Low-PU runs with forward proton/neutron detectors (CMS perspectives)

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Michael Pitt* (michael.pitt@cern.ch)
The University of Kansas (US)

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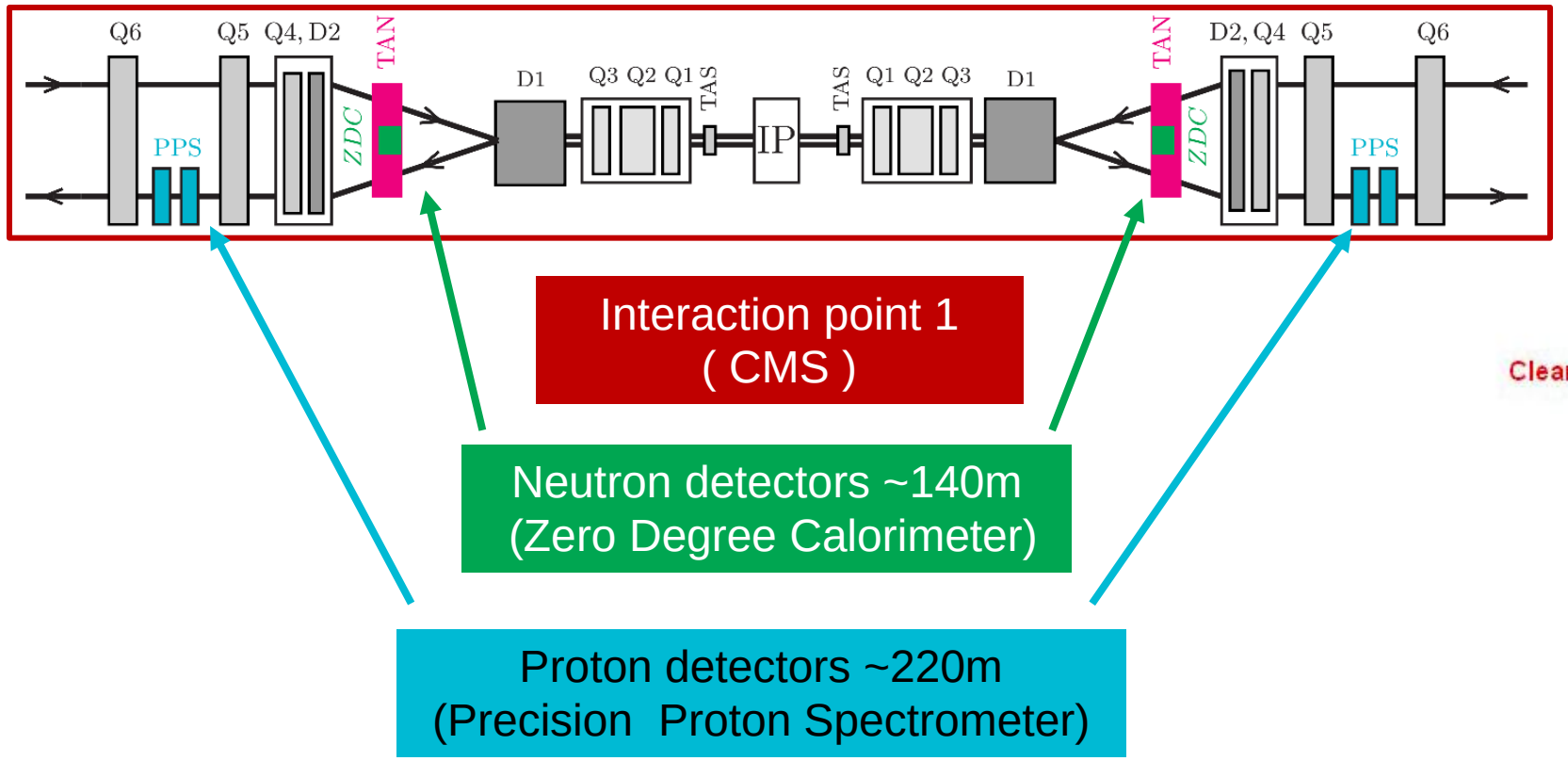
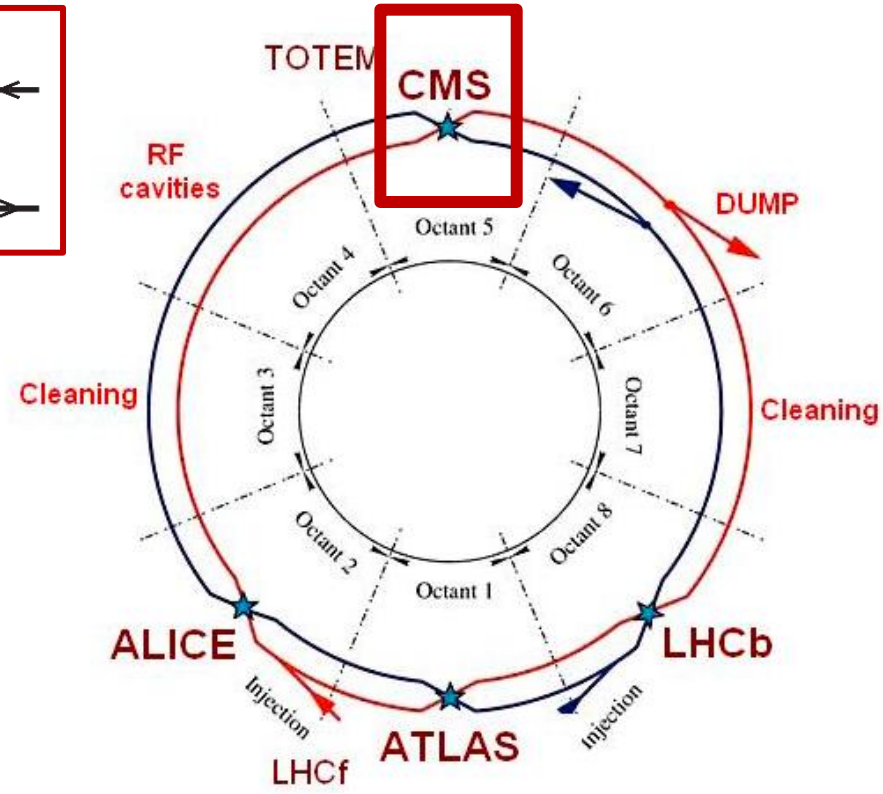
Grant DE-SC0023908

Forward detectors in CMS

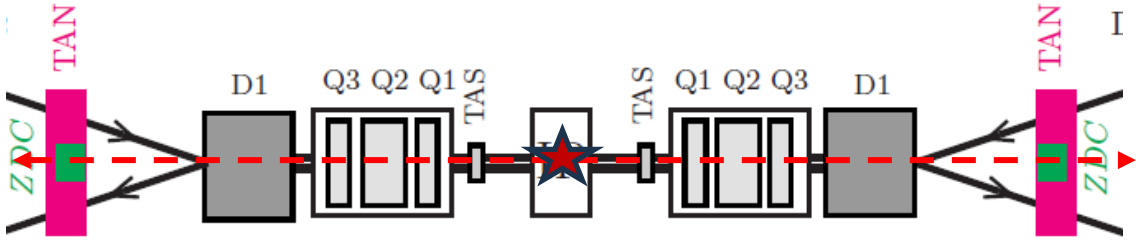
- CMS interaction point is equipped with forward neutron / proton detectors at about 140 m / 220 m from the IP, respectively on both sides.





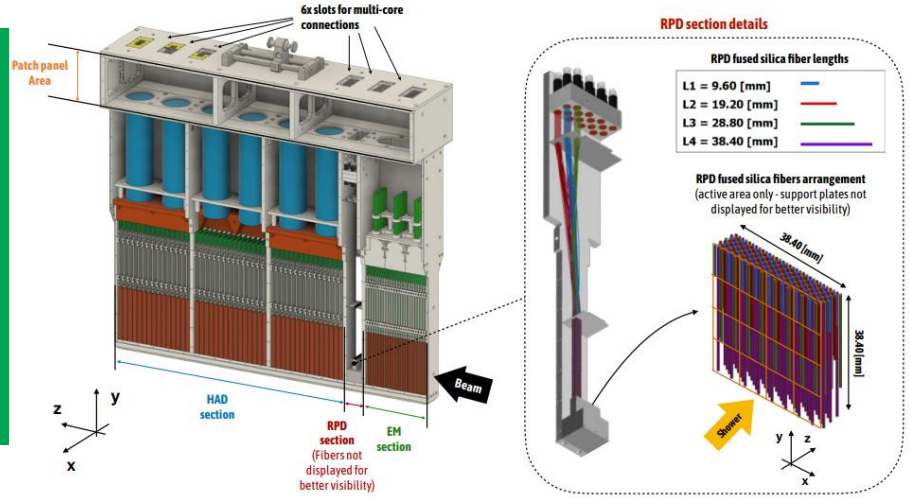
Forward neutron detectors

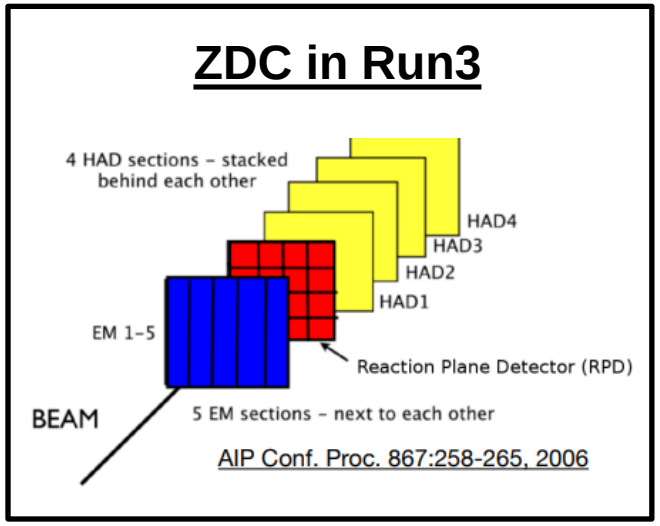
- The Zero Degree Calorimeter (ZDC) aims to detect forward neutral particles produced during heavy ion (AA or pA) collisions
- Located in the Target Absorber for Neutrals (TAN) ~ 140 m from the IP



ZDC Final design (HL-LHC phase):

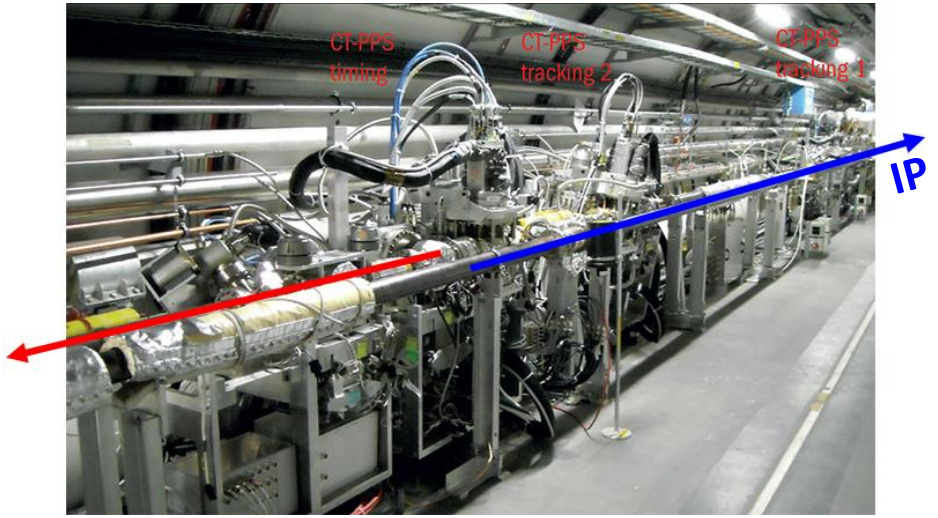
- EM section – photons, ~30 rad. length
- Reaction Plane Detector (RPD) – transverse profile of neutron showers
- Had section – neutrons (3 modules each ~1.15 int. length)

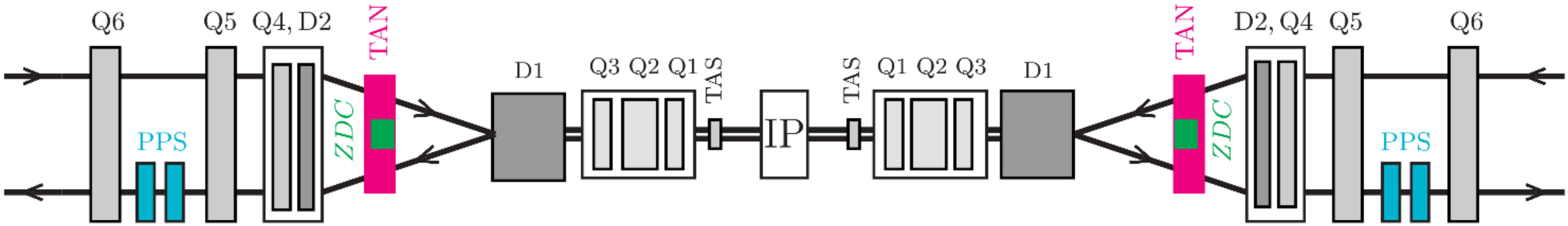




Forward proton detectors

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





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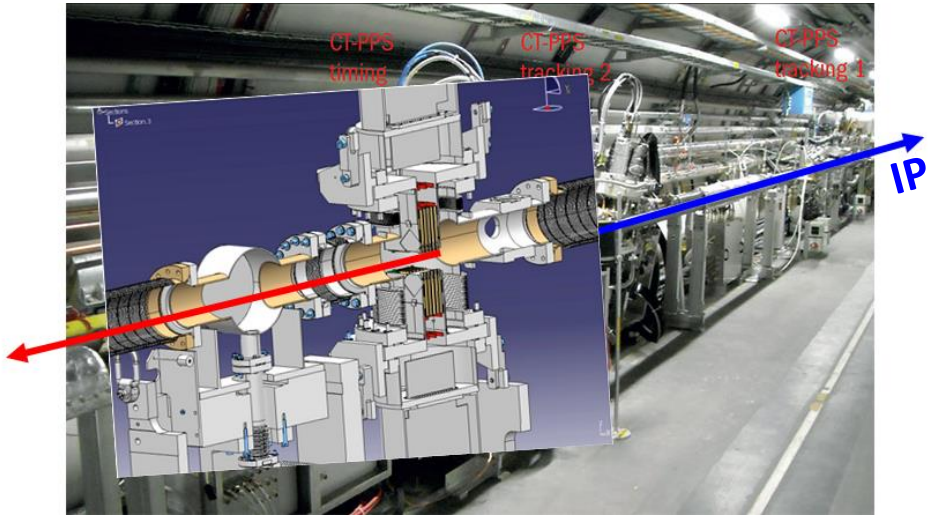

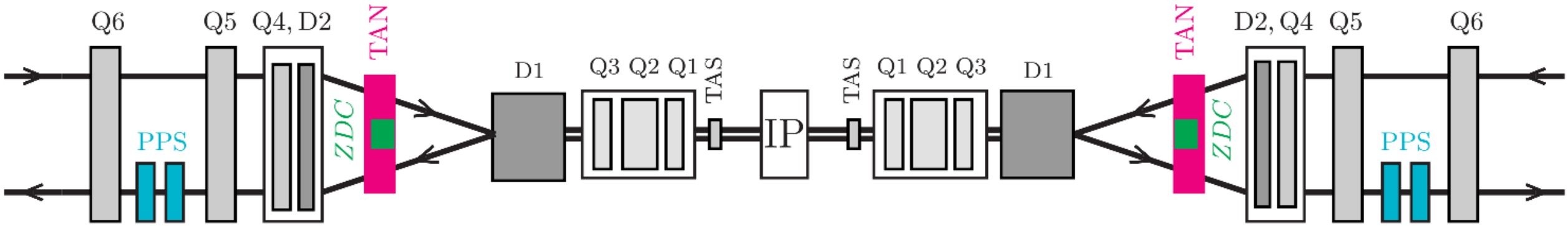

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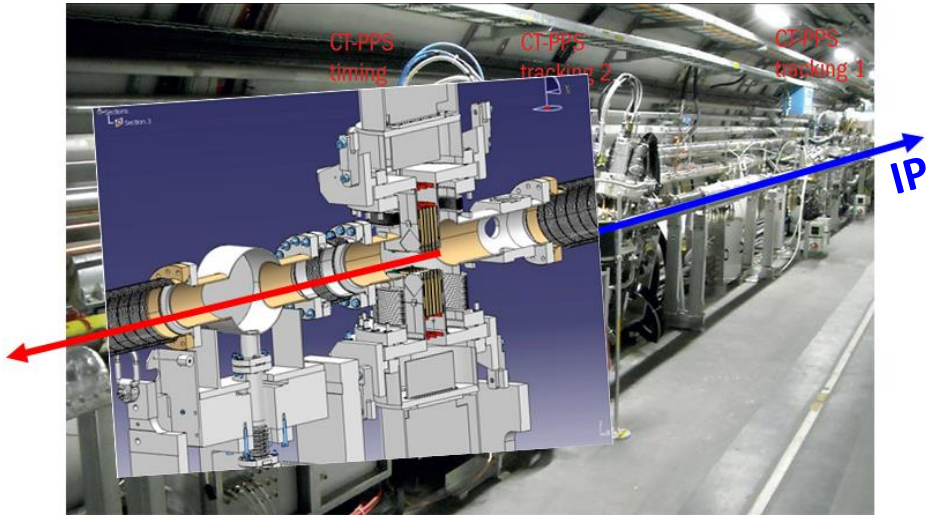
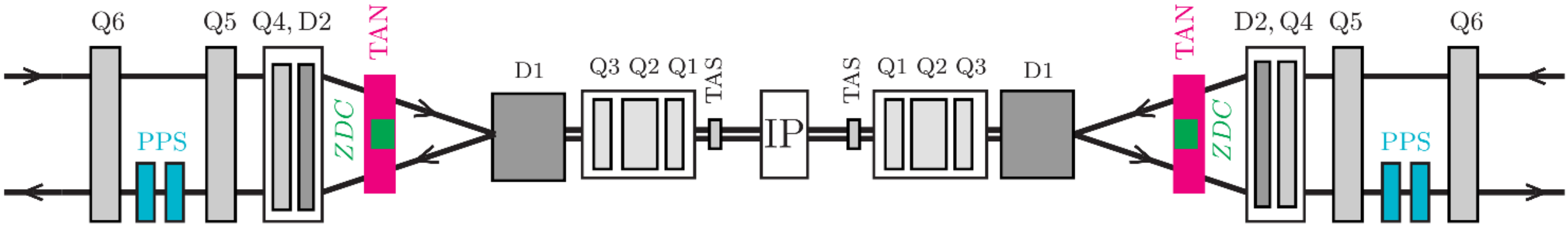
- Off-momentum protons → smaller magnetic rigidity

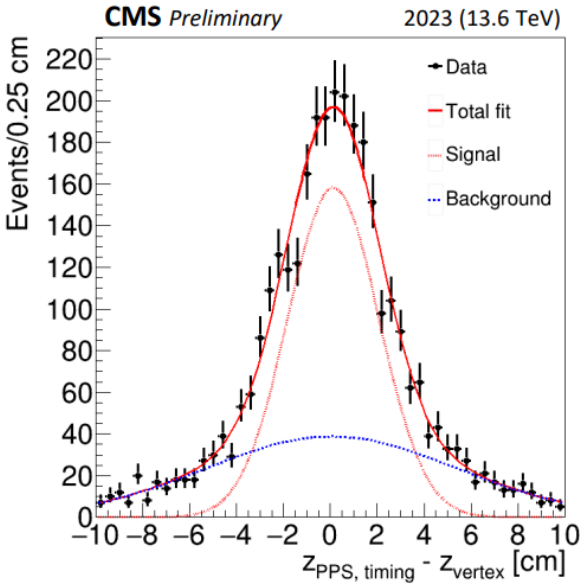




Forward detectors - performance in 2023

Precision Proton Spectrometer

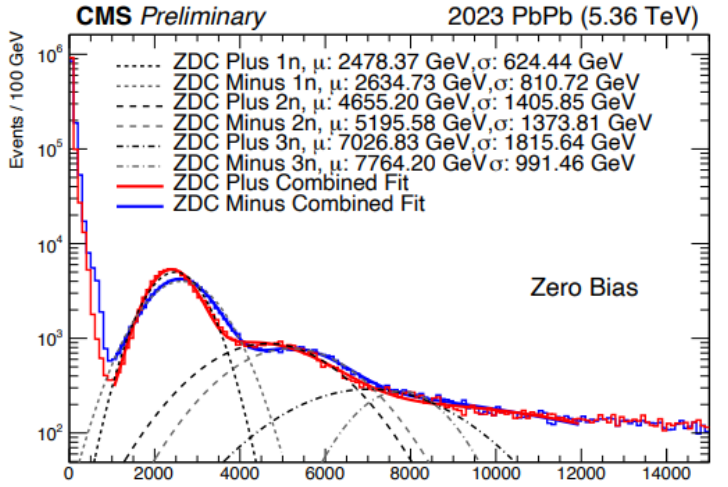
- Operated during standard *pp* runs (high PU)
  - Measured proton momentum loss ($\xi = \Delta p_Z/p$) in range between 3% - 15% with unprecedented resolution
  - Timing resolution of 60ps
- Additional vertical detectors can be inserted at very low PU, and mostly efficiency for high β* LHC optics ($\xi \sim 0$)



CMS DP-2024/009

Zero Degree Calorimeter

- Operated at very low pileup – can sustain integrated luminosity up to ~ 1fb^{-1} and at pileup rate up to μ ~ several
  - Measures neutral particles with |η|>8.3 (can resolve single neutrons)
  - EM has 5 horizontal divisions (can be up to 3 in Run 4)

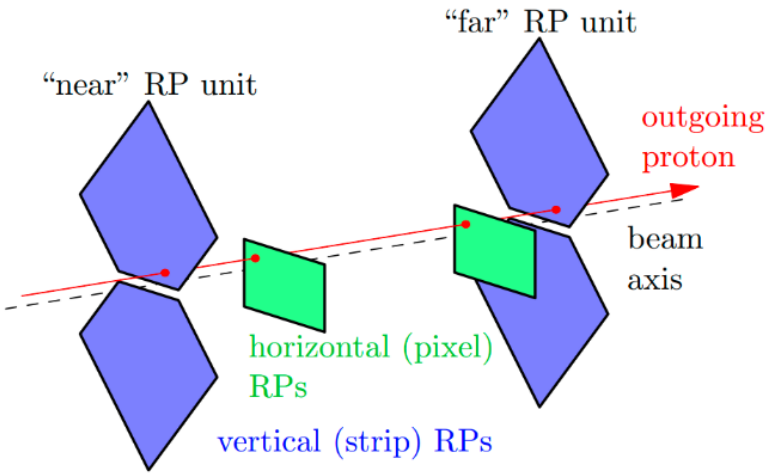


CMS DP-2024/002

Forward detectors - commissioning

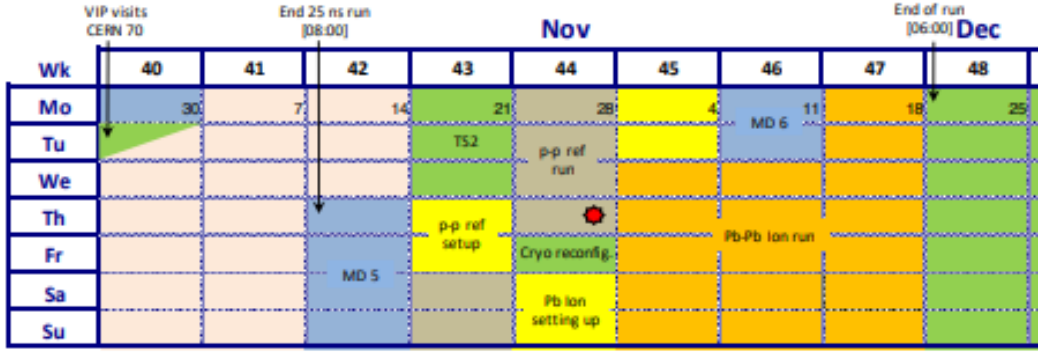
Precision Proton Spectrometer

- **Only if LHC optics changes** (e.g. high beta*), a special alignment run is required (2-3 bunches / beam) to approximately 12h, where **vertical** detectors are used with **horizontal** to measure the beam center



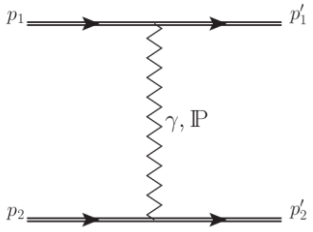
Zero Degree Calorimeter

- ZDC is not installed during standard pp runs
- Before data taking: Need access, installation often takes ~ 1 day (usually after MD/TS)
- After data taking – access is needed to deinstall the detectors (offer done during the YETS)

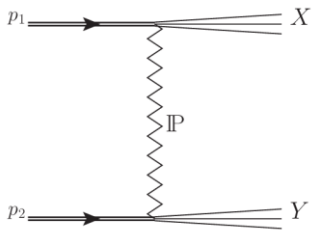


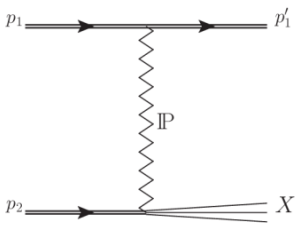
Diffractive/exclusive processes at the LHC

- t-channel exchange of color neutral particles (QED, QCD)

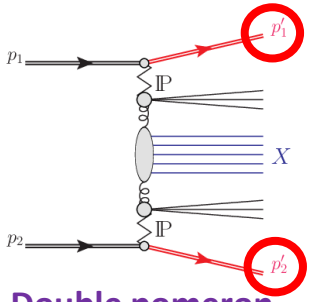


Elastic scattering

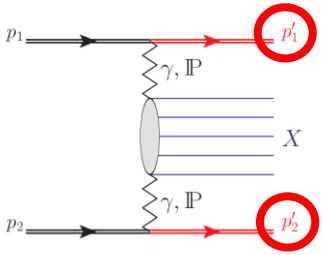




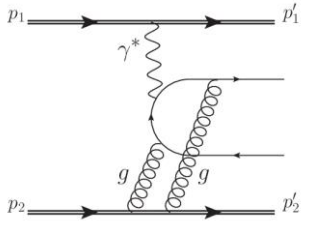
Single/double diffractive dissociation



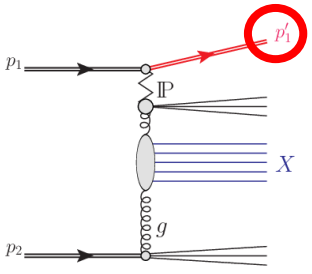
Double pomeron exchange



Central exclusive production



Exclusive photoproduction

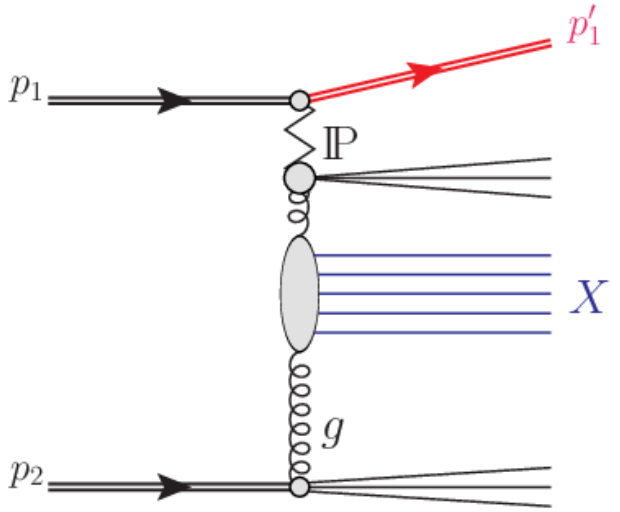


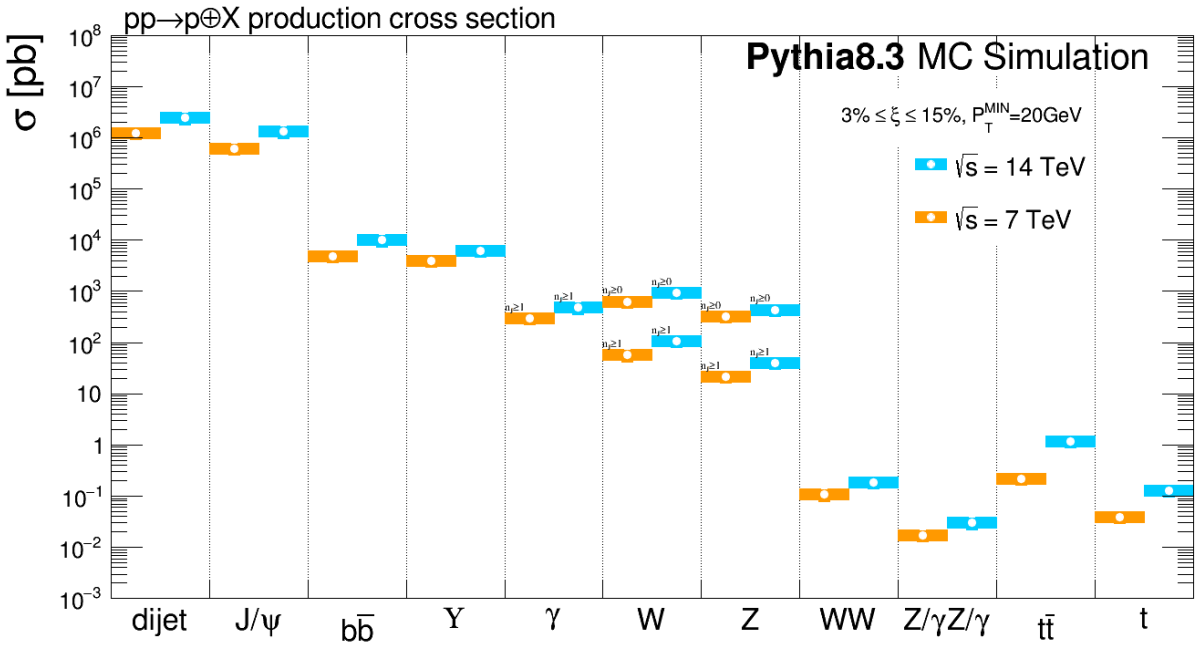
Single-diffraction with central system

- Spans over large kinematic region (MeV – TeV), and large cross-section range
- Provide a rich scientific program for LHC experiments
- Sometimes protons loose substantial fraction (~ a few%) of their kinetic energy but emerge intact
  - **Hard diffraction with forward protons**

Single diffraction (SD) with high mass central system

- Production of hard process + a diffractive proton
- Hard SD events comprise up to a few % of the inclusive σ
- Could have impact in precision measurement at the HL-LHC

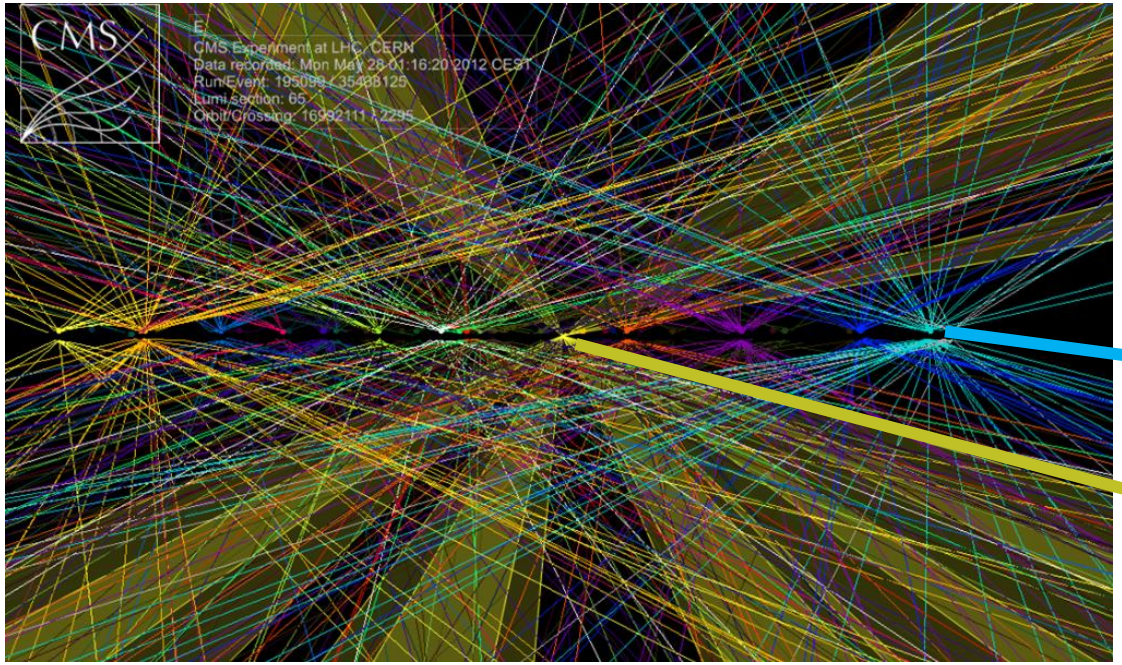


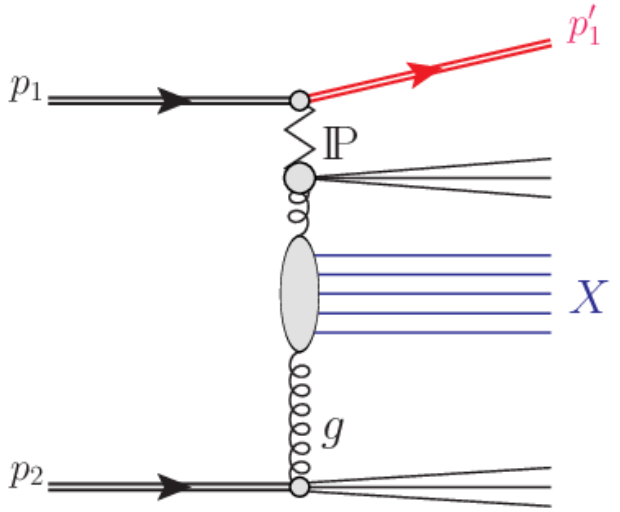


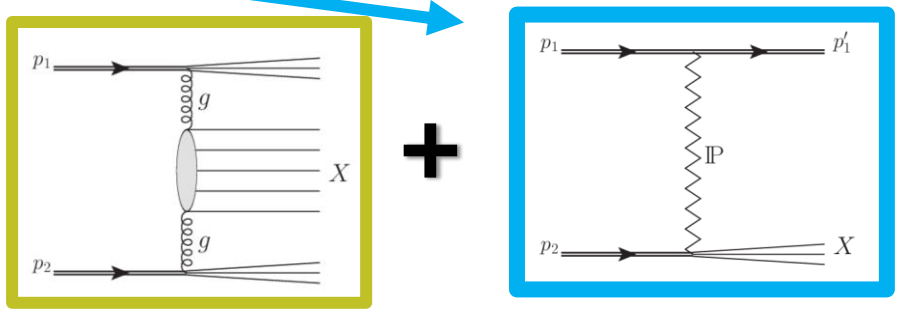
Large fraction of diffractive SM processes are accessible by the LHC data

Challenge – combinatorial backgrounds

- Multiple *pp* collision can fake the signal

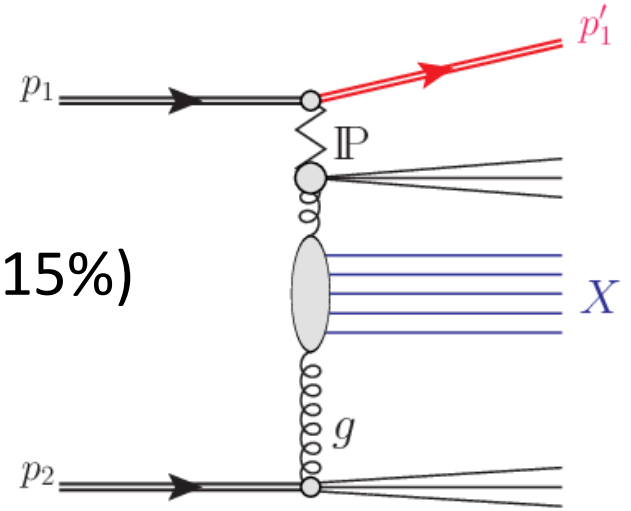


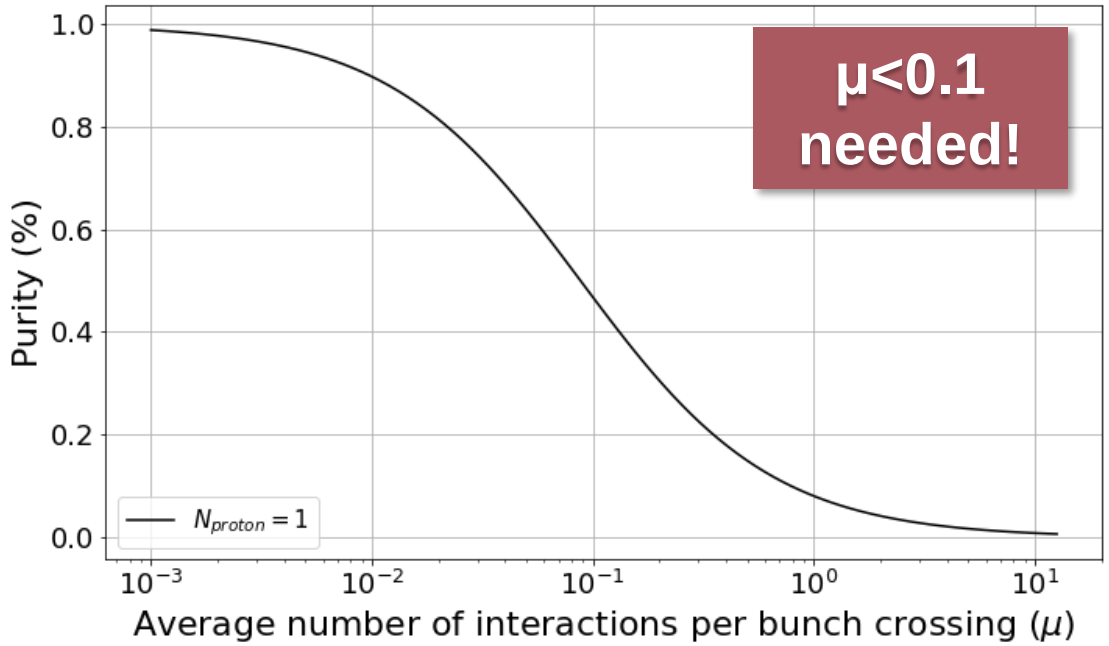




Challenge – combinatorial backgrounds

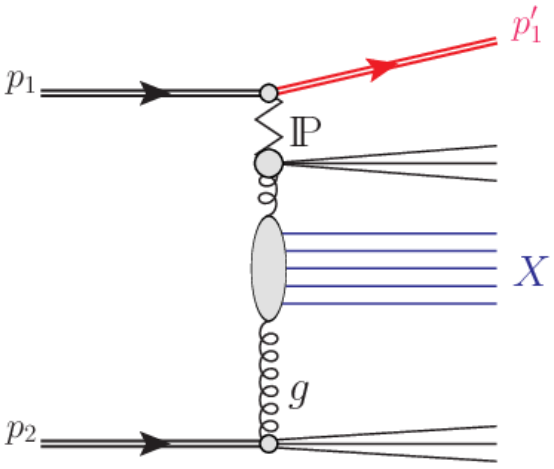
- Multiple *pp* collision can fake the signal
- 0.5% fraction of diffractive events (σ_SD/σ_ND)
- 2.2% (40%) of soft-diffractive (signal) events have proton $\xi \in (3\%, 15\%)$





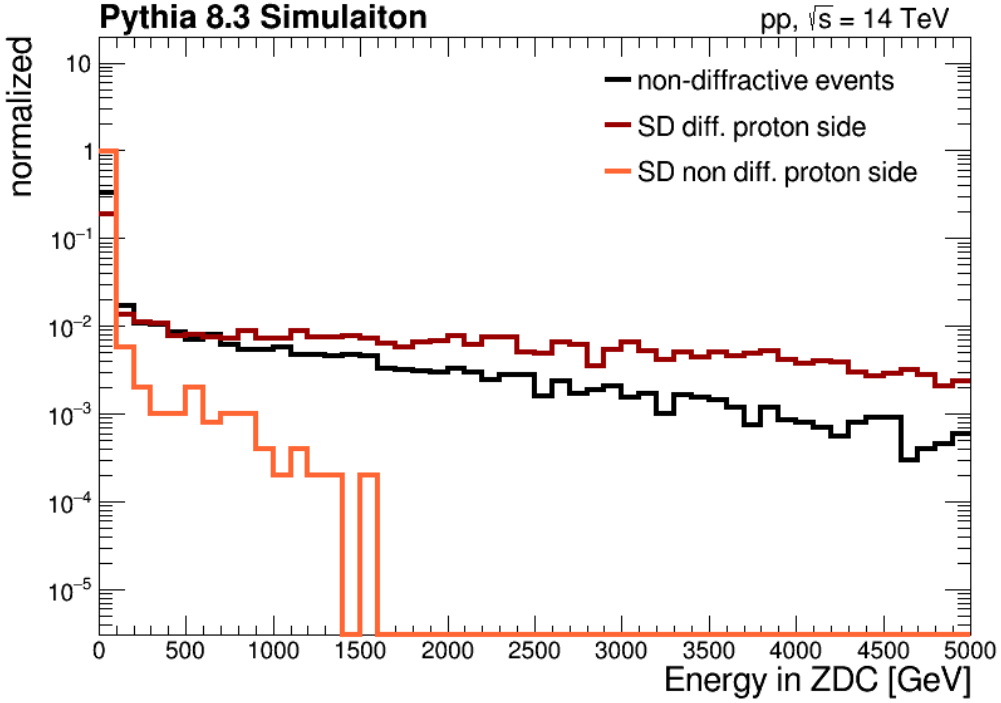
Challenge – combinatorial backgrounds

- Multiple *pp* collision can fake the signal
- ZDC can be used to reject inclusive integrations
- 33% of inclusive events have sufficient (>50GeV) signal in the ZDC, while 60% of SD events has a ZDC signal on opposite side



No radiation

Forward radiation



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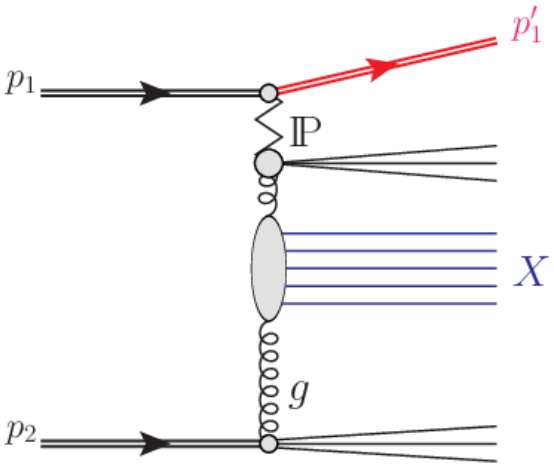
- Rapidity gaps can gain × 3 in purity



No radiation in ZDC

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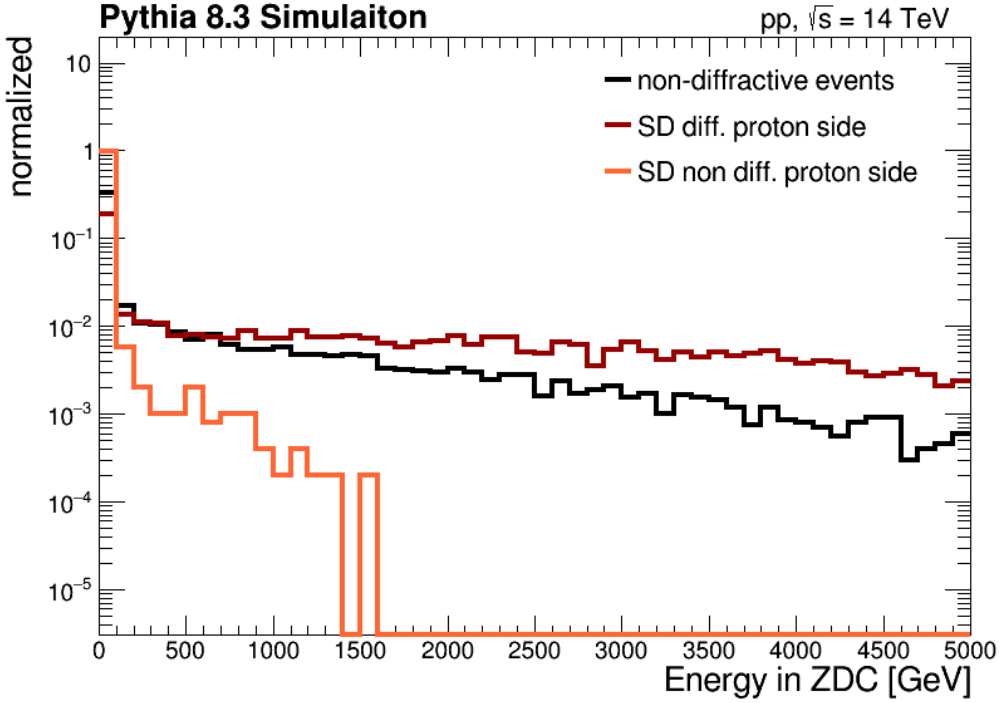

Challenge – combinatorial backgrounds

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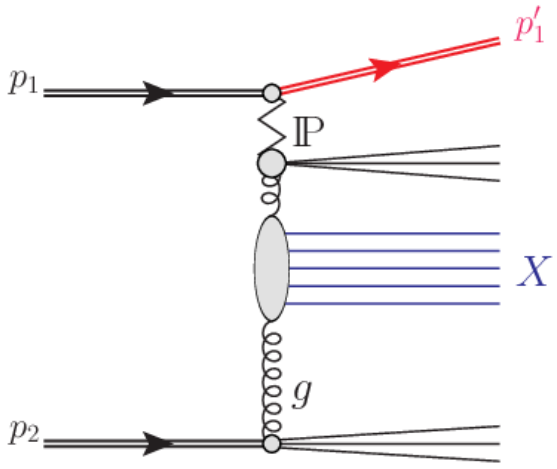
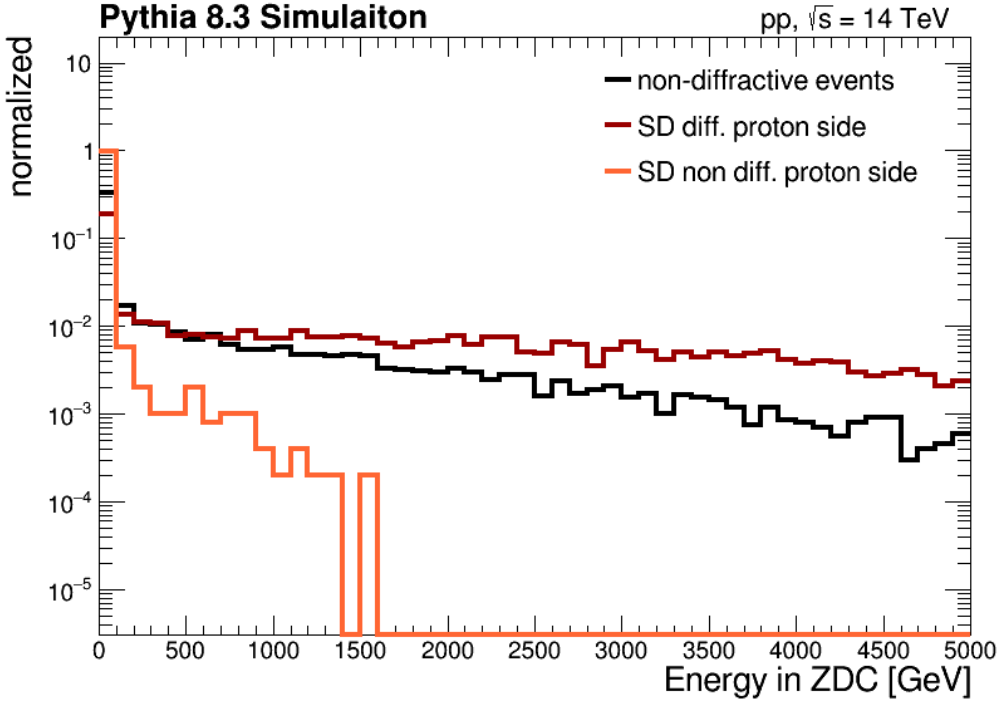
- Rapidity gaps can gain $\times 3 - 10$ in purity



No radiation in ZDC + FCAL

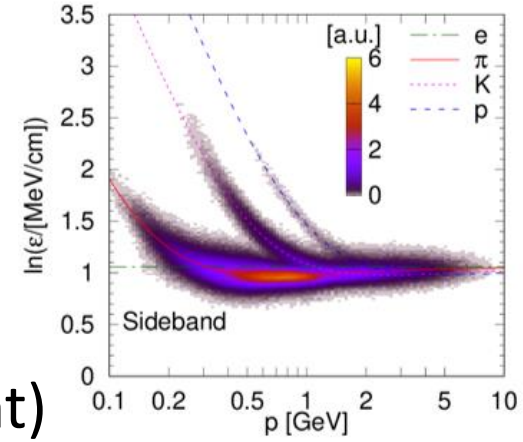
Forward radiation



Discussion

Low PU runs - summary

- A few special low PU runs with nominal LHC optics have been taken in Run 2 and Run 3
- Data is currently being analyzed, and much experience was gained

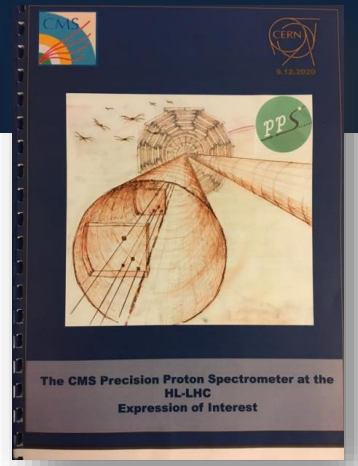


Low PU runs – future opportunities

- CMS PPS+ZDC continue to operate during the HL-LHC phase
  - Can benefit from low pT tracking performance (dE/dX measurement)
  - Correlation between CMS ECAL and PPS timing detectors (probably from Run 4) can be investigated to get a cleaner sample of diffractive events
  - Joint data taking at low-PU with ZDC + PPS can be explored
  - The forward physics program can further benefit from having special runs (different LHC optics) at HL-LHC

Backup

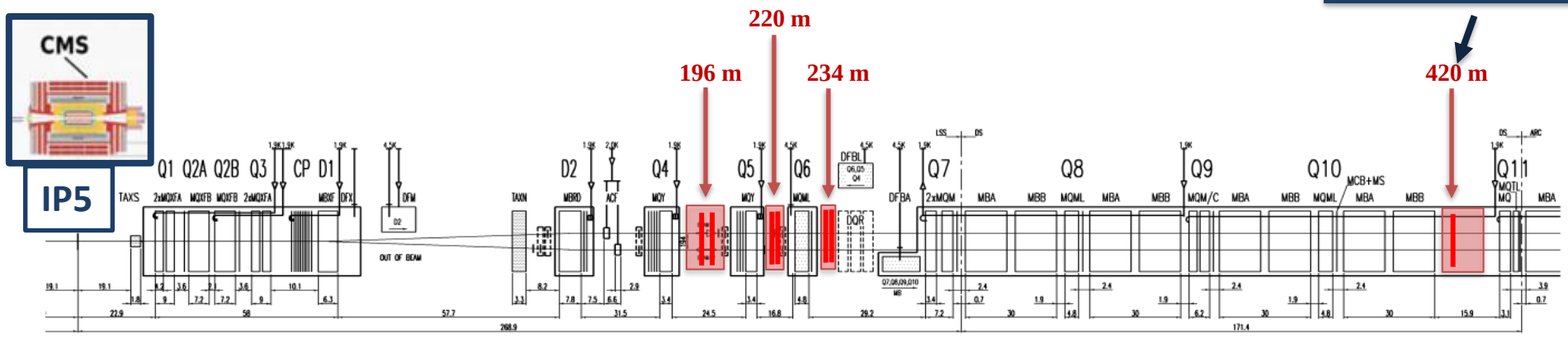
CMS Precision Proton Spectrometer (PPS)



CMS-NOTE-2020-008, arxiv:2103.02752

- Since during the LS3 the whole beamline will be rearranged, a new spectrometer design was proposed (2020), and approved in Sep 2023
- PPS Upgrade with extended acceptances in pp collisions:
  1.42% < ξ < 20% for the first 3 stations (from Run 4)
  0.33% < ξ < 20% for 4 stations (from Run 5+)
- Higher ξ is defined by the TCL position

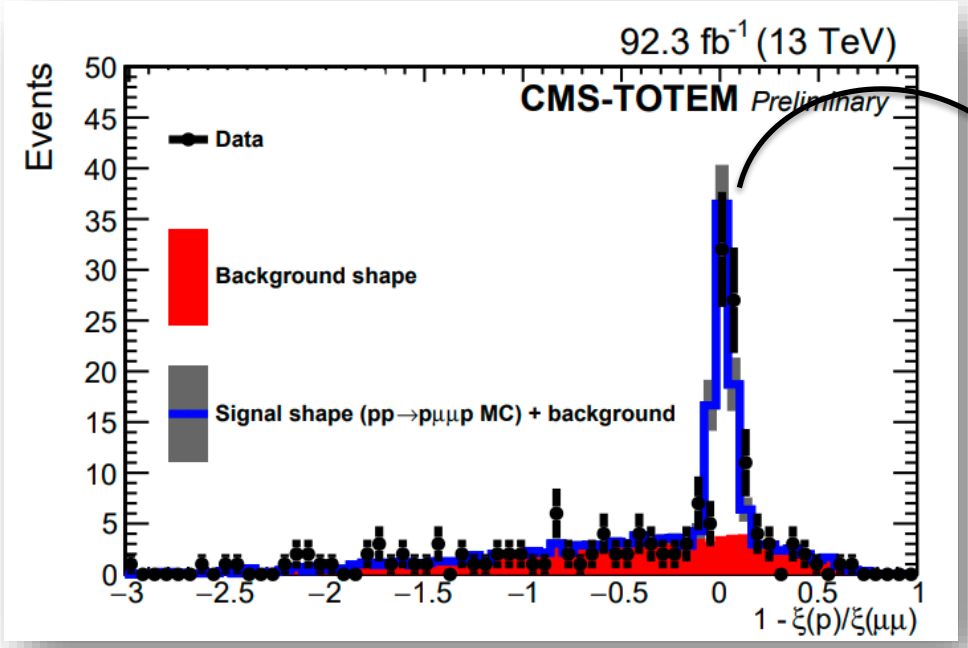
Staged installation



Main goal to extends current LHC physics program (WW, di-τ, top, ALPs, SUSY, etc…)

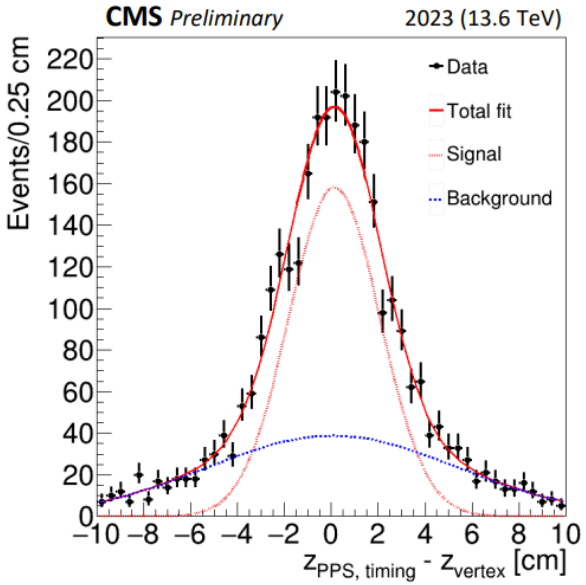
PPS | Performance

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



- Timing:
  - Using central diffractive events in μ~1 sample
  - Compare Z(PV) vs Z(PPS)
  - **All track resolution: $\sigma_z = 1.9\ cm$**

Validation of the calibration sequence



PPS | Tracking efficiency in 2023

CMS DP-2024/008

- Challenges in the standard LHC runs:
  - Efficiency drop due to irradiation
  - Higher x -> Higher ξ -> Higher minimal accepted mass
  - Detectors were shifted by 0.5mm using internal movement system