Forward physics at LHC with TOTEM and CMS

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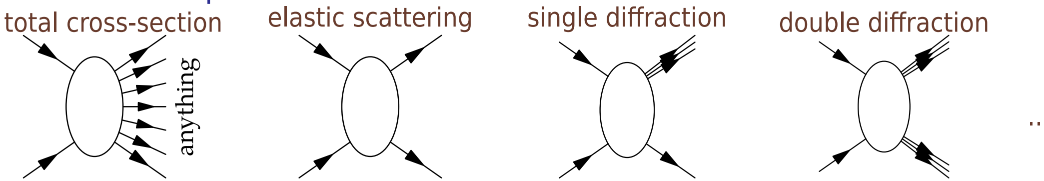
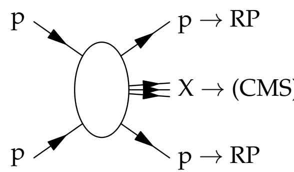
- TOTEM: LHC experiment dedicated to measurement of:



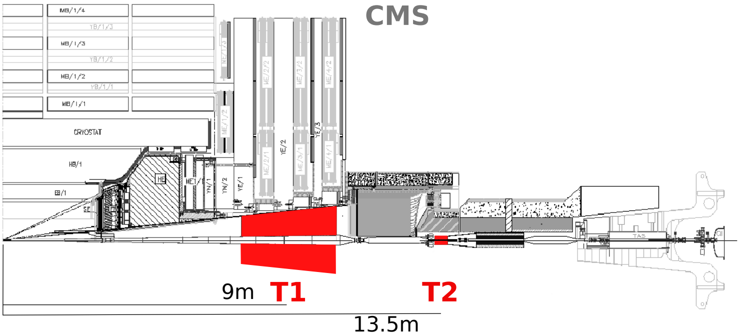
- TOTEM + CMS: first collaboration of experiments at IP5
  - excellent pseudorapidity coverage: optimal for e.g. central exclusive diffraction
  - low pile-up conditions ⇒ clean signal
  - cooperation mode: independent experiments, exchange of triggers, data merged offline



- PPS (Precision Proton Spectrometer)
  - (upgraded) forward-proton taggers fully integrated under CMS
  - high luminosity conditions ⇒ low cross-section processes (high mass, etc.)
- common features: rapidity gaps, particles in very forward region, surviving protons ⇒ special detectors

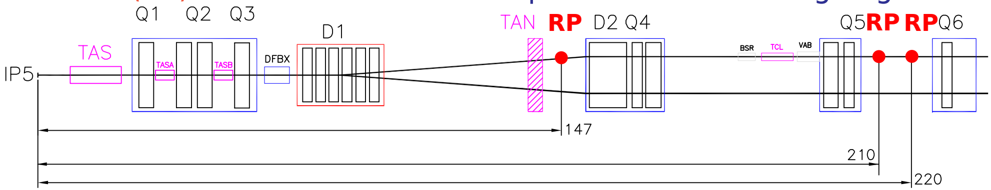
Detector apparatus of TOTEM

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



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

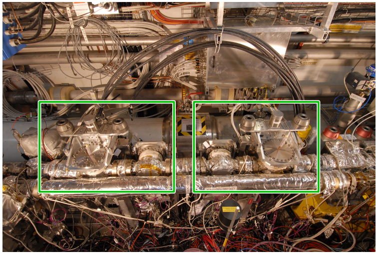
- Roman Pots (RP): elastic and diffractive protons close to outgoing beam



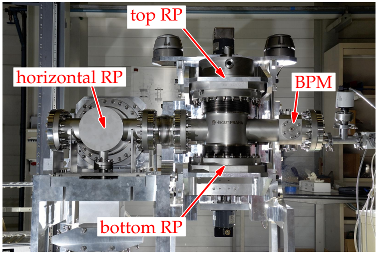
  - station at 147m in Run I $\rightarrow$ station 210m in Run II

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

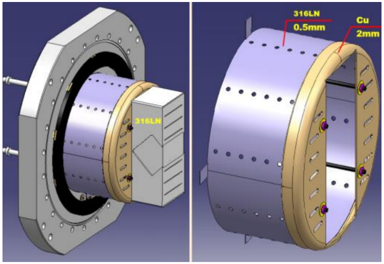
Roman Pots (RPs)



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

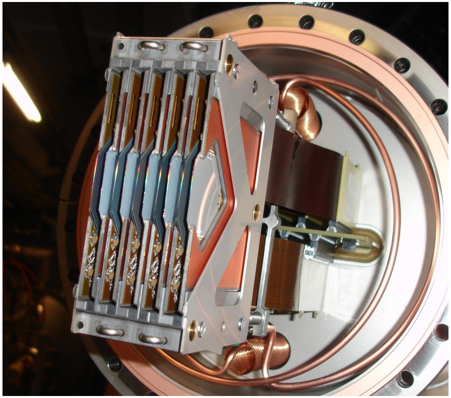


- each unit contains 3 *Roman Pots*: top, bottom and horizontal
- Roman Pot = movable beam-pipe insertion
  - beam unstable ⇒ RPs retracted to safe position
  - beam stable ⇒ RPs as close to beam as reasonable
- typical approach: 10 σ_{beam} (record 3 σ_{beam})

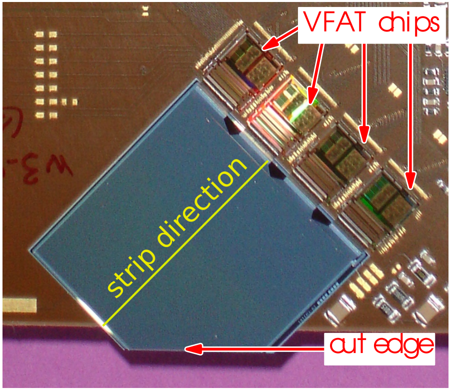


- Roman Pot: container for sensors
- LS1: improved RF shield ⇒ possible close approach to high-intensity beam

"Edgeless" silicon sensors

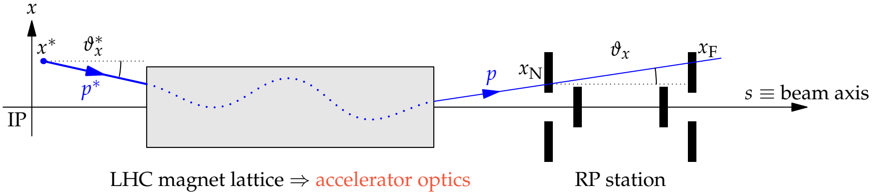


- each RP contains a *package* of 10 silicon sensors
- 5 pairs of back-to-back mounted strip sensors



- 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 ≈ -20 °C, bias voltage ≈ 100 V

- *proton transport*: described as in linear optics



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

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

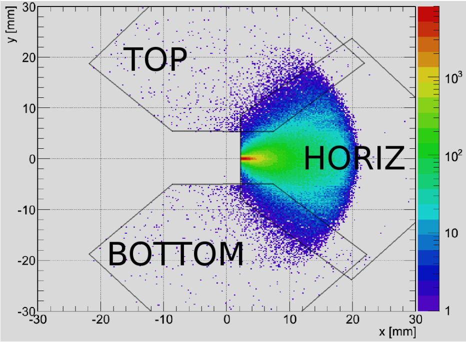
LHC optics

- 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

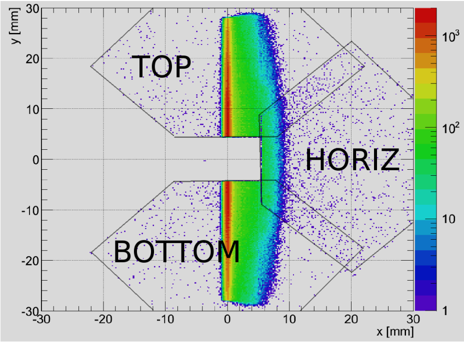
diffractive protons in *horizontal RPs*



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

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

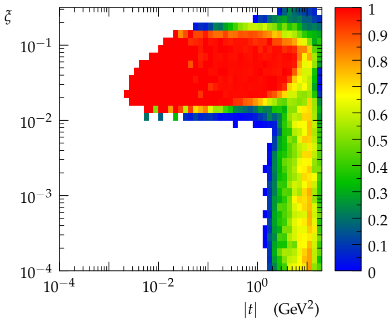
diffractive protons in *vertical RPs*

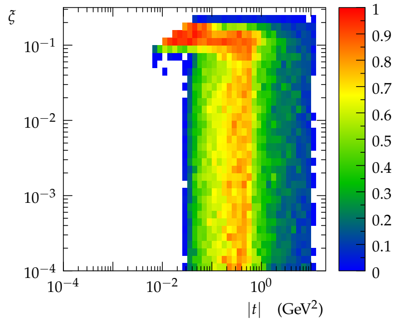


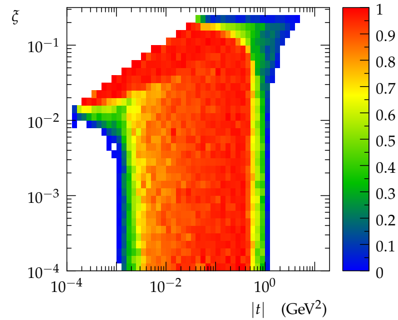
- optics typically “labelled” by *$\beta^* \equiv$ betatron function at IP*
  - beam width: $\sqrt{\varepsilon\beta}$, ε: beam emittance
  - beam angular divergence: $\sqrt{\varepsilon/\beta}$
  - luminosity $\propto$ (beam width at IP)$^{-2}$ $\propto 1/\beta^*$

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

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







$\beta^* = 0.55$ m

$\mathcal{L} \approx 10^{33}\ \mathrm{cm^{-2}s^{-1}}$

elastic scattering: high $|t|$

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

medium $\beta^* = 90$ m

$\mathcal{L} \approx 10^{28}\ \mathrm{cm^{-2}s^{-1}}$

elastic scattering: low to mid $|t|$

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

high $\beta^* = 1535$ m

$\mathcal{L} \approx 10^{27}\ \mathrm{cm^{-2}s^{-1}}$

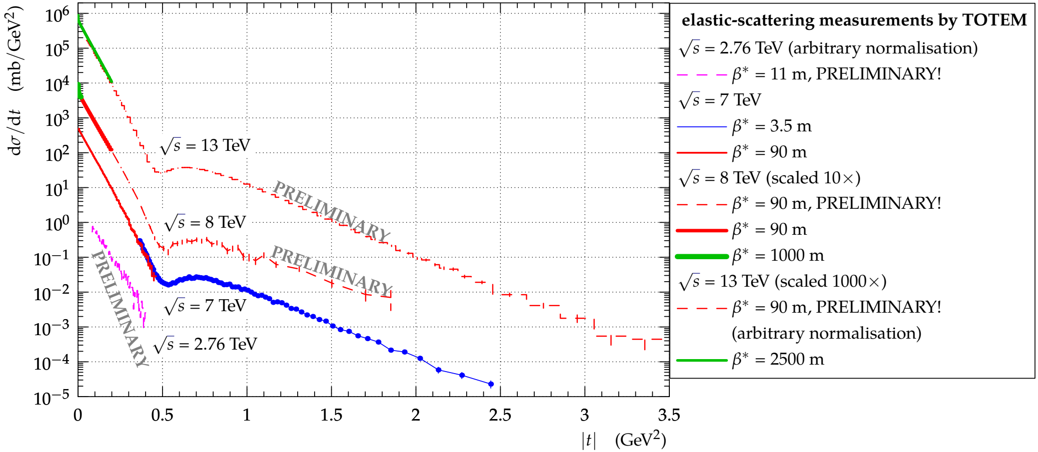
elastic scattering: very low $|t|$ (Coulomb-nuclear interference)

details depend on RP approach to beam and precise optics

TOTEM

list of TOTEM publications

- $p + p \to p + p$, forward protons measured by RPs
- strong selection: two anti-collinear protons from the same vertex
- results overview (selection):

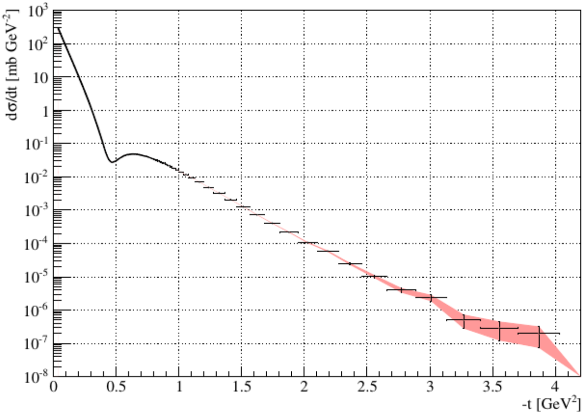


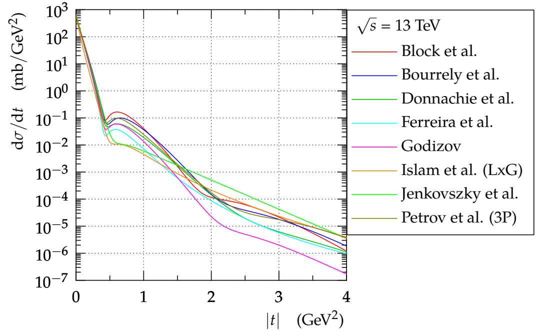
- different $|t|$ probe *different physics regimes* – from lowest to highest $|t|$:
  - Coulomb interference: phase determination
  - diffractive cone: non-perturbative, Pomeron
  - dip-bump: amplitude interference, Odderon effects
  - transition to perturbative QCD

Elastic scattering

- $\sqrt{s} = 13$ TeV:

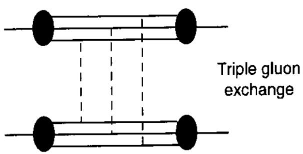
model predictions:





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? $\Rightarrow$ e.g. Donnachie-Landshoff $\Rightarrow$



- 3 methods to determine *total cross-section*

elastic observables only:

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

$$\sigma_{\rm tot}$$

ϱ-independent:

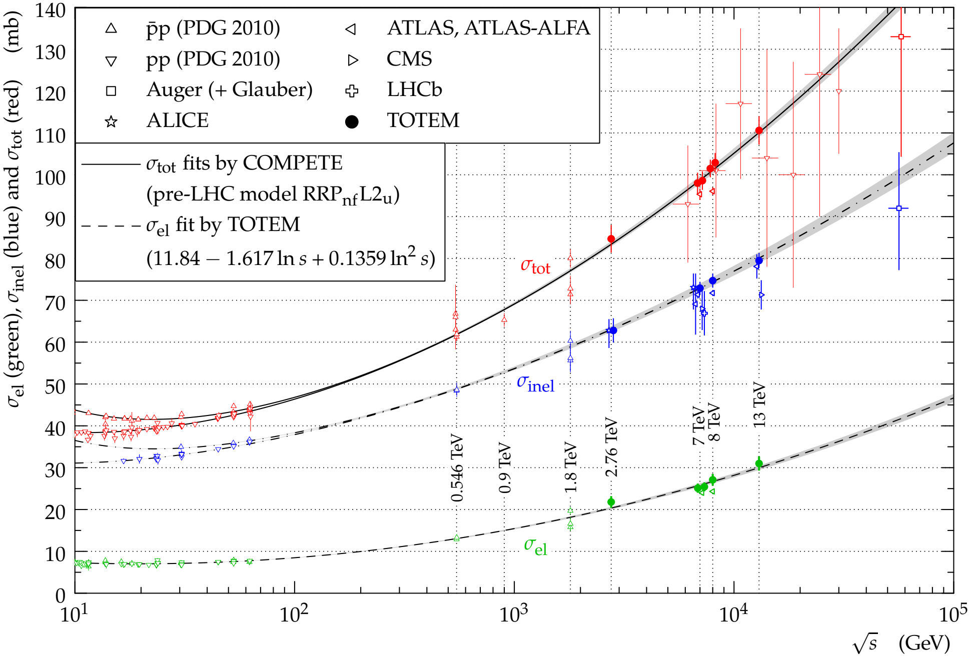
$$\sigma_{\rm tot} = \frac{1}{\mathcal{L}}\,(N_{\rm el} + N_{\rm inel})$$

luminosity-independent:

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

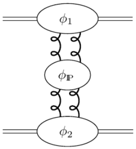
- *inelastic cross-section*: event counting with T2 (and T1)
  - 95 % of inelastic events have at least 1 track in the T2 region
  - only one significant MC correction: contribution from low mass diffraction

Cross-section results

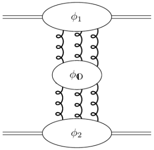


- $\sqrt{s}$ = 7 TeV: all 3 methods consistent
- energy dependence: in general compatible with $\ln^2(s)$ at high energies

- scattering at high energy and low $|t| \Rightarrow$ gluon dominated regime



- *Pomeron*: standard exchange, 2 mutually interacting gluons
  - amplitude crossing even = same for pp and p$\bar{\text{p}}$
  - $\mathcal{A}_{\text{el}}(t = 0) \sim$ imaginary



- *Odderon*: (so far) hypothetical exchange, 3 mutually interacting gluons
  - amplitude crossing odd = opposite sign for pp and p$\bar{\text{p}}$
  - $\mathcal{A}_{\text{el}}(t = 0) \sim$ real
- solid theoretical basis: axiomatic field theory, Regge theory, perturbative and (semi-)non-perturbative QCD, lattice QCD, AdS/CFT
- (generalised) Pomeranchuk theorem:

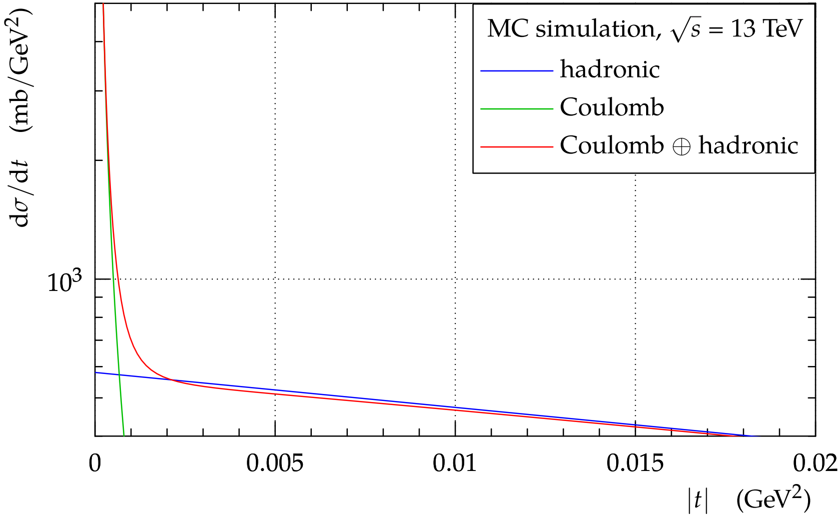
$$\sigma^{\text{pp}}_{\text{tot}} / \sigma^{\text{p}\bar{\text{p}}}_{\text{tot}} \to 1 \quad \text{for } s \to \infty$$

  - allows for pp vs. p$\bar{\text{p}}$ difference non vanishing at high energies
- ρ parameter

$$\rho = \left. \frac{\Re \mathcal{A}_{\text{el}}}{\Im \mathcal{A}_{\text{el}}} \right|_{t=0}$$

  - sensitivity to Pomeron/Odderon ratio

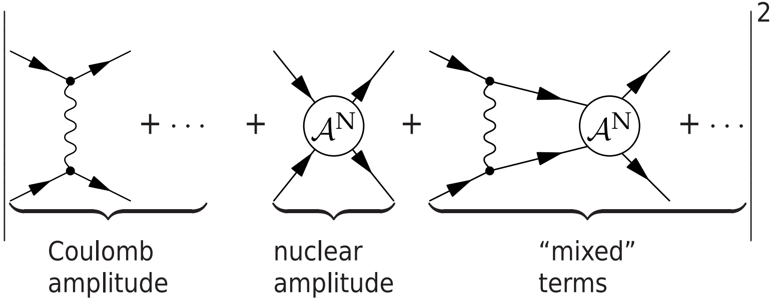
- interactions responsible for proton-proton elastic scattering:
  - *electromagnetic* (“Coulomb”): very low $|t|$
  - *strong* (“nuclear”): higher $|t|$
  - at 13 TeV, contributions of similar size at $|t| \approx 6 \cdot 10^{-4}$ GeV^2



  – sizeable *interference* effect ⇒ can *determine nuclear phase* wrt. Coulomb phase (known from QED)

- observed cross-section

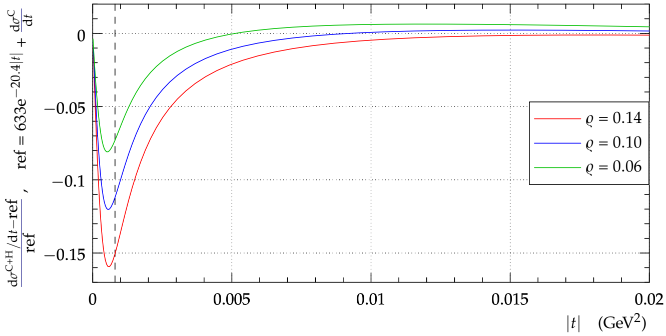
$$\frac{d\sigma}{dt} \propto$$



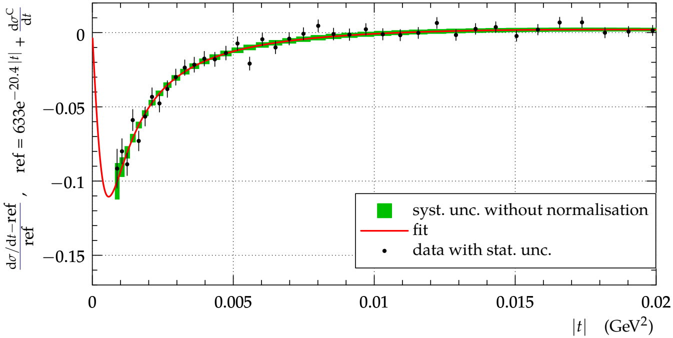
- our modelling
  - "*interference formula*" = summation for practical applications
    - considered: West-Yennie, Cahn and Kundrát-Lokajíček
  - *Coulomb amplitude*: QED + experimental form factors
  - *modulus of $\mathcal{A}^{\rm N}$*: empirical guidance ⇒ at low $|t|$: $a \exp\left(\sum_{n=1}^{N_b} b_n t^n\right)$
  - *phase of $\mathcal{A}^{\rm N}$*
    - different assumptions ⇒ different behaviour in b space
    - assume slow variation with $|t|$ ⇒ fair comparison with pre-LHC data

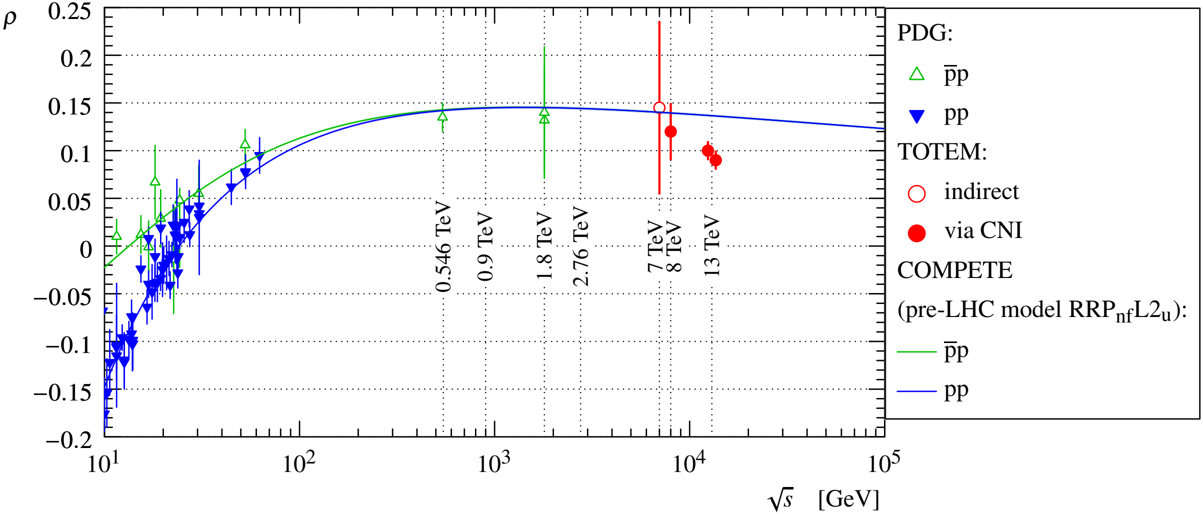
Effect of ρ on differential cross-section

- simulation (with realistic nuclear component):



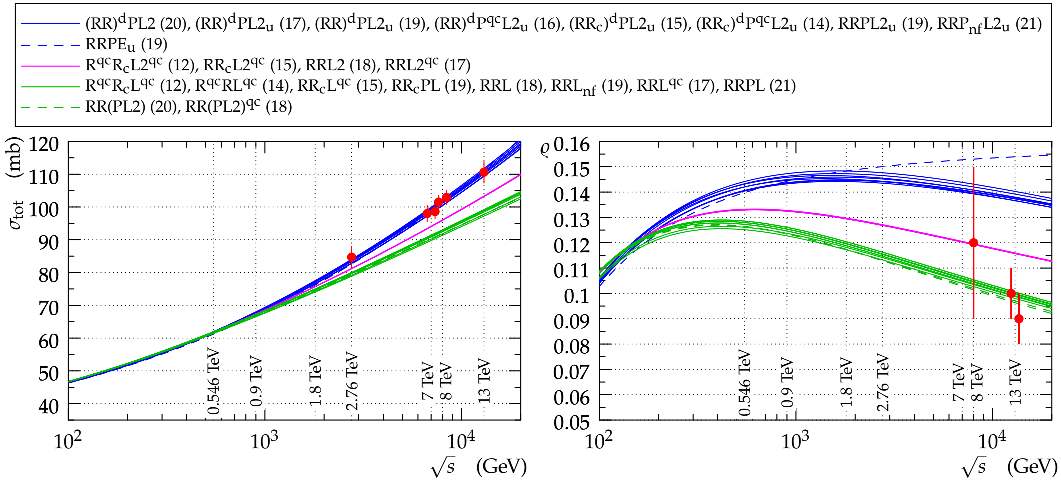
- TOTEM data, $\sqrt{s}$ = 13 TeV, β^* = 2500 m:



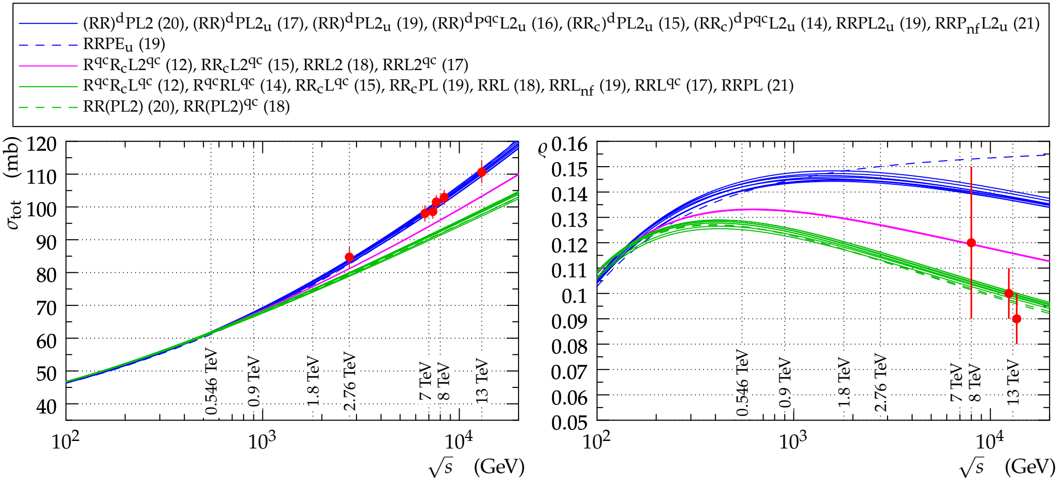


⇒ 13 TeV measurement significantly lower than extrapolations (more than 4 σ effect)

Comparison to COMPETE



- comprehensive study of pre-LHC data by COMPETE
  - ○ 256 models considered to describe σ_{tot} and ρ data in pp, pπ, pK, ...
    - – various assumptions on energy dependence, reaction dependence
    - – asymptotic component: *only crossing-even*
  - ○ 23 models (shown above) found to give reasonable description
    - – predictions cluster in 3 bands
- red: selection of TOTEM measurements

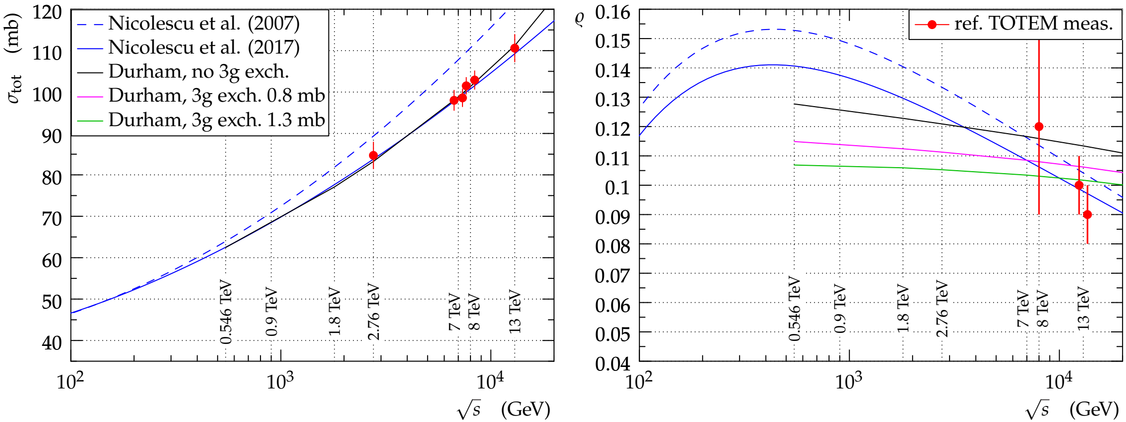


- simple version of derivative dispersion relation for *crossing-even* amplitude

$$\rho \approx \frac{\pi}{2\sigma_{\mathrm{tot}}} \frac{\mathrm{d}\sigma_{\mathrm{tot}}}{\mathrm{d}\ln s}$$

  - faster σ_{tot} rise $\Rightarrow$ higher value of ρ
  - TOTEM data show the opposite $\Rightarrow$ *model-independent argument for crossing-odd component*

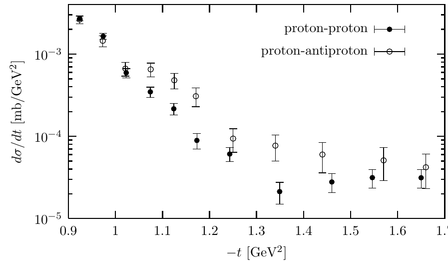
Models compatible with TOTEM data



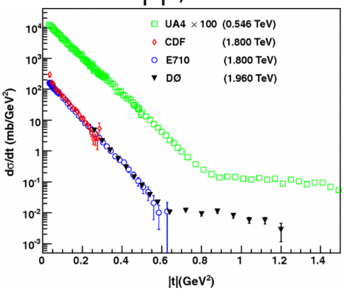
- Nicolescu et al. (updated version of original model)
  - crossing-odd effect: strong energy dependence, increase with energy
  - TOTEM's ρ measurement at $\sqrt{s} = 13$ TeV correctly predicted long before LHC
  - considered as first experimental evidence for "Odderon"
- Durham group (model enhanced with crossing-odd contribution)
  - crossing-odd effect: mild energy dependence, decrease with energy

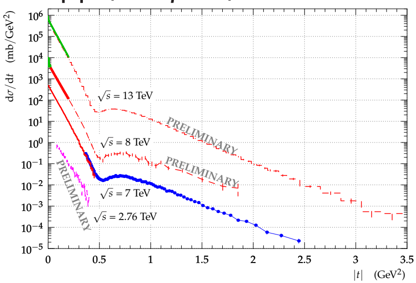
$\Rightarrow$ *crossing-odd component needed to describe data*

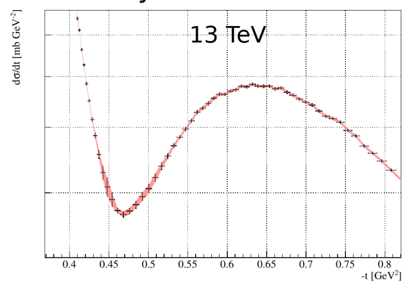
- dip: crossing-even contribution suppressed → crossing-odd effect significant
  - prediction: $p\bar{p}$ shallow while pp pronounced dip
- low energy (ISR, 53 GeV):
  - secondary (mesonic) reggeons complicate interpretation



- high energy: *gluon-dominated regime*, secondary reggeons negligible
  - left: $p\bar{p}$, other: pp (*unique*!) LHC measurements by TOTEM

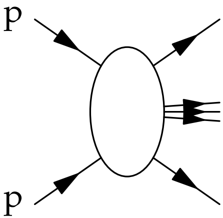






TOTEM + CMS

- exclusive central diffraction



$p \to$ RP: ξ_1

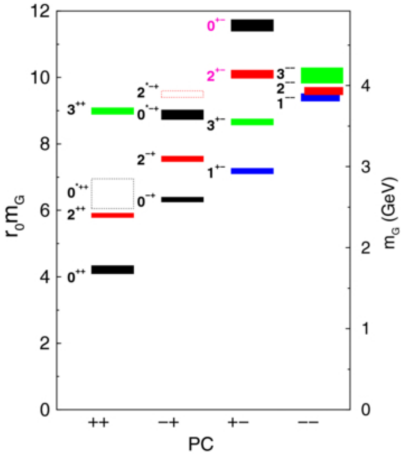
$X \to$ CMS: $M_X = \sqrt{\xi_1 \xi_2 s}, \quad y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$

$p \to$ RP: ξ_2

  - exchange of colour singlets with vacuum quantum numbers $\Rightarrow$ selection rules for system X: $J^{PC} = 0^{++}, 2^{++}$
  - kinematics matching RP vs. CMS (M_X, y_X, vertex) $\Rightarrow$ strong background suppression
  - low M_X (few GeV) $\Rightarrow x \sim 10^{-4} \Rightarrow$ probing gluon content of proton $\Rightarrow$ optimal for *glueball searches* via mass spectroscopy

- other processes of interest (non-exhaustive)
  - SD + jet-gap-jet: BFKL effects
  - SD + di-jet, SD + jet + γ: Pomeron structure functions

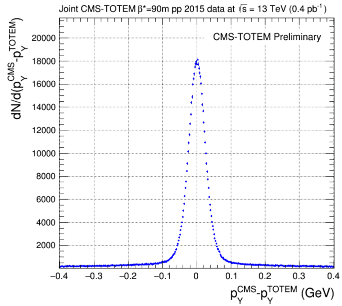
- glueball = hypothetical particle composed solely of gluons (no valence quarks)
  - features: charge neutral, no coupling to photons, flavour symmetry in decays
  - in experimental reach (due to selection rules): scalar and tensor



- tensor glueball: theory
  - lattice QCD predictions – narrow state
  - $SU(3)_f$ decay modes – equi-flavour ?
    - raw: $\pi\pi$ – $K\overline{K}$: $\eta\eta$: $\eta\eta'$: $\eta'\eta'$ =
      $\rho\rho$: $K^*\overline{K}^*$: $\omega\omega$: $\omega\varphi$: $\varphi\varphi$ = 3 : 4 : 1 : 0 : 1
    - with phase space correction
      $\rho\rho$: $K^*\overline{K}^*$: $\omega\omega$: $\varphi\varphi$ = 1 : 0.84 : 0.32 : 0.11
  - $q\overline{q}$ mesons: branching ratios different
    – depend on quark flavour

- tensor glueball: experiment
  - previous studies (searched for decades): MARK3, BES, CLEO, PANDA, ...
  - only not-yet excluded candidate: fJ(2220)
    - already shown: flavour symmetry in 2-particle decays, no $\gamma\gamma$ decays
    - decays to vector mesons not yet observed ⇒ decisive glueball signature

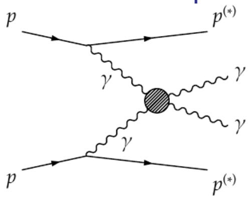
- tensor glueball: CMS + TOTEM
  - sensitivity only to charged decays $\rightarrow \rho\rho : K^*\overline{K}^* : \varphi\varphi = 0.33 : 0.10 : 0.03$
  - CMS mass resolution: about 25 MeV
- 2015 data (13 TeV, 0.4 pb^{-1})
  - $\beta^* = 90$ m $\Rightarrow$ low ξ available, low pile-up ($\mu \approx 0.1$)
  - CMS and TOTEM: separate DAQ, trigger exchange
    - trigger: RP double arm, T2 veto, 5 pixel clusters
    - offline event merging
  - CMS: optimised low p_T track reconstruction



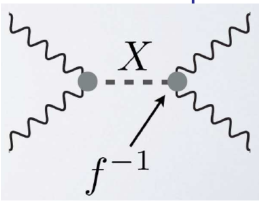
- analysis strategy
  - final states of interest: $\rho\rho \rightarrow \pi\pi\pi\pi$, $\varphi\varphi \rightarrow$ KKKK and $K^*K^* \rightarrow \pi\pi$KK
  - per-pair mass compatible with vector meson hypothesis
  - effect in mass spectrum: excess or deficit (depending on phases)
  - analysis of azimuthal-angle distribution $\Rightarrow$ spin, parity
- publication in CMS review
- new run in few weeks, goal: higher statistics (profit from timing detectors)

Precision Proton Spectrometer

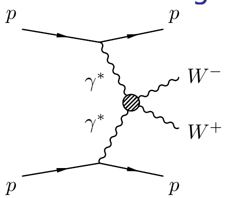
- anomalous photon couplings



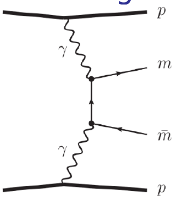
- resonance production



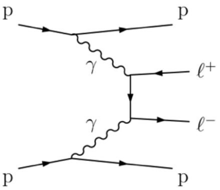
- anomalous gauge couplings



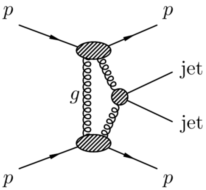
- missing mass



- anomalous di-lepton

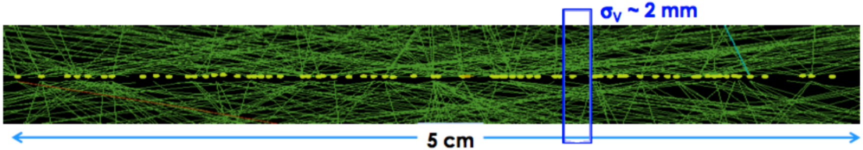


- QCD studies

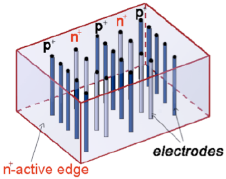


(model independent studies)

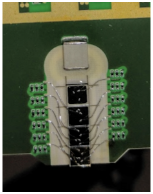
- conditions
  - high mass, low cross-sections $\rightarrow$ need low β^* and long integration times $\rightarrow$ standard LHC fills
  - high pile-up (up to $\mu \approx 50$), high track multiplicity, high radiation dose



- tracking RPs: pixels sensors
  - 3D technology: radiation hardness
  - pixel size 100 x 150 μm: tracking efficiency
  - insensitive edge 200 μm: little acceptance loss



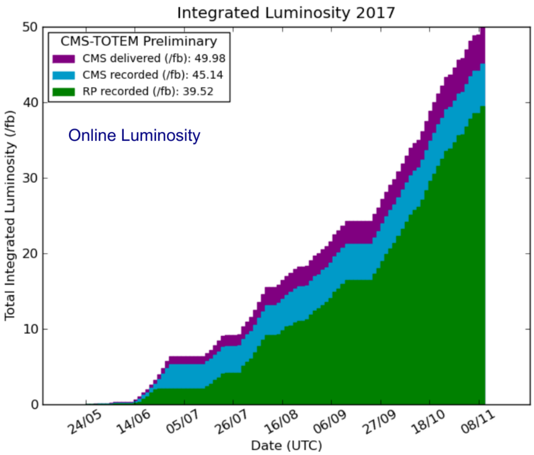
- timing RPs: diamond sensors
  - 2018: 1 RP per arm
    - 2 planes of (single) diamond, resolution $\approx$ 100 ps
    - 2 planes of double diamond, resolution $\approx$ 50 ps
  - plan to use 2 timing RPs with double diamonds



History and luminosity collected

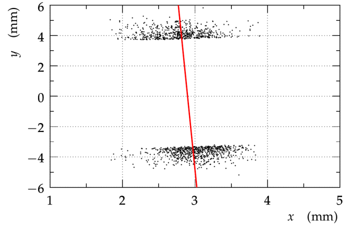
- *2016*: $\mathcal{L}_{\text{int}} = 15\ \text{pb}^{-1}$
  - "accelerated": "750 GeV excess" reported by ATLAS and CMS
  - tracking: strips (TOTEM)
  - timing: none

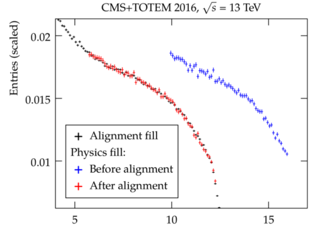
- *2017*: $\mathcal{L}_{\text{int}} = 40\ \text{pb}^{-1}$
  - tracking: strips and pixels
  - timing: diamond + UFSD



- *2018*: $\mathcal{L}_{\text{int}} > 10\ \text{pb}^{-1}$
  - tracking: pixels
  - timing: diamond + double diamonds

- alignment
  - special calibration fill
    - beam based alignment: as for LHC collimators
    - relative alignment: track-hit residual minimisation
    - alignment wrt. beam: symmetry of elastic scattering
  - for each physics fill
    - hit distributions match to calibration fill

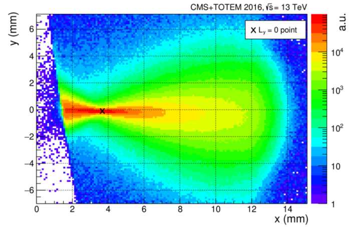




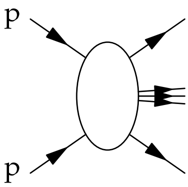
- optics
  - special calibration fill
  - leading approximation

$$x \approx D_x \xi \,, \quad y \approx L_y(\xi)\, \theta_y^*$$

  - for $\xi = \xi_0$: $L_y = 0 \Rightarrow$ “pinch” in hit distributions
  - D_x estimated as x_0/ξ_0



- 2016: no timing RPs $\rightarrow$ background suppressed by matching CMS and RPs



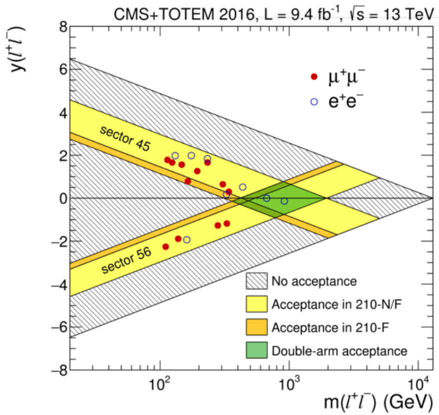
$p \rightarrow \text{RP}: \quad \xi_1$

$X \rightarrow \text{CMS}: \quad M_X = \sqrt{\xi_1 \xi_2 s}, \quad y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$

$p \rightarrow \text{RP}: \quad \xi_2$

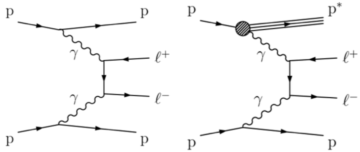
  - typical remaining background: pile-up of unrelated central activity and forward protons (mainly SD)

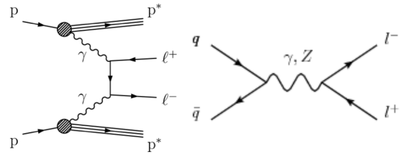
- acceptance:



Di-lepton analysis of 2016 data

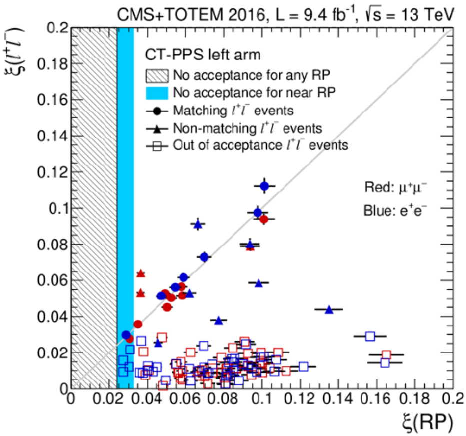
- $\gamma\gamma \rightarrow l^+ l^-$, lepton l: μ or e
- known (QED) physics $\Rightarrow$ verification of the full chain: DAQ, reconstruction, alignment, optics, ...
- 2016 pre-TS2, 9.4/*fb*
- to enhance statistics: only single proton tag required
  - signal processes: left
  - main backgrounds: right

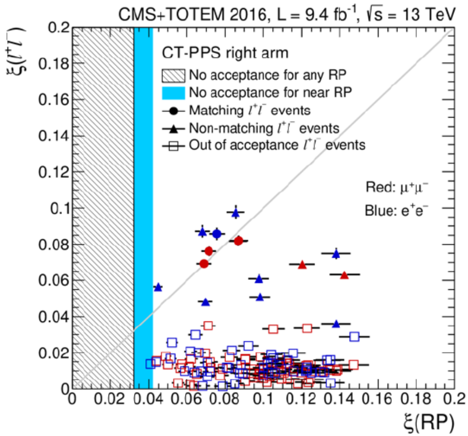




- central selection
  - $p_T(l) > 50$ GeV, $m(ll) > 110$ GeV to avoid Z peak
  - *ll* vertex separation
  - *ll* acoplanarity (back-to-back)
- RP – central matching within 2 σ

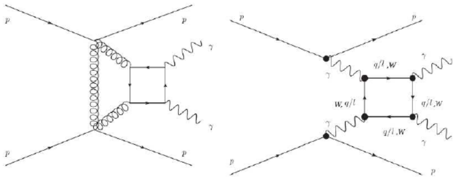
- data-driven background estimate
  - $\mu\mu$: 1.5 ± 0.5 events
  - ee: 2.36 ± 0.5 events
- matching events observed
  - $\mu\mu$: 12
  - ee: 8





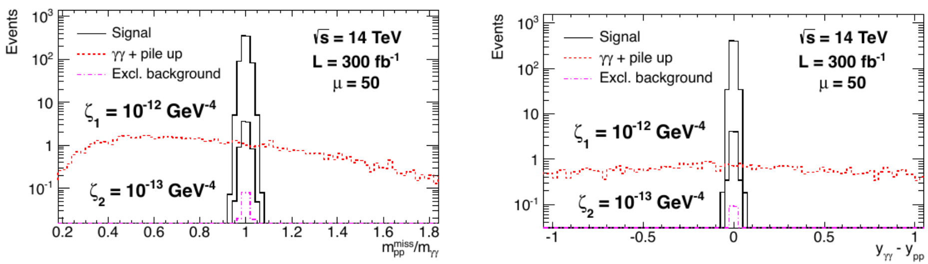
- $\Rightarrow$ PPS works as desired

- di-photon production



  - high masses (> 200 GeV): $\gamma\gamma \to \gamma\gamma$ dominant
  - SM: no direct $\gamma\gamma\gamma\gamma$ coupling ⇒ sensitivity to anomalous couplings

- proto-analysis
  - $\zeta_{1,2}$: 2 different levels of anomalous quartic coupling



  - after cuts: background negligible

- analysis of 2016 data: publication in preparation

Summary

- TOTEM
  - recent results on σ_{tot} and ρ
    - rule out most of the pre-LHC models
    - indicate existence of an Odderon, crossing-odd amplitude at high energies
  - Odderon hypothesis independently supported by pp and $p\bar{p}$ data in the dip region

- CMS + TOTEM
  - low-mass spectroscopy: important contribution to glueball searches

- PPS
  - rich extension to the LHC physics programme
  - di-lepton analysis: PPS works as designed
  - di-photon and other analyses in progress