TOTEM: diffractive studies, status & plans

K. Österberg,
Department of Physics,
University of Helsinki & Helsinki
Institute of Physics

on behalf of
TOTEM collaboration

- Introduction
- Soft diffraction @ √s = 7 TeV
- Soft & semi-hard diffraction @ √s = 8 TeV with CMS
- Further plans on diffraction

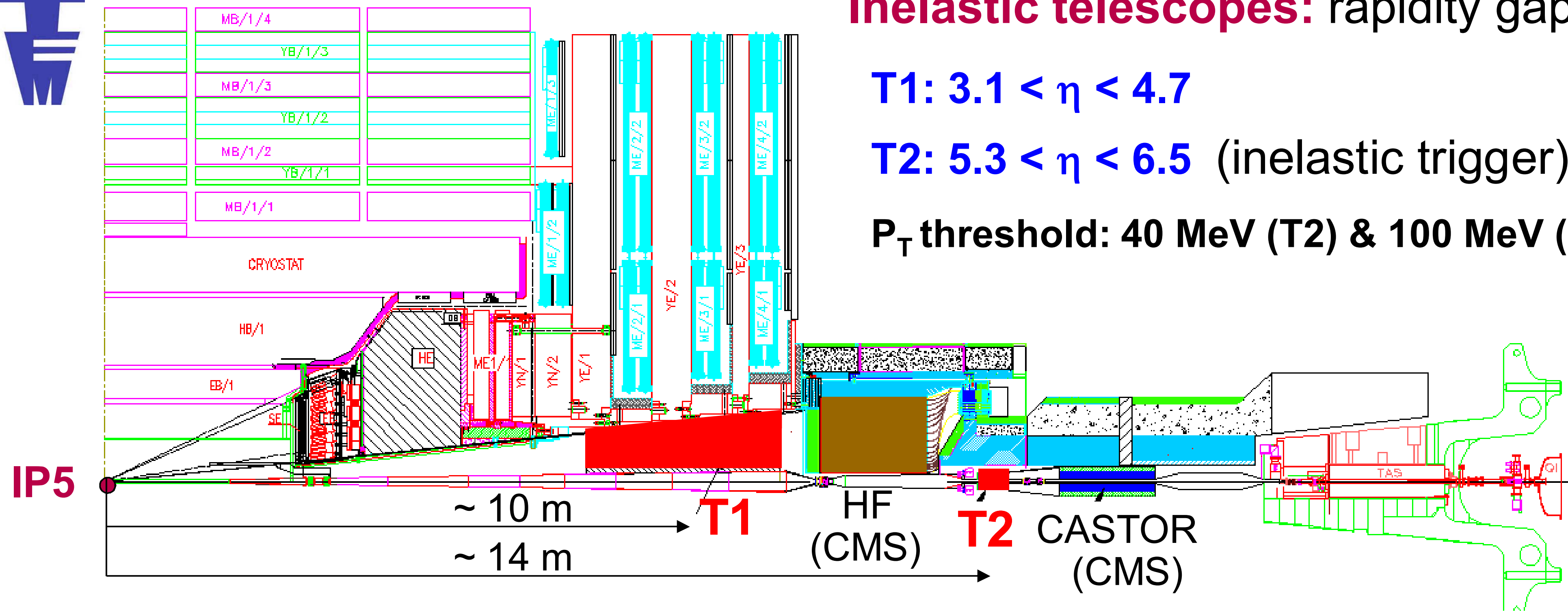
Experimental setup @ IP5

Inelastic telescopes: rapidity gaps

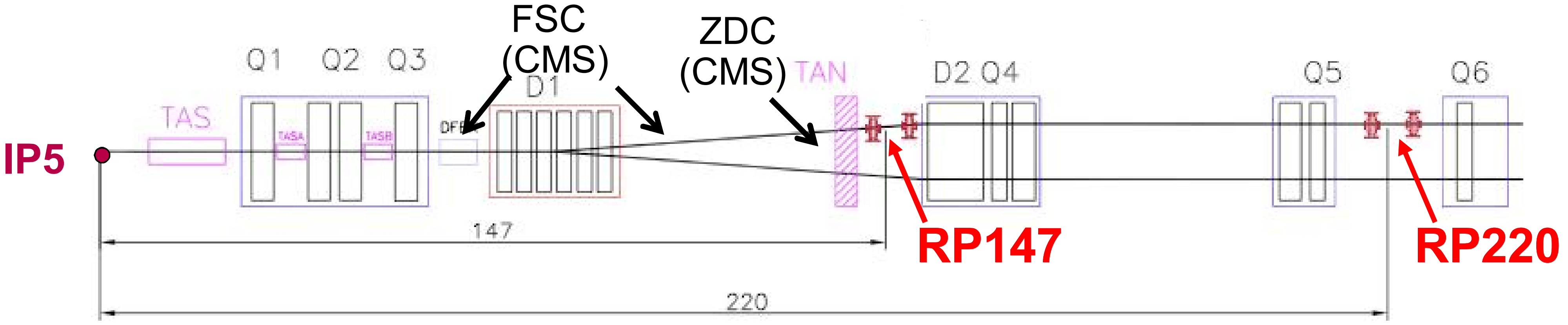
T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$ (inelastic trigger)

P_T threshold: 40 MeV (T2) & 100 MeV (T1)

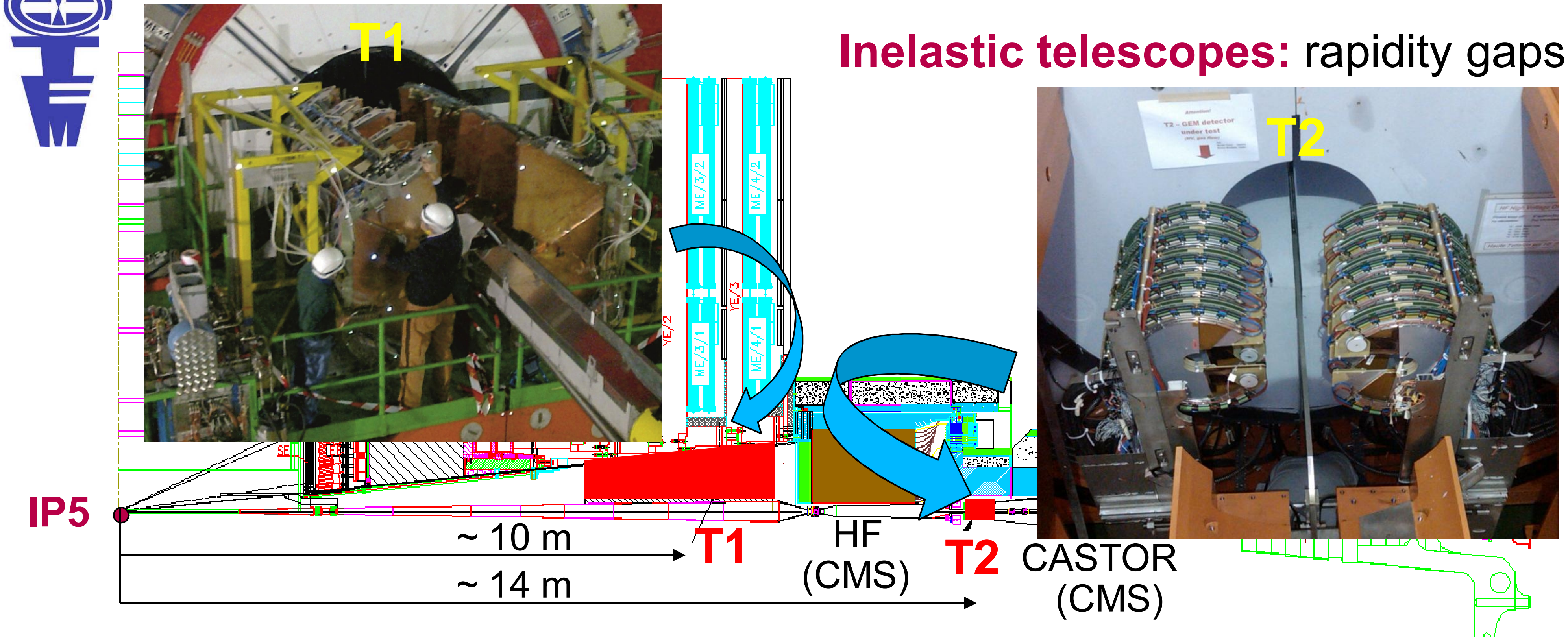


Roman Pots: diffractive protons (di-proton trigger)

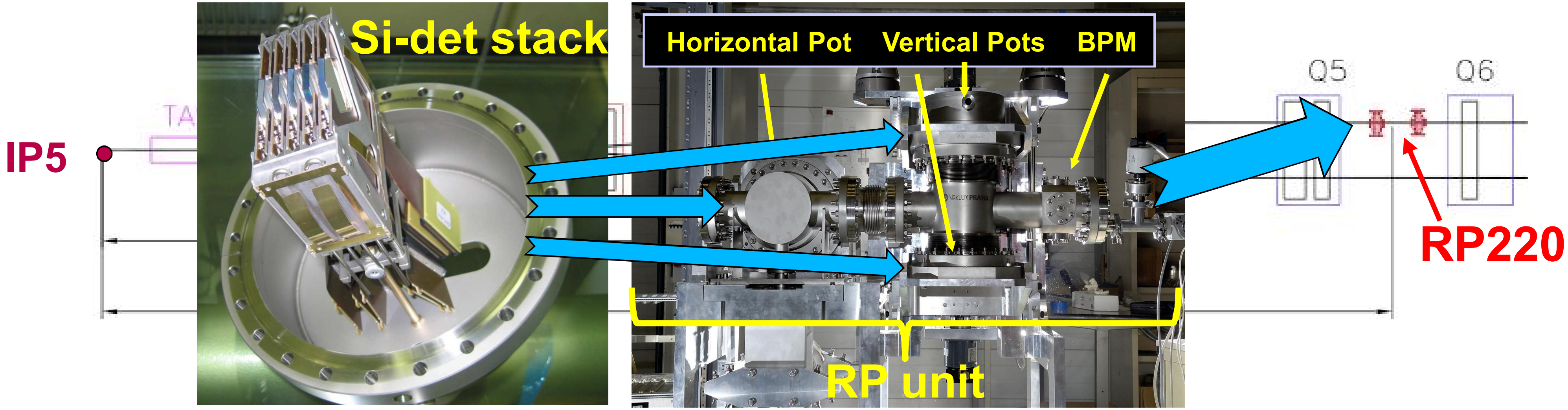


Experimental setup @ IP5

Inelastic telescopes: rapidity gaps



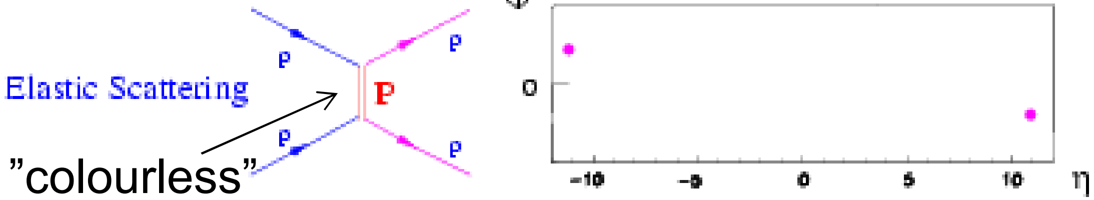
Roman Pots: diffractive protons (di-proton trigger)



Soft pp processes

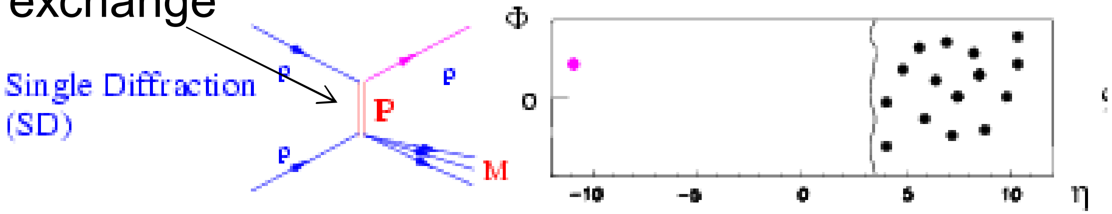
σ @ LHC

Diffraction a large fraction of total pp cross-section !!

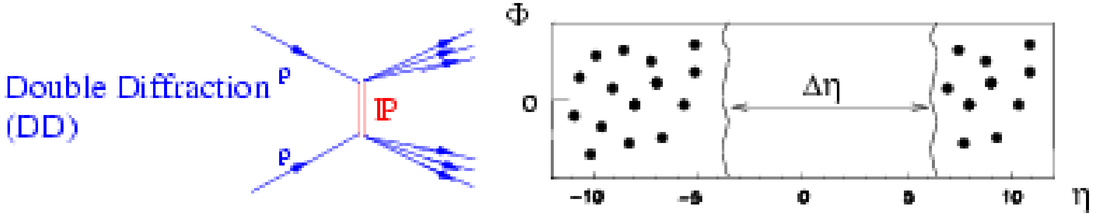


"colourless" exchange

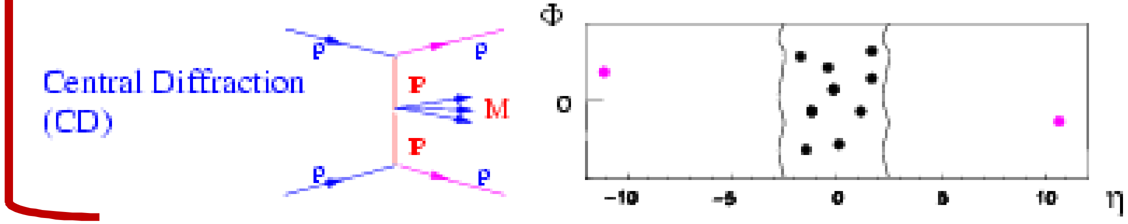
~25 mb



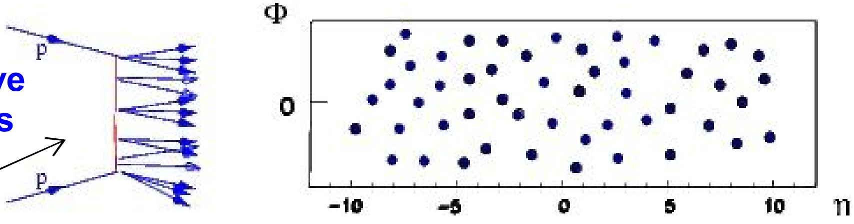
~10 mb



~5 mb



~1 mb



Non-diffractive minimum bias (MB)

exchange of colour

~60 mb

Measure σ (M,ξ,t)

Diffractive protons @ RP220

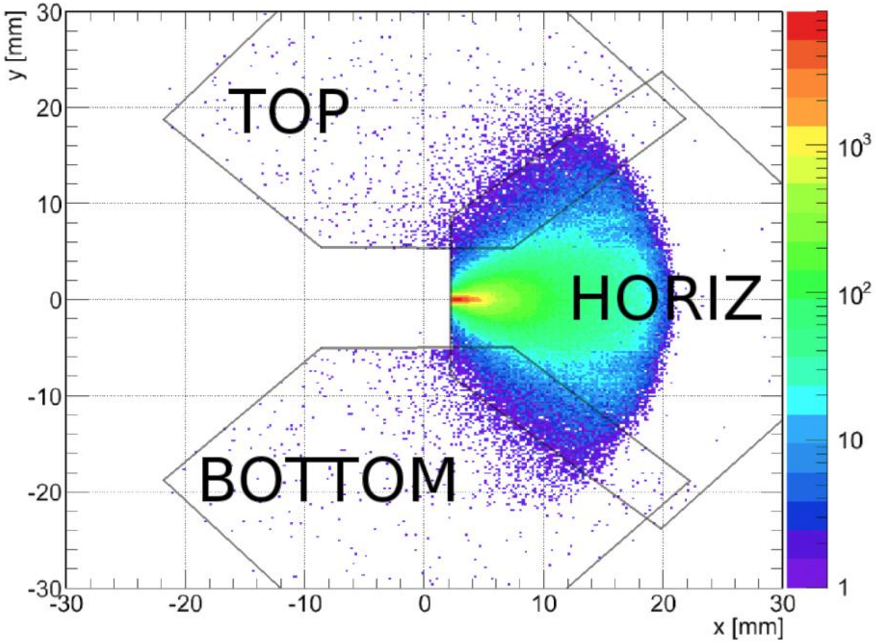
$$\begin{aligned} y(s) &= v_y(s)\cdot y^* + L_y(s)\cdot \Theta^*_y \\ x(s) &= v_x(s)\cdot x^* + L_x(s)\cdot \Theta^*_x + \xi\cdot \boxed{D(s)} \end{aligned}$$

ξ =Δp/p

dispersion shifts diffractive protons in horizontal direction

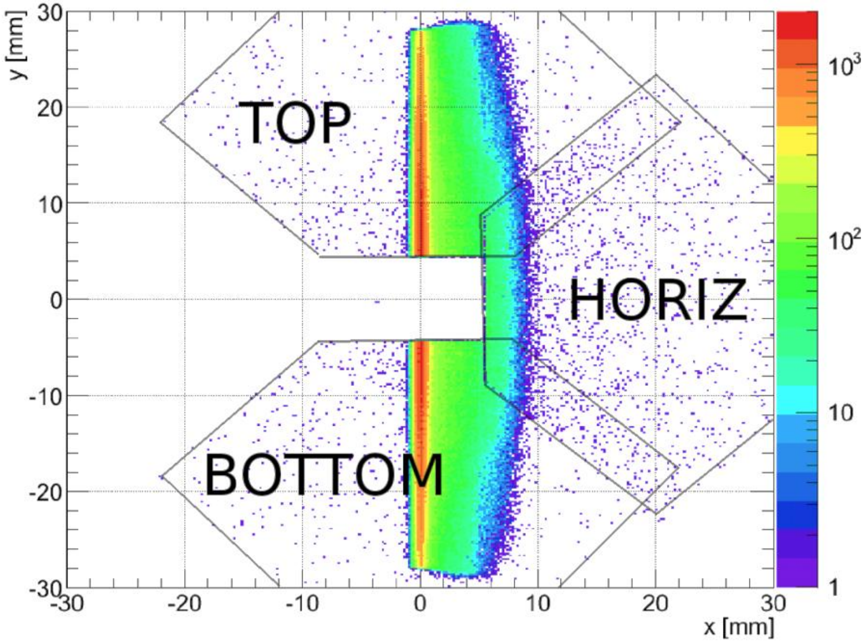
Generally $v_{x,y}$, $L_{x,y}$ & D_x functions of ξ → reconstruction non-linear problem

Low β^*: 0.5 – 3 m, ξ > 2%



- L_x & L_y low, protons shifted due to ξ
- vertex not critical: small transverse σ_{beam}

β^*= 90 m, full ξ-coverage, $|t_y|$ > 0.01 GeV^2



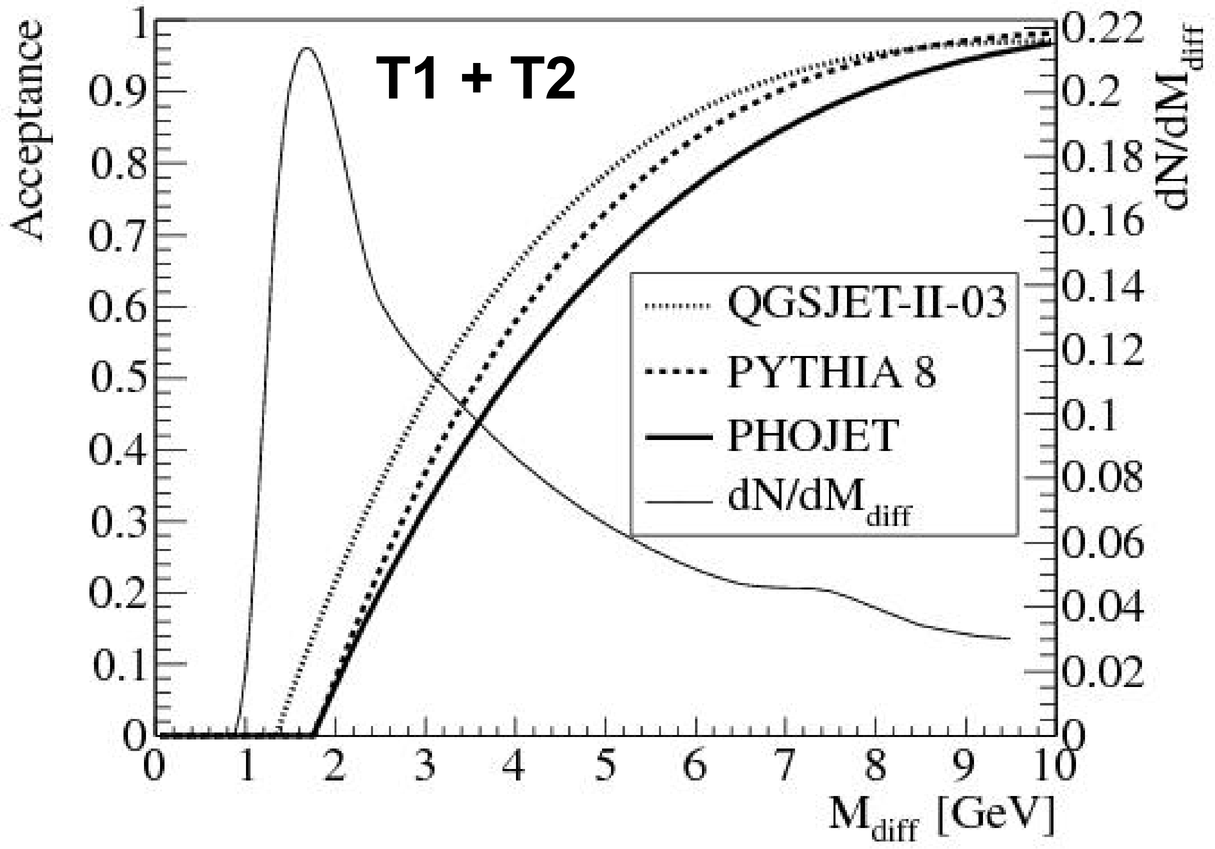
- L_x=0, L_y large
- large transverse σ_{beam} (~200 μm) → v_x, v_y important (worse ξ-resolution)
- CMS vertex improves ξ-resolution

Soft diffraction @ √s = 7 TeV

Based on $\beta^* = 90$ m Oct 2011, $\mathcal{L} = 0.1$ nb, inelastic pileup ~ 0.03

T2 or RP45+RP56 trigger, RP approach: 4.8, 5.5 and 6.5σ_{beam}

M_{diff} acceptance (50 % @ 3.4 GeV)



Already estimated low mass (M_{diff} < 3.4 GeV) diffraction (mainly SD):

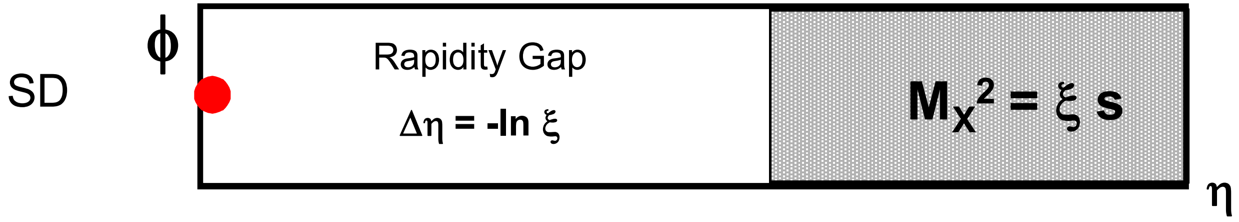
σ_{inel} (from elas.) – $\sigma_{inel, |\eta| < 6.5}$ (from inelas.) = 2.62 ± 2.17 mb

$\sigma_{inel, |\eta| > 6.5} <$ 6.3 mb @ 95 % CL

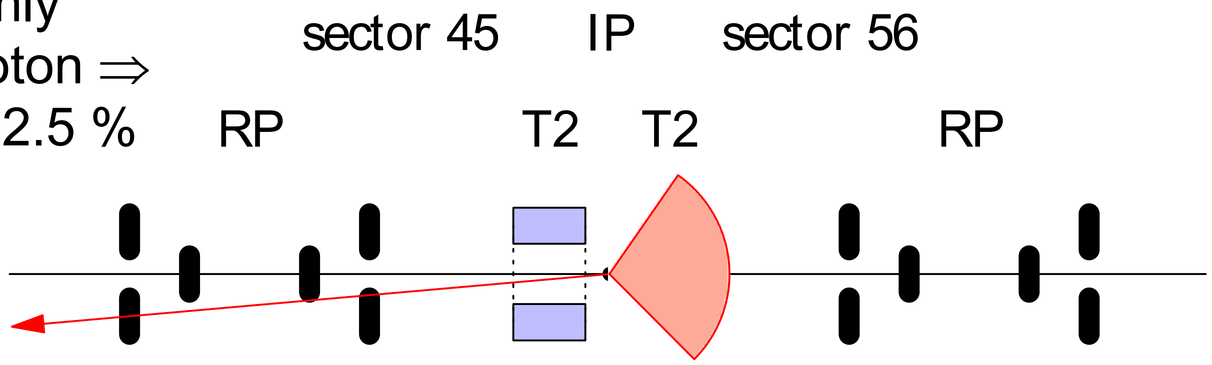
EPL **101 (2013) 21003**

NB! Single proton trigger swamped by beam halo !!

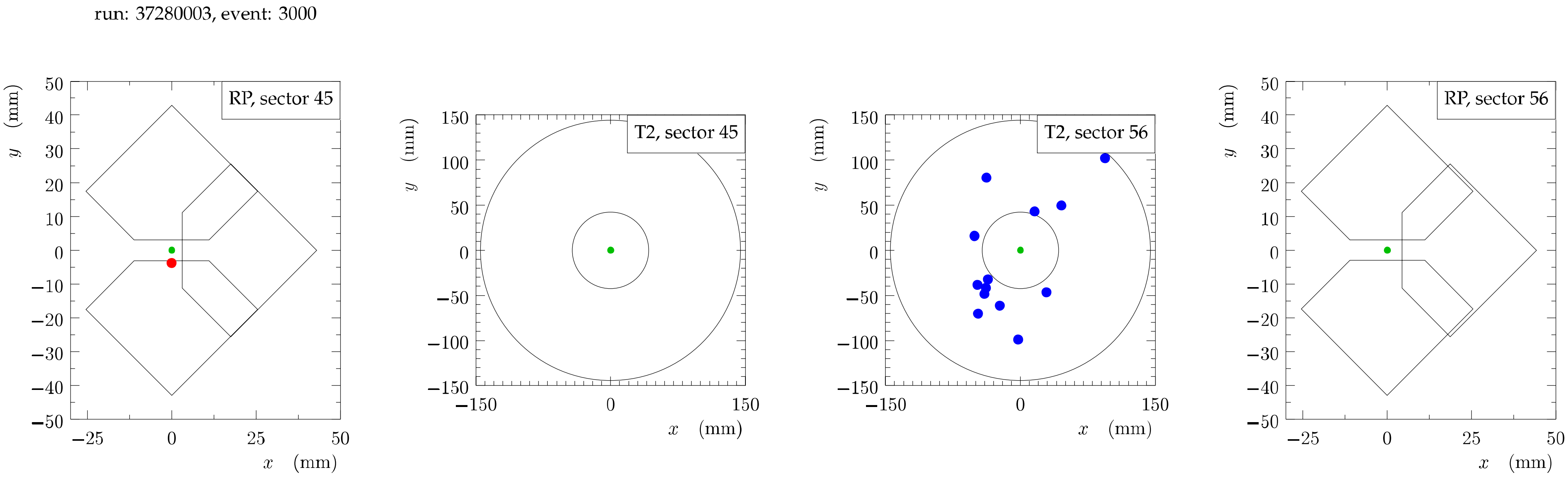
SD candidate: small ξ



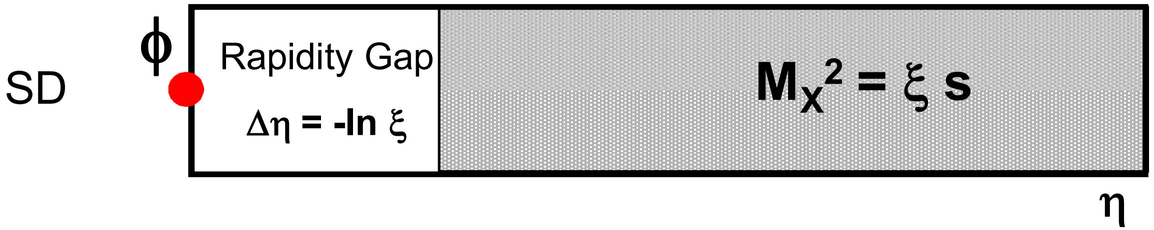
Tracks in T2 only opposite to proton ⇒ $2 \times 10^{-7} < \xi < 2.5$ %



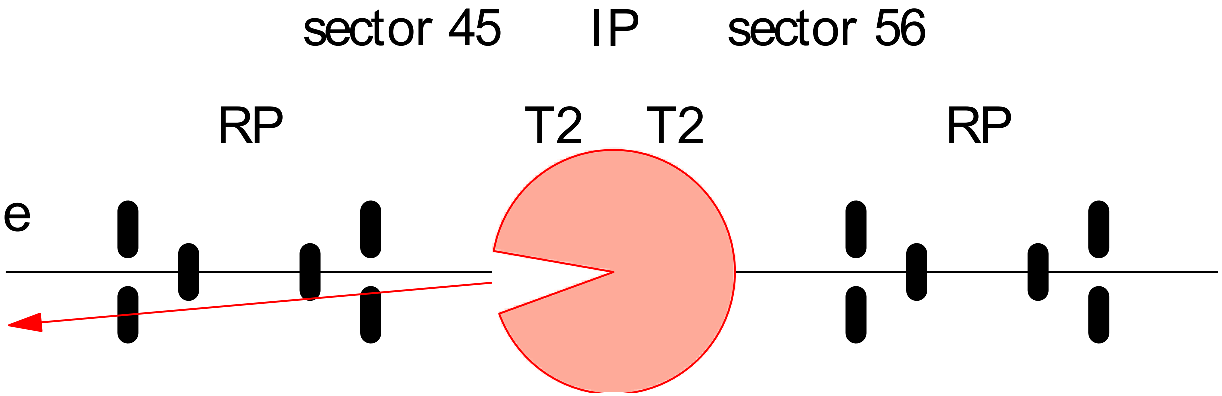
Correlation between proton in RP & tracks in T2 (& T1) !!



SD candidate: large ξ

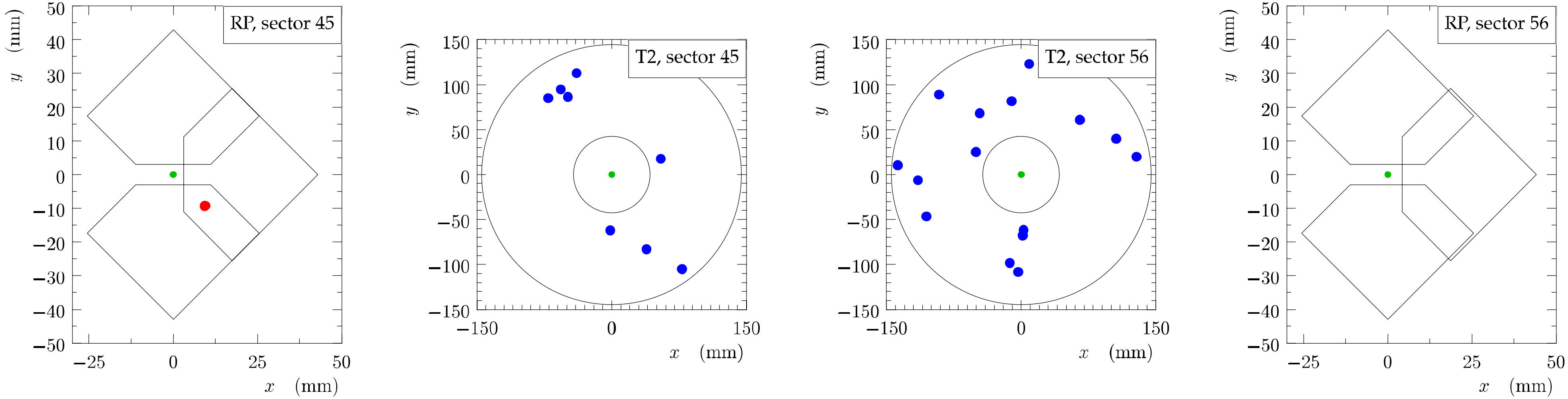


Tracks in T2
on proton side
$\Rightarrow \xi > 2.5\%$



Correlation
between proton
in RP & tracks
in T2 (& T1) !!

run: 37280006, event: 9522



Soft SD cross-section @ $\sqrt{s}$ = 7 TeV

- tracks in T2 (T2 trigger) $\Rightarrow \xi > 2 \times 10^{-7}$
- exactly 1 proton (only 1 RP track + veto RP45+RP56 trigger)

- ξ–classification based on rapidity gap
  - low M_{diff}: p + T2 opposite only + no T1 ($1 \times 10^{-6} > \xi > 2 \times 10^{-7}$)
  - medium M_{diff}: p + T2 opposite + T1 opposite ($0.25\ \% > \xi > 1 \times 10^{-6}$)
  - high M_{diff}: p + T2 opposite + T1 same ($2.5\ \% > \xi < 0.25\ \%$)
  - very high M_{diff}: p + T2 both ($\xi > 2.5\ \%$)

Inelastic + beam halo background estimated from data:

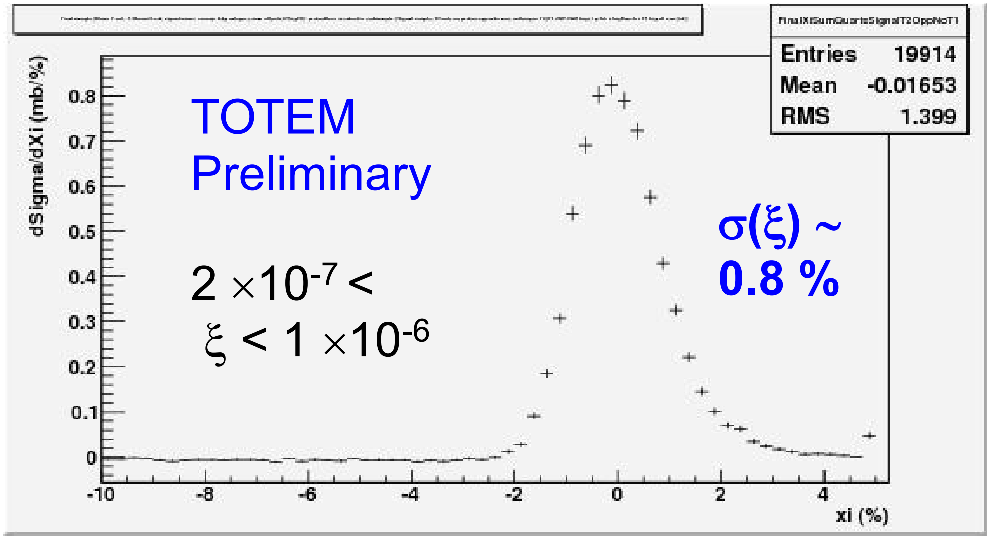
- p X gap events i.e. p + T2 same only for low M_{diff} class etc..
- beam halo ($\xi \sim 0$) from single RP trigger data for very high M ($\xi > 2.5\ \%$)

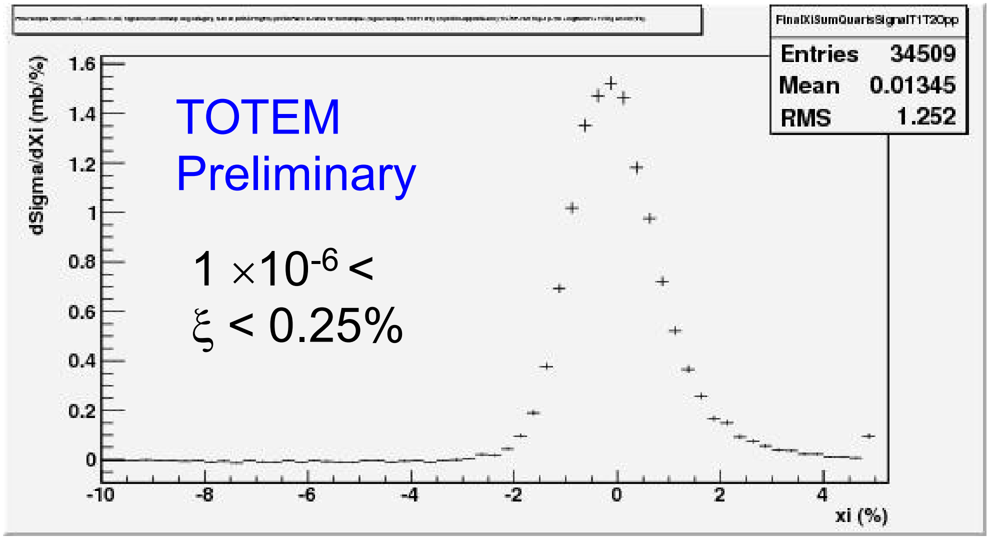
- Separate analysis top RP45, bot RP45, top RP56, bot RP56...

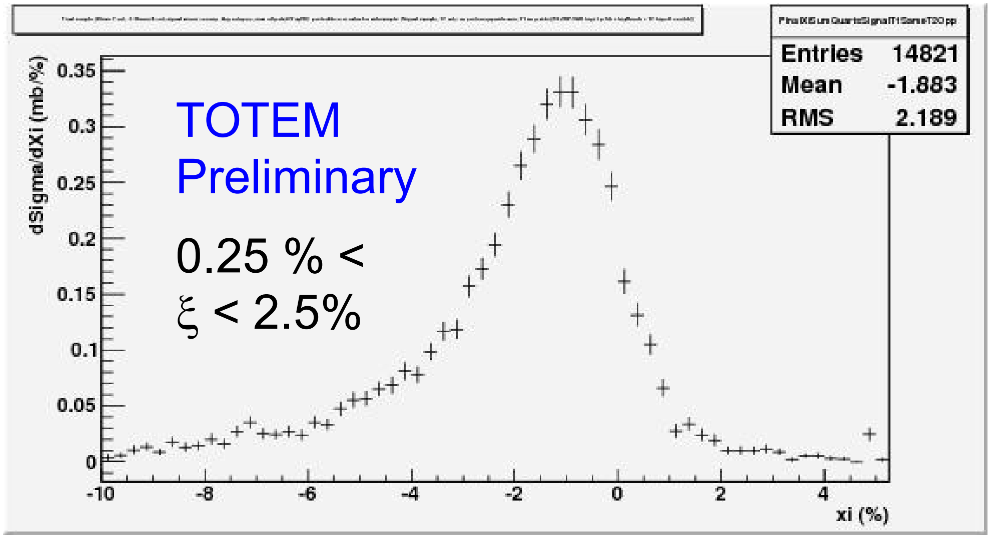
- Correct for T2 trigger efficiency, ϕ acceptance, p reco inefficiency ...

Soft SD cross-section @ √s = 7 TeV

rapidity gap based ξ-classification (T1, T2)







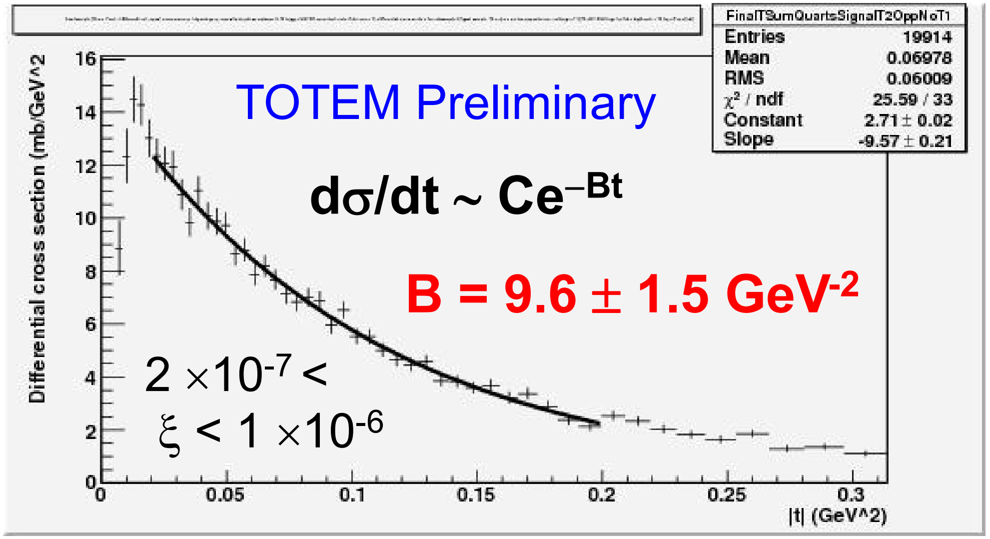
rapidity gap reconstruction using T1 & T2: $\sigma(\xi)/\xi \sim 1$

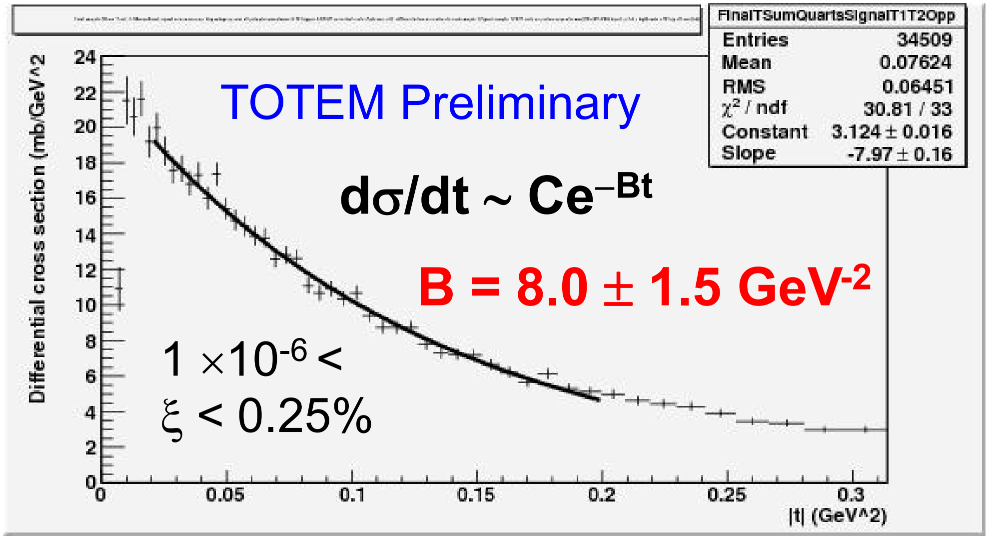
proton ξ (& MC) for class migration

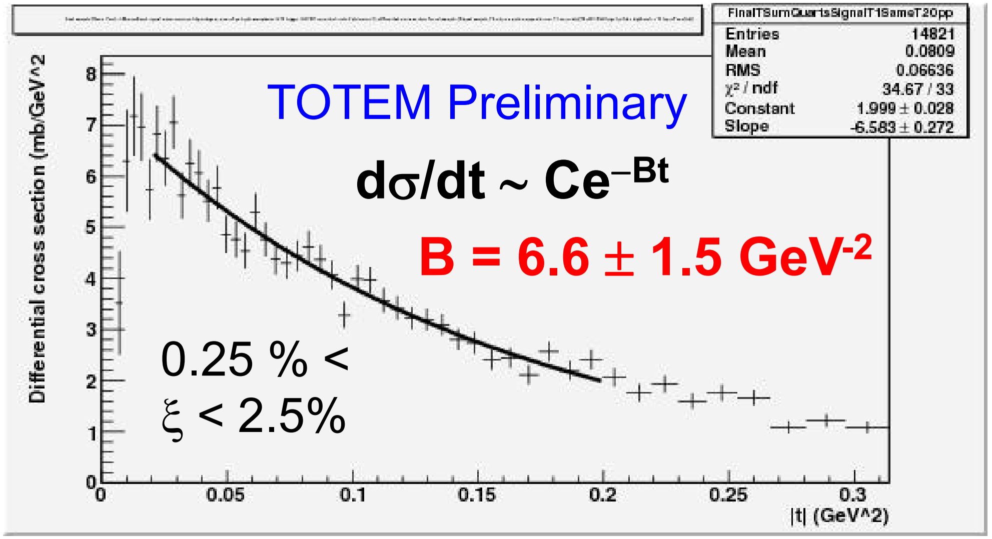
background & acceptance in highest M_{diff} class ($\xi > 2.5$ %) under study!

Soft SD cross-section @ √s = 7 TeV

t-distributions (acceptance/inefficiency corrected, background subtracted)







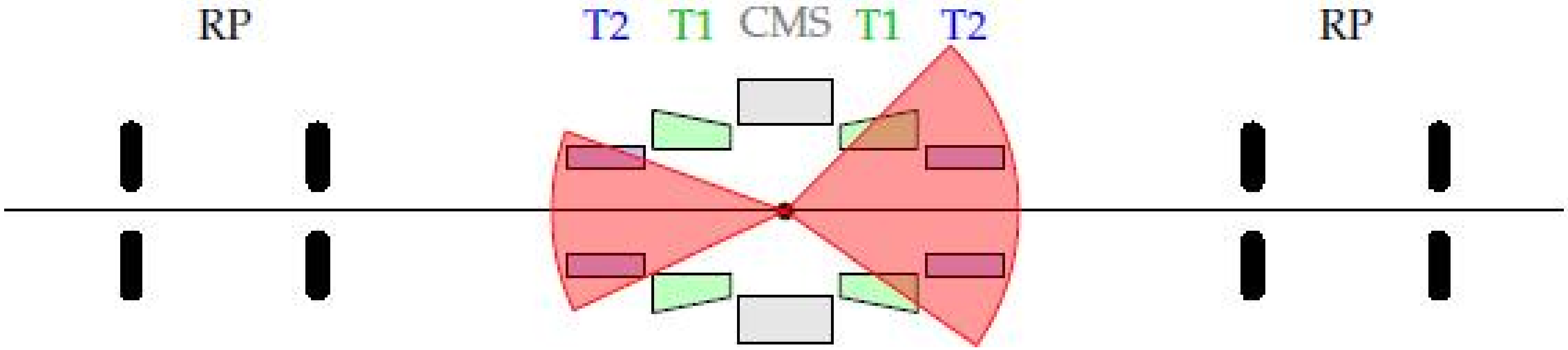
t-distributions still to be corrected for beam divergence & effect of ξ on proton ϕ-acceptance correction

$$\frac{d\sigma_{SD}^{class\ i}}{dt} = e^{-B_i t} - \text{backgr.}$$

$$\sigma_{SD}(\xi > 2\times 10^{-7}) = \sum_i \int_0^\infty dt \frac{d\sigma_{SD}^{class\ i}}{dt}$$

Soft DD cross-section @ √s = 7 TeV

σ_{DD} require large η coverage ⇒
CMS + TOTEM @ √s = 8 TeV

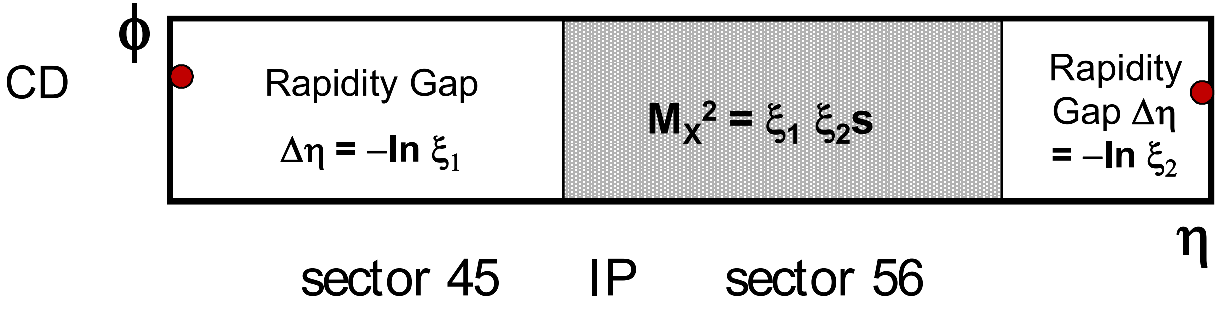


Select clean DD sample (S/B >> 1):

Require $3.4 < M_{diff} < 8$ GeV on both sides:
require tracks in both T2s & no tracks on both T1s
⇒ σ_{DD} ($|\eta_{min}|$) for $3.4 < M_{diff} < 8$ GeV region

TOTEM

CD candidate: large ξ & small ξ



CD

ϕ

Rapidity Gap

$\Delta\eta = -\ln \xi_1$

$M_X^2 = \xi_1 \xi_2 s$

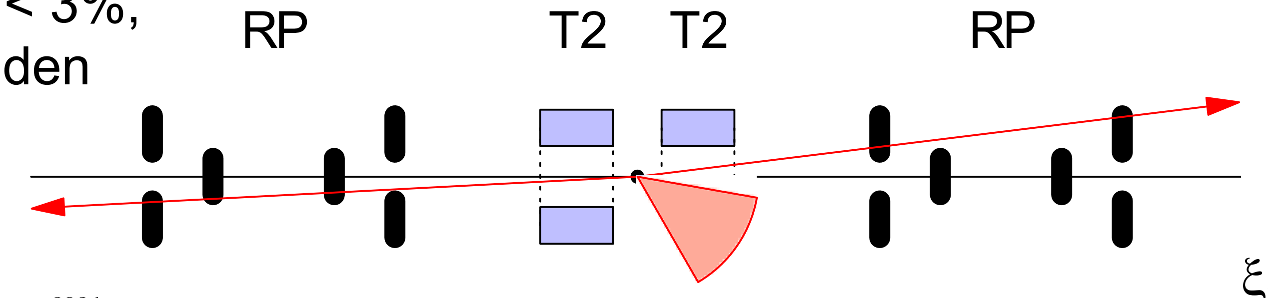
Rapidity Gap $\Delta\eta$ $= -\ln \xi_2$

η

sector 45 IP sector 56

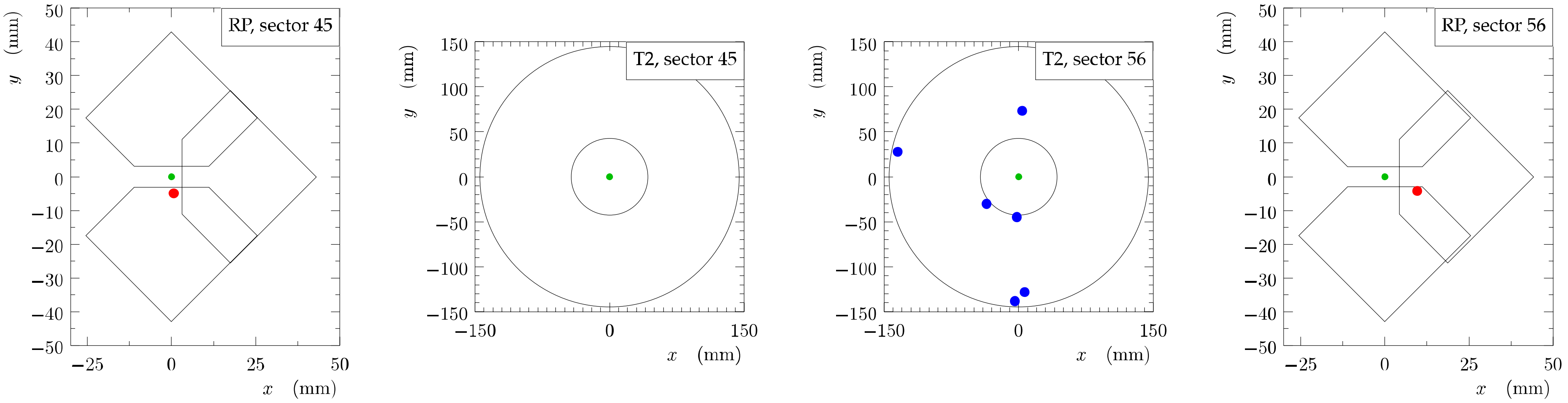
Correlation between proton in RP & tracks in T2 (& T1) !!

$5\times10^{-7} < \xi_1 < 3\%$,
T2 forbidden



$\xi_2 > 10\%$, T2 full

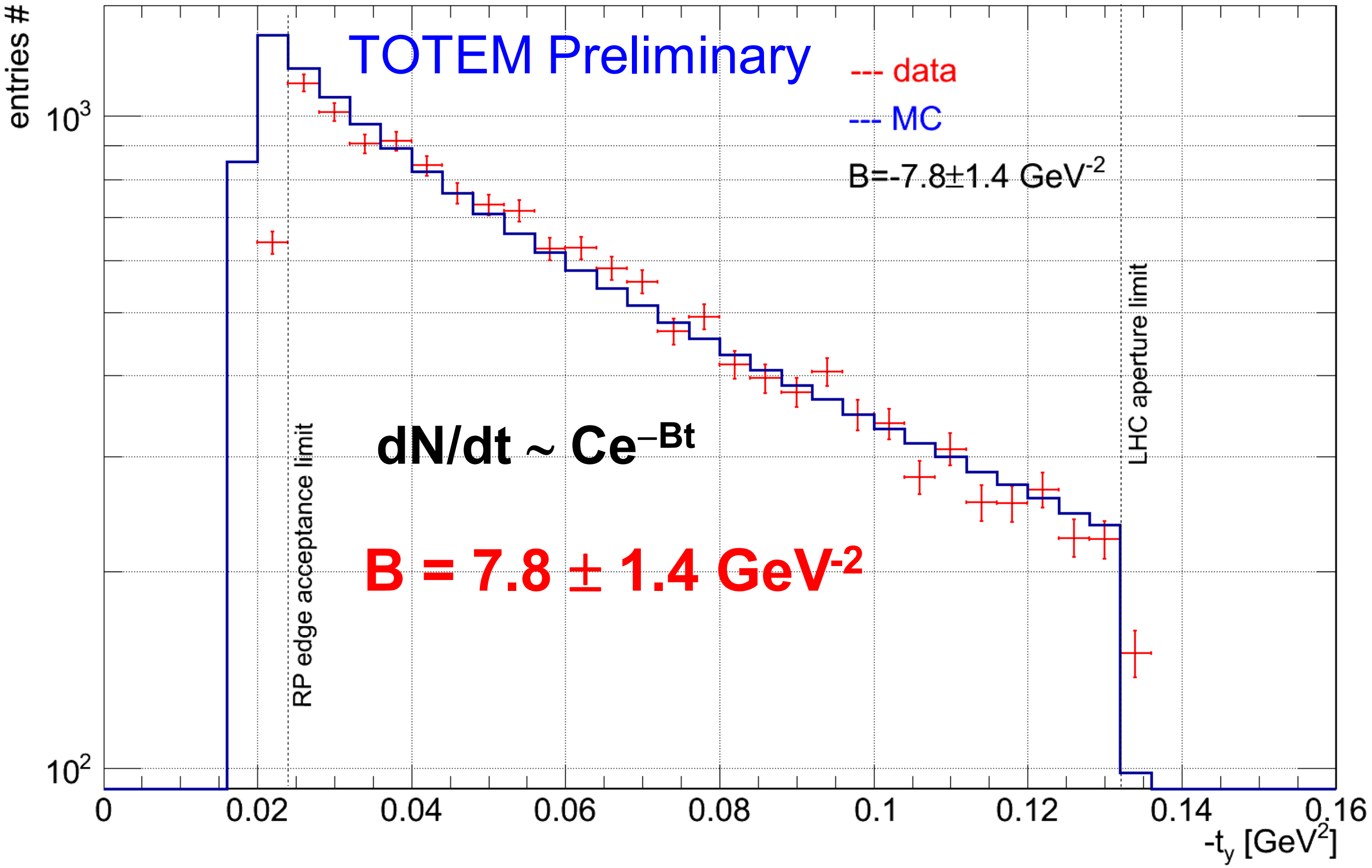
run: 37220007, event: 9904



Soft CD cross-section @ $\sqrt{s}$ = 7 TeV

- **2 protons with top RP45 + top RP56 or bot RP45 + bot RP56 topology**
  removing elastic background)
- **$y_{RP} < 11\sigma_{beam}$ removed : protection against pile-up**
  beam halo × beam halo
  beam halo × elastic proton

1 arm CD rate (integrated ξ, acceptance corrected)



σ_{DPE} estimation:

$$\frac{d^2\sigma_{CD}}{dt_1 dt_2} =$$

$$C(\Delta\varphi_{1,2})e^{-Bt_1}e^{-Bt_2} - \text{backgr.}$$

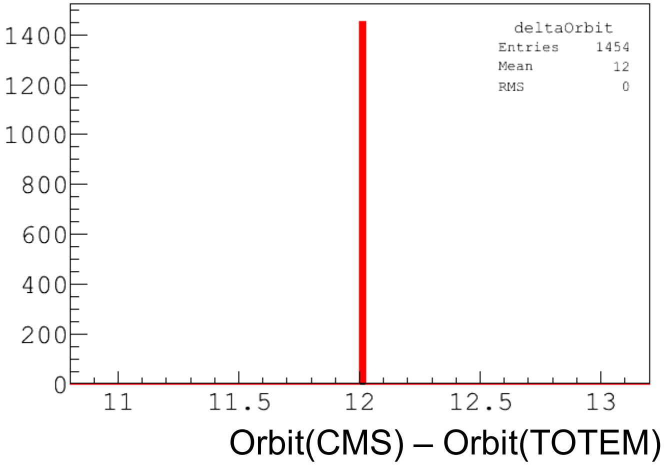
$$\sigma_{CD} = \int_0^\infty dt_1 \int_0^\infty dt_2 \frac{d^2\sigma_{CD}}{dt_1 dt_2}$$

$$\approx 1\,\text{mb}$$

CMS-TOTEM common runs 2012

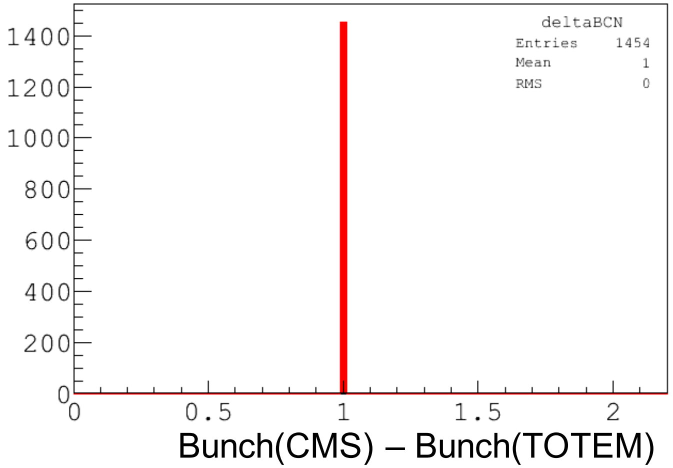
Separate data taking with bidirectional exchange of trigger information (RP & T2 trigger to CMS, combined dijet & lepton/γ trigger to TOTEM)

Orbit number difference



Offline matching with orbit & bunch number

Bunch number difference



Unique setup !

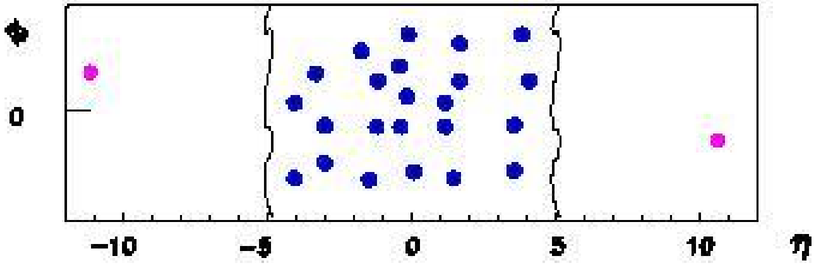
Large η-coverage:
CMS: -5.5<η<5.5,
T1: 3.1 < |η| < 4.7
T2: 5.3 < |η| < 6.5
FSC: 6 < |η| < 8
RP: diffractive protons

On-going analysis:

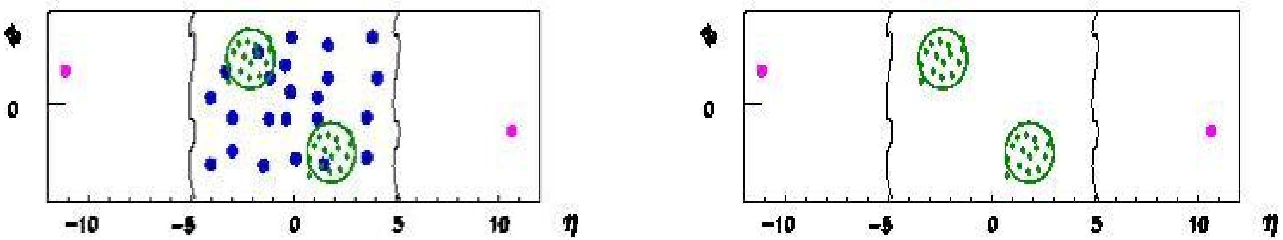
- **dN/dη with CMS tracker (|η| < 2.4) & T2 (5.3 < |η| < 6.5) with same T2 trigger**
- **SD dijet with proton**
- **Soft & semi-hard CD**
- **…**

CMS + TOTEM @ √s = 8 TeV

Soft CD



Semi-hard CD



2-arm proton reconstruction, $\xi_{1,2}=\Delta p_{1,2}/p_{1,2}$ (never before)

Mass to be seen in CMS from reconstructed protons: $M^2 = s \cdot \xi_1 \xi_2$

Initial vs. final state comparison: M_{TOTEM} (pp) =? M_{CMS} (never before)

Prediction of central particle flow topology from proton ξ's (rapidity gaps):

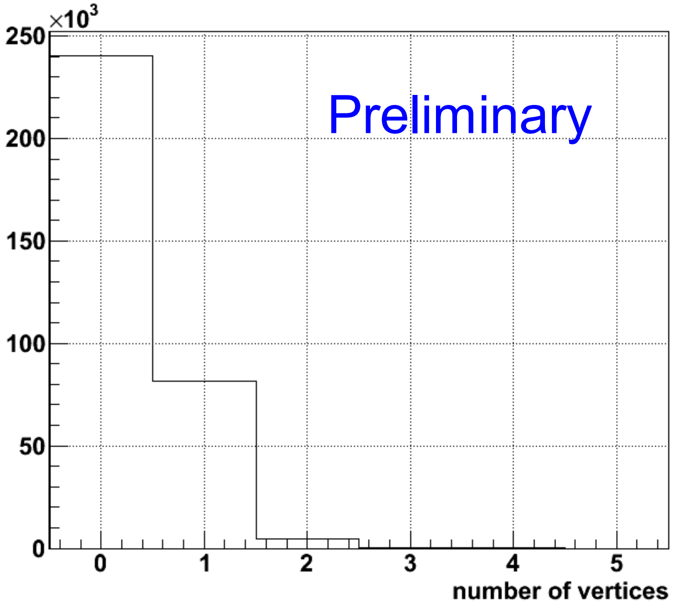
$\Delta\eta_{1,2} = -\ln\xi_{1,2}$

CMS-TOTEM CD samples

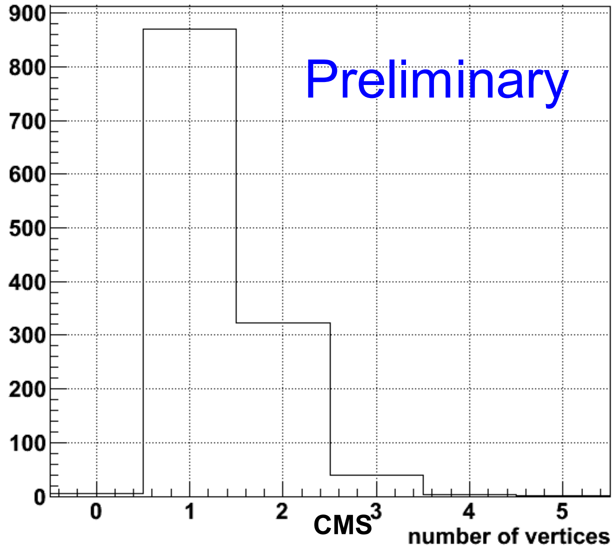
Jul 2012, β^*=90m, ~7×10^{10} p/bunch, inelastic pileup 0.03-0.05, RP@$9\sigma_{beam}$

- **Soft CD sample (RP45×RP56 trigger): 0.8 nb^{-1} (2-3 bx)**
  - **inelastic proton pair (+ CMS vertex): 330 k (80 k of which 48 k good)**
  - **$RP_{inelastic\ trigger}/T2_{trigger} = 0.5\% \approx \sigma_{DPE}/\sigma_{Min.Bias}$ (as expected)**
- **Semi-hard CD sample (CMS dijet pT > 20 trigger): 43 nb^{-1} (112 bx)**
  - **Inelastic proton pair (+ 1 valid CMS vertex)) / dijet: 1248 (860) / 2.5 M**

# of vertices, soft CD, 2 inelastic p in RPs



# of vertices, dijet, 2 inelastic p in RPs



Soft CD pileup

$N = 7\times10^{10}$, $\beta^{*}=90m$, $\varepsilon_N= 3.5\ \mu m$, $L/bx \approx 6.0\times10^{27} cm^{-2}\ s^{-1}$

Soft CD pile-up estimation

Events & Pile-up	Acc. t	Rate/bx	Expected events #	Fraction
CD (~1mb)	35%	0.022 %	263k	80 %
Soft SD × Soft SD		6.9×10^{-6}	9 k	3 %
SD × beam halo		1.9×10^{-5}	5k – 25k	1.5% - 8%
beam halo × beam halo		2.5×10^{-5}	7k – 34k	2% - 10%
CD + QCD			10k	3%

Pile-up removal:

- **0 or 1 vertex in CMS**
- **RP near edge area removed (1 elastic p. + beam halo or SD)**
- **top RP45 + top RP56 or bot RP45 + bot RP56 topology**
- **$\xi > 1.5$ % (far enough from resolution effects)**
- **FSC empty : QCD background protection**
- **M_{CMS}(Particle Flow + missing momentum) $\leq M_{TOTEM}$(pp)**

Semi-hard CD pileup

$N = 0.7\times10^{11}$, β^{*}=90m, ε_N= 3.5 μm, L/bx $\approx 6.0\times10^{27}$ cm^{-2} s^{-1}

Semi-hard CD pile-up estimation

Pile-up case	Accept.	Rate/bx	Events in 2.5M	Fraction of accepted semi-hard CD canditates
2×Soft SD (+QCD JJ)	25%	1.7×10^{-5} $(\cdot\ 4.9\times10^{-5})$	42.5	3.4 %
Soft CD (+QCD JJ)	35%	$2.9\ \times10^{-4}$ $(\cdot\ 4.9\times10^{-5})$	721	58 %
Semi-hard SD + Soft SD		7.2×10^{-10} $-\ 7.2\times10^{-9}$	37-370	3 % – 30 %
Semi-hard CD + SD		3.5×10^{-11} 3.5×10^{-10}	2 – 20	0.1 % – 1.5%
Beam halo (+QCD JJ)				~1%

Soft & semi-hard CD - logic 0

- CMS and TOTEM consistent (within resolution)

  M_{CMS}(Particle Flow) = M_{TOTEM}(pp)

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

- Few semi-hard (pp → p + Xjj + p) candidates observed of which none exclusive (pp → p + jj + p)
- Soft (pp → p + X + p) sample many candidates

- Constraints & checks applied:
  - Pile-up rejection
  - Selection criteria (kinematics, rapidity gaps…)
  - Single, well defined CMS vertex
  - Jets resolutions & detector thresholds (checked with elastic scattering)

Selected semi-hard CD 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
243.97	219.344	138.422	-343.07	-254.548	-0.0955	-0.00973	3.3627	5.64E-01

only 1 additional track in T2

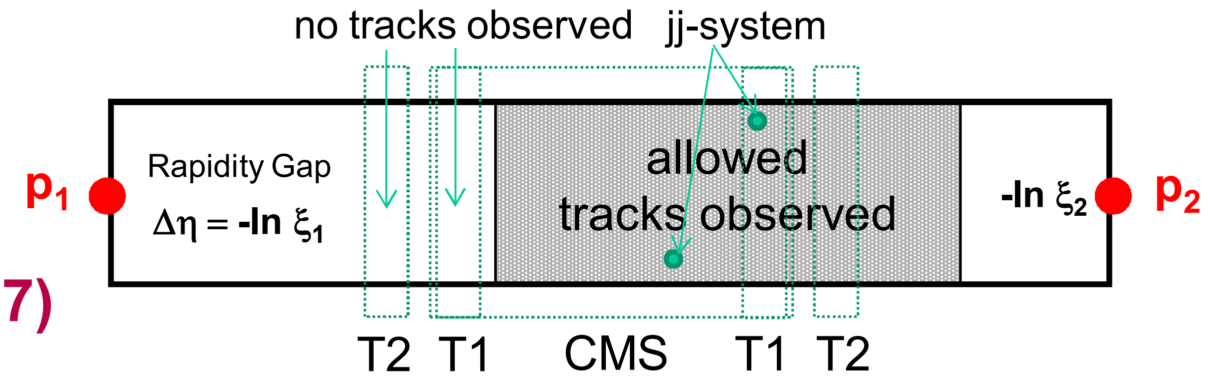
Semi-hard CD - logic 1

- M_{CMS}(Particle Flow + missing momentum) $\leq M_{TOTEM}$(pp)
- Additional momentum undetected by CMS
- Tracks in forward detectors, when allowed by ξ-predicted gaps
- No tracks in forward detectors when forbidden by ξ-predicted gaps

~ 50 candidates

no exclusive

(largest M_{jj}/M_{TOTEM} ~ 0.57)



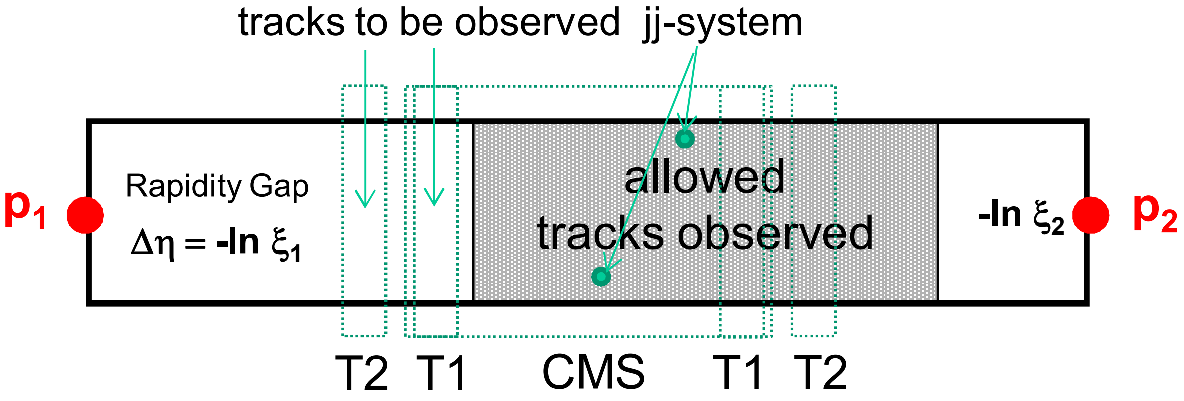
Best events in terms: M_{CMS}(Particle Flow + missing p) $\approx M_{TOTEM}$(pp)

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	-0.0146	-0.0973
138.422	219.344	250.076	243.97	-254.548	-343.07	-0.0955	-0.00973
93.3026	254.456	341.96	335.624	319.223	612.358	-0.0107	-0.164
81.0462	179.616	198.14	204.673	-295.344	-364.838	-0.0979	-0.00668
123.347	188.163	251.145	234.579	-140.216	-286.387	-0.081	-0.0105
61.3357	162.727	215.088	198.103	-359.435	-639.511	-0.164	-0.00375

NB! Almost all soft CD events statisfy logic 1

Soft & semi-hard CD - logic 2

- Look for secondaries (decay products) violating ξ-predicted gaps
- Standard pile-up protection
- M_{CMS}(Particle Flow + missing p) ≤ M_{TOTEM}(pp)
- Normally discarded due to presence of tracks in forbidden gaps



Semi-hard CD sample: no candidates

Soft CD sample: some candidates
expect background from 2 × soft SD & soft SD + beam halo

Soft & semi-hard CD - logic 3

- **Check escaping-mass candidates**
- **Standard pile-up protection**
- **p_{CMS}(Particle Flow) ≠ p_{TOTEM}(pp)**

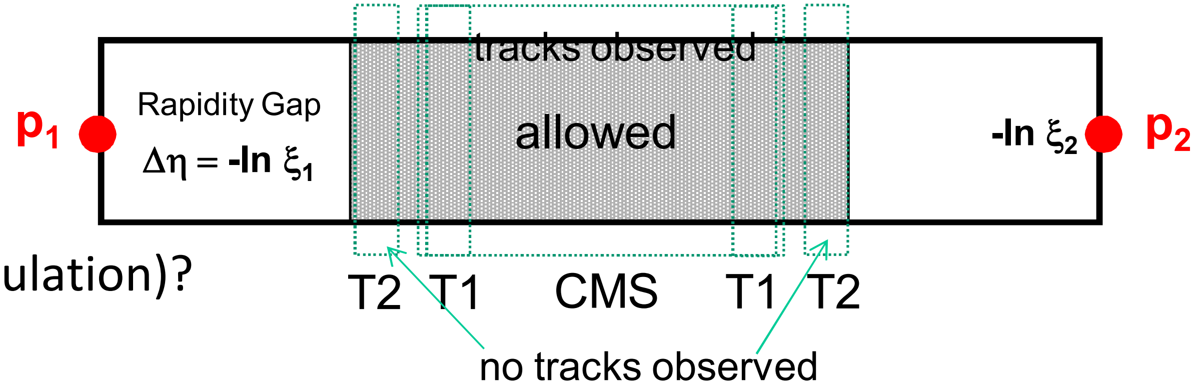
  M_{CMS}(Particle Flow + missing p) ≤ M_{TOTEM}(pp)

  → existence of tracks undetected by CMS

- **No tracks observed in forward detectors ‘allowed’ by gaps**
- **More forward regions excluded by gaps → ‘allowed’ = ‘required’ ?**

- Energetic gammas in T2, N*→p
- Detector ‘inefficiencies‘?
- Acceptance gaps between detectors?
- High energy neutrinos?
- Neutral particle flow in T2 (under simulation)?
- Real escaping energy?

  This depends on amount of missing energy



~ 10 candidates with $\Delta M = M_{TOTEM} - M_{CMS}$ ~ 400 GeV or more

Semi-hard CD - logic 4

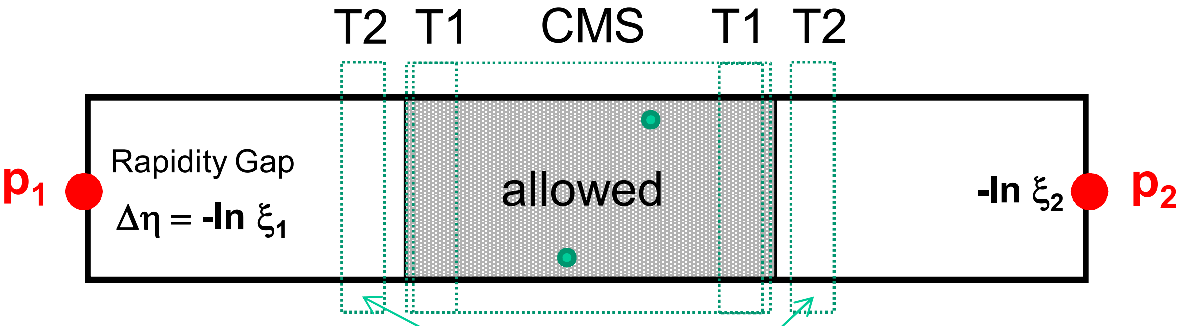
- Same selection as Logic-3 (escaping-mass candidate search)

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

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

  → existence of energy undetected by CMS

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



no tracks observed

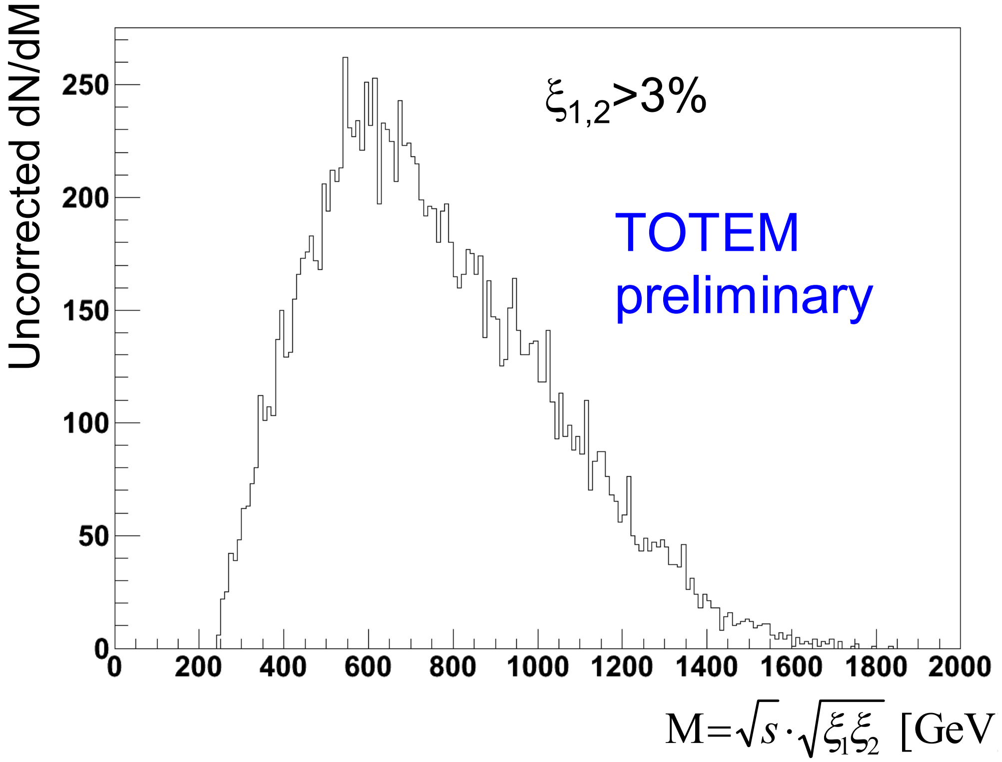
tracks forbidden by rapidity gaps

Semi-hard CD sample: no candidates observed

NB! In soft CD events overwhelmed by pileup

Soft & semi-hard CD – highest mass

Soft CD M_{TOTEM} distribution



Highest soft CD M_{TOTEM} candidates:

M_{TOTEM}	Pz_{TOTEM}	Xi_{left}	Xi_{right}
1830.91	-91.5223	-0.240589	-0.217709
1792.09	-147.443	-0.243199	-0.206338
1719.7	220.329	-0.189179	-0.244261
1718.48	-17.6895	-0.217033	-0.212611
1716.62	-103.546	-0.227911	-0.202024

M_X = 1.8 TeV with pp survival (never before)

In semi-hard CD candidates up to M_{TOTEM} of 1.45 TeV:

M_{TOTEM}	xileft	xiright
1402.31	0.191	0.161
1432.62	0.241	0.133
1436.38	0.189	0.171
1453.09	0.180	0.183

Future plans – diffraction

- Lots of potential studies & measurements ahead
- TOTEM alone: soft SD, CD, DD
- CMS + TOTEM data analysis:
  - Homework: beam halo pile-up, optics, resolutions, acceptance, reconstruction …
  - SD & CD cross-sections
  - Further studies of particular events (event displays)
  - pA data with p measured in RP (+ Castor & ZDC)
- Upgrade of TOTEM Roman Pot detectors to profit from low-β^* optics after LHC shut-down
- Data taking: 1000 bunches + x-angle @ $\beta^* = 90$ m

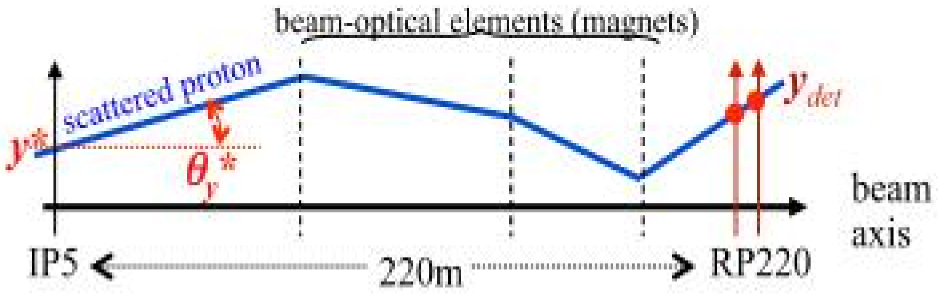
The End

Optics

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

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

$\xi = \Delta p/p$: momentum loss (diffraction)



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

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

Elastic: $\xi = 0$

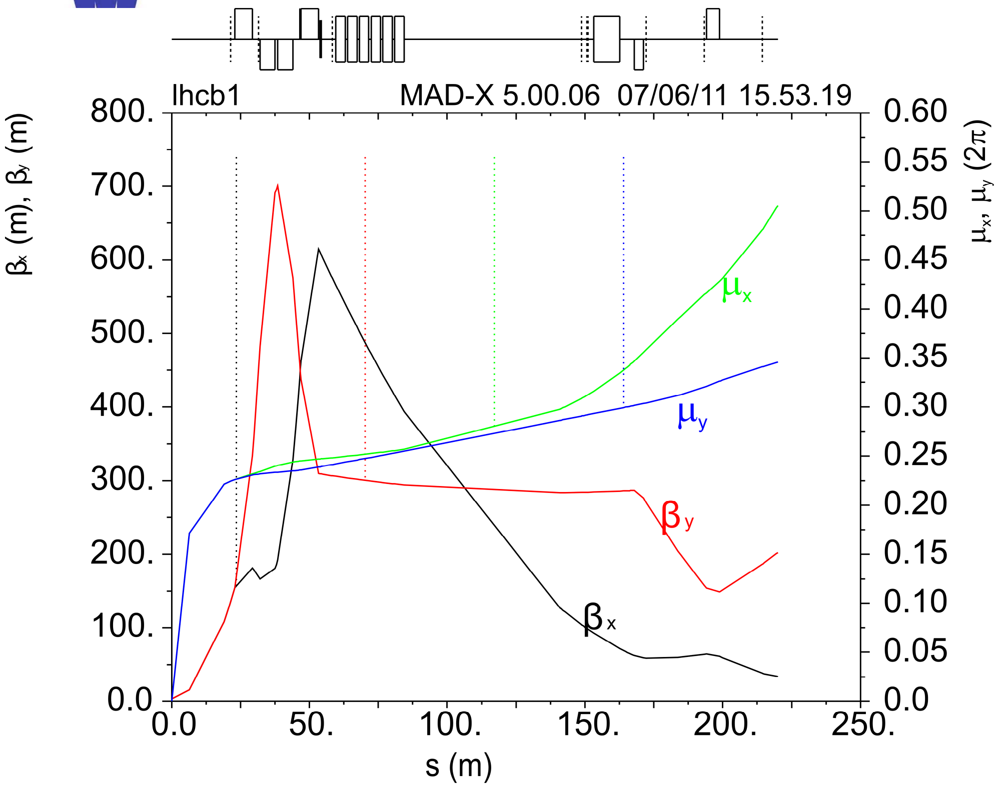
$\beta^* = 3.5$ m: $L_y \approx 25$ m, v_y small
$\beta^* = 90$ m: $L_y \approx 260$ m, $v_y \approx 0$
$\Rightarrow$ θ^*_y reconstructed from track position

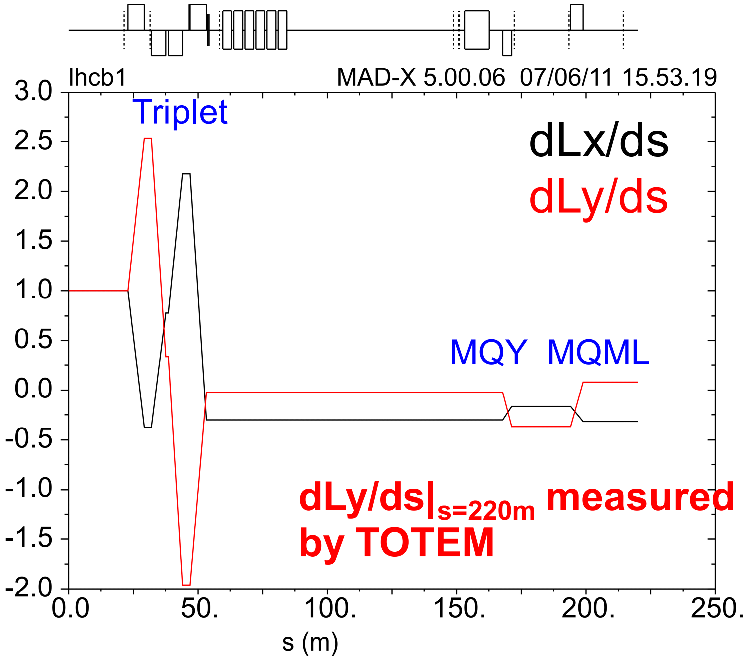
$\beta^* = 3.5$ m & 90 m: $L_x \approx 0$ m, v_x sizable
$\Rightarrow$ θ^*_x reconstructed from track angle

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

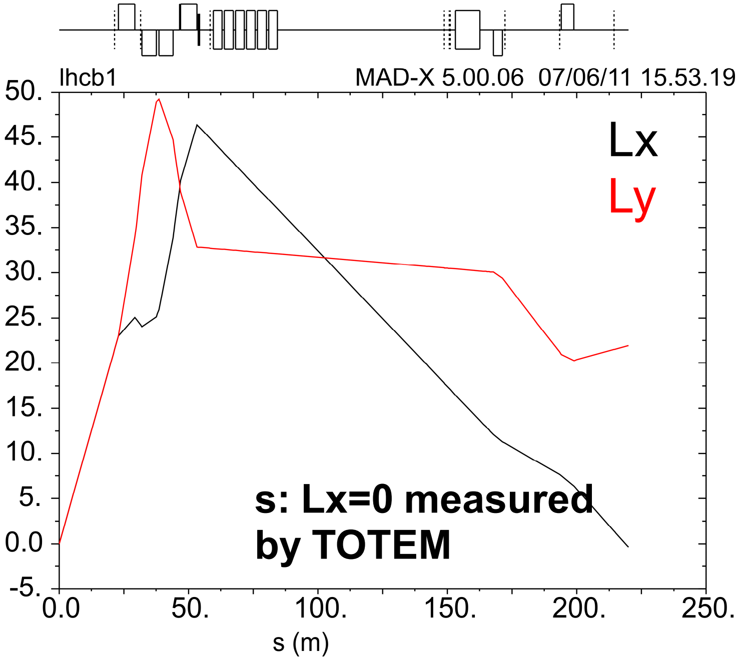
	Beam width @ vertex $\sigma^*_{x,y} = \sqrt{\varepsilon\beta^*}$	Angular beam divergence $\sigma^*_\Theta = \sqrt{\frac{\varepsilon}{\beta^*}}$	Min. reachable |t| $\left\|t_{\min}\right\| = n_\sigma^2 \frac{p^2\varepsilon}{\beta^*}$
Standard optics $\beta^* \sim 1$–3 m	$\sigma_{x,y}{}^*$ small	$\sigma(\theta_{x,y}{}^*)$ large	$\|t_{\min}\| \sim 0.3$–1 GeV^2
Special optics $\beta^* = 90$ m	$\sigma_{x,y}{}^*$ large	$\sigma(\theta_{x,y}{}^*)$ small	$\|t_{\min}\| \sim 10^{-2}$ GeV^2

Optics verification





$dLy/ds|_{s=220m}$ measured by TOTEM

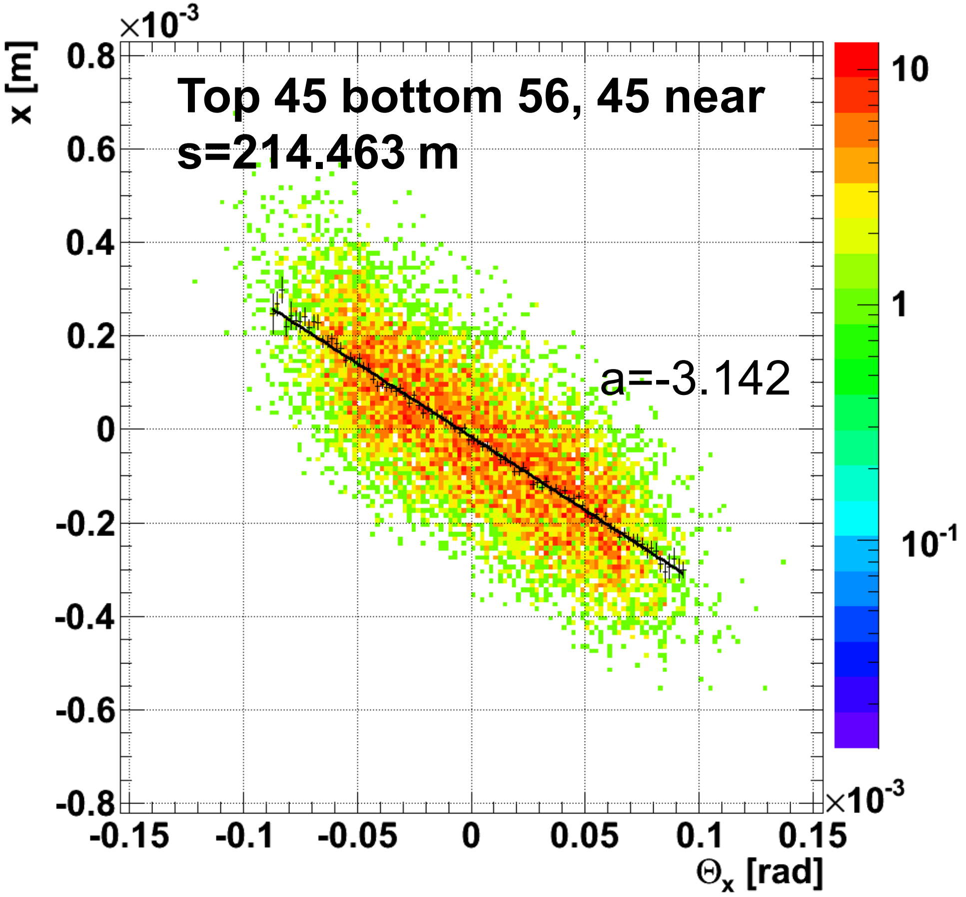


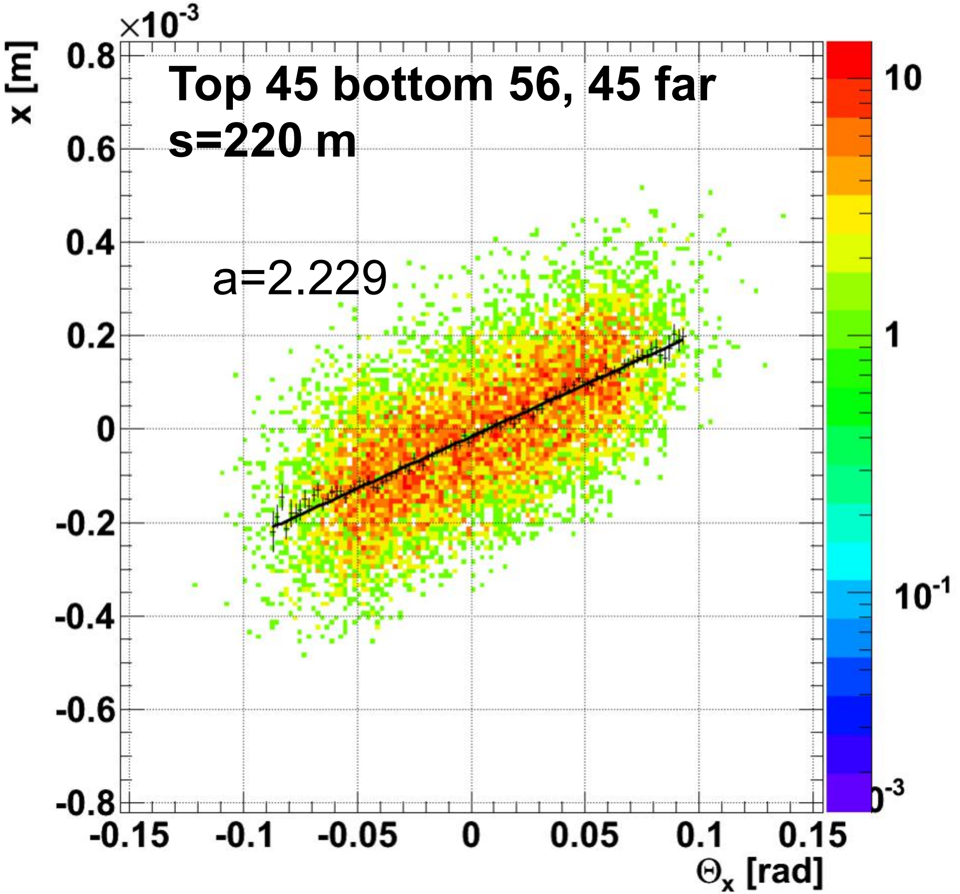
s: Lx=0 measured by TOTEM

$$\begin{cases} L_y(s) = \int\limits_0^s \frac{dL_y(\tau)}{d\tau}\, d\tau + C_1 \\ \frac{dL_y(s)}{ds} = \int\limits_0^s L_y(\tau)k(\tau)\, d\tau + C_2 \end{cases}, \quad \text{with} \quad \begin{cases} L_y(0) = 0 \\ \frac{dL_y}{ds}(0) = 1 \end{cases}$$

s: Lx(s)==0 determination

- Four fits per diagonal, 8 in total, diagonals averaged





Interpolation: Lx(s) = 0 for s = 217.8 m (nominally 222.1m)

Matched parameters

- Perturbation of (nominal) actual LHC settings
  - ~30 parameters per beam
  - Magnet positions, rotations, k
  - Beam energy, displacement, crossing angle, harmonics...
- Selected fitted parameters
  - 6 strengths per beam (MQXA, MQXB, MQXB, MQXA, MQY, MQML)
  - 6 corresponding rotations per beam
  - Mean ξ per beam
  - Total of 26 fitted parameters

Constraints

- TOTAL of 36
- LHC design constraints (a total of 26):
  - sigma(k)/k = 0.1%
  - sigma (rot) = 1mrad
  - Sigma(ξ)/ ξ = 10^{-3}
- Measured constraints of individual arms (a total of 8):
  - (dLy/ds)/Ly; near unit rotation (coupling); far unit rotation (coupling)
  - s: Lx==0 (1 m precision)
- Measured elastic scattering kinematics constraints between arms (a total of 2):
  - Ratio of Ly56 / Ly45 (0.2 % precision)
  - Ratio of (dLx/ds 56) / (dLx/ds 45) (0.5 % precision)

Matching solution

56	**dLx/ds**	**Ly [m]**	**ROT [mrad]**
RP215	-0.311962	22.1464676	0.0432331
RP220	-0.311962	22.6191755	0.0396463
∆ RP215	-2.84%	+0.78%	
∆ RP220	-2.84%	+0.81%	

45	**dLx/ds**	**Ly [m]**	**ROT [mrad]**
RP215	-0.314508	20.3883272	0.0400268
RP220	-0.314508	20.6709463	0.0372828
∆ RP215	-4.51%	+10.19%	
∆ RP220	-4.51%	+10.79%	

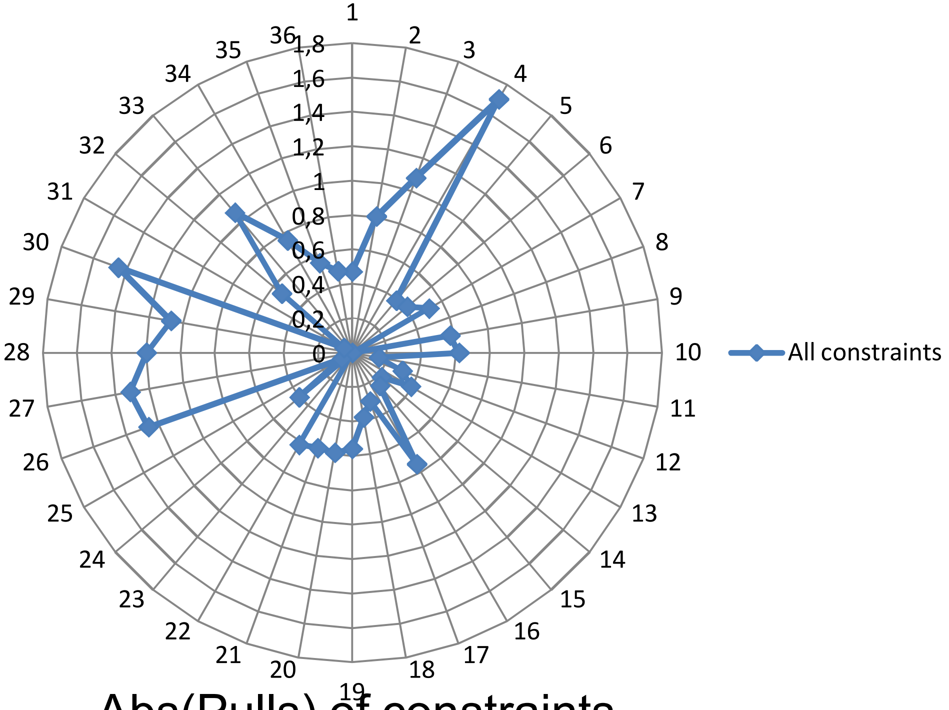
Strong correlations between fitted parameters

Principle Component Analysis (PCA) ideally should be applied

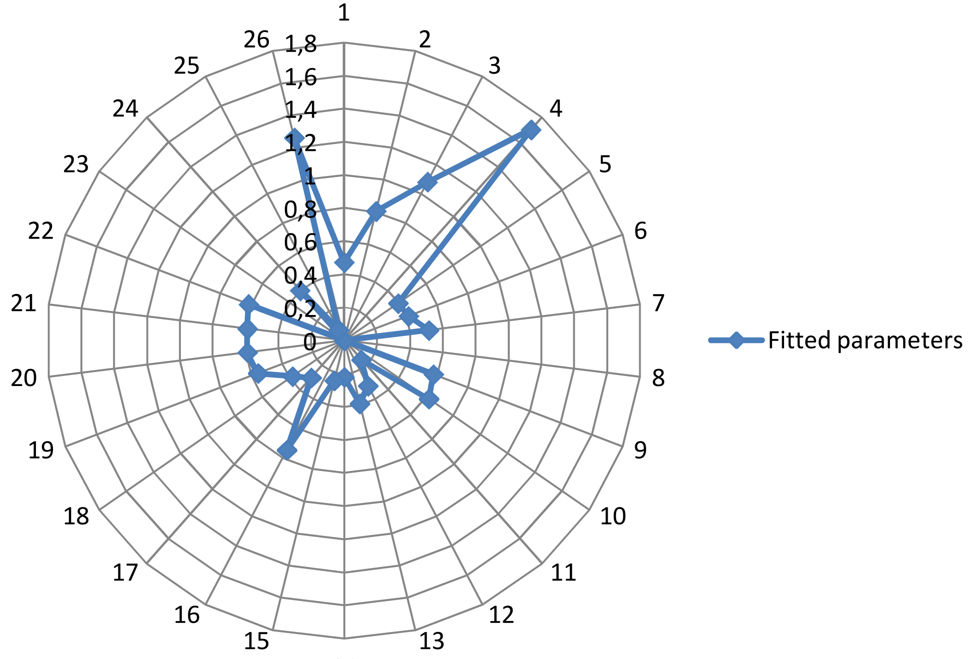
χ^2/NDF = 25.8/(36-26)=2.6

(would be lower in correlations are elmininated)

Matching results within the LHC tolerance

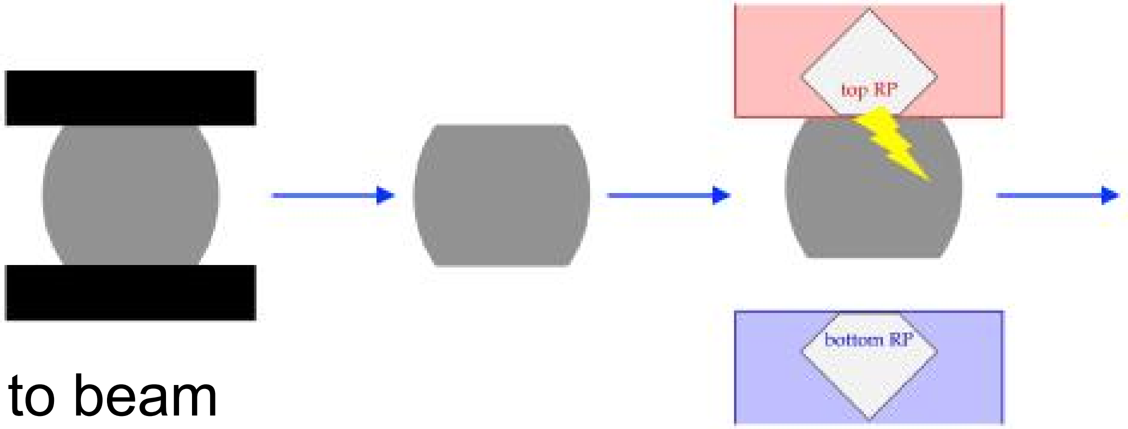


Abs(Pulls) of constraints



Abs(Pulls) of fitted parameters

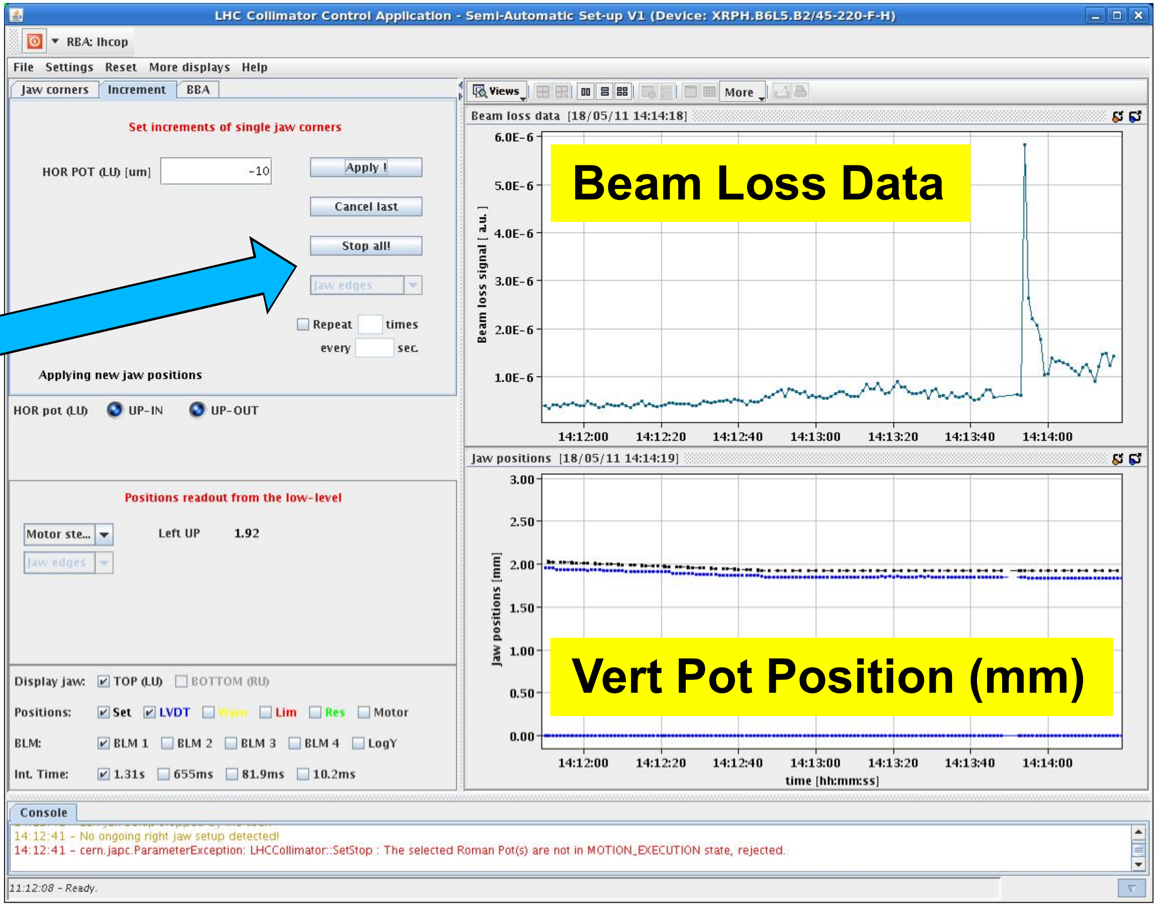
Beam-based RP alignment (scraping)



- Sharp edges to beam scraped by collimators

- Each RP approaches beam in 10 μm steps until touches beam edge (spike in beam loss monitors downstream of RP) $\Rightarrow$ RPs at same distance (in σ_{beam}) as collimators & beam centre in middle

Alignment of RPs w.r.t. beam



Beam Loss Data

Vert Pot Position (mm)

```
14:12:41 - No ongoing right jaw setup detected!
14:12:41 - cern.japc.ParameterException: LHCCollimator::SetStop : The selected Roman Pot(s) are not in MOTION_EXECUTION state, rejected.
11:12:08 - Ready.
```