Recent & planned measurements from TOTEM

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on behalf of
TOTEM collaboration

Trento meeting 26.9.2016

Outline:
- Introduction
- Elastic scattering
- Total, inelastic & elastic cross-section
- Hard diffraction & exclusive reactions (with CMS)

TOTEM projects & physics programme

TOTEM

LHC experiment dedicated to measurement of:

total cross-section, elastic scattering, soft diffraction & forward multiplicity

common features: rapidity gaps, particles in very forward region, surviving protons Þ special detectors

TOTEM + CMS (special runs at high b*)

both experiments at LHC Interaction Point 5

excellent pseudorapidity coverage of both tracking & calorimetry: optimal for studies of *exclusive production & hard diffraction*

cooperation mode: independent DAQs, exchange of triggers, offline event merging

CT-PPS (CMS-TOTEM Precision Proton Spectrometer, standard runs)

proton detectors fully integrated in CMS

exclusive production & BSM searches

dedicated detectors for high-pileup environment (timing, strips ® pixels)

® **see Jan Kaspars talk tomorrow**

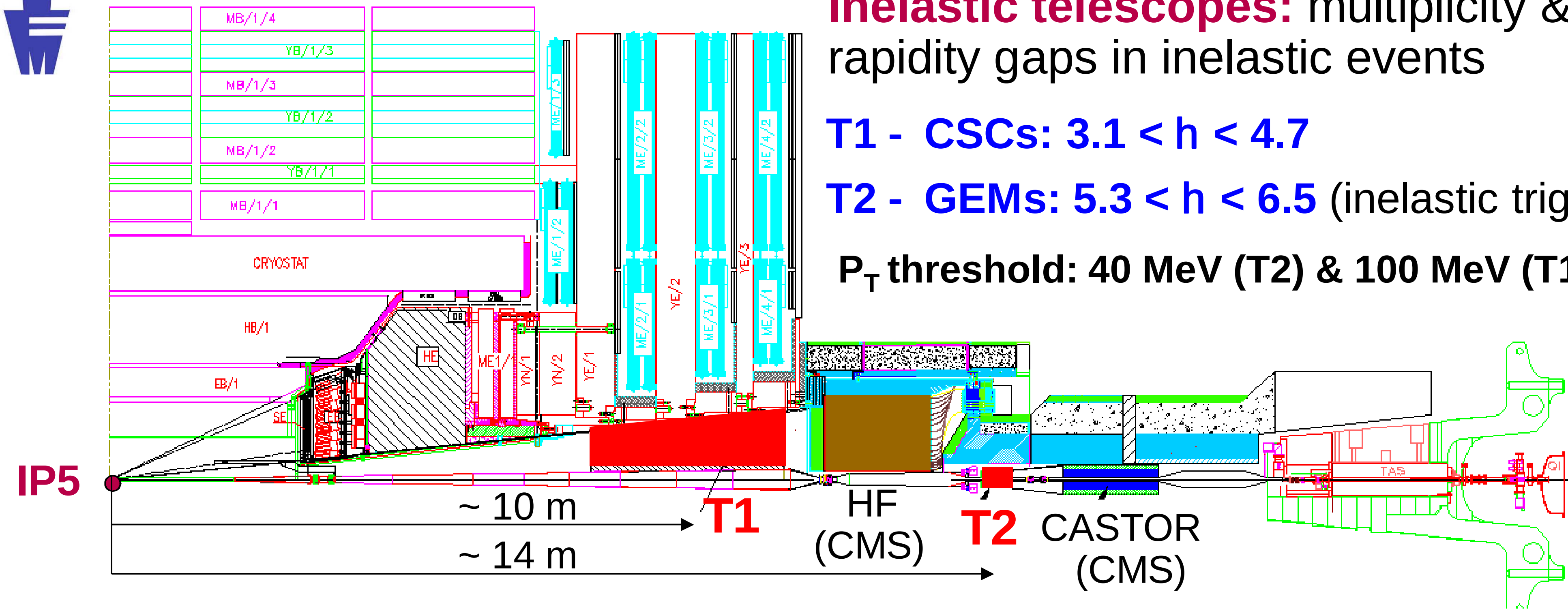
Experimental apparatus @ LHC IP5

Inelastic telescopes: multiplicity & rapidity gaps in inelastic events

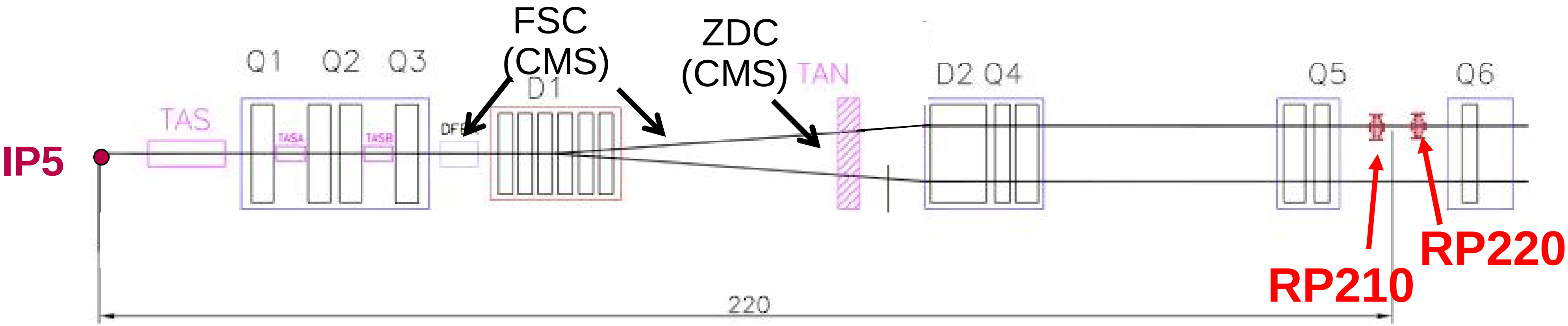
T1 - CSCs: 3.1 < h < 4.7

T2 - GEMs: 5.3 < h < 6.5 (inelastic trigger)

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

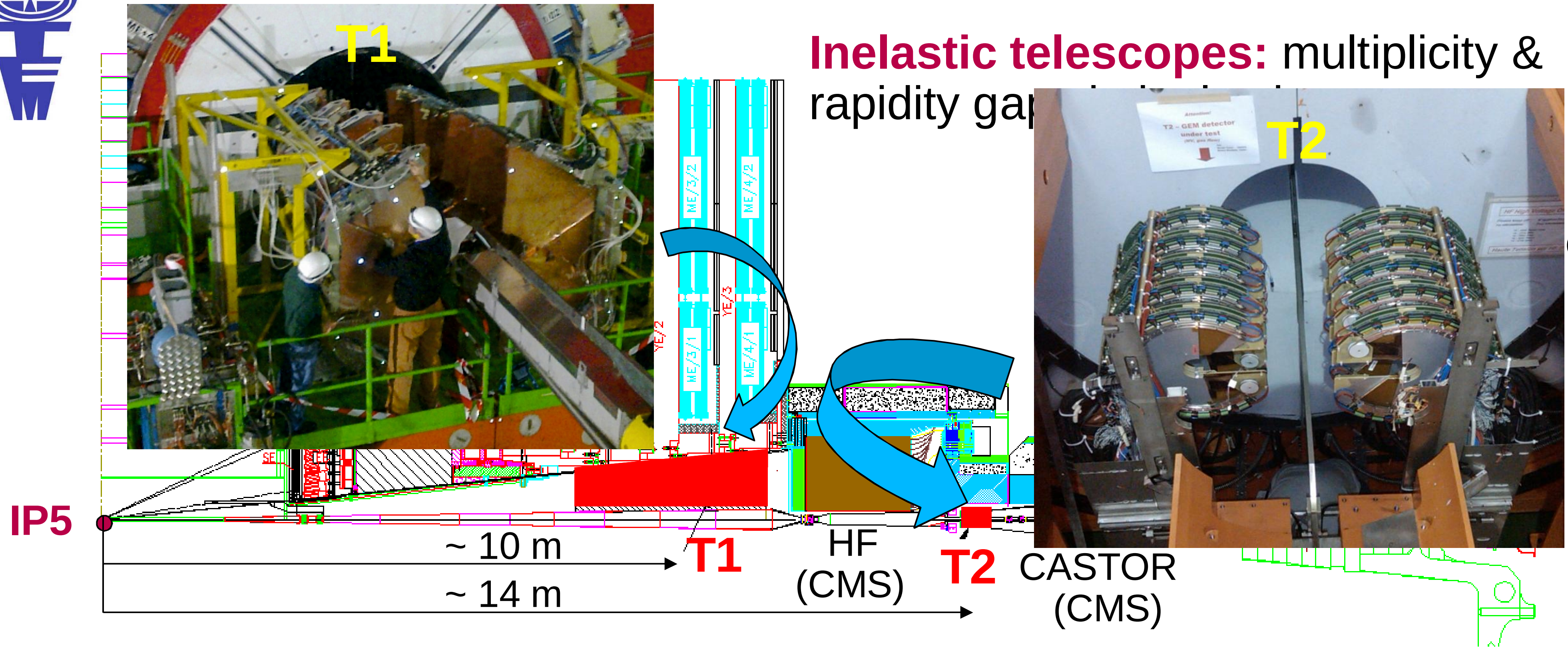


Roman Pots - Si mstrip sensors: elastic & diffractive protons (proton trigger)

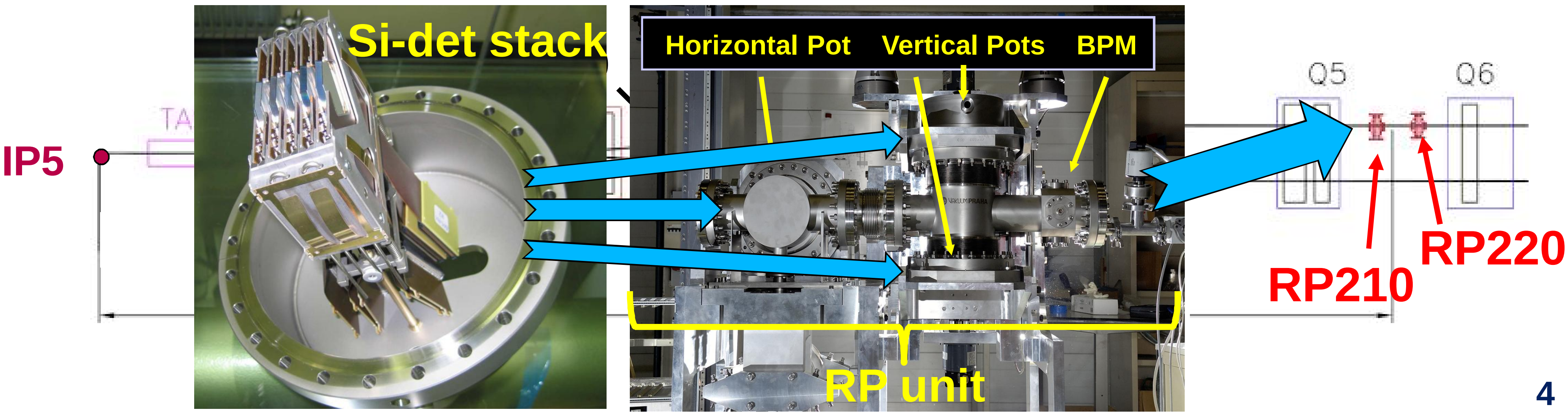


Experimental apparatus @ LHC IP5

Inelastic telescopes: multiplicity & rapidity gap[...] [...]er)



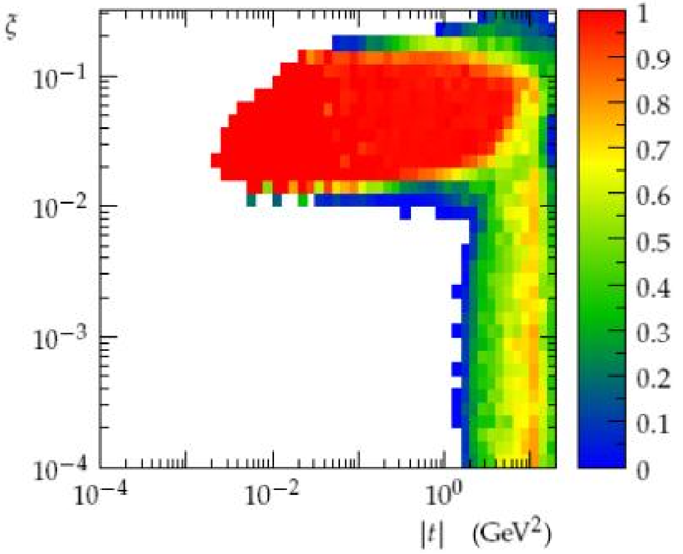
Roman Pots - Si mstrip sensors: elastic & diffractive protons (proton trigger)



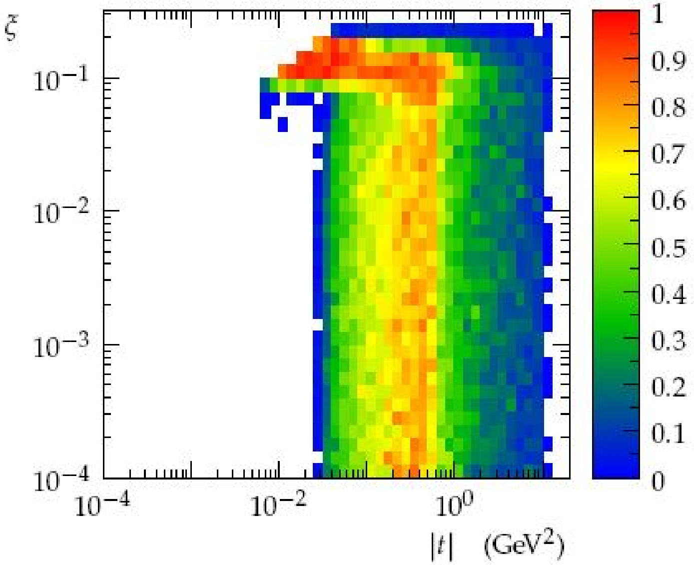
LHC Optics & proton acceptance

t » - p^2 $Q^{*\,2}$: four-momentum transfer squared; x = Dp/p: fractional momentum loss

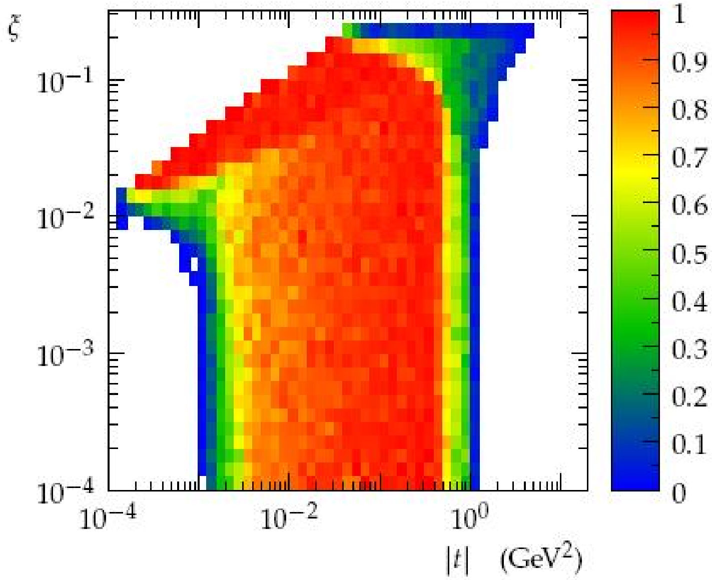
b* = 0.55 m



b* = 90 m



b* = 1 km



> 10^{33} cm^{-2} s^{-1} ← L µ $\frac{1}{b^*}$ → ~10^{27} cm^{-2} s^{-1}

Diffraction:
x > ~0.03, low cross-section processes (hard diffraction)
Elastic scattering: large |t|

Diffraction: all x if |t| > ~10^{-2} GeV^2, soft & semi-hard diffraction
Elastic scattering:
low to mid |t|
Total cross-Section

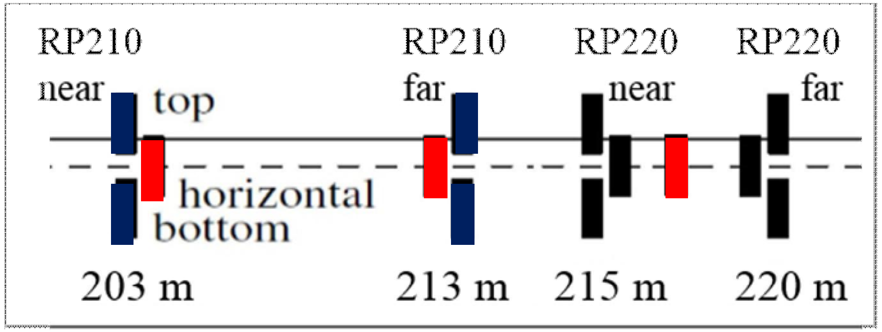
Elastic scattering:
very low |t|, Coulomb-Nuclear Interference
Total cross-Section

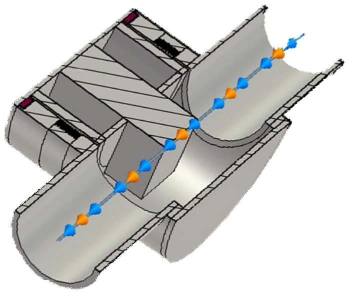
Roman Pot system 2015 ®

Movable beam pipe section allowing insertion of detector to O(mm) distance from the beam

High luminosity standard running:

- 2-3 horizontal RPs (+ 4 vertical for RP alignment runs)

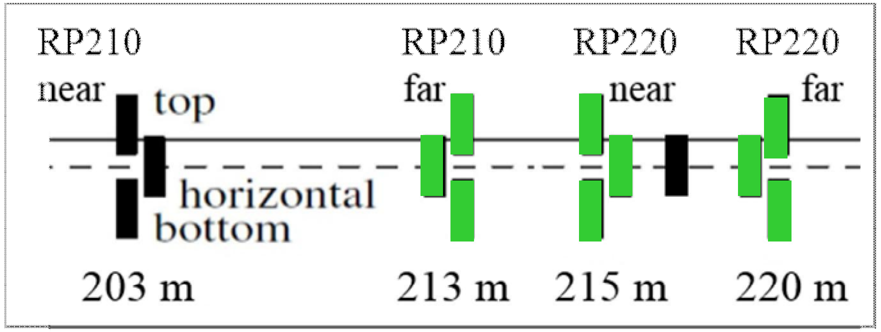


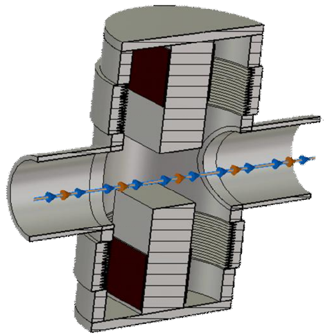


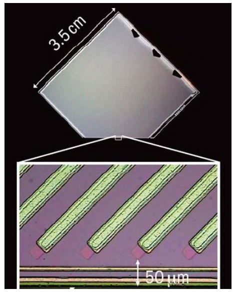
Special high b* runs (90 m, 1 km, 2.5 km):

- 4-6 vertical RPs & 2-3 horizontal RPs

2010-13 data: only RP220



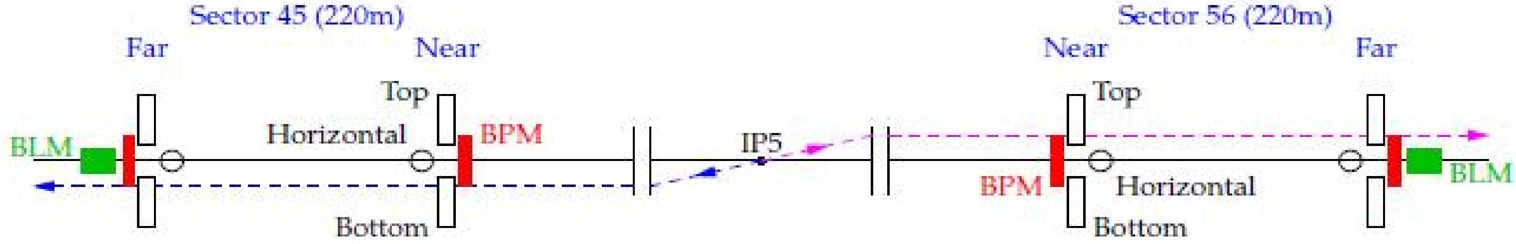




For more details see Joachim Baechlers talk Thursday

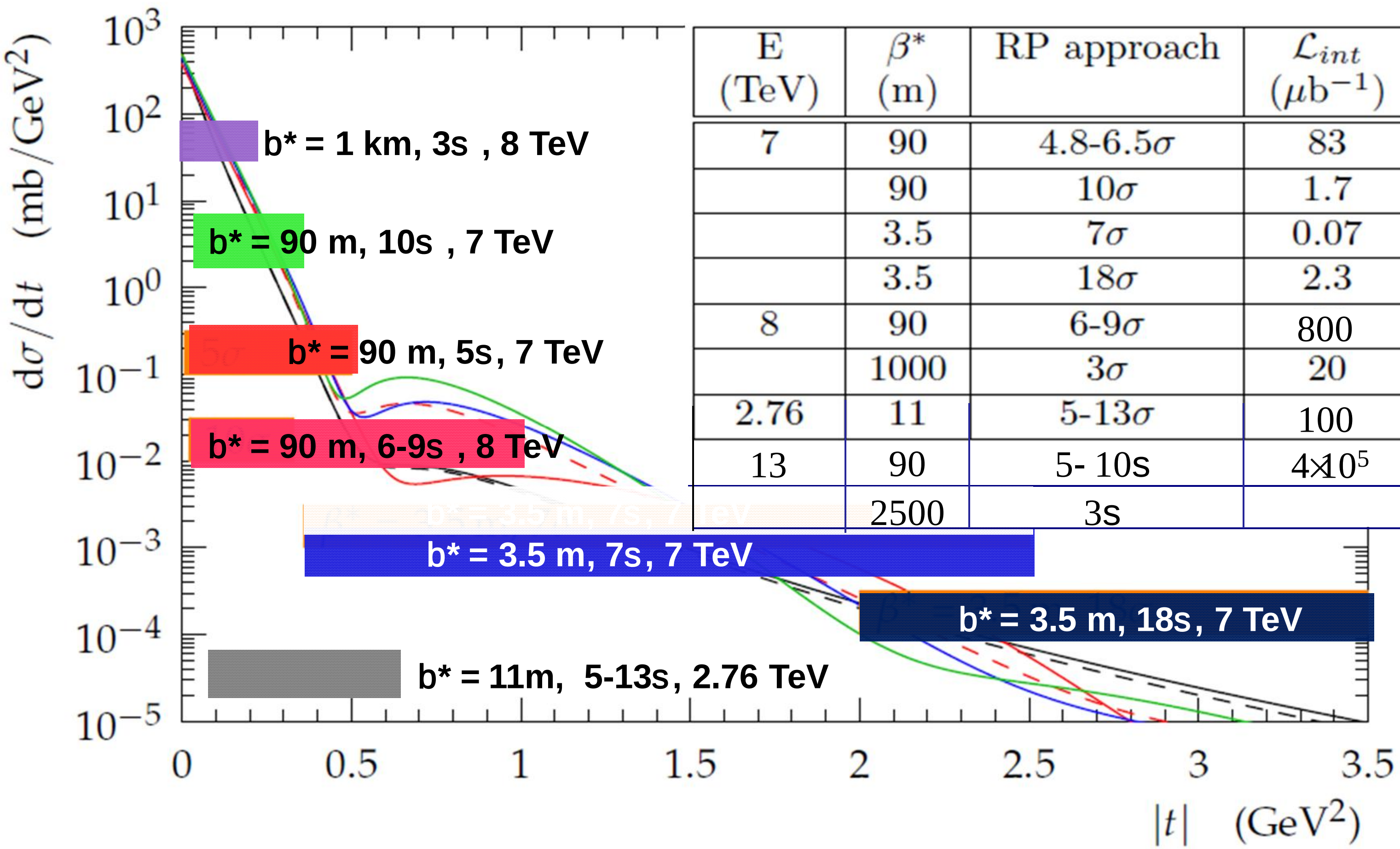
Elastic pp scattering: selection & data sets

Selected based on topology, low |x|, anti-collinearity & vertex



Key issues:
RP alignment
& optics

Data sets at different conditions to measure over as wide |t|-range as possible

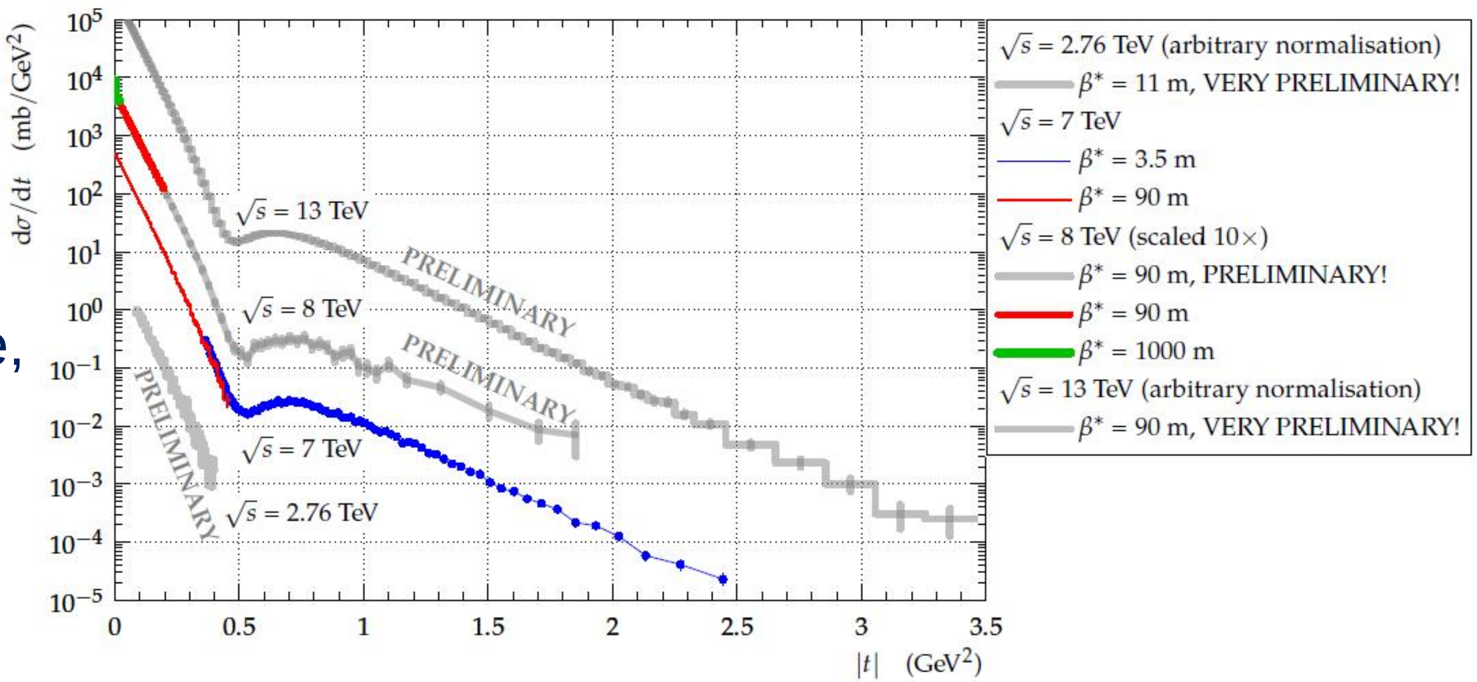


E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events	
7	90	4.8-6.5σ	83	$7{\cdot}10^{-3}$ - 0.5	1M	Ö
	90	10σ	1.7	0.02 - 0.4	14k	Ö
	3.5	7σ	0.07	0.36 - 3	66k	Ö
	3.5	18σ	2.3	2 - 3.5	10k	
8	90	6-9σ	800	0.01 - 1	7M	Ö
	1000	3σ	20	$6{\cdot}10^{-4}$ - 0.2	0.4M	Ö
2.76	11	5-13σ	100	0.05-0.6	45k	O
13	90	5- 10s	$4{\times}10^5$	0.01 – 3.5	~ 1400M	O
	2500	3s		$6{\times}10^{-4}$ – 0.2	~ 5M	O

ÖData published
O Analysis on-going
O Analysis starting

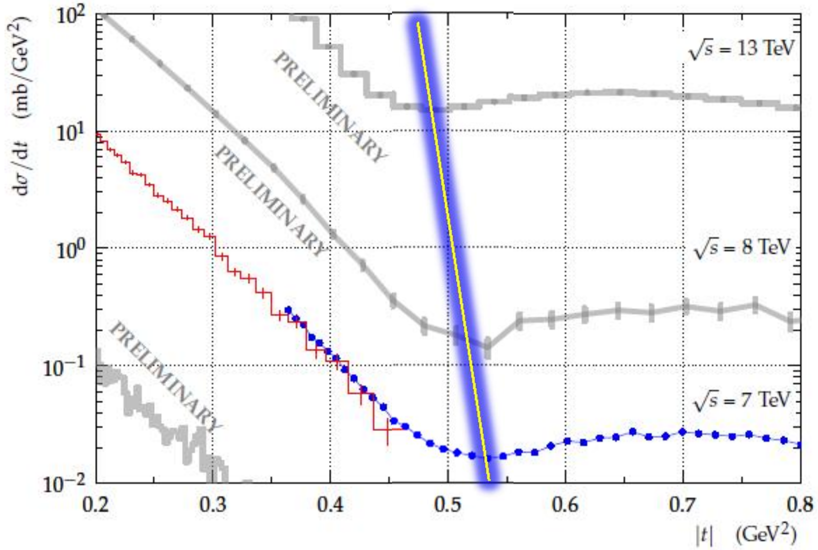
Elastic pp scattering: data summary & trends

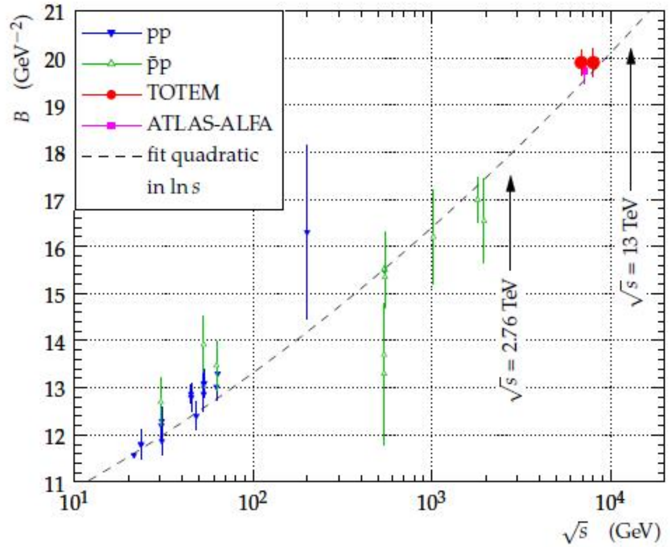
different |t|-ranges probes different physics regimes: Coulomb interference, diffractive cone, dip-bump, transition to pQCD etc…



Trends:

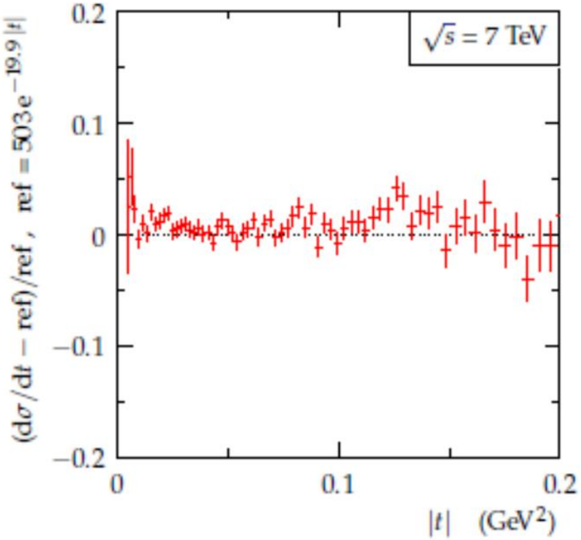
- dip position in |t| decreases with increasing $\sqrt{s}$
- Forward slope $B = \frac{d}{dt}\ln(\frac{d\sigma}{dt}\Big|_{t=0})$ increase with $\sqrt{s}$

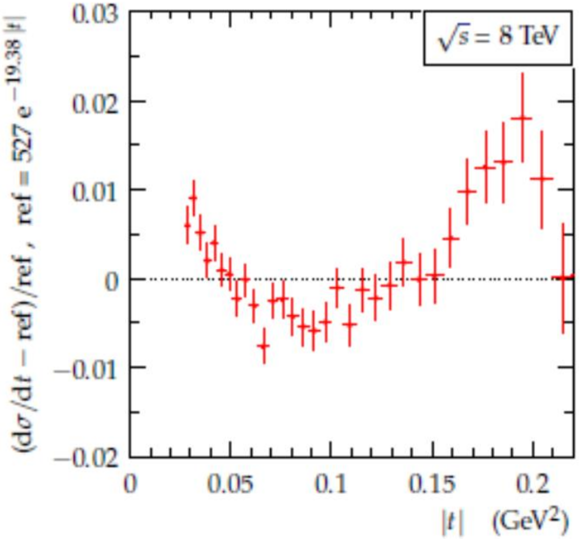


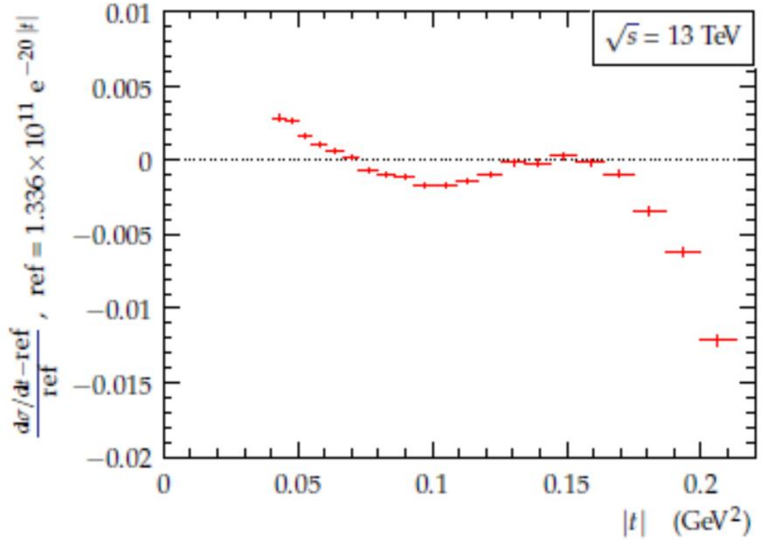


Elastic pp scattering: non-exponentiality at low |t|

- Diffraction cone ”looks almost exponential”
  Magnify deviation Þ show (ds/dt – ref. exp.)/ref. exp.
- b* = 90 m measurements at different energies (stat. uncert. only)

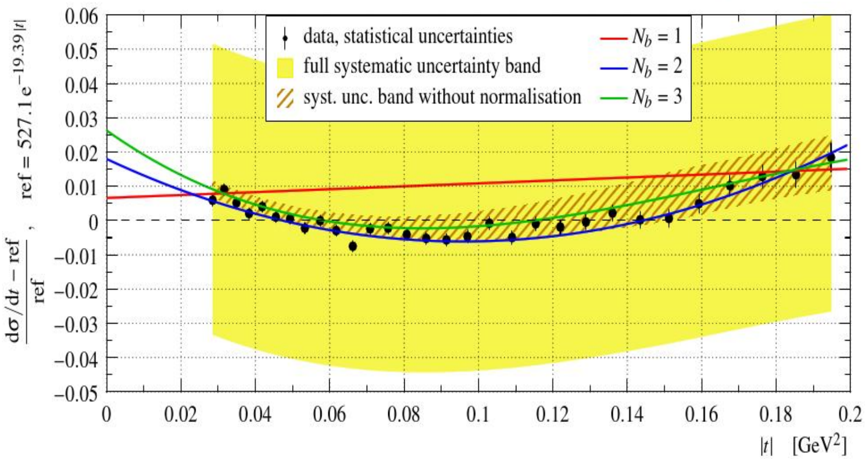






Non-exponentiality observed at 8 & 13 TeV

- 8 TeV: **7s significance**
- 13 TeV: preliminary high significance
- observed cross-section non-exponential



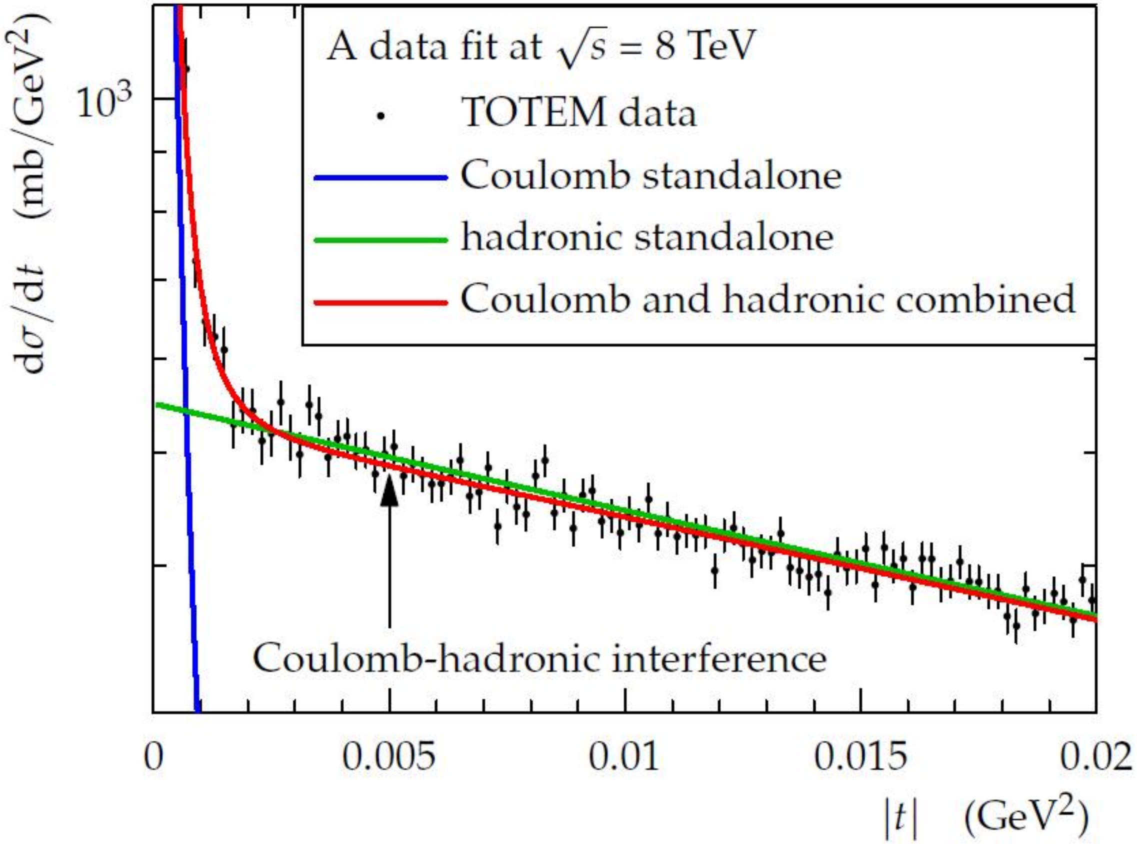
ds/dt = hadronic + Coulomb + interference

Nucl. Phys. B 899 (2015) 527

Coulomb-hadronic interference region

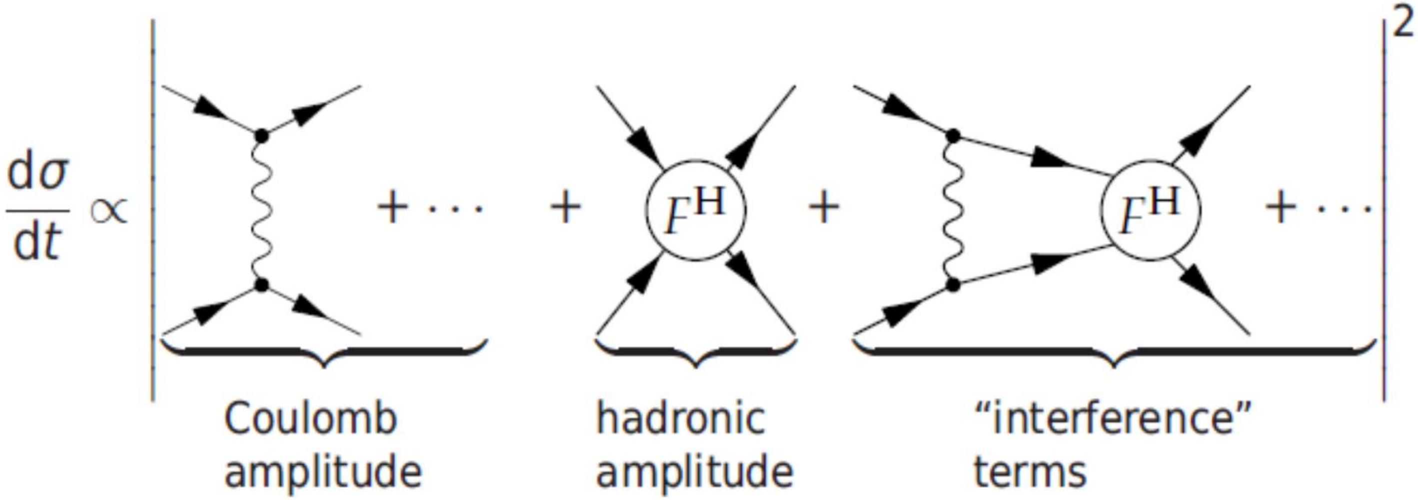
Elastic scattering at very low |t| ³ **6×10^{-4} GeV^2**: 0.4 M at 8 TeV in 2012

- special optics developed for measurements at very low |t|: **b* = 1000 m**
- RP approach very close: **3s**



Possibility to study interference, r , s$_{tot}$, hadronic cross-section …

Coulomb-hadronic interference



Interference formula:

- simplified West-Yennie (SWY): QFT framework, traditional but simplified (require constant hadronic phase, constant exponential)
- Cahn or Kundrat-Lokajicek (KL): eikonal framework, no explicit simplifications (no requirement on hadronic phase & exponential)

Interference Þ sensitivity to phase of hadronic amplitude in cross-section

- include t-dependence of phase
- constraints from data Þ determine **r** (~ phase at |t| = 0)

$$r \text{ º Â } F^{\mathrm{H}}/\text{Á } F^{\mathrm{H}}|_{t=0}$$

Coulomb-hadronic interference – analysis strategy

Central question:

Observed non-exponentiality due to hadronic Coulomb or both

- fits with 2 different assumptions on hadronic amplitude
  - purely-exponential – non-exponentiality due to Coulomb (& interference)

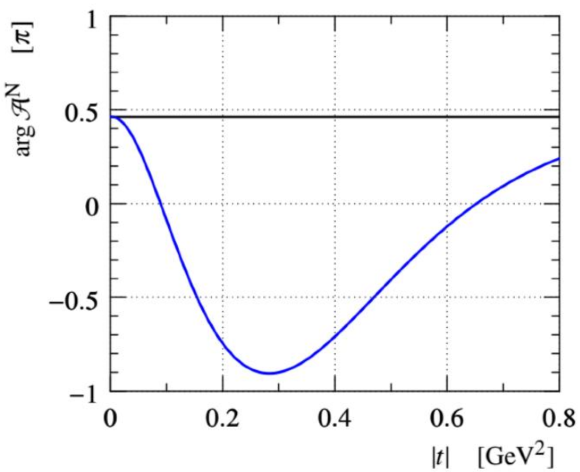
    Þ $|F^{H}| = a \exp(b_1 t)$

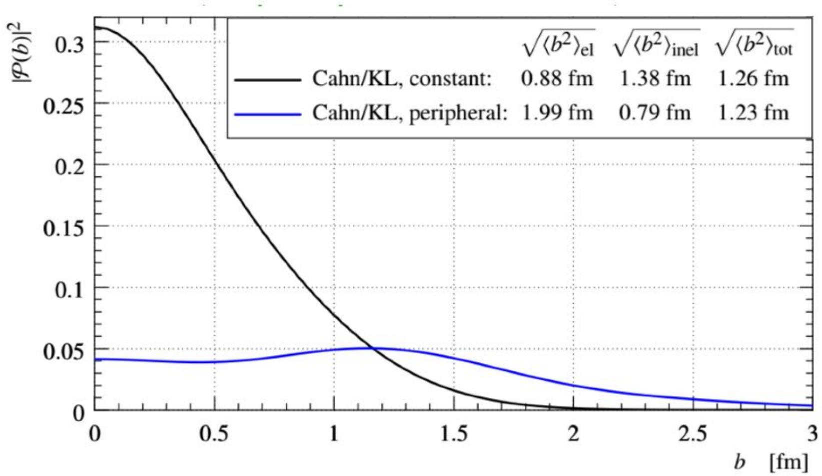
  - flexible enough to describe non-exponentiality even without Coulomb

    Þ $|F^{H}| = a \exp(b_1 t + b_2 t^2 + b_3 t^3)$

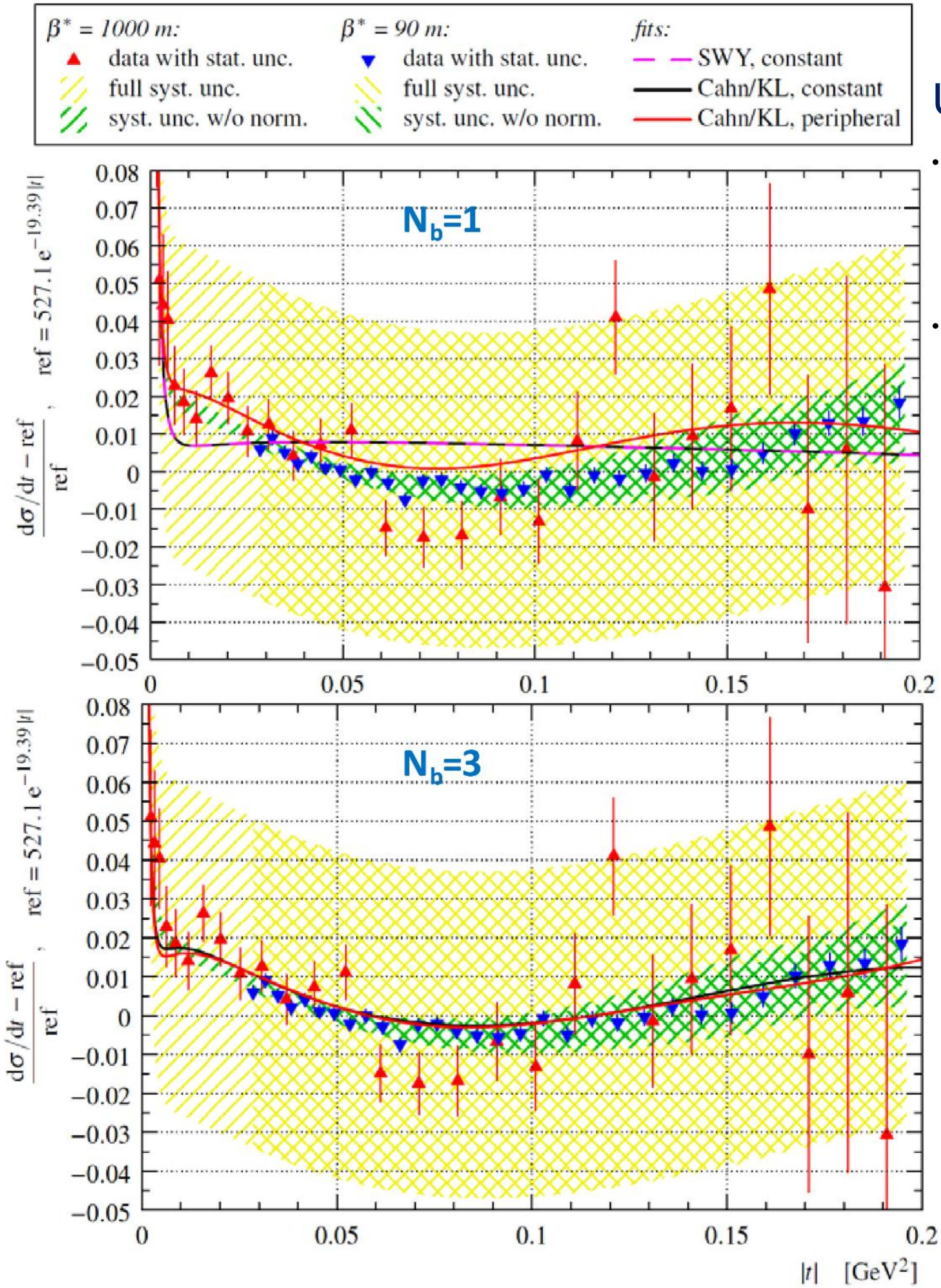
- role of |t|-dependence of hadronic phase?
  - large impact at low |t|
  - controls behaviour in impact parameter space (b)

  - consider 2 options:
    + central: black
    + peripheral: blue





Coulomb-hadronic interference – fits



Ü **Purely-exponential hadronic amplitude**

- Central phase excluded (with SWY, Cahn & KL) Þ application of SWY formula excluded too
- Periheral phase not explicitly excluded by data but disfavoured
  - r value outside a consistent pattern of other fits & theoretical predictions
  - several theoretical reasons for non-expontential hadronic amplitude

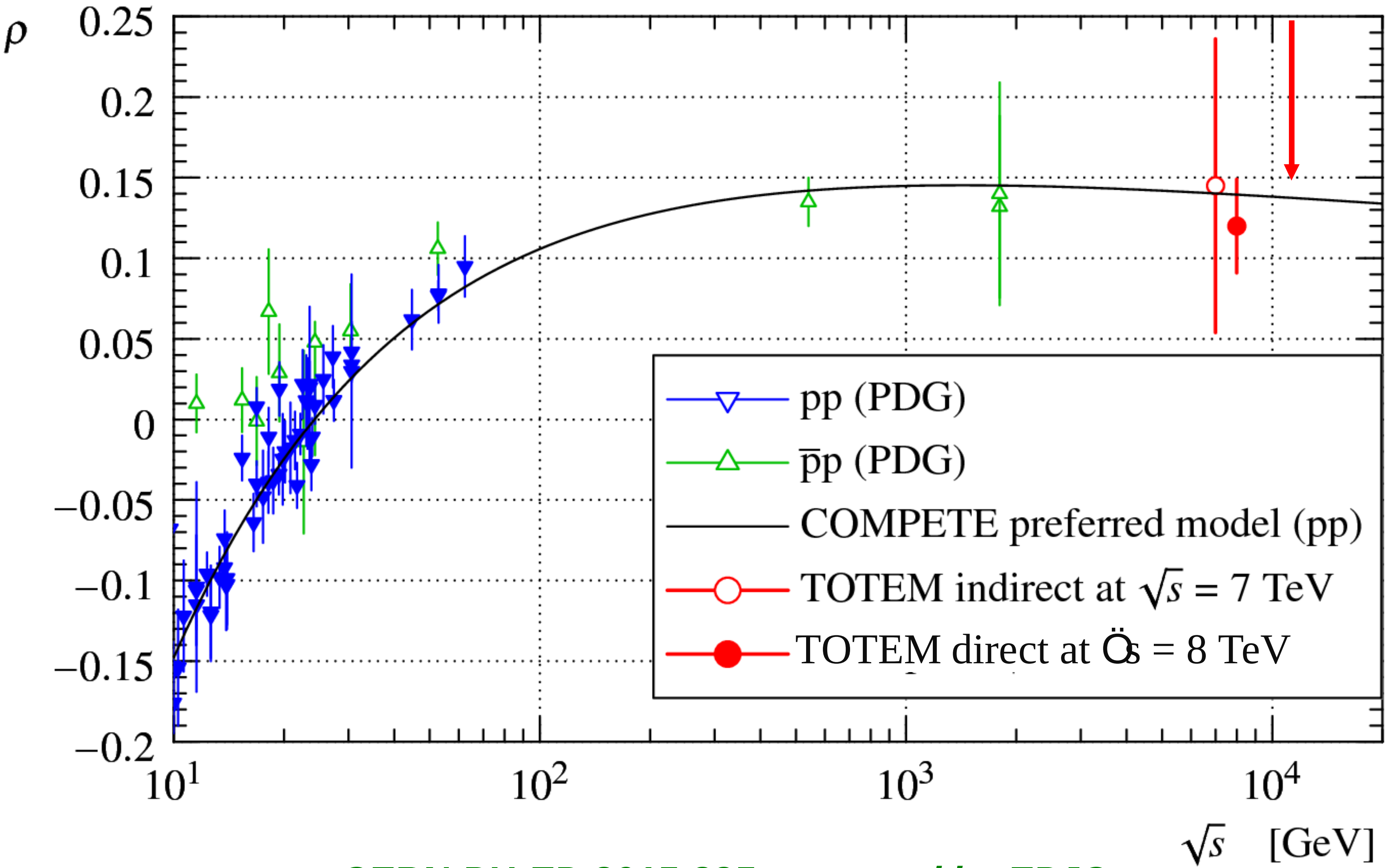
Ü **Non-exponential hadronic amplitude**

- Both central & peripheral phase compatible with data Þ centrality not a necessary description for elastic scattering

Not one single hadronic scattering amplitude Þ multiple exchange channels for elastic scattering

r vs Ös

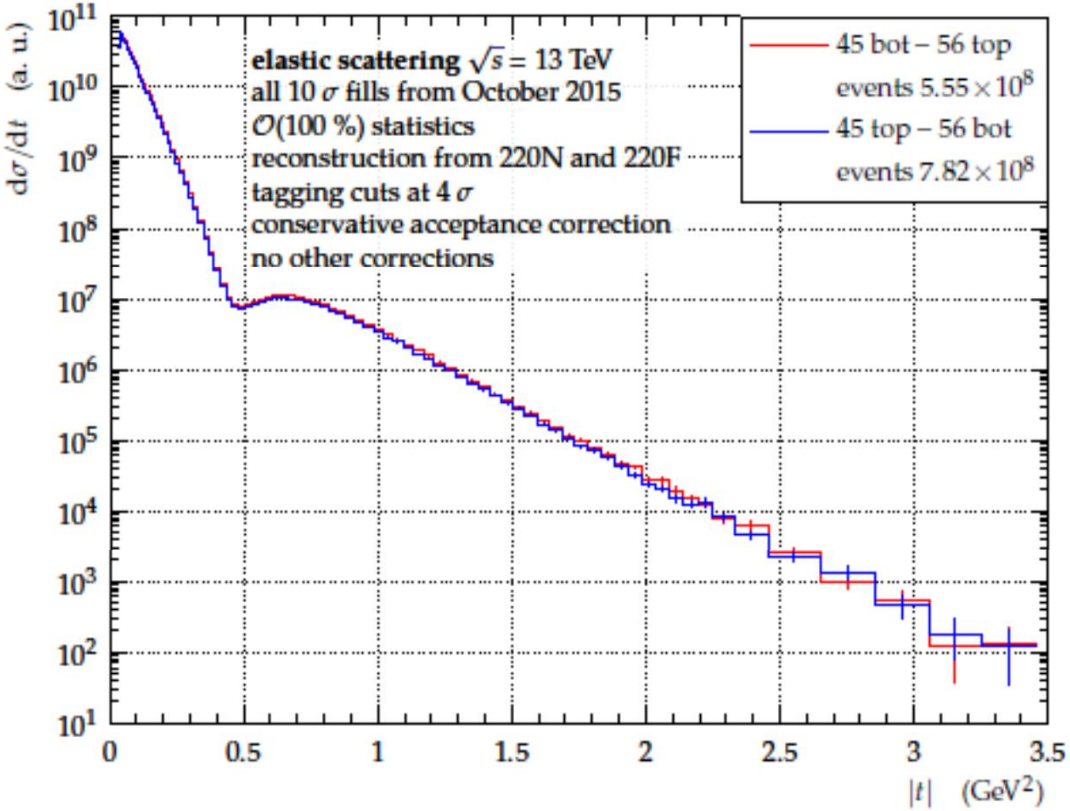
First direct r determination at LHC (8 TeV): r = 0.12 ± 0.03



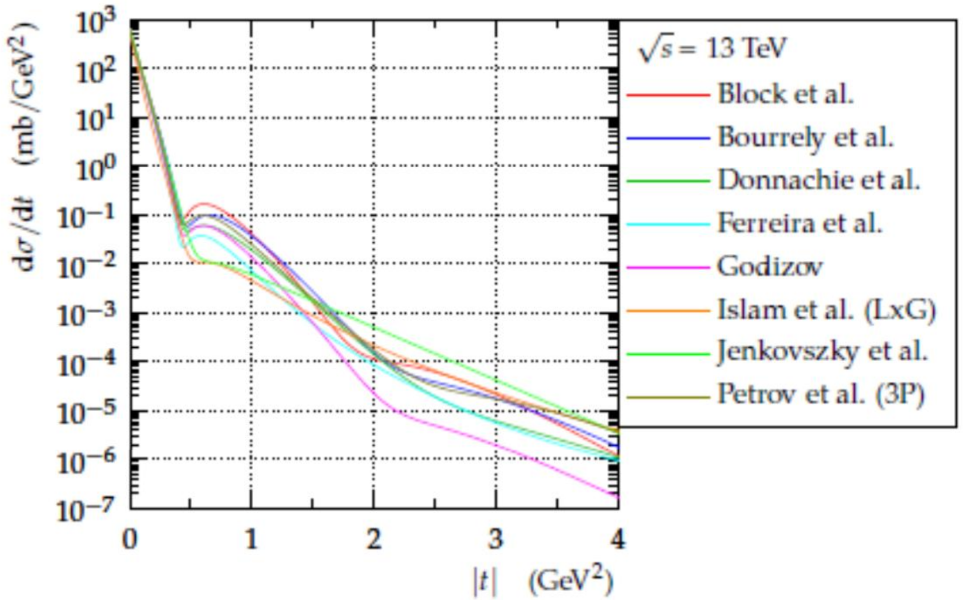
CERN-PH-EP-2015-235, accepted by EPJC

Elastic pp scattering: structures at high |t| ?

Very preliminary 13 TeV data give already very strong indications



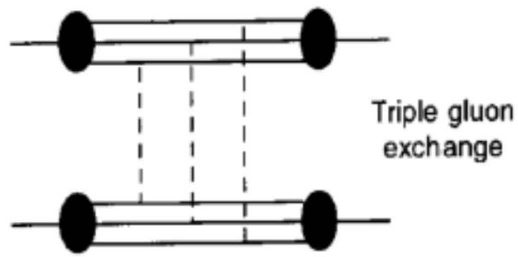
model predictions:



oscillations in almost each model

No structures at high-|t| !

- Rules out many modules
- Rules out "optical" models?
- Physics interpretation: transition between diffraction & pQCD a la Donnachie-Landshoff



Total pp cross-section: methods & results

Excellent agreement between 7 TeV s measurements:

$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)} \frac{1}{\mathcal{L}} \left(\frac{dN_{el}}{dt} \right)_{t=0}$$

based on elastic scattering Þ low mass diffraction independent

s_{total} = 98.3 mb ± 2.0 mb
EPL 96 (2011) 21002

s_{total} = 98.6 mb ± 2.3 mb
EPL 101 (2013) 21002

testing validity of optical theorem at ~3.5 % level

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

optical theorem & r independent

s_{total} = 99.1 mb ± 4.3 mb
EPL 101 (2013) 21004

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

L independent

s_{total} = 98.1 mb ± 2.4 mb
EPL 101 (2013) 21004

7 TeV

s_{total} = 101.7 mb ± 2.9 mb **8 TeV**
PRL 111(2013) 012001

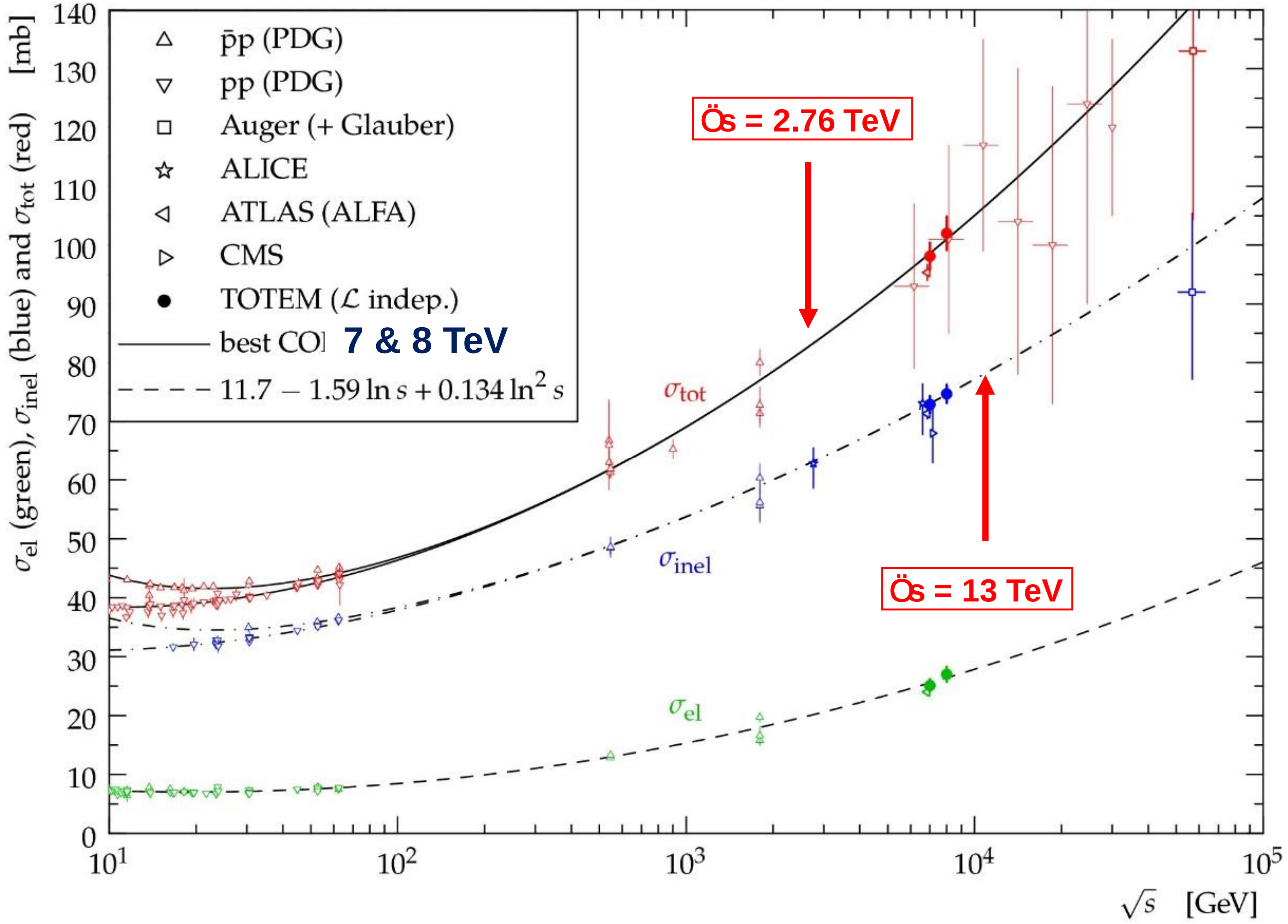
compatible

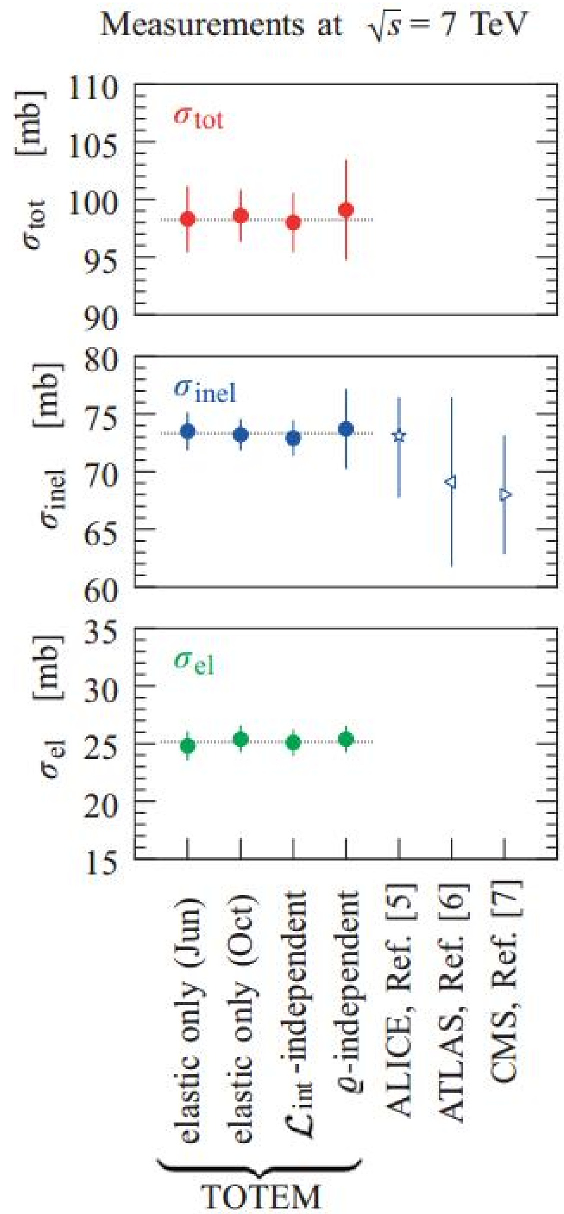
Combining 8 TeV b* = 90 m & 1 km data: Improved extrapolation of hadronic amplitude to t = 0 (Coulomb interference measured) & simultaneous r determination

s_{total} = 102.9 mb ± 2.3 mb (central hadronic phase)
s_{total} = 103.0 mb ± 2.3 mb (peripheral hadronic phase)
CERN-PH-EP-2015-235, accepted by EPJC

8 TeV

pp cross-sections: summary





Ös = 2.76 and 13 TeV analyses on-going

3g J^{PC} = 1$^{- -}$ search

- Originally predicted as Odderon in Regge theory framework [Lukaszuk, Nicolescu], confirmed in QCD [Vacca, Braun, Dosch et al.]: Colorless 3-gluon bound state with strong internal coupling

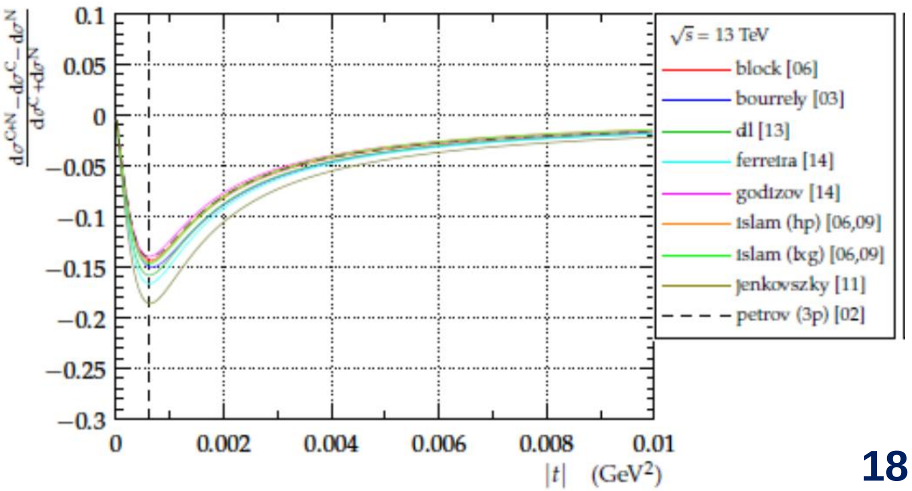
Theory: 3g J^{PC}=1$^{- -}$ existence would imply for pp elastic scattering :

- persistence of dip at LHC energies, faster increase of s_{tot} with √s
- non-constant hadronic phase & low-t deviation from pure exponential
- faster decrease of r with √s: @14 TeV r » 0.14 (without 3g J^{PC} = 1$^{- -}$) vs r » 0.10 (with 3g J^{PC} = 1$^{- -}$); TOTEM @8 TeV: r = 0.12 ± 0.03
  Þ need r with ± 0.01 precision @13 TeV
- pQCD (without oscillatory effects) at large |t|

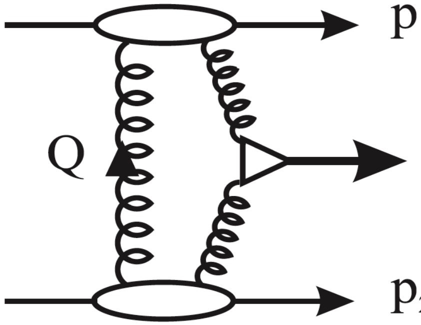
Þ TOTEM measurements consistent with existence of 3g J^{PC} = 1$^{- -}$

Coulomb-hadronic interference 13 TeV:

- equality point (Coulomb = nuclear) has optimal sensitivity to ρ
  Þ b* = 2.5 km with RP at 3s
- ± 0.01 precision on r requires ≤ 1% error on data points Þ successful data taking last week



(Exclusive) central diffraction



p_1 (x_1) $M_X^2 = x_1 x_2 s$

X at rapidity y_X **gg collider**

p_2 (x_2) $y_X = \frac{1}{2} \ln \frac{x_1}{x_2}$

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

ø <u>with double-arm proton detection</u>

b* = 90 m: all M_X, t > 0.02 (RP at 10s)

ø Comparison of prediction from forward to central system:

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

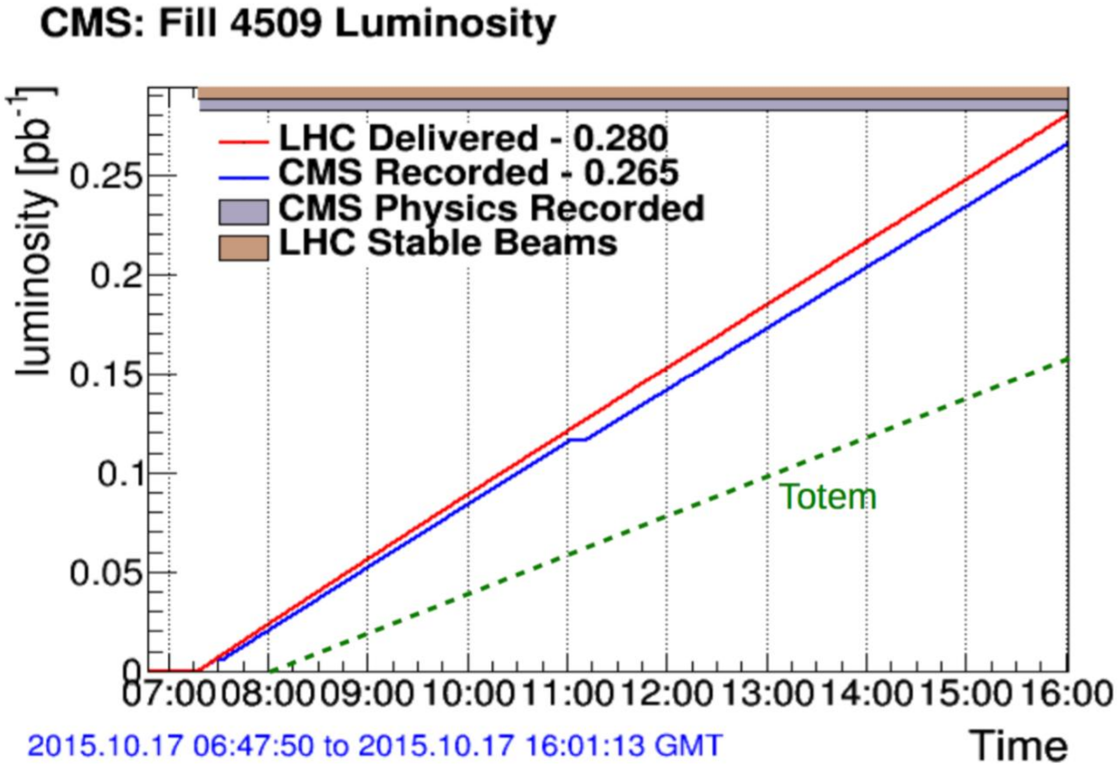
ø prediction of rapidity gaps from proton x's : $Dh_{1,2} = -\ln x_{1,2}$

<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)

CMS-TOTEM joint data taking b* = 90 m

CMS-TOTEM 13 TeV, Oct 2015
β* = 90m, low Pile Up
L1 Trigger exchange
Independent DAQs, Offline merging
TOTEM DAQ running at ~ 50 kHz
CMS HLT running at ~ 8 kHz



Triggers:

- Dedicated exclusive low mass resonance trigger
- Inclusive central diffractive trigger (non-diagonal configuration)
- Central CMS triggers (dijets pT ³ 40 GeV, dimuons, dielectrons)
- Minimum bias & Zerobias

Integrated Luminosity
LHC delivered : 0.74/pb
CMS recorded : 0.68/pb
Totem recorded : 0.4/pb
Totem Trigger & CMS data : 0.55/pb

Low mass resonance & glueball studies

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

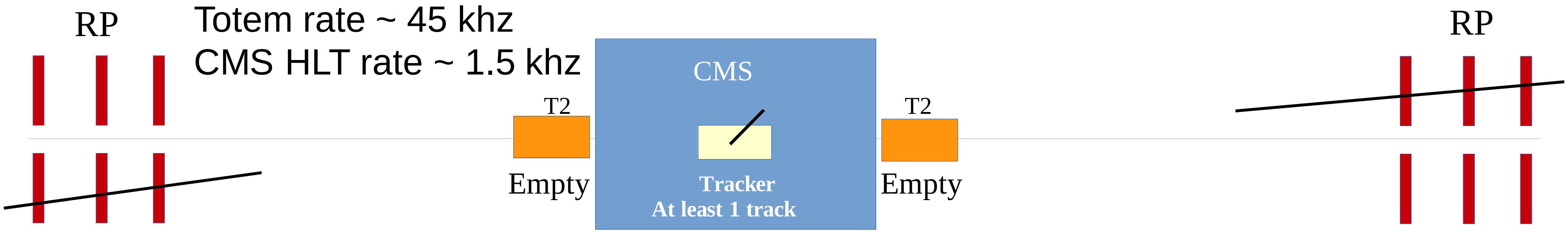
Decays and branching ratios of $f_0(1710)$ poorly explored (unlike $f_0(1500)$)
à Goal: characterize $f_0(1710)$ and compare with known $f_0(1500)$

CMS+TOTEM advantages:

- ü Good particle ID & mass resolution (s(M) ~ 30 MeV) using CMS tracker
- ü RP protons assure exclusivity ($p_{T,RP}$ ~ $p_{T,tracker}$)

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

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

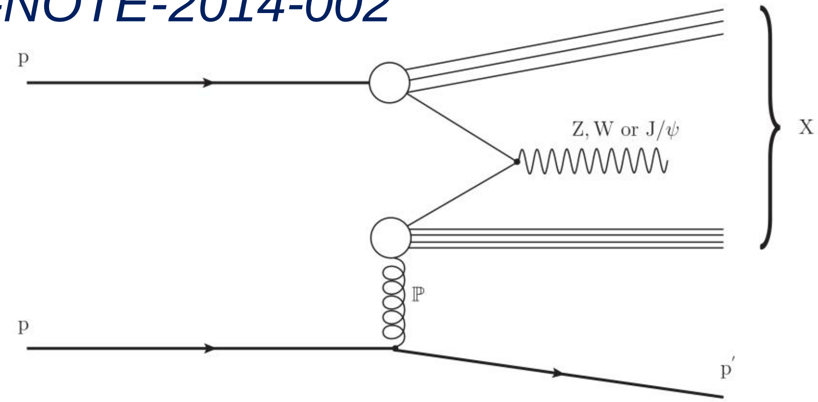


b* = 90 m common CMS-TOTEM physics runs:
100 M TOTEM0 triggers in ~0.4 pb^{-1} Þ ´ 500-750 statistics (2012)
Þ should allow full decay characterization

SD processes at b* = 90 m

Single diffractive processes: study rapidity gap survival probability
Triggered using CMS lepton & jet triggers
Visible s estimate at Ös = 13 TeV (both proton + central object)

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



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

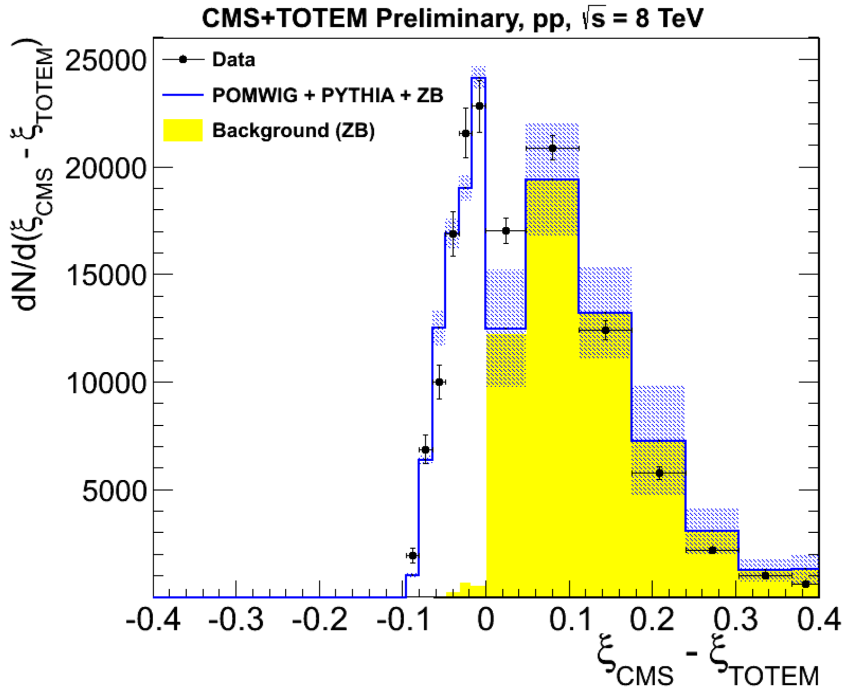
0.4 pb^{-1}: 120 ± 4 events

- 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



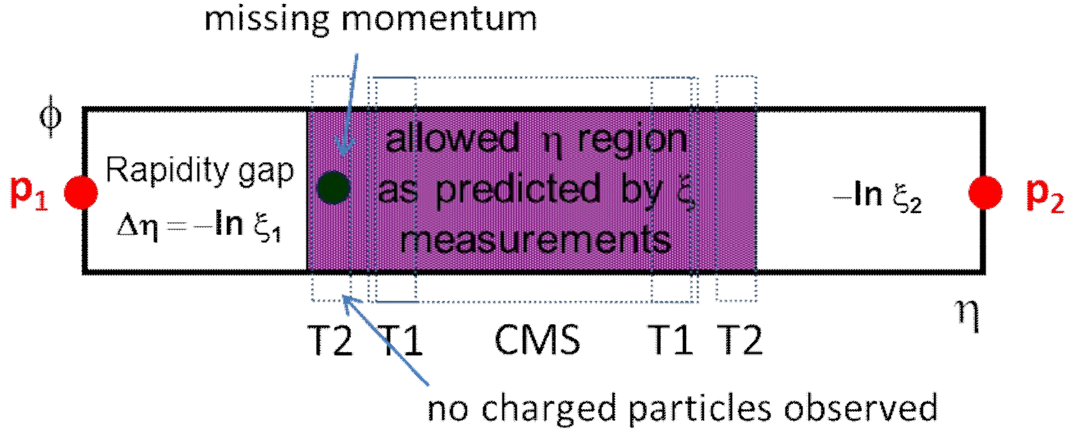
Background removal demonstrated on common CMS+TOTEM b* = 90 m data at Ös = 8 TeV (SD dijets)

Missing mass & momentum searches

new physics that escaped standard searches ?

preliminary search on existing CMS-TOTEM data 2012 b* = 90 m samples (~0.05 pb^{-1} @ m» 0.05)

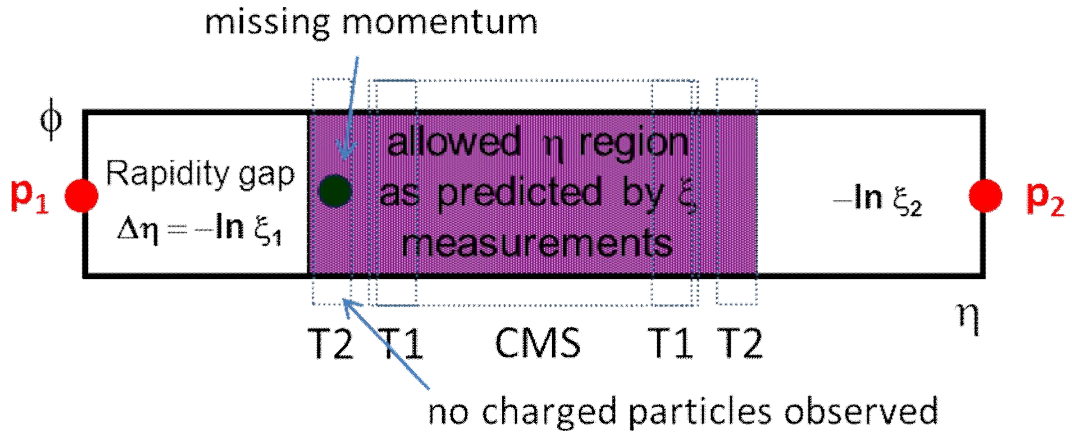
- several topologies examined for missing mass candidates (no evident signal found)



- M_{Pflow} (particle flow + p_{miss}) ≤ M_{pp}
- p_{Pflow} (particle flow) ≠ p_{pp}
- p_{miss} pointing in the instrumented region
- |h| > 6.5 to be forbidden by $x_{1,2}$ measurements

~ 10 candidates with DM = M_{pp} – M_{Pflow} > 250 GeV (mostly without jet activity)

Missing mass & momentum



Explaination of observed events

- N*® pp^0 decays, where p^0 goes undetected
- pileup? Additional protection available in 2016 using precise timing
- Detector ‘inefficiencies‘? unlikely
- Acceptance gaps between detectors?
- High energy neutrinos?
- Neutral particle flow in T2? unlikely
- Real escaping energy?

search for missing mass in 150 < M_{miss}< 700 TeV at Ös = 13 TeV

L_{int} » 50 pb^{-1} of b* = 90 m data would allow search for O(pb) processes

Future tests using 2015 b* = 90 m data

Summary

- Elastic scattering: extensive studies published based on 7 & 8 TeV data (Run I, 2010-13), latest Coulomb-hadronic interference; analysis of 2.76 & 13 TeV data on-going including search for the Odderon
- s_{tot}, s_{inel} & s_{el}: 7 & 8 TeV result (Run I, 2010-13) published with several different methods, latest result taking effects of Coulomb-hadronic interference into account & simultaneous determination of r ; analysis of 2.76 & 13 TeV data on-going
- Exclusive production & hard diffraction (CMS-TOTEM): high potential due to large combined h coverage, SD dijet 8 TeV analysis soon to be published; analysis 13 TeV data on-going

Stay tuned for more results !

Backup

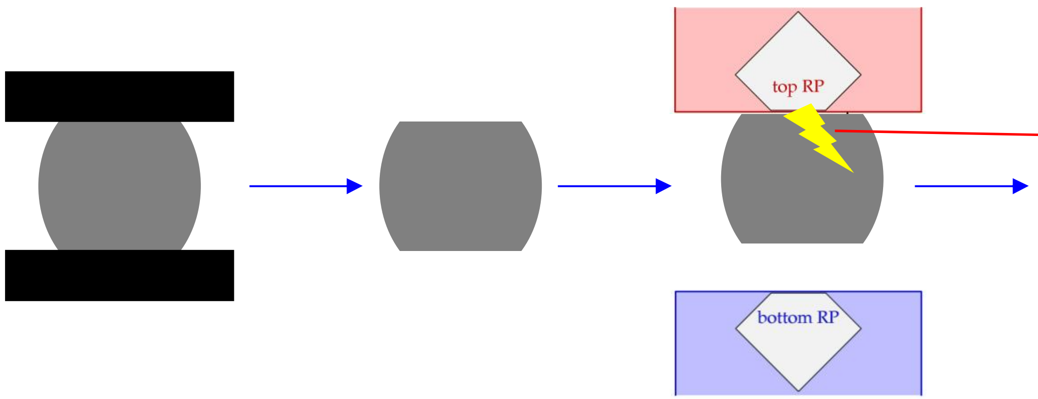
Beam-Based RP Alignment

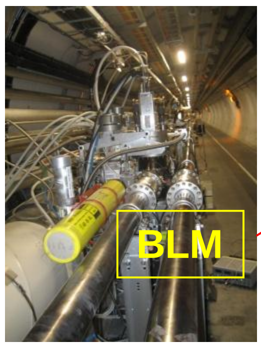
Standard Procedure for LHC Collimators

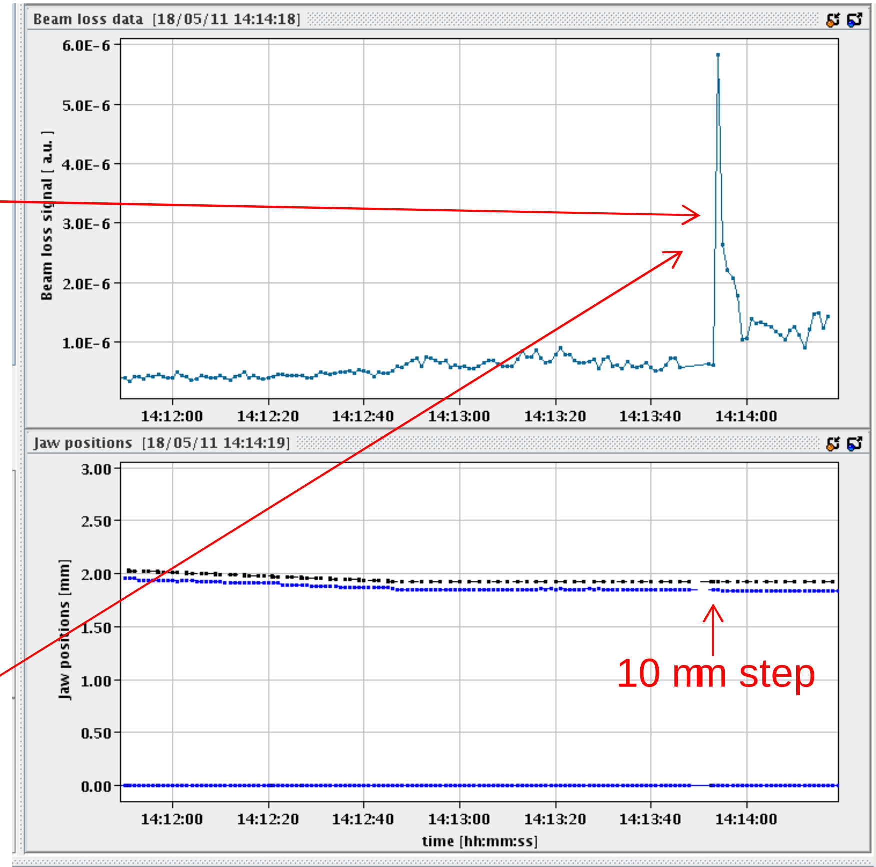
A primary collimator cuts a sharp edge into the beam, symmetrical to the centre

The top RP approaches the beam until it touches the edge

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





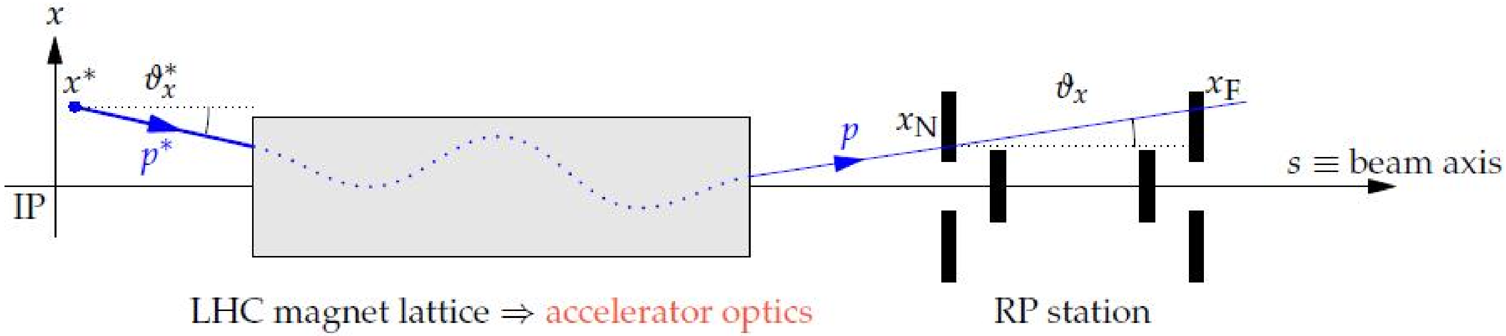


When both top and bottom pots are touching the beam edge:

- 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

à Alignment of the RP windows relative to the beam (~ 20 mm)

Proton transport & reconstruction



(x*, y*): vertex position
(qx*, qy*): emission angle: t » - p² (qx* ² + qy* ²)
x = Dp/p: momentum loss (elastic case: x = 0)

Measured in RP

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

Values at IP5 to be reconstructed

Product of all lattice element matrices

$$x_{RP} = L_x Q_x^* + v_x x^* + D_x x$$

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

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 ~ 0

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

Excellent optics understanding needed.

Optics reconstruction

Machine imperfections alter the optics:

- **Strength conversion error, σ(B)/B ≈ 10^{-3}**
- **Beam momentum offset, σ(p)/p ≈ 10^{-3}**
- Magnet rotations, σ(ϕ) ≈ 1 mrad
- Magnetic field harmonics, σ(B)/B ≈ 10^{-4}
- Power converter errors, σ(I)/I ≈ 10^{-4}
- Magnet positions Δx, Δy ≈ 100 μm

$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

→ Precise model of the LHC optics is indispensable!

Novel method from TOTEM:

- Use **measured** proton data from RPs
- Based on kinematics of elastic candidates
- Published in New Journal of Physics
- http://iopscience.iop.org/1367-2630/16/10/103041/