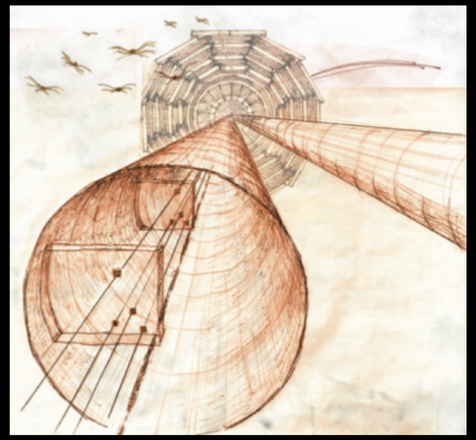
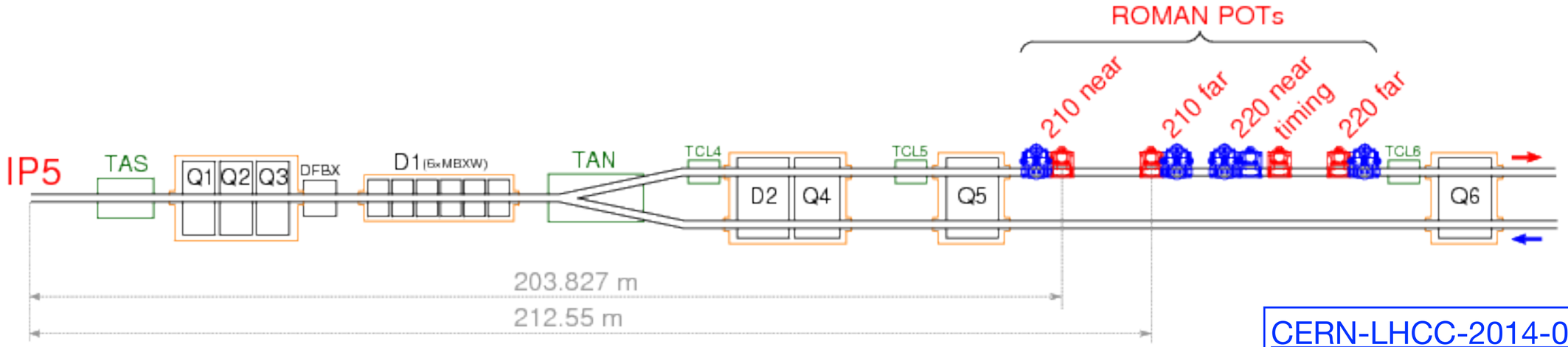
New physics results with the CMS-TOTEM Precision Proton Spectrometer



Enrico Robutti (INFN Genova)
on behalf of the CMS and TOTEM Collaborations

A Precision Proton Spectrometer



CERN-LHCC-2014-021

CT-PPS conceived as a joint CMS-TOTEM project; from 2018 a CMS subdetector

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

- during Run 2 (2016-2018) two tracking stations and one timing station per side

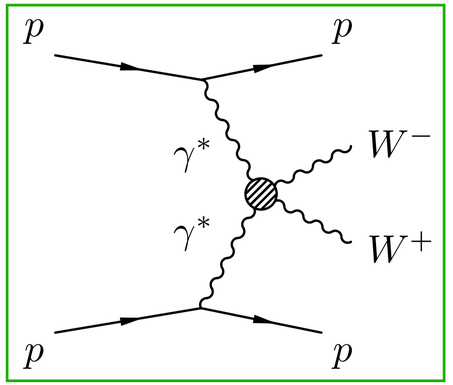
Detects intact protons emerging from the IP and driven by LHC magnets in proximity of the proton beam ⟹ detectors approaching the beam at few mm

Designed to operate continuously at standard LHC running conditions

The CT-PPS physics program

Main target of the CT-PPS physics program is the study of Central Exclusive Production (CEP) processes:

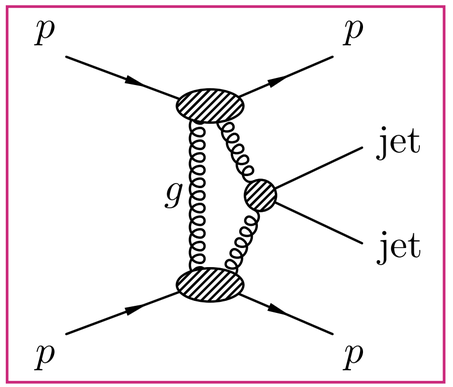
- interacting protons remain intact and get detected in the roman pots; main reconstructed kinematic variable is their fractional momentum loss, $\xi \equiv (|\boldsymbol{p}_f| - |\boldsymbol{p}_i|)/|\boldsymbol{p}_i|$
- energy lost by protons goes into exclusive final state reconstructed by CMS



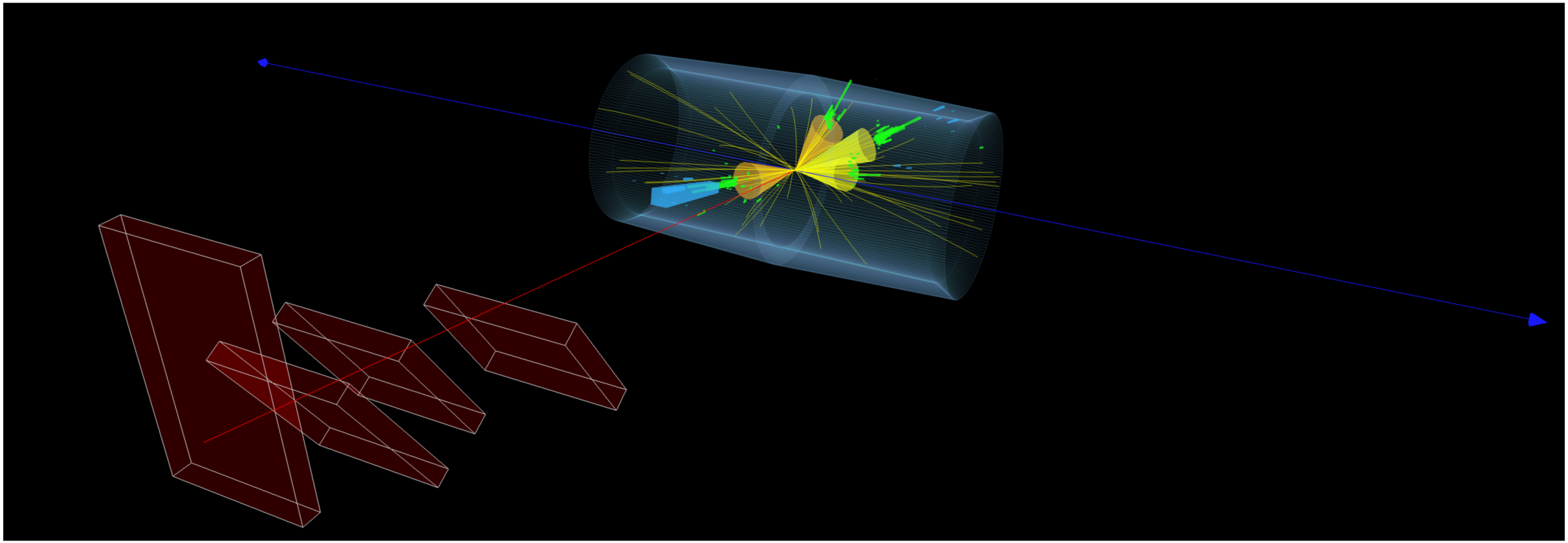
Final state generated via $\gamma\gamma$ fusion or gluon exchange

Wide range of physics measurements accessible:

- rare SM processes $\Longrightarrow$ anomalous gauge couplings, BSM contributions;
- direct search for new resonances, including invisible states;
- diffractive physics;
- jet characterisation (dominant gluon component)



Event signature



Events of interest characterised by distinct signature:

- two leading protons reconstructed on opposite sides of the IP;
- large rapidity gap between central system and leading protons (colour-singlet exchange)

Signal and background

The proton tag is a powerful tool for the identification of signal events:

- discriminates against inclusive events containing same final state;
- allows kinematic closure of the event through the relations

mass of the central system → $m_X = \sqrt{s\xi_1\xi_2}$

rapidity of the central system → $y_X = \frac{1}{2}\ln(\frac{\xi_1}{\xi_2})$

fractional momentum loss of the two protons

- reduces theoretical uncertainties related to proton dissociation

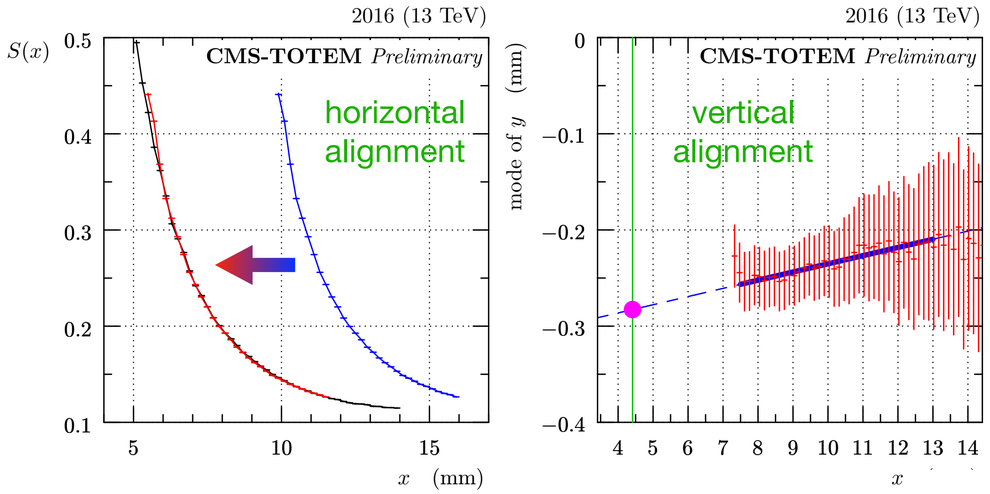
A large source of background is often induced by pileup protons

- uncorrelated protons from other interactions in the same bunch crossing
- precision timing can help associating protons to primary vertex

CT-PPS calibration

Proton kinematics (ξ) is determined from reconstructed tracks in tracking stations through knowledge of the LHC optics parameters

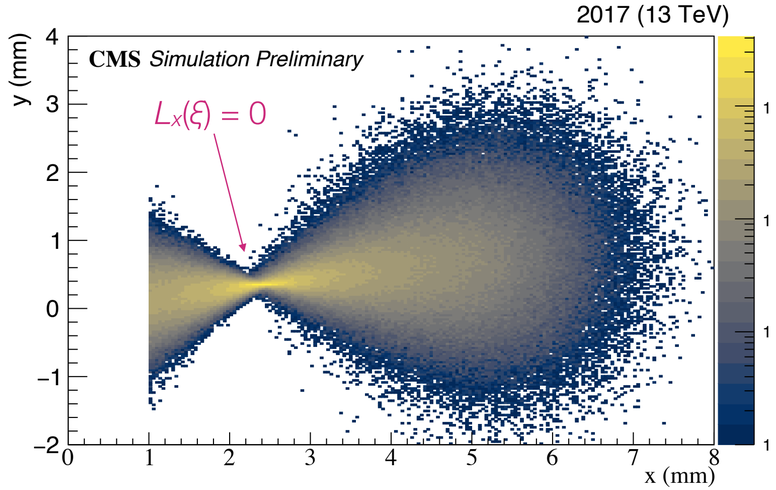
CMS-PAS-PRO-21-001
CERN-TOTEM-NOTE-2022-001

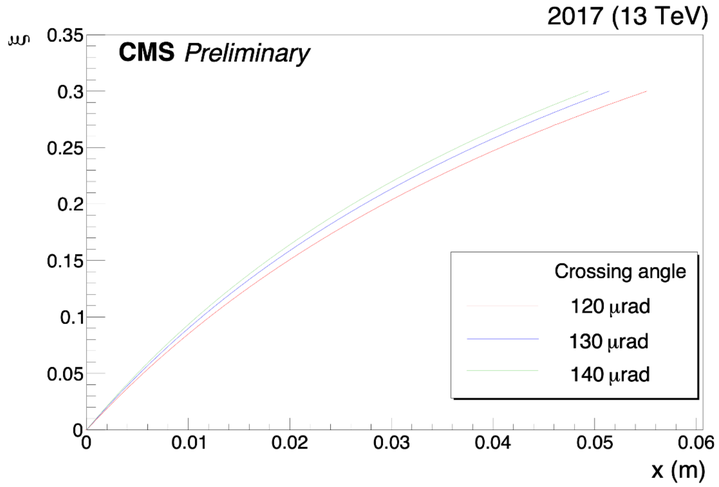


Detector alignment is performed in various steps

- relative and absolute (wrt. beam) alignment
- reference determined using also vertical pots
- final alignment on fill-by-fill basis

Detailed behaviour of proton transfer matrix parameters (as function of ξ) is based on hit distributions in data





Proton reconstruction

CMS-PAS-PRO-21-001
CERN-TOTEM-NOTE-2022-001

Two reconstruction algorithms:

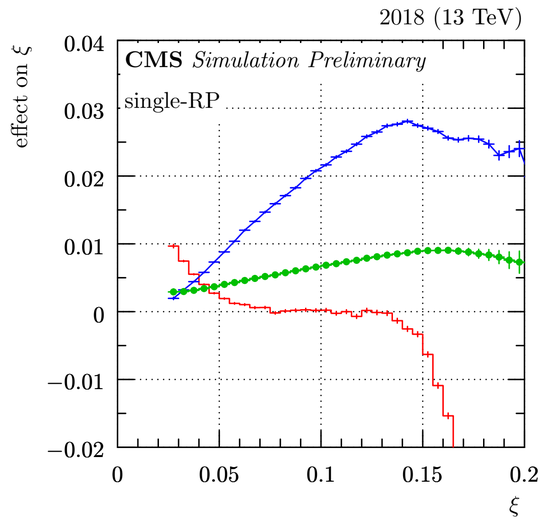
Single-RP

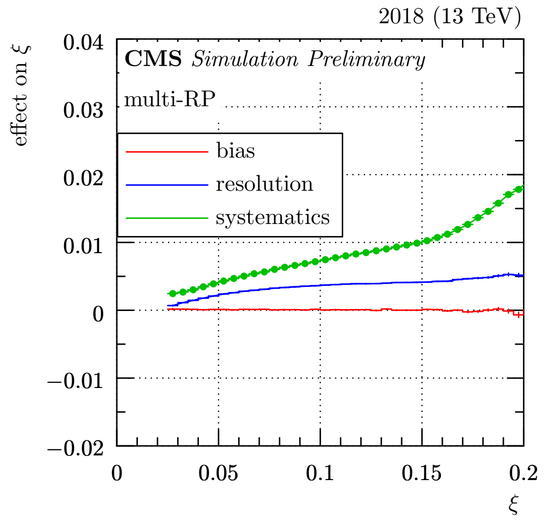
- maximises acceptance and efficiency
- for some samples, only way to reconstruct multiple proton tracks

Multi-RP

- combines tracks from two stations
- resolution on measured ξ significantly improved

Different contributions to effective resolution evaluated through dedicated simulation studies





Resolution from data

Special data samples used to evaluate the detector performance

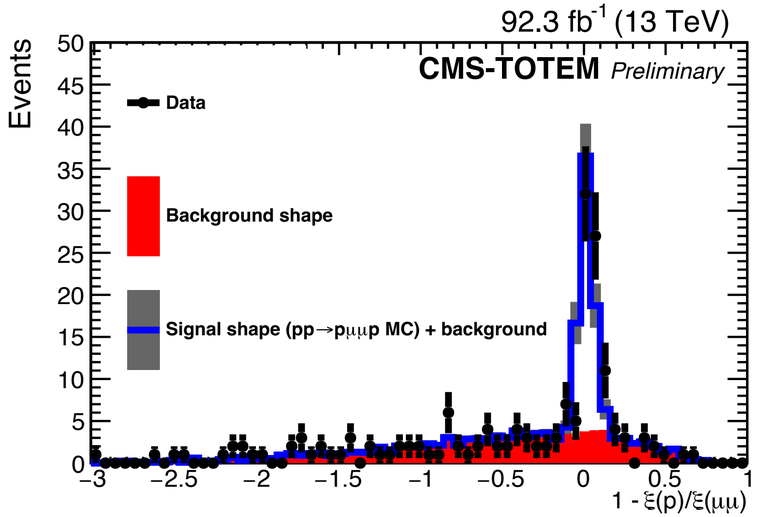
CMS-PAS-PRO-21-001
CERN-TOTEM-NOTE-2022-001

ξ resolution

Exclusive dimuon sample

- ξ from multi-RP reconstruction compared to ξ estimated from $\mu^+\mu^-$ pair:

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

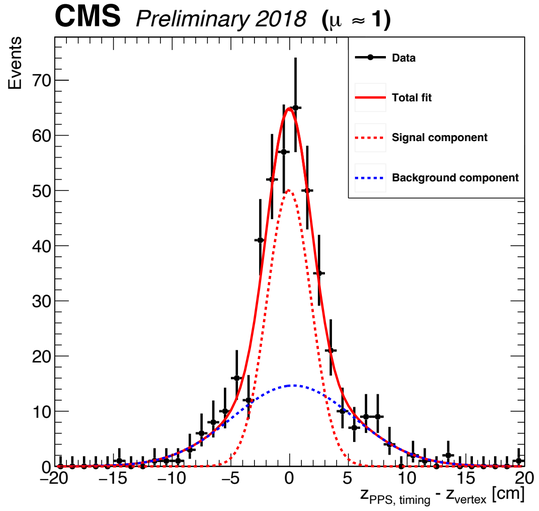


Timing resolution

Low pileup sample (μ ~1), proton reconstructed in both arms

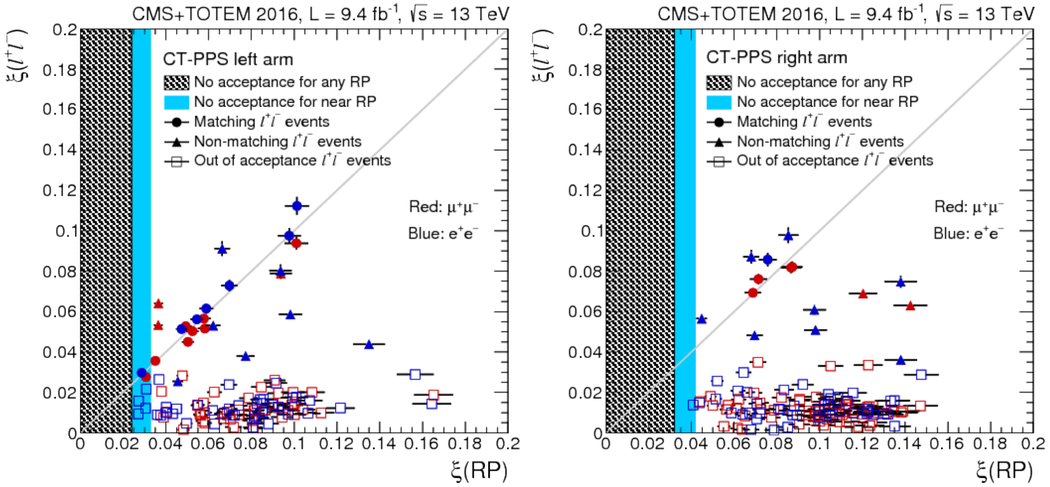
- z from CMS primary vertex compared to

$$z_{\mathrm{PPS}} \equiv \Delta t_{\mathrm{PPS}} \cdot \frac{c}{2}$$



CT-PPS data sample and first results

CT-PPS collected ~110 fb^{-1} of data during LHC Run 2 with various detector configurations



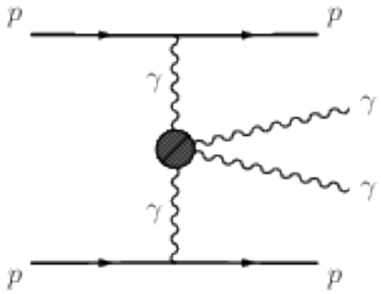
Observation of (semi)exclusive dilepton production

5.1 σ excess in e^+e^- and $\mu^+\mu^-$ final states, combined

- consistent with expectations based on the SM

10.1007/JHEP07(2018)153

Analyses based on 9.4 fb^{-1} (2016)



Search for exclusive diphoton production

Upper limits to four-photon coupling parameters:

$|\xi_1| < 2.88 \times 10^{-13}$ GeV^{-4}, $|\xi_2| < 6.02 \times 10^{-13}$ GeV^{-4}

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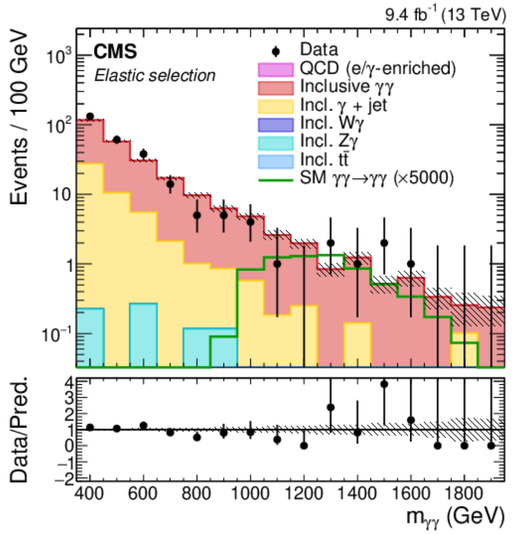
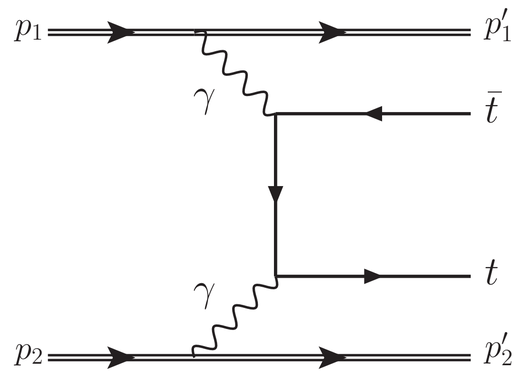


Central exclusive $t\bar{t}$ production

DIS 2022

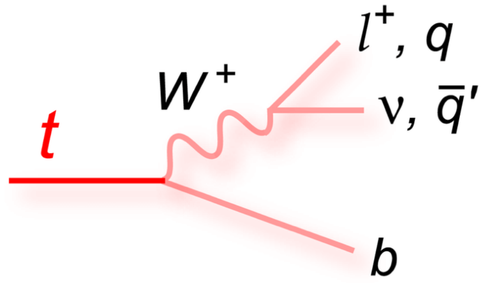
First search for exclusive production to top quark-antiquark pairs with proton tag

- Predicted to occur in SM with very low cross section ~0.1 fb (dominant $\gamma\gamma$ fusion process)
- Sensitive to top-photon coupling; may be enhanced by BSM contributions



Top quark pair reconstructed in dilepton ($\ell^+\ \ell^-$, $\ell = e, \mu$) or ℓ + jets mode

- final state containing only top quark decay products and one proton in each CT-PPS arm



ℓ + jets selection

Leptons:	**Jets:**
$p_T > 30$ GeV $\lvert\eta\rvert < 2.1$ (electrons) $\lvert\eta\rvert < 2.4$ (muons)	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$ $\Delta R(j,l) > 0.4$ *tightLepVeto* jet ID, loose PU ID b-tagging Deep CSV medium

Signal regions:

- =1 lepton
- ≥2 b-jets, ≥2 light jets
- =1 proton on each side of CT-PPS

dilepton selection

Leptons:	**Jets:**
$p_T > 30/20$ GeV $\lvert\eta\rvert < 2.1$	$p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$ $\Delta R(j,l) > 0.4$ *tightLepVeto* jet ID, loose PU ID b-tagging Deep CSV medium

Signal regions:

- ≥2 leptons (=1 OS pair)
- $m(ll) > 20$ GeV
- $m(ll)$ off-Z (15GeV) - only for $ee, \mu\mu$
- ≥2 b-jets
- =1 proton on each side of CT-PPS

CMS-PAS-TOP-21-007
TOTEM-NOTE-2022-002

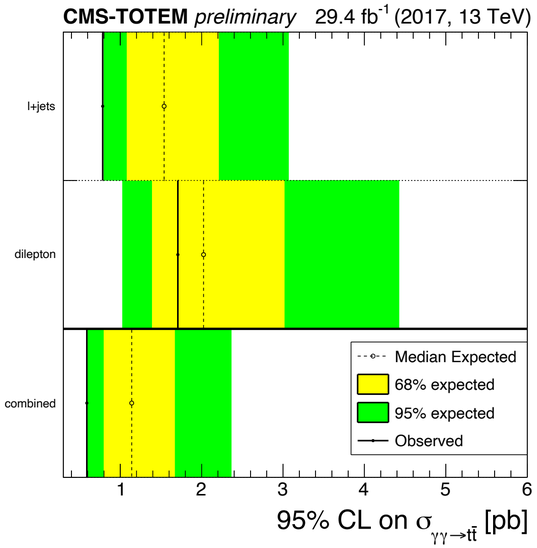
Central exclusive $t\bar{t}$ production

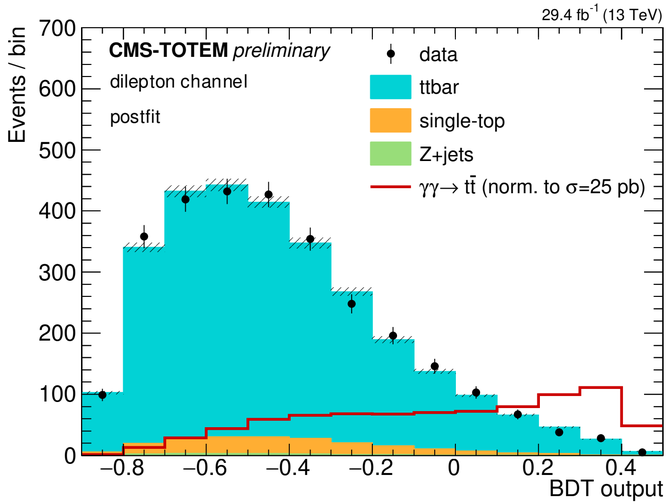
Background dominated by inclusive $t\bar{t}$ events with random coincidence of pileup protons

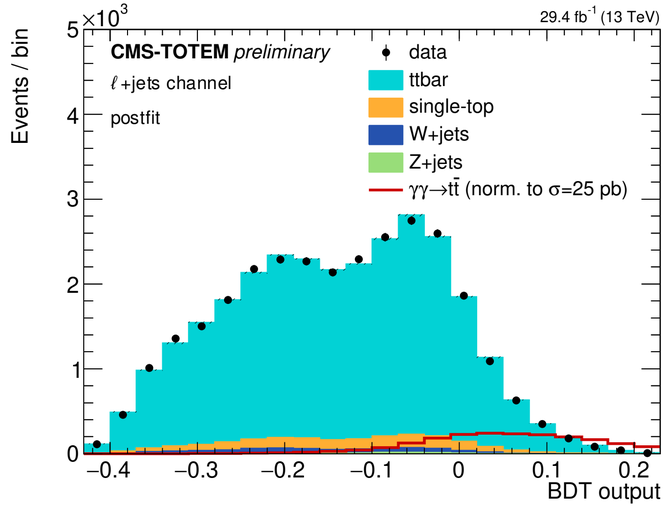
- estimated by mixing random protons from data to simulated background

Multivariate analysis to discriminate signal from background

- boosted decision tree exploiting event topology and kinematics matching between protons and $t\bar{t}$ systems







Analysis performed on 29.4 fb^{-1} of data (2017)

Combined upper limit: $\sigma(pp \rightarrow pt\bar{t}p) < 0.59$ pb at 95% CL

CMS-PAS-TOP-21-007
TOTEM-NOTE-2022-002

Central exclusive Z/γ + X production

DIS 2022

First search for new physics in central production associated to a Z^0 or a photon

- Look for generic weakly interacting BSM particle X

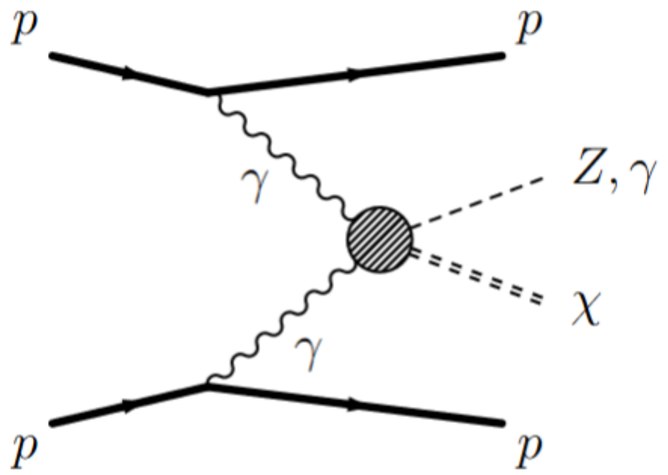
CMS-PAS-EXO-2019-009
TOTEM-NOTE-2022-003

Missing mass technique:

- reconstruct $Z^0 \to e^+e^-$, $\mu^+\mu^-$ or γ inclusively;
- tag one proton per side;
- determine missing mass from kinematic balance:

$$m^2_{\text{miss}} = \left[(p^{\text{in}}_{p_1} + p^{\text{in}}_{p_2}) - (p_V + p^{\text{in}}_{p_1} + p^{\text{in}}_{p_2})\right]^2;$$

- look at m_{miss} distribution in acceptance region
  $600 < m_{\text{miss}} < 1600$ GeV



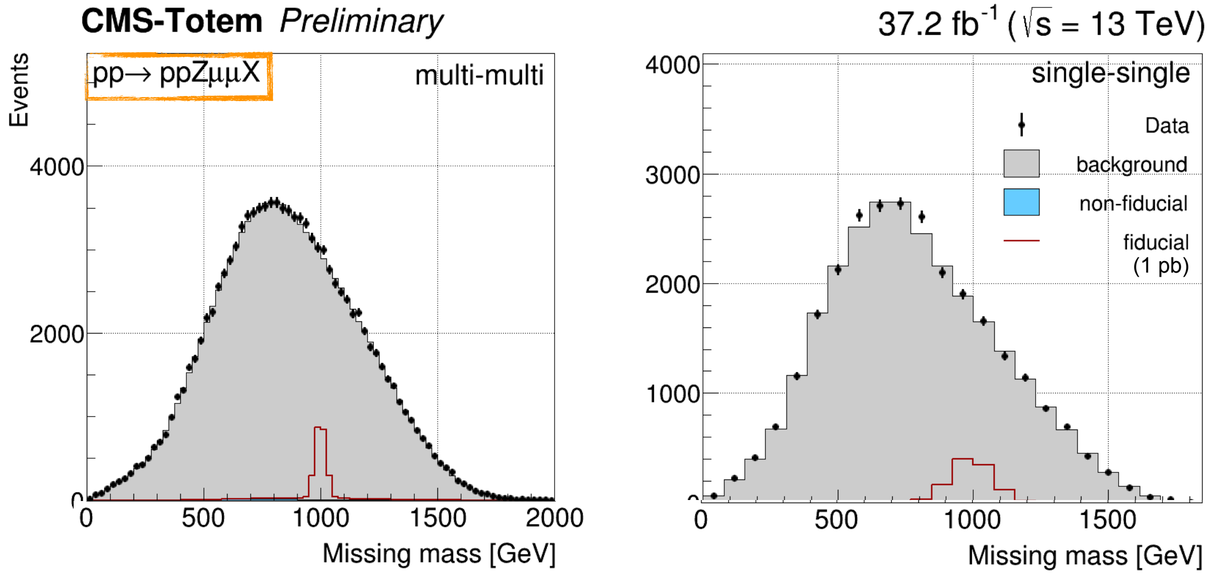
Selection / Analysis	$Z \to e^+e^- / Z \to \mu^+\mu^-$	γ
Leptons/Photons	≥ 2 same flavour leptons (e or μ) opposite electric charge $p_T(\ell_1, \ell_2) > 30, 20$ GeV $\lvert\eta(\ell)\rvert < 2.4$ $\lvert m(\ell_1\ell_2) - m_Z\rvert < 10$ GeV	$=1\gamma$ within $\lvert\eta(\gamma)\rvert < 1.4442$
Boson p_T	$p_T(Z) > 40$ GeV	$p_T(\gamma) > 95$ GeV
Protons	$0.02 < \xi^{gen}_+ < 0.16 \quad \wedge \quad 0.03 < \xi^{gen}_- < 0.18$	

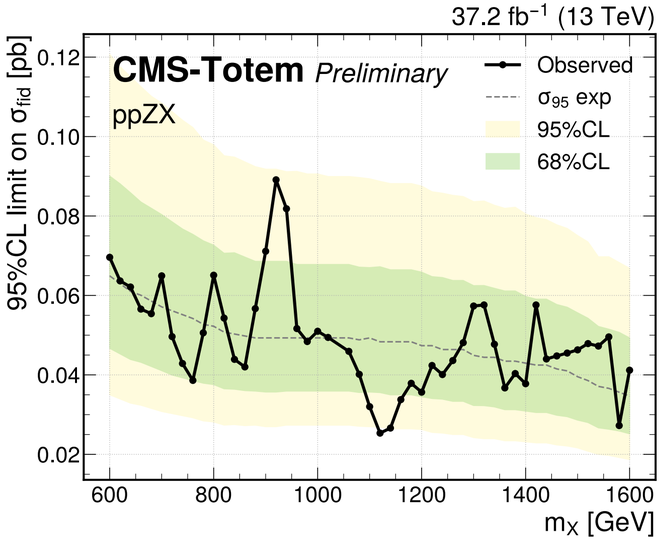
Central exclusive $Z/\gamma + X$ production

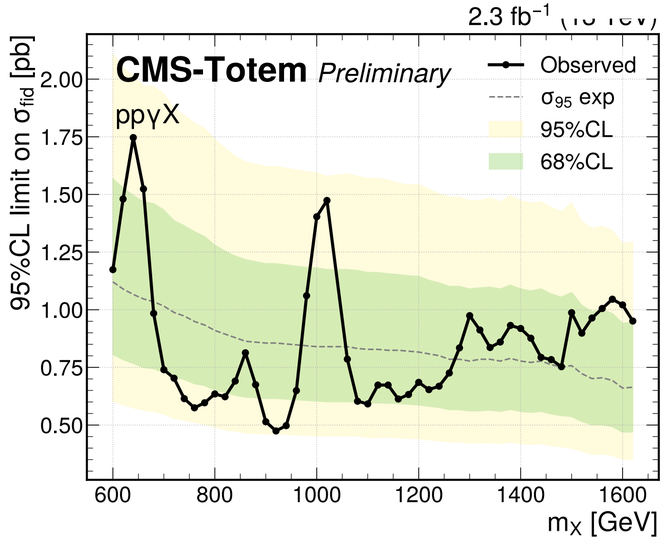
CMS-PAS-EXO-2019-009
TOTEM-NOTE-2022-003

Background dominated by random coincidence of pileup protons

- estimated by mixing random protons from data to simulated background







Analysis performed on 37.2 (2.3) fb^{-1} of data (2017) for Z^0 (γ)

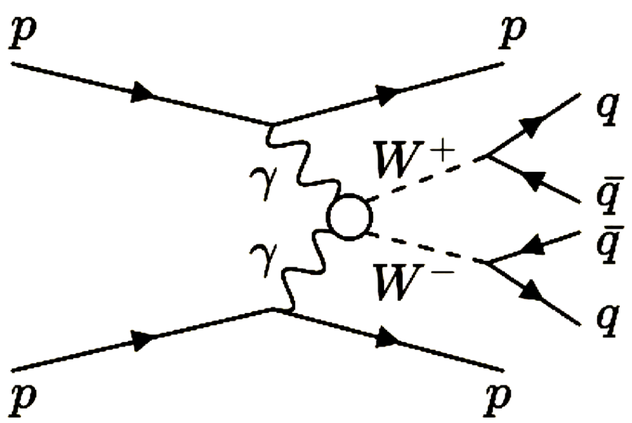
No significant deviations from background-only hypothesis
$\Longrightarrow$ upper limits in the (600-1600) GeV m_{miss} range

Central exclusive *WW / ZZ* production

DIS 2022

First search for exclusive, high-mass, *WW* or *ZZ* production with proton tag

- Look for enhancements to the SM cross section ⟹ probe Anomalous Quartic Gauge Couplings

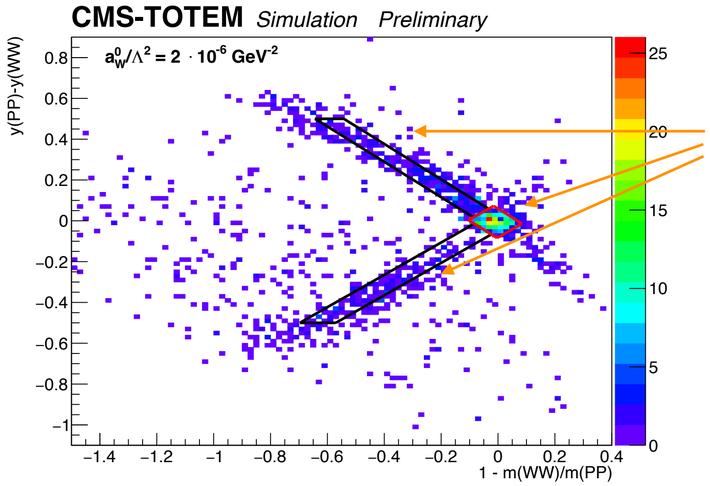


Vector bosons reconstructed through hadronic decays

- merged jets from $V \to q\bar{q}$ decay
- proton tag on both arms of CT-PPS (suppresses QCD background)
- suffers from high p_T threshold in jet triggers

Selection

At least two fat jets, with $|\eta| < 2.5$
$p_T > 200$ GeV
$|\eta(j_1) - \eta(j_2)| < 1.3$
$1126 < m_{jj} < 2500$ GeV
both jets V-tagged
$p_T^{(j1)}/p_T^{(j2)} < 1.3$ and $|1 - \Delta\phi_{jj}/\pi| < 0.01$
At least one multi-RP proton in each arm



Signal regions are defined based on the kinematics matching between protons and the VV system

CMS-PAS-SMP-21-014
TOTEM-NOTE-2022-004

Central exclusive *WW / ZZ* production

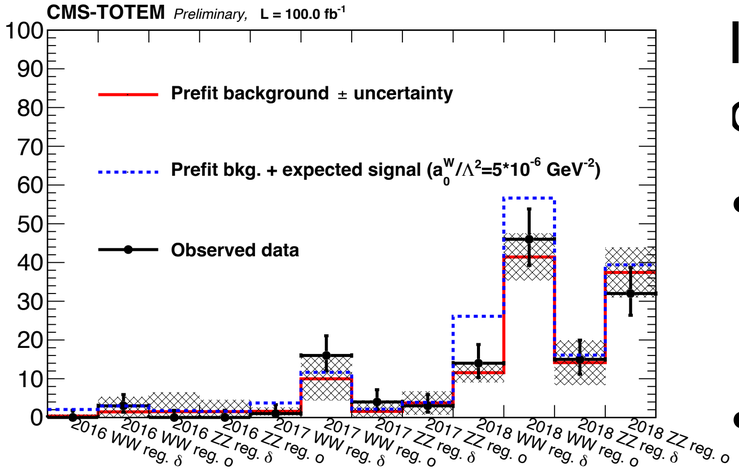
CMS-PAS-SMP-21-014
TOTEM-NOTE-2022-004

Background dominated by inclusive QCD dijet production

- Estimation entirely based on data, projecting yields in control regions to signal regions

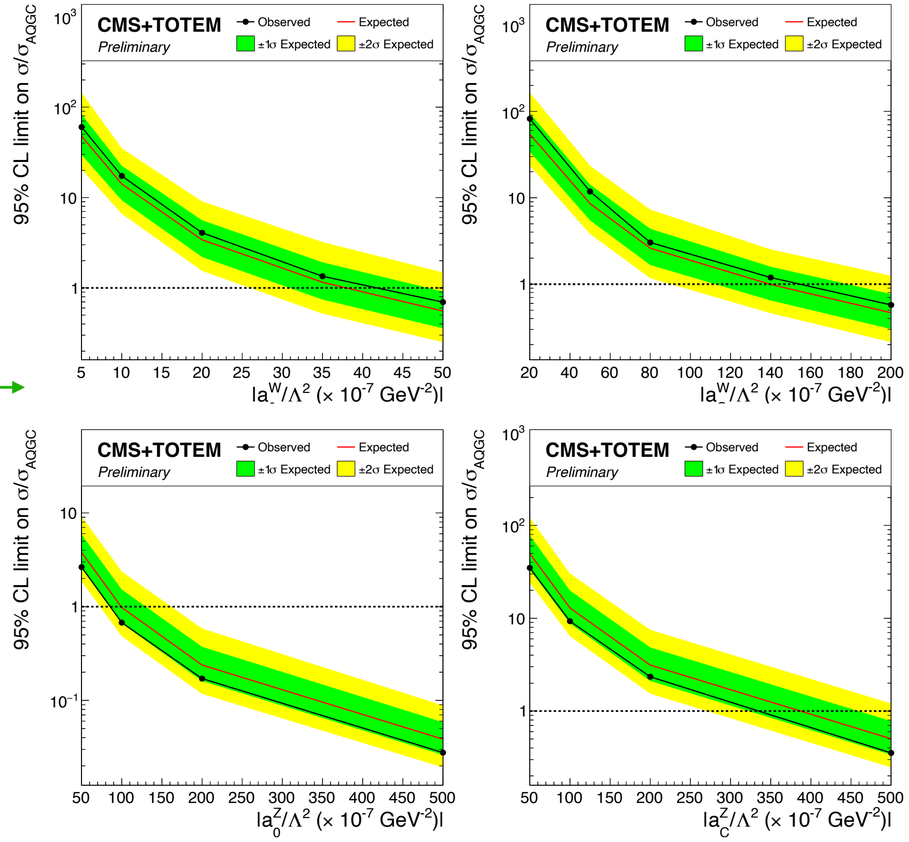
Analysis performed on full Run 2 statistics (100 fb^{-1})

Yields extracted separately per each channel, year and signal region type



Interpretation as upper limits on dim-6 and dim-8 AQGCs →

- Dim-6 *γγWW* limits 15-20 times more stringent than Run 1 results with no proton tag
- First *γγZZ* limits



Interpretation as fiducial cross sections:

$\sigma(pp \to pWWp)_{0.04<\xi<0.20,\ m>1\ \mathrm{TeV}} < 63$ fb, $\sigma(pp \to pZZp)_{0.04<\xi<0.20,\ m>1\ \mathrm{TeV}} < 43$ fb

Summary/outlook

CT-PPS allows to extend the CMS physics program with the study of forward proton-tagged processes

- results in broad range of topics obtained from data collected in LHC Run 2
- more studies in progress

PPS setup upgraded for Run 3 data taking:

- new silicon pixel tracker with internal motion to mitigate radiation damage;
- two new timing stations, double-diamond detectors in all planes $\Longrightarrow$ expected factor ~2 improvement in *pp* vertex determination
- dedicated dijet Level-2 trigger (HLT) line with proton tag, to afford lower p_T threshold

Expression of interest for a new setup for HL-LHC [arXiV:2103.02752]