Physics at the HL-LHC with proton tagging

18 January 2023

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* Also at Kansas University

Outline

- Physics with the tagged protons at the LHC
- Experimental apparatus
- Highlights from LHC Run 2 (2015-2018)
- Physics with tagged protons at the HL-LHC (>2029)

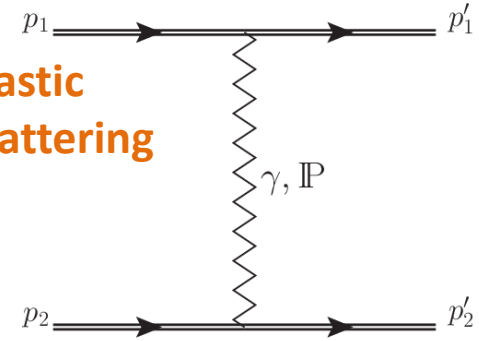
Physics with tagged protons at the LHC

Introduction

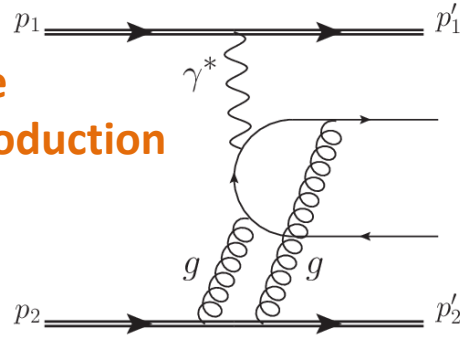
Diffractive and Exclusive production in pp collisions at the LHC

- t-channel exchange of color neutral particles
- Pomerons for QCD / photons for QED interactions

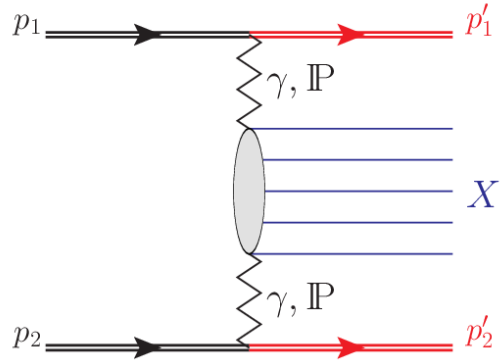
Elastic scattering

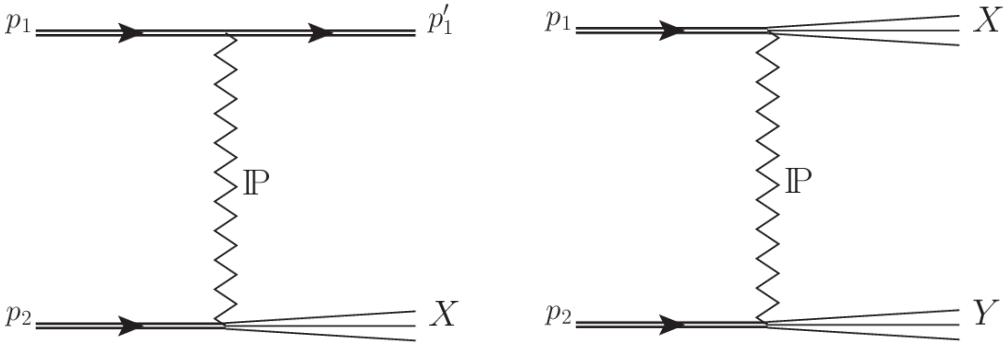


Exclusive photoproduction

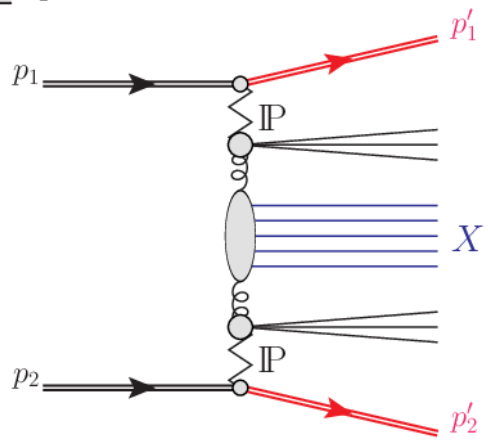


Central exclusive production

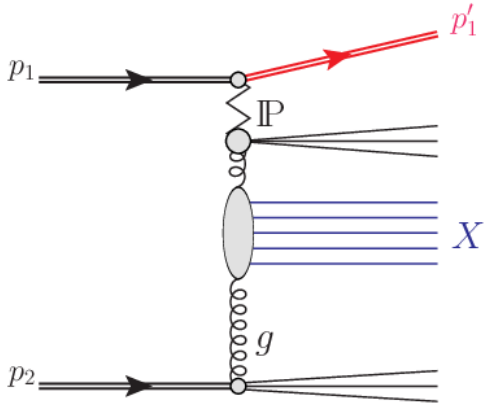




Single/double diffractive dissociation



Double pomeron exchange



Single-diffraction with central system X

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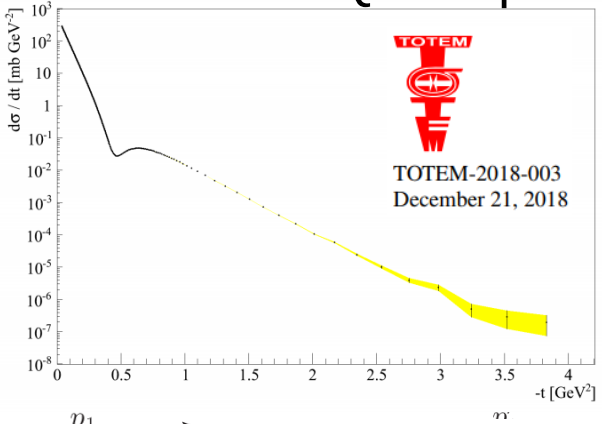
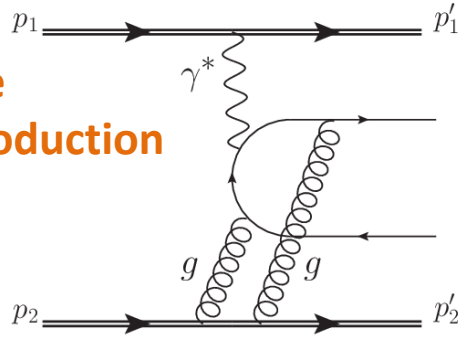
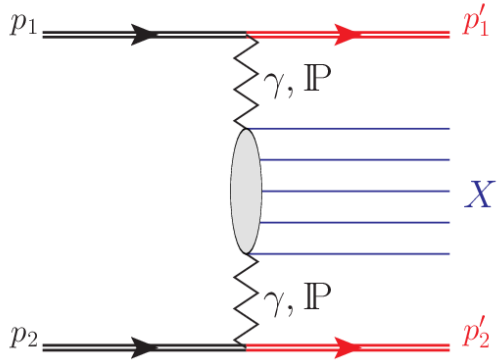
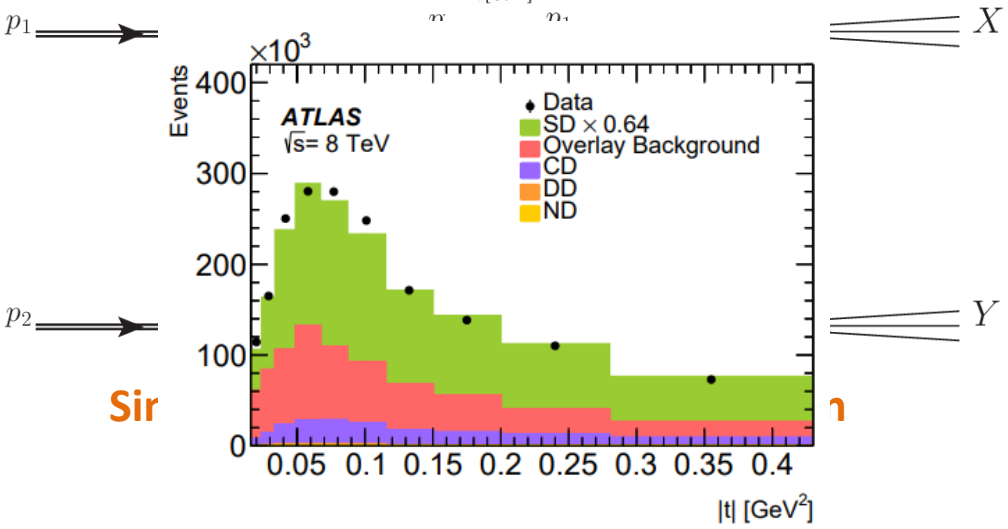




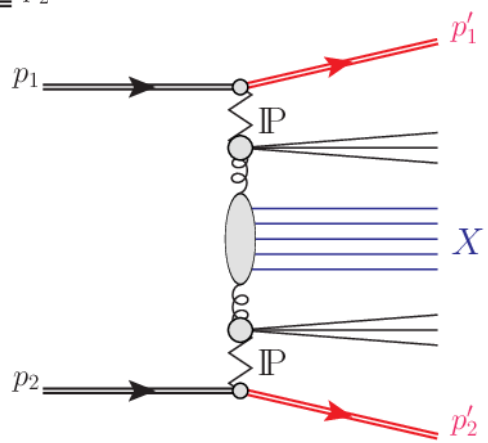
Exclusive photoproduction

Central exclusive production





Sir **n**



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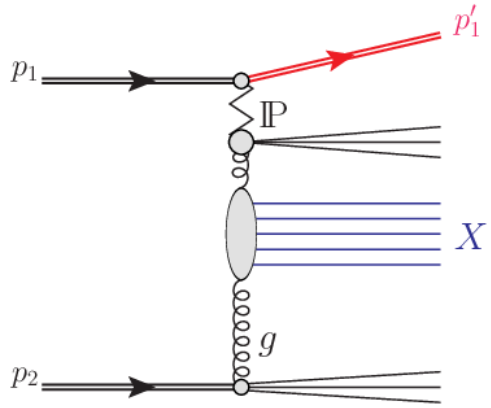

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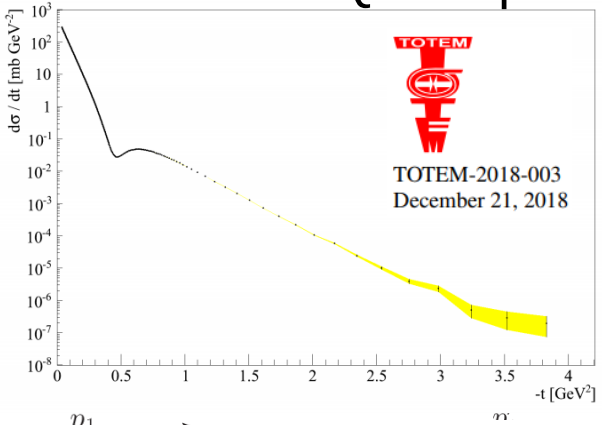

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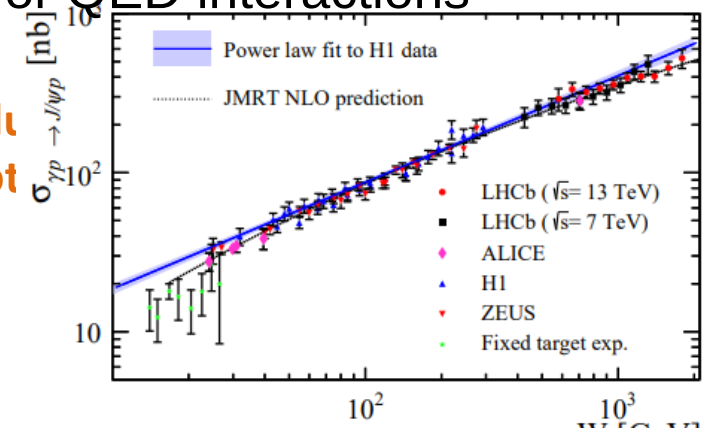

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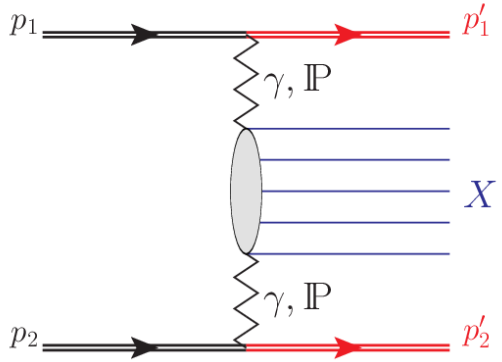

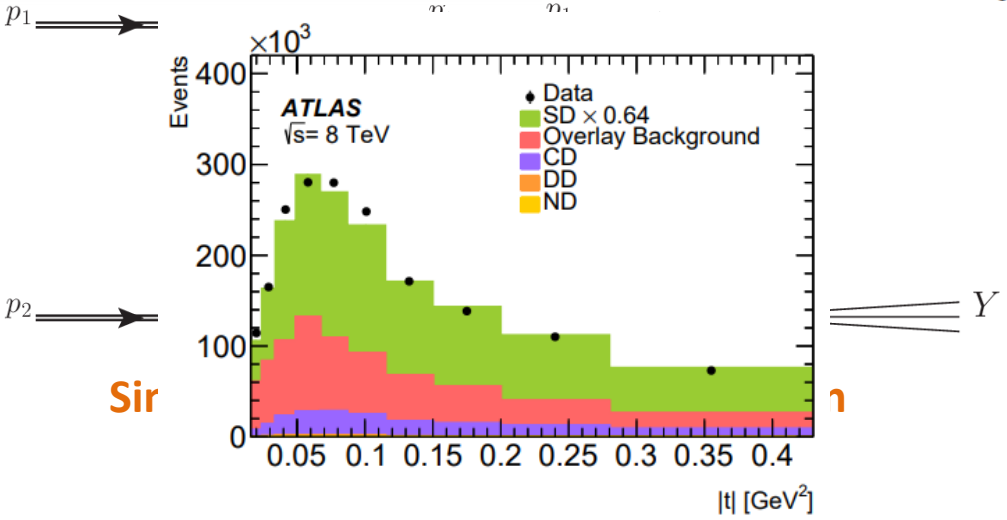

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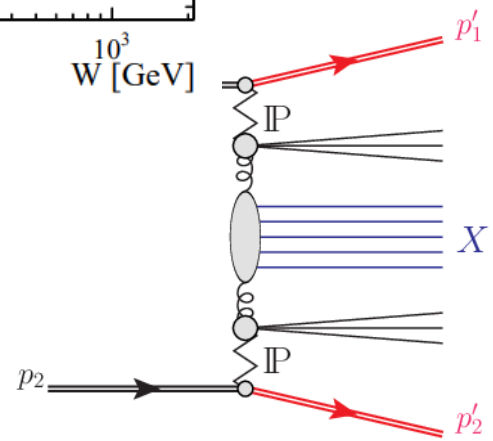

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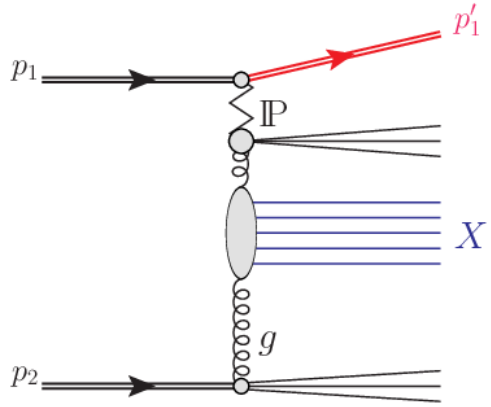

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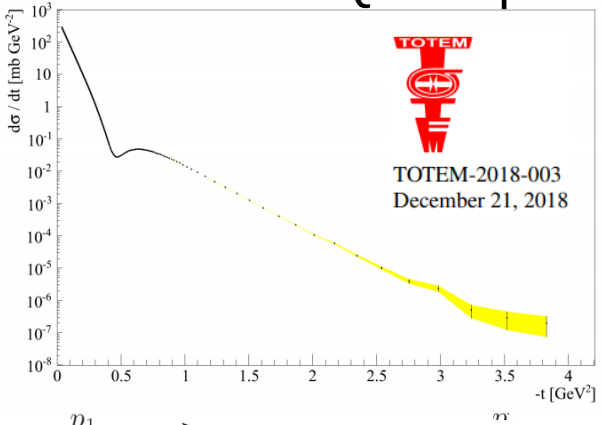

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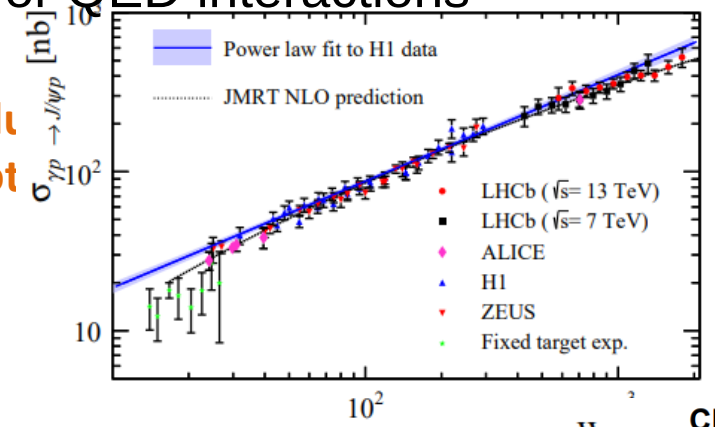

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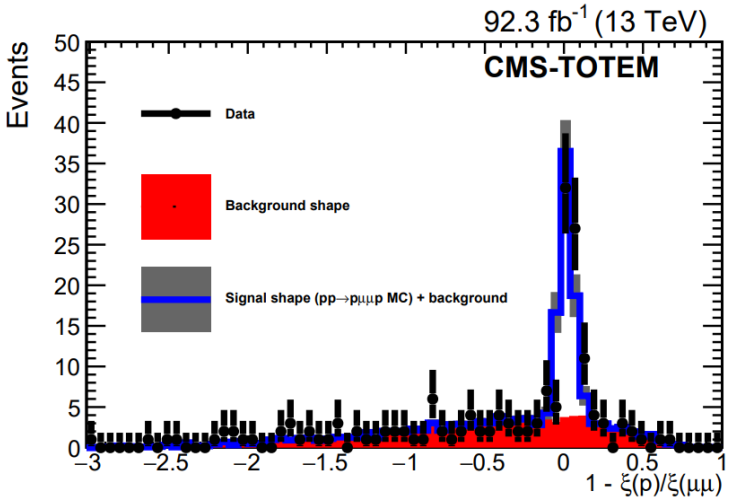

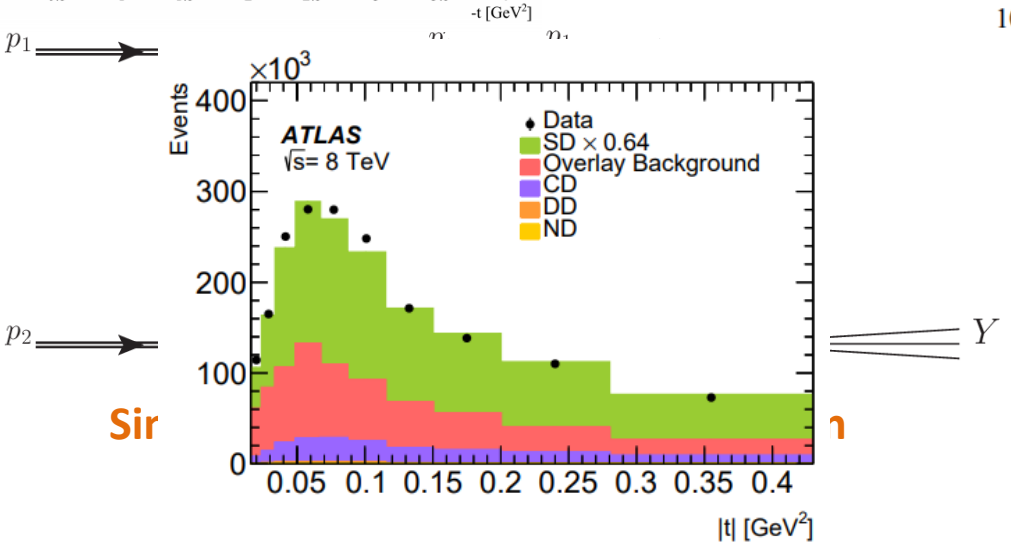

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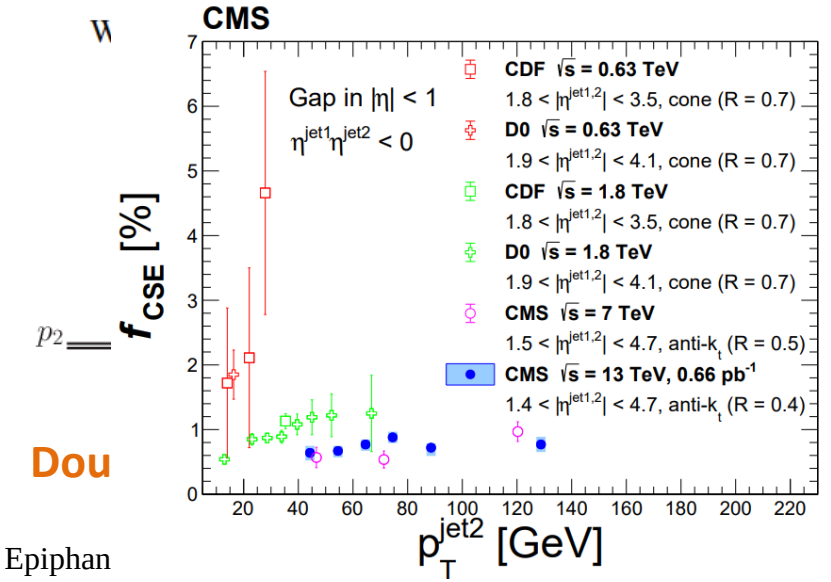

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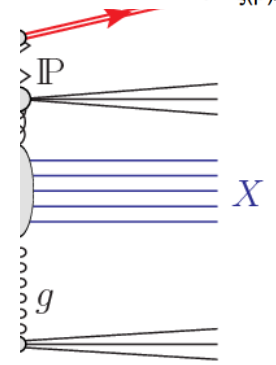

fraction with stem X

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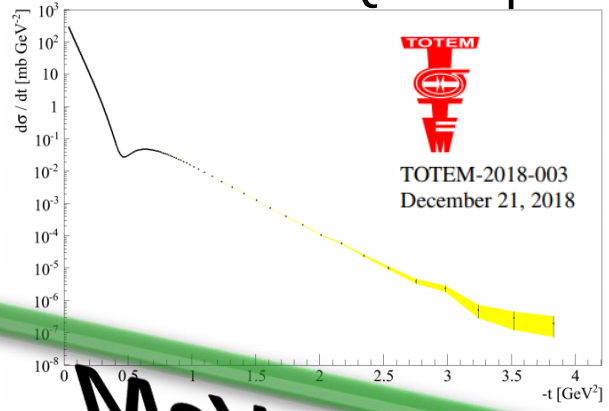

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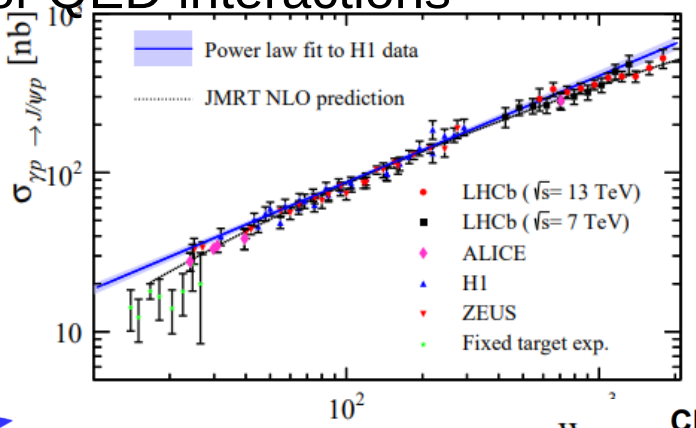
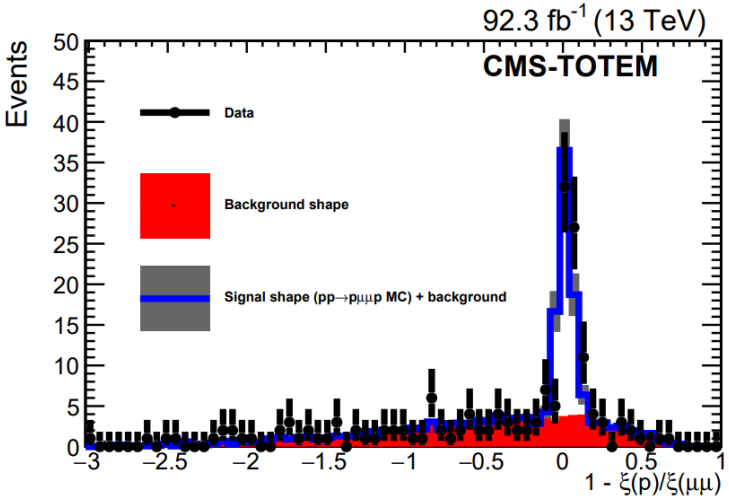


Central exclusive production

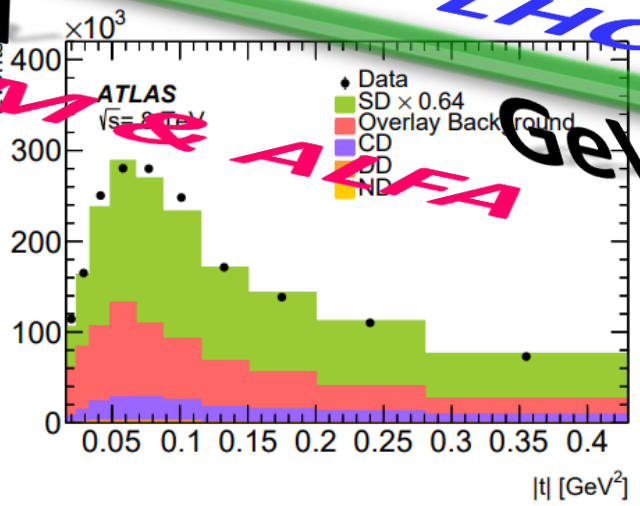


MeV

TOTEM & ALFA

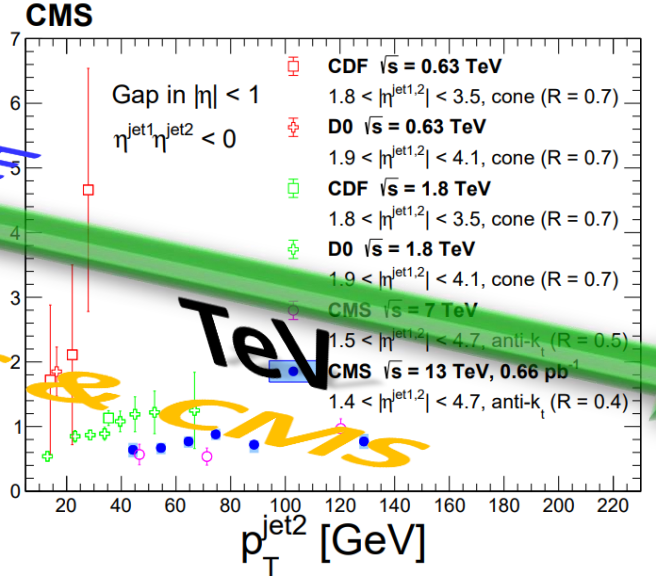
LHCb&ALICE

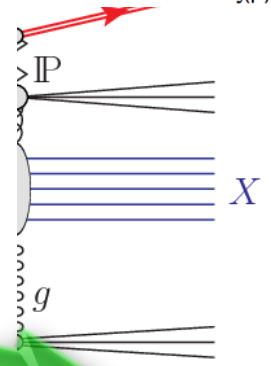
GeV



ATLAS&CMS

TeV





Sir

Dou

fraction with
stem X

Introduction

Diffractive and Exclusive production in pp collisions at the LHC with proton tag

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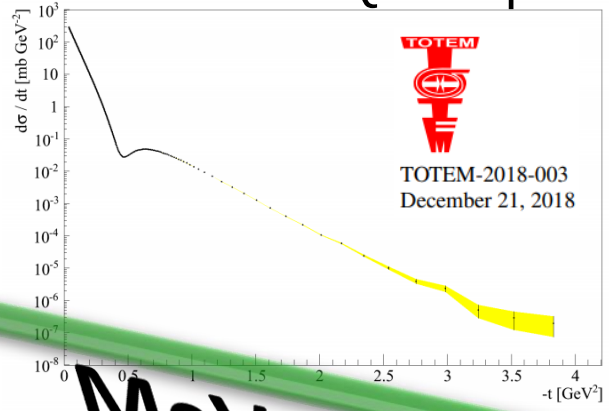
Central exclusive production



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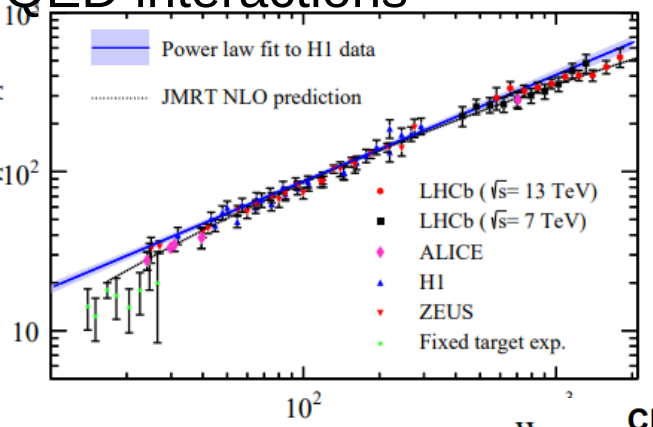

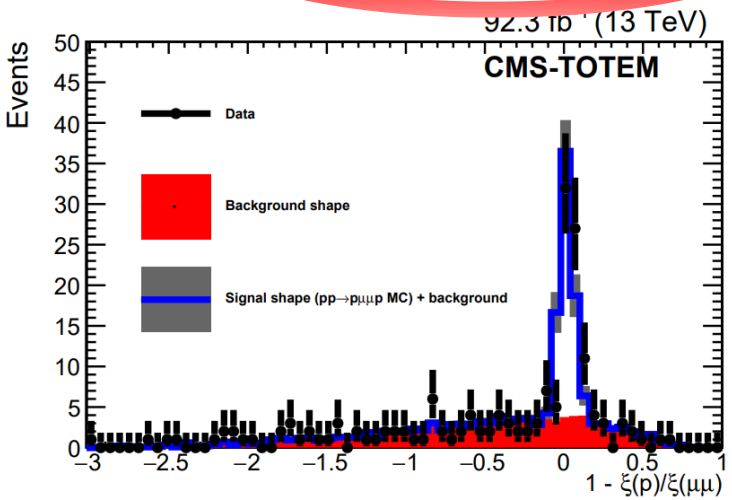

MeV

TOTEM & ALFA

LHCb&ALICE

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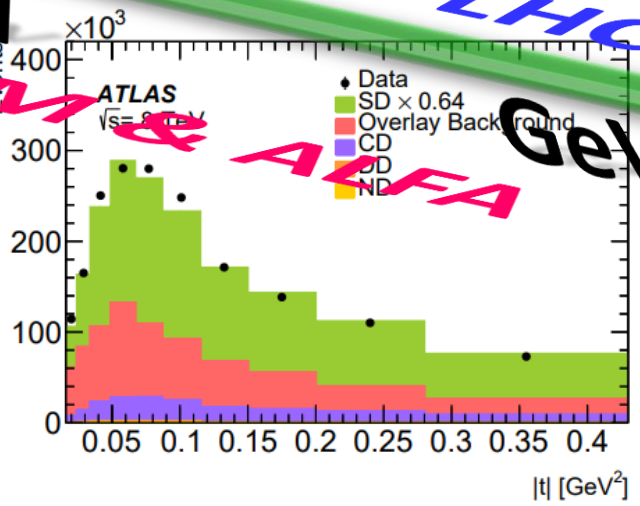
ATLAS

TeV

CMS & ATLAS



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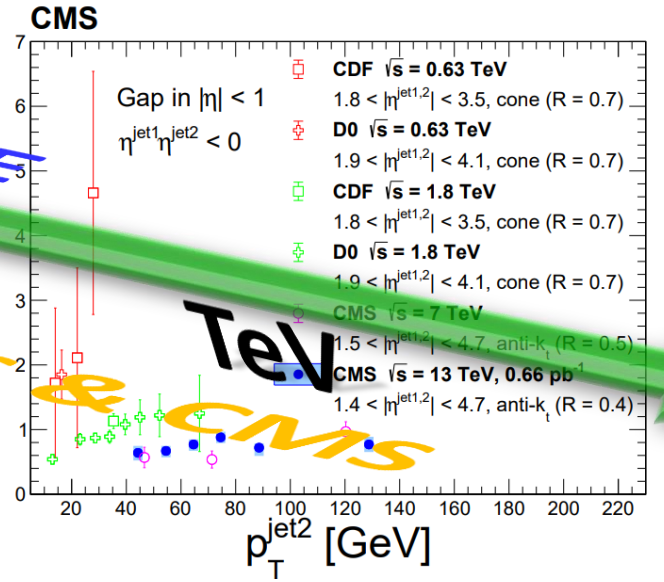
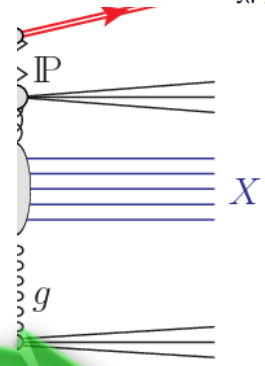




fraction with
stem X

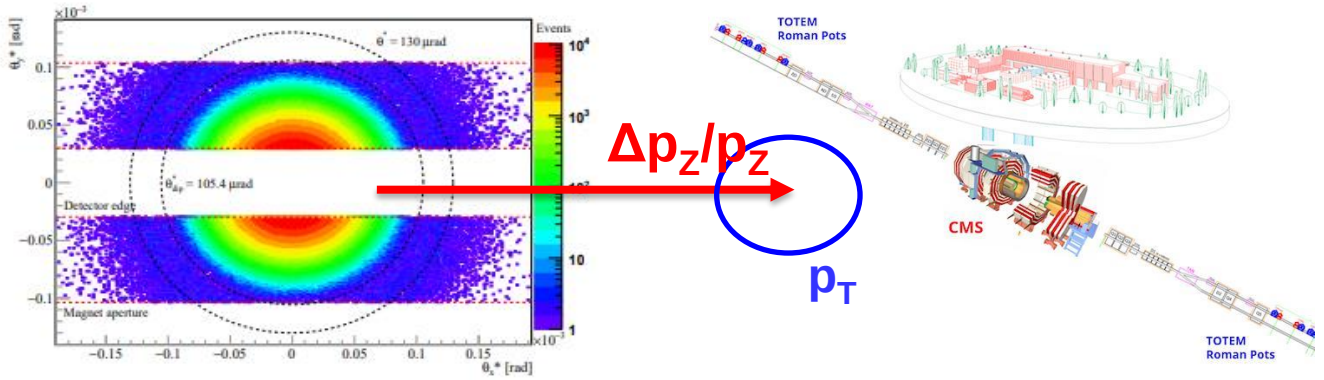
Proton spectrometers

Two type of forward detectors are installed: vertical and horizontal

Vertical detectors (ALFA, TOTEM)

- Very low pileup (μ~0.02), special LHC optics
- Proton kinematics:

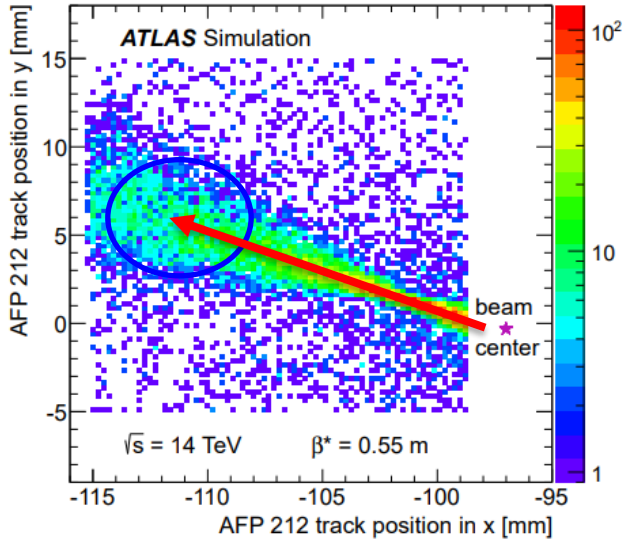
$\Delta p_Z/p_Z < 20\%$ and $p_T \sim 0.15 - 2$ GeV

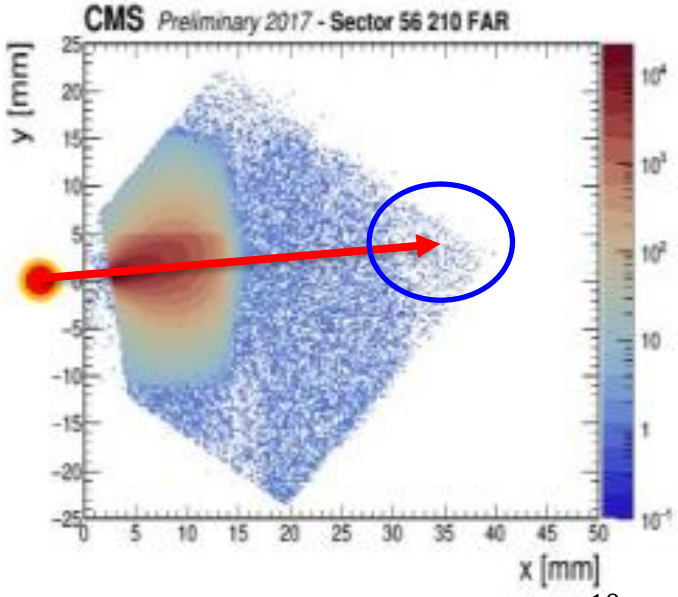


Horizontal detectors (AFP, PPS)

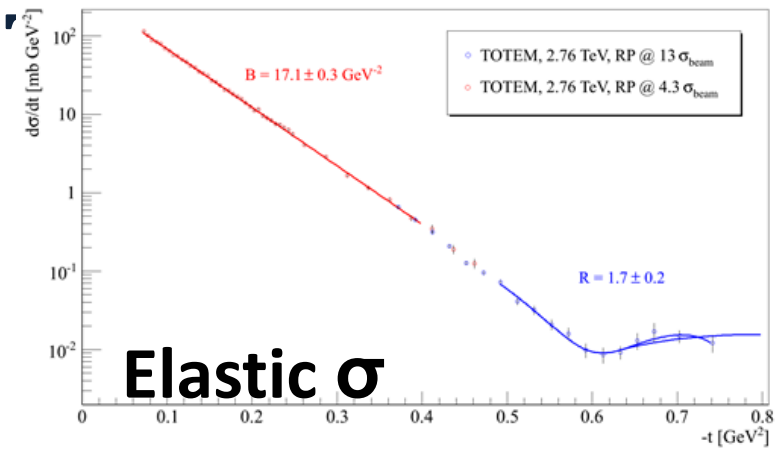
- Standard LHC optics (high pileup)
- Proton kinematics:

$3\% < \Delta p_Z/p_Z < 20\%$ and $p_T < 4$ GeV

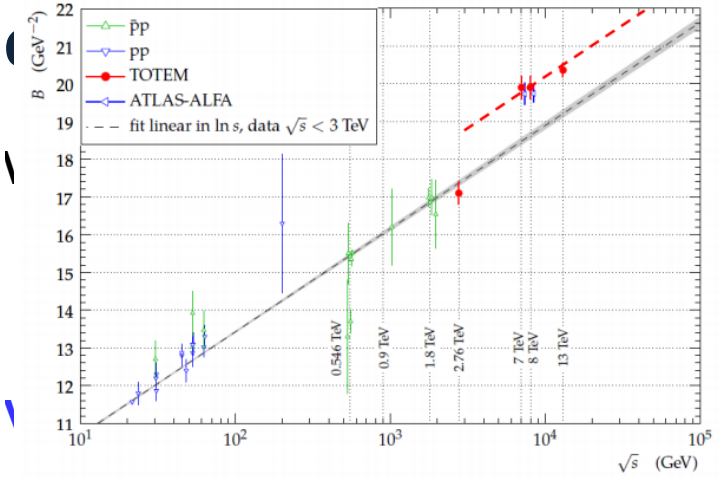


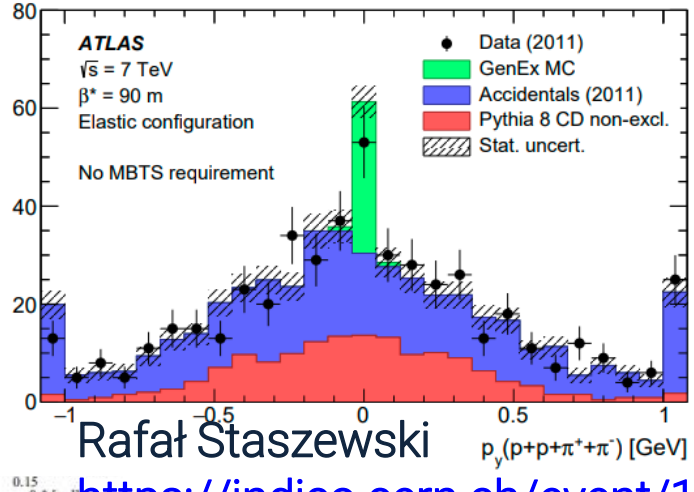


Proton spectrometers



Elastic σ





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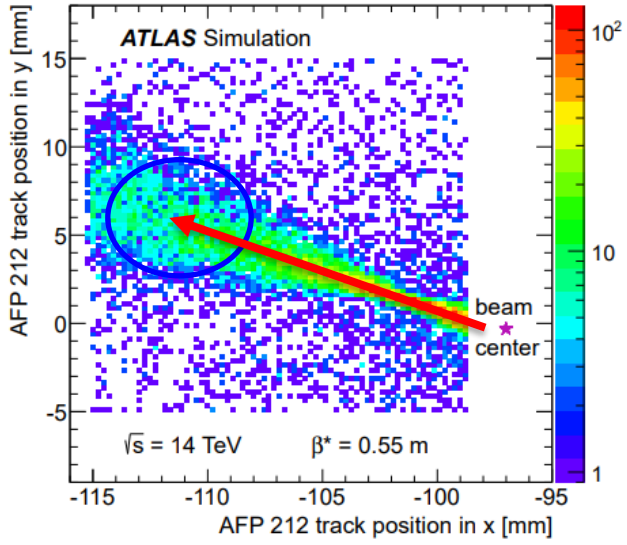
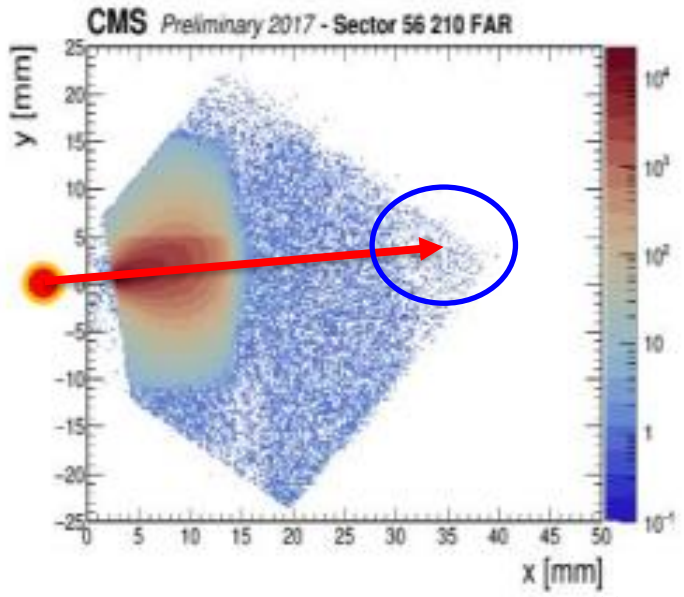
https://indico.cern.ch/event/1187936/

Horizontal detectors (AFP, PPS)

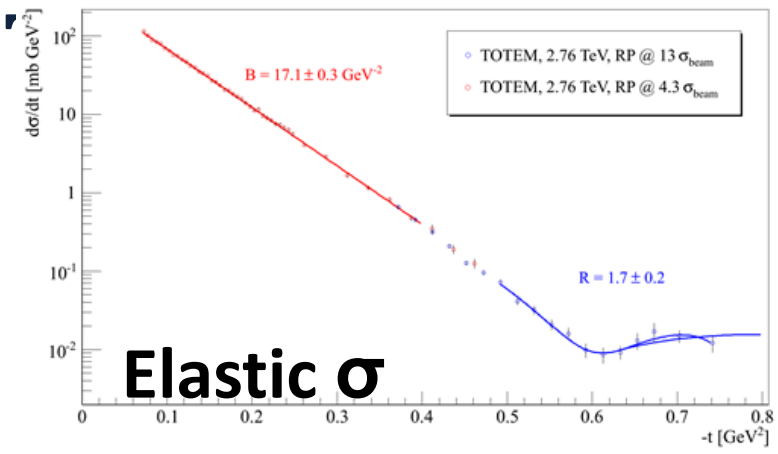
- Standard LHC optics (high pileup)
- Proton kinematics:

$3\% < \Delta p_Z/p_Z < 20\%$ and **$p_T < 4$ GeV**





Proton spectrometers



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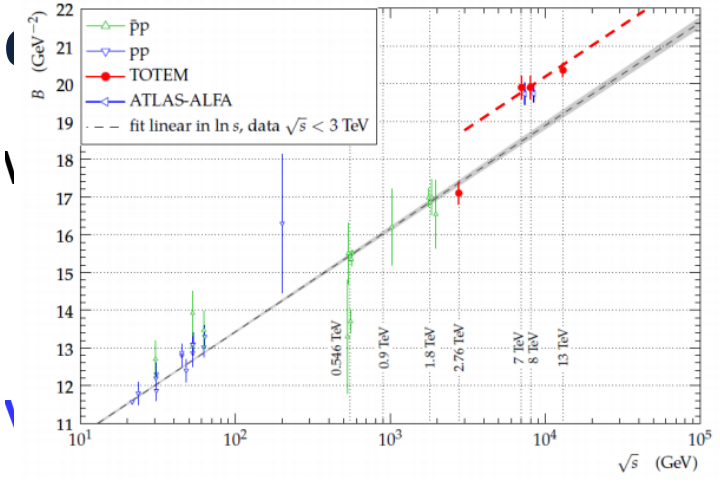

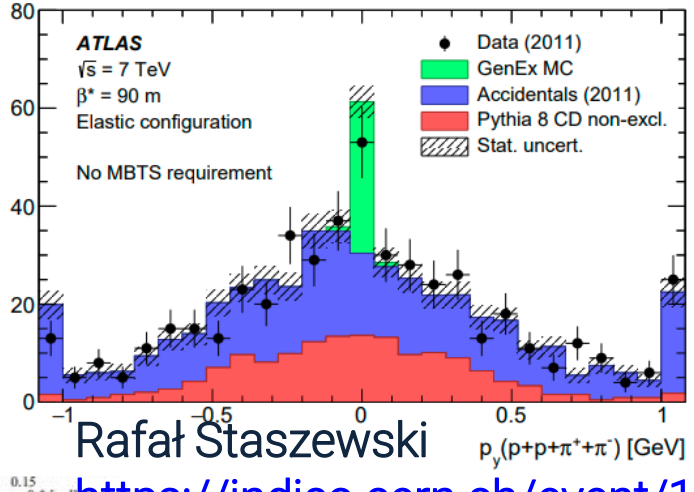

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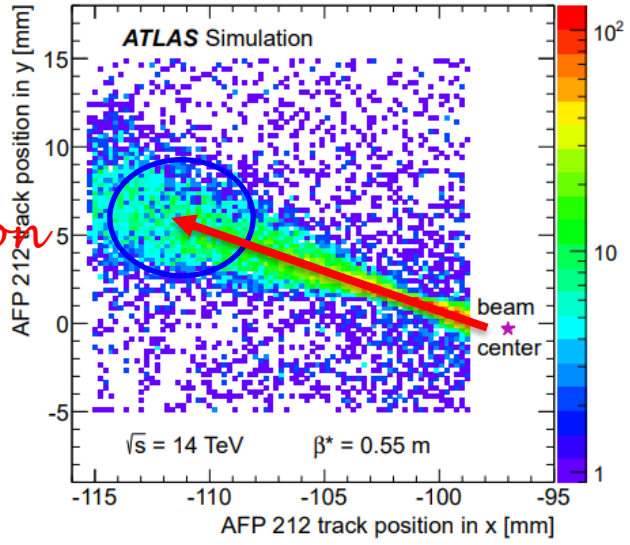
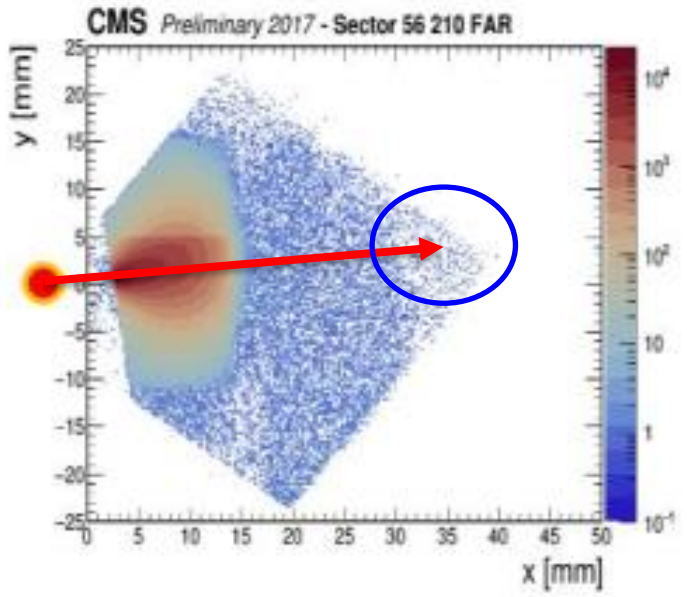
Horizontal detectors (AFP, PPS)

- Standard LHC optics (high pileup)
- Proton kinematics: *I'll focus on the horizontal configuration*

$3\% < \Delta p_Z/p_Z < 20\%$ and **$p_T < 4$ GeV**

Planned to be used also during the HL-LHC phase





Experimental apparatus

Proton spectrometers at the LHC in Run 2+3

PPS Overview

- TOTEM+CMS expertise: PPS TDR (TOTEM-TDR-003)
- PPS successfully integrated during 2016, ~220m from IP5 (initially “CT-PPS”)
- Covered mass range between 350 GeV and 2 TeV
- Collected >100 fb^{-1} during LHC Run 2

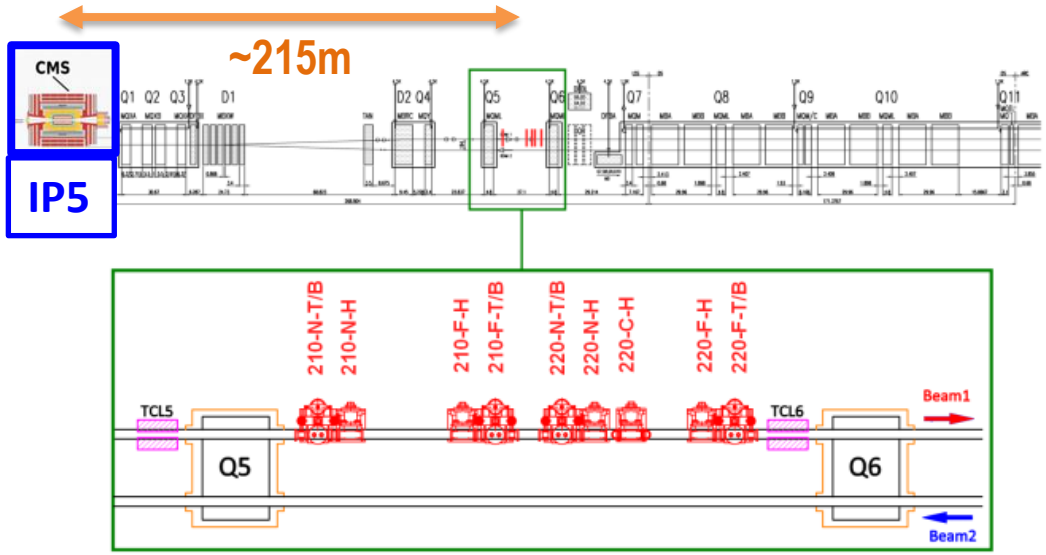
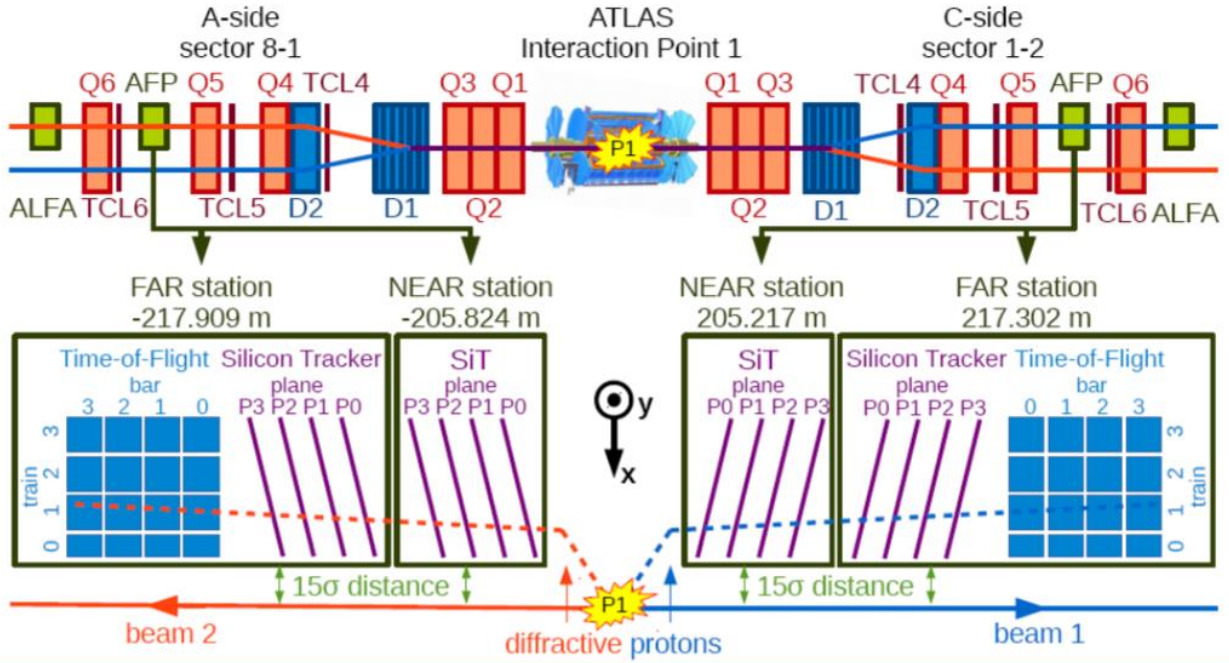


Figure 54: Schematic overview of the PPS units in Sector 5-6 (outgoing Beam 1) in the pre-LS3 configuration (top drawing adapted from [123]). The instrumentation in Sector 4-5 (outgoing Beam 2) is mirror-symmetric.

AFP Overview (1)

- 2 stations at $z \simeq 210$ m on each side of IP ("A-NEAR","A-FAR","C-NEAR","C-FAR")
- 4 planes of silicon tracking /stations
- FAR stations also have time-of-flight (ToF)



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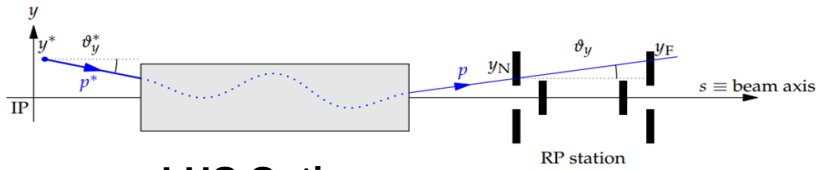
Proton spectrometers (AFP / PPS)

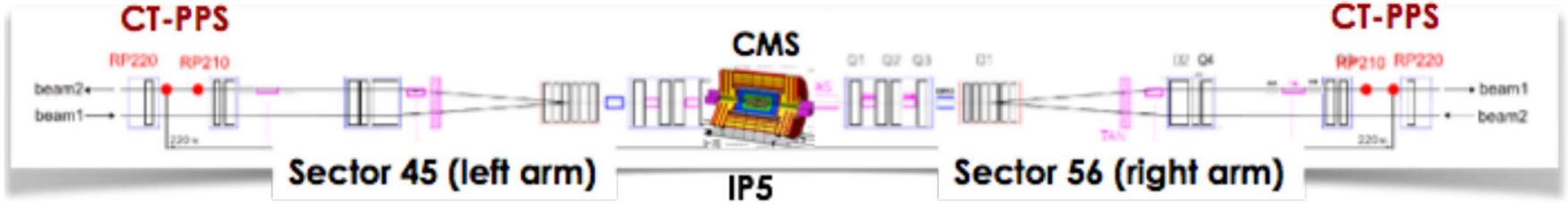
- Proton kinematics :

- Intact protons lose a fraction of momentum ($\boldsymbol{\xi = \Delta p_z / p}$) and are scattered at small angles ($\boldsymbol{\theta_x^*, \theta_y^*}$) → they are deflected away from the beam and measured by the spectrometers

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



LHC Optics



Proton spectrometers (AFP / PPS)

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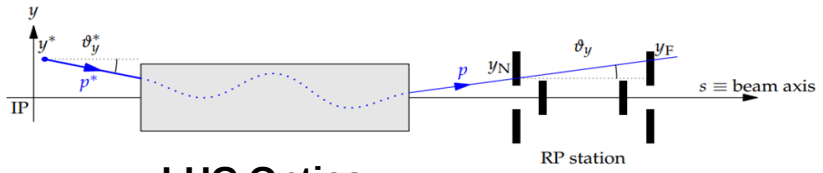

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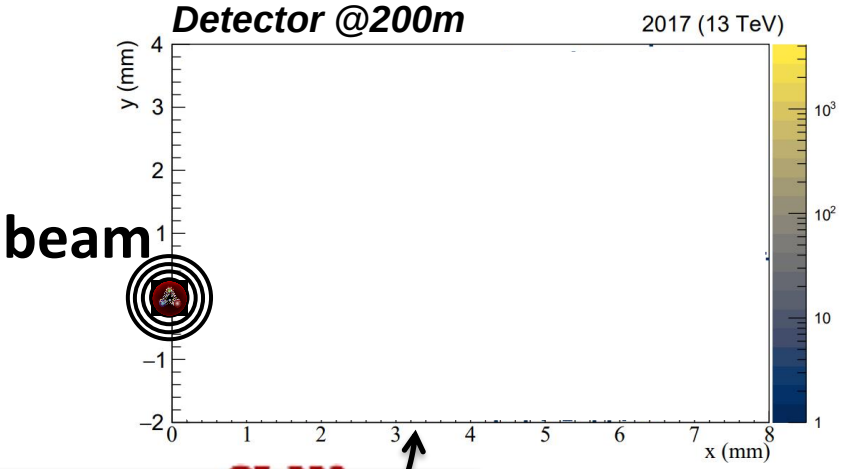

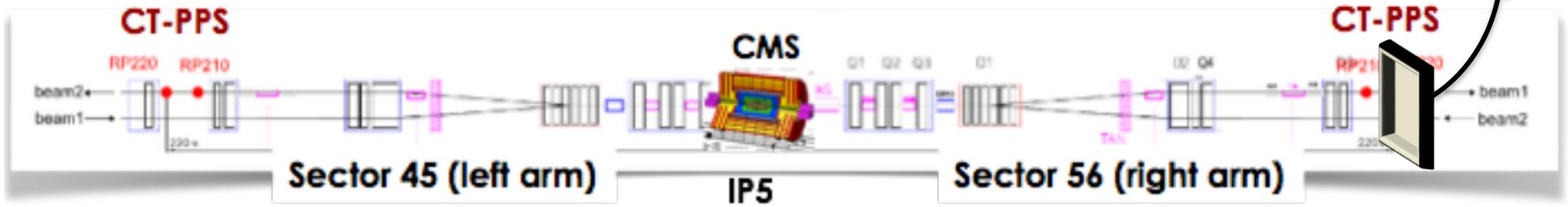

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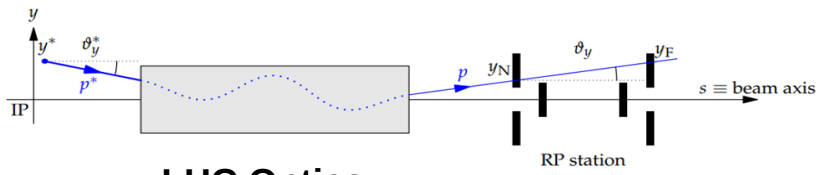

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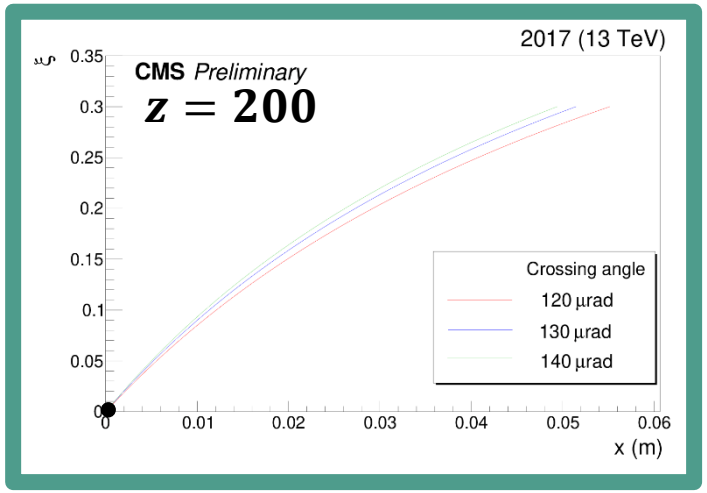

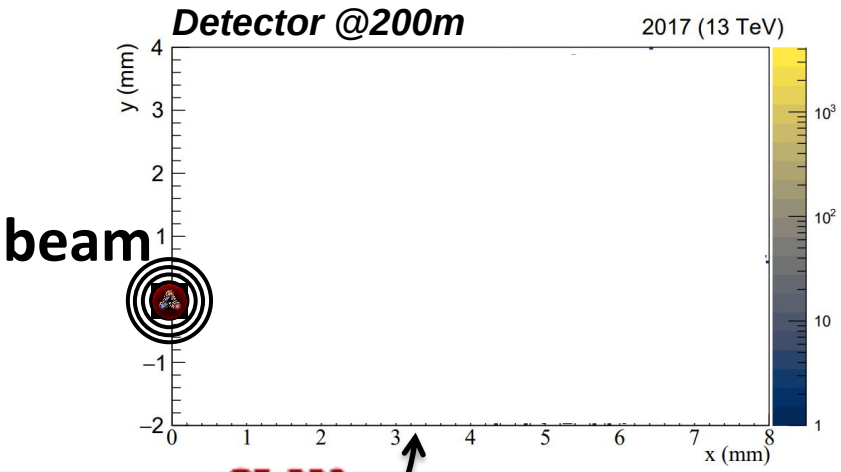

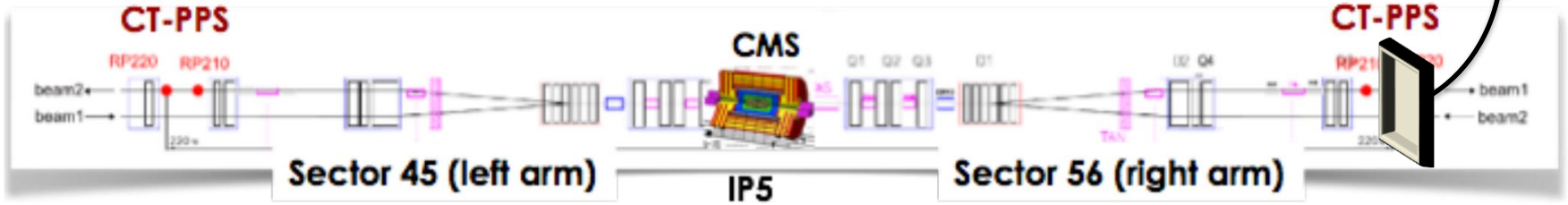

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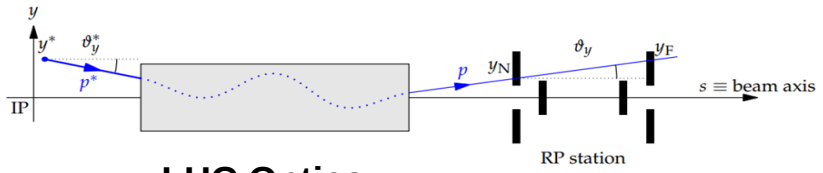

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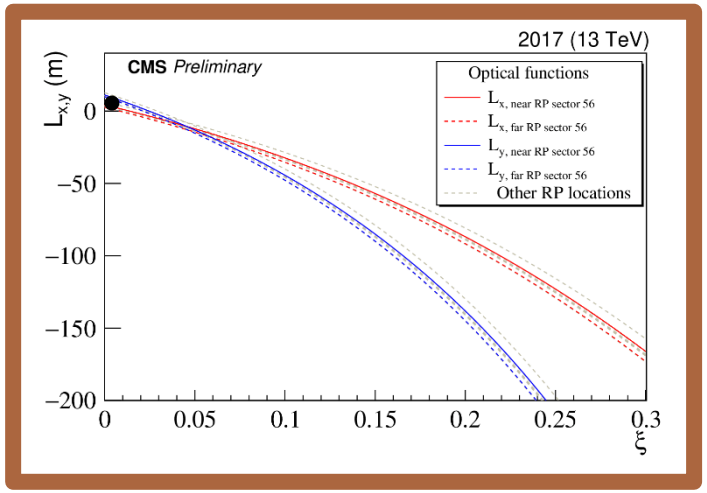

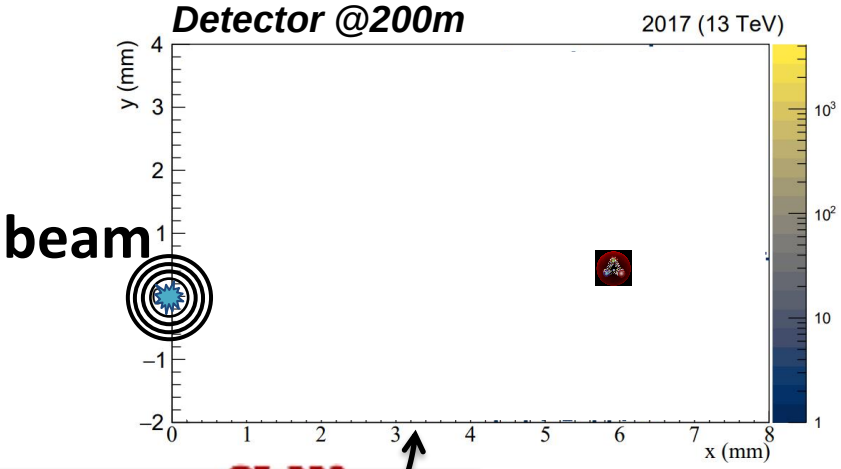

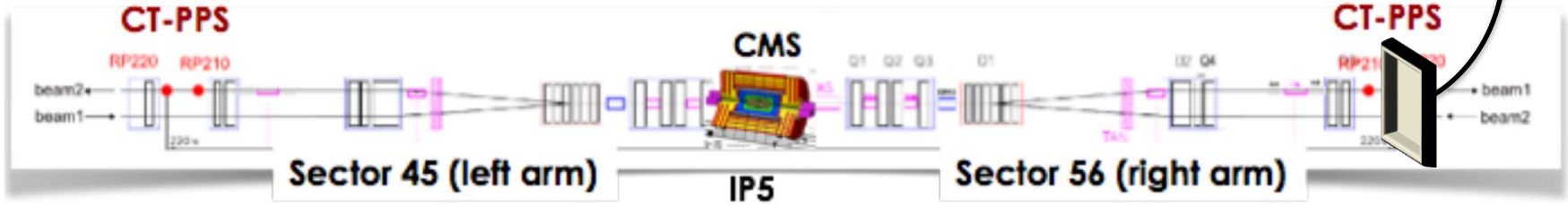

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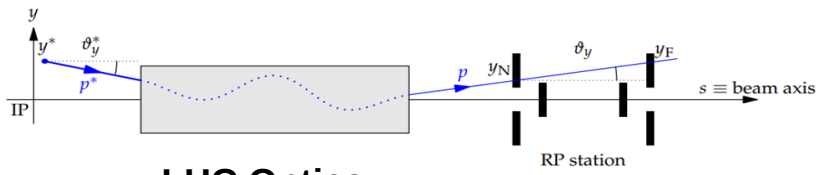
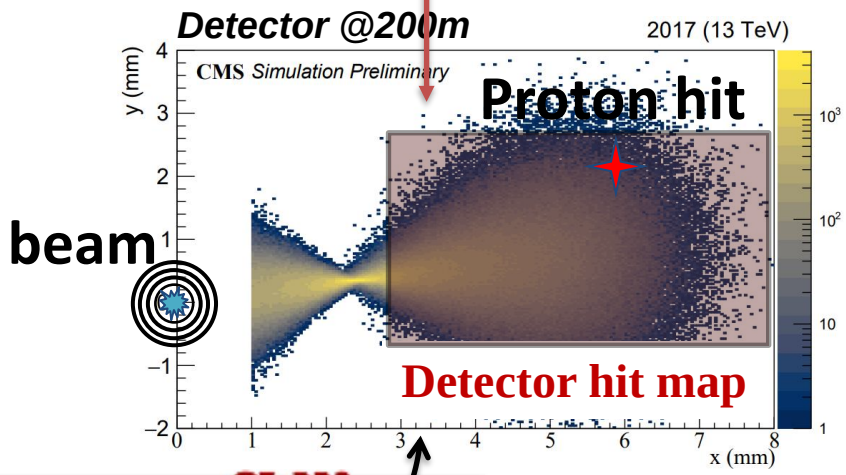
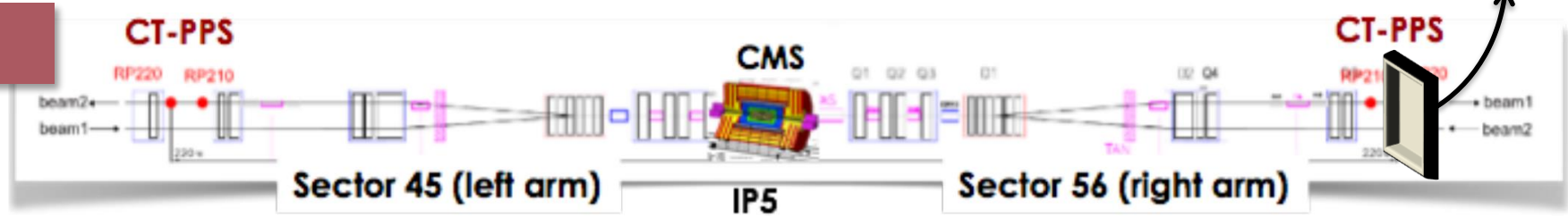


LHC Optics

acceptance

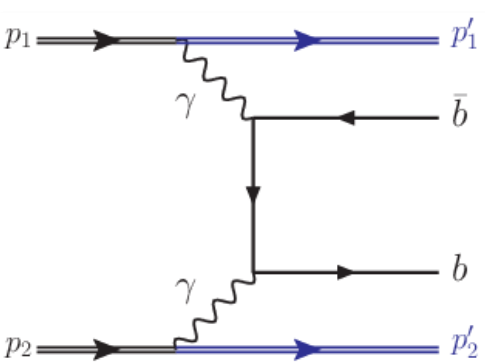


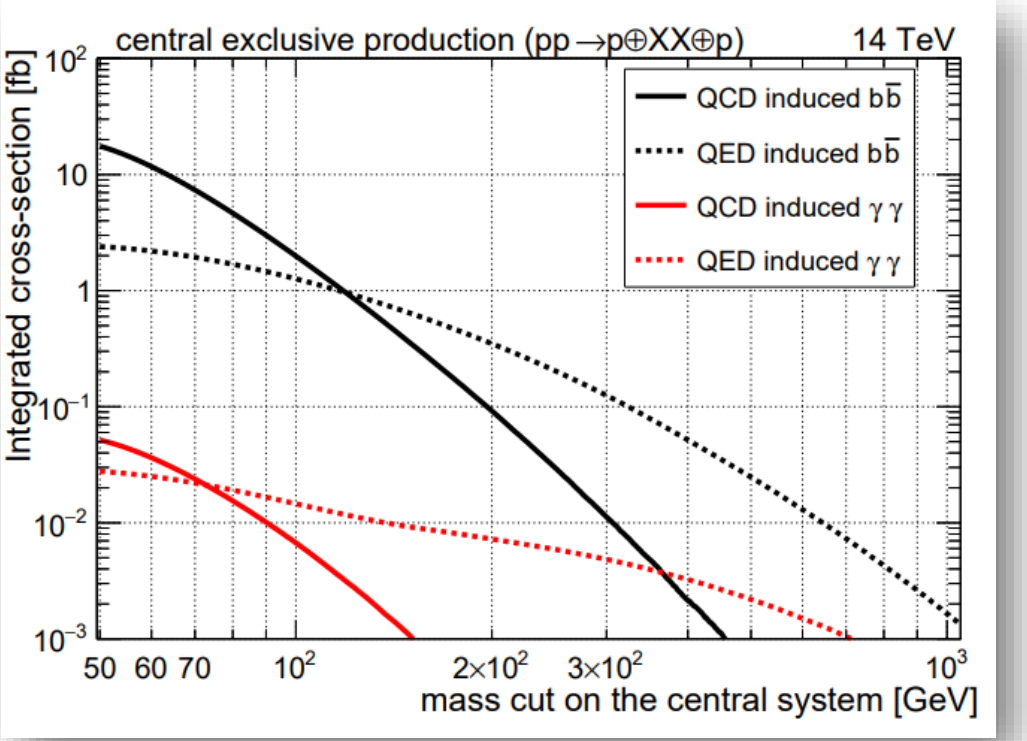
2 stations



Tagging exclusive production at the LHC

Central exclusive production processes are generated by the exchange of color singlets via **QCD (Pomeron)** or **QED (γ)**





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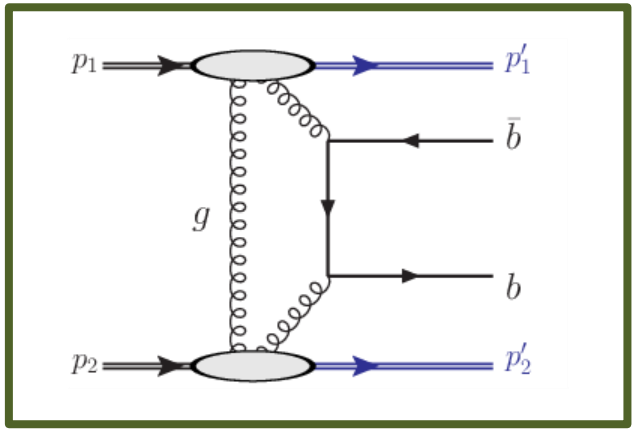

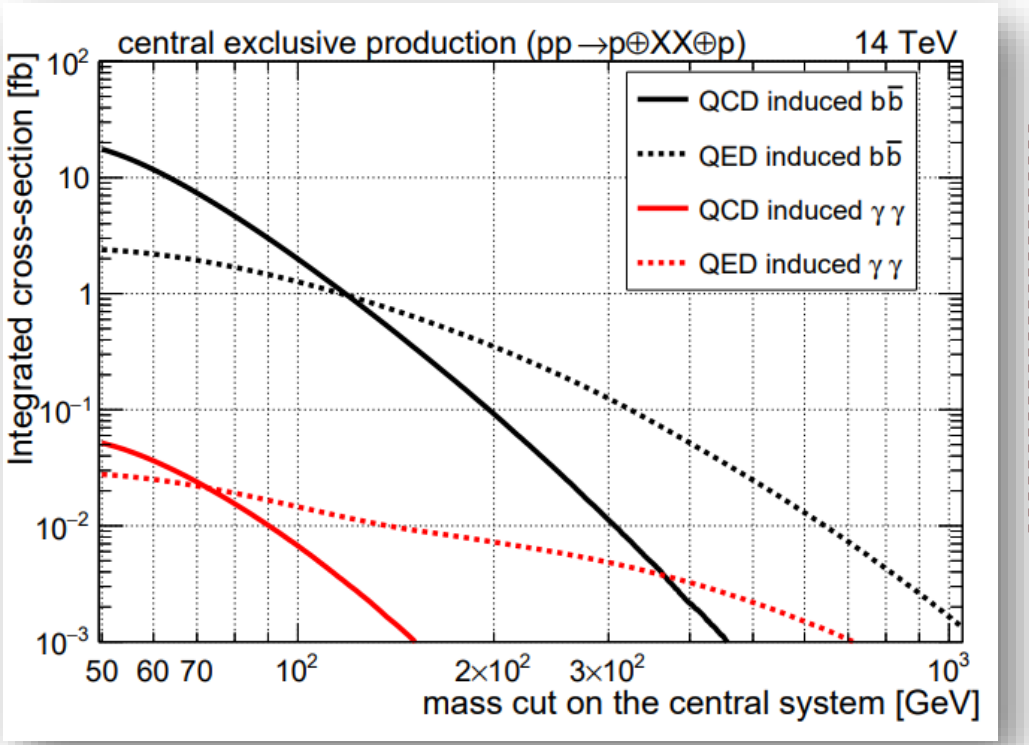

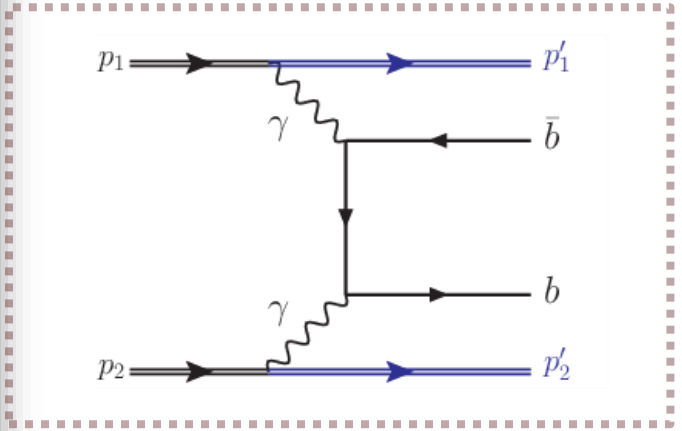

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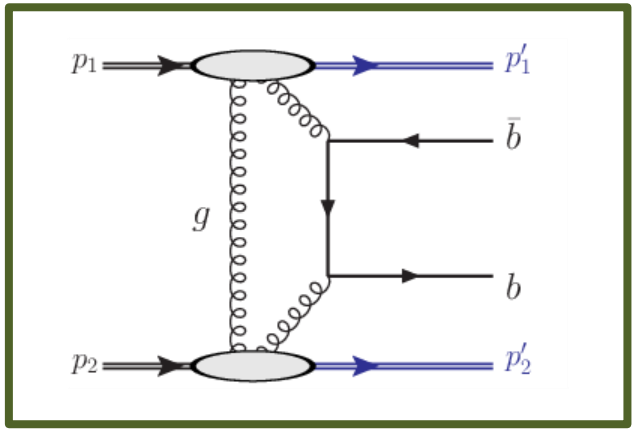
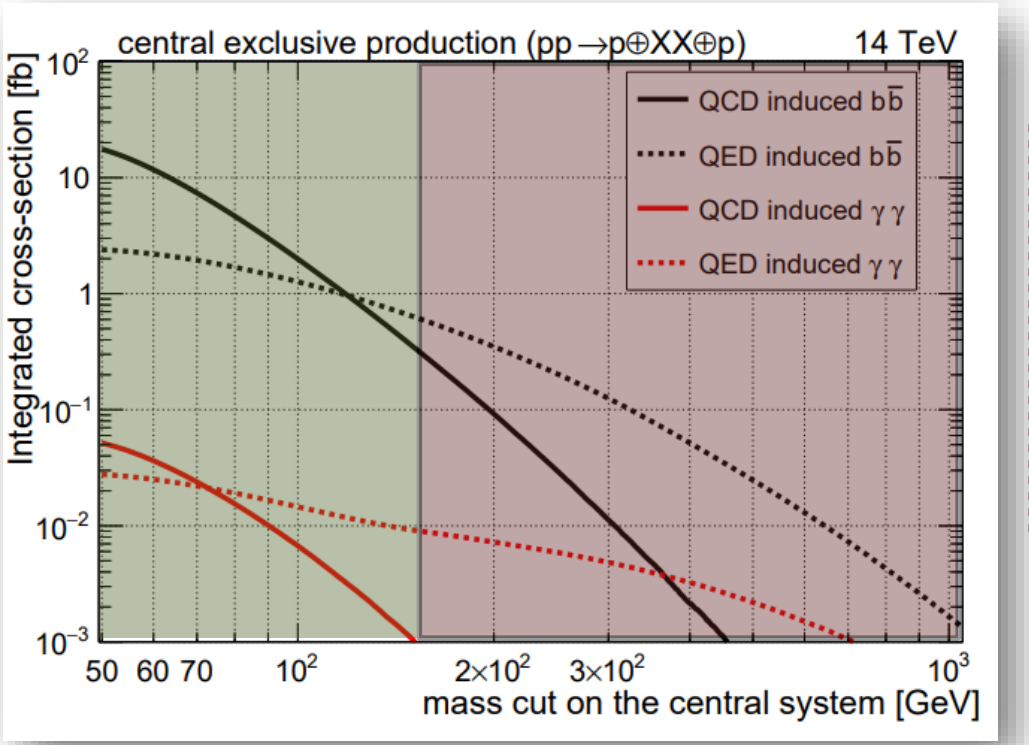
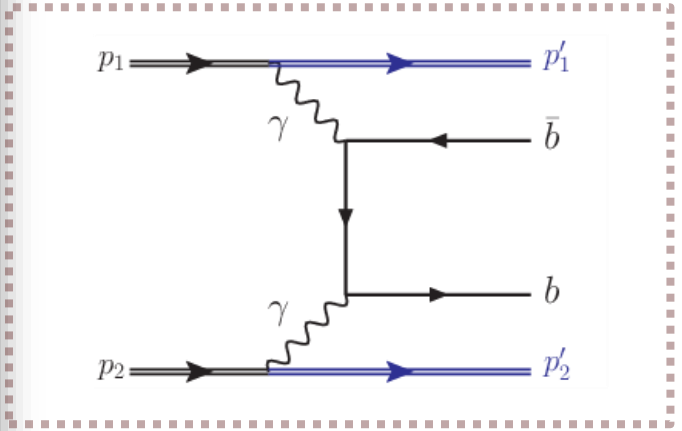
High mass range is dominated by photon-photon interactions

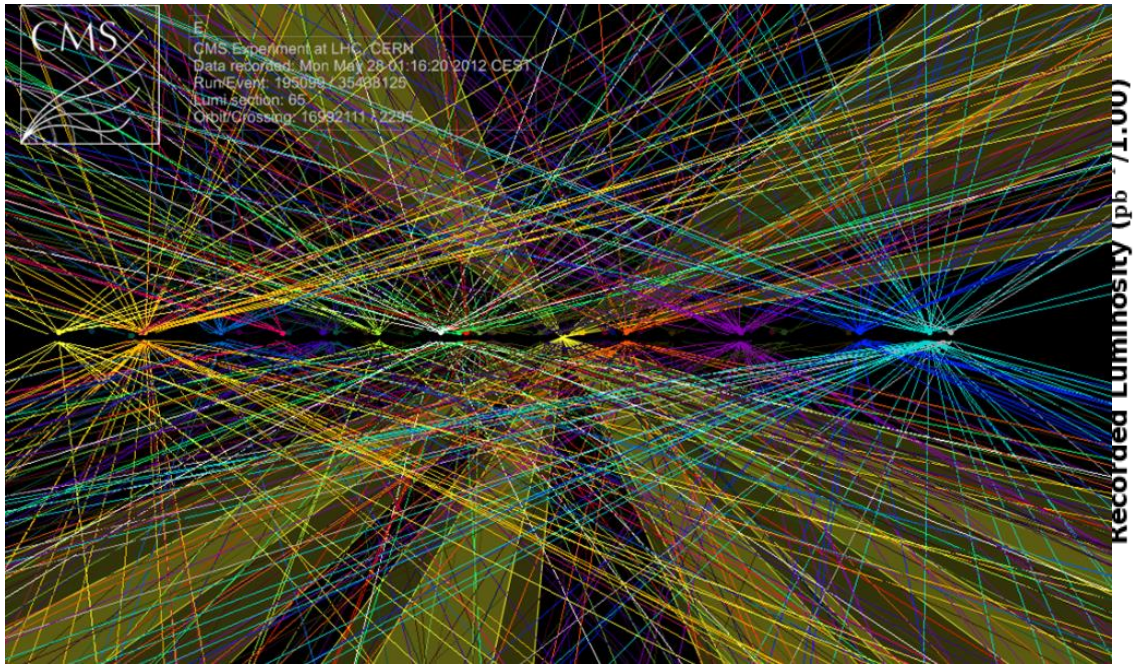




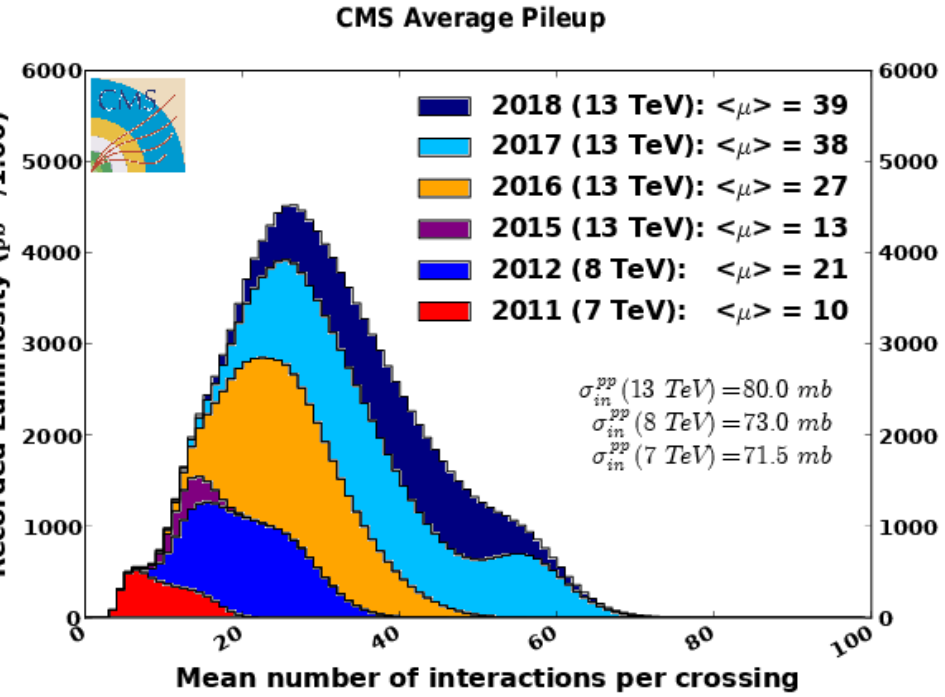


Tagging exclusive production at the LHC

- Main challenge is the background:
  - In the standard LHC runs, tens of interaction occur per bunch crossing



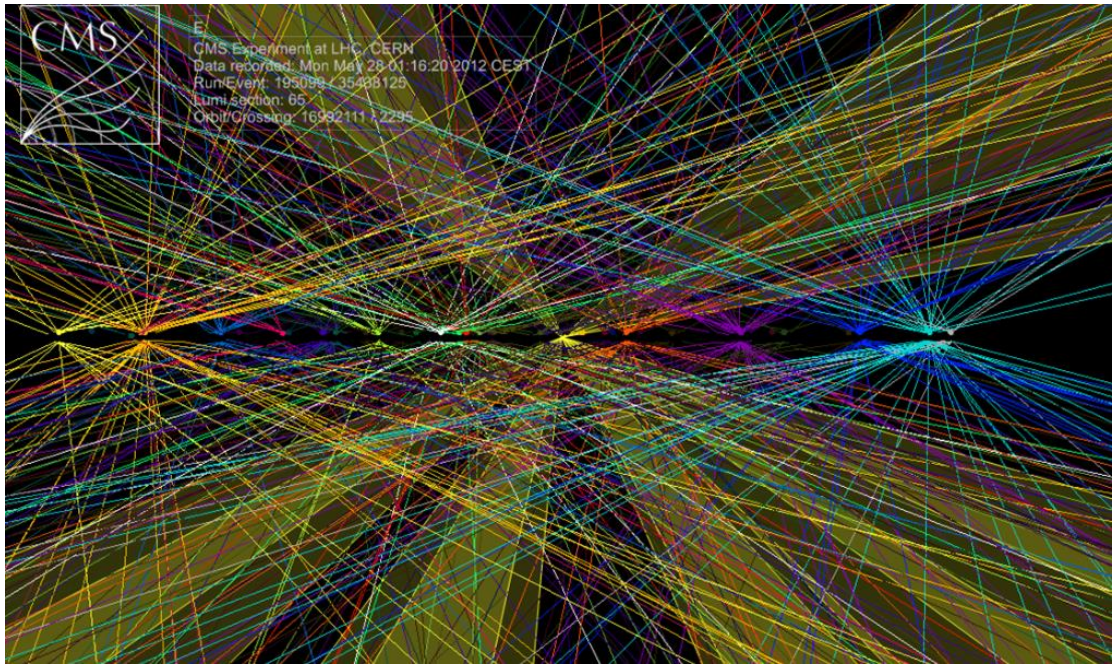
https://cds.cern.ch/record/2746227



https://cds.cern.ch/record/2654205

Tagging exclusive production at the LHC

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



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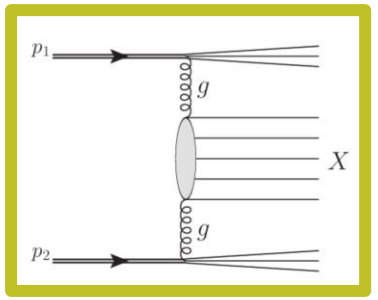

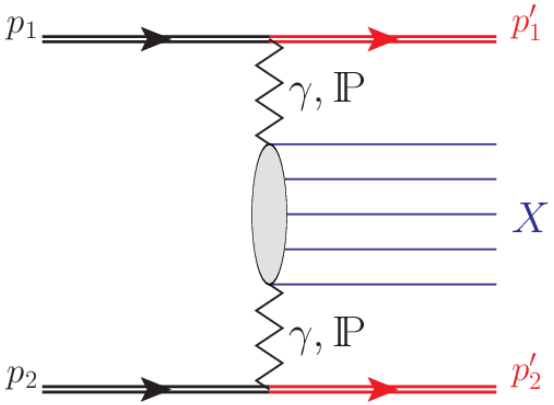

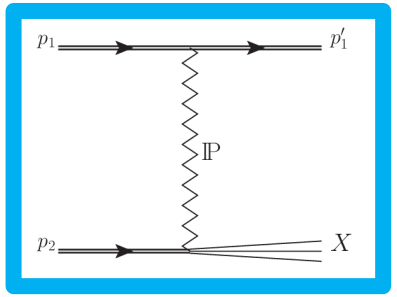

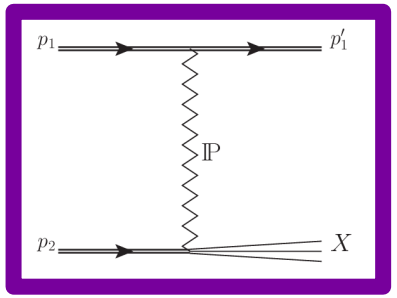

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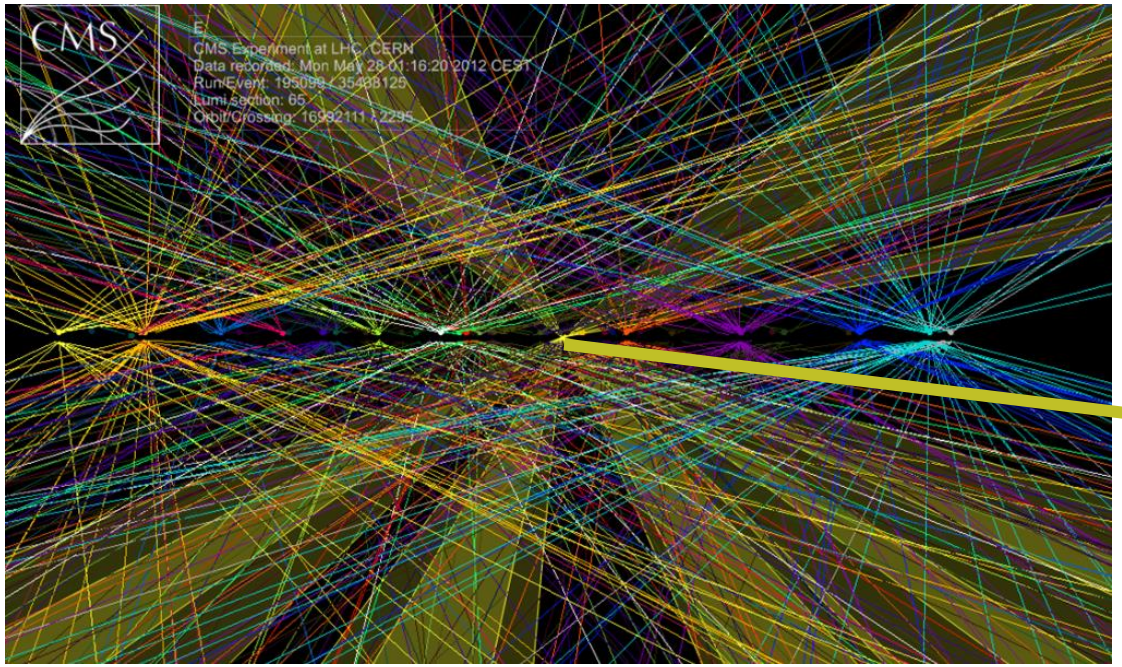

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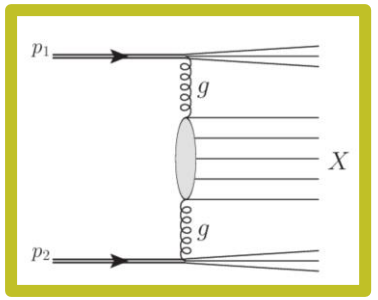

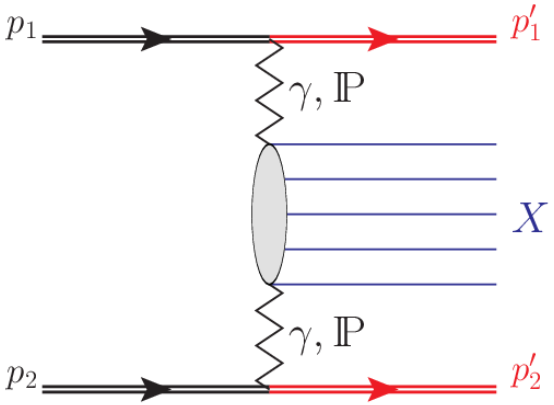

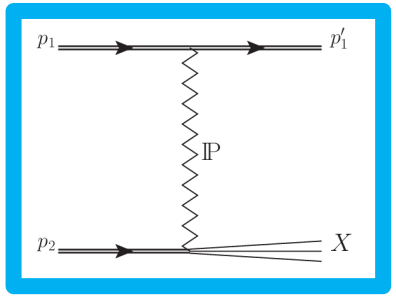

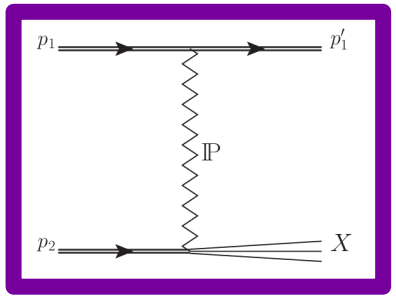

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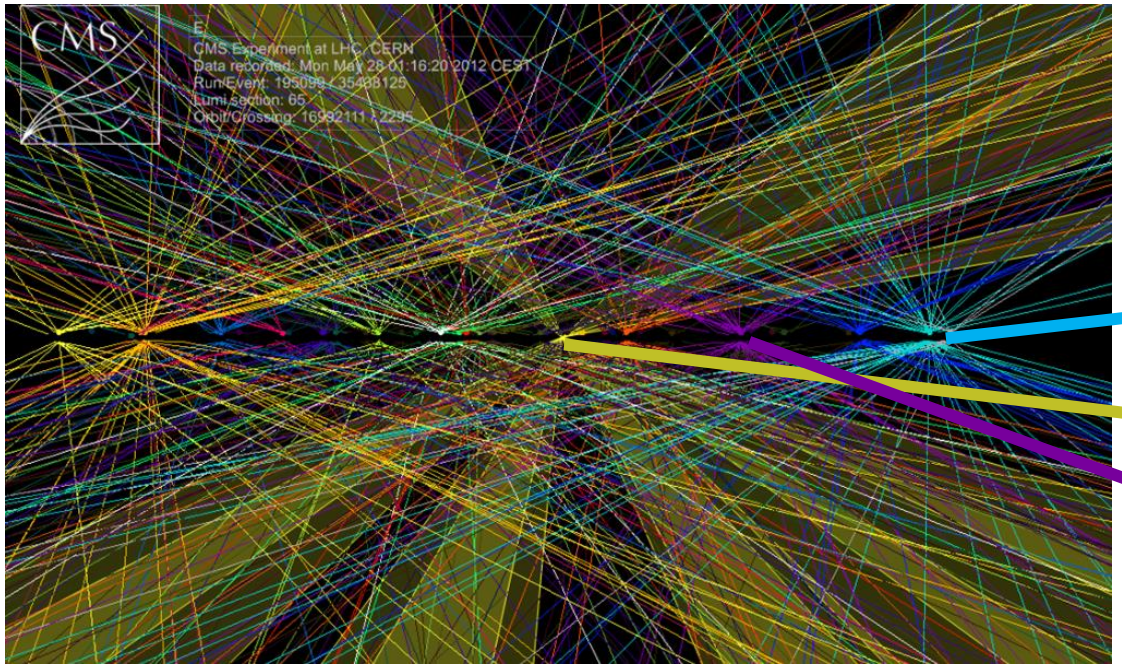

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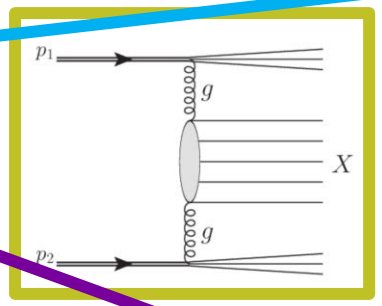

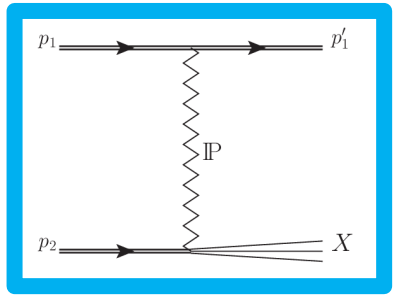

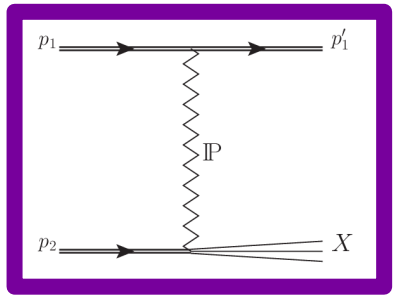

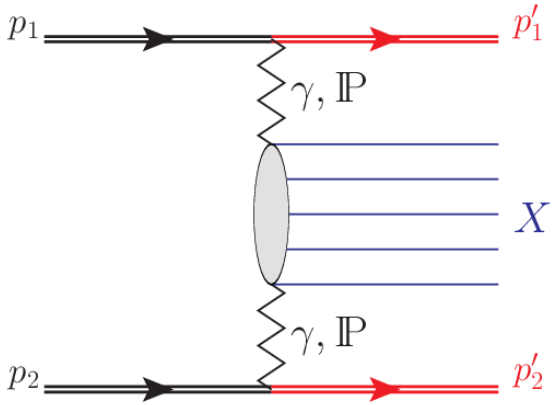

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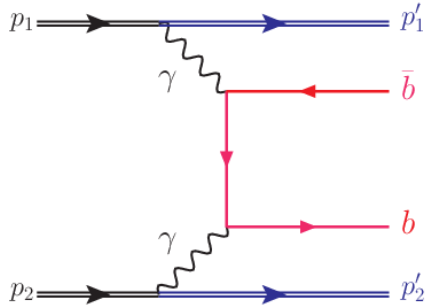


- In Central Exclusive production (CEP) processes:

  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:

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

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

Highlights from Run 2

Example of AFP result with tagged protons

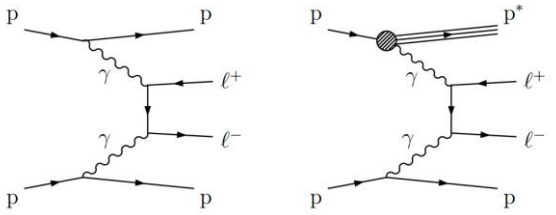
PHYSICAL REVIEW LETTERS **125,** 261801 (2020)

Observation and Measurement of Forward Proton Scattering in Association with Lepton Pairs Produced via the Photon Fusion Mechanism at ATLAS

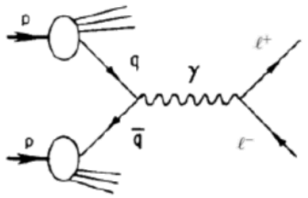
G. Aad *et al.**
(ATLAS Collaboration)

(Received 2 October 2020; revised 30 October 2020; accepted 23 November 2020; published 23 December 2020)

Signal



Background



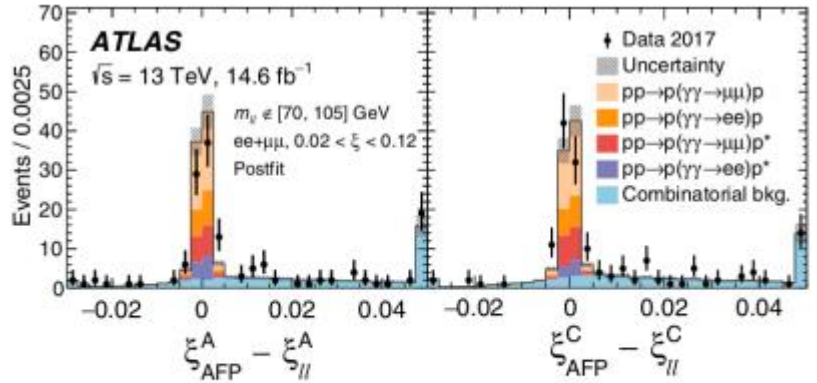
Drell-Yan

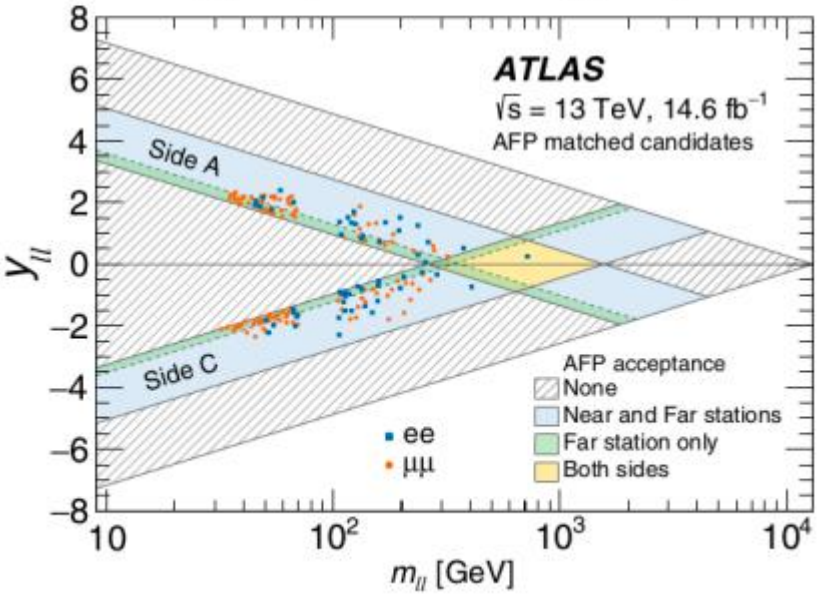
+ pileup proton

- Powerful background rejection due to proton tagging and matching between proton and di-lepton kinematics
- Measured cross sections:

$$\sigma_{ee+p} = 11.0 \pm 2.6(\text{stat}) \pm 1.2(\text{syst}) \pm 0.3(\text{lumi}),$$

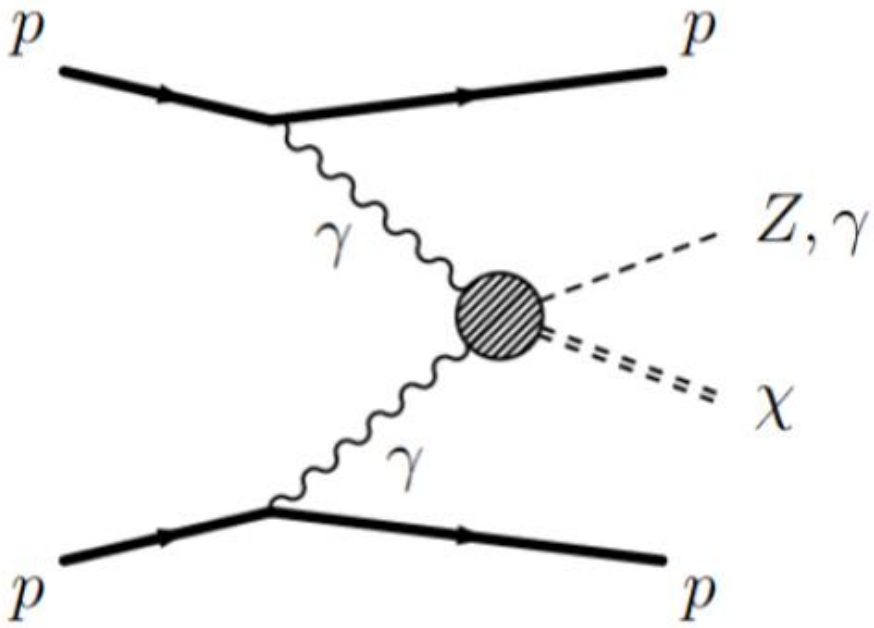
$$\sigma_{\mu\mu+p} = 7.2 \pm 1.6(\text{stat}) \pm 0.9(\text{syst}) \pm 0.2(\text{lumi}).$$





Example of PPS result with tagged protons

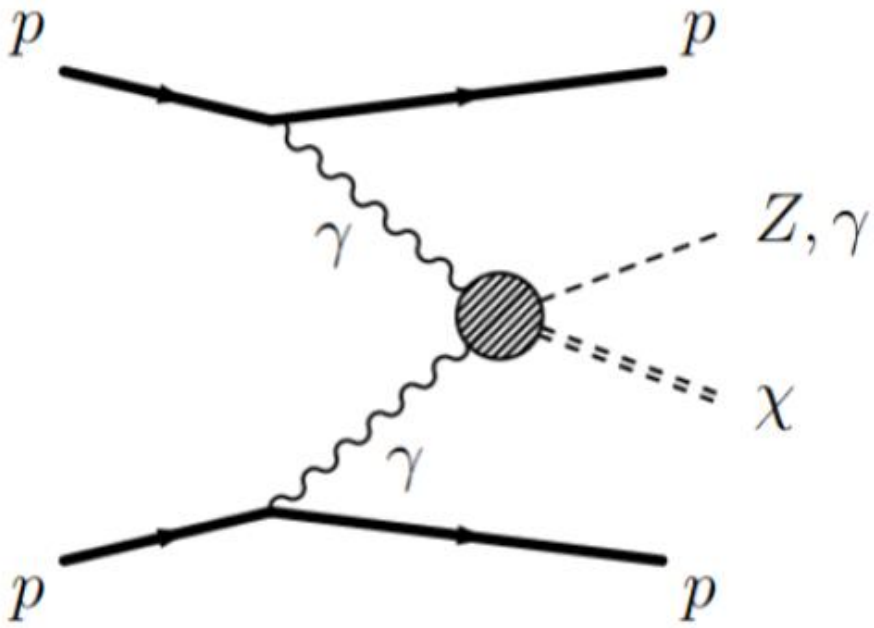
- Searching for unknown particles using the “missing mass”
  - Implemented for the first time at hadron collider, based on 4π event reconstruction



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

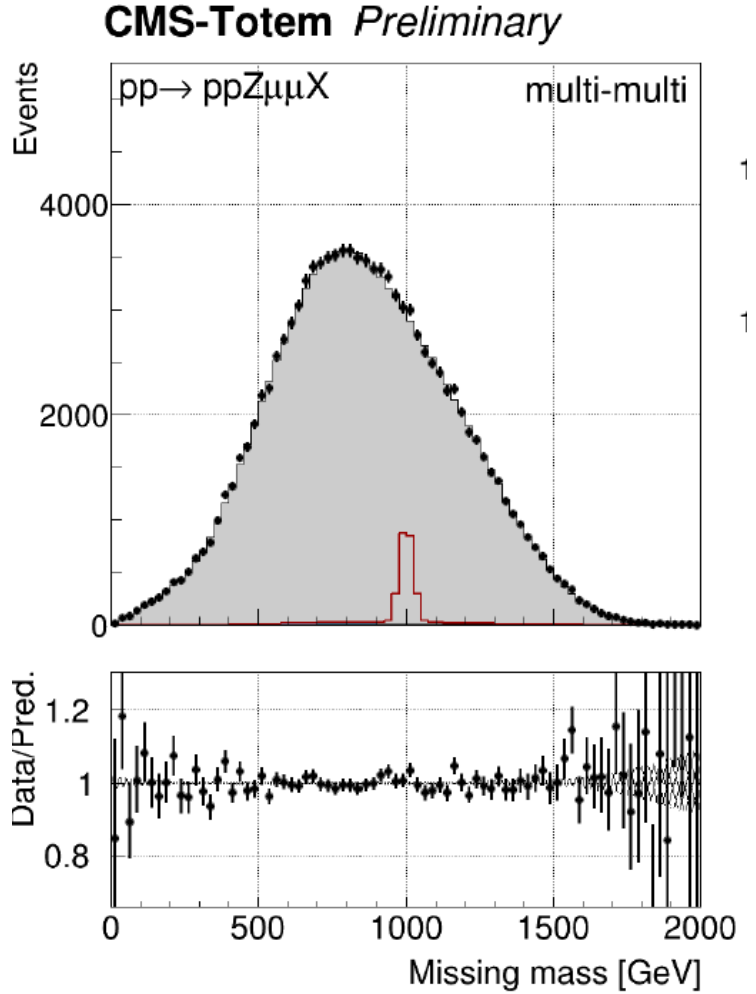
$$m^2_{\text{miss}} = \left[(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2}) - (P_V + P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}) \right]^2$$



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

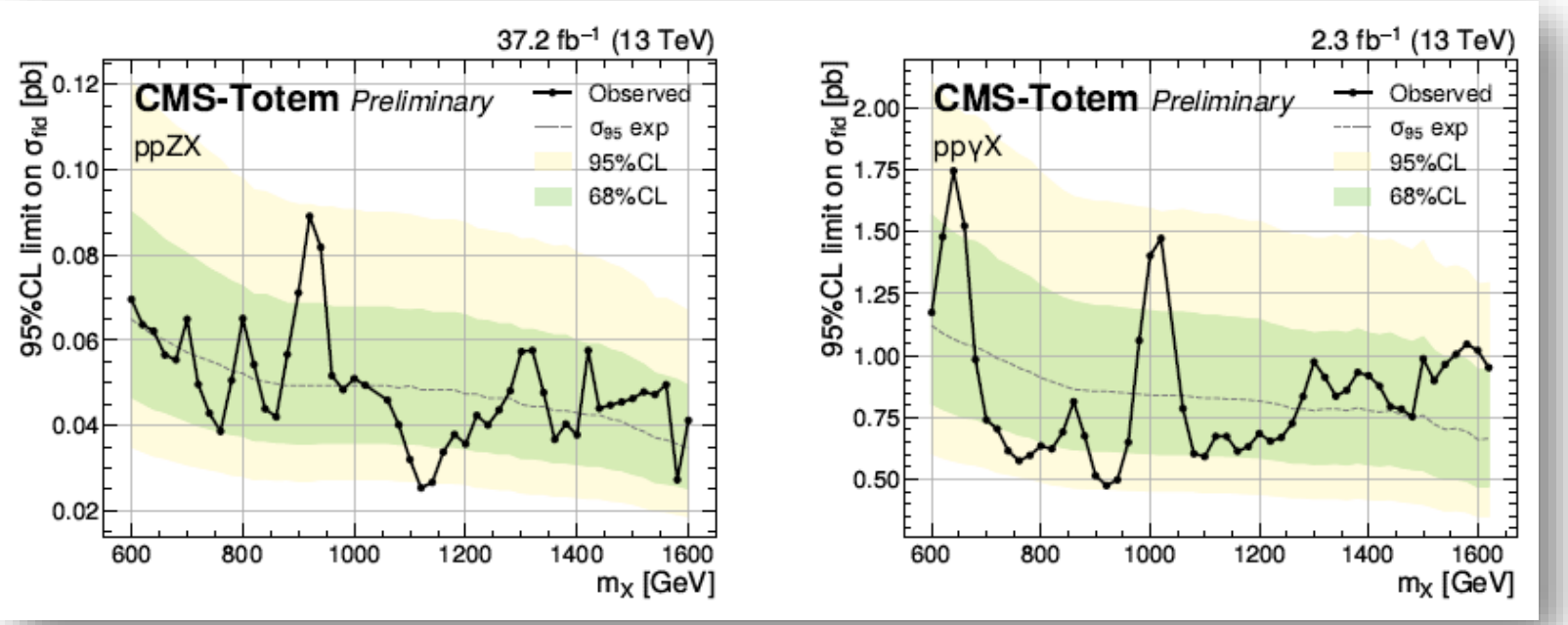
Example of PPS result with tagged protons

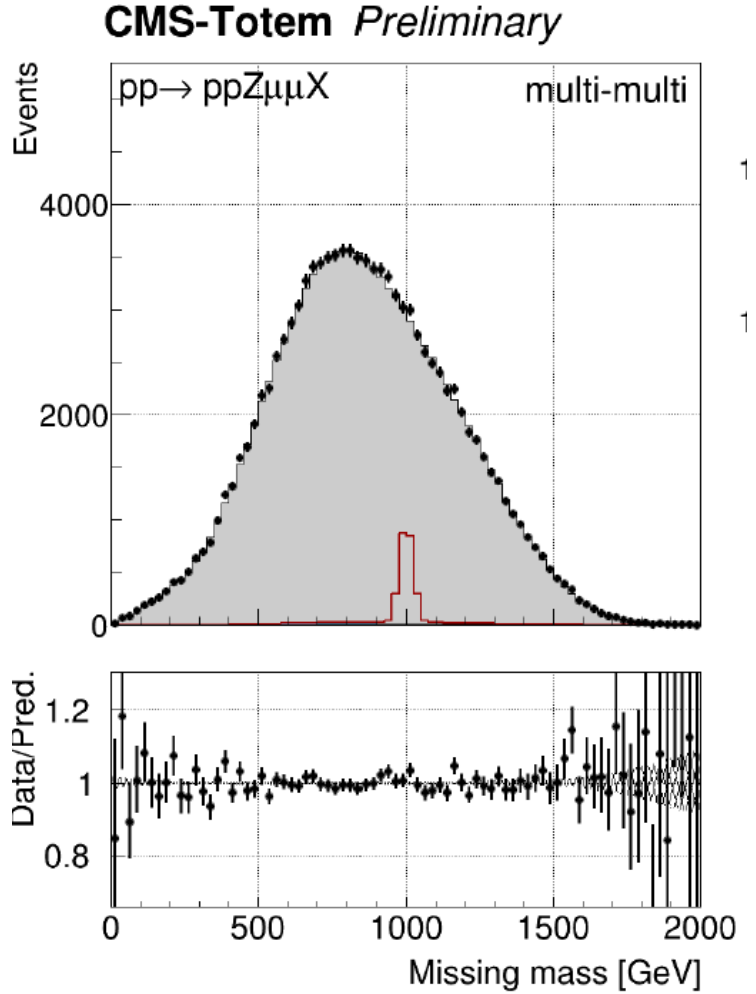
- Searching for unknown particles using the “missing mass”
  - Benefit from supreme mass resolution



Example of PPS result with tagged protons

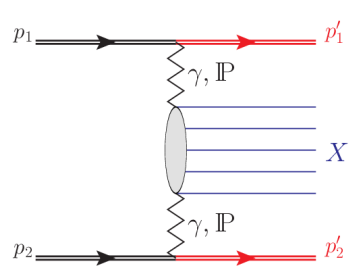
- Searching for unknown particles using the “missing mass”
  - Benefit from supreme mass resolution
  - Data agree with the background-only model, a limit on the production cross-section of Z/γ+χ was derived





Physics with tagged protons at the HL-LHC

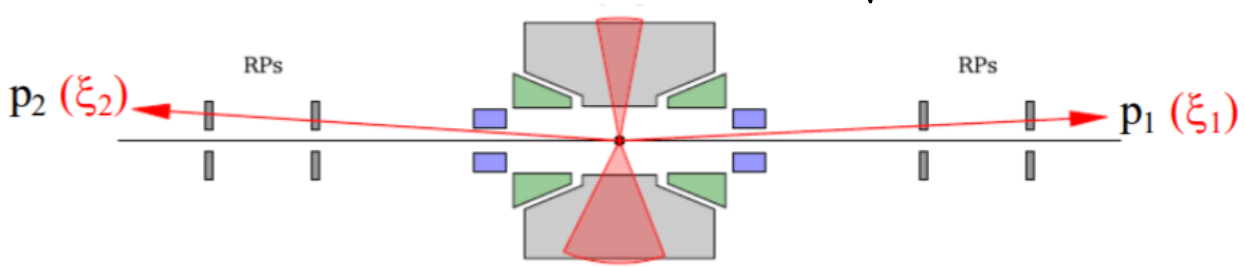
Proton spectrometers at the HL-LHC



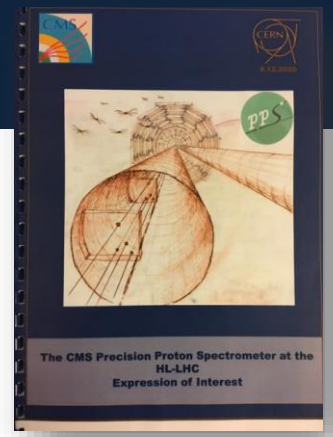
- HL-LHC allows to probe rare processes in the Standard Model.

GOAL: Study of central exclusive production (CEP)

- Using a set of near-beam detectors installed in movable vessels (Roman Pots) with tracking and timing capabilities, operated in **standard LHC runs.**
- Tracking detectors measure the proton momentum loss $\boldsymbol{\xi = \frac{\Delta p}{p}}$
- Timing detectors measure the vertex position $z_{PV} = c/2\left(t_{proton_2} - t_{proton_1}\right)$, and interaction time during the bunch crossing $t_{PV} = \frac{1}{2}\left(t_{proton_2} + t_{proton_1}\right) - c \cdot Z_{RP}$
- Acceptance vs ξ translated into acceptance vs mass ($m_X = \sqrt{s\xi_1\xi_2}$)



PPS @ HL-LHC proposed stations



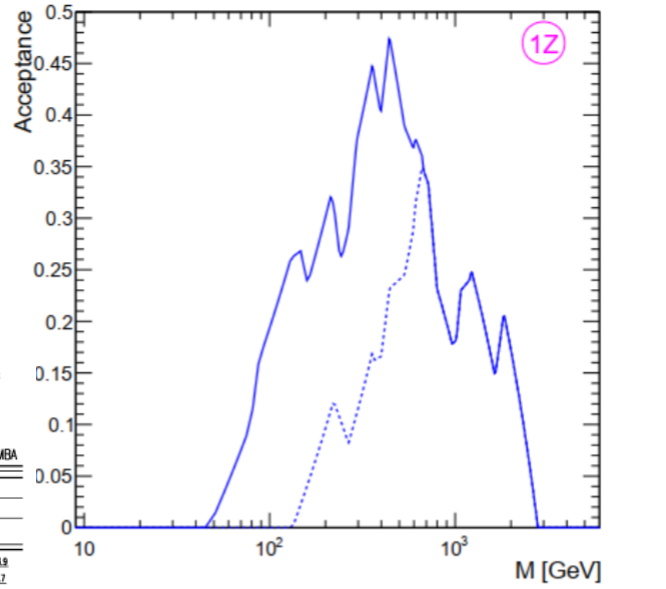
- Locations from maximization of accepted central mass range
- Farther away → smaller mass
- "Warm region" – suitable for RP, "cold region" – new development needed
- In current proposal the covered masses are:

  133 GeV – 2.7 TeV for the first 3 stations

  43 GeV – 2.7 TeV for all stations
- Run 2+3 acceptance between 350 GeV and 2 TeV

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

Dashed line: mass acceptance w/o 420m station



Detector acceptance by the end of the fill

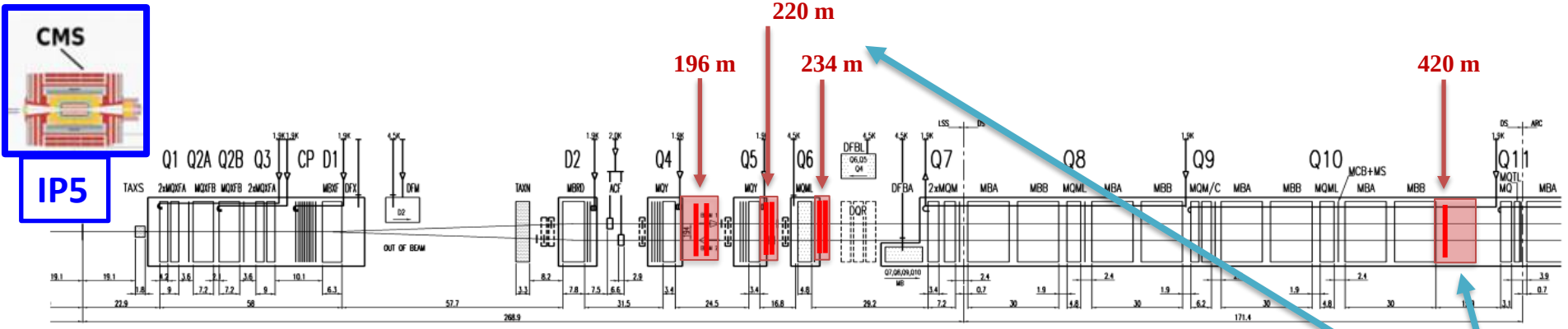


Figure 13: Layout of Long Straight Section LSS5 (Sector 5-6) at HL-LHC [63].

Staged installation

Detector technologies

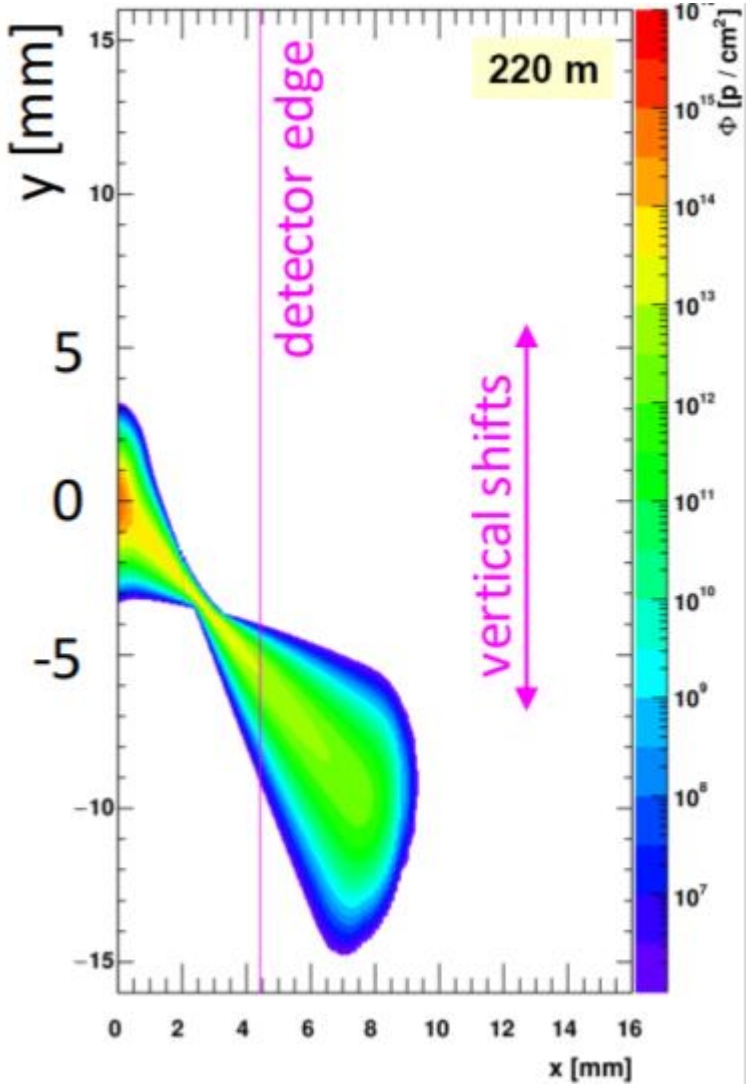
PPS Options

1. Tracking – 3D silicon pixel detectors (used by PPS and CMS tracker in Runs 2+3)
2. Timing:
    1. Diamonds (own developments by TOTEM+PPS, operating in Runs 2+3)
    2. 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)

AFP Options

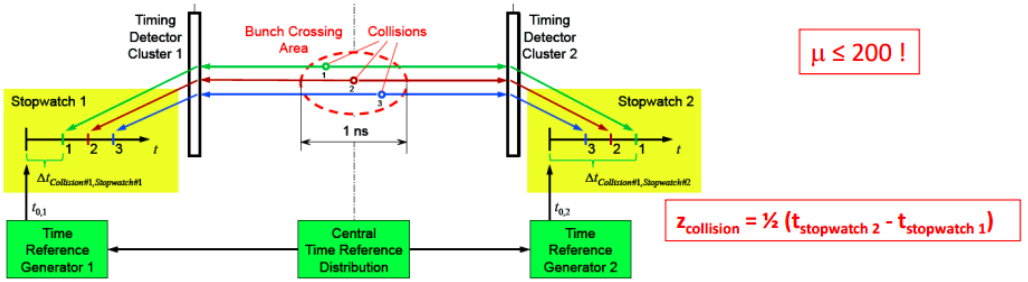
1. Tracking – 3D silicon pixel detectors (used in Runs 2+3)
2. Timing:
    1. Cherenkov quartz bars (Used in Run 2+3)
    2. Diamonds
    3. LGAD

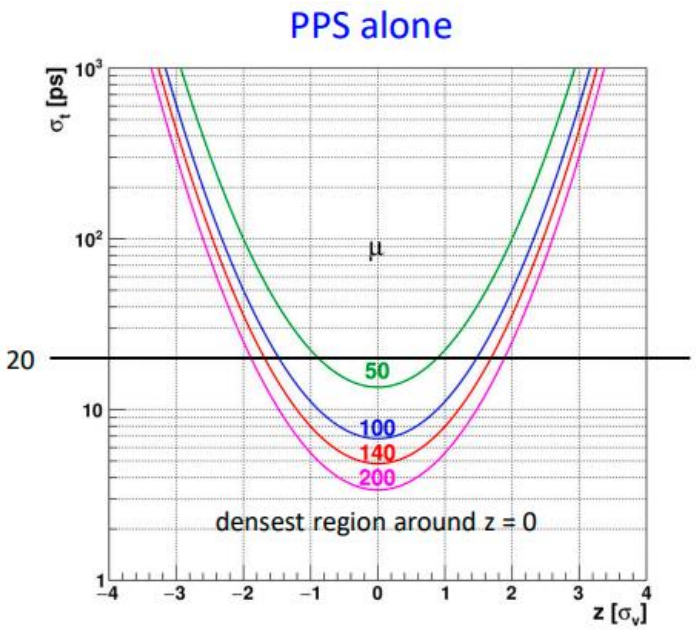


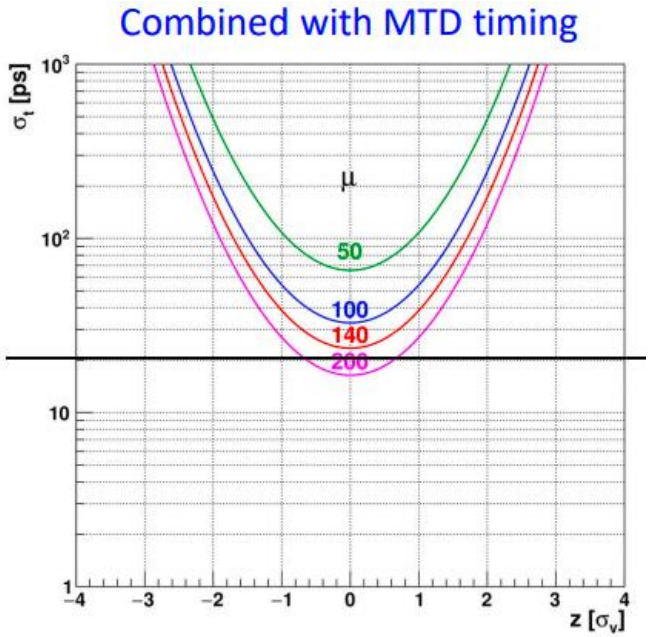
Detector technologies

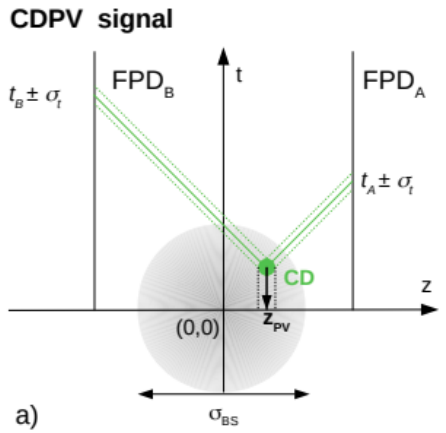
Timing

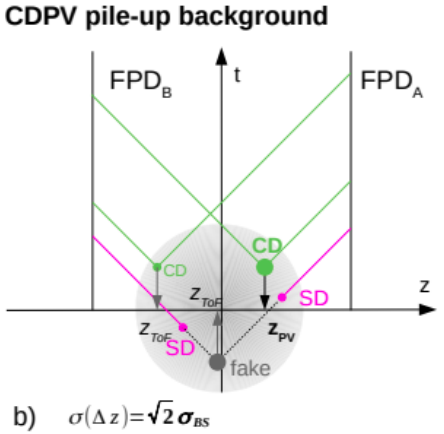
- The pp vertex is reconstructed using the ToF method
- Used to suppress combinatorial background
- Goal to reach 15 – 20 ps / arm timing resolution
- Preliminary studies show a decent PU suppression











2021 JINST 16 P01030

Standard Model processes

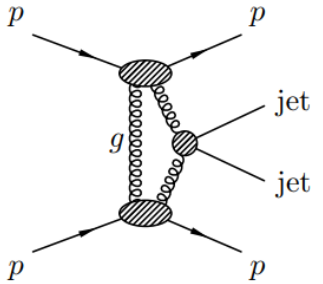
- Fiducial cross sections of CEP of SM processes in pp collisions at $\sqrt{s} = 14$ TeV, calculated with the FPMC generator (using KMR exclusive model for pomeron fluxes and EPA for photon fluxes, survival probabilities of 3% and 90% are considered for QCD and QED processes respectively).
- A central detector selection cut of $p_T > 20$ GeV on the generated objects was applied for all processes with 2 particles in the final state.
- Two scenarios are considered in PPS EoI: with and w/o 420m station:

Process	fiducial cross section [fb]			
	all stations		w/o 420	
	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$
jj	$\mathcal{O}\left(10^6\right)$	60	$\mathcal{O}\left(10^4\right)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

QCD Physics

Process	fiducial cross section [fb] all stations $\mathbb{P}-\mathbb{P}$	all stations $\gamma-\gamma$	w/o 420 $\mathbb{P}-\mathbb{P}$	w/o 420 $\gamma-\gamma$
jj	$\mathcal{O}(10^6)$	60	$\mathcal{O}(10^4)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

- 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

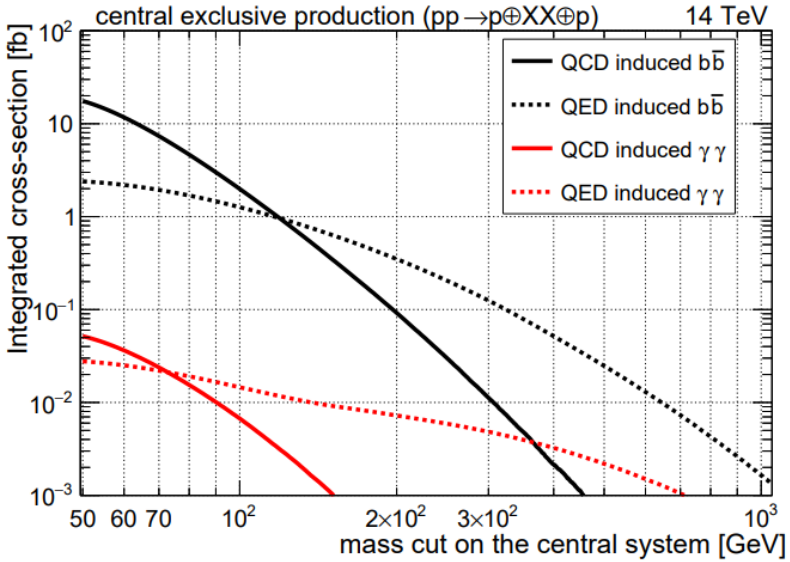
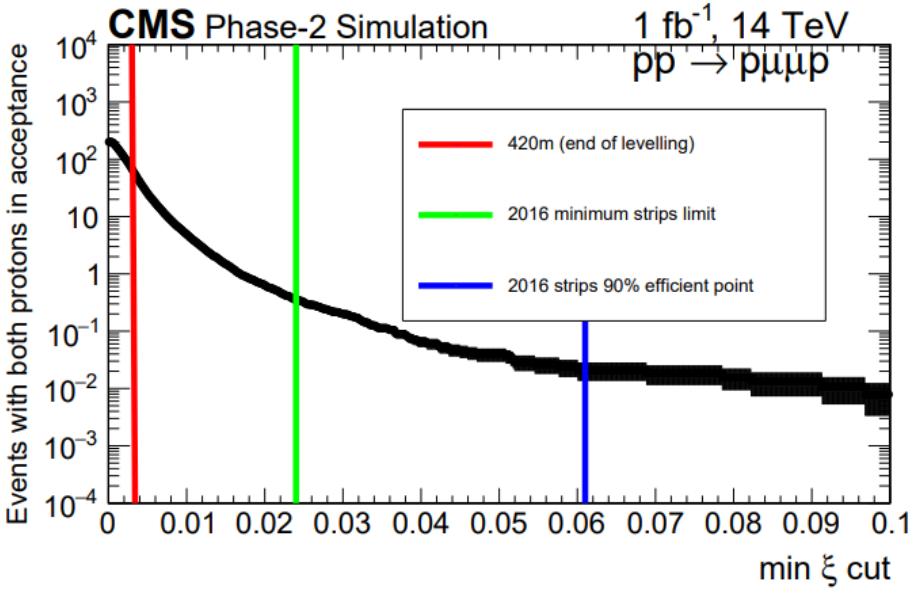


Figure 7: Integrated cross sections of different exclusive processes with intact protons at $\sqrt{s}$ =14 TeV, plotted as a function of the required minimum central system mass. Both photons or b-quarks are required to have a transverse momentum above 20 GeV.

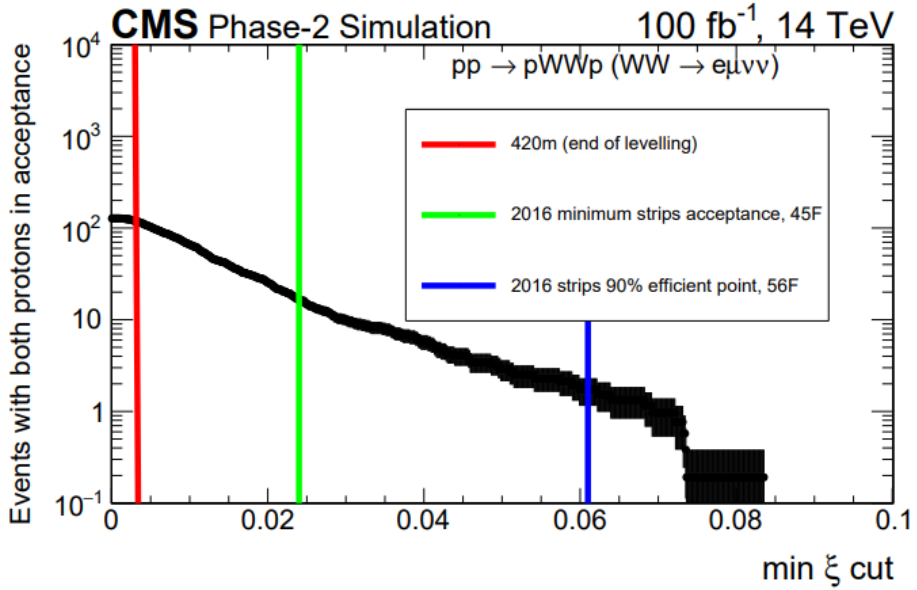
Electroweak physics

Process	fiducial cross section [fb] all stations $\mathbb{P}-\mathbb{P}$	all stations $\gamma-\gamma$	w/o 420 $\mathbb{P}-\mathbb{P}$	w/o 420 $\gamma-\gamma$
jj	$\mathcal{O}(10^6)$	60	$\mathcal{O}(10^4)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

$$pp \to p \oplus \mu\mu \oplus p$$



$$pp \to p \oplus WW \oplus p$$



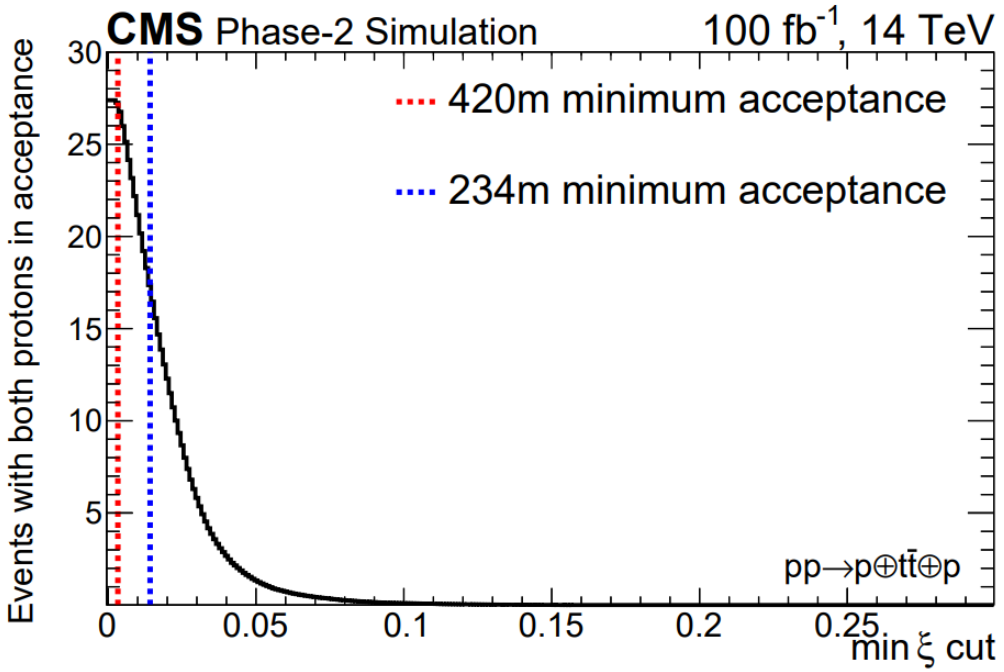
τ – lepton electric and magnetic moments in $\gamma\gamma \to \tau\tau$ events

- Exclusive $\tau\tau$ production can be measured already in Run2+3
- Phenomenological study suggests improved constraints compared to those obtained at LEP

Top physics

Process	fiducial cross section [fb] all stations $\mathbb{P}-\mathbb{P}$	all stations $\gamma-\gamma$	w/o 420 $\mathbb{P}-\mathbb{P}$	w/o 420 $\gamma-\gamma$
jj	$\mathcal{O}(10^6)$	60	$\mathcal{O}(10^4)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

- Production of final state above m_{tt} mass threshold (>350 GeV)
- Exclusive ttbar has low cross-section (~0.1fb)
- A few phenomenological studies were published (PRD105,114002, PRD102,074014(2020), 2008.04249)
- Although a low cross-section for CEP, a significance of 3σ expected for inclusive diffractive γ-IP+IPIP at PU rate of 200 and Integrated luminosity of 4 ab^{-1} (PRD105,114002)

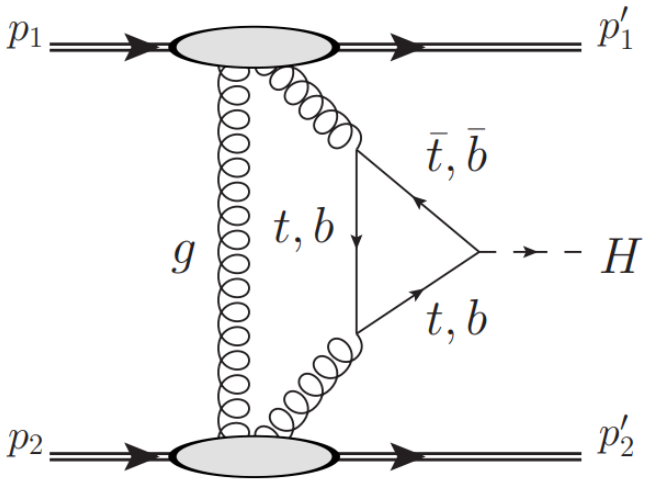


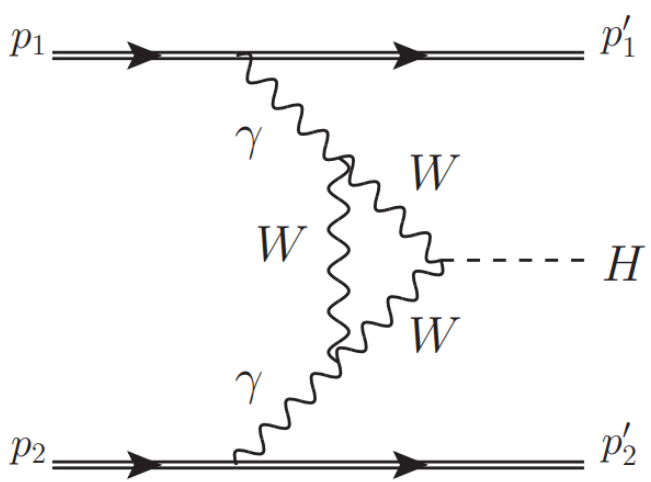
Higgs physics

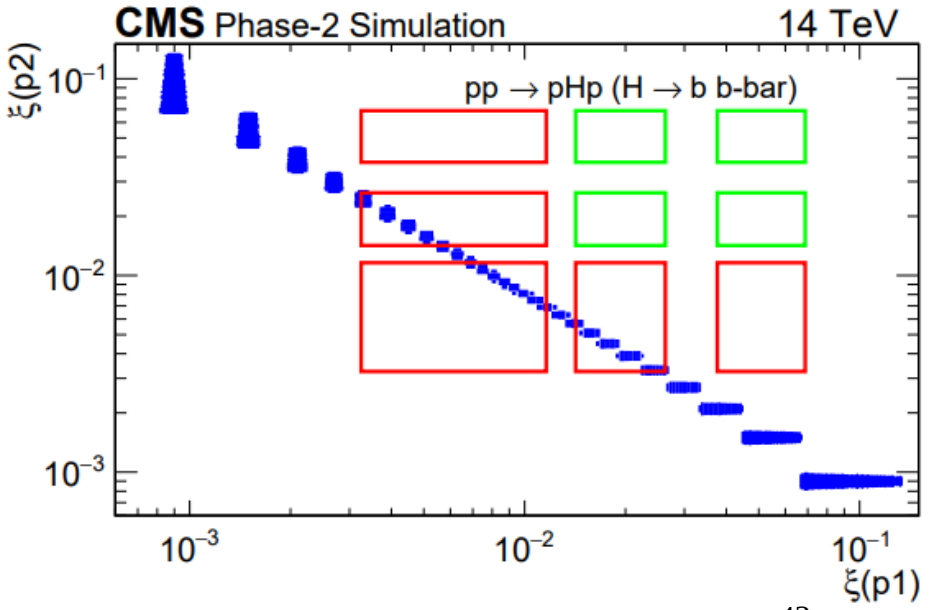
Process	fiducial cross section [fb] all stations		w/o 420	
	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$
jj	$\mathcal{O}(10^6)$	60	$\mathcal{O}(10^4)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

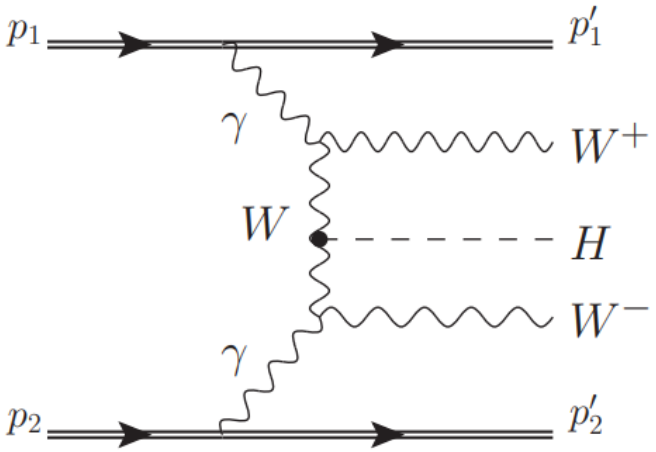
Cannot be measured w/o the 420m station

- 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



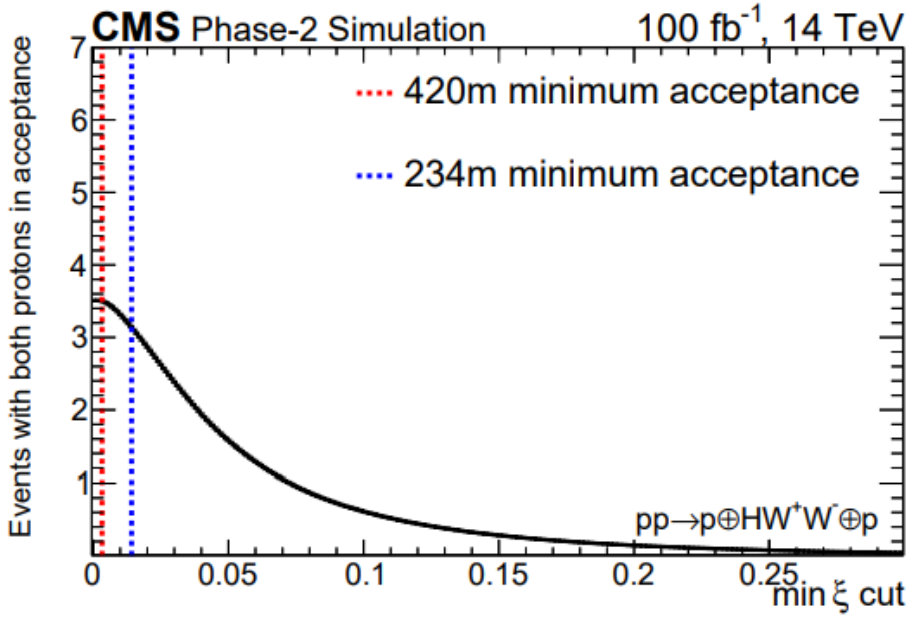






Associated production with WW pairs

- Low cross section (~0.04 fb).
- Detectable with only stations at 200m
- Inclusive Higgs boson production (all decay modes)

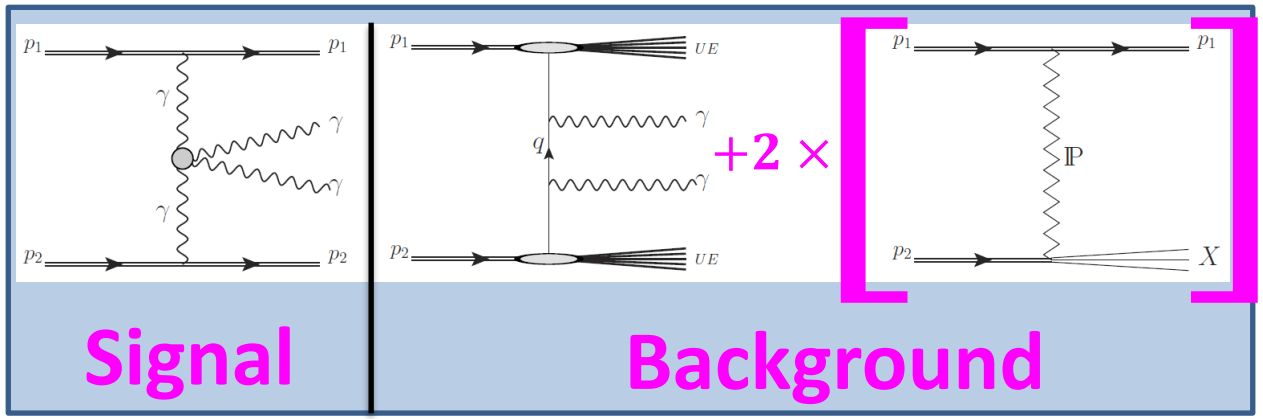


High mass searches

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:



- Recently single dissociation and double dissociation were properly modeled (2208.10526) allowing to probe semi-exclusive processes and probing lower ALP masses.

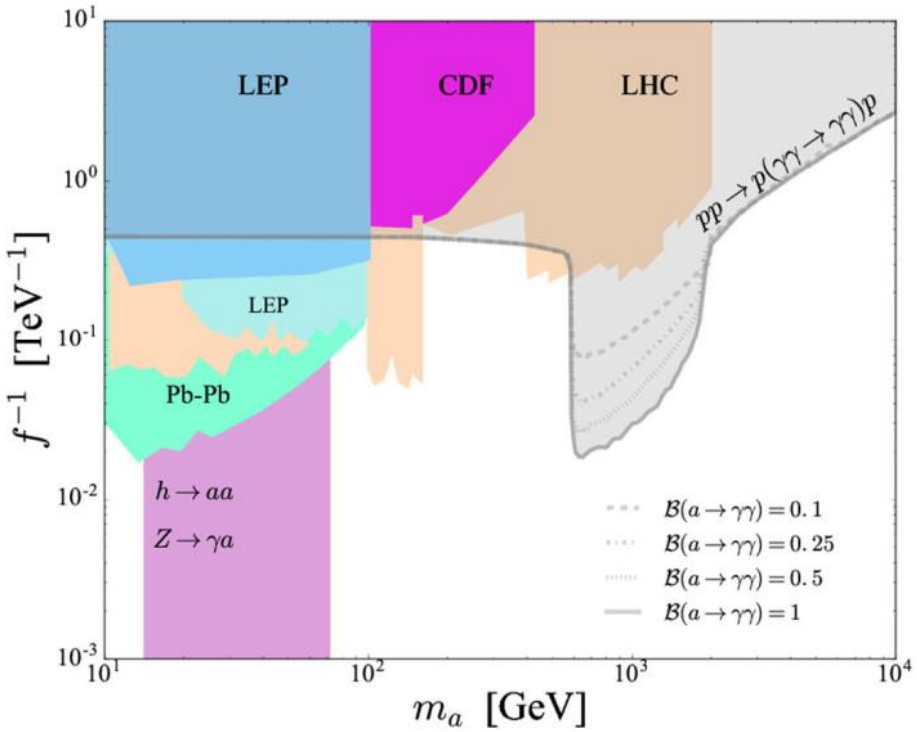


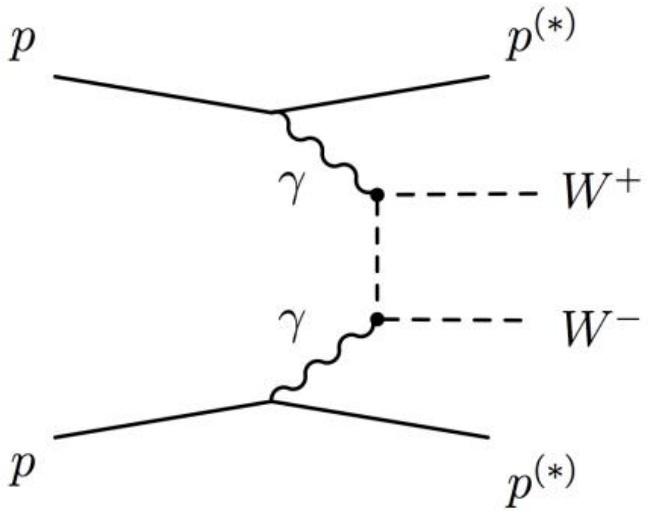
Figure 2: Exclusion regions on the ALP–photon coupling and mass plane. The light-shaded grey regions show the expected 95% CL exclusion limit for 300 fb^{-1} in central exclusive diphoton production events for different branching ratios of the ALP into two photons [16].

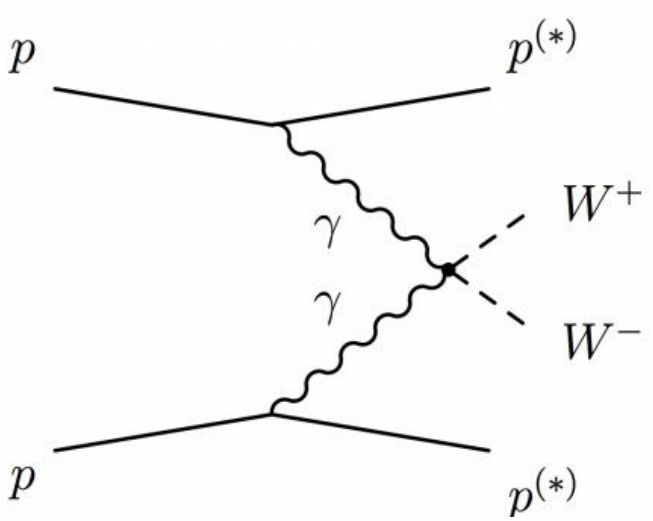
[16] C. Baldenegro, S. Fichet, G. von Gersdorff and C. Royon, "Searching for axion-like particles with proton tagging at the LHC", JHEP **1806**, 131 (2018), doi:10.1007/JHEP06(2018)131 , [arXiv:1803.10835 [hep-ph]].

<μ>~50, Lumi=300fb^{-1}

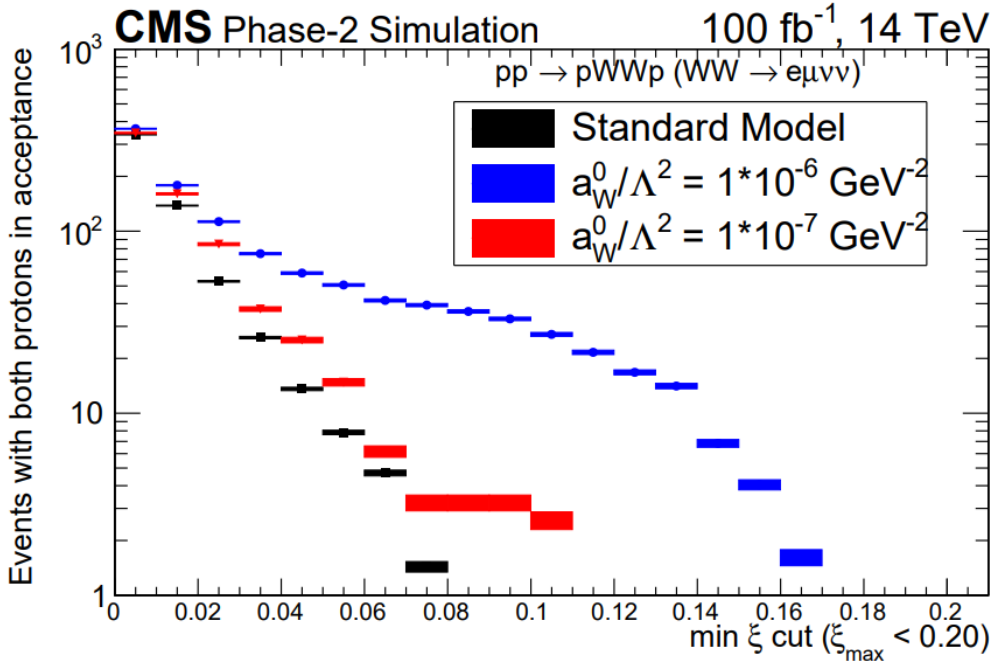
The sensitivity will exceed the existing limits at high masses

Anomalous gauge couplings



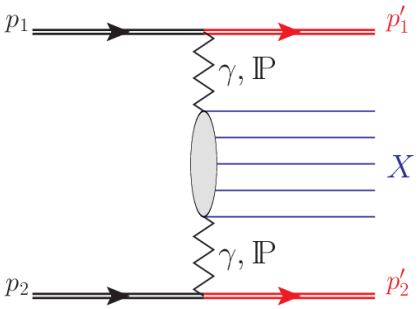


- Exclusive WW production sets stringent upper limit on the anomalous quartic gauge coupling operators (JHEP08(2016)119).
- Deviation due to aQGC expected to be visible at high masses
- **A few % resolution in m_{WW}**



Summary

- Proton Spectrometers at HL-LHC extends current CEP studies (both larger mass range and high statistics)
- Challenging environment: large radiation, pileup up to 200
- CMS proposed stagged installation program, starting with 200m during LHC Run 4 (PPS-EOI), where the 420m station is planned for Run5+
- ATLAS/AFP upgrade program: reserve space for Run5 if possible for the machine w/o constrains or additional costs.



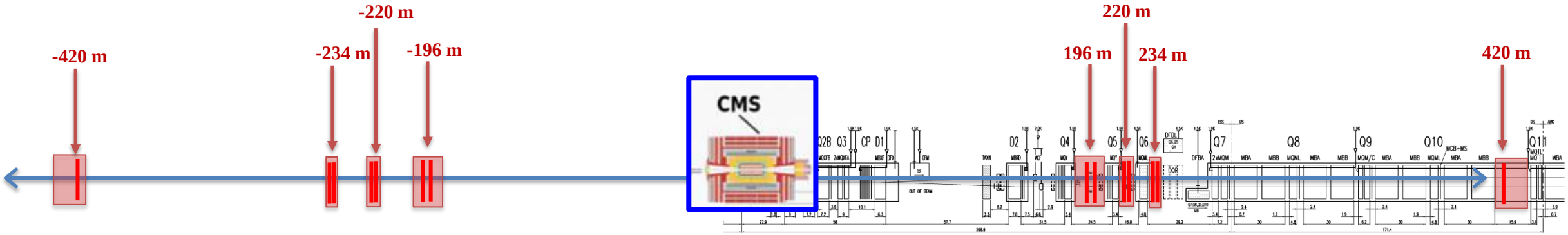


Figure 13: Layout of Long Straight Section LSS5 (Sector 5-6) at HL-LHC [63].

Backup

Introduction

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

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

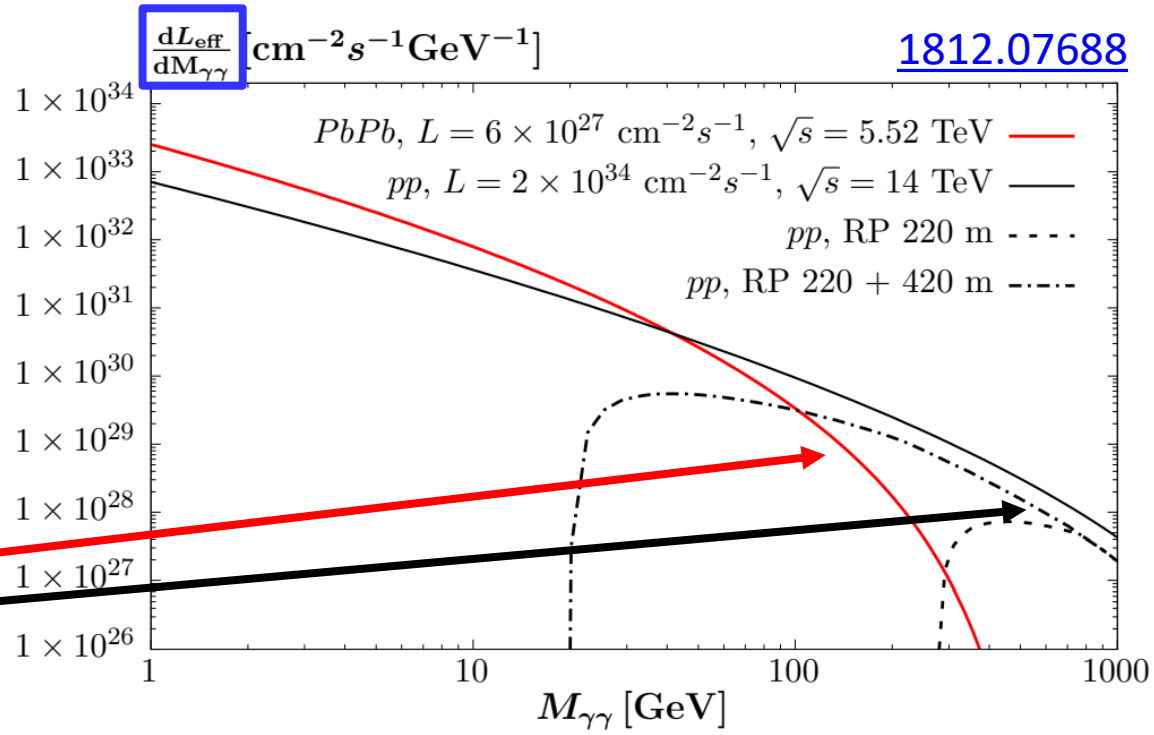
Photon energy is related to charge size:

- Transverse momentum

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

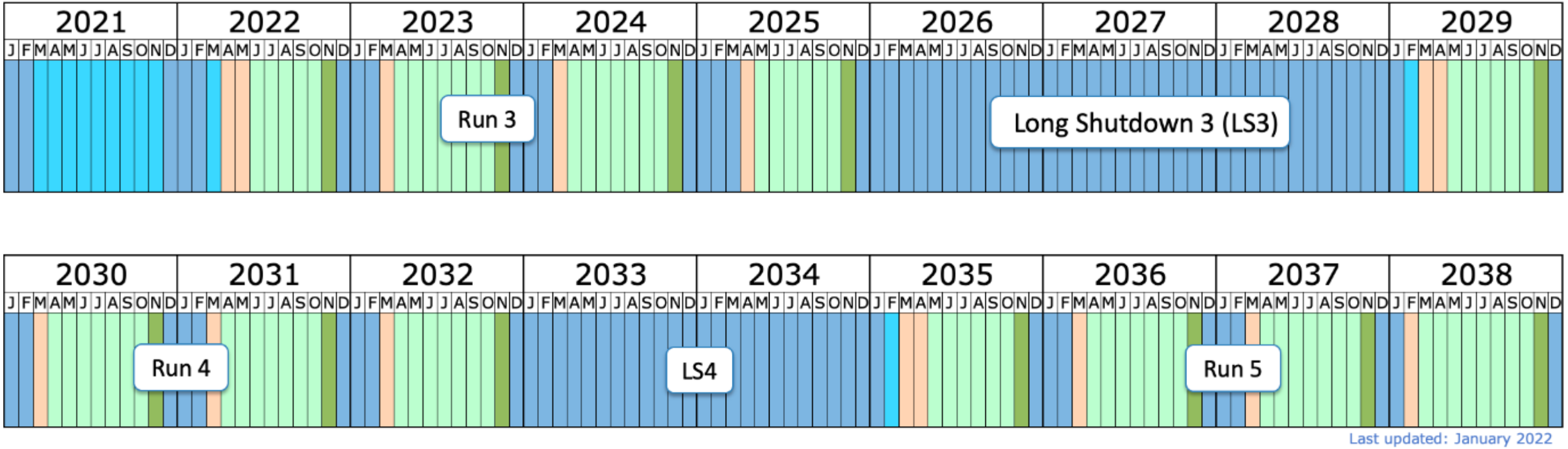
- Longitudinal momentum

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



Photon fluxes are harder in pp collisions

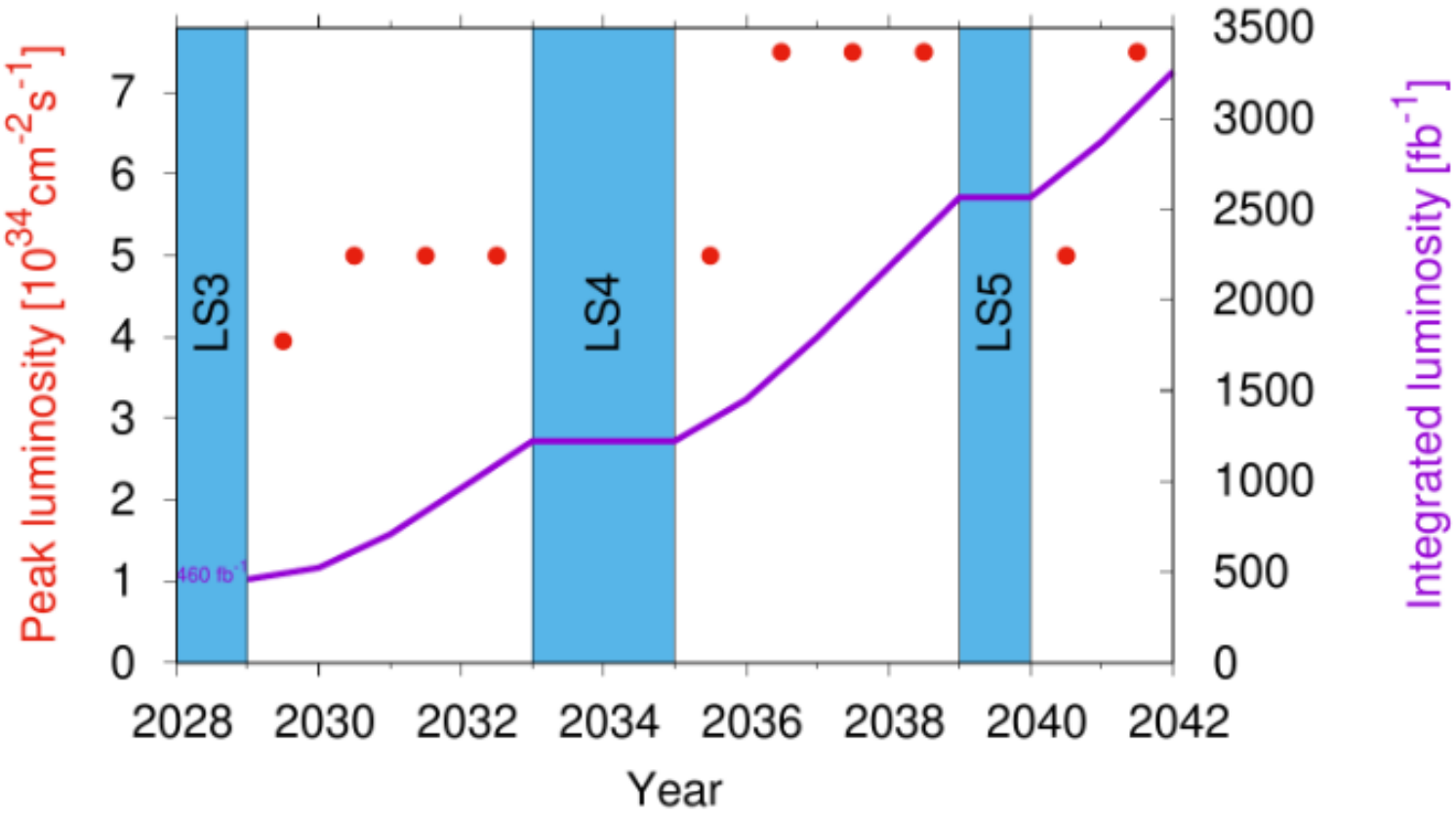
LHC Run schedule



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