Cross sections and forward multiplicities measurements with TOTEM

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(on behalf of the TOTEM Collaboration)

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Outlook:

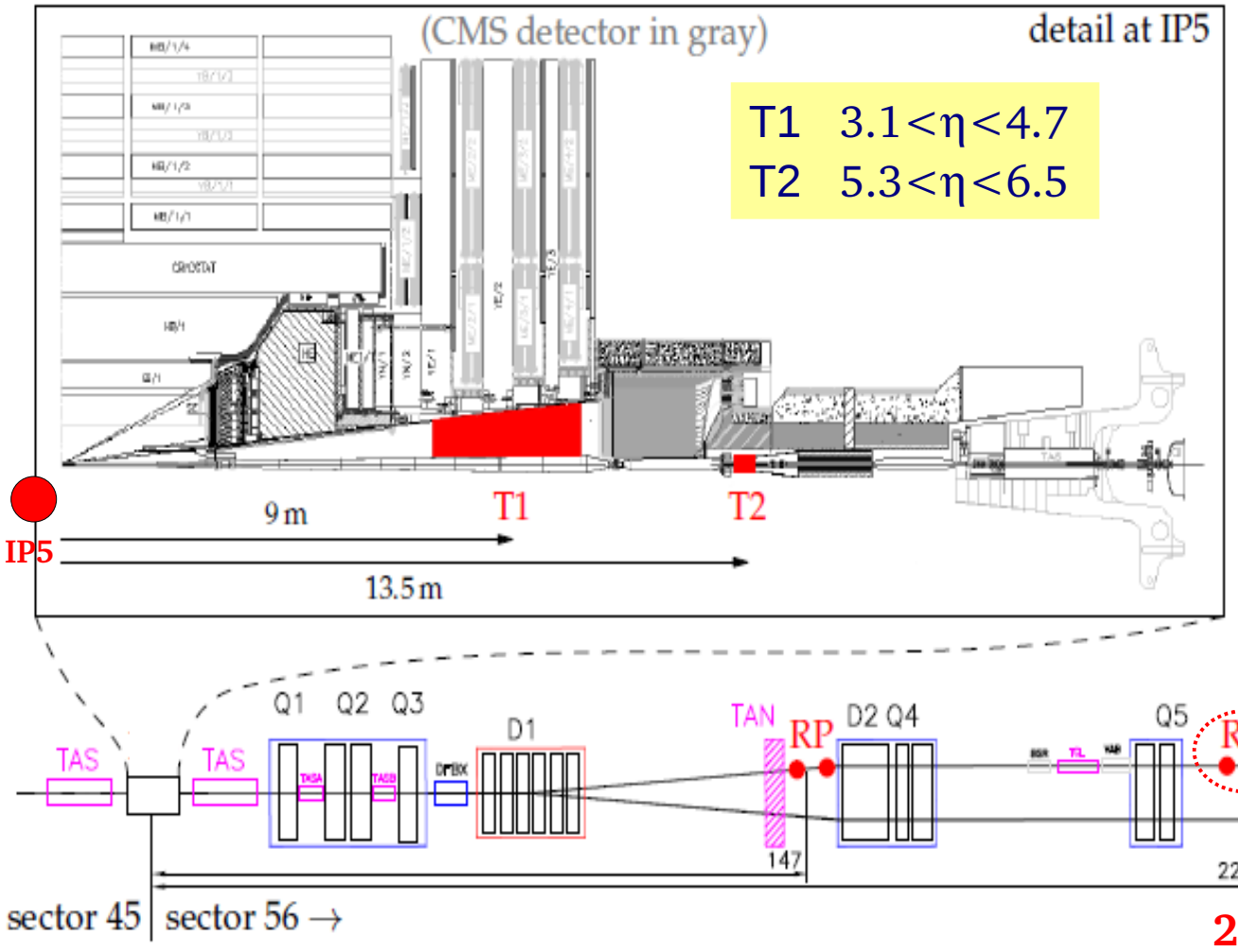
- The TOTEM experiment
- Elastic pp cross section
- Inelastic and total pp cross section
- Single diffractive and double diffractive pp cross sections
- Very forward pp $dN_{CH}/d\eta$

The TOTEM experiment

Physics programme:

- Measure the total pp cross section with a precision of about 1÷2 %.
- Study the elastic pp cross section over a wide range of the pp 4-momentum transfer $|t|$.
- Studies on diffractive processes, partially in cooperation with the CMS experiment.

Experimental layout (symmetrically placed with respect to IP5):



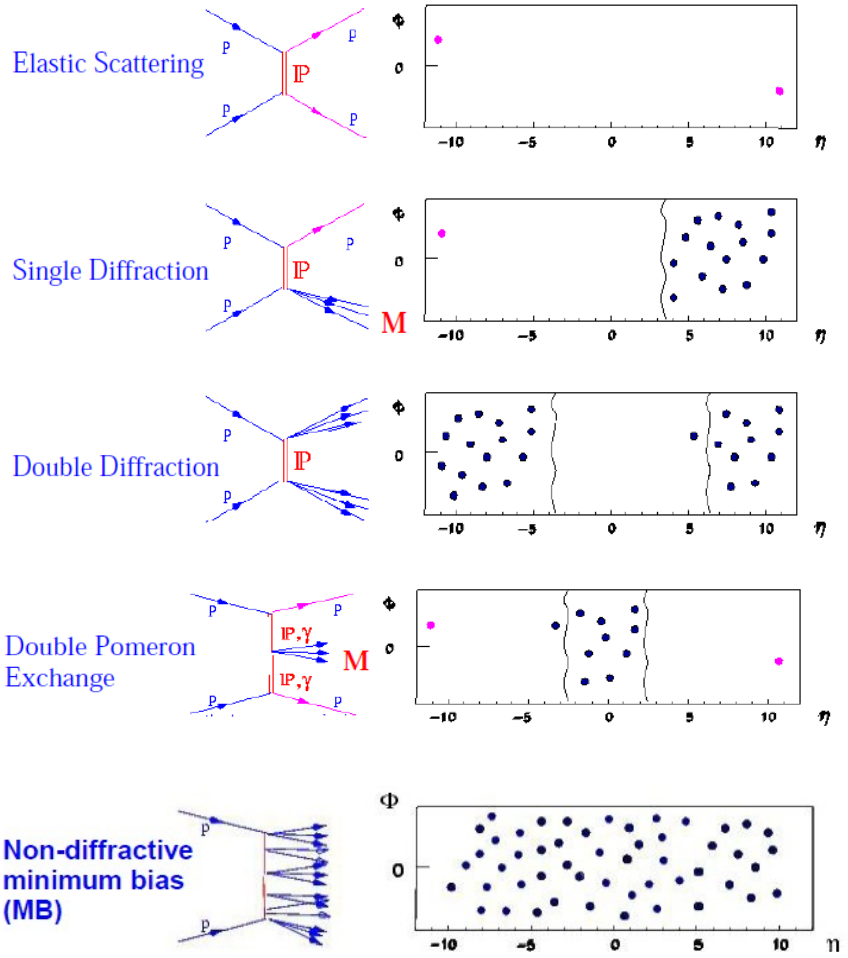
- Inelastic telescopes T1,T2: tracking of charged particles from inelastic collision. P_T threshold = 100 MeV (T1), 40 MeV (T2).

- RP stations at 220m: reconstruction of the leading proton from elastic and diffractive interaction.

TOTEM Physics

TOTEM stand-alone

- *Precise cross sections measurement for the different soft inelastic and the elastic pp scattering:*

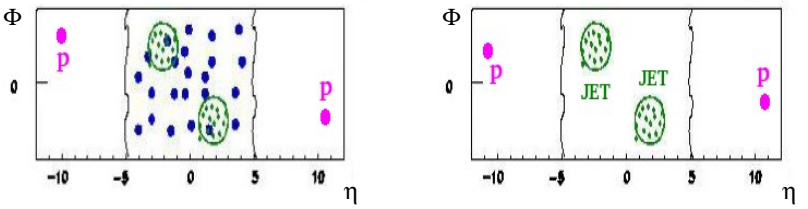


TOTEM with CMS

- *Unique experiment to make precise studies on hard and semi-hard diffraction.*

- *Common (same trigger) TOTEM+CMS runs already done at 8 TeV, joint analyses are ongoing:*

  - Soft and Hard central diffractive masses reconstruction both with the protons and CMS (search for missing masses)

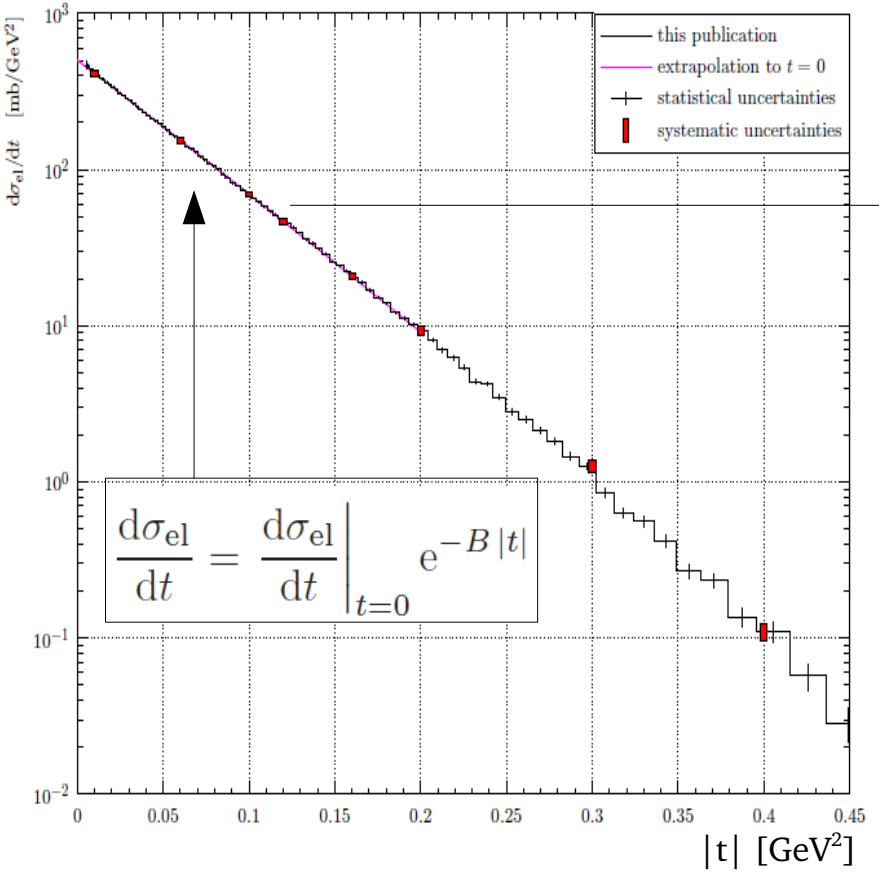


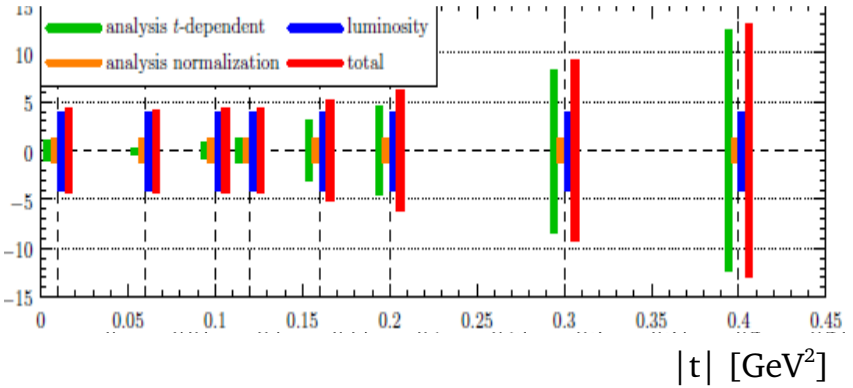
  - Single diffractive dijets production

  - Multiplicity measurements in a wide range of pseudorapidity

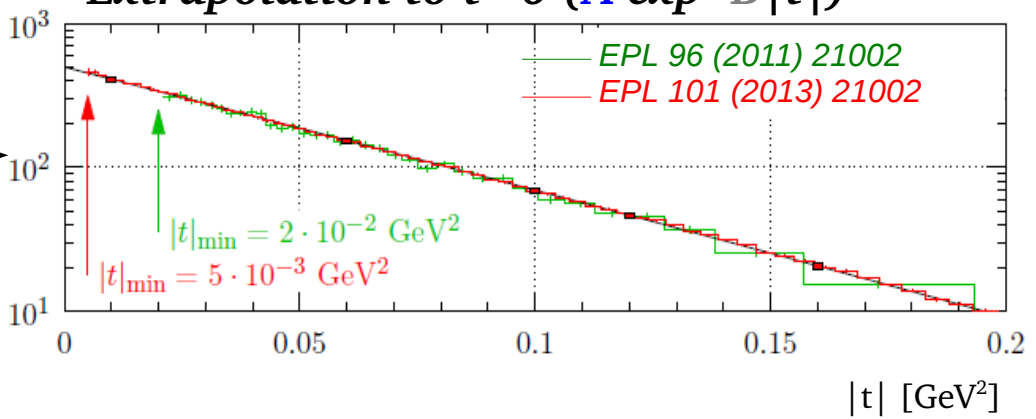
Elastic scattering results: $5 \cdot 10^{-3} < |t| < 0.45$ GeV^2 @ 7 TeV

- Elastic analysis performed in a wide range of $|t|$, with different beam conditions





Extrapolation to t=0 (A exp -B|t|)



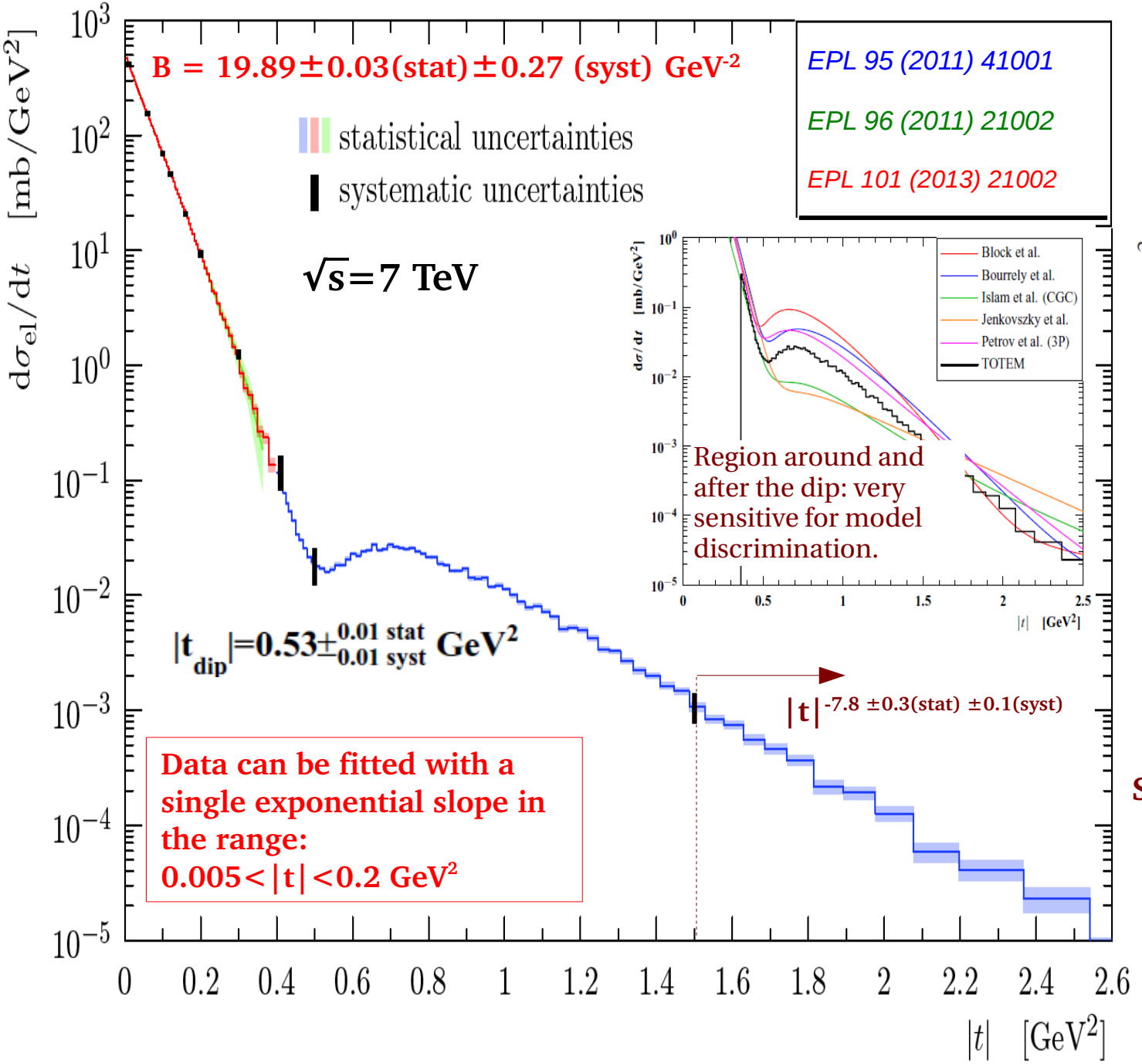
A (mb/GeV^2) = $506.4 \pm 23^{syst} \pm 0.9^{stat}$
$503 \pm 26.7^{syst} \pm 1.5^{stat}$

B (GeV^{-2}) = $19.89 \pm 0.27^{syst} \pm 0.03^{stat}$ ($5\ 10^{-3} < |t| < 0.2$ GeV^2)
$20.1 \pm 0.3^{syst} \pm 0.2^{stat}$ ($2\ 10^{-2} < |t| < 0.33$ GeV^2)

(Luminosity dependent) elastic cross section σ_{el}:

$25.43 \pm 1.07^{syst} \pm 0.03^{stat}$ mb *(91% measured)*
$24.8 \pm 1.2^{syst} \pm 0.2^{stat}$ mb *(67% measured)*

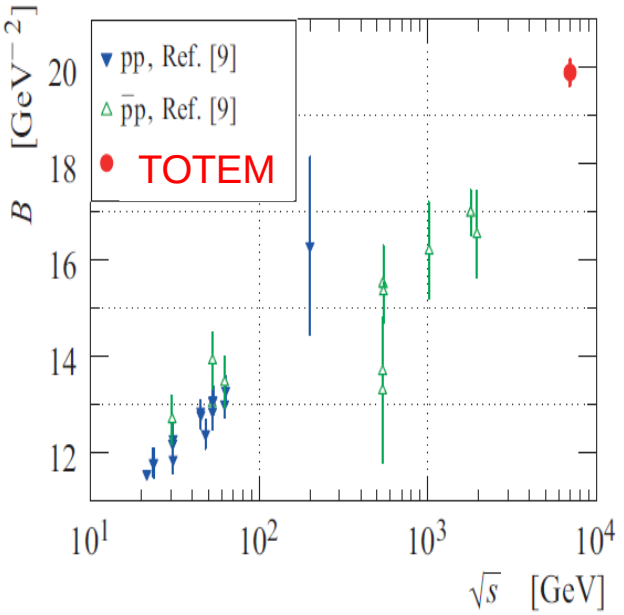
Elastic scattering results: $5\cdot10^{-3}<|t|<2.5$ GeV^2@ 7 TeV



0.36 <|t|< 2.5 GeV²

0.02 <|t|< 0.33 GeV²

5·10³ <|t|< 0.4 GeV²



Shrinkage of the forward peak:

- minimum moves to lower |t| with increasing CM energy
- exponential slope grows with the CM energy

Inelastic pp cross section measurement @ 7 TeV:

- **Luminosity dependent inelastic cross section obtained triggering with T2:**

$$\sigma_{Inel,T2vis} = \frac{N_{T2}}{\mathcal{L}_{int}}$$

(EPL, 101 (2013) 21003)

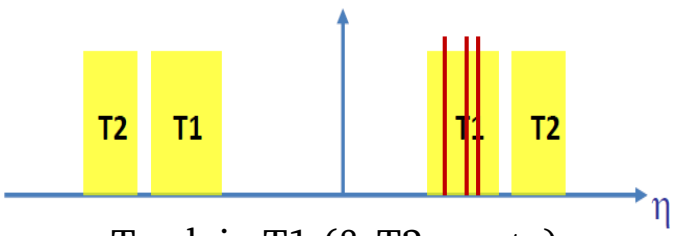
- **Cross section for events with at least a stable particle in the T2 acceptance:**

$\sigma_{Inel,T2\ vis}$ (mb): 69.7 ± 0.1stat ± 0.7syst ± 2.8lumi

- **Cross section for events with at least a stable particle with $|\eta|<6.5$:**

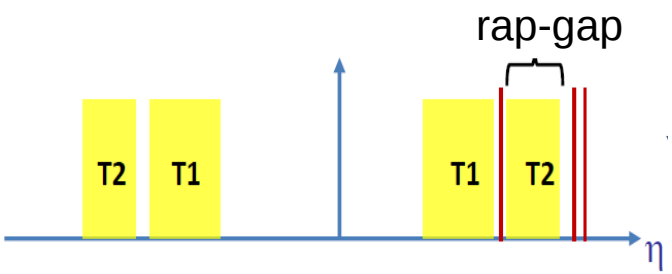
$\sigma_{Inel,|\eta|<6.5}$ (mb): 70.5 ± 0.1stat ± 0.8syst ± 2.8lumi

Correction sizes:



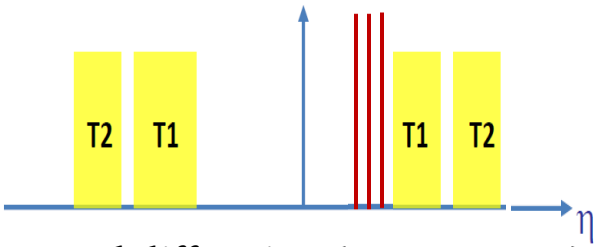
Track in T1 (& T2 empty)

~ 1.6%



Rapidity gap in T2 for 1-arm events (hadronization fluctuation)

~ 0.35%



Central diffraction (T1,T2 empty)

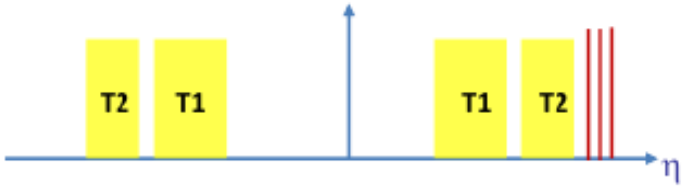
~ 0.35%

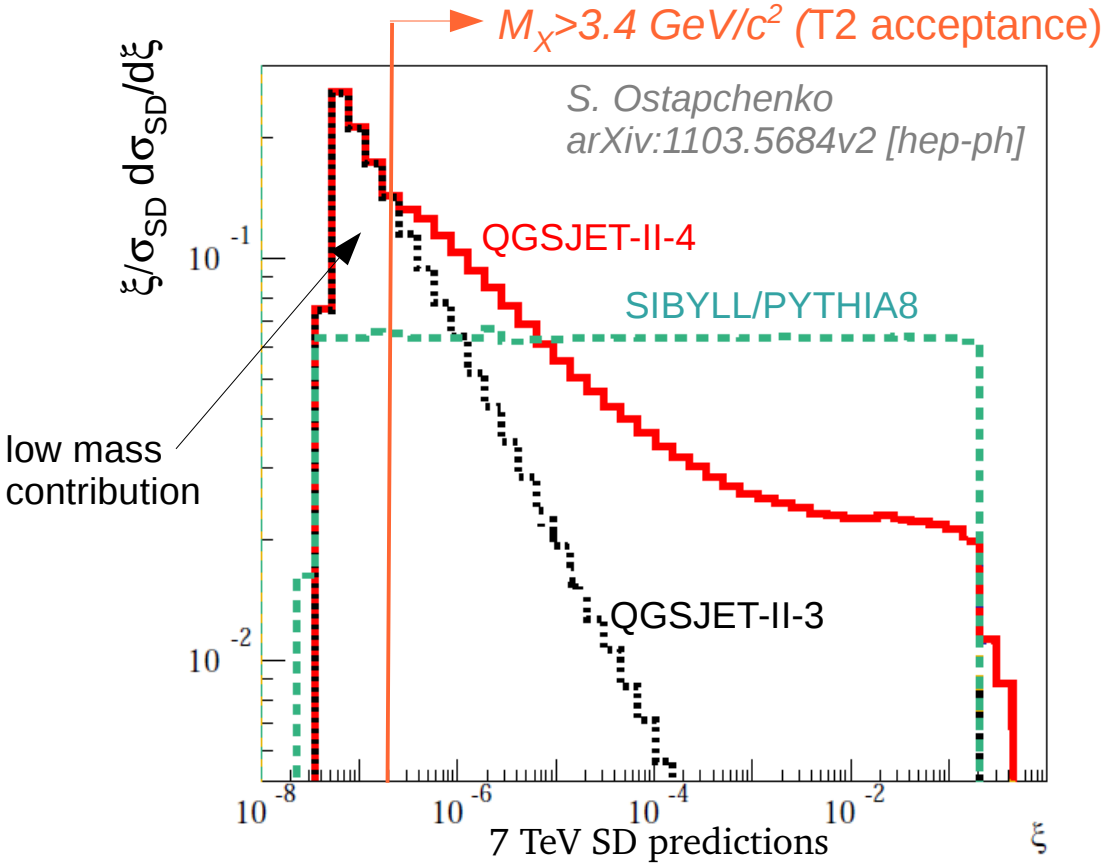
Inelastic cross section measurement @ 7 TeV:

Correction for events having particles only at $|\eta|>6.5$:

σ_{inel} (mb): 73.74 ± 0.09stat ± 1.74syst ± 2.95lumi

(EPL, 101 (2013) 21003)





QGSJET-II-03/QGSJET-II-04 are the most reliable:

➔ predicts a low mass diffraction x-section compatible with the one deduced comparing σ_{tot} - σ_{el} (obtained from elastic measurements) with $\sigma_{inel,\ |\eta|<6.5}$

Correction based on **QGSJET-II-03**
=4.2% ± 2.1% (syst)
(imposing the observed 2arm/1arm event ratio)

Total cross section measurements @ 7 TeV: three methods

Use of the optical theorem: $\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = \sigma_{tot}^2 \frac{1}{16\pi}(1+\rho^2)$ → $\rho = \frac{\mathcal{R}[f_{el}(0)]}{\mathcal{I}[f_{el}(0)]}$

- Method 1a): *(low) luminosity-dependent* σ_{tot} *measurement*
- Method 1b): *(high) luminosity-dependent* σ_{tot} *measurement*
  - → Cross check with the CMS $\mathcal{L}$

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

($\mathcal{L}$ from CMS, ρ from COMPETE)

- Method 2): *(high) luminosity-dependent* σ_{tot} *measurement using* N_{el} *and* N_{inel}

$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$ → ρ independent measurement, minimize the efficiency biases in the elastic measurement

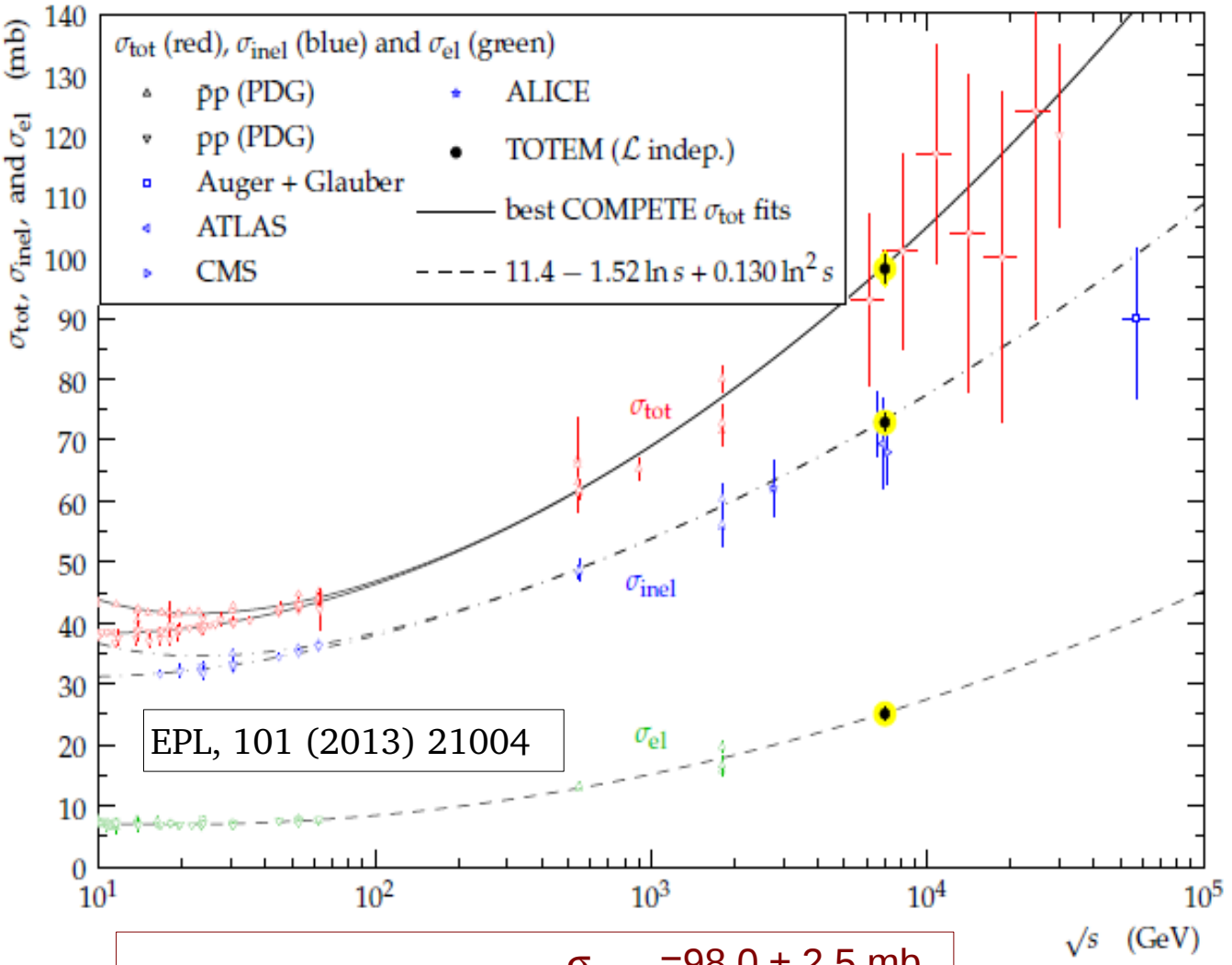
- Method 3): *luminosity-independent* σ_{tot} *measurement:*

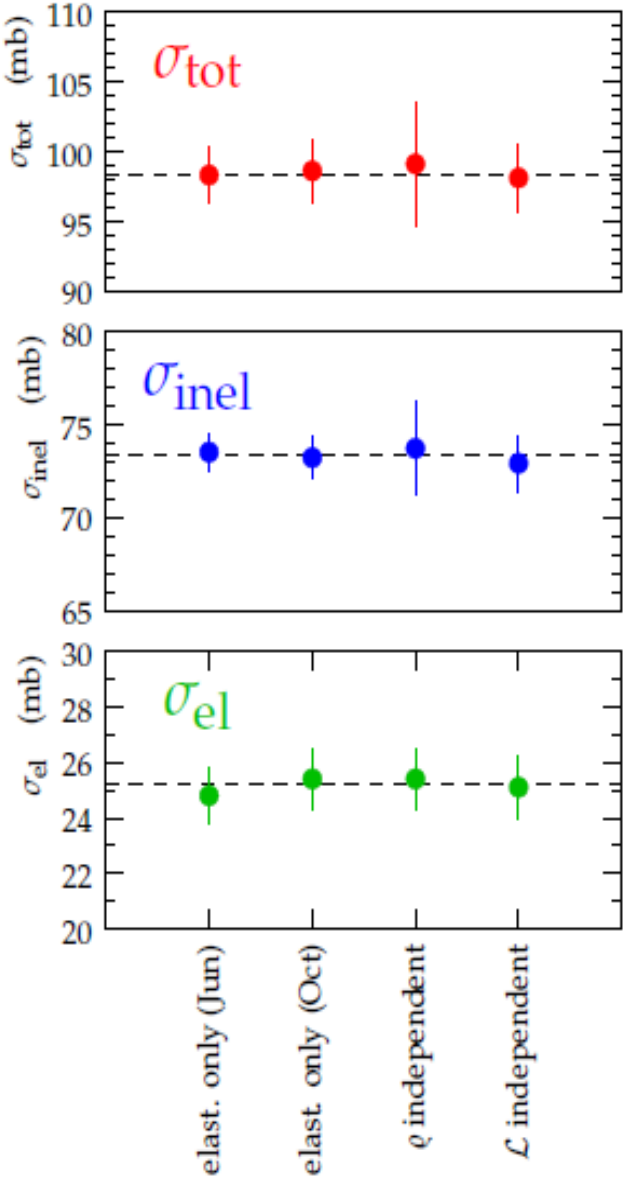
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

Three cross section measurements (7 Tev): results

- Totem measurements compatible with the COMPETE best fit.
- All four measurements give consistent results.

Precise pp measurements are valuable for p-Air x-sect estimates in CR Physics





Lumi-independent cross sections:

σ_{TOT} =98.0 ± 2.5 mb
σ_{INEL} =72.9 ± 1.5 mb
σ_{EL} =25.1 ± 1.1 mb

Method: (1a) (1b) (2) (3)

$\mathcal{L}$ calibration, low mass diffraction, cross section ratios

- ***Absolute calibration of the CMS luminosity:***

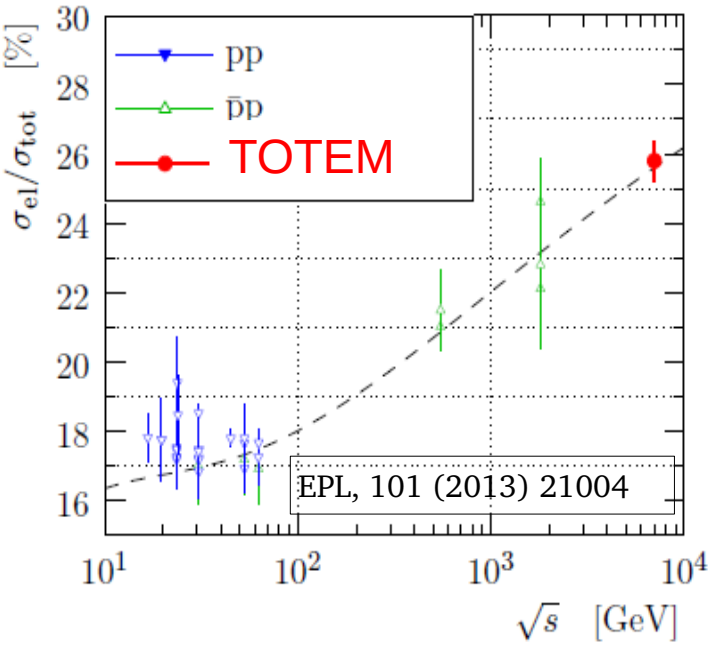
$$\mathcal{L} = \frac{(1+\rho^2)}{16\pi} \frac{(N_{el}+N_{inel})^2}{(dN_{el}/dt)_{t=0}}$$

$\mathcal{L}_{\text{int, CMS}}$ = 82.8 ± 3.3 μb^{-1} $\mathcal{L}_{\text{int, TOTEM}}$ = 83.7 ± 3.2 μb^{-1}

$\mathcal{L}_{\text{int, CMS}}$ = 1.65 ± 0.07 μb^{-1} $\mathcal{L}_{\text{int,, TOTEM}}$ = 1.65 ± 0.07 μb^{-1}

- ***Luminosity and ρ independent ratios:***

$\sigma_{el}/\sigma_{inel}$=0.345 ± 0.009 σ_{el}/σ_{tot} = 0.257 ± 0.005



- ***Low mass diffraction:***

From method (1b): σ_{inel}= 73.15± 1.26 mb

Measure $\sigma^{\eta<6.5}_{inel}$= 70.53 ± 2.93 mb → 2.62 ± 2.17 mb (upper limit ~ 6.3 mb at 95%CL)

(Uncertainty dominated by luminosity)

- ***ρ measurement:***

$$\rho^2 = 16\pi\,(\hbar c)^2\,\mathcal{L}_{\text{int}}\,\frac{dN_{\text{el}}/dt|_0}{(N_{\text{el}}+N_{\text{inel}})^2} - 1$$

TOTEM |ρ| = 0.14 ± 0.09

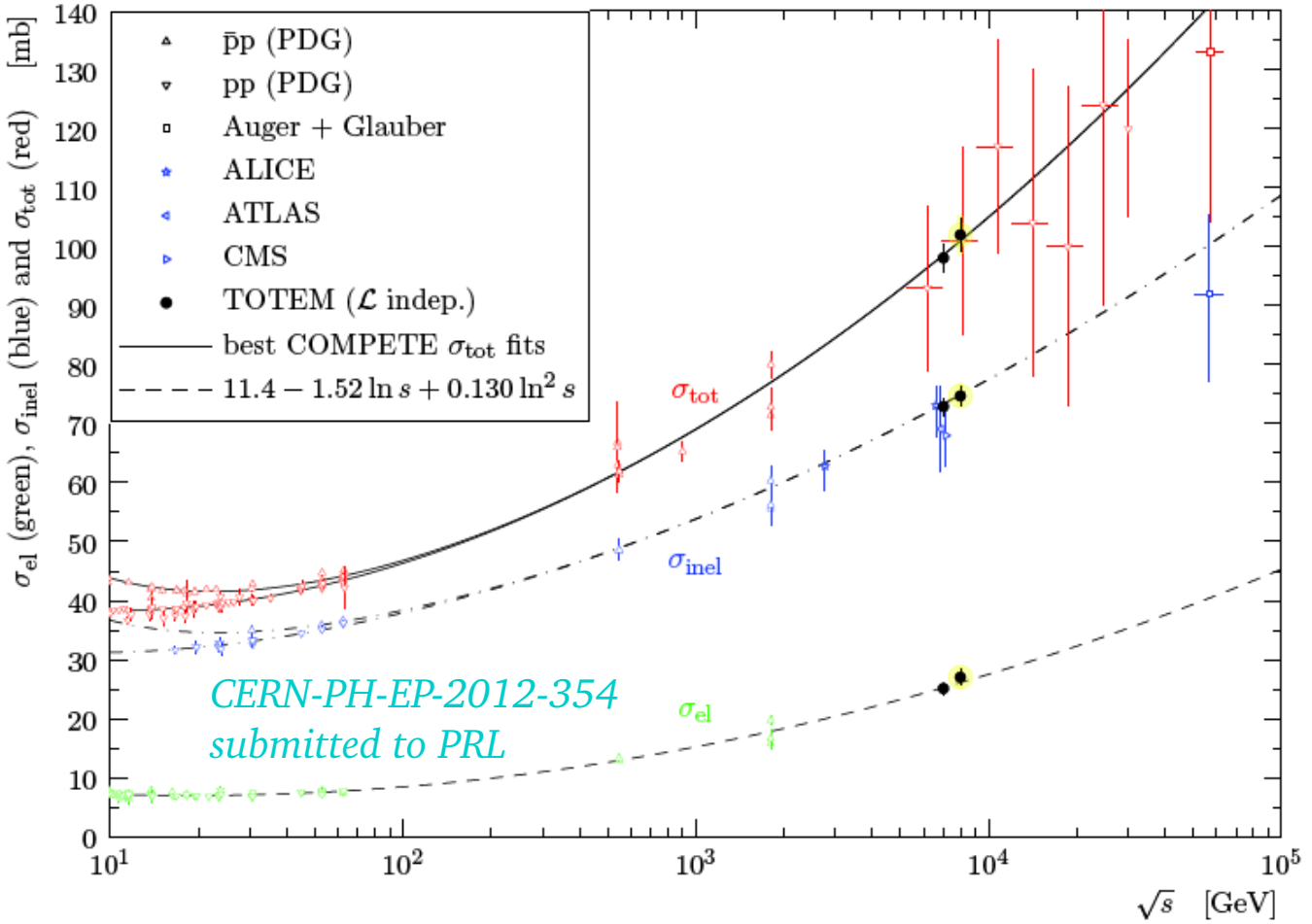
COMPETE extrapolation |ρ| = 0.141 ± 0.091

[A direct ρ measurement at 8 TeV is ongoing]

Total, elastic and inelastic cross section @ 8 TeV:

- Dedicated fill with $t_{min} = 0.01$ GeV^2, 90% of the nuclear elastic scattering events detected
- With the same analysis performed at 7 TeV, the luminosity independent cross sections are found:

$\sigma_{TOT} = 101.7 \pm 2.9$ mb $\sigma_{EL} = 27.1 \pm 1.4$ mb $\sigma_{INEL} = 74.7 \pm 1.7$ mb

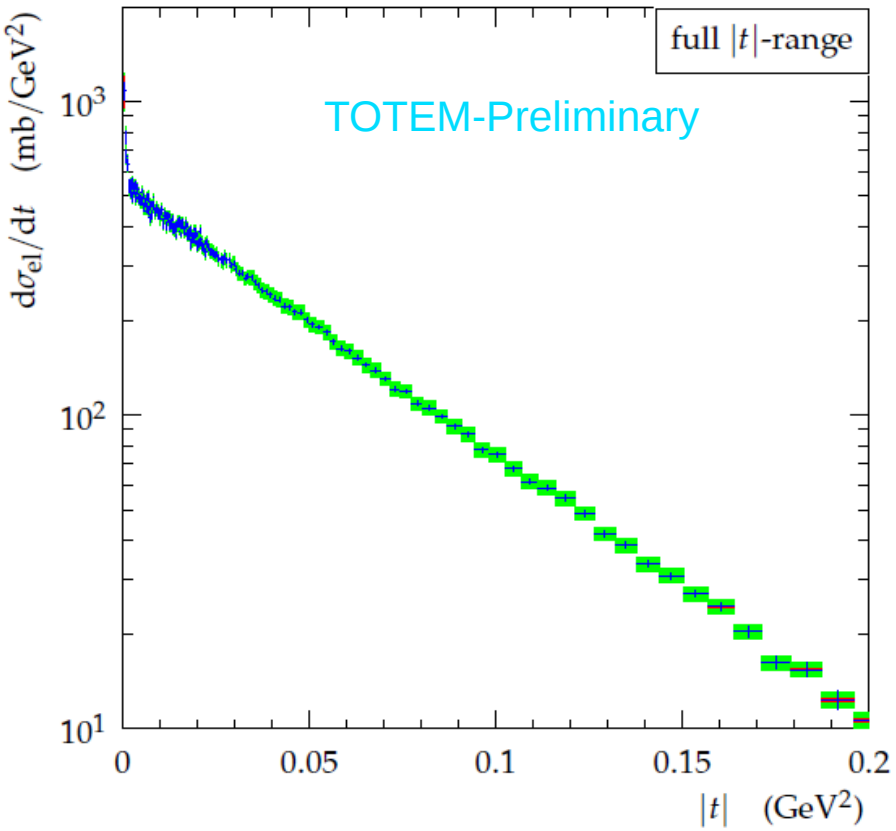


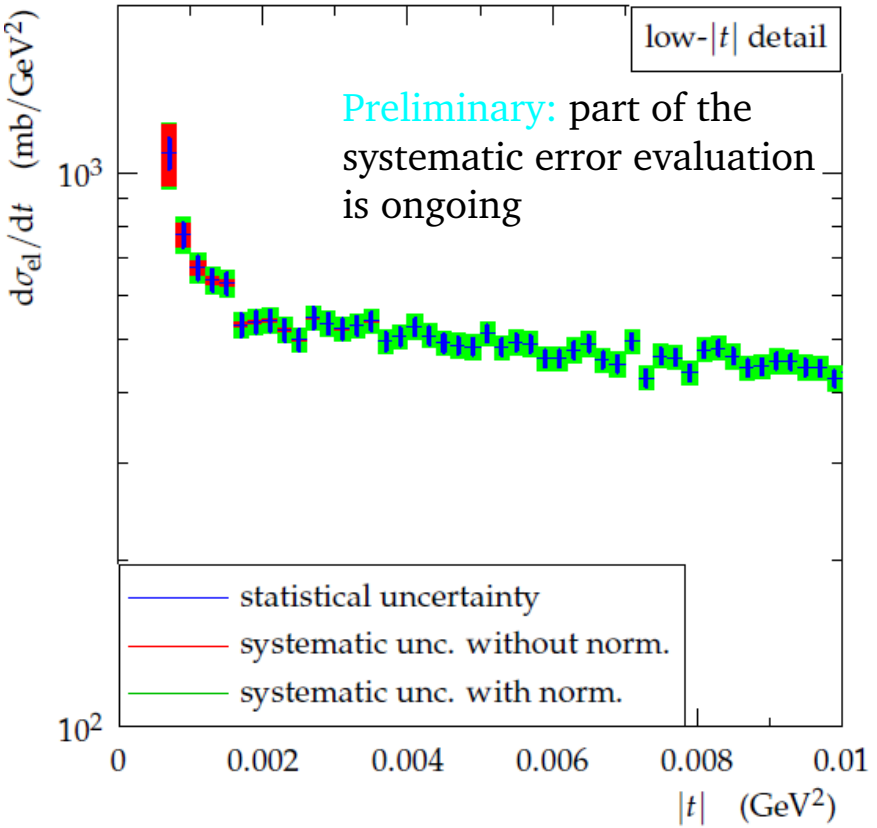
Comparison of 7 and 8 TeV measurements:

- consistent in terms of detectors performance.
- comparable systematics uncertainties.
- both in good agreement with the extrapolation of the lower energy measurements.

Probing the Hadronic-Coulomb interference at 8 TeV:

Dedicated $\beta^*=1$ Km run allowed to probe the Hadronic-Coulomb interference region (down to $|t|=6*10^{-4}$ GeV^2)



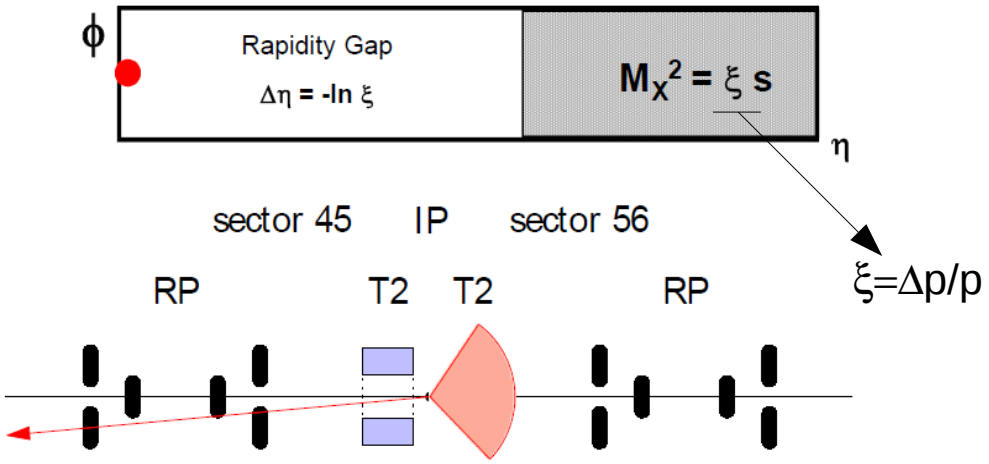


Fits of $d\sigma_{EL}/dt$ in this region with several models are ongoing and will allow TOTEM to:

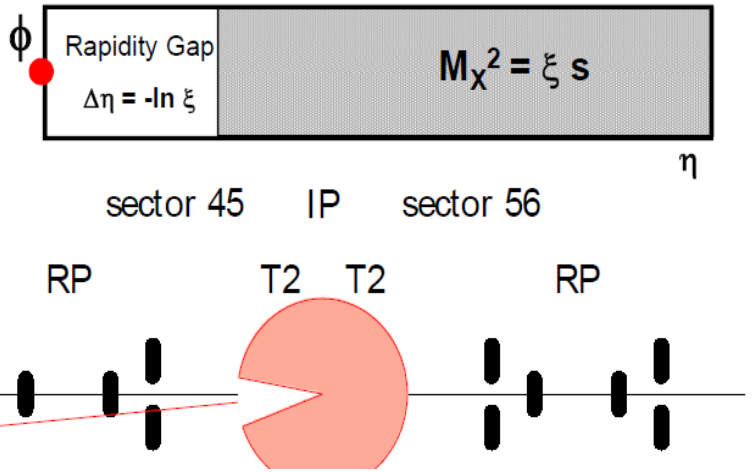
- Validate the models describing the Coulomb/Hadronic interferences.
- Make constraints on the ρ parameter, furthermore improving the total cross section measurement (at 7 and 8 TeV).

Soft Single Diffractive cross section (7 TeV)

Low mass SD:
Tracks in the T2 hemisphere opposite to the proton ($2 * 10^{-7} < \xi < 0.025$)



Very High mass SD:
Tracks in the same T2 hemisphere of the proton ($\xi > 2.5\%$)



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

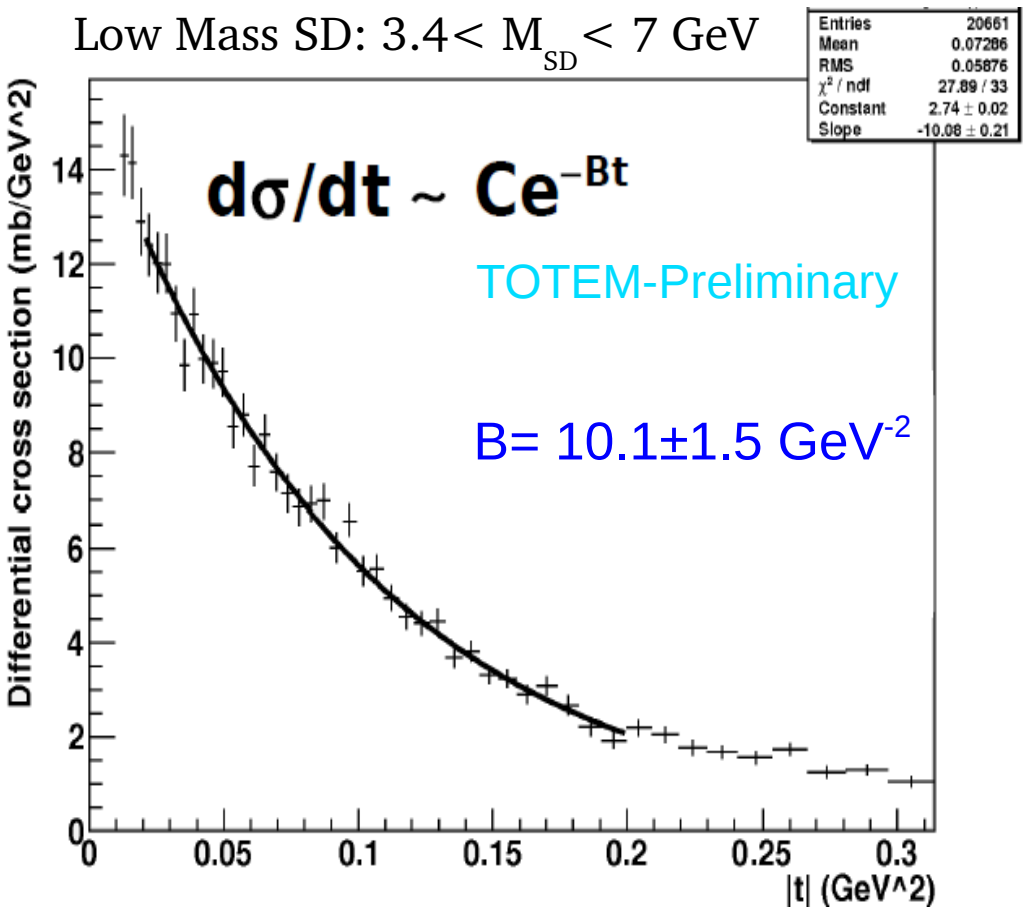
- SD experimentally classified into 4 categories, based on the rapidity gap:

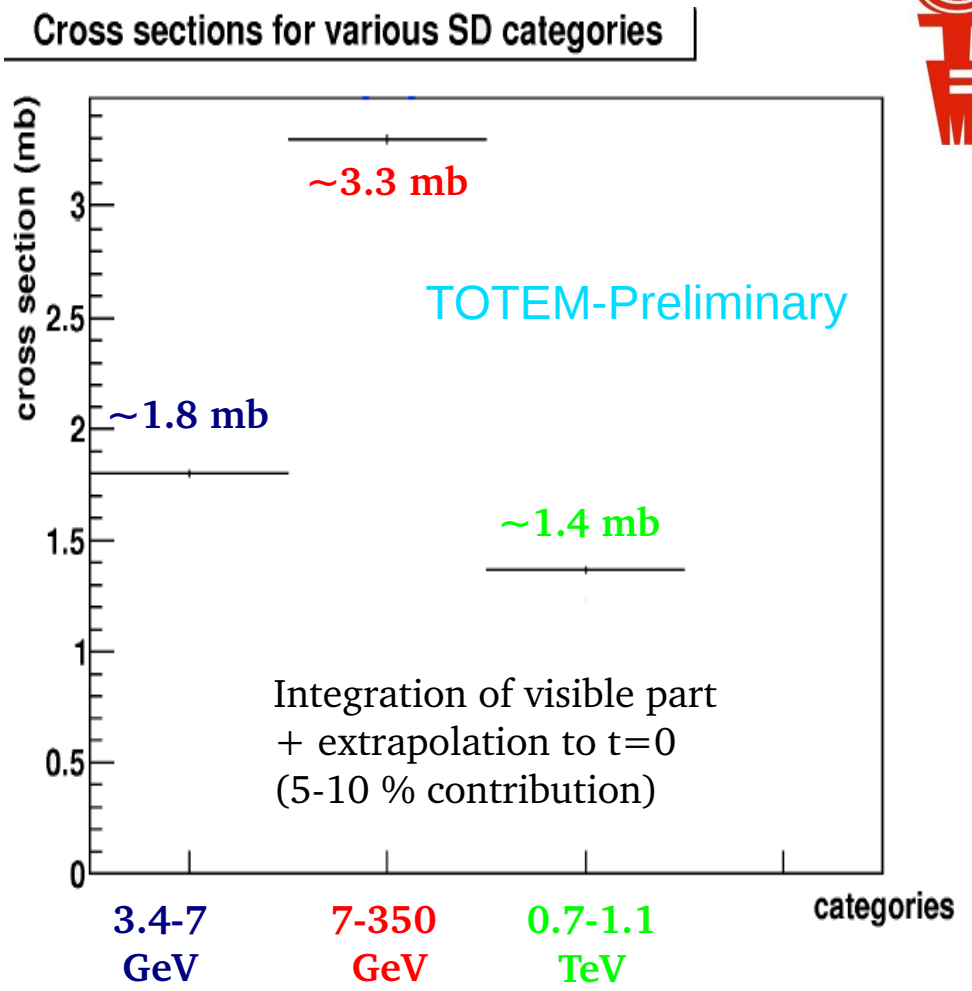
SD class	Inelastic telescopes configuration	Mass	ξ
Low Mass	p + T2 opposite only (no T1)	3.4 - 7 GeV	$2 \cdot 10^{-7} < \xi < 10^{-6}$
Medium Mass	p + T2 opposite + T1 opposite	7 - 350 GeV	$10^{-6} < \xi < 0.25\%$
High Mass	p + T2 opposite + T1 same	0.35 - 1.1 TeV	$0.25\% < \xi < 2.5\%$
Very High Mass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

- Inelastic+beam halo background estimated from data, used mirrored events (wrt the proton)

Soft Single Diffractive cross section (7 TeV)

Low Mass SD: $3.4 < M_{SD} < 7$ GeV





Estimation of B for different SD classes:

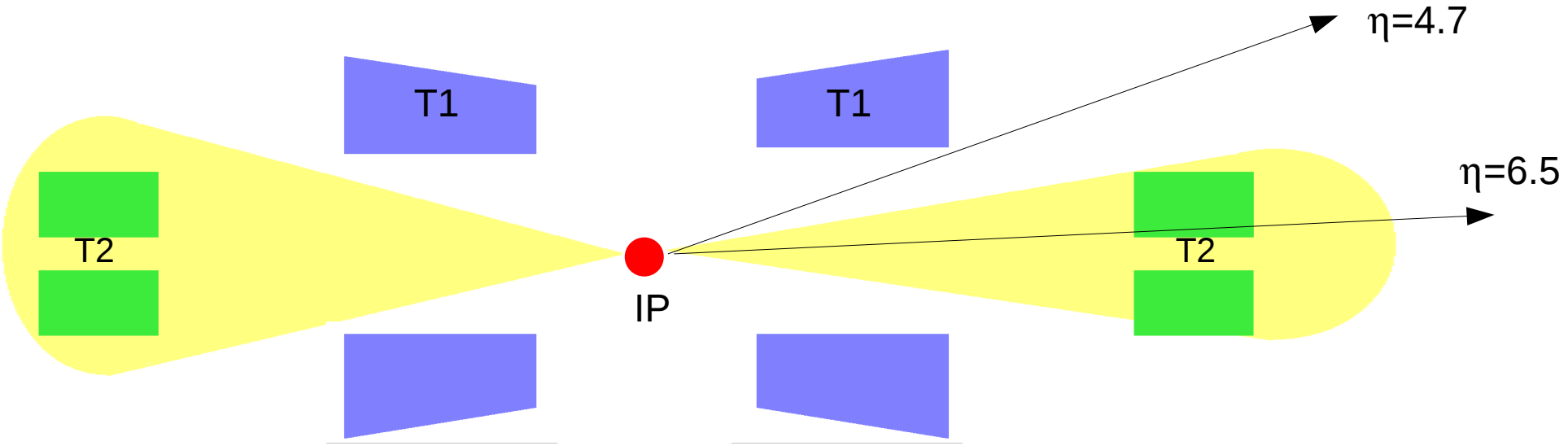
SD class	Mass range	B value (GeV^{-2})
Low Mass	3.4 - 7 GeV	10.1 ± 15%
Medium Mass	7 - 350 GeV	8.5 ± 15%
High Mass	0.35 - 1.1 TeV	6.8 ± 15%

Very Preliminary:
$\sigma_{SD}(3.4 < M_{SD} < 1100\ \text{GeV}) = 6.5 \pm 1.3$ mb

- Corrected for T2 trigger efficiency, ϕ acceptance, p reco inefficiency ...
- Effect of beam divergence, smearing and category migration (ξ resolution) still to be applied.
- Very high masses measurement ongoing (a better understanding of beam halo and N* production is needed)

Soft Double Diffractive cross section (7 TeV)

Goal: Measurement of soft double diffractive cross section with particle η_{min} visible to TOTEM T2 ($4.7<|\eta_{min}|<6.5$). → $\sigma_{DD}(|\eta_{min}|)$ for $3.4 < M_{DIFF} < 8$ GeV



Event selection: Trigger with T2, at least one track in <u>both</u> T2 hemispheres , <u>no tracks in T1</u> "(0T1+2T2) topology".

- ND background estimated scaling the MC prediction using a control sample from data dominated by ND (2T1+2T2 events)

- SD background estimated completely from data using a SD-dominated control sample (0T1+1T2) with protons in the RP

Soft Double Diffractive cross section

Results from 7 TeV data:

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 120 \pm 25 \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	66±19 μb	27±4 μb
$5.9<\eta_{min}<6.5$	28±5 μb	12±4 μb

- σ_{DD} uncertainty dominated by migrations from generator-η_{min} to track reconstructed η_{min}, in particular:

  "Internal migration": real DD events that have a $|\eta_{min}|$ smaller than T1 but with no tracks in T1 η-range

MC comparisons:

Pythia 8

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 159 \ \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	70 μb	37 μb
$5.9<\eta_{min}<6.5$	35 μb	17 μb

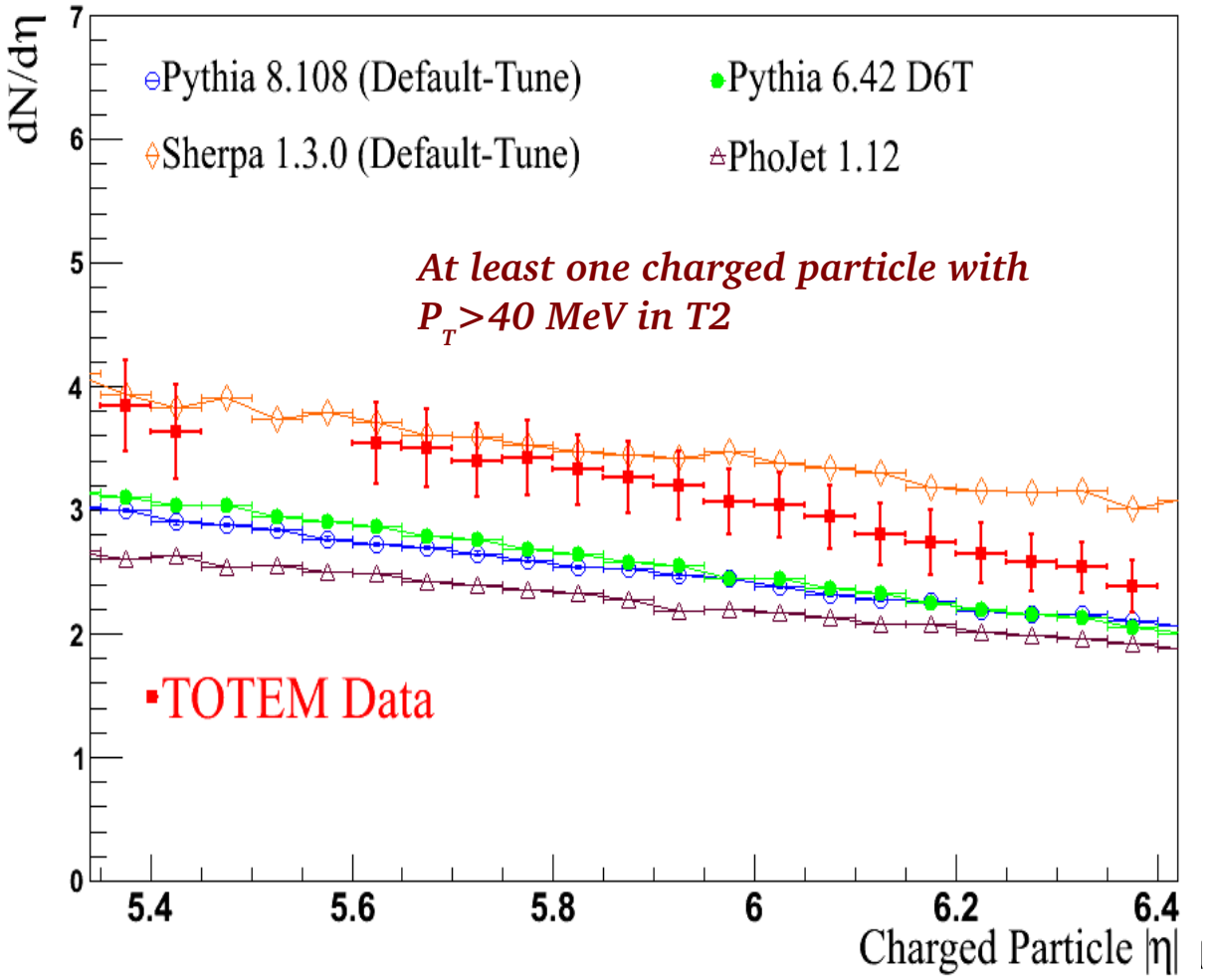
Phojet

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 101 \ \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	44 μb	23 μb
$5.9<\eta_{min}<6.5$	23 μb	12 μb

- Improvement expected with the 8 TeV data, including also CMS information.

Very forward $dN_{CH}/d\eta$ measurements at 7 TeV



The TOTEM measurement (EPL 98 (2012) 31002):

- **High visible cross section:**

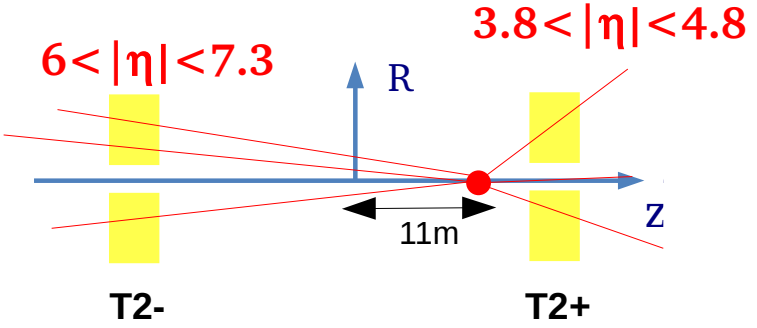
measured on data:

~94% σ_{INEL}

- M_{Diff} > 3.4 GeV
- ND events > 99%

- **We will fill the LHCB-T2 gap:**

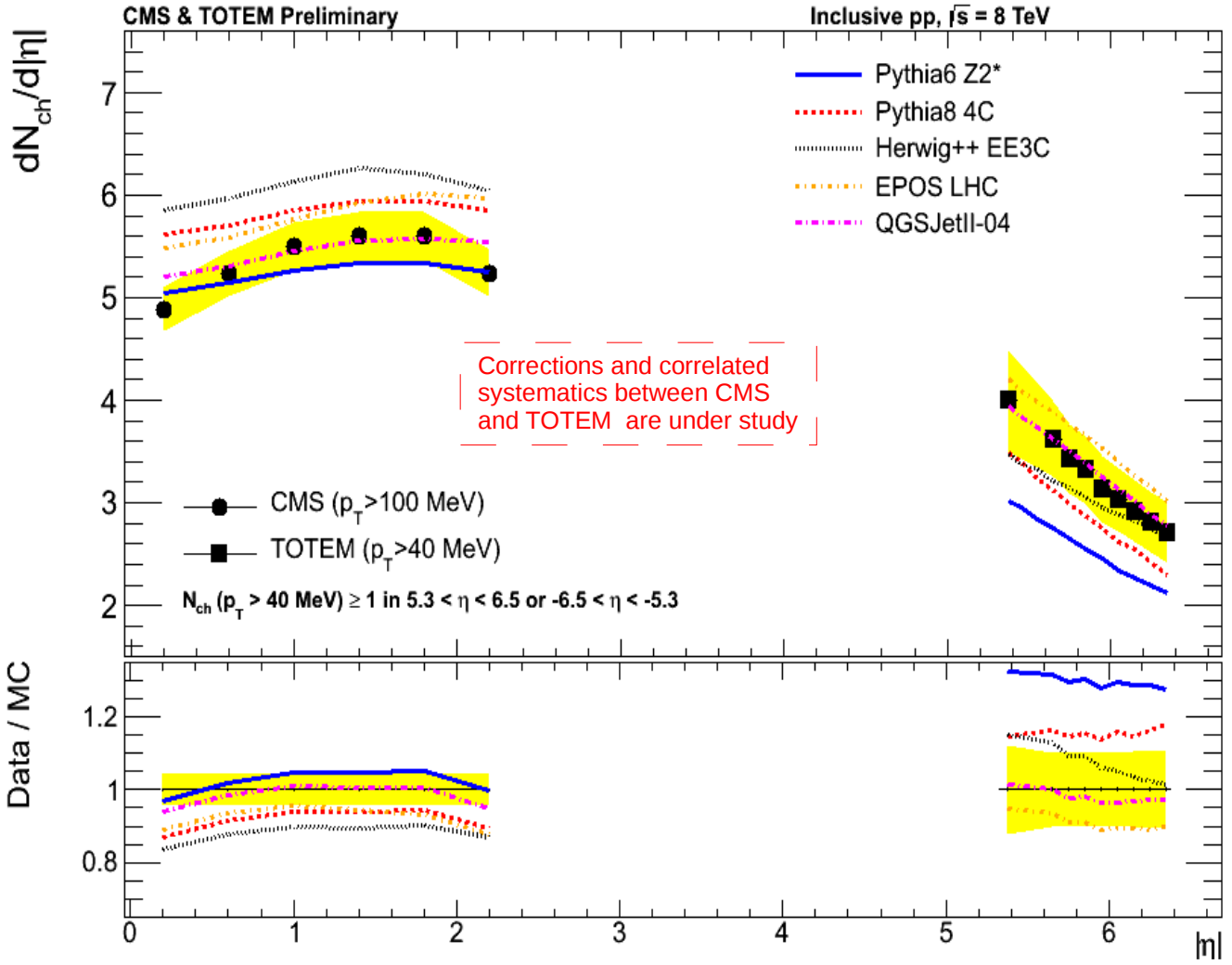
- using T1 (analysis ongoing)
- using runs with displaced vertex (we had ~500K MB triggers with collisions at ~11m from the IP):



Main contributions to the systematical error ~10%:
- Subtraction of a large fraction of secondaries from the data
- Track efficiency and misalignment uncertainties (θ<10mrad!)

Very forward $dN_{CH}/d\eta$ measurements at 8 TeV (with CMS!)

- Inclusive TOTEM analysis very similar to the 7 TeV case but:
  - Improved simulation of the T2 detector response, of the secondary particle production and improved alignment procedures.
  - Uses of the vertex information from CMS to reduce the pile-up correction
  - Better MC tuning to the LHC measurements (important for the estimation of the secondaries)



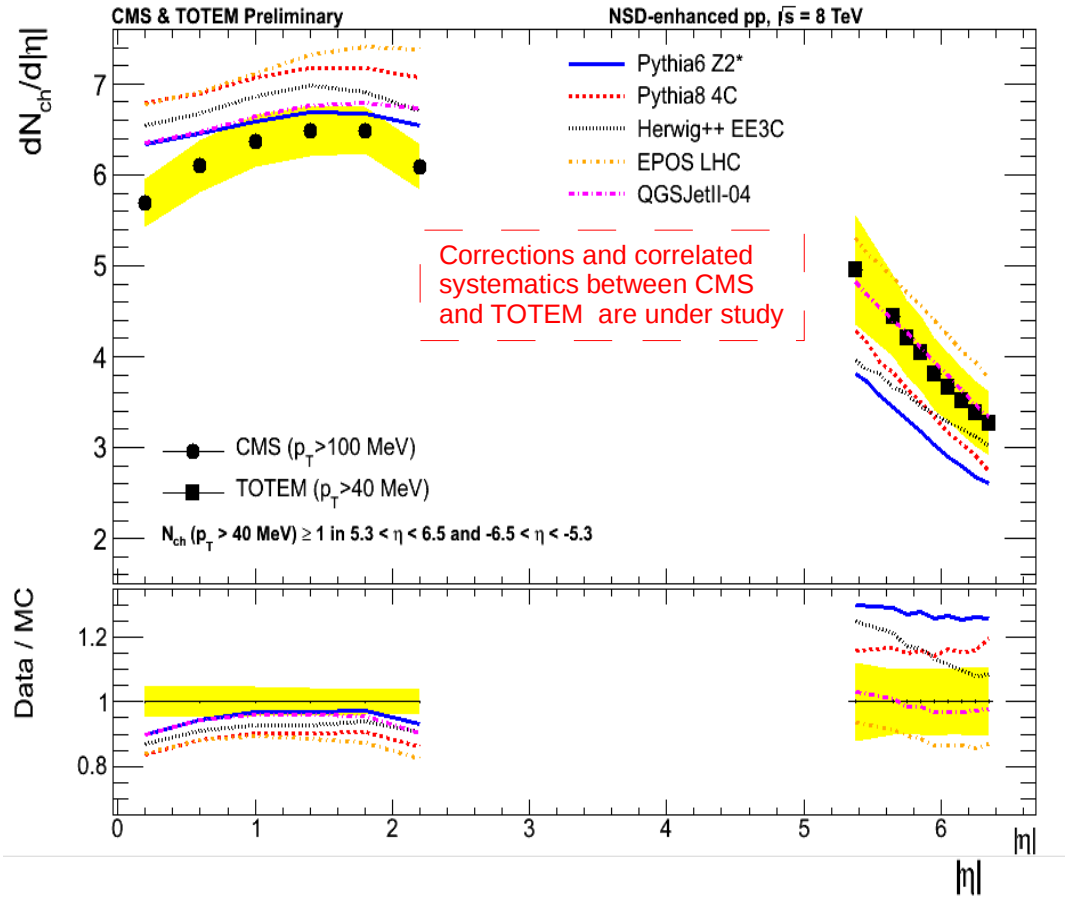
- Both CMS and TOTEM analysis obtained triggering with T2, on the same data sample.
- Same event selection as CMS (at least a track reconstructed in T2)
- Measurements are representative for an inelastic event with at least a primary charged particle with P_T>40 MeV/c produced in the range $5.3<|\eta|<6.5$.
- See Panagiotis Katsas talk for more details on the CMS analysis.

Very forward $dN_{CH}/d\eta$ measurements at 8 TeV

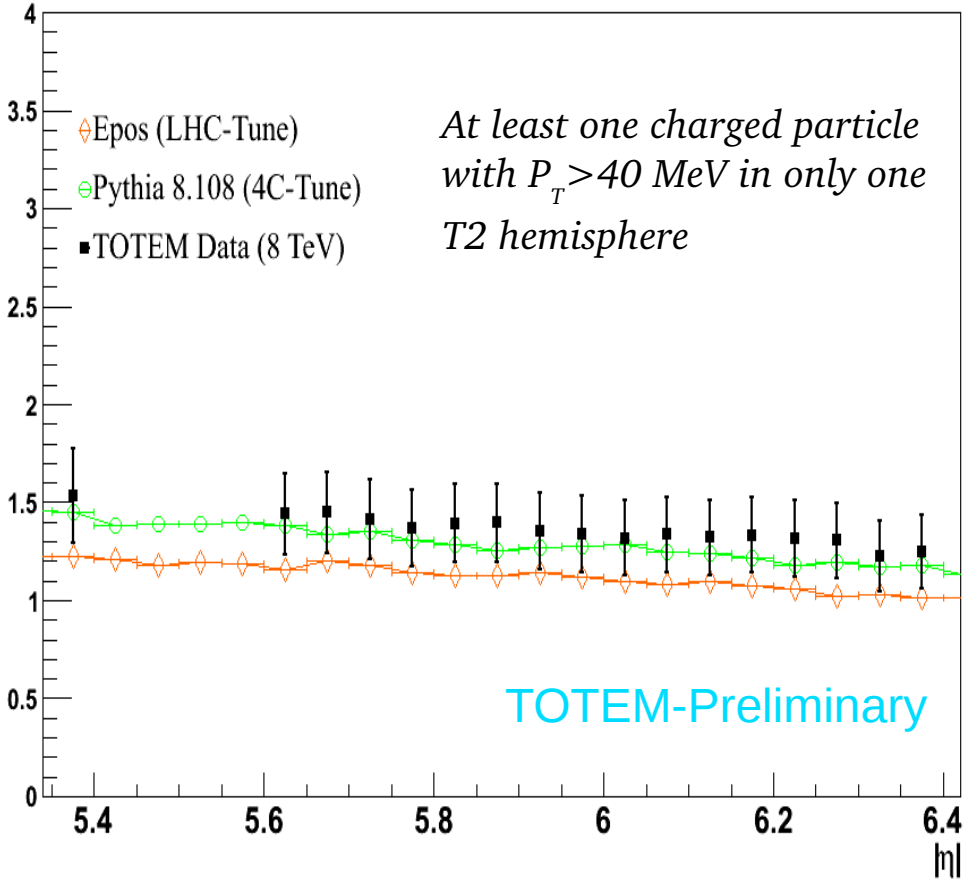
TOTEM-T2 stand alone dN/dη analysis performed also for a sample of pp events:

- "Non-Single diffractive enhanced": requiring both hemisphere of T2 ON
- "Single diffractive enhanced": requiring only one hemisphere of T2 ON

NSD-enhanced dN/dη



SD-enhanced dN/dη



The same analyses are well advanced in TOTEM and CMS, hopefully soon a common NSD-enhanced and SD-enhanced dN/dη measurement will be achieved!

Conclusions and outlooks

- **TOTEM has measured the inelastic & elastic cross section and the <u>total cross section</u> with the <u>luminosity independent method at √s=7 and 8 TeV</u>**

  - Measurement of the elastic differential cross section in $5 \cdot 10^{-3} < |t| < 2.5$ GeV^2, ρ–constraint, luminosity calibration.

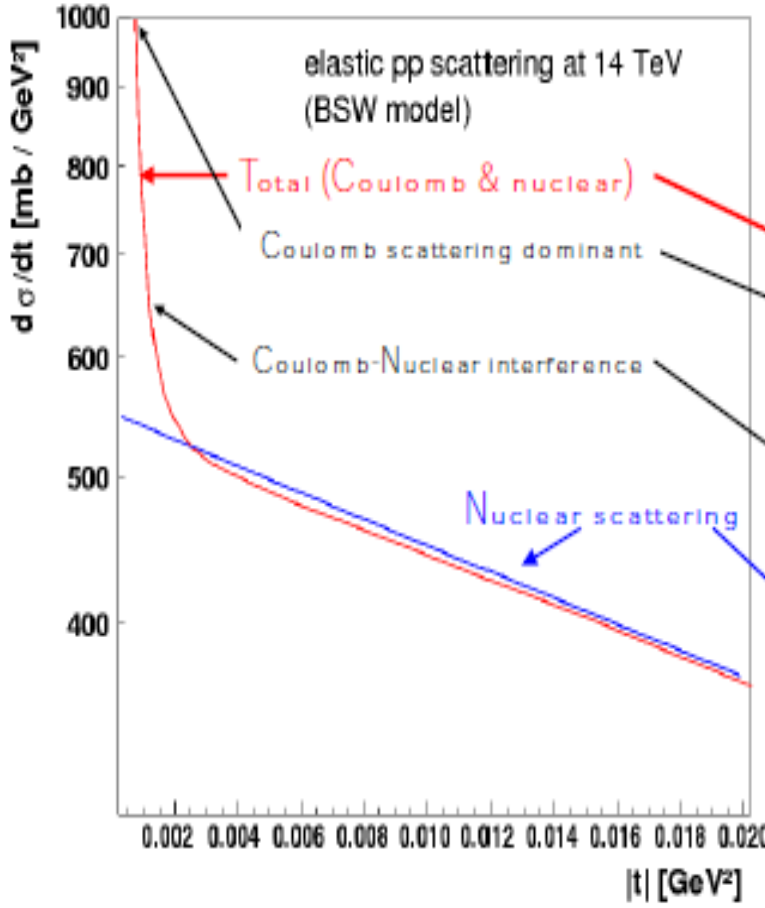
  - Constraint on the low mass diffractive cross section, study of the Hadronic/Coulomb interference.

- Analysis on Single and Double diffractive visible cross sections (at 7 TeV) are well advanced

- Measurement of the forward charged particle dN/dη distribution with T2 both stand-alone (7 TeV) and with CMS (8 TeV)

- **Common analyses with CMS for the studies of soft/hard CD and SD are ongoing, results are expected soon… stay TUNED!**

Thank you for your attention



Optical Theorem: $\sigma_{tot} = \frac{4\pi}{s}\Im\left(T_{elastic,nuclear}(t=0)\right)$

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2(\hbar c)^2 G^4(t)}{|t|^2} + \frac{\alpha(\rho-\alpha\phi)\sigma_{tot}G^2(t)}{|t|}e^{-B|t|/2} + \frac{\sigma_{tot}^2(1+\rho^2)}{16\pi(\hbar c)^2}e^{-B|t|}$$

α = *fine structure constant*

ϕ = *relative Coulomb-nuclear phase*

$G(t)$ = *nucleon el.-mag. form factor* = $(1 + |t| / 0.71)^{-2}$

ρ = $\Re / \Im\ [T_{elastic,nuclear}(t = 0)]$

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

$|t| \sim 6 \cdot 10^{-4}\ GeV^2$

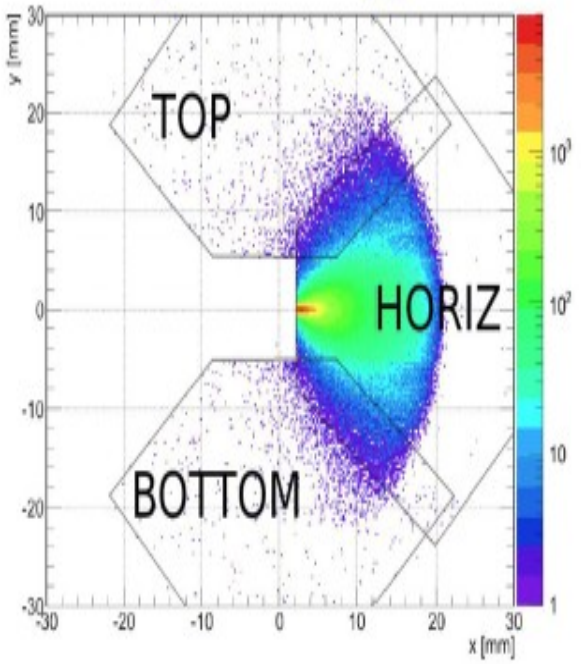
Reached with $\beta^* = 1000$ m and RP approaching the beam centre @ ~ 3σ

$$y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^* \qquad \xi = \Delta p/p$$
$$x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot \boxed{D(s)}$$

dispersion shifts diffractive protons in horizontal direction

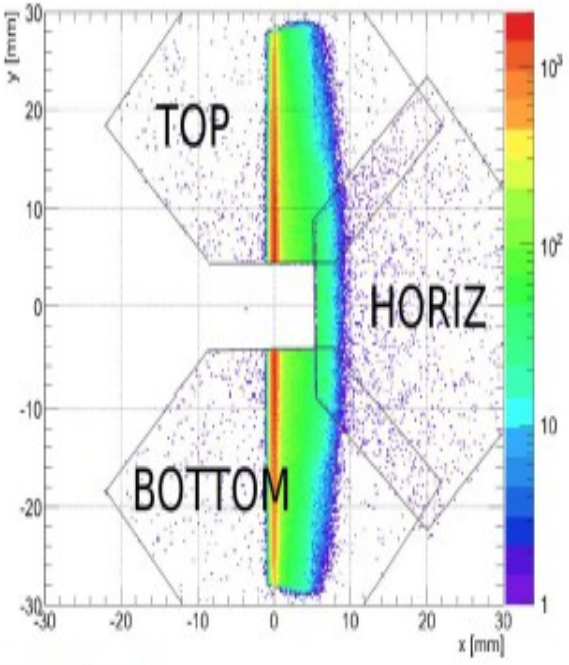
Generally $v_{x,y}$, $L_{x,y}$ & D_x functions of ξ → reconstruction non-linear problem

Low β^*: 0.5 – 3 m, ξ > 2%

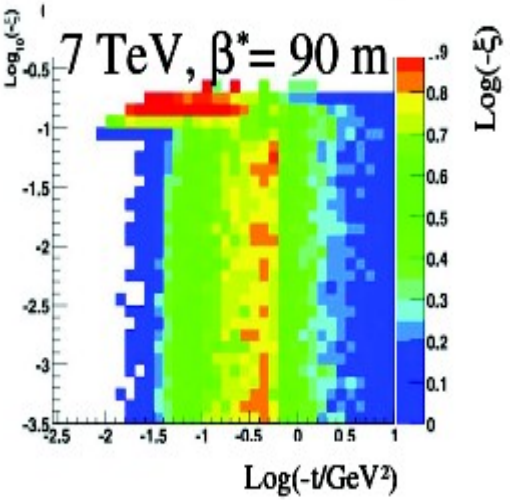


· L_x & L_y low, protons shifted due to ξ
· vertex not critical: small transverse σ_{beam}

β^* = 90 m, full ξ-coverage, $|t_y|$ > 0.01 GeV²



· L_x=0, L_y large
· large transverse σ_{beam} (~200 μm) → v_x, v_y important (worse ξ-resolution)
· CMS vertex improves ξ-resolution



β^* = 90 m

$L \approx 10^{30}\,cm^{-2}s^{-1}$

elastic acceptance
$3 \cdot 10^{-2}\ GeV^2 < -t_y < 10\ GeV^2$

resolution
$\sigma(\Theta) = 1.7\ \mu rad$
$\sigma(\xi) = 6 - 15 \cdot 10^{-3}$

all ξ seen, universal optics

diffraction, mid |t| elastic scattering, total cross-section

8 TeV- elastic Systematic Uncertainties

Table 2: Overview of the analysis steps, associated corrections and systematic uncertainties to the differential and total elastic rate.

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		$\mathrm{dN_{el}/dt}\lvert_{t=0}$	$\pm 2.5\,\%$	
		B	$(19.9 \pm 0.3)\,\mathrm{GeV}^{-2}$	

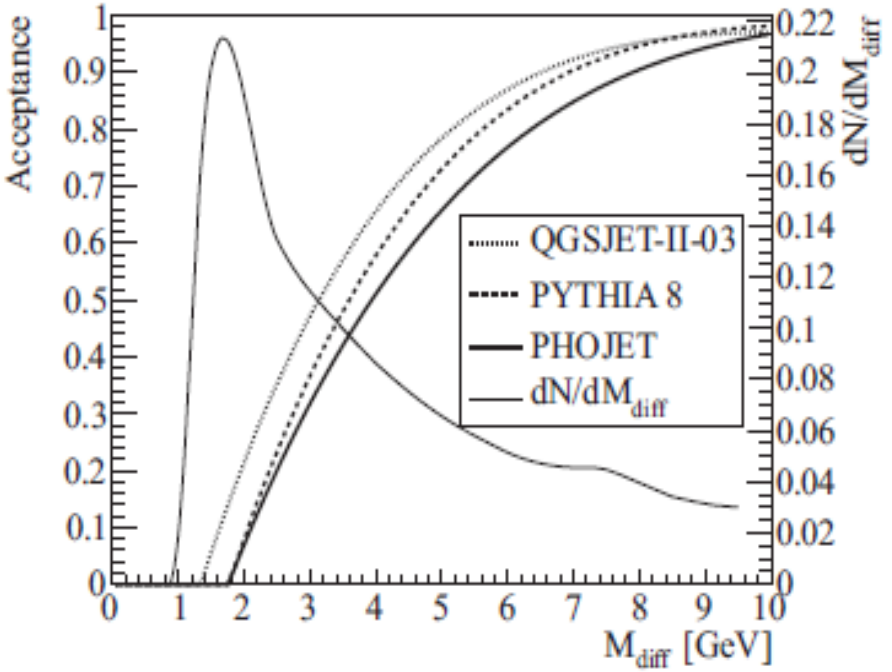


Fig. 3: The acceptance of the combined T1 and T2 detector as a function of the diffractive mass for PYTHIA8, PHOJET and QGSJET-II-03 and the diffractive mass distribution ($\mathrm{d}N/\mathrm{d}M_{\mathrm{diff}}$) for QGSJET-II-03 in single diffractive events.

well as the combined T1 and T2 acceptance as a function of M_{diff} for all the three MCs used. The M_{diff} distribution is expected to peak at masses of 1–2 GeV, whereas the acceptance is smoothly changing from 0% to 100% from about 2 GeV to 10 GeV, and thus implying that a majority of the events below 3 GeV will not be detected. The T2 acceptance edge of $|\eta| = 6.5$ corresponds to a diffractive mass of about 3.4 GeV (at 50% efficiency). The