Measurement of high-mass dimuon production with the CMS-TOTEM Precision Proton Spectrometer

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CT-PPS in a nutshell

- Joint CMS and TOTEM project at CERN
  [Link](http://cds.cern.ch/record/1753795)
- Proton spectrometer designed for operation at highest LHC intensities
- Measurement of processes in which proton(s) stay(s) intact after interaction

**Operation principle:**
- LHC magnets bend scattered protons out of the beam envelope
- CT-PPS detectors housed in Roman Pot (RP) stations along the beamline
  ⇒ detect scattered protons a few mm from beam, on both sides of CMS

**2016:** first CT-PP data taking (15 fb$^{-1}$). Results with 10 fb$^{-1}$ public (this talk)!
CT-PPS physics motivation

Primary goal: study central exclusive production in $\gamma\gamma$ or gg collisions

- proton tag advantages:
  - closure of event kinematics
  - effective background rejection
  - reduced theory uncertainties related to proton dissociation

Opportunity to access a variety of topics: from diffraction to BSM physics

- proton structure (generalized parton distributions)
- anomalous couplings with high sensitivity
- new resonances in very clean final state
First physics: $\gamma\gamma \rightarrow \mu^+\mu^-$ with proton tag

- Idea: look at "simple" SM process, explore correlation between kinematics of the dilepton system and that of the forward proton(s)

  ⇒ Validation of the optics and alignment
  ⇒ Observation of the first proton-tagged $\gamma\gamma$ collisions at the EWK scale

Key proton variable: relative momentum loss $\xi = \Delta p/p$

- Defines dimuon system:
  
  \[ M = \sqrt{\xi_1 \xi_2} \sqrt{s}, \text{ Rapidity} = Y = \frac{1}{2} \ln \left( \frac{\xi_1}{\xi_2} \right) \]

SM contribution in double-tagged region very low — hence consider both double and single-tagged $\mu^+\mu^-$ events
**Strategy**

**Look for correlation** between
- direct proton $\xi$ measurement by CT-PPS
- dimuon system measured by CMS

$\xi$ can be derived from muon $p_T$ and $\eta$:

$$\xi^\pm = \frac{1}{\sqrt{s}} \times (p_T(\mu_1)e^{\pm\eta(\mu_1)} + p_T(\mu_2)e^{\pm\eta(\mu_2)})$$

($\pm\eta$ solutions correspond to the protons in the $+z$ and $-z$ direction.)

**Expected backgrounds:**

- will fake signal by overlapping with pileup or beam halo protons
- can be largely suppressed by selection cuts

[Diagrams: Drell-Yan, Double dissociation, pileup proton]
Event selection

- **Pair of opposite sign muons** with $p_T(\mu) > 50$ and $M(\mu\mu) > 110$ GeV (above Z-peak)

- **To suppress background:**
  - Veto additional tracks around dimuon vertex (within 0.5mm)
  - Require back-to-back muons: $|1 - \Delta \phi / \pi| < 0.009$

Signal candidates required to have $\xi(\mu\mu)$ and $\xi(\text{proton})$ matching within $2\sigma$ of resolution
Data-driven background estimate

Use sample of background protons from Z-peak events (data)

Drell-Yan contribution:
- count number of Z-peak events with $\xi(\mu\mu)$ and $\xi$(proton) correlated within 2$\sigma$
- use MC to extrapolate to the signal region

Double-dissociative contribution:
- mix double-dissociative simulated events (LPAIR) and protons from data to derive number of matching events

Total number of expected matching background events: $1.47 \pm 0.06$ (stat.) $\pm 0.52$ (syst)
Final result: $\xi$ correlations

- **Left arm**
  - Total 17 events with $\xi(\mu\mu)$ within acceptance
  - 12 with matching $\xi(\mu\mu)$ and $\xi$(RP) (red points)

- **Right arm**
  - Matching events
  - Non-matching events
  - Out of acceptance events
  - No acceptance for far RP
  - No acceptance for near RP

**Estimated significance** for observing 12 events for a background of $1.47 \pm 0.06$ (stat.) $\pm 0.52$ (syst.): $4.3\sigma$
Signal candidates properties

- Dimuon M and Y consistent with single arm acceptance
- No double-tagged events observed, consistent with SM xsection*efficiency

Mass extends up to 341 GeV – first tagged $\gamma\gamma$ collisions at EWK scale!
Conclusions

• Proven for the first time the feasibility of operating a near-beam spectrometer at a high luminosity collider on a regular basis

• More than $4\sigma$ evidence for electroweak scale single proton-tagged $\gamma\gamma$ collisions at the LHC
  Ref.: CMS-PAS-PPS-17-001; TOTEM-NOTE-2017-003

• Next: diphoton production, $\gamma\gamma \rightarrow \gamma Z/ZZ/WW$ with timing, ...

▶ 2017: restarted data taking after major upgrade
   Tracking: 3D Si pixels & strips
   Timing: Diamonds & Ultra Fast Silicon Detector

Expect much more physics in 2017.
Backup
Using suppression factors by Durham model arXiv:1601.03772

- Good description of the data at $Y=0$, but values too large for non-zero rapidities.

- A $Y$ dependence of the rapidity gap survival probability is expected in several models, see e.g. arXiv:1410.2983, arXiv:1508.02718, arXiv:1502.03323
Alignment

- Alignment procedure performed in 2 steps
  - 1: Absolute alignment
  - 2: Fill-by-fill alignment
- Step 1: Use elastic scattering (pp→pp) events, in special alignment runs where both horizontal and vertical RPs approach very close to the beam
- Step 2: Use inclusive sample of protons triggered by central CMS detectors
  - Match distribution of proton track positions to that of alignment runs
Optics determination

- Final physics variable of interest is the proton momentum loss "\( \xi \)"

- Reconstruction from measured RP track position requires precise knowledge of LHC optics & dispersion \( D_x \)
  - Dispersion calibration using \( L_y(x) = 0 \) point
  - LHC lattice/optics matching of crossing-angle and quadrupole positions using measured dispersions and the beam position as measured by RPs and BPMs

- Final result is a (non-linear) calibration of \( \xi \) vs. the measured track x position
- Overall \( \xi \) resolution of \( \sim 5.5\% \)
Expect up to 2 orders of magnitude improvements for 95% CL limits on $a_{QGC}$ with CT-PPS wrt to Run 1 CMS only results.
- In particular, search for exclusive diphoton production
- Multiple extensions of SM predict extra yields/different kinematic differences wrt SM
- Very low expected background after proton tag requirement:

Also, part of program is to explore quartic gauge couplings with photons: $\gamma\gamma \rightarrow \gamma Z/ZZ/WW$ (with timing detector)