Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS–TOTEM precision proton spectrometer

The CMS and TOTEM Collaborations
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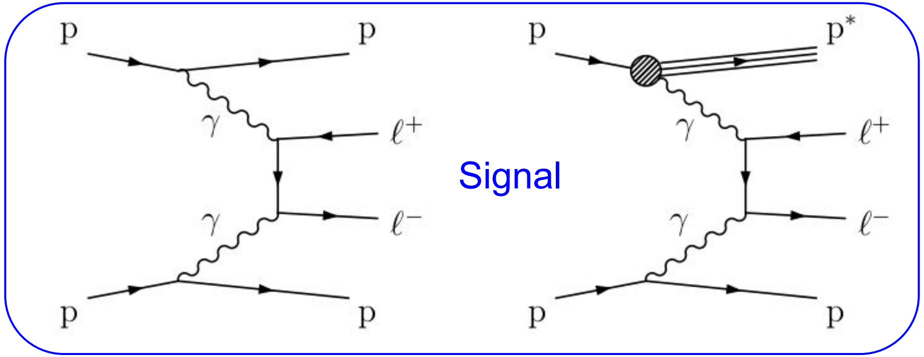
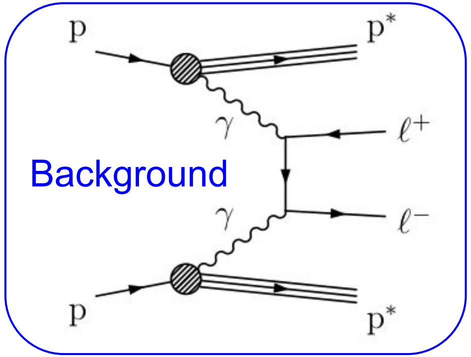
Introduction

$pp \rightarrow p\ell^+\ell^-p^{(*)}$

$\ell = e, \mu$

$m(\ell^+\ell^-) > 110$ GeV



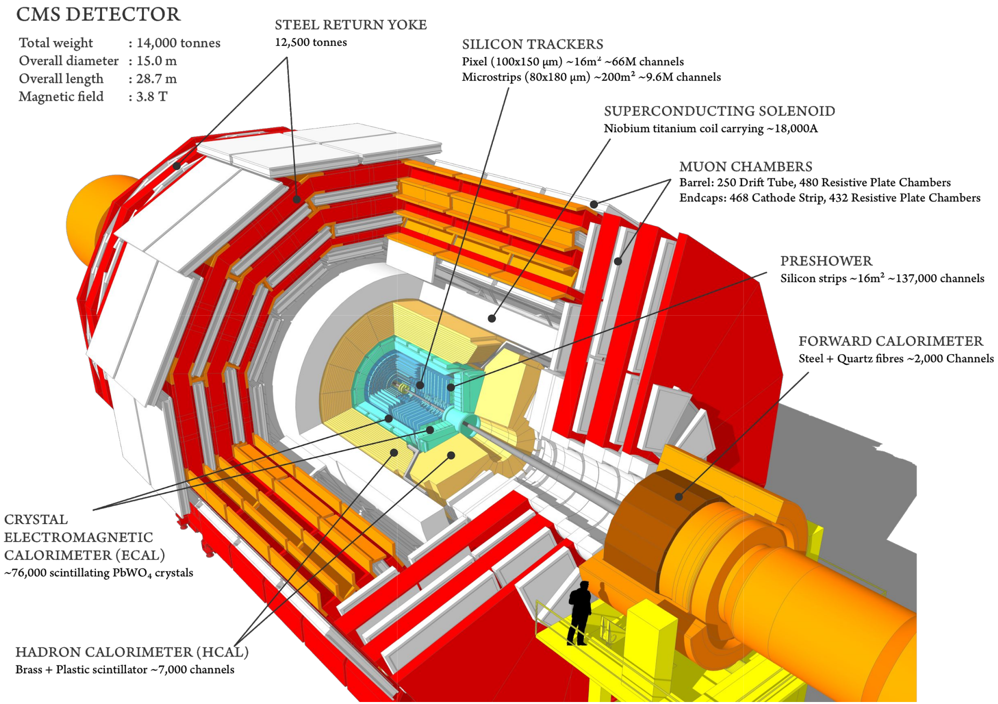


Search for new physics   Background to exclusive reaction

First measurement done with the simultaneous detection of the scattered protons

The experiment

Experimental setup - CMS apparatus

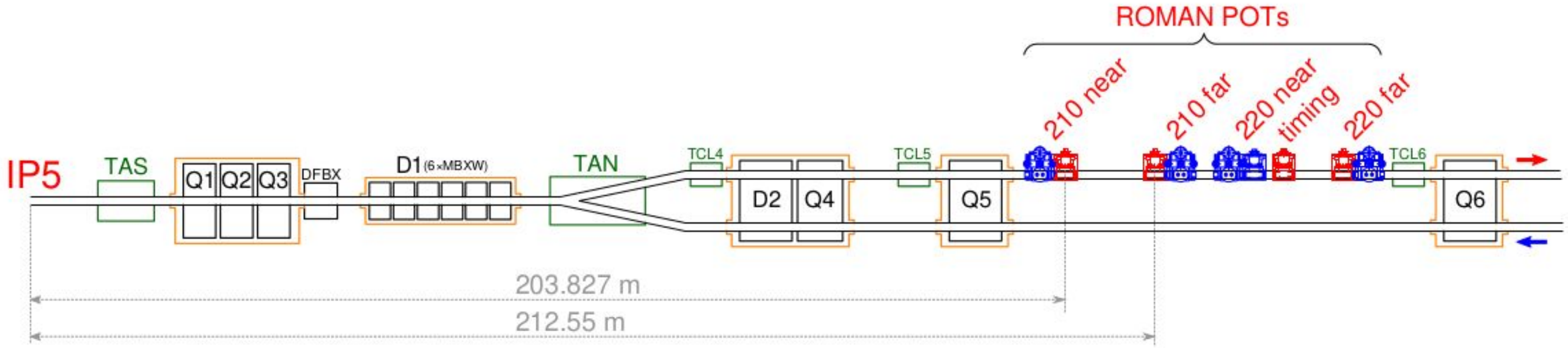


Experimental setup - CT-PPS

Measures protons scattered at small angles and carrying ~84-97% of the incoming beam momentum

- Silicon tracking system measures the position and direction of the protons
- Timing counters measure proton arrival time (not used in the analysis)

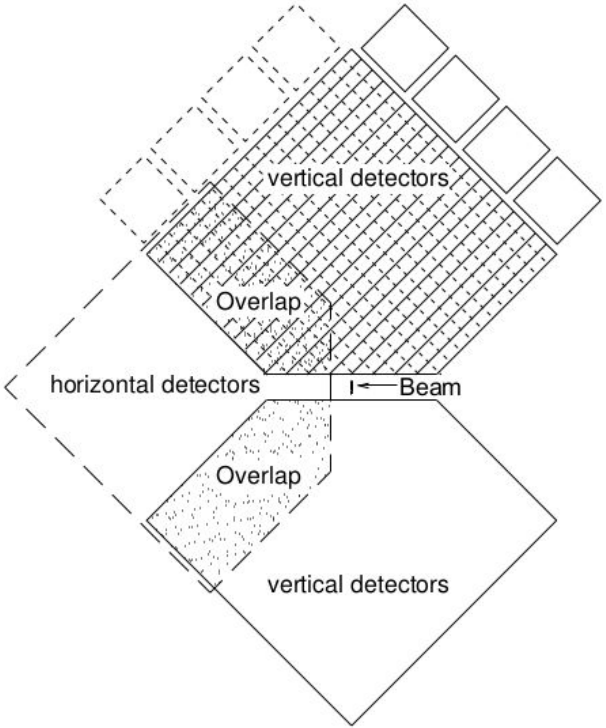
The detector planes are inserted horizontally into the beam pipe using Roman Pots (RPs), allowing the detectors to be brought very close to the beam



Experimental setup - Silicon strip detectors

Each tracking RP contains 10 planes of edgeless silicon strip sensors

Five planes are oriented with the silicon strips at a +45º angle with respect to the bottom of the RP, the other five at −45º



CT-PPS alignment - alignment fill

Special low-luminosity calibration fill. Horizontal and vertical RPs are used, brought very close to the beam so that they overlap

The relative position of all the sensors in each arm is determined by minimizing the residuals between hit positions on each sensor and fitted tracks. The relative alignment between RPs is determined by reconstructing the tracks when the detectors overlap

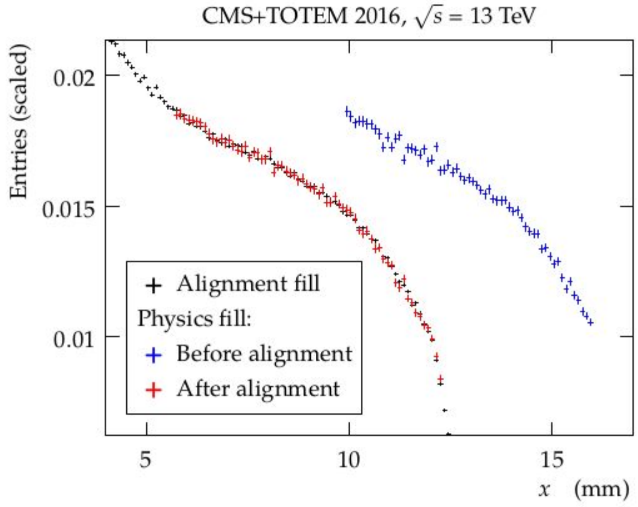
The alignment with respect to the beam is performed with a sample of elastic scattering events, whose hit distribution in the vertical RPs has an elliptical shape centered on the beam position.

CT-PPS alignment - physics fills

Only horizontal RPs are used, at a greater distance from the beam

Horizontal alignment (*x*): the spatial distribution of the track impact points is matched to the one obtained in the alignment fill

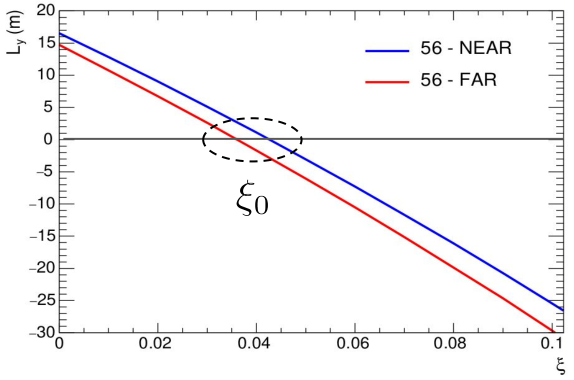
Vertical alignment (*y*): a straight line is fitted to the *y* coordinate of the maximum of the track impact point distribution as a function of *x* and extrapolated to *x* = 0

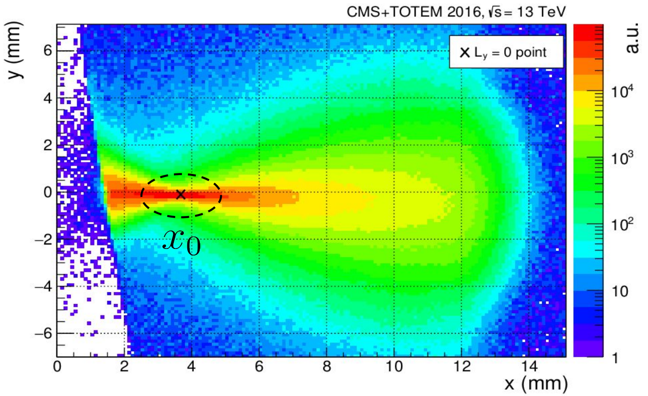


The LHC beam optics

The elements of the beam line that affect the trajectory of the scattered proton between the IP and the RPs can be treated as optical lenses. From the resulting transport matrix, $x = D_x(\xi)\xi$ $y = L_y(\xi)\,\Theta_y^*$

$\xi = \Delta p/p$ can be determined by inverting the equation for x: $\xi \approx \frac{x}{D_x}$



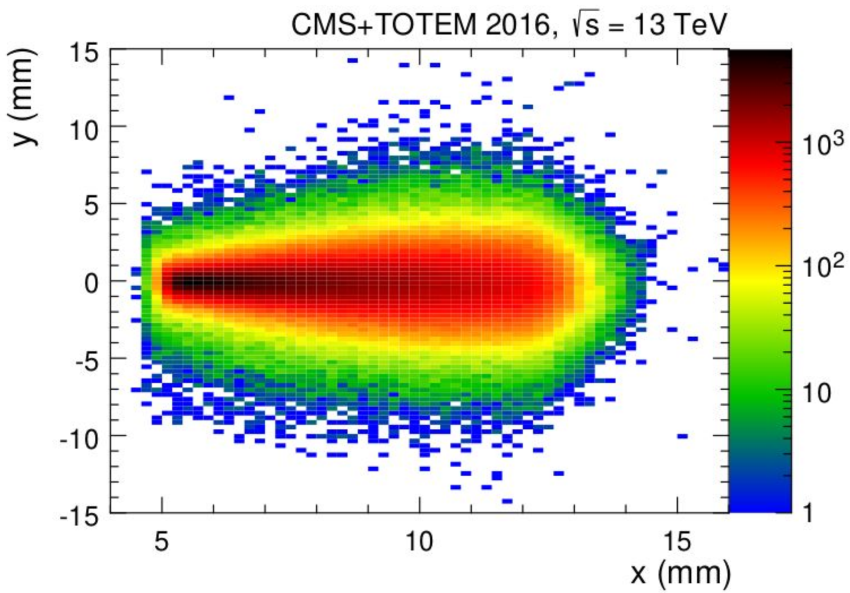


$$\Longrightarrow \quad D_x \approx \frac{x_0}{\xi_0}$$

Proton track reconstruction

Search for linear patterns along *z* among the hits detected in the 10 detector planes. Done independently in each strip orientation (-45º or +45º)

If a single pattern is found in each orientation, they can be matched together and a track is fitted to obtain a “track impact point”



The analysis

Data sets and Monte Carlo samples

May–September 2016, 9.4 fb^{-1} of data collected at CT-PPS

Monte Carlo samples (LPAIR, Madgraph + Pythia 8):

For signal, $pp \rightarrow p\ell^+\ell^-p^{(*)}$ with $\gamma\gamma \rightarrow \ell^+\ell^-$

For background, $pp \rightarrow p^*\ell^+\ell^-p^*$ with $\gamma\gamma \rightarrow \ell^+\ell^-$; $pp \rightarrow \gamma^*/Z^* \rightarrow \ell^+\ell^- + X$

GEANT 4 was used to reconstruct central detector information in the same way as the collision data. Only generator-level forward proton information was used

Event selection

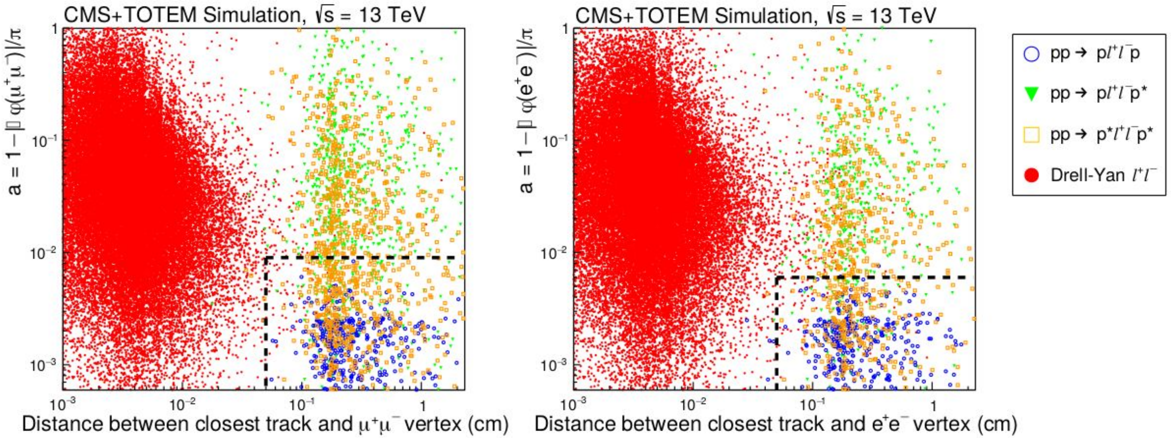
Online: At least two muon (electron) candidates of any charge, each with transverse momentum p_T > 38 (33) GeV. No requirement on forward protons

Offline: The tracks of the two highest-p_T lepton candidates of the same flavor in the event are fitted to a common vertex. Requirements:

- $|z| < 15$ cm (collision in CMS)
- Fit $\chi^2 < 10$ (probability greater than 0.16% for 1 degree of freedom)
- $p_T > 50$ GeV
- Standard CMS quality criteria
- Opposite charge

$\gamma\gamma \to \ell^+\ell^-$ enriched sample

Require two back-to-back leptons with no other tracks near the dilepton vertex



Based on the simulated distributions:

- Extra-track veto region distance of at least 0.5 mm around the vertex
- Acoplanarity a < 0.009 (0.006) for the muons (electrons)

Matching central and proton variables

First, require at least one reconstructed track in CT-PPS. Then determine:

$$\xi(l^+l^-) = \frac{1}{\sqrt{s}}\left[p_{\mathrm{T}}(l^+)\mathrm{e}^{\pm\eta(l^+)} + p_{\mathrm{T}}(l^-)\ \mathrm{e}^{\pm\eta(l^-)}\right]$$

The formula is exact for exclusive events and holds approximately for the single-dissociation case, in the conditions of the analysis

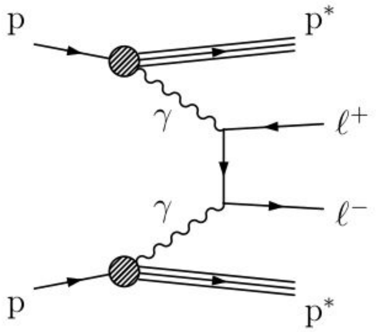
Signal candidates must have a value of $\xi(\ell^+\ell^-)$ within the CT–PPS coverage

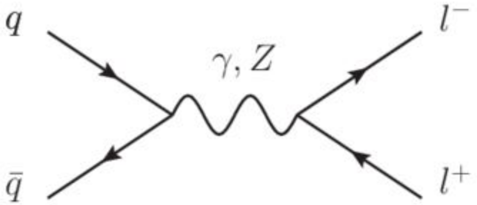
The signal region is defined by requiring that the estimate from the leptons and ξ (RP), measured in CT-PPS, agree within 2σ of the combined uncertainty on $\xi(\ell^+\ell^-)$ and D_x

Backgrounds

Main background expected to be prompt $\ell^+\ell^-$ (from Drell-Yan or double dissociative $\gamma\gamma \rightarrow \ell^+\ell^-$) combined with unrelated proton tracks

Samples of RP tracks from $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$ events in data are used (Z control samples). For the double dissociative background estimate, LPAIR simulated events are also used in conjunction with the RP tracks





Drell-Yan background

Events from Z control sample with 80 < $m(\ell^+\ell^-)$ < 110 GeV and a proton track that matches the kinematics of the $\ell^+\ell^-$ pair

$\xi(\ell^+\ell^-)$ distribution is reweighted to match the shape predicted by the simulation for events in the signal region

Simulated DY sample is used to extrapolate the results obtained from the Z control sample to the expected number of events passing the track multiplicity and acoplanarity selections, at the higher invariant mass required for signal events

Double dissociation background

Select MC events passing the central detector requirements and fit an exponential function to the obtained $\xi(\ell^+\ell^-)$ distribution

In a fast simulation, the fit is sampled and each sampled value of $\xi(\ell^+\ell^-)$ is randomly assigned to a proton from the Z boson sample

Background estimated from the number of events passing both proton and central detector requirements, normalized to the number of MC events passing the central signal selection and scaled by the fraction of double dissociation events passing the central selection that do not have a background proton in CT–PPS (obtained from data)

Background estimate and systematics

$\mu^+\mu^-$ Background	Full RP	2σ
Drell-Yan	11.36 ± 0.18	1.38 ± 0.06
Double dissociation	1.17 ± 0.02	0.108 ± 0.005
Full	12.52 ± 0.18	1.49 ± 0.07

e^+e^- Background	Full RP	2σ
Drell-Yan	12.33 ± 0.19	2.30 ± 0.09
Double dissociation	0.56 ± 0.01	0.067 ± 0.003
Full	12.89 ± 0.19	2.36 ± 0.09

	$\mu^+\mu^-$		e^+e^-	
Sources of uncertainty	Drell–Yan	Double diss.	Drell–Yan	Double diss.
Statistics of Z sample	5%	5%	4%	4%
$\xi(\ell^+\ell^-)$ reweighting	25%	—	11%	—
Track multiplicity modeling	28%	—	14%	—
Survival probability	—	100%	—	100%
Luminosity	—	2.5%	—	2.5%

difference of the background estimates with and without reweighting

difference between data and simulation in the low-multiplicity region

Results

	Observed Full RP	$\geq 2\sigma$ Observed	$\geq 2\sigma$ Estimated	$< 2\sigma$ Observed	$< 2\sigma$ Estimated	Significance
$\mu^+\mu^-$	17	5	11.0 ± 4.0(stat+syst)	12	1.49 ± 0.07(stat) ± 0.53(syst)	4.3σ
e^+e^-	23	15	10.5 ± 2.1(stat+syst)	8	2.36 ± 0.09(stat) ± 0.47(syst)	2.6σ

Significance estimated by performing pseudo-experiments according to a Poisson distribution, including the systematic uncertainties profiled as log-normal nuisance parameters

No events with matching protons in both arms. Highest-mass events:

- $m(\mu^+\mu^-)$ = 342 GeV (below the threshold required to detect both protons)
- $m(e^+e^-)$ = 650 and 917 GeV (double-arm acceptance is nonzero). Likely to be semiexclusive events or background events with uncorrelated proton

$|t|$ as a discriminating observable

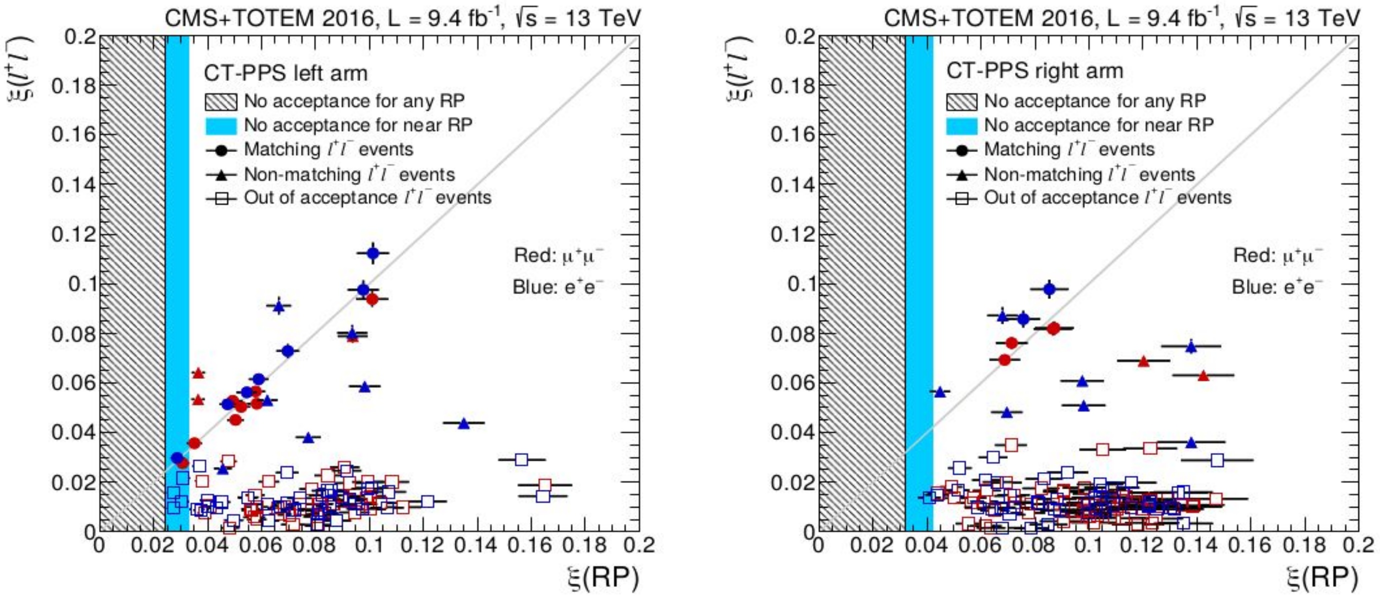
$|t|$ is the absolute value of the four-momentum squared exchanged at the proton vertices. Expected to be very small for $\gamma\gamma$ induced production

From ξ, only the vertical component of the scattering angle, and hence of the proton transverse momentum, can be measured ($y = L_y(\xi)\,\Theta_y^*$)

For 11 of 12 (6 of 8) candidate dimuon (dielectron) events, Θ_y is compatible with zero within at most 2.5σ, where σ is the uncertainty of Θ_y.

Total background	Full RP	2σ
$\mu^+\mu^-$	12.52 ± 0.18	1.49 ± 0.07
e^+e^-	12.89 ± 0.19	2.36 ± 0.09

Combined results



Combined results

Combined signal significance of 5.1σ: joint distribution; luminosity and survival probability uncertainties fully correlated; remaining uncertainties independent

Fractions of (semi)exclusive contributions estimated by comparing acoplanarity distribution to simulation. Approximately 70% from single proton dissociation

All yields are consistent with simulation predictions, within uncertainties

Summary

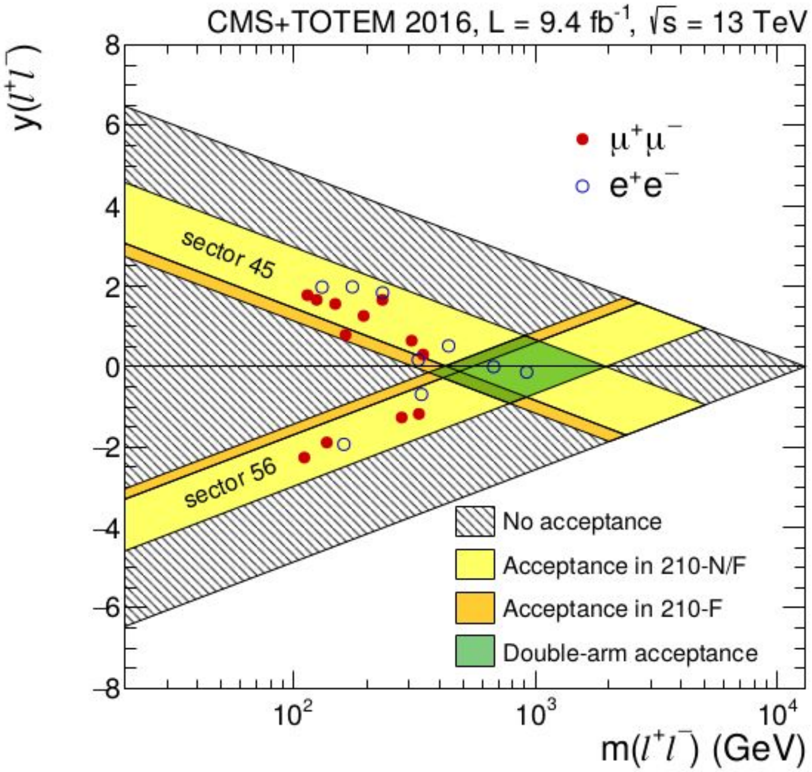
Studied proton-tagged $\gamma\gamma \to \mu^+\mu^-$ and $\gamma\gamma \to e^+e^-$ production, with forward protons reconstructed in the CT–PPS. RP alignment and LHC optics corrections determined using a high statistics sample of forward protons

12 dimuon and 8 dielectron events observed with $m(\ell^+\ell^-) > 110$ GeV and a forward proton with consistent kinematics. This corresponds to an excess larger than 5σ over expected background

First observation of proton-tagged $\gamma\gamma$ collisions at the electroweak scale, demonstrating that the CT–PPS can be used for high-mass exclusive (proton-tagged) measurements

Backup

Combined results



Rapidity gap survival probability

Soft interactions can occur between the colliding protons, suppressing the visible (semi-)excluse cross section. The rapidity gap survival probability quantifies this effect:

0.89 → exclusive process,

0.76 → single dissociative process,

0.13 → double dissociative process