Jan Kašpar
on behalf of the TOTEM collaboration

QCD at Cosmic Energies – VII
19 May, 2016

- TOTEM projects and physics programme
- detector apparatus,
  principle of proton measurement
- physics analyses and results: TOTEM alone
- physics analyses and results: TOTEM + CMS
- upgrades, outlook for 2016

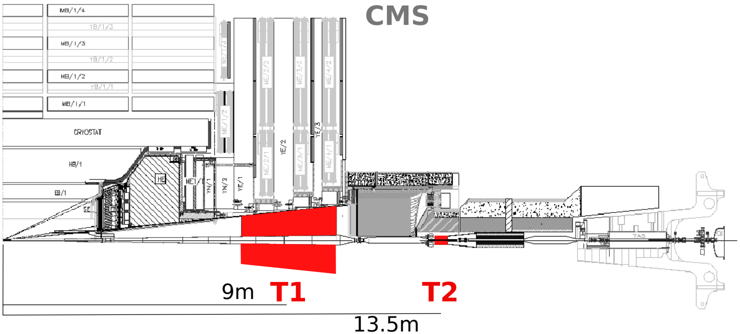
list of TOTEM publications:
http://totem.web.cern.ch/Totem/publ_new.html

- **TOTEM**
  - LHC experiment dedicated to measurement of:
    total cross-section, elastic scattering and diffractive processes
  - common features: rapidity gaps, particles in very forward region, surviving protons $\Rightarrow$ special detectors

- TOTEM + CMS
  - both experiments at LHC Interaction Point 5
  - excellent pseudorapidity coverage: optimal for hard diffraction studies
  - cooperation mode: independent experiments, exchange of triggers

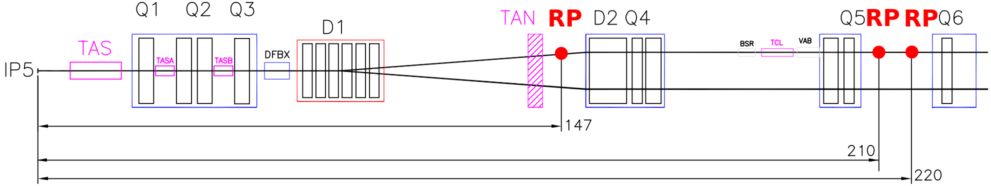
- CT-PPS (CMS-TOTEM Precision Proton Spectrometer)
  - all subdetectors fully integrated under CMS
  - dedicated detectors for high-pileup environment (timing, pixels instead of strips)

- Inelastic telescopes T1 and T2: charged particles from inelastic collisions



- T1: $3.1 < |\eta| < 4.7$, $p_T > 100 MeV$
- T2: $5.3 < |\eta| < 6.5$, $p_T > 40 MeV$

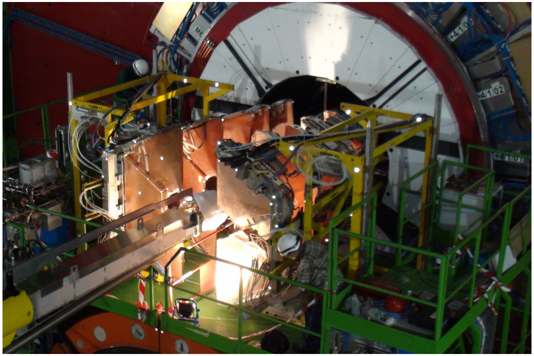
- Roman Pots (RP): elastic and diffractive protons close to outgoing beam



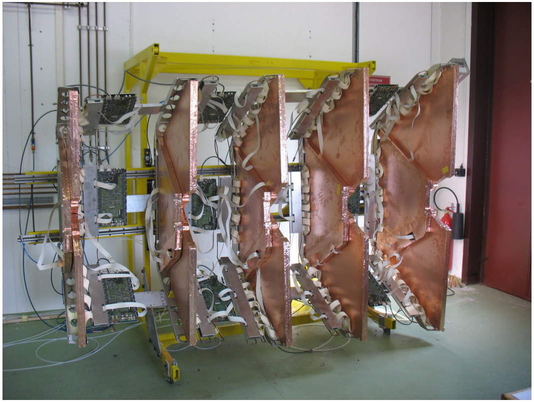
  - station at 147m in Run I $\rightarrow$ station 210m in Run II

- all detectors: symmetric about IP5, trigger capable, radiation tolerant

Telescope 1 (T1)

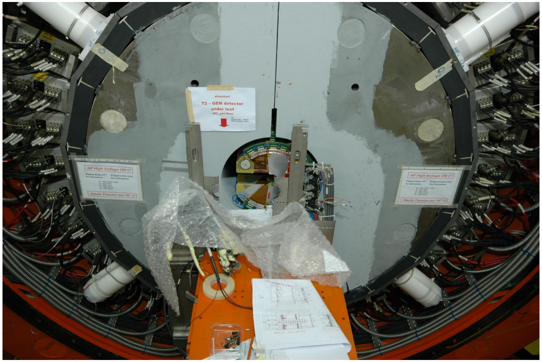


- installed inside CMS end-caps
- at 7.5 to 10.5 m from the IP
- one *telescope* on each side of IP
- each telescope consists of two *quarters*

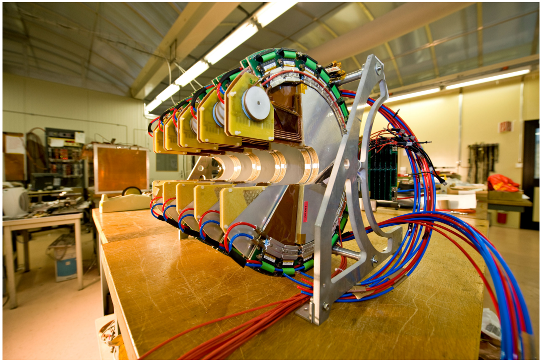


- each quarter formed by 5 *planes* equally spaced along beam
- each plane consists of 3 trapezoidal *CSC detectors*, each covering 60 ° in azimuth
- Cathode Strip Chamber: gaseous detector with 3 read-out coordinates (at 60 ° wrt. each other)

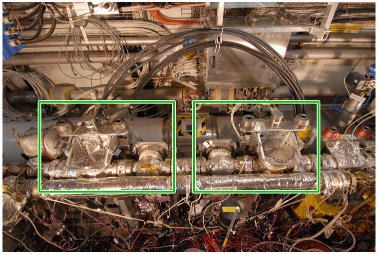
Telescope 2 (T2)



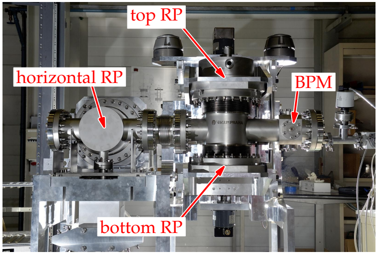
- installed inside CMS shielding between HF and Castor calorimeters
- centred about 13.5 m from the IP
- one *telescope* on each side of IP
- each telescope consists of two *quarters*



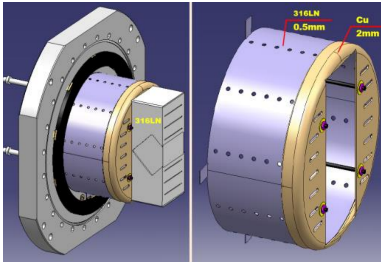
- each quarter formed by 10 semi-circular *planes*, assembled in 5 back-to-back mounted pairs
- each plane equipped with a *Gas Electron Multiplier* detector
  - gaseous detector, electron multiplication by 3 perforated foils (2 mm separation)
  - radial segmentation: *strips* (resolution ≈ 0.15 mm)
  - coarse radial$\times$azimuthal segmentation: *pads* (for triggering, azimuthal resolution $0.8\,^\circ$)



- *stations* installed at ± 220 m in the outgoing LHC beam-pipe
- each station has two *units*, separated by ≈ 5 m

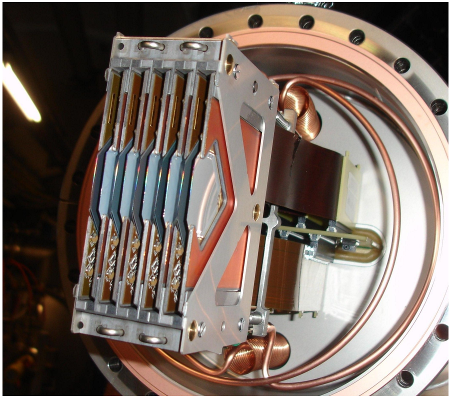


- each unit contains 3 *Roman Pots*: top, bottom and horizontal
- Roman Pot = movable beam-pipe insertion
  - beam unstable $\Rightarrow$ RPs retracted to safe position
  - beam stable $\Rightarrow$ RPs as close to beam as reasonable
- typical approach: 10 σ_{beam} (record 3 σ_{beam})

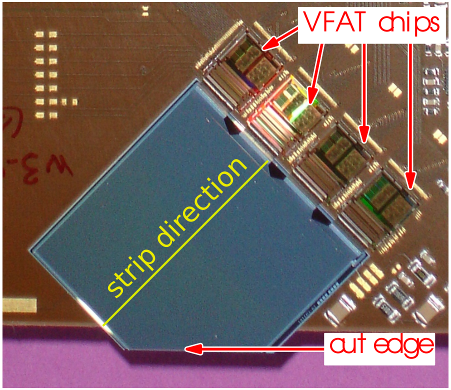


- Roman Pot: container for sensors
- LS1: improved RF shield $\Rightarrow$ possible close approach to high-intensity beam

“Edgeless” silicon sensors

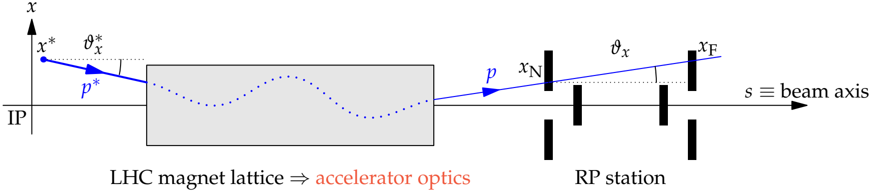


- each RP contains a *package* of 10 silicon sensors
- 5 pairs of back-to-back mounted strip sensors



- custom developed *“edgeless” sensors*
  $\Rightarrow$ insensitive edge $\approx 50\ \mu$m (standard about 1 mm)
- single-sided p^+-n
- 512 strips at pitch of 66 μm, at 45 $^\circ$ wrt. cut edge
- operated at $\approx -20\ ^\circ$C, bias voltage ≈ 100 V

- *proton transport*: described as in linear optics



$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \\ \xi \end{pmatrix}_{\mathrm{RP}} = \underbrace{\begin{pmatrix} v_x & L_x & \cdot & \cdot & D_x \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ v_y & L_y & \cdot & \cdot & D_y \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & 1 \end{pmatrix}}_{\text{product from all lattice elements}} \begin{pmatrix} x^* \\ \theta_x^* \\ y^* \\ \theta_y^* \\ \xi \end{pmatrix}_{\mathrm{IP}}$$

θ_x^*, θ_y^*: scattering angles
x^*, y^*: vertex
$\xi = \Delta p/p$: momentum loss

optical functions:
effective length L
magnification v
dispersion D

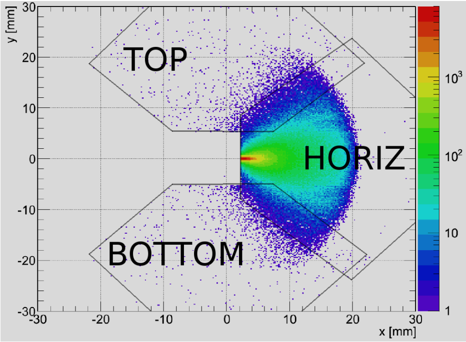
- *proton reconstruction*: inverted transport RPs $\longrightarrow$ IP
  - optical parameters functions of ξ ⇒ reconstruction is non-linear problem
  - good knowledge of optics is crucial

- simulation of central diffraction for 2 different optics

low β^* (LHC standard)

$L_x \approx 1.7$ m, $L_y \approx 14$ m, $D_x \approx 8$ cm

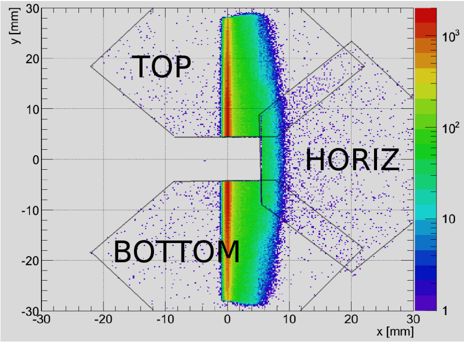
diffractive protons in *horizontal RPs*



$\beta^* = 90$ m (special for TOTEM)

$L_x \approx 0$, $L_y \approx 260$ m, $D_x \approx 4$ cm

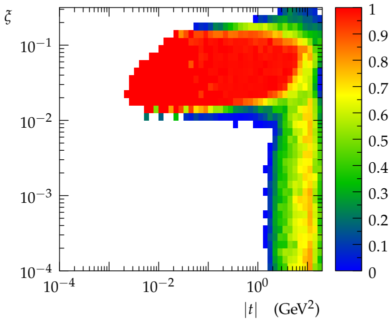
diffractive protons in *vertical RPs*

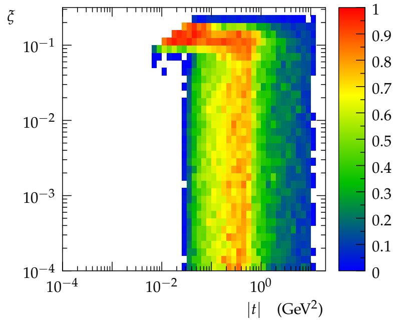


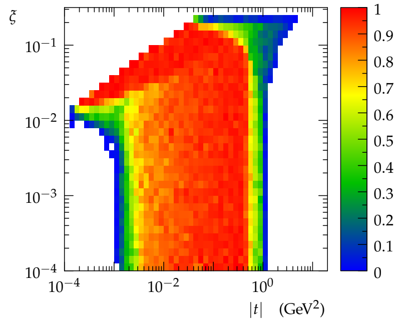
- optics typically "labelled" by *$\beta^* \equiv$ betatron function at IP*
  - beam width: $\sqrt{\varepsilon\beta}$, ε: beam emittance
  - beam angular divergence: $\sqrt{\varepsilon/\beta}$
  - luminosity $\propto$ (beam width at IP)$^{-2} \propto 1/\beta^*$

$t \approx -p^2\theta^2$: four-momentum transfer squared

$\xi = \Delta p/p$: fractional momentum loss







$\beta^* =$ **0.55** m	**medium** $\beta^* =$ **90** m	**high** $\beta^* =$ **1535** m
$\mathcal{L} \approx 10^{33}$ cm^{-2}s^{-1}	$\mathcal{L} \approx 10^{28}$ cm^{-2}s^{-1}	$\mathcal{L} \approx 10^{27}$ cm^{-2}s^{-1}

elastic scattering: high $|t|$

diffraction: $\xi \gtrsim 0.03$, low cross-section processes

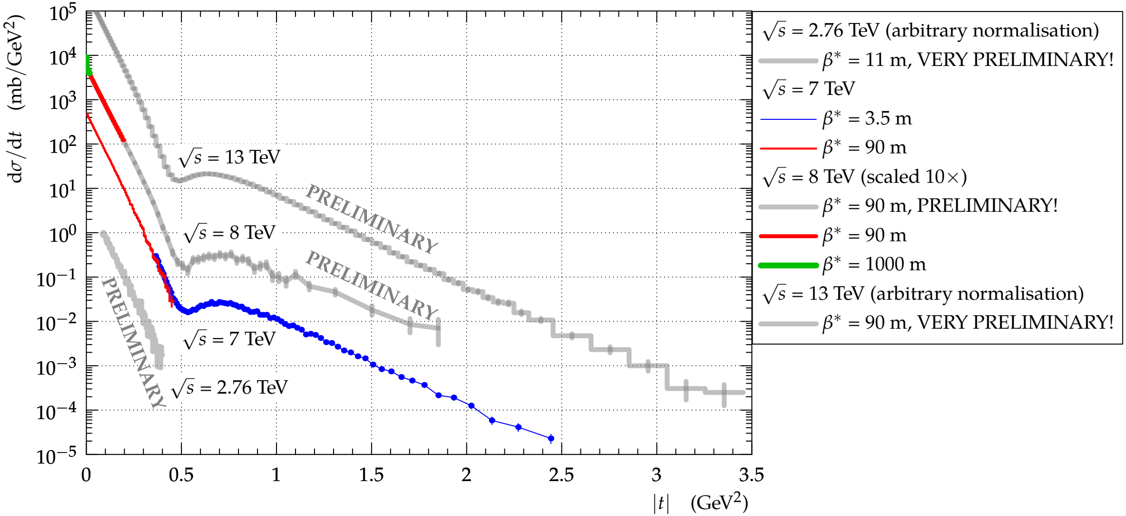
elastic scattering: low to mid $|t|$

diffraction: any ξ for $|t| \gtrsim 0.01$ GeV^2

elastic scattering: very low $|t|$ (Coulomb-nuclear interference)

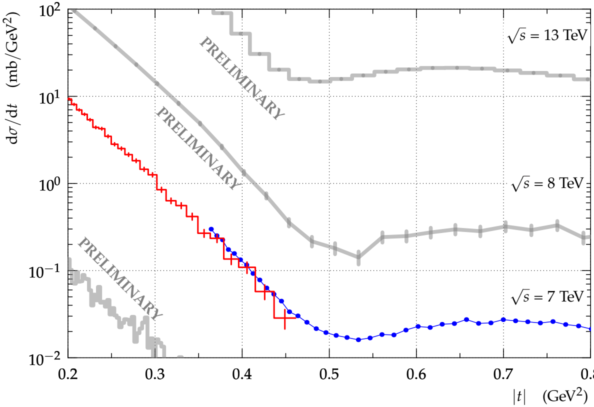
details depend on RP approach to beam and precise optics

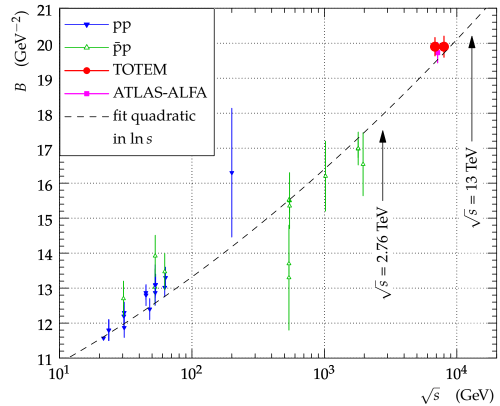
- selection: two anti-collinear protons from the same vertex
- (almost) purely data-driven analysis
- data overview (selection), gray = preliminary



- different $|t|$ probe *different physics regimes* – from lowest to highest $|t|$: Coulomb interference, diffractive cone, dip-bump, transition to pQCD

(gray = preliminary)

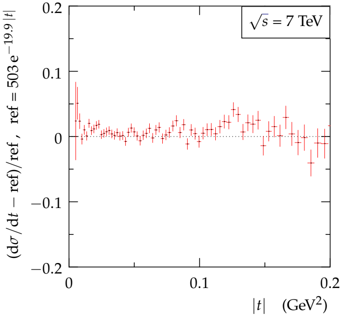


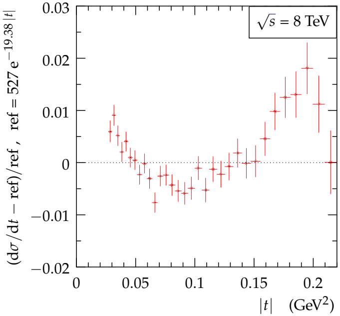


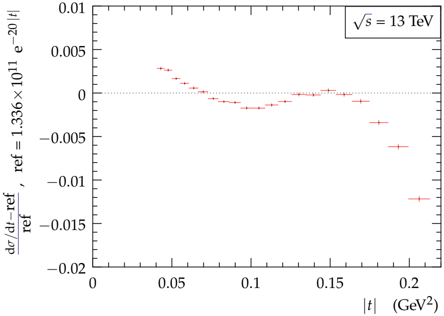
- *dip position*
  - $\sqrt{s} = 8$ TeV: limited statistics
  - $\sqrt{s} = 7 \rightarrow 13$ TeV: dip moves to lower $|t|$
    - 13 TeV results preliminary! (the yet missing unfolding correction likely to move the dip to lower $|t|$)
- *forward slope* $B = \frac{d}{dt} \ln \frac{d\sigma}{dt}\Big|_{t=0}$
  - increase wrt. previous experiments

Elastic scattering : *Non-exponentiality at low $|t|$*

- diffraction cone: "looks almost exponential"
  - magnify deviations ⇒ plot (dσ/dt − ref. exp.)/ref. exp.
- β^* = 90 m measurements at different energies (stat. unc. only):

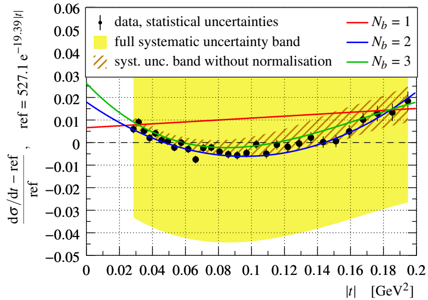




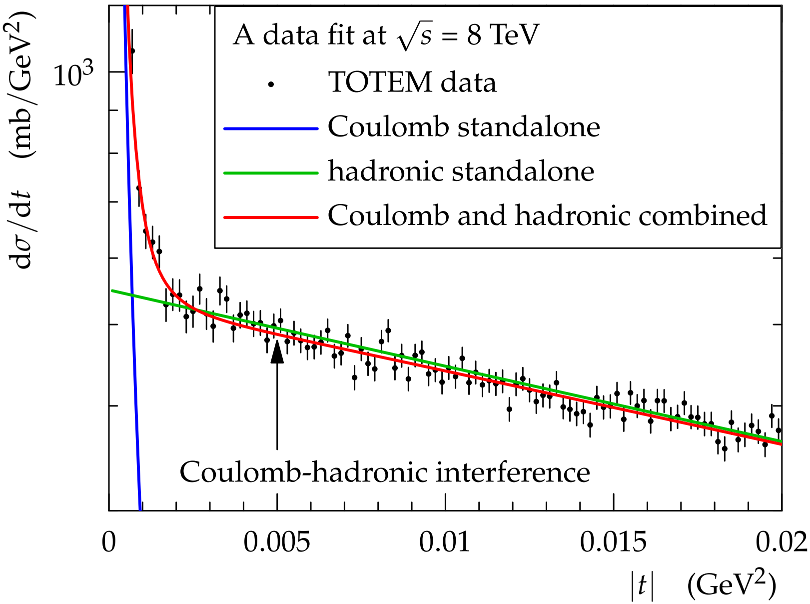


- non-exponentiality observed at 8 and 13 TeV!
  - 8 TeV: *7 σ significance* ⟶
  - 13 TeV: preliminary results
  - non-exponentiality of observed cross-section:

dσ/dt = nuclear + Coulomb + interference

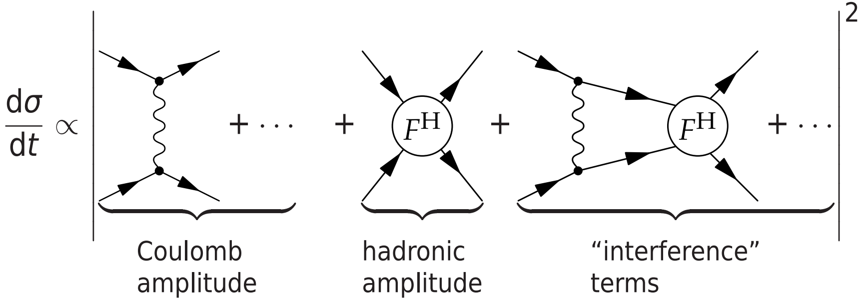


- 8 TeV data with $\beta^* = 1000$ m optics
  - RPs very close to the beam: $\approx 3\ \sigma_{\text{beam}}$
  - $|t|_{\text{min}} \approx 6 \cdot 10^{-4}$ GeV^2



Elastic scattering : *Coulomb interference*

- observed cross-section



  - 2 meanings of "interference": sum of amplitudes, additional terms

- interference formula = summation for practical applications
  - simplified West-Yennie (SWY): QFT framework, traditional but *heavy simplifications (constant hadronic phase, constant slope)*
  - Cahn or Kundrát-Lokajíček (KL): eikonal framework, no explicit simplifications

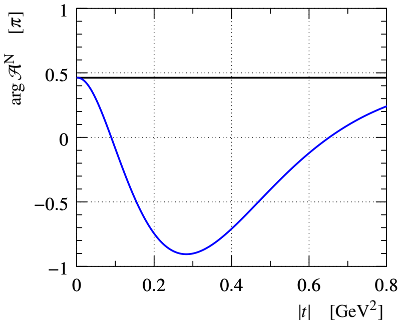
- interference ⇒ phase of hadronic amplitude exposed in cross-section
  - phase t-dependence needs to be considered in analysis
  - constraints from data ⇒ determination of ρ parameter

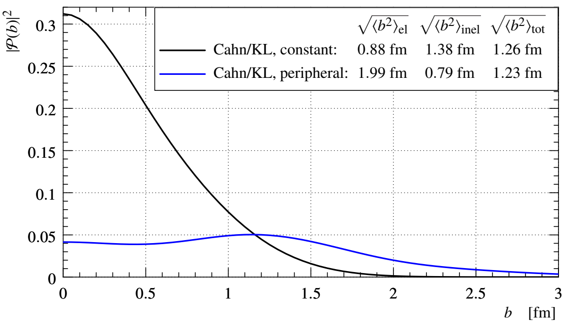
$$\rho = \Re\mathcal{A}^{\mathrm{N}}/\Im\mathcal{A}^{\mathrm{N}}\Big|_{t=0}$$

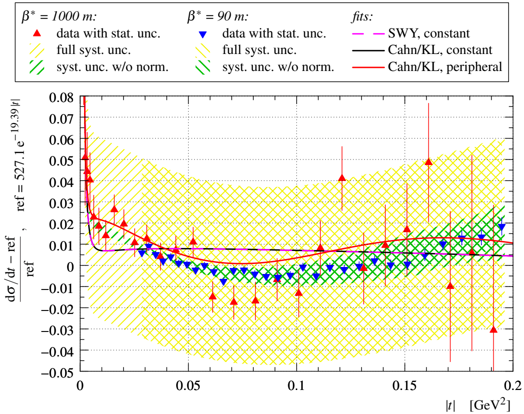
central question:

observed non-exponentiality – due to hadronic, Coulomb or both?

- fits with 2 different assumptions on hadronic component
  - *purely-exponential* – non-exponentiality due to Coulomb (+interference)
    $\rightarrow |\mathcal{A}^{\mathrm{N}}| = a \exp(b_1 t)$
  - *flexible enough* to describe non-exponentiality even without Coulomb
    $\rightarrow |\mathcal{A}^{\mathrm{N}}| = a \exp(b_1 t + b_2 t^2 + b_3 t^3)$
- role of hadronic phase t-dependence?
  - largest impact: rate of change at low $|t|$
    - same quantity controls behaviour in impact-parameter space
  - considered two families: *central* (black ↓), *peripheral* (blue ↓)

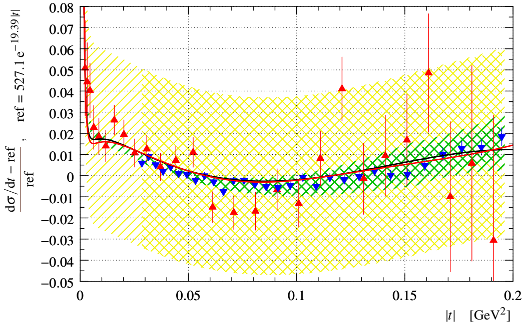






⇐ **purely-exponential hadronic amplitude**

- *constant phase excluded* (with both SWY and KL formulae) ⇒ application of SWY formula excluded too
- *peripheral phase* not excluded by data, but *disfavoured*
  - ρ value outside a consistent pattern of other fits and theoretical predictions
  - number of theoretical reasons for non-exponential hadronic amplitude

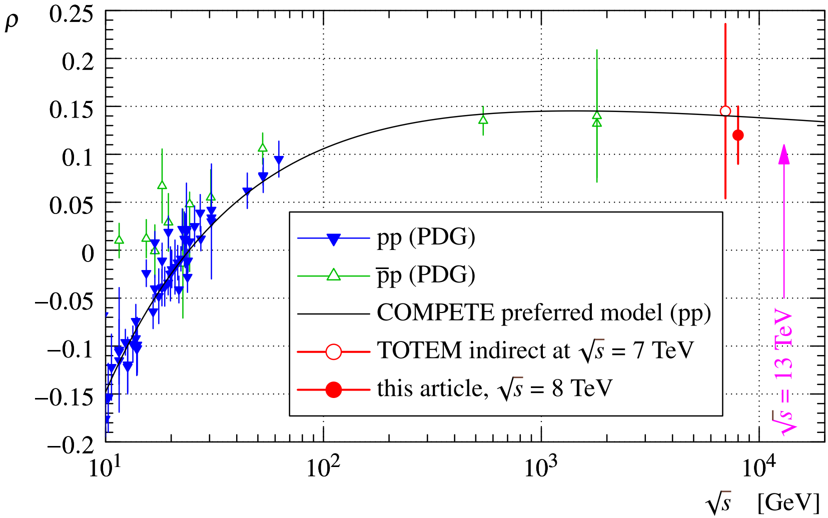


⇐ **non-exponential hadronic amplitude**

- both constant and peripheral phases compatible with data ⇒ *centrality not necessity*

- $\sqrt{s}$ = 8 TeV: first LHC determination from Coulomb-hadronic interference

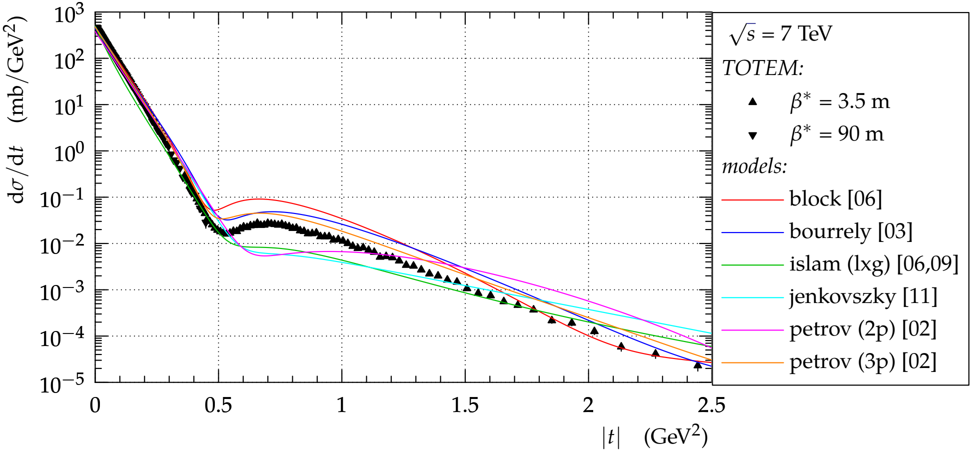
$$\rho = 0.12 \pm 0.03$$



  - leading uncertainty: statistics

- plans for $\sqrt{s}$ = 13 TeV: ρ measurement with higher statistics

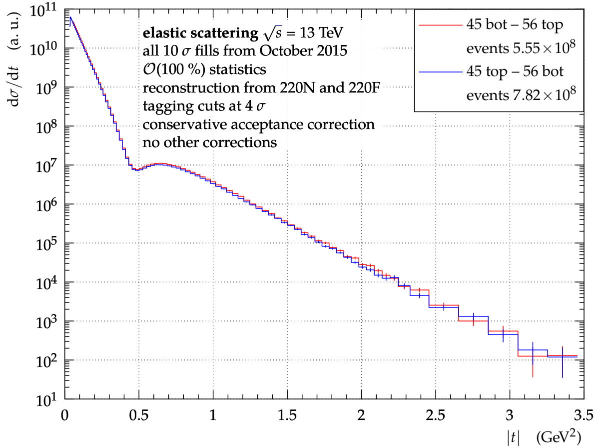
- model predictions (prior to Run I) vs. TOTEM data at $\sqrt{s}$ = 7 TeV:



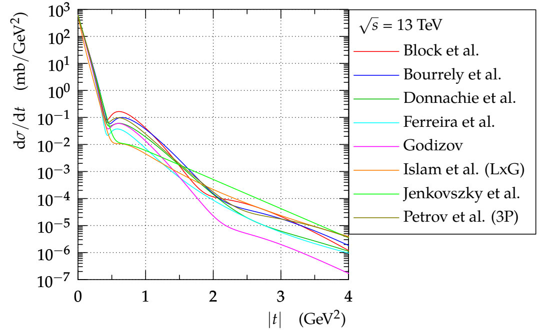
  - *no model compatible with data!*

- surprisingly?: little reaction after Run I (statement from 2015)
  - most often: no change at all or simple parameter refit
  - only Islam abandoned one mechanism of large $|t|$ scattering
  - exclusion of physics mechanisms (model independent)?

- $\sqrt{s}$ = 13 TeV: very preliminary, but already very strong results

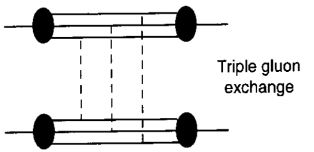


model predictions:



oscillations in almost each model

- *high-|t|: no structures!*
  - rules out many models
  - rules out physics mechanism: "optical" models
  - physics interpretation: transition between diffraction and pQCD? ⇒ e.g. Donnachie-Landshoff ⇒



- *inelastic cross-section*: event counting with T2 (and T1)
  - 95 % of inelastic events have at least 1 track in the T2 region
  - only one significant MC correction: contribution from low mass diffraction
- 3 methods to determine *total cross-section*

elastic observables only:

$$\sigma_{\mathrm{tot}}^2 = \frac{16\pi}{1+\varrho^2}\,\frac{1}{\mathcal{L}}\,\left.\frac{\mathrm{d}N_{\mathrm{el}}}{\mathrm{d}t}\right|_0$$

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

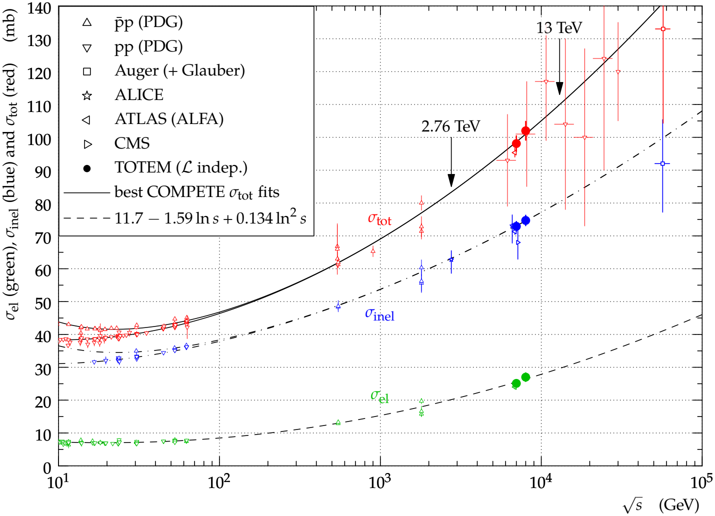
ϱ-independent:

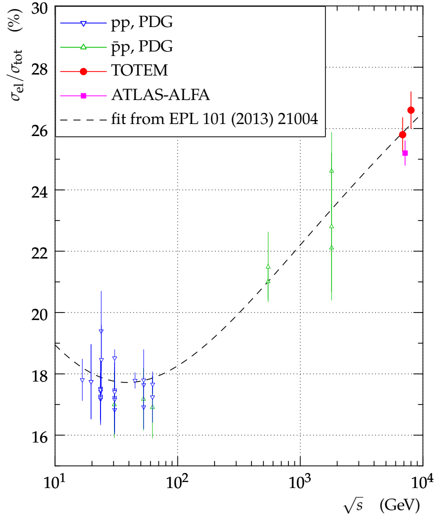
$$\sigma_{\mathrm{tot}} = \frac{1}{\mathcal{L}}\,(N_{\mathrm{el}} + N_{\mathrm{inel}})$$

luminosity-independent:

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

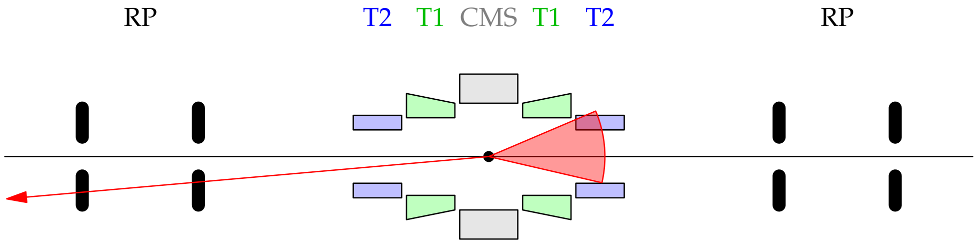
Cross-section results





- $\sqrt{s}$ = 7 TeV: all 3 methods consistent
- $\sqrt{s}$ = 8 TeV: results from CNI study superior
  - Coulomb component explicitly separated
  - determined in the same analysis as ρ
- $\sqrt{s}$ = 2.76 and 13 TeV analyses ongoing

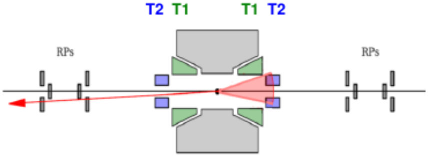
Single diffraction: $p + p \to p + X$



- double determination of $\xi \approx e^{-\Delta\eta}$
  - from RPs
  - from rapidity gap $\Delta\eta$ (T1/T2)
- mass of diffractive system: $M_X = \sqrt{s\xi}$
- available data
  - 7 TeV: TOTEM-standalone analysis in progress
  - 8 and 13 TeV: common data with CMS
- ξ resolution from RPs: ≈ 0.9 % $\Rightarrow$ mass bins given by arms where T1/T2 active

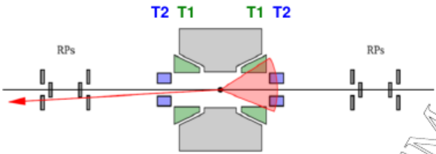
Low mass

M_{diff} = 3.4 - 8 GeV



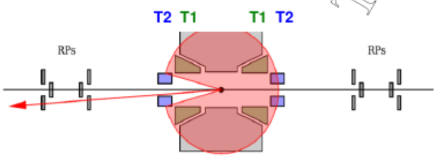
Medium mass

M_{diff} = 8 - 350 GeV

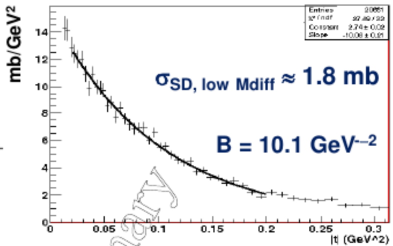


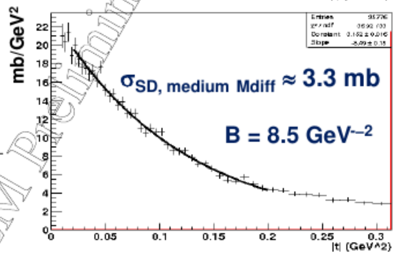
High mass

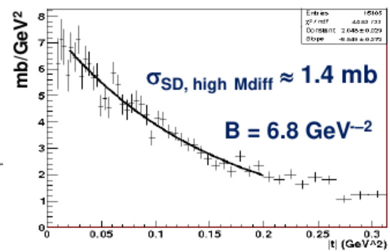
M_{diff} = 0.35 - 1.1 TeV



$d\sigma/dt \sim A \cdot e^{-Bt}$







<u>Corrections included:</u>

- Trigger efficiency
- Proton acceptance & reconstruction efficiency
- Background subtraction
- Extrapolation to t = 0

<u>Missing corrections:</u>

- Class migration
- ξ resolution & beam divergence effects

<u>Estimated uncertainties:</u>

B ~ 15% ; σ ~ 20%

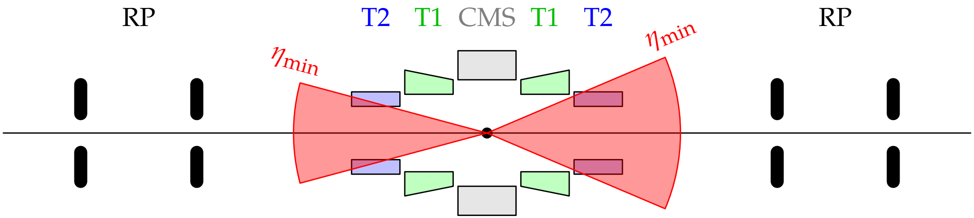
TOTEM preliminary:

$$\sigma_{SD} = 6.5 \pm 1.3 \text{ mb}$$

3.4 GeV < M_{diff} < 1.1 TeV

Analysis of very high mass SD events ongoing

courtesy of H. Saarikko



- experimental challenge: background (non-diffractive, SD pile-up)
  - sub-sample with signal $\gg$ background: 2$\times$T2 and T1 veto
  - non-diffractive background: control sample 2$\times$T2 + 2$\times$T1
  - SD background: control sample 1$\times$T2 + 0$\times$T1
- cross-section as function of η_{min} on both sides
  - challenge: reconstructed $\eta_{\text{min}} \longrightarrow$ true/generator η_{min}
    $\Rightarrow$ 2 η_{min} bins only
- available data
  - 7 TeV: results published
  - 8 and 13 TeV: common data with CMS (improvement expected)

- measurement

Measurement

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 120 \pm 25 \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	66±19 μb	27±4 μb
$5.9<\eta_{min}<6.5$	28±5 μb	12±4 μb

- comparison to Monte Carlos

Pythia

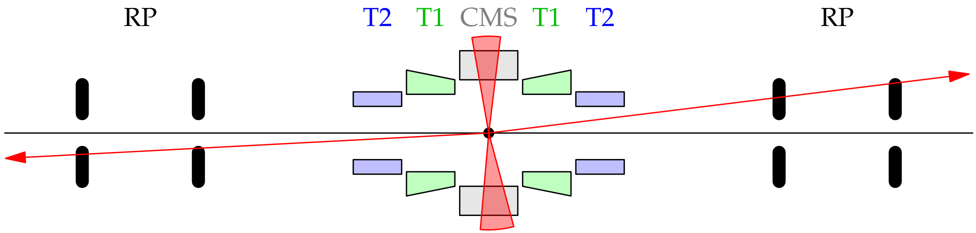
$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 159\ \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	70 μb	37 μb
$5.9<\eta_{min}<6.5$	35 μb	17 μb

Phojet

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 101\ \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	44 μb	23 μb
$5.9<\eta_{min}<6.5$	23 μb	12 μb



- available data
  - 7 TeV: TOTEM only, analysis started
  - 8 TeV: common data with CMS, analysis started
  - 13 TeV: common data with CMS
- $\beta^* = 90$ m: all ξ visible, but resolution ≈ 0.9 %
- experimental challenge: background (pileup ES/beam halo + inelastic)
  - anti-elastic cuts: anti-collinearity
  - anti-beam-halo cuts: $|y| > 11$ mm

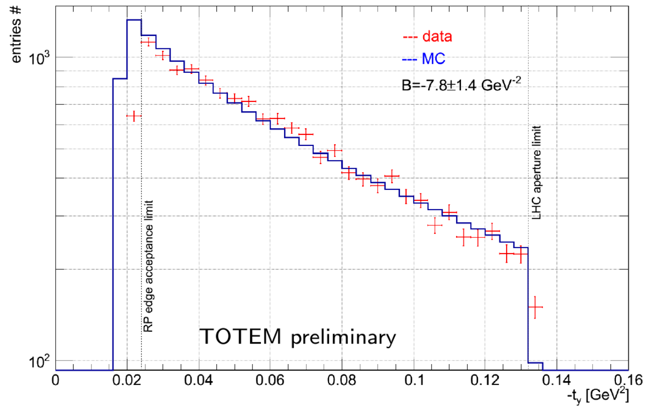
- $|t_y|$ distribution: all ξ values, only acceptance correction

- estimate of σ_{CD}

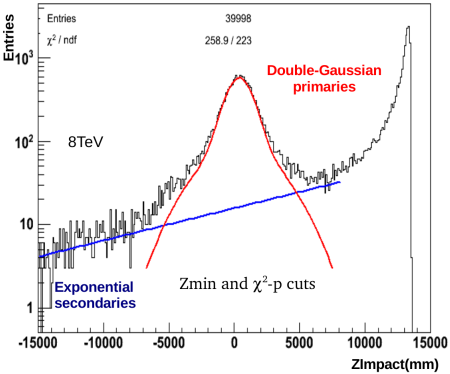
$$\frac{d^2\sigma_{CD}}{dt_1 dt_2} = C e^{-Bt_1} e^{-Bt_2}$$

$$\Downarrow$$

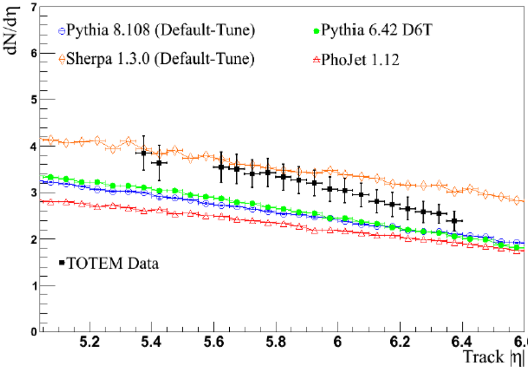
$$\sigma_{CD} = \int_{-\infty}^{0} dt_1 \int_{-\infty}^{0} dt_2 \, C e^{-Bt_1} e^{-Bt_2} \approx 1 \text{ mb}$$

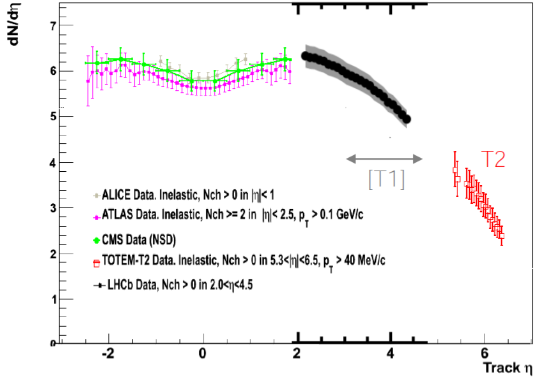


- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$: mean number of charged particles per event and per unit of pseudorapidity
- probes (non-)perturbative strong interactions and hadronisation
- measurement based on T2
  - $\approx$ 95 % of inelastic events seen
  - almost all non-diffractive events visible
  - diffraction with $M_X \gtrsim 3.4$ GeV detected
  - selection of primary particles: lifetime > 30 ps (LHC convention)



- available data
  - $\sqrt{s} = 7$ TeV: TOTEM only, published
  - $\sqrt{s} = 8$ TeV: TOTEM + CMS, TOTEM + shifted vertex, published
  - $\sqrt{s} = 13$ TeV

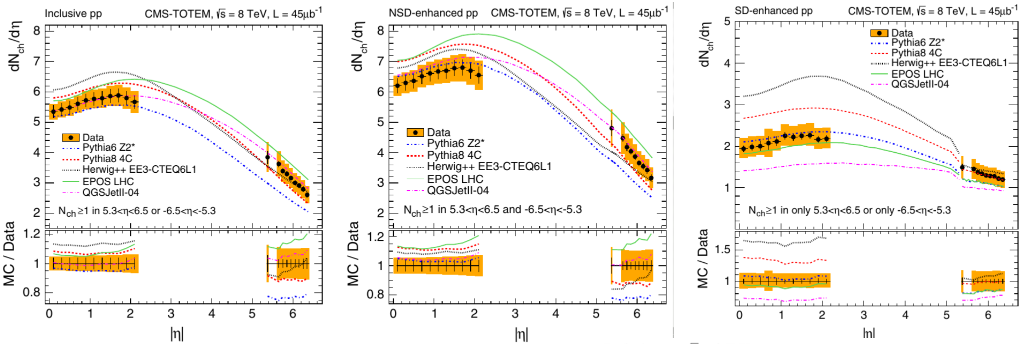




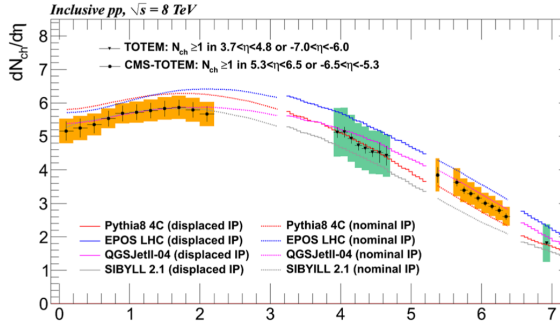
↑ NB: each experiment has different event selection!

- main contributions to systematic uncertainty (≈ 10 %)
  - subtraction of a large fraction of secondaries (about 80 % of all T2 tracks)
  - track efficiency and misalignment uncertainties

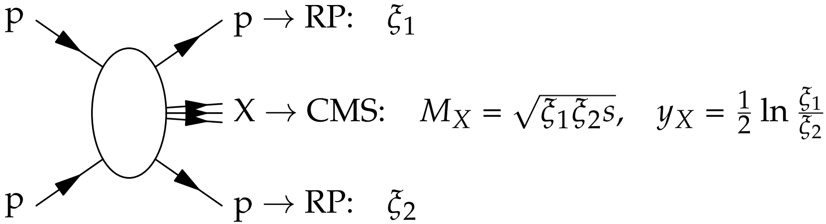
- TOTEM + CMS
  - *non-single-diffractive enhanced*: requiring both hemispheres of T2 on
  - *single-diffractive enhanced*: requiring only one hemisphere of T2 on



- TOTEM only, with *displaced vertex* ($z = 11.25$ m)



- $\sqrt{s} = 8$ TeV: analysis in review
  - classes considered: non-diffractive (ND), single diffractive (SD) with proton left/right, double diffractive (DD)
    - central diffraction not take into account: low cross-section not worth added complexity
  - experimental definition of diffraction: rapidity gap $\Delta\eta \geq 3$
  - boosted decision tree
    - ordered binarisation: ND $\rightarrow$ SD (left) $\rightarrow$ SD (right) $\rightarrow$ DD
  - training sample: Pythia 8-4C
  - control samples: Pythia 8-4C+MBR, QGSJET-II-04, Pythia 8-Monash
  - discriminators: $\Delta\eta$, η_{min}, η_{max}, N_{CMS}, $N_{\mathrm{T2+}}$, $N_{\mathrm{T2-}}$, ξ_L, ξ_R, ...
- possible improvement: use of CMS FSC ($6 < |\eta| < 8$) $\Rightarrow$ better distinction between low-mass DD (more forward than T2) and SD with undetected proton
- other available data
  - $\sqrt{s} = 13$ TeV

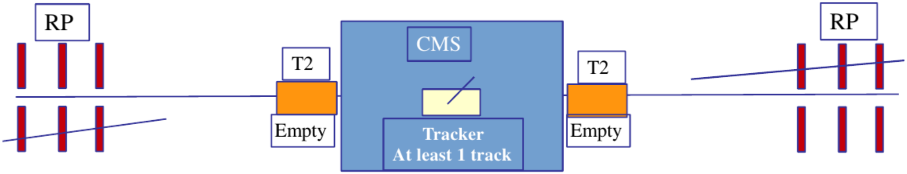


- exchange of colour singlets with vacuum quantum numbers $\Rightarrow$ selection rules for system X: $J^{PC} = 0^{++}, 2^{++}, \ldots$
- double-arm proton tagging: mass reach and luminosity depending on optics
- event selection via comparison CMS to RP protons:

  $M(pp)$ vs. $M(CMS)$, $p_T(pp)$ vs. $p_T(CMS)$, vertex(pp) vs. vertex(CMS)
- prediction of rapidity gap from proton ξ: $\Delta\eta_{1,2} = -\ln \xi_{1,2}$
- analysis examples:
  - studies of glueball candidates
  - exclusive dijets: mainly gg ($p_T > 30 GeV$: $\sigma_{gg} \approx 100 pb$)
  - exclusive χ_c and J/Ψ production: $\mathcal{O}(10pb - 10nb)$
  - search for missing mass signals of $\mathcal{O}(pb) \Rightarrow$ SUSY searches

- CD production at LHC
  - $M_X = 1$ to 4 GeV $\Rightarrow x \sim 10^{-4} \Rightarrow$ pure gluon content
  - Pomeron $\sim$ colour-less gluon ladder $\Rightarrow$ fusion likely to produce glueballs
- 0^{++} glueball candidates: $f_0(1500)$, $f_0(1710)$, $f_0(1370)$
  - lattice QCD: m(0++) glueball $\sim$ 1700($\pm$100) MeV
- CMS + TOTEM:
  - both protons measured and tagged by TOTEM
  - effective selection with high purity (p_T balance + x-vertexing) in required ξ-range.
  - CMS tracker: charged particle invariant mass with $\sigma(M) \sim 20 - 30$ MeV
- available data
  - 8 TeV, $\beta^* = 90$ m, Jul 2012: $\mathcal{L} \approx 1\ \mathrm{nb}^{-1}$: proof of principle
  - 13 TeV, $\beta^* = 90$ m, Oct 2015: $\mathcal{L} \approx 0.4\ \mathrm{pb}^{-1}$ for (CMS + TOTEM): should allow full production and decay characterisation

- CMS + TOTEM: trigger exchange, independent DAQ, offline data merging
- trigger: RP double arm & T2 veto & at least one track in CMS:



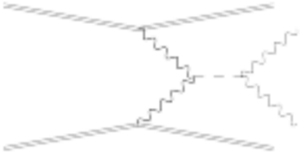
- analysis strategy – verify the following glueball conditions
  - resonance *enhancement with increasing collision* energy (increasingly pure gluon contribution to CEP)
  - final states *branching ratio to $\pi\pi$, KK, ...*, with equi-flavour partitioning selection rules (or with proportionality of gluon coupling to quarks)
  - *suppression of photon-photon* channel (in production and final state)

- upgrade projects: interest in lower cross-section processes
  $\Rightarrow$ higher luminosity needed $\Rightarrow$ higher pile-up
  - need *timing*: association of RP proton vertex with CMS vertex
  - need *pixels*: more tracks in RPs

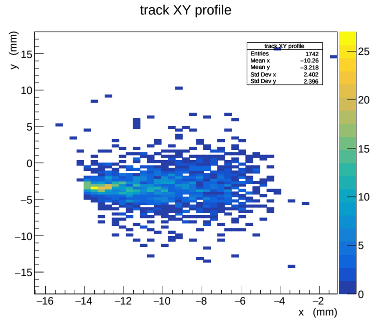
project	**CT-PPS**	**timing in vertical RP**
optics	low (standard) β^*	high lumi $\beta^* = 90$ m
RPs used	horizontal	vertical
tracking	3D pixel (10 μm)	current Si strip (20 μm/RP)
timing	L-bar cherenkov (30 ps/module)	diamond (100 ps/plane)
	or ultrafast silicon or diamond	

- priorities for 2016
  - *glueball* searches (2015 data)
  - *odderon* searches: TOTEM only, special run with $be^* = 2500$ m
  - *di-photon* searches with "accelerated" CT-PPS: standard low β^* runs
    - motivated by "the 750 GeV may-be-resonance", start CT-PPS programme with current detectors now

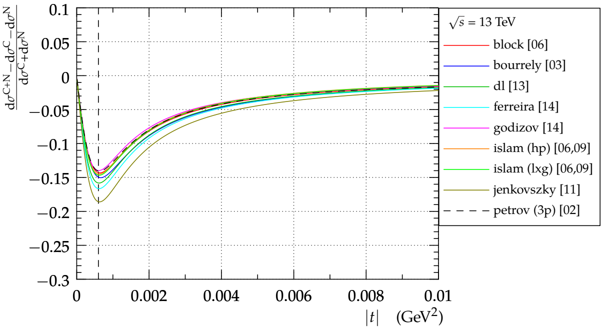
Outlook : *CT-PPS plan for 2016*



- motivation: di-photon excess at 750 GeV observed by ATLAS and CMS
  - CT-PPS: can see *exclusive and complete* events
- background suppressible even *without timing* detectors
  - large mass: low background from inelastic photon pair + pileup
  - strong correlation between proton pair (RP) and photon pair (CMS ECal)
  - nevertheless: install 2 RPs with 4 diamond planes (originally for vertical RPs)
    - can also be used for (coarse) tracking
- *tracking: use current Si strip* detectors in station 210m
  - functional at least for 10/*fb*, then replaceable with detectors from 220m
  - detector/beam shift: irradiation distributed
- *CMS-TOTEM integration* successfully ongoing
  - trigger, DAQ, offline SW, DQM, ...
  - DQM snapshot: from Monday, beam with 900 bunches, RPs inserted in physics positions, RPs included in global CMS DAQ, data processed with CMSSW 8.1.X (next release) →



- Odderon = (hypothetical) cross-odd partner of Pomeron
- overview of past Odderon searches
  - comparison pp vs. anti-pp (dip): not applicable at LHC
  - spin analyses: not applicable at LHC
  - structures in $d\sigma/dt$: where Pomeron contribution small
    - high-$|t|$: disfavoured by 13 TeV measurements
    - low-$|t|$: shifts of ρ value $\Rightarrow$ within reach of TOTEM
- Coulomb-nuclear interference at $\sqrt{s}$ = 13 TeV
  - needs special optics: $\beta^* = 2500$ m
  - $|t| = 6 \cdot 10^{-4}$ GeV^2 reachable
  - $\sim$ 1 week data-taking time approved in 2016



Summary

- *performance* in Run II
  - all detectors functional
  - RPs equipped with RF shields $\Rightarrow$ less impedance $\Rightarrow$ close approach possible
  - DAQ throughput increased 50$\times$ wrt. Run I
- many *analyses* ongoing
  - Run I and Run II
  - TOTEM standalone, TOTEM + CMS
- *upgrade* projects
  - timing in vertical RPs (diamonds)
  - CT-PPS (pixel tracking, timing with fast silicon, diamond or Cherenkov)
- *priorities* for 2016
  - glueball analysis of 2015 data
  - TOTEM special run: $\beta^* = 2500$ m $\Rightarrow$ Odderon searches via CNI
  - CT-PPS runs with LHC standard optics: di-photon searches with existing RPs, ...

↓ Backup

Vertex reconstruction by time measurement

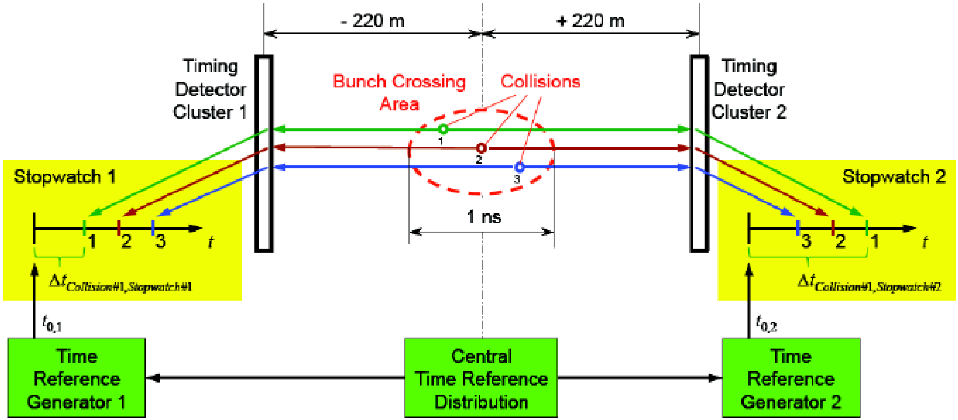
Pileup problem:

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



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

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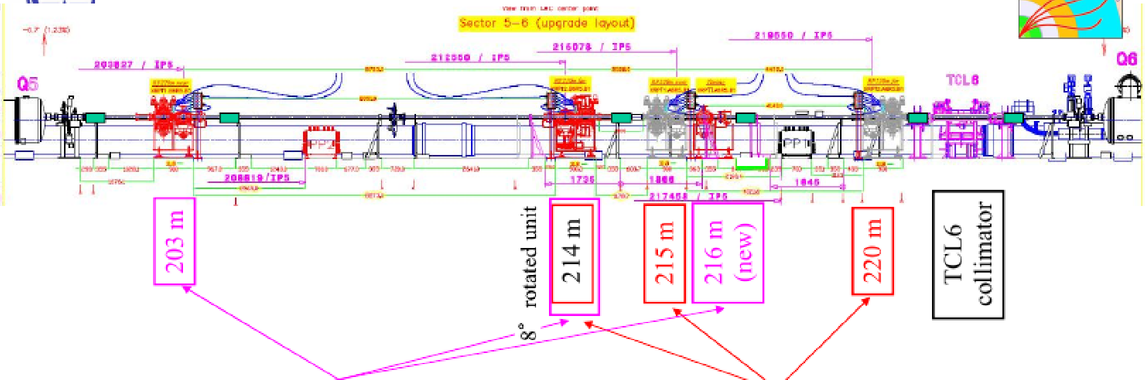
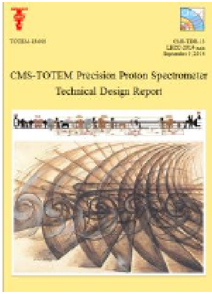
Roman Pot upgrades



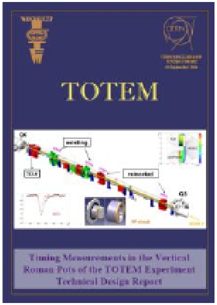
low β^* (< 1 m), high lumi, standard runs, M_X > 250 GeV

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

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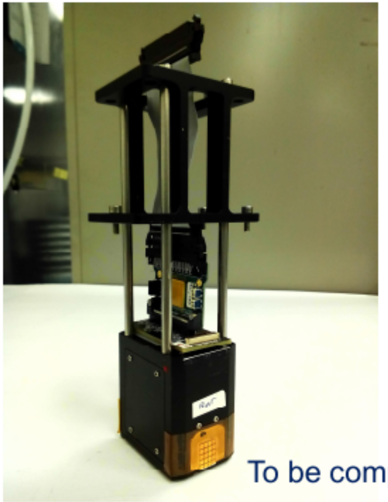
CT-PPS detectors

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 in spring 2016

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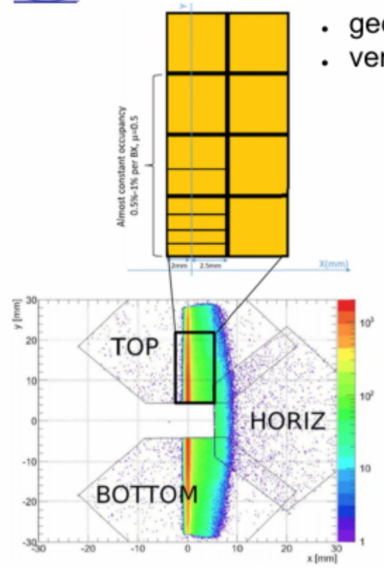
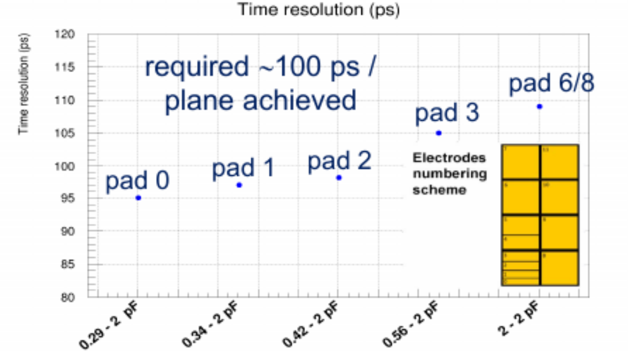
Diamond timing detectors

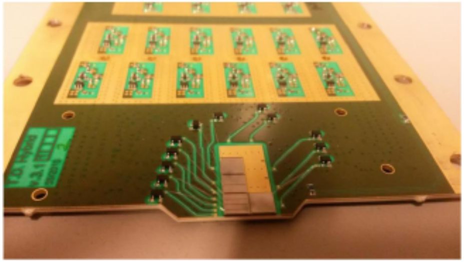
- geometry adjusted to track occupancy in β^* = 90m runs
- vertex z-position reconstruction resolution ~few cm





currently 2 completed planes being tested inside RPs with MIPs

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



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