Status of TOTEM @ LHC

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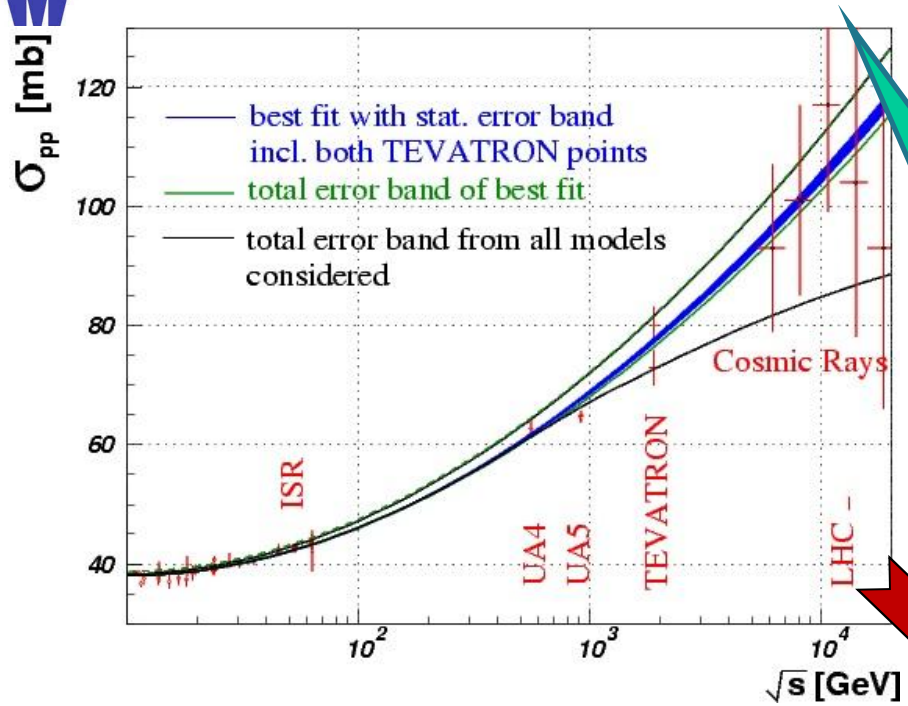
on behalf of
TOTEM collaboration

Particle Physics Day 30.10.2015

- Physics menu & experiment
- Latest physics results
- 2015 data taking
- RP upgrades

TOTEM physics menu

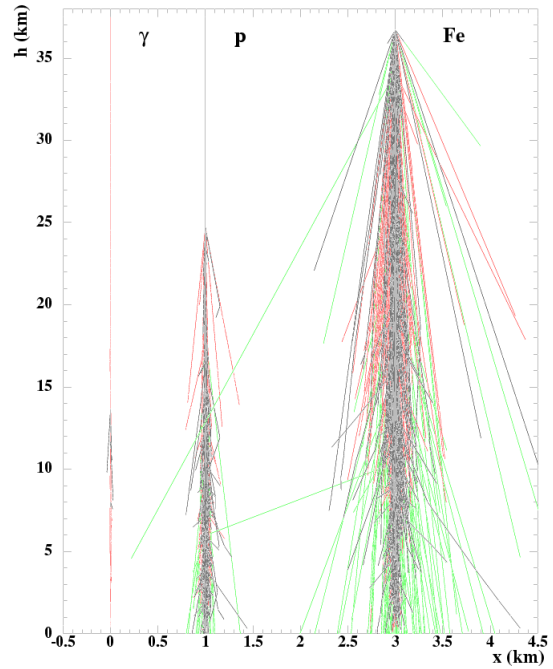
Total pp cross-section

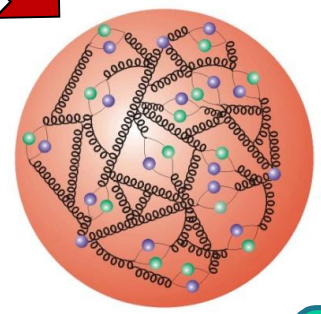


Ultimately ~1-2 % precision

Forward particle production

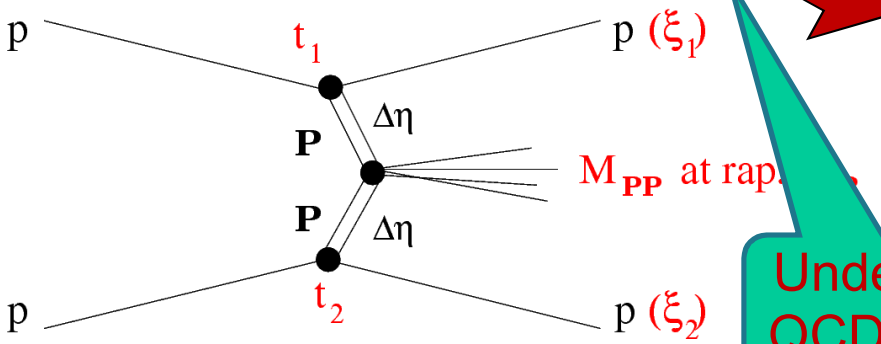
Cosmic ray connection





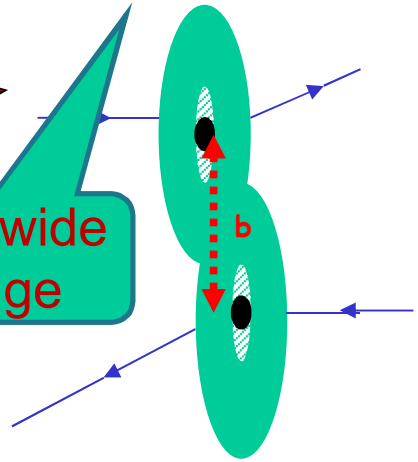
Proton

Diffraction: soft and hard



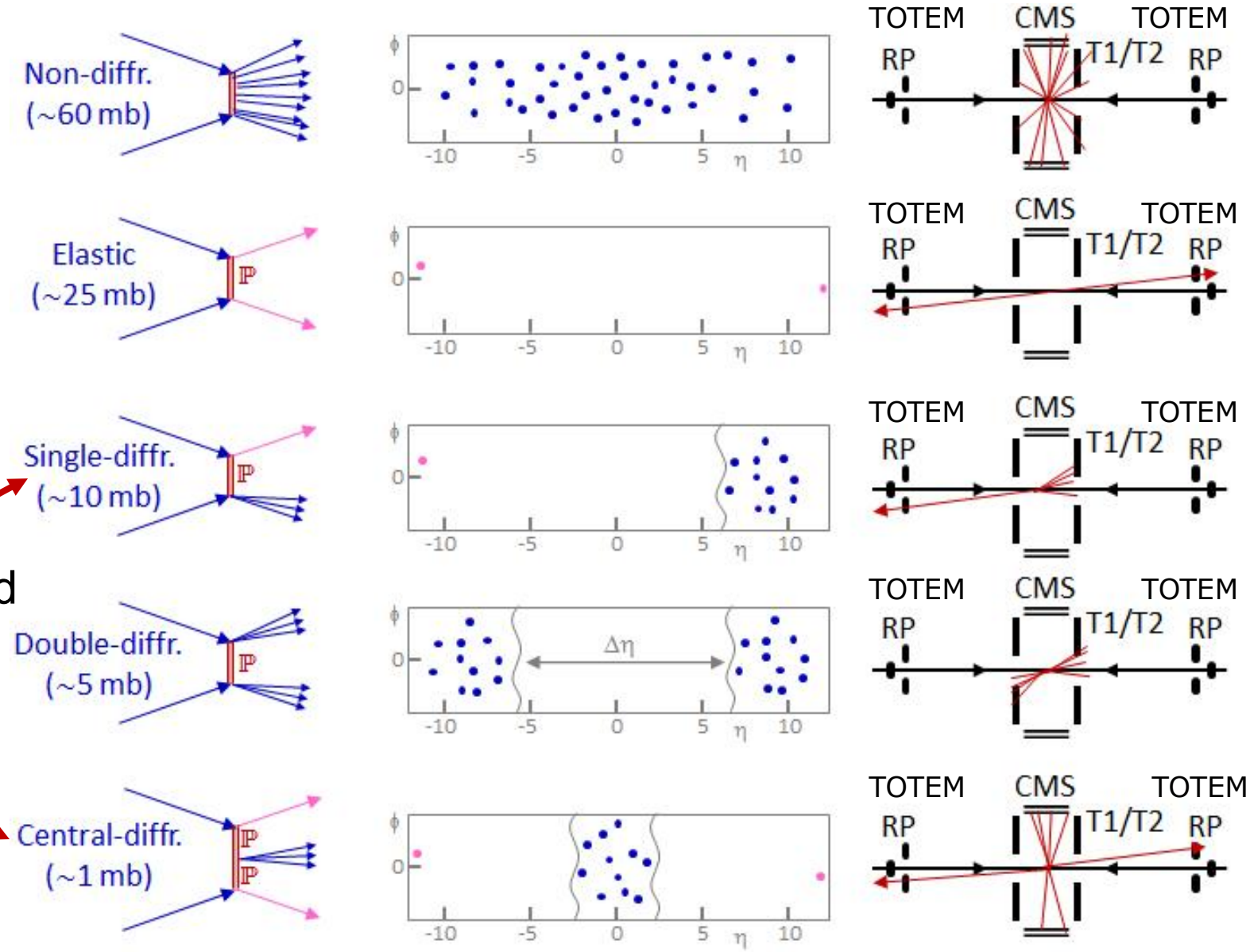
Understand QCD nature

Elastic pp scattering



Over a wide $|t|$ range

Main soft processes @ LHC



Also studies of hard (cc, bb, jets, W, Z etc..) SD & CD process with CMS

Elastic & diffractive scattering:
Pomeron (≈ colourless gluon pair/ladder) exchange

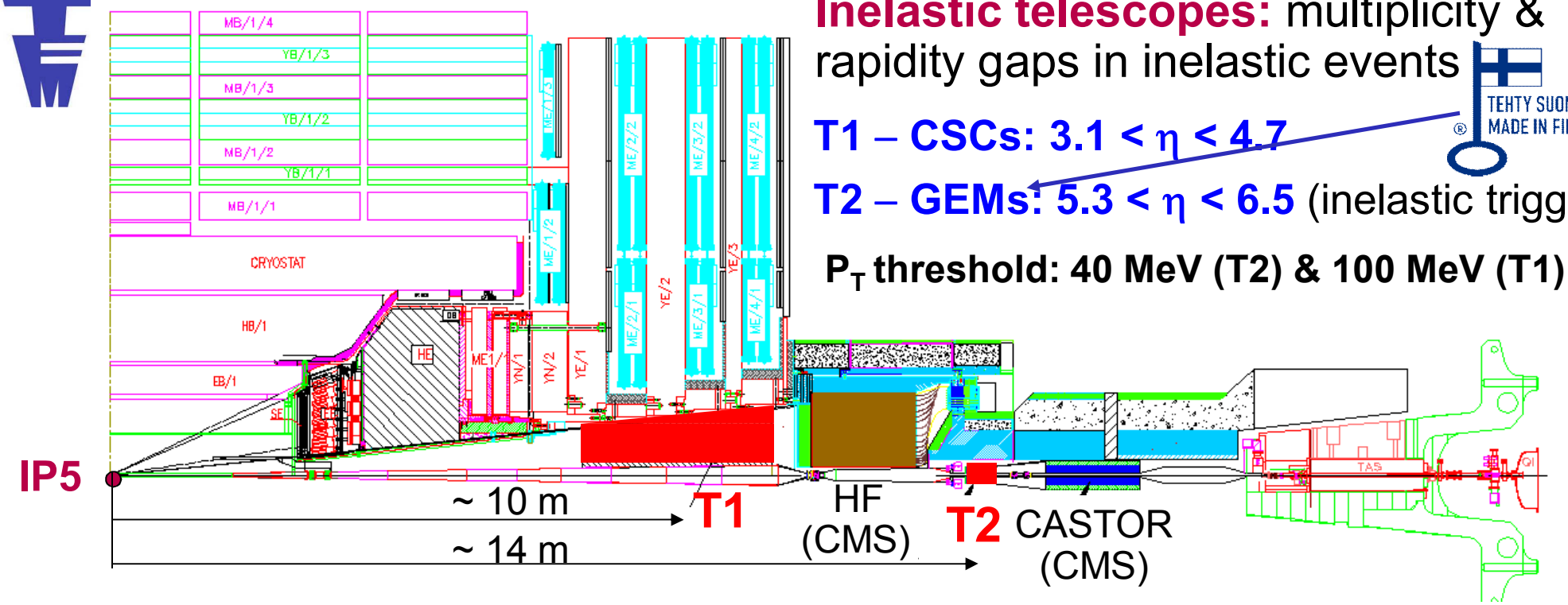
Experimental apparatus @ LHC IP5

Inelastic telescopes: multiplicity & rapidity gaps in inelastic events

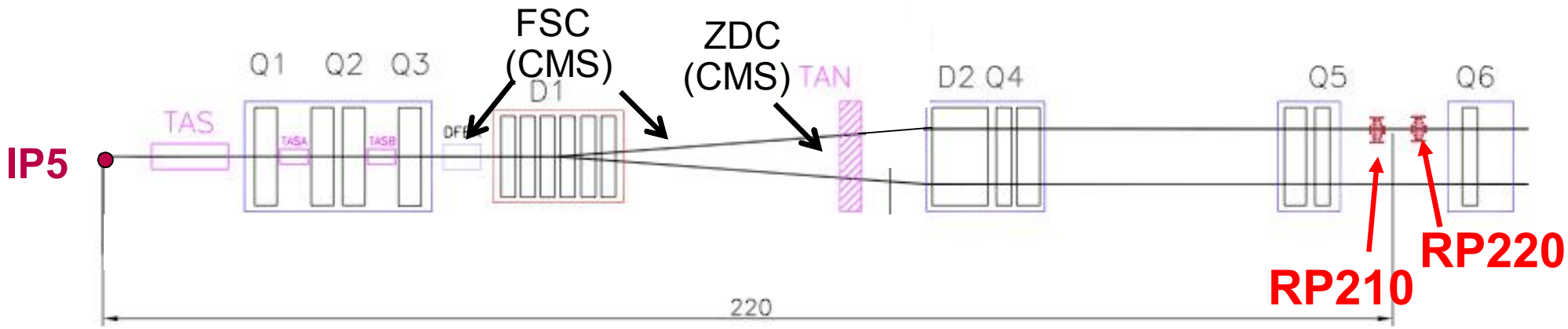
T1 – CSCs: 3.1 < η < 4.7

T2 – GEMs: 5.3 < η < 6.5 (inelastic trigger)

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



Roman Pots – Si μstrip sensors: elastic & diffractive protons (proton trigger)

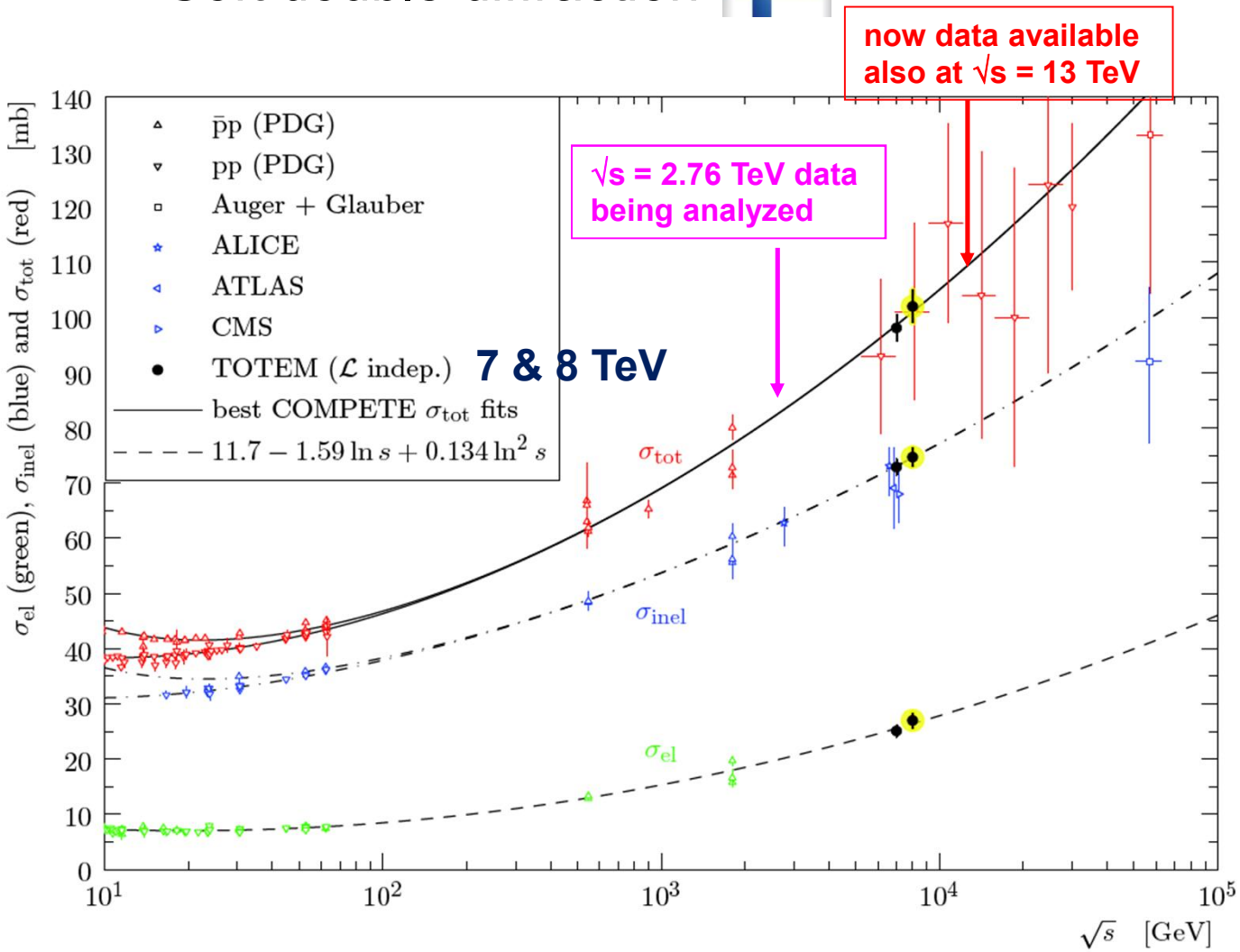


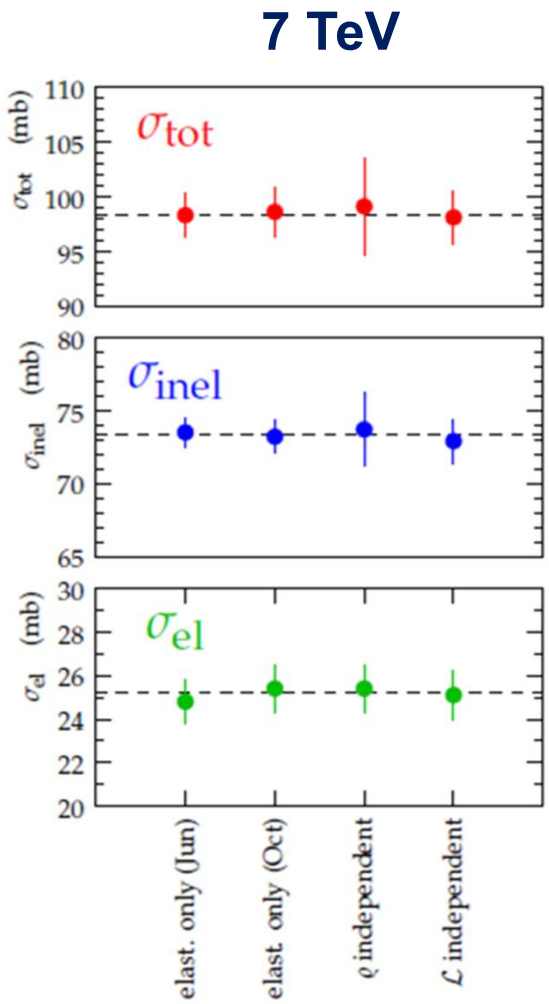
Consolidation & upgrade: RP relocation, DAQ upgrade, new RPs, timing & Si sensors

Published run 1 results

Physics coordination

- ✓ Total, elastic, inelastic pp cross-section at 7 & 8 TeV
- ✓ Elastic pp |t|-differential cross-section over wide-range at 7 & 8 TeV
- ✓ Forward $dN_{charged}/d\eta$ at 7 & 8 TeV (covering $3.8 \leq |\eta| \leq 7.0$)
- ✓ Soft double diffraction



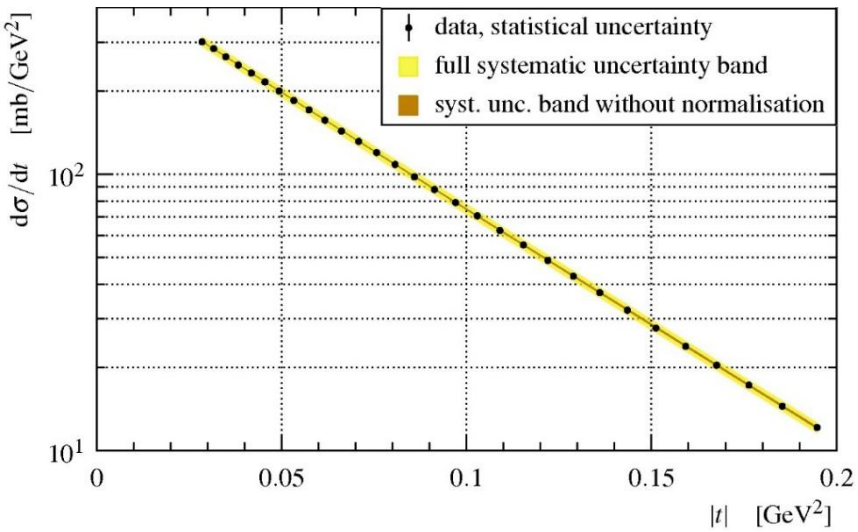


Non-constant exponential elastic dσ/d|t|

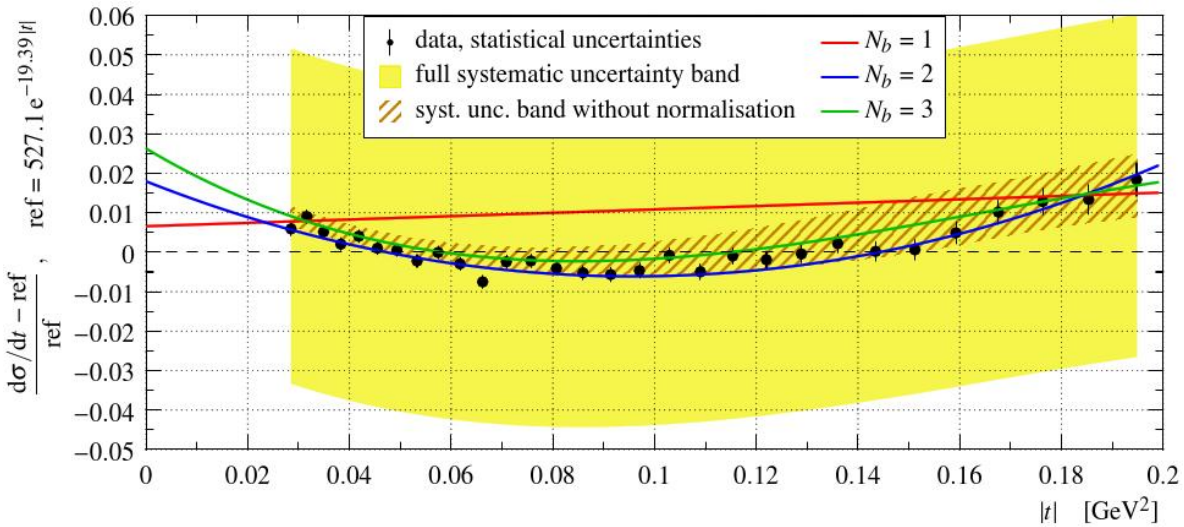
Published in *Nucl. Phys. B899 (2015) 527*

High statistics data set (β* = 90 m, 2012): dominated by hadronic interaction

Differential cross-Section dσ/d|t|



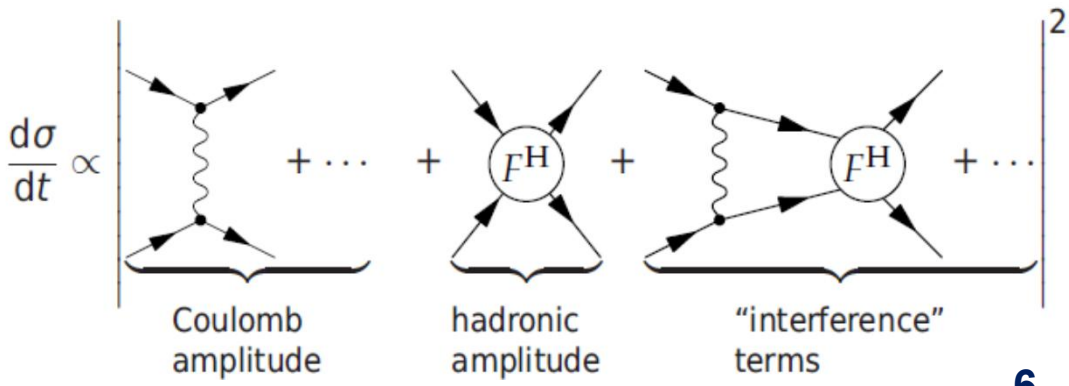
Relative deviation of dσ/d|t| from exponential



Pure constant exponential form ($ae^{-b|t|}$) excluded > 7σ significance.

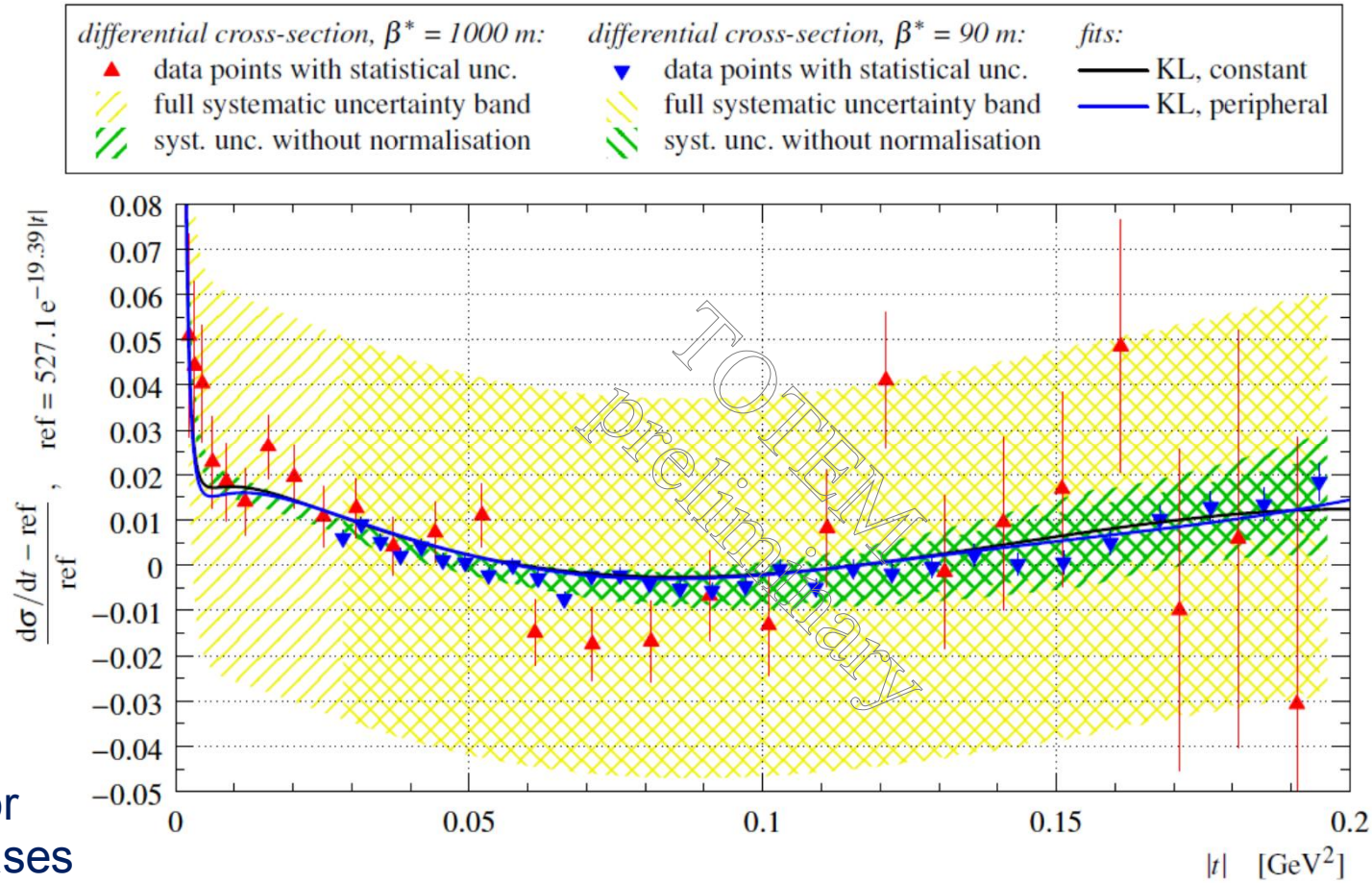
Low-|t| data set (β* = 1 km, 2012) to study Coulomb-hadronic interference:

- ✓ Sensitivity to |t|-dependence of phase of hadronic amplitude
- ✓ Measurement of ρ (~ phase at t = 0)

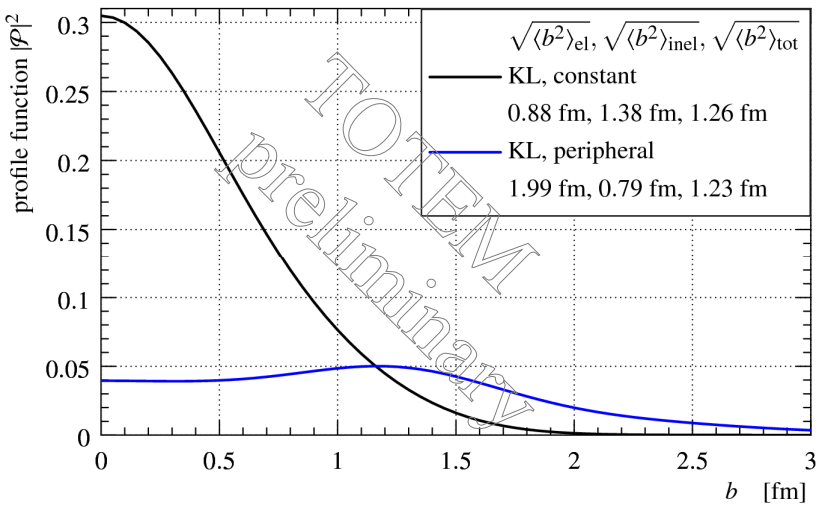


Elastic Coulomb-hadronic interference studies

Variable exponential slope with central or peripheral hadronic phase compatible with data ⇒ both centrality & peripherality of elastic collisions possible !



Impact parameters for central & peripheral phases



$\rho = 0.12 \pm 0.03$ @ 8 TeV
(first direct ρ measurement at LHC)

$\sigma_{tot} = 102.9 \pm 2.3$ mb @ 8 TeV
(first σ_{tot} taking Coulomb-hadronic interference into account at LHC)

2015 data taking

- ✓ LHCf run: very low pileup (μ ~ 0.003) with CMS solenoid off
  + dN/dη with T1 & T2 — June 2015

- ✓ β^* = 90 m RP alignment run: low pileup (μ ~ 0.1) with few bunches & RPs @ 5σ
  + total, elastic and inelastic cross-section & soft diffraction

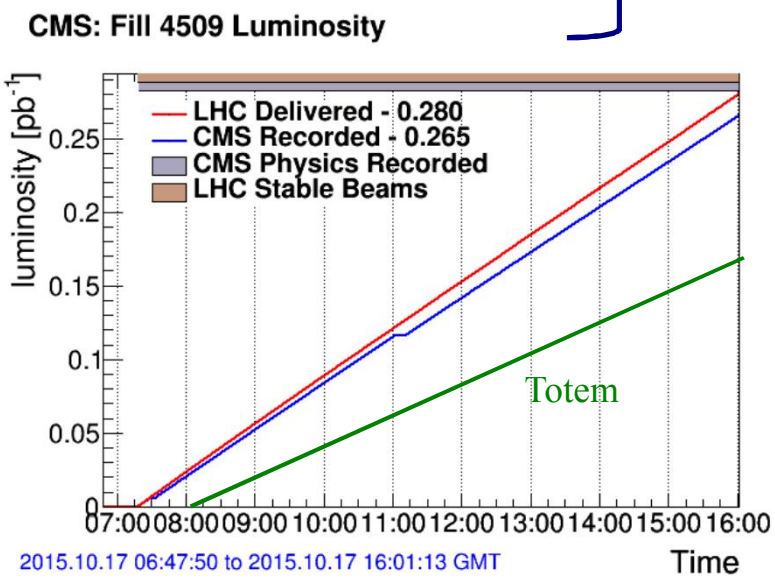
- ✓ β^* = 90 m common CMS-TOTEM physics runs:
  low pileup (μ ~ 0.1) with upto 700 bunches & RPs @ 10σ
  + exclusive low mass resonance production
  + hard single & central diffraction

  October 13-18 2015

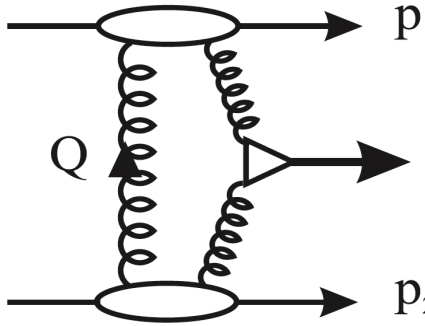
trigger exchange & offline data merging

Integrated Luminosity

LHC delivered : 0.74/pb
CMS recorded : 0.68/pb
Totem recorded : 0.4/pb
Effective luminosity
Totem Trigger & CMS data : 0.55/pb



(Exclusive) central diffraction



p_1 (ξ_1) $\boxed{M_X^2 = \xi_1\, \xi_2\, s}$

X at rapidity y_X **gg collider**

p_2 (ξ_2) $\boxed{y_X = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}}$

- exchange of colour singlets with vacuum quantum numbers
  $\Rightarrow$ selection rules for system X: $J^{PC} = 0^{++}, 2^{++}, \ldots$

- <u>with double-arm proton detection</u>
  $\beta^* = 90$ m: all M_X, $t > 0.04$
- Comparison of prediction from forward to central system:

M(pp) =? M(central), $p_{T,z}$(pp) =? $p_{T,z}$(central), vertex(pp) =? vertex(central)

- prediction of rapidity gaps from proton x's : $\Delta\eta_{1,2} = -\ln\xi_{1,2}$

<u>Examples (0.4 pb^{-1} reach):</u>

- Exclusive low mass resonance and glueball studies (see next slide)
- Exclusive charmonium production: ~ O(few 100 events)
- (Non-exclusive) central diffractive jets (p^T_{jet} > 30/40 GeV): x 100 statistics (2012)
- Missing mass & momentum signals (high mass): x 100 statistics (2012)
- Low mass exclusive central diffractive jets (p^T_{jet} > 40 GeV): ~ O(10 events)

Low mass resonance & glueball studies

CD@LHC: $x \sim 10^{-3} - 10^{-4}$ gluons $\Rightarrow$ pure gluon pair $\Rightarrow M_X \sim 1 - 4$ GeV
Candidates for 0^{++} glueball: $f_0(1500)$ or $f_0(1710)$; lattice QCD favours $f_0(1710)$

Decays and branching ratios of $f_0(1710)$ poorly explored (unlike $f_0(1500)$)
→ Goal: characterize $f_0(1710)$ and compare with known $f_0(1500)$

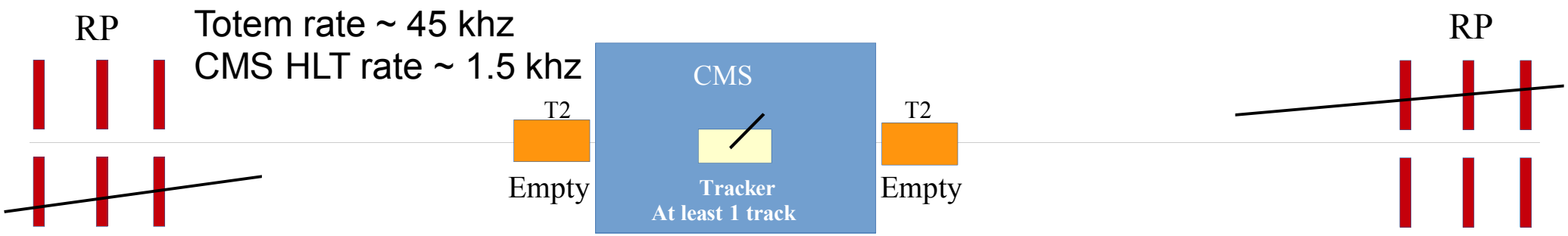
CMS+TOTEM advantages:

- ✓ Good particle ID & mass resolution ($\sigma(M) \sim 30$ MeV) using CMS tracker
- ✓ RP protons assure exclusivity ($p_{T,RP} \sim p_{T,tracker}$)

CMS+TOTEM data from 2012: ($\mathcal{L} = 3$ nb^{-1} of double arm RP trigger)
show sensitivity to $f_0(1710) \rightarrow \rho^0\rho^0 \rightarrow 4\pi^{\pm}$ (channel not yet reported in PDG)

Dedicated "TOTEM0" trigger: double arm RP & T2 Veto & at least 1 track in CMS tracker

Totem rate ~ 45 khz
CMS HLT rate ~ 1.5 khz

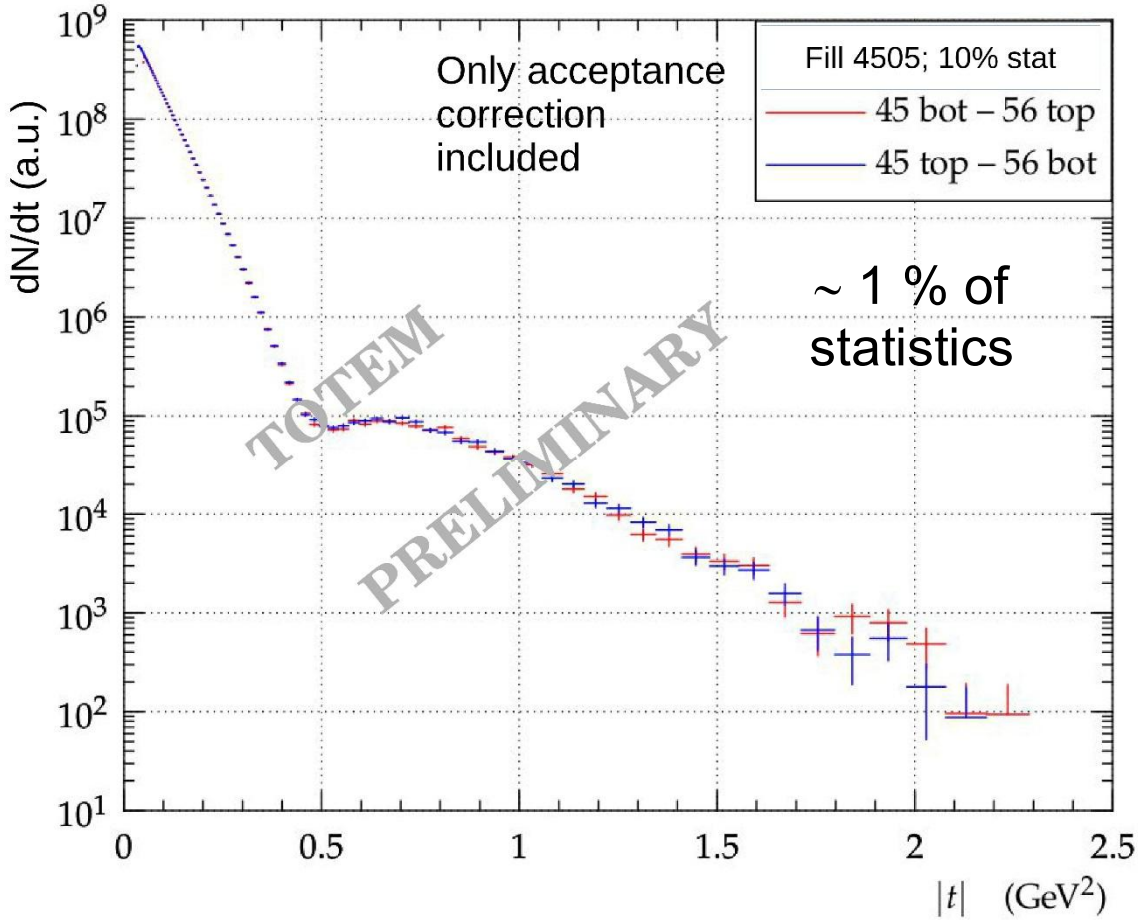


$\beta^* = 90$ m common CMS-TOTEM physics runs:
100 M TOTEM0 triggers in ~0.4 pb^{-1} $\Rightarrow \times$ 500-750 statistics (2012)
$\Rightarrow$ should allow full decay characterization

β* = 90 m physics runs

Very high statistics β* = 90 m data at 13 TeV:

~ 3 · 10^9 elastic events ⇒ access higher |t|-values



Common CMS-TOTEM data taking:

8 – 10 kHz @ CMS HLT

Vertex reconstruction by time measurement

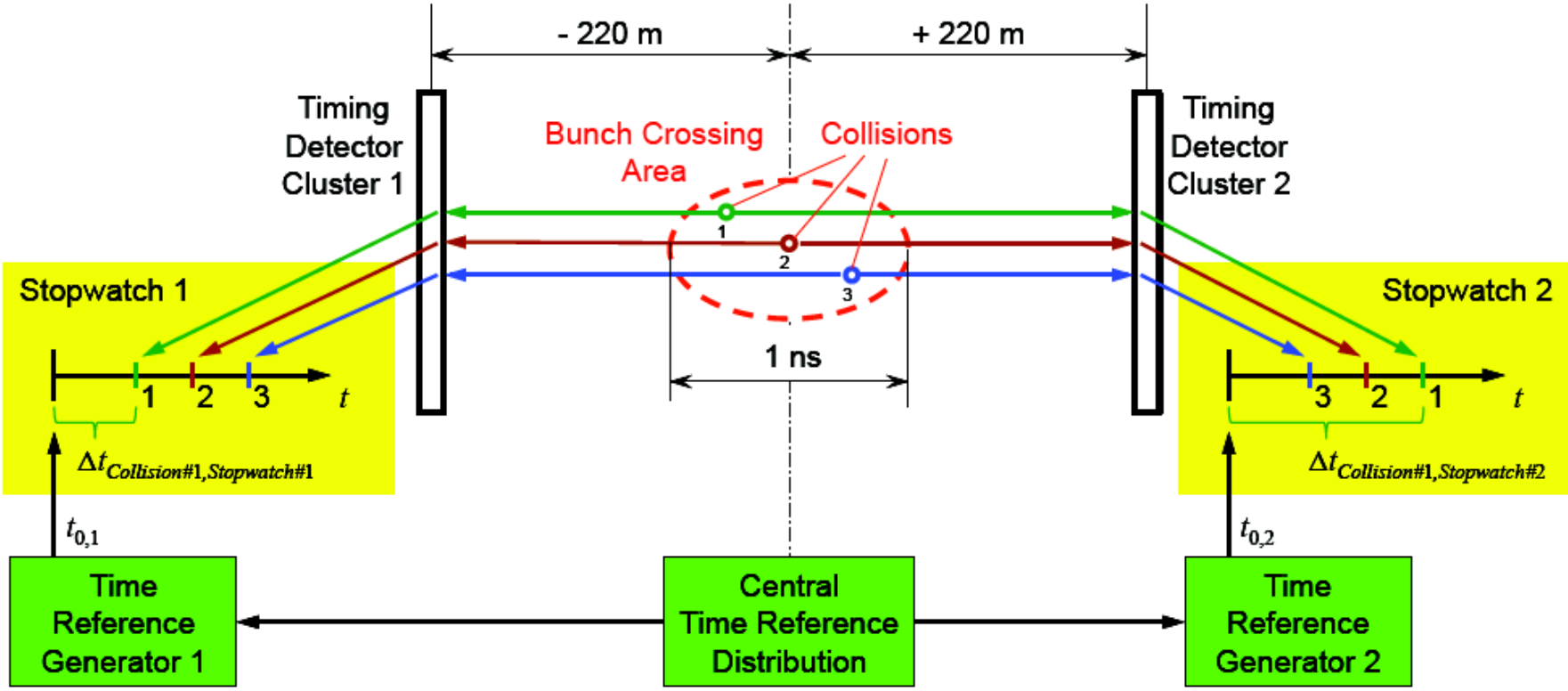
Pileup problem:

High luminosity → multiple events in 1 bunch collision !

– CMS tracker can separate multiple vertices longitudinally

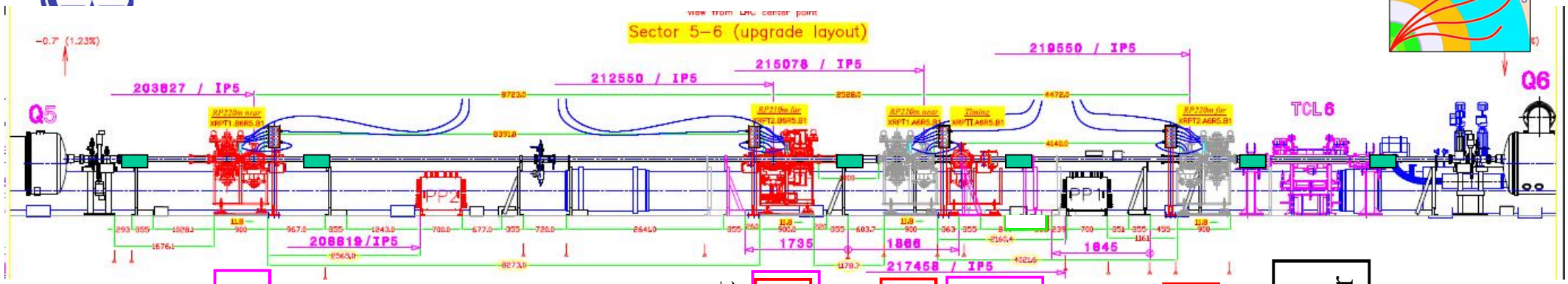
– leading proton tracks have angles in μrad range → insufficient vertex precision

– for double-arm events (CD) reconstruct vertex from time-of-flight difference



Position of Collision $\sim \Delta t_{Collision\#1,Stopwatch\#1} - \Delta t_{Collision\#1,Stopwatch\#2}$

Roman Pot upgrades



203 m

214 m

rotated unit

8°

215 m

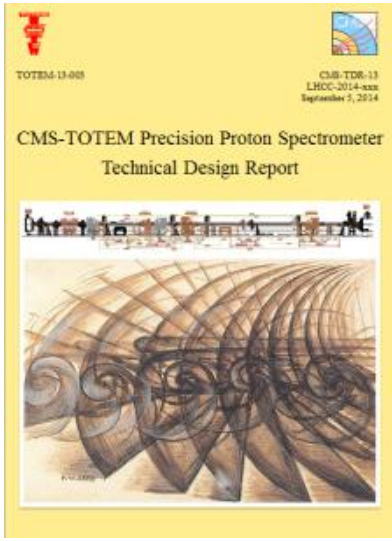
216 m (new)

220 m

TCL6 collimator

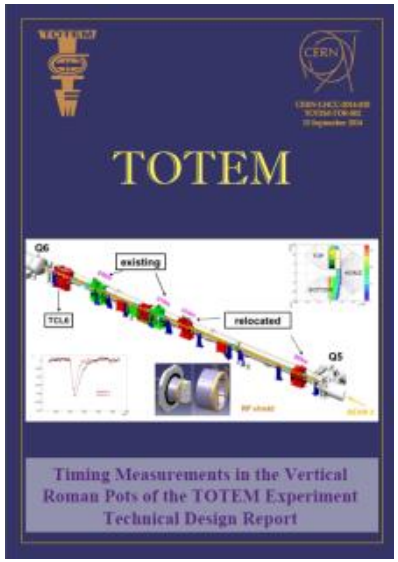
low β^* (< 1 m), high lumi, standard runs, M_X > 250 GeV

high β^* (19 m, 90 m, > 1 km), low – medium lumi, special runs, all M_X



CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

Quartz sensors for Timing & pixel sensors for tracking in horizontal RPs



Timing Measurements in the Vertical Roman Pots of the TOTEM Experiment

Thin diamond sensors in vertical RPs

High luminosity RP insertions

Final goal: Establish insertions for physics in regular fills from 2016

Experience from 2012:

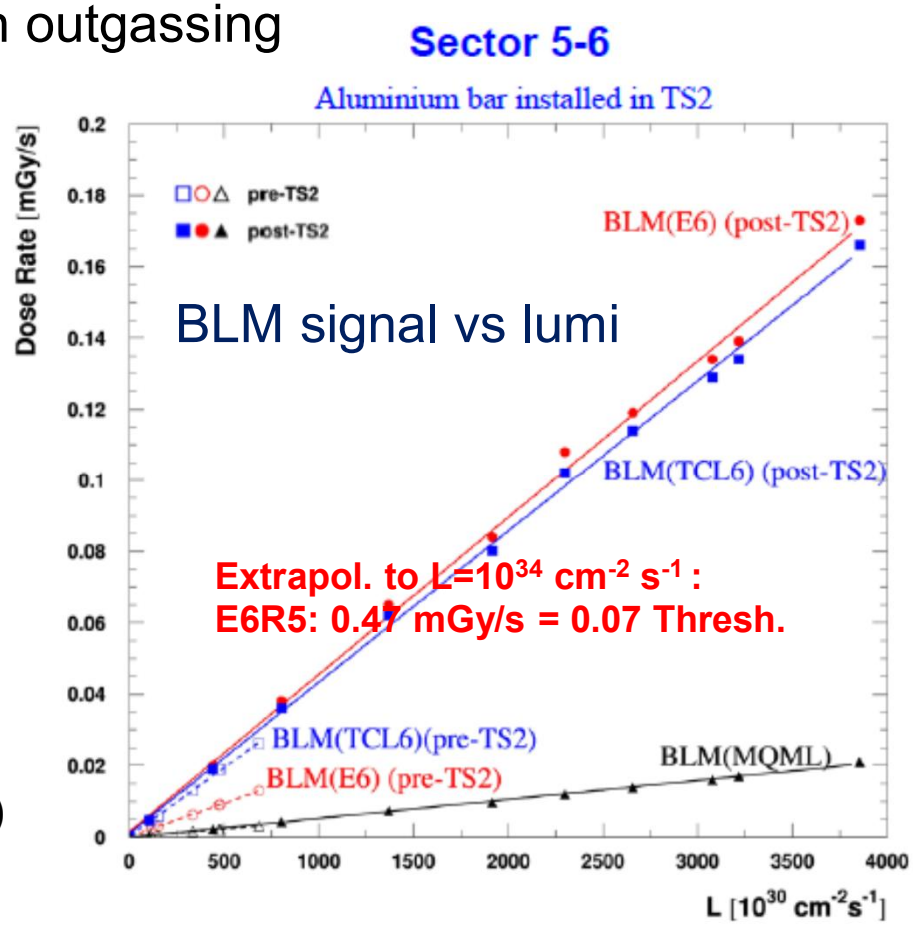
- Collision debris showers from IP ⇒ beam dump due to BLMs
- Impedance heating combined with outgassing

Technical Improvements during LS1

- New ferrite material & ferrite bake-out at 1000 ºC ⇒ less outgassing
- RF shields & cylindrical geometry for horizontal RPs ⇒ impedance reduction
- TCL6 to intercept showers from RPs

July: Beam-based alignment/loss maps at ~ $30\sigma_{beam,hor}$ & successful RP insertions in 50 ns intensity ramp-up (up to $L \approx 1.3 \cdot 10^{33}$ cm^{-2} s^{-1})

Aug - Oct: RPs closer (~ $25\sigma_{beam,hor}$), final TCL con-figuration & successful RP insertions in 25 ns intensity ramp-up so far (up to $L \approx 4 \cdot 10^{33}$ cm^{-2} s^{-1})



Main conclusion:

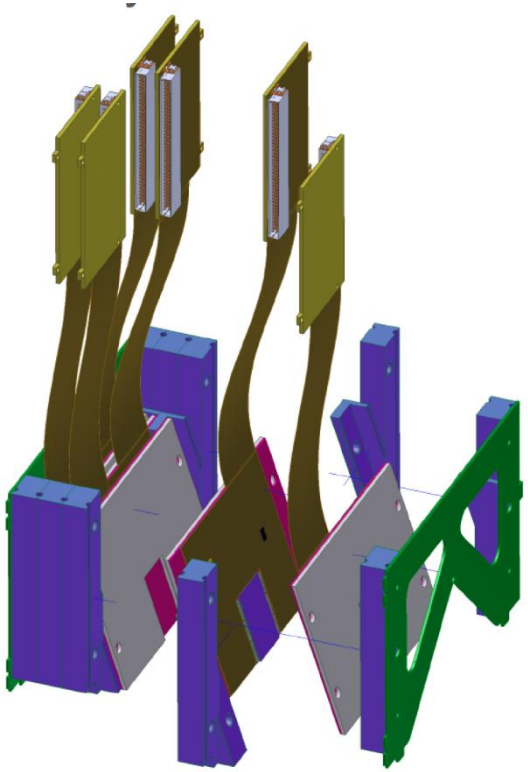
* Linearity of BLM response with lumi, proving debris-hypothesis for losses
* Extrapolation to $L \approx 10^{34}$ cm^{-2} s^{-1} indicates no problem with BLM threshold for RPs

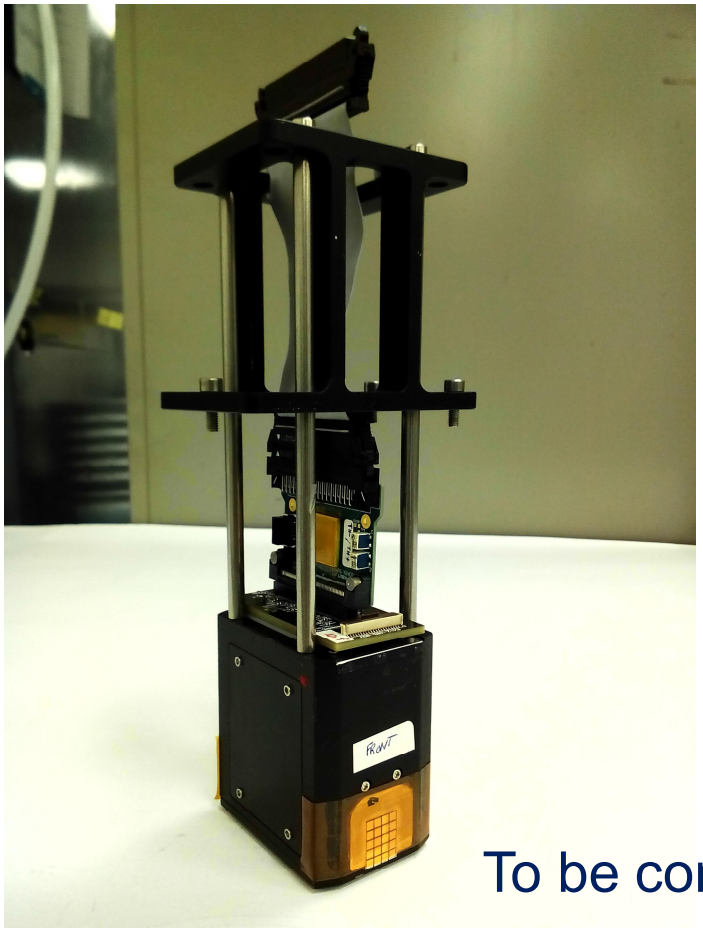
Aim for ~ $20\sigma_{beam,hor}$ (goal: ~ $15\sigma_{beam,hor}$) RP insertion in 2016 if all 2015 insertions succesful.

CT-PPS detectors

Tracking: 3D silicon sensors

- PSI46dig ROC, with same readout Phase I CMS pixel upgrade
- 6 detector planes per station
- 10 μm (position) & 1-2 μrad (angle)





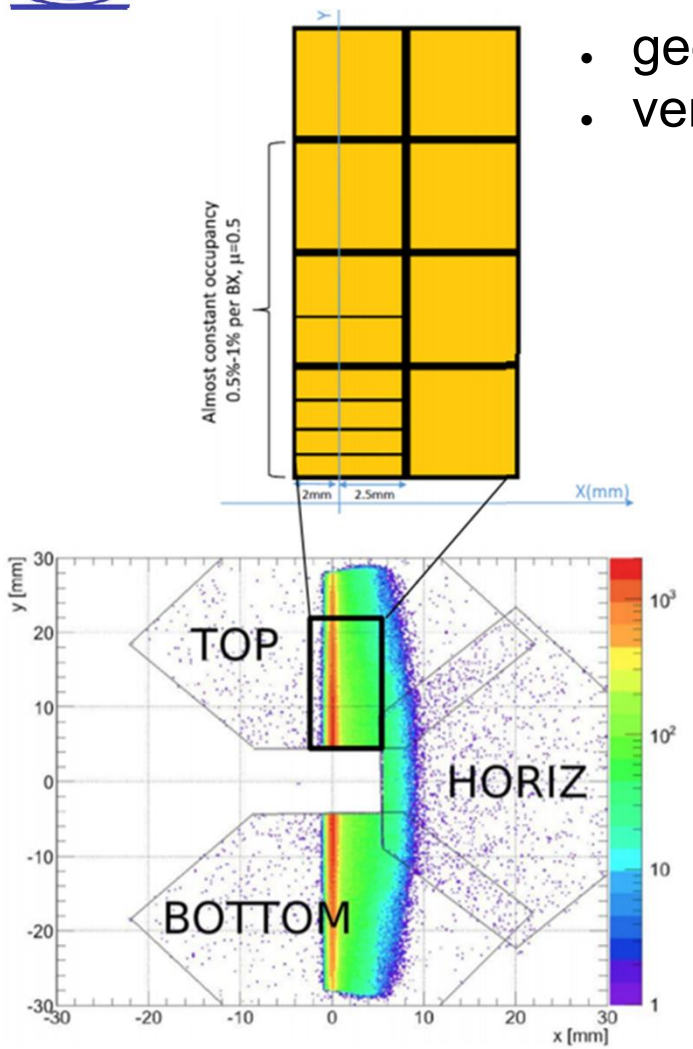
Timing baseline: Quartic detector

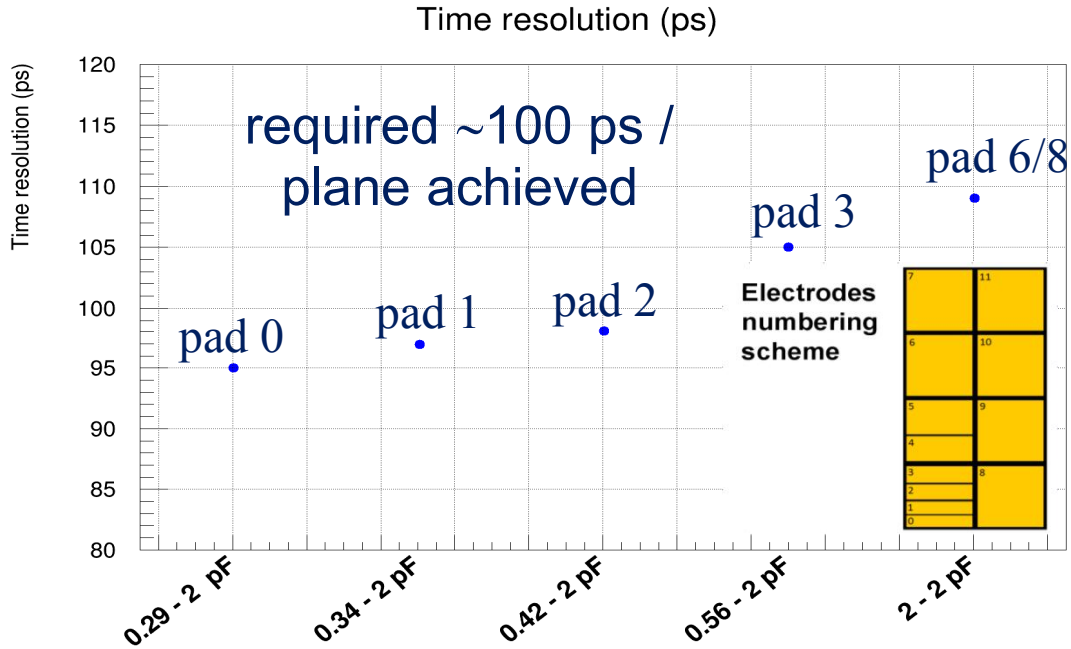
- 20 (4 x 5) quartz bars, 3 x 3mm^2, SiPM for light detection.
- 2 modules/RP unit
- In beam tests: σ(t) = 30 ps/module (~ 20 ps/RP unit)
- Currently modules tested in RPs with MIPs

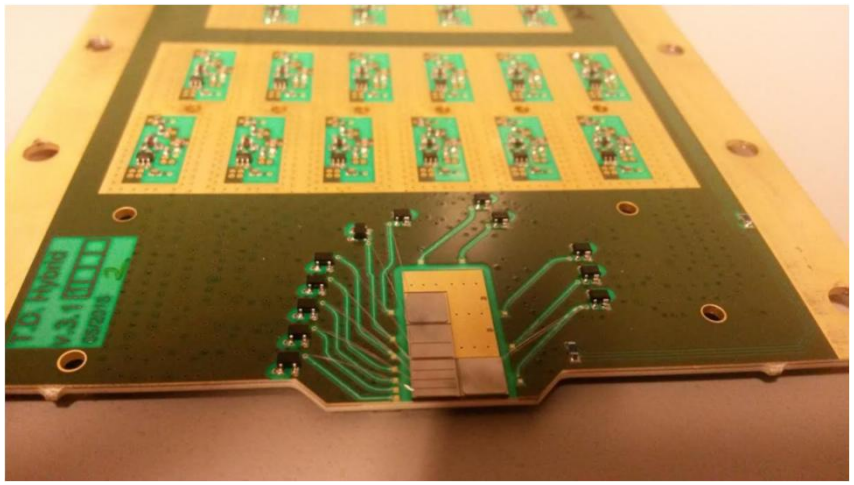
To be completed & installed during 2016

Diamond timing detectors

- geometry adjusted to track occupancy in $\beta^* = 90$m runs
- vertex z-position reconstruction resolution ~few cm







currently 2 completed planes being tested inside RPs with MIPs

total 12 planes (each with 4 diamonds) to be completed & installed spring 2016

Summary

Many interesting physics results published using Run 1 data
More Run 1 physics results being finalized

High luminosity RP insertions progressing successfully !

2015 data taking:

- LHCf run with very low pileup for dN/dη
- $\beta^* = 90$ m run: ~0.4 pb^{-1} with CMS for exclusive low mass resonance production, hard single & central diffraction + dedicated sample for total cross-section & soft diffraction …. stay tuned for results…

2016 plans:

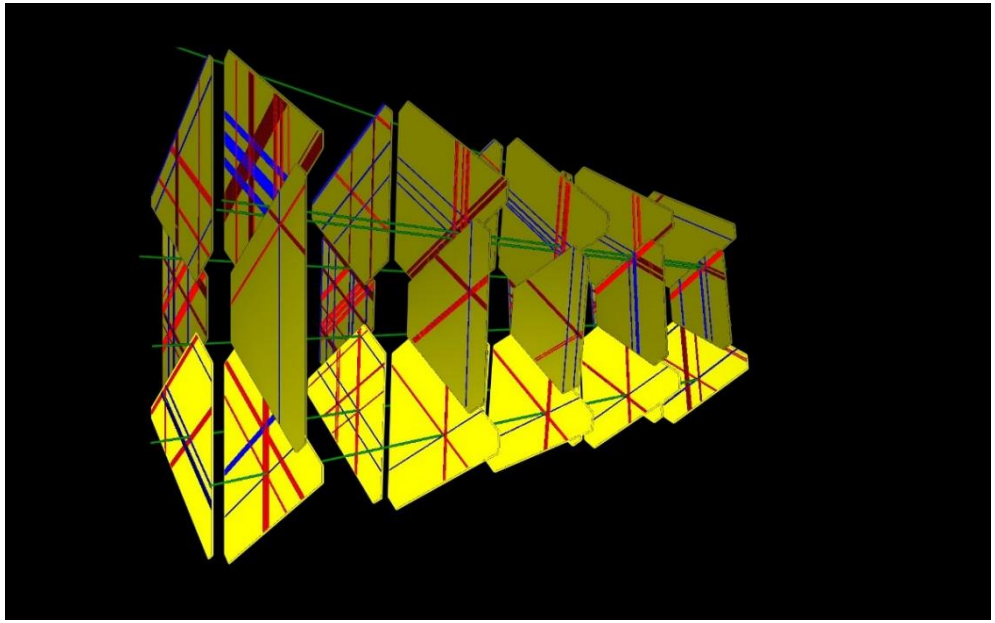
- Completing & installing diamond timing sensors for 2016 runs
- Dedicated run at $\beta^* = 90$ m with timing sensors with $\mu \sim 0.5$
- Completing & installing CT-PPS detectors $\Rightarrow$ high lumi data taking

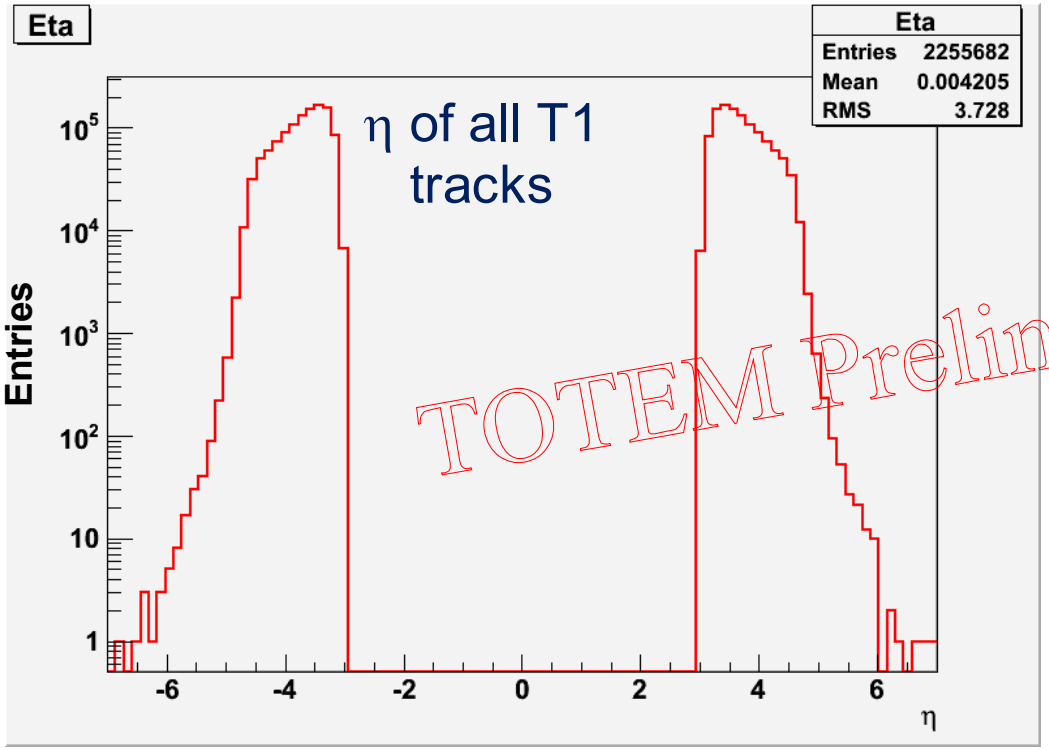
Backup

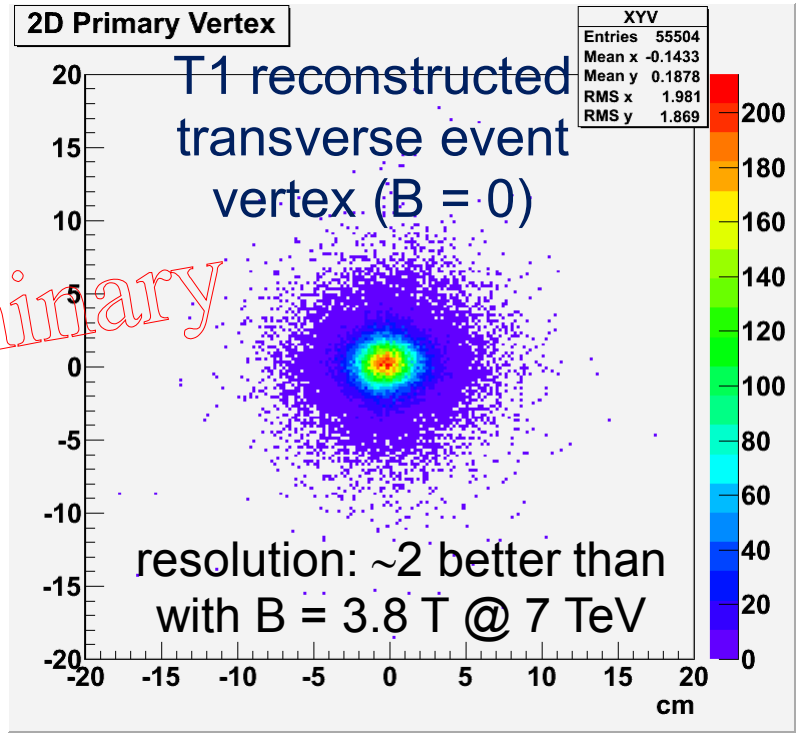
T1 telescope

- Reinstalled & commissioned.
- Fully operational.
- Tracking performance & efficiency (at least) as in Run I

Performance plots from LHCf run ($\mu \sim 0.003$) without CMS B field

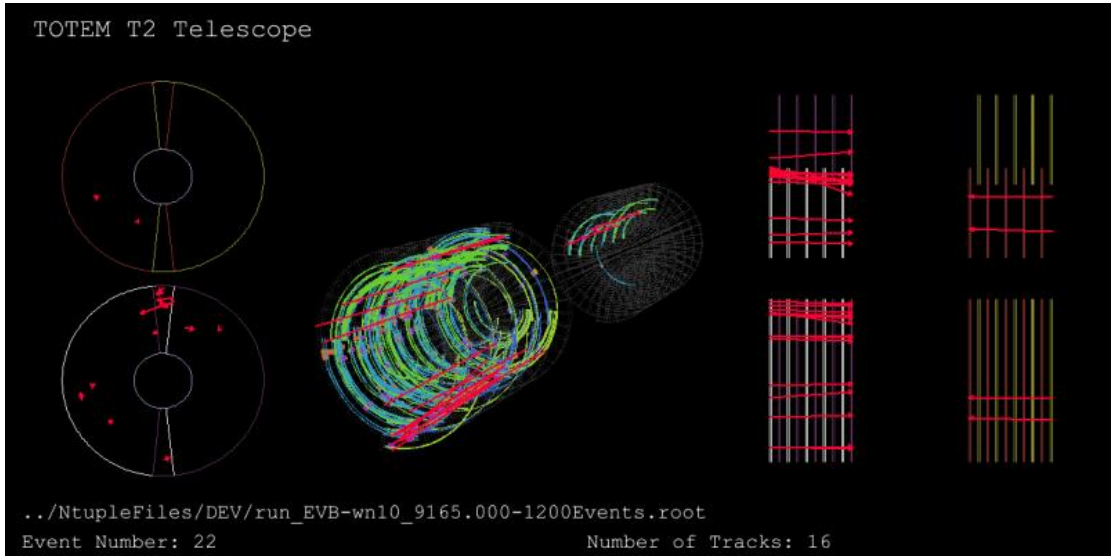




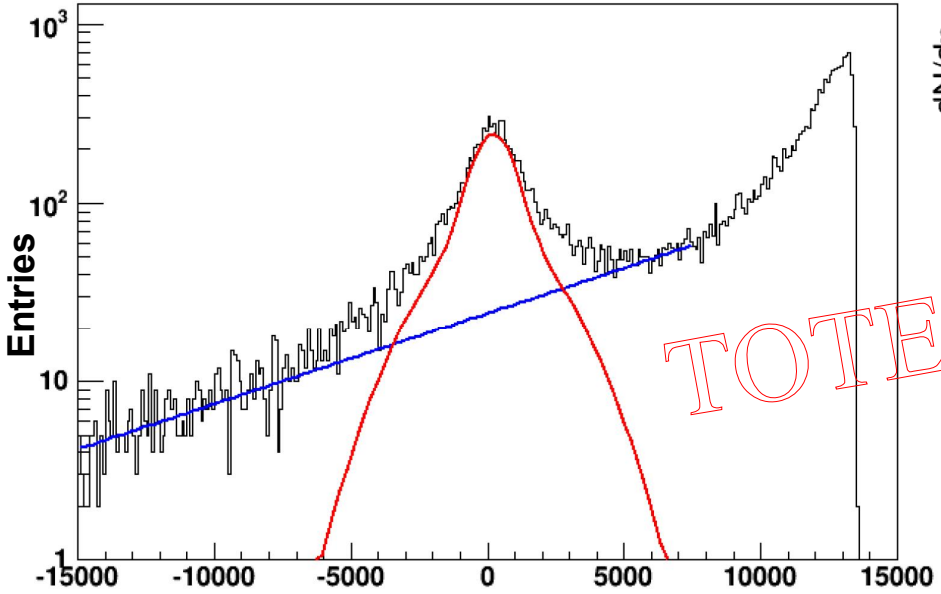


T2 telescope

- Reinstalled & commissioned.
- Similar efficiency & tracking performance as in Run I
- 3 out of 4 half-arms operational (missing half-arm ≤ 1 % effect on measurements)



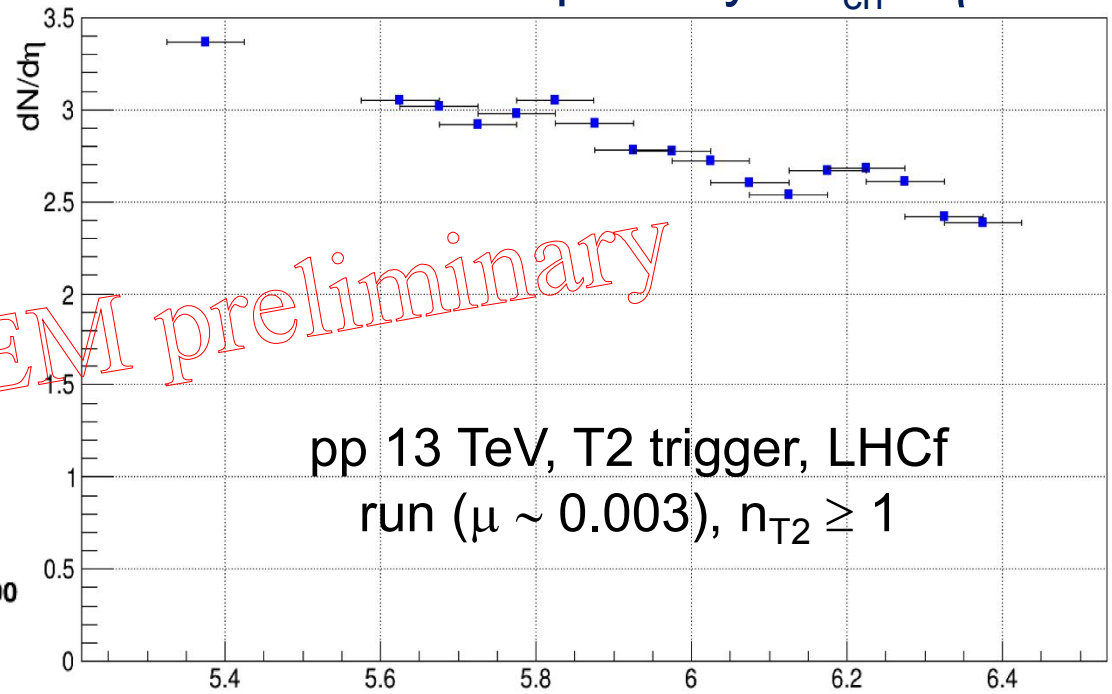
Primary/secondary separation



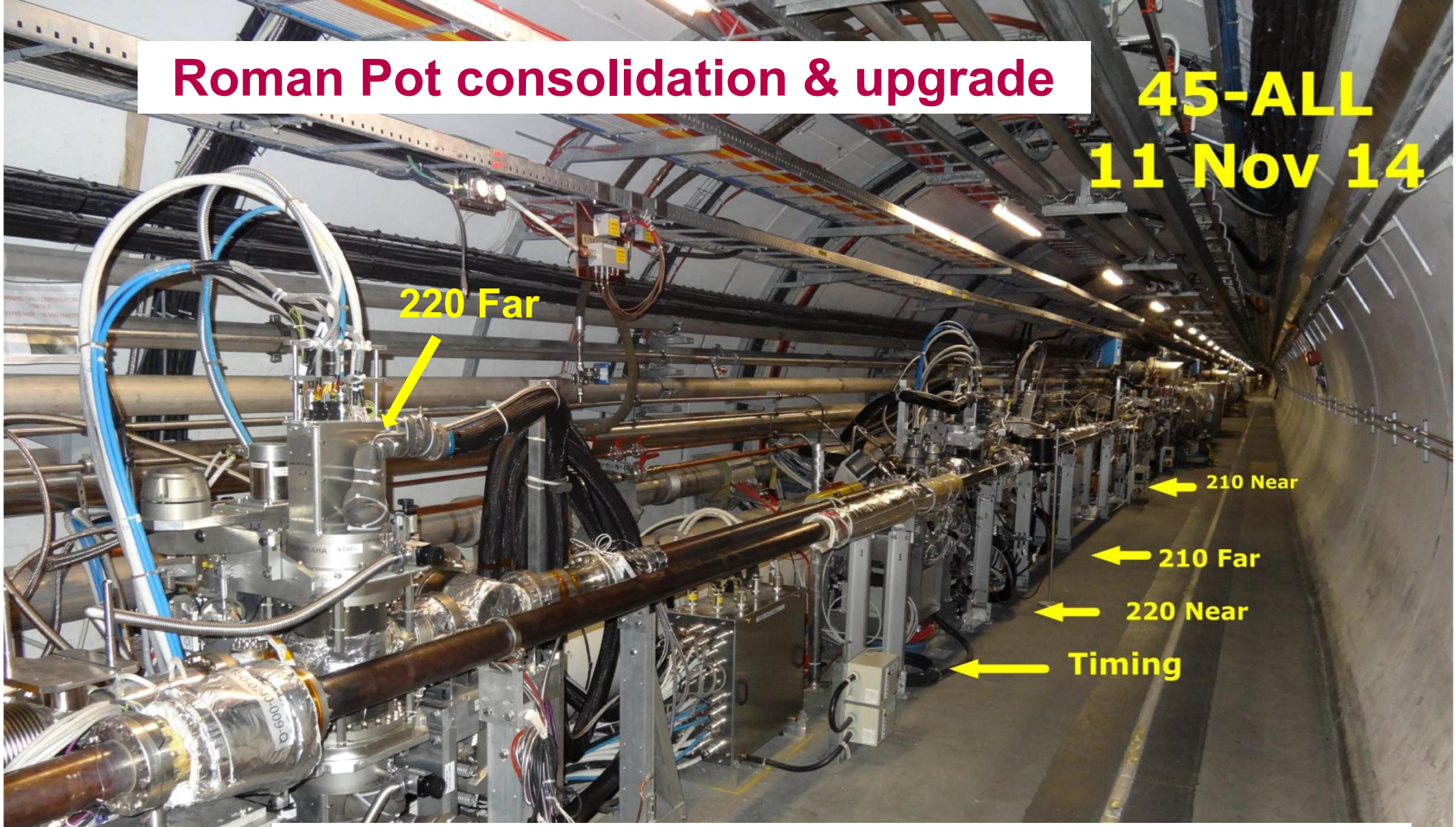
identical method as in Eur. Phys. J. C 74 (2014) 3053

ZImpact

Uncorrected primary $dN_{ch}/d\eta$



Roman Pot consolidation & upgrade



- ✓ Relocate RPs to 203m & 214m (“RP210”, improve lever arm)
- ✓ RPs @ 214m rotated by 8° (improve multitrack capability)
- ✓ new cylindrical horizontal RP @ 216 m for timing (to improve proton right-left correlation)
- ✓ RF-shield added to all current horizontal RPs (reduce impedance)

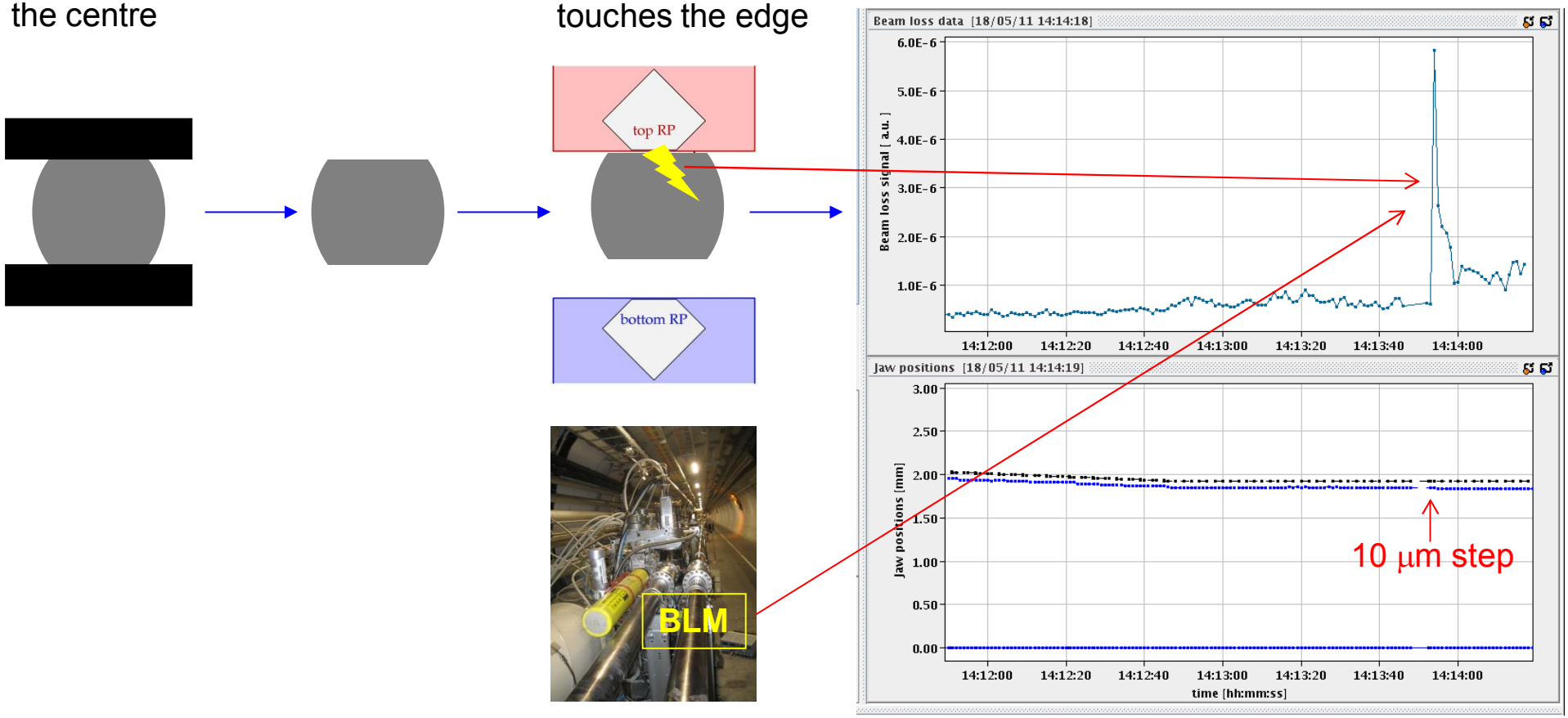
Beam-Based RP Alignment

Standard Procedure for LHC Collimators

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

The top RP approaches the beam until it touches the edge

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

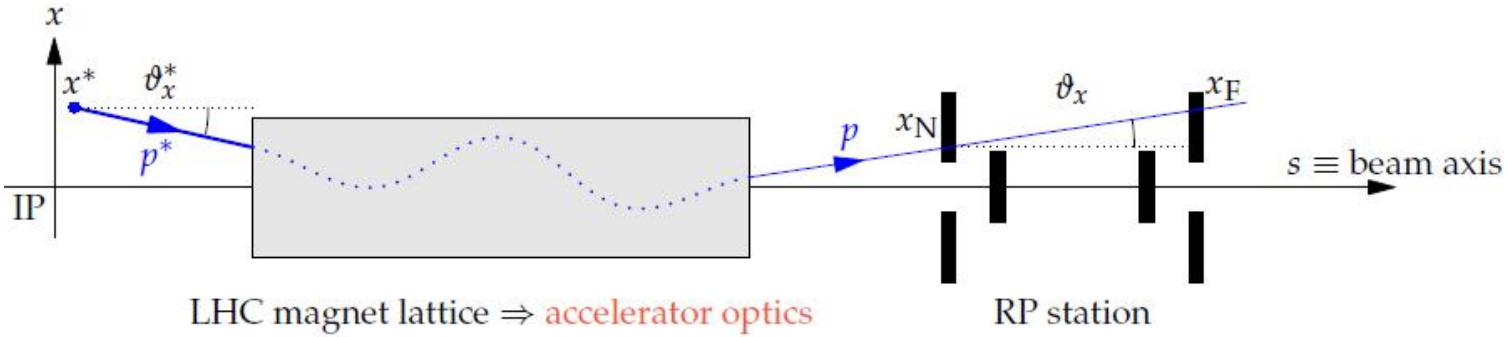


When both top and bottom pots are touching the beam edge:

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

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

Proton transport & reconstruction



(x^*, y^*): vertex position
(θ_x^*, θ_y^*): emission angle: $t \approx -p^2 (\theta_x^{*2} + \theta_y^{*2})$
$\xi = \Delta p/p$: momentum loss (elastic case: $\xi = 0$)

Measured in RP

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

Values at IP5 to be reconstructed

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

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

L_x, L_y: effective lengths (sensitivity to scattering angle)
v_x, v_y: magnifications (sensitivity to vertex position)
D_x : dispersion (sensitivity to momentum loss); $D_y \sim 0$

Reconstruction of proton kinematics = inversion of transport equation
Transport matrix elements depend on ξ ➔ non-linear problem (except in elastic case!)

Excellent optics understanding needed.

Exclusive χ_c at $\beta^* = 90$ m

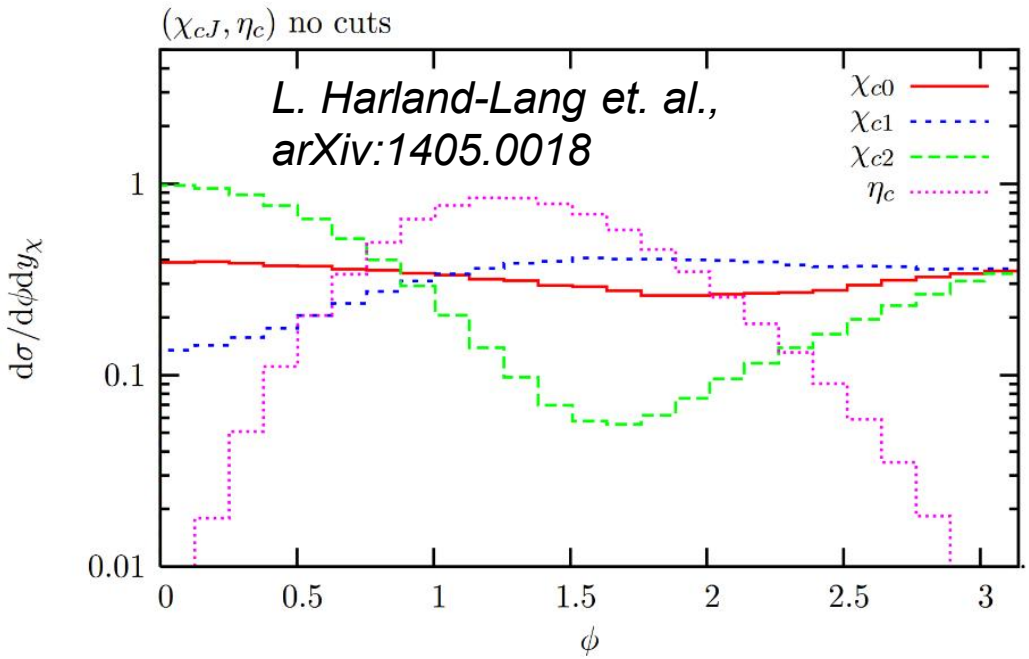
SuperChic/Durham predictions $\sqrt{s}$ = 13 TeV:

	J/ψ ($\rightarrow \mu^+\mu^-$)γ	$2(\pi^+\pi^-)$	$3(\pi^+\pi^-)$	$\pi^+\pi^-K^+K^-$
χ_{c0} :	264 pb	**7.6 nb**	**4.1 nb**	**6.0 nb**
χ_{c1} :	166 pb	61 pb	46 pb	45 pb
χ_{c2} :	53 pb	49 pb	38 pb	40 pb

χ_c selection identical to glueball except $\Gamma\chi \ll \sigma(M)$.
In 0.4 pb^{-1}, expect $\geq$ few hundred χ_{c0} in all-hadronic decay modes.

Sofar exclusive χ_{c0}, χ_{c1} and χ_{c2} only seen in $J/\psi\gamma$ mode by LHCb and CDF (without proton tag).

Possibilities for first azimuthal angular correlation (ϕ) measurement between leading proton for exclusive χ_{c0}



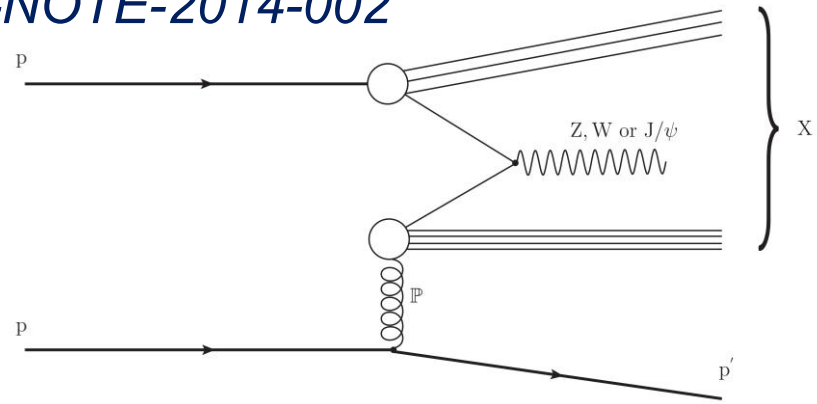
SD processes at $\beta^* = 90$ m

Single diffractive processes: study rapidity gap survival probability

Triggered using CMS lepton & jet triggers

Visible σ estimate at $\sqrt{s} = 13$ TeV (both proton + central object)

CMS PAS FSQ-14-001, TOTEM-NOTE-2014-002



- J/ψ production (POMPYT): $\mu^+\mu^-$
  $3.05 < M_{\mu\mu} < 3.15$ GeV,

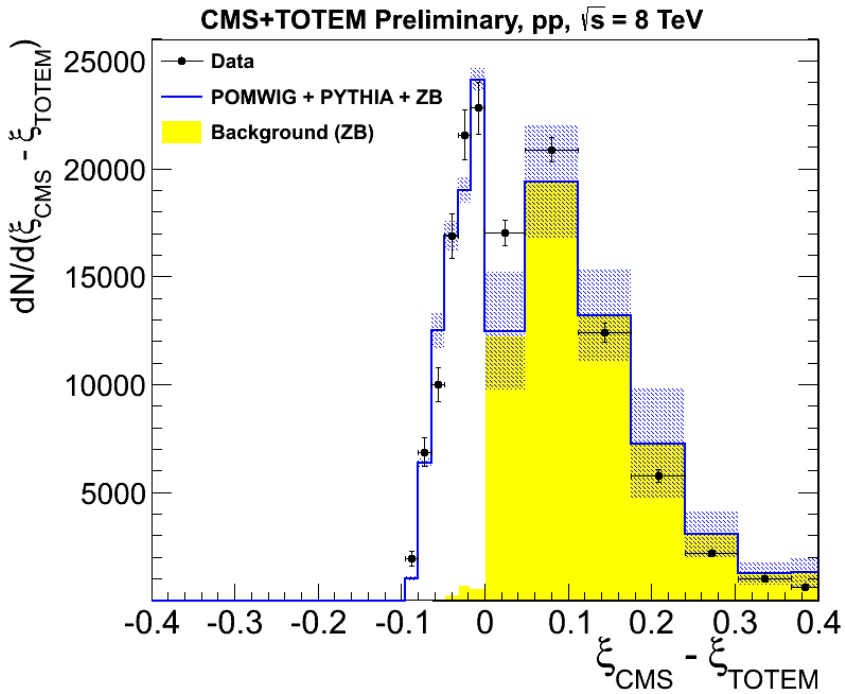
0.4 pb^{-1}: 120 ± 4 events

- W production (POMWIG): $\mu^\pm/e^\pm$
  ($p_T > 20$ GeV), $60 < M_T < 110$ GeV

0.4 pb^{-1}: 14 ± 1 events

- SD jet production: $p_{T,jet} > 40$ GeV

0.4 pb^{-1}: O(10k) events



Background removal demonstrated on common CMS+TOTEM $\beta^* = 90$ m data at $\sqrt{s} = 8$ TeV (SD dijets)