

Latest results from TOTEM



Mirko Berretti

University of Siena and Pisa INFN
(on behalf of the TOTEM Collaboration)



CERN 12/07/2012

Outlook:

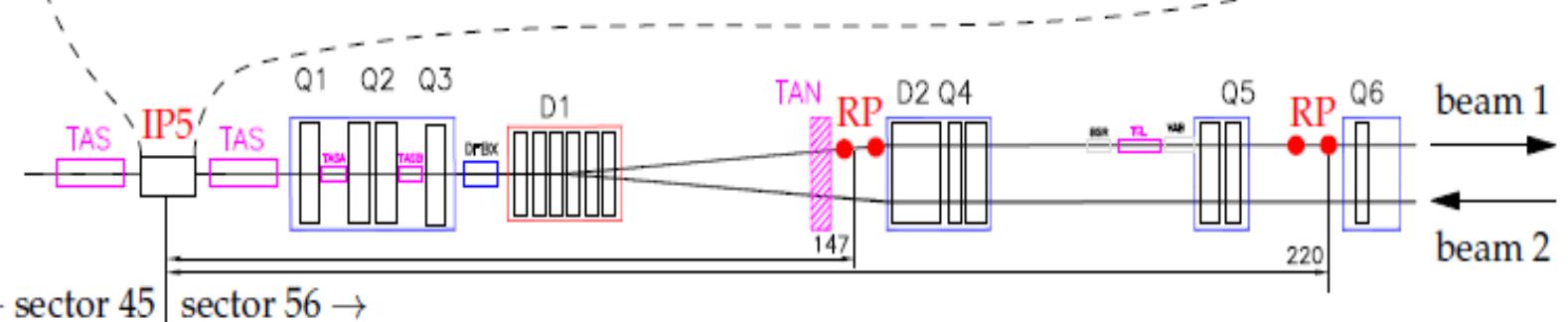
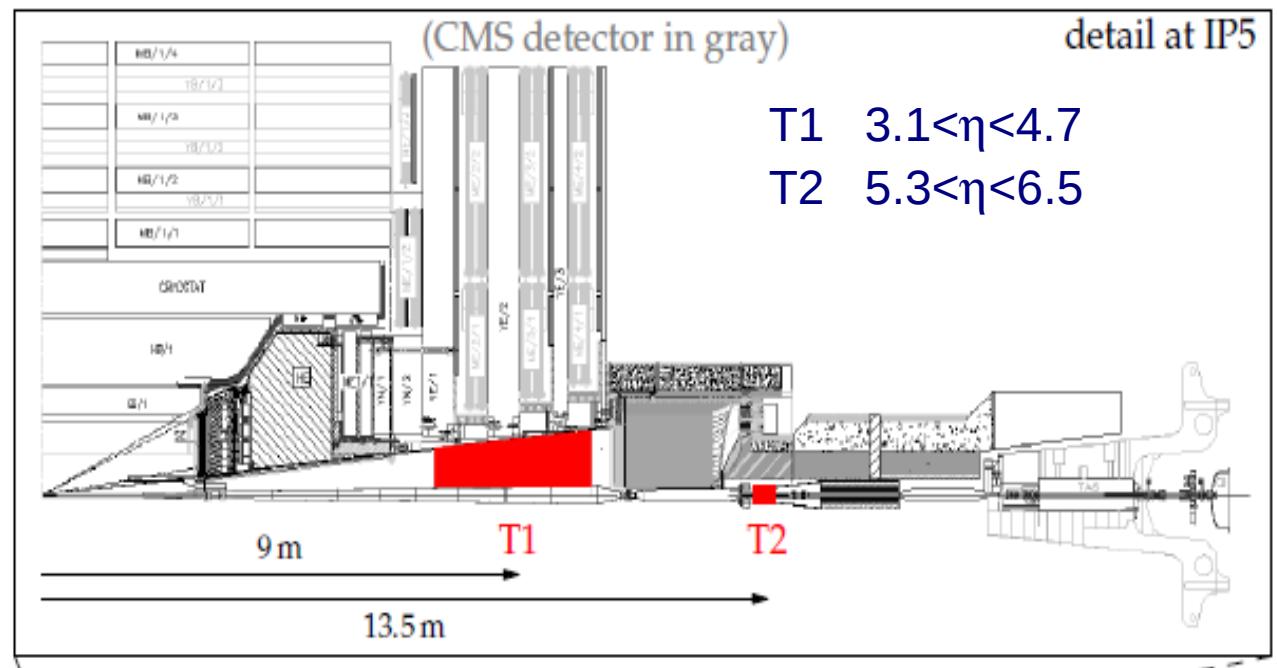
- The TOTEM experiment
- Inelastic analysis at 7 TeV: forward $dN/d\eta$, pp inelastic cross section
- Differential elastic cross section at 7 TeV
- Measurement of σ_{TOT}
- Physics perspective with CMS

The TOTEM experiment

Physics programme:

- Measure the total pp cross section with a precision of about $1\div 2\%$.
- Study the elastic pp cross section over a wide range of t ($10^{-3}\text{ GeV}^2 < |t| < 10\text{ GeV}^2$).
- Studies on diffractive processes, partially in cooperation with the CMS experiment.

Experimental layout:



- **Inelastic telescopes T1,T2:** tracking of charged particles from inelastic collision.

- **RP stations:** reconstruction of the leading proton from elastic and diffractive interaction.

Last publication: forward $dN_{\text{CH}}/d\eta$



A LETTERS JOURNAL EXPLORING
THE FRONTIERS OF PHYSICS

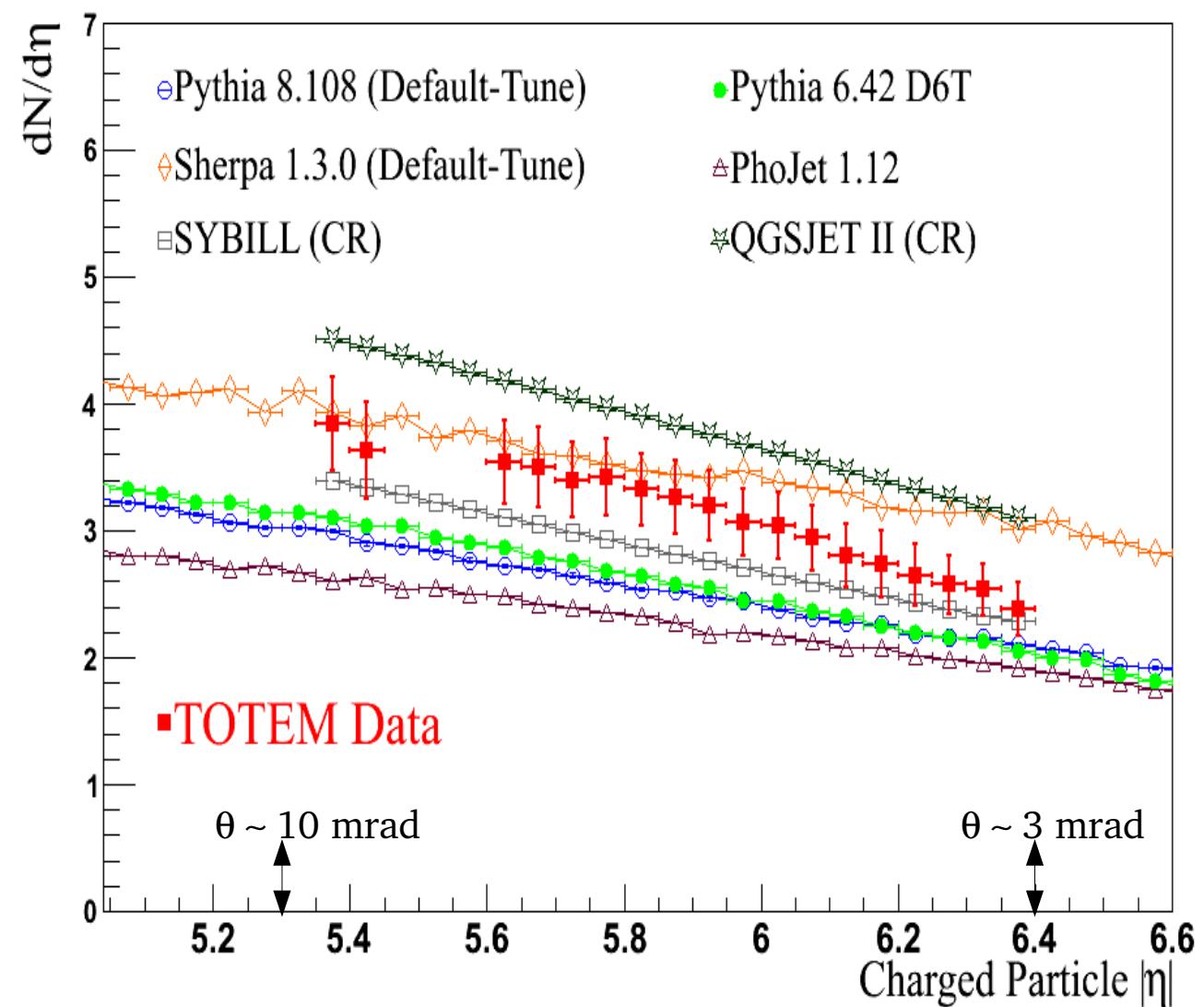
EPL, 98 (2012) 31002
doi: 10.1209/0295-5075/98/31002

May 2012

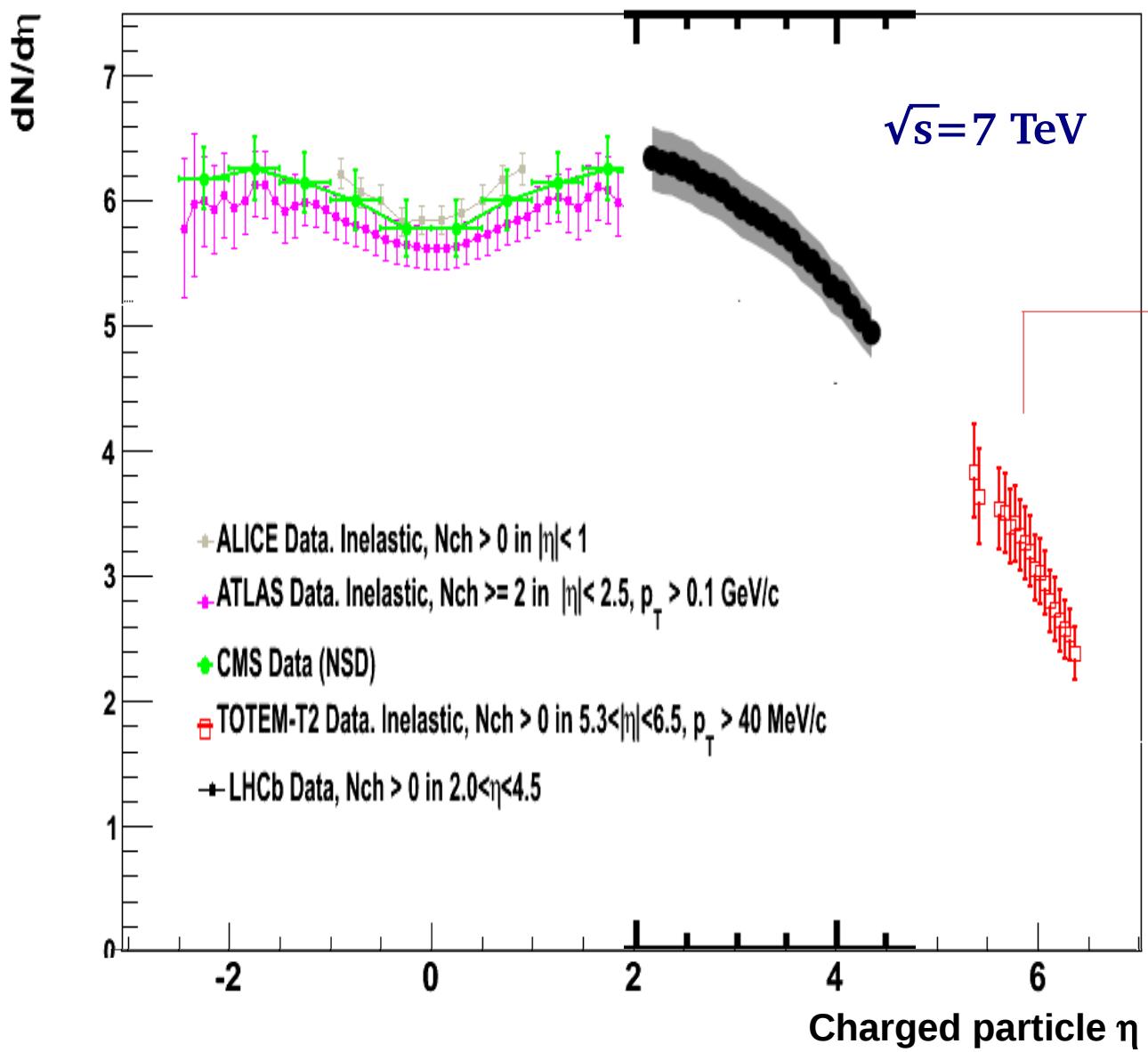
www.epljournal.org

Measurement of the forward charged-particle pseudorapidity density in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ with the TOTEM experiment

Pseudorapidity:
 $\eta \equiv -\ln[\tan(\theta/2)]$



- Measured with T2
- At least 1 ch. particle in $5.3 < |\eta| < 6.4$
- P_T acceptance: $> 40 \text{ MeV}/c$
- Cosmic Ray (CR) MCs show a better agreement for the slope and contain the data:
 - SYBILL (CR): 4–16% lower
 - QGSJET-II (CR): 18–30% higher

$dN_{\text{ch}}/d\eta$ RESULTS: “the LHC picture”

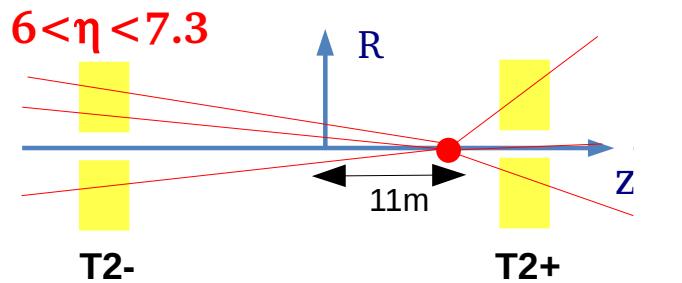
The TOTEM measurement:

- High visible cross section:
measured on data (see later):
 $\sim 95\% \sigma_{\text{INEL}}$

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

We will fill the gap:

- using T1
- using runs with displaced vertex
(we had $\sim 500K$ MB triggers with collisions at $\sim 11\text{m}$ from the IP):



Inelastic cross section measurement (1):

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

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

- We used a low luminosity run triggered by T2

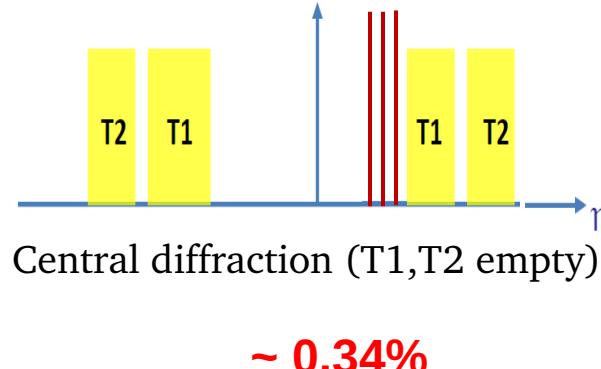
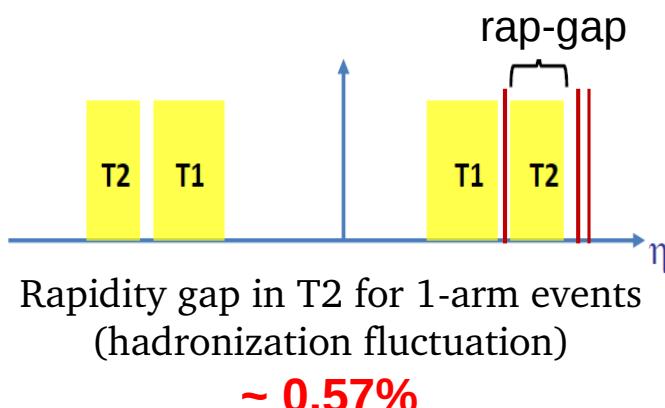
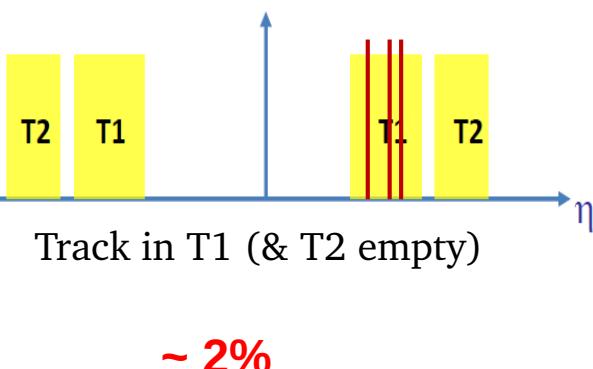
$$\sigma_{\text{Inel}, \text{T2 vis}} = \frac{N_{T2}}{\mathcal{L}_{int}}$$

{

- Trigger efficiency $\sim 2.3\%$
- Track reconstruction efficiency $\sim 1\%$
- Beam-gas background $\sim 0.57\%$
- Pile-up ($\mu \sim 0.03$) $\sim 1.5\%$

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

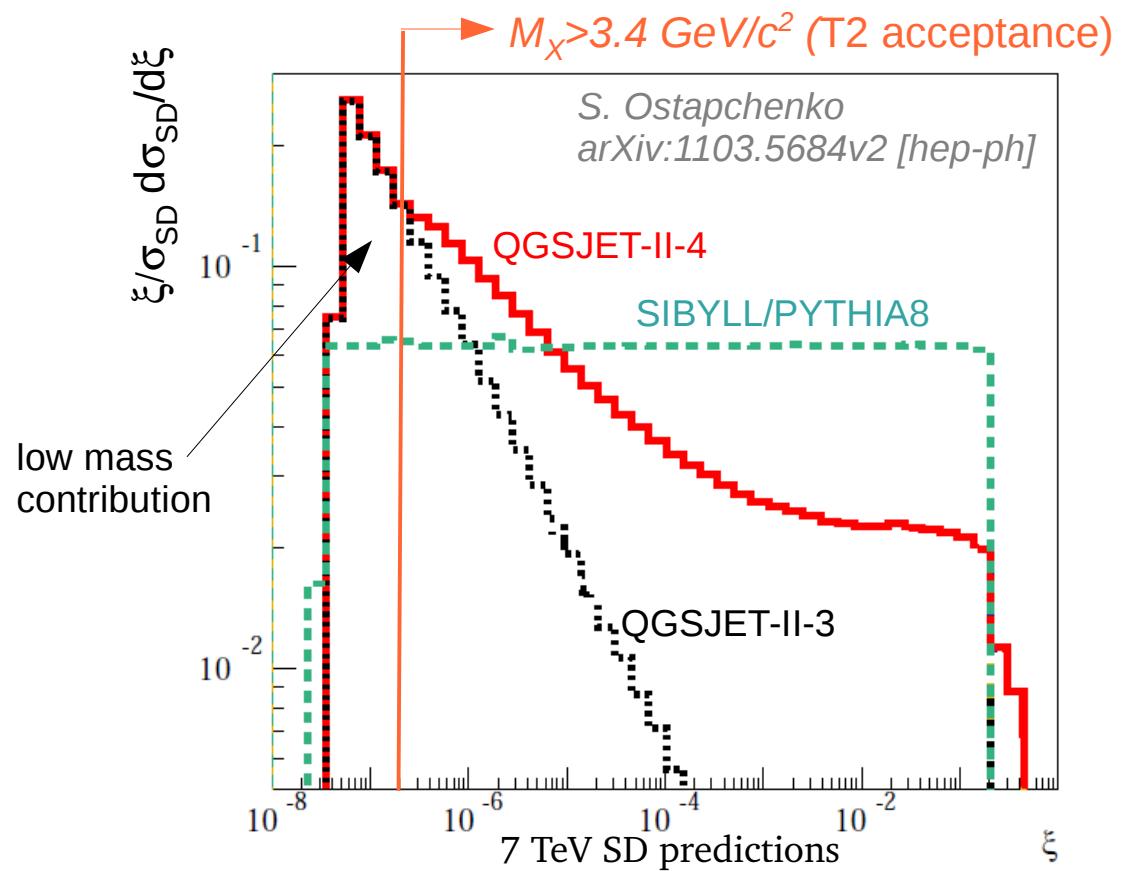
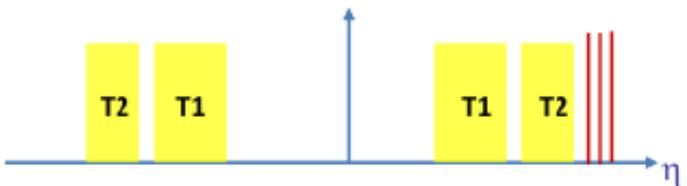
$$\sigma_{\text{Inel}, |\eta| < 6.5} \text{ (mb)}: 71.0 \pm 0.1\text{stat} \pm 0.7\text{syst} \pm 2.8\text{lumi}$$



Inelastic cross section measurement (2):

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

$$\sigma_{\text{inel}} \text{ (mb)}: 73.7 \pm 0.1\text{stat} \pm 1.7\text{syst} \pm 2.9\text{lumi}$$

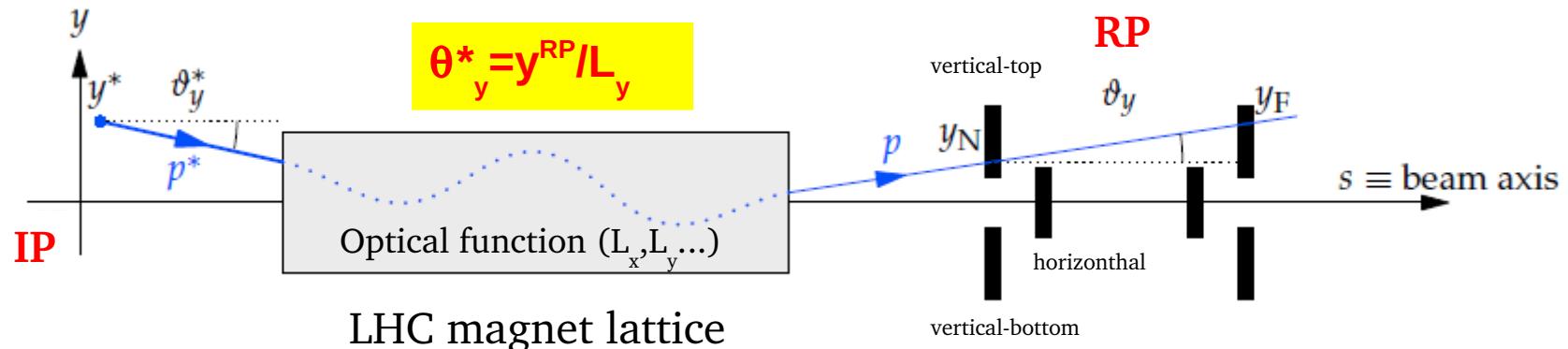


QGSJET-II-4 is the most reliable:

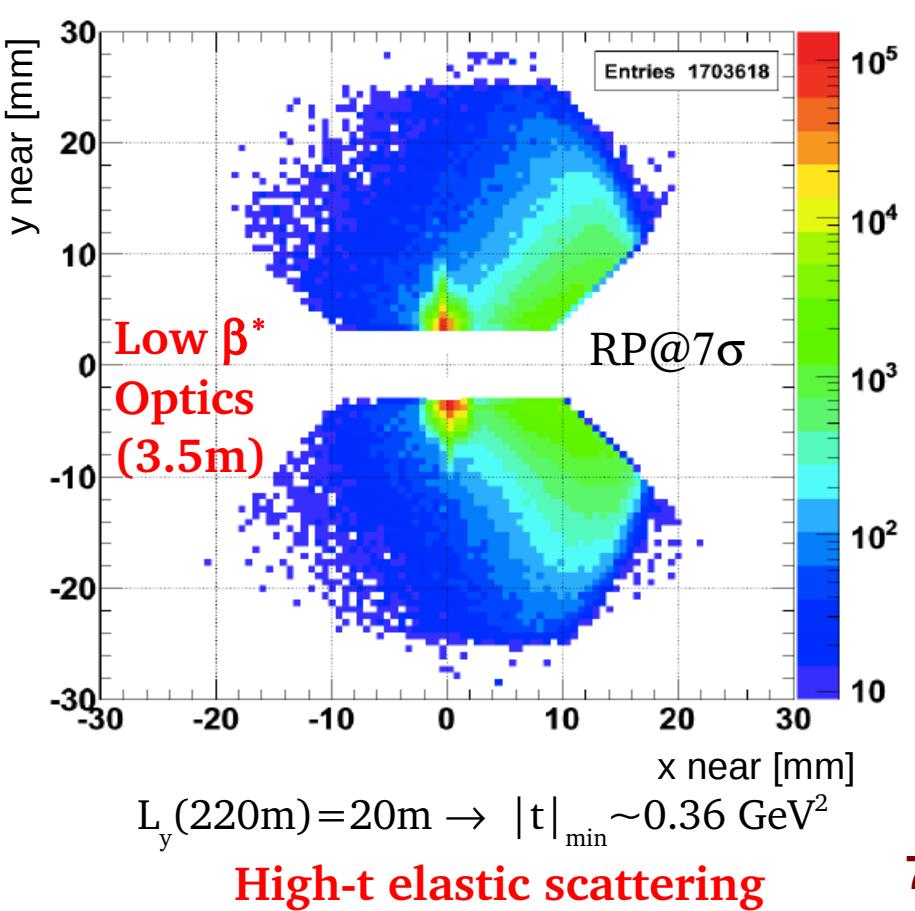
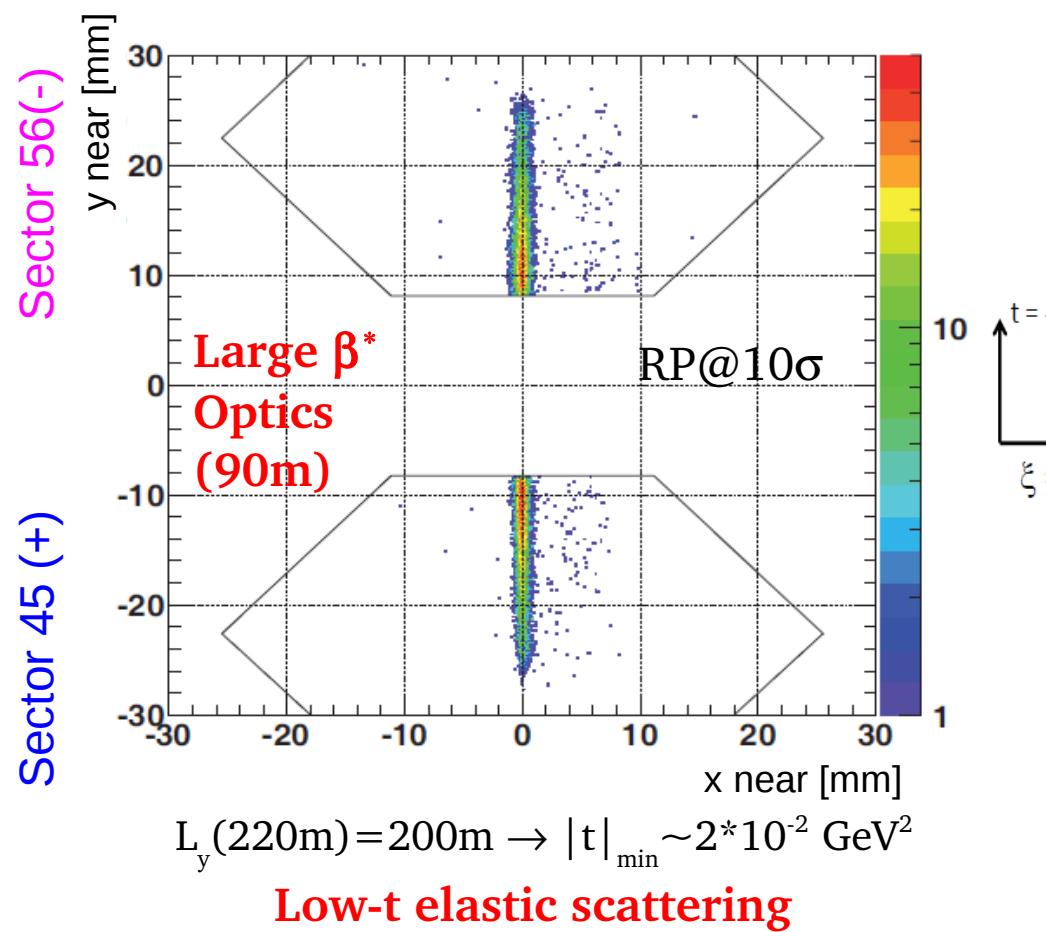
→ predicts a low mass diffraction x-section compatible with the one deduced comparing $\sigma_{\text{tot}} - \sigma_{\text{el}}$ (obtained from elastic measurements) with $\sigma_{\text{inel}, |\eta| < 6.5}$

Correction based on **QGSJET-II-4**
 $\sim 3.7\% \pm 2\% \text{ (syst)}$
(imposing the observed 2arm/1arm event ratio)

Elastic scattering: OPTICS



The optical functions describe the explicit path of the proton through the magnet elements as a function of the particle parameter at IP

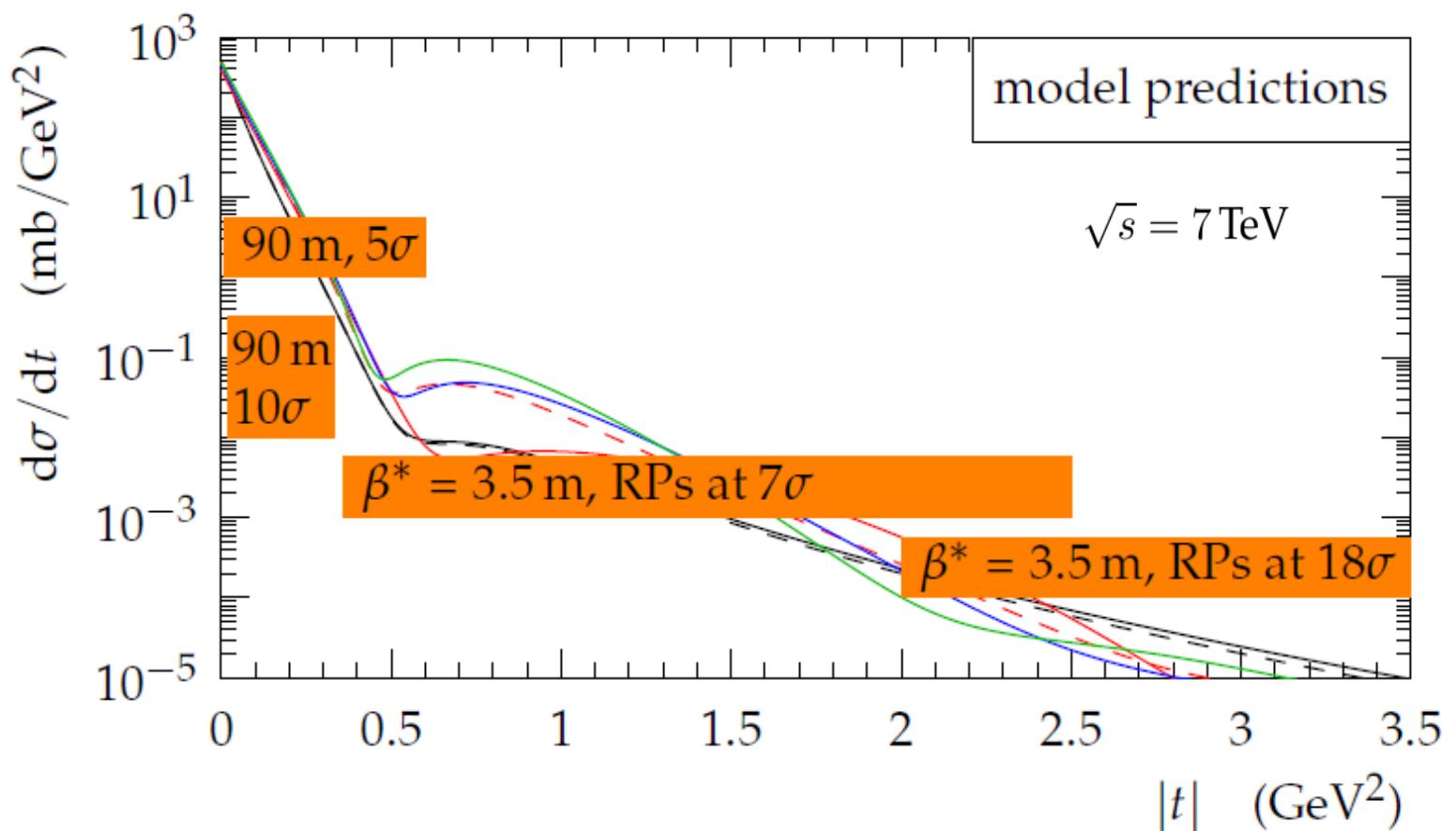


Elastic Scattering: Data Collection 2010-2011

Several data sets at different conditions to measure wide range and very low-t

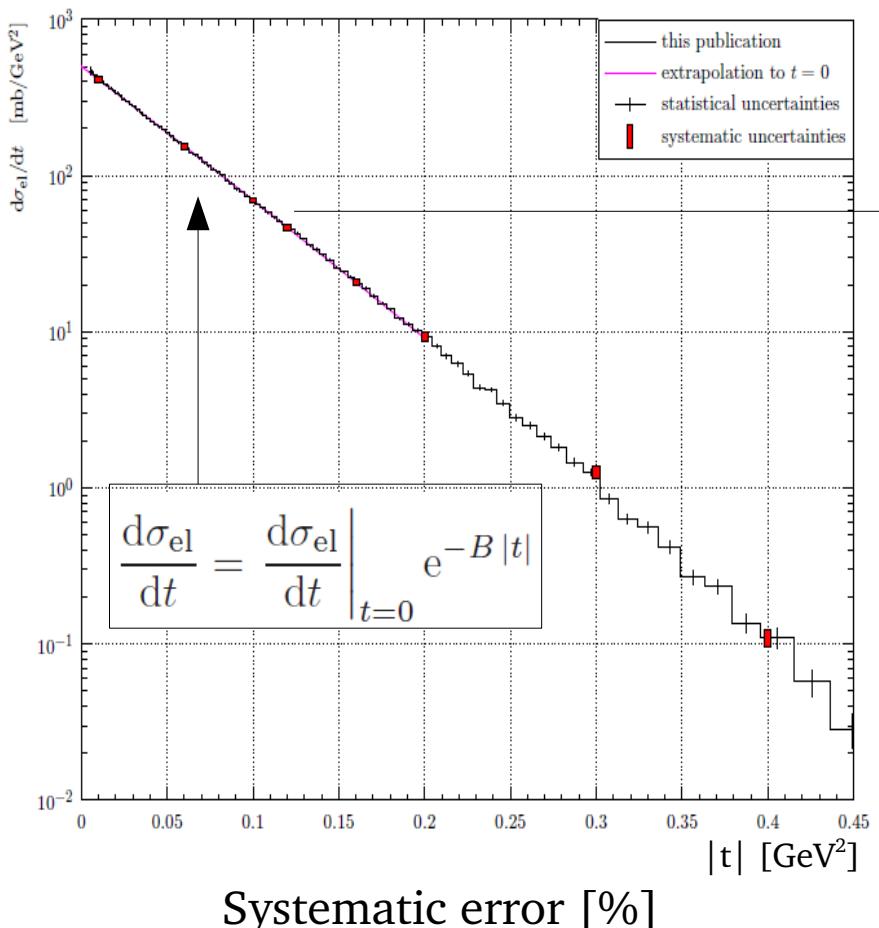
Set	$\beta^*(\text{m})$	RP approach	$\mathcal{L}_{int} (\mu\text{b}^{-1})$	t range (GeV^2)	Elastic events
1	90	4.8-6.5 σ	83	$5 \cdot 10^{-3} - 0.45$	1M
2	90	10 σ	1.7	0.02 - 0.4	14k
3	3.5	7 σ	0.07	0.36 - 3	66k
4	3.5	18 σ	2.3	2 - 3.5	10k

New data analysis

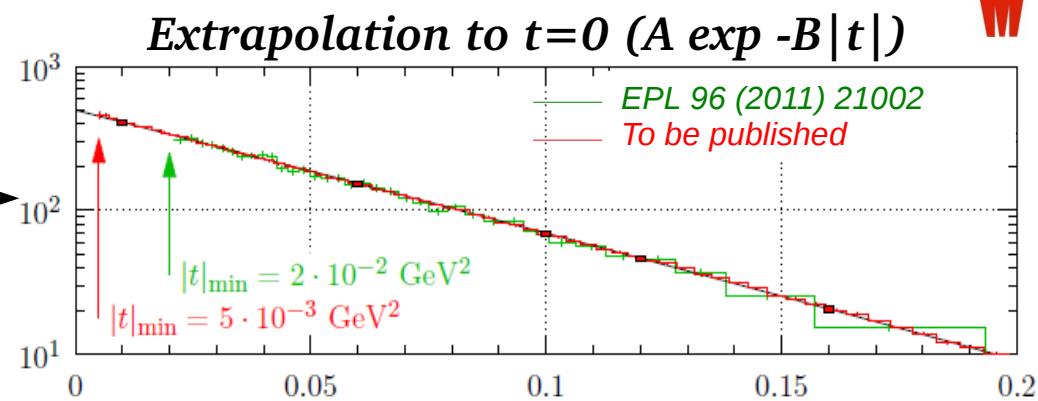
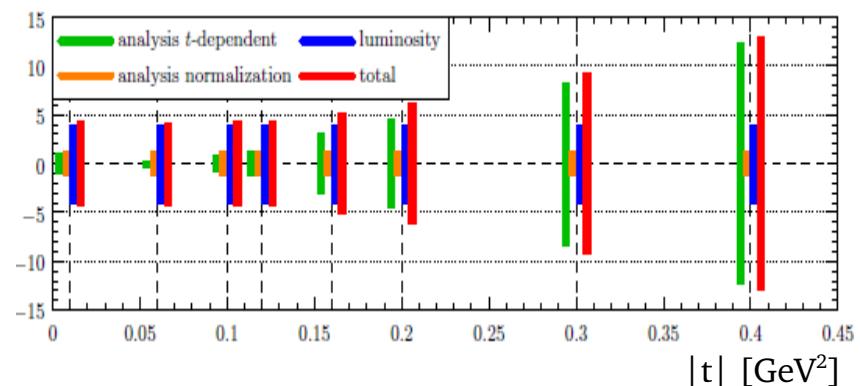


Elastic scattering results: $5 \cdot 10^{-3} < |t| < 0.45 \text{ GeV}^2$

New elastic analysis combined with the published -EPL96 (2011) 21002- analysis



Systematic error [%]



$$A \text{ (mb/GeV}^2\text{)} = 506 \pm 22.7^{\text{syst}} \pm 1.0^{\text{stat}}$$

$$503 \pm 26.7^{\text{syst}} \pm 1.5^{\text{stat}}$$

$$B \text{ (GeV}^{-2}\text{)} = 19.89 \pm 0.27^{\text{syst}} \pm 0.02^{\text{stat}} \quad (5 \cdot 10^{-3} < |t| < 0.2 \text{ GeV}^2)$$

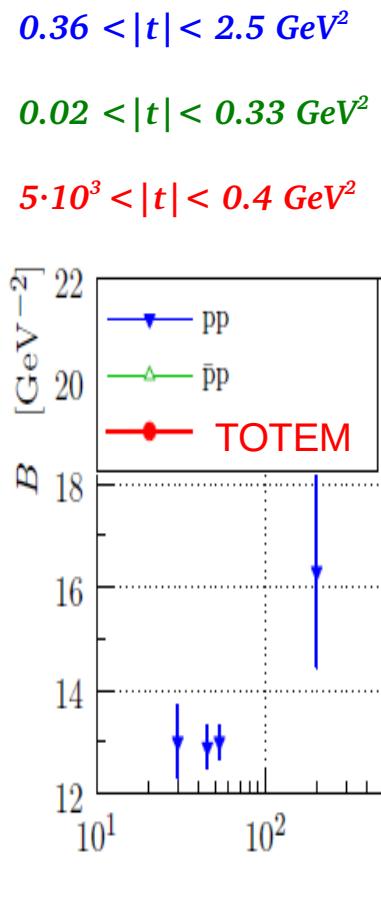
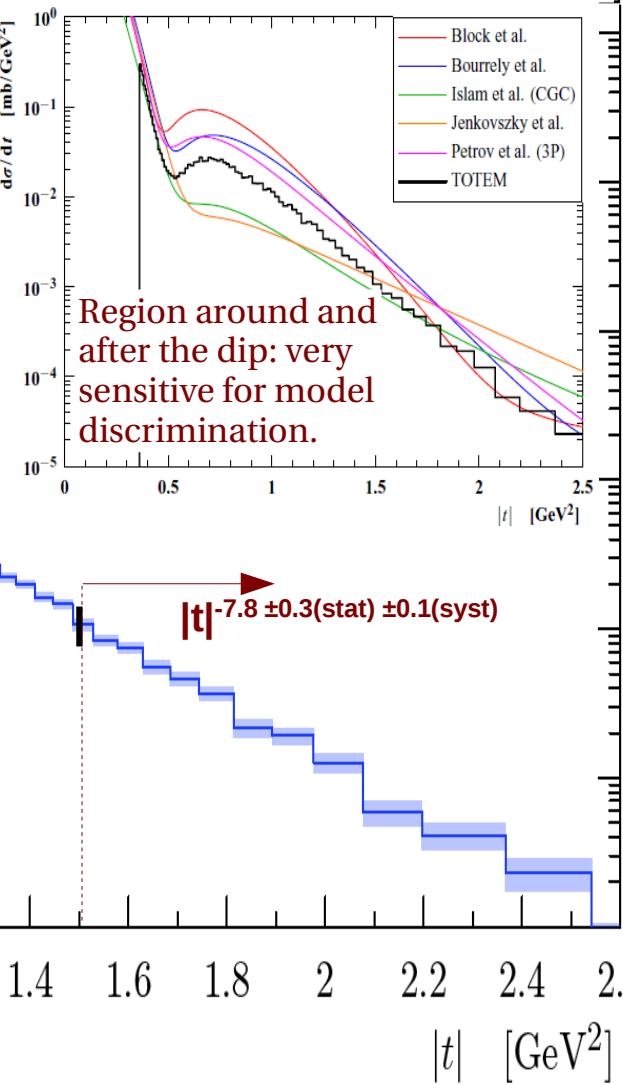
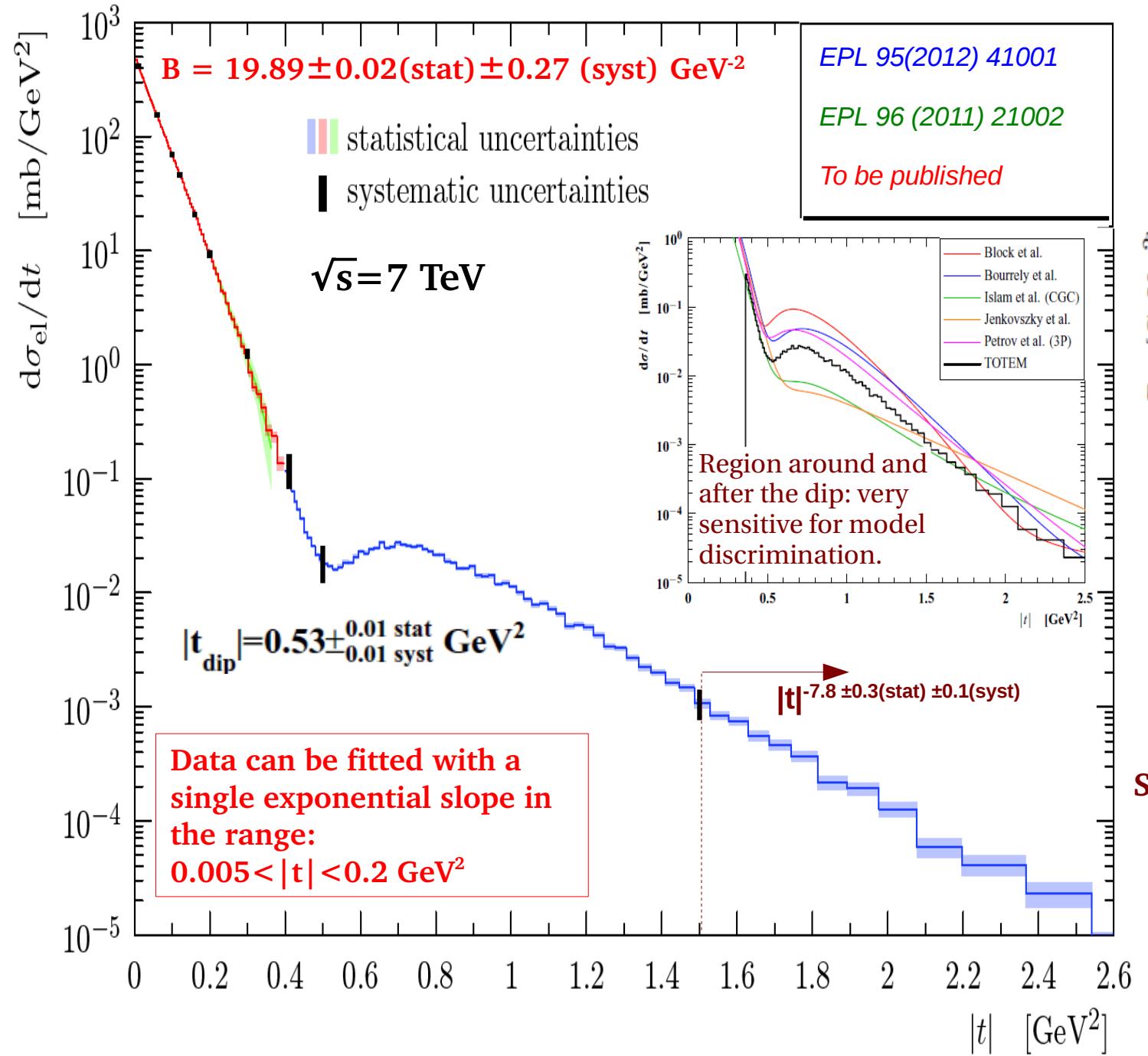
$$20.1 \pm 0.3^{\text{syst}} \pm 0.2^{\text{stat}} \quad (2 \cdot 10^{-2} < |t| < 0.33 \text{ GeV}^2)$$

(Luminosity dependent) elastic cross section σ_{el}

$$25.4 \pm 1.0^{\text{lumi}} \pm 0.3^{\text{syst}} \pm 0.03^{\text{stat}} \text{ mb (91\% measured)}$$

$$24.8 \pm 1.0^{\text{lumi}} \pm 0.2^{\text{syst}} \pm 0.2^{\text{stat}} \text{ mb (67\% measured)}$$

Elastic scattering results: $5 \cdot 10^{-3} < |t| < 2.5 \text{ GeV}^2$



- Shrinkage of the forward peak:
- minimum moves to lower $|t|$ with increasing CM energy
 - exponential slope grows with the CM energy

Total cross section measurements: three methods

- Method 1a): (low) luminosity-dependent σ_{tot} measurement
- Method 1b): (high) luminosity-dependent σ_{tot} measurement

→ Cross check with the CMS \mathcal{L}

Use of the optical theorem:

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

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

$$\rightarrow \rho = \frac{\mathcal{R}[f_{el}(0)]}{\mathcal{I}[f_{el}(0)]}$$

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

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} \longrightarrow \rho \text{ independent measurement, minimize the efficiency biases in the elastic measurement}$$

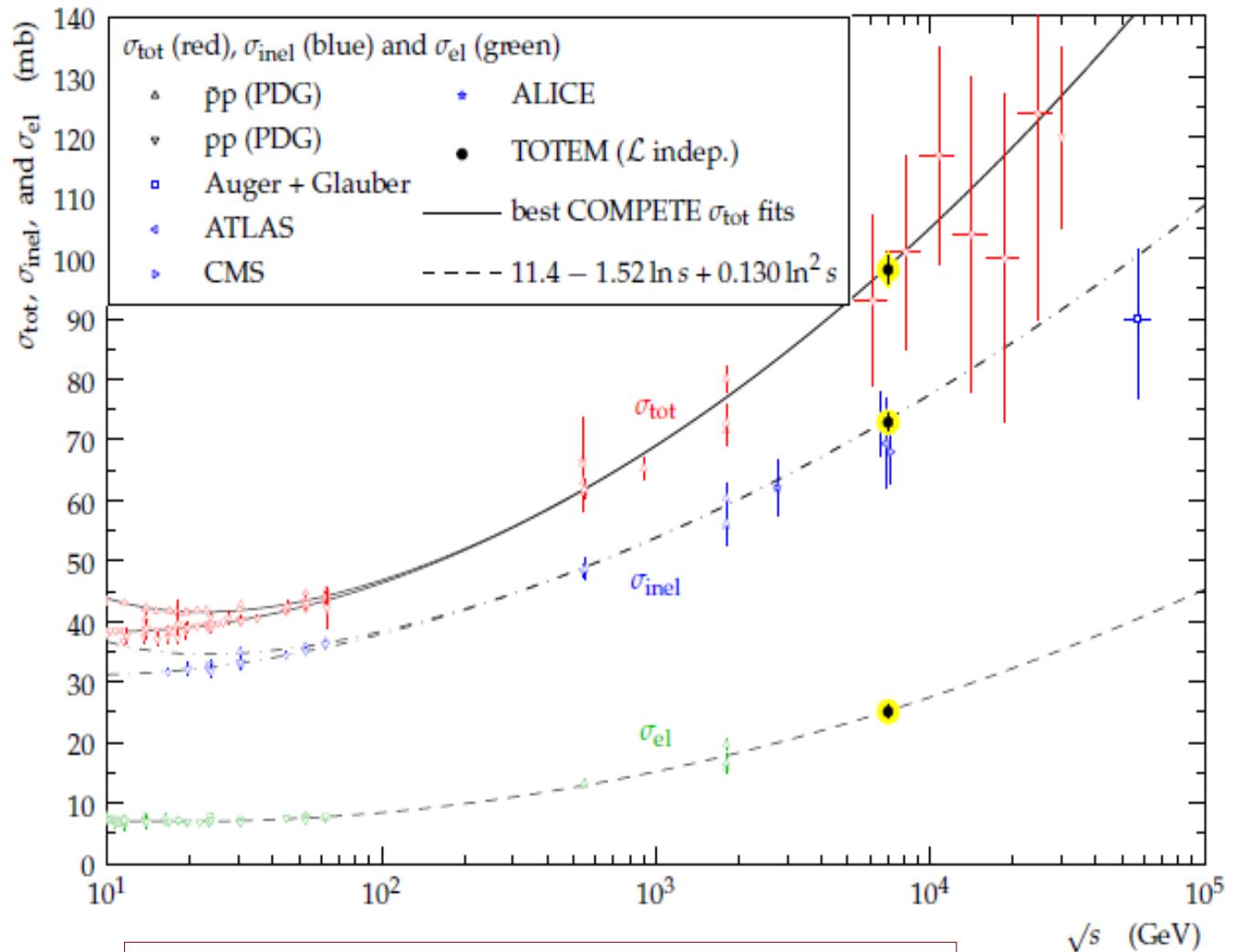
- Method 3): luminosity-independent σ_{tot} measurement:

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

Three cross section measurements (7 TeV): results

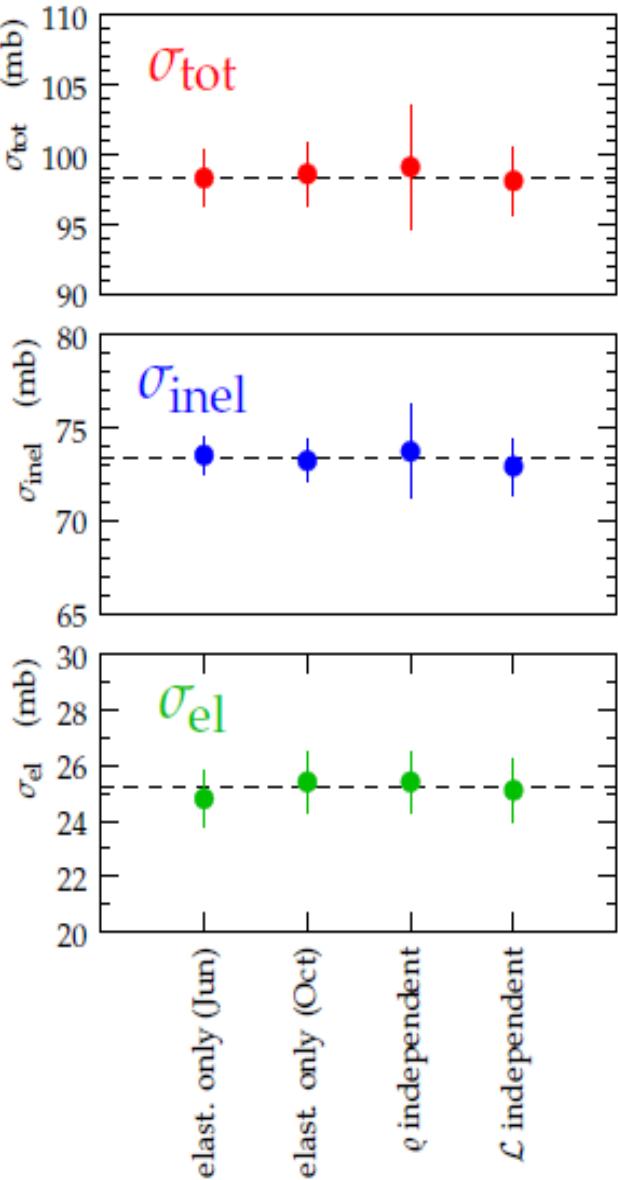
- Totem measurements compatible with the COMPETE best fit.
- All four measurements give consistent results.

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



Lumi-independent cross sections:

$$\begin{aligned}\sigma_{\text{TOT}} &= 98.0 \pm 2.5 \text{ mb} \\ \sigma_{\text{INEL}} &= 72.9 \pm 1.5 \text{ mb} \\ \sigma_{\text{EL}} &= 25.1 \pm 1.1 \text{ mb}\end{aligned}$$



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

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

➤ Absolute calibration of the CMS luminosity:

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

$$\mathcal{L}_{int, CMS} = 82/\mu b \pm 4\%$$

$$\mathcal{L}_{int, CMS} = 1.65/\mu b \pm 4\%$$

$$\mathcal{L}_{int, TOTEM} = 83.7/\mu b \pm 3.8\%$$

$$\mathcal{L}_{int, TOTEM} = 1.65/\mu b \pm 4.5\%$$

➤ Luminosity and ρ independent ratios:

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

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

➤ Low mass diffraction:

From method (1b): $\sigma_{inel} = 73.15 \pm 1.26$ mb

Measure $\sigma_{inel}^{|\eta| < 6.5} = 71.0 \pm 2.8$ mb

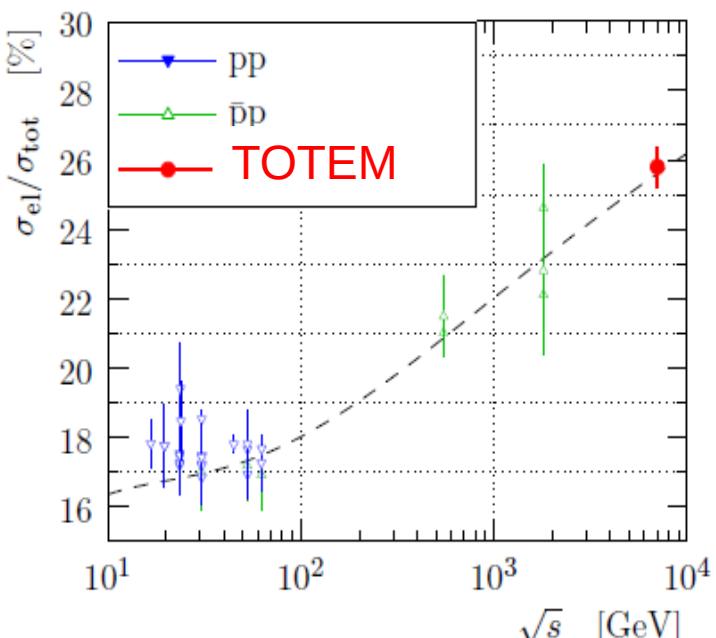
$$\rightarrow \sigma_{inel}^{|\eta| > 6.5} = 3.0\% \quad \sigma_{inel}^{|\eta| < 6.5} \text{ (upper limit } \sim 6.9 \text{ mb at 95%CL)}$$

➤ ρ measurement:

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

TOTEM $|\rho| = 0.14 \pm 0.09$

COMPETE extrapolation $|\rho| = 0.141 \pm 0.007$



The two experiments have now the possibility to exchange the trigger information

April 2012: CMS Jet Trigger to TOTEM

May 2012: Low pile-up run, 8M event T1+T2+CMS recorded.

Trigger exchange and same event recording by both experiment:

Totem MB L1 → 7 CMS Trigger menu → TOTEM “High Level Trigger”

Physics potential due to large coverage: CMS+T1+T2 = $-6.5 < \eta < +6.5$

- $dN_{\text{ch}}/d\eta$ over the complete range with several event-selection strategies.
- multiplicity distributions and correlations (forw./back., forw./cent.)
- rapidity gap distributions, multi-gap and central-gap events
- jets – underlying event studies extended to forward region



A common WG has started to analyze the data

TODAY: Special run at $\beta^* = 90$ m, 156 bunches (RP already aligned for $\beta^*=3.5$ and 90m)
 CMS + TOTEM T1, T2 and Roman Pots = very large acceptance
 Proton acceptance: $|t| > 0.02$ GeV 2 , any ξ
 Soft and medium-hard diffraction.

Conclusions and outlooks

- TOTEM has measured the inelastic & elastic cross section and the total cross section with the luminosity independent method at $\sqrt{s}=7 \text{ TeV}$
 - Measurement of elastic differential cross section in $5 \cdot 10^{-3} < |t| < 2.5 \text{ GeV}^2$, ρ -constraint, luminosity calibration.
 - Very soon these analysis will be repeated at $\sqrt{s}=8 \text{ TeV}$ (data from a successful special run at $\beta^*=90\text{m}$ on 7th July)
 - Constraint on the low mass diffractive cross section.
- Measurement of the forward charged particle $dN/d\eta$ distribution with T2.
- Several analysis on diffractive physics are ongoing (DPE, SD, DD) results are expected soon.
- Common analysis with CMS is now technically possible: a very rich Physics program is already achievable this year!

Thank you for your attention



Backup

The uncertainty of the extrapolation of the hadronic production cross section to ultrahigh energies is a major problem for the interpretation of existing cosmic ray data for example in terms of the primary mass composition.

When the uncertainties of the extrapolation of the nucleon-nucleon data is propagated into the proton-air cross section using the Glauber approach, the uncertainty of the predicted cross section at 10^{19} eV might get as large as $\gg 50\%$ (c.f. Fig. 2).

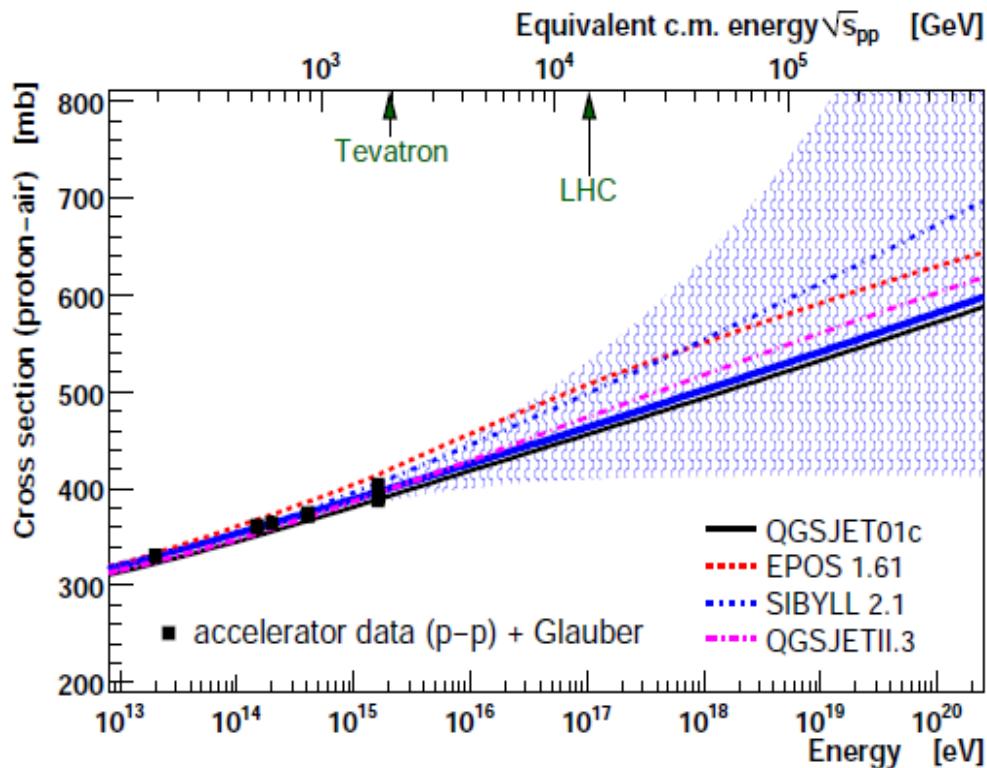


Figure 2: Resulting uncertainty from extreme assumptions on the extrapolation of nucleon-nucleon scattering parameters on the proton-air production cross section (from [28]).

In order to use the composition information of cosmic ray data to constrain astrophysical source and propagation scenarios this uncertainty must be reduced drastically. The LHC will certainly help a lot by providing another high precision data point of nucleon-nucleon scattering parameters at energies that are already significant in terms of cosmic ray physics. For the still needed extrapolation to energies above $E_{\text{lab}} \gg 10^{17}$ eV it is required to rely on cosmic ray data itself to constrain the proton-air cross section.

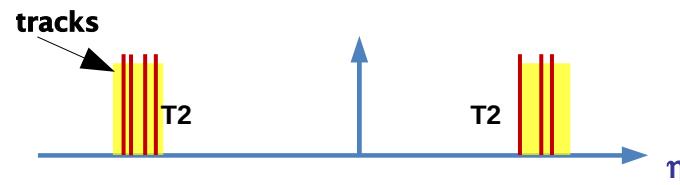
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Cross section for events with at least a stable particle in the T2 acceptance:

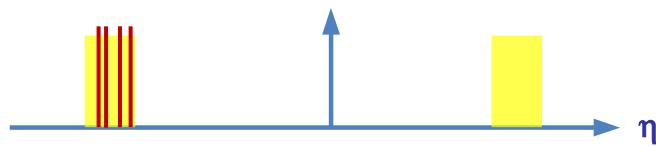
$$\sigma_{\text{inel}, \text{T2 vis}} (\text{mb}): 69.7 \pm 0.1\text{stat} \pm 0.7\text{syst} \pm 2.8\text{lumi}$$

- We used a low luminosity run triggered by T2

“2h” events: mainly ND, DD



“1h” events: mainly SD with $M > 3.4 \text{ GeV}$



- 2h/1h event ratio of data used to improve the accuracy of the corrections:

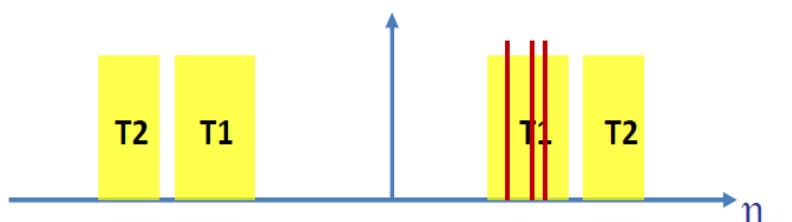
$$\sigma_{\text{Inel}, \text{T2 vis}} = \frac{N_{\text{T2}}}{\mathcal{L}_{\text{int}}}$$

- Trigger efficiency $\sim 2.3 \%$
Measured from zero bias data wrt track multiplicity
- Track reconstruction efficiency $\sim 1\%$
Based on MC tuned with data
- Beam-gas background $\sim 0.57\%$
Measured with non colliding bunch data
- Pile-up ($\mu \sim 0.03$) $\sim 1.5 \%$
Contribution measured from zero bias data

Inelastic cross section measurement (2):

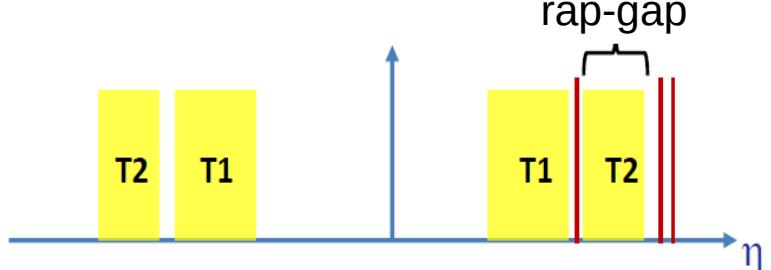
Cross section for events with at least a stable particle with $|\eta| < 6.5$:

$$\sigma_{\text{inel}, |\eta| < 6.5} \text{ (mb)}: 71.0 \pm 0.1\text{stat} \pm 0.7\text{syst} \pm 2.8\text{lumi}$$



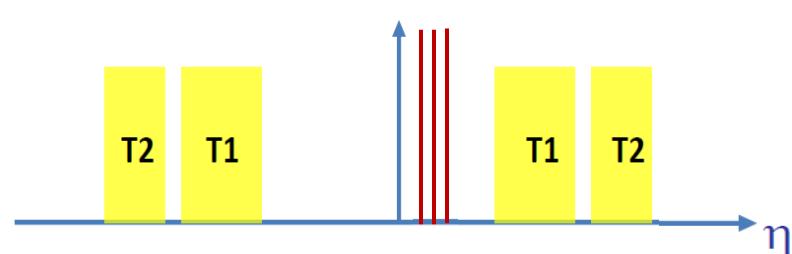
- Tracks in T1 (& T2 empty)
Estimated from bunch crossing data

$\sim 2\%$



- Rapidity gap in T2 (hadronization fluctuation)
Estimated from T1 gap probability transferred to T2 η-region (scaled by the fraction of T2 1h events)

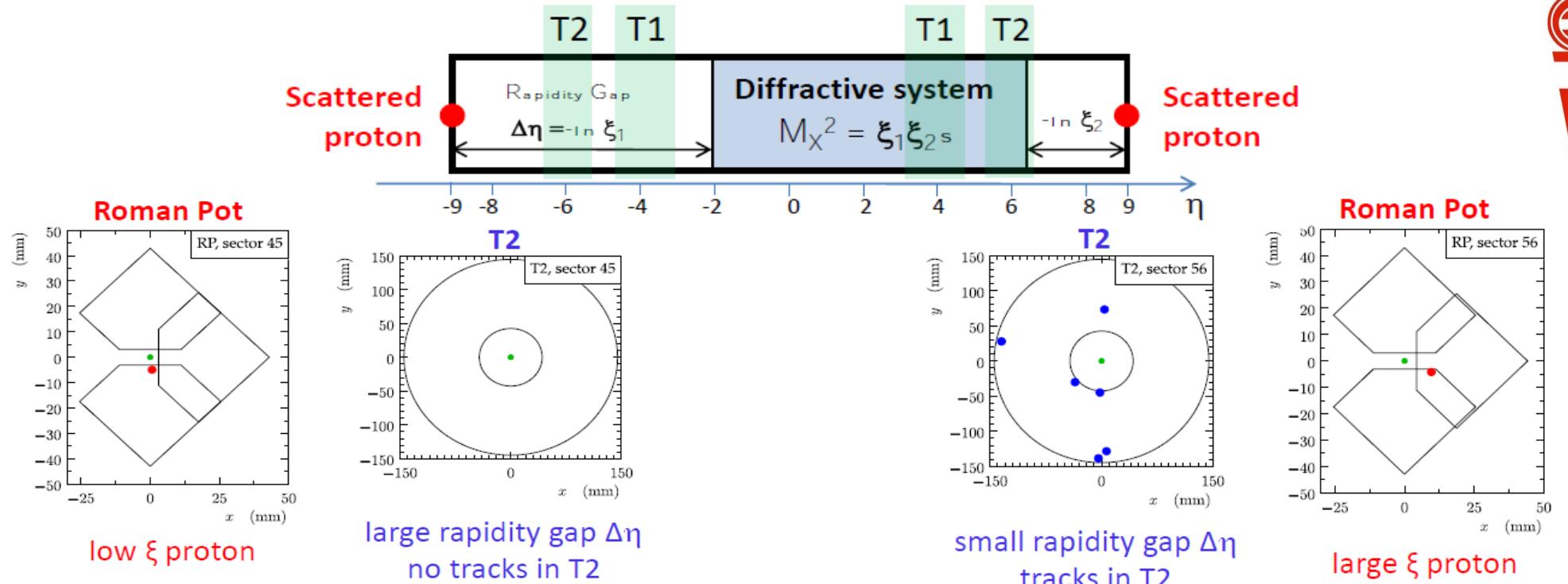
$\sim 0.57\%$



- Central diffraction (T1 & T2 empty)
Estimated from MC corr max ~ 0.25 σ_{CD}

$\sim 0.34\%$

Double Pomeron Exchange

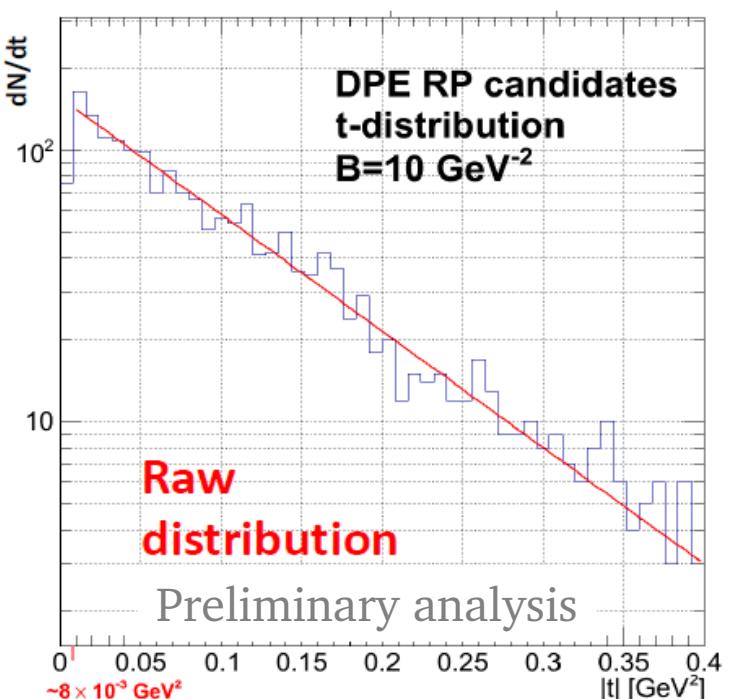


DPE rate as a function of t (ξ -integrated):

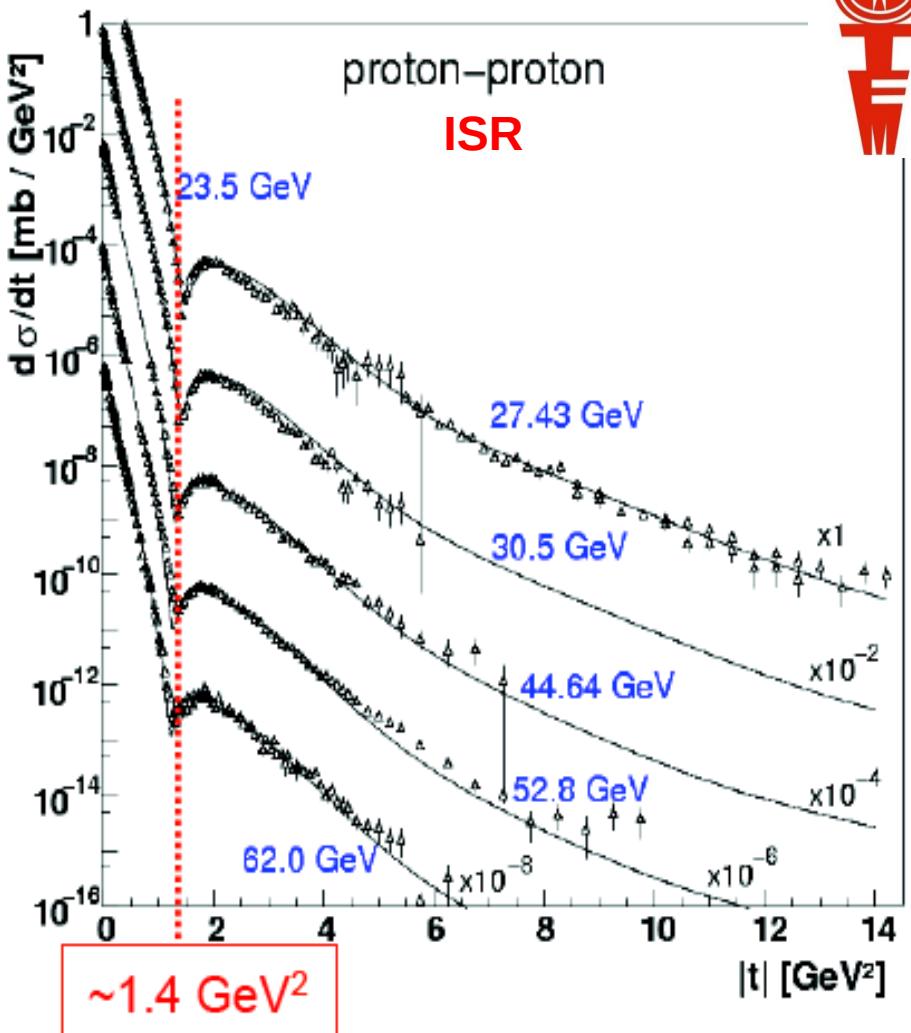
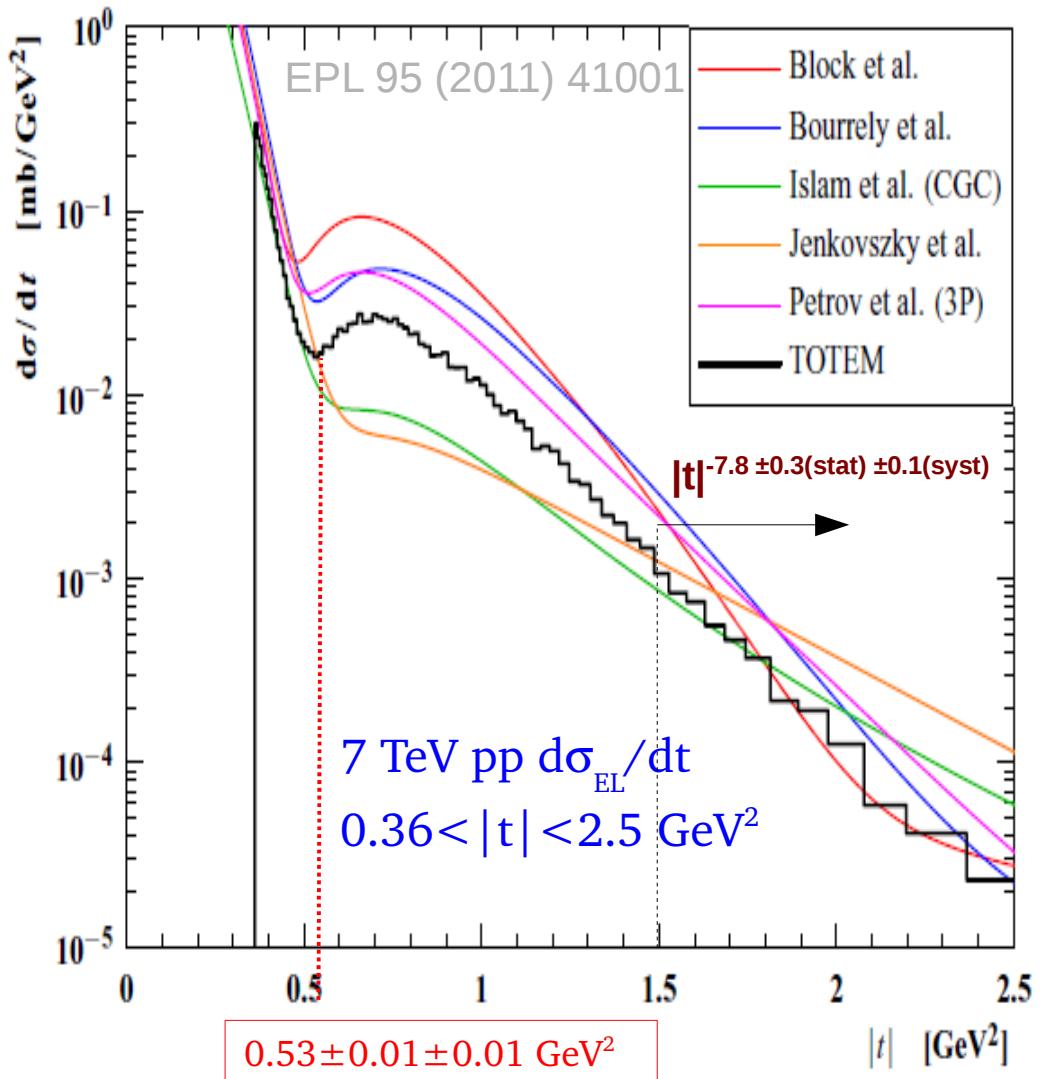
Excellent RP acceptance in $\beta^* = 90m$ runs:

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

Preliminary: to be corrected for efficiency,
acceptance, resolution...



Elastic Scattering: results $0.36 < |t| < 2.5 \text{ GeV}^2$



-minimum moves to lower $|t|$ with increasing s
-exponential slope grows with energy

} **Shrinkage of the forward peak**

Totem findings:

-region around and after the dip very sensitive for model discrimination.
 $-1.5 < |t| < 2$ compatible with $|t|^{-8}$ (triple gluon exchange).

Elastic Analysis

Proton selection cuts

+ collinearity cuts (left-right)

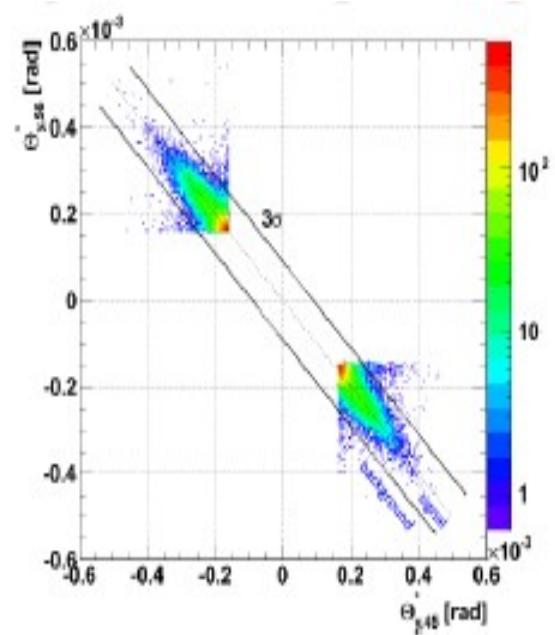
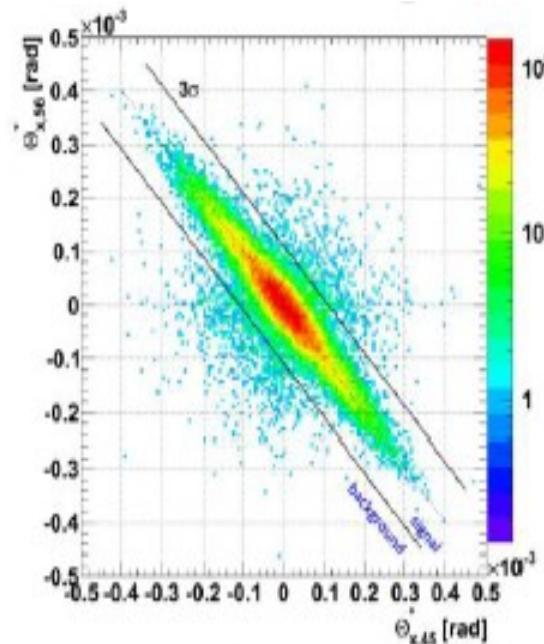
$$\theta_{x,45}^* \leftrightarrow \theta_{x,56}^*$$

$$\theta_{y,45}^* \leftrightarrow \theta_{y,56}^*$$

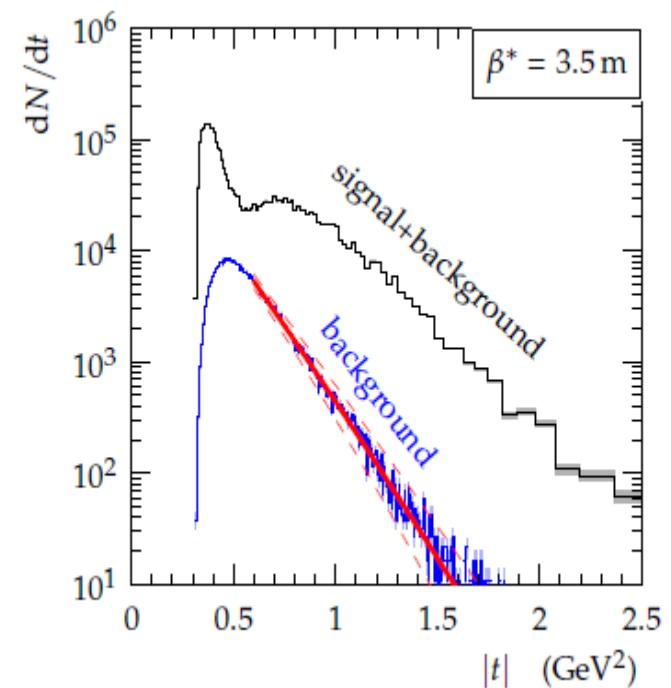
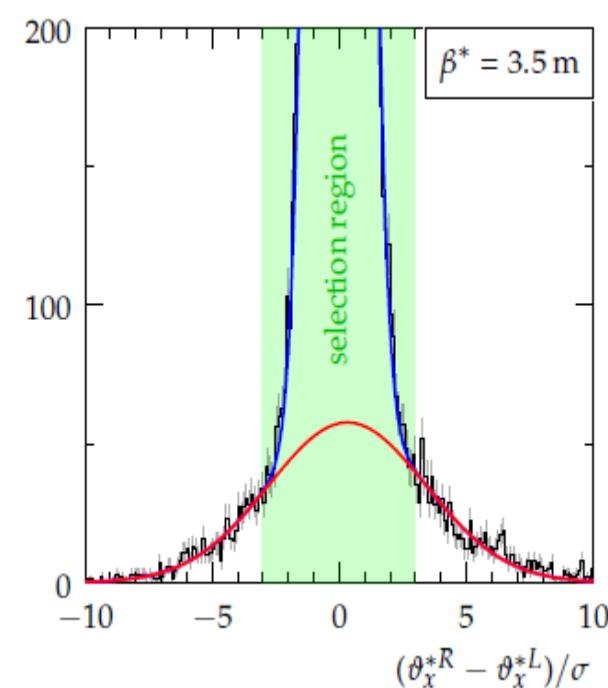
+ low ξ cuts

+ vertex cuts

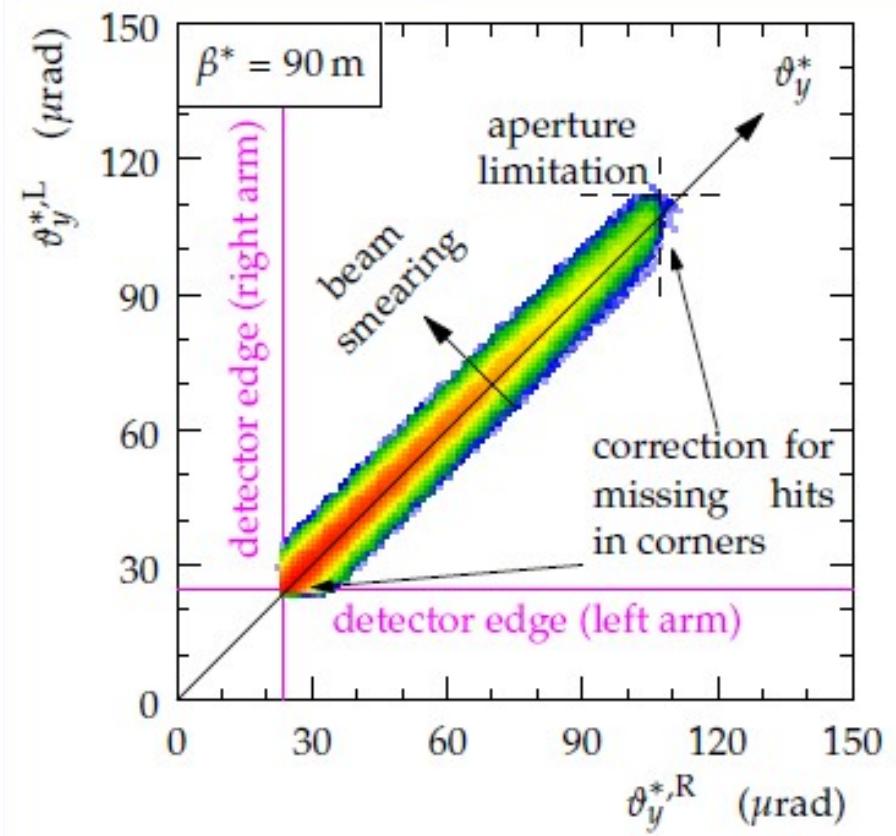
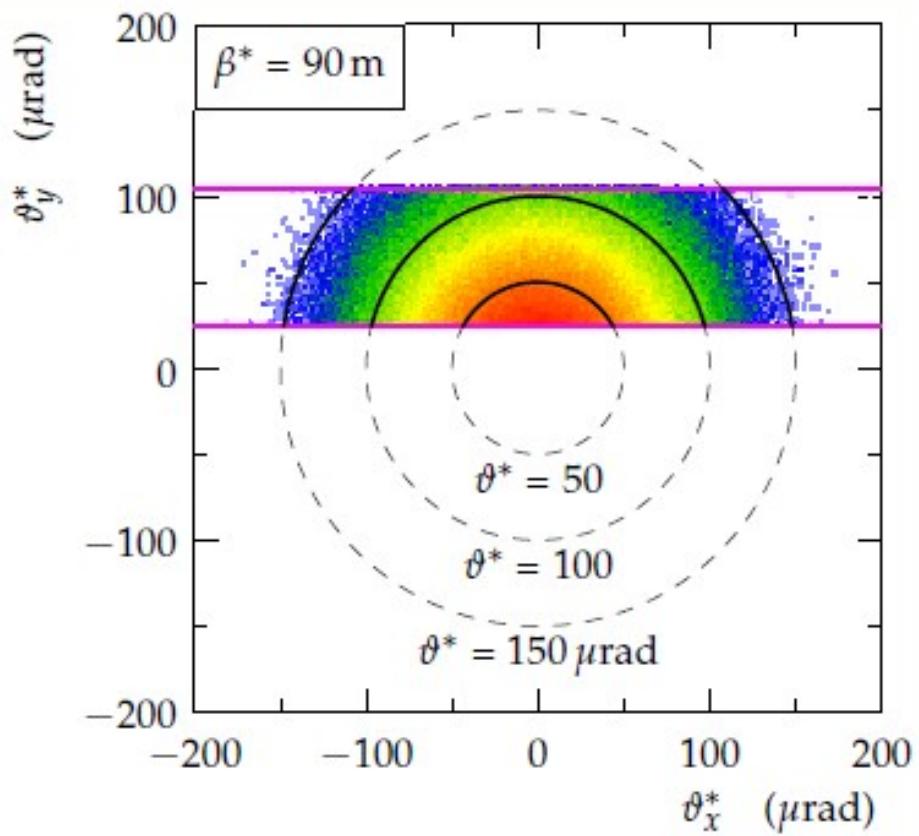
+ optics related cuts



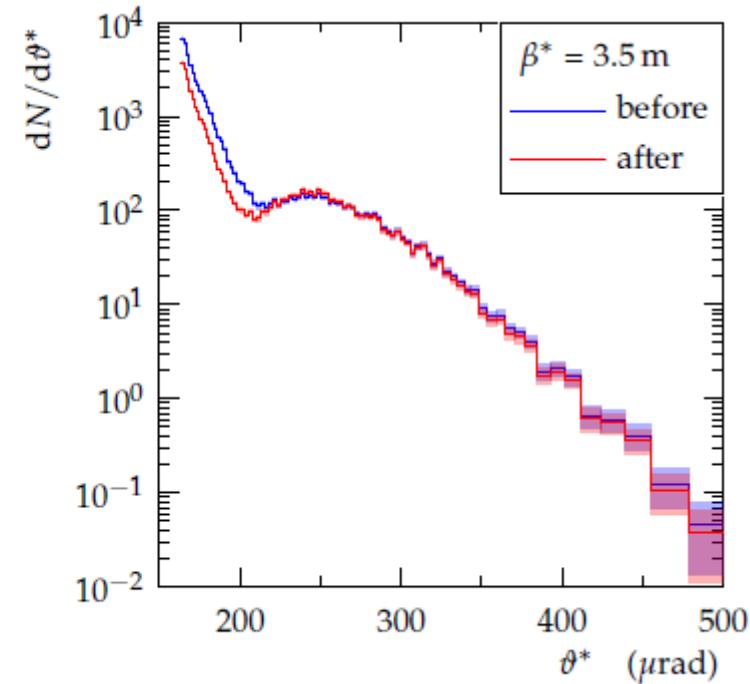
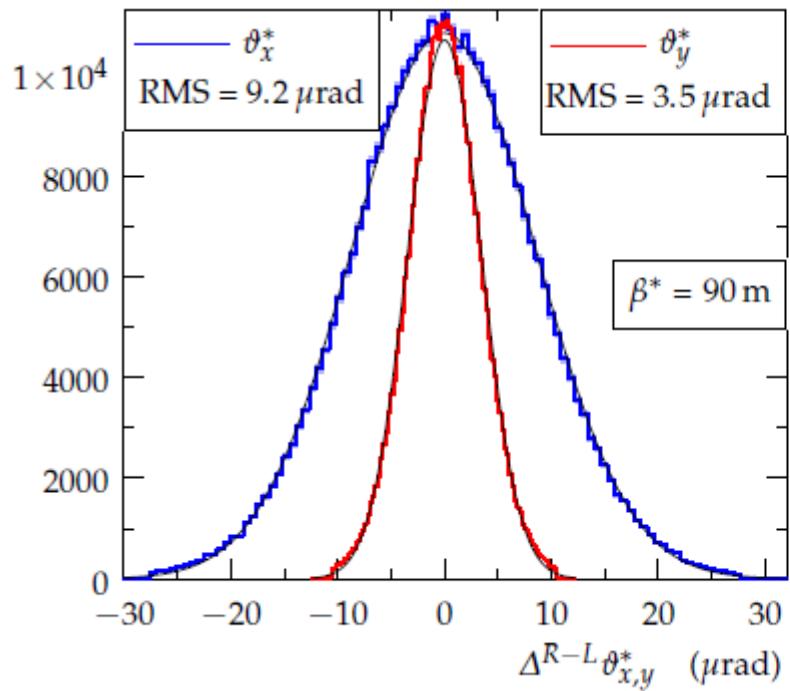
Background subtraction



Acceptance Correction



Resolution unfolding



Normalization

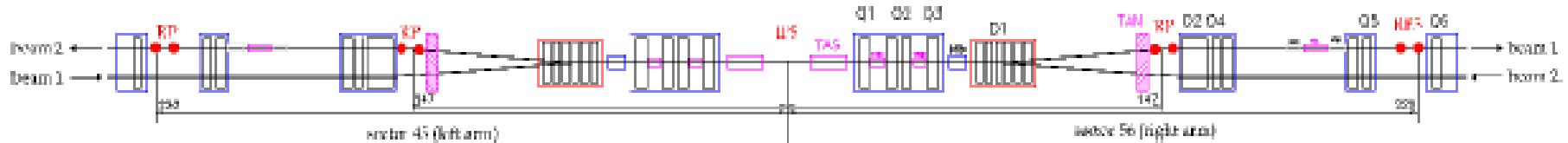
Reconstruction efficiency

- 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% ($\beta^*=90\text{m}$); 30% ($\beta^*=3.5\text{m}$)

Luminosity from CMS systematic error of 4%



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:

$$\text{measured in Roman Pots} \quad \begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{\text{RP}} = \underbrace{\begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{Proton transport matrix}} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{\text{IP5}} \quad \text{reconstructed}$$

Elastic proton reconstruction:

- Scattering angle reconstructed in both projections
- High Θ^* -reconstruction resolution available
 $\sigma(\Theta_x^*) = 1.7 \mu\text{rad}$ for $\beta^* = 90 \text{ m}$ and low t-range
 $\sigma(\Theta_y^*) = 12.5 \mu\text{rad}$ for $\beta^* = 3.5 \text{ m}$ and high t-range

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

Excellent optics calibration and alignment required

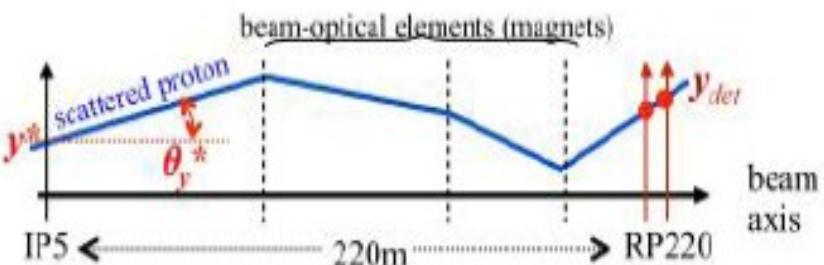


Optics

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

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

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



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

$\beta^* = 3.5 \text{ m}$: $L_y \approx 25 \text{ m}$, v_y small

$\beta^* = 90 \text{ m}$: $L_y \approx 260 \text{ m}$, $v_y \approx 0$

$\Rightarrow \theta_y^*$ reconstructed from track position

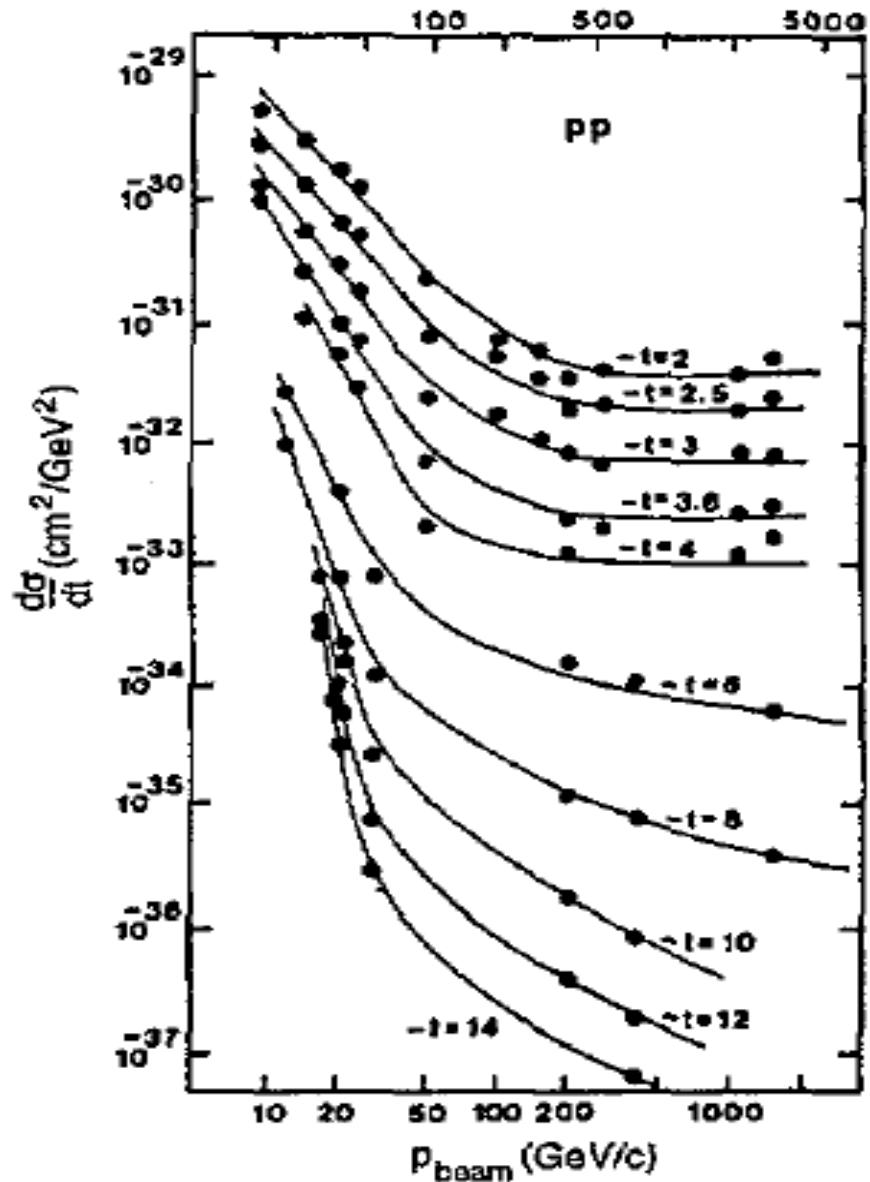
$$x_{\text{det}} = L_x \theta_x^* + v_x x^* + \cancel{D\xi} \quad \text{Elastic: } \xi = 0$$

$\beta^* = 3.5 \text{ m \& } 90 \text{ m}$: $L_x \approx 0 \text{ m}$, v_x sizable
 $\Rightarrow \theta_x^*$ reconstructed from track angle

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

	Beam width @ vertex	Angular beam divergence	Min. reachable $ t $
	$\sigma_{x,y}^* = \sqrt{\epsilon \beta^*}$	$\sigma_\theta^* = \sqrt{\frac{\epsilon}{\beta^*}}$	$ t_{\min} = n_\sigma^{-1} \frac{p^2 \epsilon}{\beta^*}$
Standard optics $\beta^* \sim 1-3 \text{ m}$	$\sigma_{x,y}^*$ small	$\sigma(\theta_{x,y}^*)$ large	$ t_{\min} \sim 0.3-1 \text{ GeV}^2$
Special optics $\beta^* = 90 \text{ m}$	$\sigma_{x,y}^*$ large	$\sigma(\theta_{x,y}^*)$ small	$ t_{\min} \sim 10^{-2} \text{ GeV}^2$

TOTEM $d\sigma_{el}/dt$: valuable input for the description of the proton



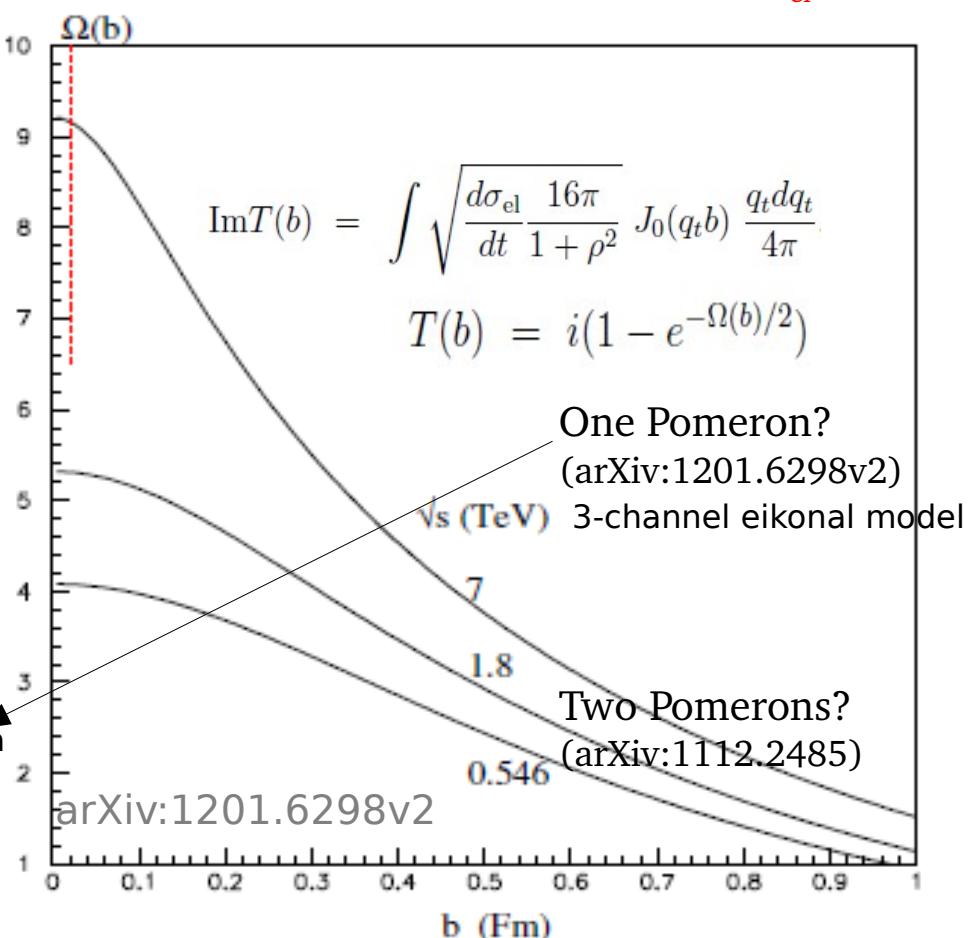
It is possible to describe all the elastic pp (and p_p) collider data for $|t| < 0.4$ GeV² in terms of a 3-channel eikonal model of a single Pomeron, and, secondly, that absorptive corrections appreciably modify the value and the behaviour of diffractive cross sections with rapidity gaps.

$ t $	[GeV ²]	$d\sigma_{el}/dt$	$\mu\text{b}/\text{GeV}^2$	\pm stat	\pm syst
1.932	± 0.024	0.192	± 0.025	± 0.051	± 0.050
2.024	± 0.029	0.126	± 0.019	± 0.033	± 0.032

TOTEM

Rising of differential cross section
for fixed “high” t.

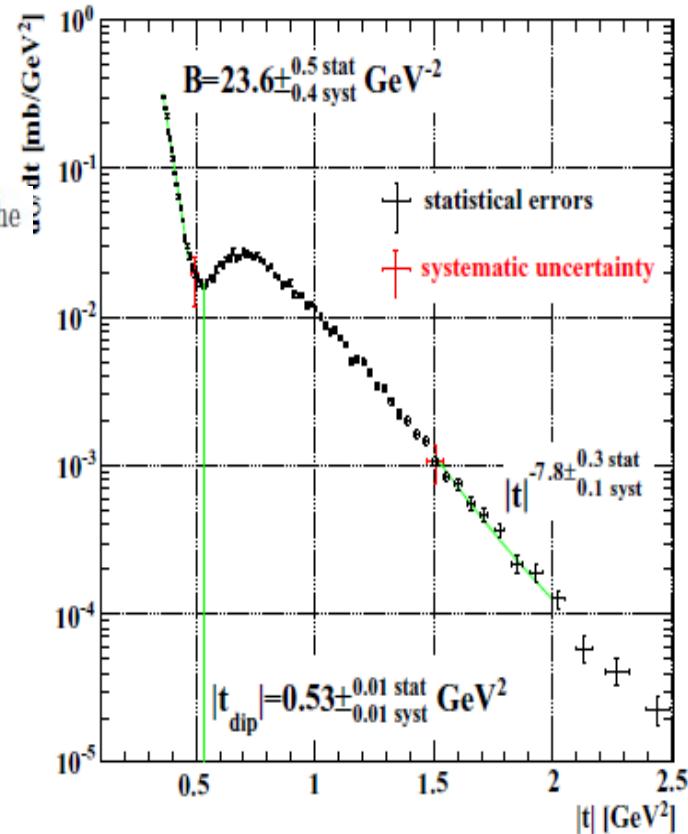
Opacity from the forward TOTEM $d\sigma_{el}/dt$



Large-t systematics

Table 2: Analysis corrections and systematics (δ denotes an uncertainty; the optical function L relates the displacement to the scattering angle: $x, y = L_{x,y} \Theta_{x,y}^*$; Δs (≈ 5 m) is the distance between the two units in one RP station).

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



Low-t systematics

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left. \frac{d\sigma_{\text{el}}}{dt} \right|_0$$

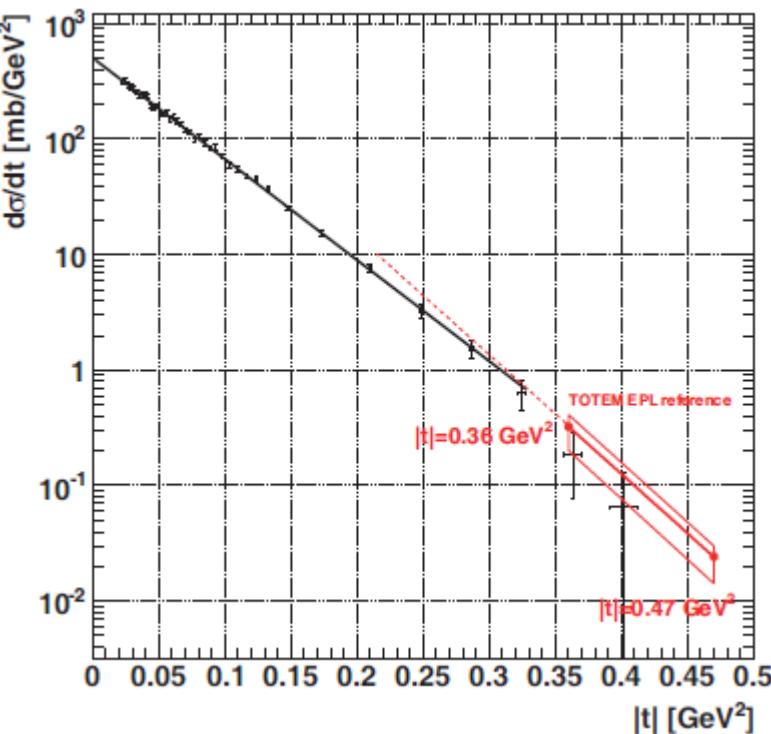


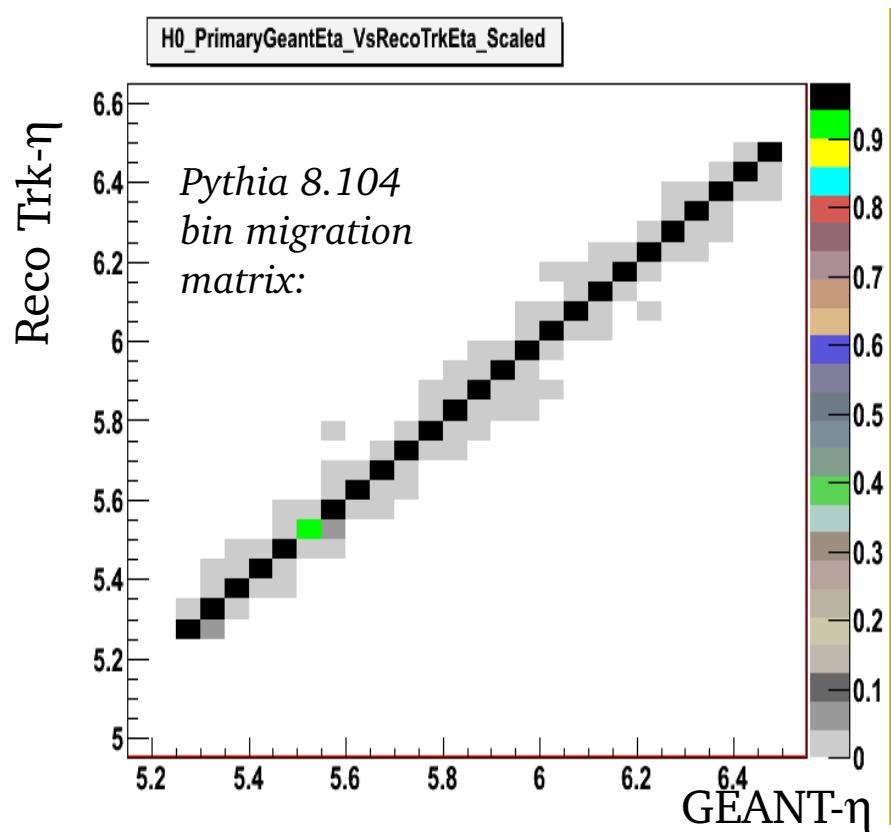
Table 1: Results of the TOTEM measurements at the LHC energy of $\sqrt{s} = 7$ TeV.

	Statistical uncertainties	Systematic uncertainties	Result
t	$\pm[3.4\text{--}11.9]\%$ single measurement ^(*)	$\pm[0.6\text{--}1.8]\%$ ^{optics} $\pm < 1\%$ ^{alignment}	
$\frac{d\sigma}{dt}$	5% / bin	$\pm 4\%$ ^{luminosity} $\pm 1\%$ ^{analysis} $\pm 0.7\%$ ^{unfolding}	
B	$\pm 1\%$	$\pm 1\%$ ^{t-scale} $\pm 0.7\%$ ^{unfolding}	$(20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}}) \text{ GeV}^{-2}$
$\frac{d\sigma}{dt} _{t=0}$	$\pm 0.3\%$	$\pm 0.3\%$ ^{optics} $\pm 4\%$ ^{luminosity} $\pm 1\%$ ^{analysis}	$(503.7 \pm 1.5^{\text{stat}} \pm 26.7^{\text{syst}}) \text{ mb/GeV}^2$
$\int \frac{d\sigma}{dt} dt$	$\pm 0.8\%$ ^{extrapolation}	$\pm 4\%$ ^{luminosity} $\pm 1\%$ ^{analysis}	
σ_{tot}	$\pm 0.2\%$	$\begin{pmatrix} +0.8\% \\ -0.2\% \end{pmatrix}^{(\rho)} \pm 2.7\%$	$(98.3 \pm 0.2^{\text{stat}} \pm 2.8^{\text{syst}}) \text{ mb}$
$\sigma_{\text{el}} = \int \frac{d\sigma}{dt} dt$	$\pm 0.8\%$	$\pm 5\%$	$(24.8 \pm 0.2^{\text{stat}} \pm 1.2^{\text{syst}}) \text{ mb}$
σ_{inel}	$\pm 0.8\%$	$\begin{pmatrix} +2.4\% \\ -1.8\% \end{pmatrix}$	$(73.5 \pm 0.6^{\text{stat}} \pm 1.8^{\text{syst}}) \text{ mb}$
σ_{inel} (CMS)			$(68.0 \pm 2.0^{\text{syst}} \pm 2.4^{\text{lumi}} \pm 4^{\text{extrap}}) \text{ mb}$
σ_{inel} (ATLAS)			$(69.4 \pm 2.4^{\text{exp}} \pm 6.9^{\text{extrap}}) \text{ mb}$
σ_{inel} (ALICE)			$(72.7 \pm 1.1^{\text{model}} \pm 5.1^{\text{lumi}}) \text{ mb}$

(*) Corrected after unfolding.

^{analysis} (includes tagging, acceptance, efficiency, background).

dN/dη Analysis procedure: bin migration corrections and summary.



- The particle pseudorapidity η is estimated from the average of the hits η composing the track (optimal to reproduce the original η of the particle).

- A bin size of 0.05 is appropriate

$$\left. \frac{dN}{d\eta} \right|_{\eta=\eta_0} = \sum_{\text{Trk} \in S} \frac{W(\eta_0, Z\text{Impact}) \sum_j B_j(\eta_0)}{\epsilon(\eta_0, m) \Delta\eta N_{\text{Ev}}} G(\eta_0) S_p(\eta_0) \frac{2\pi}{\Phi} P$$

Annotations pointing to various terms:

- Primary/secondary separation
- Bin migration
- Particles lost in propagation
- Secondary contamination
- Azimuthal acceptance
- Pile-up
- Number of events
- Bin-width
- Track efficiency

- The procedure is repeated for each quarter (important cross check for the analysis!)

Systematic errors evaluation

$\eta_0 = 6.025 \text{ d}N/\text{d}\eta$ error summary (one quarter)	
1. Primary track efficiency	4%
2. Global alignment	3%
3. Non-primeries in the central peak	2%
4. Primary to secondary separation	2%
5. B-field and energy spectrum	2%
6. Primaries not arriving in T2	2%
7. Track quality criterion	1%
8. Trigger bias	1%
9. Pile-up probability	1%
10. Statistical	0.7%
Total (single quarter measurement)	10% (*)

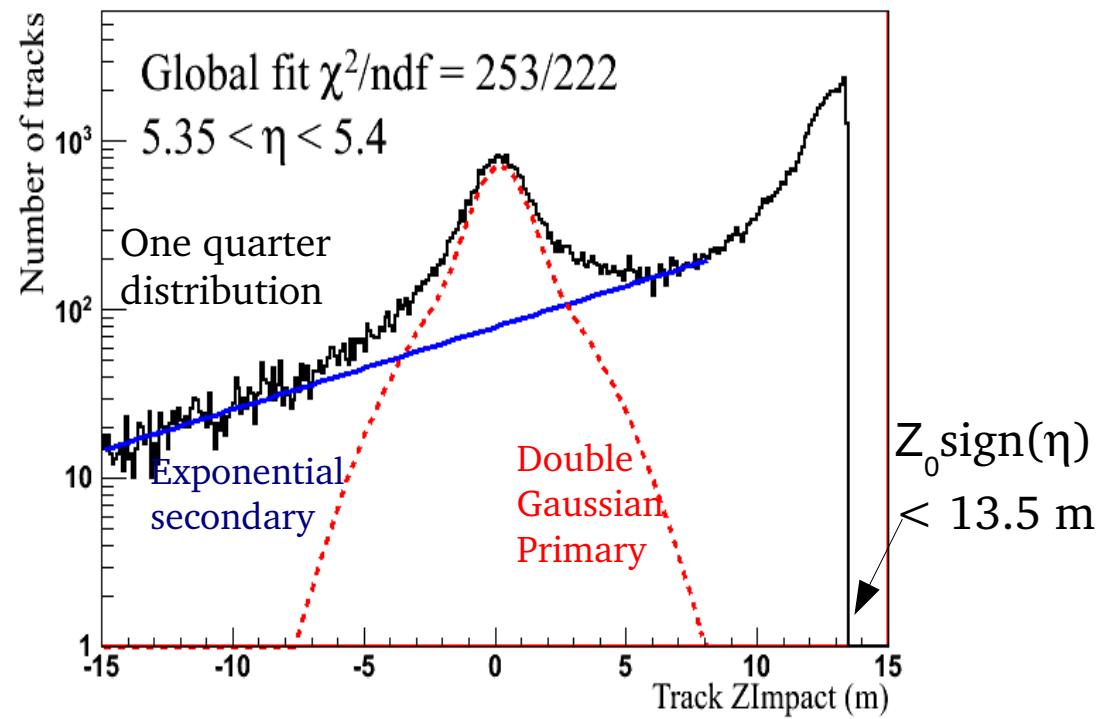
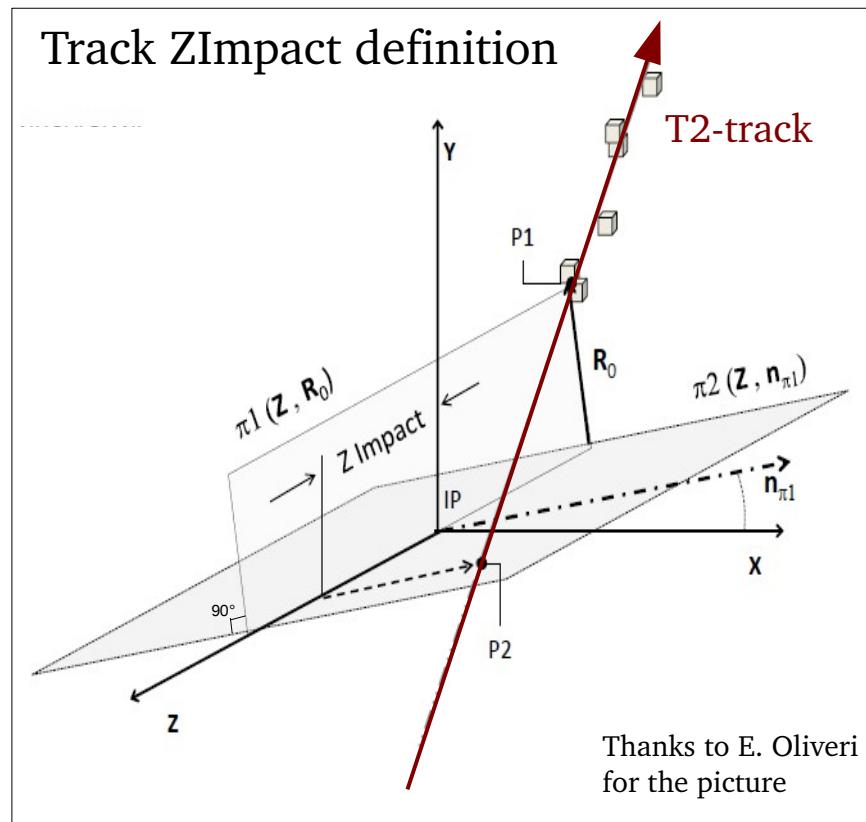
(*) not all the contributions have been added in quadrature

Evaluation method

1. Data/MC comparison of “half quarter” trk efficiencies
2. Effect of wrong misalignment parameters on the measured $\text{d}N/\text{d}\eta$
3. Maximum variation of the secondaries contamination from different MC.
4. Fit/fitting-interval uncertainty
5. MC spectrum and B intensity variation
6. Different MC estimates
7. Data/MC discrepancy on the effect of the cut on the track χ^2 -probability.
- 8-9. Dedicated analysis on bunch-crossing samples

Analysis procedure: primary track selection.

- A fit on the distribution of the track Zimpact parameter is used to separate primary from secondary 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 contribution can be therefore extracted from the primary region by fitting the track-ZImpact distribution. The fit is repeated for each bin.

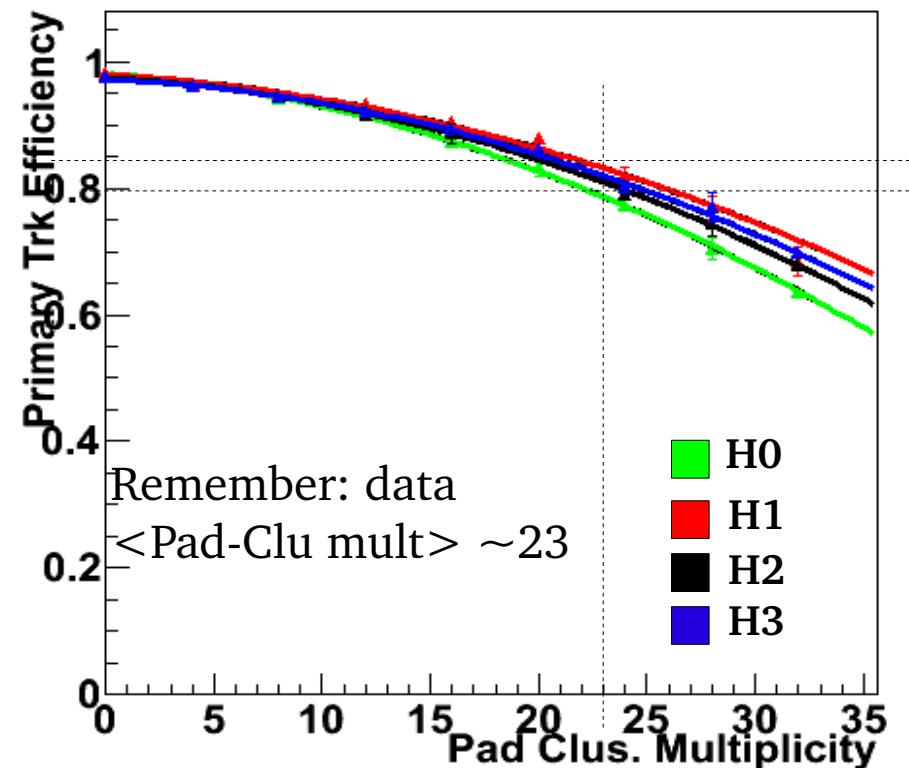
Analysis procedure: reconstructed track efficiency correction

- *Primary track efficiency definition:* probability to reconstruct a primary GEANT track within the primary selection requirements on the track parameter ZImpact and Z_0 .
- For each bin, the reconstructed track ZImpact is required to be in the range covered by 96% of the double gaussian distribution. In addition, $Z_0 * \text{sign}(\eta) < 13.5\text{m}$.

• Track efficiency evaluated with MC methods for each quarter as a function of the track η and of the event pad cluster multiplicity (to reduce the dependence from the tuning of the MC multiplicity).

- average efficiency of 80% (including selection)
- fraction of primary tracks within the cuts of 75% – 90% (η dependent)

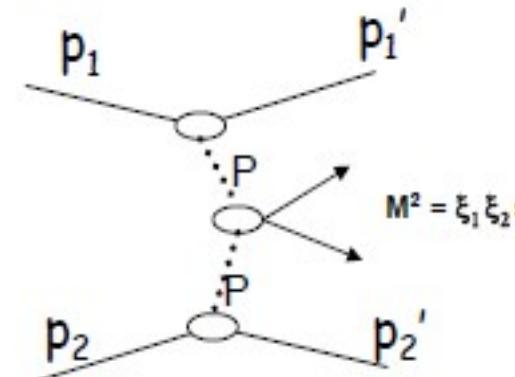
Primary Trk efficiency vs Event Cluster multiplicity





Detection Prospects for Double Pomeron Events

In collaboration with CMS



$$\beta^* = 1540 \text{ m}$$

$$\beta^* = 172 \text{ m}$$

$$\beta^* = 0.5 \text{ m}$$

$$\sigma_\xi = 0.5\%$$

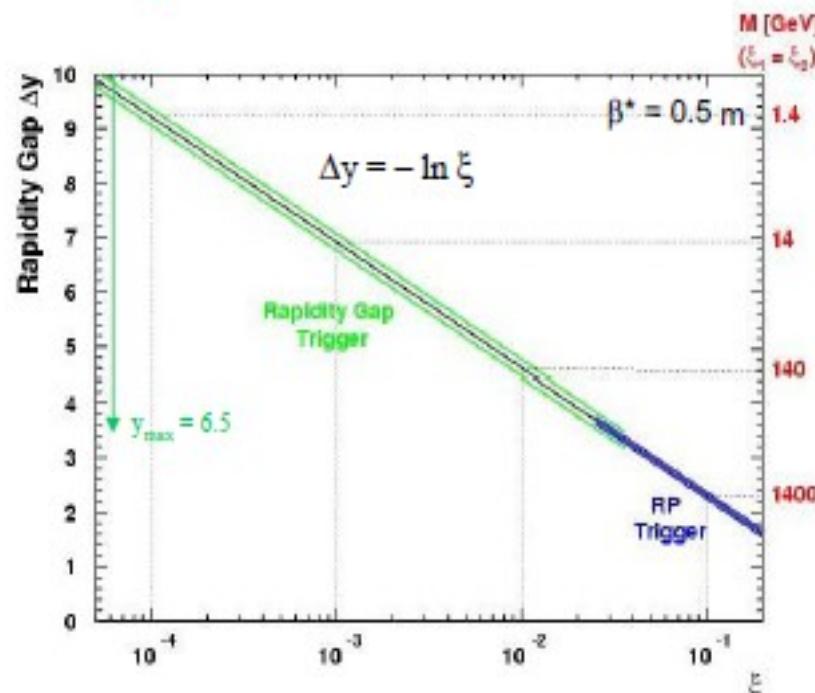
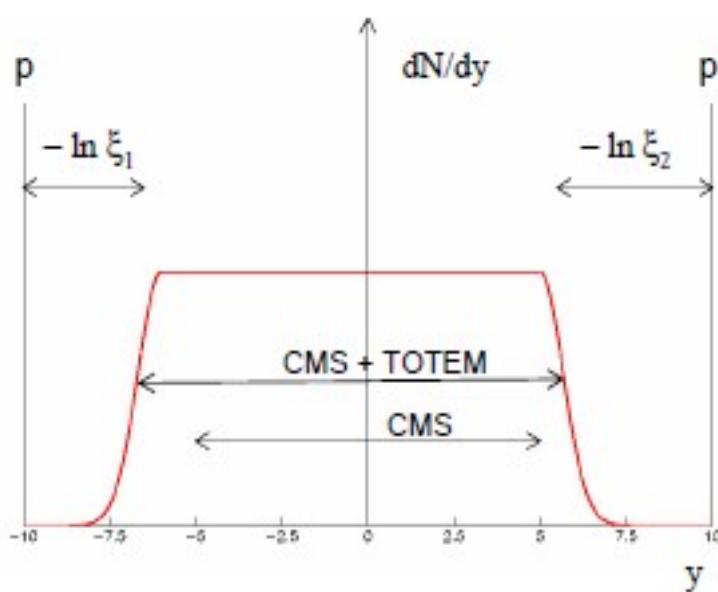
$$\sigma_\xi \sim \text{few } 10^{-4}$$

$$\sigma_\xi \sim 1\%$$

$$\mathcal{L} \leq 2.4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\mathcal{L} \sim 4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\mathcal{L} \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$



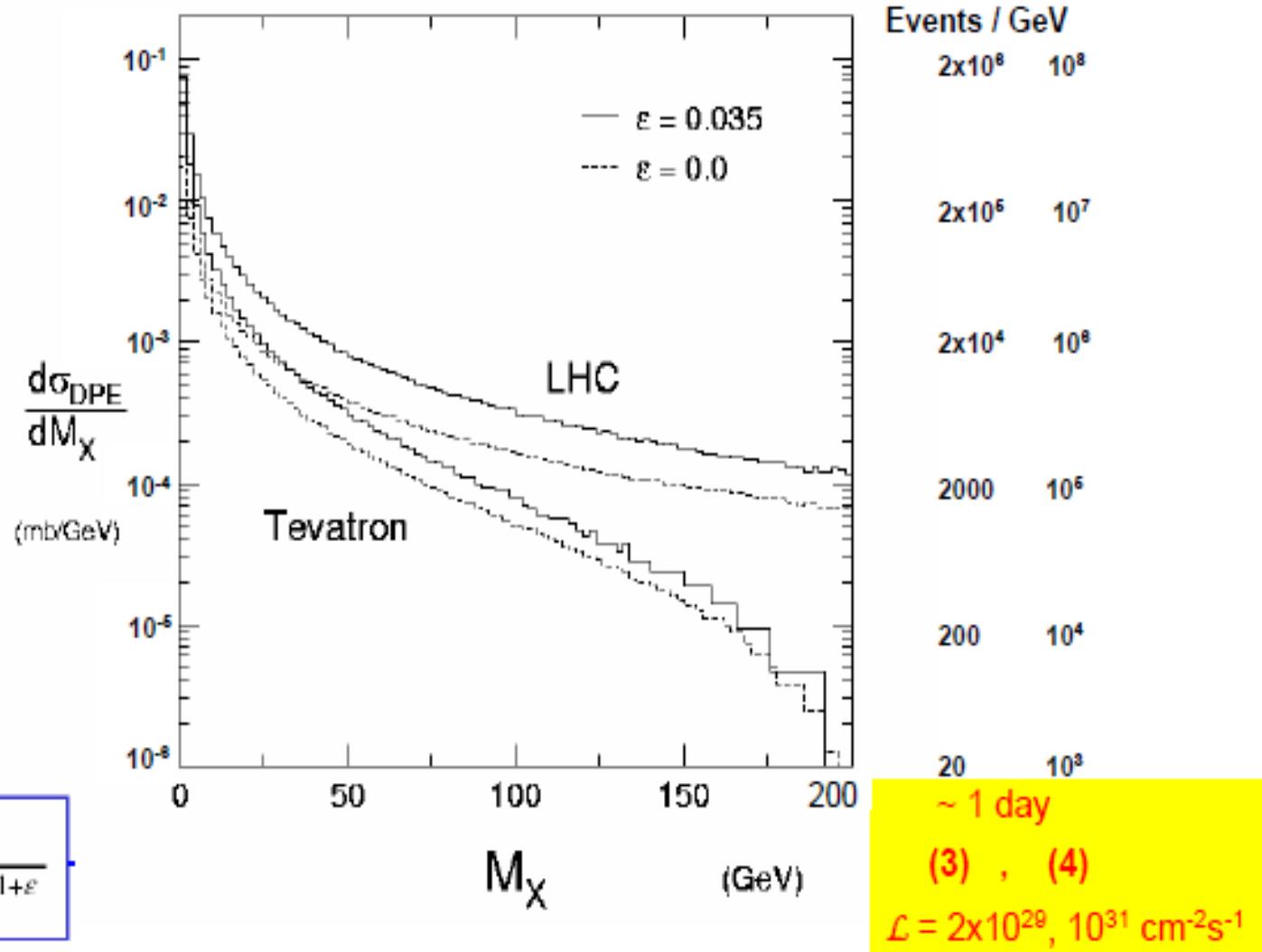
Trigger via Roman Pots $\xi > 2.5 \times 10^{-2}$

Trigger via rapidity gap $\xi < 2.5 \times 10^{-2}$

14 TeV

Double Pomeron Exchange: Cross-Section

$\sigma_{\text{DPE}} = 0.5 - 1 \text{ mb} \Rightarrow (1-2) \times 10^7 \text{ events per day}$ at $\beta^* = 1540 \text{ m}$, $\mathcal{L} = 2 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$



$$\frac{d\sigma}{dM^2} \propto \frac{1}{(M^2)^{1+\epsilon}}$$

[ϵ from Pomeron trajectory $\alpha(t) = 1 + \epsilon + \alpha' t$]

14 TeV