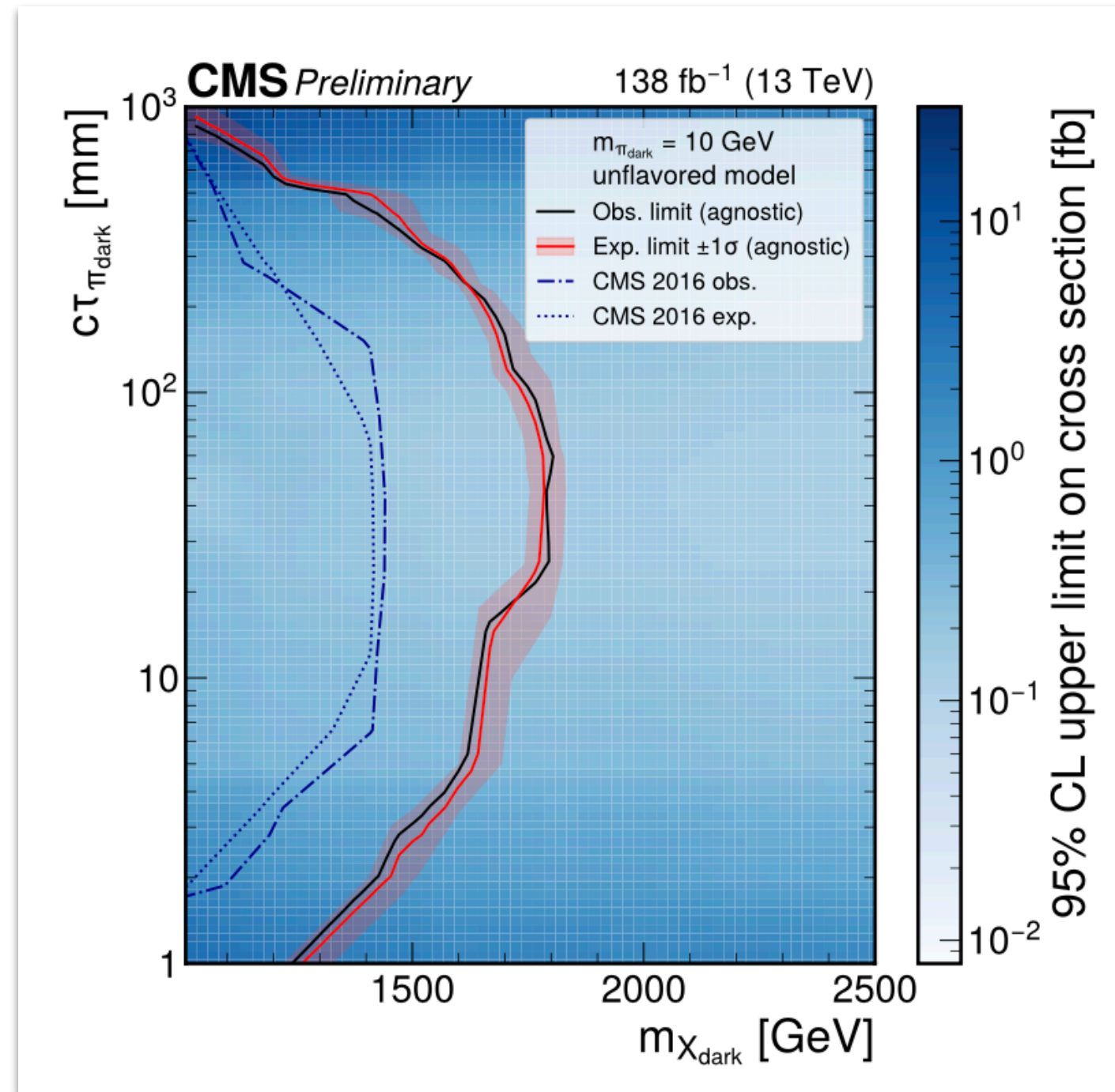


# CMS Status

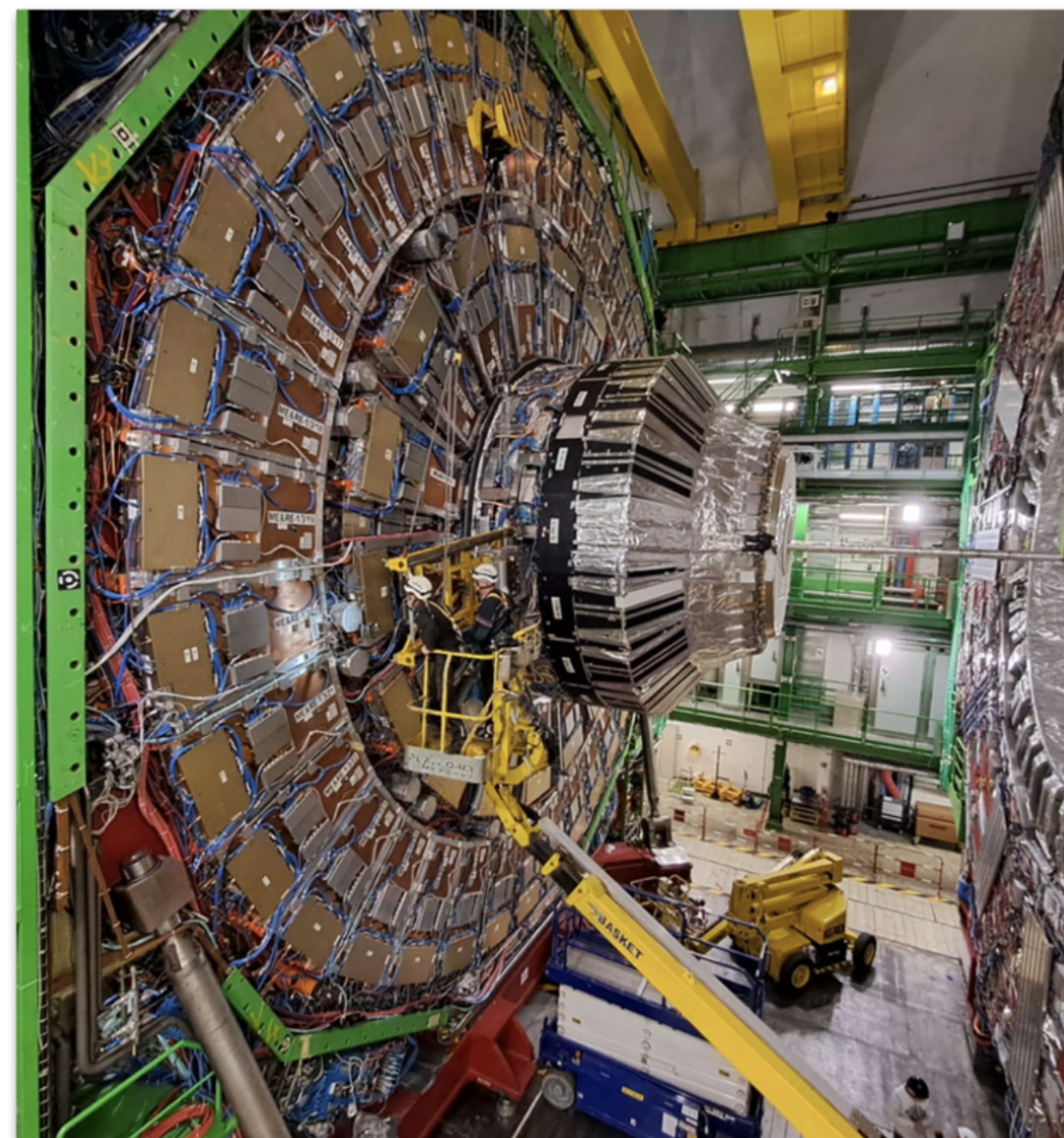
Matthew Nguyen  
LHCC Open Session  
February 28th, 2024



## Recent physics results

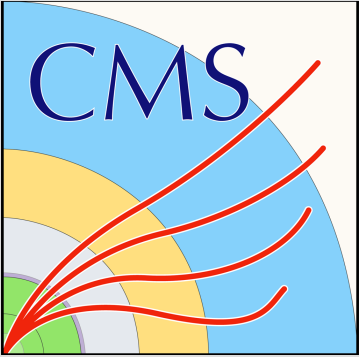


## Preparation for 2024



## Progress on Phase-2 upgrades

- L1-Trigger** <https://cds.cern.ch/record/2714892>
  - Tracks in L1-Trigger at 40 MHz
  - Particle Flow selection
  - 750 kHz L1 output
  - 40 MHz data scouting
- DAQ & High-Level Trigger** <https://cds.cern.ch/record/2759072>
  - Full optical readout
  - Heterogenous architecture
  - 60 TB/s event network
  - 7.5 kHz HLT output
- Barrel Calorimeters** <https://cds.cern.ch/record/2283187>
  - ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
  - ECAL and HCAL new Back-End boards
- Muon systems** <https://cds.cern.ch/record/2283189>
  - DT & CSC new FE/BE readout
  - RPC back-end electronics
  - New GEM/RPC 1.6 < η < 2.4
  - Extended coverage to η ≈ 3
- Calorimeter Endcap** <https://cds.cern.ch/record/2293646>
  - 3D showers and precise timing
  - Si, Scint+SIPM in Pb/W-SS
- Tracker** <https://cds.cern.ch/record/2272264>
  - Si-Strip and Pixels increased granularity
  - Design for tracking in L1-Trigger
  - Extended coverage to η ≈ 3.8
- MIP Timing Detector** <https://cds.cern.ch/record/2667167>
  - Precision timing with:
    - Barrel layer: Crystals + SIPMs
    - Endcap layer: Low Gain Avalanche Diodes
- Beam Radiation Instr. and Luminosity** <http://cds.cern.ch/record/2759074>
  - Beam abort & timing
  - Beam-induced background
  - Bunch-by-bunch luminosity: 1% offline, 2% online
  - Neutron and mixed-field radiation monitors



# New results since last LHCC

LUM-22-001 **Luminosity** measurement in pp collisions at 13.6 TeV in 2022

EXO-22-022 **Search** for new resonances decaying to pairs of highly merged photons

EXO-23-002 **Search** for soft unclustered energy patterns in proton-proton collisions at 13 TeV

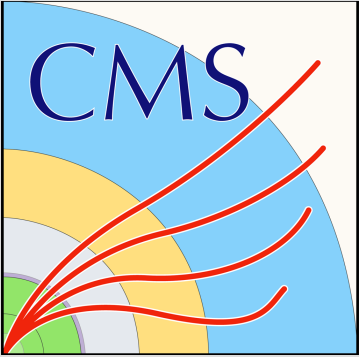
EXO-22-015 **Search** for new physics with emerging jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV

TOP-22-003 **Search** for baryon number violation in top production and decay

HIN-23-013 **Observation** of double- $J/\psi$  meson production in pPb collisions at 8.16 TeV

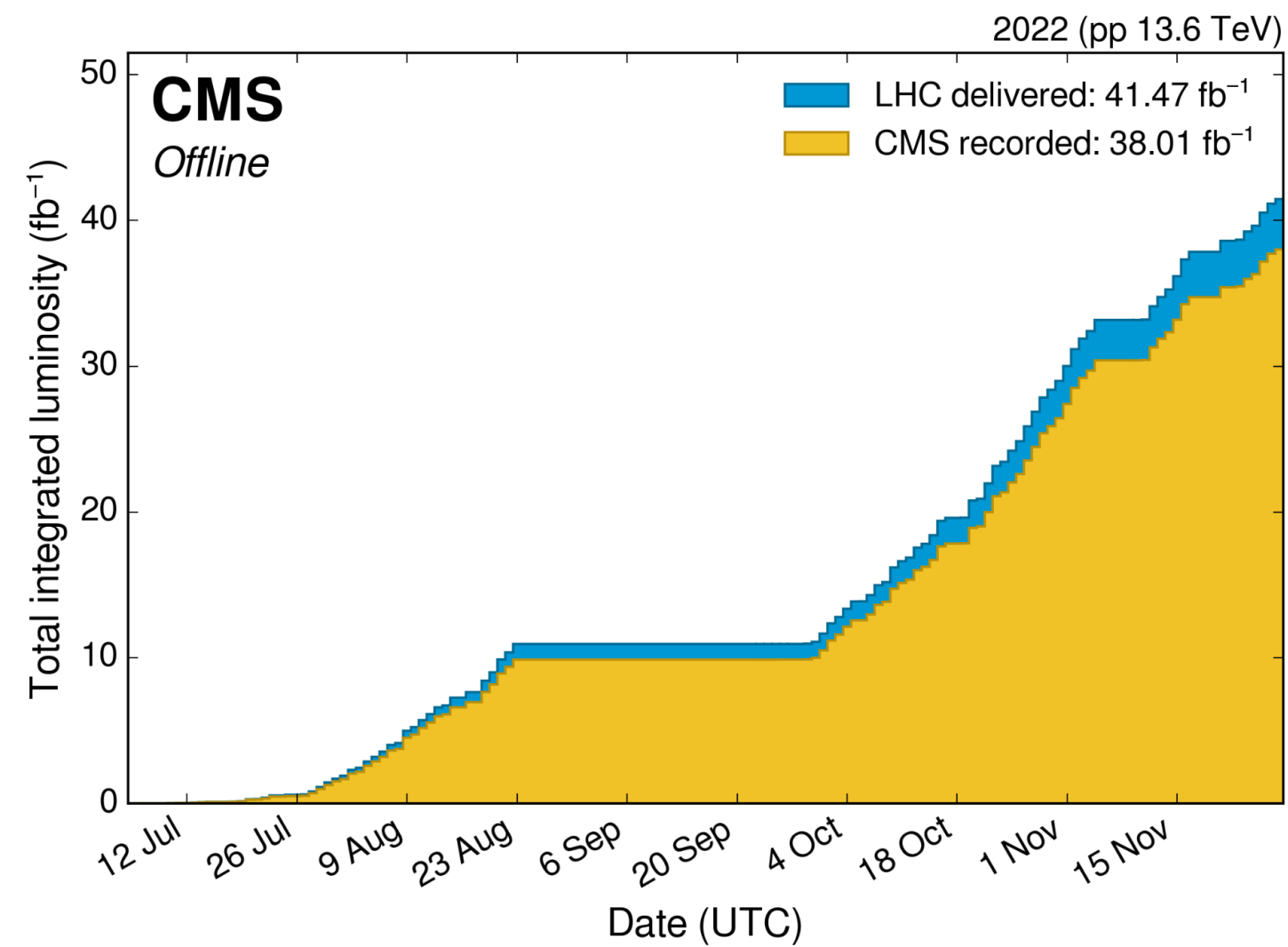
BPH-23-002 **Observation** of the  $\Xi_b^- \rightarrow \psi(2S) \Xi^-$  decay and studies of  $\Xi_b^{*0}$  baryon

+ many more coming from spring conferences

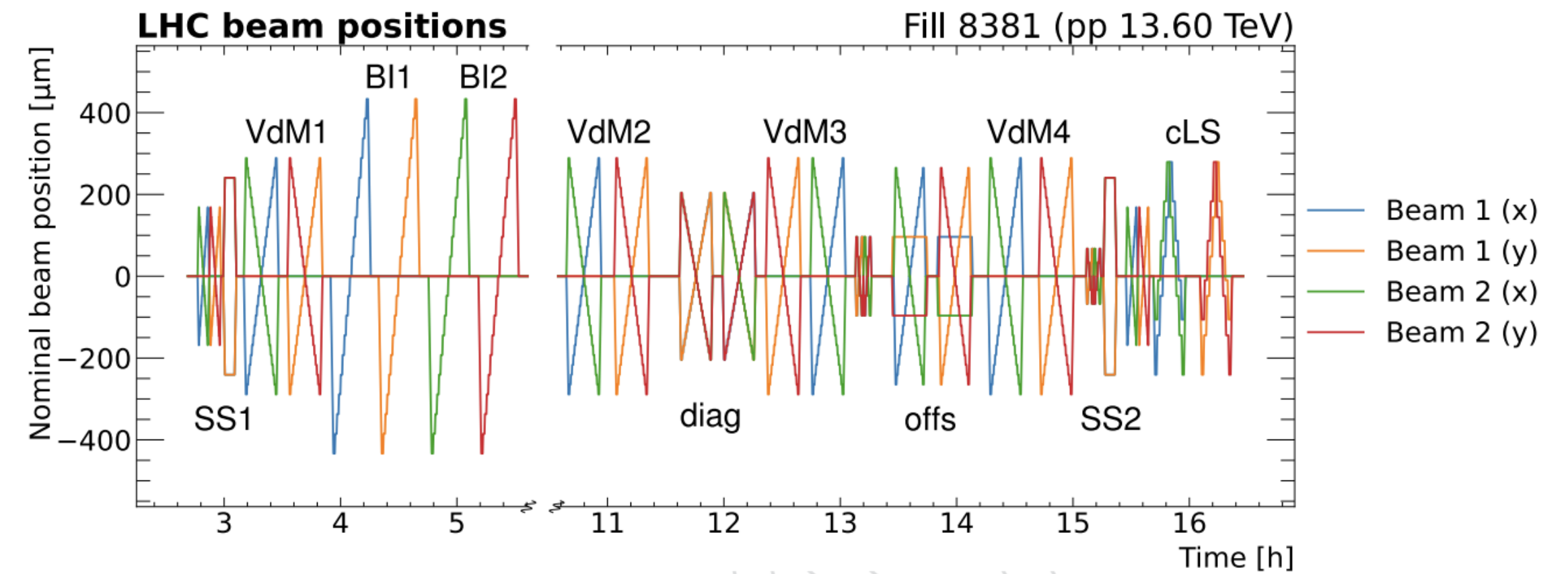


# Luminosity measurement in pp collisions at 13.6 TeV in 2022

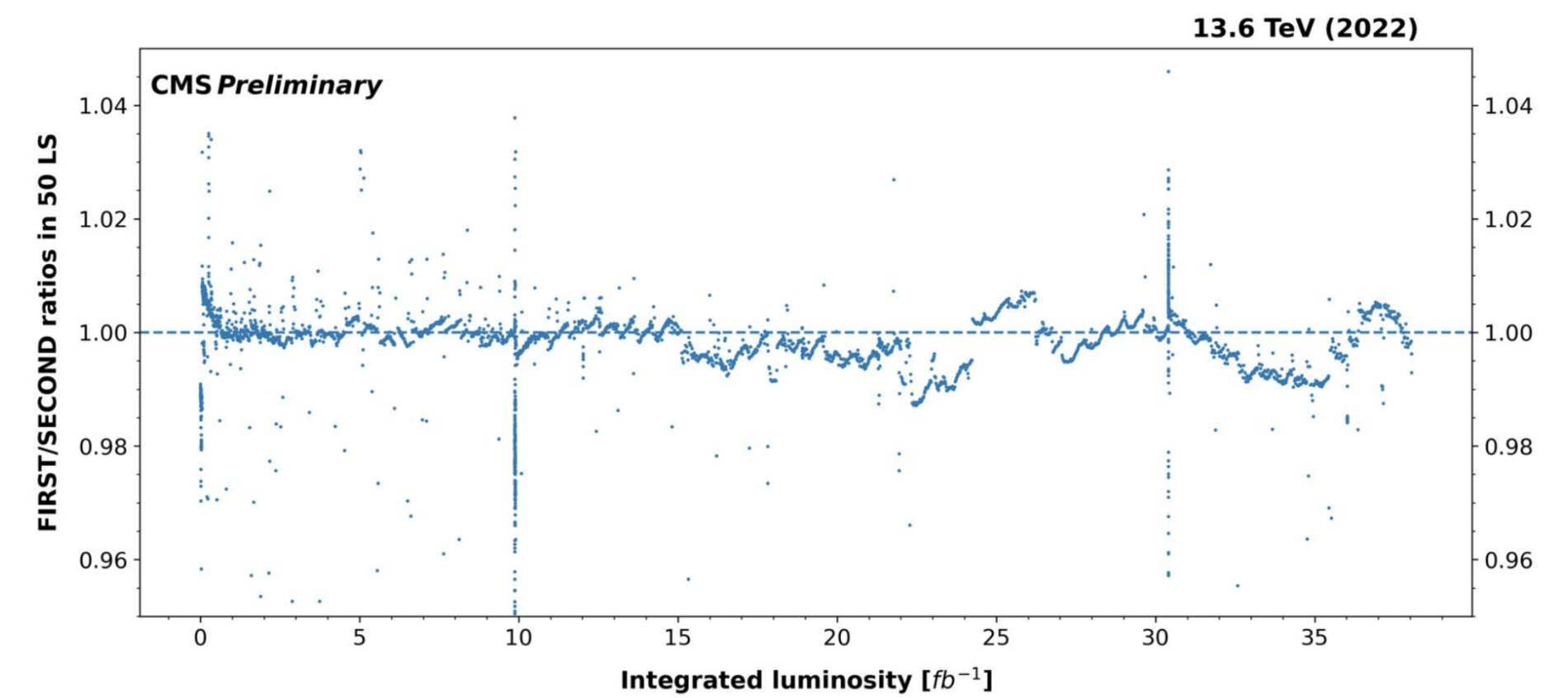
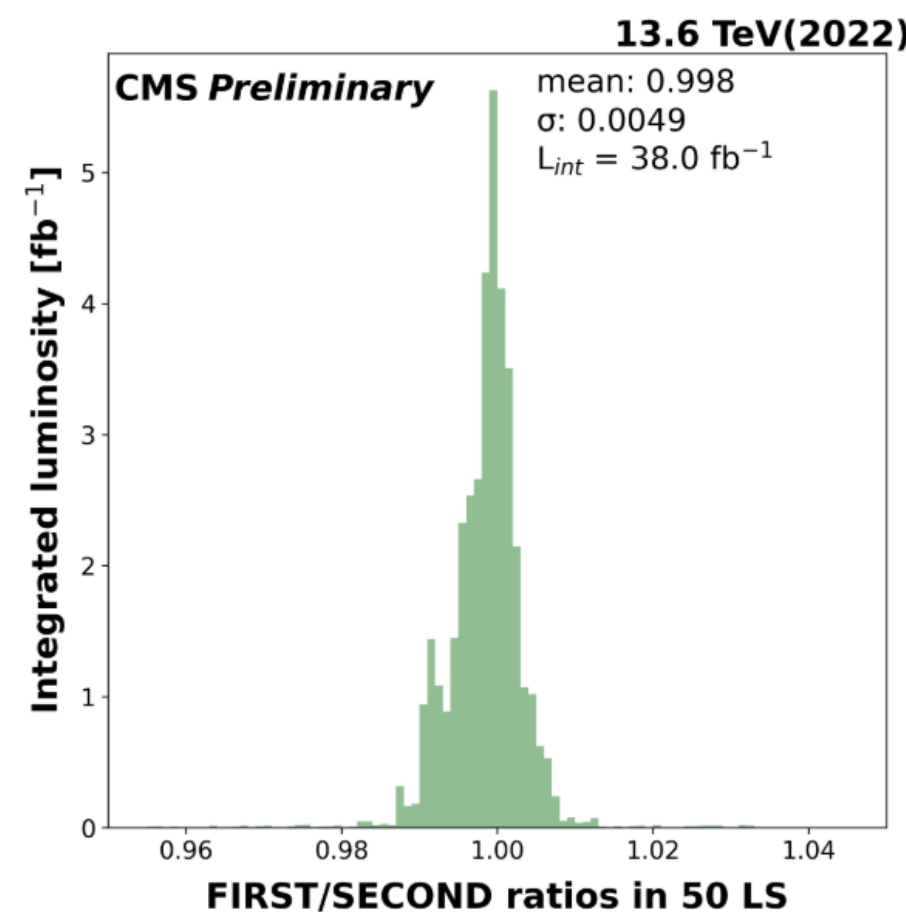
CMS-PAS-LUM-22-001



Extensive Van der Meer scan program + novel non-factorization analyses



Source	Correction (%)	Uncertainty (%)
<b>Calibration</b>		
Beam current	3.4	0.2
Ghost and satellite charges	0.4	0.2
Orbit drift	0.1	0.1
Residual beam positions	0.0	0.3
Beam-beam effects	1.0	0.4
Length scale	-1.0	0.1
Factorization bias	1.0	0.8
Scan-to-scan variation	-	0.5
Bunch-to-bunch variation	-	0.1
Cross-detector consistency	-	0.4
<b>Integration</b>		
HFET OOT pileup corrections		0.2
Cross-detector stability		0.5
Cross-detector linearity		0.5
<b>Total</b>		
Calibration		1.2
Integration		0.8
<b>Total</b>		<b>1.4</b>



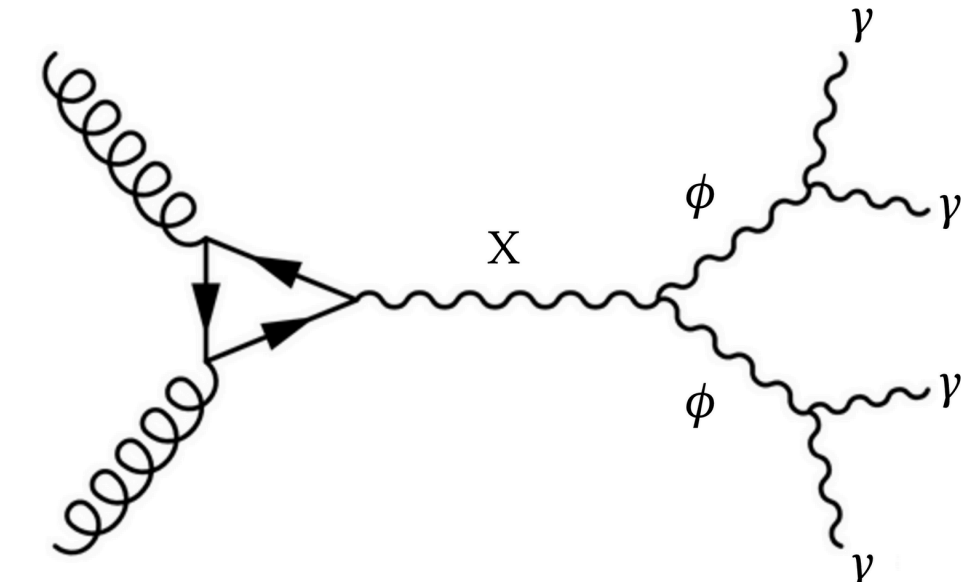
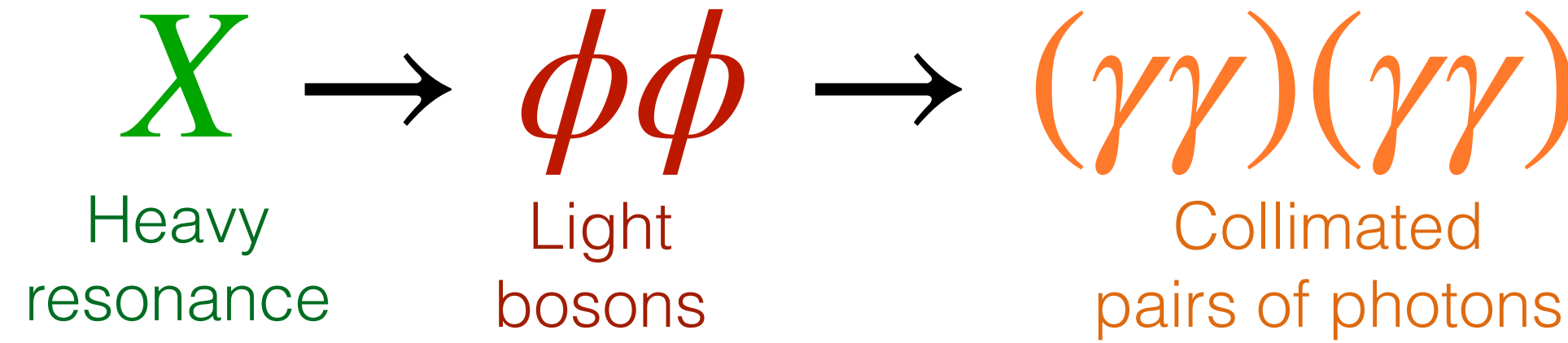
**1.4% uncertainty**

Cross-detector stability (0.5%) & co-linearity (0.5%) with several luminometers

# Search for new resonances decaying to pairs of highly merged photons

CMS-PAS-EXO-22-022

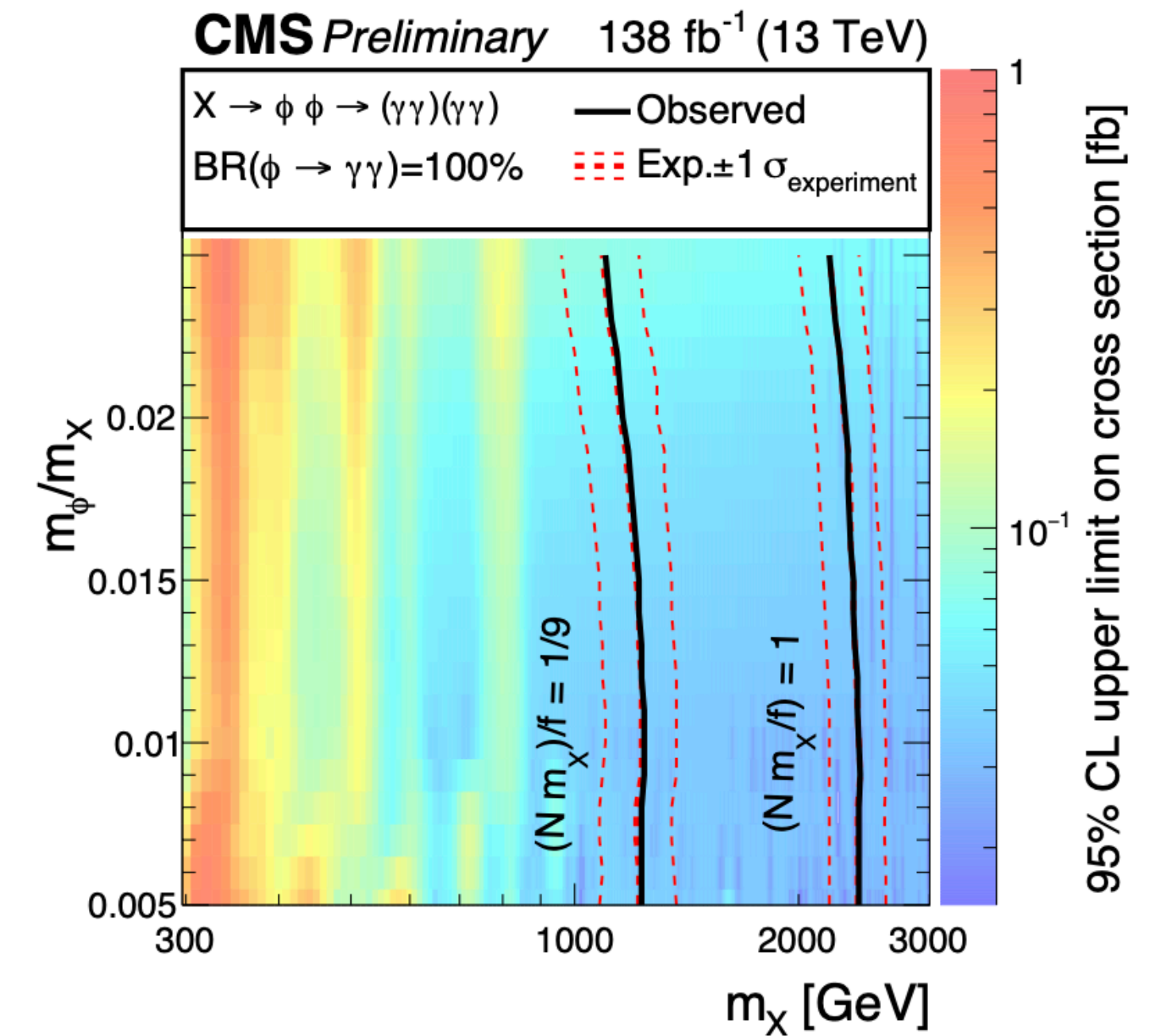
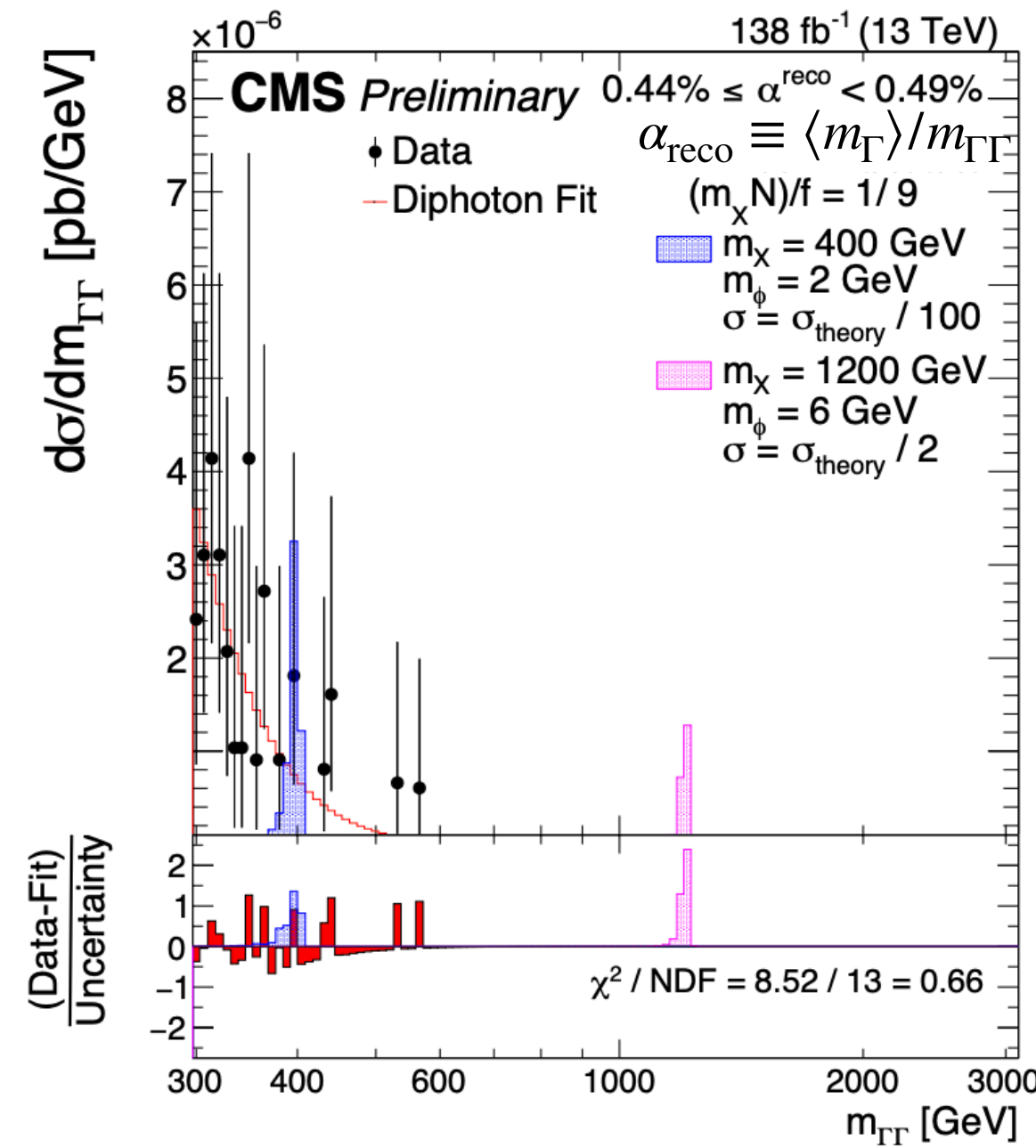
Extended Higgs sectors predicted by many BSM theories with spin-0 particles  $X$  and  $\phi$  with unknown masses



Probe range of  $m_X / m_\phi$  where photons from  $\phi$  overlap in ECAL

Merged diphoton candidates ( $\Gamma$ ) identified & characterized w/ CNNs

ML model validated on  $\eta \rightarrow \gamma\gamma$

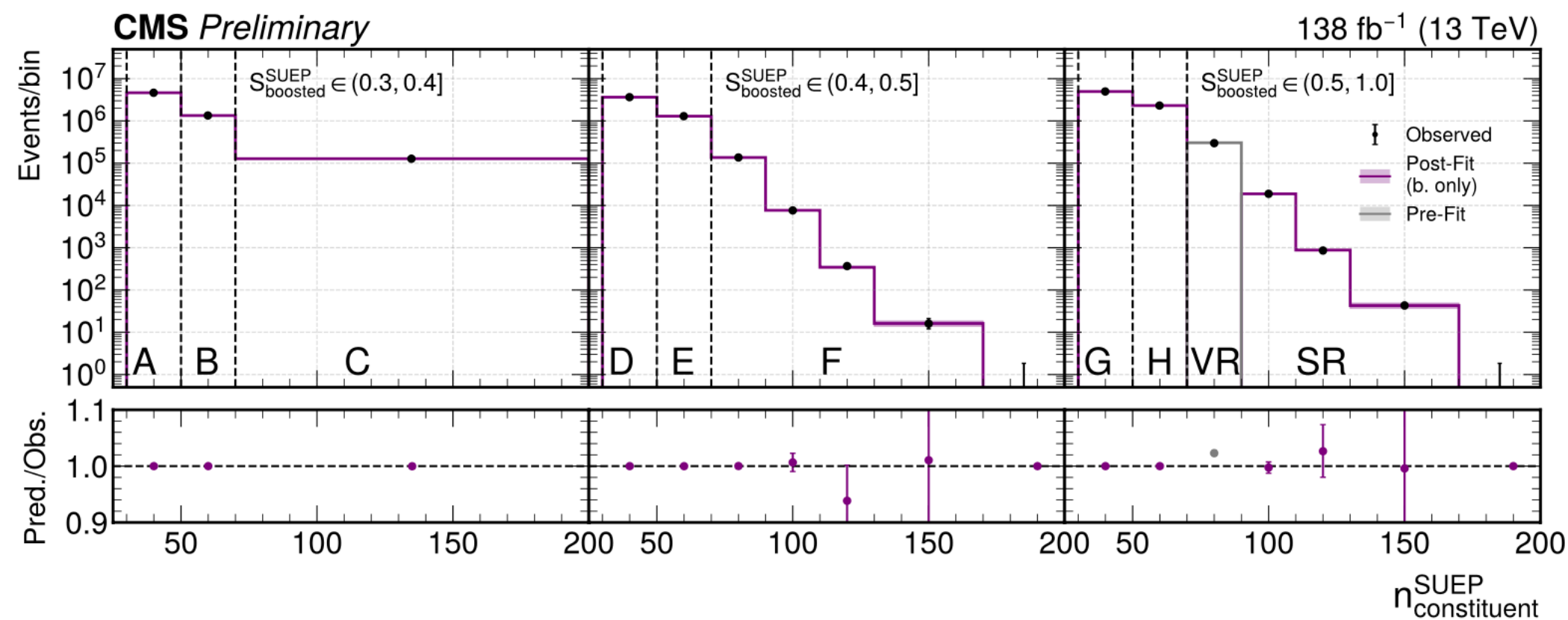
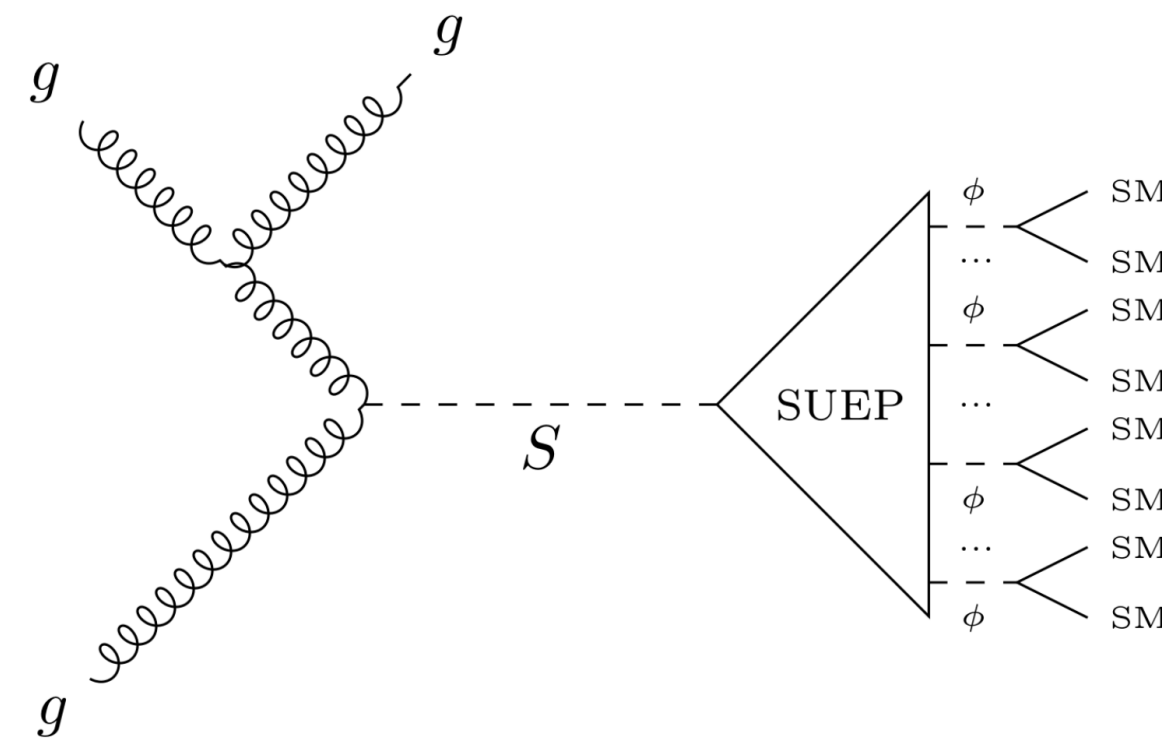


Most sensitive search of its kind at the LHC

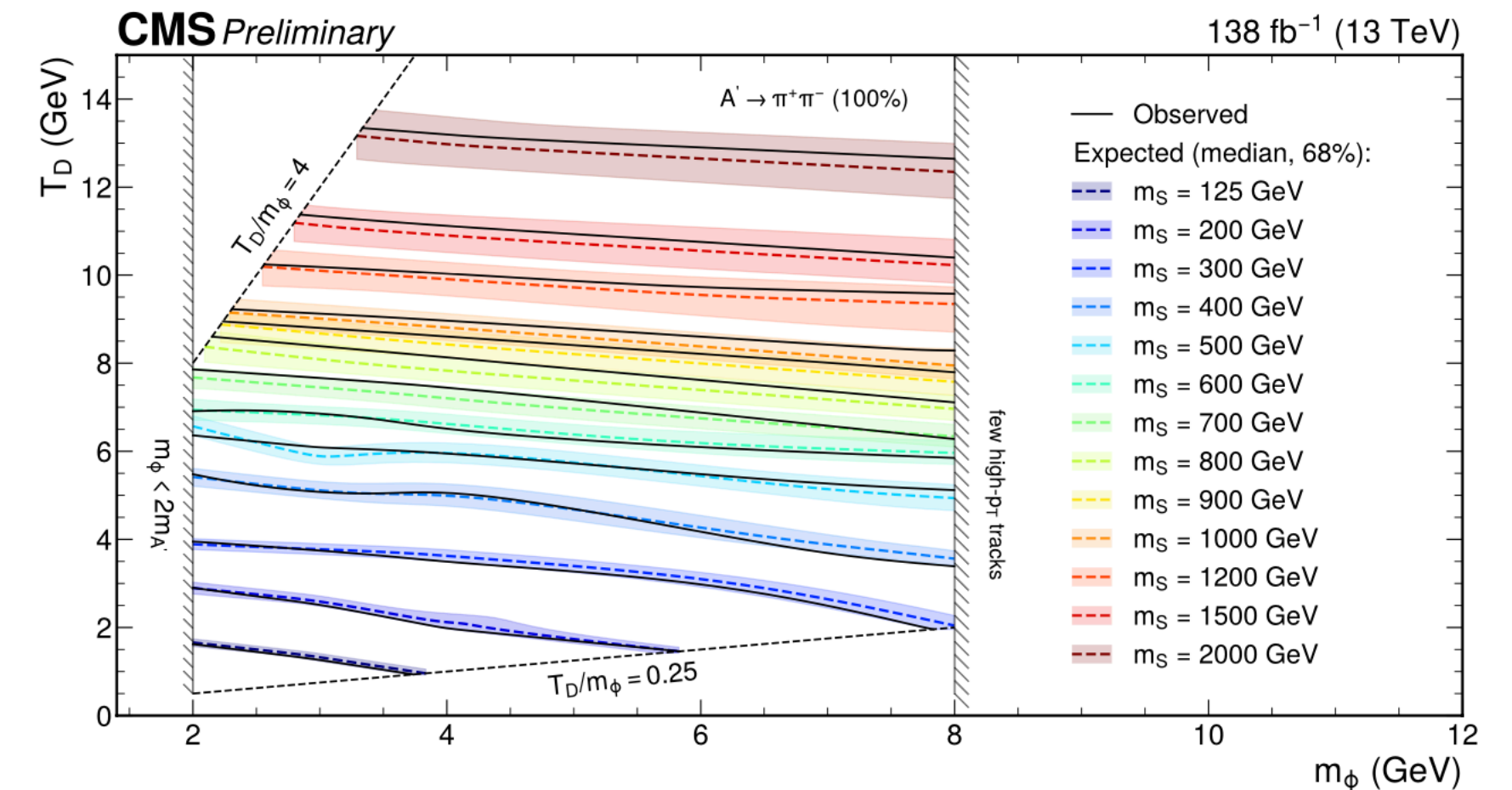
# Search for soft unclustered energy patterns in pp collisions

Hidden Valley models include a dark sector that extends the SM via new non-Abelian gauge group “Dark QCD” w/ large coupling above its confinement scale → isotropic particle production  
**Soft Unclustered Energy Patterns** = high multiplicity, isotropic, low  $p_T$  tracks final state

SUEP production by gluon fusion  
 Initial State Radiation → wide jet



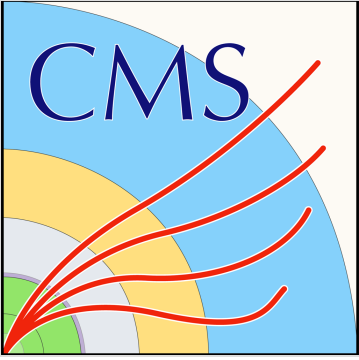
QCD background subtracted using track multiplicity & sphericity in an extended ABCD method



Limits set in  $T_D - m_S - m_\phi - m_{A'}$  parameter space

- $T_D$  depends on dark confinement scale
- $S$  = mediator particle
- $\phi$  = dark meson
- $A'$  = dark photon

First dedicated SUEP search at the LHC

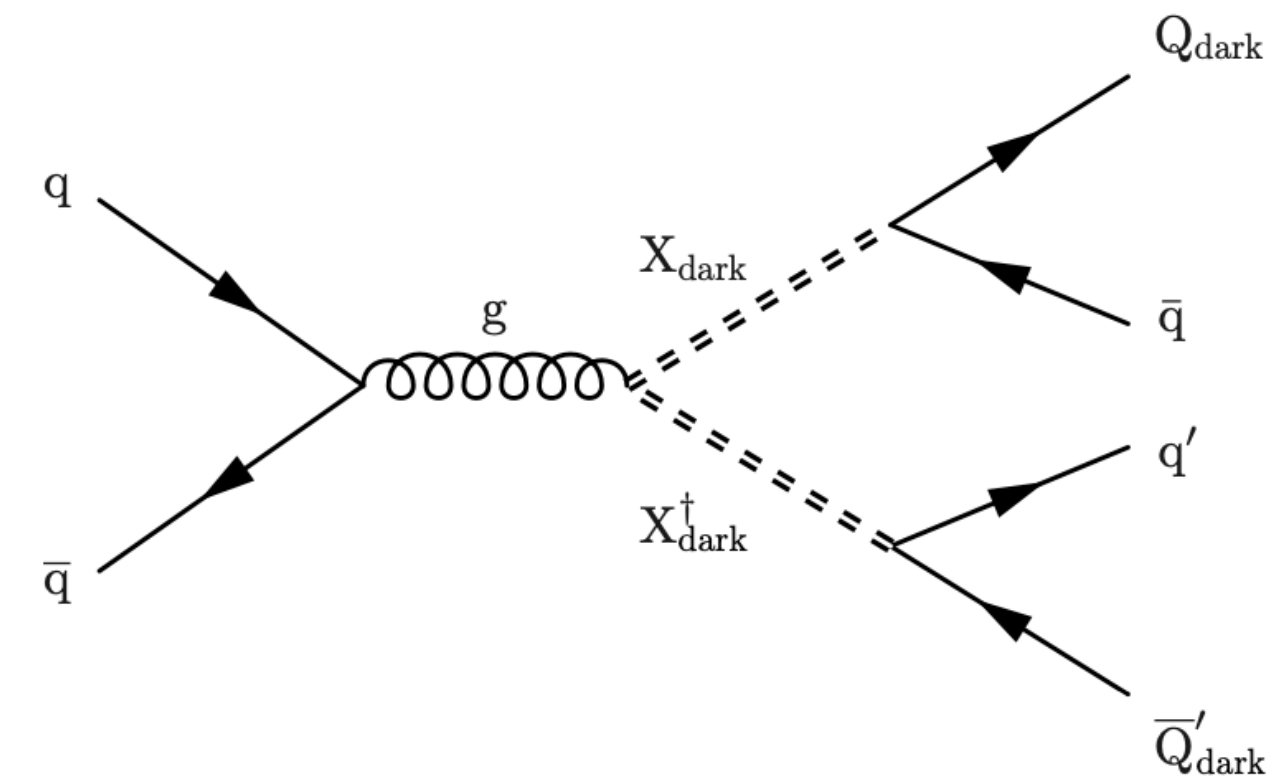


# Search for new physics with emerging jets in pp collisions

CMS-PAS-EXO-22-015

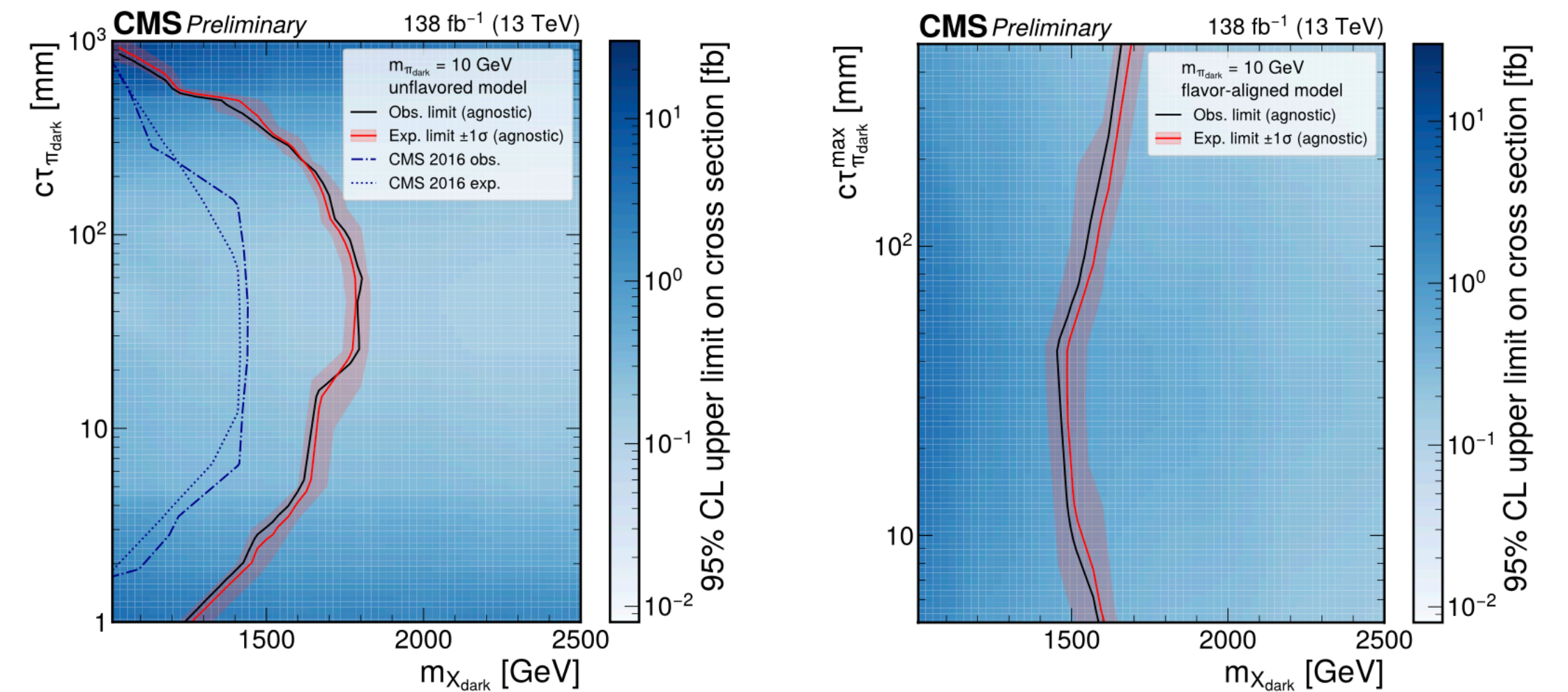
In this dark QCD scenario the mediator ( $X_{\text{dark}}$ ) decays to a SM quark & a dark quark ( $Q_{\text{dark}}$ )

Dark hadrons tend to decay into b quarks giving rise to **emerging jets** containing a large # of displaced vertices

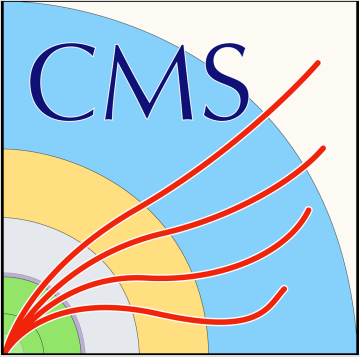


Limits in dark mass vs dark pion lifetime:

Limits set for “unflavored” model where mediator couples only to one quark flavor and “flavor-aligned” model where three dark flavors couple to SM down-type quarks (d, s, b)



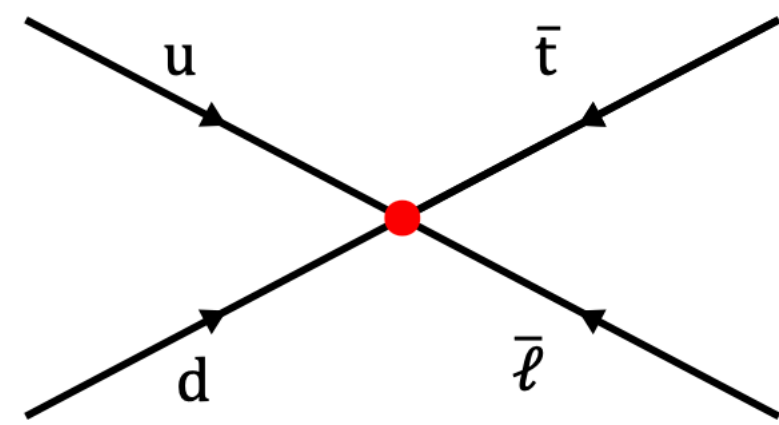
Improved limits for unflavored scenario & first direct exclusion of flavor aligned scenario



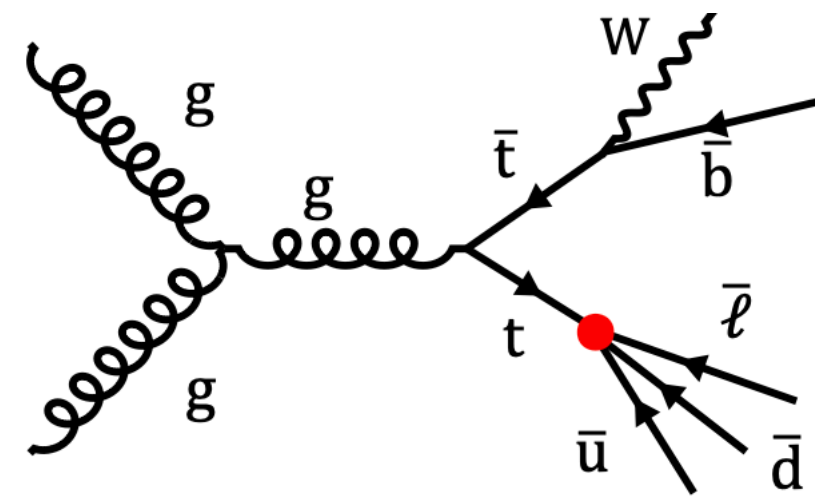
# Search for Baryon Number Violation (BNV) in top production & decay

TOP-22-003 to appear on arXiv

LHC provides highest sensitivity for BNV processes involving top quarks  
Looking at dilepton final state: two oppositely charged leptons (e or  $\mu$ ) + one b-jet

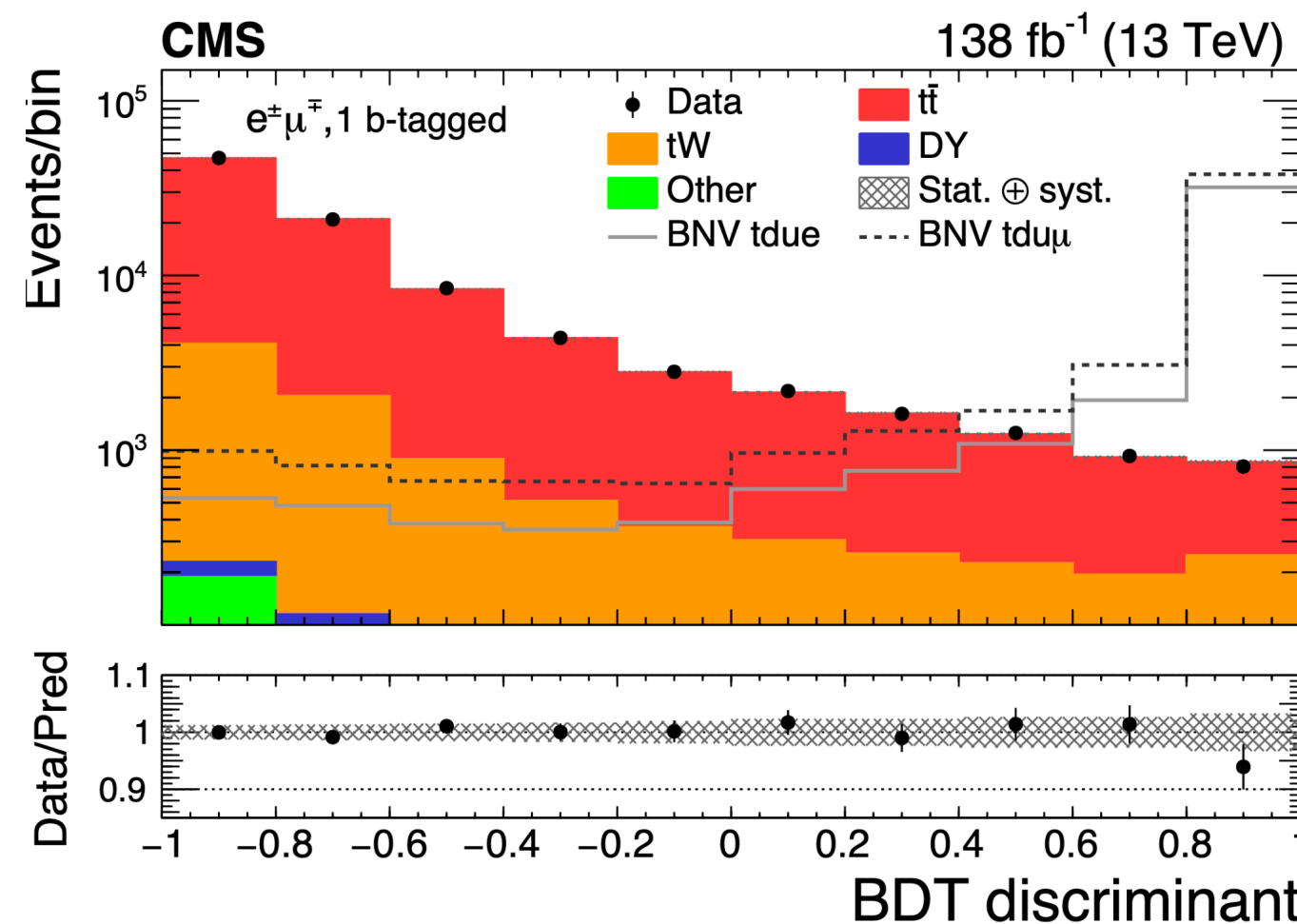


single top BNV production

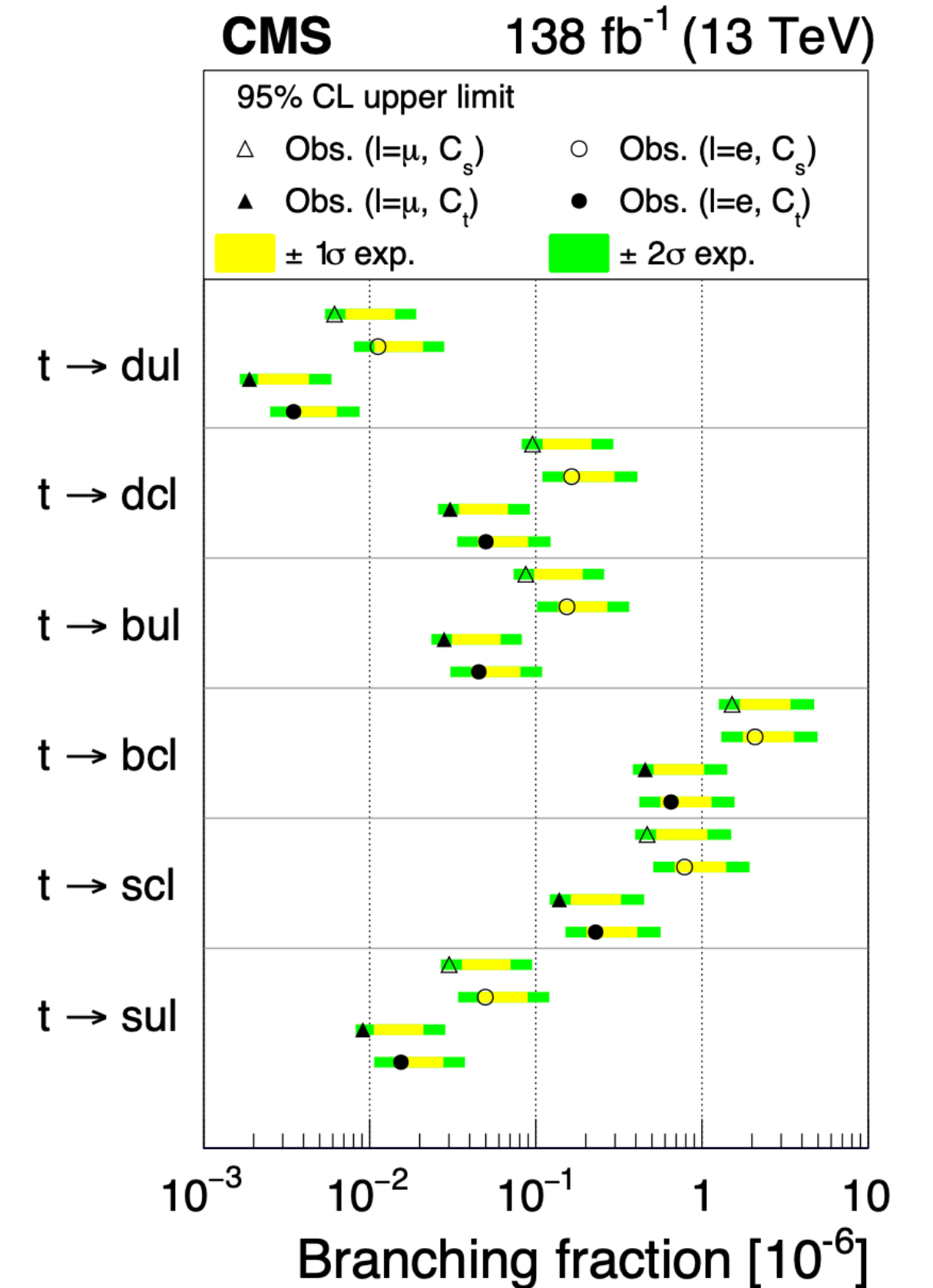


top quark BNV decay

Upper limits on top quark BNV decays



BDT trained using kinematics of leptons and t quark system

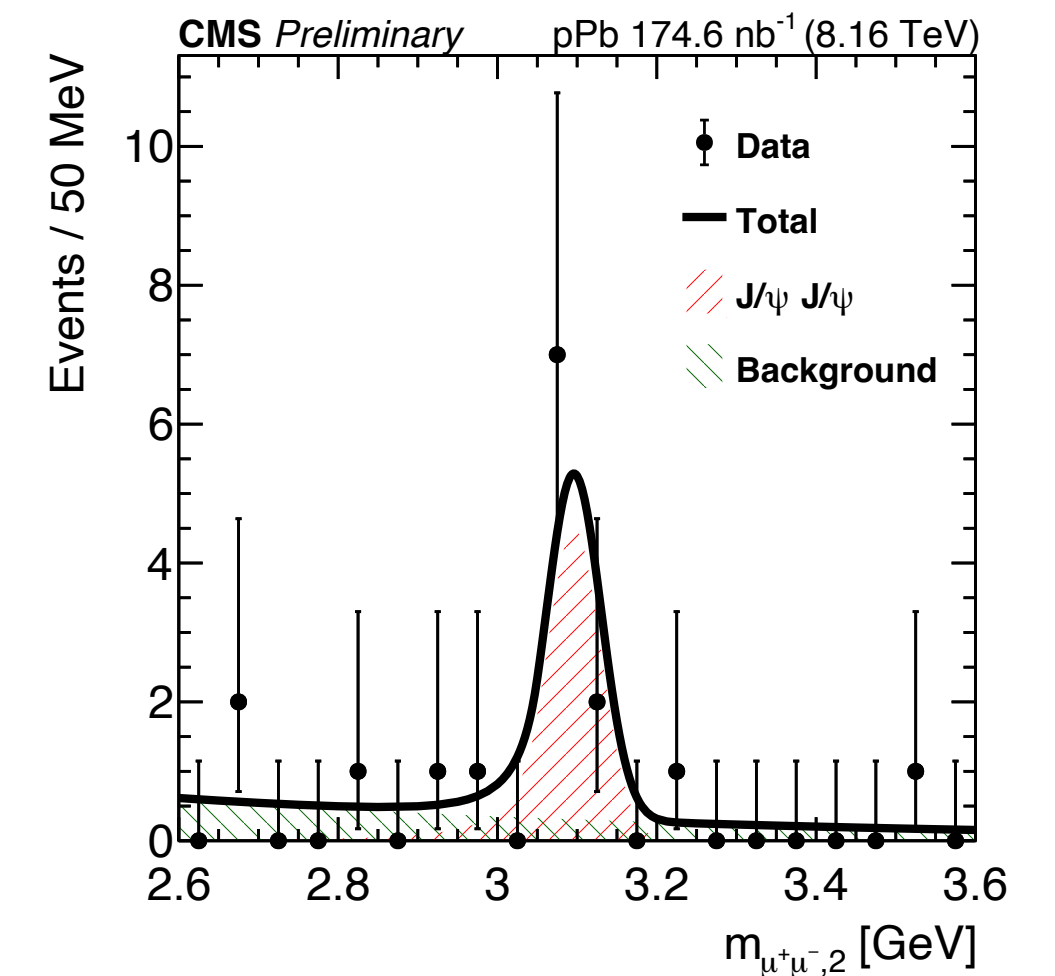
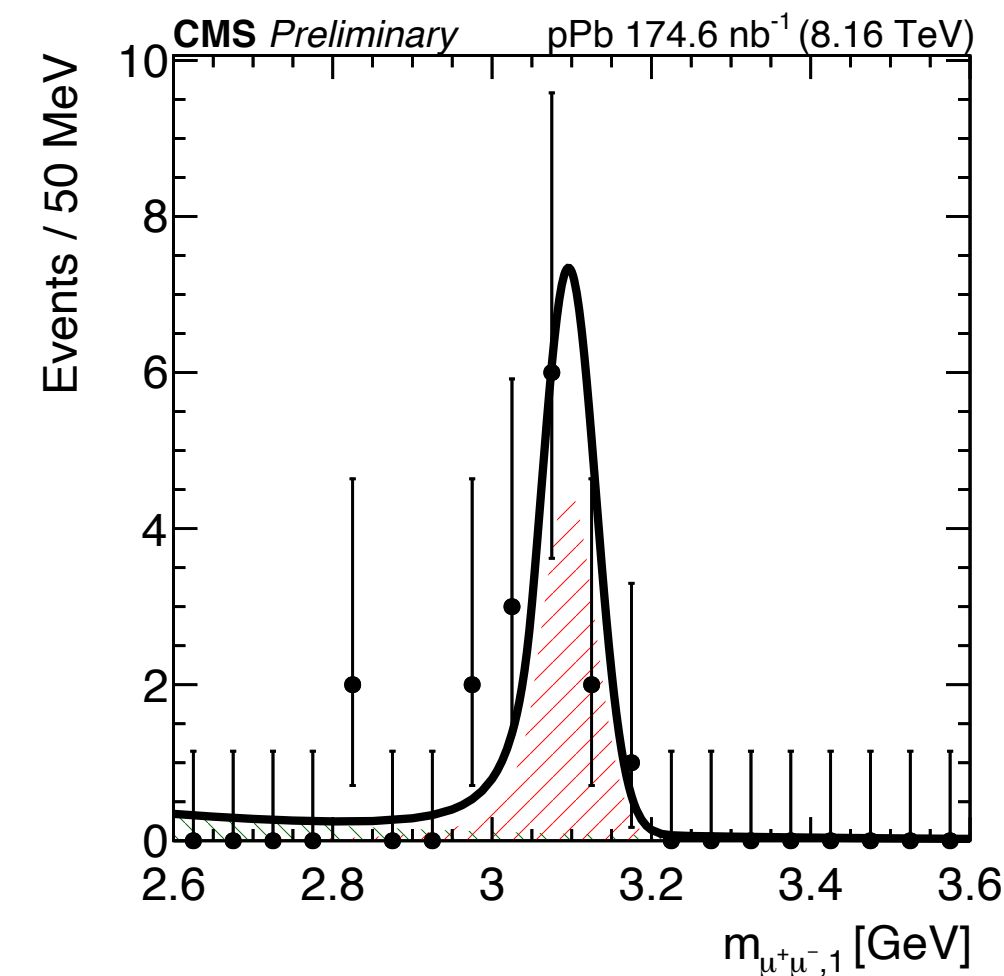
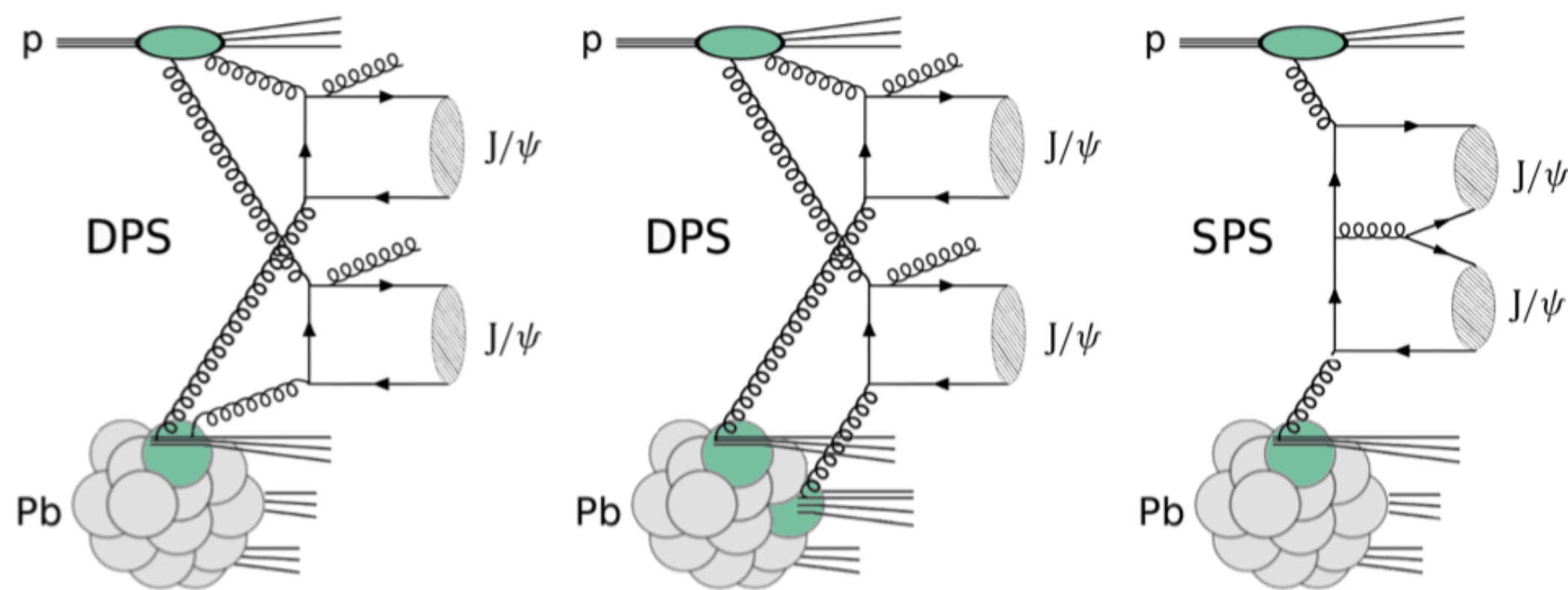


Improves previous top BNV bounds by orders of magnitude

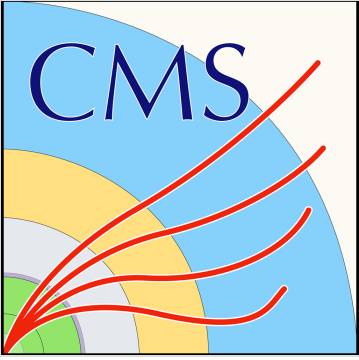


# Observation of double- $J/\psi$ production in pPb collisions

Double Parton Scattering (DPS) of great interest, e.g., to probe flavor correlations in the parton distributions  
Should be enhanced in pA by large parton density & probe impact parameter dependence of nuclear PDFs



Upper limit on DPS corresponding to  $\sigma_{\text{eff}} > 1 \text{ mb}$  (95% CL)

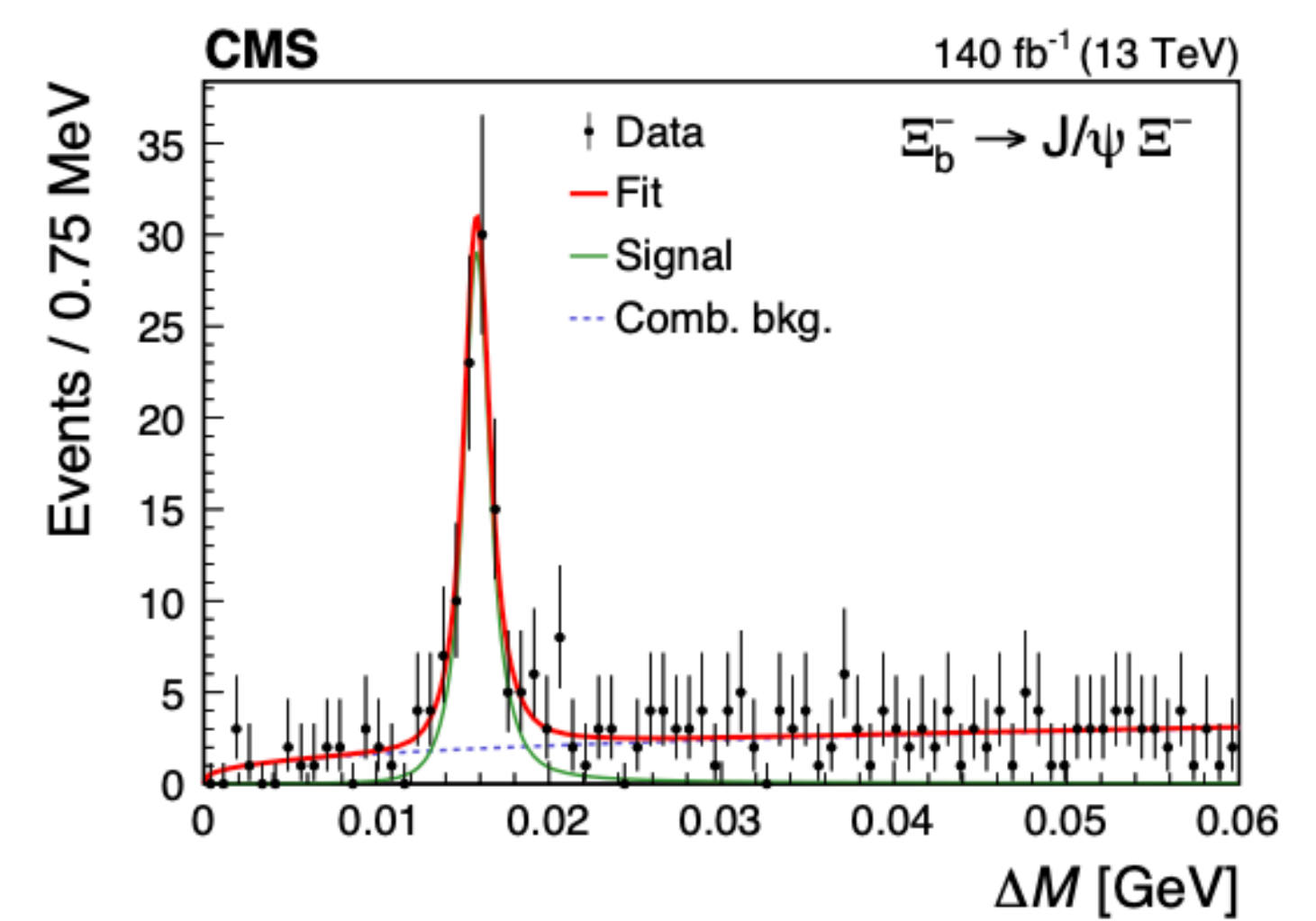
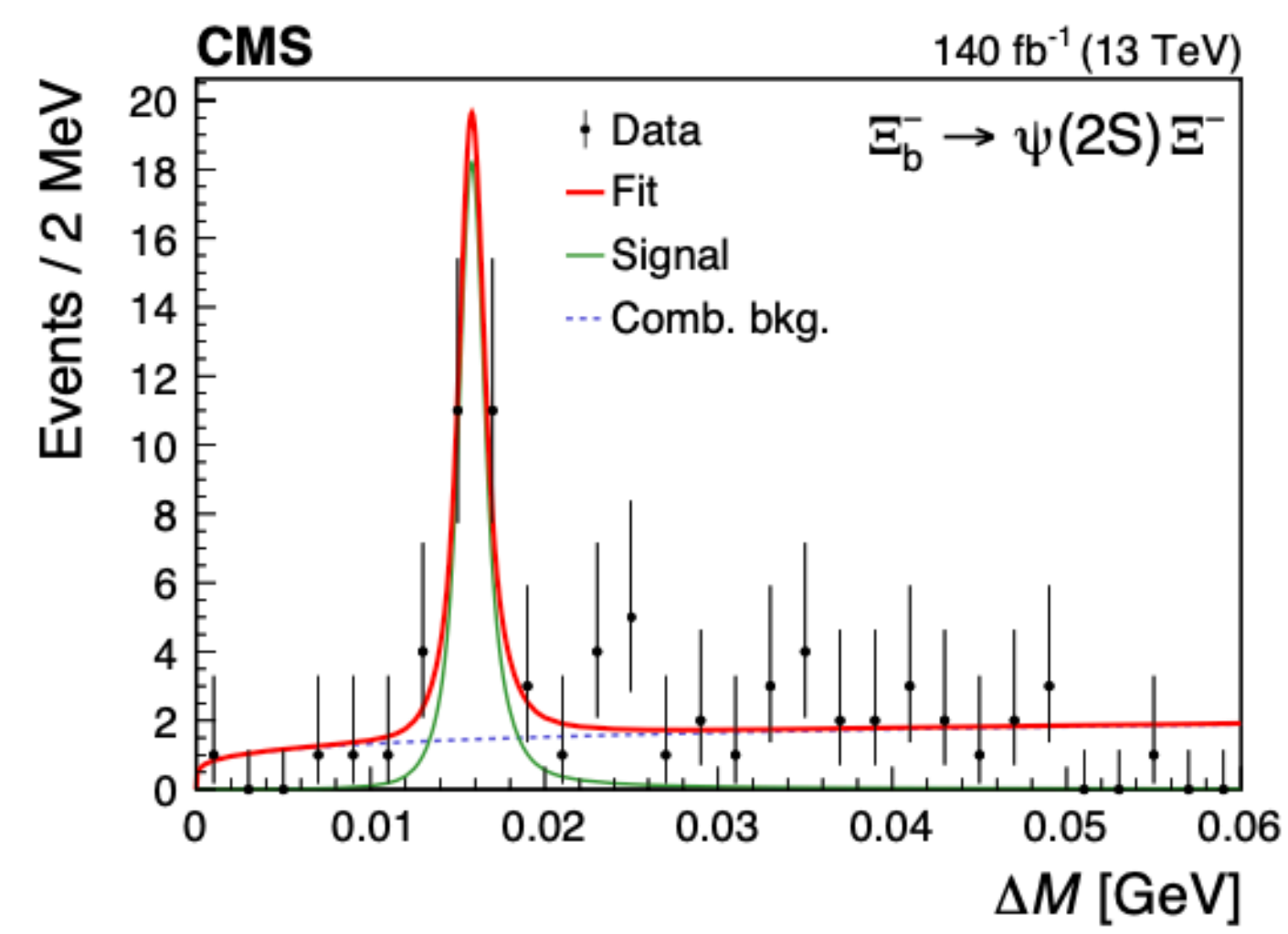
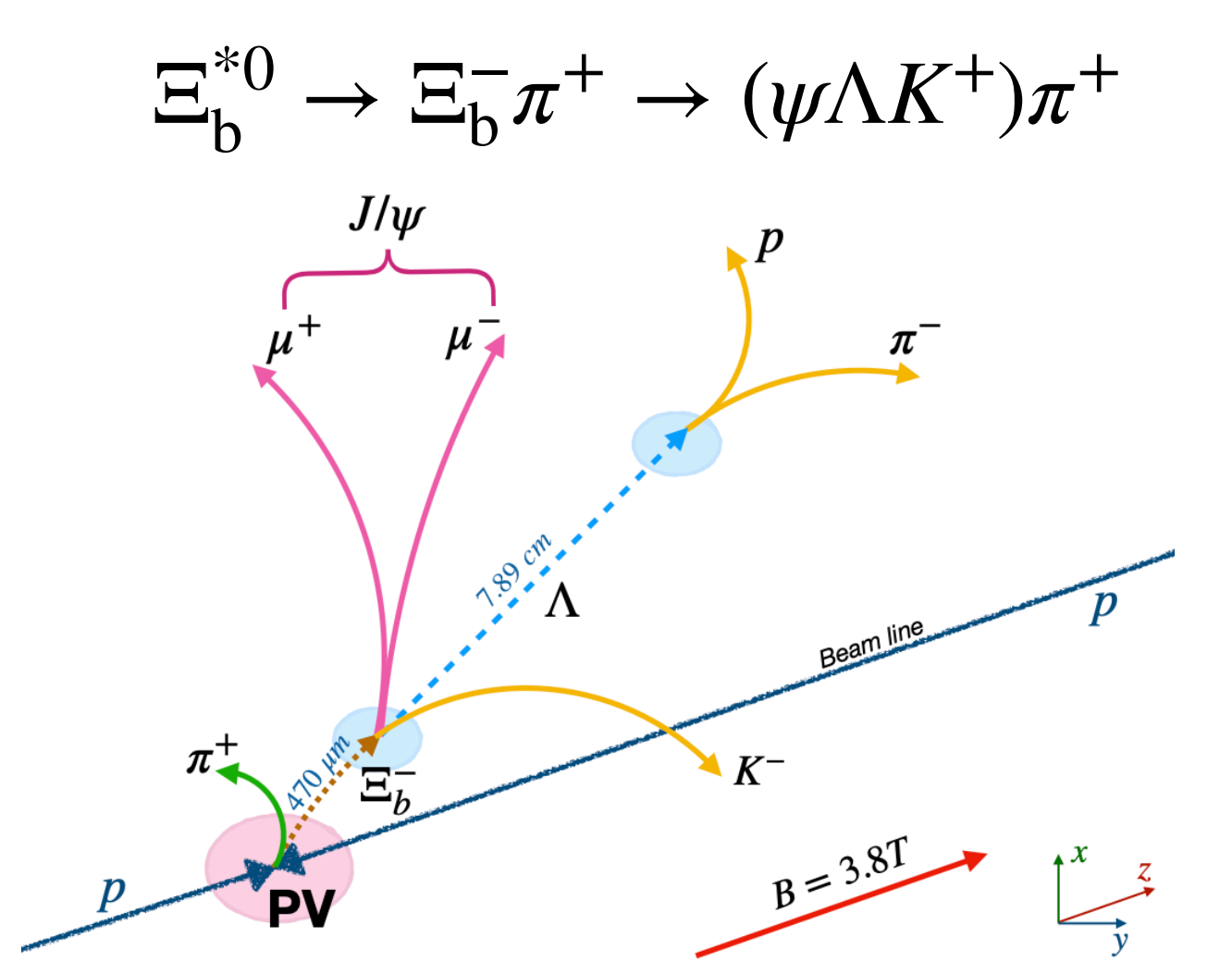
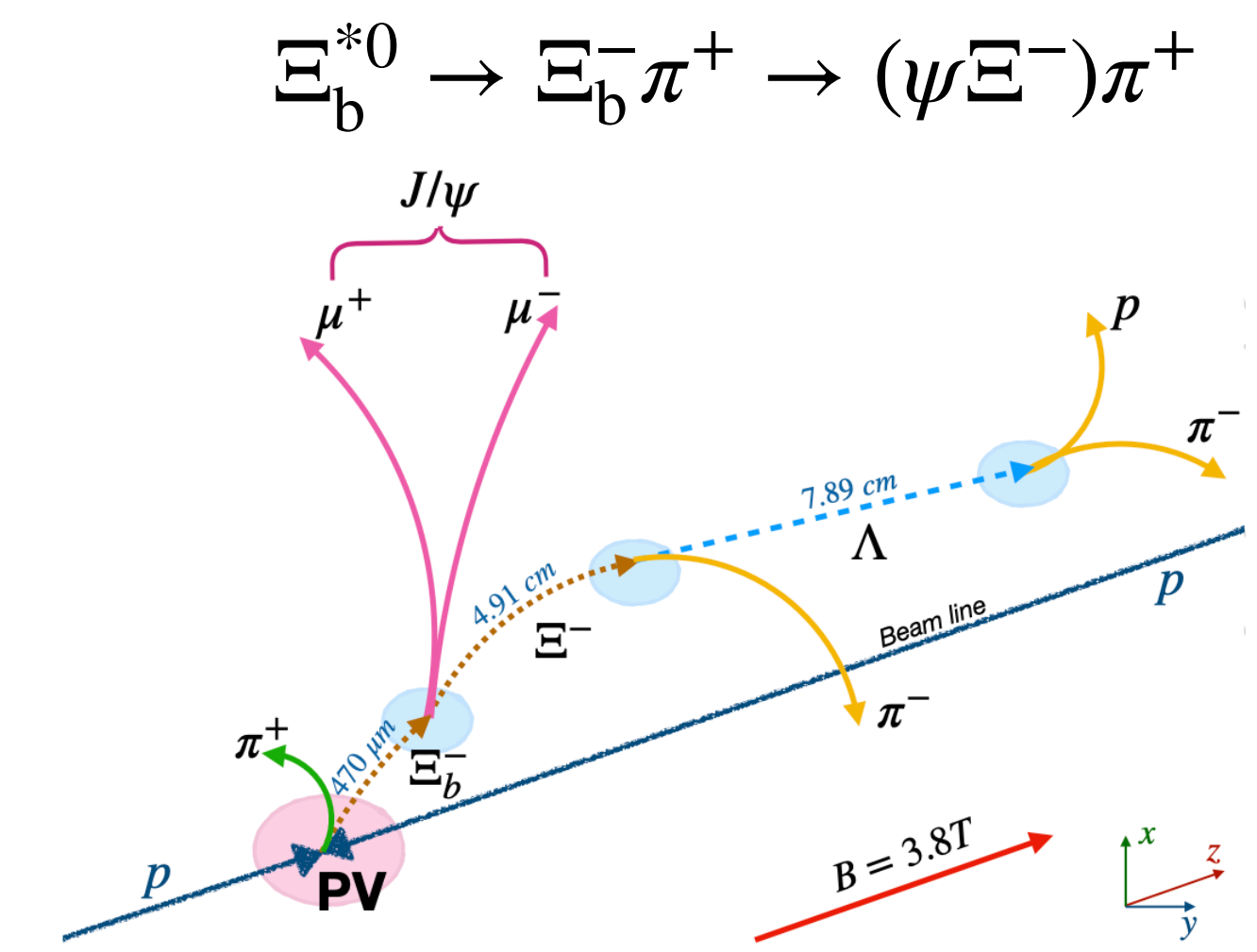


# Observation of $\Xi_b^- \rightarrow \psi(2S) \Xi^-$ decay & studies of $\Xi_b^{*0}$ baryon

[arxiv:2402.17738](https://arxiv.org/abs/2402.17738)

$\Xi_b^-$  branching fraction compared in  $\psi(2S)$  &  $J/\psi$  channels

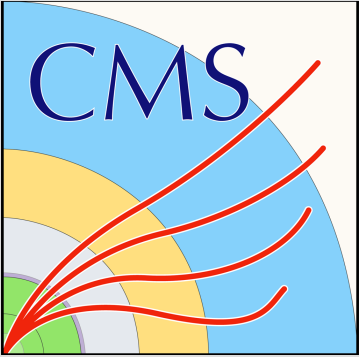
$$R = \frac{\mathcal{B}(\Xi_b^- \rightarrow \psi(2S) \Xi^-)}{\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Xi^-)} = 0.84 \pm 0.21 \text{ (stat)} \pm 0.10 \text{ (syst)} \pm 0.02 \text{ (}\mathcal{B}\text{)}$$



$\Xi_b^{*0}$  properties (mass & width) measured

$$M(\Xi_b^{*0}) - M(\Xi_b^-) - m^{\text{PDG}}(\pi^\pm) = 15.810 \pm 0.077 \text{ (stat)} \pm 0.032 \text{ (syst)} \text{ MeV}$$

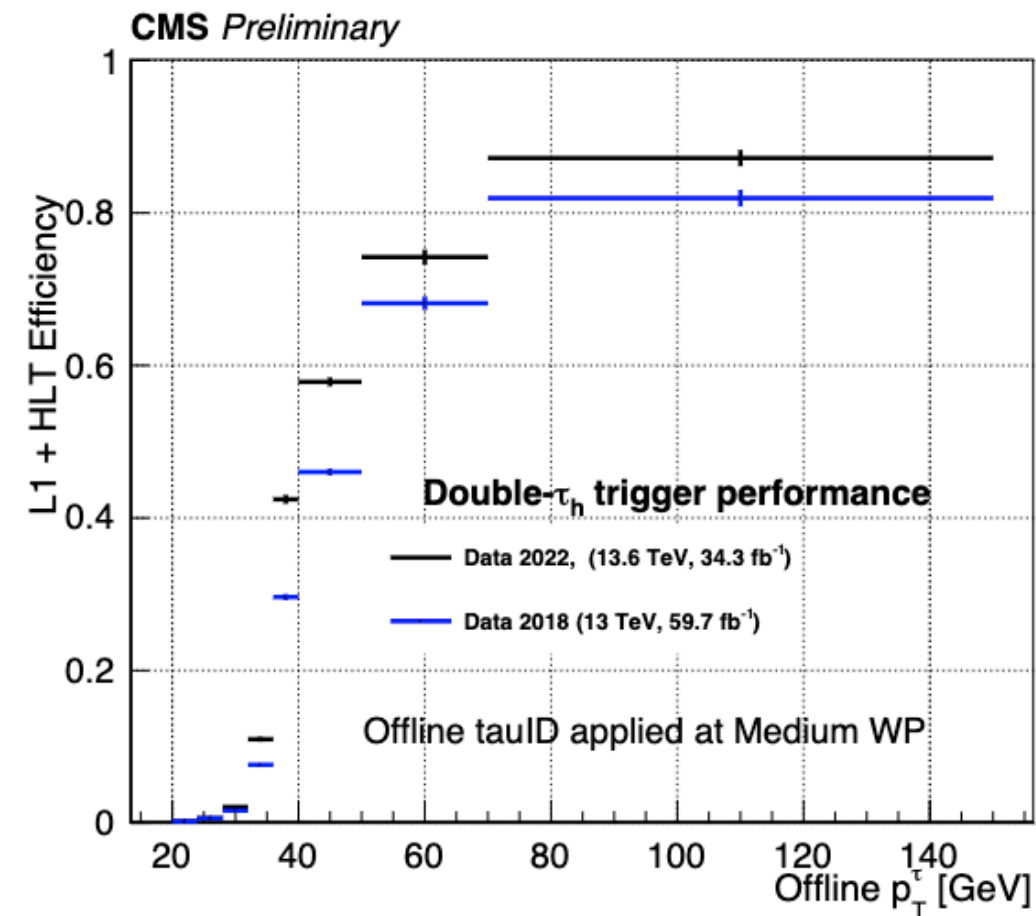
$$\Gamma(\Xi_b^{*0}) = 0.87 \pm 0.21 \text{ (stat)} \pm 0.16 \text{ (syst)} \text{ MeV}$$



# Run 3 performance plots

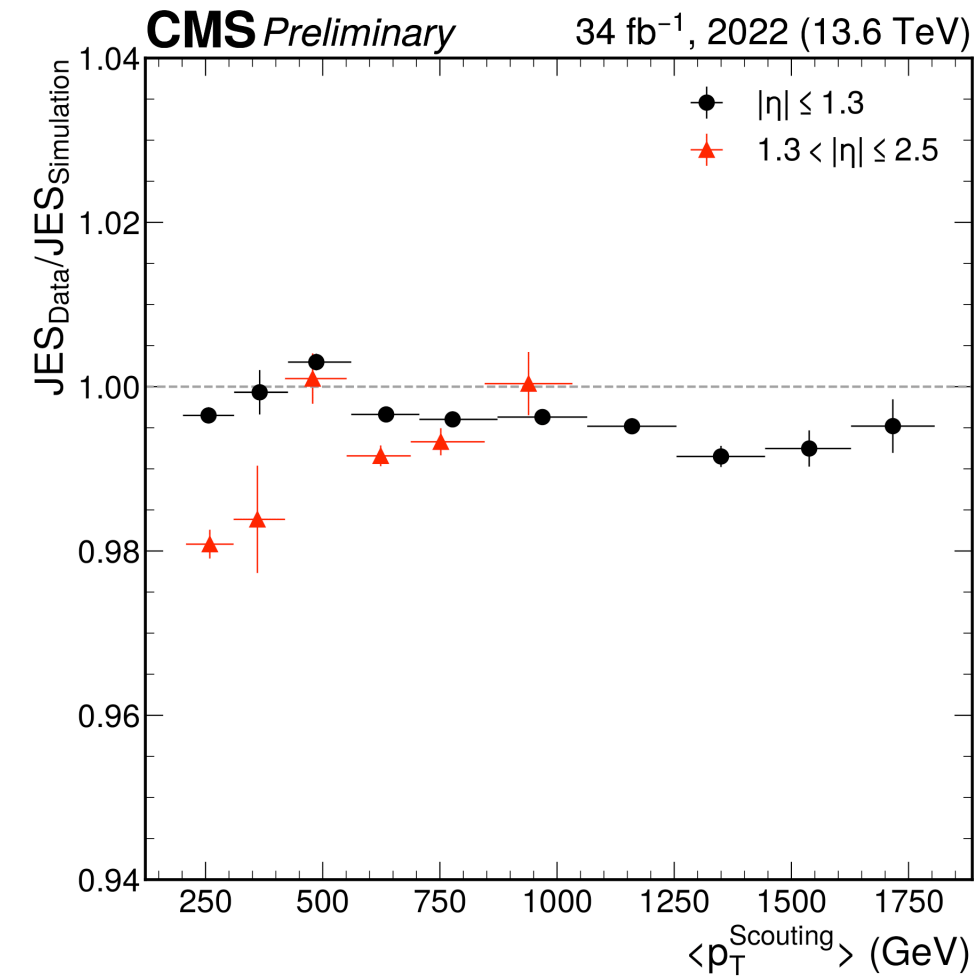
## $\tau$ lepton reconstruction @ HLT

[DP-2023-024](#)



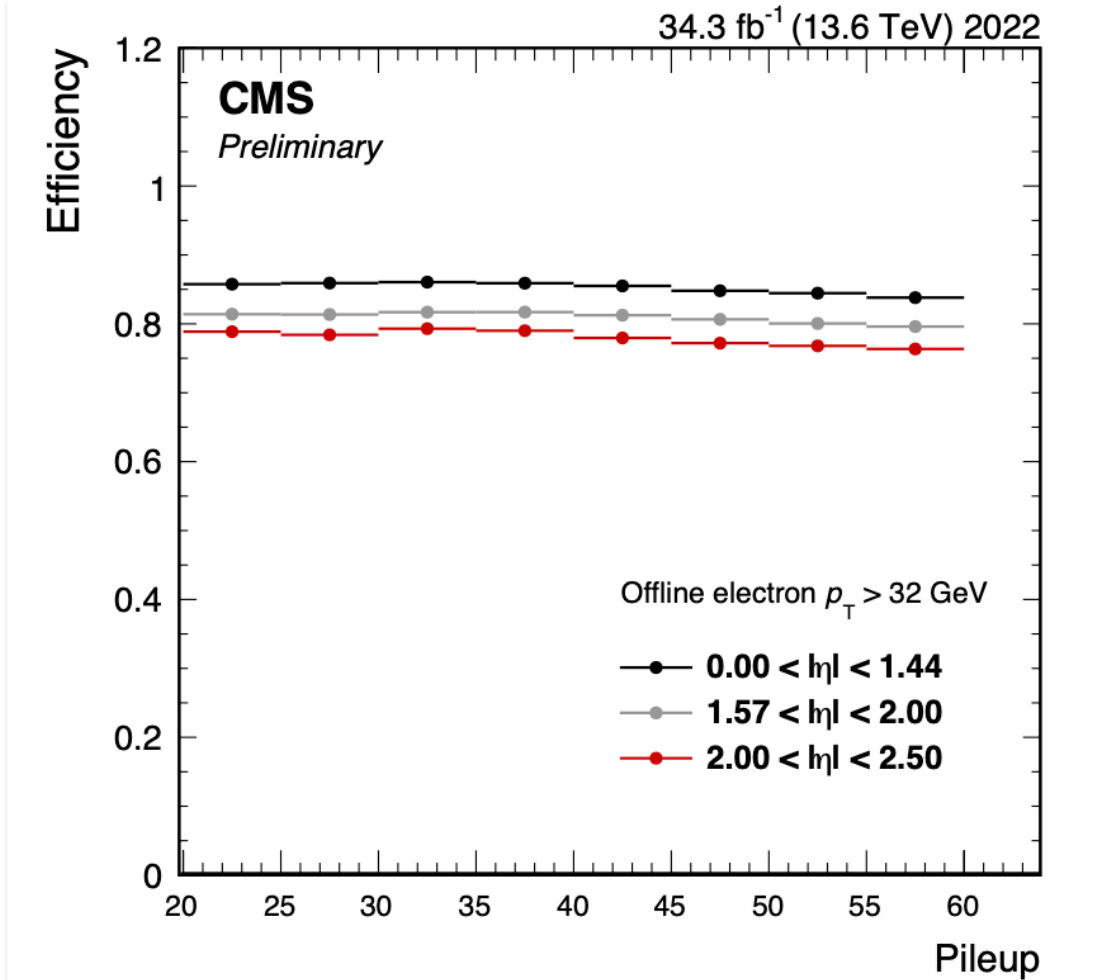
## Jet Energy Scale in scouting

[DP-2023-072](#)



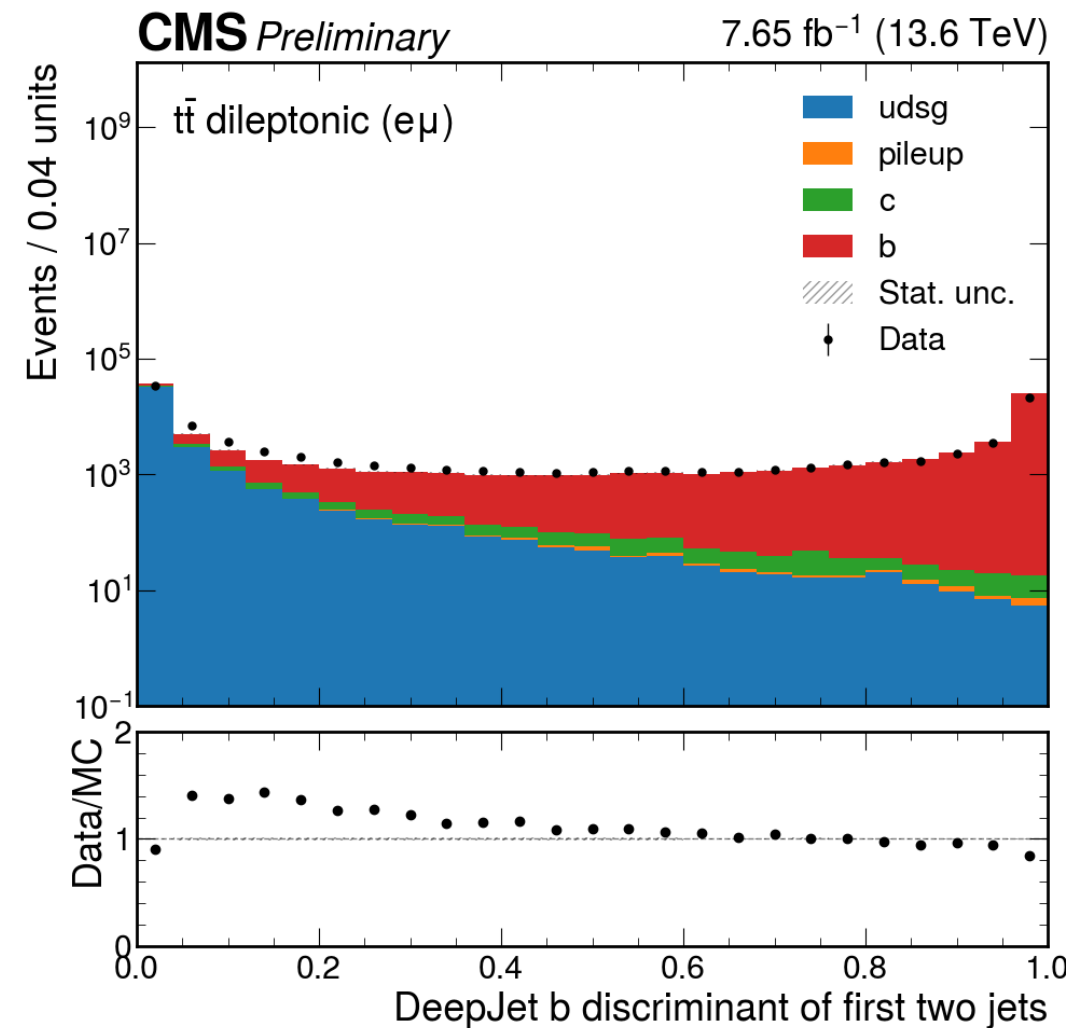
## Electron reconstruction @ HLT

[DP-2023-015](#)



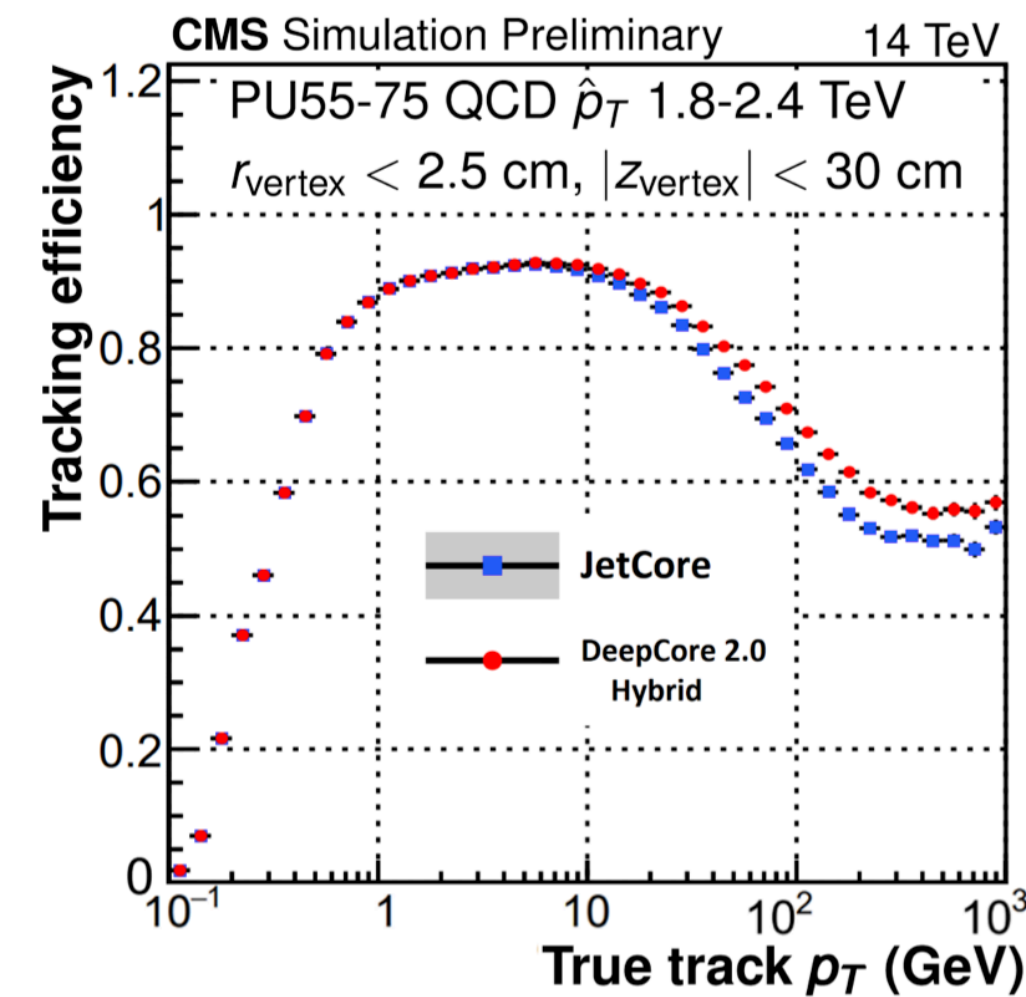
## Heavy flavor jet tagging

[DP-2023-012](#)



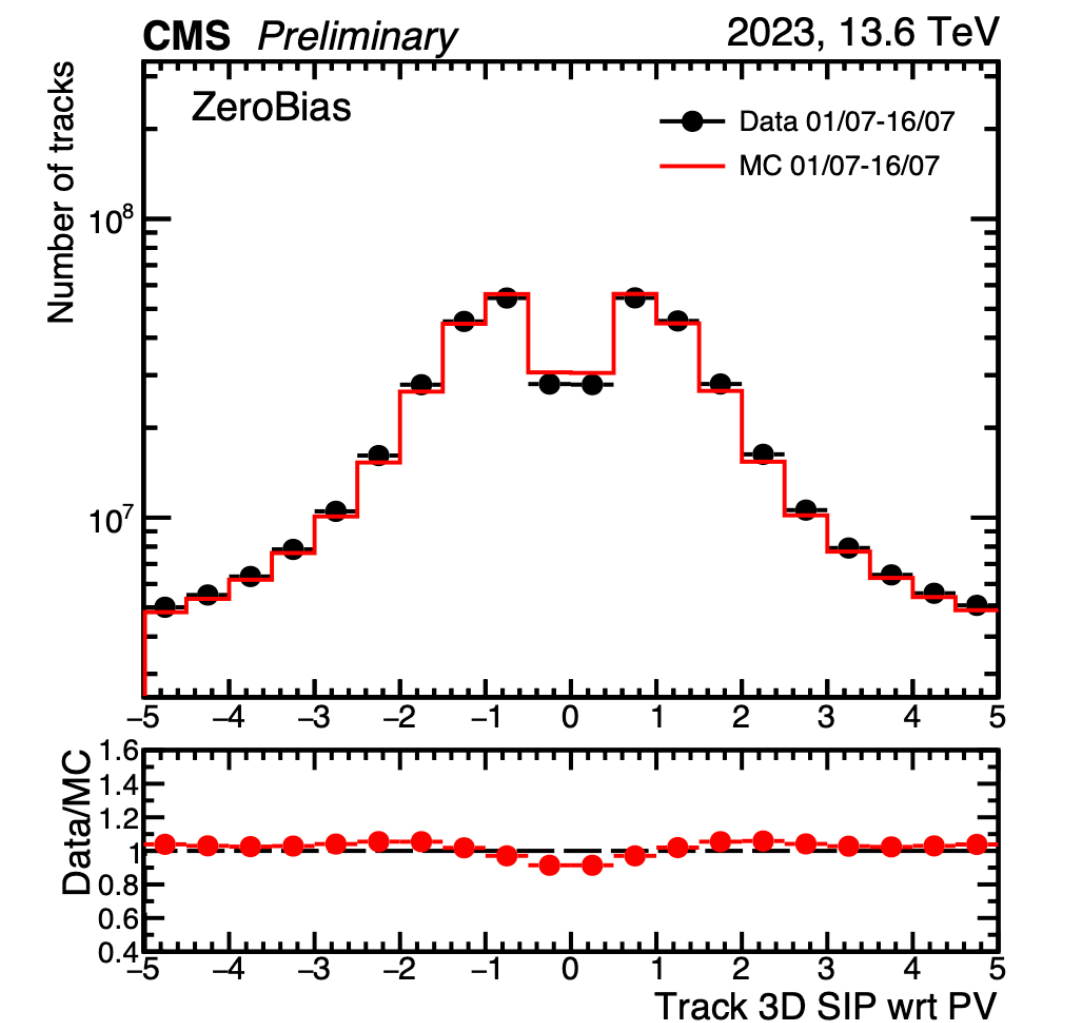
## ML for Tracking in Jets

[DP-2024-003](#)



## Tracking in 2023

[DP-2023-090](#)



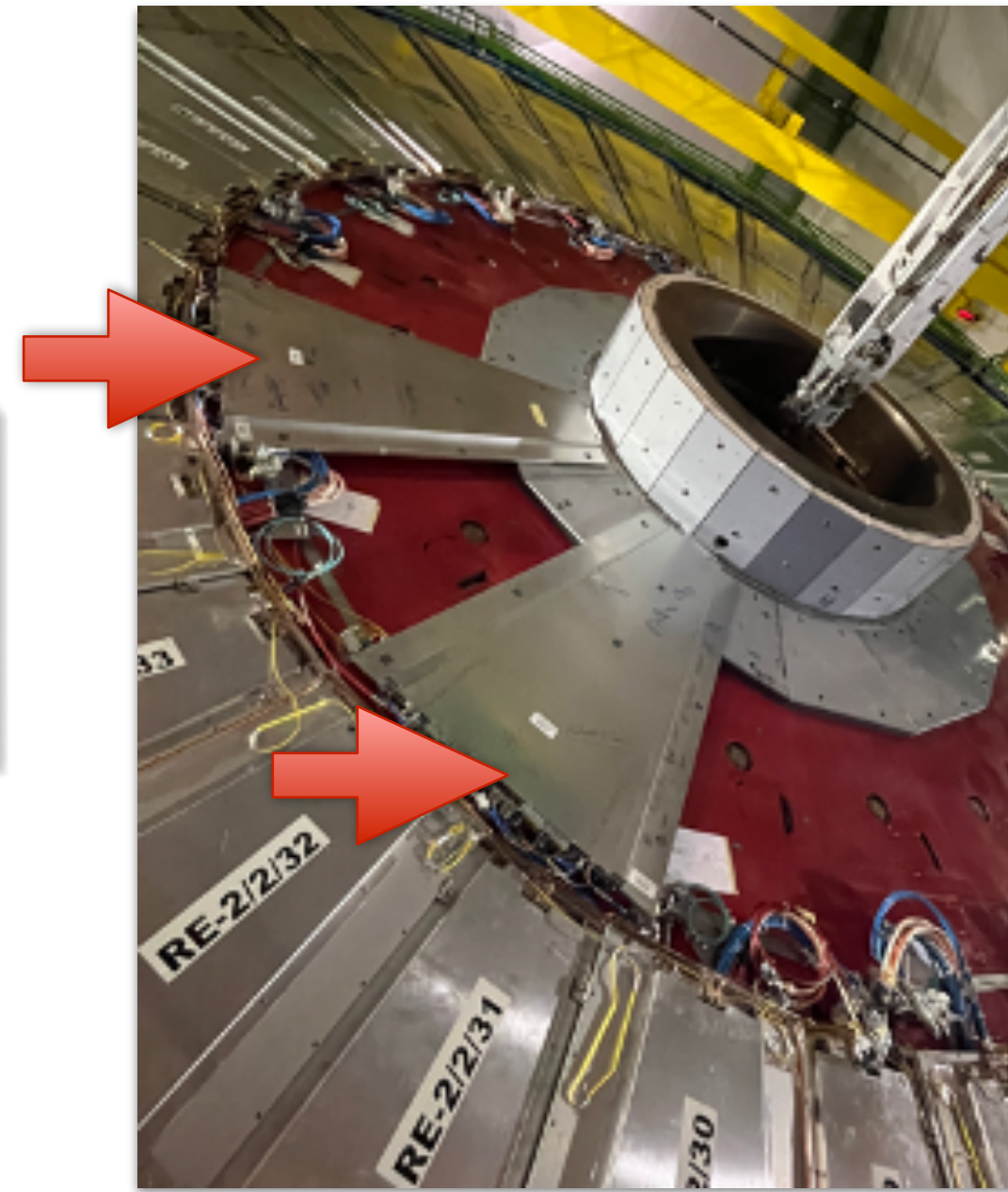
Readiness for 2024 data taking

# Year-end technical stop activities

Two iRPC (RE-3/1) chambers

Two GEM (GE-2/1) chambers

New forward shielding



Installed some chambers of Phase-2 forward muon upgrades on the -z end

- +
- Relocation of CMS control room into new building
  - Preparation of Phase-2 infrastructure: CO<sub>2</sub> cooling, electricity, cranes, laser labs
  - Consolidation of the magnet system to ensure operational stability
  - Standard maintenance & repair

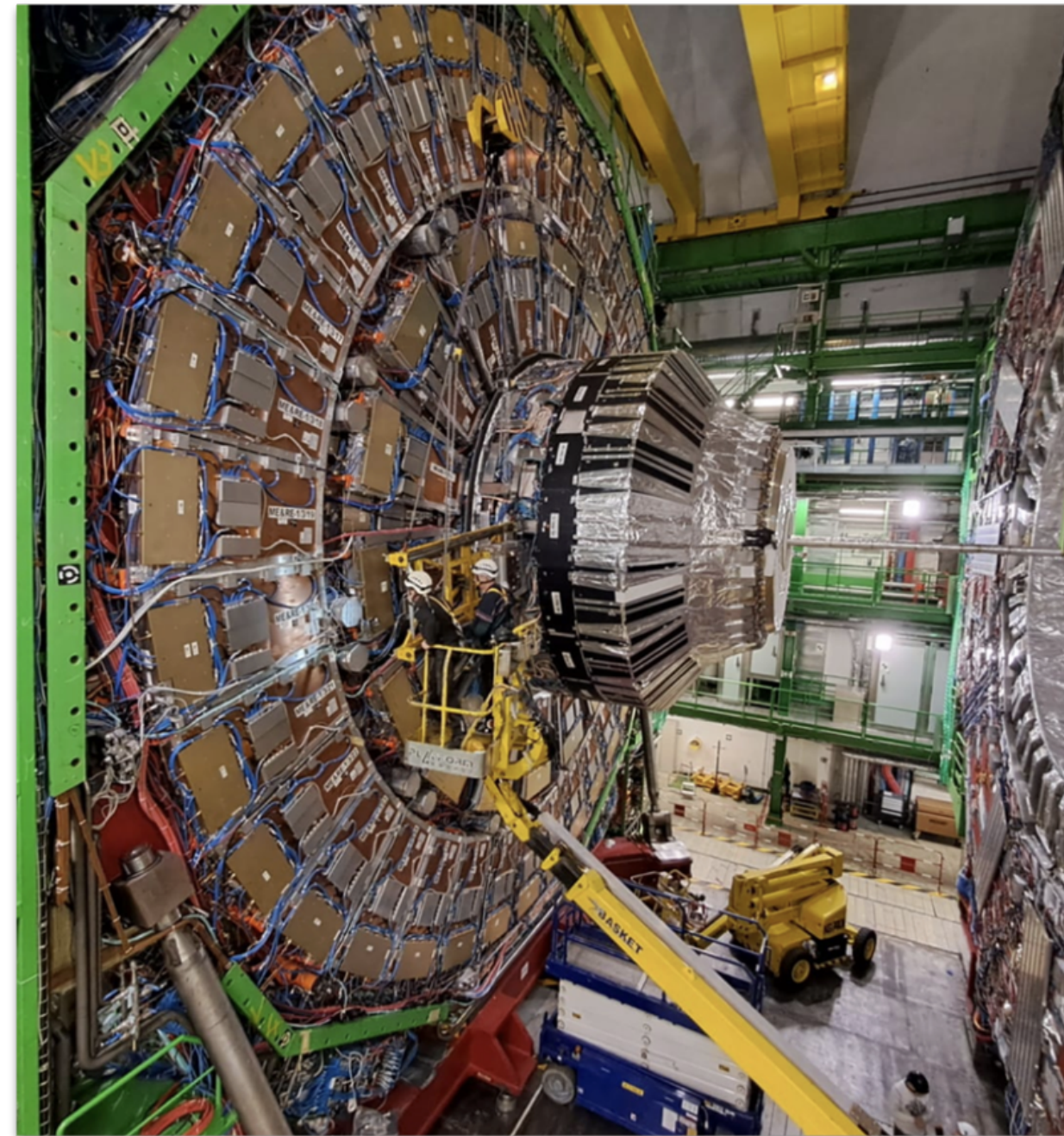


# Muon systems

Maintenance of a few muon chambers to ensure optimal functionality in 2024 run

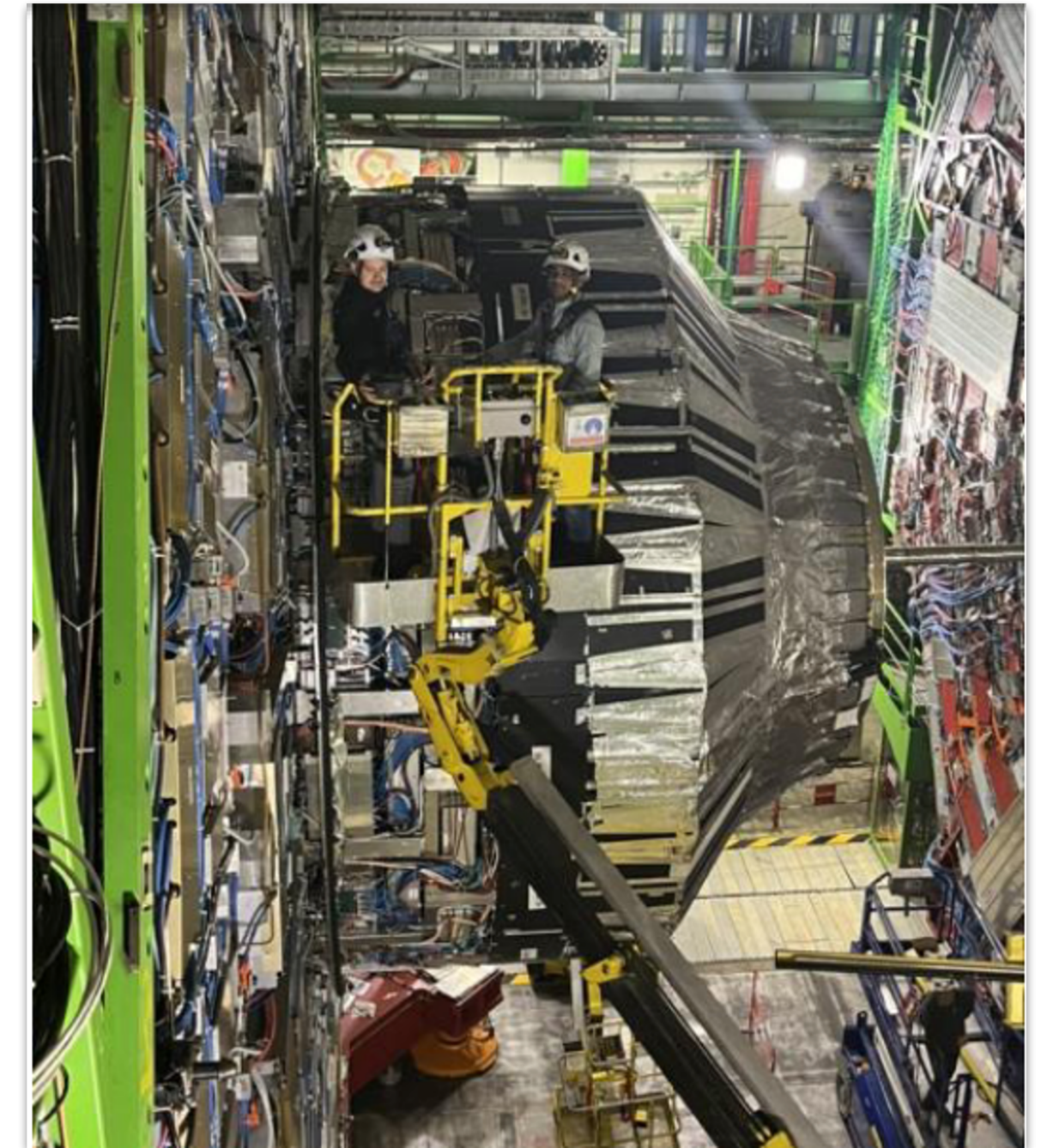


Two full RPC chambers extracted using a new procedure including replacement of the gas pipes



Two CSC chambers extracted for repairs

Two GEM (GE-1/1) chambers replaced



Muon system **successfully restarted** last week & **commissioning** ongoing to validate interventions

# Calorimeters

## ► New laser facilities

- ECAL: New lab commissioned in Nov 23, old one removed to make way for Phase-2 cooling plant
- HCAL: New laser room completed, ready to install upgraded laser box with reduced timing jitter

## ► Operations

- HCAL: No showstoppers, during YETS replaced a few sub-performing components
- ECAL: Preparing for '24 data: HV calibration, new laser commissioning

## ► Detector performance

- ECAL: New “cross-correlation” timing algorithm deployed for offline reconstruction
- HCAL: Using timing & (new) depth- and  $\eta$ -dependent pulse shape to improve energy determination



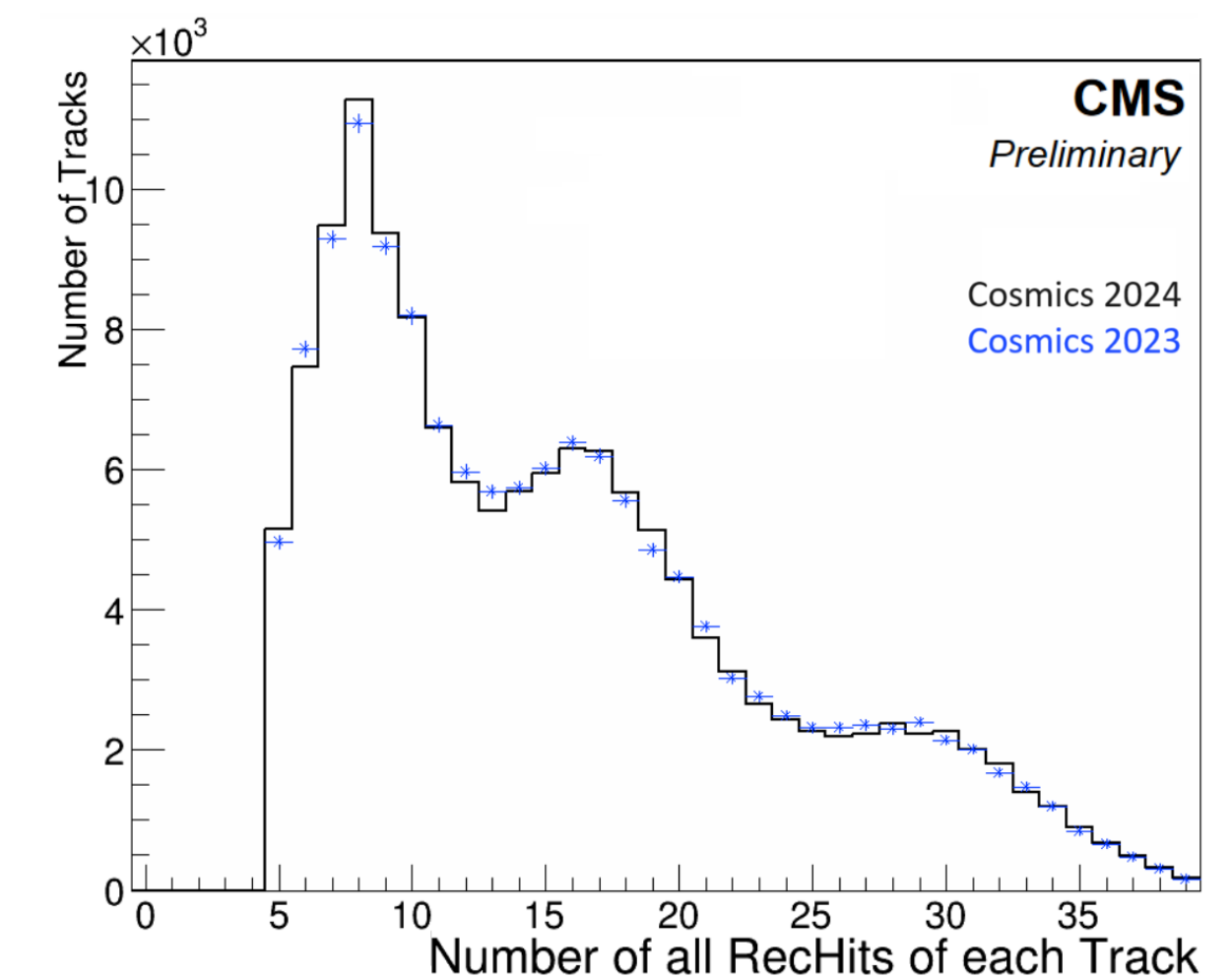
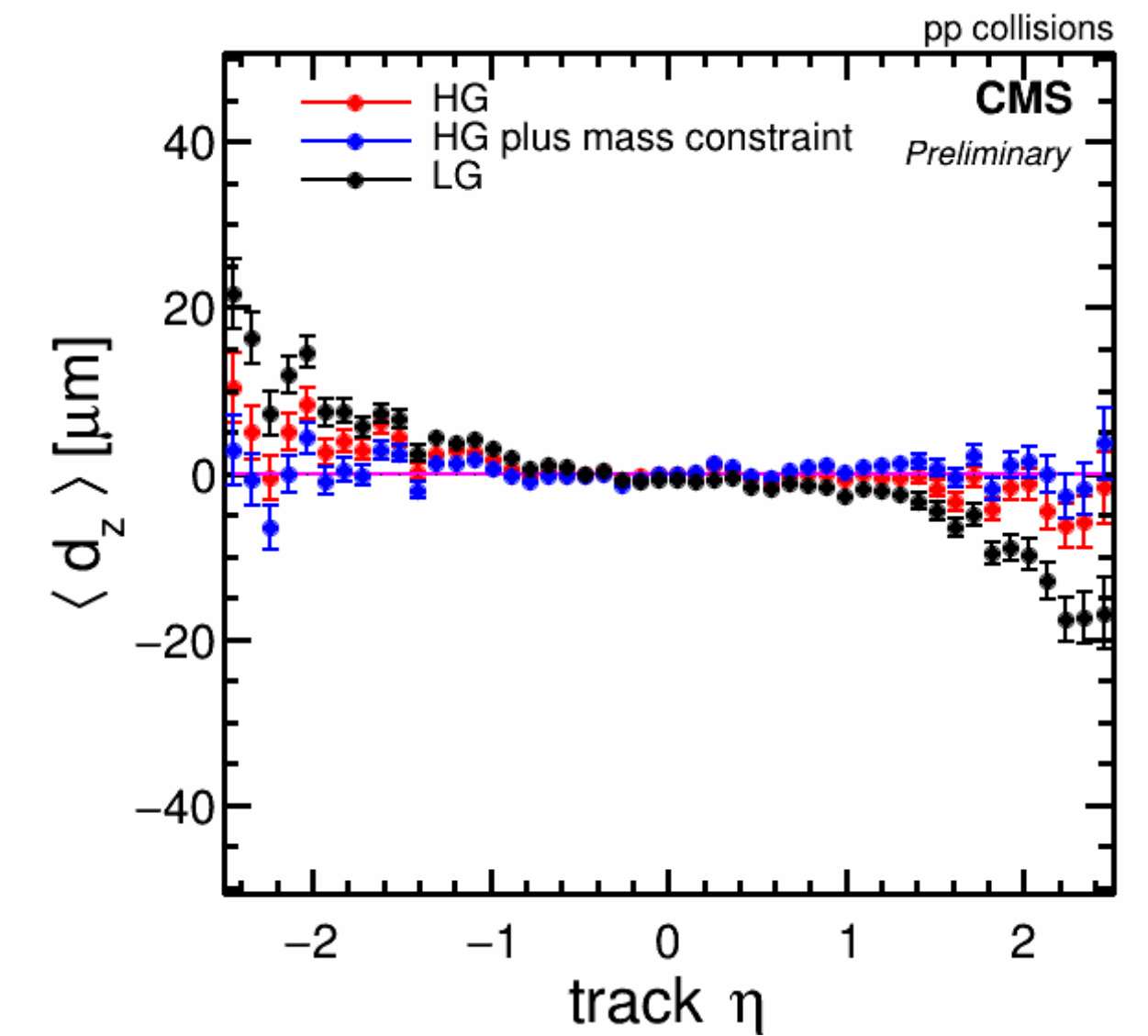
## ▶ Activities over technical stop

- DCS migration complete, new Detector Safety System panel successfully tested
- Improved “high-granularity” alignment procedure → significant bias reduction!

## ▶ Strip and pixel detectors are powered ON

- Initial hiccups: pixel rack turbine failure, faulty strips cooling valves → swiftly addressed
- Two previously problematic strip FEDs now running without issue

## ▶ Starting to derive alignment calibrations from cosmic ray data



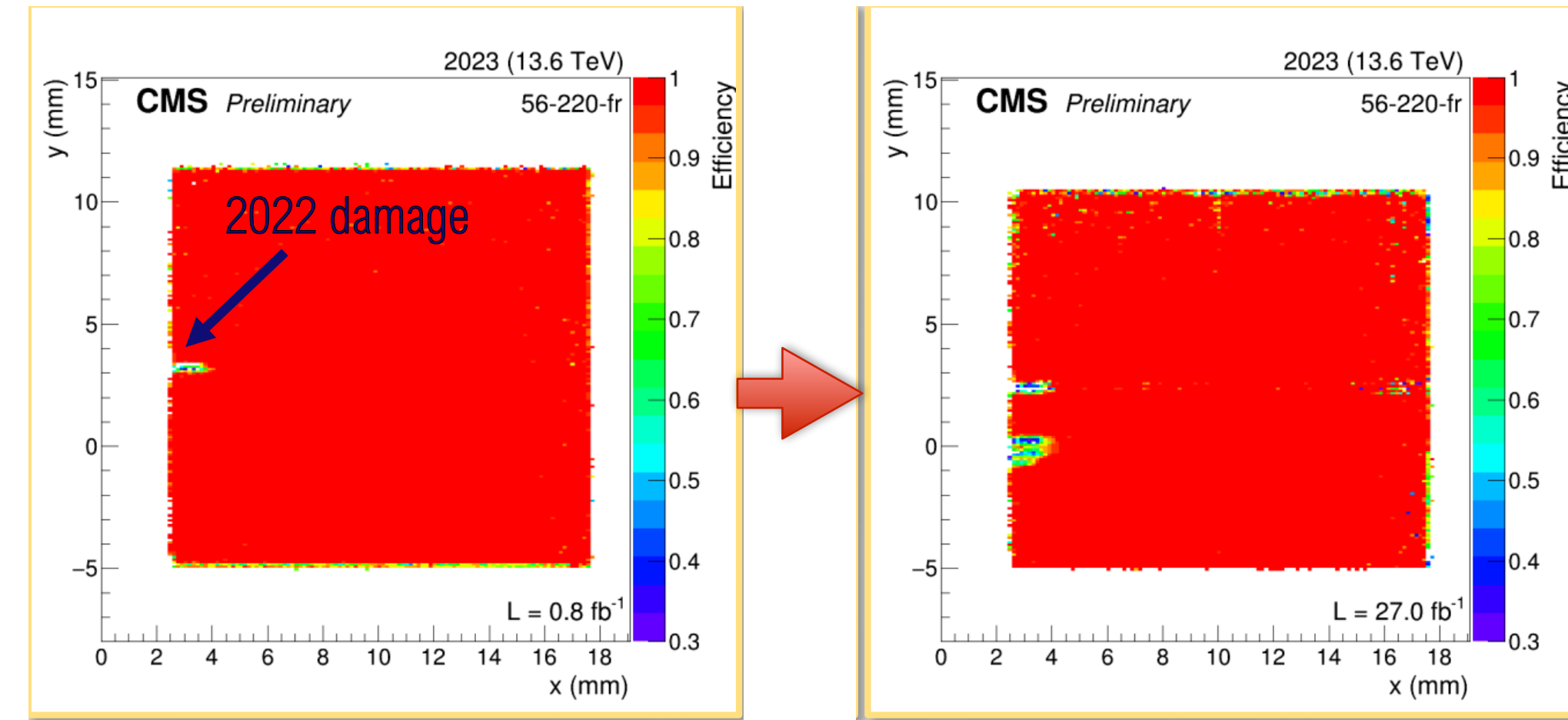
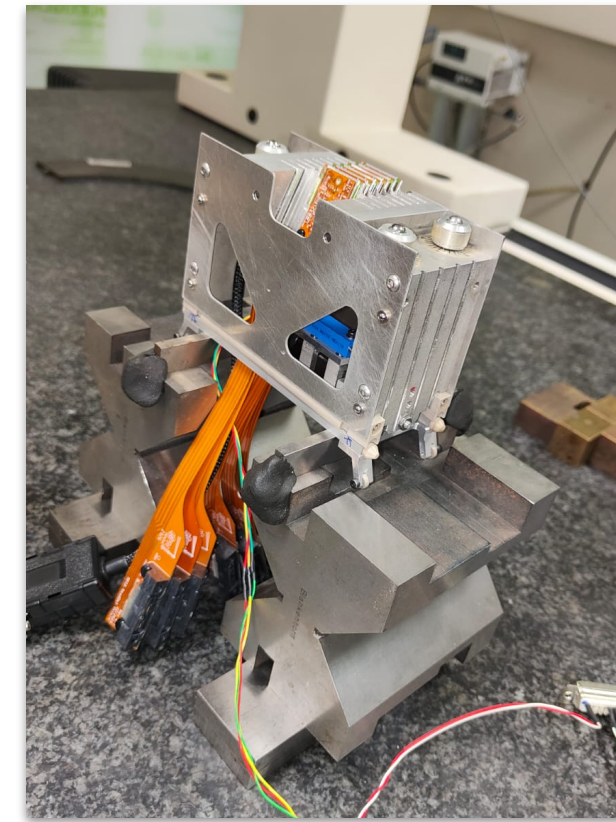


# Precision Proton Spectrometer (PPS)

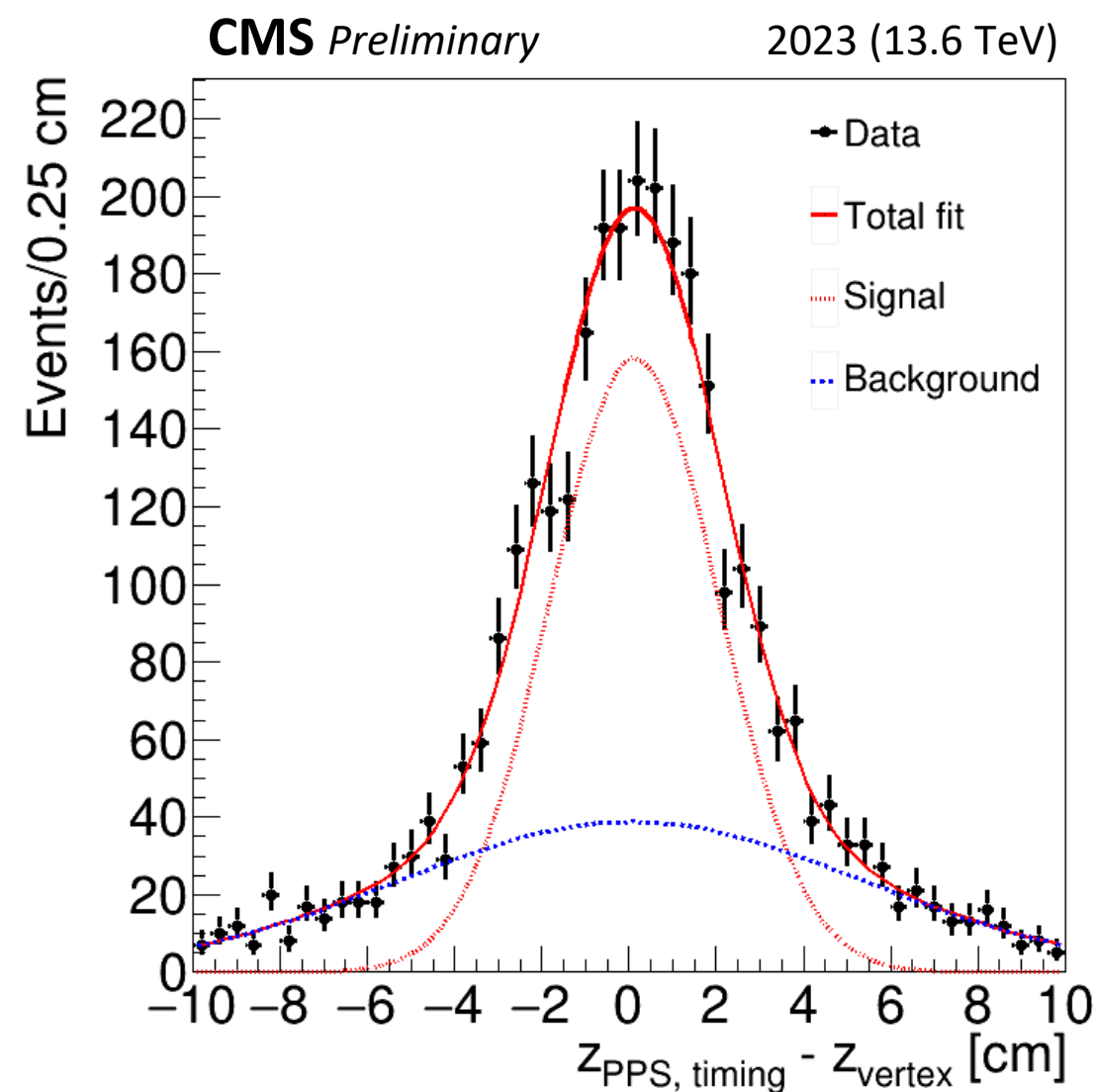
## Tracking

Two new detector packages installed on sector 45

Good performance already in '23, new detector packages will provide extra redundancy against any future problems



efficiency loss w/ radiation damage

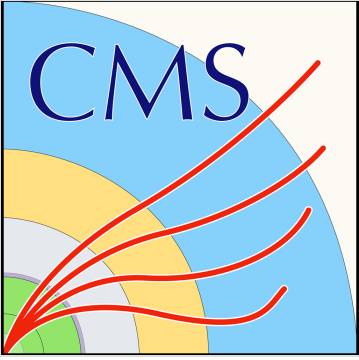


vertex position resolution

## Timing

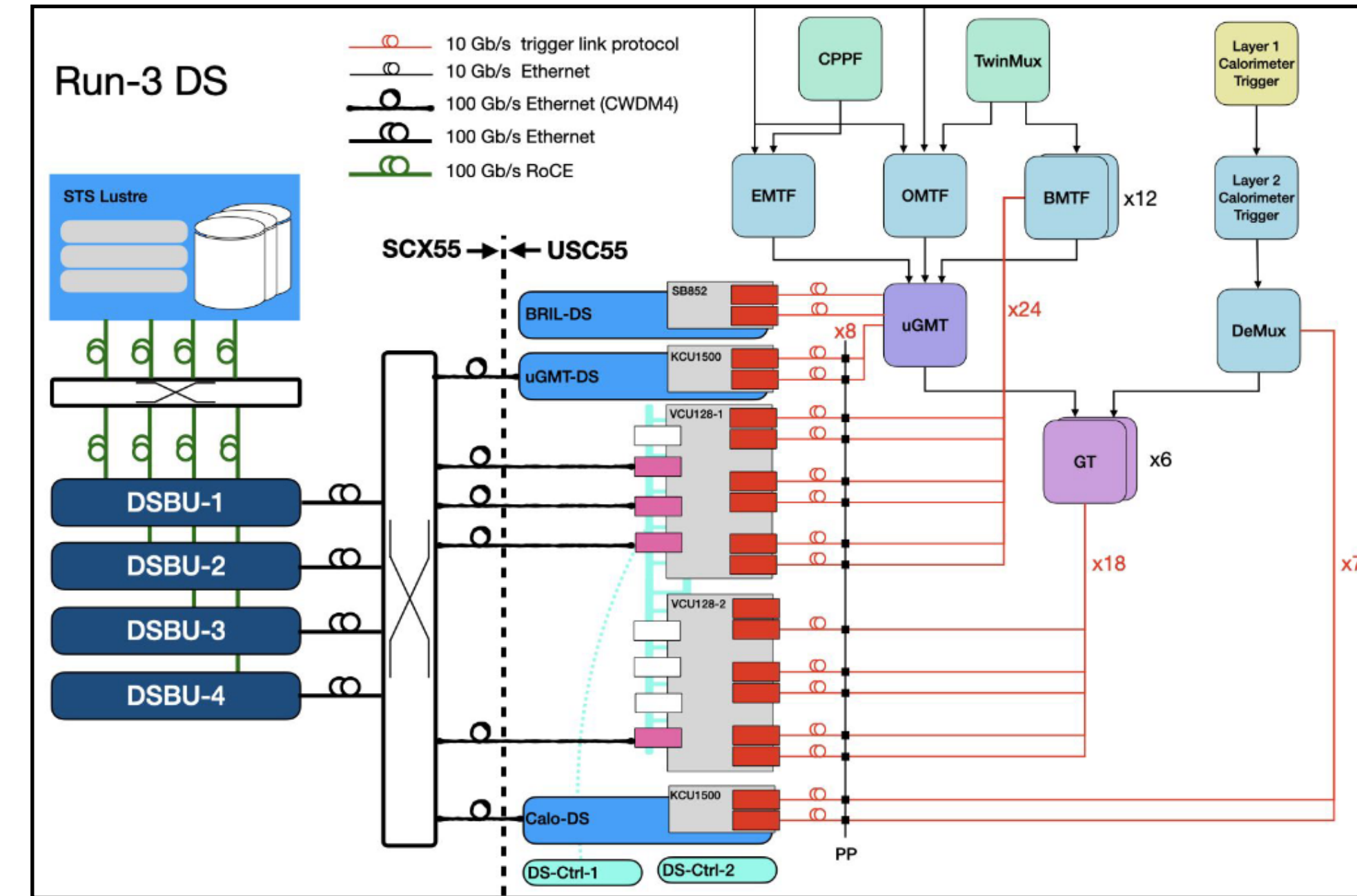
During YETS, investigated localized efficiency losses seen in 2023 with diamond detectors

Diamond cylindrical detector packages reinstalled with hybrid board mitigations to reduce polarization effects

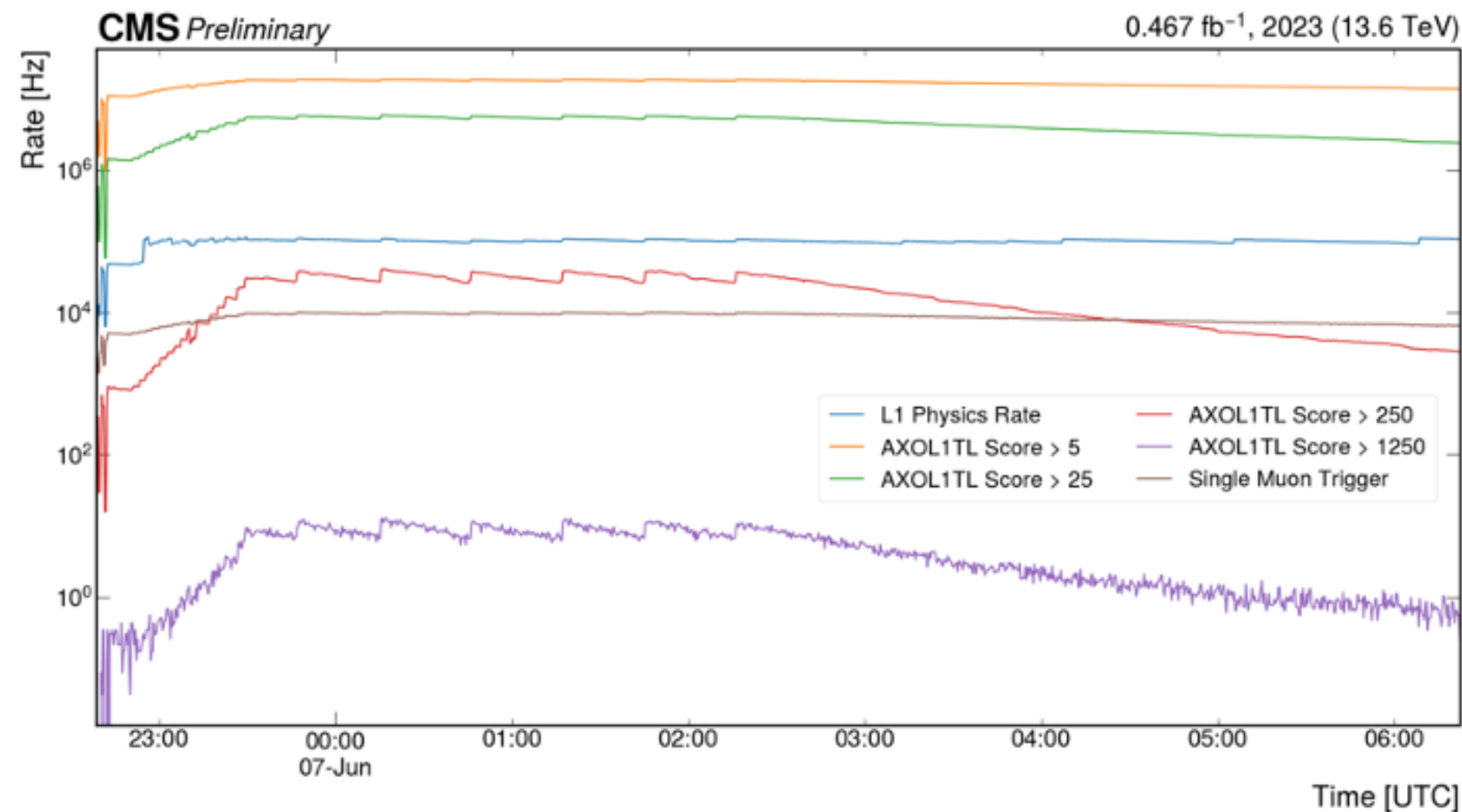


# Level-1 Trigger

- ▶ L1 Trigger restarted after YETS & running in cosmics
- ▶ Preparing to collect data at ~110 kHz, pushing towards 115 kHz
- ▶ New seeds for 2024:
  - Low  $p_T$  “very high quality” single muon seeds for B physics
  - Displaced dimuon seeds for LLP searches
  - Lepton+HT seeds for  $HH \rightarrow bbWW$
  - Anomaly detection: AXOL1TL ([DP-2023-079](#)) & CICADA ([DP-2023-086](#))

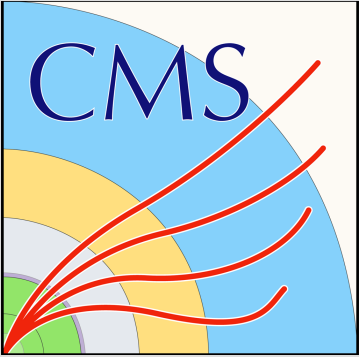


Dedicated system to readout, process & analyze data from L1 Trigger @40Mhz



## Phase-2 scouting @40 MHz

- Goal: scout every bunch crossing in Phase-2
- Demonstrator taking data with muons & (as of last year) calorimeter information
- Output now stored as a standard dataset
- Plans for 2024: 100 Gb/s acquisition

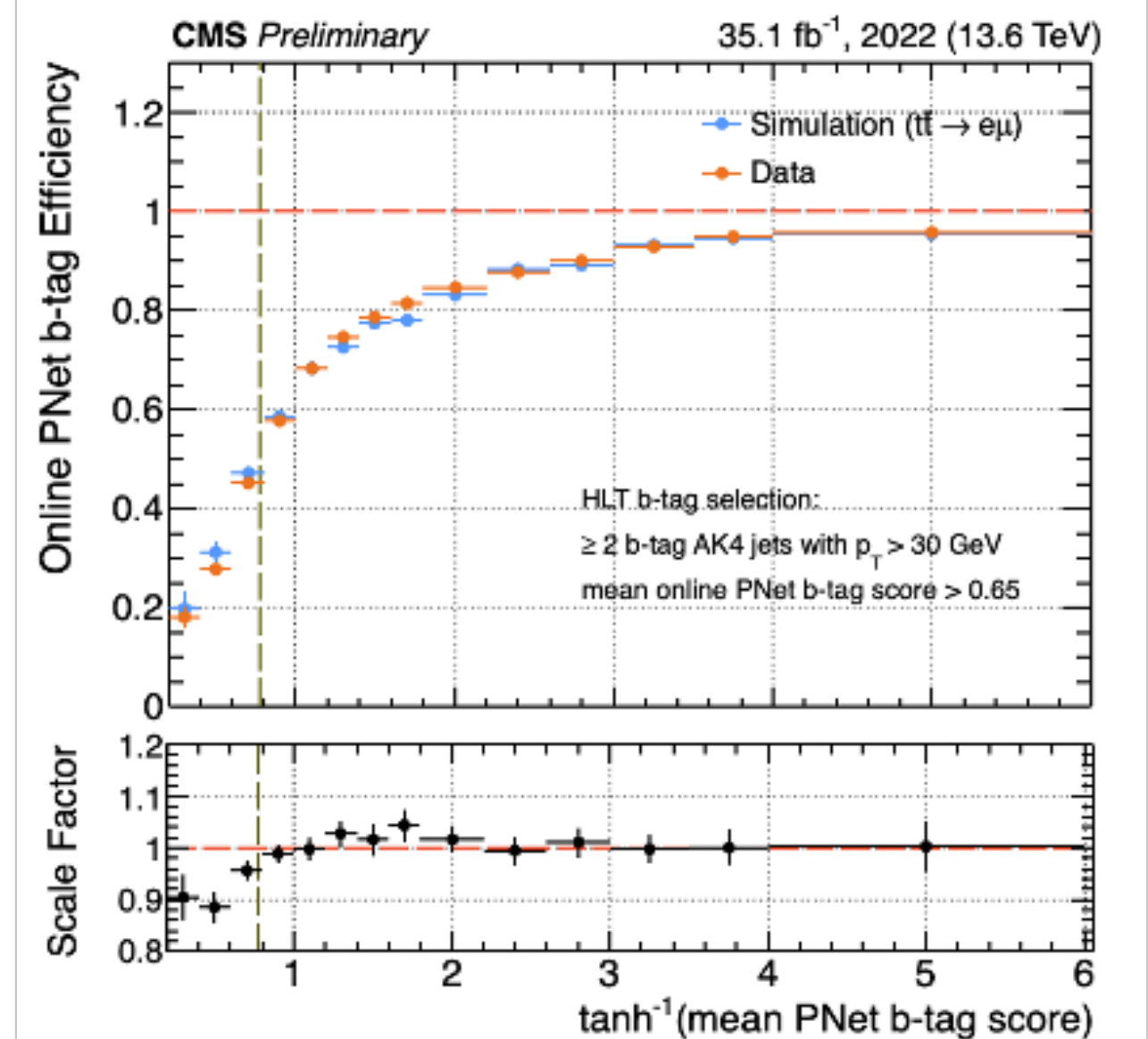
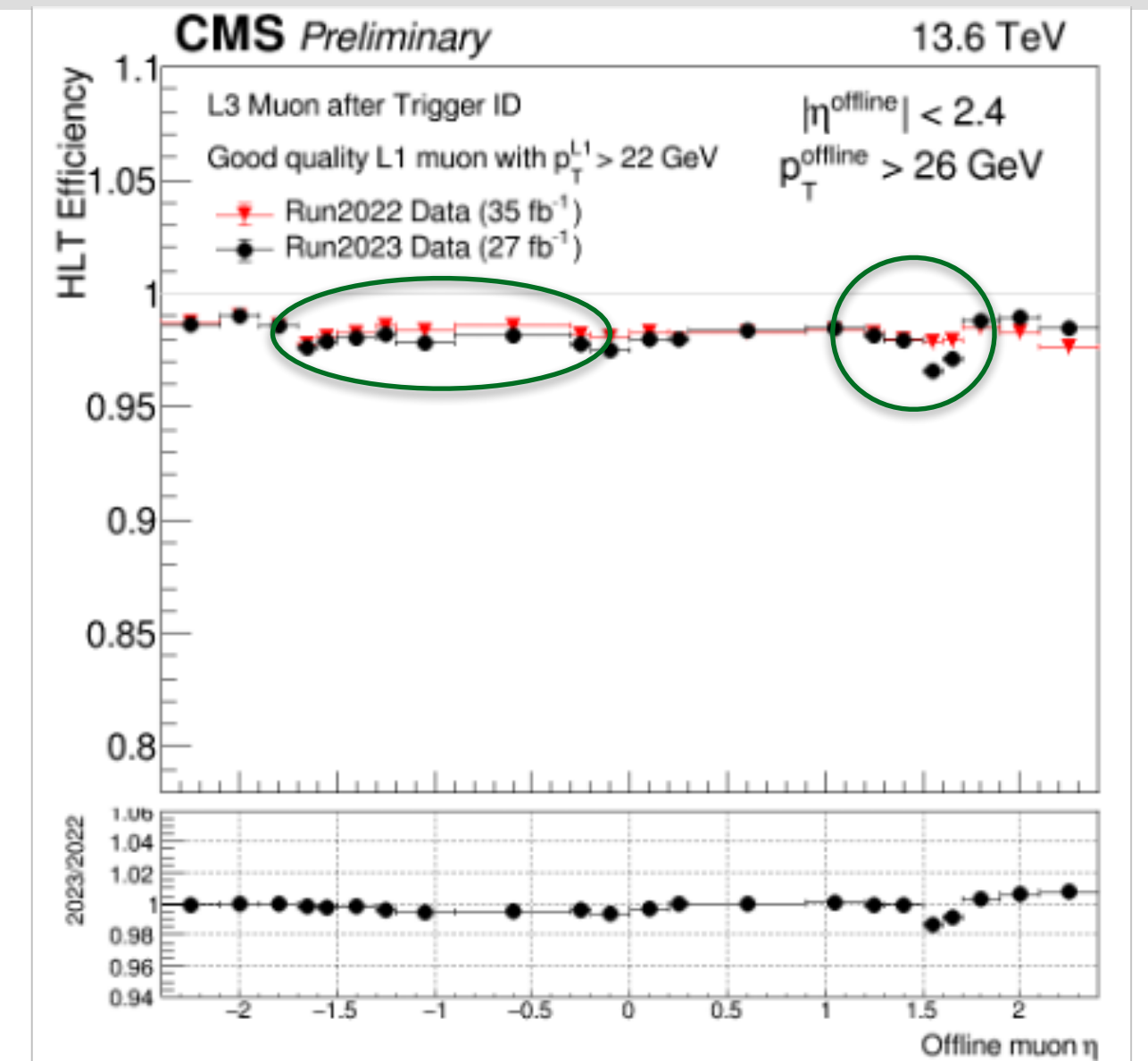


# High Level Trigger

- ▶ Improvements in HLT reconstruction
  - Recovery of muon inefficiency from 2023
  - [ParticleNet](#) for b-tagging &  $\tau$ -ID
  - Migration of heterogeneous (CPU+GPU) HLT reconstruction (Pixel, ECAL, Particle-Flow clustering) to [Alpaka](#) framework
- ▶ Parking
  - New triggers to increase efficiency for HH  $\rightarrow$  bb+X
  - Addition of low  $p_T$  single-muon triggers
- ▶ Scouting
  - Reconstruction improvements, e.g., full tracking in particle flow
  - More information to extend coverage, e.g., low- $p_T$  tracks
  - New single-muon scouting triggers

Latest results on HLT performance on 2023 data

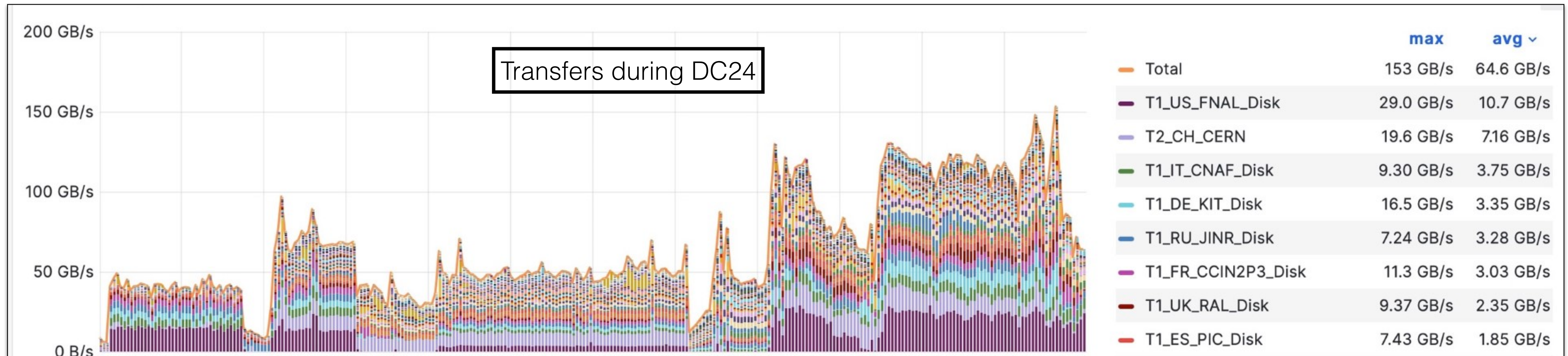
- [CMS-DP-2023-089](#): PNet b-tagging at HLT
- [CMS-DP-2023-094](#): jet-substructure triggers
- [CMS-DP-2024-005](#): HLT muons



▸ **Offline Software and Computing is ready for data taking**

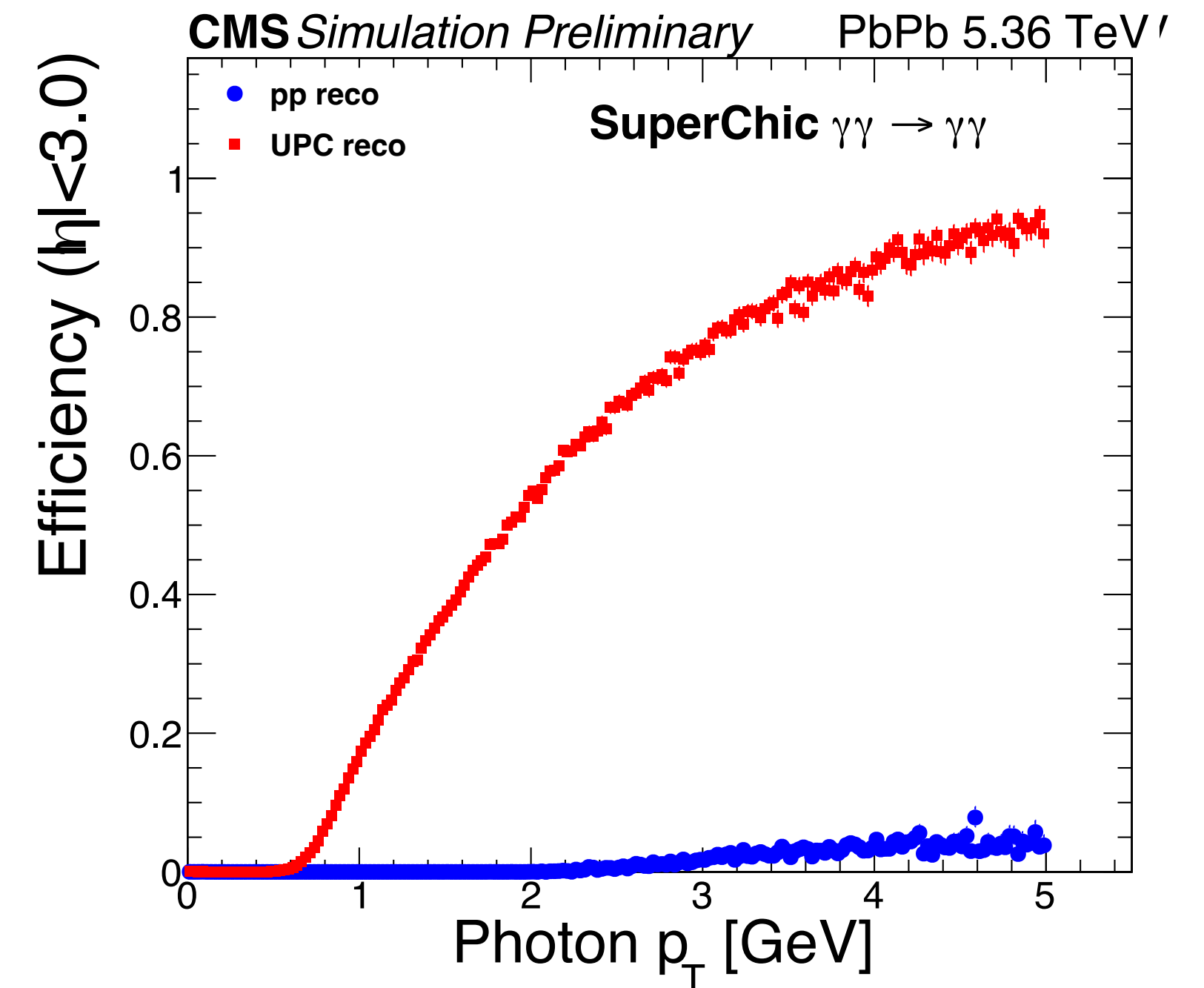
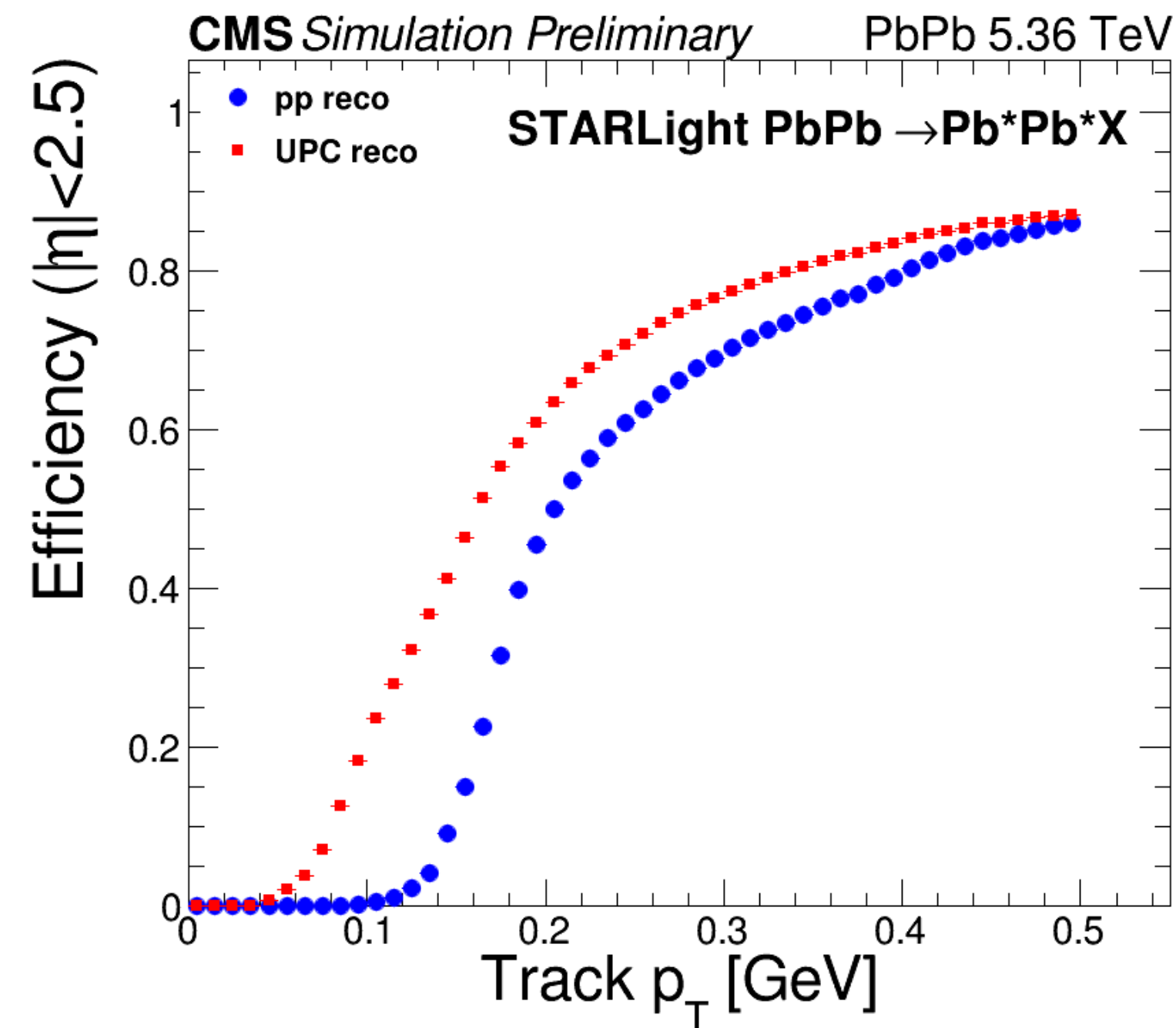
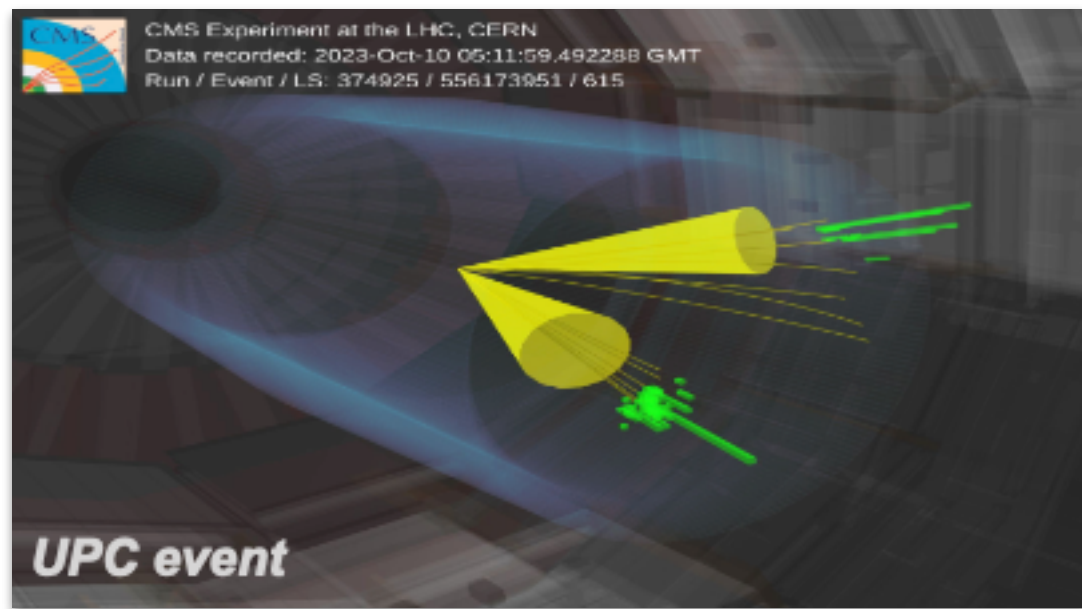
- Expect to fit into approved resource request for '24, including expanded physics program based on increased parking & scouting
  - CMSSW data taking release is frozen and undergoing physics validation & testing at Tier-0
- Data challenge DC24 was a great success: reached target rate of 125 GB/s, 25% of Run 4 goal
- Technology testing for required Run 4 operations also successful: ~ 50% of transfers were done with token authorization

We sincerely thank the File Transfer System & Rucio teams, as well as all operational teams that made DC24 a success

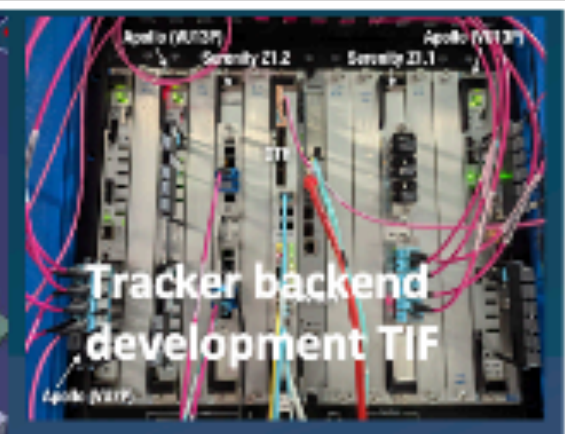
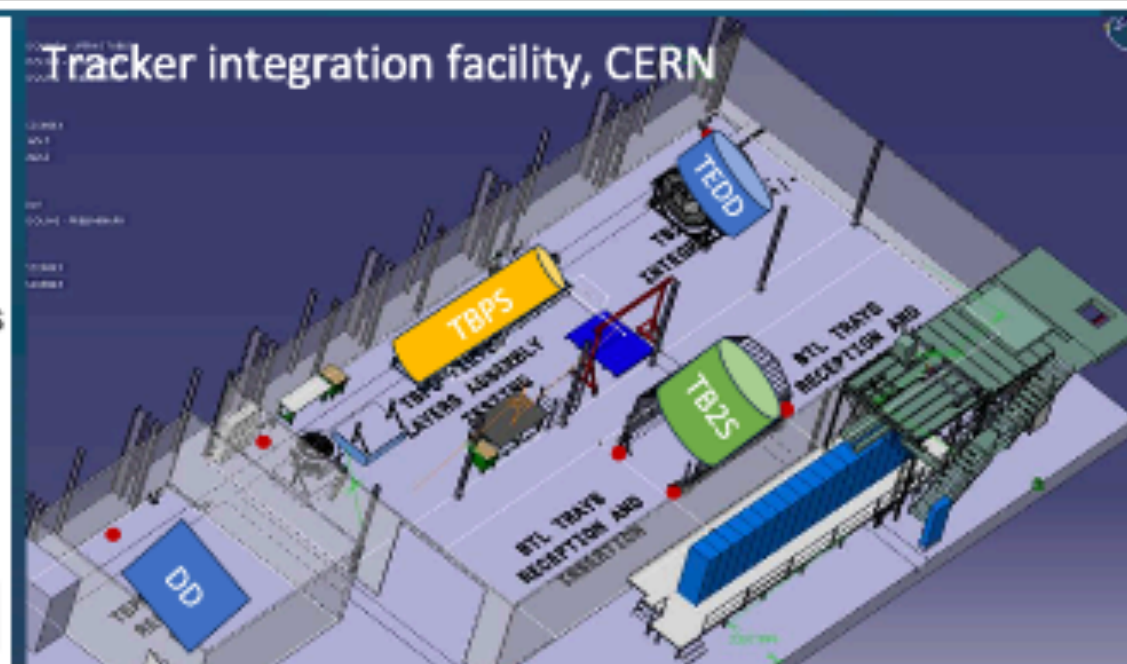
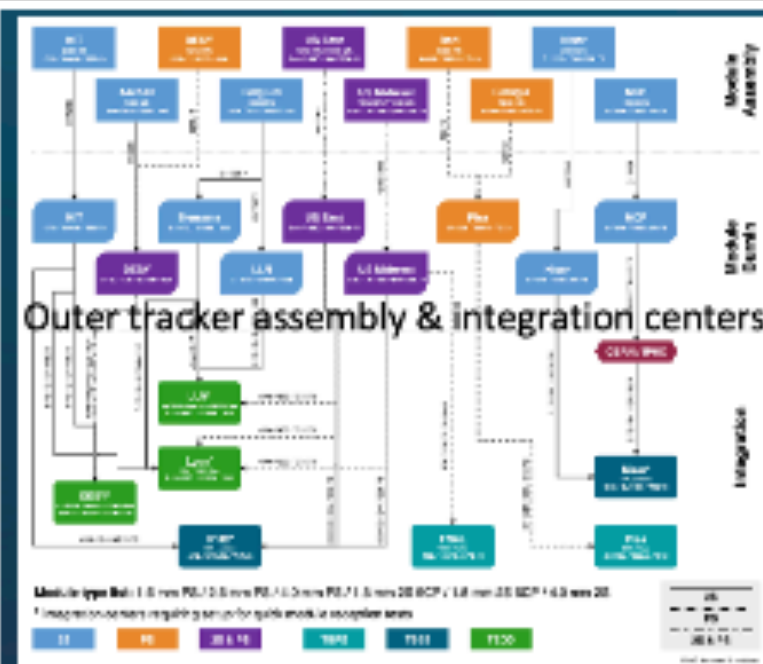


# Improved reconstruction of Ultra-Peripheral Collisions

From the last LHCC: Integration of the Zero Degree Calorimeters into the L1 trigger system allowed us to collect a large sample of ultra-peripheral collisions



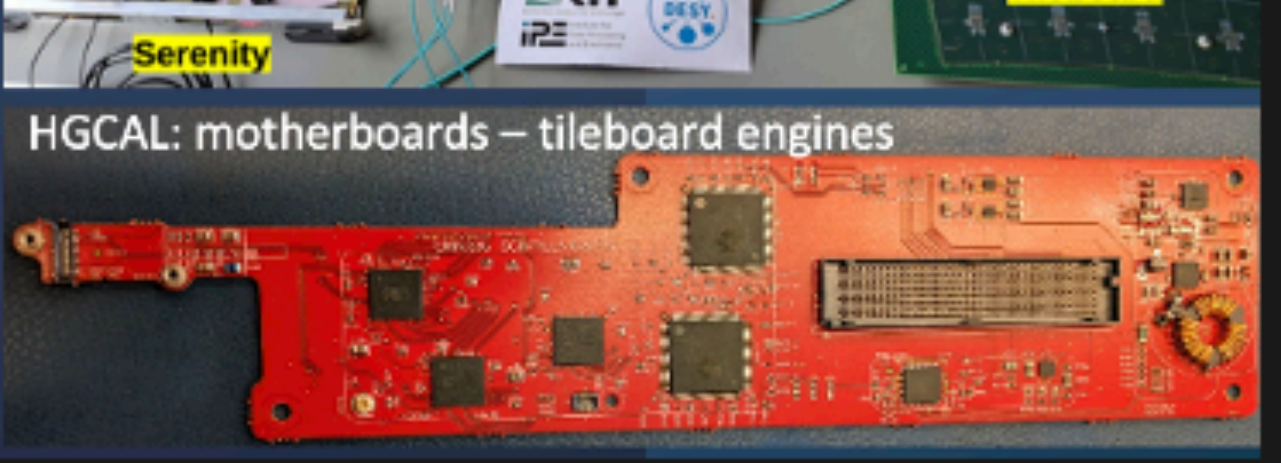
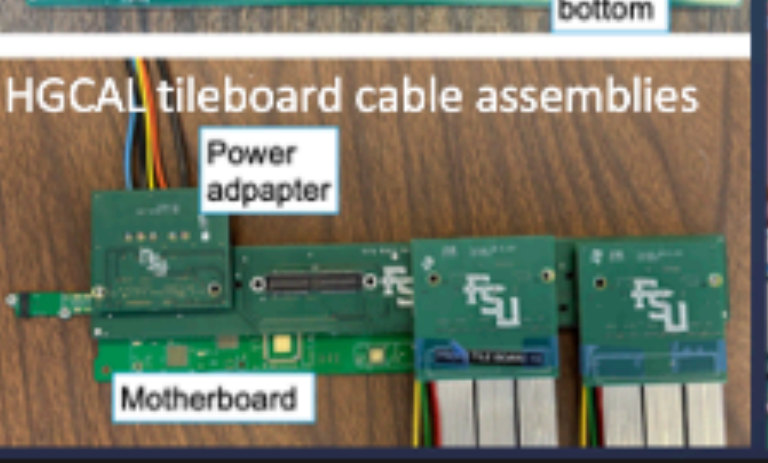
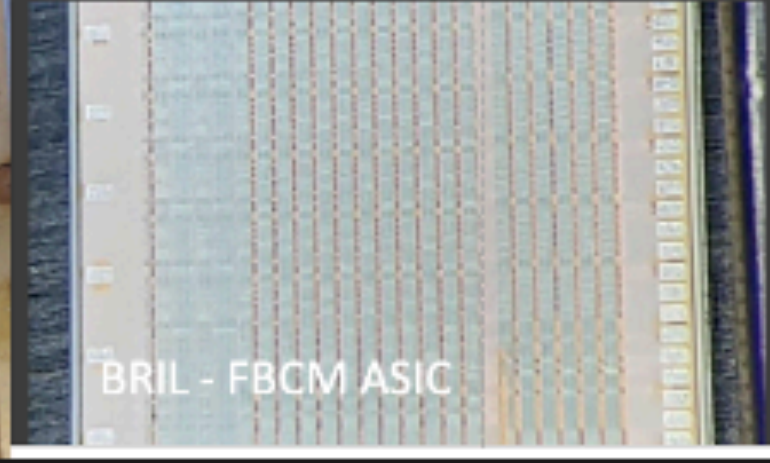
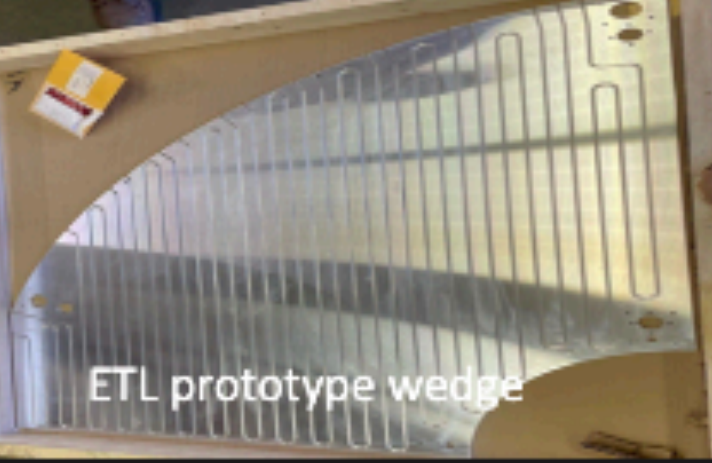
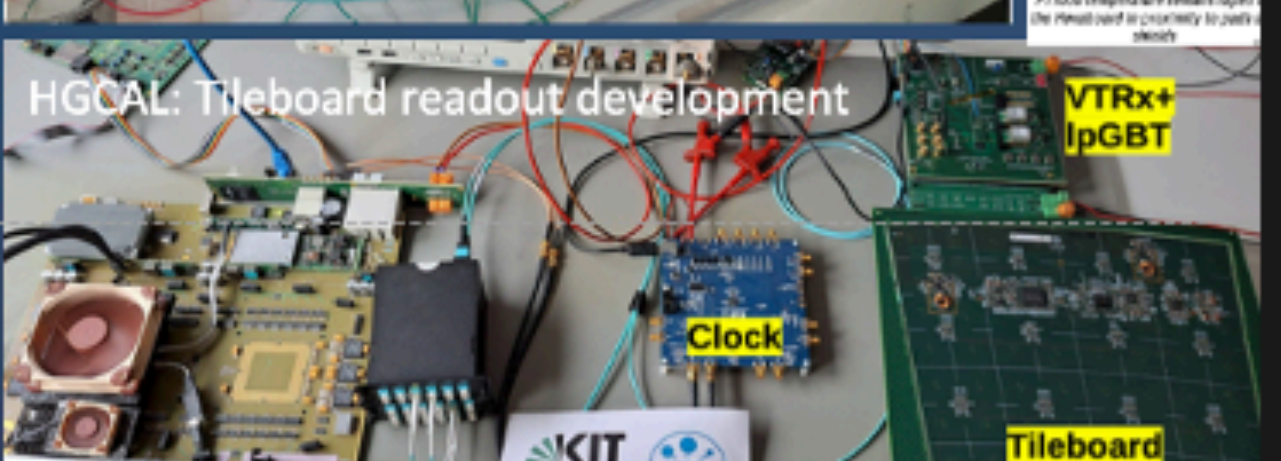
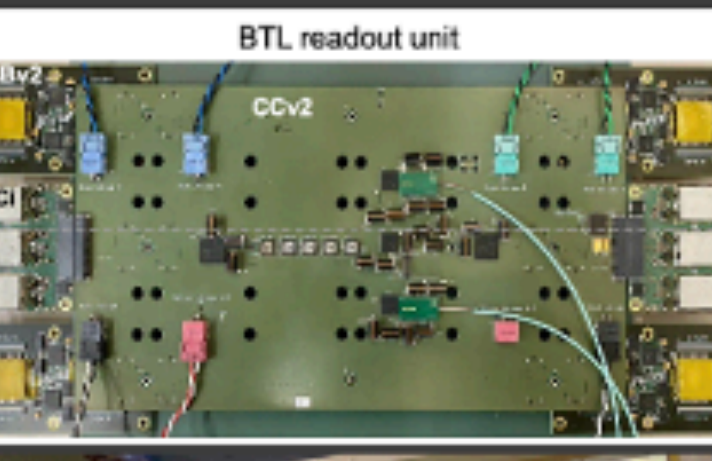
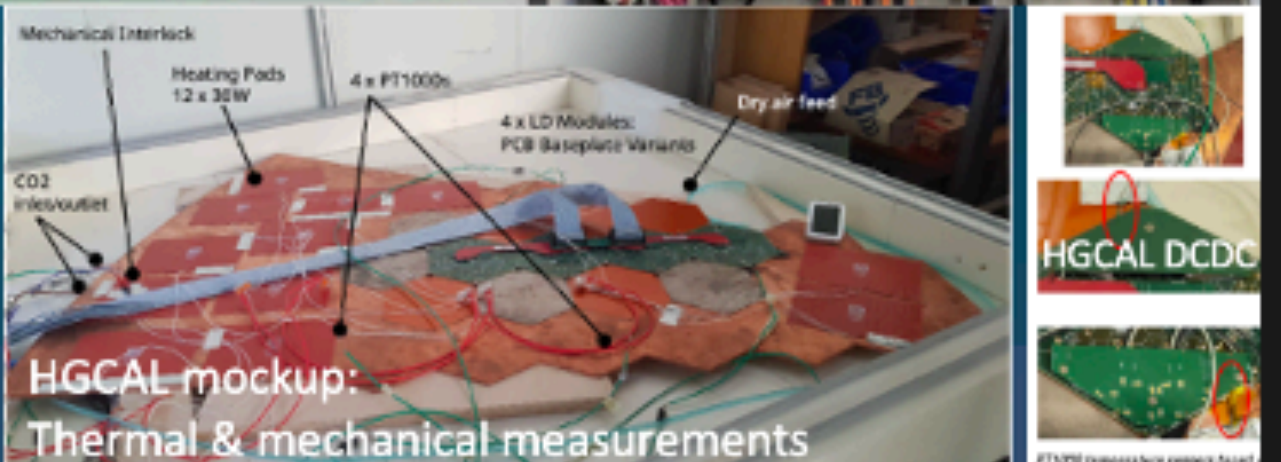
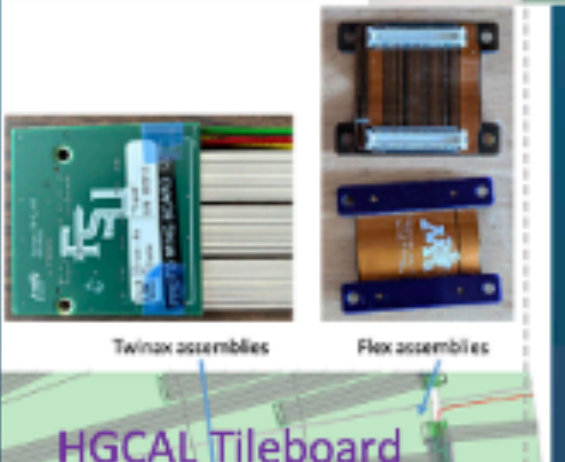
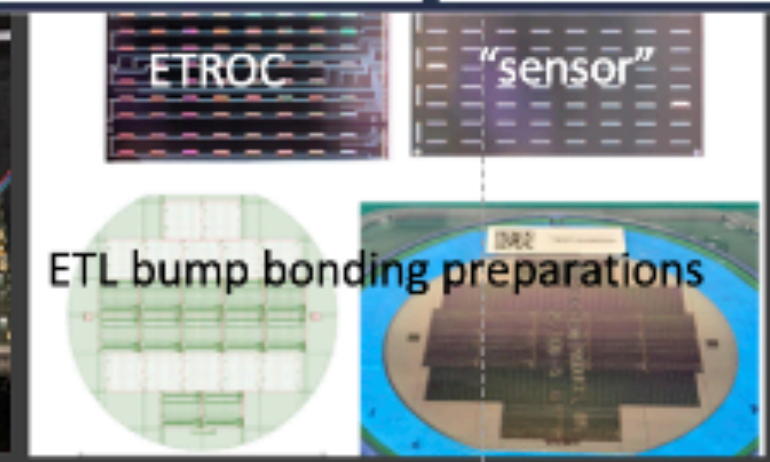
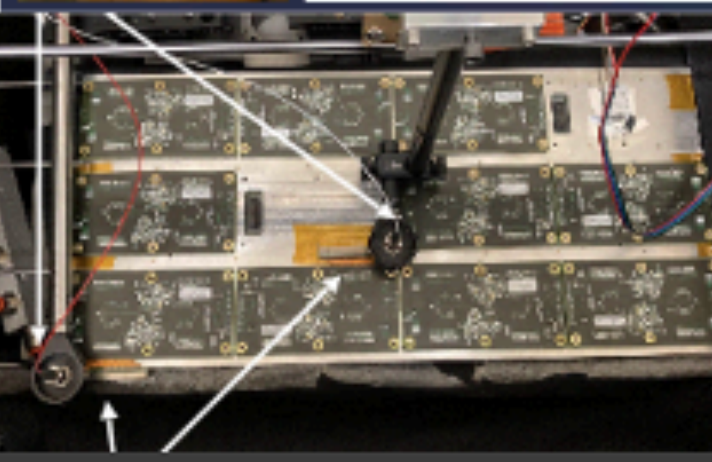
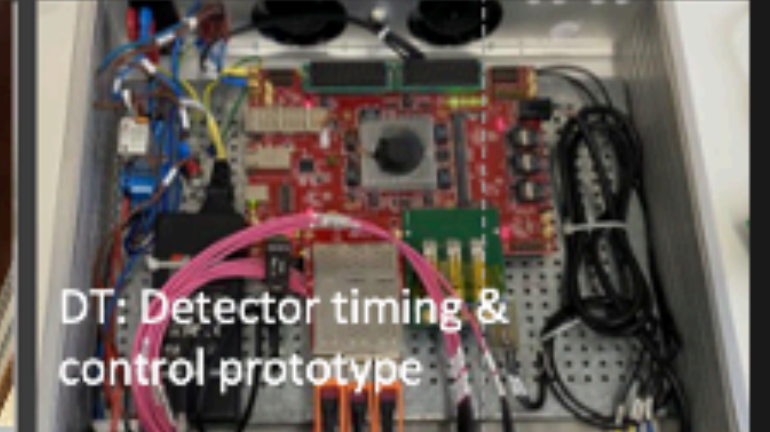
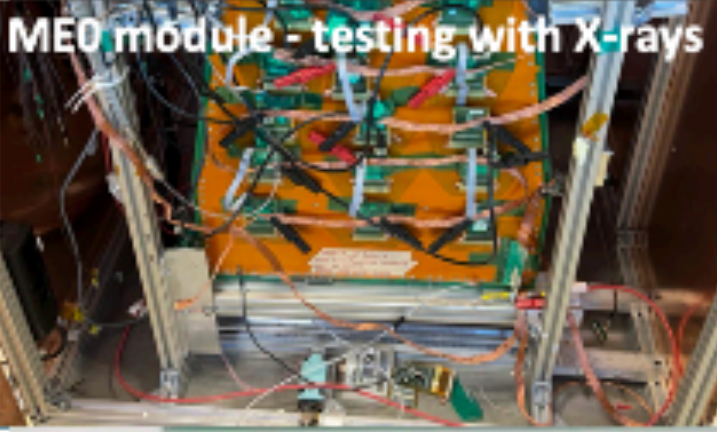
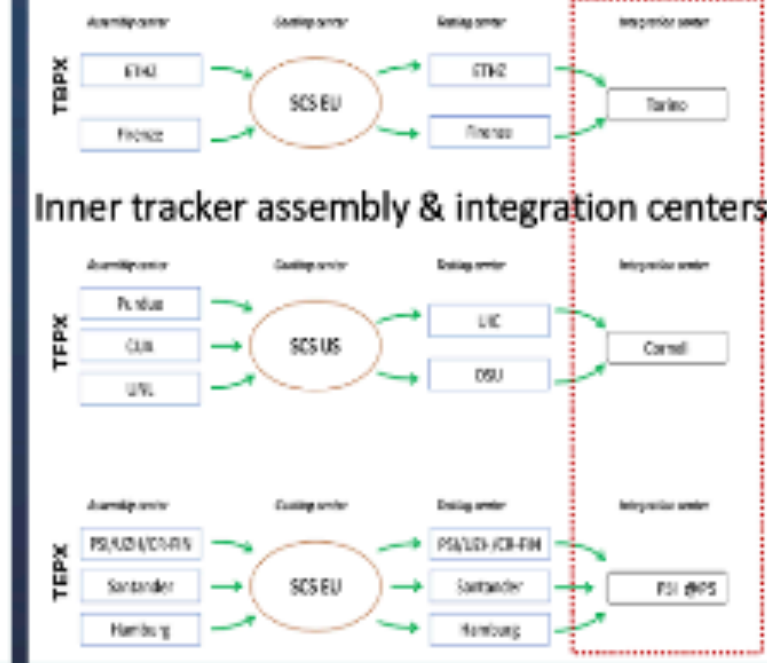
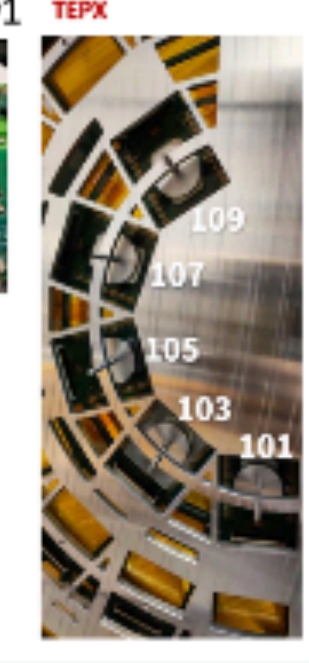
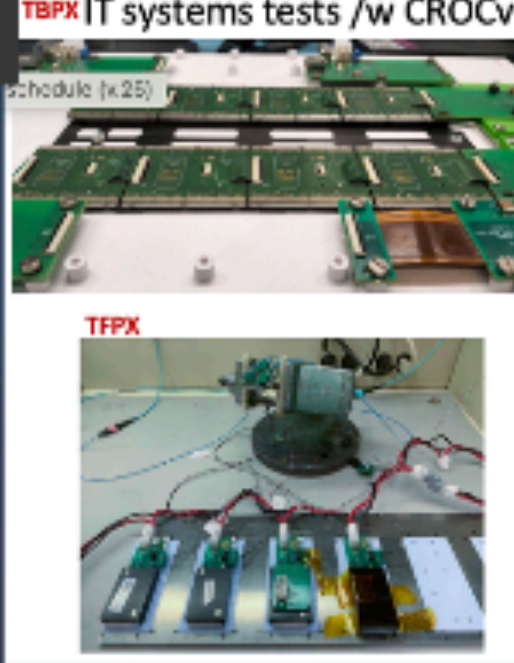
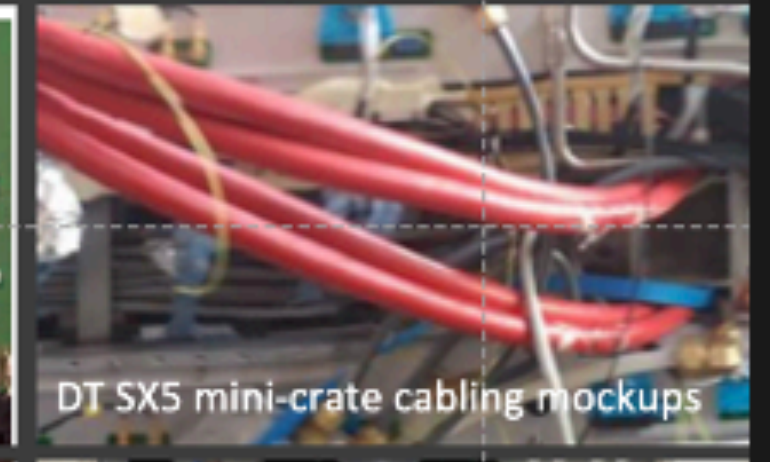
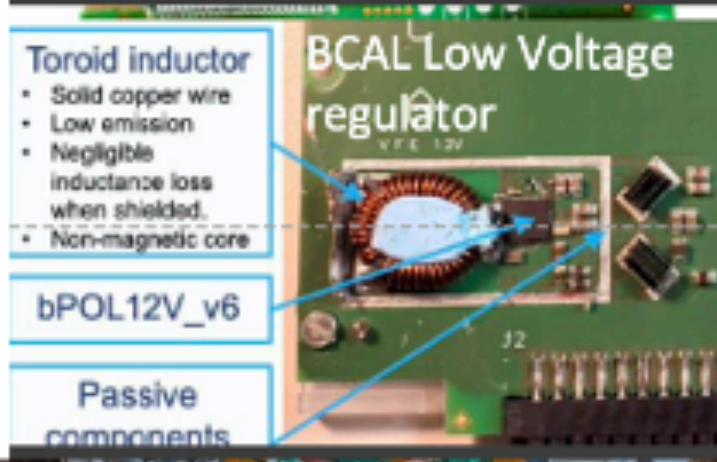
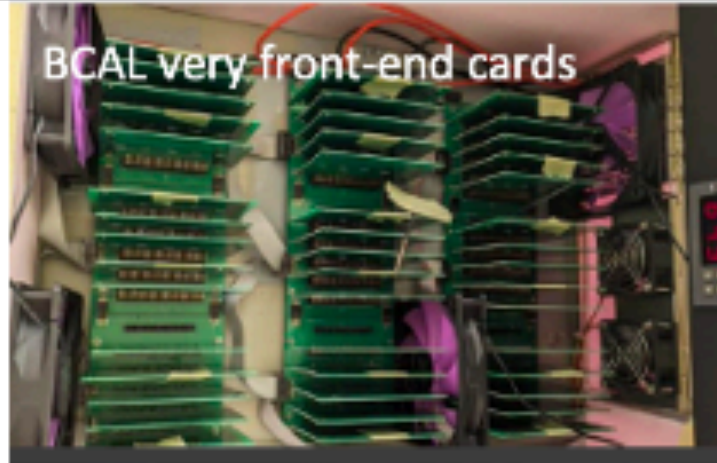
Data reprocessed w/ aggressive settings to improve low  $p_T$  reach of charged hadrons & photons/electrons



# CMS Phase-2 Upgrades

## transitioning into production

**Huge progress** although little end-float left in the schedule



# Phase-2 Highlights: Tracker

## ► Outer Tracker

- **Assembly** of pre-production **mechanical structures** (e.g. ladders) **ongoing**
- Pre-production of **hybrid** circuits **ongoing**
- **Macro-pixel ASIC** wafer testing: **high throughput** verified with company

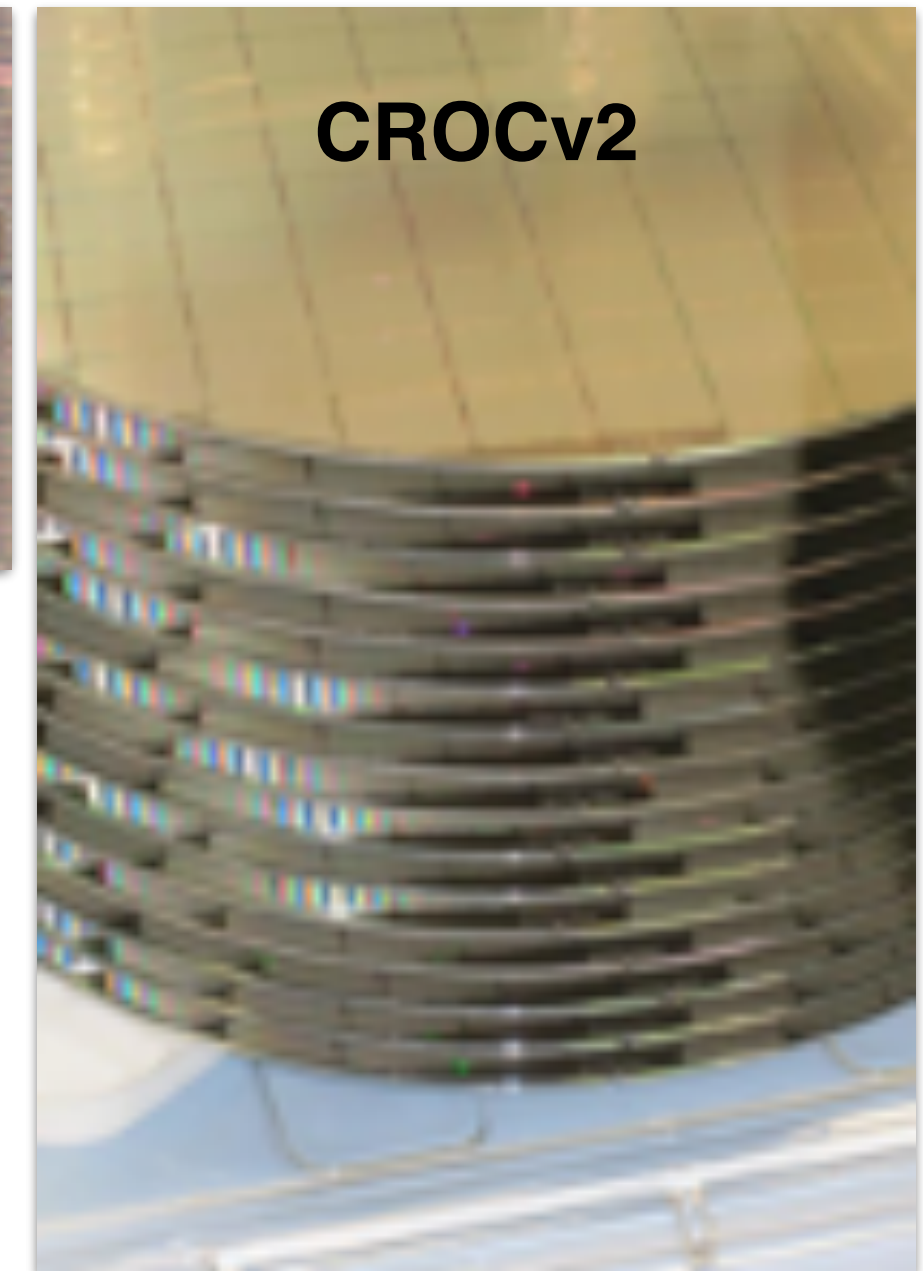
## ► Inner Tracker

- Final **ASIC** (CROCv2): First 16 wafers **received & tested**, 25 more ordered
- **Sensors**
  - First **planar production sensors** received: **good IV curves**, next batches ordered
  - **3D sensor** pre-production **ordered**
  - **Bump bonding contracts signed** for 80% of volume, rest in progress

**First 2S pre-prod. ladder assembled at New-2 (Pakistan)**



**CROCv2**



# Phase-2 Highlights: Timing & trigger

## ▶ MIP Timing Detector (MTD)

- Barrel (BTL): First [LYSO crystal production](#) batch received, SiPM [gluing tests successful](#)
- Endcap (ETL): [Completing sensor studies](#) to freeze [LGAD sensor](#) specifications
- [ASIC \(ETROC2\)](#): last prototype testing continues: [all looks good](#)

## ▶ Level-1 Trigger

- [Important milestone](#): Phase-2 back-end [Electronics Systems Review \(ESR\)](#)
- New SAMTEC12 Firefly [optical system](#) received: [extensive testing](#), only 1/400 channels failed

LGAD+ETROC2 test suitcase



SAMTEC firefly



# Phase-2 Highlights continued

## ▶ High Granularity Calorimeter (HGCal)

- Silicon sensor: production going according to plan, excellent quality
- ASIC: First HGCROC V3b arrived in early Feb. and are being tested
  - Several issues with previous version have been fixed
  - Bug identified in final version of HGCROC (v3b), investigations are ongoing
- Final Endcap Concentrator ASIC pre-production engineering run ongoing w/ vendor
- Hexaboards:
  - Pre-production bare low-density PCBs being tested at CERN
  - Design complete for all 10 other hexaboard PCB variants

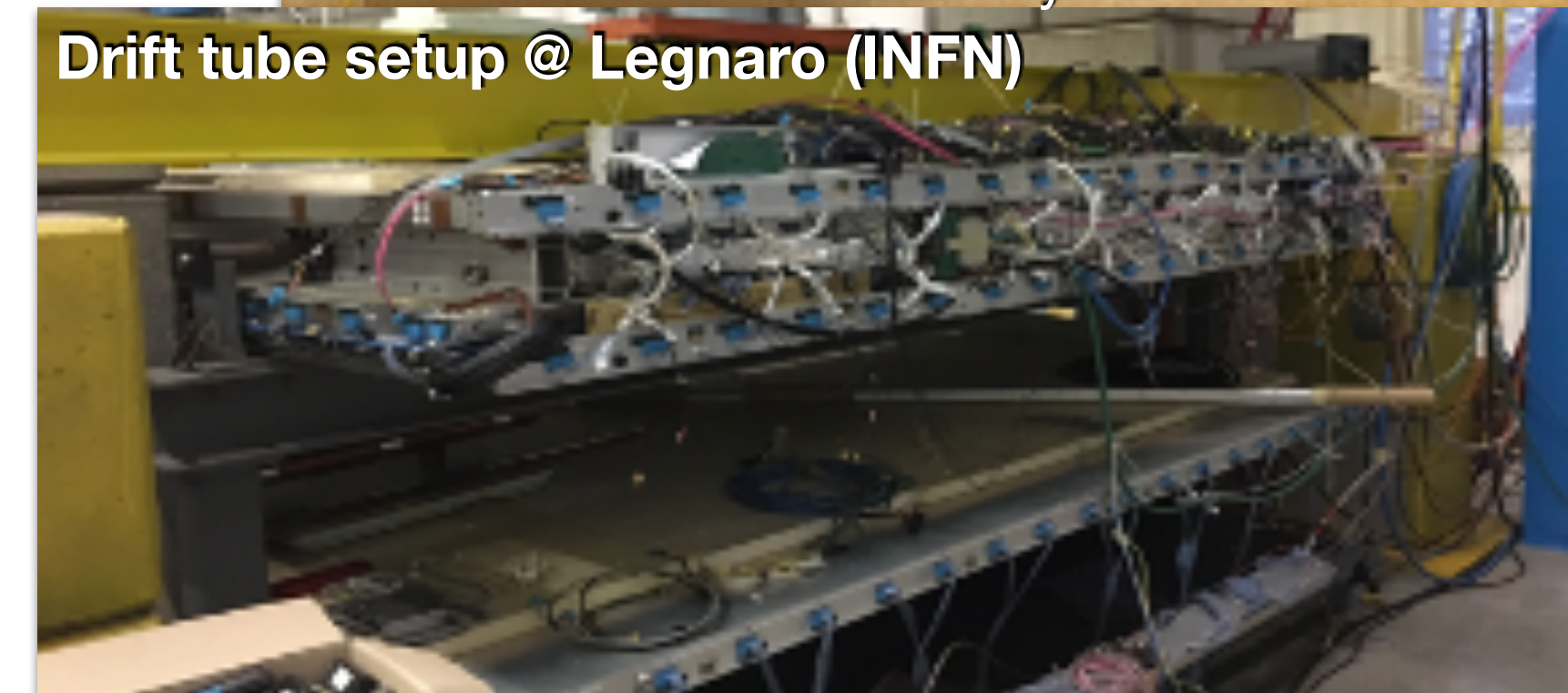
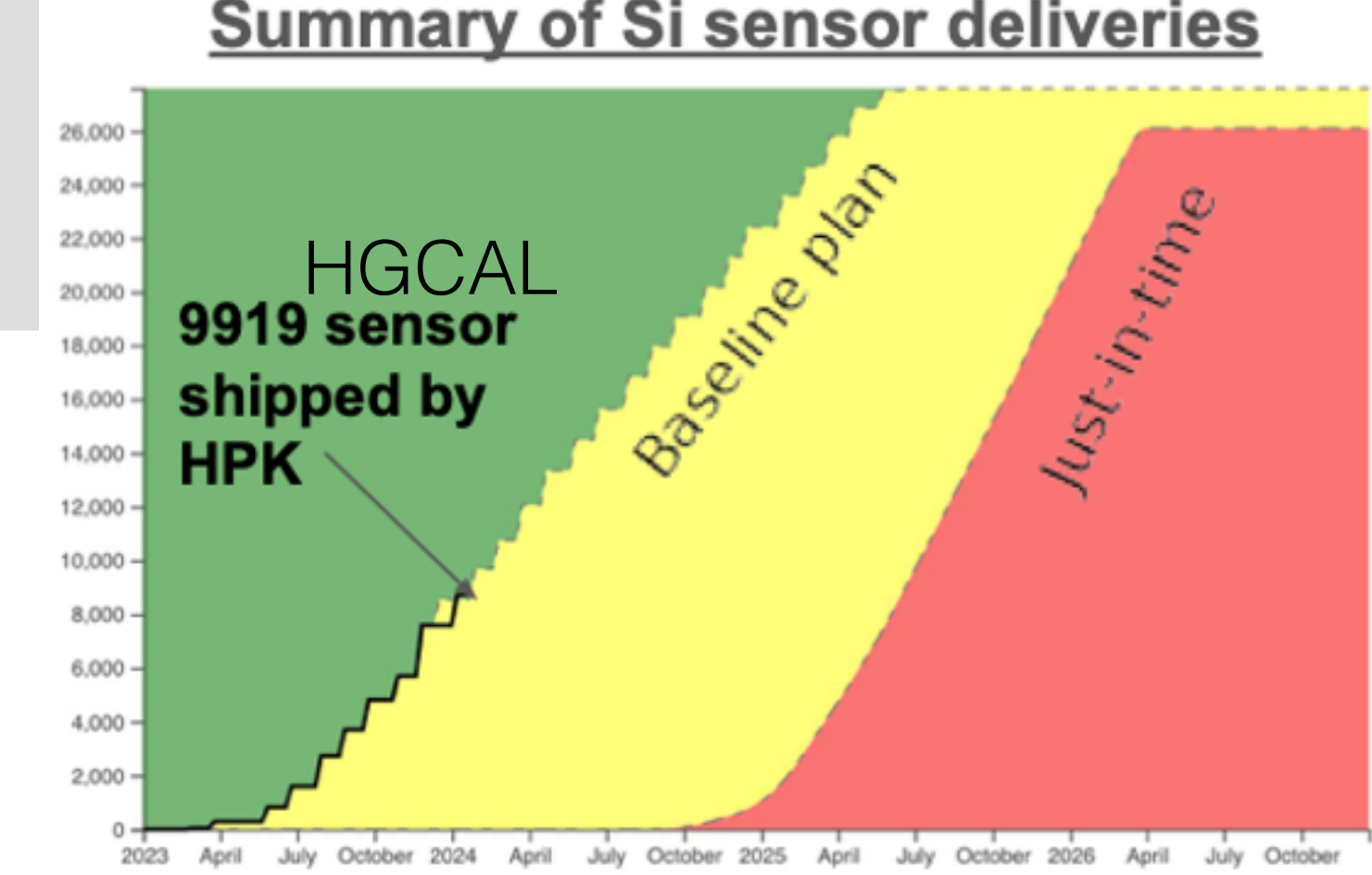
## ▶ Fast Beam Condition Monitor (Luminosity)

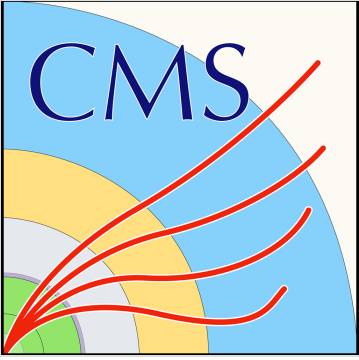
- ASIC prototype passed initial irradiation tests, further beam tests planned

## ▶ Muons

- All projects are in production
- Prototype Phase-2 electronics for drift tubes operational

## ▶ Barrel Calorimeter & DAQ progressing smoothly





# Summary

CMS released a number of new results since the last LHCC

- ▶ Luminosity for 2022, 4 BSM searches, 2 observations of rare processes + more coming!

After a lot of work during the YETS, we are ready for data taking in '24

- ▶ Several interventions were conducted to ensure robust performance for the rest of Run 3
- ▶ Expanded program of scouting & parking to make the most out of the data

Work on the Phase-2 upgrades is continuing with high priority

- ▶ We are entering the production phase for many of the components
- ▶ We continue to hit major milestones → now entering a critical phase w/ little contingency