The TOTEM Experiment: Results and Perspectives

ZIMÁNYI SCHOOL 2012
Budapest, 3 December

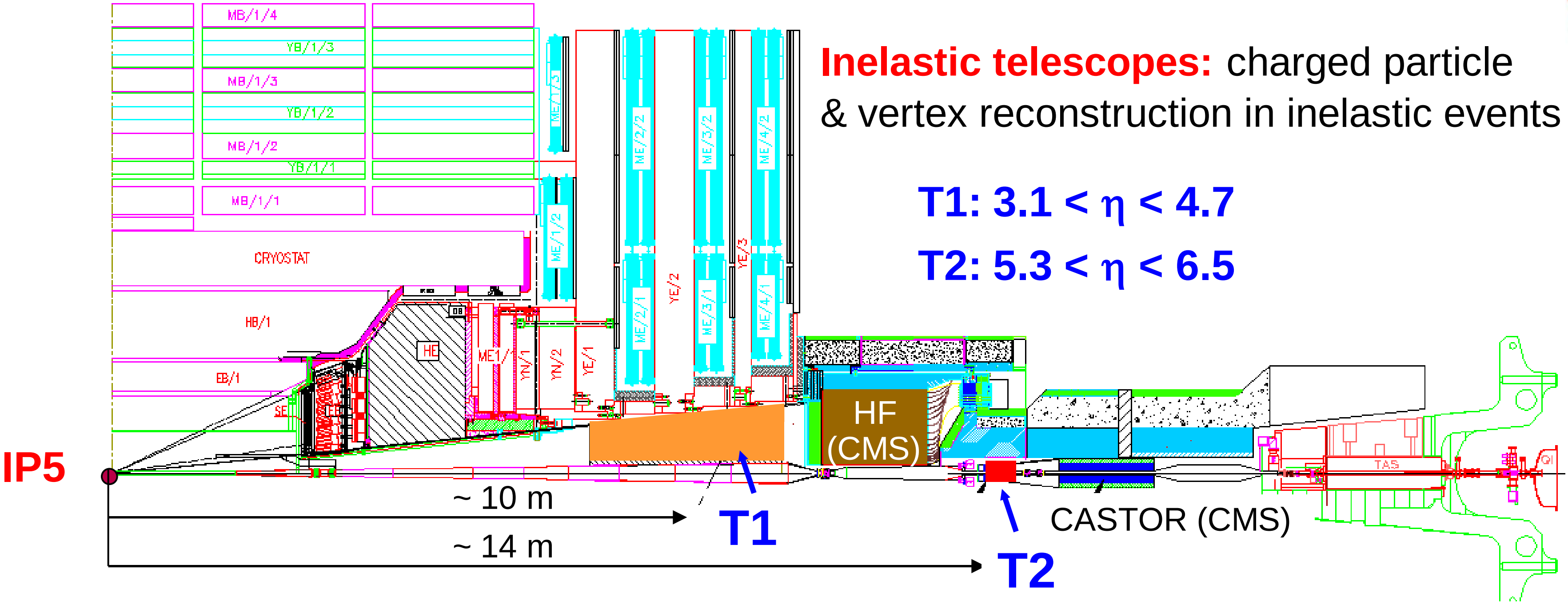
Mario Deile
on behalf of the TOTEM Collaboration

Experimental Setup @ IP5

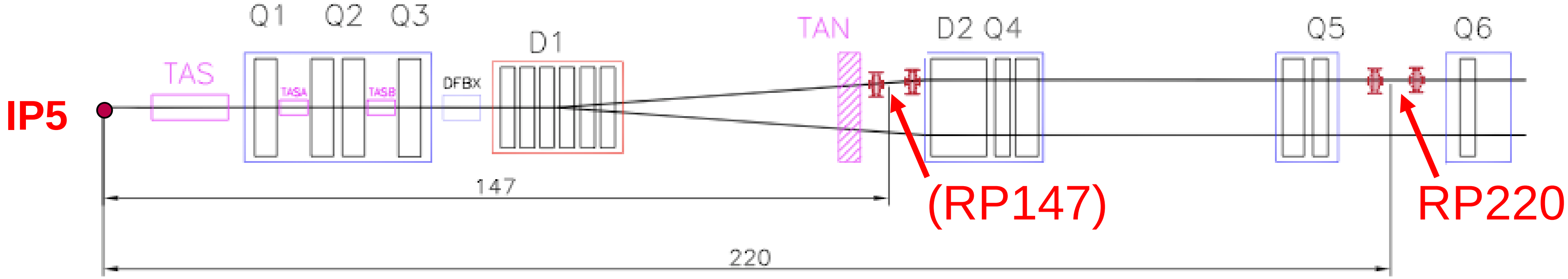
Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

T1: 3.1 < η < 4.7

T2: 5.3 < η < 6.5



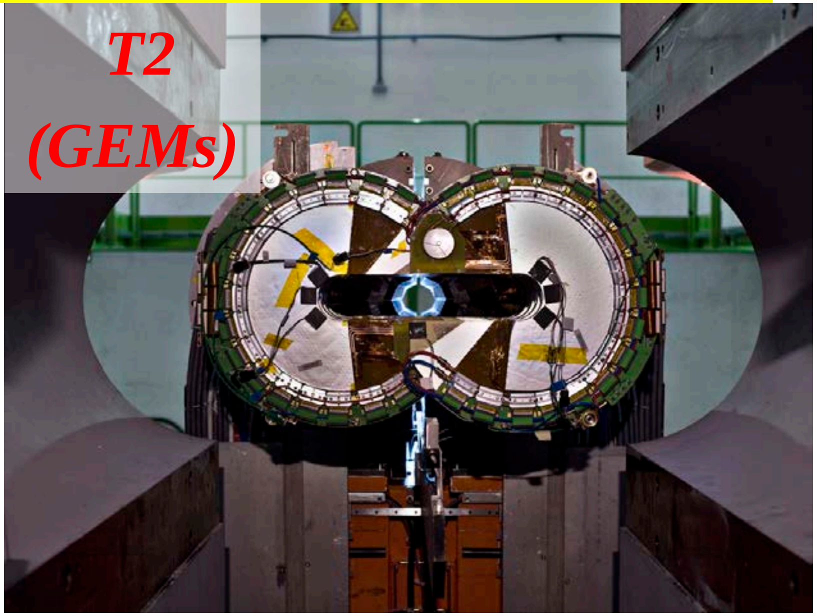
Roman Pots: measure elastic & diffractive protons close to outgoing beam



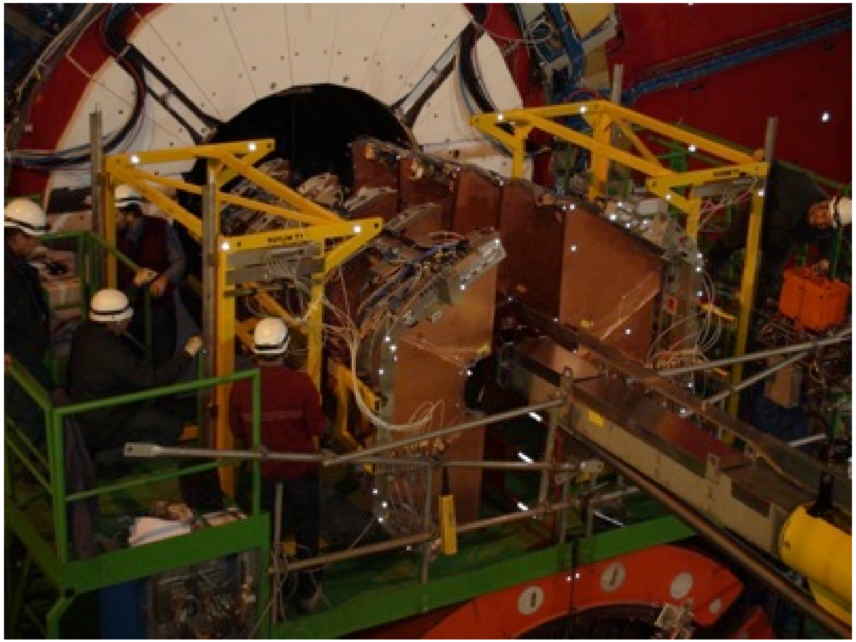
Inelastic Telescopes T1, T2

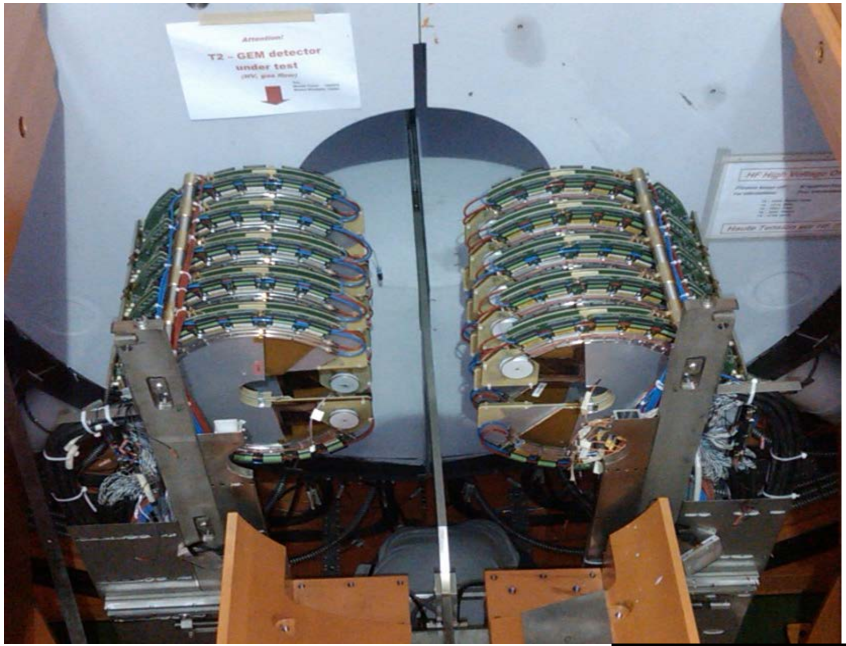

T1

(CSCs)

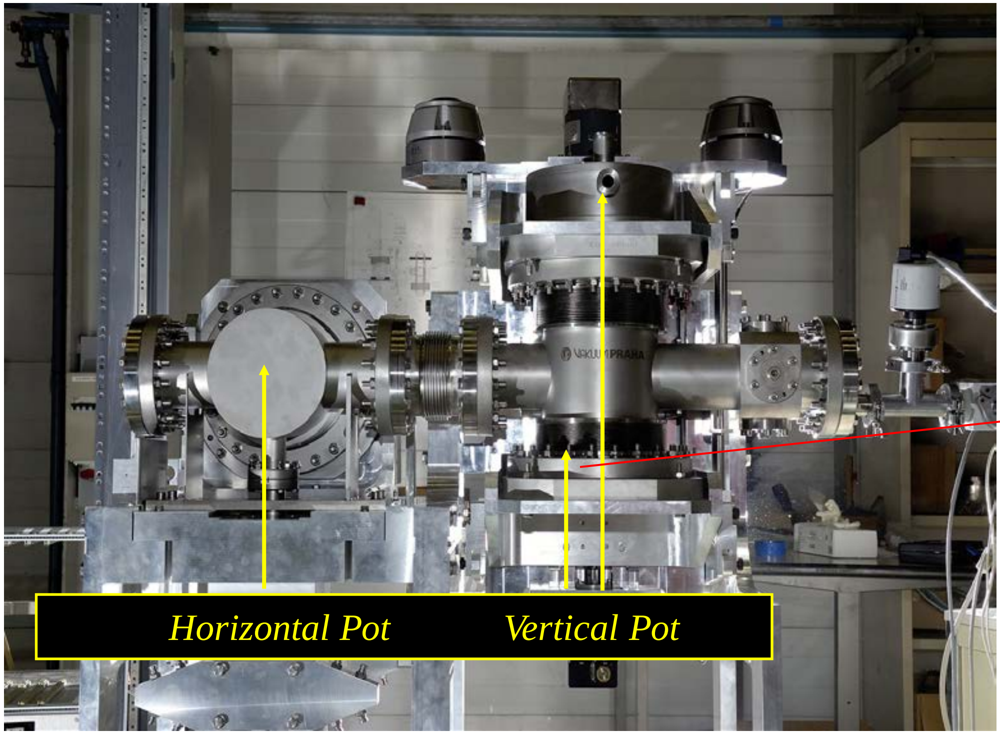

T2

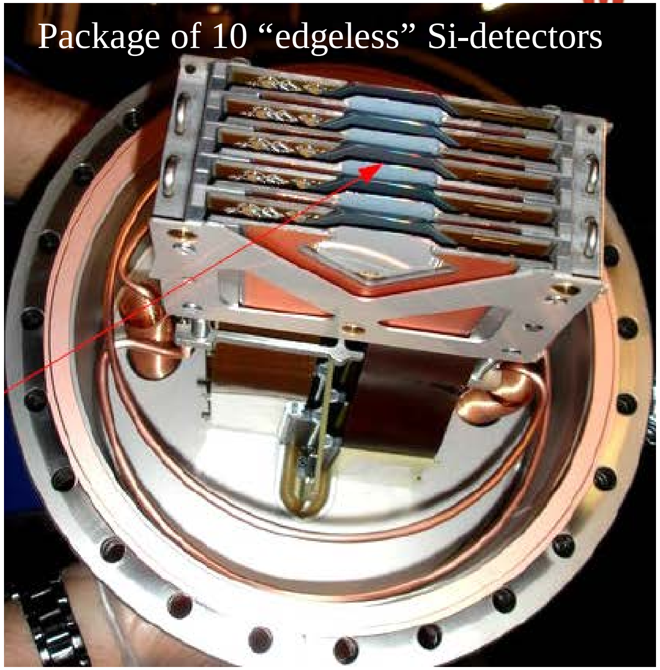
(GEMs)





Roman Pots




Package of 10 “edgeless” Si-detectors

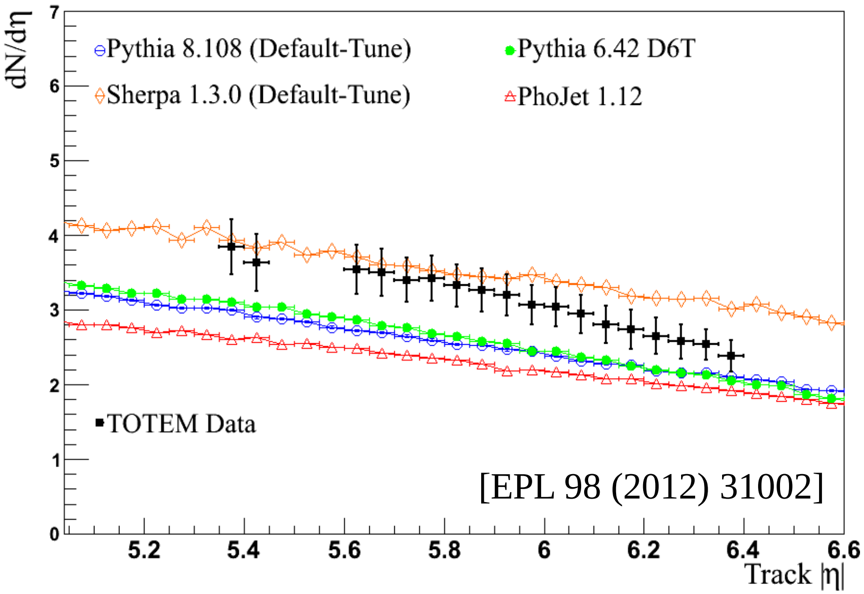
Roman Pot = movable box inside the beam pipe, housing silicon detectors.

Detectors can approach the beam centre to < 1mm .

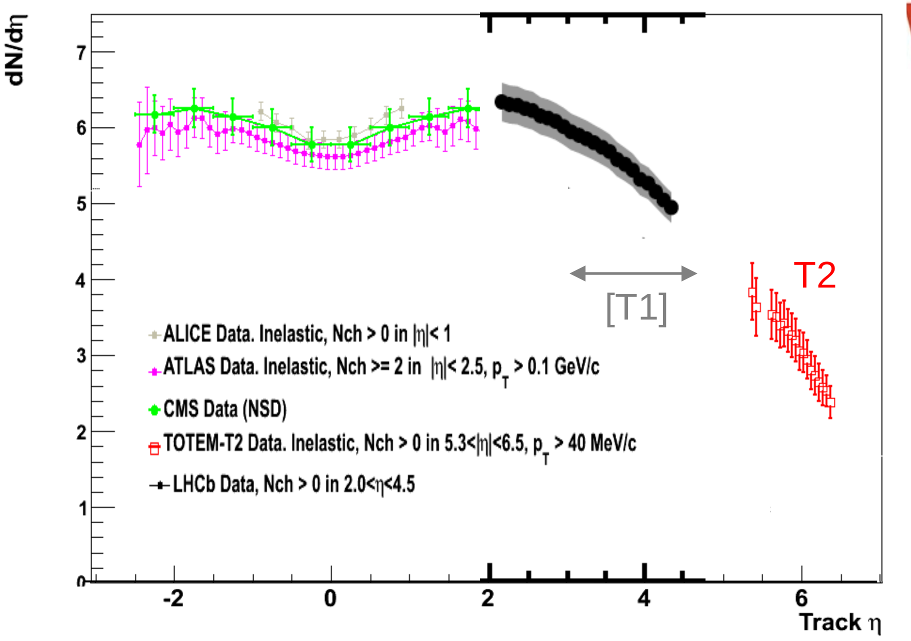
Overview

- Charged Particle Pseudorapidity Density dN / dη
- pp Elastic Scattering (7 TeV, 8 TeV)
- Total pp Cross-Section (7 TeV, 8 TeV)
- Coulomb-Nuclear Interference (CNI), ρ Parameter
- Outlook: Diffractive Physics Analyses
  Future Runs

Charged Particle Pseudorapidity Density dN / dη



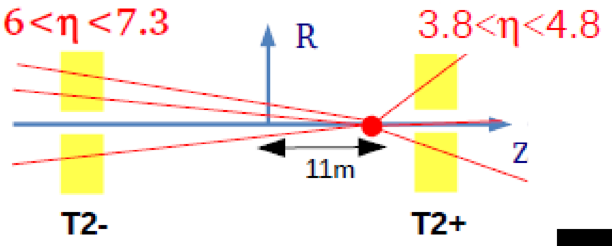
[EPL 98 (2012) 31002]



Analyses in progress:

- T1 measurement at 7 TeV (3.1 < |η| < 4.7)
- **NEW**: combined analysis CMS + TOTEM (0 < |η| < 6.5) on low-pileup run of 1st May 2012 (8 TeV):
  common trigger (T2, bunch crossings), both experiments read out

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

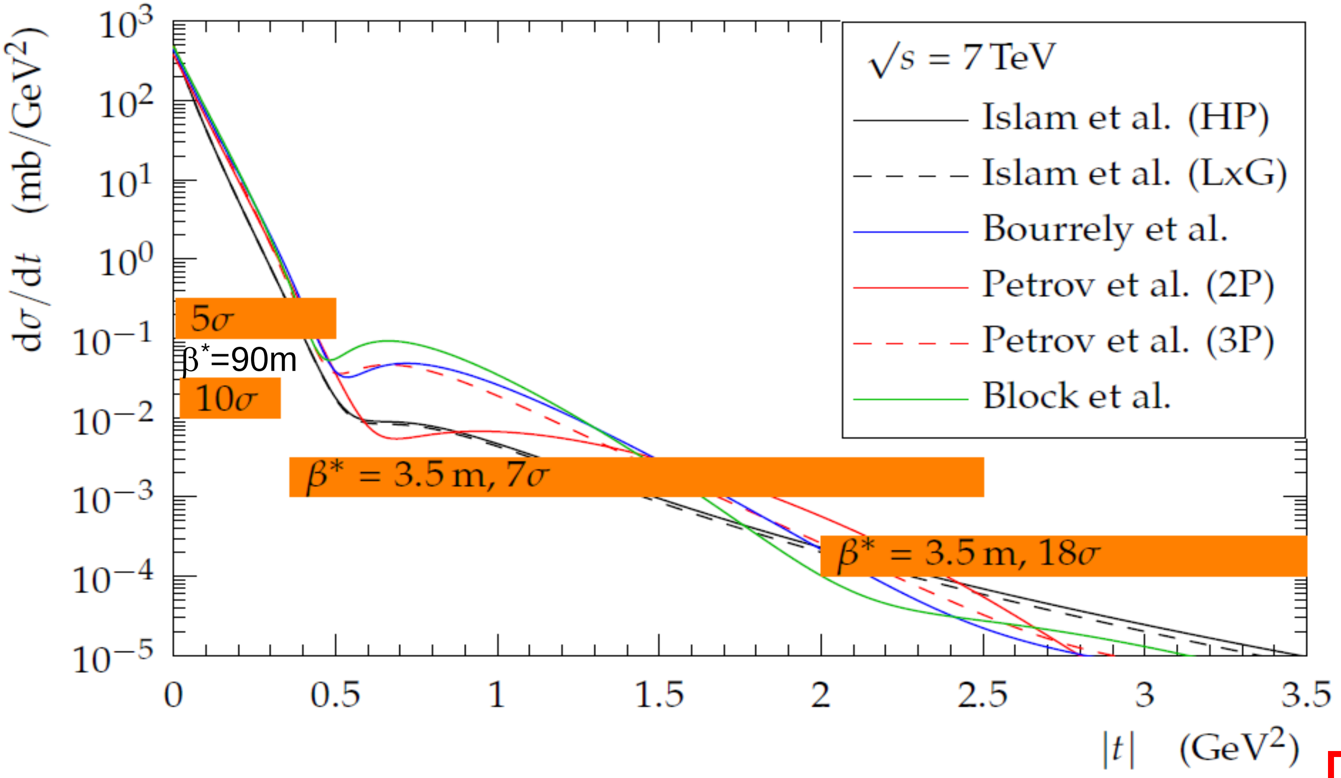


pp Elastic Scattering
7 TeV
8 TeV

“Measurement of proton-proton elastic scattering and total cross-section at √s = 7 TeV”
[CERN-PH-EP-2012-239]

Elastic Scattering at 7 TeV: 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}

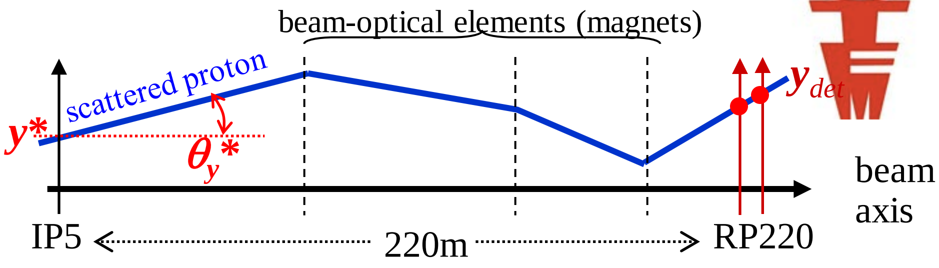
Set	β^*(m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events	
1	90	4.8-6.5σ	83	$7 \cdot 10^{-3}$ - 0.5	1M	← new
2	90	10σ	1.7	0.02 - 0.4	14k	← [EPL 96]
3	3.5	7σ	0.07	0.36 - 3	66k	← [EPL 95]
4	3.5	18σ	2.3	2 - 3.5	10k	← analysis in progress

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.

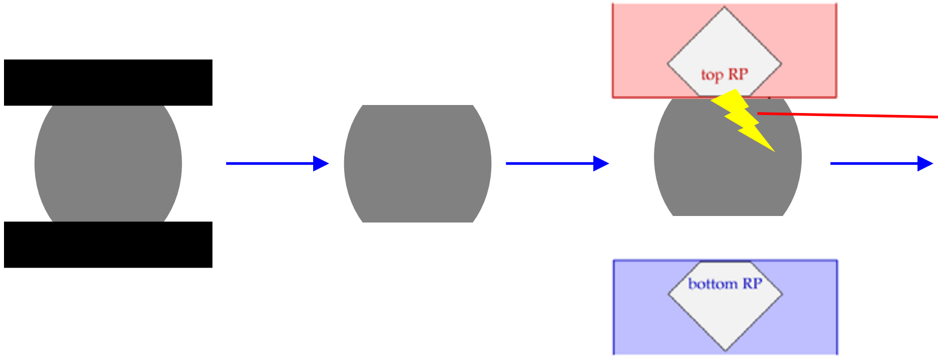
See talk by F. Nemes (later today).

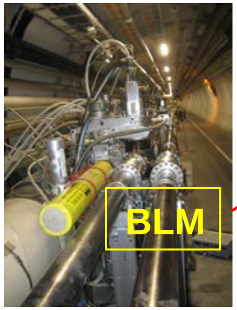
Beam-Based Roman Pot Alignment (Scraping)

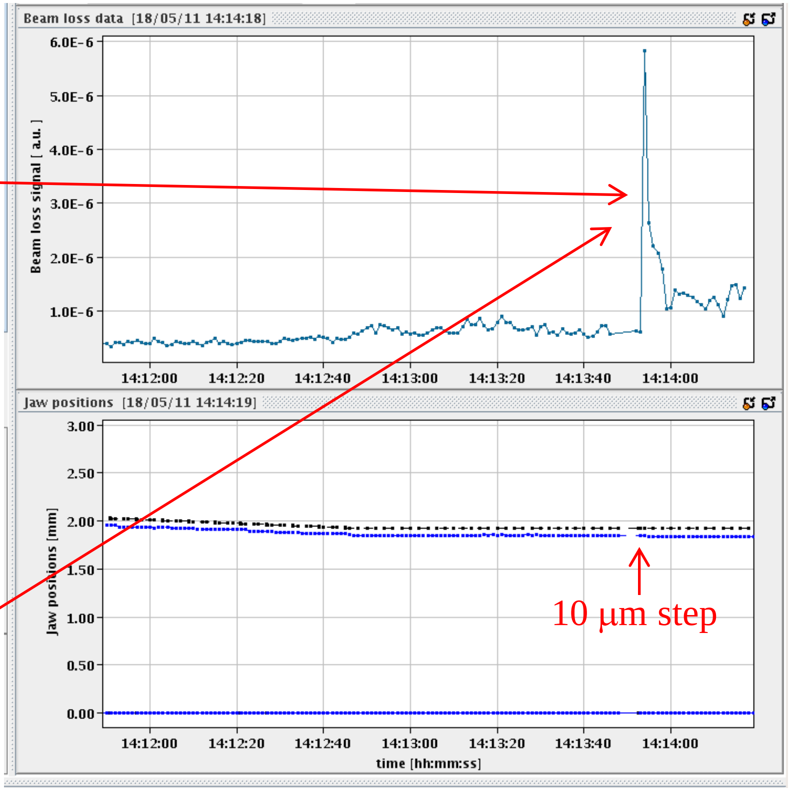
A primary collimator cuts a sharp edge into the beam, symmetrical to the centre

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







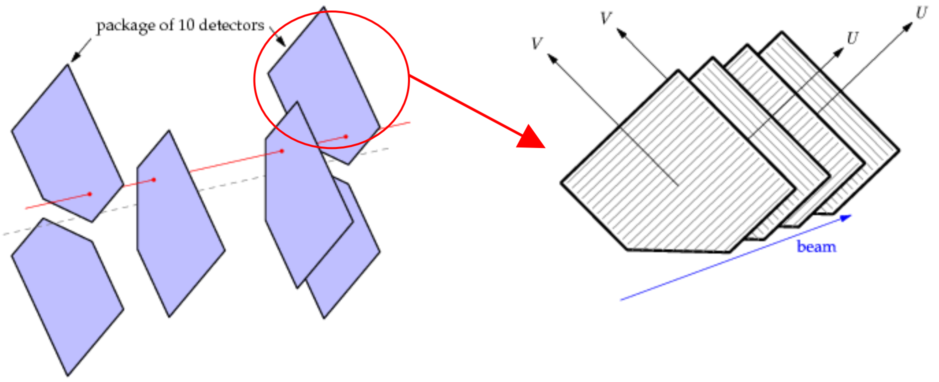
When both top and bottom pots are touching the beam edge:

- 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

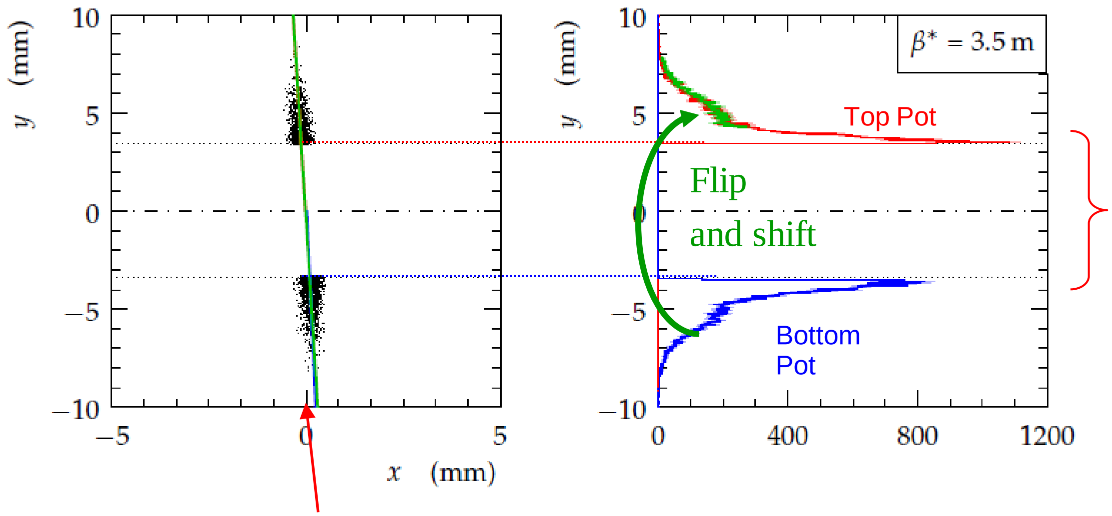


Residual-based alignment technique:
shifts and rotations within a RP unit

Important: overlap between horizontal and vertical detectors !

Alignment Exploiting Symmetries of Hit Profiles

Map of all track intercepts after elastic selection

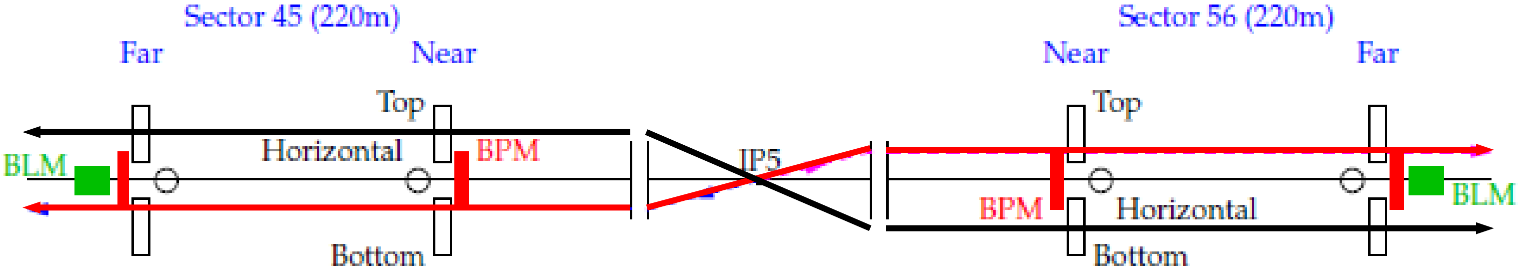


Fine vertical alignment: about 20 μm precision

→ Fine horizontal alignment: precision better than 10 μm

Elastic pp Scattering: Event Topology and Hit Maps

Two diagonals analysed independently

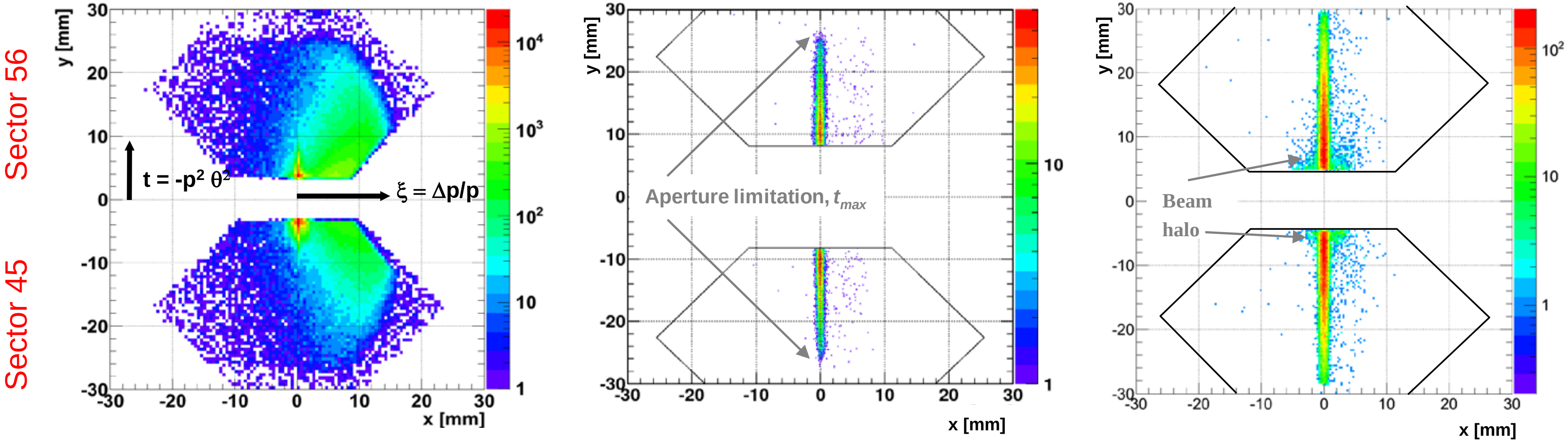


Hit Maps of a single diagonal (left-right coincidences)

β*=3.5m
RP @ 7σ

β*=90m
RP @ 10σ

β*=90m
RP @ 5σ



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

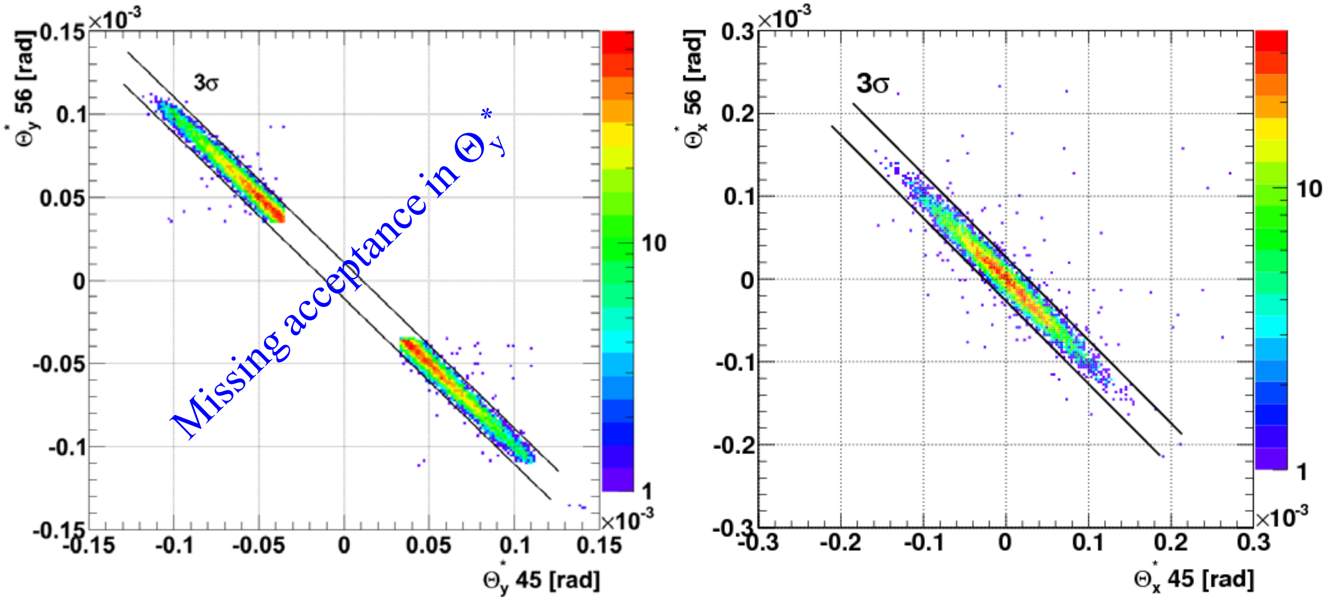
6 x10^{10} protons per bunch
Inelastic pile-up ~ 0.03 ev. / bx

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	
3	$\lvert x^{*R}\rvert$	$200\,\mu$m	low $\lvert\xi\rvert$
4	$\lvert x^{*L}\rvert$	$200\,\mu$m	
5	$\alpha\, y^{R,N} - (y^{R,F} - y^{R,N})$	$17\,\mu$m	
6	$\alpha\, y^{L,N} - (y^{L,F} - y^{L,N})$	$17\,\mu$m	
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

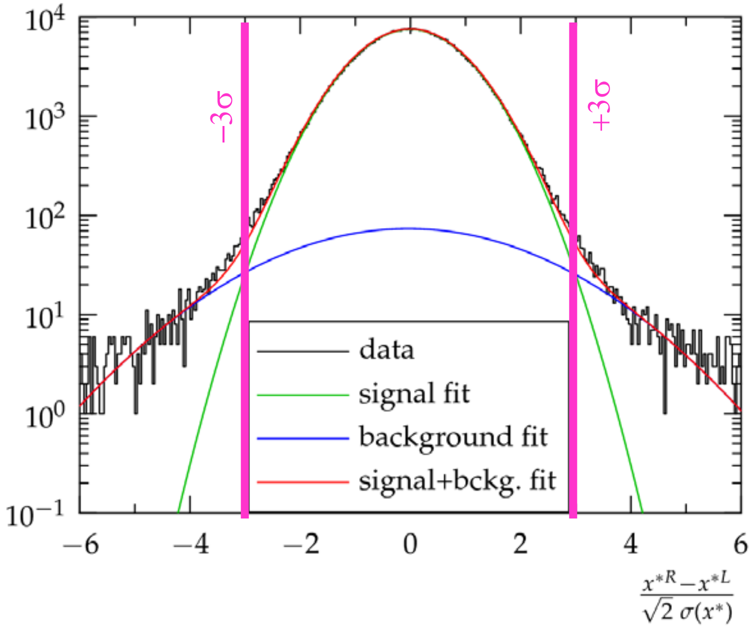
Collinearity in x

Missing acceptance in Θ_y^*

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

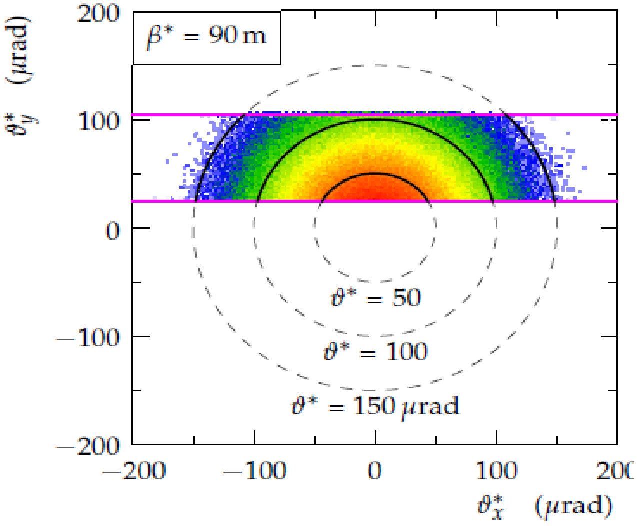
Analysis Overview I

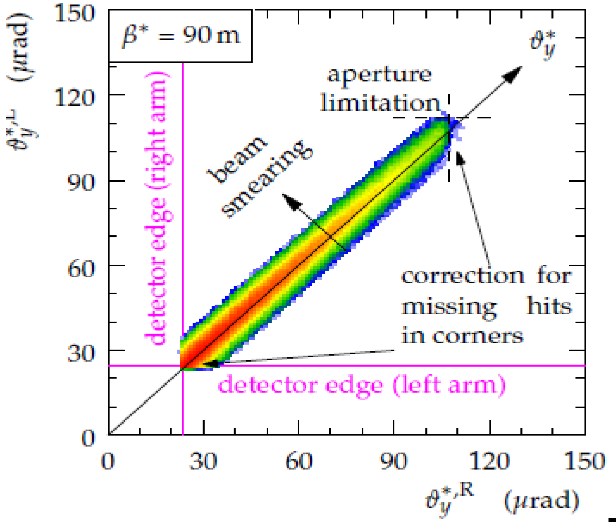
Background subtraction



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

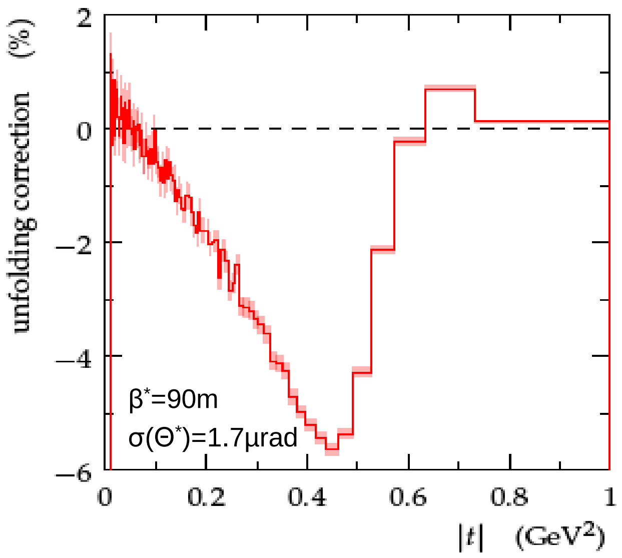
Acceptance correction





Analysis Overview II

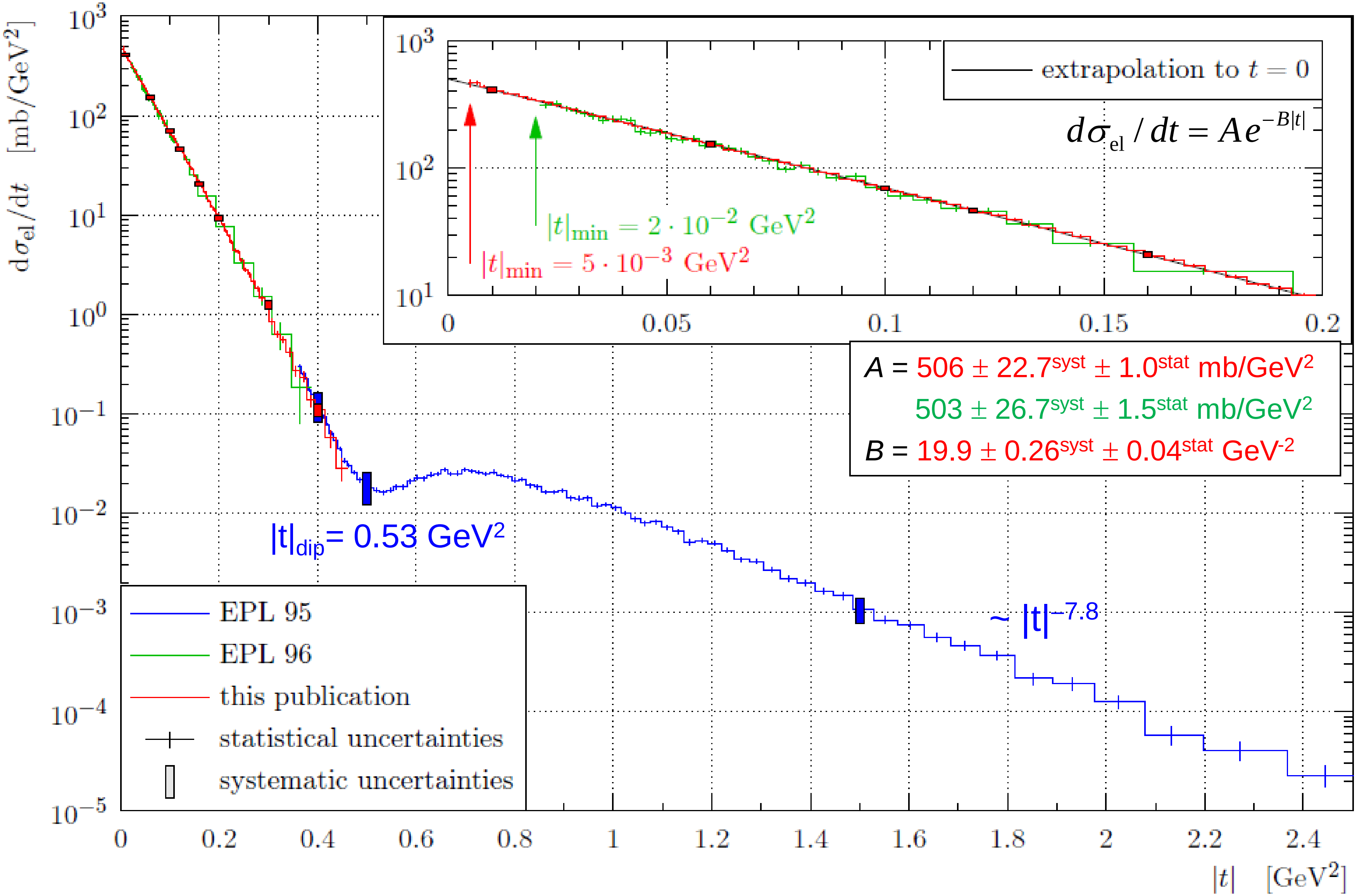
Resolution unfolding



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 at 7 TeV: Differential Cross-Section



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

$A = 506 \pm 22.7^{syst} \pm 1.0^{stat}$ mb/GeV^2

$503 \pm 26.7^{syst} \pm 1.5^{stat}$ mb/GeV^2

$B = 19.9 \pm 0.26^{syst} \pm 0.04^{stat}$ GeV^{-2}

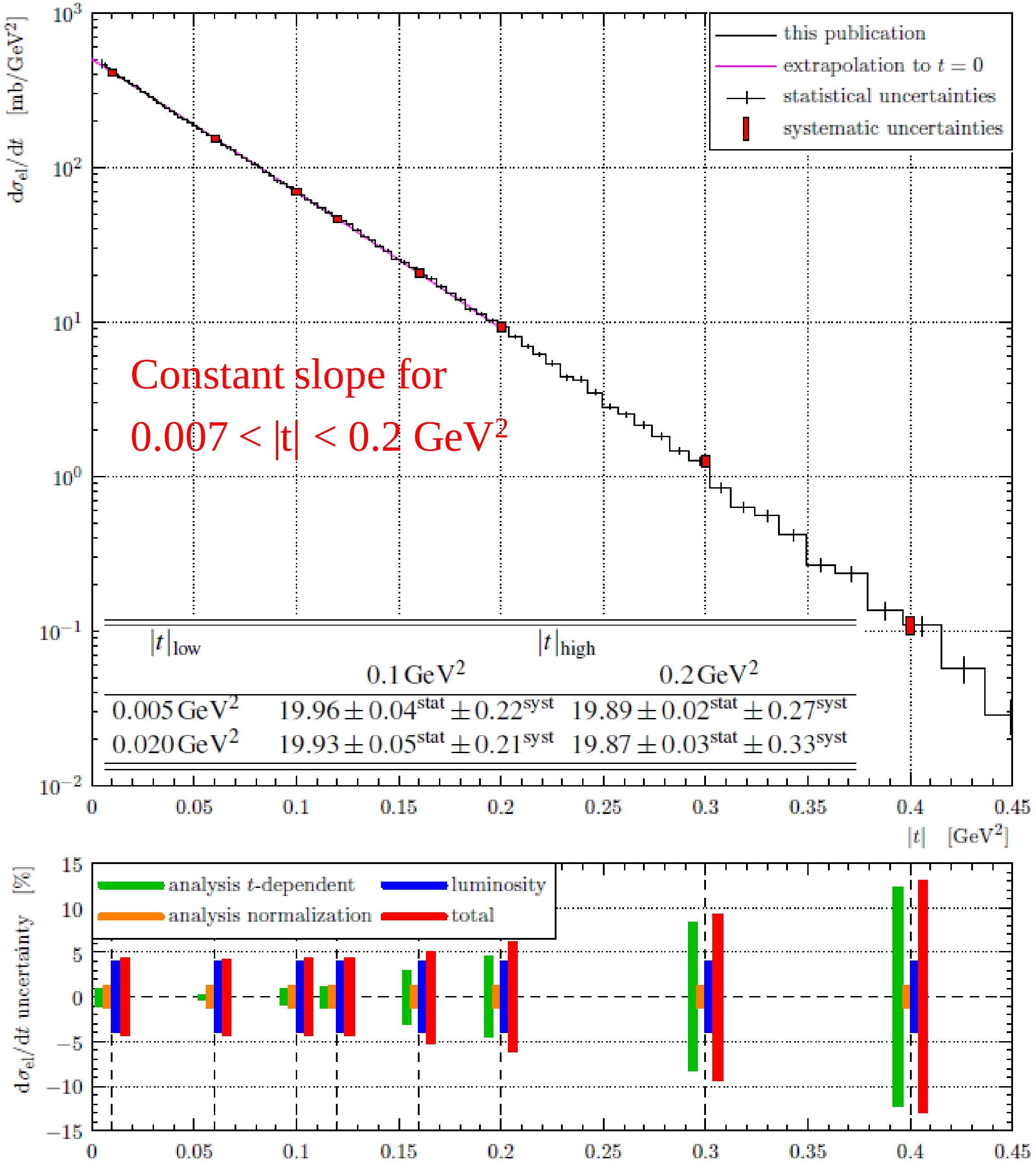
$|t|_{dip} = 0.53$ GeV^2

$\sim |t|^{-7.8}$

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

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

7 TeV: Elastic Scattering at low |t|: Systematics



Constant slope for

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

$\|t\|_{\text{low}}$	$\|t\|_{\text{high}}$: 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

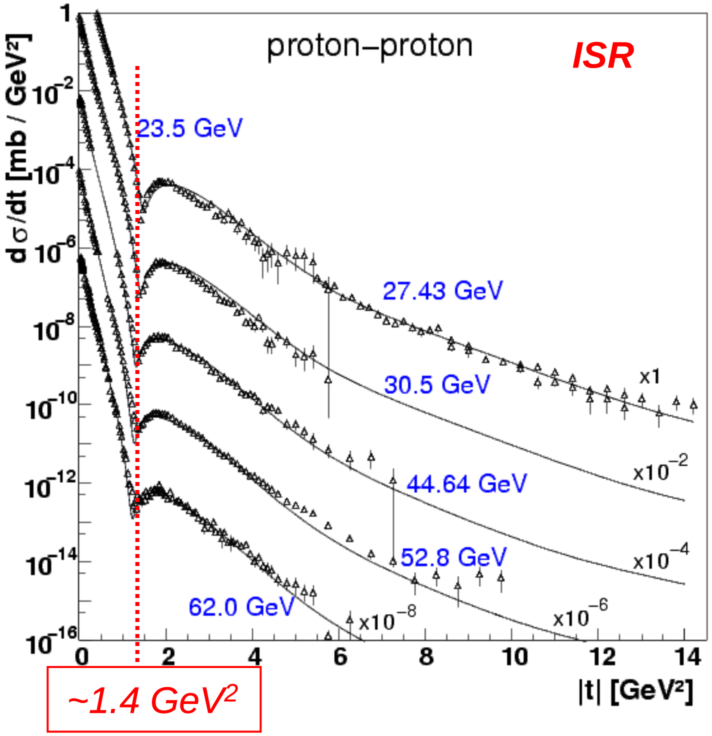
– reconstruction efficiency

– trigger efficiency

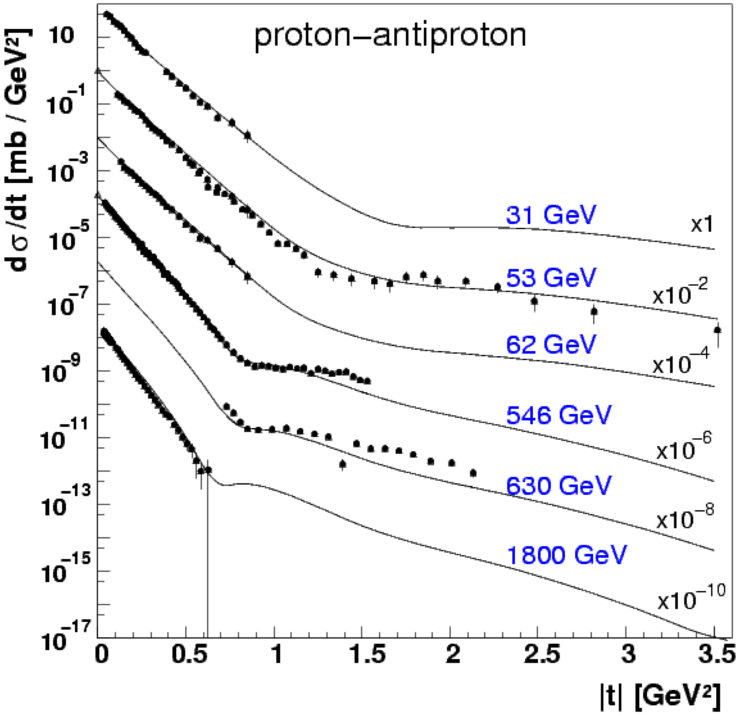
– “pile-up” correction

Luminosity from CMS (± 4%)

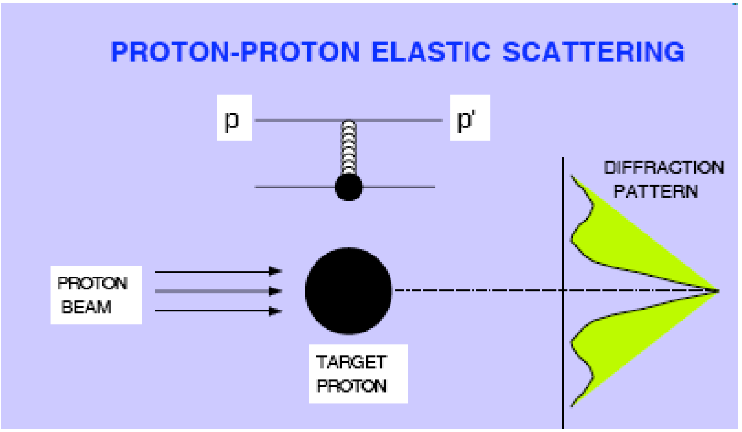
Elastic scattering – from ISR to Tevatron



~1.4 GeV^2



Diffractive minimum: analogous to Fraunhofer diffraction: $|t| \sim p^2 \theta^2$



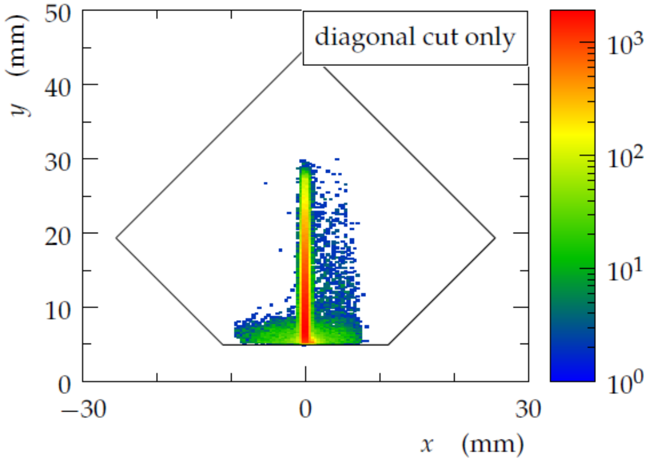
- *exponential slope B at low |t| increases*
- *minimum moves to lower |t| with increasing s*
  → *interaction region grows (as also seen from σ_{tot})*
- *depth of minimum changes*
  → *shape of proton profile changes*
- *depth of minimum differs between pp, $\bar{p}p$*
  → *different mix of processes*

Elastic Scattering at 8 TeV

July 2012: runs at $\beta^* = 90$ m

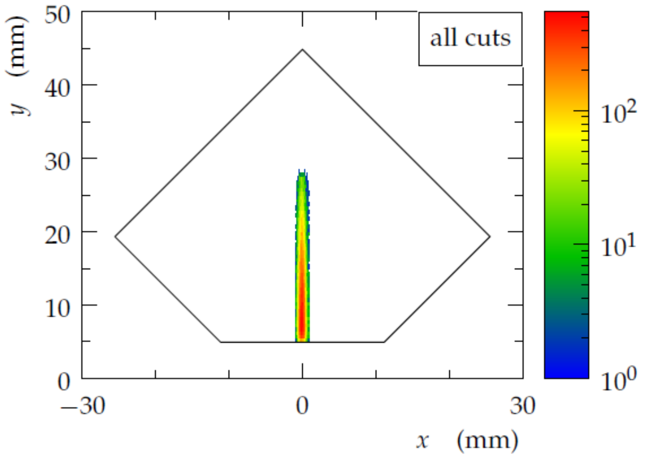
dataset	date	bunches	RPs	$\lvert t\rvert_{\min}$ (GeV^2)	$\mathcal{L}$ (mb^{-1})
1	7 July, 1st fill	1	3σ	$4 \cdot 10^{-3}$	–
2	7 July, 2nd fill	1	6σ	$7 \cdot 10^{-3}$	≈ 40
3a	12–13 July	1	9.5σ	$15 \cdot 10^{-3}$	≈ 30
3b	12–13 July	2 or 3	9.5σ	$15 \cdot 10^{-3}$	≈ 820

only RP alignment, RPs moving



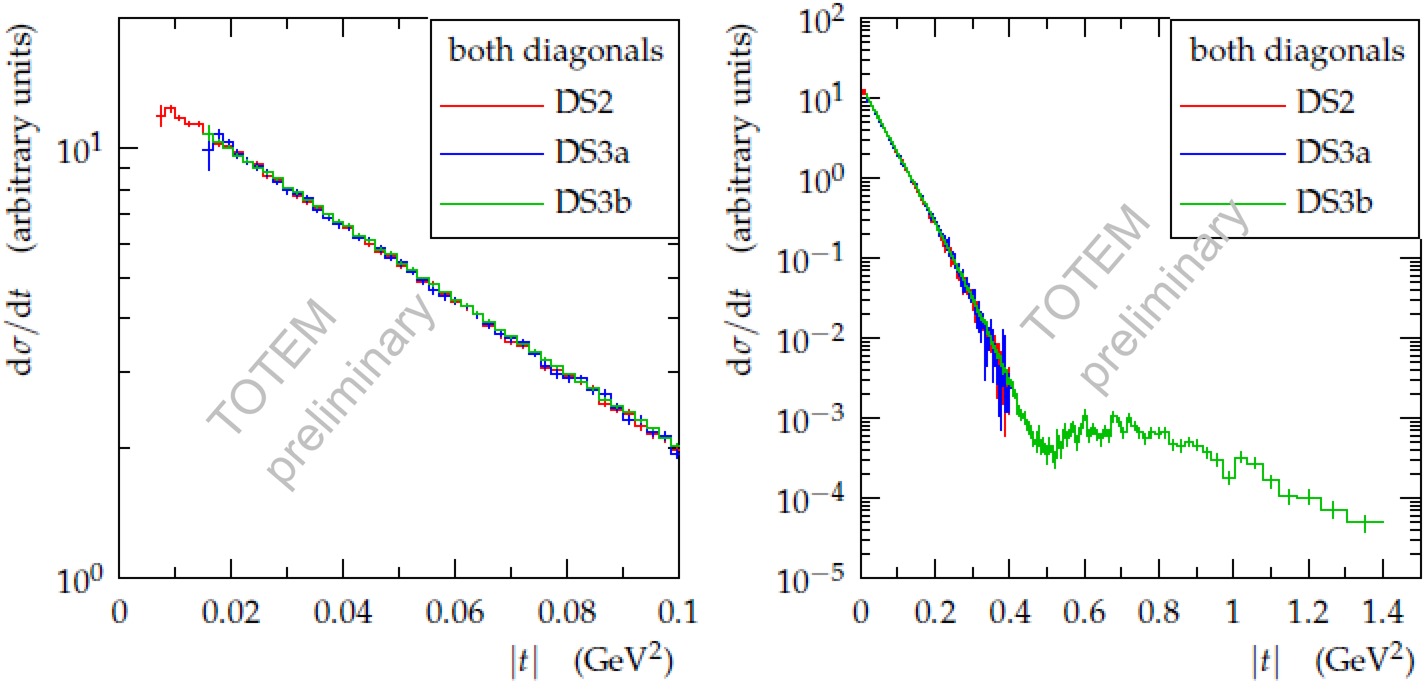
collinearity,
low ξ,
common vertex

cut	quantities
diagonal	4 RP hits
1	ϑ_x^{*R} vs. ϑ_x^{*L}
2	ϑ_y^{*R} vs. ϑ_y^{*L}
3	$\lvert x^{*R}\rvert$
4	$\lvert x^{*L}\rvert$
5	ϑ_y^{*R} vs. $y^{R,F} - y^{R,N}$
6	ϑ_y^{*L} vs. $y^{L,F} - y^{L,N}$
7	x^{*R} vs. x^{*L}



Elastic Scattering at 8 TeV

Unnormalised t-distributions

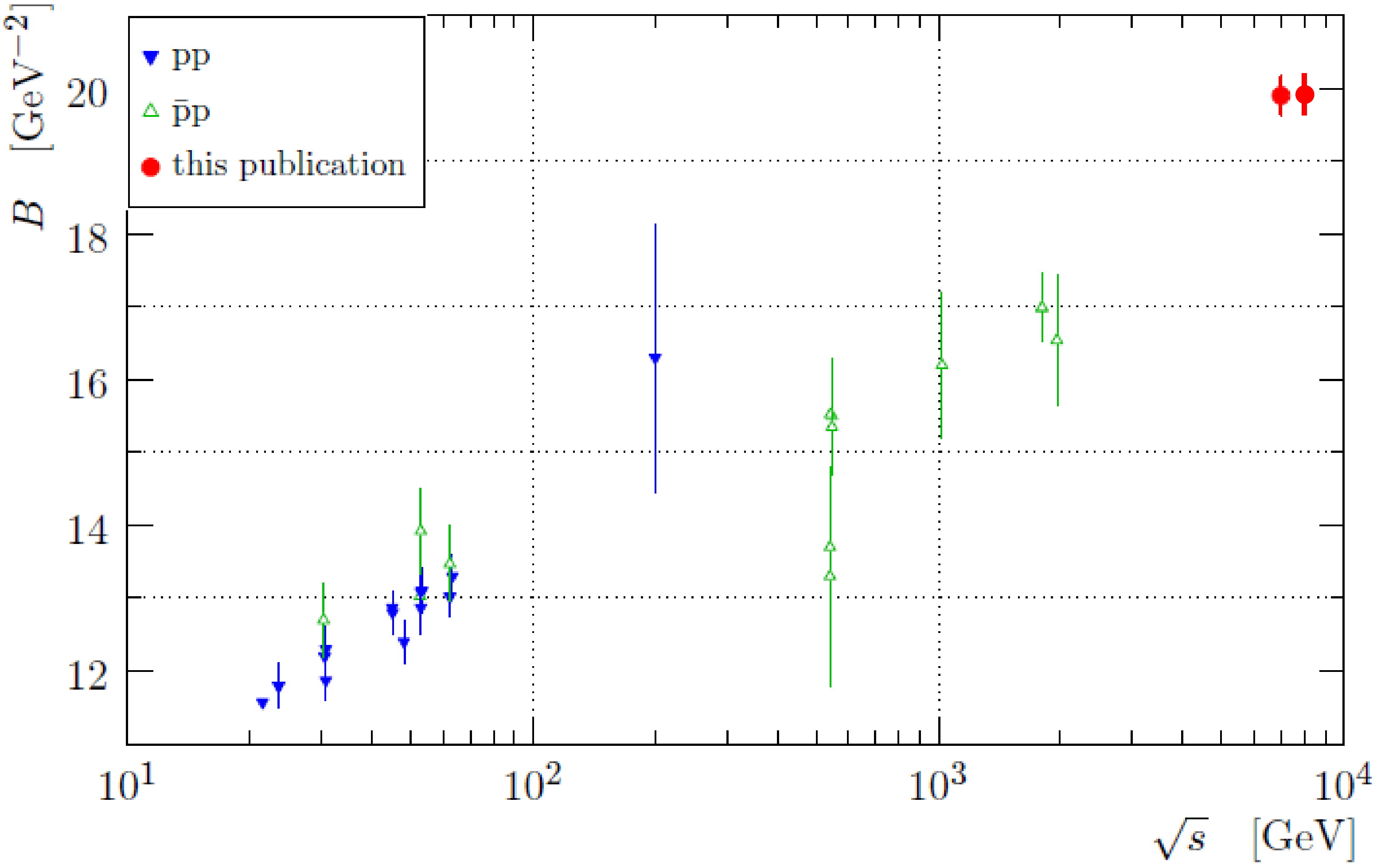


down to |t| ~ 6 x 10^{-4}:
at β* = 1km

larger |t|:

- possible at β*=0.6m
- difficult due to 2xSD and other background

Energy dependence of the exponential slope B



Ongoing Elastic Analyses

Data already available and being analysed:

7 TeV:

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

8 TeV:

$\beta^* = 90$ m: July 2012: Elastic scattering for $7 \times 10^{-3}\ \mathrm{GeV}^2 < |t| < \sim 1\ \mathrm{GeV}^2$
(low |t| part done for total cross-section, $d\sigma/dt$ not yet published)

$\beta^* = 1$km: October 2012: Elastic scattering for $6 \times 10^{-4}\ \mathrm{GeV}^2 < |t| < 0.2\ \mathrm{GeV}^2$

Total pp Cross-Section Measurements

7 TeV

8 TeV

Measurement of proton-proton elastic scattering and total cross-section at $\sqrt{s}$ = 7 TeV
[CERN-PH-EP-2012-239]

Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s}$ = 7 TeV
[CERN-PH-EP-2012-352]

Luminosity-independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s}$ = 7 TeV
[CERN-PH-EP-2012-353]

A luminosity-independent measurement of the proton-proton total cross-section at $\sqrt{s}$ = 8 TeV
[CERN-PH-EP-2012-354]

3 Ways to the Total Cross-Section

7 TeV

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

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

different bunch intensities !

$$\sigma_{\mathrm{tot}}$$

ϱ independent:

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

σ_{tot} = (99.1 ± 4.3) mb

luminosity independent:

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

σ_{tot} = (98.0 ± 2.5) mb

Excellent agreement between cross-section measurements at 7 TeV using

- runs with different bunch intensities,
- different methods.

Inelastic Cross-Section Visible in T2

Corrections to the T2 visible events

▪ Trigger Inefficiency: *(measured from zero bias data with respect to track multiplicity)*	**2.3 ± 0.7 %**
▪ Track reconstruction efficiency: *(based on MC tuned with data)*	**1.0 ± 0.5 %**
▪ Beam-gas background: *(measured with non colliding bunch data)*	**0.6 ± 0.4%**
▪ Pile-up (μ =0.03): *(contribution measured from zero bias data)*	**1.5 ± 0.4%**

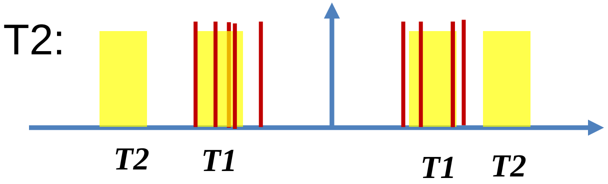
$$\sigma_{\text{inelastic, T2 visible}} = 69.7 \pm 0.1\ (\text{stat}) \pm 0.7\ (\text{syst}) \pm 2.8\ (\text{lumi})\ \ \text{mb}$$

Corrected Inelastic Cross-Section

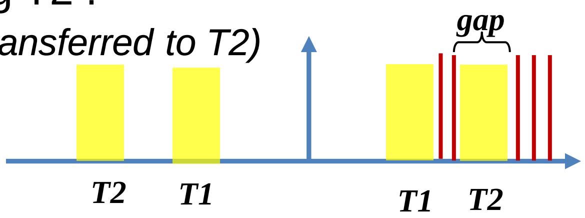
$\sigma_{\text{inelastic, T2 visible}} \Rightarrow \sigma_{\text{inelastic}}$

Missing inelastic cross-section

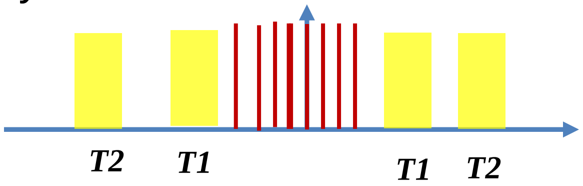
- Events visible in T1 but not in T2: *(estimated from zero bias data)* **1.6 ± 0.4 %**



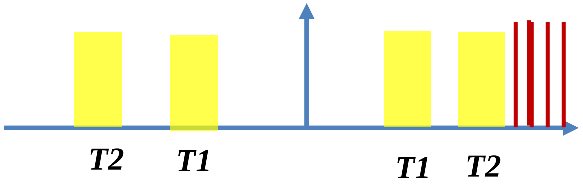
- Fluctuation rapidity gap covering T2 : *(estimated from T1 gap probability transferred to T2)* **0.35 ± 0.15 %**



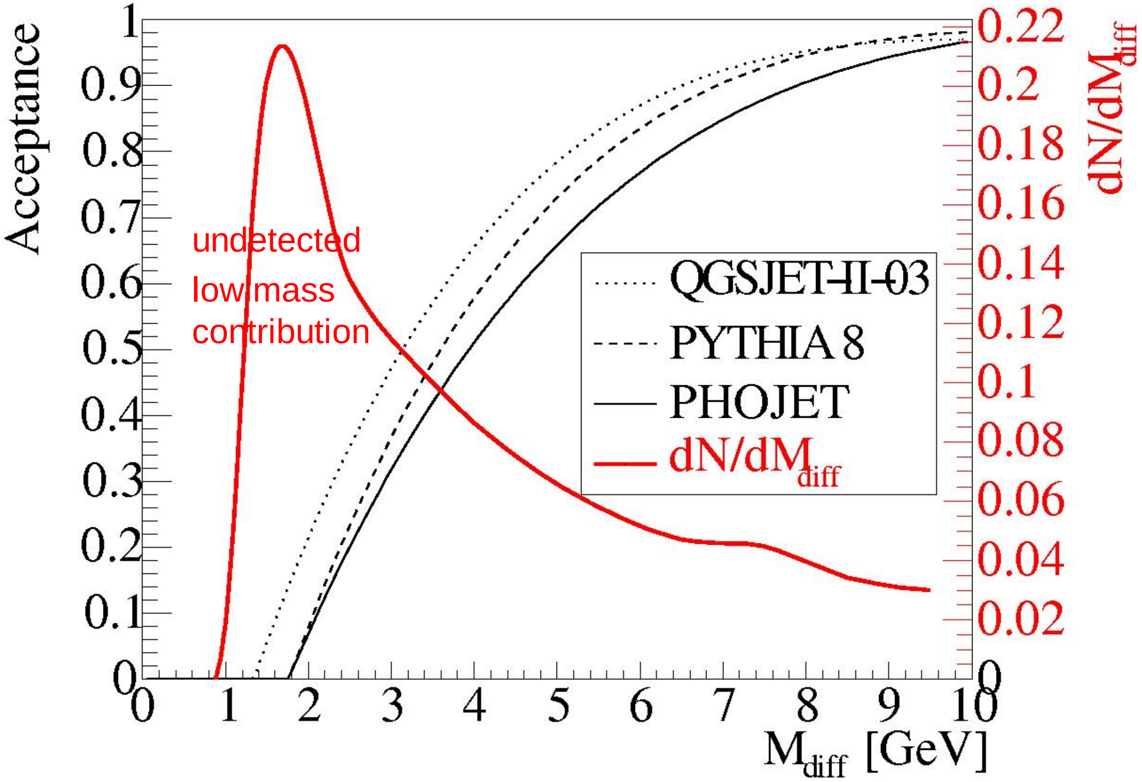
- Central Diffraction: T1 & T2 empty : *(based on MC)* **0.0 ± 0.35 %**



- Low Mass Diffraction : *(Several models studied, correction based on* ***QGSJET-II-3****)* **4.2 ± 2.1 %**



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

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

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)

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

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

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

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

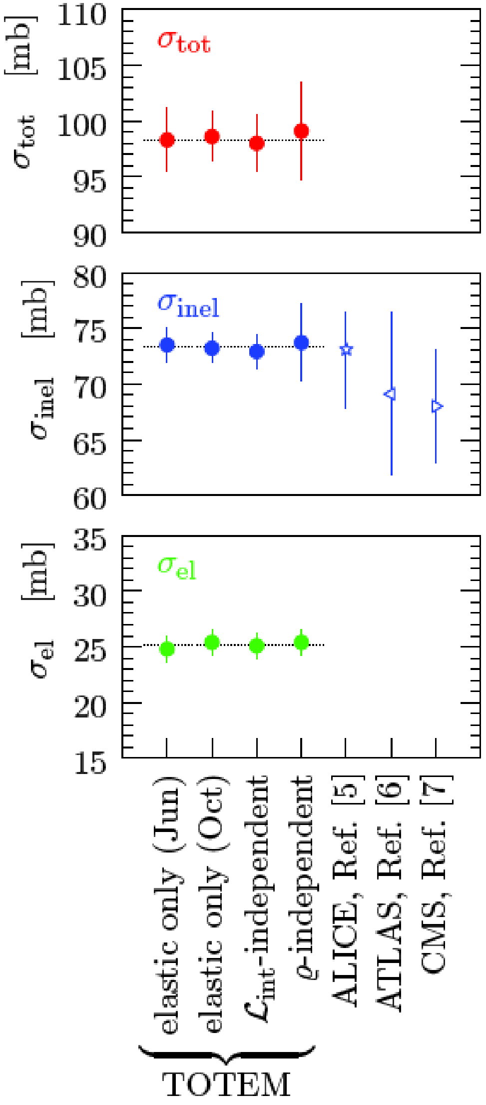
$$\sigma_{\text{inel, } |\eta| > 6.5} = \sigma_{\text{inel}} - \sigma_{\text{inel, } |\eta| < 6.5} = 2.62 \pm 2.17 \text{ mb} \qquad [\text{MC: } 3.2 \text{ mb}]$$

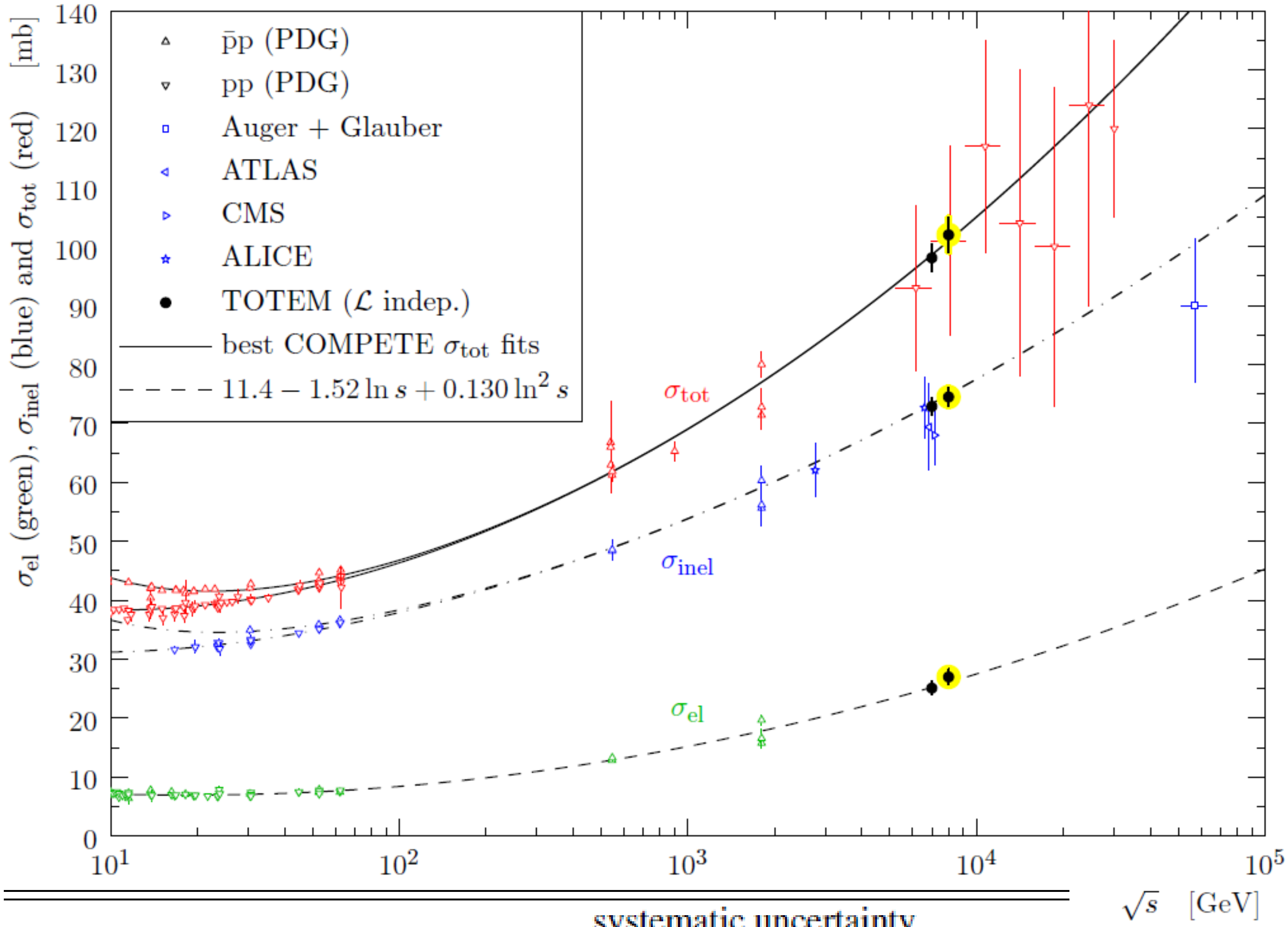
or

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

pp Cross-Section Measurements

7 TeV





8 TeV

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

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

Elastic to Total Cross-Section Ratio

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

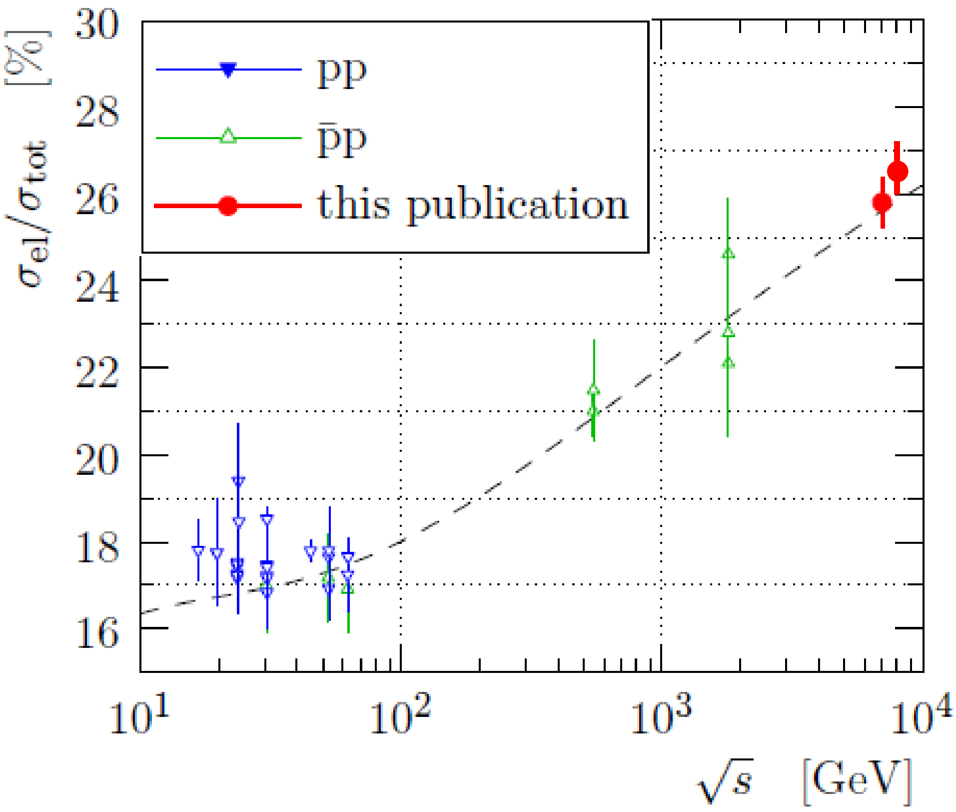
7 TeV

$$0.257 \pm 0.005$$

8 TeV

$$0.266 \pm 0.006$$

independent of luminosity and ρ



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

➔ proton grows / becomes “blacker”

Elastic Scattering in the Coulomb-Nuclear Interference Region

Measurement of the ρ Parameter

A First, Very Crude ρ Estimate at 7 TeV

$$\rho = \frac{\mathrm{Re}\, T(t=0)}{\mathrm{Im}\, T(t=0)}$$ where $T(t=0)$ = forward elastic scattering amplitude

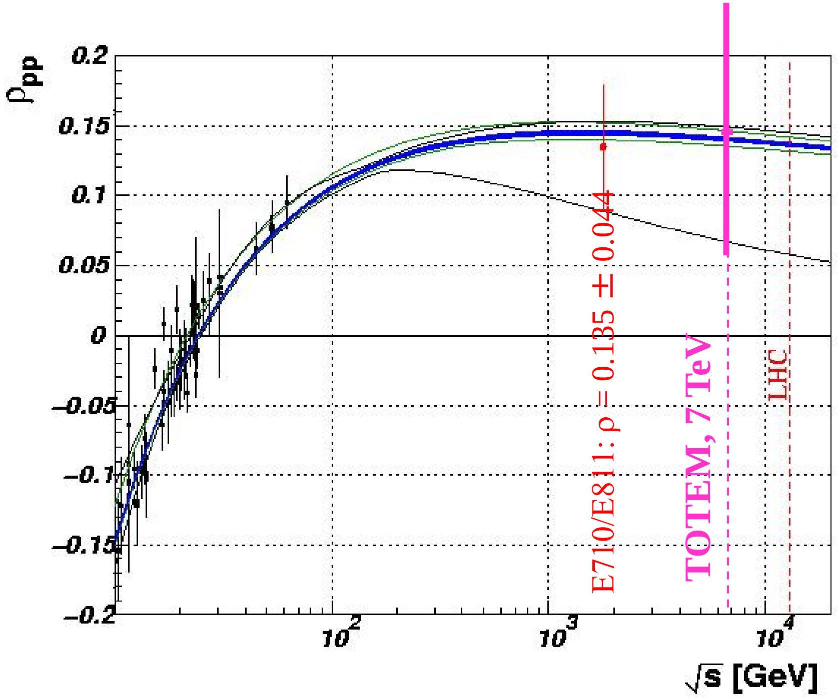
From optical theorem:

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

ρ < 0.32 (95% CL),

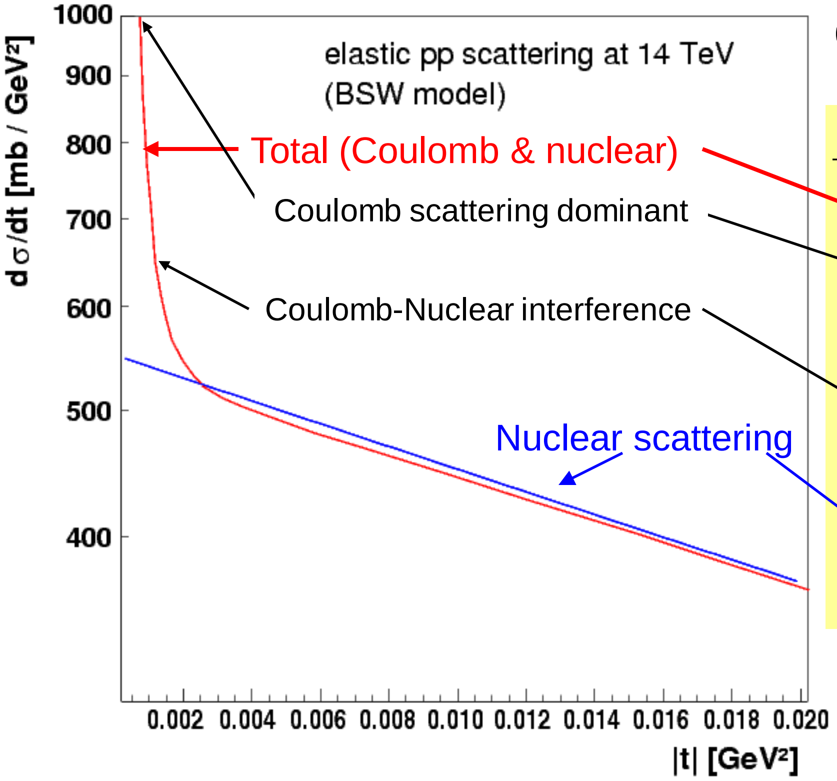
or, using Bayes' approach (with uniform prior |ρ| distribution):

|ρ| = 0.145 ± 0.091 [COMPETE extrapolation: ρ = 0.141 ± 0.007]



Not so exciting, but …

ρ Measurement: Elastic Scattering at Low |t|



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

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

α = fine structure constant

ϕ = relative Coulomb-nuclear phase

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

ρ = ℜ / ℑ [$T_{elastic,nuclear}$(t = 0)]

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

|t| ~ 6 x 10^{-4} GeV²

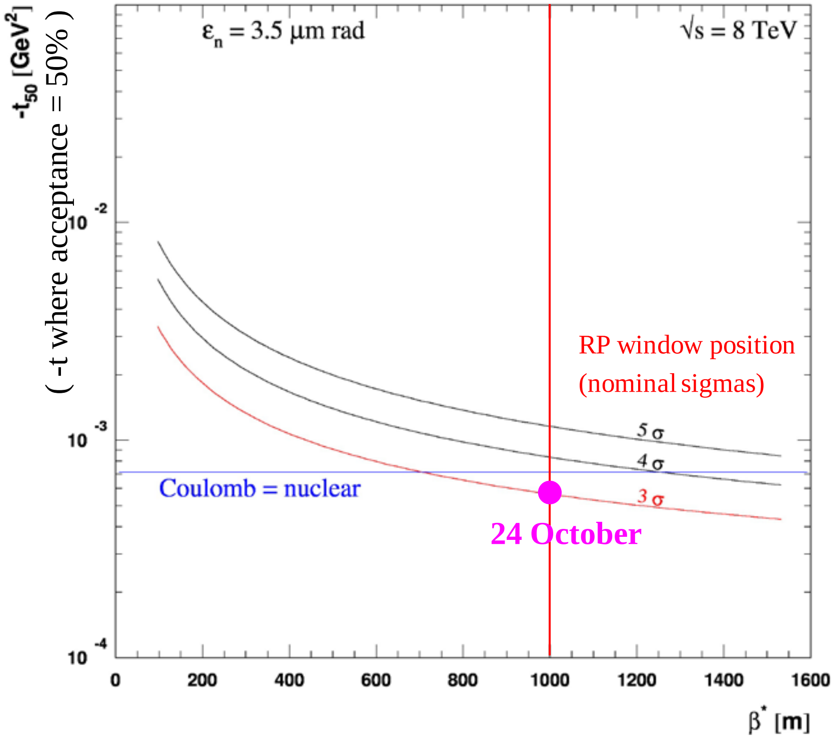
The Run at β* = 1 km

Objective:

Measure pp elastic scattering at very small momentum transfers (CNI region: |t| ~ 6 x 10^{-4} GeV^2)

→ special optics optimising acceptance for small scattering angles

→ Roman Pots very close to the beam (3 nominal beam sigmas)



Difficulty: intense beam halo background

Strategy:

Beams with 3 bunches of ~ 10^{11} p (2 colliding, 1 non-colliding)

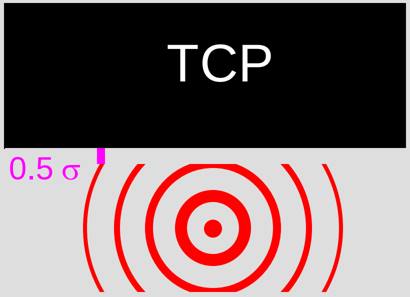
Roman Pot beam-based alignment → beam cleaning → data taking ↰

Beam Cleaning with Primary Collimators (TCPs)

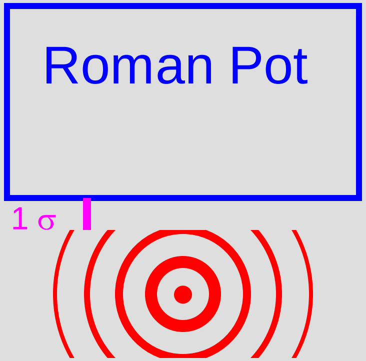
1. Scrape the beam with TCP at 2 σ

1 σ
contour lines

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

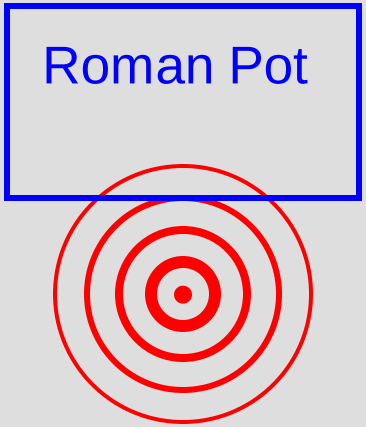


RP at 3 σ is protected by the gap

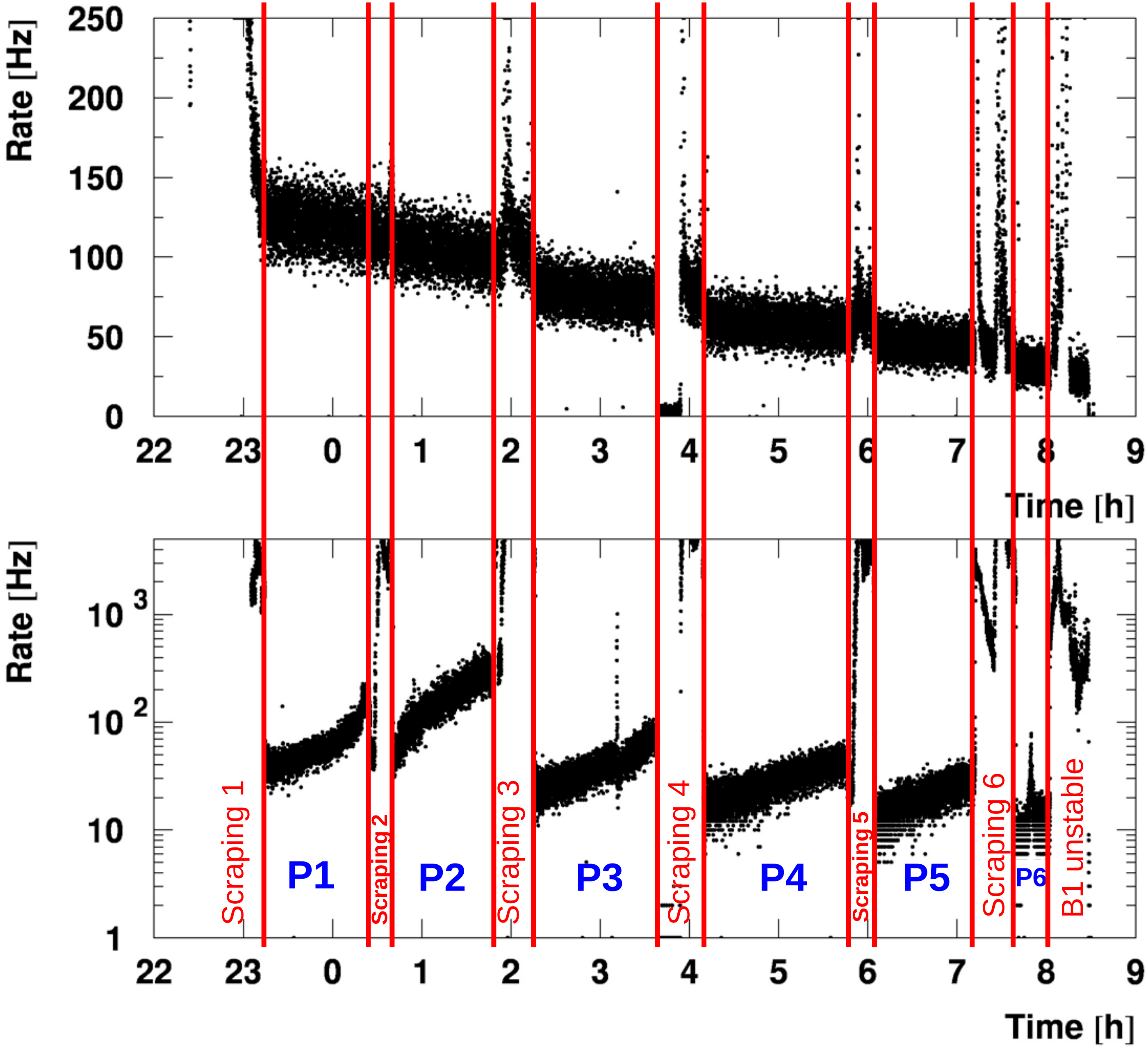


3. Gap refills within ~ 1h

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)

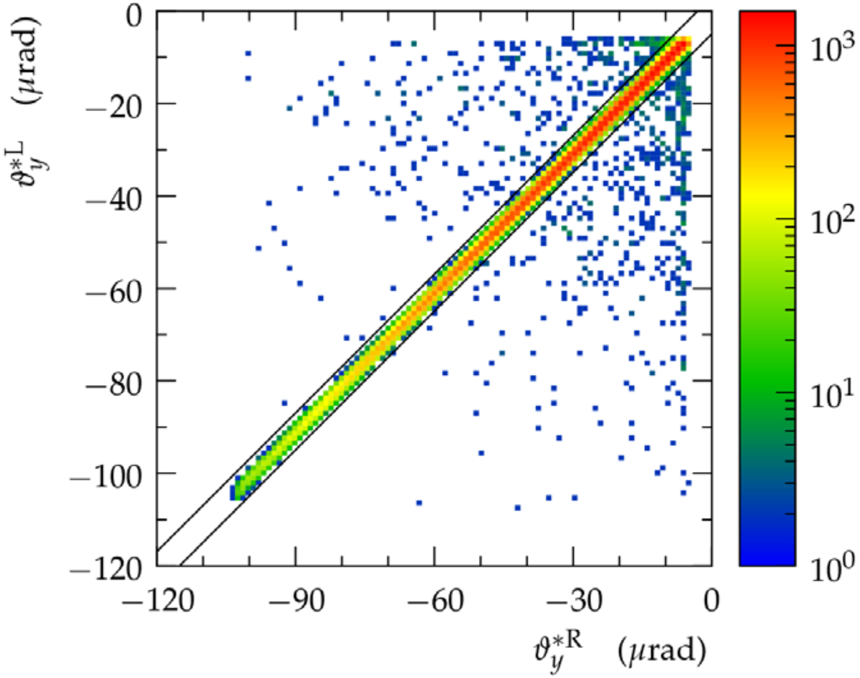
Total: 6.75 h in 6 periods

int. lumi.: 27 μb^{-1}

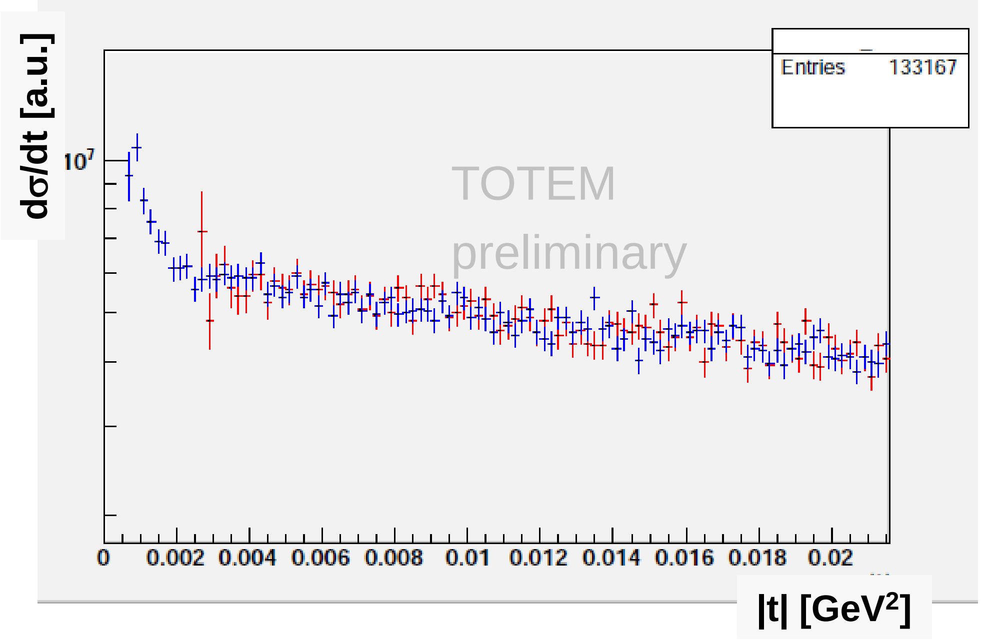
400k elastic events

The Run at β* = 1 km: First Look at the Data

Raw correlation between the scattering angles of the 2 protons



Preliminary t-distribution on a subsample, without corrections (acceptance etc.)



… to be continued soon.

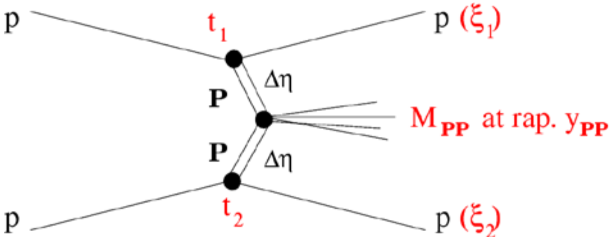
Ongoing Analyses of Diffractive Processes

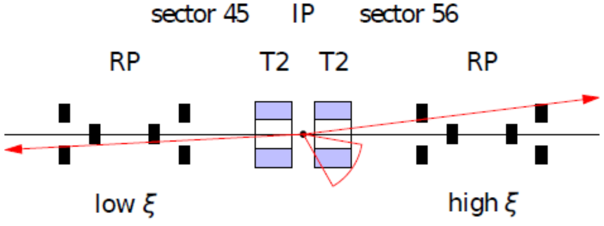
Common Runs with CMS

Diffractive Analyses Ongoing

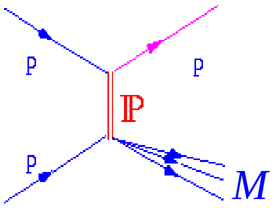
Based on $\beta^* = 90$ m (7 TeV) run in Oct. 2011 (RP @ $4.8\sigma - 6.5\sigma$):

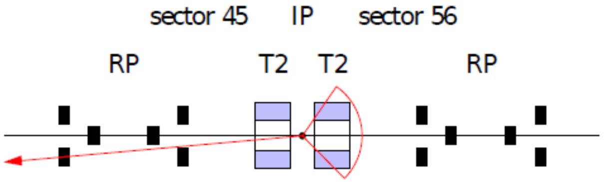
- Central Diffraction
  ($d^2\sigma_{DPE} / dt_1\ dt_2,\ \ \sigma_{DPE}$)



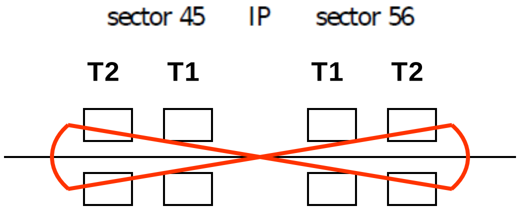


- Single Diffraction
  ($d\sigma_{SD}/dt$, $d\sigma_{SD}/d\xi$, σ_{SD})





- Double Diffraction
  Select diff. masses 3.4 GeV < M < 10 GeV
  requiring tracks in both T2s, veto on T1s



→ Extend studies over full η range with CMS (2012 data)

Joint Data Taking with CMS

Realisation of common running much earlier than ever anticipated

1. Hardware: electrical from RP220 to CMS → trigger within CMS latency
2. Trigger: 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

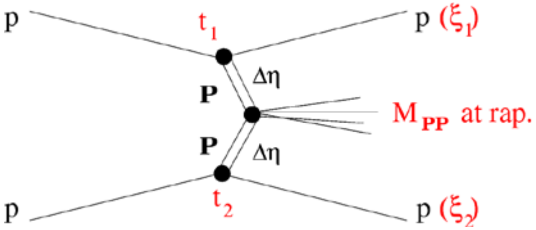
Hard Diffraction with CMS in 2012

July 2012: $\beta^* = 90$ m, $\sqrt{s} = 8$ TeV:

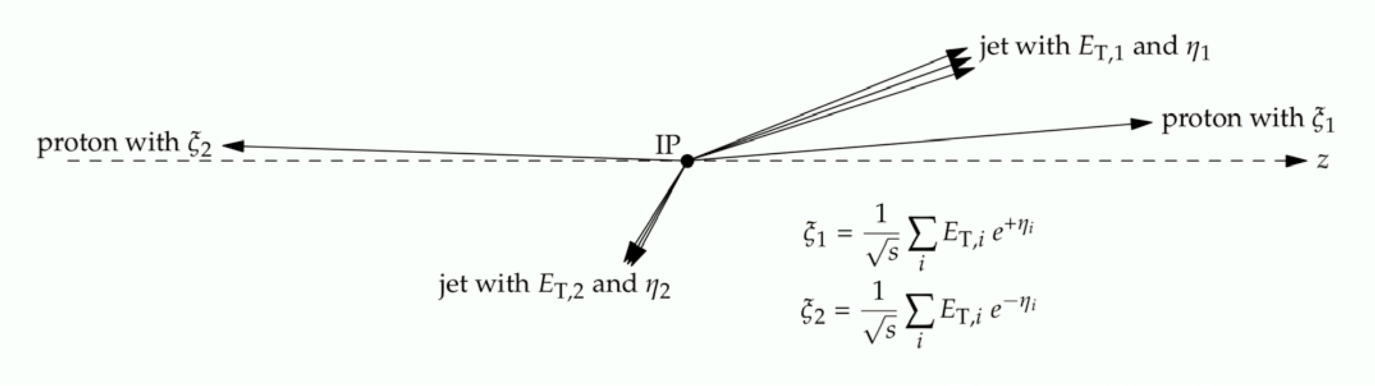
mixed trigger:

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

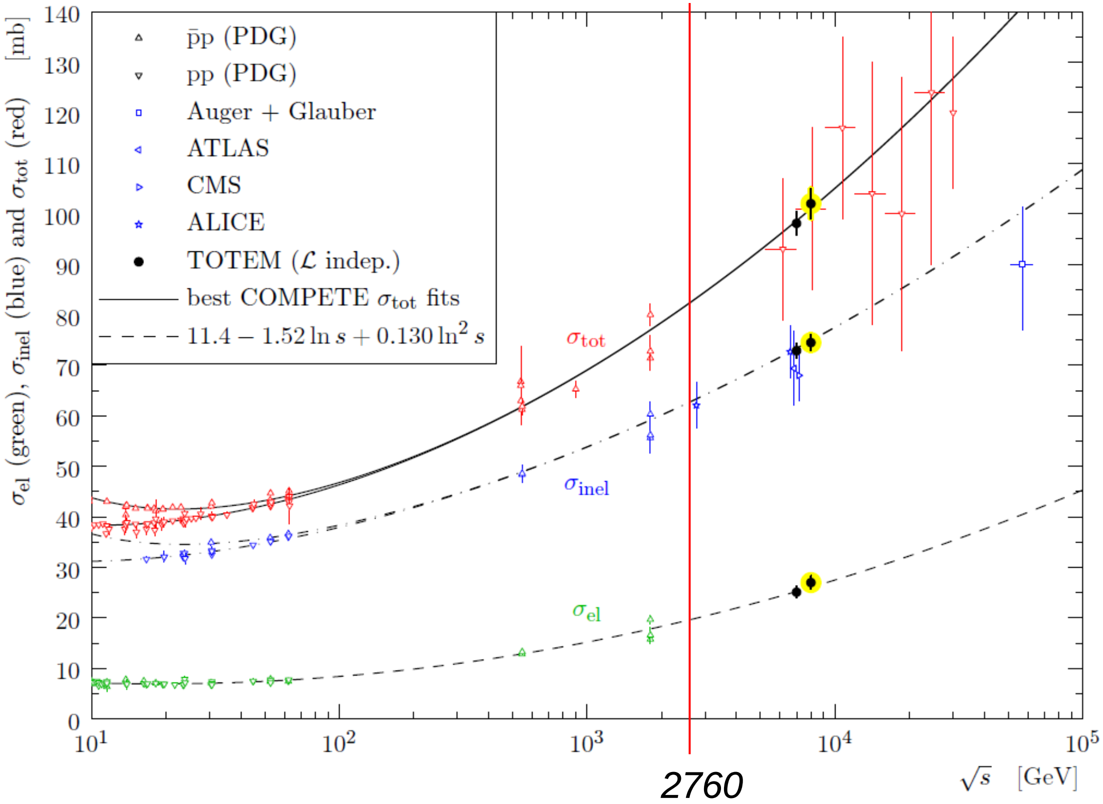
Analysis in progress

Requested a low-pileup run ($\mu \sim 30$ %) at $\beta^* = 0.6$ m to increase statistics

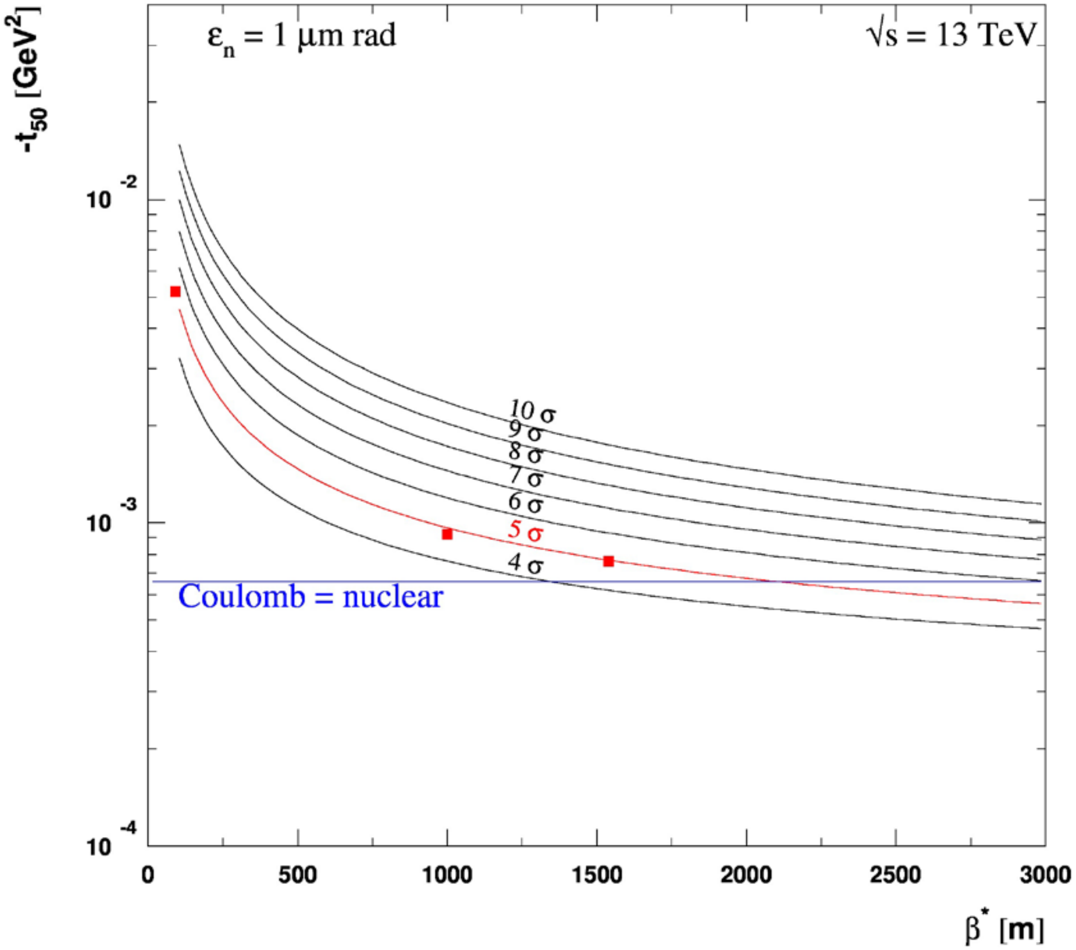
Runs Still Planned for 2012 / 2013

- p-Pb runs with insertions of the RPs on the proton side
  → study diffractive/electromagnetic and quasi-elastic p-Pb scattering
  → $dN_{ch} / d\eta$
  p-Pb test run in September with CMS was successful (T2 trigger given to CMS)

- Low-energy pp run ($\sqrt{s}$ = 2.76 TeV) with insertions of the RPs
  if possible with β^* = 90m optics
  → measure elastic scattering and total cross-section near Tevatron energy



After LS1: Low-|t| Elastic Scattering at 13 TeV

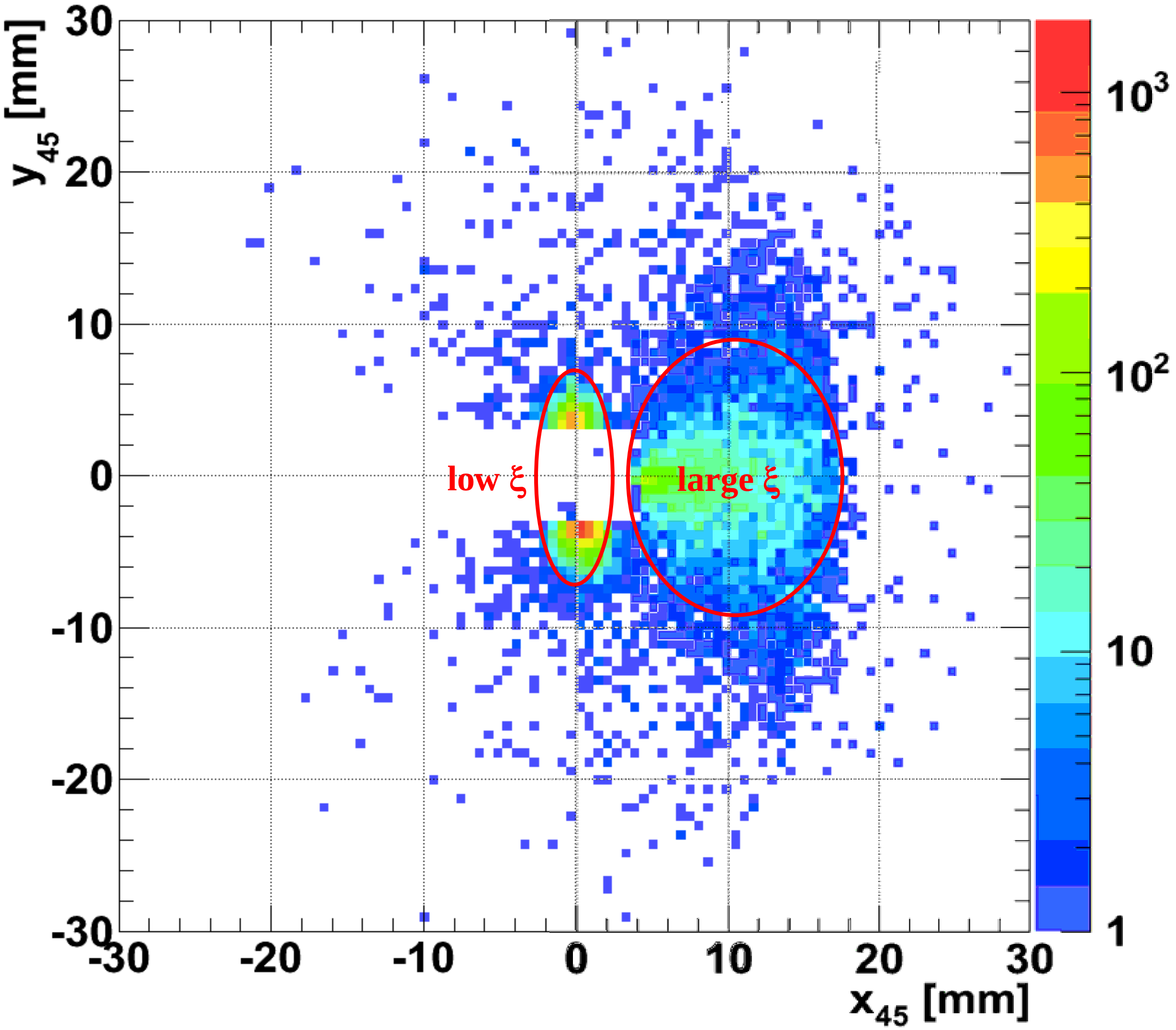


- To reach CNI region, push β* to > 2000 m
- At 13 TeV: good t-resolution needs parallel-to-point focussing in both x and y (phase advance π/2)

Backup

Track distribution for an inclusive trigger (global “OR”)

$\beta^* = 3.5$ m



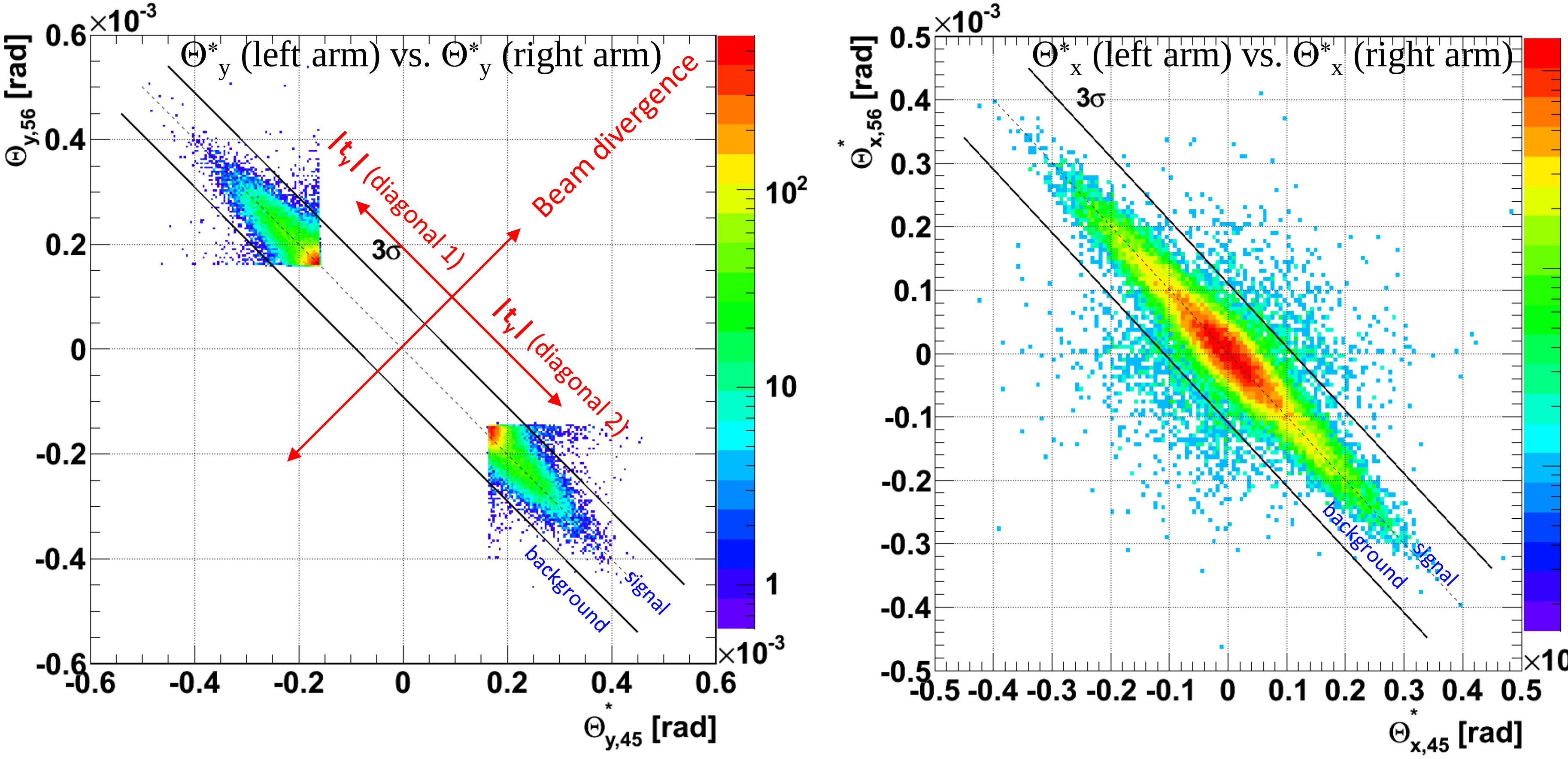
$\xi = \Delta p / p$

Elastic Tagging

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

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

2. Elastic collinearity :



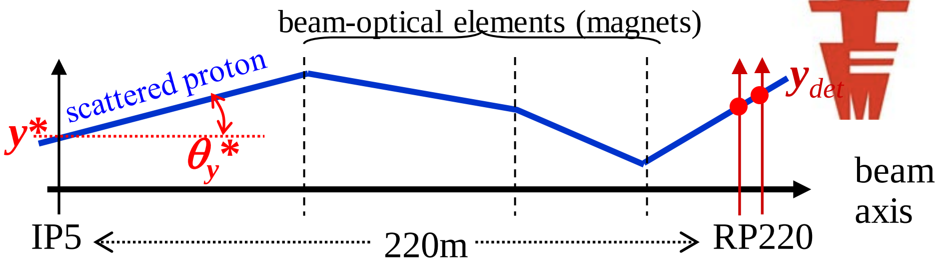
Data outside the 3σ cuts used for background estimation

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)



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

$\beta^* = 90$ 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

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

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):

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

	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| $\lvert t_{\min}\rvert = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$
Standard optics $\beta^* \sim 1$–3.5 m	$\sigma_{x,y}^*$ small	$\sigma(\theta_{x,y}^*)$ large	$\lvert t_{\min}\rvert \sim 0.3$–$1$ GeV^2
Special optics $\beta^* = 90$ m	$\sigma_{x,y}^*$ large	$\sigma(\theta_{x,y}^*)$ small	$\lvert t_{\min}\rvert \sim 10^{-2}$ GeV^2

pA Minimum Bias Physics

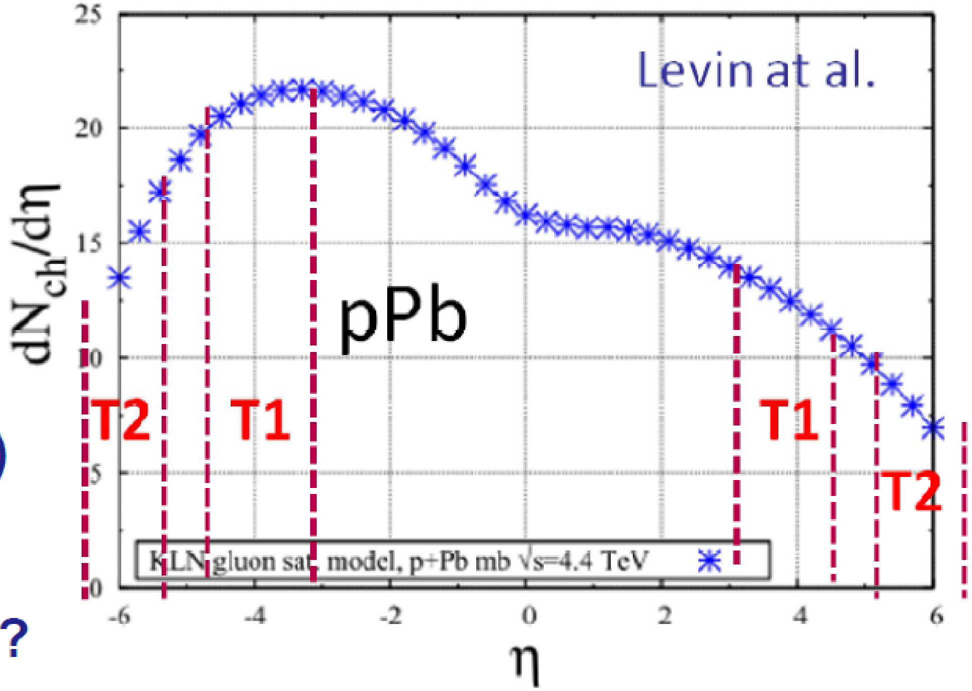
Charged particle acceptance (together with CMS): |η| ≤ 6.5

Trigger: one T2 track(?)

dN/dη_{pPb} using T1 & T2 (vs centrality from CMS)

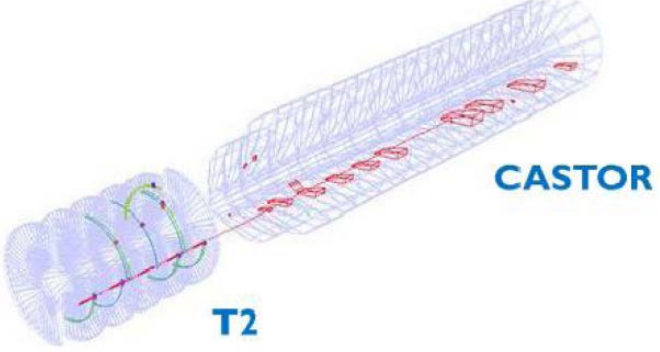
Forward-backward multiplicity correlations?

Central-forward multiplicity correlations?



Pattern recognition at high multiplicity to be optimized

Energy flow & small x: T1+HF, T2+Castor



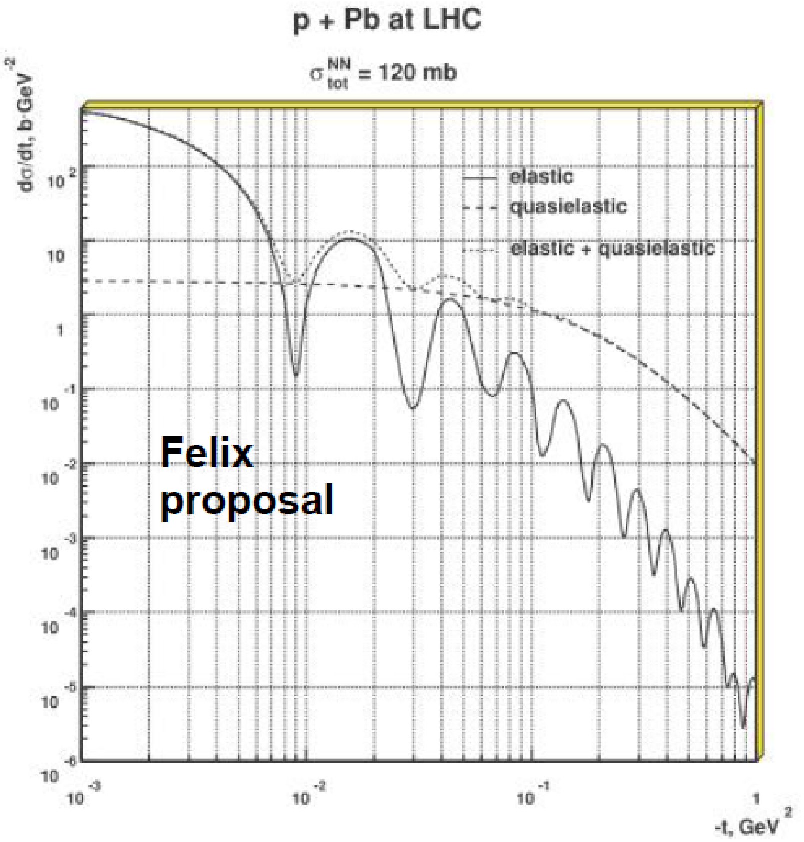
[K. Oesterberg, pA @ LHC workshop, June 2012]

Cross-sections

Test of dynamics:

- **knockout: p Pb → p + d + (A–2)*** $\xi^{p}_{fragment} = (1-(A/Z)_{fragment}/(A/Z)_{Pb})$
  - measure both p & d (= "p with Δp/p = -0.21") + veto hadron activity. Need large t for p or significant Δp/p. Study Δp/p & t dependence.

- **quasielastic: p Pb → p Pb***
  dominates at large t
  - measure xi & t of p + only γ on opposite side (veto hadrons)



Diffraction & γγ

- very large Pomeron & γ fluxes
  but nothing measured in RP on outgoing Pb side (rate problem?)

p with signficant Δp/p (or large t)
+ central object (jets, J/Ψ, Υ etc..)

[K. Oesterberg, pA @ LHC workshop, June 2012]

pA run scenarios at LHC

J. Jowett

- $\boxed{P_A = Z \cdot P_p}$ (both beams in same dipole ⇒ same B-field)
  $Z = 82$, $A = 208$ for Pb ⇒ cm frame boosted $\beta = 0.98 – 0.975$
- $P_p > 2.7$ TeV (RF unequal for injection+ramp, then matched)

	p-p	Pb-Pb	p-Pb
$E\,/\,\mathrm{TeV}$	0.45-7	287-574	(2.7-7,287-574)
$E_N\,/\,\mathrm{TeV}$	0.45-7	1.38-2.76	(2.7-7, 1.38-2.76)
$\sqrt{s}\,/\,\mathrm{TeV}$	7-14	73.8-1148	48.9-126.8
$\sqrt{s_{\mathrm{NN}}}\,/\,\mathrm{TeV}$	7-14	0.355-5.52	3.39-8.79
y_{CM}	0	0	-2.20
y_{NN}	0	0	+0.46

(soft interactions)

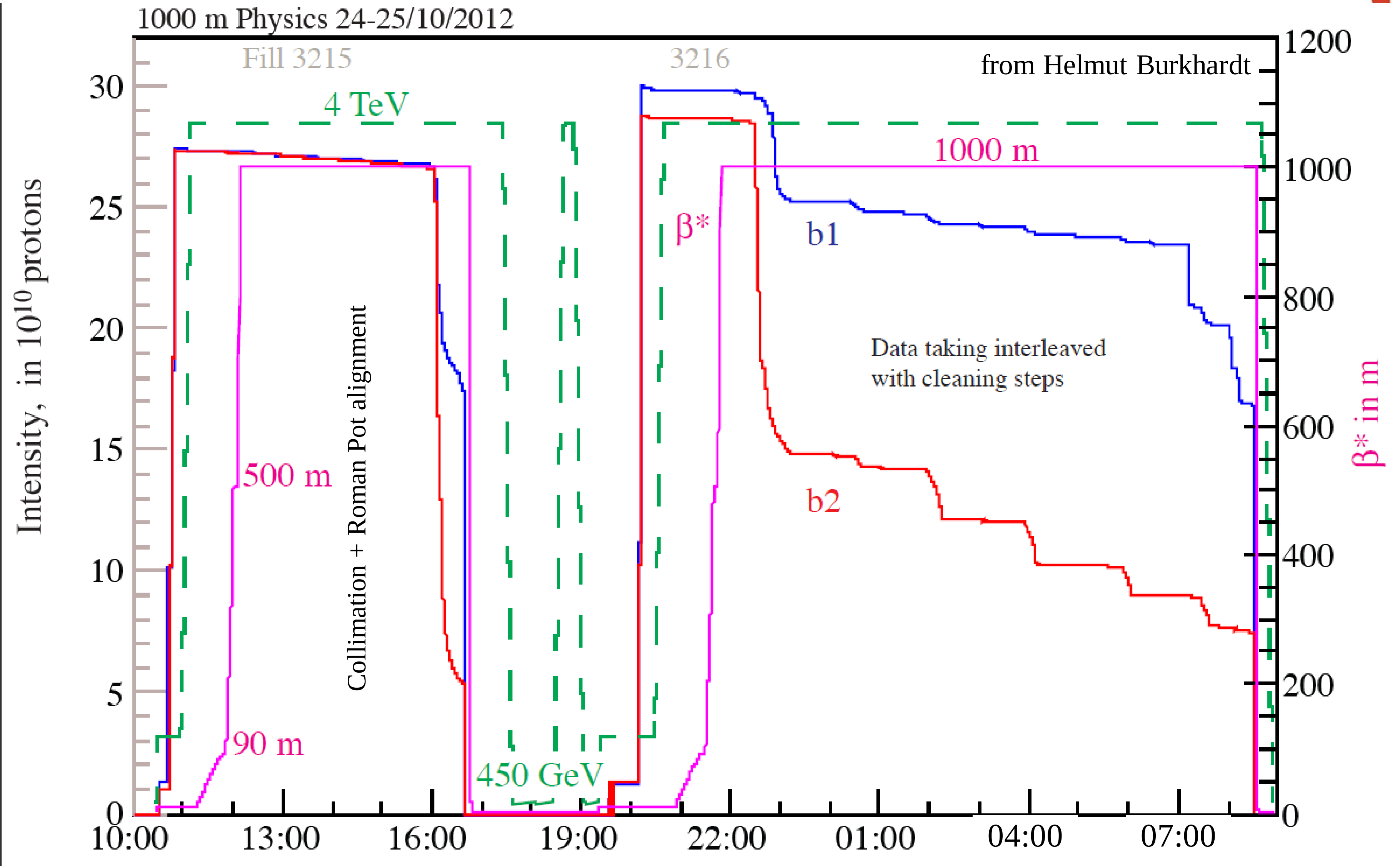
(hard interactions

- Pb filling scheme (few-300 bunches, $N_p = \sim 10^{10}$, $N_{Pb} = \sim 10^8$)
- Rates: $\mathcal{L} = 10^{26} – 10^{28}$ cm^{-2}s^{-1}, $\sigma_{\mathrm{inelastic}} \sim 2$ b ⇒ 200 Hz – 20 kHz

$$\sqrt{s_{NN}} \approx 2P_p\sqrt{Z_1Z_2/A_1A_2} \qquad y_{NN} = ½ \log\,(Z_1A_2/A_1Z_2)$$

The Run at β* = 1 km: Overview

2 fills with 3 bunches of ~10^{11} p (2 colliding, 1 non-colliding)



All RPs aligned in < 2 hours (record)

Joint Data Taking with CMS in 2012

May 2012: low pileup run: β* = 0.6 m, √s = 8 TeV, T1 & T2 & CMS read out

Date	Trigger	Inelastic events	
May 1	T2 || BX	~5 M	**no RP**

dN/dη,
correlations,
underlying event

July 2012: β* = 90 m, √s = 8 TeV, RP & T1 & T2 & CMS read out

Date, Set	Trigger	Inelastic events	RP position
July 7, DS 2	T2 || RP$_{2arms}$ || BX	~2 M	6 σ
July 12-13, DS 3a	T2 || RP$_{2arms}$ || BX	~10 M	9.5 σ V, 11σ H
July 12-13, DS 3b	T2 || RP$_{2arms}$ || CMS (CMS = 2 jets @ p^T > 20GeV, 2 μ, 2 central e/γ)	~3.5 M	9.5 σ V, 11σ H

σ_{tot}, σ_{inel} with CMS,
soft & semi-hard diffraction,
correlations

Analyses in progress:

- hard diffraction: p + dijets
- combined dN_{ch} / dη and multiplicity correlations

•requested a low-pileup run (μ ~ 30 %) with RPs at β* = 0.6 m

→ study hard central diffraction (e.g. di-jets)
with 2 leading protons defining Pomeron-Pomeron mass $M^2 = \xi_1 \xi_2 s$
(good ξ resolution at β* = 0.6 m → σ(M) ~ 5 GeV)

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

Data sample:

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

Selection:

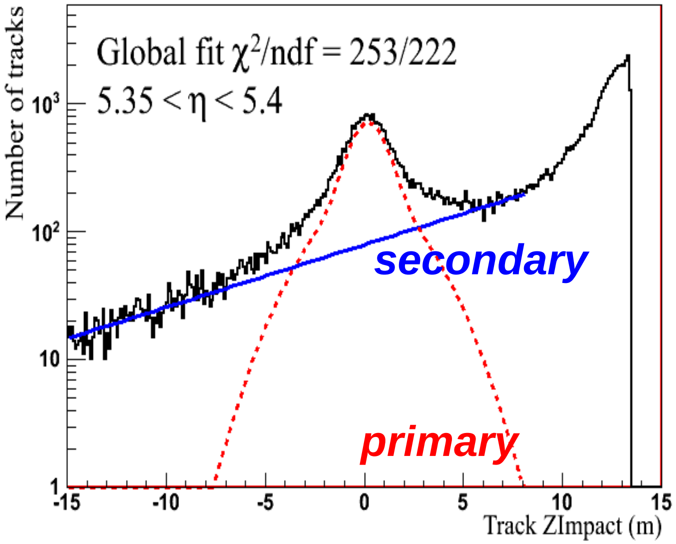
at least one track reconstructed in T2

Primary particle definition:

charged particle with $t > 0.3 \times 10^{-10}$ 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:

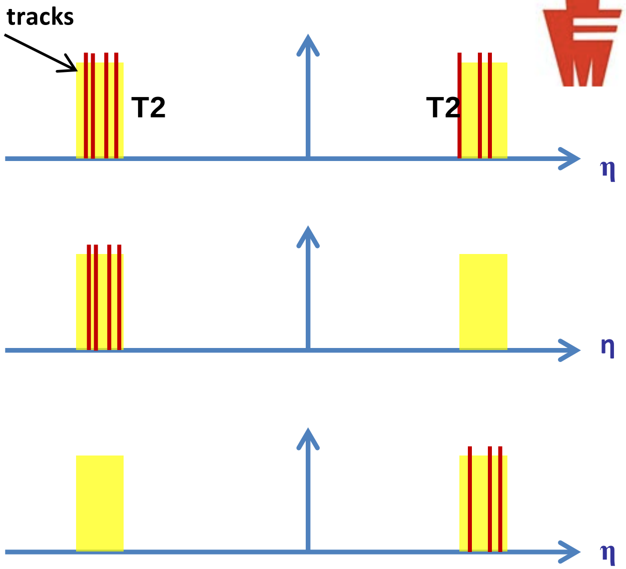
- *evaluated as a function of the track η and multiplicity*
- *efficiency of 80%*
- *fraction of primary tracks within the cuts of 75% – 90% (η dependent)*

Un-folding of (η) resolution effects:

MC driven bin “migration” corrections

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%**

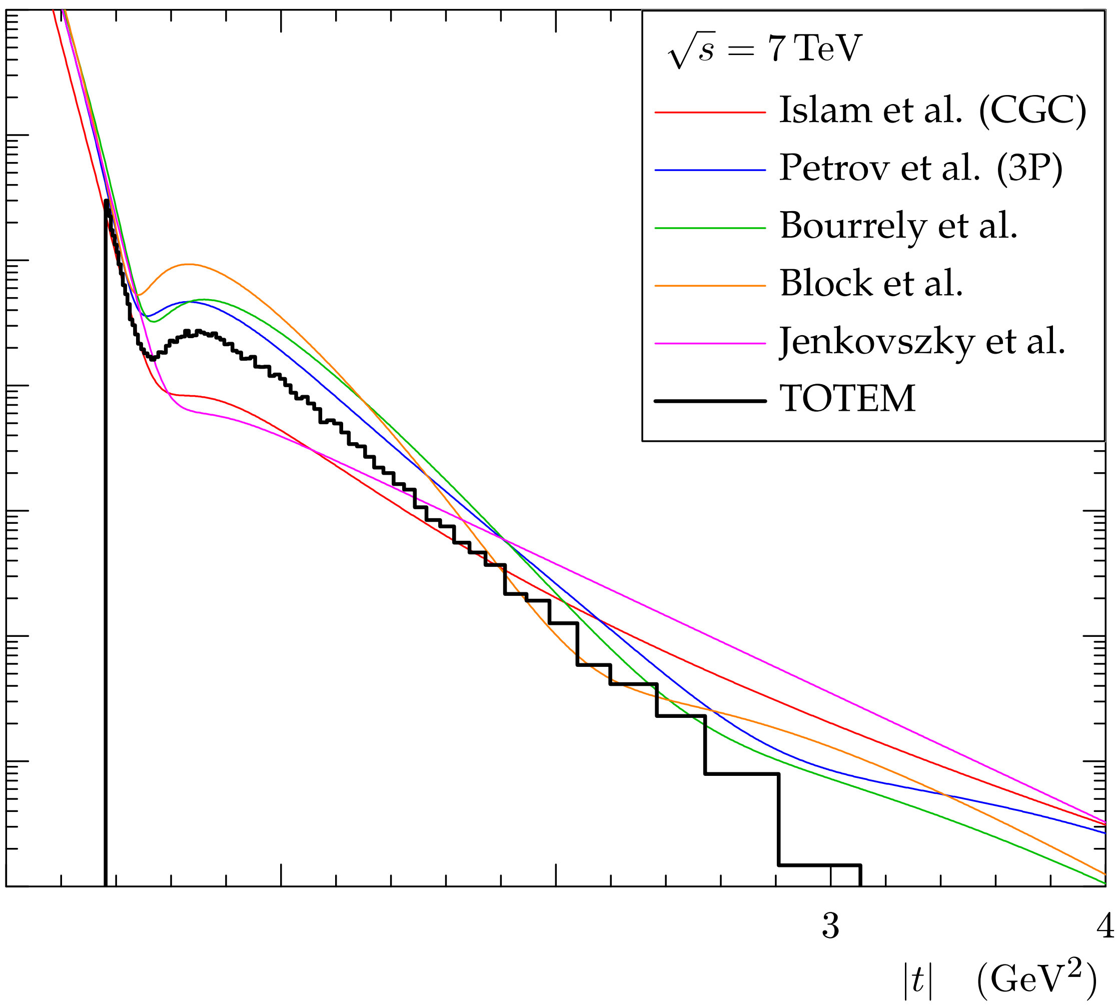
  (measured with non colliding bunch data)

- Pile-up (μ =0.03): **1.5 %**

  (contribution measured from zero bias data)

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

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 fits