Physics results with the CMS-TOTEM Precision Proton Spectrometer

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on behalf of the CMS and TOTEM Collaborations

LHC Working Group on Forward Physics and Diffraction

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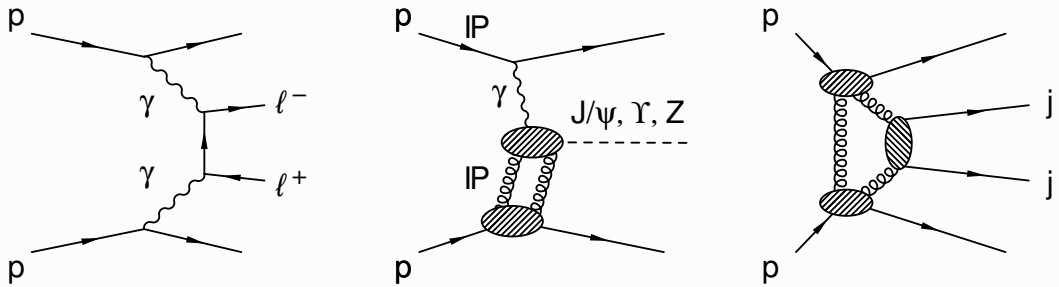
Introduction - CTPPS physics case



Central exclusive production

Very clean production processes at the LHC

- colour-singlet exchanges, involving large rapidity gaps between the central system and scattered beam kinematics
- two-photon, photoproduction, or two-pomeron exchanges yield a large phenomenology of processes at LHC energies

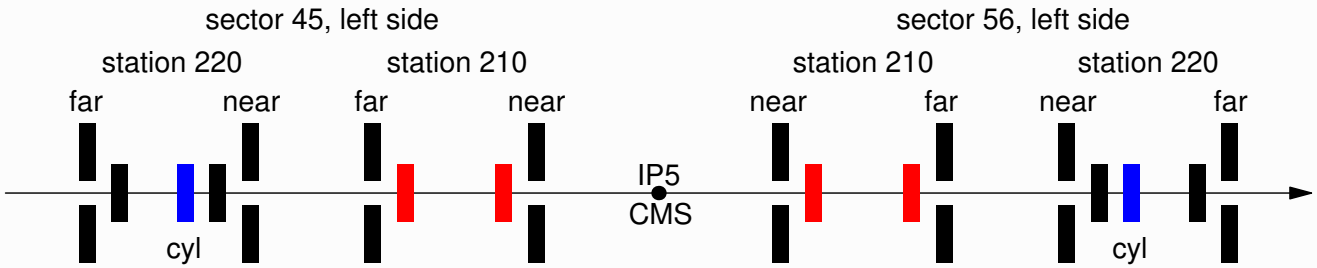
Tagging forward protons at the LHC

- Overconstraint of event kinematics through central/forward systems matching
- Reduced theory uncertainty related to proton dissociation (study of semi-exclusive processes) and proton inner structure (GPDs)
- Direct probe of BSM physics through EWK ($\gamma\gamma \longrightarrow X$), or QCD (exclusive di-jets, ...) production rates

Introduction - CTPPS apparatus

Joint CMS + TOTEM project including horizontal Roman Pots (RPs) within the CMS environment

- started **one year ahead** of initial plan, thanks to TOTEM silicon strips availability
- over **15 fb^{-1} ⊕ 40 fb^{-1}** collected as one component of the CMS data acquisition system in 2016 and 2017



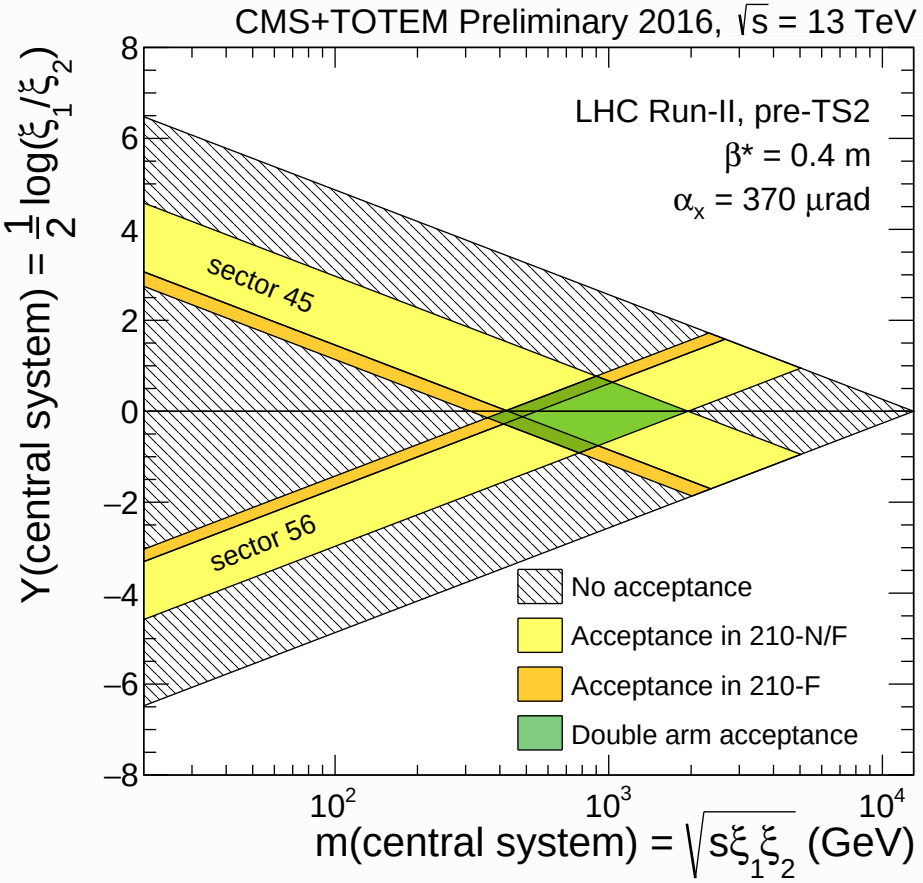
2016 layout: for each arm, multiple sensors technology

- two stations of **TOTEM silicon strips** in two horizontal RPs with RF shielding for insertion at high-luminosity,
- **timing detectors** in a cylindical RP (diamond + UFSD) ; fully operational after 2016 TS2

2017+ layouts: see N. Minafra's talk this afternoon

Single- and double-arm acceptance

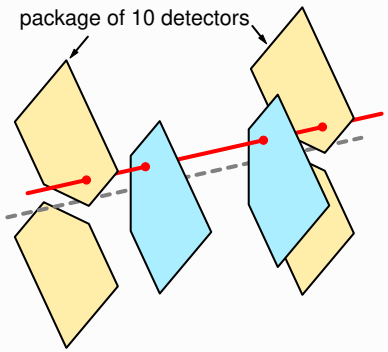
Physics observable: proton longitudinal momentum loss $\xi = \Delta p/p$

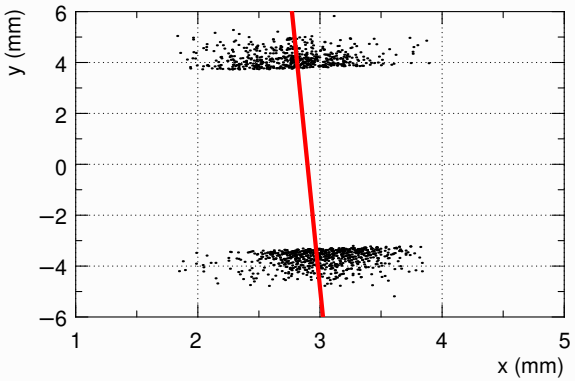


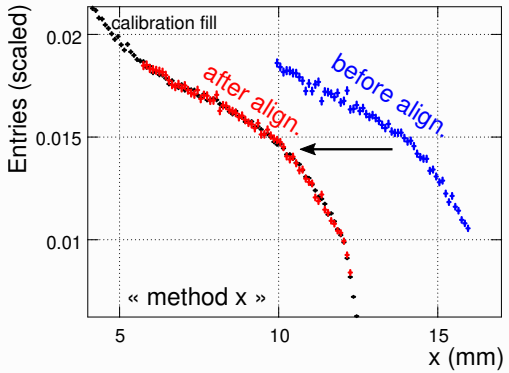
- $360 < m(\text{central}) < 1950$ GeV (central $|y|$) for double-arm tagging
- Single-arm tagging extends acceptance to low-mass, forward-region events

CTPPS alignment and calibration

CTPPS detectors alignment with elastics







Alignment technique developed and **extensively used** by the TOTEM Collaboration

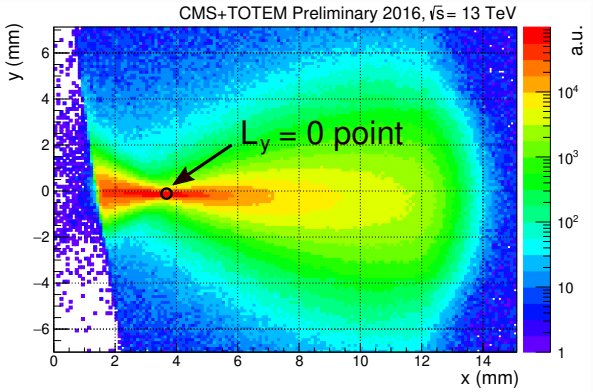
Absolute and fill-by-fill Roman Pots alignment using dedicated low-bunches population *alignment runs*:

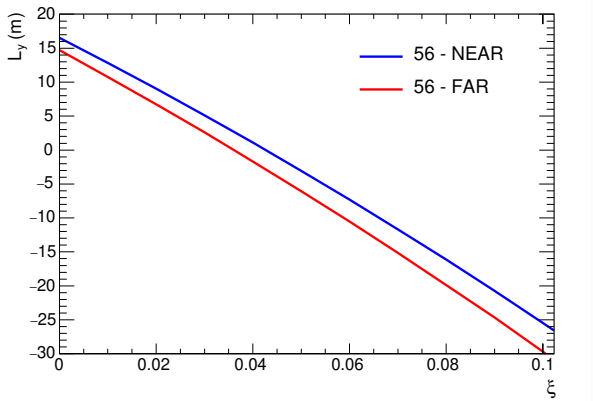
- **beam-based absolute alignment** between LHC collimators and RPs with BLMs
- use **elastic *pp* → *pp* scattering events** with both horizontal and vertical pots inserted very close to the beam to **align each RP** with overlaps
- match **inclusive sample** of protons triggered by central CMS detectors distributions to **alignment run** distributions to extract **per-fill relative alignments**

Full documentation of the technique: CERN-TOTEM-NOTE-2017-001

"x-to-ξ" calibration

- Optics matching uses **elastic events**, and MAD-X modelling of full beamline optical components (quadrupole strengths, RPs/BPMs positions, …)
- Dispersion calibration uses the **vertical pinch point** $\mathbf{L_y(x) = 0}$.
- Final result is a (non-linear) calibration of ξ vs. the measured track x position





Overall ξ **resolution**:

$$\frac{\delta\xi}{\xi} = 2\%\ \text{(digi.)} \oplus 1\%\ \text{(fit err.)}$$

$$\oplus\ 4\%\ \text{(x-align)} \oplus 3\%\ \text{(det.ineff.)} = \mathbf{5.5}\%$$

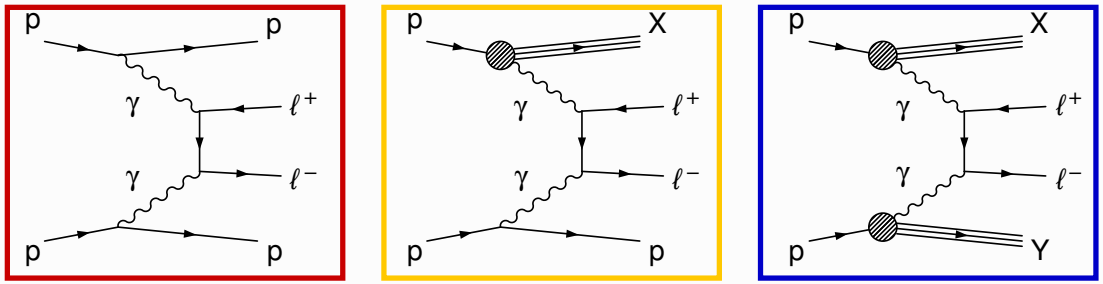
Full documentation: New J. Phys. 16 (2014) 103041, CERN-TOTEM-NOTE-2017-002

Search for central exclusive production of lepton pair

The analysis in a nutshell

Search for **two-photon production** of an opposite-charge **muon pair** with forward **proton tagging** using CTPPS strips detectors (2016 pre-TS2 dataset, no timing detectors)

Analysis documentation: CMS-PAS-PPS-17-001



$\gamma\gamma \to \ell^+\ell^-$ signals

Elastic contribution:

- simple QED process, with low theoretical uncertainty

Single-dissociation component (SD):

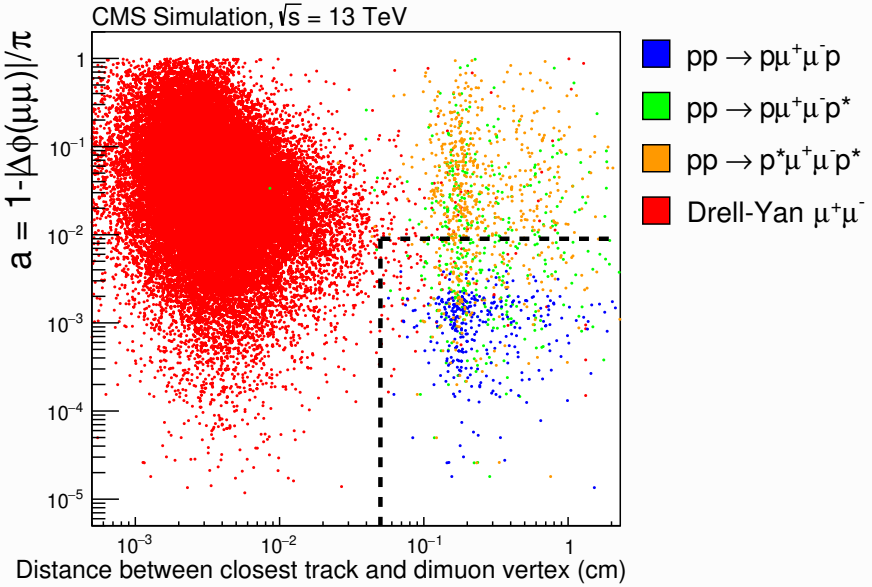
- increased virtuality spectrum, broader ξ range
- differential spectra sensitive to proton structure functions

Backgrounds

Double-dissociation contribution (DD):

Inclusive contributions: Drell-Yan, dibosons, ...

Central detector selection



Dataset: ~15 fb^{-1} (~10 fb^{-1} with RPs inserted) of pre-TS2 data collected at 13 TeV in 2016

Pre-selection:

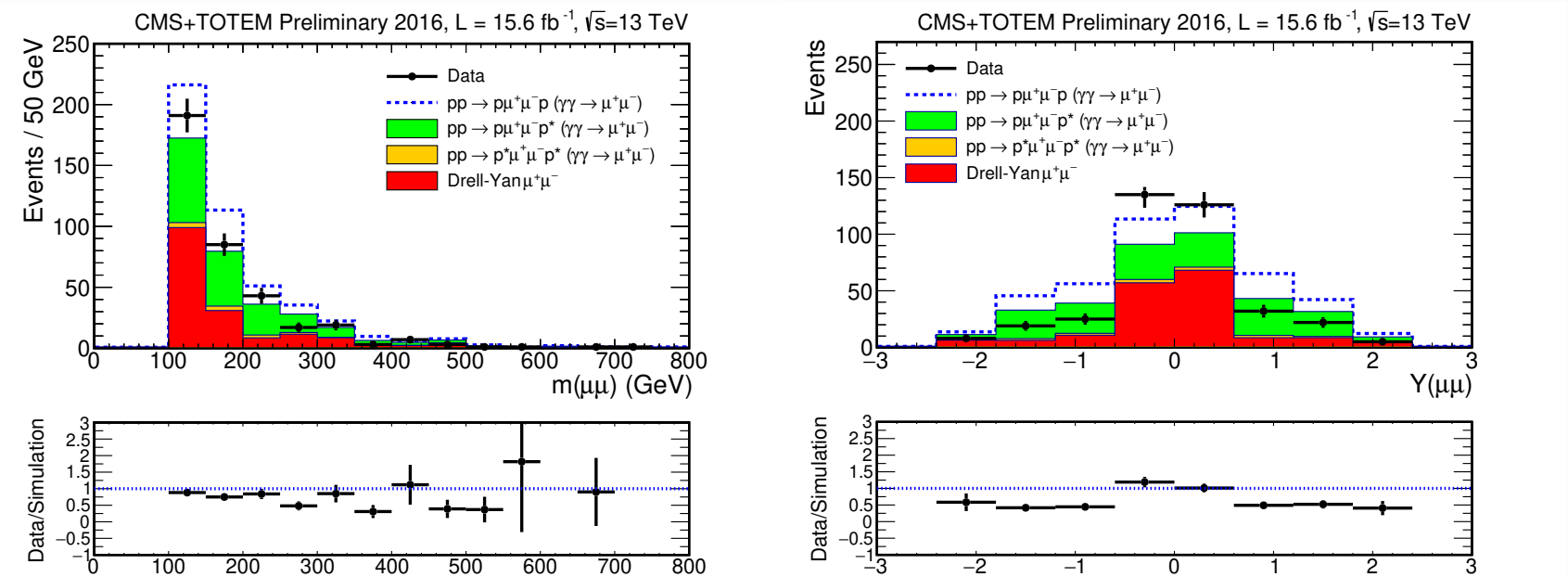
- trigger: $\geq$ 2 muons with $p_T(\mu^{\pm}) > 38$ GeV
- offline selection: $p_T(\mu^{\pm}) > 50$ GeV
- dimuon system: $m(\mu^+\mu^-) > 110$ GeV (above Z peak)
- refitted dilepton vertex ($\chi^2 < 10$, $|z| < 15$ cm) clearly separated from other tracks
- muons produced back-to-back in transverse plane, $a \equiv 1 - |\Delta\phi/\pi| < 9 \times 10^{-3}$

A note on survival probability

Rapidity gaps survival probability evaluated at $\sqrt{s}$ = 13 TeV following Durham model prescription (arXiv:1601.03772).

- modified photon PDF accounting for experimental rapidity gap veto

Rescaling of $\gamma\gamma \to \mu^+\mu^-$ prediction (LPAIR) accordingly



Good description of data at low-rapidities, increasing discrepancy in forward regions

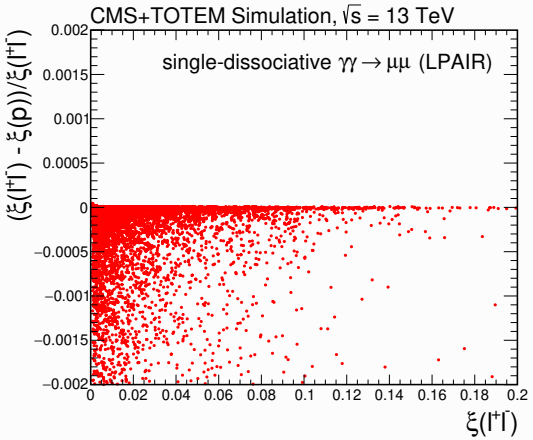
Central / forward systems matching

Selecting events with at least one track in at least one CTPPS arm

Accurate prediction of outgoing proton ξ from central system kinematics:

$$\xi^{\pm}(\mu_1\mu_2) = \frac{1}{\sqrt{s}}\left[p_T^{\mu_1} e^{\pm\eta_{\mu_1}} + p_T^{\mu_2} e^{\pm\eta_{\mu_2}}\right]$$

… without experimental knowledge of second proton's final state



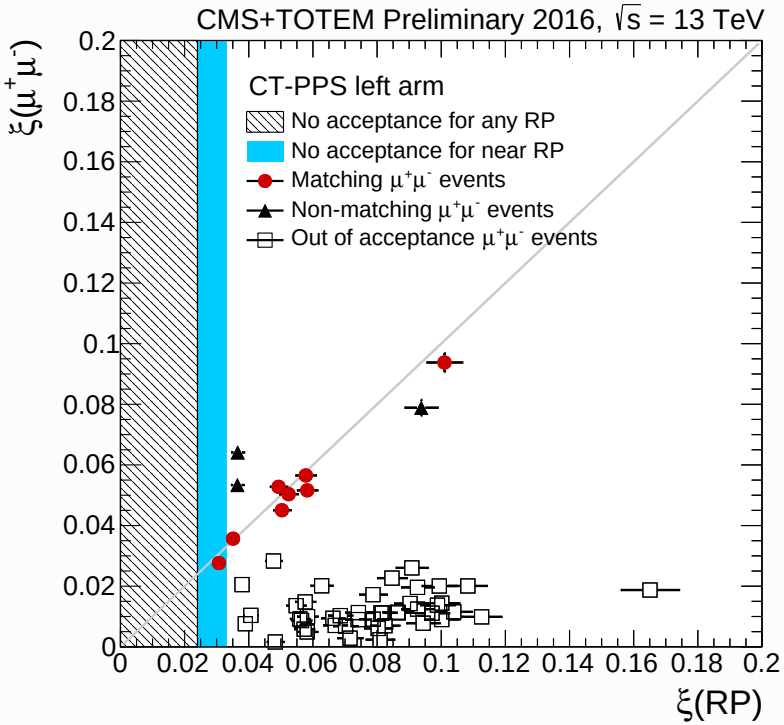
Central-forward selection: 2-σ matching of $\xi(\mu^+\mu^-)$ and ξ(RP)

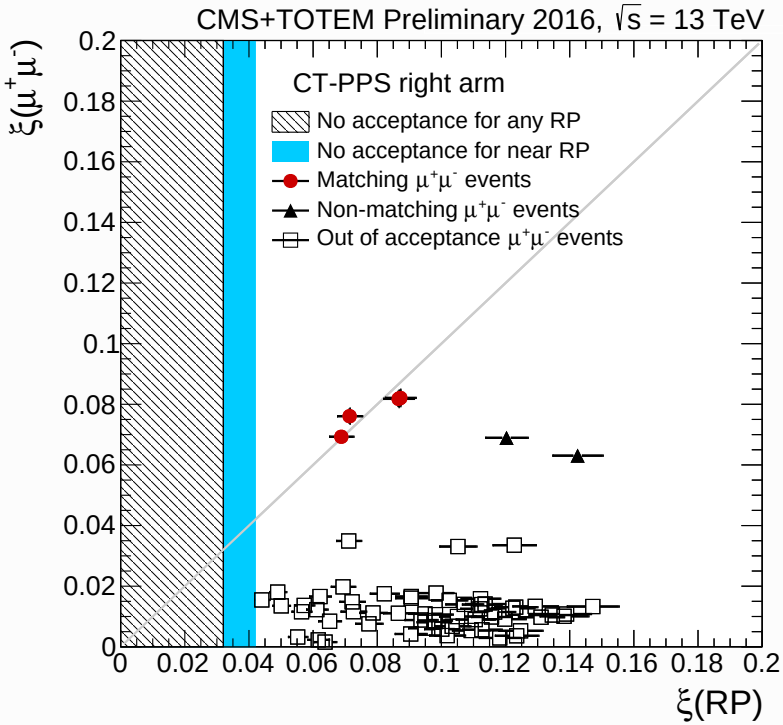
Data-driven estimate of remaining background using inclusive DY $\to \mu^+\mu^-$ and DD $\gamma\gamma \to \mu^+\mu^-$ events in coincidence with pileup protons

- extract yield of 2-σ matching events in Z peak control region
- for DY, MC-based reweighting of $\xi(\mu\mu)$ shape according to track-based exclusivity efficiency
- for DD, toy simulation of MC events mixed with protons from Z peak sample

Expected combined backgrounds expectations: **1.47 ± 0.06** (stat.) **± 0.52** (syst.)

Results



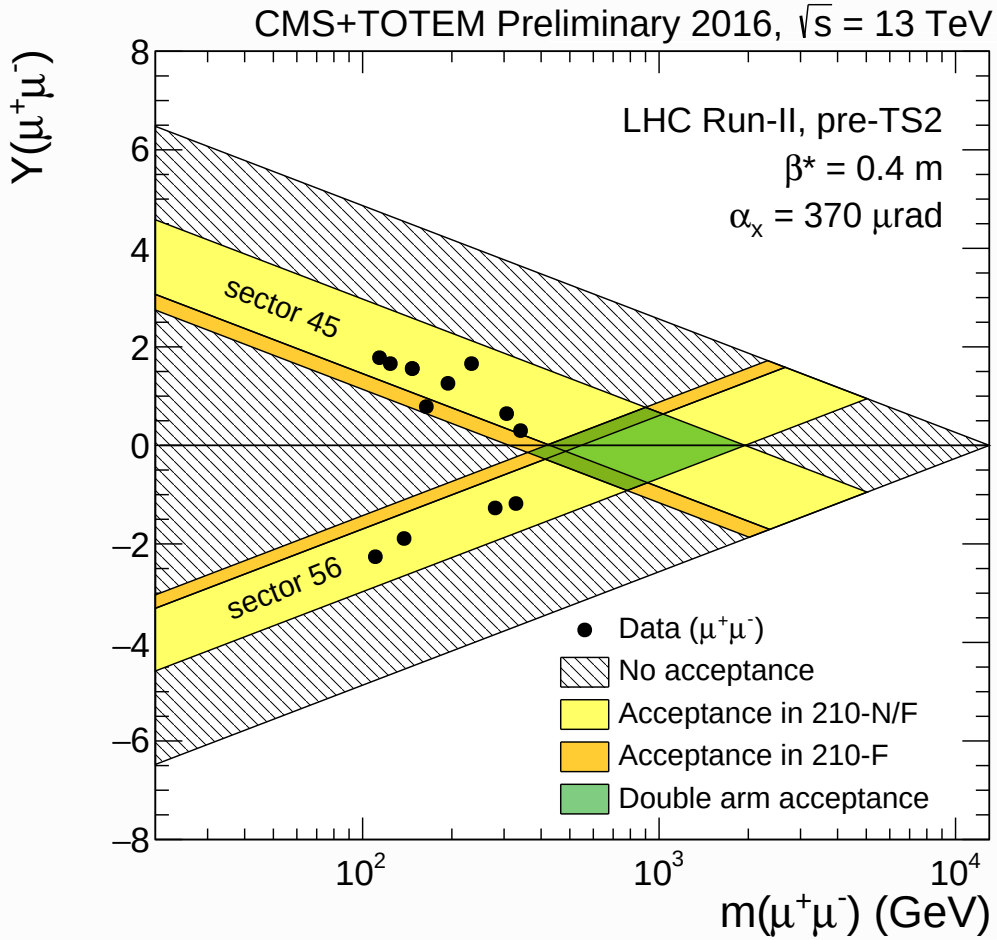


- **17 events** with $\xi(\mu\mu)$ consistent with RPs acceptance (black triangles)
- **12 events** with matching $\xi(\mu\mu)$ / ξ(RP) (red dots)

Signal significance: **4.3σ** over background-only hypothesis, **first evidence** for a two-photon production of a lepton pair at such mass range

Central (semi-)exclusive $\gamma\gamma \to \mu^+\mu^-$ events

First observation of central exclusive (two-photon) production of dimuon with tagged protons



- mass range up to the EWK scale: $m_{\text{max}}(\mu^+\mu^-) = 341$ GeV

Prospects and overview

Search for two-photon production of a gauge boson pair

Addition of CTPPS within CMS allows to study numerous additional intermediate and final states

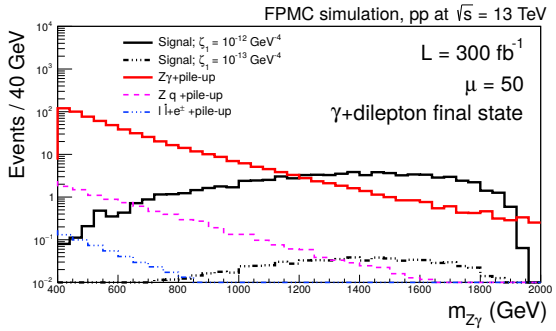
Search for exclusive two-photon production of a photon pair

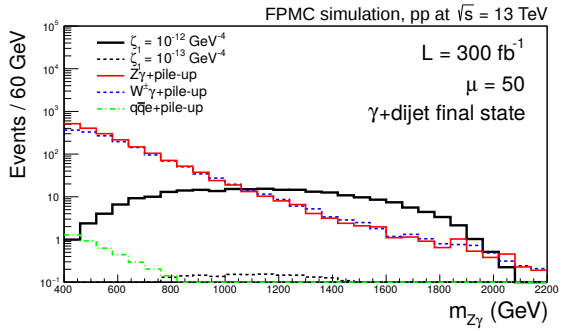
- Multiple SM extensions predict difference in yield and differential distributions
- Very low background expected after central/forward systems matching

Search for anomalous $\gamma\gamma \to W^+W^-, \gamma\gamma \to \gamma Z, \ldots$

From 2017 on, addition of timing detectors opens the possibility to probe final states more complex than a dilepton system, even in a high-$\langle\mu\rangle$ environment

- for exclusive W^+W^- production, CTPPS TDR expectations (100 fb^{-1}): 2 orders of magnitude improvement wrt Run-I attempts (arXiv:1604.04464, arXiv:1607.03745)
- for exclusive γZ production, combined dilepton+dijet final states yields 3 orders of magnitude lower than inclusive limits on $Z \to \gamma\gamma\gamma$ BR (300 fb^{-1}, arXiv:1703.10600)





Overview

CTPPS data taking operations since 2016

- proven **for the first time** the feasibility of **operating a near-beam spectrometer** at a **high-luminosity hadron collider** on a regular basis
- first evidence at **more than** 4σ for electroweak-scale **single-proton tagged** two-photon production of a lepton pair at the LHC with **~10 fb^{-1}** collected in 2016 before TS2 (15 fb^{-1} in total)

More than **40 fb^{-1}** collected in 2017, more to come from next year on…

- rich physics programme ahead, with more final states to be probed
- study of electroweak, and intermediate-x_{Bj} QCD with unachieved precision, and test of anomalous behaviours