Upgrades toward a comprehensive QGP detector at CMS for the high luminosity LHC era

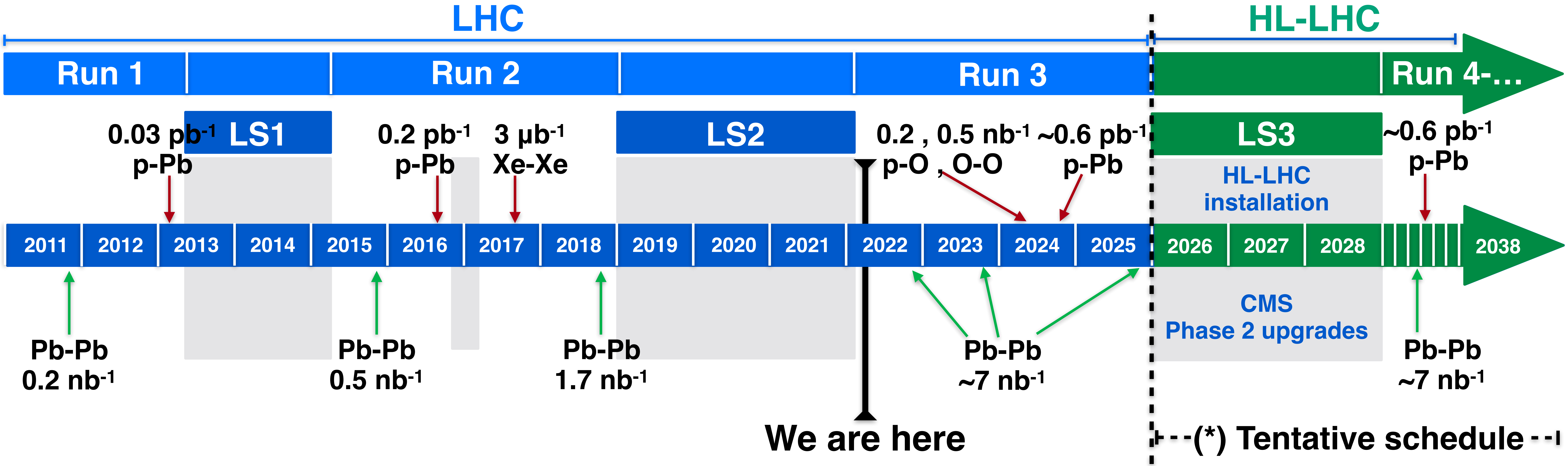
Andre Ståhl
on behalf of the CMS Collaboration

European Organisation for Nuclear Research

29th International Conference on
Ultra-relativistic Nucleus-Nucleus Collisions

April 7th, 2022

Heavy Ion Program at LHC



- Successful HI program at LHC: Pb-Pb, Xe-Xe and p-Pb, with all 4 main LHC experiments participating.
- By the end of Run 3+4, we expect an increase of 5-7x HI data.
- CMS major upgrade for High Luminosity LHC will bring new opportunities for the HI programme.

CMS Phase 2 upgrades for HL-LHC

CMS Phase 2 upgrades for HL-LHC

CMS Phase 2 upgrades for HL-LHC

CMS Phase 2 upgrades for HL-LHC

Trigger / HLT / DAQ
- Track info. in L1
- L1/HLT rate x7.5
- DAQ: 6 → **51 GB/s**

CMS Phase 2 upgrades for HL-LHC

New MIP Timing Detector
- Precision timing
- $|\eta| < 3$

CMS Phase 2 upgrades for HL-LHC

Zero Degree Calorimeter

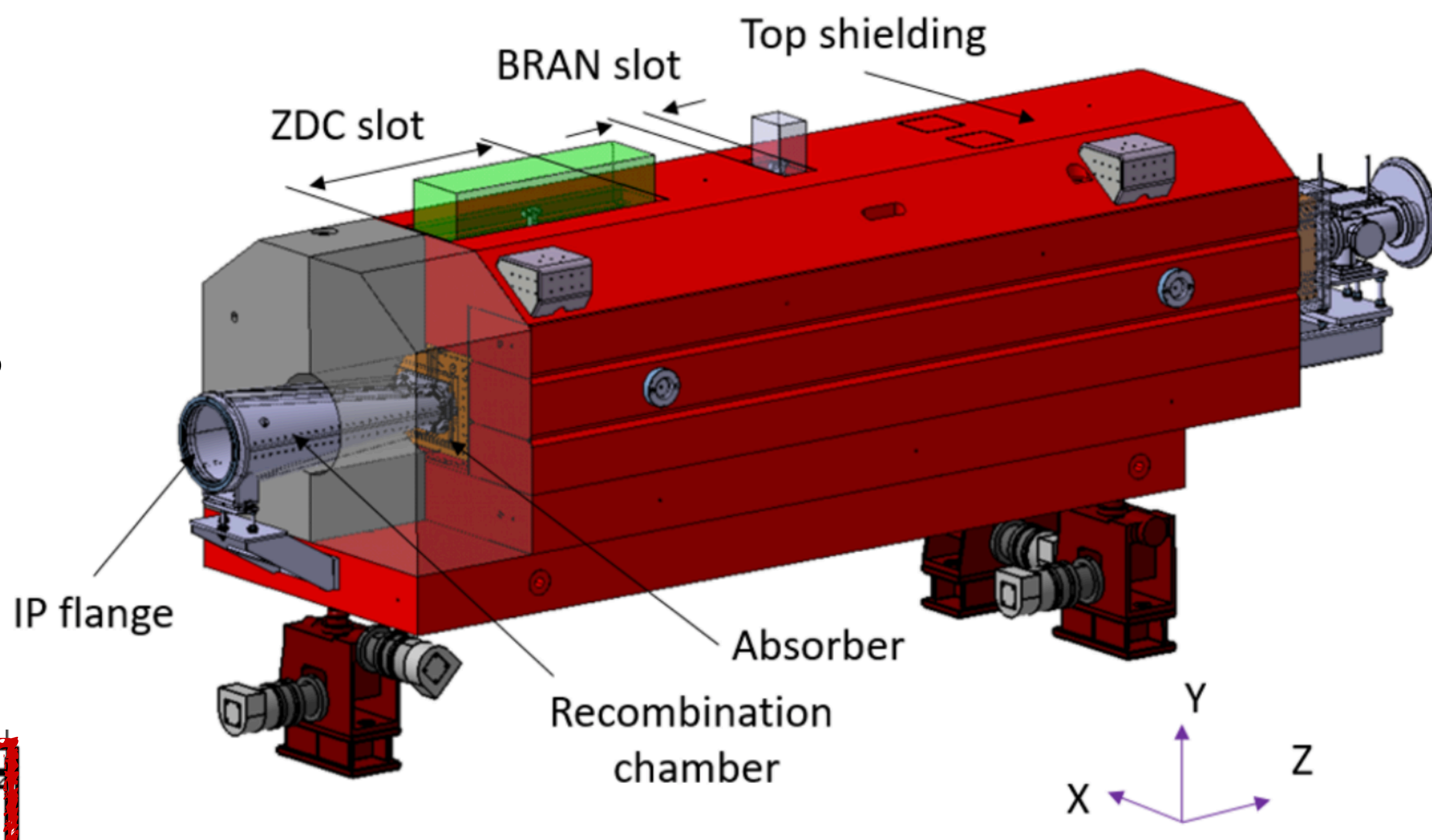
New ZDCs for the High-Luminosity LHC

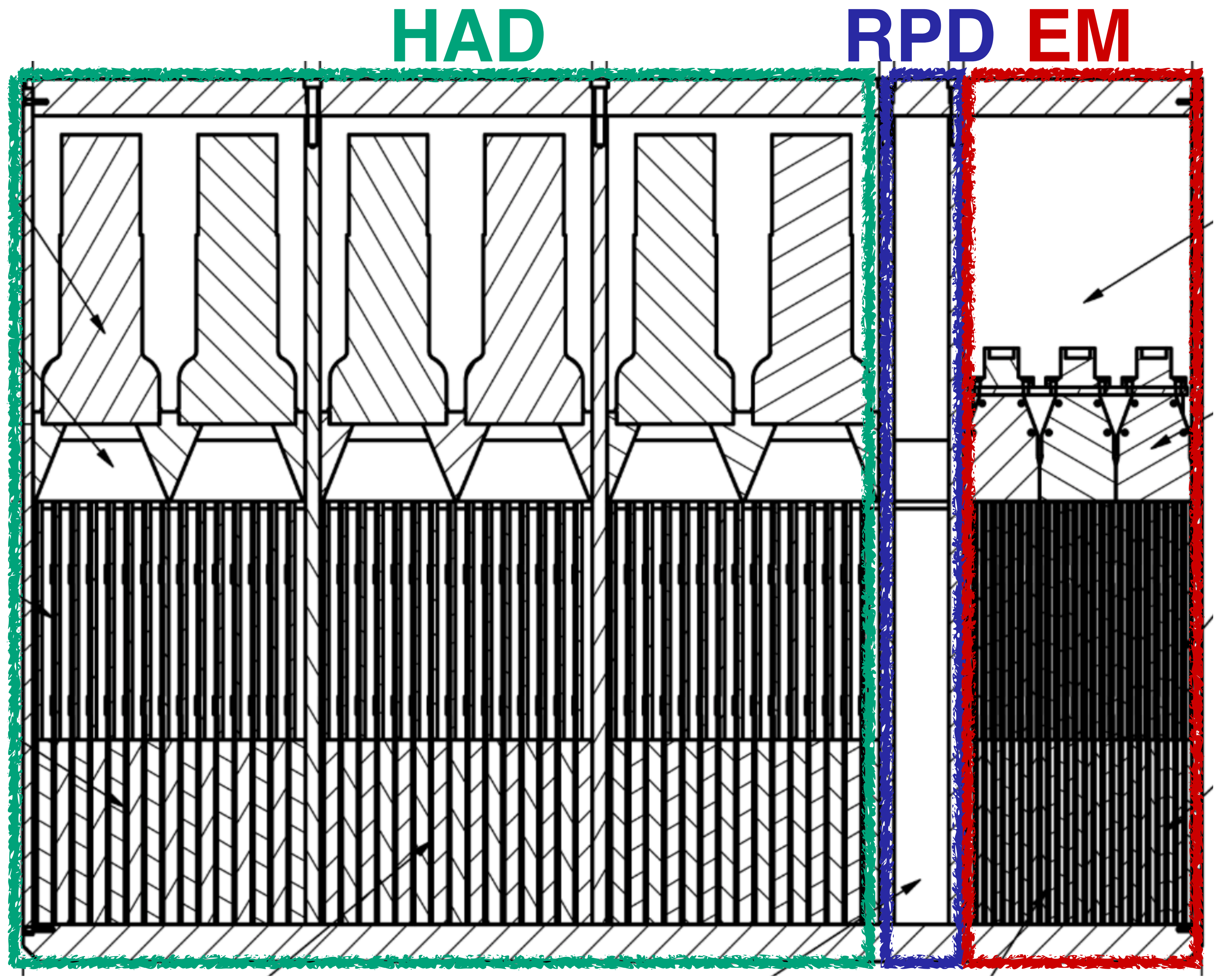
Zvi Citron, April 6, 11:50, T15

Shir Shenkar, Poster Session 3 T15

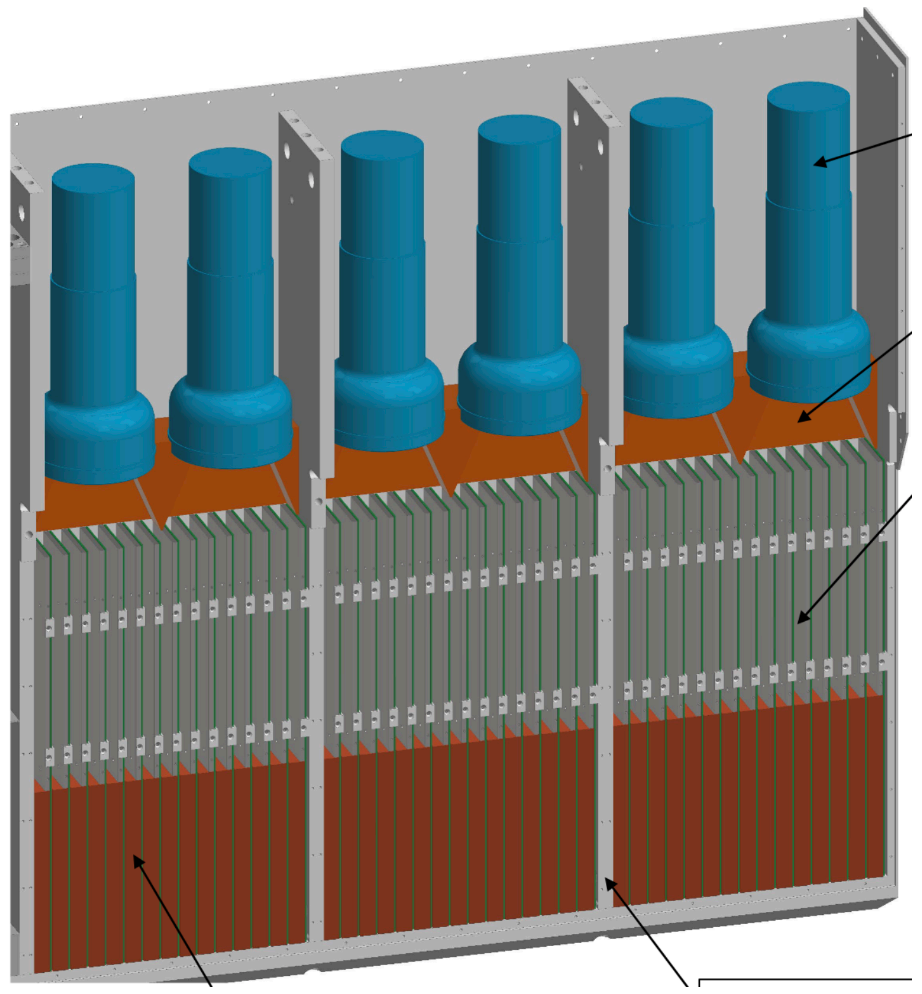
- The HL-LHC requires thinner, more radiation hard ZDCs.
- ATLAS and CMS have collaborated with several CERN teams and private companies on new ZDCs based on fused silica fibers + PMT and tungsten plates.

CERN-LHCC-2021-018

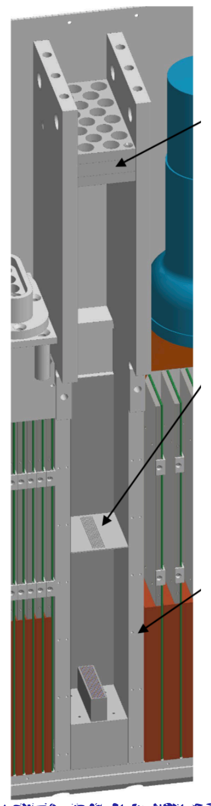




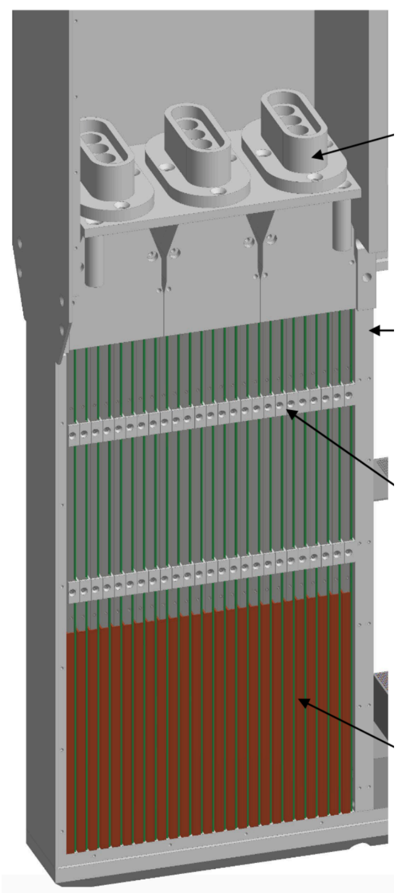
Hadronic module



Reaction Plane Detector

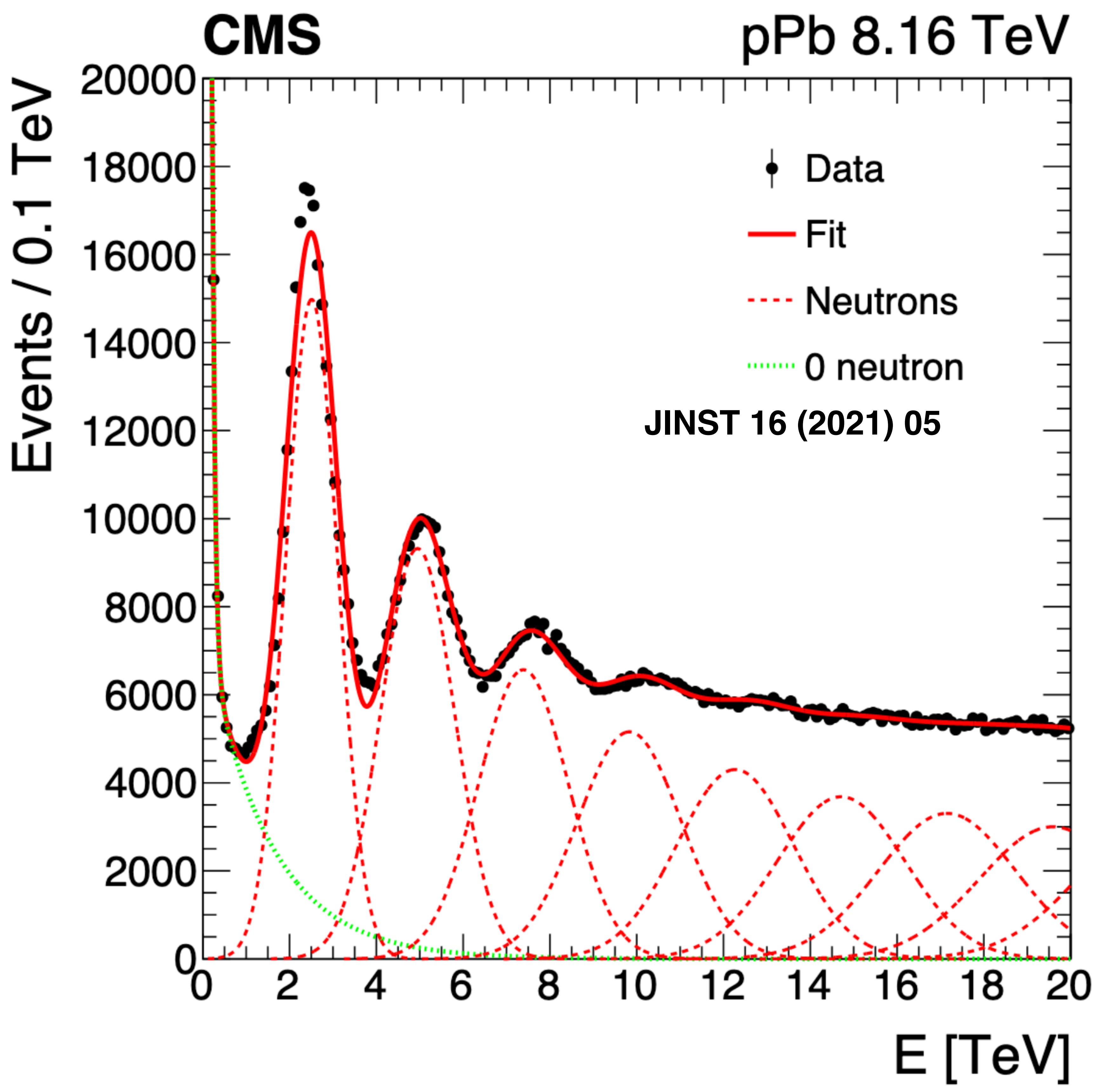


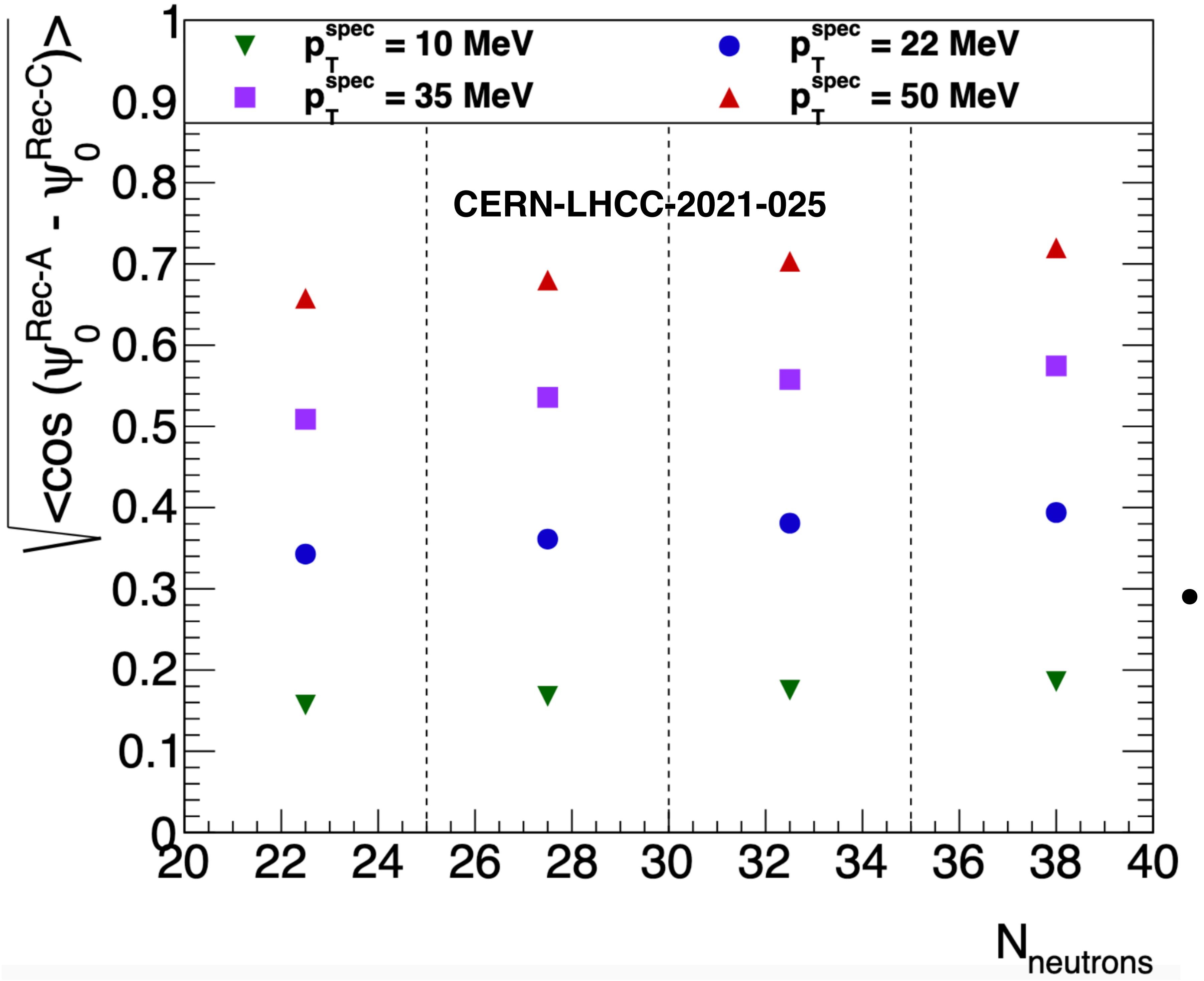
EM module



Expected Performance of ZDC

- Energy Resolution for neutrons should be equal to current ZDCs.
- Photon/Neutron resolution should be superior because of finer segmentation of electromagnetic section.





- Reaction plane detector should have sufficient resolution to measure first order reaction plane.

MIP Timing Detector

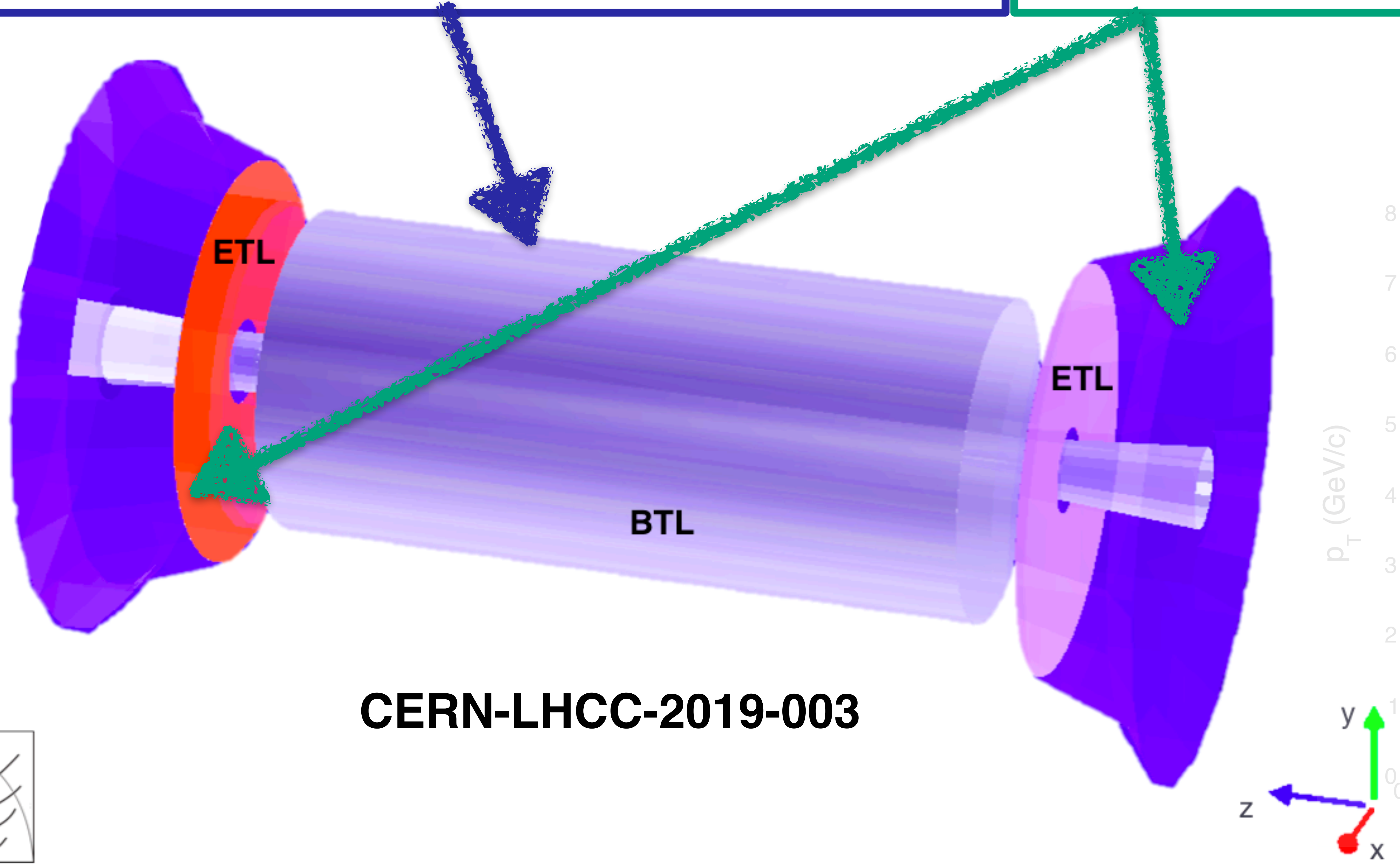
CMS MIP Timing Detector (MTD)

Barrel Timing Layer (BTL)

- 72 trays covering a surface of ~38 m²
- Coverage: $|\eta| < 1.45$, $p_T > 0.7$ GeV
- Timing resolution: ~ 30 ps
- **L(Y)SO:Ce bars** as scintillators.
- **SiPMs** as detectors.

Endcap Timing Layer (ETL)

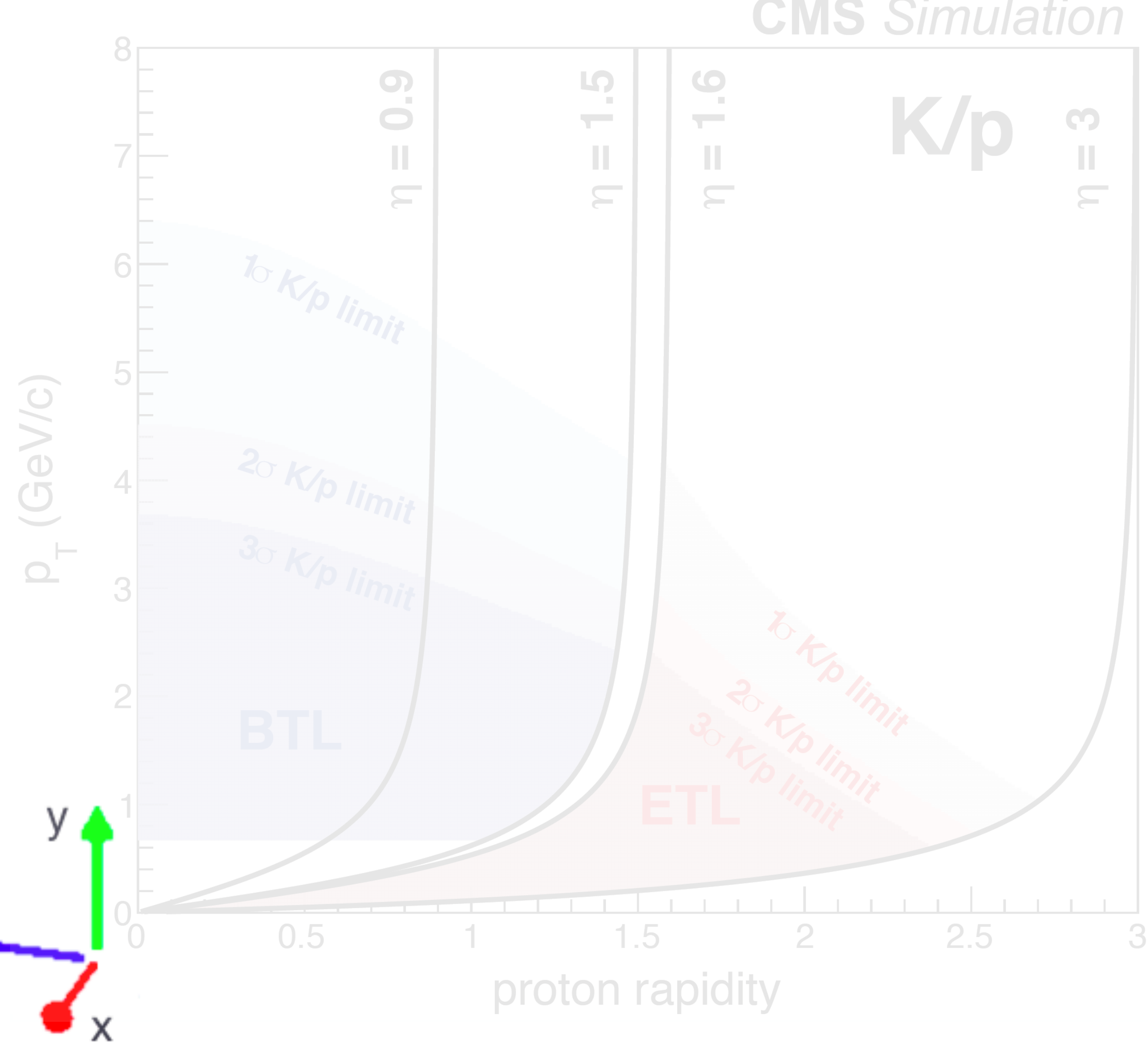
- 2 disks covering a surface of ~14 m²
- Coverage: $1.6 < |\eta| < 3.0$, $p > 0.7$ GeV
- Timing resolution: ~ 30-40 ps
- **Si with internal gain (LGAD)**



CERN-LHCC-2019-003

Pileup mitigation in pp

TOF Particle ID in HI



4D vertex reconstruction

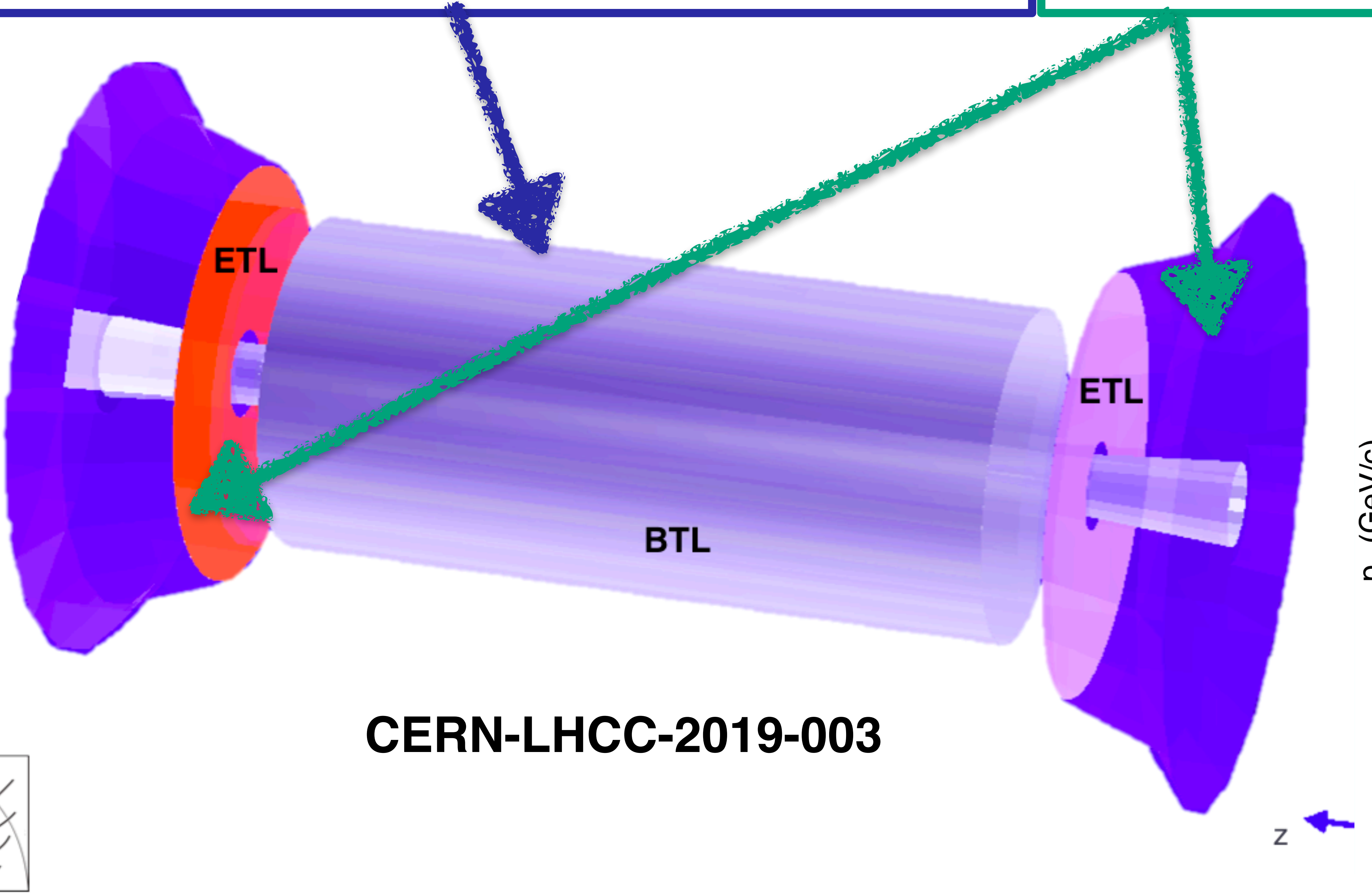
CMS MIP Timing Detector (MTD)

Barrel Timing Layer (BTL)

- 72 trays covering a surface of ~38 m²
- Coverage: $|\eta| < 1.45$, $p_T > 0.7$ GeV
- Timing resolution: ~ 30 ps
- **L(Y)SO:Ce bars** as scintillators.
- **SiPMs** as detectors.

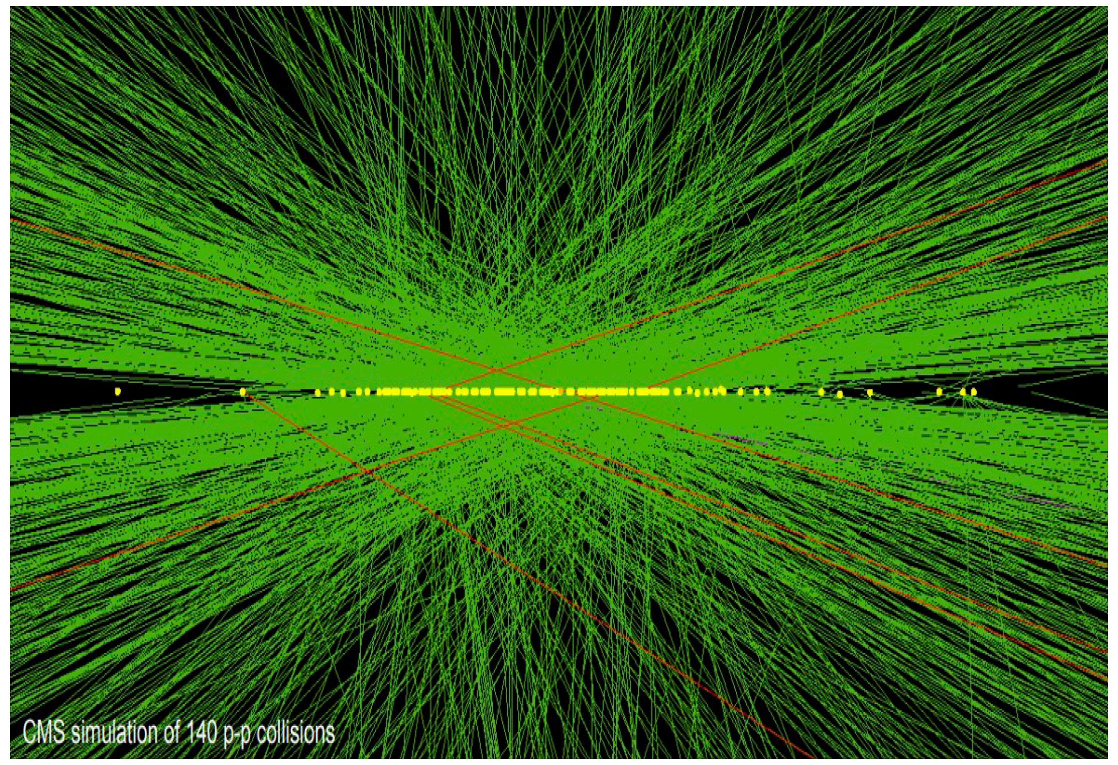
Endcap Timing Layer (ETL)

- 2 disks covering a surface of ~14 m²
- Coverage: $1.6 < |\eta| < 3.0$, $p > 0.7$ GeV
- Timing resolution: ~ 30-40 ps
- **Si with internal gain (LGAD)**

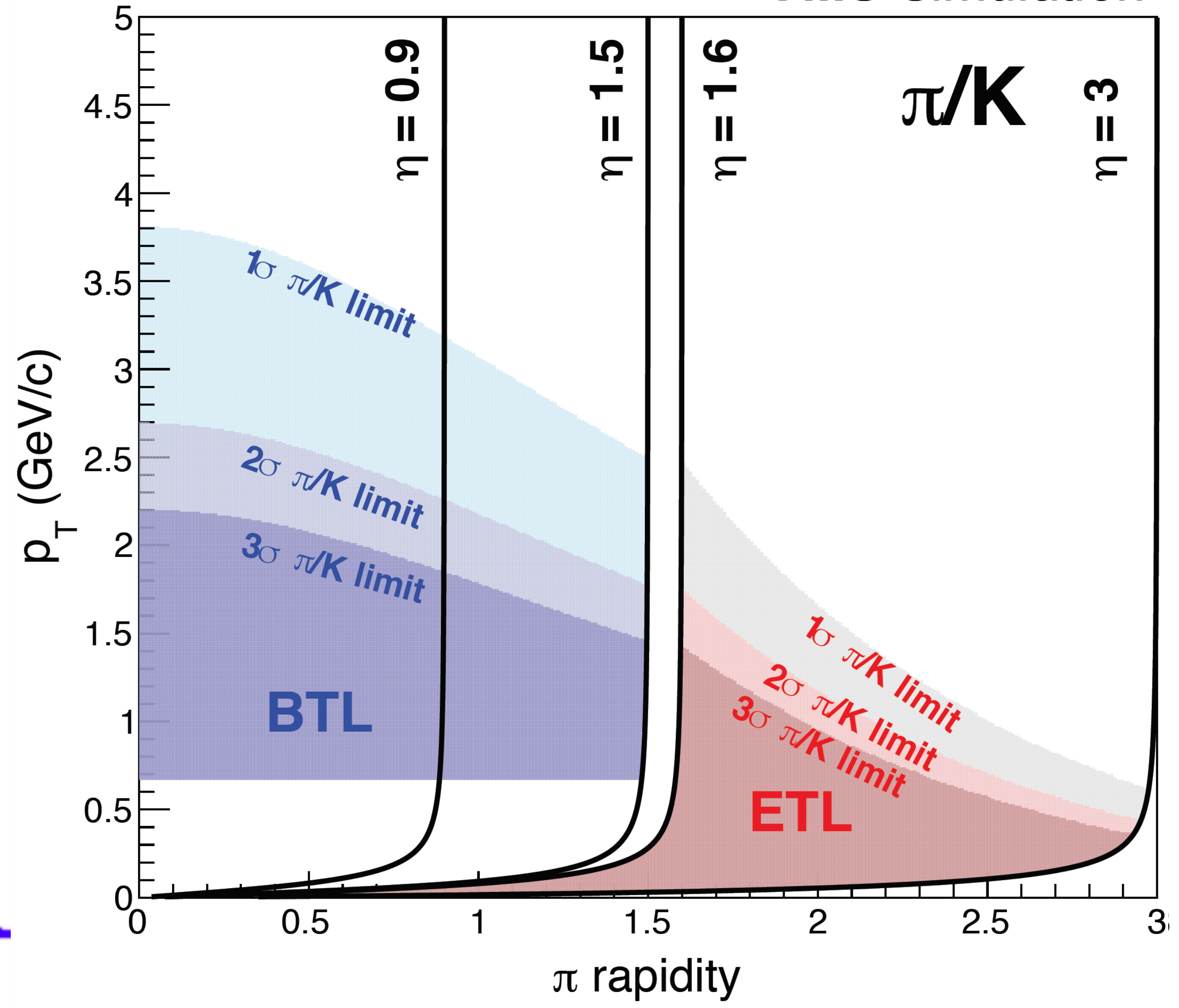


CERN-LHCC-2019-003

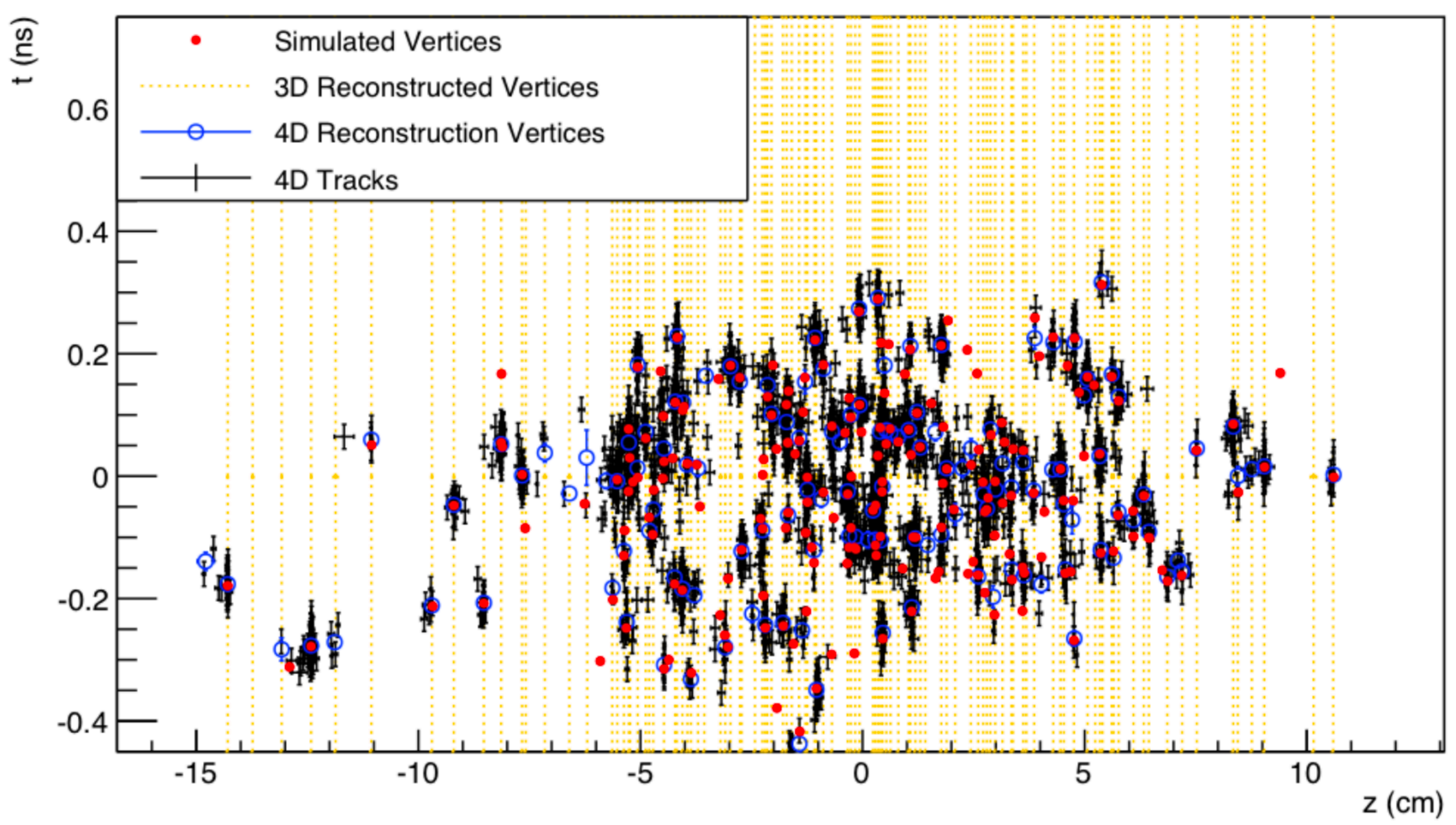
Pileup mitigation in pp



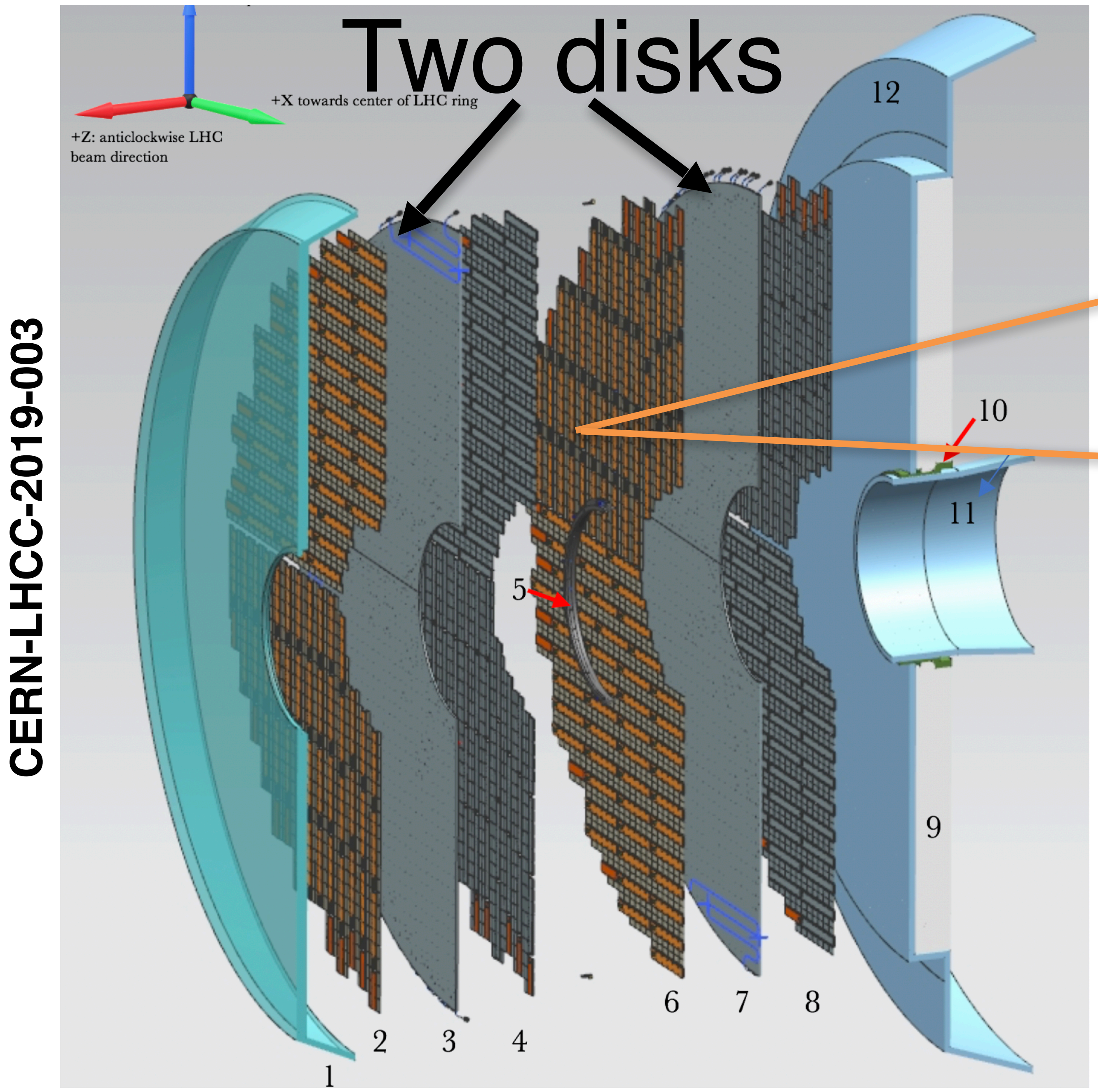
TOF Particle ID in HI

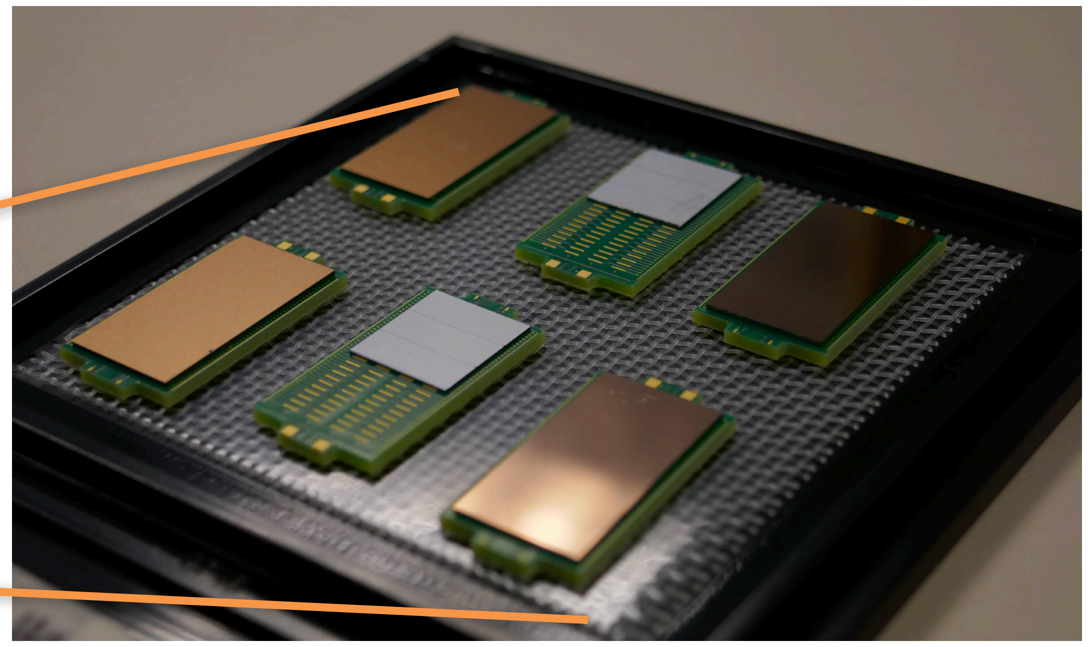


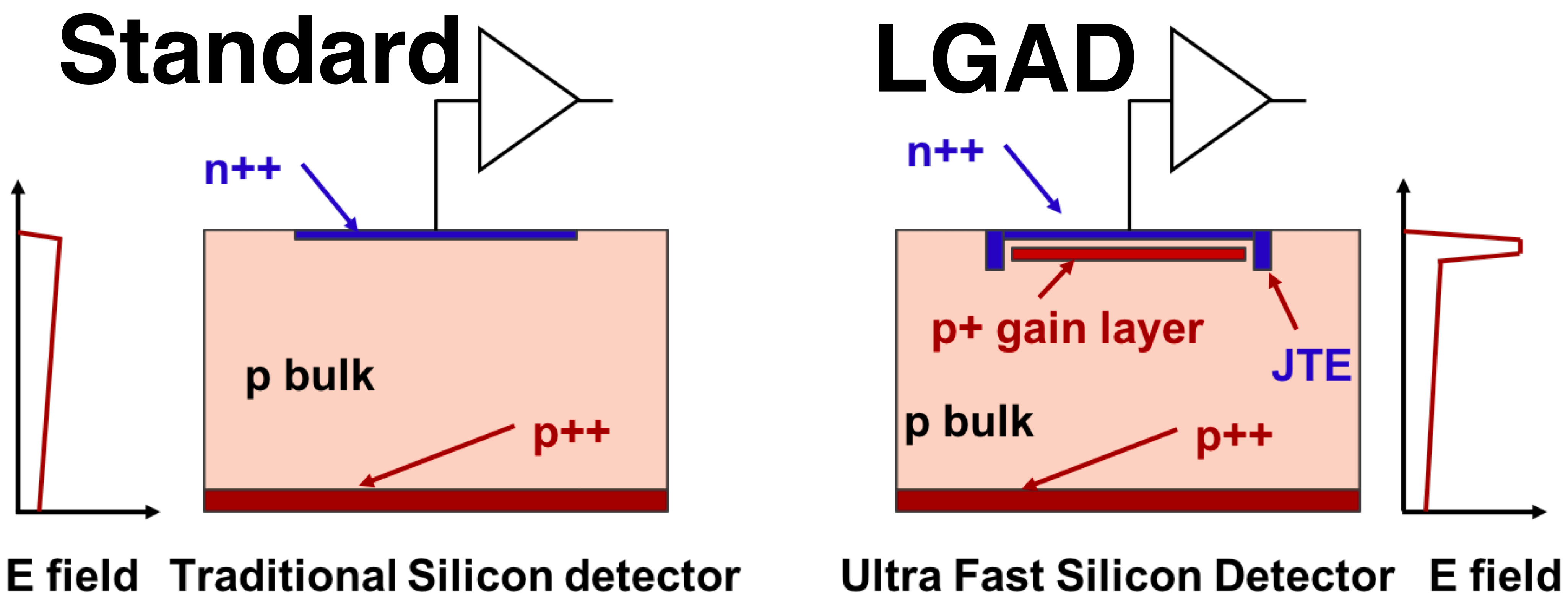
4D vertex reconstruction



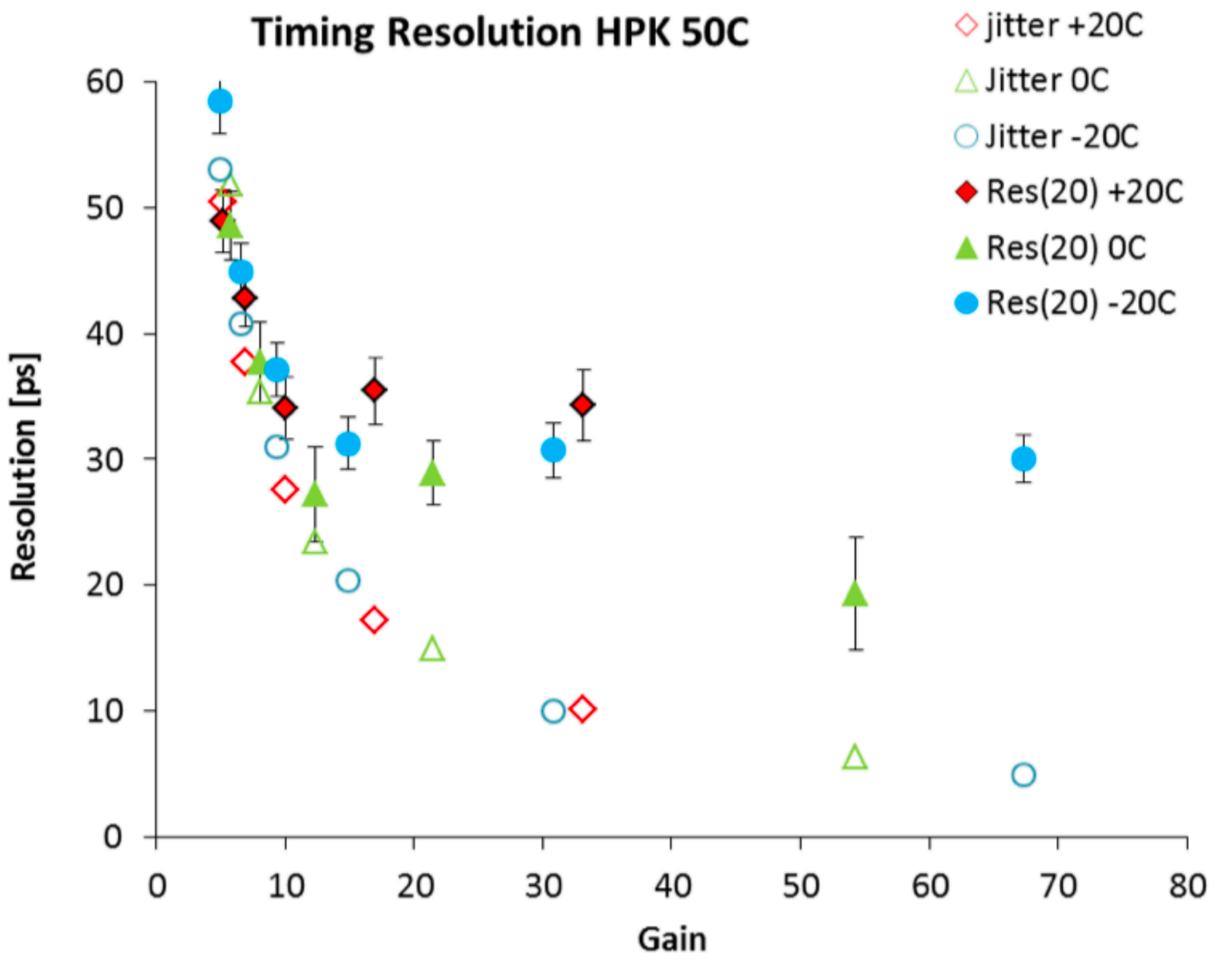
Endcap Timing Layer (ETL)







Time resolution vs gain

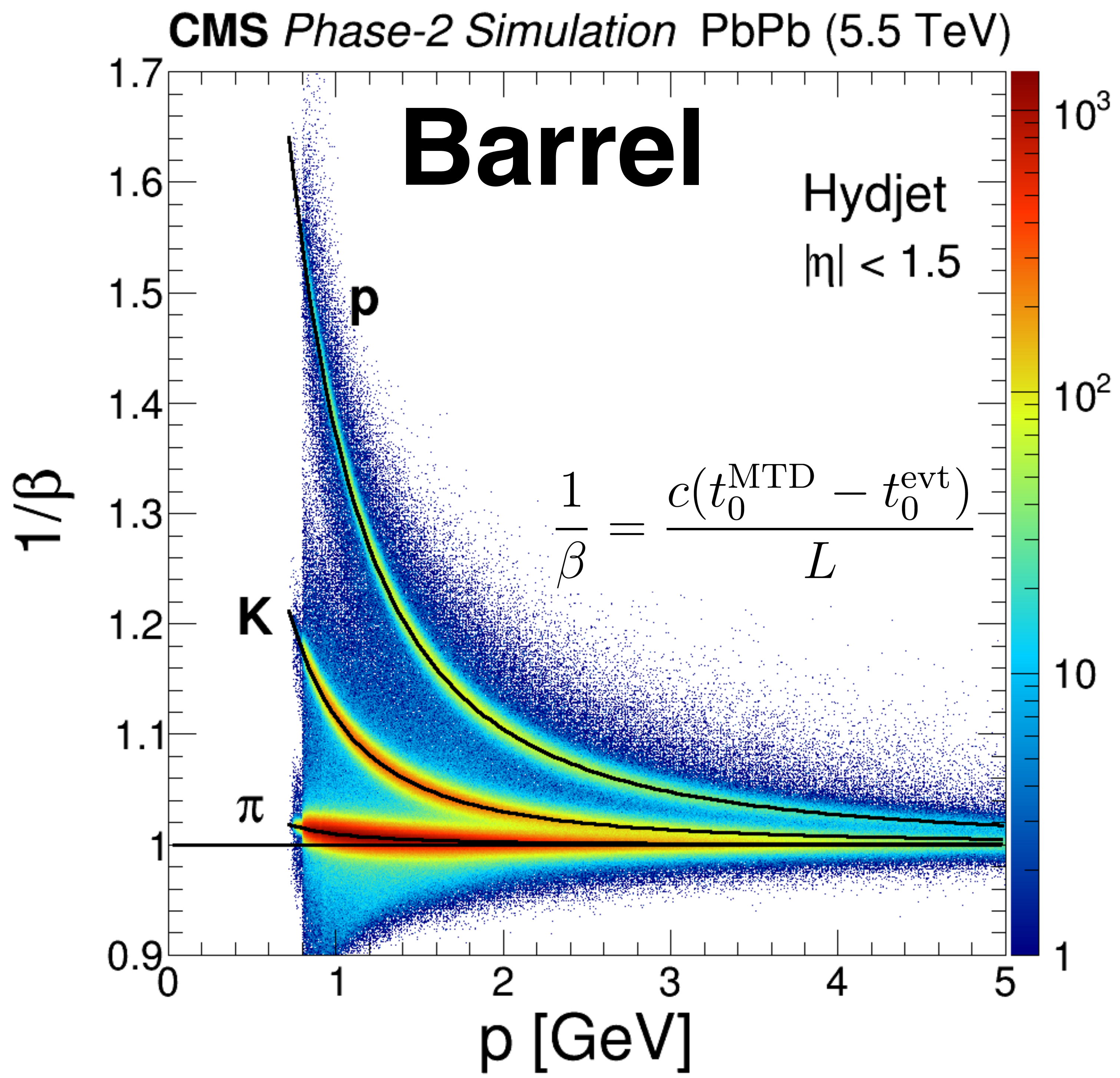


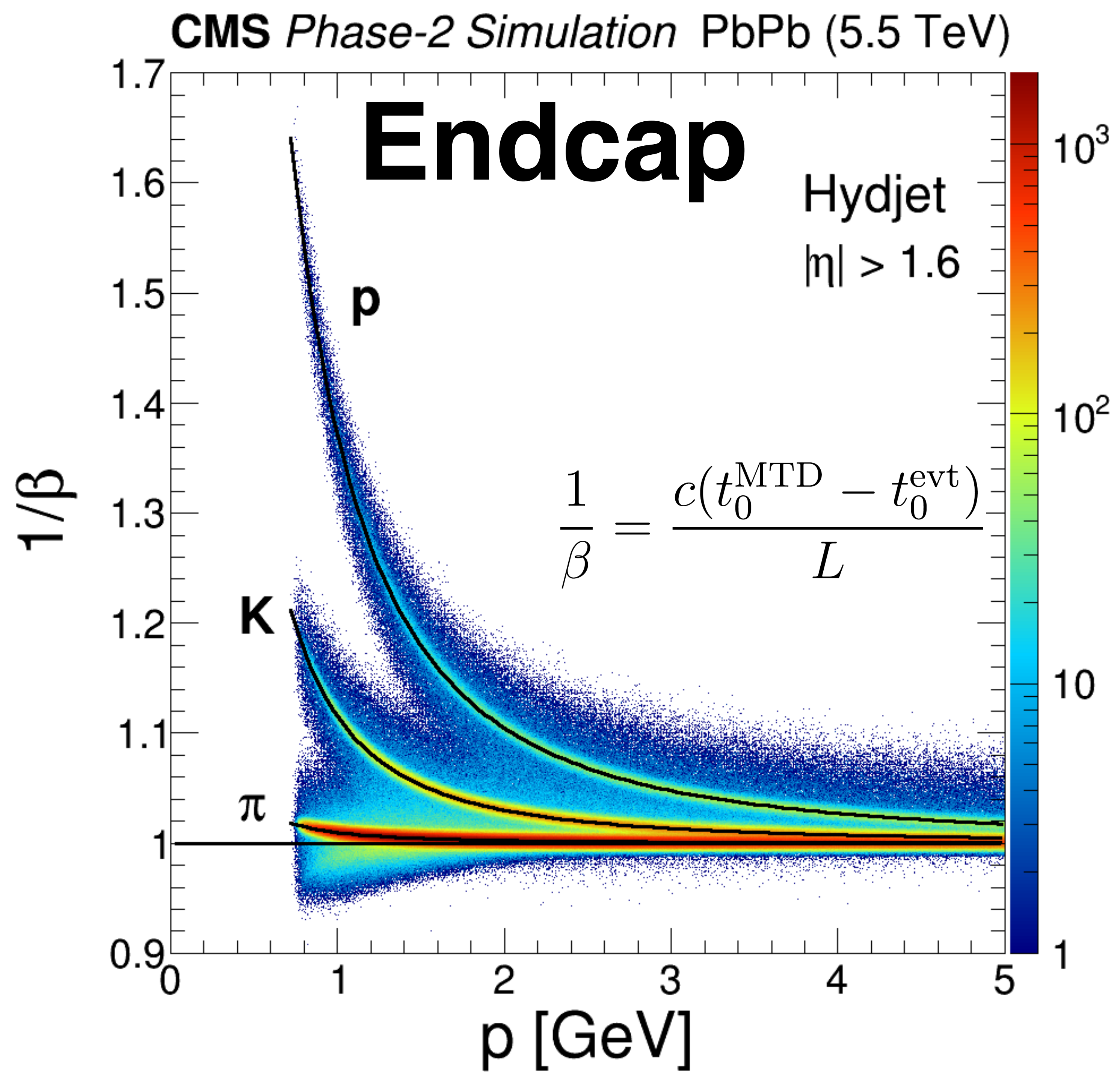
CERN-LHCC-2019-003

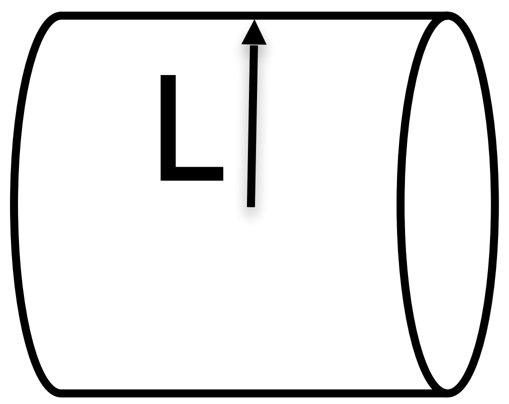
- Needs to sustain x10 higher radiation than BTL and high magnetic fields (4T).
- ETL design: 2 disks using low gain avalanche diodes (LGADs) optimised for precision timing.
- LGAD design: 1.3 x 1.3 mm^2 pixel size and 50 µm thickness.
- LGAD+ASIC: 42-46 ps time resolution per hit demonstrated in recent beam test.

TOF-PID performance with MTD

CERN-LHCC-2019-003





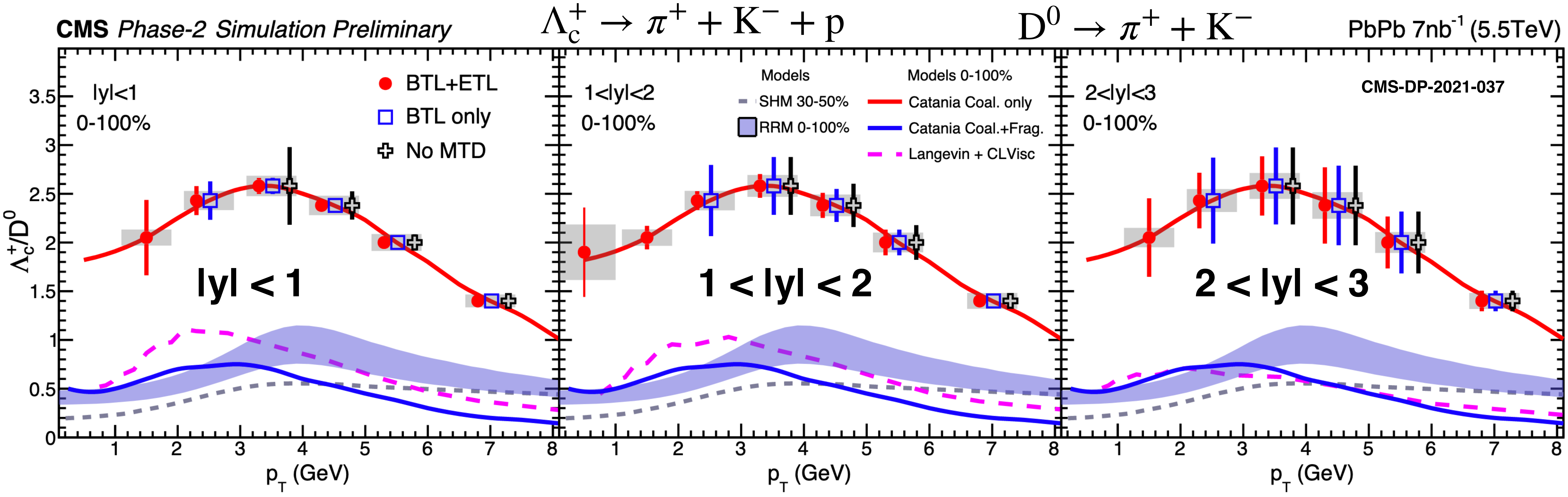


Experiment	η coverage	r (m)	σ_T (ps)	r/σ_T (x100) ($m \times ps^{-1}$)
CMS	$\lvert\eta\rvert < 3.0$	1.16	30	3.87
ALICE	$\lvert\eta\rvert < 0.9$	3.7	56	6.6
STAR	$\lvert\eta\rvert < 0.9$	2.2	80	2.75

- Clear identification of π/K up to p ~ 2.5 GeV and p/K up to p ~ 5 GeV.
- Competitive momentum coverage compared to ALICE and STAR.
- **Unique hermetic coverage** up to $\lvert\eta\rvert = 3$.

Physics impact

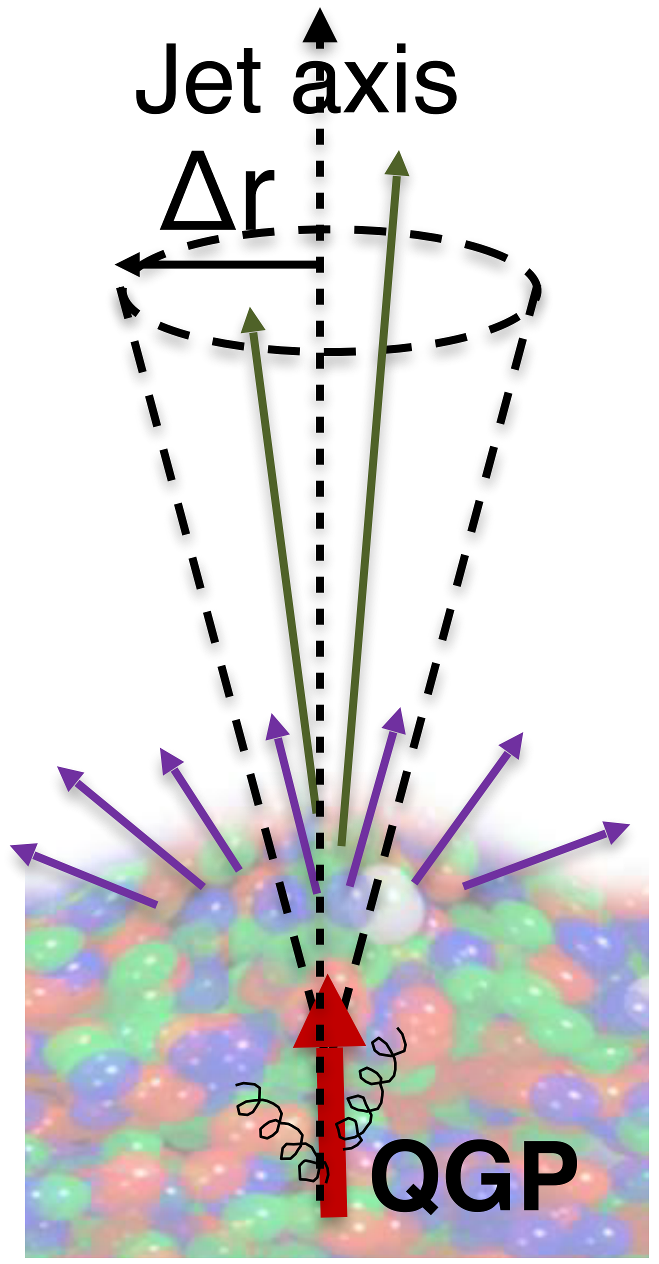
Heavy quark dynamics in QGP



- 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 the production yield and correlation will constrain the 3D HF dynamics in QGP.

QGP response to parton energy loss

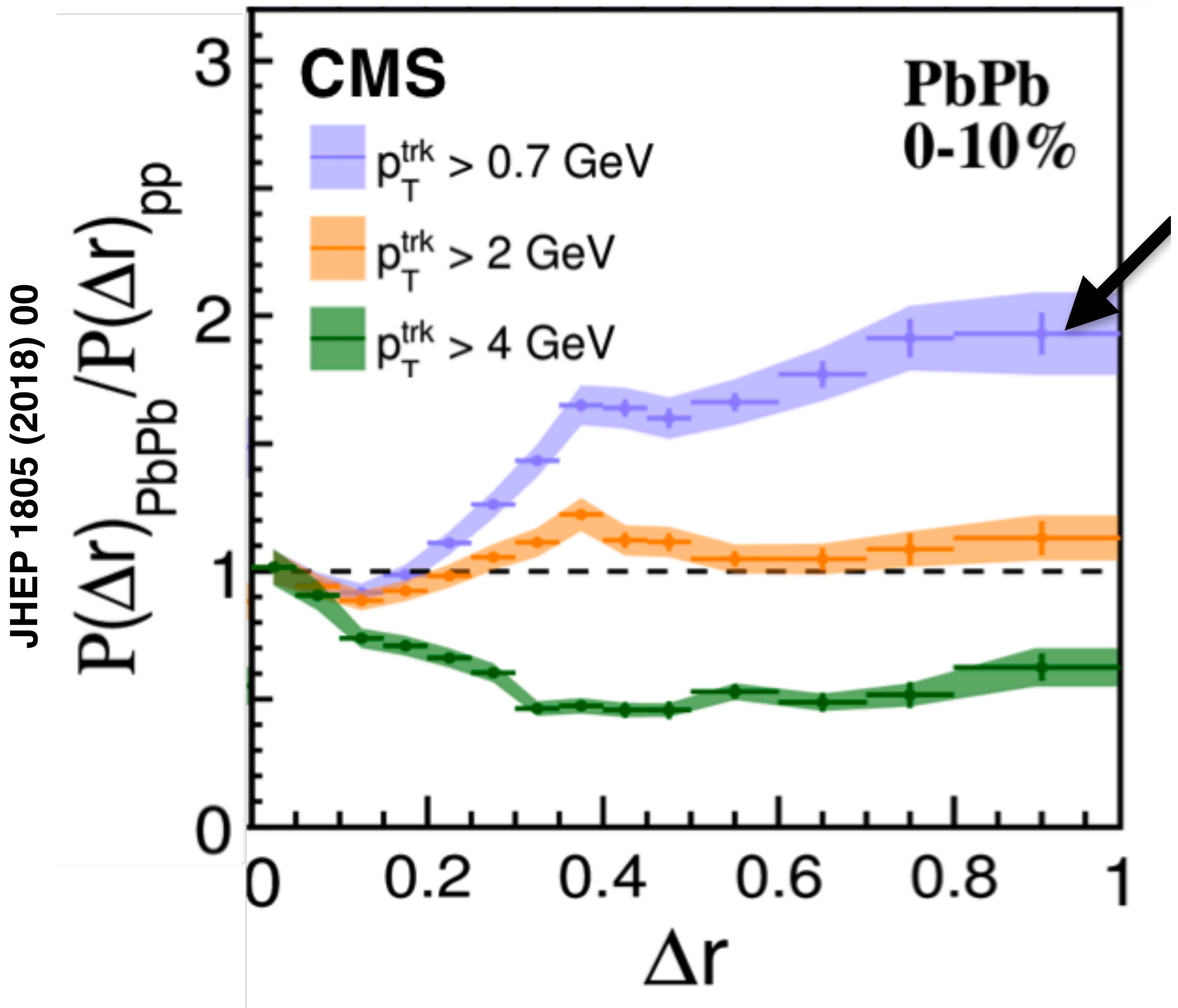
Radial momentum distribution



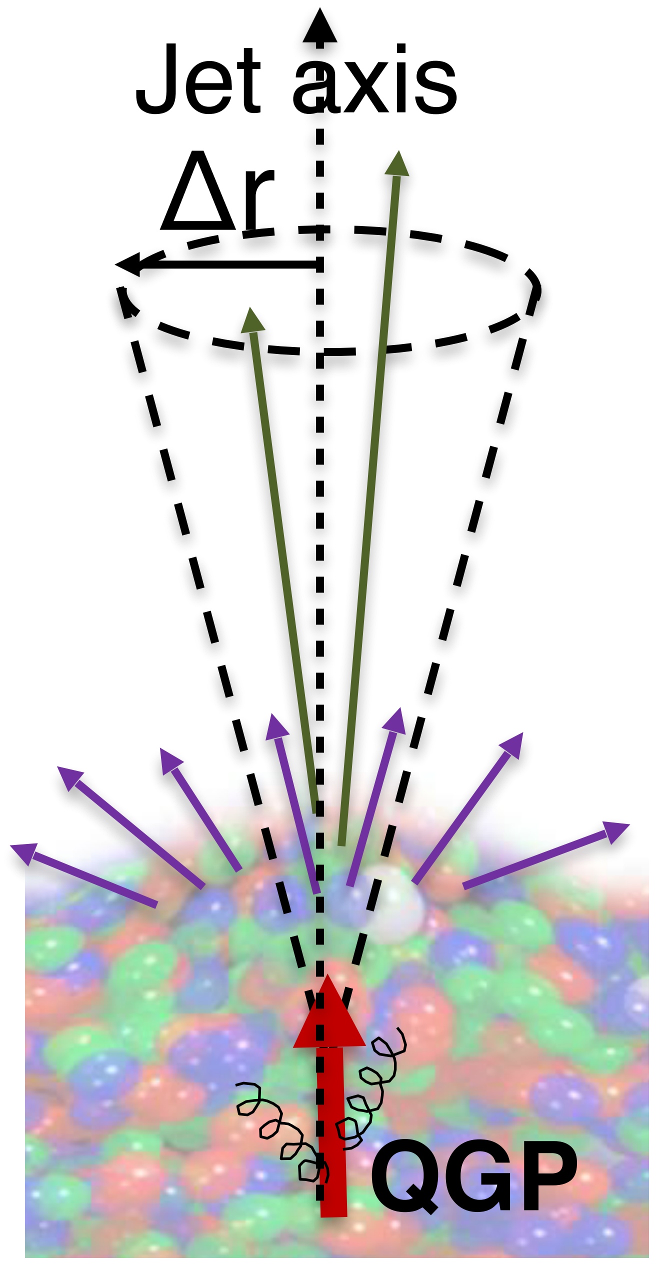
- CMS HL upgrades + MTD provides a unique opportunity to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.

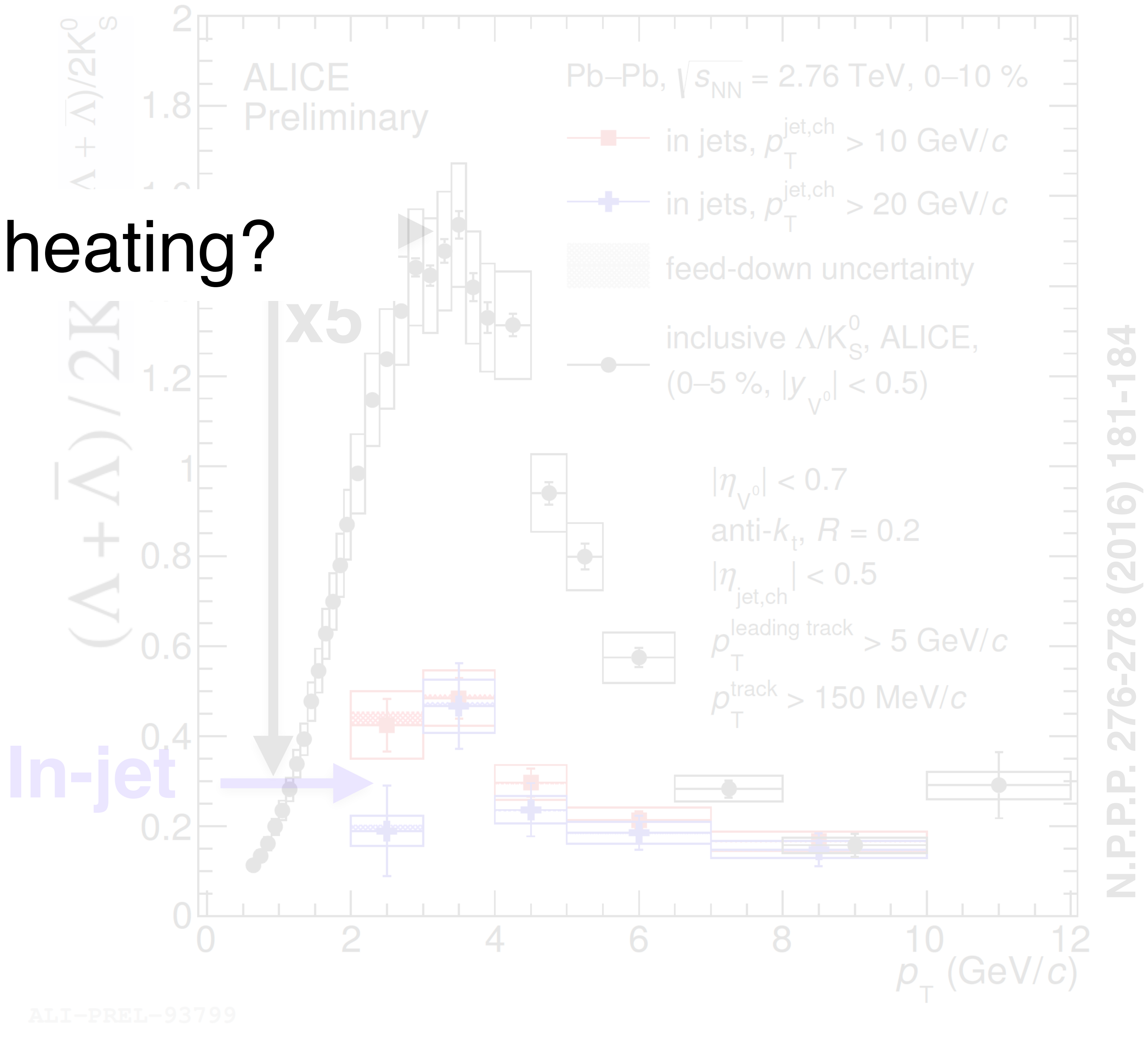
QGP response to parton energy loss

Radial momentum distribution



Jet fragmentation or medium reheating?

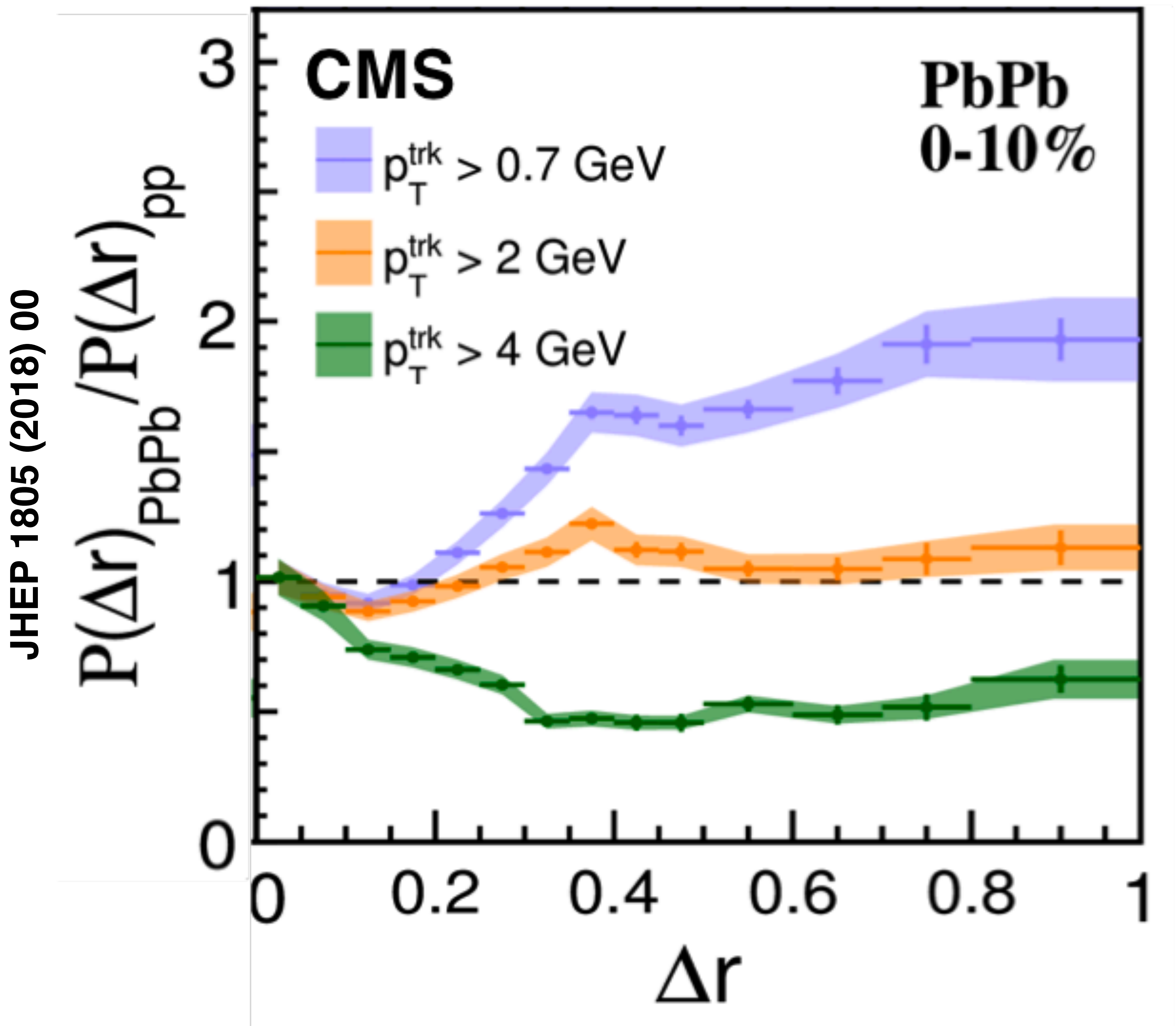


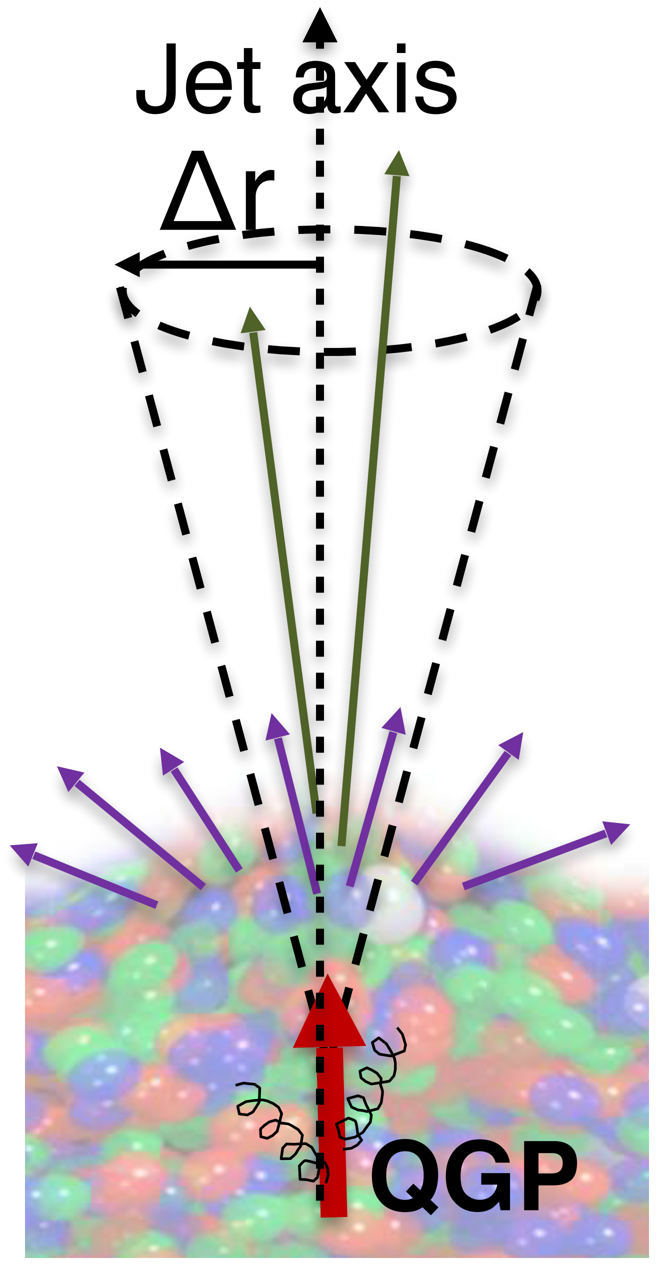


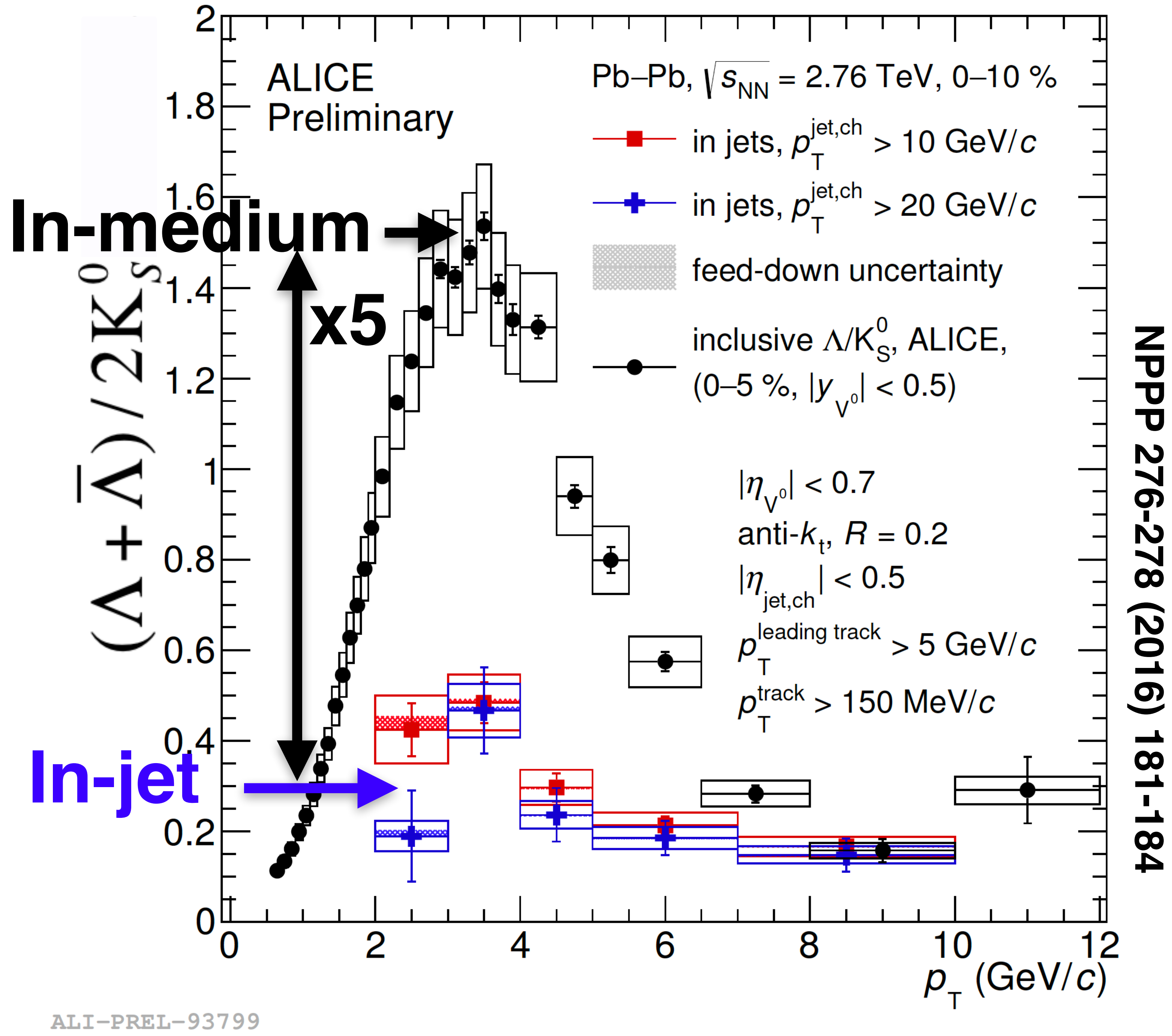
- CMS HL upgrades + MTD provides a unique opportunity to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.

QGP response to parton energy loss

Radial momentum distribution



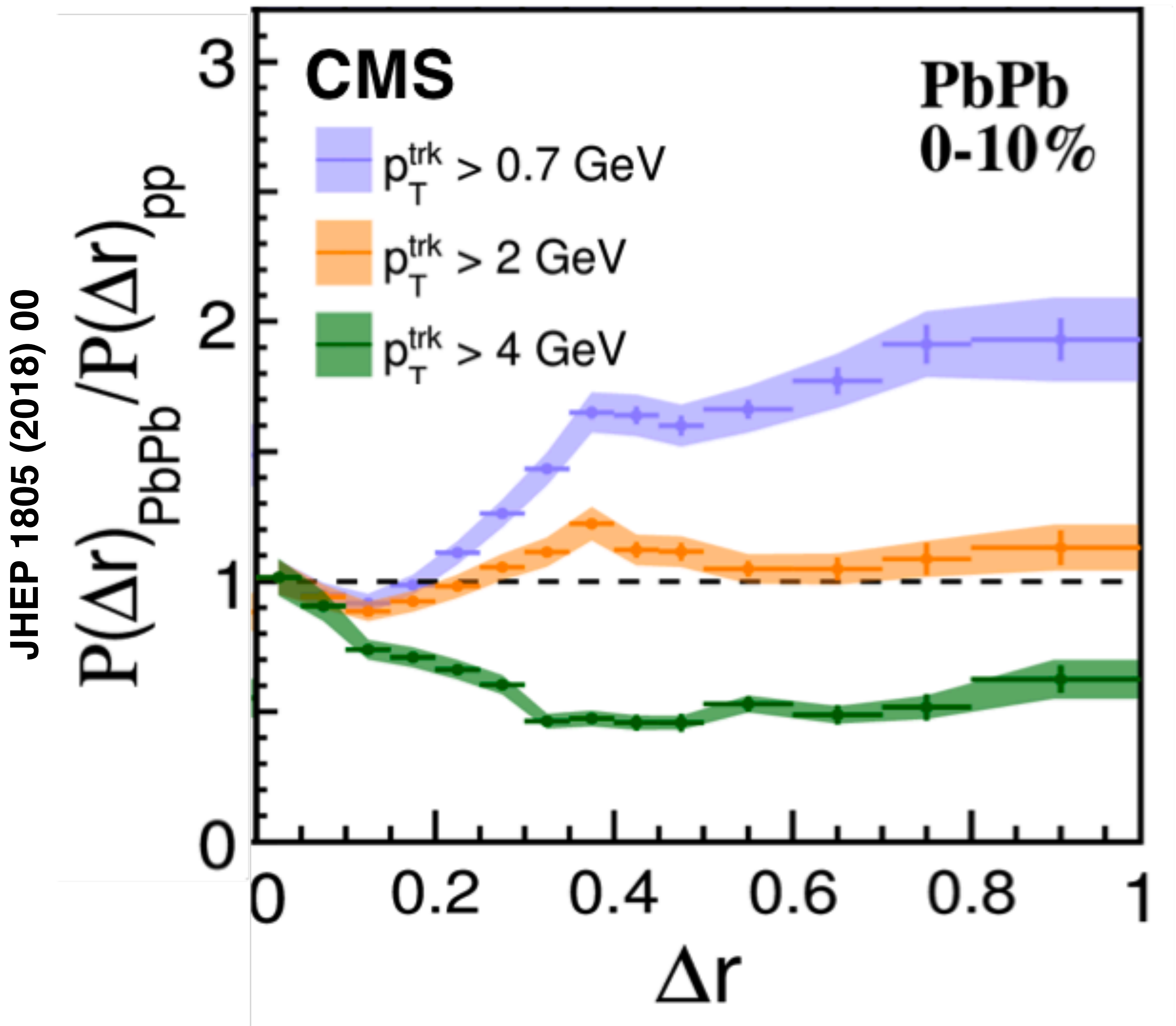


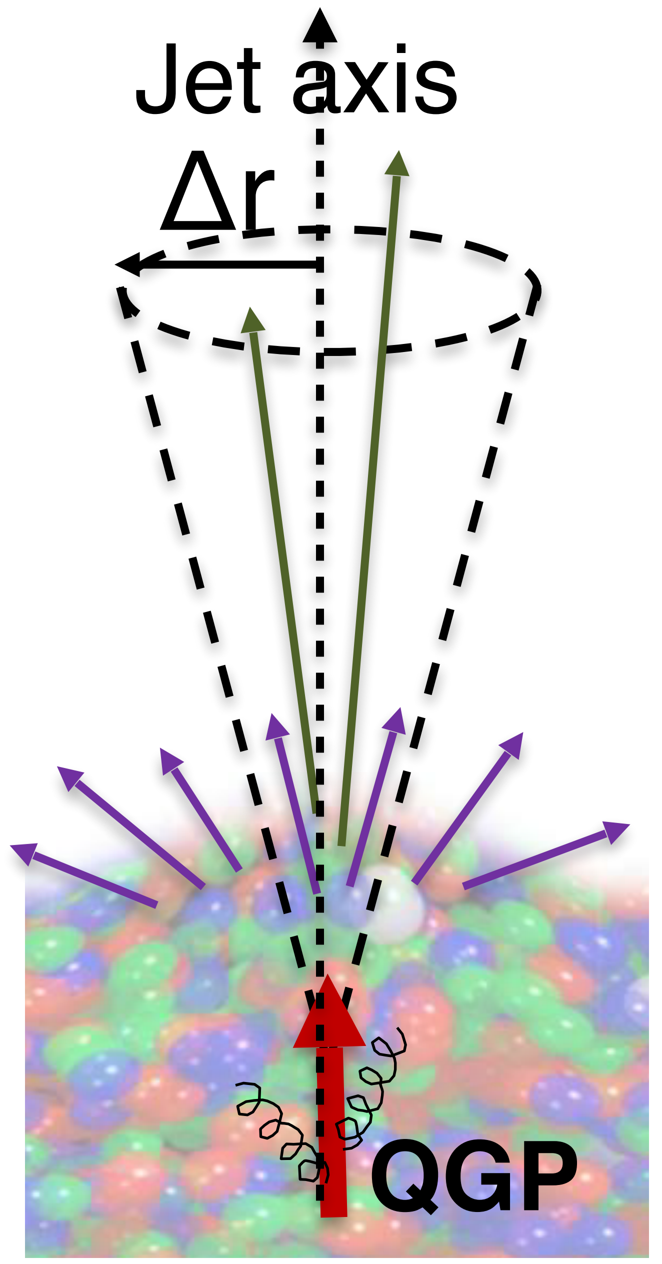


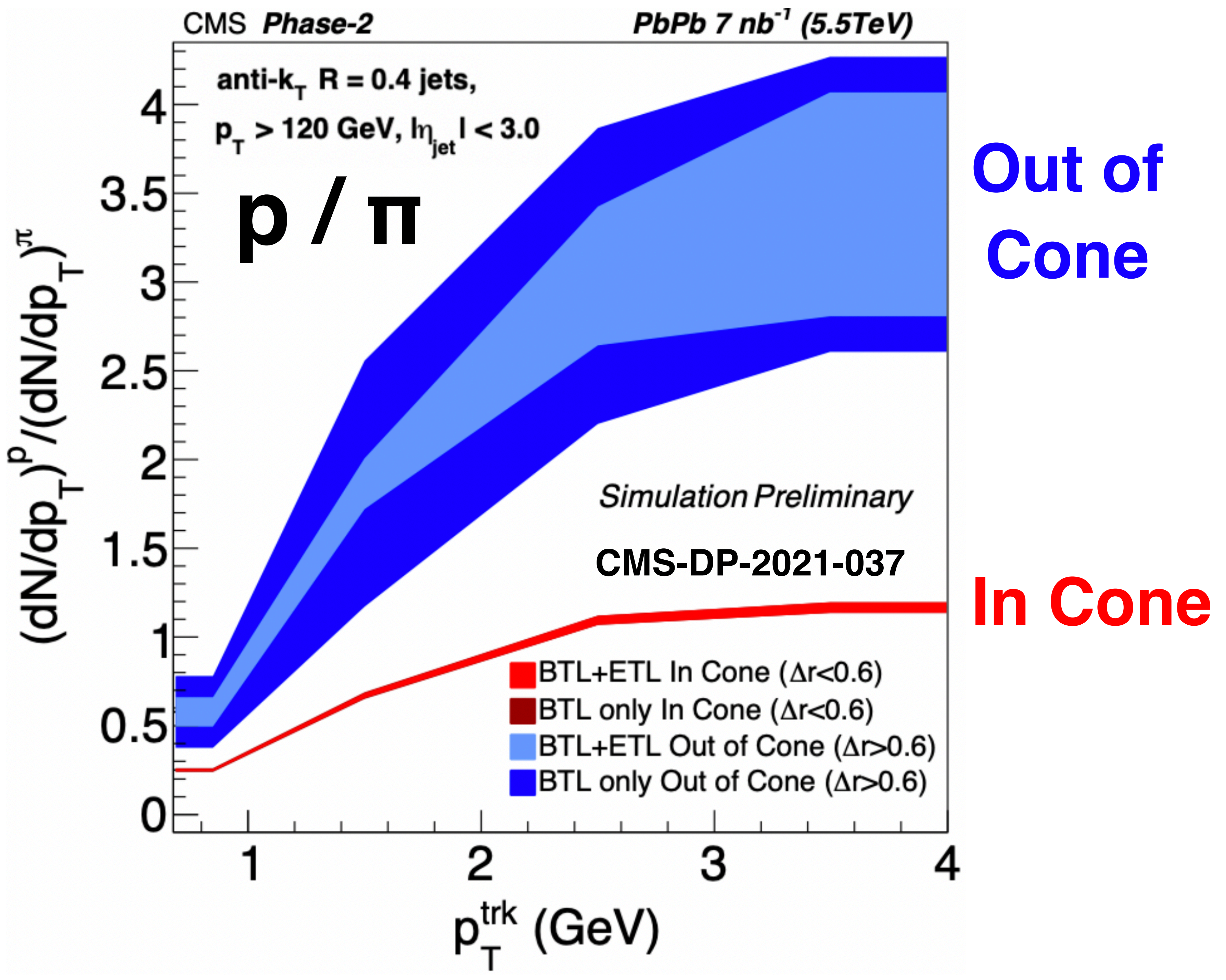
- CMS HL upgrades + MTD provides a unique opportunity to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.

QGP response to parton energy loss

Radial momentum distribution

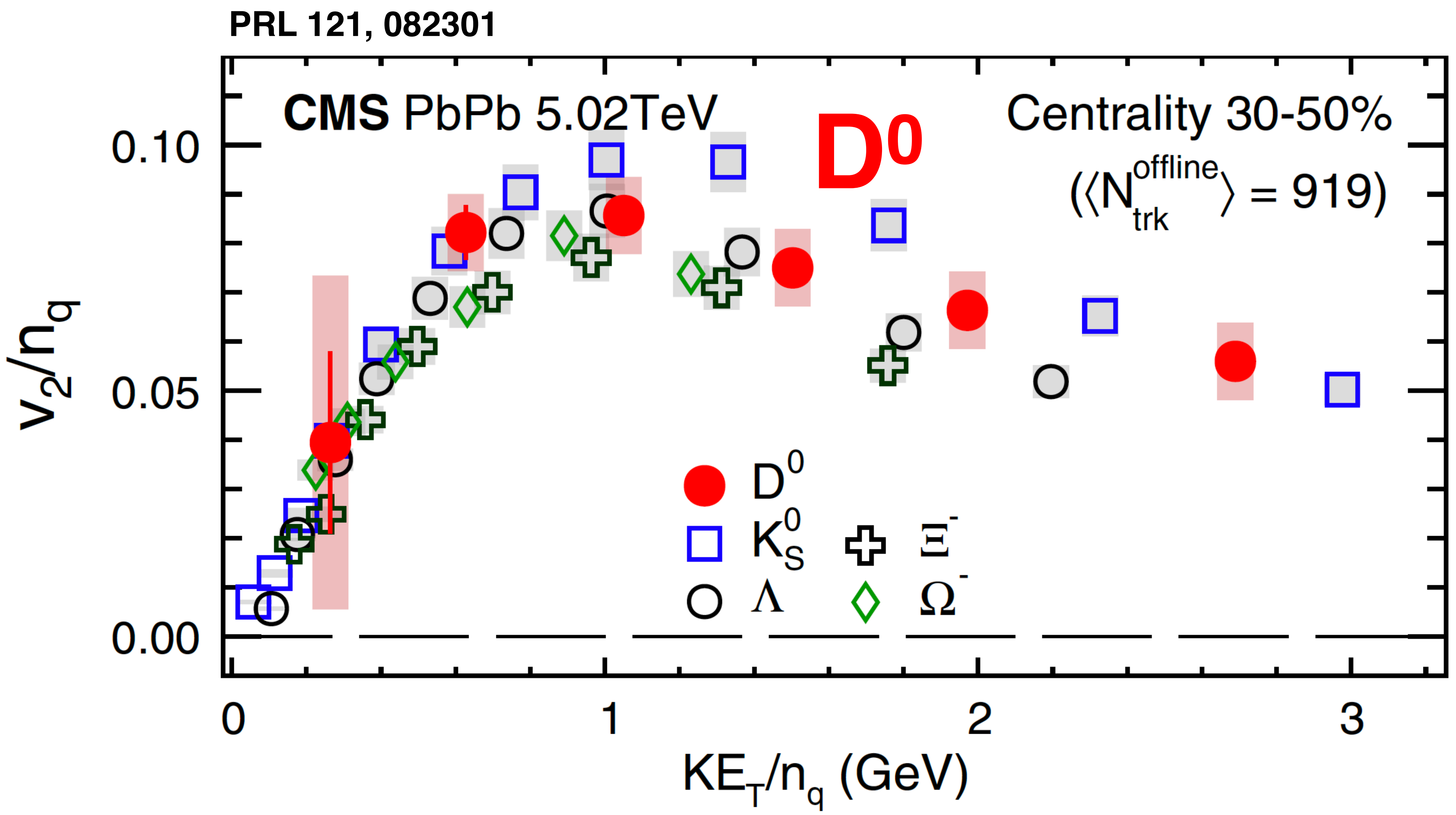






- CMS HL upgrades + MTD provide a unique opportunity to measure baryon-to-meson ratios differential in jet radii, distinguishing between QGP medium effects and jet fragments.

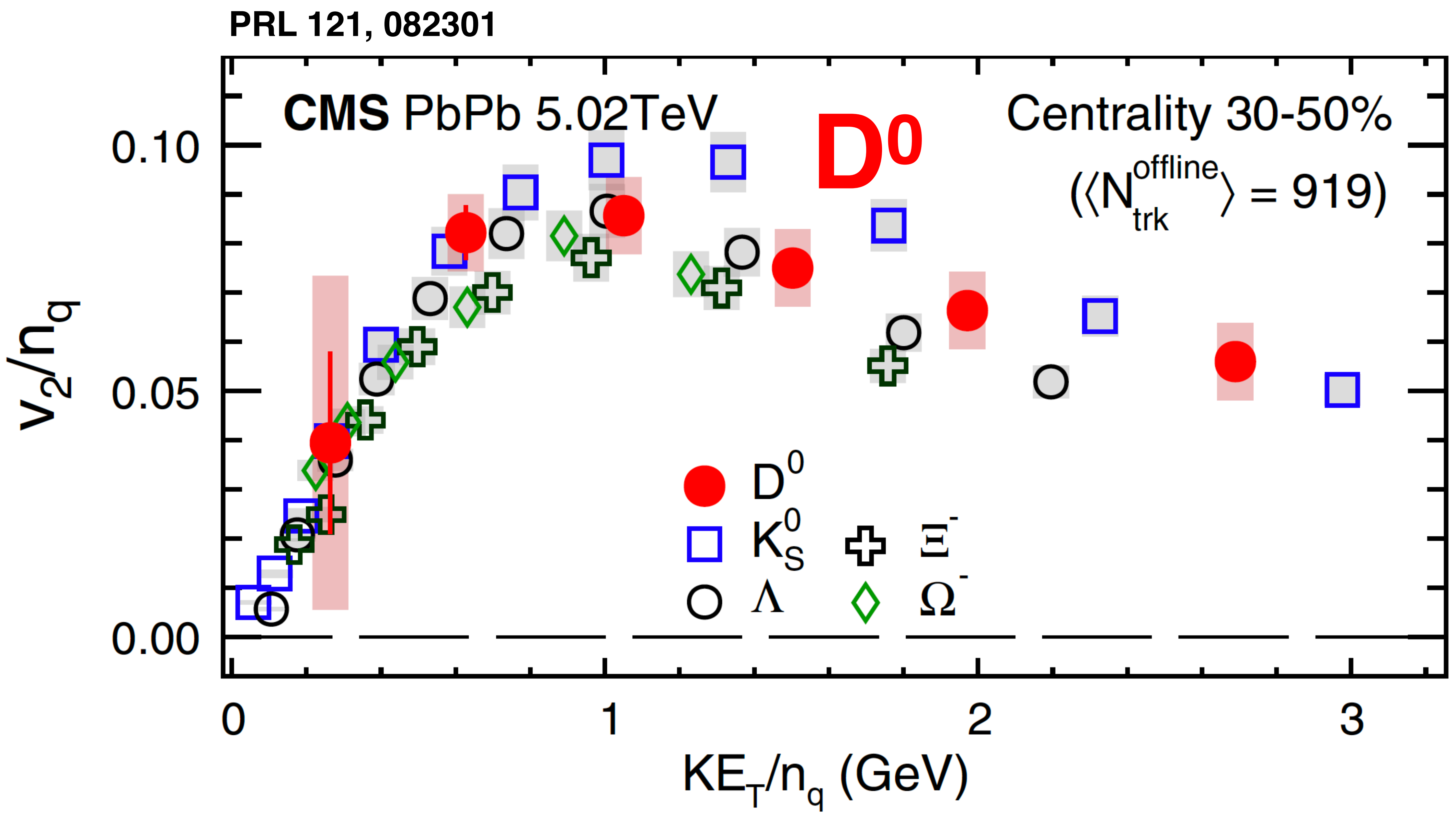
Universal scaling of elliptic flow

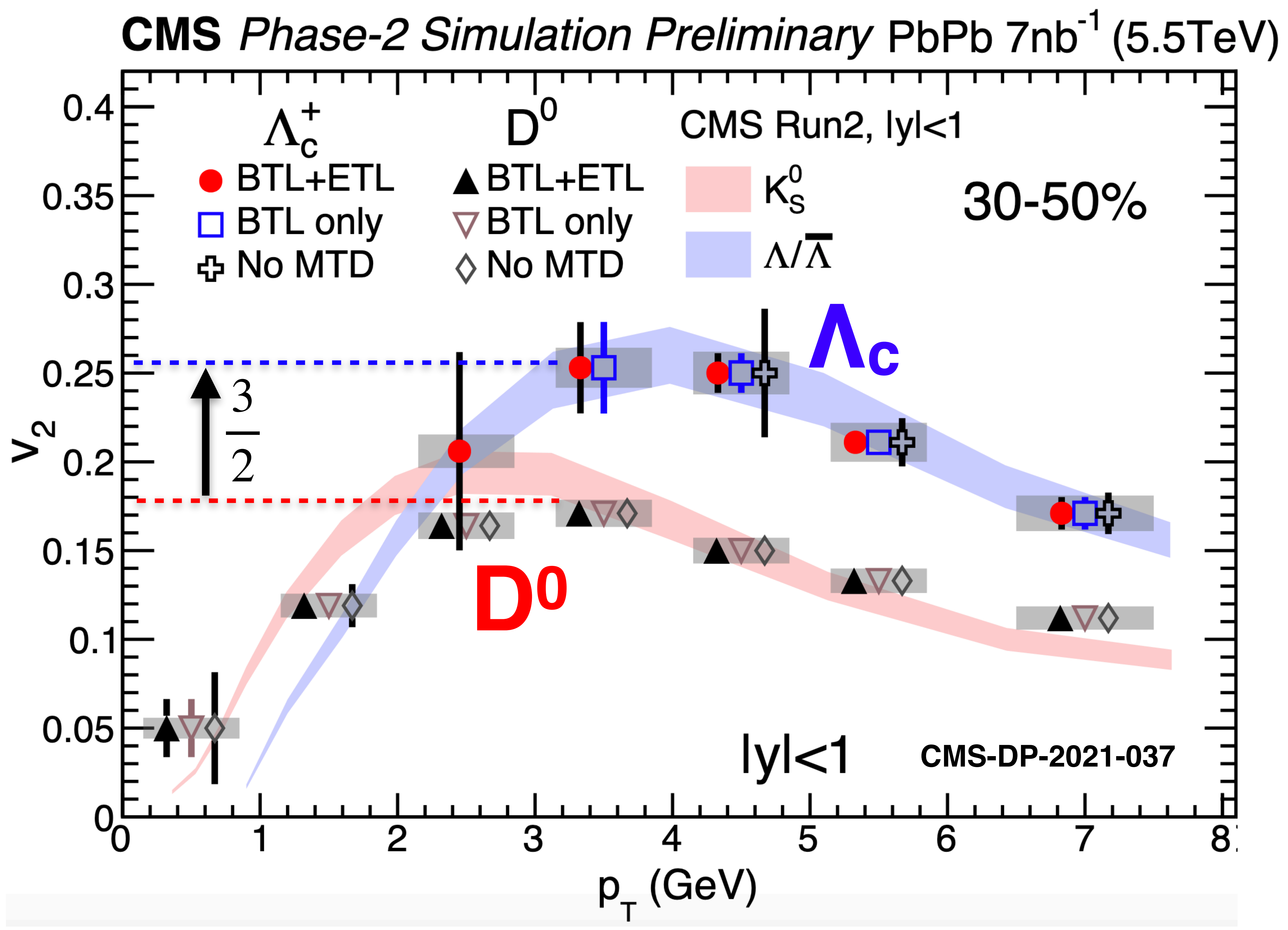


- MTD will allow to derive the v_2 of charm baryons and to measure precisely the N_q-scaling of v_2 in the charm quark sector:

$$v_2(\Lambda_c) = \frac{3}{2} v_2(D^0)?$$

Universal scaling of elliptic flow

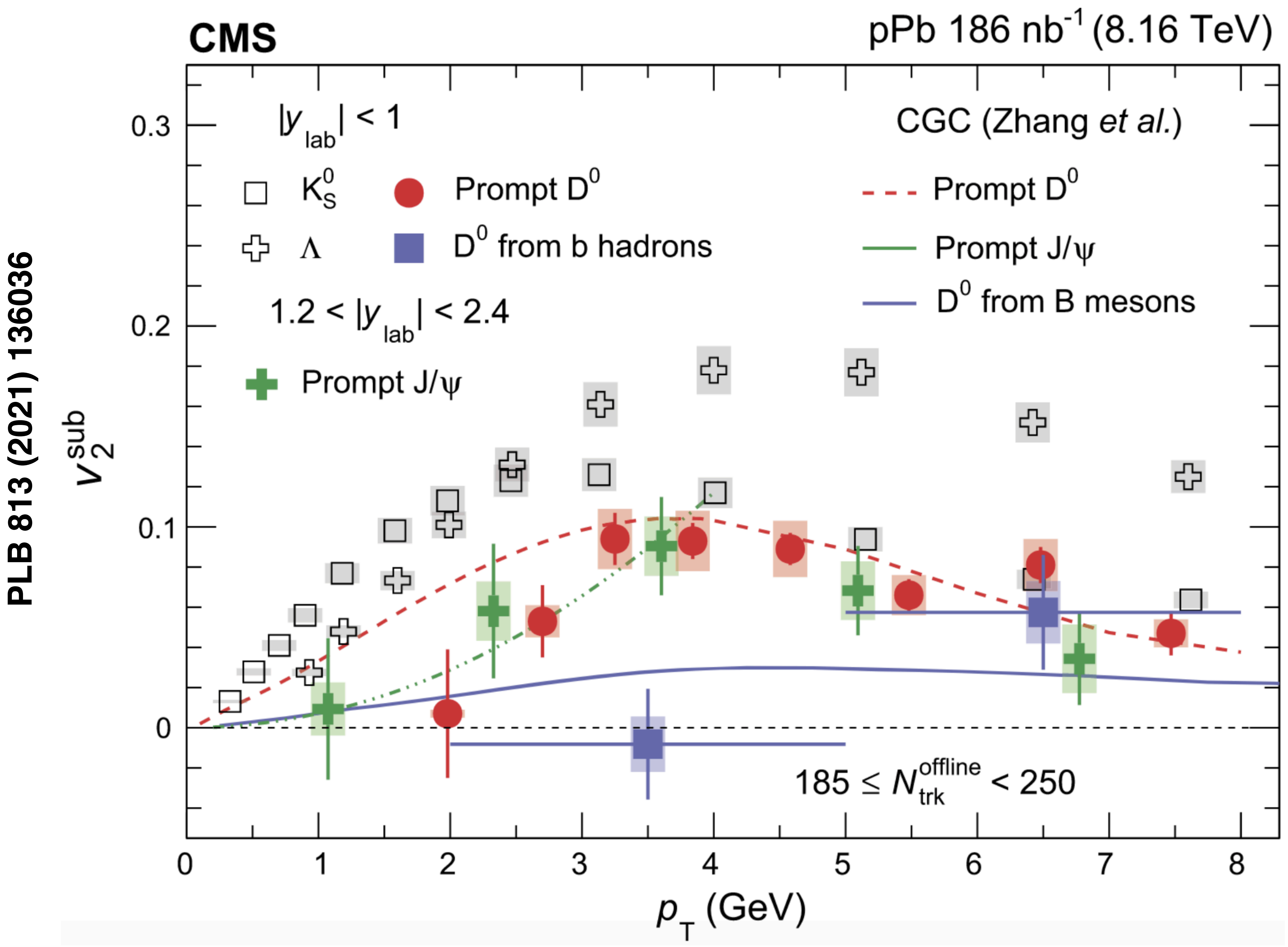




- MTD will allow to derive the v_2 of charm baryons and to measure precisely the N_q-scaling of v_2 in the charm quark sector:

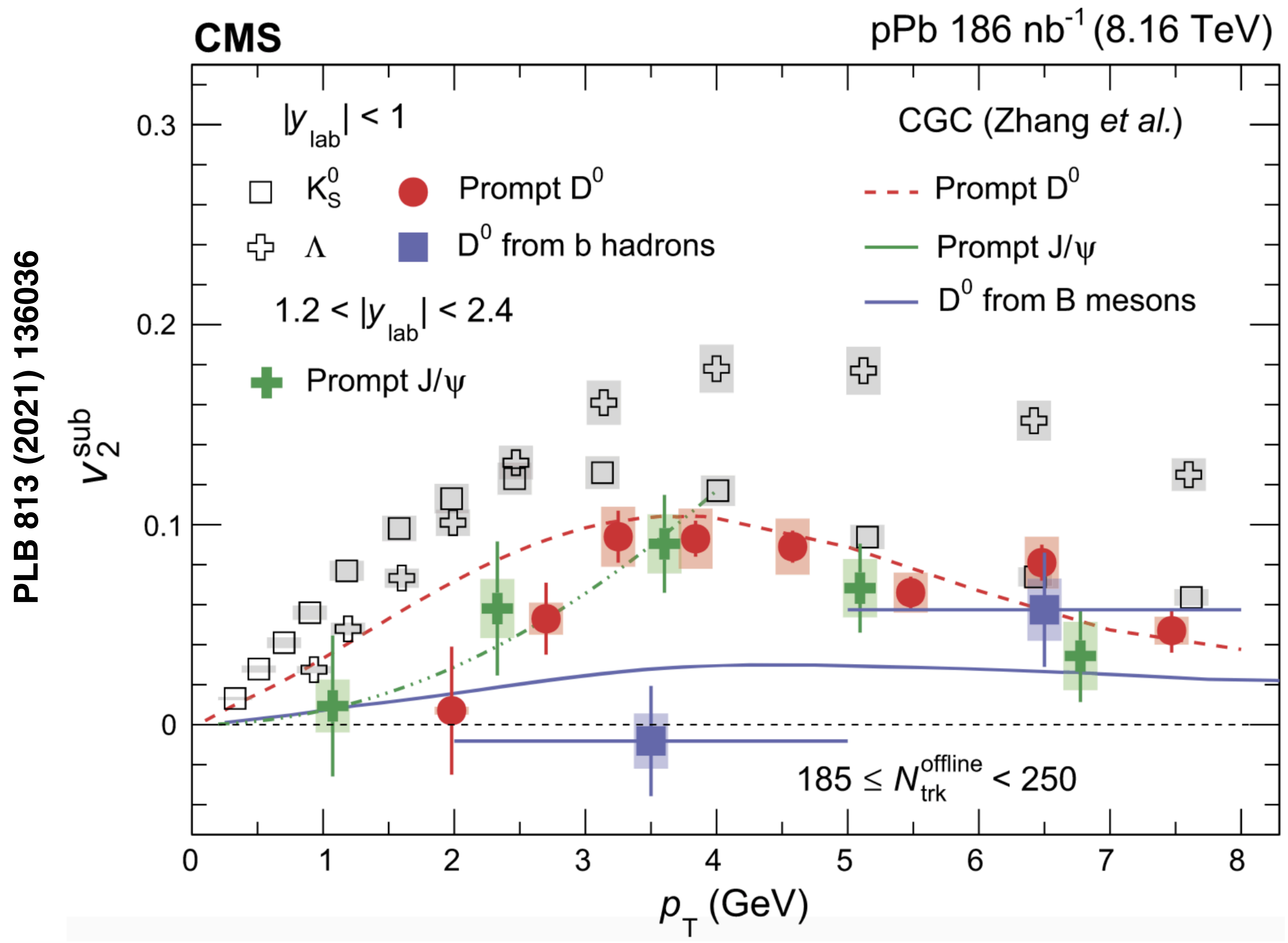
$$v_2(\Lambda_c) = \frac{3}{2}\, v_2(D^0)?$$

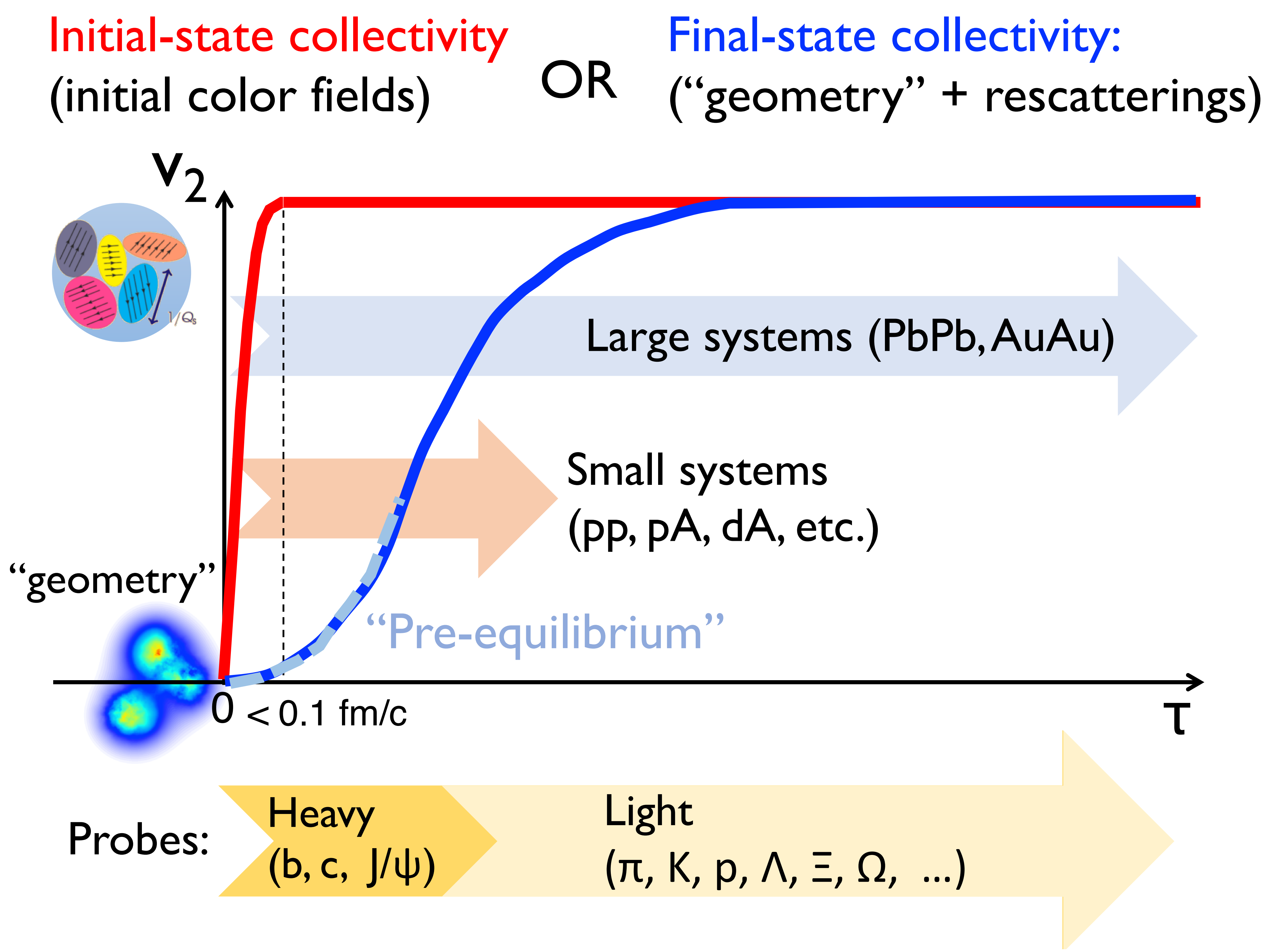
Origin of collectivity in small systems



- Collect more data by triggering on high MIP-multiplicity with MTD.
- Reduce the HF background using TOF-PID, allowing to measure v_2 down to very low p_T for a variety of HF hadrons in small systems.

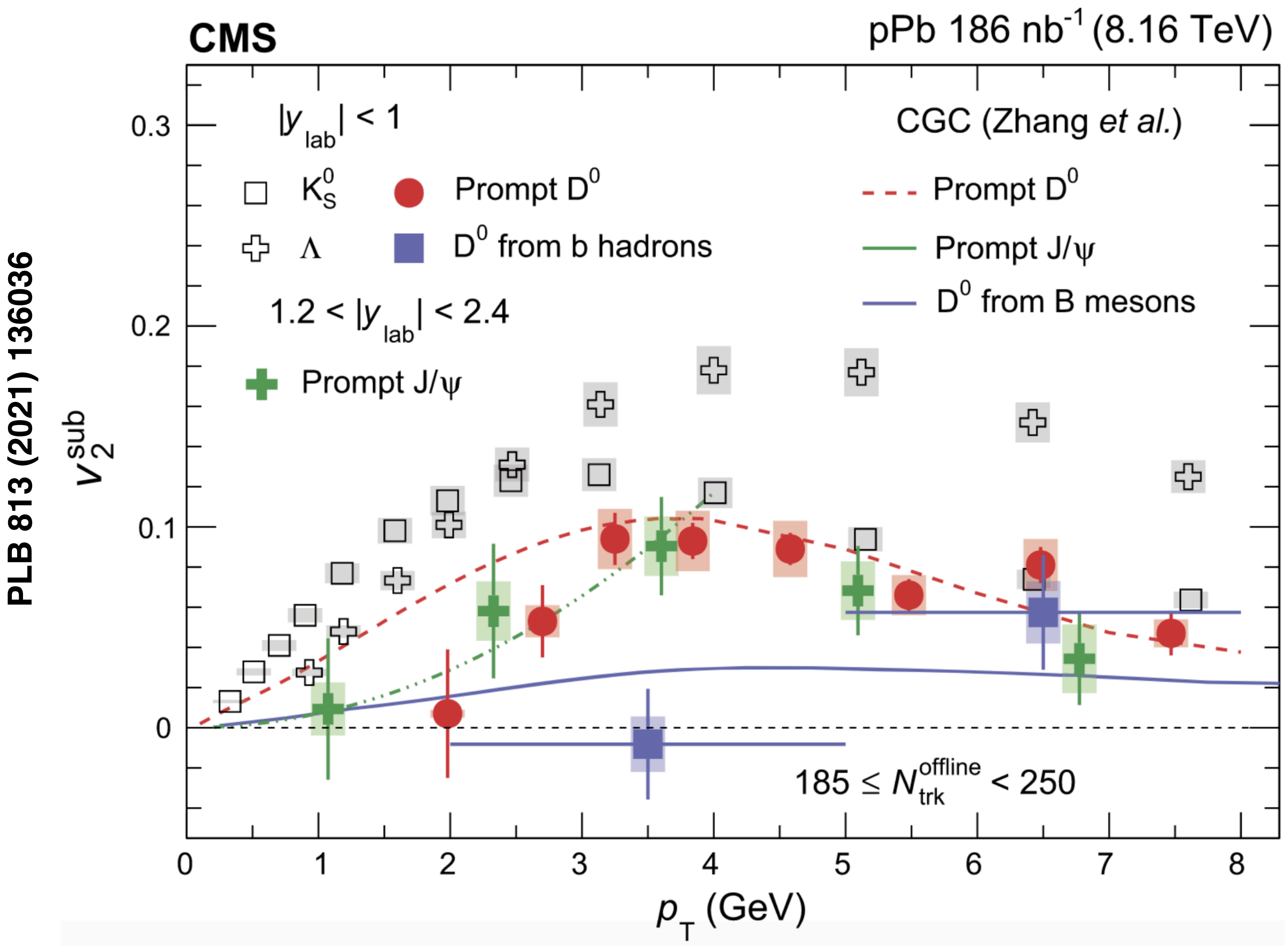
Origin of collectivity in small systems

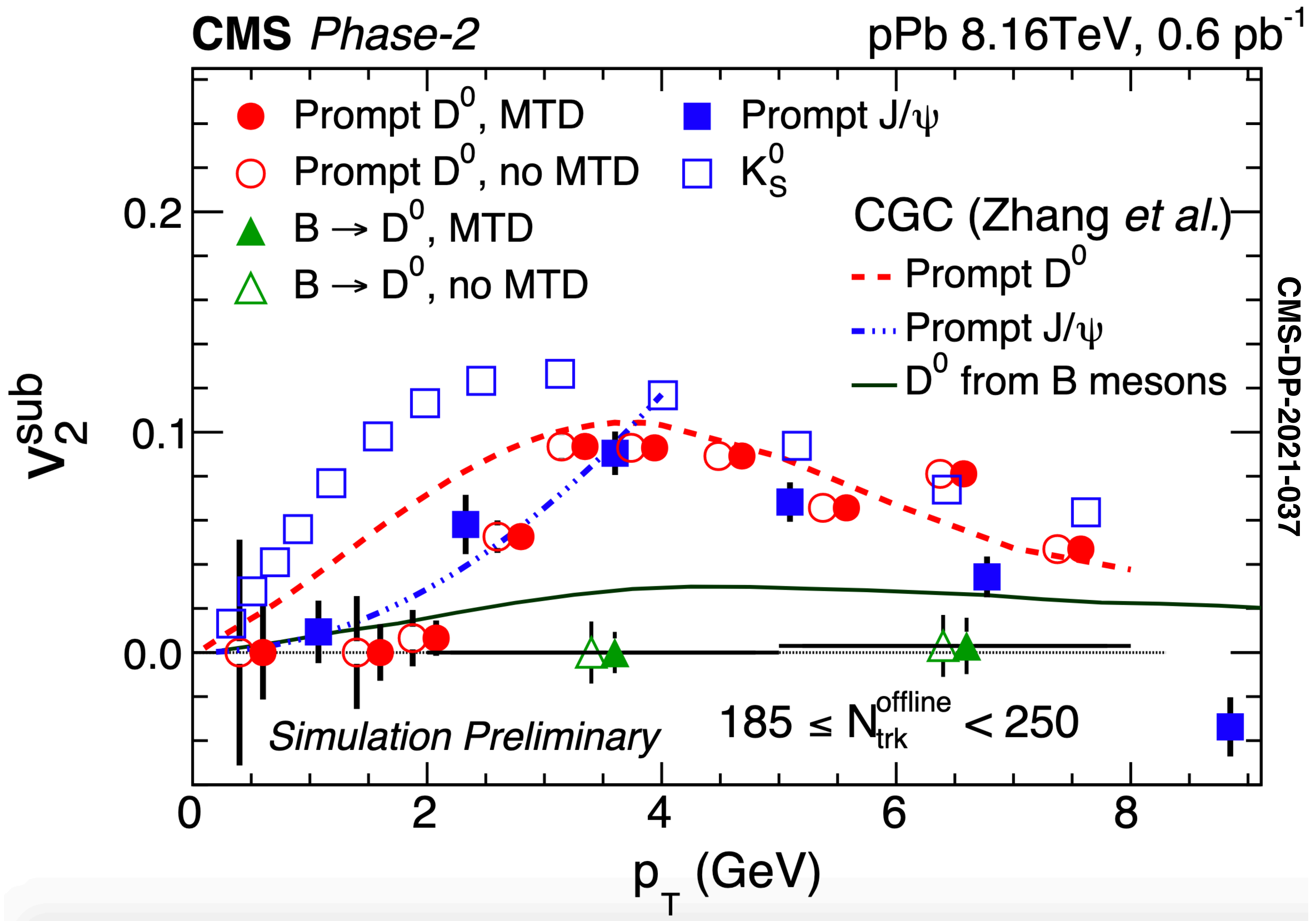




- Collect more data by triggering on high MIP-multiplicity with MTD.

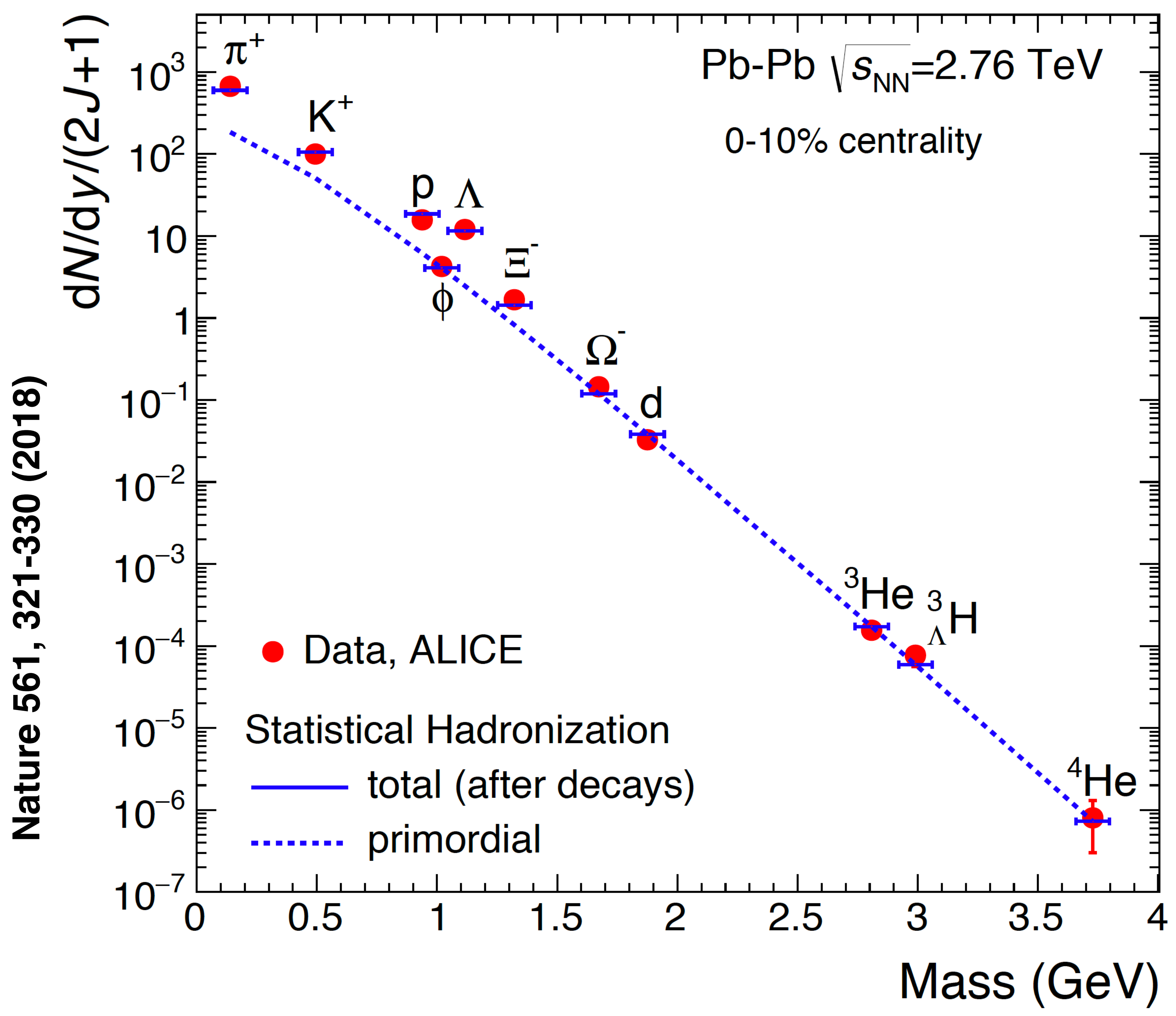
Origin of collectivity in small systems

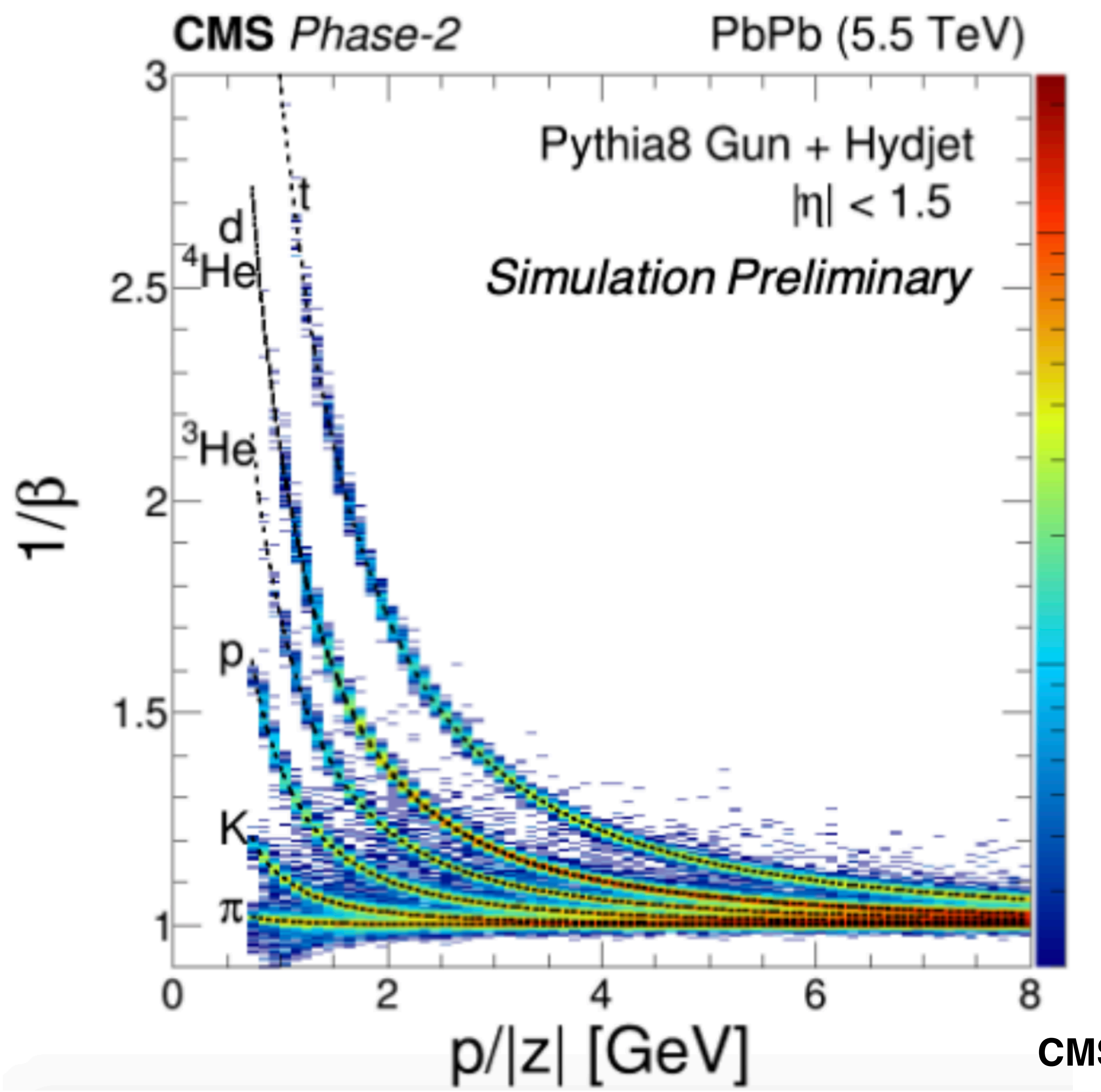




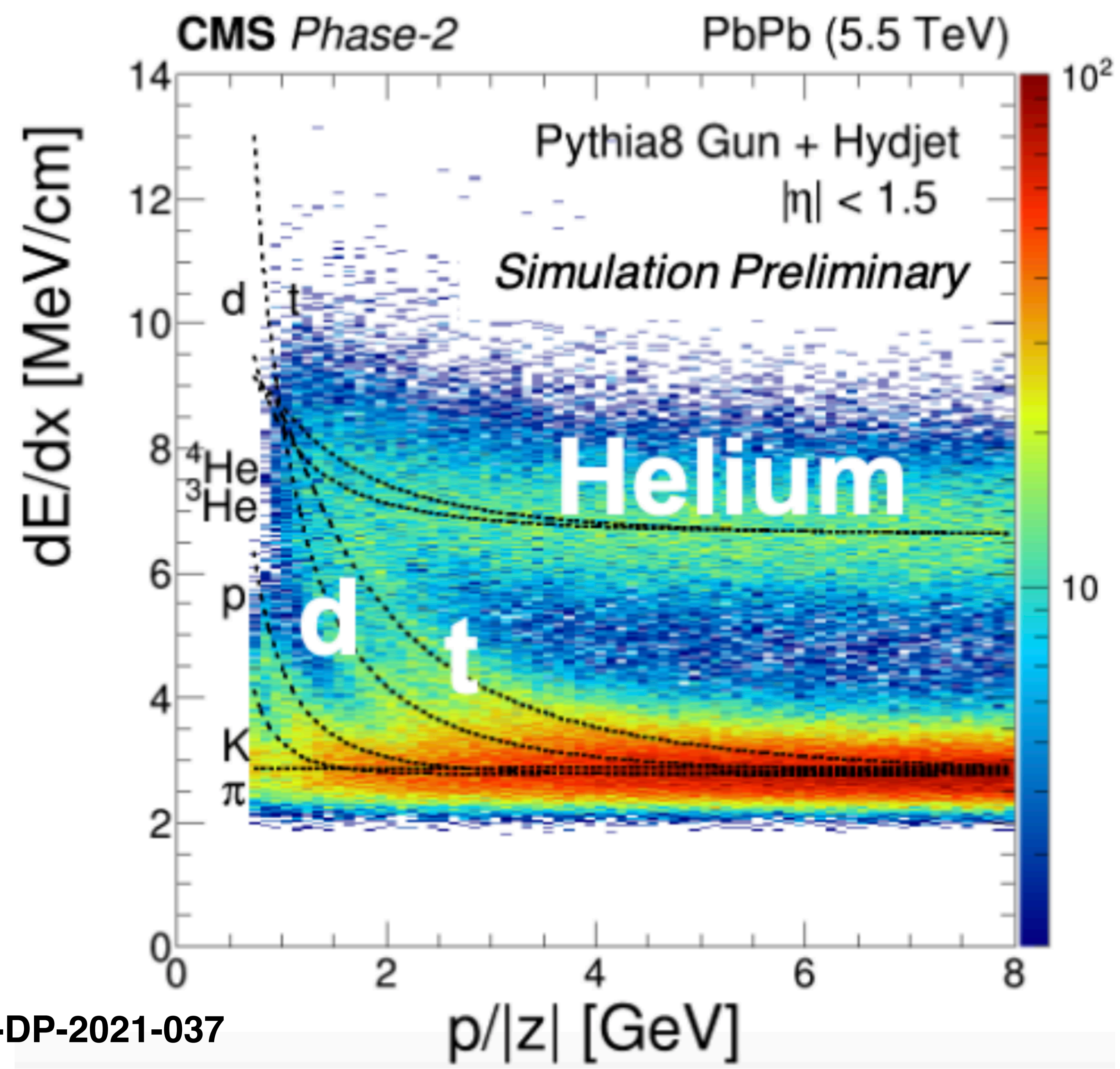
- Collect more data by triggering on high MIP-multiplicity with MTD.
- Reduce the HF background using TOF-PID, allowing to measure v_2 down to very low p_T for a variety of HF hadrons in small systems.

Light nuclei production





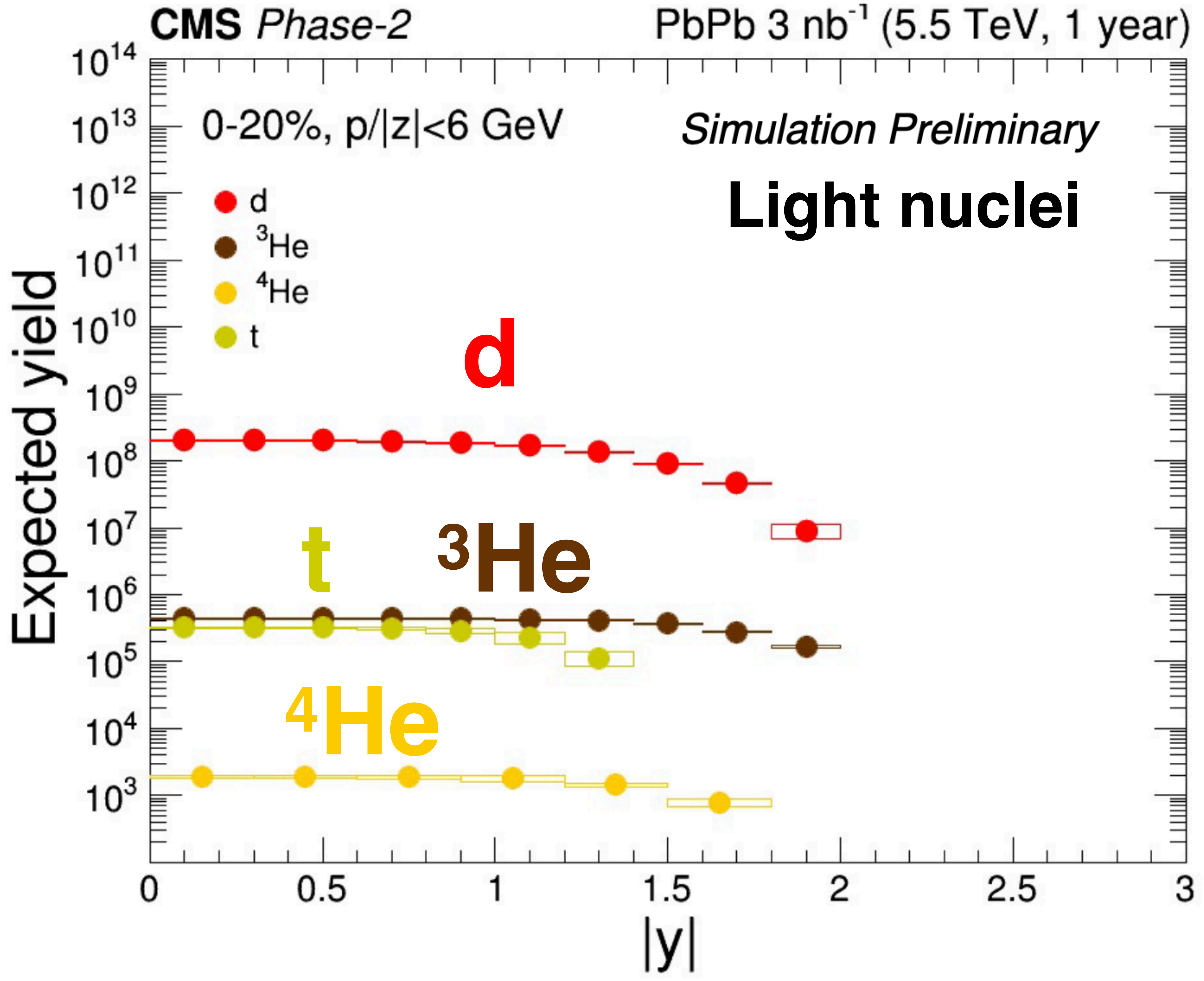
CMS-DP-2021-037

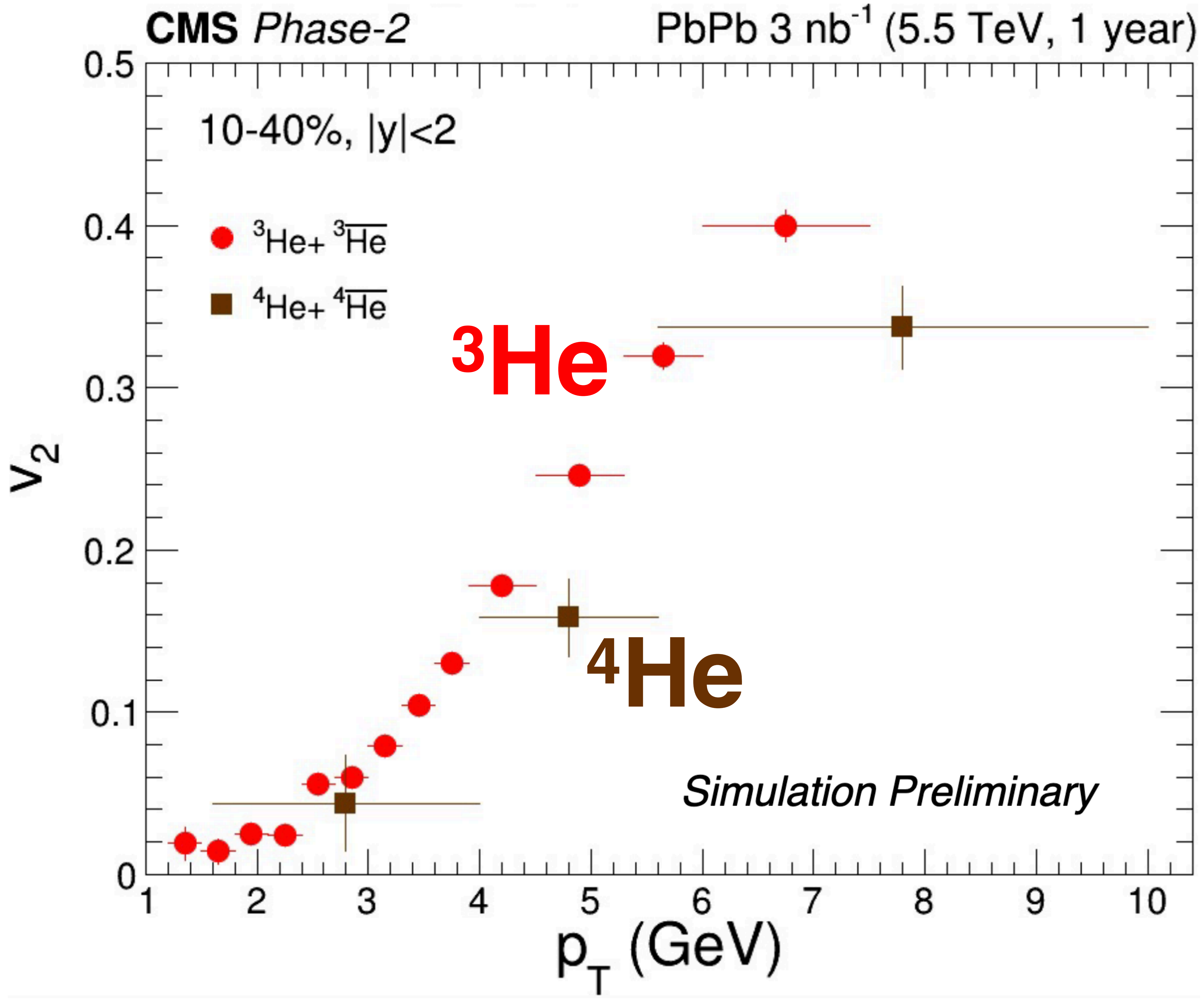


- Precise measurements of nucleus yields and anisotropies can probe production mechanism.
- Light (d, t, ^{3}He, ^{4}He) nuclei can be identified via PID using MTD TOF and pixel tracker dE/dx.

Light nuclei projection in PbPb

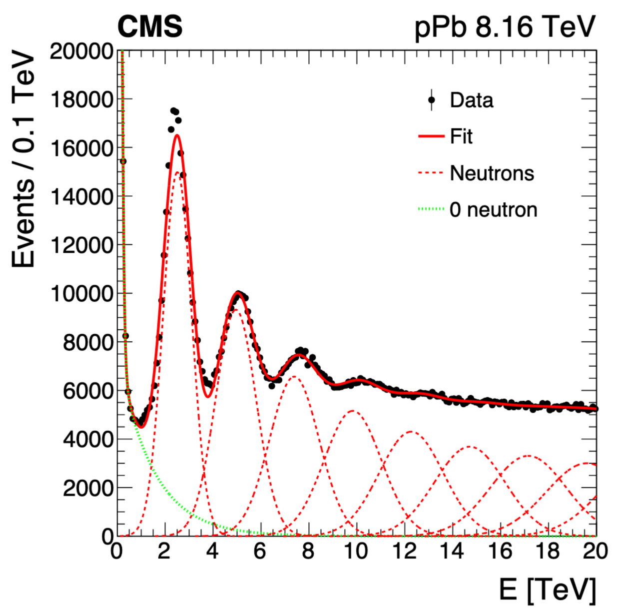
CMS-DP-2021-037

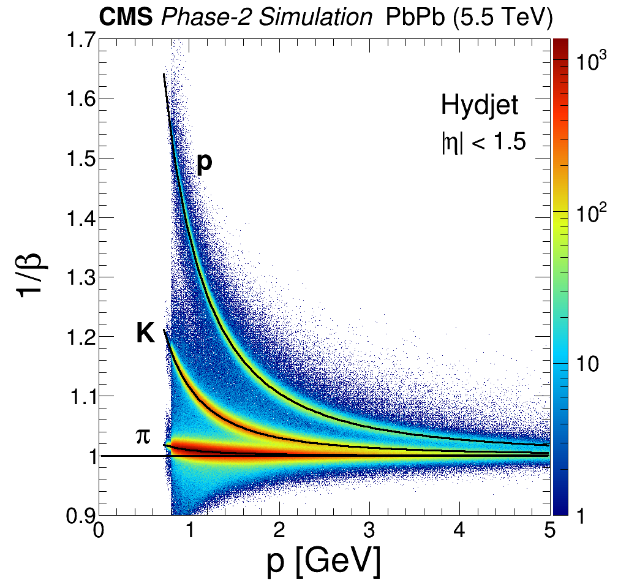


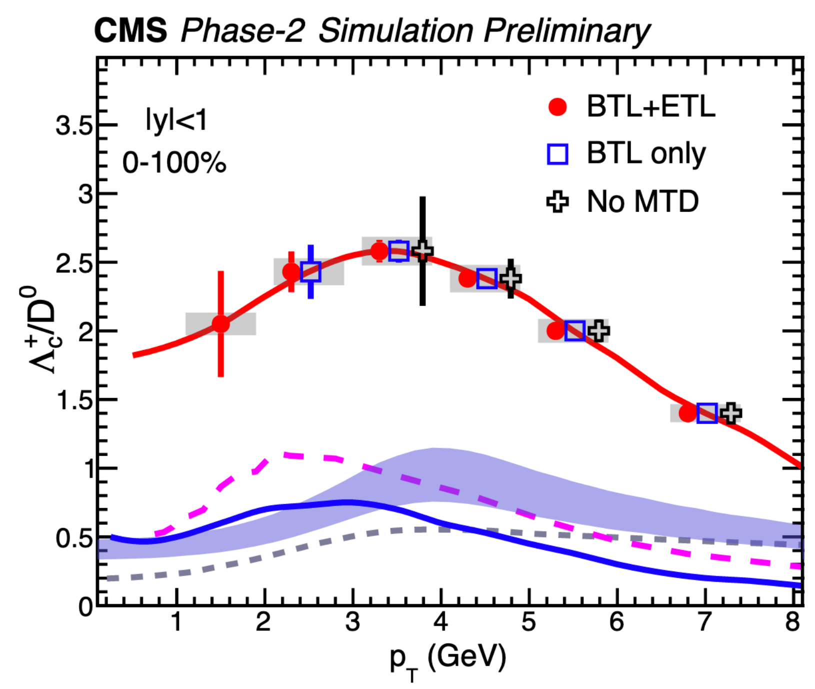


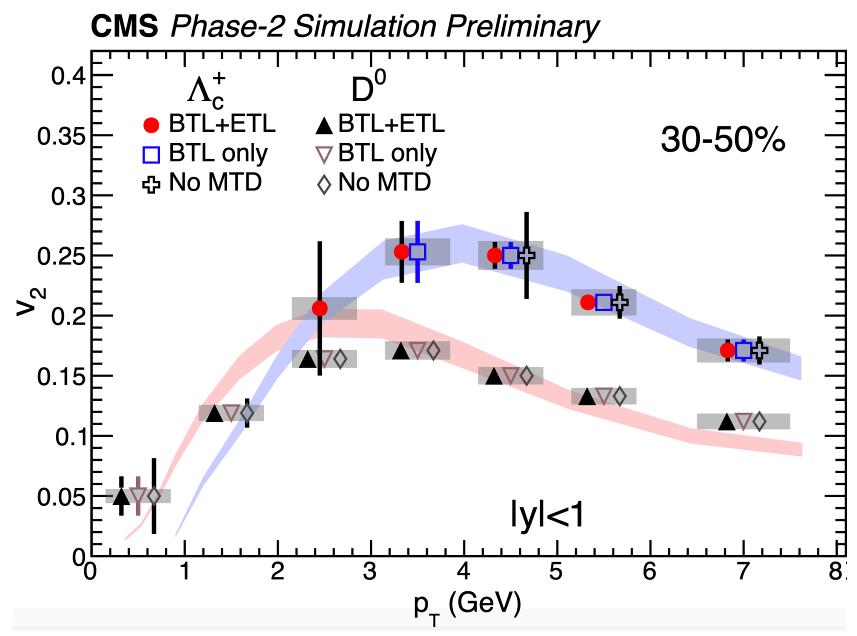
- CMS will be able to measure precisely light (anti)nuclei in PbPb collisions over a wide rapidity range.
- CMS Phase-2 will be crucial to measure for the first time the anisotropic flow of ^{4}He.
- Precise measurements of ^{3}He v_2 and yields will impose strong constrains to production models.

SUMMARY









CMS will add a new upgrades for HL-LHC:

- ZDC documentation: CERN-LHCC-2021-018 , CERN-LHCC-2021-025
- MTD documentation: CERN-LHCC-2019-003 , CMS-DP-2021-037

- ZDC will provide precise neutron detection and reaction plane measurement.
- MTD will bring a completely new capability to CMS: particle identification via time-of-flight

High impact on CMS Heavy Ion physics program:

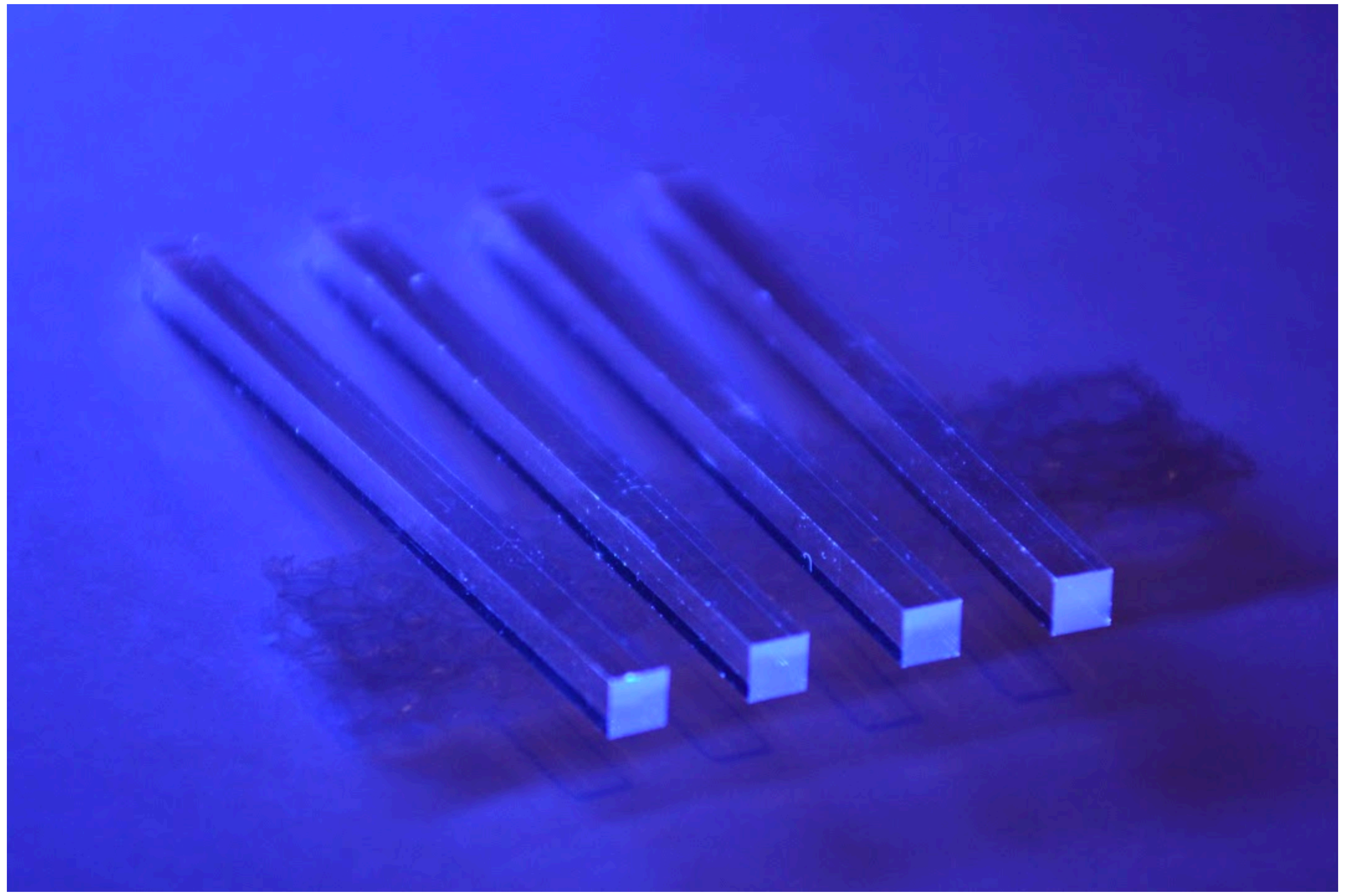
- Heavy quark dynamics in QGP → D and Λ_C $p_T > 0$
- QGP response to parton energy loss
- Universal scaling of elliptic flow
- Origin of collectivity in small systems
- Light nuclei physics
- …. among other topics

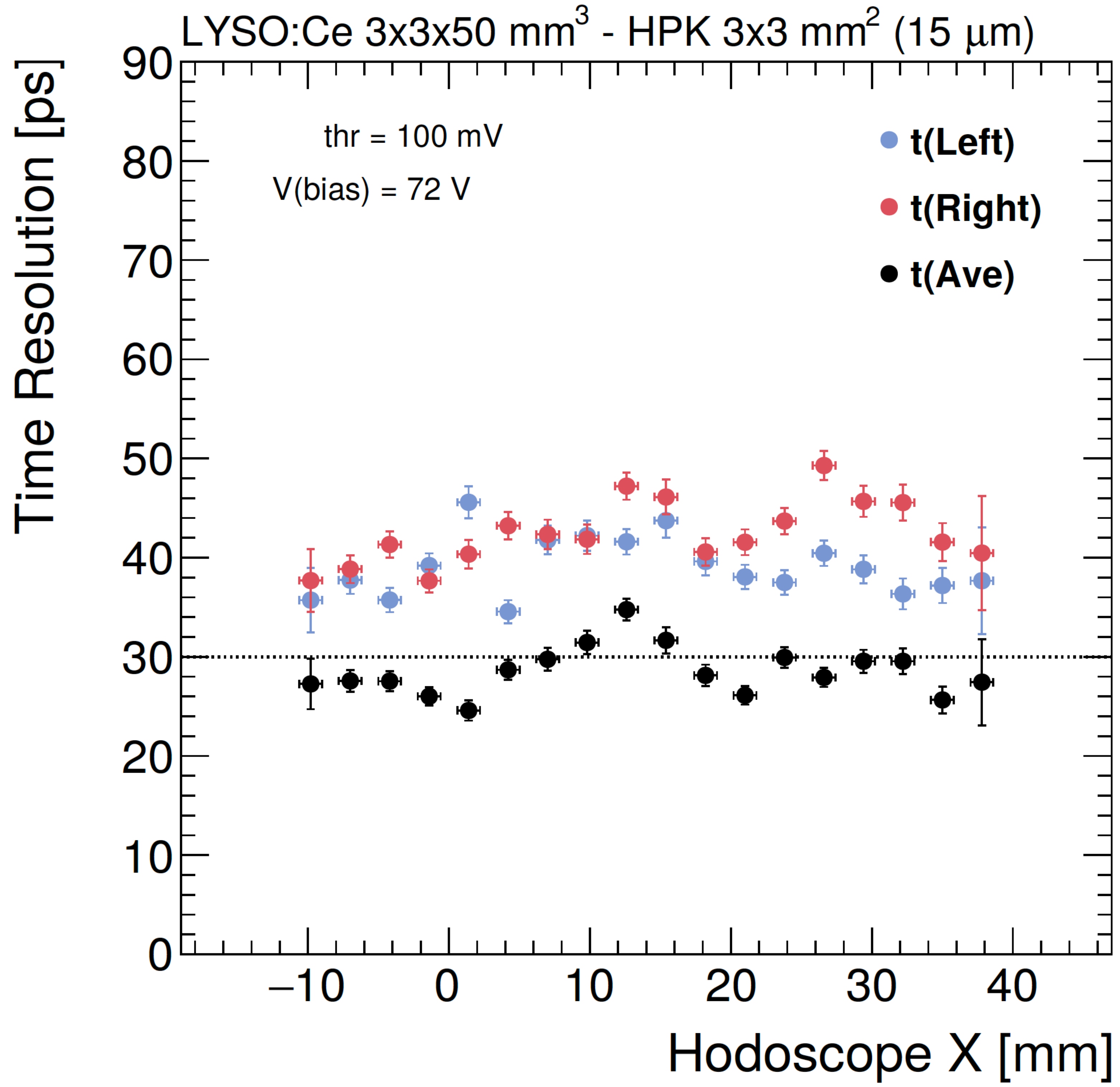
Thank you for your attention!

BACKUP

Lutetium-Yttrium Oxyorthosilicate crystal

CERN-LHCC-2019-003

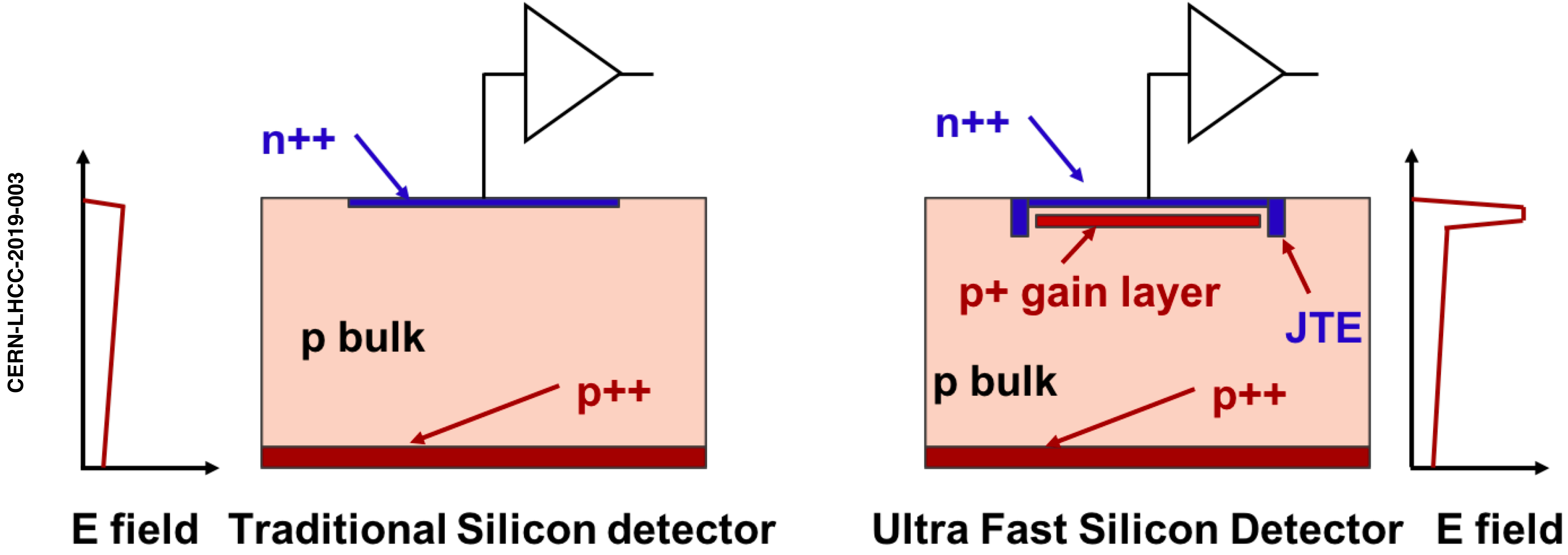




CERN-LHCC-2019-003

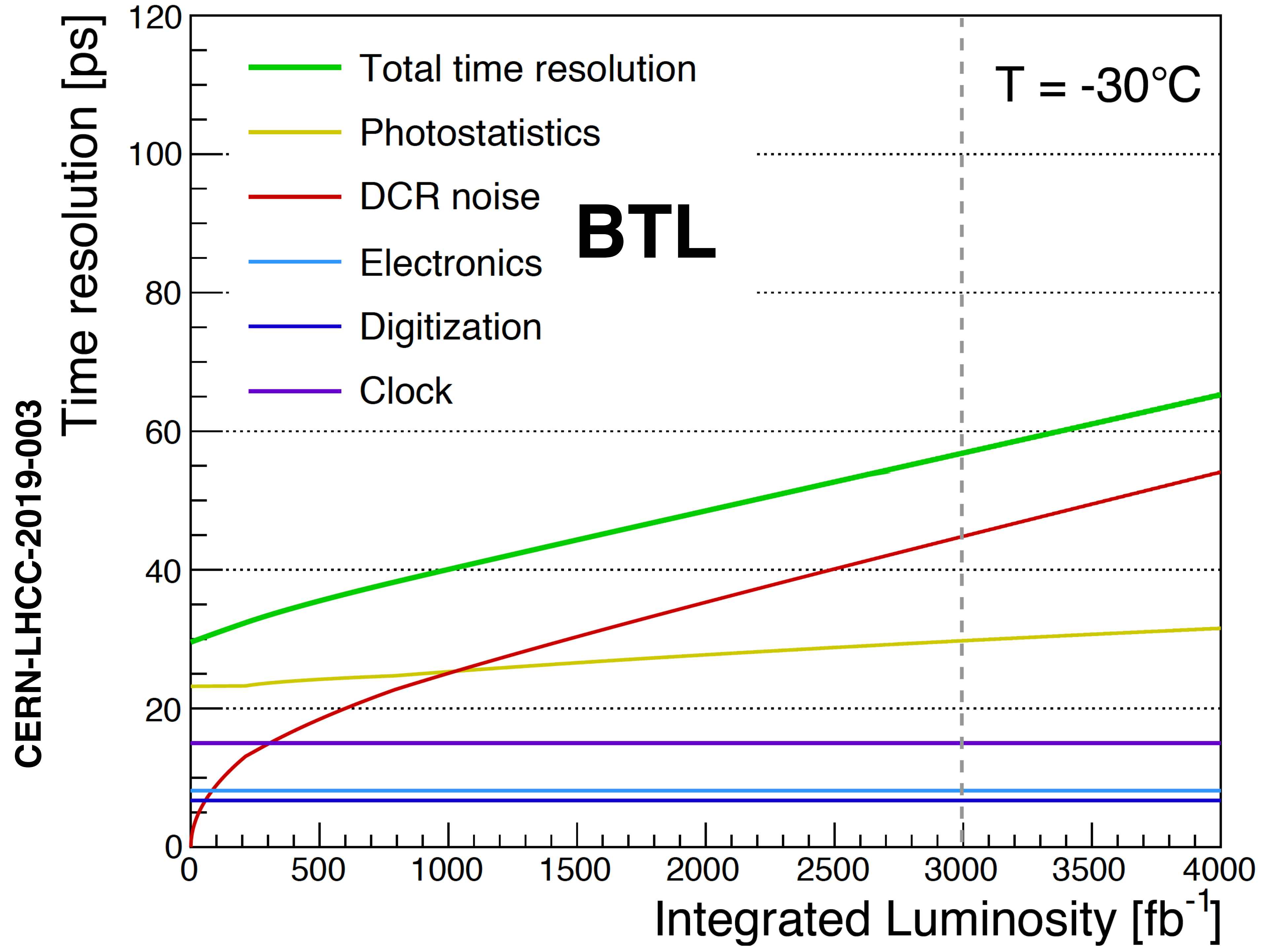
- LYSO:Ce crystal bar size: 3 x 3 x 50 mm^3 and time resolution: ~30 ps.
- LYSO:Ce optimal due to their high light yield (40k photons/MeV), fast scintillation rise time (<100 ps) and short decay time (~40 ns). Also, the light wavelength (420 nm) matches the sensitive range of SiPMs.

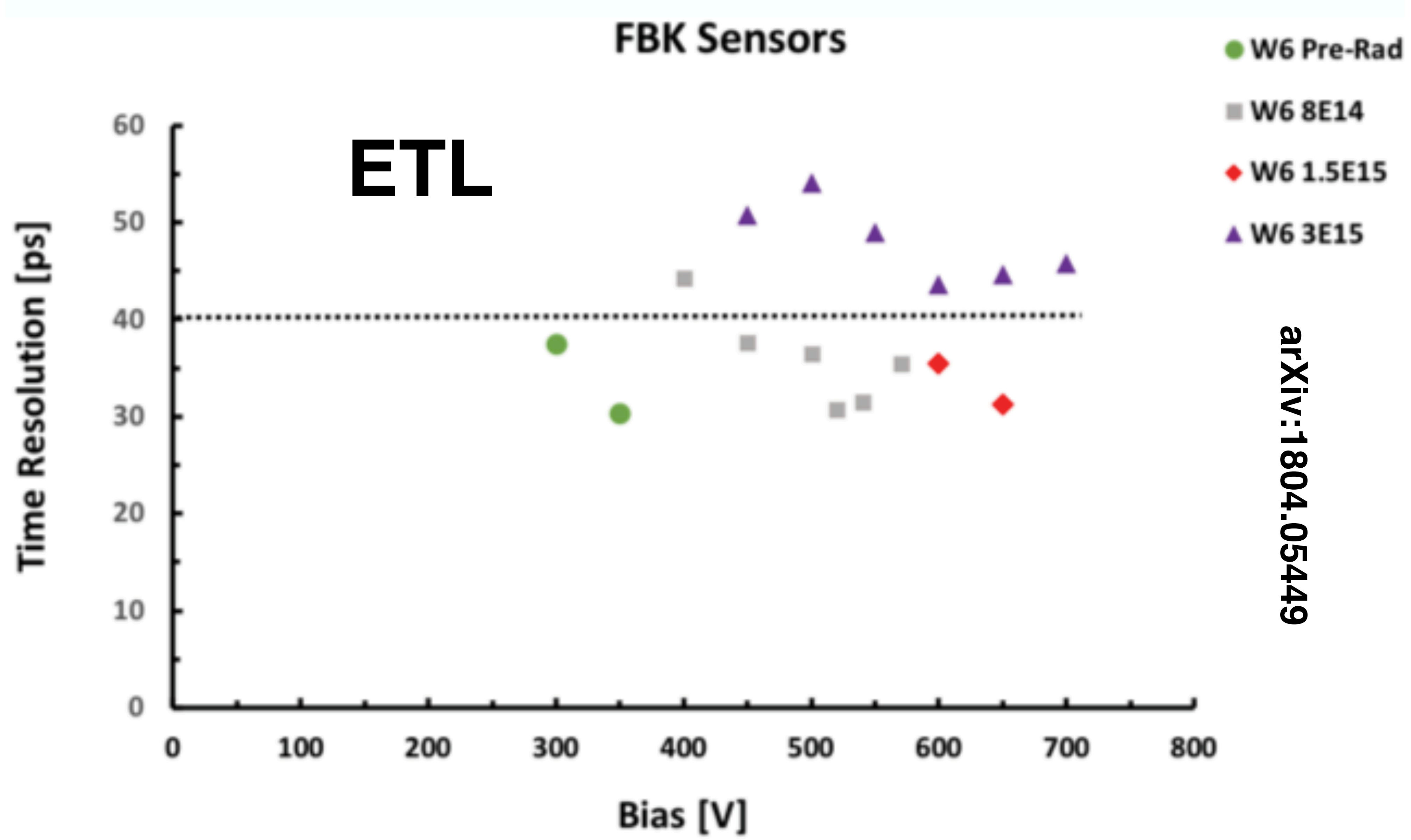
Ultra Fast Silicon Detector



- LGAD sensor pixel size: 1.3 x 1.3 mm^2 and time resolution: 30-50 ps.
- Extra *p*-type implant near the *n*-electrode generates a large electric field, resulting in an electron-avalanche effect that offers a gain factor of 10-30.
- Additional gain allows to extract signals with thinner pixels (depths of 30-50 μm), resulting in: low noise, large slew-rate and fast rising pulse.

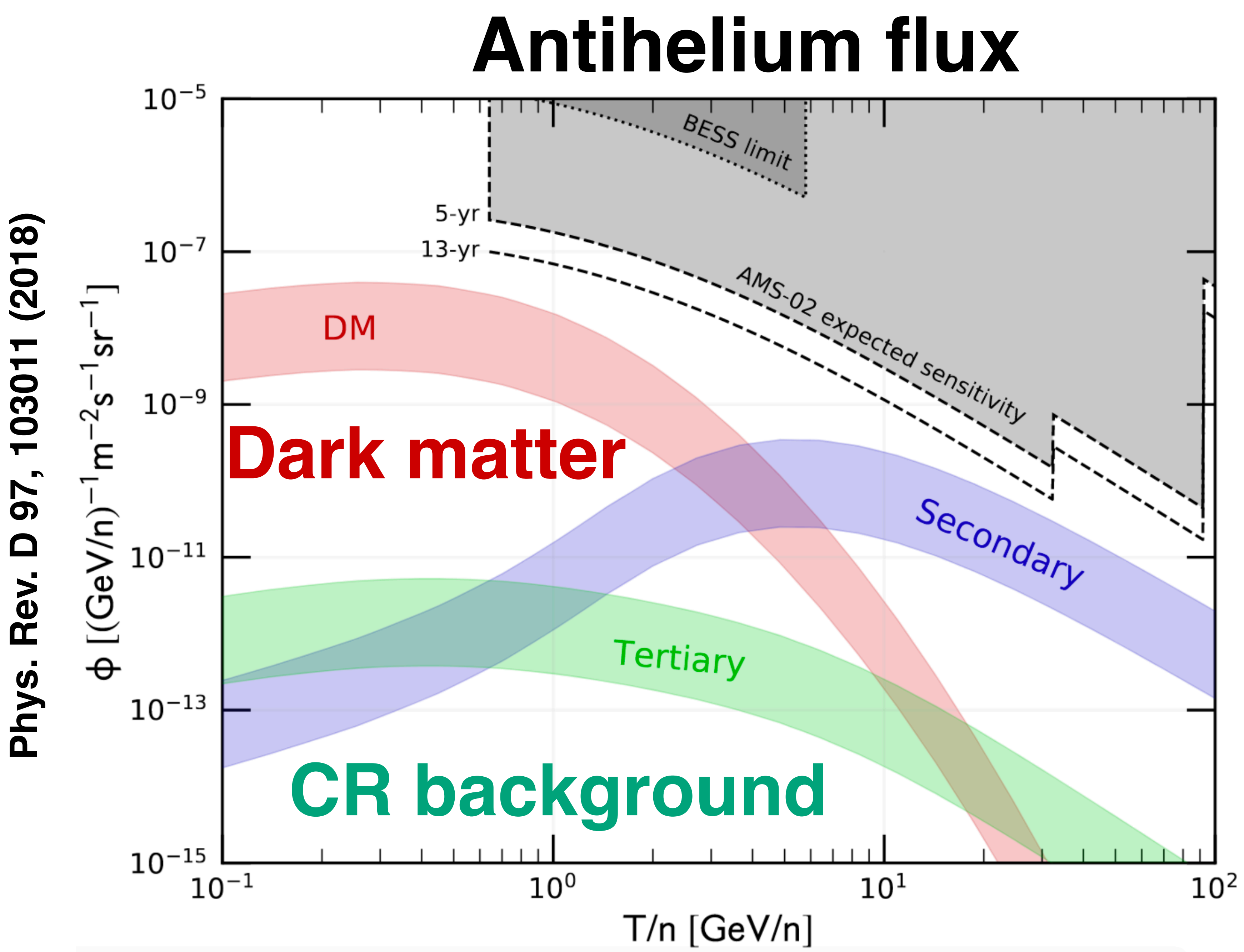
Impact of radiation damage



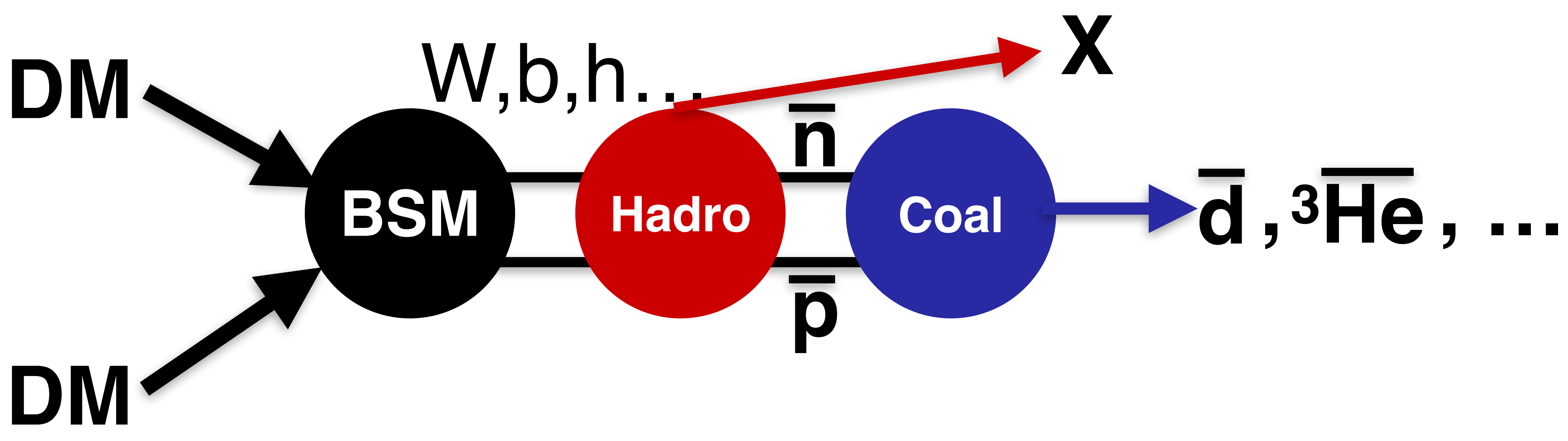


- **BTL**: Radiation damage leads to worse time resolution up to 60 ps by the end of Run 4. Dominated by the dark count rate (DCR) noise of SiPMs.
- **ETL**: The UFSD is also affected by radiation dose, however the time resolution can be recovered by increasing the bias voltage.

Implications for dark matter searches

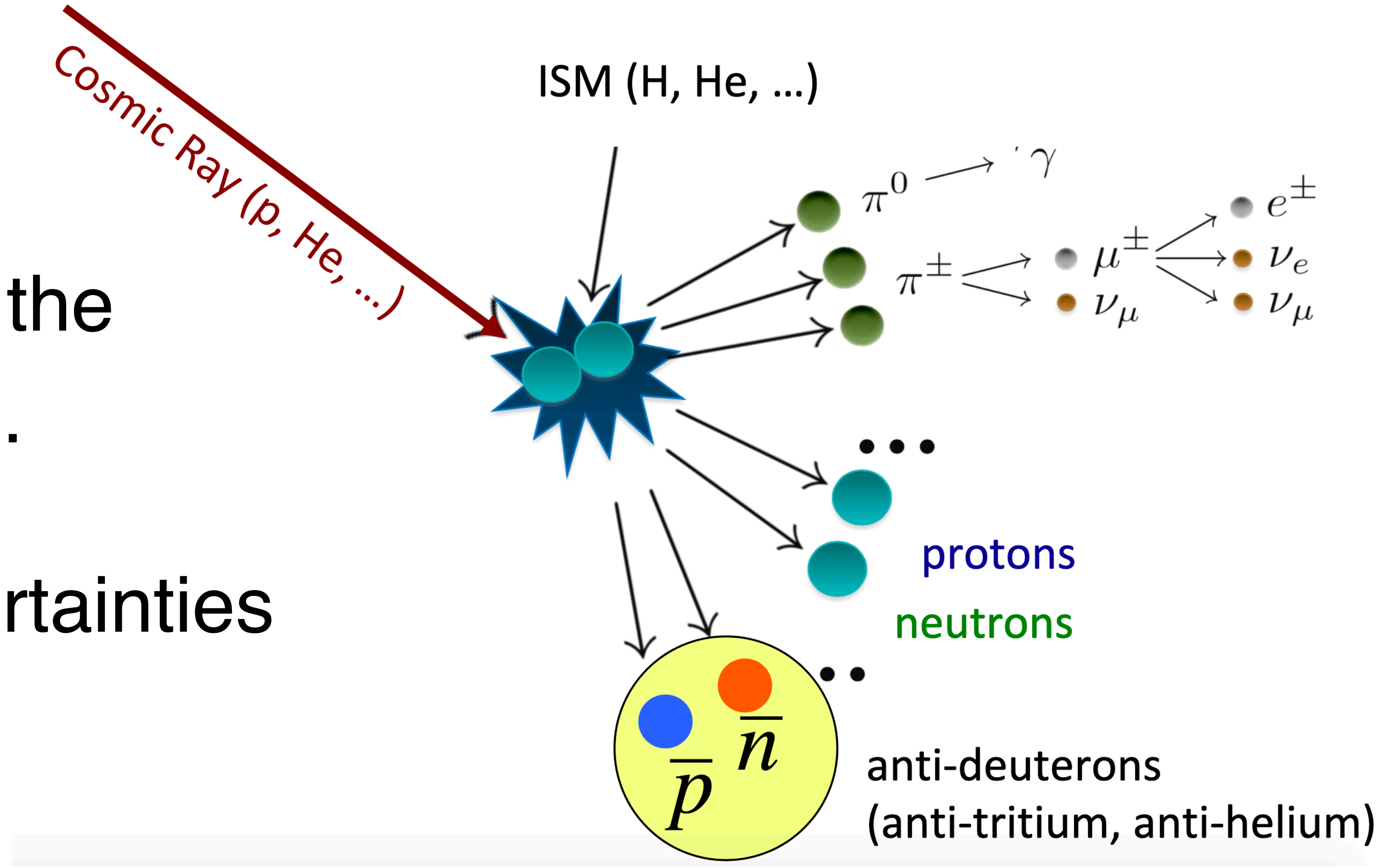


- Light antinuclei may also be produced in dark matter annihilation.

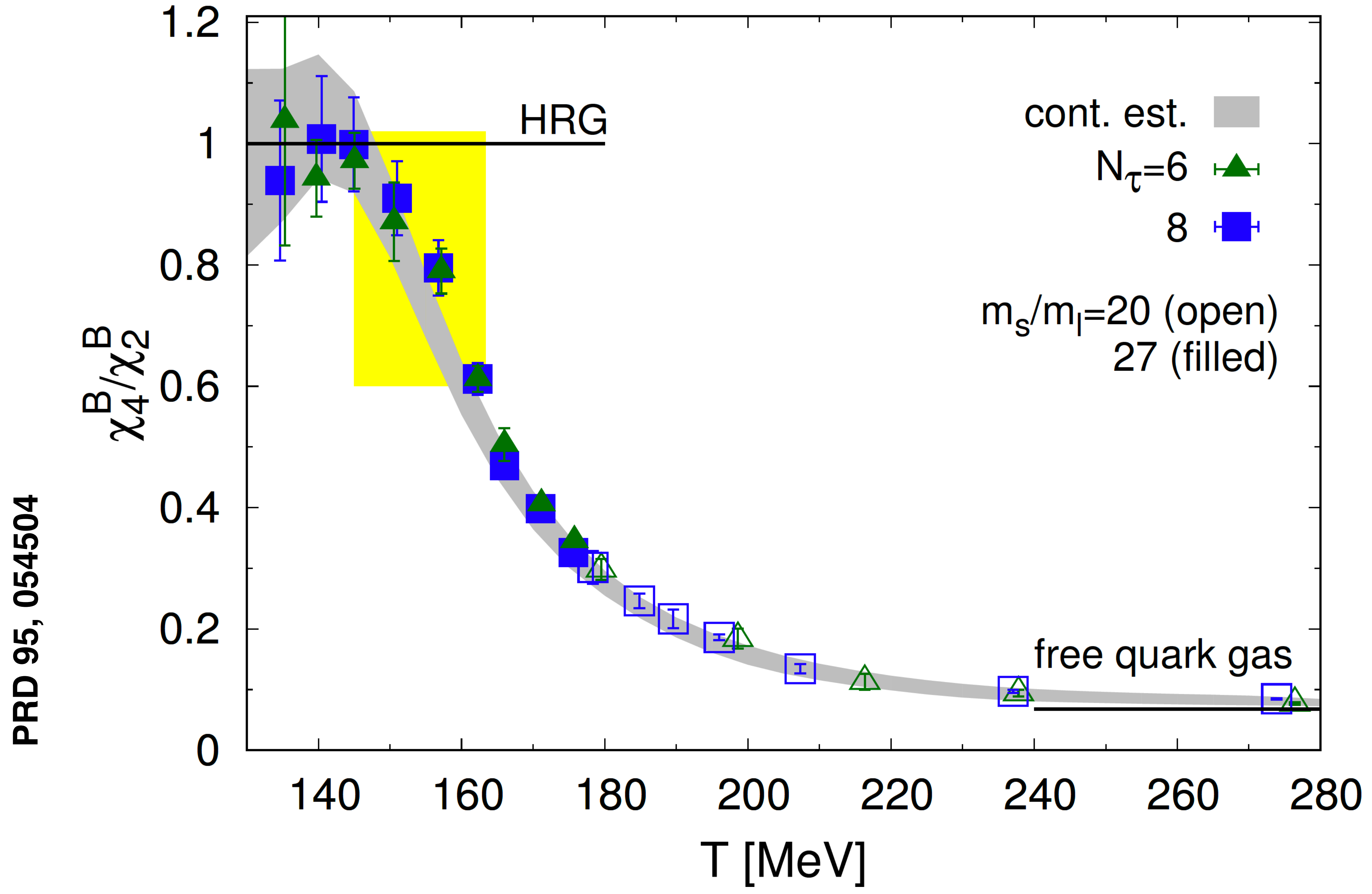


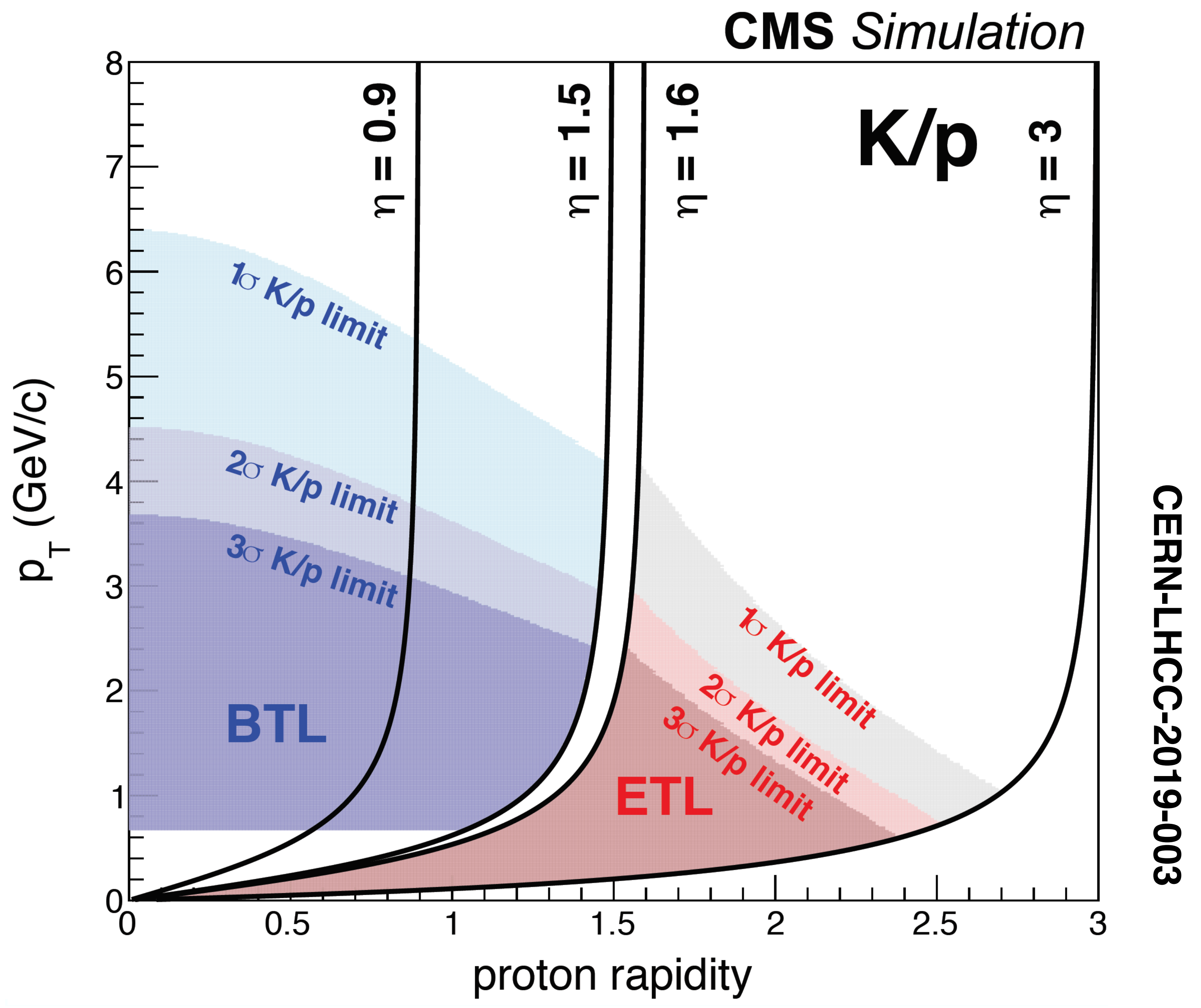
- Light nuclei measurements at LHC can be used to estimate the background of secondary antinuclei in dark matter searches.

- LHC data can also improve the antinucleus production uncertainties and constrain model parameterisations.



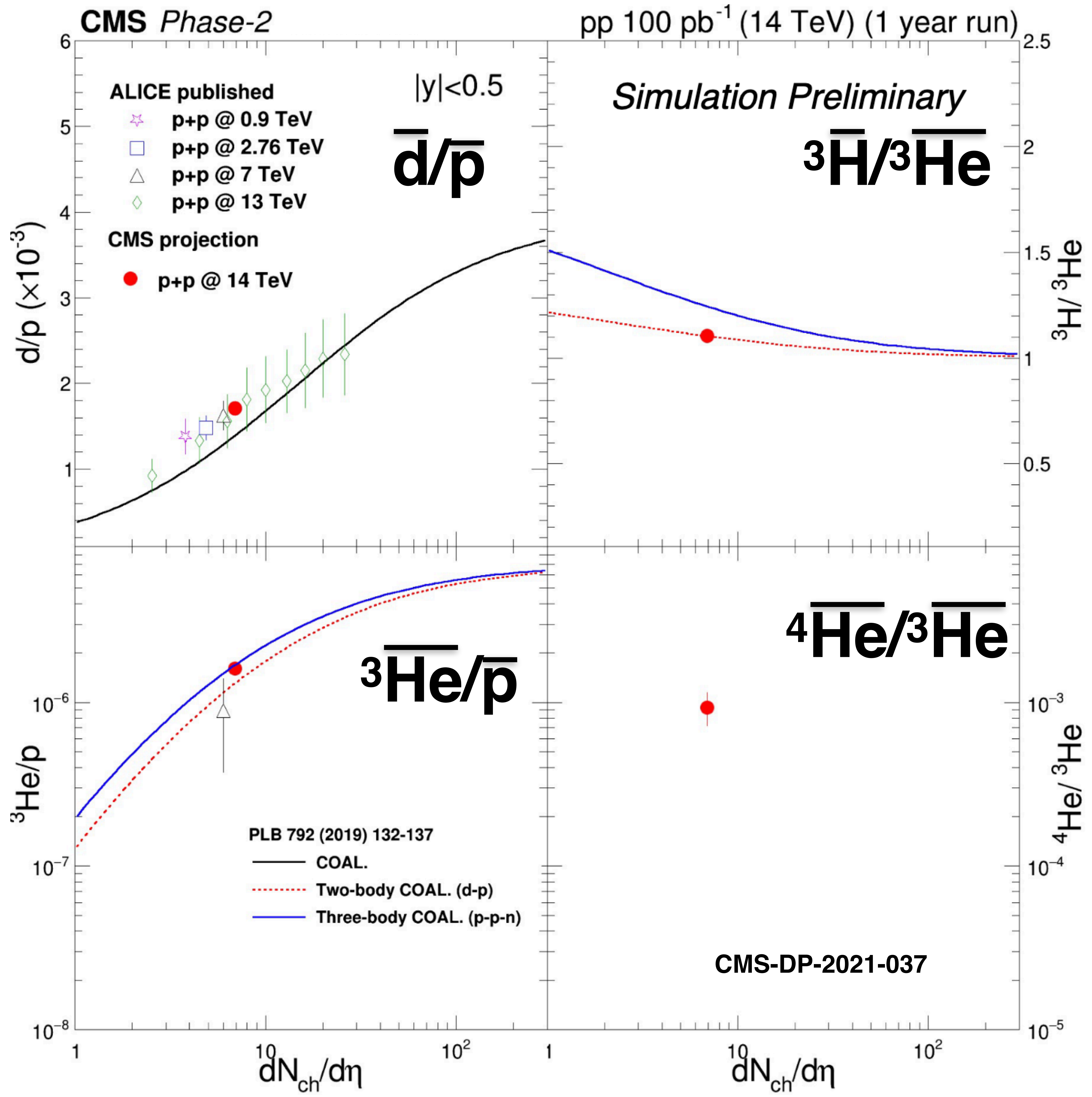
Fluctuations of conserved charges





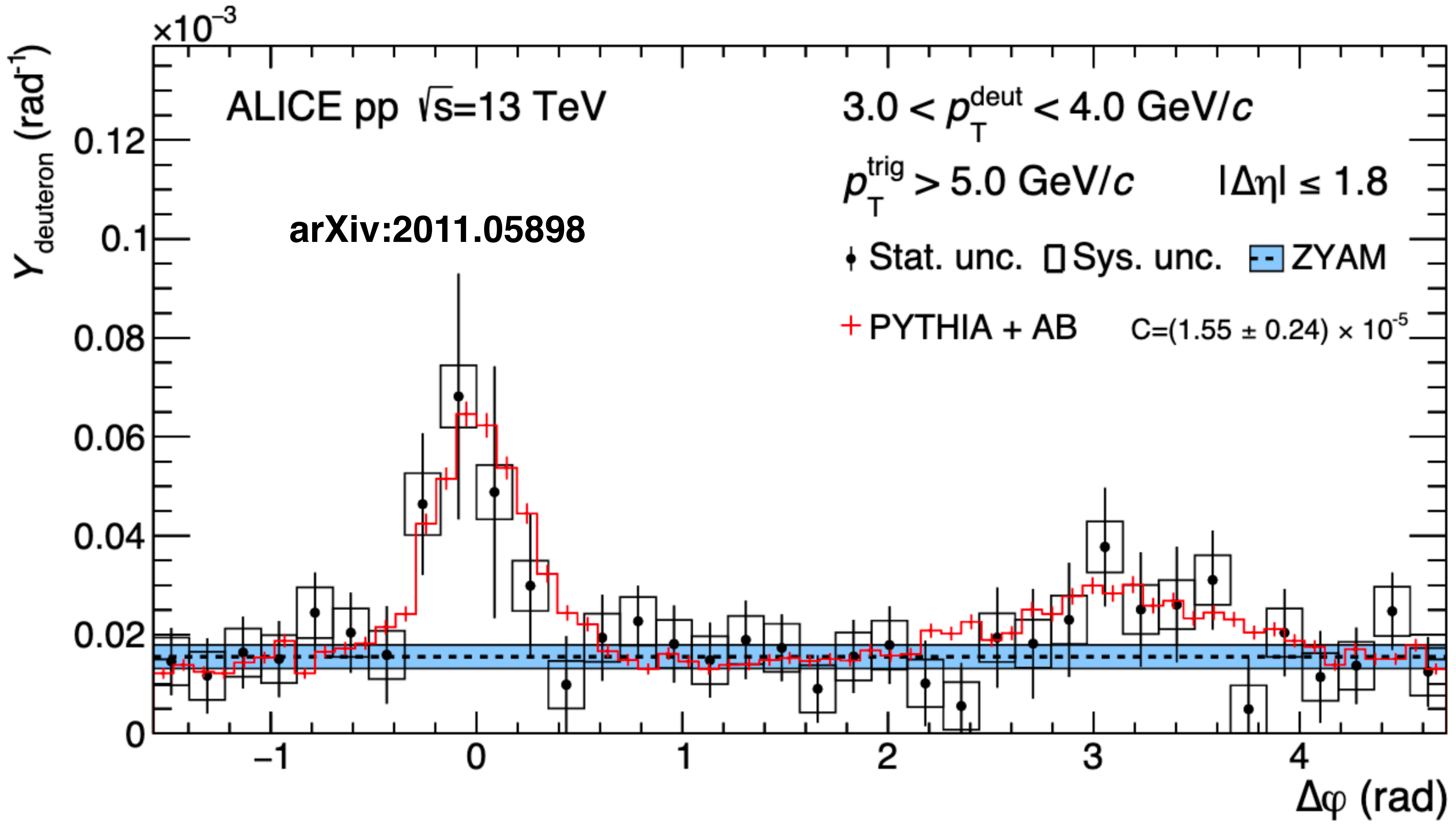
- Can be studied experimentally by measuring the higher cumulants of net strangeness or baryon number (κ_n).
- The PID capabilities of MTD allows to measure the net kaon and proton cumulants in a **wide rapidity range**, directly testing the lattice QCD calculations at LHC energies.

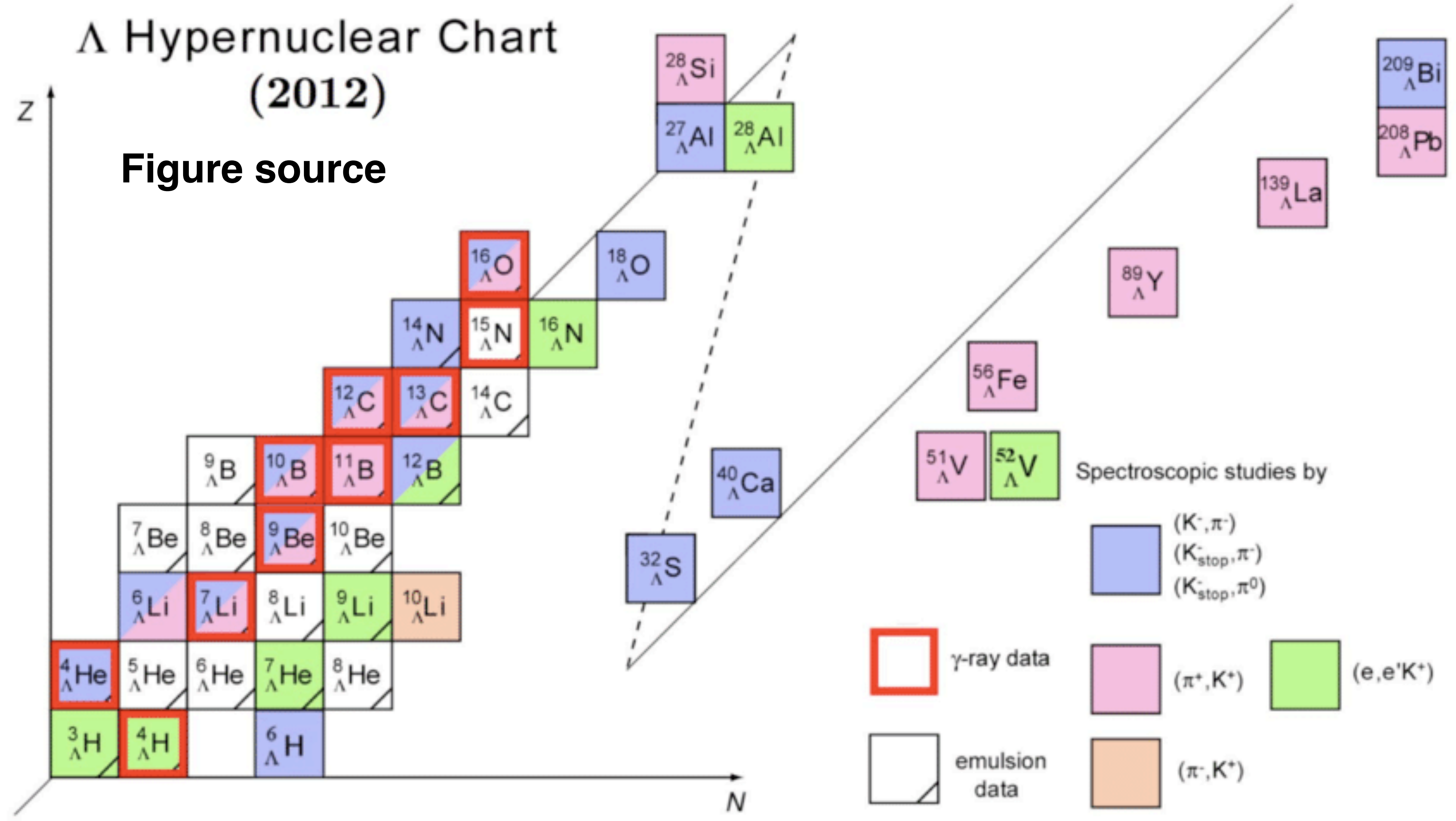
Projected light antinucleus ratios in pp



Other prospects using light nuclei

- The possibility to measure light nuclei in CMS will provide access to new physic topics:
  - Study of light nuclei production in association with jets, taking advantage of the CMS full calorimetry and large acceptance in HL-LHC.





- Study of hypernuclei with identification of light nuclei and excellent secondary vertex reconstruction.

THE JOINT ZERO DEGREE CALORIMETER PROJECT

Ben Gurion University of the Negev
Zvi Citron
Yftach Moyal
Lion Sudit
Shir Shenkar

Brookhaven National Laboratory
Peter Steinberg

Columbia University
Brian Cole

Kansas University
Allen Hase
Bill Burley
Christian Hornhuber
Juan Marquez
Cole Le Mahieu
Michael Murray
Matthew Nickel
Sorina Popescu*
Quan Wang

University of Maryland
Eric Adams
Samuel Lascio
Alice Mignerey
Timothy Koeth

UIUC
Jacob Fritchie
Matthias Grosse Perdekamp
Matthew Hoppesch
Chad Lantz
Riccardo Longo
Xuesi Ma
Daniel MacLean
Paul Malachuk
Jain Pranay
Anna Przybyl
Farah Rafee
Aric Tate
Aryan Vaidya
Sheng Yang

* On leave from IFIN-HH, Magurele, Buchrest Romania