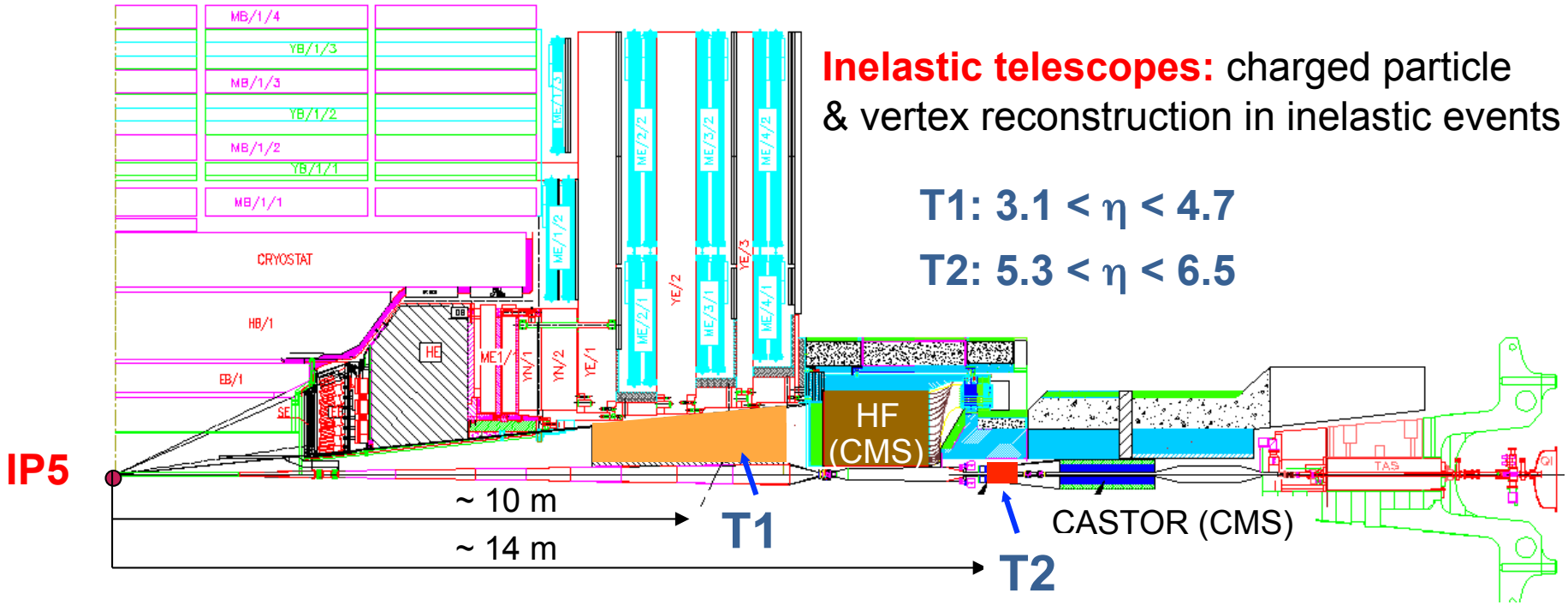
TOTEM
Cross-Sections
and
Forward Multiplicities

Nicola Turini 11 feb 2013

Totem experimental setup

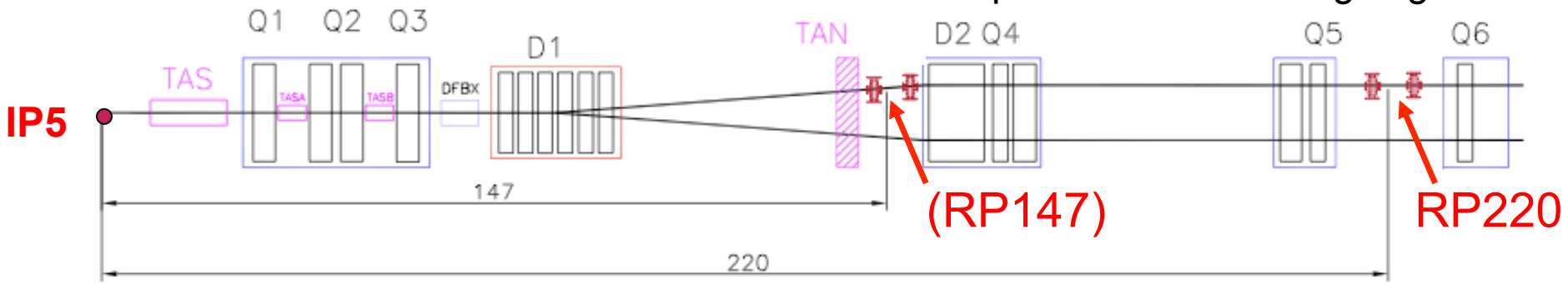


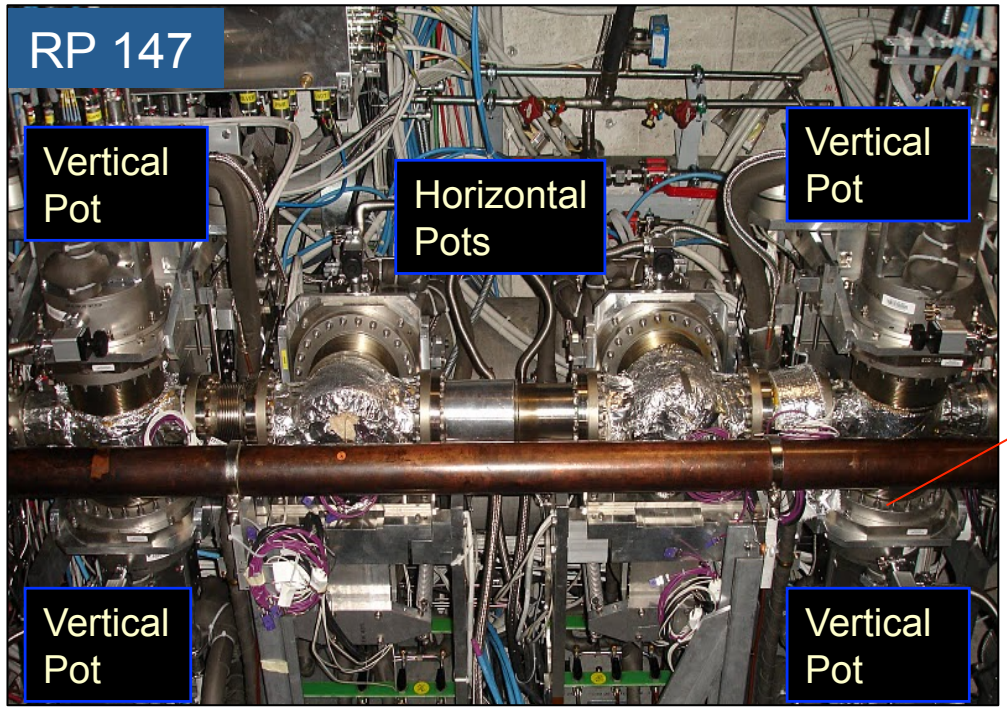
Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

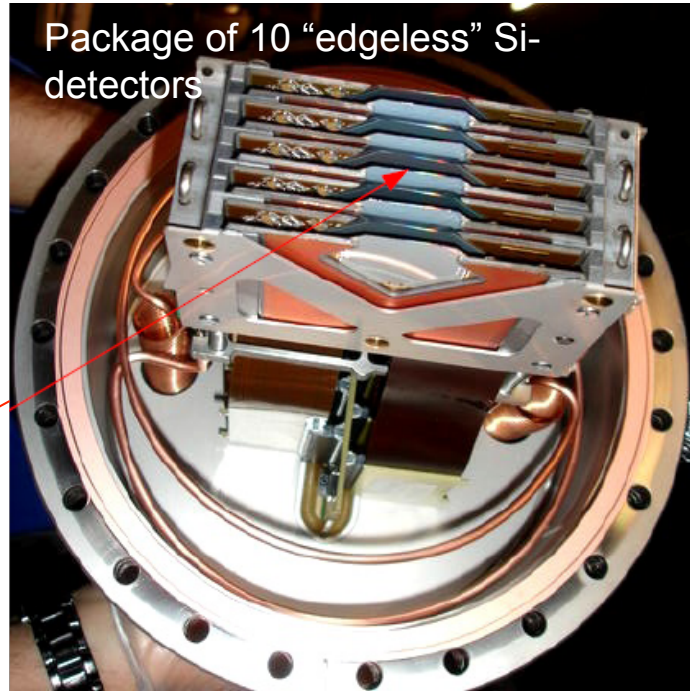
T1: 3.1 < η < 4.7

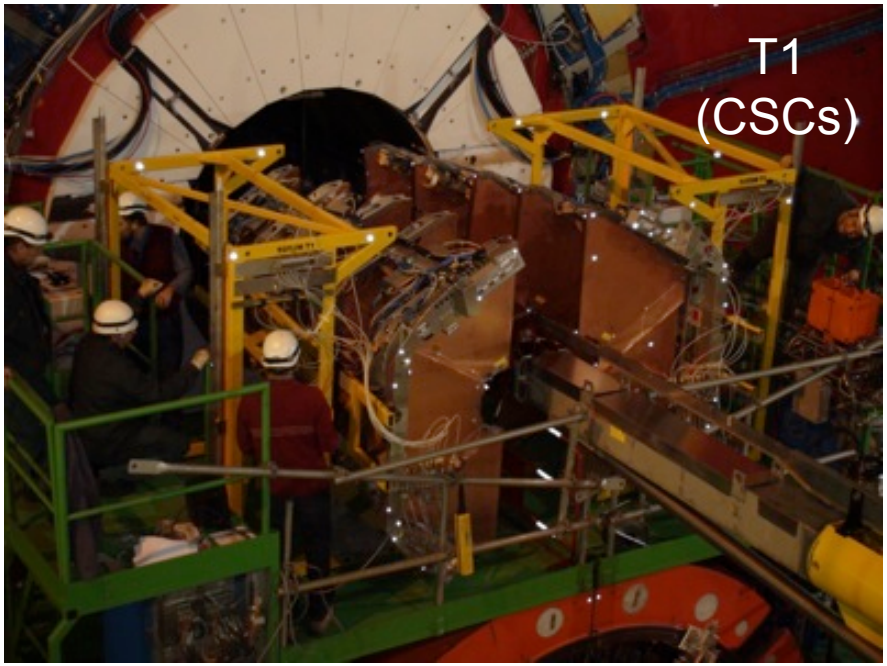
T2: 5.3 < η < 6.5

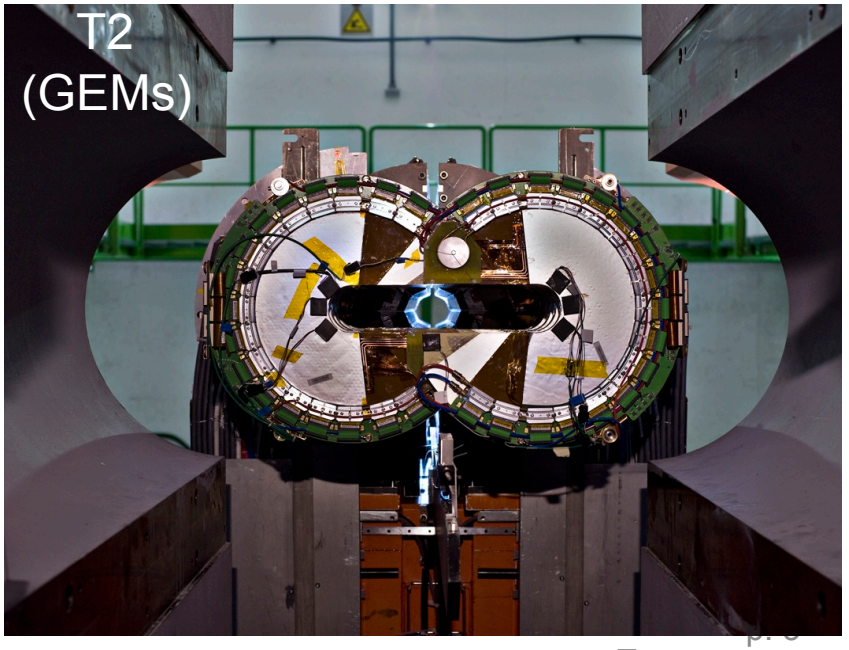
Roman Pots: measure elastic & diffractive protons close to outgoing beam




RP 147
Vertical Pot
Horizontal Pots
Vertical Pot
Vertical Pot
Vertical Pot


Package of 10 “edgeless” Si-detectors


T1
(CSCs)


T2
(GEMs)

Totem publications

2011 publications

- Proton-proton elastic scattering at the LHC energy of $\sqrt{s}$ = *7 TeV.*
  2011 EPL 95 41001
- First measurement of the total proton-proton cross-section at the LHC energy of $\sqrt{s}$ = *7 TeV.*
  2011 EPL 96 21002

2012 publications

- Measurement of the forward charged particle pseudorapidity density in pp collisions at $\sqrt{s}$ = 7 TeV with the TOTEM experiment.
  2012 EPL 98 31002
- Measurement of proton-proton elastic scattering and total cross-section at $\sqrt{s}$ = 7 TeV
  2013 EPL 101 21002
- Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s}$ = 7 TeV
  2013 EPL 101 21003
- Luminosity-independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s}$ = 7 TeV
  2013 EPL 101 21004
- A luminosity-independent measurement of the proton-proton total cross-section at $\sqrt{s}$ = 8TeV
  CERN-PH-EP-2012-354

7TeV low β^*=3m elastic scattering measurements (2010 data)

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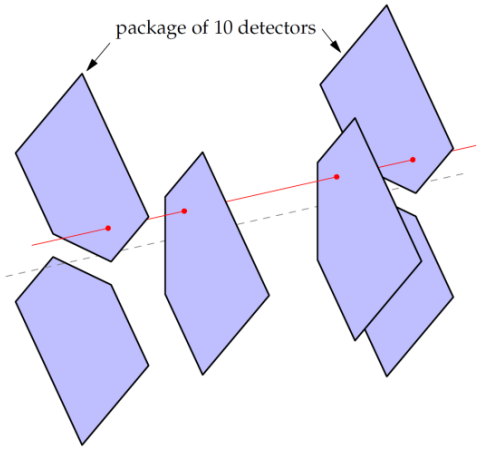
Proton reconstruction

Both angle projections reconstructed: Θ_x^* and Θ_y^*

- Θ_x^* from Θ_x @ RP220 (through dL_x/ds) $\quad \Theta_{x,RP} \approx dL_x/ds\ \Theta_x^*$
- Θ_y^* from y @ RP220 (through L_y) $\quad y_{,RP} \approx L_y\ \Theta_y^*$



Track based alignment

→ **Alignment**

- Alignment between pots with overlapping tracks (~1μm)
- Alignment with respect to the beam – collimator like scraping exercise (~20μm)
- Mechanical constraints between top and bottom pots (~10μm)

→ **Optics errors**

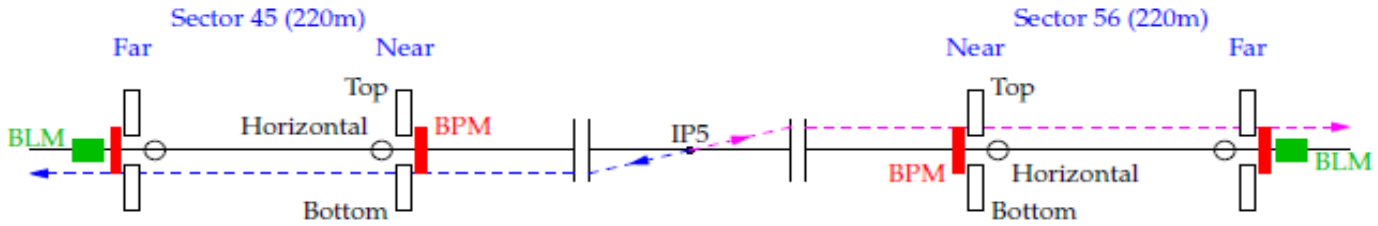
- Depend on LHC imperfections and LHC configuration
- Optics estimation with elastic scattering
  - $\Theta_{left}^* = \Theta_{right}^*$ (proton pair collinearity)
  - Proton position ↔ angle correlations (+Liouville's theorem)
  - L_x=0 determination, coupling estimation

A difficult measurement, data driven analysis

Elastic scattering: difficult precise measurement

1. **Kinematics reconstruction**
   - proton tracks in RPs → proton kinematics at IP
2. **Elastic tagging**
   - Topology : diagonals
   - Proton co-linearity : compare left and right reconstructed angles
   - No forward momentum loss : remove protons shifted due to dispersion
3. **Acceptance corrections**
   - Finite size of RP sensors, LHC apertures
   - Azimuthal symmetry of el. scattering → geometrical corrections
   - Beam divergence → correction for missing protons at RP edges
4. **Unfolding of resolution effects**
   - Numerical, kernel function based and completely analytical unfolding
5. **Inefficiency corrections**
   - RP inefficiencies
   - pile-up related inefficiencies : elastic event + another track in a RP
6. **Luminosity**
   - from CMS (if available, uncertainty 4%)
   - TOTEM luminosity measurement

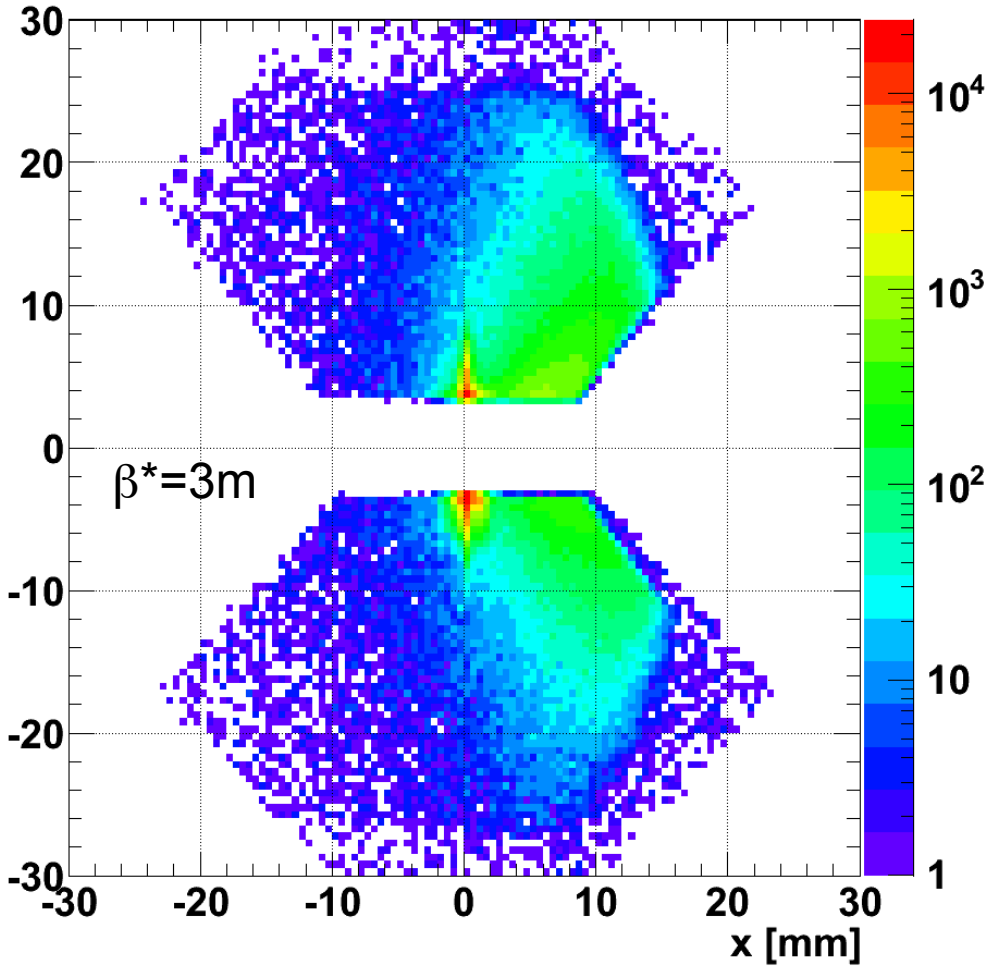
Elastic tagging : topology



Single diagonal

Sector 56

Sector 45



$t = -p^2 \theta^2$

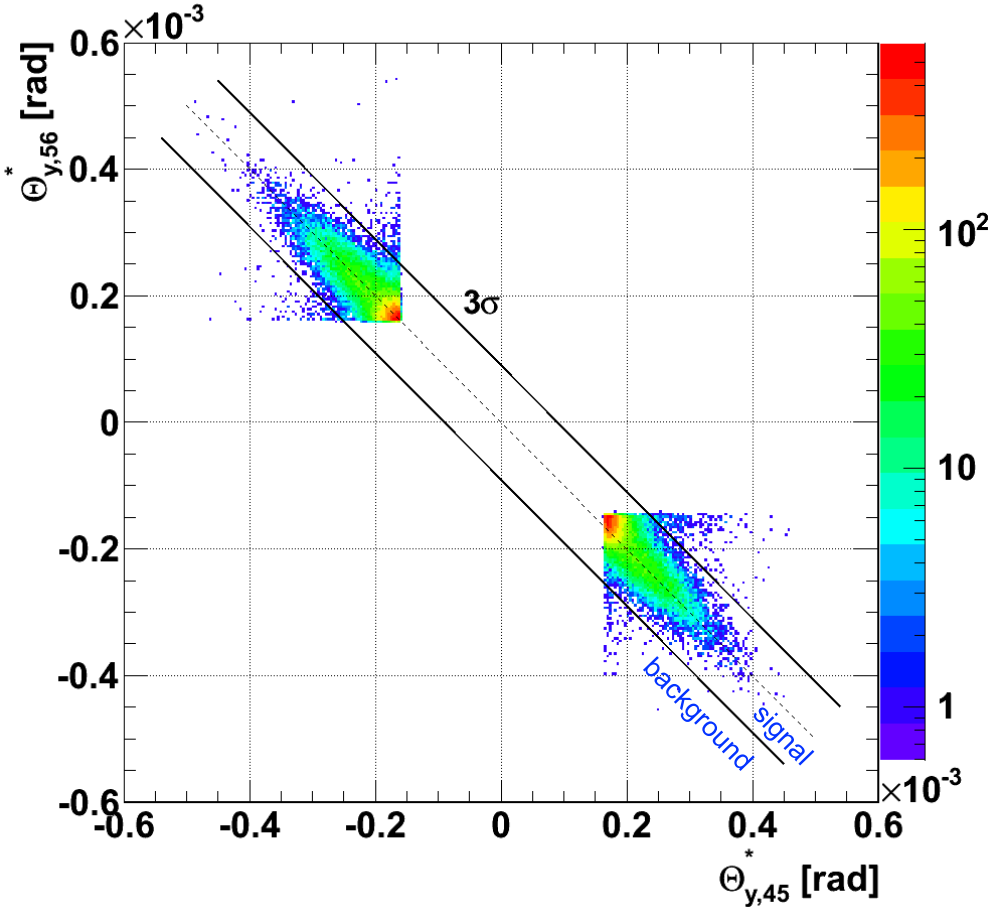
$\xi = \Delta p/p$

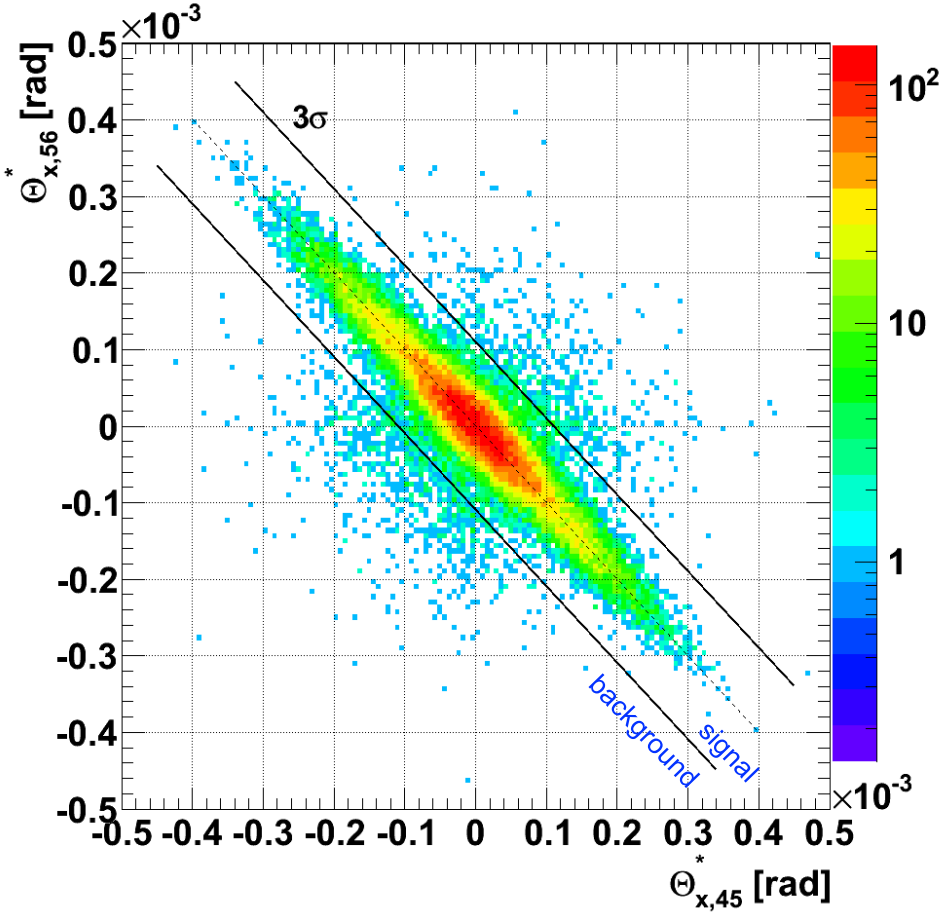
$y = L_y \Theta_y$

$x = L_x \Theta_x + \xi D$

$L_x \sim 0$

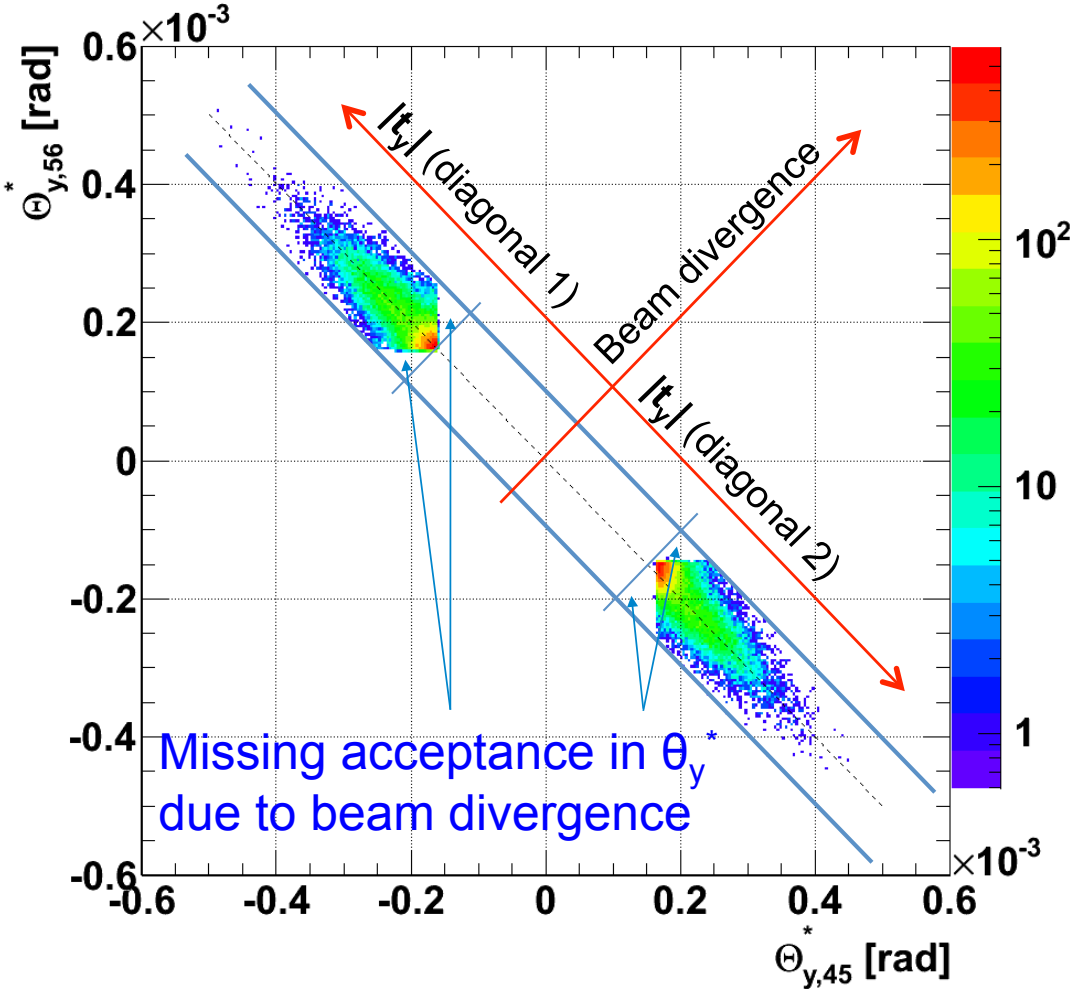
Elastic tagging : collinearity cuts

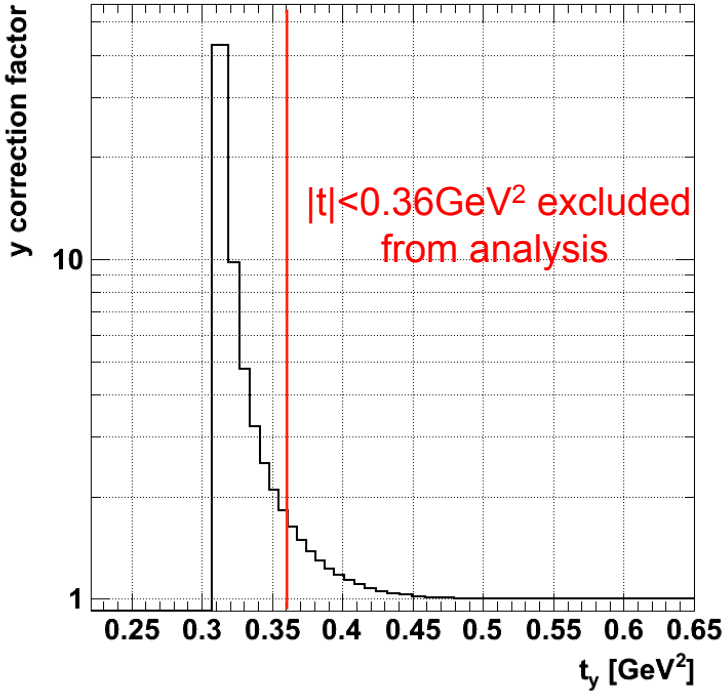




Data outside the 3σ cuts used for background estimation

t_y-acceptance corrections

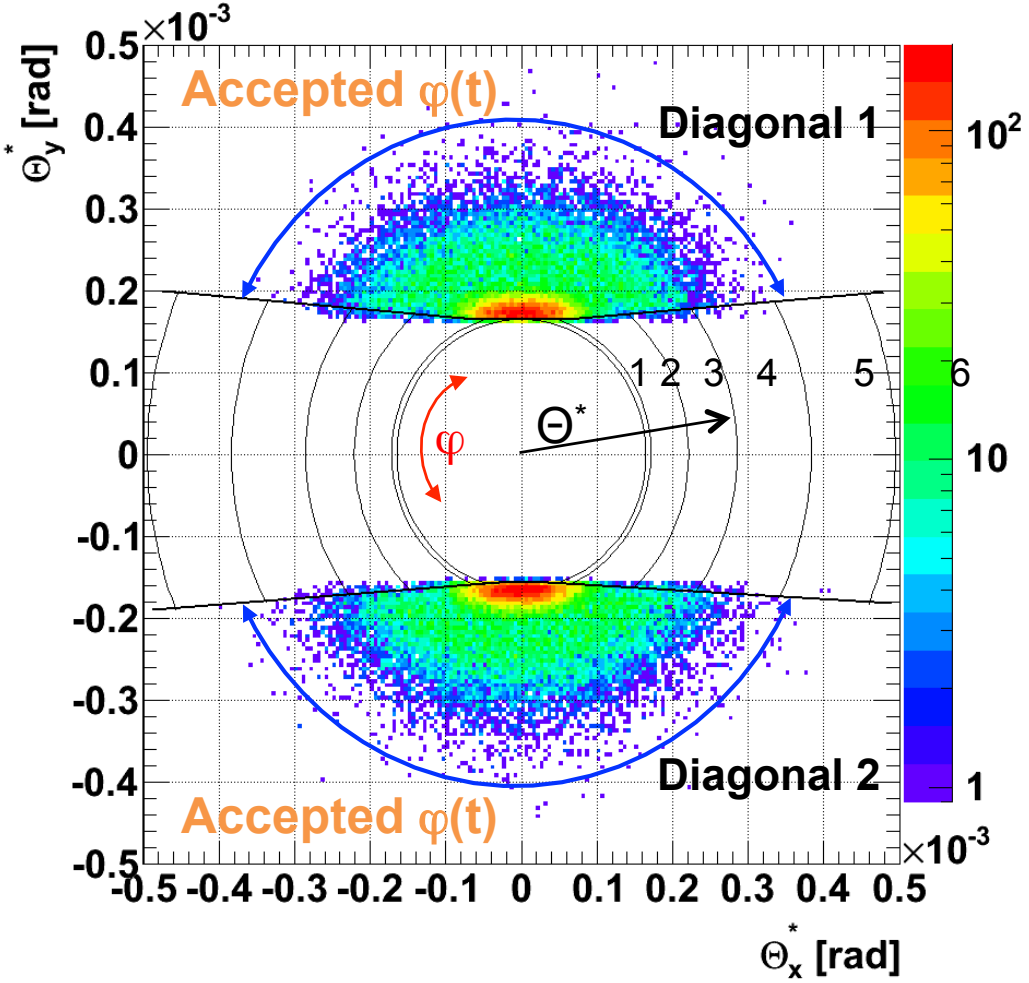




Correction error (t_y):

0.31 GeV² : 30%
0.33 GeV² : 11%
0.35 GeV² : 2%
0.4 GeV² : 0.8%
0.5 GeV² : 0.1%

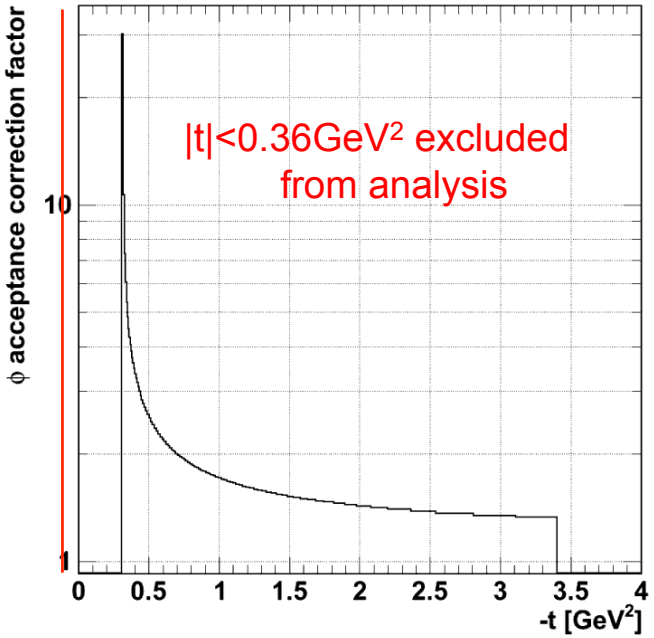
φ-acceptance correction



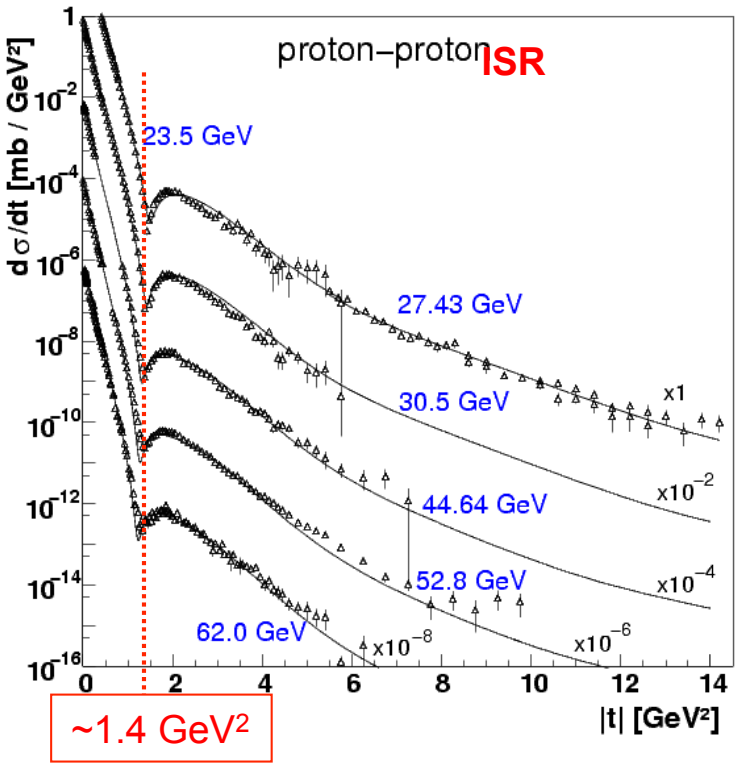
Critical at low t-acceptance limit

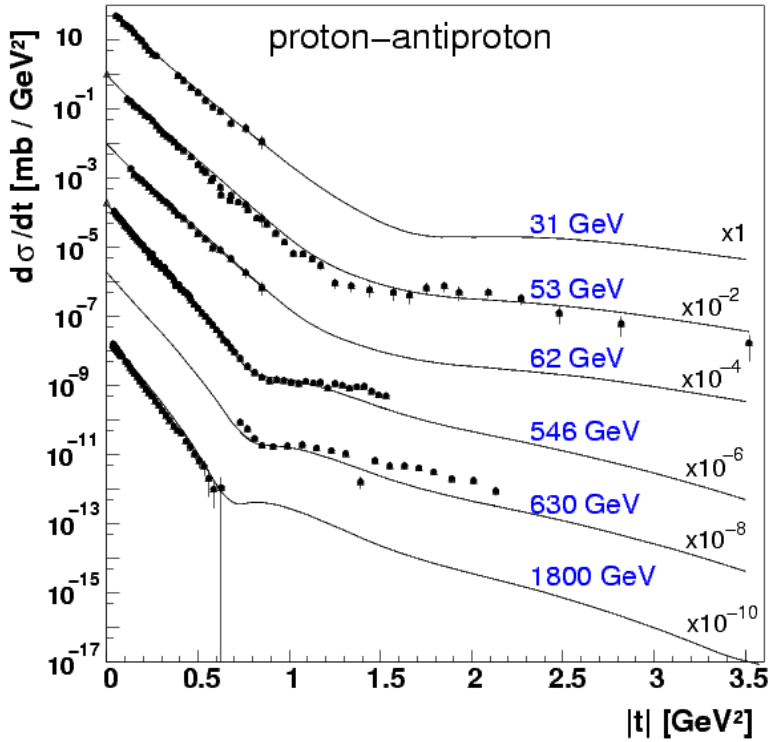
Total φ-acceptance correction

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**

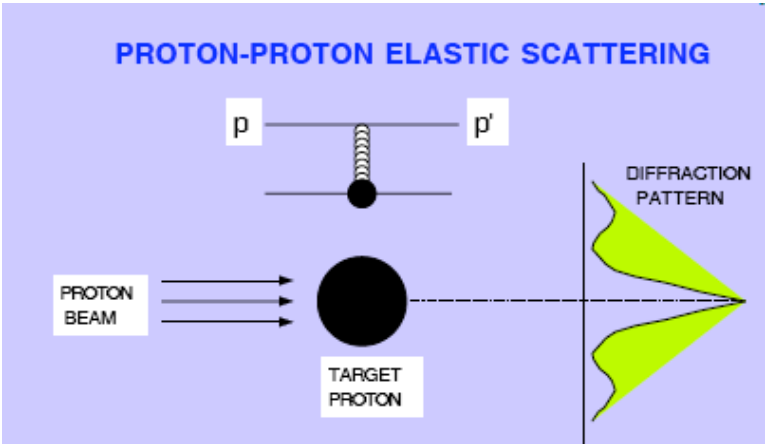


Elastic scattering – from ISR to Tevatron



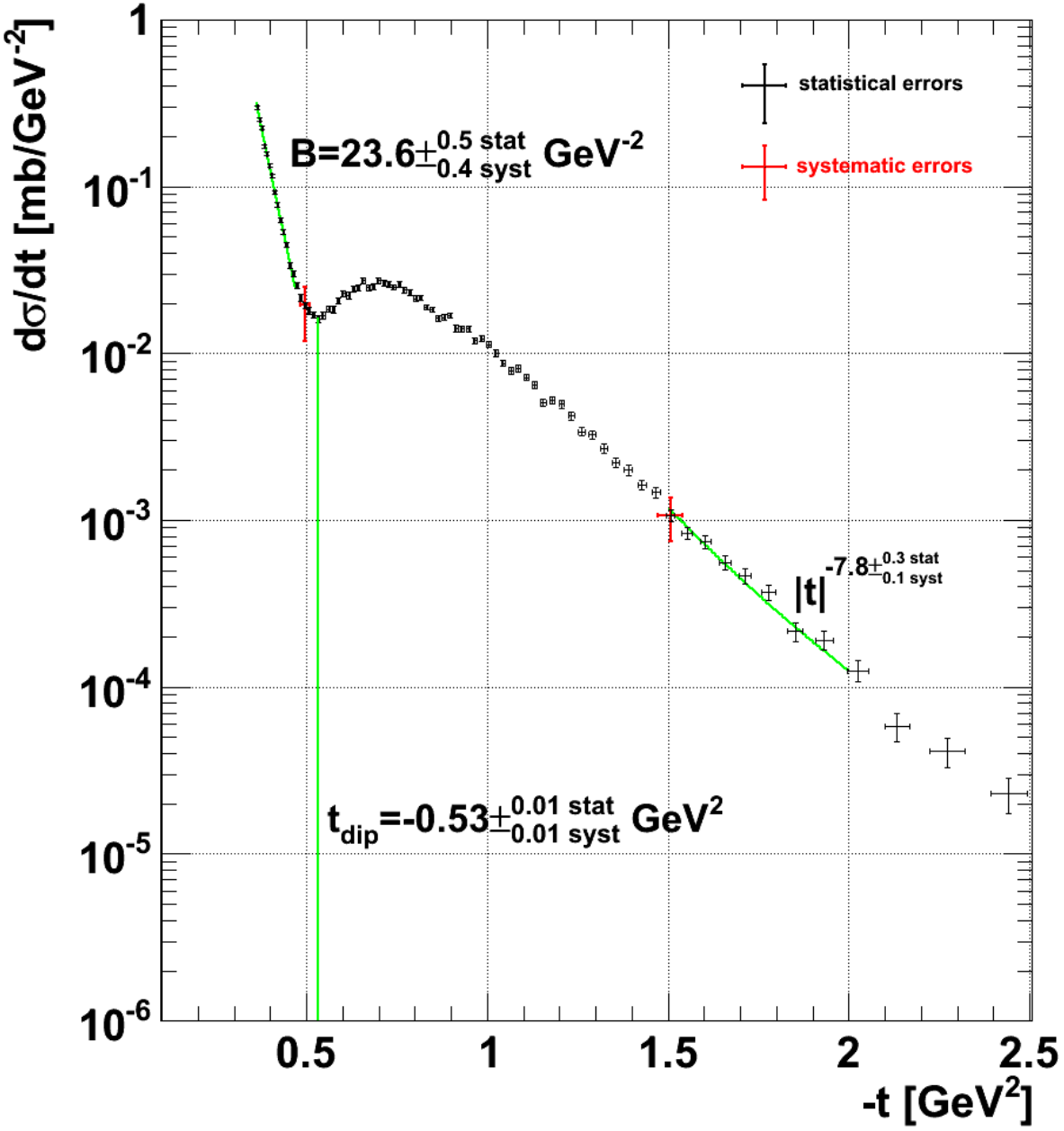


Diffractive minimum: analogous to Fraunhofer diffraction:



- minimum moves to lower |t| with increasing s
  → interaction region grows (as also seen from σ_{tot})
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, $p^{-}p$
  → different mix of processes

TOTEM first dσ/dt result



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

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

The TOTEM Collaboration
G. Antchev[1], P. Aspell[2], I. Atanassov[2,a], V. Avati[2], J. Baechler[2], V. Berardi[56,5a], M. Berretti[3b], M. Bozzo[6b,6a], E. Brücken[3a,3b], A. Buzzo[6a], F. S. Cafagna[5a], M. Calicchio[5b,5a], M. G. Catanesi[5a], C. Covault[7], M. Csanád[4,b], T. Csörgő[4], M. Deile[2], E. Dobrowolski[8], M. Doubek[9], K. Eggert[10], V.Eremin[c], F. Ferro[6a], A. Fiergolski[c,d], F. Garcia[3a], S. Giani[2], V. Greco[57,2], L. Grzanka[8,d], J. Heino[3a], T. Hilden[3a,3b], M. Janda[9], J. Kašpar[1a,2], J. Kopal[1a,2], V. Kundrát[1a], K. Kurvinen[3a], S. Lami[5a], G. Latino[57], R. Lauhakangas[3a], T. Leszko[10], E. Lippmaa[a], M. Lokajíček[1a], M. Lo Vetere[6b,6a], F. Lucas Rodríguez[2], M. Macrí[6a], L. Magaletti[56,5a], G. Magazzú[7a], A. Mercadante[56,5a], S. Minutoli[6a], F. Nemes[4,b], H. Niewiadomski[2], E. Noschis[2], T. Novák[4,f], E. Oliveri[57], F. Oljemark[3a,3b], R. Orava[3a,3b], M. Oriunno[2,g], K. Österberg[3a,3b], A.-L. Perrot[2], P. Palazzi[57], E. Piedigrossi[7a], J. Petäjäjärvi[3a], J. Procházka[1a], M. Quinto[5a], E. Radermacher[2], E. Radicioni[5a], F. Ravotti[2], E. Robutti[6a], L. Ropelewski[2], G. Ruggiero[2], H. Saarikko[3a,3b], A. Santroni[56,6a], A. Scribano[7b], G. Sette[57,7a], W. Snoeys[2], F. Spinella[7a], J. Sziklai[4], C. Taylor[8], N. Turini[7b], V. Vacek[9], M. Vitek[1b], J. Welti[3a,3b] and J. Whitmore[10]

[1a] *Institute of Physics of the Academy of Sciences of the Czech Republic, Praha, Czech Republic.*
[1b] *Czech Technical University, Praha, Czech Republic.*
[2] *National Institute of Chemical Physics and Biophysics NICPB, Tallinn, Estonia.*
[3a] *Helsinki Institute of Physics, Finland.*
[3b] *Department of Physics, University of Helsinki, Finland.*
[4] *MTA KFKI RMKI, Budapest, Hungary.*
[5a] *INFN Sezione di Bari, Italy.*
[5b] *Dipartimento Interateneo di Fisica di Bari, Italy.*
[6a] *Sezione INFN, Genova, Italy.*
[6b] *Università degli Studi di Genova, Italy.*
[7a] *INFN Sezione di Pisa, Italy.*
[7b] *Università degli Studi di Siena and Gruppo Collegato INFN di Siena, Italy.*
[8] *CERN, Geneva, Switzerland.*
[9] *Case Western Reserve University, Dept. of Physics, Cleveland, OH, USA.*
[10] *Penn State University, Dept. of Physics, University Park, PA, USA.*

[EPL 95 (2011) 41001]

7TeV Cross Section Measurements

Nicola Turini 11 feb 2013

7 TeV Cross Section measurement

elastic observables only:

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

(ρ=0.14 [COMPETE])

June 2011 (EPL96): σ_{tot} = (98.3 ±2.8) mb
Oct. 2011 (EPL101): σ_{tot} = (98.6 ±2.2) mb

σ_{tot}

ϱ independent:

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

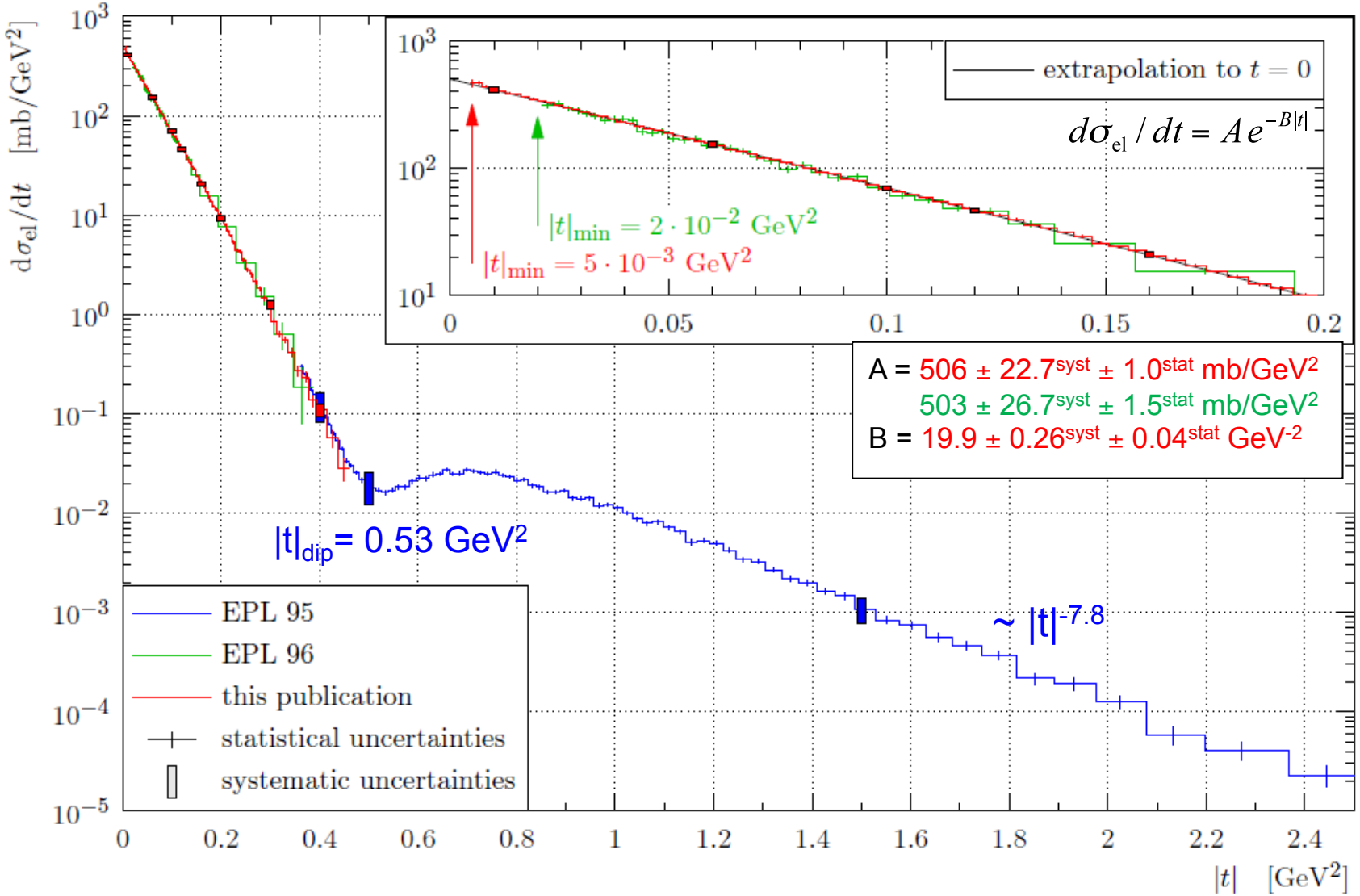
σ_{tot} = (99.1 ± 4.3) mb

luminosity independent:

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

σ_{tot} = (98.0 ± 2.5) mb

7 TeV elastic differential cross section



8TeV Total, Elastic and Inelastic cross section

July 2012: runs at $\beta^* = 90$ m

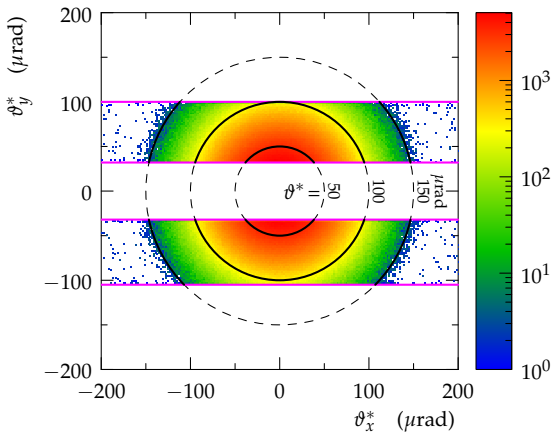
dataset	date	bunches	RPs	$\lvert t\rvert_{\min}$ (GeV^2)	$\mathcal{L}$ (mb^{-1})	
1	7 July, 1st fill	1	3σ	$4 \cdot 10^{-3}$	–	
2	7 July, 2nd fill	1	6σ	$7 \cdot 10^{-3}$	≈ 40	Ds2
3*a*	12–13 July	1	9.5σ	$15 \cdot 10^{-3}$	≈ 30	Ds3
3*b*	12–13 July	2 or 3	9.5σ	$15 \cdot 10^{-3}$	≈ 820	Ds4

The analysis has been performed on two datasets Ds2 and Ds3

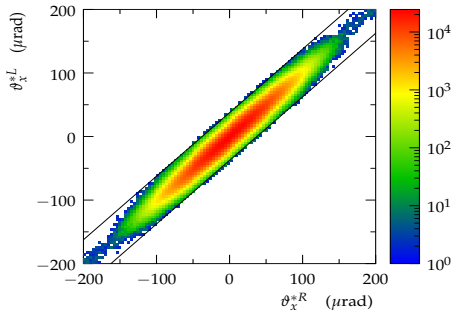
	Dataset	RP position	$\lvert t\rvert_{\min}$ [GeV^2]	elastic events	inelastic events
Ds2	1	$6.0\,\sigma_{\text{beam}}$	0.01	416k	2.30M
Ds3	2	$9.5\,\sigma_{\text{beam}}$	0.02	238k	1.72M

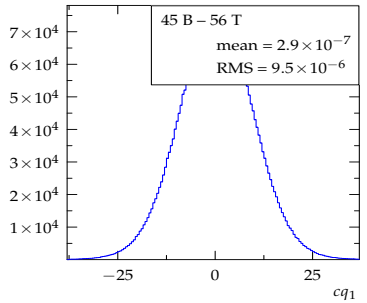
Elastic scattering analysis

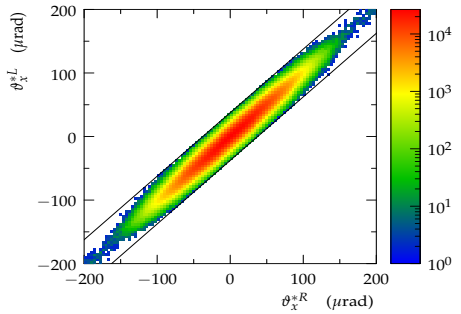
Source	Effect on	$\lvert t\rvert = 0.01\,\mathrm{GeV}^2$	$0.1\,\mathrm{GeV}^2$	$0.2\,\mathrm{GeV}^2$
Alignment	t	$\pm 0.21\,\%$	$\pm 0.3\,\%$	$\pm 0.57\,\%$
Kinematics Reconstruction: Optics, Beam Energy	t	$\pm 1.09\,\%$	$\pm 0.72\,\%$	$\pm 4.3\,\%$
Selection	norm.		$\pm 0.5\,\%$	
Acceptance (corr. factor)	dN/dt	3.3 ± 0.024	1.2 ± 0.002	1.8 ± 0.004
Resolution Unfolding	t	$(0.5 \pm 0.1)\,\%$	$(-0.2 \pm 0.003)\,\%$	$(-2.6 \pm 0.1)\,\%$
Efficiency	norm.	Uncorrelated ineff: $(10 \pm 0.6)\,\%$ Correlated ineff. : $(3 \pm 1)\,\%$ Pile-up: $(4.7 \pm 0.4)\,\%$		
Extrapolation/Fit		$dN_{el}/dt\lvert_{t=0}$	$\pm 2.5\,\%$	
		B	$(19.9 \pm 0.3)\,\mathrm{GeV}^{-2}$	

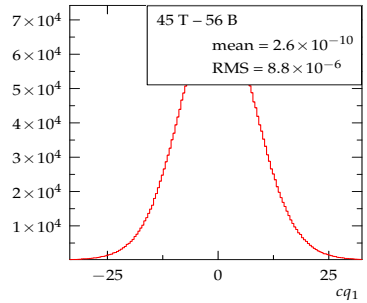


cut 1

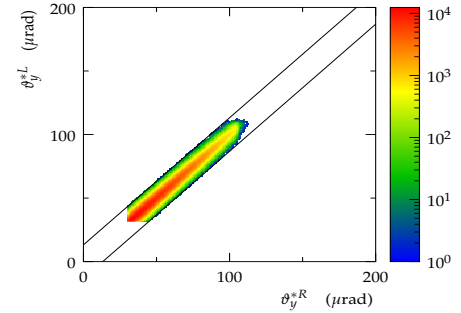


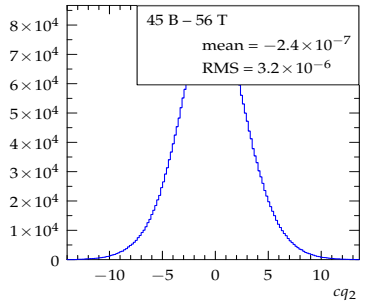


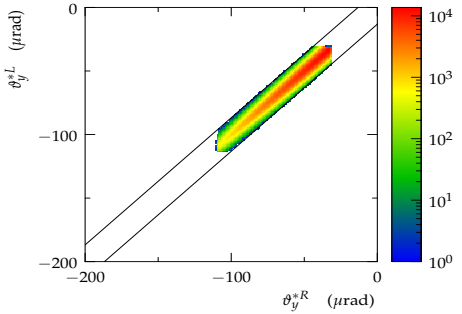


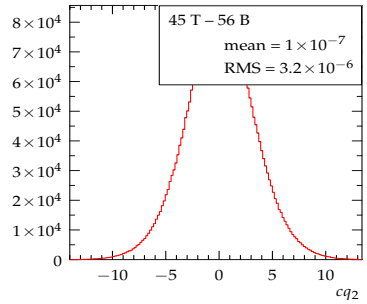


cut 2

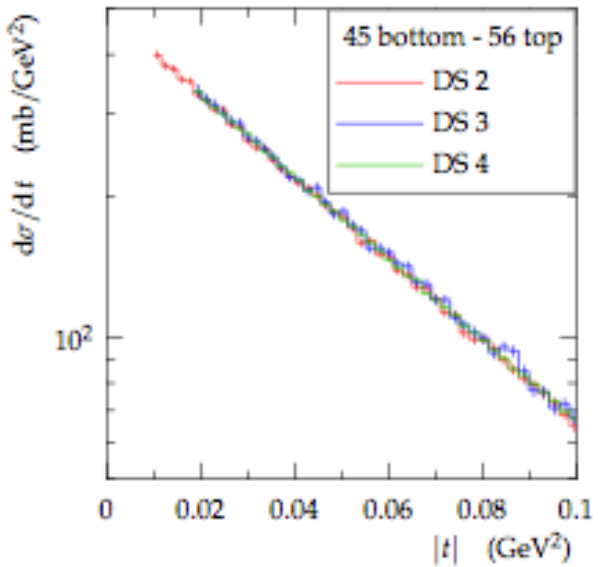


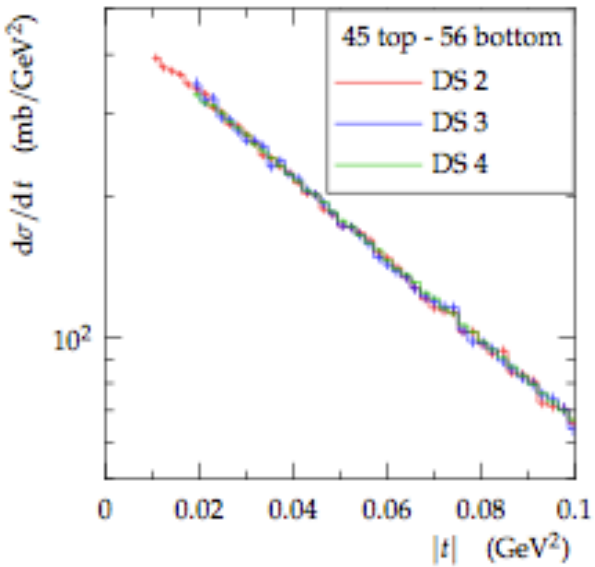


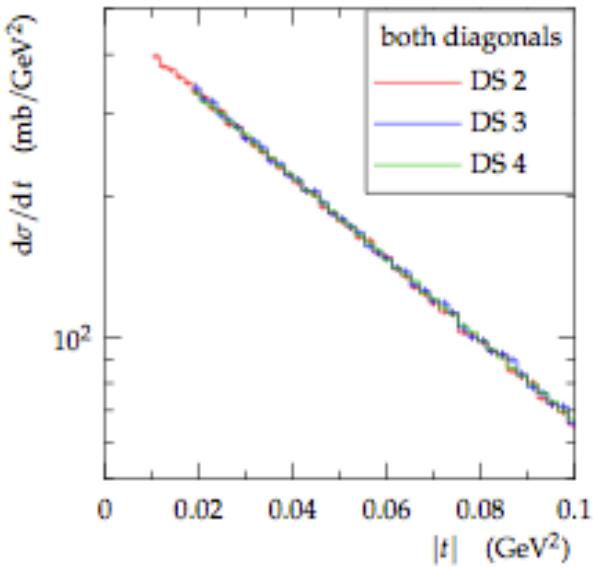




Differential elastic cross section

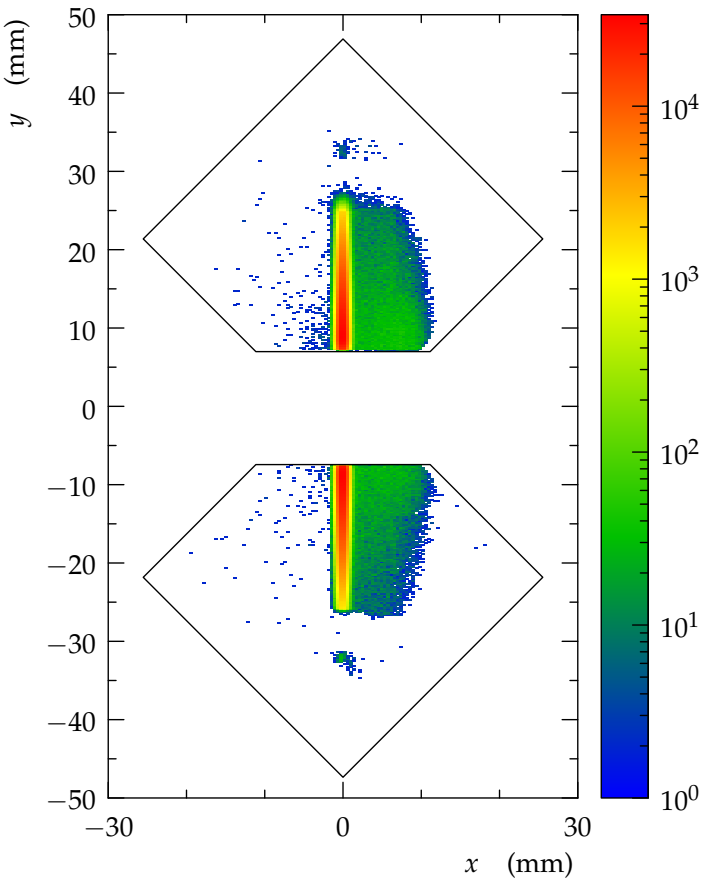




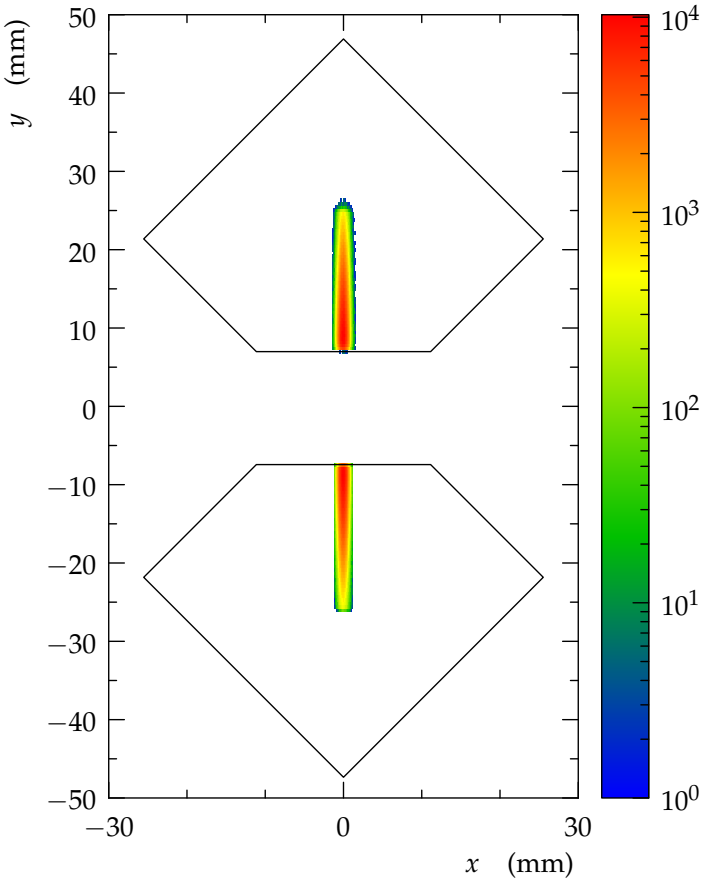


Comparison between the 3 different datasets, at different distance from the beam, and the two diagonals.

β*= 90m hit distribution



Raw hit distribution



Elastic protons hit distribution

Inelastic rate

- The trigger required at least one track in T2.
- Non colliding bunches used to estimate the beam-gas event rate.
- No-bias trigger subsample used to estimate the trigger efficiency and central diffraction events getting in T1 and not in T2.
- Central diffraction rate outside Totem inelastic detectors acceptance estimated via MonteCarlo.

Source	Correction	Uncertainty	Effect on
Beam gas	0.45 %	0.45 %	all rates
Trigger Efficiency	1.2 %	0.6 %	all rates
Pile up	2.8 %	0.6 %	all rates
T2 reconstruction	0.35 %	0.2 %	N_{T2vis}
	0.8 %	0.4 %	N_{inel}, $N_{\lvert\eta\rvert<6.5}$
"T1 only"	1.2 %	0.4 %	N_{inel}, $N_{\lvert\eta\rvert<6.5}$
Internal Gap covering T2	0.4 %	0.2 %	N_{inel}, $N_{\lvert\eta\rvert<6.5}$
Central diffraction	-	0.35 %	N_{inel}, $N_{\lvert\eta\rvert<6.5}$
Low mass diffraction (seen)	0.4 %	0.2 %	$N_{\lvert\eta\rvert<6.5}$
Low mass diffraction	4.8 %	2.4 %	N_{inel}

The T2 acceptance edge at $|\eta| = 6.5$ corresponds approximately to diffractive masses of 3.6GeV (at 50% efficiency). The contribution of events with all final state particles at $|\eta| > 6.5$ is estimated with QGSJET-II-03 after tuning the MonteCarlo prediction with the observed fraction of "1h" events.

8TeV cross sections

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

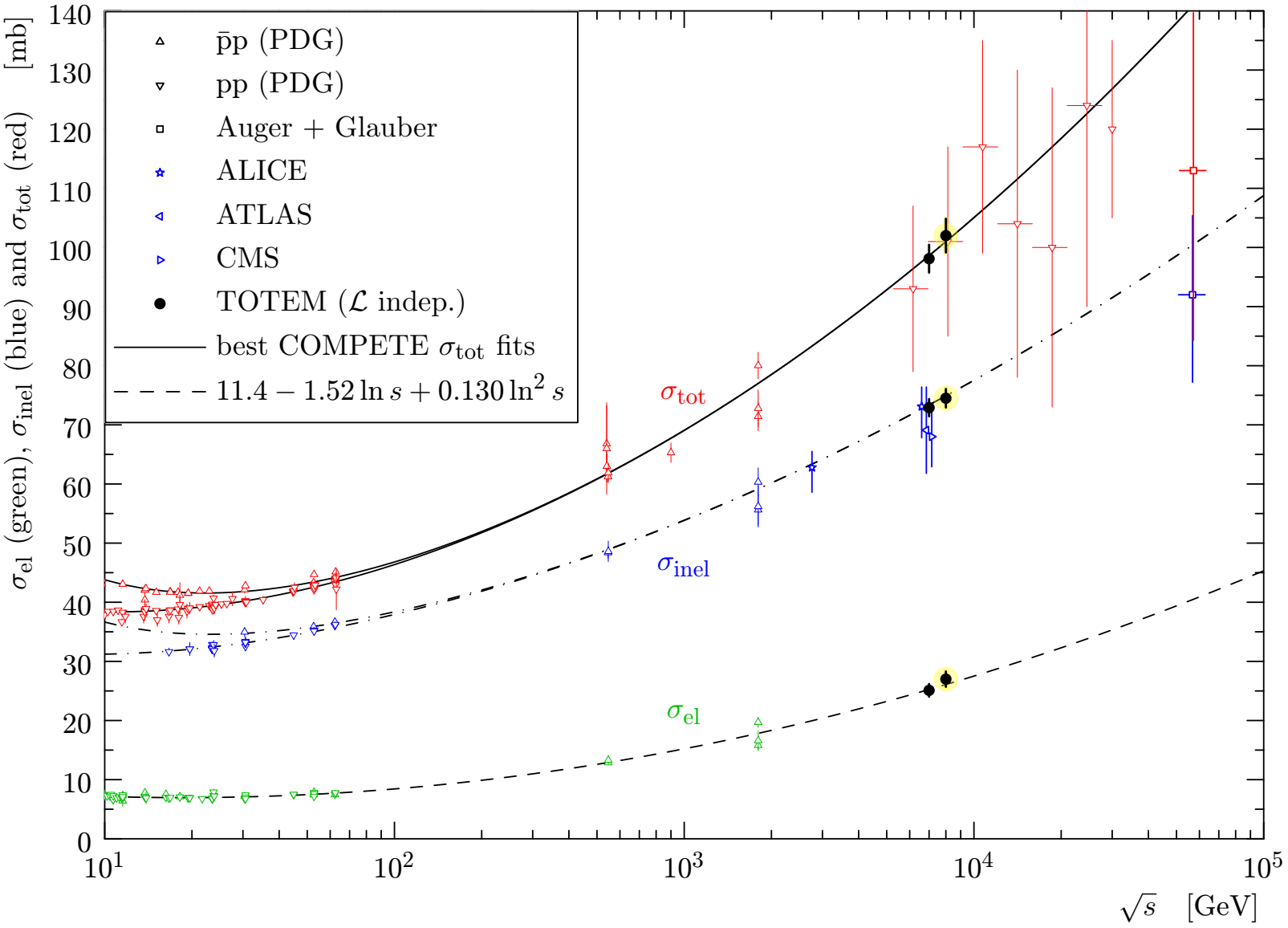
$$\sigma_{tot} = (101.7 \pm 2.9)mb$$

$$\frac{\sigma_{el}}{\sigma_{inel}} = 0.362 \pm 0.011$$

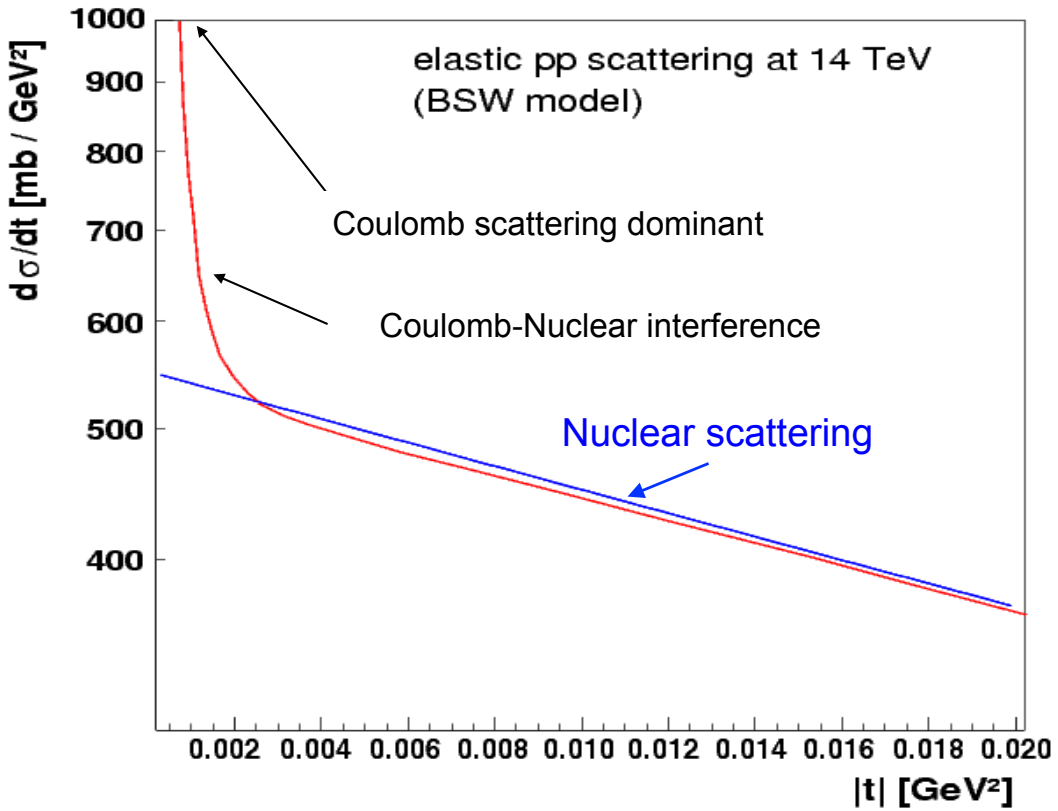
$$\sigma_{inel} = (74.7 \pm 1.7)mb$$

$$\sigma_{el} = (27.1 \pm 1.4)mb$$

8TeV cross sections



ρ measurement: elastic scattering at low |t|



Measurement of ρ by studying the Coulomb – Nuclear interference region down to

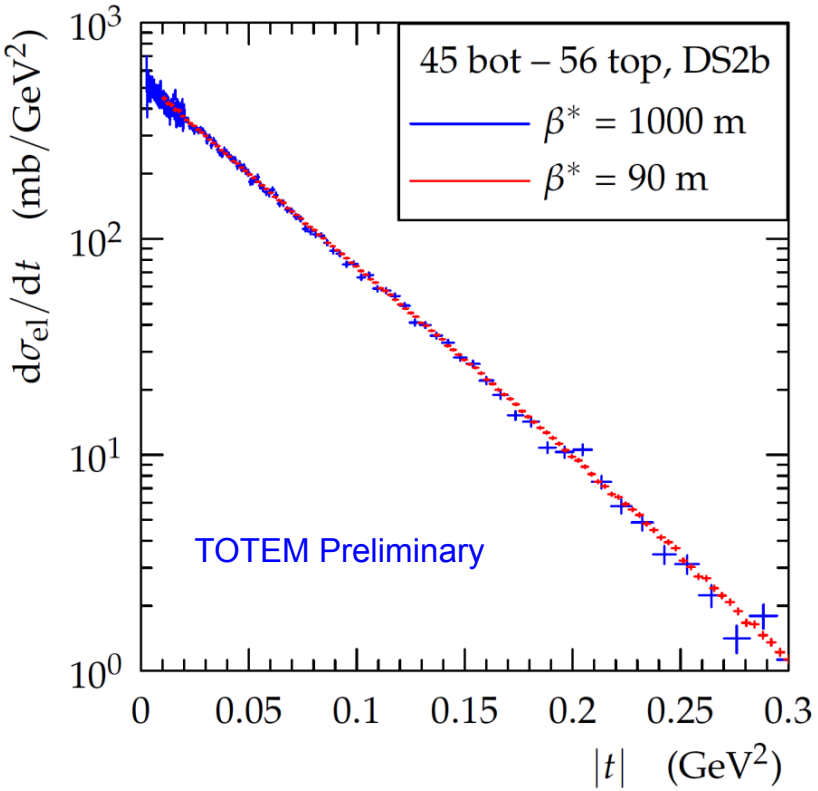
$|t| \sim 6 \times 10^{-4}$ GeV²

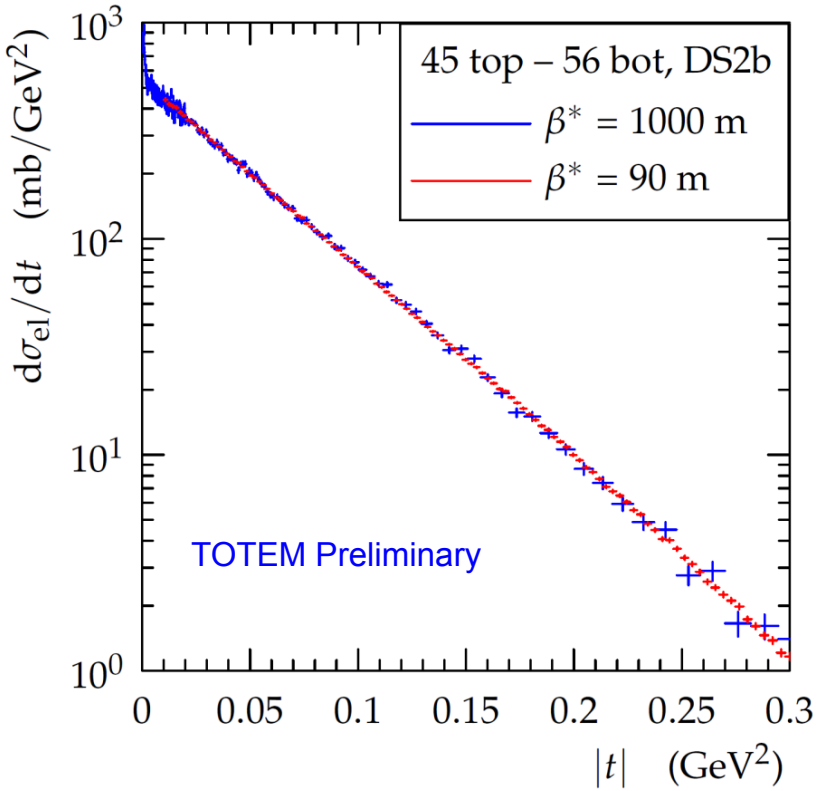
Reachable with β* ~ 1000 m!

First Coulomb interference region measurement

sqrt s = 8 TeV, β^* = 1000m

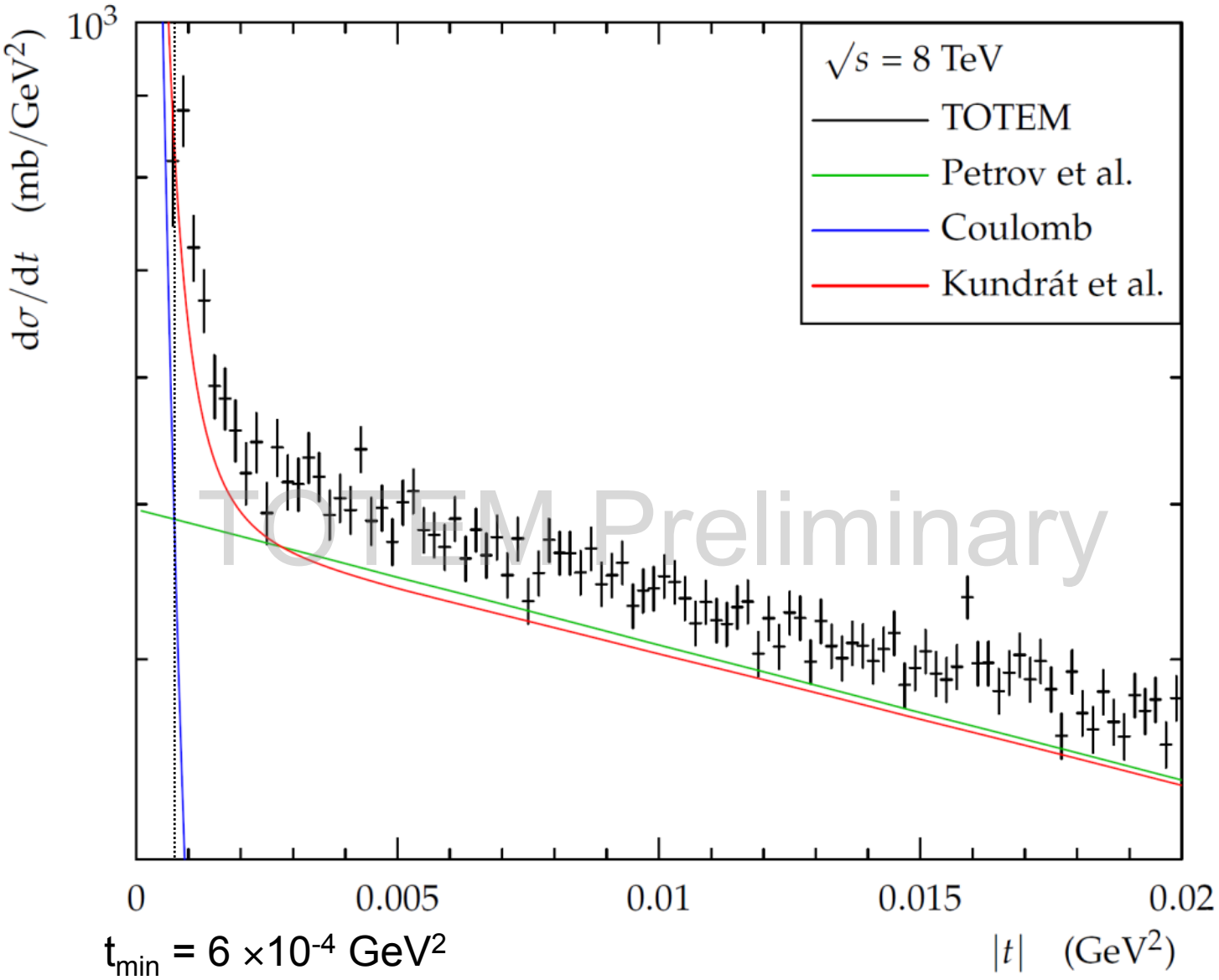
Luminosity calibration with luminosity independent total cross-section @ β^*=90m,
integration region: 0.01 GeV^2 < |t| < 0.3 GeV^2
L_{int} = 5.73 + 14.45 μb^{-1} = 20.18 μb^{-1}
t_{min} = 6 $\times 10^{-4}$ GeV^2





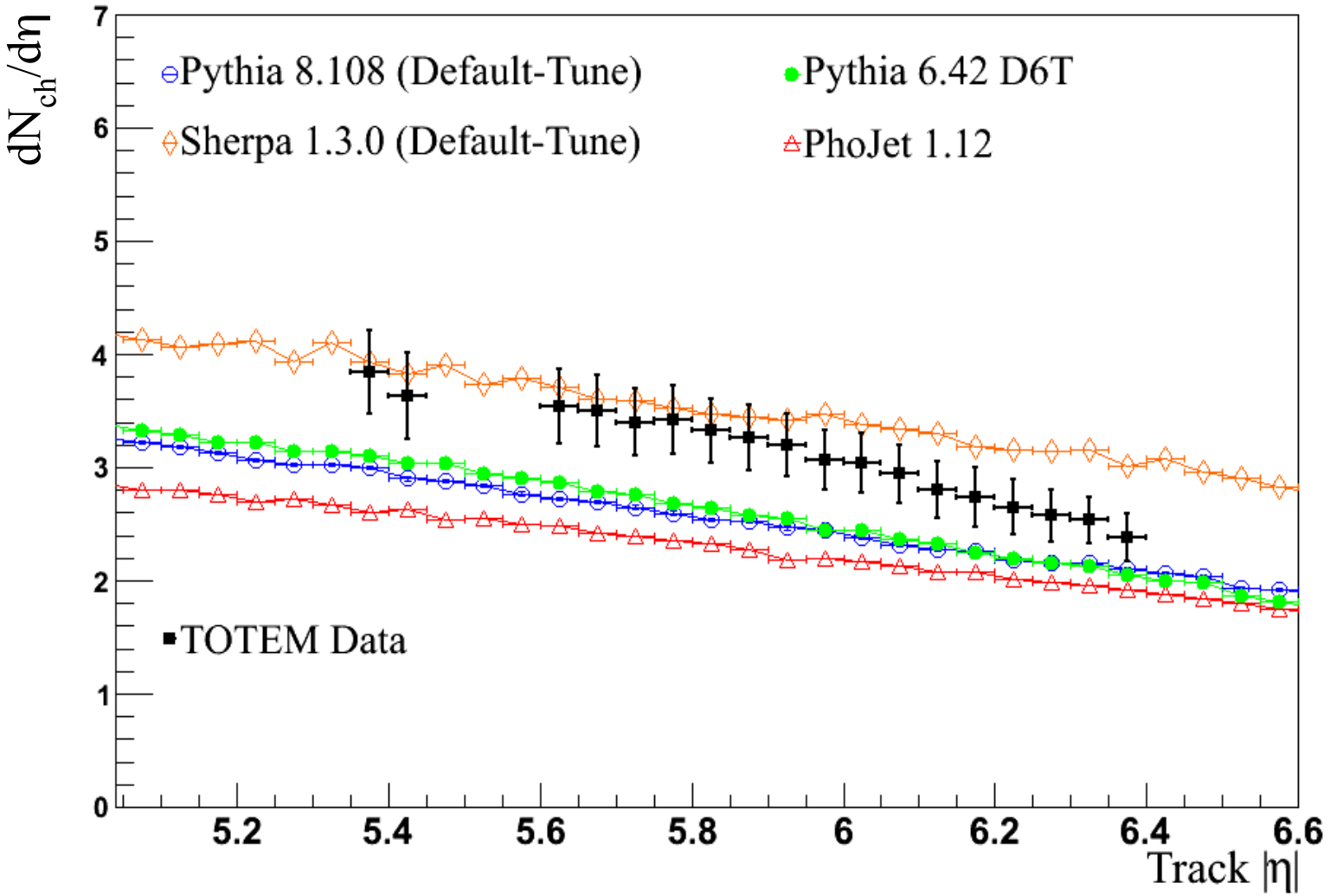
First Coulomb interference region measurement

sqrt s = 8 TeV, β^* = 1000m



t_{min} = 6 ×10^{-4} GeV^2

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



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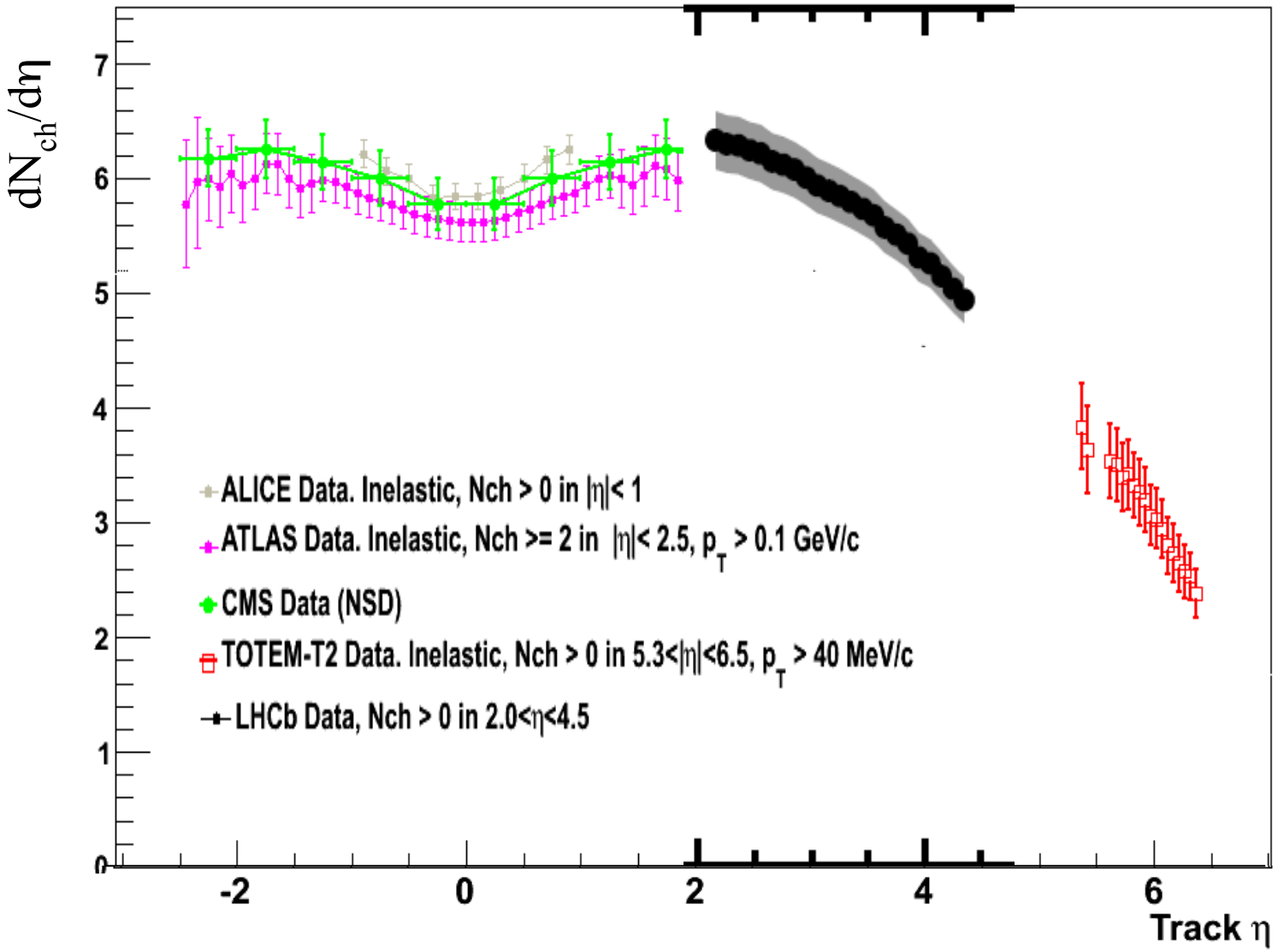
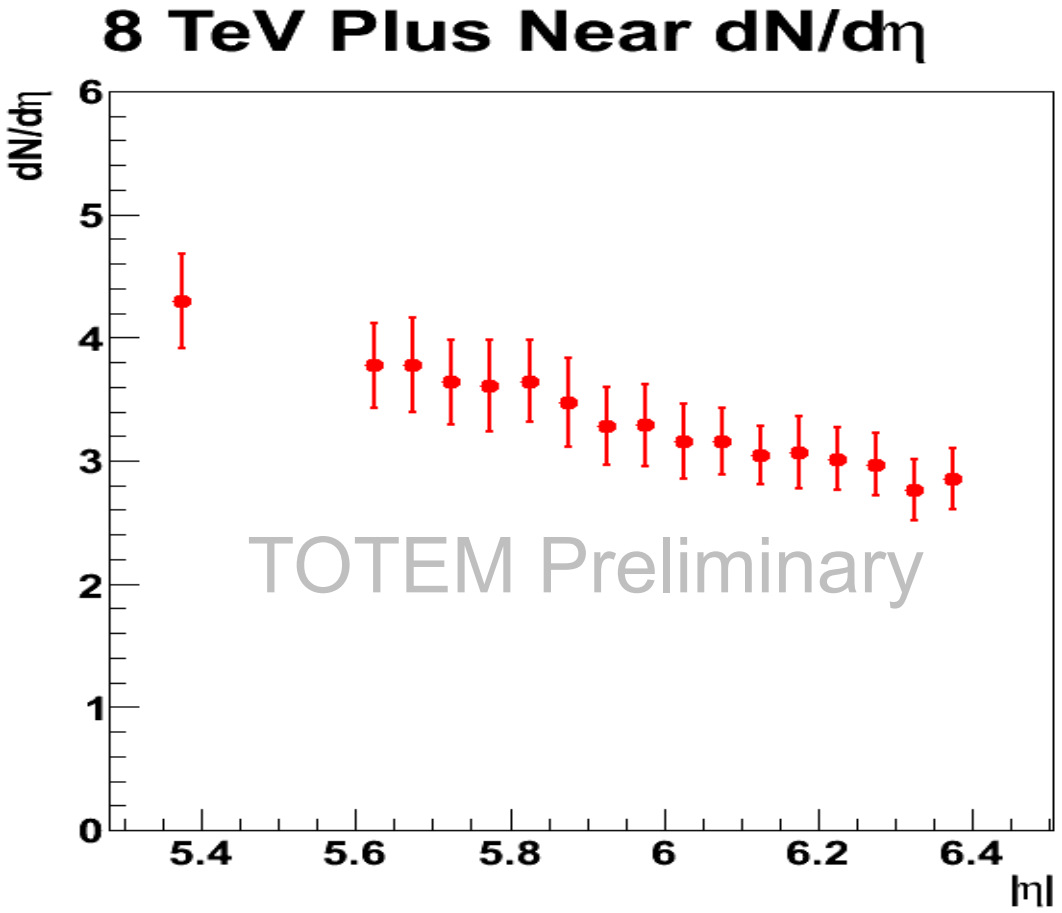
$dN_{ch}/d\eta$ combined with other LHC exp.



Ongoing activities within ***LPCC*** framework

First common CMS-TOTEM analysis $dN_{ch}/d\eta$ @ 8 TeV



Further steps:

Error estimation not complete.

Correction factors: high multiplicity events, trigger, pileup.

Include the other quarters

Conclusions

- Totem has measured the elastic, inelastic and total pp cross sections at $\sqrt{s}$ =7 and 8 TeV.
- The Fraunhofer peak has been detected and precisely measured at $\sqrt{s}$ =7.
- A forward charged tracks multiplicity has been measured in the T2 region at $\sqrt{s}$ = 7 TeV, while at 8 TeV the analysis is quite advanced (data in common with CMS).
- We are attempting to repeat the measurement at $\sqrt{s}$ = 2.7 TeV with the current data tacking although the optics is not optimal (β^*=11m)

Backup

Joint Data Taking with CMS

May 2012: low pileup run: $\beta^* = 0.6$ m, $\sqrt{s} = 8$ TeV, T1 & T2 & CMS read out

Date	Trigger	Inelastic events	
May 1	T2 || BX	~5 M	no RP

dN/dη,
correlations,
underlying event

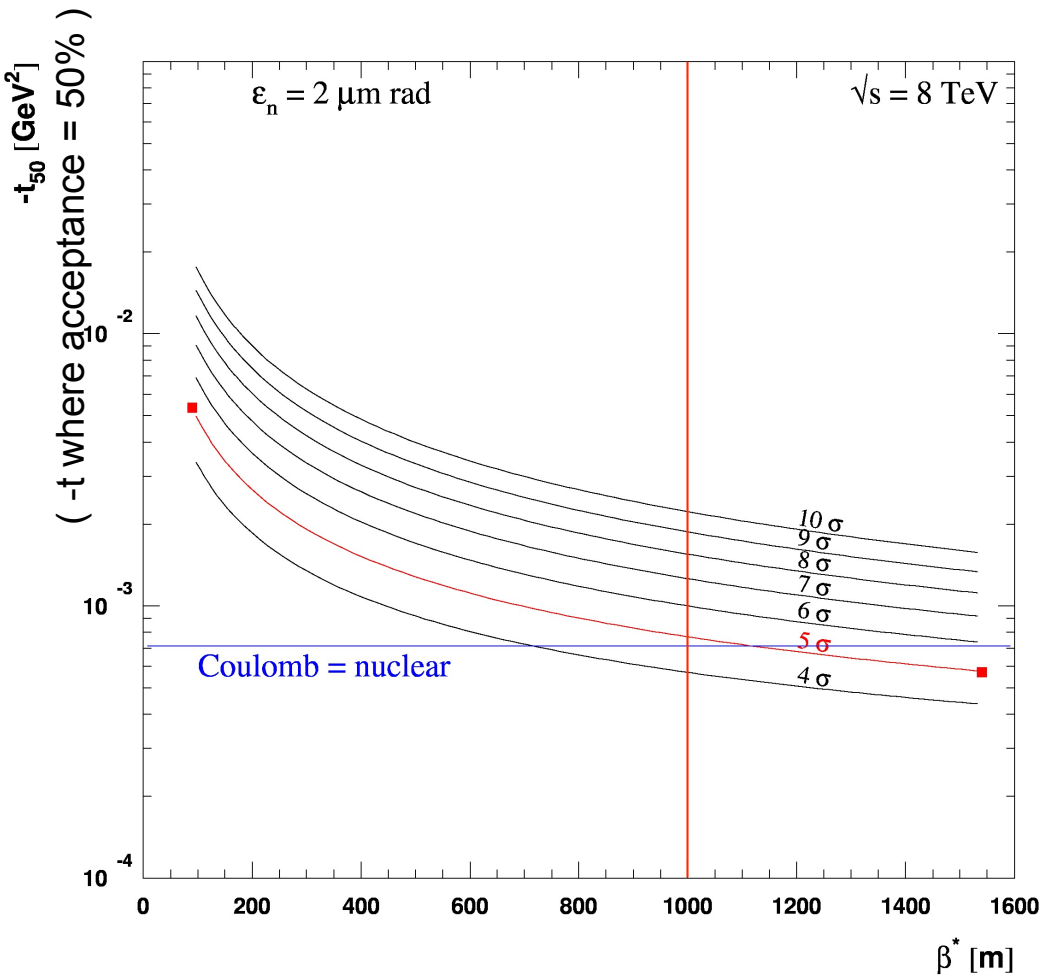
July 2012: $\beta^* = 90$ m, $\sqrt{s} = 8$ TeV, RP & T1 & T2 & CMS read out

Date, Set	Trigger	Inelastic events	RP position
July 7, DS 2	T2 || RP_{2arms} || BX	~2 M	6 σ
July 12-13, DS 3a	T2 || RP_{2arms} || BX	~10 M	9.5 σ V, 11σ H
July 12-13, DS 3b	T2 || RP_{2arms} || CMS (CMS = 2 jets @ $p^T > 20$GeV, 2 μ, 2 central e/γ)	~3.5 M	9.5 σ V, 11σ H

σ_{tot}, σ_{inel} with CMS,
soft & semi-hard diffraction,
correlations

- Combined $dN_{ch} / d\eta$ and multiplicity correlations
- Soft and hard diffraction: p + dijets (90m runs)
- $M_{jj}/M_{\zeta\zeta}$ correlation and search for exclusive dijet production (90m runs)

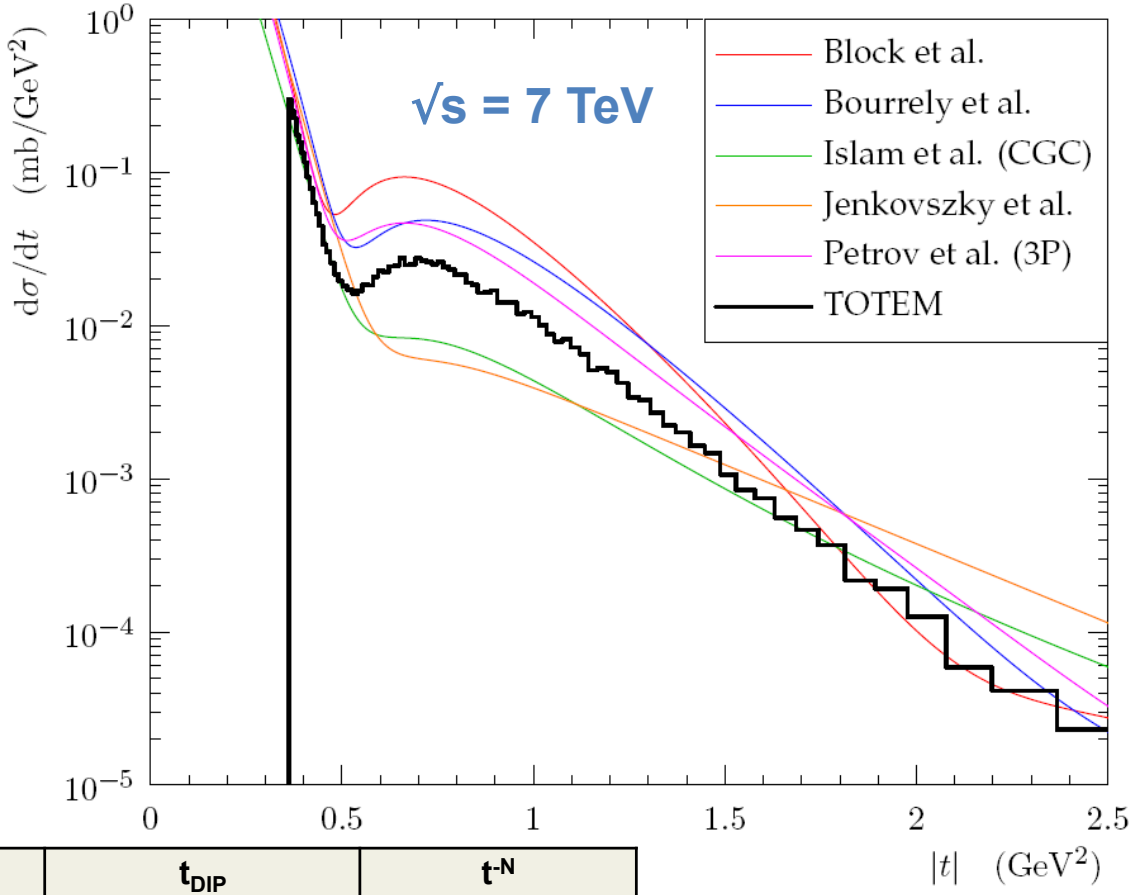
Reaching the Coulomb-Nuclear Interference Region



RP window position
(real σ for ε_n=2μm rad)

In October the beam was unsqeezed to reach the β* = 1Km
Totem could approach one vertical diagonal (Top – Bottom) up to 3σ from the beam axis. The other diagonal had to be put to 10σ due to safety (anti-collision) switches blocking the contemporary approach of top-bottom telescopes.

TOTEM Result + some models



	B (t=-0.4 GeV²) [GeV⁻²]	t_{DIP} [GeV²]	t^{-N} [1.5–2.0 GeV²] [N]
Islam	19.9	0.65	5.0
Jenkovsky	20.1	0.72	4.2
Petrov	22.7	0.52	7.0
Bourrely	21.7	0.54	8.4
Block	24.4	0.48	10.4
TOTEM	23.6 ± 0.5 ± 0.4	0.53 ± 0.01 ± 0.01	7.8 ± 0.3 ± 0.1