The CMS Precision Proton Spectrometer (PPS): results, status and prospects
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Outline

• PPS physics case
• Experimental apparatus
• Operation in LHC Run 2
• Tracking efficiency
• Detector alignment and proton reconstruction
• (Semi)Exclusive $\gamma \gamma \rightarrow \ell^+ \ell^-$ results with 2016 data
• Prospects for LHC Run 3
PPS physics case

- **Central exclusive production** ($J^{PC} = 0^{++}$ central final state)
  - Colour-singlet exchanges with large rapidity gaps between the central system and the outgoing protons
  - Two-photon, photon-pomeron or two-pomeron exchanges at LHC energies allow access to a large variety of processes

- **Electroweak physics**: diboson and dilepton production, anomalous coupling searches
- **QCD**: dijet, trijet, $t\bar{t}$ production
- **BSM direct searches**: new resonances, missing mass...

- **Advantages of the forward proton measurement**
  - Strong background suppression by requiring kinematic match with the central system
  - Reduced theory uncertainties related to proton dissociation
Introduction to PPS

- Near beam magnetic spectrometer at IP5 of the LHC
  - Joint CMS+TOTEM project to include horizontal Roman Pots in the standard, high luminosity, CMS data taking, TDR in 2014 [CERN-LHC-2014-021]
  - Started in 2016 (one year early) thanks to the availability of the legacy TOTEM silicon strips detectors
  - Collected data throughout the whole LHC Run 2

- Two complementary measurements
  - Tracking detectors measure the proton displacement with respect to the beam, which is translated into energy-momentum loss thanks to the knowledge of the beam optics
  - Timing detectors measure the proton arrival time in both arms w.r.t. the reference clock that keeps the two stations synchronized, allowing the calculation of the longitudinal position of the interaction
Experimental challenges

• **Roman Pots need to operate at few mm from the beam to maximize acceptance**
  - RF shielding installed to limit the impedance caused by the RP insertion

• **Detectors must tolerate high levels of non-uniform irradiation**
  - For $\sim 100 \text{ fb}^{-1}$ (Run 2): $\sim 5 \cdot 10^{15}$ protons/cm$^2$
  - in tracking detectors
  - Spatial resolution required: $\sim 10$-30 μm
  - Timing resolution required: $\sim 20$ ps, to reject high pileup
PPS detectors for Run 2

2016 Detectors
- Tracking: 2 stations of TOTEM Si-strips detectors (10 planes), 20 μm resolution. Limited radiation resistance ($\Phi_{\text{max}} \sim 5 \cdot 10^{14}$ p/cm$^2$), no multi-track capability.
- Timing: diamond detectors in cylindrical RP

2017 Detectors
- Tracking: 1 station of TOTEM si-strips, 1 station of silicon 3D pixels (6 planes with CMS Phase 1 tracker readout chips), $\sigma_x \sim 15$ μm and $\sigma_y \sim 30$ μm, $\Phi_{\text{max}} \sim 5 \cdot 10^{15}$ p/cm$^2$
- Timing: 1 station with 3 planes of single-layer diamond with expected $\sigma_t = 80$ ps/plane and 1 plane of UFSD with expected $\sigma_t = 30$ ps/plane ($\Phi_{\text{max}} \sim 10^{14}$ p/cm$^2$)

2018 Detectors
- Tracking: two 3D pixels stations
- Timing: 1 station of diamond detectors (2 single-layer + 2 double-layer)
LHC Run 2 operation

- \( \sim 115 \text{ fb}^{-1} \) collected by PPS during Run 2
  - Always inserted and taking data, fully integrated in CMS runs, in 2017 and 2018
  - Very high stability in both 2017 and 2018

2016: 40% of the CMS statistics
2017: 88% of the CMS statistics
2018: 92% of the CMS statistics
2018 data: hit maps

- Less than 0.05% bad or noisy pixels

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Tracking efficiency studies

- Main strips inefficiency due to no multi-tracking:
  - 30% efficiency at pileup of 50
  - No problem for pixel detectors

- Radiation damage effects on the sensors reduced when moving to pixels:
  - However, non-uniform irradiation does affect the readout chip performance
  - Efficiency loss mitigated by moving the stations vertically during technical stops
2017 Pixel detector efficiency

- Efficiency computed with tracks reconstructed within the same station
  - Evolution of the radiation damage vs. integrated luminosity after LHC second Technical Stop (~18 fb⁻¹ taken before TS2)
  - Inefficiency spot caused by radiation damage is moved away from the high-occupancy region when the station is lifted
  - The radiation effect starts to be visible at ~8 fb⁻¹

- Very high performance overall: average efficiency ~98%
  - Few damaged pixels: ~1.5 × 0.3 mm², caused by non-uniform irradiation of the readout chip

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Detector alignment

Two step detector alignment procedure:

• **Absolute RP alignment** in dedicated low-luminosity runs:
  • Beam-based alignment, to establish the position of the RPs w.r.t. the LHC collimators and the beam
  • Exploit the geometrical properties of elastic scattering events \((pp \rightarrow pp)\) to extract positions of all the RPs, with both horizontal and vertical pots inserted very close to the beam

• **Fill-by-fill alignment**:
  • Need to redetermine the RPs positions w.r.t. the beam: the RP position during standard data taking differs from that of the alignment run; the beam position may also change due to the RP or beam movement
  • Use inclusive sample of protons and match the proton tracks distribution with those of the alignment run

See CERN-LHC-2014-021 and CERN-TOTEM-NOTE-2017-001 for further details
LHC optics and dispersion corrections

• Very good knowledge of the LHC beam optics is needed in order to correctly reconstruct the proton fractional momentum loss $\xi$
  • Significant data-driven corrections need to be made to the nominal optics
    • MADX software is used to simulate LHC optics
    • The model parameters are tuned to measurements performed with RPs and beam-position monitors
  • The dispersion is calibrated by using the effective length pinch point ($L_y(x) = 0$)

• In the end: **non-linear calibration of $\xi$ vs. the measured track position**, $\xi = x/D_x(\xi)$

• For the full documentation, see:
Proton reconstruction

- Knowledge of beam optics allows the proton fractional momentum loss $\xi$ to be computed:
  - From $\xi$ the invariant mass and rapidity of the centrally produced state X is determined
- Double arm mass acceptance in the $\sim 400 - 2000$ GeV range
  - Lower limit mainly due to the minimum distance from the beam (can vary depending on beam conditions, e.g. crossing angle)
  - Upper limit due to collimators

\[
\begin{align*}
\xi &= 1 - \frac{|p_f|}{|p_i|} \\
M_X &= \sqrt{s\xi_1\xi_2} \\
\gamma_X &= \frac{1}{2} \log\left(\frac{\xi_1}{\xi_2}\right)
\end{align*}
\]
(Semi)exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$

- Search for **opposite-charge lepton pairs produced by two photons, with forward proton tagging**

- **Known EWK process:**
  - Proton $\xi$ related to $p_T$ and $\eta$ of the leptons: $\xi(\ell^+\ell^-) = \frac{1}{\sqrt{2}} [p_T(\ell^+)e^{\pm\eta(\ell^+)} + p_T(\ell^-)e^{\pm\eta(\ell^-)}]
  - Elastic contribution: low theoretical uncertainty (E-M proton form factors, ...)
  - **Single dissociation component:**
    - Wider photon virtuality spectrum than for exclusive production
    - Sensitive to rapidity gap survival probability
    - Provides acceptance towards lower masses

- **Backgrounds:**
  - **Double dissociation** contribution
  - **Inclusive** (Drell-Yan, VBF) contribution

\[ \begin{array}{c}
\text{Signal} \\
\text{Backgrounds}
\end{array} \] + pileup proton
(Semi)Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ data selection

- 9.4 fb$^{-1}$ of 2016 data used

- Pre-selection:
  - Trigger: $\geq 2$ leptons with $p_T(\mu^\pm) > 38$ GeV and $p_T(e^\pm) > 33$ GeV
  - Offline selection: $p_T(\ell^\pm) > 50$ GeV, $m(\ell^+\ell^-) > 110$ GeV (above Z mass peak), well-reconstructed protons with $\xi(\ell^+\ell^-)$ in PPS coverage $\geq 1$
  - Refitted dilepton vertex ($\chi^2 < 10$, $z < 15$ cm) separated from neighbouring tracks (0.5 mm veto)
  - Leptons produced back-to-back in transverse plane: $a \equiv 1 - \left|\frac{\Delta \phi}{\pi}\right| < \begin{cases} 0.009 (\mu^+\mu^-) \\ 0.006 (e^+e^-) \end{cases}$

- Strong background suppression by requiring 2$\sigma$ matching between $\xi$ measurements (central tracker vs. PPS)

- Data-driven background estimation, using inclusive $DY \rightarrow \ell^+\ell^-$ data and double dissociative simulated events together with randomly selected protons from the data passing the $\xi$ match requirement

- Expected background:
  $\begin{align*}
  &1.49 \pm 0.07 \ (stat.) \pm 0.53 \ (syst.) \ (\mu^+\mu^-) \\
  &2.36 \pm 0.09 \ (stat.) \pm 0.47 \ (syst.) \ (e^+e^-)
  \end{align*}$
(Semi)Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ 2016 results

- First observation of (semi)exclusive (two-photon) production of dileptons with tagged protons
  - 20 matching events, with a total estimated background of 3.85 events
  - Combined significance of 5.1$\sigma$ over background only hypothesis

This measurement proves that PPS performs according to expectations
PPS analysis prospects

• Search for two-photon production of a boson pair:
  • Study neutral quartic gauge coupling, suppressed in SM
  • Sensitive to resonances (axion-like particles, new particle exchanges)
  • Provides model-independent bounds on massive charged particles, only parameterized by spin, mass and "effective charge"
    • See arXiv: 1411.6629

• Search for anomalous quartic gauge couplings:
  \( \gamma \gamma \rightarrow W^+ W^-, \gamma \gamma \rightarrow \gamma Z, \gamma \gamma \rightarrow ZZ \ldots \)
  • \( \gamma \gamma \rightarrow W^+ W^- \): PPS TDR expectations with two order of magnitude improvement w.r.t. Run 1 searches
  • \( \gamma \gamma \rightarrow \gamma Z \): the combined sensitivity in the \( \gamma Z \) channel, for 300 fb\(^{-1}\), goes beyond the one expected for \( Z \rightarrow \gamma \gamma \) decay searches by \( \sim 3 \) orders of magnitude
    • See arXiv: 1703.10600
PPS prospects for Run 3

- PPS approved for operation as standard CMS subsystem in LHC Run 3 (2021-2023)

**Experimental apparatus:**

- **Tracking:**
  - 2 horizontal stations with silicon 3D pixels sensors (similar to the 3D pixels designed for the CMS Phase2 Tracker R&D)
  - PROC600 readout chip (same as CMS pixel detector layer 1)
  - New internally motorized detector package, to distribute the radiation damage and reduce its impact

- **Timing:**
  - 2 horizontal stations equipped with double-layer diamond sensors
  - Optimized readout electronics
Summary

• PPS has proven the feasibility of continuously operating a near-beam proton spectrometer at a high-luminosity hadron collider

• **PPS has successfully collected \( \sim 115 \text{ fb}^{-1} \) worth of data** during LHC Run 2, with very good overall performance

• **PPS has for the first time observed at more than 5\( \sigma \) significance the proton-tagged two-photon production of lepton pairs** with \( \sim 10 \text{ fb}^{-1} \) of 2016 data

• 2017 and 2018 detector performance studies are being finalized

• **The preparation for LHC Run 3 is ongoing:**
  • New detectors are getting ready to be installed for the future data taking
  • A rich physics programme lies ahead, with many final states to be studied
Backup Slides
RPs for timing detectors

- **New cylindrical RP design to host larger detectors and reduce the impedance**
- **Timing RPs are equipped with a 300 μm thick window towards the beam**
  - The thickness is required to compensate the pressure gradient on the larger window
  - No vertical stations needed because the alignment is done by propagating tracks from the tracking stations
Silicon strips detectors

- 300 μm thickness
- 66 μm pitch
- strips oriented at 45° w.r.t. edge facing beam
- Dead area close to the cut edge: only ~50 μm
- operated at −20 °C, bias voltage ~100 V
- 5+5 planes per RP (2 strip orientations for 2D reconstruction)
3D pixel detectors

- 3D technology grants high radiation hardness (up to $\sim 5 \times 10^{15}$ p/cm$^2$)
- Pixel size $100 \times 150 \, \mu$m, $230 \, \mu$m thickness
- Low dead region close to the edge ($\sim 50 \, \mu$m)
- 6 planes per RP
  - $18^\circ$ planes tilt to improve hit cluster size
- Operation at -20 °C and in vacuum (P < 20 mbar)
- Pixel tracker works as expected
  - Residuals according with test beam measurements
Timing detectors

**Diamond Sensors**
- CVD diamond sensors
- Radiation hard
- Macro-pixels of varying size
- Single-plane resolution in test-beam: $\sigma_t \sim 80$ ps

**Ultra-Fast Silicon Detectors**
- Based on LGAD technology
- Limited radiation hardness
- Macro-pixels of varying size
- Single-plane resolution in test-beam: $\sigma_t \sim 30$ ps

**Common readout electronics**
Timing detectors performance

- Horizontal position of the reconstructed track in the PPS pixels vs. horizontal position of in the PPS timing in low pile-up data (<PU> ~ 0.8)

- The data sample is selected requiring a single vertex reconstructed in CMS, a single track reconstructed in the PPS pixels in each of the arms and a single track reconstructed in the PPS timing in each of the arms

- Blue points show all the events passing the double arm selection

- Red points represent the subsample with a single hit per diamond detector plane and all the diamond planes firing
Proton transport model

- The propagation of the proton from the IP to the RPs is approximately modeled with this linear formula:

\[ d(s) = T(s) \cdot d^* \]

where \( d = (x, \theta_x, y, \theta_y, \frac{\Delta p}{p})^T \), the * symbol refers to quantities at the IP,

\[
T = \begin{pmatrix}
    v_x & L_x & m_{13} & m_{14} & D_x \\
    \frac{dv_x}{ds} & \frac{dL_x}{ds} & m_{23} & m_{24} & \frac{dD_x}{ds} \\
    m_{31} & m_{32} & v_y & L_y & D_y \\
    \frac{dv_y}{ds} & \frac{dL_y}{ds} & \frac{dD_y}{ds} & 0 & 0 \\
    0 & 0 & 0 & 0 & 1
\end{pmatrix}
\]

\( v_{x,y} = \sqrt{\beta_{x,y}/\beta^*} \cos(\Delta \mu_{x,y}) \)

\( L_{x,y} = \sqrt{\beta_{x,y}/\beta^*} \sin(\Delta \mu_{x,y}) \)

\( \beta \) is the betatron amplitude and \( \Delta \mu_{x,y} \) is the relative phase advance \( \left( \Delta \mu_{x,y} = \int_{IP}^{RP} \frac{ds}{\beta_{x,y}} \right) \)

The leading terms are:

- \( x \approx D_x(\xi) \cdot \xi \)
- \( y \approx L_y(\xi) \cdot \theta_y^* \)