Lara Lloret Iglesias

LIP-Lisbon

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Results on high-mass dimuon production with CT-PPS

CT-PPS Physics Motivation

- **Physics:**
  - LHC as a $\gamma\gamma$ collider with tagged protons
  - Allows to study in a clean way several EWK, QCD and BSM processes
  - Offers an independent measurement with respect to the CMS central detector
    - By measuring the protons one adds a second way of determining the mass of the system.

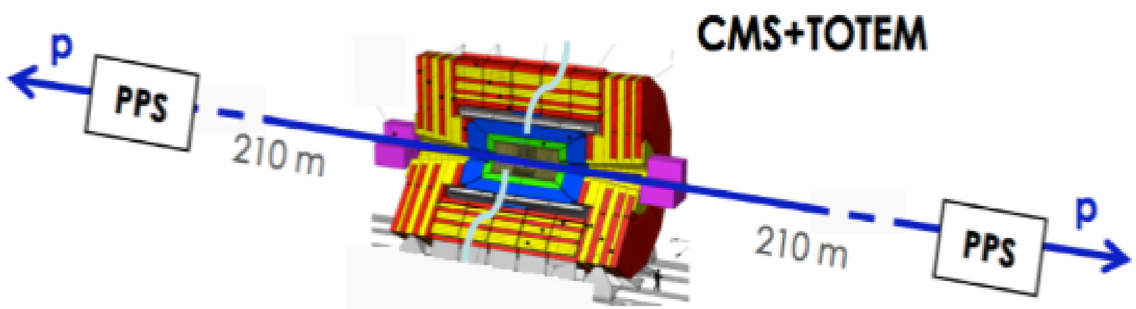
- **Experimental strategy**
  - High p_T system detected by the CMS detector together with very low angle scattered protons detected by CT-PPS.
  - Strong kinematical constraints coming from requiring a momentum balance between the CMS detector and the protons detected.

The mass and rapidity in the central system of CMS is measured via the momentum loss of the two protons

This talk will be about on the $\gamma\gamma \rightarrow \mu\mu$ with one or both protons intact

CT-PPS project

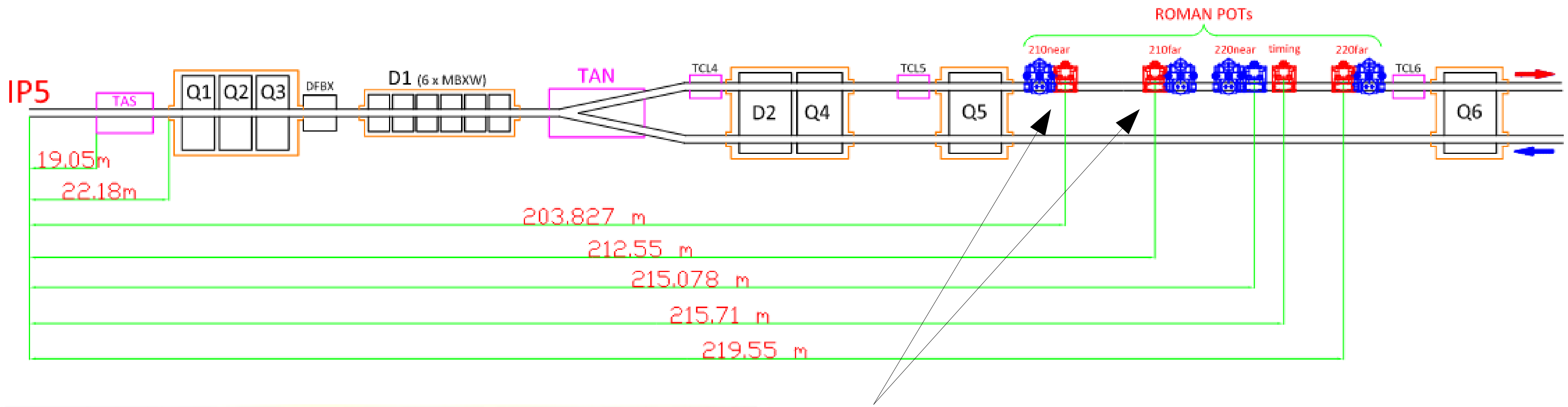
- The CMS-Totem Precision Proton Spectrometer (CT-PPS) aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside Roman Pots in order to be able to move them as close as possible to the circulating beams (~ 15 σ*) in a range [203,220] m from CMS
  - Tracking to measure the proton momentum
  - Timing to disentangle pile-up → allows reconstructing the vertex

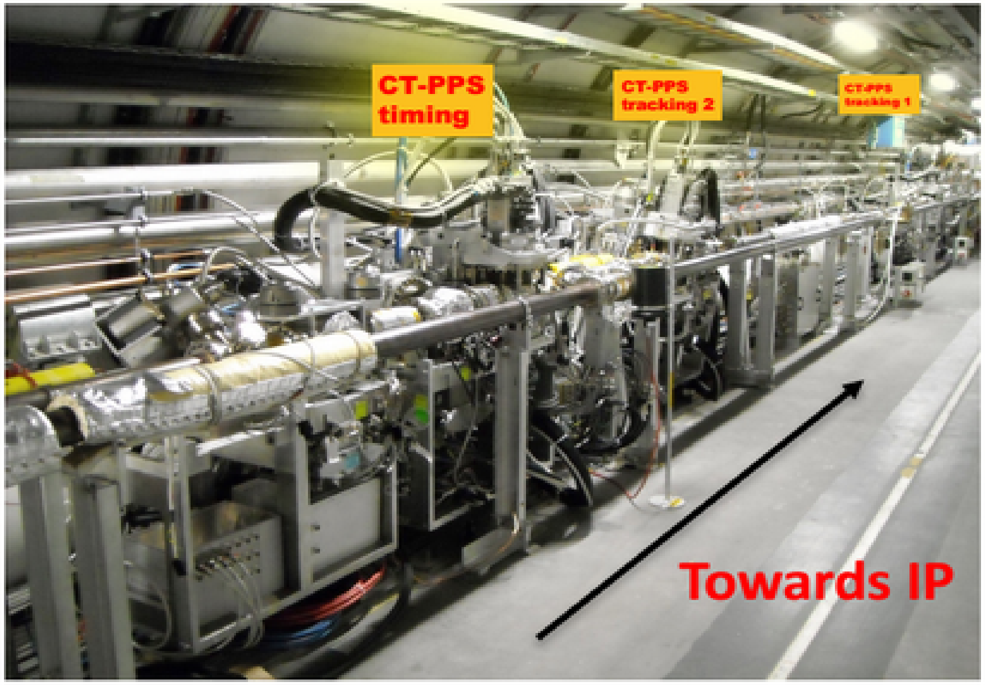


- CT-PPS already took data in 2016 using Si strip detectors from Totem
- CT-PPS started data taking with an improved detector configuration in mid-May 2017 and the final detector commissioning is currently ongoing:
  - 3D silicon pixels & Strips for tracking
  - Diamonds + Ultra Fast Silicon Detector for timing

*** σ being the nominal standard deviation of the beam profile in the transverse plane**

CT-PPS in 2016





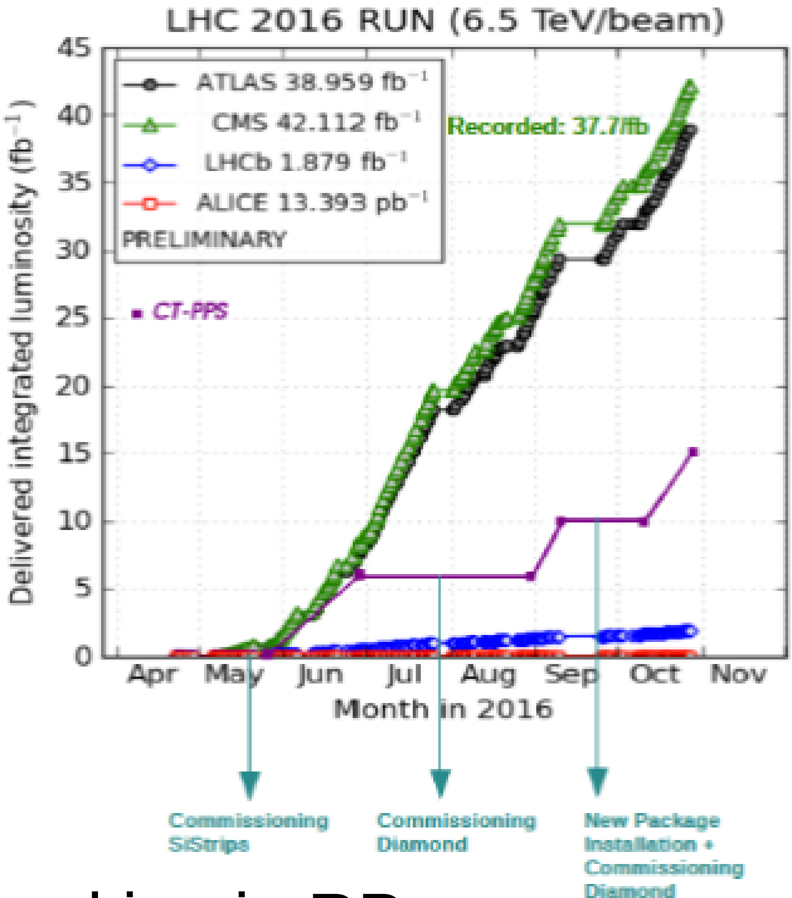
- 2 horizontal Roman Pots (per arm), equipped with Si-strips detectors
  - Used for this analysis

- 1 cylindrical Roman Pot, equipped with fast-timing diamond detectors
  - Commissioned after TS2
  - Not used for this analysis

For more details on the detector check Margherita's talk on thursday

CT-PPS:2016 operations

- **Original idea:** commissioning in 2016 and physics data-taking in 2017
  - Decision in early 2016 to **advance data-taking by 1 year** → thanks to the availability of TOTEM Si-strip detectors.
- **Data acquisition and reconstruction software fully integrated**



- Total of **~15 fb^{-1}** collected with Si-strip tracking in RPs inserted 15σ from the beam
  - 2.5 fb^{-1} also together with diamond timing detectors
- RP alignment and determination of LHC optics done

$\gamma\gamma \rightarrow \mu\mu$ with forward protons

Study a well-known SM process $\gamma\gamma \rightarrow \mu\mu$ with one or both protons intact

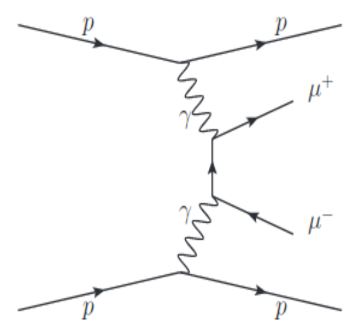
•Single arm events may be used to extend acceptance to lower masses

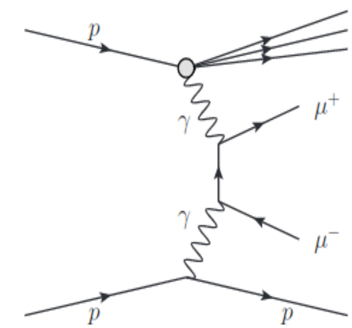
•ξ (fractional momentum loss) of the $\mu\mu$ pair can be related to the true ξ of the proton → direct and indirect measurement

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

Reconstruction of ξ from measured RP track position requires precise knowledge of LHC optics & dispersion Dx

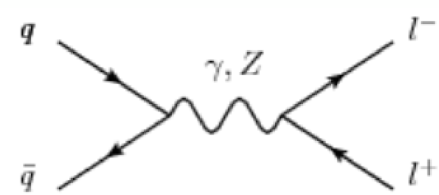
Starting from proton transport matrix corresponding to nominal LHC optics, find best-fit to actual data observed in RPs

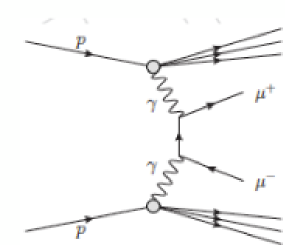




Backgrounds primarily Drell-Yan or double proton dissociation events

Can fake a signal when overlapping with pile-up protons or beam background





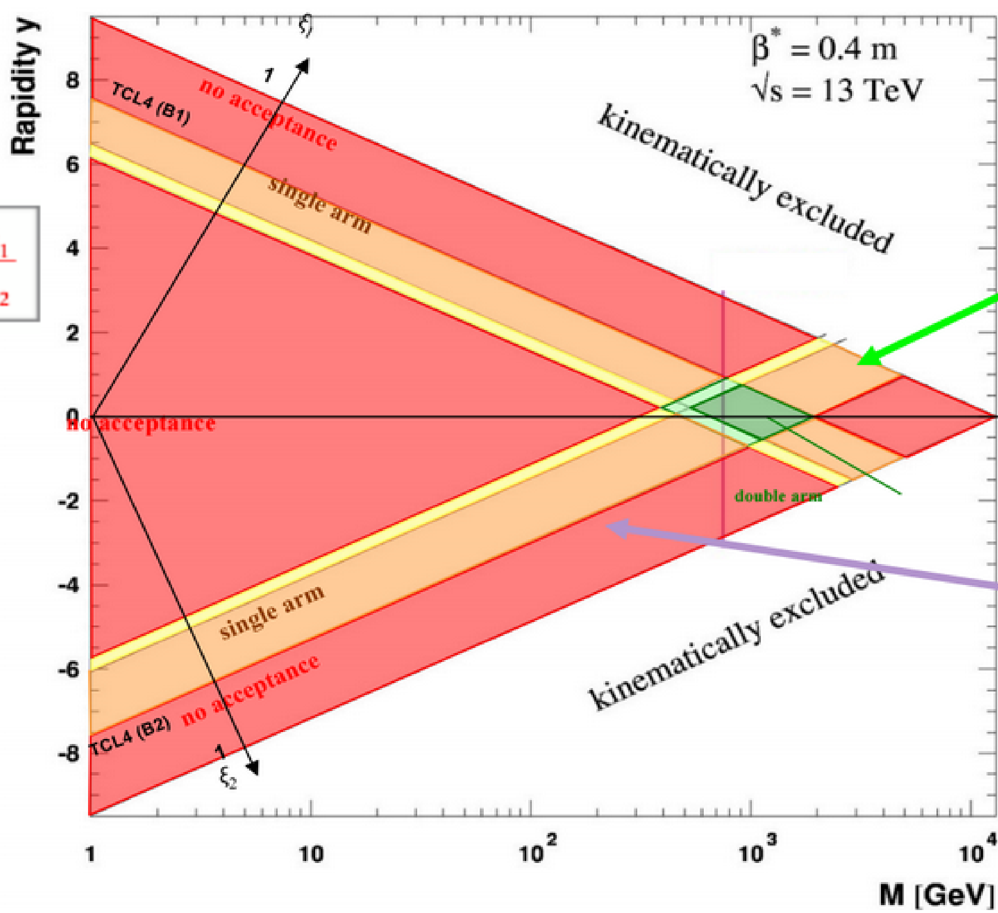
Physics Acceptance

Overall acceptance depends on invariant mass and rapidity of the central system

2016 optics before TS2 (data-calibrated): β* = 0.4 m, αX = 370 μrad, mild orbit bump, RPs @ 15σ

Y(pp)

$$y = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}$$



RP are limiting the acceptance

Acceptance for seeing both protons at mid-rapidity and m = 360 - 2000GeV

Acceptance for seeing 1 proton at lower masses and forward rapidity

$$M^2 = \xi_1 \, \xi_2 \, s$$

Different acceptance in the final months of 2016 due to change of LHC crossing angle

Event selection

- Data sample based on ~10fb^{-1} taken with the same optics collected in 2016 prior to TS2

  - Events selected with **m(μμ)>110GeV**, above the Z-peak

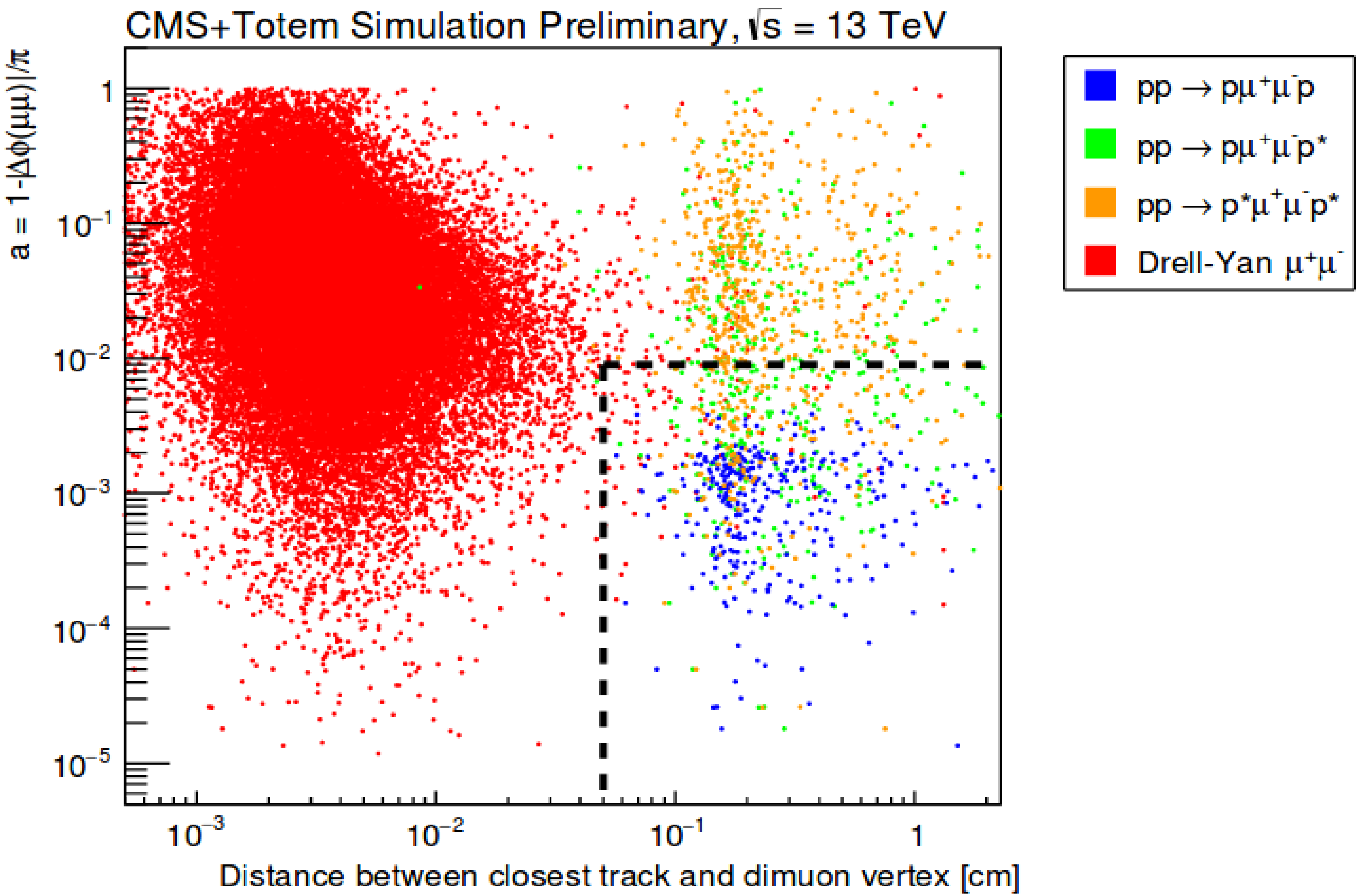
  - Backgrounds are suppressed by requiring the μμ vertex to be **separated from other tracks**, and the t**wo muons be back to back in φ**

- Signal candidates required to have **ξ(μμ) and ξ(RP) matching within 2σ of resolution**

- Data-driven estimate of remaining backgrounds

  → See next slides

Background



CMS+Totem Simulation Preliminary, √s = 13 TeV
a = 1-|Δφ(μμ)|/π
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻³
10⁻²
10⁻¹
1
Distance between closest track and dimuon vertex [cm]
pp → pμ⁺μ⁻p
pp → pμ⁺μ⁻p*
pp → p*μ⁺μ⁻p*
Drell-Yan μ⁺μ⁻

Background estimation

DY background:

- Select data sample without acoplanarity and track separation cuts.
- Mass within the Z peak and a proton track matching the kinematics
- Events in this sample are going to concentrate on mid-rapidity range → apply a correction to the shape of $\xi(\mu\mu)$ to account for this effect
- Scale factor calculated in MC to go from the control region to the signal region.
- Count # of events within 2-σ along the diagonal

Double dissociation background:

- Use LPAIR+theory predictions to find the yield and $\xi(\mu\mu)$ shape of events passing the central selection

- Perform a toy simulation, sampling the $\xi(\mu\mu)$ distribution and mixing with forward proton data from the Z-peak sample (accounting for events with no forward proton)

- Count # of events matching within 2-σ

Background estimation

Arm	1σ	2σ	3σ	full
Left	0.373 ± 0.034	0.752 ± 0.048	1.054 ± 0.057	6.135 ± 0.132
Right	0.319 ± 0.031	0.610 ± 0.043	0.850 ± 0.050	4.444 ± 0.111

Table 1: Estimated backgrounds from Drell-Yan production, with proton kinematics matching within 1σ, 2σ, 3σ, and within the full acceptance range in at least one of the FAR and NEAR Roman Pots of a given arm.

Arm	1σ	2σ	3σ	full
Left	0.028 ± 0.003	0.046 ± 0.003	0.072 ± 0.004	0.572 ± 0.012
Right	0.027 ± 0.002	0.059 ± 0.004	0.087 ± 0.005	0.482 ± 0.011

Table 2: Estimated backgrounds from double-dissociation $\gamma\gamma \rightarrow \mu\mu$ production, with proton kinematics matching within 1σ, 2σ, 3σ, and within the full acceptance range in at least one of the FAR and NEAR Roman Pots of a given arm.

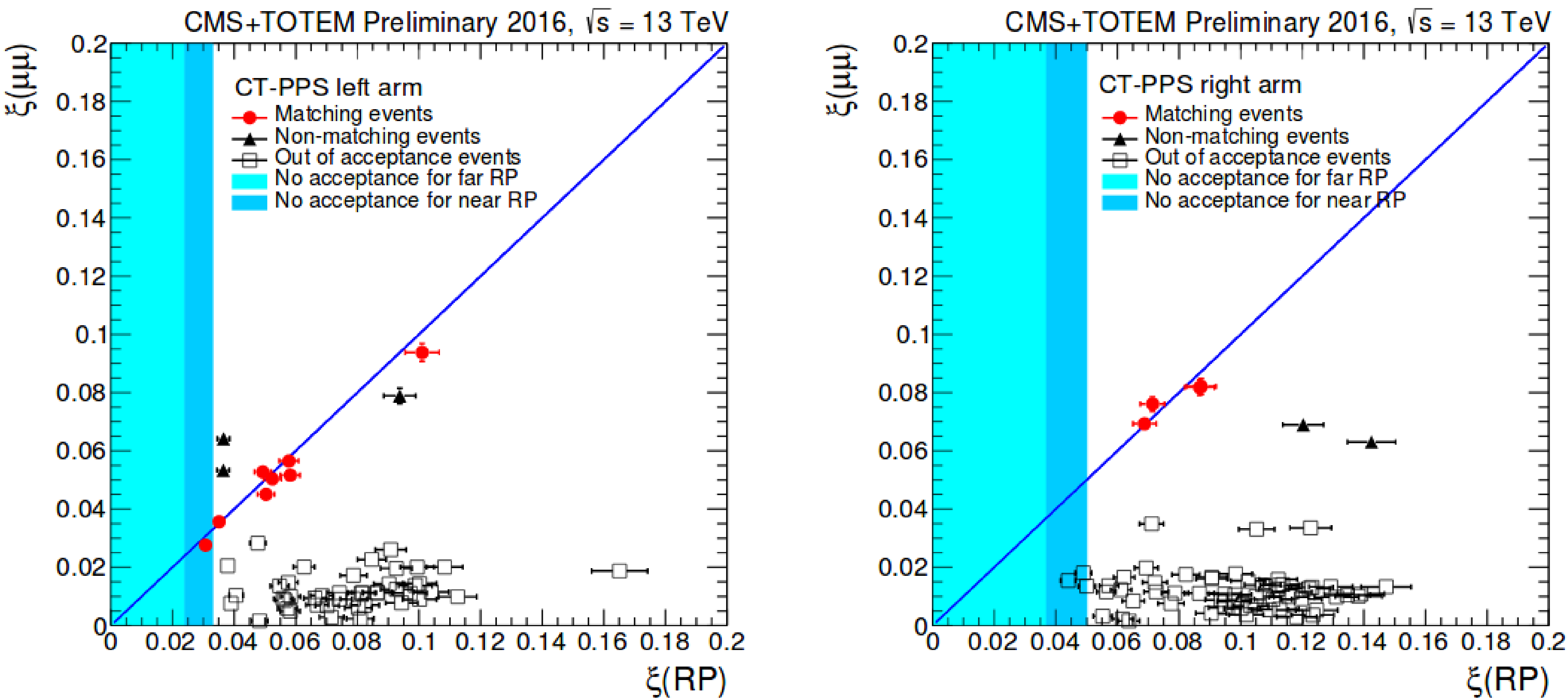
- **Total background estimate:** 1.47 ±0.06 (stat.) ±0.52 (syst.)

Background systematics

Include the following sources of uncertainty on background yields:

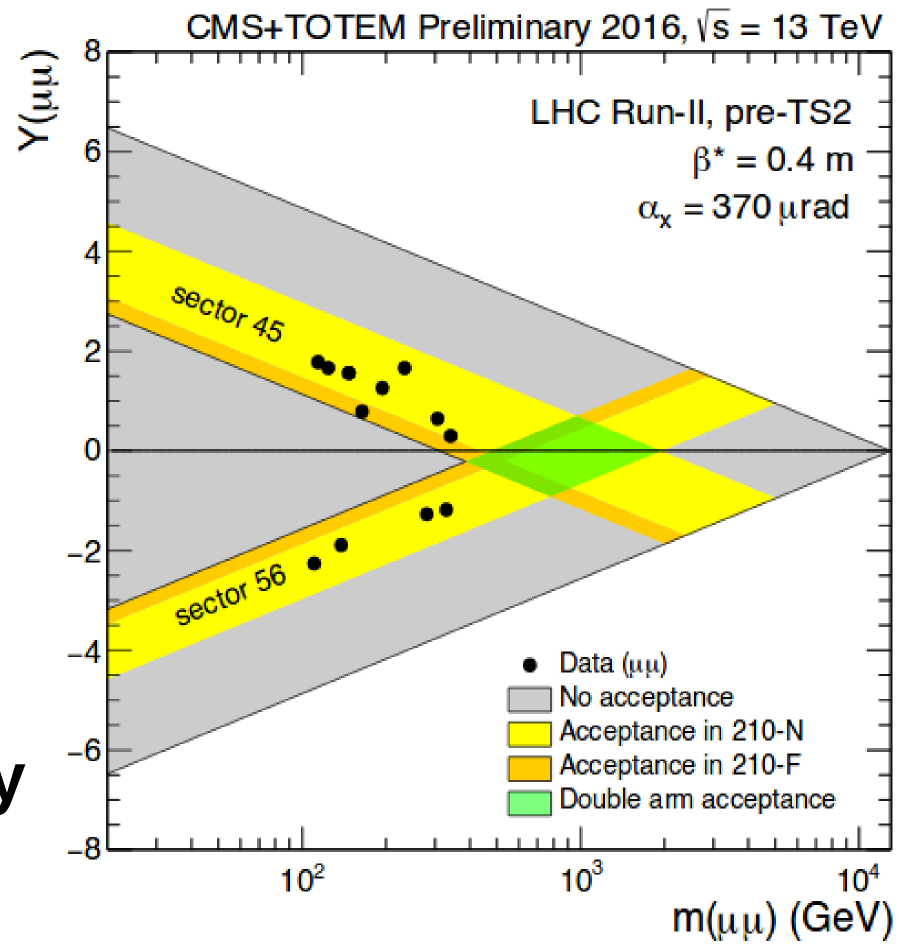
- Statistics of MC/Z-peak control sample (both DY and double-dissociation): 5%
- Uncertainty in survival probability predictions (double-dissociation): 100%
- Bias on $\xi(\mu\mu)$ distribution due to extra tracks veto (DY): 25%
- Data-MC differences in # of extra tracks distribution at low multiplicity DY-dominated region (1-5 extra tracks) (DY): 28%
- Luminosity (double-dissociation): 2.5%

Observed ξ correlations



- Total of **17 events** have ξ(μμ) consistent with RP acceptance
- **12** with matching ξ(μμ) and ξ(RP) (red points)
- Estimated significance for observing 12 events for a background of 1.47 ±0.06 (stat.) ±0.52 (syst.): **4.3σ**

Event properties



Dimuon invariant mass + rapidity consistent with single arm acceptance (yellow bands)

No double-tagged events observed (green diamond):

Consistent with SM xsec *efficiency

Spectrum extends to m(μμ)=341 GeV

Tagged γγ collisions at the EWK scale!

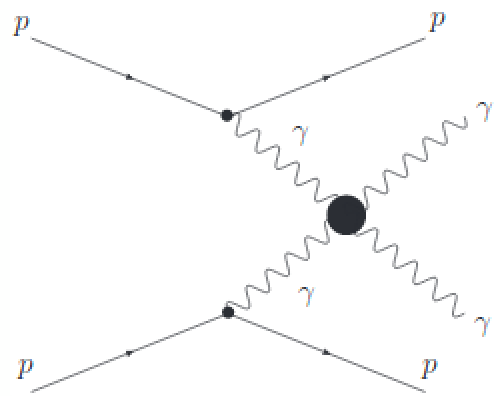
First measurement with proton tags

Physics prospects - 2016 data

Several additional physics analysis on-going with the 2016 data

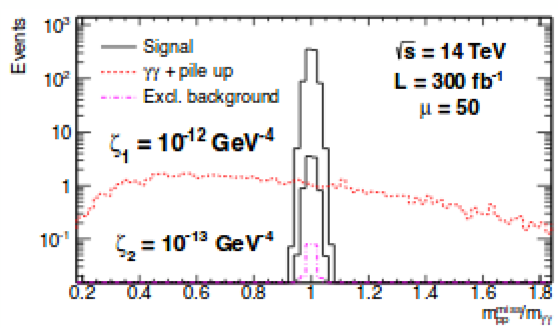
→ ee channel !

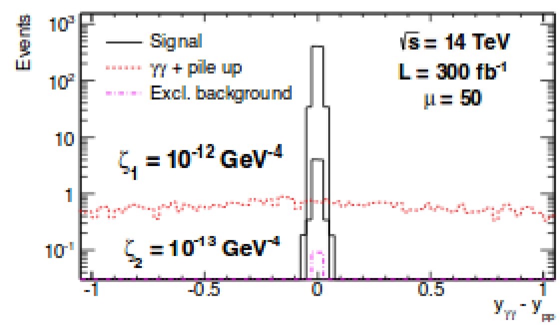
Example search:



For γγ –> γγ and neutral quartic gauge couplings (forbidden in SM)

Expect this channel to provide best sensitivity at LHC





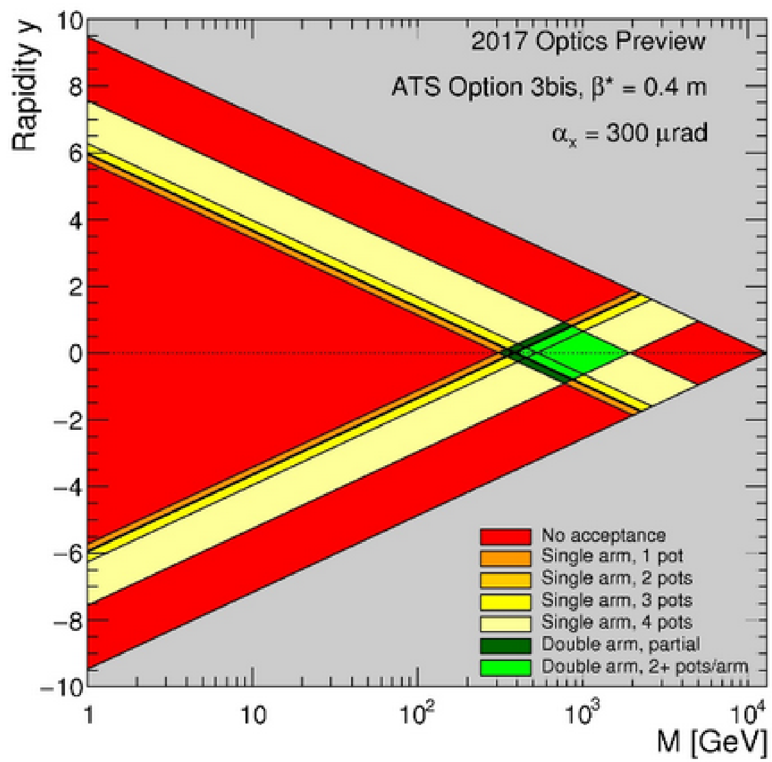
Part of program to explore quartic gauge couplings with photons: γγ→γZ, γγ→ZZ, γγ→WW (with timing detectors)

Mass vs Rapidity for 2017 optics

- Optics is again asymmetric (higher dispersion on one side than the other) just like in 2016.
- Added gain at low mass (dark green) by equipping one of the horizontal with RF shield and putting the pixel detector inside.
- Possible decrease in crossing angle during a fill for 2017 (increasing acceptance at low mass).

Check Margherita's talk on thursday!

Y(pp)



Conclusions

Ref: PPS-17-110, TOTEM-NOTE-2017-003

- With its 2016 operation, **CT-PPS has proven for the first time the feasibility of operating a near-beam proton spectrometer at a high luminosity hadron collider on a regular basis**.
- **Results show a good understanding of the spectrometer**
  - Collected >15 fb^{-1} of data in high luminosity runs with good physics acceptance
- **First physics analysis** of the "**standard candle**" $\gamma\gamma \rightarrow \mu\mu$ process with single proton tagging has been performed
- **12 events** observed with **m(μμ) > 110 GeV**
- The **significance** of this observation over the background estimate, including the systematics uncertainties is **4.3 σ**.

CT-PPS is taking data → Expect much more physics in 2017

Backup

Proton reconstruction

The trajectory of protons produced with transverse vertex position[1] (x^*, y^*) and angles (Θ_x^*, Θ_y^*) at the interaction point is described approximately by:

$$\vec{d}(s) = T(s, \xi)\vec{d}^* \,, \tag{1}$$

where s indicates the distance from the interaction point along the nominal beam orbit and $\vec{d} = (x, \Theta_x, y, \Theta_y, \xi)$, with

$$\xi = \Delta p / p, \tag{2}$$

and p and Δp the nominal beam momentum and the proton longitudinal momentum loss, respectively. The symbol $T(s, \xi)$ denotes the so-called single pass transport matrix, whose elements are the optical functions. The leading term in the horizontal transport is:

$$x = D_x(\xi)\xi, \tag{3}$$

where the dispersion D_x has a mild dependence on ξ. In the vertical plane, the leading term reads:

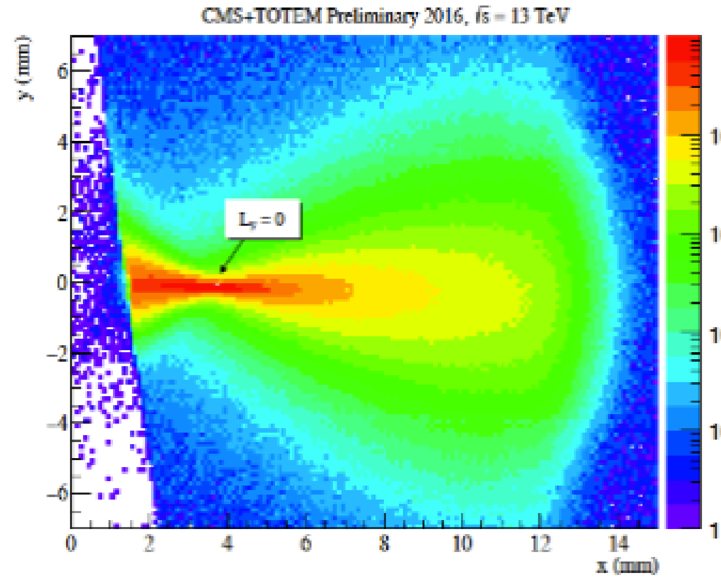
$$y \approx L_y(\xi)\Theta_y^* \,, \tag{4}$$

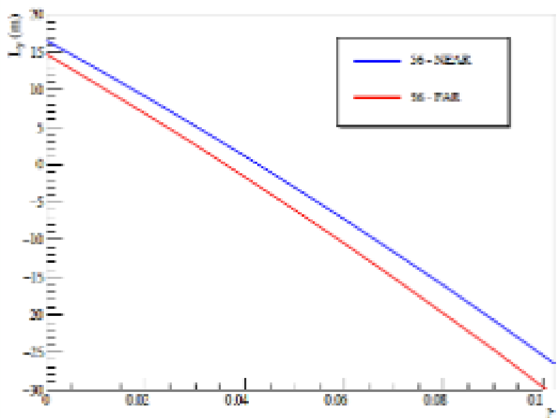
where $L_y(\xi)$ is the so-called vertical effective length. The ξ dependence of $L_y(\xi)$ is shown in Fig. 5. At any location s in the RP region, there is a value of ξ, ξ_0, where L_y vanishes and the values of y concentrate around zero. Consequently, the distribution of the track impact points exhibits a 'pinch' at $x_0 \approx D_x \xi_0$, cf. Fig. 6. The horizontal dispersion D_x can then be estimated as:

$$D_x \approx \frac{x_0}{\xi_0}. \tag{5}$$

Optics determination

- Final physics variable of interest is the proton momentum loss "ξ"
- Reconstruction from measured RP track position requires precise knowledge of LHC optics & dispersion D_x
    - Standard TOTEM optics matching with elastic events [New J. Phys. 16 (2014) 103041] using measured quadrupole strengths
    - 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 ξ vs. the measured track x position
- Overall ξ resolution of ~5.5%

Timing detector

Proton timing measurement from both sides of CMS allows to **determine the primary vertex**, correlate it with that of the central detector and **reject pile-up**

- Time resolution ~10 ps
  → **Vertex z-by-timing: ~2 mm**

$$\sigma_{V_z} = \frac{c}{2}\sqrt{2\sigma_{\Delta t}^2}$$

Tracking detectors

Proton position and angle measurements, combined with the beam magnets, allow to **determine the momentum of the scattered protons**

- Position resolution of ~10 μm
- Angular resolution of ~1-2 μrad
  → **$\Delta p/p \sim 2\ 10^{-4}$**
  Mass resolution: ~5 GeV/c^2

Alignment procedure

- 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