LHC Seminar

New physics results with the CMS Precision Proton Spectrometer

24 May 2022

Michael Pitt (CERN)
On behalf of the CMS and TOTEM Collaborations

Outline

- Physics with the PPS
- Experimental apparatus
- Results from Run 2
- Looking forward

di-lepton (June 2018)

PPS Performance (March 2022)

WW/ZZ (March 2022)

ttbar (March 2022)

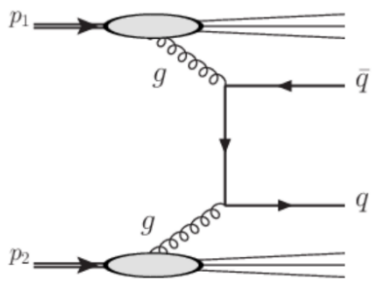
Di-photon (Sep 2020, Today)

ZX/γX (March 2022)

Physics with the PPS

Introduction

- In typical pp collisions at the LHC:
  - Protons dissociate into multiparticle states



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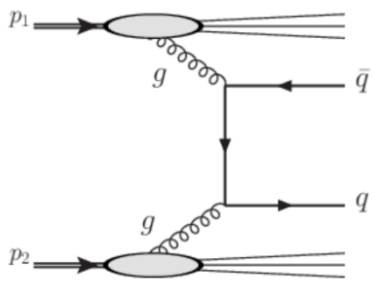

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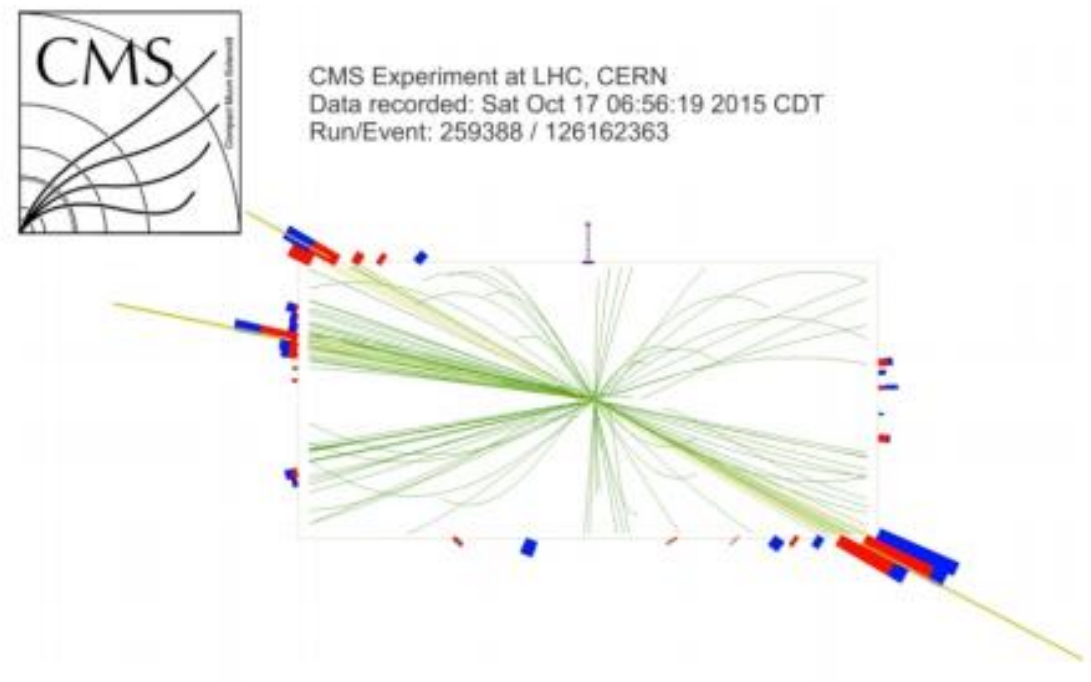
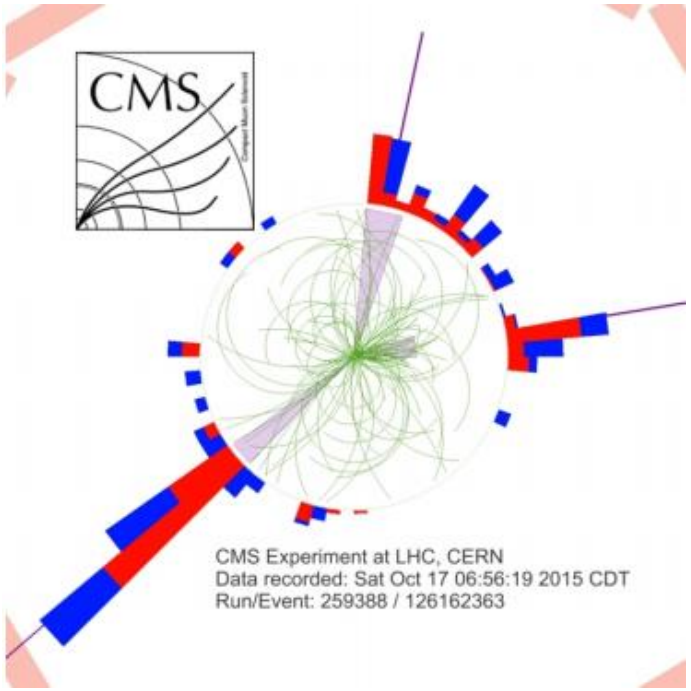
- Protons dissociate into multiparticle states
- A large number of energetic particles are produced

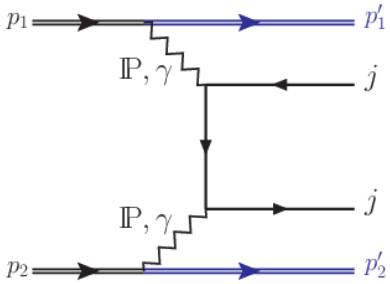




Introduction

- In rare cases:

- Protons remain intact (**tagged by PPS**)



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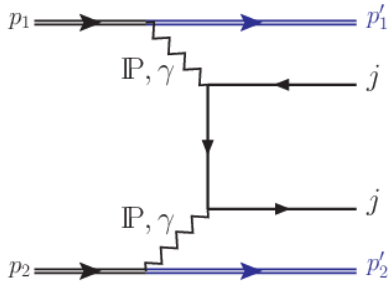

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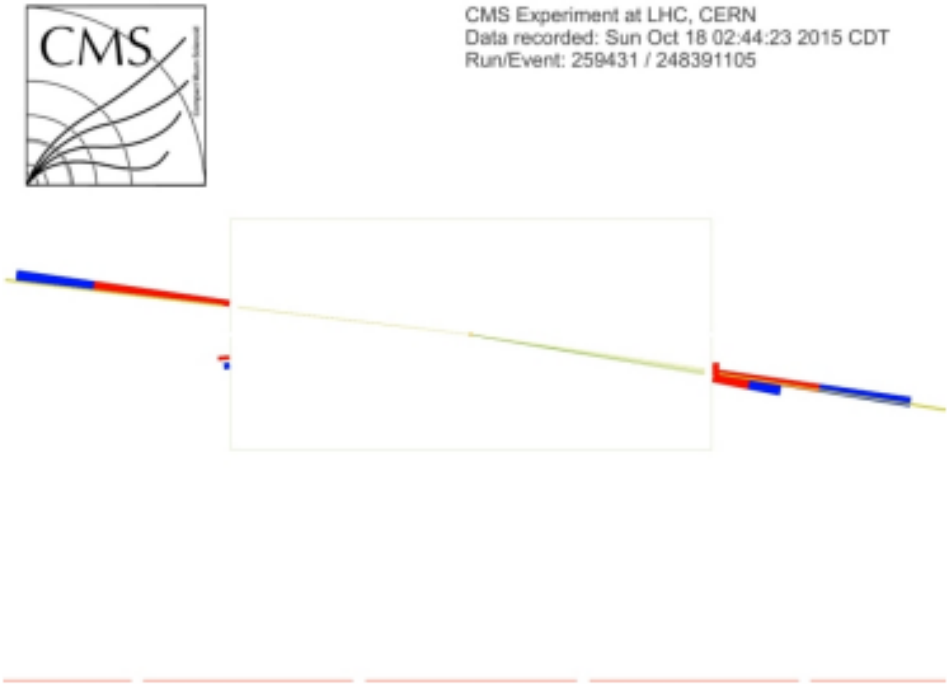
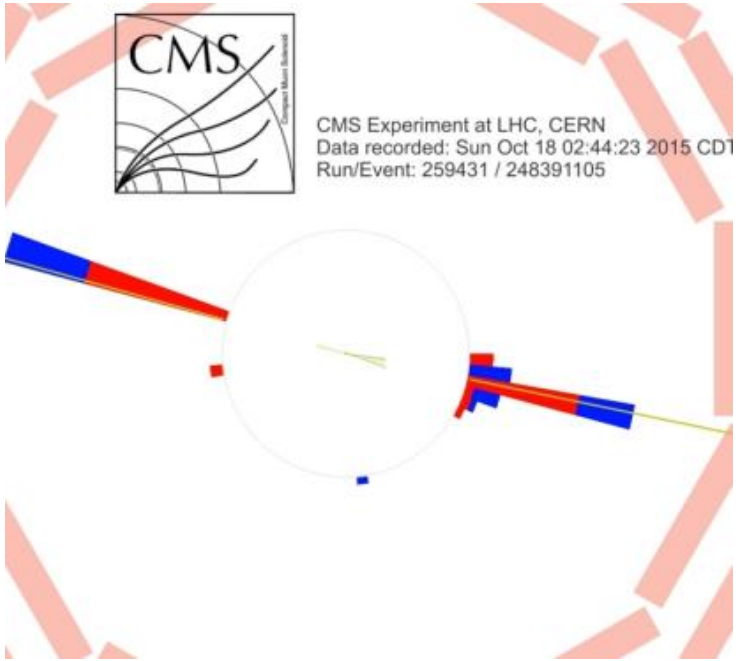
- Protons remain intact (**tagged by PPS**)
- Low track activity due to exchange of color singlets via QCD (Pomeron) or QED (γ)





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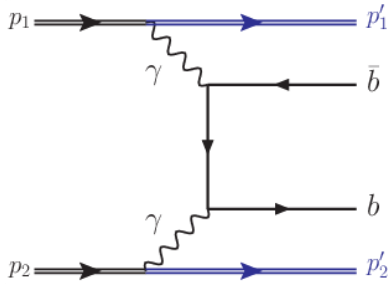

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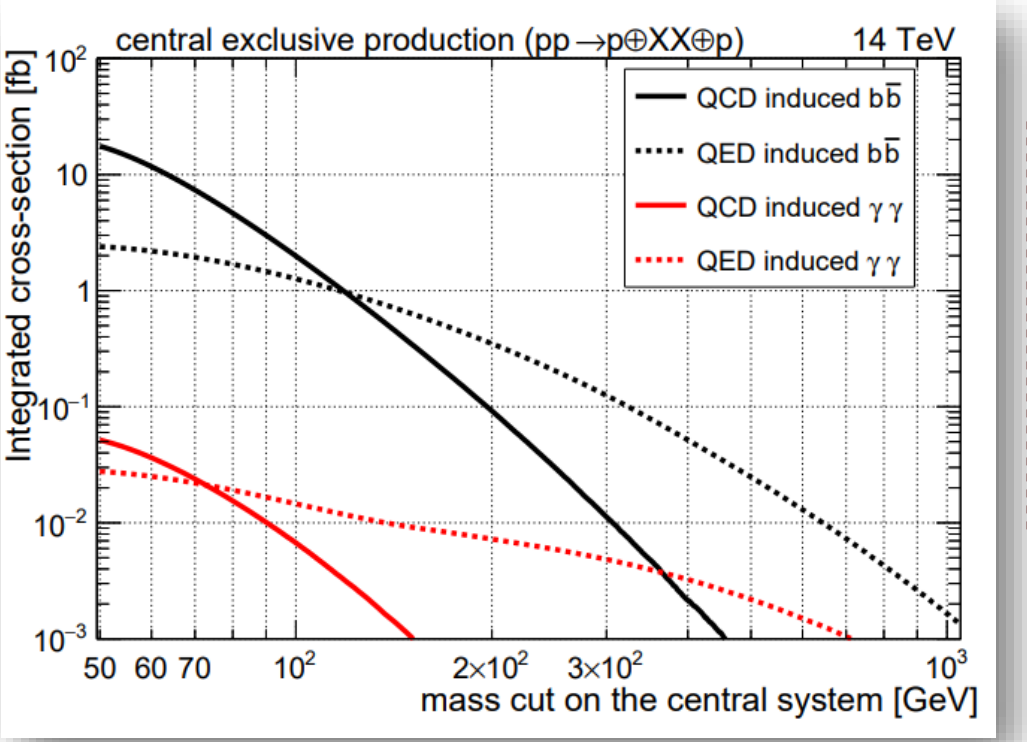

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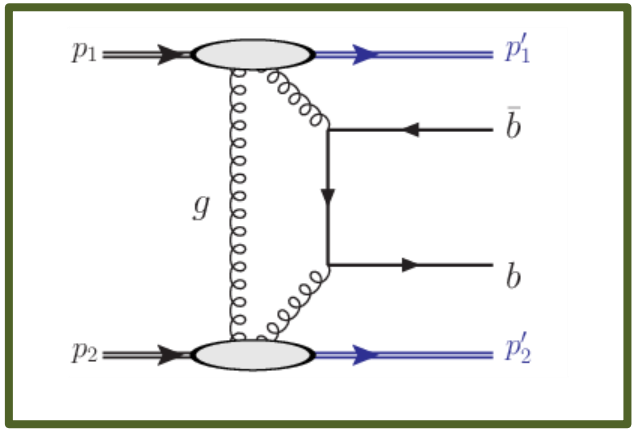
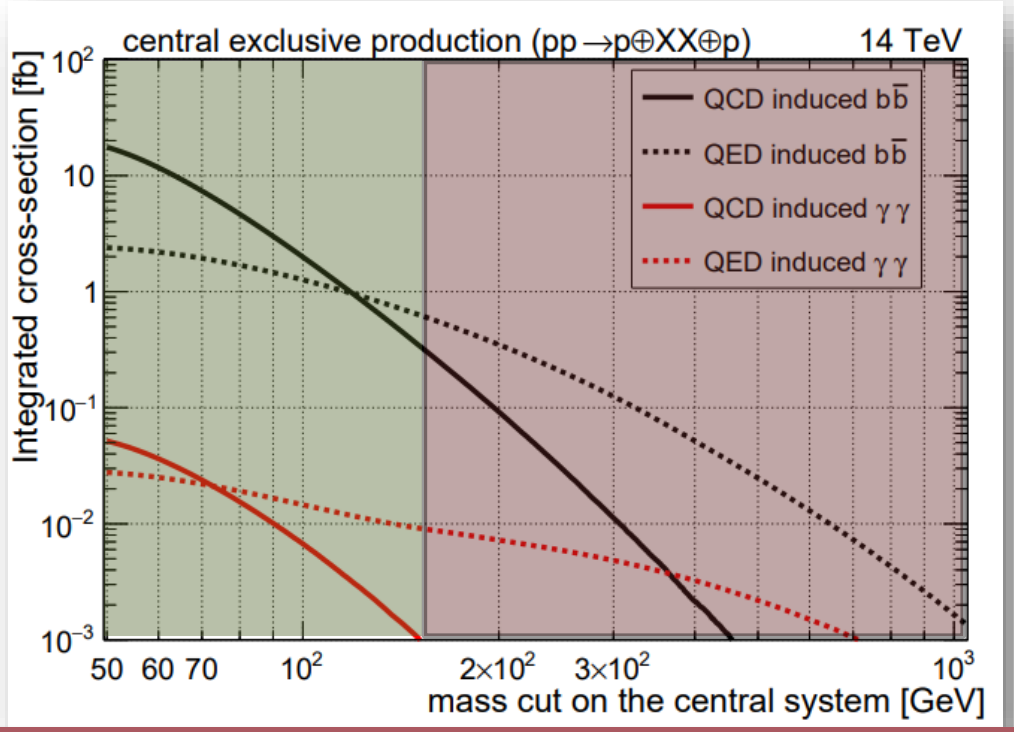
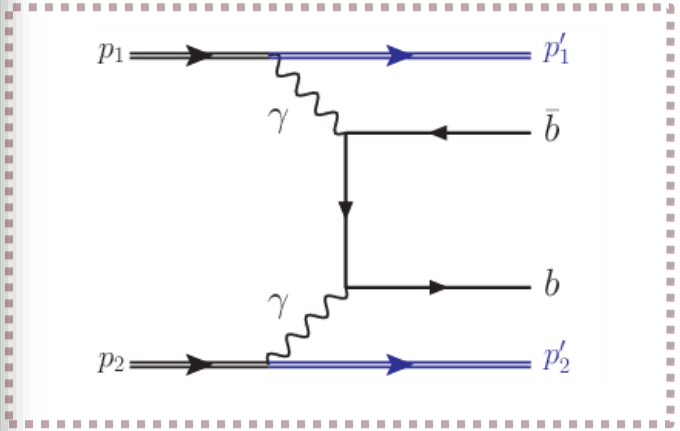
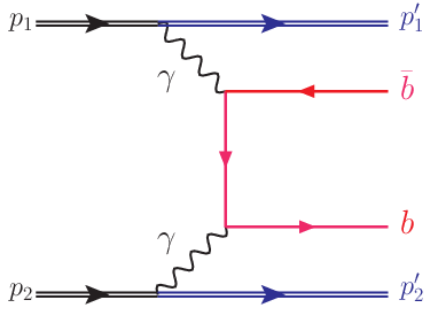






High mass range is dominated by photon-photon interactions

Introduction



- Photon-Photon fusion in pp collisions:
  - In Central Exclusive production (CEP) processes:

    Central system kinematics = Proton kinematics

  - For given proton momentum loss $\xi = \Delta p/p$:

Proton kinematics can be inferred from the central system:

$$\xi_{\pm} = \frac{\sum E \pm p_Z}{\sqrt{s}}$$

Central system kinematics can be inferred from the protons:

$$m = \sqrt{s\xi_+\xi_-}$$

$$Y = \frac{1}{2} log\left(\frac{\xi_+}{\xi_-}\right)$$

Introduction

- Central exclusive production processes:
  - Allows exploring the Electro-Weak sector in a new phase-space

    For example: $\gamma\gamma \rightarrow ll$ contributes to high m(ll) spectra

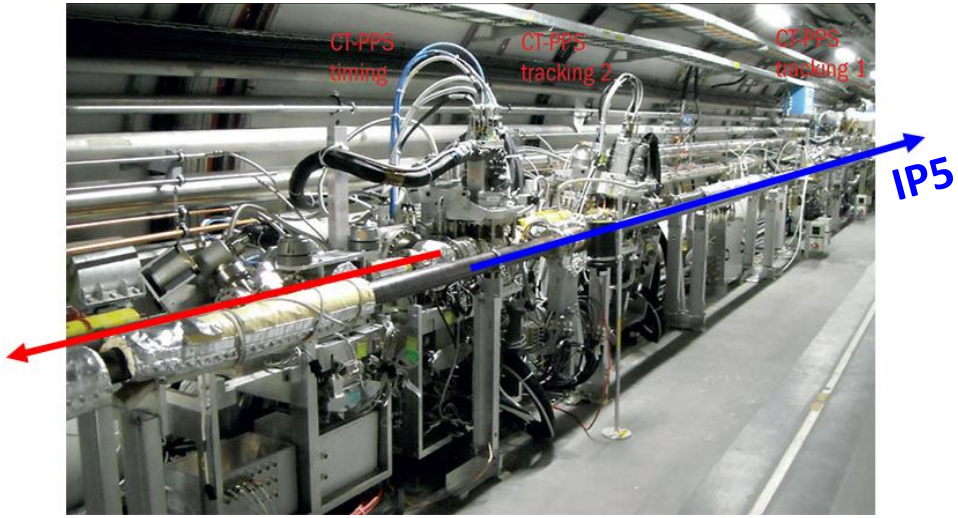
  - Opens a door to search new physics

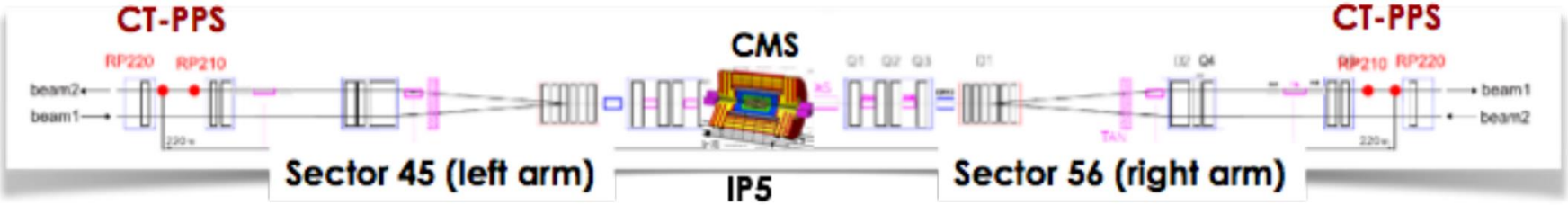
    For example: $\gamma\gamma \rightarrow \gamma\gamma$ search for ALPs

Experimental apparatus

The Precision Proton Spectrometer (PPS)

- CMS+TOTEM expertise: PPS TDR (TOTEM-TDR-003)
- Operated in standard LHC runs since 2016 NEW
- Located ~ 200m from the CMS interaction point in both arms, equipped with tracking/timing detectors





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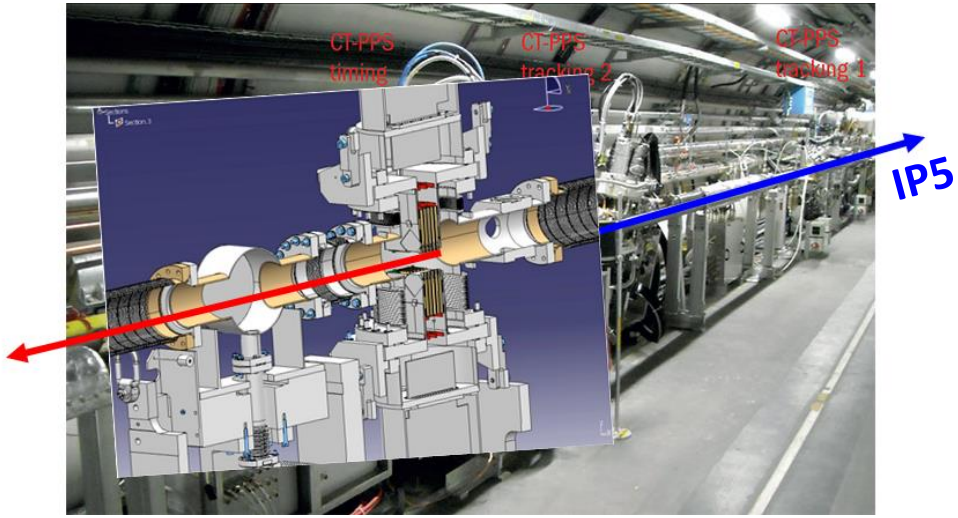
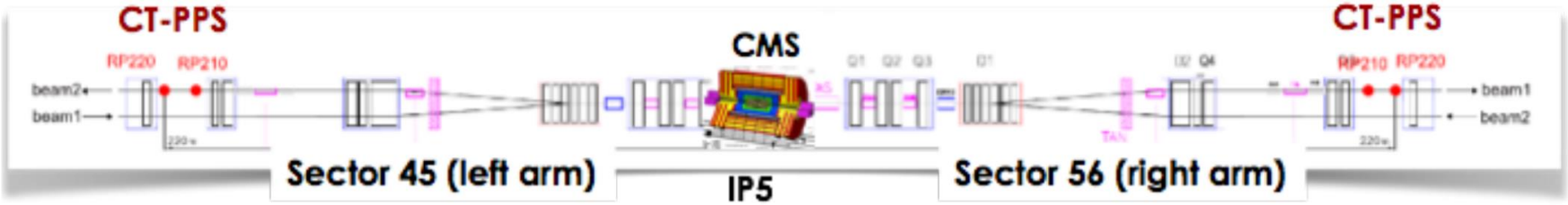
- A set of near-beam detectors, which approach the beam down to a few mm



PPS is the farthest and, at the same time, the closest CMS subsystem

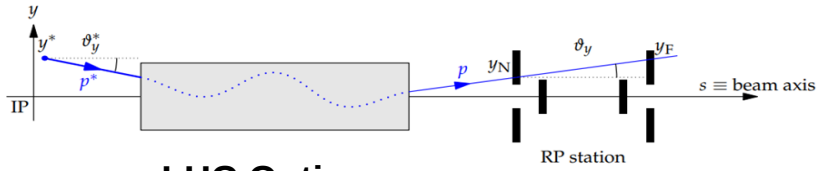


PPS | Tracking

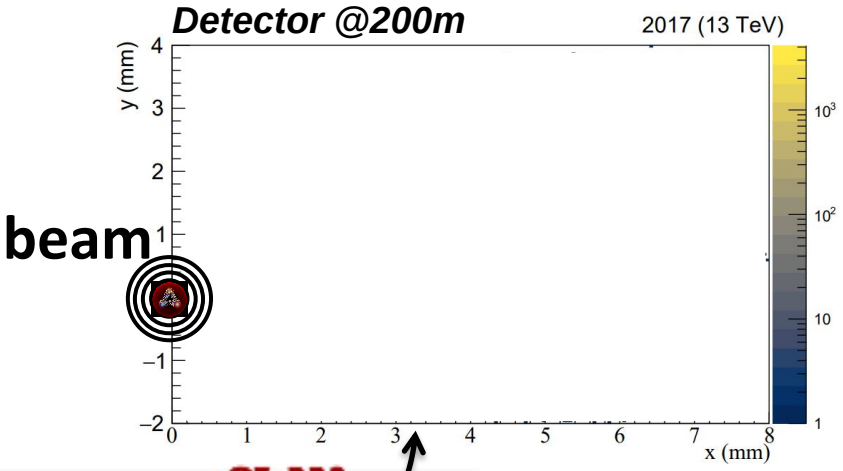
- Proton kinematics :

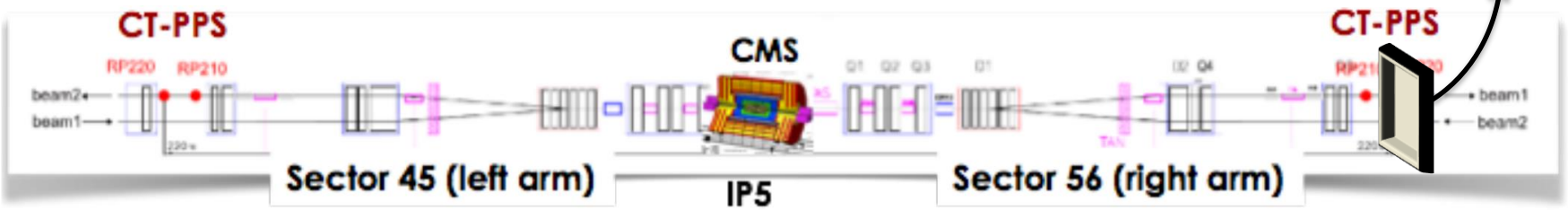
- Intact protons lose a fraction of momentum ($\xi = \Delta p/p$) and are scattered at small angles (θ_x^*, θ_y^*) → they deflected away from the beam and measured by PPS

$$\delta x(z) = x_D(\xi) + v_x(\xi)x^* + L_x(\xi)\theta_x^*$$
$$\delta y(z) = y_D(\xi) + v_y(\xi)y^* + L_y(\xi)\theta_y^*$$



LHC Optics





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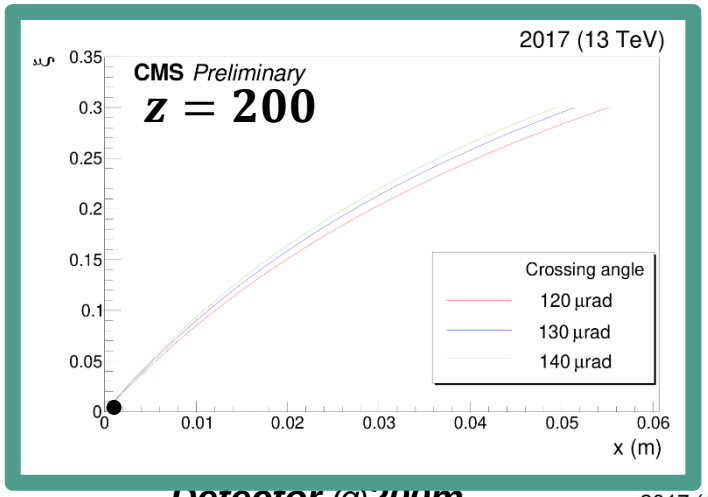

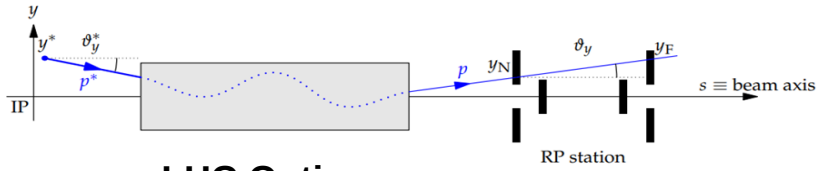

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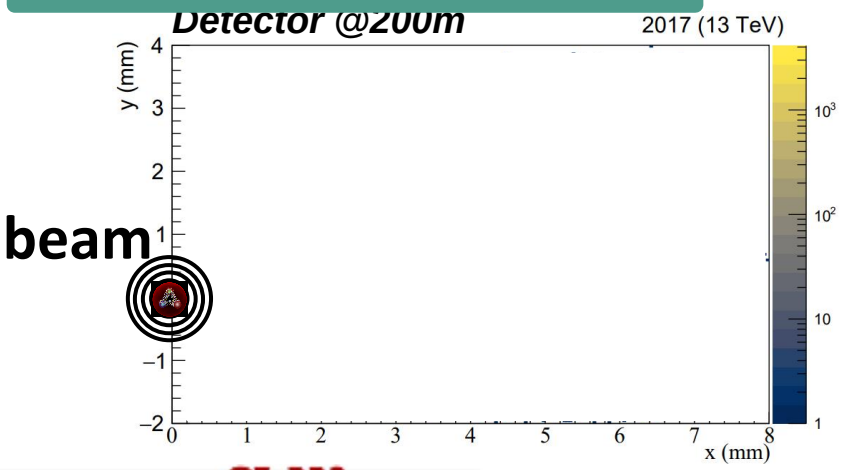

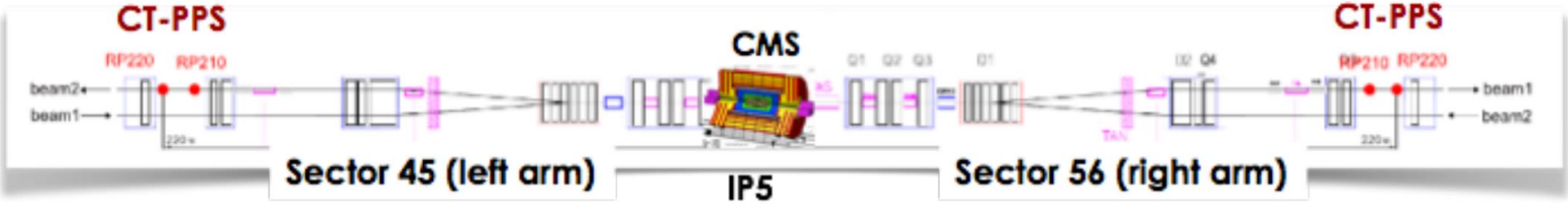

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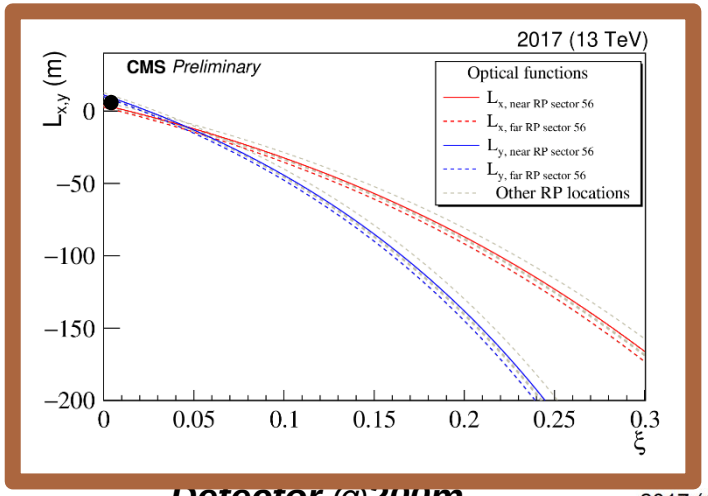

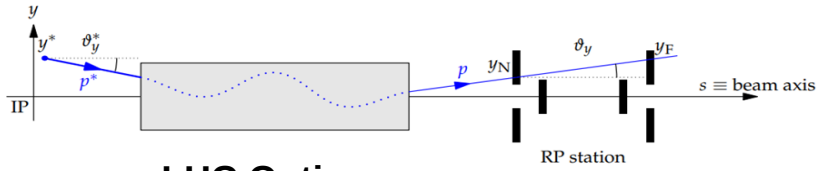

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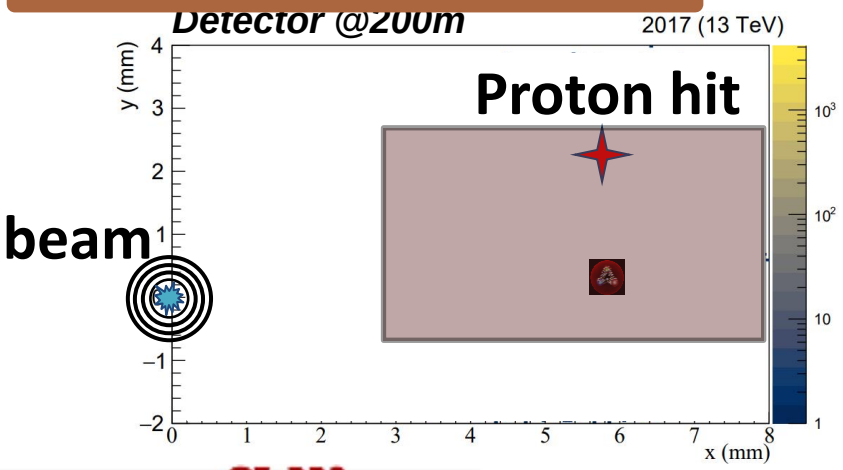

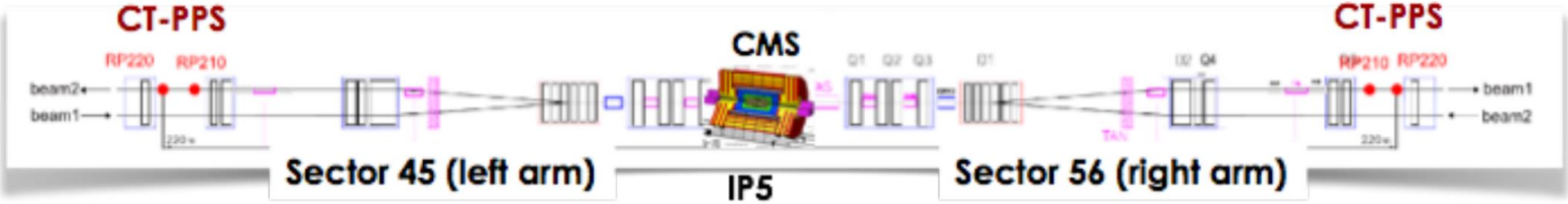

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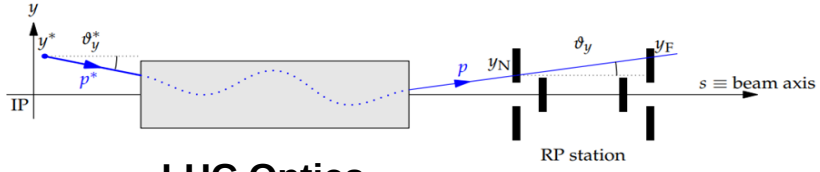
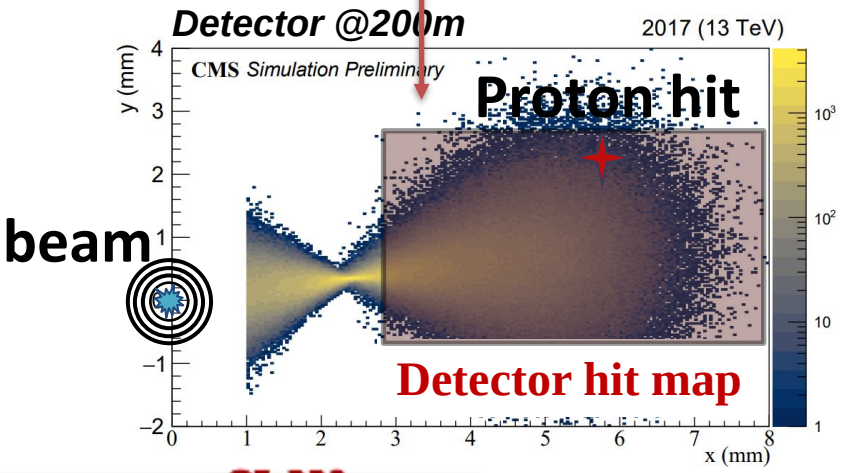
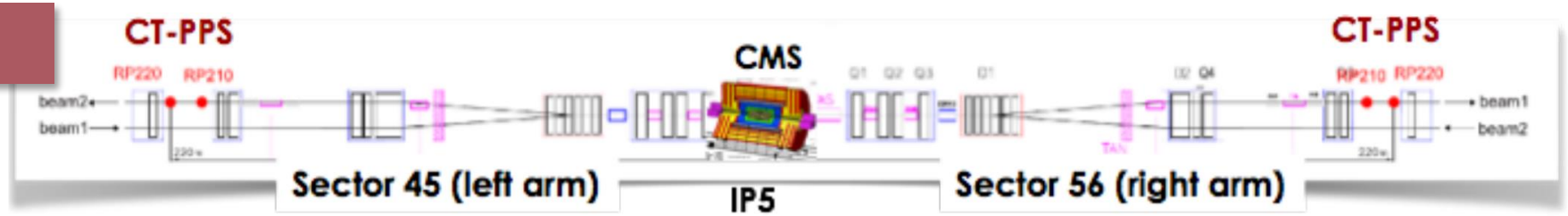


LHC Optics

acceptance



2 stations



PPS | Tracking technology

- Rapid detector evolution since commissioning in 2016!

2016: PPS inherits from TOTEM Silicon strip tracker

(used in special runs, cannot resolve multiple tracks)

SiStrip

+

SiStrip

PPS | Tracking technology

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SiStrip + SiStrip

2017: 3D Silicon pixels - a suitable detector technology was developed, and half of the stations were upgraded

SiStrip + 3D Pixel

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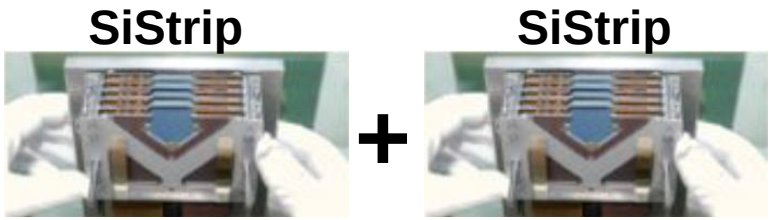
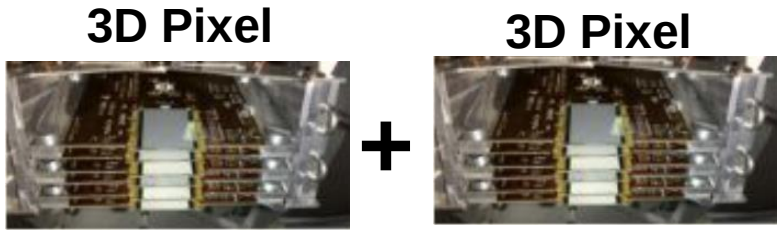


2017: 3D Silicon pixels - a suitable detector technology was developed, and half of the stations were upgraded

2018: Both stations per arm are equipped with 3D pixel detectors

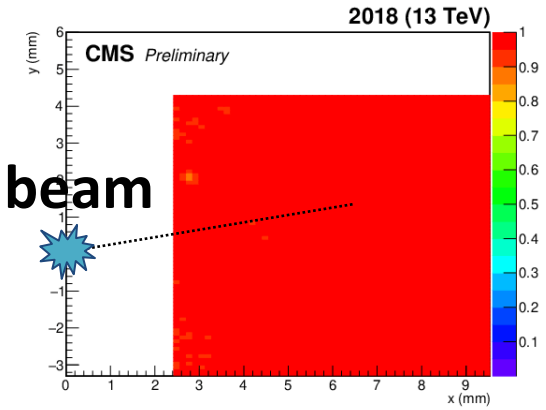


PPS | Tracking efficiency

CMS-PAS-PRO-21-001

- Challenges in the standard LHC runs:
  - Efficiency drop due to irradiation
  - Higher x -> Higher ξ -> Higher minimal accepted mass

LHC Sector 45 efficiency



$\int \mathcal{L} dt = 0\ \mathrm{fb}^{-1}$

PPS | Tracking efficiency

CMS-PAS-PRO-21-001

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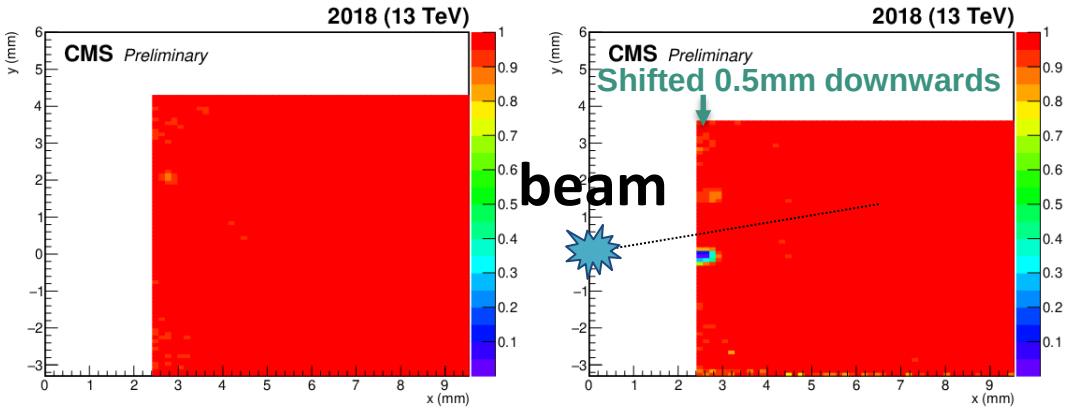
  - Higher x -> Higher ξ -> Higher minimal accepted mass
  - Detectors were shifted during LHC Technical Stops (TS) by 0.5mm

LHC Sector 45 efficiency



$\int \mathcal{L} dt$ = 0 fb^{-1} TS ~21 fb^{-1}

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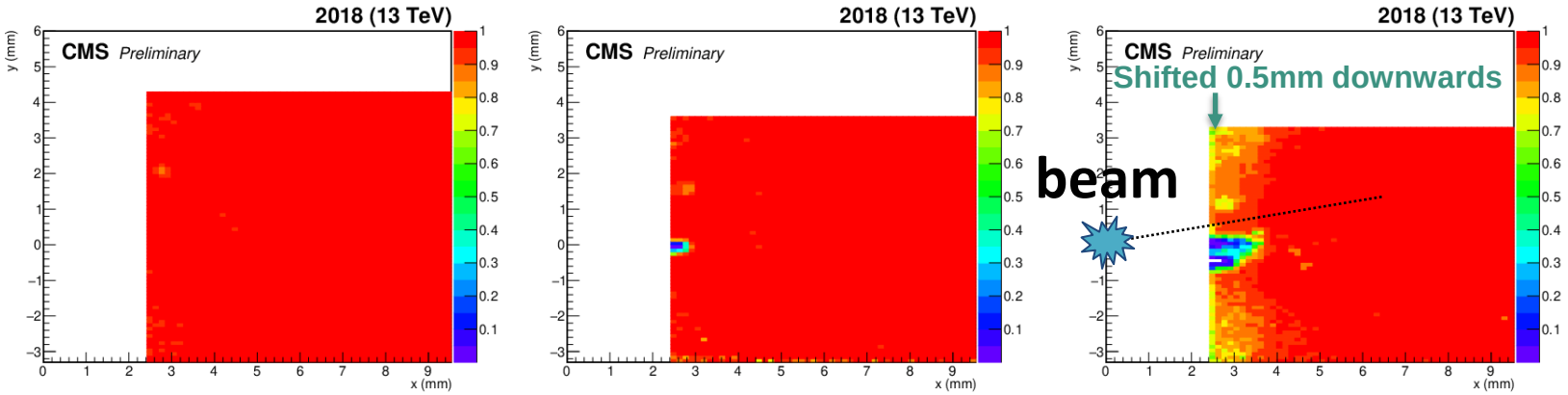

$\int \mathcal{L}dt$ = 0 fb^{-1} TS ~21 fb^{-1} TS ~50 fb^{-1}

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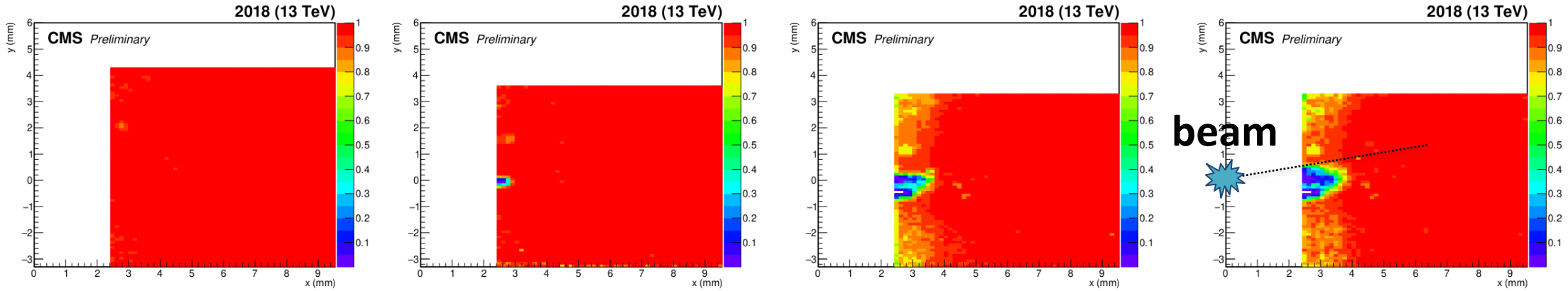


$\int \mathcal{L}dt$ = 0 fb^{-1} TS ~21 fb^{-1} TS ~50 fb^{-1} ~58 fb^{-1}

PPS | Tracking efficiency

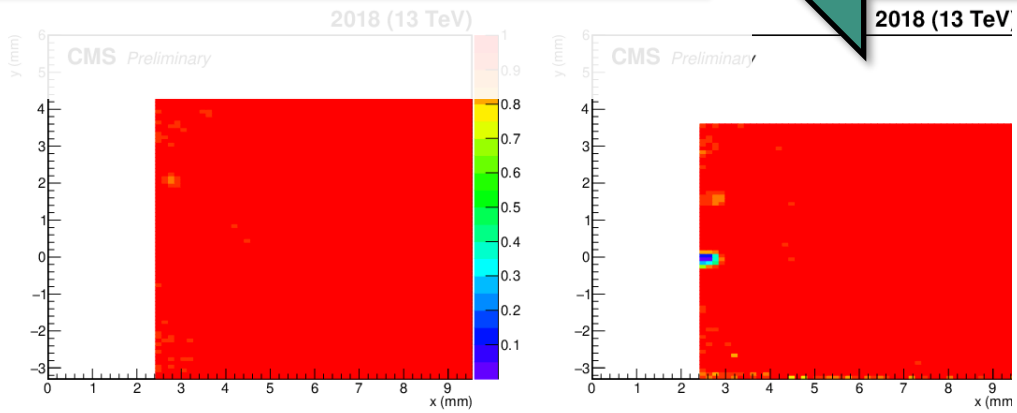
CMS-PAS-PRO-21-001

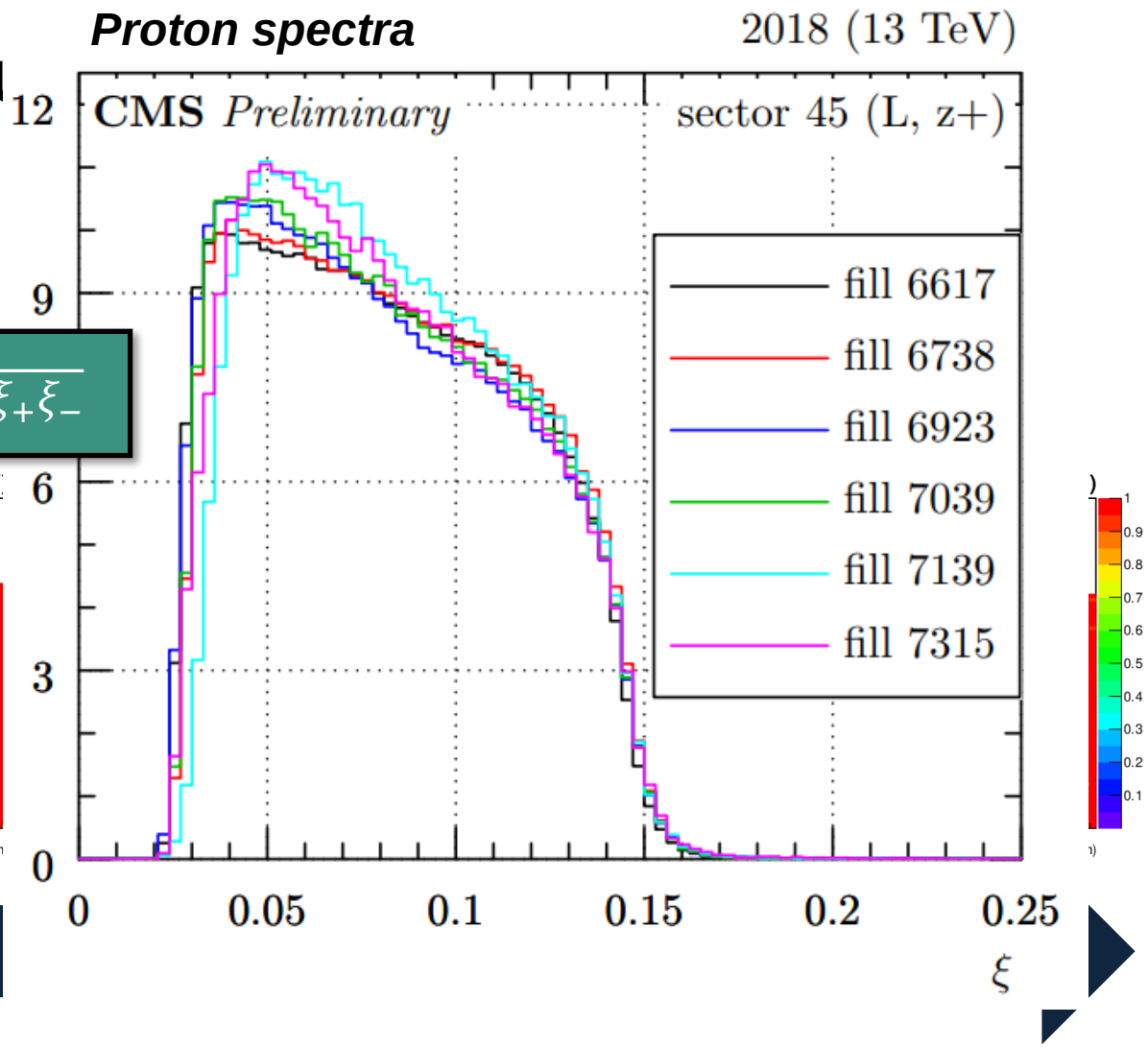
- Challenges in the standard LHC ru
  - Efficiency drop due to irradiation
  - Higher x -> Higher ξ -> Higher m himal

350 GeV < m_X < 2 TeV

$m = \sqrt{s\xi_+\xi_-}$

LHC Sector 45 efficiency





$\int \mathcal{L}dt$ = 0 fb^{-1} TS ~21 fb^{-1}

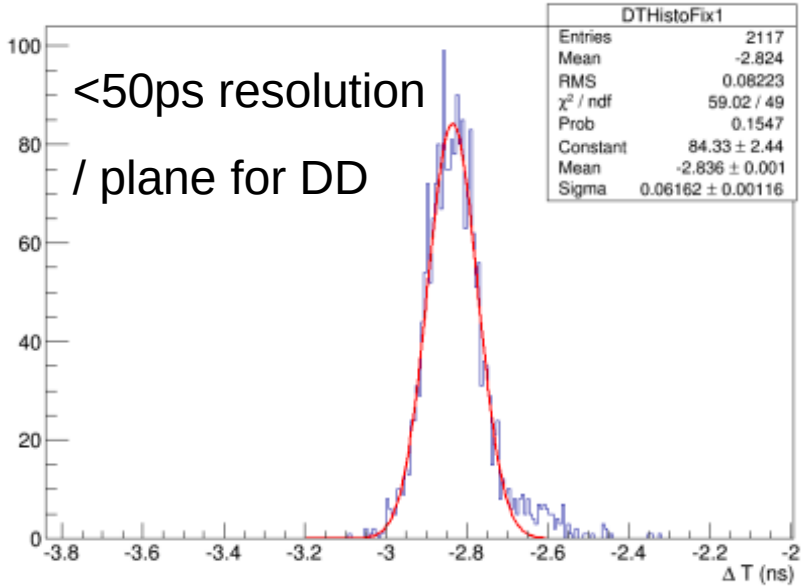
PPS | Timing

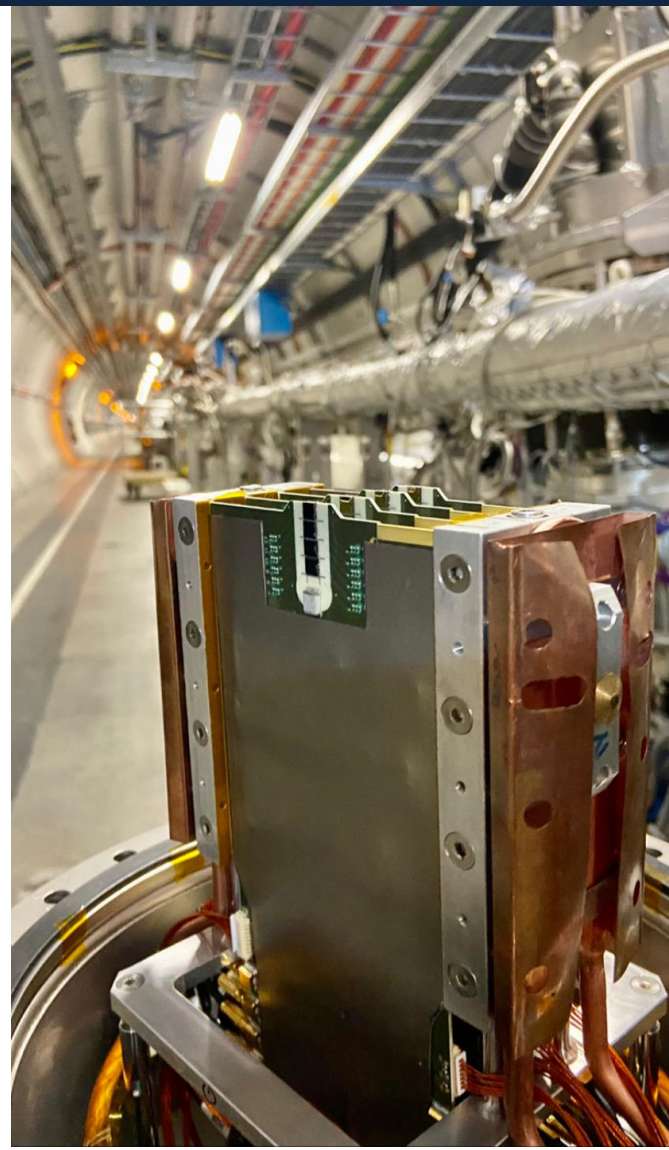
- Vertex z-coordinate is reconstruction using ToF:

$t_{PPS\,1}$ $t_{PPS\,2}$

$$V_{Z,PPS} = \frac{c}{2}(t_{PPS\,1} - t_{PPS\,2})$$

- Diamond detectors technology was used with 2018 data



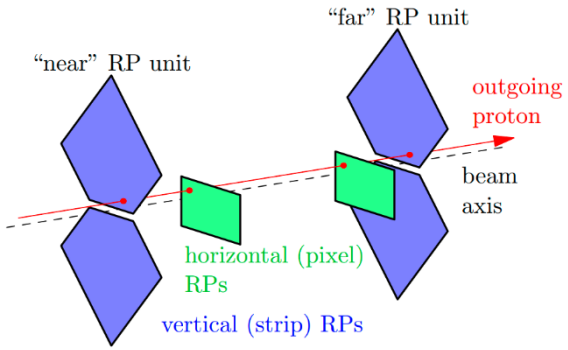


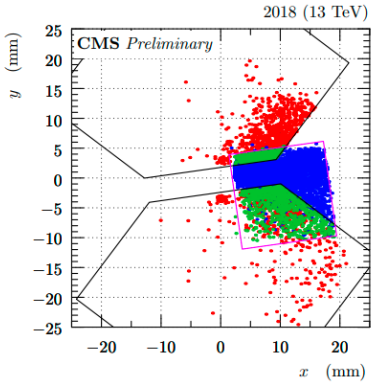
Credit: Nicola Turini

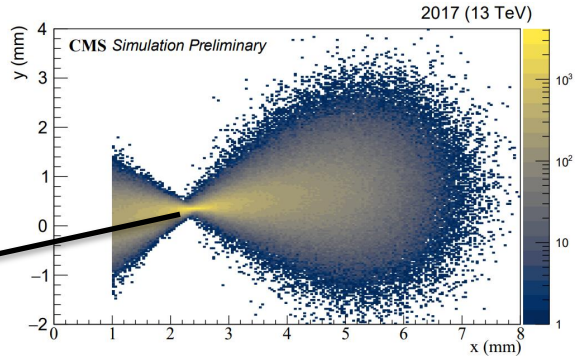
PPS | Calibration

CMS-PAS-PRO-21-001

- Alignment (2 steps):
  - Global alignment – performed in special runs (2-3 bunches / beam), vertical detectors are used, PPS position w.r.t. the beam
  - Local alignment – match distribution of proton tracks from physics run to that of the alignment run (fill-by-fill)
- Optics:
  - Optical functions validated in data





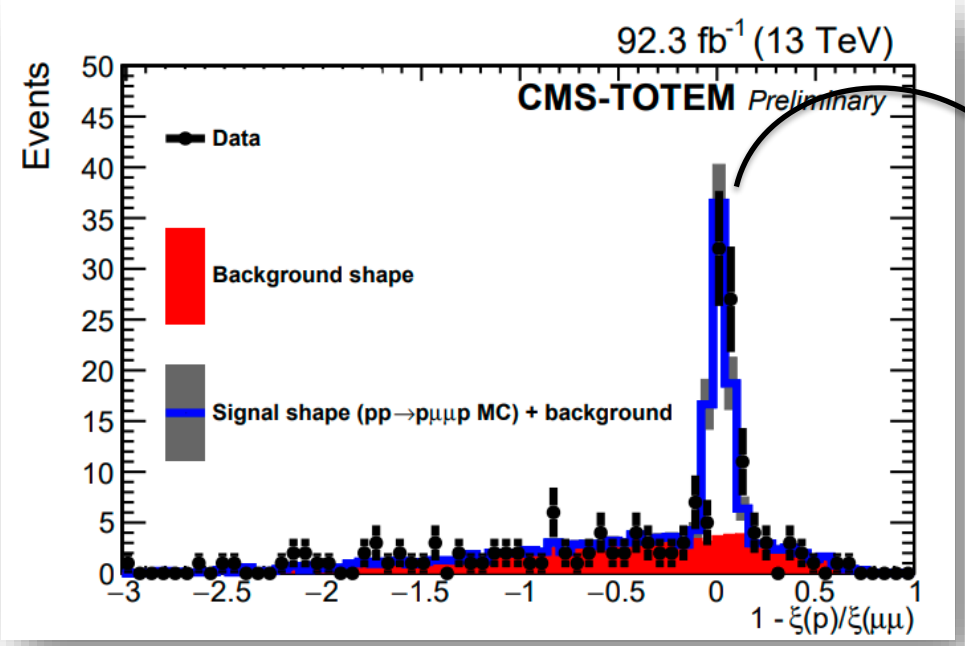


$L_y(\xi_0) = 0$

PPS | Performance

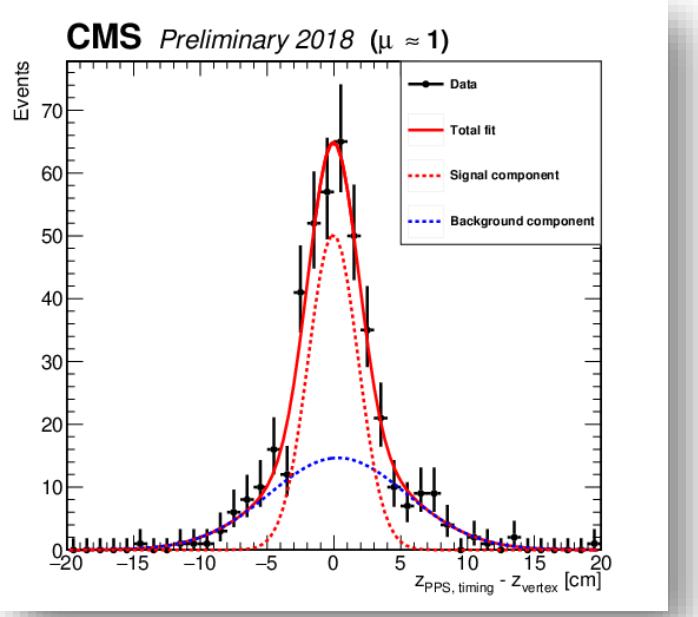
CMS-PAS-PRO-21-001

- Tracking:
  - Using (semi)-exclusive di-muon sample
  - Compare ξ(CMS) vs ξ(PPS)
  - **A few% resolution(!!!)**



Validation of the calibration sequence

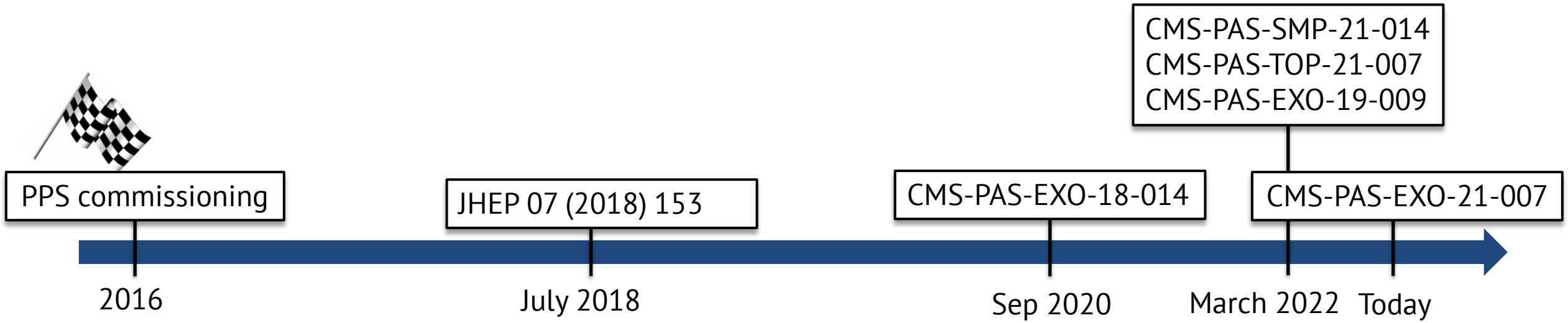
- Timing:
  - Using central diffractive events in μ~1 sample
  - Compare Z(PV) vs Z(PPS)
  - **All track resolution: $\sigma_z = 2.77 \pm 0.17cm$**



Physics results from Run 2

Physics results from Run 2

- PPS analyses covers many physic groups (Top physics, Standard Model, Exotic searches)



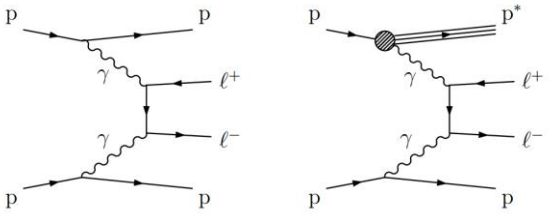
Physics | di-lepton events

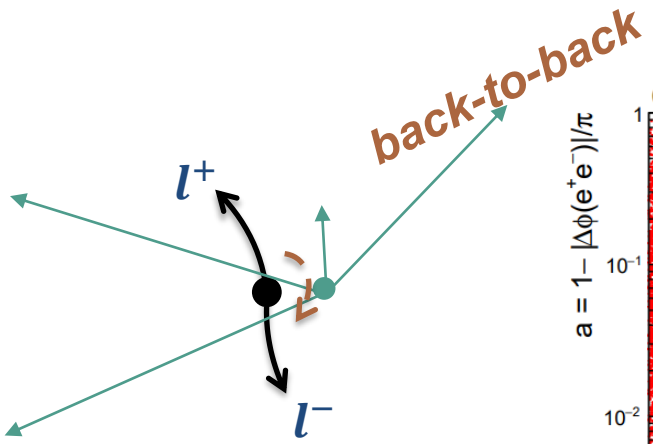
JHEP 07 (2018) 153

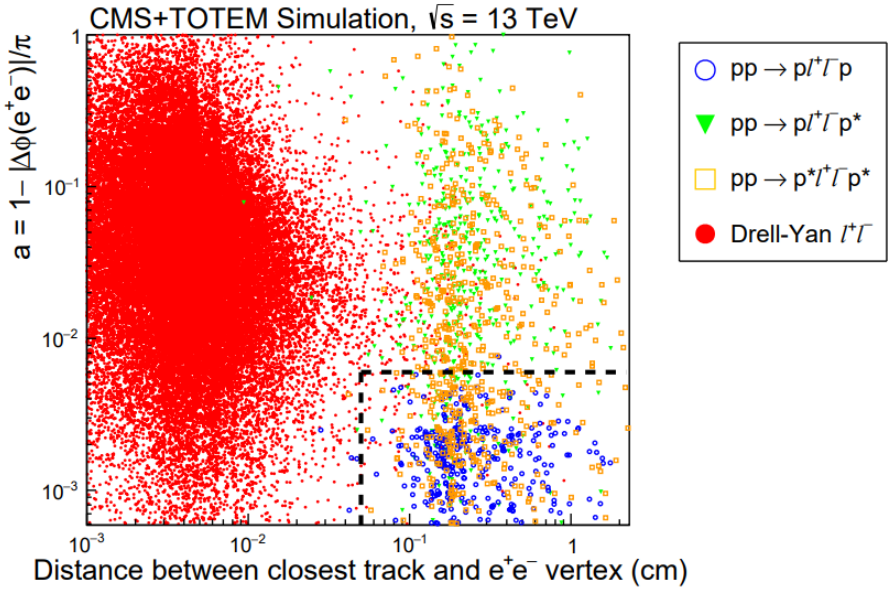
- Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process

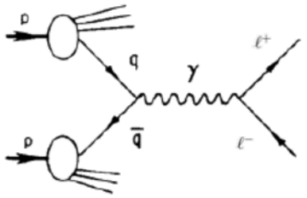
Signal







Background



Drell-Yan

+ **pileup proton**

No additional radiation

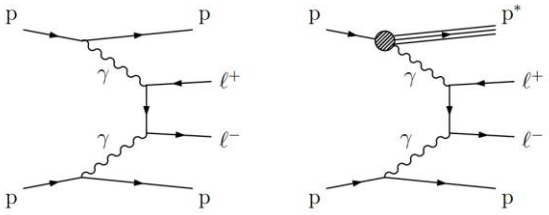
Physics | di-lepton events

JHEP 07 (2018) 153

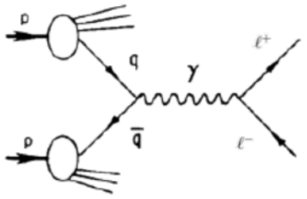
- Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process

Signal

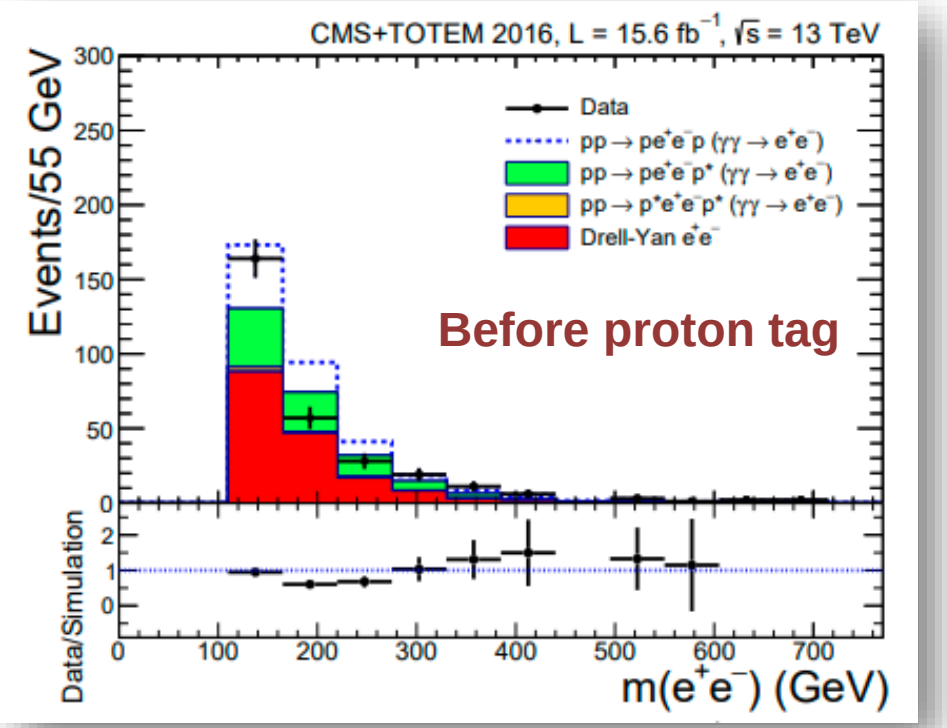


Background



Drell-Yan

+ **pileup proton**

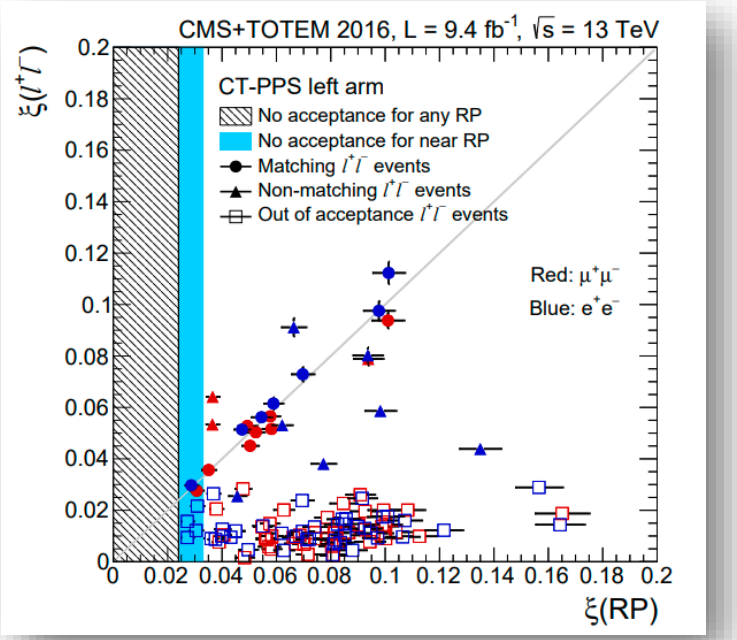


Physics | di-lepton events

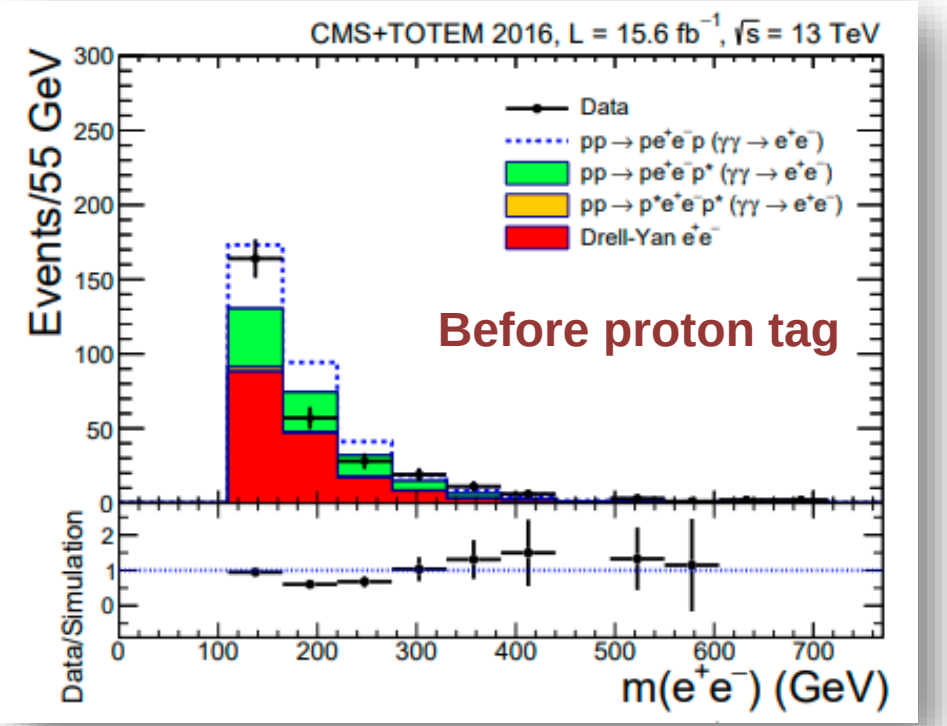
JHEP 07 (2018) 153

Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process
- PPS selects a clean sub-sample of signal events: $\xi_{\pm} = \frac{1}{\sqrt{s}}\left[p_T(l_1)e^{\pm\eta(l_1)} + p_T(l_2)e^{\pm\eta(l_2)}\right]$



20 Total events observed (12μμ, 8ee)
Estimated 4 Background (1.5±0.6μμ, 2.4±0.6 ee)

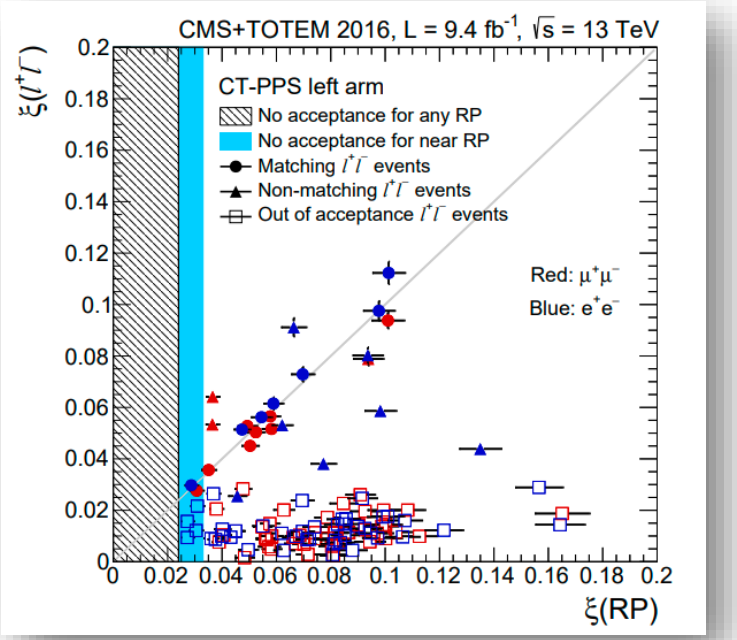


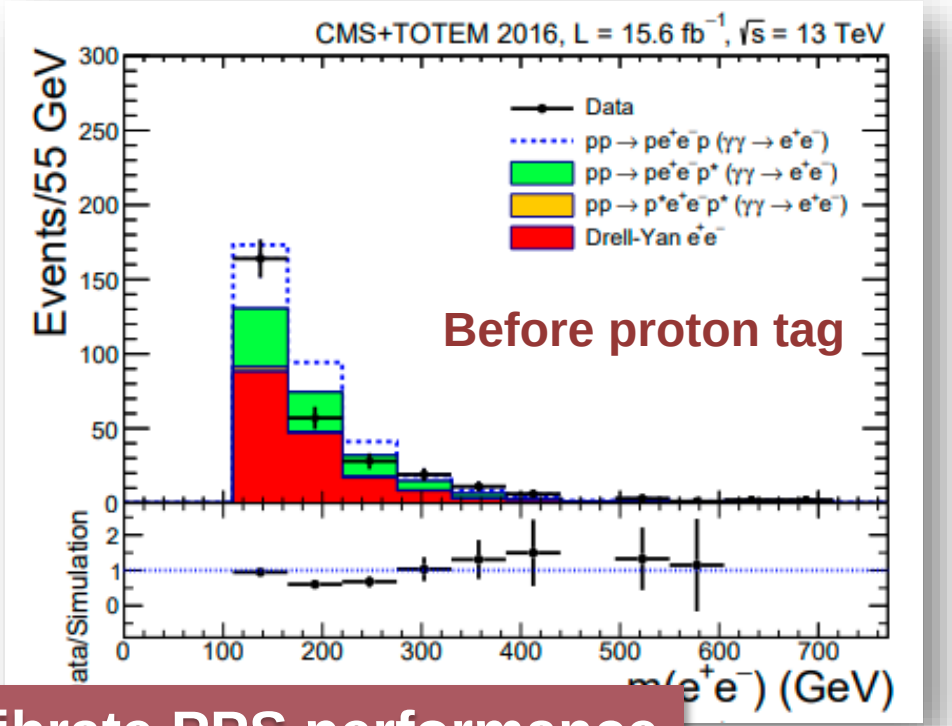
Physics | di-lepton events

JHEP 07 (2018) 153

Observation of (semi)-exclusive dilepton production

- Exclusive di-lepton production is the cleanest and most common CEP process
- PPS selects a clean sub-sample of signal events: $\xi_{\pm} = \frac{1}{\sqrt{s}}\left[p_T(l_1)e^{\pm\eta(l_1)} + p_T(l_2)e^{\pm\eta(l_2)}\right]$





20 Total events observed (12μμ, 8ee)

Estimated 4

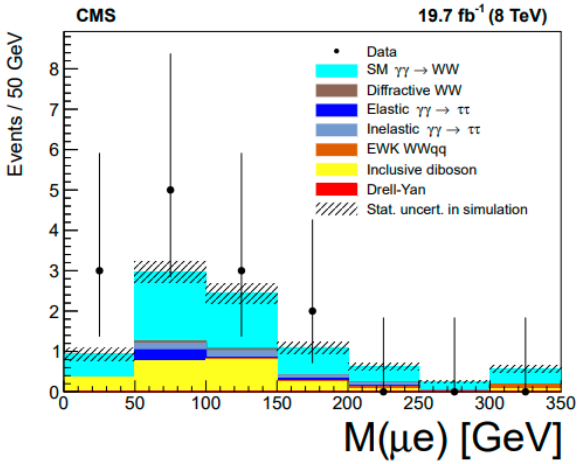
(Semi)-exclusive di-muons used to calibrate PPS performance

CMS-PAS-SMP-21-014

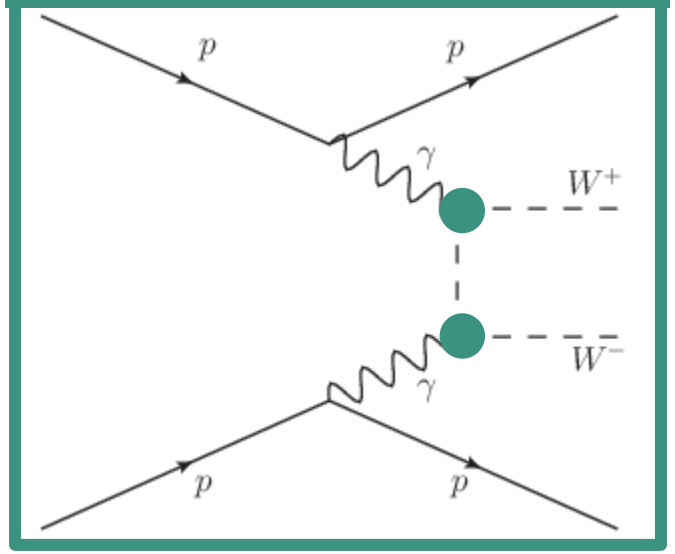
Exclusive production of weak bosons

- Exclusive WW production is the second most common CEP process
  - Sensitive to TGC and QGC
  - QGC enhance high mass spectra
  - Run 1 results w/o proton tagging:

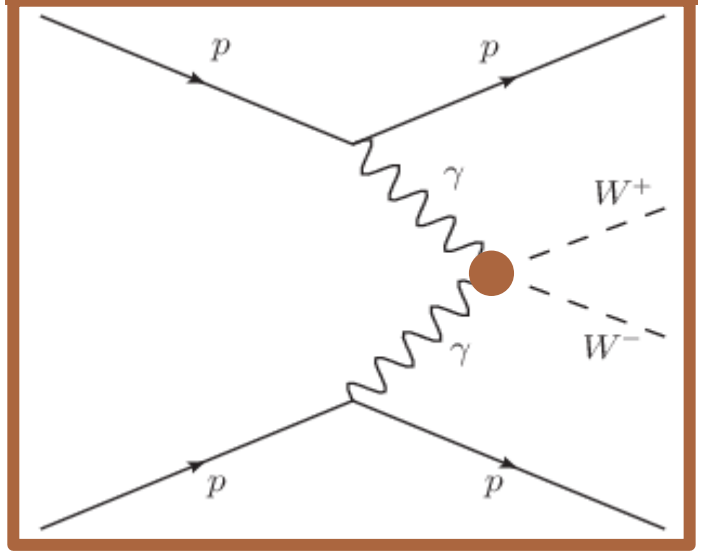
JHEP 08 (2016) 119



Triple Gauge Coupling (TGC)



Quartic Gauge Coupling (QGC)



QGC probed in WW same-sign (PLB 809 (2020) 135710) and VBS WW (2205.05711)

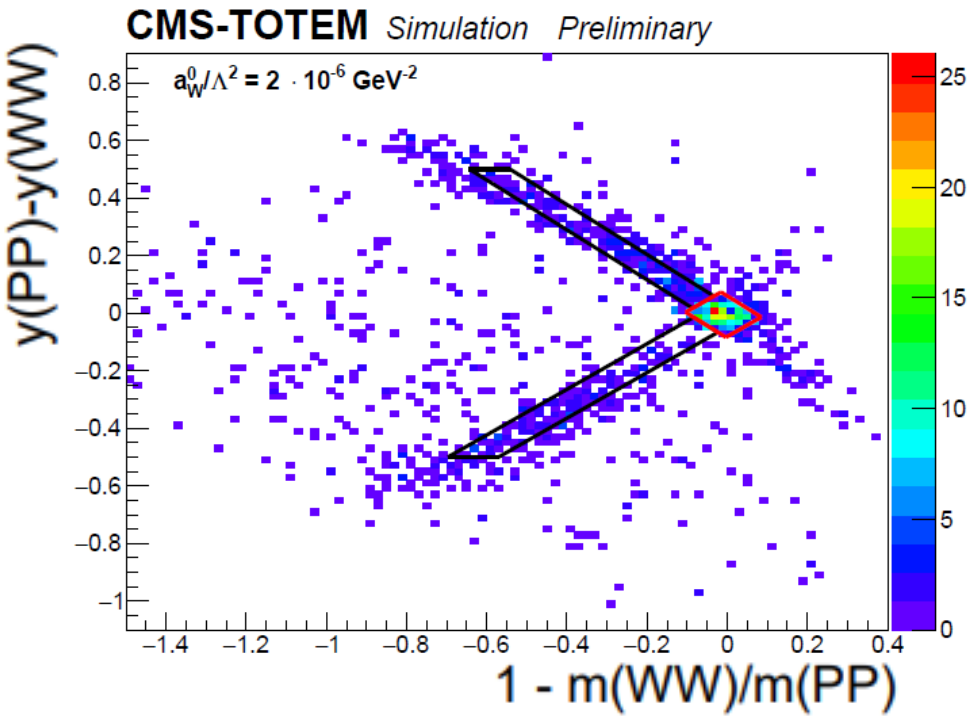
Physics | Exclusive VV

CMS-PAS-SMP-21-014

- Exclusive production of weak bosons (WW/ZZ)
  - Search with fully hadronic vector boson decays with 2 tagged protons with 100fb^{-1}
  - Signal region defined based on the correlation between central system and tagged protons

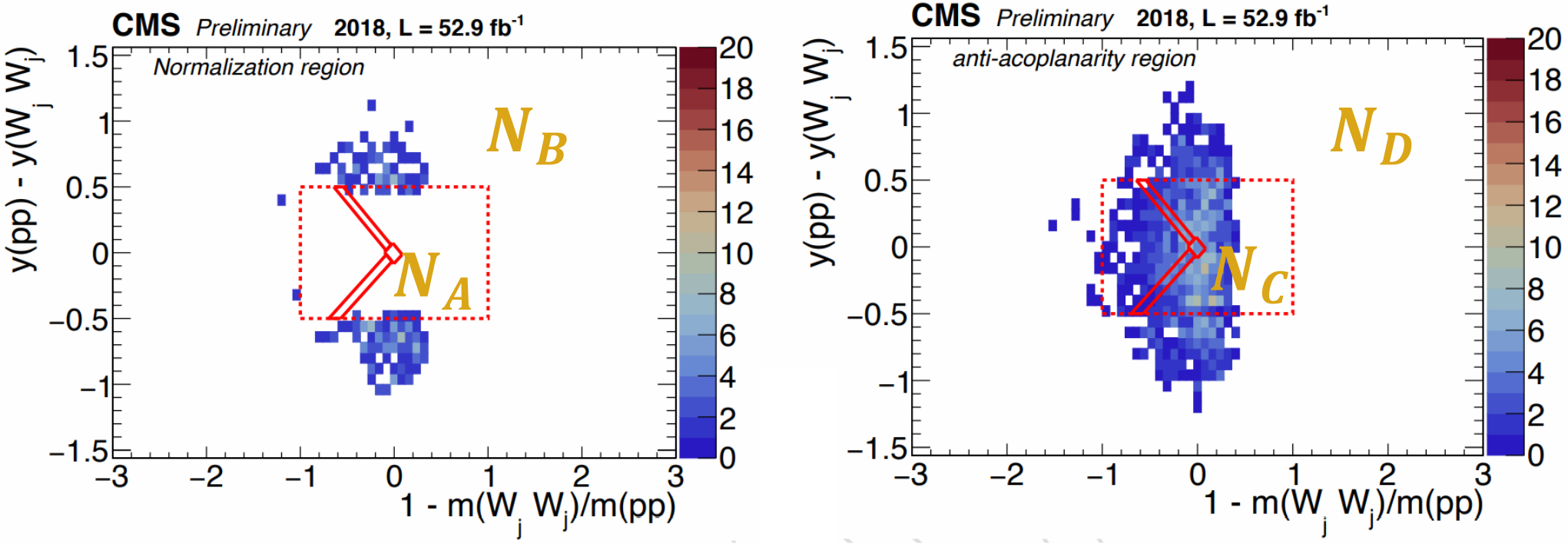
Event Selection

At Least two V-tagged AK8 jets
Jet pT > 200 GeV, $|\eta|<2.5$
$|\Delta\eta_{jj}|<1.3$, $1126<m_{jj}/\text{GeV}<2500$
Jet1 pT / jet2 pT < 1.3, $|1-\varphi_{jj}/\pi|<0.01$



CMS-PAS-SMP-21-014

- Exclusive production of weak bosons (WW/ZZ)
  - Background dominated by inclusive QCD dijet production
  - Estimated using the ABCD method – $N_A = N_B \cdot N_C / N_D$



Physics | Exclusive VV

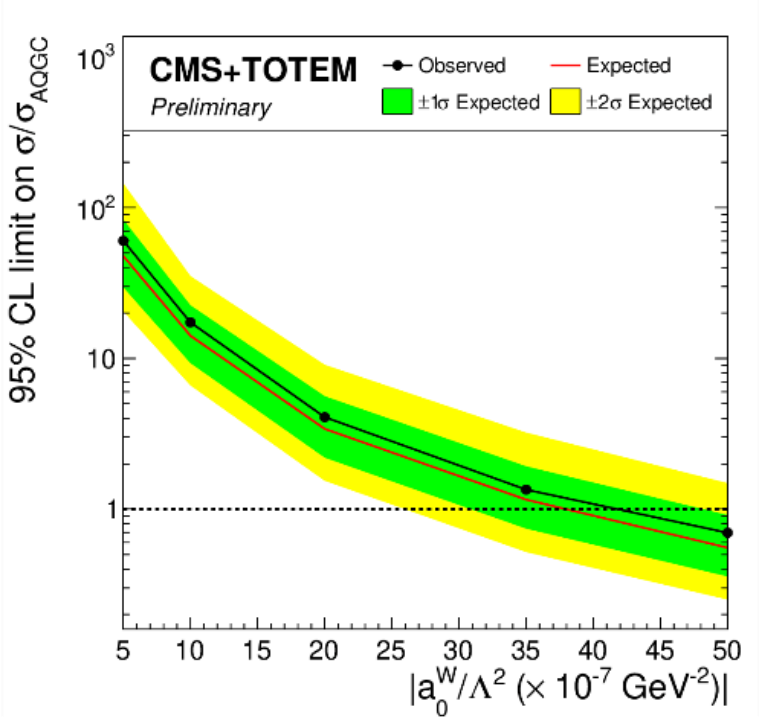
CMS-PAS-SMP-21-014

- Exclusive production of weak bosons (WW/ZZ)
  - Background dominated by inclusive QCD dijet production

- At high mass, SM cross-sections are very small.
- The obtained limit on SM fiducial cross-section:

$\boldsymbol{\sigma_{WW} < 67}$**fb and** $\boldsymbol{\sigma_{ZZ} < 43}$**fb** for $0.04 < \xi < 0.2$ and m>1TeV

- Limits on EFT operators were extracted



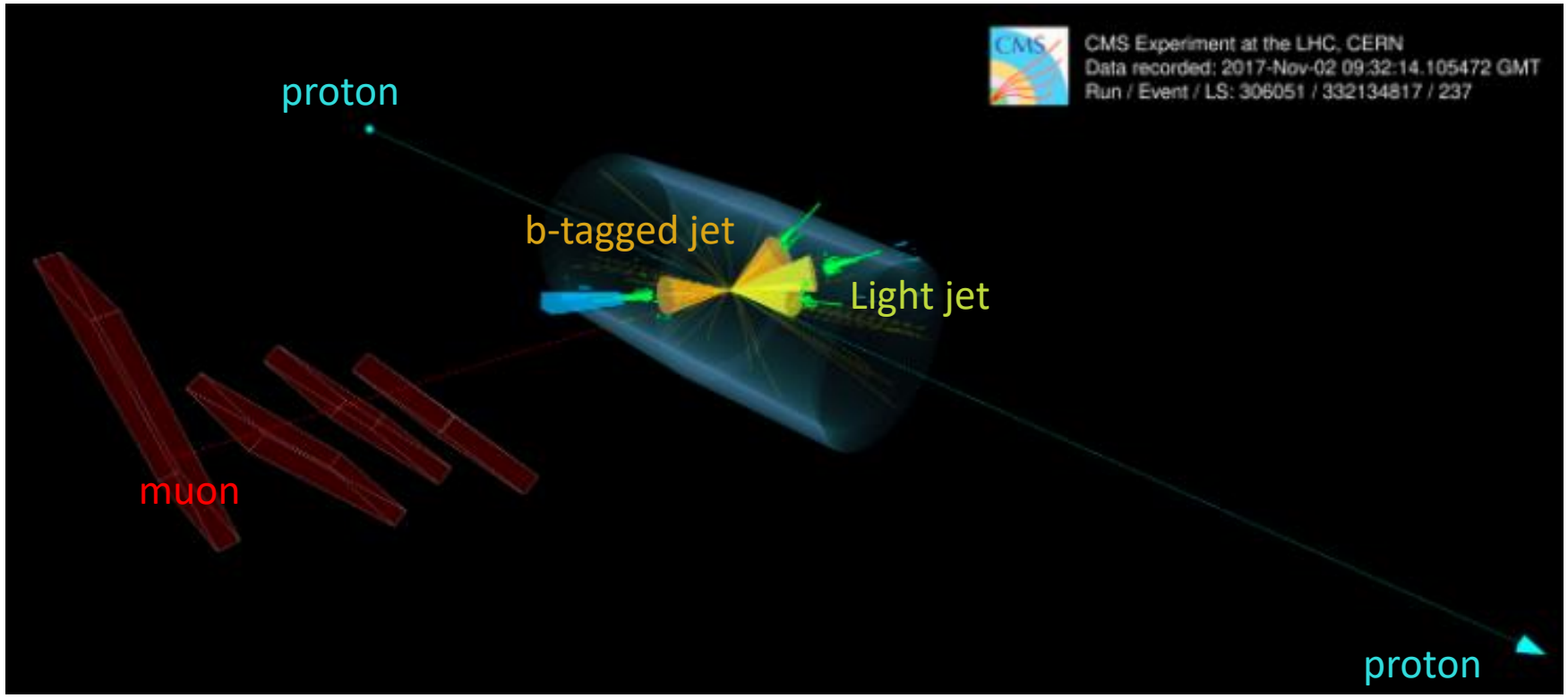
- Limit on γγWW is 15-20 times more stringent than Run1
- Competitive with the inclusive VBS measurements
- First limit on γγZZ coupling

$|a_0^W/\Lambda^2| < 4.3 \times 10^{-6}$ GeV^{-2}
$|a_C^W/\Lambda^2| < 1.6 \times 10^{-5}$ GeV^{-2}
$|a_0^Z/\Lambda^2| < 0.9 \times 10^{-5}$ GeV^{-2}
$|a_C^Z/\Lambda^2| < 4.0 \times 10^{-5}$ GeV^{-2}

Physics | Exclusive ttbar

CMS-PAS-TOP-21-007

- Exclusive production of top quark pairs
  - Searched in di-lepton and semi-leptonic ttbar decay mode.



https://cms.cern/news/detecting-creation-top-quarks-out-light

Physics | Exclusive ttbar

CMS-PAS-TOP-21-007

- Exclusive production of top quark pairs
  - Searched in **di-lepton** and **semi-leptonic** ttbar decay mode.

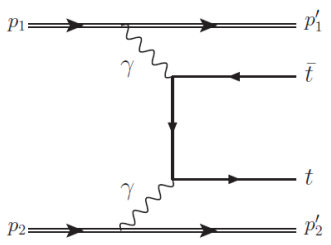
dilep channel ($\bar{t}t \rightarrow l\nu b + l\nu\bar{b}$)	**Semilep channel ($\bar{t}t \rightarrow l\nu b + jj\bar{b}$)**
Object selection	
Leptons: pT>30(20)GeV, |η|<2.1 Jets: pT>30GeV, |η|<2.4, ΔR(j,l)>0.4	Leptons: pT>30GeV, |η|<2.1(2.4) for e(μ) Jets: pT>25GeV, |η|<2.4, ΔR(j,l)>0.4
Event selection	
≥2 leptons (OS pair),|m(ll)-m(Z)|>15GeV ≥2 b-jets 1 proton / side	=1 lepton ≥2 b-jets, ≥2 non b-jets 1 proton / side

Physics | Exclusive ttbar

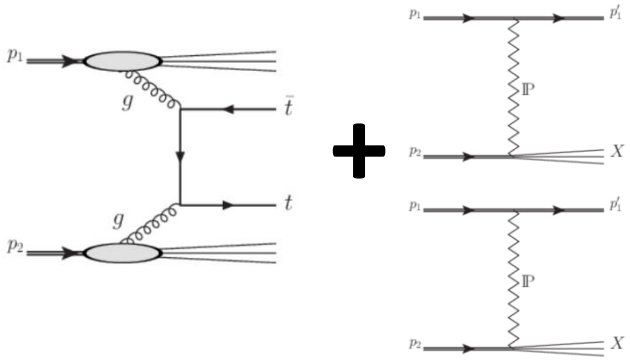
CMS-PAS-TOP-21-007

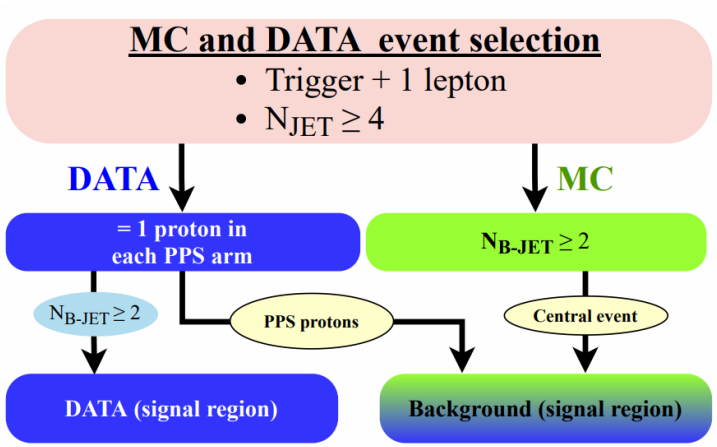
- Exclusive production of top quark pairs
  - Searched in di-lepton and semi-leptonic ttbar decay mode.
  - Challenging due to huge background rate
  - PU protons from data added to MC Simulation

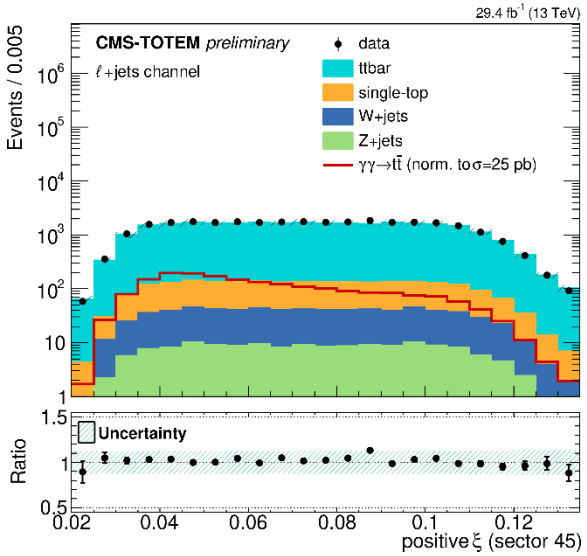
Signal



Background



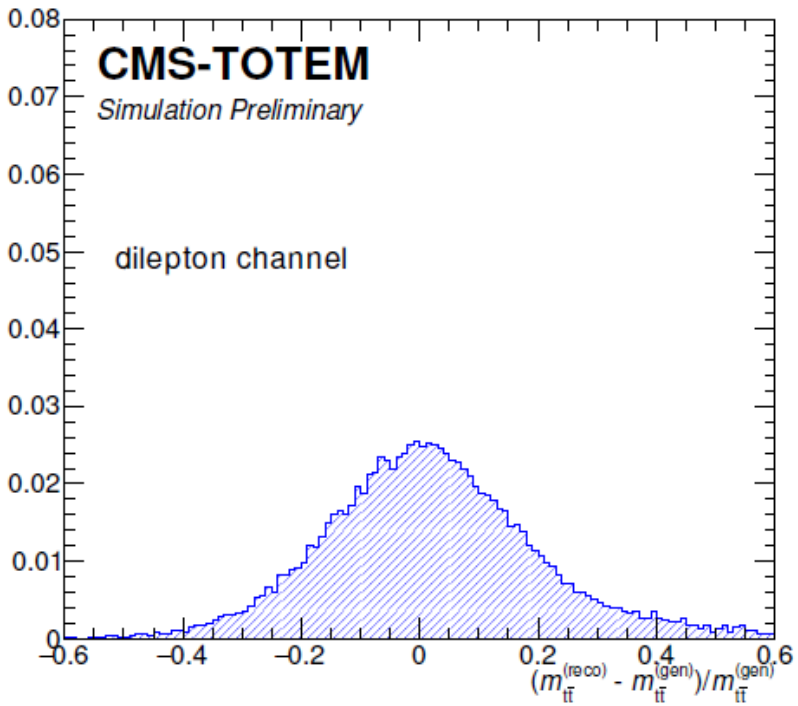


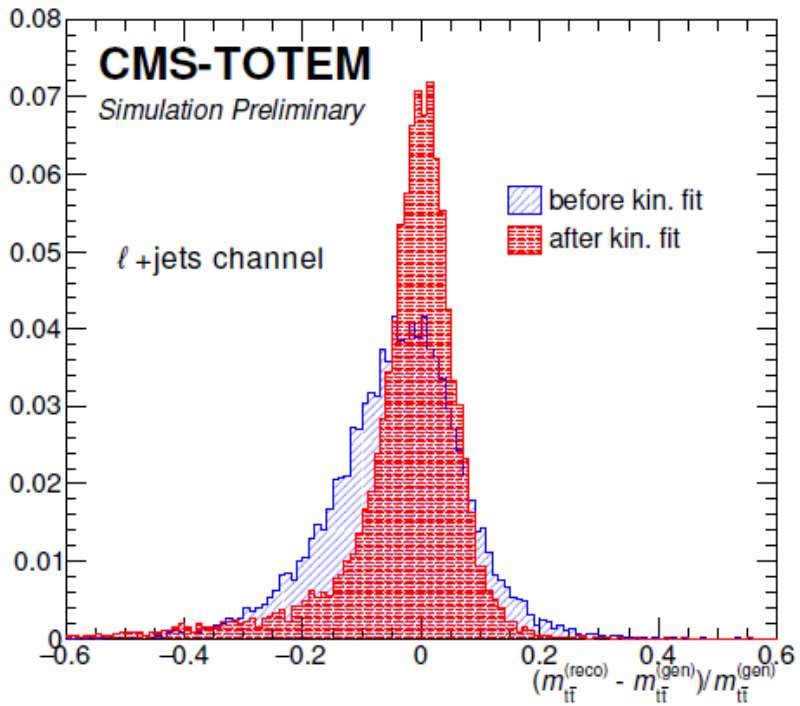


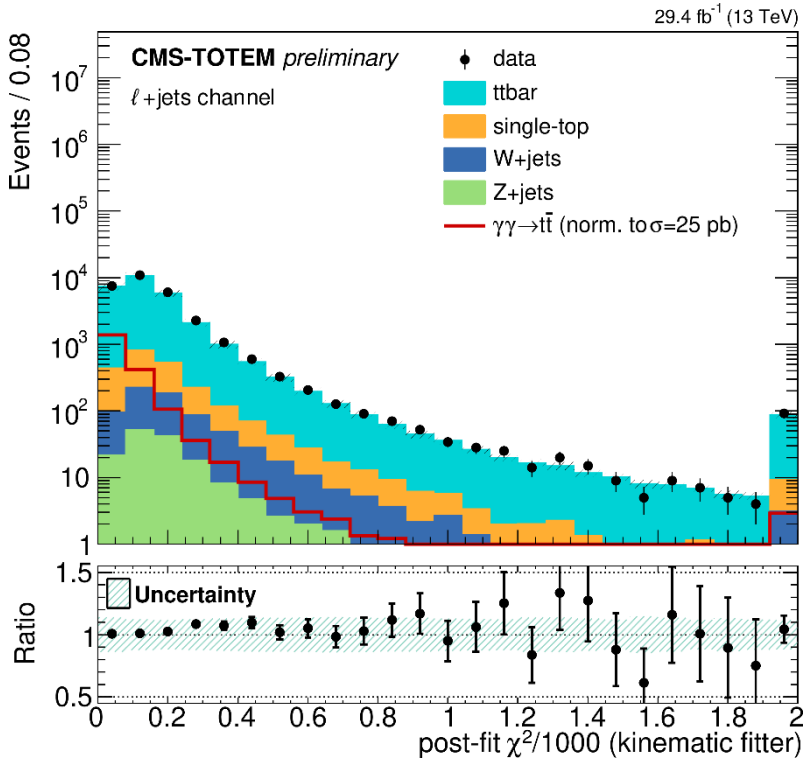
Physics | Exclusive ttbar

CMS-PAS-TOP-21-007

- Semi-leptonic analysis relies on kinematic-fitter:
  - Use t / W mass constraints to minimize $\chi^2 = \sum_{i=1}^{6} \frac{p_{x,i} - p_{x,i,initial}}{\sigma_{x,i}} + \sum_{i=1}^{6} \frac{p_{y,i} - p_{y,i,initial}}{\sigma_{y,i}} + \sum_{i=1}^{6} \frac{p_{z,i} - p_{z,i,initial}}{\sigma_{z,i}} + \sum_{j=1}^{2} \frac{\xi_j - \xi_{j,initial}}{\sigma_{\xi,j}}$
  - The output of the kinematic-fitter used as a discriminating variable



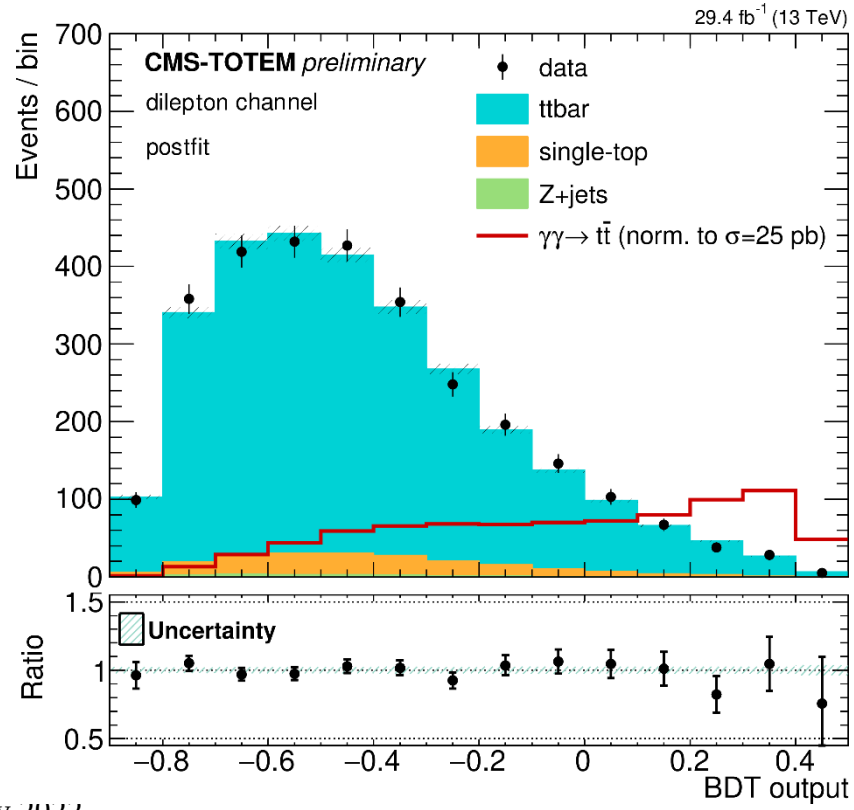




Physics | Exclusive ttbar

CMS-PAS-TOP-21-007

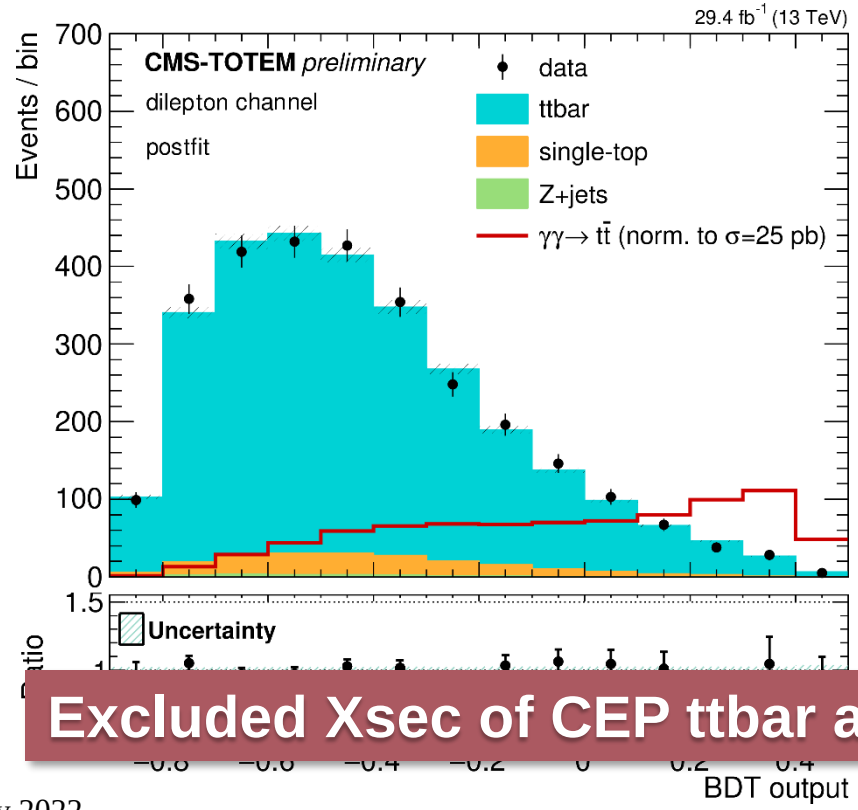
- Exclusive production of top quark pairs
  - Multivariate Analysis (MVA) approach developed to tag exclusive ttbar events

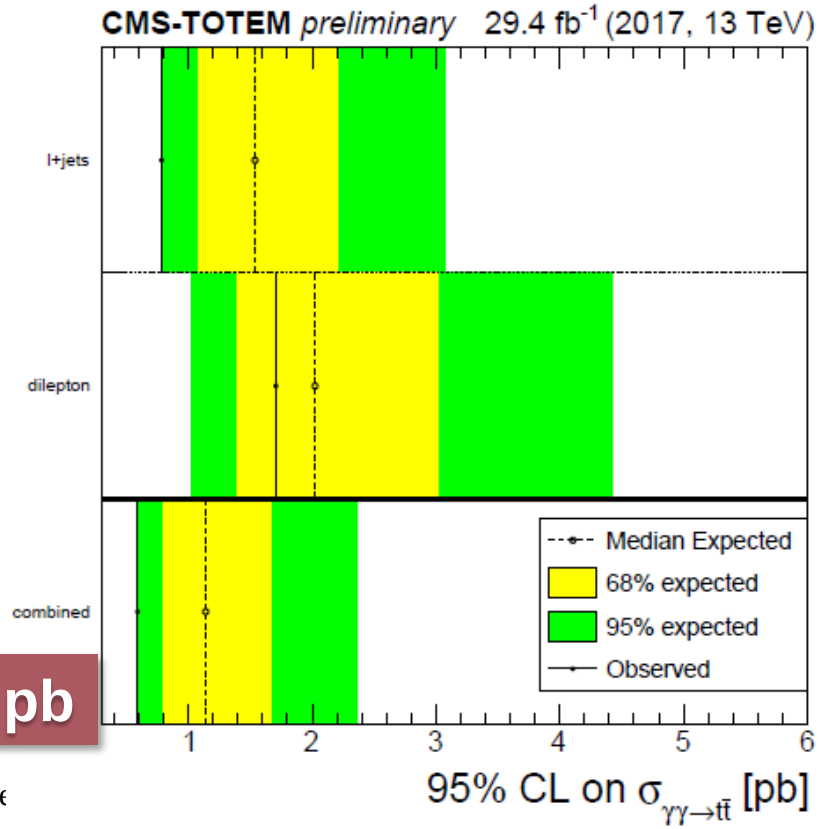


Physics | Exclusive ttbar

CMS-PAS-TOP-21-007

- Exclusive production of top quark pairs
  - Multivariate Analysis (MVA) approach developed to tag exclusive ttbar events
  - Results were interpreted as an upper limit of the CEP of top quark pairs

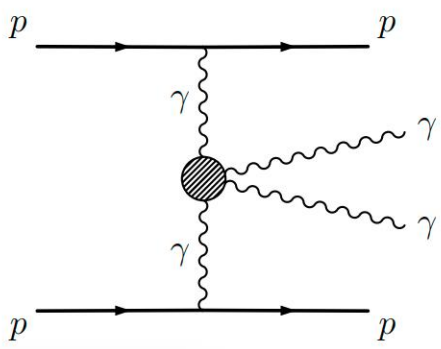




Excluded Xsec of CEP ttbar above 0.6 pb

Physics | exclusive diphoton

arXiv: 2110.05916, accepted by PRL



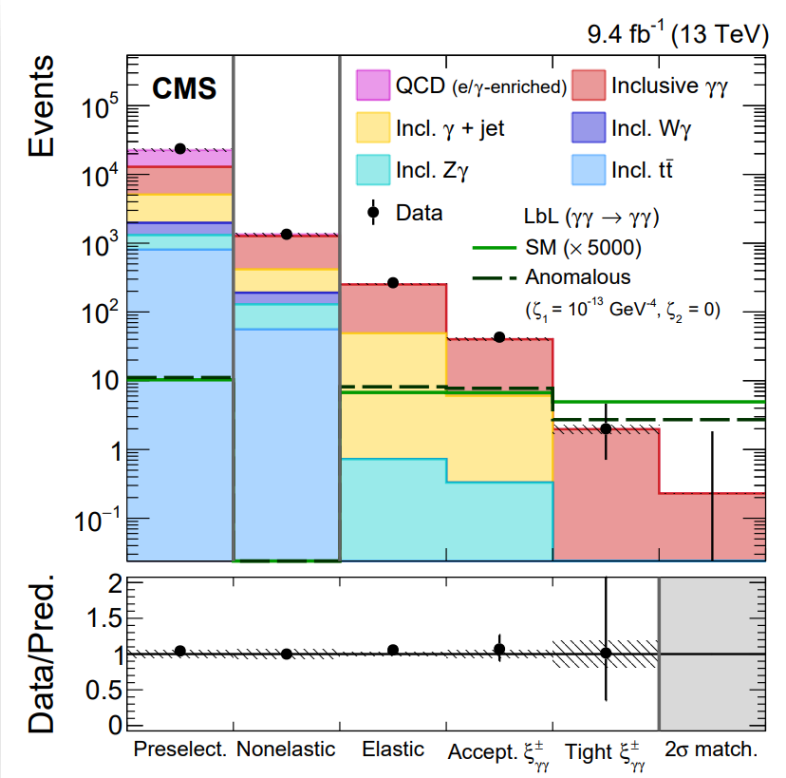
- Light-by-light scattering
  - Motivated by sensitivity to BSM :

PRD 89 (2014) 114004, JHEP 1502 (2015) 165, *JHEP 1806 (2018) 131*

- Almost background free after requiring matching between proton and photon kinematics

- First measurement with 2016 (~10fb^{-1}) publish the first limit on 4-photon coupling!

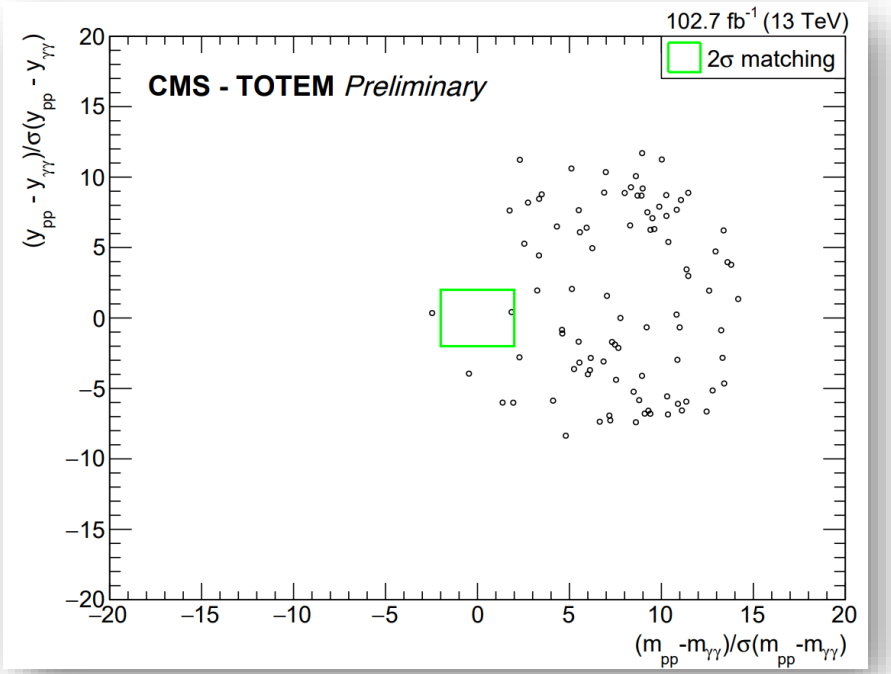
$$|\zeta_1| < 2.9 \times 10^{-13}\ \text{GeV}^{-4}\ (\zeta_2 = 0)$$
$$|\zeta_2| < 6.0 \times 10^{-13}\ \text{GeV}^{-4}\ (\zeta_1 = 0)$$

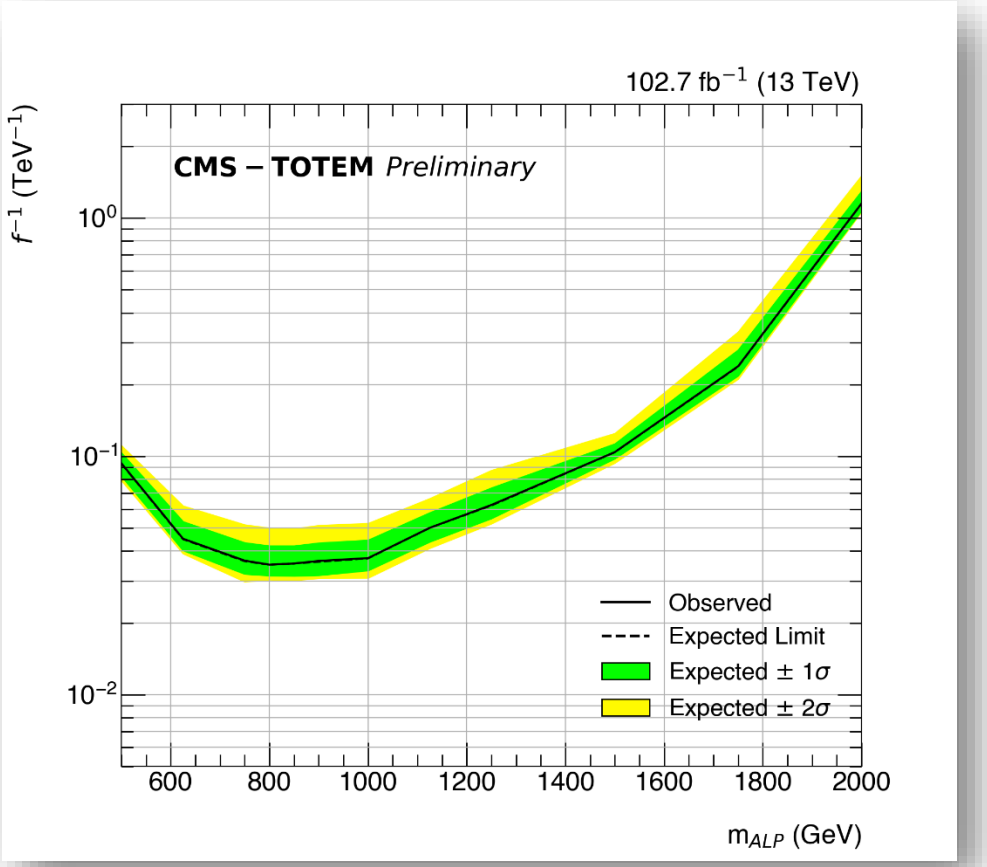


Physics | exclusive diphoton

NEW! CMS-PAS-EXO-21-007

- The full Run 2 data – low background





- Limit on 4-photon coupling improved by x4(!)

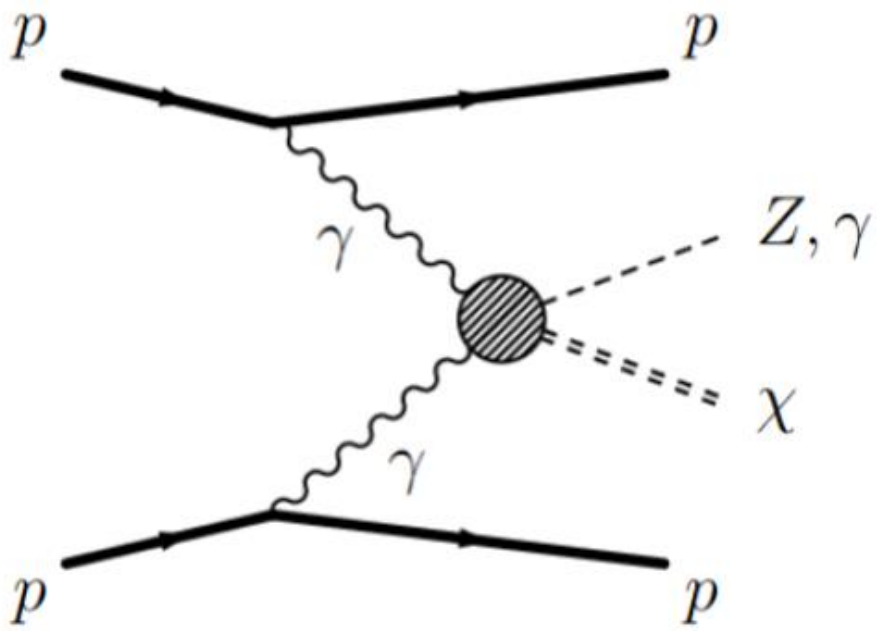
$$|\zeta_1| < 7.3 \times 10^{-14}\ \text{GeV}^{-4}\ (\zeta_2 = 0)$$
$$|\zeta_2| < 1.5 \times 10^{-13}\ \text{GeV}^{-4}\ (\zeta_1 = 0)$$

First search for ALPs in mass range between 500 GeV to 2000 GeV

Physics | Missing mass (Z/γ+X)

CMS-PAS-EXO-19-009

- Searching for unknown particles using the “missing mass”
  - Implemented for the first time in hadron collider, based on 4π event reconstruction

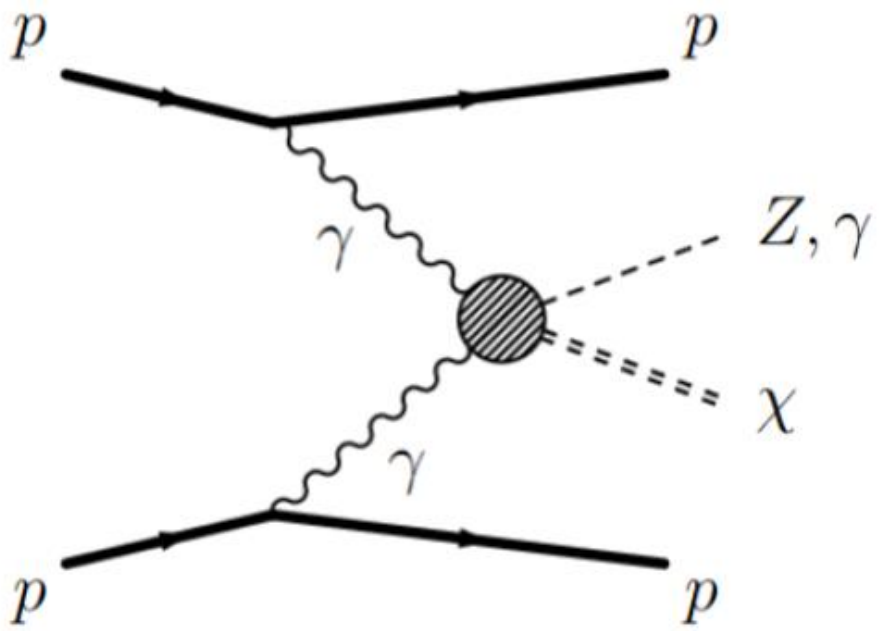


Physics | Missing mass (Z/γ+X)

CMS-PAS-EXO-19-009

- Searching for unknown particles using the "missing mass"
  - Implemented for the first time in hadron collider, based on 4π event reconstruction
  - The 4-vector of unknown state χ is determined from protons and measured boson

$$m^2_{\text{miss}} = \left[(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2}) - (P_V + P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}) \right]^2$$

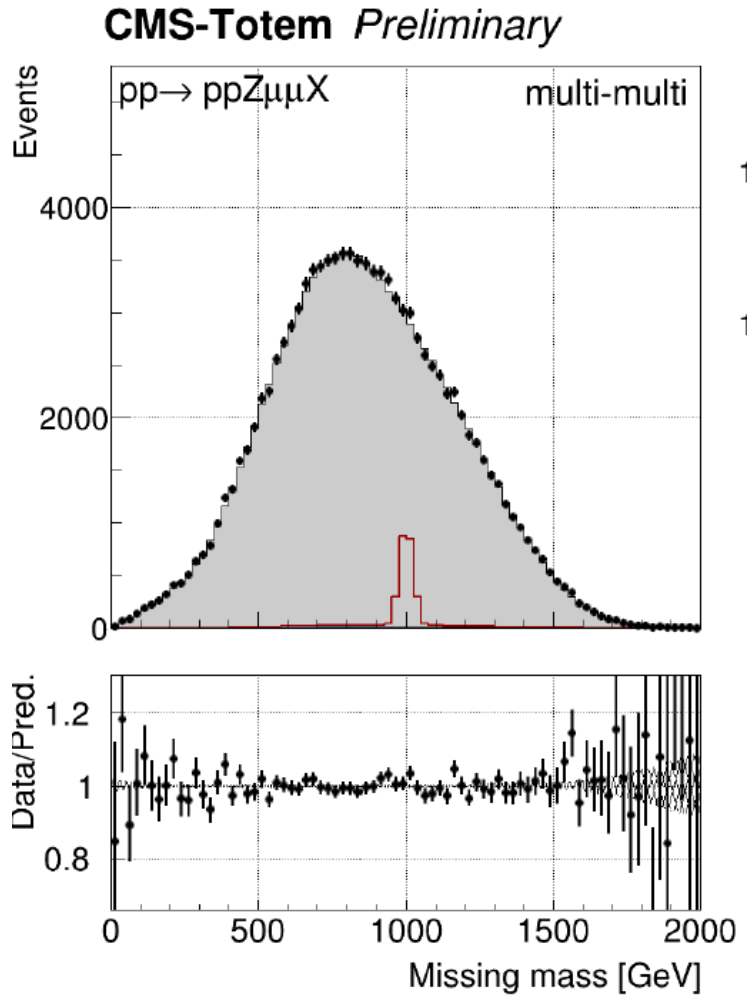


  - Bump hunt of mass of χ state is performed in Z+χ and γ+χ channels

Physics | Missing mass (Z/γ+X)

CMS-PAS-EXO-19-009

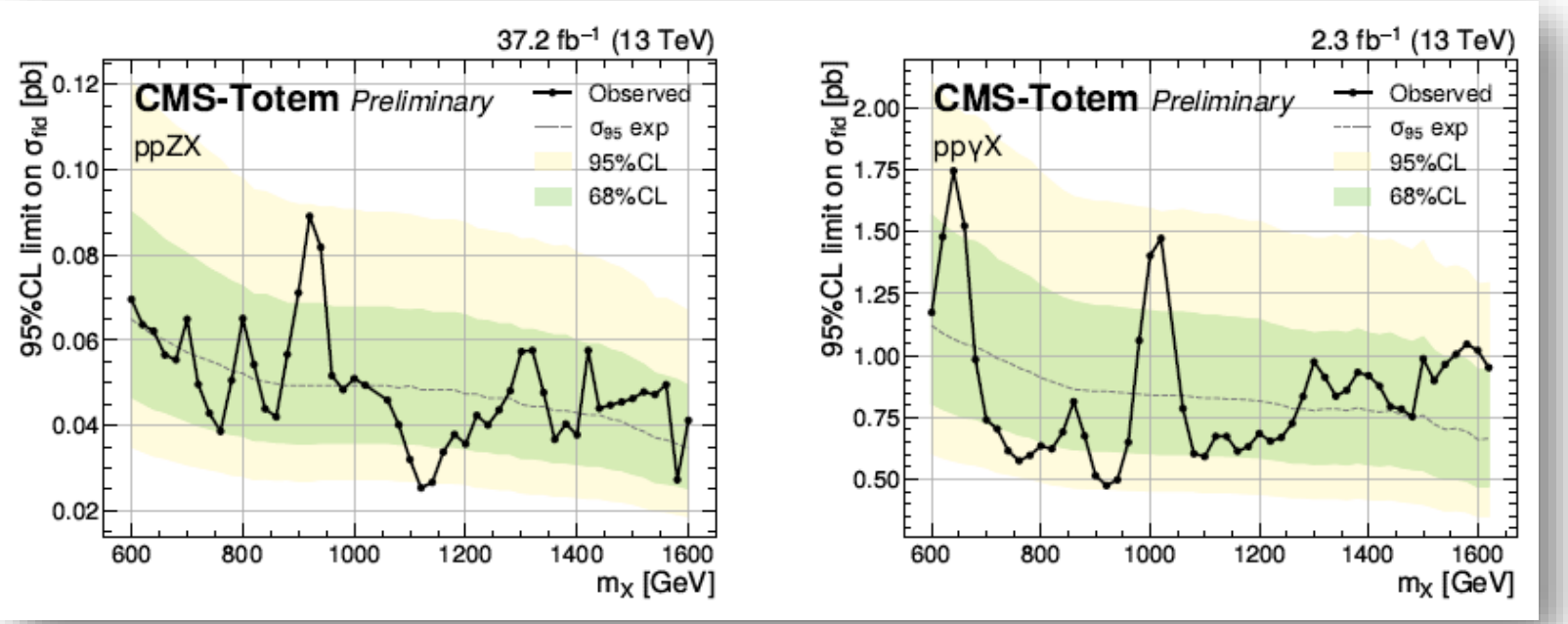
- Searching for unknown particles using the “missing mass”
  - Benefit from supreme mass resolution

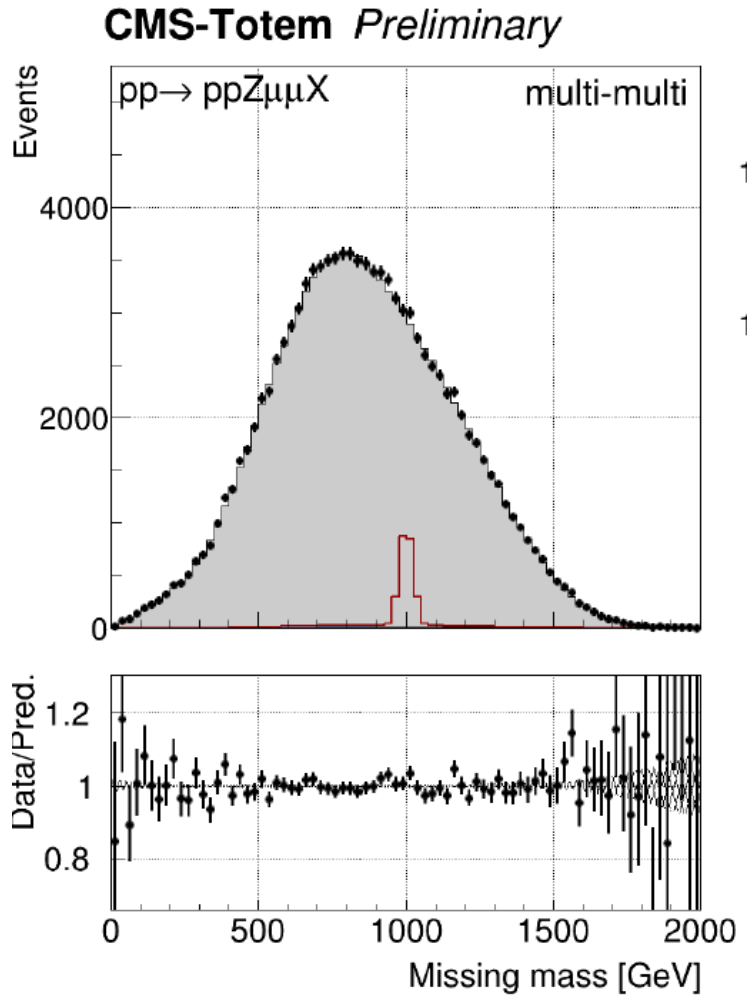


Physics | Missing mass (Z/γ+X)

CMS-PAS-EXO-19-009

- Searching for unknown particles using the "missing mass"
  - Benefit from supreme mass resolution
  - Data agree with the background-only model, a limit on the production cross-section of Z/γ+χ was derived

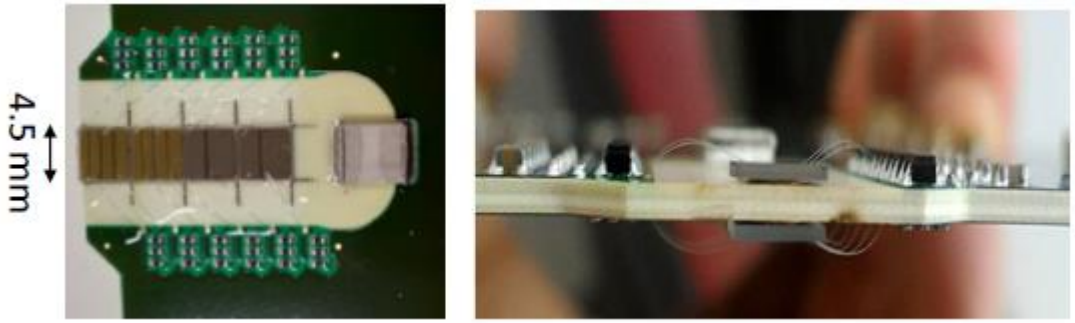




Looking forward

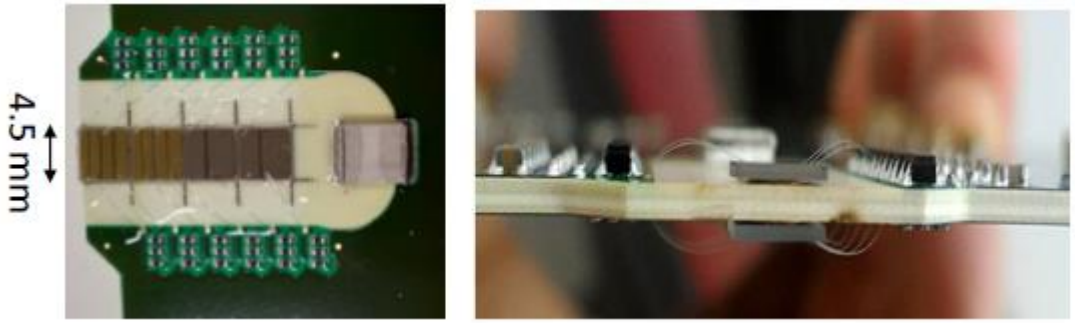
PPS in Run 3

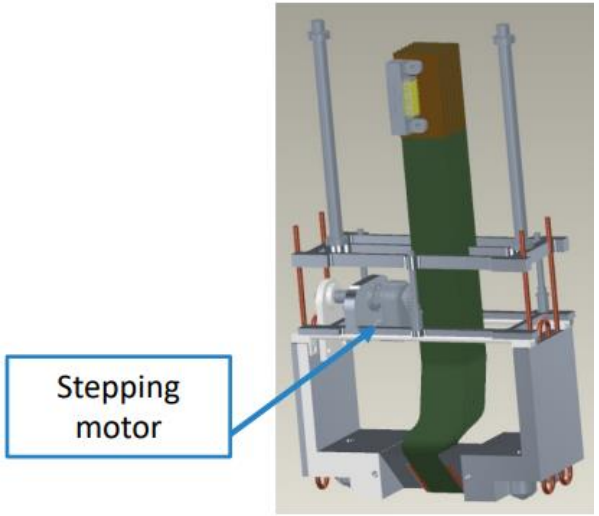
- Several detector upgrades are taking place
  - Timing detectors: two new stations, Double-Diamond detectors in all planes, with a goal of < 30 ps (<1 cm vertex resolution) × **10 *less background***



PPS in Run 3

- Several detector upgrades are taking place
  - Timing detectors: two new stations, Double-Diamond detectors in all planes, with a goal of < 30 ps (<1 cm vertex resolution) $\times$ **10 *less background***
  - New Silicon pixel tracker with internal motion **Efficiency to lower ξ**

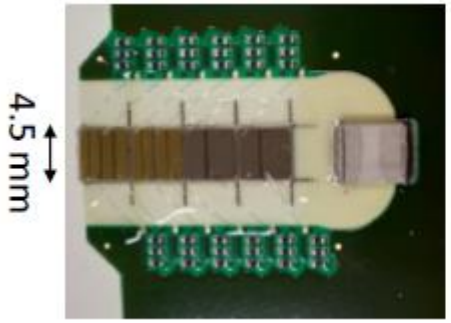


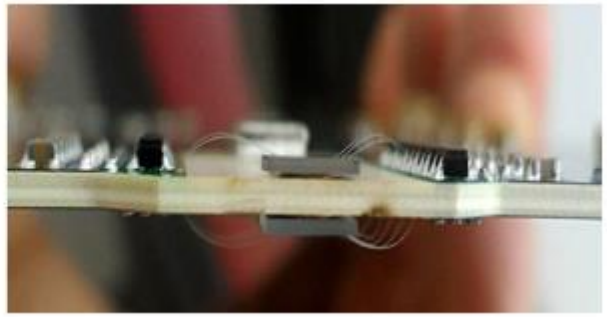


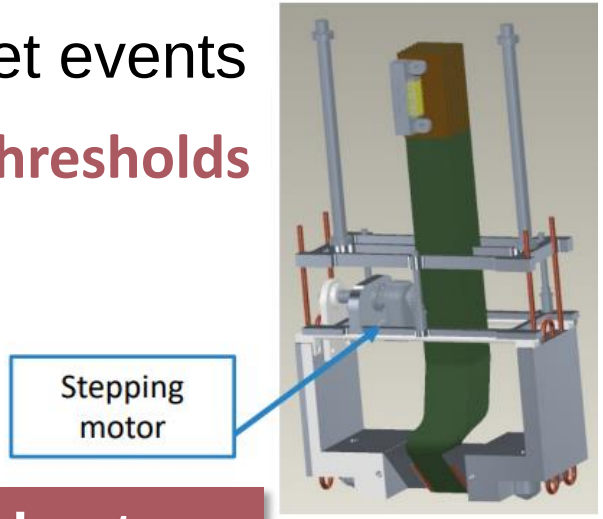
PPS in Run 3

- Several detector upgrades are taking place
  - Timing detectors: two new stations, Double-Diamond detectors in all planes, with a goal of < 30 ps (<1 cm vertex resolution) $\times$ **10 *less background***
  - New Silicon pixel tracker with internal motion **Efficiency to lower ξ**
  - Dedicated HLT line with proton tag for hadronic WW / multijet events

Lower trigger thresholds







While $\mathcal{L} \rightarrow x2$, sensitivity to searches will increase by ~4-5, due to improved acceptances (tracking) and background rejection (timing)

PPS in Run 3

- Several detector upgrades are taking place
  - PPS Will continue to operate in Run 3
  - By the end of Run 3, PPS will be dismounted
  - Since after LS3 the whole beamline will be rearranged, a new spectrometer design is proposed
  - HL-LHC PPS research proposal: CMS-NOTE-2020-008

nd

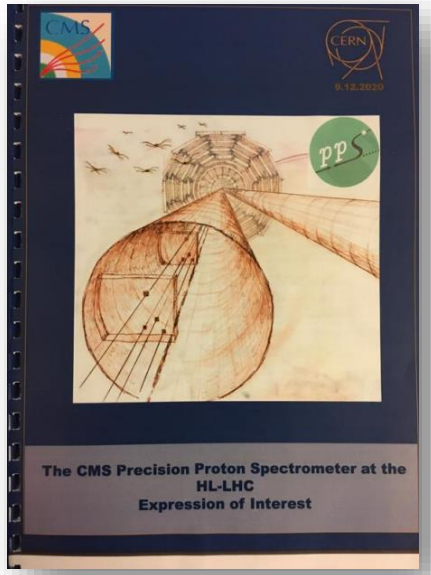
While $\mathcal{L} \rightarrow x2$, sensitivity to searches will increase by ~4-5, due to improved acceptances (tracking) and background rejection (timing)

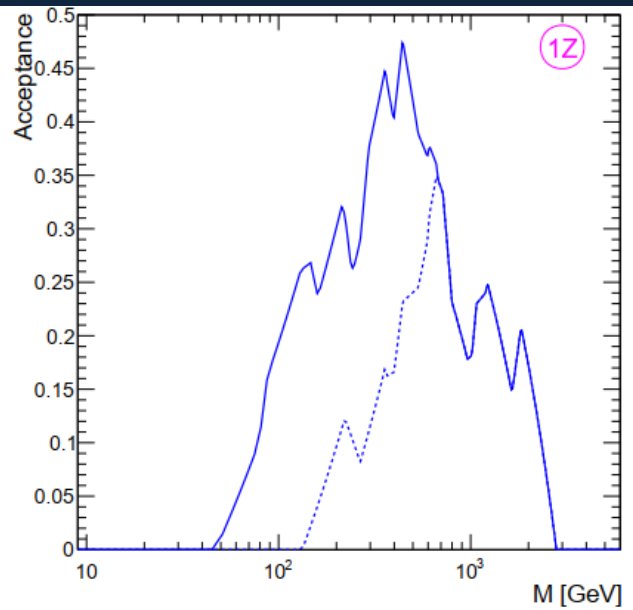
PPS in HL-LHC

CMS-NOTE-2020-008, arxiv:2103.02752

- New proposal with extended mass range:
  - 133 GeV – 2.7 TeV for the first 3 stations
  - 43 GeV – 2.7 TeV for all stations

Run 2+3 acceptance between 350 and 2 TeV





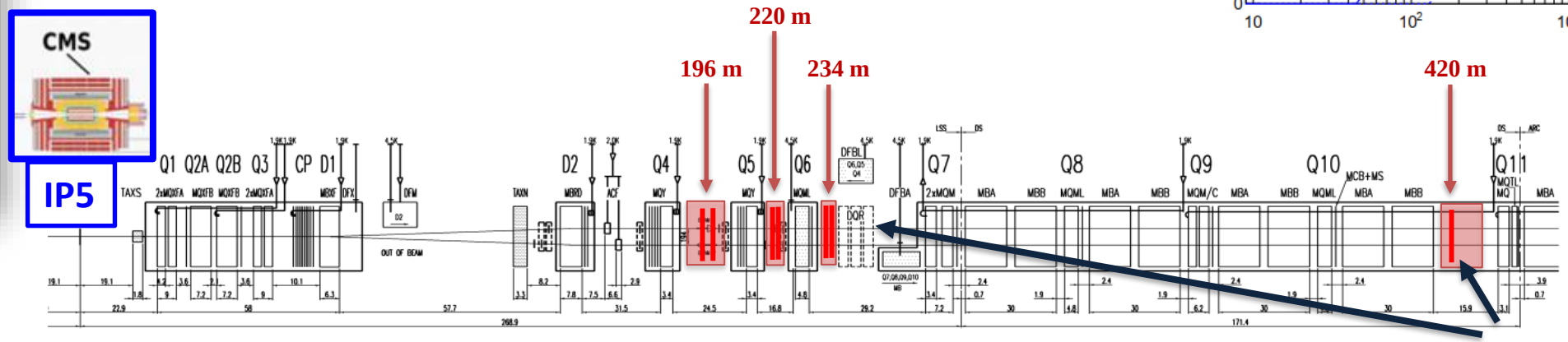


Figure 13: Layout of Long Straight Section LSS5 (Sector 5-6) at HL-LHC [63].

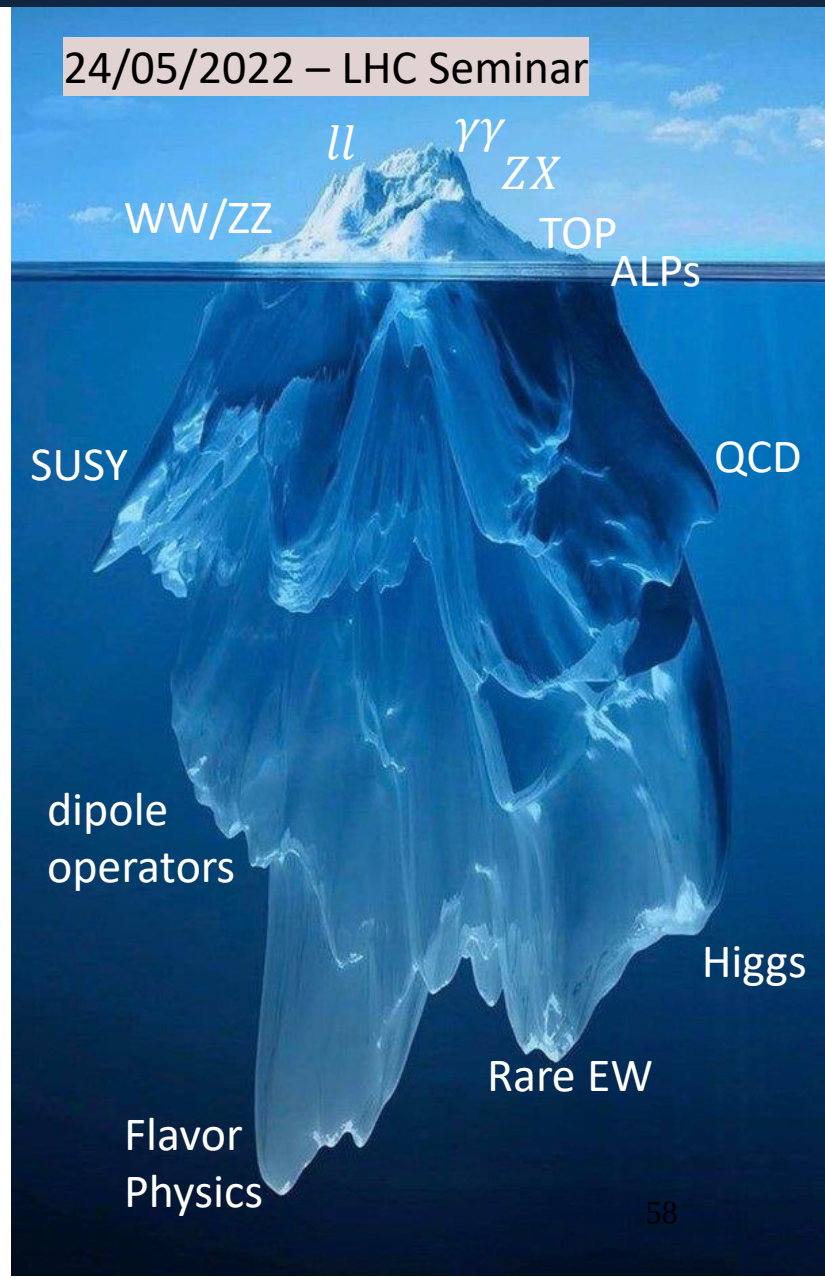
Staged installation

Extends current LHC physics program (WW, di-τ, top, ALPs, SUSY, etc…)

Summary

- Run 2:
  - First set of results delivered by CMS using the PPS sub-detector
  - Many more analysis are in progress
- Run 3:
  - Expecting increase in sensitivity by factor 4-5(!!!)
  - High expectation from Run 3 results
- HL-LHC:
  - Feasibility studies are ongoing in context of a TDR

Stay tuned for more new exiting results



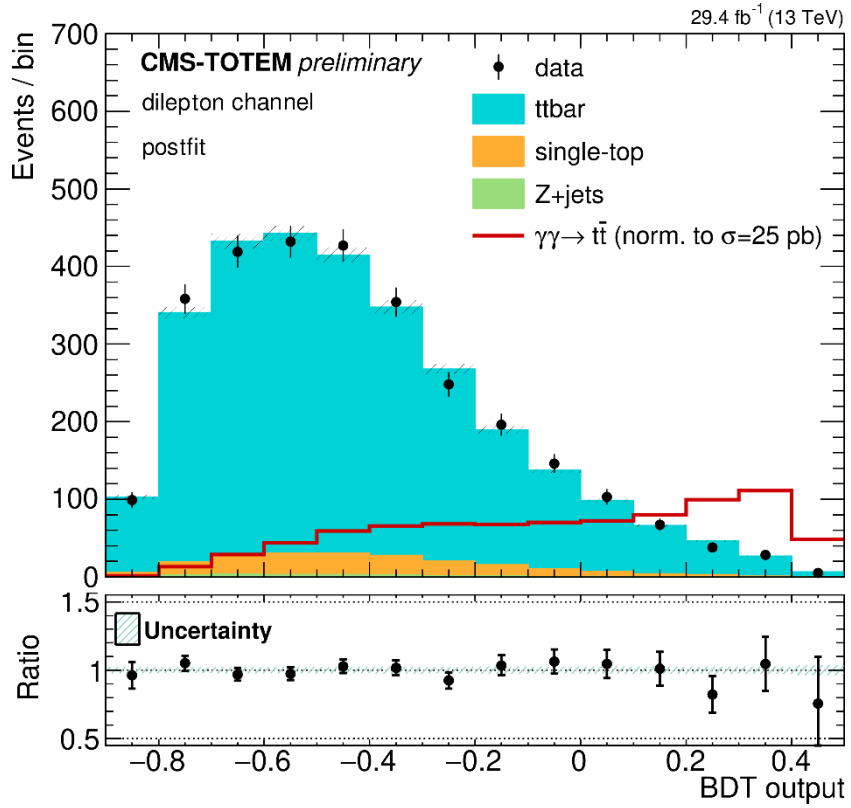
Backup

Physics | Exclusive ttbar

CMS-PAS-TOP-21-007

Exclusive production of top quark pairs

- Multivariate Analysis (MVA) approach developed to tag exclusive ttbar events



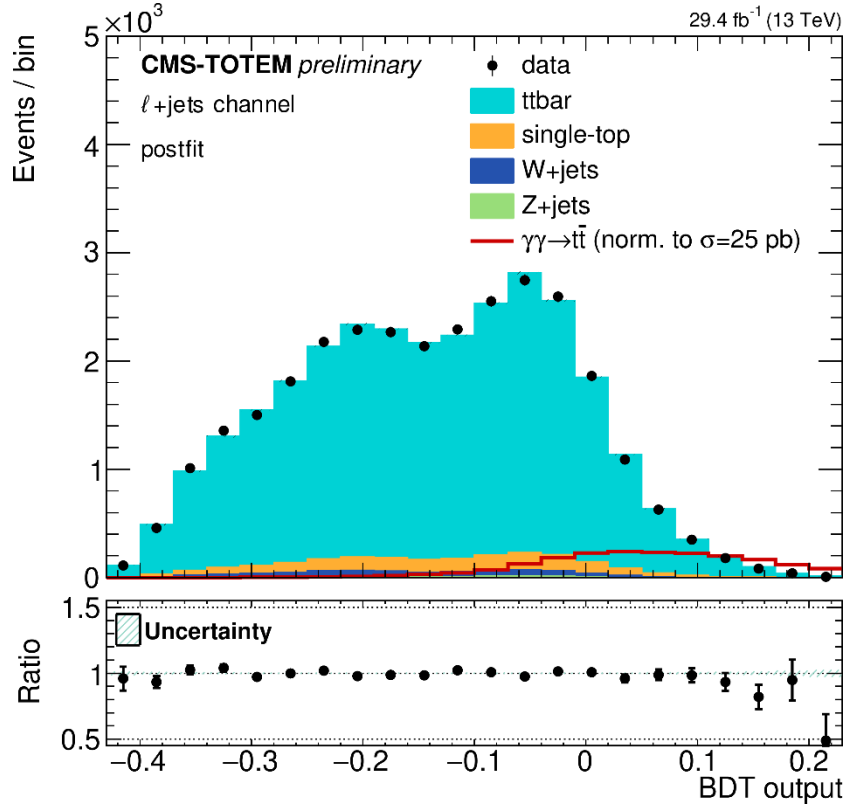
15 variables used in MVA:

- The mass and the rapidity of the central system reconstructed both from the tt decay products and from proton kinematics
- Missing energy, the number of light-flavour jets
- The invariant mass and the angular distance ΔR of the two leptons
- |Δϕ| of the two selected b-tagged jets
- the rapidity of the system formed by the two b-jets and the two leptons, and the sum of the absolute values of their individual rapidities
- the rapidity of the system formed by all other reconstructed jets, and the sum of the absolute values of their individual rapidities
- the squared energy sum for all objects used for the tt reconstruction
- the minimum absolute value of the rapidity difference for any two systems formed by a lepton and a b-tagged jet

Physics | Exclusive ttbar

CMS-PAS-TOP-21-007

- Exclusive production of top quark pairs
  - Multivariate Analysis (MVA) approach developed to tag exclusive ttbar events



10 variables used in MVA:

- Number of light-flavour jets and of b-tagged jets
- Sum of the invariant mass of all jets
- Total energy of all lightflavour jets
- Mean ΔR for all pairs of light-flavour jets
- Total energy of all extra jets (not used for tt reconstruction)
- Lepton momentum and its isolation
- Difference in central system rapidity reconstructed from the tt and the pp systems
- χ2 of the kinematic fit

Introduction

- (Elastic) Photon-Photon collisions at the LHC:

$$\frac{dN_X}{dt} = \int \hat{\sigma}_{\gamma\gamma\to X} \frac{d\mathcal{L}_{eff}}{dm} dm$$

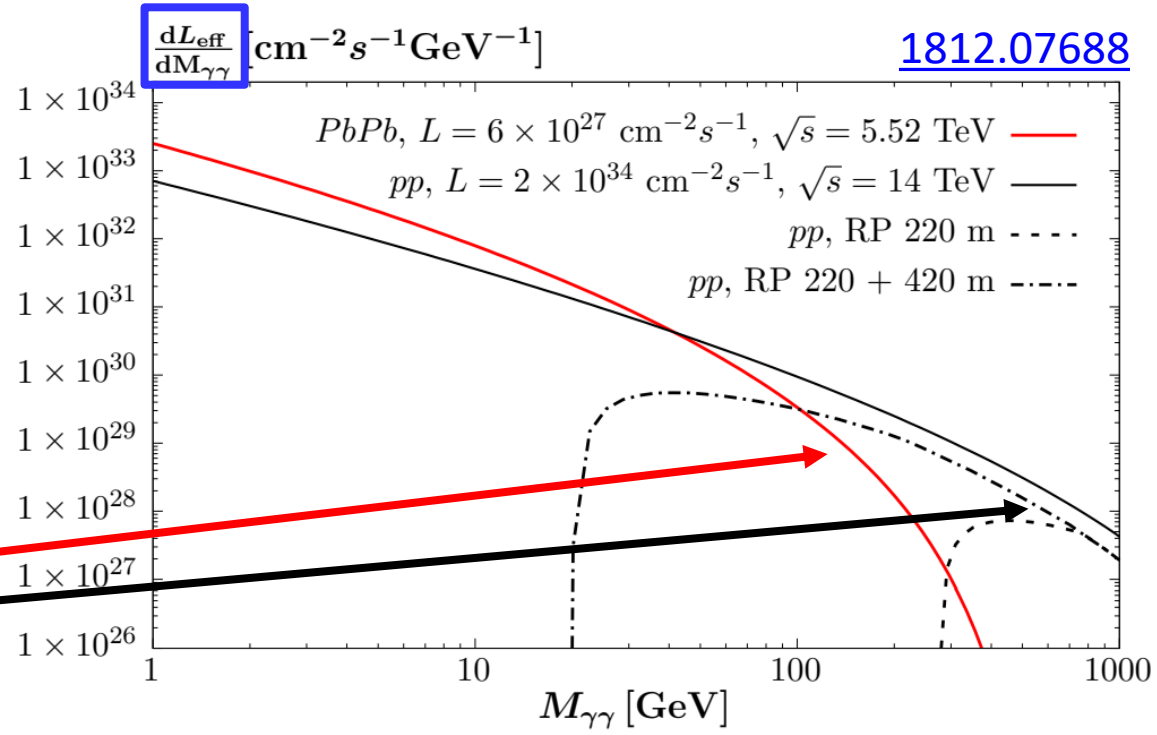
Photon energy is related to charge size:

- Transverse momentum

$k_\perp < 1/R$ (0.06GeV for **Pb**, 0.3GeV for **p**)

- Longitudinal momentum

$E < \gamma/R$ (80GeV for **Pb**, 2TeV for **p**)

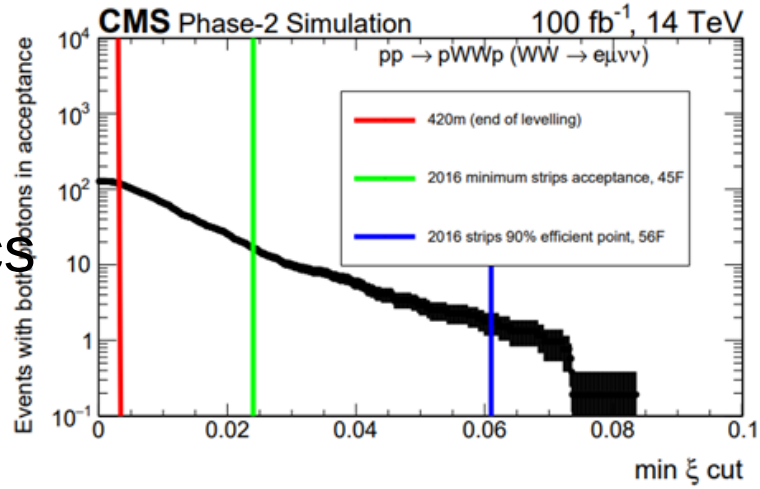


Photon fluxes are harder in pp collisions

PPS in HL-LHC

CMS-NOTE-2020-008

- Electro-weak physics:
  - Exclusive WW gives stringent constraints on new physics
  - Exclusive di-tau to constrain electromagnetic moments
- TOP physics:
  - Near-threshold production of ttbar (although Xsec~0.1fb)
- BSM physics:
  - Best sensitivity to ALPs
  - SUSY program is complementary to LHC searches



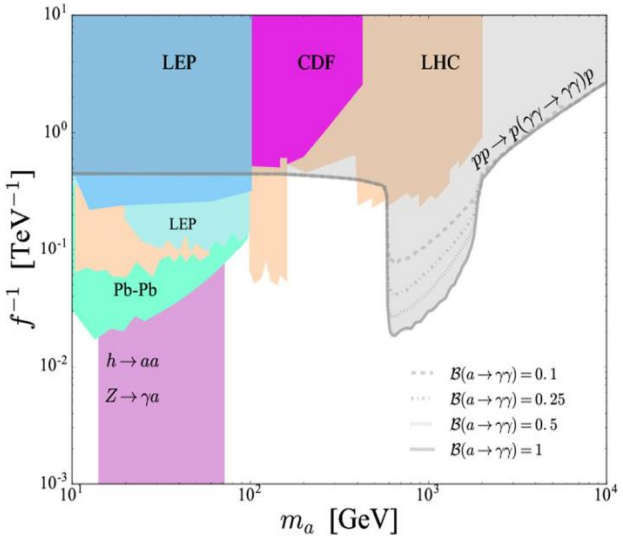


Figure 2: Exclusion regions on the ALP–photon coupling and mass plane. The light-shaded grey regions show the expected 95% CL exclusion limit for 300 fb^{-1} in central exclusive diphoton production events for different branching ratios of the ALP into two photons [16].

[16] C. Baldenegro, S. Fichet, G. von Gersdorff and C. Royon, "Searching for axion-like particles with proton tagging at the LHC", JHEP **1806**, 131 (2018), doi:10.1007/JHEP06(2018)131 , [arXiv:1803.10835 [hep-ph]].

Physics | Exclusive VV

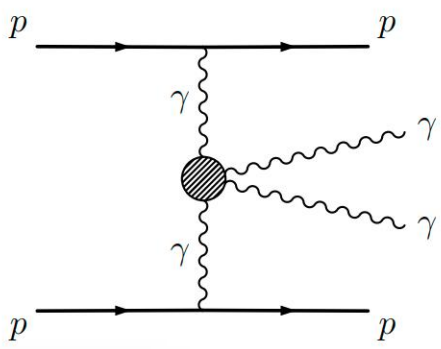
CMS-PAS-SMP-21-014

- Exclusive production of weak bosons (WW/ZZ)

Coupling	Observed (expected) 95% CL upper limit
$\lvert f_{M,0}/\Lambda^4 \rvert$	66.0 (60.0) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4 \rvert$	245.5 (214.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4 \rvert$	9.8 (9.0) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4 \rvert$	73.0 (64.6) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4 \rvert$	36.0 (32.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4 \rvert$	67.0 (58.9) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4 \rvert$	490.9 (429.6) TeV^{-4}

Physics | exclusive diphoton

arXiv: 2110.05916, accepted by PRL



- Light-by-light scattering
  - Motivated by sensitivity to BSM :

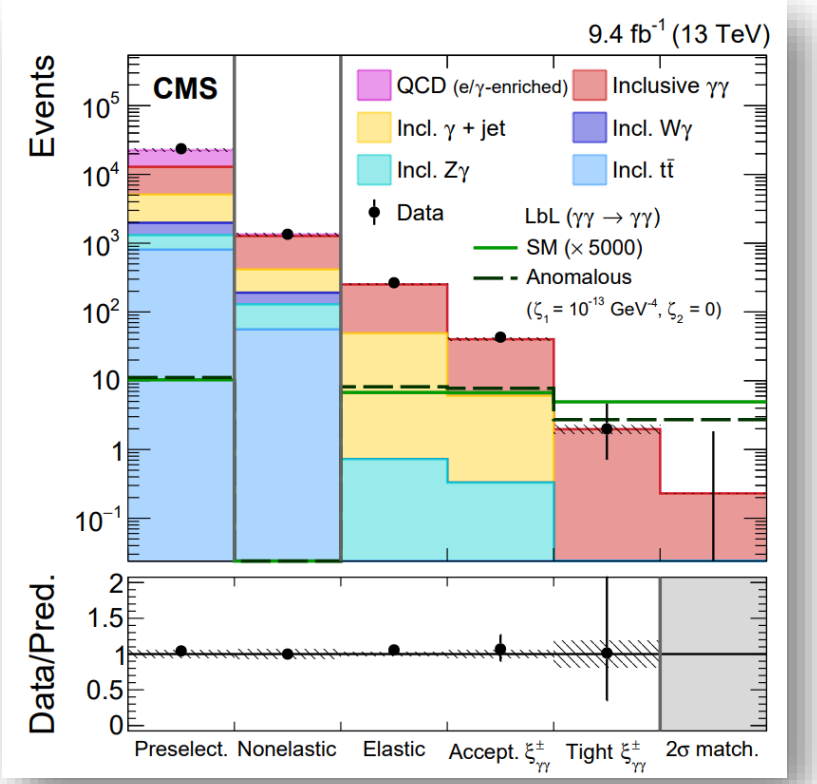
PRD 89 (2014) 114004, JHEP 1502 (2015) 165, *JHEP 1806 (2018) 131*

  - Almost background free after requiring matching between protons and photons

First limit on 4-photon coupling!

$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}.$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s}\left(s^2+t^2+st\right)^2\left[48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2\right]$$



Physics | exclusive diphoton

NEW! CMS-PAS-EXO-21-007

- The full Run 2 data – event selection

Table 3: A summary of the selection regions defined in the text.

Region	Selection
Preselection	Double photon HLT $p_T^\gamma > 75$ (100) GeV for 2016 (2017-2018) $H/E < 0.10$ MVA WP90 photon ID with electron veto $\lvert\eta^\gamma\rvert < 2.5$ (transition veto) $m_{\gamma\gamma} > 350$ GeV
Exclusive selection	$a < 0.0025$
$\xi \in$ PPS	$0.02 < \xi_{\gamma\gamma}^{\pm} < 0.20$
Asymmetric ξ acceptance	$0.035 < \xi_{PPS} < 0.15$ (0.18) for sector-45 (sector-56)

The Precision Proton Spectrometer (PPS)

- CMS+TOTEM expertise: PPS TDR (TOTEM-TDR-003)
- Operated in standard LHC runs since 2016 **NEW**
- Located ~ 200m from the CMS interaction point in both arms, equipped with tracking/timing detectors