New measurements of forward physics in the TOTEM experiment at the LHC

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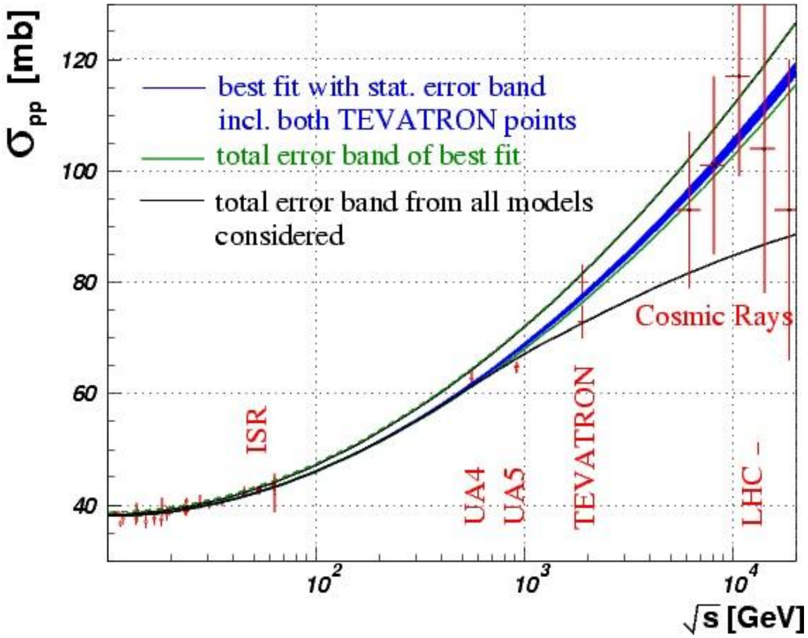
on behalf of the TOTEM Collaboration

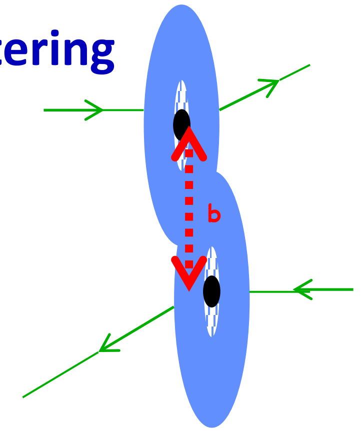
ICHEP 2012, 4-11 July 2012, Melbourne

TOTEM Physics Overview

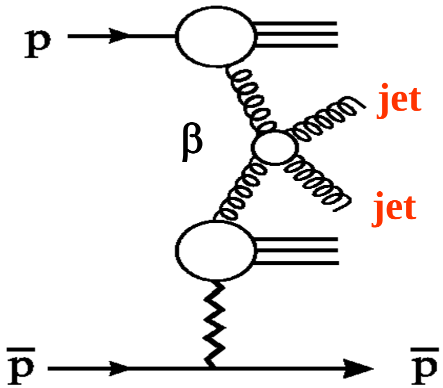
Total cross-section



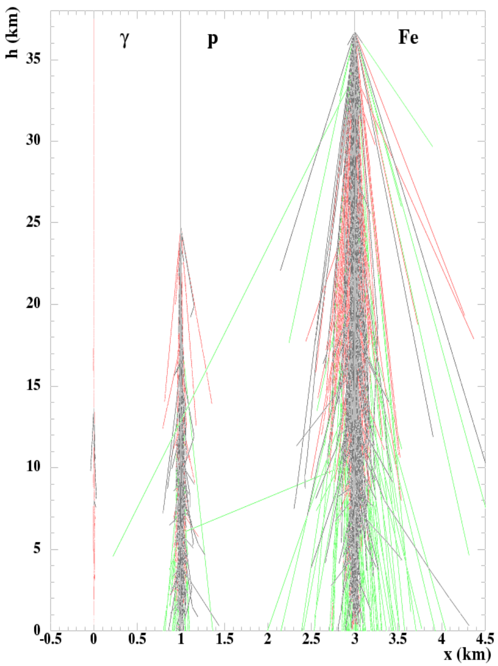
Elastic scattering



Soft and hard diffraction



Forward physics



TOTEM Setup in LHC IP5

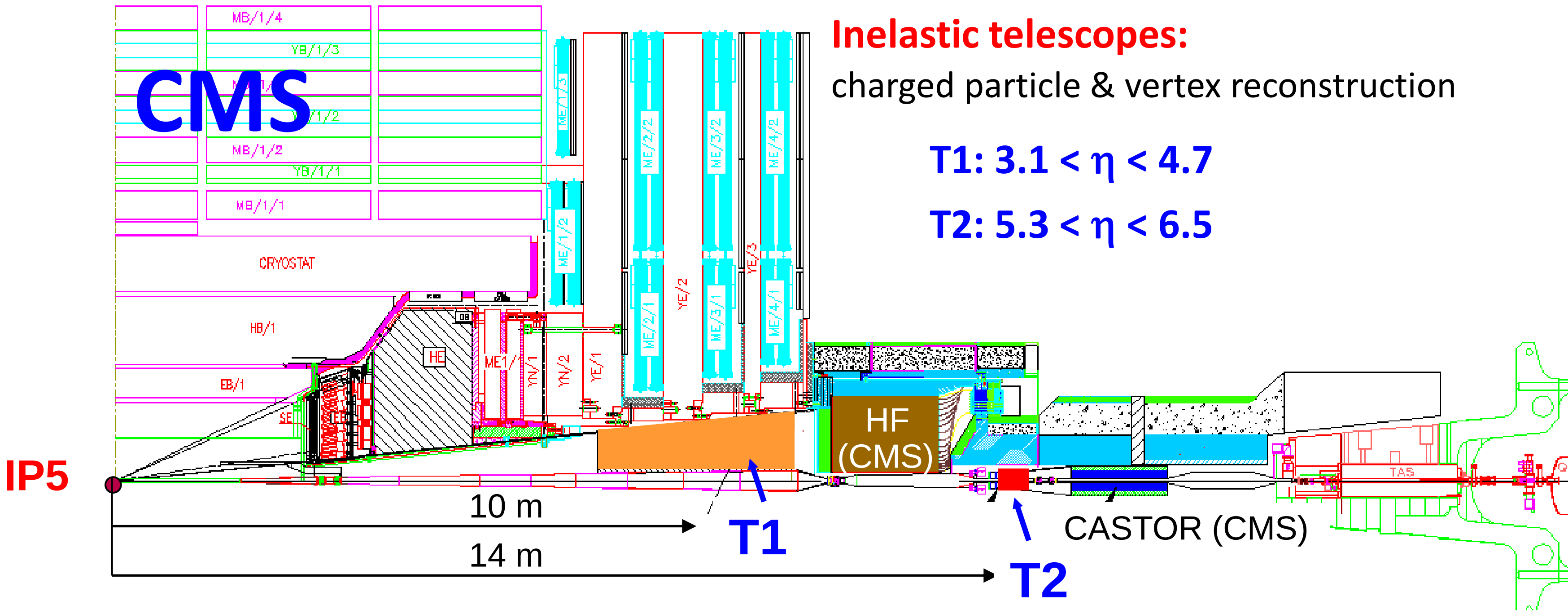
(together with CMS)

Inelastic telescopes:

charged particle & vertex reconstruction

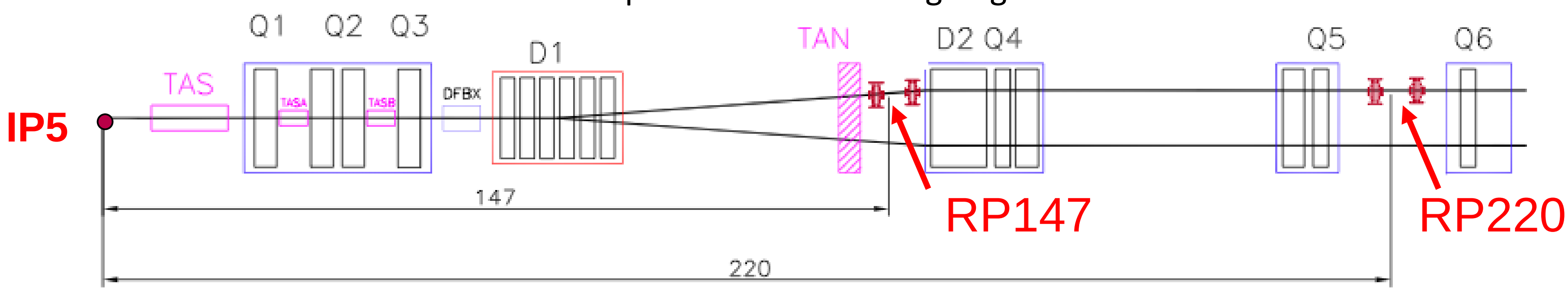
T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$

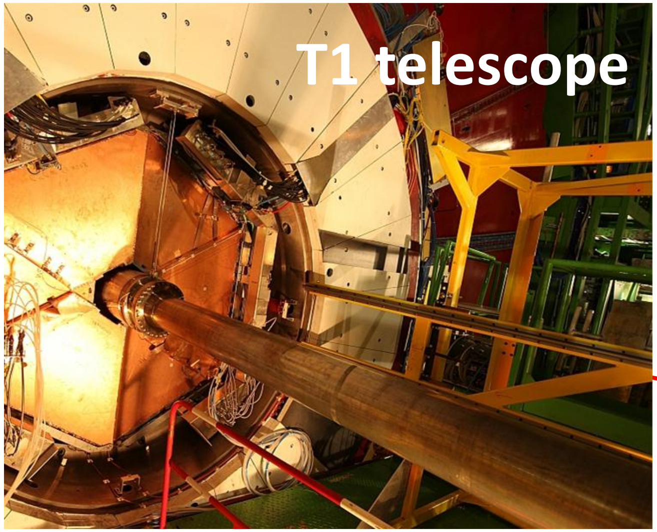


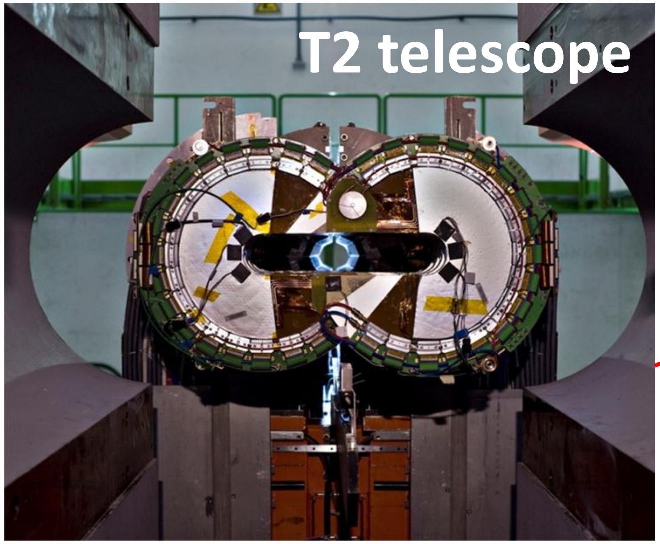
24 Roman Pots (on both sides of CMS):

measure elastic & diffractive protons close to outgoing beam



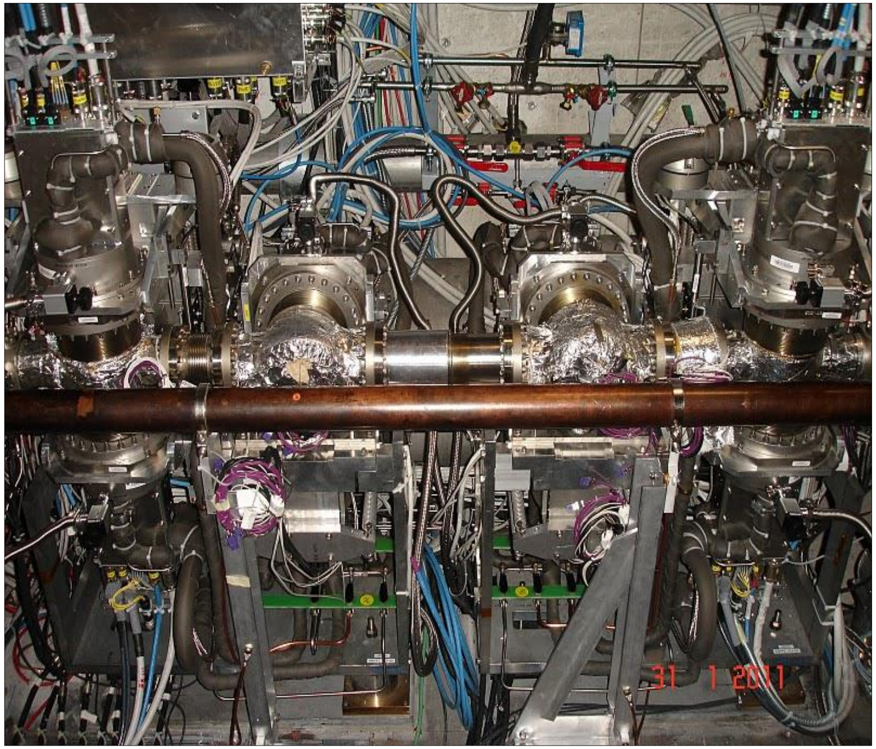
TOTEM inelastic telescopes

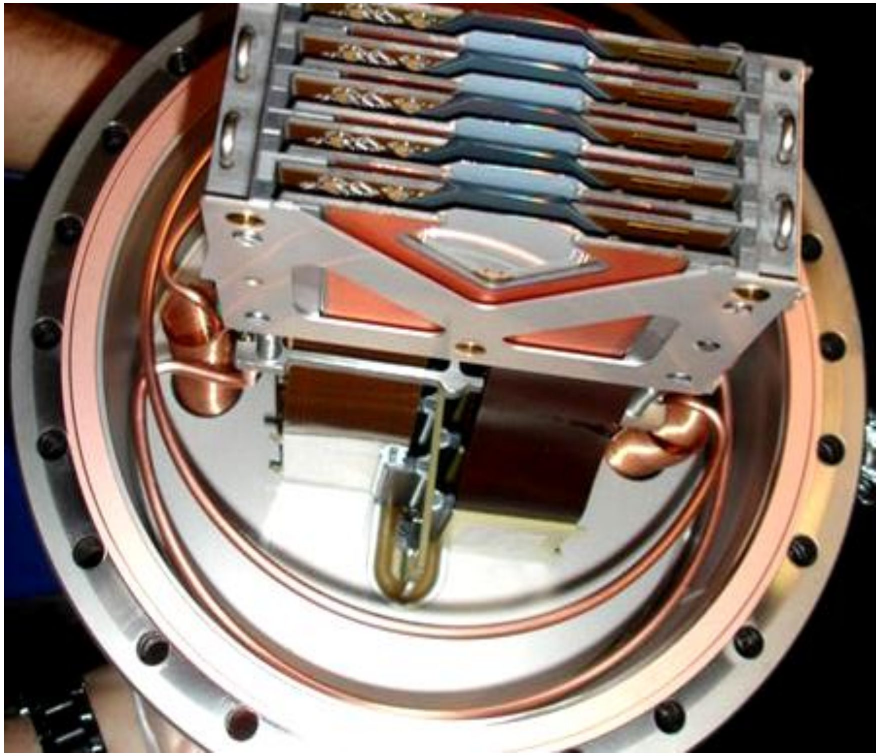




- charged particle detection
- vertex reconstruction
- trigger

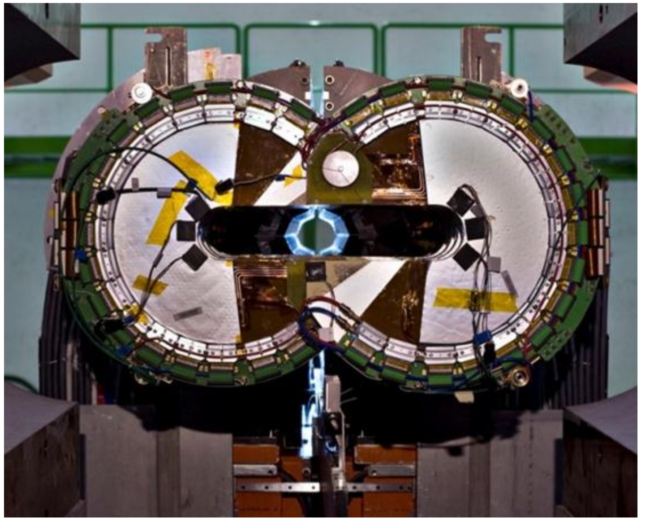
Roman Pot detectors





- detect protons scattered at Interaction Point 5
- near-beam movable devices
- equipped with edgeless silicon microstrip detectors
- resolution of ~16μm
- trigger capability with FPGA processing

T2 telescope:



Measurement of the forward charged particle density

$5.3 < \eta < 6.5$

$\sqrt{s} = 7\,\text{GeV}$

$dN_{ch}/d\eta$ in T2

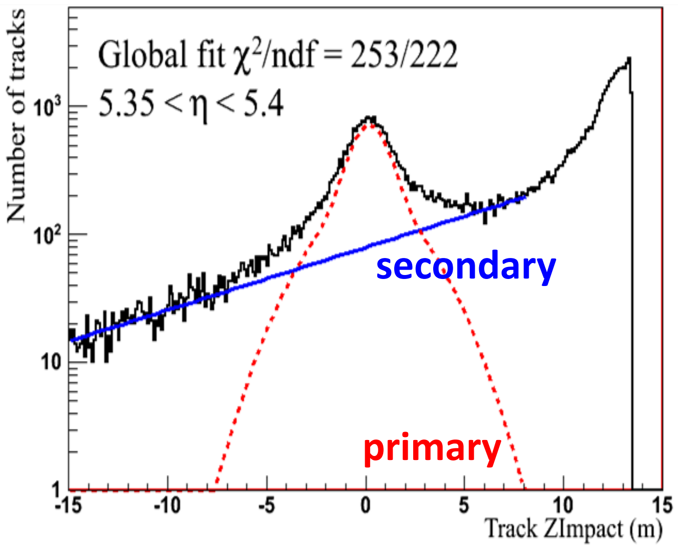
Data sample: events at low luminosity and low pile-up, triggered with T2

Selection: at least one track reconstructed

Primary particle definition: charged particle with $t > 0.3\times10^{-10}$ s & $p_t > 40$ MeV/c

Primary particle selection:

- primary/secondary discrimination with primary vertex reconstruction

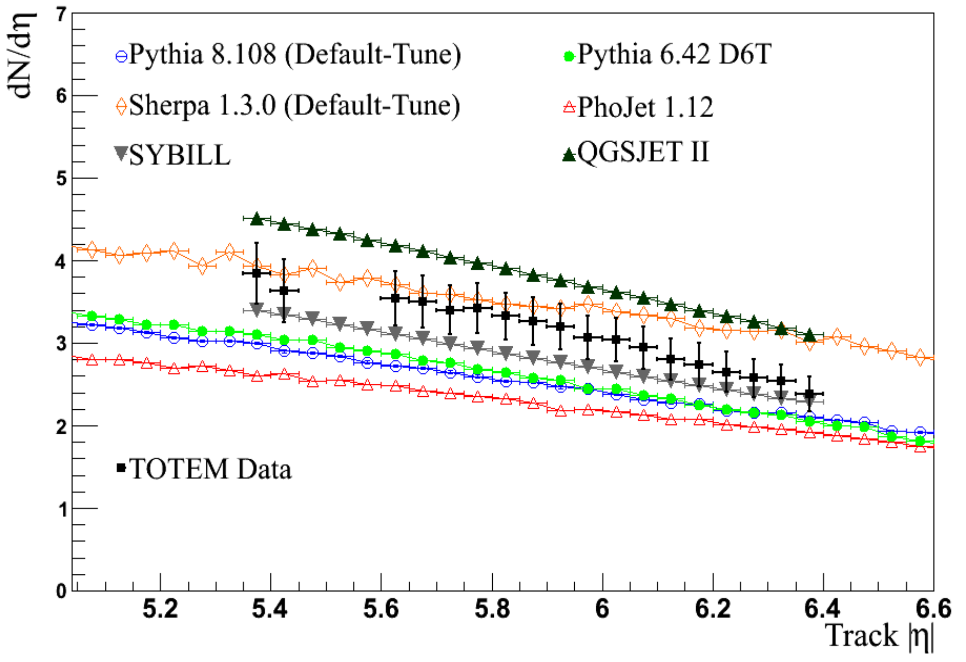


Primary track reconstruction efficiency

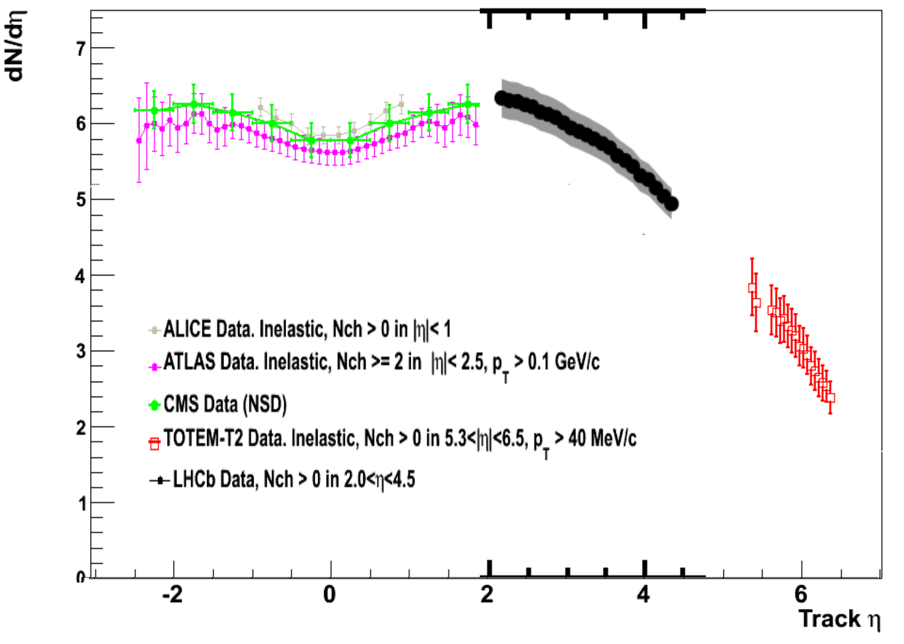
- evaluated as a function of the track η and the multiplicity
- efficiency of 80%
- fraction of primary tracks within the cuts of 75% – 90% (η dependent)

$dN_{ch}/d\eta$ in T2 : results

TOTEM measurements compared to MC predictions

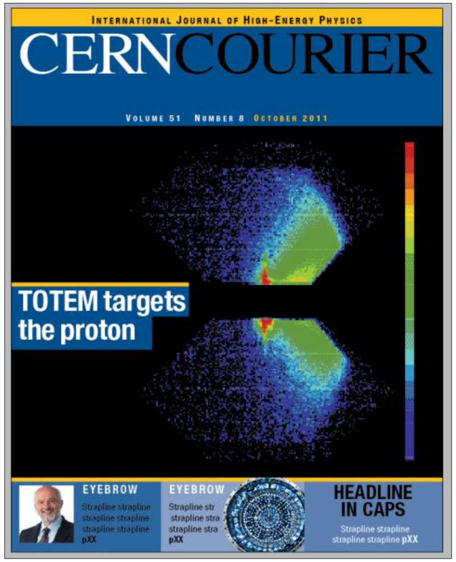


TOTEM measurements combined with the other LHC experiments



Published: EPL 98 (2012) 31002

Roman Pots:



Measurement of the Elastic pp Cross Section

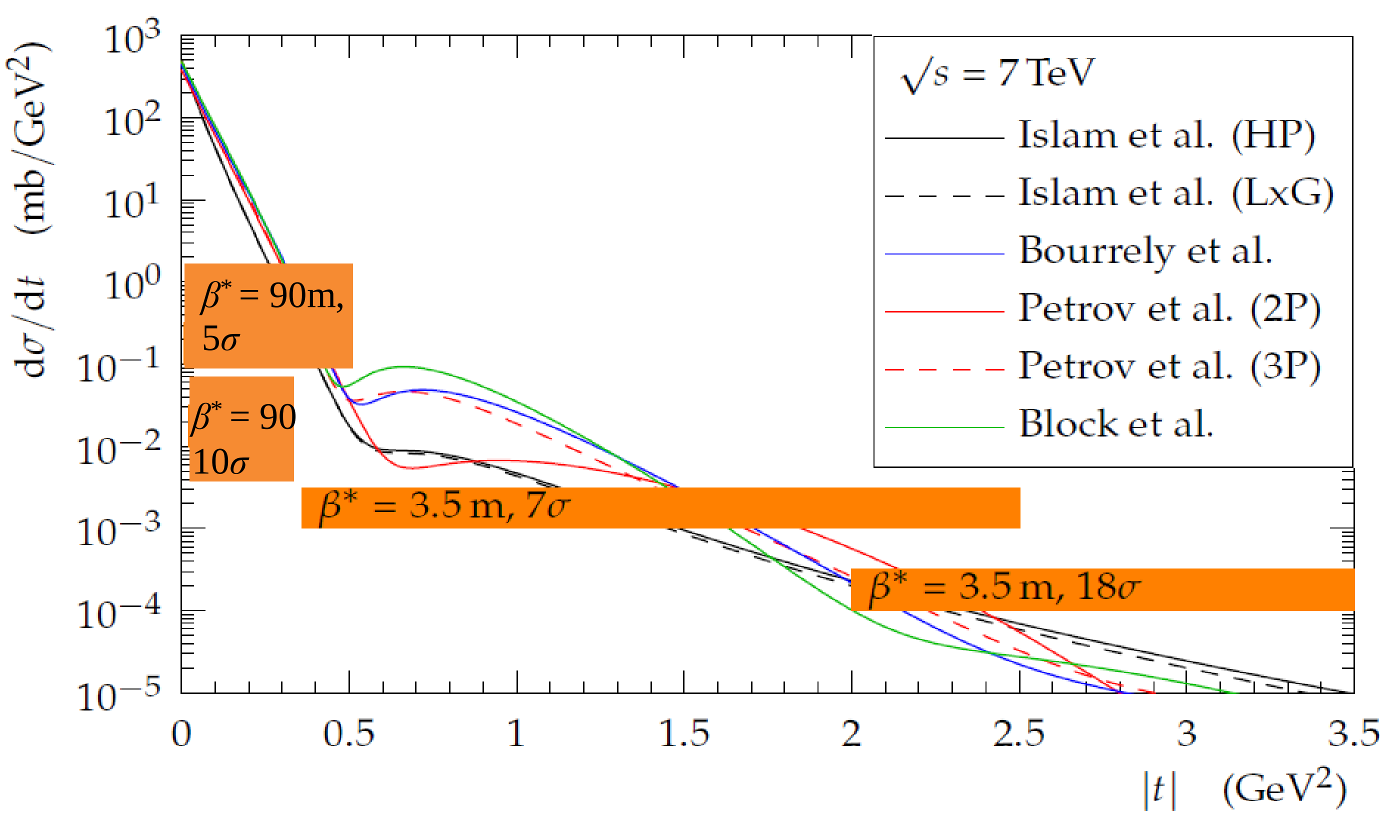
$7 \times 10^{-3}\ \text{GeV}^2 < |t| < 3.5\ \text{GeV}^2$

$\sqrt{s} = 7\ \text{GeV}$

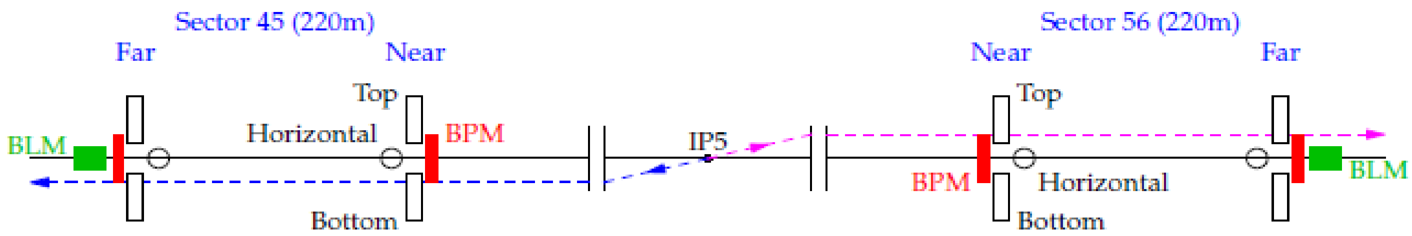
Data samples

Wide range of |t| measured with various LHC configurations

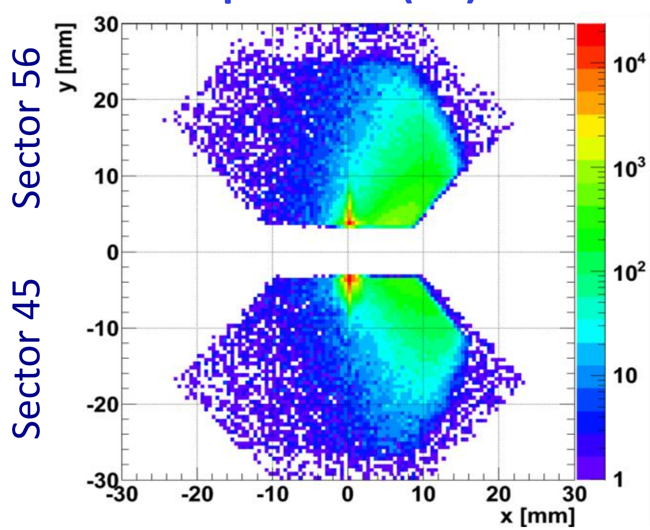
Set	β^*(m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events
1	90	4.8-6.5σ	83	$7 \cdot 10^{-3}$ - 0.5	1M
2	90	10σ	1.7	0.02 - 0.4	14k
3	3.5	7σ	6.8×10^3	0.36 - 3	66k
4	3.5	18σ	2.3×10^6	2 - 3.5	10k



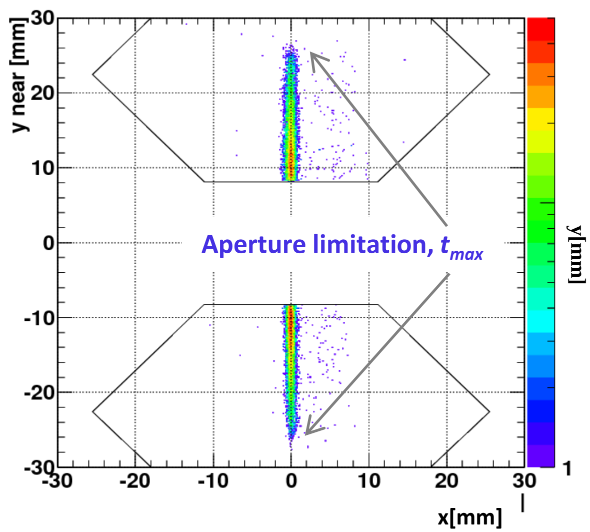
Elastic pp scattering in Roman Pots



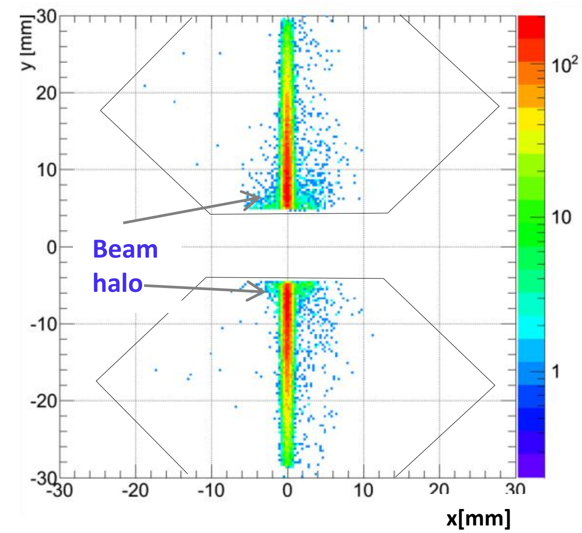
β^*=3.5m (7σ)

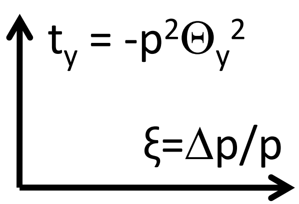


β^*=90m (10σ)



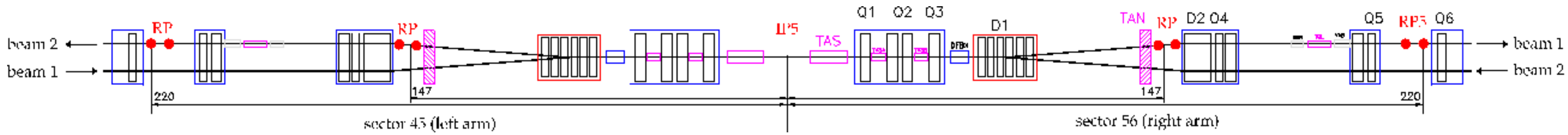
β^*=90m (5σ)





Diagonals analysed independently

LHC optics in brief



Proton position at a given RP (x, y) is a function of position (x^*, y^*) and angle (Θ_x^*, Θ_y^*) at IP5:

measured in Roman Pots

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

reconstructed

Proton transport matrix

Elastic proton reconstruction:

- Scattering angle reconstructed in both projections
- High Θ^*-reconstruction resolution available

  $\sigma(\Theta_y^*)$=**1.7 μrad** for β^*=90 m and low t-range

  $\sigma(\Theta_y^*)$=**12.5 μrad** for β^*=3.5 m and high t-range

$$\begin{cases} \Theta_x^* = \left(\Theta_{x,RP} - \frac{dv_x}{ds} x^*\right) / \frac{dL_x}{ds}, \\ \Theta_y^* = \left(y_{RP} - v_y y^*\right) / L_y \end{cases} \qquad \frac{\Delta p}{p} = 0$$

Excellent optics calibration and alignment required

Calibrations per beam fill

Novel method of TOTEM

- **Optics determination** **Special TOTEM runs, optics can change from fill to fill !!**
  - Analysis of transport matrix sensitivity to LHC imperfections (MADX)
  - Machine tolerances and measured errors combined
    - magnet currents
    - magnet conversion curves, field imperfections
    - magnet displacements
  - Measured optics constraints from RP proton tracks distributions
  - Optics matched with MADX
  - Procedure verified with MC studies

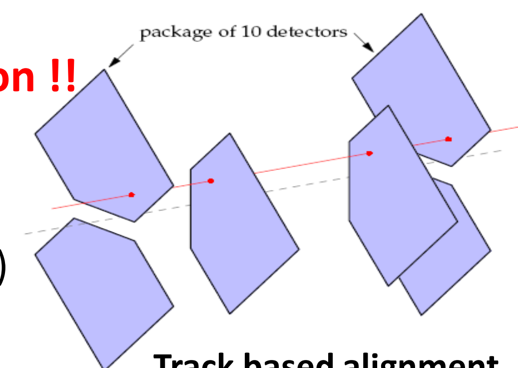
$$\begin{cases} \frac{\delta dL_x'}{dL_x'} < 1\% \\ \frac{\delta L_y}{L_y} < 1\% \end{cases} \Rightarrow \frac{\delta t}{t} \approx 0.8\% - 2.6\% \text{ for } \beta^* = 90\text{m}$$

Optics related systematic errors

H. Niewiadomski, ***Roman Pots for beam diagnostic***, OMCM, CERN, 20-23.06.2011
H. Niewiadomski, F. Nemes, ***LHC Optics Determination with Proton Tracks***, IPAC'12, Louisiana, USA, 20-25.05.2012

- **Alignment of Roman Pots** **Movable devices be definition !!**
  - internal components alignment: metrology, tracks
  - with respect to LHC beams : beam touching exercise (<200 μm)
  - relative between RPs with overlapping tracks (Millepede, a few μm)
  - physics based : exploits co-linearity of elastically scattered protons, constraints especially the 2 sides of IP5 (a few μm)

  Final precision of 10 μm achieved

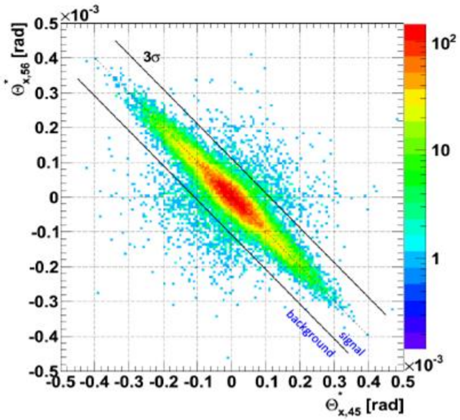


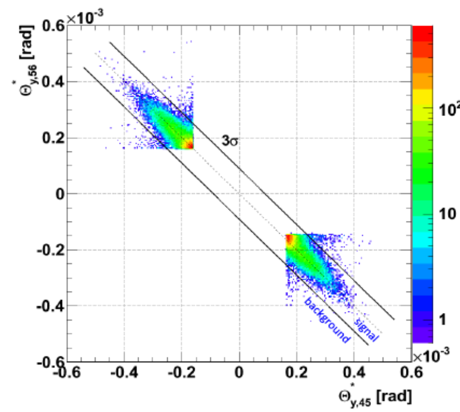
Track based alignment

Elastic pp scattering : analysis highlights

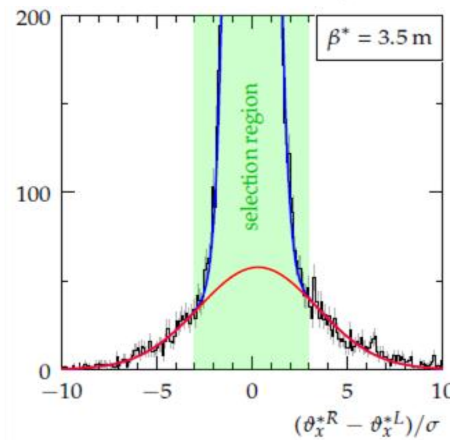
Proton selection cuts

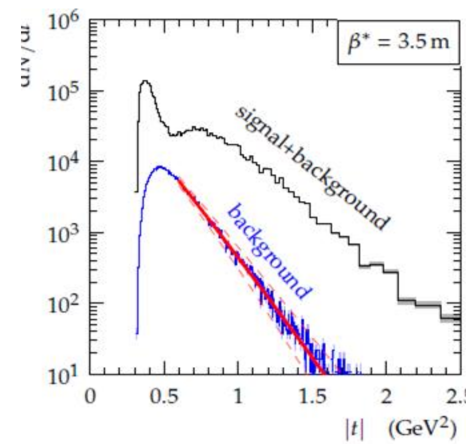
+ collinearity cuts (left-right)
  - $\Theta^*_x,45 \leftrightarrow \Theta^*_x,56$
  - $\Theta^*_y,45 \leftrightarrow \Theta^*_y,56$
+ low ξ cuts
+ vertex cuts
+ optics related cuts



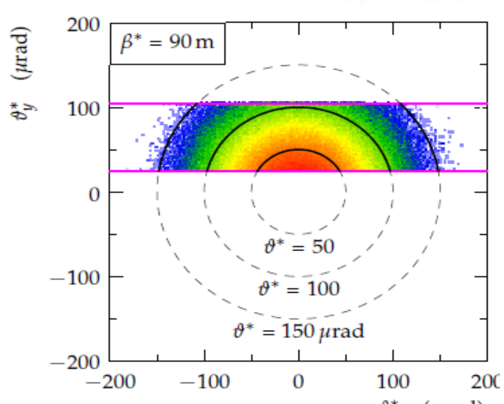


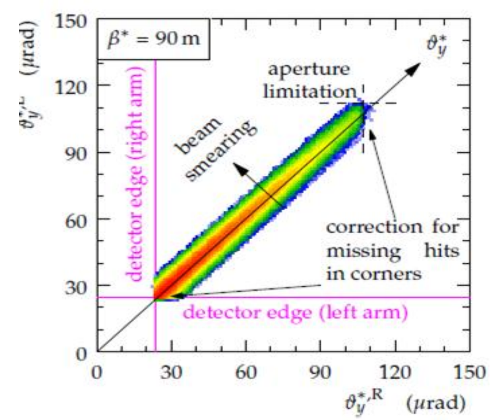
Background subtraction





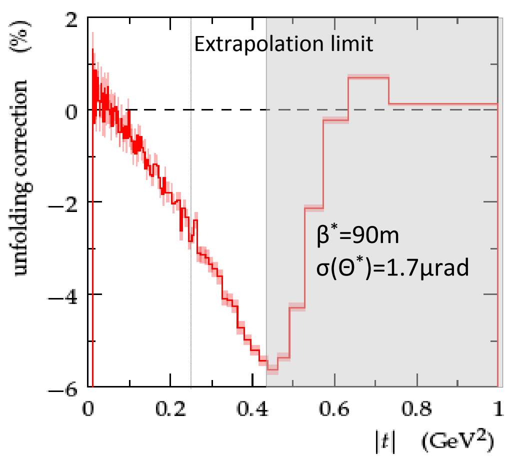
Acceptance correction

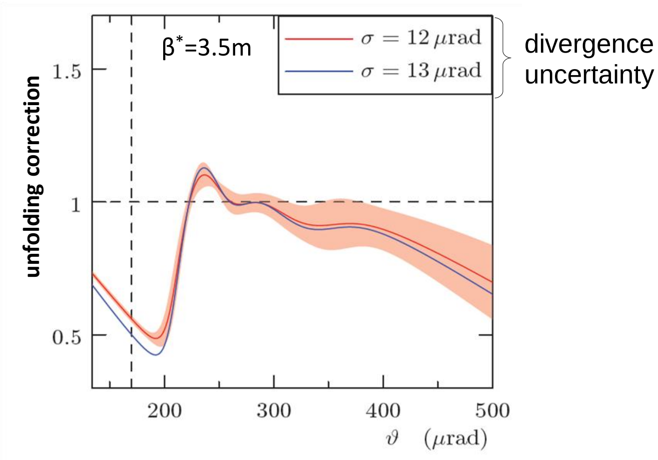




Elastic pp scattering : analysis highlights/ II

Resolution unfolding





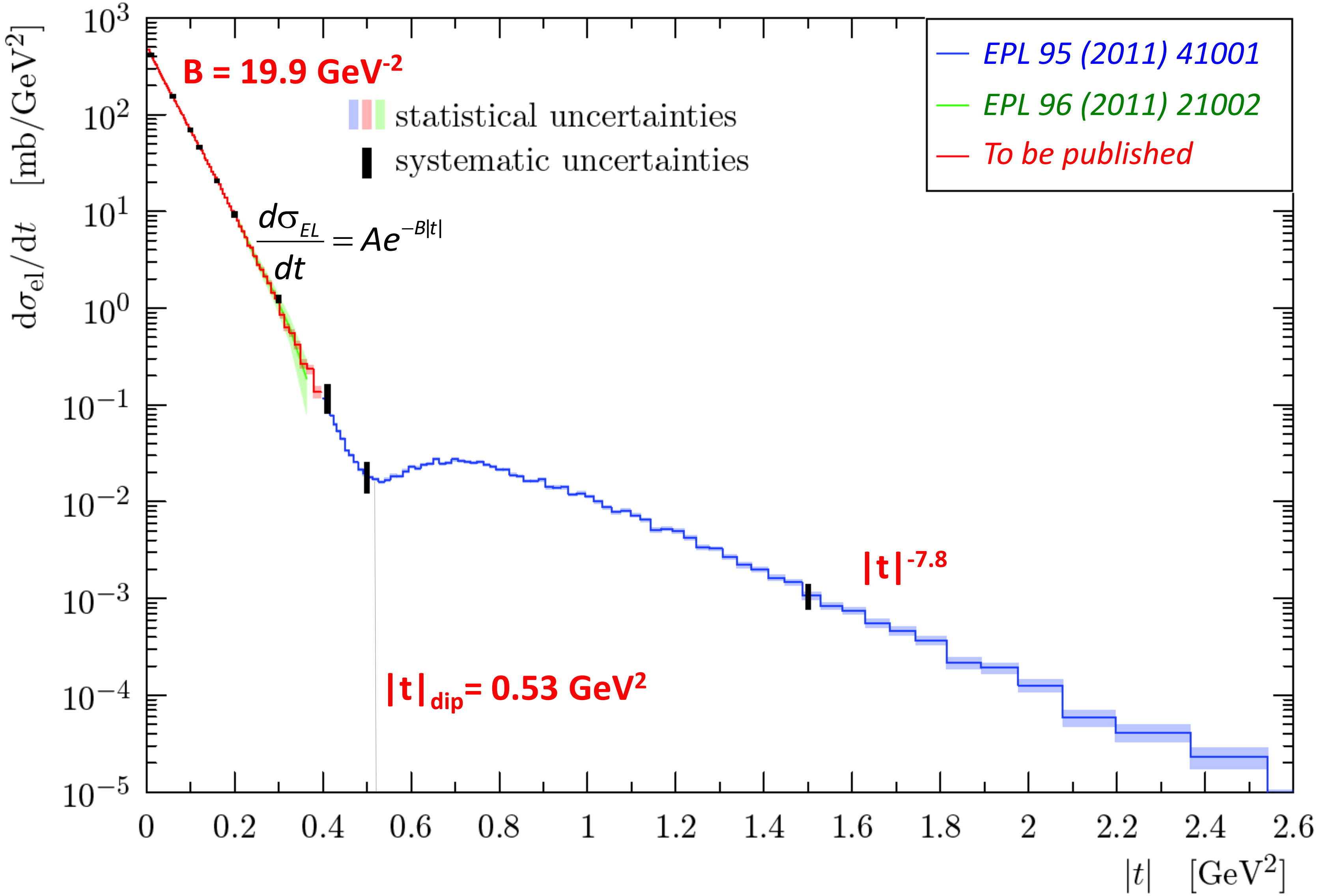
Normalization

Reconstruction efficiency

- intrinsic detector inefficiency: 1-2% / pot
- elastic proton lost due to interaction: 1.5%/pot
- event lost due to overlap with beam halo (depends on dataset and diagonal) 4% - 8% (β*=90m); 30% (β*=3.5m)

Luminosity from CMS systematic error of 4%

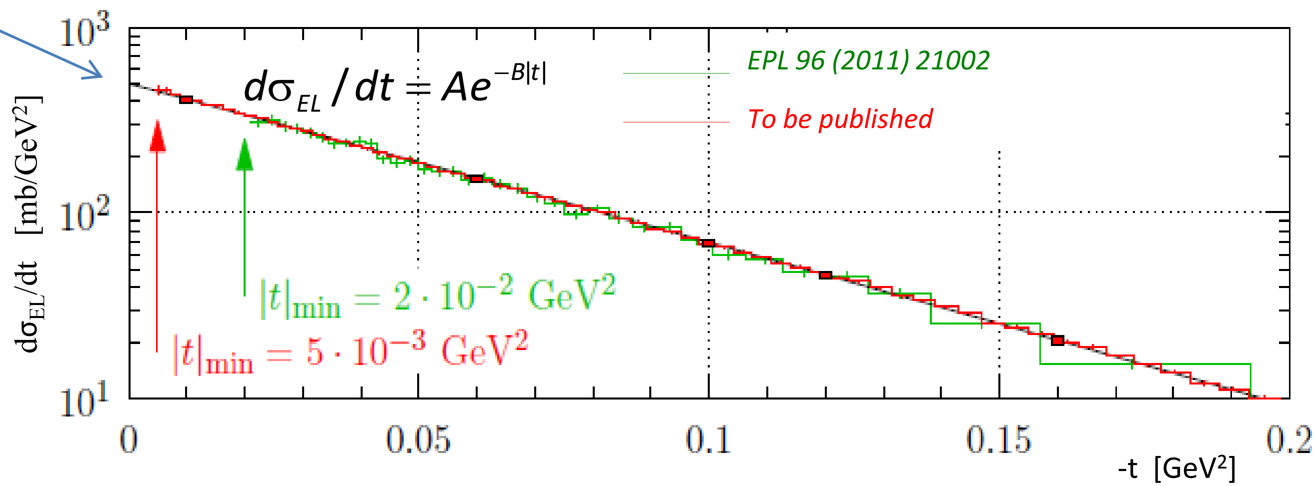
Elastic scattering cross-section



Elastic scattering cross-section

Extrapolation to t=0

$$A = \left.\frac{d\sigma_{EL}}{dt}\right|_{t\to 0}$$



$$\left.\frac{d\sigma_{EL}}{dt}\right|_{t\to 0} = A = 506 \pm 22.7^{syst} \pm 1.0^{stat}\ \text{mb/GeV}^2$$

$$503 \pm 26.7^{syst} \pm 1.5^{stat}\ \text{mb/GeV}^2$$

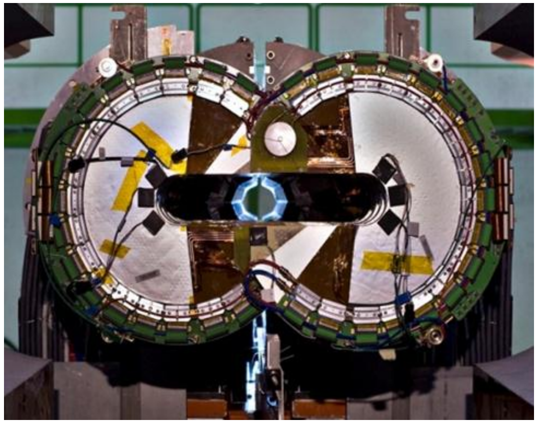
$$B = 19.9 \pm 0.26^{syst} \pm 0.04^{stat}\ \text{GeV}^{-2}$$

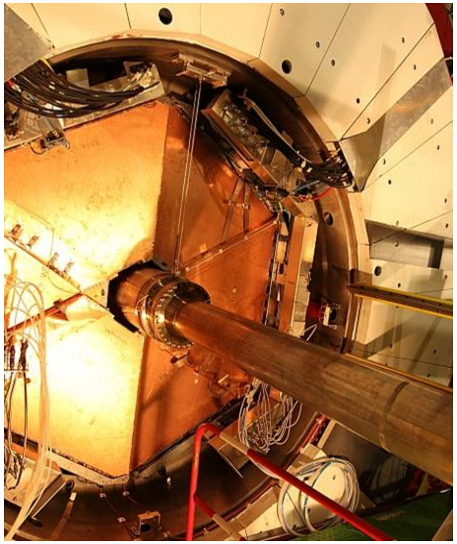
Elastic cross-section

$$\sigma_{EL} = \sigma_{EL,extrapol.} + \sigma_{EL,meas} = 25.4 \pm 1.0^{lumi} \pm 0.3^{syst} \pm 0.03^{stat}\ \text{mb}$$ *(90% directly measured)*

$$24.8 \pm 1.0^{lumi} \pm 0.2^{syst} \pm 0.2^{stat}\ \text{mb}$$ *(50% directly measured)*

T2 and T1 telescopes:





Measurement of the Inelastic pp Cross Section

$\sqrt{s} = 7\,\text{GeV}$

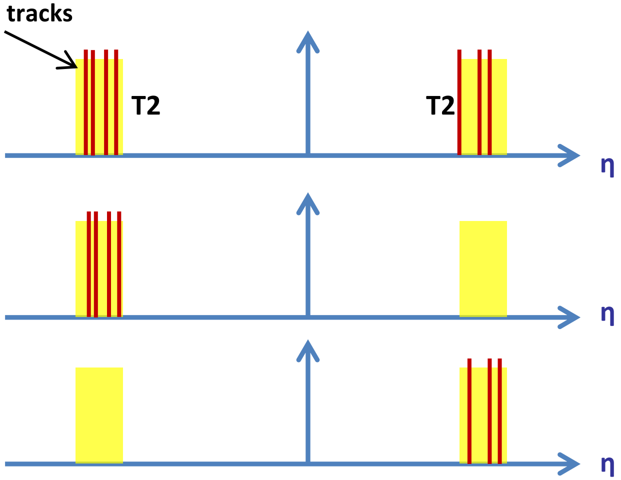
Inelastic Cross Section

direct T1 and T2 measurement

Inelastic events in T2: classification

- **tracks in both hemispheres**
  non-diffractive minimum bias
  double diffraction

- **tracks in a single hemisphere**
  mainly single diffraction
  $M_X > 3.4\ GeV/c^2$



Corrections to the T2 visible events

- Trigger Efficiency: **2.3 %**
  (measured from zero bias data with respect to track multiplicity)
- Track reconstruction efficiency: **1 %**
  (based on MC tuned with data)
- Beam-gas background: **0.54 %**
  (measured with non colliding bunch data)
- Pile-up (μ =0.03): **1.5 %**
  (contribution measured from zero bias data)

$$\sigma_{\text{inelastic, T2 visible}} = 69.7 \pm 0.1^{\text{stat}} \pm 0.7^{\text{syst}} \pm 2.8^{\text{lumi}}\ \text{mb}$$

Inelastic Cross Section

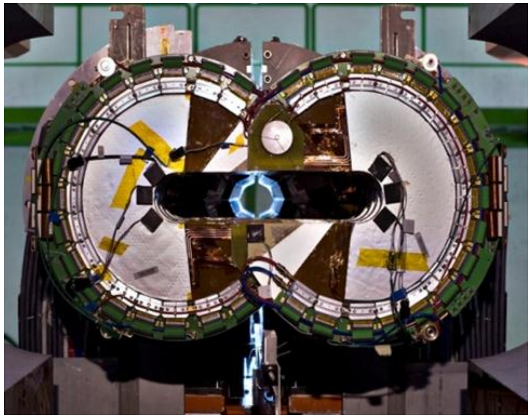
$\sigma_{inelastic,\ T2\ visible} \Rightarrow \sigma_{inelastic}$

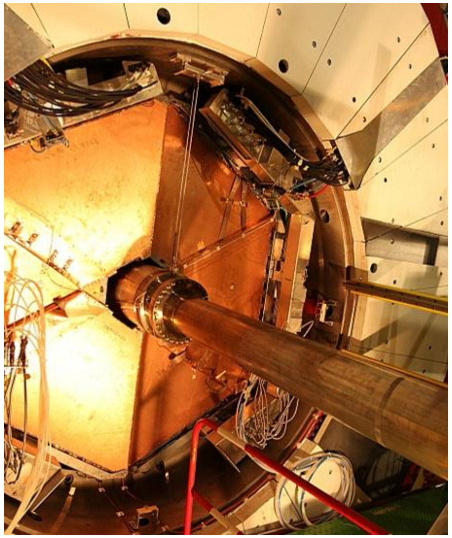
Missing inelastic cross-section

- Events visible in T1 but not in T2: **2.0 %**
  (estimated from zero bias data)
- Rapidity gap in T2 : **0.57 %**
  (estimated from T1 gap probability transferred to T2)
- Central Diffraction: T1 & T2 empty : **0.54 %**
  (based on MC, correction max ~$0.25 \times \sigma_{CD}$, quoted in systematic error)
- Low Mass Diffraction : **3.7 % ± 2 % ^{syst}**
  (Several models studied, correction based on ***QGSJET-II-4****,*
  imposing observed 2hemisphere/1hemisphere event ratio and the effect of 'secondaries')
  - constrained by the Total cross-section measurement (see later)
  - will be measured with a single proton trigger, large β^* optics and clean beam conds.

$$\sigma_{inelastic} = 73.7 \pm 0.1^{stat} \pm 1.7^{syst} \pm 2.9^{lumi}\ \text{mb}$$

Roman Pots, T2 and T1 telescopes:





Total Cross Section Measurement

$\sqrt{s} = 7\,\mathrm{GeV}$

Total Cross Section

4 approaches

1) CMS Luminosity (small bunches) + Elastic Scattering+ Optical Theorem

depends on CMS luminosity for low-L bunches & elastic efficiencies & ρ

2) CMS Luminosity (large bunches) + Elastic Scattering + Optical Theorem

compare the CMS luminosity measurement for high-L vs. low-L bunches

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

ρ=0.14±0.09 (Compete)

3) CMS Luminosity (large bunches) + Elastic Scattering + Inelastic Scattering

minimizes dependence on elastic efficiencies and ***no dependence on ρ***

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

4) (L-independent) + Elastic Scattering + Inelastic Scattering+ Optical Theorem

eliminates dependence on luminosity

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

Total Cross Section

4 approaches

1) CMS Luminosity (small bunches) + Elastic Scattering + Optical Theorem

depends on CMS luminosity for low-L bunches & elastic efficiencies & ρ

σ_{TOT} = 98.3 mb ± 2.0 mb *EPL 96 (2011) 21002*

2) CMS Luminosity (large bunches) + Elastic Scattering + Optical Theorem

compare the CMS luminosity measurement for high-L vs. low-L bunches

σ_{TOT} = 98.6 mb ± 2.3 mb

3) CMS Luminosity (large bunches) + Elastic Scattering + Inelastic Scattering

*minimizes dependence on elastic efficiencies and **no dependence on ρ***

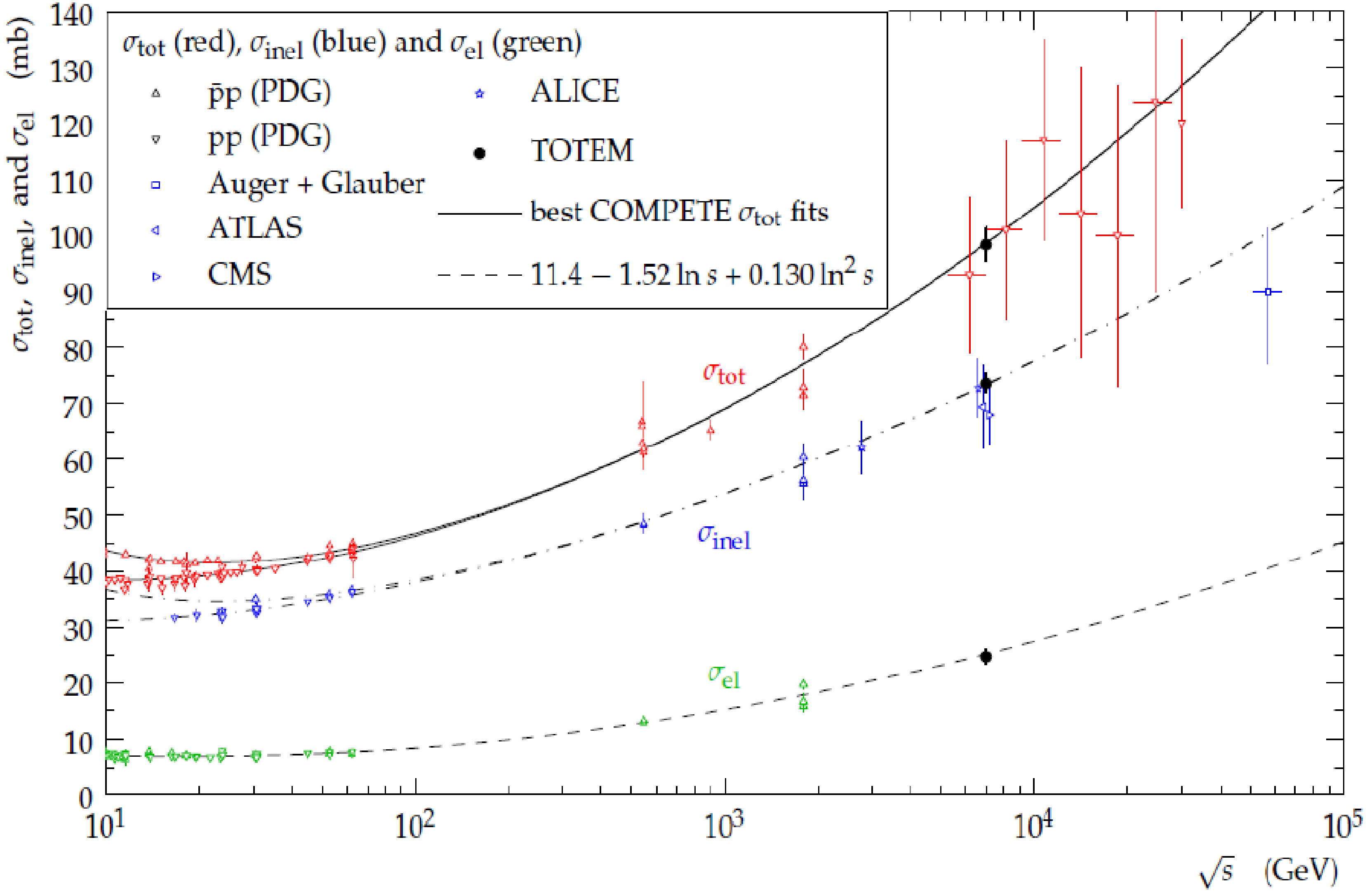
σ_{TOT} = 99.1 mb ± 4.4 mb

4) (L-independent) + Elastic Scattering + Inelastic Scattering + Optical Theorem

eliminates dependence on luminosity

σ_{TOT} = 98.1 mb ± 2.4 mb

Cross Sections: Summary



Total Cross Section
calibrations & implications

Luminosity calibration:

$$\mathcal{L} = \frac{(1+\rho^2)}{16\pi}\frac{(N_{el}+N_{inel})^2}{(dN_{el}/dt)_{t=0}}$$

	Estimated by CMS	Estimated by TOTEM
1)	$\int Ldt =$ 82/µb ±4%	$\int Ldt =$ 83.7/µb ±3.8%
2)	$\int Ldt =$ 1.65/µb ±4%	$\int Ldt =$ 1.65/µb ±4.5 %

Luminosity and ρ independent ratios:

$\sigma_{el}/\sigma_{tot} = 0.257 \pm 2\%$ $\sigma_{el}/\sigma_{inel} = 0.354 \pm 2.6\%$

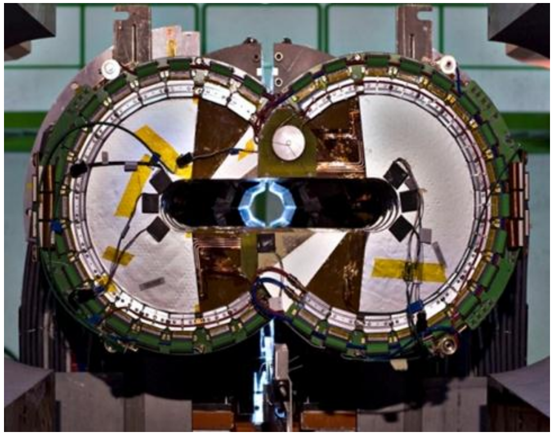
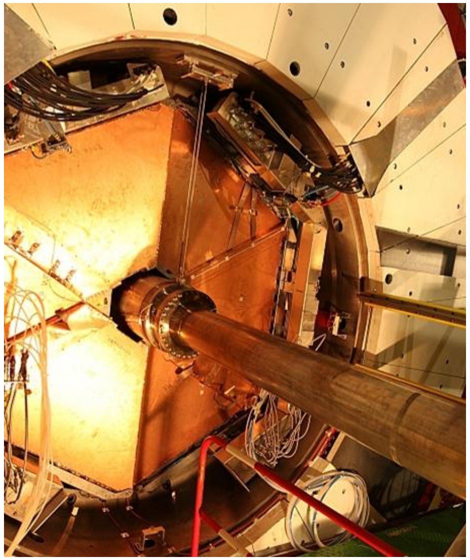
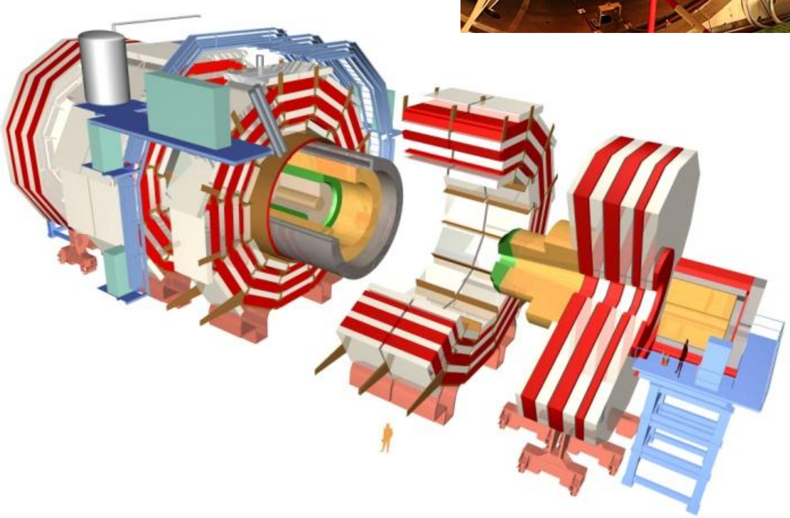
Low mass diffraction cross-section constrained:

From method (2) inclusive estimation of $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ = 73.2± 1.3mb

However, T1+T2 visible $\sigma^{\eta<6.5}_{inel}$= 70.9 ± 2.8 mb

→ $\sigma^{\eta>6.5}_{inel} = 3.2\%\ \sigma^{\eta<6.5}_{inel}$ (upper limit of 4.5 mb)

TOTEM and CMS :

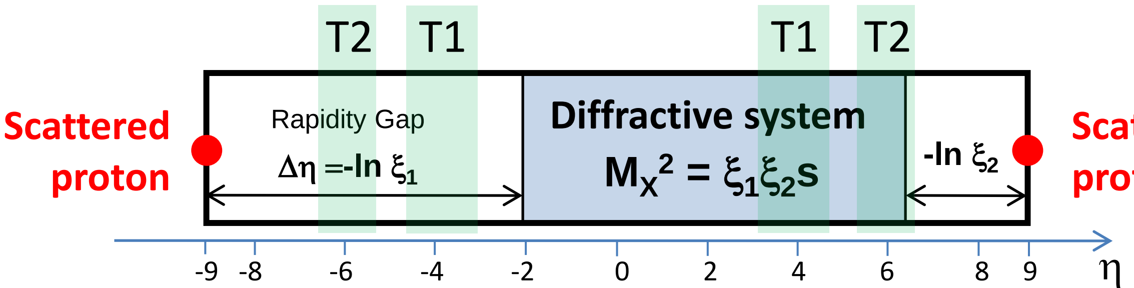





Diffractive physics
DPE, SD, di-jets…

Double Pomeron Exchange

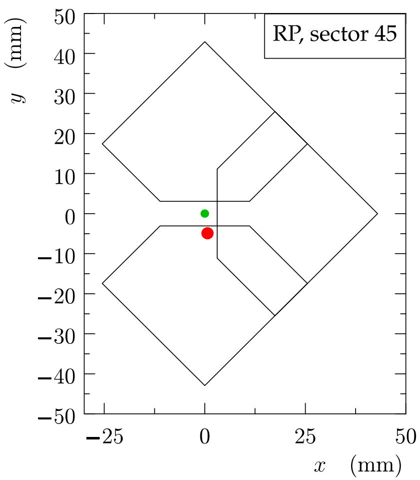
Excellent RP acceptance in $\beta^* = 90$m runs

- DPE protons of $-t > 0.02\,\text{GeV}^2$ detected by RP
- nearly complete ξ-acceptance



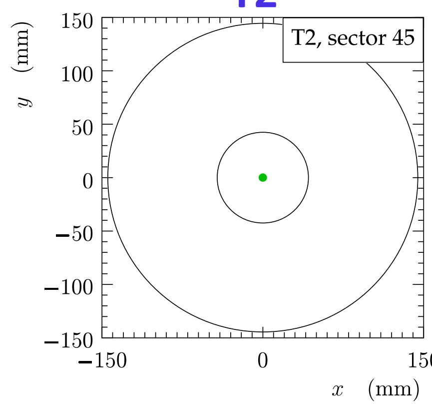
$\xi = \Delta p/p$

Roman Pot



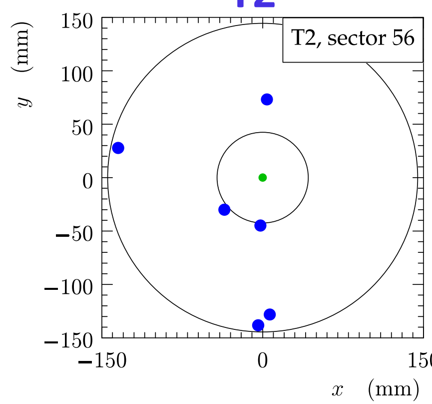
low ξ proton

T2



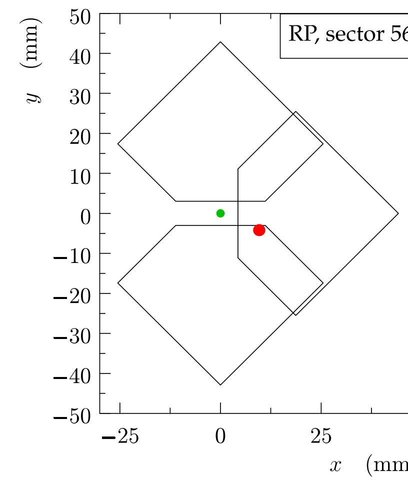
large rapidity gap $\Delta\eta$
no tracks in T2

T2



small rapidity gap $\Delta\eta$
tracks in T2

Roman Pot

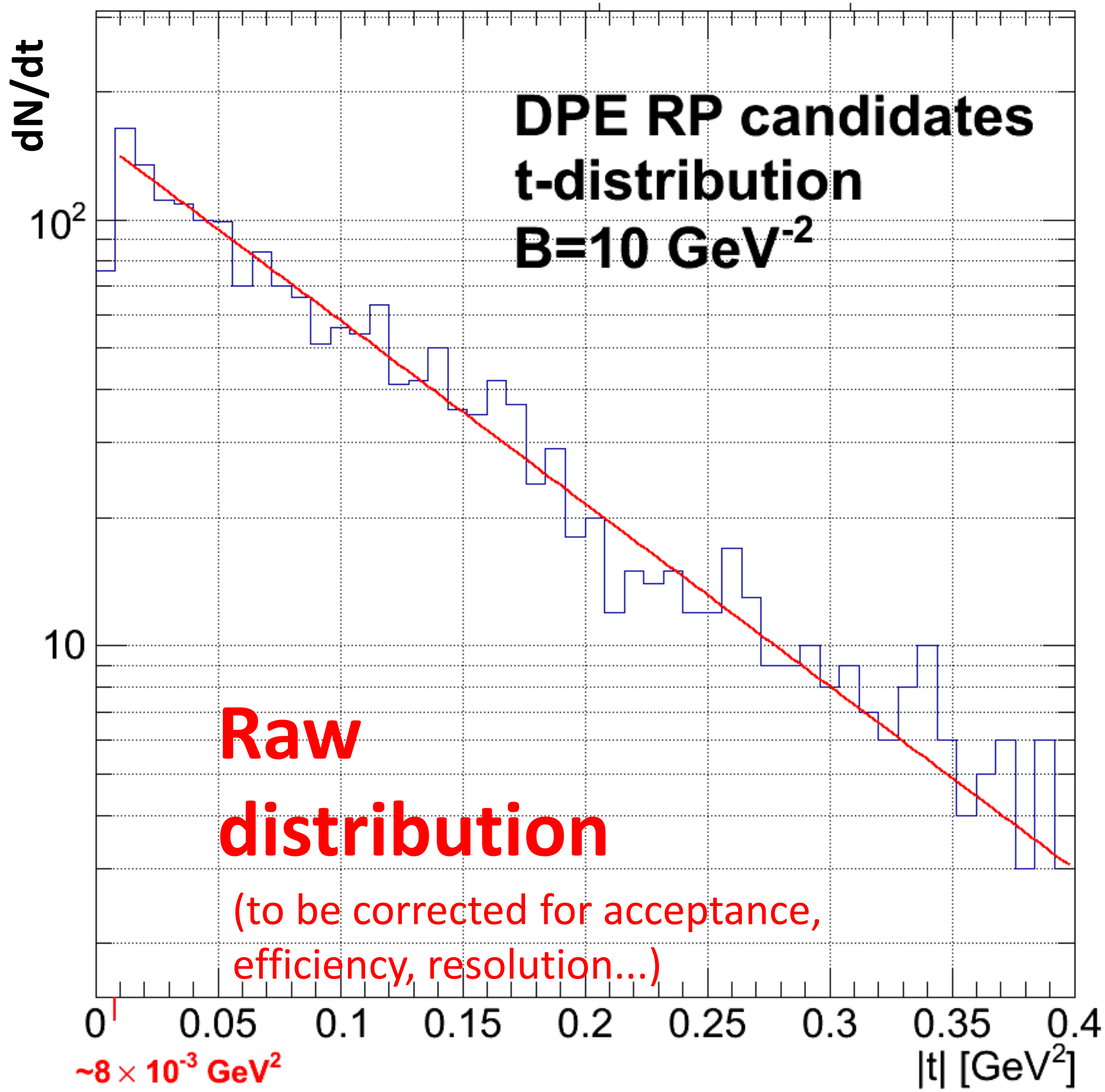


large ξ proton

Run 37220007, event 9904

Data Oct'11: DPE Cross-Section

Preliminary



Distribution integrated over ξ

Data Taking with CMS

Semi-hard and hard diffraction (CMS-TOTEM TDR):

inclusive and exclusive dijets + protons + rapidity gaps …

CMS ↔ TOTEM trigger exchange

Offline data synchronization

Towards common data taking:

2011 Ion run : proof of principle

2012 CMS jet trigger to TOTEM; low statistics collected

2012 Low pile up run; 8M events collected
Run with a complete trigger menu; exchange of trigger in both directions (CMS jets trigger; TOTEM min bias; RPs were NOT inserted)

2012 First common runs with standard optics with Roman Pots inserted

Data taking foreseen in 2012:

β^*=90m, 156 bunches
expected integrated luminosity of 6nb^{-1}/h
Proton coverage : full range in ξ , -t > 0.02 GeV^2

β^*=0.6m, ~1400 bunches, full luminosity
Proton coverage : ξ > 2-3%, full range of t

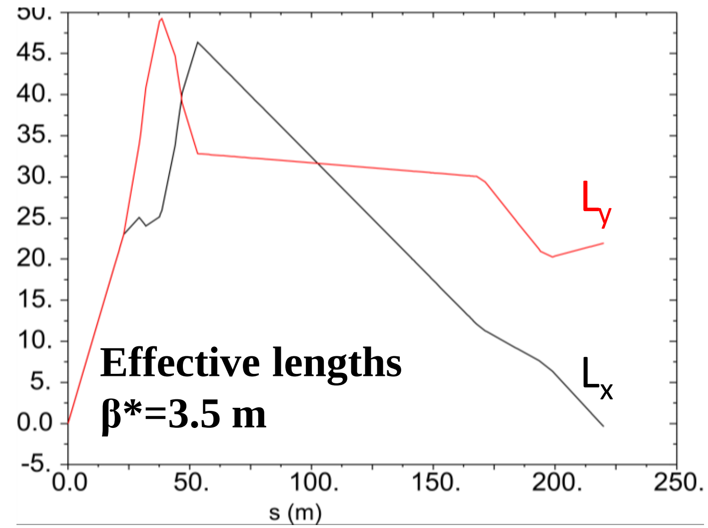
Thank you!

OPTICS

Low β*=3.5m optics

Objective:

- to measure elastic scattering at high |t|

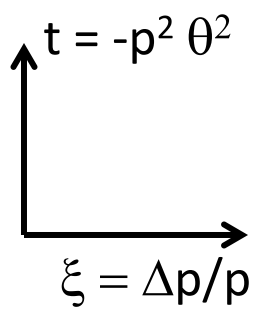


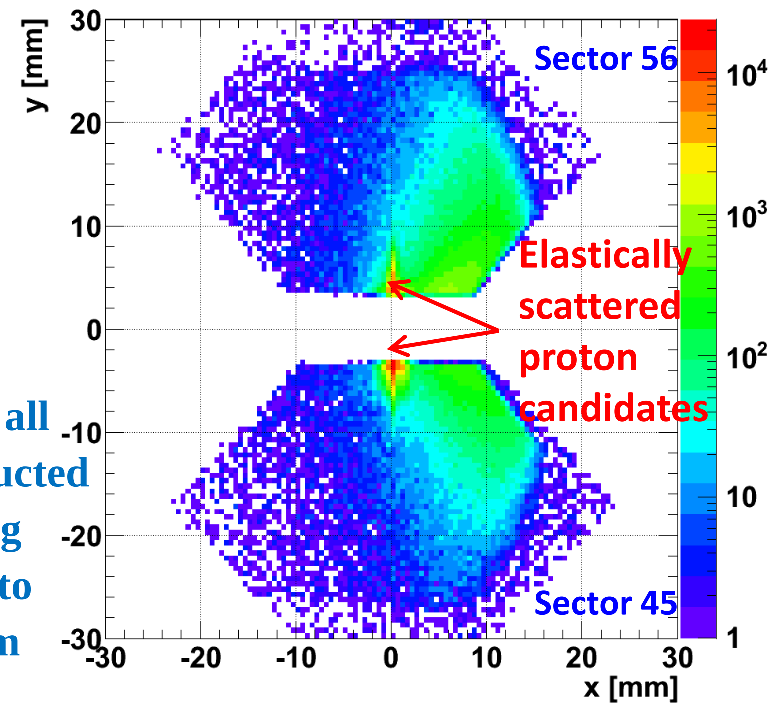
Properties of the optics:

- $\sigma_{IP} \approx 37$ µm (magnification is not crucial)
- $L_x \approx 0$, $L_y = 22.4$ m
- beam divergence $\sigma_{\Theta*} \approx 17$-$18$ µrad

Data sources to improve our optics understanding:

- TIMBER database magnet currents
- FIDEL team conversion curves, implemented with LSA
- WISE field harmonics, magnet's displacements`





The intercepts of all selected reconstructed tracks in a scoring plane transverse to the beam at 220 m

The effect of machine imperfections β*=3.5m

Machine imperfections:

- **Strength conversion error, σ(B)/B ≈ 10^{-3}**
- **Beam momentum offset, σ(p)/p ≈ 10^{-3}**
- Magnet rotations, σ(ϕ) ≈ 1 mrad
- Beam harmonics, σ(B)/B ≈ 10^{-4}
- Power converter errors, σ(I)/I ≈ 10^{-4}
- Magnet positions Δx, Δy ≈ 100 µm

Imperfections alter the optics !

Perturbed element	$\delta L_{y,b1}/L_{y,b1}$ [%]
MQXA.1R5	0.98
MQXB.A2R5	−2.24
MQXB.B2R5	−2.42
MQXA.3R5	1.45
MQY.4R5.B1	−0.10
MQML.5R5.B1	0.05
Δp/p	−2.19

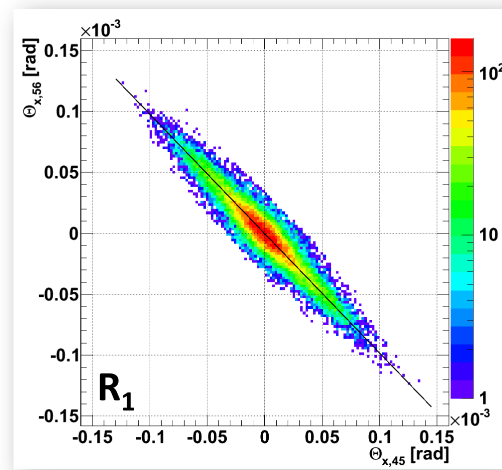
Constraints from proton tracks in the Roman Pots β*=3.5m

Optics imperfections can be determined from proton tracks *measured* in the Roman Pots. The method is based on:

- elastic events are easy to tag
- the elements of the transport matrix are mutually correlated
- elastic scattering ensures that

$$\Theta^*_{y,b1} = \Theta^*_{y,b2}$$
$$\Theta^*_{x,b1} = \Theta^*_{x,b2}$$

$$\rightarrow R_1 \equiv \frac{\Theta_{x,b1,RP}}{\Theta_{x,b2,RP}} \approx \frac{\frac{dL_{x,b1,RP}}{ds}}{\frac{dL_{x,b2,RP}}{ds}}$$



Matching the optics β*=3.5m

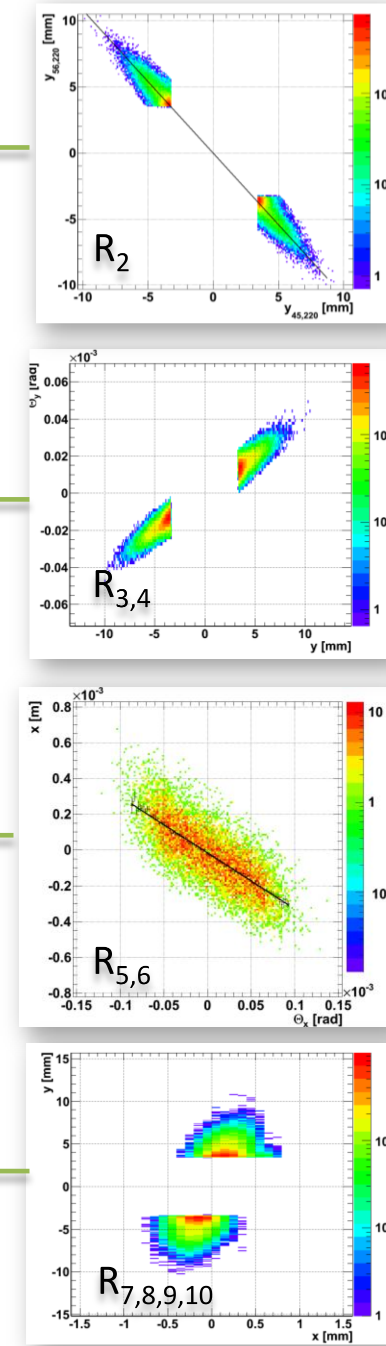
On the basis of constraints R_1-R_{10} the optics can be estimated.

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

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

Match → dL_x/ds, L_y

R1



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

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

Monte-Carlo confirmation of the method (presented @IPAC 2012)

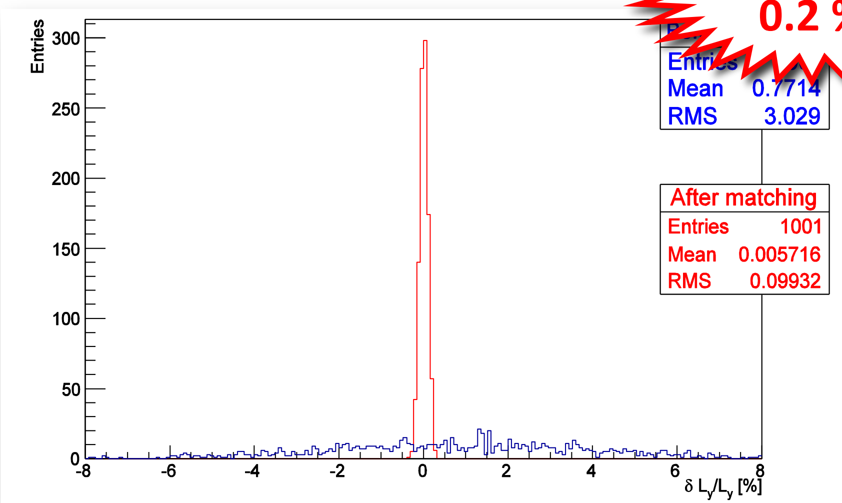
The Monte-Carlo study included the effect of:

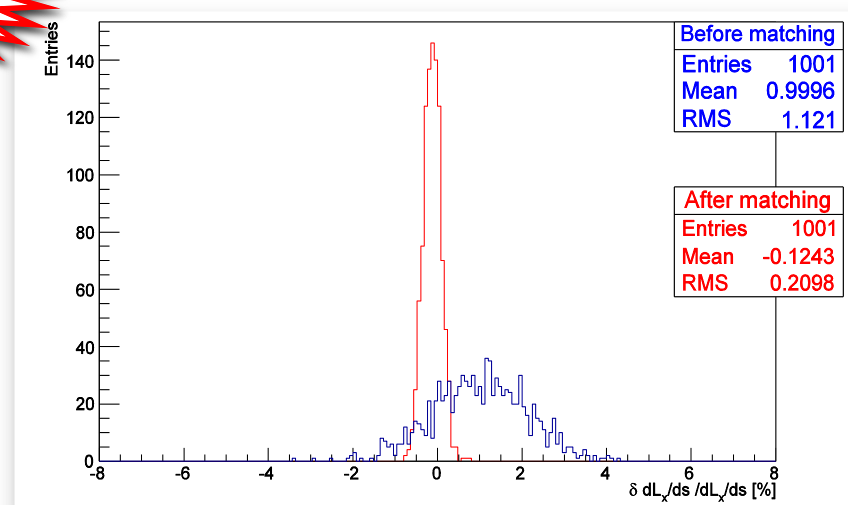
- magnet strengths
- beam momenta
- displacements, rotations
- kickers, field harmonics
- elastic scattering Θ-distributions

Optical function relative error	Before		Matched	
	Mean [%]	RMS [%]	Mean [%]	RMS [%]
$\delta L_{y,b1}/L_{y,b1}$	0.77	3.0	$5.7 \cdot 10^{-3}$	$9.9 \cdot 10^{-2}$
$\delta (dL_{x,b1}/ds)/(dL_{x,b1}/ds)$	1.0	1.1	$-1.2 \cdot 10^{-1}$	$2.1 \cdot 10^{-1}$
$\delta L_{y,b2}/L_{y,b2}$	2.0	3.8	$1.5 \cdot 10^{-1}$	$9.5 \cdot 10^{-2}$
$\delta (dL_{x,b2}/ds)/(dL_{x,b2}/ds)$	-1.14	1.2	$-7.6 \cdot 10^{-2}$	$2.1 \cdot 10^{-1}$

Conclusion: for β*=3.5m TOTEM can measure the transfer matrix between IP5 and RPs with a precision

RMS < 0.2 %



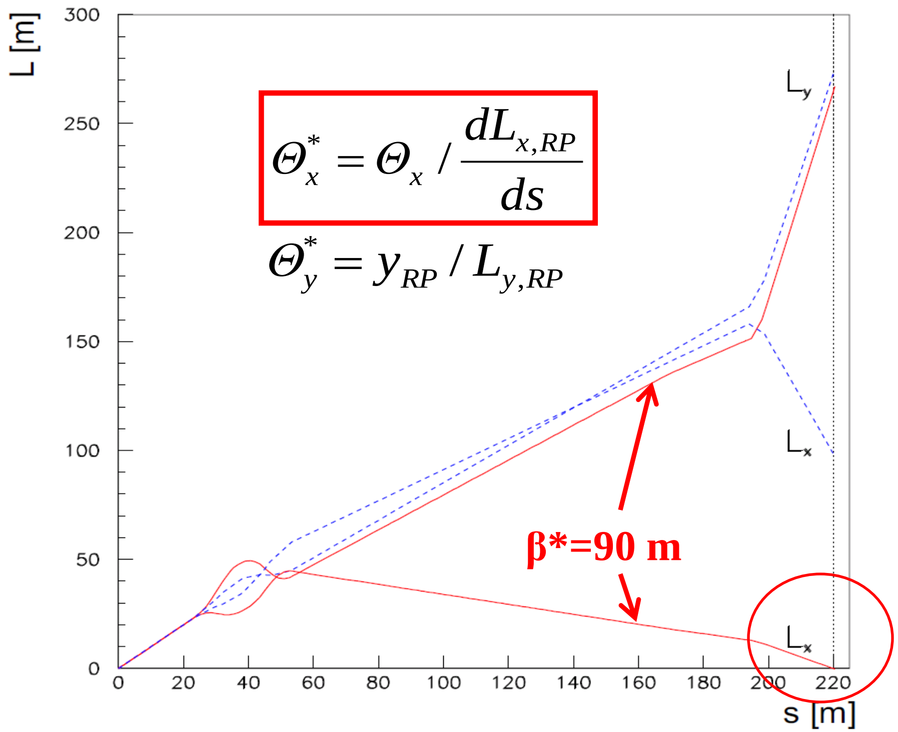


Relative error distribution before and after matching

β* = 90m optics achievable using the standard LHC injection optics. Properties:

- $\sigma_{\Theta*}$ = 2.5 μrad, $L_x \approx$ 0, $L_y \approx$ 260 m
- vertex size $\sigma_{IP} \approx$ 212 μm
- Acceptance: |t| > 3 · 10^{-2} GeV^2, RP distance from beam center 10 $\sigma_{beam\ size@RP}$
- parallel to point focusing **only** in **vertical** plane @RP220

Effective lengths from IP5 to RP @220 m



$$\Theta_x^* = \Theta_x \,/\, \frac{dL_{x,RP}}{ds}$$

$$\Theta_y^* = y_{RP} \,/\, L_{y,RP}$$

Intermediate β*=90 m optics: robustness

Objectives:

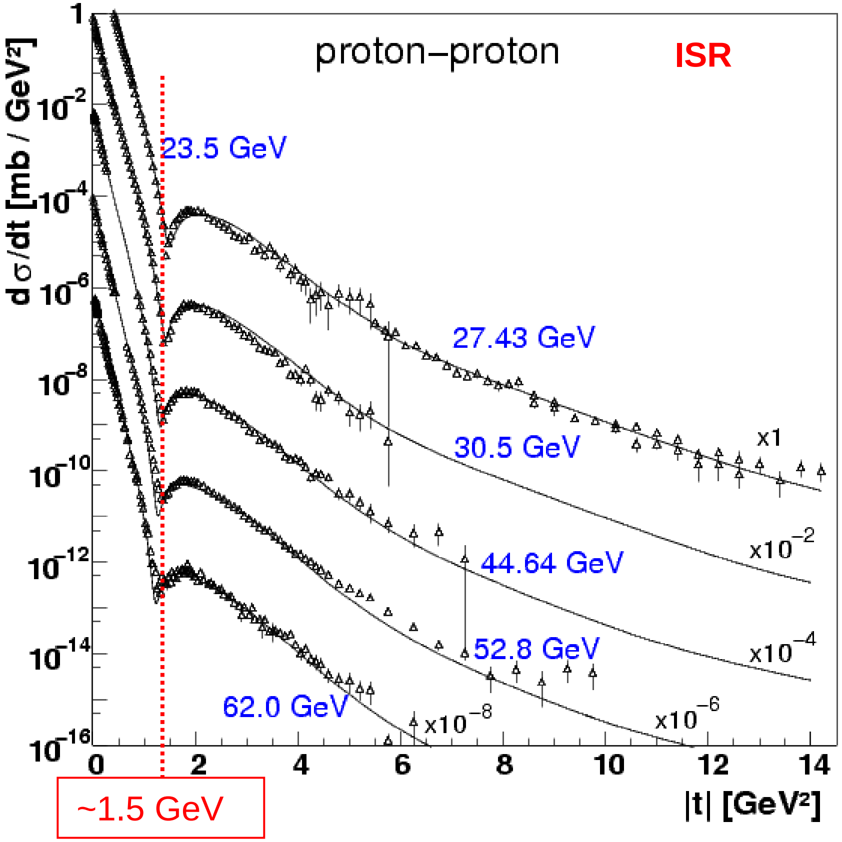
- First measurement of σ_{tot} elastic scattering in a wide |t| range
- inclusive studies of diffractive processes
- measurement of forward charged multiplicity

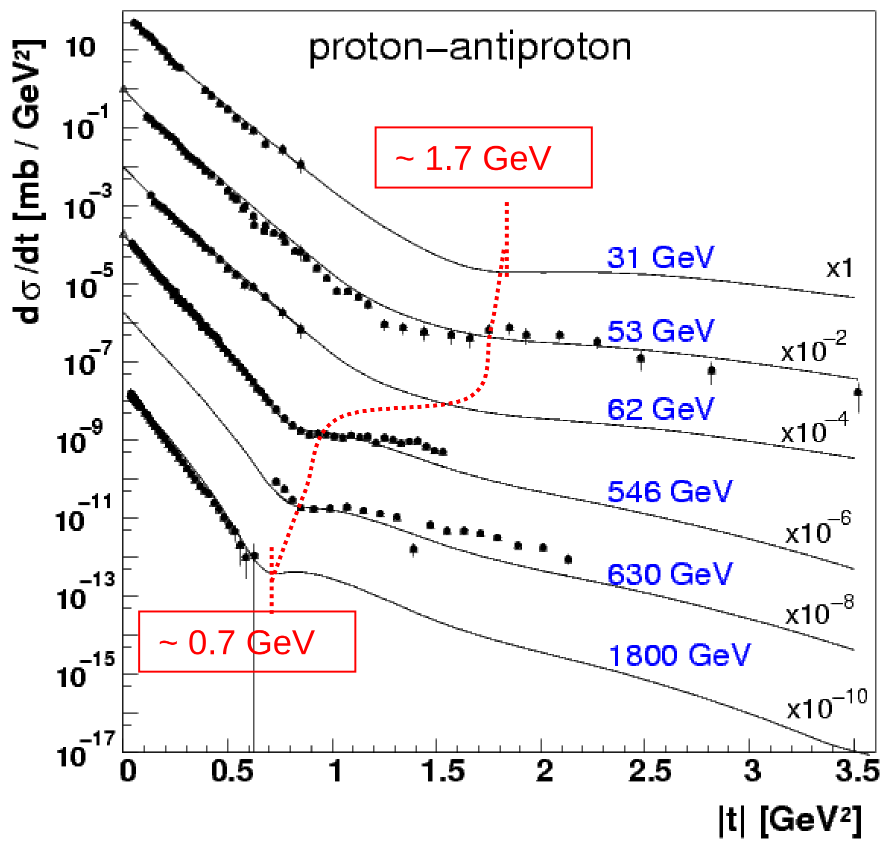
Sensitivity of the effective length L_y :

- 1 ‰ perturbations magnet strength, beam momenta
- **Conclusion: not necessary to match the β*=90 m optics**

Perturbed element	$\delta_{Ly,b1}/L_{y,b1}$ [%]
MQXA.1R5	0.14
MQXB.A2R5	−0.23
MQXB.B2R5	−0.25
MQXA.3R5	0.20
MQY.4R5.B1	−0.01
MQML.5R5.B1	0.04
Δp/p	0.01

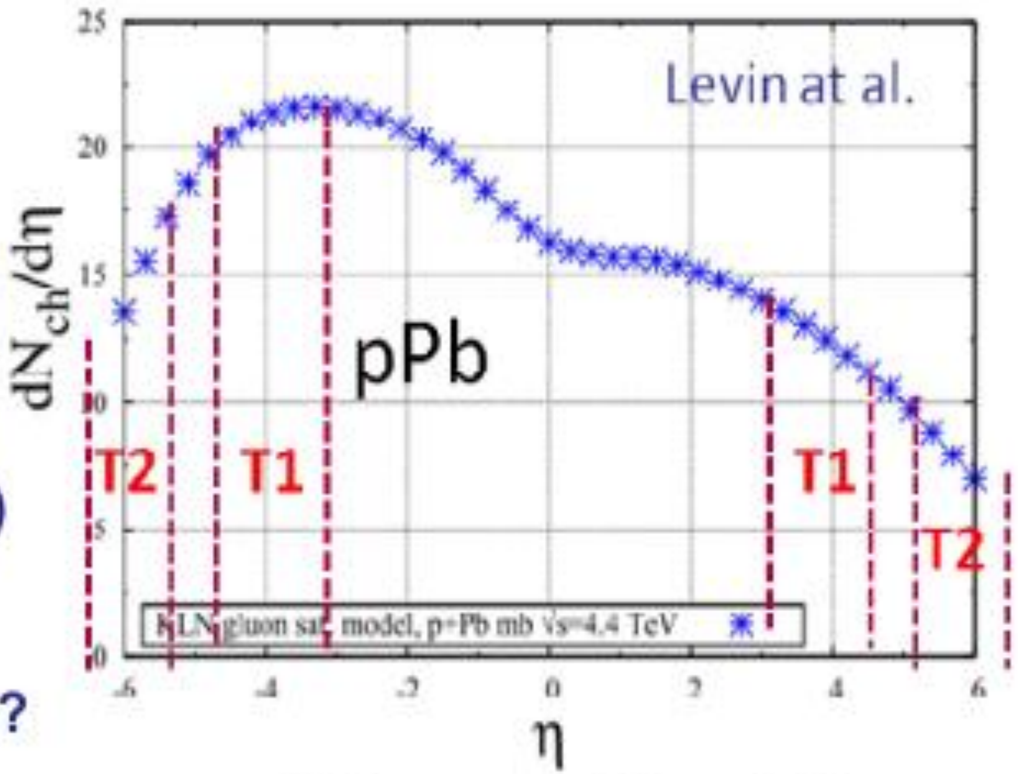
Elastic pp Scattering – from ISR to Tevatron





Minimum bias physics

- Charged particle acceptance (together with CMS): $|\eta| \leq 6.5$
- Trigger: one T2 track(?)
- $dN/d\eta_{pPb}$ using T1 & T2 (vs centrality from CMS)
- Forward-backward multiplicity correlations?
- Central-forward multiplicity correlations?
- Energy flow & small x: T1+HF, T2+Castor



Pattern recognition at high multiplicity to be optimized

Cross-sections

Test of dynamics:

- **knockout: p Pb → p + d + (A–2)*** $\xi^{p}_{fragment} = (1-(A/Z)_{fragment}/(A/Z)_{Pb})$
  - measure both p & d (= "p with $\Delta p/p = -0.21$") + veto hadron activity.

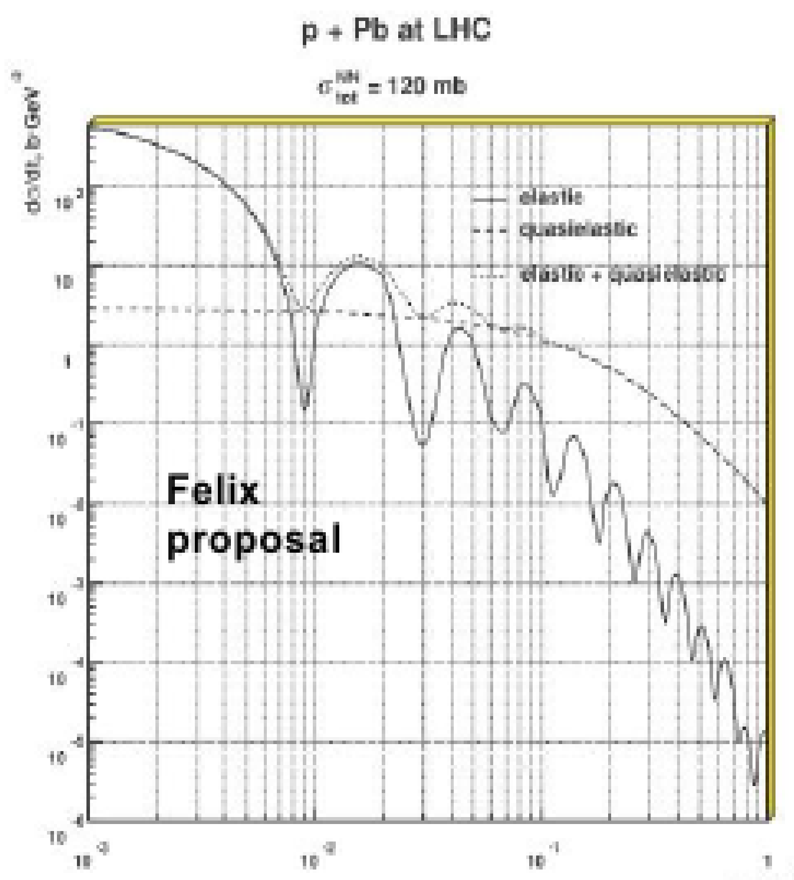
Need large t for p or significant Δp/p. Study Δp/p & t dependence.

- **quasielastic: p Pb → p Pb***

dominates at large t

- measure xi & t of p + only γ

on opposite side (veto hadrons)



Diffraction & γγ

- very large Pomeron & γ fluxes

but nothing measured in RP on outgoing Pb side (rate problem?)

p with signficant Δp/p (or large t)

+ central object (jets, J/Ψ, Υ etc..)