



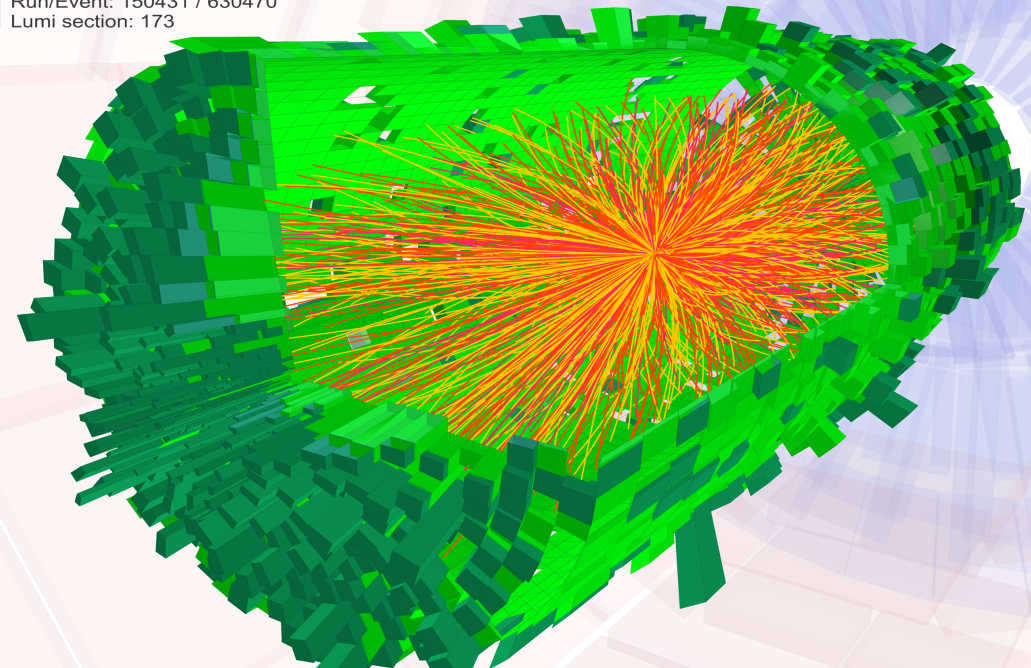
New opportunities for understanding high-density QCD matter with CMS Phase II detector at the High-Luminosity LHC era



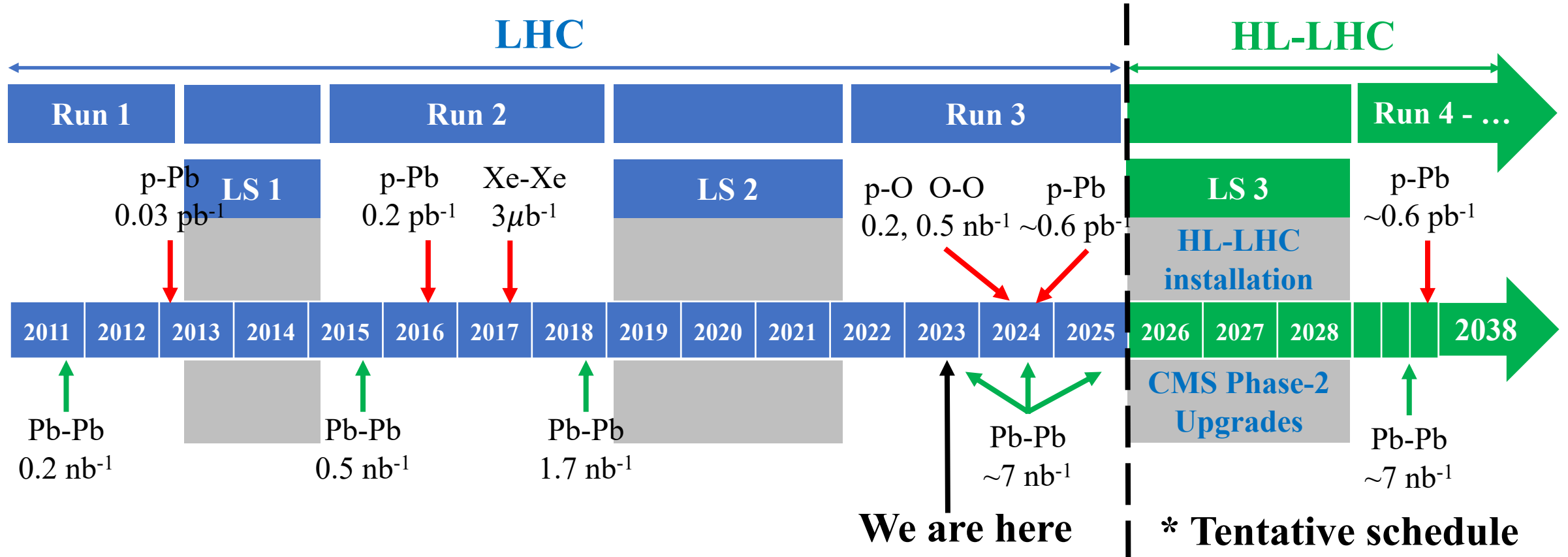
Zhenyu Ye @ University of Illinois at Chicago
on behalf of CMS collaboration



CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173



High-Luminosity LHC



The HL-LHC will deliver much higher luminosities, requiring **detector upgrades** for

- enhanced pileup interaction and radiation damage levels in pp collisions
- better discovery potentials and precision measurements

CMS Phase-2 Upgrades for HL-LHC

Trigger/HLT/DAQ

- Track info in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL

- Replace FE/BE electronics
- Lower ECAL operation temp. (8°C)

Muon Systems

- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in $1.5 < |\eta| < 2.4$
- Muon identification up to $|\eta| = 2.8$

New Endcap Calorimeters

- Radiation tolerant – high granularity
- Coverage up to $|\eta| < 5$
- 3D capable

New Tracker

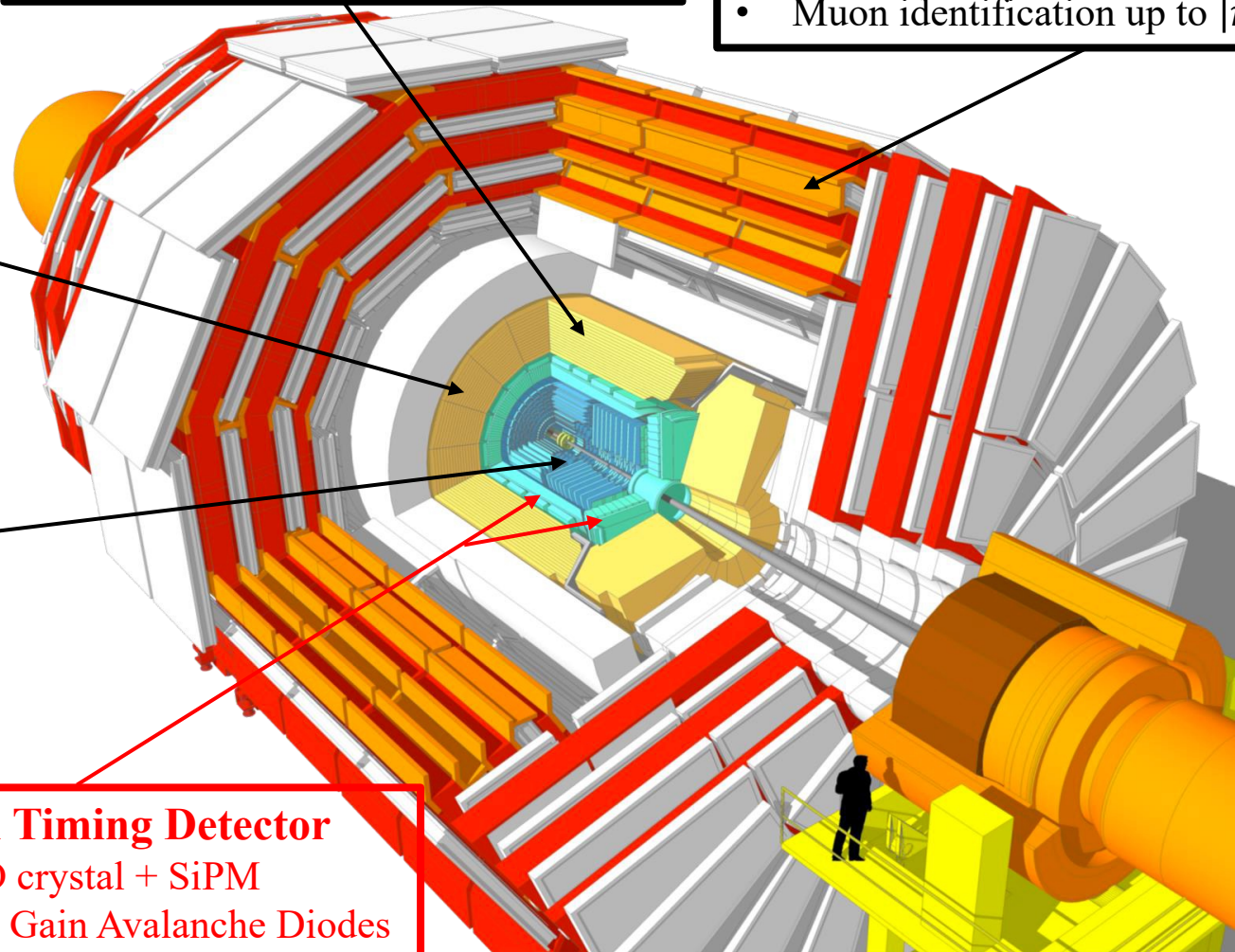
- Radiation tolerant – high granularity – significant less material
- 40 MHz selective readout ($p_T > 2$ GeV) in Outer Tracker for L1-Trigger
- Extended coverage to $|\eta| = 4$

New ZDC

- EM + Hadronic Calorimeters
- Reaction Plane Detector

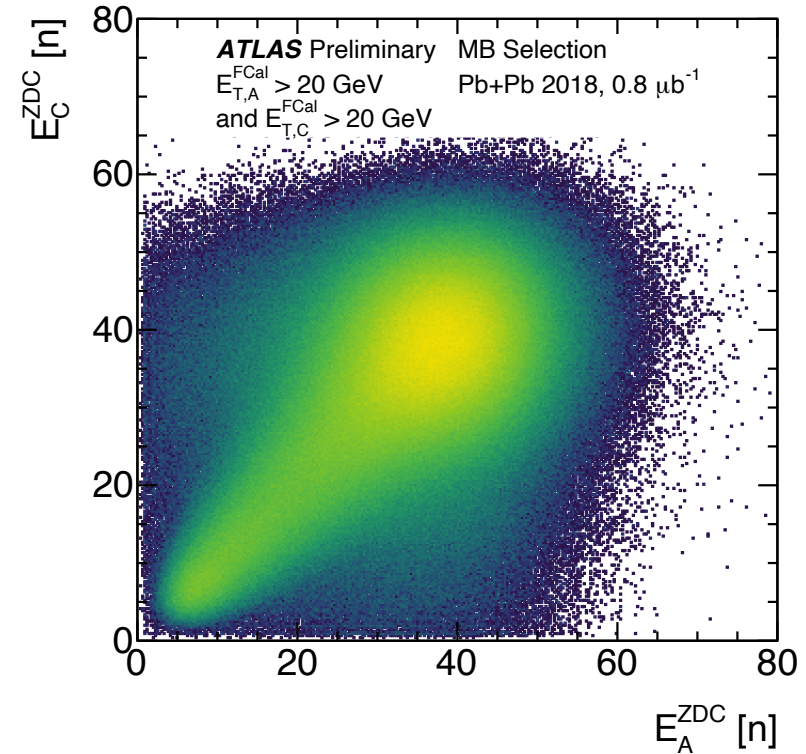
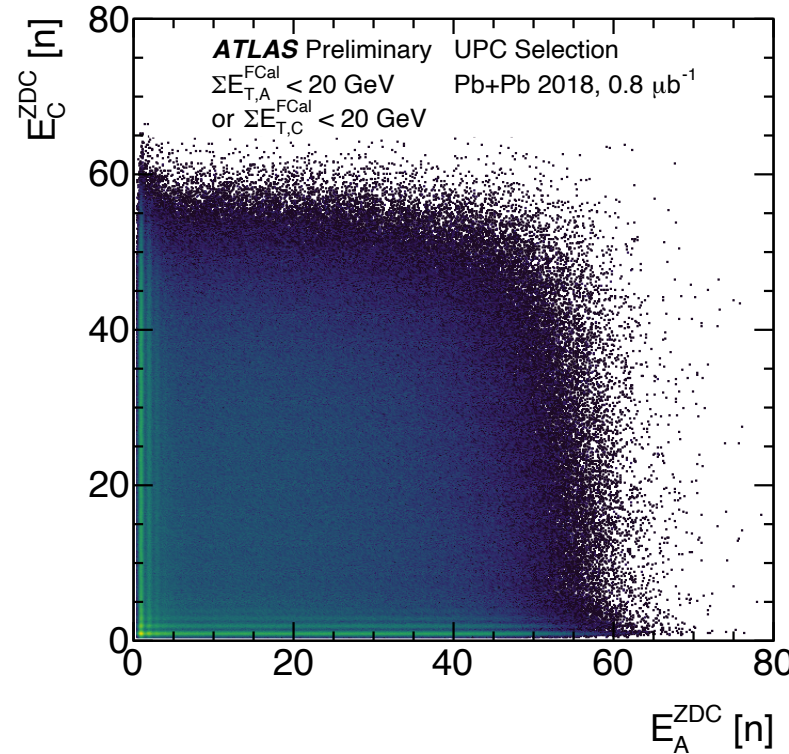
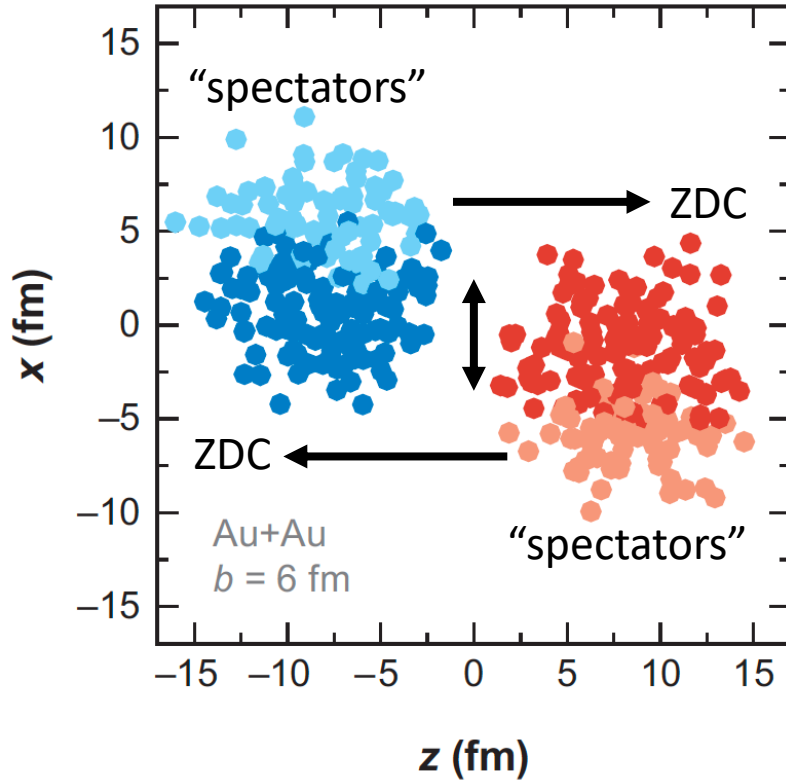
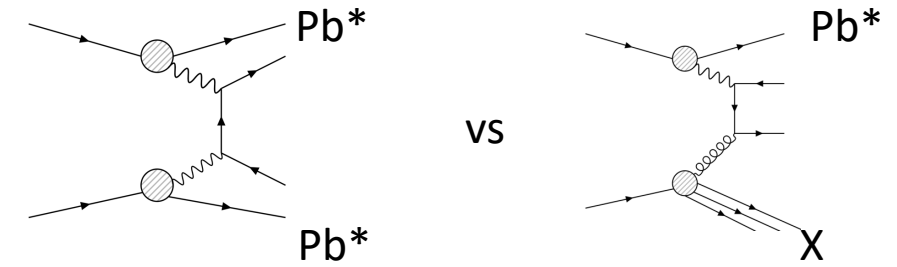
MIP Precision Timing Detector

- Barrel: LYSO crystal + SiPM
- Endcap: Low Gain Avalanche Diodes



ZDCs in Heavy Ion Collisions

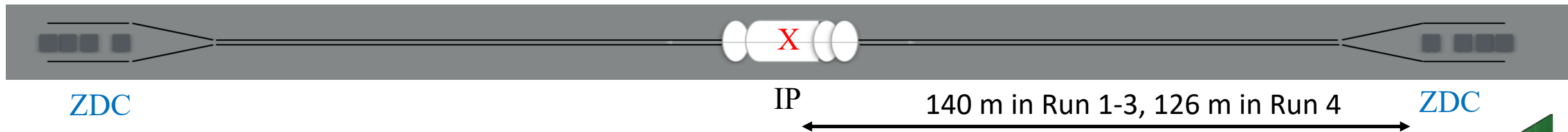
[Ann. Rev. Nucl. Part. Sci. 57 \(2007\) 205](#)



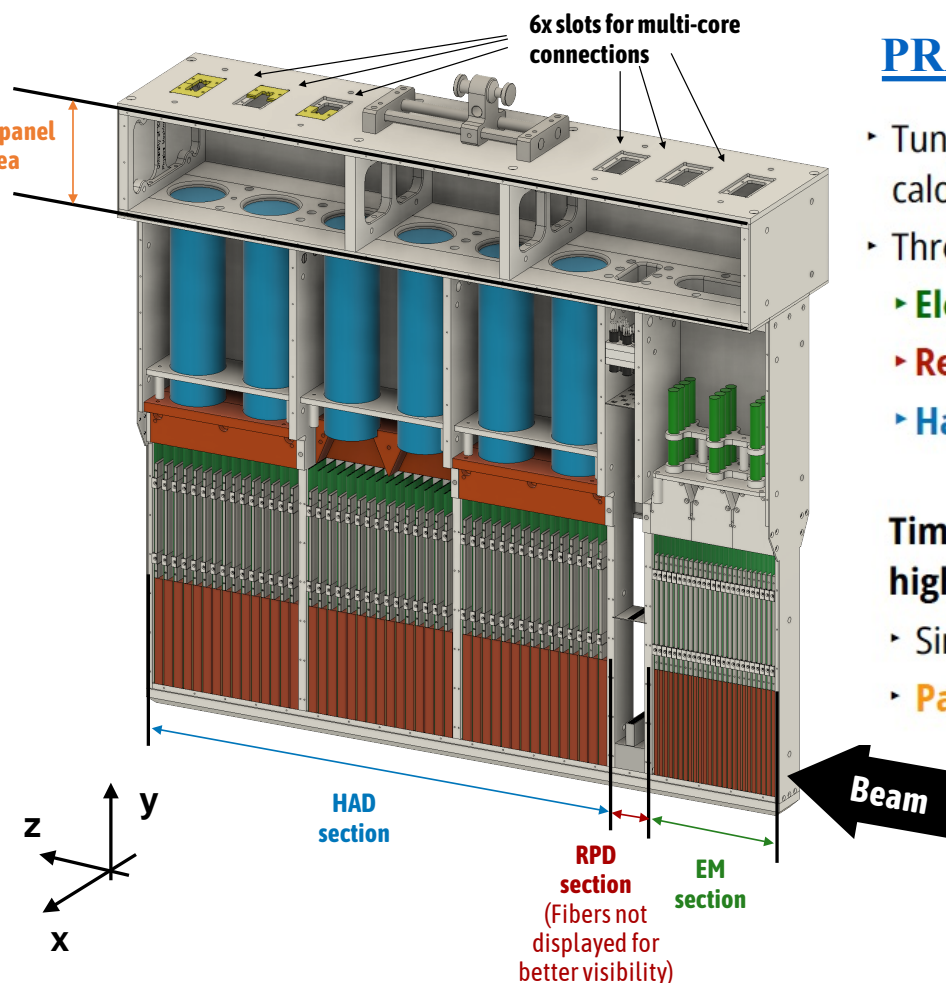
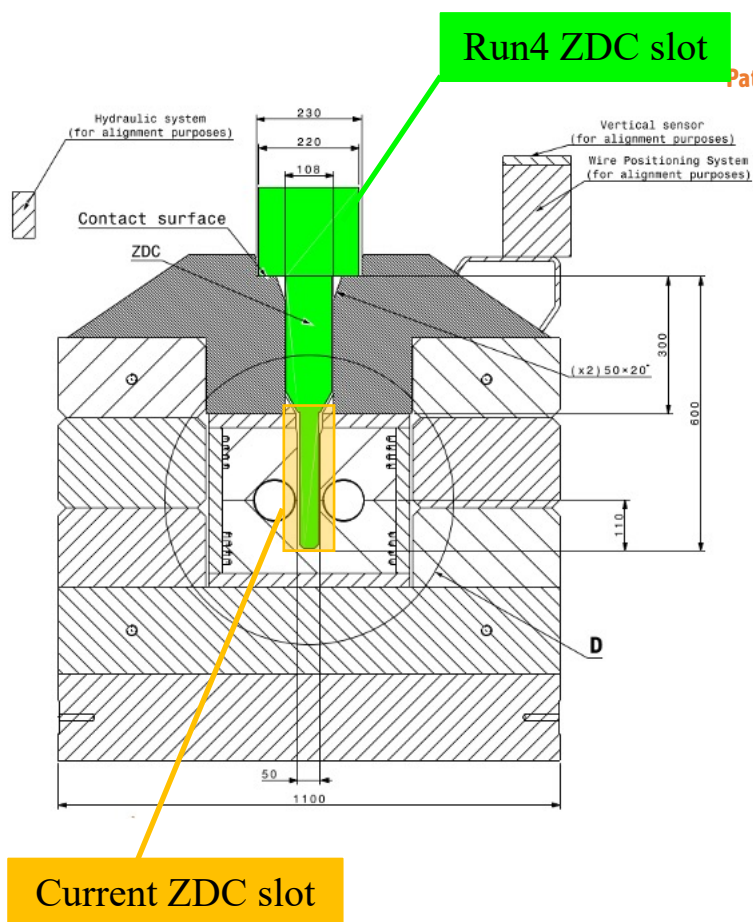
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/HION-2018-002/>

Correlation of the number of “spectator” neutrons is different between **gamma-gamma (OnOn)**, **photonuclear (XnOn/OnXn)** and **hadronic (XnXn)** processes. **ZDCs are critical to distinguish these processes and have played a key role in both trigger and analysis.**

ZDCs for ATLAS/CMS at HL-LHC



CERN-EDMS-2349145

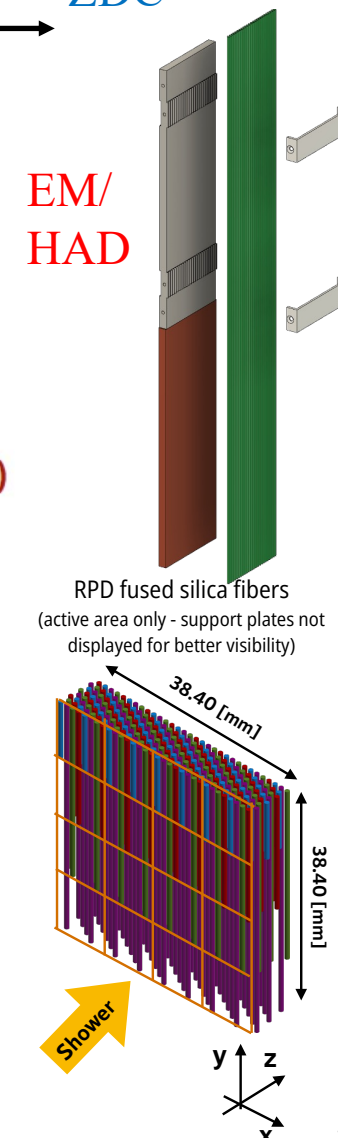


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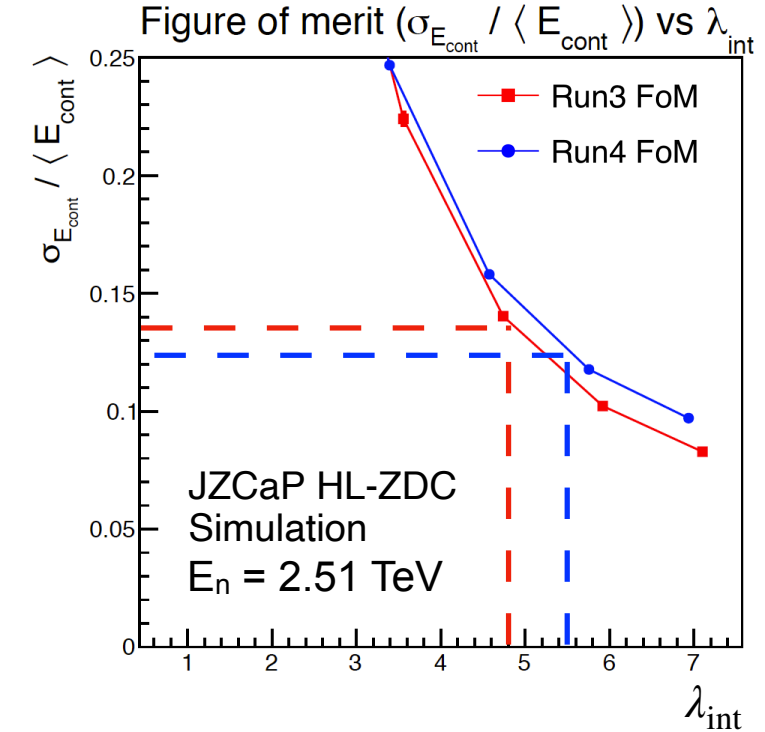
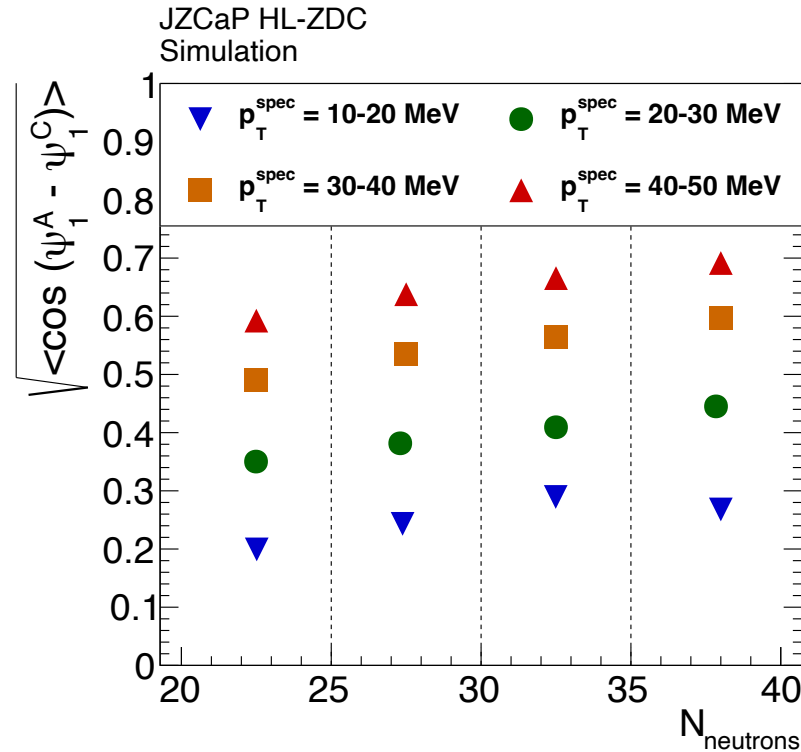
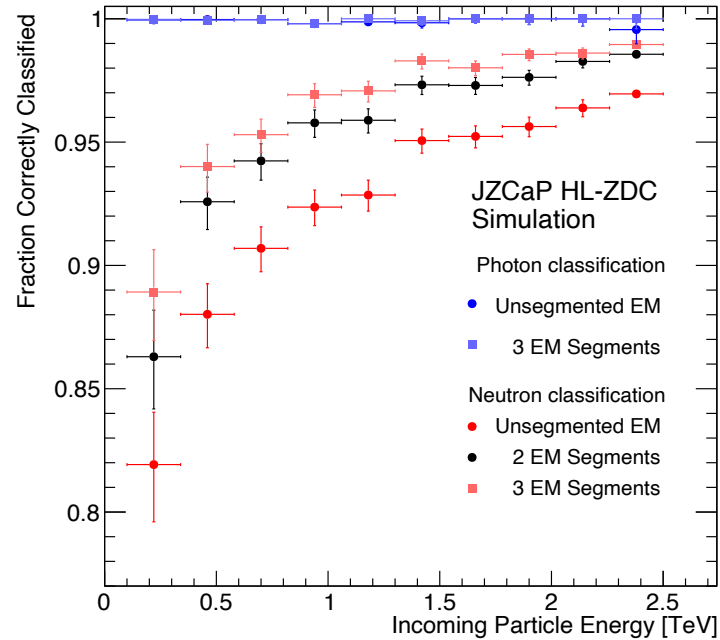
- ▶ Tungsten - fused silica sampling calorimeter
- ▶ Three sections:
 - ▶ **Electromagnetic (EM)**
 - ▶ **Reaction Plane Detector (RPD)**
 - ▶ **Hadronic (HAD)**

Time-efficient installation in high-radiation environment

- ▶ Single module structure
- ▶ **Patch panels** for rapid cabling



ATLAS/CMS HL-LHC ZDC Performance in Simulation



• EM Section

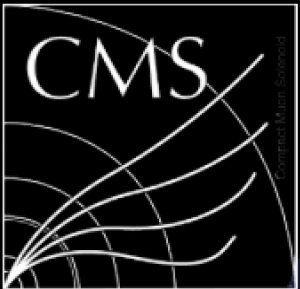
- Basic γ/n discrimination algorithms using the light fraction in the longitudinal segments show $\sim 99\%$ purity for neutron identification and even higher performance for photons

• Reaction Plane Detector

- Performance comparable w/ STAR SMD, will be sufficient to provide access to new physics measurements also in cases of low p_T kick

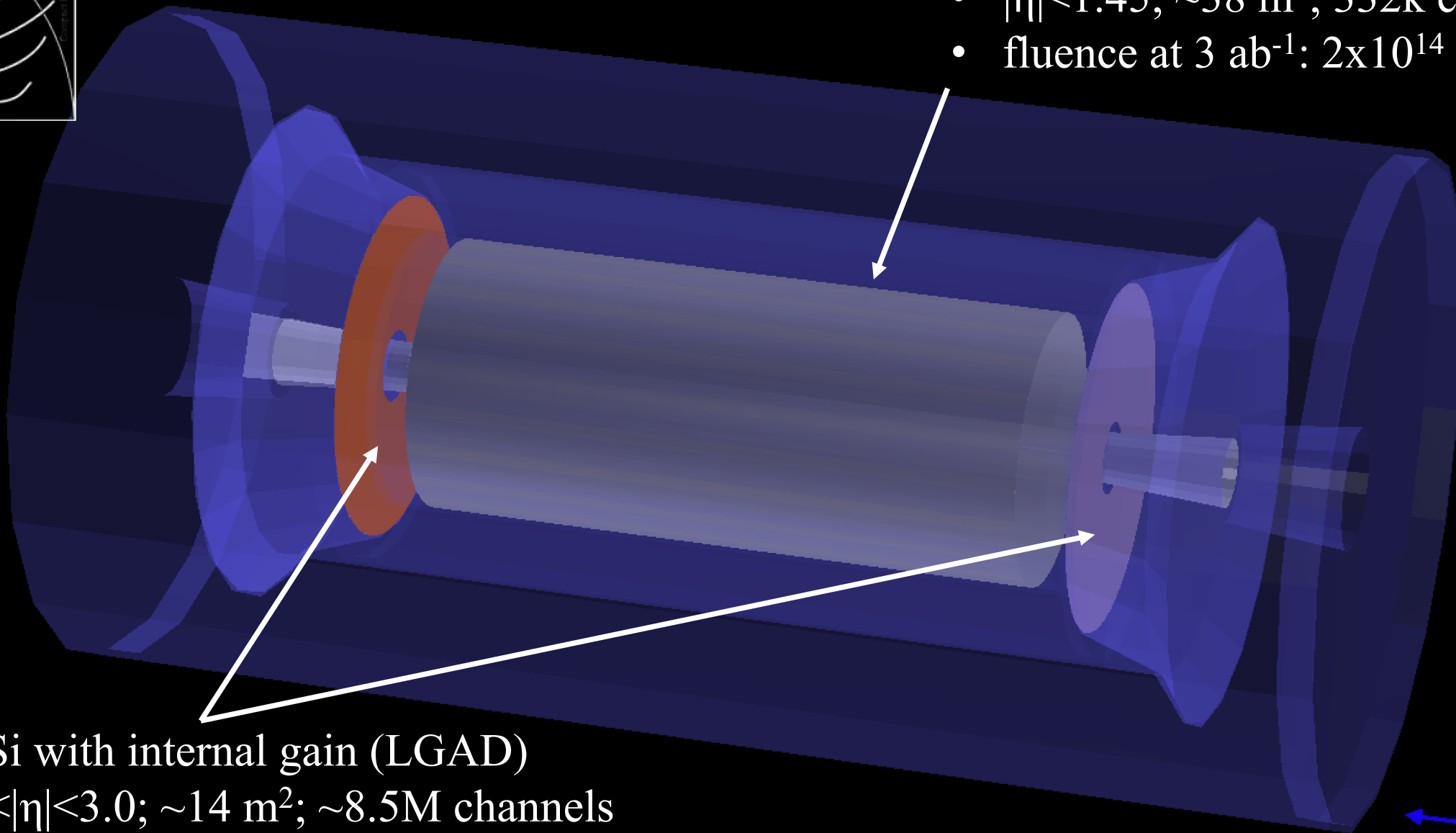
• Hadronic Section

- Similar containment, but HL-ZDC has better resolution!



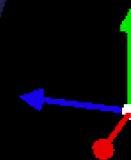
BTL: LYSO bars + SiPM

- $|\eta| < 1.45$; $\sim 38 \text{ m}^2$; 332k channels
- fluence at 3 ab^{-1} : $2 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$



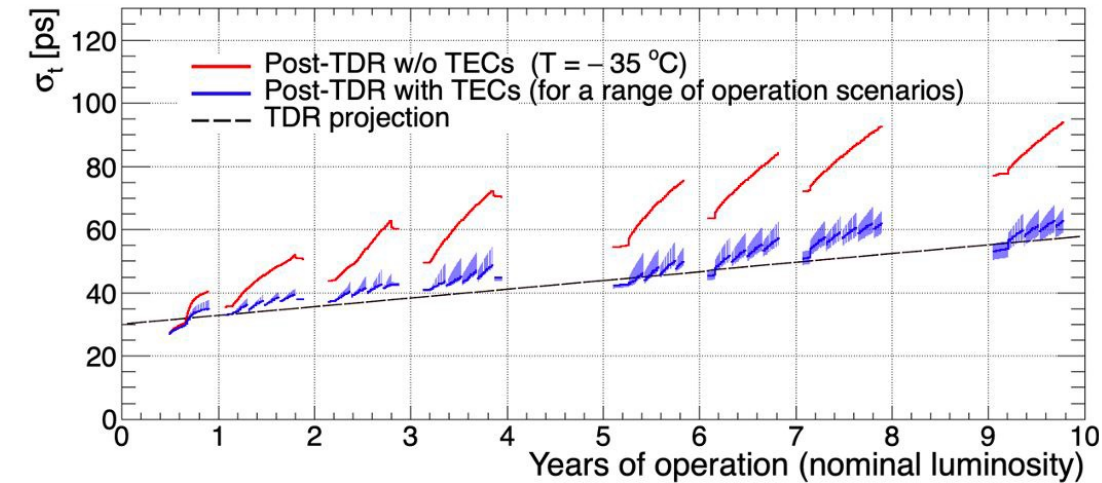
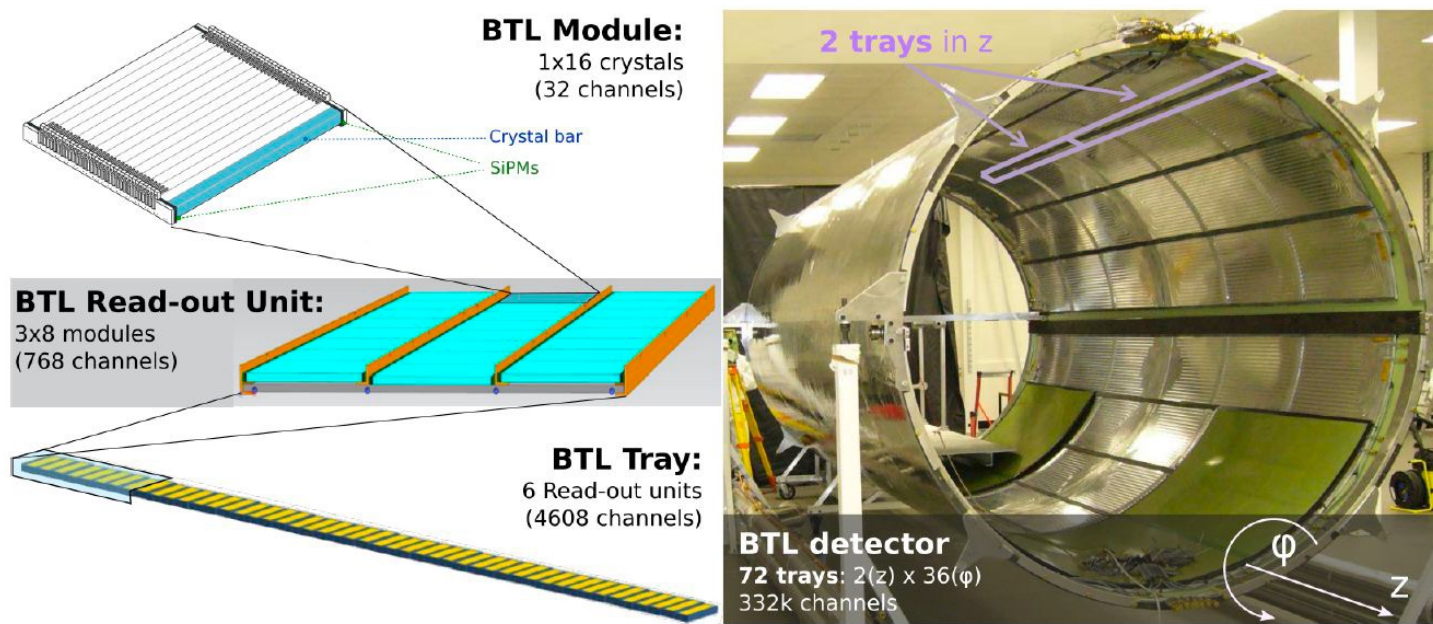
ETL: Si with internal gain (LGAD)

- $1.6 < |\eta| < 3.0$; $\sim 14 \text{ m}^2$; $\sim 8.5 \text{ M}$ channels
- fluence at 3 ab^{-1} : $\sim 2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$

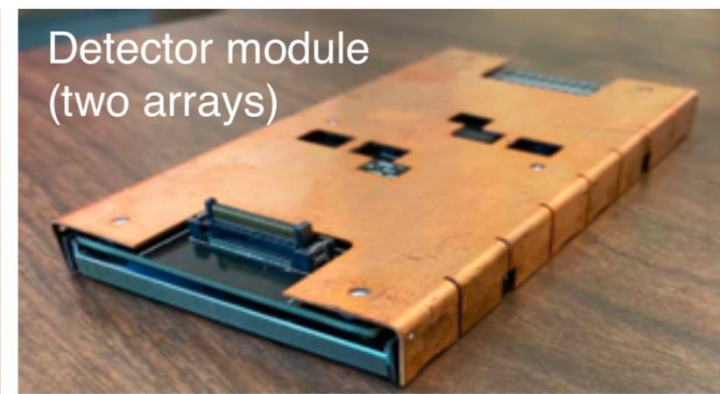
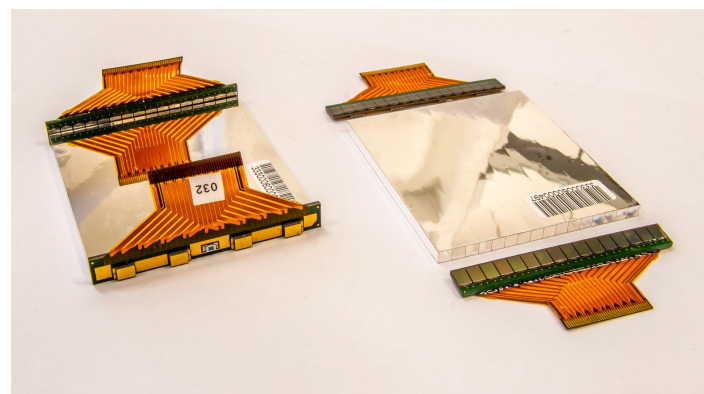


CMS MTD Barrel Timing Layer

CERN-LHCC-2019-003



- One layer of **LYSO+SiPM** in the barrel region optimized for precise timing measurements
 - Surface $\sim 38\text{ m}^2$; $\sim 332\text{k}$ channels
 - 30-40 ps at the beginning of operation
 - 50-60 ps at the end of operation due to radiation damage
- SiPM dark current increases due to radiation damage. To reduce such effect,
 - Thermoelectric Cooler to work at -45°C
 - In-situ annealing up to 60°C during shutdown/technical stops

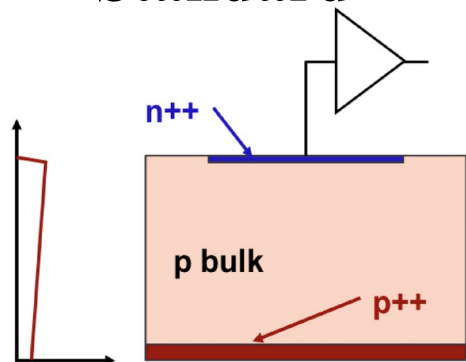


BTL modules are made of 16 bars of LYSO crystals coupled at each end with Silicon Photon Multipliers (SiPMs)

CMS MTD Endcap Timing Layer

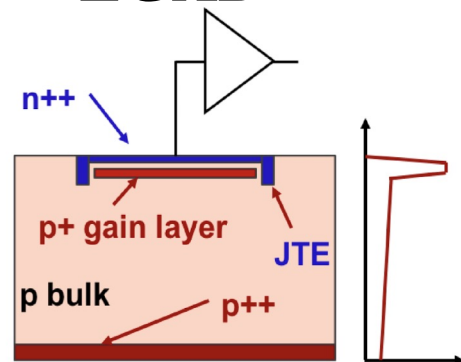
CERN-LHCC-2019-003

Standard

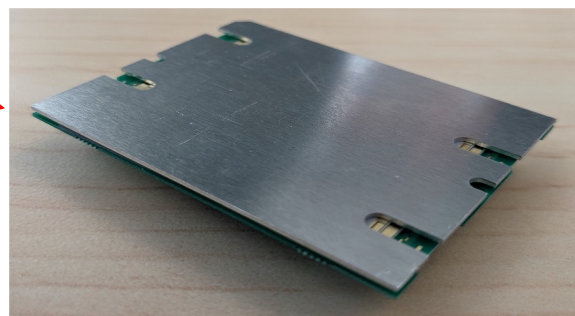
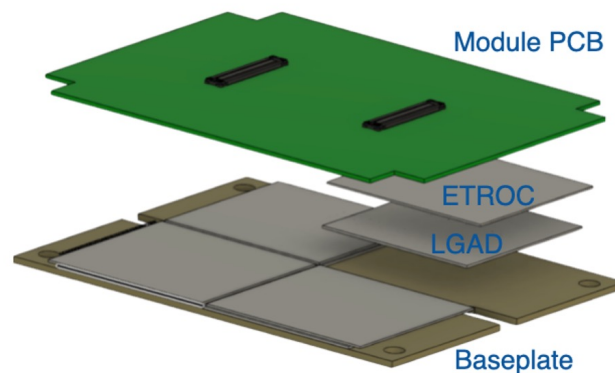
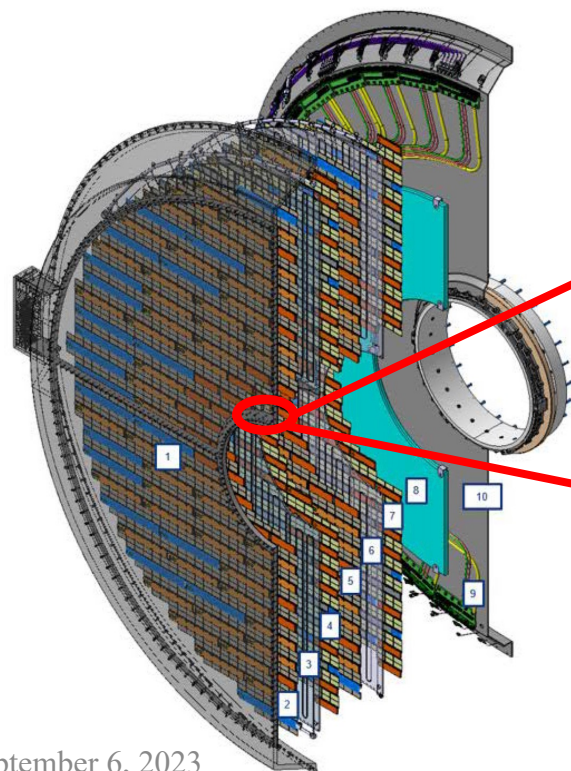
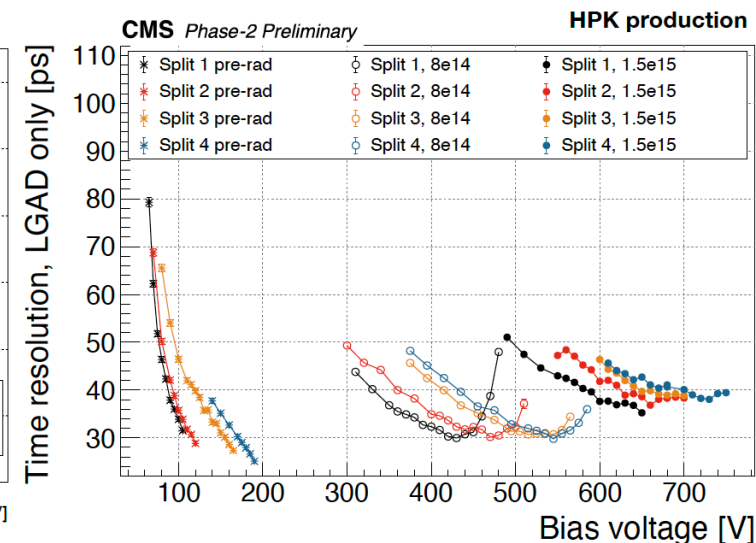
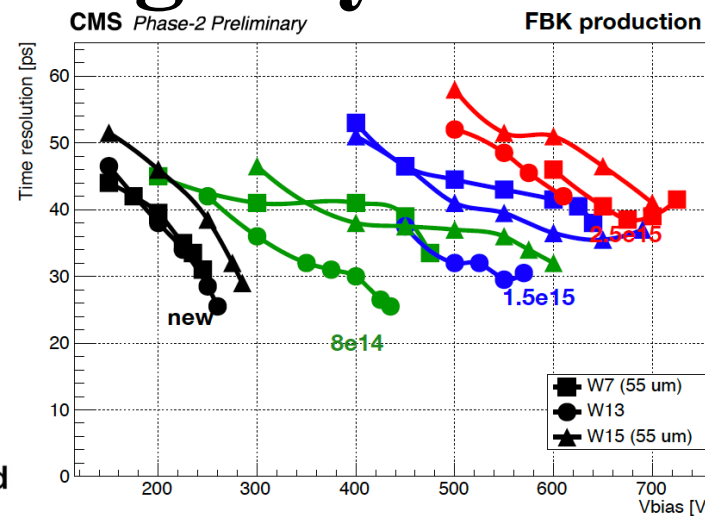


E field Traditional Silicon detector

LGAD



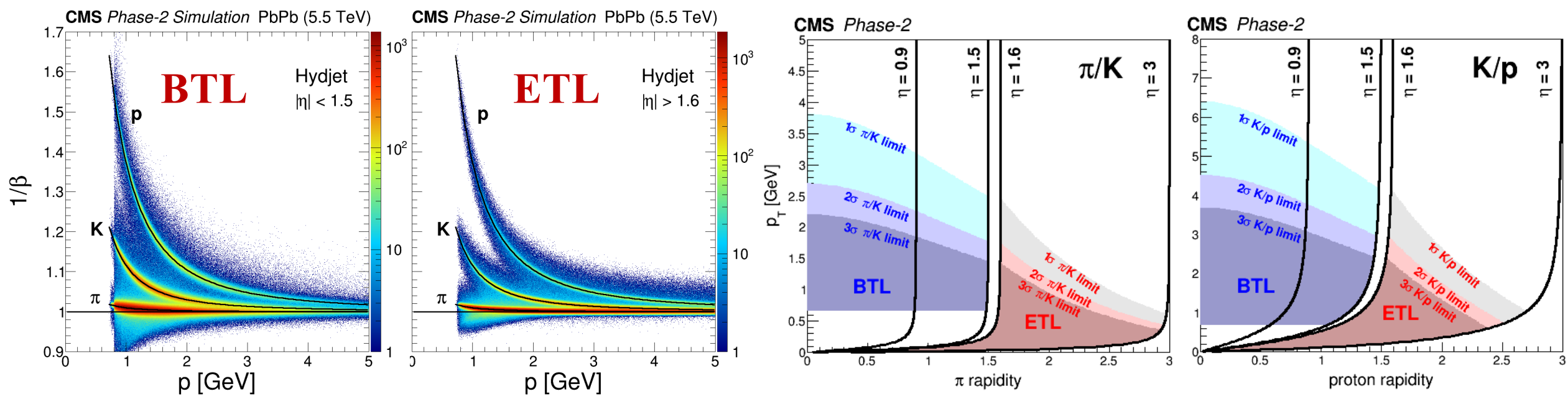
Ultra Fast Silicon Detector E field



- Two disks on each side with **Low Gain Avalanche Diode** sensors optimized for precise timing measurements
 - Surface $\sim 14 \text{ m}^2$; $\sim 8.6\text{M}$ channels
 - $< 50 \text{ ps per hit} \rightarrow < 35 \text{ ps per track}$
- Only 12% of surface will reach higher fluences than $1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, where degradation begins

TOF-PID Performance with CMS MTD

CMS-DP-2021-037



Experiment	η coverage	L (m)	σ_T (ps)	L/σ_T (x100) (m*ps ⁻¹)
CMS BTL	$ \eta < 1.45$	1.16	35	3.87
ETL	$1.6 < \eta < 3.0$	3.0	35	8.57
ALICE	$ \eta < 0.9$	3.7	56	6.6
STAR	$ \eta < 0.9$	2.2	80	2.75

Momentum coverage competitive to ALICE and STAR in barrel. Unique hermetic coverage up to $|\eta| = 3$.

New Physics Opportunities with MTD

Questions

- What is the (3+1)D dynamics of heavy flavors in QGP?
- How does QGP medium response to energy loss?
- What is origin of collectivity in smallest systems?

Measurements

Heavy flavor hadrons over wide y
($D/D_s/\Lambda_c$, $B/B_s/\Lambda_b$)



Jet – identified hadron
correlations over wide angles



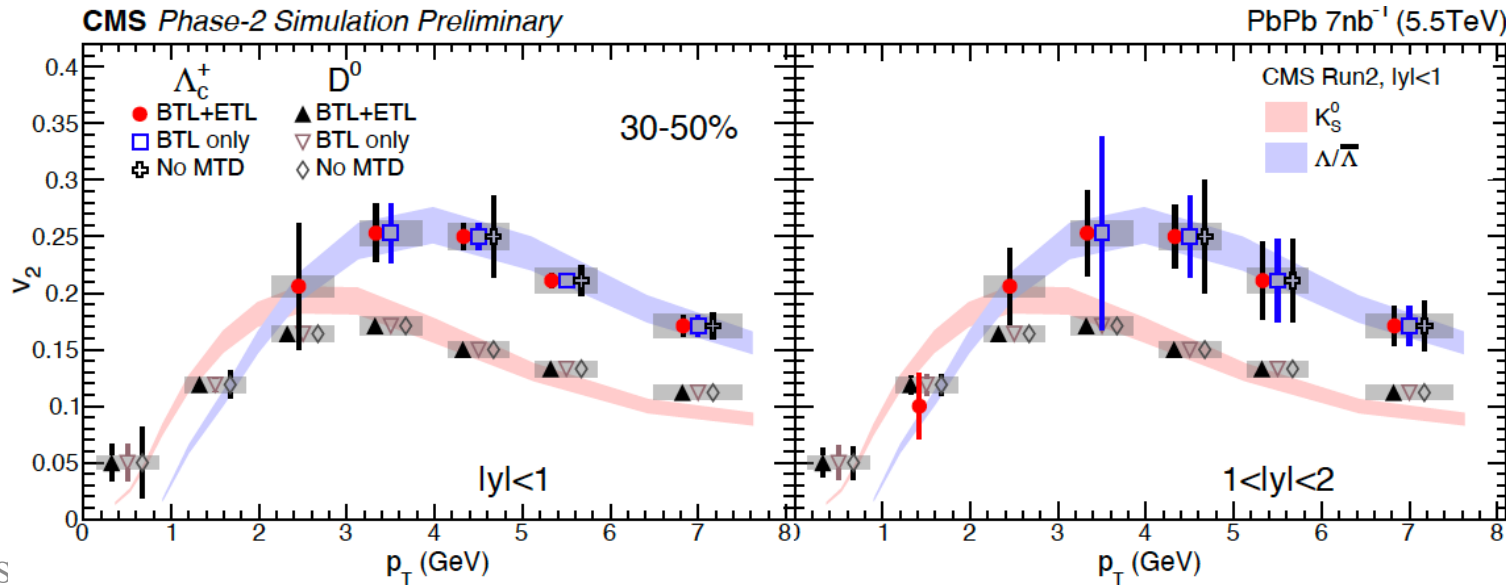
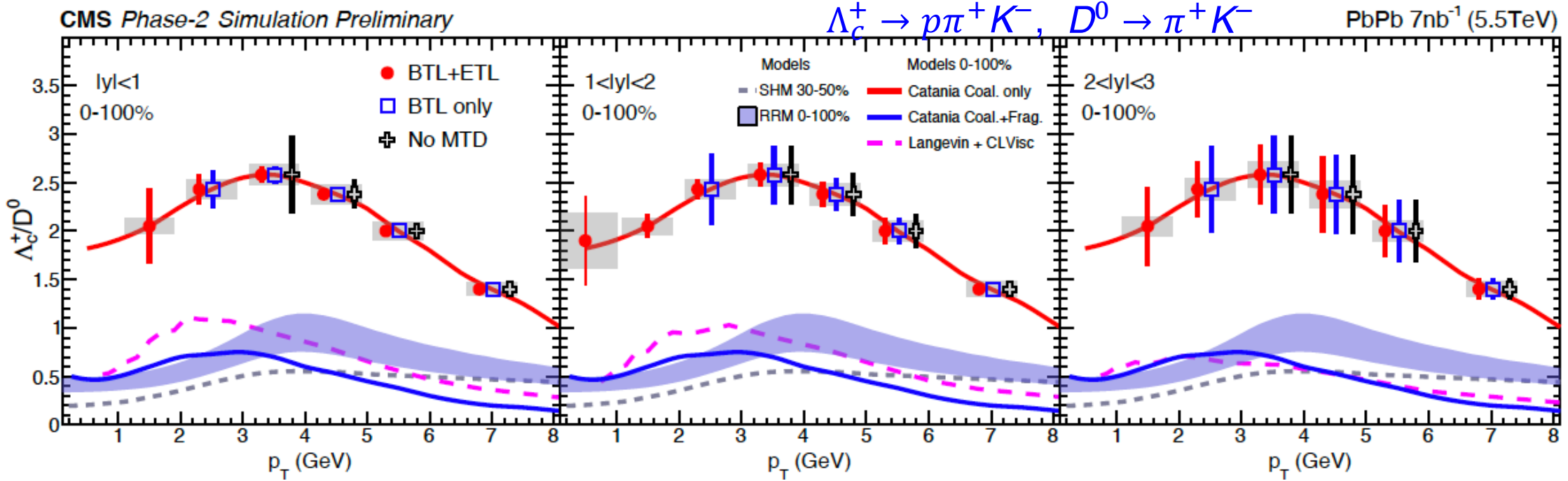
Correlations with a wide range
of identified probes



Wide-coverage Tracking	Precision vertex	Full calorimetry (ECAL+HCAL)	High rate/HLT	Lepton PID	Hadron PID (MTD)
✓	✓	✓	✓	✓	✓

3+1 Dimensional Heavy Quark Dynamics with MTD

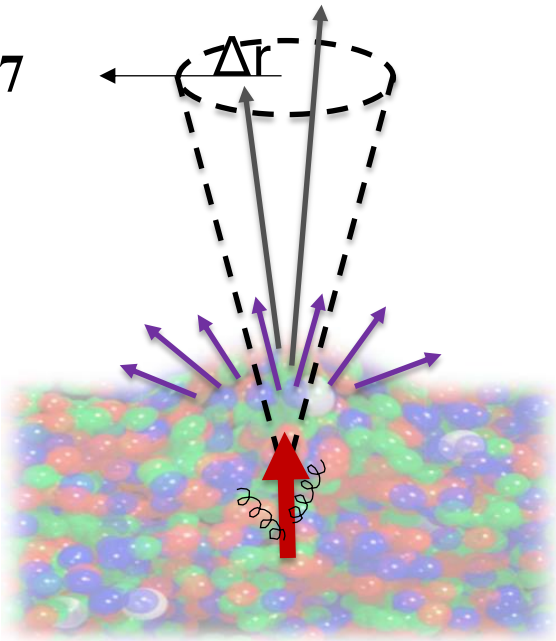
CMS-DP-2021-037



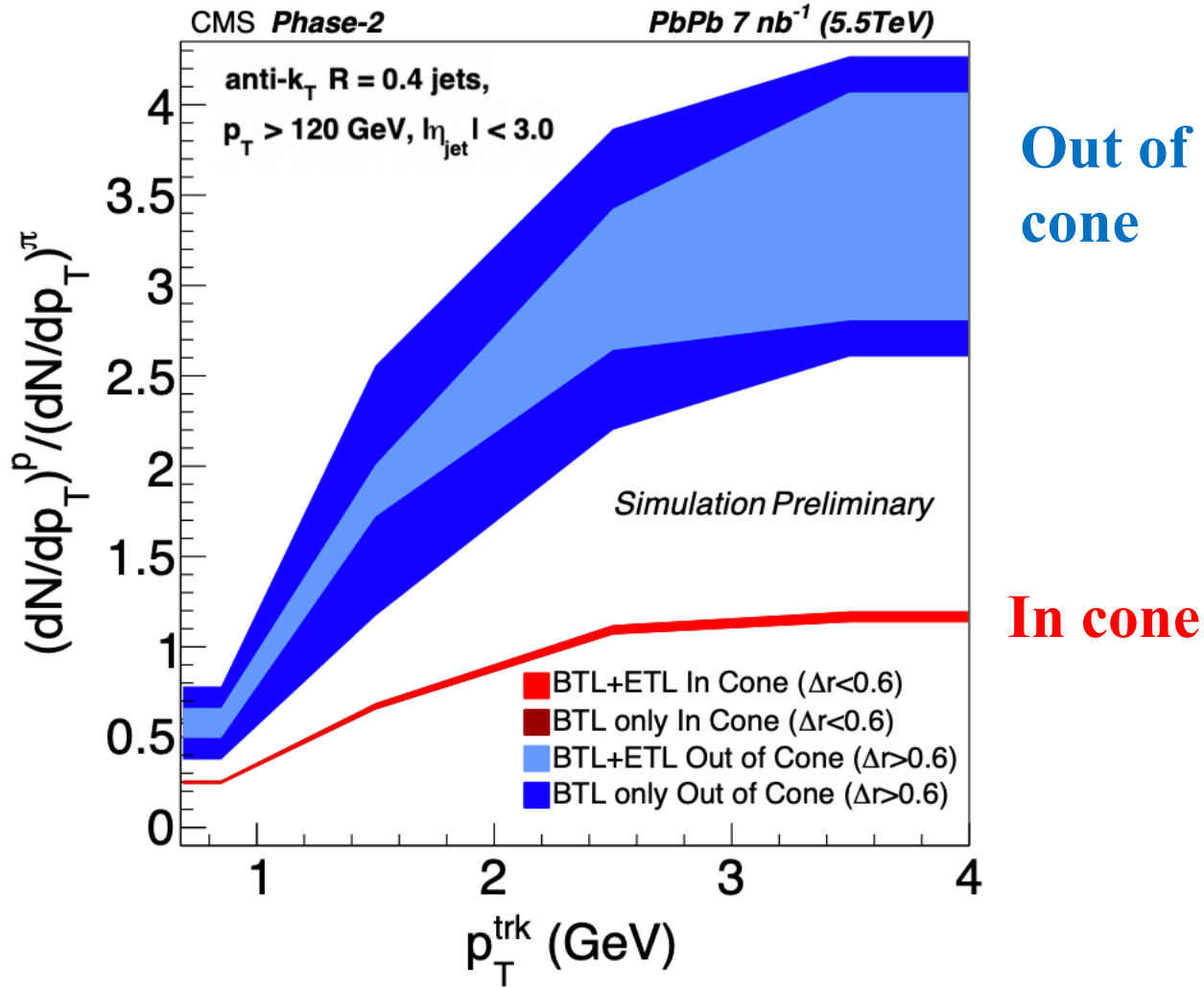
- CMS will be able to study c and b-hadrons over 6 units of rapidity ($|\eta| < 3$) with MTD.
- Capable of measuring Λ_c and D hadrons down to $p_T \sim 0$ GeV with BTL+ETL.
- Measurements of HF hadron production yield and correlation will constrain the (3+1)D HF dynamics in QGP.

Jet Quenching and Medium Response with MTD

CMS-DP-2021-037



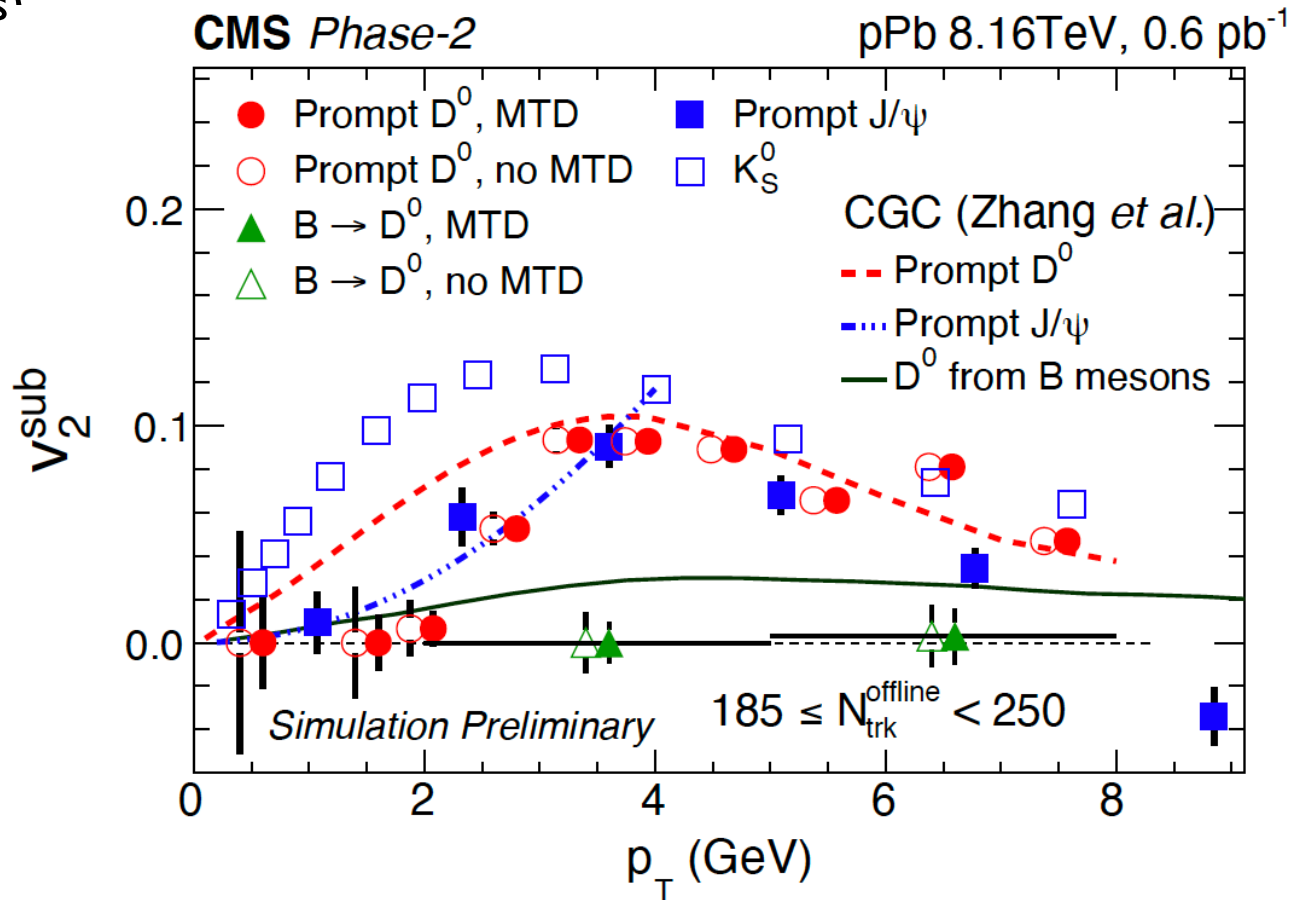
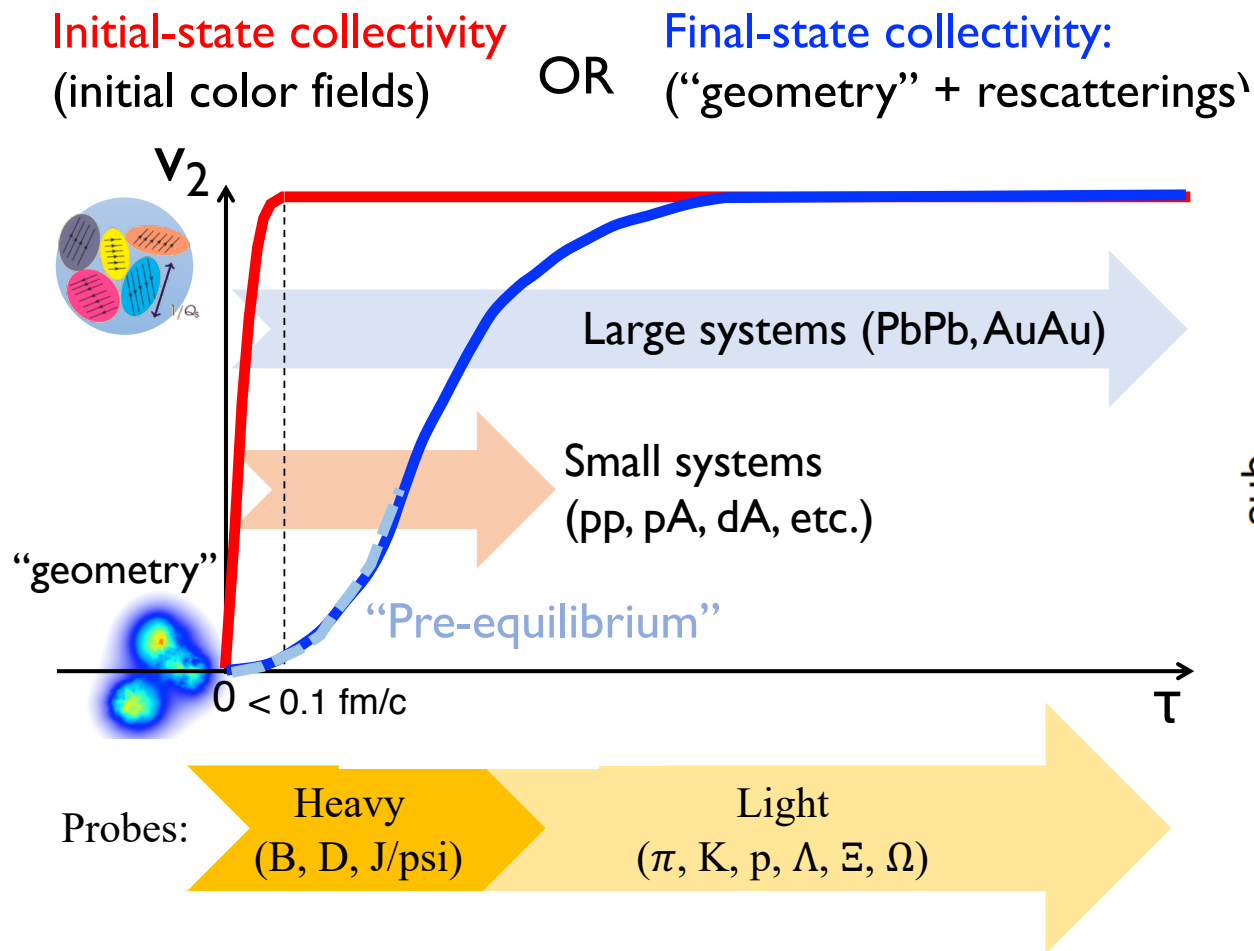
Wide-coverage Tracking	Full calorimetry (ECAL+HCAL)	High rate/HLT	Wide-coverage Hadron PID
✓	✓	✓	✓ (MTD)



Unique measurement only possible by CMS with the MTD to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.

Origin of Collectivity in Small Systems with MTD

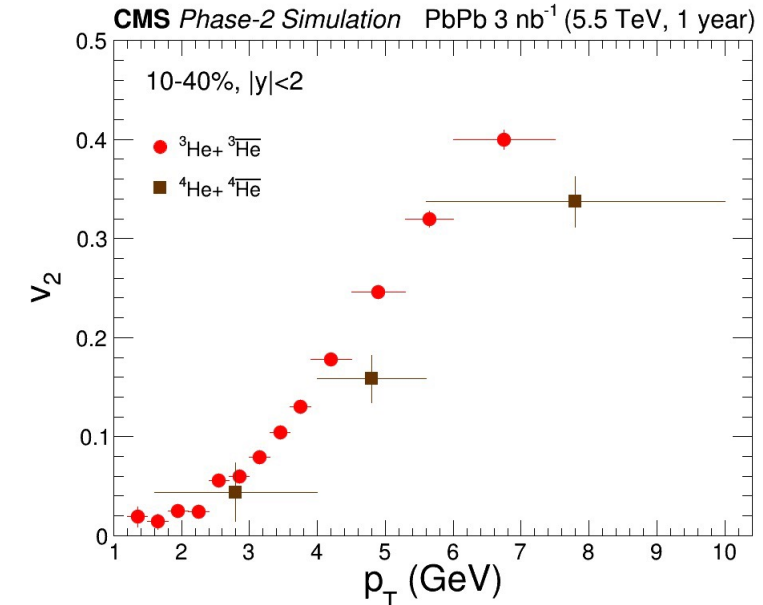
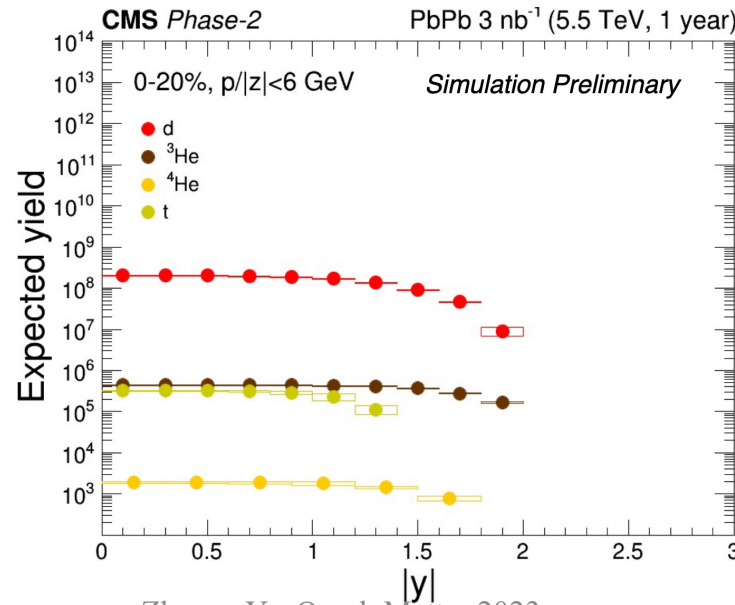
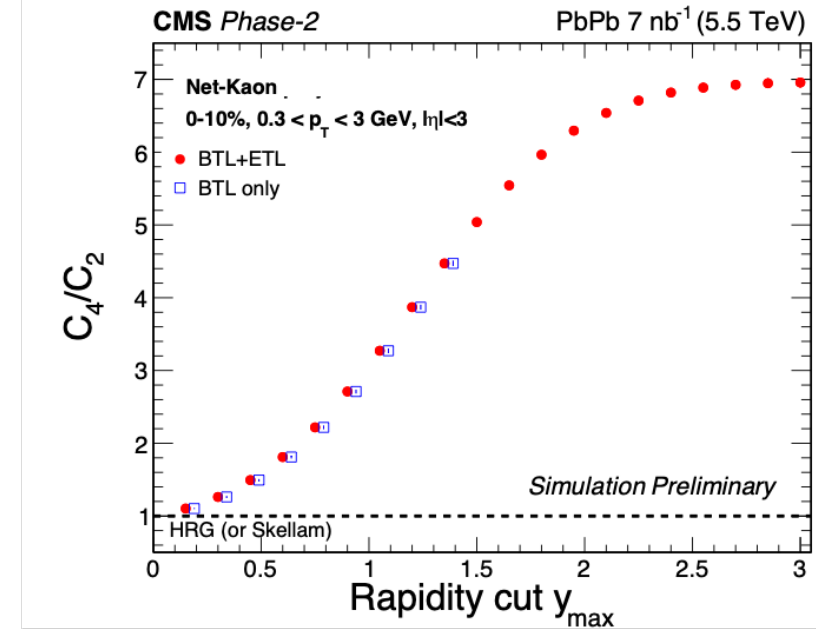
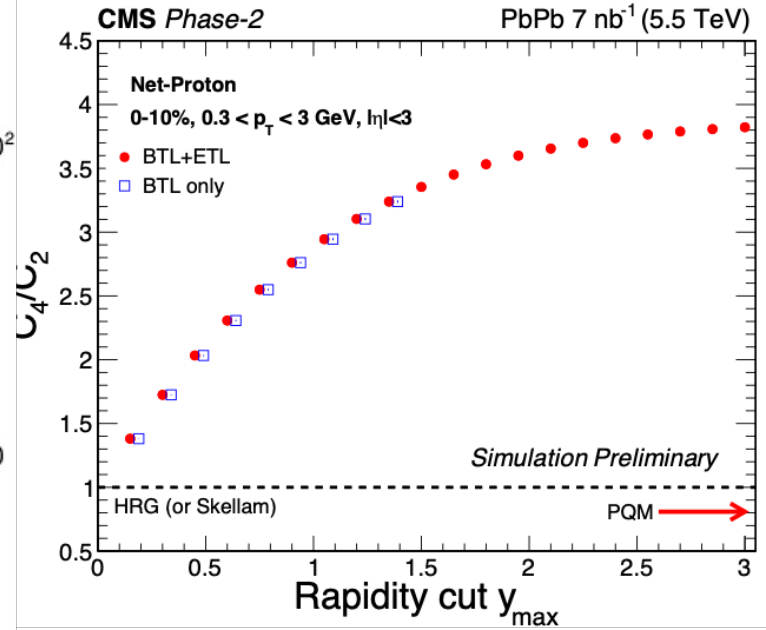
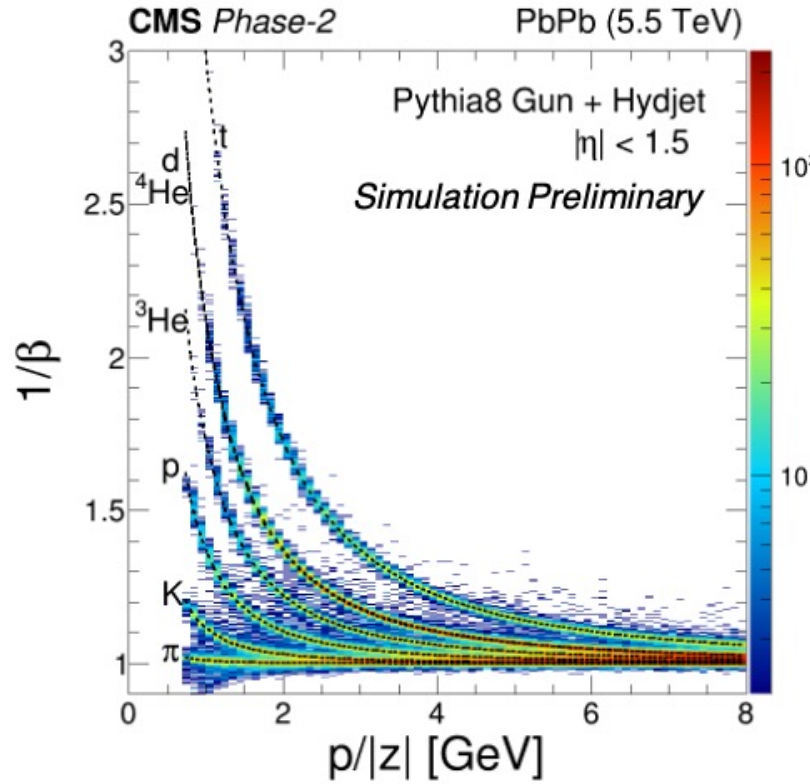
CMS-DP-2021-037



Collect data by triggering on high MIP-multiplicity in small systems with MTD, which can reduce the background, allowing to measure v_2 down to very low p_T for a variety of HF hadrons

Net-Proton/Kaon Cumulants and Light Nuclei Production

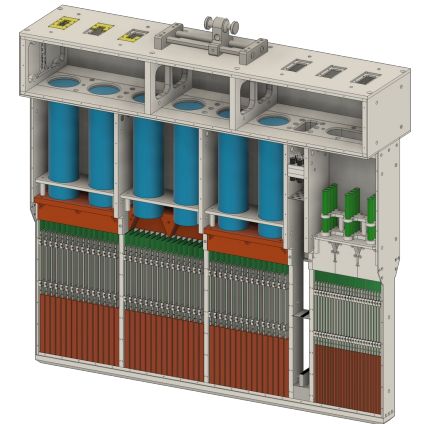
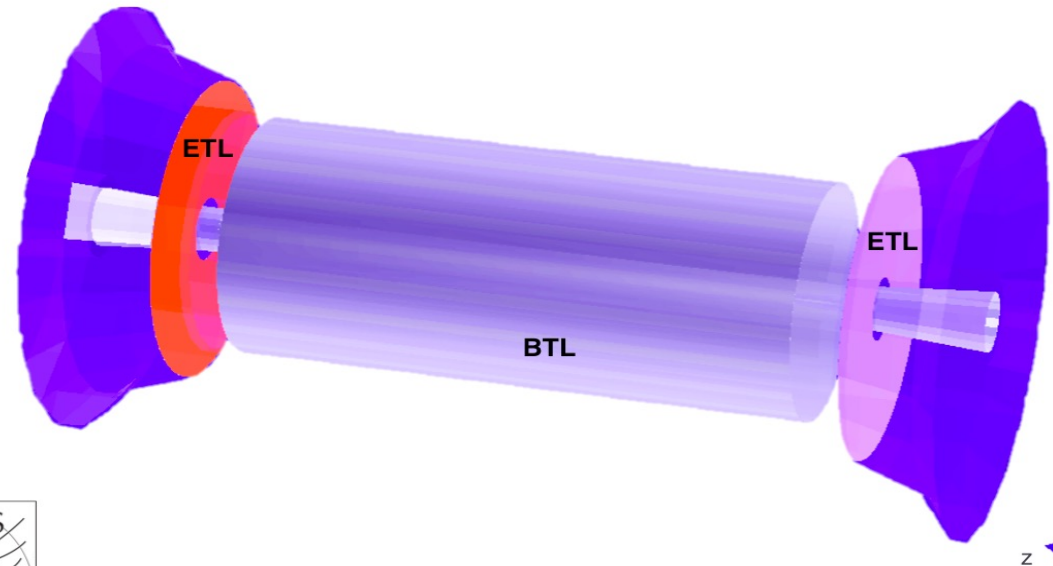
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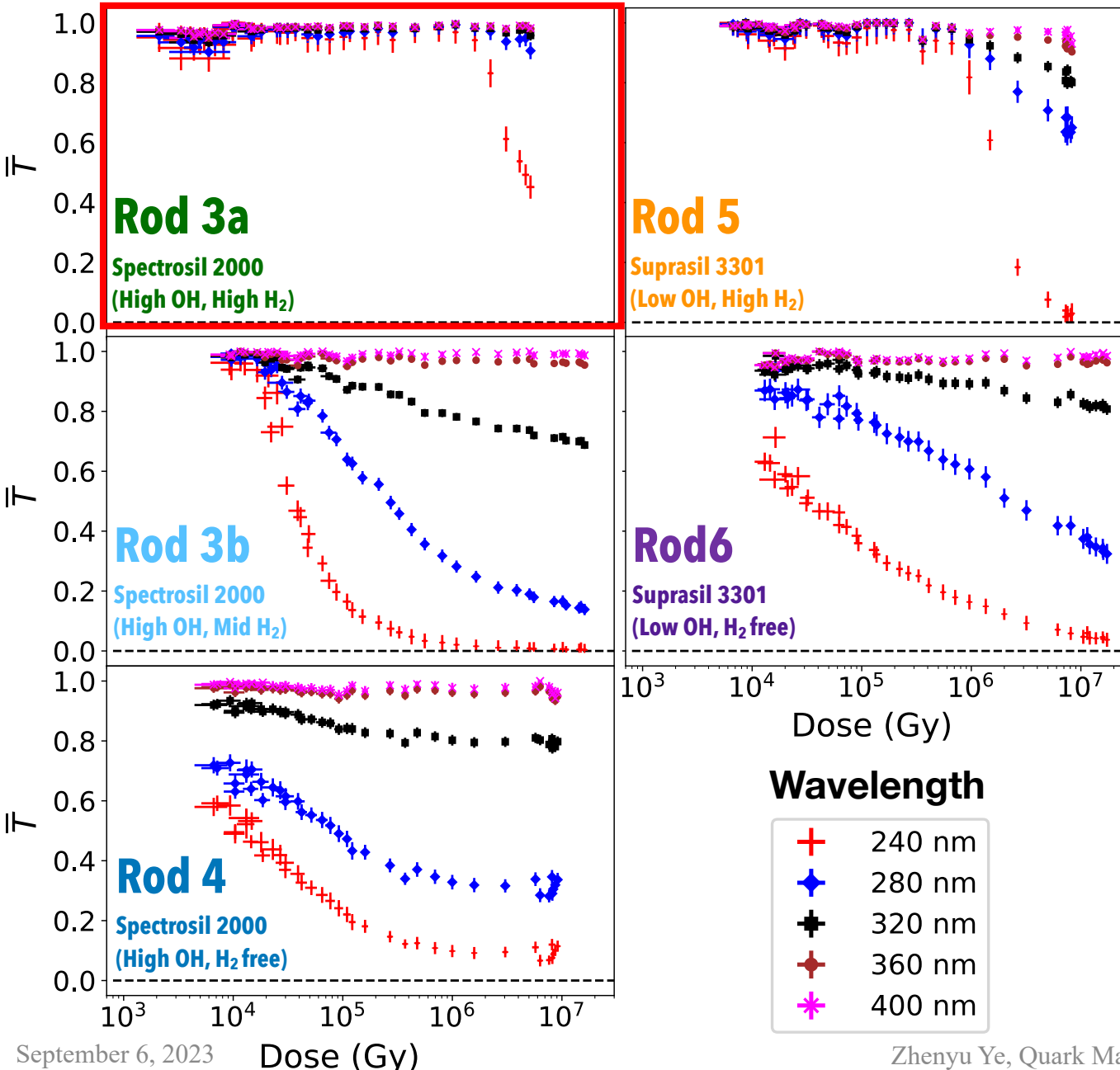
- MTD allows for measurement of net proton and net kaon cumulants in wide rapidity range to study phase transition.
- MTD allows for precise measurement of nucleus yields and anisotropies can probe production mechanism.

Summary and Outlook

- CMS will have new or upgraded detectors for the HL-LHC, including new MTD and ZDCs.
- The new **ZDCs** are developed through joint ATLAS/CMS efforts and will provide precise neutron detection and reaction plane measurement at the HL-LHC.
- The **MTD** will bring a completely new capability to CMS: particle identification via time-of-flight over 6 units in rapidity, which will have high impact on CMS Heavy Ion program:
 - Heavy quark dynamics in QGP
 - QGP response to parton energy loss
 - Origin of collectivity in sm
 - Phase Transition
 - Light nuclei production
 -
- Stay Tuned!!!



ZDC R&D on Fused Silica Transmission vs Dose

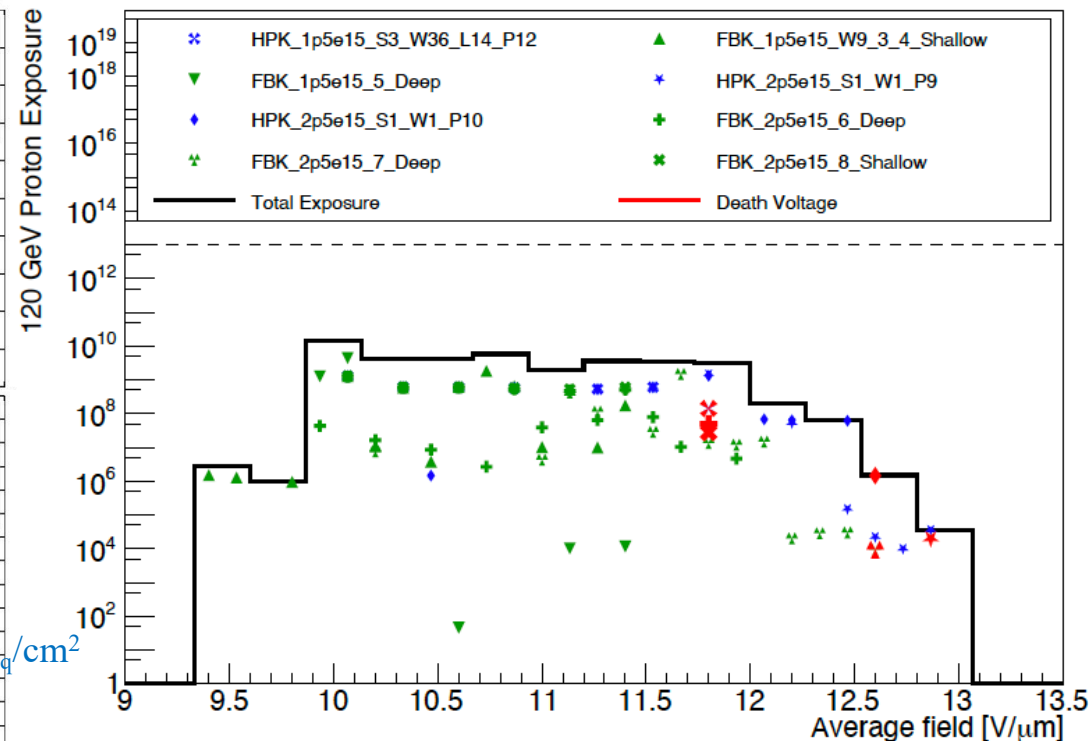
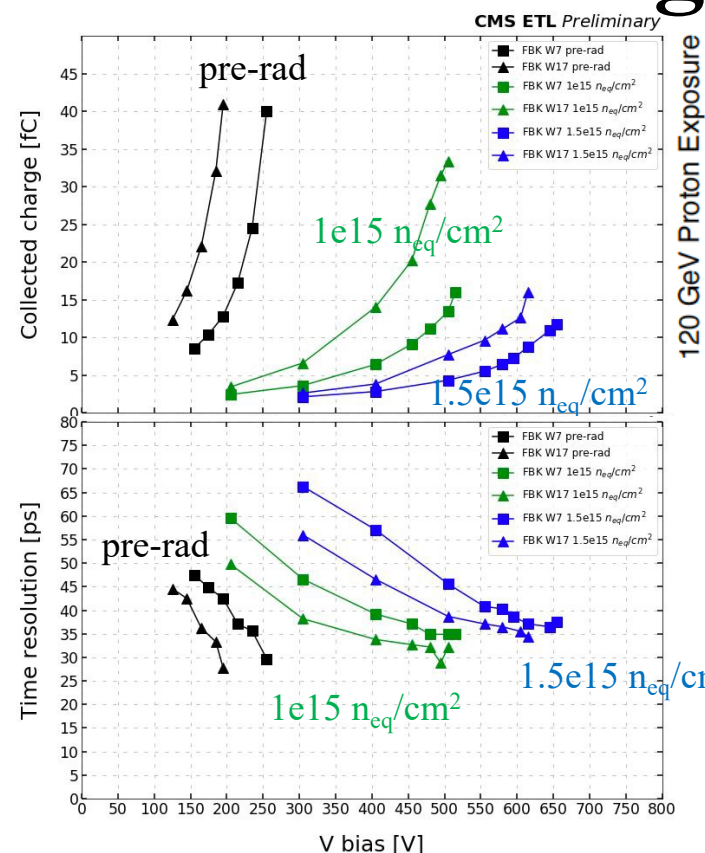
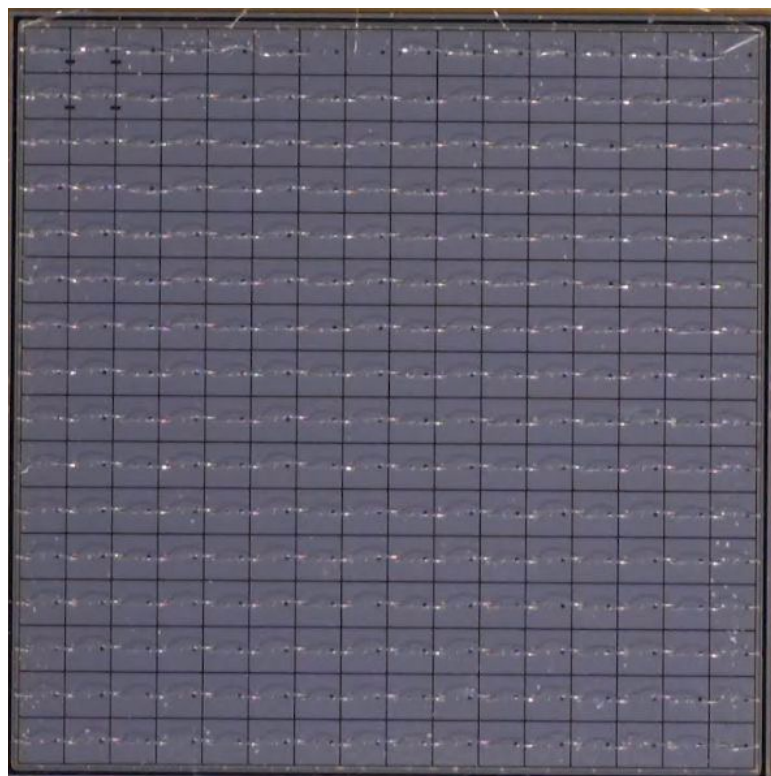


[NIM-A 1055\(2023\)168523](#)

- Analysis that correlates wavelength, transmittance, dose received and material composition
- Results informed the choice of the Spectrosil 2000, High OH and High H₂ for ATLAS Run 3 ZDC refurbishment
- New campaign in Run 3 - will extend the irradiation range of ~ 1 order of magnitude

Towards Final ETL Sensor Design

CMS Phase-2 Preliminary



- Path to freeze the sensor geometry and specifications
 - Complete stress tests of full size LGAD 16x16 pads – ongoing
 - Perform detailed test of sensors with ETROC2 (see next slide)
- Vendor qualification (market survey) based on full size sensors almost complete
 - 3 vendors qualify for the low fluence area, two of them also qualify for high fluence area
 - 1 additional vendor may qualify for the low fluence area

Performance consistent
with 5x5 sensors