Large Hadron Collider Physics Conference, Belgrade, 2023

Physics perspectives of a CMS near-beam proton spectrometer at HL-LHC

24 May 2023

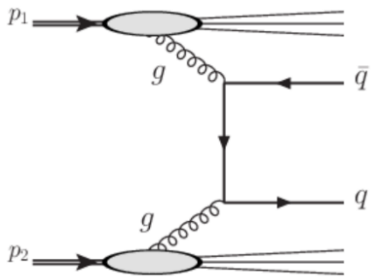
Michael Pitt (The University of Kansas)
On behalf of the CMS Collaboration

Outline

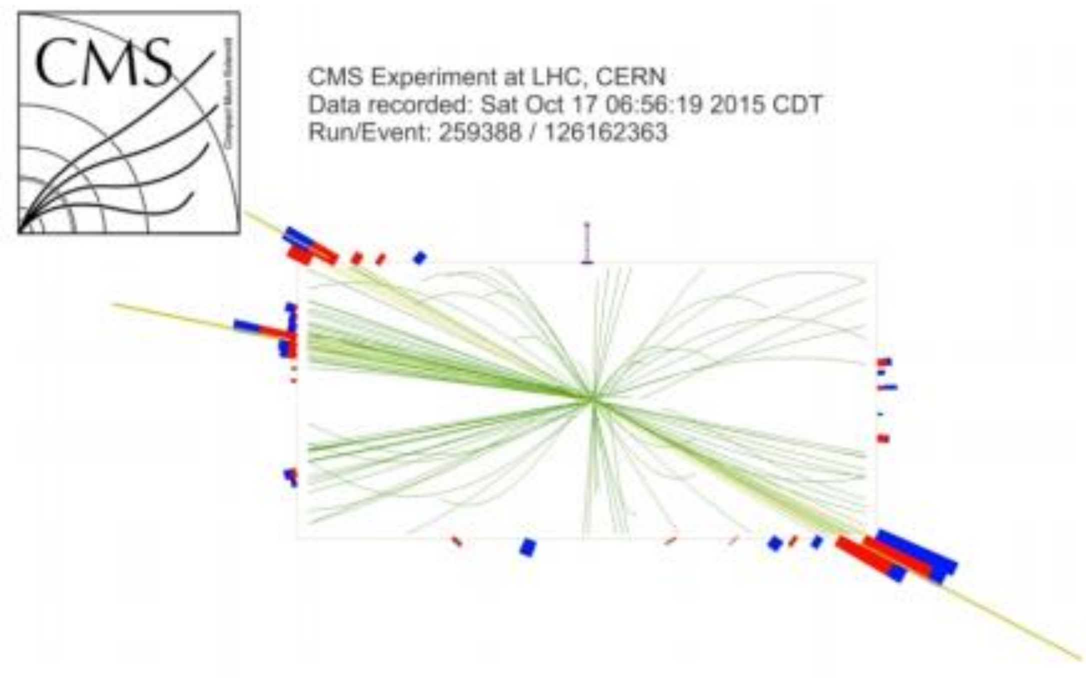
- Physics with tagged protons
- The CMS Precision Proton Spectrometer (PPS) - highlights from LHC Run 2 (2015-2018)
- Physics with PPS subdetector at the HL-LHC (>2029)

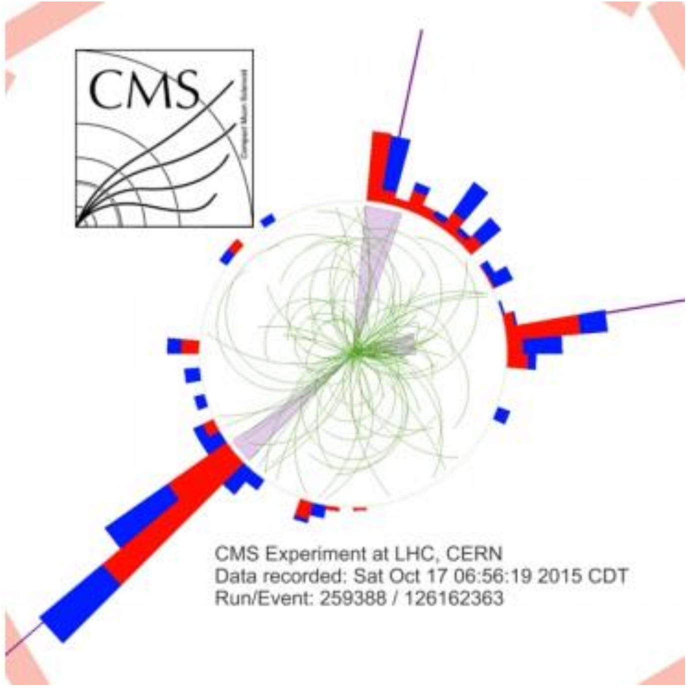
Physics with tagged protons

Introduction



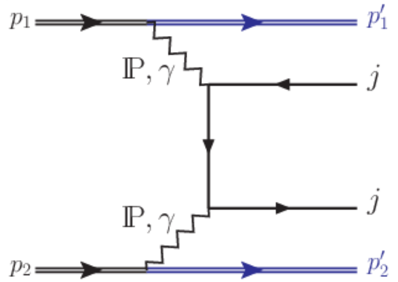
- In typical hard scattering of protons at the LHC:
  - Protons dissociate into multiparticle states
  - Many energetic particles are produced



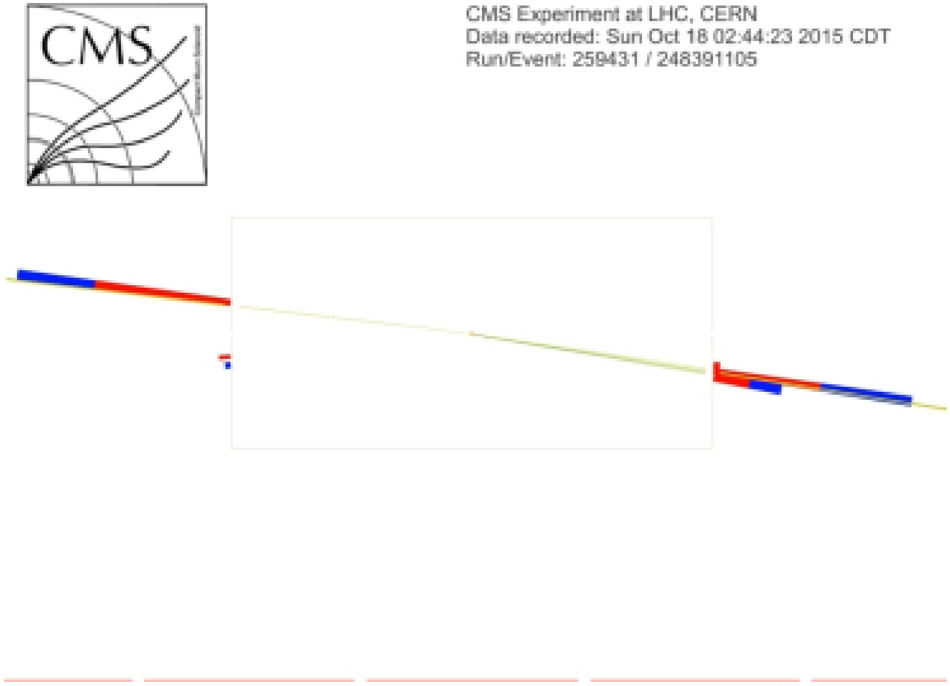


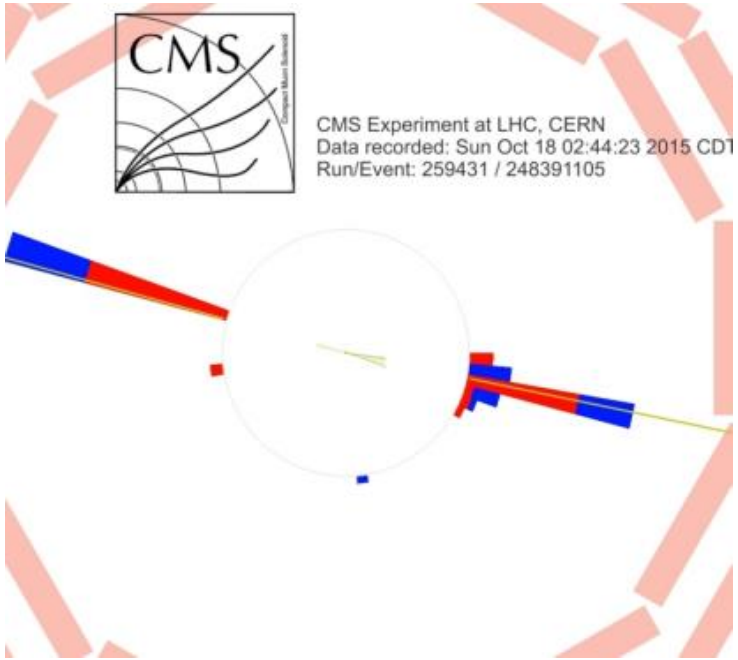
Introduction

- In other cases of hard scattered events:



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

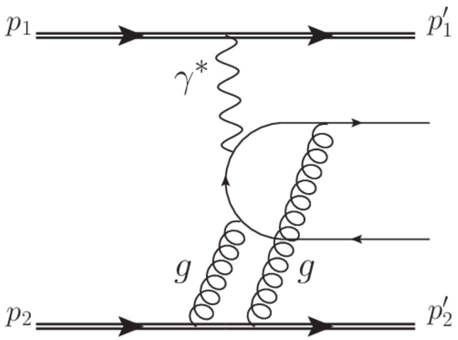




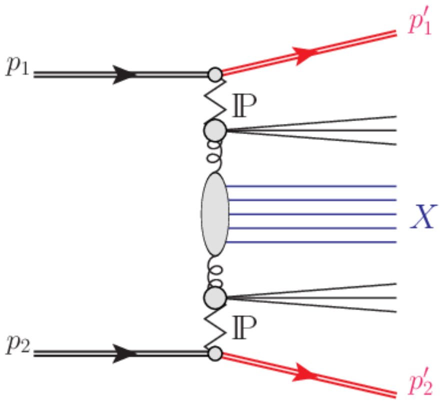
Introduction

- In other cases of hard scattered events:

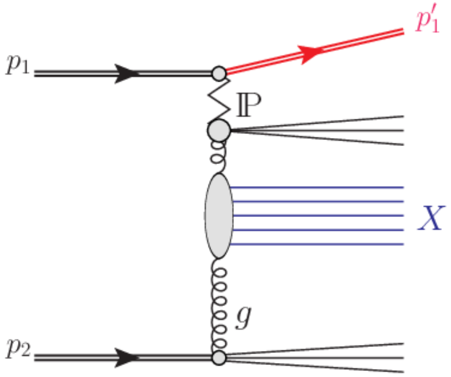
- Protons could remain intact (**tagged by PPS**)
- Low track activity due to exchange of color singlets via **QCD (Pomeron)** or **QED (γ)**
- **Many final state topologies are associated with an intact proton**



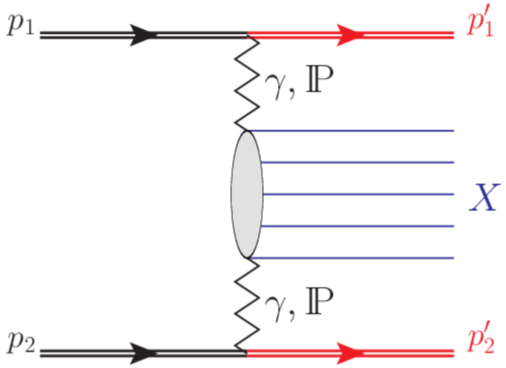
Exclusive photoproduction



Double pomeron exchange



Single-diffraction with central system X



Central exclusive production (CEP)

Introduction

So far measured only in Heavy Ion UPC (pPb w/o proton tag)
[EPJC 79 (2019) 3, 277](#)
[EPJC 79 (2019) 8, 702](#)
[arXiv:2303.16984](#)

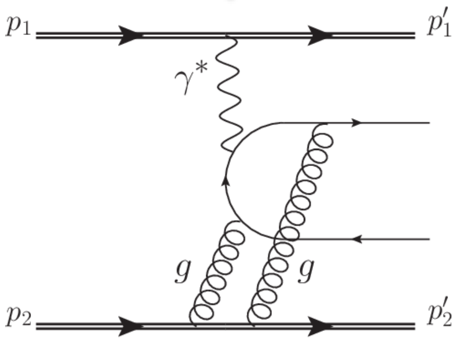
of hard scattered events:

The focus of the talk

- ain intact (**tagged by PPS**)

Measured using special LHC runs

- ue to exchange of color singlets via **QCD (Pomeron)** or **QED (γ)**
- **opologies are associated with an intact proton**



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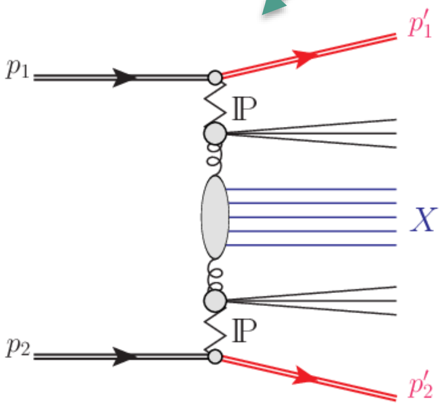

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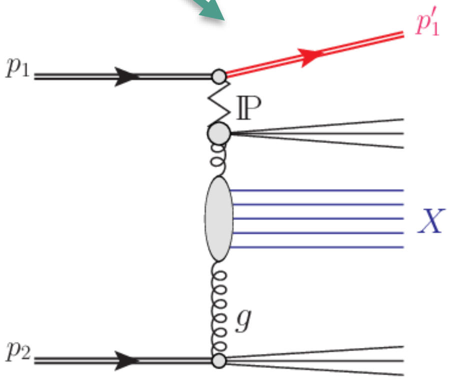
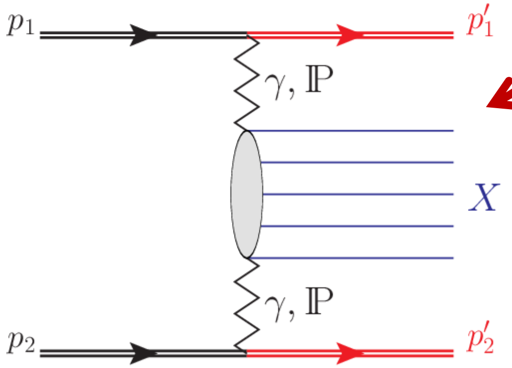
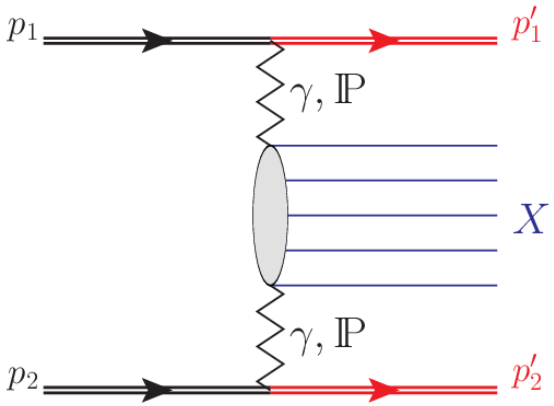


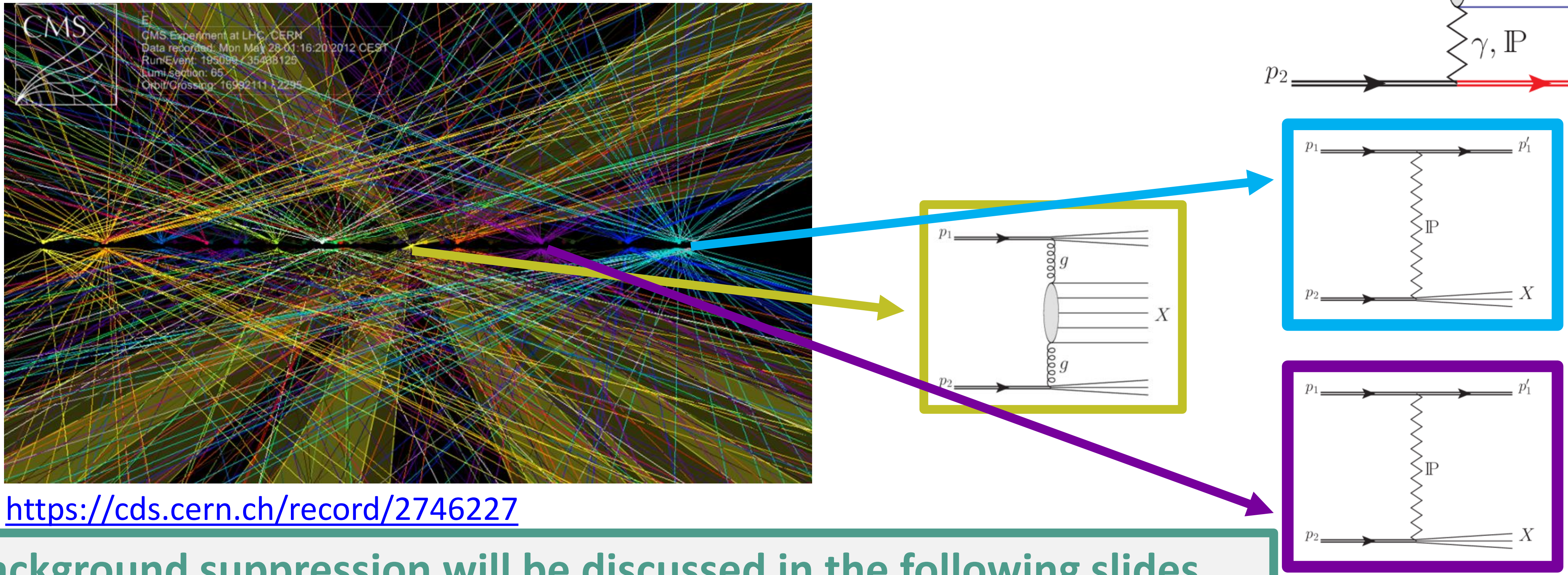
Single-diffraction with central system X



Central exclusive production (CEP)

- Main challenge is the background:
  - Multiple pp collision can fake the signal:





https://cds.cern.ch/record/2746227

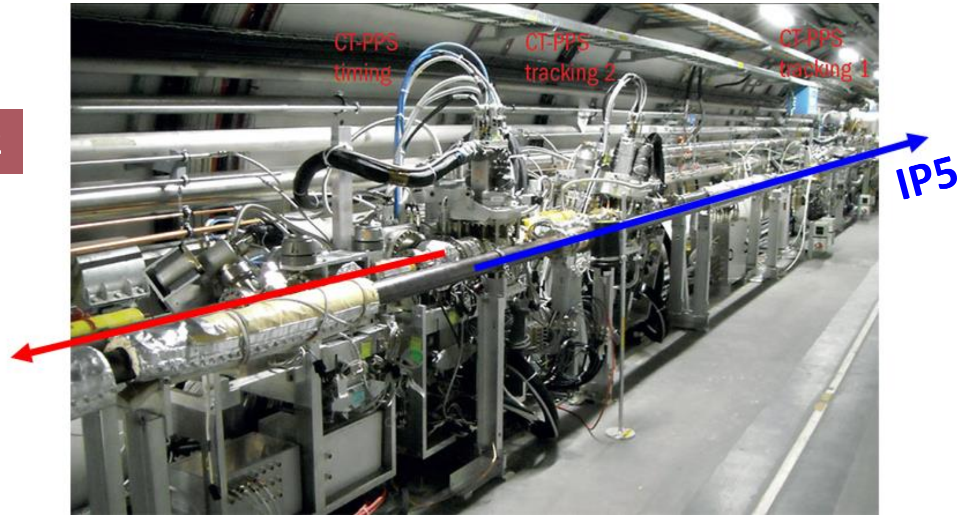
Background suppression will be discussed in the following slides

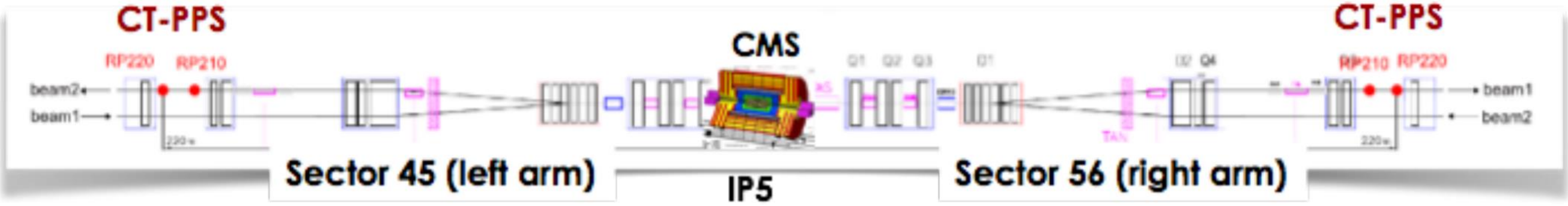
The CMS Precision Proton Spectrometer (PPS)

Highlights from LHC Run 2 (2015-2018)

The Precision Proton Spectrometer (PPS)

- CMS+TOTEM expertise: PPS TDR (TOTEM-TDR-003)
- Operated in standard LHC runs since 2016 **NEW in Run 2**
- Located ~ 200m from the CMS interaction point in both arms, equipped with tracking/timing detectors





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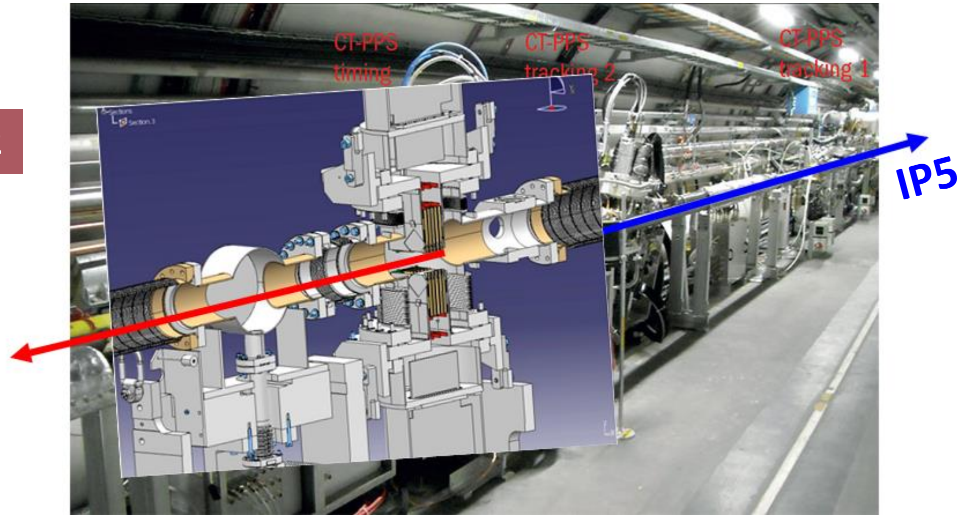
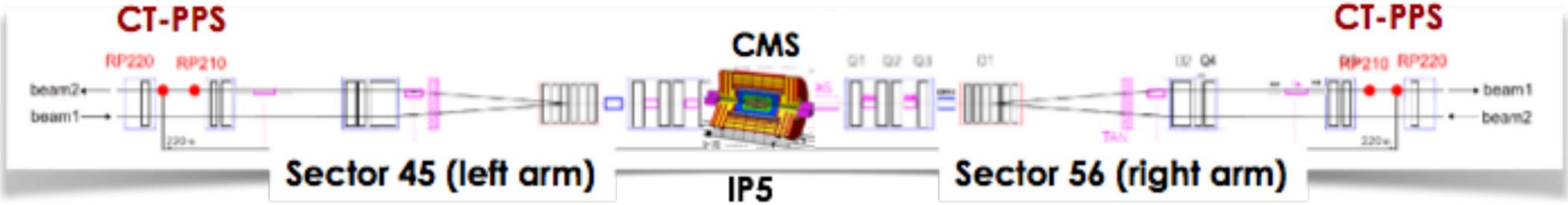
- Operated in standard LHC runs since 2016 **NEW in Run 2**
- Located ~ 200m from the CMS interaction point in both arms, equipped with tracking/timing detectors
- A set of near-beam detectors, which approach the beam down to a few mm



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

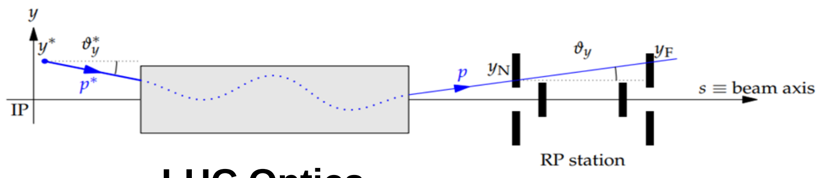


PPS | Tracking

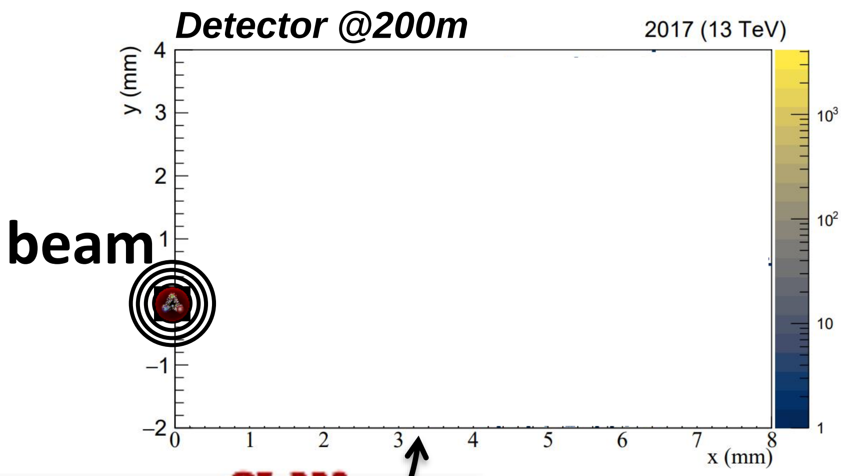
- Proton kinematics :

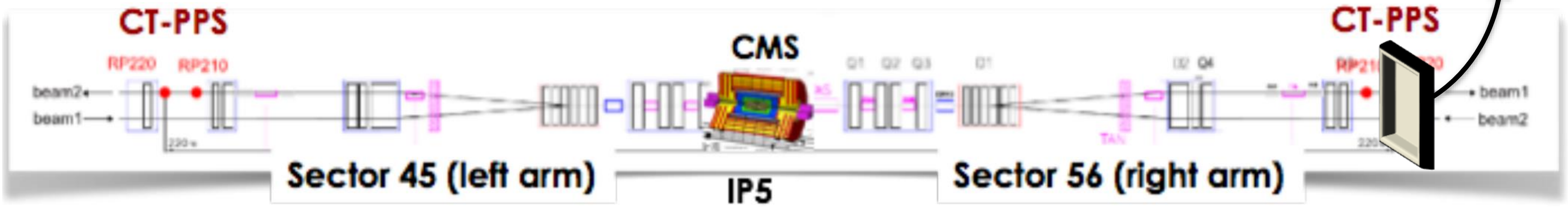
• Intact protons lose a fraction of momentum ($\xi = \Delta p/p$) and are scattered at small angles (θ_x^*, θ_y^*) → they deflected away from the beam and measured by PPS

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



LHC Optics





PPS | Tracking

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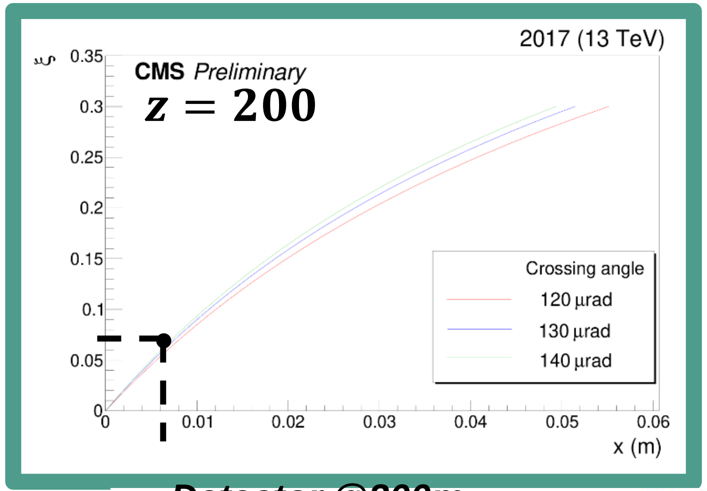

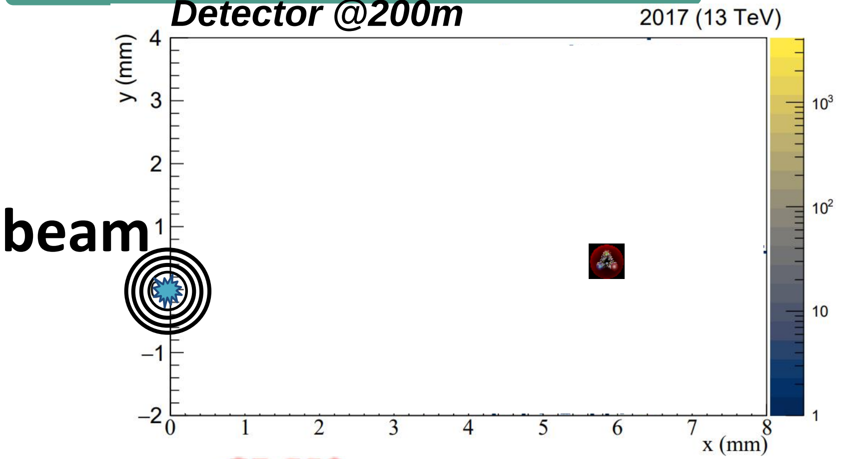

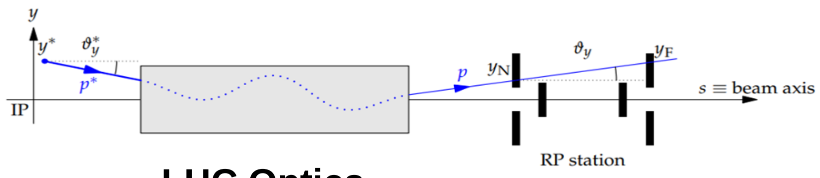

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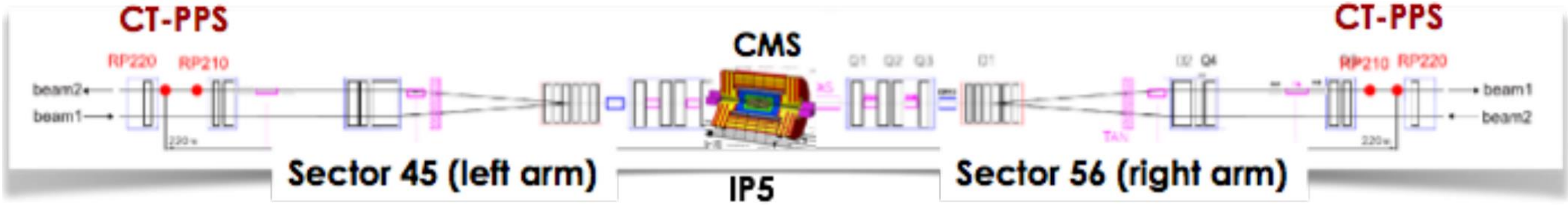
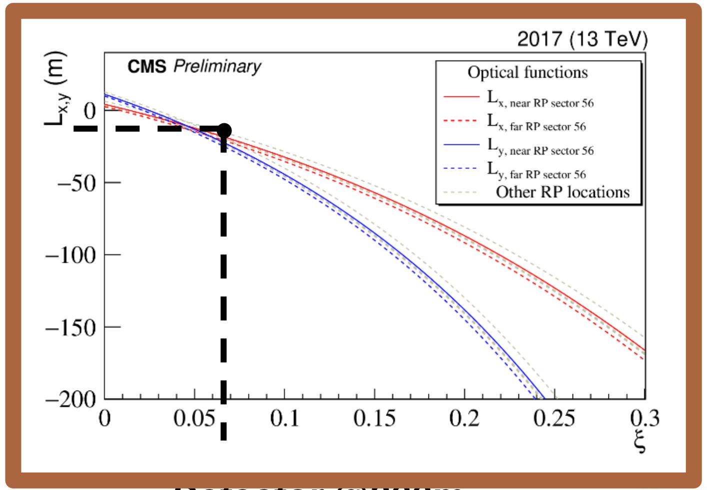
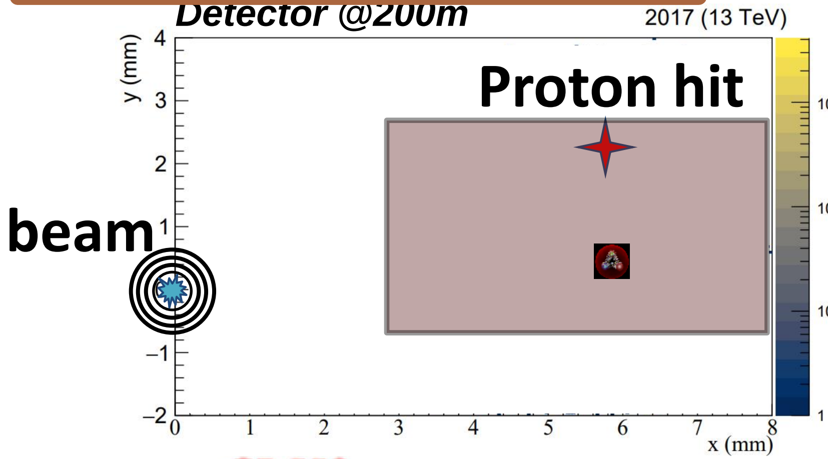


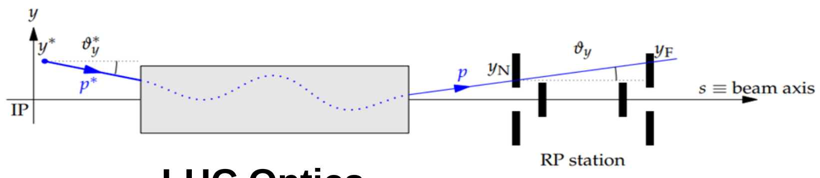
PPS | Tracking

- 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

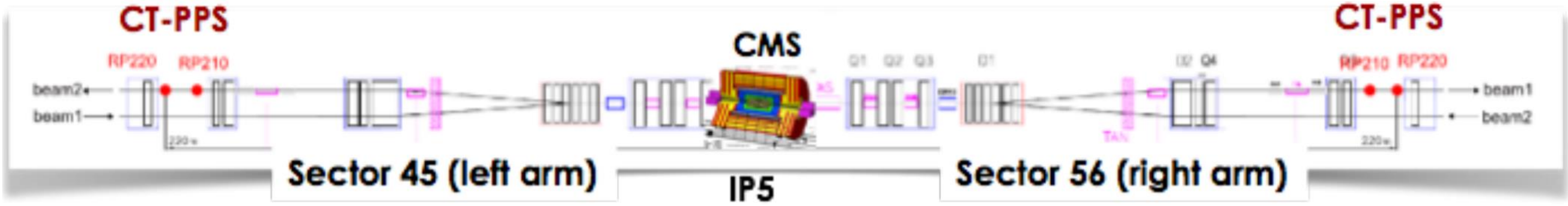
$$\delta x(z) = x_D(\xi) + v_x(\xi)x^* + L_x(\xi)\theta^*_x$$
$$\delta y(z) = y_D(\xi) + v_y(\xi)y^* + L_y(\xi)\theta^*_y$$







LHC Optics



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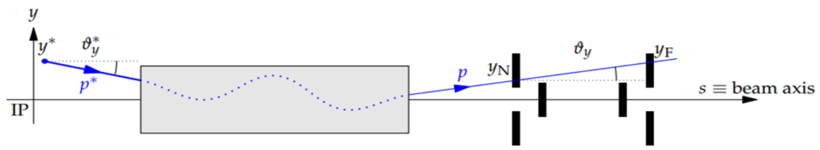
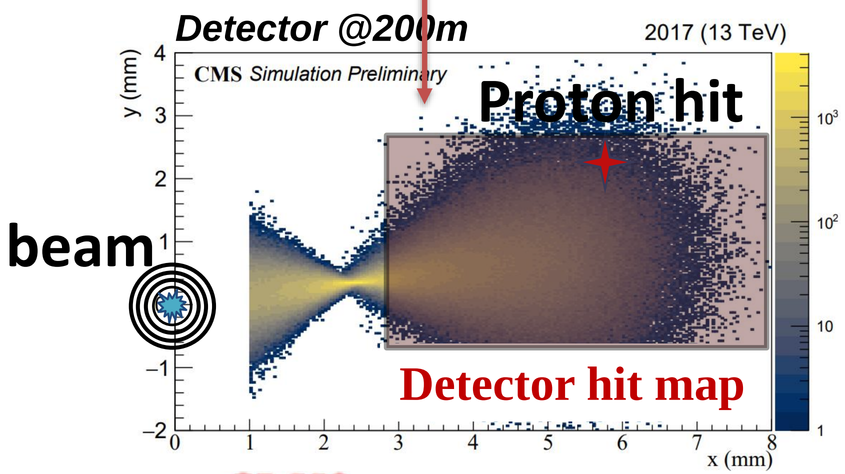
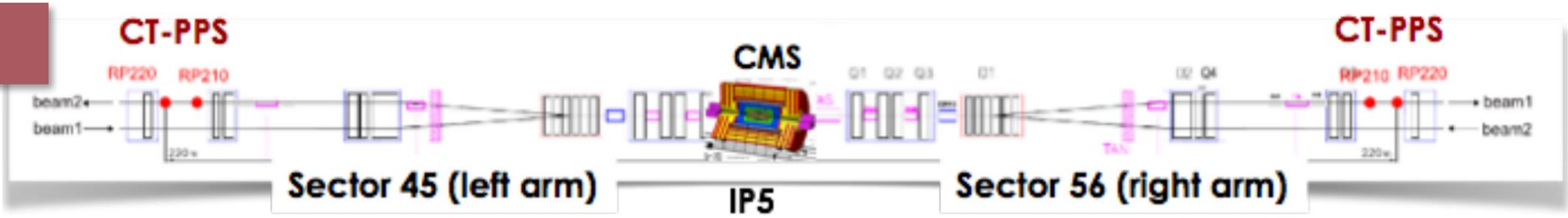


LHC Optics

acceptance



≥2 stations



PPS | results from Run 2

- PPS analyses covers many physic groups (Top physics, Standard Model, Exotic searches)
  - ✓ Exclusive di-lepton, JHEP 07 (2018) 153
  - ✓ Exclusive di-photons, PRL 129 (2022) 011801, CMS-PAS-EXO-21-007
  - ✓ Exclusive WW and ZZ, arXiv:2211.16320
  - ✓ Exclusive tops, CMS-PAS-TOP-21-007
  - ✓ BSM searches using exclusive signature, arXiv:2202.06075

See talk from D. ZULIANI (Tuesday morning)

I will show two examples

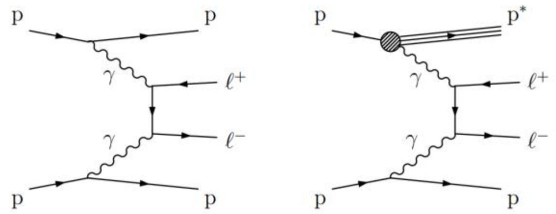
JHEP 07 (2018) 153

Observation of (semi)-exclusive dilepton production

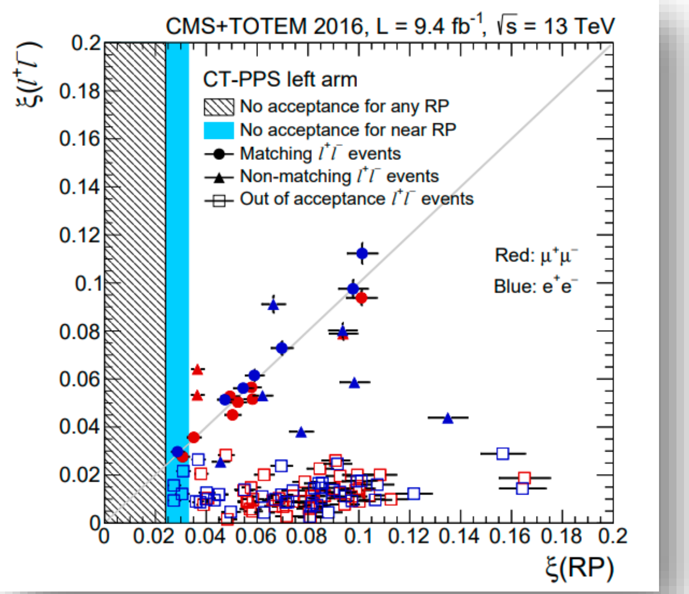
- Exclusive di-lepton production is the cleanest and most common CEP process
- Main background – DY + PU proton(s)
- In Central Exclusive production (CEP) processes:

Central system kinematics = Proton kinematics

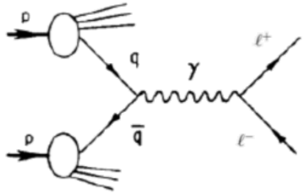
Signal



$$\xi_{\pm}(ll) = \frac{1}{\sqrt{s}}\Sigma\left(p_T(l_i)e^{\pm\eta(l_i)}\right)$$



Background



Drell-Yan

\+ **pileup proton**

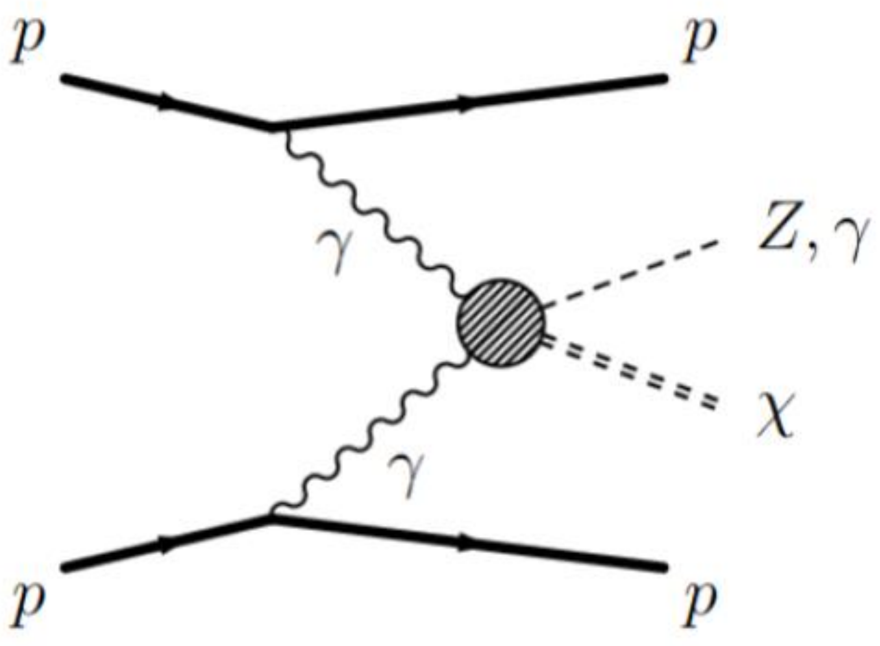
20 Total events observed (12μμ, 8ee)
Estimated 4 Background (1.5±0.6μμ, 2.4±0.6 ee)

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

Example of PPS result with tagged protons

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

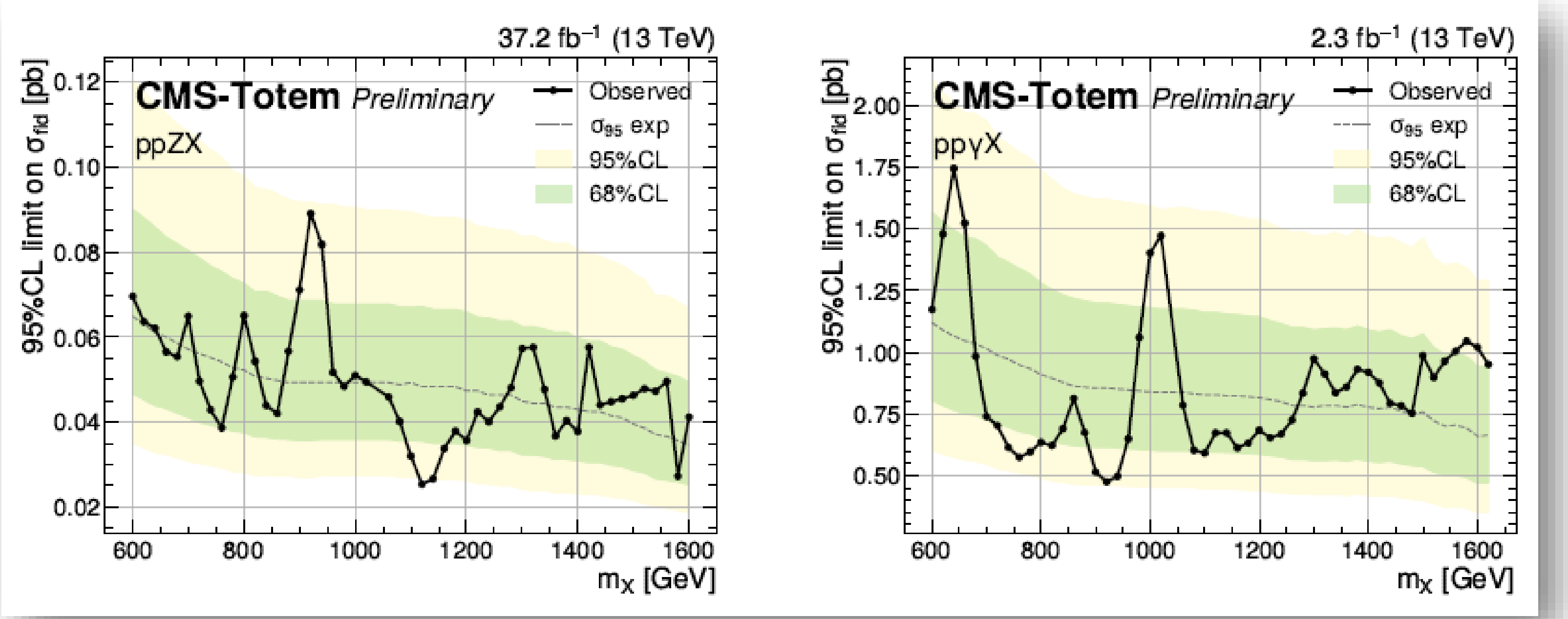
$$m^2_{\text{miss}} = \left[(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2}) - (P_V + P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}) \right]^2$$

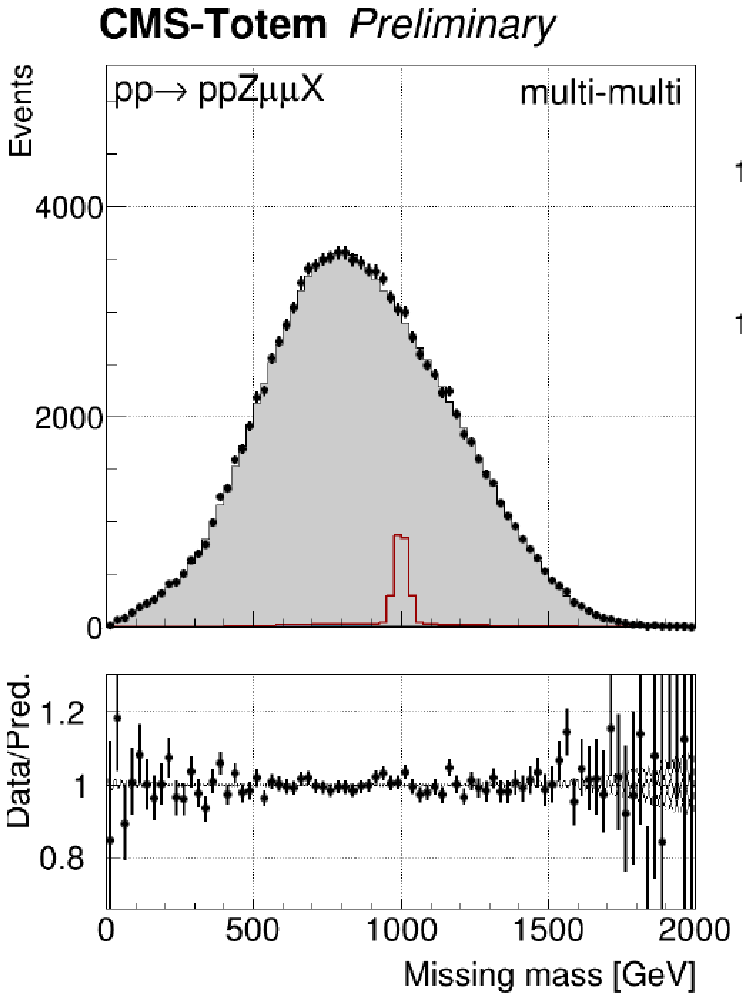


  - Bump hunt of χ state is performed in Z+χ and γ+χ channels

Example of PPS result with tagged protons

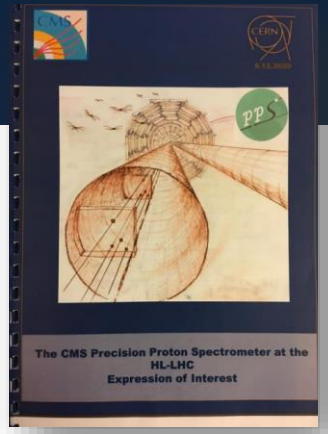
- Searching for unknown particles using the “missing mass”
  - Benefit from supreme mass resolution
  - Data agree with the background-only model, a limit on the production cross-section of Z/γ+χ was derived





Physics with tagged protons at the HL-LHC

PPS @ HL-LHC | proposed stations



- Since after LS3 the whole beamline will be rearranged, a new spectrometer design is proposed
- Run 2+3 design: ξ acceptance translated to mass range between 350 GeV and 2 TeV

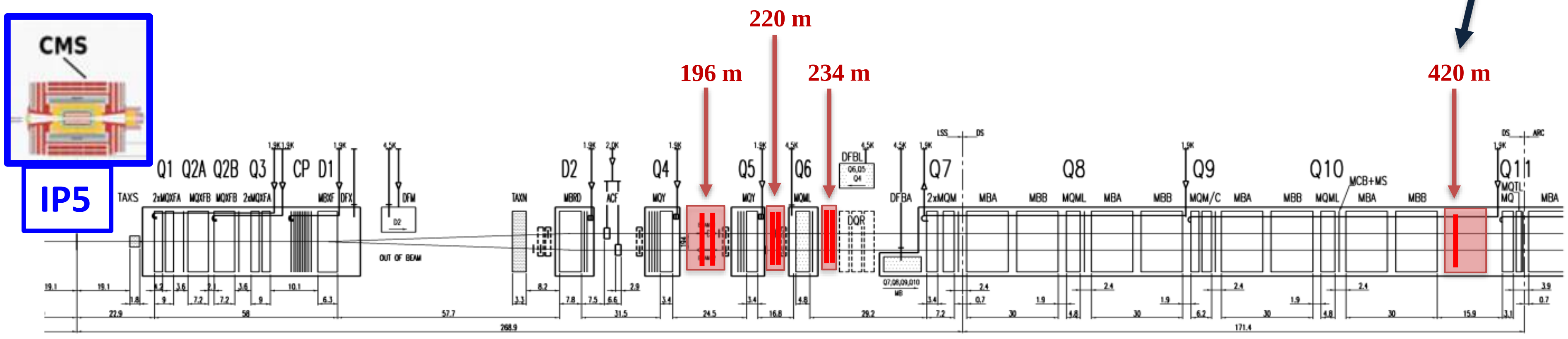
https://cds.cern.ch/record/2750358

- New proposal with extended mass range:

133 GeV – 2.7 TeV for the first 3 stations (0.0142 < ξ < 0.1967)

43 GeV – 2.7 TeV for 4 stations (0.00325 < ξ < 0.1967)

Staged installation



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

Detector technologies

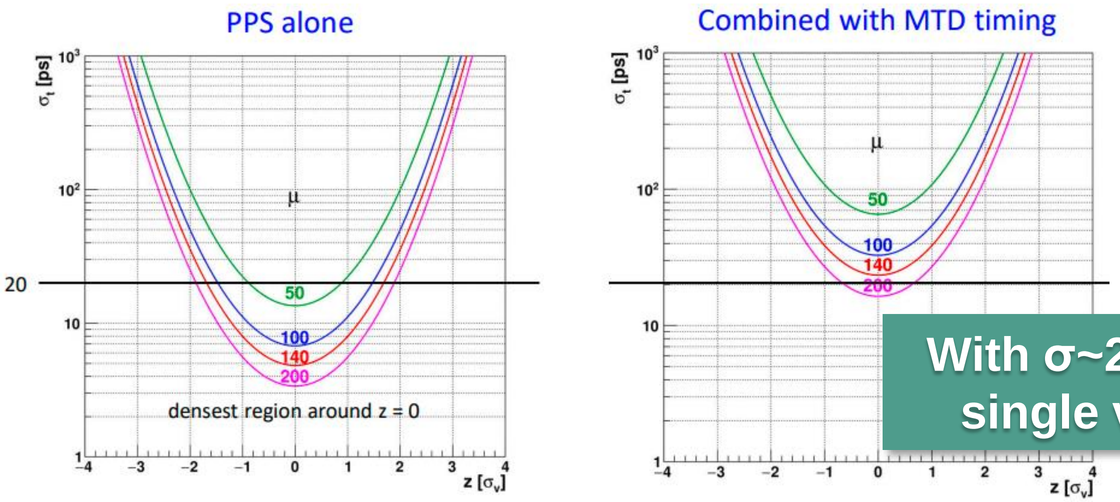
Tracking technology

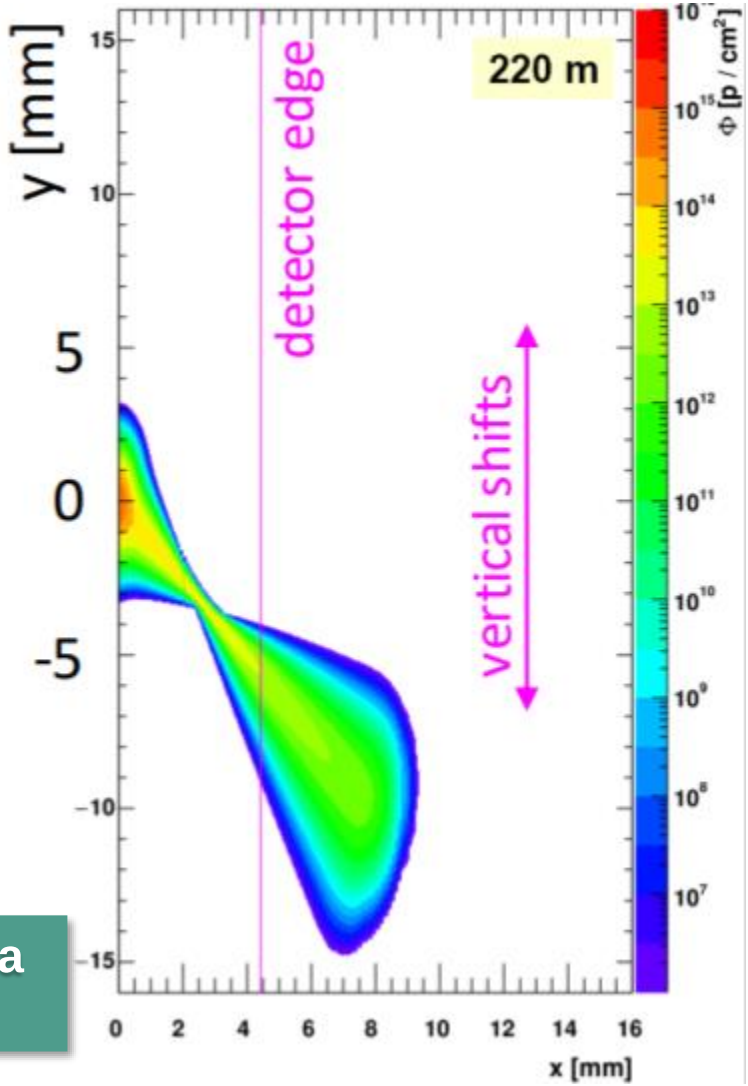
Tracking – 3D silicon pixel detectors (used by PPS and CMS tracker in Runs 2+3)

Timing technology

Ultra-Fast Silicon Detectors (UFSD a.k.a LGAD) from CMS MIP Timing Detector (MTD)

Each RP houses both tracking and timing (10 timing + 6 tracking planes)





With σ~20ps can resolve a single vertex at PU=150

Standard Model processes

- Fiducial cross sections of CEP of SM processes in pp collisions at $\sqrt{s} = 14$ TeV
- Two scenarios are considered: with and w/o 420m station
- Fiducial cross-sections for photon-induced processes are computed where at least one (1-tag) or both (2-tag) protons are detected [(1)] :

Process	fiducial cross section [fb] 2 tag w/o 420	fiducial cross section [fb] 2 tag all stations	fiducial cross section [fb] 1 tag w/o 420	fiducial cross section [fb] 1 tag all stations
jj	2	60	219	526
$b\bar{b}$	0.04	1.7	6.3	15
W^+W^-	15	37	152	178
$\mu\mu$	1.3	46	172	417
$t\bar{t}$	0.1	0.15	0.65	0.74
H	0	0.07	0.23	0.30
HW^+W^-	0.01	0.01	0.06	0.07
ZZ	0.03	0.06	0.23	0.26
$Z\gamma$	0.02	0.04	0.15	0.17
$\gamma\gamma$	0.003	0.02	0.19	0.33

(1) see more details on backup slide

QCD Physics

Process	fiducial cross section [fb]			
	2 tag		1 tag	
	w/o 420	all stations	w/o 420	all stations
jj	2	60	219	526
$b\bar{b}$	0.04	1.7	6.3	15
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$t\bar{t}$	0.1	0.15	0.65	0.74
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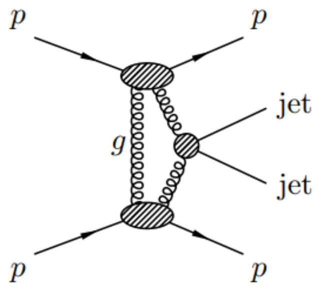
HW^+W^-	0.01	0.01	0.06	0.07
ZZ	0.03	0.06	0.23	0.26
$Z\gamma$	0.02	0.04	0.15	0.17
$\gamma\gamma$	0.003	0.02	0.19	0.33

- Systematic study of screening effects in central exclusive di-jet production was never performed.
- Exclusive $b\bar{b}$ production – the dominant background for exclusive Higgs searches never measured.



QCD contribution is dominant at low di-jet masses

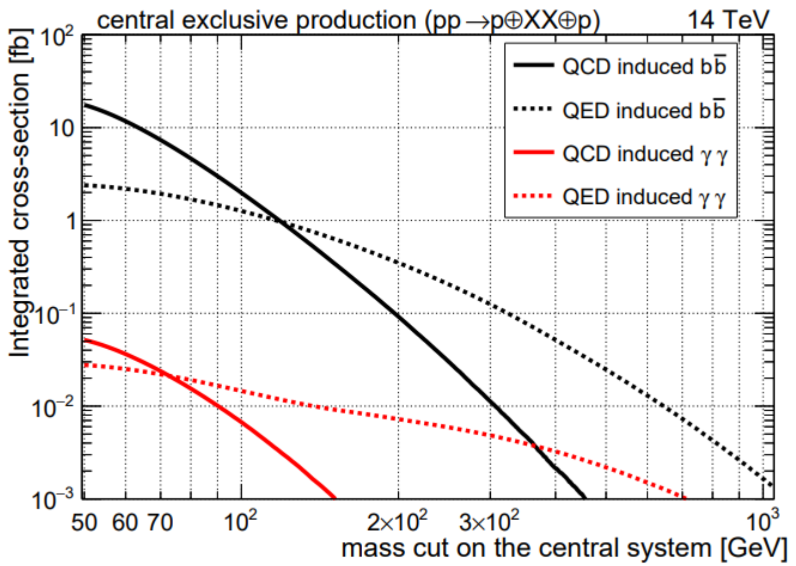


Figure 7: Integrated cross sections of different exclusive processes with intact protons at $\sqrt{s}$ =14 TeV, plotted as a function of the required minimum central system mass. Both photons or b-quarks are required to have a transverse momentum above 20 GeV.

Electroweak physics

Process	fiducial cross section [fb]			
	2 tag		1 tag	
	w/o 420	all stations	w/o 420	all stations
jj	2	60	219	526
$b\bar{b}$	0.04	1.7	6.3	15
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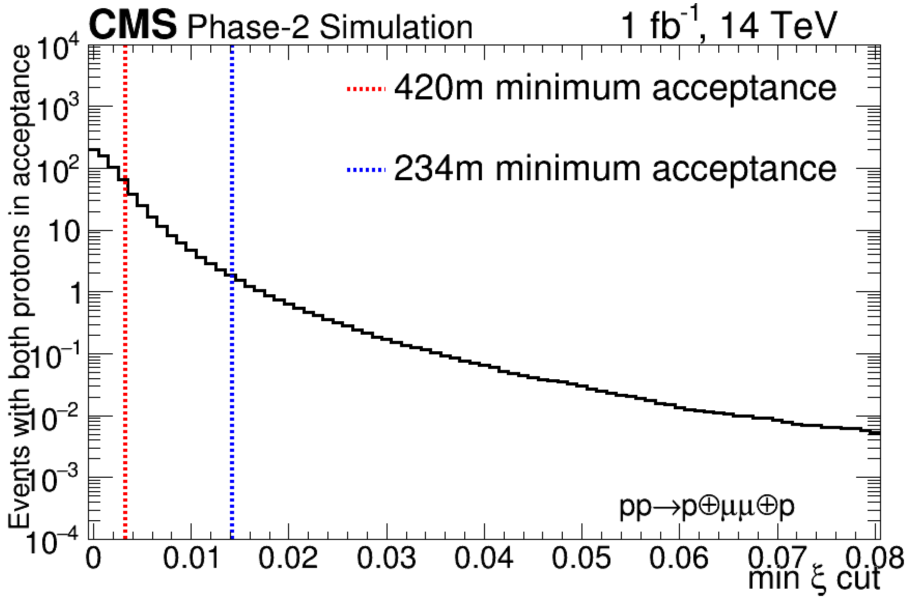
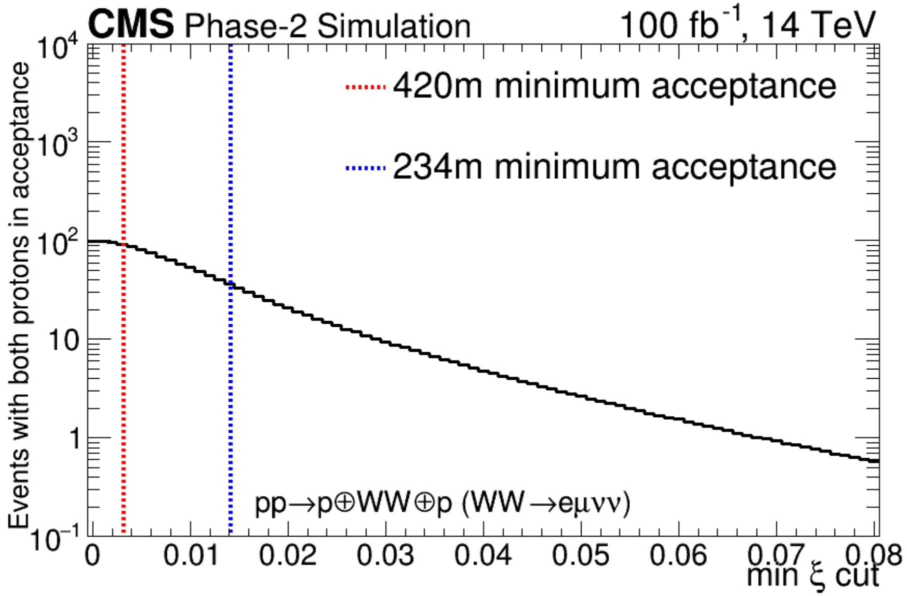
$\mu\mu$	1.3	46	172	417
$t\bar{t}$	0.1	0.15	0.65	0.74
H	0	0.07	0.23	0.30
HW^+W^-	0.01	0.01	0.06	0.07
ZZ	0.03	0.06	0.23	0.26
$Z\gamma$	0.02	0.04	0.15	0.17
$\gamma\gamma$	0.003	0.02	0.19	0.33

$$pp \rightarrow p \oplus \mu\mu \oplus p$$



$$pp \rightarrow p \oplus WW \oplus p$$



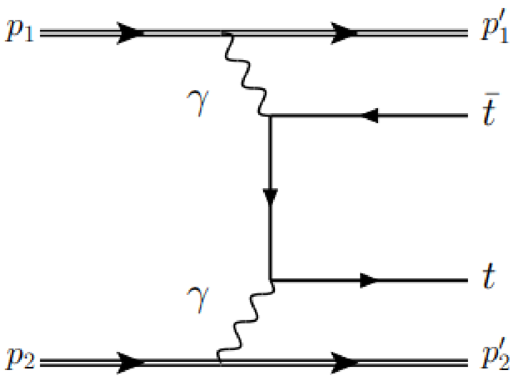
τ – lepton electric and magnetic moments in $\gamma\gamma\rightarrow\tau\tau$ events

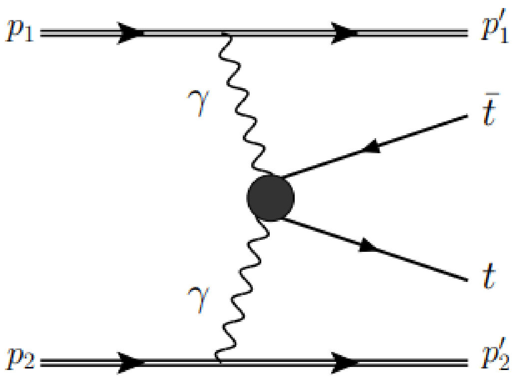
- Exclusive $\tau\tau$ production can be measured already in Run2+3
- Phenomenological study suggests improved constraints compared to those obtained at LEP [JHEP 11 (2010) 060]

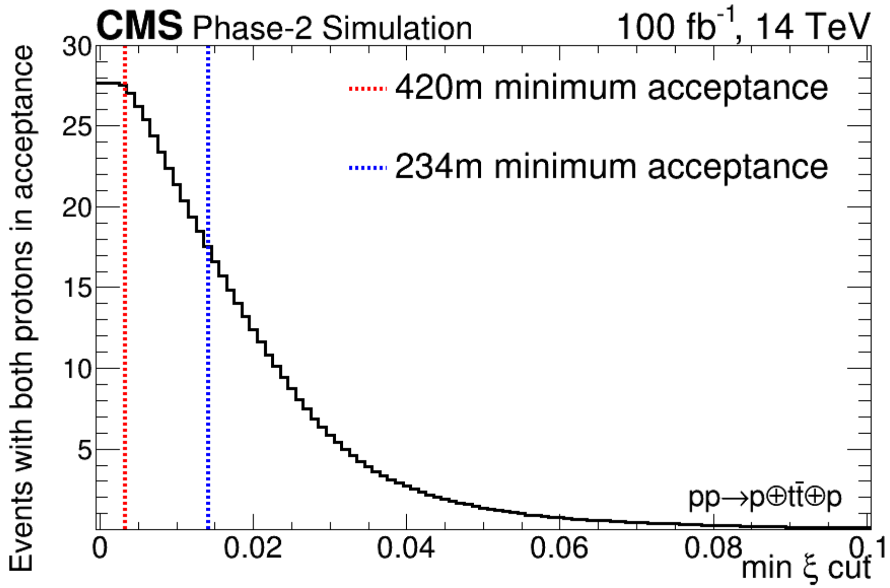
Top physics

Process	fiducial cross section [fb]			
	2 tag		1 tag	
	w/o 420	all stations	w/o 420	all stations
jj	2	60	219	526
$b\bar{b}$	0.04	1.7	6.3	15
W^+W^-	15	37	152	178
$\mu\mu$	1.3	46	172	417
$t\bar{t}$	0.1	0.15	0.65	0.74
H	0	0.07	0.23	0.30
HW^+W^-	0.01	0.01	0.06	0.07
ZZ	0.03	0.06	0.23	0.26
$Z\gamma$	0.02	0.04	0.15	0.17
$\gamma\gamma$	0.003	0.02	0.19	0.33

- Production of final state above m_{tt} mass threshold (>350 GeV)
- Exclusive ttbar has low cross-section – of the order of 0.1fb
- A few phenomenological studies (including inclusive diffractive production modes) were published (PRD105,114002, PRD102,074014(2020), 2008.04249).
- A promising signature to probe anomalous top quark interaction (JHEP 08 (2022) 021)







Higgs physics

Process	fiducial cross section [fb]			
	2 tag		1 tag	
	w/o 420	all stations	w/o 420	all stations
jj	2	60	219	526
$b\bar{b}$	0.04	1.7	6.3	15
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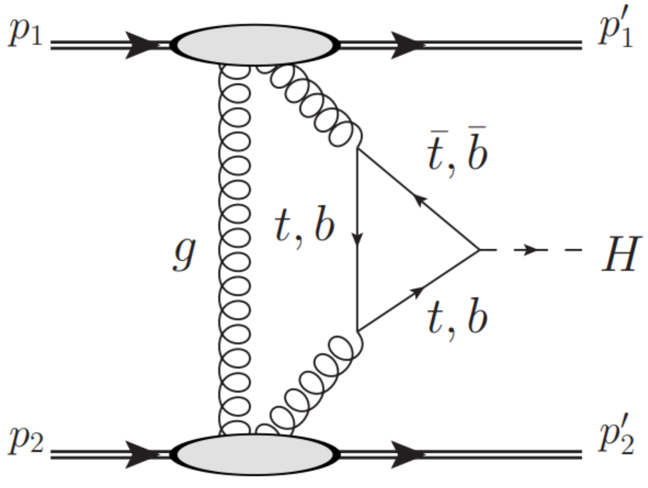
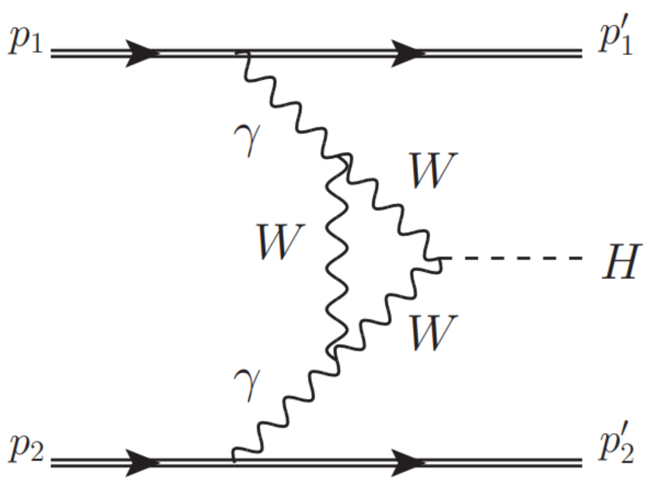
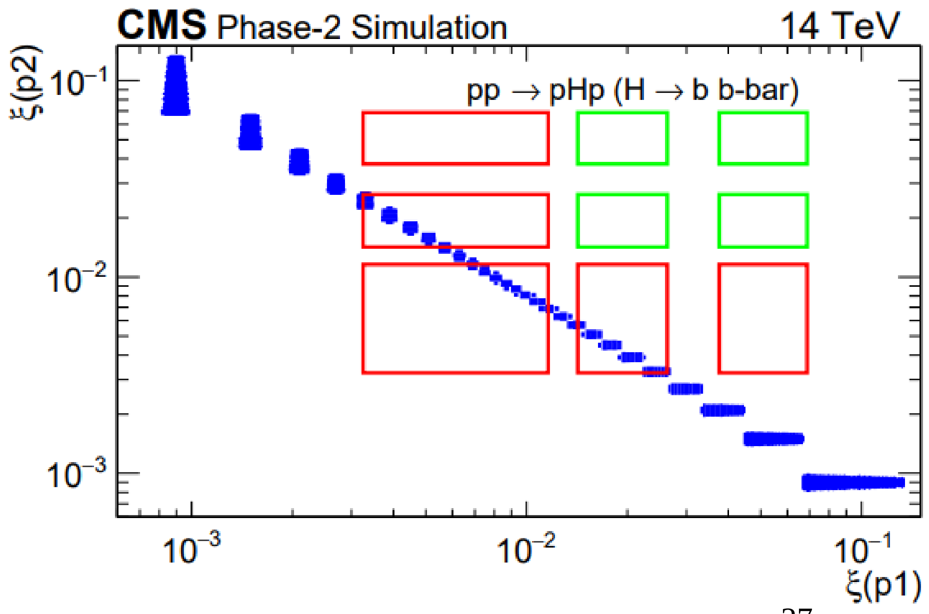
$Z\gamma$	0.02	0.04	0.15	0.17
$\gamma\gamma$	0.003	0.02	0.19	0.33

Cannot be measured w/o the 420m station

- Exclusive Higgs boson production is broadly discussed in the literature.
- Cross-section estimates vary by an order of magnitude due to the lack of knowledge of screening effects
- Measurement of the central exclusive production of the Higgs boson is possible only with all 4 stations







Higgs physics

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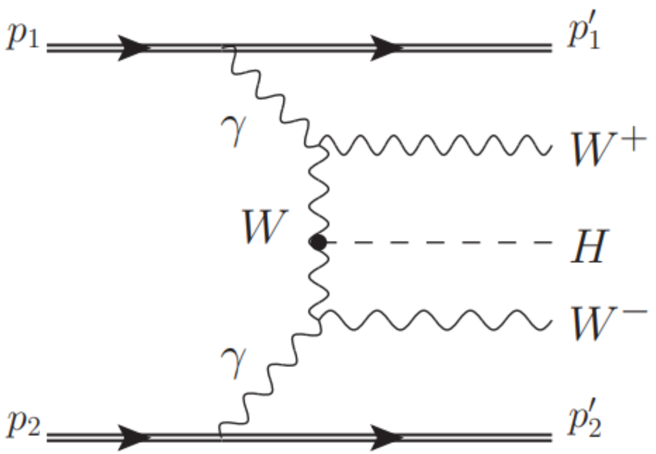
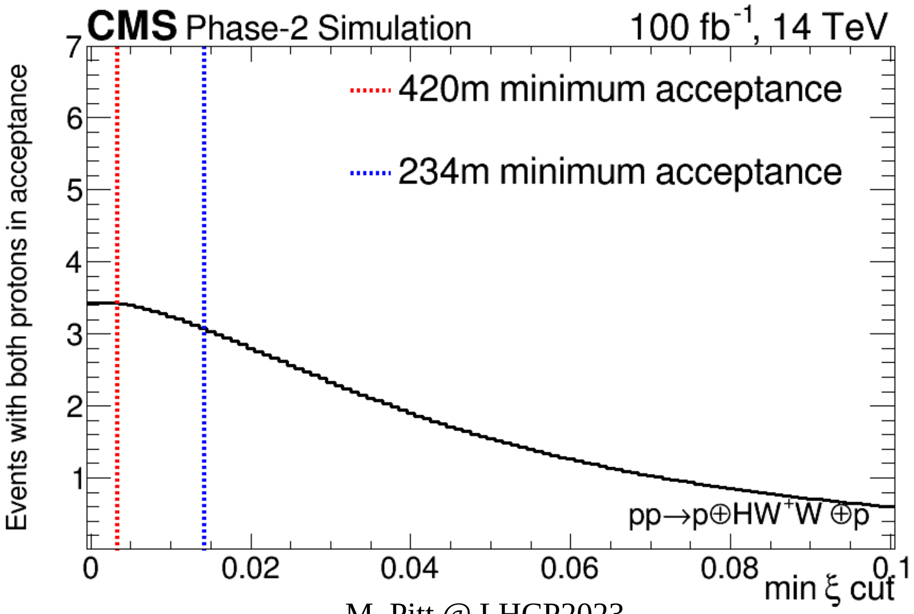


Associated production with WW pairs

- Low cross section O(0.01 fb).
- Detectable with only stations at 200m
- Inclusive Higgs boson production (all decay modes)



High mass searches

Search for Axion like particles (ALPs)

- PPS provides the best sensitivity to anomalous couplings and can probe high di-photon masses in searches for ALPs (~TeV)
- Signal / Background is a function of pileup – requires a good performance of timing detectors
- Recently single dissociation and double dissociation were properly modeled (PRD 107 (2023) 3, 033001) allowing to probe semi-exclusive processes and probing lower ALP masses.

The sensitivity will exceed the existing limits at high masses

CMS to be the only experiment probing masses at O(100GeV)

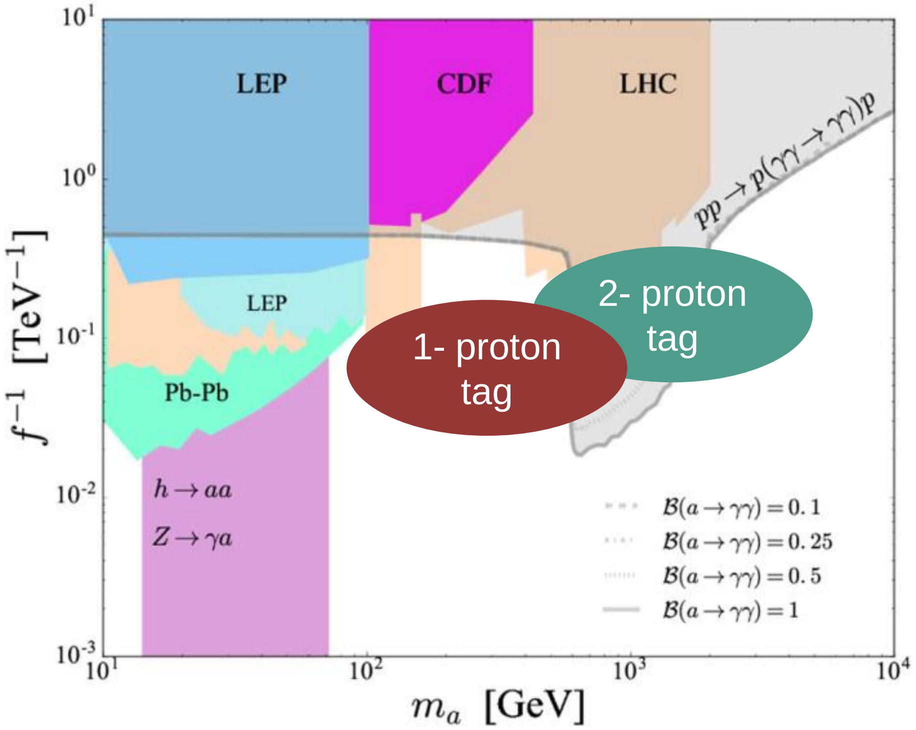


Figure 2: Exclusion regions on the ALP–photon coupling and mass plane. The light-shaded grey regions show the expected 95% CL exclusion limit for 300 fb^{-1} in central exclusive diphoton production events for different branching ratios of the ALP into two photons [16].

[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]].

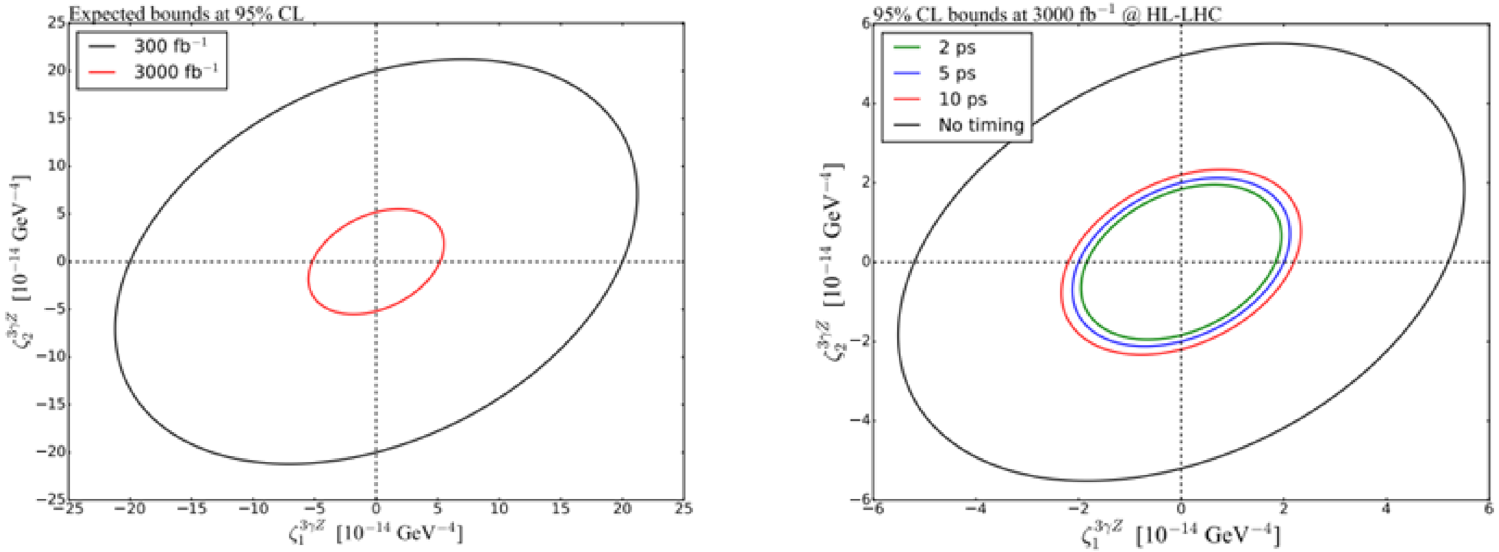
<μ>~50, Lumi=300fb^{-1}

Anomalous gauge couplings

Exclusive γZ

- γγγZ coupling can be probed in γγ→Zγ channel search.
- Sensitivity is improved with timing detectors

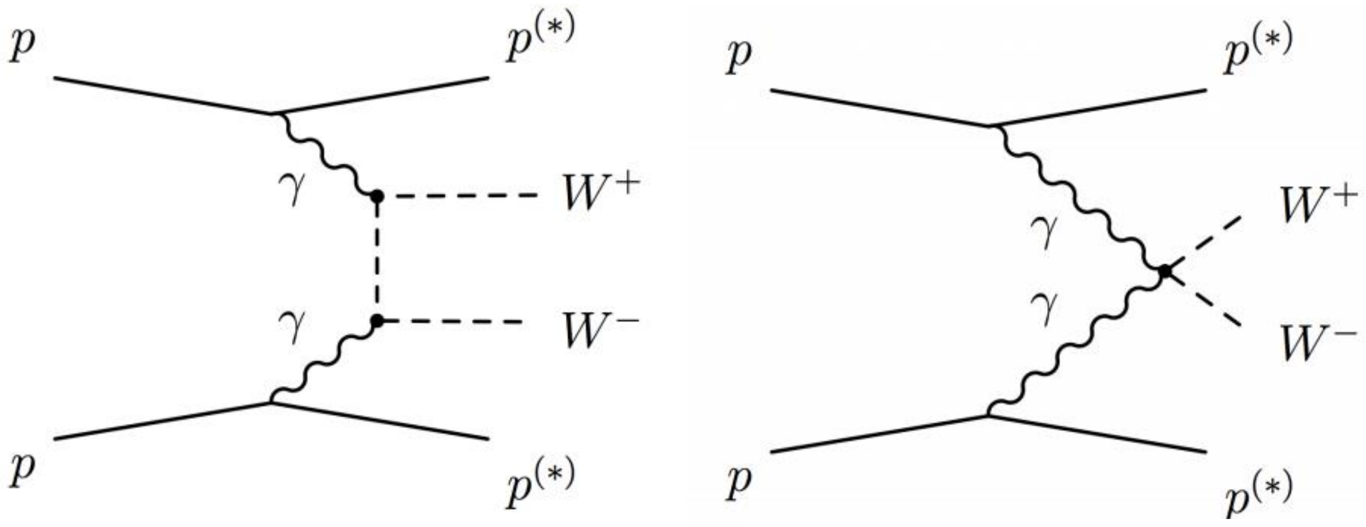
CERN Yellow Rep.Monogr. 7 (2019) 1-220



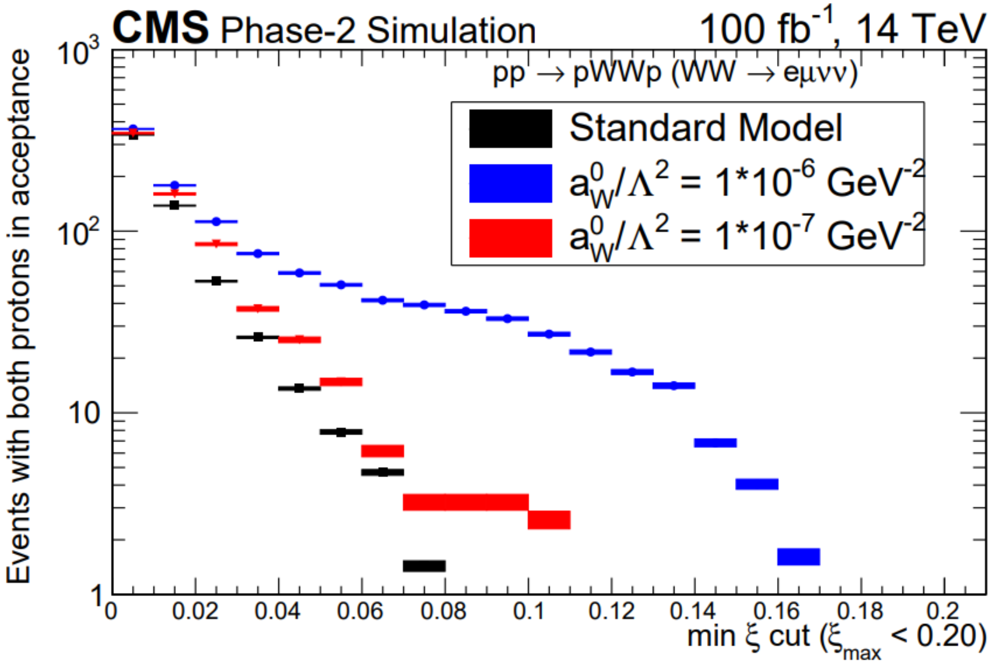
<μ>=200, Lumi=3000fb^{-1}

Figure 6: Expected bounds on the anomalous $\gamma\gamma\gamma Z$ couplings at 95% CL with $300\,\text{fb}^{-1}$ and $3000\,\text{fb}^{-1}$ at the HL-LHC without time-of-flight measurement (left). Expected bounds at 95% CL for timing resolutions of $\delta t = 2, 5, 10\,\text{ps}$ at the HL-LHC (right).

Anomalous gauge couplings



- Exclusive WW production sets stringent upper limit on the anomalous quartic gauge coupling operators (JHEP08(2016)119).
- Deviation due to aQGC expected to be visible at high masses
- **A few % resolution in m_{WW}**

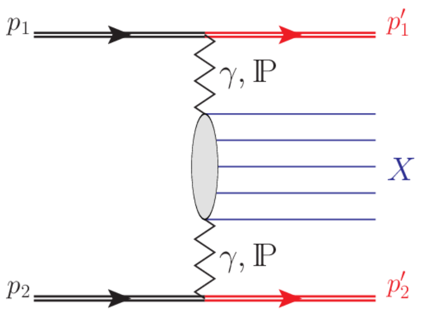


Scenarios with compressed spectra

- $pp \rightarrow \tilde{\ell}\tilde{\ell} \rightarrow \ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$, where both neutralinos ($\tilde{\chi}_1^0$) produced at rest.
- Neutralinos remain undetected (true MET), but these events will have low MET.
- At the LHC such searches require ISR jets to boost neutralinos and obtain high MET (if protons are not tagged).
- In the exclusive production, the di-slepton mass ($m_{\tilde{\ell}\tilde{\ell}}$) is measured by PPS independently of the event kinematics measured by the central detector (JHEP **1904**, 010 (2019), PRL **123** (2019) 141801)

Complementary to the standard LHC searches

Summary



- Proton Spectrometers at HL-LHC extend current CEP studies (both larger mass range and high statistics)
- Challenging environment: large radiation, high pileup
- CMS proposed staged installation program, starting with 200m during LHC Run 4 (PPS-EOI), while the 420m station is planned for Run5+

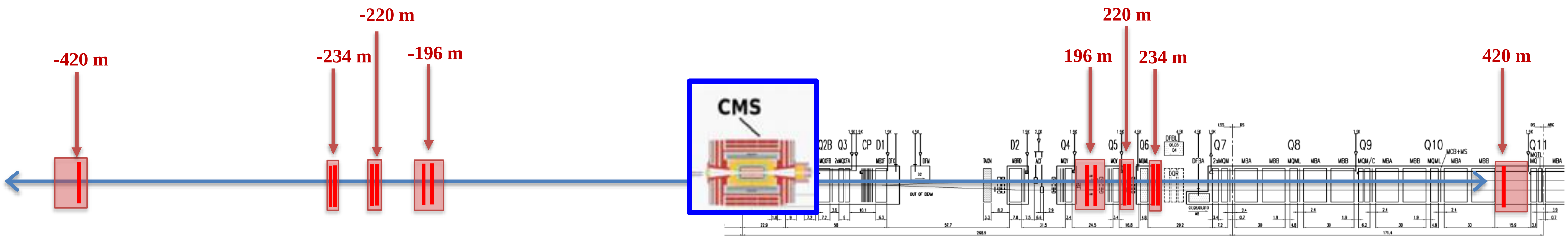
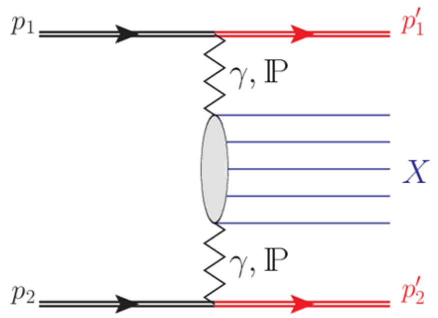


Figure 13: Layout of Long Straight Section LSS5 (Sector 5-6) at HL-LHC [63].

Backup

Introduction



- 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:

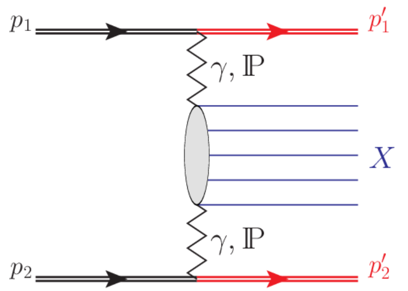
$$\xi_{\pm} = \frac{\sum E \pm p_Z}{\sqrt{s}}$$

Central system kinematics can be inferred from the protons:

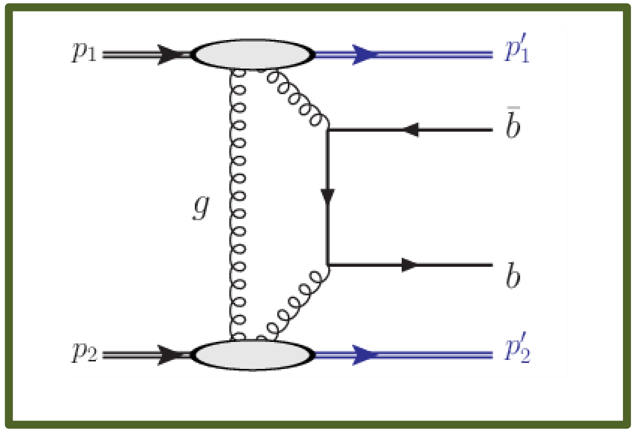
$$m = \sqrt{s \xi_+ \xi_-}$$

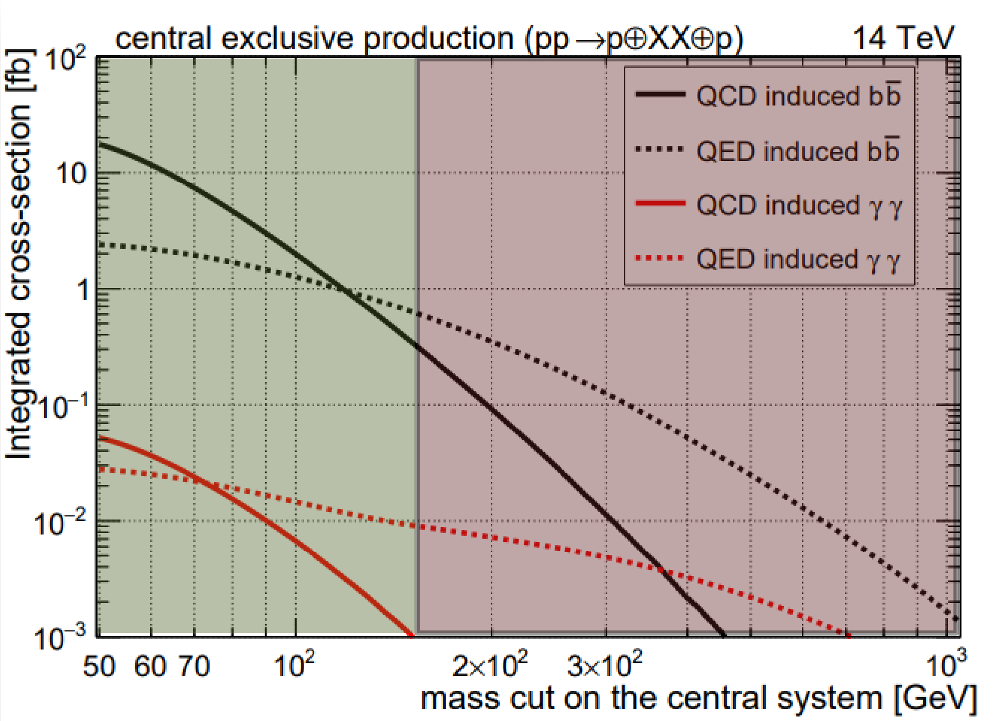
$$Y = \frac{1}{2} log\left(\frac{\xi_+}{\xi_-}\right)$$

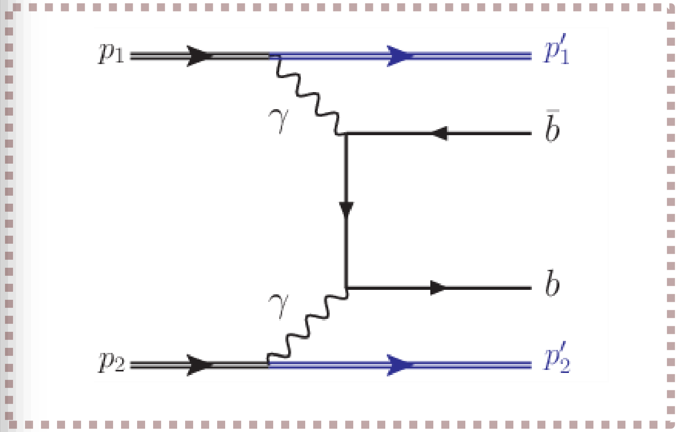
Introduction



- In other cases of hard scattered events:
  - Protons could remain intact (**tagged by PPS**)
  - Low track activity due to exchange of color singlets via **QCD (Pomeron)** or **QED (γ)**







High mass range is dominated by photon-photon interactions

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:

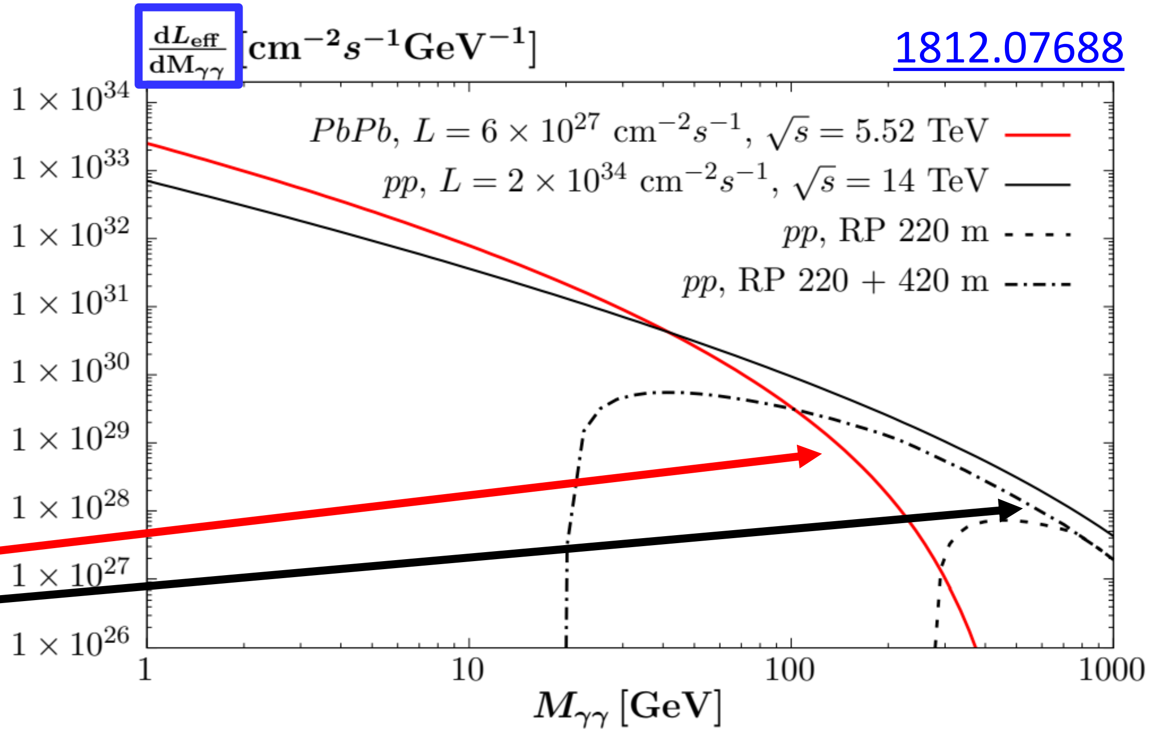
- Transverse momentum

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

- Longitudinal momentum

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

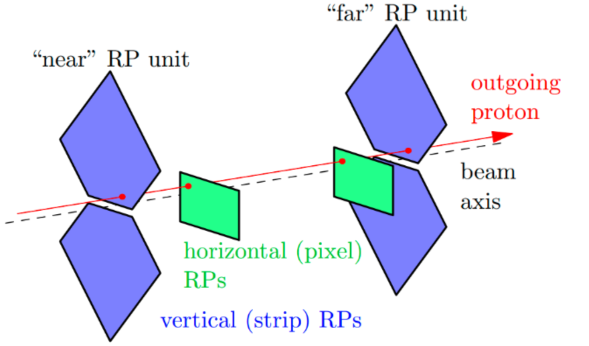
[1812.07688](1812.07688)



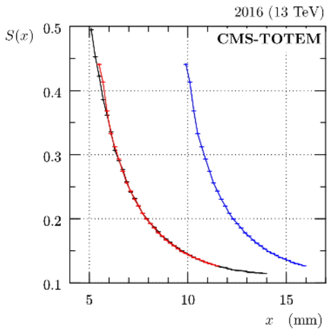
Photon fluxes are harder in pp collisions

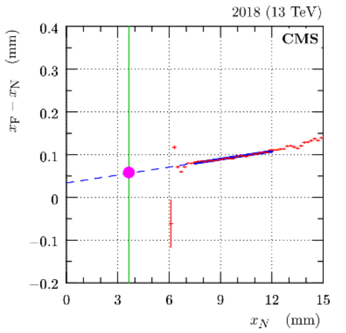
PPS | Calibration

arXiv:2210.05854



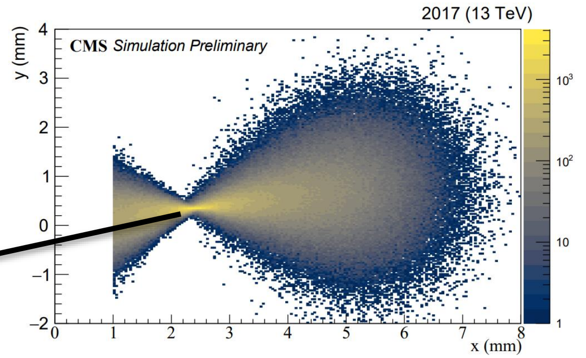
- Alignment (2 steps):
  - Global alignment – performed in special runs (2-3 bunches / beam), vertical detectors are used, PPS position w.r.t. the beam is obtained.
  - Local alignment – match proton tracks in a single station from physics run to that of the alignment run (fill-by-fill)





- Optics:
  - LHC magnetic fields (optics) validated in data

$L_y(\xi_0) = 0$



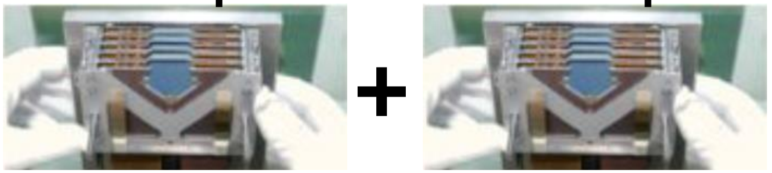
PPS | Tracking technology

arXiv:2210.05854

- <u>Rapid detector evolution</u> since commissioning in 2016!

2016: PPS inherits from TOTEM Silicon strip tracker (used in special runs, cannot resolve multiple tracks)

SiStrip **SiStrip**



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

SiStrip **3D Pixel**

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

3D Pixel **3D Pixel**

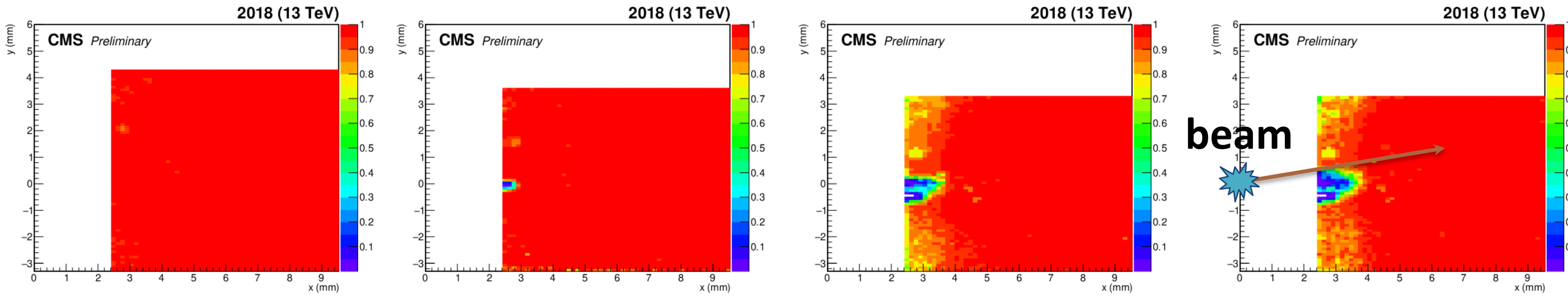
PPS | Tracking efficiency

arXiv:2210.05854

- Challenges in the standard LHC runs:
  - Efficiency drop due to irradiation
  - Higher x -> Higher ξ -> Higher minimal accepted mass
  - Detectors were shifted during LHC Technical Stops (TS) by 0.5mm

Proton spectra

LHC Sector 45
efficiency



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

PPS | Tracking efficiency

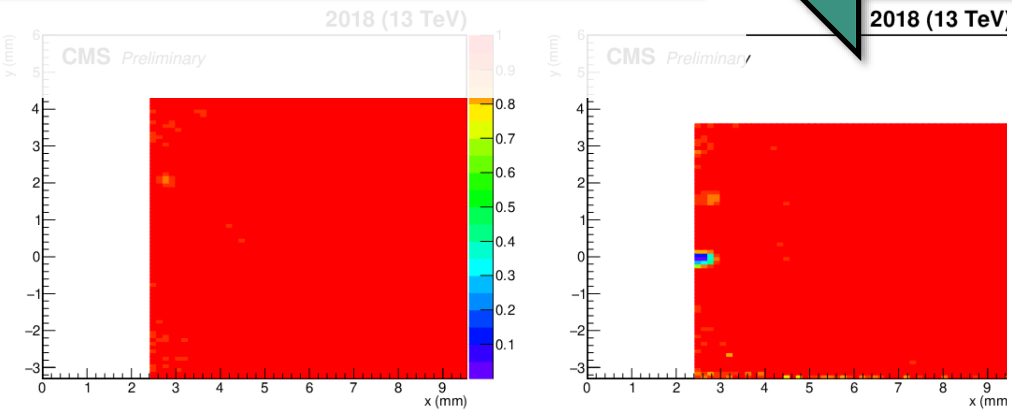
arXiv:2210.05854

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

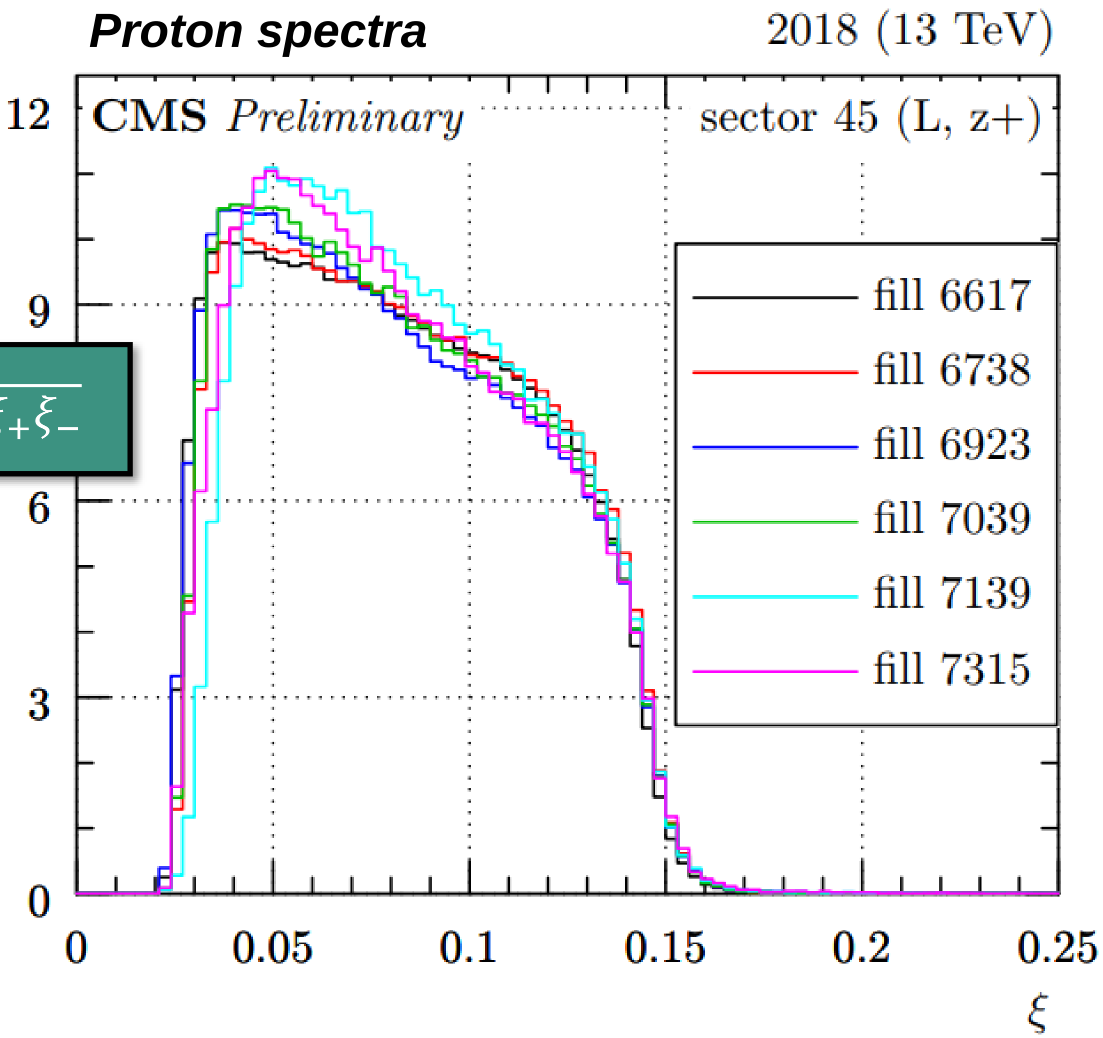
350 GeV $< m_X <$ 2 TeV

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

LHC Sector 45 efficiency



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



PPS | Timing

- Vertex z-coordinate is reconstruction using ToF:

CMS

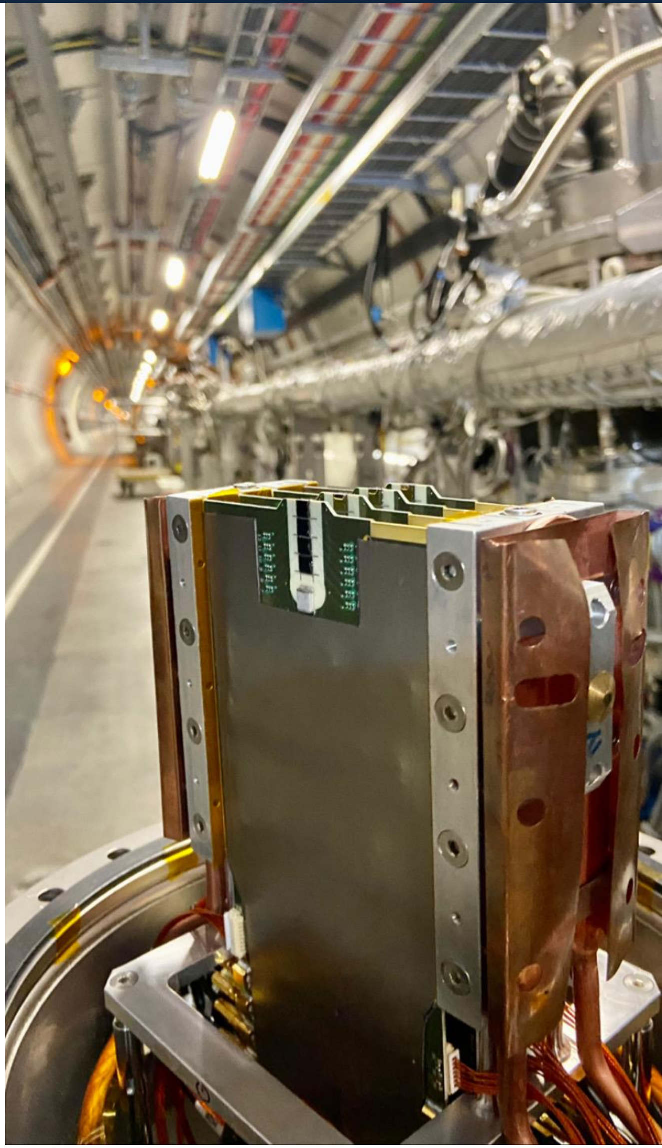
$t_{PPS\,1}$ $t_{PPS\,2}$

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

- Vertex time coordinate:

$$V_{t,PPS} = \frac{1}{2}(t_{PPS\,1} + t_{PPS\,2}) - c \cdot Z_{RP}$$

Timing detectors can be used for background discrimination during the standard LHC runs

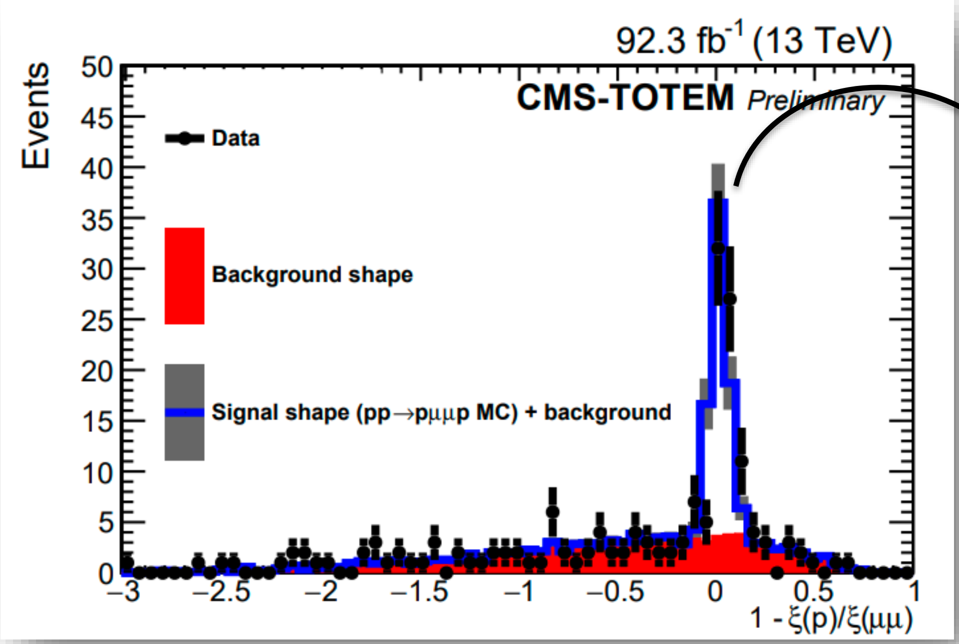


Credit: Nicola Turini

PPS | Performance in Run 2

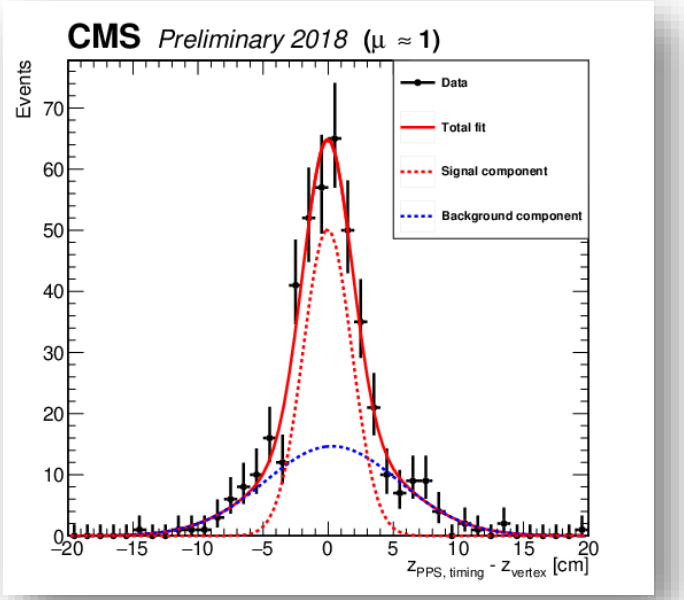
arXiv:2210.05854

- 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: $\sigma_z = 2.77 \pm 0.17cm$**



Cross-section of photon induced processess

Simulation setup:

BACK TO SLIDE 33

- Fiducial cross sections of CEP of SM processes in pp collisions at $\sqrt{s} = 14$ TeV, using EPA for photon fluxes, with survival probability of 90% for elastic interactions, and cross sections of semi-exclusive processes were obtained using *MMHT2015qed_nlo_inelastic* PDFSet, with survival probability of 70%.
- Selection cuts of $p_T > 20$ GeV on the generated objects is applied for all processes with 2 particles in the final state.
- Single Higgs boson production generated using the *HEFT* model
- CEP of ZZ, Zγ and γγ generated using the *loop_qcd_qed_sm* model
- Two scenarios are considered: with and w/o 420m (station acceptances are listed on the next slide)
- Fiducial cross-sections are computed for two selections:
  - At least one proton is within the PPS acceptance - 1 tag events
  - Both protons are within the PPS acceptance - 2 tag events

PPS acceptance

Table 4: Lower and upper ξ limits, and minimum and maximum central mass accepted by each station at rapidity y = 0. The top and bottom blocks represent vertical (officially chosen for implementation) and horizontal crossing (for comparison), respectively. The ranges in the minimum values indicate the beginning and the end of the levelling trajectories, (1A) to (1Z) and (2A) to (2Z).

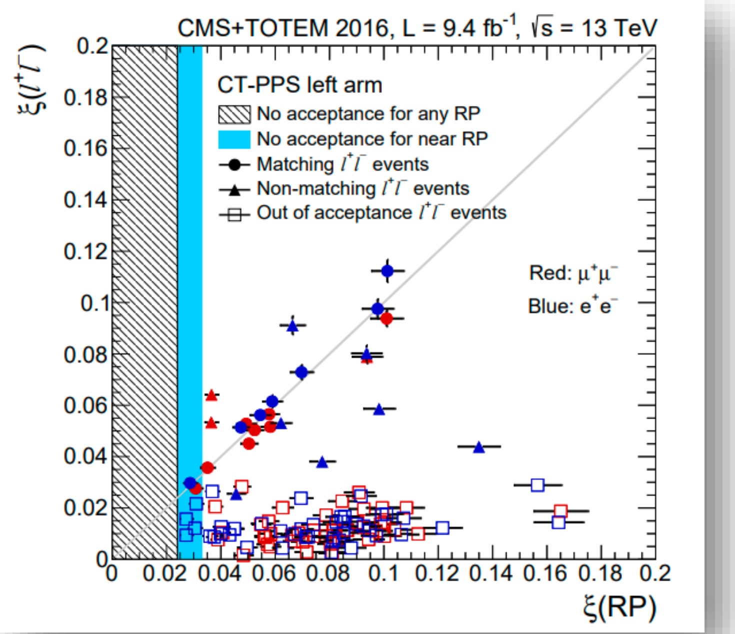
Vertical Crossing-Angle				
Station	$\lvert\xi_{\mathrm{min}}\rvert$	$\lvert\xi_{\mathrm{max}}\rvert$	M_{min} [GeV] @ y = 0	M_{max} [GeV] @ y = 0
196 m	0.0786–0.0856	0.1967	1100.87–1197.80	2754.27
220 m	0.0371–0.0381	0.0688	519.89–533.18	962.70
234 m	0.0189–0.0095	0.0263	264.96–132.80	368.11
420 m	0.0031–0.0034	0.0116	43.38–47.04	162.66

Horizontal Crossing-Angle				
Station	$\lvert\xi_{\mathrm{min}}\rvert$	$\lvert\xi_{\mathrm{max}}\rvert$	M_{min} [GeV] @ y = 0	M_{max} [GeV] @ y = 0
196 m	0.1654–0.1779	0.2871	2316.15–2490.07	4018.94
220 m	0.0984–0.1014	0.1488	1377.48–1419.13	2083.04
234 m	0.0564–0.0312	0.0732	789.48–437.07	1024.60
420 m	0.0032–0.0034	0.0118	44.55–48.20	165.28

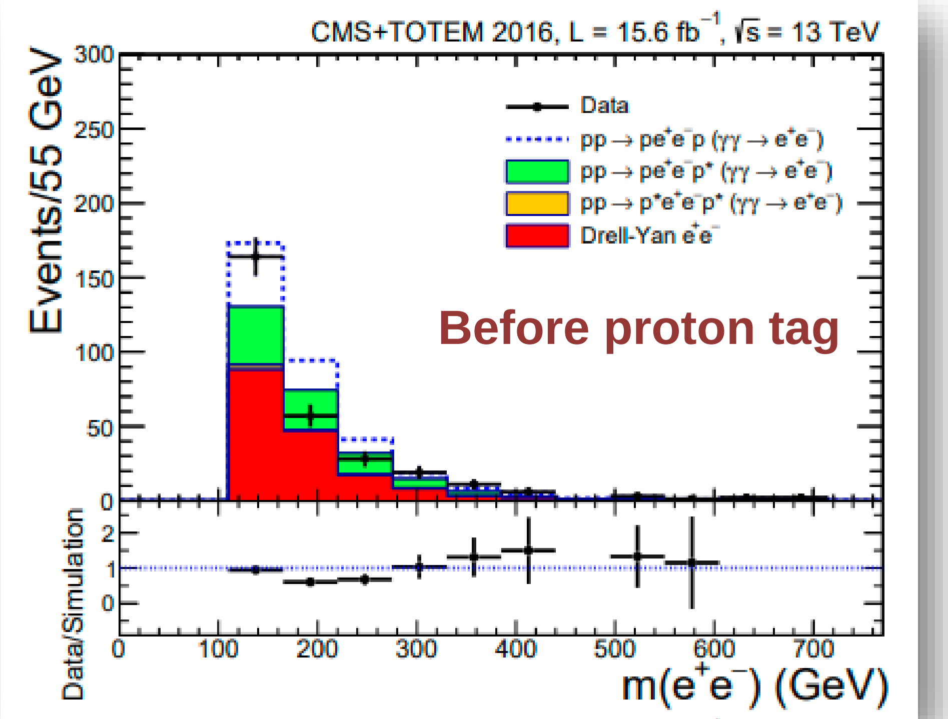
Physics | di-lepton events

○ Observation of (semi)-exclusive dilepton production

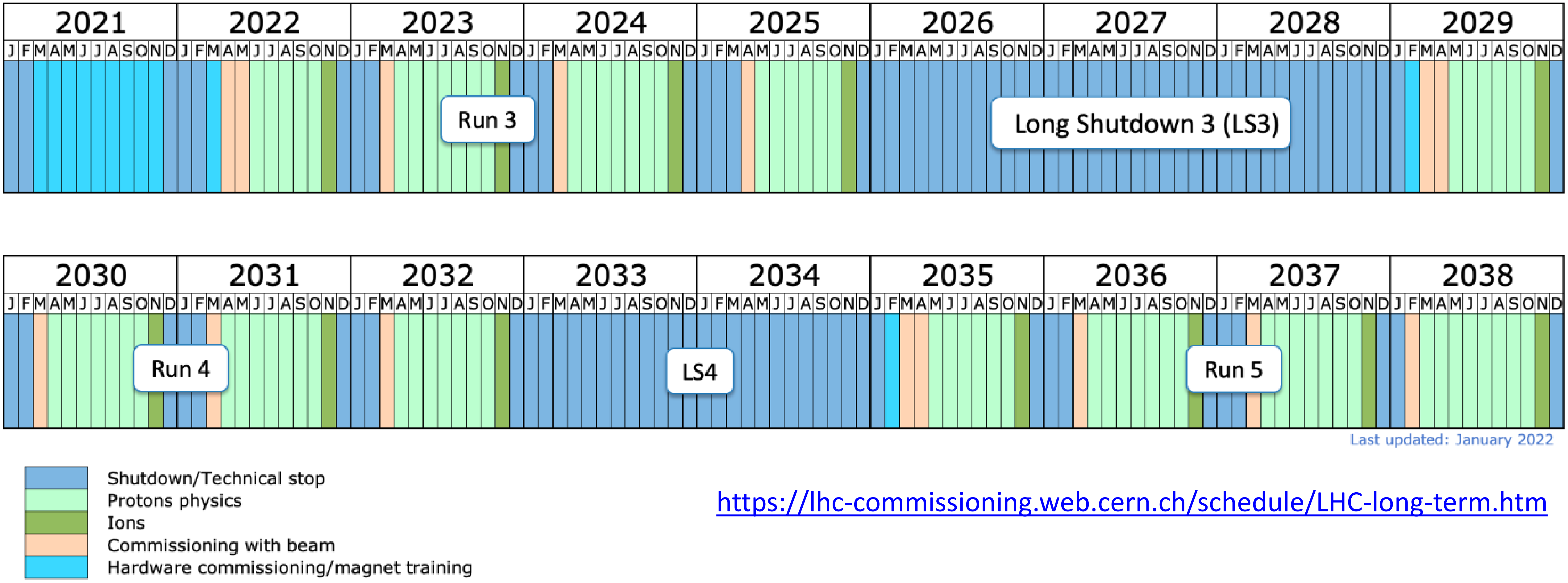
- Exclusive di-lepton production is the cleanest and most common CEP process
- PPS selects a clean sub-sample of signal events: $\xi_{\pm} = \frac{1}{\sqrt{s}}\left[p_T(l_1)e^{\pm\eta(l_1)} + p_T(l_2)e^{\pm\eta(l_2)}\right]$



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



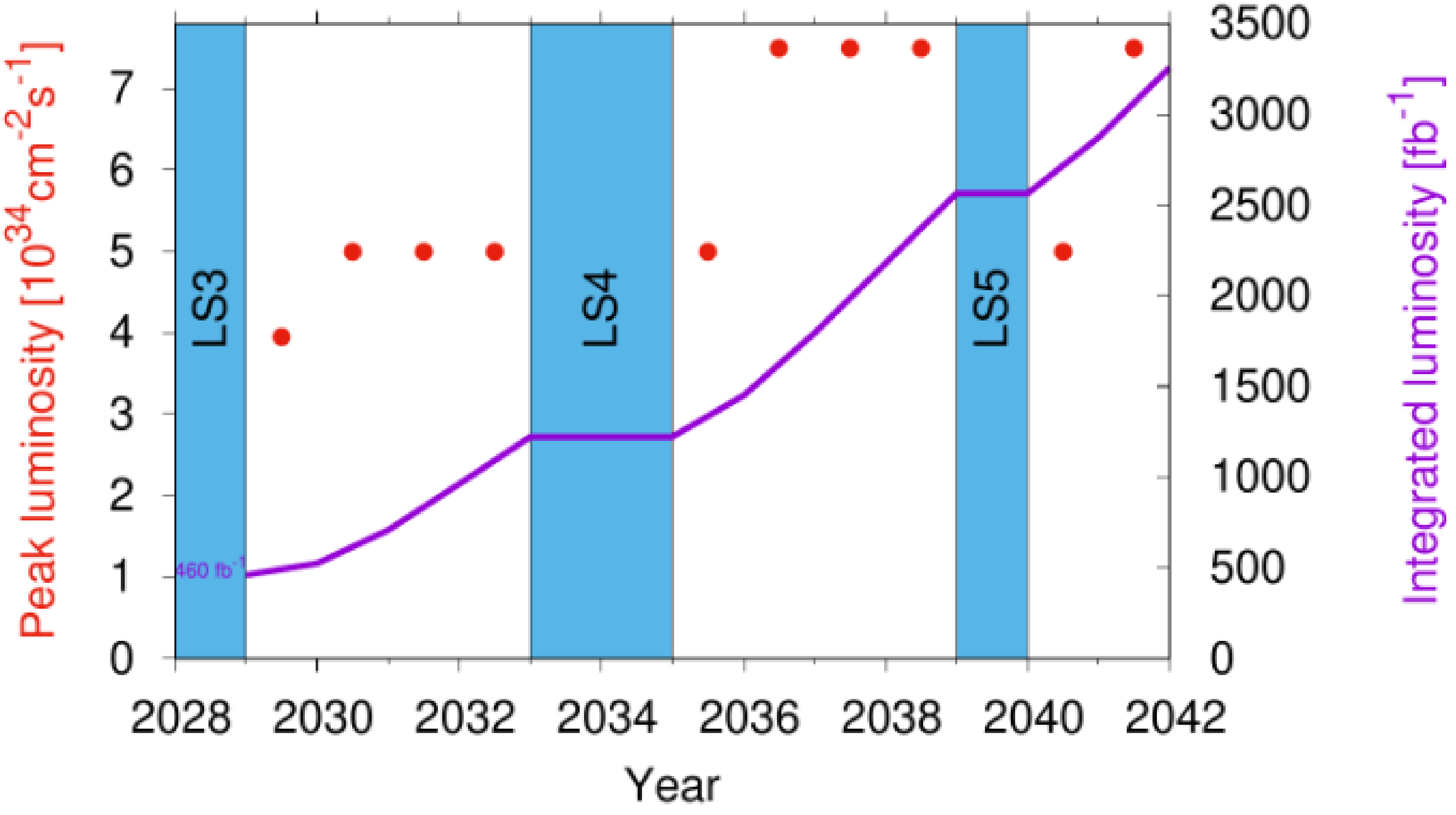
LHC Run schedule



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

HL-LHC Integrated luminosity

HL-LHC preliminary optimistic schedule
DG, 13/1/2022



R. Tomas in LHC performance workshop, January 2022

https://docs.google.com/presentation/d/1YYookjpit3yuvffIMGl-L7KILBiIci_nISQZaCa4aYg/edit#slide=id.g11065058479_2_22