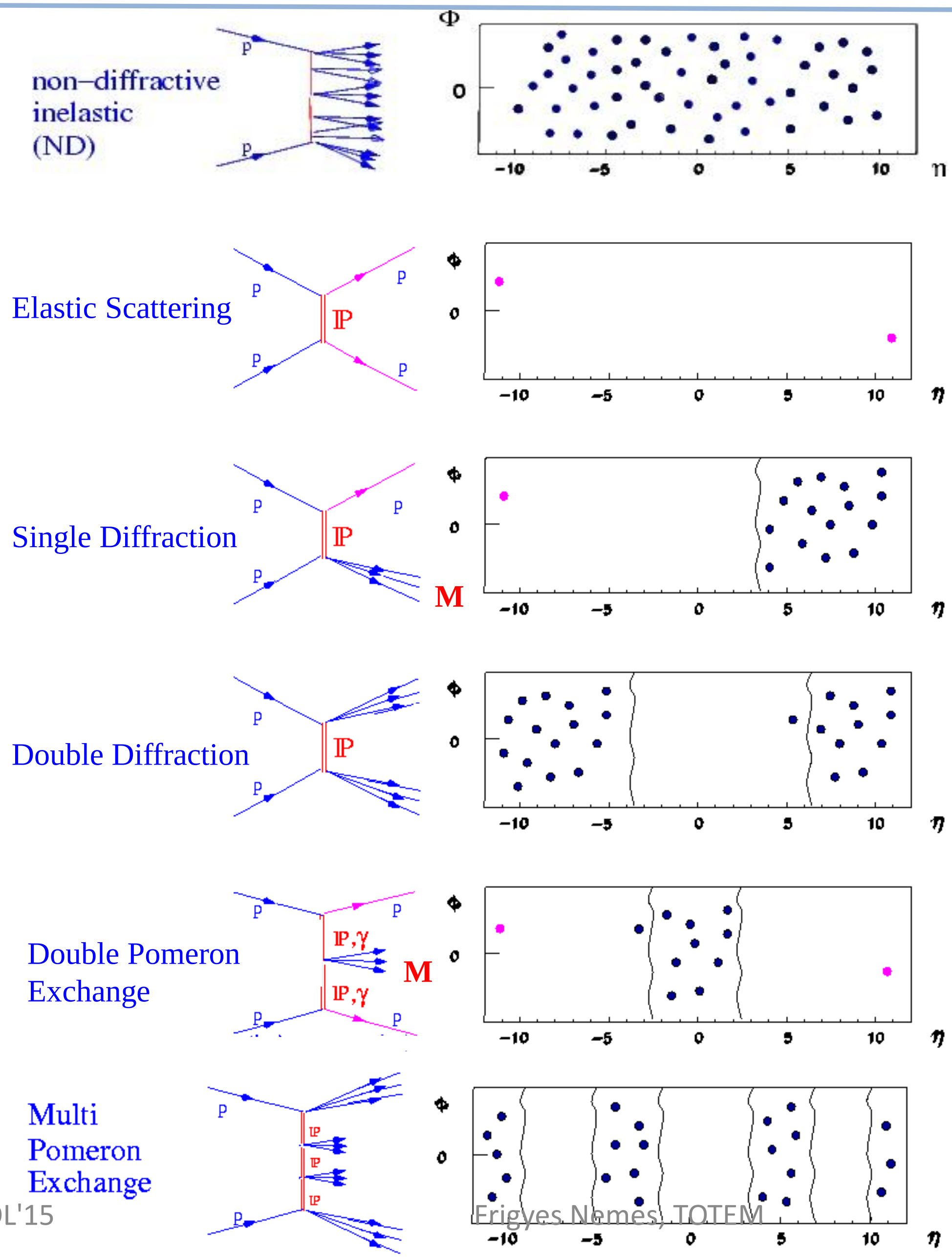
Thank you for your attention !

Backup slides

Forward and diffractive physics
(Based on LHC Run I data)

Inelastic and Diffractive Processes

All the drawings show soft interaction.
In case of hard interactions there should be jets,
which fall in the same rapidity intervals.



~60 mb

~25 mb

~10 mb

~5 mb

~1 mb

<< 1 mb

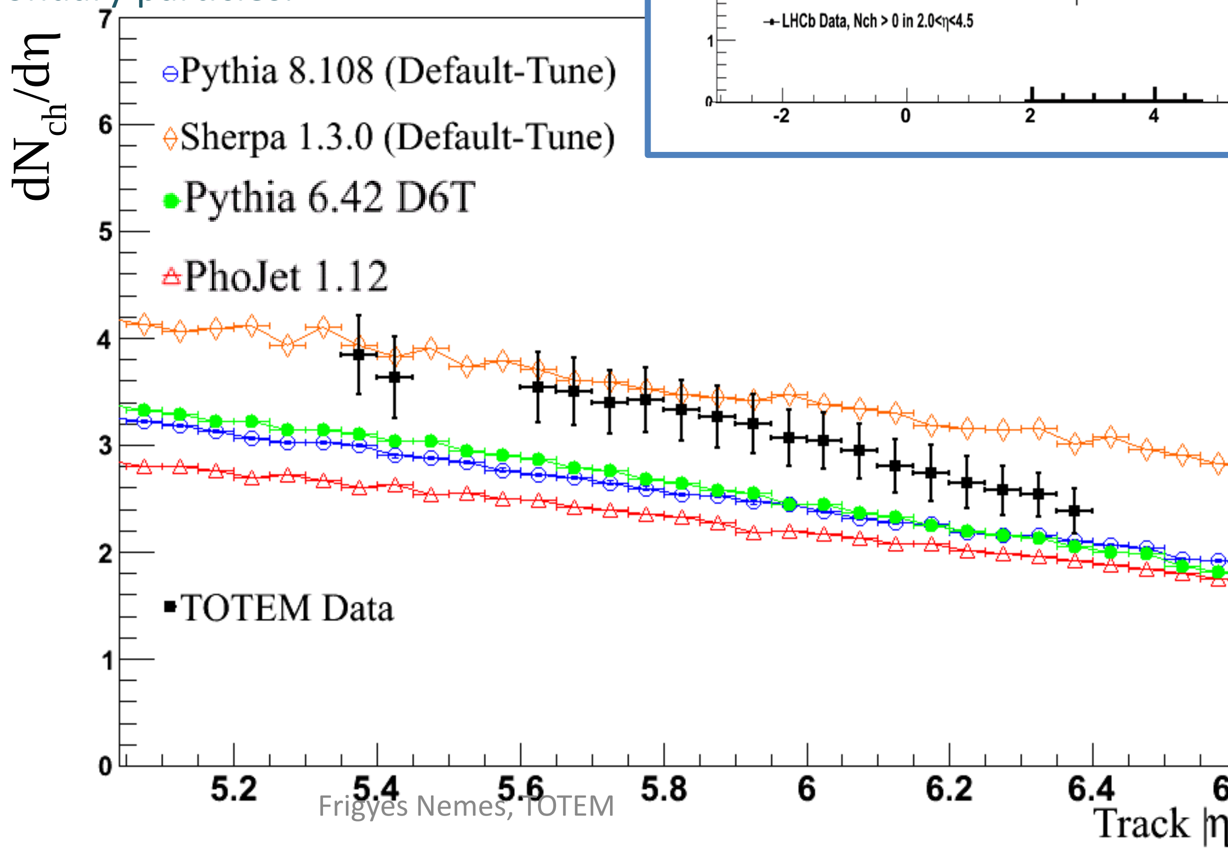
Measure σ (M,ξ,t)

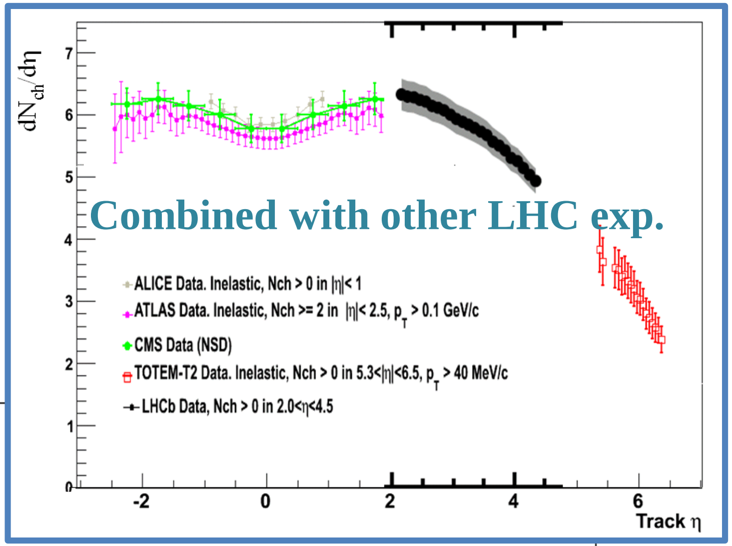
$dN_{ch}/d\eta$ measured with T2, $\sqrt{s}$=7 TeV

Very forward measurement with T2 :

- Published EPL, 98 (2012) 31002
- Visible cross section measured on data: ~ 94% σ_{inel}
- Diffractive mass M_{diff} > 3.4 GeV

- Main contributions to the systematical error:
- Subtraction of secondary particles.
- Track efficiency
- Misalignment uncertainties



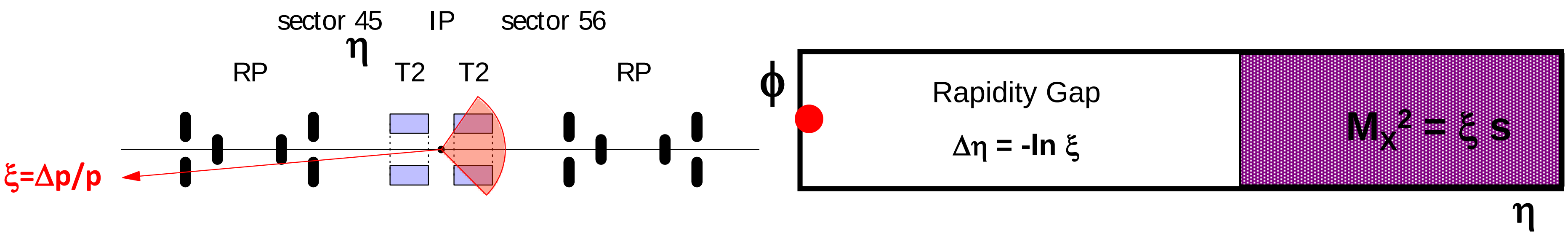


Diffractive physics

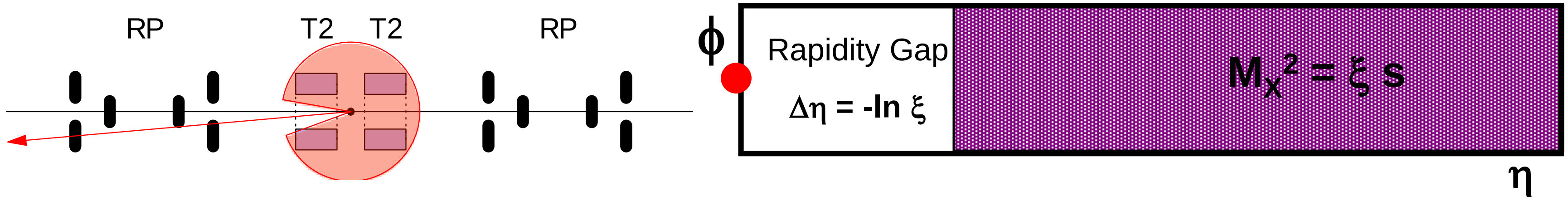
Soft Single Diffractive cross-section 7 TeV

Low mass diffraction ($2 \cdot 10^{-7} < \xi < 10^{-6}$)

- Tracks in the T2 hemisphere opposite to the proton



Very high mass ($\xi > 2.5$ %)



- SD events are triggered with T2, only 1 proton required in RP
- M obtained from the rapidity gap estimation based on charged track η in T1 and T2 $\Delta\eta = -\ln(M^2/s)$. This allows a better ξ resolution ($\sigma(\xi)/\xi \sim 1$) for low medium mass

SD class	Inelastic telescopes configuration	Mass	ξ
Low Mass	p + T2 opposite only (no T1)	3.4 - 7 GeV	$2 \cdot 10^{-7} < \xi < 10^{-6}$
Medium Mass	p + T2 opposite + T1 opposite	7 - 350 GeV	$10^{-6} < \xi < 0.25\%$
High Mass	p + T2 opposite + T1 same	0.35 - 1.1 TeV	$0.25\% < \xi < 2.5\%$
Very High Mass	p + both T2 arms	> 1.1 TeV	> 2.5%

Soft Single Diffractive cross-section 7 TeV

$$\frac{d\sigma}{dt} \propto C \cdot e^{-\mathbf{B} \cdot t}$$

Corrections included:

- Trigger efficiency
- Reconstruction efficiency
- Proton acceptance
- Background subtraction
- Extrapolation to t = 0

Missing corrections:

- ξ – resolution
- Beam divergence effects

Estimated uncertainty:

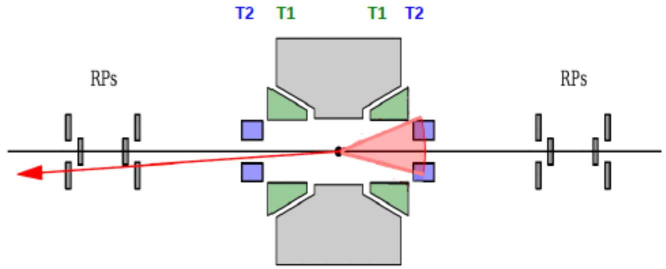
- B ~ 15 %, σ ~ 20 %

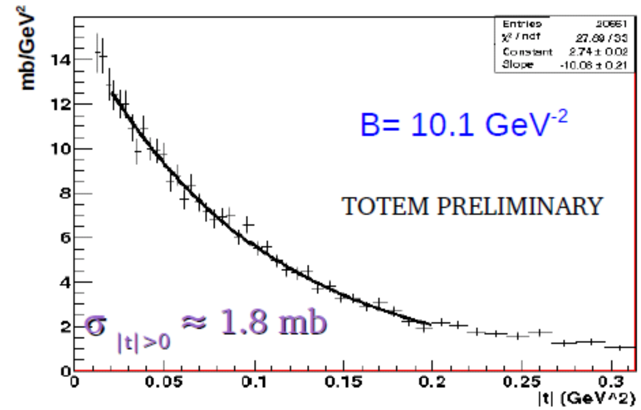
Very preliminary result:

- **σ_{SD} = 6.5 ± 1.3 mb**
- 3.4 < M_{SD} < 1100 GeV
- Very-high masses: ongoing

Low Mass

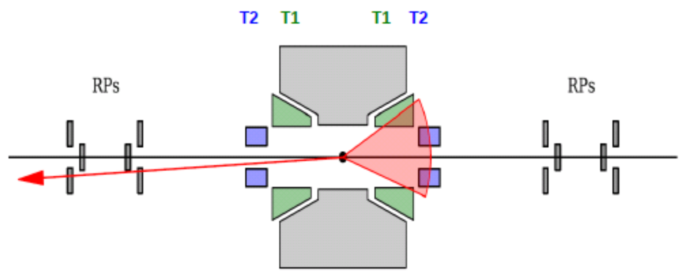
M=3.4 - 7 GeV

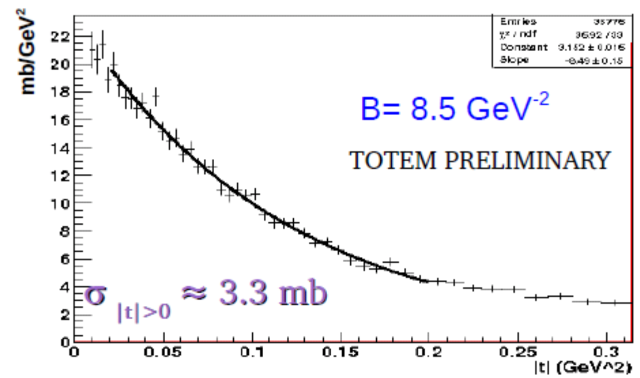




Medium Mass

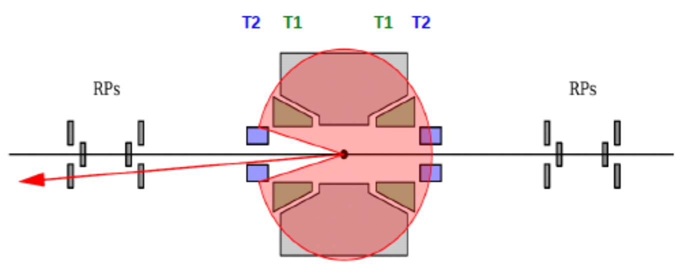
M=7 - 350 GeV

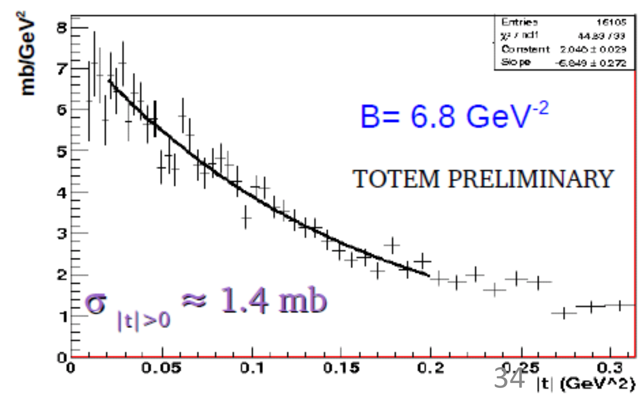




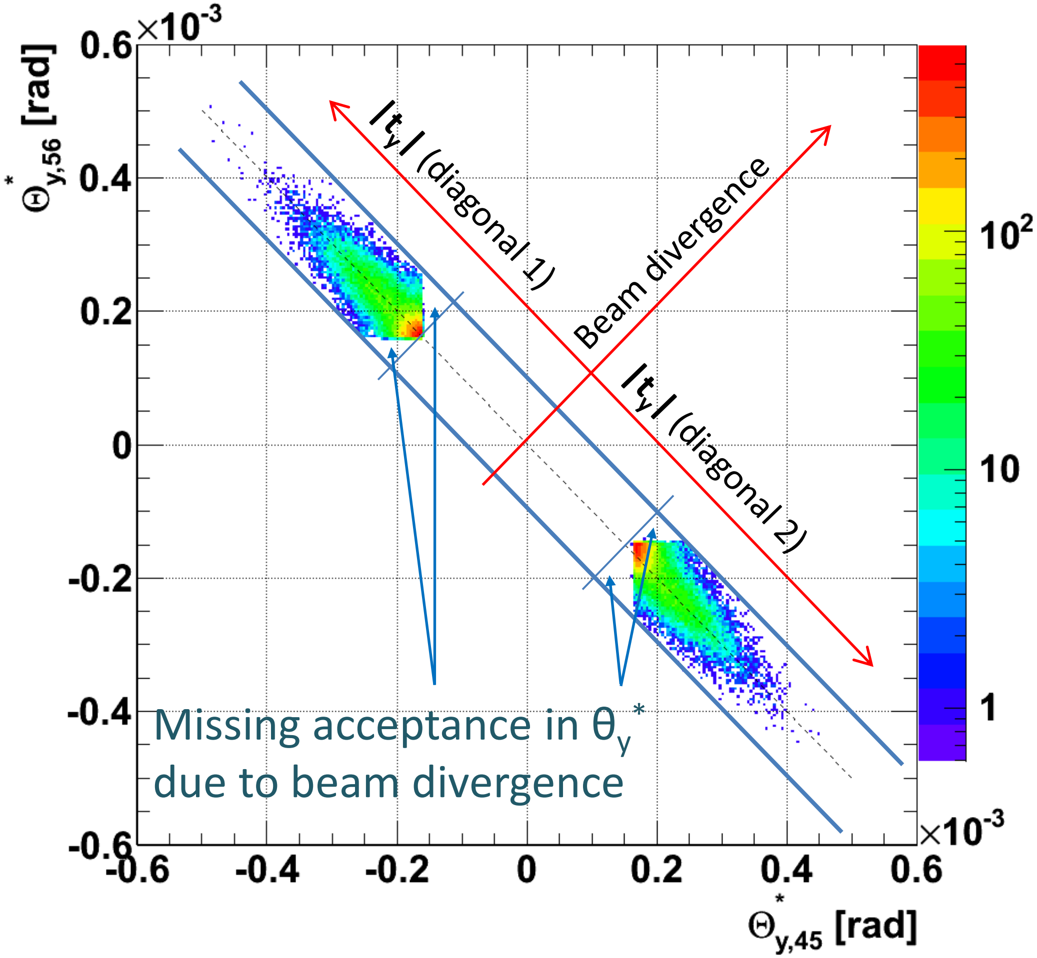
High Mass

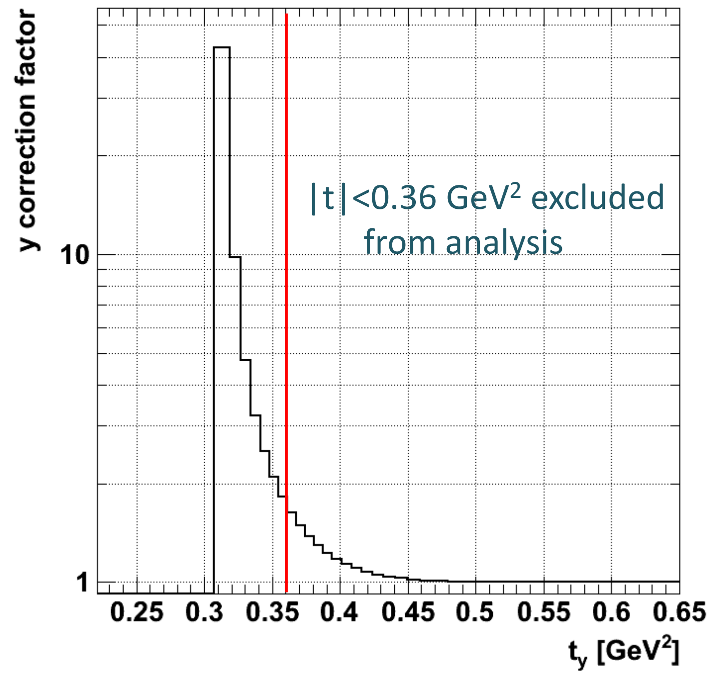
M=0.35 - 1.1 TeV





t_y-acceptance corrections





Correction error (t_y):

0.31 GeV^2 : 30%

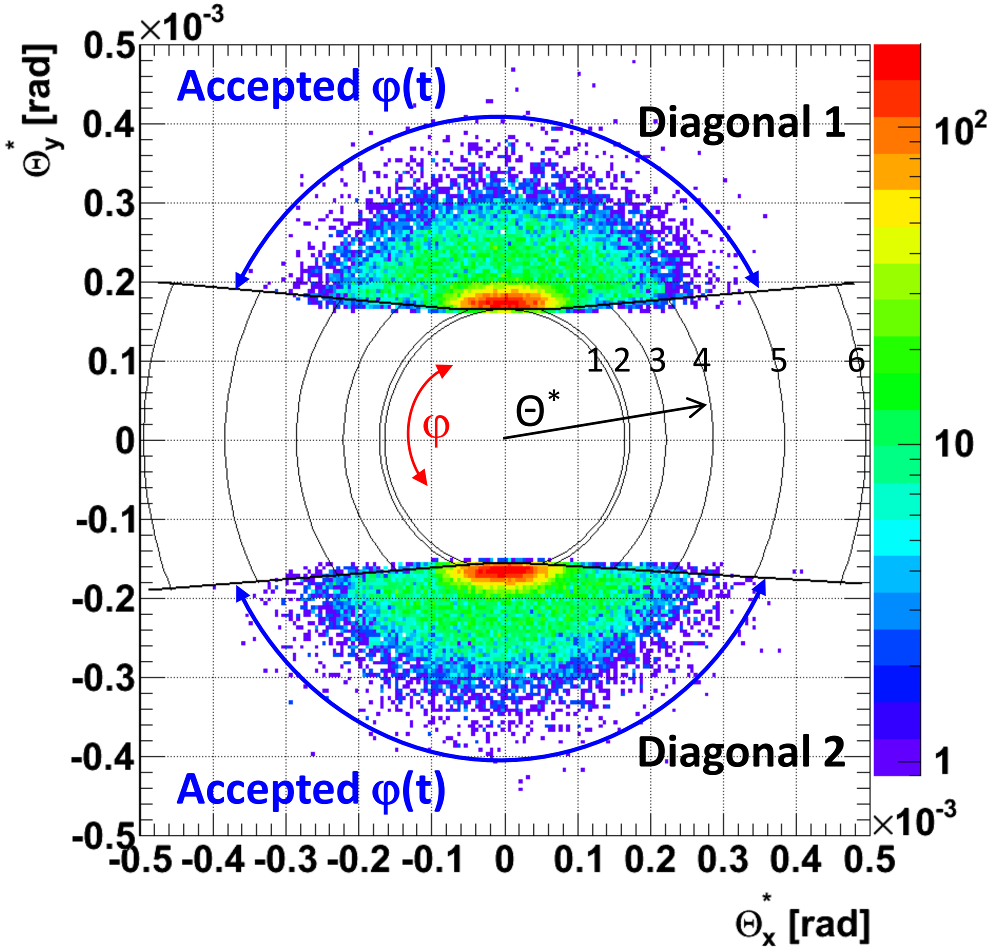
0.33 GeV^2 : 11%

0.35 GeV^2 : 2%

0.4 GeV^2 : 0.8%

0.5 GeV^2 : 0.1%

φ-acceptance corrections



Critical at low t-acceptance limit

Total φ-acceptance correction

No.	t [GeV²]	Θ* [rad]	Accepted φ (2 diag.) [°]	φ accept. correct. factor
1	**0.33**	1.65E-04	38.6	**9.3±4.7%**
2	**0.36**	1.71E-04	76.4	**4.7±1.8%**
3	**0.60**	2.21E-04	162.5	**2.2±0.3%**
4	**1.00**	2.86E-04	209.8	**1.7±0.1%**
5	**1.80**	3.83E-04	246.3	**1.5**
6	**3.00**	4.95E-04	269.0	**1.3**