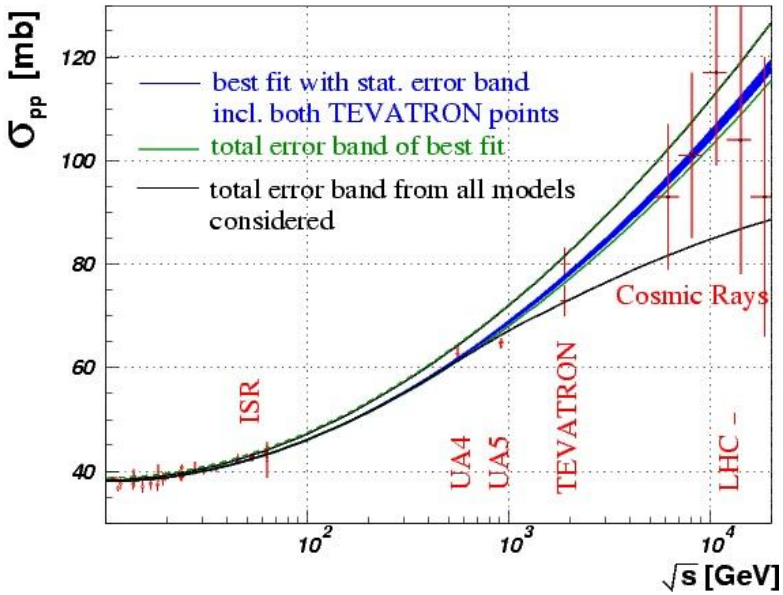
TOTEM PHYSICS PROGRAMME, ANALYSIS AND RESULTS

CERN-LHC Seminar
Main Auditorium, Tuesday, 29th of January 2013

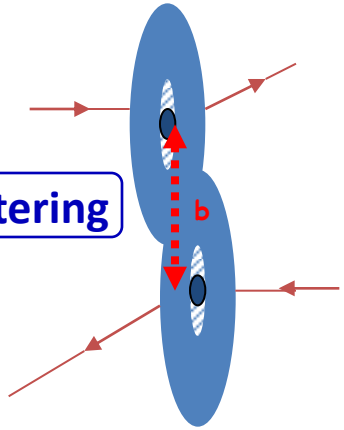
Hubert Niewiadomski
CERN, on behalf of the the TOTEM collaboration

TOTEM Physics Overview

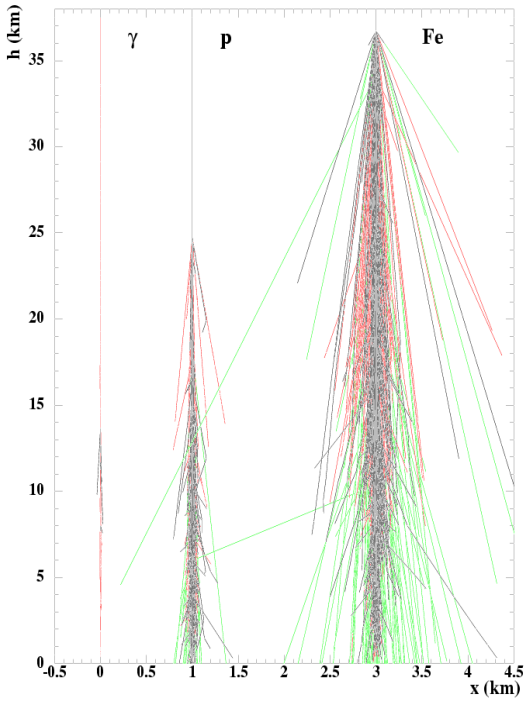
Total cross-section



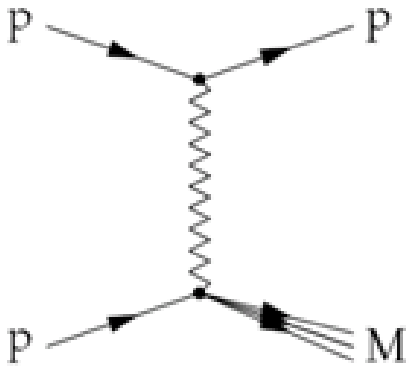
Elastic Scattering

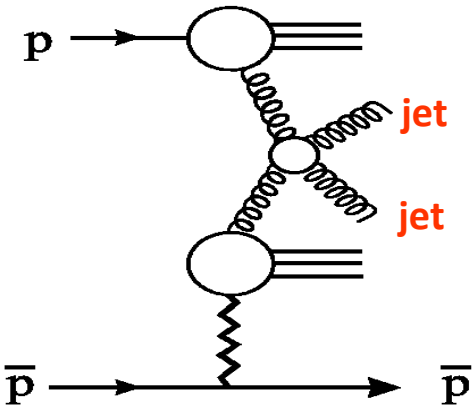


Forward physics

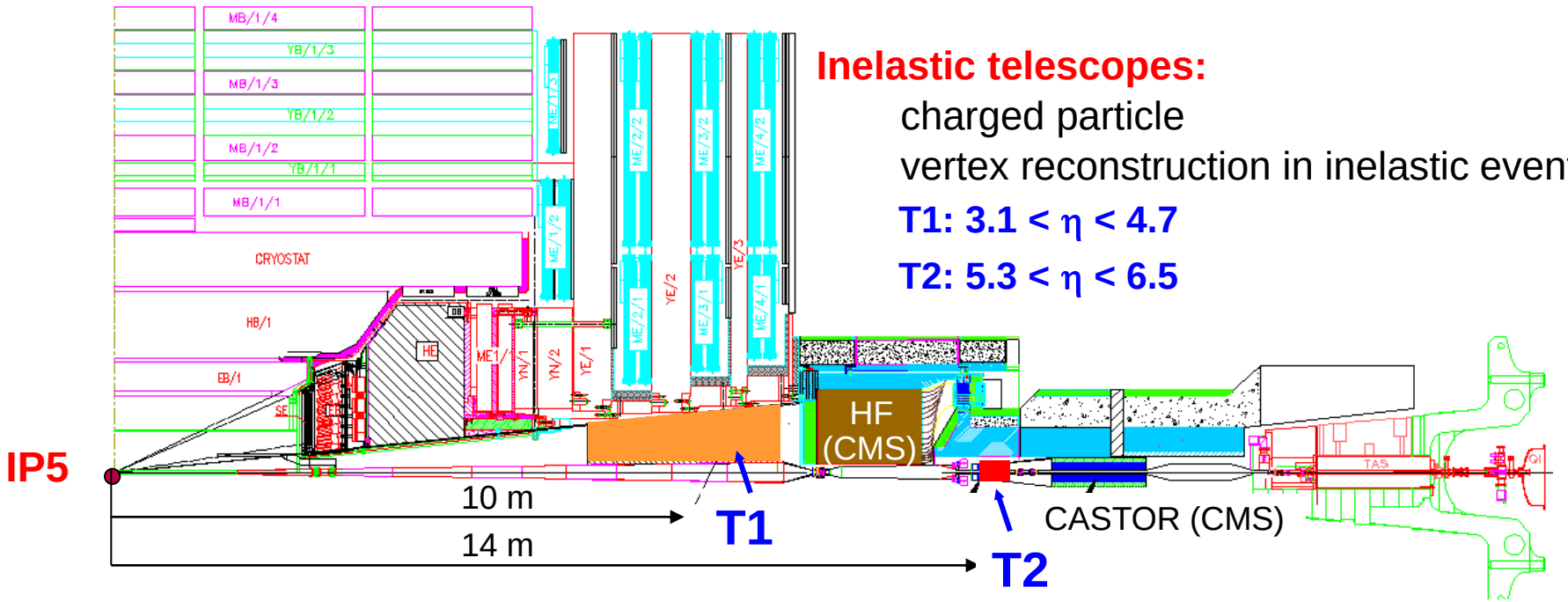


Diffraction: soft (and hard with CMS)





Experimental Setup @ IP5



Inelastic telescopes:

charged particle

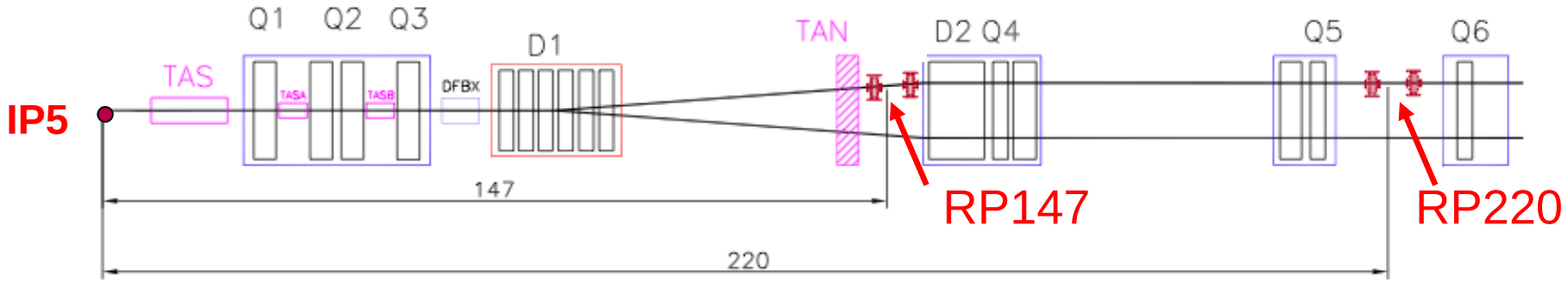
vertex reconstruction in inelastic events

T1: 3.1 < η < 4.7

T2: 5.3 < η < 6.5

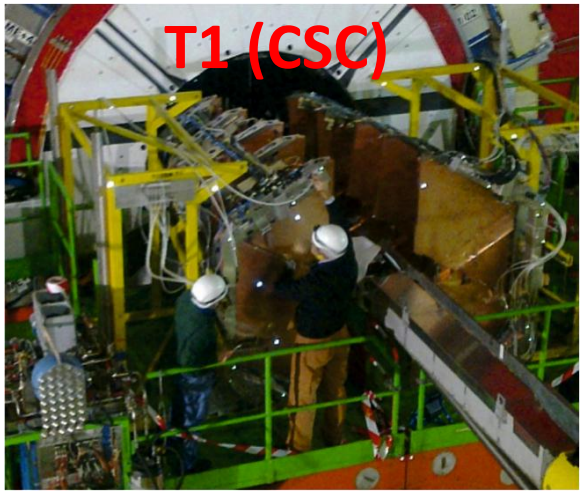
Roman Pots:

measure elastic & diffractive protons close to outgoing beam

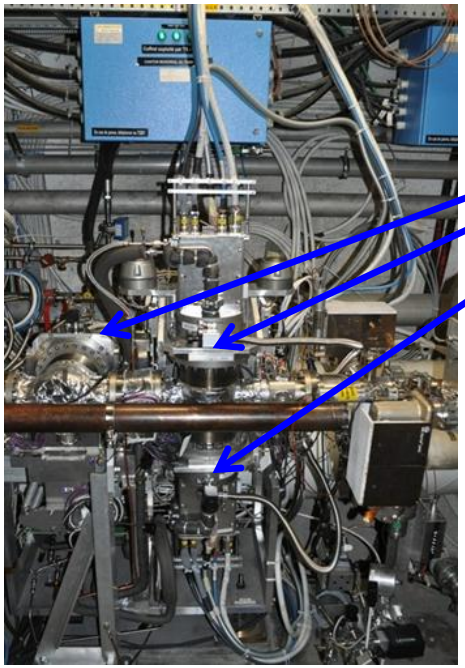


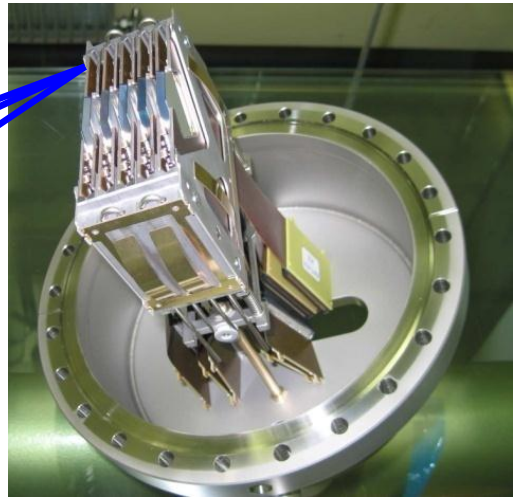
TOTEM Trackers

(all with trigger capability)



Roman Pots

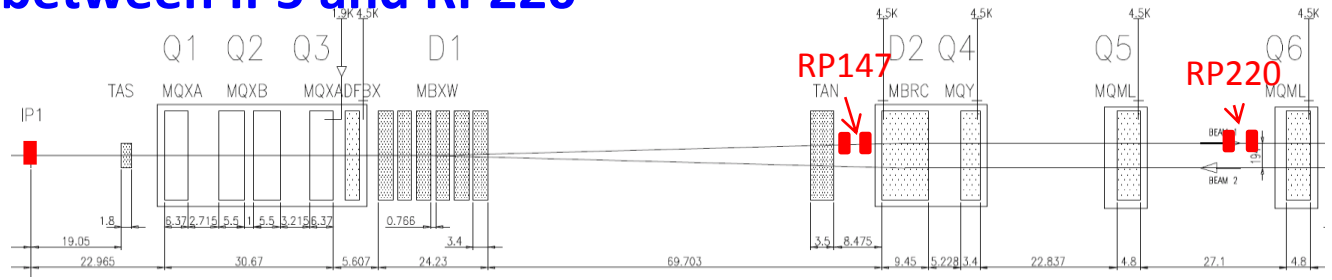




Microstrip silicon dets.

LHC Optics

Lattice between IP5 and RP220



- 6 quardupole magnets (Q1-Q5)
- Dipoles, correctors, drift spaces

Proton transport IP5 → Roman Pot

Kinematics measured in Roman Pots

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

Reconstructed collision kinematics

Optics carefully optimised for TOTEM special runs
Essential for TOTEM results

Optics systematic errors

- Optics is a product of lattice elements $\mathbf{T}_i$ and imperfections $\Delta\mathbf{T}_i$

$$\mathbf{T}_{IP5\to RP220} = \prod_{i=M}^{1}\left[\mathbf{T}_i(k_i) + \Delta\mathbf{T}_i\right] = \begin{pmatrix} v_x & L_x & re_{13} & re_{14} \\ \frac{dv_x}{ds} & \frac{dL_x}{ds} & re_{23} & re_{24} \\ re_{31} & re_{32} & v_y & L_y \\ re_{41} & re_{42} & \frac{dv_y}{ds} & \frac{dL_y}{ds} \end{pmatrix}$$

$\Delta\mathbf{T}_i$ – magnet imperfections

$\frac{dL_x}{ds}$, L_y – values needed for prot. reconstr.

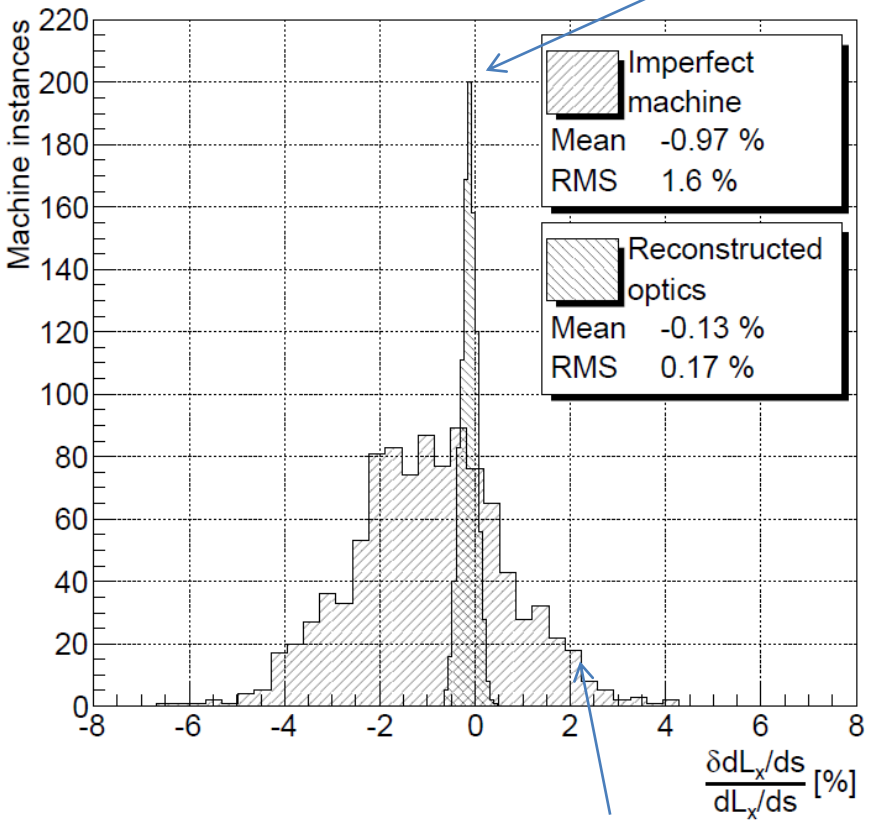
- Imperfections $\Delta\mathbf{T}_i$
  - Beam momentum offset ($\Delta p/p = 10^{-3}$)
  - Magnet transfer function error, I→B, ($\Delta B/B = 10^{-3}$)
  - Magnet rotations and displacements ($\Delta\psi < 1$mrad, Δx, $\Delta y < 0.5$mm, WISE database)
  - Power converter errors, k→I, ($\Delta I/I < 10^{-4}$)
  - Magnet harmonics ($\Delta B/B = O(10^{-4})$ @ $R_{ref} = 17$mm, WISE database)

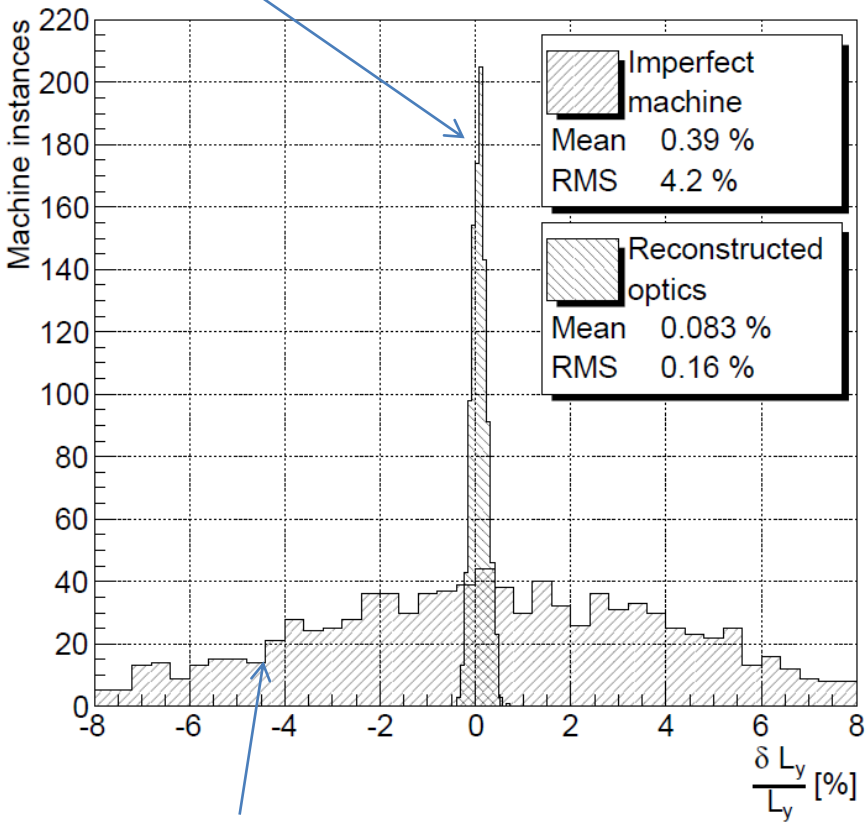
Optics estimation

- Measured rations of certain $\mathbf{T}_{IP5\to RP220}$ elements constrain the others
- Elastic scattering correlates Beam 1 and Beam 2
- Optics estimation with
  - MADX-based numerical algorithms
  - Analytical solutions (+PCA)
- Intensive MC validation

Low β* optics estimation

LHC estimated optics error



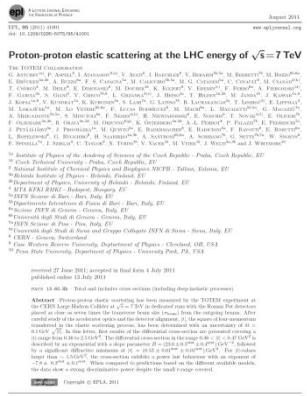


LHC optics spread (w.r.t. nominal) due to imperfections

Difficult direct optics measurements no longer critical!

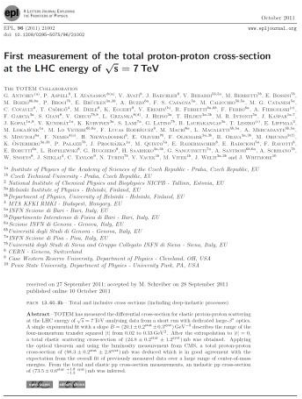
H. Niewiadomski, ***Roman Pots for beam diagnostic***, OMCM, CERN, 20-23.06.2011
H. Niewiadomski, F. Nemes, ***LHC Optics Determination with Proton Tracks***, IPAC'12, Louisiana, USA, 20-25.05.2012

2011 Results



Proton-proton elastic scattering at the LHC energy of $\sqrt{s}$=7 TeV

1. Proton-proton elastic scattering at the LHC energy of sqrt s = 7 TeV , **EPL 95 (2011) 41001**



First measurement of the total proton-proton cross-section at the LHC energy of $\sqrt{s} = 7$ TeV

2. First measurements of the total proton-proton cross section at the LHC energy of sqrt s = 7TeV

EPL 96 (2011) 21002

2012 Results

3. Measurement of the forward charged particle pseudorapidity density in pp collisions at sqrt s = 7 TeV with the TOTEM experiment, **EPL 98 (2012) 31002**

4. Measurement of proton-proton elastic scattering and total cross-section at sqrt s = 7 TeV, CERN-PH-EP-2012-239, **accepted by EPL**

5. Measurement of proton-proton inelastic scattering cross-section at sqrt s = 7 TeV, CERN-PH-EP-2012-352, **accepted by EPL**

6. Luminosity-independent measurements of total, elastic and inelastic cross-sections at sqrt s = 7 TeV, CERN-PH-EP-2012-353 **accepted by EPL**

7. A luminosity-independent measurement of the proton-proton total cross-section at sqrt s = 8 TeV, CERN-PH-EP-2012-354, **submitted to PRL**

ELASTIC SCATTERING

Large-t pp Elastic Scattering (80nb^{-1})

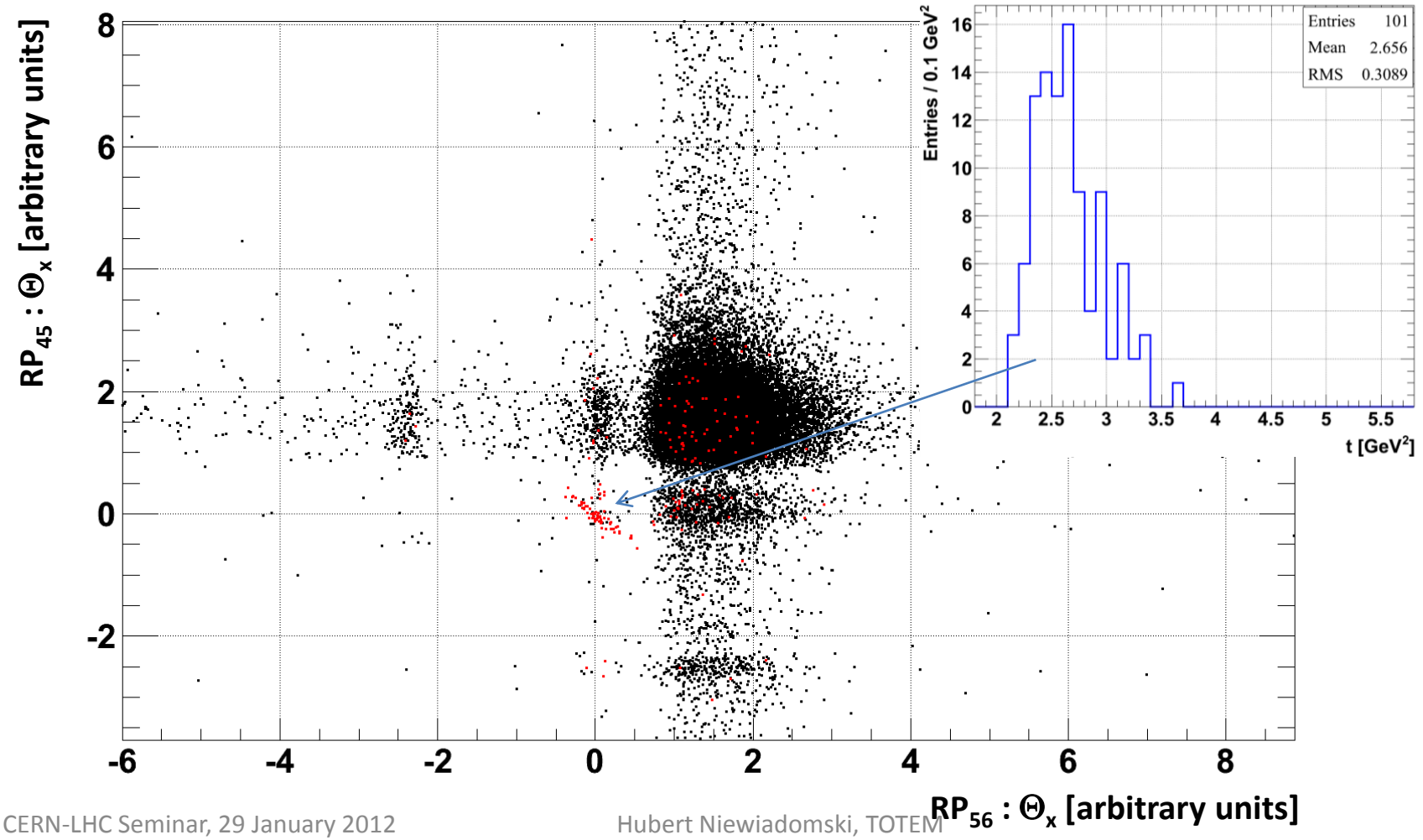
100 Events : First statistically significant sample

[LHCC Sep 2010]

$\sqrt{s}$ = 7 TeV

β^* = 3.5 m

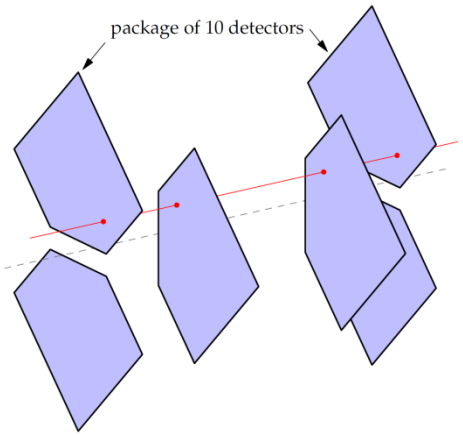
2010 Data from Runs with RPs at 20σ (total 185nb^{-1})



Proton reconstruction

Both angle projections reconstructed: Θ_x^* and Θ_y^*

- Θ_x^* from Θ_x @ RP220 (through dL_x/ds) $\quad \Theta_{x,RP} \approx dL_x/ds\ \Theta_x^*$
- Θ_y^* from y @ RP220 (through L_y) $\quad y_{,RP} \approx L_y\ \Theta_y^*$



Track based alignment

→ **Alignment**

- Alignment between pots with overlapping tracks (~1μm)
- Alignment with respect to the beam – collimator like scraping exercise (~20μm)
- Mechanical constraints between top and bottom pots (~10μm)

→ **Optics errors**

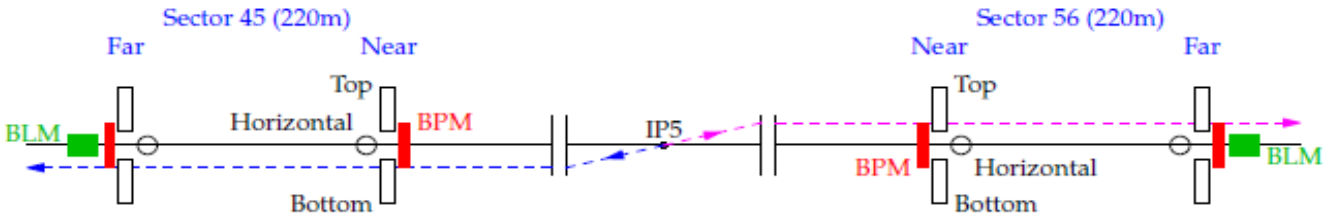
- Depend on LHC imperfections and LHC configuration
- Optics estimation with elastic scattering
  - $\Theta_{left}^* = \Theta_{right}^*$ (proton pair collinearity)
  - Proton position ↔ angle correlations (+Liouville's theorem)
  - L_x=0 determination, coupling estimation

A difficult measurement, data driven analysis

Elastic scattering: difficult precise measurement

1. **Kinematics reconstruction**
   - proton tracks in RPs → proton kinematics at IP
2. **Elastic tagging**
   - Topology : diagonals
   - Proton co-linearity : compare left and right reconstructed angles
   - No forward momentum loss : remove protons shifted due to dispersion
3. **Acceptance corrections**
   - Finite size of RP sensors, LHC apertures
   - Azimuthal symmetry of el. scattering → geometrical corrections
   - Beam divergence → correction for missing protons at RP edges
4. **Unfolding of resolution effects**
   - Numerical, kernel function based and completely analytical unfolding
5. **Inefficiency corrections**
   - RP inefficiencies
   - pile-up related inefficiencies : elastic event + another track in a RP
6. **Luminosity**
   - from CMS (if available, uncertainty 4%)
   - TOTEM luminosity measurement

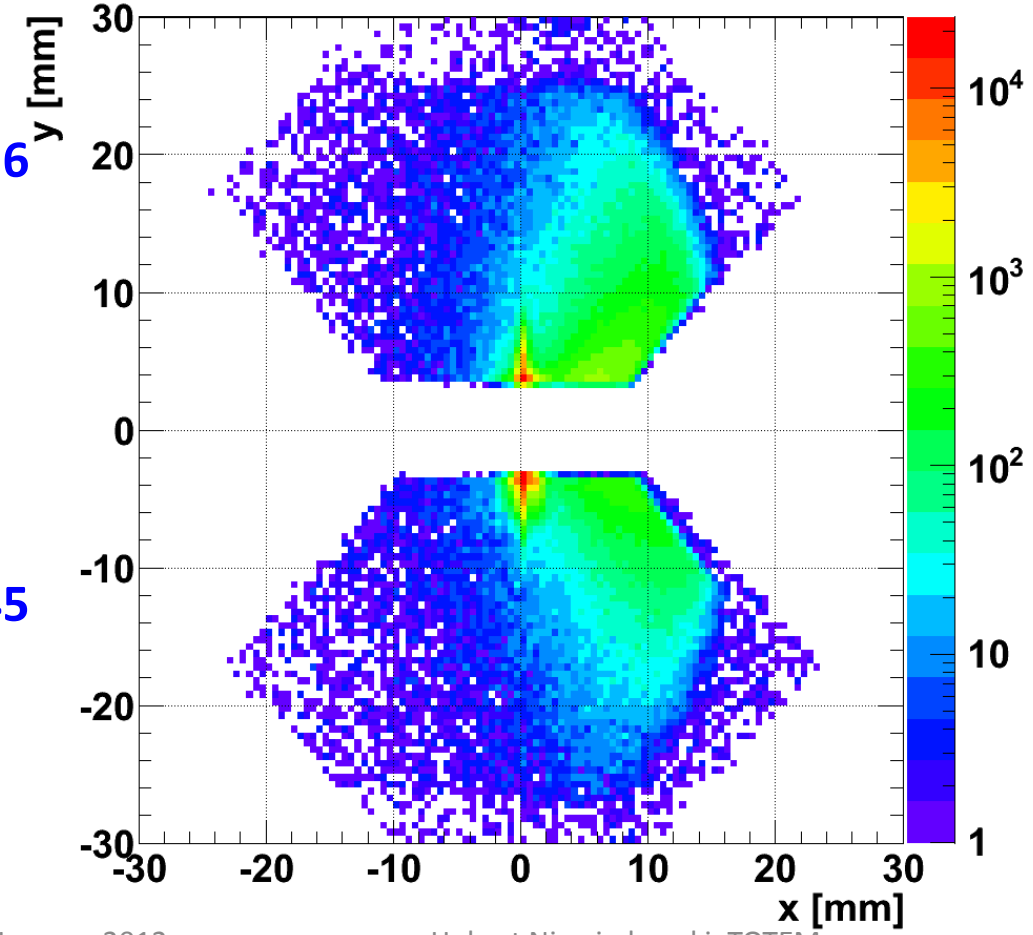
Elastic tagging : topology



Single diagonal

Sector 56

Sector 45



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

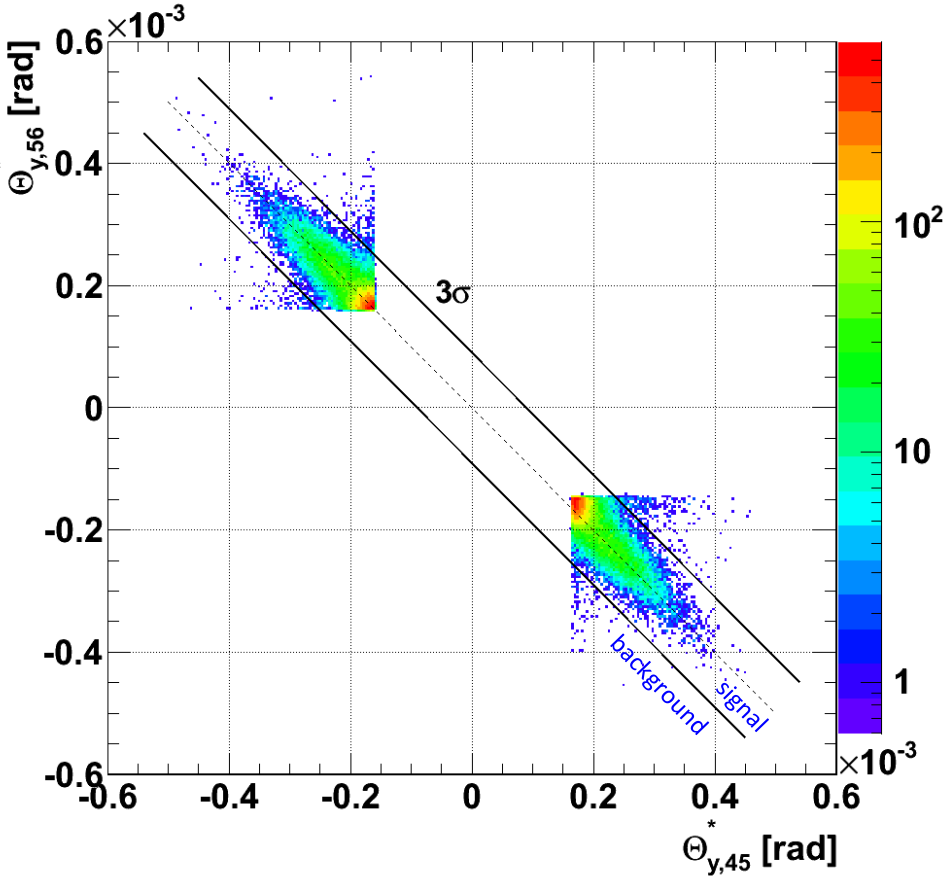
$\xi = \Delta p/p$

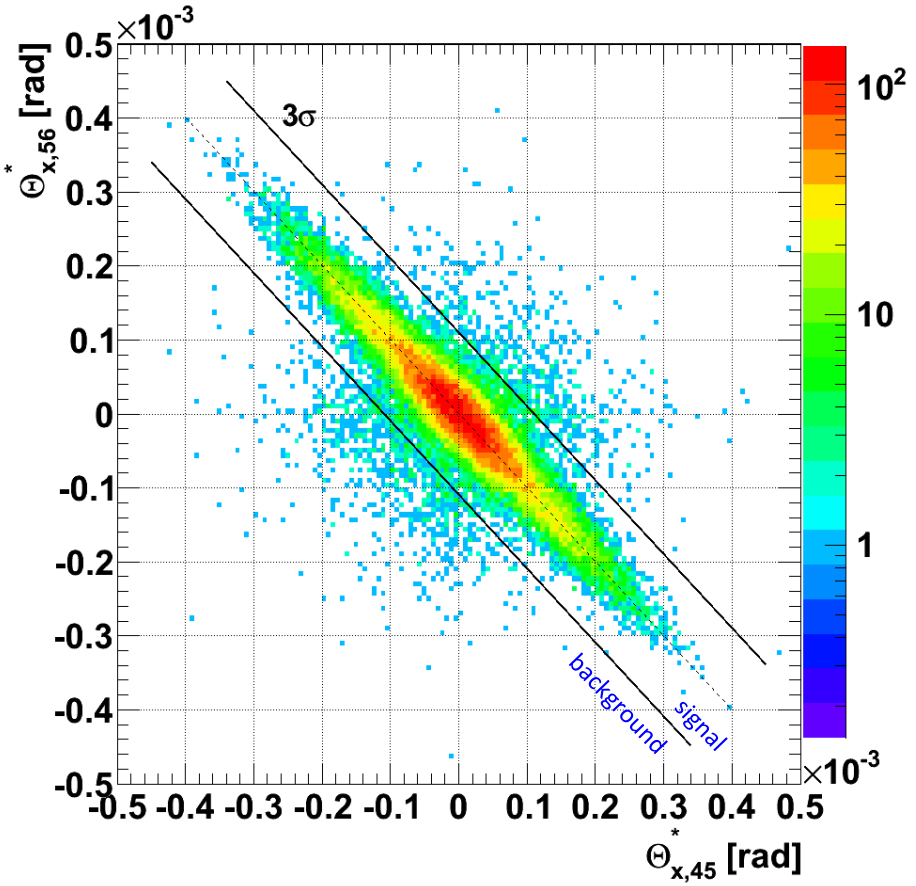
$y = L_y \Theta_y$

$x = L_x \Theta_x + \xi D$

$L_x \sim 0$

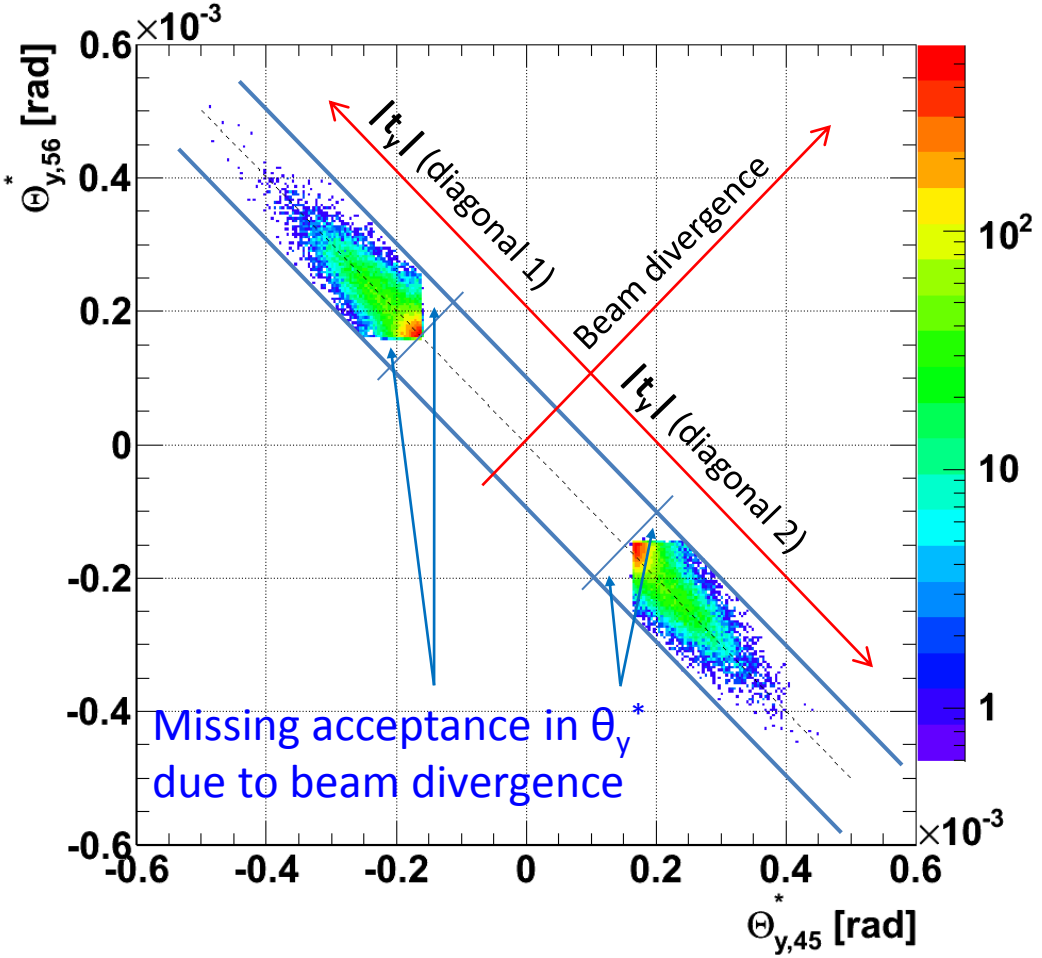
Elastic tagging : collinearity cuts

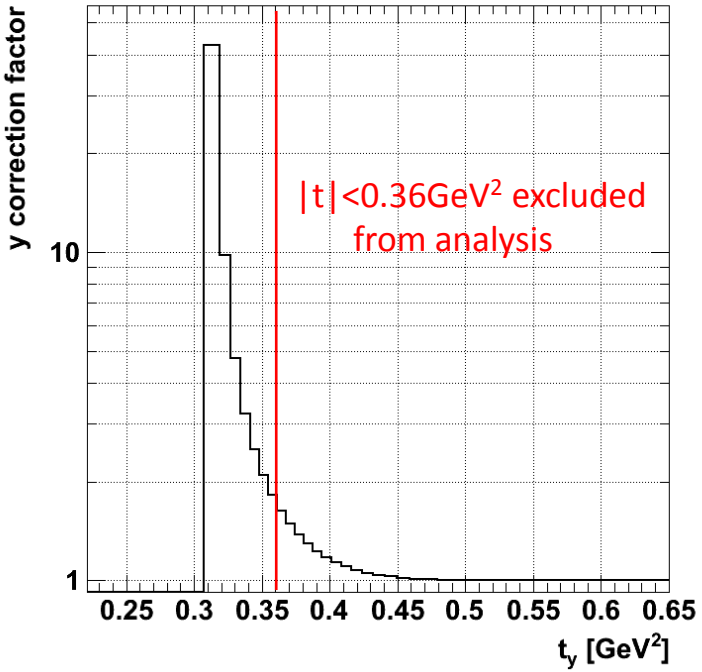




Data outside the 3σ cuts used for background estimation

t_y-acceptance corrections





Correction error (t_y):

0.31 GeV^2 : 30%

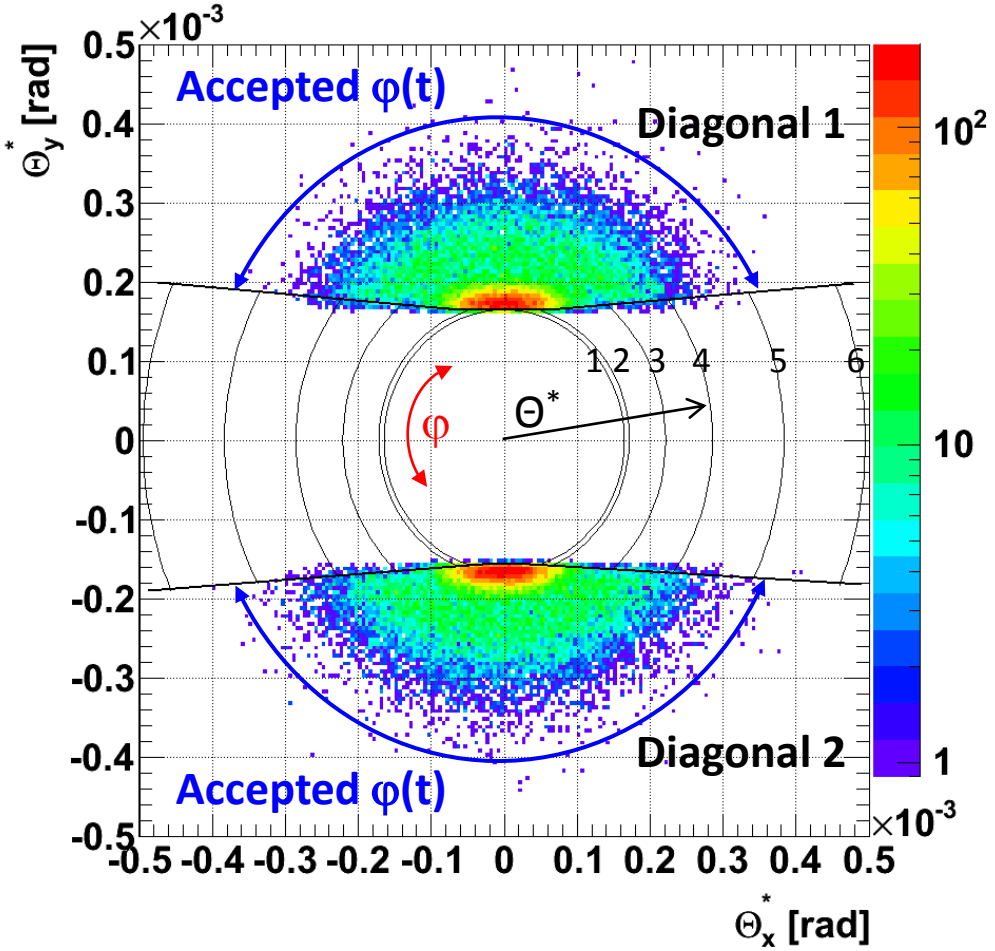
0.33 GeV^2 : 11%

0.35 GeV^2 : 2%

0.4 GeV^2 : 0.8%

0.5 GeV^2 : 0.1%

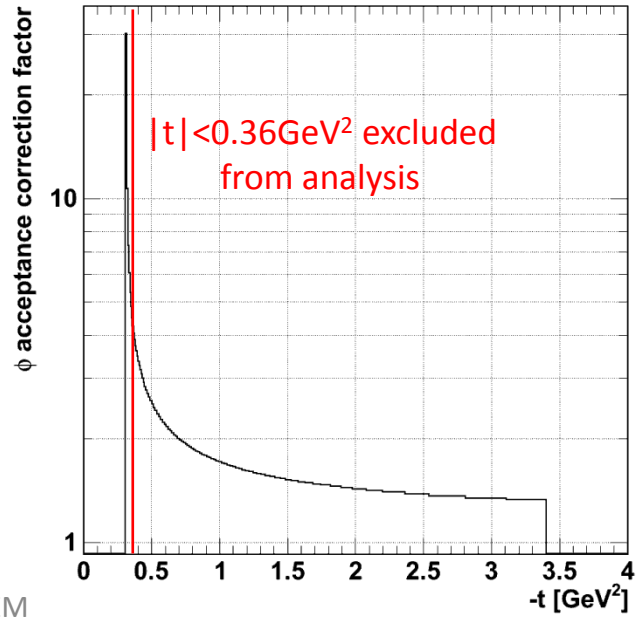
φ-acceptance correction



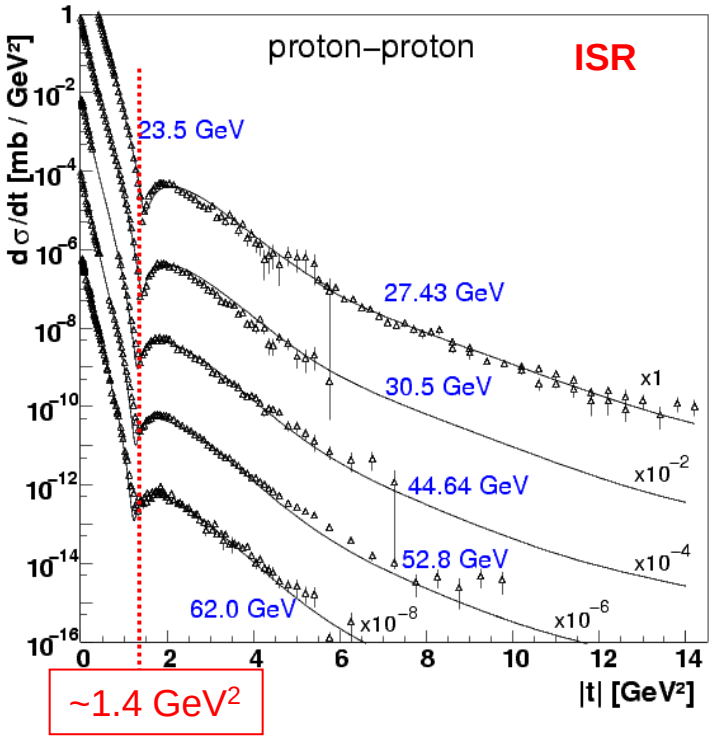
Critical at low t-acceptance limit

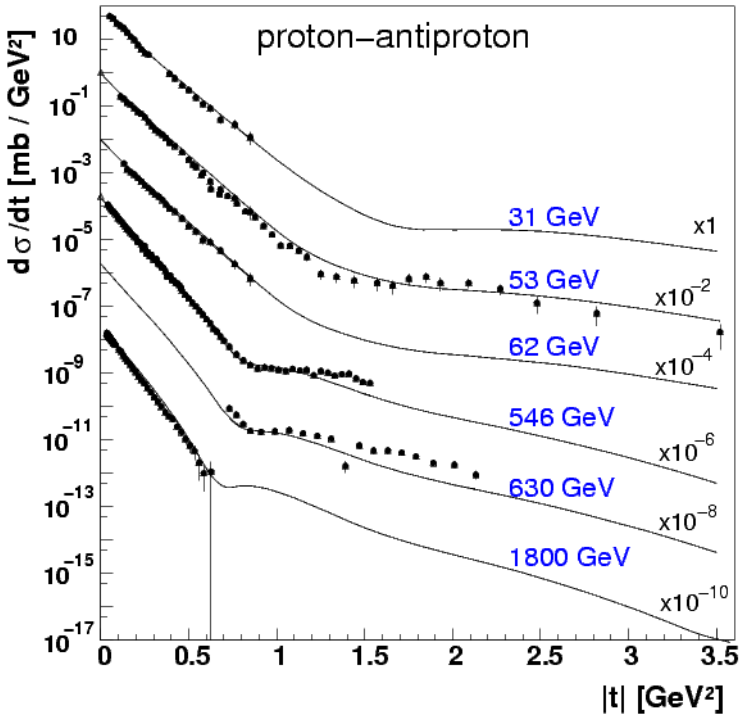
Total φ-acceptance correction

No.	t [GeV²]	Θ* [rad]	Accepted φ (2 diag.) [°]	φ accept. correct. factor
1	**0.33**	1.65E-04	38.6	**9.3±4.7%**
2	**0.36**	1.71E-04	76.4	**4.7±1.8%**
3	**0.60**	2.21E-04	162.5	**2.2±0.3%**
4	**1.00**	2.86E-04	209.8	**1.7±0.1%**
5	**1.80**	3.83E-04	246.3	**1.5**
6	**3.00**	4.95E-04	269.0	**1.3**

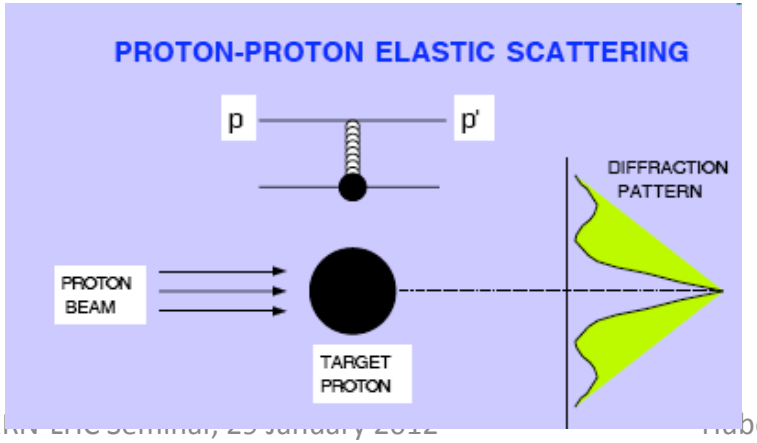


Elastic scattering – from ISR to Tevatron



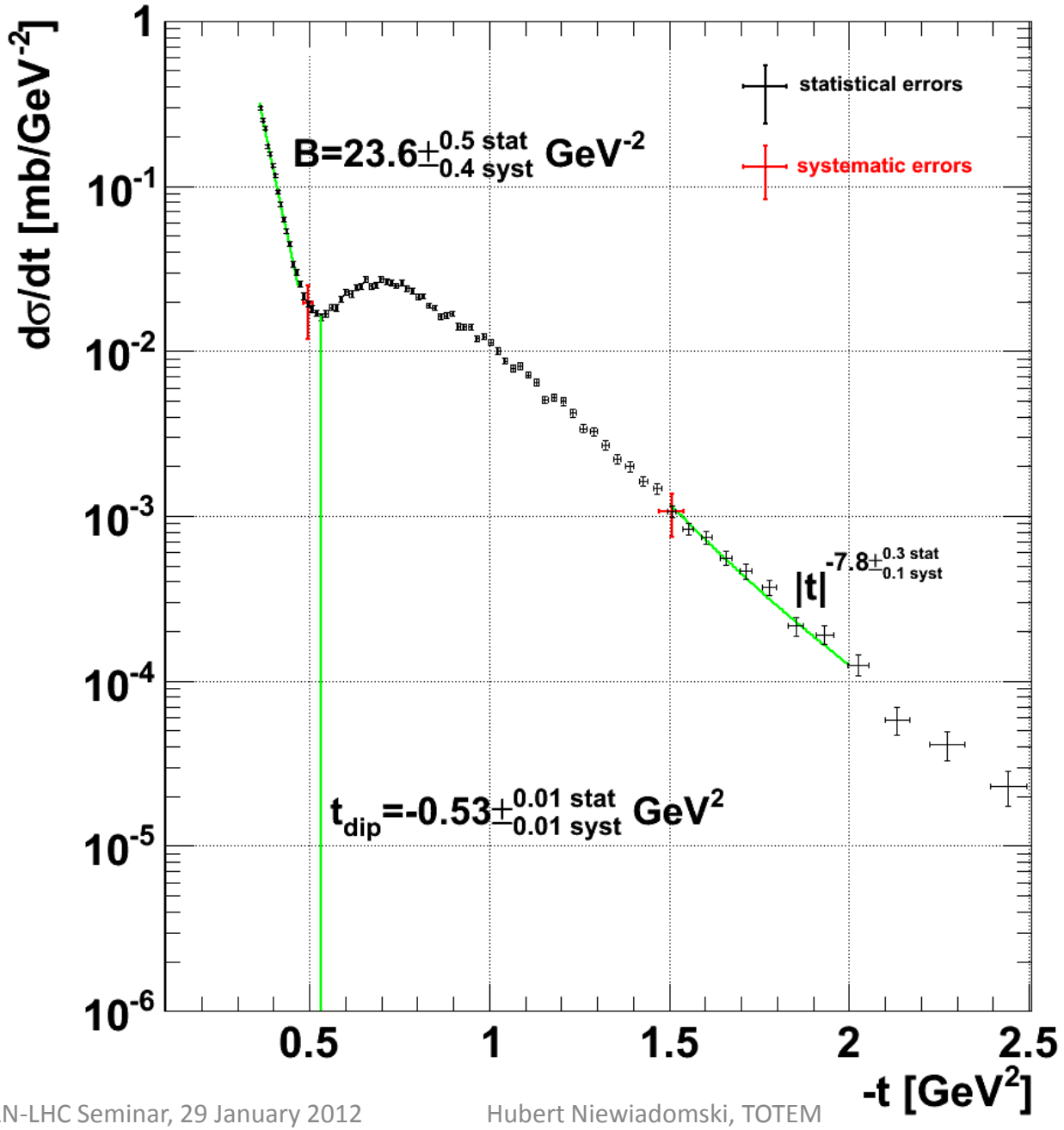


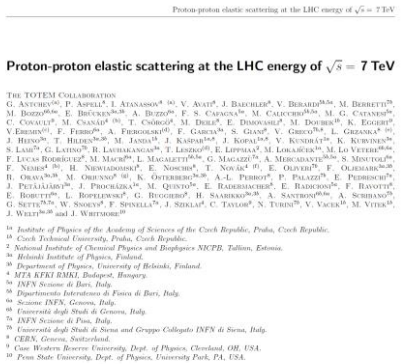
Diffractive minimum: analogous to Fraunhofer diffraction:



- minimum moves to lower |t| with increasing s
  → interaction region grows (as also seen from σ_{tot})
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, $p^{-}p$
  → different mix of processes

TOTEM first dσ/dt result



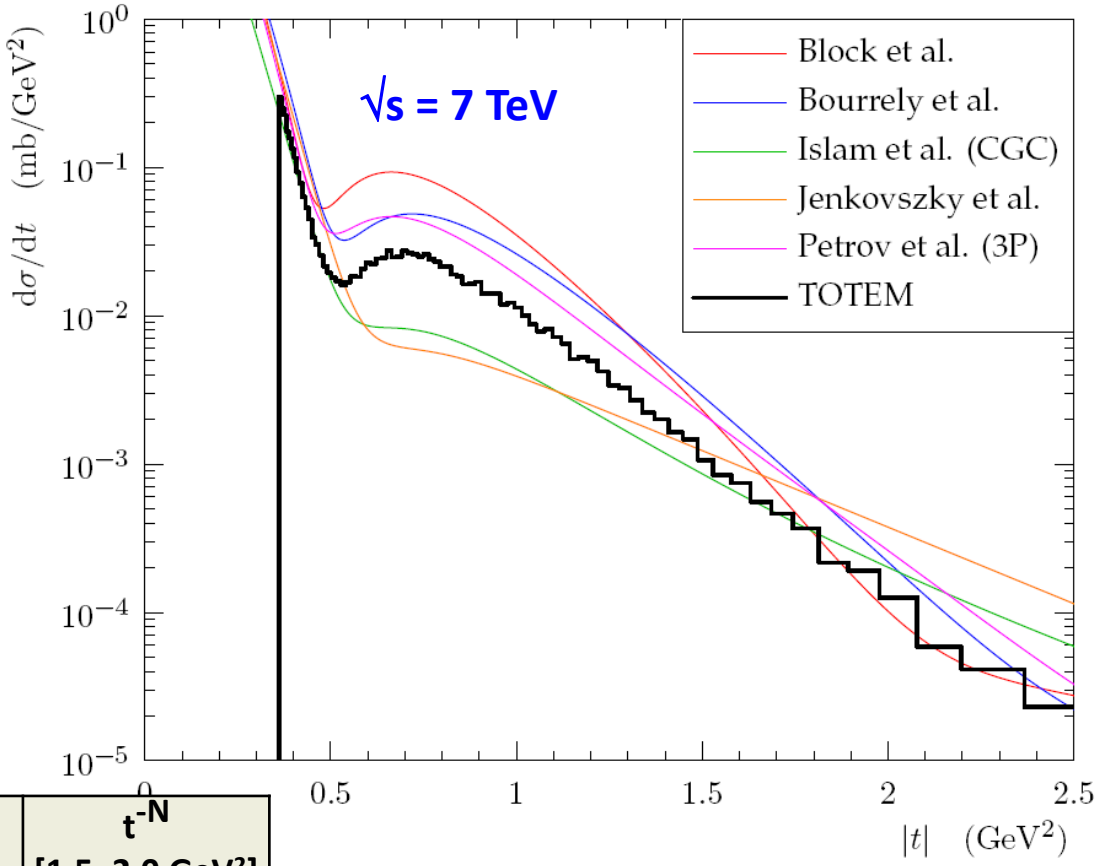


Proton-proton elastic scattering at the LHC energy of $\sqrt{s} = 7$ TeV

The TOTEM Collaboration

[EPL 95 (2011) 41001]

TOTEM Result + some models



	B (t=-0.4 GeV²) [GeV⁻²]	t_{DIP} [GeV²]	t^{-N} [1.5–2.0 GeV²] [N]
Islam	19.9	0.65	5.0
Jenkovsky	20.1	0.72	4.2
Petrov	22.7	0.52	7.0
Bourrely	21.7	0.54	8.4
Block	24.4	0.48	10.4
TOTEM	23.6 ± 0.5 ± 0.4	0.53 ± 0.01 ± 0.01	7.8 ± 0.3 ± 0.1

TOTAL, ELASTIC, INELASTIC CROSS-SECTIONS @ √s = 7 TeV

Cross-Section Formulae

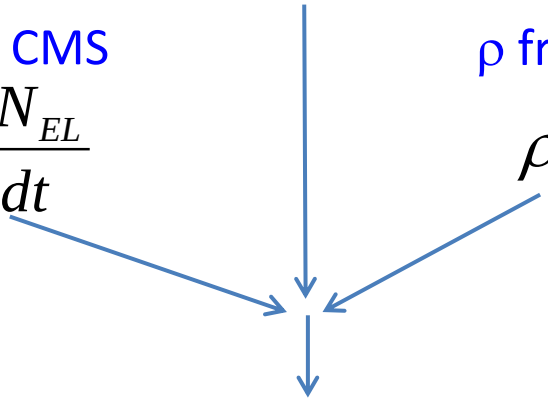
Optical Theorem: $$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

luminosity from CMS

$$\frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt}$$

ρ from COMPETE fit:

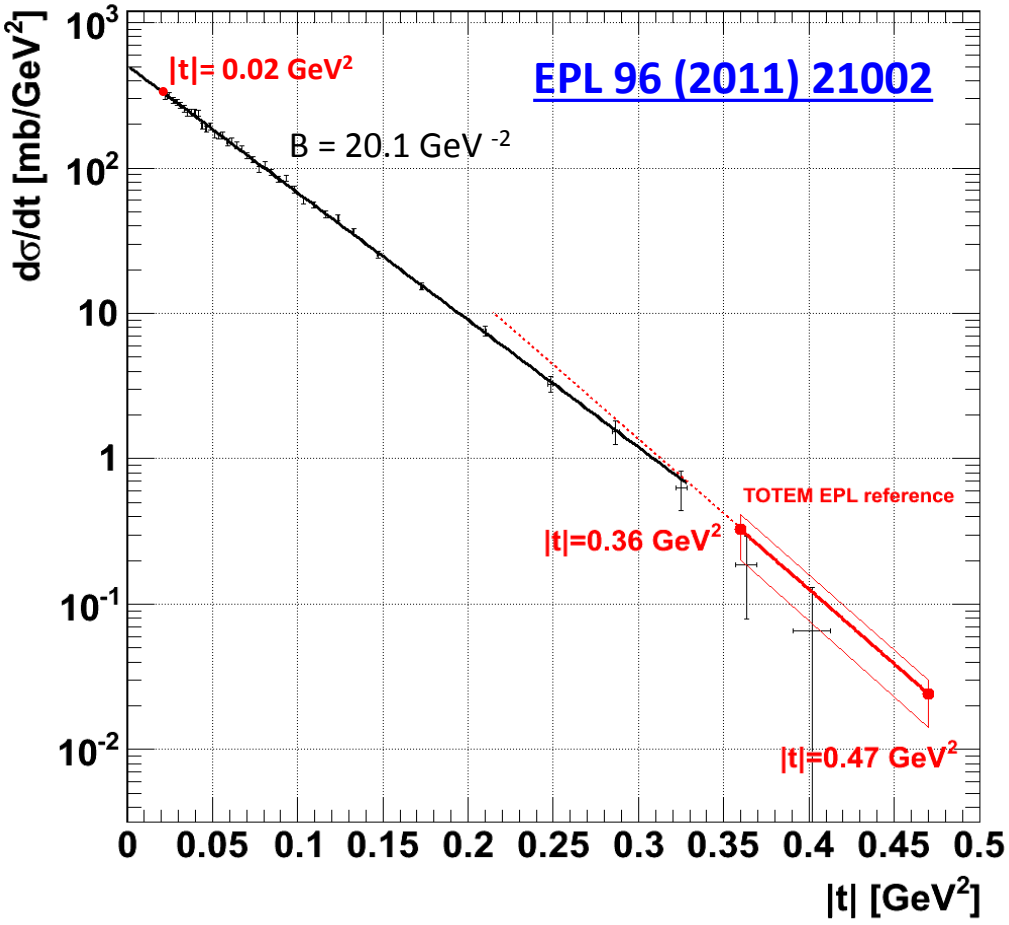
$$\rho = 0.14^{+0.01}_{-0.08}$$



$$\sigma_{TOT} = \sqrt{19.20\,\text{mb}\,\text{GeV}^2 \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}}$$

$$\sigma_{TOT} = \sigma_{EL} + \sigma_{INEL}$$

1st TOTEM low-t measurement



RP 10σ
Low luminosity: 1-2·10¹⁰ p/bunch
Integrated luminosity : 1.65 μb⁻¹
β*= 90 m

Exponential slope:

$$B\big|_{t=0} = 20.1\,\mathrm{GeV}^{-2}$$

Extrapolation to t = 0:

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = 5.037\times10^{2}\,\mathrm{mb}/\mathrm{GeV}^{2}$$

Integral Elastic Cross-Section

$$\sigma_{EL} = 8.3\,\mathrm{mb}^{(\mathrm{extrapol.})} + 16.5\,\mathrm{mb}^{(\mathrm{measured})} = 24.8\,\mathrm{mb}$$

1st pp Total Cross-Section

Elastic exponential slope: $B\big|_{t=0} = (20.1 \pm 0.2^{(stat)} \pm 0.3^{(syst)})\ \mathrm{GeV}^{-2}$

Elastic diff. cross-section at optical point: $\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = (503.7 \pm 1.5^{(stat)} \pm 26.7^{(syst)})\ \mathrm{mb/GeV}^2$

↓ Optical Theorem, $\rho = 0.14^{+0.01}_{-0.08}$

Total Cross-Section

$$\sigma_T = \left(98.3 \pm 0.2^{(stat)} \pm 2.7^{(syst)} \left\{^{+0.8}_{-0.2}\right\}^{(syst\ from\ \rho)}\right)\ \mathrm{mb}$$

1st pp Inelastic Cross-Section

$$\sigma_{el} = \left(24.8 \pm 0.2^{(stat)} \pm 1.2^{(syst)}\right) \text{ mb} \qquad \sigma_T = \left(98.3 \pm 0.2^{(stat)} \pm 2.7^{(syst)} \begin{bmatrix} +0.8 \\ -0.2 \end{bmatrix}^{(syst\ from\ \rho)}\right) \text{ mb}$$

Inelastic Cross-Section

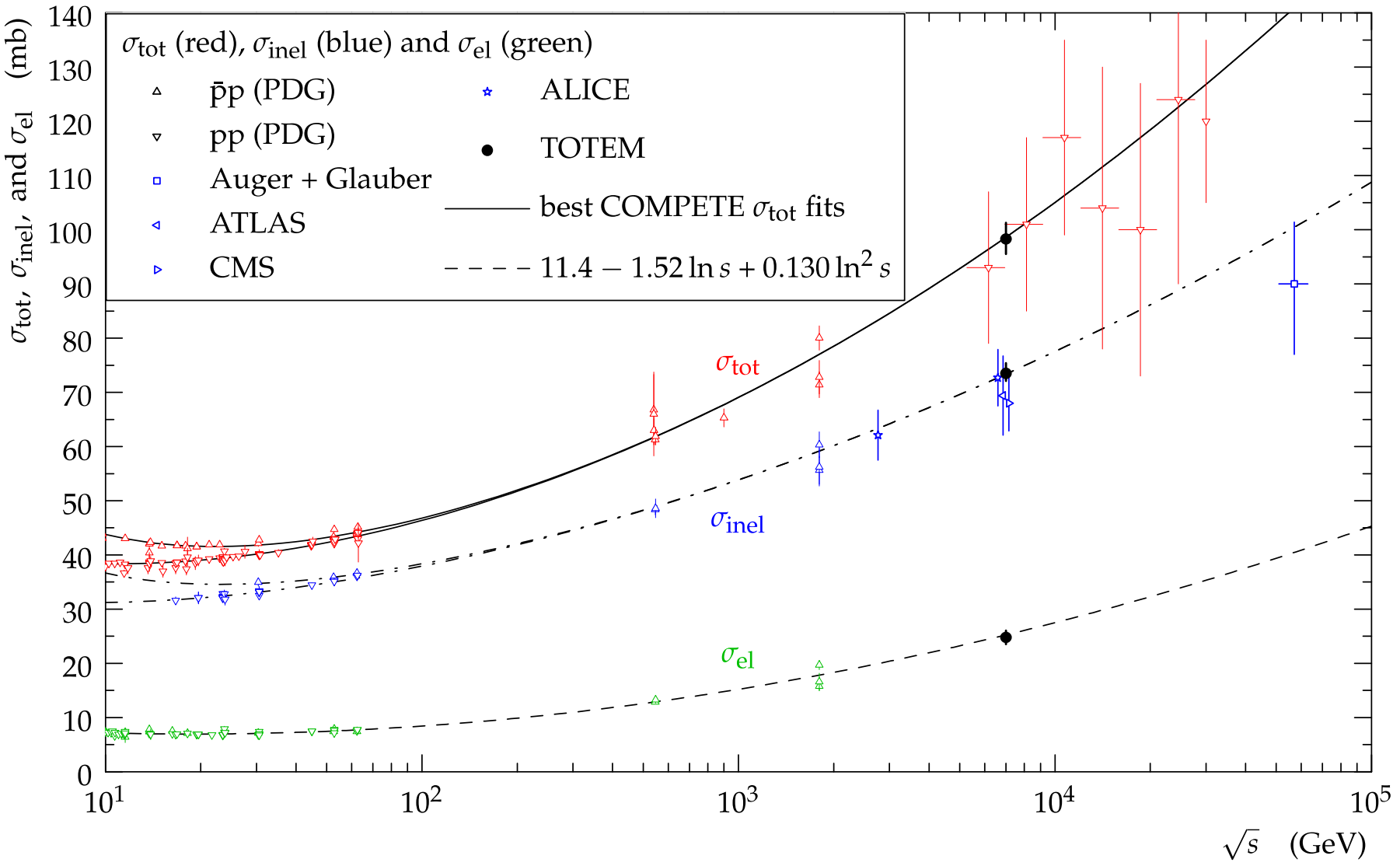
$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left(73.5 \pm 0.6^{(stat)} \begin{bmatrix} +1.8 \\ -1.3 \end{bmatrix} (syst)\right) \text{ mb}$$

σ_{inel} (CMS) $= (68.0 \pm 2.0^{(syst)} \pm 2.4^{(lumi)} \pm 4.0^{(extrap)})$ mb

σ_{inel} (ATLAS) $= (69.4 \pm 2.4^{(exp)} \pm 6.9^{(extrap)})$ mb

σ_{inel} (ALICE) $= (73.2^{+2.0}_{-4.6}{}^{(mod)} \pm 2.6^{(lumi)})$ mb

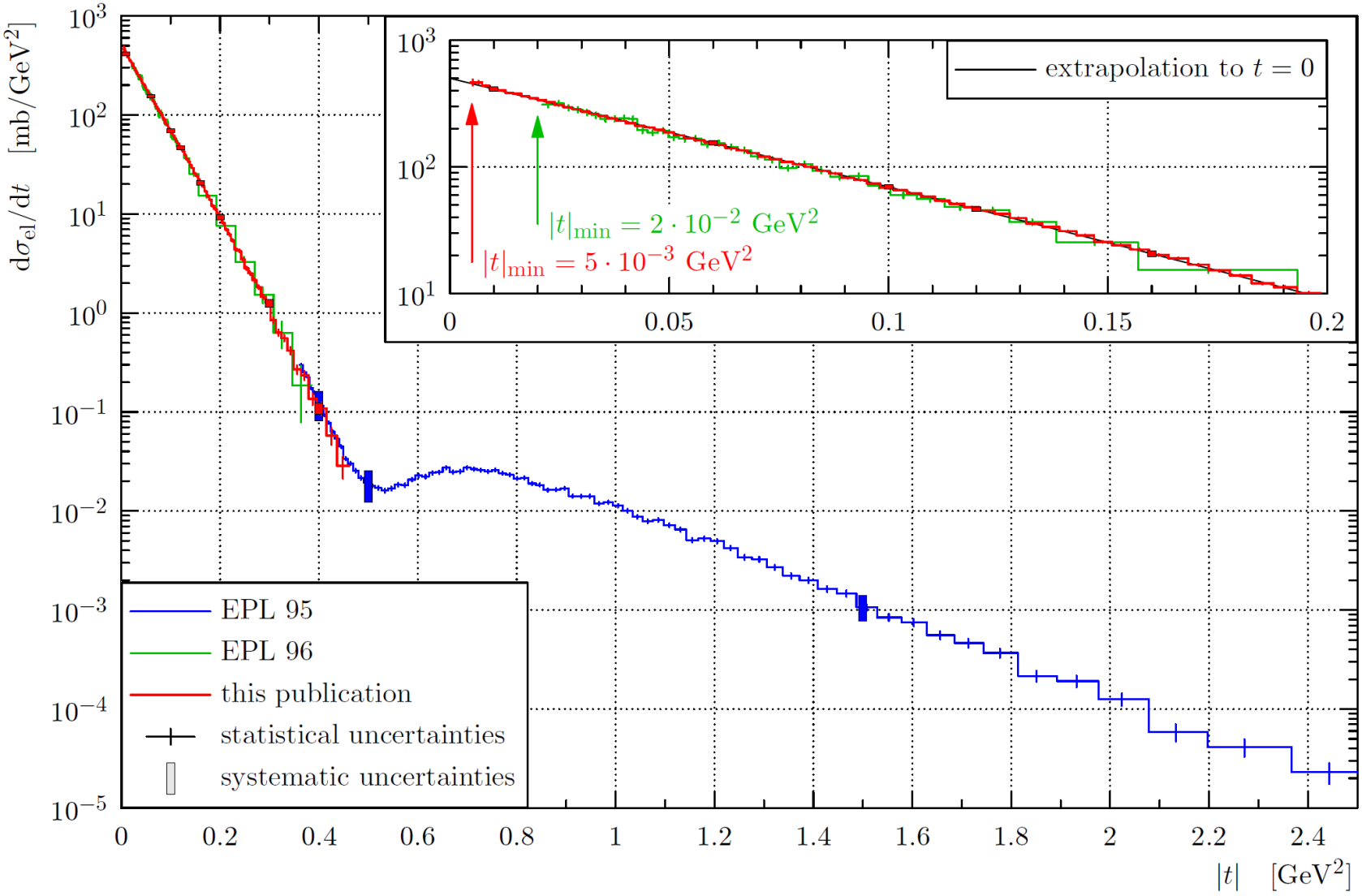
1st Total, Elastic, Inelastic Cross-Section



Subsequent pp Cross-Sections measurements
(& Luminosity calibration)

2. High luminosity (CMS) + Elastic + Optical T.
   - checks the CMS luminosity for high-L vs. low-L bunches
3. High luminosity (CMS) + Elastic + Inelastic
   - minimizes dependence on elastic efficiencies and no dependence on ρ
4. Luminosity-indep.: + Elastic + Inelastic + Optical T.
   - eliminates dependence on luminosity

2. October'11 data : RP 6.5/5.5/4.8σ ; L: bunches $7 \cdot 10^{10}$ p



$|t_{min}| \approx 5 \cdot 10^{-3}$ GeV^2 → 91% of cross-section measured (9% extrapolated) ; B = 19.9 ± 0.3 GeV^{-2}

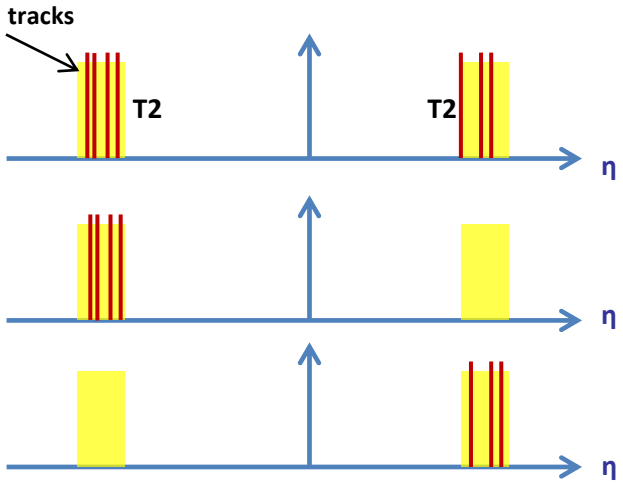
3. Inelastic Cross Section

direct T1 and T2 measurement

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)

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

3. 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 %**
  (estimated from zero bias data)
- Rapidity gap in T2 : **0.35 %**
  (estimated from T1 gap probability transferred to T2)
- Central Diffraction: T1 & T2 empty : **0.0 % ± 0.35 % syst**
  (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-4**,*
  imposing observed 2hemisphere/1hemisphere event ratio and the effect of 'secondaries')

Invisible Low Mass Diffraction constrained by Total cross-section measurement :
upper limit = 6.3 mb at 95% C.L. for $\eta \geq 6.5$, i.e. $M_{SD} \leq 3.4$ GeV

To be measured precisely with Roman Pots: single arm trigger, large β^* and clean beams

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

pp Total Cross-Sections @ √s=7TeV

Published EPL96

1. σ_{TOT} = 98.3 mb ± 2.8 mb

$$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

accepted EPL

2. σ_{TOT} = 98.6 mb ± 2.2 mb

$$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

accepted EPL *ρ - independent*

3. σ_{TOT} = 99.1 mb ± 4.3 mb

$$\sigma_{TOT} = \sigma_{EL} + \sigma_{INEL}$$

accepted EPL *L - independent*

4. σ_{TOT} = 98.0 mb ± 2.5 mb

$$\sigma_{TOT} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\left.\frac{dN_{EL}}{dt}\right|_{t=0}}{N_{EL}+N_{INEL}}$$

LUMINOSITY INDEPENDENT CROSS-SECTIONS @ √s = 8 TeV

July 2012 $\sqrt{s}$ = 8 TeV β^* = 90m

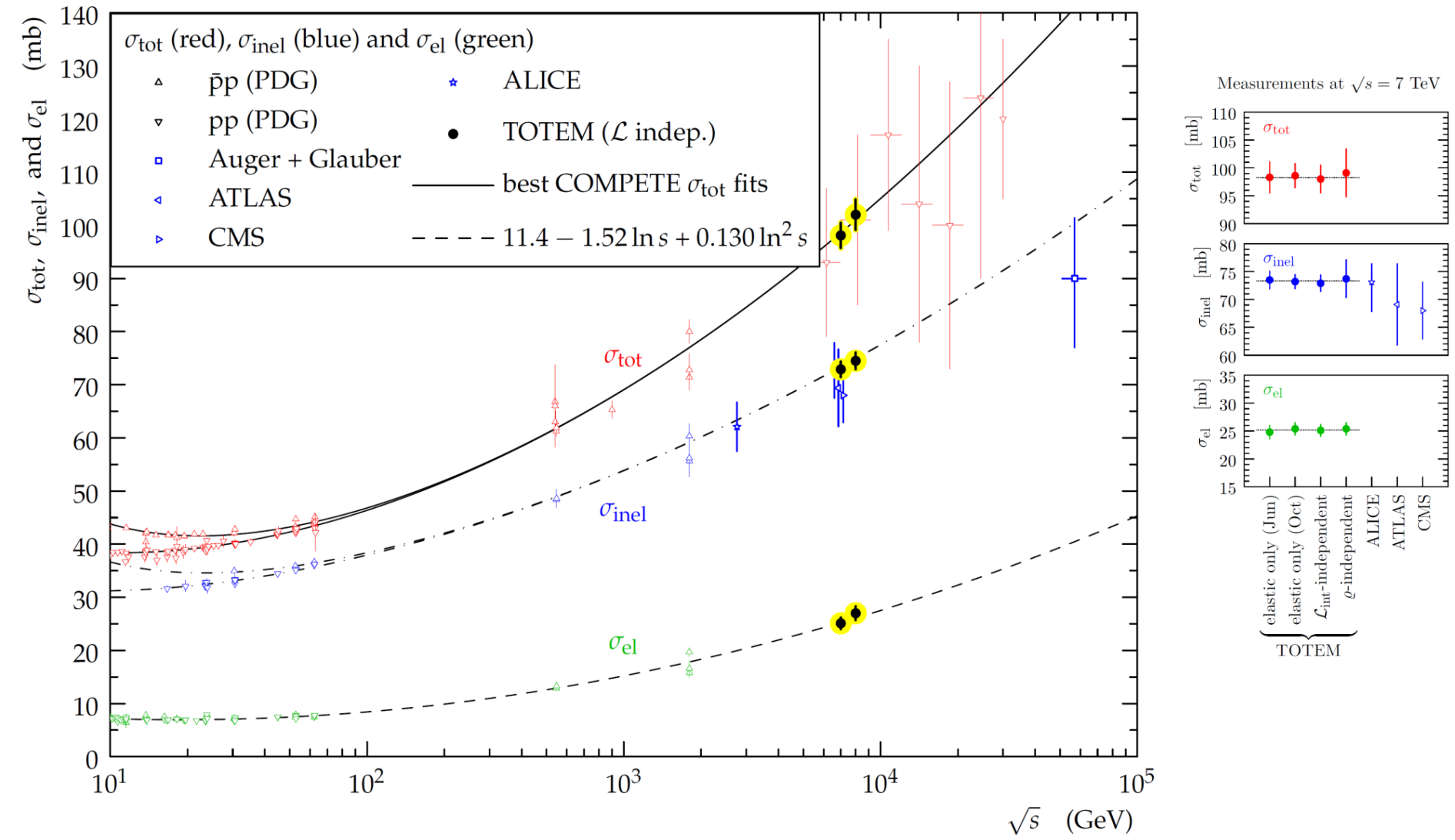
Two data samples triggered by TOTEM RPs pp coincidences

Luminosity-independent Elastic, Inelastic, Total Cross-Sections:

DS	σ_{tot} (mb)	σ_{el} (mb)	σ_{inel} (mb)
2	102 ± 2.8	27.1 ± 1.3	74.9 ± 1.6
3	101 ± 2.8	26.9 ± 1.3	74.2 ± 1.6

Submitted to PRL

CERN preprint: CERN-PH-EP-2012-354


σ_{tot} (red), σ_{inel} (blue) and σ_{el} (green)
$\bar{p}p$ (PDG)
pp (PDG)
Auger + Glauber
ATLAS
CMS
ALICE
TOTEM ($\mathcal{L}$ indep.)
best COMPETE σ_{tot} fits
$11.4 - 1.52 \ln s + 0.130 \ln^2 s$
σ_{tot}, σ_{inel}, and σ_{el} (mb)
$\sqrt{s}$ (GeV)
σ_{tot}
σ_{inel}
σ_{el}
Measurements at $\sqrt{s} = 7$ TeV
elastic only (Jun)
elastic only (Oct)
$\mathcal{L}_{int}$-independent
ϱ-independent
TOTEM
ALICE
ATLAS
CMS

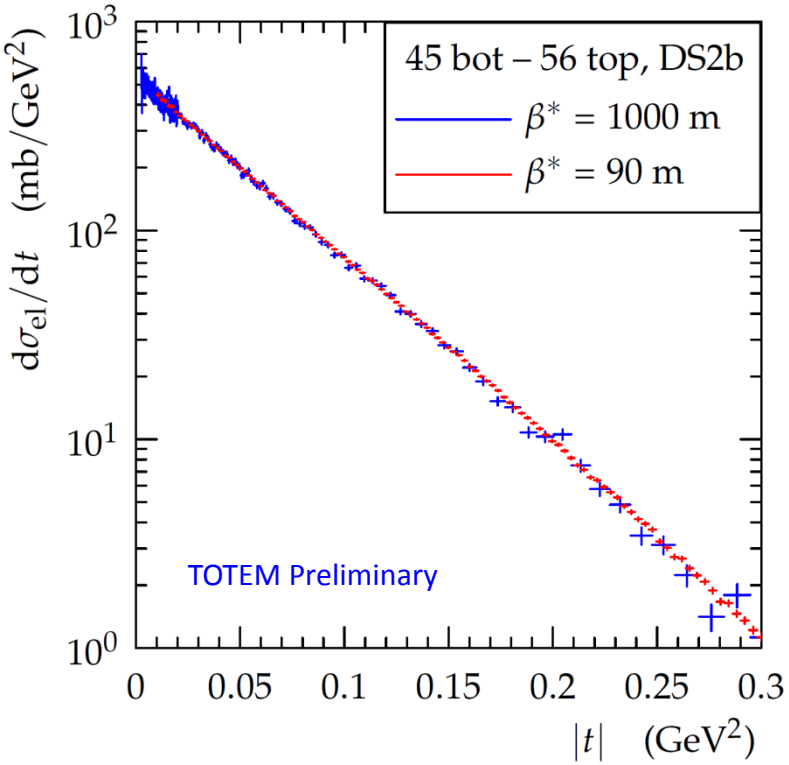
First Coulomb interference region measurement

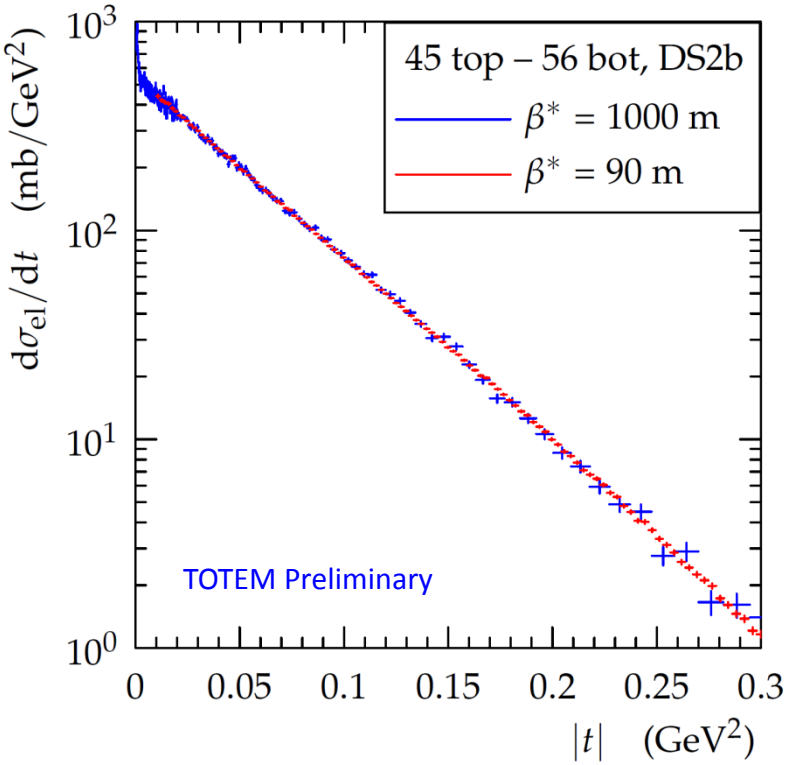
sqrt s = 8 TeV, β^* = 1000m

Luminosity calibration with luminosity independent total cross-section @ β^*=90m,
integration region: 0.01 GeV^2 < |t| < 0.3 GeV^2

L_{int} = 5.73 + 14.45 μb^{-1} = 20.18 μb^{-1}

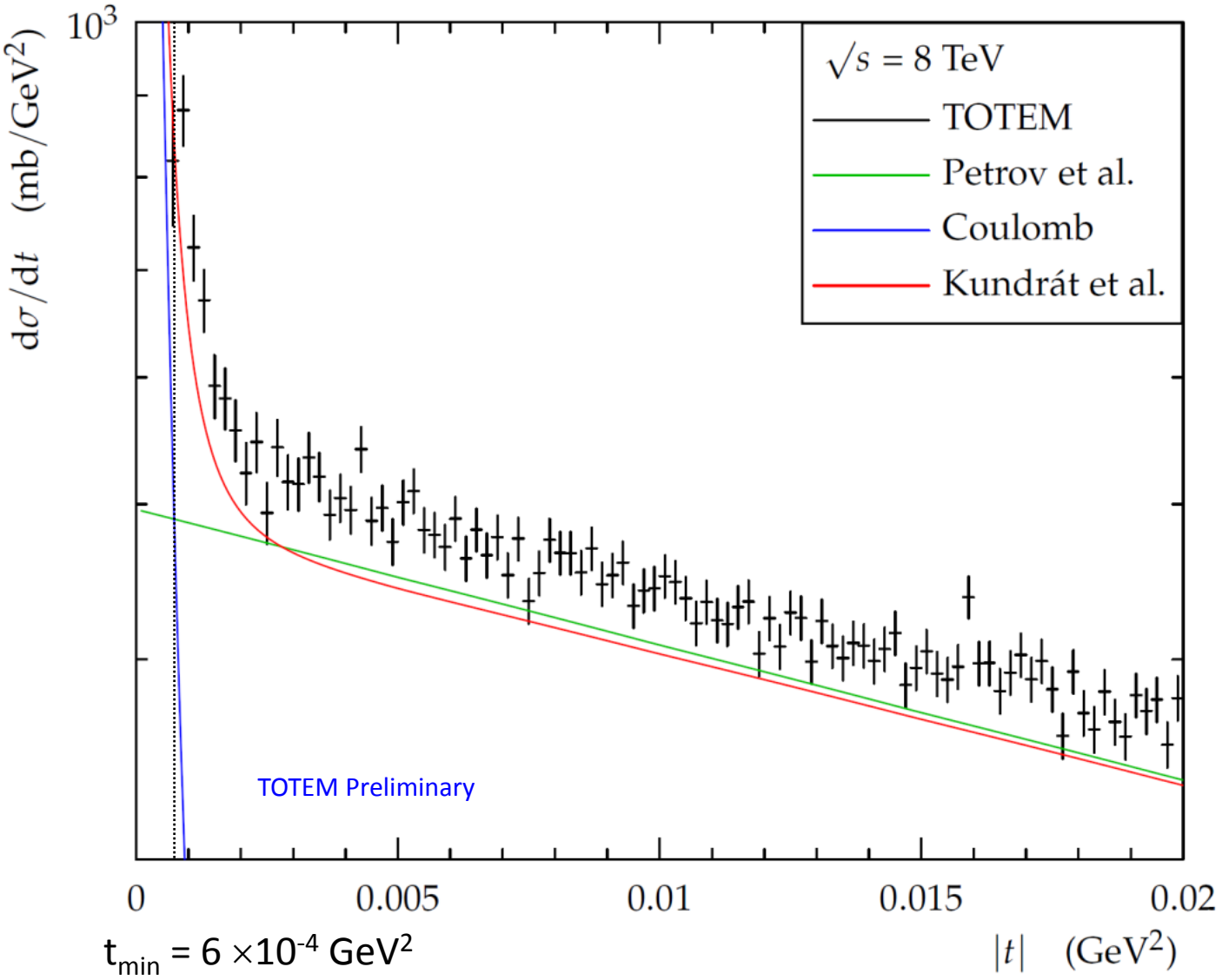
t_{min} = 6 $\times 10^{-4}$ GeV^2





First Coulomb interference region measurement

sqrt s = 8 TeV, β^* = 1000m



$t_{min} = 6 \times 10^{-4}$ GeV^2

FORWARD AND DIFFRACTIVE PHYSICS

pp Interactions

Non-diffractive

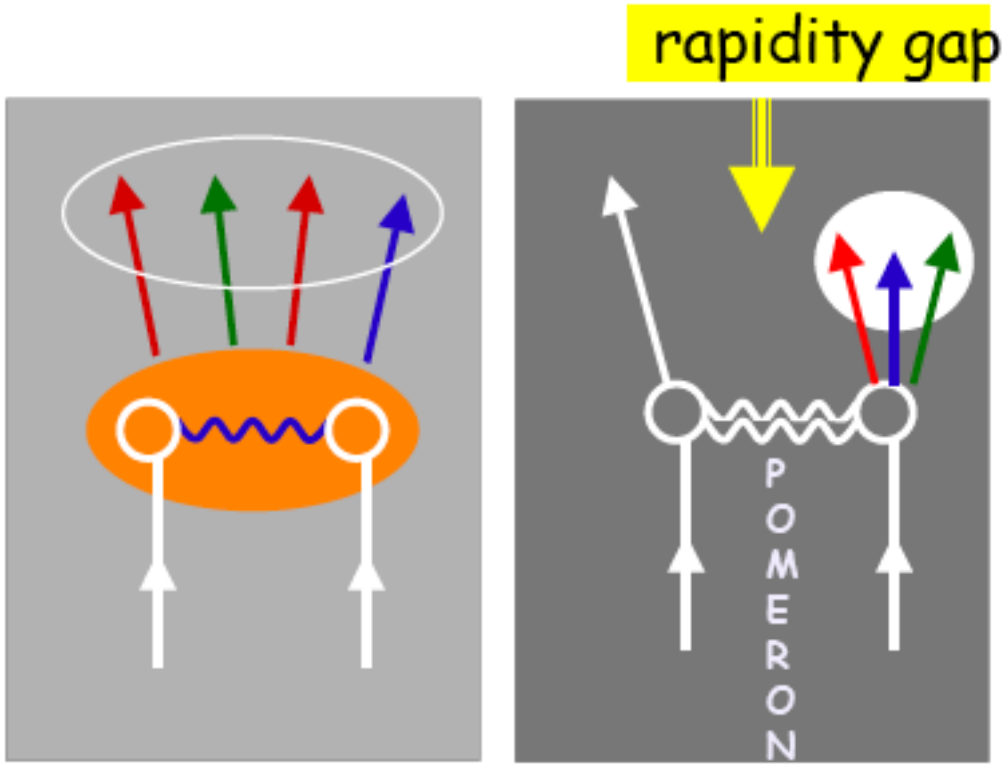
Colour exchange

$dN / d\Delta\eta = \exp(-\Delta\eta)$

Diffractive

Colourless exchange with vacuum quantum numbers

$dN / d\Delta\eta = \text{const}$



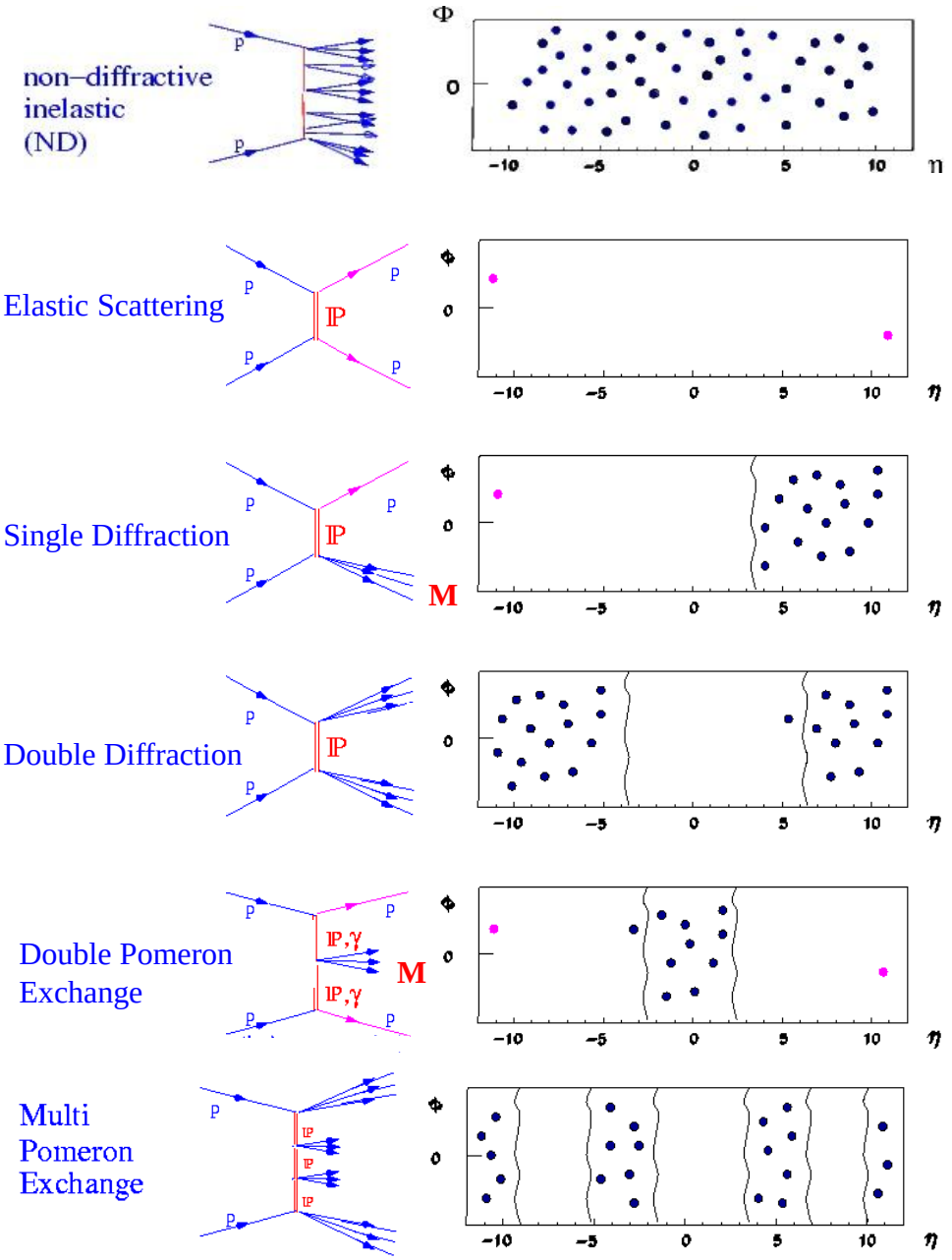
Incident hadrons acquire colour and break apart

Incident hadrons retain their quantum numbers remaining colourless

GOAL: understand the QCD nature of the diffractive exchange

Inelastic and Diffractive Processes ($\eta = -\ln \tan \theta/2$)

All the drawings show soft interactions.
In case of hard interactions there should be jets,
which fall in the same rapidity intervals.



~60 mb

~25 mb

~10 mb

~5 mb

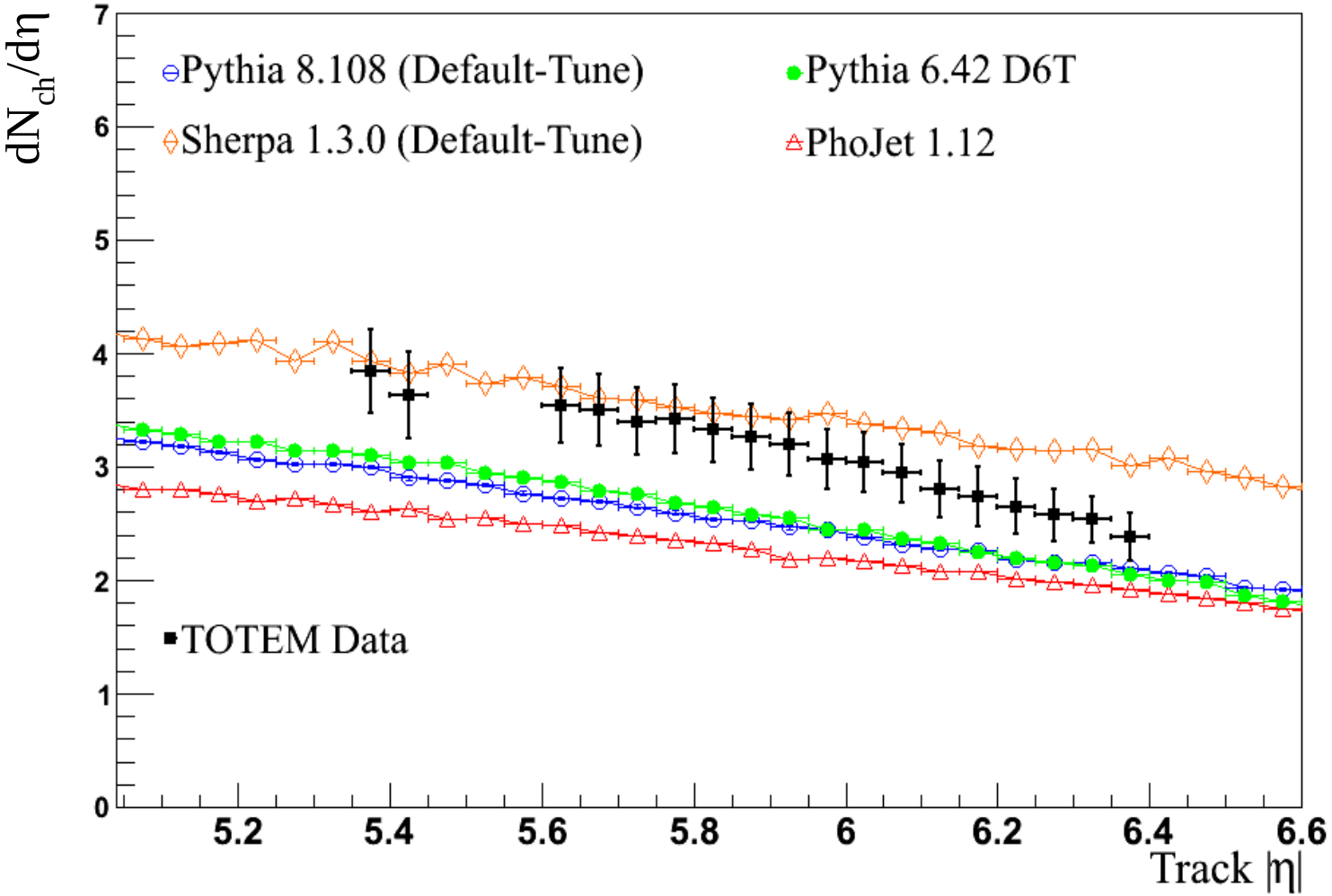
~1 mb

<< 1 mb

Measure σ (M,ξ,t)

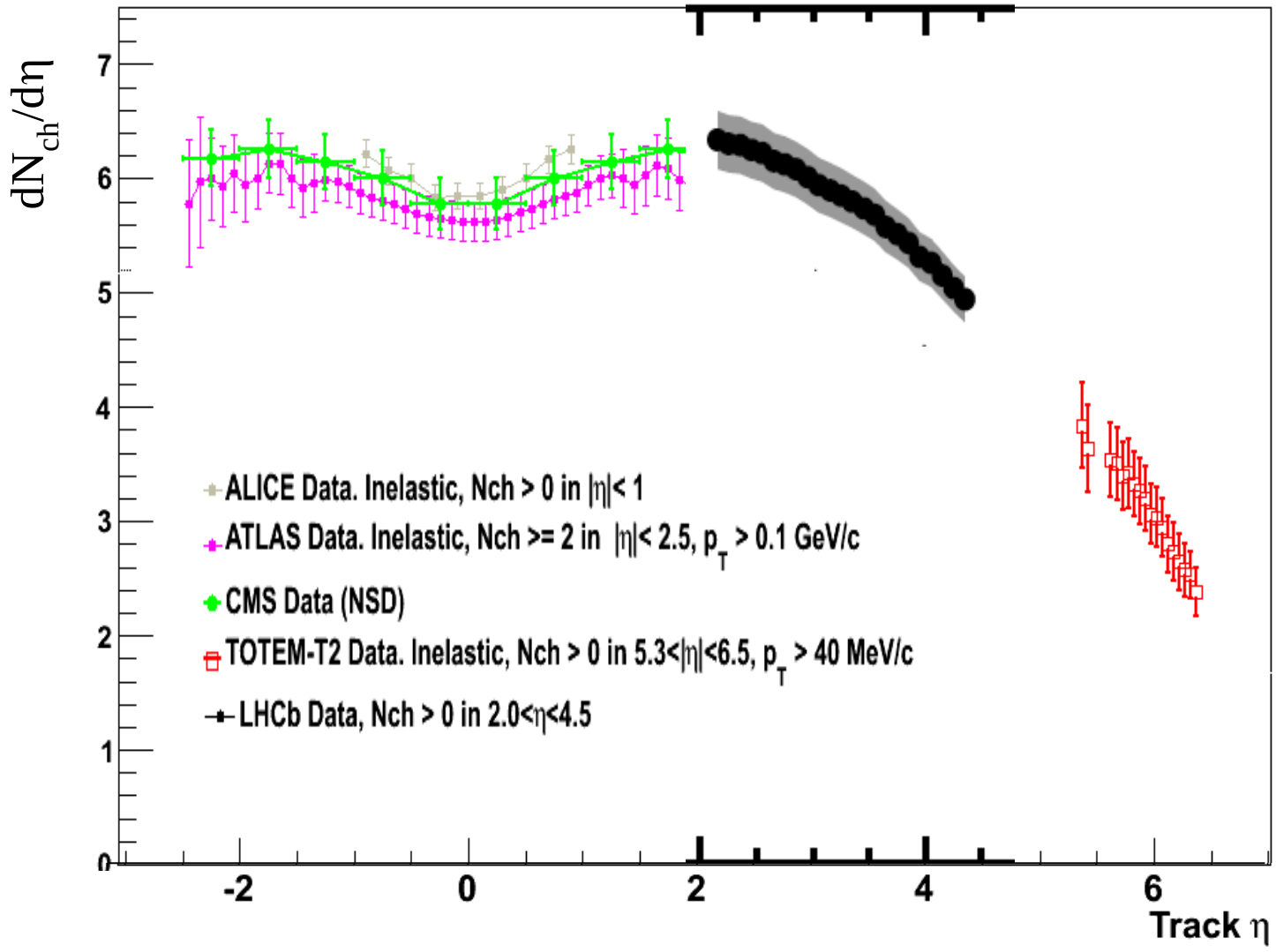
Diffractive scattering is a unique laboratory of confinement & QCD:
A hard scale + hadrons which remain intact in the scattering process.

$dN_{ch}/d\eta$ measured in T2, sqrt s = 7 TeV



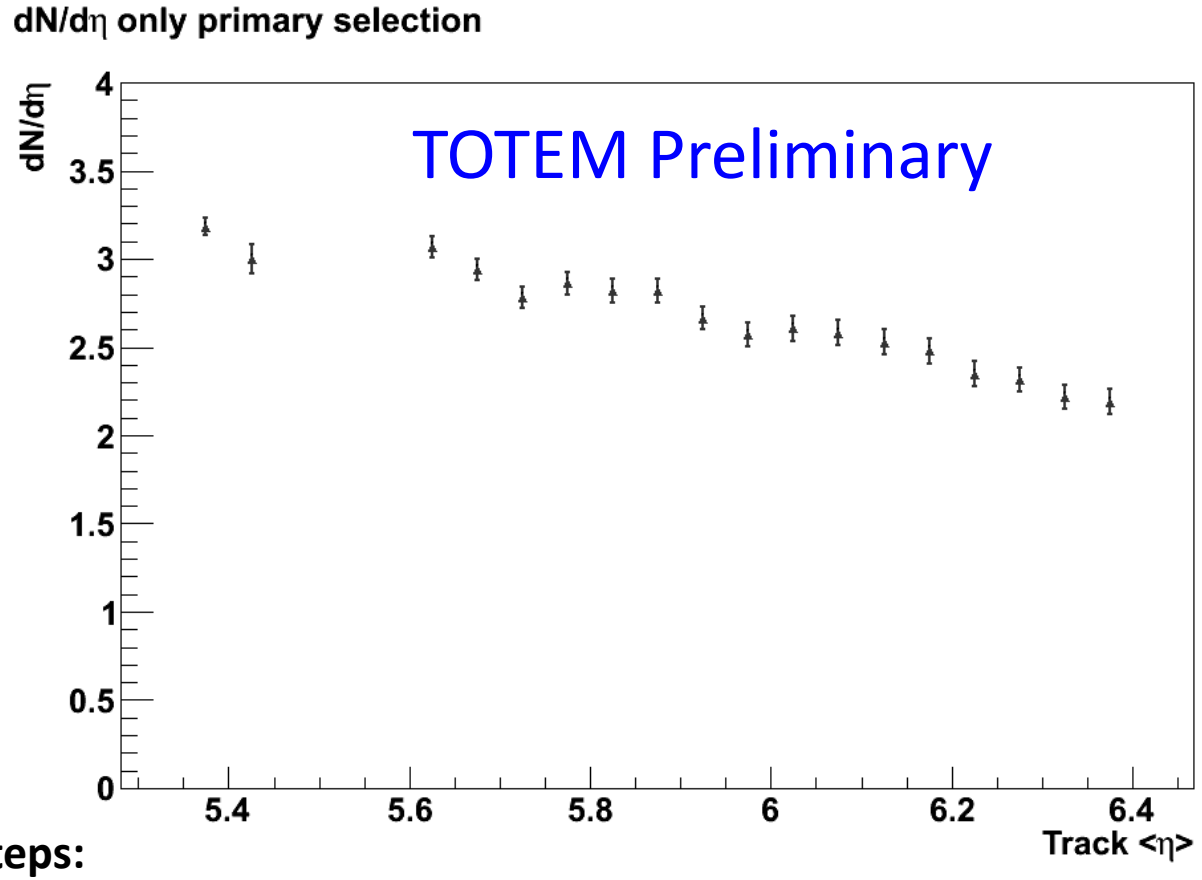
Published **EPL, 98 (2012) 31002**

$dN_{ch}/d\eta$ combined with other LHC exp.



Ongoing activities within ***LPCC*** framework

First common CMS-TOTEM analysis
$dN_{ch}/d\eta$ @ 8 TeV



Further steps:

Error estimation

Primary track selection efficiencies and errors

Correction factors: high multiplicity events, trigger, pileup

Diffractive forward protons @ RPs

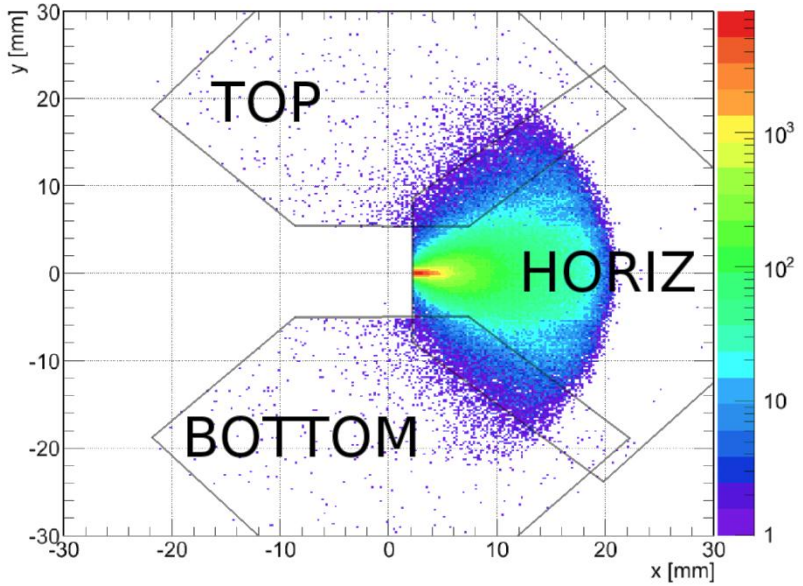
$$y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^*$$
$$x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot \boxed{D(s)}$$

ξ=Δp/p

Dispersion shifts diffractive protons in the horizontal direction

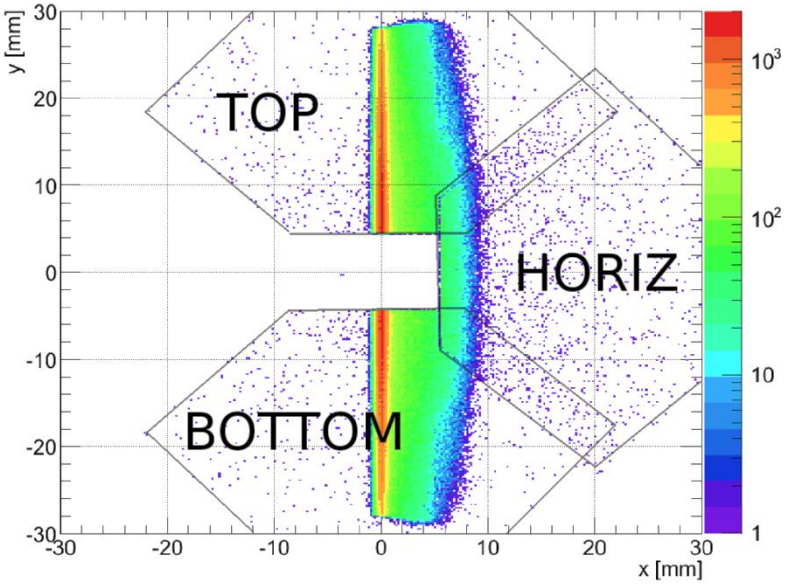
Generally $v_{x,y}$, $L_{x,y}$ and D_x are functions of ξ → reconstruction is a non-linear problem

Low β*: 0.5 – 2 m, ξ>2%



- L_x, L_y are low, protons shifted due to ξ
- vertex not critical: small IP beam size

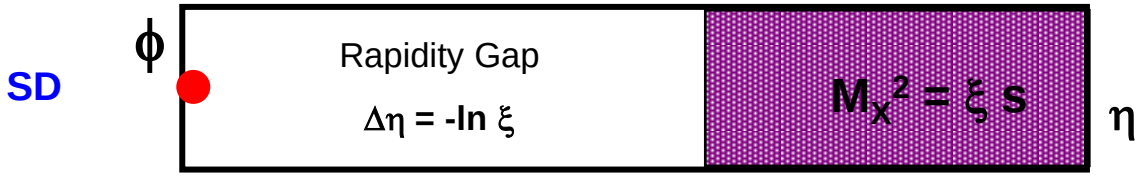
β*= 90 m, complete ξ-coverage due to t

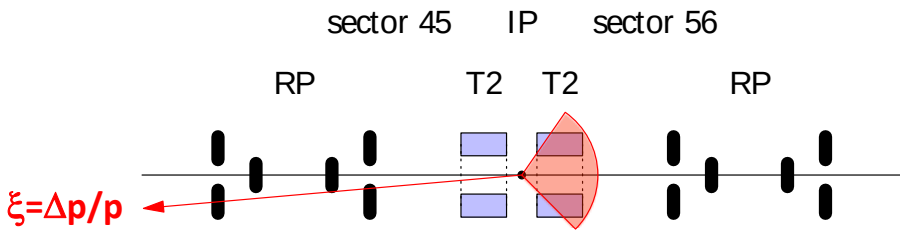


- L_x=0, L_y is large
- large beam σ = 212 μm → v_x, v_y important (deterioration of ξ-resolution)
- vertex from CMS improves ξ-resolution

Single diffraction low ξ

Correlation between leading proton and forward detector T2

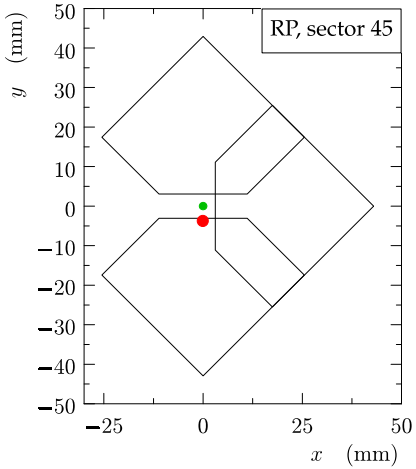


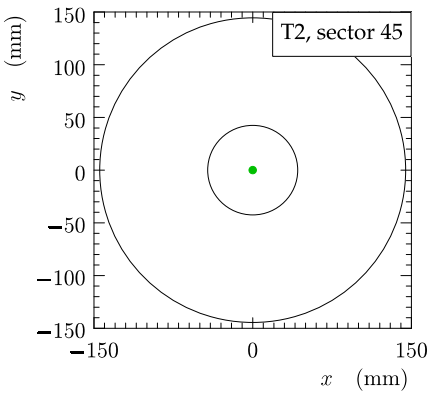


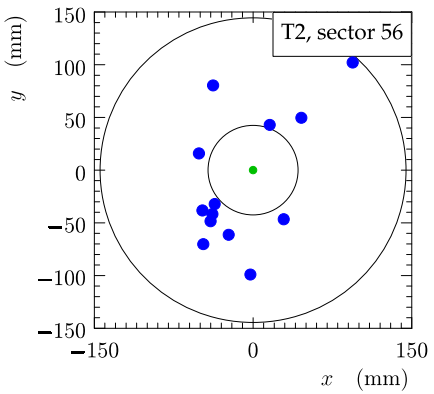
$5\times10^{-7}<\xi<3\%$, large rapidity gap

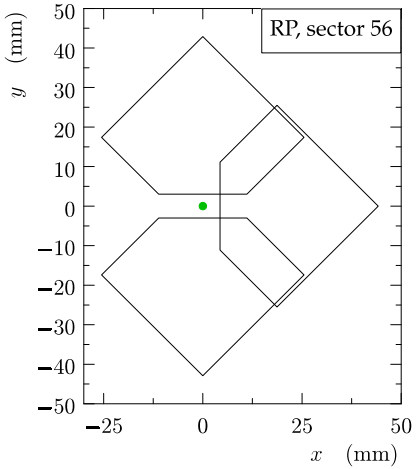
T2 forbidden on proton's side

run: 37280003, event: 3000



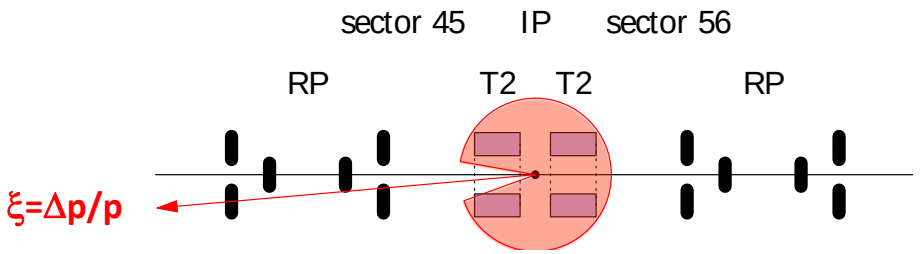






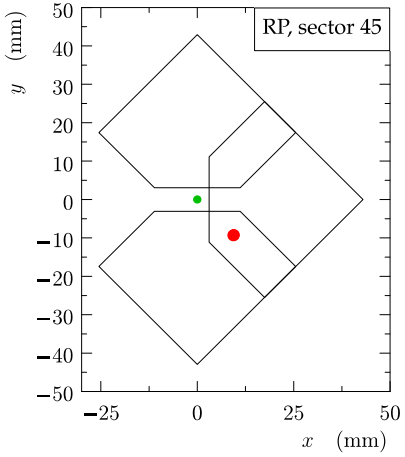
Single diffraction large ξ

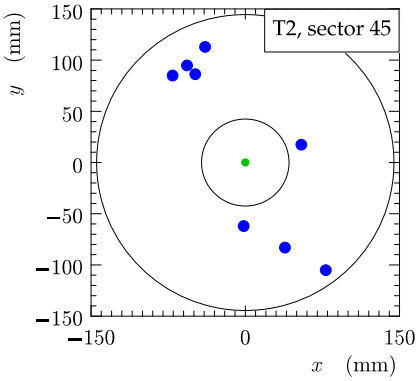
correlation between leading proton and forward detector T2

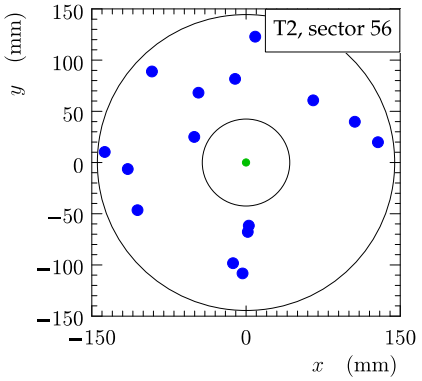


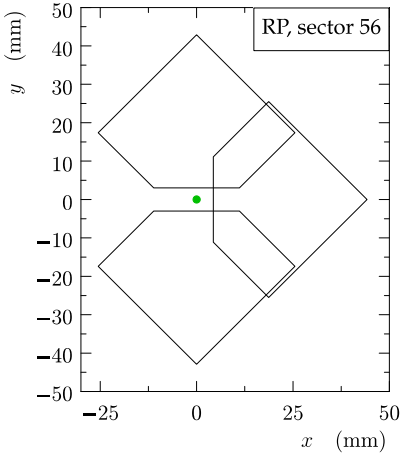
ξ>10%, small rapidity gap
T2 full

run: 37280006, event: 9522





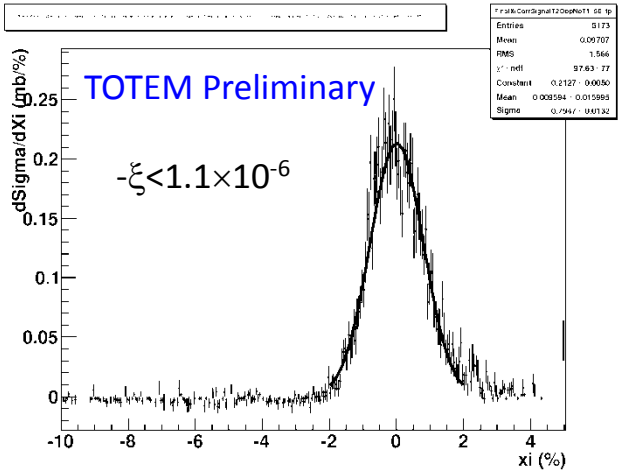


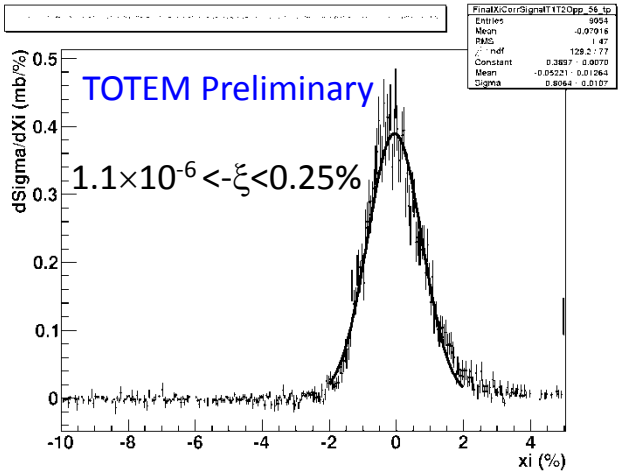


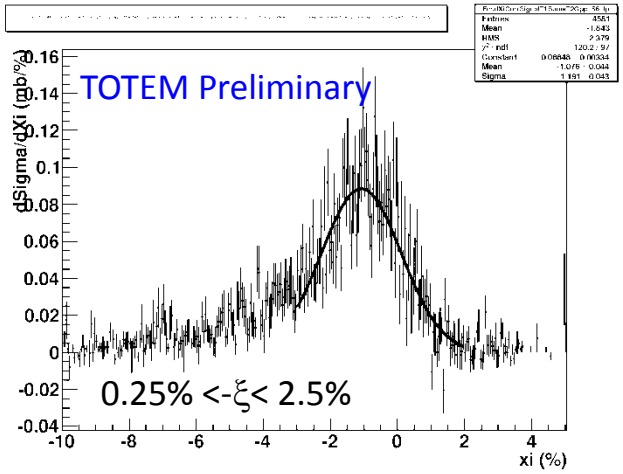
Soft SD cross-section

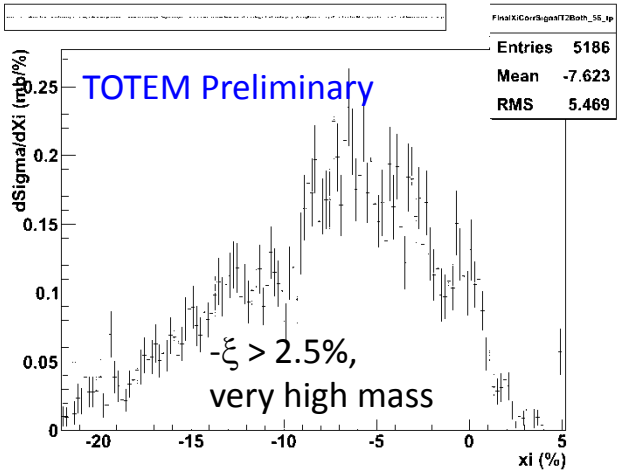
Data sample: β*=90m, October 2011, RP @ 4.8, 5.5 and 6.5 σ

Rapidity gap based ξ-classification (T1, T2)





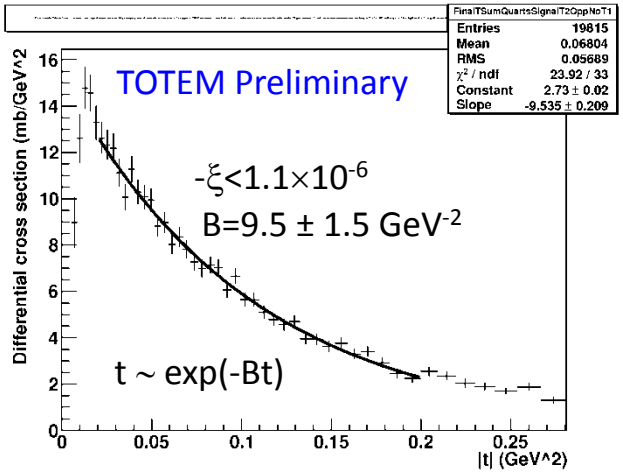


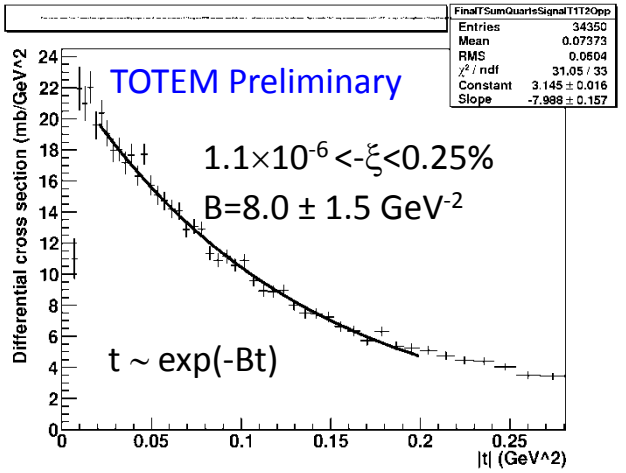


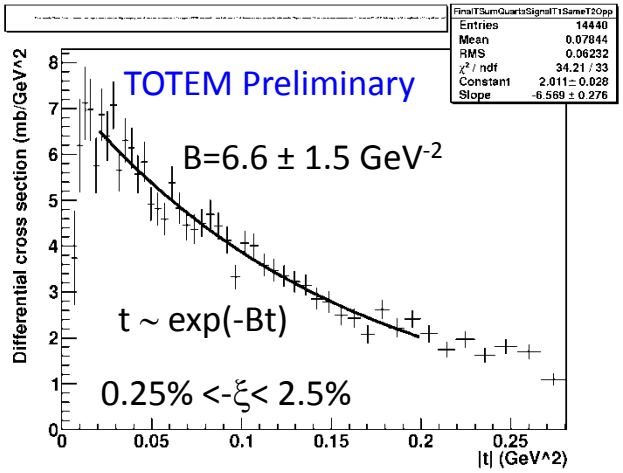
Soft SD cross-section, dσ/dt

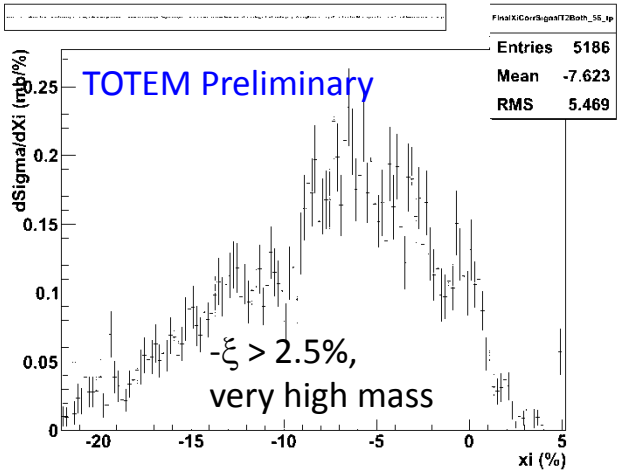
Data sample: β*=90m, October 2011, RP @ 4.8, 5.5 and 6.5 σ

t-distributions, rapidity gap based ξ-classification

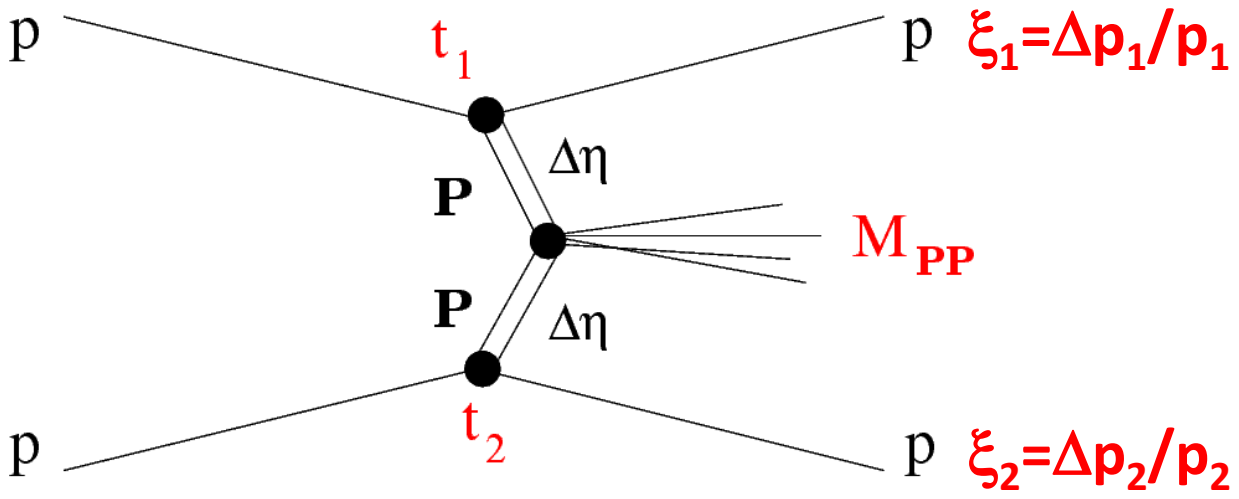


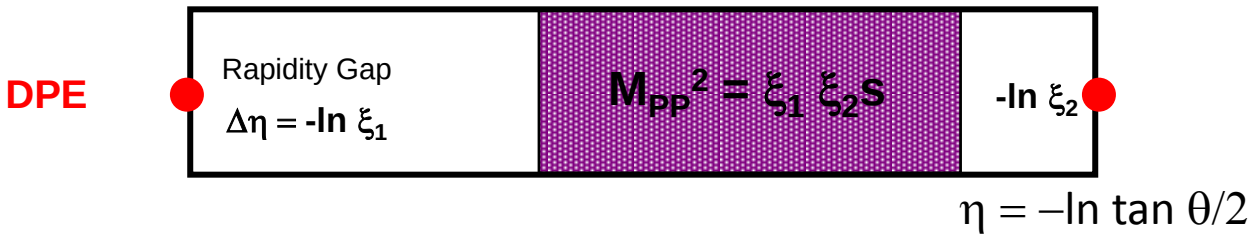






Double Pomeron Exchange (DPE) (or Central Diffraction)

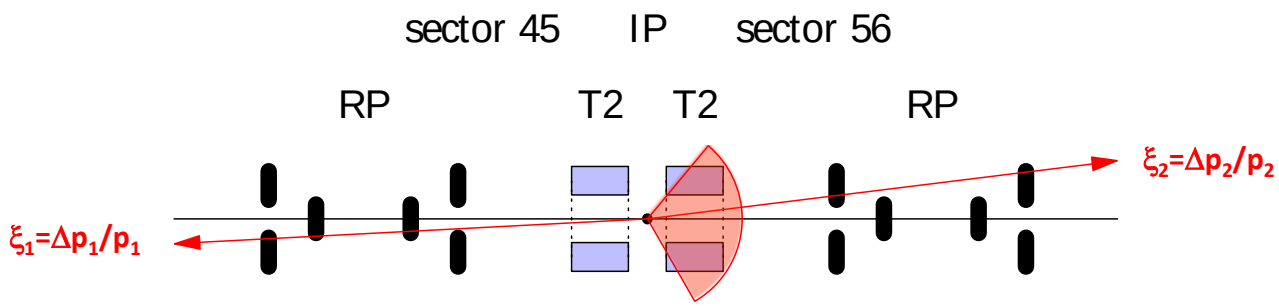




LHC as a Pomeron-Pomeron (gluon–gluon) collider

Double Pomeron Exchange (DPE)

correlation between leading protons and forward detector T2



low ξ

$5\times10^{-7}<\xi_1<3\%$, large rapidity gap

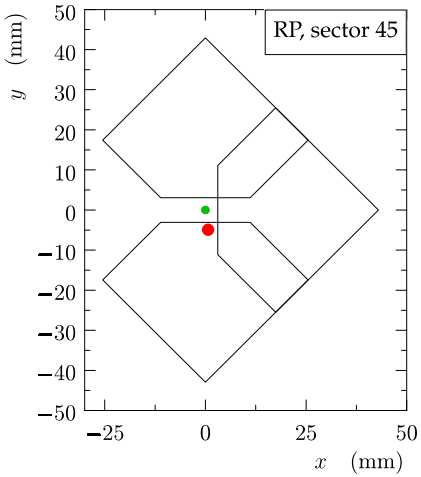
T2 forbidden on left side

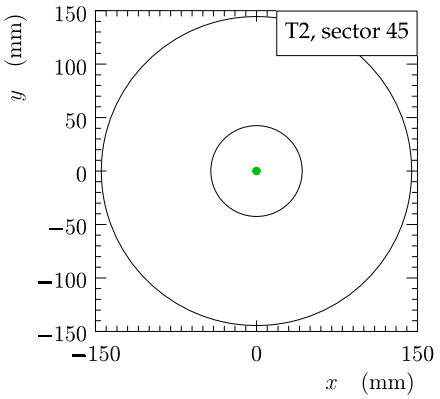
high ξ

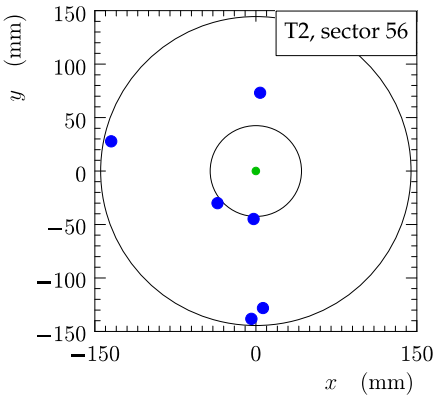
$\xi_2>10\%$, small rapidity gap

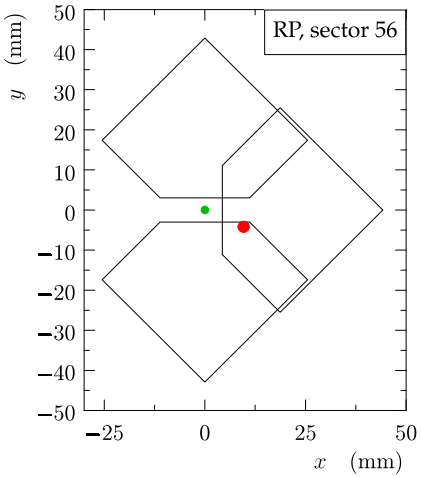
T2 full

run: 37220007, event: 9904









Soft Double Pomeron Exchange

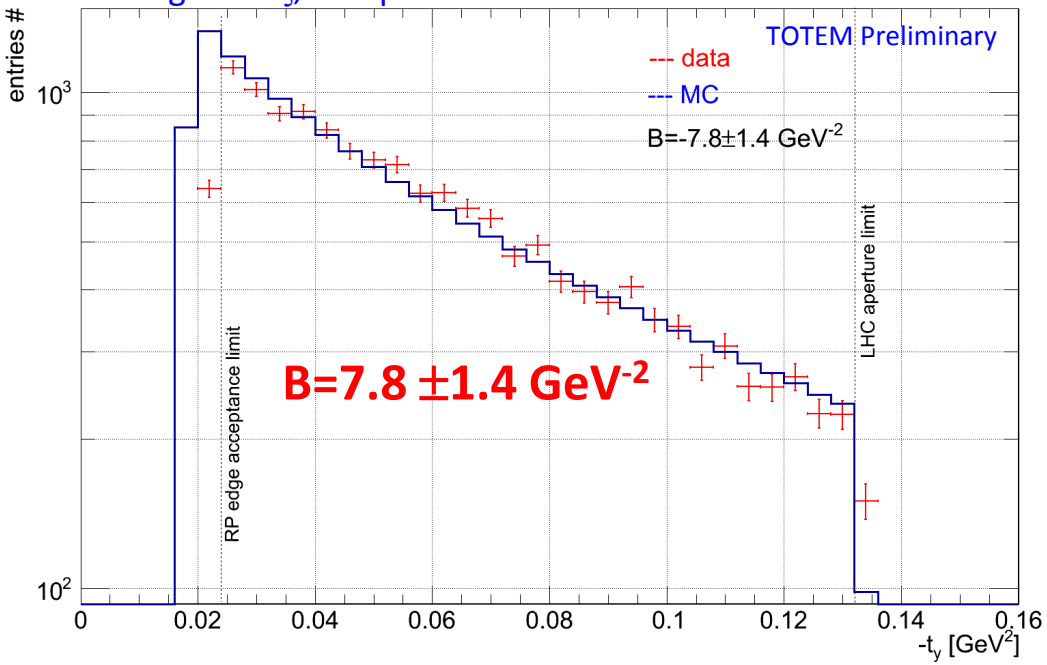
TOTEM alone, 20.10.2011 data

$\beta^* = 90$m optics runs:

- $y < 11\sigma$ removed : protection against pile-up
  - beam halo × beam halo
  - beam halo × elastic proton
- DPE protons of $-t > 0.02\text{GeV}^2$ detected by RP
- nearly complete ξ-acceptance

Single arm DPE event rate in RP

integrated ξ, acceptance corrected

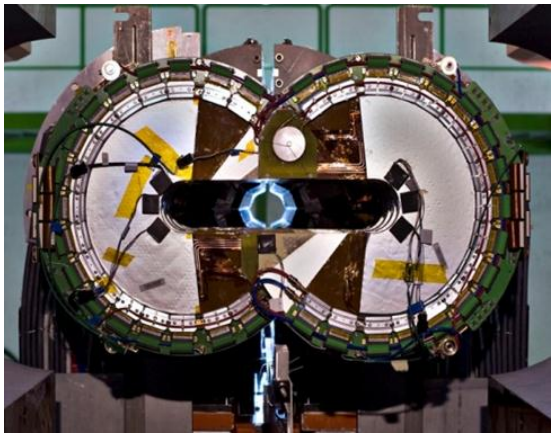


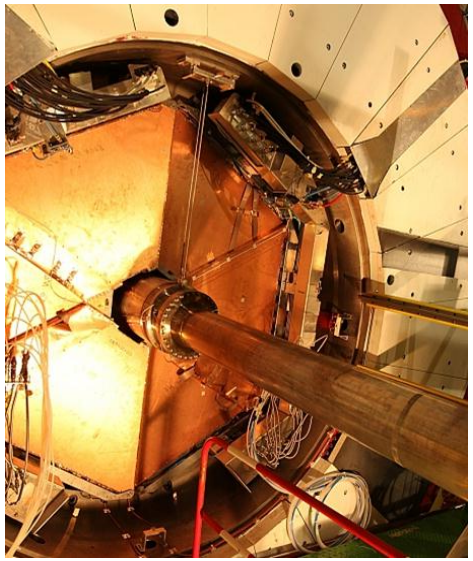
σ_{DPE} estimation:

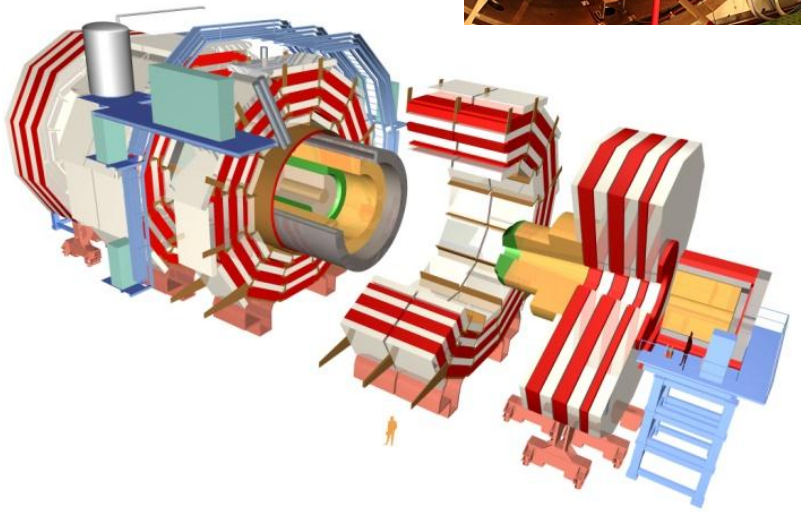
$$\frac{d^2\sigma_{DPE}}{dt_1 dt_2} = C(\Delta\varphi_{1,2})e^{-Bt_1}e^{-Bt_2} - \text{backgr.}$$

$$\sigma_{DPE} = \int_0^\infty dt_1 \int_0^\infty dt_2 \frac{d^2\sigma_{DPE}}{dt_1 dt_2} \approx 1\text{mb}$$

TOTEM + CMS :







Diffractive physics

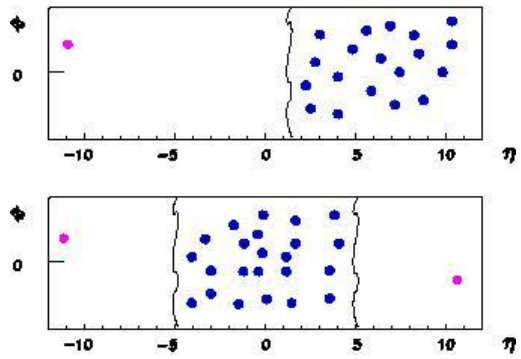
DPE, SD, di-jets…

TOTEM + CMS common data taking

- July 2012 – first pp common data taking, ~11h, β^*=90m, 43nb^{-1}
  2 years before expected

- Important:
  - 2-arm proton reconstruction, $\xi_{1,2}=\Delta p_{1,2}/p_{1,2}$ (never before)
  - Prediction of mass to be seen in CMS from reconstructed protons:
    $M^2 = s\cdot\xi_1\xi_2$
  - Initial vs. final state comparison: M_{TOTEM} =? M_{CMS} (never before)
  - Prediction of central particle flow topology from leading protons (rapidity gaps) : $\Delta\eta_{1,2} = -\ln\xi_{1,2}$
  - Large η-coverage:
    - CMS: $-5.5<\eta<5.5$
    - T1: $3.1 < |\eta| < 4.7$
    - T2: $5.3 < |\eta| < 6.5$
    - FSC: $6 < |\eta| < 8$
  - Sqrt s = 8 TeV $\rightarrow$ up to M_X=1.8 TeV with pp survival (never before)

More data welcome !!

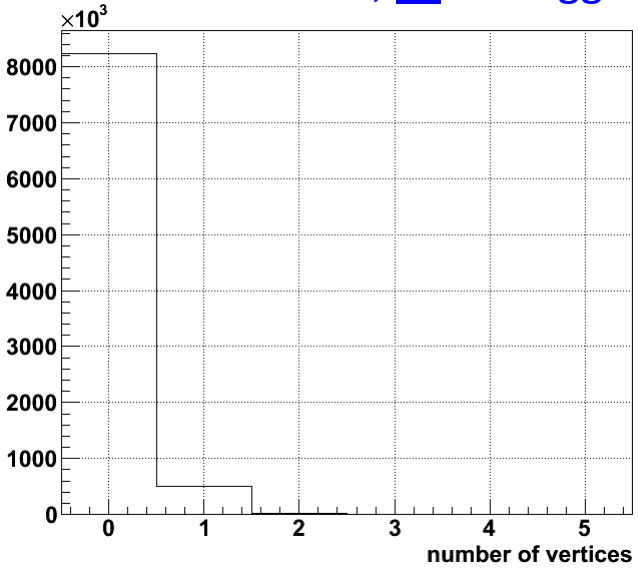


TOTEM + CMS : SOFT DPE

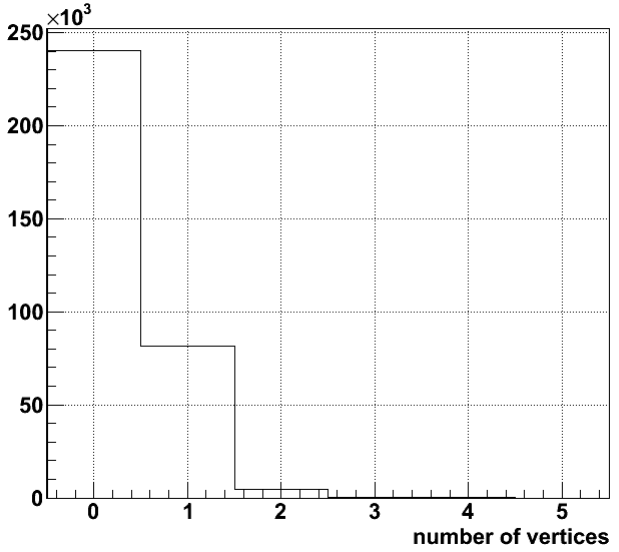
Soft DPE in CMS-TOTEM runs

- 11.5h, β^*=90m, ~7×10^{10} protons per bunch
- RP45×RP56 trigger: 8'759'611 events (2–3 bx)
  - int. lumi. ≈ 0.8 nb^{-1}
  - inealistic proton pair tagging: 327'116 DPE candidates
  - inelastic + well defined CMS vertex: 47'730
  - elastic candidates: 7'127'722 (elastic topology + no top-bot pile-up)
- $RP_{\text{inelastic trigger}}/T2_{\text{trigger}} = 0.5\% \approx \sigma_{DPE}/\sigma_{\text{Min.Bias}}$ (as predicted)

Vertices number, all RP triggers



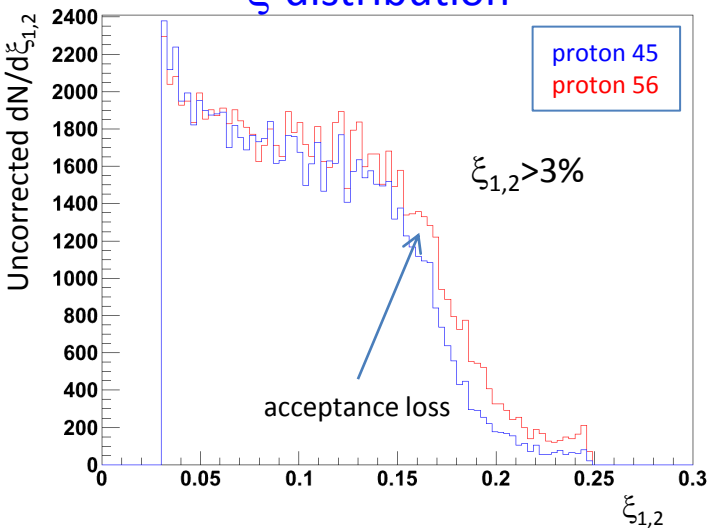
Vertices number, RP inelastic candidates



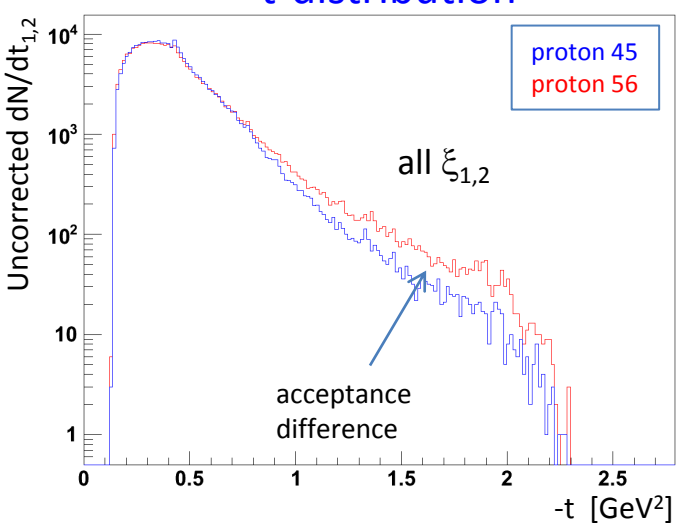
Differential DPE distributions (uncorrected)

RP reconstruction alone

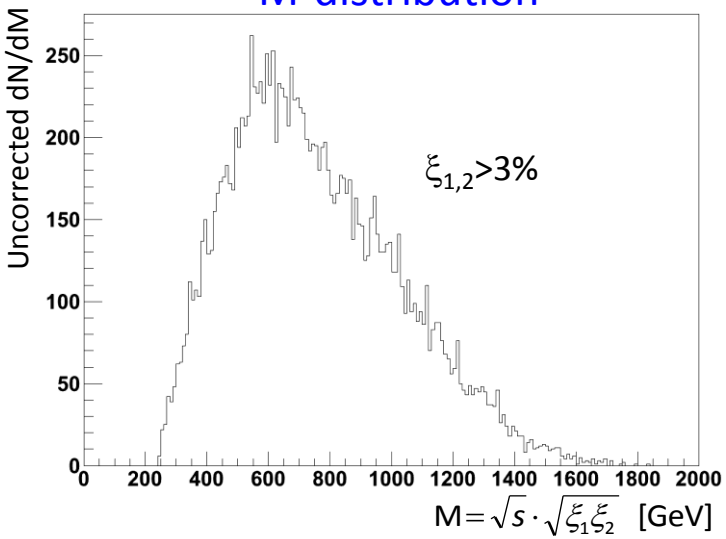
ξ-distribution



t-distribution



M-distribution



Soft DPE Pile-up

- $N=0.7\times10^{11}$, $\beta^*=90$m, $\varepsilon_N=3.5\mu$m, L/bx$\approx6.0\times10^{27}$, bx=(2)3, R/bx$=5.3\times10^{-4}$/mb
- Int. lumin ≈ 0.75 nb^{-1}, low pile-up ~3-4%

Soft diffraction pile-up estimation

Events & Pile-up	Accept.	Rate/bx	Expected events # in 327k (RP inelastic data)	Fraction
~~1×Soft SD (~14mb)~~	~~50%~~	~~0.37 %~~	~~5.3 M~~	~~removed (trig)~~
~~Elastic~~	~~33%~~	~~0.78 %~~	~~7.4 M~~	~~removed~~
DPE (~1mb)	35%	0.022 %	263k	80 %
Soft SD × Soft SD		6.9×10^{-6}	9 k	3 %
SD × DPE	25%	4.9×10^{-7}	600	0.2 %
SD × beam halo		1.9×10^{-5}	5k – 25k	1.5% - 8%
beam halo × beam halo		2.5×10^{-5}	7k – 34k	2% - 10%
DPE + QCD			10k	3%

Protection against pile-up

CUTS:

- 0 or 1 vertex in CMS
- RP near edge area removed (1 elastic p. + beam halo or SD)
- top RP 45 + top RP 56 or bot RP 45 + bot RP 56 topology
  (no remnants of elastic scattering)
- $\xi > 1.5$ % (far enough from resolution effects)
- Forward Shower Counters (FSC) empty : QCD background protection

- M_{CMS}(Particle Flow + missing momentum) $\leq M_{TOTEM}$(pp)

Soft DPE: Logic-0

- CMS and TOTEM consistent (within resolution)

$$M_{CMS}(\text{Particle Flow}) = M_{TOTEM}(pp)$$

$$p_{CMS}(\text{Particle Flow}) = p_{TOTEM}(pp)$$

- Standard protection against pile-up

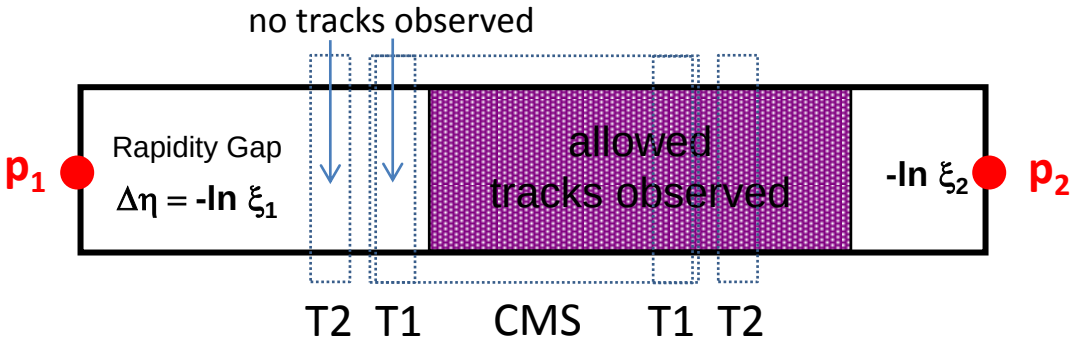
Best events:

M_{CMS}	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}	$\#T2_{right}$	$\#T2_{left}$	$\#FSC_{right}$	$\#FSC_{left}$
366.841	335.869	86.7358	95.3509	-0.0317239	-0.0555616	20	14	0	0
185.614	164.599	43.2926	13.2545	-0.0189846	-0.0222982	0	0	0	0
164.504	162.526	-8.82434	6.42943	-0.0195279	-0.0211353	0	0	0	0
157.137	172.303	6.62721	30.5829	-0.0180517	-0.0256974	0	0	0	0
82.3631	129.867	4.29839	6.84464	-0.0154003	-0.0171115	0	0	0	0
550.082	556.323	-188.57	-146.68	-0.0902519	-0.0535818	5	16	0	0
252.606	272.868	115.791	150.129	-0.0201641	-0.0576963	3	0	0	0
90.3626	138.743	2.06612	-0.259705	-0.0173754	-0.0173105	0	0	0	0

Soft DPE: Logic-1

- M_{CMS}(Particle Flow + missing momentum) $\leq M_{TOTEM}$(pp)

- Additional momentum undetected by CMS
- Additional tracks indeed observed in forward detectors where allowed by xi-predicted gaps
- Additional tracks not observed where forbidden by xi-predicted gaps

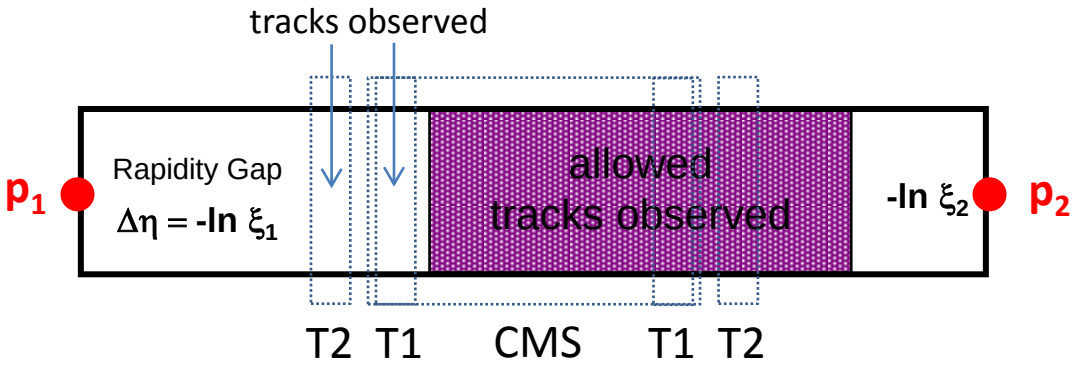


- Majority of 300k events

Soft DPE: Logic-2

- Look for secondaries (decay products) which might violate the xi-predicted rapidity gaps
- Standard pile-up protection
- M_{CMS}(Particle Flow + missing momentum) $\leq M_{TOTEM}$(pp)
- Normally discarded because of presence of tracks in forbidden gaps

- Polluted by
  - 2×Soft SD
  - SD + beam halo

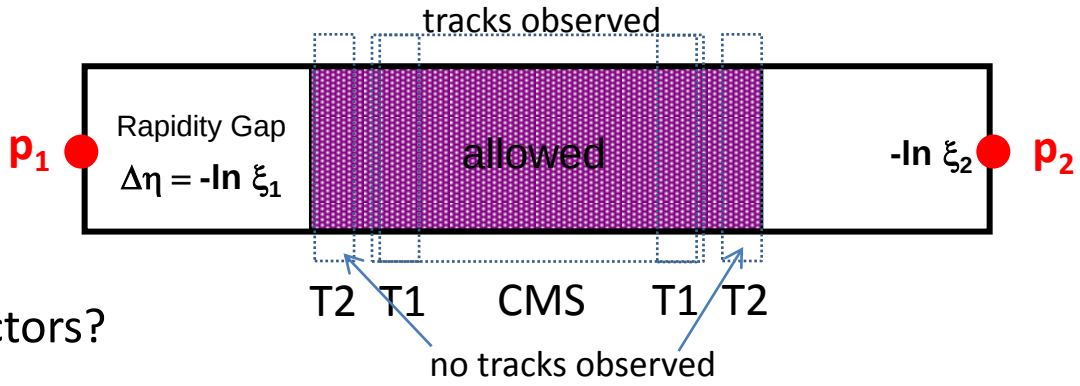


- Indeed found events of this type

Soft DPE: Logic-3

- Check escaping-mass candidates
- Standard pile-up protection
- p_{CMS}(Particle Flow) $\neq$ p_{TOTEM}(pp)
  M_{CMS}(Particle Flow + missing momentum) $\leq$ M_{TOTEM}(pp)
  $\rightarrow$ existence of tracks undetected by CMS

- No tracks observed in forward detectors 'allowed' by rapidity gaps
- More forward regions excluded by rapidity gaps $\rightarrow$ 'allowed' = 'required' ?



- Energetic gammas in T2, N*$\rightarrow$p
- detectors' 'inefficiency'?
- acceptance gaps between detectors?
- high energy neutrinos?
- neutral particle flow in T2 (under simulation)?
- real escaping energy?

  This depends on amount of missing energy

Soft DPE: Logic-3

$3\% < \xi_{1,2} < 10\%$
T2 allowed by rapidity gaps
more forward than T2 forbidden

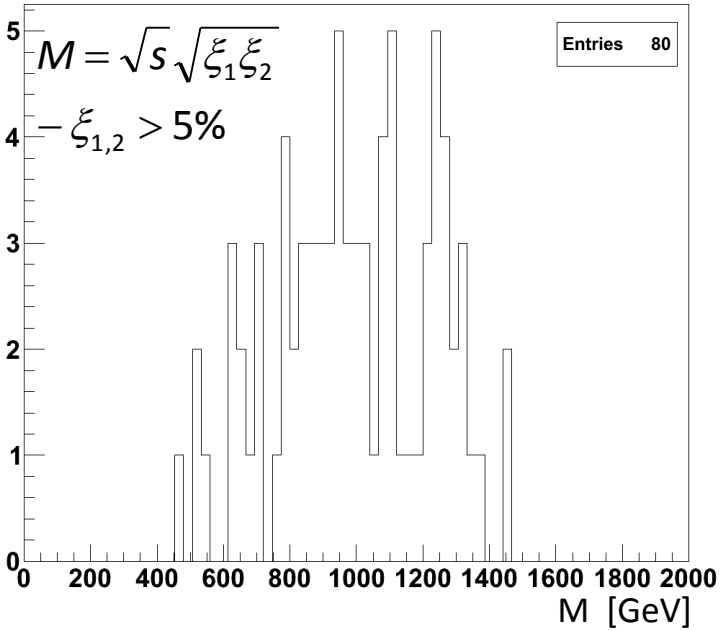
selected events

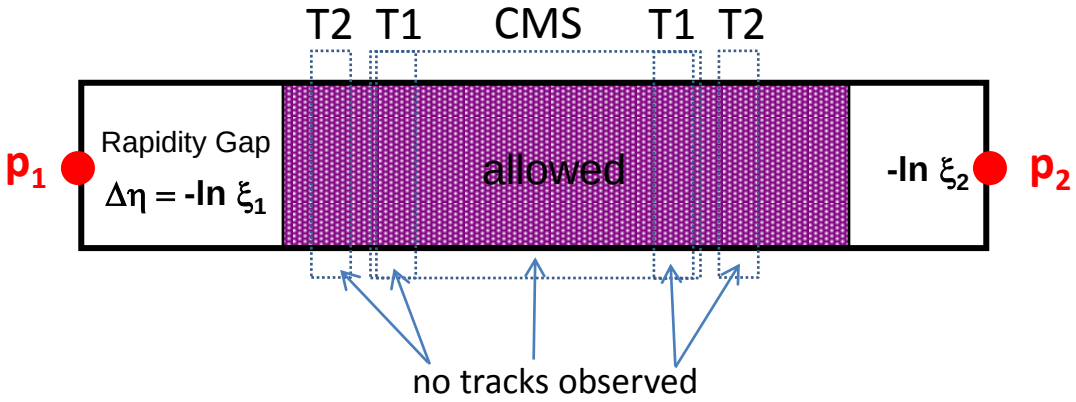
ΔM	M_{CMS}	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}	$\#T2_{right}$	$\#T2_{left}$	$\#FSC_{right}$	$\#FSC_{left}$
301.383	178.86	480.243	-113.033	-16.1065	-0.0620774	-0.0580508	0	0	0	0
338.2276	69.2494	407.477	-20.7135	-6.27609	-0.0517251	-0.0501561	0	0	0	0
346.8	136.96	483.76	-44.4907	31.3176	-0.0566819	-0.0645113	0	0	0	0
352.8003	75.8707	428.671	-101.837	-10.1703	-0.0548702	-0.0523276	0	0	0	0
390.801	122.051	512.852	55.5703	88.2933	-0.0540129	-0.0760862	0	0	0	0
428.189	140.775	568.964	-186.701	-6.75768	-0.0719702	-0.0702807	0	0	0	0
446.1199	34.7091	480.829	-11.7553	52.5331	-0.0538947	-0.0670279	0	0	0	0
455.4364	42.1396	497.576	-28.1272	94.9103	-0.0514546	-0.0751822	0	0	0	0
459.56784	9.82716	469.395	-5.50888	10.275	-0.0574041	-0.0599728	0	0	0	0
462.4347	48.3963	510.831	74.0196	-71.6533	-0.0734356	-0.0555223	0	0	0	0
508.3268	24.0222	532.349	-6.02981	58.9093	-0.0595862	-0.0743135	0	0	0	0
515.088	13.228	528.316	-18.6829	-25.1323	-0.0692557	-0.0629726	0	0	0	0

Soft DPE: Logic-3’

DPE candidates in Roman Pots + CMS, T1, T2 empty

7k – 34 k predicted by pileup of beam halo
standard pile-up protection
60k events observed before any ξ cut
$-\xi_{1,2} > 1.5\%$: 369 events
$-\xi_{1,2} > 5\%$: 80 events
} enhanced pile-up protection





Soft DPE: Logic-4

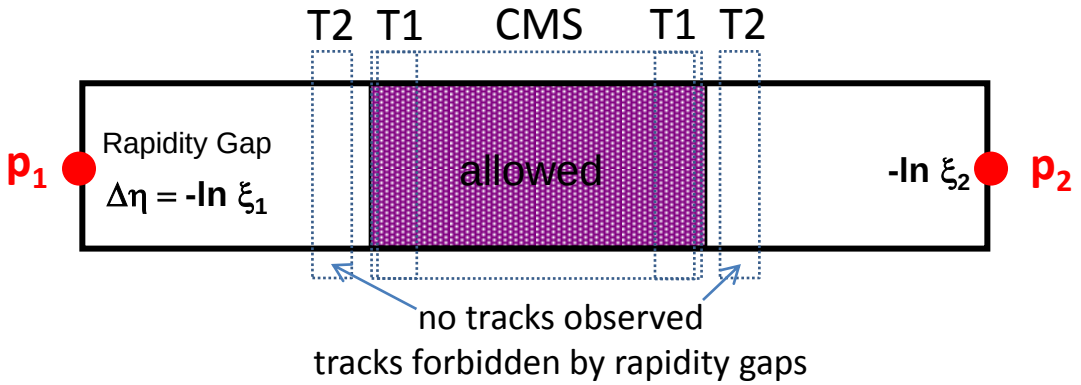
- Same selection as Logic-3 (escaping-mass candidate search)

  p_{CMS}(Particle Flow) $\neq$ p_{TOTEM}(pp)

  M_{CMS}(Particle Flow + missing momentum) $\leq$ M_{TOTEM}(pp)

  $\rightarrow$ <u>existence of tracks undetected by CMS</u>

- <u>additional tracks</u> would be required to appear in forbidden rapidity regions
- those tracks not observed in the detectors.

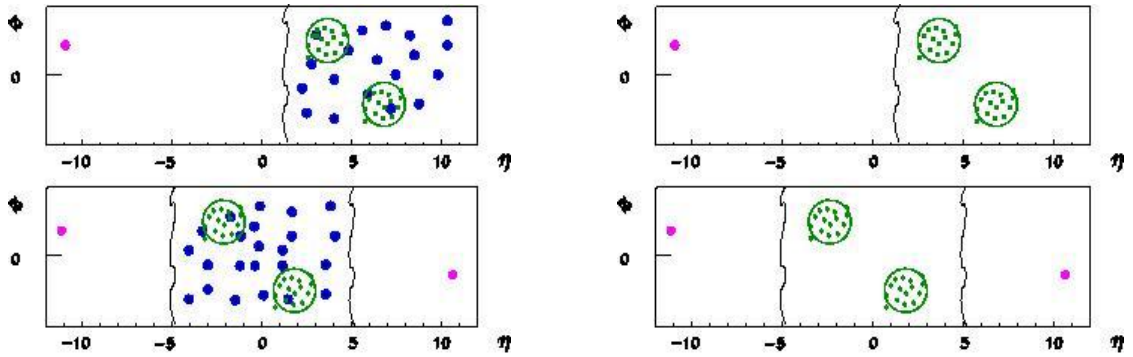


- Skipped, not possible to eliminate pile-up

Soft DPE: Largest mass events

M_{CMS}	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}	$\#T1_{right}$	$\#T1_{left}$	$\#T2_{right}$	$\#T2_{left}$	$\#FSC_{right}$	$\#FSC_{left}$
495.574	**1830.91**	-62.073	-91.5223	-0.240589	-0.217709	33	17	2	12	0	0
116.262	**1792.09**	7.8118	-147.443	-0.243199	-0.206338	0	0	23	10	0	0
57.7559	**1719.7**	-65.8128	220.329	-0.189179	-0.244261	0	0	1	8	0	0
74.7342	**1718.48**	-82.6207	-17.6895	-0.217033	-0.212611	0	0	1	1	0	0
41.8044	**1716.62**	-75.0976	-103.546	-0.227911	-0.202024	0	0	0	3	0	0
148.818	**1691.48**	71.9651	-39.4706	-0.216427	-0.206559	2	5	158	16	0	0
181.299	**1690.63**	13.3104	57.4586	-0.204268	-0.218633	0	1	4	8	0	0
217.43	**1689.17**	259.099	121.802	-0.19647	-0.22692	1	2	14	9	0	0
171.385	**1680.12**	51.4771	232.609	-0.182942	-0.241094	3	0	61	2	0	0
93.2098	**1678.36**	16.9669	-133.847	-0.227192	-0.193731	0	0	7	3	0	0

M_X=1.8 TeV with pp survival (never before)

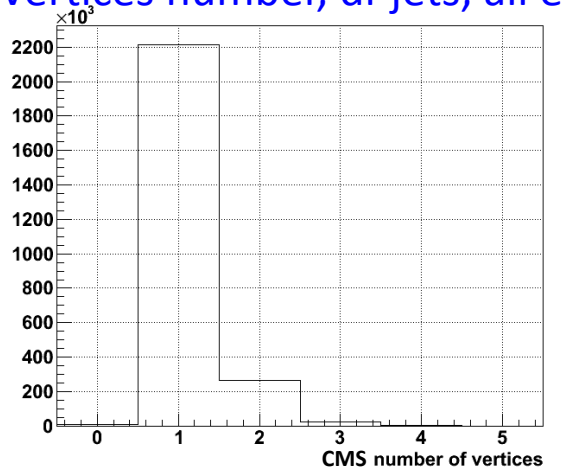


TOTEM + CMS : HARD DPE

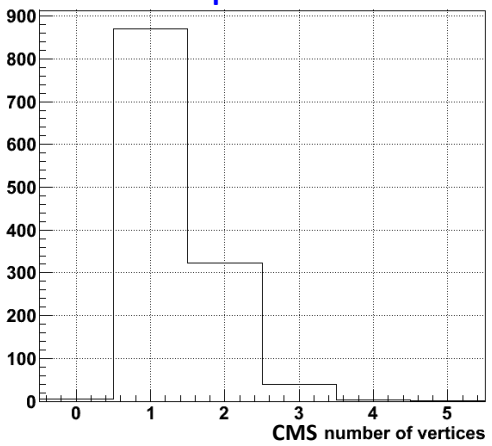
Hard DPE sample

- 11.5h, β^*=90m, ~7×10^{10} protons per bunch
- Approx. int. luminosity: $43nb^{-1}$ (112 bx)
- CMS di-jet triggers: 2'513'072
  - vertex selection according to CMS: 2'192'405
  - + 2 protons inelastic: 1243
  - + 2 protons inelastic (1 or more valid vertices): 1228
  - **+ 2 protons inelastic (1-valid vertex): 860**
- Obvious pile-up
  - + 2 protons elastic (1-valid vertex): 19188
  - + 2 protons elastic: 21908

Vertices number, di-jets, all events



Vertices number, di-jets,
2 inelastic protons in RPs



Hard DPE Pile-up

- $N \approx 0.7\times10^{11}$, β^*=90m, $\varepsilon_N \approx 3.5\mu m$, L/bx$\approx 9.3\times10^{27}$, bx=112, R/bx = 8.25×10^{-4}
- Int. lumin $\approx 43 nb^{-1}$

Hard diffraction pile-up estimation

Pile-up case	Accept.	Rate/bx	Events in 2.5M (CMS dijet triggers)	Fraction of accepted hard DPE canditates' (1243)
2×Soft SD (+QCD JJ)	25%	1.7×10^{-5} ($\cdot 4.9\times10^{-5}$)	42.5	3.4 %
Soft DPE (+QCD JJ)	35%	2.9×10^{-4} ($\cdot 4.9\times10^{-5}$)	721	58 %
Elastic (+ QCD JJ)	33%	8.3×10^{-3} ($\cdot 4.9\times10^{-5}$)	20.6 k	~0
Hard SD + Soft SD (as Hard DPE)		7.2×10^{-10} - 7.2×10^{-9}	37-370	3 % – 30 %
Hard DPE + SD		3.5×10^{-11} 3.5×10^{-10}	2 – 20	0.1 % – 1.5%
Beam pile-up				~1%

Pessimistically #true events ~5% corresponding to ~60 events

Hard DPE: Logic-0

- CMS and TOTEM consistent (within resolution): ~3-5 events

$$M_{CMS}(\text{Particle Flow}) = M_{TOTEM}(pp)$$

$$p_{CMS}(\text{Particle Flow}) = p_{TOTEM}(pp)$$

- No exclusive $pp \rightarrow jj+pp$ events observed

- Constraints and checks applied:
  - Not pile-up
  - Selection criteria (kinematics, rapidity gaps…)
  - Single, well defined CMS vertex
  - Jets resolutions and detector thresholds (checked with elastic scattering)

Selected events :

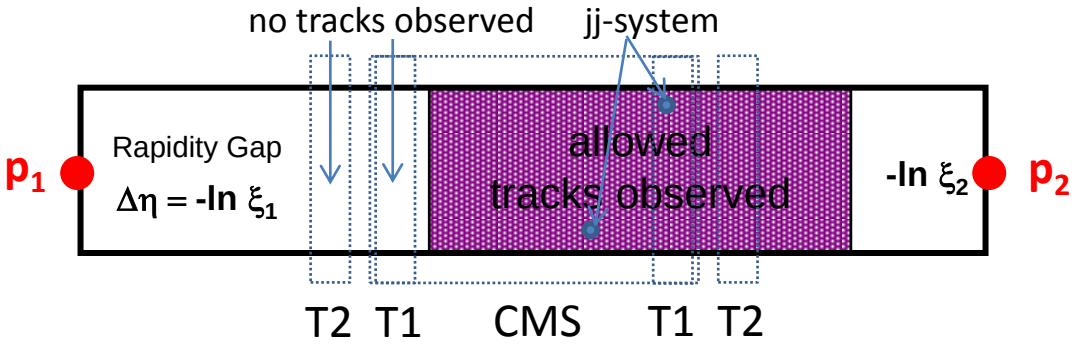
M_{TOTEM}	M_{CMS}	M_{dijet}	Pz_{TOTEM}	Pz_{CMS}	Xi_{left}	Xi_{right}	pT_{CMS}	pT_{TOTEM}	
204.673	179.616	81.0462	-364.838	-295.344	-0.0979	-0.00669	3.50267	4.94E-01	only 1 additional track in T2
243.97	219.344	138.422	-343.07	-254.548	-0.0955054	-0.00973	3.3627	5.64E-01	

Common CMS-TOTEM visualisation coming soon

Hard DPE: Logic-1

- M_{CMS}(Particle Flow + missing momentum) $\leq M_{TOTEM}$(pp)

- Additional momentum undetected by CMS
- Additional tracks indeed observed in forward detectors where allowed by xi-predicted gaps
- Additional tracks not observed where forbidden by xi-predicted gaps



46 events observed

Hard DPE: Logic-1

Best events in terms of CMS-TOTEM mass agreement:

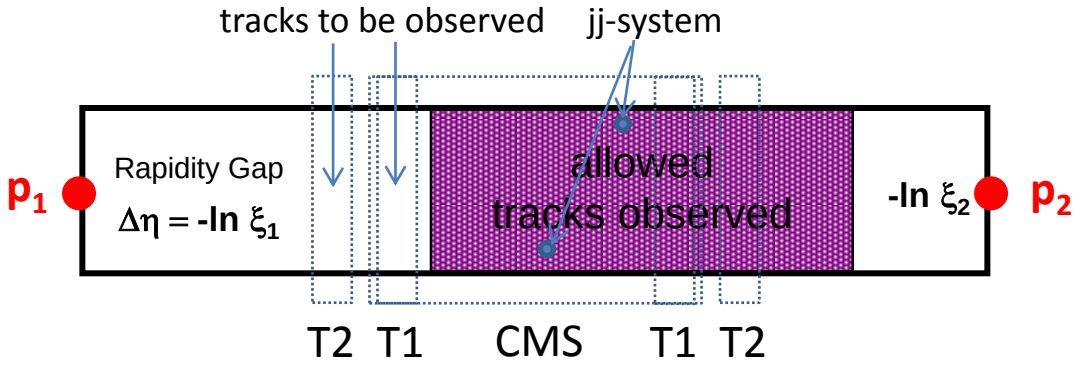
M_{CMS}(Particle Flow + missing momentum) ≈ M_{TOTEM}(pp)

M_{jj}	M_{CMS}	$M_{CMS+missing\ p}$	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}
107.171	266.948	297.845	301.281	254.787	331.096	-0.0145699	-0.0973439
138.422	219.344	250.076	243.97	-254.548	-343.07	-0.0955054	-0.00973789
93.3026	254.456	341.96	335.624	319.223	612.358	-0.010743	-0.163832
81.0462	179.616	198.14	204.673	-295.344	-364.838	-0.0978957	-0.0066862
123.347	188.163	251.145	234.579	-140.216	-286.387	-0.0820728	-0.0104761
61.3357	162.727	215.088	198.103	-359.435	-639.511	-0.163625	-0.0037476

Tracks indeed observed in TOTEM forward detectors according to xi-predictions

Hard DPE: Logic-2

- Look for secondaries (decay products) which might violate the xi-predicted rapidity gaps
- Standard pile-up protection
- M_{CMS}(Particle Flow + missing momentum) $\leq M_{TOTEM}$(pp)
- Normally discarded because of presence of tracks in forbidden gaps

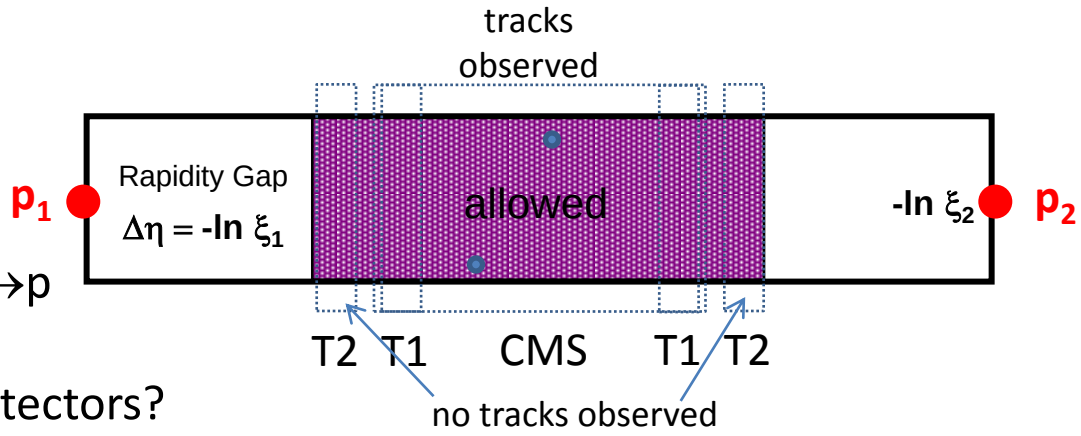


No events observed

Hard DPE: Logic-3

- Check <u>escaping-mass candidates</u>
- p_{CMS}(Particle Flow) $\neq$ p_{TOTEM}(pp)
  M_{CMS}(Particle Flow + missing momentum) $\leq$ M_{TOTEM}(pp)
  $\rightarrow$ <u>existence of tracks undetected by CMS</u>

- No tracks observed in forward detectors 'allowed' by rapidity gaps
- More forward regions excluded by rapidity gaps $\rightarrow$ 'allowed' = 'required' ?



- Energetic gammas in T2, N*$\rightarrow$p
- detectors' 'inefficiency'?
- acceptance gaps between detectors?
- high energy neutrinos?
- neutral particle flow in T2 (under simulation)?
- real escaping energy?

This depends on amount of missing energy

Hard DPE: Logic-3

Interesting event:

M_{jj}	M_{CMS}	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}	$\#T2_{right}$	$\#T2_{left}$	$\#T1_{right}$	$\#T1_{left}$	$\#FSC_{right}$	$\#FSC_{left}$
68.5	500.4	894.9	202.7	62.7	-0.104	-0.120	0	0	0	0	0	0

- Significant mass discrepancy:
  - RP predicted mass $M(\xi_1\xi_2) \approx 900$ GeV
  - CMS visible mass $M(CMS) \approx 500$ GeV
- More forward η than T2 forbidden
  - ξ_1 and ξ_2 forbid $\eta > 6.7$ and 6.9 respectively
- Gap definition tolerances applied
  - resolutions, secondaries, pseudorapidity $\leftrightarrow$ rapidity conversion …
- No tracks observed in T2
  - But tracks are allowed (required) in ~T2 on both sides

~400 GeV missing mass?

Weaker requirement – tracks not observed at least in one T2 arm:

M_{jj}	M_{CMS}	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}	$\#T2_{right}$	$\#T2_{left}$	$\#T1_{right}$	$\#T1_{left}$	$\#FSC_{right}$	$\#FSC_{left}$
171.482	298.486	678.547	-85.3117	-15.2752	-0.0867	-0.0829	2	0	0	0	0	0

Hard DPE: Logic-4

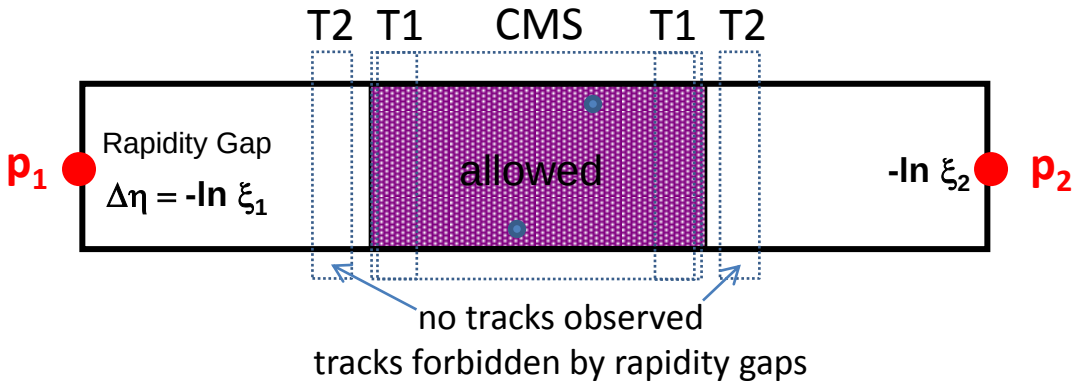
- Same selection as Logic-3 (escaping-mass candidate search)

  p_{CMS}(Particle Flow) ≠ p_{TOTEM}(pp)

  M_{CMS}(Particle Flow + missing momentum) < M_{TOTEM}(pp)

  → <u>existence of tracks undetected by CMS</u>

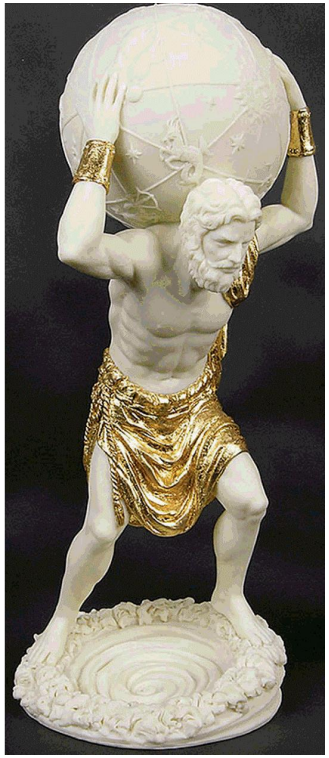
- <u>additional tracks</u> would be required to appear in forbidden rapidity regions
- those tracks not observed in the detectors.



- No events observed

Hard DPE: Large-masses

- $pp \rightarrow jj + X + pp$
- $M_{TOTEM} > 1$ TeV
- pile-up removed



M_{TOTEM}	run	event_id	lumi_sect
1037.73	198902	6939048	366
1051.18	198902	7304277	385
1072.09	198902	220206	20
1073.21	198902	12489009	676
1074.81	198903	6933634	333
1115.18	198902	16707008	922
1117.01	198902	1830833	100
1153.79	198902	18564152	1033
1189.46	198902	13251940	720
1196.07	198902	2589805	138
1210.66	198902	4985608	262
1223.96	198903	6816731	327
1282.46	198903	13852945	677
1391.98	198903	13077469	638
1402.31	198903	13219371	645
1432.62	198903	11123205	540
1436.38	198903	4523333	216
1453.09	198903	11851377	576

Largest M_{jj}/M_{CMS}

M_{jj}/M_{CMS}	M_{jj}	M_{CMS}	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}
0.717437648	397.454	553.991	1223.96	218.031	-123.799	-0.16925	-0.1383
0.655532703	123.347	188.163	234.579	-140.216	-286.387	-0.0820728	-0.0104761
0.633250532	146.329	231.076	558.98	152.203	439.008	-0.0339696	-0.143722
0.631072653	138.422	219.344	243.97	-254.548	-343.07	-0.0955054	-0.00973789
0.602023414	558.461	927.64	1391.98	31.9048	15.981	-0.172011	-0.176006

Largest M_{jj}/M_{TOTEM}

M_{jj}/M_{TOTEM}	M_{jj}	M_{CMS}	M_{TOTEM}	Pz_{CMS}	Pz_{TOTEM}	Xi_{left}	Xi_{right}
0.567373038	138.422	219.344	243.97	-254.548	-343.07	-0.0955054	-0.00973789
0.525822857	123.347	188.163	234.579	-140.216	-286.387	-0.0820728	-0.0104761
0.401199011	558.461	927.64	1391.98	31.9048	15.981	-0.172011	-0.176006
0.395978952	81.0462	179.616	204.673	-295.344	-364.838	-0.0978957	-0.0066862

No exclusive jj events observed

Next steps

- Lots of potential studies and measurements ahead
- TOTEM alone: soft SD, DPE, Double Diffraction
- CMS + TOTEM data :
  - Homework: beam halo pile-up, optics, resolutions, acceptance, reconstruction …
  - Soft and Hard DPE (differential) cross-sections
  - Further studies of particular events (common visualisation soon)
- Upgrade of TOTEM Roman Pot detectors to profit from low-β^* optics after LHC shut-down
- Data taking : 1000 bunches + x-angles @ β^*=90m
- More data welcome, especialy with Castor and ZDC

Thank you !

BACKUP

Runs & Data Statistics 2010-2011

Date	Detector configuration	β* [m]	$\int L\,dt$ [nb^{-1}]	Analysis
Oct 2010	RP at 7σ; T2 in readout	3.5	6.8	Elastic scattering 0.36 < |t| < 2.5 GeV^2
Sep/Oct 2010	RP at 18σ	3.5	2300	Elastic scattering - large |t| (in progress)
May 2011	RP at 5σ; T1, T2 in readout	1.5	0.72	Alignment of 220m pots
June 2011	RP at 10σ; T1, T2 in readout	90	0.0017	Total cross section + elastic scattering 0.02 < |t| < 0.33 GeV^2
Aug/Sep 2011	RP at 5σ; T1, T2 in readout	90	beam lost	Alignment of RPs
18. Oct 2011	RP at 5σ; T1, T2 in readout	90		Several hours of data taking;

RP position (V) [sigma]	trigger schema	trigger on bunch	Run time [min]	Events	Integ. Lumi [ub^{-1}]
6.5	RP_all_OR + T2 + BX	1950,2000,2050 2100, 2200, 2300	64.9	2.4E+6	1.6
6.5	RP_V_and + T2 + BX	all	13.4	5.8E+5	5.2
6.5	RP_all_and + T2 + BX	all	217.5	9.3E+6	77
5.5	RP_all_and + T2 + BX	all	50.7	1.9E+6	16
4.8	RP_all_and + T2 + BX	all	16.4	6.2E+5	4.9
		sum	363	1.5E+7	104

Runs & Data 2012

- **Joint data-taking TOTEM-CMS @ √s = 8 TeV**
  - **~25 M events, ~43nb^{-1}**
  - Special optics β^* 90m (July 2012) : ~100 bunches
  - Bi-directional exchange of triggers (via new TOTEM electrical trigger)
  - TOTEM triggers on RP pp coincidences $\rightarrow$ full CMS readout
  - CMS triggers on di-jets $\rightarrow$ TOTEM RPs readout for protons signature
  - Ideal for studies of diffraction

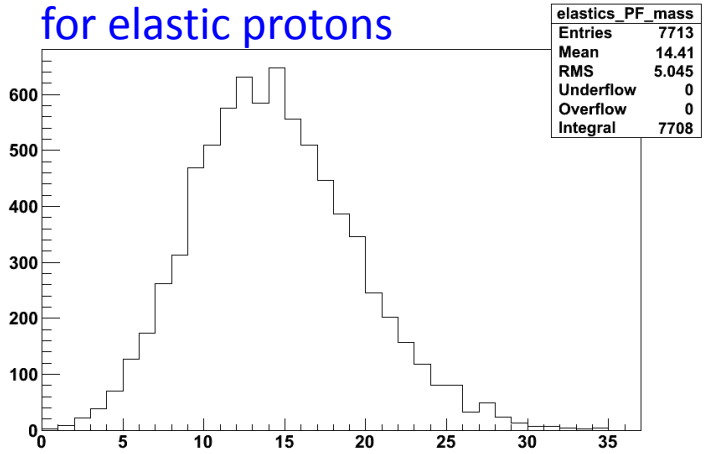
- **β^*=1km optics runs + pPb ion runs**

FSC and CMS Mass calibration

Elastic scattering based calibration:

- Elastically scattered protons selected
- T1, T2 vetoed

Particle Flow Mass distribution for elastic protons



digifC signal distribution for selected FSC detectors