Study of central exclusive production with the CMS Precision Proton Spectrometer (PPS)

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On behalf of the CMS Collaboration

Istituto Nazionale di Fisica Nucleare

XXXIII International workshop on High Energy Physics

Hard Problems of Hadron Physics:

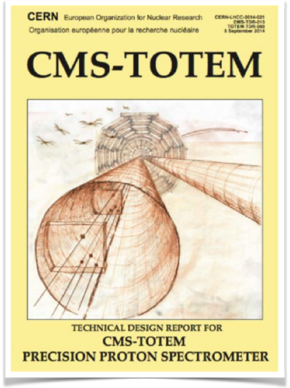
Non perturbative QCD & Related Quests

8-12 November 20211

Outline

- The CMS Precision Proton Spectrometer (PPS)
- PPS Physics program
- LHC-Run2: first results and ongoing studies
- Prospects for LHC-Run3
- PPS@HL-LHC?

Precision Proton Spectrometer (PPS)



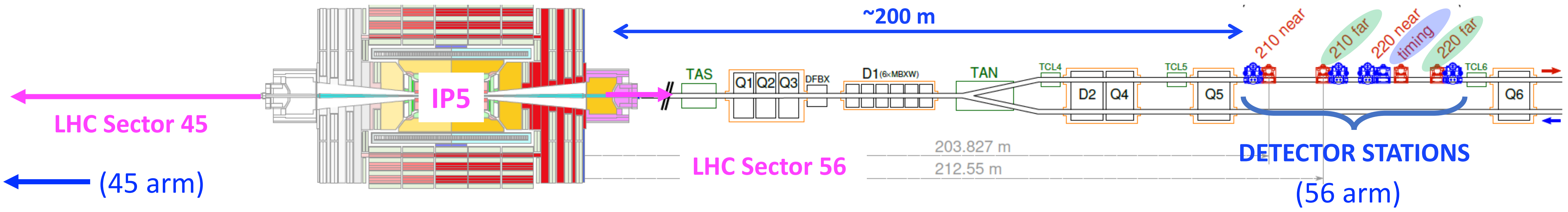
CERN-LHCC-2014-021

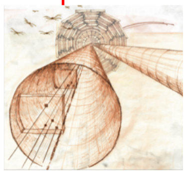
The Precision Proton Spectrometer (PPS) is the CMS subdetector **designed for measuring the scattered protons** on **both sides** of the interaction point (IP).

LHC magnets used to bend proton trajectories

Detectors located in horizontal roman pots (RP) along the LHC beam line (~1 mm from the beam), at ±~200 m from the CMS interaction point

- **Tracking detectors** measure the proton displacement w.r.t. the beam
- **Timing detectors** measure the proton time of flight





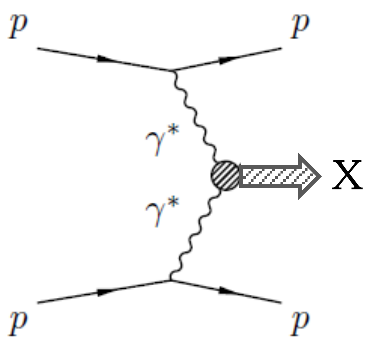
Designed to operate continuously at **standard LHC running conditions**

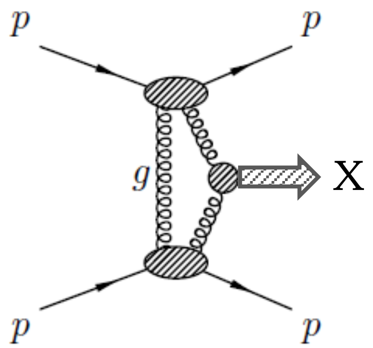
The PPS physics program

Primary goal: study of Central Exclusive Production (CEP)

$$p\ p \rightarrow p\ X\ p$$

CEP is a t-channel exchange whose carrier must be neutral in flavour, colour and electric charge.





ELECTROWEAK PHYSICS

(LHC as $\gamma\gamma$ collider with tagged protons)

- Measurement of $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for anomalous QGC with high sensitivity
- Search for SM suppressed $ZZ\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings

TEST of QCD

(LHC as gg collider with tagged protons)

- Exclusive two- and three-jets events
- Tests of pQCD mechanism of exclusive production
- Gluon jet samples with small component of quark jets

SEARCH FOR NEW PHYSICS

- CEP of new resonances
- Search for invisible decays

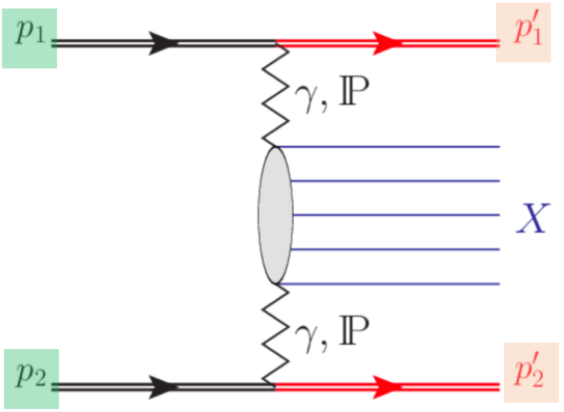
→ N. Turini's talk

CEP advantages

- Striking signature: two final state protons in very forward near-beam detectors

- Particularly clean experimental conditions due to absence of proton remnants

- Possibility to "close" the event by matching central system and leading protons kinematics



CEP processes are exclusive

the energy lost by the protons in the interaction goes into producing the X system

If the fractional momentum loss of the two protons emerging intact from the IP is measured

$$\xi_i = \frac{|p'_i| - |p_i|}{|p_i|}$$

mass and rapidity of the central system X produced in the interaction can be determined as

$$M_X = \sqrt{\xi_1 \xi_2 s}$$

$$y_X = \frac{1}{2} \ln\left(\frac{\xi_1}{\xi_2}\right)$$

CEP events resemble e^+e^- annihilation events more than normal LHC events!

Proton kinematics

The reconstruction of the scattered proton momentum requires:

- the measurement of the proton transverse position (x,y) and direction (θ_x, θ_y) along the beam line at a given distance s from the IP → TRACKING DETECTORS in RP at s~220 m from IP
- the precise knowledge of the magnetic fields traversed by the proton

LHC magnet lattice parametrised by the **transport matrix T** which relates the transverse position and direction of a proton along the beam line to the proton kinematics at the IP

RP $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ IP

$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \end{pmatrix} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ v'_x & L'_x & \mathbf{T} & m_{24} & D'_x \\ m_{31} & m_{32} & & L_y & D_y \\ m_{41} & m_{42} & v'_y & L'_y & D'_y \end{pmatrix} \begin{pmatrix} x^* \\ \theta^*_x \\ y^* \\ \theta^*_y \\ \xi \end{pmatrix}$$

The reconstruction of the proton kinematics requires the inversion of the transport matrix

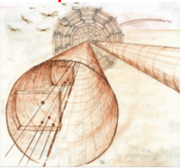
Leading terms of the inversion equations, in high luminosity runs:

$$x \simeq D_x(\xi)\,\xi$$
$$y \simeq L_y(\xi)\,\theta^*_y$$

Proton transverse position measured by tracking detectors ← (x, y)

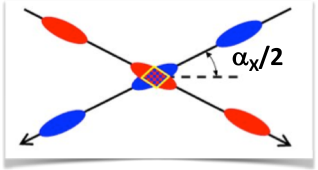
(ξ, θ^*_y) → Momentum loss and vertical scattering angle at IP

(D_x, L_y) ↓ D_x: horizontal dispersion; L_y: vertical effective length



ξ reconstructed by inverting the first equation

Proton acceptance

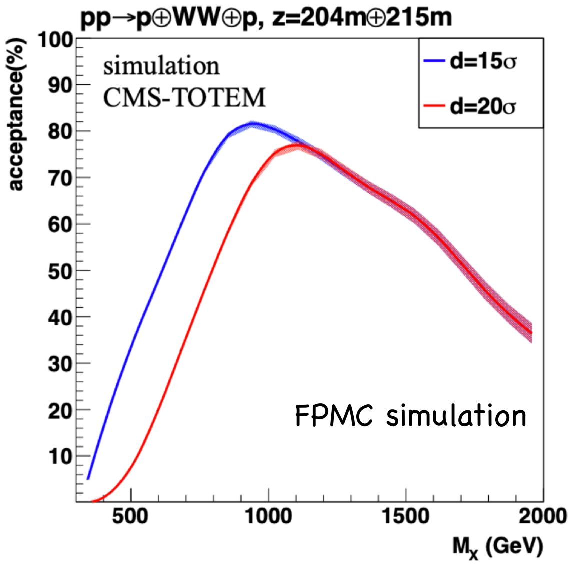


Proton acceptance depends on:

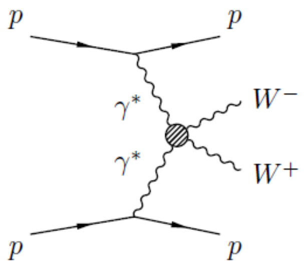
- accelerator optics (mainly D_x)
- minimum attainable distance of detectors from beam
- detector size
- collision parameters (crossing angle α, betatron function β^*)

This translates into limits in ξ and hence y_X and M_X

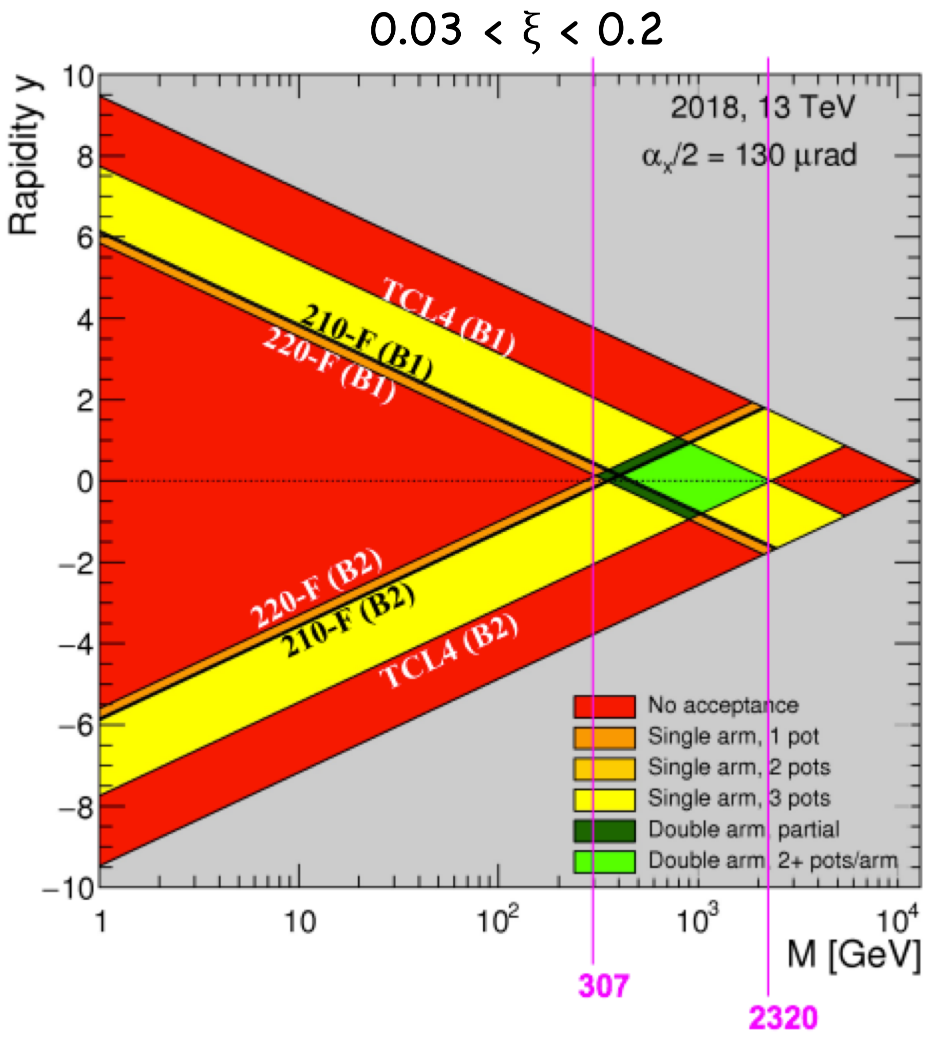
Central system mass acceptance in high-luminosity conditions, with PPS detectors at 15σ from the beam (double arm measurement): 350 GeV < M_X < 2 TeV



Example: pp→ppWW



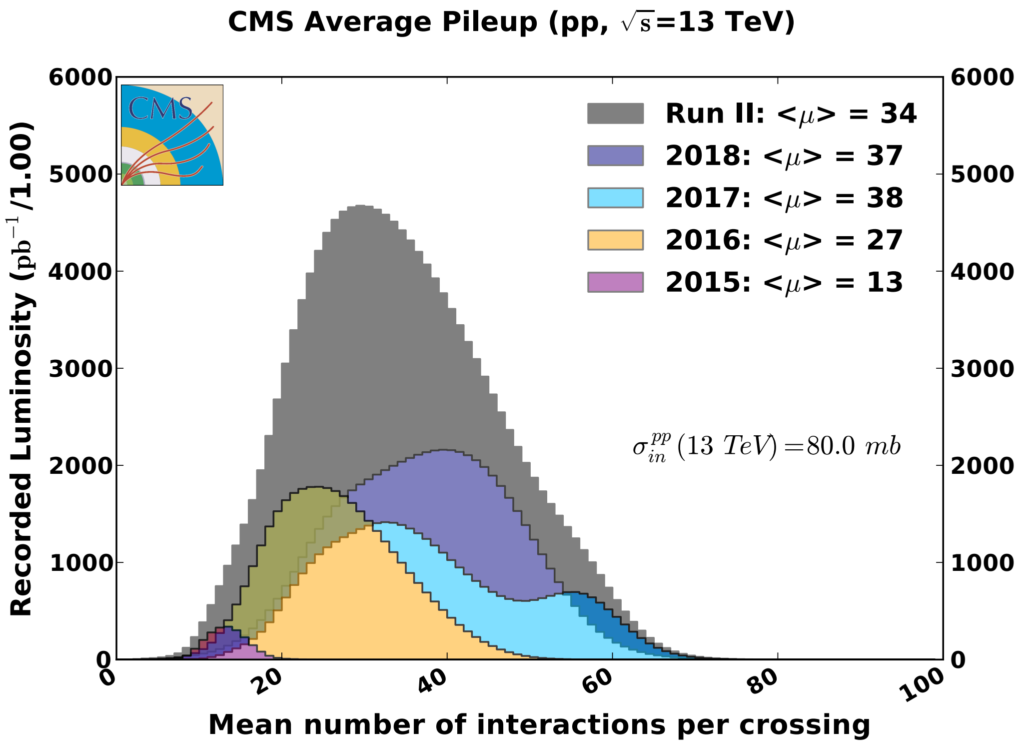
TDR [CERN-LHCC-2014-021]



Cross sections of CEP reactions at such high masses ~1 fb

The high luminosity challenge

Large background due to pile-up: "standard" inelastic events overlapping with two protons from single diffraction events occurring in the same bunch crossing emulate CEP

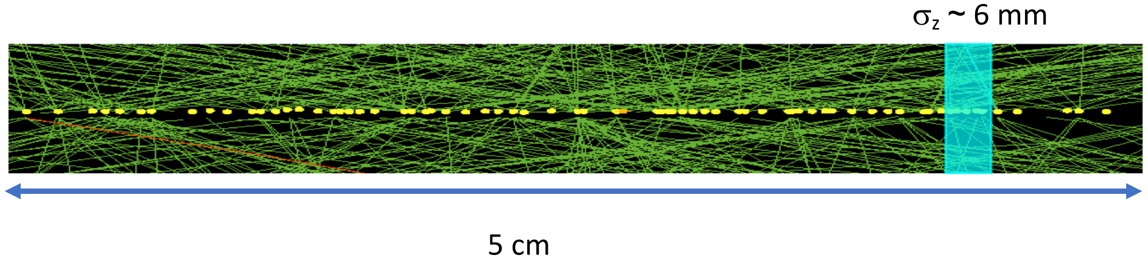


Pile-up background rejection using PPS

- ✓ Momentum balance between the central system and detected protons creates **strong kinematical constraints**
- ✓ **Precise proton time of flight measurements from both sides of CMS** allows to determine the longitudinal position of the primary vertex

$$z_{vtx} = \frac{c}{2}(t_2 - t_1)$$

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



$\sigma_{\Delta t}$ ~ 30 ps → σ_{Zvtx} ~ 6 mm

TIMING DETECTORS
IN RP AT ~220 m FROM IP

PPS@LHC RUN2

Exploratory phase in 2015 and 2016; very high stability in both 2017 and 2018

Data taking with CMS

Exploratory phase 2015	Tracking 2016	Tracking+timing 2017	Tracking+timing 2018
Data recorded with tracking RPs inserted ⇨	L_{INT}~15 fb^{-1} 39% OF DATA RECORDED BY CMS	L_{INT}~40 fb^{-1} 88% OF DATA RECORDED BY CMS	L_{INT}~60 fb^{-1} 93% OF DATA RECORDED BY CMS

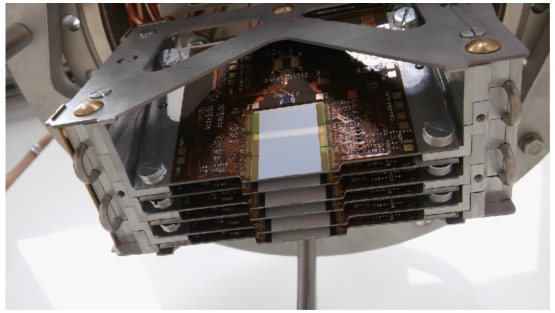
PPS integrated luminosity in LHC-Run 2: ~115 fb^{-1}

Two public results:
- ✓ Dilepton production with proton tag
- ✓ Exclusive diphoton production

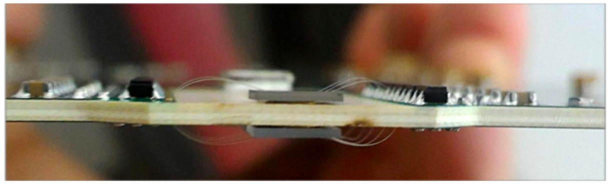
Many other analyses in progress

DETECTOR CONFIGURATION IN 2018

3D SILICON PIXEL SENSORS (tracking)



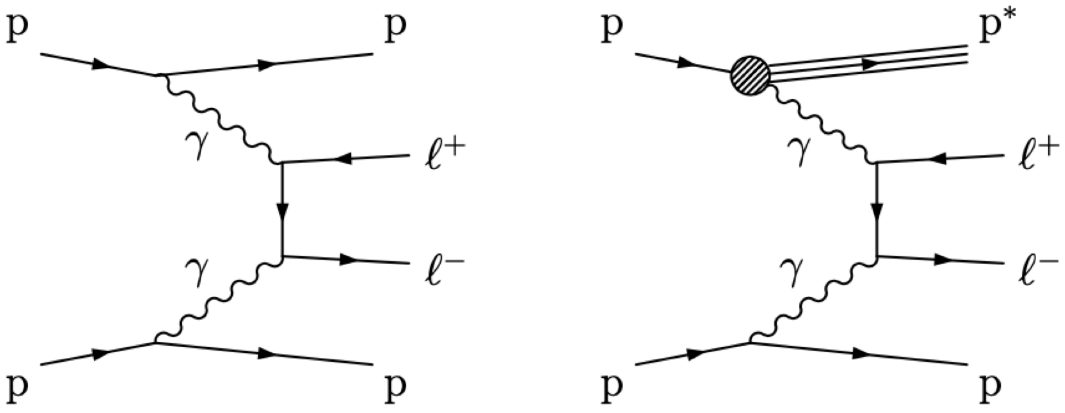
DIAMOND DETECTORS (timing)



(Semi-)exclusive dilepton product

(Semi-)exclusive dilepton production via photon exchange in proton-proton collisions

$pp \rightarrow p\gamma\gamma p^{(*)}$



EXCLUSIVE PROCESS   SEMIEXCLUSIVE PROCESS

JHEP07(2018)153 First analysis with proton tag performend by CMS - 2016 data (9.4 fb^{-1} at $\sqrt{s}$ = 13 TeV)

Physics motivation

- Look for "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 γγ collisions at the TeV scale

(Semi-)exclusive dilepton production: analysis strategy

Final state: at least 1 forward proton + 2 pT >50 GeV opposite sign leptons, back to back in azimuth and with M(ll)>110 GeV

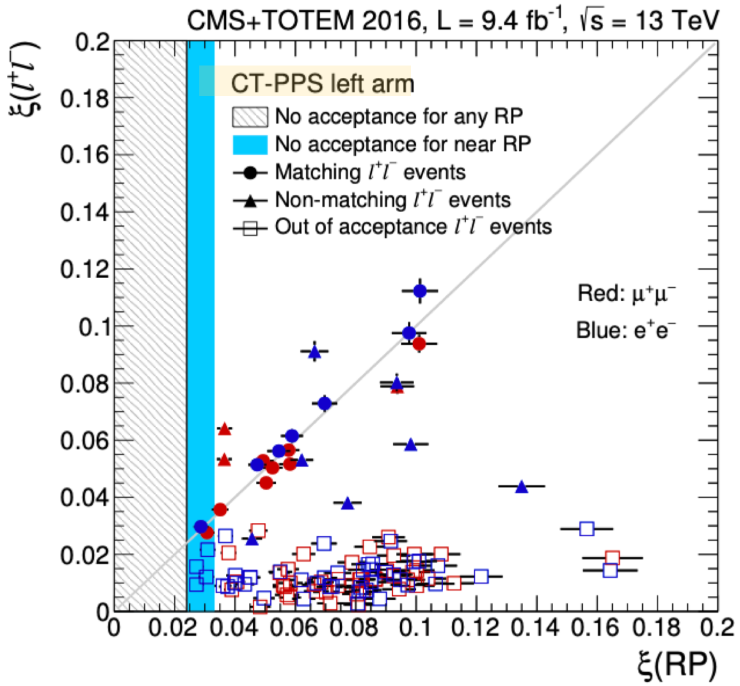
Look for correlation between:

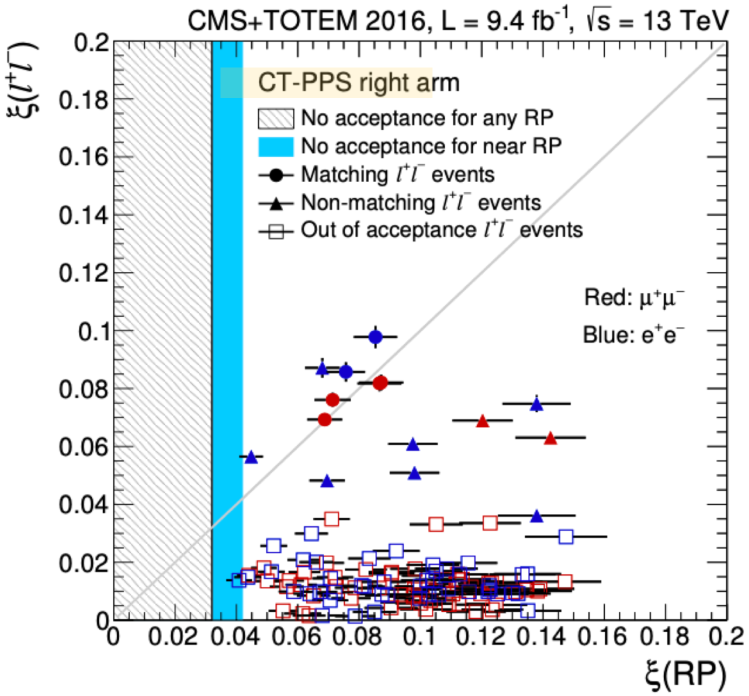
- direct proton ξ measurement by PPS → ξ(RP)
- ξ inferred from the dilepton system $\xi^{\pm}(\ell^{+}\ell^{-}) = \frac{1}{\sqrt{s}}\left[p_{T}(\ell^{+})e^{\pm\eta(\ell^{+})} + p_{T}(\ell^{-})e^{\pm\eta(\ell^{-})}\right]$

EXACT FOR EXCLUSIVE EVENTS, MOSTLY WITHIN RESOLUTION FOR SEMIEXCLUSIVE EVENTS

Two solutions corresponding to protons moving in the ±z direction

Lepton p_T and η from CMS central detector



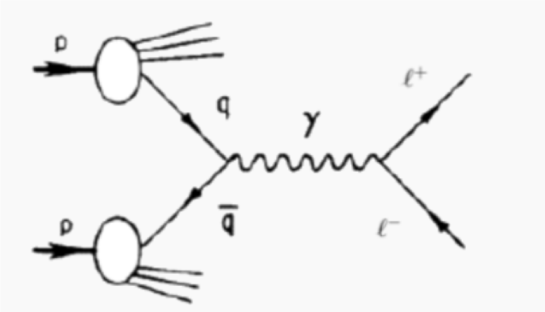


(Semi-)exclusive dilepton production: results

Signal defined by requiring that $\xi(l_+l_-)$ and $\xi(RP)$ agree within 2σ of the combined uncertainty on $\xi(l_+l_-)$ and D_x

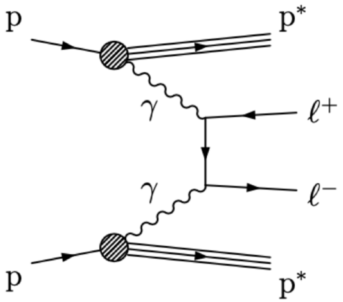
☞ 20 events with matching kinematics ($12\mu_+\mu_- + 8e_+e_-$)

Expected background



DRELL-YAN

or



DOUBLE DISSOCIATION

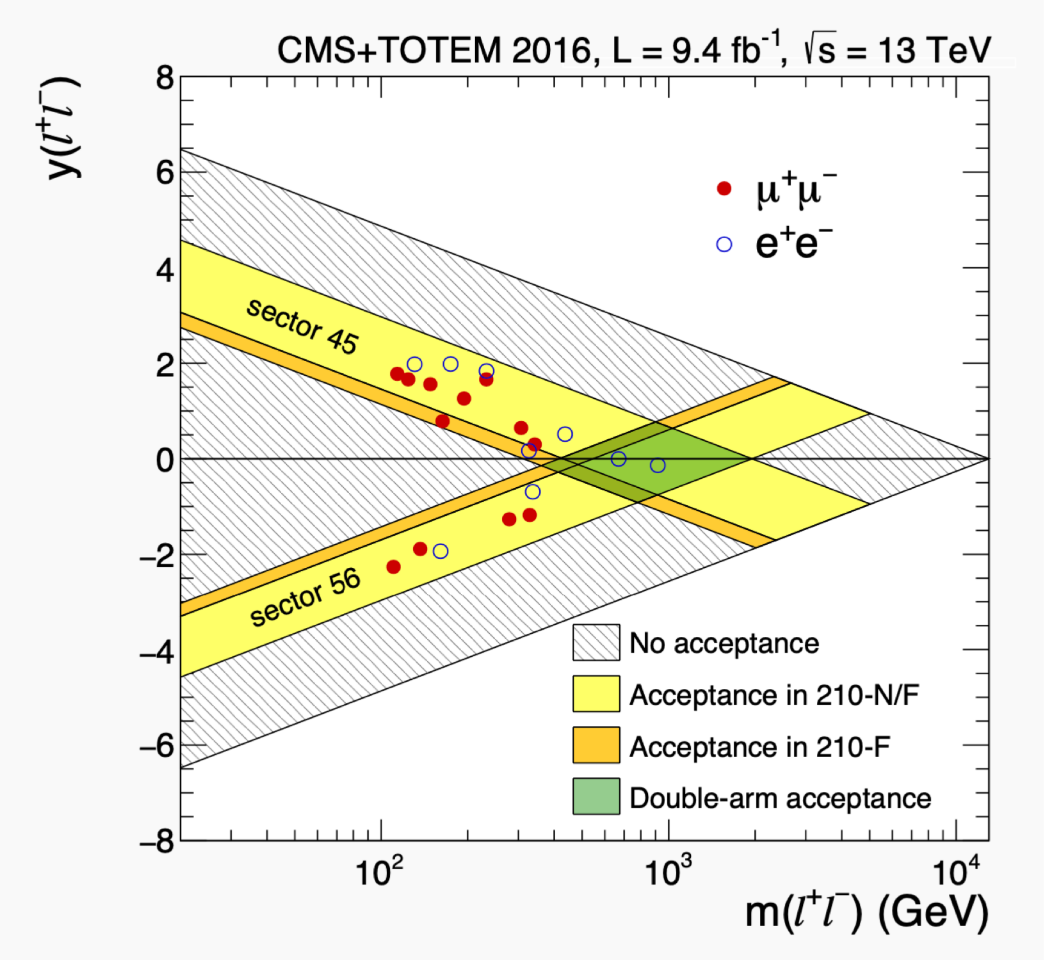
+ pileup or beam halo proton(s)

☞ $\mu_+\mu_-$ estimated background: 1.49 ± 0.07 (stat) ± 0.53 (syst)

☞ e_+e_- estimated background: 2.36 ± 0.09 (stat) ± 0.47 (syst)

Combined significance: > 5.1 σ

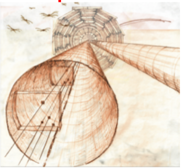
Signal candidates properties



- ✓ Dilepton invariant mass and rapidity within expected range of acceptance
- ✓ No double-tagged events observed, consistent with SM cross section*efficiency

Mass extends up to ~900 GeV

→ first tagged γγ collisions at TeV scale!



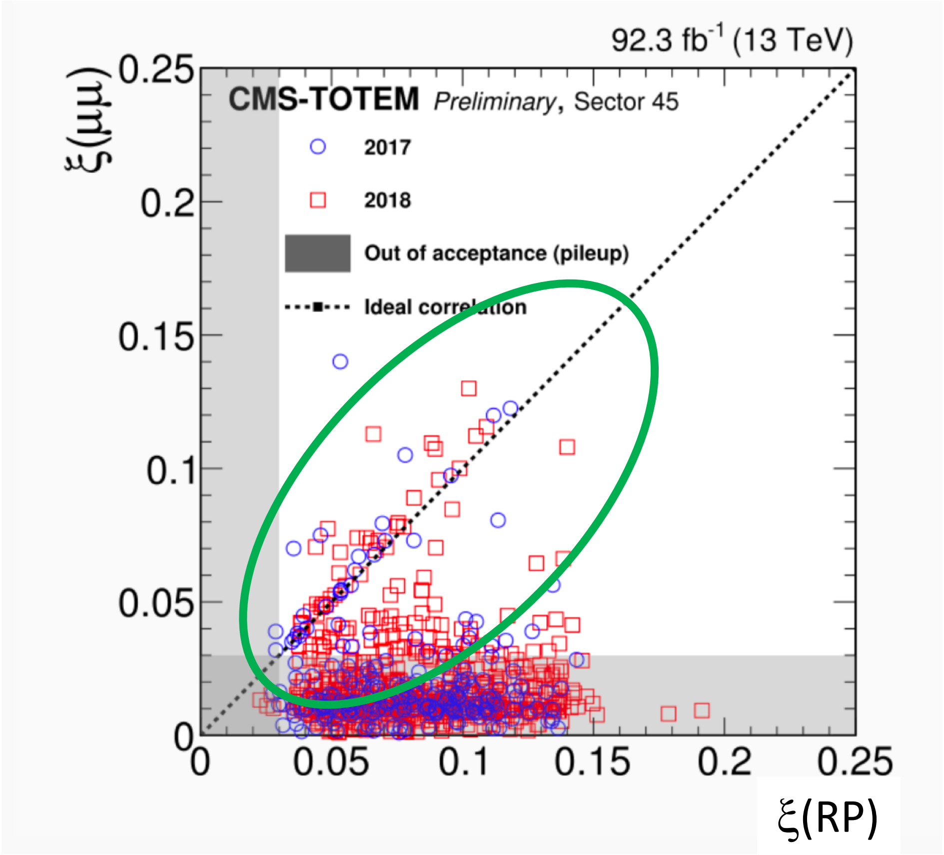
Excellent potential for high-mass (proton-tagged) measurements

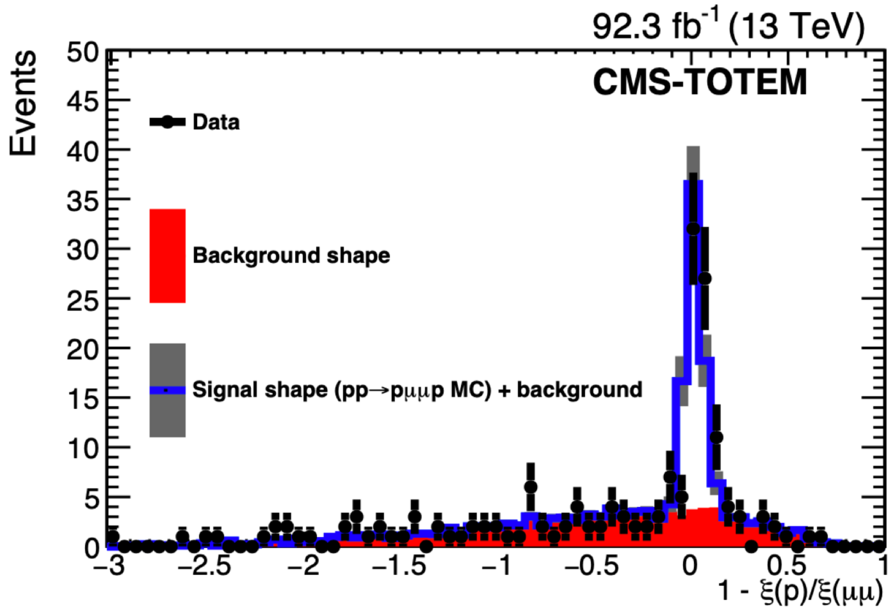
Dilepton analysis with 2017 and 2018 data

Analysis performed on 92.3 fb^{-1} data collected in 2017 and 2018

Preliminary results for μμ channel:

- ✓ Correlations between fractional momentum loss reconstructed from dimuon pair ξ(μμ) vs that measured with proton(s) ξ(RP) in data: **signal on the diagonal as expected**

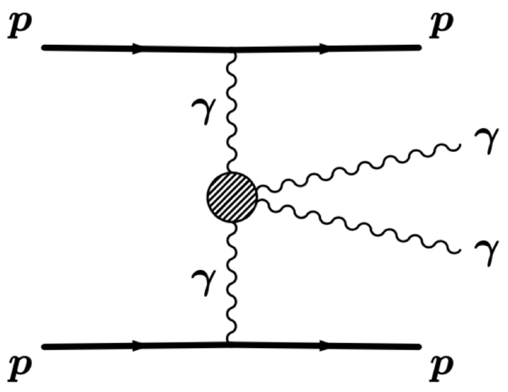




- ✓ Correlation peak width consistent between data and simulation: **well described ξ resolution**
- ✓ **Peak position at 0 as expected**

Excellent reconstruction and MC performance ⇒ full dataset ready for any Run 2 analysis

Exclusive di-photon production at high mass



Light-by-light (LBL) scattering only allowed through loops in the SM

Physics motivation

- Evidence of this process searched for in laboratory experiments for decades
- Observation of LbL events with diphoton masses of a few GeV in ultraperipheral lead-lead collisions reported by CMS and ATLAS[1]: results consistent with standard model expectations

This analysis explores for the first time the $m_{\gamma\gamma}$ spectrum above 350 GeV

- Contributions to the 4γ cross-section from BSM physics expected at higher di-photon invariant mass, where SM production is negligible → **opportunity for new physics discovery**

Challenges

- low cross-section (only few fb)
- large theoretical uncertainties (survival probability, particles in loop)

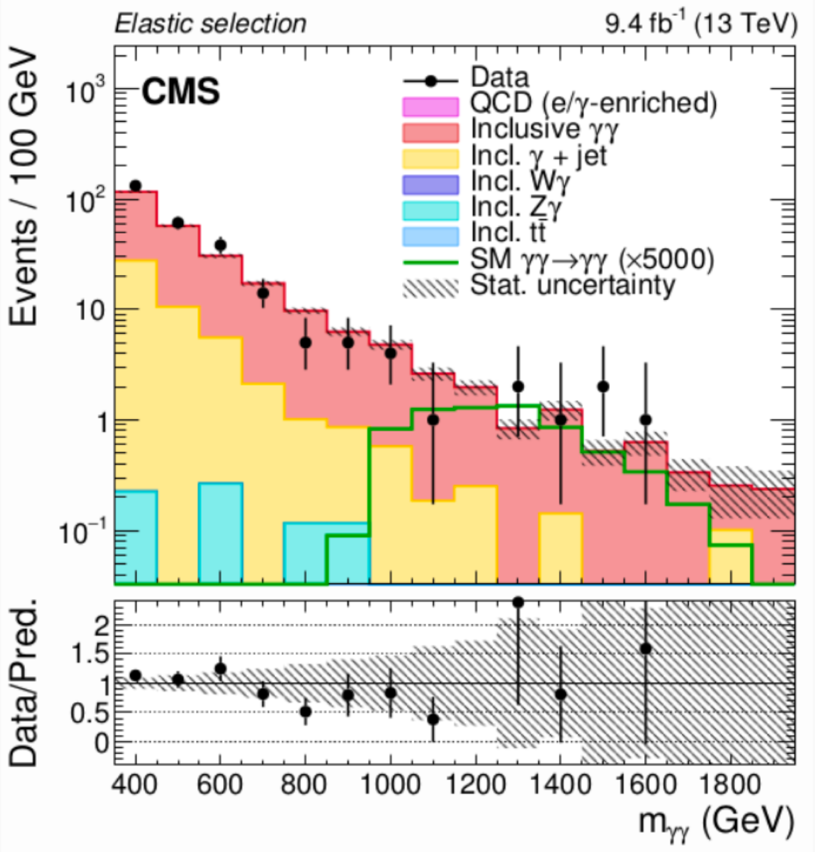
CMS-PAS-EXO-18-014 Analysis performed 2016 data (9.4 fb^{-1} at $\sqrt{s}$ = 13 TeV)

[1]Phys. Rev. Lett. 123 (2019) 052001, Phys. Lett. B 797 (2019) 134826

Exclusive di-photon production: analysis strategy and results

Final state: 2 forward protons + 2 high pT photons (>75 GeV), back-to-back in azimuth with $|\eta|<2.5$ and $M(\gamma\gamma)$ above 350 GeV

$\xi^{\pm}(\gamma\gamma)$ within the most efficient area of PPS tracker ($\varepsilon>90\%$)



DI-PHOTON MASS SPECTRUM BEFORE MATCHING WITH PPS

Signal candidates selected by requiring the difference in mass and rapidity as determined by the central and the two-proton systems to be within the 2σ window

No events observed with a pair of proton tracks compatible with the diphoton kinematics (expected background $0.23^{+0.08}_{-0.04}$)

Upper limit on the exclusive diphoton production cross-section: 3.0 fb (95% confidence level)

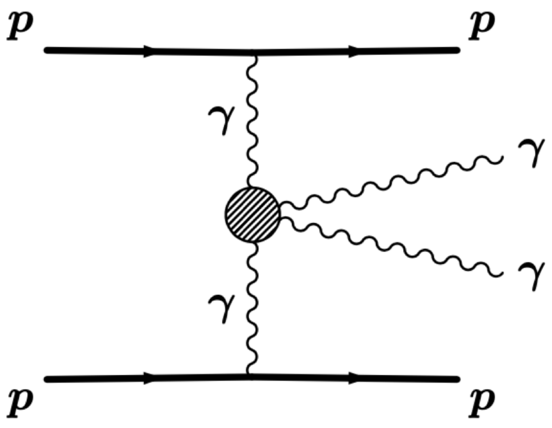
→ first ever collider limit on the four-photon AQGC

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}.$$

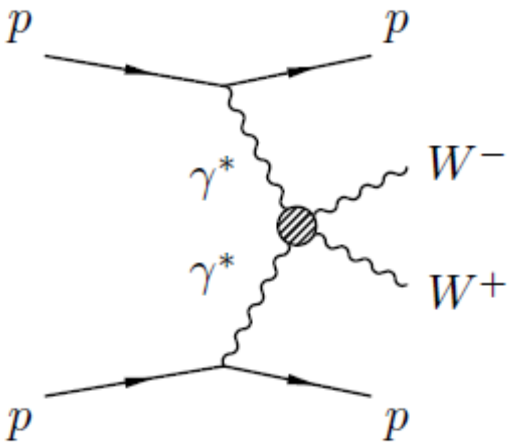
$$|\zeta_1| < 3.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_2 = 0),$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_1 = 0).$$

Ongoing analyses and prospects

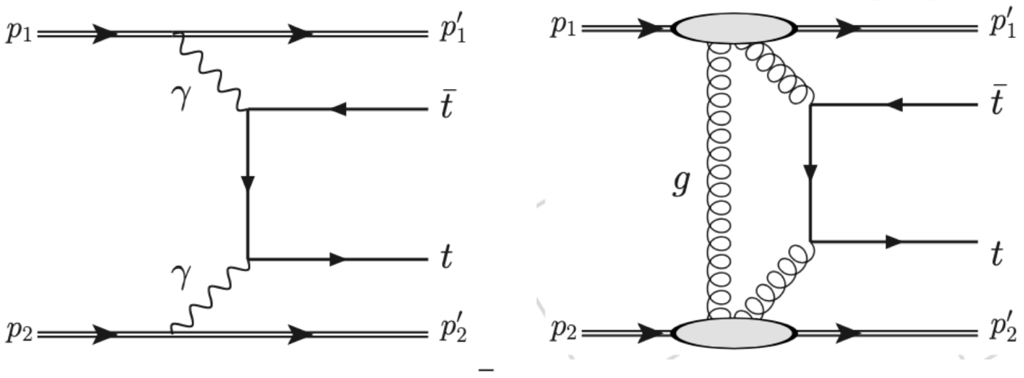
Ongoing analyses



EXCLUSIVE DI-PHOTON
2016-2017-2018 DATA



EXCLUSIVE $\gamma\gamma \rightarrow$WW/ZZ
2016-2017-2018 DATA



EXCLUSIVE PRODUCTION OF TOP QUARK PAIRS
2017 DATA

LHC-Run3 prospects

- Goal to acquire >150 fb^{-1} of data at $\sqrt{s}$=13.6 TeV
- New opportunities with introduction of PPS in High Level Trigger for calibration and physics
- Upgrade of PPS timing system to reach 30 ps resolution – additional tool to suppress background

http://arxiv.org/abs/2103.02752

Studies of a proton spectrometer for HL-LHC published by the CMS Collaboration in an EoI

Conclusions

PPS has proven the feasibility of continuously operating a near-beam proton spectrometer at a high-luminosity hadron collider and has collected ~115 fb^{-1} of data during LHC-Run2

- ✓ Public PPS results based on 2016 data: first observation of tagged $\gamma\gamma$ collisions at the TeV scale, first collider limit on 4-photon AQGC
- ✓ Extensive work on full Run 2 analyses, to be released very soon

PPS will continue its program in LHC-Run3 with the goal of a total integrated luminosity of ~300 fb^{-1}

- ✓ Benefit from acquired LHC-Run 2 experience, more data, more powerful tools for signal extraction
- ✓ Upgrade of PPS timing system: additional tool to suppress background

Studies of a PPS detector for HL-LHC have been published by the CMS Collaboration in an EoI