Review of TOTEM Results

Mario Deile
on behalf of the TOTEM Collaboration

WE-Heraeus-Summerschool

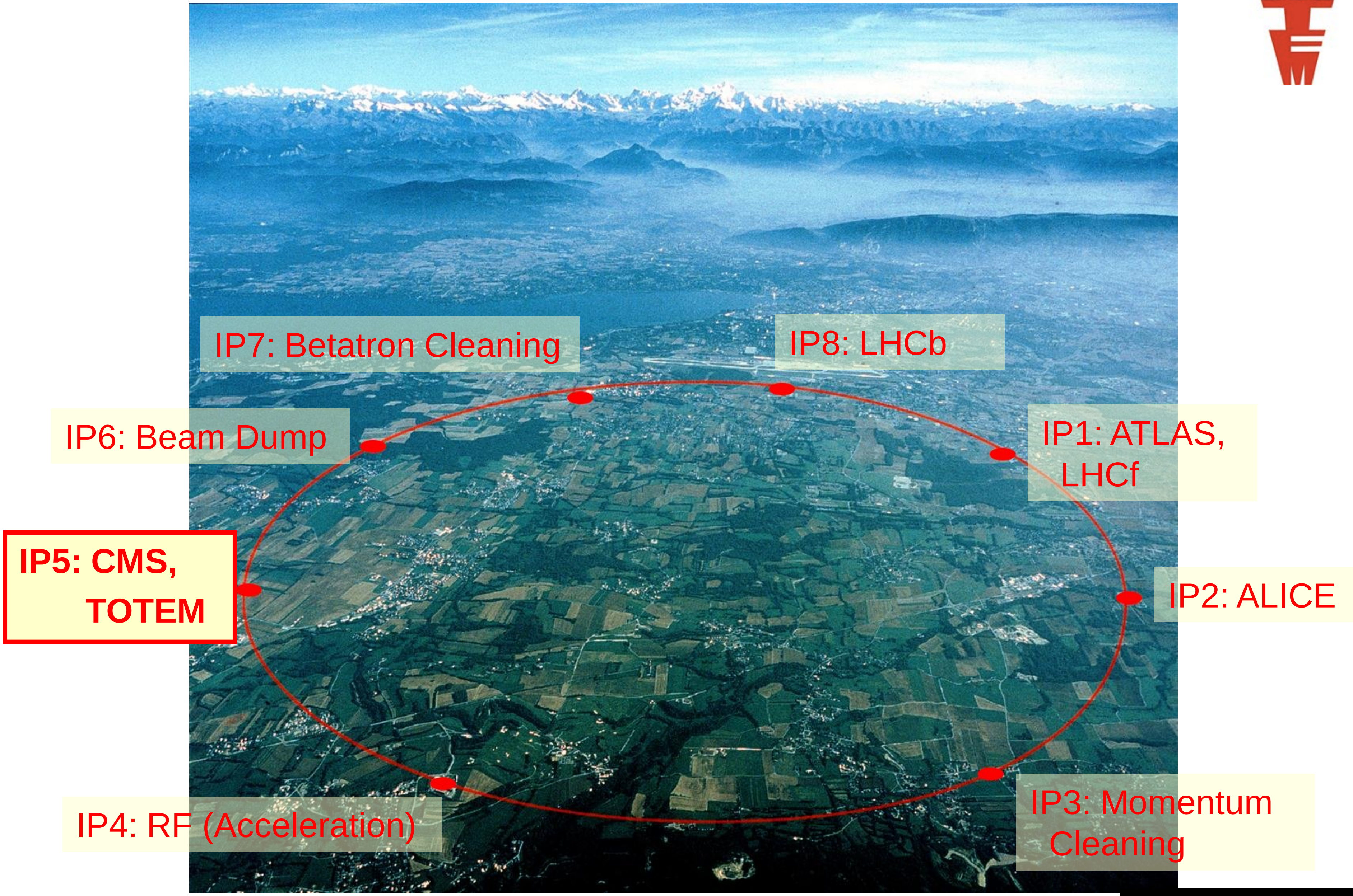
Diffractive and electromagnetic processes
at high energies

Heidelberg, September 2 - 6, 2013

Outline

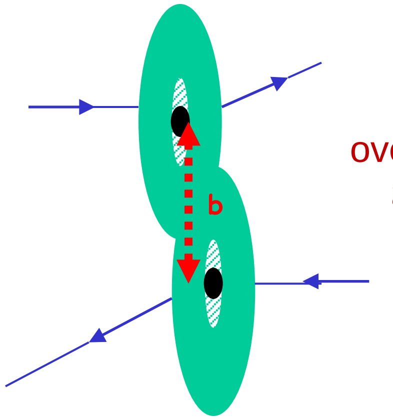
1. The TOTEM Experiment at the LHC:
   Physics objectives and detector apparatus
2. Results:
   a. Elastic pp Scattering
   b. Inelastic and Total Cross-Sections
   c. Diffraction
   d. Forward particle production: pseudorapidity distribution
3. Consolidation and Upgrade Plans

The TOTEM Experiment at the LHC



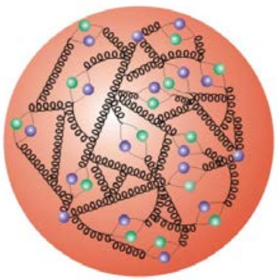
TOTEM Physics Overview

Elastic pp scattering

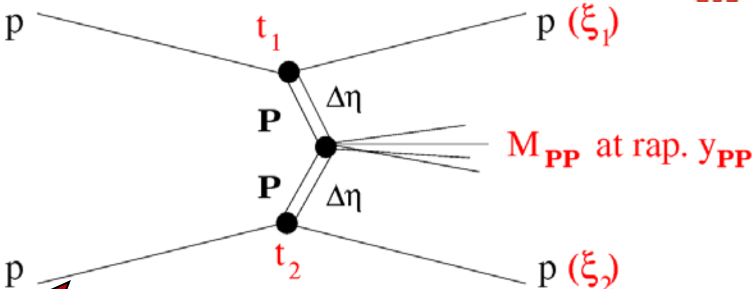


over a wide
t-range

Proton



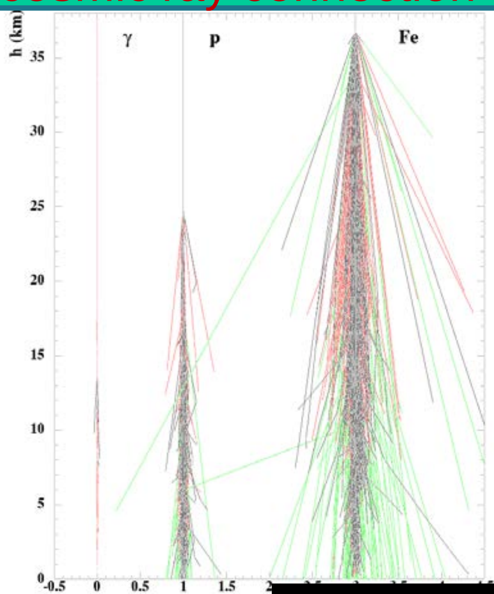
Diffraction: soft and hard



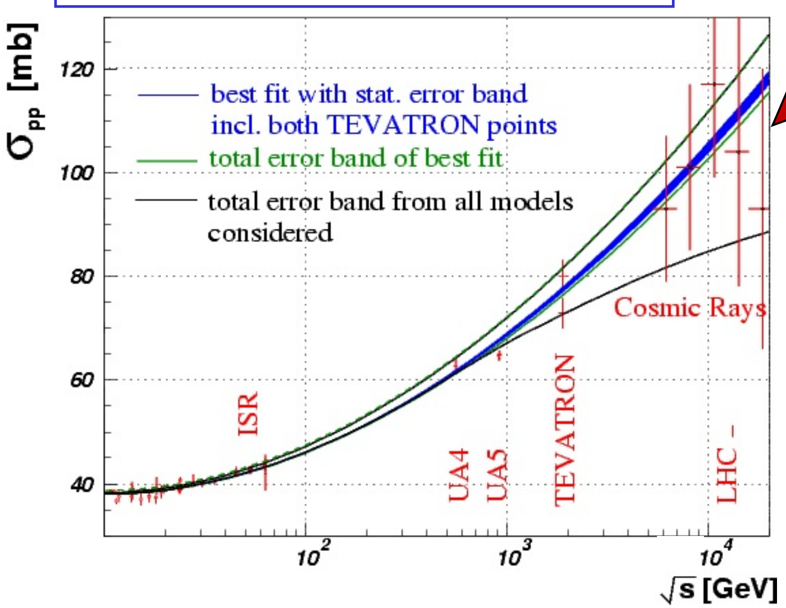
understand
QCD nature

Forward particle production

→ cosmic ray connection



Total pp cross-section



Experimental Setup at IP5

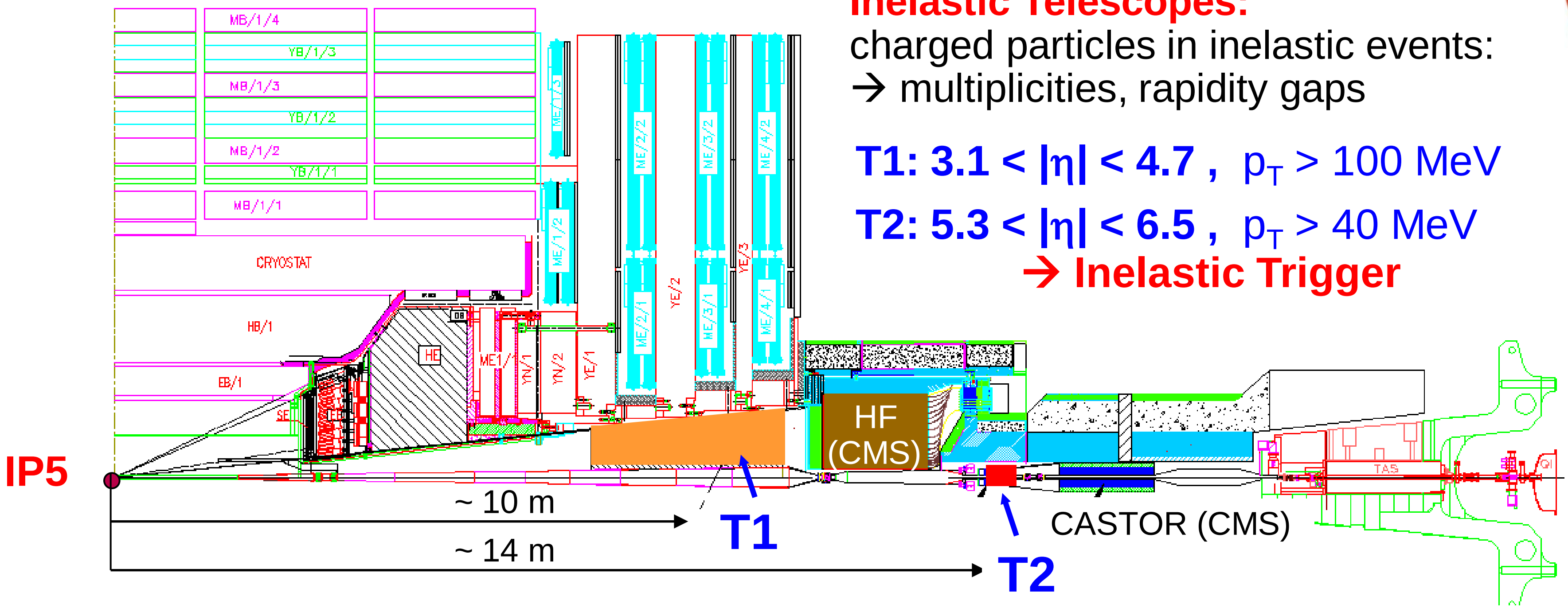
[Ref.: JINST 3 (2008) S08007]

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

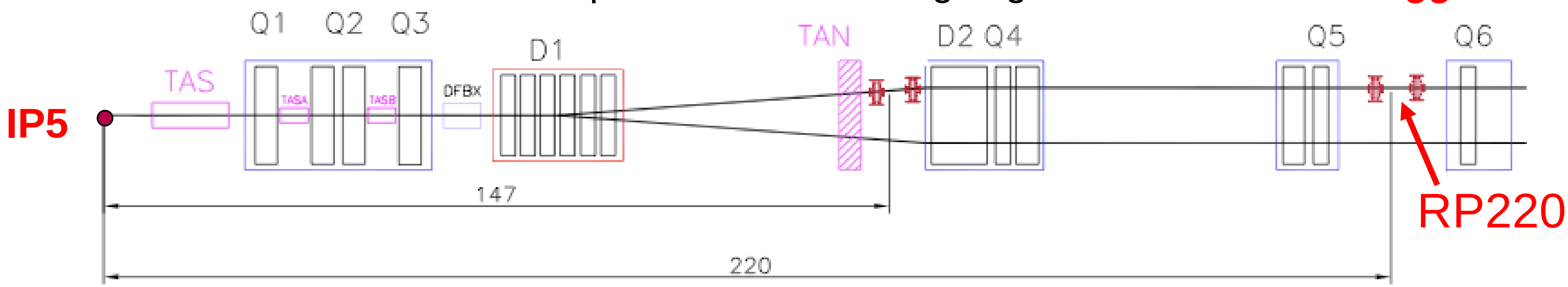
T1: 3.1 < |η| < 4.7 , p_T > 100 MeV

T2: 5.3 < |η| < 6.5 , p_T > 40 MeV

→ Inelastic Trigger

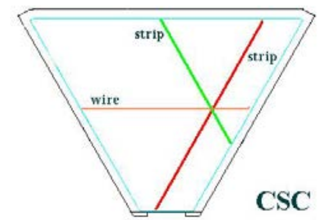


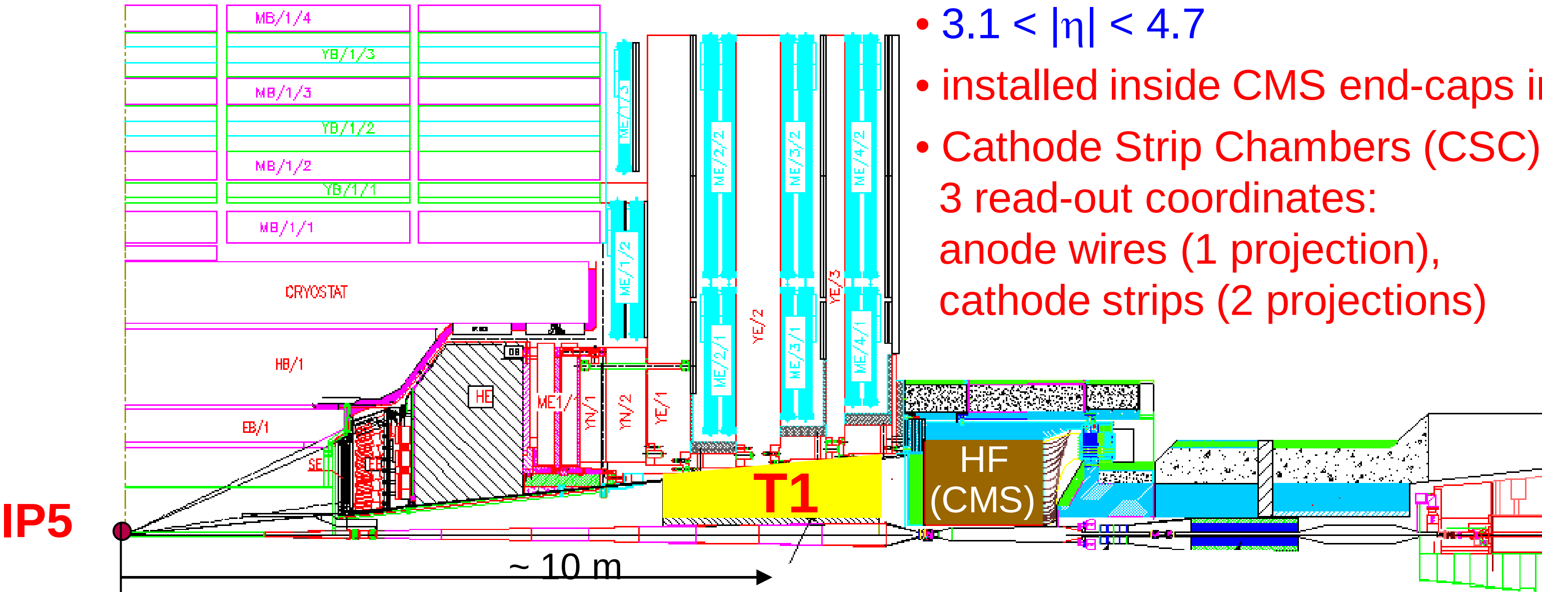
Roman Pots: elastic & diffractive protons close to outgoing beams **→ Proton Trigger**

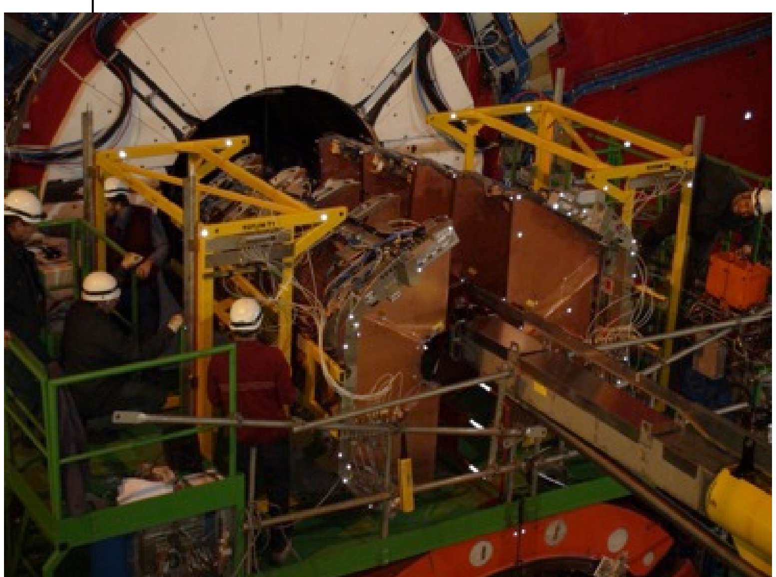


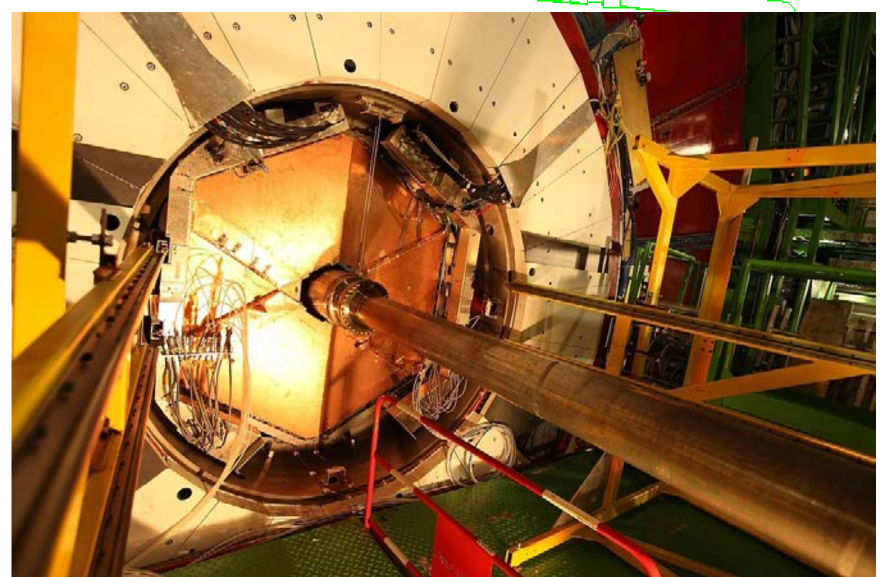
Experimental Setup: T1

- telescope of 5 planes on each side of IP5
- 3.1 < |η| < 4.7
- installed inside CMS end-caps in front of HF
- Cathode Strip Chambers (CSC) with
  3 read-out coordinates:
  anode wires (1 projection),
  cathode strips (2 projections)



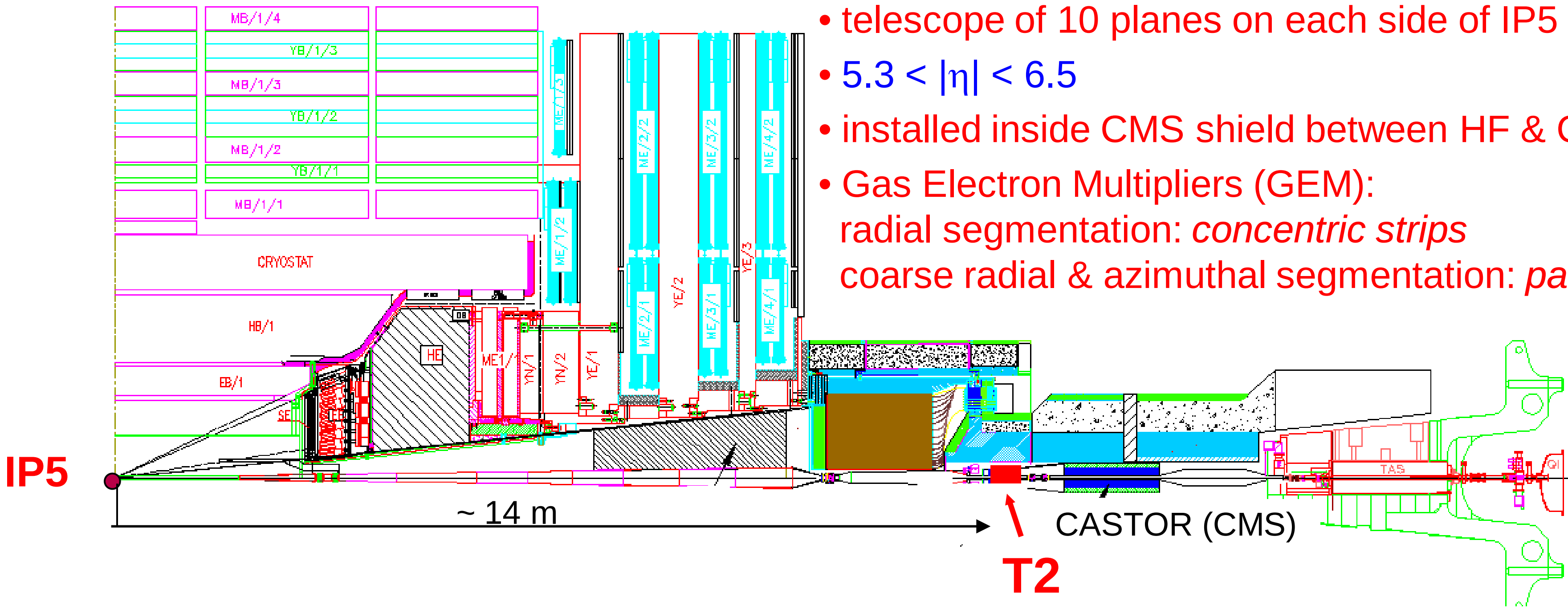


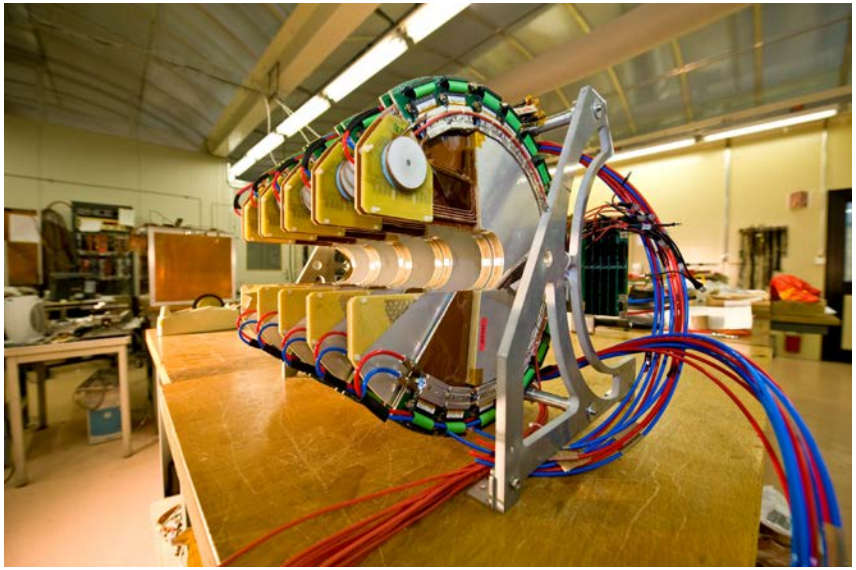


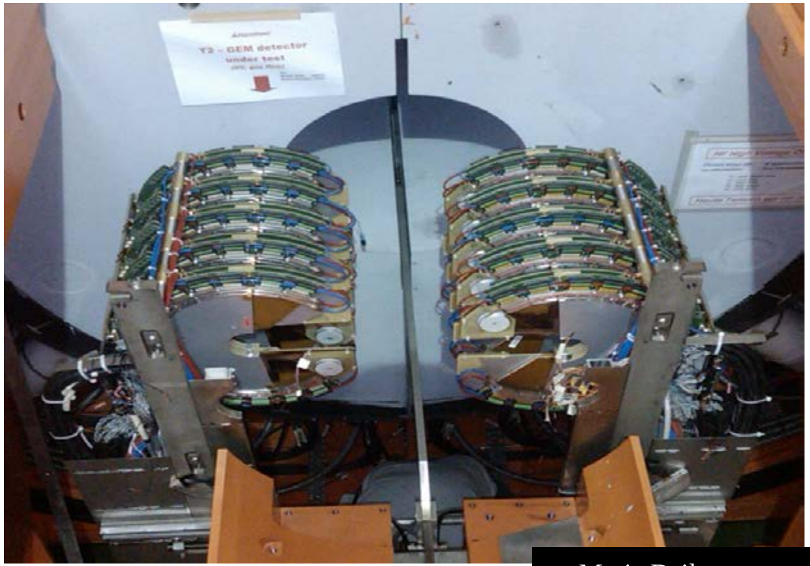


Experimental Setup: T2

- telescope of 10 planes on each side of IP5
- 5.3 < |η| < 6.5
- installed inside CMS shield between HF & Castor
- Gas Electron Multipliers (GEM):
  radial segmentation: *concentric strips*
  coarse radial & azimuthal segmentation: *pads*



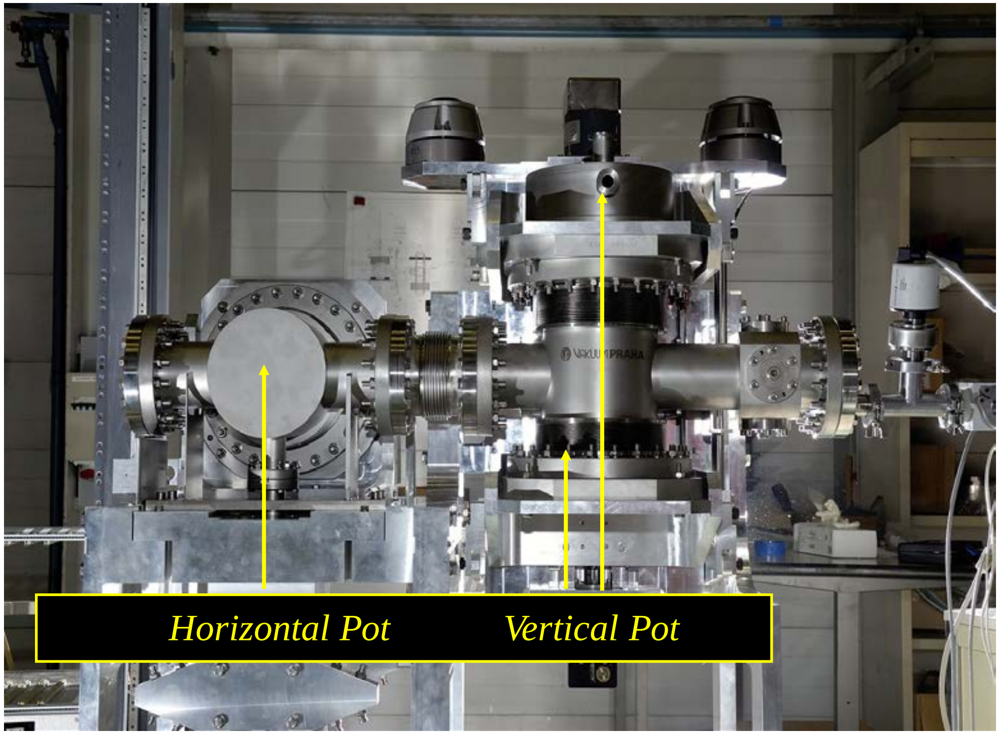


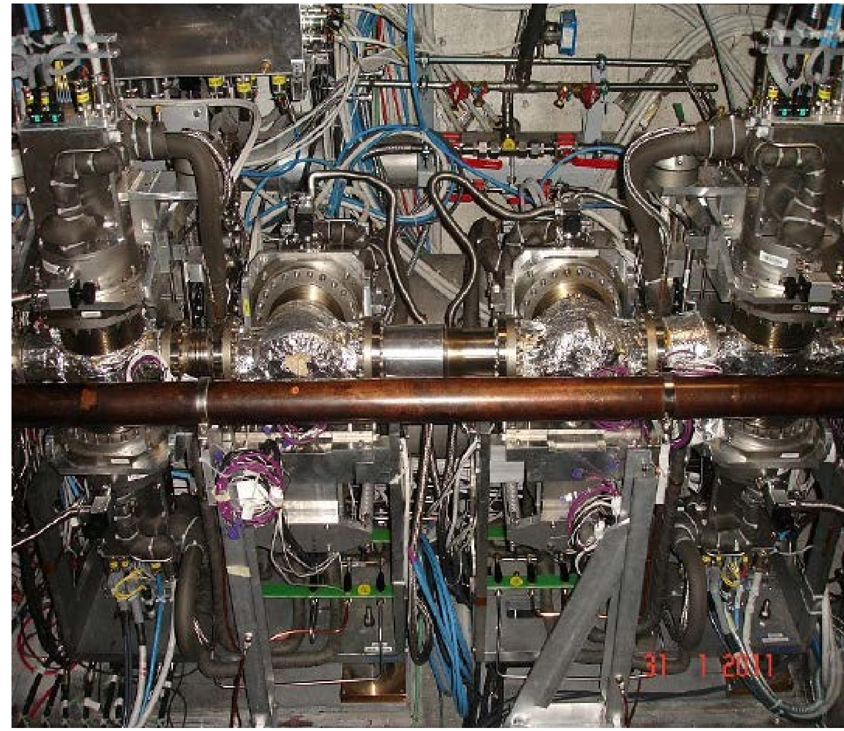


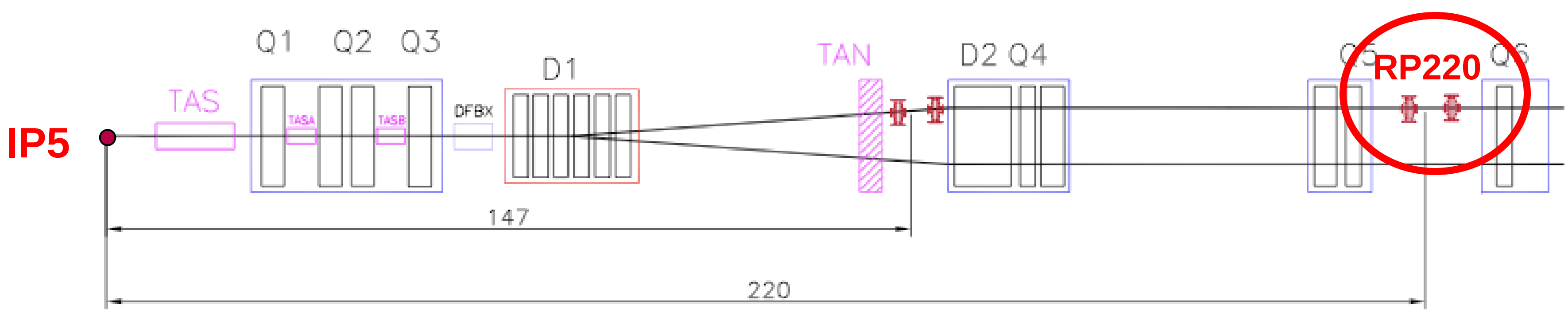
Roman Pots

Roman Pot = movable box inside the beam pipe, housing silicon detectors.

Detectors can approach the beam centre to < 1mm when the beams are stable.

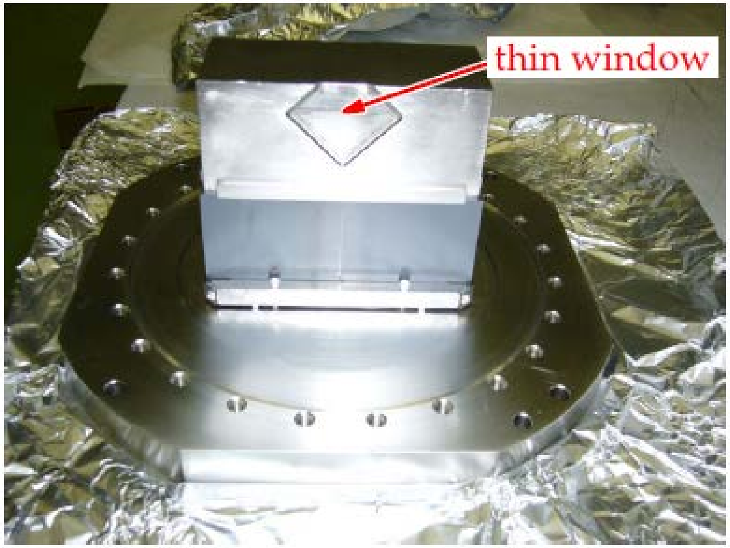




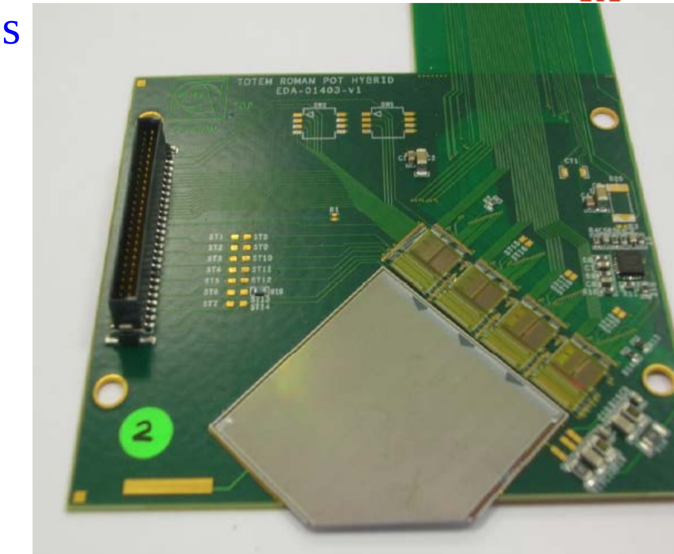


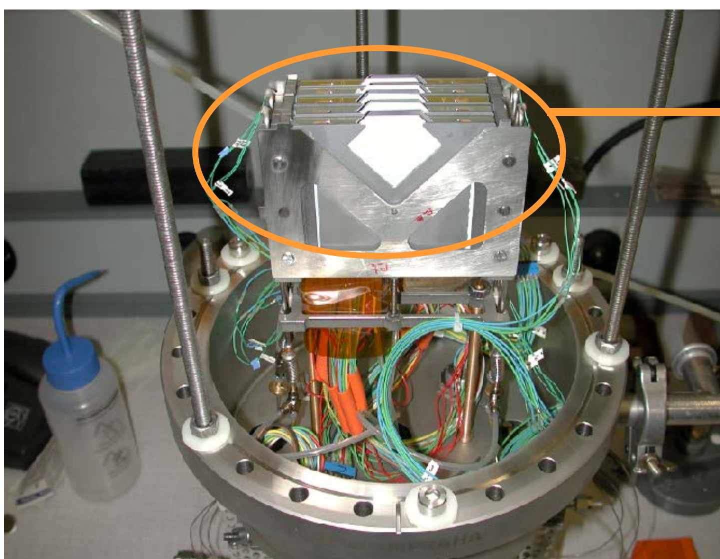
Roman Pot Detector Packages

Detector housing



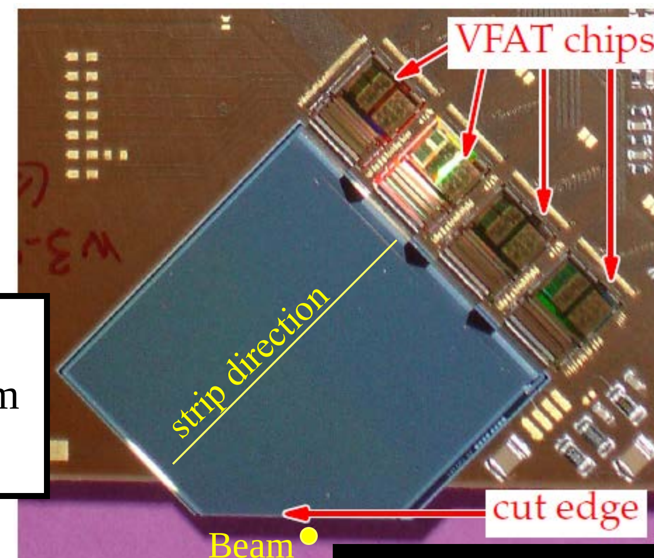
Hybrid board with silicon detector and read-out chips



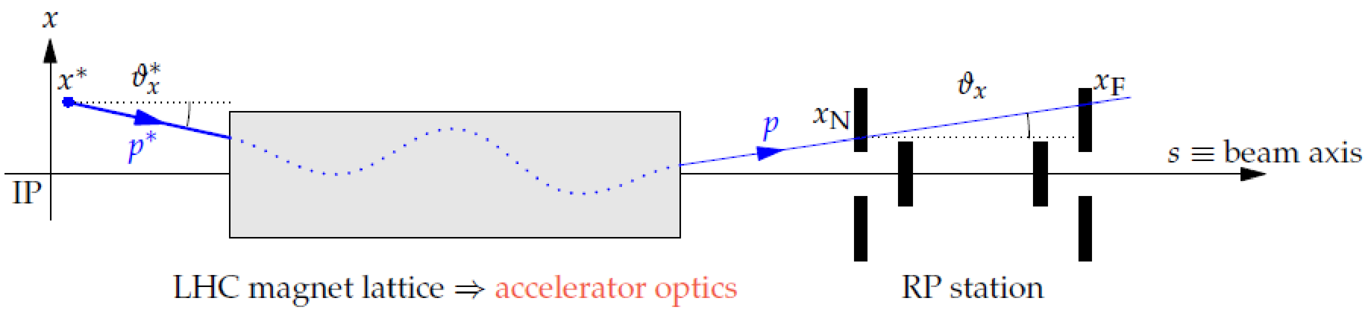


Stack of 10 silicon strip detectors (5 pairs back to back)

"edgeless" silicon sensor (full efficiency at ~ 50 μm from cut edge)



Proton Transport and Reconstruction via Beam Optics



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

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

$\xi = \Delta p/p$: momentum loss (elastic case: $\xi = 0$)

Measured in RP

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

Values at IP5 to be reconstructed

Product of all lattice element matrices

$$x_{RP} = L_x \Theta_x^* + v_x x^* + D_x \xi$$

$$y_{RP} = L_y \Theta_y^* + v_y y^*$$

L_x, L_y: effective lengths (sensitivity to scattering angle)

v_x, v_y: magnifications (sensitivity to vertex position)

D_x : dispersion (sensitivity to momentum loss); $D_y \sim 0$

Reconstruction of proton kinematics = inversion of transport equation

Transport matrix elements depend on ξ ➔ non-linear problem (except in elastic case!)

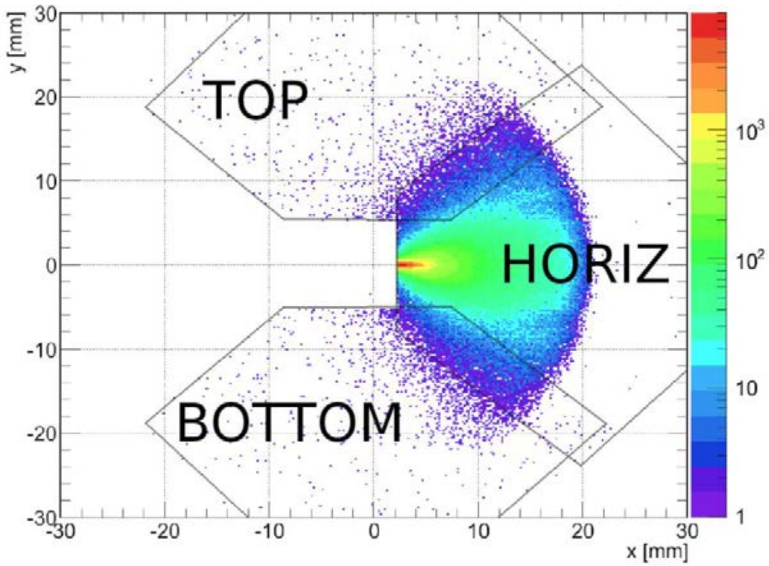
Excellent optics understanding needed.

Different LHC Optics

Hit maps of simulated diffractive events for 2 optics configurations

(labelled by β* = betatron function at the interaction point)

β* = 0.55 m (low β* = standard at LHC)



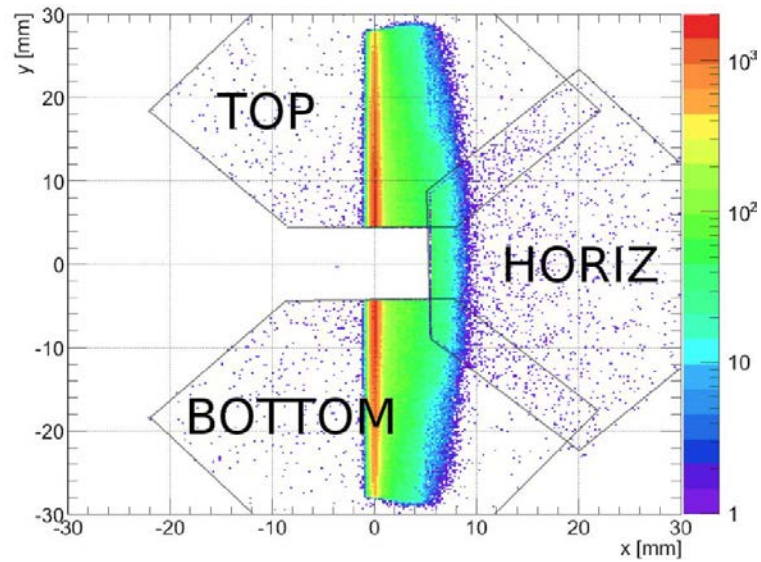
L_x = 1.7 m, L_y = 14 m, D_x = 8 cm

diffractive protons: mainly in **horizontal** RP

elastic protons: in vertical RP near x ~ 0

sensitivity only for large scattering angles

β* = 90 m (special development for RP runs)



L_x = 0, L_y = 260 m, v_y = 0, D_x = 4 cm

diffractive protons: mainly in **vertical** RP

elastic protons: in narrow band at x ≅ 0,

sensitivity for small vertical scattering angles

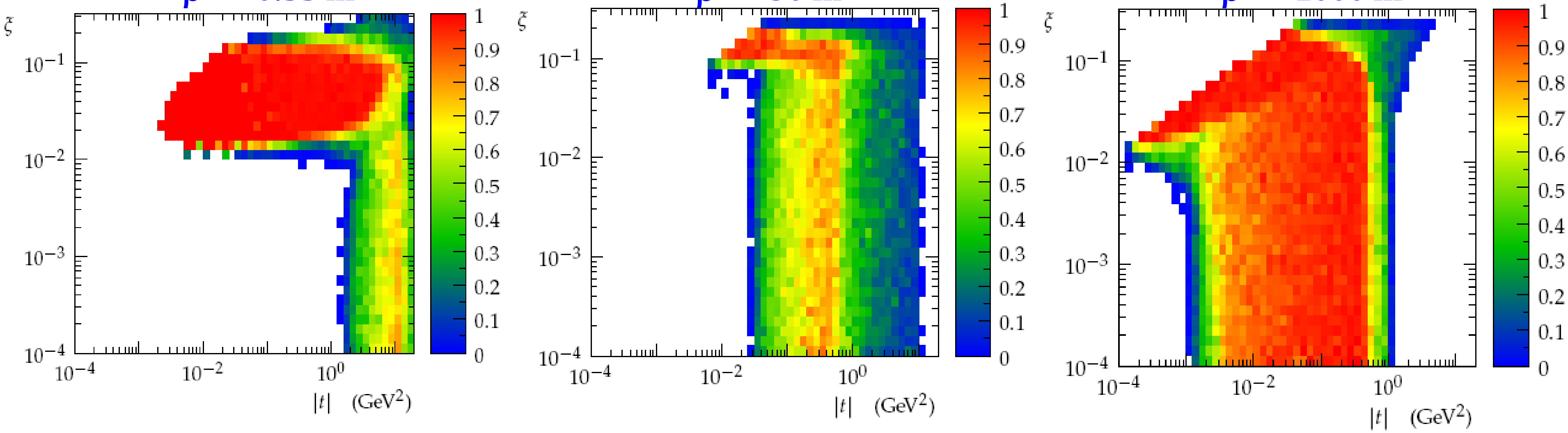
	Beam width @ vertex	Angular beam divergence	Min. reachable |t|
	$\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}}$	$\sigma(\Theta^*_{x,y}) = \sqrt{\frac{\varepsilon_n}{\beta^* \gamma}}$	$\|t_{\min}\| = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$
β* ~ 0.5–3.5 m	small	large	~ 0.3–1 GeV²
β* = 90 m	large	small	~ 10^{-2} GeV²

LHC Optics and TOTEM Running Scenario

Acceptance for diffractive protons:

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

β* = 0.55 m **β* = 90 m** **β* = 1000 m**



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

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

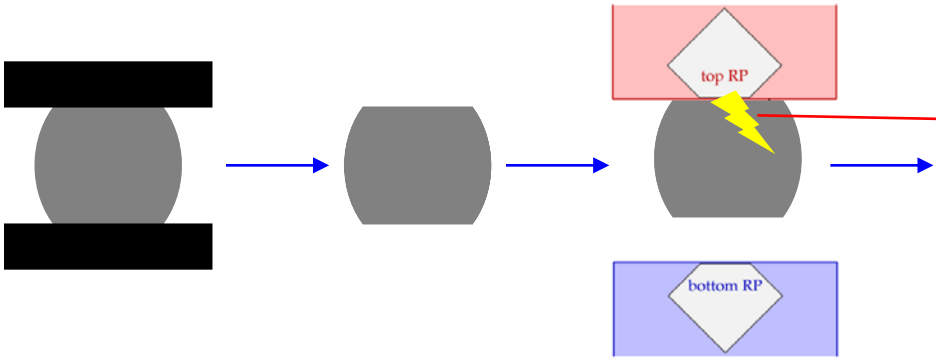
Beam-Based Roman Pot Alignment (Scraping)

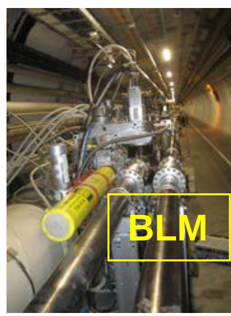
Standard Procedure for LHC Collimators

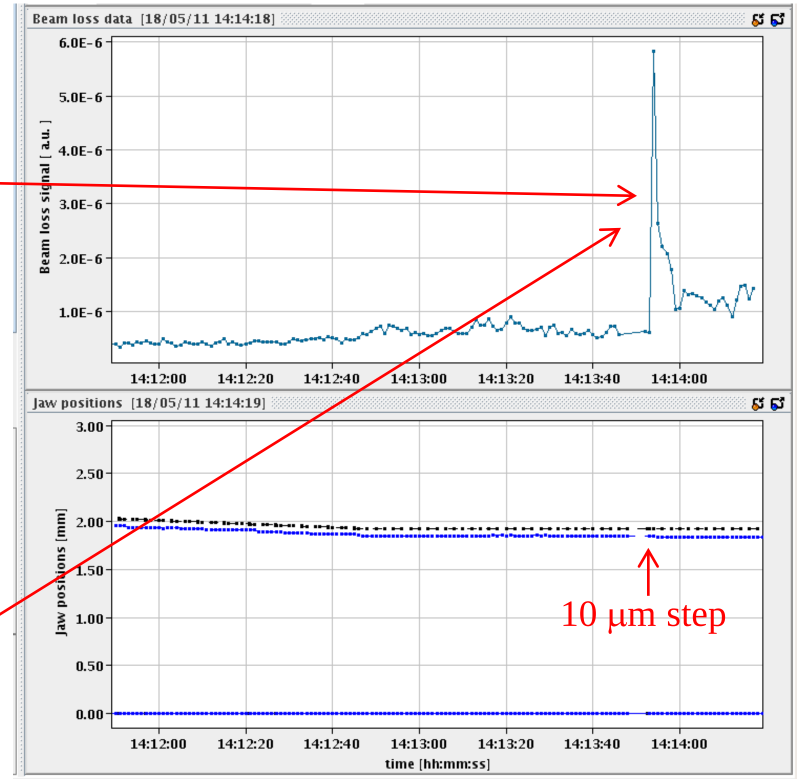
A primary collimator cuts a sharp edge into the beam, symmetrical to the centre

The top RP approaches the beam until it touches the edge

The last 10 μm step produces a spike in a **Beam Loss Monitor** downstream of the RP







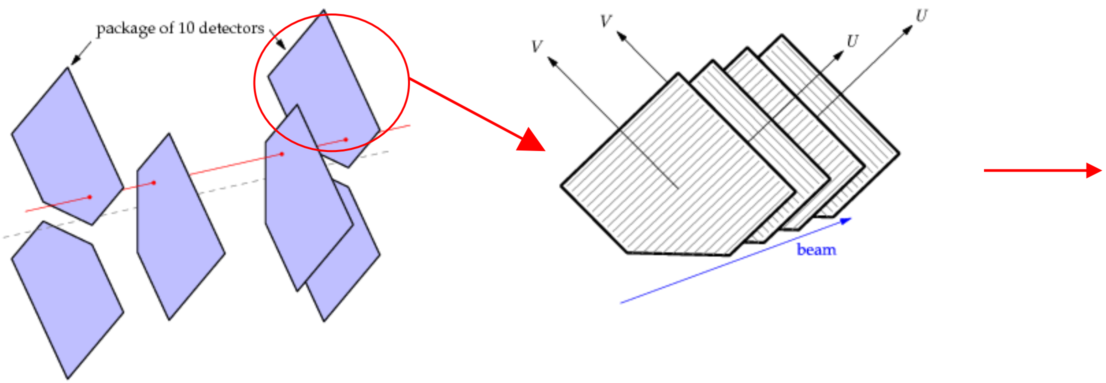
When both top and bottom pots are touching the beam edge:

- they are at the same number of sigmas from the beam centre as the collimator
- the beam centre is exactly in the middle between top and bottom pot

→ **Alignment of the RP windows relative to the beam (~ 20 μm)**

Software Alignment

Track-Based Alignment

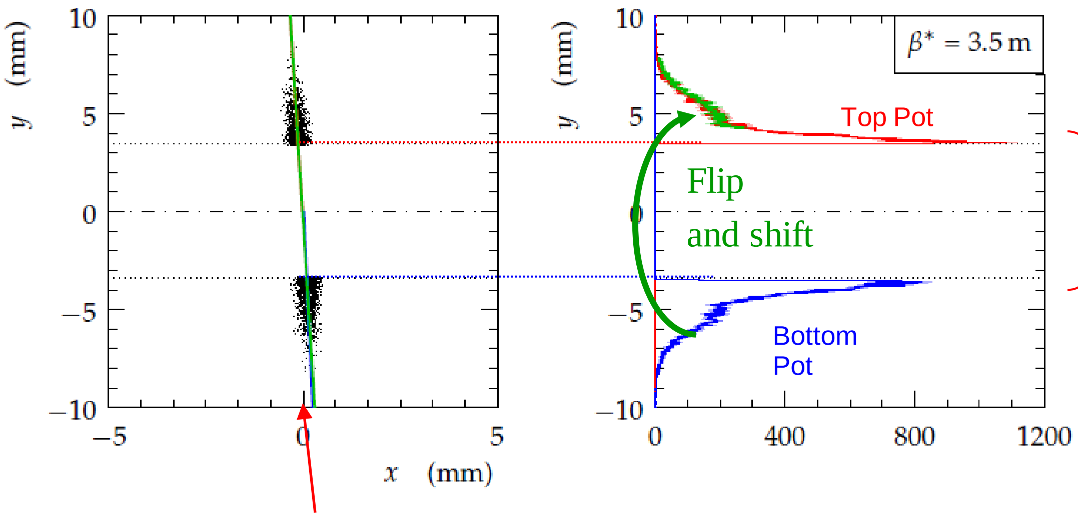


Residual-based alignment technique: shifts and rotations within a RP unit

Important: overlap between horizontal and vertical detectors !

Alignment Exploiting Symmetries of Hit Profiles

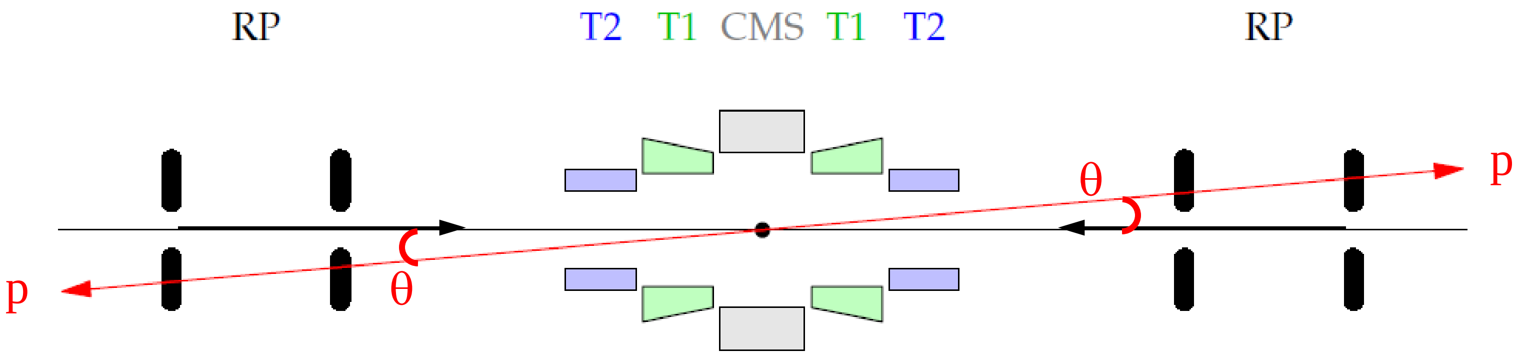
Map of all track intercepts after elastic selection



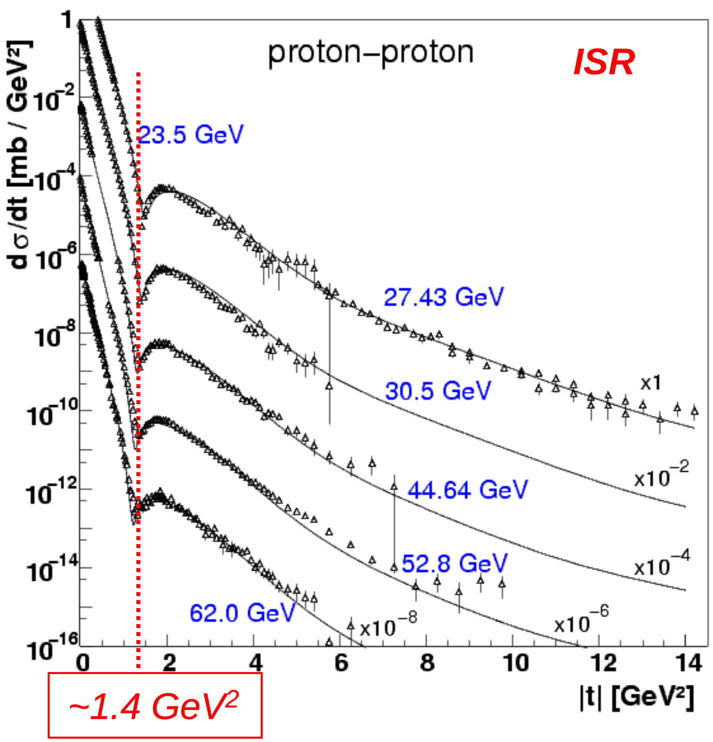
Fine vertical alignment: about 20 μm precision

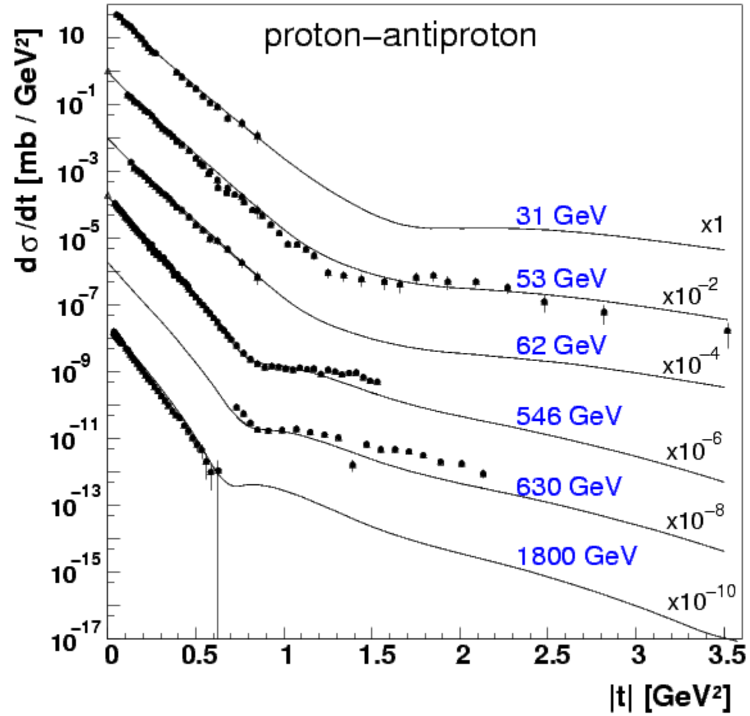
→ Fine horizontal alignment: precision better than 10 μm

pp Elastic Scattering
7 TeV
8 TeV



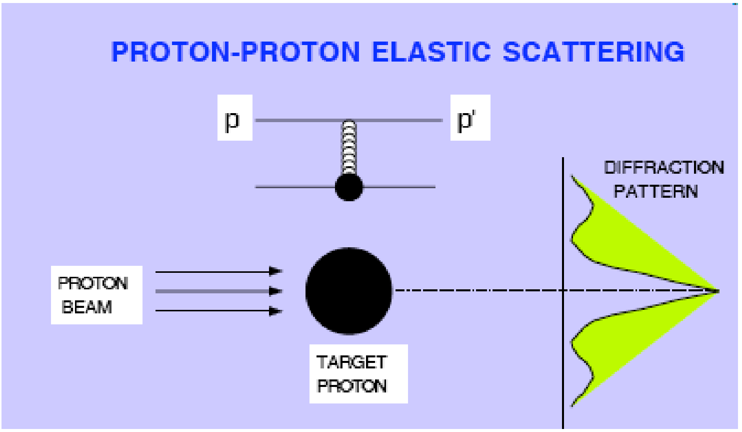
Elastic scattering – from ISR to Tevatron





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

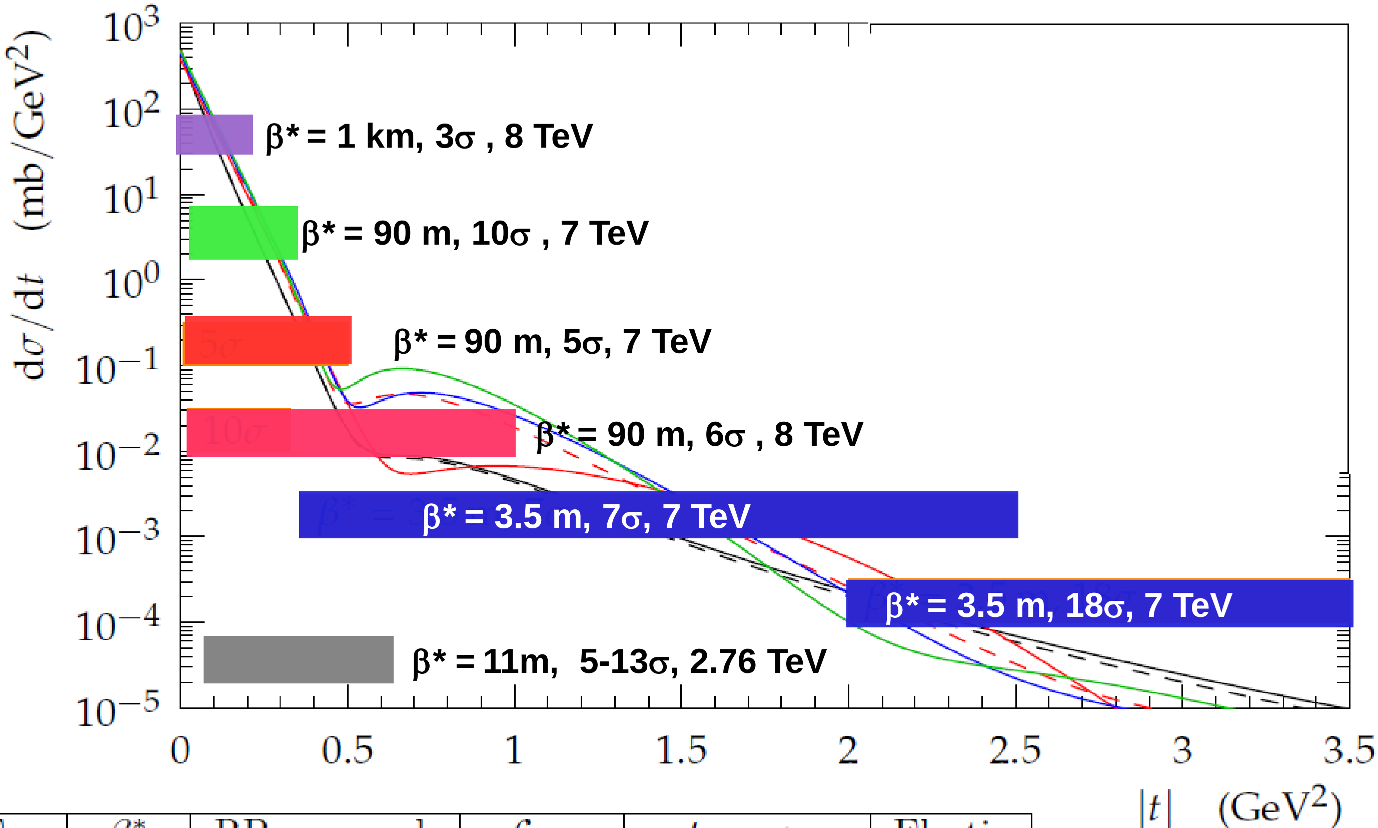
Diffractive minimum: analogous to Fraunhofer diffraction:



- *exponential slope B at low |t| increases*
- *minimum or shoulder moves to lower |t| with increasing s*
  → *interaction region grows (as also seen from σ_{tot})*
- *depth of minimum changes*
  → *shape of proton profile changes*
- *depth of minimum differs between pp, $\bar{p}p$*
  → *different mix of processes*

Elastic Scattering: Data Collection

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

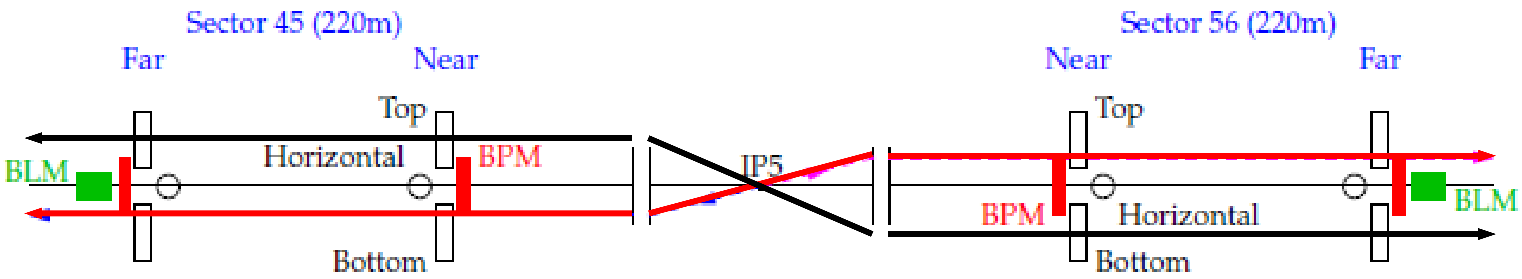


E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events
7	90	4.8-6.5σ	83	$7\cdot10^{-3}$ - 0.5	1M
	90	10σ	1.7	0.02 - 0.4	14k
	3.5	7σ	0.07	0.36 - 3	66k
	3.5	18σ	2.3	2 - 3.5	10k
8	90	6-9σ	60	0.01 - 1	0.6M
	1000	3σ	20	$6\cdot10^{-4}$ - 0.2	0.4M
2.76	11	5-13σ		0.05-0.6	45k

[EPL 101 (2013) 21002]
[EPL 96 (2011) 21002]
[EPL 95 (2011) 41001]

Elastic pp Scattering: Event Topology and Hit Maps

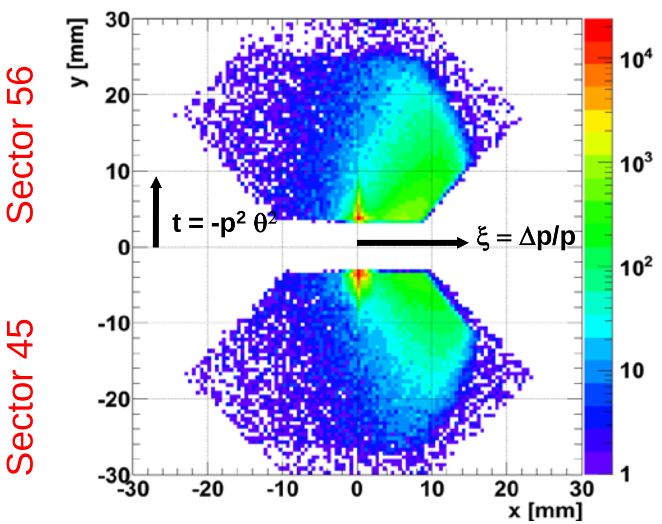
Two diagonals analysed independently



Hit Maps of a single diagonal (left-right coincidences)

β^*=3.5m

RP @ 7σ

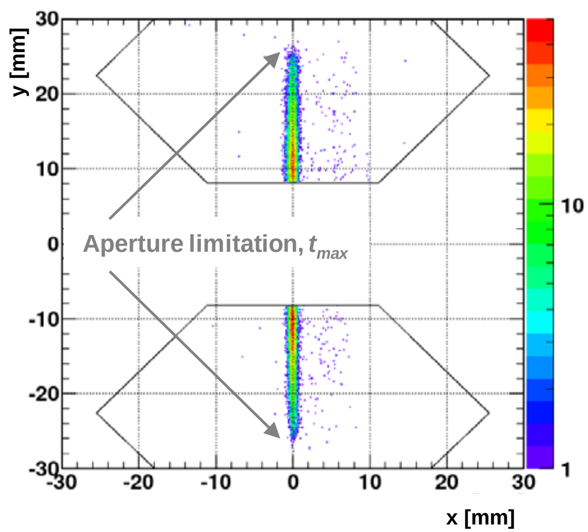


7 x10^{10} protons per bunch

Inelastic pile-up ~ 0.8 ev. / bx

β^*=90m

RP @ 10σ

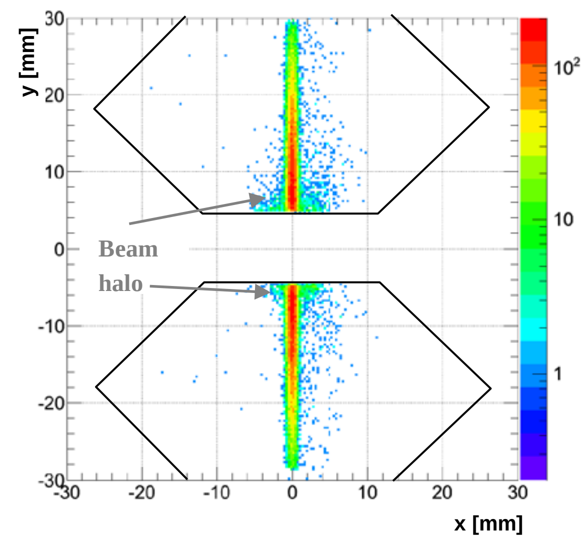


1.5 x10^{10} protons per bunch

Inelastic pile-up ~ 0.005 ev. / bx

β^*=90m

RP @ 5σ



6 x10^{10} protons per bunch

Inelastic pile-up ~ 0.03 ev. / bx

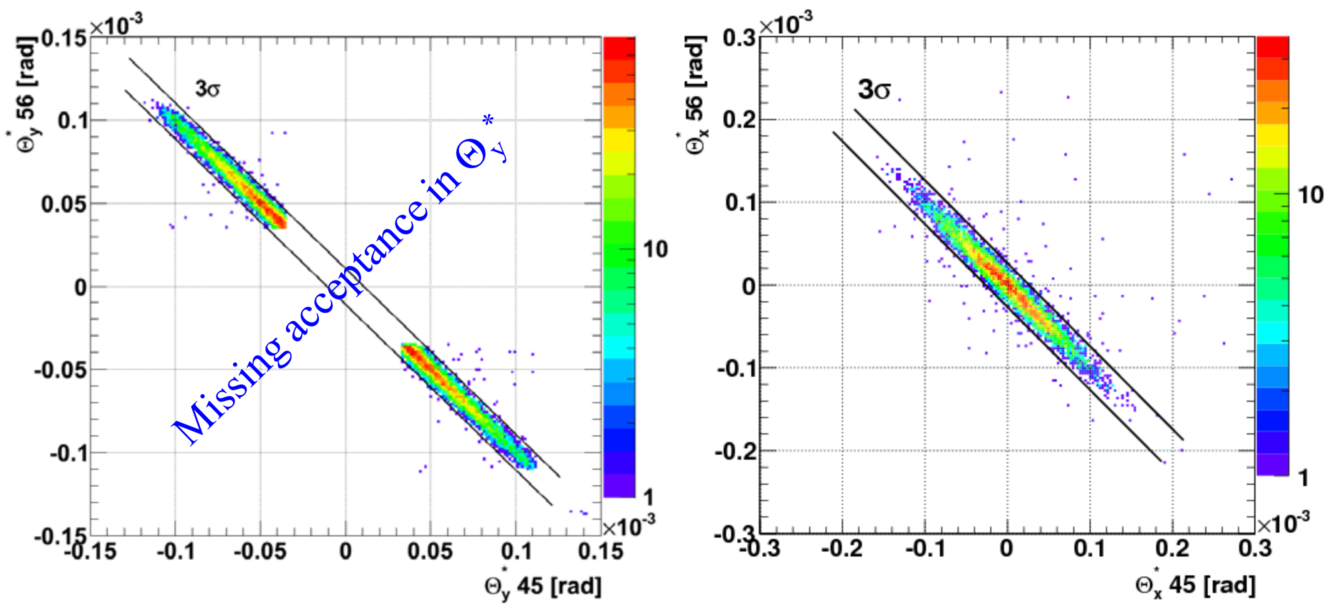
Elastic Tagging

Selection cuts:

number	cut	RMS	
diagonal	track reconstructed in all 4 diagonal RPs		
1	$\theta_x^{*R} - \theta_x^{*L}$	$9.2\,\mu$rad	collinearity
2	$\theta_y^{*R} - \theta_y^{*L}$	$3.5\,\mu$rad	collinearity
3	$\lvert x^{*R} \rvert$	$200\,\mu$m	low $\lvert\xi\rvert$
4	$\lvert x^{*L} \rvert$	$200\,\mu$m	low $\lvert\xi\rvert$
5	$\alpha\, y^{R,N} - (y^{R,F} - y^{R,N})$	$17\,\mu$m	low $\lvert\xi\rvert$
6	$\alpha\, y^{L,N} - (y^{L,F} - y^{L,N})$	$17\,\mu$m	low $\lvert\xi\rvert$
7	$x^{*R} - x^{*L}$	$9\,\mu$m	common vertex for both protons

Example: elastic collinearity : Scattering angle on one side versus the opposite side

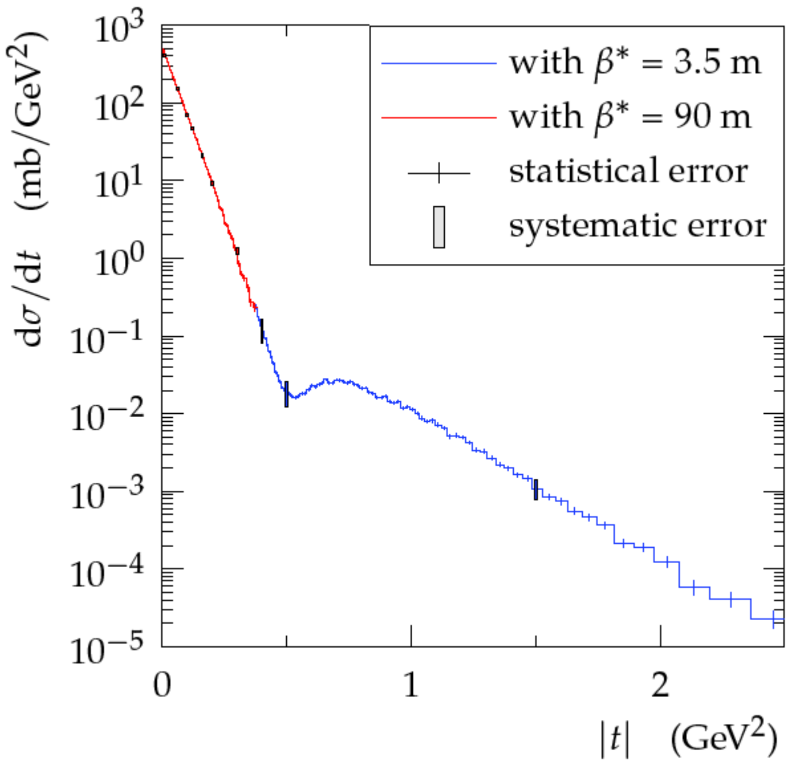
Collinearity in y | Collinearity in x



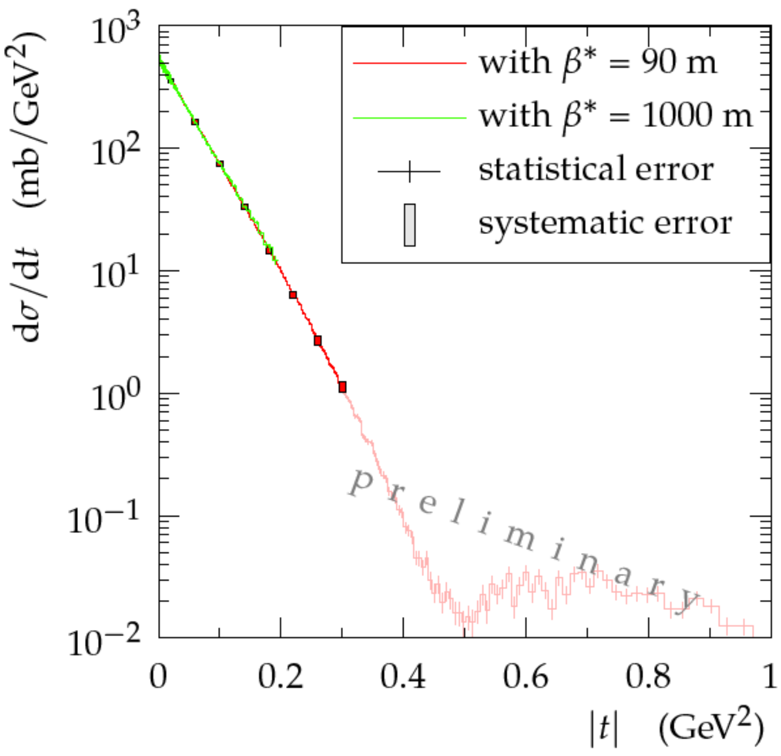
Width of correlation band in agreement with beam divergence (~ 2.4 μrad)

Elastic pp Scattering at 7 and 8 TeV: Differential Cross-Sections

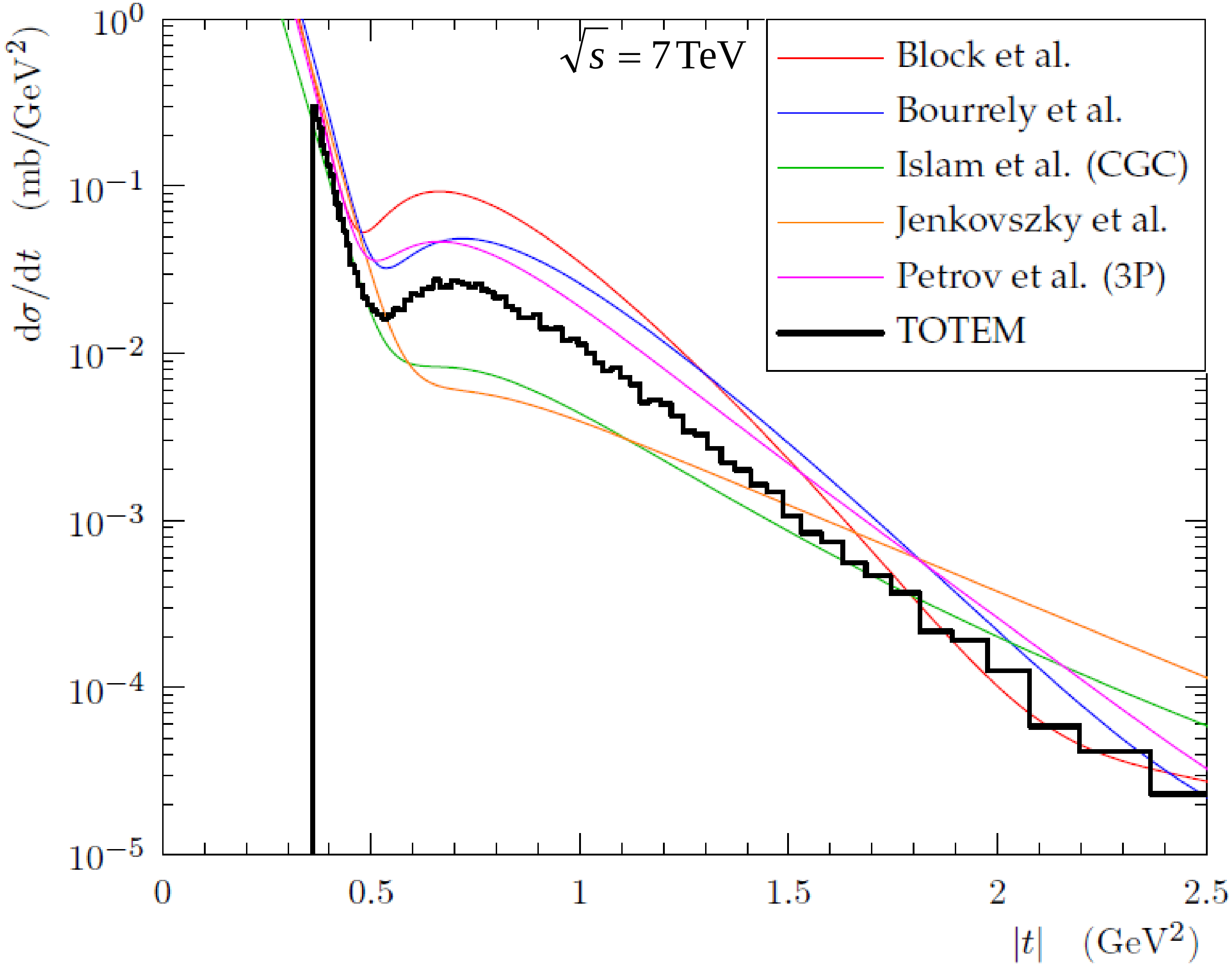
$\sqrt{s} = 7\,\mathrm{TeV}$



$\sqrt{s} = 8\,\mathrm{TeV}$

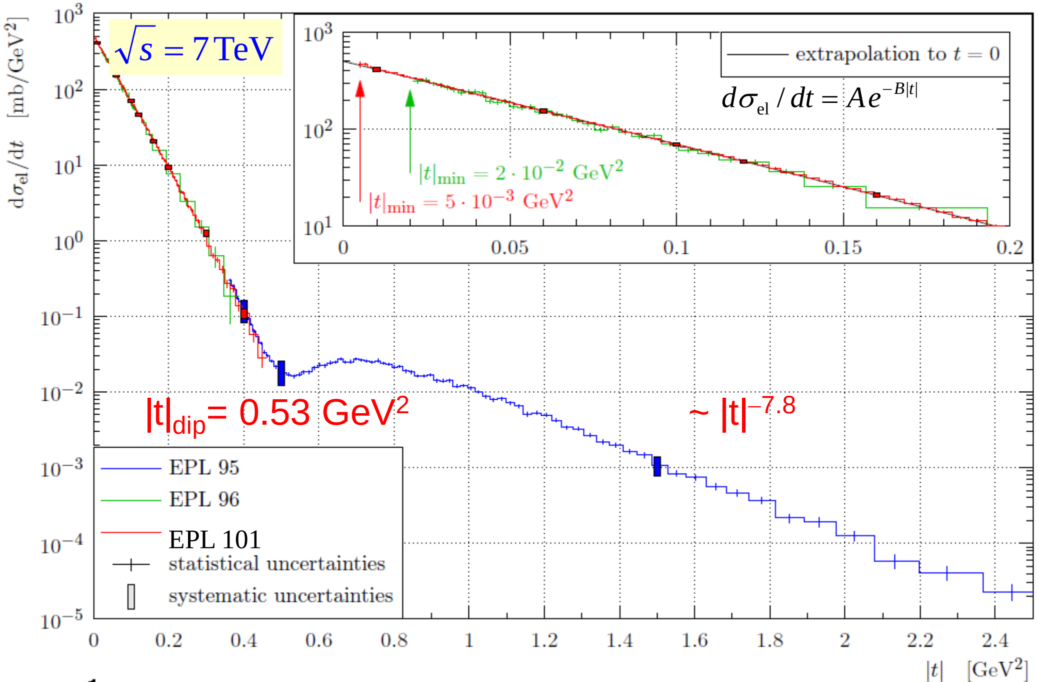


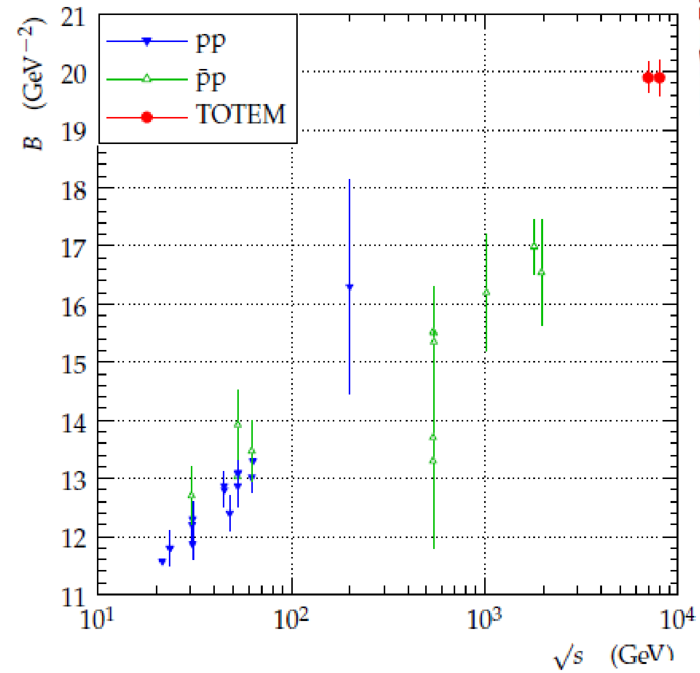
Model Comparisons

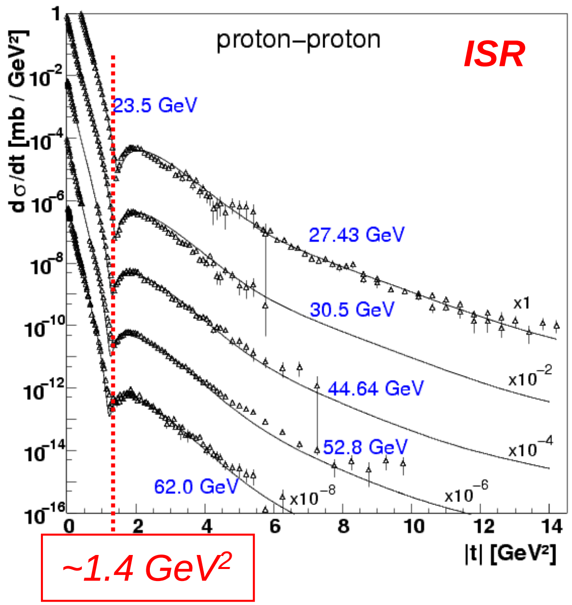


No theoretical / phenomenological model describes the TOTEM data completely.

Some Lessons on Hadronic Elastic pp Scattering







At low |t|: nearly exponential decrease:

B_{7TeV} = (19.89 ± 0.27) GeV^{-2}

B_{8TeV} = (19.90 ± 0.30) GeV^{-2}

Old trends for increasing s are confirmed:

- "shrinkage of the forward peak": minimum moves to lower |t|
- forward exponential slope B increases

Inelastic and Total pp Cross-Section Measurements

7 TeV

8 TeV

First measurements of the total proton-proton cross section at the LHC energy of $\sqrt{s}$ = 7TeV
[EPL 96 (2011) 21002]

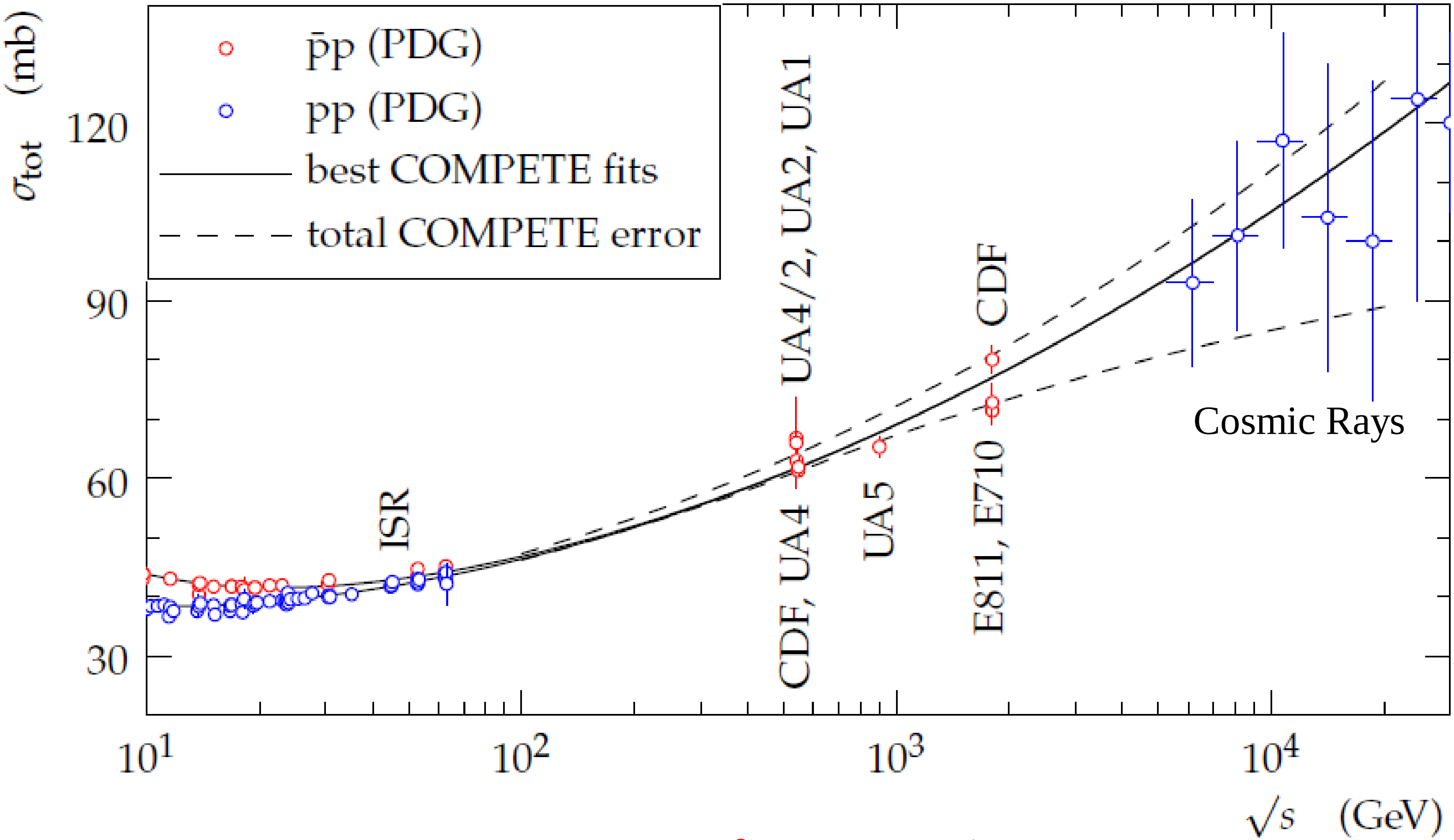
Measurement of proton-proton elastic scattering and total cross-section at $\sqrt{s}$ = 7 TeV
[EPL 101 (2013) 21002]

Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s}$ = 7 TeV
[EPL 101 (2013) 21003]

Luminosity-independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s}$ = 7 TeV
[EPL 101 (2013) 21004]

A luminosity-independent measurement of the proton-proton total cross-section at $\sqrt{s}$ = 8 TeV
[Phys. Rev. Lett. 111, 012001 (2013)]

Total pp Cross-Section: Status before TOTEM



$\sigma_{tot} \propto \ln s$? $\ln^2 s$? $s^{\alpha-1}$?

[COMPETE: J. Cudell et al., PRL 89 (2002) 201801]

3 Ways to the Total Cross-Section

Optical Theorem: $\sigma_{tot}^2 \propto \left[\Im F_{el,had}(t=0)\right]^2 = \frac{1}{1+\rho^2}\left|F_{el,had}(t=0)\right|^2$ with $\rho = \left.\frac{\Re F_{el,had}}{\Im F_{el,had}}\right|_{t=0}$

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

7 TeV

elastic observables only:

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

(ρ=0.14 [COMPETE extrapol.])

June 2011 (EPL96): σ_{tot} = (98.3 ±2.8) mb

Oct. 2011 (EPL101): σ_{tot} = (98.6 ±2.2) mb

different beam intensities !

σ_{tot}

ϱ independent:

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

σ_{tot} = (99.1 ± 4.3) mb

luminosity independent:

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

σ_{tot} = (98.0 ± 2.5) mb

Excellent agreement between cross-section measurements at 7 TeV using

- runs with different bunch intensities,
- different methods with different external inputs.

Inelastic Cross-Section Measurement

7 TeV

T2 sees ~95 % of inelastic events (detection of 1 track is enough!)

Corrections to the T2 visible events

- Trigger Inefficiency: **2.3 ± 0.7 %**
  (measured from zero bias data with respect to track multiplicity)

- Track reconstruction efficiency: **1.0 ± 0.5 %**
  (based on MC tuned with data)

- Beam-gas background: **0.6 ± 0.4%**
  (measured with non colliding bunch data)

- Pile-up (μ =0.03): **1.5 ± 0.4%**
  (contribution measured from zero bias data)

$$\sigma_{\text{inelastic, T2 visible}} = 69.7 \pm 0.1\ (\text{stat}) \pm 0.7\ (\text{syst}) \pm 2.8\ (\text{lumi})\ \text{mb}$$

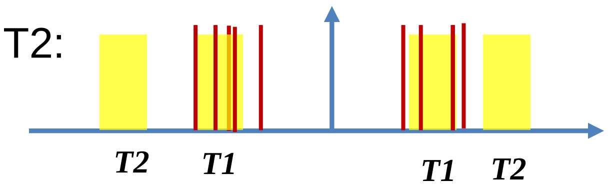
Corrected Inelastic Cross-Section

7 TeV

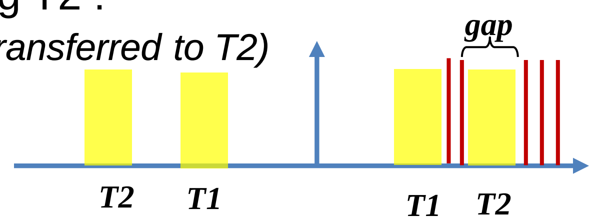
$\sigma_{\text{inelastic, T2 visible}} \Rightarrow \sigma_{\text{inelastic}}$

Missing inelastic cross-section

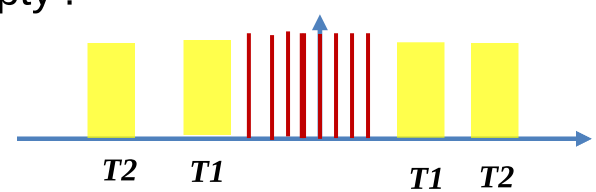
- Events visible in T1 but not in T2: **1.6 ± 0.4 %**
  (estimated from zero bias data)



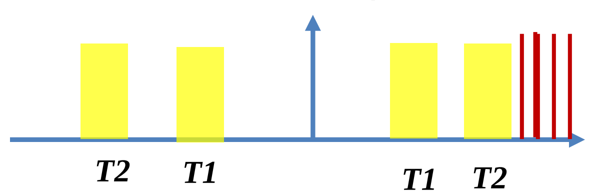
- Fluctuation rapidity gap covering T2 : **0.35 ± 0.15 %**
  (estimated from T1 gap probability transferred to T2)



- Central Diffraction: T1 & T2 empty : **0.0 ± 0.35 %**
  (based on MC)

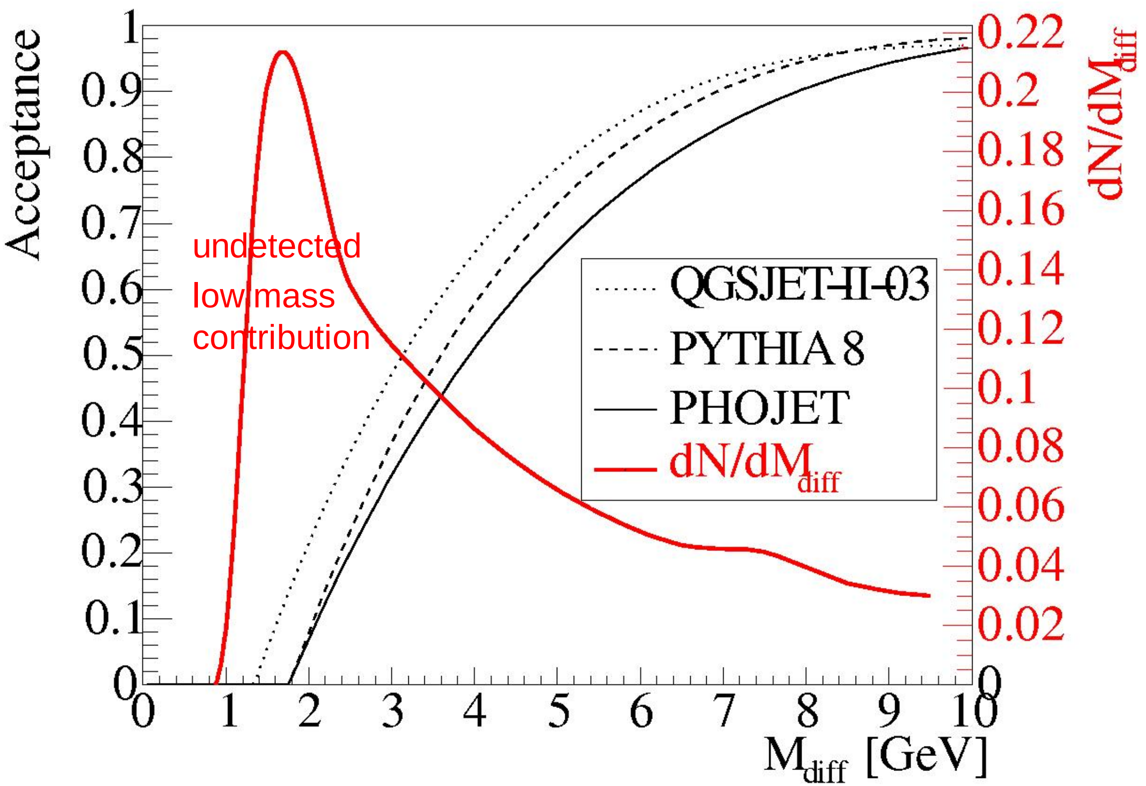


- Low Mass Diffraction : $\sigma_{\text{Mx < 3.4 GeV}}$ **= 3.2 ± 1.6 mb ➔ 4.2 ± 2.1 %**
  *(Several models studied, correction based on **QGSJET-II-3**)*



Low-Mass Diffraction

7 TeV



Correction based on QGSJET-II-3

Correction for the low mass diffractive cross-section: **$\sigma_{Mx < 3.4\ GeV} = 3.2 \pm 1.6$ mb**

$\sigma_{inelastic} = 73.7 \pm 0.1^{(stat)} \pm 1.7^{(syst)} \pm 2.9^{(lumi)}$ mb

Estimate of the Low-Mass Diffractive Cross-Section from the Data

7 TeV

Use the total cross-section determined from elastic observables, $\mathcal{L}$ and ρ

(via the Optical Theorem)

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

➔ $\sigma_{inel} = \sigma_{tot} - \sigma_{el} = 73.15 \pm 1.26$ mb

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

$\sigma_{inel,\ |\eta| < 6.5} = 70.53 \pm 2.93$ mb

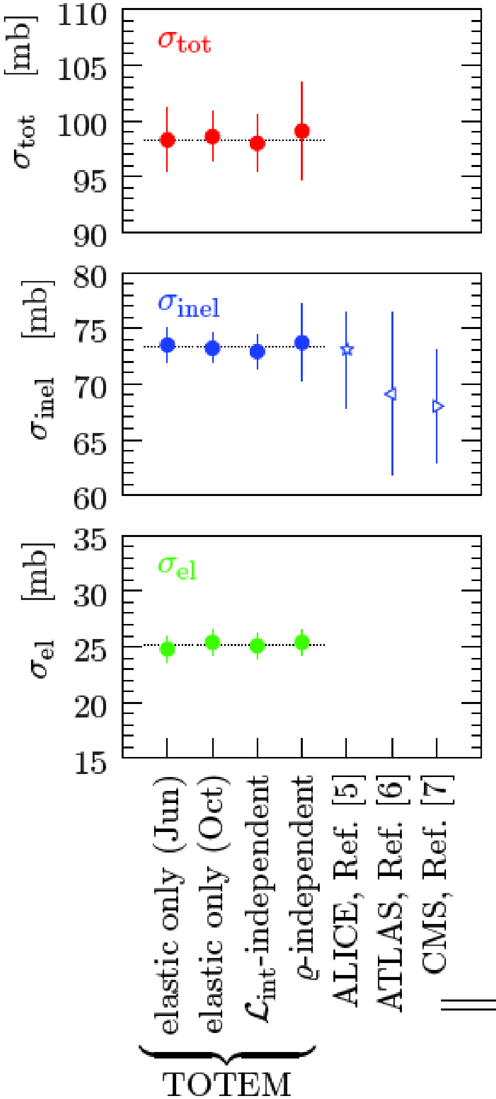
to obtain the low-mass diffractive cross-section ($|\eta| > 6.5$ or $M < 3.4$ GeV):

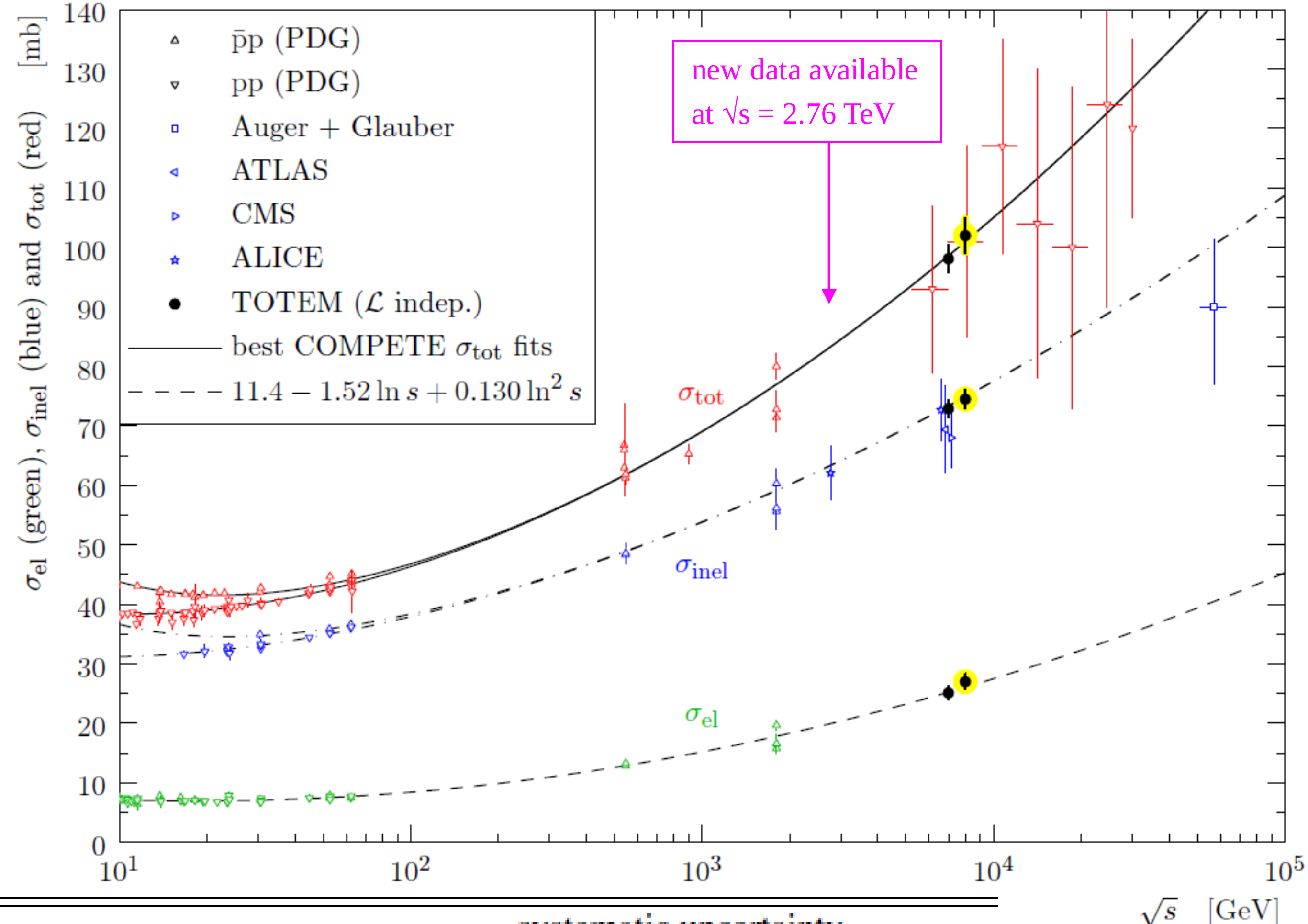
$\sigma_{inel,\ |\eta| > 6.5} = \sigma_{inel} - \sigma_{inel,\ |\eta| < 6.5} = 2.62 \pm 2.17$ mb [MC: 3.2 mb]

< 6.31 mb (95% CL)

pp Cross-Section Measurements

7 TeV





8 TeV

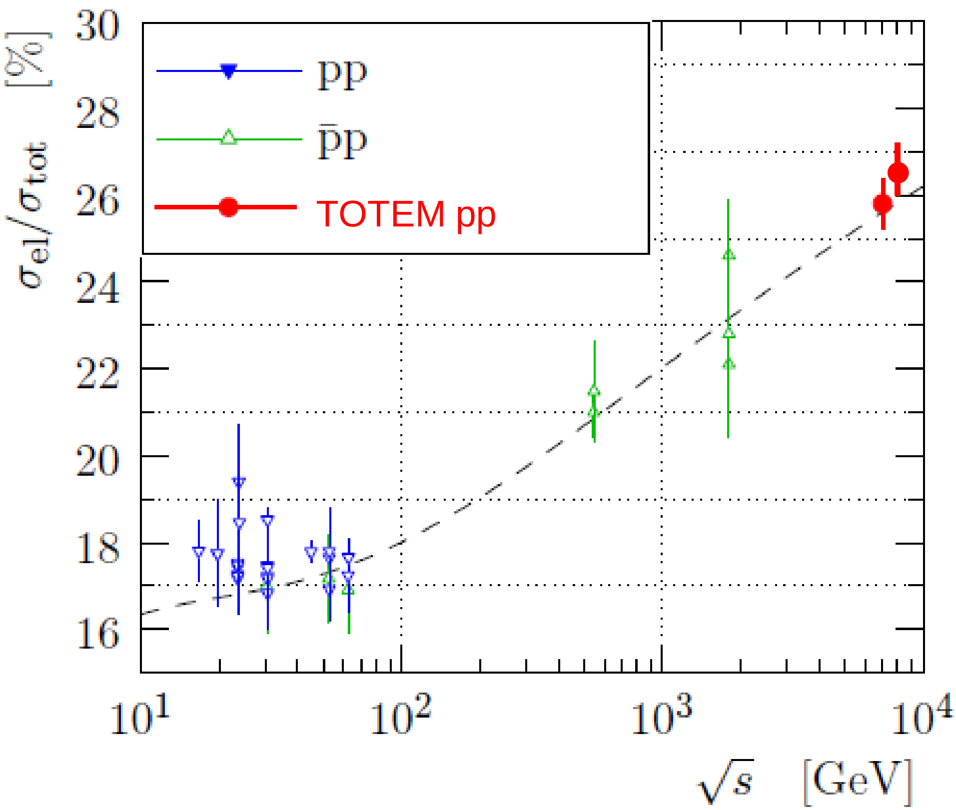
quantity		value	systematic uncertainty				
			el. t-dep	el. norm	inel	ρ	$\Rightarrow$ full
σ_{tot}	[mb]	101.7	±1.8	±1.4	±1.9	±0.2	$\Rightarrow$ ±2.9
σ_{inel}	[mb]	74.1	±1.2	±0.6	±0.9	±0.1	$\Rightarrow$ ±1.7
σ_{el}	[mb]	27.1	±0.5	±0.7	±1.0	±0.1	$\Rightarrow$ ±1.4

Elastic to Total Cross-Section Ratio

$$\frac{\sigma_{el}}{\sigma_{tot}} = \frac{N_{el}}{N_{el} + N_{inel}} =$$

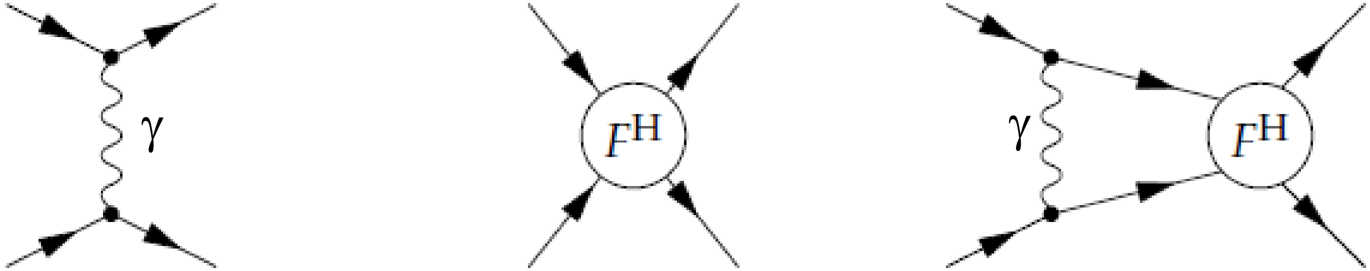
7 TeV	8 TeV
0.257 ± 0.005	0.266 ± 0.006

independent of luminosity and ρ



- ➔ σ_{el} / σ_{tot} increases with energy
- ➔ proton grows / becomes "blacker"

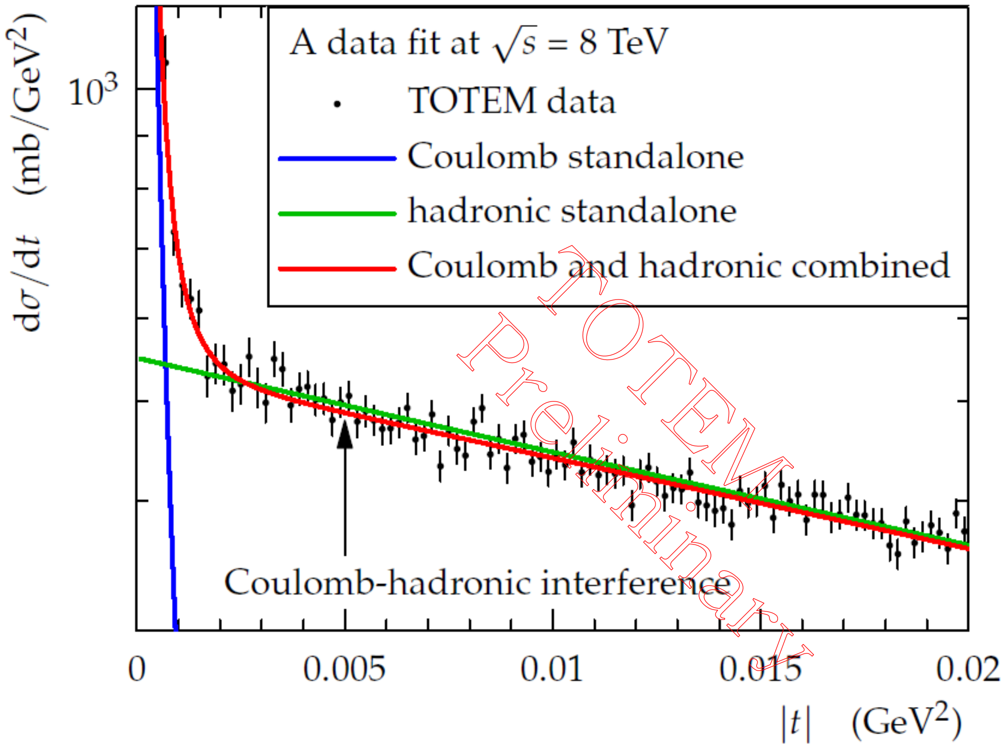
Interference between Hadronic and Coulomb Elastic pp Scattering



Elastic Scattering in the Coulomb-Nuclear Interference Region

Measure elastic scattering at |t| as low as 6 x 10^{-4} GeV^2:

- β^* = 1000 m optics: large effective lengths L_x and L_y, small beam divergence
- RP approach to 3 σ from the beam centre



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

Elastic Scattering in the Coulomb-Nuclear Interference Region

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

Kundrát-Lokajíček formula:

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

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

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

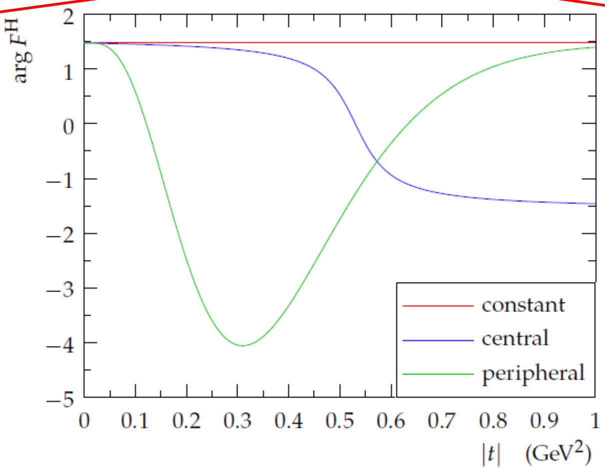
$$F^C = \frac{\alpha s}{t}\mathcal{F}^2(t)$$

- Modulus constrained by measurement: $d\sigma/dt \cong A\, e^{-B(t)\,|t|}$
  $B(t) = b_0 + b_1\, t + \ldots$: described by n > 1 parameters
- Phase $\Phi(t) = \arg(F^H)$: very little guidance by data

?

"central phase":

$$\Phi = \frac{\pi}{2} - \operatorname{atan}\frac{\cot p_0}{1 - \frac{t}{t_d}}$$



?

"peripheral phase":

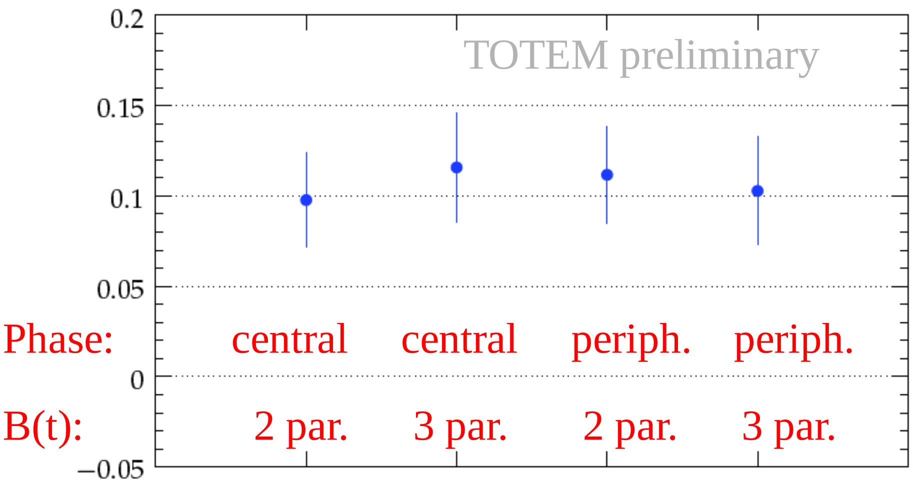
$$\Phi = p_0 + p_A \exp\left[\kappa\left(\ln\frac{t}{t_m} - \frac{t}{t_m} + 1\right)\right]$$

Only 1 free parameter: p_0 ➔ $$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot\Phi(0) = \cot p_0$$

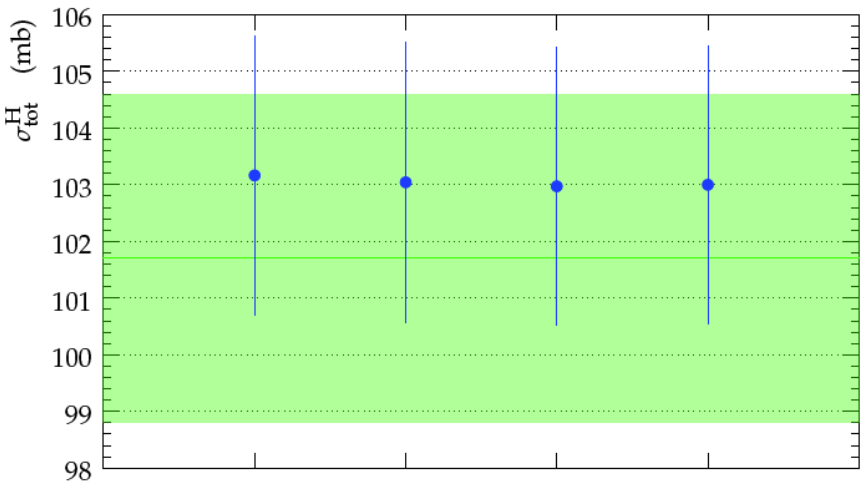
Preliminary Result for ρ

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

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



$$\rho = 0.104 \pm 0.027^{\rm (stat)} \pm 0.010^{\rm (syst)}\ {}^{+0.012}_{-0.006}\ {\rm (model)}$$



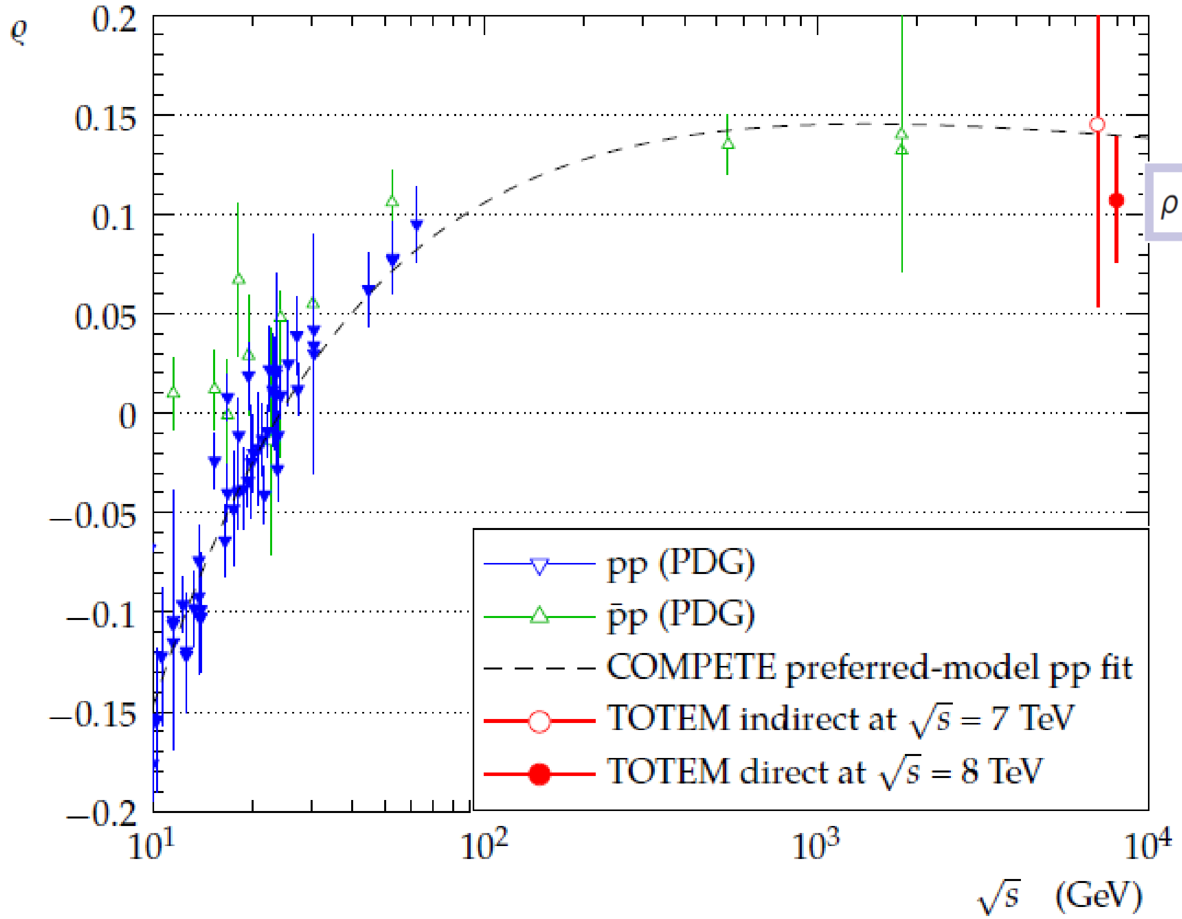
$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)}\frac{1}{\mathcal{L}}\left(\frac{dN_{el}}{dt}\right)^{had}_{t=0}$$

σ_{total}= 101.7 ± 2.9 mb

luminosity independent

PRL111(2013)012001

Synopsis of ρ Measurements



$\rho = 0.104 \pm 0.027^{(stat)} \pm 0.010^{(syst)} {}^{+0.012}_{-0.006} \text{(model)}$

Indirect crude measurement at 7 TeV:

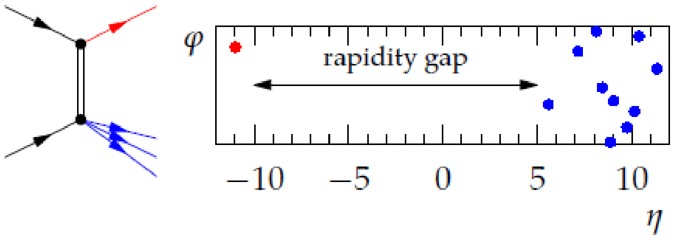
From optical theorem:

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

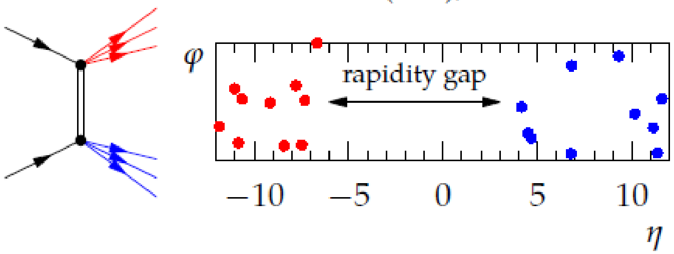
Ongoing Analyses of Diffractive Processes: Standalone and Common Runs with CMS

- A Selection -

Single Diffraction (SD), $\approx 10\,\text{mb}$

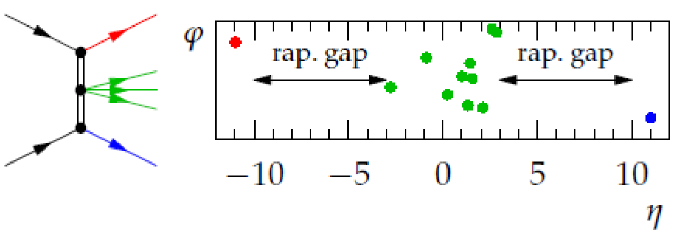


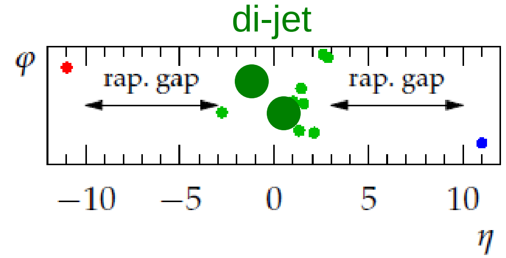
Double Diffraction (DD), $\approx 5\,\text{mb}$



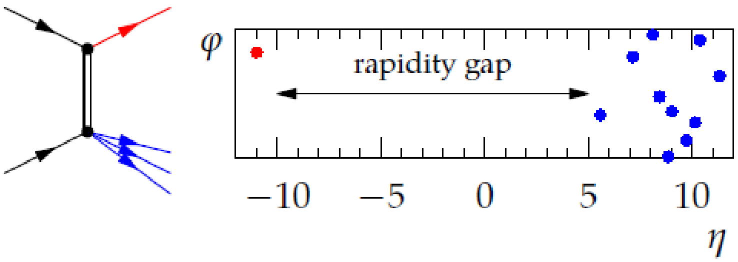
→ Measure topologies and σ (M,ξ,t)

Central Diffraction (CD), $\approx 1\,\text{mb}$



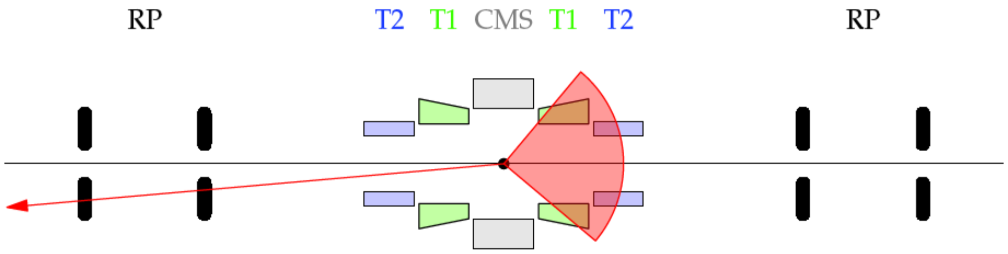


Soft Single Diffraction (SD)



- 1 proton breaks up
  → diffractive mass M
- 1 proton survives with momentum loss ξ
- rapidity gap $\Delta\eta$ between proton and M

$$\Delta\eta = -\ln\xi, \quad M^2 = \xi s$$



Trigger on T2, require 1 proton

2 ways for measuring ξ:

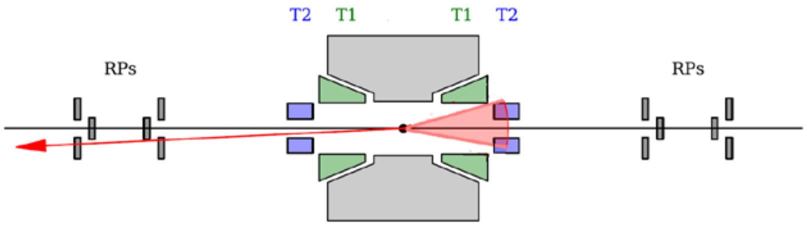
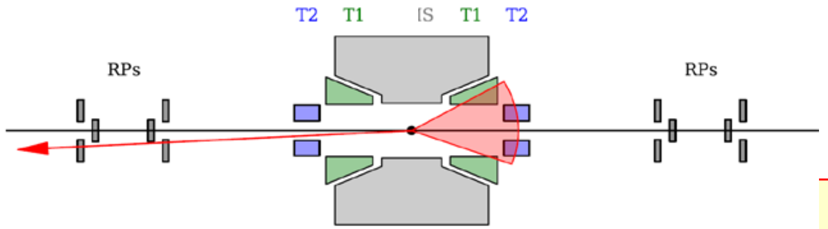
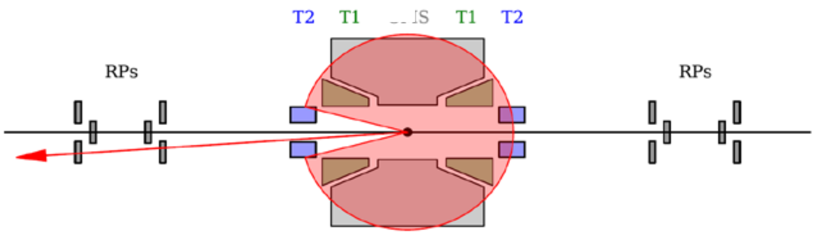
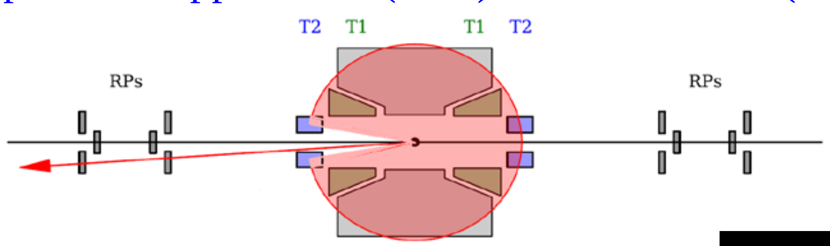
1. via the proton trajectory (RP): $x_{RP} = L_x \Theta_x^* + v_x x^* + D_x \xi$
2. via the rapidity gap (T1, T2)
   Note: $\eta_{max,T2} = 6.5 \quad \Leftrightarrow \quad M_{min} = 3.4$ GeV

resolution at β^*=90m:
$\delta\xi \sim 0.004 - 0.01$
(dependent on t, ξ)

$\delta\xi \sim \xi$

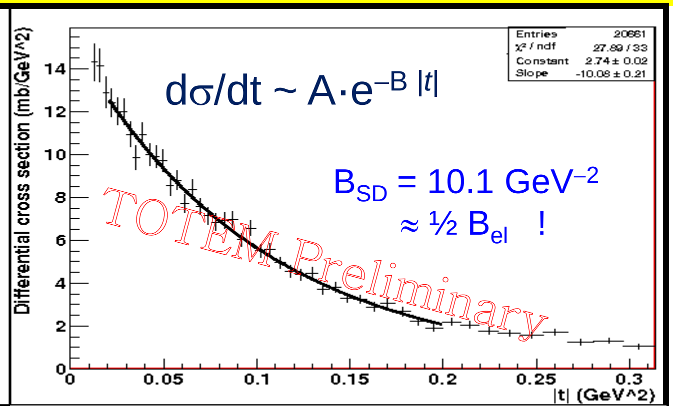
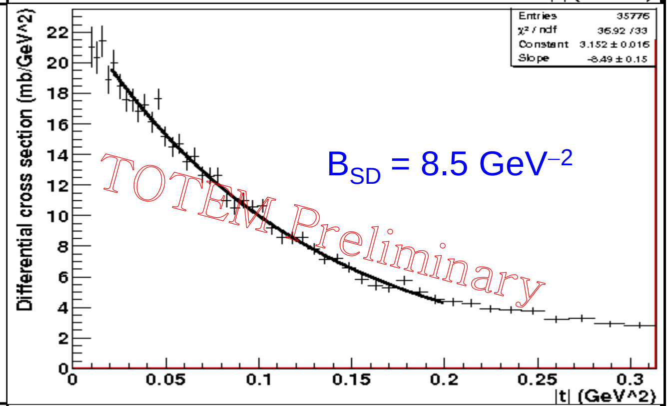
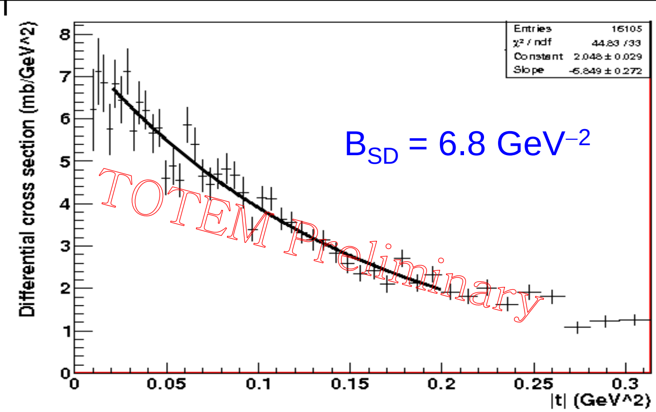
Full differential cross-section: $\dfrac{d^2\sigma}{d\xi\, dt}$

SD Topologies for Different Mass Ranges

M = 3.4 – 7 GeV	$2 \times 10^{-7} < \xi < 1 \times 10^{-6}$	proton & opposite T2 
M = 7 – 350 GeV	$1 \times 10^{-6} < \xi < 2.5 \times 10^{-3}$	proton & opposite T1 + T2 
M = 0.35 – 1.1 TeV	$2.5 \times 10^{-3} < \xi < 2.5 \times 10^{-2}$	proton & opposite T2 (+ T1) & same side T1 
M > 1.1 TeV	$\xi > 2.5 \times 10^{-2}$	proton & opposite T2 (+ T1) & same side T2 (+ T1) 

$$\Delta\eta = -\ln \frac{M^2}{s}$$

SD for Different Mass Ranges (7 TeV Data)

M = **3.4 – 7 GeV**	$2 \times 10^{-7} < \xi < 1 \times 10^{-6}$	
M = **7 – 350 GeV**	$1 \times 10^{-6} < \xi < 2.5 \times 10^{-3}$	
M = **0.35 – 1.1 TeV**	$2.5 \times 10^{-3} < \xi < 2.5 \times 10^{-2}$	
M > **1.1 TeV**	$\xi > 2.5 \times 10^{-2}$	in progress

Work in progress !
Some corrections still missing !

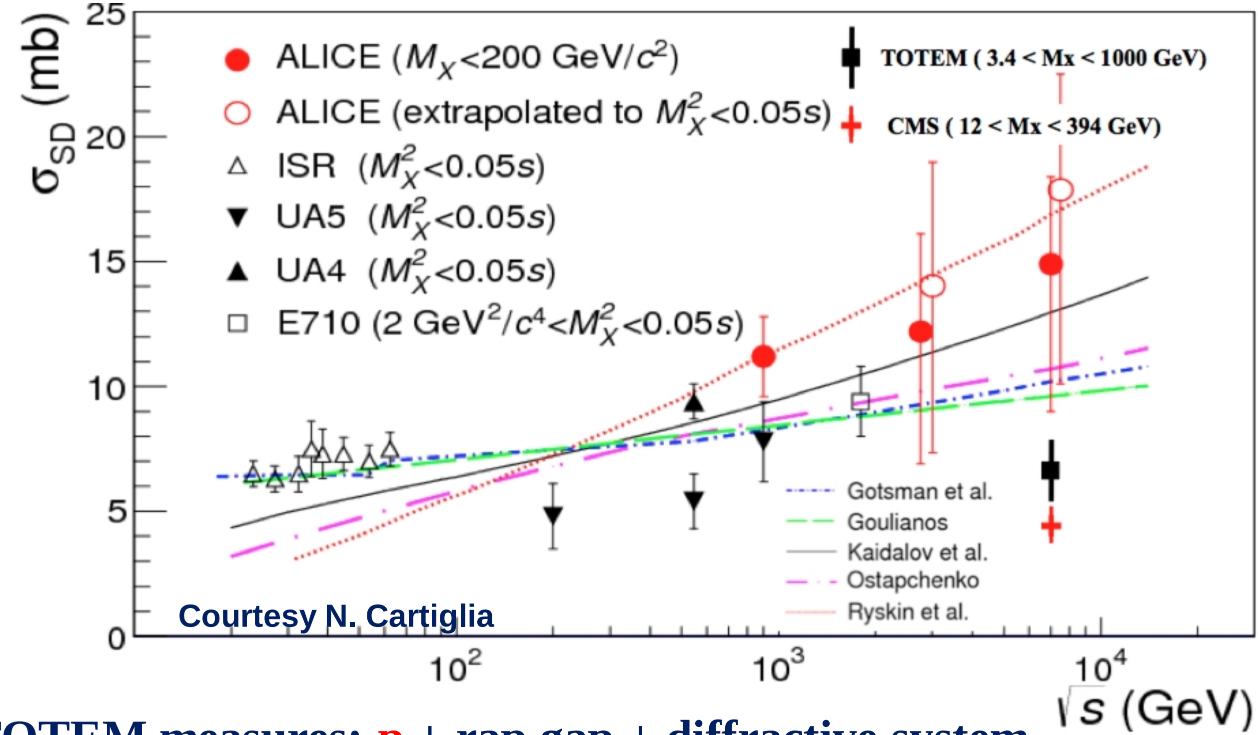
estimated uncertainty:
$\delta B/B \sim 15\ \%$

SD Cross-Section Measurements

very preliminary TOTEM result: $\sigma_{SD} = 6.5 \pm 1.3$ mb ($3.4 < M_{diff} < 1100$ GeV)

(sum of cross-sections for proton on either side, extrapolated to t=0 and integrated)

Estimate on M < 3.4 GeV from $\sigma_{tot} - \sigma_{el} - \sigma_{inel,visible} \sim 2.6 \pm 2.2$ mb, or MC: 3.2 mb

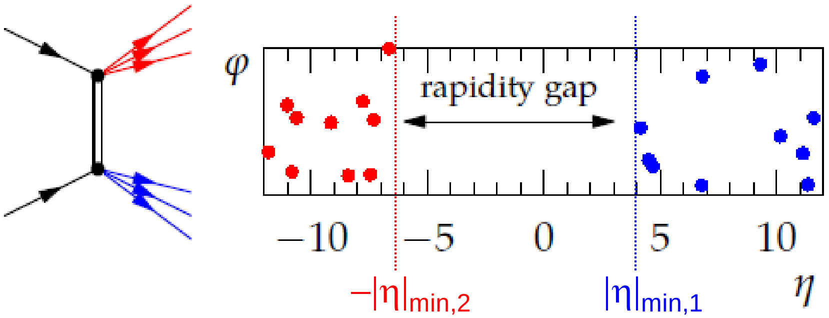


8 TeV TOTEM analysis has started.

TOTEM measures: p + rap gap + diffractive system,
ALICE & CMS: "rap gap + diffractive system"

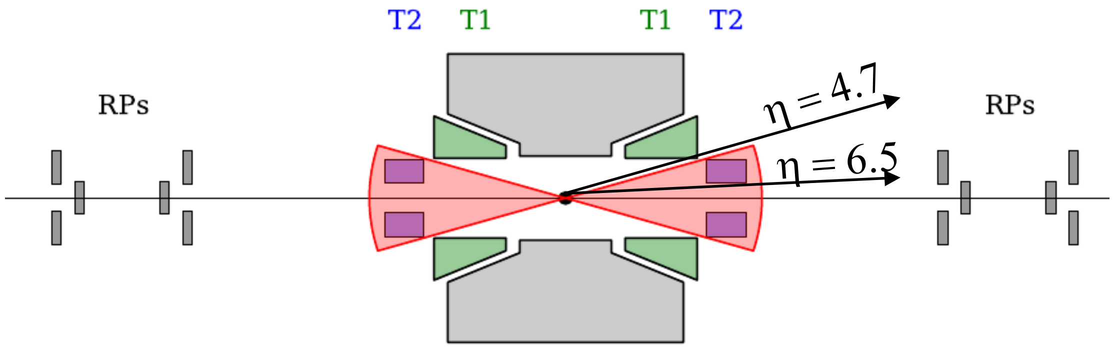
NB: Very different mass ranges → results not directly comparable

Soft Double Diffraction



- Both protons break up
  → 2 diffractive masses M_1, M_2
- Central rapidity gap

Ultimate goal: 2-dim. cross-section $\frac{d^2\sigma}{dM_1\,dM_2}$ or $\frac{d^2\sigma}{d|\eta|_{min,1}\,d|\eta|_{min,2}}$



Difficulties:

- no leading protons to tag
- for large masses (→ small central gap) not easy to separate from non-diffractive events

First step: sub-range with particles **triggering both T2** hemispheres, **veto on T1**:

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

Double Diffraction: Results at 7 TeV

Partial 2-dim. cross-section in 2 x 2 bins:

	$-4.7>\eta_{min2}>-5.9$	$-5.9>\eta_{min2}>-6.5$
$4.7<\eta_{min1}<5.9$	65±20 μb	26±5 μb
$5.9<\eta_{min1}<6.5$	27±5 μb	12±5 μb

Sum:

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

[CERN-PH-EP-2013-170] ***NEW!***

Leading systematics:

- missing DD events with unseen particles at $\eta < \eta_{min}$
- backgrounds from non-diffractive, single diffractive, central diffractive events

So far, only a small part of DD measured: 116 μb out of ~5 mb, but:

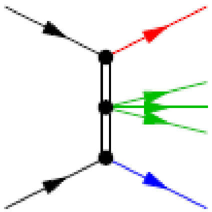
benchmark for Monte Carlos:

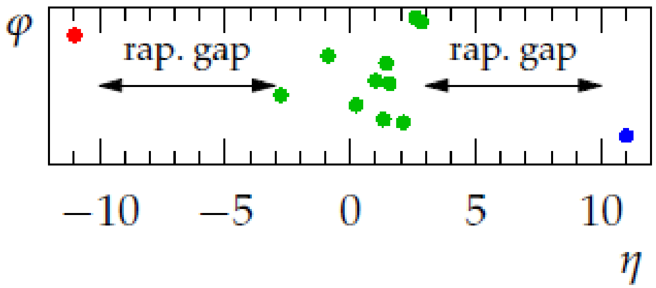
Pythia 8: $\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 159 \ \mu b$

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

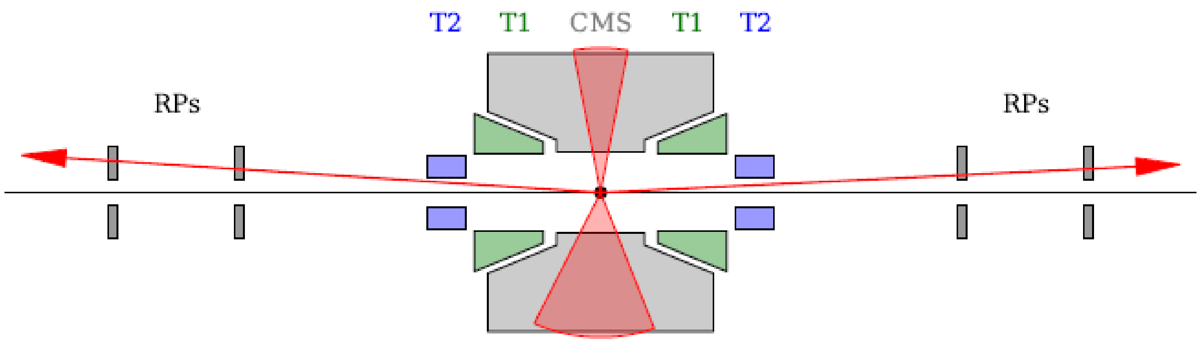
Improvement expected with 8 TeV data: also CMS detector information available (joint run).

Central Diffraction ("Double Pomeron Exchange")





- both protons survive with momentum losses ξ_1, ξ_2
- diffractive mass M in the centre
- 2 rapidity gaps $\Delta\eta_1$, $\Delta\eta_2$



$$\Delta\eta_{1,2} = -\ln \xi_{1,2}, \quad M^2 = \xi_1 \xi_2 s$$

Joint data taking CMS + TOTEM:

kinematic redundancy between protons and central diffractive system

$M_{CMS} = M_{TOTEM}(pp)$?

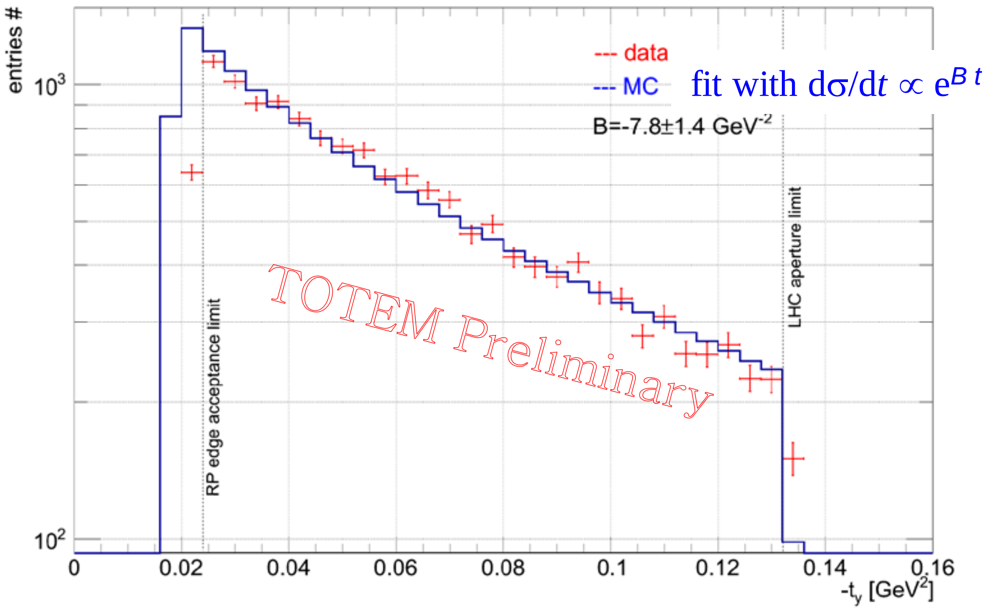
Central Diffraction ("Double Pomeron Exchange")

Soft DPE: study differential cross-section with correlations:

$$\frac{d^5\sigma}{d\xi_1\, d\xi_2\, dt_1\, dt_2\, d\Delta\Phi}$$

(in progress: $d\sigma/dM$, $d\sigma\ dt_1$)

Single arm CD event rate (integrated ξ, acceptance corrected)

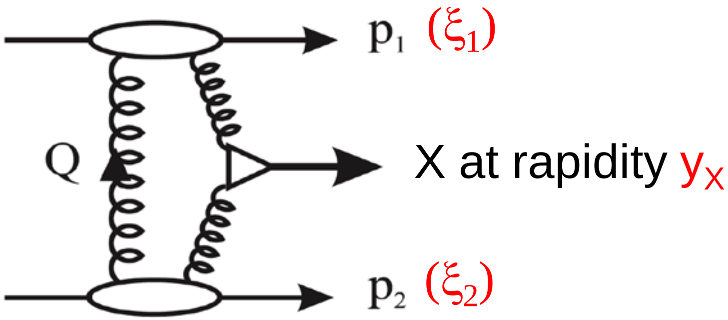


Estimate on the integral:

$\sigma_{CD} \sim 1$ mb

Central Production of Particles or Di-Jets

Exclusive Particle Production:



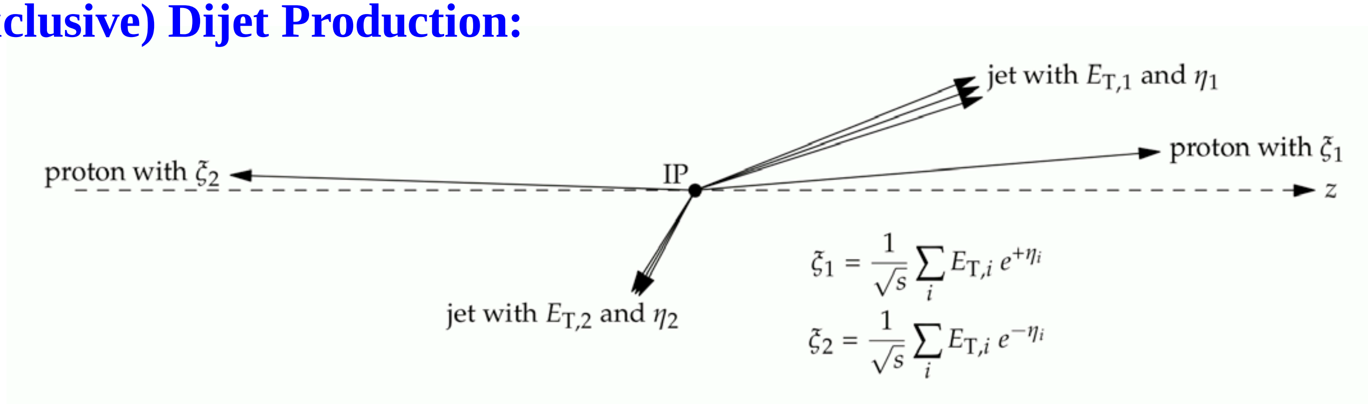
$$M_X^2 = \xi_1 \xi_2 s$$

$$y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$$

exchange of colour singlets with vacuum quantum numbers

⇒ Selection rules for system X: $J^{PC} = 0^{++}$ (mainly) ➔ X = χ_{c0}, χ_{b0}, H, glueballs?

(Exclusive) Dijet Production:



Joint analysis of special run at 8 TeV, β* = 90 m together with CMS in progress

Forward Particle Production:

Charged Particle Multiplicity

Charged Particle Pseudorapidity Density dN / dη

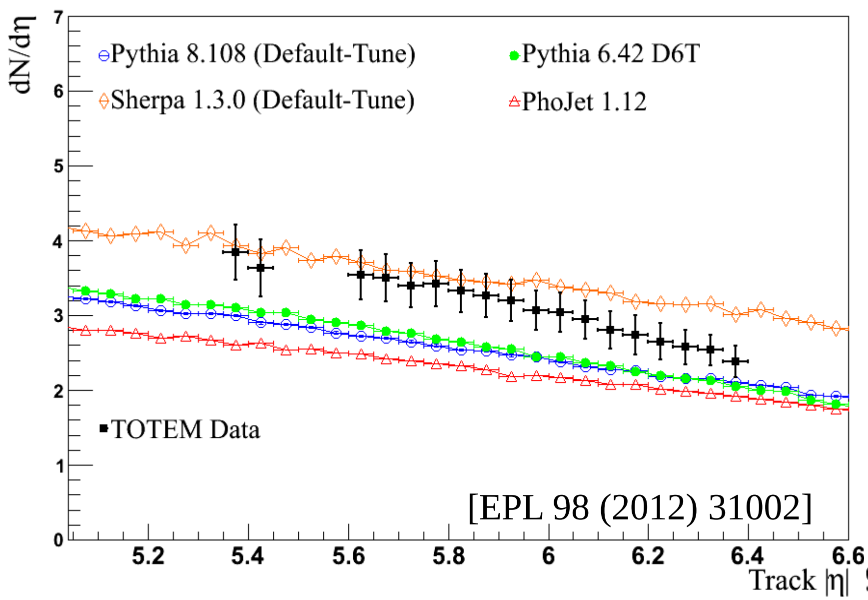
$dN_{ch}/d\eta$: mean number of charged particles per event and per unit of pseudorapidity:
primary particles only, i.e. lifetime > 30 ps (convention among LHC experiments)

→ probes hadronisation → constrains theoretical models

→ input for cosmic ray simulations

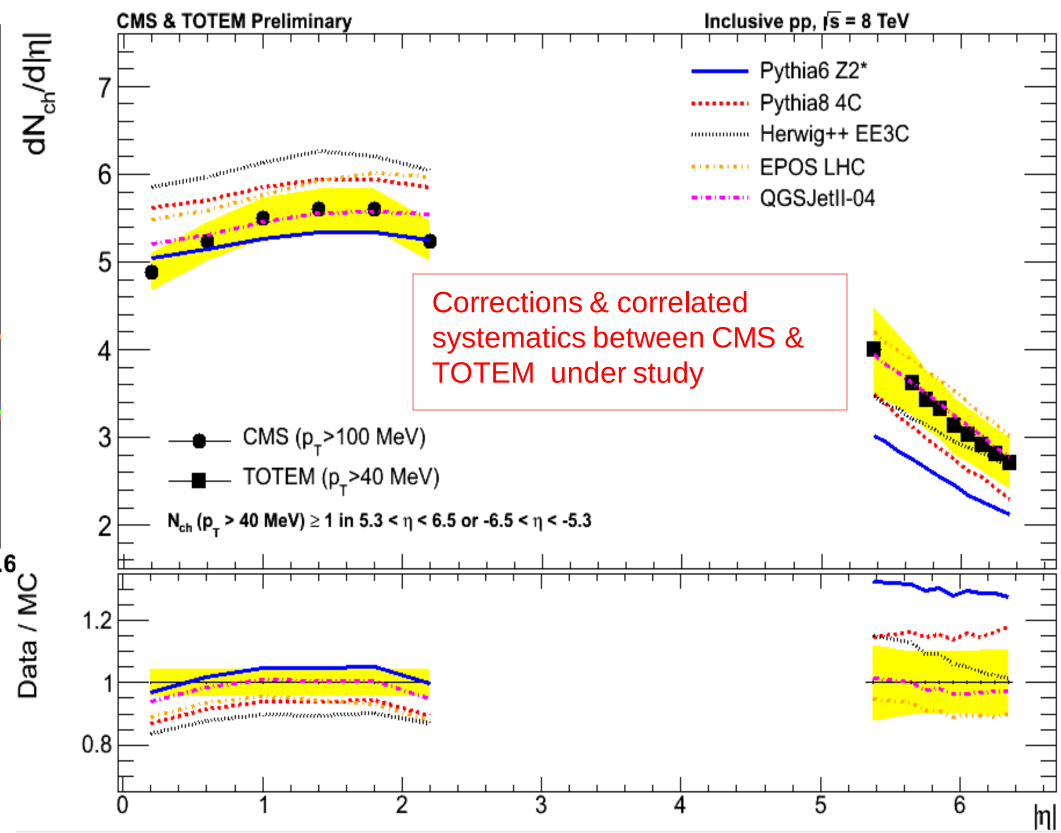
7 TeV

TOTEM standalone (T2)



8 TeV

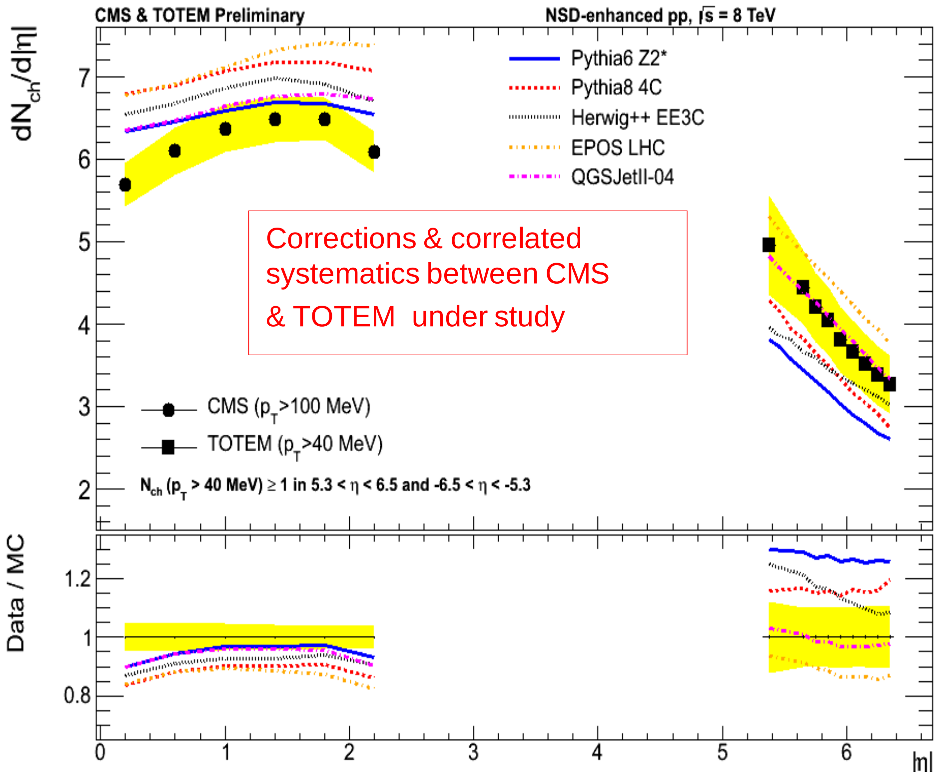
CMS + TOTEM (T2)



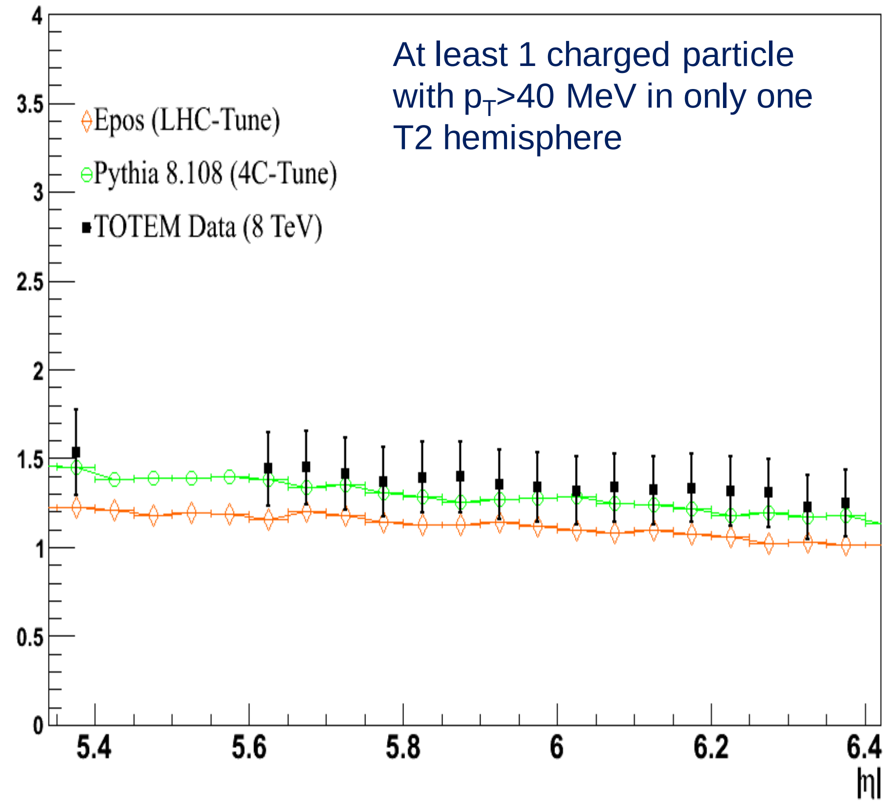
dN / dη for Different Event Classes

"Non-Single diffractive enhanced": primary tracks in both T2 hemispheres
"Single diffractive enhanced": primary tracks in only one T2 hemispheres

NSD-enhanced



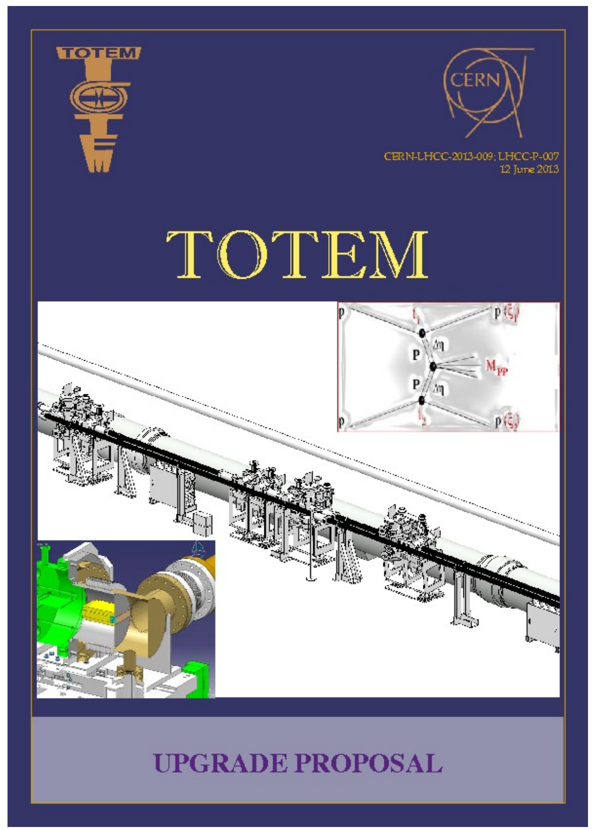
SD-enhanced



Updated analysis with a common p_T = 0 threshold ongoing in both CMS & TOTEM !

Outlook:

The TOTEM Consolidation and Upgrade Programme



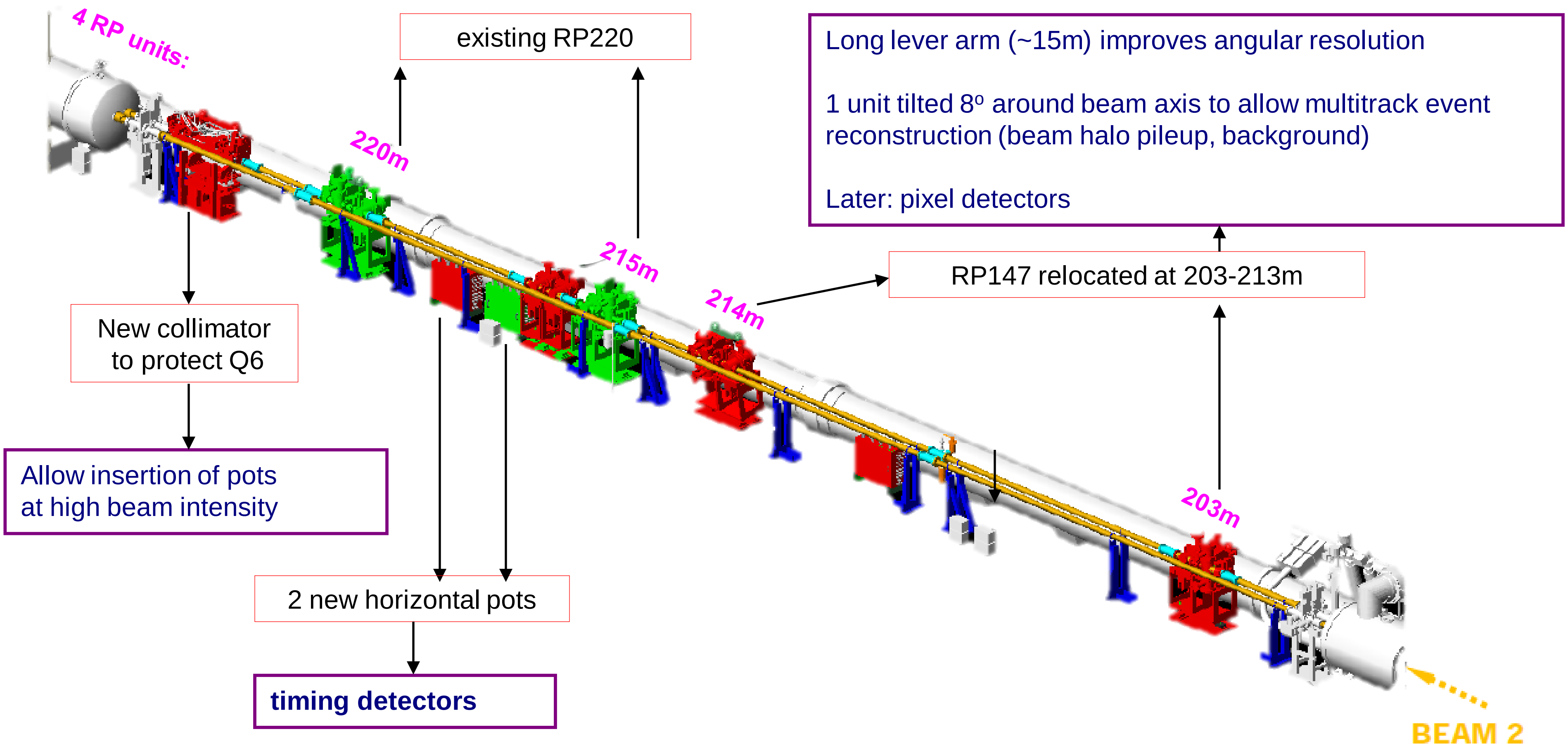
Consolidation and Upgrade

In 2012: successful data taking together with CMS in special runs
→ first studies of central production, diffractive dijets, other hard diffractive processes

Problems: limited statistics, pileup

→upgrade RP system for operation at higher luminosities

→resolve event pileup: timing measurement, multi-track resolution



Backup

Optics Corrections from Data

- Optics defined by the magnetic lattice elements $\mathbf{T}_i$ between IP5 and RP:

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \end{pmatrix}_{RP} = \mathbf{T} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \end{pmatrix}_{IP5} \quad \text{with} \quad \mathbf{T} = \prod_{i=M}^{1} \left[\mathbf{T}_i(k_i) + \Delta\mathbf{T}_i \right] = \begin{pmatrix} v_x & L_x & re_{13} & re_{14} \\ \frac{dv_x}{ds} & \frac{dL_x}{ds} & re_{23} & re_{24} \\ re_{31} & re_{32} & v_y & L_y \\ re_{41} & re_{42} & \frac{dv_y}{ds} & \frac{dL_y}{ds} \end{pmatrix}$$

- Magnet currents are continuously measured, but tolerances and imperfections lead to $\Delta\mathbf{T}_i$
  - Beam momentum offset ($\Delta p/p = 10^{-3}$)
  - Magnet transfer function error, I→B, ($\Delta B/B = 10^{-3}$)
  - Magnet rotations and displacements ($\Delta\psi < 1$mrad, Δx, $\Delta y < 0.5$mm, WISE database)
  - Power converter errors, k→I, ($\Delta I/I < 10^{-4}$)
  - Magnet harmonics ($\Delta B/B = O(10^{-4})$ @ $R_{ref} = 17$mm, WISE database)
- The elements of **T** are correlated and cannot take arbitrary values
- The TOTEM RP measurements provide additional constraints:
  - single-beam constraints (position-angle correlations, x-y coupling)
  - two-beam constraints via elastic scattering (Θ^*_{left} vs. Θ^*_{right})

→ Matching by a fit with 26 parameters (magnet strengths, rotations, beam energy) and 36 constraints.

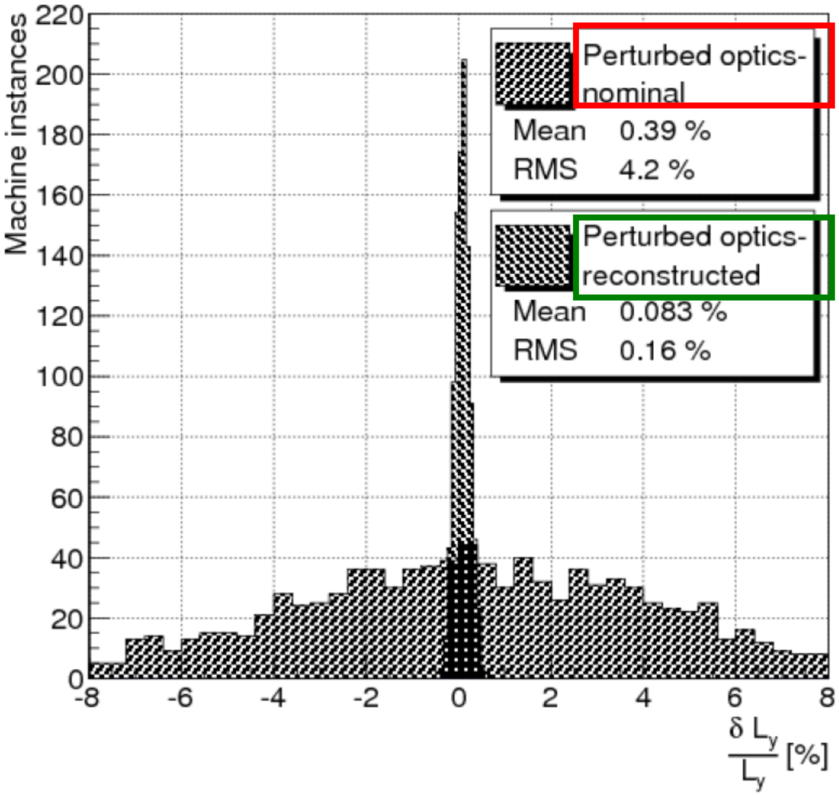
→ Error propagation to relevant optical functions L_y (1%) and dL_x/ds (0.7%) ⇒ **$\delta t / t \sim 0.8 – 2.6$ %**

H. Niewiadomski: "Roman Pots for beam diagnostics", Optics Measurements, Corrections and Modelling for High-Performance Storage Rings workshop (OMCM) CERN, 20-23.06.2011.

H. Niewiadomski, F. Nemes: "LHC Optics Determination with Proton Tracks Measured in the Roman Pots Detectors of the TOTEM Experiment", IPAC'12, Louisiana, USA, 20-25.05.2012; arXiv:1206.3058 [physics.acc-ph]

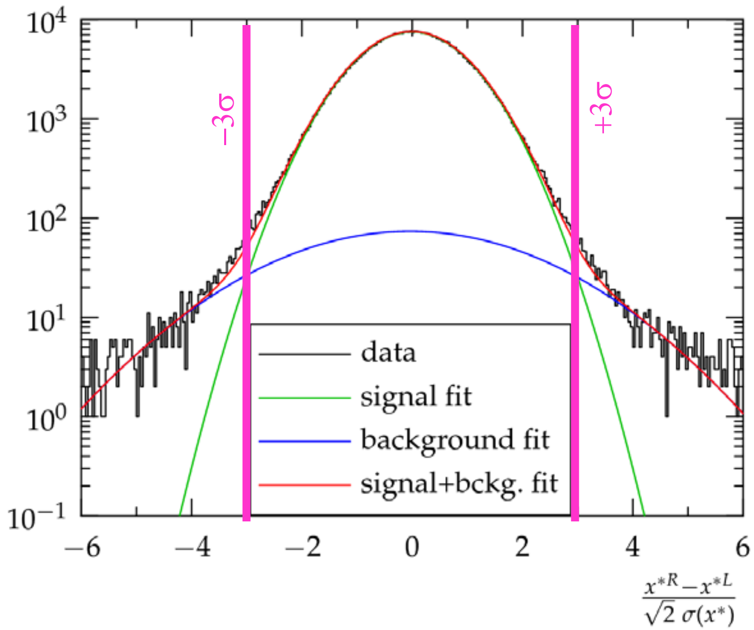
Performance of Optics Corrections

- Generate 1000 perturbed machines with imperfections ΔT_i within tolerances
  → determine deviations in optical functions from their design values
- Generate physics events, track the protons through the imperfect machines
  → simulated RP measurements
- Perform the optics reconstruction fit using the constraints from the simulated RP measurements
  → compare reconstructed and true (perturbed) optical functions



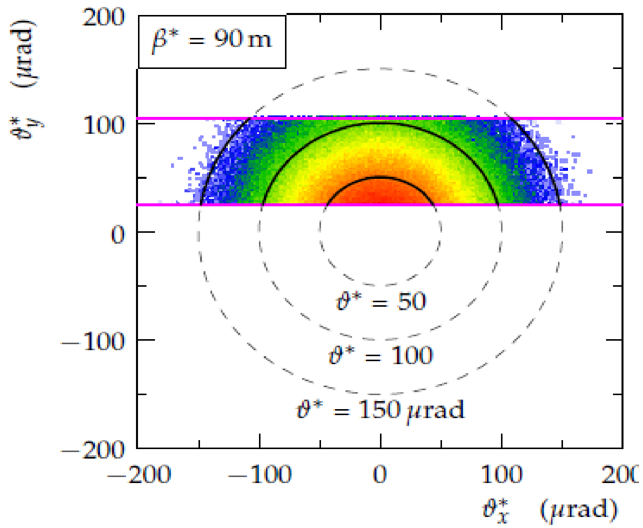
Analysis Overview I

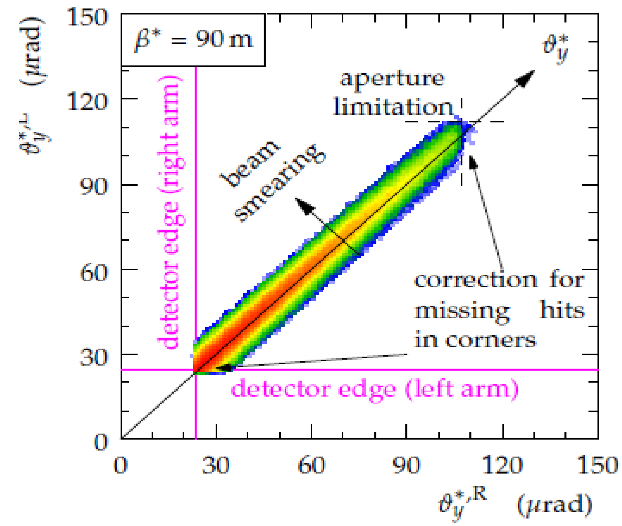
Background subtraction



Use strongest cut (common vertex for both protons):
Interpolation of background population from outside 3σ into the signal region.

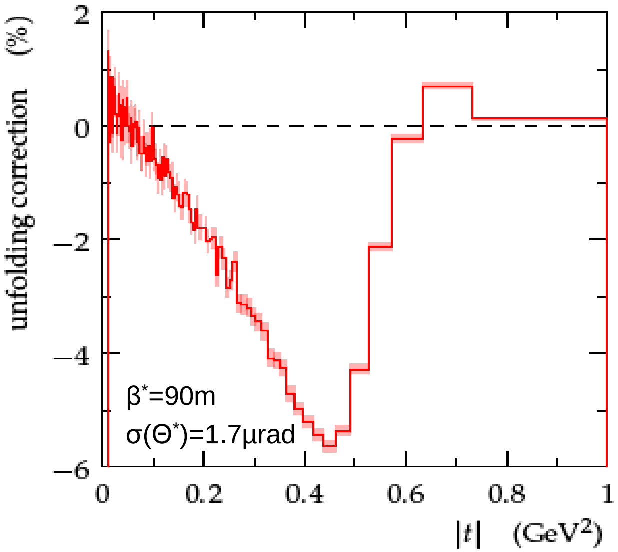
Acceptance correction





Analysis Overview II

Unfolding of resolution effects



Efficiency (→ normalisation)

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 → advantage from 3 data sets, 2 diagonals	4 – 8 %

Absolute Luminosity Calibration

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

7 TeV

June 2011: $\mathcal{L}_{int}$ = (1.65 ± 0.07) μb^{-1} [CMS: (1.65 ± 0.07) μb^{-1}]

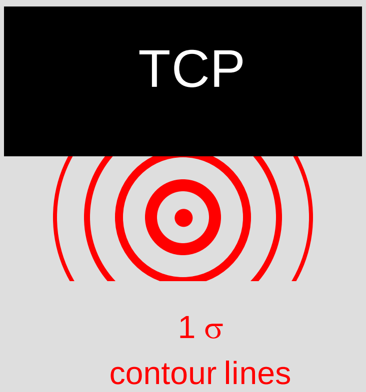
October 2011: $\mathcal{L}_{int}$ = (83.7 ± 3.2) μb^{-1} [CMS: (82.0 ± 3.3) μb^{-1}]

Excellent agreement with CMS luminosity measurement.

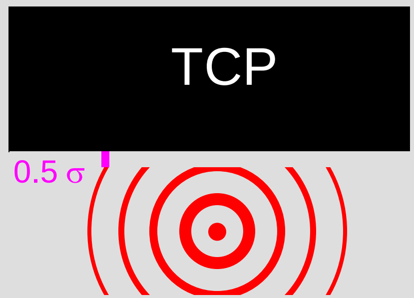
Absolute luminosity calibration for T2

Beam Cleaning with Primary Collimators (TCPs)

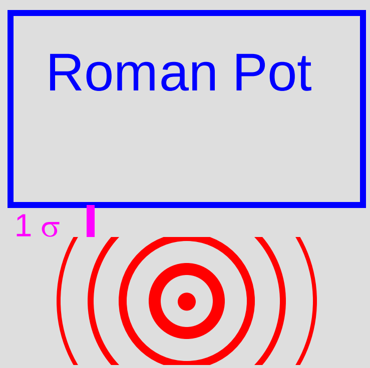
1. Scrape the beam with TCP at 2 σ



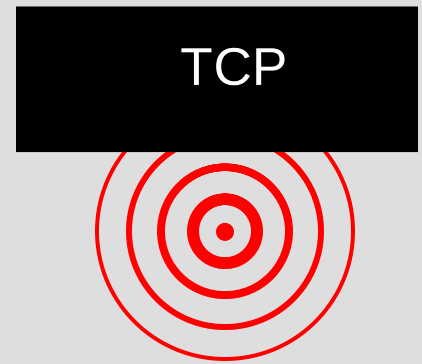
2. Retract TCP from 2 σ to 2.5 σ → gap of 0.5 σ



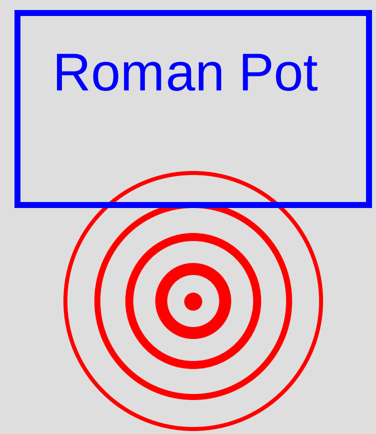
RP at 3 σ is protected by the gap



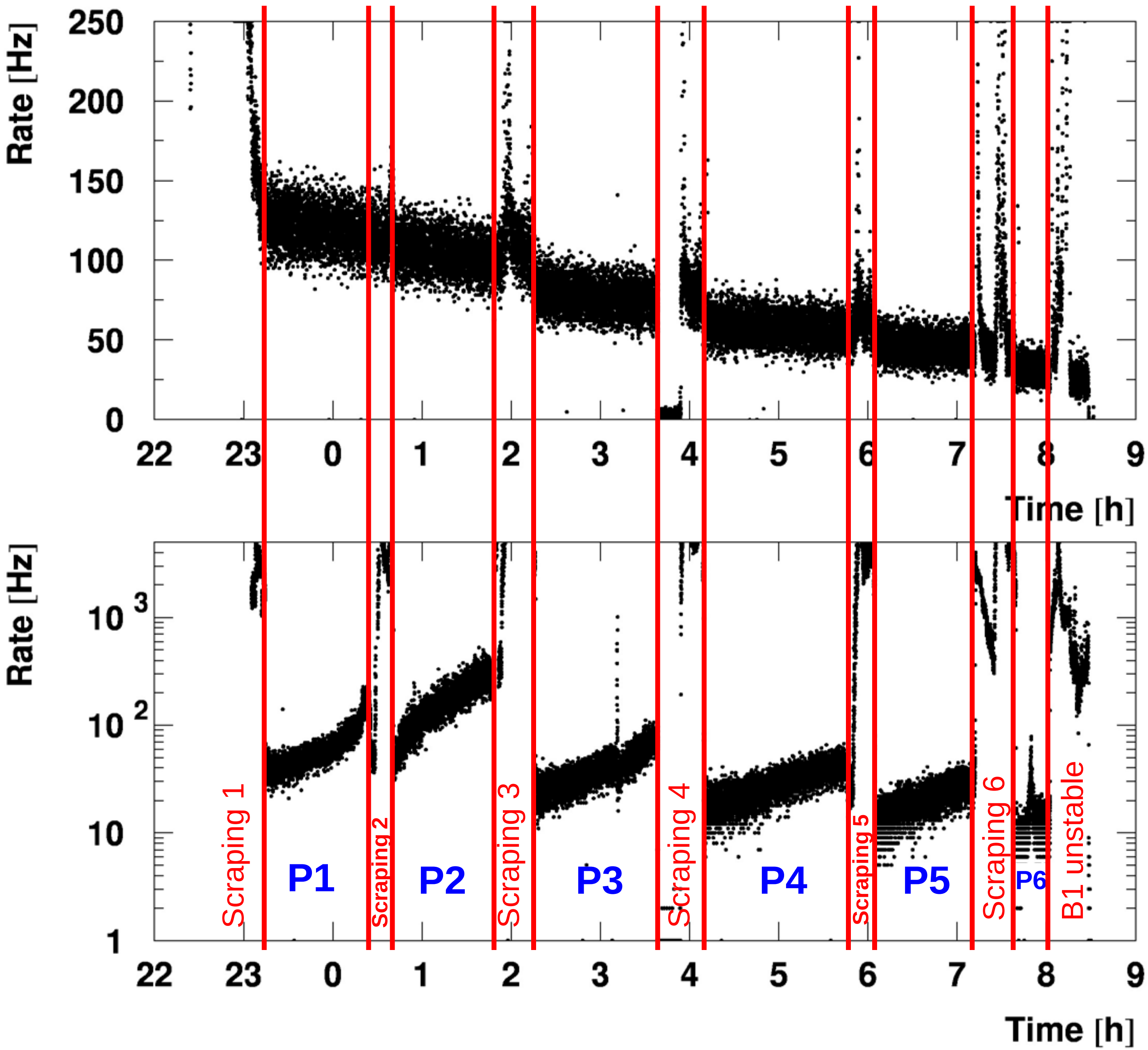
3. Gap refills within ~ 1h



Scatter products from TCP edge hit the RP



Data Taking Periods as Seen by T2 and Roman Pots



T2 Trigger

(sees 70 mb inelastic cross-section)

→ luminosity candle

Roman Pot Double Arm Trigger

(Sector 45 AND Sector 56)

Total: 6.75 h in 6 periods

int. lumi.: 27 μb^{-1}

400k elastic events

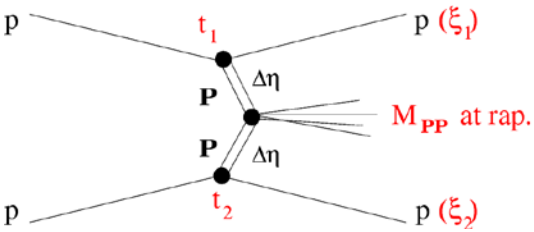
Hard Diffraction with CMS in 2012

July 2012: β* = 90 m, √s = 8 TeV:

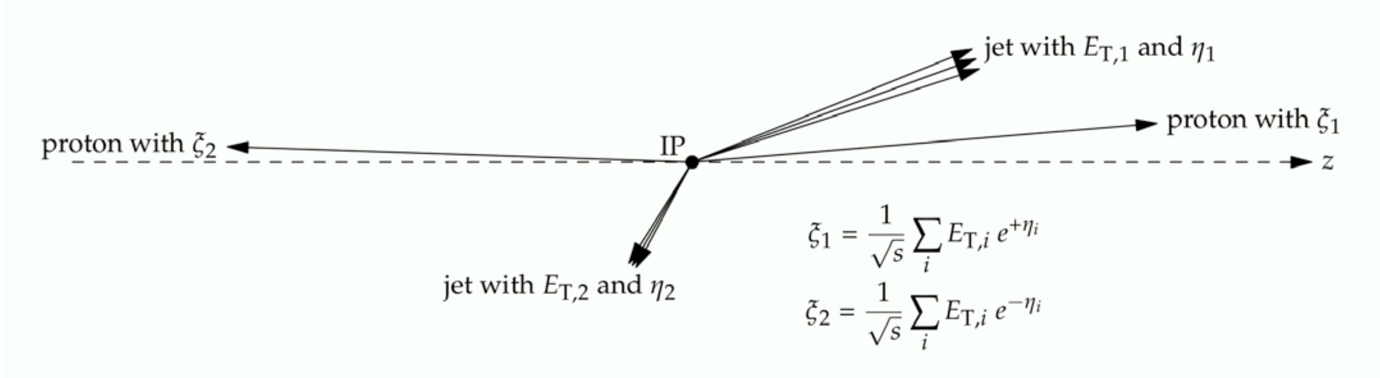
mixed trigger:

CMS [dijet(20GeV) .or. di-muon .or. zero-bias] **.or. TOTEM** [T2 .or. RP double-arm]

Study dijets in central diffraction:



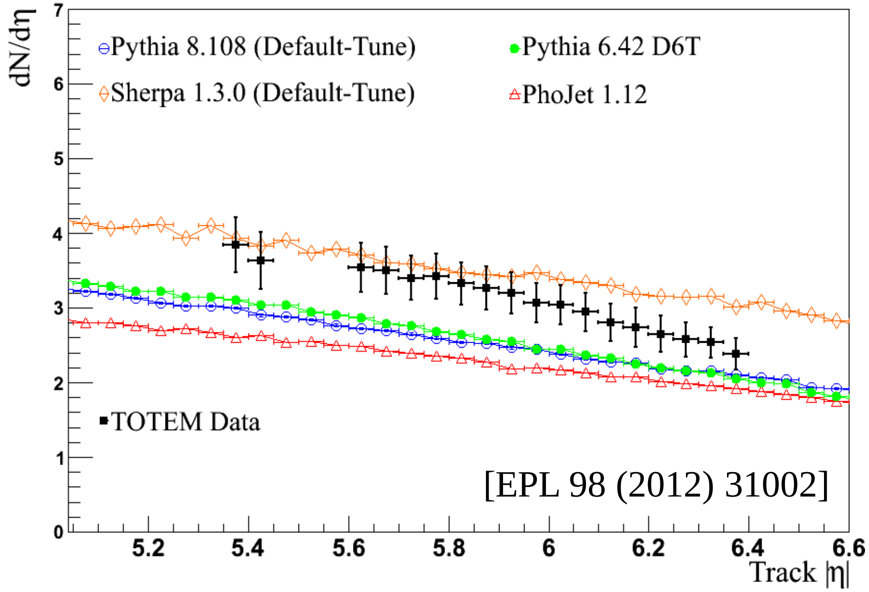
$M^2 = \xi_1 \xi_2 s$

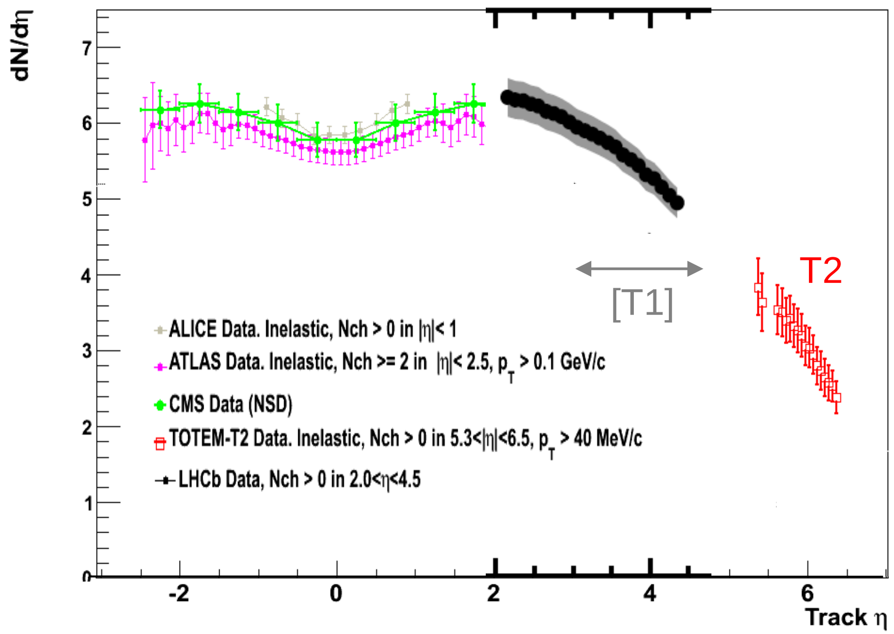


Compare ξ_1, ξ_2 from RPs and from CMS :
kinematics of final state over-constrained

Analysis in progress

Charged Particle Pseudorapidity Density dN / dη

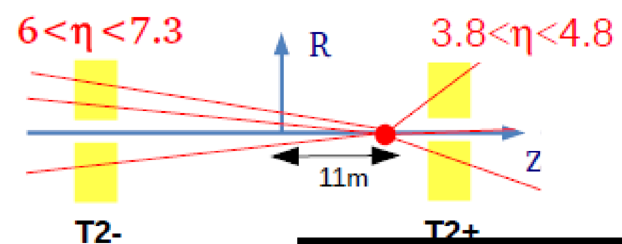




Analyses in progress:

- T1 measurement at 7 TeV (3.1 < |η| < 4.7)

- Parasitical collision at β* = 90 m (7 July 2012) → vertex at ~11m → shifted η acceptance:



$dN_{ch}/d\eta$ in T2: Analysis Highlights

Data sample:

*events at low luminosity and low pile-up, triggered with T2 (**$5.3 < |\eta| < 6.5$**)*

Selection:

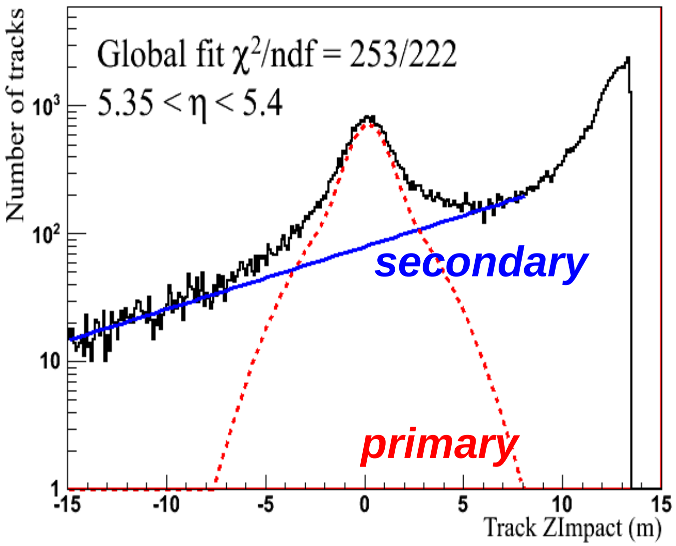
at least one track reconstructed in T2

Primary particle definition:

charged particle with $t > 0.3\times10^{-10}$ s, $p_T > 40$ MeV/c

Primary particle selection:

-primary/secondary discrimination, data-driven based on reconstructed track parameters (Z_{Impact})



Primary track reconstruction efficiency:

- evaluated as a function of the track η and multiplicity

- efficiency of 80%

- fraction of primary tracks within the cuts of 75% – 90% (η dependent)

Un-folding of (η) resolution effects:

MC driven bin "migration" corrections

Systematic uncertainties (< 10%):

dominated by primary track efficiency and global alignment correction uncertainty

Joint Data Taking with CMS

Realisation of common running much earlier than ever anticipated

1. Hardware: fast electrical trigger cable from RP220 to CMS
   → trigger within CMS latency
2. Trigger Logic: bi-directional level-1 exchange → same events taken
3. Synchronisation: orbit number and bunch number in data streams
4. Offline:
   - common repository for independently reconstructed data
   - merging procedure → common n-tuples

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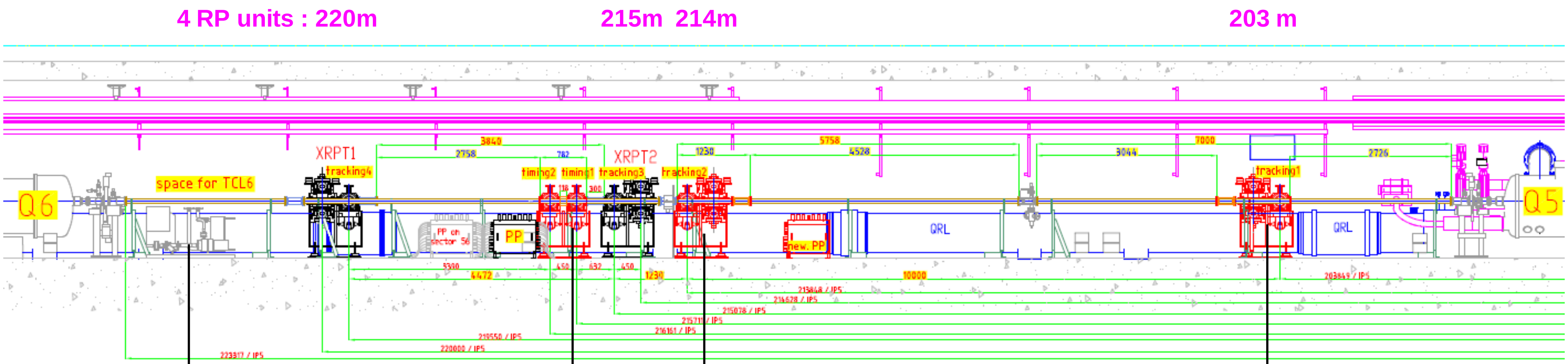


New collimator to protect Q6 → Allow insertion of pots at high beam intensity

2 new horizontal pots → **timing detectors**

RP147 relocated at 203-213m →

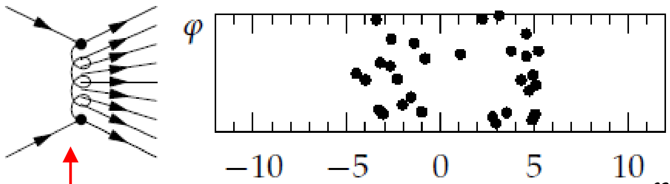
Long lever arm (~15m) improves angular resolution

1 unit tilted around beam axis to improve multitrack event reconstruction (beam halo pileup, background)

Later: pixel detectors

Classes of pp Events

Non-Diffractive process (ND) ≈ 60 mb @ $\sqrt{s} = 7 - 8$ TeV



$$\eta = -\ln\tan\frac{\theta}{2}$$

Non-diffractive

Colour exchange

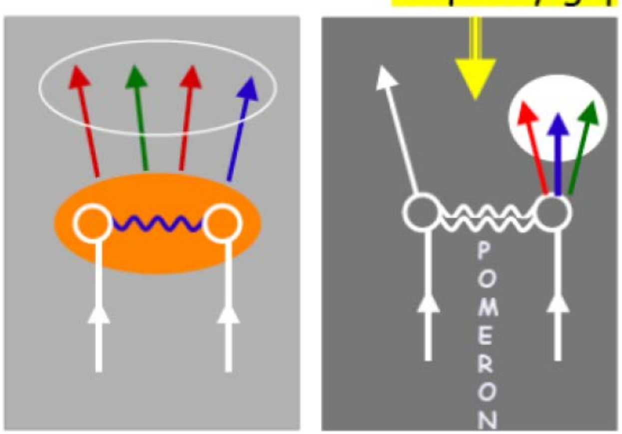
dN / dΔη = exp (-Δη)

Diffractive

Colourless exchange with vacuum quantum numbers

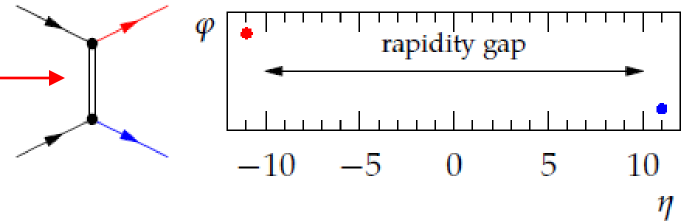
dN / dΔη = const

rapidity gap

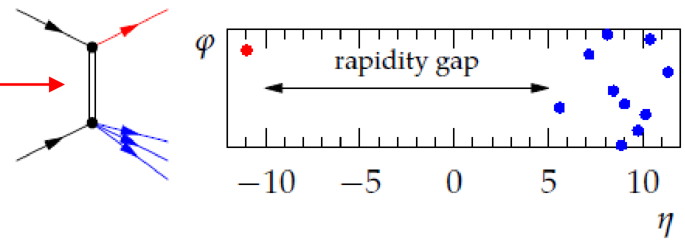


Incident hadrons retain their quantum numbers remaining colourless

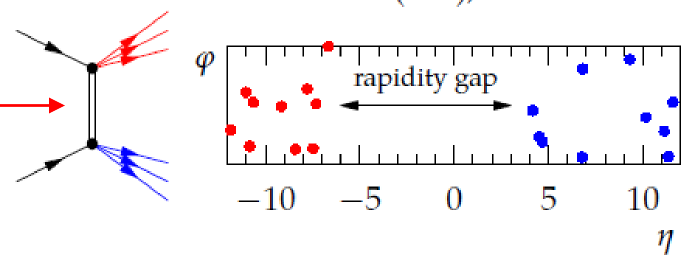
Elastic Scattering (ES), ≈ 25 mb



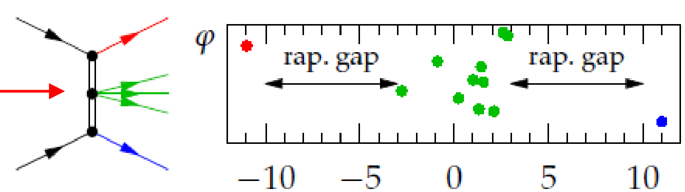
Single Diffraction (SD), ≈ 10 mb



Double Diffraction (DD), ≈ 5 mb



Central Diffraction (CD), ≈ 1 mb



→ Measure topologies and σ (M,ξ,t)

Substantial fraction of particle and energy flow goes forward; often surviving protons.