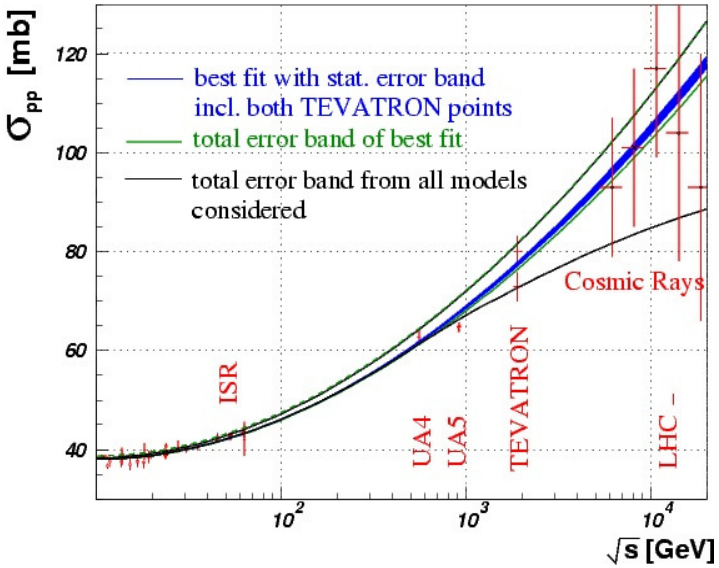
TOTEM status and results

Fabrizio Ferro (INFN – Genova)

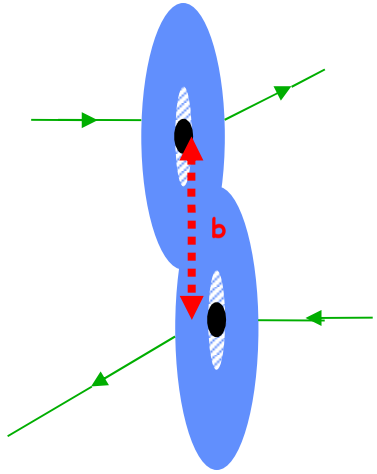
On behalf of the TOTEM Collaboration

TOTEM physics

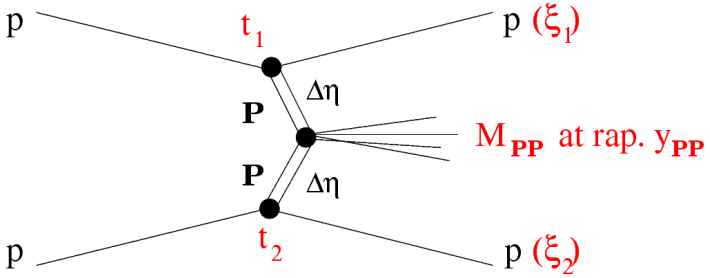
Total p-p cross section



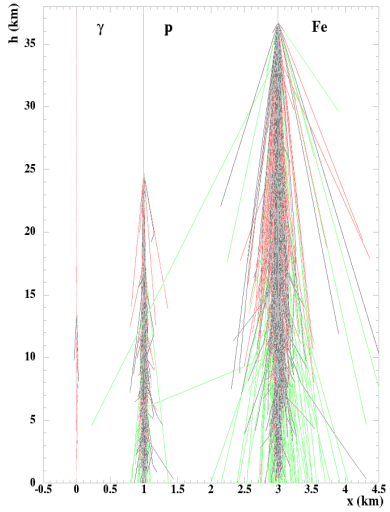
Elastic scattering



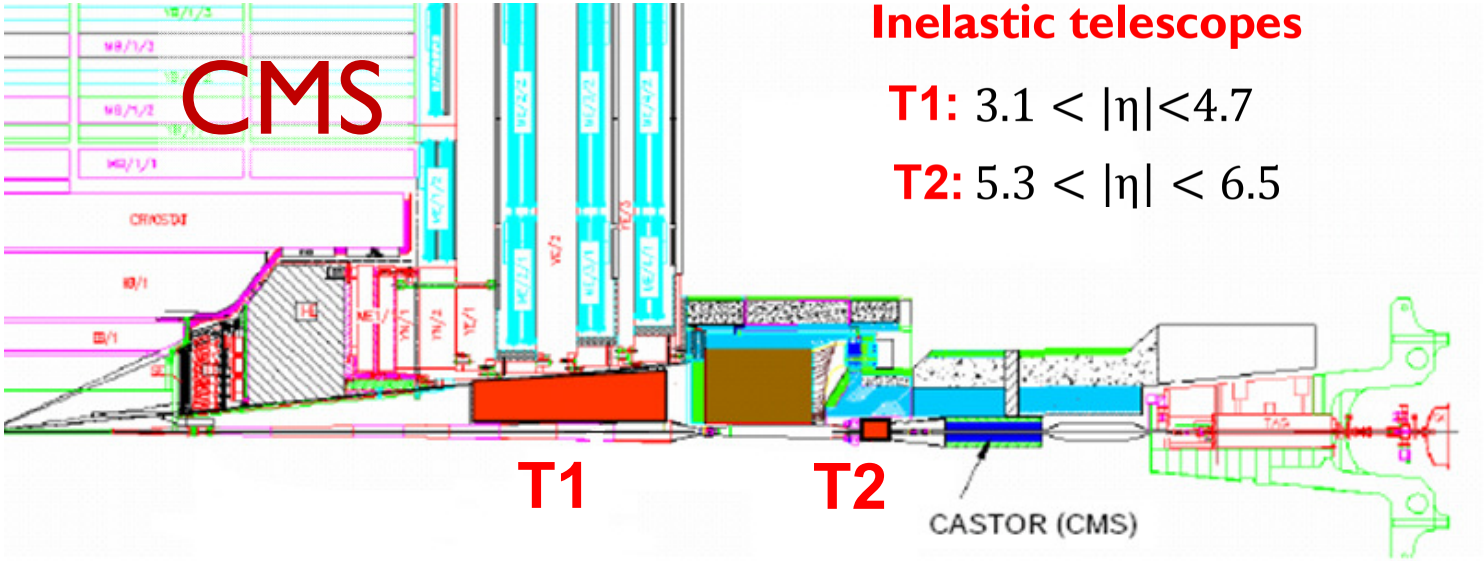
Diffraction

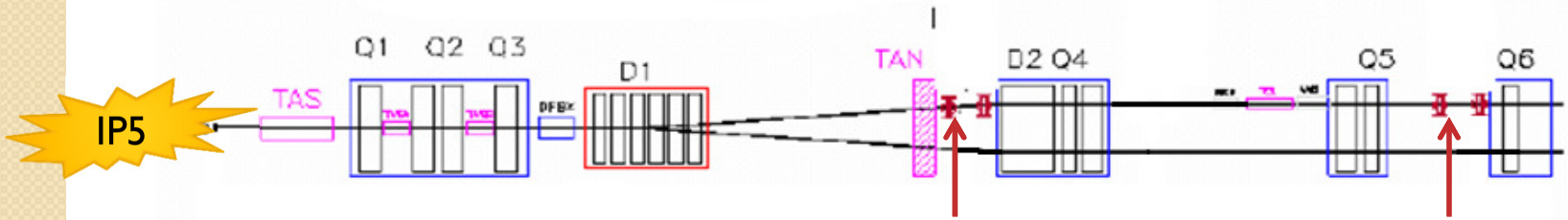


Forward particle production



TOTEM detectors





Roman Pots
(inside LHC tunnel)

RP (147m)

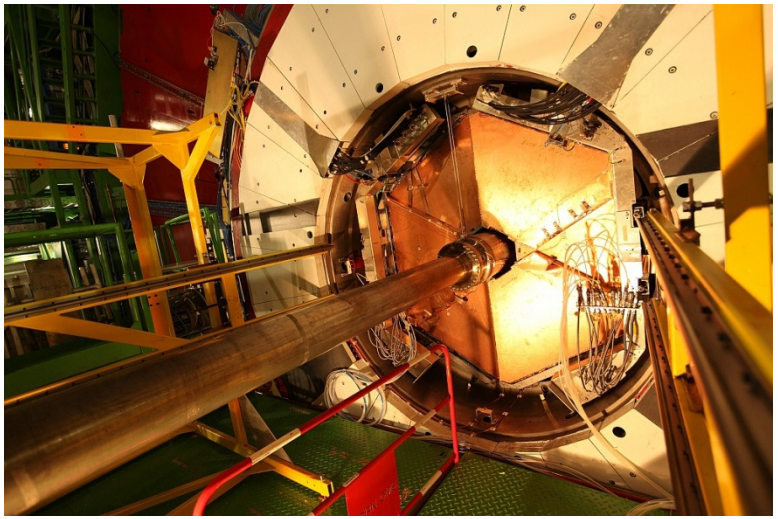
RP (220m)

Inelastic telescopes

Inelastic event counting, charged multiplicity, rapidity gaps

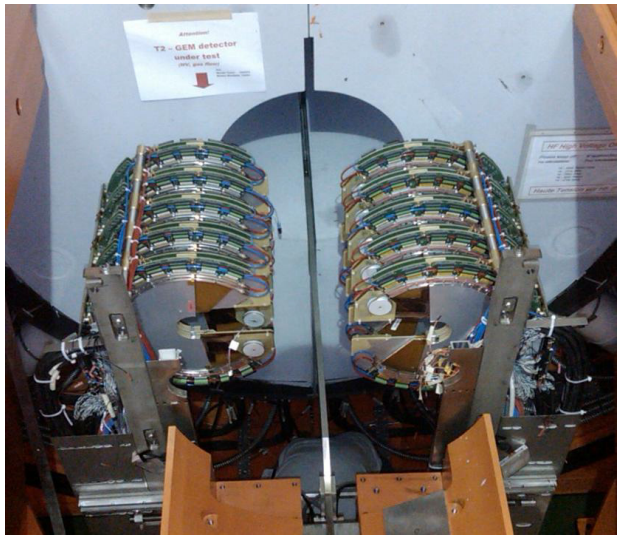
T1

- 5 planes of Cathode Strip Chambers (CSC)
- 6 chambers per plane
- $3.1<|\eta|<4.7$
- $\Delta\phi = 2\pi$



T2

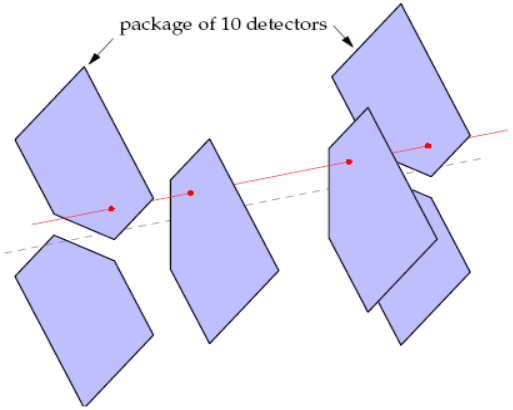
- 10 planes of Gas Electron Multipliers (GEM)
- $5.3<|\eta|<6.5$
- $\Delta\phi = 2\pi$



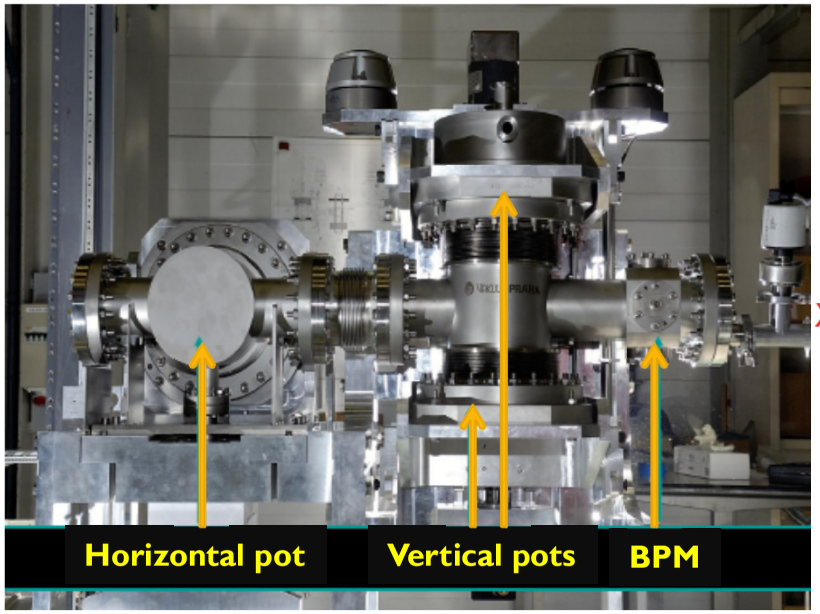
Roman pot detectors

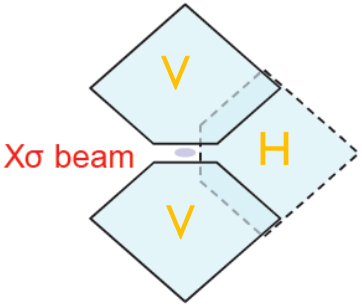
Leading proton detection

- Roman pot stations in the LHC tunnel at 147m and 220m from IP (both sides)
- 10 *edgeless* (<50μm) Si micro strip detectors per pot
- Resolution ~15μm

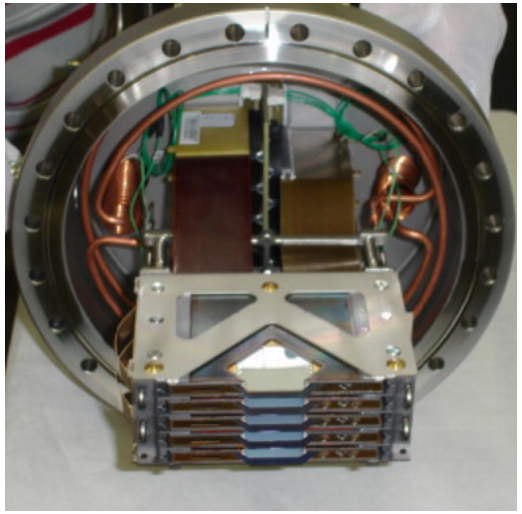


Roman pot unit





10 *edgeless* Si detectors

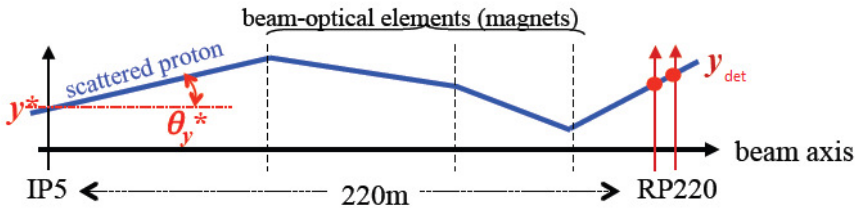


Beam optics and proton transport

(x^*, y^*): vertex position

(θ_x^*, θ_y^*): emission angle: $t \approx -p^2 (\theta_x^{*2} + \theta_y^{*2})$

$\xi = \Delta p/p$: momentum loss (diffraction)



$$y_{det} = L_y \theta_y^* + v_y y^*$$

$\beta^* = 90$ m: $L_y = 263$ m, $v_y \approx 0$

$\beta^* = 3.5$ m: $L_y \sim 20$ m, $v_y = 4.3$

→ Reconstruct via track positions

$$x_{det} = L_x \theta_x^* + v_x x^* + \cancel{D\xi}$$

Elastic: $\xi = 0$

$\beta^* = 90$ m: $L_x \approx 0$, $v_x = -1.9$

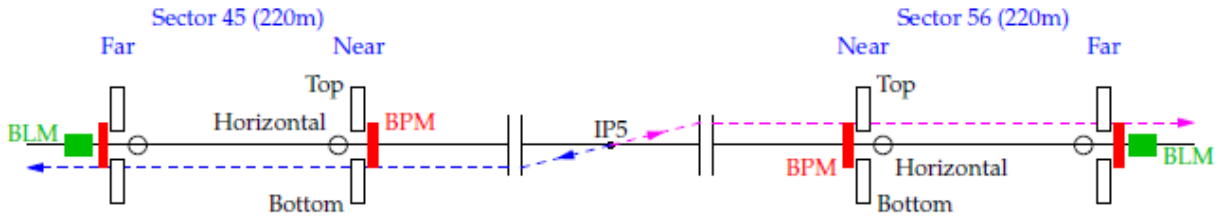
$\beta^* = 3.5$ m: $L_x \approx 0$, $v_x = 3.1$

→ Use derivative (reconstruct via local track angles):

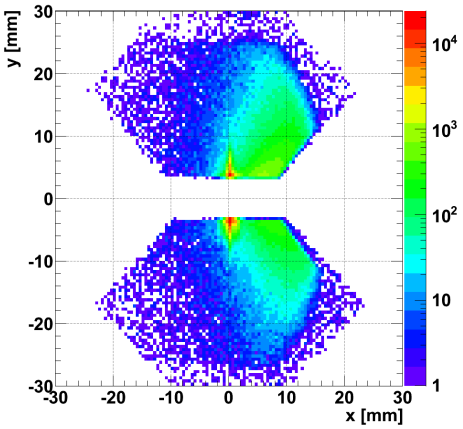
$$\frac{dx_{det}}{ds} = \frac{dL_x}{ds}\theta_x^* + \frac{dv_x}{ds}x^*$$

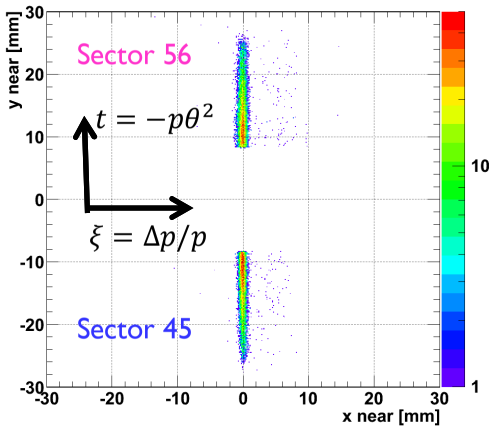
		Beam width @ vertex $\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}}$	Angular beam divergence $\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n}{\beta^* \gamma}}$	Min. reachable |t| $\lvert t_{min}\rvert = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$
Standard optics	$\beta^* \sim 1$–3.5 m	$\sigma_{x,y}^*$ small	$\sigma(\theta_{x,y}^*)$ large	$\lvert t_{min}\rvert \sim 0.3$–$1$ GeV^2
Special optics	$\beta^* = 90$ m	$\sigma_{x,y}^*$ large	$\sigma(\theta_{x,y}^*)$ small	$\lvert t_{min}\rvert \sim 10^{-2}$ GeV^2

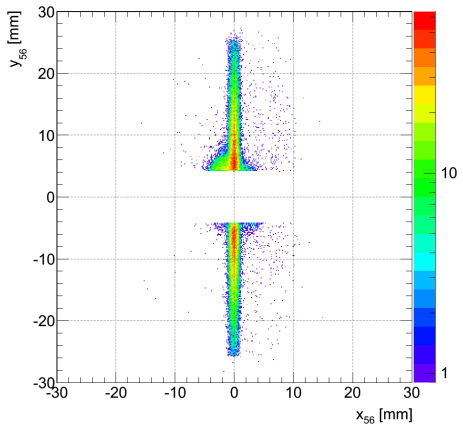
Elastic scattering: proton tracks



Left-right coincidence







$\beta^* = 3.5$ m
Roman pots at 7 σ_{beam}
$\int L \sim 6.2$ nb^{-1}

$d\sigma/dt$ in $0.36<|t|<2.5$ GeV^2

$\beta^* = 90$ m
Roman pots at 10 σ_{beam}
$\int L \sim 1.65$ μb^{-1}

$d\sigma/dt$ for $|t|>0.02$ GeV^2

$\beta^* = 90$ m
Roman pots at 6.5, 5.5, 4.8 σ_{beam}
$\int L \sim 83$ μb^{-1}

$d\sigma/dt$ for $|t|>7\cdot10^{-3}$ GeV^2

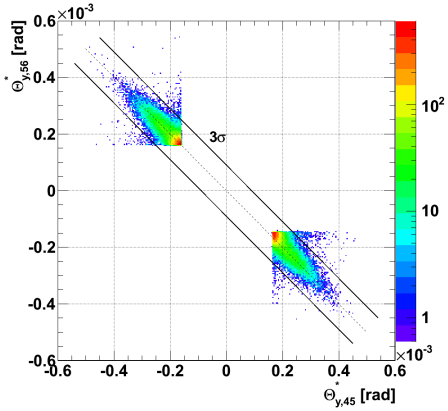
Several data sets with different running conditions:

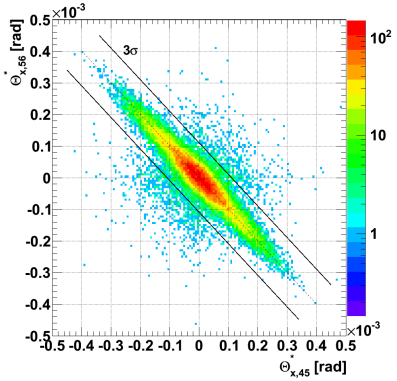
- measurement of $d\sigma/dt$ in a wide t range
- measurement of the elastic peak at very low t

Elastic scattering analysis: an overview

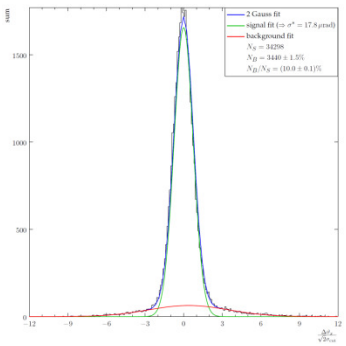
Low ξ selection: $|x|<3\sigma_x$ at $L_x=0$ ($x=L_x\Theta_x+\xi D+v_x x^*$)

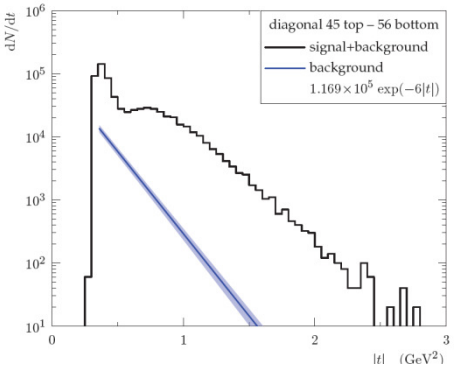
Collinearity cuts



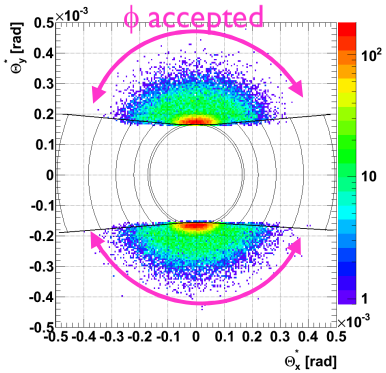


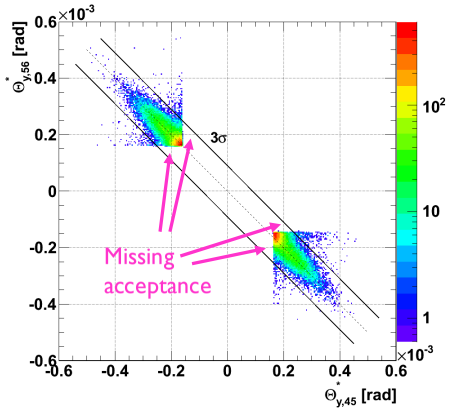
Background subtraction





Acceptance corrections

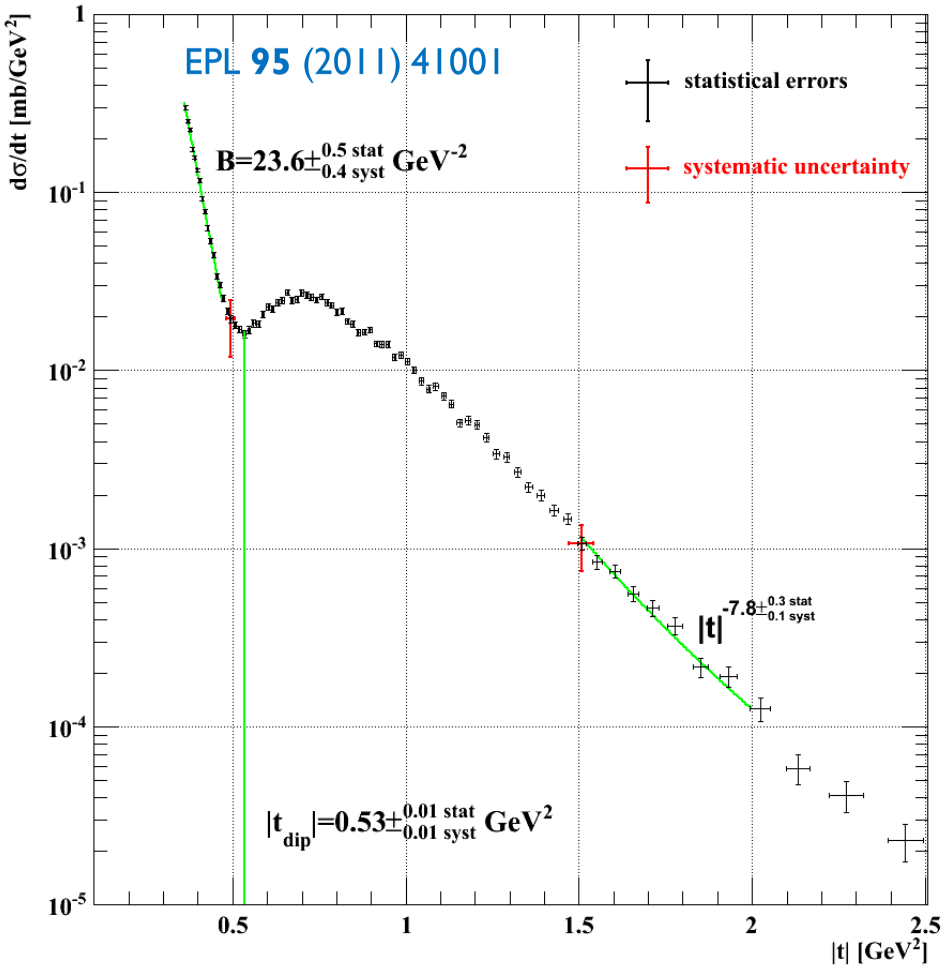


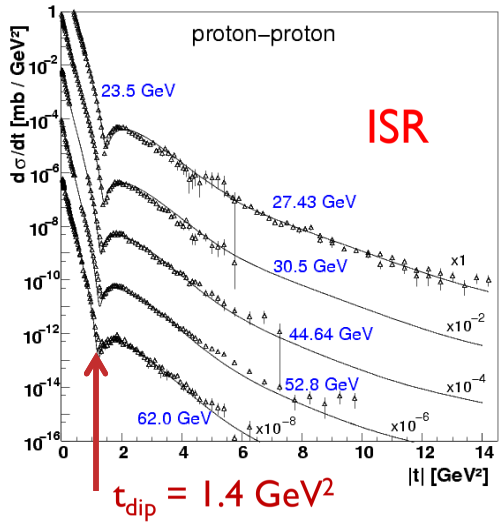


Elastic scattering: $d\sigma_{el}/dt$

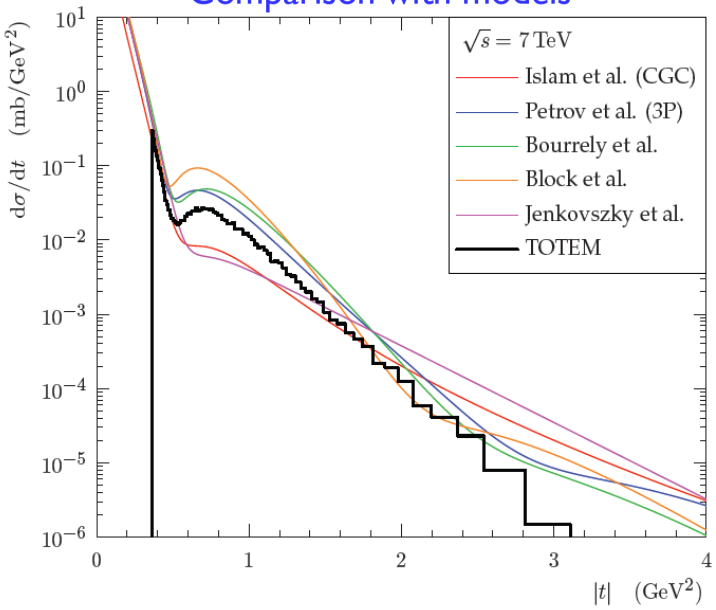
$0.36<|t|<2.5\ GeV^2$

$\sqrt{s} = 7\ TeV$



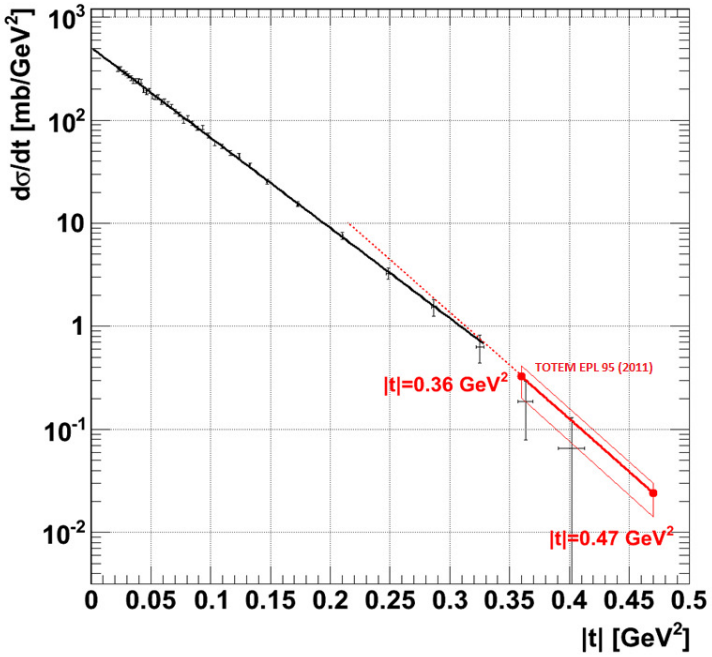


Comparison with models



Elastic scattering: $d\sigma_{el}/dt$

0.02<|t|<0.33 GeV^2



Luminosity provided by CMS

$$\frac{d\sigma_{el}}{dt} \propto e^{-B|t|}$$

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

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

$$\sigma_{el} = 24.8 \pm 1.2\ mb$$

EPL **96** (2011) 21002

October 2011 data sets at β^*=90m

PRELIMINARY

t_{min} (GeV^2)	B (GeV^{-2})	$\left.\frac{d\sigma_{el}}{dt}\right\|_{t=0}$ (mb/Gev^2)	σ_{el}
$10.5\cdot10^{-3}$	$19.87\pm0.03^{(stat)}$	$504.0\pm1.1^{(stat)}$	25.34
$9\cdot10^{-3}$	$19.87\pm0.07^{(stat)}$	$501.5\pm2.7^{(stat)}$	25.18
$7\cdot10^{-3}$	$19.84\pm0.08^{(stat)}$	$502.0\pm2.9^{(stat)}$	25.31

Systematics:
~2% analysis
~4% luminosity

Inelastic cross section

Using T1 and T2 telescopes

Analysis

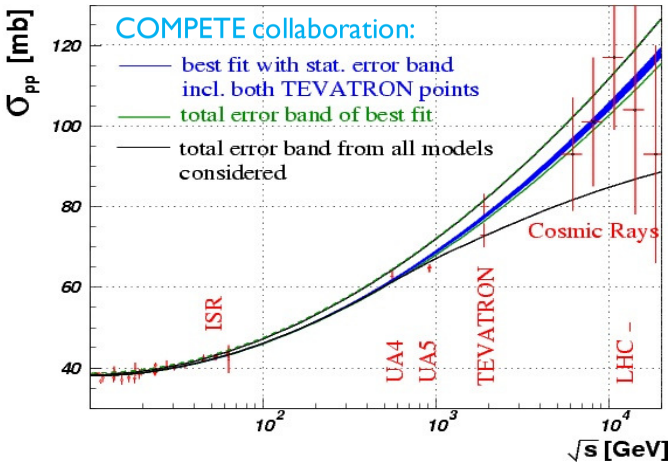
- Event classification (using T2)
  - tracks in both hemispheres (minimum bias + double diffraction)
  - tracks in one hemisphere only (mainly single diffraction with M_x>3.4 GeV/c^2)
- Corrections to T2 visible events
  - reconstruction efficiency (from data tuned MC) *~1%*
  - trigger efficiency (from BX triggered data) *~2.5%*
  - beam-gas background (from non-colliding bunches data) *~0.85%*
  - Pile-up *~1.5%*
- From T2 visible cross section to Inelastic cross section
  - measuring T1 only events (from BX triggered data) ~2%
  - estimating low diffractive mass events (from MC) ~4%

Luminosity provided by CMS

PRELIMINARY

$$\sigma_{inel} = 73.4 \pm 0.1^{(stat)} \pm 1.9^{(syst)} \pm 2.9^{(lumi)}\ mb$$

Total cross section: the methods



Optical theorem

$$\sigma_{tot} = \frac{8\pi}{k\sqrt{s}} \operatorname{Im} \mathcal{F}_{el}(s,t)\Big|_{t=0}$$

$$\varrho = \frac{Re\mathcal{F}_{el}}{Im\mathcal{F}_{el}}\Bigg|_{t=0} = 0.14^{+0.01}_{-0.08}$$

Total cross section measurement: 4 methods

1. (*low*) Luminosity + Elastic scattering + Optical theorem
2. (*high*) Luminosity + Elastic scattering + Optical theorem

$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)} \frac{1}{L} \frac{dN_{el}}{dt}\Bigg|_{t=0}$$

3. (*high*) Luminosity + Elastic scattering + Inelastic scattering $\quad \sigma_{tot} = \sigma_{el} + \sigma_{inel}$

4. Elastic scattering + Inelastic scattering + Optical theorem $\quad \sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$

Luminosity independent

Total cross section: results

Total cross section measurement: 4 methods

1. (*low*) Luminosity + Elastic scattering + Optical theorem

$$\sigma_{tot} = 98.3 \pm^{2.2}_{2.0} mb$$

2. (*high*) Luminosity + Elastic scattering + Optical theorem

$$\sigma_{tot} = 98.2 \pm^{2.4}_{2.2} mb$$

3. (*high*) Luminosity + Elastic scattering + Inelastic scattering

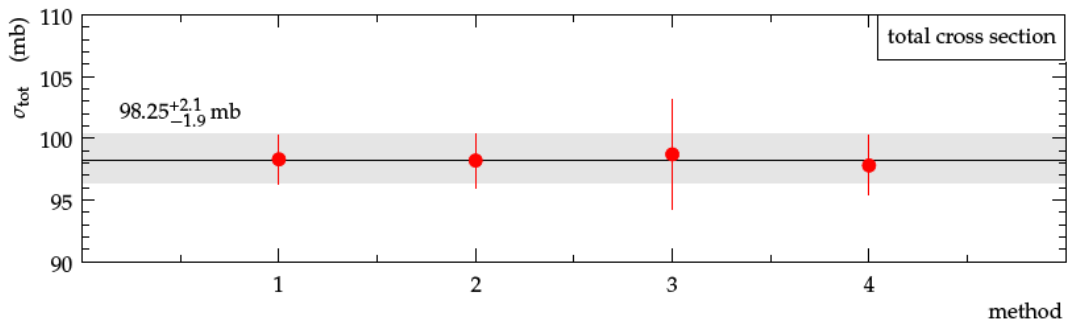
$$\sigma_{tot} = 98.7 \pm 4.4\, mb$$

4. Elastic scattering + Inelastic scattering + Optical theorem

$$\sigma_{tot} = 97.8 \pm^{2.9}_{2.4} mb$$

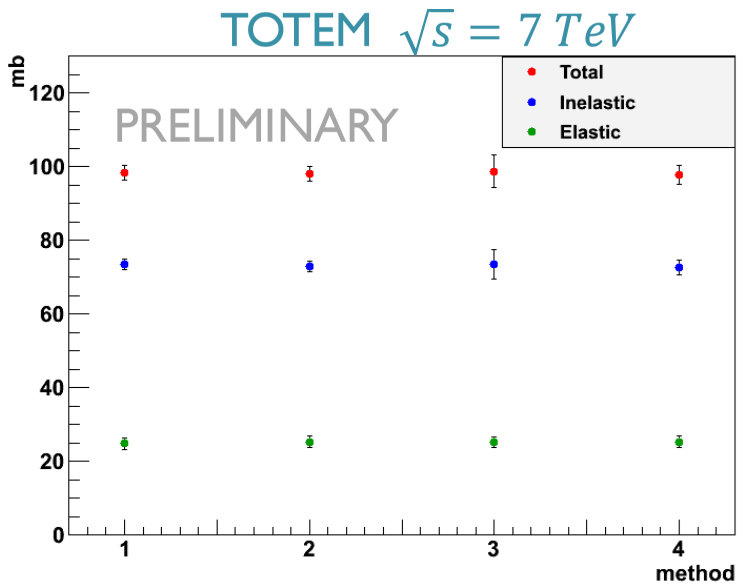
PRELIMINARY

internal review in progress

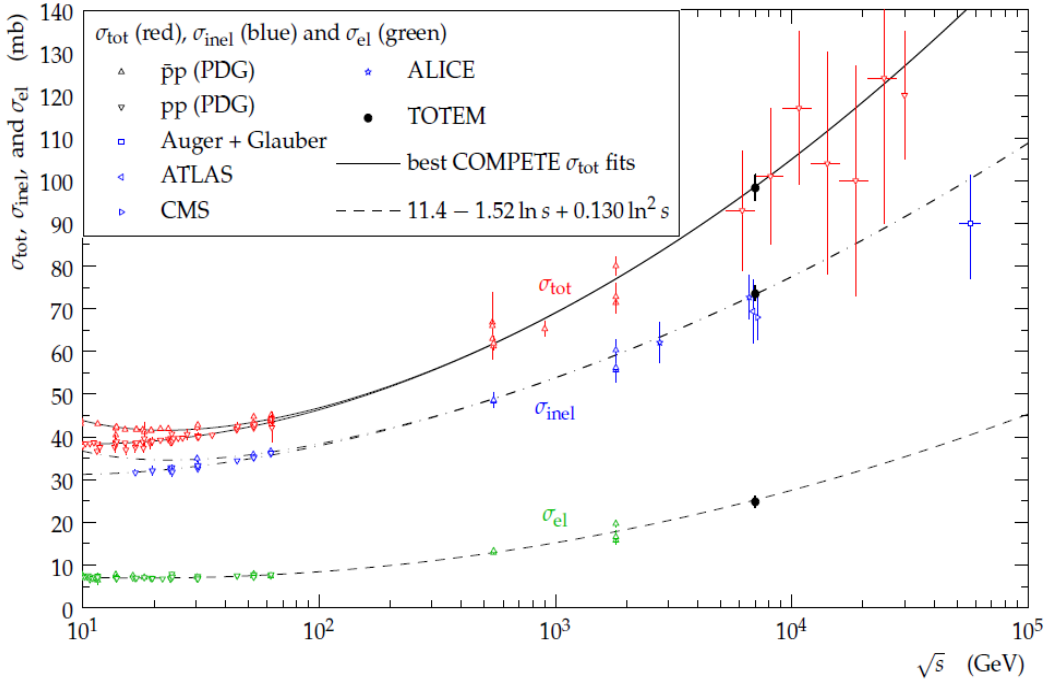


Cross sections

Total, elastic and inelastic cross sections well constrained by the 4 methods



TOTEM results in agreement with COMPETE predictions



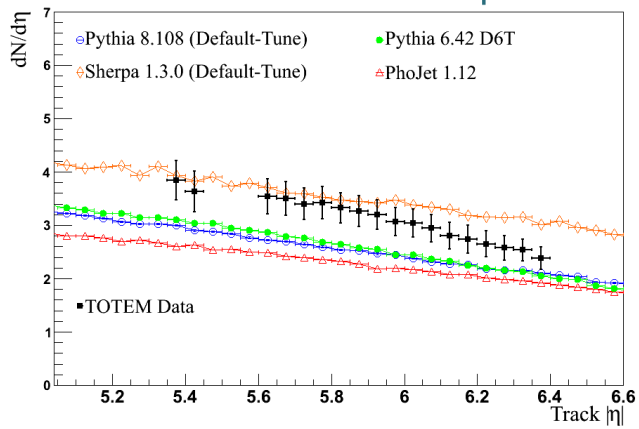
Forward charged multiplicity

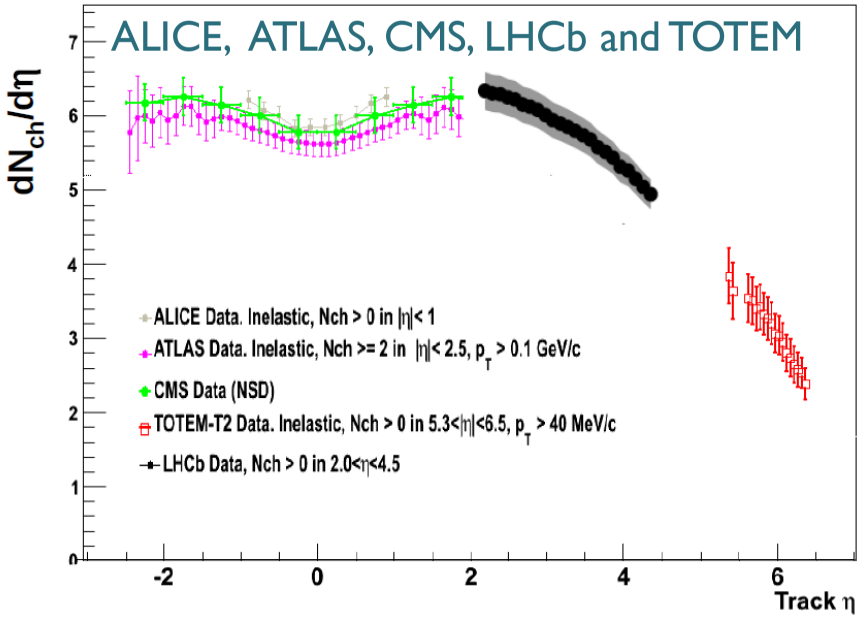
$\frac{dN_{ch}}{d\eta}$ in the pseudorapidity range $5.3 < |\eta| < 6.5$ using T2 telescope

EPL **98** (2012) 31004

- Low luminosity/low pile up data sets
- Full control of primary-secondary particles separation
- Measurement done separately on the 4 T2 quarters and then combined

Data vs Monte Carlo comparison

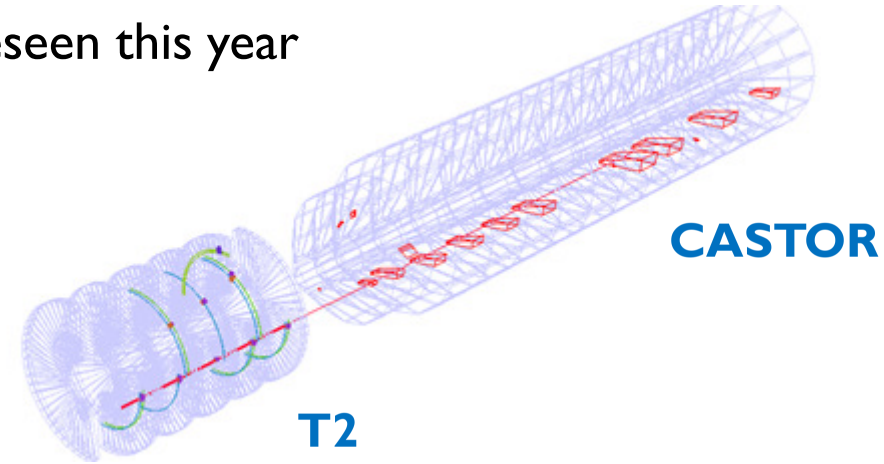




CMS + TOTEM

detector with the largest acceptance

- Successful common runs to prove trigger exchange and data combination
  - PbPb runs in 2011
  - p-p runs last April and May
- A common working group to share the effort of combining data
- Main physics goals
  - multiplicity distributions and correlations
  - rapidity gap studies
  - diffractive jet production (protons in RPs + jets in CMS)
- More common runs foreseen this year



Summary and outlook

- TOTEM has measured:
  - the total, elastic and inelastic p-p cross section at 7 TeV
  - the elastic differential cross section in the range $7 \cdot 10^{-3} < |t| < 2.5$ GeV^2
  - the charged multiplicity in the range $5.3 < |\eta| < 6.5$
- Newest results to be published soon
- More analyses ongoing (e.g. charged multiplicity in T1, study of single, double, central diffractive processes,...)
- Plans for this year
  - measure the total, elastic and inelastic cross section at 8 TeV using β^*=90m runs
  - carry on the common CMS-TOTEM physics program both in special and standard optics runs
  - measure very low-t elastic scattering and determine ρ if β^*~500m optics available (necessary to have access to the Coulomb-Nuclear interference region)

Back up slides

Results:

Elastic cross-section
Inelastic cross-section

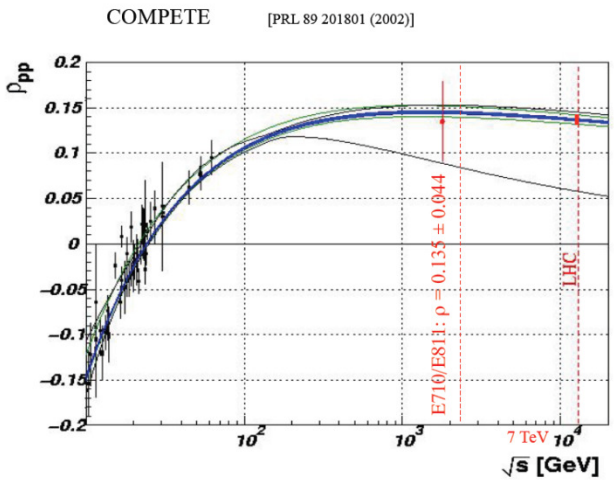
Total cross-section via elastic & Optical Point (ref. LHCC method 2)
Total cross-section via sum elastic + inelastic (ref. LHCC method 3)
Total cross-section via $\mathcal{L}$-independent method (ref. LHCC method 4)

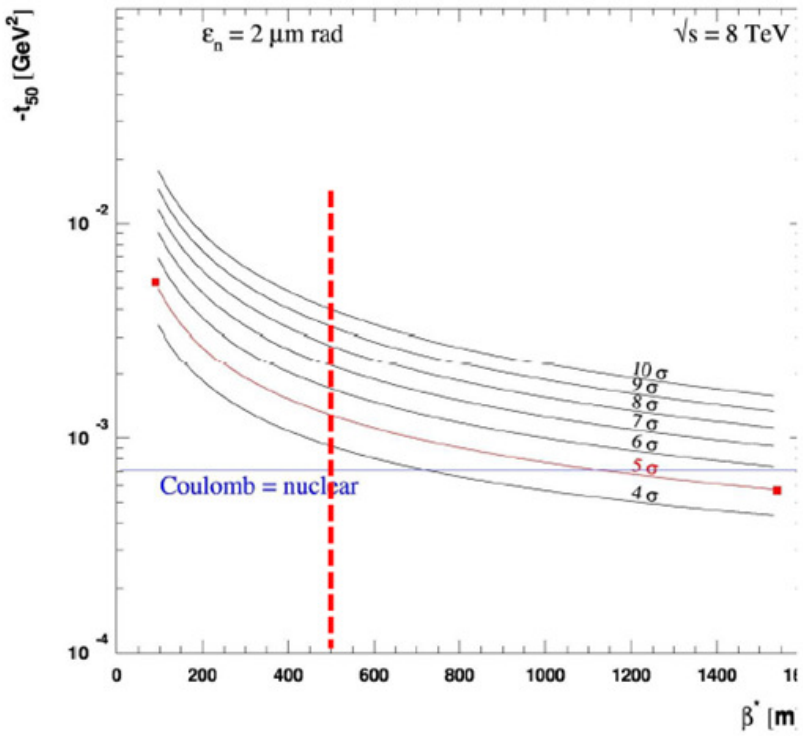
Elastic cross-section $\mathcal{L}$-independent
Inelastic cross-section $\mathcal{L}$-independent
Ratio elastic / inelastic $\mathcal{L}$-independent and ρ-independent

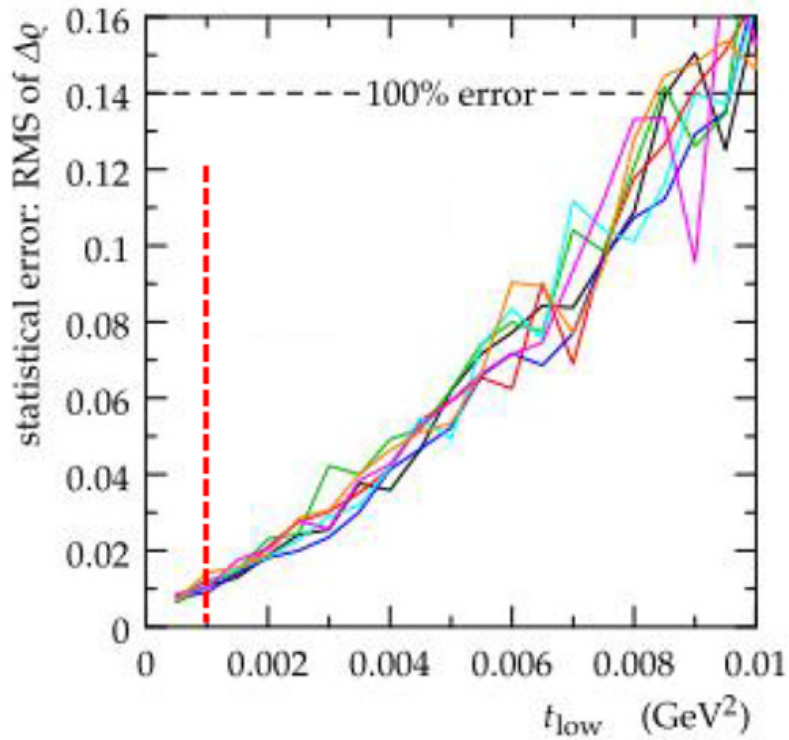
Luminosity calibration June runs
Luminosity calibration October runs

Upper limit of inclusive low mass diffraction for $\eta > 6.5$ ($M_x < \sim 3$GeV)

ρ







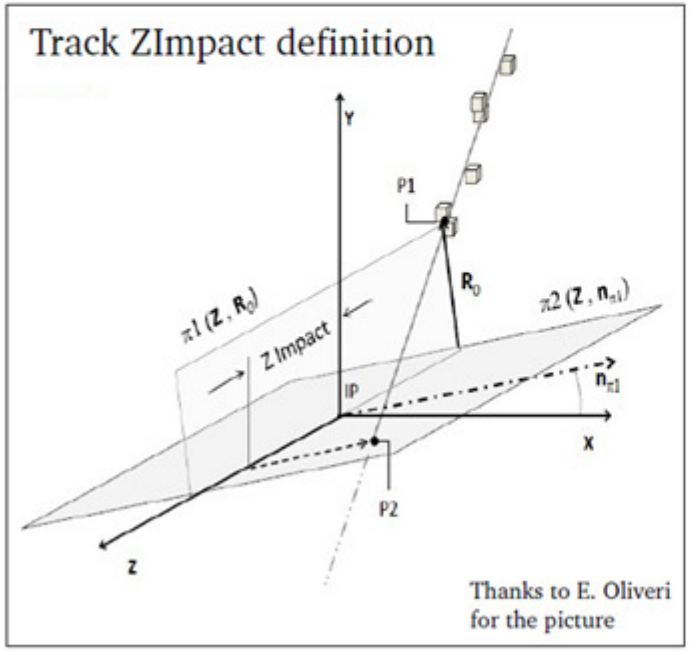
~10-15 % measurement of ρ with β* ≈ 500 m, RP@5σ at √s = 8 TeV

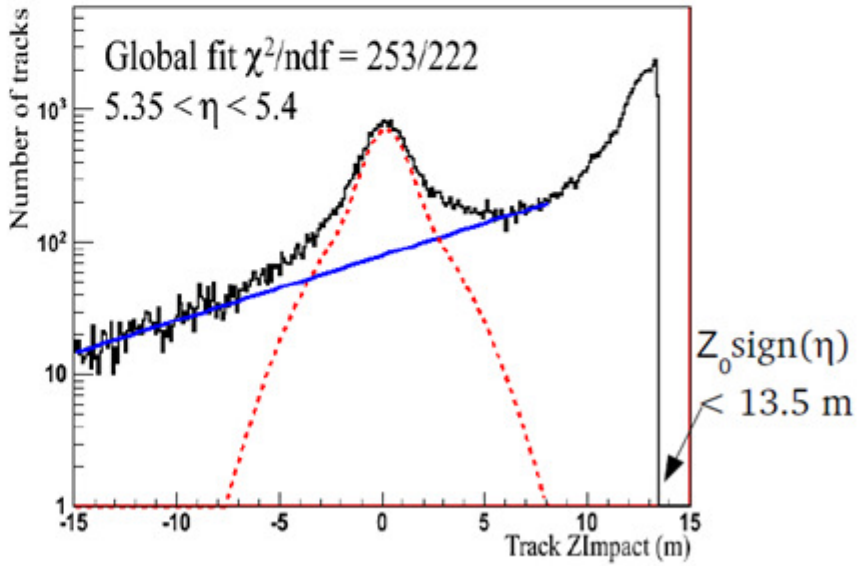
T2

Analysis procedure: primary track selection.

•A cut on the Zimpact parameter has been used to select primary tracks.

•We know from MC and data comparison, the shape of the primary and secondary track Zimpact distribution (double-gaussian for primaries, exponential for secondaries).





•A large part of the secondary can be therefore extracted from the primary region by fitting the track-ZImpact distribution. The fit is repeated for each η bin.

Elastic scattering systematics

Correction	Effect on	Functional form	Total values or integral	Details
Recorded Luminosity	$d\sigma/dt$	const(t) mult. factor	Efficiency-corrected int. Luminosity $(6.03 \pm 0.36)\,\mathrm{nb}^{-1}$	Int. Luminosity $(6.1 \pm 0.2)\mathrm{nb}^{-1}$ Trigger eff. $(99 \pm 1)\,\%$ DAQ eff. $(99 \pm 1)\,\%$
Inefficiency	$d\sigma/dt$	Ineff. = const(t) mult. corr. factor = (1 + ineff.)	Tot. ineff. = $(30 \pm 10)\%$	Detector 1% Event reconstruction $(29 \pm 10)\%$
Acceptance	$d\sigma/dt$	Hyperbola function: $f_A \approx 1.3 + \frac{0.3}{(\lvert t\rvert - 0.3)}$ mult. corr. factor	$f_A = \begin{cases} 4.96 \pm 0.05\lvert_{\lvert t\rvert=0.4\,\mathrm{GeV}^2} \\ 2.92 \pm 0.03\lvert_{\lvert t\rvert=0.5\,\mathrm{GeV}^2} \\ 1.55 \pm 0.02\lvert_{\lvert t\rvert=1.5\,\mathrm{GeV}^2} \end{cases}$	y: $2.2\lvert_{\lvert t\rvert=0.36\,\mathrm{GeV}^2}$, $1.5\lvert_{\lvert t\rvert=0.4\,\mathrm{GeV}^2}$, $1.1\lvert_{\lvert t\rvert=0.5\,\mathrm{GeV}^2}$, $1.0\lvert_{\lvert t\rvert=1.5\,\mathrm{GeV}^2}$ ϕ: $4.5\lvert_{\lvert t\rvert=0.36\,\mathrm{GeV}^2}$, $3.5\lvert_{\lvert t\rvert=0.4\,\mathrm{GeV}^2}$, $2.6\lvert_{\lvert t\rvert=0.5\,\mathrm{GeV}^2}$, $1.5\lvert_{\lvert t\rvert=1.5\,\mathrm{GeV}^2}$
Background	$d\sigma/dt$	Parameterisation bkg. $= 1.16e^{-6.0\lvert t\rvert}$ mult. corr. factor $= (1 - \frac{\mathrm{bkg.}}{\mathrm{total}})$	$\frac{\int \mathrm{bkg.}\,dt}{\mathrm{total}} = (8 \pm 1)\%$	$\frac{\mathrm{bkg.}}{\mathrm{total}} = \begin{cases} (11 \pm 2)\%\lvert_{\lvert t\rvert=0.4\mathrm{GeV}^2} \\ (19 \pm 3)\%\lvert_{\lvert t\rvert=0.5\mathrm{GeV}^2} \\ (0.8 \pm 0.3)\%\lvert_{\lvert t\rvert=1.5\mathrm{GeV}^2} \end{cases}$
Resolution unfolding	$t \to d\sigma/dt$	$f_u(\Theta^*) = \frac{\mathrm{unsmeared}}{\mathrm{measured}}$ mult. corr. factor	$f_u = \begin{cases} 0.55\ ^{+0.02}_{-0.09}\lvert_{\lvert t\rvert=0.36\mathrm{GeV}^2,\Theta=170\mu\mathrm{rad}} \\ 0.51\ ^{+0.02}_{-0.10}\lvert_{\lvert t\rvert=0.4\mathrm{GeV}^2,\Theta=181\mu\mathrm{rad}} \\ 0.54\ ^{+0.04}_{-0.15}\lvert_{\lvert t\rvert=0.5\mathrm{GeV}^2,\Theta=202\mu\mathrm{rad}} \\ 0.91\ ^{+0.10}_{-0.13}\lvert_{\lvert t\rvert=1.50\mathrm{GeV}^2,\Theta=350\mu\mathrm{rad}} \end{cases}$	Dominant contribution $\delta\Theta^* = \frac{\text{Beam divergence}}{\sqrt{2}} = 12\text{–}13\ \mu\mathrm{rad}$
Alignment	t	$\delta t_x = 2p/(\Delta s\, dL_x/ds)\sqrt{\lvert t_x\rvert}\,\delta x$ $\delta t_y = 2p/L_y\sqrt{\lvert t_y\rvert}\,\delta y$	$\delta t/t = 0.6\%\lvert_{\lvert t\rvert=0.4\mathrm{GeV}^2}$ $\delta t/t = 0.3\%\lvert_{\lvert t\rvert=1.5\mathrm{GeV}^2}$	Track based alignment for 2 mechanically constrained diagonals: $\delta x < 10\mu\mathrm{m}$; $\delta y = 10\mu\mathrm{m}$
Optics	t	$t_x = f(k, \psi, p)$; $t_y = f(k, \psi, p)$ k: magnet strength ψ: magnet rotation p: LHC beam momentum	$\frac{\delta(dL_x/ds)}{dL_x/ds} = 1\%$ $\frac{\delta L_y}{L_y} = 1.5\%$ $\frac{\delta t}{t} = 2\%$	$\frac{\delta k}{k} = 0.1\%$ $\delta\psi = 1\mathrm{mrad}$ $\frac{\delta p}{p} = 10^{-3}$