TOTEM results on total, elastic, inelastic and diffractive scattering

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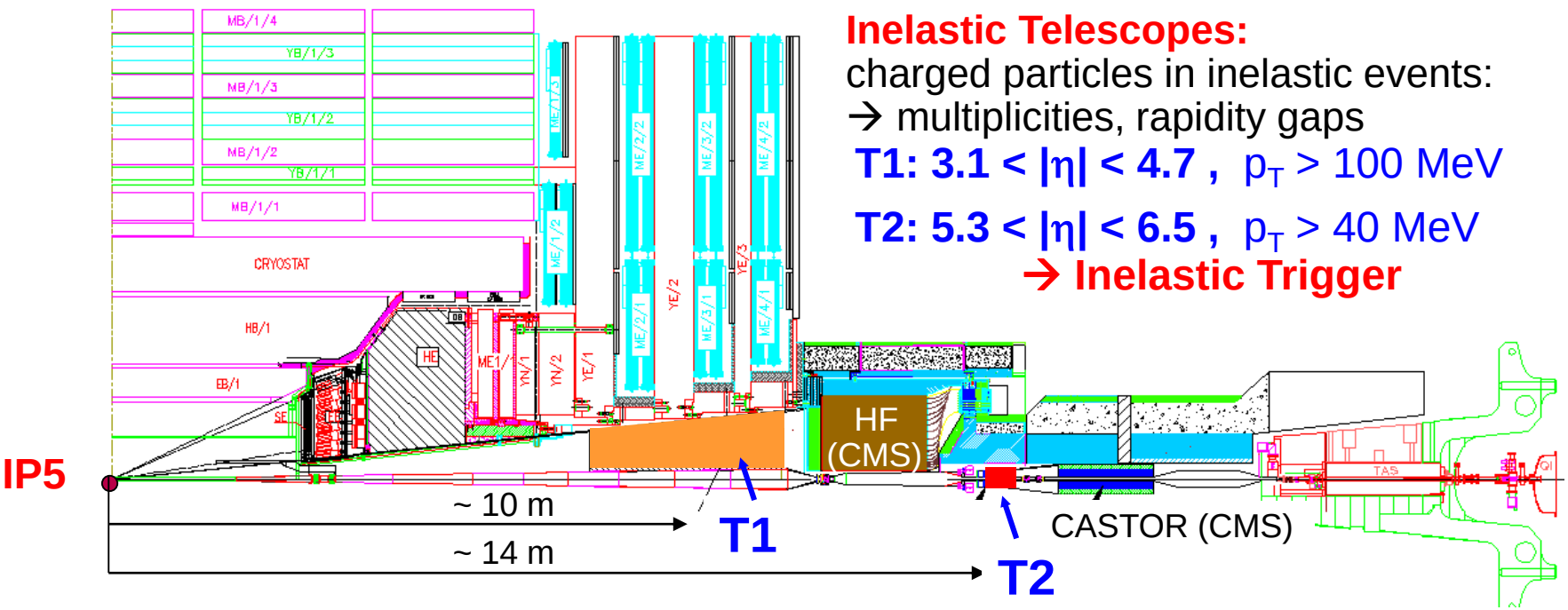
Overview

- TOTEM detector setup @ IP5 of LHC
- Elastic p-p scattering
- Inelastic and total p-p cross-sections
- Measurement in Coulomb (interference) region
- Diffractive cross-sections
- Summary

Experimental Setup at IP5

[Ref.: JINST 3 (2008) S08007]



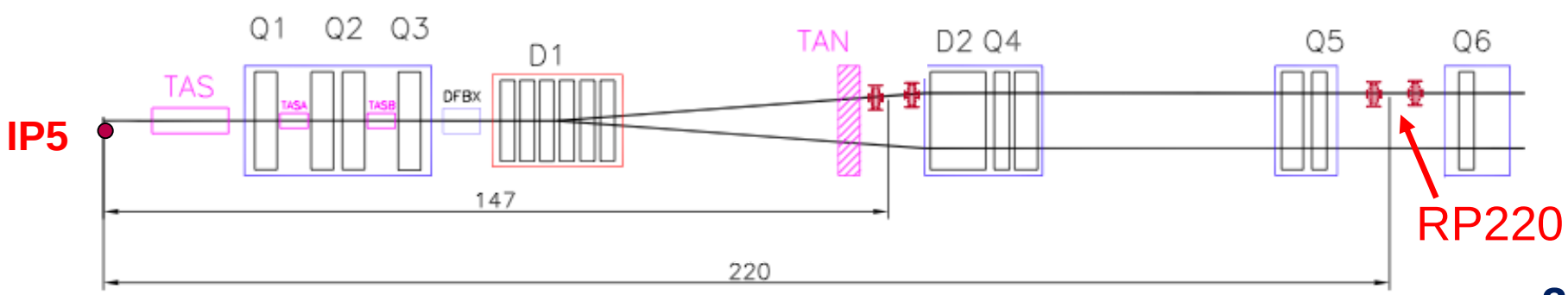
Inelastic Telescopes:
charged particles in inelastic events:
→ multiplicities, rapidity gaps

T1: 3.1 < |η| < 4.7 , p_T > 100 MeV

T2: 5.3 < |η| < 6.5 , p_T > 40 MeV

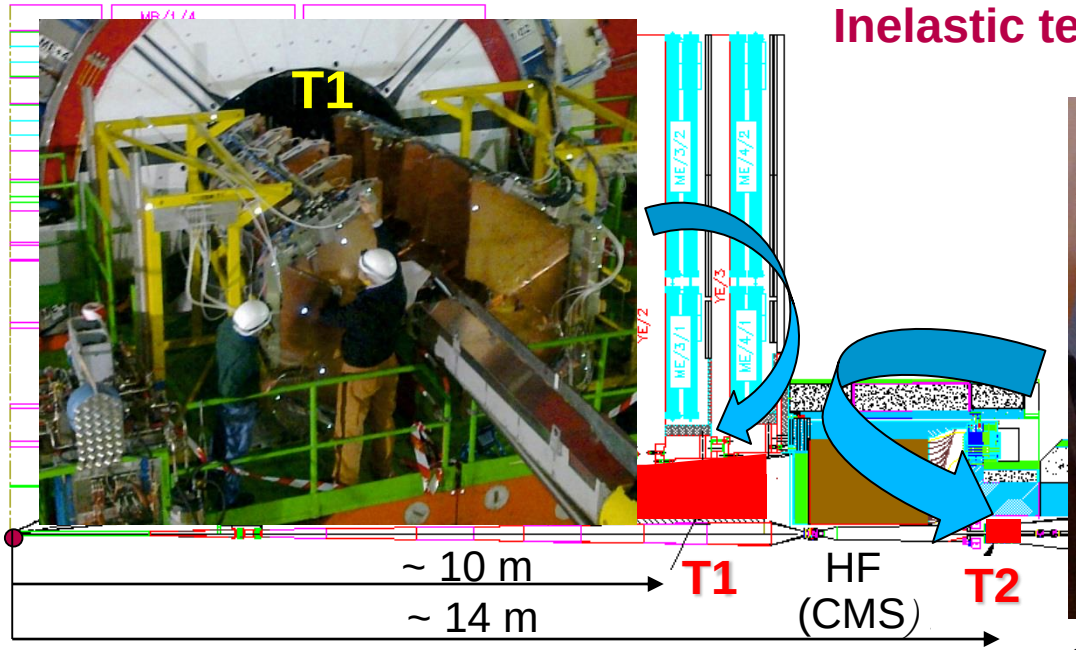
→ Inelastic Trigger

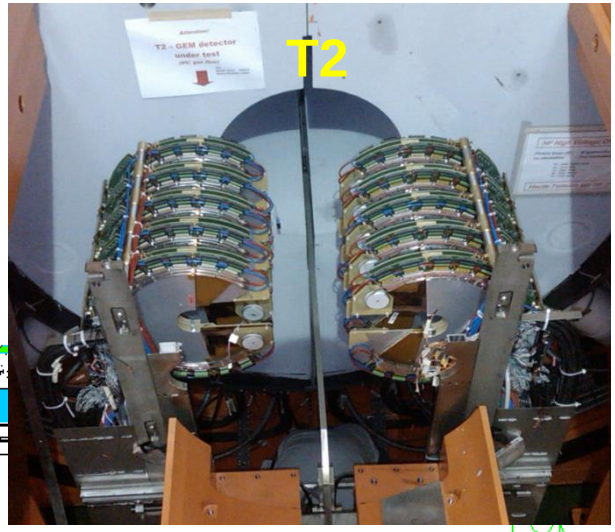
Roman Pots: elastic & diffractive protons close to outgoing beams **→ Proton Trigger**



Experimental Setup at IP5

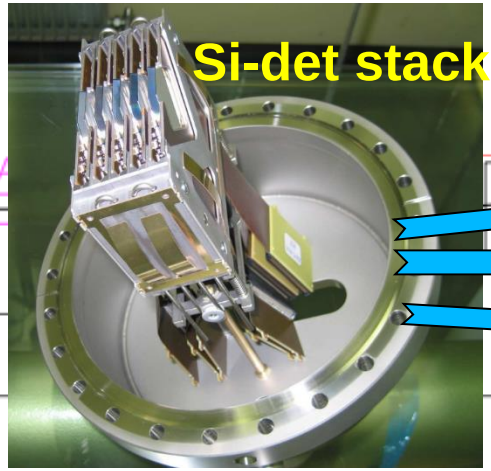
Inelastic telescopes: rapidity gaps

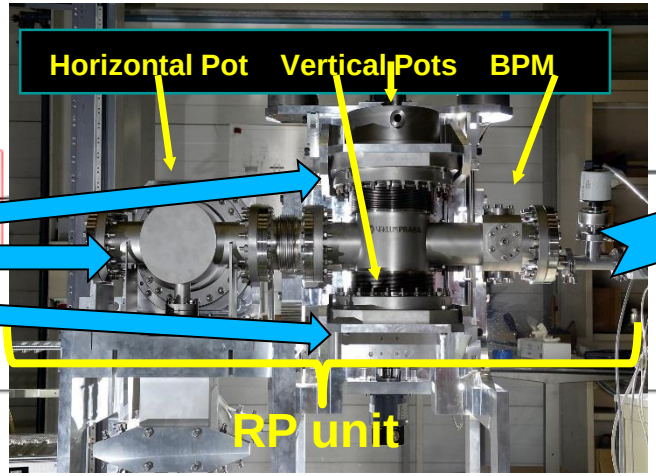


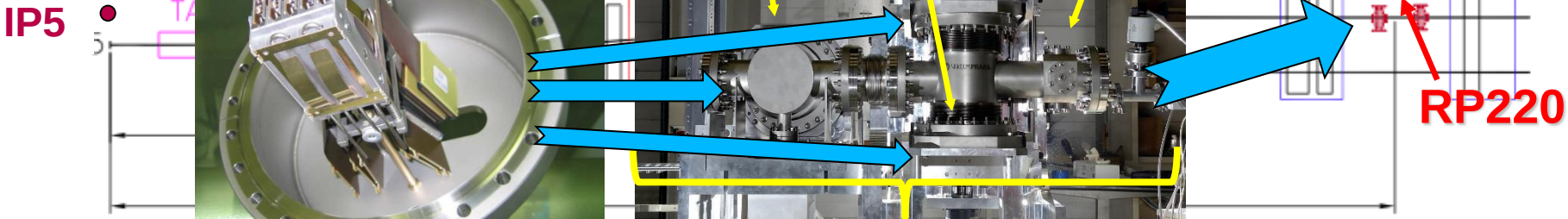


CASTOR
(CMS)

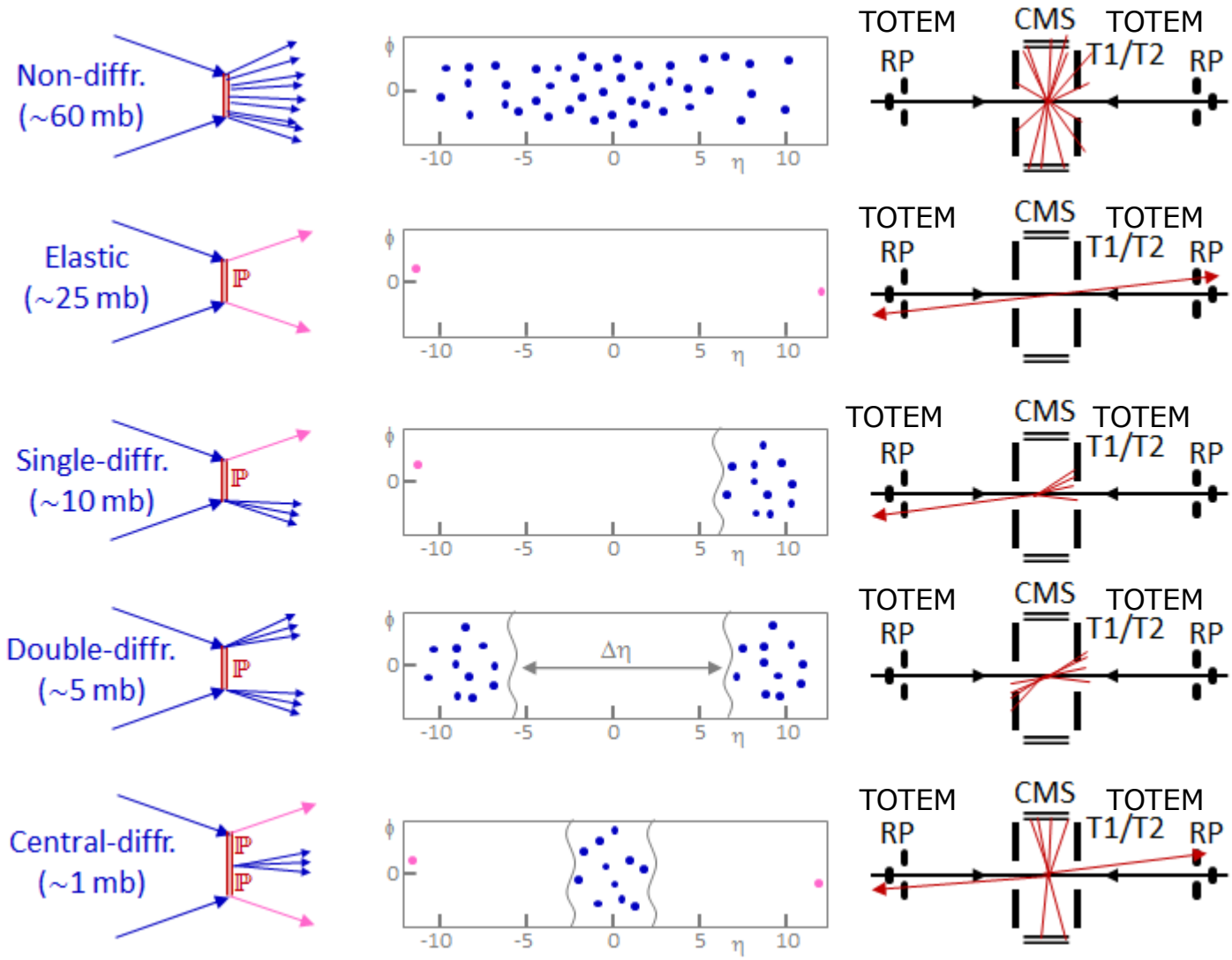
Roman Pots: diffractive protons (di-proton trigger)







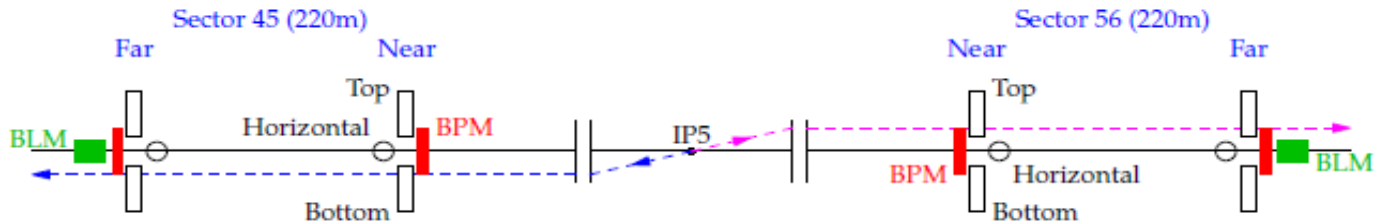
TOTEM Physics at LHC



Elastic and diffractive scattering: Pomeron exchange

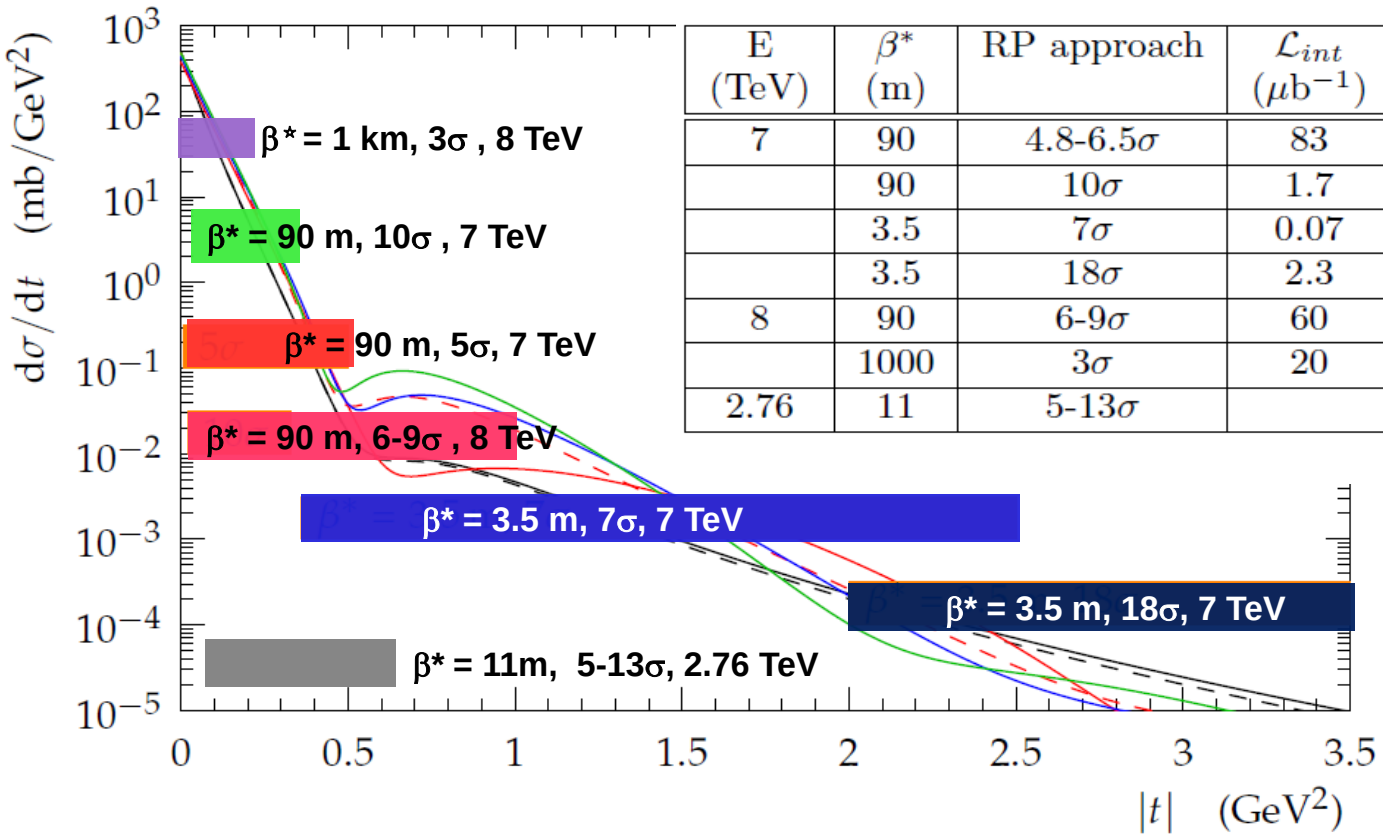
Elastic pp Scattering: selection&data sets

Selected based on topology, low |ξ|, collinearity, & vertex



Key issues:
RP alignment
& optics

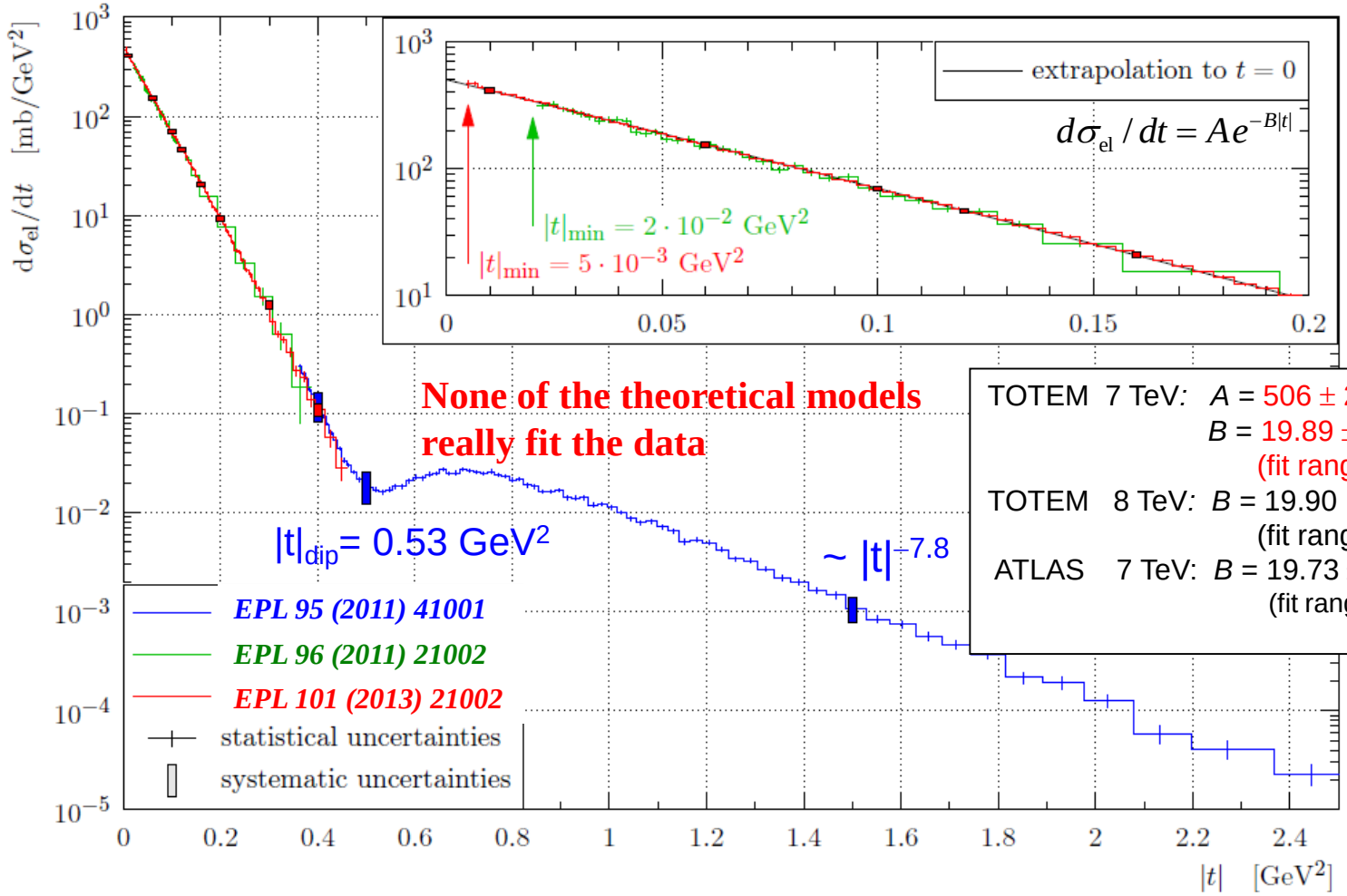
Data sets at different conditions to measure elastics over wide t-range including very low |t|



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

Show results from data sets indicated by arrows

TOTEM $d\sigma_{el}/d|t|$ Measurement @ 7 TeV



TOTEM 7 TeV: $A = 506 \pm 23.0^{syst} \pm 0.9^{stat}$ mb/GeV^2
$B = 19.89 \pm 0.27^{syst} \pm 0.03^{stat}$ GeV^{-2}
(fit range: $5 \cdot 10^{-3} < |t| < 0.2$ GeV^2)

TOTEM 8 TeV: $B = 19.90 \pm 0.30$ GeV^{-2}
(fit range: $1 \cdot 10^{-2} < |t| < 0.2$ GeV^2)

ATLAS 7 TeV: $B = 19.73 \pm 0.26^{syst} \pm 0.14^{stat}$ GeV^{-2}
(fit range: $0.01 < |t| < 0.1$ GeV^2)

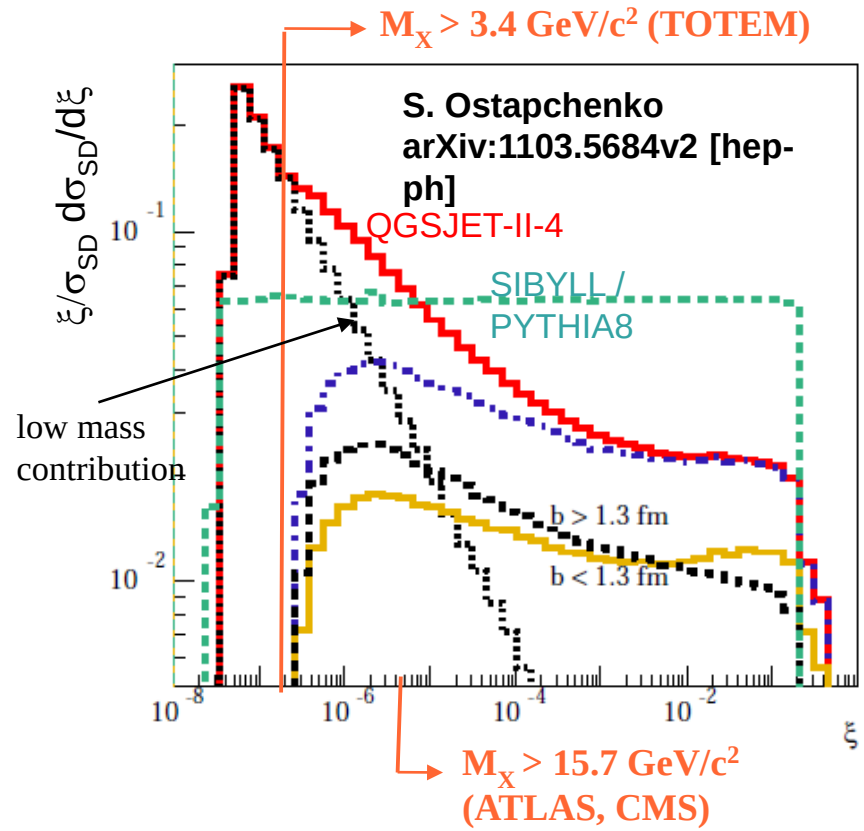
TOTEM results:	**7 TeV**	$\sigma_{el} = 25.4 \pm 1.0^{lumi} \pm 0.3^{syst} \pm 0.03^{stat}$ mb	**(91% directly measured)**
($\mathcal{L}$ from CMS with 4% unc.)		$\sigma_{el} = 24.8 \pm 1.0^{lumi} \pm 0.7^{syst} \pm 0.2^{stat}$ mb	**(67% directly measured)**
($\mathcal{L}$ independent)	**8 TeV**	$\sigma_{el} = 27.1 \pm 1.2^{syst+stat}$ mb	
ATLAS result:	**7 TeV**	$\sigma_{el} = 24.00 \pm 0.57^{syst} \pm 0.19^{stat}$ mb	**(90% directly measured)**
($\mathcal{L}$ with 2.3% uncertainty)			

Direct σ_{inel} Measurement

- Count events with charged particles in T1 & T2 (~ 95 % of inelastic).
- Trigger: at least one track in T2.

Impact of Low-Mass diffraction:

- Extrapolation to low M_X region: main source of systematic uncertainty on σ_{inel}
- Minimal M_X depends on maximal $|\eta|$ coverage: lower M_X reachable → minimal model dependence on corrections for low mass diffraction
- TOTEM (T1+T2: $3.1 < |\eta| < 6.5$) gives an unique forward charged particle coverage @ LHC → direct measurement of σ_{inel} with lower sys. unc.
- Low mass diffraction @ $M_{diff} < 3.4$-3.6 GeV (tuned QGSJETII-03 to observed 1hemi fraction)



$\sigma_{inelastic}$	@ 7 TeV	@ 8 TeV
Direct	73.7 ± 3.4 mb *EPL 101 (2013) 21003*	
Indirect	73.15 ± 1.26 mb *EPL 101 (2013) 21002*	
$\mathcal{L}$ independent	72.9 ±1.5 mb *EPL 101 (2013) 21004*	74.7 ± 1.7 mb *PRL 111 (2013) 012001*

Low-Mass Diffraction: Constraint from N_{el}

Constraint on low mass diffraction cross-section from TOTEM data:

Use total cross-section determined from elastic observables (via the Optical Theorem)
→ <u>no assumption on low mass diffraction</u>

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

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = 73.2 \pm 1.3 \text{ mb}$$

and the measured "visible" inelastic cross-section for $|\eta| < 6.5$ (T1, T2)

$$\sigma_{inel,\,|\eta|<6.5} = 70.5 \pm 2.9 \text{ mb}$$

to obtain the low-mass diffractive cross-section ($|\eta| > 6.5$ or $M_X < 3.4$ GeV/c^2

$$\sigma_{inel,\,|\eta|>6.5} = \sigma_{inel} - \sigma_{inel,\,|\eta|<6.5} = 2.6 \pm 2.2 \text{ mb}$$

(or < 6.3 mb @ 95% CL) [MC: 3.1 ± 1.5 mb]

Total Cross Section Measurements @ 7 TeV

1) Elastic Scatt. + Inelastic Scatt. + $\mathcal{L}$
(*no dependence on ρ*)
$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$

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

2) Elastic Scatt. + $\mathcal{L}$ + Optical Th.
(*no assumption on low mass diffr.*)
$\sigma_{inel} = \sigma_{tot} - \sigma_{el}$

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

3) Elastic Scatt. + Inel. Scatt. + Optical Th.
(*no dependence on $\mathcal{L}$*)
σ_{el} **and** σ_{inel} **: from** σ_{tot} **and** N_{el}/N_{inel}

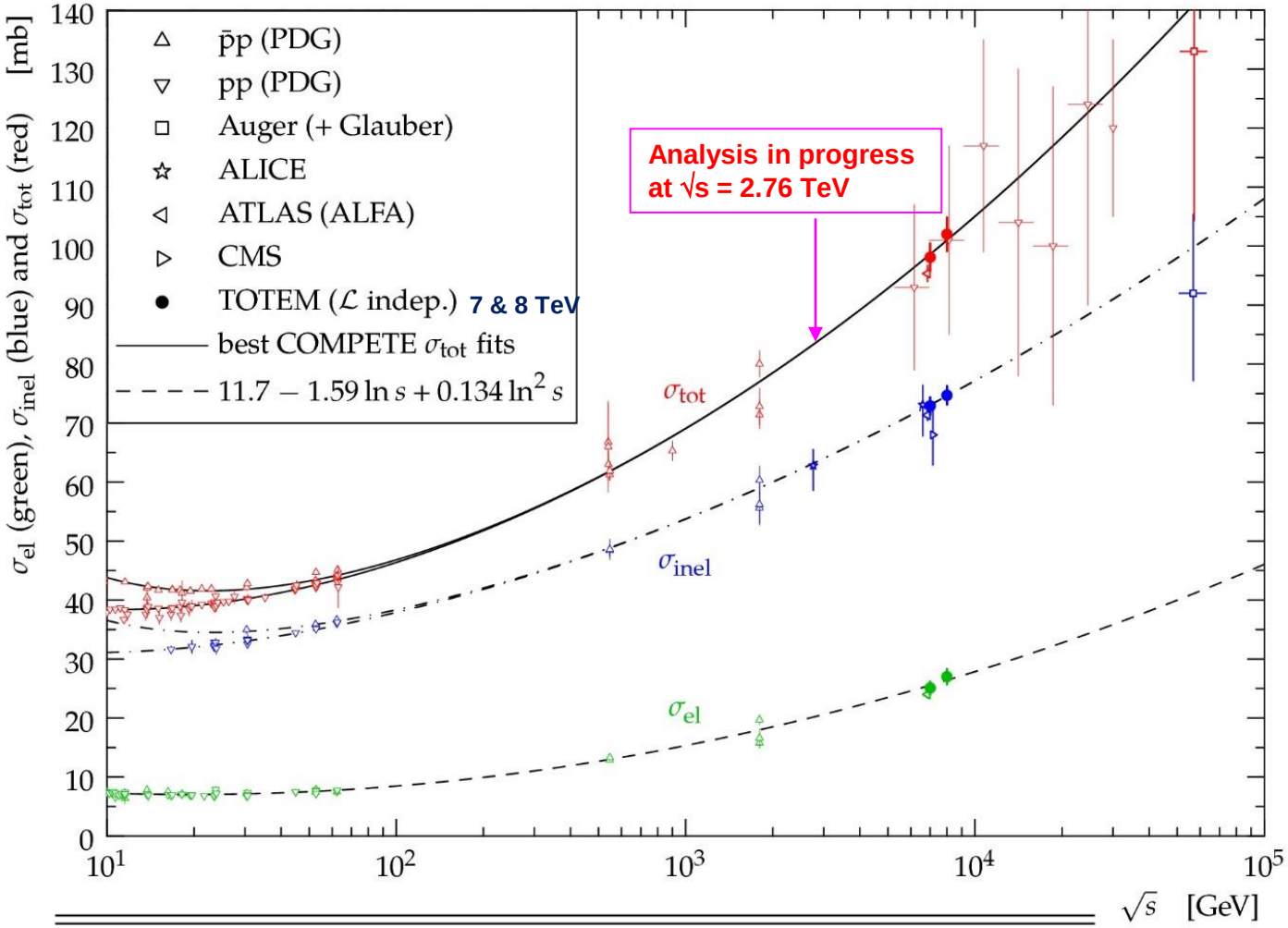
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

Method	σ_{tot} (mb)	σ_{inel} (mb)	σ_{el} (mb)	Reference
1	99.1 ± 4.3	73.7 ± 3.4	25. 4 ± 1.1	EPL 101 (2013), 21002 EPL 101 (2013), 21003
2	98.3 ± 2.8	73.5 ± 1.6	24.8 ± 1.2	EPL 96 (2011), 21002
2	98.6 ± 2.2	73.2 ± 1.3	25.4 ± 1.1	EPL 101(2013), 21002
3	98.0 ± 2.5	72.9 ± 1.5	25.1 ± 1.1	EPL 101 (2013), 21004
2	95.35± 1.36	71.3 ± 0.9	24.0 ± 0.6	*ATLAS / Nucl. Phys. B 889 (2014)*

$\rho = 0.140 \pm 0.007$
(from Compete)

Proper tracking acceptance in very forward region required: elastically scattered p detection mandatory

TOTEM σ_{tot} Measurement @ 8 TeV & Summary



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	$\Rightarrow \pm2.9$
σ_{inel}	[mb]	74.1	±1.2	±0.6	±0.9	±0.1	$\Rightarrow \pm1.7$
σ_{el}	[mb]	27.1	±0.5	±0.7	±1.0	±0.1	$\Rightarrow \pm1.4$

σ_{tot} from $\mathcal{L}$–independent Method

TOTEM @ 8 TeV

PRL 111 (2013) 012001

$d\sigma_{el}/d|t|$ Measurement @ 8 TeV with High Statistics

High statistic data sample allows a precise $d\sigma_{el}/d|t|$ measurement (for $0.027 < |t| < 0.2$ GeV^2)

"Purely" exponential slope excluded with a significance > 7 σ **($\rightarrow d\sigma_{el}/d|t| = Ae^{-B(|t|)|t|}$)**

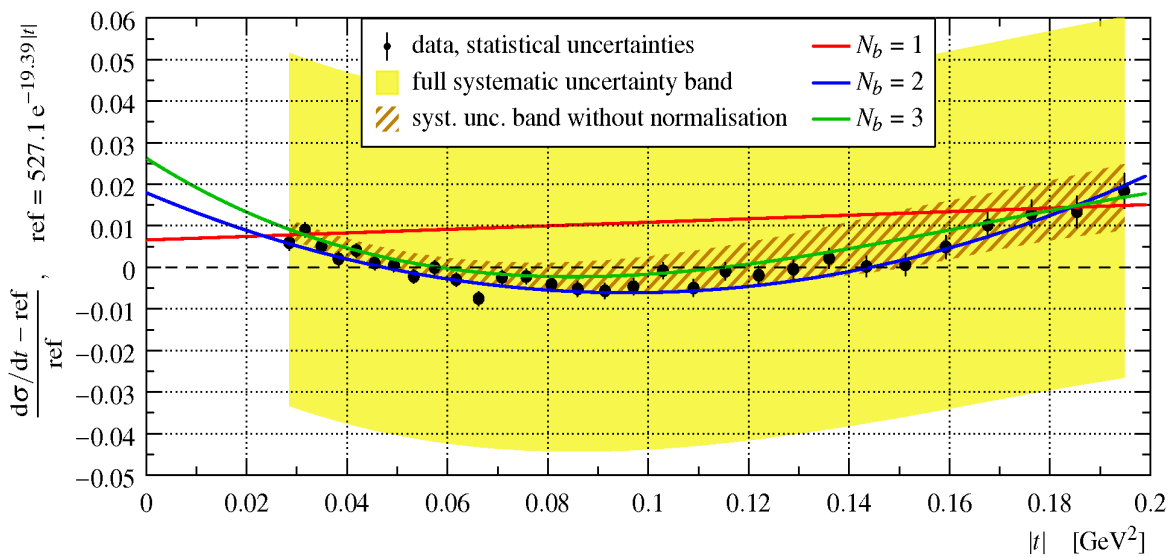
Plotting relative deviation from exponential and fitting

$d\sigma/dt = A\, e^{-B(t)\,|t|}$,

with $B(t) = b_1$ **($N_b = 1$)**

or $B(t) = b_1 + b_2\, t$ **($N_b = 2$)**

or $B(t) = b_1 + b_2\, t + b_3\, t^2$ **($N_b = 3$)**



TOTEM New!

Nucl. Phys. B899 (2015) 527

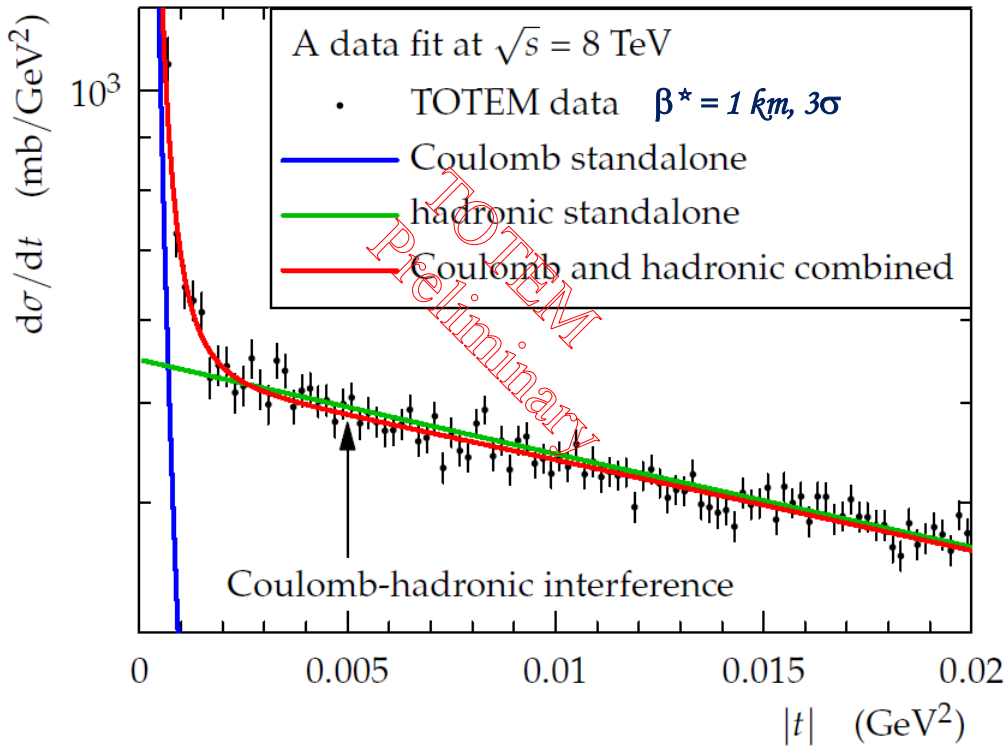
N_b	χ^2/ndf	p-value	significance
1	117.5/28 = 4.20	$6.1 \cdot 10^{-13}$	7.2 σ
2	29.3/27 = 1.09	0.35	0.94 σ
3	25.5/26 = 0.98	0.49	0.69 σ

- **Quadratic and cubic polynomials in the exponent well describe data**
- **Using the new parametrisations for extrapolation to t = 0 and applying the optical theorem, new results for σ_{tot} are found in agreement with previous measurement:**

$N_b = 2$ (quadratic polynomial) $\rightarrow$ **$\sigma_{tot} = 101.5 \pm 2.1$ mb**

$N_b = 3$ (cubic polynomial) $\rightarrow$ **$\sigma_{tot} = 101.9 \pm 2.1$ mb**

Elastic Scattering in the Coulomb-Nuclear Interference (CNI) Region



Measurement of ρ by studying the CNI down to $|t| \sim 6 \cdot 10^{-4}$ GeV^2

Reached @ √s = 8 TeV, with β* = 1000 m and RP approaching the beam centre @ ~ 3σ

Analysis of CNI Region

$d\sigma/dt \propto |F^{C+H}|^2$ = Coulomb + "interference" + hadronic

ψ (phase of F^H) accessible via interference with F^C (known)!

from QED

modulus constrained by measurement $e^{-B(t)}$

$B(t) = b_1 t + b_2 t^2 + \ldots$ N_b = # parameters in exp.

- **Interference formulae:**

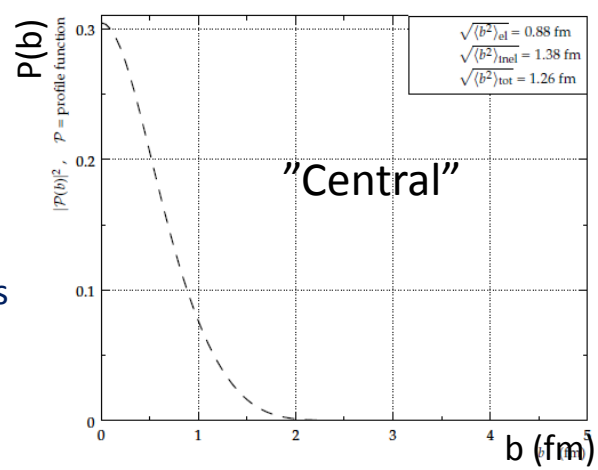
+ *Simplified West-Yennie (SWY)* [1]: past "standard", only compatible with pure exponential hadronic amplitude with constant phase

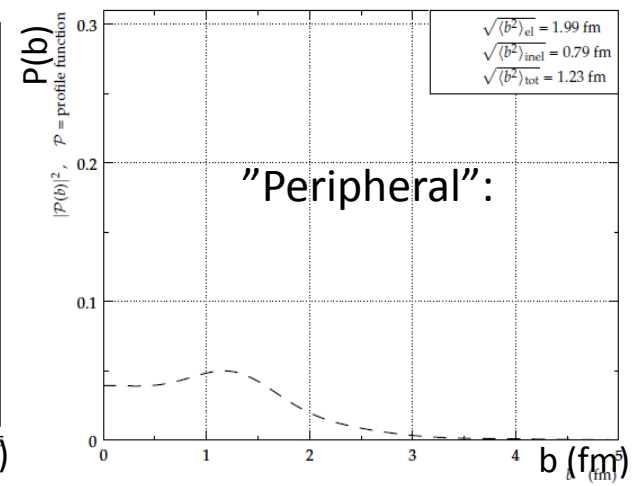
+ *Kundrát-Lokajícek (KL)* [2]: no limitations on hadronic amplitude

- **phase of F^H**: *central or peripheral* ↔ b = impact parameter of elastic pp collisions

⇒ $\rho \equiv \mathrm{Re}\, F^H / \mathrm{Im}\, F^H|_{t=0} = 1 / \tan(\psi|_{t=0})$

[1] G. B. West and D. R. Jennie, Phys. Rev. 172 (1968)1413.
[2] V. Kundrát and M. Lokajıcek, Z. Phys. C 63 (1994) 619.





Best fit method retained: 2-stage fit:

Fit 1: only b*=1km data (very low |t|): all parameters free → determines ρ

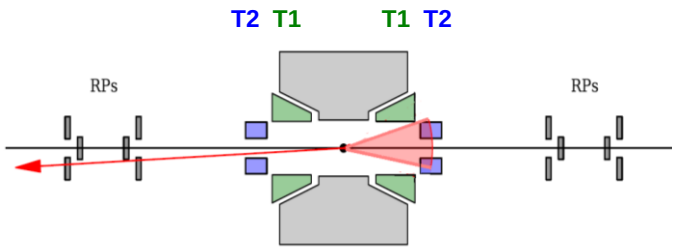
Fit 2: combined b*=1km and 90m data with fixed ρ

Results coming soon

Soft Single Diffraction @ 7 TeV

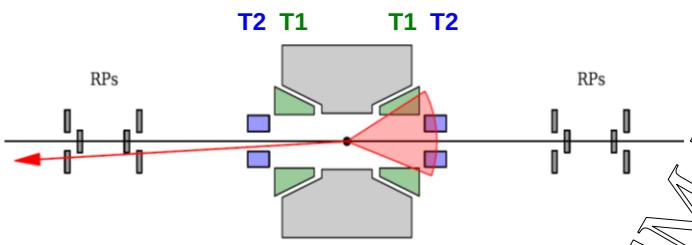
Low mass

M_{diff} = 3.4 - 8 GeV



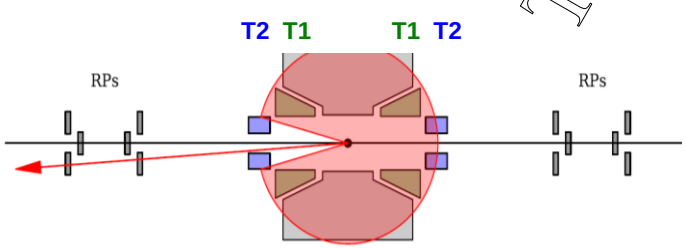
Medium mass

M_{diff} = 8 - 350 GeV

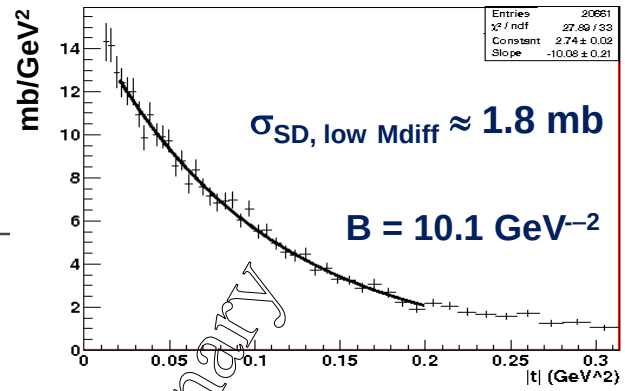


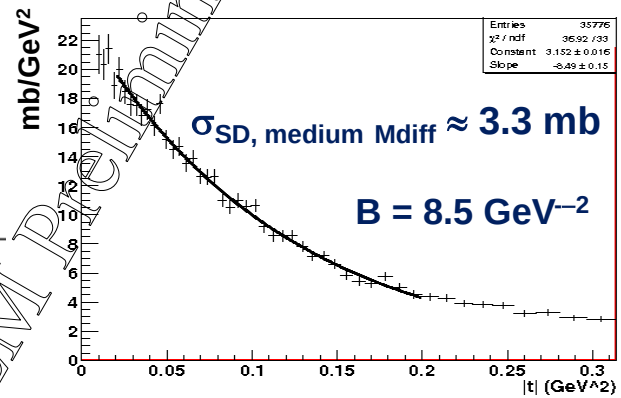
High mass

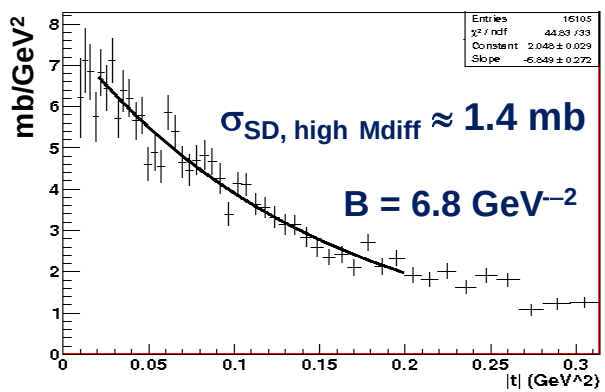
M_{diff} = 0.35 - 1.1 TeV



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







Corrections included:
- Trigger efficiency
- Proton acceptance & reconstruction efficiency
- Background subtraction
- Extrapolation to t = 0

Missing corrections:
- Class migration
- ξ resolution & beam divergence effects

Estimated uncertainties:

B ~ 15% ; σ ~ 20%

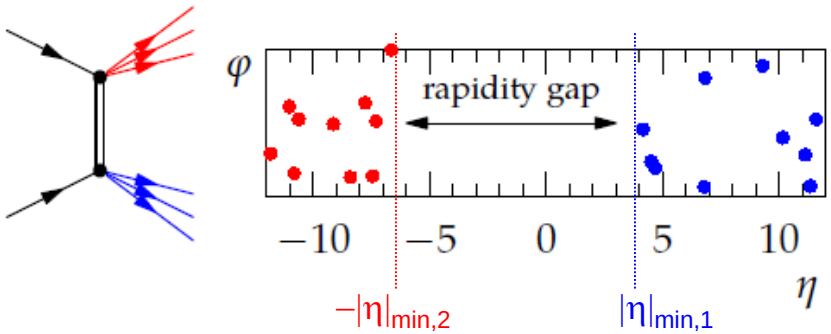
TOTEM preliminary:

σ_{SD} = 6.5 ± 1.3 mb

3.4 GeV < M_{diff} < 1.1 TeV

Analysis of very high mass SD events ongoing

Soft Double Diffraction @ 7 TeV



- Both protons break up

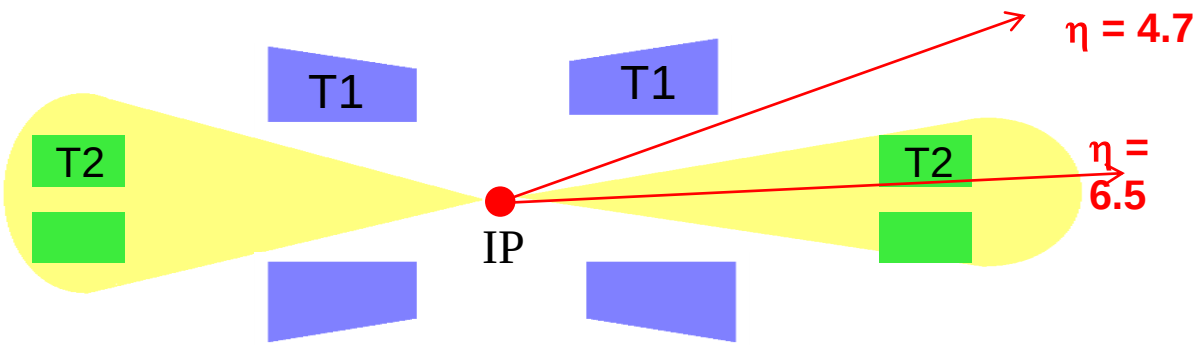
⇒ 2 diffractive masses M_{diff1}, M_{diff2}

- Central rapidity gap

For large masses (→ small central gap) not easy to separate from ND events

Select: sub-range with particles **in both T2** hemispheres, **veto on both T1** ("0T1+2T2")

$4.7 < |\eta|_{min,1/2} < 6.5$ or $3.4\ GeV < M_{diff1/2} < 8\ GeV$



Event selection with high DD purity (~ 70 %)

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 116 \pm 25\ \mu b$$

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

SD & DD results combined seems to indicate factorisation breaking since

$$\sigma_{DD}\ (4.7 \le |\eta_{min}| \le 6.5) >> \sigma_{SD}\ (-4.7 \ge \eta_{min} \ge -6.5) \times \sigma_{SD}\ (4.7 \le \eta_{min} \le 6.5)\ /\ \sigma_{elastic}$$

PRL 111 (2013) 262001

Summary and Outlook

- **Extensive programme of σ_{tot}, σ_{el}, σ_{inel} and diffractive scattering measurements @ LHC in Run I**
- **@ $\sqrt{s}$ = 7 TeV collision data taken in special runs with different beam conditions (β^* = 3.5 m, 90 m) allowed measurements of:**
  - **elastic scattering in a wide $|t|$ range ($5 \cdot 10^{-3} < |t| < 3.5$ GeV^2)**
  - **elastic, inelastic and total p-p cross-section (very good agreement among results from different experiments)**
  - **soft single and double diffraction**
- **@ $\sqrt{s}$ = 8 TeV collision data taken in special runs with different beam conditions (β^* = 90 m, 1000 m) and high statistics gave measurements of:**
  - **elastic scattering down to very low $|t|$ ($6 \cdot 10^{-4} < |t| < 0.2$ GeV^2)**
    - **$\rightarrow$ evidence for non-exponential slope**
    - **$\rightarrow$ study of Coulomb-Nuclear interference feasible, more to come soon …**
  - **elastic, inelastic and total p-p cross-section ($\mathcal{L}$-independent only)**
- **Looking forward for new data during LHC Run II, so to perform new measurements at higher $\sqrt{s}$ ....**