Total, Elastic and Inelastic p-p Scattering @ LHC

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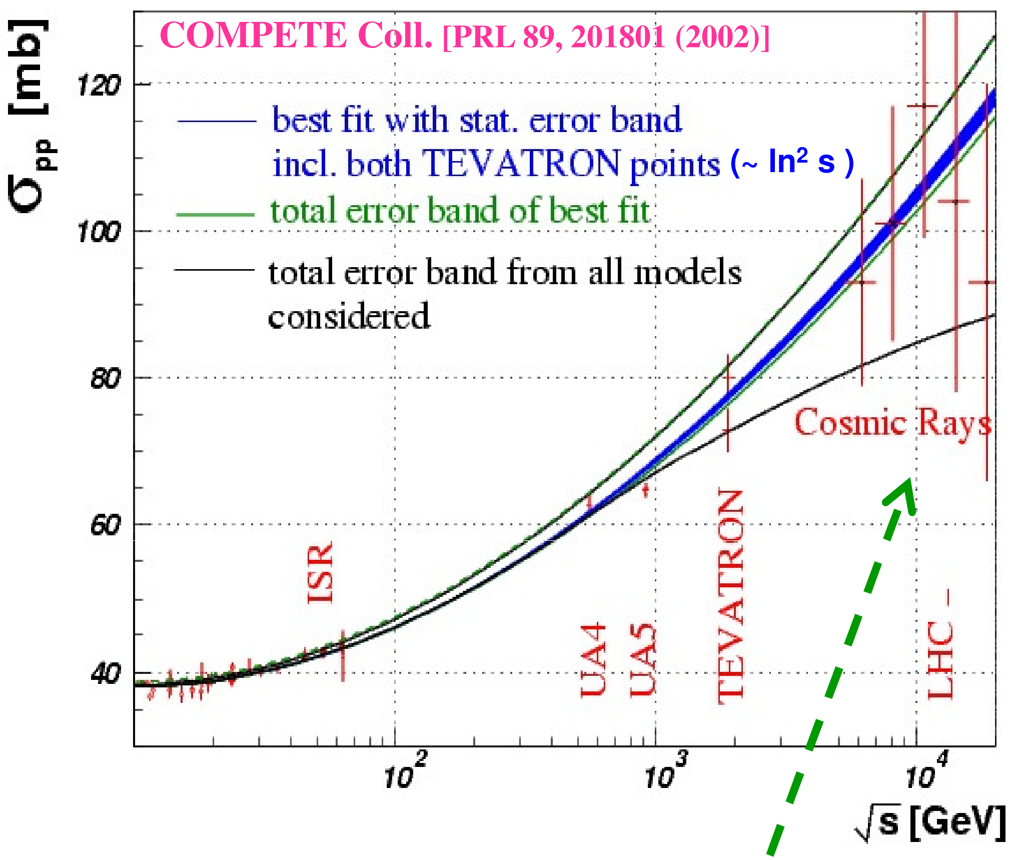
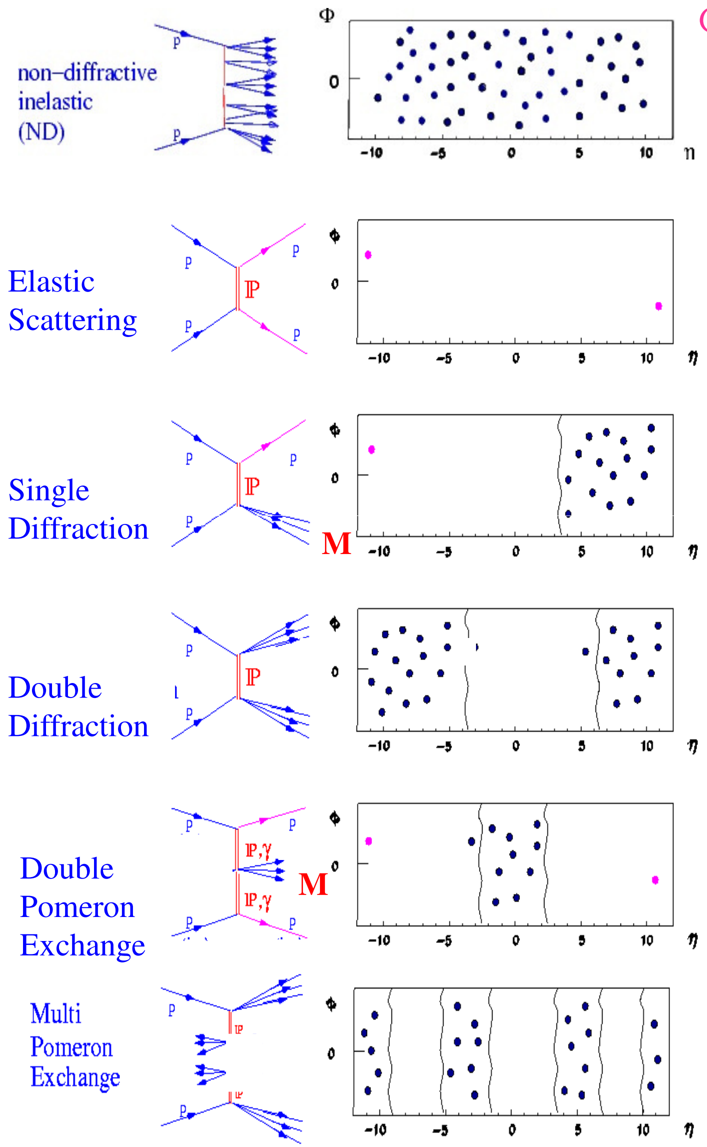
Overview

- **General aspects on p-p scattering measurements**
- **The LHC experiments**
- **Elastic p-p scattering**
- **Inelastic p-p cross-section**
- **Total p-p cross-section**
- **Summary**

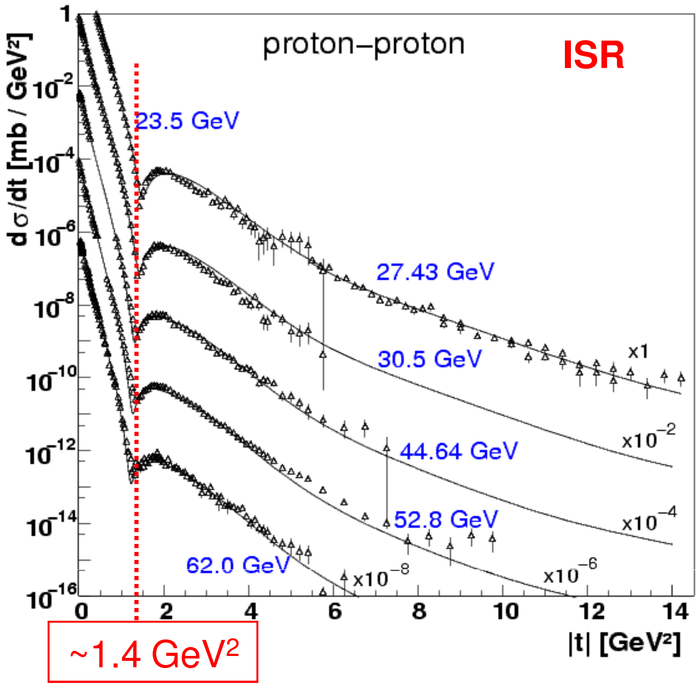
Total Cross Section: from ISR to Tevatron

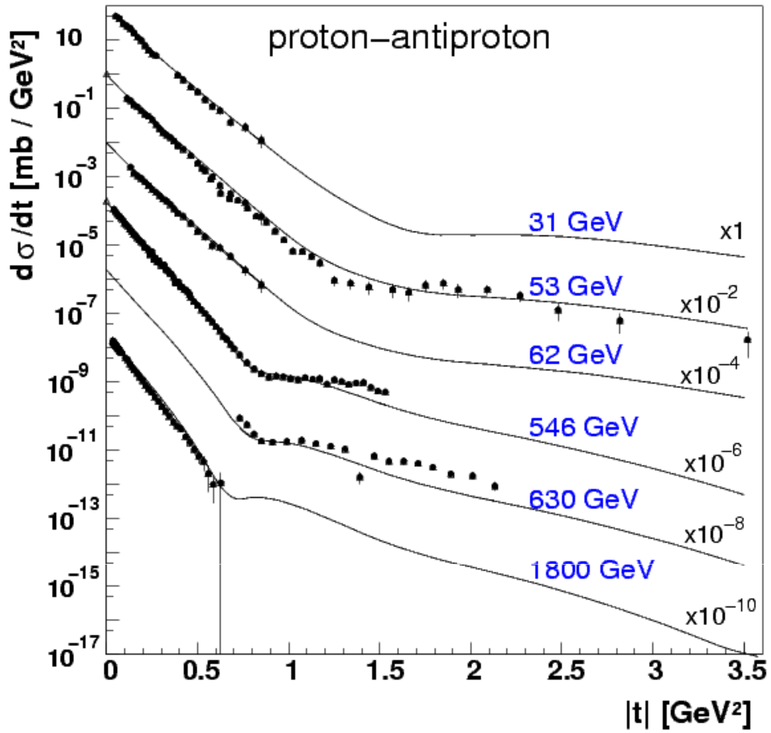


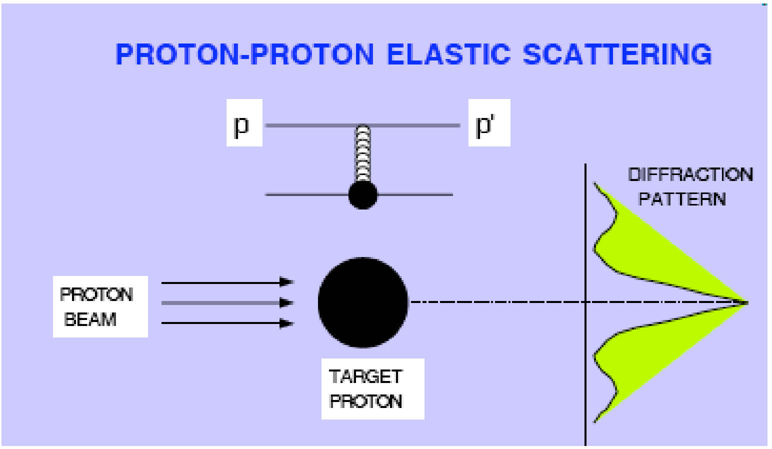


Importance of performing σ_T measurement @ LHC with adequate resolution (abs. error ~ O(1 mb)), allowing to distinguish among different models

Elastic Scattering: from ISR to Tevatron







Diffractive minimum analogous to Fraunhofer diffraction:

- minimum moves to lower |t| with increasing s
  → interaction region grows (as also seen from σ_T)
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, pbarp
  → different mix of processes

Three Methods for σ_T Measurement

Optical Theorem: $$\sigma_T = \frac{8\pi}{p\sqrt{s}} \operatorname{Im} F(s,t)\big|_{t=0}$$

$$\rightarrow \quad \mathcal{L}\sigma_T^2 = \frac{16\pi}{1+\rho^2} \times \frac{dN_{el}}{dt}\bigg|_{t=0} \qquad \left(\rho = \frac{\operatorname{Re} F}{\operatorname{Im} F}\bigg|_{t=0}\right)$$

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

1) Elastic Scattering + Inelastic Scattering + $\mathcal{L}$:

no dependence on ρ

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

2) Elastic Scattering + $\mathcal{L}$ + Optical Th.:

no dependence on N_{inel}

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

3) Elastic Scattering + Inelastic Scattering + Optical Th.:

$\mathcal{L}$-independent

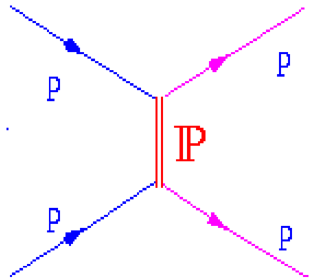
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

→ σ_T

Proper tracking acceptance in very forward region required: elastically scattered p detection <u>mandatory</u>

Elastic Scattering Cross Section $d\sigma_{el}/dt$ @ LHC

Wide range of predictions;
big uncertainties at large |t|.
→ Importance of measuring
whole |t| range with good statistics



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

Angular divergence @ IP:

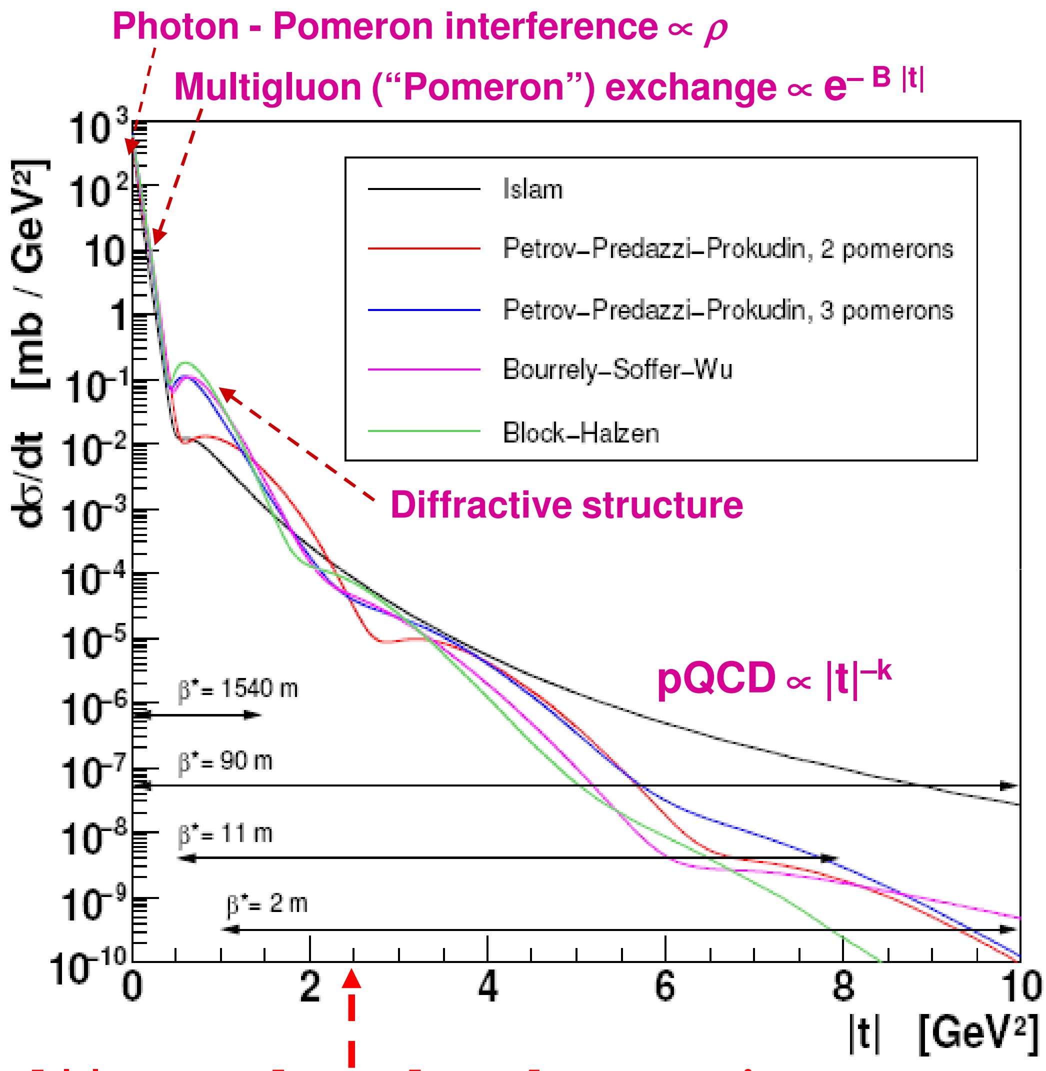
$$\sigma_{\theta^*} = \sqrt{(\varepsilon/\beta^*)}$$

Beam size @ IP:

$$\sigma^* = \sqrt{(\varepsilon\beta^*)}$$

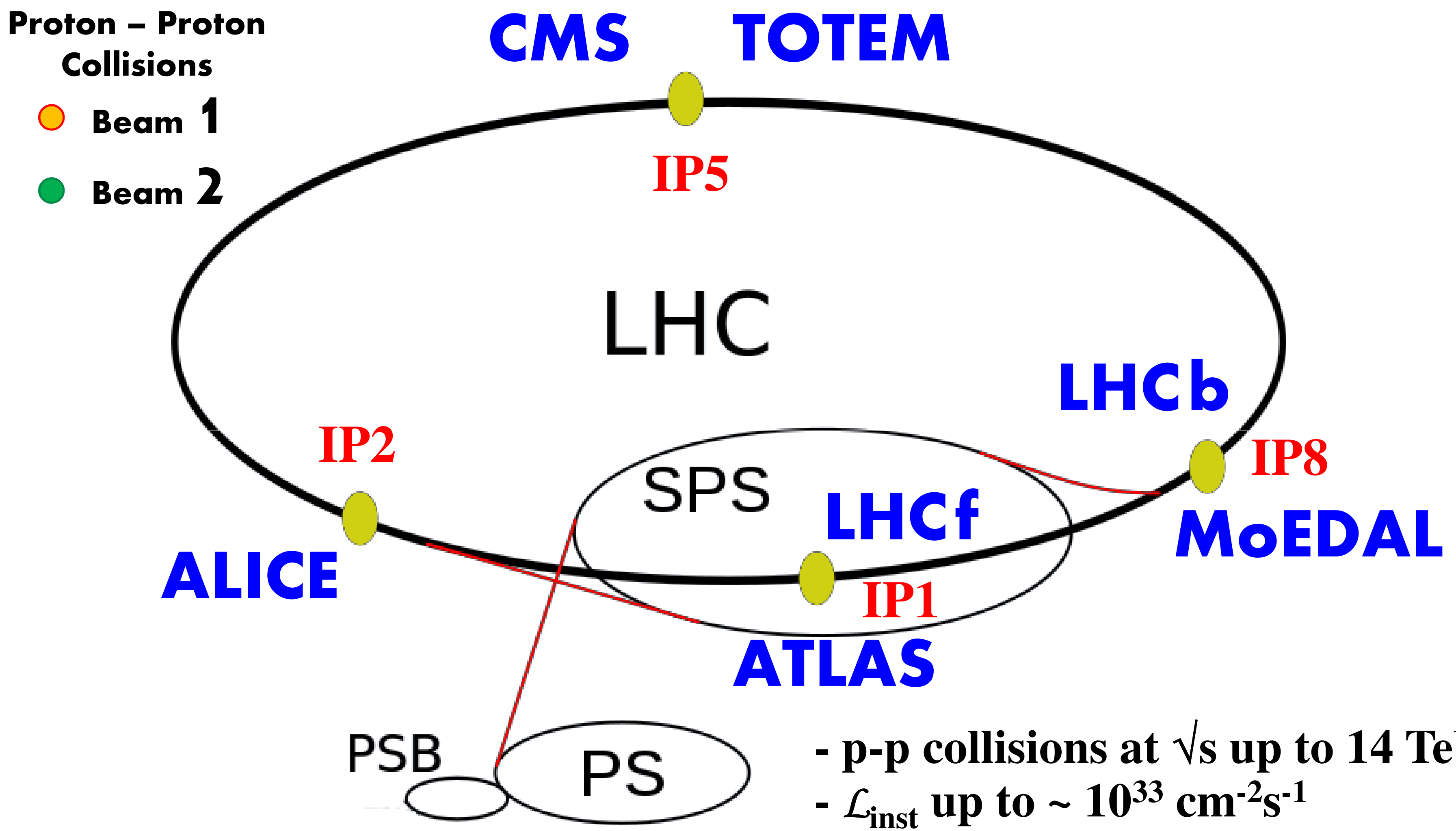
Minimal reachable |t|:

$$|t_{min}| = n_\sigma^2 p^2 \varepsilon/\beta^*$$



Allowed |t| range depends on beam optics
(special high β*– low ℒ runs required for low |t|)
and on proton detector approach to the beam

The LHC Collider and its Experiments



- p-p collisions at $\sqrt{s}$ up to 14 TeV
- $\mathcal{L}_{inst}$ up to ~ 10^{33} $cm^{-2}s^{-1}$
- started in Fall 2009
- 7 experiments

CMS/TOTEM Detector Setup @ IP5 of LHC

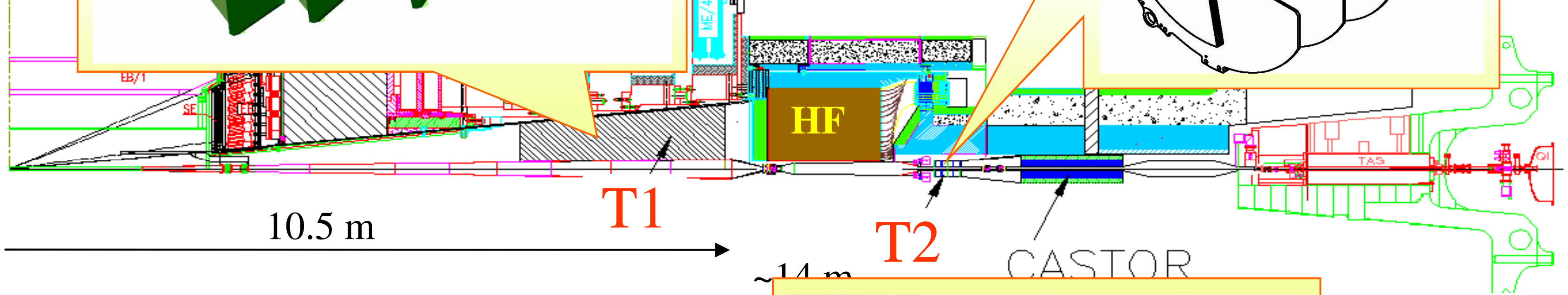
Det[…]

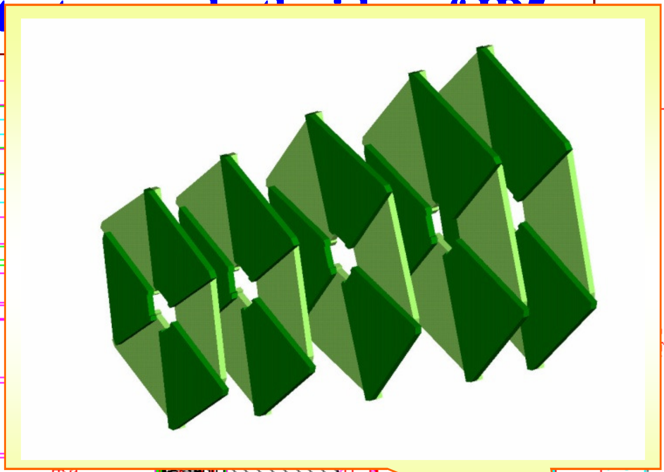
CMS Tracker/Calorimeters

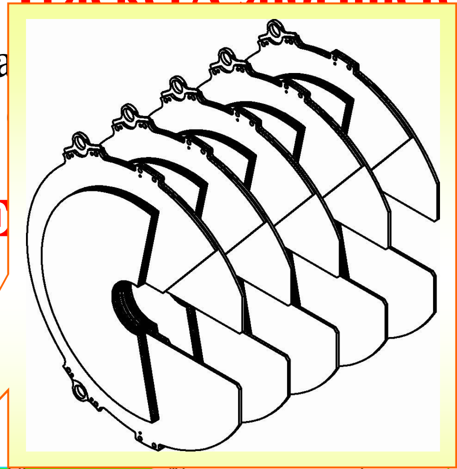
Uniform covera[…] **for Z < 0)**
ZDC: |η| > 8.3 […]

TOTE[…]**pes**

T1: 3.1 < |η| < […]
T2: 5.3 < |η| […]

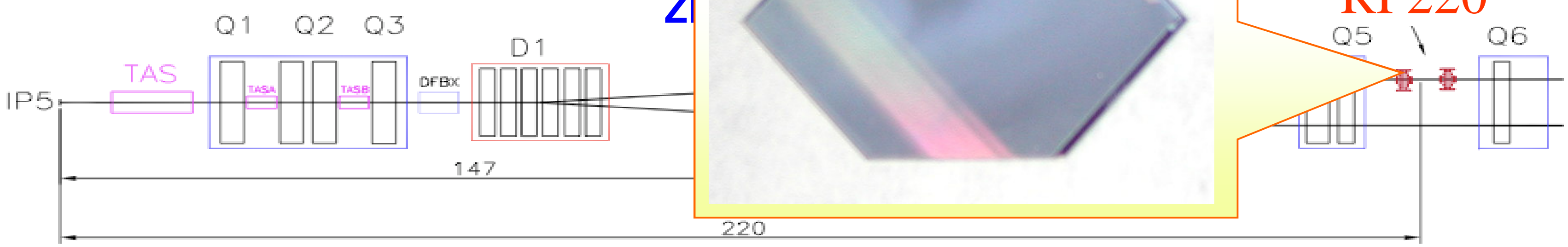




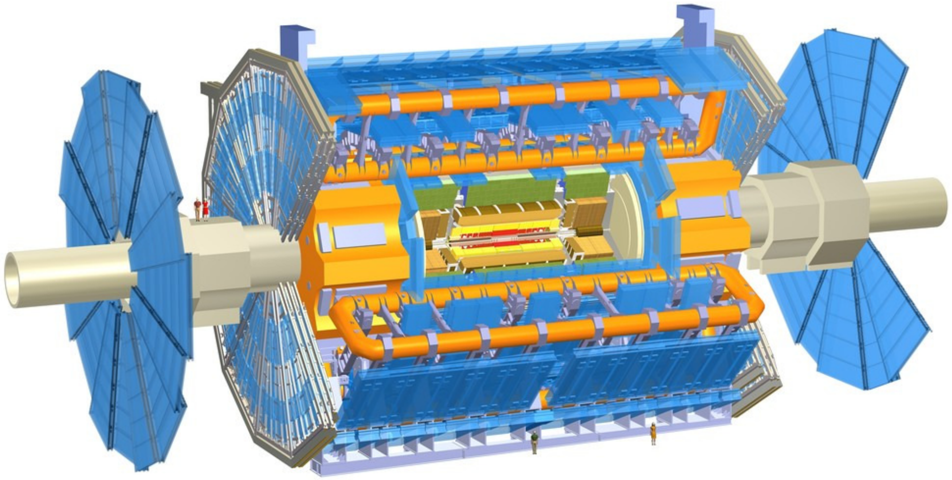


TOTEM Elastic Detectors (RP): r[…] diffractive p

Silicon detectors with active area very close […]rad)



ATLAS Detector Setup @ IP1 of LHC



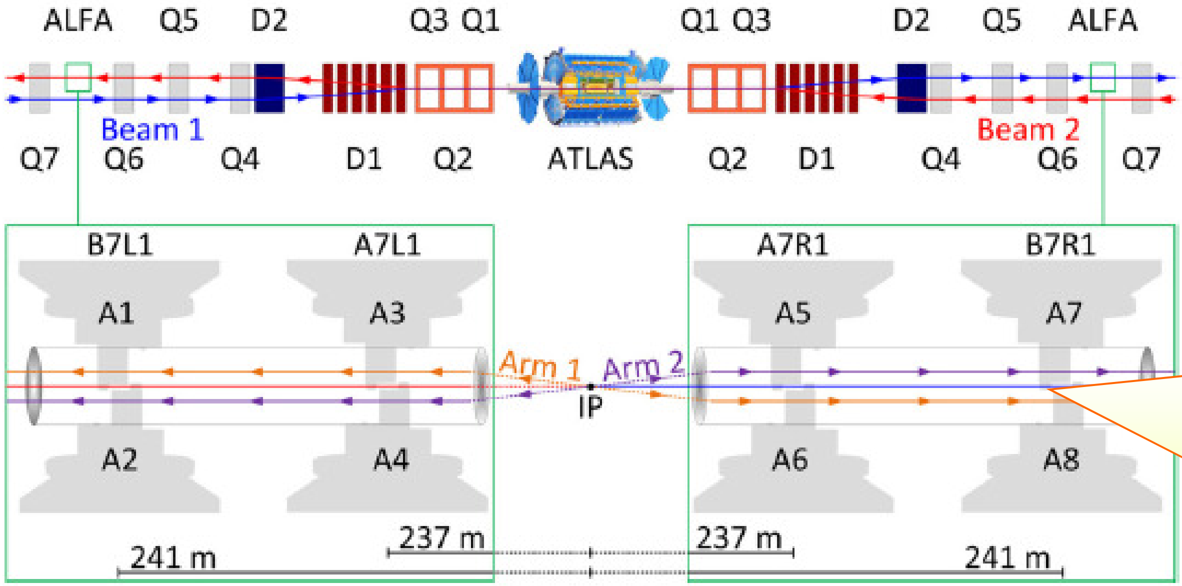
Atlas Tracker/Calorimeters

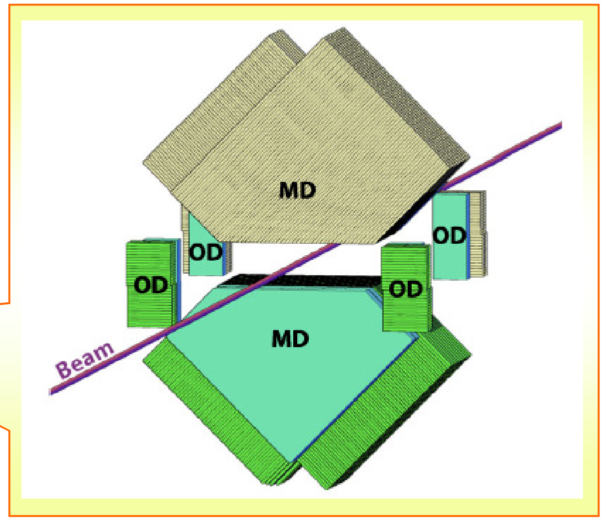
Uniform coverage up to |η| < 4.9

LUCID: **|η| ~ 5.8**

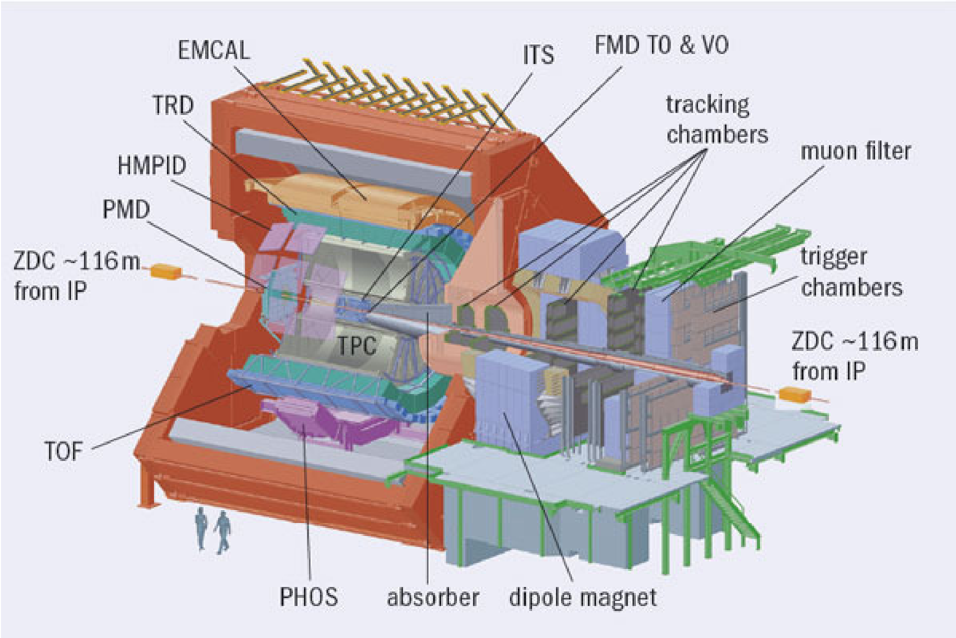
ZDC: |η| > 8.3 (for n)

Elastic Detectors (ALFA RP): Sci-Fiber detectors with active area very close to the beam (θ down to ~ 10 μrad)





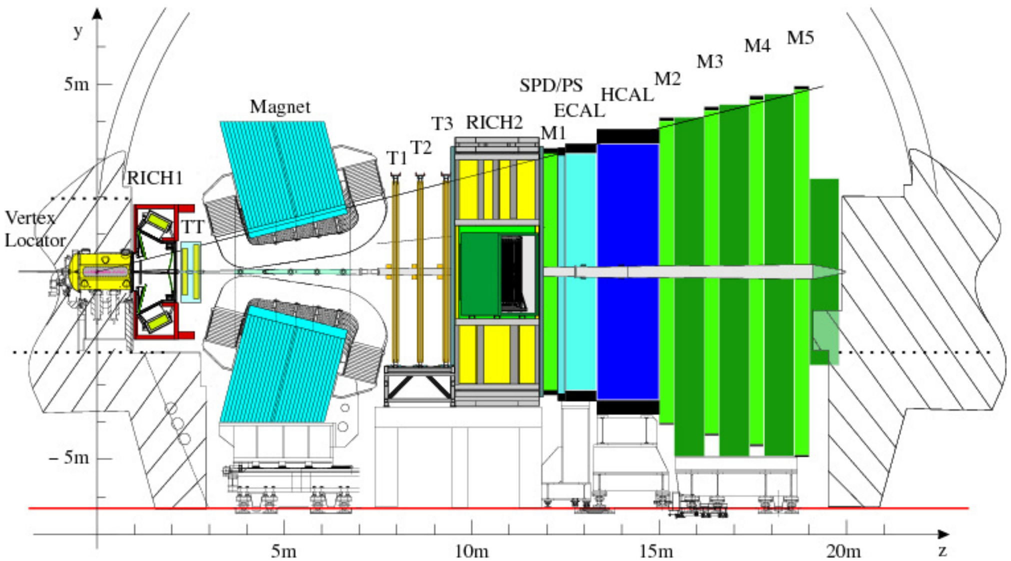
ALICE/LHCb Detector Setup @ IP2/IP8 of LHC



ALICE Tracker/Calorimeters

Uniform coverage for -3.7 < |η| < 5.1

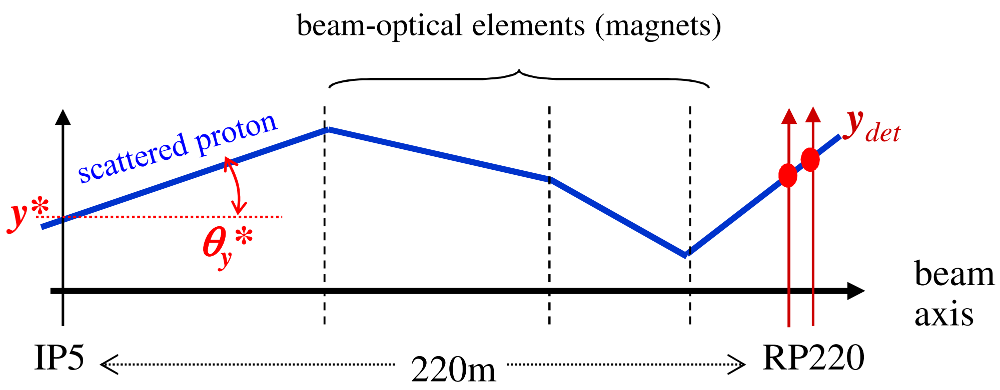
ZDC: $|\eta| > 8.8$ (ZN, for n)
$6.5 < |\eta| < 7.5$ (ZP, for p)
$4.8 < \eta < 5.7$ (ZEM, for e/γ)



LHCb Tracker/Calorimeters

Uniform coverage for 2 < |η| < 5

Proton Transport from IP5 to RP Location



$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \\ \Delta p/p \end{pmatrix}_{IP5}$$

Measured in RP — Proton transport matrix — Reconstructed

Optical functions:

L (effective length), **v** (magnification), **D** (machine dispersion)

- Describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP
- Define t and ξ-range (acceptance)
- Depend on LHC machine optics configuration

With: $\xi = \Delta p/p$; $t = t_x + t_y$; $t_i \sim -(p\theta_i^*)^2$

(x, y): vertex position at RP location (s)

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

(θ_x^*, θ_y^*): emission angle at IP

→ **Elastic proton kinematics reconstruction (θ_x^*, θ_y^*)**

(for β^* = 90 m @ RP220m:

L_y = 263 m, $v_y \approx 0$, $L_x \approx 0$, v_x = -1.9):

$$\begin{cases} \Theta_x^* \approx \left(\Theta_x - \dfrac{dv_x}{ds} x^* \right) / \dfrac{dL_x}{ds}, \\ \Theta_y^* \approx y / L_y \end{cases} \qquad \frac{\Delta p}{p} = 0$$

(θ_x measured with ~ 5m lever arm spectrometer)

Excellent optics determination (~ 0.25% using constraints from proton tracks in RPs, TOTEM: *New J. Phys. 16 (2014) 103041*) and detector alignment required.

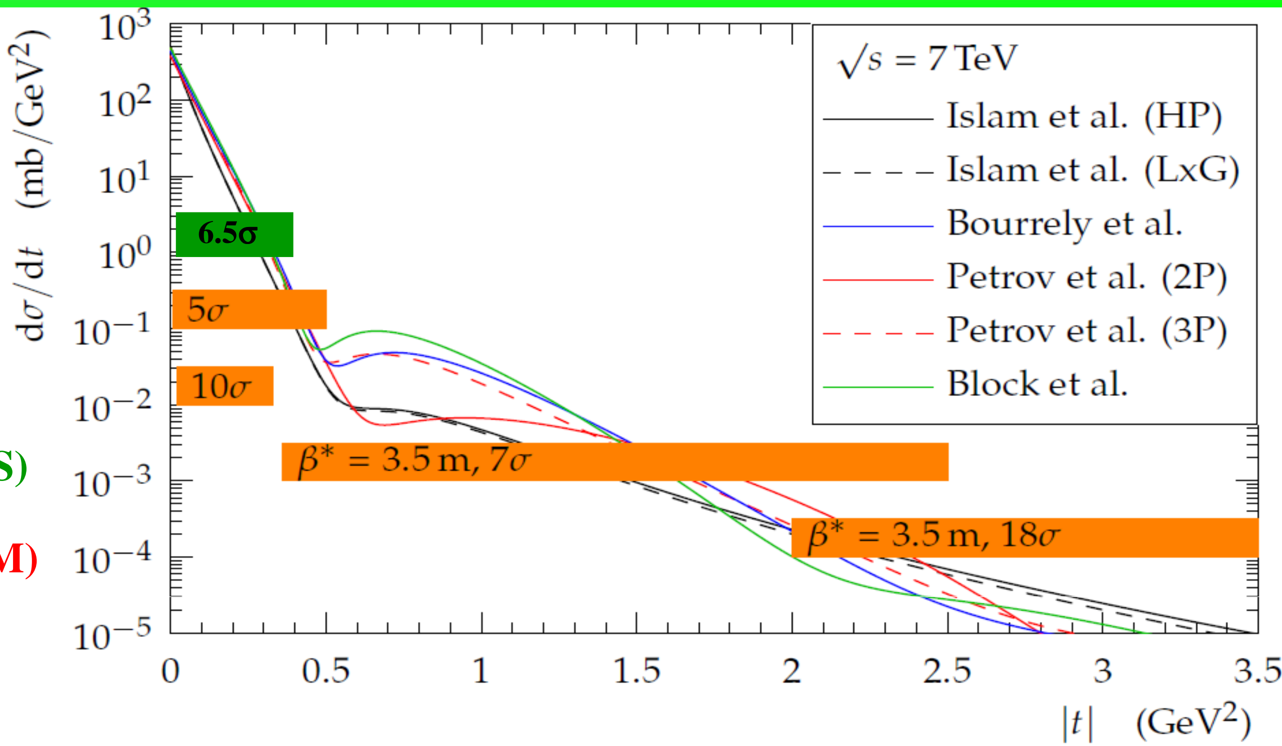
Similar procedure in ATLAS (from IP1 to ALFA RP location)

Elastic Scattering Cross Section Measurements @ 7 TeV

Data taking in various LHC configurations and different RP detector approach to the beam allowed the measurement in a wide range of |t|:

$1.0\cdot10^{-2}$ - 0.38 GeV^2 (ATLAS)

$5\cdot10^{-3}$ - 3.5 GeV^2 (TOTEM)

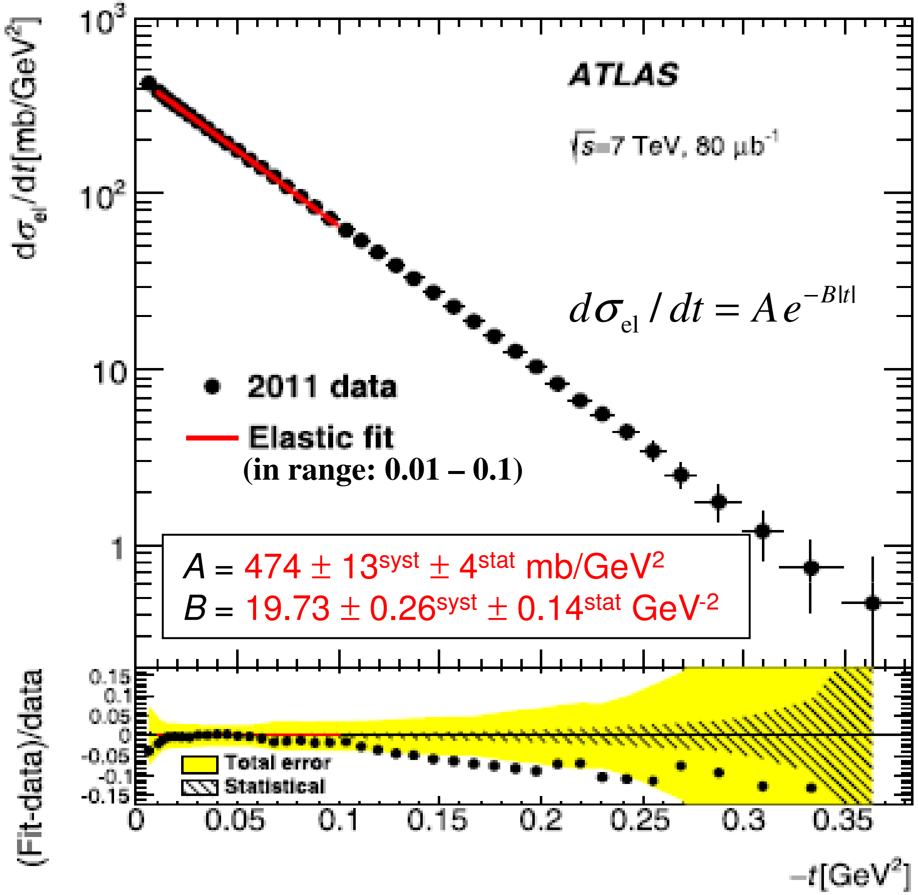


Experiment	β*(m)	RP approach (beam σ)	$\mathcal{L}_{int}$ (μb^{-1})	|t|- range (GeV^2)	Elastic events	Reference
ATLAS	90	6.5	80	0.01– 0.38	805K	Nucl. Phys. B 889 (2014), 486
TOTEM	90	4.8 – 6.5	83	$5\cdot10^{-3}$ – 0.4	1M	EPL 101 (2013), 21002
"	90	10	1.7	0.02 – 0.33	15K	EPL 96 (2011), 21002
"	3.5	7	$6.1\cdot10^3$	0.36 – 2.5	66K	EPL 95 (2011), 41001
"	3.5	18	$2.3\cdot10^6$	2 – 3.5	10K	Ongoing

$d\sigma_{el}/d|t|$ Measurement @ 7 TeV (I): ATLAS

(Common) Analysis steps:

- Alignment procedures/corrections
- LHC optics calibration
- Elastic candidate event selection
- Background subtraction
- Acceptance correction
- Unfolding of resolution effects
- Normalization (recon. efficiencies)
- Luminosity determination



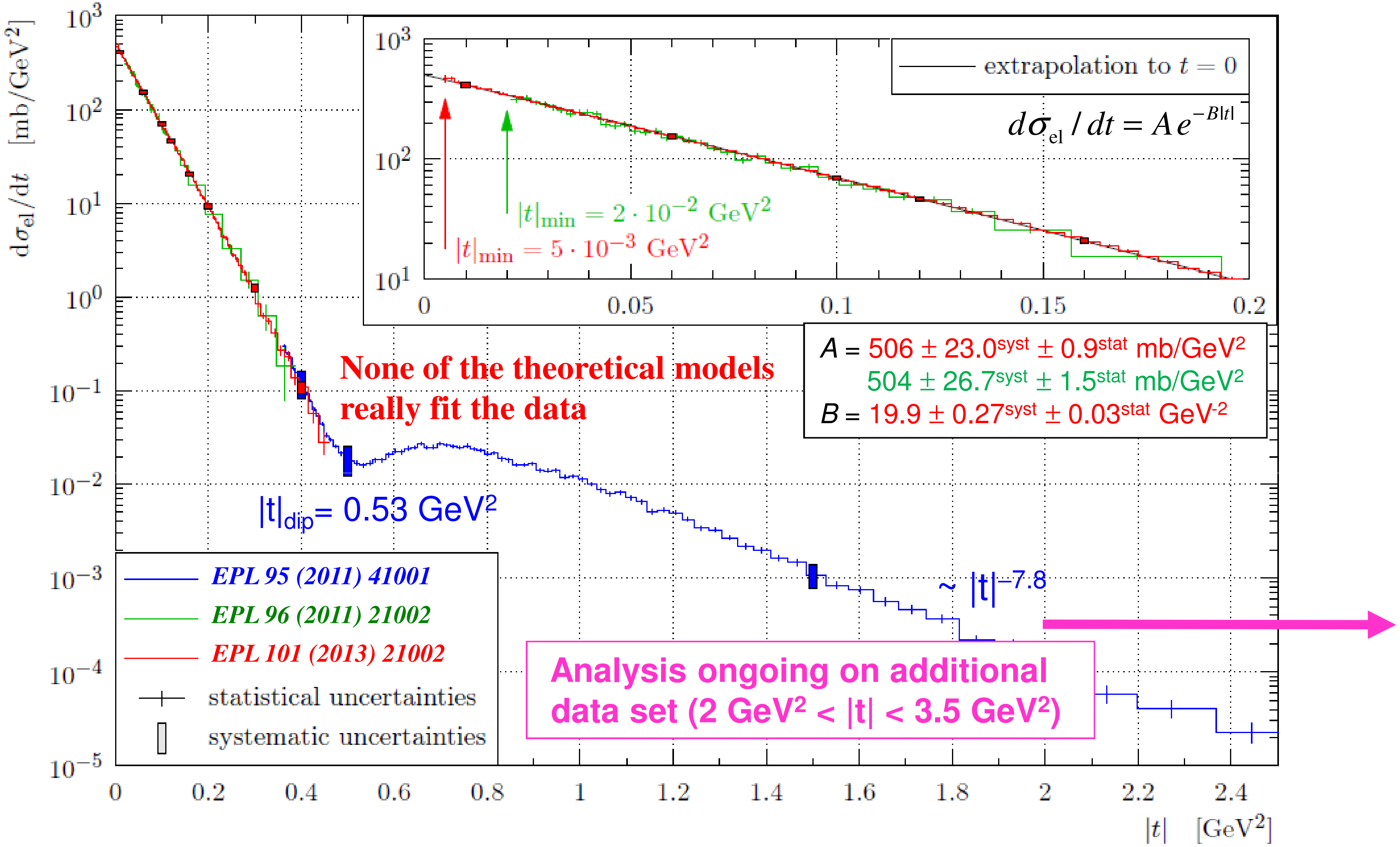
Systematic uncertainties:

dominated by $\mathcal{L}$ and by analysis t-dependent effects
(energy offset, acceptance correction, misalignments, optics imperfections and un-smearing correction)

Integrated elastic cross-section: $\sigma_{el} = \sigma_{el,\,Meas.} + \sigma_{el,\,Extr.}$

ATLAS result: $\sigma_{el} = 24.00 \pm 0.57^{syst} \pm 0.19^{stat}$ mb (90% directly measured)
($\mathcal{L}$ with 2.3% uncertainty)

$d\sigma_{el}/d|t|$ Measurement @ 7 TeV (II): TOTEM



TOTEM results:
($\mathcal{L}$ from CMS, with 4% unc.)

$\sigma_{el} = 25.4 \pm 1.0^{lumi} \pm 0.3^{syst} \pm 0.03^{stat}$ mb (91% directly measured)

$\sigma_{el} = 24.8 \pm 1.0^{lumi} \pm 0.7^{syst} \pm 0.2^{stat}$ mb (67% directly measured)

Inelastic Cross Section Measurement @ 7 TeV

All experiments performed <u>direct</u> measurement: $\sigma_{inel} = N_{inel} / \mathcal{L}$

General analysis steps for the measurement

- **Corrections to the "visible" σ_{inel} in the given kinematic acceptance region**

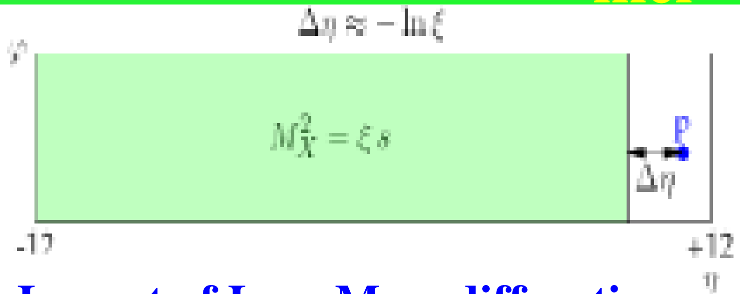
  trigger and event reconstruction efficiency, background rejection and pile-up (experimental uncertainty dominated by uncertainty on $\mathcal{L}$)

- **Corrections for "missing" σ_{inel}**

  events lost due to (eventually) limited acceptance in *central* region, events lost due limited acceptance in *forward* region, related to <u>low mass diffraction</u> → leading contribution (and uncertainty)

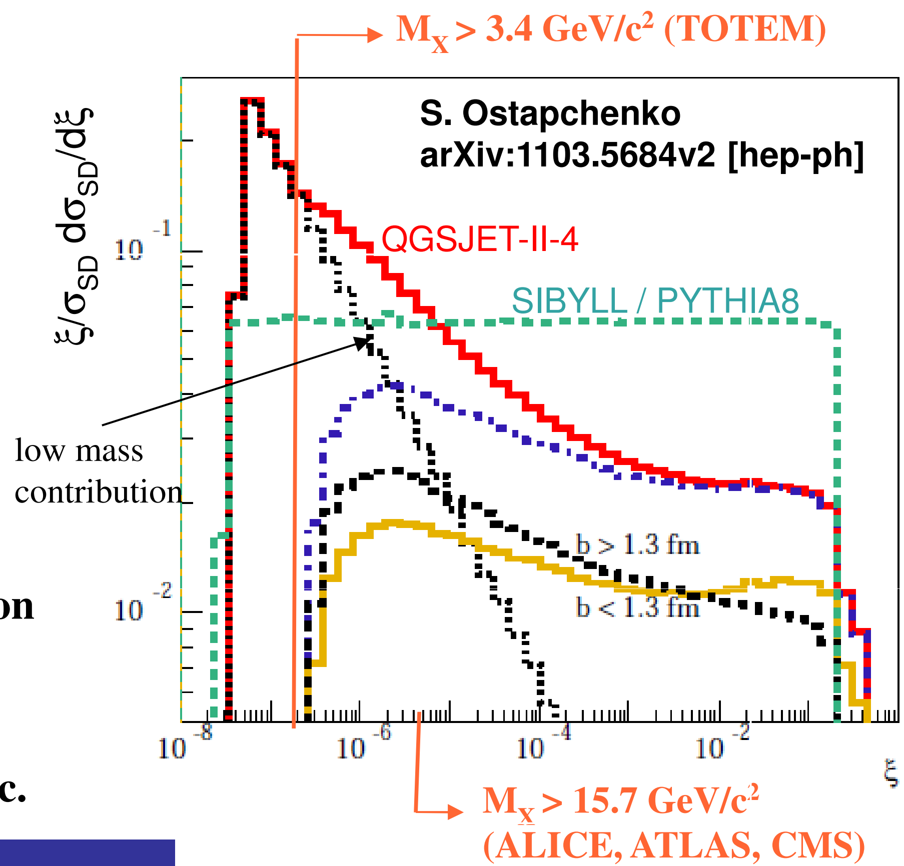
Experiment	Acceptance η range	"Visible" ξ range	M_X range (GeV/c^2)	Reference
ALICE	$-3.7 < \eta < 5.1$	$\xi > 5\cdot10^{-6}$	$M_X > 15.7$	EPJ C73 (2013), 2456
ATLAS	$2.09 < \lvert\eta\rvert < 3.84$	$\xi > 5\cdot10^{-6}$	$M_X > 15.7$	Nat. Commun. 2 (2011), 463
CMS	$3 < \lvert\eta\rvert < 5$	$\xi > 5\cdot10^{-6}$	$M_X > 15.7$	Phys. Lett. B 722 (2013), 5
LHCb	$2 < \eta < 4.5$	$\xi > \sim 1.5\cdot10^{-6}$ *(n)*	$M_X > \sim 8.6$ *(n)*	arXiv: 1412.2500 (2014)
TOTEM	$3.1 < \lvert\eta\rvert < 6.5$	$\xi > 2.4\cdot10^{-7}$	$M_X > 3.4$	EPL 101 (2013), 21003

Direct σ_{inel} Measurement @ 7 TeV

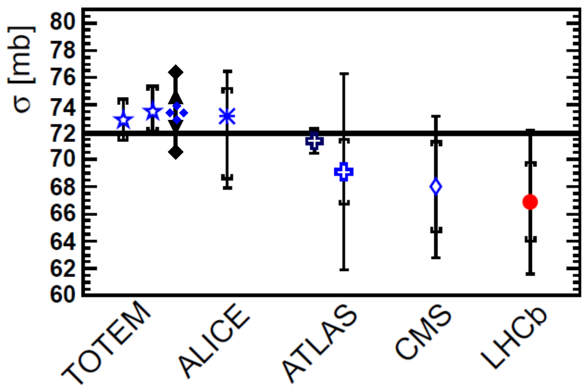


Impact of Low-Mass diffraction:

- 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.



Experiment	σ_{inel} (mb)
ALICE	$73.2^{+2.0}_{-4.6}$ (model) ± 2.6 (exp)
ATLAS	69.1 ± 6.9 (model) ± 2.4 (exp)
CMS	68.0 ± 4.0 (model) ± 3.1 (exp)
LHCb	66.9 ± 4.4 (model) ± 2.9 (exp)
TOTEM	73.7 ± 1.5 (model) ± 2.9 (exp)



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)
→ no assumption on low mass diffraction

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

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

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*)

$\sigma_T = \sigma_{el} + \sigma_{inel}$

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

2) Elastic Scatt. + $\mathcal{L}$ + Optical Th.

(*no assumption on low mass diffr.*)

$\sigma_{inel} = \sigma_T - \sigma_{el}$

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

3) Elastic Scatt. + Inel. Scatt. + Optical Th.

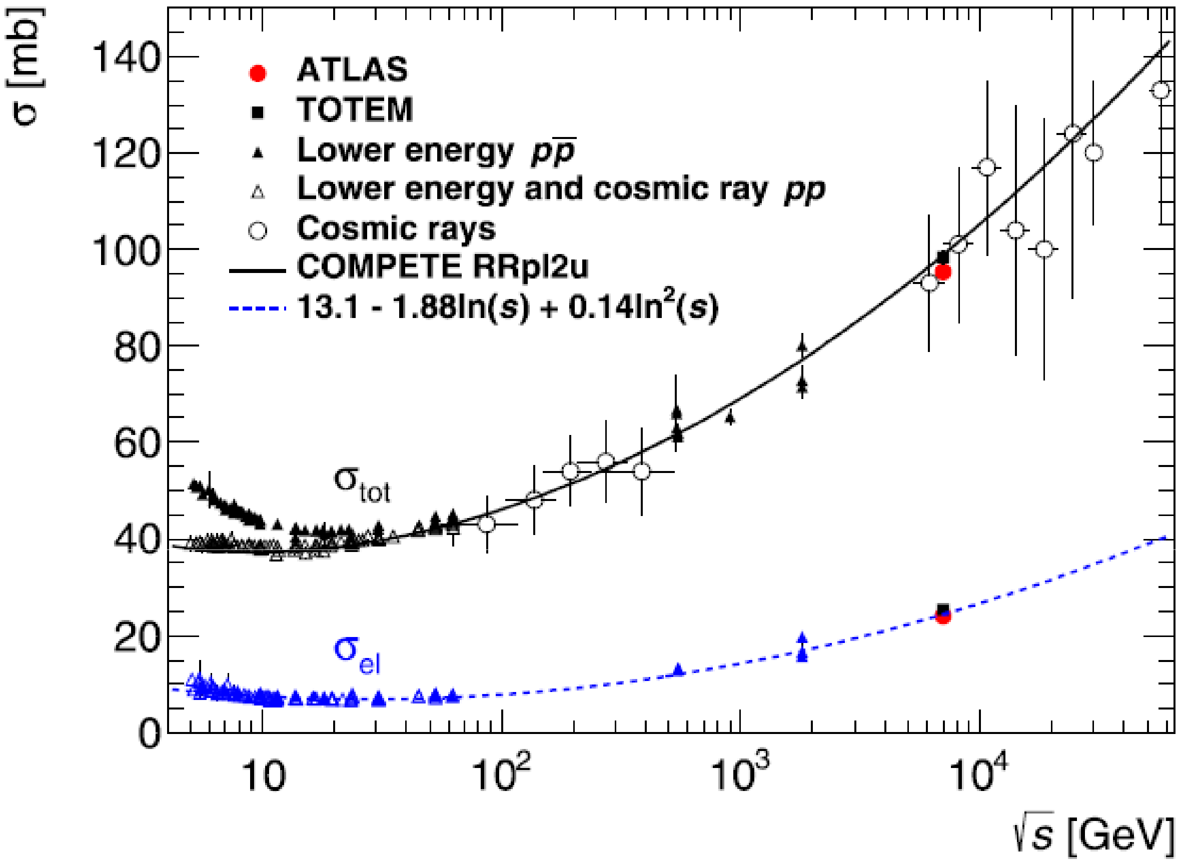
(*no dependence on $\mathcal{L}$*)

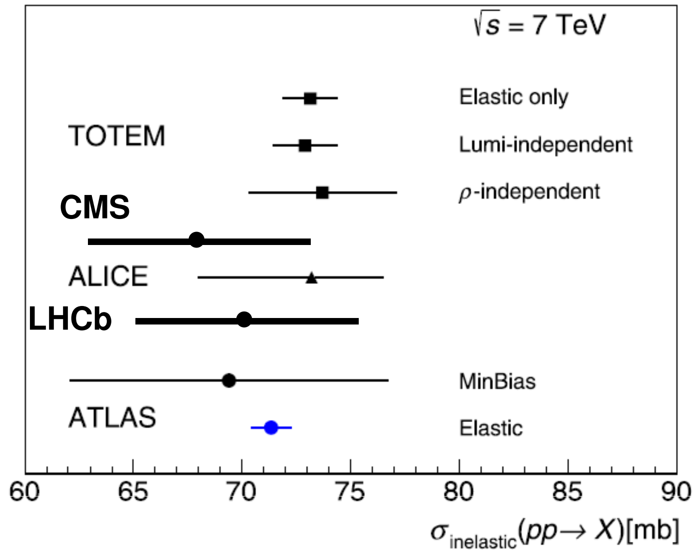
σ_{el} and σ_{inel} : from σ_T and N_{el}/N_{inel}

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

Experiment	Method	σ_T (mb)	σ_{inel} (mb)	σ_{el} (mb)	Reference
ATLAS	2	95.35 ± 1.36	71.3 ± 0.9	24.0 ± 0.6	Nucl. Phys. B 889 (2014), 486
TOTEM	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

σ_T , σ_{el} and σ_{inel} Measurement @ 7 TeV: Summary





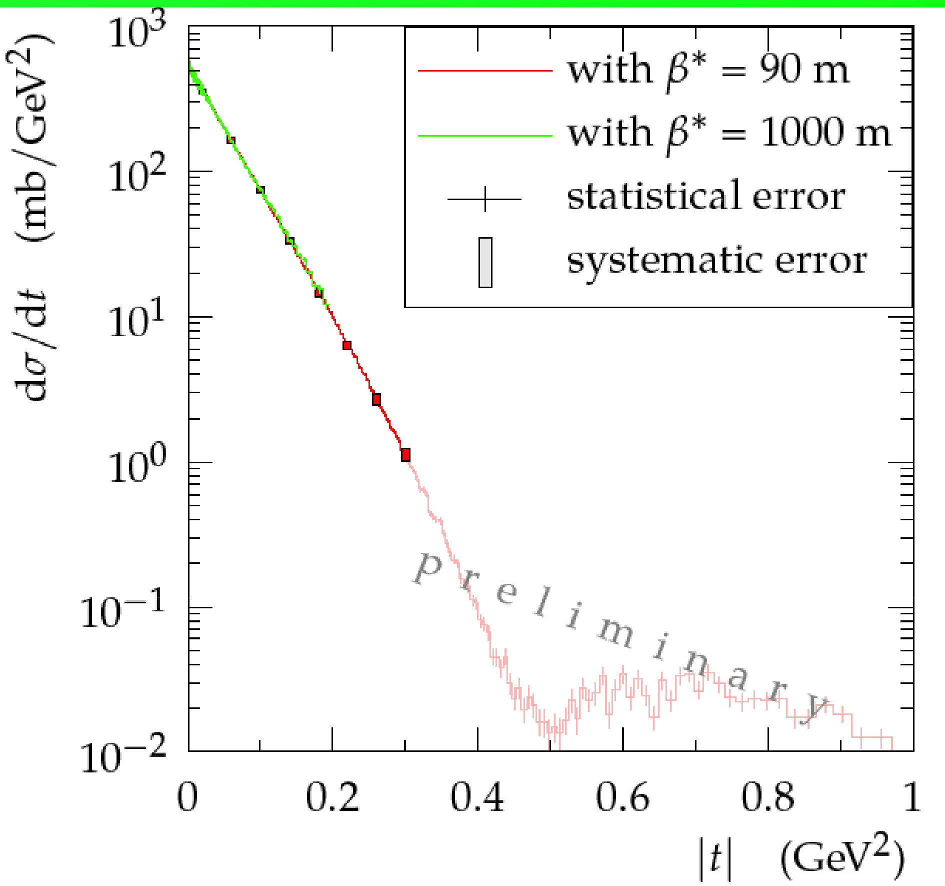
Very good agreement:

- **among TOTEM measurement with different methods (understanding of systematic uncertainties and corrections)**
- **among LHC experiments**

$d\sigma_{el}/d|t|$ Measurement @ 8 TeV: TOTEM

β* = 90 m data

Follow the same analysis steps as @ 7 TeV (optical functions basically the same):
N_{el}, $(dN_{el}/dt)|_{t=0}$ measurement
→ σ_T, σ_{el} and σ_{inel} with $\mathcal{L}$-indep. method



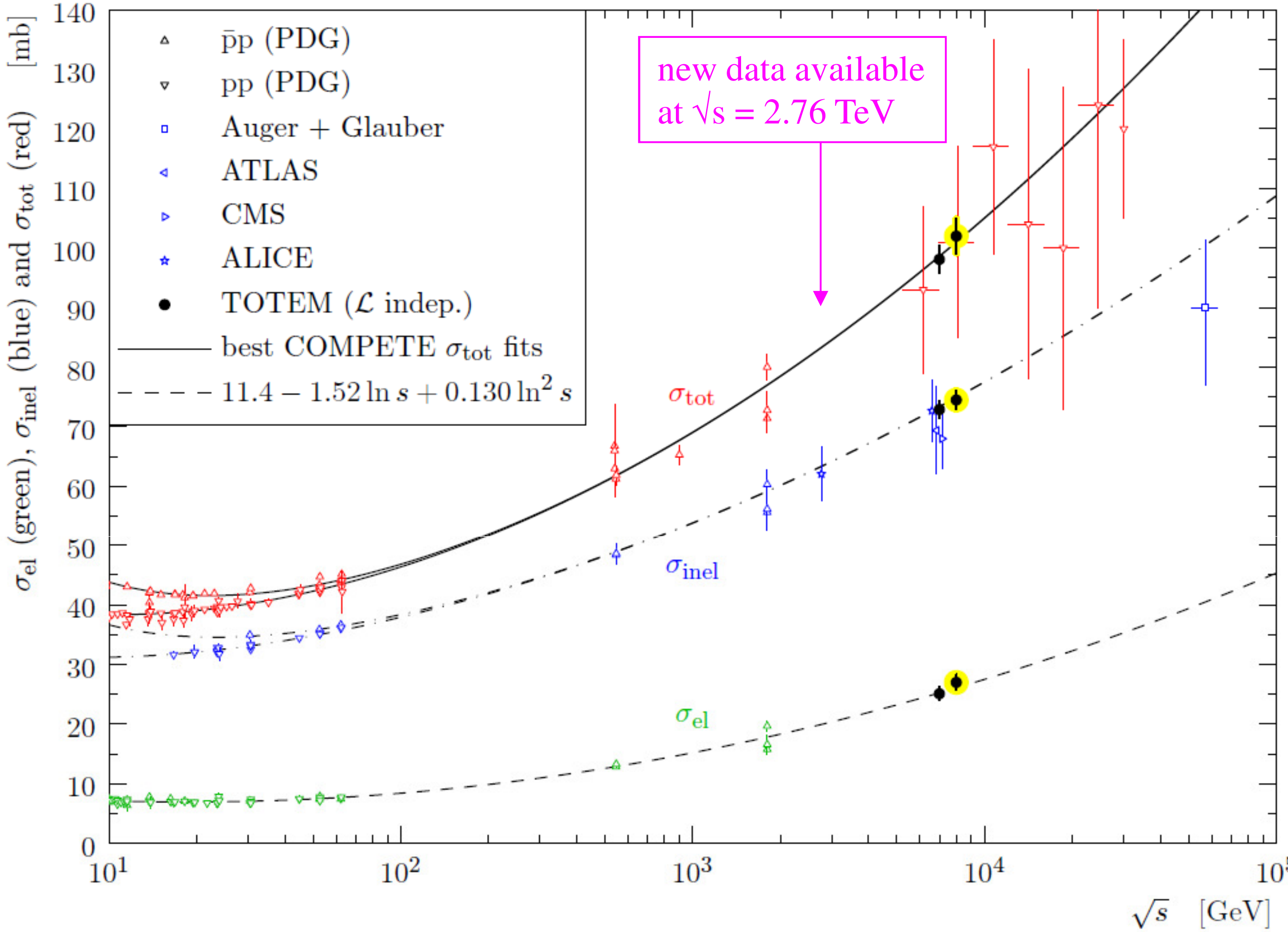
β* = 1000 m data

Preliminary studies towards
ρ measurement

β*(m)	RP approach (beam σ)	$\mathcal{L}_{int}$ (μb⁻¹)	|t|- range (GeV²)	Elastic events	Reference
90	6 – 9.5	60	0.01 – 0.1	0.6M	PRL 111 (2013), 012001
90	9.5	735	0.027 – 0.2	7.2M	arXiv:1503.08111 (2015)
1000	3	20	$6\cdot10^{-4}$ – 0.2	0.4M	Analysis Ongoing

← **Possibility of ρ measurement**

σ_T Measurement @ 8 TeV: TOTEM



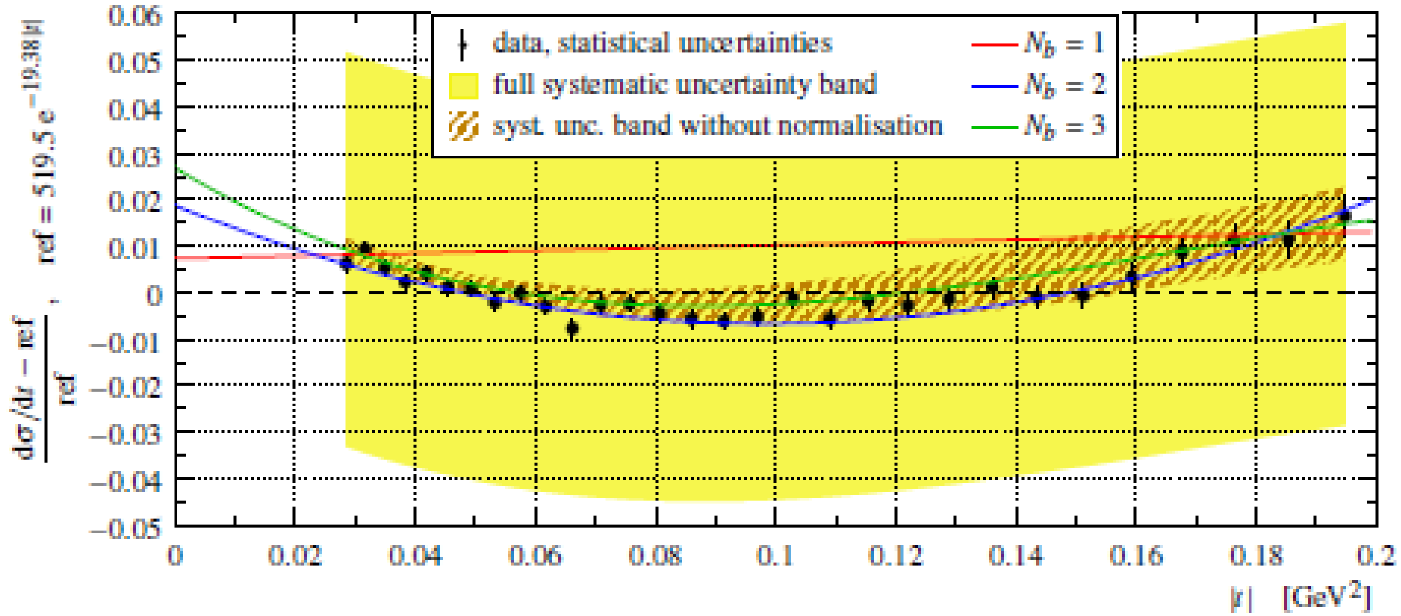
σ_T from
$\mathcal{L}$–independent
Method

σ_{el} and σ_{inel} from
$\mathcal{L}$ - and ρ-indepen.
$\sigma_{el} / \sigma_{inel}$ ratio
($\sigma_{el} / \sigma_{inel} = N_{el} / N_{inel}$)

quantity		value	systematic uncertainty				
			el. t-dep	el. norm	inel	ρ	⇒ full
σ_{tot}	[mb]	101.7	±1.8	±1.4	±1.9	±0.2	⇒ ±2.9
σ_{inel}	[mb]	74.1	±1.2	±0.6	±0.9	±0.1	⇒ ±1.7
σ_{el}	[mb]	27.1	±0.5	±0.7	±1.0	±0.1	⇒ ±1.4

PRL 111 (2013) 012001

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



TOTEM

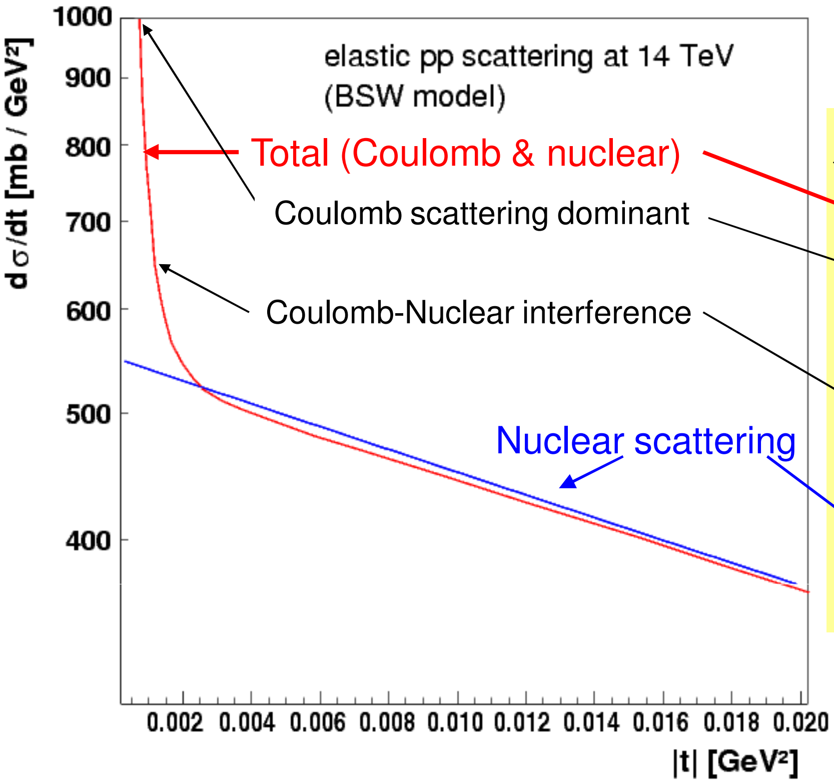
arXiv:1503.08111 (2013)
(sub. to Nucl. Phys. B)

$N_b = 1$: $B = b_1$ (Reference)
$N_b = 2$: $B = b_1 + b_2 t$
$N_b = 3$: $B = b_1 + b_2 t + b_3 t^2$

- **High statistic data sample allowed a precise $d\sigma_{el}/d|t|$ measurement** (for $0.027 < |t| < 0.2$ GeV²)
- **"Purely" exponential slope excluded with a significance > 7σ ($\rightarrow d\sigma_{el}/d|t| = Ae^{-B(t)|t|}$)**
- **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_T are found in agreement with previous measurement:**

$N_b = 1$ (previous, purely exponential) → $\sigma_T = 101.7 \pm 2.9$ mb (with $\mathcal{L}$-indep. method)
$N_b = 2$ (quadratic polynomial) → $\sigma_T = 100.8 \pm 2.1$ mb
$N_b = 3$ (cubic polynomial) → $\sigma_T = 101.2 \pm 2.1$ mb

Elastic Scattering at Low |t|: ρ Measurement



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* = $(1 + |t| / 0.71)^{-2}$

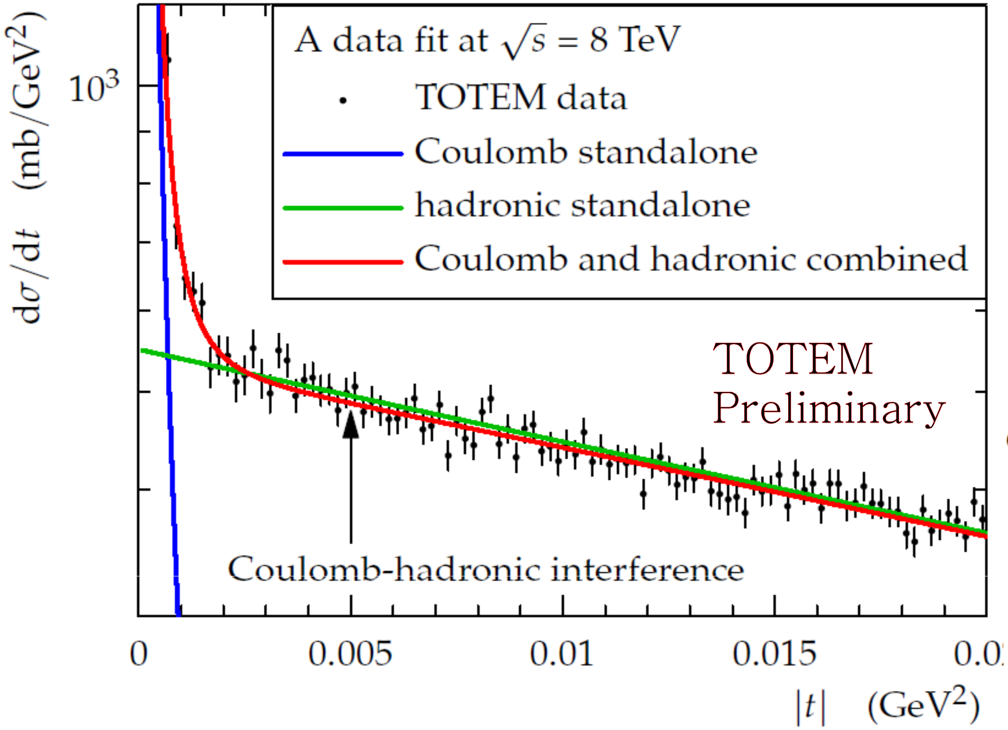
ρ = $\Re / \Im\ [T_{elastic,nuclear}(t = 0)]$

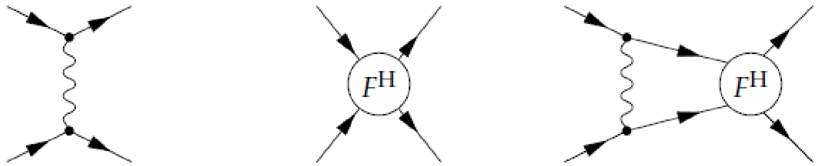
Measurement of ρ by studying the Coulomb – Nuclear interference region down to

$|t| \sim 6\cdot 10^{-4}$ GeV²

Reached @ $\sqrt{s}$ = 8 TeV, with β* = 1000 m and RP approaching the beam centre @ ~ 3σ

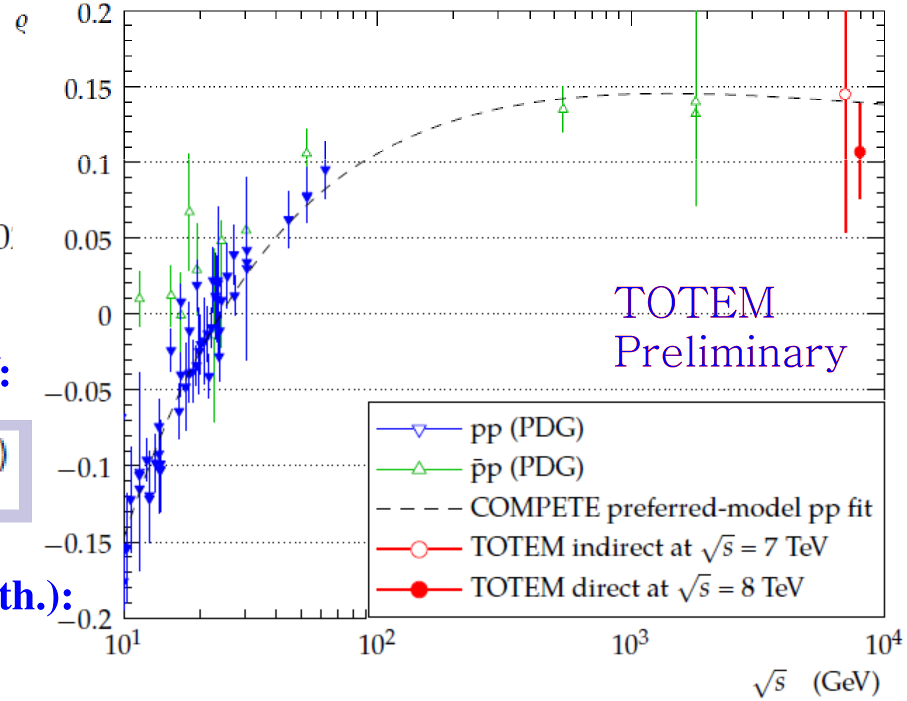
Elastic Scattering in the Coulomb-Nuclear Interference Region





$d\sigma/dt \propto |F^{C+H}|^2$ = Coul. + Had. + Interf.

Constrained by measured $e^{-B(t)|t|}$ ρ



Preliminary results on direct ρ measurement @ 8 TeV:

$$\rho = 0.107 \pm 0.027^{(stat)} \pm 0.010^{(syst)} {}^{+0.009}_{-0.009} (model)$$

Indirect crude ρ measurement @ 7 TeV (from optical th.):

$$\rho^2 = 16\pi \mathcal{L}_{int} \frac{\left.\frac{dN_{el}}{dt}\right|_{t=0}}{(N_{el}+N_{inel})^2} - 1 = 0.009 \pm 0.056 \rightarrow |\rho| = \mathbf{0.145 \pm 0.091}$$

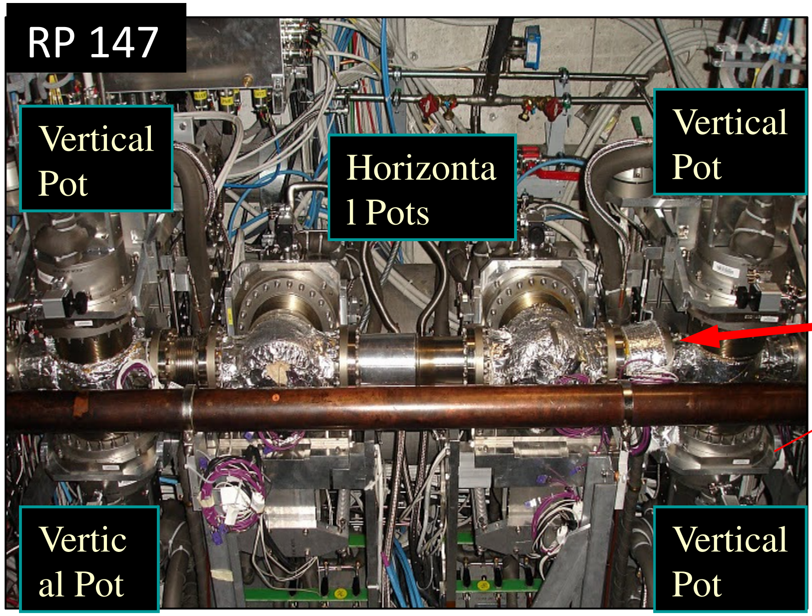
Analysis Ongoing

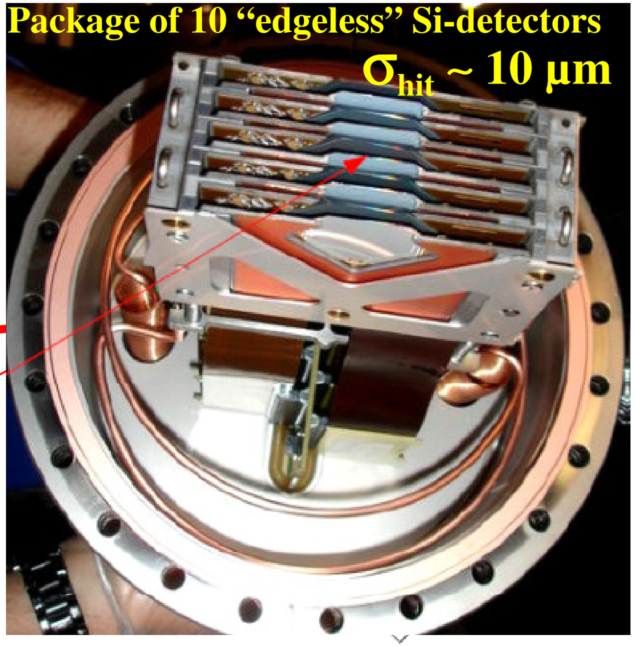
Summary & Outlook

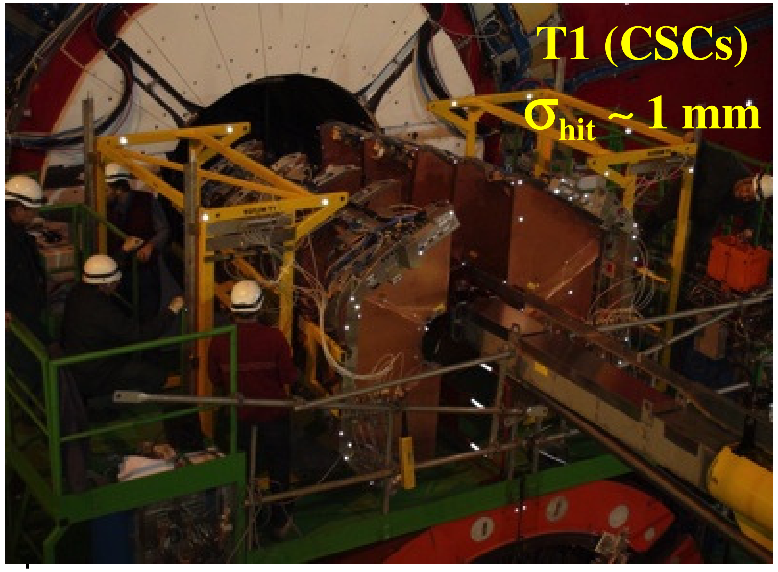
- **Extensive programme of σ_T, σ_{el} and σ_{inel} measurements @ LHC in Run I**
- **@ $\sqrt{s}$ = 7 TeV collision data taken in special runs with different beam conditions (β^* = 3.5, 90 m) allowed measurements of:**
  - **elastic scattering in a wide |t| range ($5 \cdot 10^{-3} < |t| < 3.5$ GeV^2)**
  - **elastic, inelastic and total p-p cross-section (very good agreement among results from different experiments)**
- **@ $\sqrt{s}$ = 8 TeV collision data taken in special runs with different beam conditions (β^* = 90, 1000 m) and higher statistics gave measurements of:**
  - **elastic scattering down to very low |t| ($6 \cdot 10^{-4} < |t| < 0.2$ GeV^2)**
    - **→ evidence for non-exponential slope**
    - **→ preliminary ρ measurement**
  - **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 $\sqrt{s}$ ....**

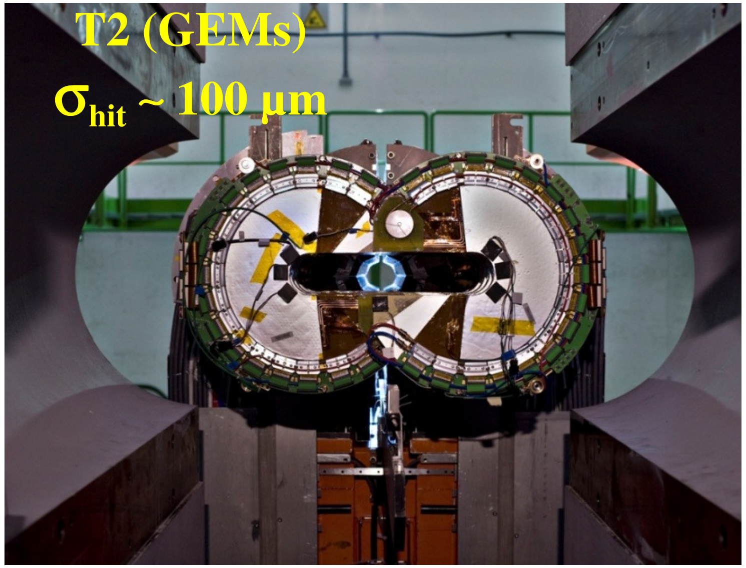
Backup Slides

TOTEM Detectors

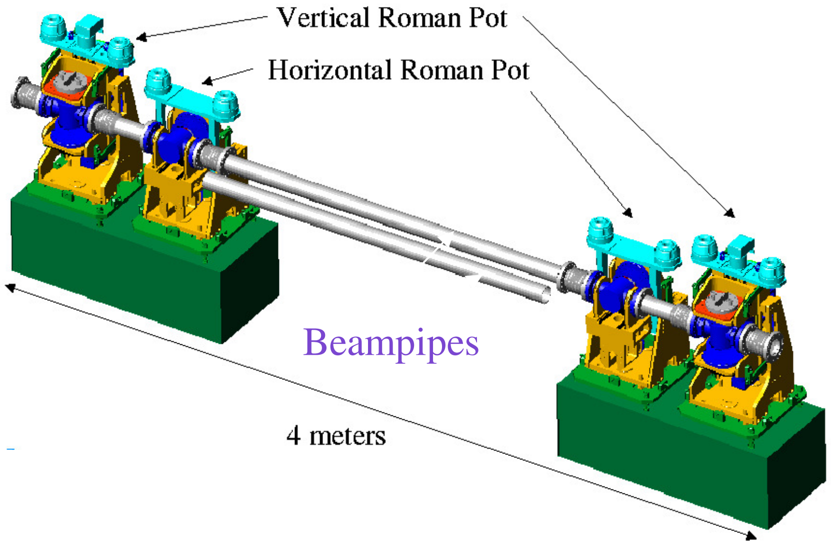








Roman Pots (I)

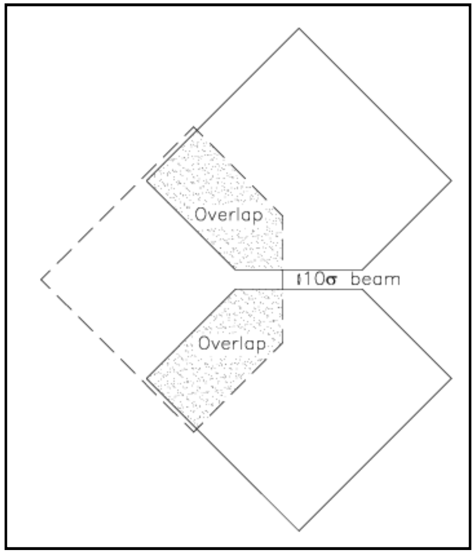


Units installed into the beam vacuum chamber allowing to put proton detectors as close as possible to the beam

Protons at few μrad angles detected down to **~ 5σ + d** from beam (σ_{beam} ~ 80μm at RP)

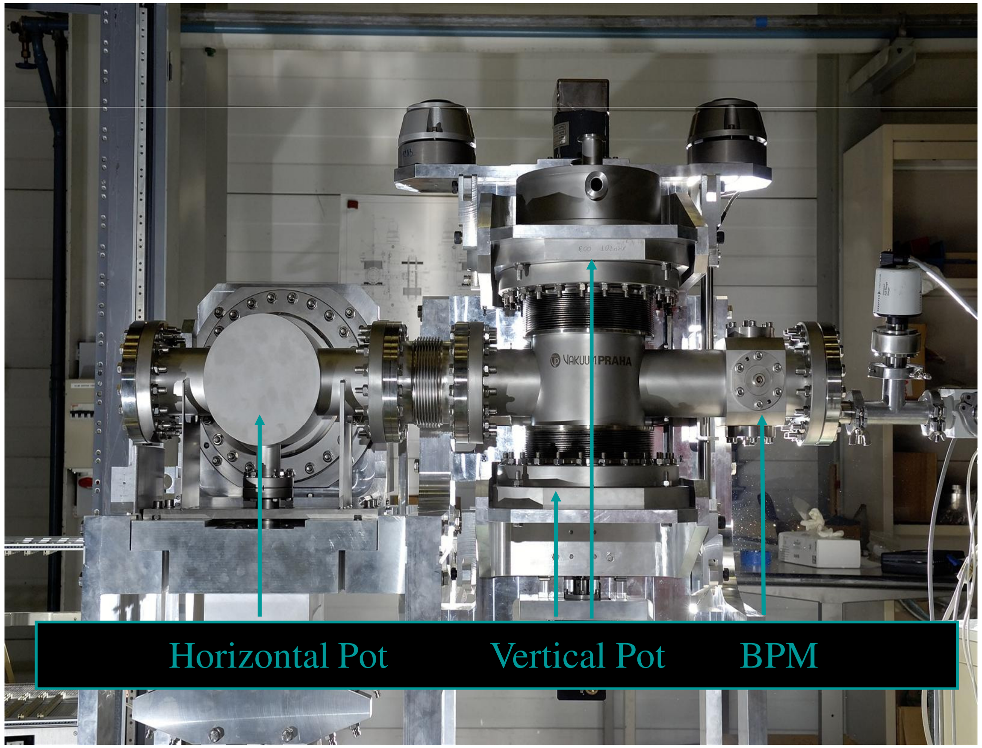
⇒ **'Edgeless' detectors to minimize d**

Each RP station has 2 units, ~5m apart.
Each unit has 3 insertions ('pots'):
2 vertical and 1 horizontal

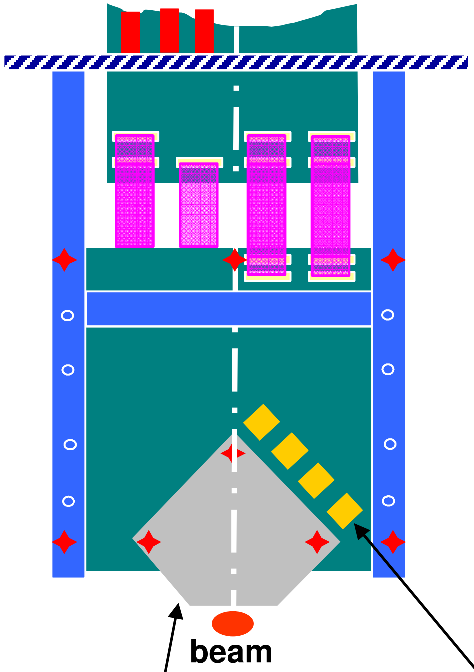


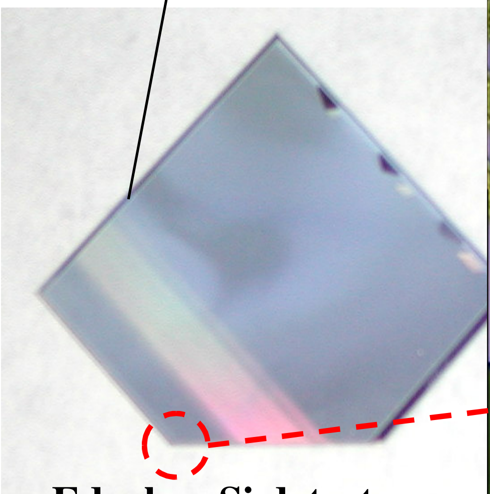
Horizontal Pot:
extend acceptance;
overlap for relative alignment using common track

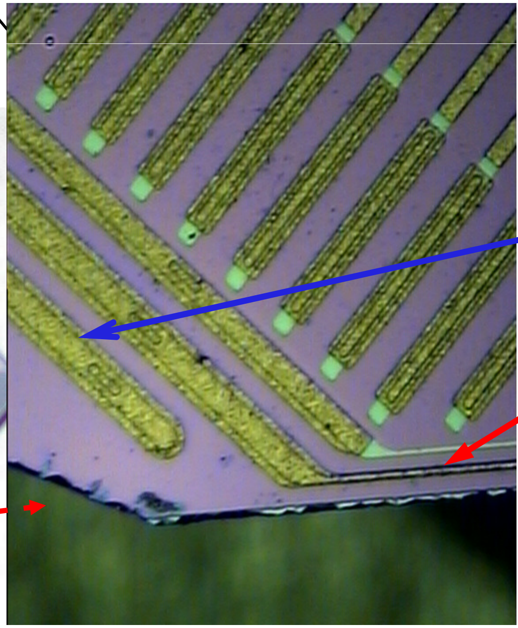
Absolute (w.r.t. beam) alignment from beam position monitor (**BPM**)



Roman Pots (II)







Edgeless Si detector:

50 µm of dead area

Each Pot:

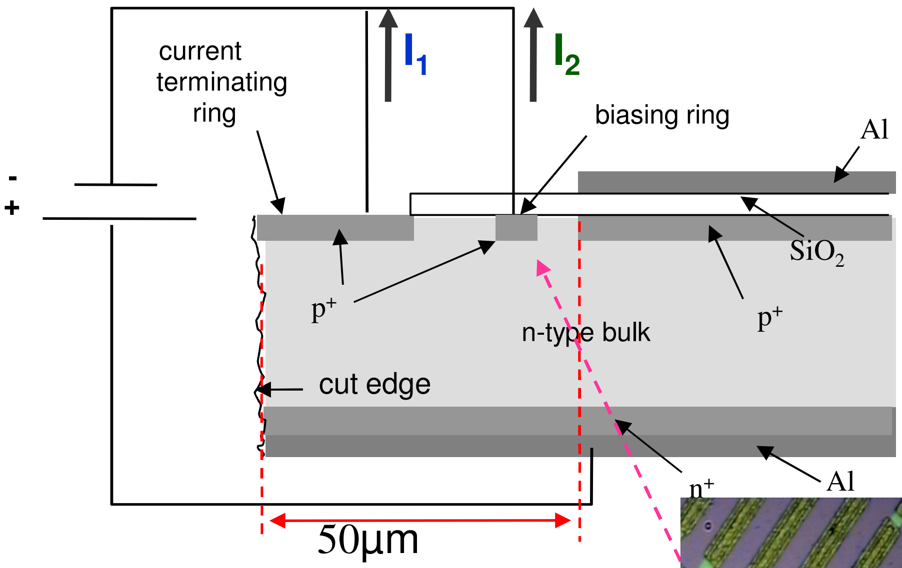
- **10 planes** of Si detectors
- 512 strips at 45° orthogonal
- Pitch: 66 µm
- Total ~ 5.1K channels
- Digital readout (VFAT): trigger/tracking
- Hit Resolution: σ ~ 10 µm

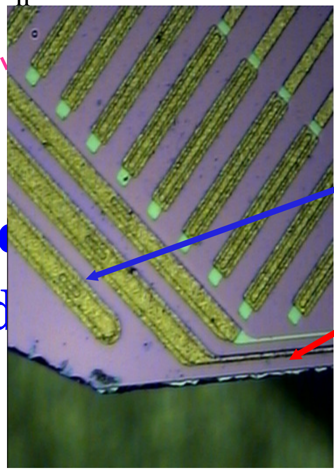
Integration of traditional Voltage Terminating Structure with the Current Terminating Structure

Detectors expected to work up to $\mathcal{L}_{int}$ ~ 1 fb^{-1} (no loss of performance during Run I)

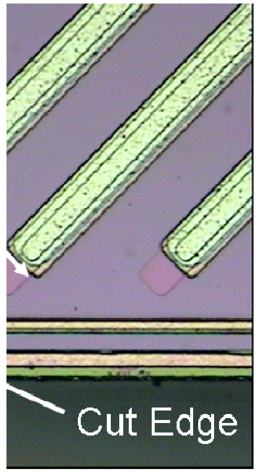
Si CTS Edgeless Detectors for Roman Pots

Planar technology with CTS
(Current Terminating Structure)





Integration of traditional Voltage Terminating Structure with the Current Terminating Structure



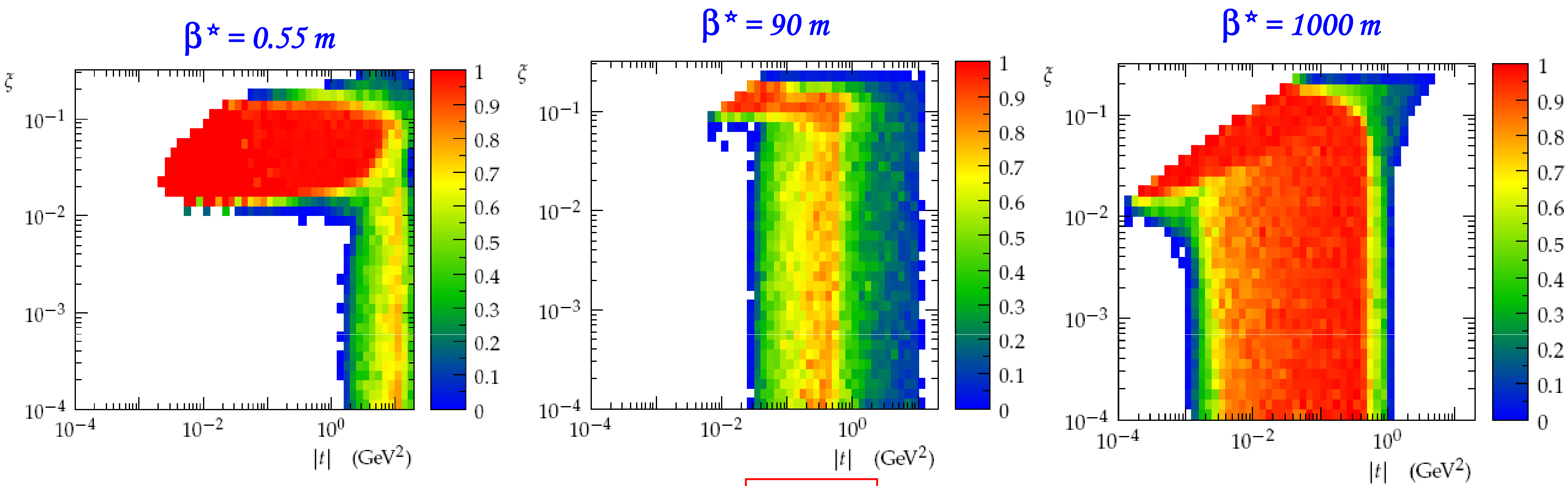
AC coupled microstrips ma
technology with novel guard
and biasing scheme

50 µm of dead area

LHC Optics and TOTEM Running Scenarios

Acceptance for diffractive protons:

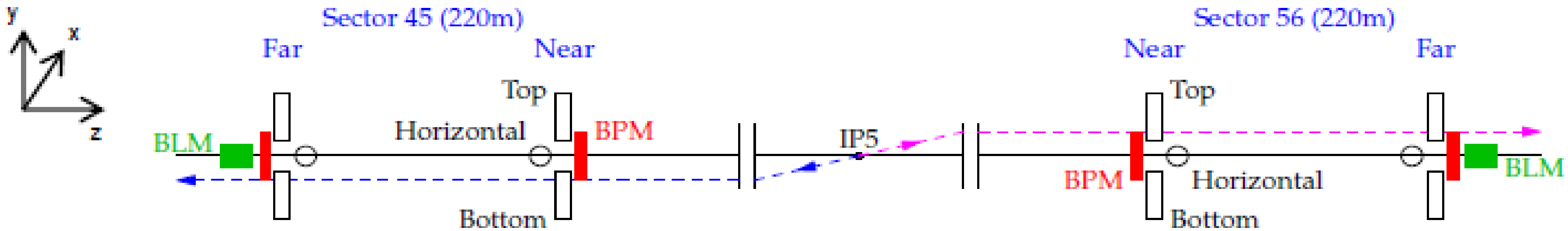
$t \approx -p^2\,\theta^{*\,2}$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss



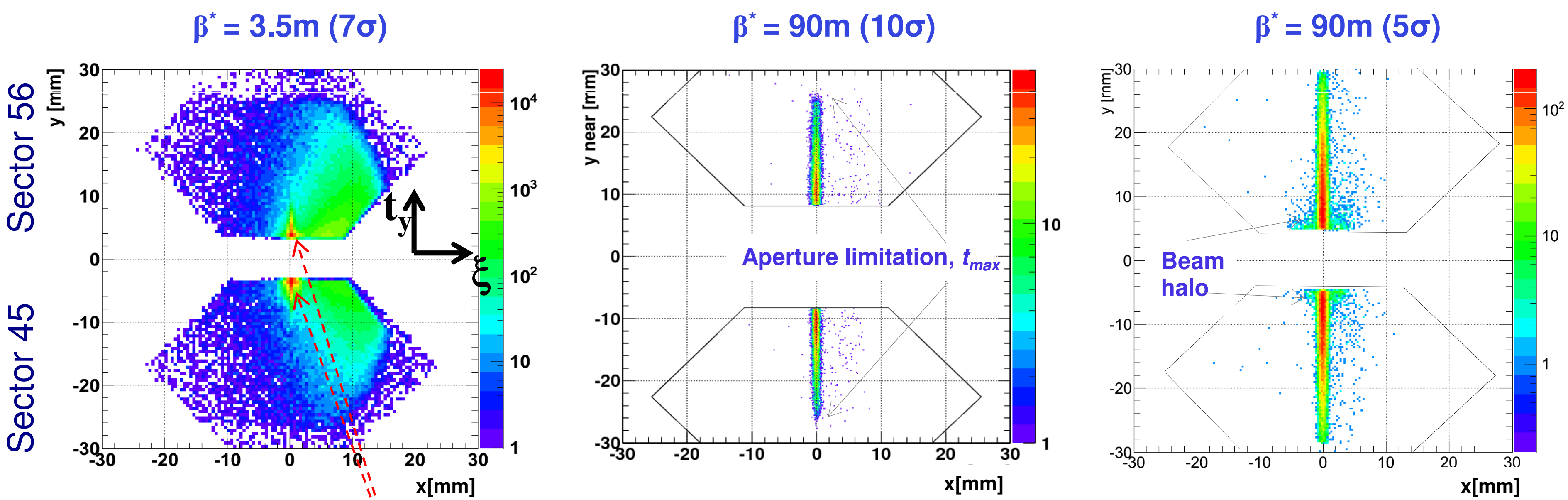
$> 10^{33}\ cm^{-2}\ s^{-1}$ ← $\mathcal{L} \propto \frac{1}{\beta^*}$ — $\sim 10^{27}\ cm^{-2}\ s^{-1}$

Diffraction: ξ > ~0.01 low cross-section processes (hard diffraction) Elastic scattering: large |t|	Diffraction: all ξ if |t| > ~10^{-2} GeV^2 Elastic scattering: low to mid |t| Total Cross-Section	Elastic scattering: very low |t| Coulomb-Nuclear Interference Total Cross-Section

Elastic pp Scattering: Hit Map in RPs



Coincidences of tracks reconstructed in left(45) and right(56) sectors: two "diagonals" analyzed independently



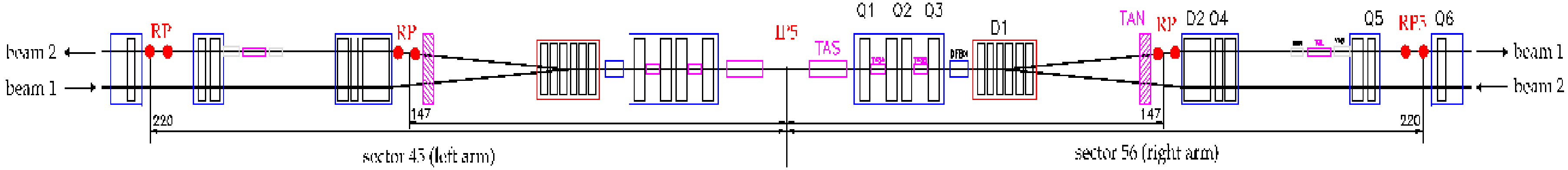
7 x10^{10} protons per bunch
Inelastic pile-up ~ 0.8 ev. / bx

1.5 x10^{10} protons per bunch
Inelastic pile-up ~ 0.005 ev. / bx

6 x10^{10} protons per bunch
Inelastic pile-up ~ 0.03 ev. / bx

Hits associated to elastic scattering candidates

Details on Optics



Proton position at a given RP (x, y) is a function of position (x^*, y^*) and angle (Θ_x^*, Θ_y^*) at IP5:

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

The *effective length* (L) and *magnification* (v) expressed with the phase advance (μ) and β:

$$L(s) = \sqrt{\beta(s)\beta^*}\,\sin \Delta\mu(s) \qquad v(s) = \sqrt{\beta(s)\beta^{*-1}}\,\cos \Delta\mu(s) \qquad \Delta\mu(s) = \int_0^s \beta^{-1}(s')ds'$$

Elastic proton reconstruction (simplified):

- Scattering angle reconstructed in both projections
- High Θ^*- reconstruction resolution available

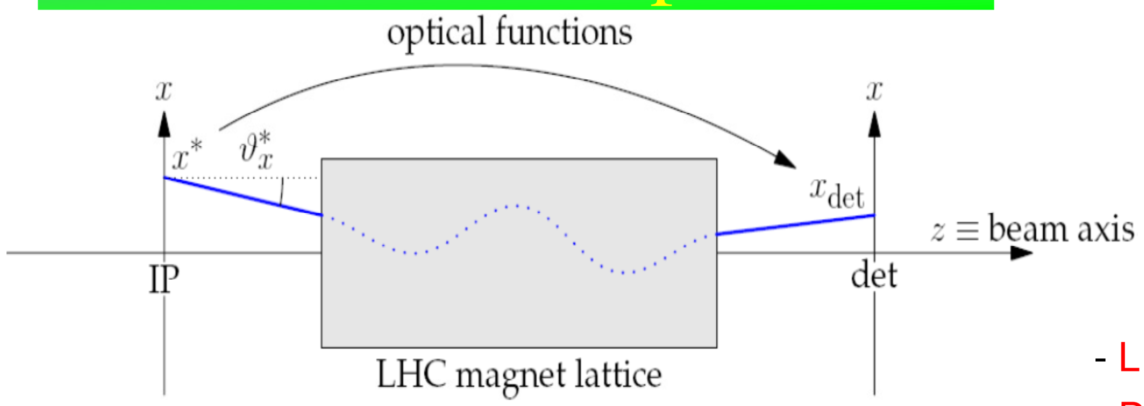
  $\sigma(\Theta_y^*)=1.7\,\mu$**rad** for $\beta^* = 90$ m and low t-range

  $\sigma(\Theta_y^*)=12.5\,\mu$**rad** for $\beta^* = 3.5$ m and high t-range

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

Excellent optics calibration and alignment required

Details on Optics



$\xi = \Delta p/p$; $t = t_x + t_y$; $t_i \sim -(p\theta_i{}^*)^2$
(x^*, y^*): vertex position at IP
$(\theta_x{}^*, \theta_y{}^*)$: emission angle at IP

Proton transport equations (from transport matrix):

$$y(s) = v_y(\xi,s)\cdot y^* + L_y(\xi,s)\cdot\theta_y{}^*$$

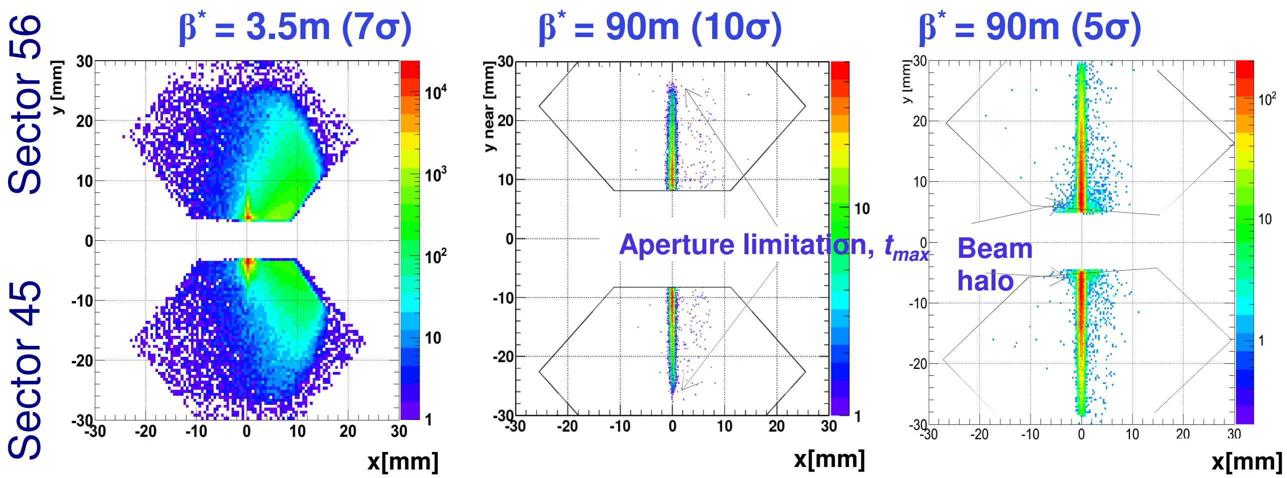
$$x(s) = v_x(\xi,s)\cdot x^* + L_x(\xi,s)\cdot\theta_x{}^* + \xi\cdot D(\xi,s)$$

Optical functions:

- L (effective length); - v (magnification);
- D (machine dispersion)

Describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP.

⇒ Define t and ξ range (acceptance)

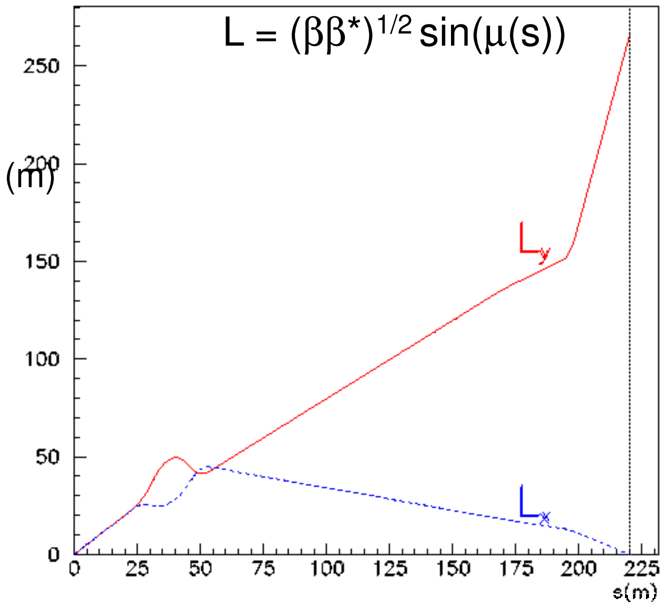


Example:

same sample of diffractive protons at different β*

- **low β*: p detected by momentum loss (ξ)**
- **high β*: p detected by trans. momentum (t_y)**

Optical Functions: Example at β* = 90 m



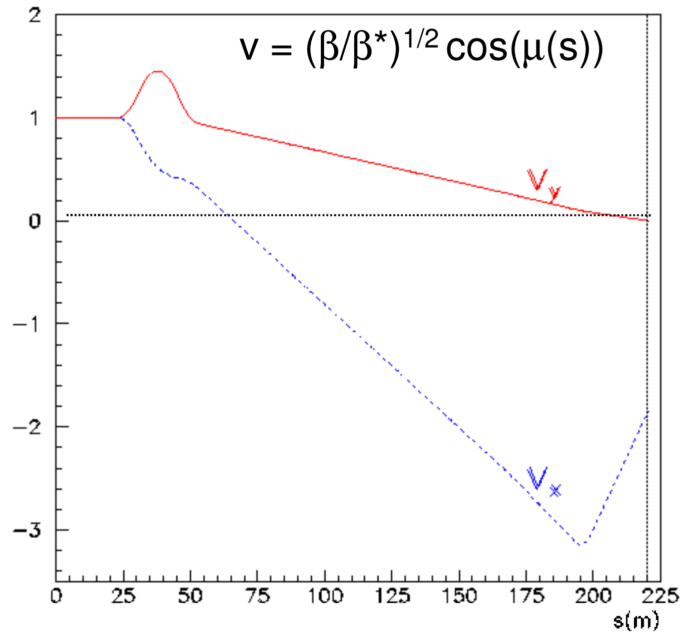
Idea:

L_y large $\quad L_x = 0$

$v_y = 0$

$\mu_y(220) = \pi/2 \quad \mu_x(220) = \pi$

(parallel-to-point focussing on y)



$$x = L_x\theta_x^* + v_x x^* + D\xi$$

$$y = L_y\theta_y^* + v_y y^*$$

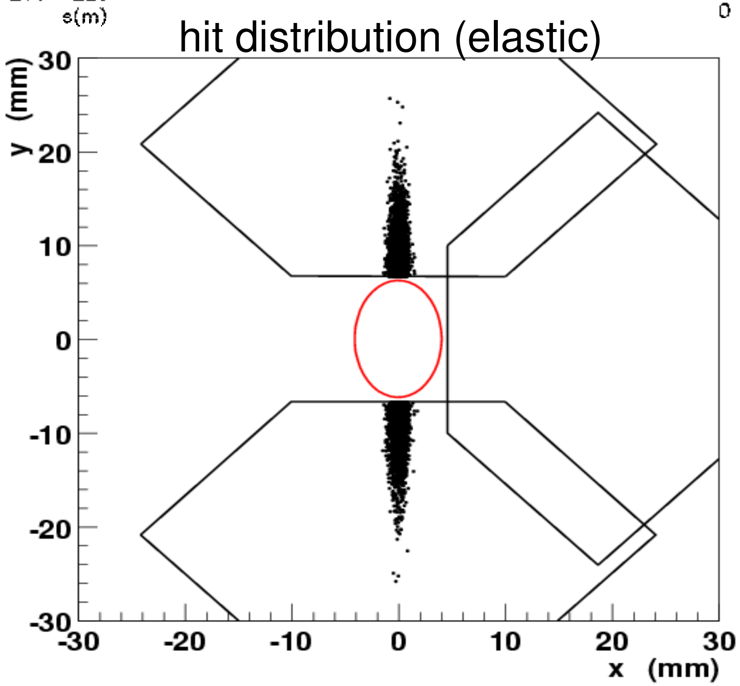
$\xi = \Delta p/p$

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

(θ_x^*, θ_y^*): emission angle at IP

$$t = t_x + t_y$$

$$t_i \sim -(p\theta_i^*)^2$$



Optical functions:

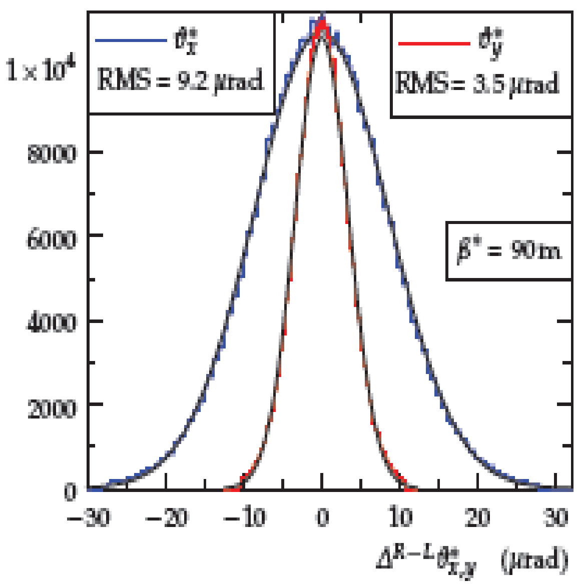
- L (effective length)
- v (magnification)

defined by β (betatron function) and μ (phase advance);

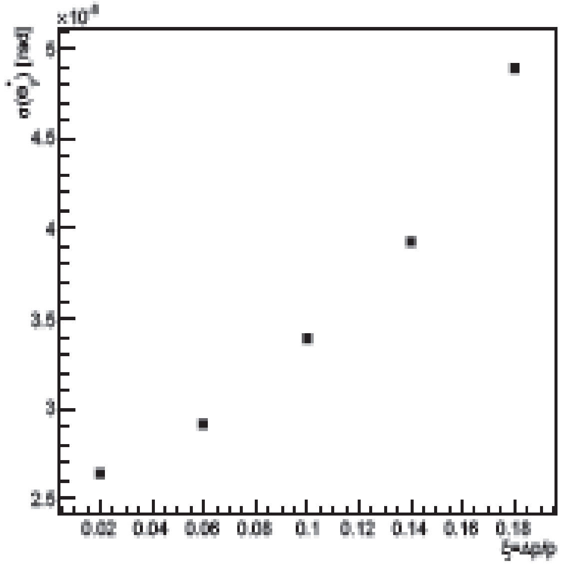
- D (machine dispersion)

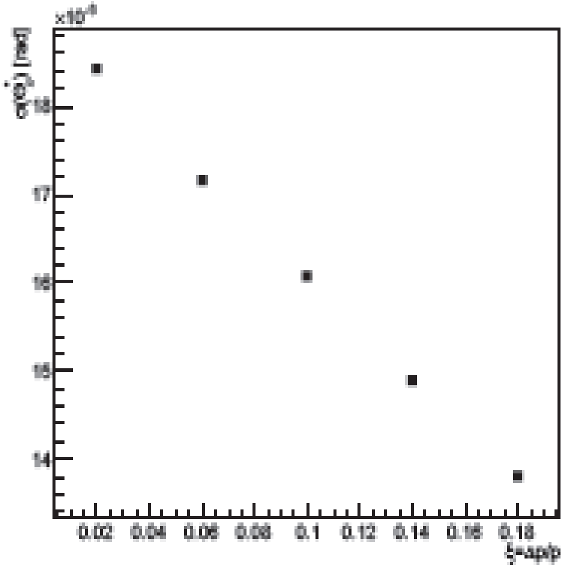
⇒ describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP

θ* and ξ Resolution (β* = 90 m)



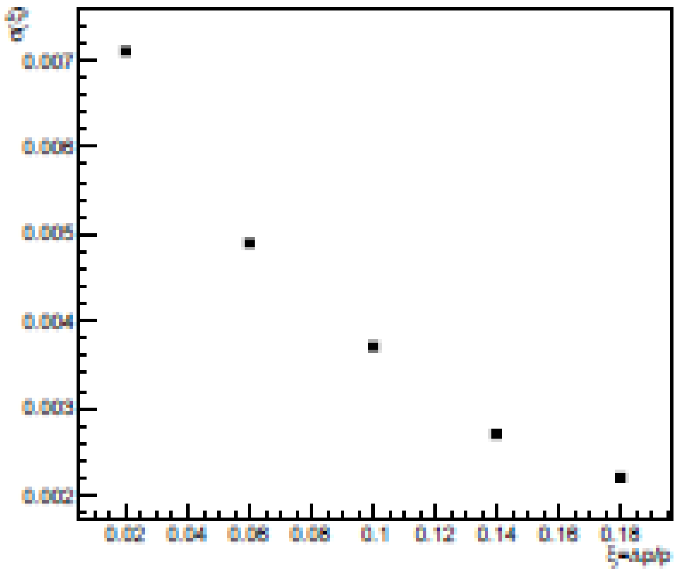
Elastic p





Diffractive p

CERN-PH-EP-2013-173



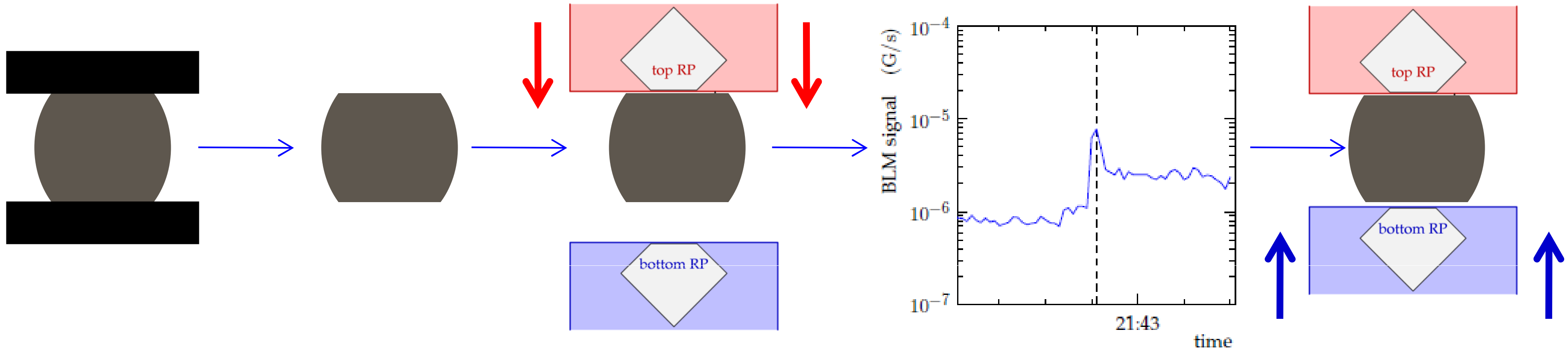
Roman Pot Alignment wrt Beam Centre: BLM

Collimator cuts a sharp beam edge symmetrically to the centre

RP approaches this edge until it scrapes …

… producing spike in BLM downstream

The second RP approaches



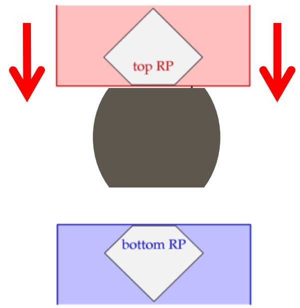
When both top and bottom pots "feel" the edge: they are at the same number of sigmas from the beam centre as the collimator and the beam centre is exactly in the middle between top and bottom pot

TOTEM Roman Pot Alignment Procedures

Critical procedures (fill-based): movable devices, beam optics variations

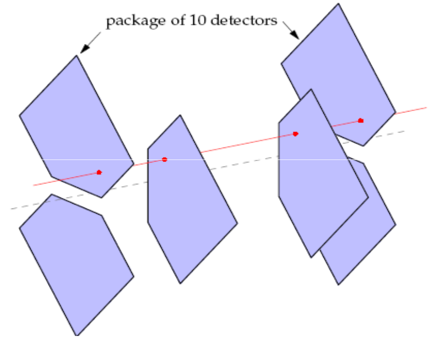
- **Pot position wrt LHC beam center:**

  alignment wrt collimators by approaching the beam "cut edge" (~ 20 μm)



- **Internal alignment of components within detector assembly:**

  metrology, local tracks (few μm)

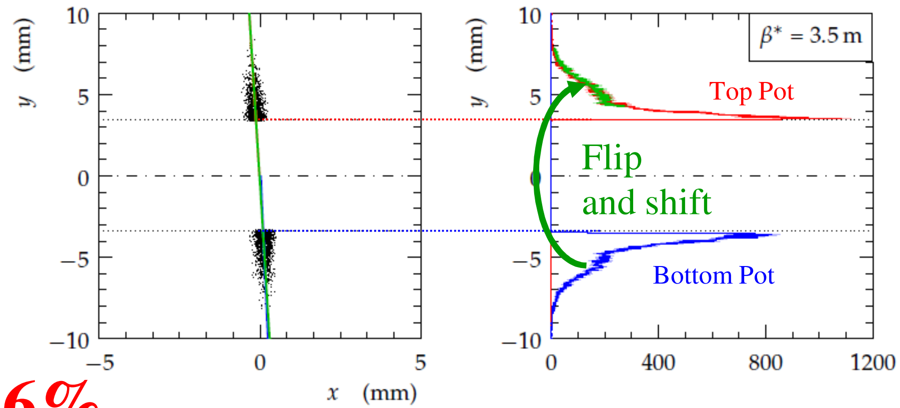


- **Relative alignment of the pots in a station:**

  tracks in overlapping regions (Millepede algorithm, few μm)

- **Global alignment:**

  track based exploiting symmetries (co-linearity) of hit profiles for elastically scattered protons, also allows "left-right" constraints (< 10 μm in x, ~ 20 μm in y)

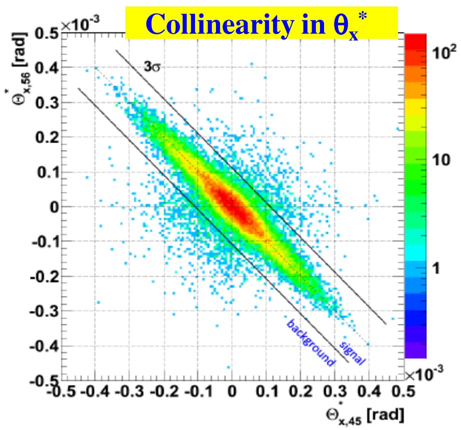


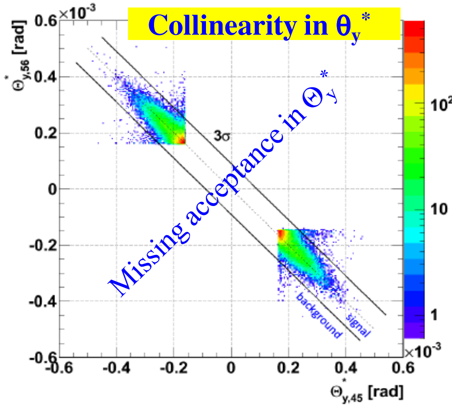
Final precision achieved:
~ 10(50) μm in x(y) → δt/t ~ 0.3-0.6%

TOTEM Elastic pp Scattering: Analysis (I)

Proton selection cuts

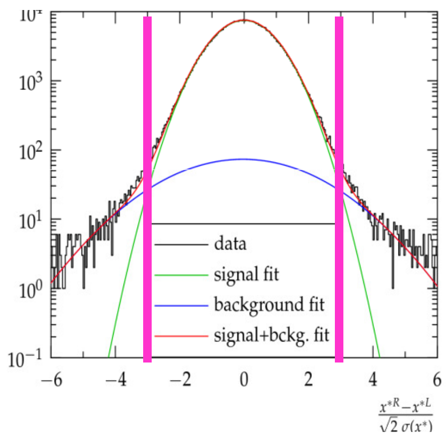
- collinearity cuts (left-right):
  $\Theta^*_{x,45} \leftrightarrow \Theta^*_{x,56}$
  $\Theta^*_{y,45} \leftrightarrow \Theta^*_{y,56}$
  (width in agreement with beam divergence)
- low ξ cuts: $|x^*| < 0.6$ mm and 2σ cut in $\Delta\theta_y^*$
- vertex cuts (beam halo): $|x^*_{45} - x^*_{56}| < 27\ \mu$m
- optics related cuts

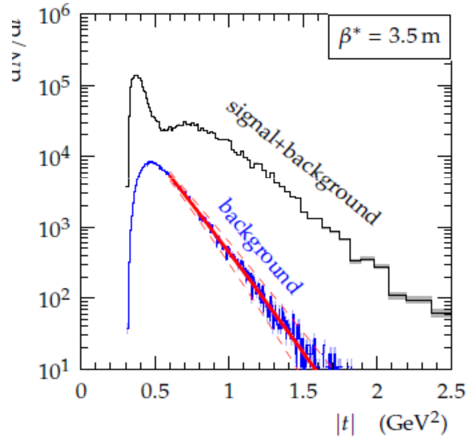




Background subtraction

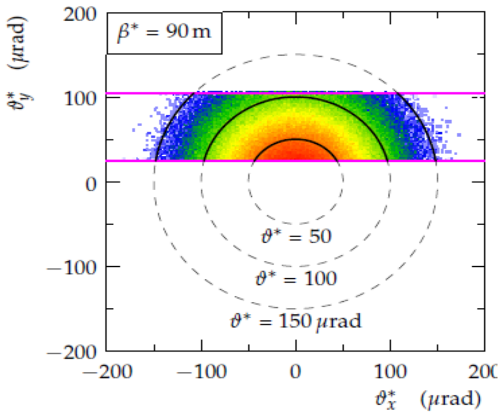
- interpolating the background tails (> 3 σ) into the signal region (< 3 σ)

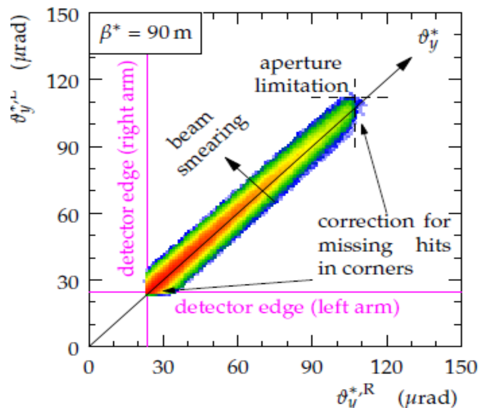




Acceptance correction

- assuming azimuthal symmetry
- correcting for smearing around limitation edges

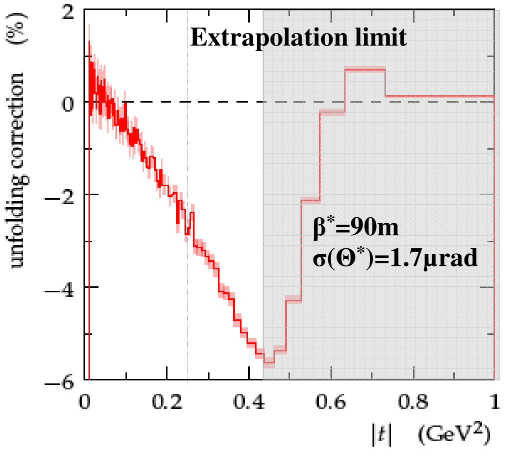


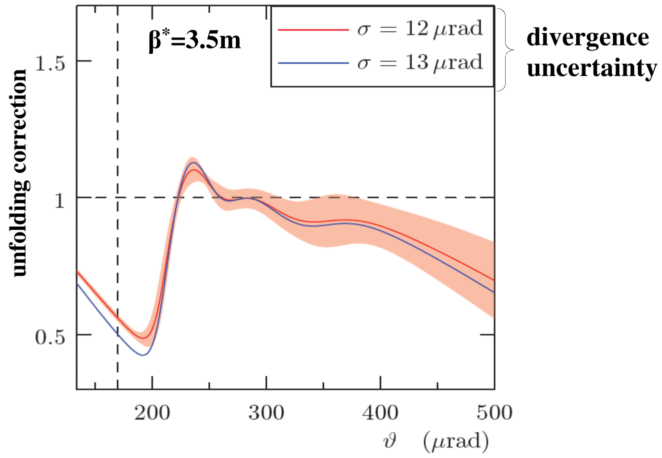


TOTEM Elastic pp Scattering: Analysis (II)

Unfolding of resolution effects:

MC based iterative procedure





Normalization (reconstruction efficiencies):

Trigger Efficiency (from zero-bias data stream) **> 99.8% (68% CL)**

DAQ Efficiency **98.142 ± 0.001 %**

Reconstruction Efficiency

– intrinsic detector inefficiency: **1.5 – 3 % / pot**

– elastic proton lost due to interaction: **1.5% / pot**

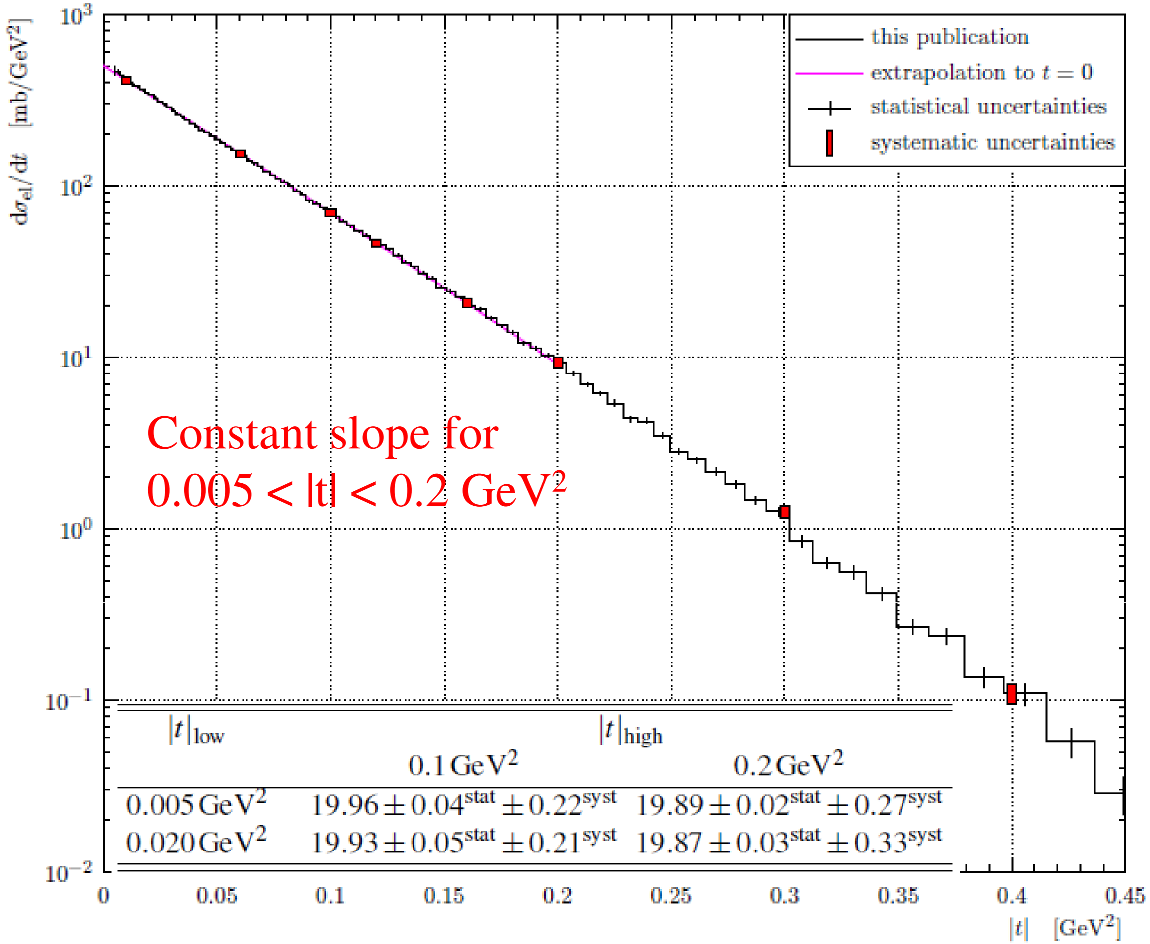
– event lost due to overlap with beam halo (depends on RP position wrt beam and diagonals): **4 – 8% (β*=90m); 30% (β*=3.5m)**

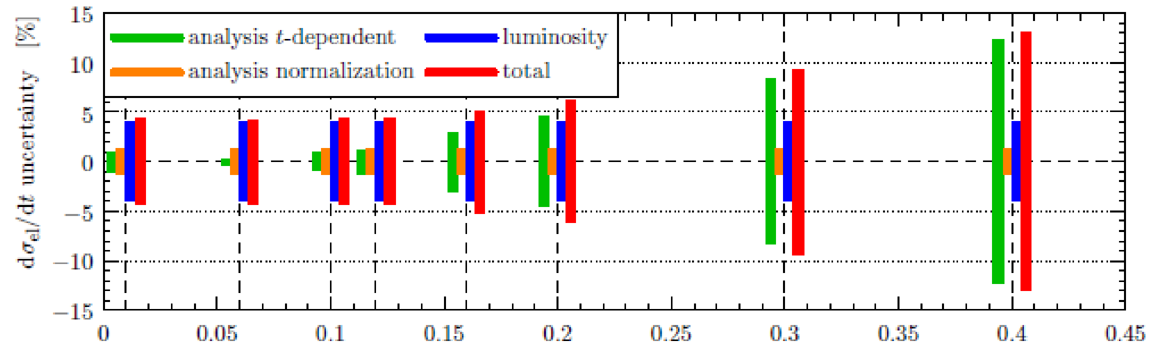
Luminosity from CMS: systematic error of 4%

Systematic uncertainties: dominated by $\mathcal{L}$ and by analysis t-dependent effects

(misalignments, optics imperfections, energy offset, acceptance correction and un-smearing correction)

Elastic Scattering at low |t|: Systematic Errors





Individual contributions to errors:

analysis t-dependent:

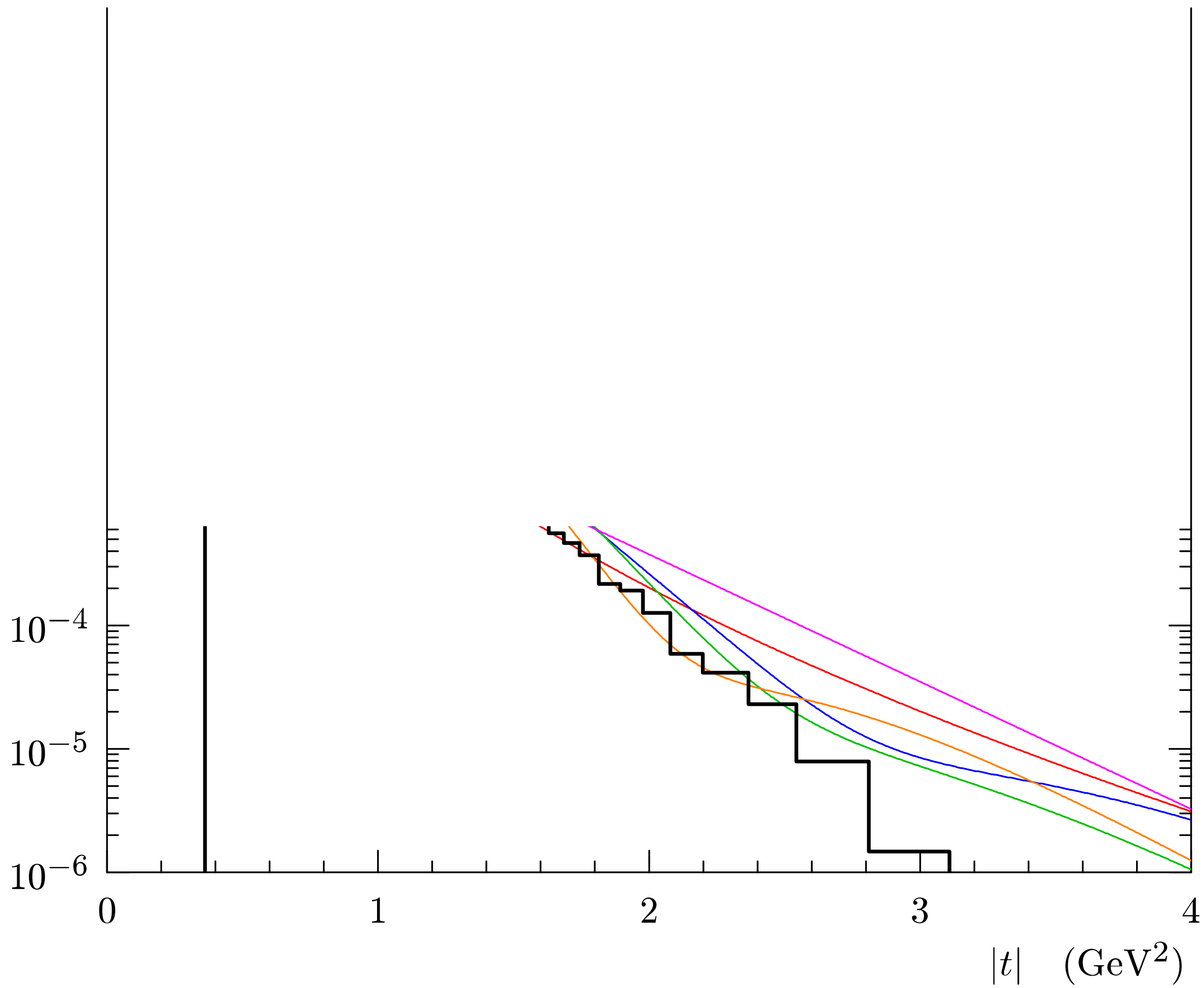
– misalignments
– optics imperfections
– energy offset
– acceptance correction
– unsmearing correction

analysis normalization:

– event tagging
– background subtraction
– detector efficiency
– reconstruction efficiency
– trigger efficiency
– “pile-up” correction

Luminosity from CMS (± 4%)

Comparison to some models



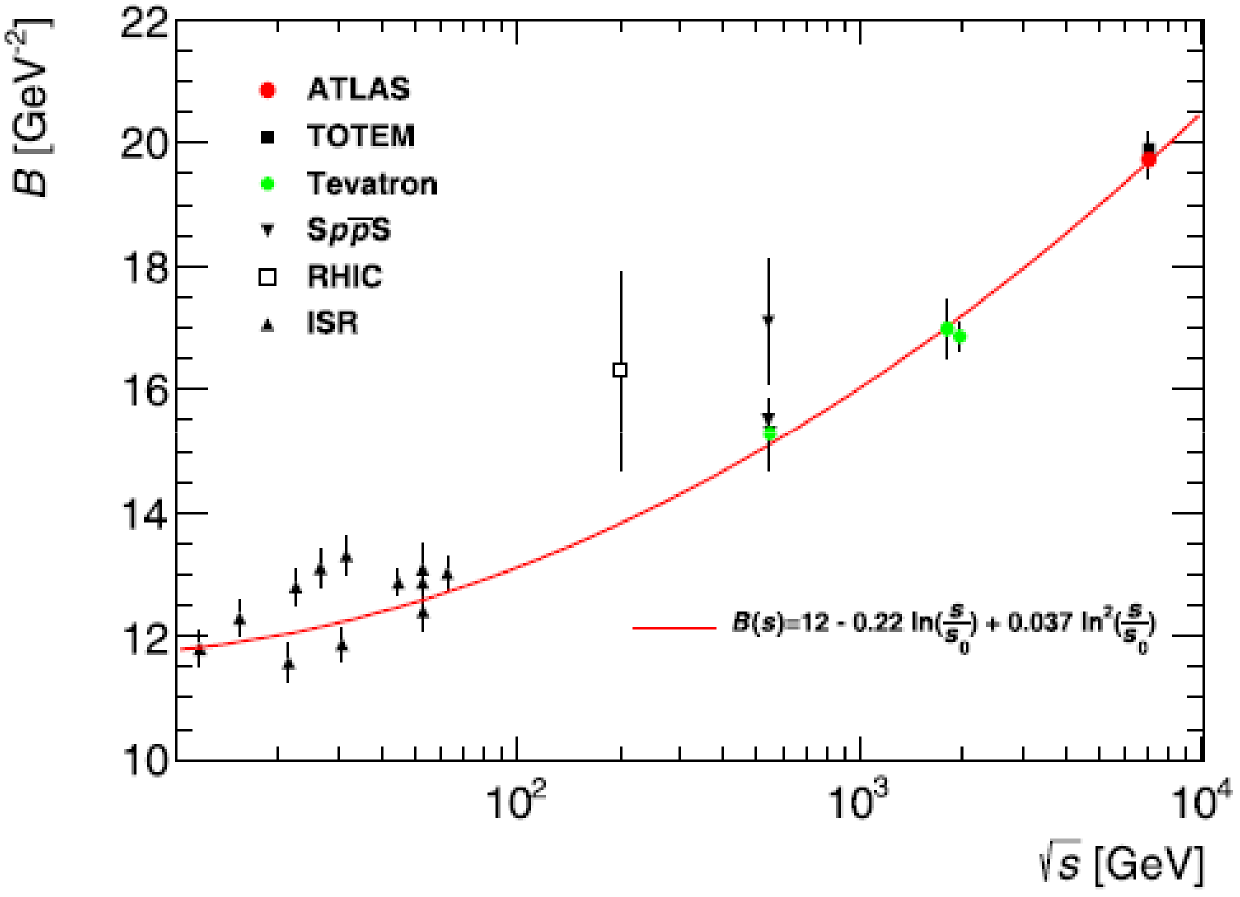
B (t=-0.4 GeV²)	t_{DIP}	t^{-n} **[1.5–2.5 GeV²]**
20.2	0.60	5.0
23.3	**0.51**	**7.0**
22.0	**0.54**	**8.4**
25.3	0.48	10.4
20.1	0.72	4.2
23.6 ± 0.5	**0.53 ± 0.01**	**7.8 ± 0.3**

None of the models really fit

Better statistics at large |t| needed (in progress)

Dependence of Nuclear Slope B on Energy

ATLAS Collaboration / Nuclear Physics B 889 (2014) 486–548



Inelastic Cross Section @ 7 TeV: TOTEM

Direct T1 and T2 measurement: $\sigma_{inel} = N_{inel}/\mathcal{L}$ ($\mathcal{L}$ from CMS)

Data sample

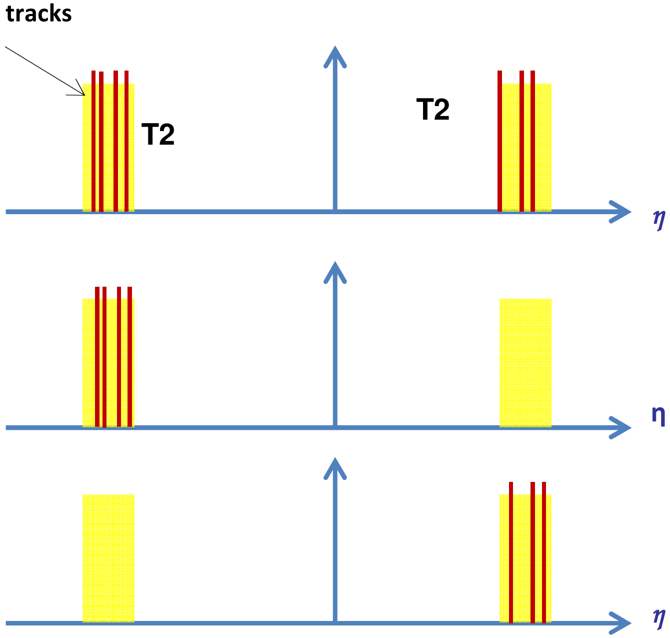
- **Oct. 2011 run with β* = 90 m:**
  same data subsets used for the $\mathcal{L}$-independent total cross section measurement
- **T2 triggered events**
- **Low pile-up:** (μ = 0.03)

Subset	Inelastic events	$\mathcal{L}_{int}$ [μb^{-1}]
DS 1a	1.14M	17.0 ± 0.7
DS 1b	1.78M	26.6 ± 1.1
DS 1c	1.64M	24.5 ± 1.0
DS 2	0.55M	8.2 ± 0.3
DS 3	0.44M	6.6 ± 0.3
Total	5.54M	82.8 ± 3.3

Inelastic events in T2: classification

- **Tracks in both hemispheres:** mainly non-Diffractive minimum bias (ND) and Double Diffraction (DD)
- **Tracks in a single hemisphere:** mainly single diffraction (SD) with $M_X > 3.4$ GeV/c^2

→ **Optimized study of trigger efficiency and beam gas background corrections**



σ_{inel} @ 7 TeV: TOTEM (Corrections)

Corrections to the "T2 visible" events (~ 95%)

- **Trigger Efficiency** (from zero bias data, vs track multiplicity): **2.3 ± 0.7 %**
- **Track reconstruction efficiency** (based on MC tuned with data): **1.0 ± 0.5 %**
- **Beam-gas background** (from non colliding bunch data): **0.6 ± 0.4 %**
- **Pile-up** ($\mu = 0.03$) (from zero bias data): **1.5 ± 0.4 %**

Corrections for "missing" inelastic cross-section

- **Events visible in T1 but not in T2** (from zero bias data): **1.6 ± 0.4 %**
- **Rapidity gap in T2** (from T1 gap probability transferred to T2): **0.35 ± 0.15 %**
- **Central Diffraction: T1 & T2 empty** (based on MC): **0.0 ± 0.35 %**
- Low Mass Diffraction (based on **QGSJET-II-03** MC): **4.2 % ± 2.1 %**
  (constrained by elastic scattering measurement, see later)

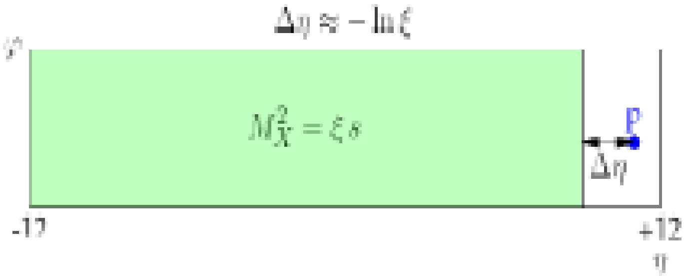
Uncertainty related to $\mathcal{L}$ (CMS): 4%

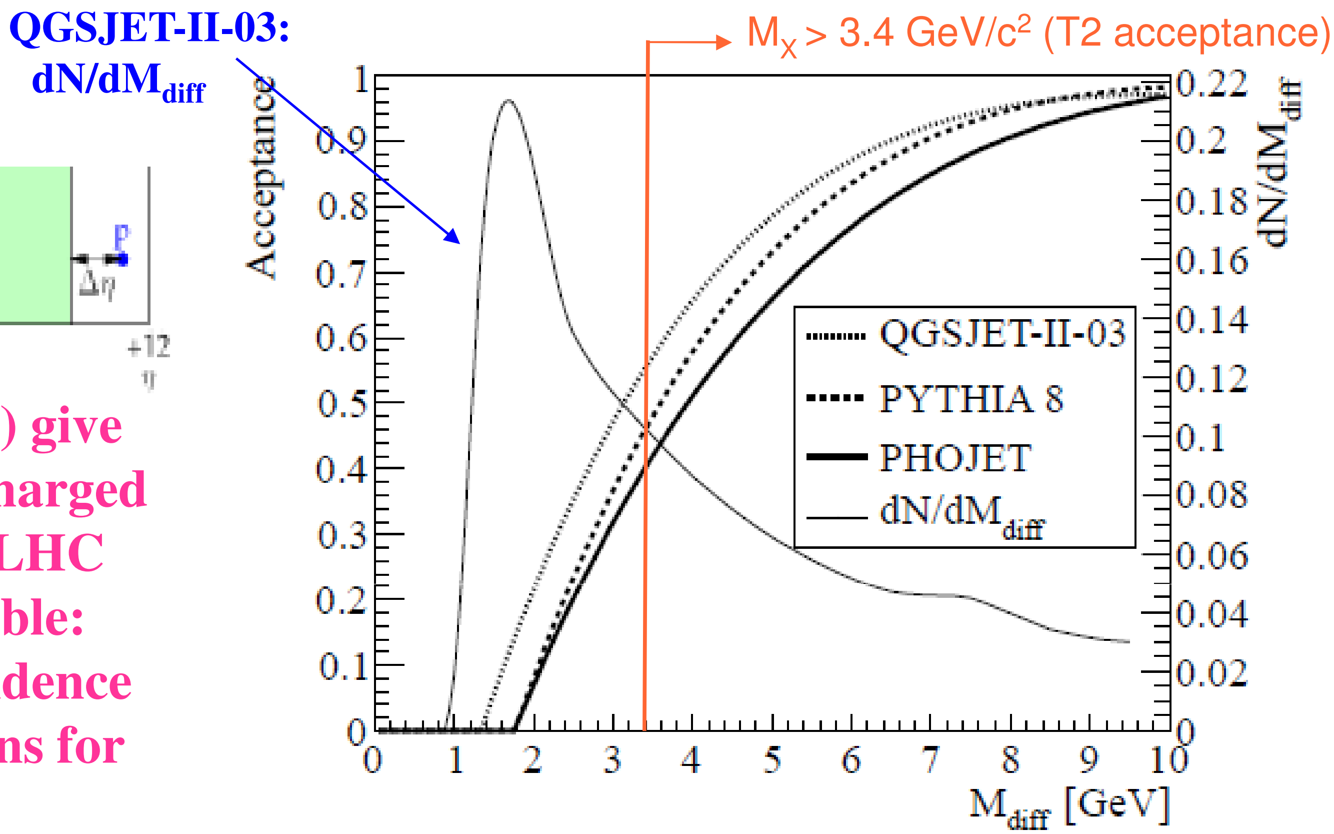
$$\sigma_{inelastic} = 73.7 \pm 0.1^{stat} \pm 1.7^{syst} \pm 3.0^{lumi} \text{ mb}$$

- EPL 101 (2013) 21003 -

Compatible with other similar meas. @ LHC

Low-Mass Diffraction: T1+T2 Acceptance





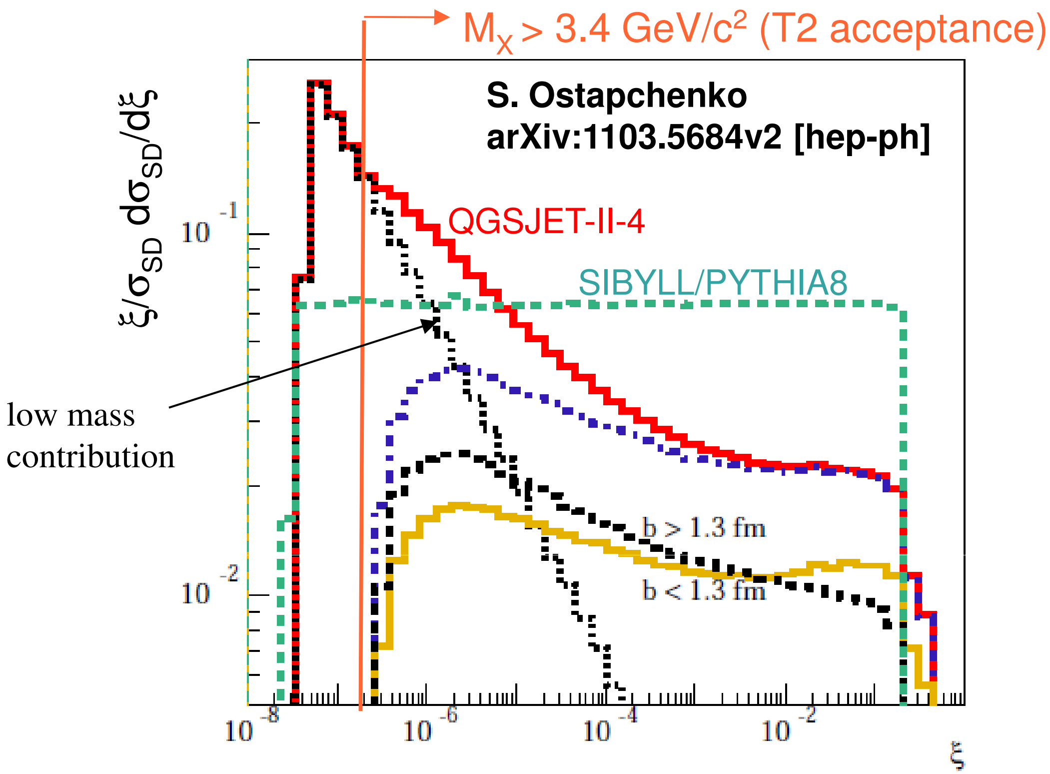
T1+T2 (3.1 < |η| < 6.5) give an unique forward charged particle coverage @ LHC → lower M_{diff} reachable: minimal model dependence on required corrections for low mass diffraction

Several models studied: correction for low mass single diffractive cross-section based on QGSJET-II-03 (well describing low mass diffraction at lower energies), imposing observed 2hemisphere/1hemisphere event ratio and the effect of "secondaries"

$$\sigma_{Mx < 3.4\ GeV} = 3.1 \pm 1.5\ mb$$

Low-Mass Diffraction: MC Predictions

$$M_x^2 \approx s \cdot \xi$$
$$\Delta\eta \approx -\log\xi$$
$$M_x^2 \approx s \cdot e^{-\Delta\eta}$$



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$$\sigma_{Mx < 3.4\ GeV} = 3.1 \pm 1.5\ \text{mb}$$

Further Measurements (TOTEM)

Absolute luminosity measurement (@ 7 TeV):

The "luminosity-independent" method also yields the luminosity calibration

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

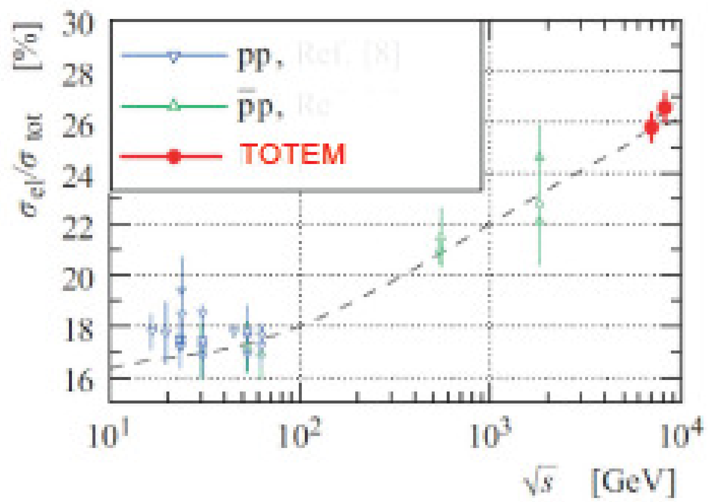
June 2011: $L_{int} = (1.65 \pm 0.07)\ \text{mb}^{-1}$ [CMS: $(1.65 \pm 0.07)\ \text{mb}^{-1}$]

October 2011: $L_{int} = (83.7 \pm 3.2)\ \text{mb}^{-1}$ [CMS: $(82.0 \pm 3.3)\ \text{mb}^{-1}$]

Excellent agreement with CMS $\mathcal{L}$ measurement

Luminosity- and ρ-independent ratios:

	7 TeV		8 TeV
$\sigma_{elastic} / \sigma_{total}$ =	0.257 ± 0.005	;	0.266 ± 0.006
$\sigma_{elastic} / \sigma_{inelastic}$ =	0.354 ± 0.009	;	0.362 ± 0.011



Elastic Scattering in the Coulomb-Nuclear Interference Region

Experimental data → **Physics parameters (ρ, …)**

↓

Theoretical/phenomenological models

Comparison

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

(QED)

$$F^{C} = \frac{\alpha s}{t}\mathcal{F}^2(t)$$

- **Modulus constrained by measurement:** $d\sigma/dt \cong A\, e^{-B(t)\,|t|}$

  $B(t) = b_0 + b_1 t + \ldots$

- **Phase $\arg F^H$ (interference term): very little guidance by data**

Simplified West-Yennie formula:

- constant slope $B(t) = b_0$
- constant hadronic phase $\arg(F^H) = p_0$ ("costant phase")
- $\Psi(t)$ acts as real interference phase:

$$\Psi(t) = \ln\frac{B(t)}{2} + \gamma_{\text{Euler}}$$

General Kundrát-Lokajíček formula:

- any slope B(t)
- any hadronic phase:

  if $\arg F^H(t)$ → "peripheral phase"

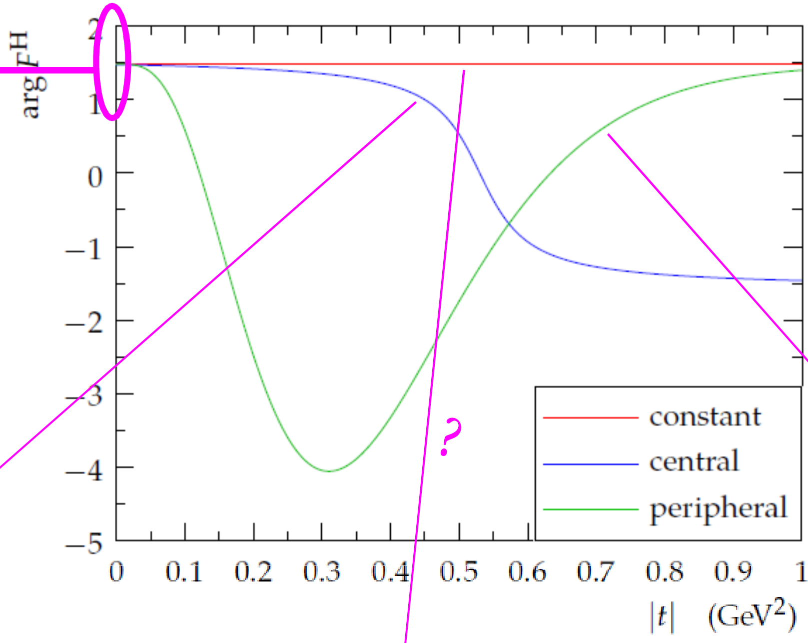
  if $\arg F^H \sim$ cost → "central phase"
- complex $\Psi(t)$:

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

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

Elastic Scattering in the Coulomb-Nuclear Interference Region

data sensitivity region



"central phase":

$$\arg F^H(t) = \frac{\pi}{2} - \operatorname{atan}\frac{\cot p_0}{1 - \frac{t}{t_d}}$$

"constant phase":

$$\arg F^H(t) = p_0$$

"peripheral phase":

$$\arg F^H(t) = p_0 + p_A \exp\left[\kappa\left(\ln\frac{t}{t_m} - \frac{t}{t_m} + 1\right)\right]$$

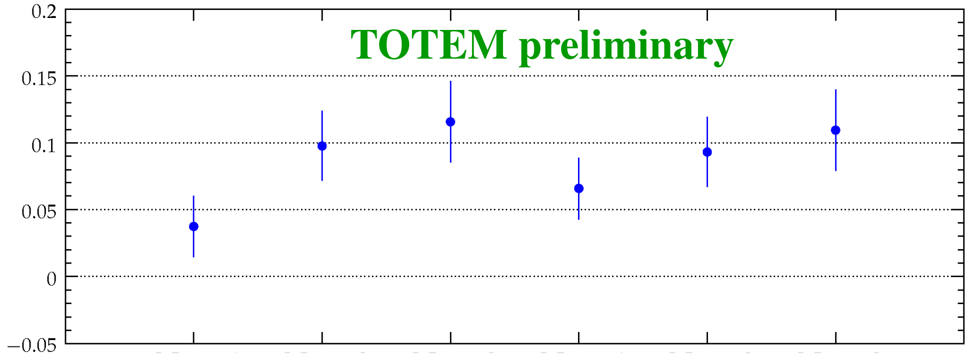
Only 1 free parameter: $p_0 = \psi(0)$ ➔

$$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0) = \cot p_0$$

Preliminary Results for ρ

Put unknown elements of the functional form into the systematic uncertainty.

$\varrho \equiv \left.\frac{\Re F^{\mathrm{H}}}{\Im F^{\mathrm{H}}}\right|_0$



Data fits:

p_0 and parameters for B(t) left free

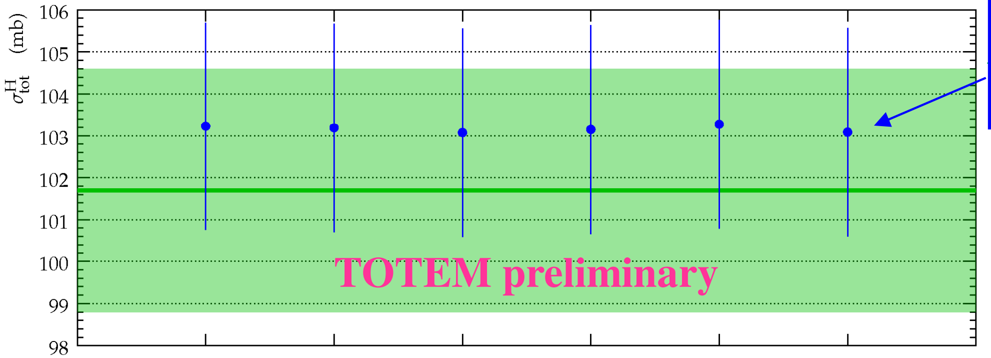
B(t): 1 par. 2 par. 3 par. | 1 par. 2 par. 3 par.

Phase: central or constant | peripheral

Data favour ≥ 2 parameters

$$\rho = 0.107 \pm 0.027^{(\mathrm{stat})} \pm 0.010^{(\mathrm{syst})} {}^{+0.009}_{-0.009} (\mathrm{model})$$

$\sigma_{\mathrm{tot}}^{\mathrm{H}}$ (mb)



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

$\sigma_t = 101.7 \pm 2.9$ mb

luminosity independent

[PRL 111 (2013) 012001]