

TOTEM RESULTS

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(on behalf of the TOTEM Collaboration)

DIFFRACTION 2014

Primošten
12/09/2014



Outlook:

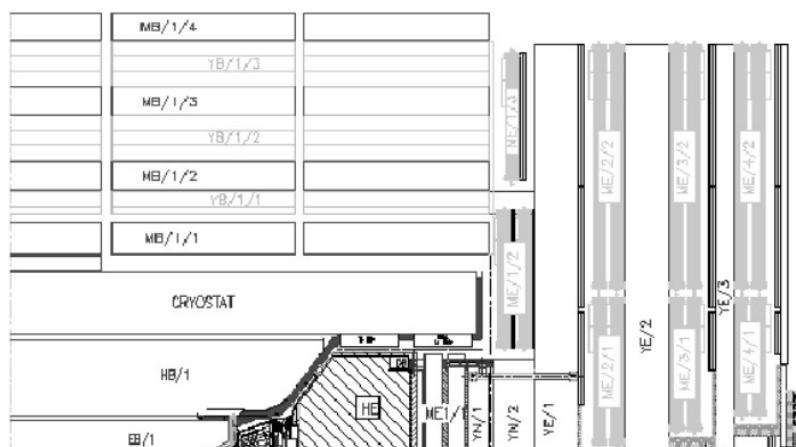
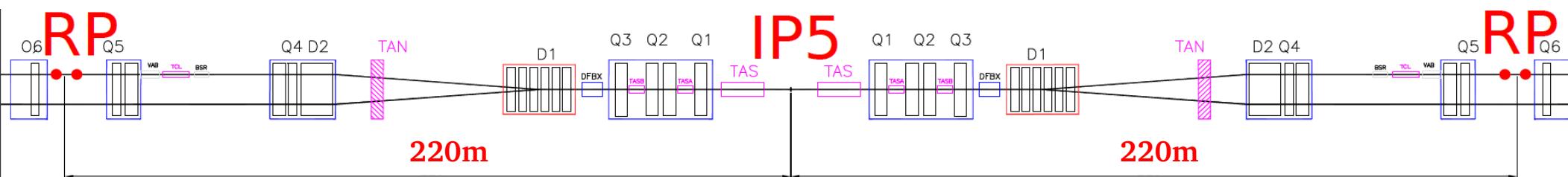
- Elastic, inelastic and total pp cross section
- Study of the elastic scattering in the Nuclear-Coulomb interference region
- Results on diffractive cross sections
- Very forward pp $dN_{\text{CH}}/d\eta$

The TOTEM experiment

Physics programme in LHC RUN1:

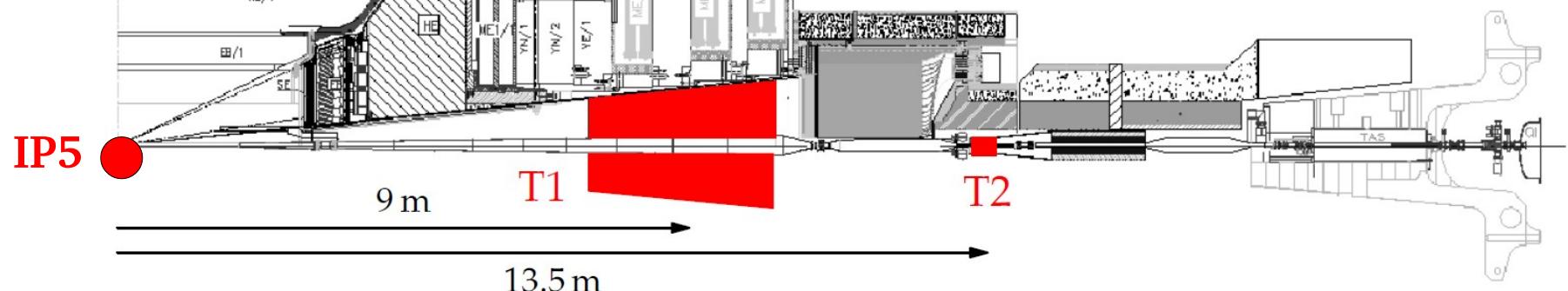
- Measure the total pp cross section with a precision of about 2%.
- Study the elastic pp cross section over a wide range of the pp 4-momentum transfer $|t|$.
- Studies on diffractive processes and forward multiplicities.

Experimental layout in LHC RUN1 (symmetrically placed with respect to IP5):



T1: $3.1 < |\eta| < 4.7$
 T2: $5.3 < |\eta| < 6.5$

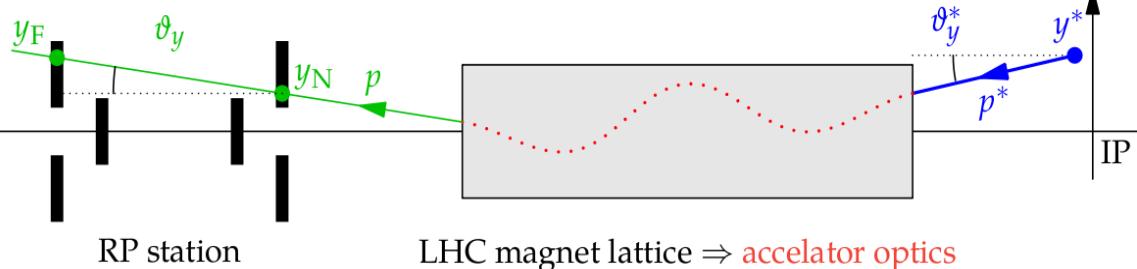
- RP stations at 220m:
Reconstruction of the proton from elastic and diffractive interaction.
- Inelastic telescopes T1,T2:
Tracking of charged particles from inelastic collision.



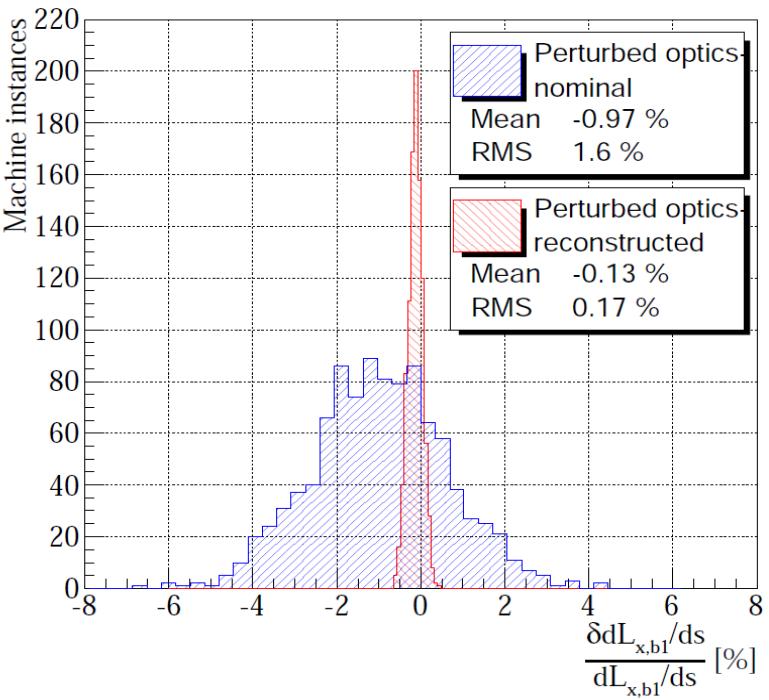
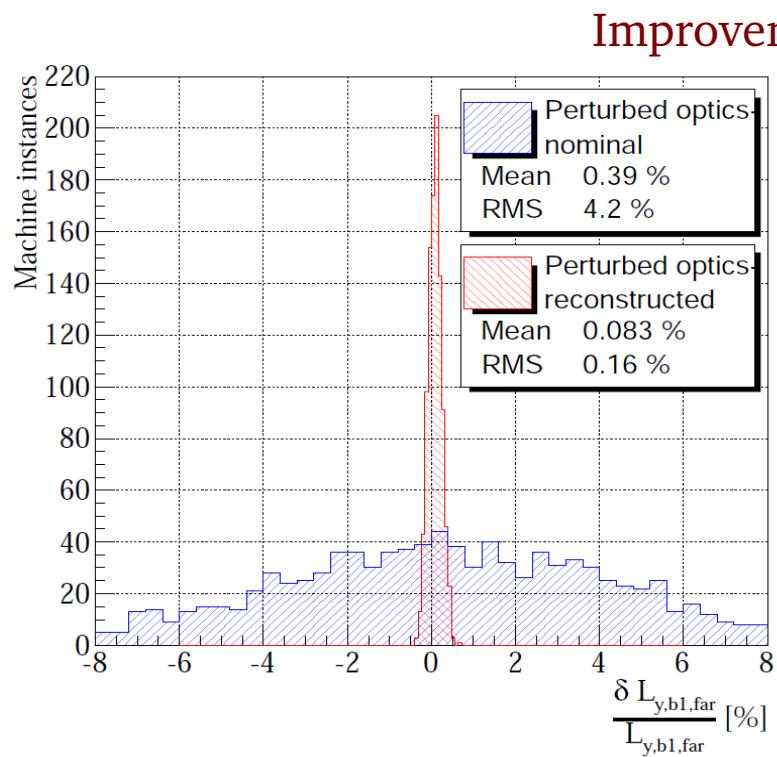
Proton transport and optics matching

- Reconstruction of proton kinematics **needs an excellent understanding of the LHC optics.**

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

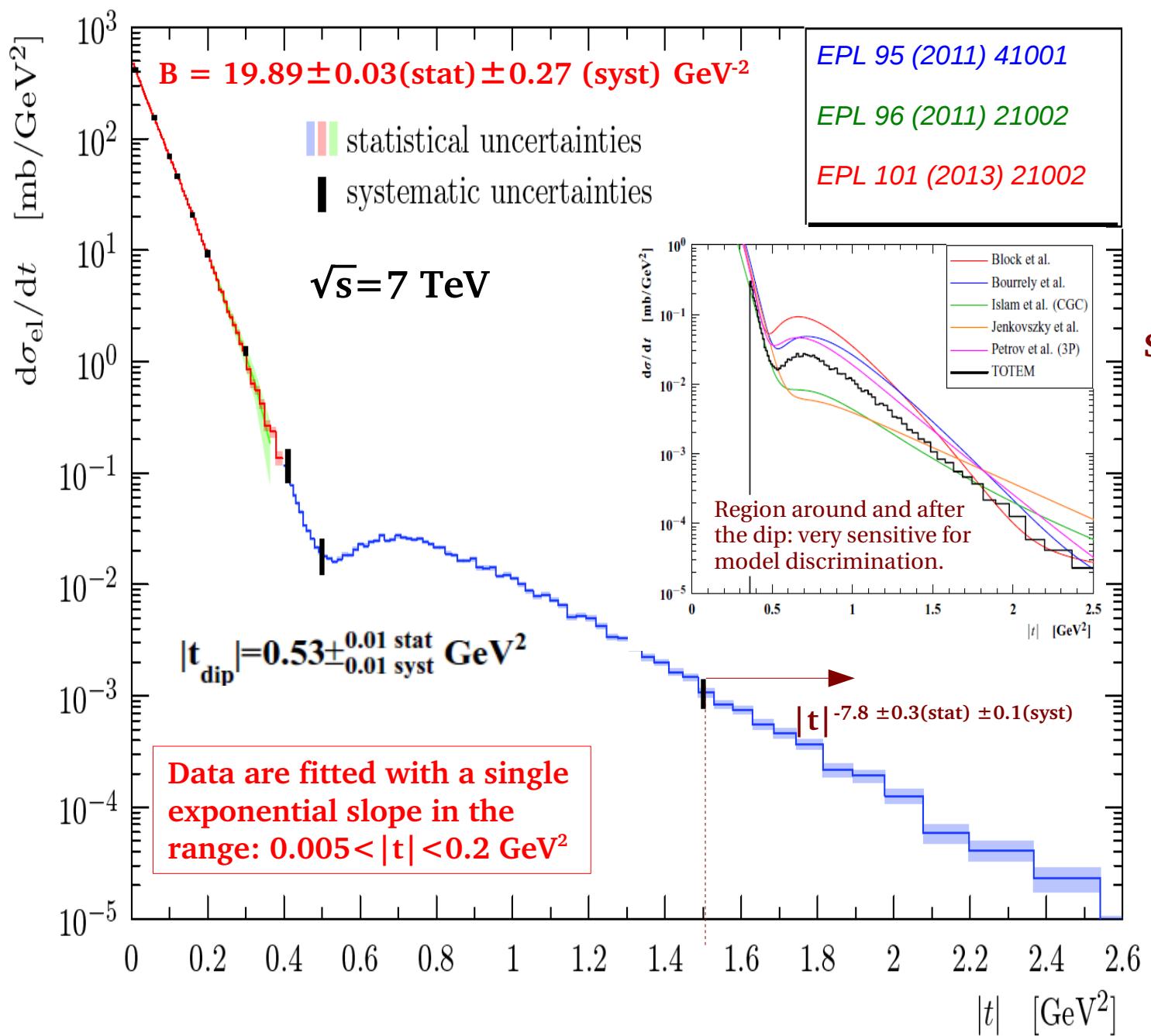


- A **novel method** of optics evaluation is proposed which exploits kinematical distributions of elastically scattered protons observed in the Roman Pots [CERN-PH-EP-2014-066].



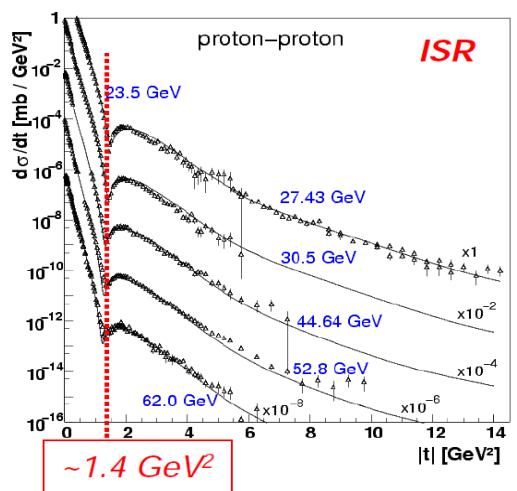
- Method of fundamental importance also for the **improvement of the high- β^* results.**

Elastic scattering results: $5 \cdot 10^{-3} < |t| < 2.5 \text{ GeV}^2$ @ 7 TeV



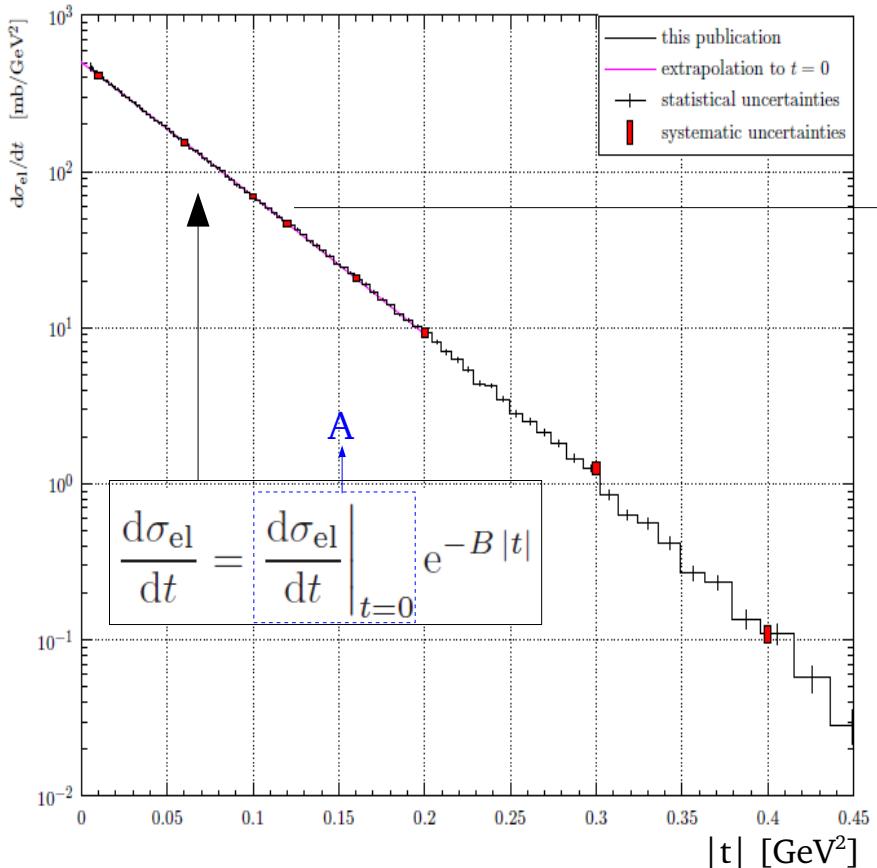
Shrinkage of the forward peak:

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

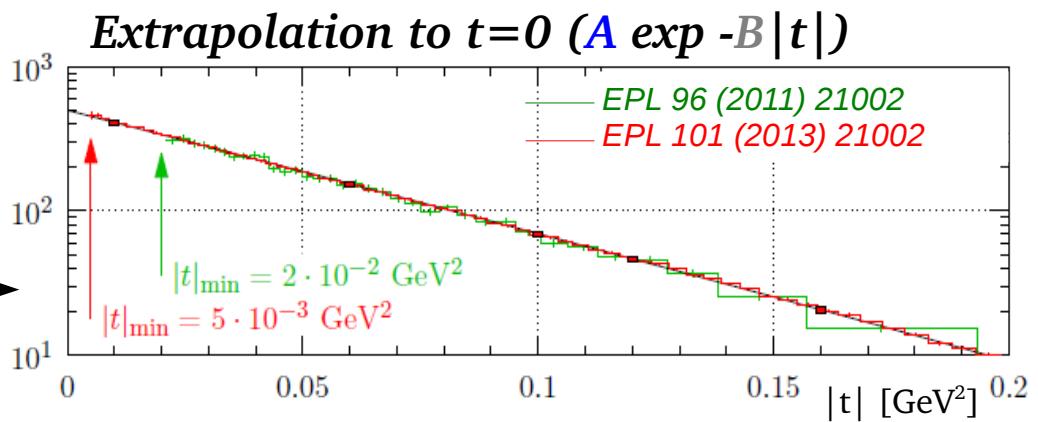


Elastic scattering results: $5 \cdot 10^{-3} < |t| < 0.45 \text{ GeV}^2$ @ 7 TeV

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



Data are fitted with a single exponential slope in the range: $0.005 < |t| < 0.2 \text{ GeV}^2$



A (mb/GeV²):

$$506.4 \pm 23^{\text{syst}} \pm 0.9^{\text{stat}}$$

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

B (GeV⁻²):

$$19.89 \pm 0.27^{\text{syst}} \pm 0.03^{\text{stat}} \quad (5 \cdot 10^{-3} < |t| < 0.2 \text{ GeV}^2)$$

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

σ_{el} (Luminosity dependent):

$$25.43 \pm 1.07^{\text{syst}} \pm 0.03^{\text{stat}} \text{ mb (91\% measured)}$$

$$24.8 \pm 1.2^{\text{syst}} \pm 0.2^{\text{stat}} \text{ mb (67\% measured)}$$

- Luminosity dependent inelastic cross section obtained triggering with T2:

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

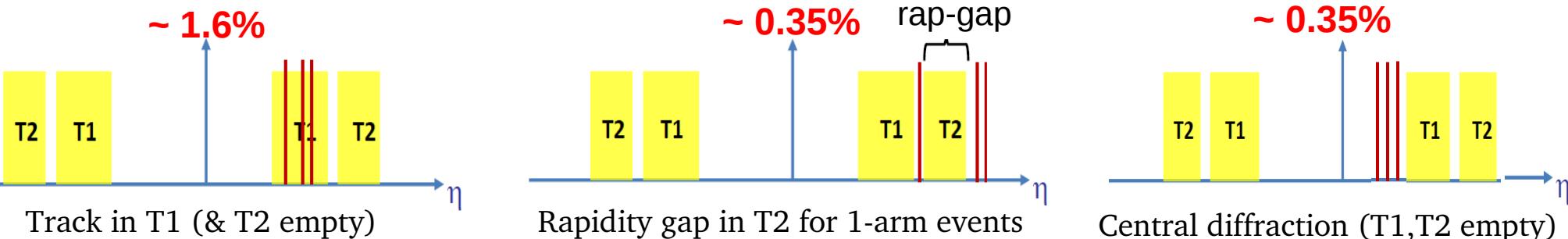
- Cross section for events with at least a stable particle in the T2 acceptance:

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

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

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

Correction sizes:



- Correction for events having particles only at $|\eta| > 6.5$: $4.2\% \pm 2.1\%$ (syst):

$$\sigma_{inel}\ (\text{mb}): 73.74 \pm 0.09\text{stat} \pm 1.74\text{syst} \pm 2.95\text{lumi}$$

elastic observables only:

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

$$\sigma_{\text{tot}} = (98.6 \pm 2.3) \text{ mb}$$

Validity of the optical theorem tested at 3.5% level

ϱ independent:

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

$$\sigma_{\text{tot}} = (99.1 \pm 4.4) \text{ mb}$$

$$\rho \equiv \left. \frac{\Re \mathcal{A}_{\text{el}}}{\Im \mathcal{A}_{\text{el}}} \right|_{t=0}$$

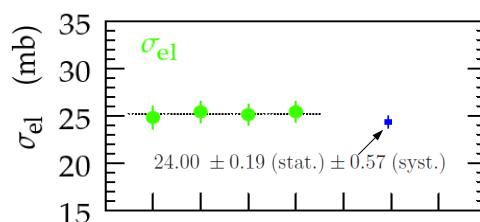
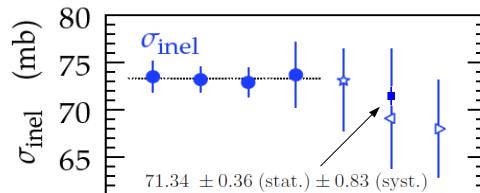
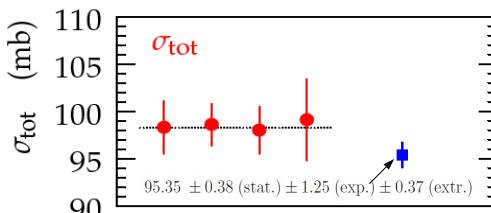
Absolute calibration of the CMS luminosity

$$\mathcal{L}_{\text{int, CMS}} = 82.8 \pm 3.3 \mu\text{b}^{-1}$$

$$\mathcal{L}_{\text{int, CMS}} = 1.65 \pm 0.07 \mu\text{b}^{-1}$$

$$\mathcal{L}_{\text{int, TOTEM}} = 83.7 \pm 3.2 \mu\text{b}^{-1}$$

$$\mathcal{L}_{\text{int, TOTEM}} = 1.65 \pm 0.07 \mu\text{b}^{-1}$$



Elastic only (1)
Elastic only (2)
 \mathcal{L} -independent
 p -independent
ALICE
ATLAS
CMS

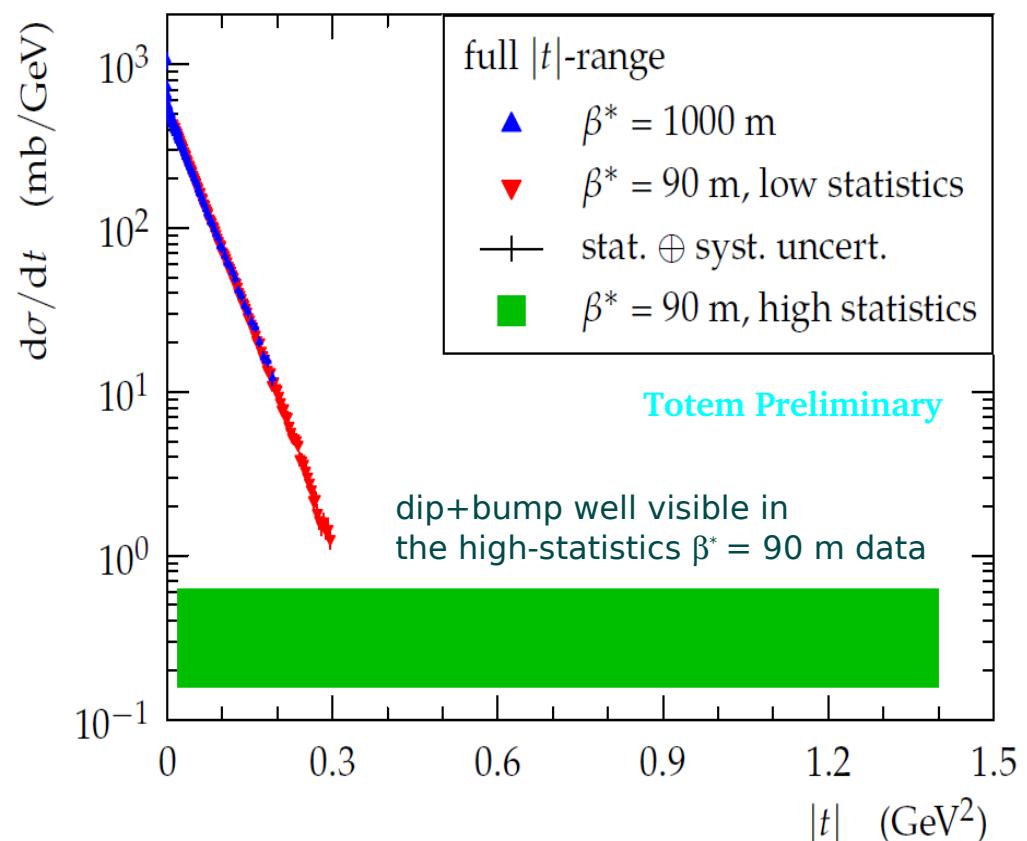
luminosity independent:

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

$$\sigma_{\text{tot}} = (98.1 \pm 2.4) \text{ mb}$$

Elastic, inelastic and total cross section @ 8 TeV

β^*	RP approach	$ t $ range	el. events	publication
1000 m	3 or 10 σ	0.0006 to 0.2 GeV^2	352 k	Work Ongoing
90 m	6 to 9.5 σ	0.01 to 0.3 GeV^2	0.68 M	PRL 111 (2013)
90 m	9.5 σ	0.02 to 1.4 GeV^2	7.2 M	Work Ongoing



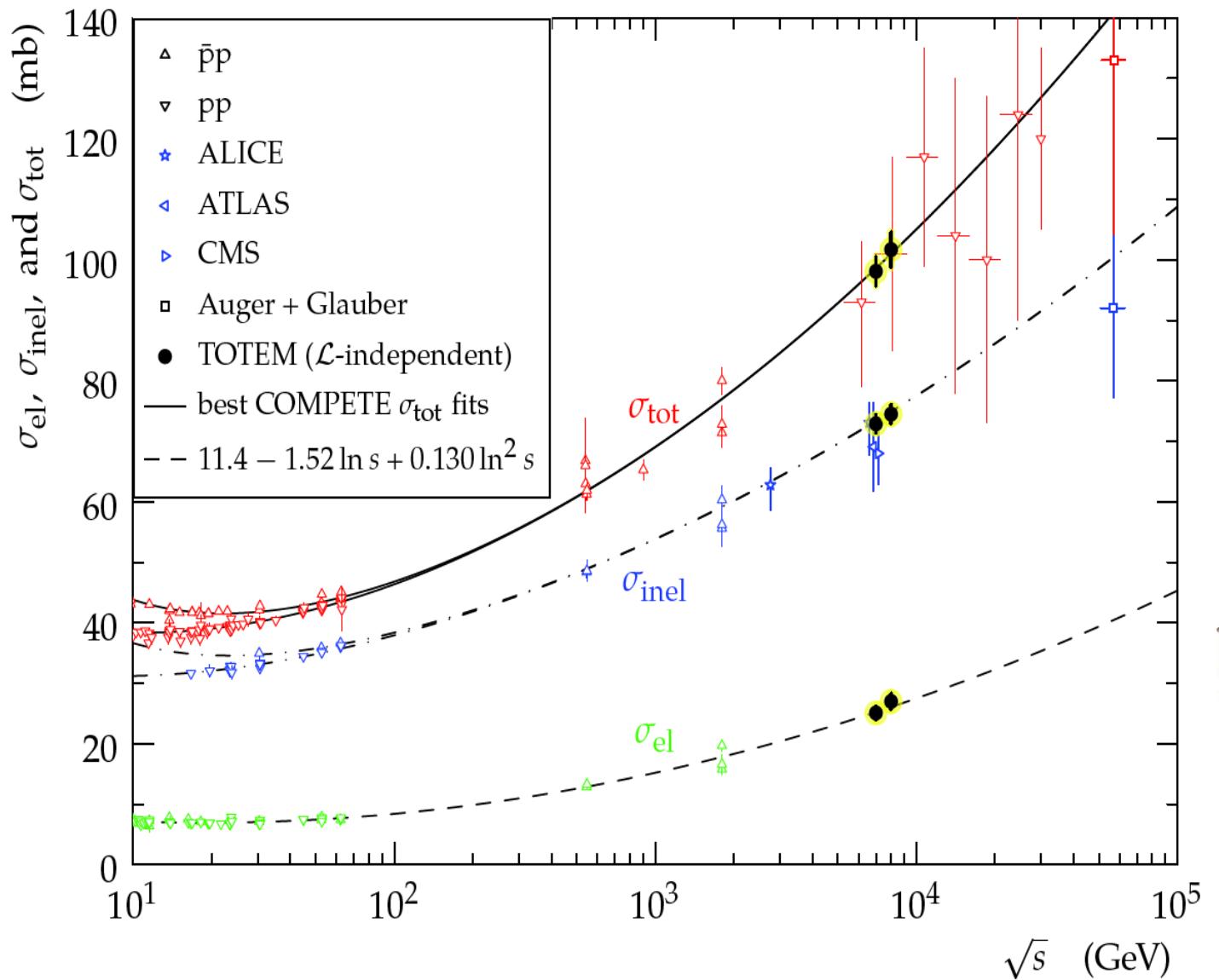
Elastic, Inelastic, Total cross-sections
all measured “luminosity-independent”

Quantity	Value	Systematic uncertainty				
		el. t -dep	el. norm	inel	ρ	\Rightarrow full
σ_{tot} (mb)	101.7	± 1.8	± 1.4	± 1.9	± 0.2	$\Rightarrow \pm 2.9$
σ_{inel} (mb)	74.7	± 1.2	± 0.6	± 0.9	± 0.1	$\Rightarrow \pm 1.7$
σ_{el} (mb)	27.1	± 0.5	± 0.7	± 1.0	± 0.1	$\Rightarrow \pm 1.4$
$\sigma_{\text{el}}/\sigma_{\text{inel}}$ (%)	36.2	± 0.2	± 0.7	± 0.9		$\Rightarrow \pm 1.1$
$\sigma_{\text{el}}/\sigma_{\text{tot}}$ (%)	26.6	± 0.1	± 0.4	± 0.5		$\Rightarrow \pm 0.6$

Results obtained with the standard exponential extrapolation (90% of the elastics is visible):

$$\frac{dN_{\text{el}}}{dt} = \left. \frac{dN_{\text{el}}}{dt} \right|_{t=0} e^{-B|t|}$$

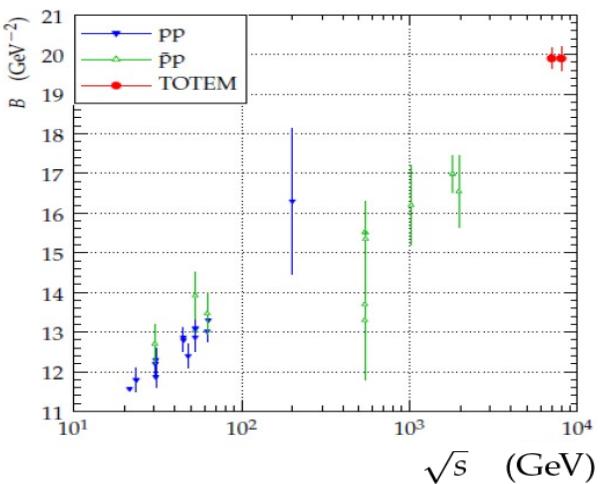
TOTEM σ_{el} , σ_{inel} and σ_{tot} @ 7 and 8 TeV



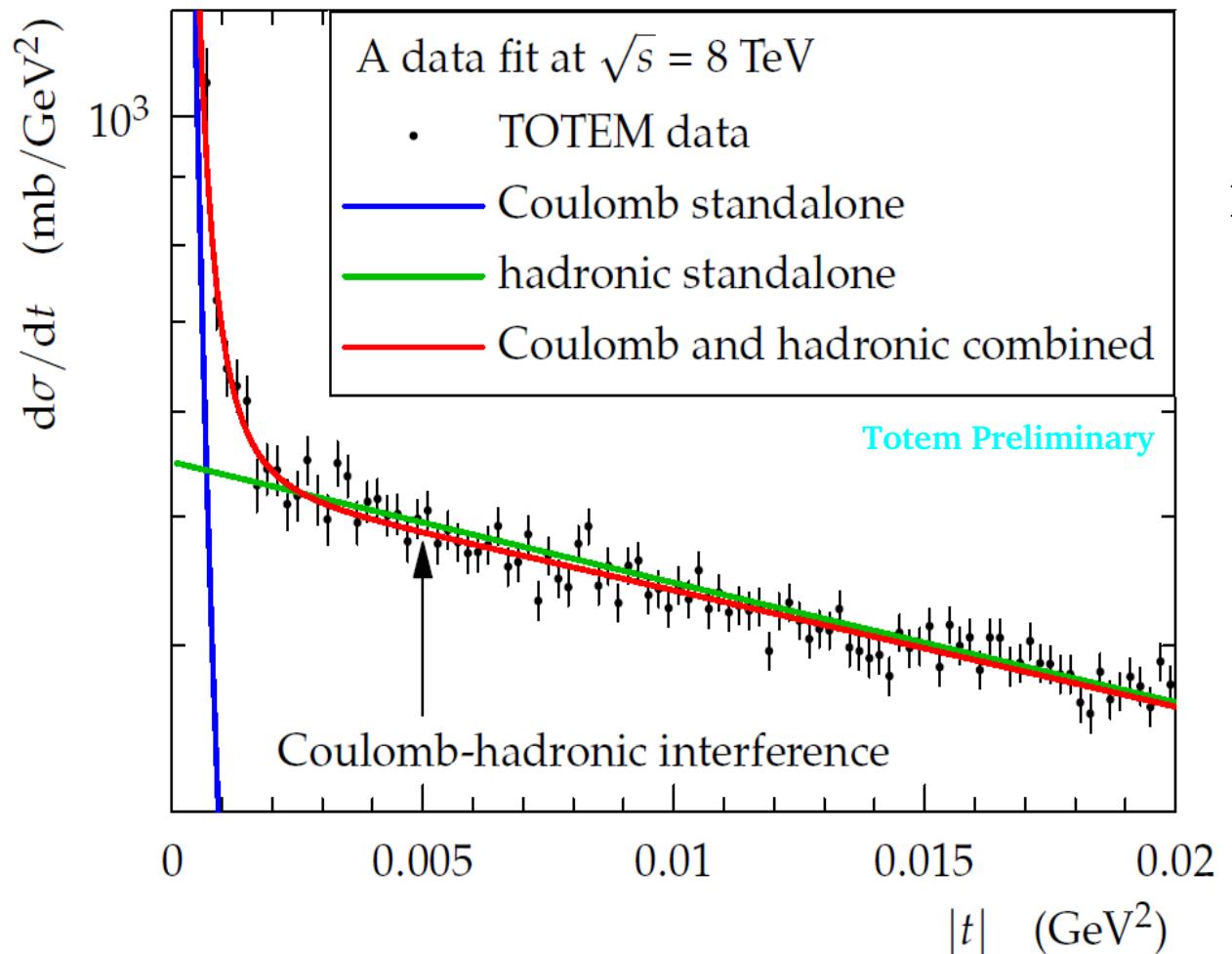
Ongoing analysis of σ_{el} , σ_{inel} and σ_{tot} also at 2.76 TeV

Comparison of 7 and 8 TeV $\sigma_{\text{tot},\text{el,inel}}$ measurements:

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



Coulomb-nuclear interference at 8 TeV



Dedicated run with $\beta^* = 1000$ m:
Elastic scattering measurement
down to $|t| \sim 6 \cdot 10^{-4}$ GeV²

→ Observed Coulomb-nuclear interference

$$\frac{d\sigma}{dt} \propto |\mathcal{A}^{C+H}|^2$$

$$\mathcal{A}^{C+H} = \text{interference formula}(\mathcal{A}^C, \mathcal{A}^H)$$

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

- Access to the hadronic phase, validate the models describing the Coulomb/Hadronic interference.
- Make constraints on the ρ parameter, furthermore improving the σ_{TOT} measurements.

$$\sigma_{tot}^{(nuclear)} \propto \Im \mathcal{A}_{el}^{nuclear}(t = 0)$$

Coulomb-nuclear interference at 8 TeV

$$\mathcal{A}^{C+N} = \text{interference formula}(\mathcal{A}^C, \mathcal{A}^N)$$

► Coulomb amplitude: known

Nuclear amplitude module: constrained with $\beta^*=90m$ data ($|t| > 2 \cdot 10^{-2}$) and

modeled with maximum 3 parameters: $\exp(b_1 t + b_2 t^2 + b_3 t^3)$

Nuclear amplitude phase: weak data constraints, test of different theoretical models



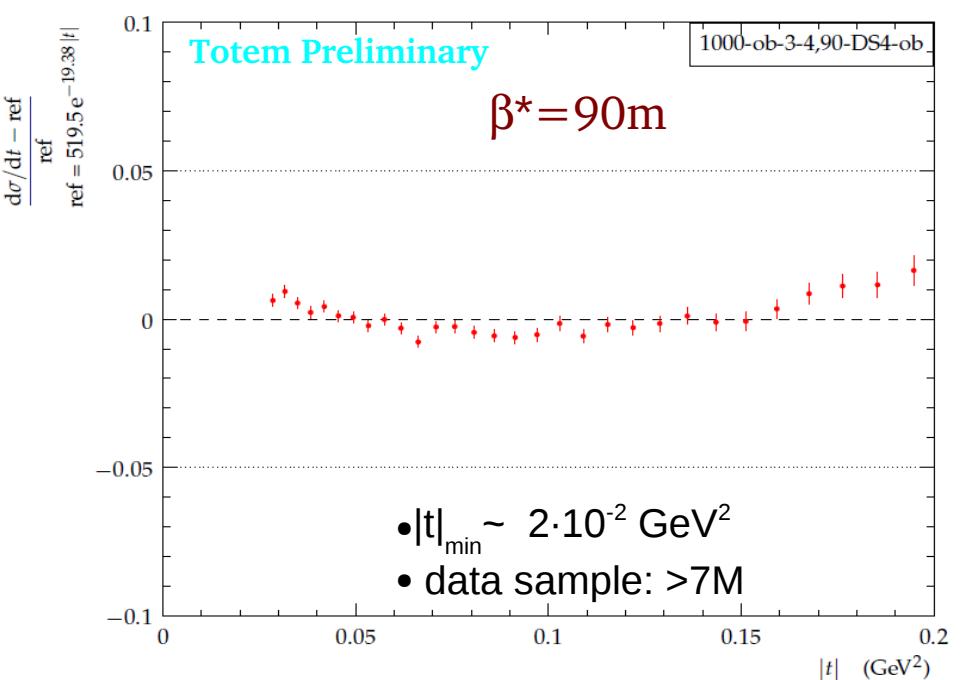
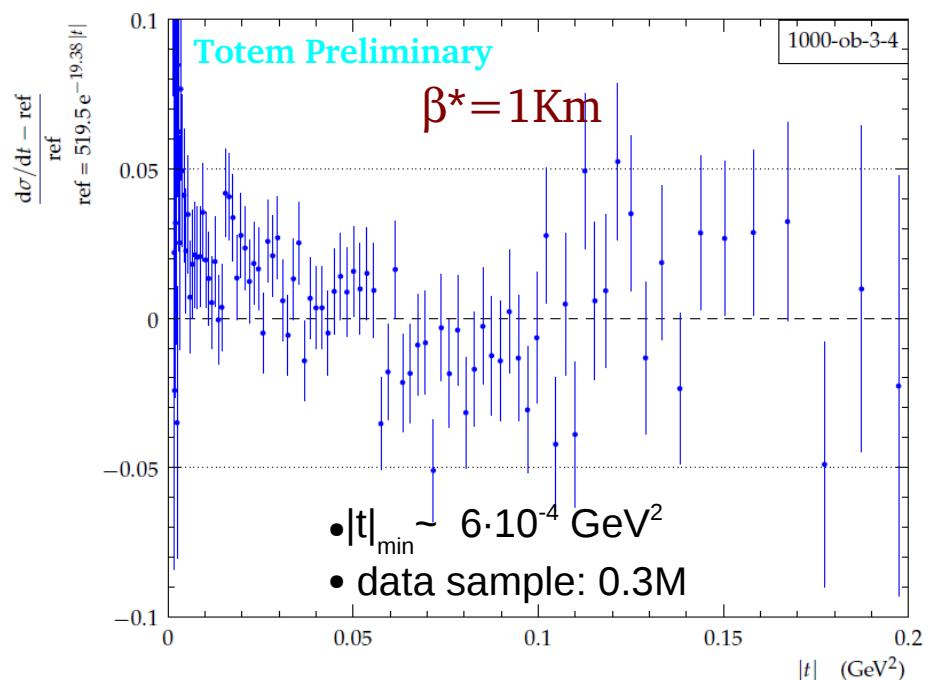
Interference formula tested with data:

Kundrát-Lokajícek (KL) [Z. Phys. C63 (1994) 619-630] (No A^N limitations)

Simplified West-Yennie (SWY) [Phys. Rev. 172 (1968) 1413-1422]

(only compatible with constant phase and purely exponential modulus)

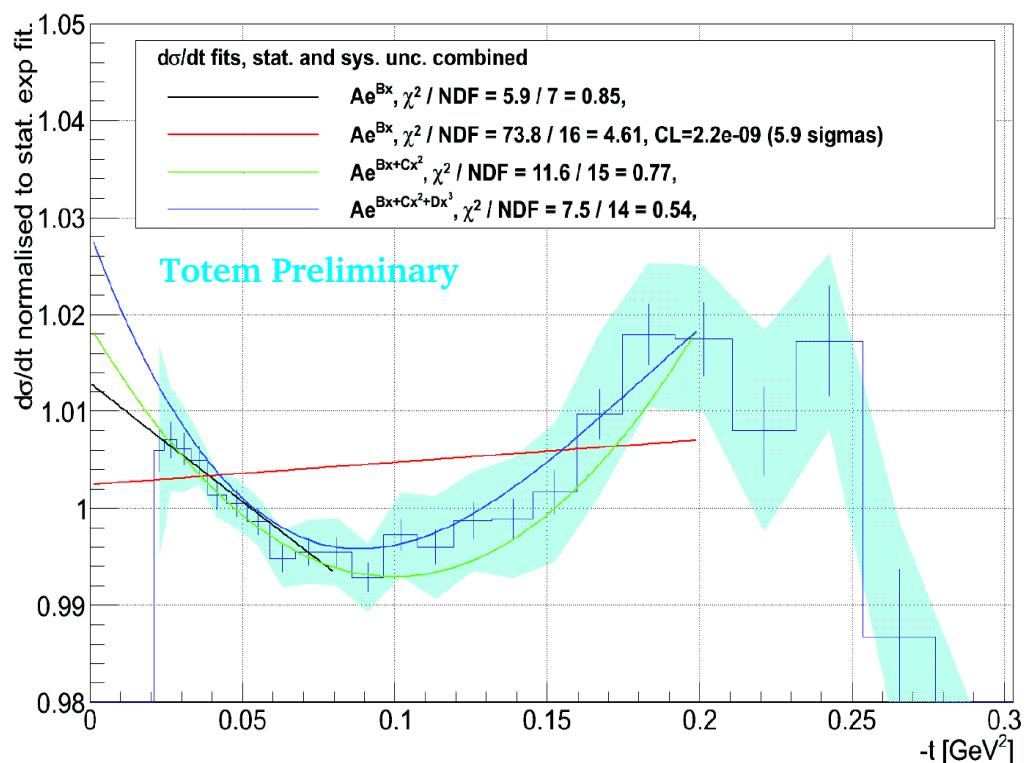
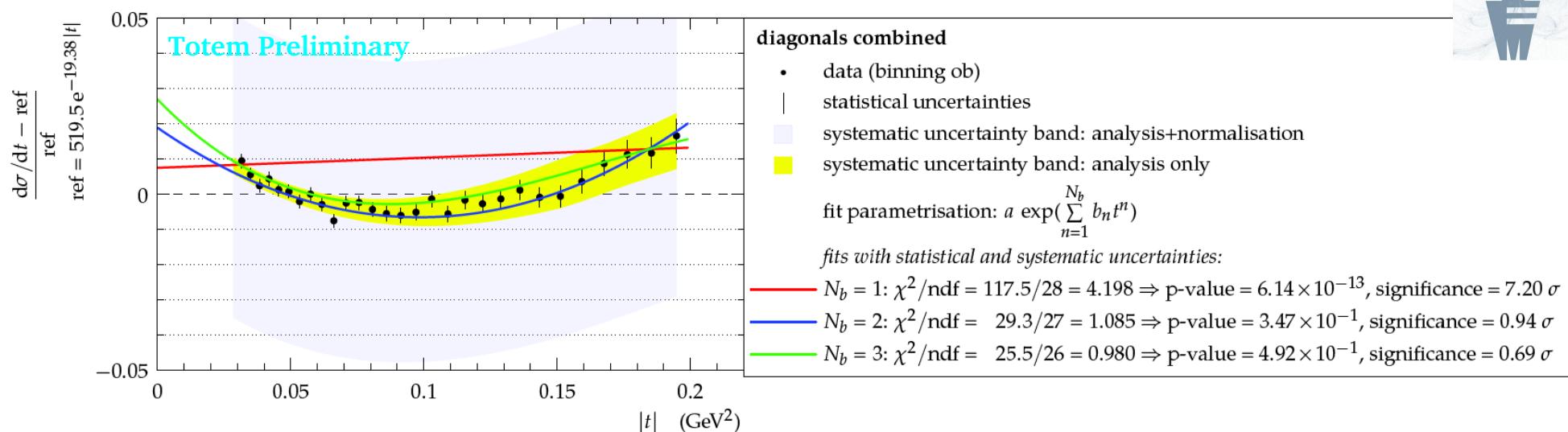
DATASETS



To constrain the nuclear phase and the interference formula as much as possible, a joint analysis of both datasets with different LHC optics is ongoing

Precise fits of the nuclear amplitude module at 8 TeV

DS4



Pure exponential excluded with $>7\sigma$ significance

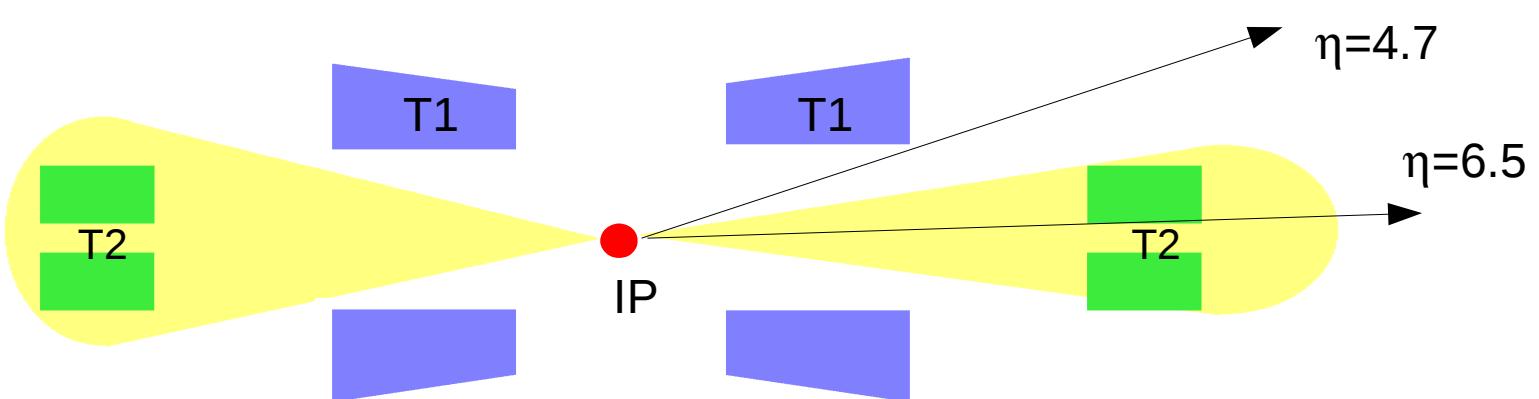
- SWY interference formula ruled out
- Reduced number of models for ρ determination

Preliminary
determination of
 $\sigma_{\text{tot}} = (101.4 \pm 2.0) \text{ mb}$

Soft Double Diffractive cross section (7 TeV)

Phys. Rev. Lett. 111, 262001

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



Event selection: Trigger with T2, at least one track in both T2 hemispheres , no tracks in T1.

Results from 7 TeV data:

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

	$-4.7 > \eta_{\min} > -5.9$	$-5.9 > \eta_{\min} > -6.5$
$4.7 < \eta_{\min} < 5.9$	$66 \pm 19 \mu\text{b}$	$27 \pm 4 \mu\text{b}$
$5.9 < \eta_{\min} < 6.5$	$28 \pm 5 \mu\text{b}$	$12 \pm 4 \mu\text{b}$

MC predictions:

Pythia

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

Pythia

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

Phojet

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

Phojet

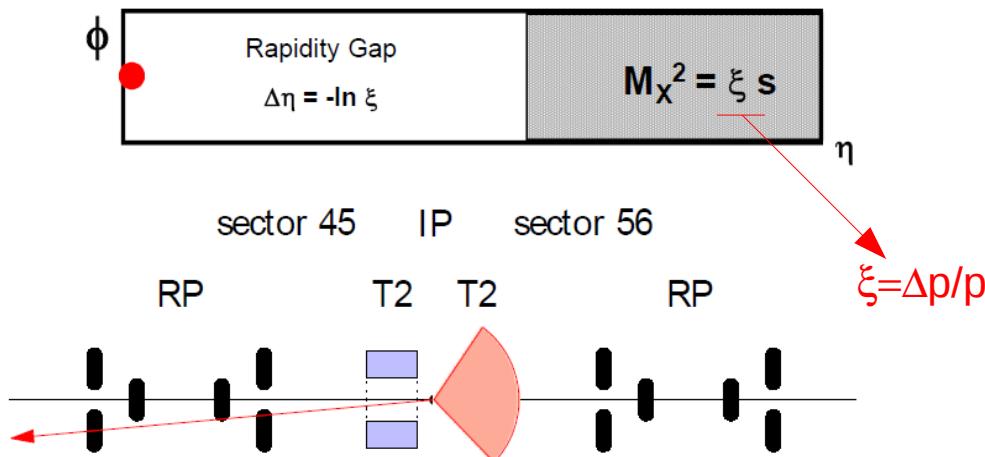
	$-4.7 > \eta_{\min} > -5.9$	$-5.9 > \eta_{\min} > -6.5$
$4.7 < \eta_{\min} < 5.9$	$44 \mu\text{b}$	$23 \mu\text{b}$
$5.9 < \eta_{\min} < 6.5$	$23 \mu\text{b}$	$12 \mu\text{b}$

- σ_{DD} uncertainty dominated by migrations from generator η_{\min} to track reconstructed η_{\min}

Soft Single Diffractive cross section (7 TeV)

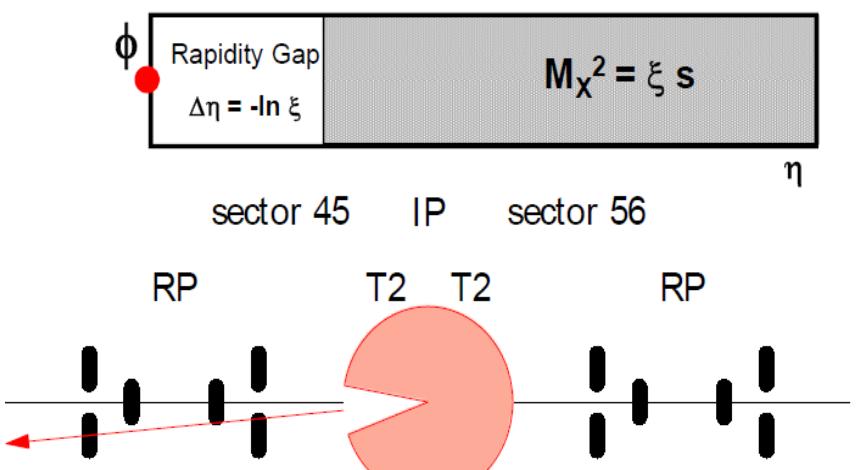
Low mass SD:

Tracks in the T2 hemisphere opposite to the proton ($2 \cdot 10^{-7} < \xi < 10^{-6}$)



Very High mass SD:

Tracks in the same T2 hemisphere of the proton ($\xi > 2.5\%$)



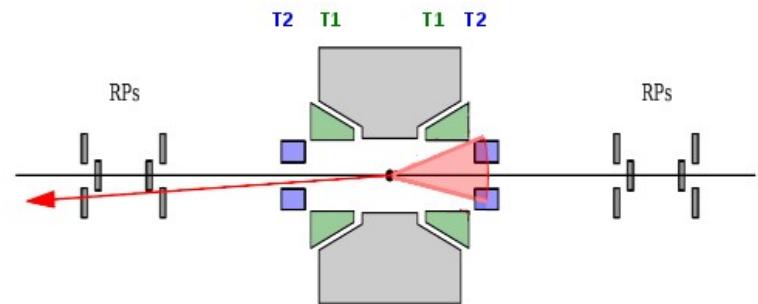
- SD events triggered with T2, only 1 proton required in the RPs
- M obtained from the rapidity gap estimation based on charged track in T1 and T2: $M^2 = \ln(\Delta\eta)$. This allows a better ξ resolution ($\sigma(\xi)/\xi \sim 1$) for low-medium mass.

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

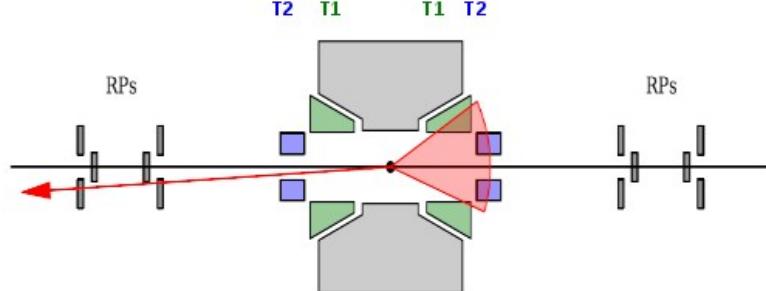
SD class	Inelastic telescopes configuration	Mass	ξ
Low Mass	p + T2 opposite only (no T1)	$3.4 - 8 \text{ GeV}$	$2 \cdot 10^{-7} < \xi < 10^{-6}$
Medium Mass	p + T2 opposite + T1 opposite	$8 - 350 \text{ GeV}$	$10^{-6} < \xi < 0.25\%$
High Mass	p + T2 opposite + T1 same	$0.35 - 1.1 \text{ TeV}$	$0.25\% < \xi < 2.5\%$
Very High Mass	p + both T2 arms	$> 1.1 \text{ TeV}$	$> 2.5\%$

Soft Single Diffractive cross section (7 TeV)

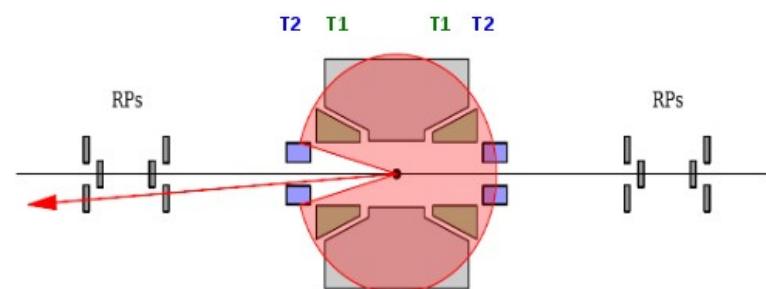
Low Mass
 $M=3.4 - 8 \text{ GeV}$



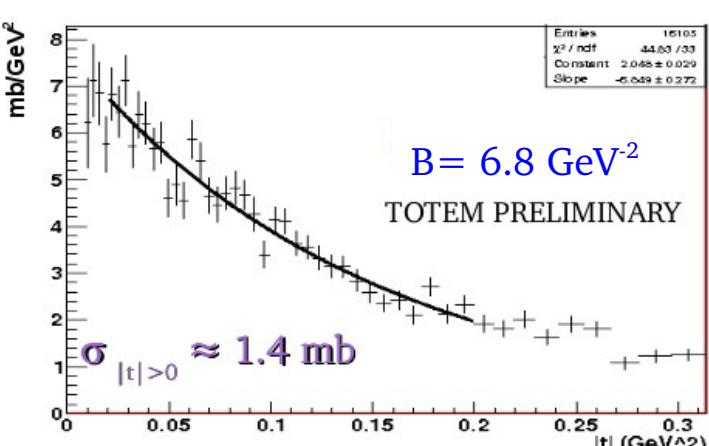
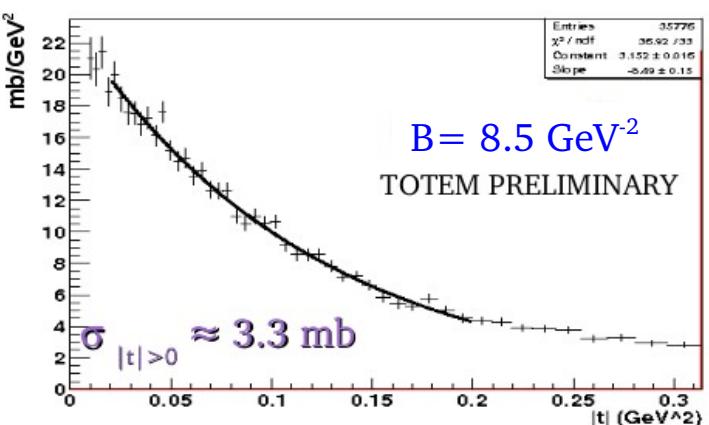
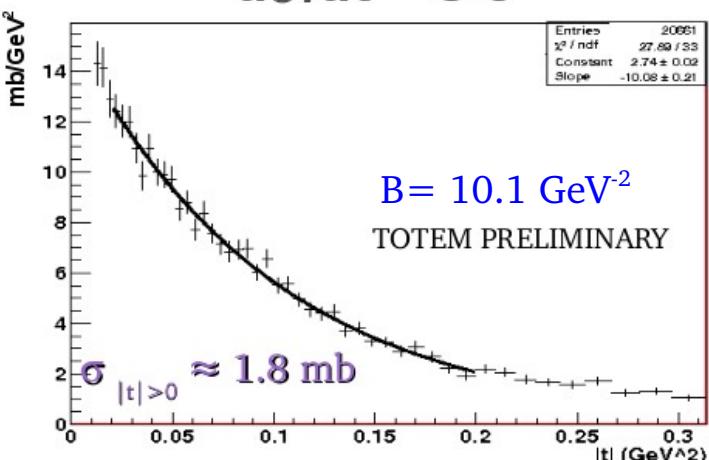
Medium Mass
 $M=8 - 350 \text{ GeV}$



High Mass
 $M=0.35 - 1.1 \text{ TeV}$



$$d\sigma/dt \sim C \cdot e^{-Bt}$$



Corrections include:

- Trigger efficiency
- Reconstruction efficiency
- Proton acceptance
- Background subtraction
- Extrapolation to $t=0$

Missing corrections:

- Class migrations
- Effects due to resolutions and beam divergence

-Estimated uncertainties:

$$B \sim 15\% \quad \sigma \sim 20\%$$

Preliminary:

$$\sigma_{SD} = 6.5 \pm 1.3 \text{ mb}$$

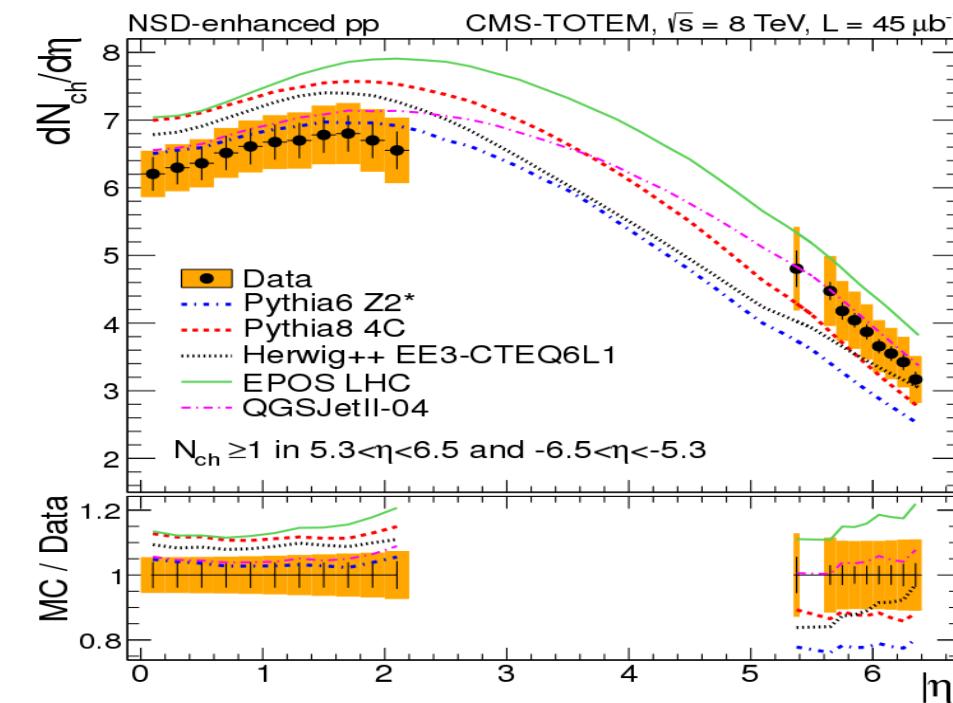
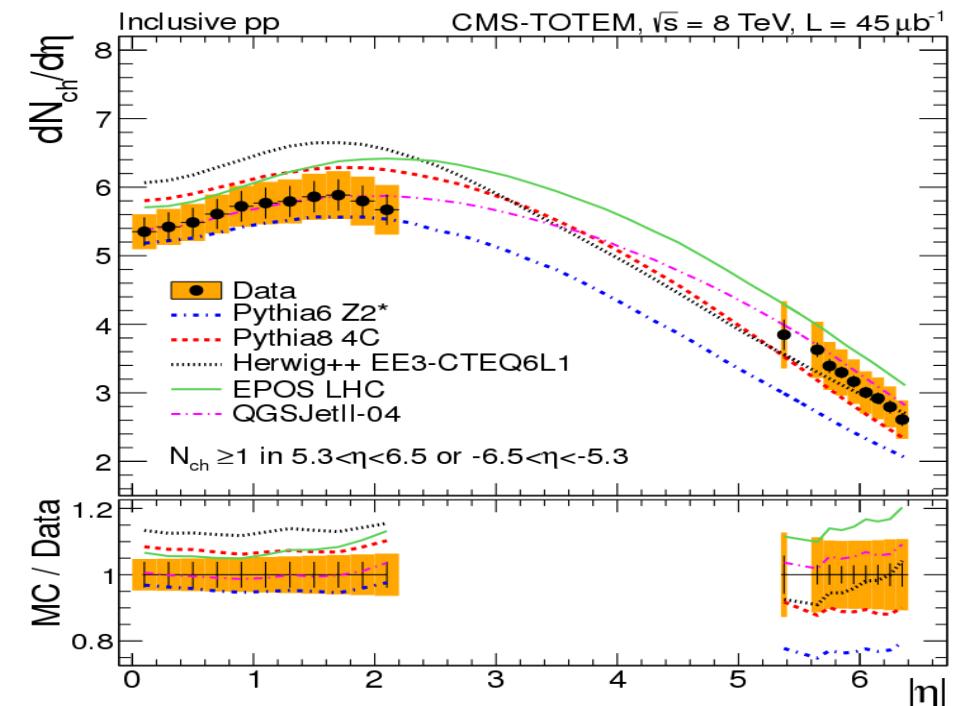
$$(3.4 < M_{SD} < 1100 \text{ GeV})$$

Very high masses measurement ongoing

TOTEM-CMS $dN_{ch}/d\eta$ measurements at 8 TeV

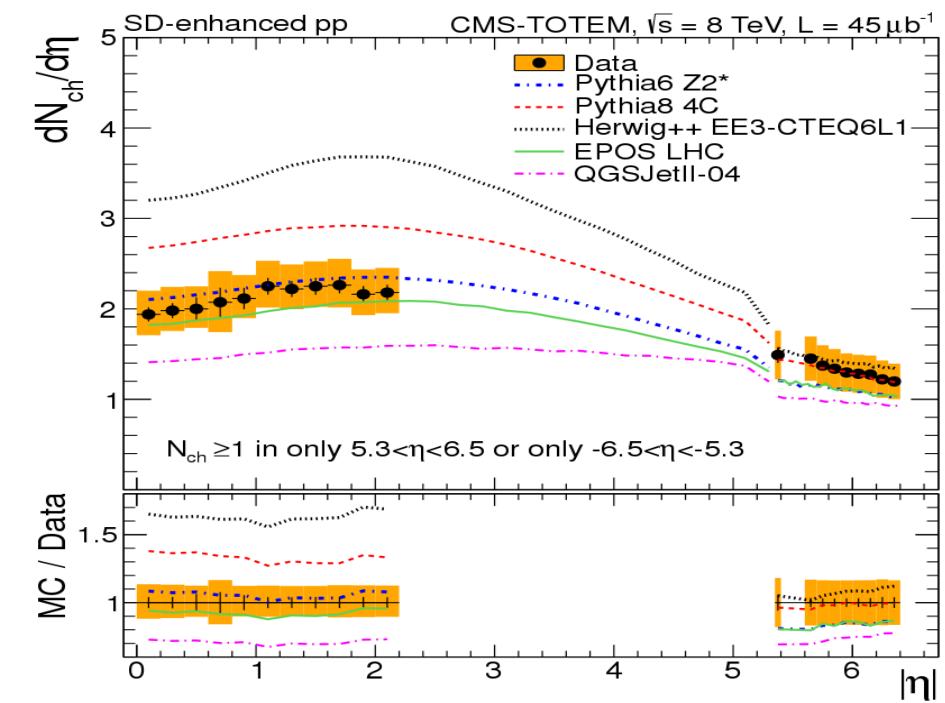


CERN-PH-EP-2014-063
(Accepted for pub. in EPJ-C)

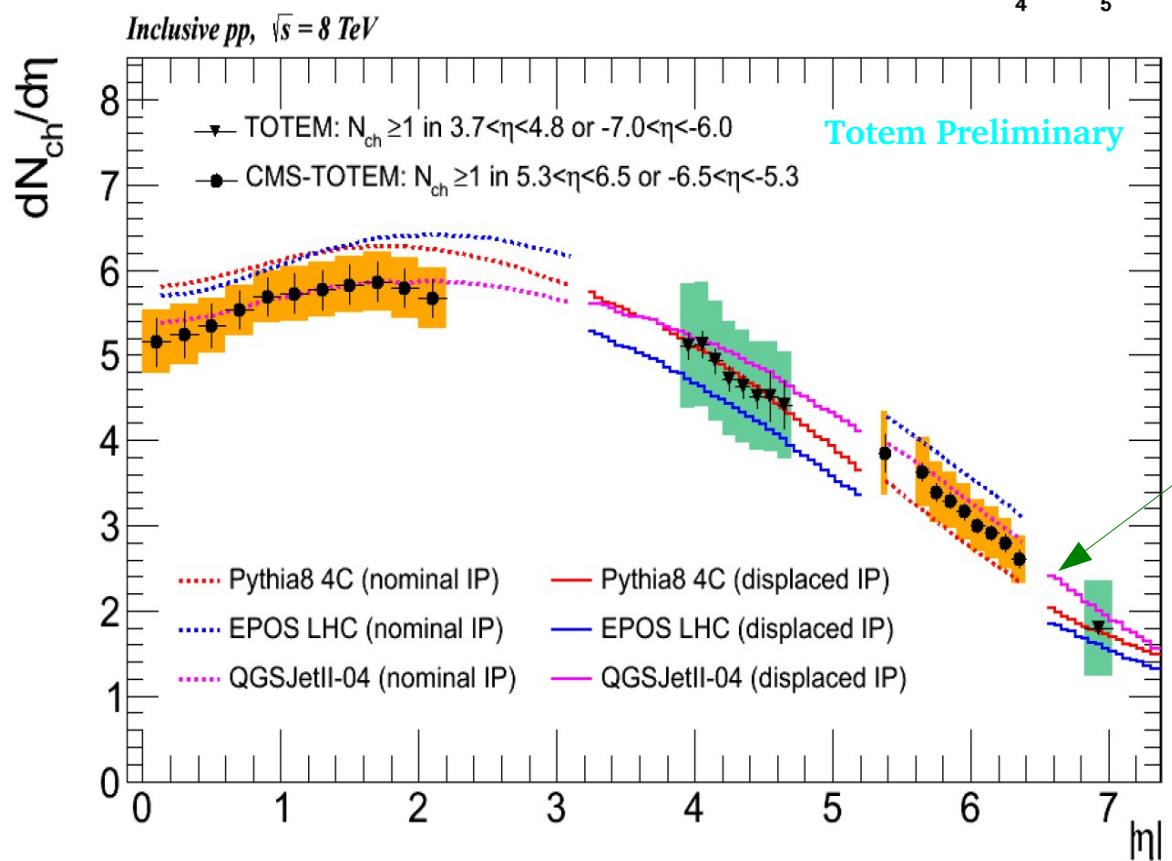
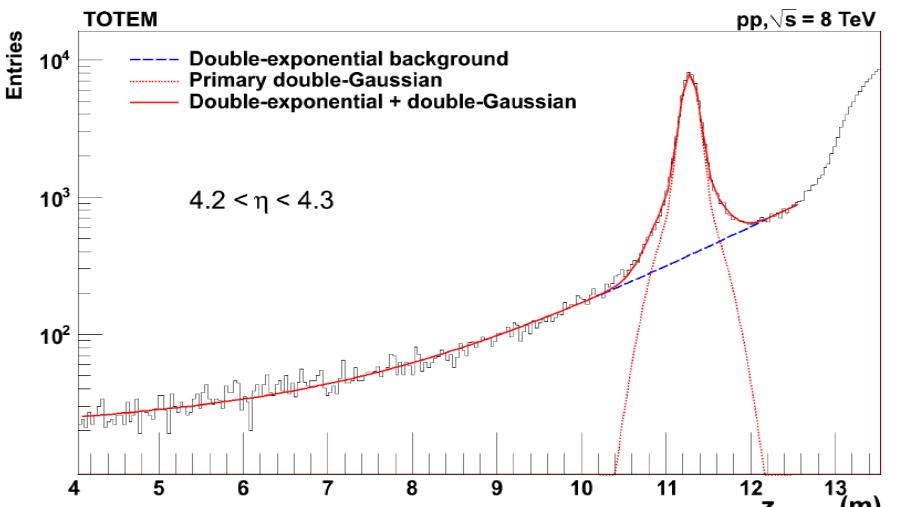
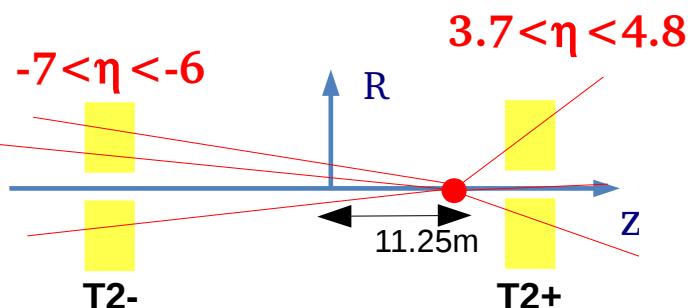


First CMS-TOTEM paper:

- Both CMS and TOTEM analysis obtained triggering with T2 on the same data sample.
- Same CMS-TOTEM event selection (based on T2 tracks)
- Distributions obtained in three samples:
Inclusive ($\sigma_{inel, VISIBLE} = 91\text{-}96\% \sigma_{inel}$), SD and NSD enhanced.
- Distributions corrected down to $P_T = 0$ MeV/c.



TOTEM $dN_{\text{ch}}/d\eta$ with displaced vertex at 8 TeV



● Measurement with bin-to-bin uncertainty

■ Total error (largely uncorrelated among the ranges)

Not possible to make reliable measurements in the range $-6.9 < \eta < -6$ because the large amount of material

- Distributions obtained in an inclusive sample (96-97% of visible σ_{inel} according to Py8-4C and EPOS-LHC MC).
- Particle P_T down to 0 MeV/c

Conclusions and outlooks

- TOTEM has measured the inelastic & elastic cross section and the total cross section with the luminosity independent method at $\sqrt{s}=7$ and 8 TeV
 - Measurement of the elastic differential cross section in $5 \cdot 10^{-3} < |t| < 2.5 \text{ GeV}^2$ (7 TeV).
 - Ongoing analysis at 8 TeV probes the elastic scattering down to $|t| \sim 6 \cdot 10^{-4} \text{ GeV}^2$.
 - ➔ Hadronic/Coulomb interference: ρ -constraints, improvement in σ_{TOT} accuracy, study of the nuclear amplitude with unprecedented precision.
 - Inelastic cross section measurement, constraints on the low mass diffractive cross section.
- Double diffractive visible cross sections (7 TeV).
- Single diffractive cross section and proton t-distribution for different mass ranges (7 TeV).
- Measurement of the forward charged particle $dN/d\eta$ distribution with CMS for inclusive, SD and NSD enhanced sample. TOTEM $dN/d\eta$ measurement with displaced vertex up to $|\eta|=7$.
 - ➔ Inclusive pp $dN/d\eta$ measured in the range $0 < |\eta| < 7$ at 8 TeV (never before).
- **Further analyses on pp diffractive processes, including joint TOTEM-CMS studies are ongoing, results are expected soon... stay TUNED!**

Thank you for your attention

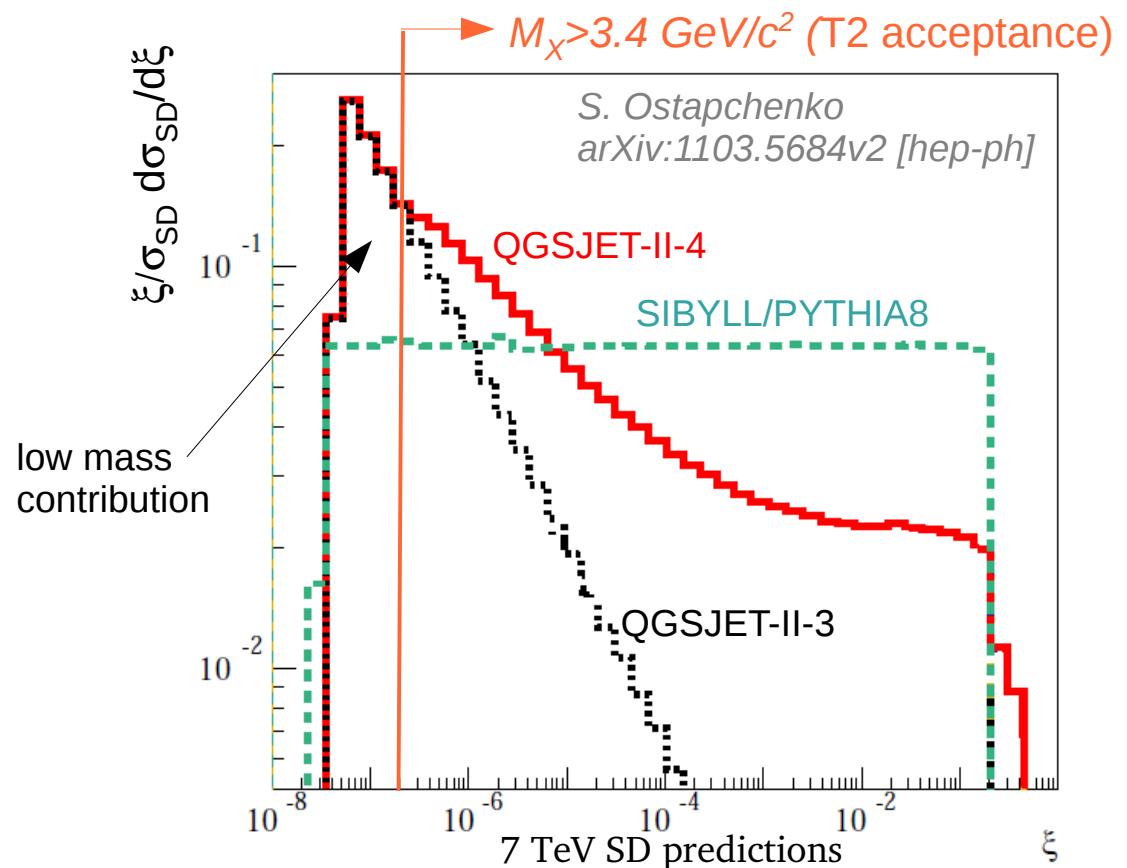
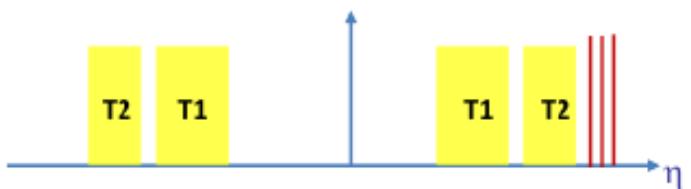


Inelastic cross section measurement @ 7 TeV:

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

$$\sigma_{\text{inel}} \text{ (mb)}: 73.74 \pm 0.09\text{stat} \pm 1.74\text{syst} \pm 2.95\text{lumi}$$

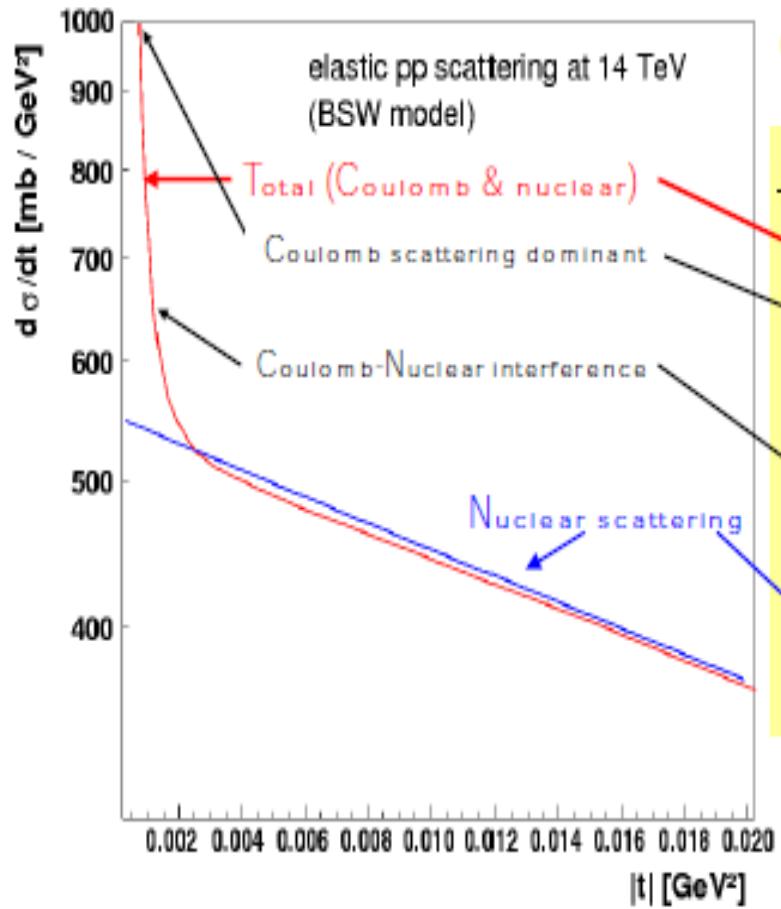
(EPL, 101 (2013) 21003)



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

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

Correction based on **QGSJET-II-03**
 $= 4.2\% \pm 2.1\% \text{ (syst)}$
(imposing the observed 2arm/1arm event ratio)



Optical Theorem:

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

$$\frac{d\sigma}{dt} =$$

$$\frac{4\pi\alpha^2(\hbar_c)^2 G^4(t)}{|t|^2} +$$

$$\frac{\alpha(\rho - \alpha\phi)\sigma_{tot} G^2(t)}{|t|} e^{-B|t|/2} +$$

$$\frac{\sigma_{tot}^2(1+\rho^2)}{16\pi(\hbar_c)^2} e^{-B|t|}$$

α = fine structure constant

ϕ = relative Coulomb-nuclear phase

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

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

Total cross section measurements @ 7 TeV: three methods

Use of the optical theorem:

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

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

- 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}

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

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

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

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

➤ Absolute calibration of the CMS luminosity:

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

$$\mathcal{L}_{int, CMS} = 82.8 \pm 3.3 \mu b^{-1}$$

$$\mathcal{L}_{int, CMS} = 1.65 \pm 0.07 \mu b^{-1}$$

$$\mathcal{L}_{int, TOTEM} = 83.7 \pm 3.2 \mu b^{-1}$$

$$\mathcal{L}_{int, TOTEM} = 1.65 \pm 0.07 \mu b^{-1}$$

➤ Luminosity and ρ independent ratios:

$$\sigma_{el}/\sigma_{inel} = 0.345 \pm 0.009$$

$$\sigma_{el}/\sigma_{tot} = 0.257 \pm 0.005$$

➤ Low mass diffraction:

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

Measure $\sigma_{inel}^{\eta < 6.5} = 70.53 \pm 2.93 \text{ mb}$

→ $2.62 \pm 2.17 \text{ mb}$ (upper limit $\sim 6.3 \text{ mb}$ at 95%CL)

(Uncertainty dominated by luminosity)

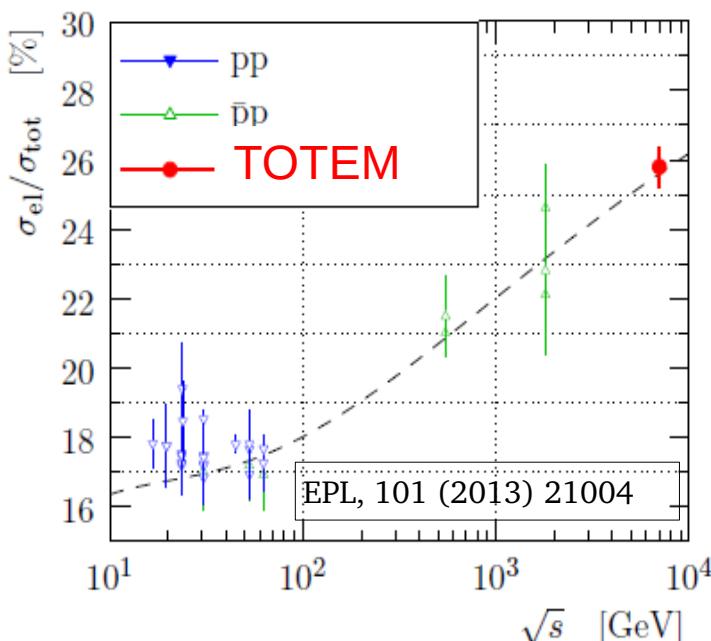
➤ ρ measurement:

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

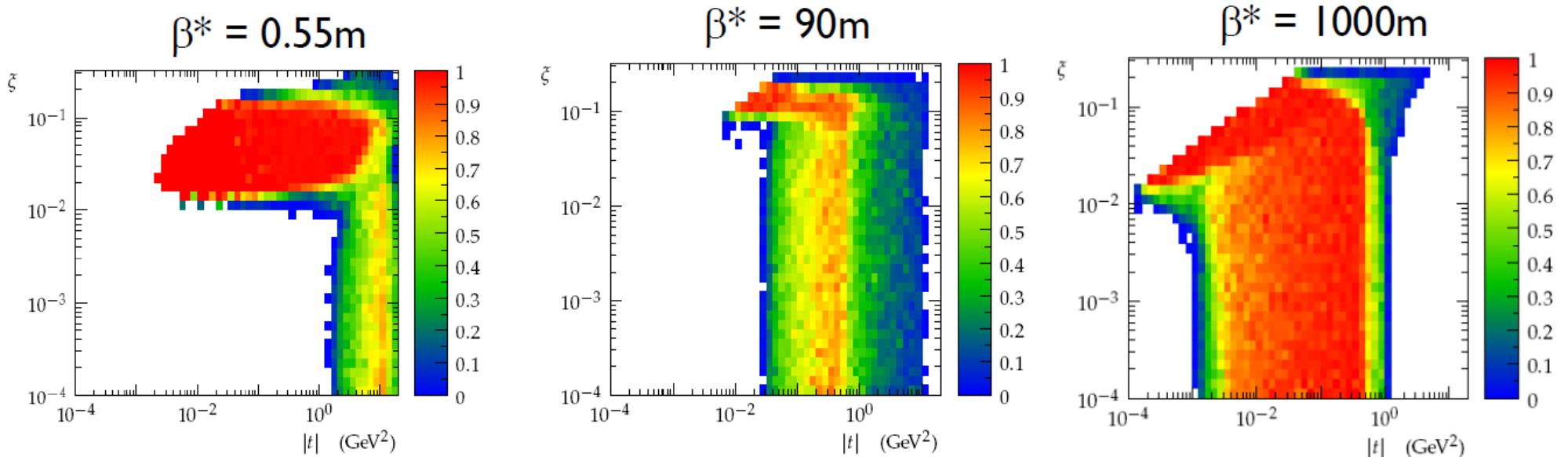
$$TOTEM |\rho| = 0.14 \pm 0.09$$

$$COMPETE \text{ extrapolation } |\rho| = 0.141 \pm 0.091$$

[A direct ρ measurement at 8 TeV is ongoing]



- Different running scenario → different kinematic acceptance



➤ Diffraction:
 $\xi > \sim 0.01$
 low cross-section processes
 (hard diffraction)
 ➤ Elastic scattering: large $|t|$

➤ Diffraction:
 all ξ if $|t| > \sim 10^{-2}$ GeV 2
 ➤ Elastic scattering:
 low to mid $|t|$
 ➤ Total Cross-Section

➤ Elastic scattering:
 very low $|t|$
 Coulomb-Nuclear Interference
 ➤ Total Cross-Section



Soft Double Diffractive cross section

Event selection: Trigger with T2, at least one track in both T2 hemispheres , no tracks in T1 “(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
- σ_{DD} uncertainty dominated by migrations from generator- η_{min} to track reconstructed η_{min} , in particular:

Pythia 8

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

	-4.7 > η_{min} > -5.9	-5.9 > η_{min} > -6.5
4.7 < η_{min} < 5.9	70 μb	37 μb
5.9 < η_{min} < 6.5	35 μb	17 μb

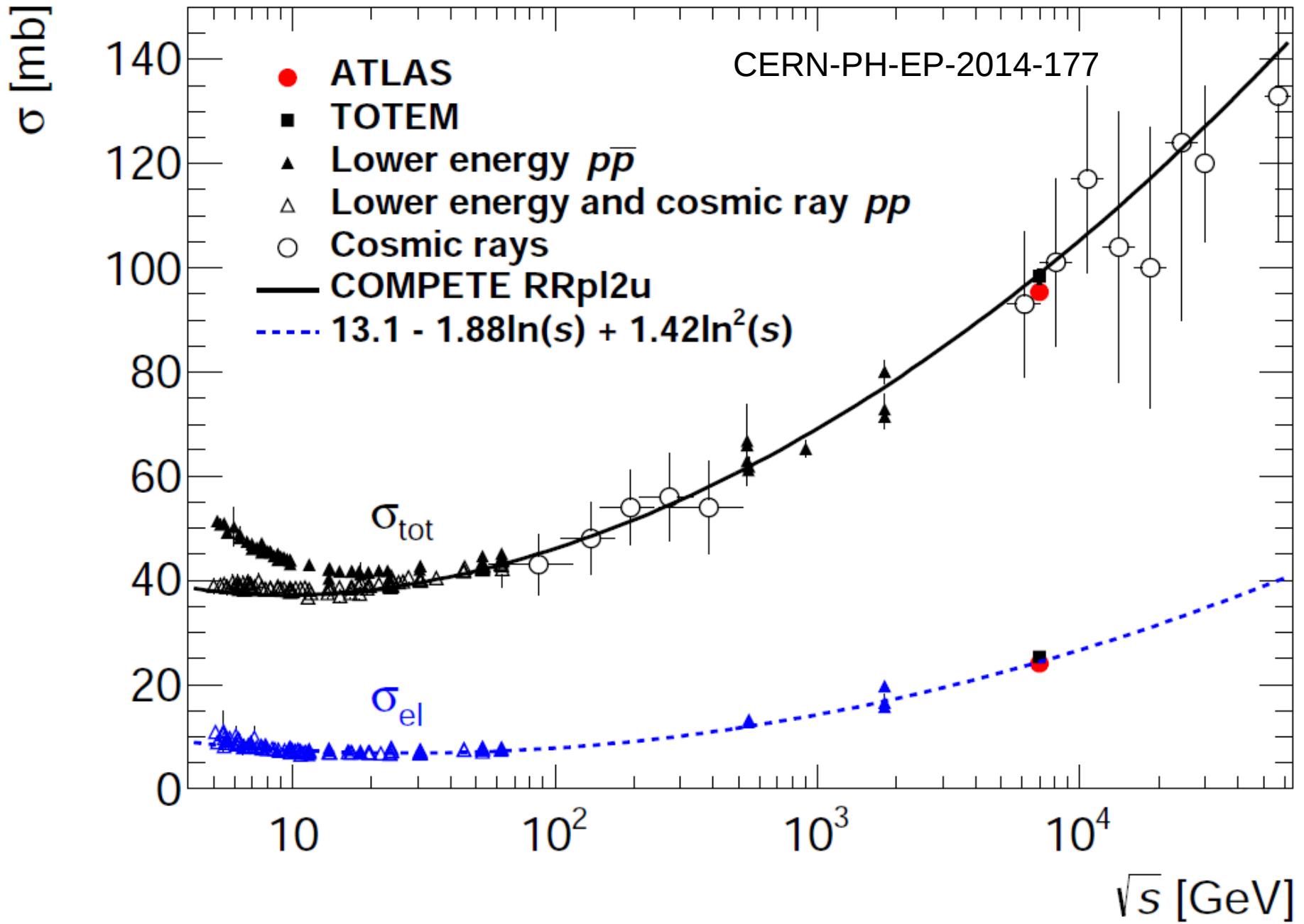
Phojet

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

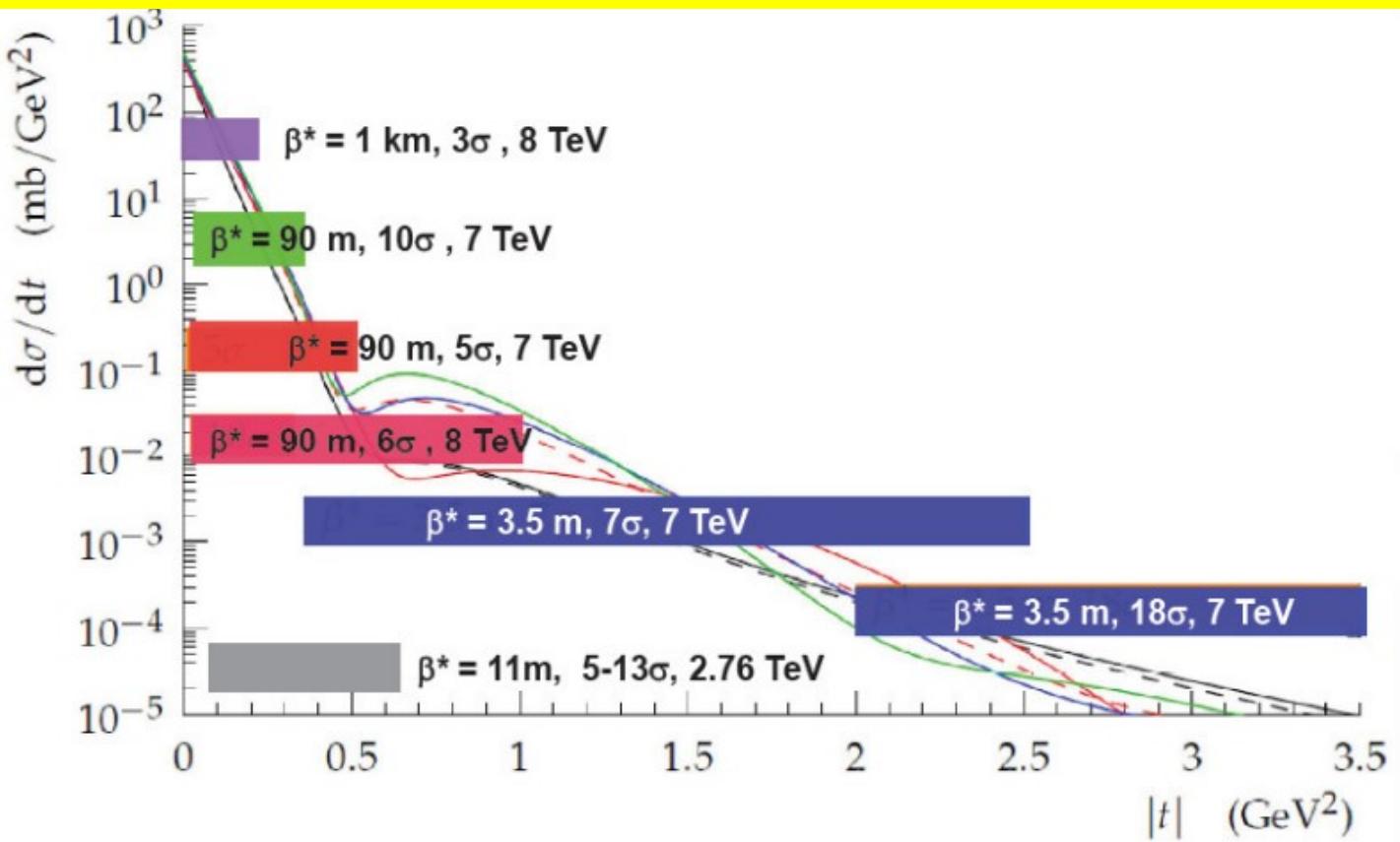
	-4.7 > η_{min} > -5.9	-5.9 > η_{min} > -6.5
4.7 < η_{min} < 5.9	44 μb	23 μb
5.9 < η_{min} < 6.5	23 μb	12 μb

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

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



TOTEM pp data (already analysed or analysis ongoing)



E (TeV)	β^* (m)	RP approach	\mathcal{L}_{int} (μb^{-1})	t range (GeV 2)	Elastic events	
7	90	$4.8\text{-}6.5\sigma$	83	$7\cdot10^{-3} - 0.5$	1M	EPL 101 (2013) 21002]
	90	10σ	1.7	0.02 - 0.4	14k	EPL 96 (2011) 21002]
	3.5	7σ	0.07	0.36 - 3	66k	EPL 95 (2011) 41001]
	3.5	18σ	2.3	2 - 3.5	10k	
8	90	$6\text{-}9\sigma$	60	$0.01 - 1$	8M	
	1000	3σ	20	$6\cdot10^{-4} - 0.2$	0.4M	
2.76	11	$5\text{-}13\sigma$		0.05-0.6	45k	

Interference formulae

- simplified West-Yennie formula (SWY)
 - *limitation*: derived for *constant slope B* (1 b_i parameter only) and *constant nuclear phase*
 - acts as simple interference phase (i.e. Φ is real-valued)

$$F^{C+H} = F^C e^{i\alpha\Phi} + F^H, \quad \Phi = -\left(\frac{B|t|}{2} + \gamma\right)$$

- Kundrát-Lokajíček formula (KL)
 - any slope B , any nuclear phase
 - more complicated effect (Ψ complex in general)

$$F^{C+H} = F^C + F^H e^{i\alpha\Psi}$$

$$\Psi(t) = \mp \int_{t_{\min}}^0 dt' \ln \frac{t'}{t} \frac{d}{dt'} \mathcal{F}^2(t') \pm \int_{t_{\min}}^0 dt' \left(\frac{F^H(t')}{F^H(t)} - 1 \right) \frac{I(t, t')}{2\pi}$$

$$I(t, t') = \int_0^{2\pi} d\varphi \frac{\mathcal{F}^2(t'')}{t''}, \quad t'' = t + t' + 2\sqrt{tt'} \cos \varphi$$

Phase of Nuclear amplitude

- constant phase - the simplest choice

$$\arg \mathcal{A}^N = p_0$$

- central phase - similar shape as in many phenomenological models

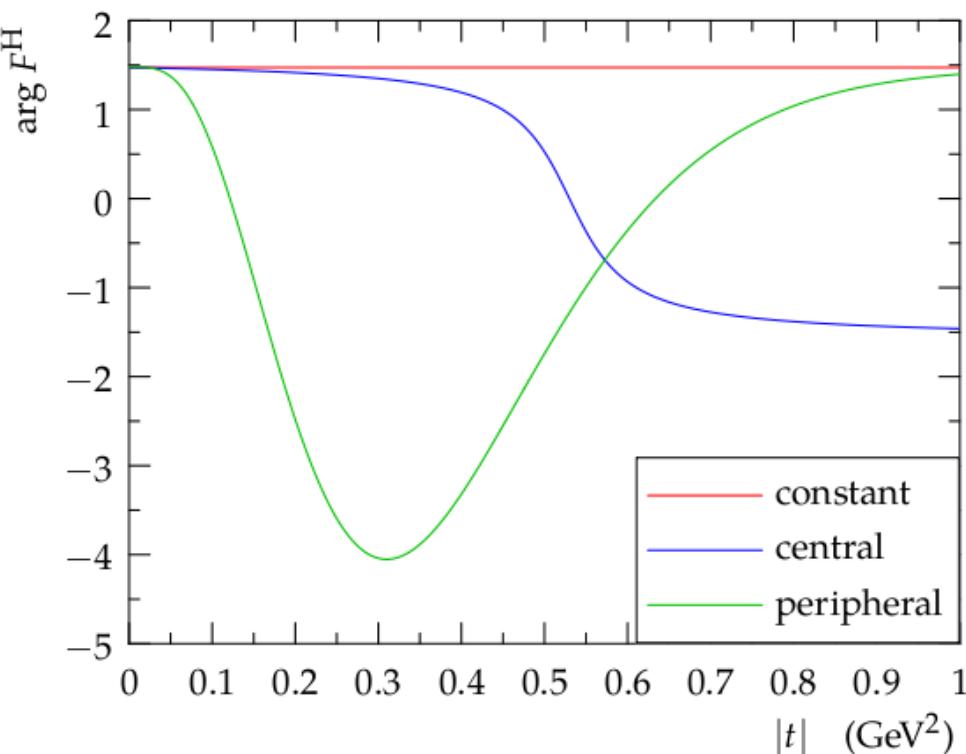
$$\arg \mathcal{A}^N = \frac{\pi}{2} - \text{atan} \frac{\rho_0}{1 - \frac{t}{t_d}}, \quad \rho_0 = \frac{1}{\tan p_0}$$

$$t_d \approx -0.53 \text{ GeV}^2$$

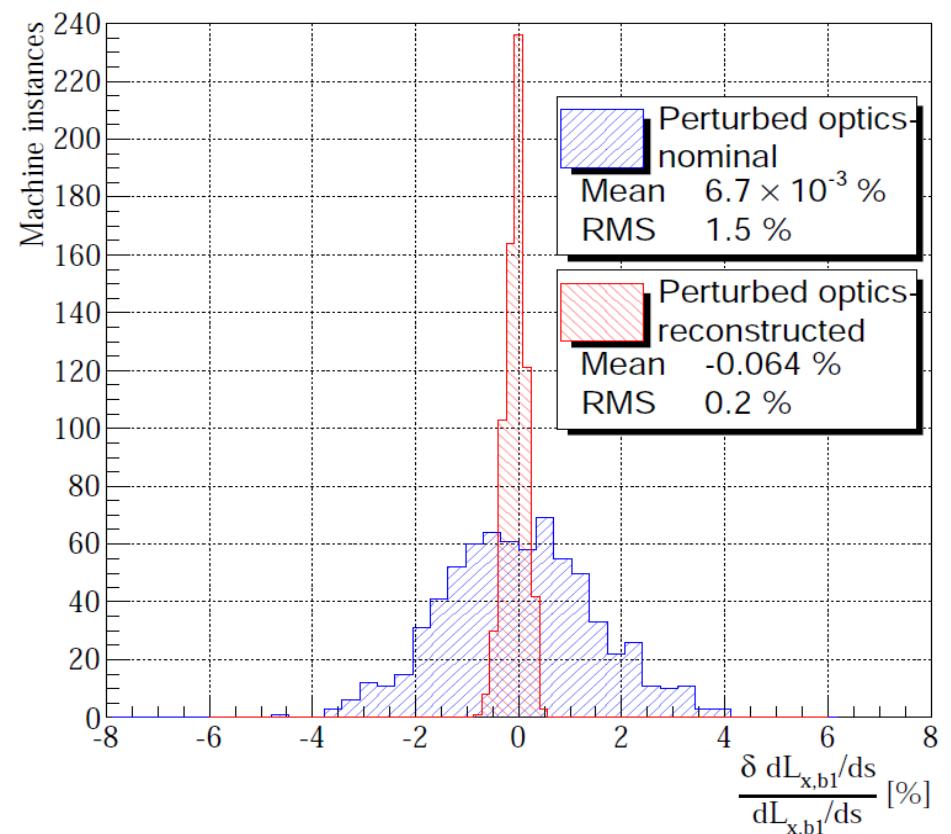
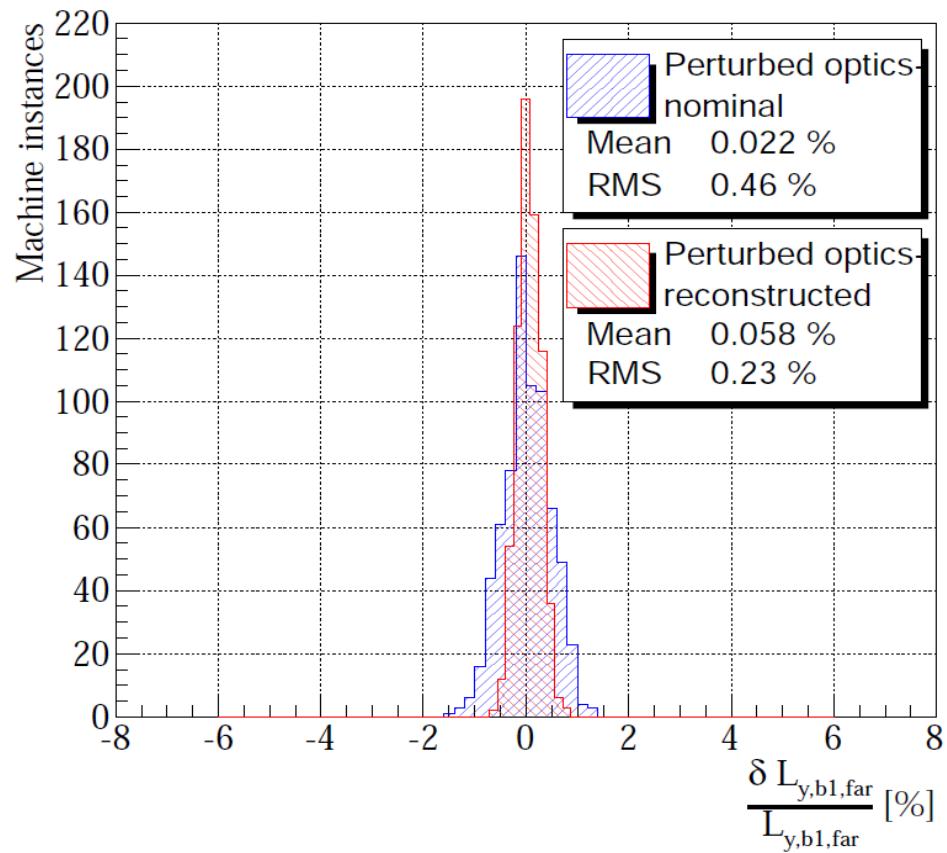
- peripheral phase [Z. Phys. C63 (1994) 619-630] - expected order in impact parameter space: elastic collisions more peripheral than inelastic $\langle b^2 \rangle_{\text{el}} > \langle b^2 \rangle_{\text{inel}}$

$$\arg \mathcal{A}^N = p_0 + A \exp \left[\kappa \left(\ln \frac{t}{t_m} - \frac{t}{t_m} + 1 \right) \right]$$

$$A \approx 5.53, \quad \kappa \approx 4.01, \quad t_m \approx -0.310 \text{ GeV}^2$$



Improvement of optics reconstruction at $\beta^* = 90\text{m}$



Relative optics distribution	Simulated optics distribution		Reconstructed optics error	
	Mean [%]	RMS [%]	Mean [%]	RMS [%]
$\frac{\delta L_{y,b1,far}}{L_{y,b1,far}}$	$2.2 \cdot 10^{-2}$	0.46	$5.8 \cdot 10^{-2}$	0.23
$\frac{\delta dL_{x,b1}/ds}{dL_{x,b1}/ds}$	$6.7 \cdot 10^{-3}$	1.5	$-6.4 \cdot 10^{-2}$	0.20
$\frac{\delta L_{y,b2,far}}{L_{y,b2,far}}$	$-5 \cdot 10^{-3}$	0.47	$5.8 \cdot 10^{-2}$	0.23
$\frac{\delta dL_{x,b2}/ds}{dL_{x,b2}/ds}$	$1.8 \cdot 10^{-2}$	1.5	$-7 \cdot 10^{-2}$	0.21

Table 5. The Monte-Carlo study of the impact of the LHC imperfections $\Delta\mathcal{M}$ on selected transport matrix elements dL_x/ds and L_y for $\beta^* = 90\text{m}$ at $E = 4\text{ TeV}$. The LHC parameters were altered within their tolerances. The relative errors of dL_x/ds and L_y (mean value and RMS) characterize the optics uncertainty before and after optics estimation.