CMS is looking forward:
boosting CMS capabilities for forward physics at the HL-LHC

WG6 – Current Upgrades and Future Experiments

Michael Pitt (CERN),

On behalf of the CMS collaboration

May 5, 2026

Outline

1. CMS forward HI program today
   - Present CMS forward detectors: HF, ZDC, FSC, PPS
   - Run-3 HI experience: light and heavy ion runs
2. Run 4 and beyond
   - New detectors, triggers and PID
   - UPC, pA and light-ion physics reach

HL-LHC is more than luminosity

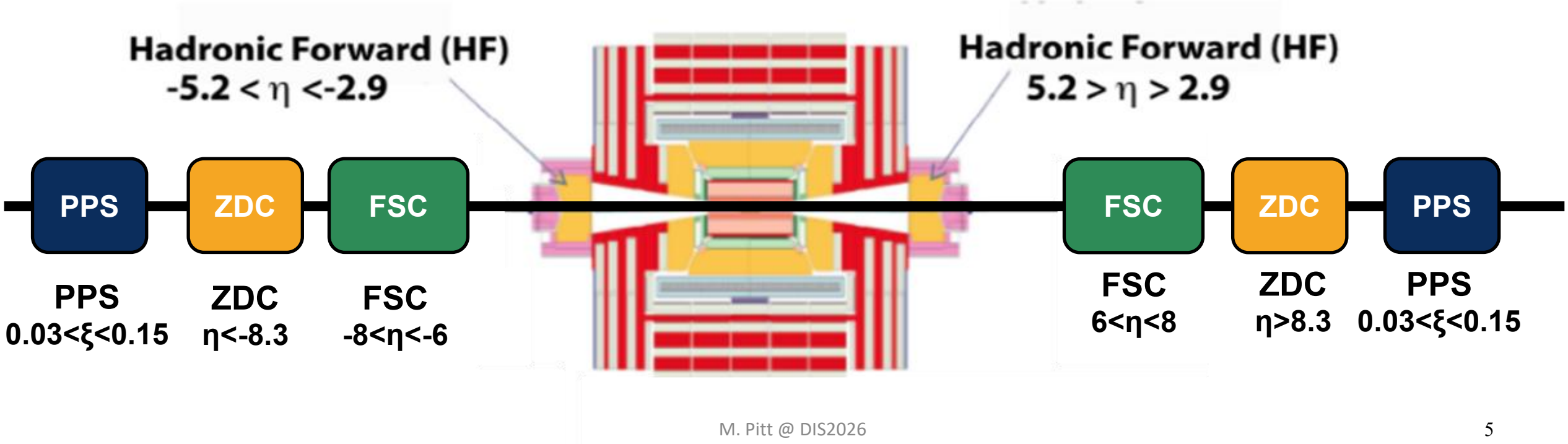
- ✓ Larger datasets
  - ➢ rare UPC and photonuclear processes become accessible
- ✓ More event classification
  - ➢ Forward activity, neutron emission, rapidity gaps and proton/remnant tags
- ✓ More reconstruction
  - ➢ low-p_T PID, heavy-flavor, and wider rapidity reach

Run 4 turns CMS into a more taggable, wider-acceptance HI experiment

CMS forward HI program today

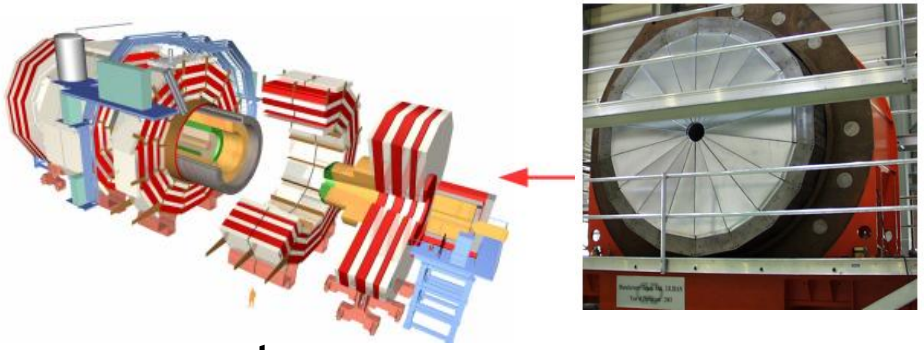
CMS forward detectors

- Hadronic Forward (HF) provides the standard CMS forward calorimetry up to $|\eta|\sim5.2$
- ZDC and FSC extend event classification beyond HF in HI or pp reference runs.
- PPS tags intact protons and can complement pA/light-ion forward measurements.

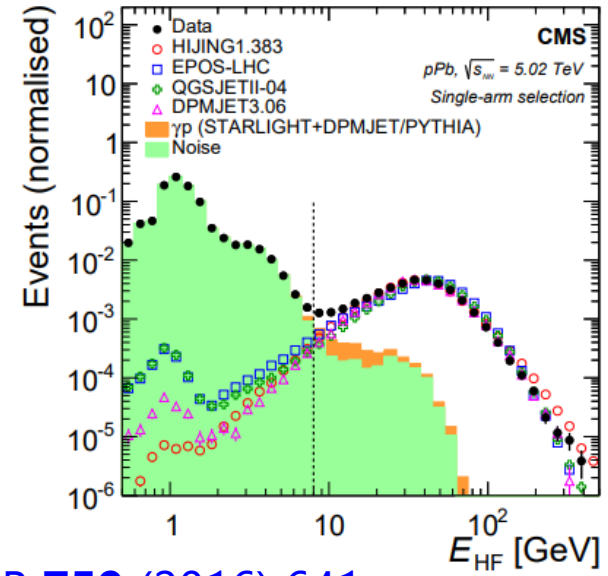


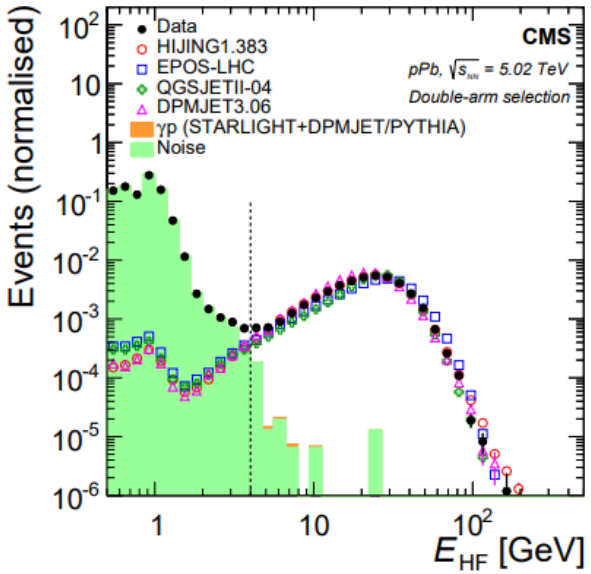
HF – Hadronic Forward calorimeter

Forward physics with HF



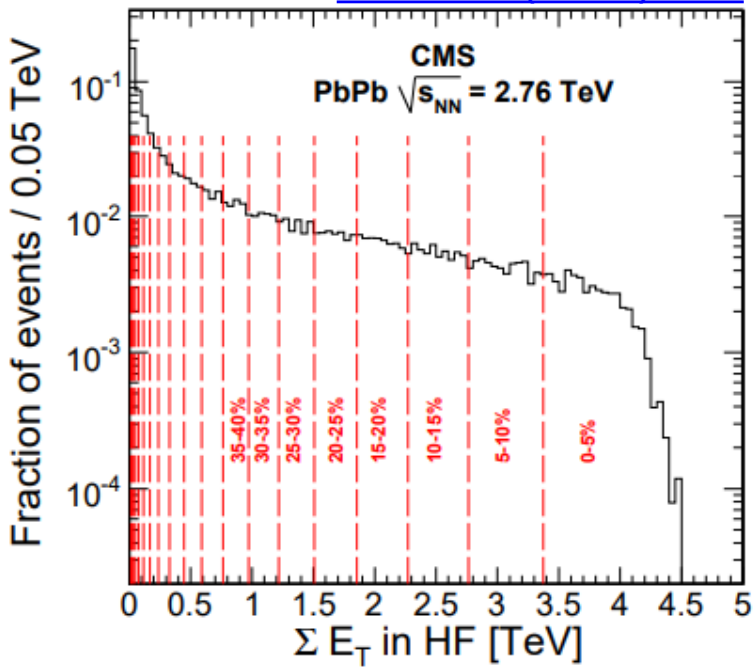
- Extends CMS rapidity coverage to |η| < 5.2
- Sensitive to forward energy flow and used in σ_{inel} measurements
- Provides a centrality estimator in heavy-ion collisions





PLB **759** (2016) 641

JHEP **08** (2011) 141

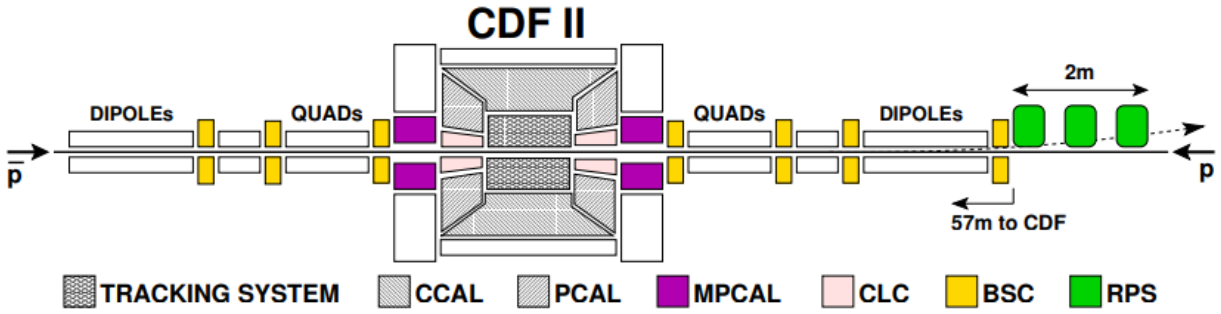


Forward Shower Counters

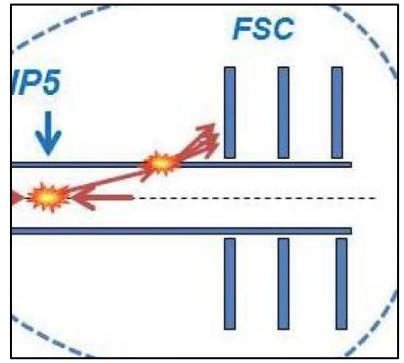
Forward physics with FSC

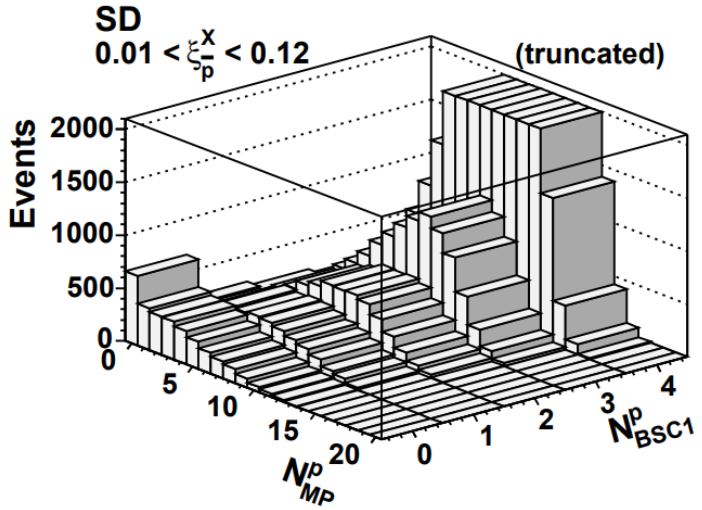
- Extends rapidity-gap tagging to $6 < |\eta| < 8$
- Used in Run 1 and revived in Run 3
- Inspired by the Beam Shower Counters in CDF

Example: "Observation of CEP di-jets" (PRD **77** (2008) 052004)



CDF vs CMS
BSC = FSC
RPS = PPS
MPCAL~HF





- Designed for low mass diffraction at the LHC JINST **4** (2009) P10001
  - ➢ Proposed in Run 1 by the CMS collaboration: CMS-NOTE-2010-015

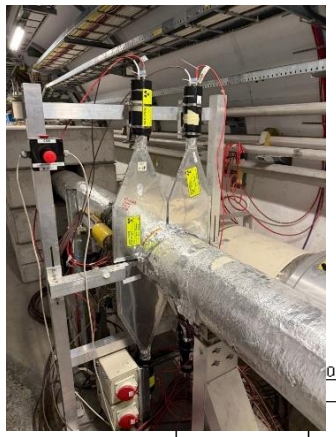
Forward Shower Counters

The refurbishment and installation supported by the MIT HI group and the Carl G and Shirley Sontheimer Research Fund

FSC revival in Run 3

- Revived for pO running on the proton-going side in July 2025
- Extended to both arms for PbPb run in November 2025

Station #3 +114 m

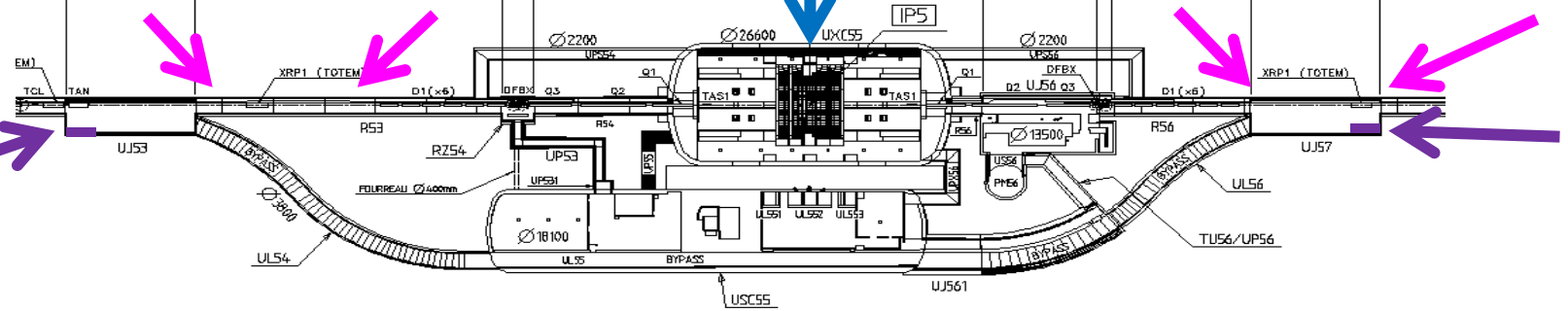


Station #2 +85 m

IP5 (CMS)

Station #2 -85 m

Station #3 -114 m



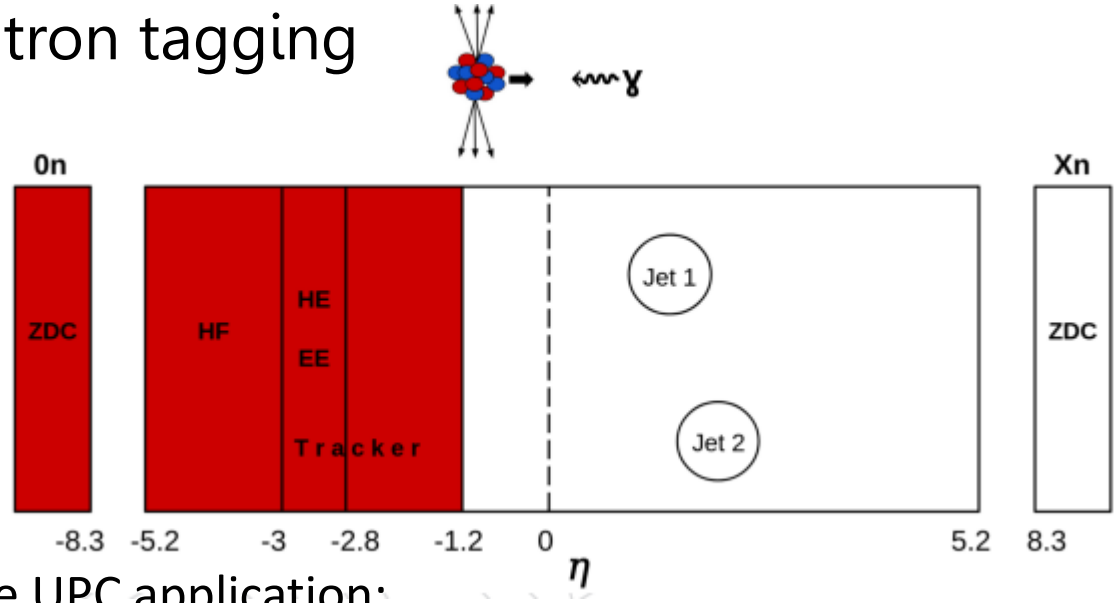
FSC+ZDC DAQ

FSC+ZDC DAQ

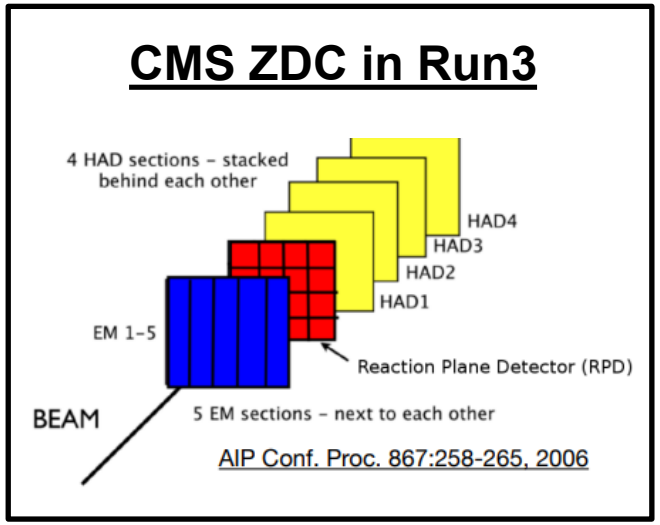
Zero Degree Calorimeter

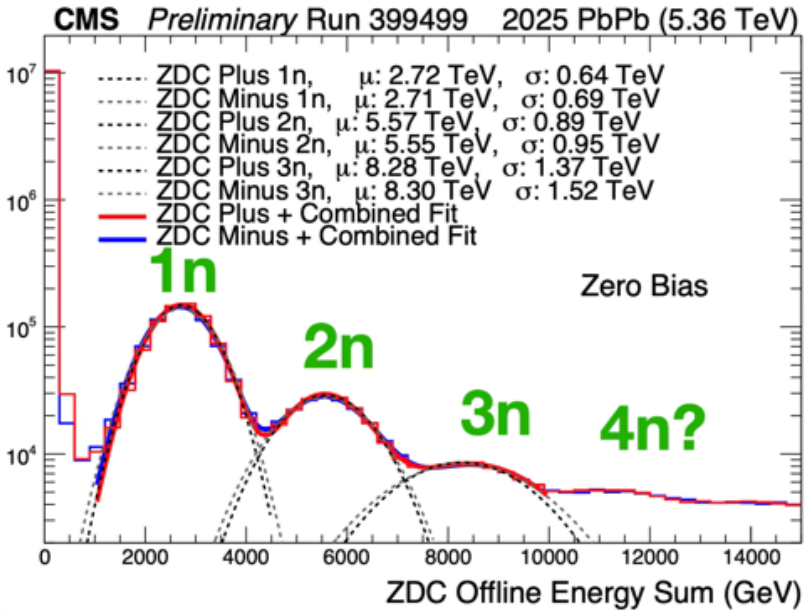
Forward physics with ZDC

- Measure neutral particles at beam rapidity, $|\eta| > 8.3$
- Operated in HI and pp reference running
- Essential for UPC event classification through neutron tagging



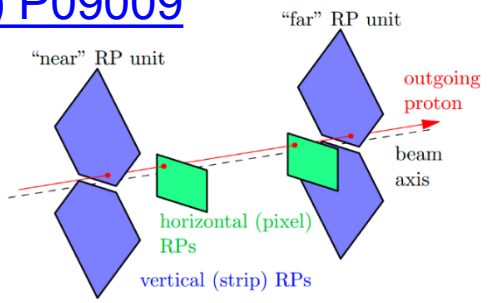
Example UPC application:
Photoproduction of dijets (HIN-24-022)





Precision Proton Spectrometer

JINST 18 (2023) P09009

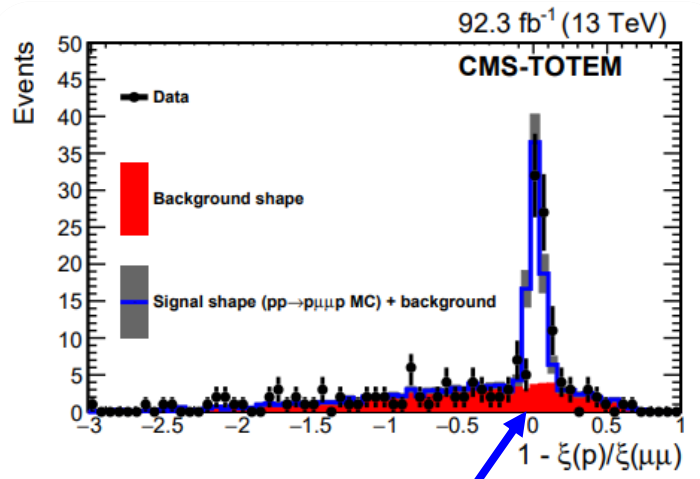


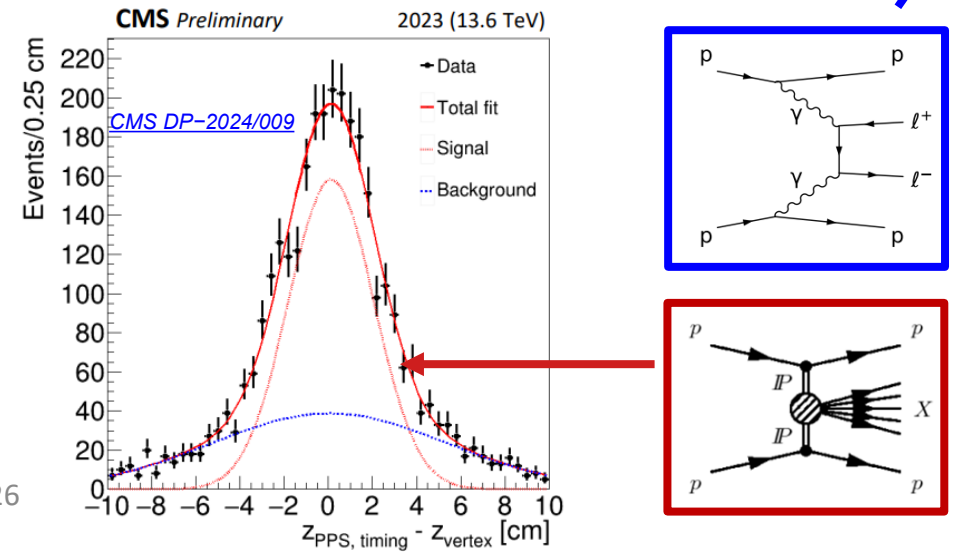
Forward proton detectors

More about PPS in Fabrizio Ferro's talk

- PPS tags intact protons with a set of near-beam detectors hosted in movable vessels (Roman Pots).
- Provides high-resolution position and timing information
- In pA, PPS can tag the proton side
- In light-ion running, PPS-like acceptance may also tag nuclear fragments

($A - n$ fragments correspond to $\xi \sim n\frac{1}{A}$)

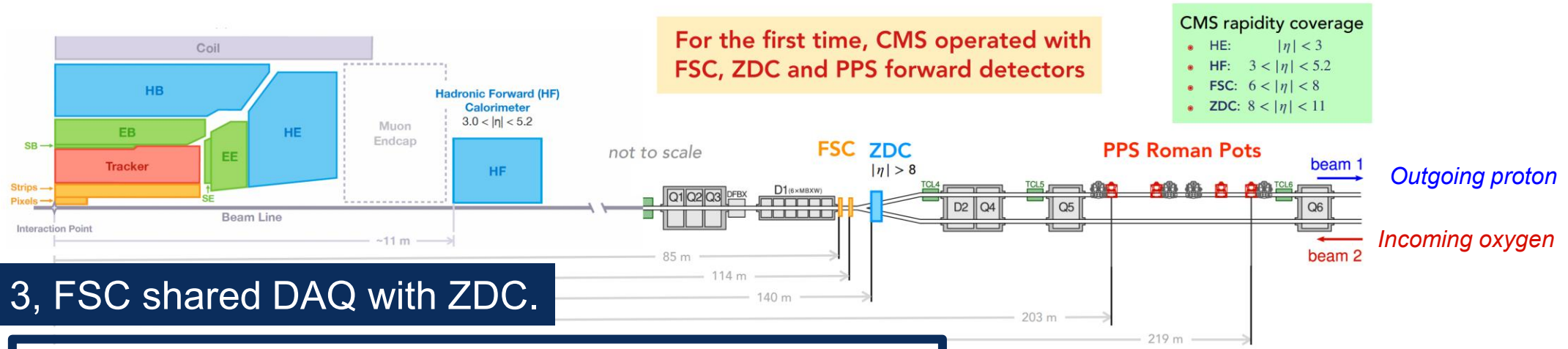




Forward detectors in Run 3

pO run with an extended forward detector array (July 2025)

- The oxygen run demonstrated that CMS can operate HF, ZDC, FSC and PPS synchronously to probe final states beyond the central detector acceptance.



For the first time, CMS operated with FSC, ZDC and PPS forward detectors

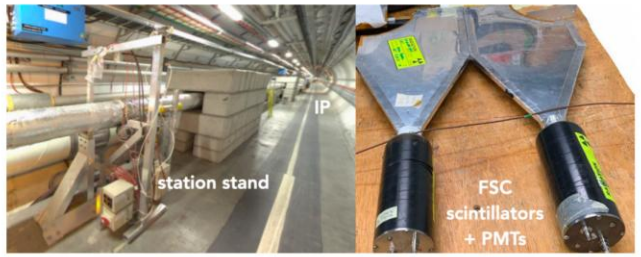
CMS rapidity coverage
- HE: $|\eta| < 3$
- HF: $3 < |\eta| < 5.2$
- FSC: $6 < |\eta| < 8$
- ZDC: $8 < |\eta| < 11$

Outgoing proton

Incoming oxygen

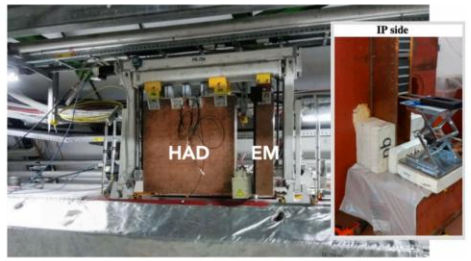
In Run 3, FSC shared DAQ with ZDC.

Forward Shower Counters (FSC)



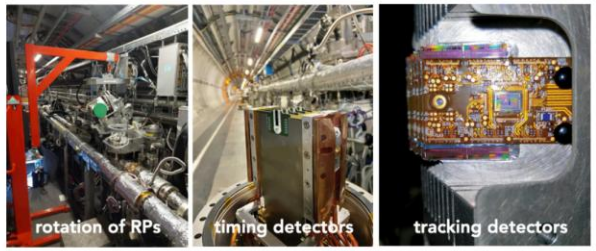
pO, OO, NeNe: in Sector 56 (proton-going side)

Zero Degree Calorimeter (ZDC)



pO, OO, NeNe: both sides

Precision Proton Spectrometer (PPS)



pO: inserted on proton-going side only

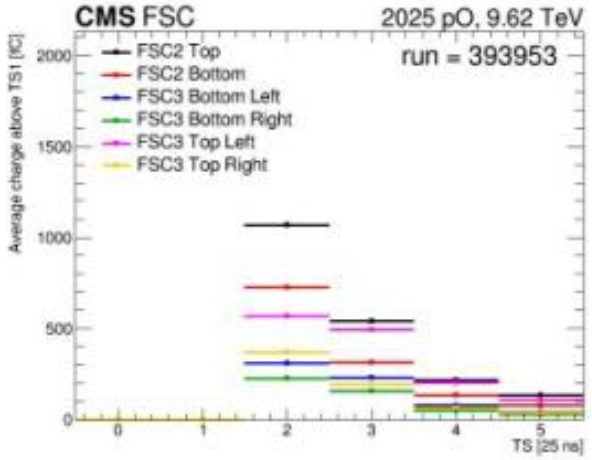
Forward detector performance in Run 3

pO run with an extended forward detector array (July 2025)

- The oxygen run demonstrated that CMS can operate HF, ZDC, FSC and PPS synchronously to probe final states beyond the central detector acceptance.

Forward Shower Counters

Average pulse shape seen by FSC channels aligned in time during the OO run

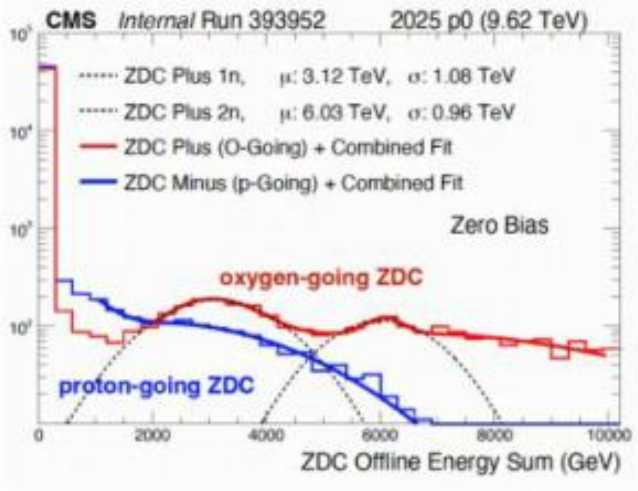


- to "purify" diffractive events in pO and photonuclear events in OO/NeNe

proton-going side only

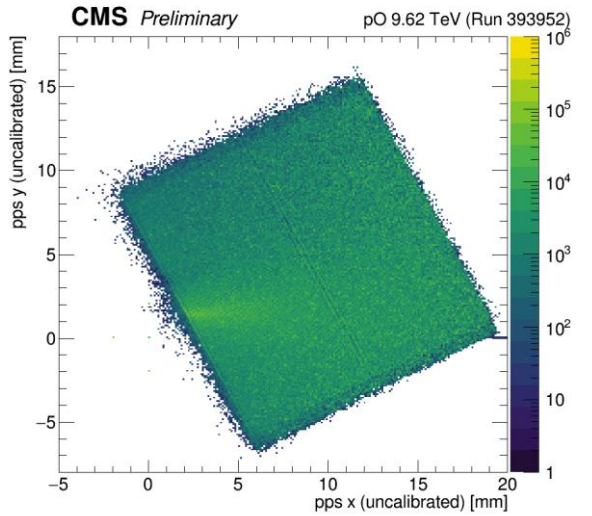
Zero Degree Calorimeter

Neutron peaks in the pO run showing expected asymmetry from O-going and p-going sides



both sides

Precision Proton Spectrometer



- to tag diffractive protons in pO

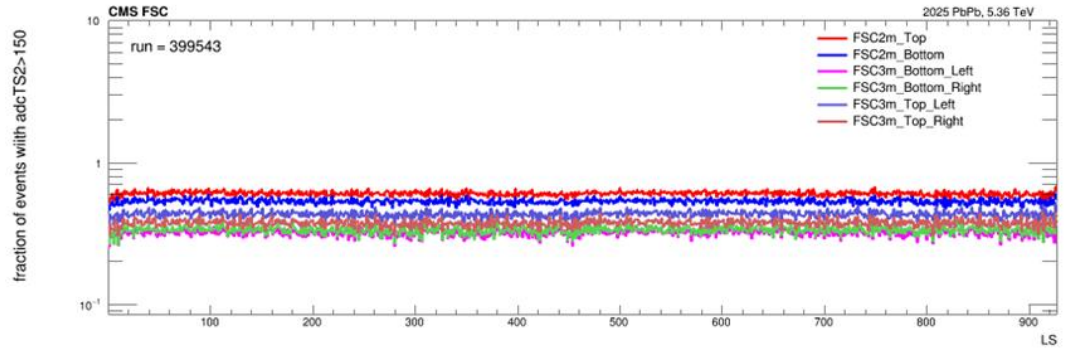
proton-going side only

Forward detector performance in Run 3

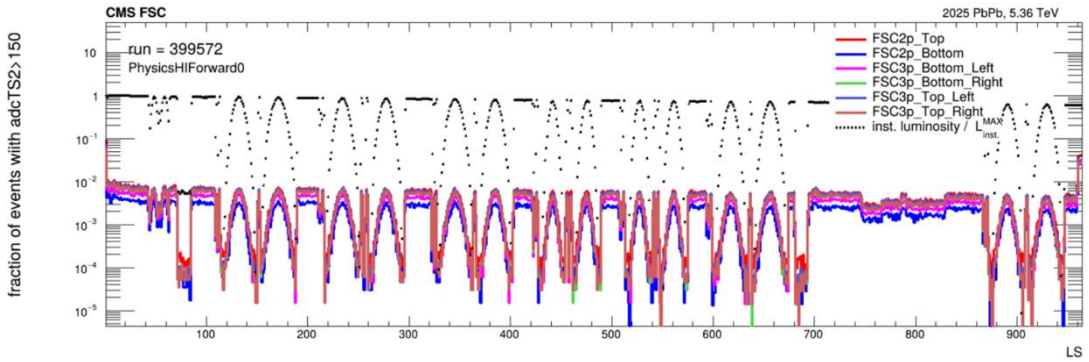
Run-3 PbPb: FSC becomes a ZDC extension

Run 3 provided the operational proof-of-principle for a unified forward HI system.

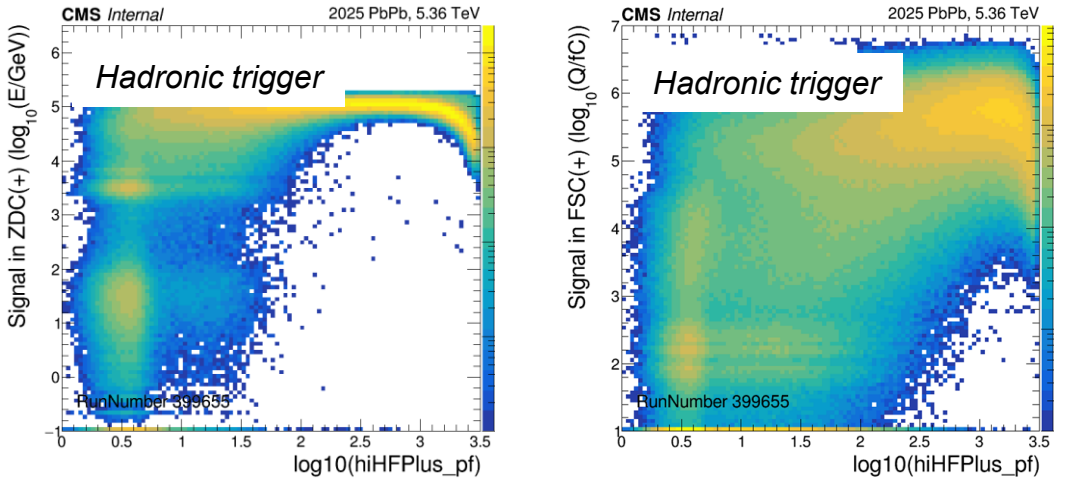
- FSC shows stable operation in the HI runs



- Follows the instantaneous luminosity profile



- In HI runs, FSC can be viewed as an extension of the ZDC system.



Rapidity slicing can help separate neutron/spectators from hadronic activity

Run 4 and beyond

From Run 3 to Run 4: what changes?

CMS subsystem	Run 3 status	HL-LHC status	Physics role
HF (CMS-TDR-023)	Part of CMS calorimeter	Same detector system	$3.0 < \|\eta\| < 5.2$
ZDC (CMS-TDR-024)	HI neutron tagging / UPC trigger	New radiation-hard ZDC (smaller dimensions)	Used for UPC trigger and tagging photon-induced processes
FSC	Operated with ZDC in HI runs in 2025 – 2026	**Not in the baseline**	ZDC rapidity extension, sensitive to the resolved photonuclear processes (needs studies)
PPS (2103.02752)	High-PU pp; first used in HI running with pO	PPS2 with extended acceptance, to be used in pA for proton tagging	Proton tag in pA, possible light-ion remnant tag
MTD (CMS-TDR-020)	**Not present**	**New Phase-2 timing/PID detector**	low-p_T PID: charm/strangeness/light nuclei
L1 tracks (CMS-TDR-021)	**Not present**	**New L1 tracking trigger**	Phase-2 tracker extended to $\|\eta\| < 4$

Physics targets enabled by forward tagging

UPC and photonuclear QCD

- vector mesons — Pranjal Verma's talk
- open heavy-flavor — Balasz Kovacs's talk
- nPDFs and saturation — Shuai Yang's talk

Longitudinal structure and event activity

- Neutron tags
- Rapidity gaps
- Forward energy flow

pA (in)coherent production

- PPS proton tag
- ZDC(FSC) ion-side classification
- Proton/nuclear breakup control

Light-ion and remnant tagging

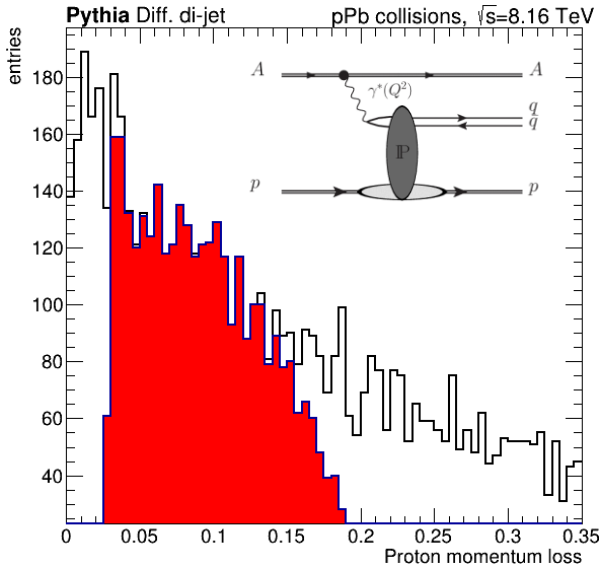
- Existing runs – pO/OO/NeNe
- Inelastic cross-section measurements
- Nuclear fragments

Check CMS UPC talks at WG2, Tuesday Morning session

pA and light ions: proton and remnant tagging

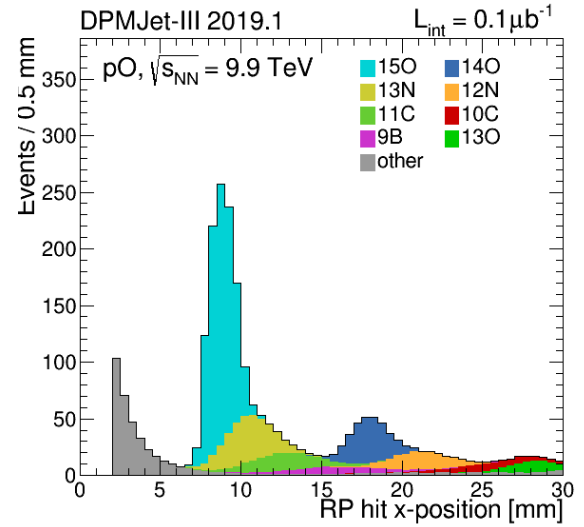
Photo-diffractive dijet production

- Higher mass dijets can be produced in $\gamma - IP$ interactions
- Good acceptance for intact proton in wide kinematic range



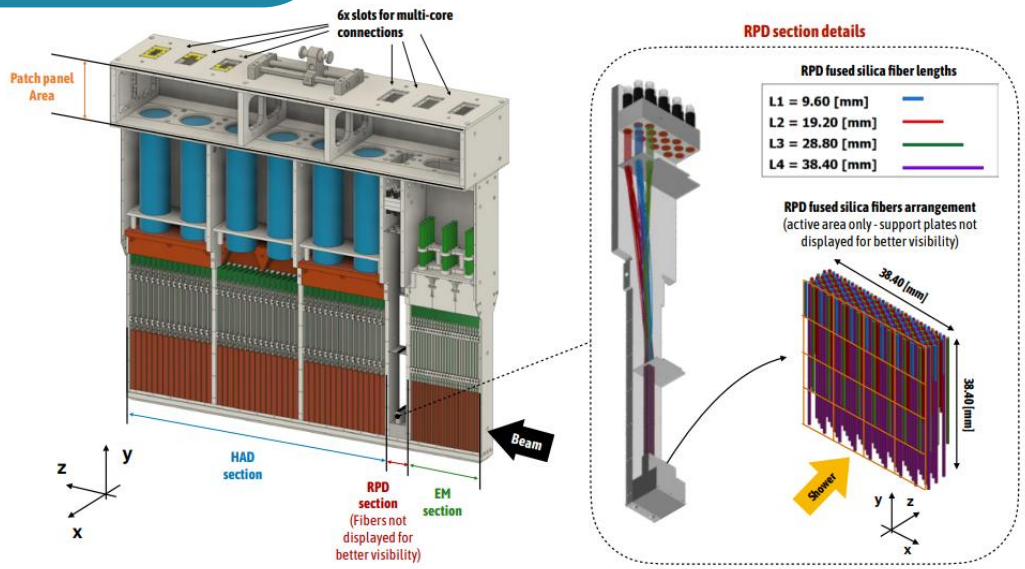
Fragment tagging

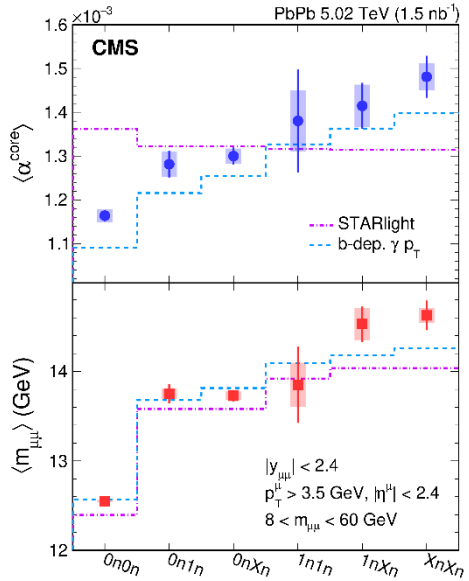
- Light-ion fragments can fall into PPS-like momentum-loss acceptance:
  - **Oxygen: A-1 → ξ~6.25%, A-2 → ξ~12.5%**
  - **Lead: A-1 → ξ~0.5%, A-2 → ξ~1%**



Run-4 ZDC: UPC classification at HL-LHC

- New radiation-hard ZDC in the constrained Run-4 TAXN region
- Preserves neutron/photon tagging at beam rapidity
- Enables real-time classification of hadronic, γA and γγ events (L1 UPC trigger)
- New segmentation / RPD can improve event characterization

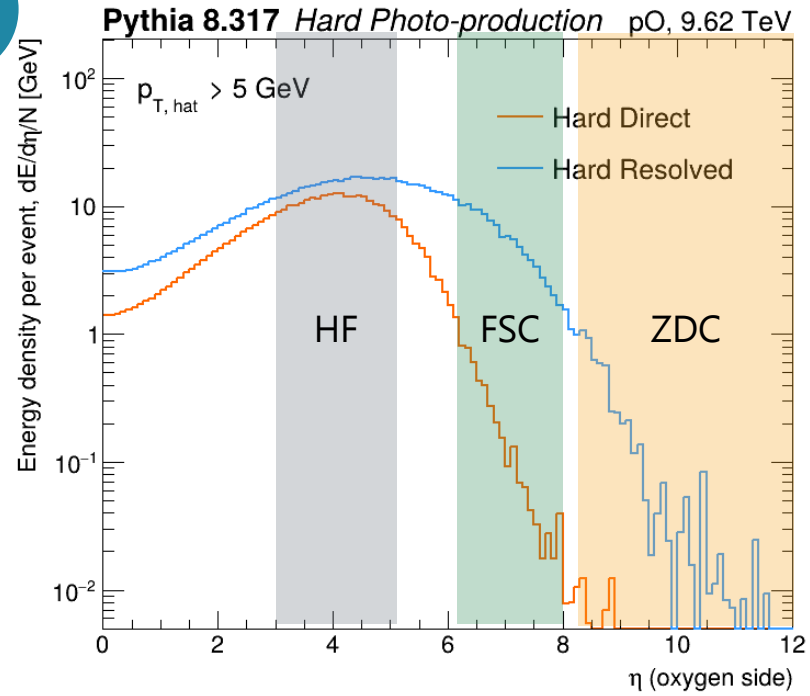




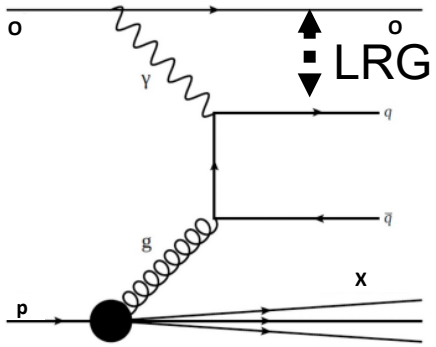
PRL **127** (2021) 122001
2018 PbPb run data

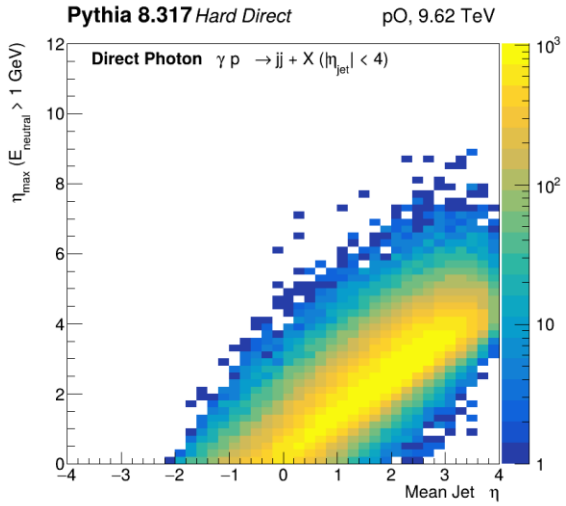
FSC tags photonuclear remnant activity

- Resolved photonuclear events produce forward hadronic remnants extending into the FSC acceptance
- HF + FSC + ZDC provides rapidity slicing: central/forward activity, rapidity gaps, and beam-rapidity neutral energy

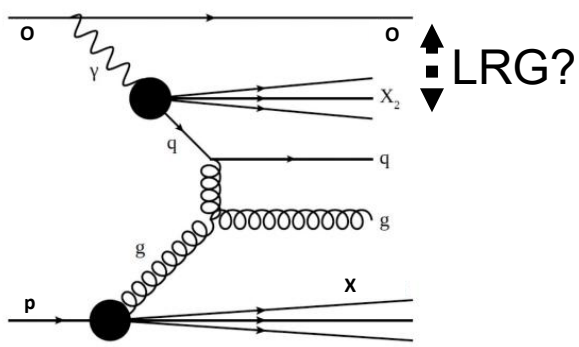


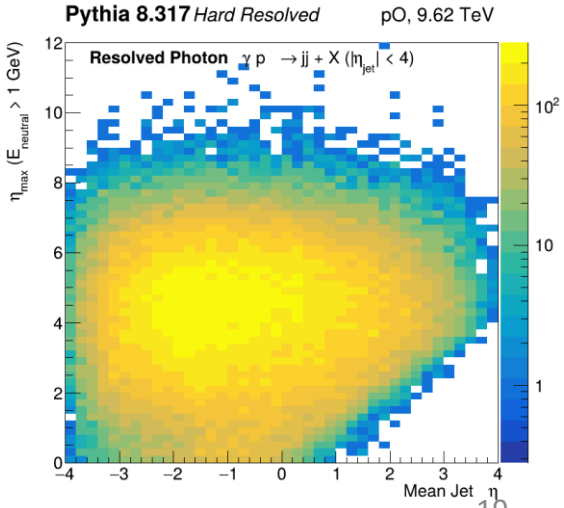
Direct photon





Resolved photon

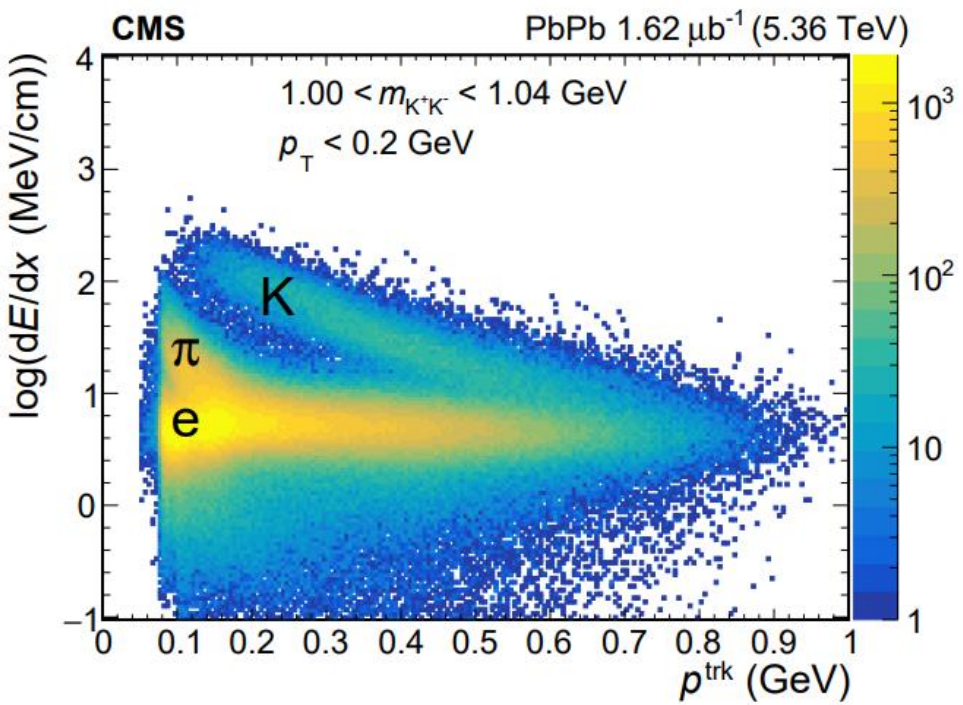


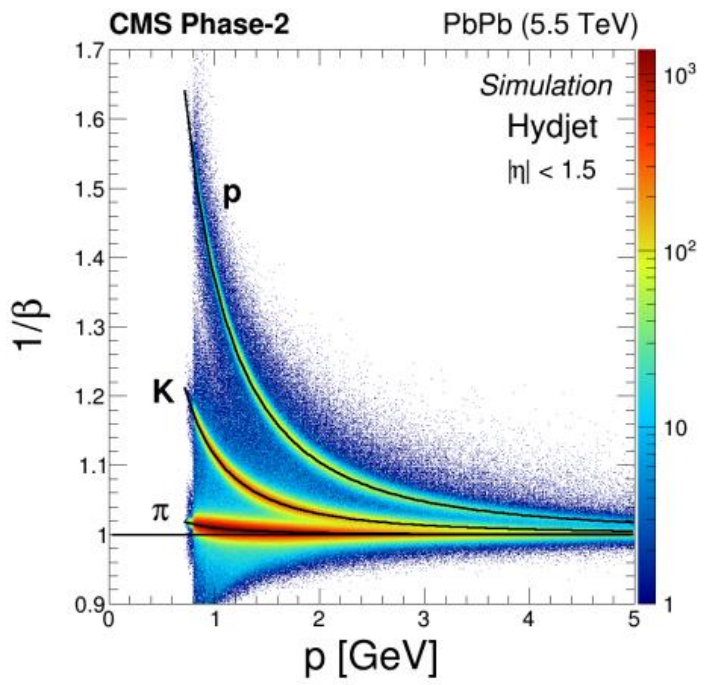


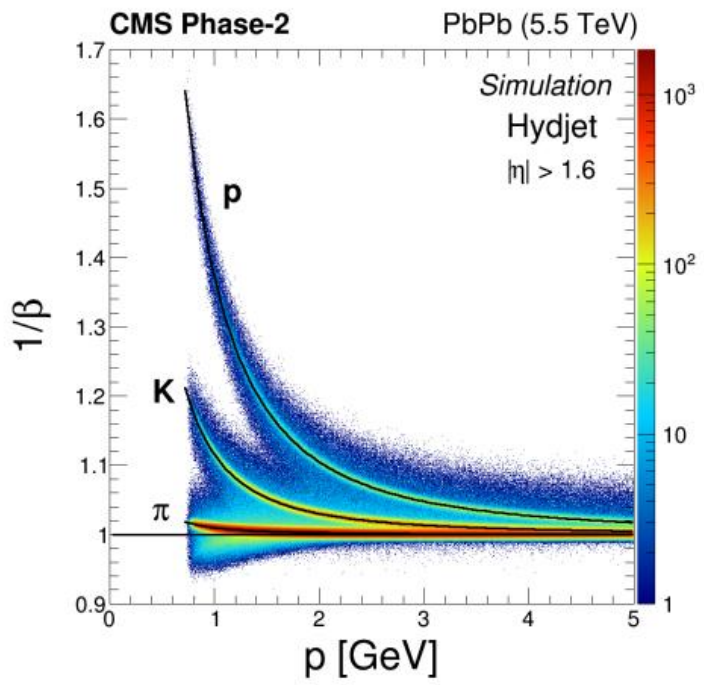
PID: from tracker dE/dx to MTD timing

- CMS already uses tracker dE/dx for low-p_T hadron identification in UPC analyses.
- MTD adds time-of-flight PID, extending this capability into the HL-LHC HI program.

CMS-TDR-020





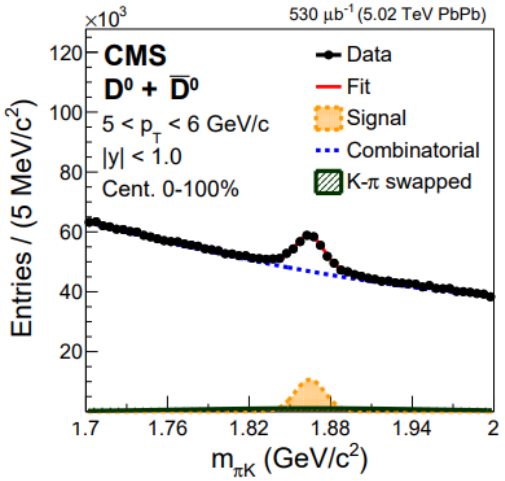


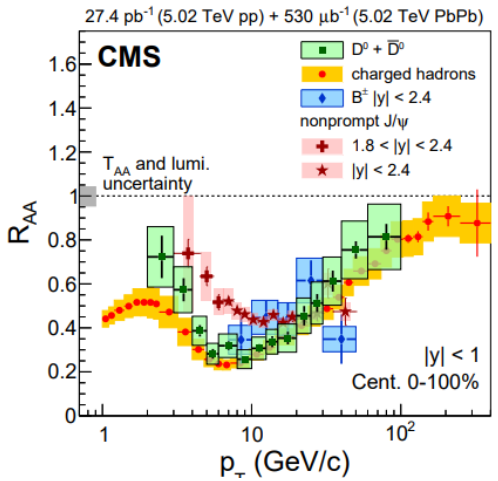
PRL **135** (2025) 262301
2023 PbPb run data

More about MTD detector in Licheng Zhang's talk

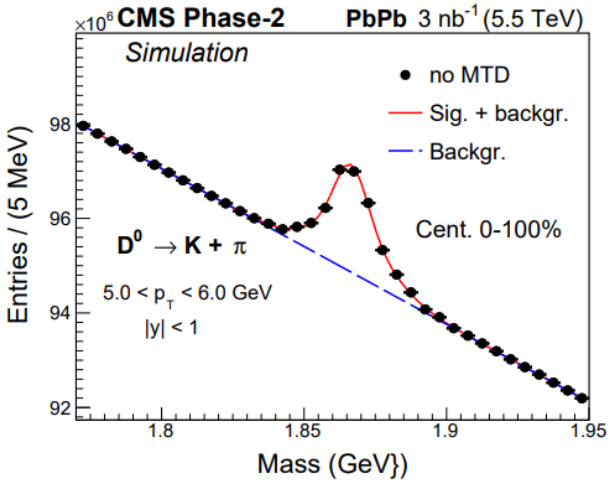
MTD PID for low-p_T tracks

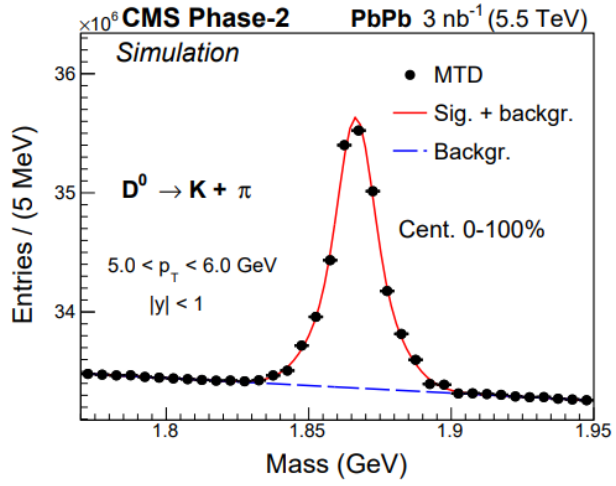
- CMS already uses tracking dE/dx for low-p_T hadron identification in UPC analyses.
- MTD adds time-of-flight PID, extending this capability into the HL-LHC HI program.
- Dramatically improves the D^0 signal-to-background ratio.
- Key for low-pT D-meson RAA and charm transport studies





[PLB 782 (2018) 474](#)
2015 PbPb+pp runs

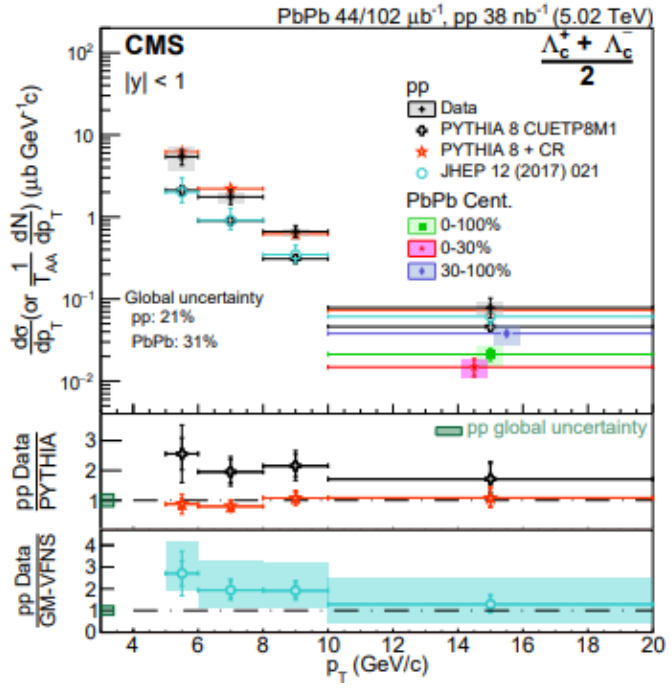




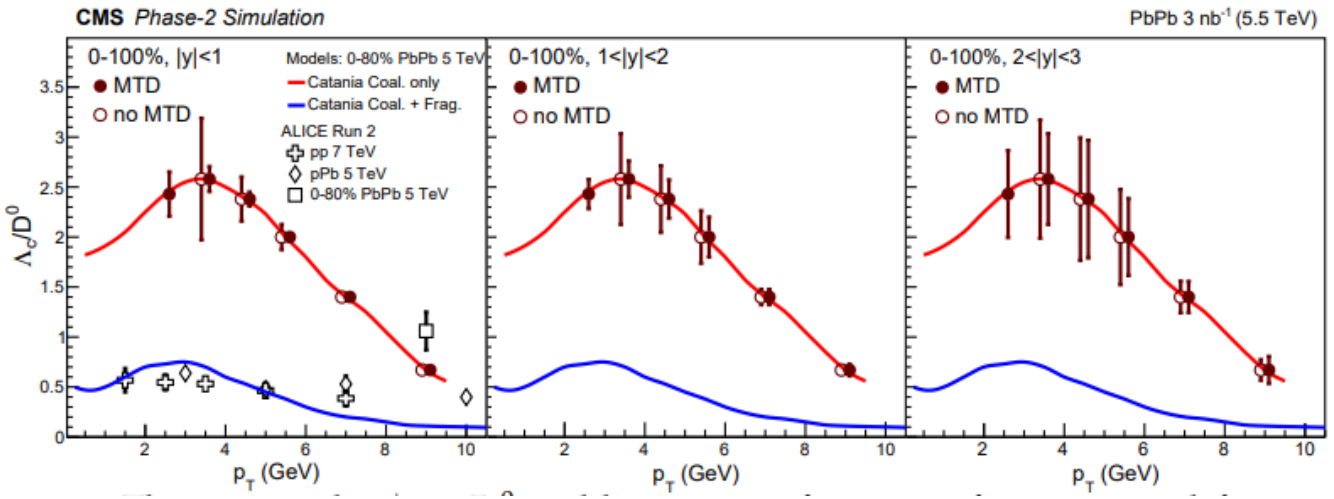
[CMS-TDR-020](#)
Run4 simulations

MTD PID for low-p_T tracks

- CMS already uses tracking dE/dx for low-p_T hadron identification in UPC analyses.
- MTD adds time-of-flight PID, extending this capability into the HL-LHC HI program.
- Heavy-flavor production and dynamics over a wide rapidity interval



PLB 803 (2020) 135328 2015 PbPb+pp runs



CMS-TDR-020
Run4 simulations

Summary

- Run 3 demonstrated integrated forward-detector operation in HI running: HF + ZDC + FSC + PPS.
- Run 4 adds new event classification and reconstruction: radiation-hard ZDC, PPS2, Phase-2 tracking/L1 tracks (with FSC-like rapidity gaps instrumentation under study)
- MTD timing/PID extends the reconstruction reach: low-pT hadrons, charm/strangeness/light nuclei, and wide-rapidity heavy flavor.
- The physics reach spans UPCs, photonuclear QCD, pA coherent/incoherent production, heavy-flavor, diffraction and light-ion remnant tagging.

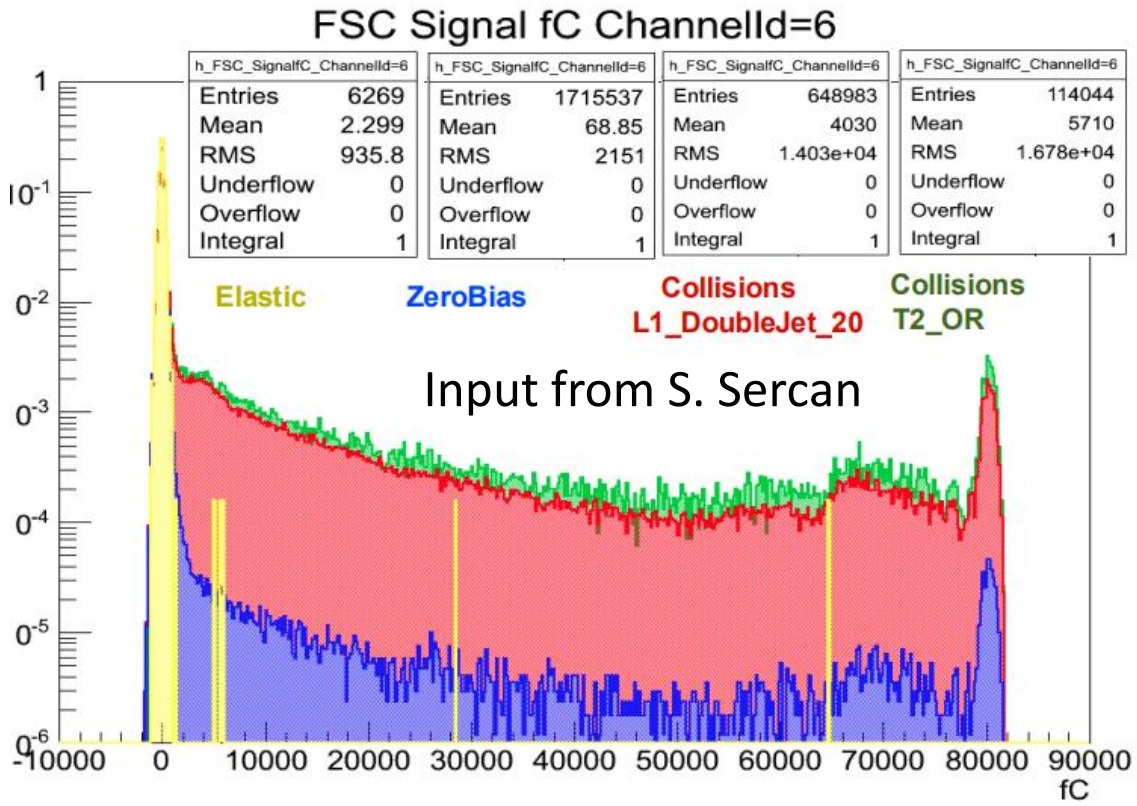
The HL-LHC phase is not only larger datasets, but also a more taggable, wider-acceptance experiment.

Backup

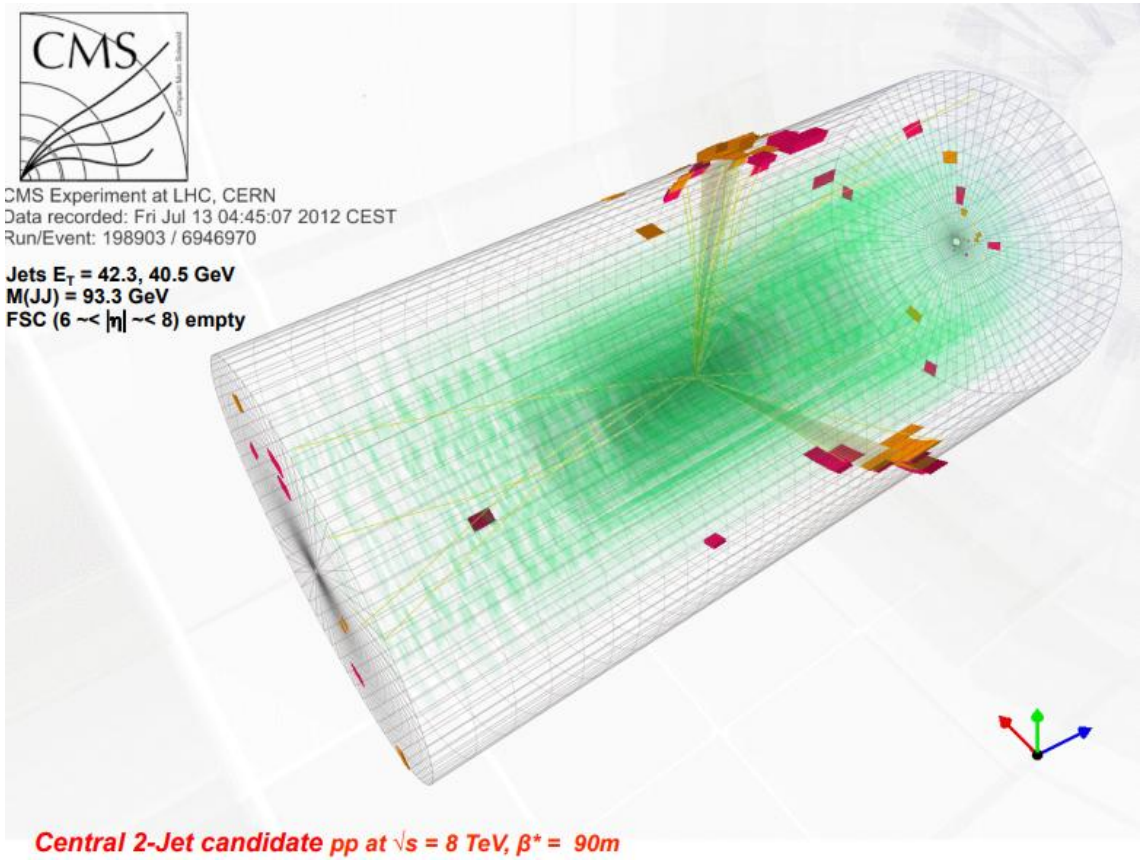
Forward Shower Counters

Forward Physics with FSC

- In Run 1 used to tag Rapidity Gaps



Input from S. Sercan



CMS-DP-2013-006