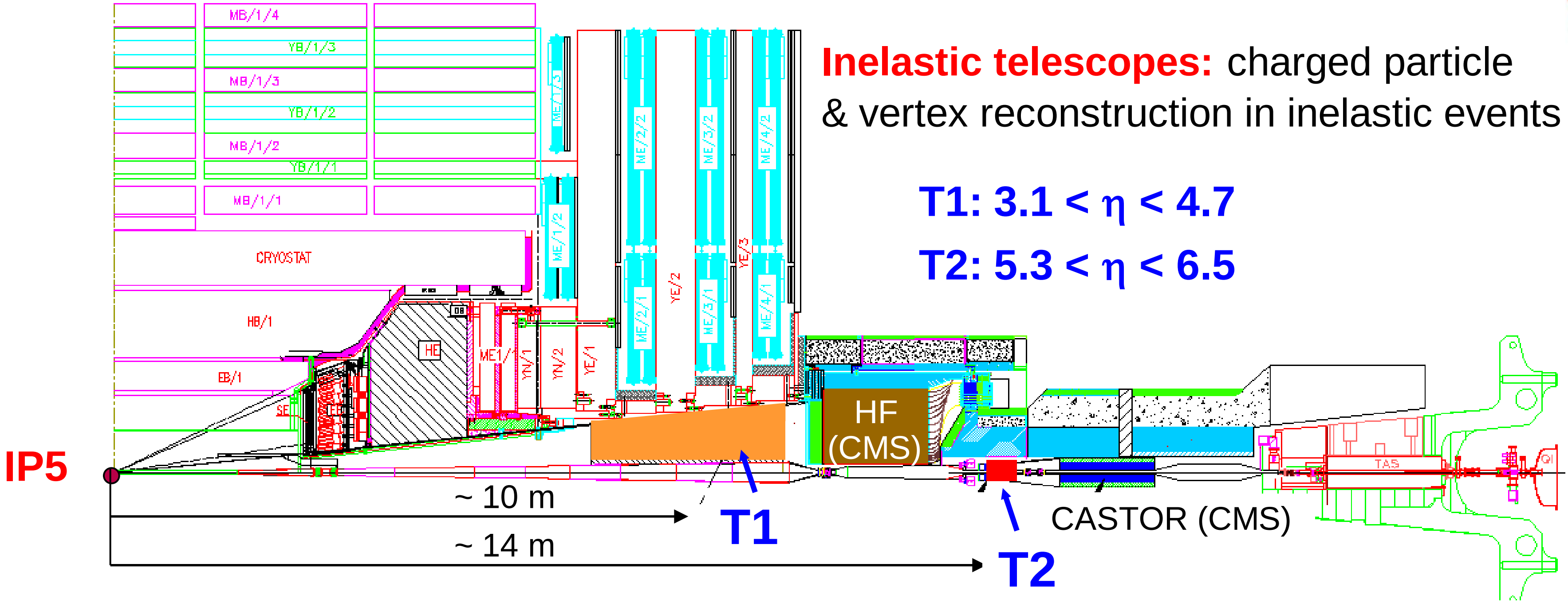
Measurements of Proton-Proton Elastic Scattering and Total Cross-Section at the LHC by TOTEM

Diffraction 2012
Lanzarote, 15 September

Mario Deile
on behalf of the TOTEM Collaboration

Experimental Setup @ IP5

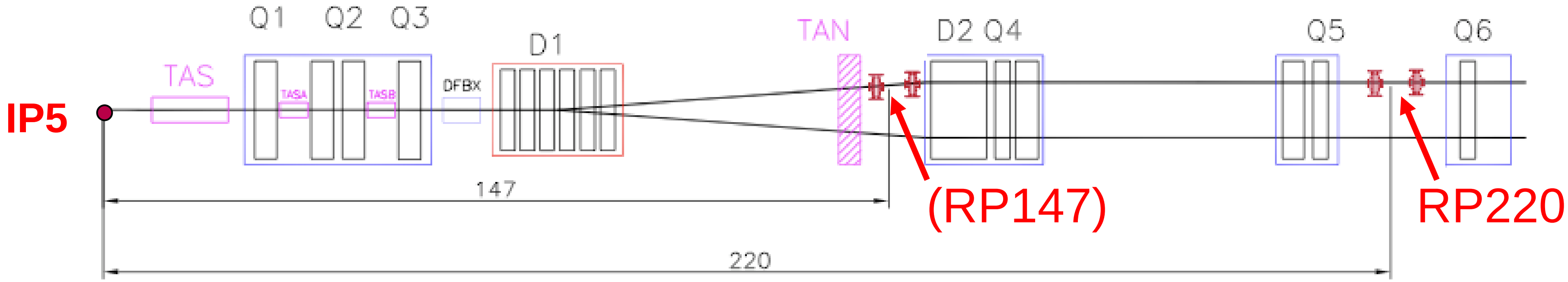


Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

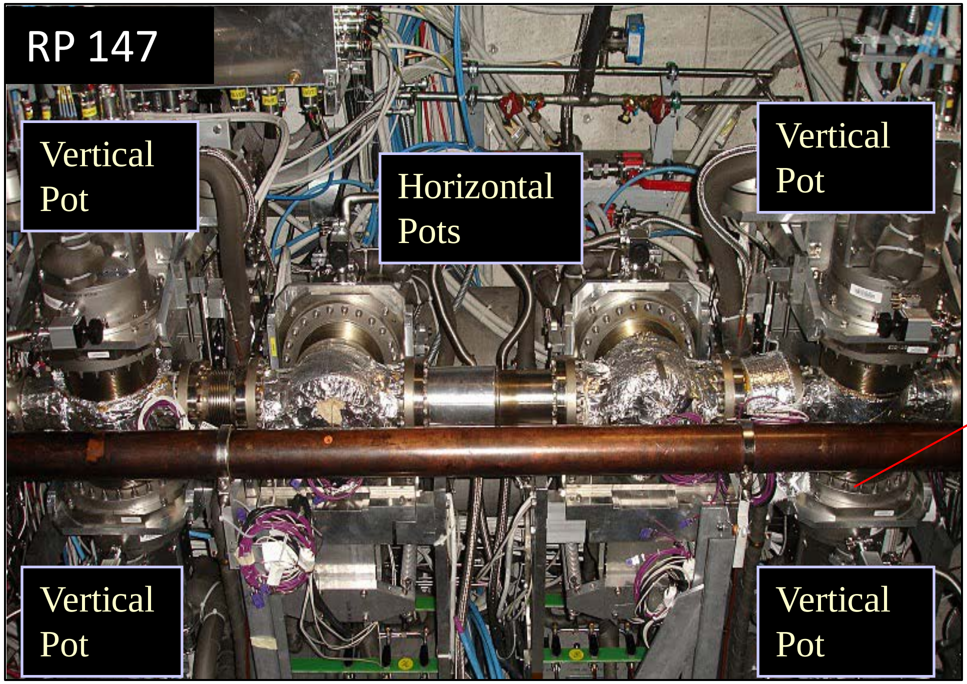
T1: $3.1 < \eta < 4.7$

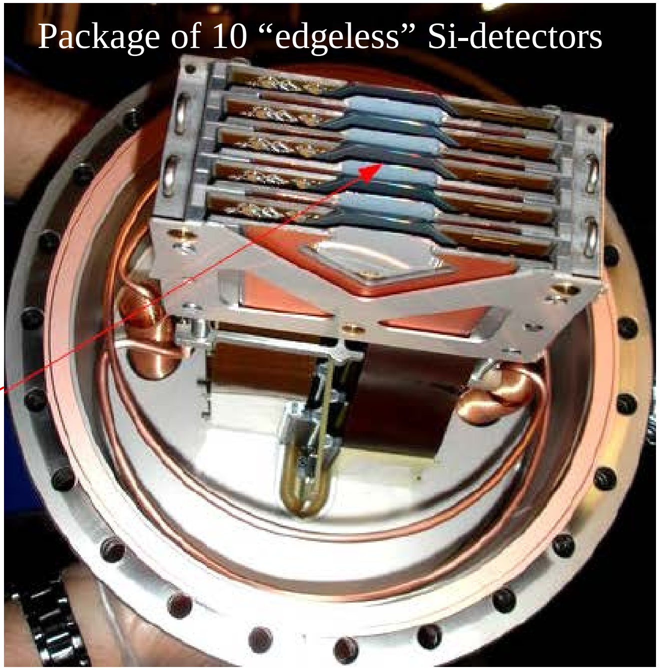
T2: $5.3 < \eta < 6.5$

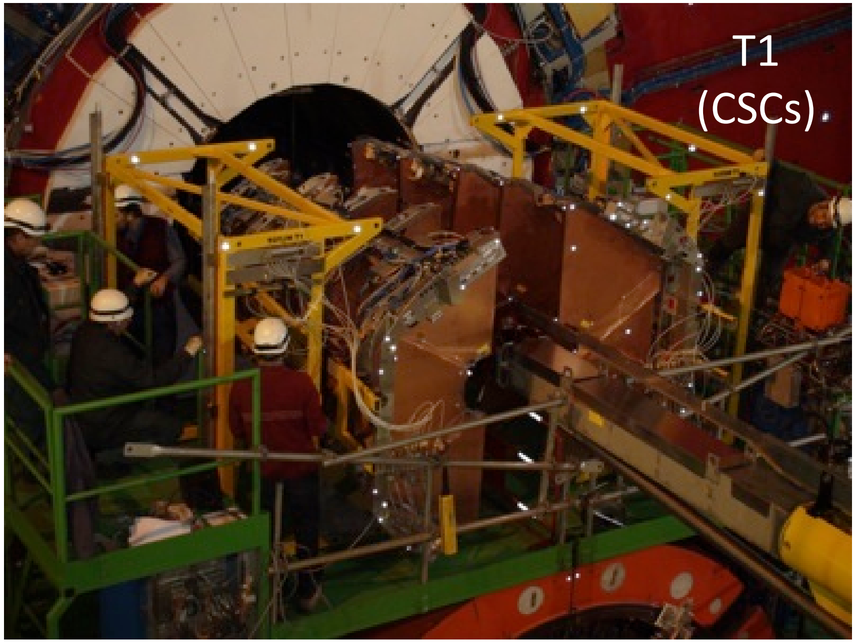
Roman Pots: measure elastic & diffractive protons close to outgoing beam

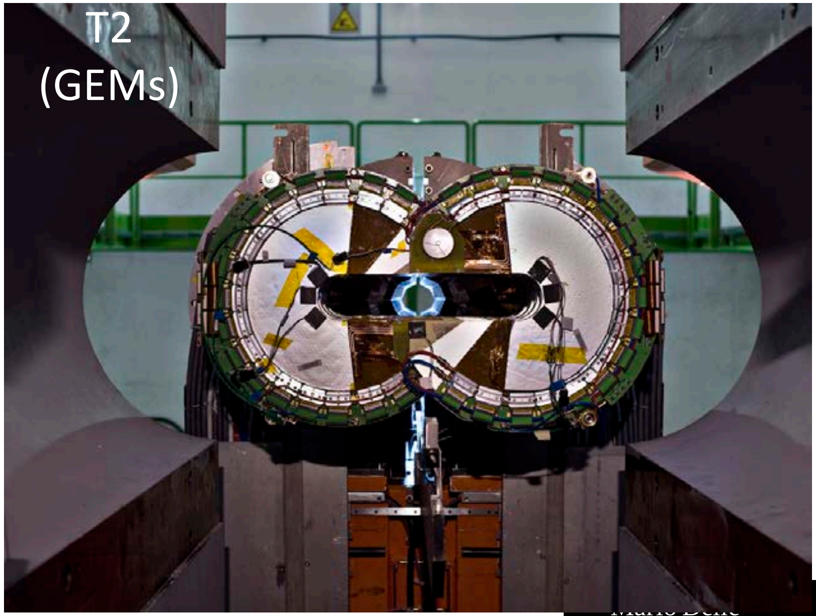


Detectors


RP 147
Vertical Pot
Horizontal Pots
Vertical Pot
Vertical Pot
Vertical Pot


Package of 10 “edgeless” Si-detectors


T1
(CSCs)


T2
(GEMs)

Outline: Recent Results

- Measurement of the forward charged particle pseudorapidity density in pp collisions at $\sqrt{s} = 7$ TeV with the TOTEM experiment [EPL 98 (2012) 31002]

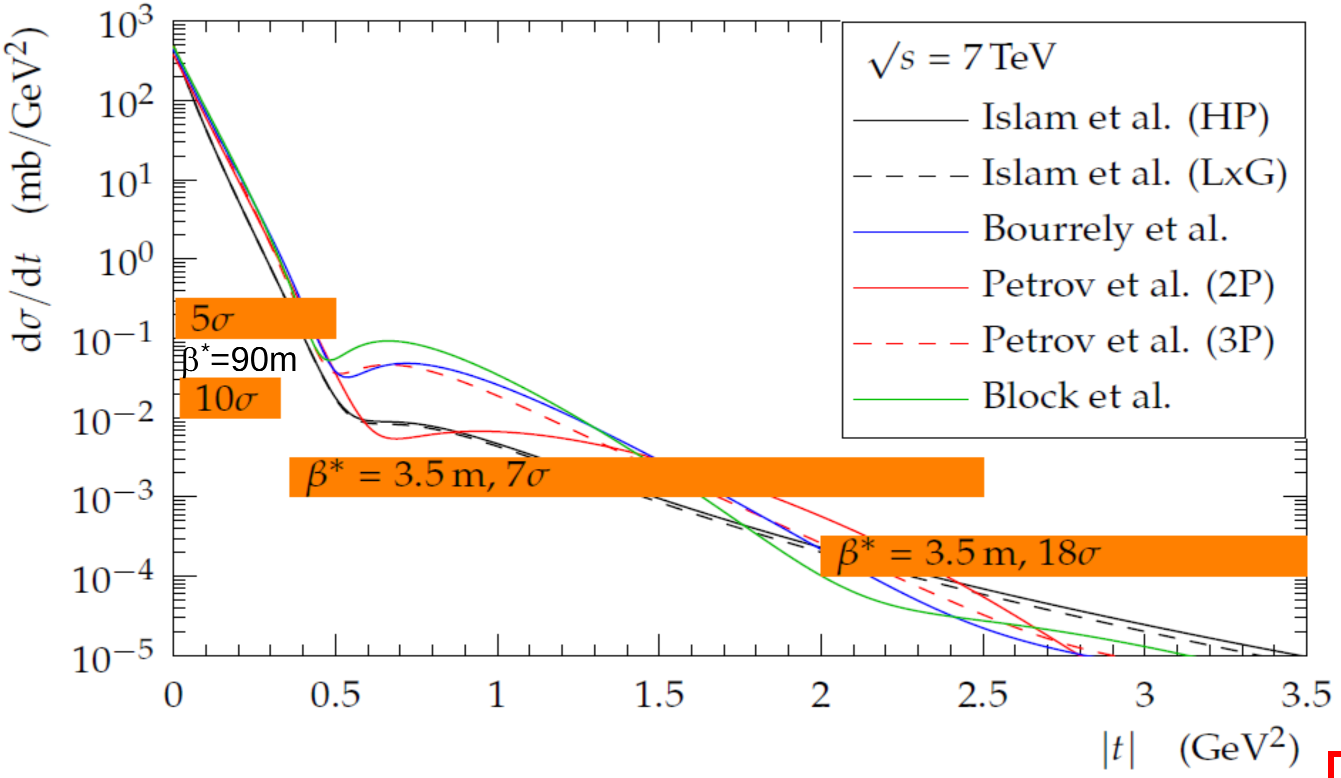
- Measurement of proton-proton elastic scattering and total cross-section at $\sqrt{s} = 7$ TeV [CERN-PH-EP-2012-239, to be submitted to EPL] → this presentation (article includes numerical table of elastic differential cross-section from 5 x 10^{-3} to 2.5 GeV^2)

- Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s} = 7$ TeV [to be submitted to EPL] → Risto Orava's talk

- Luminosity independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s} = 7$ TeV [to be submitted to EPL] → this presentation

Elastic Scattering: Data Collection

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



Subset	RP pos.	$\lvert t\rvert_{min}$ [GeV^2]
1a	6.5 σ	7.3 x 10^{-3}
1b	5.5 σ	5.7 x 10^{-3}
1c	4.8 σ	4.6 x 10^{-3}

Set	β^*(m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events
1	90	4.8-6.5σ	83	$7 \cdot 10^{-3}$ - 0.5	1M
2	90	10σ	1.7	0.02 - 0.4	14k
3	3.5	7σ	0.07	0.36 - 3	66k
4	3.5	18σ	2.3	2 - 3.5	10k

← new

← [EPL 96]

← [EPL 95]

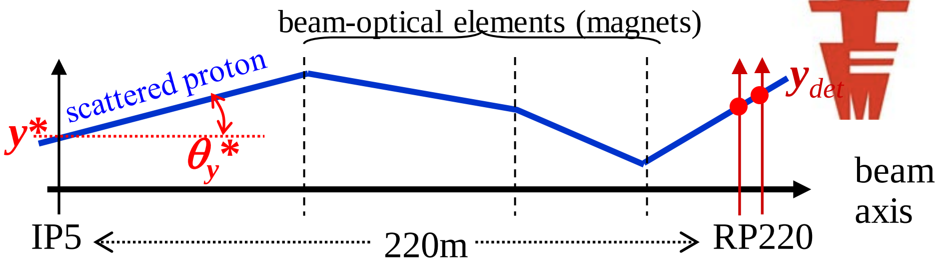
← analysis in progress

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: $\xi = 0$)



Measured in RP

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

Reconstructed

Reconstruction of scattering angles Θ_x^* and Θ_y^* :

Optics with $\beta^* = 90$ m:

$L_y = 263$ m, $v_y \approx 0$ → Reconstruct via track positions

$$\boxed{\Theta_y^* = \frac{y}{L_y}}$$

$L_x \approx 0$, $v_x = -1.9$ → Use derivative (reconstruct via local track angles):

$$\boxed{\Theta_x^* = \frac{1}{\frac{dL_x}{ds}} \left(\Theta_x - \frac{dv_x}{ds} \cdot x^* \right)}$$

Excellent optics understanding (transfer matrix elements) needed.

Optics Matching

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]

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

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \end{pmatrix}_{\mathrm{RP}} = \mathbf{T} \begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \end{pmatrix}_{\mathrm{IP5}}$$

with

$$\mathbf{T} = \prod_{i=M}^{1} \left[\mathbf{T}_i(k_i) + \Delta \mathbf{T}_i \right] = \begin{pmatrix} v_x & L_x & re_{13} & re_{14} \\ \boxed{\frac{dv_x}{ds}} & \frac{dL_x}{ds} & re_{23} & re_{24} \\ re_{31} & re_{32} & \boxed{v_y} & L_y \\ re_{41} & re_{42} & \frac{dv_y}{ds} & \frac{dL_y}{ds} \end{pmatrix}$$

- 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 ($\Delta B/B = O(10^{-4})$ @ $R_{\mathrm{ref}} = 17$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. $\Theta^*_{\mathrm{right}}$)

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

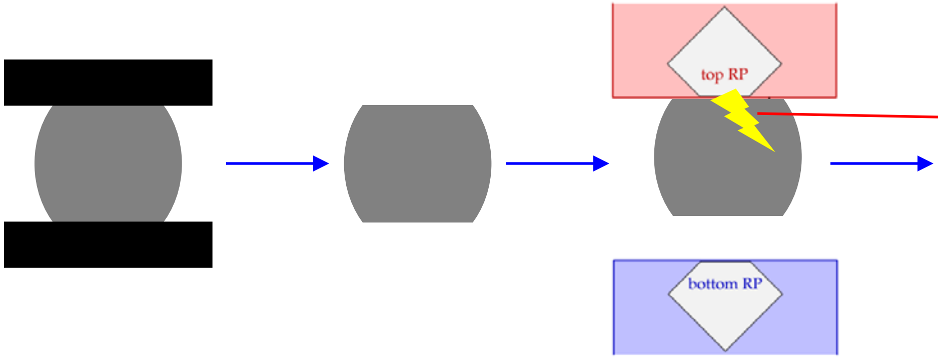
→ Error propagation to relevant optical functions L_y (1%) and dL_x/ds (0.7%) ⇒ **$\delta t / t \sim 0.8 – 2.6$ %**

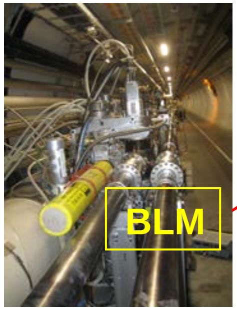
Beam-Based Roman Pot Alignment (Scraping)

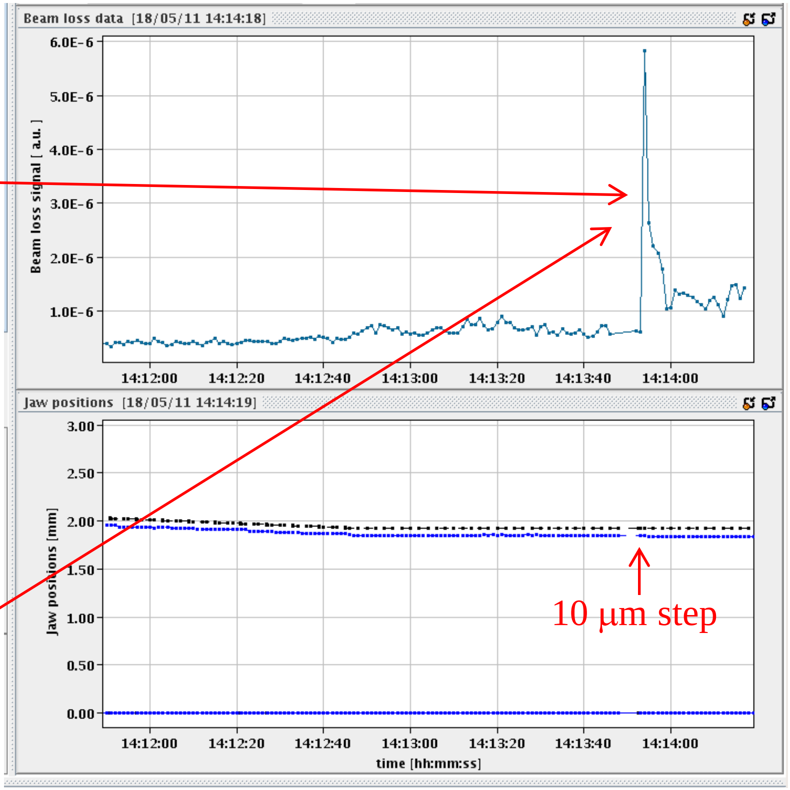
A primary collimator cuts a sharp edge into the beam, symmetrical to the centre

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







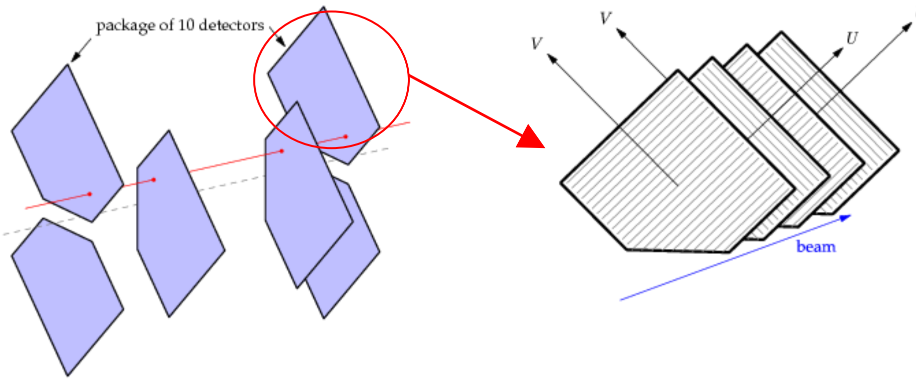
When both top and bottom pots are touching the beam edge:

- 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

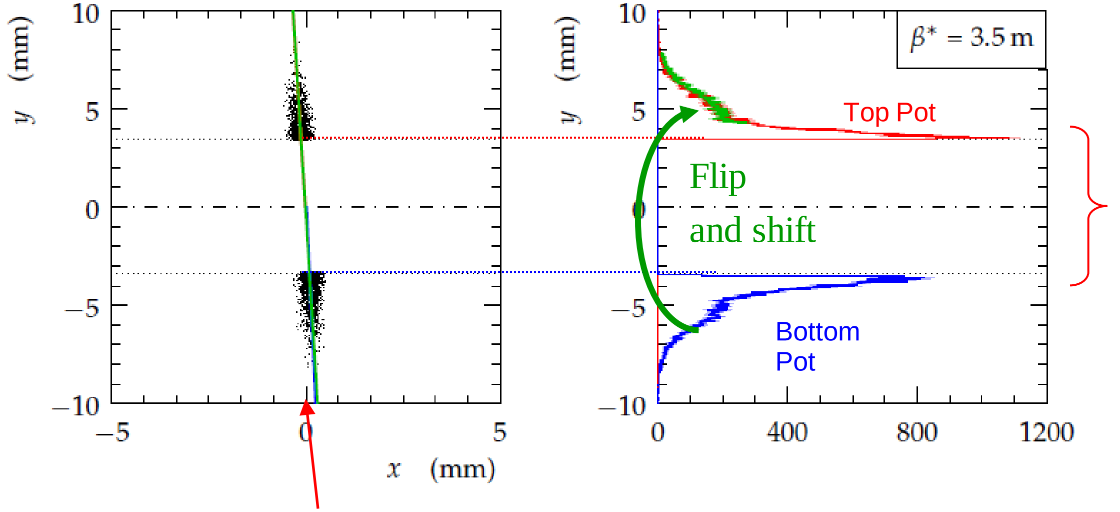


Residual-based alignment technique:
shifts and rotations within a RP unit

Important: overlap between horizontal and vertical detectors !

Alignment Exploiting Symmetries of Hit Profiles

Map of all track intercepts after elastic selection

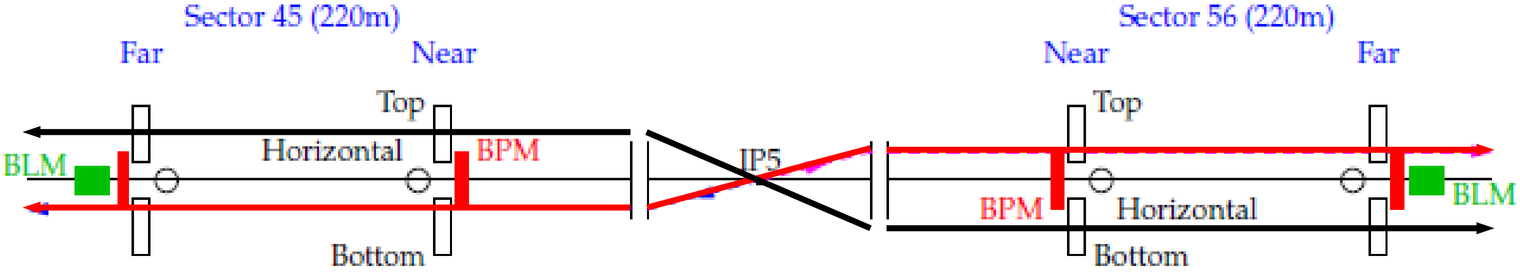


Fine vertical alignment: about 20 μm precision

→ Fine horizontal alignment: precision better than 10 μm

Elastic pp Scattering: Event Topology and Hit Maps

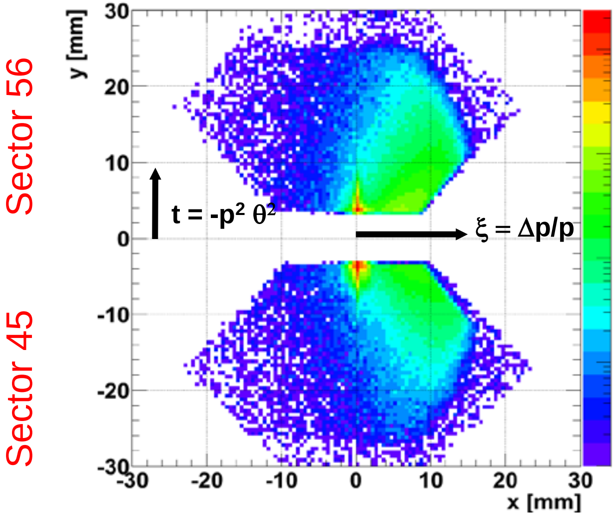
Two diagonals analysed independently



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

β^*=3.5m

RP @ 7σ

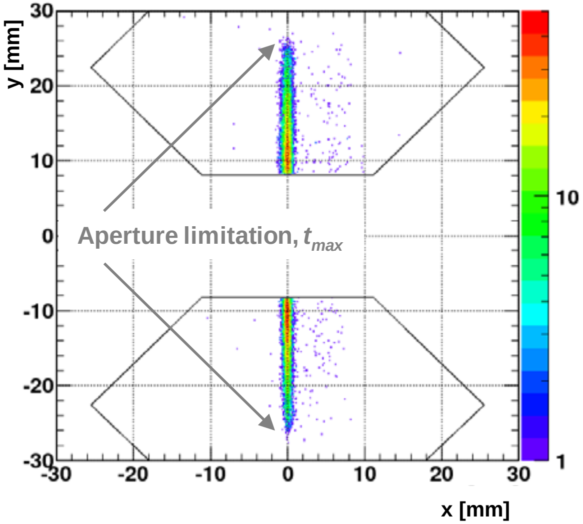


7 x10^{10} protons per bunch

Inelastic pile-up ~ 0.8 ev. / bx

β^*=90m

RP @ 10σ

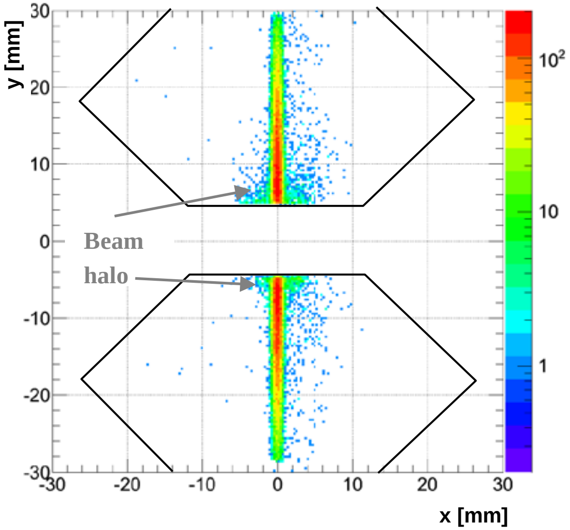


1.5 x10^{10} protons per bunch

Inelastic pile-up ~ 0.005 ev. / bx

β^*=90m

RP @ 5σ



6 x10^{10} protons per bunch

Inelastic pile-up ~ 0.03 ev. / bx

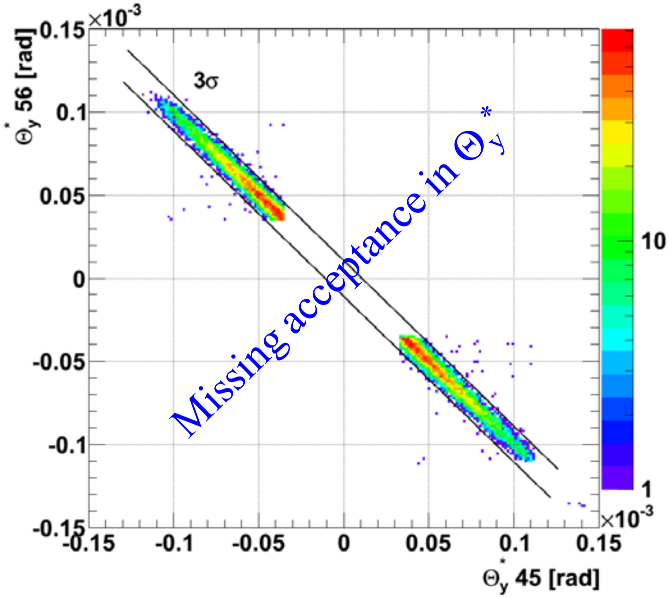
Elastic Tagging

Selection cuts:

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

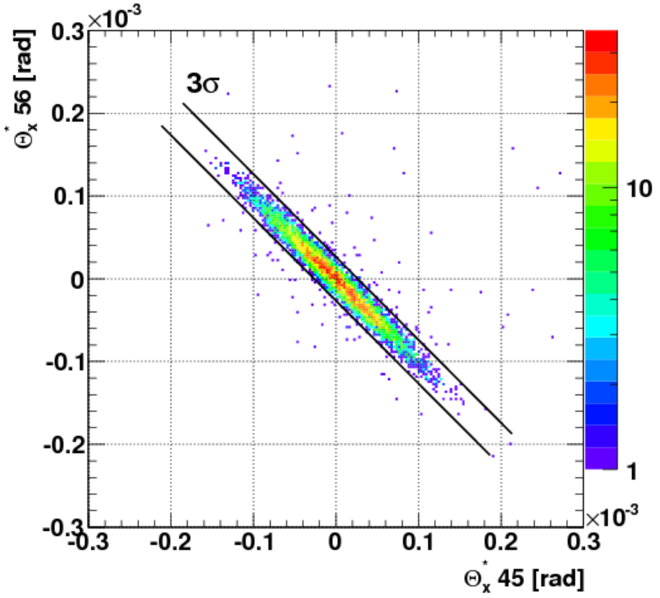
Example: elastic collinearity : Scattering angle on one side versus the opposite side

Collinearity in y



Missing acceptance in Θ_y^*

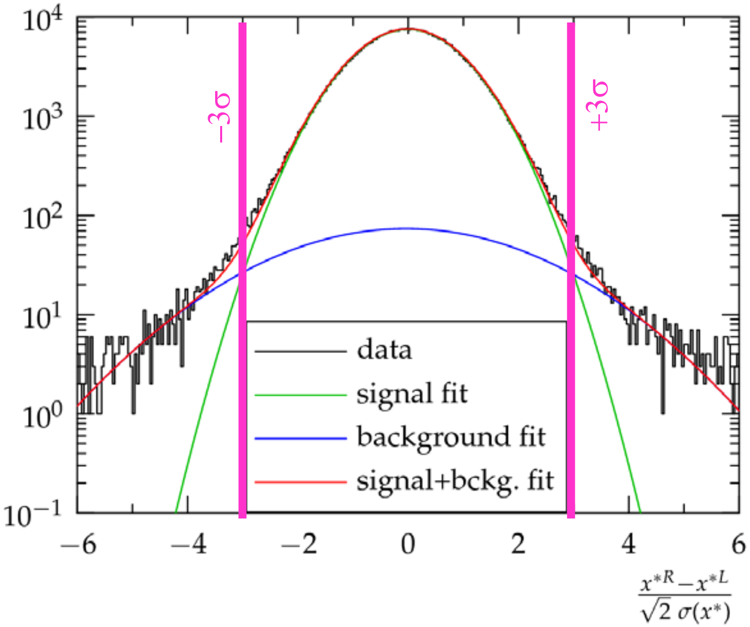
Collinearity in x



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

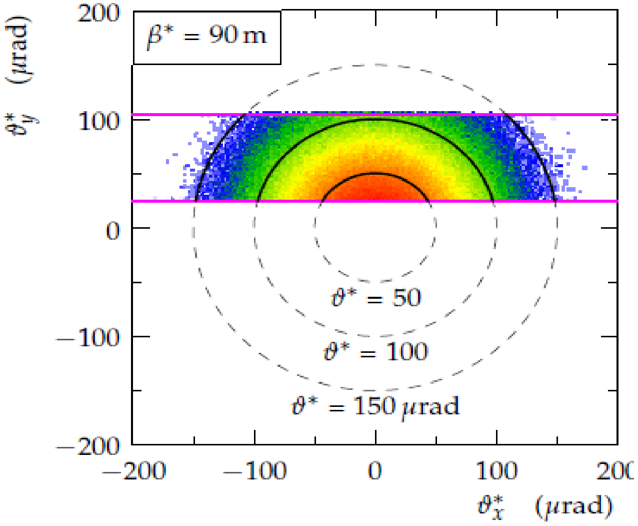
Analysis Overview I

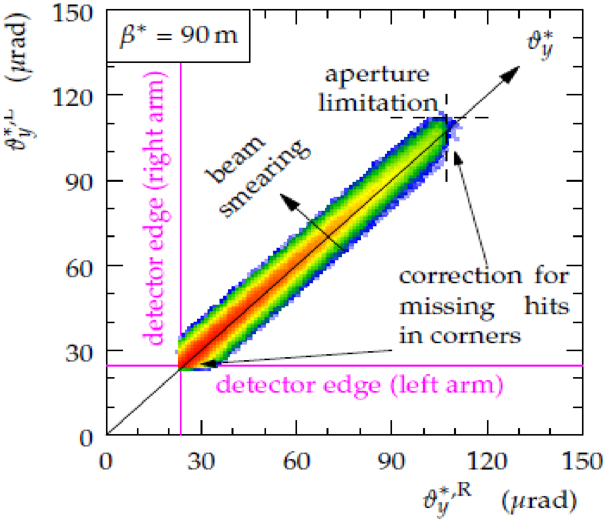
Background subtraction



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

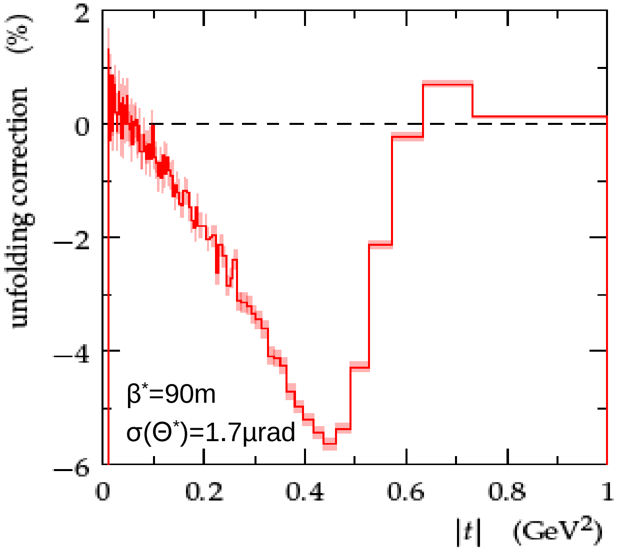
Acceptance correction





Analysis Overview II

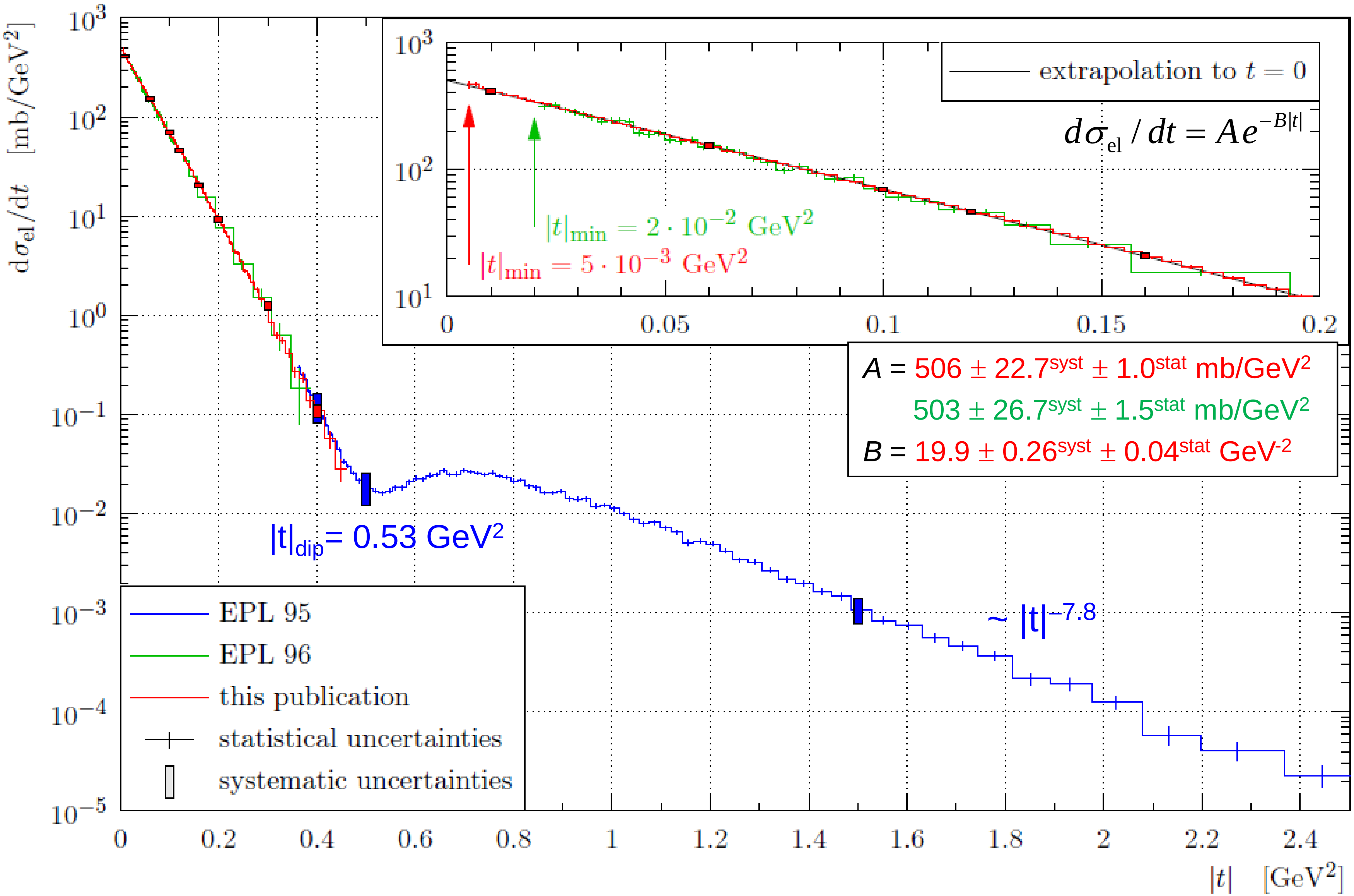
Resolution unfolding



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 %

Elastic pp Scattering: Differential Cross-Section



$$d\sigma_{el} / dt = A e^{-B|t|}$$

$|t|_{dip}$= 0.53 GeV^2

~ $|t|^{-7.8}$

A = 506 ± 22.7^{syst} ± 1.0^{stat} mb/GeV^2

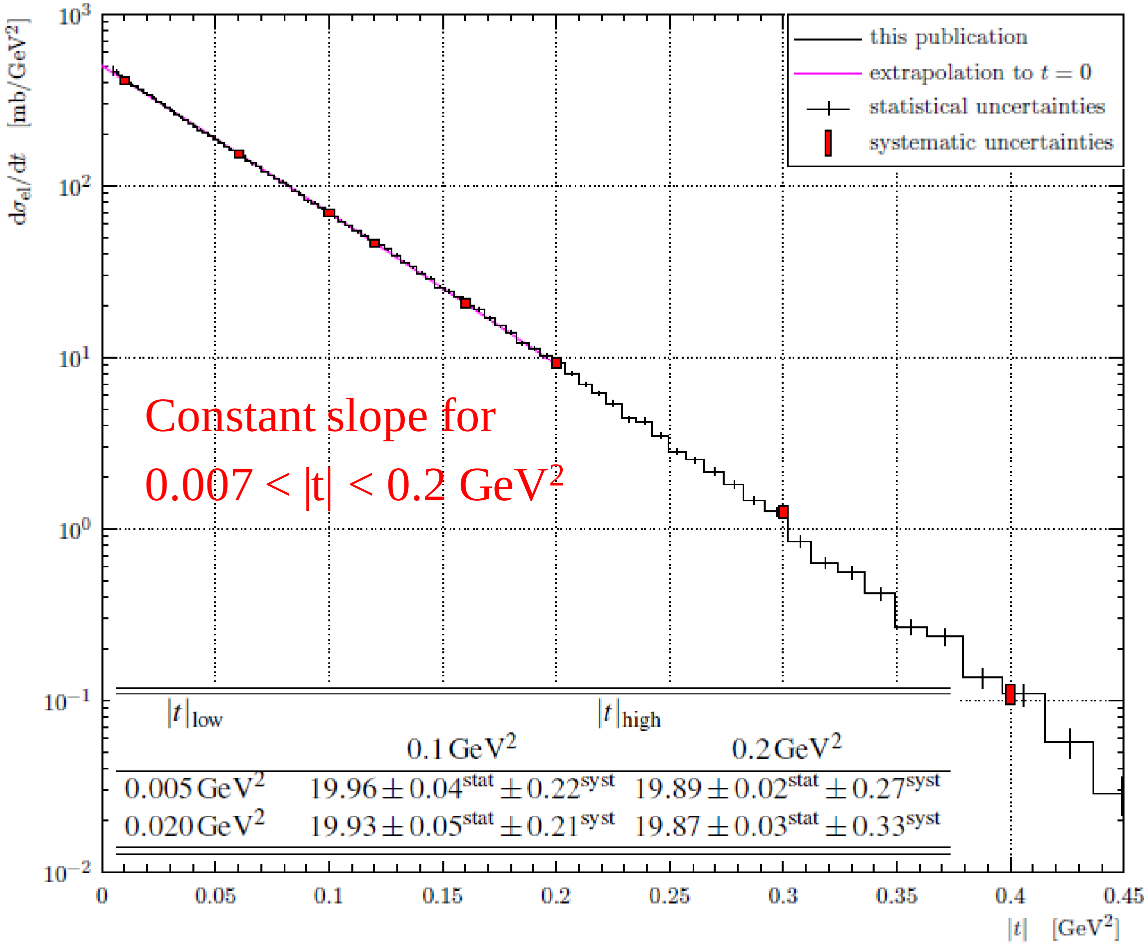
503 ± 26.7^{syst} ± 1.5^{stat} mb/GeV^2

B = 19.9 ± 0.26^{syst} ± 0.04^{stat} GeV^{-2}

Integrated elastic cross-section: 25.4 ± 1.0^{lumi} ± 0.3^{syst} ± 0.03^{stat} mb *(90% measured)*

24.8 ± 1.0^{lumi} ± 0.2^{syst} ± 0.2^{stat} mb *(50% measured)*

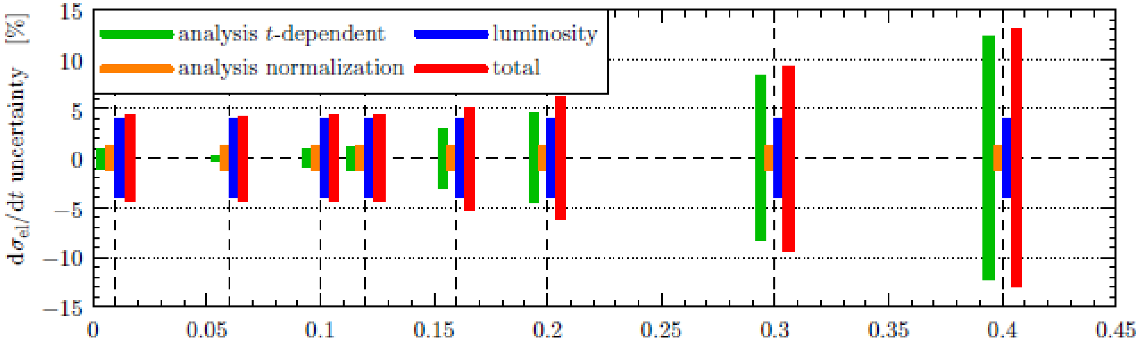
Elastic Scattering at low |t|: Systematics



Constant slope for

$0.007 < |t| < 0.2$ GeV^2

$\lvert t\rvert_{\text{low}}$ \ $\lvert t\rvert_{\text{high}}$	0.1 GeV^2	0.2 GeV^2
0.005 GeV^2	$19.96 \pm 0.04^{\text{stat}} \pm 0.22^{\text{syst}}$	$19.89 \pm 0.02^{\text{stat}} \pm 0.27^{\text{syst}}$
0.020 GeV^2	$19.93 \pm 0.05^{\text{stat}} \pm 0.21^{\text{syst}}$	$19.87 \pm 0.03^{\text{stat}} \pm 0.33^{\text{syst}}$



Individual contributions:

analysis t-dependent:

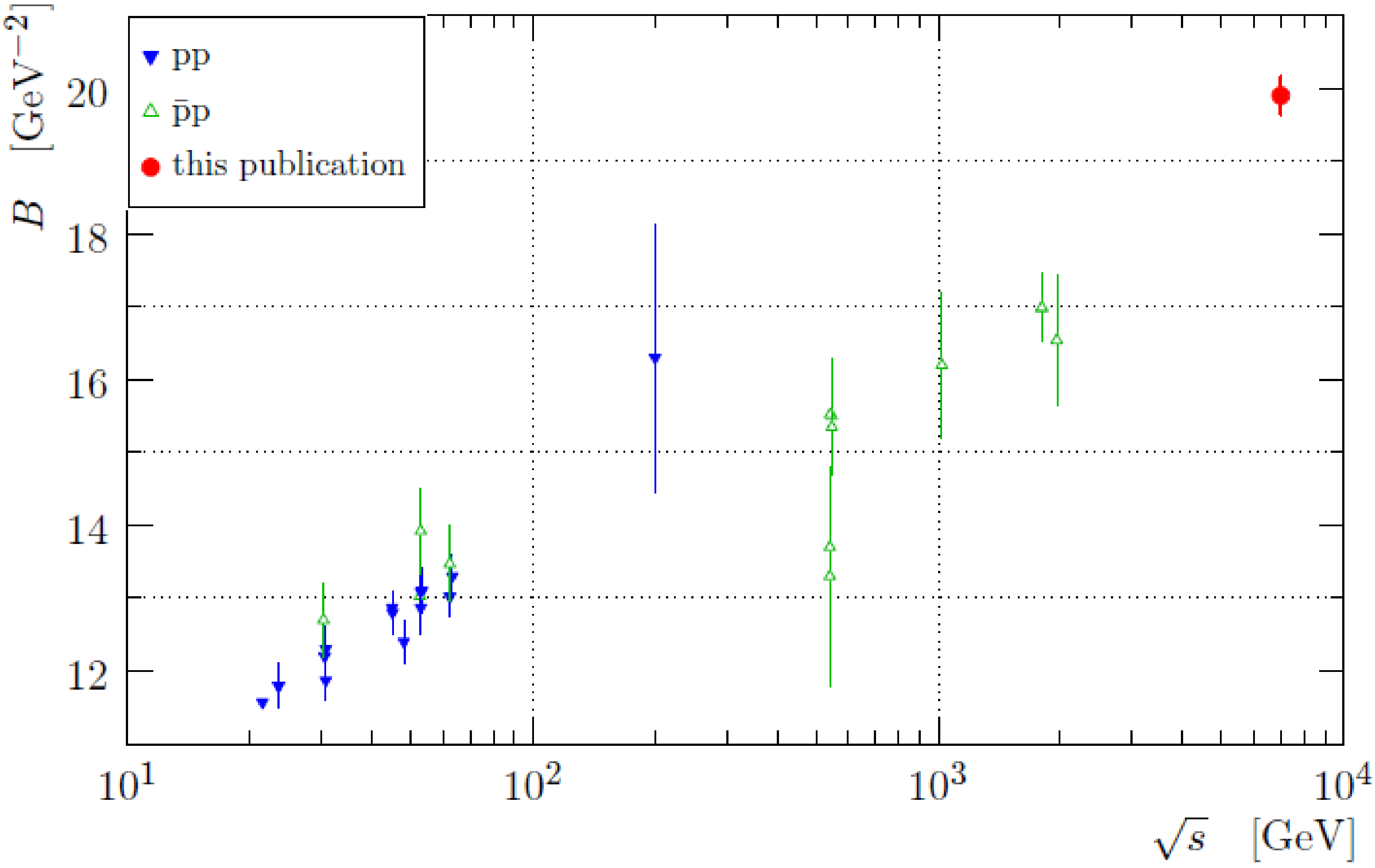
- – misalignments
- – optics imperfections
- – energy offset
- – acceptance correction
- – unsmearing correction

analysis normalization:

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

Luminosity from CMS (± 4%)

Energy dependence of the exponential slope B



3 Ways to the Total Cross-Section

elastic observables only:

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

(ρ=0.14 [COMPETE])

June (EPL96): $\sigma_{\mathrm{tot}} = (98.3 \pm 2.0)$ mb

October: $\sigma_{\mathrm{tot}} = (98.6 \pm 2.2)$ mb

different bunch intensities !

σ_{tot}

ϱ independent:

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

$\sigma_{\mathrm{tot}} = (99.1 \pm 4.3)$ mb

luminosity independent:

$$\sigma_{\mathrm{tot}} = \frac{16\pi}{1+\varrho^2}\,\frac{\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t|_0}{N_{\mathrm{el}} + N_{\mathrm{inel}}}$$

$\sigma_{\mathrm{tot}} = (98.0 \pm 2.5)$ mb

Excellent agreement between cross-section measurements using
- runs with different bunch intensities,
- different methods.

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

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

(via the Optical Theorem)

$$\sigma_{\mathrm{tot}}^2 = \frac{16\pi}{1+\varrho^2}\,\frac{1}{\mathcal{L}}\,\left.\frac{\mathrm{d}N_{\mathrm{el}}}{\mathrm{d}t}\right|_0 \quad \Rightarrow \quad \sigma_{\mathrm{inel}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} = 73.15 \pm 1.26 \text{ mb}$$

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

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

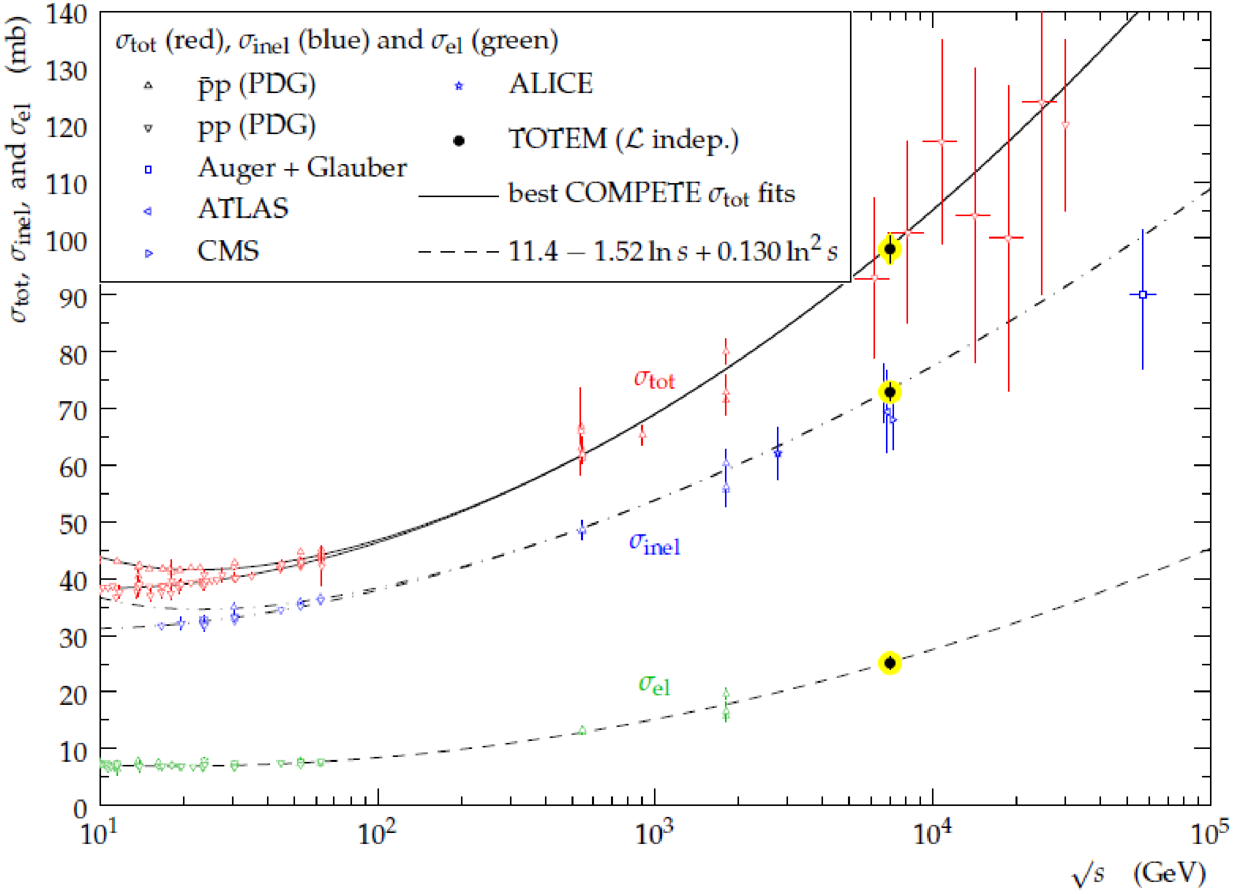
to obtain the low-mass diffractive cross-section (|η| > 6.5 or M < 3.4 GeV):

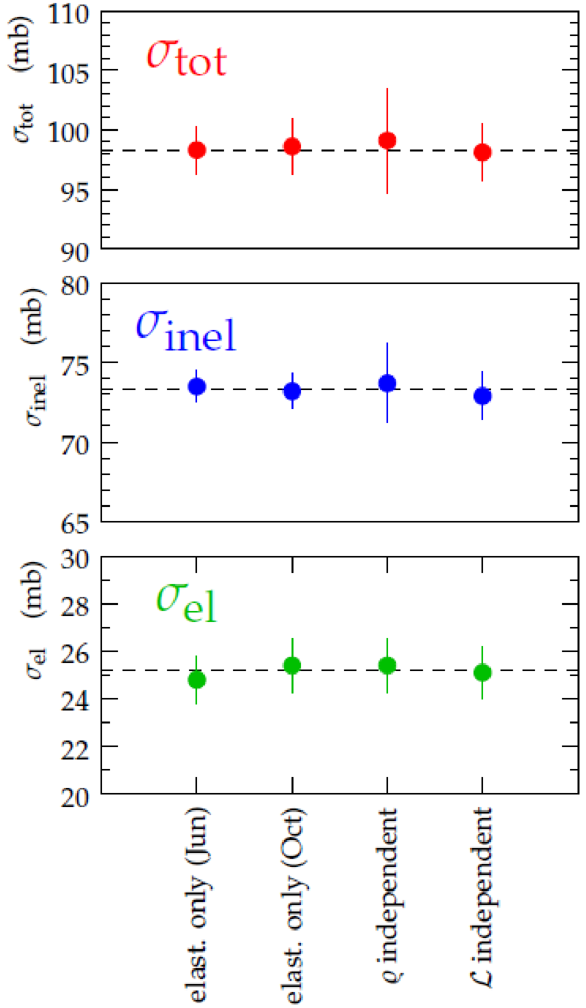
$$\sigma_{\mathrm{inel},\,|\eta|>6.5} = \sigma_{\mathrm{inel}} - \sigma_{\mathrm{inel},\,|\eta|<6.5} = 2.62 \pm 2.17 \text{ mb}$$ [MC: 3.2 mb]

or

$$\sigma_{\mathrm{inel},\,|\eta|>6.5} < 6.31 \text{ mb} \quad (95\%\ \mathrm{CL})$$

Cross-Section Measurements





Absolute Luminosity Calibration

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

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

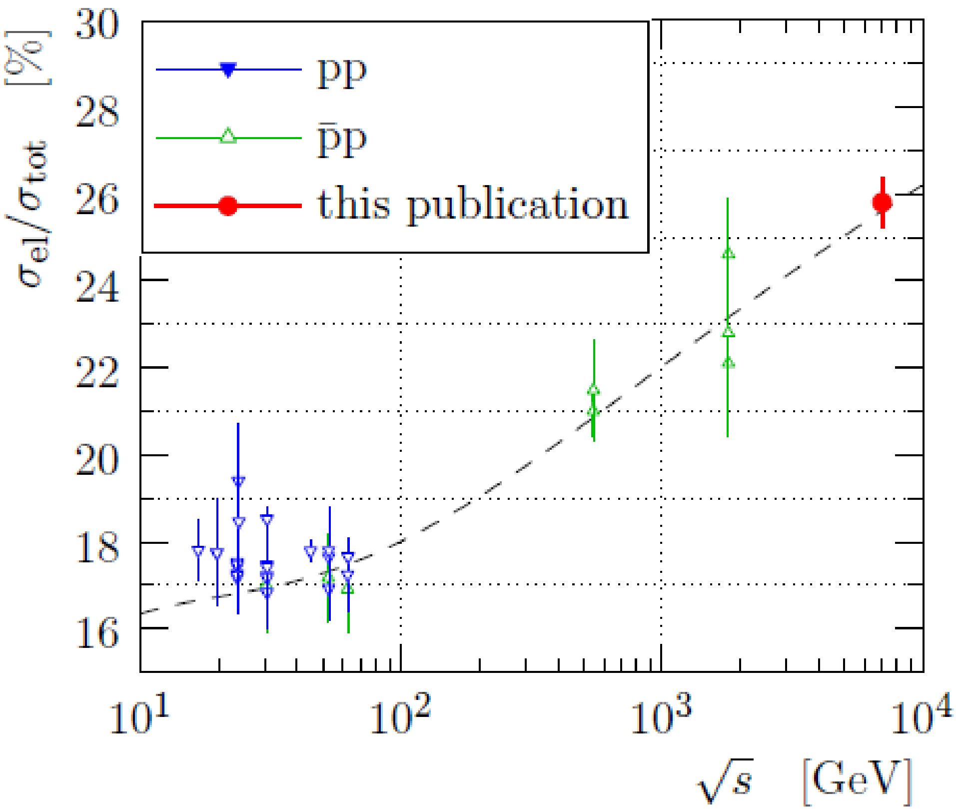
October 2011: $\mathcal{L}_{\text{int}}$ = (83.7 ± 3.2) μb^{-1} [CMS: (82.0 ± 3.3) μb^{-1}]

Excellent agreement with CMS luminosity measurement.

Elastic to Total Cross-Section Ratio

$$\frac{\sigma_{el}}{\sigma_{tot}} = \frac{N_{el}}{N_{el} + N_{inel}} = 0.257 \pm 0.005$$

independent of luminosity and ρ



➔ σ_{el} / σ_{tot} increases with energy

A First, Very Crude ρ Estimate

$$\rho^2 = 16\pi\,\mathcal{L}_{\text{int}}\,\frac{\left.\dfrac{\mathrm{d}N_{\text{el}}}{\mathrm{d}t}\right|_{t=0}}{\left(N_{\text{el}}+N_{\text{inel}}\right)^2}-1 \quad = \quad 0.009 \pm 0.056$$

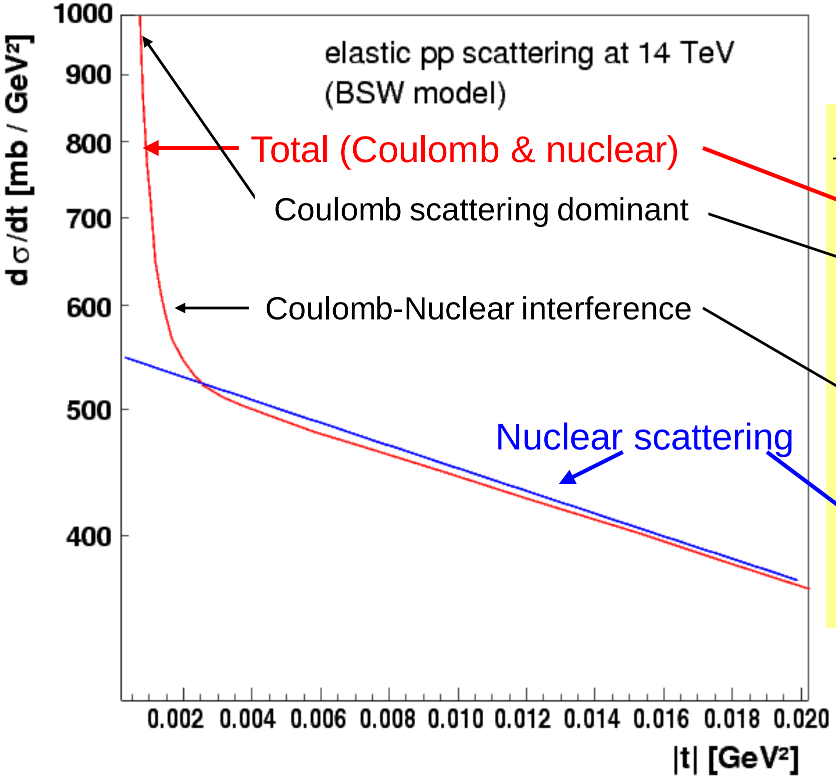
$\rho < 0.32$ (95% CL),

or, using Bayes’ approach (with uniform prior |ρ| distribution):

$|\rho| = 0.145 \pm 0.091$ [COMPETE extrapolation: $\rho = 0.141 \pm 0.007$]

Not so exciting, but …

ρ Measurement: Elastic Scattering at Low |t|



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

$$\frac{d\sigma}{dt} = \boxed{\frac{4\pi\alpha^2(\hbar c)^2 G^4(t)}{|t|^2} + \frac{\alpha(\rho-\alpha\phi)\sigma_{tot}G^2(t)}{|t|}e^{-B|t|/2} + \boxed{\frac{\sigma_{tot}{}^2(1+\rho^2)}{16\pi(\hbar c)^2}e^{-B|t|}}}$$

α = fine structure constant

ϕ = relative Coulomb-nuclear phase

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

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

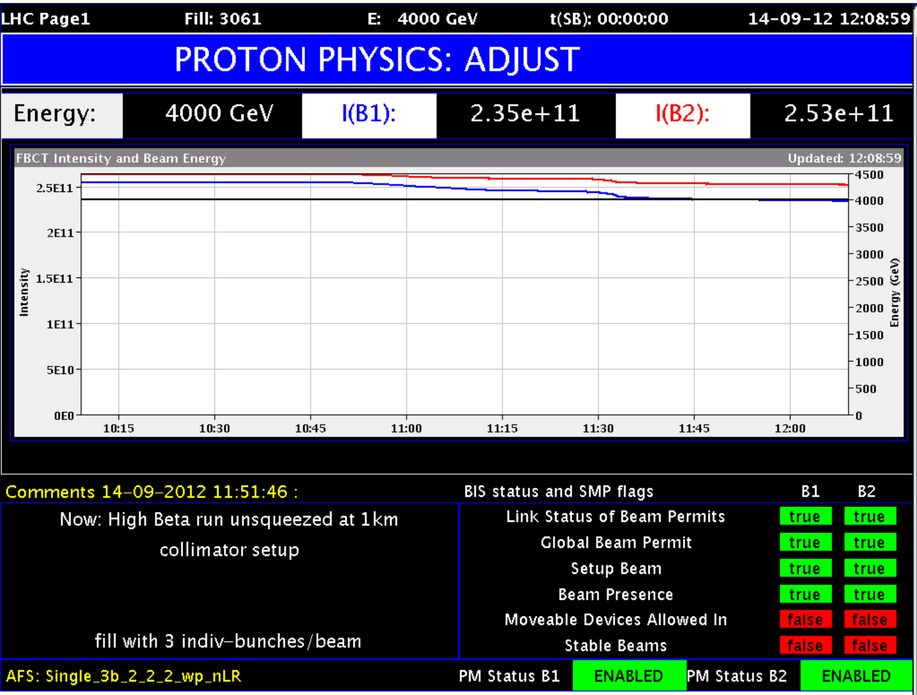
Measurement of ρ in the Coulomb – Nuclear interference region at

|t| ~ 6 x 10^{-4} GeV^2

Reachable with β* ~ 1000 m still in 2012 if RPs can approach beam centre to ~ 4σ

LATEST NEWS

Yesterday at CERN:



LHC Page1 Fill: 3061 E: 4000 GeV t(SB): 00:00:00 14-09-12 12:08:59

PROTON PHYSICS: ADJUST

Energy:	4000 GeV	I(B1):	2.35e+11	I(B2):	2.53e+11

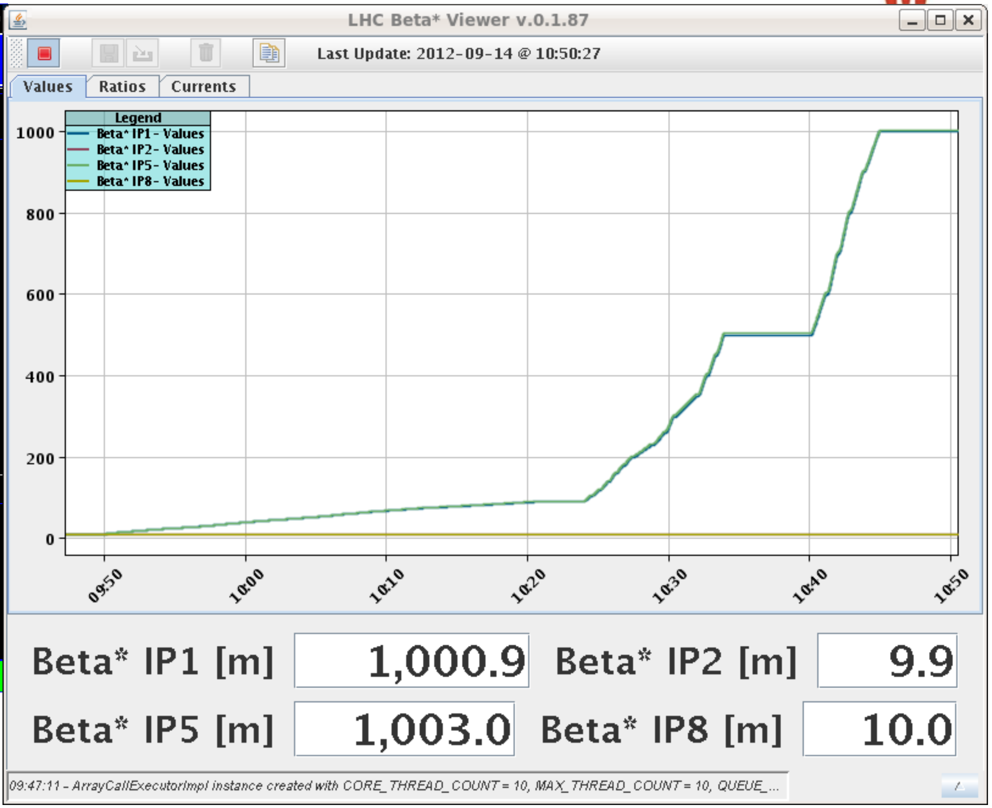
Comments 14-09-2012 11:51:46 :

Now: High Beta run unsqueezed at 1km
collimator setup

fill with 3 indiv-bunches/beam

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: Single_3b_2_2_2_wp_nLR PM Status B1 ENABLED PM Status B2 ENABLED



LHC Beta* Viewer v.0.1.87

Last Update: 2012-09-14 @ 10:50:27

Beta* IP1 [m]	1,000.9	Beta* IP2 [m]	9.9
Beta* IP5 [m]	1,003.0	Beta* IP8 [m]	10.0

09:47:11 - ArrayCallExecutorImpl instance created with CORE_THREAD_COUNT = 10, MAX_THREAD_COUNT = 10, QUEUE_...

- special beam optics with β* = 1000 m fully commissioned
- collisions in IP1 and IP5 found
- 4 vertical TOTEM RPs (out of 8) aligned at ~4 σ
- time slot ended → no physics data taken yet, but some diagnostics

Physics run scheduled for October 2012

Outlook

Data already available and being analysed:

7 TeV:

β* = 3.5 m: Elastic scattering extended to larger |t|: up to 3.5 GeV^2

β* = 90 m: Diffractive events (SD, DD, DPE)

8 TeV:

β* = 90 m: July 2012: common run with CMS (common trigger, offline data combination)

- triggers from TOTEM: protons (RP), inelastic min. bias (T2), bunch crossings
- triggers from CMS: dijets ($p_T > 20$ GeV)

→ Elastic scattering for 7×10^{-3} GeV^2 < |t| < ~1 GeV^2

→ total cross-section measurement with inelastic coverage in $-6.5 < \eta < 6.5$

→ study diffractive dijets with proton information

Data still to be taken this year:

- β* = 1000 m: attempt to measure ρ
- β* = 0.6 m (standard runs): hard diffraction with CMS
- participation in pA runs, if possible with Roman Pots inserted on the proton side

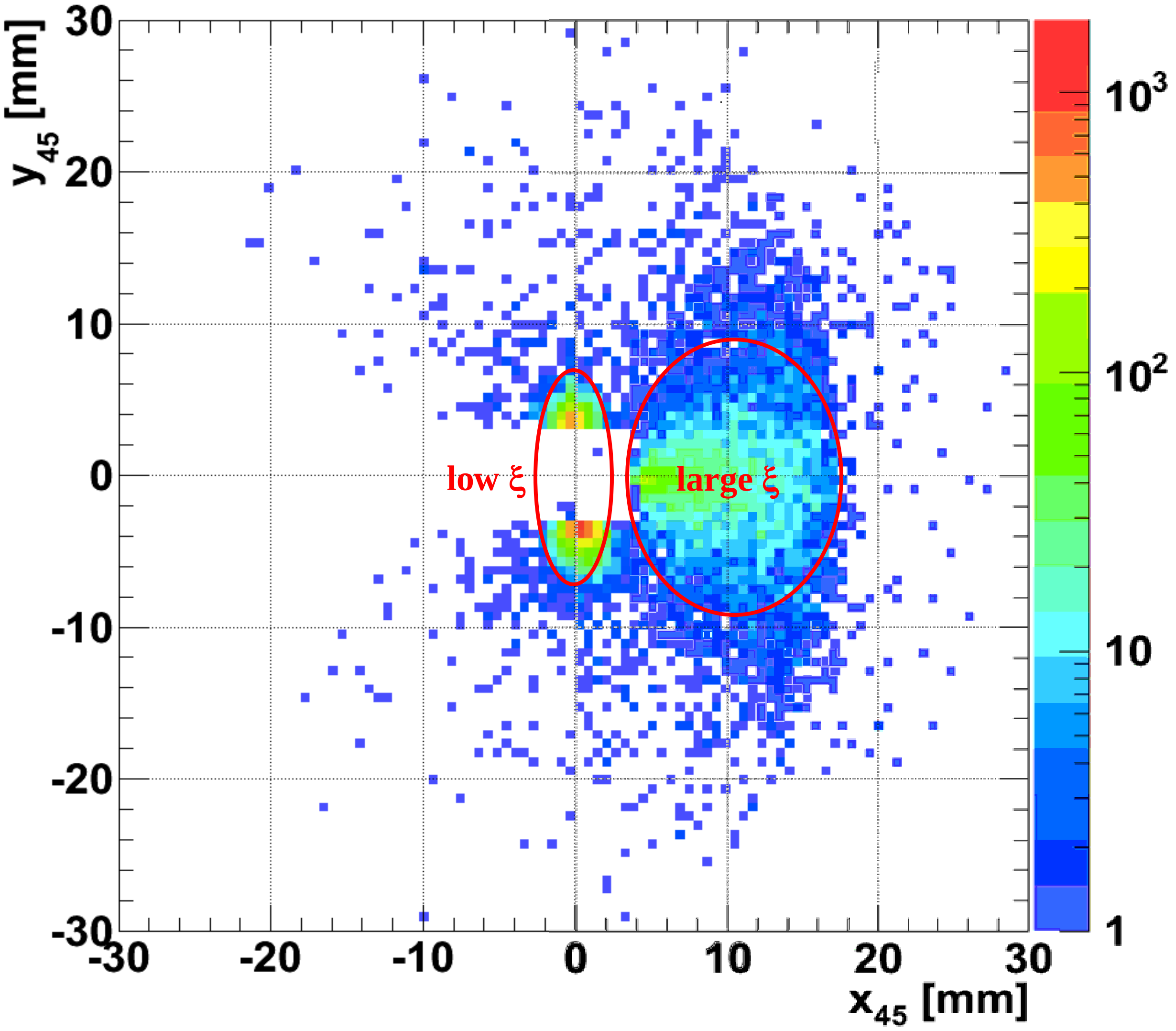
Long-term plans (after the long shutdown):

- Measurements of elastic scattering and σ_{tot} at $\sqrt{s} = 14$ TeV
- Diffraction together with CMS, discussions on common upgrade of forward proton detectors

Backup

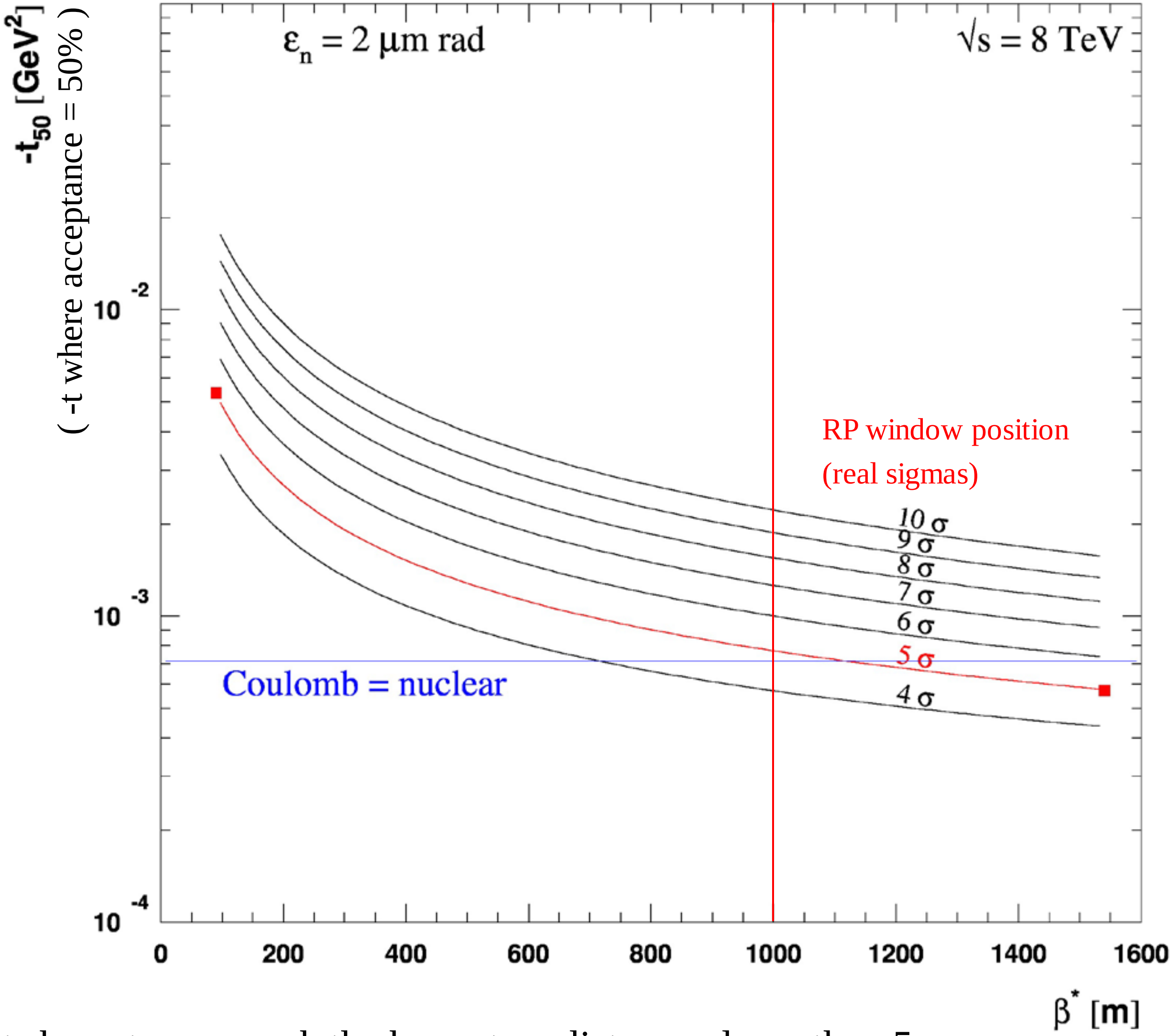
Track distribution for an inclusive trigger (global "OR")

β* = 3.5 m



$\xi = \Delta p / p$

How to reach the Coulomb Region ?



5 real σ = 3.8 nom σ

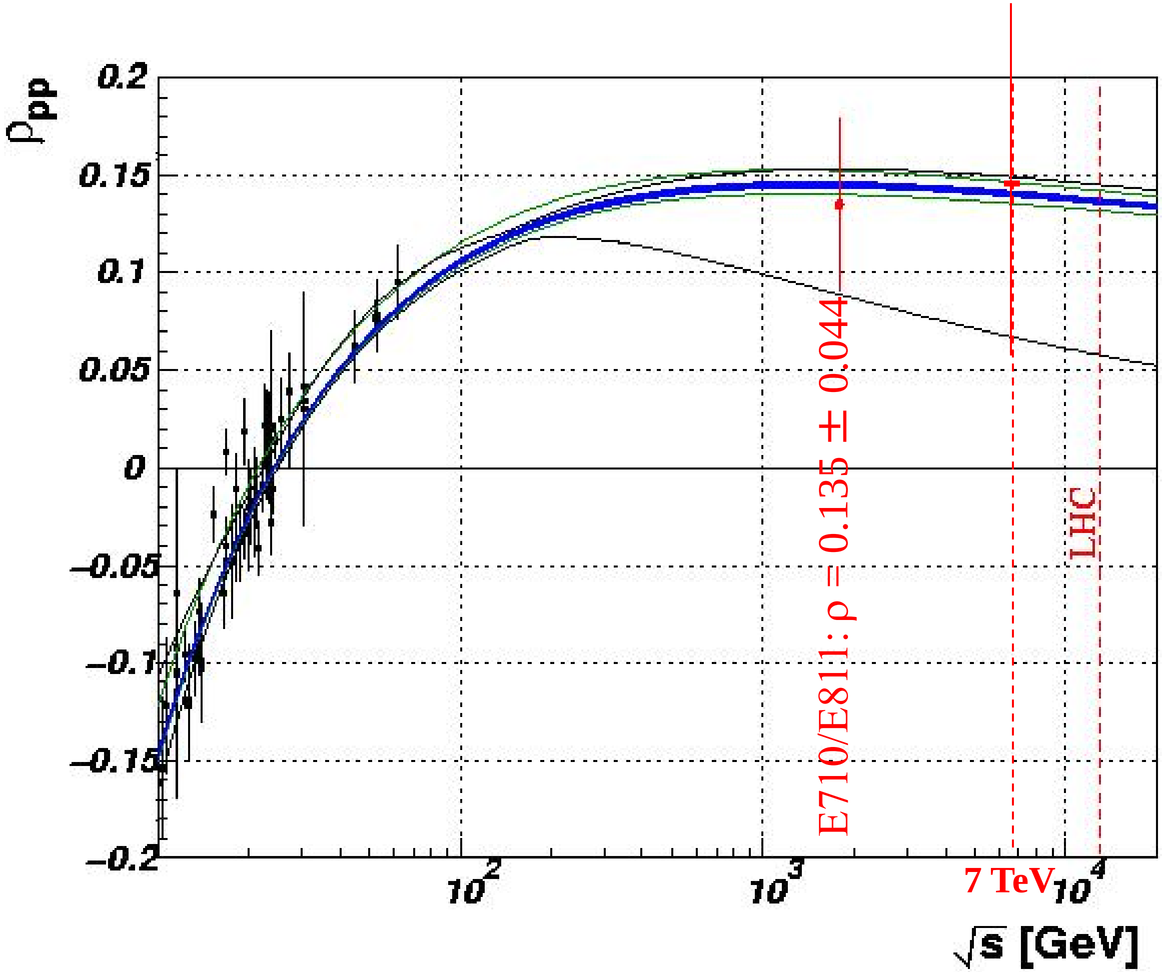
The pots have to approach the beam to a distance closer than 5σ,

Beam emittance $\varepsilon_n < 2\ \mu$m rad

→ Challenging but not impossible

Elastic Scattering: $\rho = \Re\, f(0) / \Im\, f(0)$

COMPETE [PRL 89 201801 (2002)]

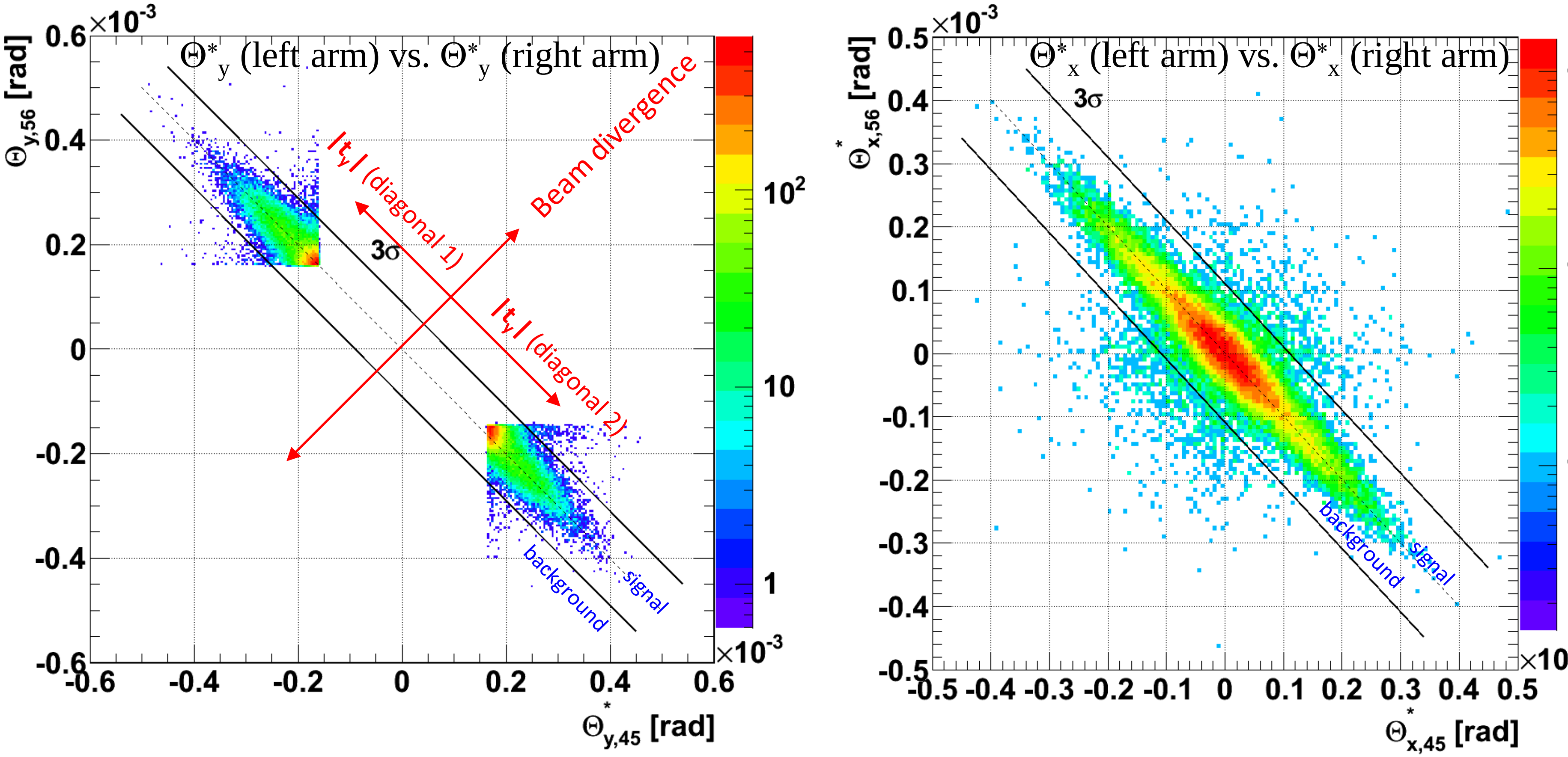


Elastic Tagging

1. Low $|\xi|$ selection : $|x| < 3\,\sigma_x$ @ $L_x = 0$

$$x = L_x \cancel{\Theta_x} + \xi D + v_x x^*$$

2. Elastic collinearity :



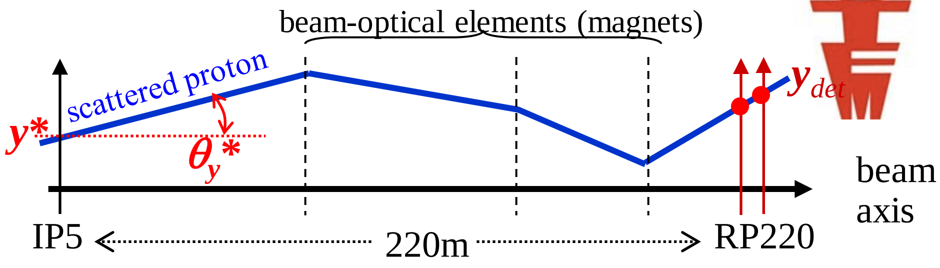
Data outside the 3σ cuts used for background estimation

Proton Transport (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 (diffraction)



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

$\beta^* = 90$ m: $L_y = 263$ m, $v_y \approx 0$

$\beta^* = 3.5$ m: $L_y \sim 20$ m, $v_y = 4.3$

→ Reconstruct via track positions

$$\boxed{x_{\rm det} = L_x \theta_x^* + v_x x^* + \cancel{D\xi}}$$

Elastic: $\xi = 0$

$\beta^* = 90$ m: $L_x \approx 0$, $v_x = -1.9$

$\beta^* = 3.5$ m: $L_x \approx 0$, $v_x = 3.1$

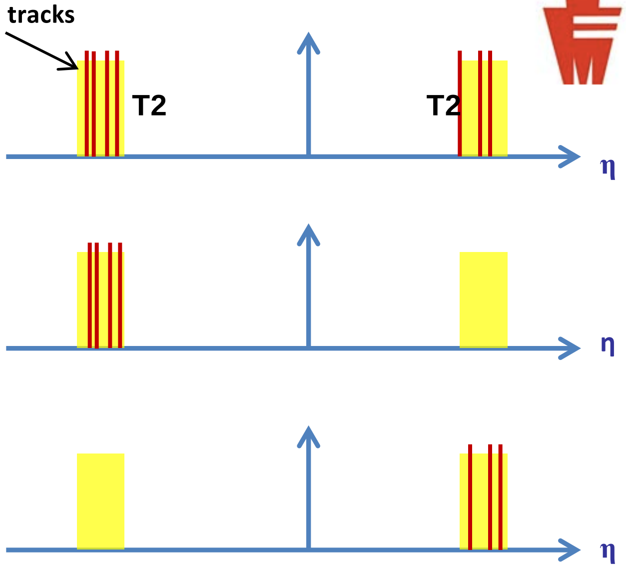
→ Use derivative (reconstruct via local track angles):

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

		Beam width @ vertex $\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}}$	Angular beam divergence $\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n}{\beta^* \gamma}}$	Min. reachable |t| $\lvert t_{\rm min}\rvert = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$
Standard optics	$\beta^* \sim 1$–3.5 m	$\sigma_{x,y}^*$ small	$\sigma(\theta_{x,y}^*)$ large	$\lvert t_{\rm min}\rvert \sim 0.3$–$1$ GeV^2
Special optics	$\beta^* = 90$ m	$\sigma_{x,y}^*$ large	$\sigma(\theta_{x,y}^*)$ small	$\lvert t_{\rm min}\rvert \sim 10^{-2}$ GeV^2

Inelastic Cross-Section Visible in T2

Inelastic events in T2: classification



tracks in both hemispheres

non-diffractive minimum bias

double diffraction

tracks in a single hemisphere

mainly single diffraction

$M_X > 3.4\ GeV/c^2$

Corrections to the T2 visible events

- Trigger Efficiency: **2.3 %**
  (measured from zero bias data with respect to track multiplicity)
- Track reconstruction efficiency: **1%**
  (based on MC tuned with data)
- Beam-gas background: **0.6%**
  (measured with non colliding bunch data)
- Pile-up (μ =0.03): **1.5 %**
  (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

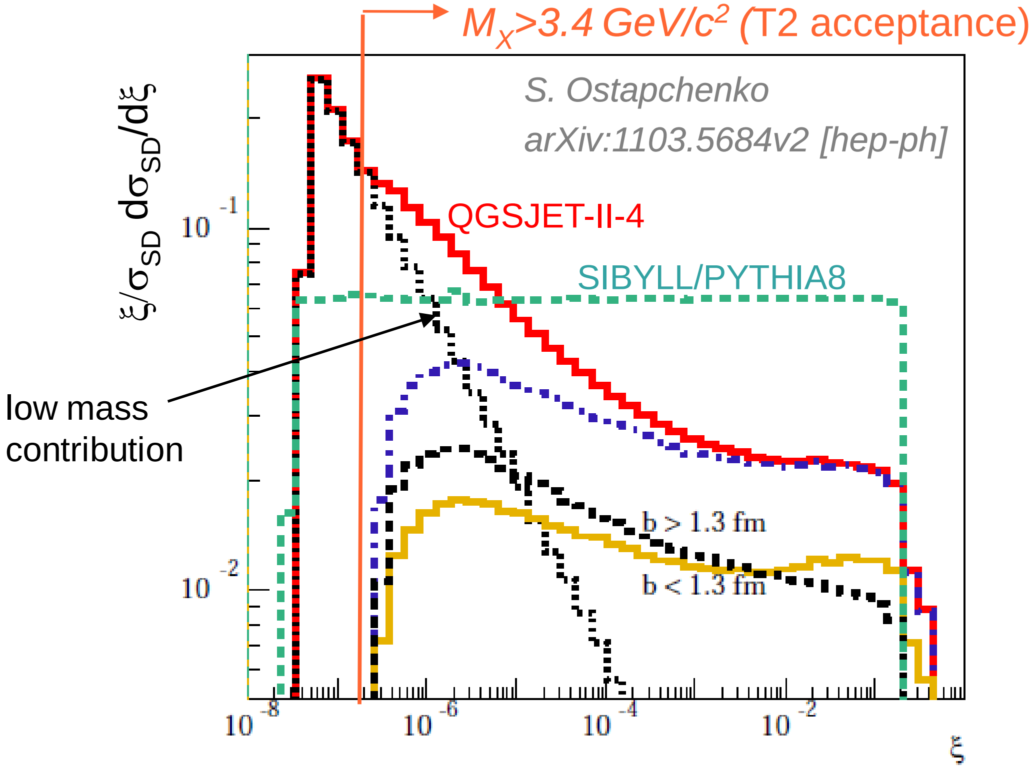
$\sigma_{\text{inelastic, T2 visible}} \Rightarrow \sigma_{\text{inelastic}}$

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 : **0.35 %**
  (based on MC, correction max ~0.25×σ_{CD} , quoted in systematic error)
- Low Mass Diffraction : **4.2 % ± 2.1 % (syst)**
  *(Several models studied, correction based on **QGSJET-II-3**,*
  imposing observed 2hemisphere/1hemisphere event ratio and the effect of 'secondaries')

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

Low-Mass Diffraction



Correction based on QGSJET-II-3

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