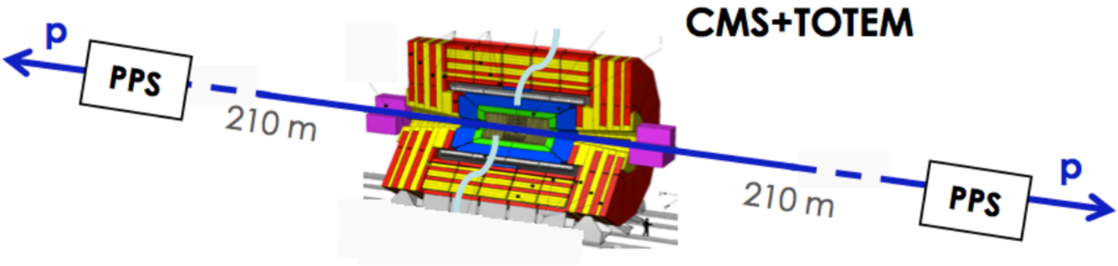
CMS(-TOTEM) Precision Proton Spectrometer at the LHC

Jan Kašpar

Seminar at CTU Prague
8 Jan 2019

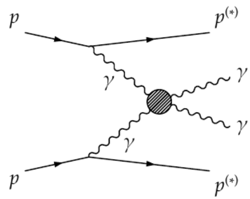
- synergy of two experiments at interaction point 5 of LHC
  - CMS experiment → central detector
  - TOTEM experiment → forward proton taggers

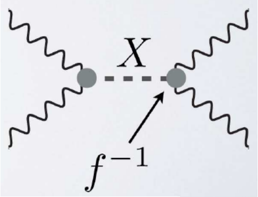


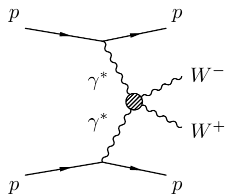
Outline

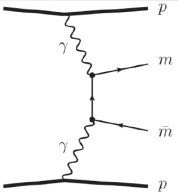
- physics motivation $\rightarrow$ experimental requirements
- detector apparatus
- detector calibration and proton reconstruction
- data-taking experience 2016 – 2018
- first physics analyses

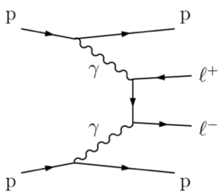
- forward protons: additional kinematics constraint $\rightarrow$ background suppression (model indep.)
- access to beyond-standard-model physics: precision measurements, missing mass signatures
- some processes of interest:

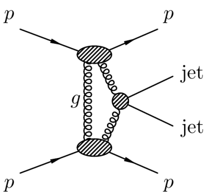






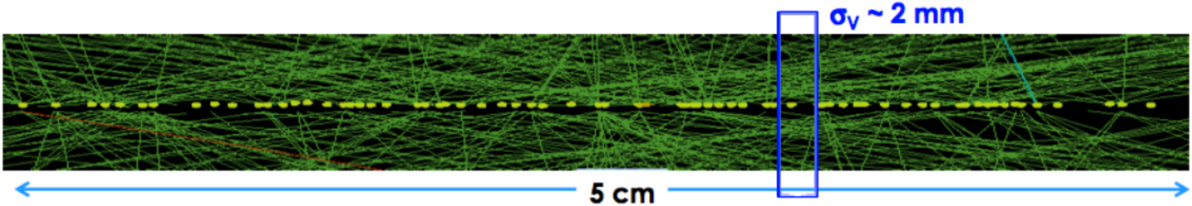




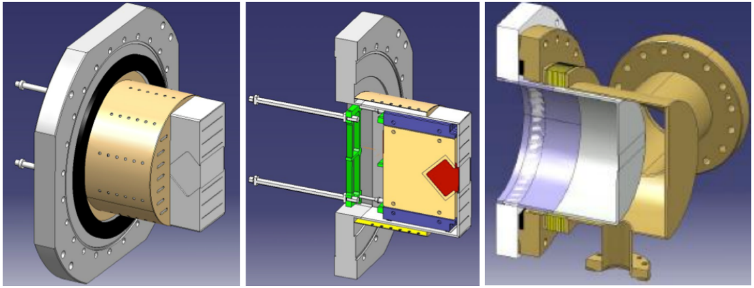


Experimental challenges

- non-standard use of LHC: magnetic proton spectrometer
- very *forward protons* – very small displacement from beam ($\sim$ mm)
  - detectors need *insertion to the LHC* beam pipe
    - movable detectors: only inserted once beams stable
    - low impedance required: beam stability, reduced heat load
    - low material budget, vacuum properties, ... required
  - *radiation hardness* required
- high pile-up ($\sim$ 50 concurrent pp interactions)
  - *multiple protons* in forward detectors $\rightarrow$ tracking with pixels
  - association of forward protons with central particles $\rightarrow$ *timing detectors*

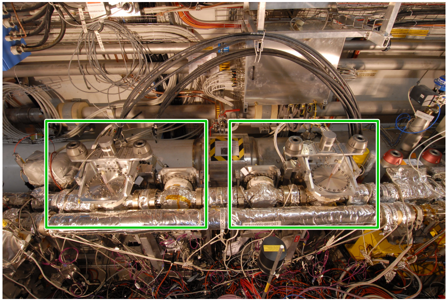


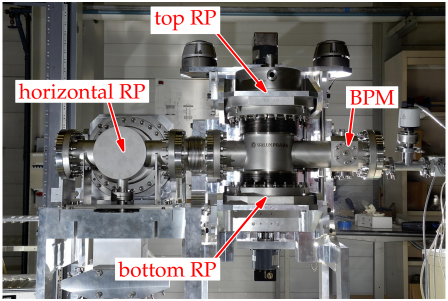
- *Roman Pot* (RP) = movable beam-pipe insertion, “container” for sensors



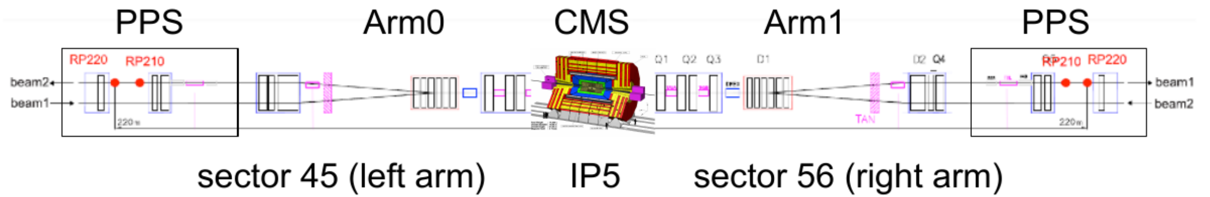
  - impedance reduction: ferrite shielding (left), circular design (right)

- left: *RP station* = 2 units (“near” and “far”, separated by few meters)
  right: *RP unit* = 1 horizontal, 2 vertical RPs





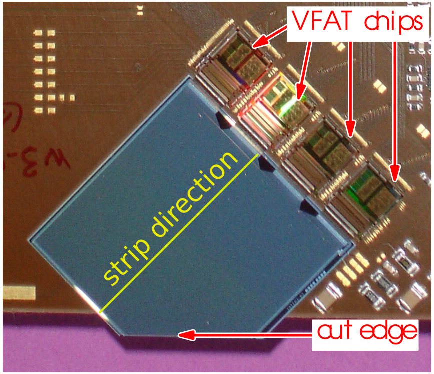
- RPs on both sides of CMS → *2 arms* (LHC sectors 45 and 56):

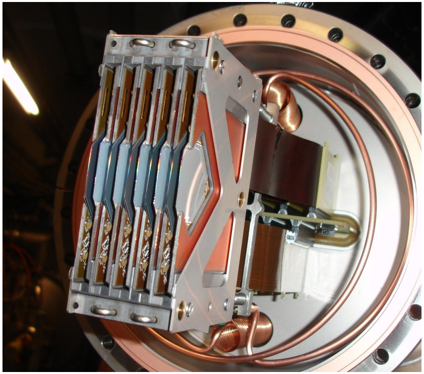


  - RP units at ≈ 210 and 220 m from the interaction point
  - 220 m station includes additional RP for timing sensors

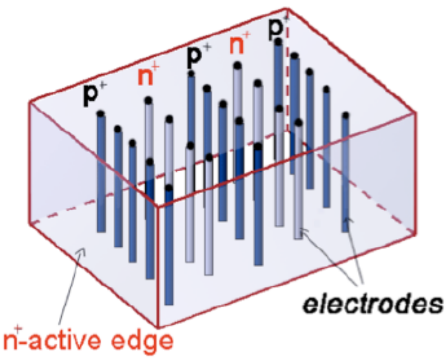
- conceived as common project between CMS (central) and TOTEM (forward)
  - TDR in 2014 [CERN-LHC-2014-021]
- “accelerated” start in 2016
  - motivated by “750 GeV excess” in di-photon spectrum observed in late 2015
  - baseline PPS sensors not ready $\rightarrow$ start with TOTEM sensors
- 2016
  - tracker: 2 Si strip RPs (TOTEM) per arm
- 2017
  - tracker: 1 strip (TOTEM) and 1 pixel (PPS) RP per arm
  - timing: 1 RP per arm, diamonds + UFSD
- 2018
  - tracker: 2 pixel RPs per arm
  - timing: 1 RP per arm, diamonds + double-diamonds
  - PPS fully under CMS

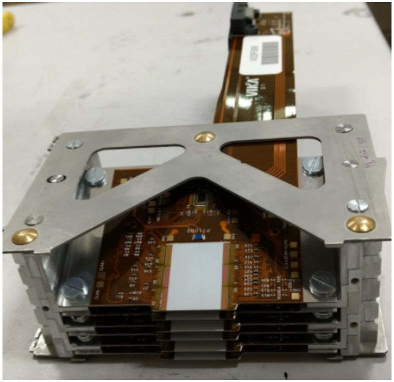
- pitch 66 μm
- strips oriented at 45° wrt. edge facing beam
- cut edge $\rightarrow$ insensitive margin only $\approx$ 50 μm
- operated at -20 °C, bias voltage $\approx$ 100 V
- 5+5 planes per RP (2 strip orientations for 2D reconstruction)



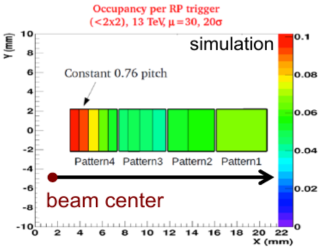


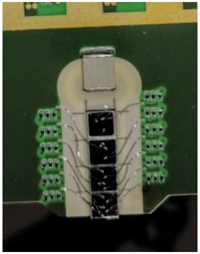
- 3D technology → radiation hardness
- pixel size 100 x 150 μm → tracking efficiency
- insensitive edge 200 μm → little acceptance loss
- 6 planes per RP
  - planes tilted by 18° for improved resolution



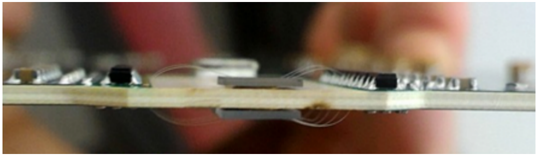


- diamonds
  - radiation hard
  - four 4 × 4 mm sensors, pad geometry reflects track occupancy
  - single plane resolution with oscilloscope: ≈ 80 ps
  - four planes per RP
  - custom electronics: amplifier + NINO (discriminator) + HPTDC

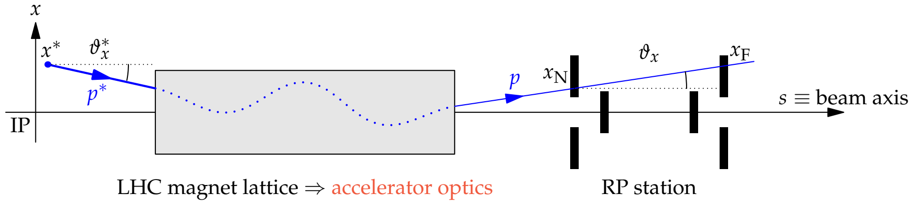




- double diamonds
  - 2 diamond sensors connected to the same amplifier input
  - single plane resolution with oscilloscope: ≈ 50 ps
  - (up to) four planes per RP



- proton transport from IP to RPs: description similar to linear optics



  - at IP (wrt. beam): vertex x^*, scattering angle θ_x^*
  - $\xi \equiv \Delta p/p$: relative momentum loss
  - at RPs (wrt. beam):

$$x = D_x(\xi)\,\xi + L_x(\xi)\,\theta_x^* + v_x(\xi)\,x^* + \dots$$

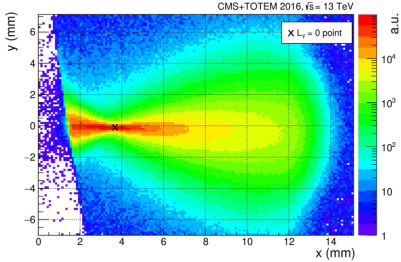
  - optical functions: dispersion D, effective length L, magnification v
    - functions of ξ
    - depend on crossing angle α, ...

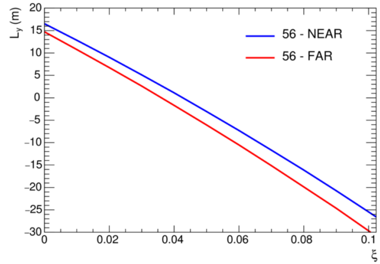
- luminosity levelling $\rightarrow$ complication
  - 2016: no levelling
  - 2017: crossing angle (6 discrete steps)
  - 2018: crossing angle (continuous), β^*

- *regular LHC fills*: $\beta^* \approx 0.3$ m $\rightarrow$ beam squeezed at IP $\rightarrow$ high luminosity
- *leading terms* in proton transport

$$x = D_x(\xi)\,\xi + \dots\,, \quad y = L_y(\xi)\,\theta^*_y + \dots$$

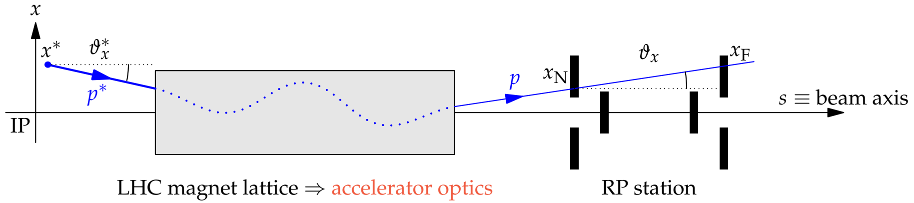
  - example track distribution in plane perpendicular to beam
    - (over)simplified interpretation: horizontal displacement due to ξ, vertical due to θ^*_y





    - "pinch" point: due to $L_y(\xi)$ crossing zero (useful) for calibration
  - diffractive protons ($\xi > 0$) displaced mainly horizontally $\rightarrow$ *PPS signal in horizontal RPs*
  - elastic protons ($\xi = 0$) displaced mainly vertically $\rightarrow$ vertical RPs used for calibration

- reconstruction of proton kinematics = inverted proton transport



- 2 key ingredients:
  - track positions at RPs
    - subject to *alignment* corrections
    - needed 2 RP measurements per arm (4 constraints) ⇒ determination of ξ, θ^*_x, θ^*_y (and y^*)
  - *optics* knowledge

Alignment

- RPs move, beam may move $\Rightarrow$ alignment delicate, possibly time-dependent

Multiple procedures:

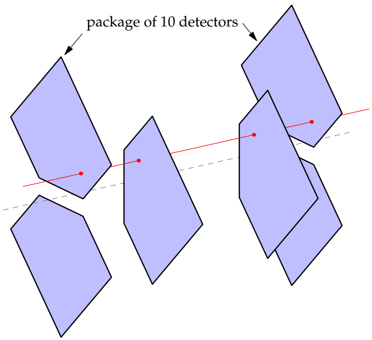
- step 0: definition of RP position wrt. beam
  - RP position critical for low-ξ acceptance $\rightarrow$ ideally as close as possible
  - LHC safety $\rightarrow$ RPs in collimator "shadow" $\rightarrow$ at $\approx 15\ \sigma_{\rm beam}$
  - in practice: the same procedure as for collimator alignment
- step 1: special calibration fill
  - low intensity $\rightarrow$ RPs allowed at $\approx 5\ \sigma$
  - both horizontal and vertical RPs inserted $\rightarrow$ data-driven beam position determination
- step 2: calibration transferred from calibration to physics (high-luminosity) fills
  - for each fill separately

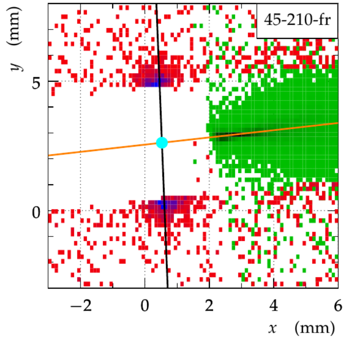
Alignment : *Step 0*

- low-intensity fill
- primary collimators scrape beam to have sharp edges
- RPs moved in slowly (10 μm steps), until beam touch $\rightarrow$ spike in beam-loss monitors downstream
  - then RPs at the same number of “sigmas” as the primary collimators
- RPs retracted by pre-defined number of sigmas
  - later: this position applied for each RP insertion (after declaration of stable beams in each fill)

[CERN-TOTEM-NOTE-2017-001]

- data taken in the low-intensity fill from Step 0
- left: red = track in the overlap between vertical and horizontal RPs
  - relative alignment by minimisation of track-hit residuals

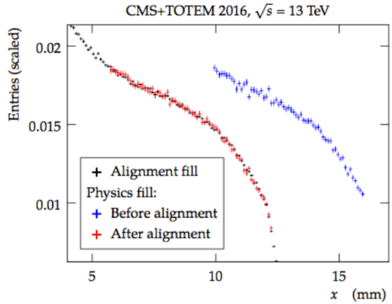




- right: alignment wrt. beam (applied per unit)
  - red-blue histogram: from vertical RPs, dominated by elastic protons
    - black line: interpolation
  - green-black histogram: from horizontal RP
    - orange line: extrapolation
  - cyan dot: beam position

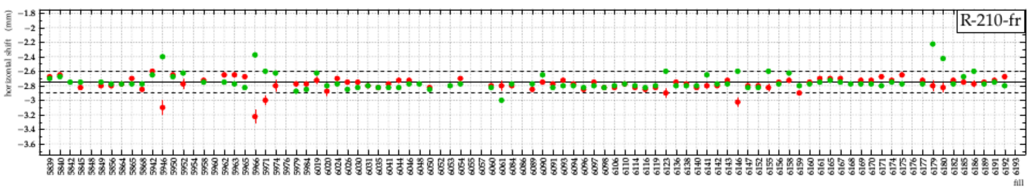
[CERN-TOTEM-NOTE-2017-001]

- data from physics fills “matched” to aligned data from calibration fill – using invariants
  - physics distributions – e.g. inclusive ξ (or x) distribution:



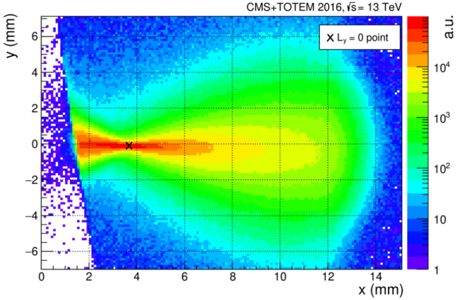
  - optics constraints

- systematic application to every fill (horizontal alignment):
  - red/green: x matching / optics-based matching



[CERN-TOTEM-NOTE-2017-002]

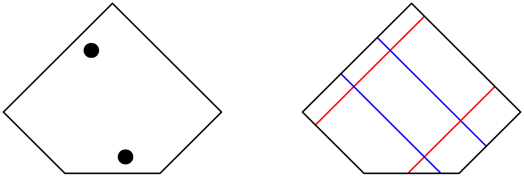
- magnetic model of LHC (e.g. MADX program)
  - certain parameters can be tuned
  - "matching" = tuning to observations in RPs and beam-position monitors (beam orbit)
  - found very significant corrections to the nominal optics
- step 1: calibration of $L_y(\xi)$
  - based on correlations in elastic-proton hit distributions (low intensity calibration fill) [New J. Phys. 16 (2014) 103041]
- step 2: calibration of $D_x(\xi)$
  - leading approximation: $x \approx D_x \xi$, $y \approx L_y(\xi)\, \theta^*_y$
  - for $\xi = \xi_0$: $L_y = 0 \Rightarrow$ "pinch" in hit distributions
  - D_x estimated as x_0/ξ_0



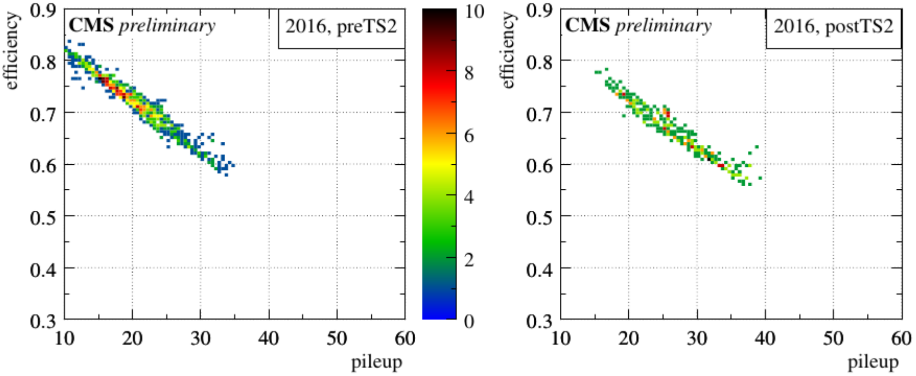
- step 3: complete optics "matching" with full ensemble of observations

- major sources for tracking inefficiency
  - radiation damage (both strips and pixels)
  - incapability to resolve multiple tracks (strips only)

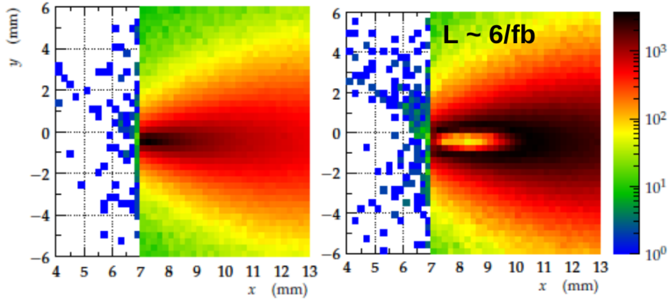
- reason:



- no mitigation possible
- time-dependent evaluation [CMS DP-2018/056]: frequency of multitrack events in zero-bias sample
- efficiency correlation with pile-up

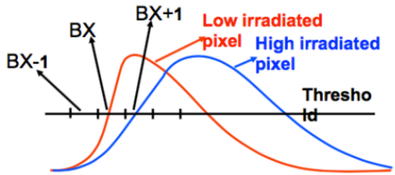


- track distribution in a RP
  - left: no radiation damage, right: with radiation damage

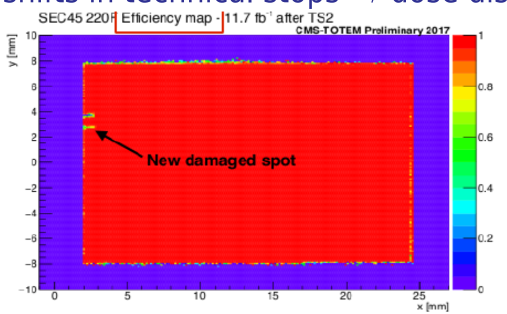


- temporary mitigation: HV increase
- efficiency evaluation: ratio between hit distribution in a sample and reference (prior to radiation damage)
  - time-dependent
  - position (x, y) dependent

- pixel sensors radiation hard, but readout chips slow down with radiation:
  - non-uniform irradiation → different pixels respond in different bunch crossing (BX) slots:

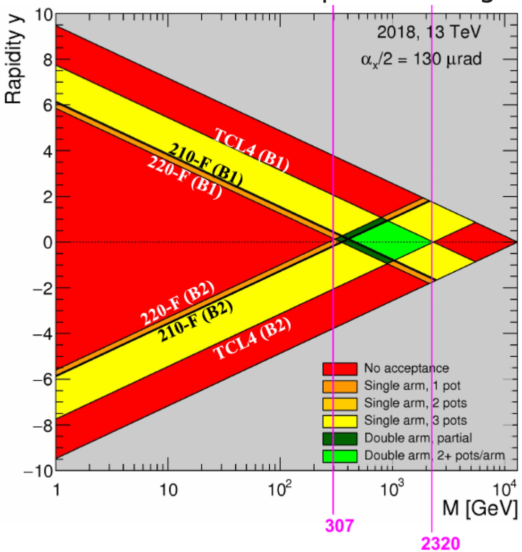


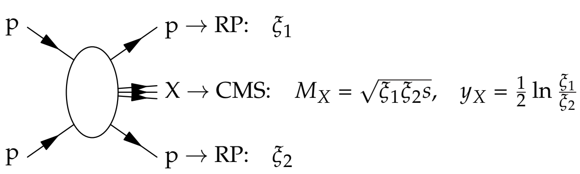
  - single latency for full read-out chip → inefficiency in irradiated zone
- mitigation: detector shifts in technical stops → dose distributed



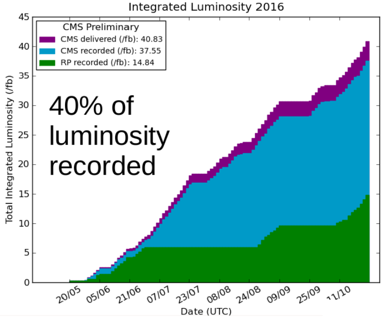
- efficiency evaluation: time and position dependent

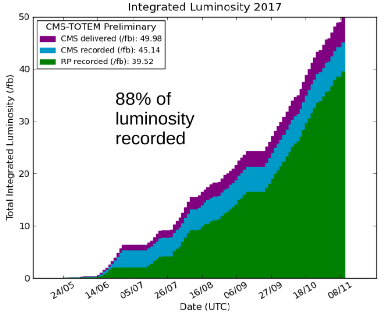
- example of proton acceptance
  - nominal 2018 optics and collimator position
  - RP position: $\sim 15\ \sigma$ from beam (safety rules)
  - y and M: rapidity and mass of products in central detector
  - yellow: single-arm acceptance, green: double-arm acceptance
  - low-mass limit: RP position, high-mass limit: collimator(s)

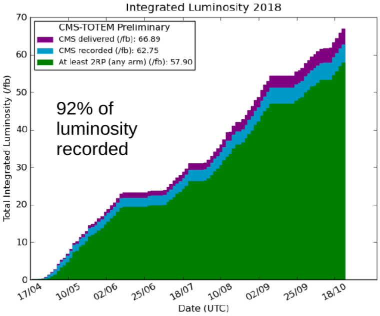




- luminosity collected in 2016 (left), 2017 (middle) and 2018 (right)



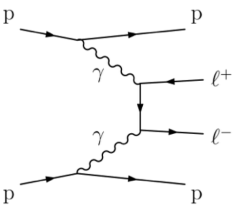


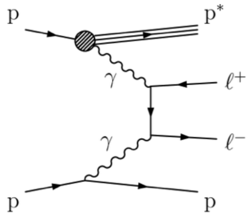


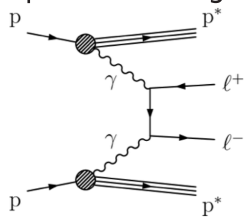
  - total with RPs: > 110 fb^{-1}

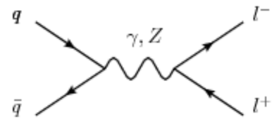
[JHEP (2018) 153]

- data from 2016 pre-TS2, 9.4 fb^{-1}
- enhance statistics $\Rightarrow$ only single proton tag required
  - signal processes: left, main background processes: right



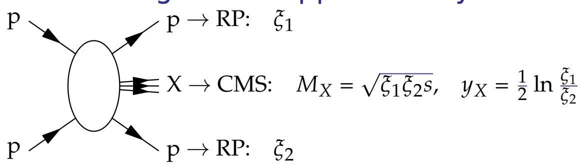






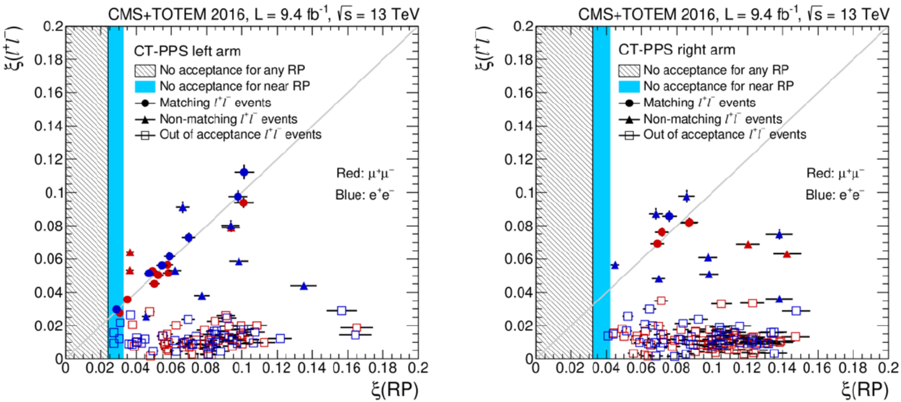
  - lepton l: μ or e
- known (QED) physics
  - verification of the full chain: DAQ, reconstruction, alignment, optics, ...
  - nevertheless first observation at such masses
- central selection
  - $p_T(l) > 50$ GeV, $m(ll) > 110$ GeV to avoid Z peak
  - ll vertex separation
  - ll acoplanarity (back-to-back)

- 2016: no timing RPs $\to$ background suppressed by matching CMS and RP data



  - remaining background: pile-up of unrelated central and forward activity

- 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



Outlook for Run III

- PPS continuation approved for Run III (2020 – 2021)
  - $\sqrt{s} = 14$ TeV
  - goal 300 fb^{-1}
- current detectors damaged by radiation $\rightarrow$ replacement needed
- replacement of tracking detectors
  - technology very similar to the existing 3D pixels
  - geometry and granularity also similar
  - detector package equipped with internal movement system $\rightarrow$ distribution of radiation dose
- replacement of timing detectors
  - double-diamonds foreseen in 2 RPs per arm
    - 8 planes $\sim$ 18 ps resolution

Summary

- Precision Proton Spectrometer: extension of CMS to tag forward protons
  - additional information $\Rightarrow$ model-independent background suppression
  - access to new-physics processes

- status
  - $> 110\ \mathrm{fb}^{-1}$ of data collected in 2016, 2017 and 2018
  - final detector apparatus as of 2018 (tracker + timing)
  - tracker calibration (alignment, optics): advanced development
  - tracker efficiency: advanced development
  - timing calibration: active development

- physics analyses
  - first publication: di-leptons $\Rightarrow$ *PPS works as desired*
  - ongoing analyses: di-photons (anomalous couplings), ...

- outlook
  - continuation in Run III confirmed