Exploring High-Density QCD Matter with CMS Phase II at HL-LHC

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For the CMS Collaboration

11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions, Aschaffenburg, Germany

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LHC Timeline and CMS Upgrade

LHC | HL-LHC

PbPb 2 nb^{-1} | PbPb 7 nb^{-1}, pPb, pO, OO | PbPb 7 nb^{-1}, pPb | AA, small systems?

Run 2 | Long shutdown 2 | Run 3 | Long Shutdown 3 | Run 4 | LS4 | Run 5

2018 | 2019 | 2020 | 2021 | 2022 | **2023** | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038

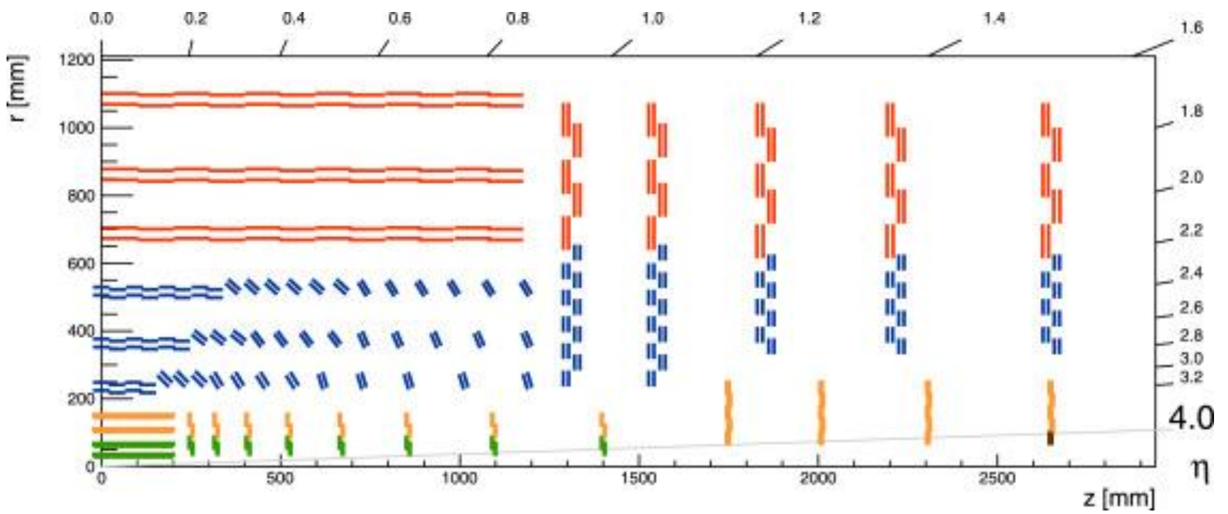
Phase 1 Upgrade | Phase 2 Upgrade | Phase 3 Upgrade

CMS Performance in Run2/3
- 2016: Major upgrade of L1 trigger
- 2017: 4-Layer Pixel Detector
- 2018 Performance:
  - pp L1 100kHz
  - PbPb L1 **35kHz** (3x of 2015)
  - DAQ: 6 GB/s
    - Up to **8.8 kHz** MinBias events to tape (27x of 2015)
- Run3: DAQ 17 GB/s
  - 25 kHz MinBias rate (3x of 2018)

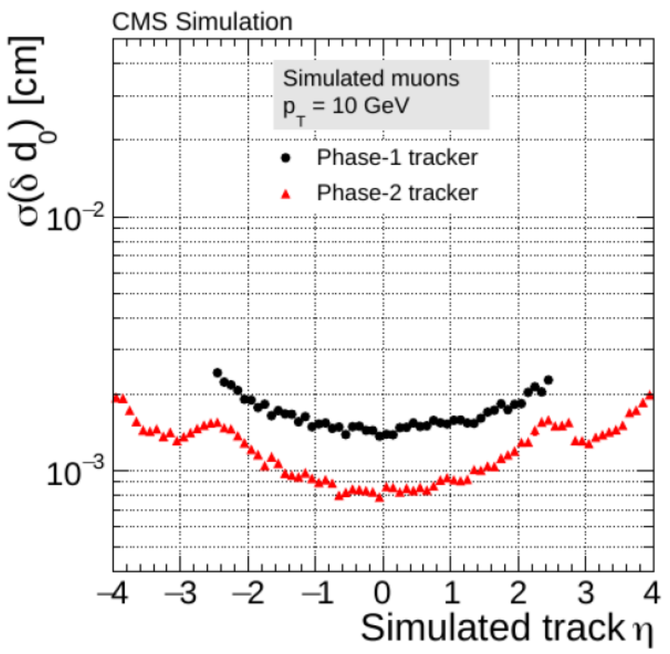
CMS Phase 2 for Run 4
- Tracker **|η|<4**
- Muon ID up to **|η|<2.8**
- High Granularity Calorimeter
- MIP timing detector
  - 4D vertexing (x, y, z, t)
  - **p/K/π PID (CMS MTD)**
- L1 trigger update: 750 kHz for CMS
- DAQ: 51 GB/s for CMS
- L1 track triggers
- ZDC

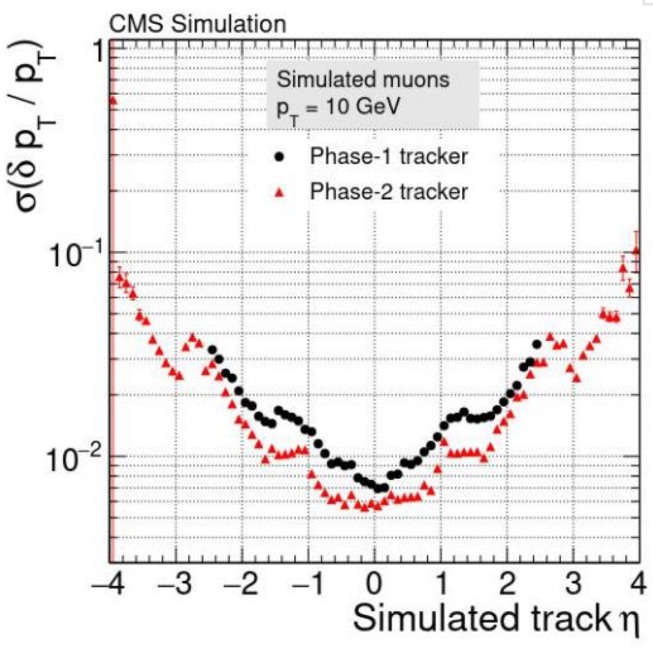
CMS Run 5
- Record smaller ion collisions at the highest rate delivered by LHC
- Possible further upgrade to be defined, e.g.:
  - Additional timing layers
  - Forward calorimeters
  - Extend muon coverage
  - …

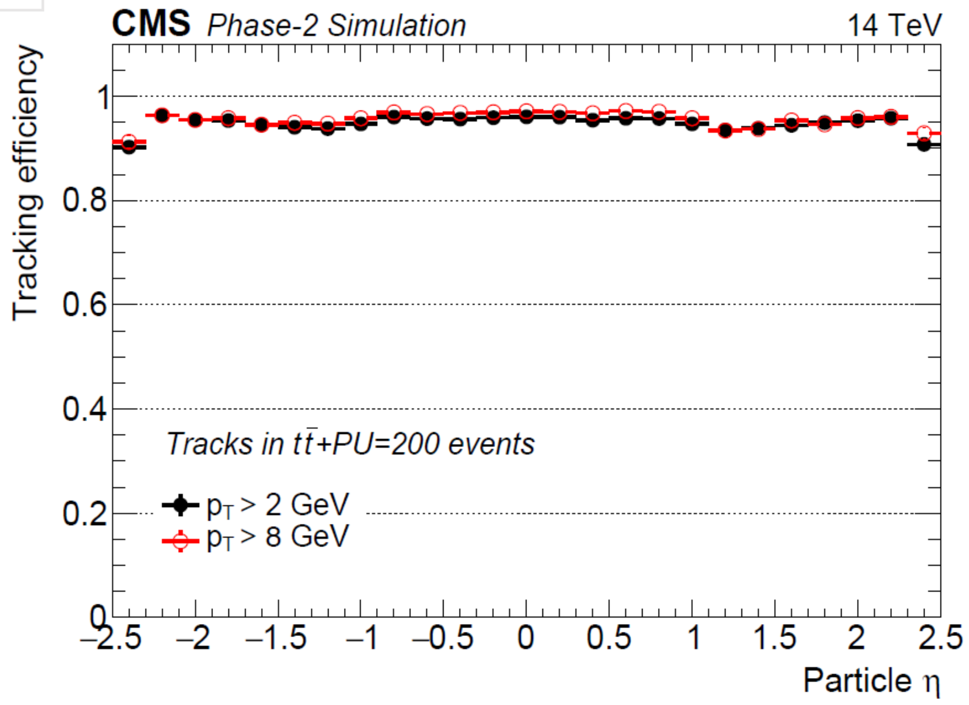
- Installation before Run 4
- Charged particle reconstruction up to **|η|<4**
- At <Pile-Up>=200 (heavy-ion like):
  - Efficiency > 90%, fake rate < 3%
- Significantly better p_T and d_0 resolution
  - Improvement on HF hadron and b/c-jet tagging
  - Level-1 track trigger



CMS-TDR-014





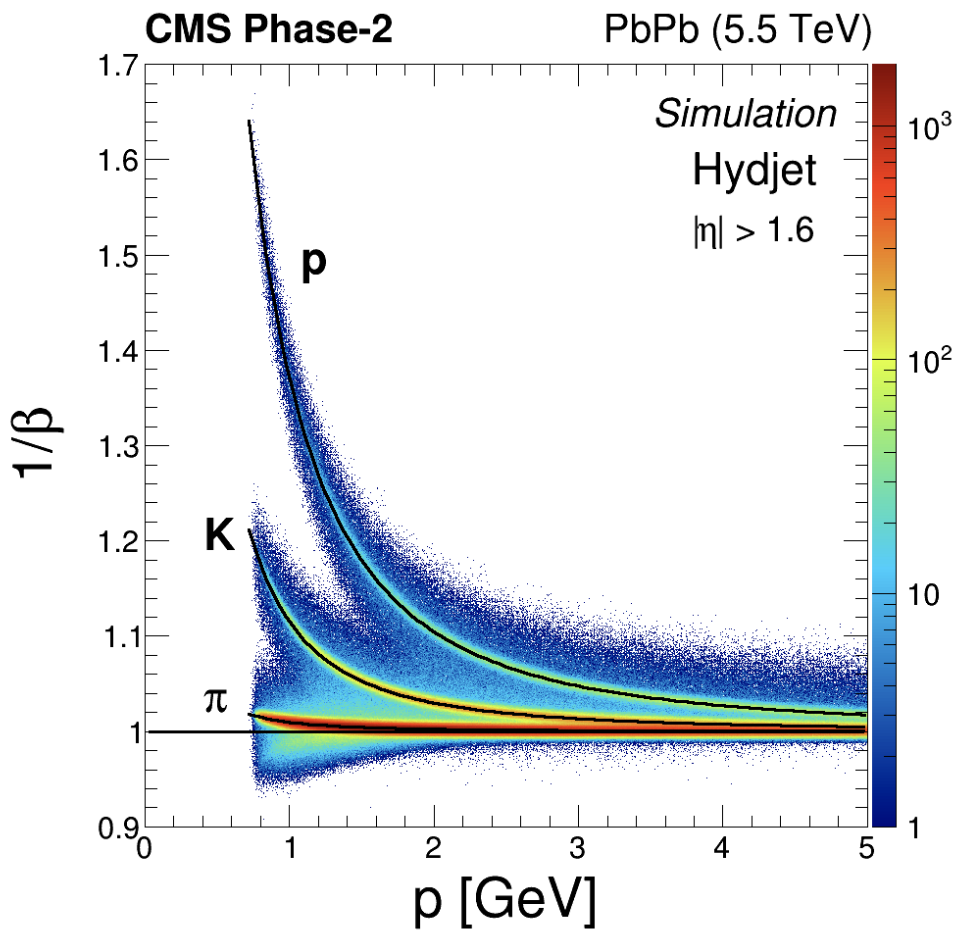


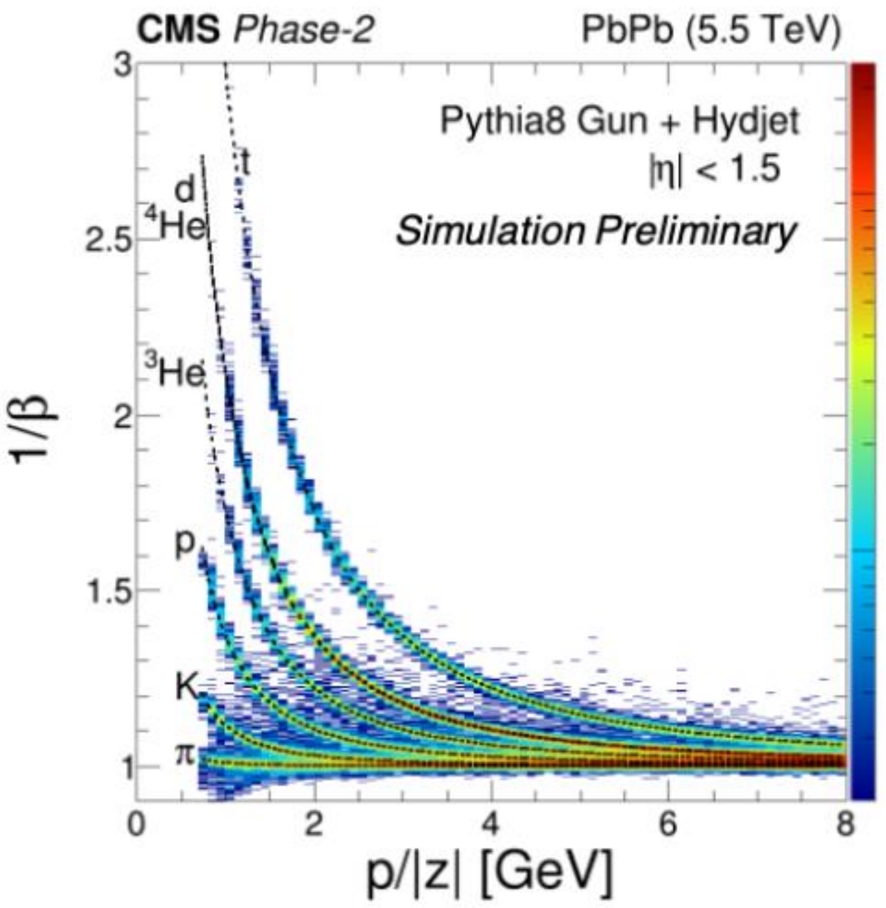
CMS MIP Timing Detector (MTD)

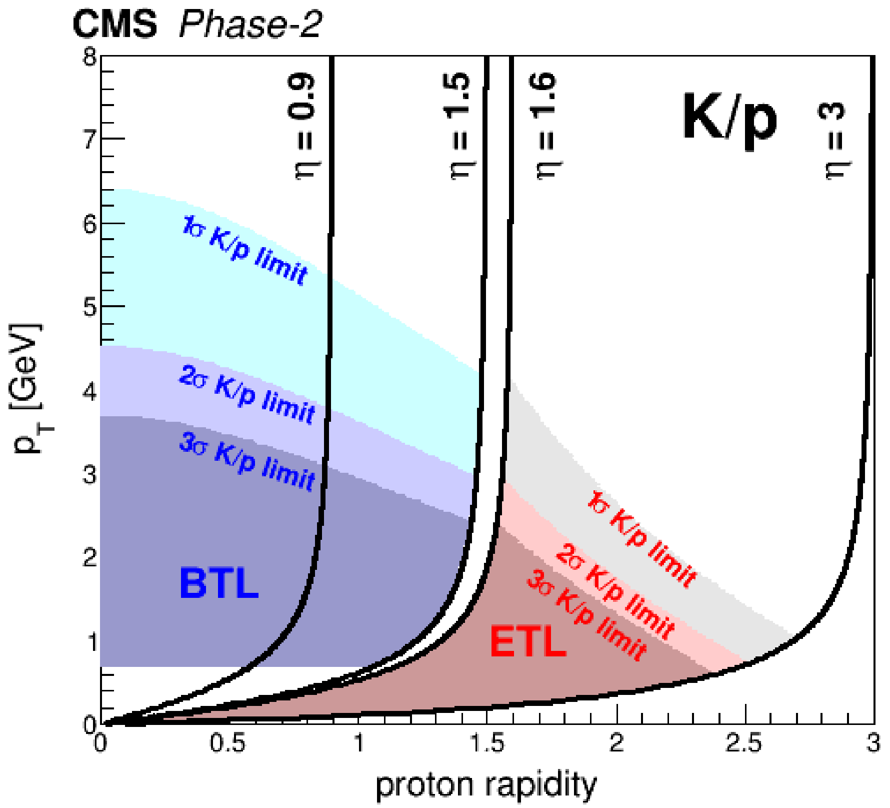
p / K / π separation

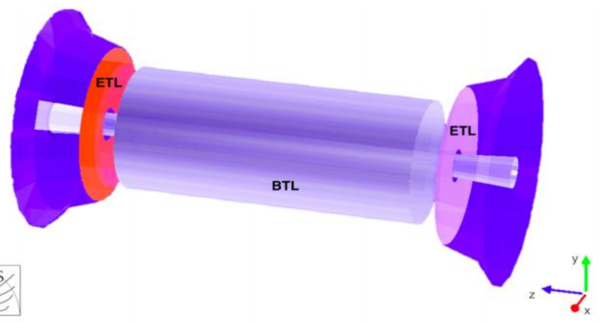
Light ion identification

CMS DP_2021_037









- Unique hermetic particle identification coverage by CMS MTD
- **Crucial Upgrade** for CMS Heavy Flavor Program with heavy ion collision

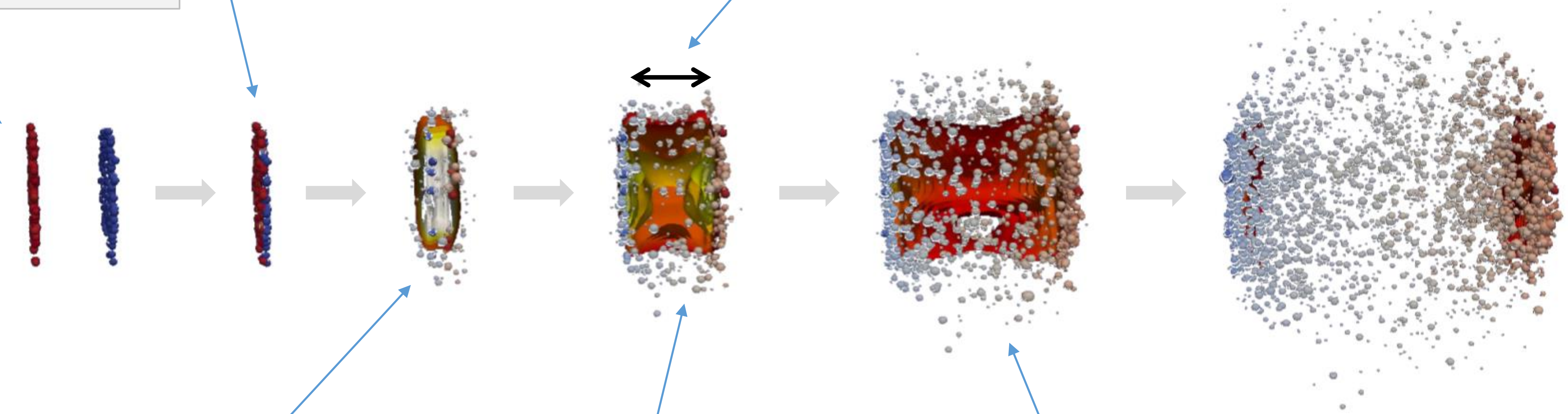
Open Questions

What are the initial conditions of the collision?

What is the longitudinal structure of the QGP?

What's the hadronization mechanism with QGP?

nPDF and initial EM field



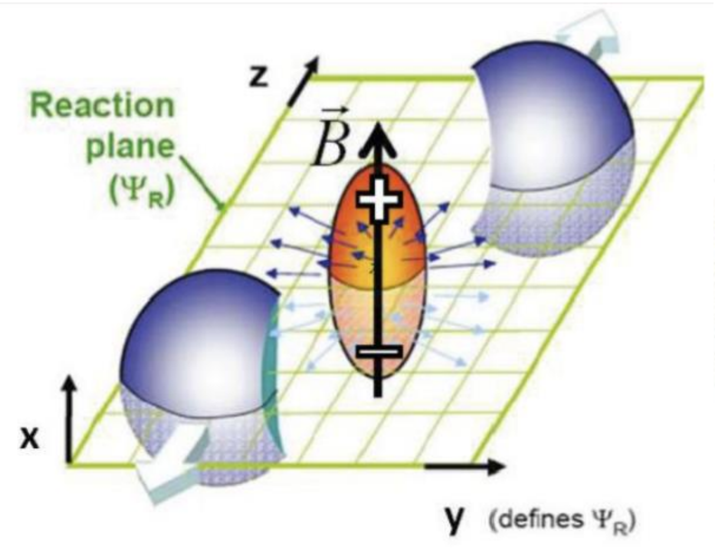
How does the system move toward hydrodynamization?

What are the transport properties of the QGP?
How does QGP respond to hard probes?
What are the inner workings of QGP at various length scales?

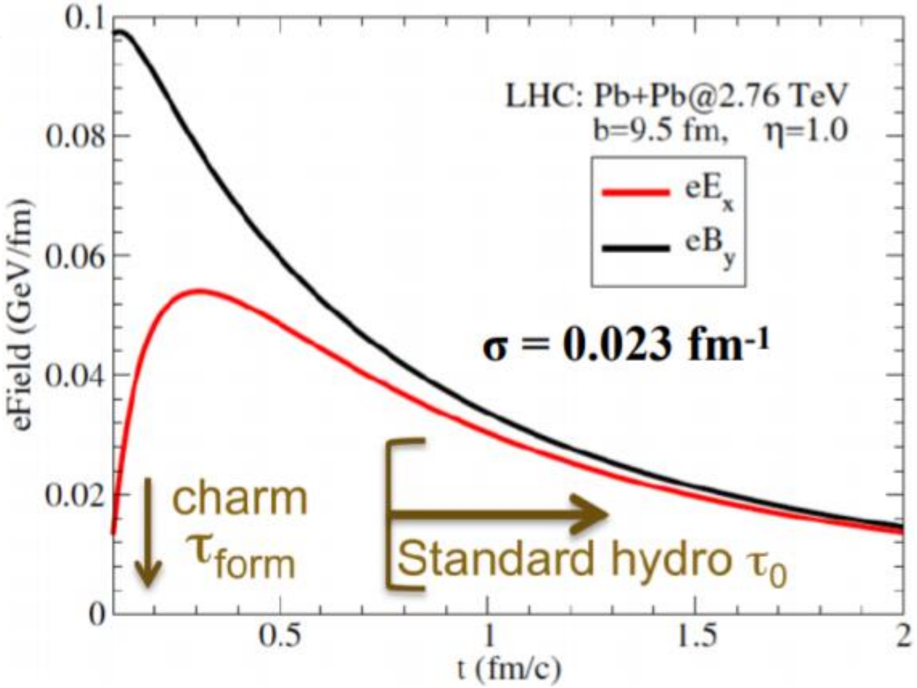
What is the in-medium color force?

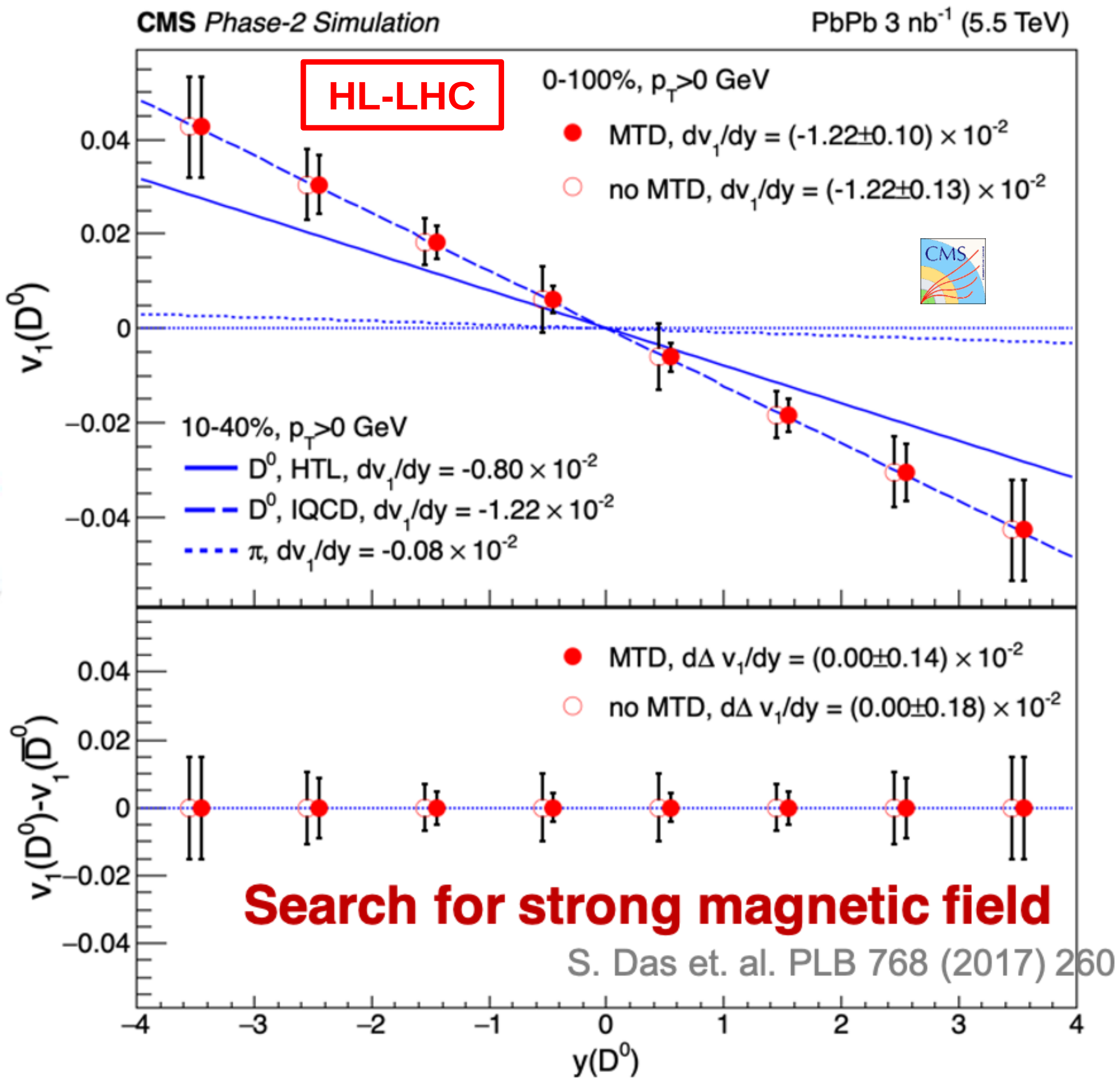
Visualization taken from Jonah E. Bernhard
arXiv:1804.06469

Initial Magnetic Field with D^0 Directed Flow v_1



CMS DP_2021_037





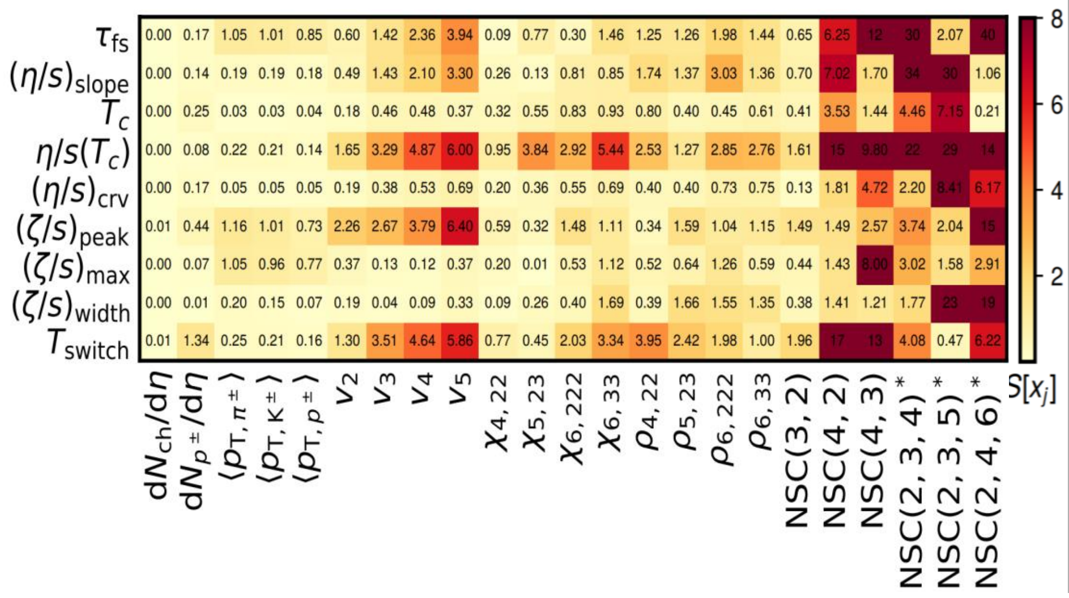
- Strong initial electromagnetic field in heavy ion collisions inducing a vorticity in the reaction plane.
- The resultant effects entails a significant directed flow (v_1) and the effects increase vs. D^0 rapidity
- MTD and the large acceptance CMS tracker could provide high precision measurement of D^0 v_1 over 8 units of D^0 rapidity.

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)]$$

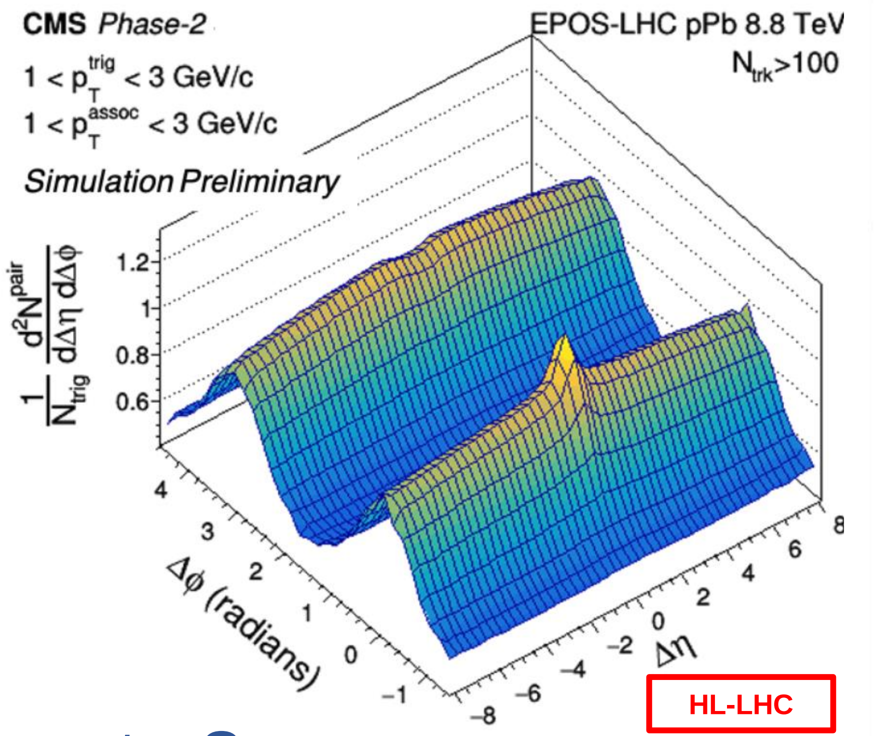
Extraction of QGP Properties with Soft Probes

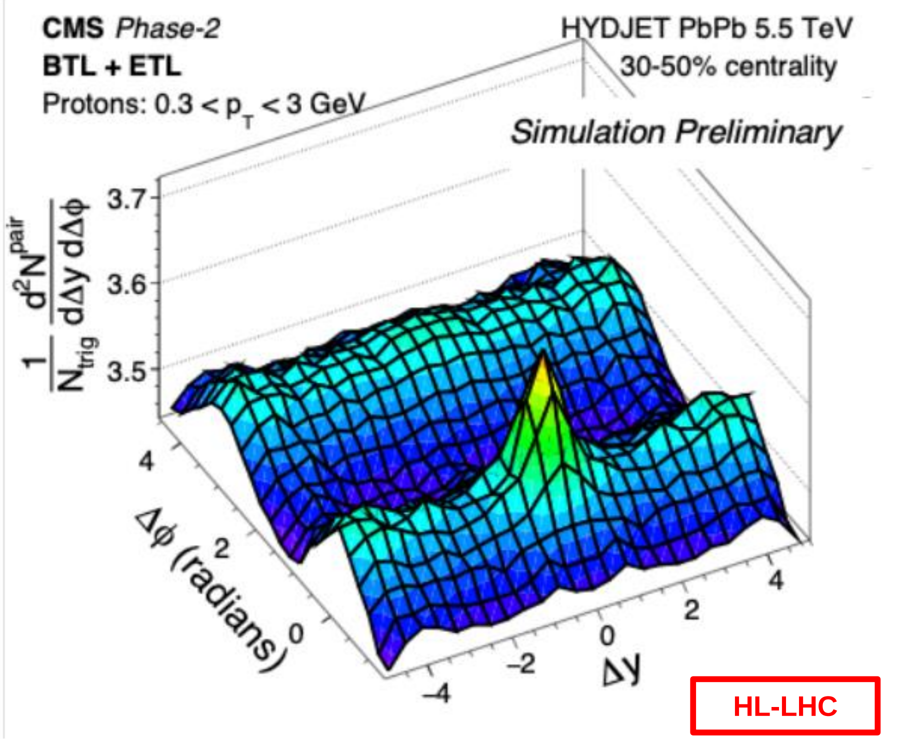
- Unprecedented high precision and differential measurements of flow harmonics and their event-by-event fluctuations: New constraints on the QGP initial density profile, formation time, properties and hadronization

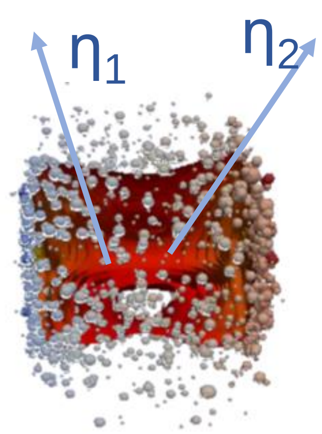
CMS DP_2021_037



arXiv: 2111.08145







|Δη| up to **8** CMS DP2021_037

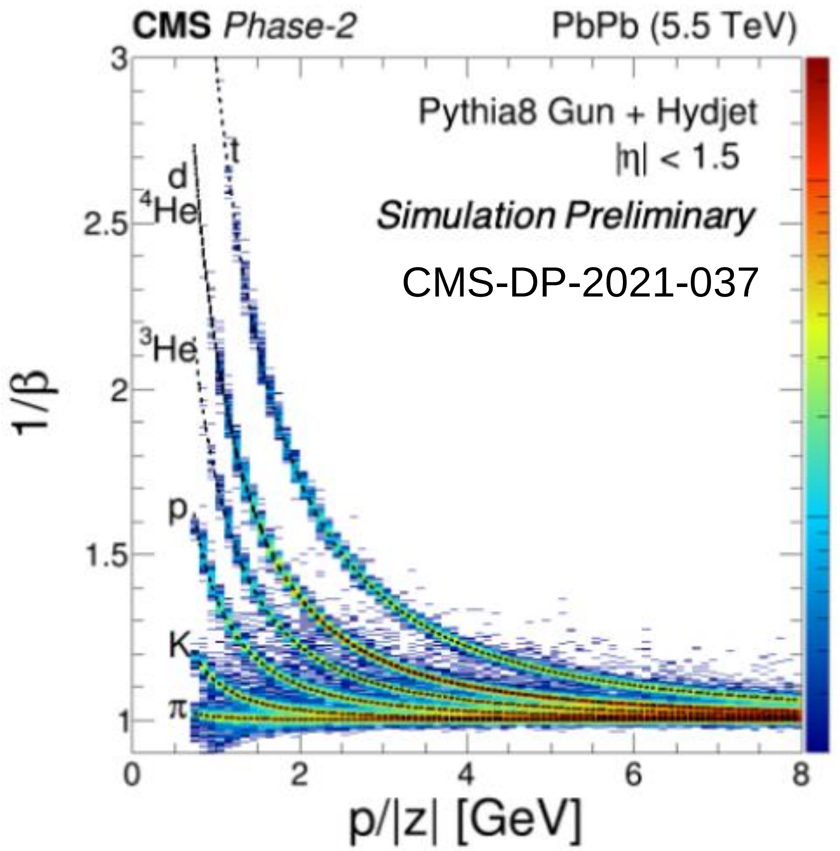
Correlation functions of protons with |Δη| up to ~**5**

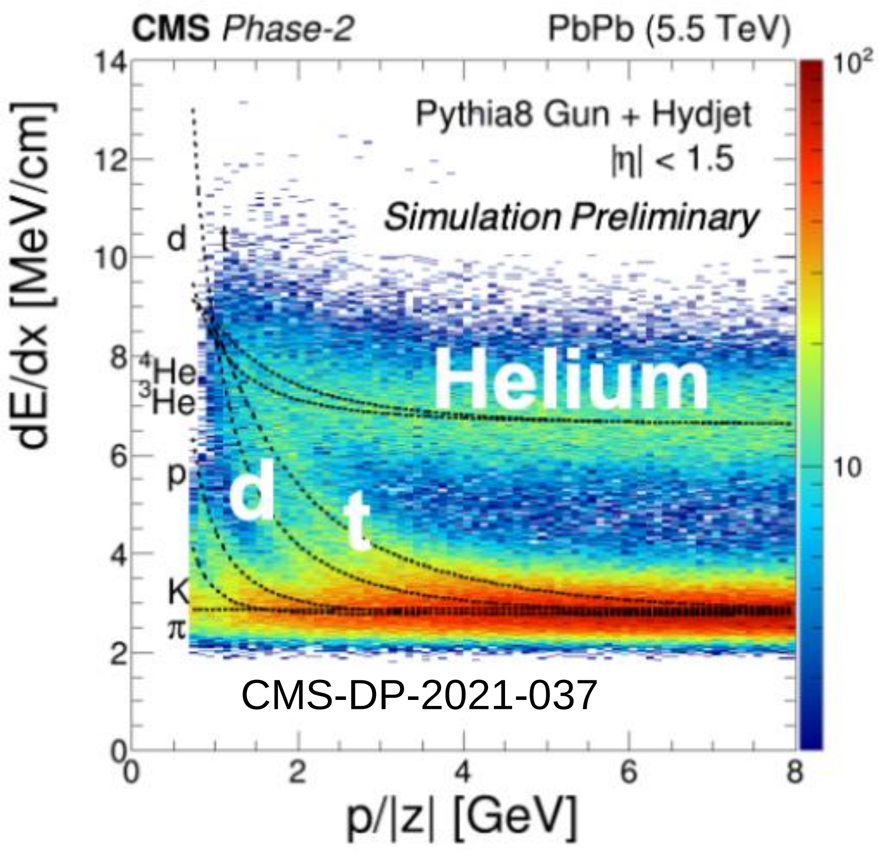
- Pseudorapidity dependence of the flow measurements over **a wide η window** enabled by CMS tracker upgrade
  New insights into the longitudinal structure of QGP (event-plane decorrelation)

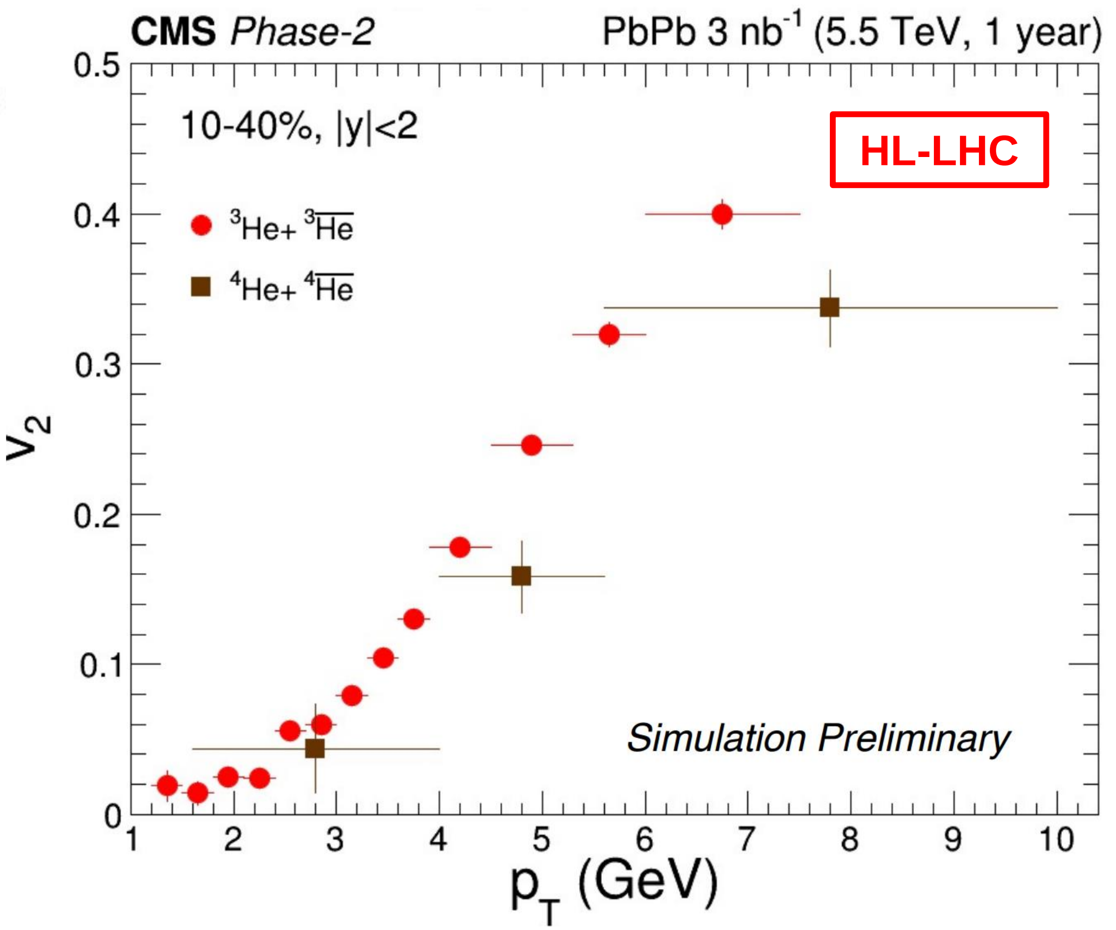
Light Nuclei Spectra and Azimuthal Anisotropy with CMS

- PID with Time of Flight with MTD and dE/dx from Pixel detector
- High accuracy measurement of **d**, **t**, **^{3}He** and **^{4}He** v_2

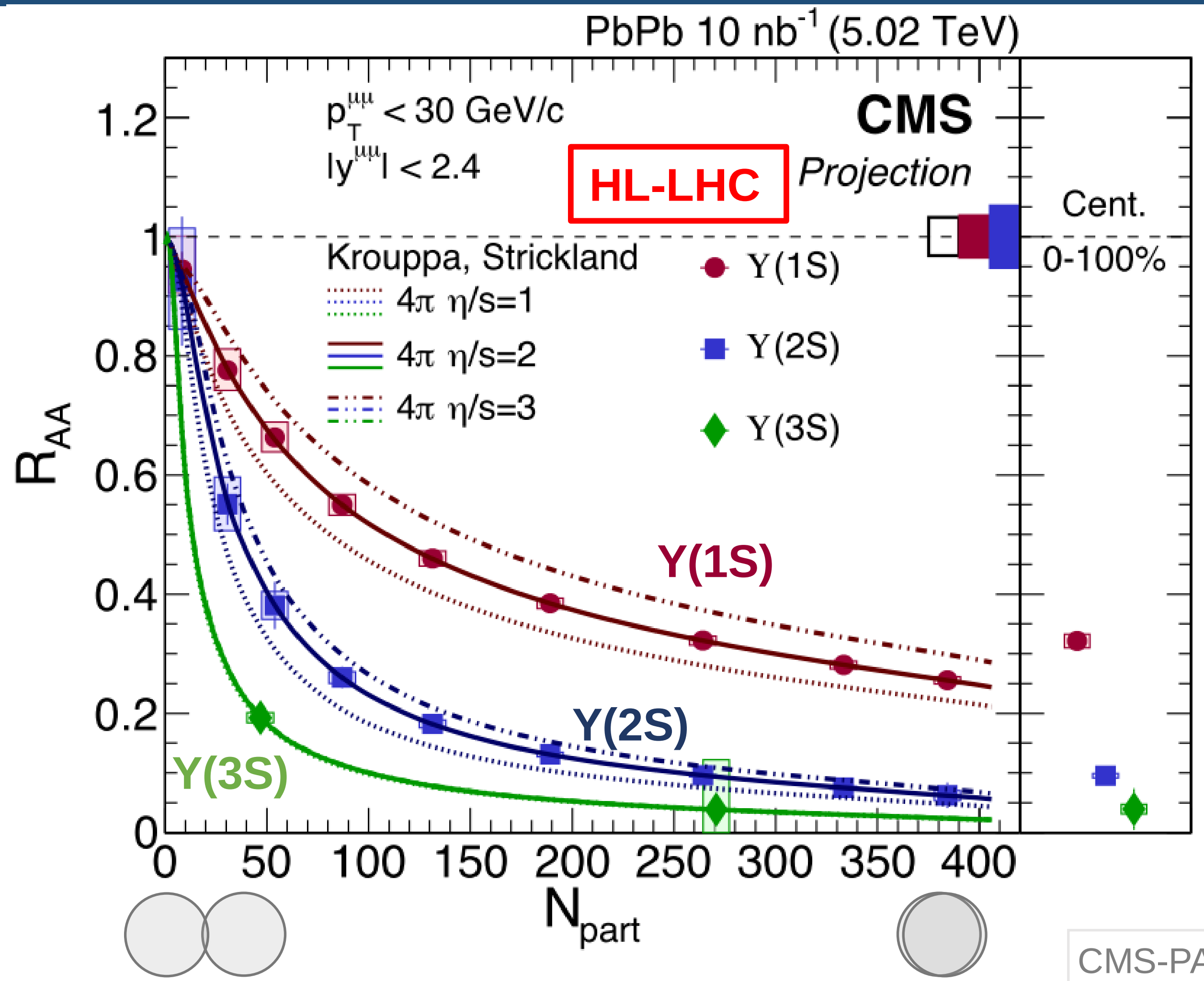
CMS DP_2021_037



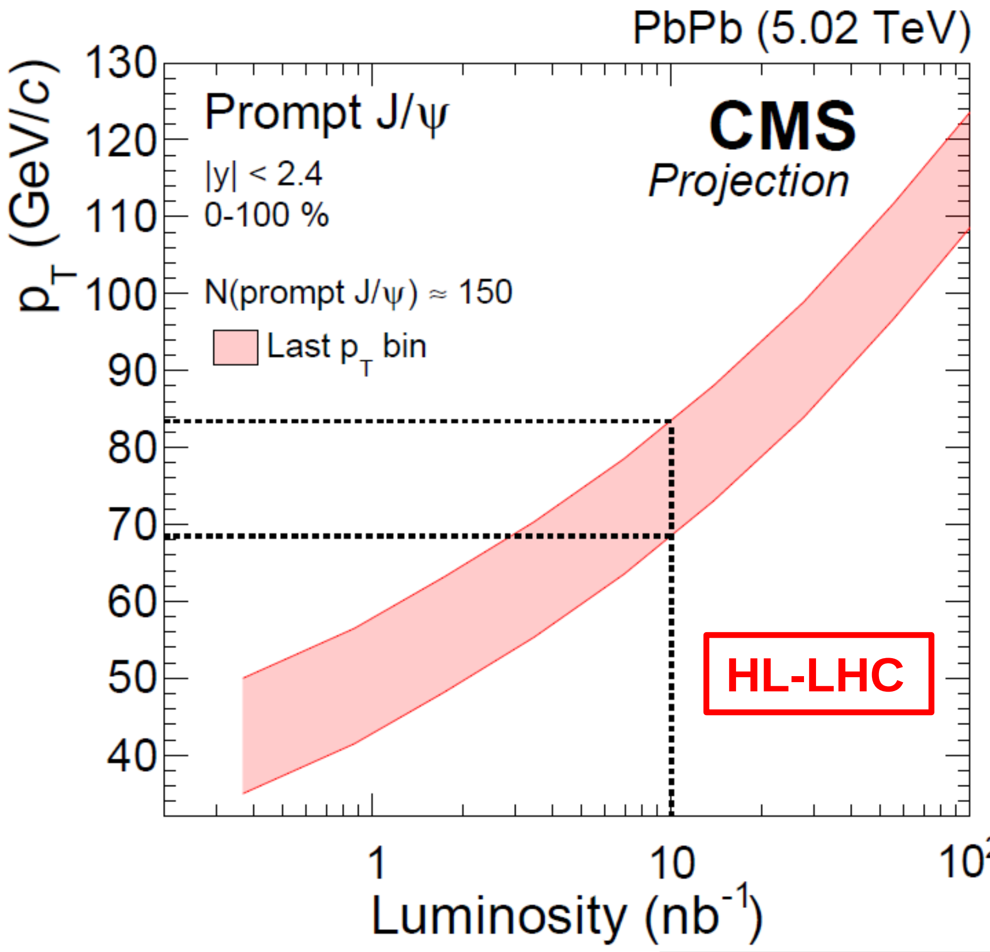




Quarkonia Production in PbPb Collisions



CMS-PAS-FTR-17-002

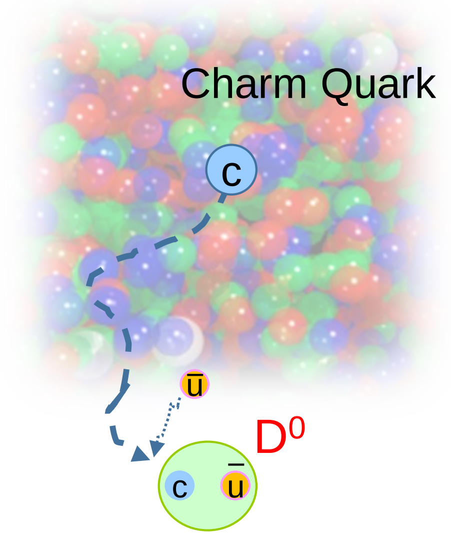


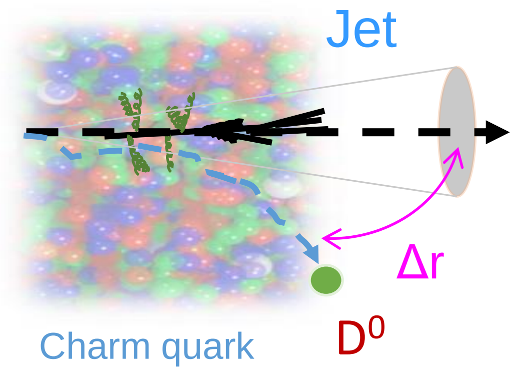
CMS-PAS-FTR-18-024

- Significant improvement on the Υ(nS) R_{AA}
- Sensitive to the medium properties such as η/s and temperature; provide strong constraints in the future Bayesian analyses.

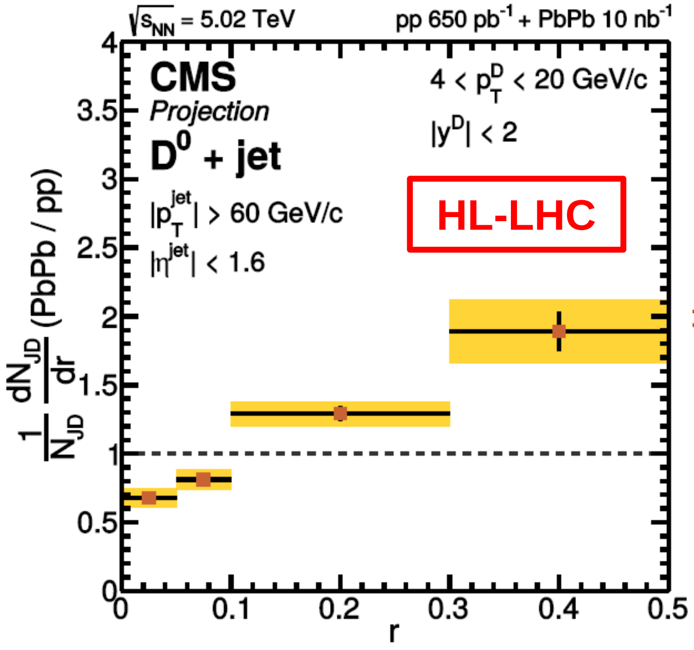
- High p_T reach of prompt J/ψ up to ~ 80 GeV
- Hadronic decays of Quarkonia enabled by CMS MTD such as J/ψ, ψ(2S) and $\eta_c \rightarrow p\bar{p}$

High Precision Measurement of HQ Diffusion



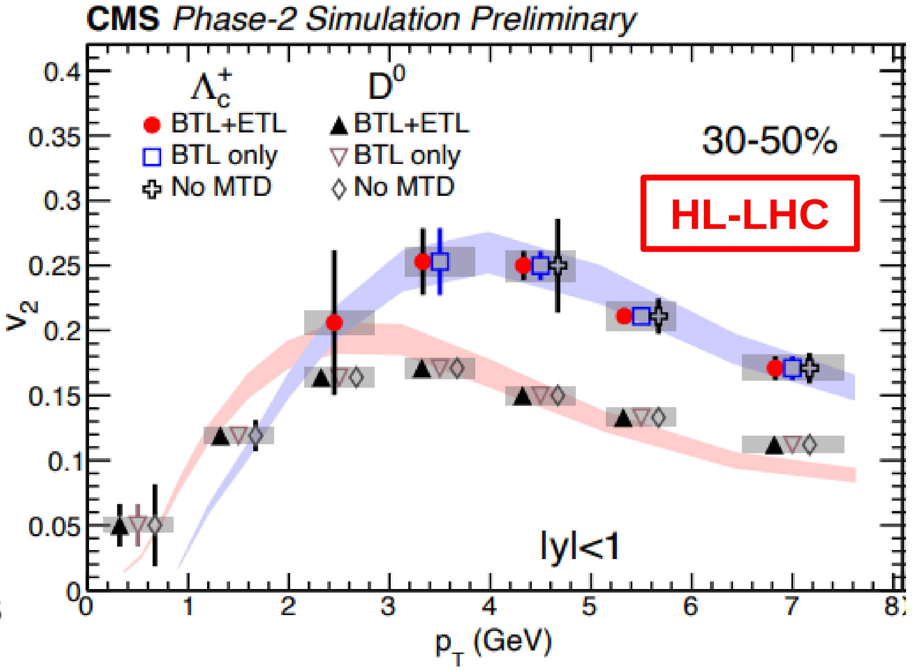


Jet-D^0 Correlation



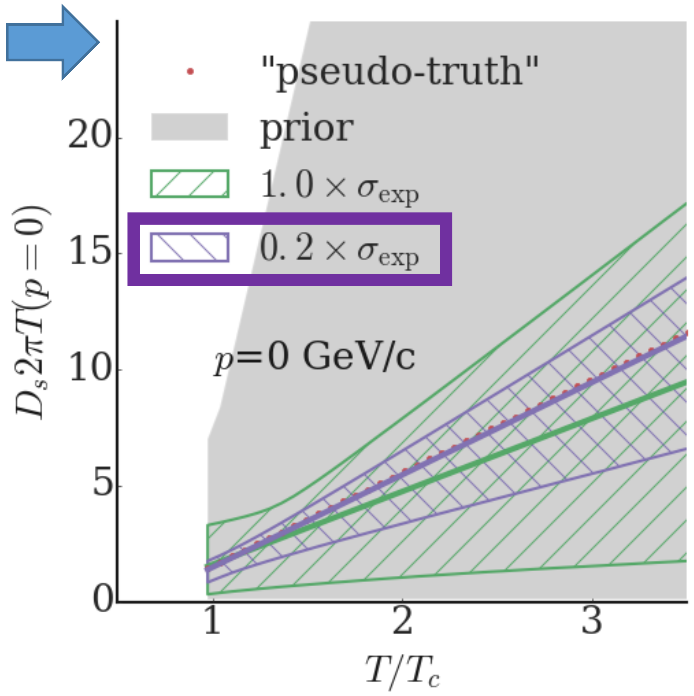
CMS PAS-FTR-18-025

D^0 and Λ_c v_2



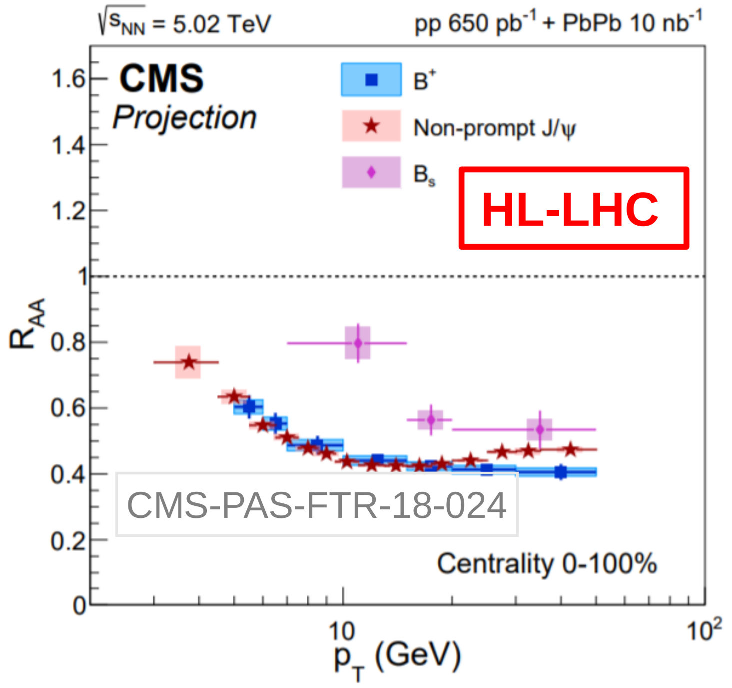
CMS DP_2021_037

D_s vs. T

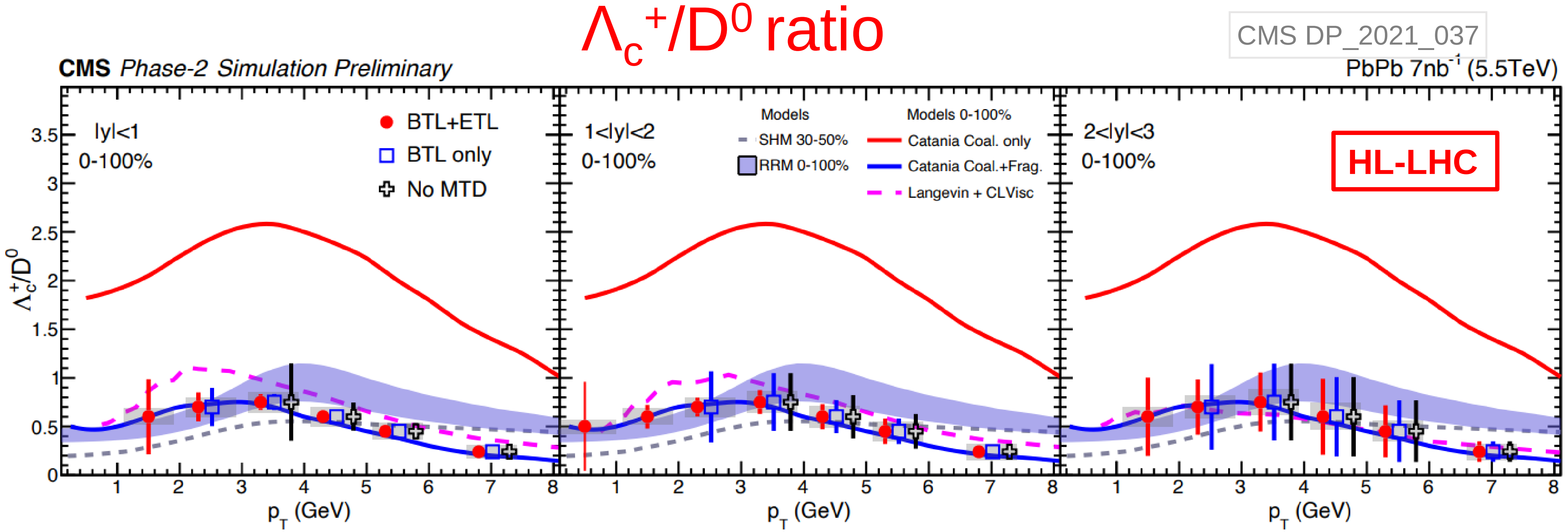


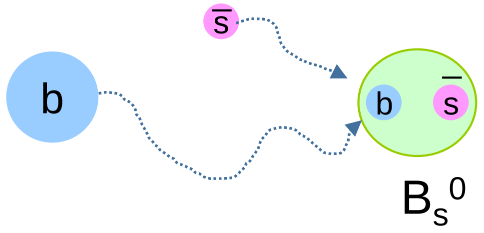
- Large improvement on the Λ_c and D^0 v_2 measurements with CMS MTD
- Direct observation of charm diffusion with D^0-Jet correlation
- Strong constraint on the HQ diffusion coefficient **D_s**

Heavy Quark Hadronization



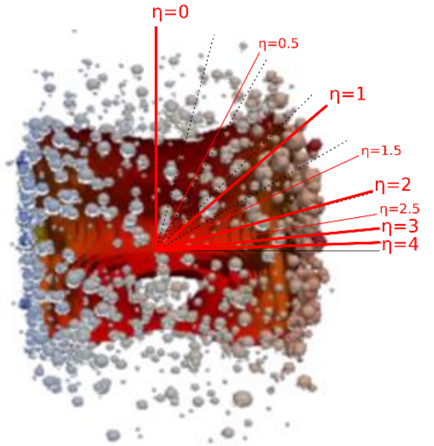
Λ_c^+/D^0 ratio





- Precise measurement of Λ_c, B_c, B_s, D_s and D^0 for HQ hadronization
- First observation of Λ_b in PbPb

- High precision Λ_c^+/D^0 ratio over a wide rapidity range down to p_T ~0 : toward **total charm cross-section**
- Unique capability of CMS thanks to the large tracker and MTD acceptance



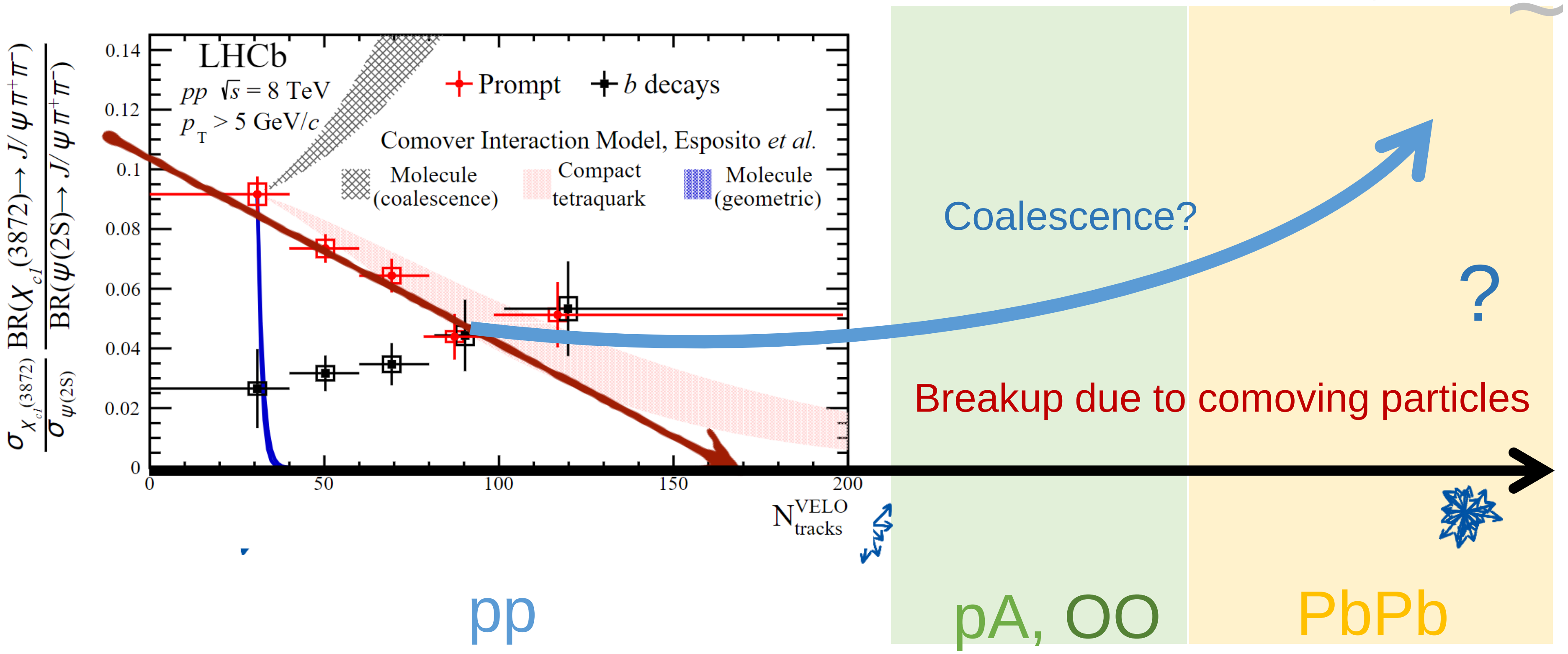
*Except for the Langevin+CLVisc model, all other models shown assume boost invariant in the longitudinal direction, and thus have no rapidity dependence.

New Frontier of Hadronization Study: Exotic Hadron

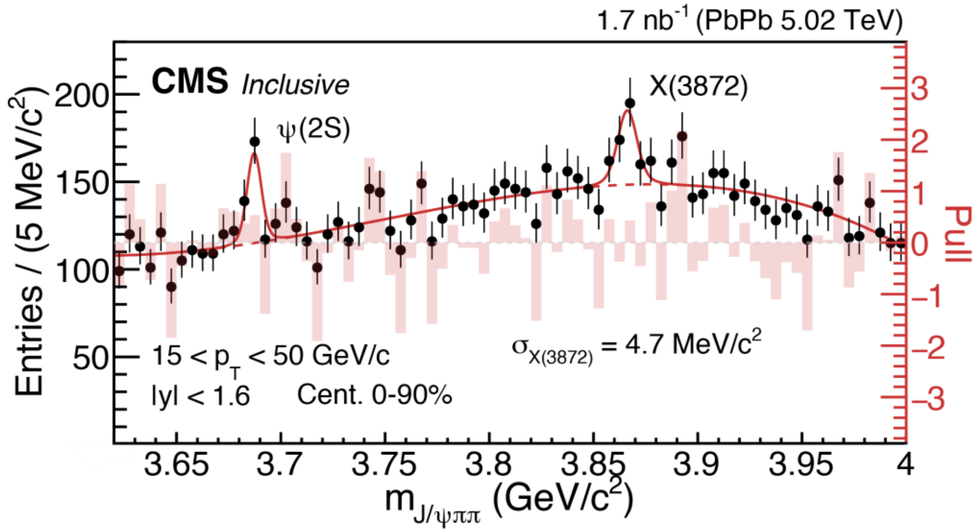
LHCb
PRL 126 (2021) 9, 092001

CMS PbPb

$$\rho^{\text{PbPb}} = 1.08 \pm 0.49\,(\text{stat}) \pm 0.52\,(\text{syst})$$

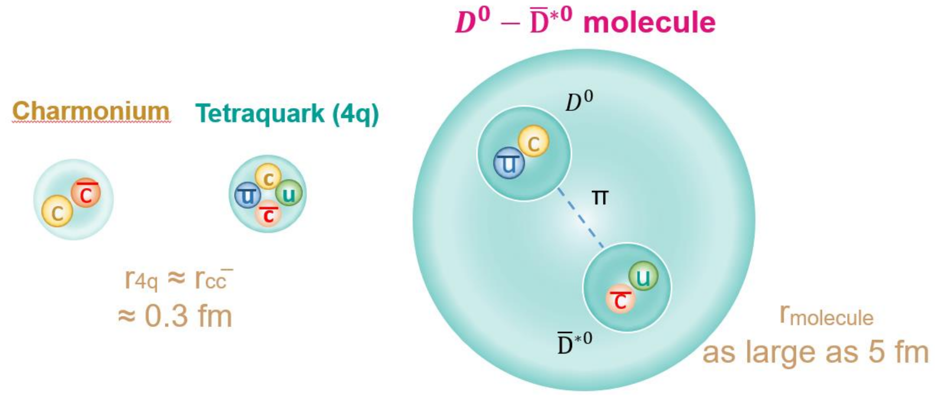


CMS
PRL 128 (2022) 032001

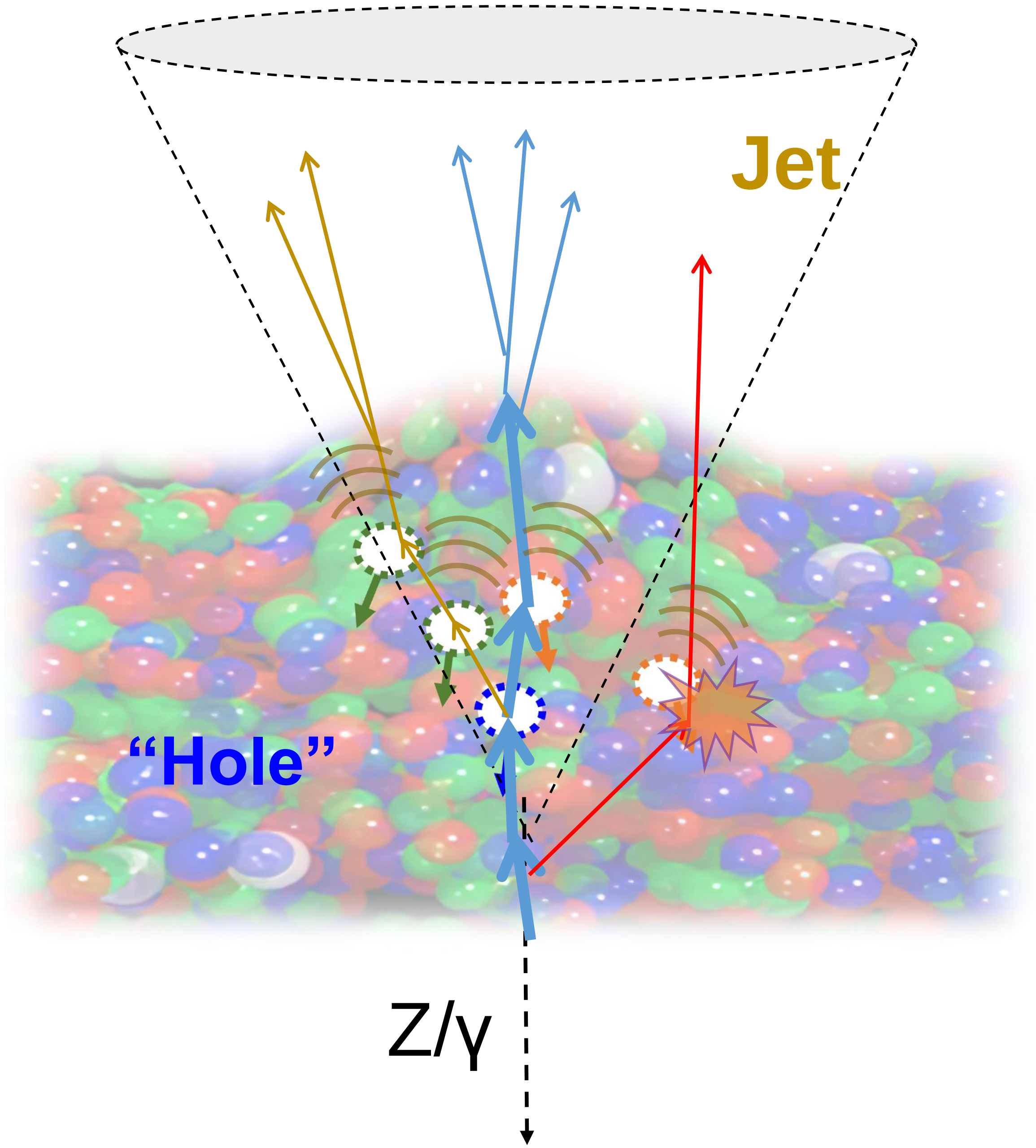


The first evidence of X(3872) in HI

- Observation **of X(3872) in PbPb is expected (>5 σ) in Run3**
- Run3+4: Differential studies
  - Centrality dependence: Probe the structure of X(3872) with QGP
- Search for other exotic hadrons such as T_{cc}
- Exotic hadron production in UPC events



QGP Transport Properties and Structure with Jets



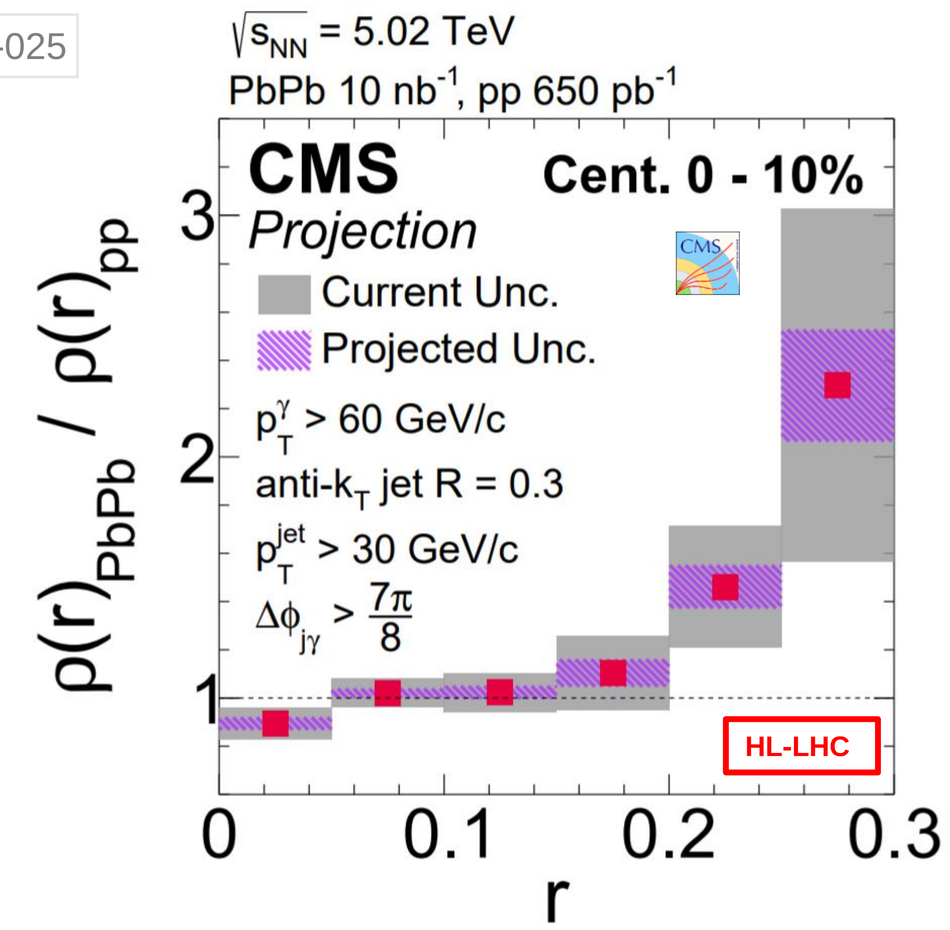
- Jet broadening effects from multiple soft scattering ($\hat{q}$)
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes)

- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

Jet Properties and Medium Response in PbPb

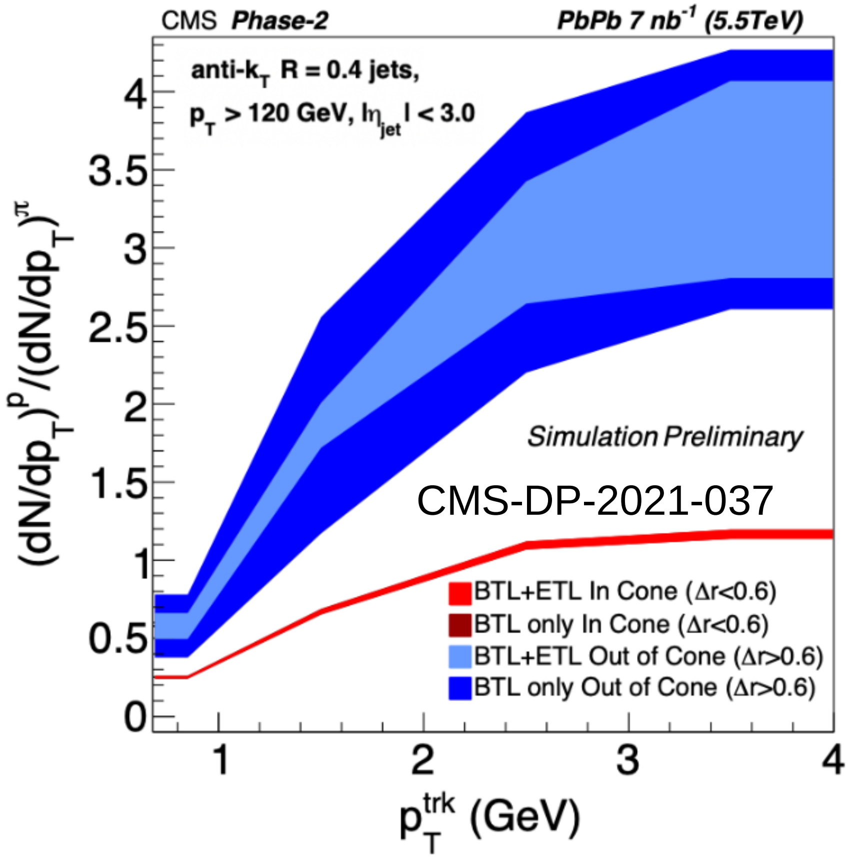
CMS PAS-FTR-19-025

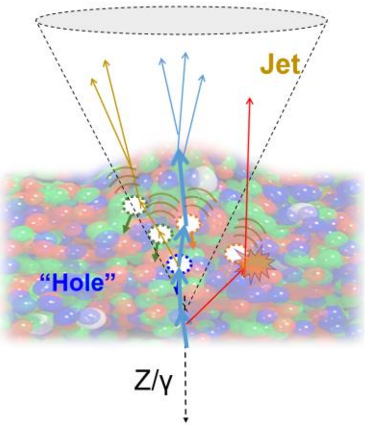
Modification of Jet Shape



p/π ratios in and out of jet cone

HL-LHC



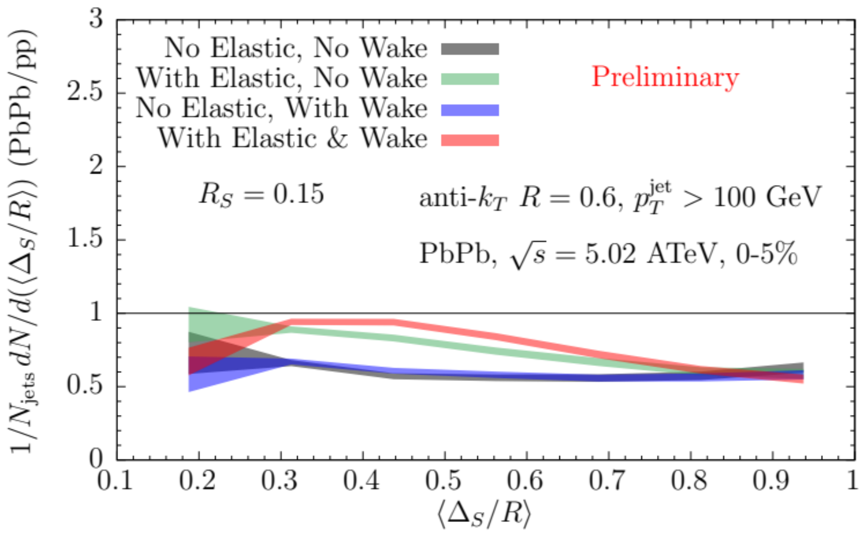


- Reveal jet broadening effect from multiple soft scattering and medium response
  - Photon-tag reduced "survival bias" which narrows the inclusive jet shape
- Particle composition in the QGP wake

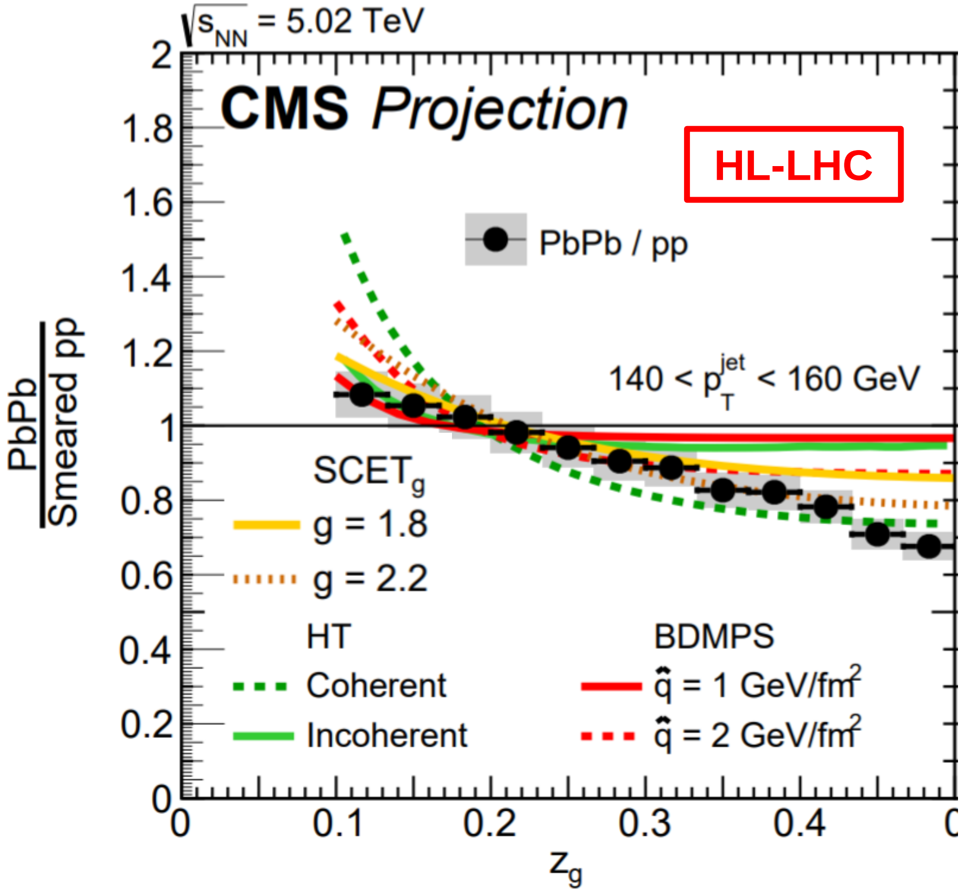
Jet Substructure and D^0-Jet Correlations

Moliere scattering

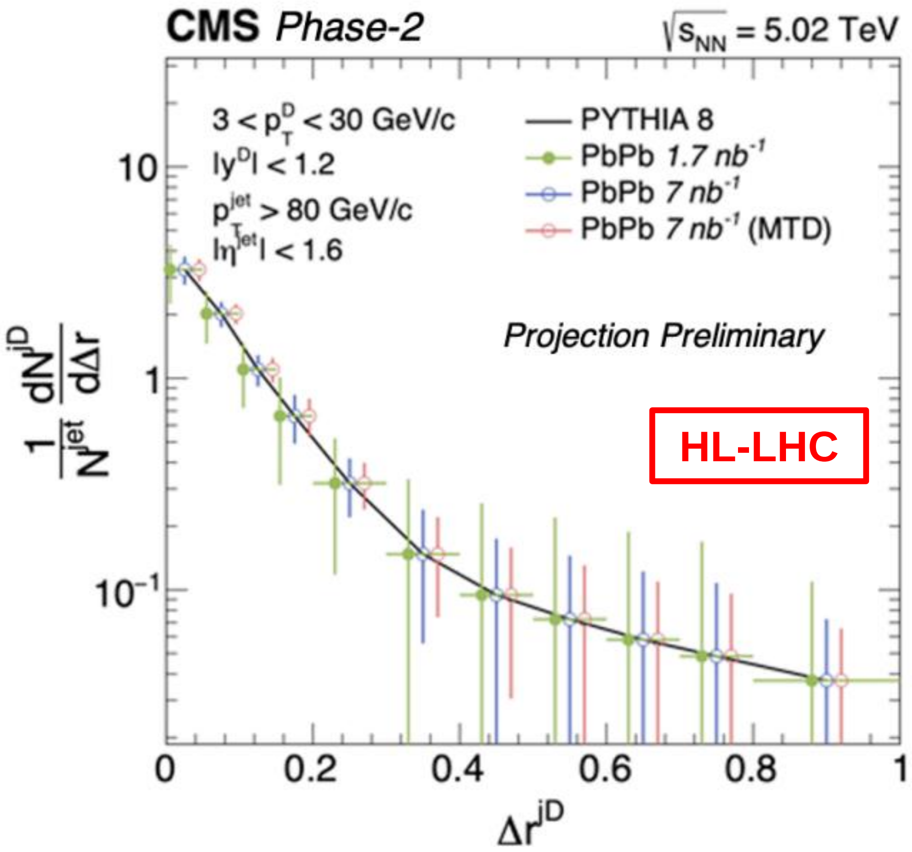
"Sprout" more subjets



arXiv:2208.13593
Hulcher, Pablos, Rajagopal



CMS PAS-FTR-17-002



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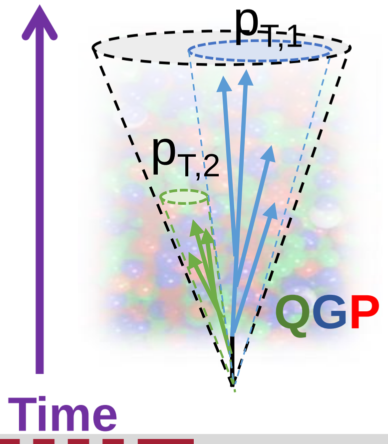
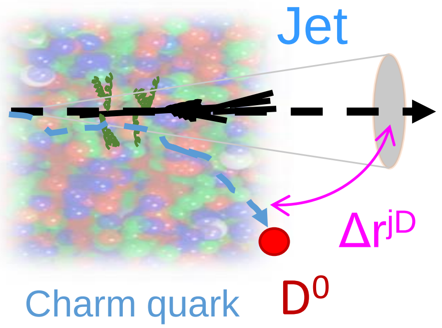


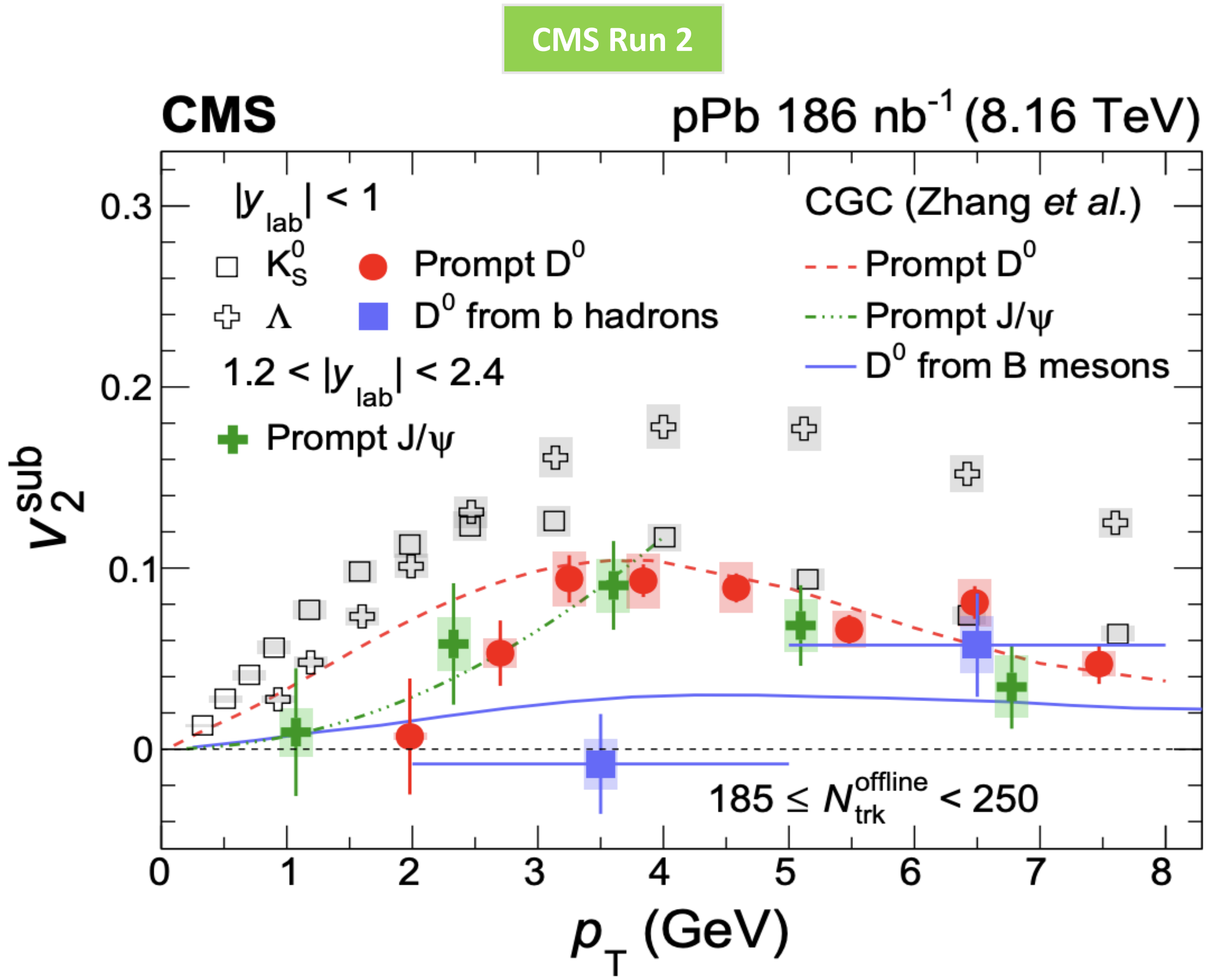
With Run 3+4 data, jet substructure observables such as Z_g and subjet multiplicity could be measured with high precision

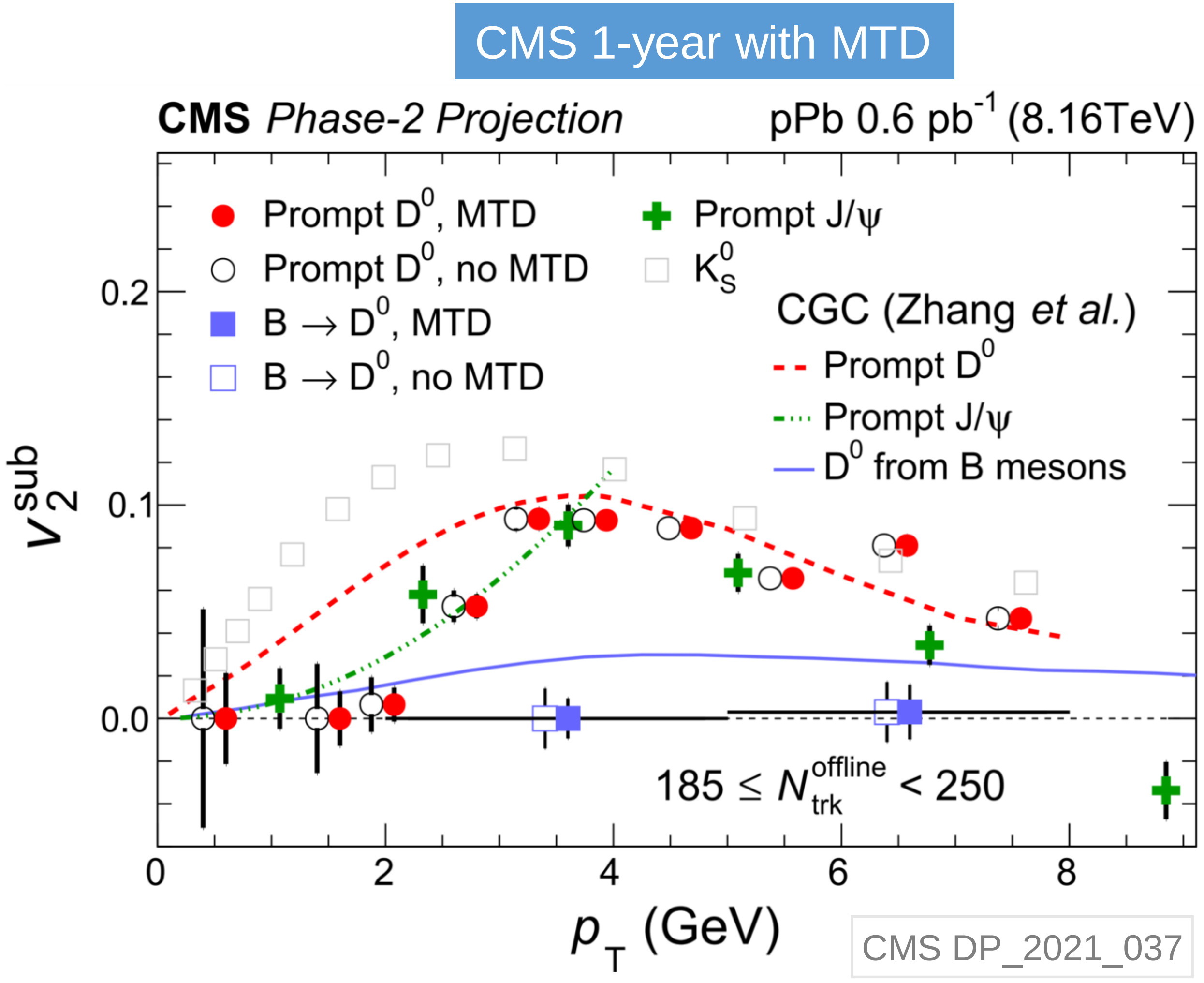


D^0-Jet angular correlation

- D^0 as a proxy of heavy quark
- Search for **large angle scattering**

Collectivity in Small System



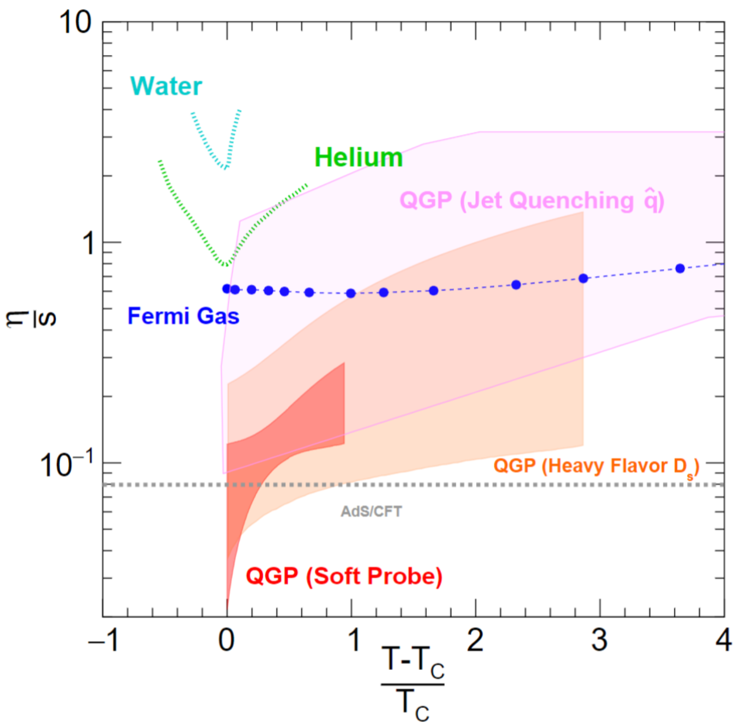


- With MTD: Unprecedented precision could be achieved with fast CMS tracking and DAQ system
- Detailed characterization of the heavy flavor hadron collective behavior in high multiplicity proton-proton and proton-lead collisions

Summary

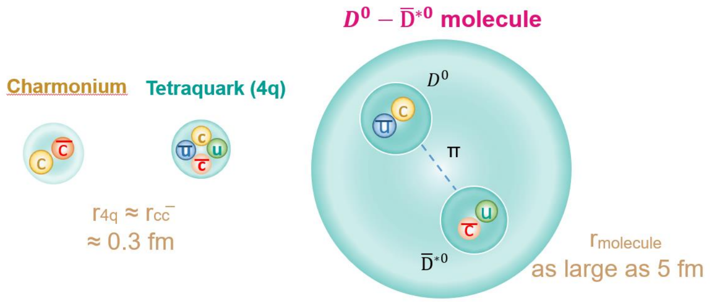
CMS Phase II Upgrade

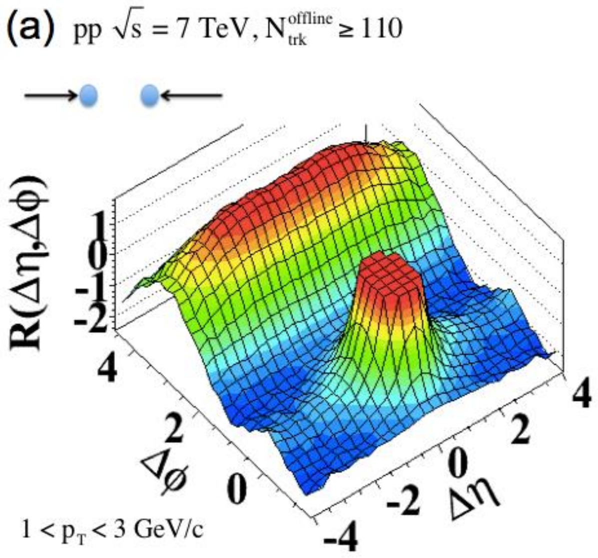
- Large acceptance and high performance tracker |η|<4
- Particle and light nucleon identification with CMS MTD + Pixel
- Improvement on the secondary vertex resolution
- L1 track trigger capability



Run 3+4 data will provide

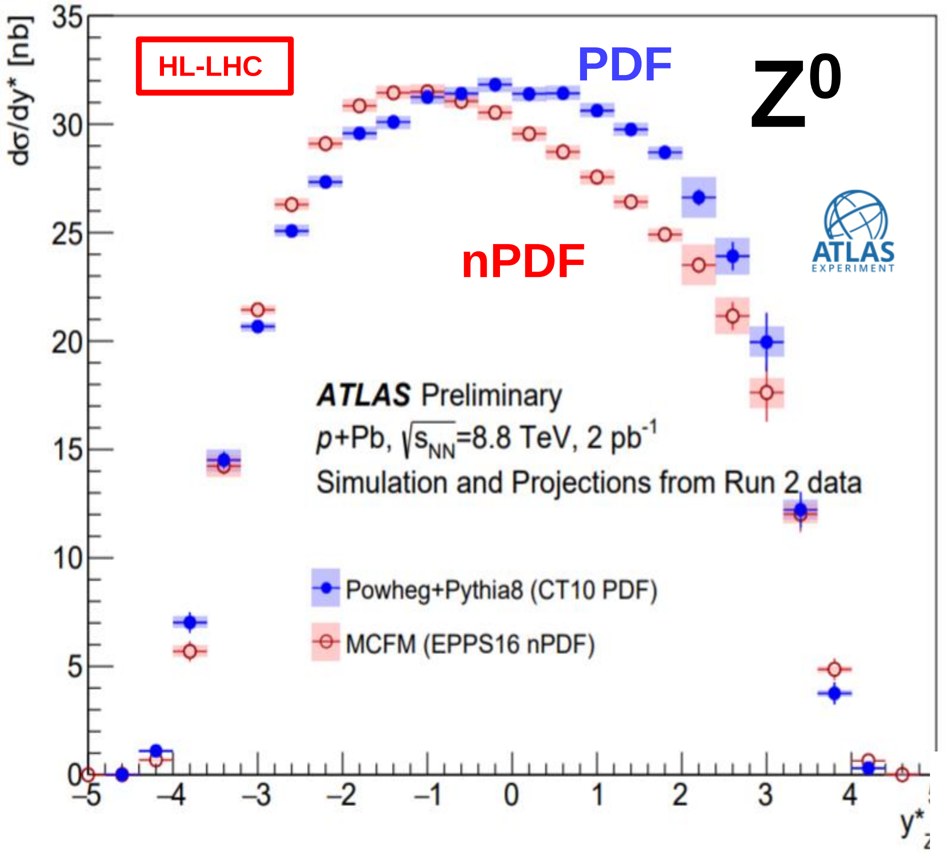
- **New constraints on the nPDF** from high precision electroweak bosons, UPC Quarkonia in PbPb, forward HF hadrons and dijets in pPb
- Improve the understanding of **initial energy density profile** and the **underlying dynamics of hydrodynamization**
- **Precise determination of medium properties** such as temperature, viscosity and transport coefficients through multiple probes
- Reveal **microscopic structure of QGP**
- Probe the **nature of X(3872)** with QGP and studies of exotic hadron in high multiplicity pp, pPb and PbPb UPC

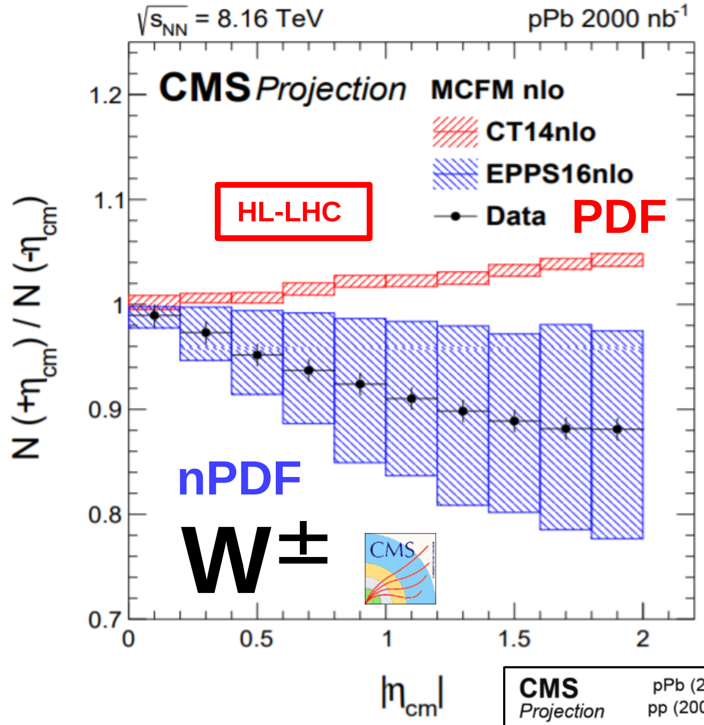


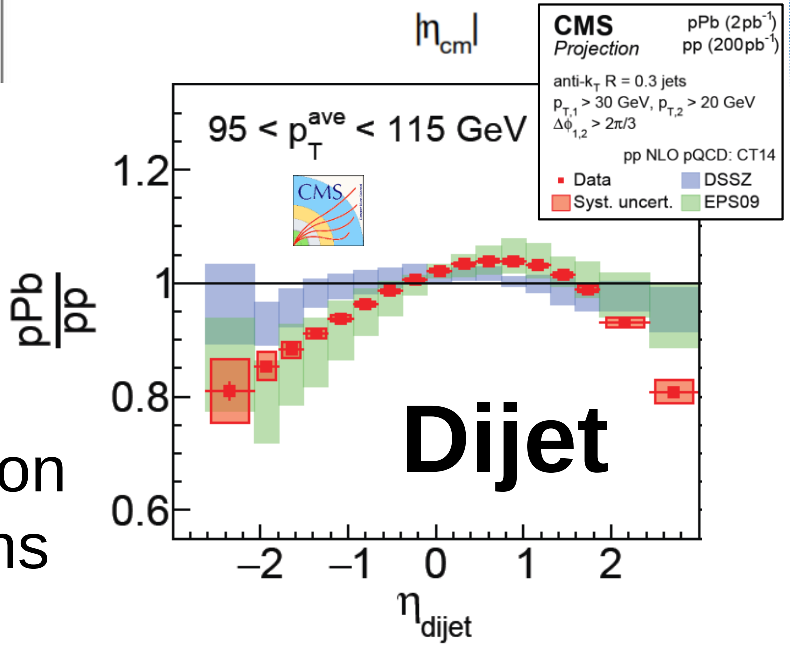


Backup Slides

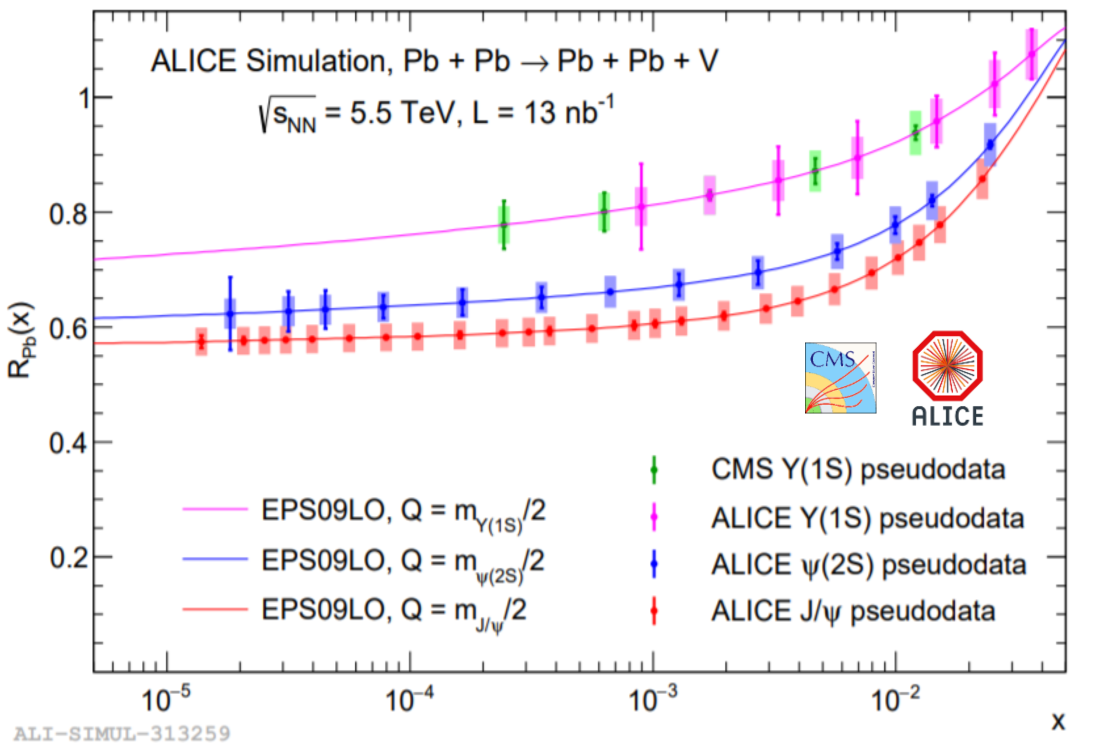
nPDF Constraint from pPb and UPC







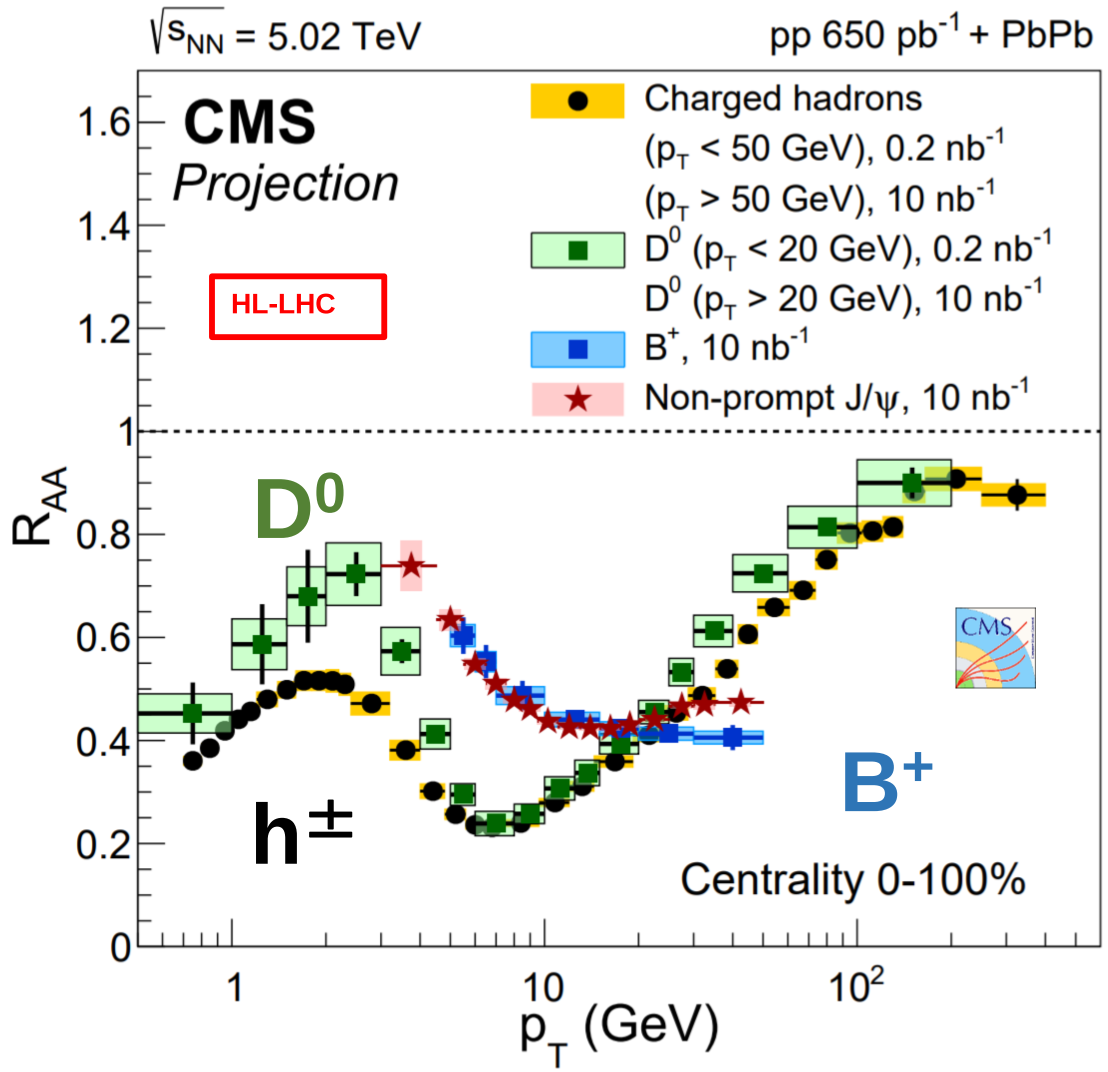
- Strong constraints on nPDF from electroweak boson, Drell-Yan and dijet cross-section measurements in pPb collisions



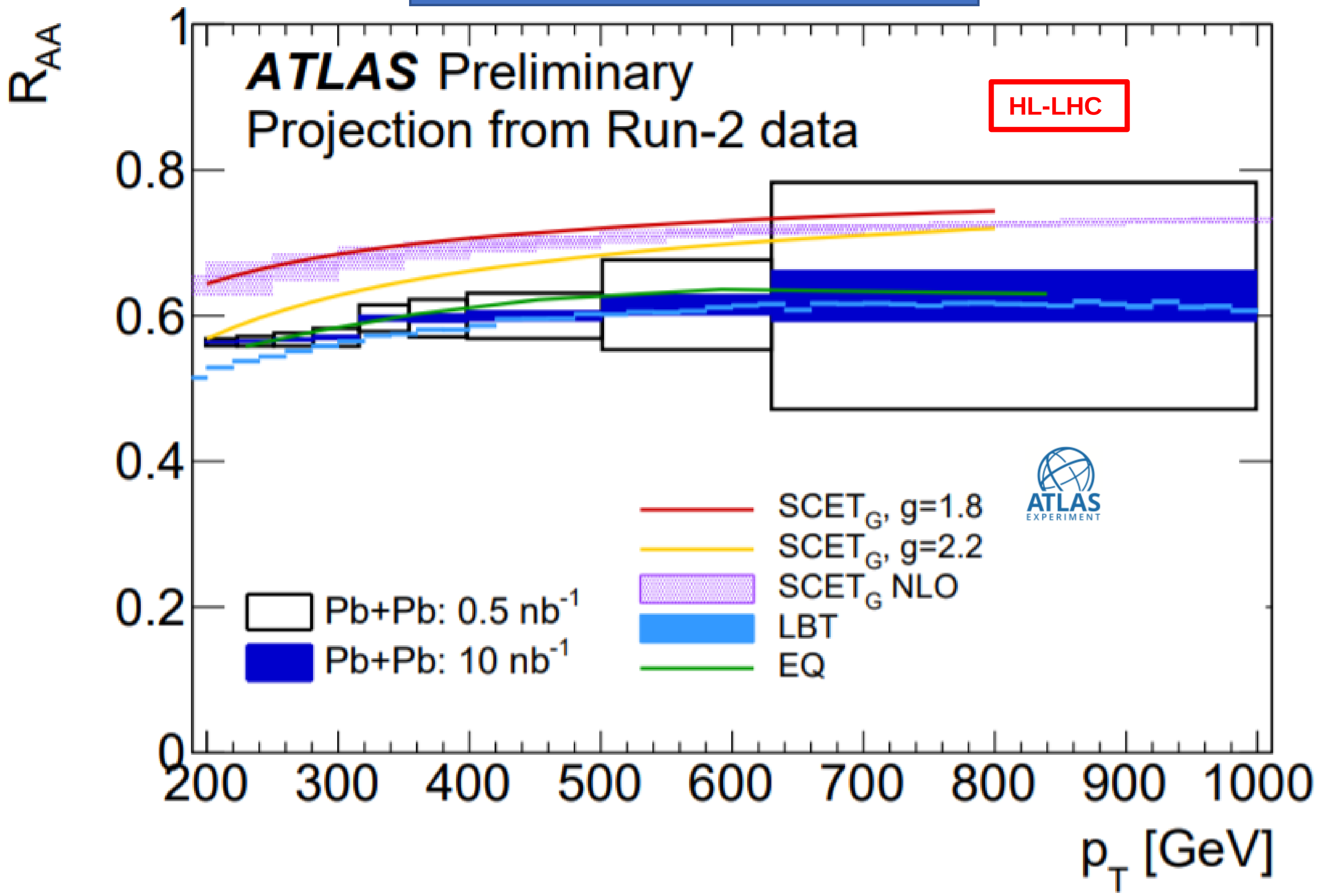
- Ultra-Peripheral PbPb Collisions (UPC): **γ+Pb** collisions!
- **Complementary to EIC efforts**
- HL-LHC data: Precise measurements of Υ(1S), J/ψ and ψ(2S) over a **very wide x range**, test **Q dependence** of nuclear modifications

Jet Quenching up to 1 TeV in PbPb

(Heavy Flavor)Hadron R_{AA}



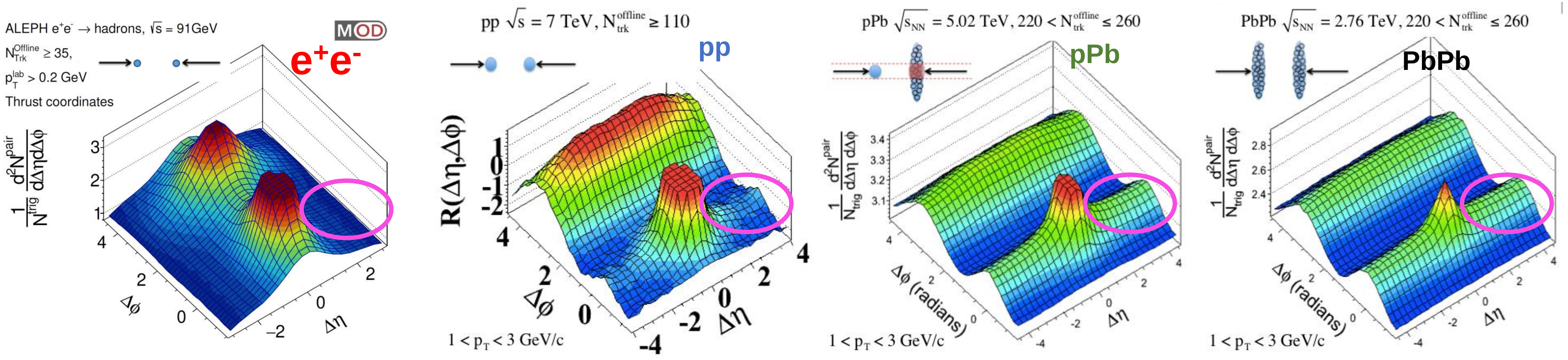
Jet R_{AA}



- Precise measurement of light and heavy flavor hadron R_{AA} up to **0.4** to **1 TeV**

- High p_T reach of charged hadrons and jet R_{AA} up to **~ 1 TeV**
- The excitement is that the quenched energy / medium response will be significant compared to UE energy density!

Small System



PRL 123 (2019) 21, 212002

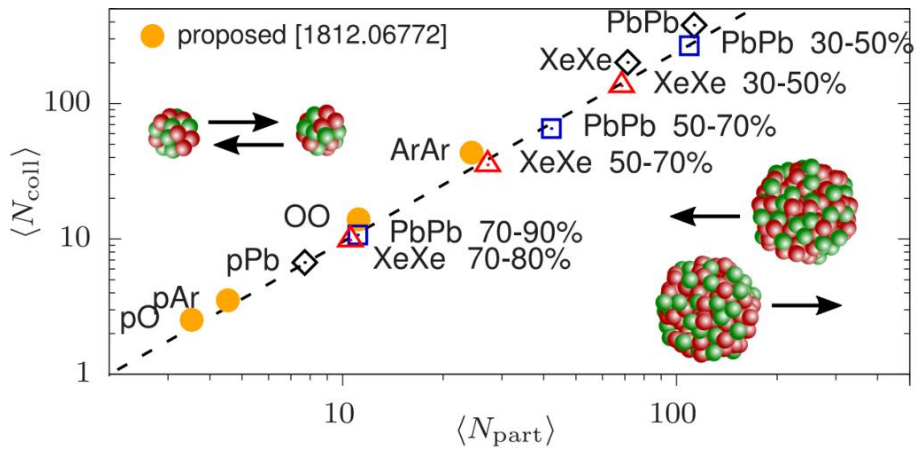
JHEP 09 (2010) 091

PLB 718 (2013) 795

- Flow-like phenomena in high multiplicity pp and pPb collisions, not yet observed in e^+e^- and ep
- Strangeness enhancement from ALICE
- OO: provide unique opportunity to smoothly connect pPb and PbPb

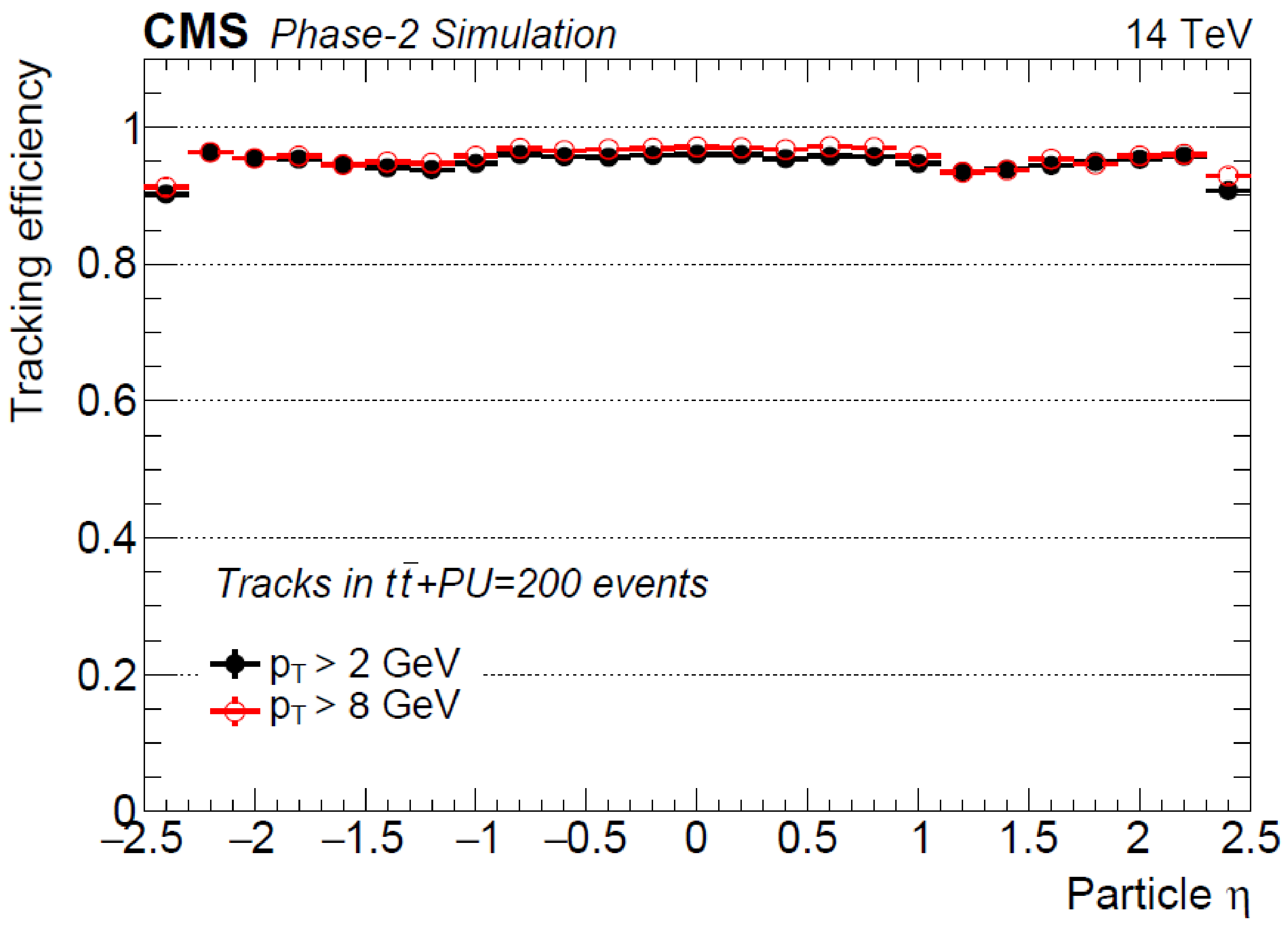
e+e-:
ALEPH LEP1: PRL 123 (2019) 21, 212002
Belle: PRL 128 (2022) 14, 142005
ep:
ZEUS I. Abt+ JHEP 04 (2020) 070

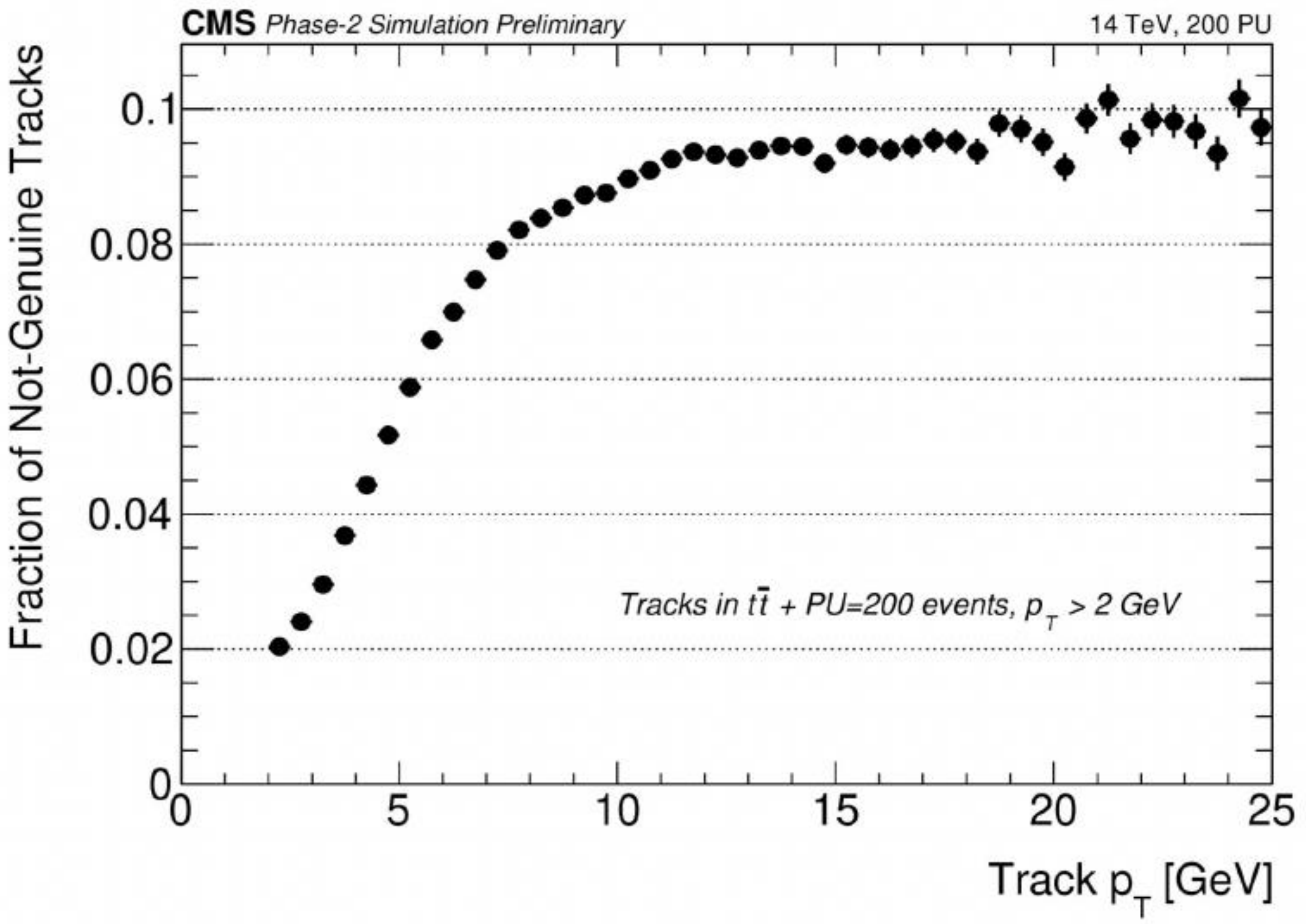
A. Huss et al, PRL 126 (2021) 19,192301



Phase 2 CMS L1 Track Trigger Performance

- Possibility to employ L1 track trigger





New access to Low p_T Charm and Beauty Hadrons with MTD

	2018 PbPb 1.7 nb^{-1} (Run 2)		Run 3 ($3nb^{-1}$)		**Run 4 MTD ($3nb^{-1}$)**		
Observables	p_T min (GeV)	|y| coverage	p_T min (GeV)	|y| coverage	**p_T min (GeV)**	**|y| coverage**	**MTD Gain**
D^0 R_{AA}	2	1	1	1	**0**	**3**	**Up to 2.4**
D_s R_{AA}	6	1	5	1	**2**	**3**	**>3**
Λ_c R_{AA}	6	1	5	1	**< 2**	**3**	**Up to 6**
B->D R_{AA}	2	2	2	2	**0**	**3**	**Up to 2.4**
B^+ ($D^0\pi$) R_{AA}	Not accessible		~15	1	**Close to 0**	**3**	**>3**
Total charm cross-section	Not accessible		Not accessible		**First measurement**		
D^0 v_2	0.5	1	0.5	1	**0**	**3**	**Up to 2.4**
D_s v_2	6		5		**2**	**3**	**>3**
B->D^0 v_2	~2		~2		**Close to 0**	**3**	**Up to 2.4**
Λ_c v_2	~6		~6		**2-3**	**3**	**Up to 6**
Photon-D^0	Not accessible		Proof of principle	1.2	**First measurement**	**3**	**Up to 2.4**
Jet-D^0	D^0 p_T > 4 GeV	2	D^0 p_T > 4 GeV	2	**D^0 p_T > 0 GeV**	**3**	**Up to 2.4**
$D^0\overline{D^0}$ p_T> 5 GeV	Proof of principle		First measurement		**Precise measurement**	**3**	**Up to 1.4**
$D^0\overline{D^0}$ p_T> 2 GeV	Not accessible		Not accessible		**First measurement**	**3**	**Up to 2**

* R_{AA}: nuclear modification factor * v_2: elliptic flow