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

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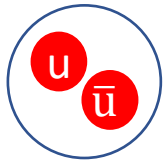
for CMS Collaboration

Rice University

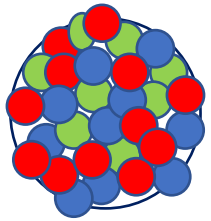
ICHEP 2022, July 7, 2022

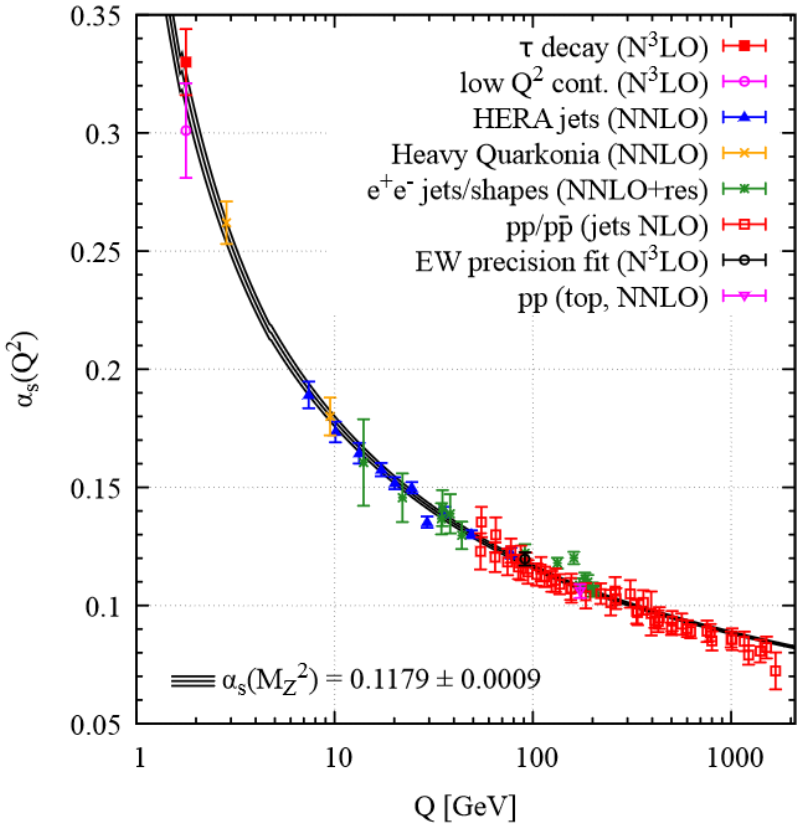
Confined to deconfined states

- QCD, confined hadron and asymptotic freedom
  - Final states confined in color-neutral states – baryon and mesons
  - Coupling strength is running



- Deconfined matters – quark-gluon plasma (QGP)
  - Partons deconfined from hadrons with increasing temperature/density



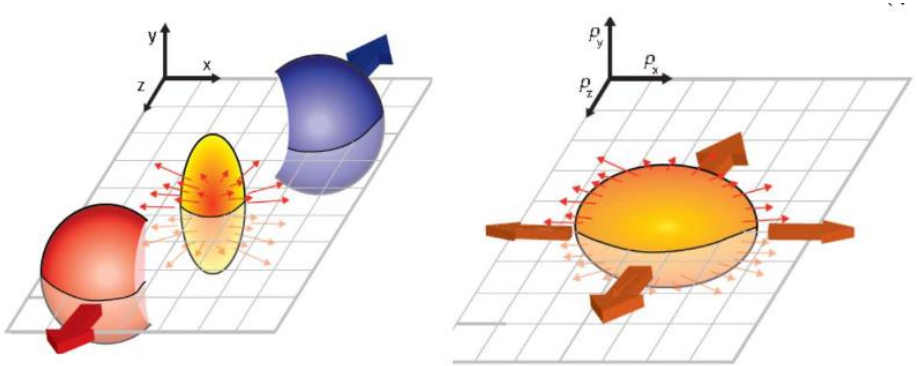


PTEP 2020 (2020) 8, 083C01

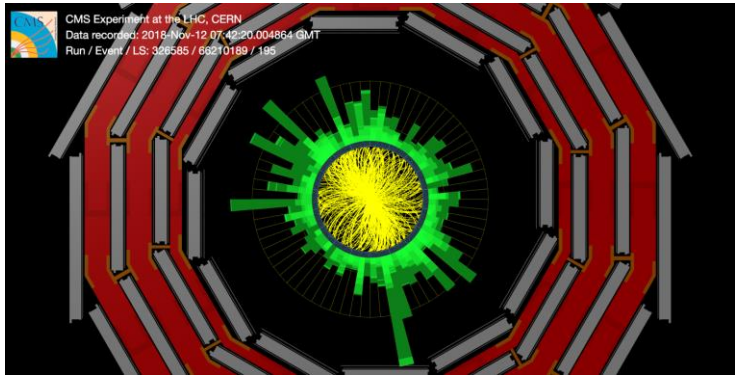
Experimental test for QGP

- QGP in Heavy ion collisions
  - Collective motions
    - Anisotropy
    - Long-range correlations

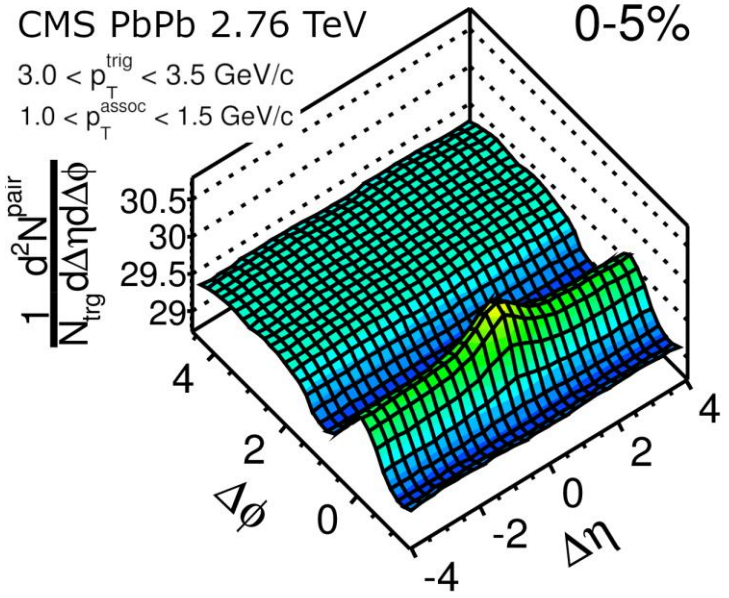
Wide coverage tracking	Fast trigger/readout
✓	✓



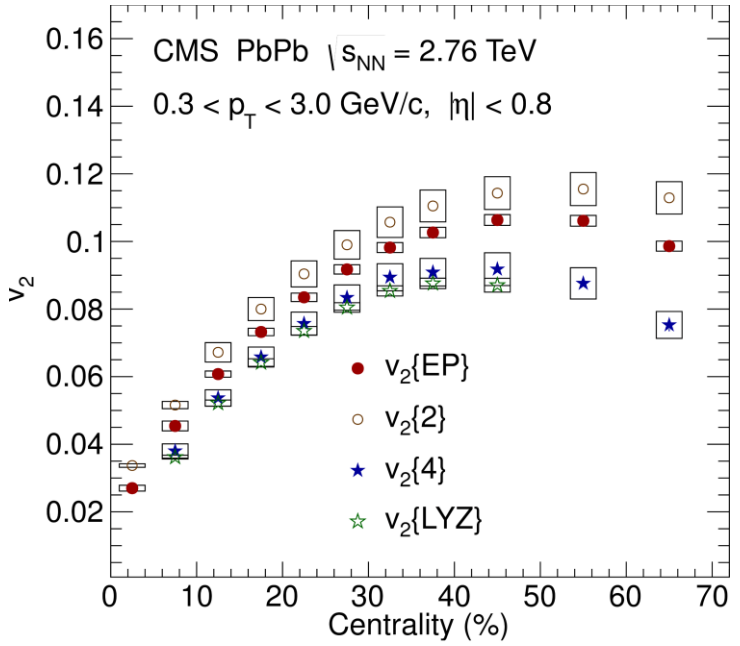
$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3\mathbf{p}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{t}\mathrm{d}p_\mathrm{t}\mathrm{d}y}\left(1+2\sum_{n=1}^{\infty}v_n\cos[n(\varphi-\Psi_\mathrm{RP})]\right)$$



EPJC 72 (2012) 2012

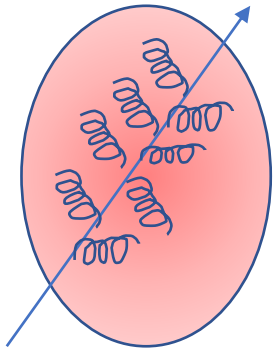


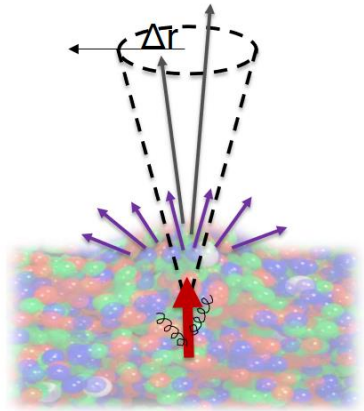
PRC 87 (2013) 014902



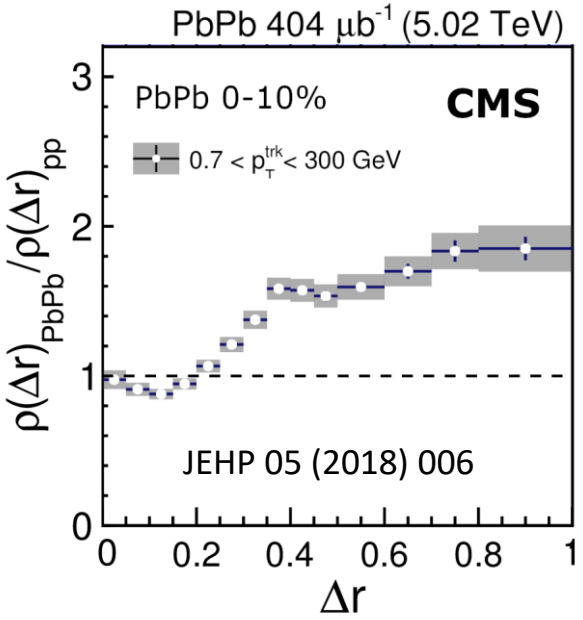
QGP tomography through hard probes

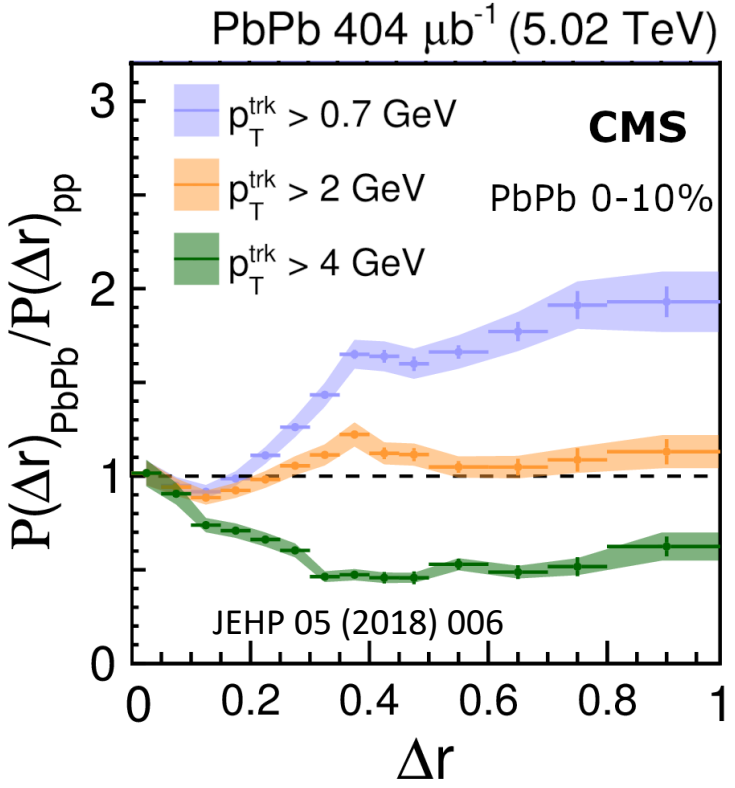
- Energy loss via gluon emissions
  - Study via jet hadron correlations
  - Modifications of jet shape





Calorimetry	Tracking
✓	✓





Hadronizations in QGP

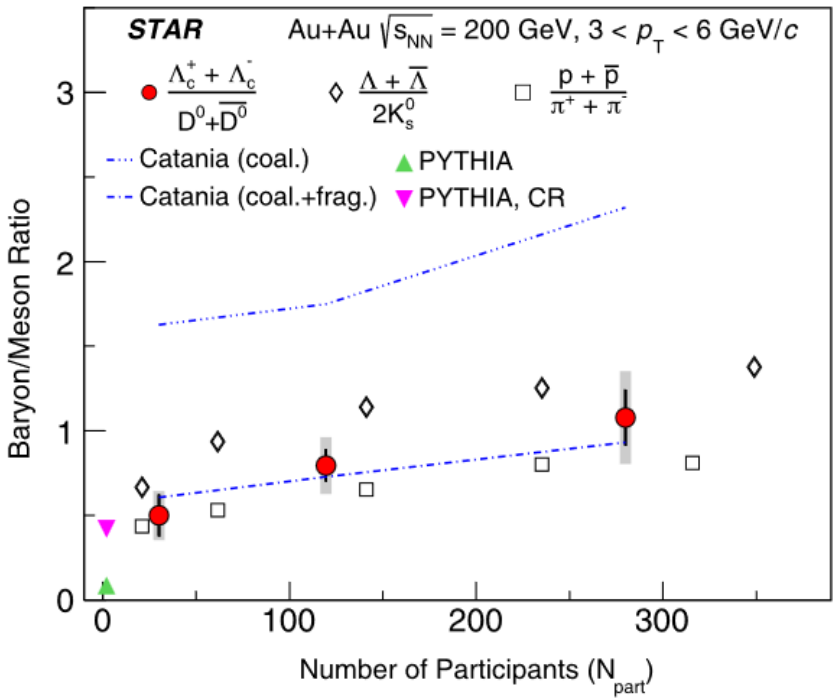
- Thermal partons from QGP and stronger coalescence in QGP
  - baryon enhancements
  - extensively studied from light to heavy quarks

$D^0 \rightarrow K\pi$

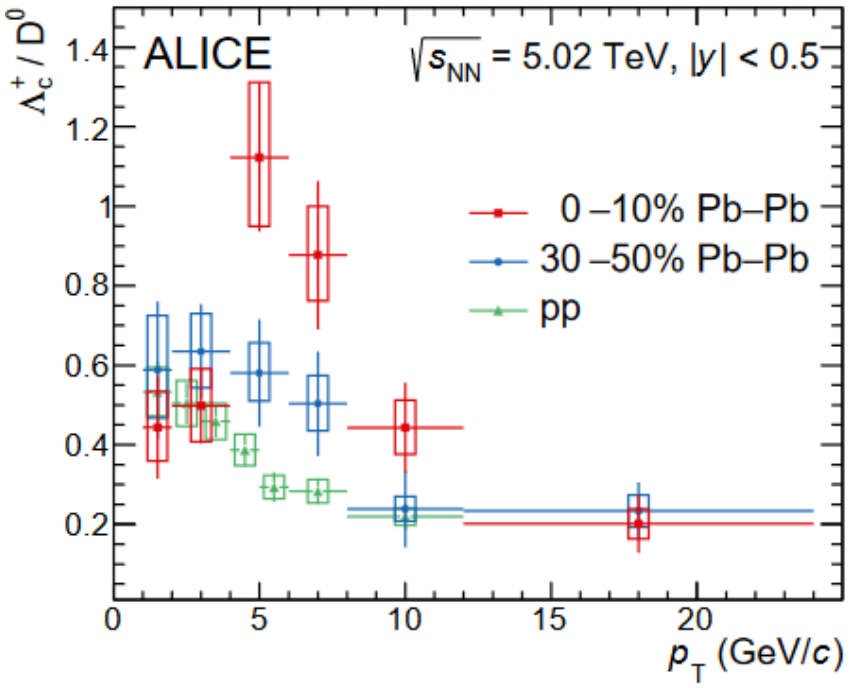
$\Lambda_c^+ \rightarrow pK\pi$

Precision Vertex	PID
✓	×

PRL 124 (2020) 172301



arXiv:2112.08156



Opportunities at HL-LHC

- Run schedule and luminosity

We are here

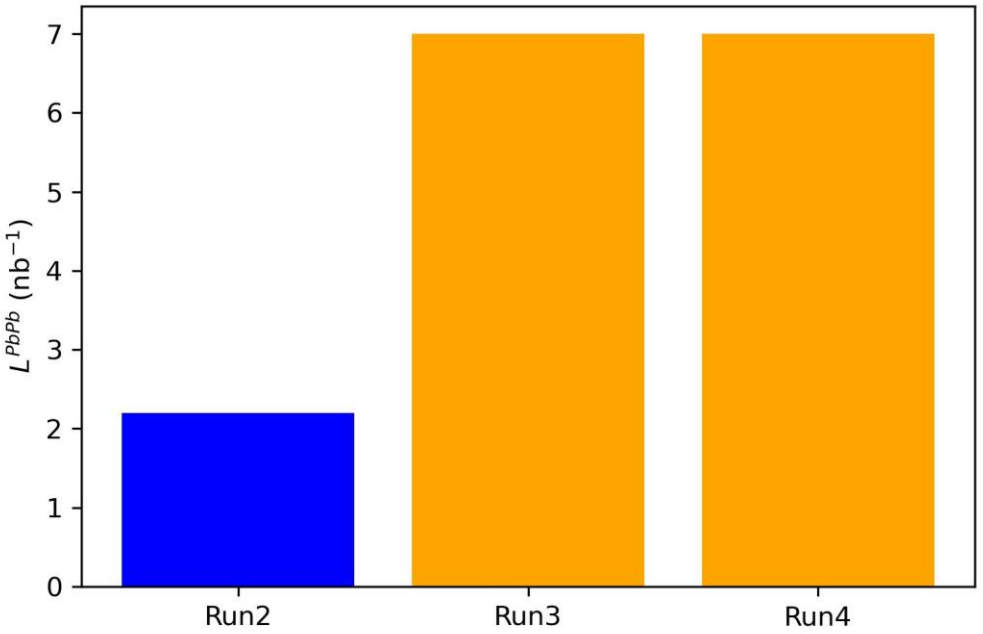
HL-LHC

Run 2	Run 3, CMS Phase 1	LS3, Upgrade	Run 4, CMS Phase 2	Future
2015 – 2018	2022 – 2025	2026 – 2028	2029 – 2032	2033 – 2038

Collisions	Run2	Run3	Run4
Pb-Pb	2.2/nb	7/nb	7/nb
p-Pb	0.186/pb	0.5/pb	0.5/pb

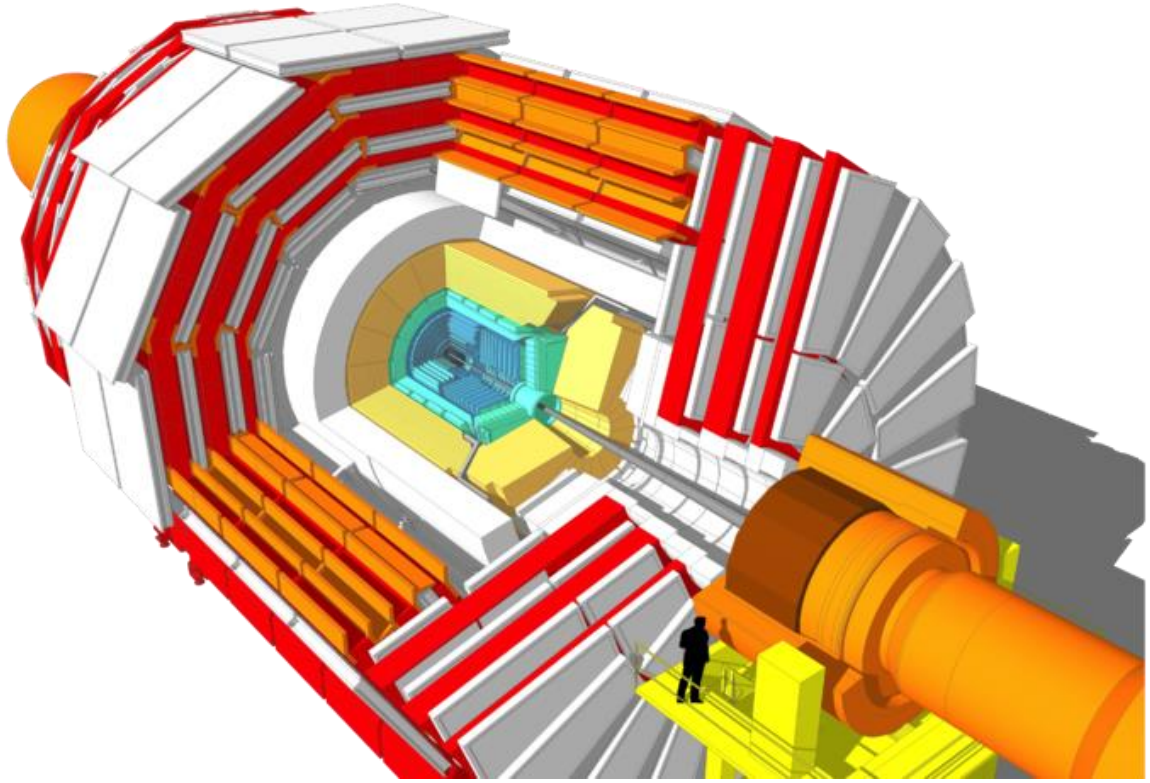
Opportunities

- Higher luminosity
- Detector upgrade



CMS Phase II

- Trigger and readout
  - L1 bandwidth: 100 kHz → 750 kHz
  - DAQ readout: 6GB/s → 51GB/s
- High granularity calorimeter
  - High granularity endcap
- Tracker
  - Extend |η| from 2.4 to 4
  - pixel size: 100x150 um^2 → 50x50 um^2
- MIP timing detector
  - Entirely new, resolution ~35ps
  - Large coverage, **|η|<3**



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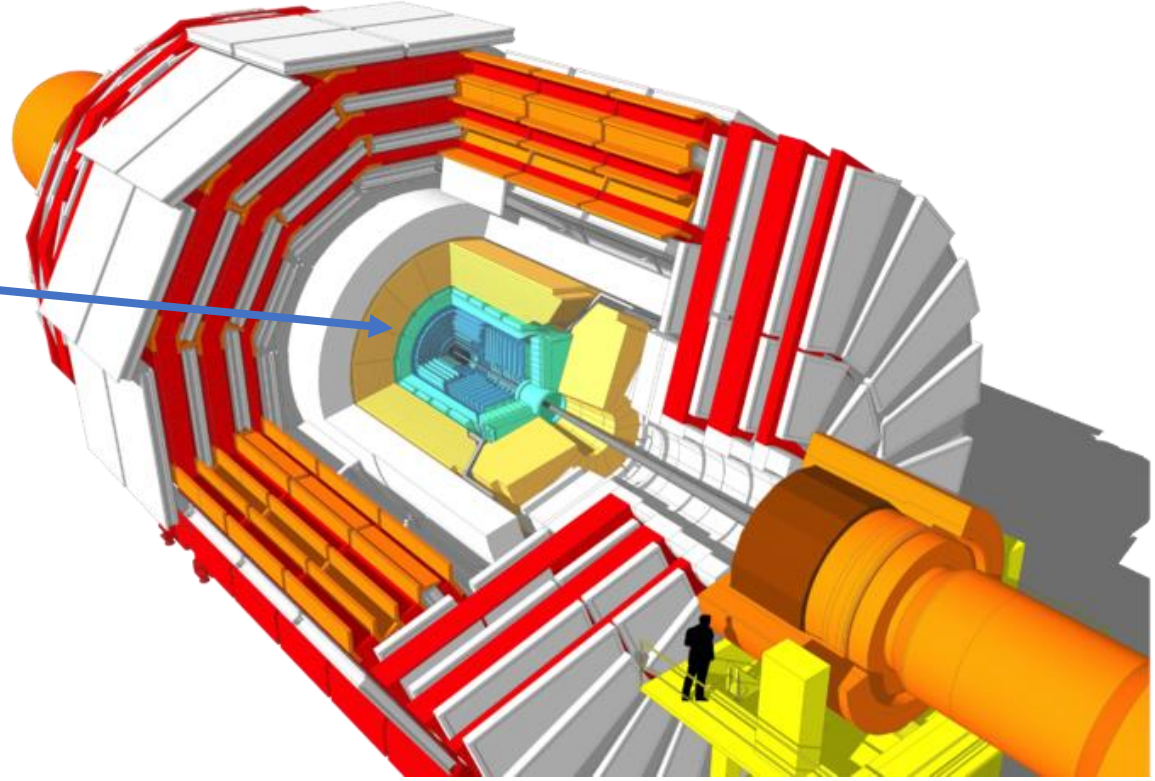

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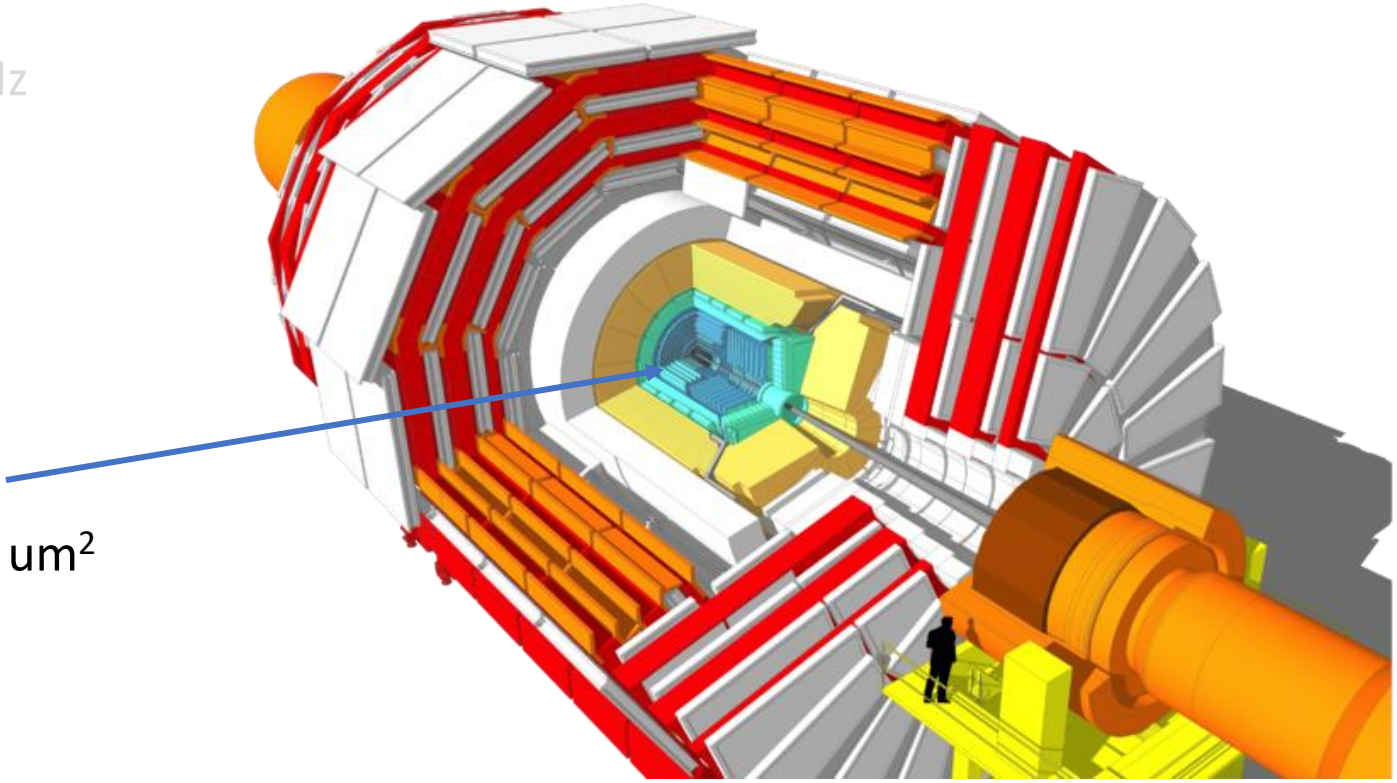

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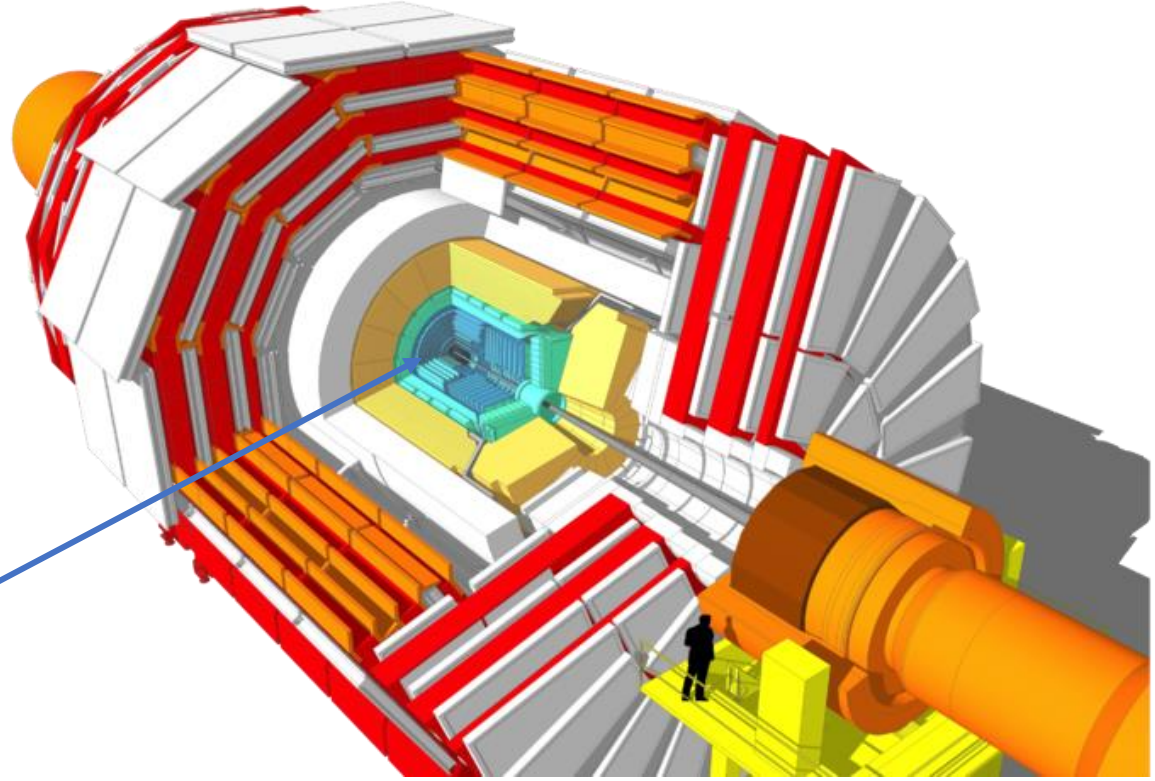

Experiment	r (m)	σ_T (ps)	r/σ_T ($\times 100$) (m $\times$ ps^{-1})
STAR-TOF	2.2	80	2.75
ALICE-TOF	3.7	56	6.6
CMS-MTD	1.16	30	3.87

Fast trigger/readout	Calorimetry	Tracking	Wide coverage PID
✓	✓	✓	✓

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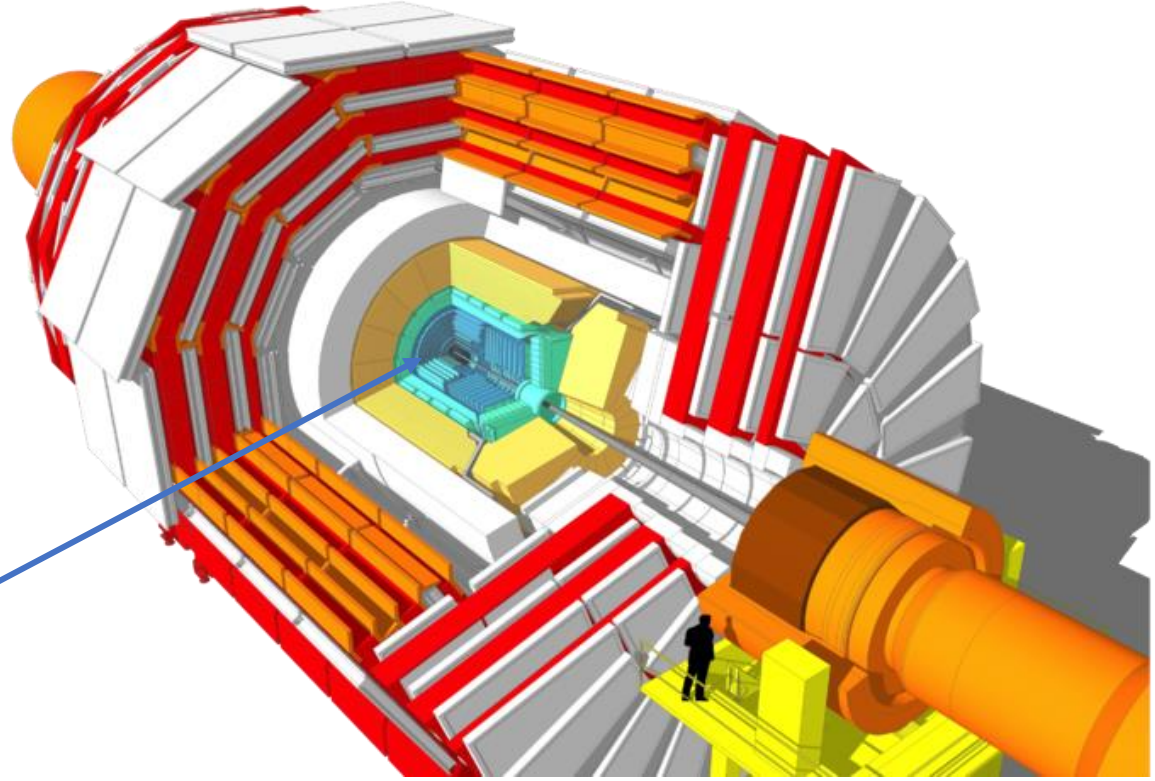
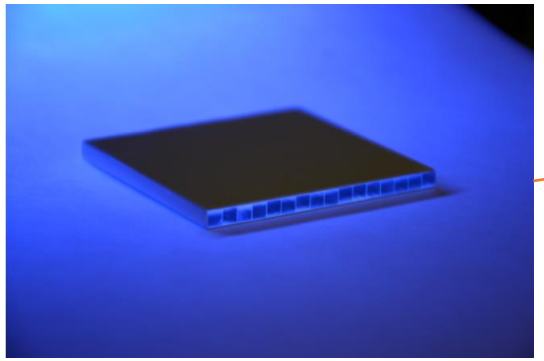
- MIP timing detector
  - Entirely new, resolution **~35ps**
  - Large coverage, **|η|<3**
  - **Benefit to PU mitigations, long-lived particles (talk by Livia Soffi, Jul 7, 2022, 12:23 PM), heavy ion physics …**

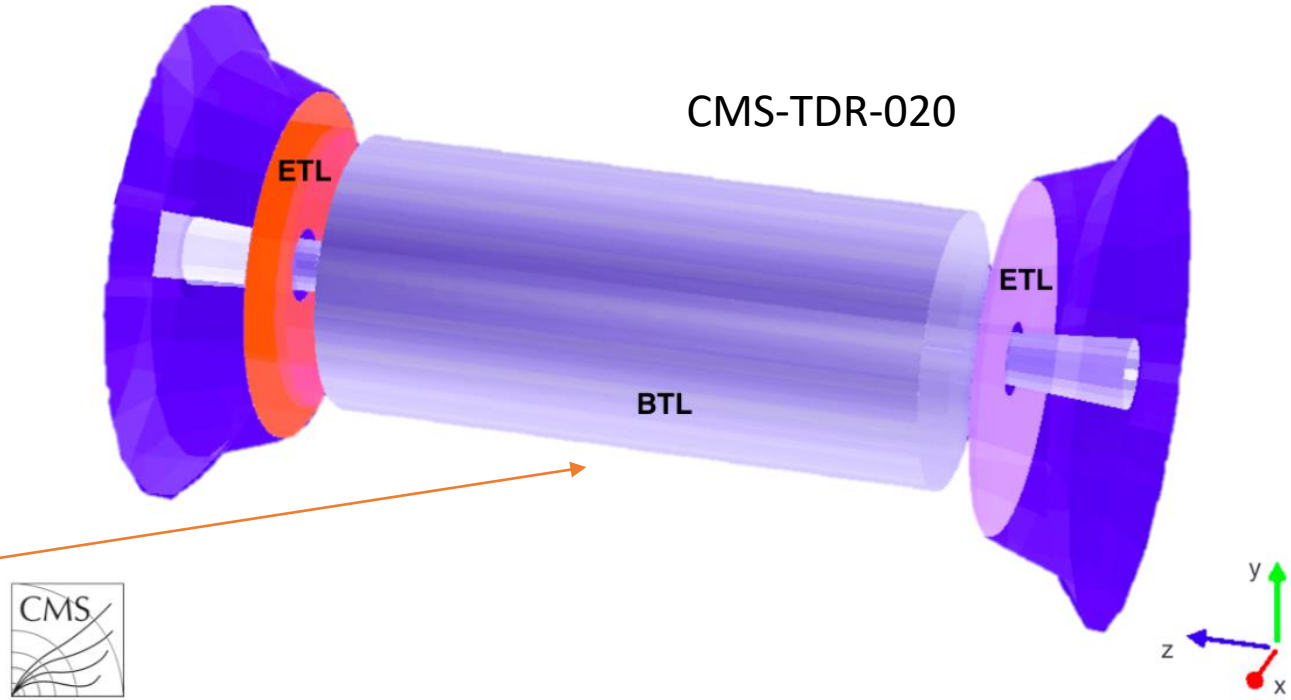


Barrel timing layer

- Barrel timing layer (BTL), talk by Marta Tornago, Jul 7, 2022, 9:53 AM, Operation
  - Fast rise time
  - Large coverage area
- General
  - LYSO bars + SiPM readout
  - $|\eta|<1.45$
  - Inner radius: 1148 mm (40mm thick)
  - Length: +/- 2.6 m along z
  - Surface ~38 m^2; 332k channels

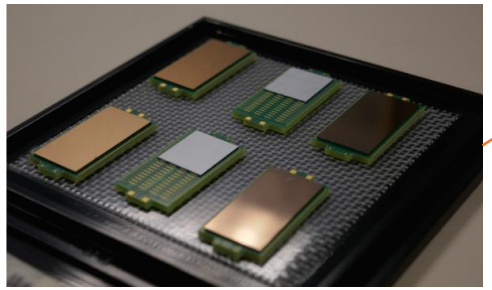


16x1 array of crystal bar

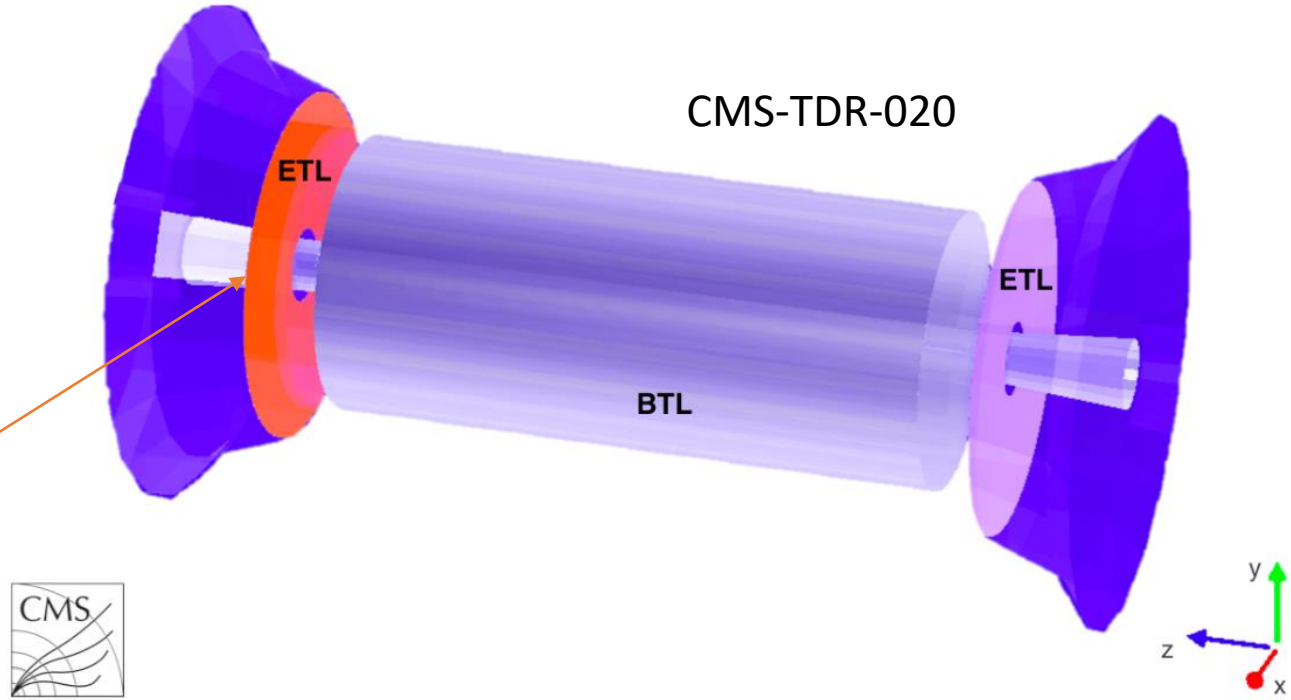


Endcap timing layer

- Endcap timing layer (ETL), talk by Maria Addesa, Jul 7, 2022, 10:10 AM, Operation
  - Good radiation tolerance
  - Low occupancy
  - High timing resolution
- General
  - Si with internal gain (LGAD)
  - $1.6 < |\eta| < 3.0$
  - Radius: $315 < R < 1200$ mm
  - Position in z: +/-3.0 m (45 mm thick)
  - Surface ~14 m^2; ~8.5M channels

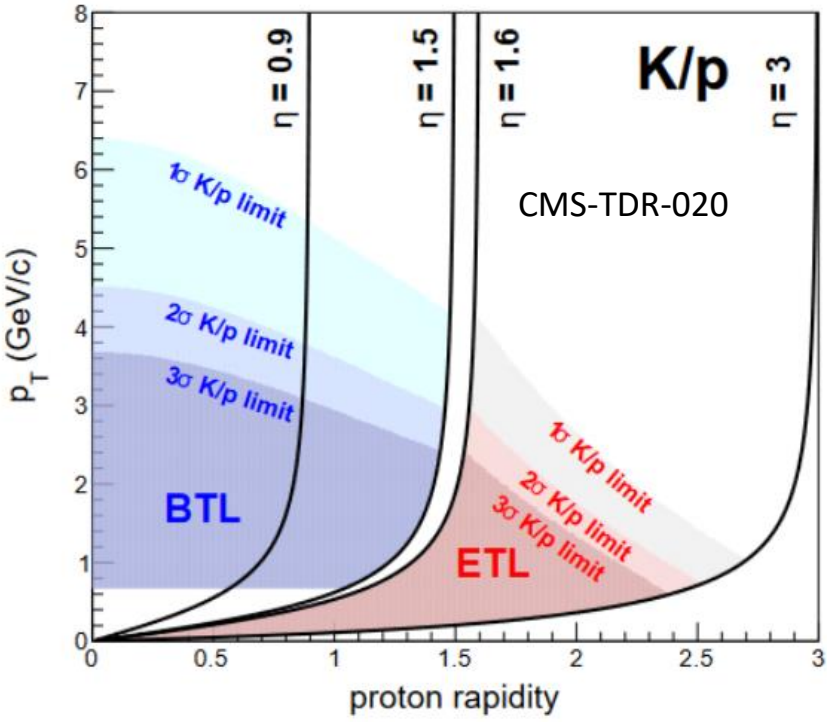


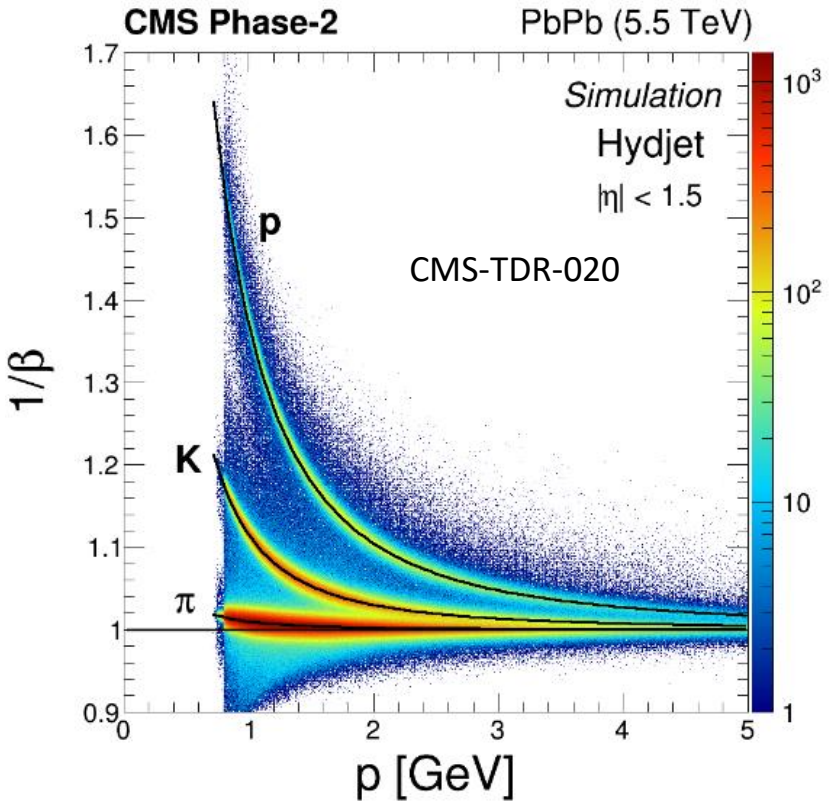
LGAD sensors on PCB

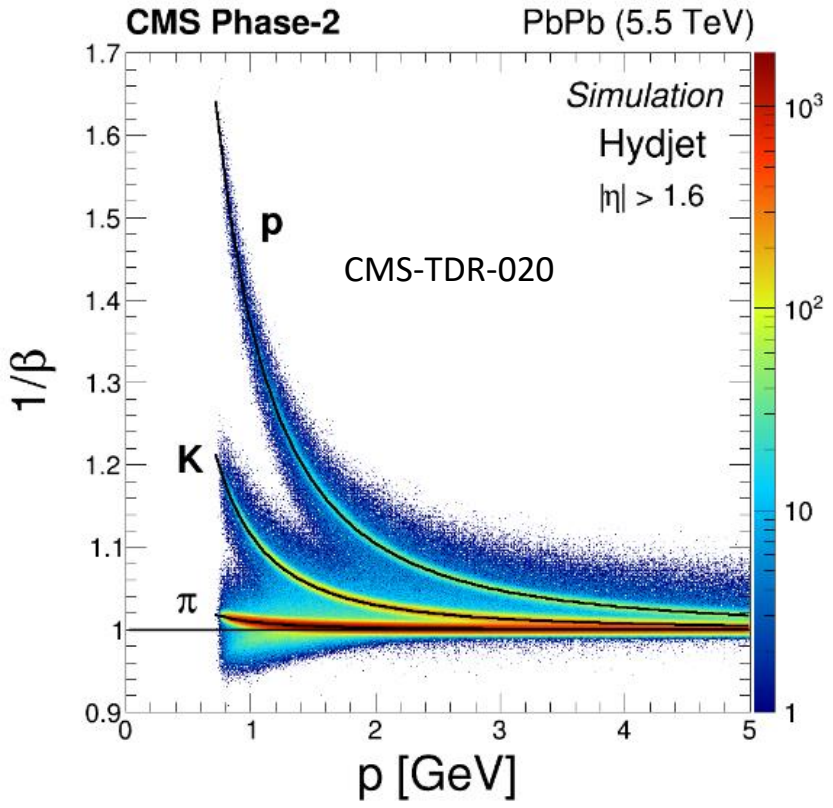


MTD Simulations

- Wide coverage up to 6 units of rapidity
- π/K separation up to 3 GeV
- K/p separation up to 5 GeV



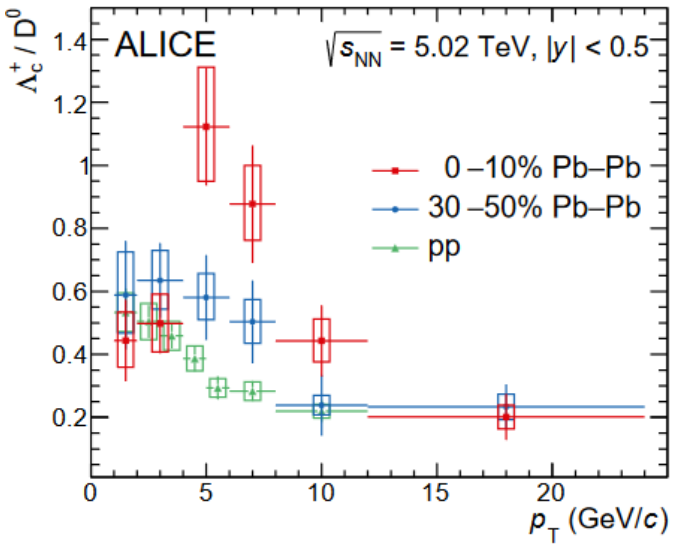




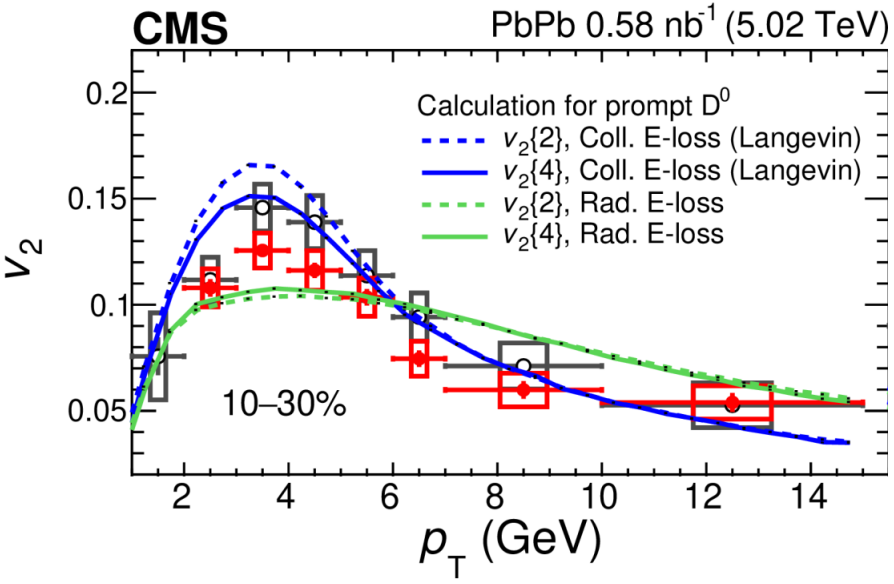
What we can explore

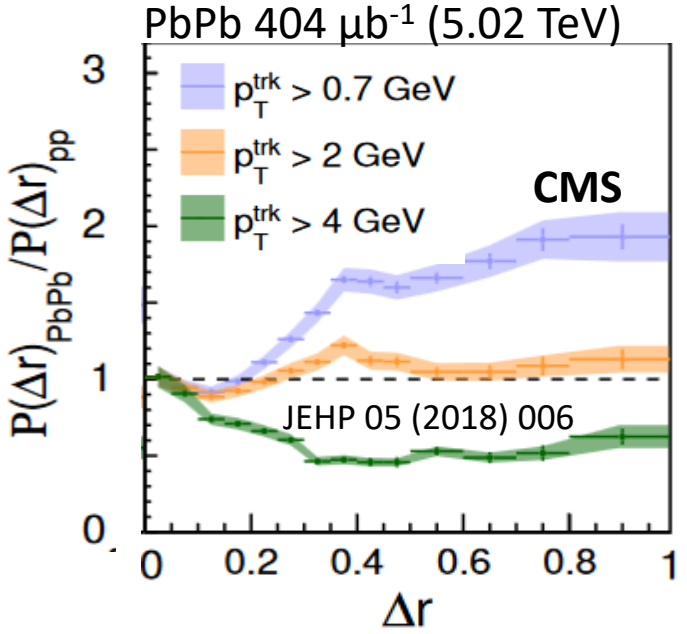
- Hard probes
  - Jet – identified hadron correlations
  - Heavy flavor
    - $D^0 \rightarrow K\pi$
    - $\Lambda_c^+ \rightarrow pK\pi$
    - $B^+ \rightarrow D^0 \pi^+$
    - …
- Light nuclei
  - d, t, ^{3}He, ^{4}He …
- Observables
  - Elliptic flow
  - Hadron productions
  - Jet shapes
  - …

arXiv:2112.08156



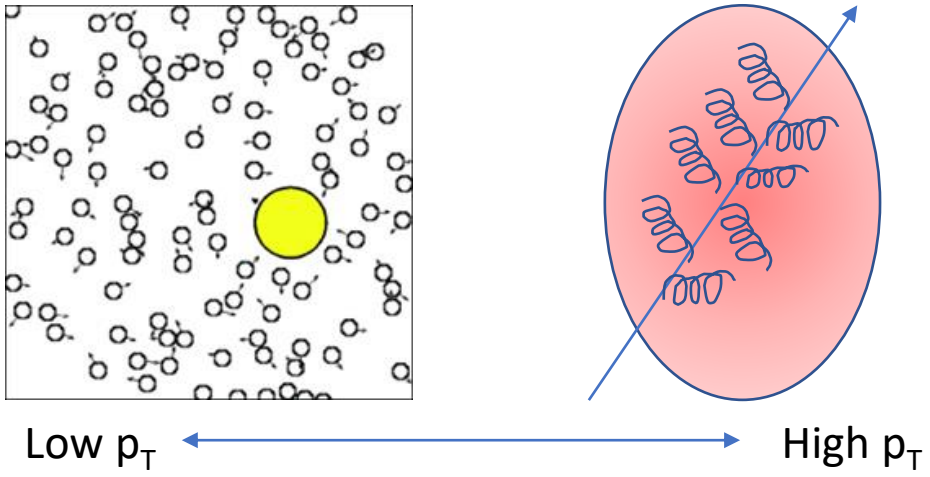
arxiv:2112.12236





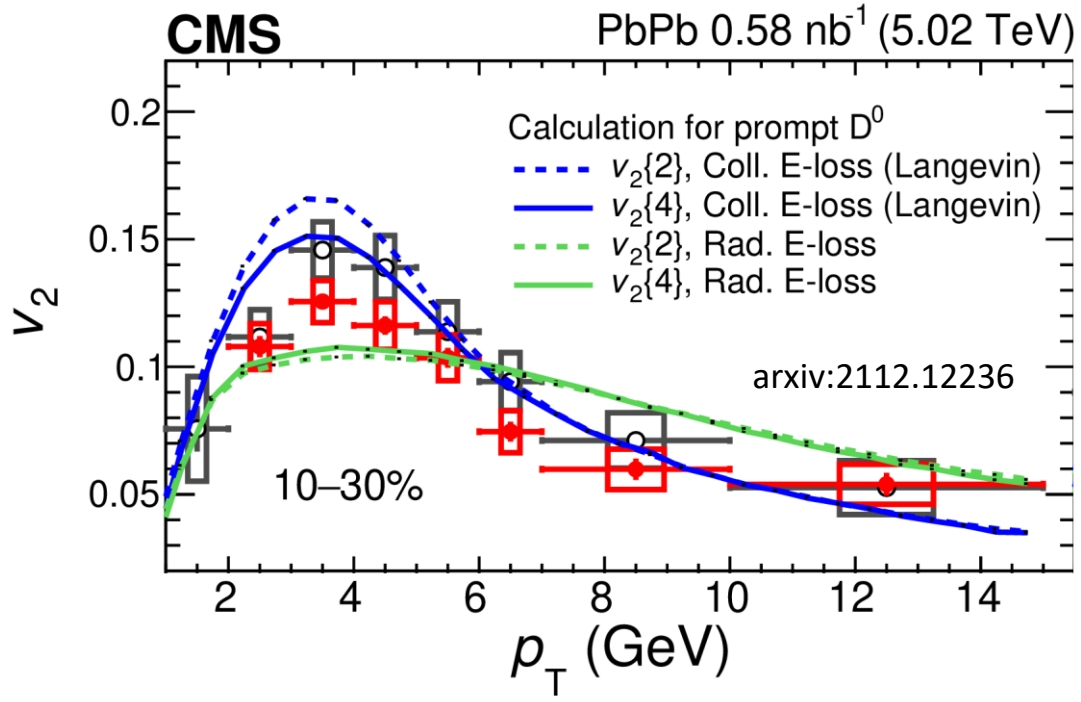
Hard probes – heavy flavor (HF)

- Dominantly created at initial stage by hard processes – sensitive to early stage
- Sensitive in full p_T range
  - Brownian motions
  - Gluon emissions



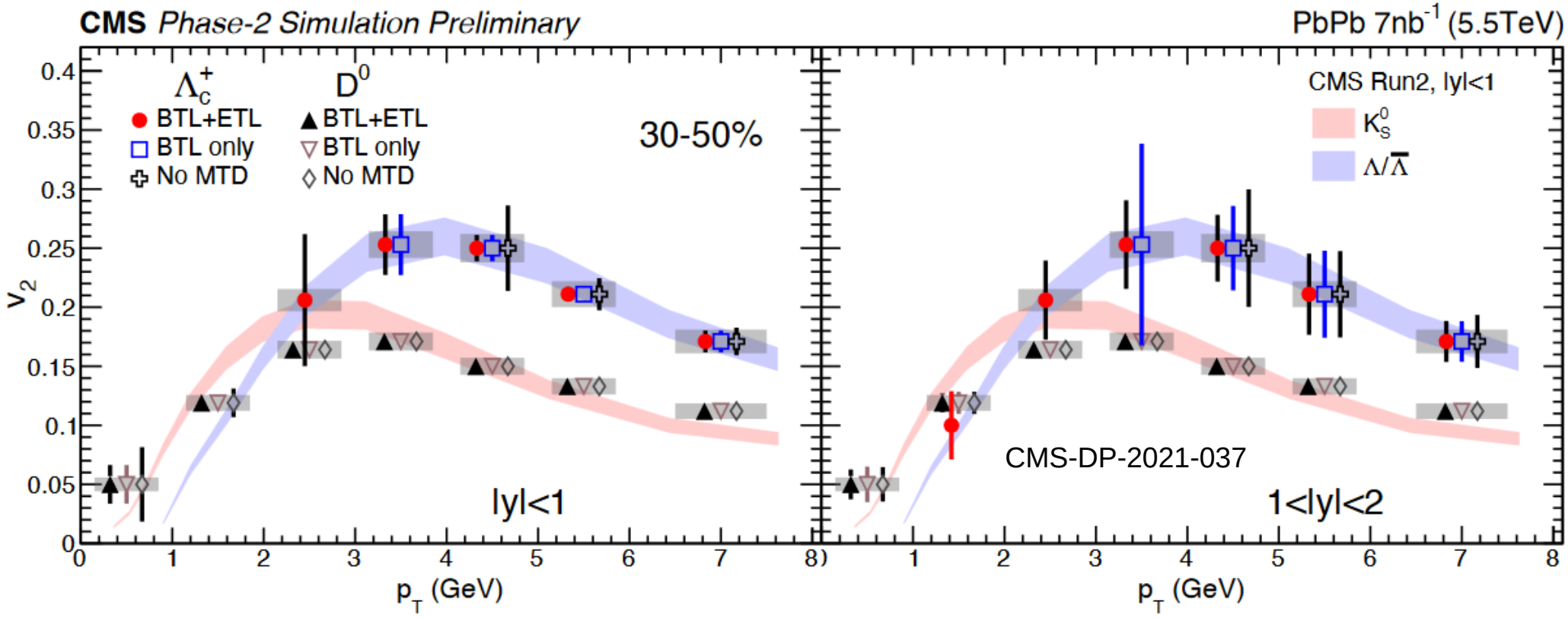
MTD benefit HF reconstructions

- $D^0 \rightarrow K\pi$
- $\Lambda_c^+ \rightarrow pK\pi$
- $B^+ \rightarrow D^0 \pi^+$
- …



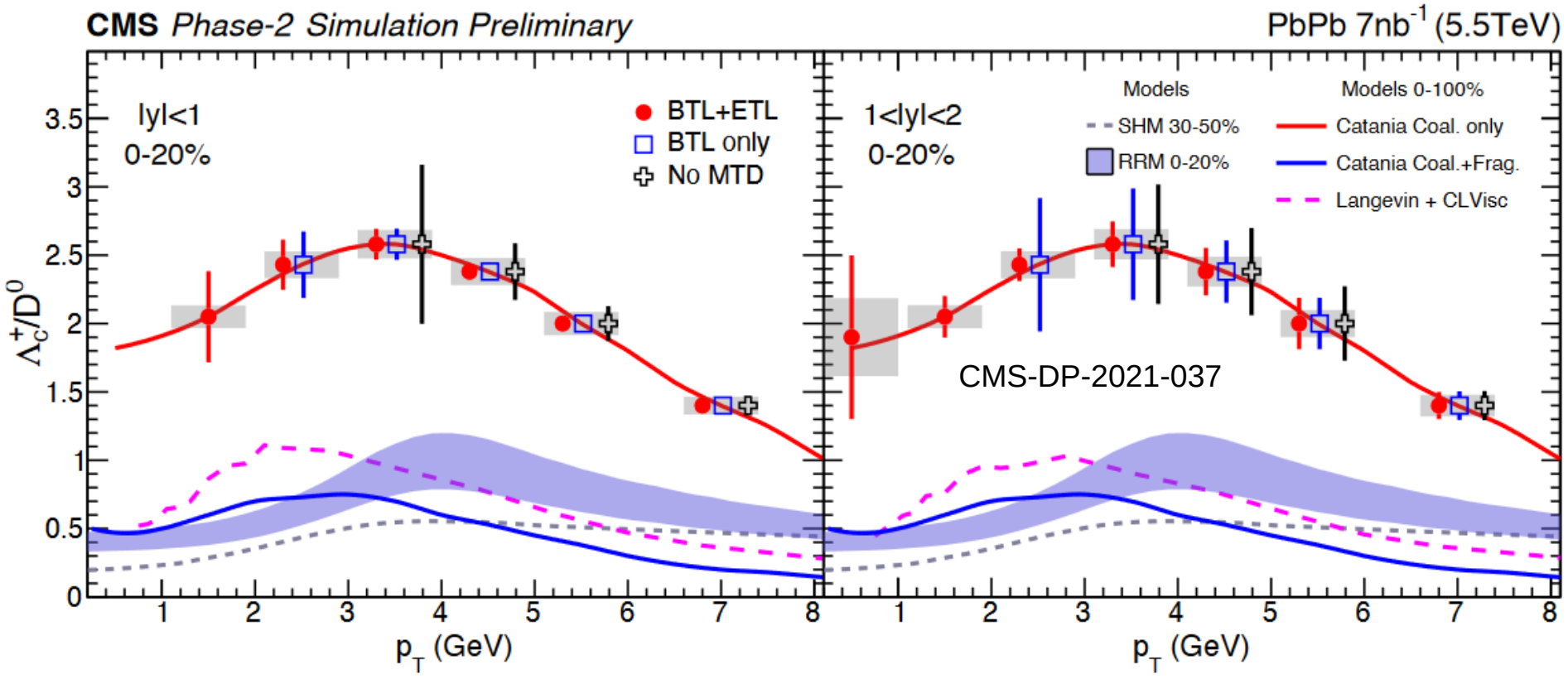
Elliptic flow – 2nd Fourier harmonic

- Precision measurements down to *low p_T with MTD*
- Number of constituent quark scaling – $v_2(\Lambda_c^+)/v_2(D^0) = 3/2$?
  - Charm similar to strangeness (K_s^0 and Λ)?



Charm hadronization

- Access full p_T range of Λ_c^+ *with MTD*
  - Total charm cross section
  - CMS *unique* access over a rapidity range of *up to 6 (4) units in MB (central) events*
- Strong constraints on hadronization models

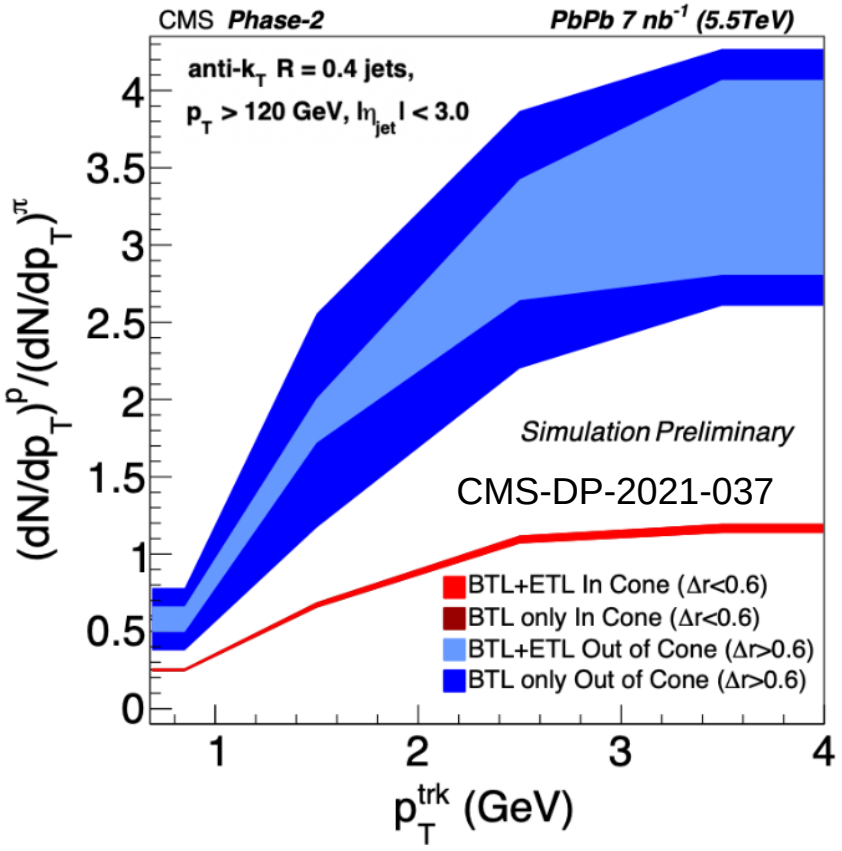


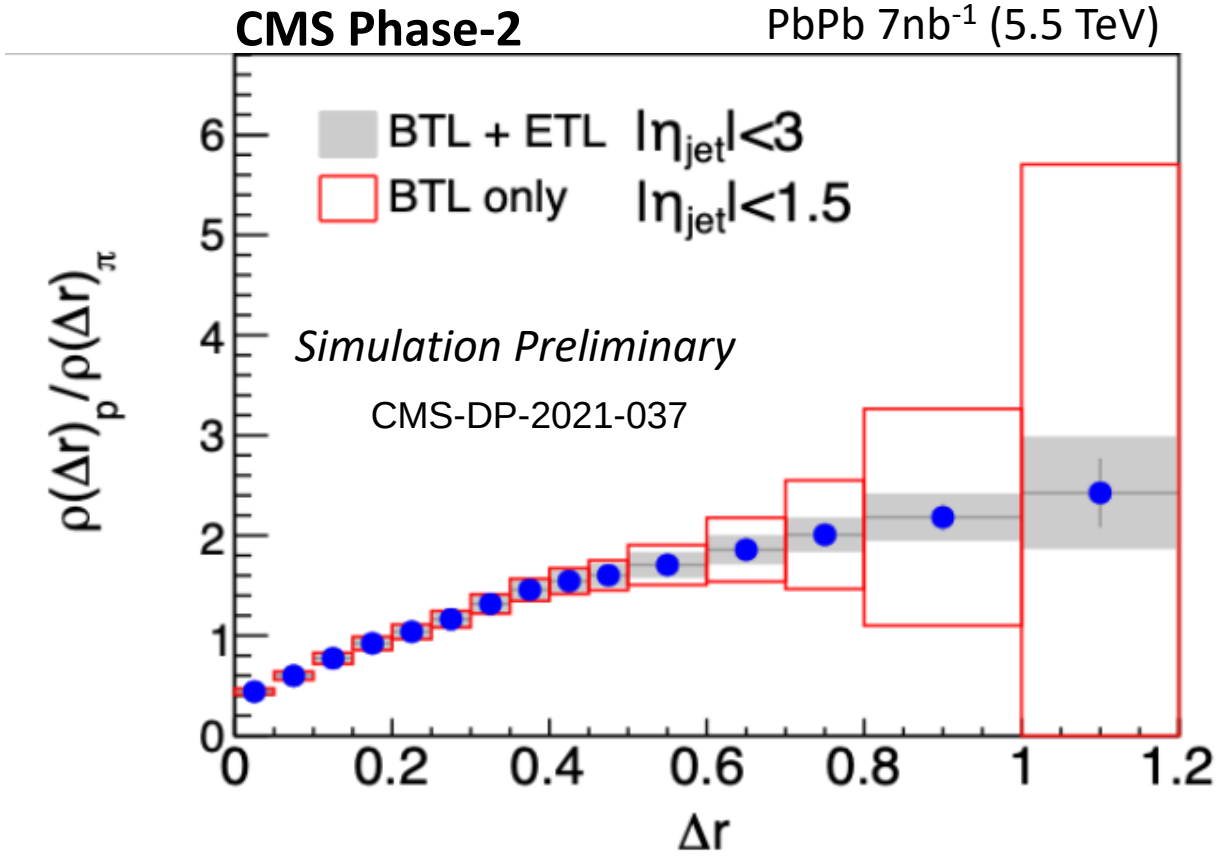
$D^0 \rightarrow K\pi$

$\Lambda_c^+ \rightarrow pK\pi$

Hard probes – jet

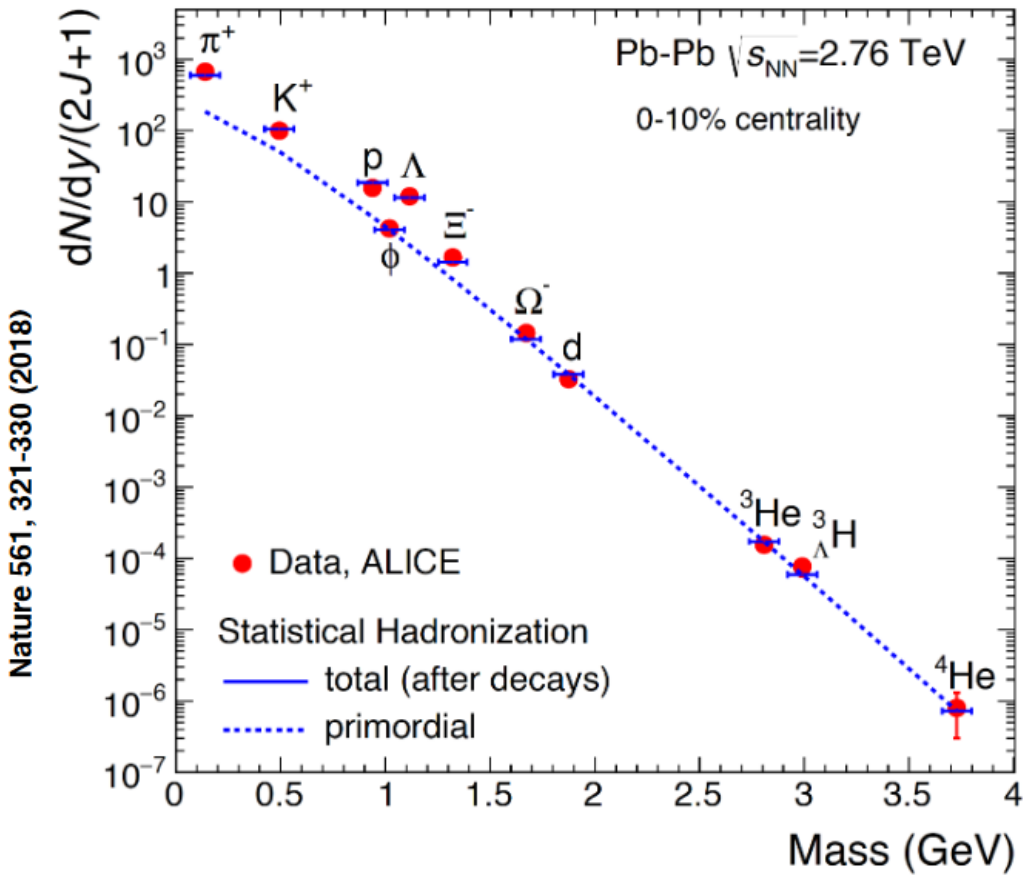
- In- and out-cone hadronizations, fragmentation vs. QGP-related effects
  - Enable measurements of jet – *identified* hadrons correlations with CMS
  - Precision access to large jet radius – benefits from large MTD coverage





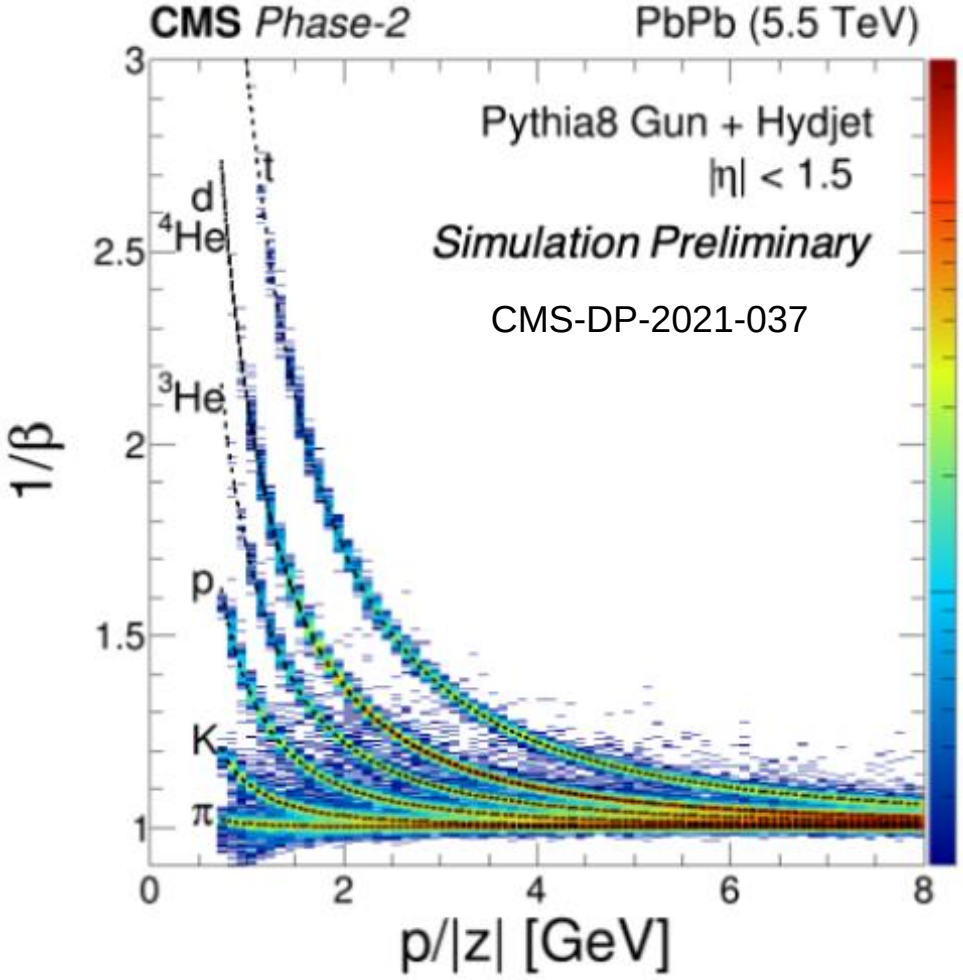
Light nuclei and anti-particles

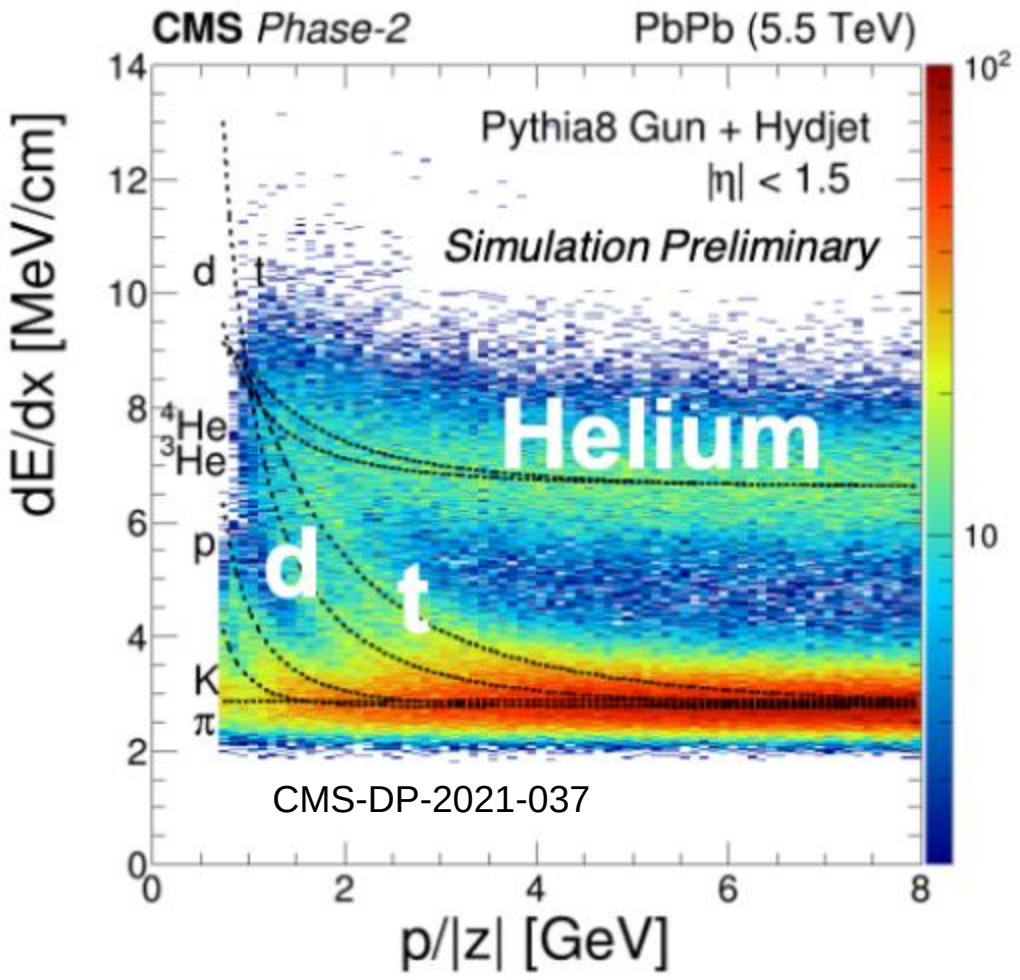
- Opportunities for studies of light (anti-)nuclei productions
  - $\overline{^4\mathrm{He}}$ was first ever observed in heavy ion collisions, Nature 473, 353–356 (2011)
- Abundant nucleons produced in heavy ion collisions – understand the formation of (anti-)nuclei
  - Statistical hadronization – Quark systems slowly form light-nuclei as hadron-gas. Formation *before chemical freeze-out,* Nature 561 (2018) 321
  - Coalescence – Close nucleons capture each other *at kinetic freeze-out,* PRC 92 (2015) 064911



Identification of light nuclei

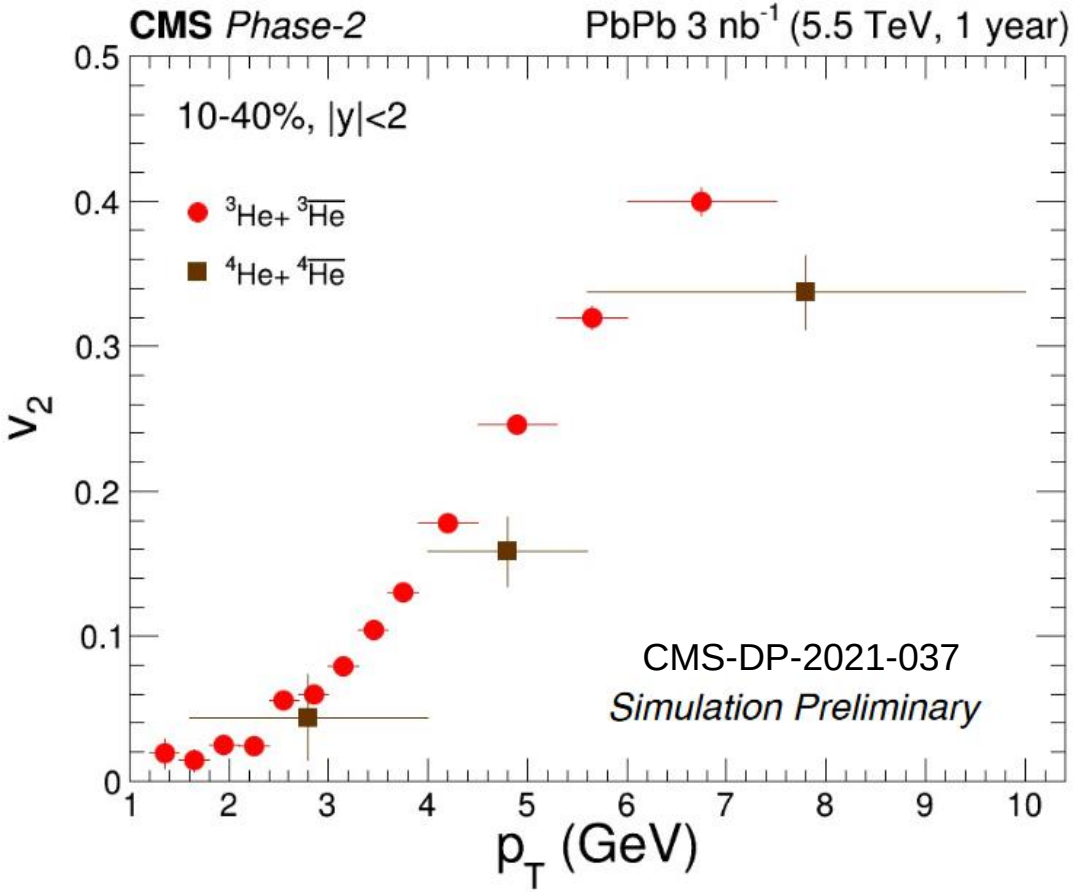
- Time of flight + dE/dx

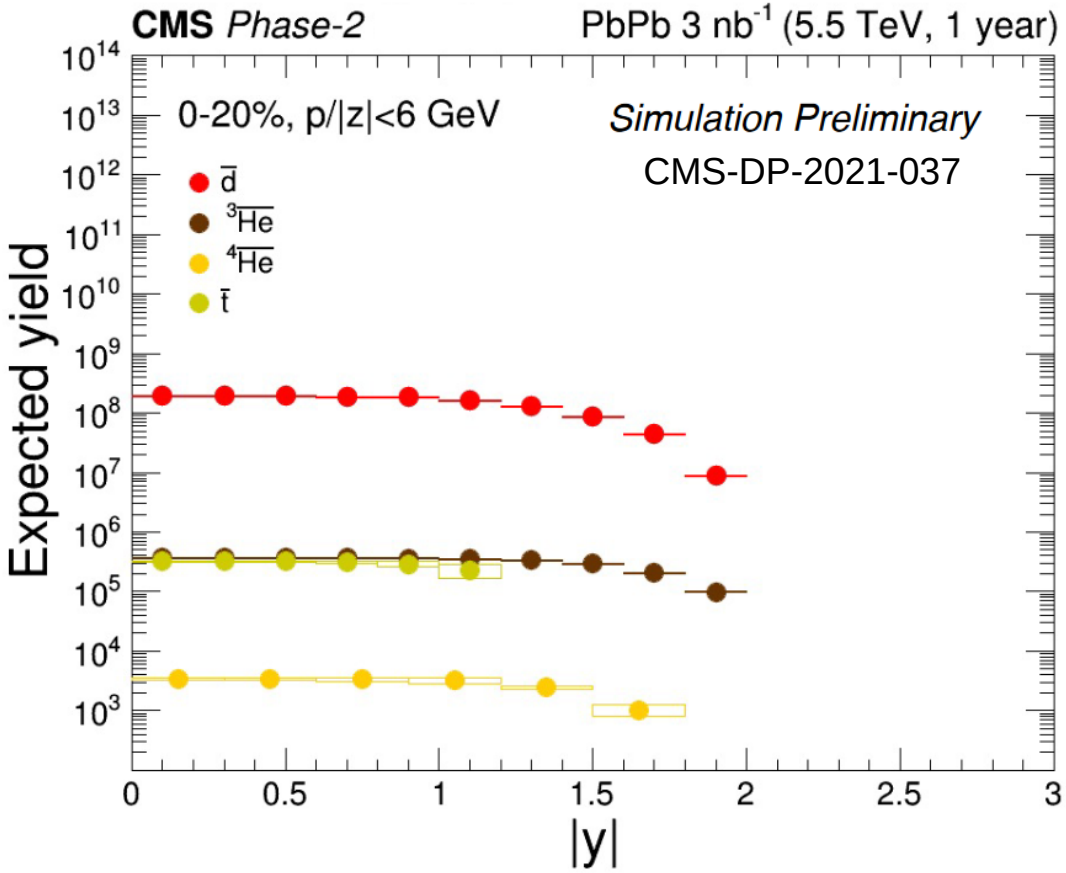




Projections for light nuclei

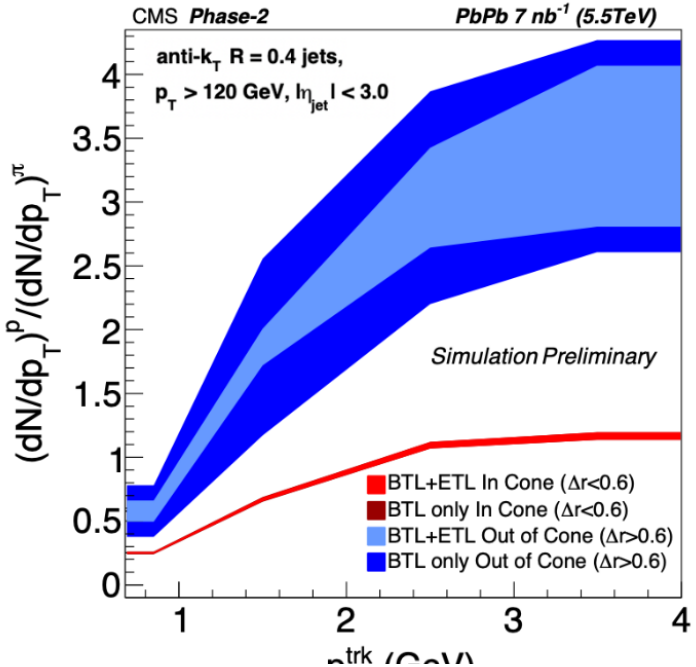
- Elliptic flow and expected yields

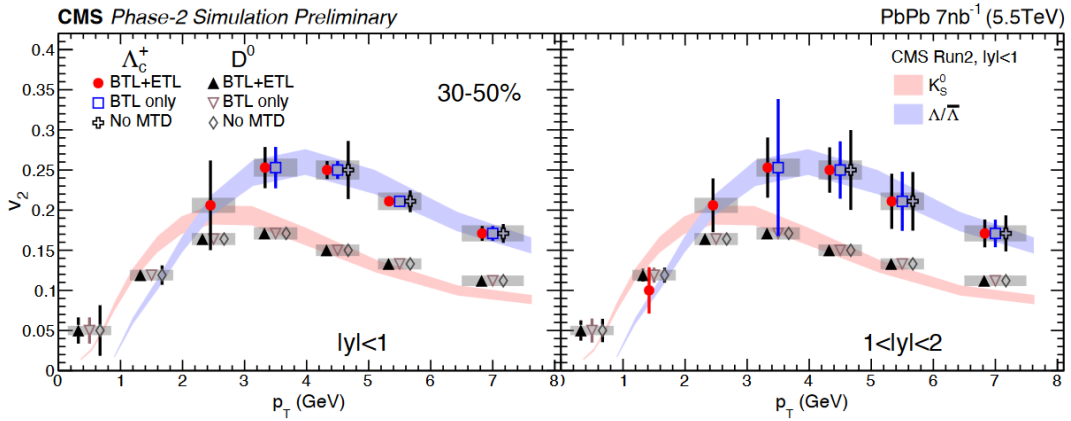


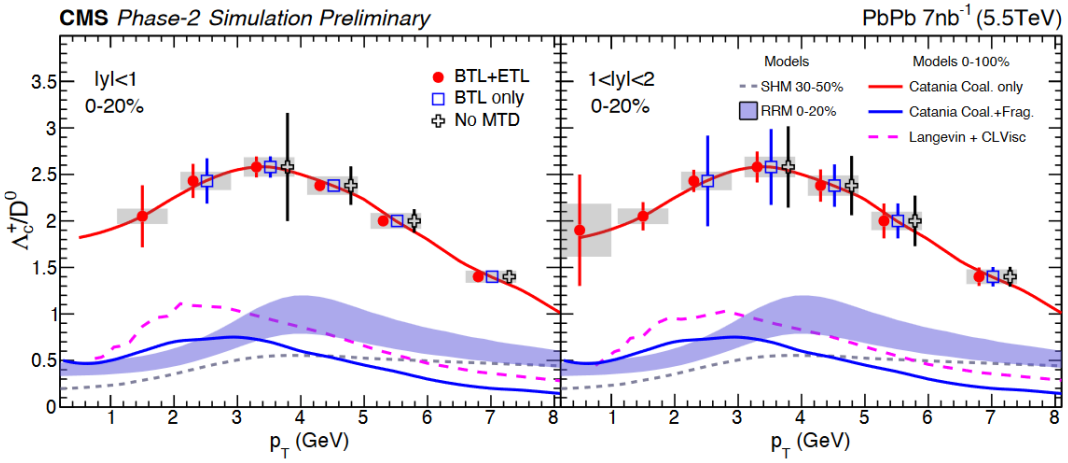


Summary

- CMS Phase II – *good PID by MTD over large rapidity*
  - *Heavy ions physics, PU mitigations, long-lived particles …*
- Interesting heavy-ion physics during HL-LHC
  - Heavy flavor dynamics and hadronizations
  - Light nuclei formation
  - QGP tomography via jet
  - And more physics findings/observations!



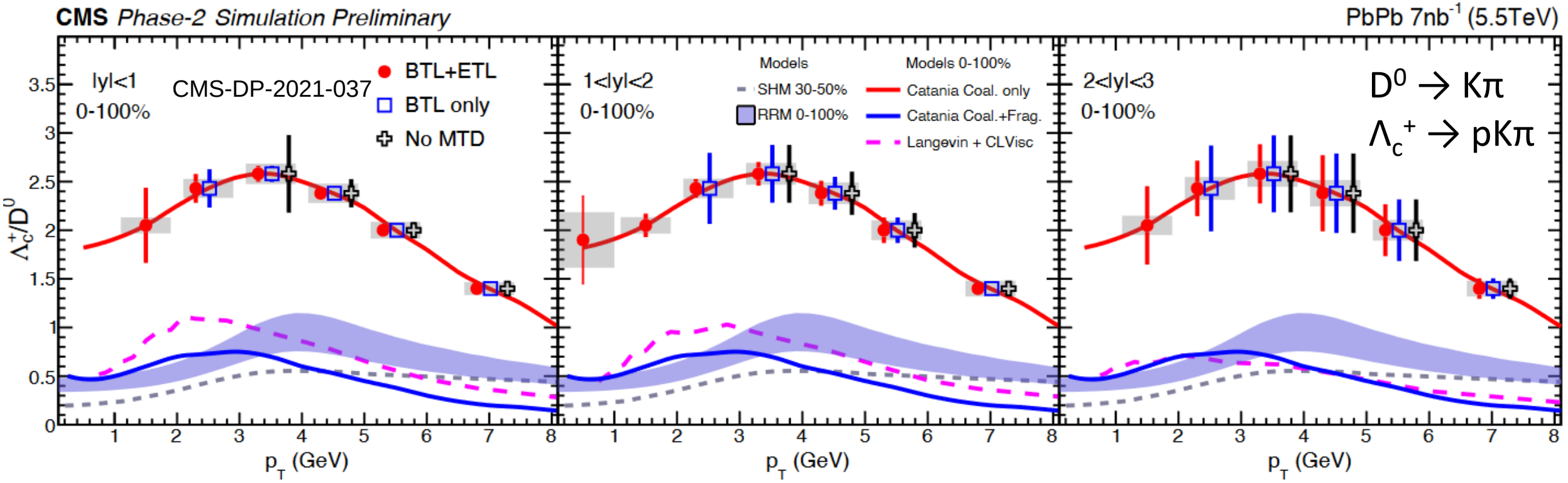




Backup

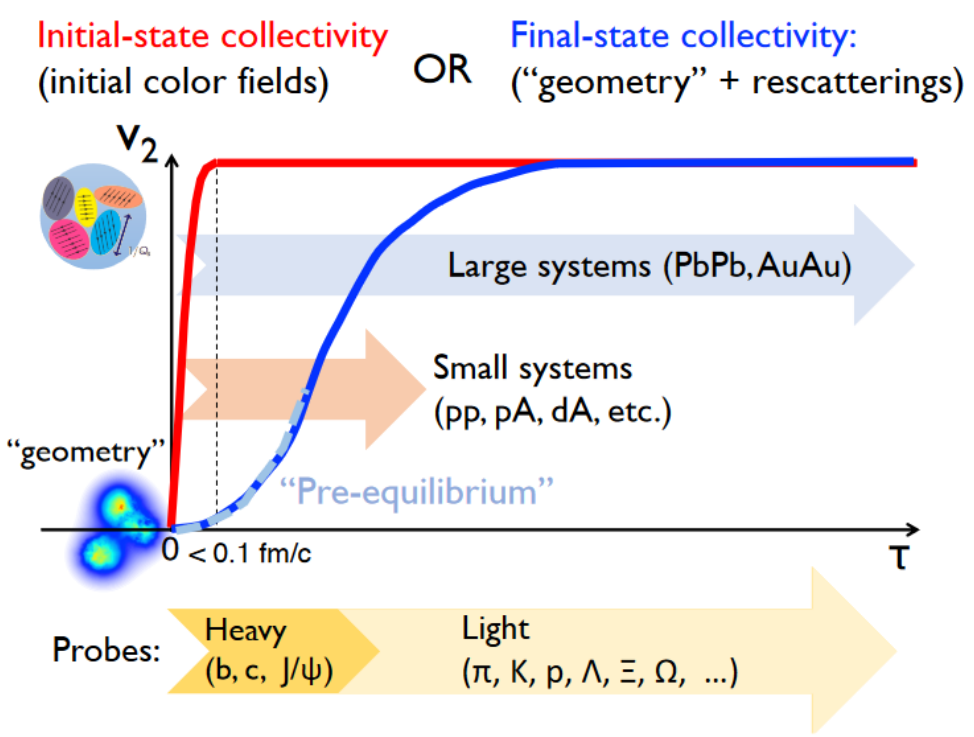
Charm hadronization

- Access full p_T range of Λ_c^+ – CMS unique access to total charm cross section
- Strong constraints on hadronization models



From large to small collisions

- Unexpected collective motions observed in p-Pb and p-p collisions
- Origin of the collectivity – tiny QGP?



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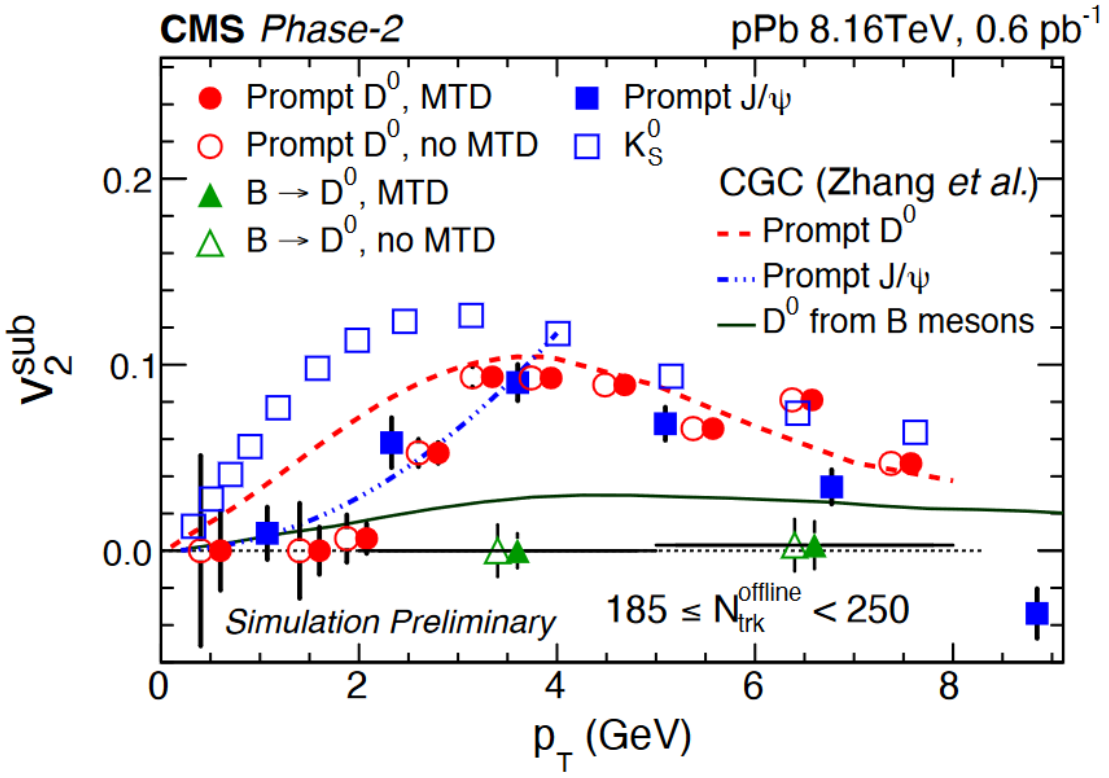
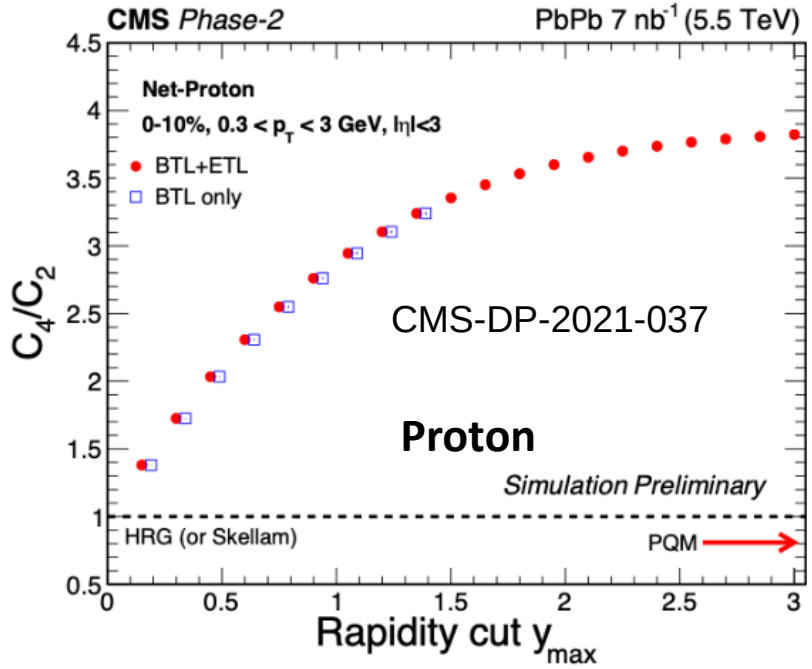


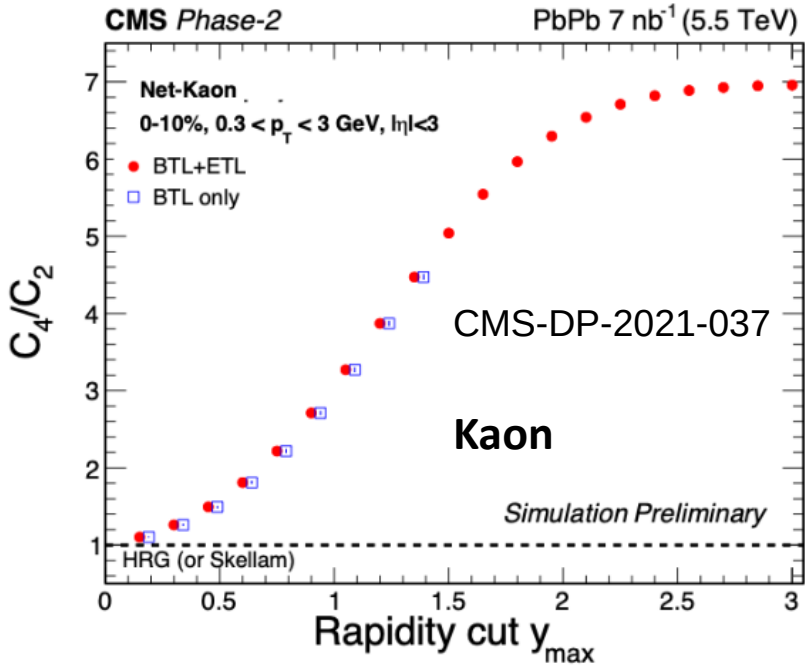
Equation of State via light flavor

- Cumulant for net quantum numbers: C_4 and C_2
  - Quantitatively test lattice QCD: $C_4/C_2 = \chi_4/\chi_2$

$$\chi_{ijk}^{BQS}(T) = \left.\frac{\partial P(T,\hat{\mu})/T^4}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\right|_{\hat{\mu}=0}$$

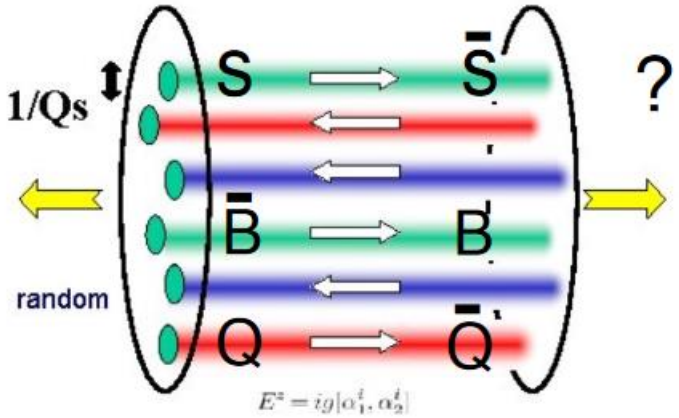
$$\hat{\mu}_X \equiv \mu_X/T$$





Diffusivity of QGP

- Conserved quantum numbers (S, B, C) diffuse
  - Large rapidity is essential
  - Measurable via balance function B(Δy) – opposite charge pairs *minus* same charge pairs



$$R_1(\Delta y) = \frac{B_1(\Delta y)}{B(\Delta y)} \equiv \frac{\int d\Delta\phi\ B(\Delta y, \Delta\phi)\cos(\Delta\phi)}{B(\Delta y)}$$

S. Pratt, C. Plumberg: Phys. Rev. C 104, 014906 (2021)

Diffusivity of QGP

- Conserved quantum numbers (S, B, C) diffuse
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