CMS Experiment at the LHC, CERN

Overview of Experimental Results on Heavy Flavor Probes from LHC

Yen-Jie Lee

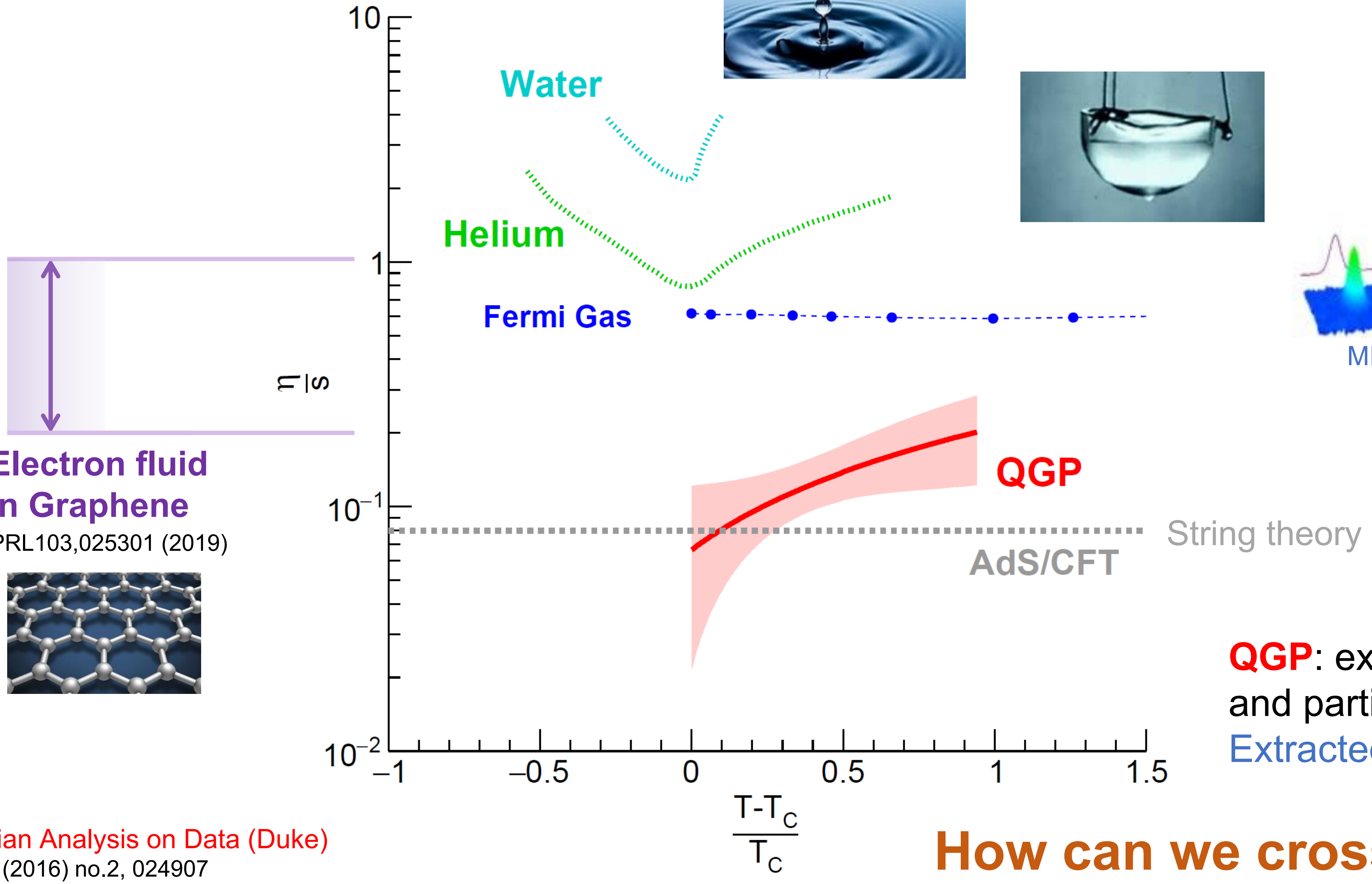
HEFTY Seminar (Online)

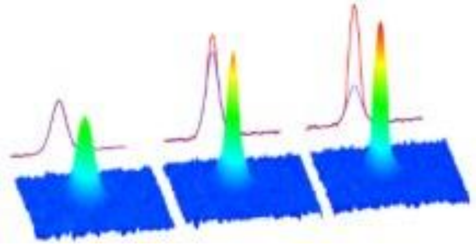
10 December 2025

MIT HIG group's work was supported by US DOE-NP

Soft Probes: Near Perfect Fluid

Specific Shear Viscosity





MIT cold atom group

Calculation from
Annals Phys.326:770-796,2011

QGP: extracted from flow correlation and particle spectra at low p_T

Extracted from hydrodynamics models

Bayesian Analysis on Data (Duke)
PRC94 (2016) no.2, 024907

How can we cross-check this result?

Open Questions

- What are the properties of QGP?
- How does the hydrodynamization happen and how QGP is created?
- How does hadronization happen in low and high parton density environment?

Goal: Answers with Hard Probes

- What are the properties of QGP?

  Extract **QGP** properties from **slow** (diffusion) and **fast** moving hard probes (energy loss / elastic scatterings)

- How does the hydrodynamization happen and how QGP is created?

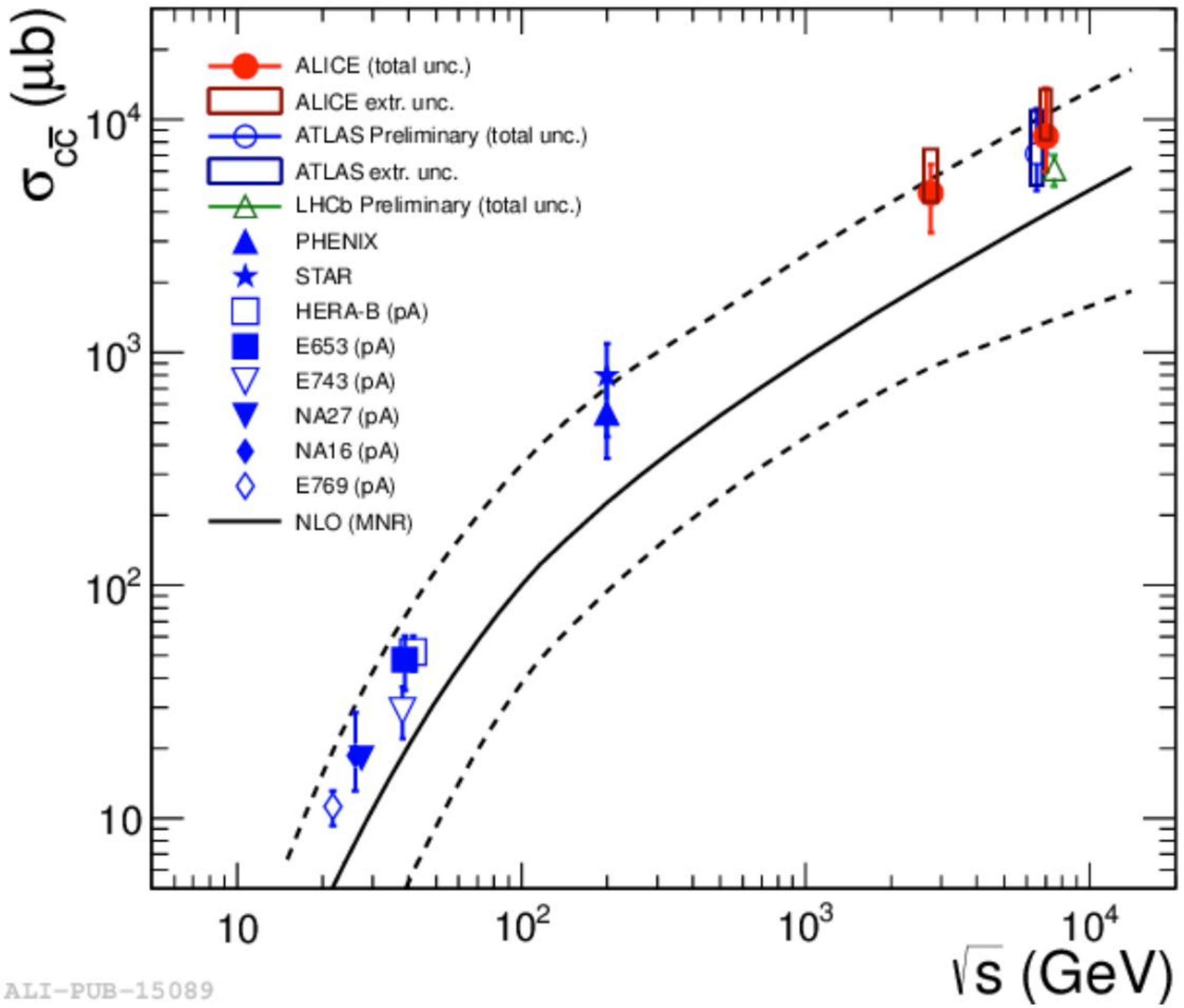
  Start from probes that are far from hydrodynamization
  Excite QGP **medium response** and see how it evolves

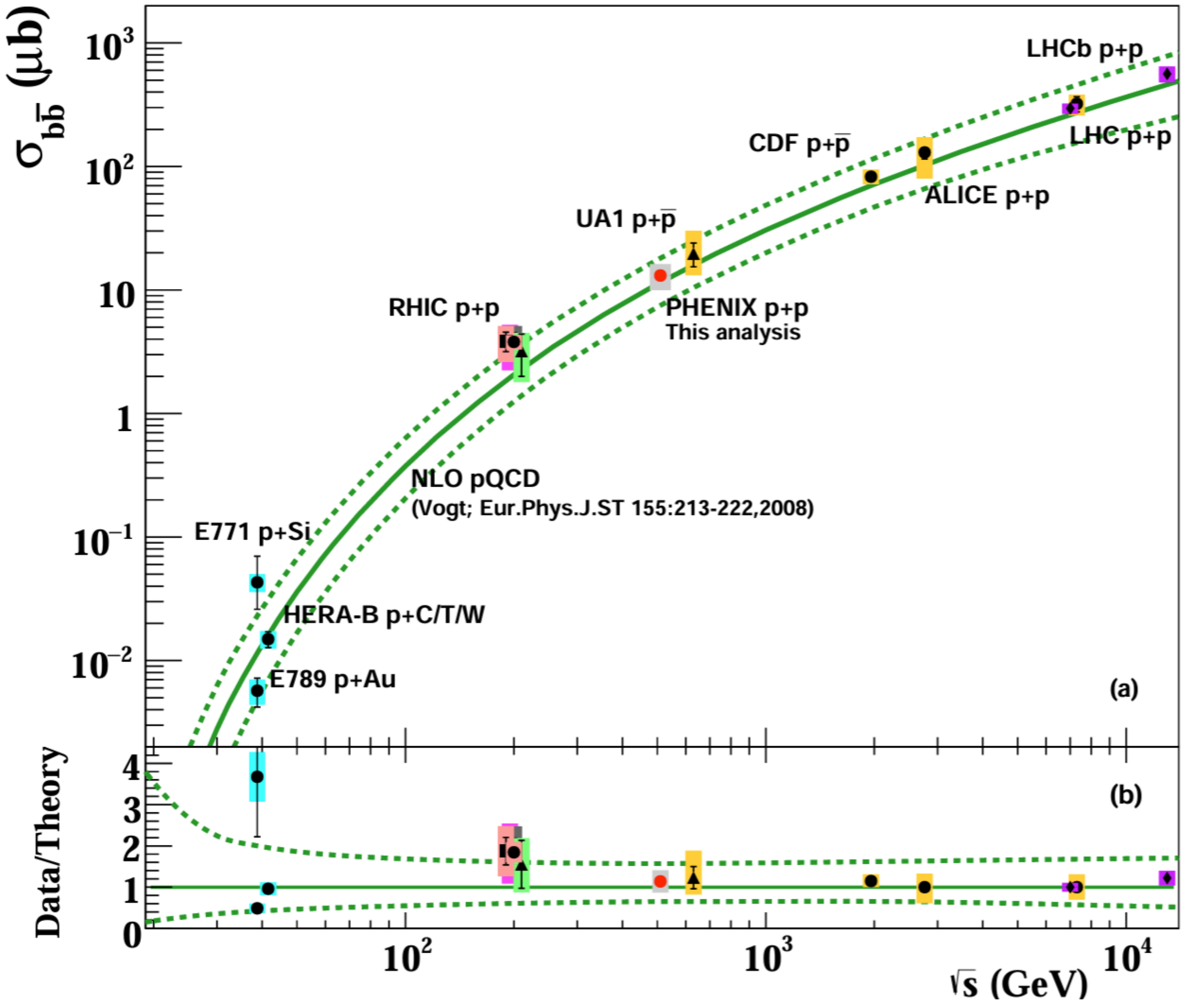
- How does hadronization happen in low and high parton density environment?

  Study how **heavy quarks** and **jets** hadronize

How many $c\bar{c}$ and $b\bar{b}$ are produced in 0-5% A+A?

Estimation with pp and pA total cross-section





~ 15 pairs of $c\bar{c}$ in 0-5% AuAu at 0.2 TeV

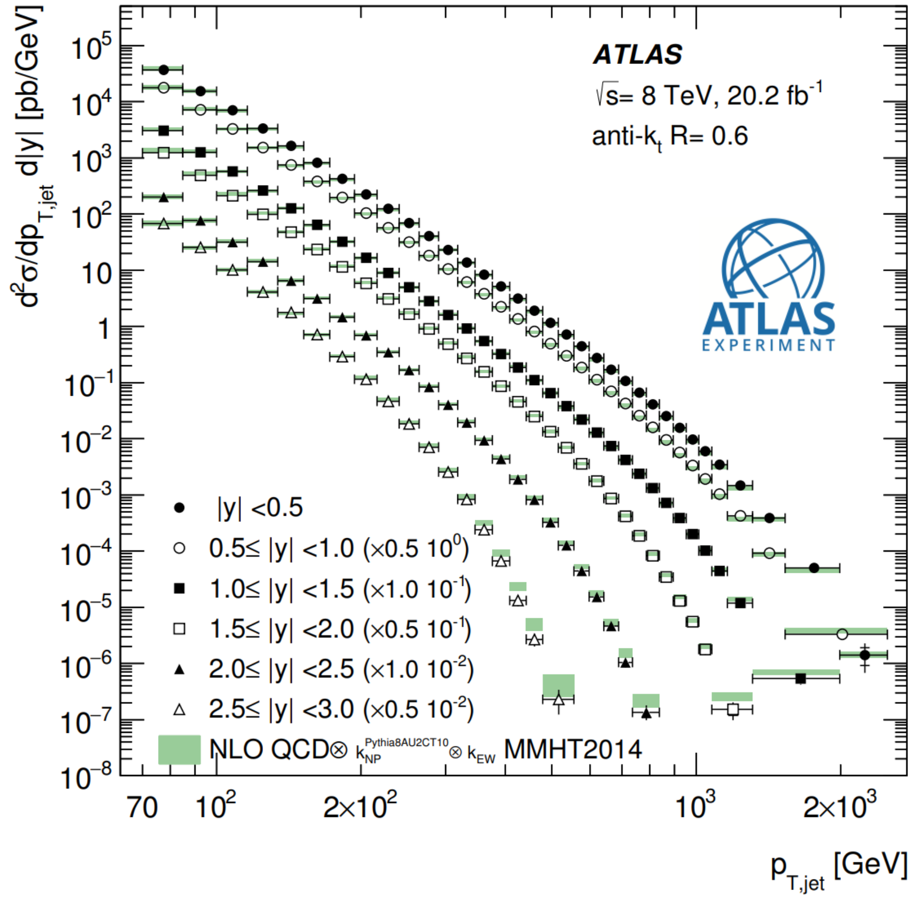
~ 210 pairs of $c\bar{c}$ in 0-5% PbPb at 5 TeV

~ 0.1 pairs of $b\bar{b}$ in 0-5% AuAu at 0.2 TeV

~ 6 pairs of $b\bar{b}$ in central PbPb at 5 TeV

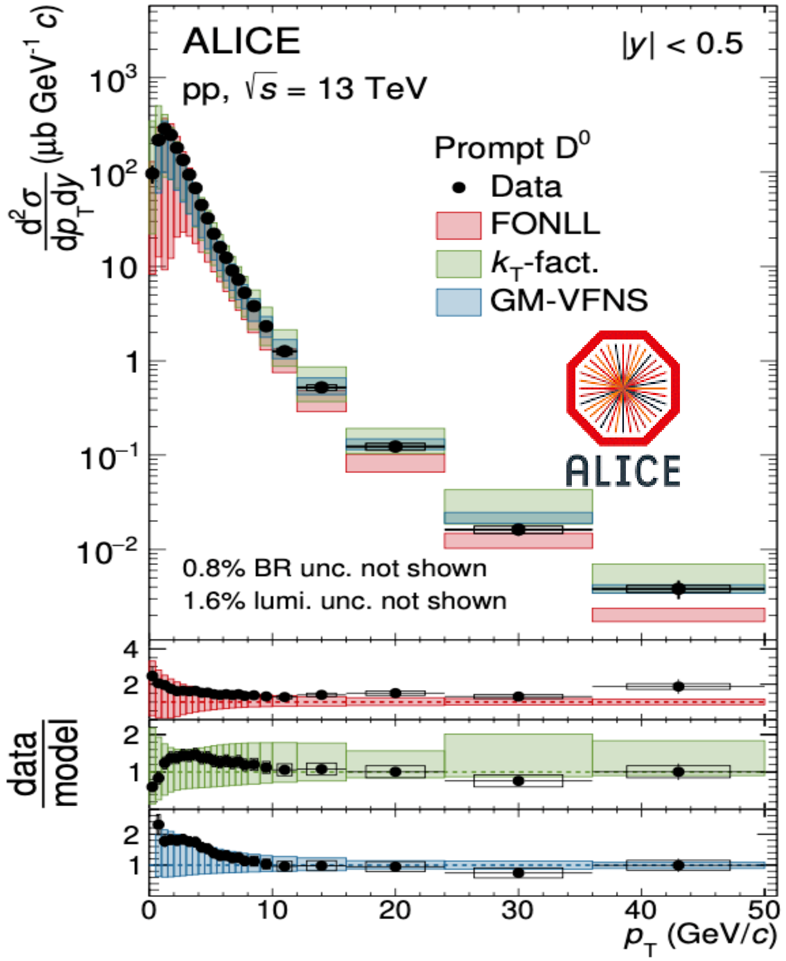
Jet and Heavy Flavor Meson Production in pp

Jet

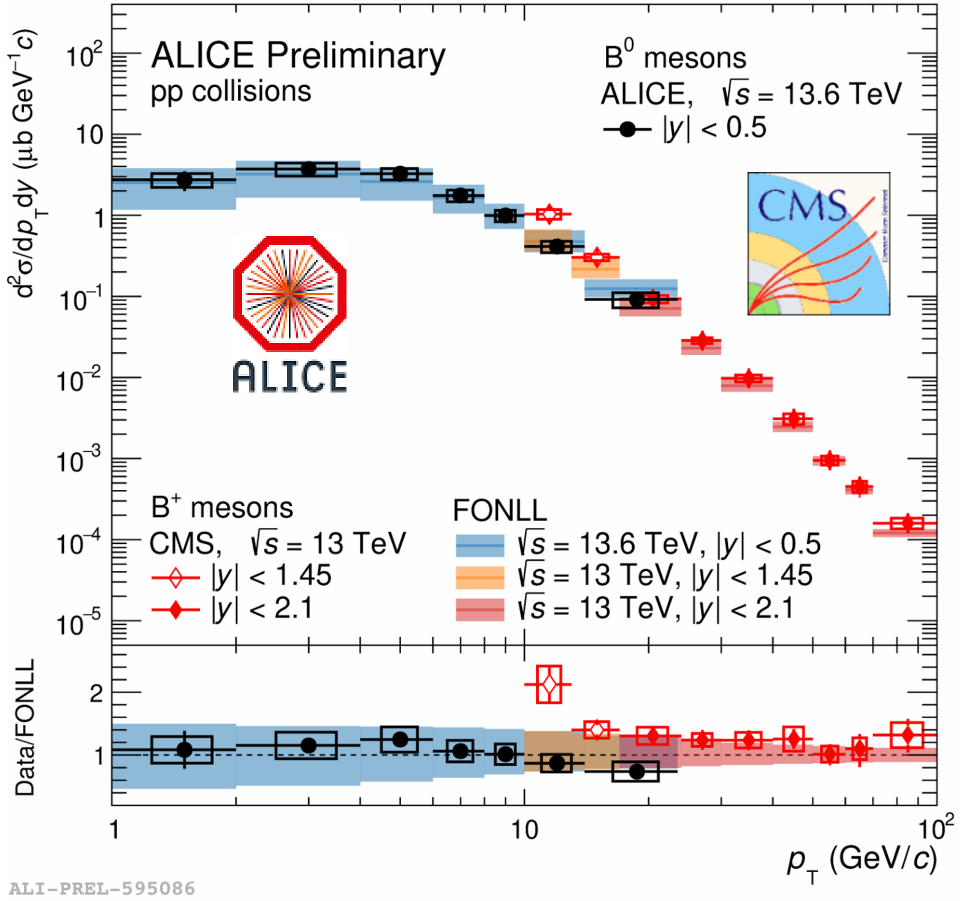


JHEP 09 (2017) 020

D^0



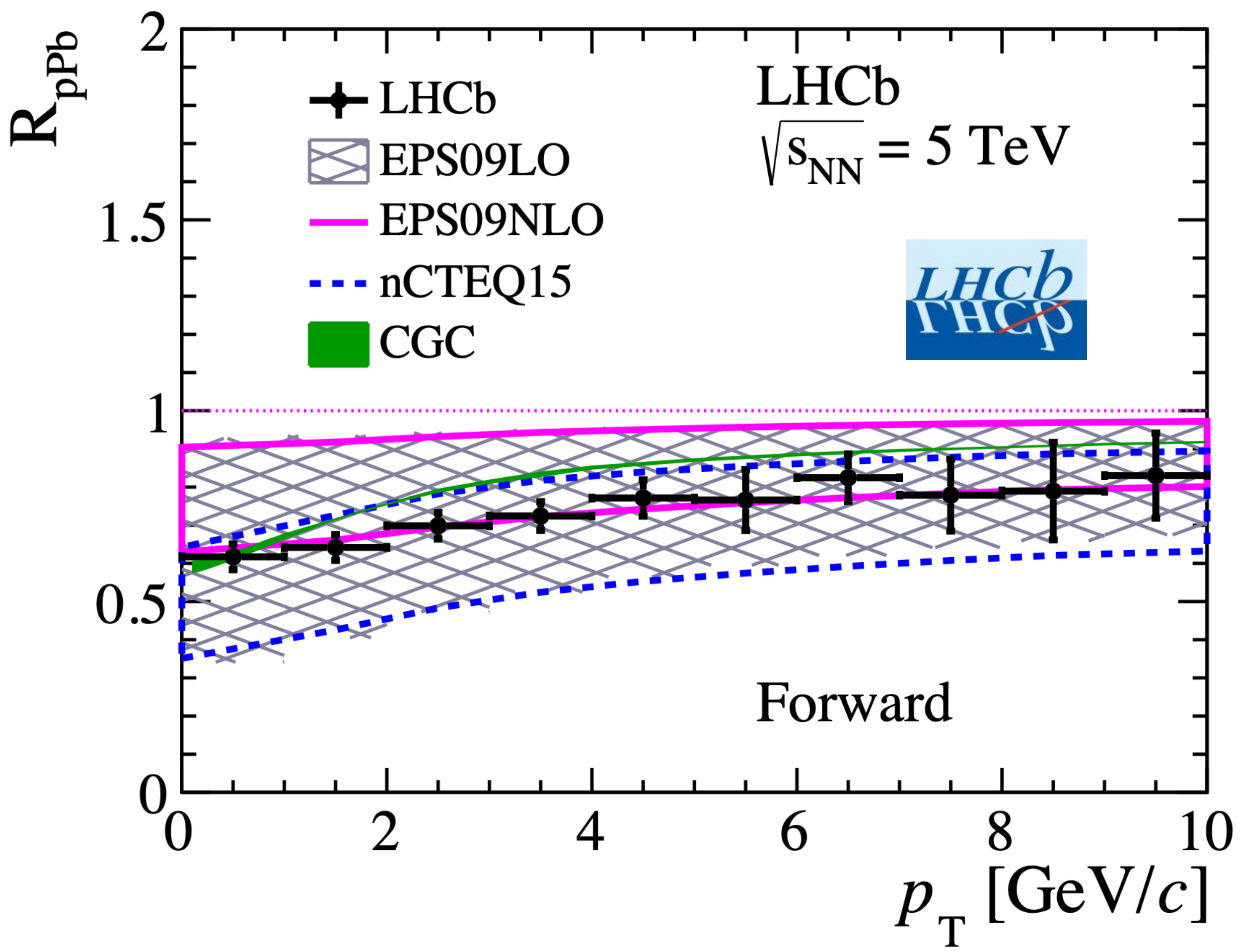
B^+



Jets and heavy flavor meson p_T spectra can be described by pQCD calculations

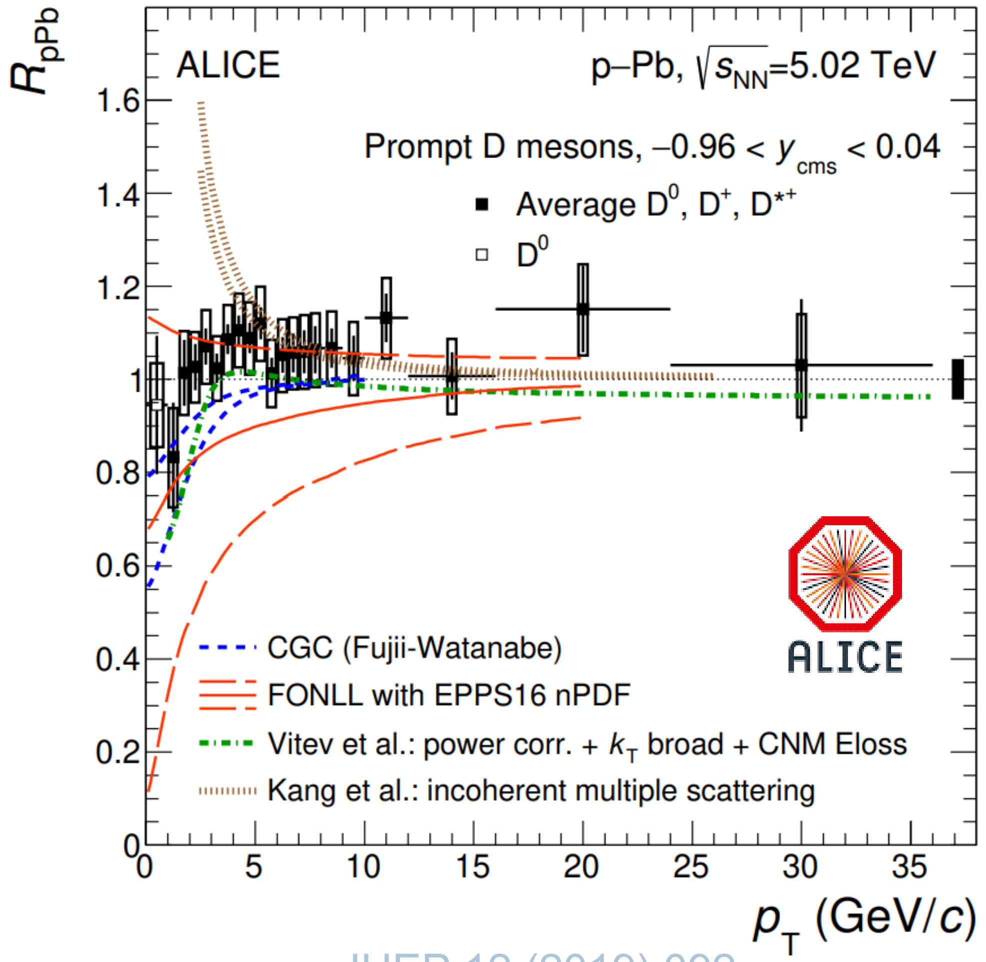
Initial Production Nuclear PDF with D^0 R_{pPb}

Forward D^0 R_{pPb}



[JHEP 10 (2017) 090]

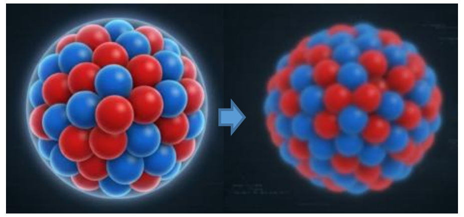
Midrapidity D R_{pPb}



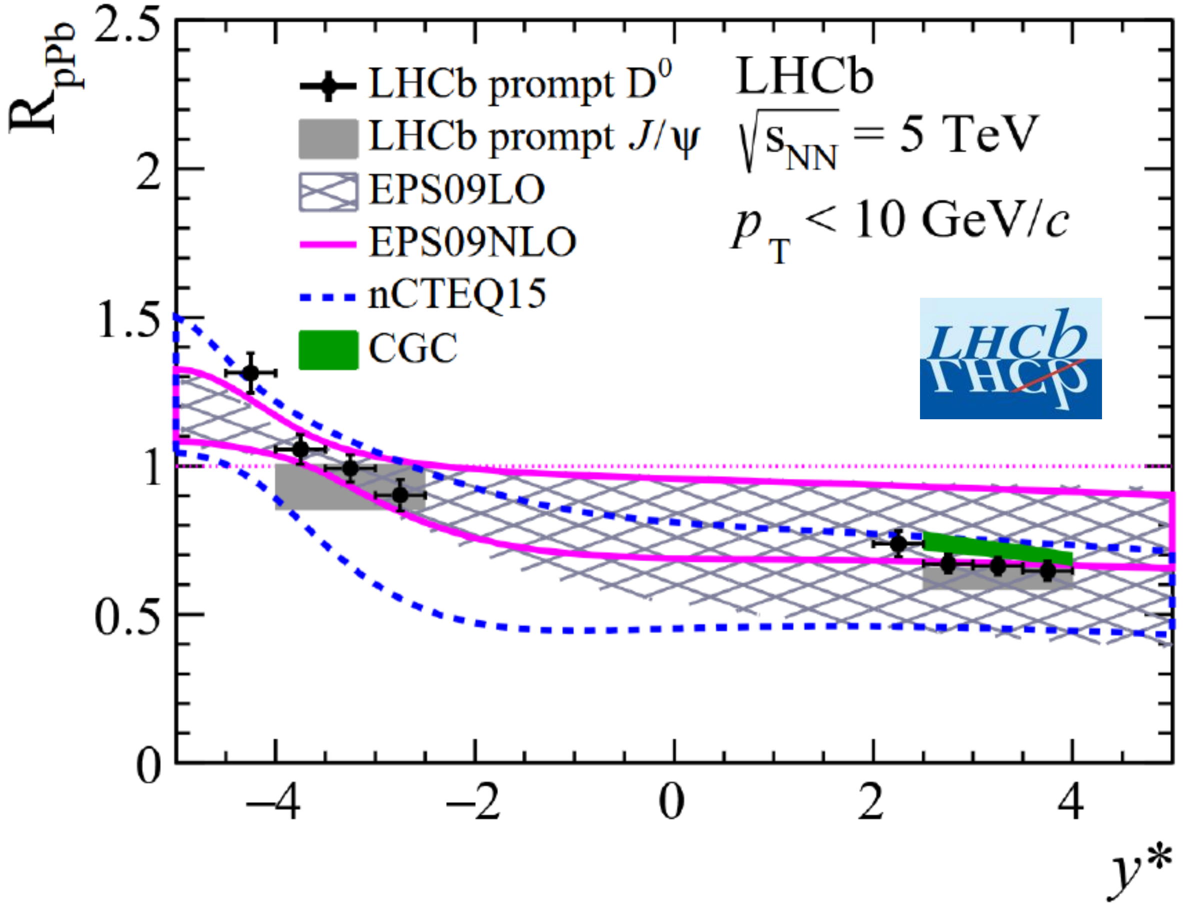
JHEP 12 (2019) 092

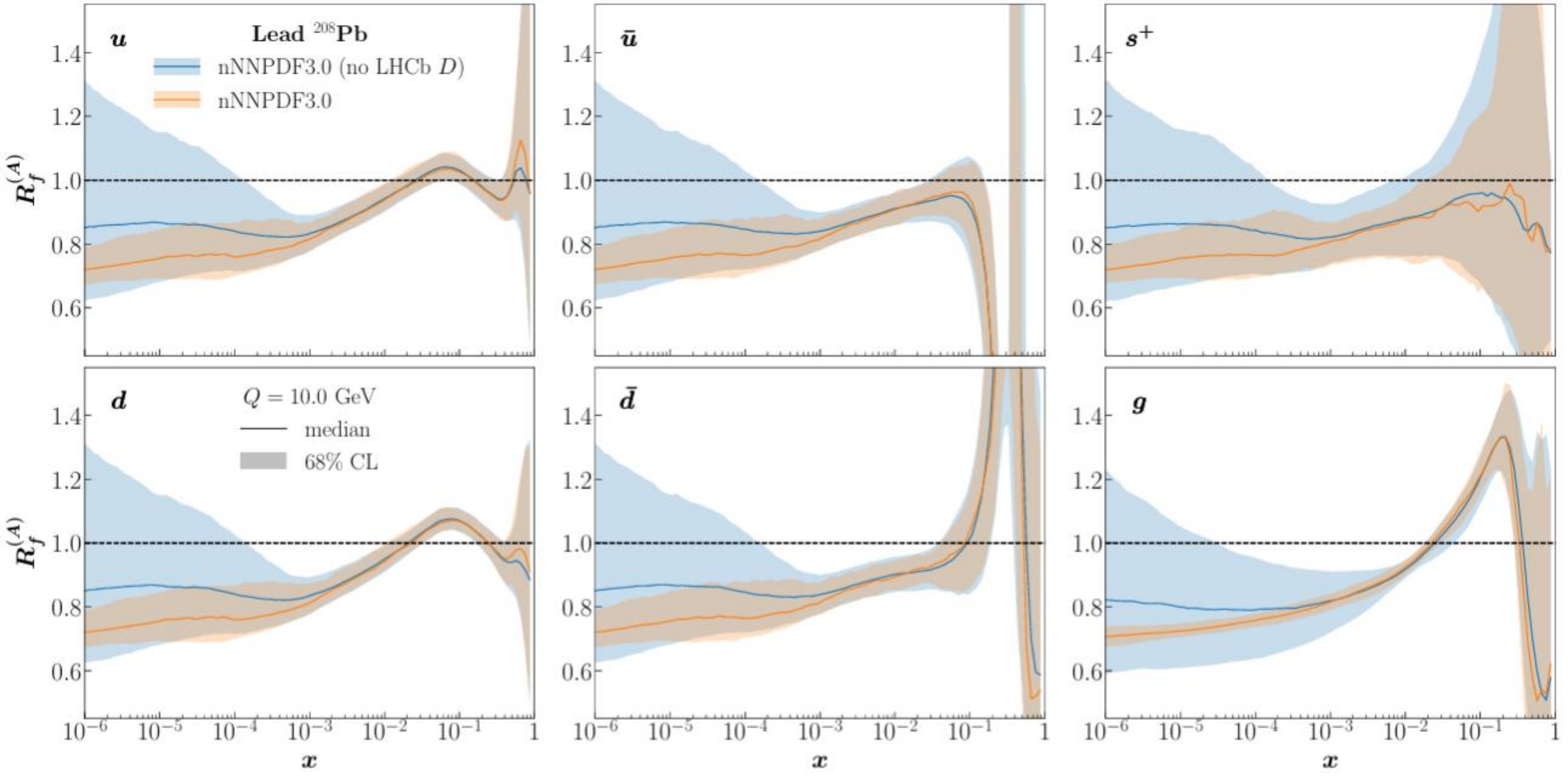
Significant suppression of D^0 in the forward region
Larger suppression at low D^0 p_T from LHCb

Small (<2%) or 0negligible suppression of prompt D in the mid-rapidity



Initial Production Nuclear PDF with D^0 R_{pPb}

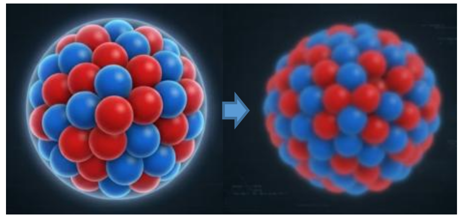




D^0 significantly suppressed in forward rapidity in pPb, sensitive to **low x parton from Pb**

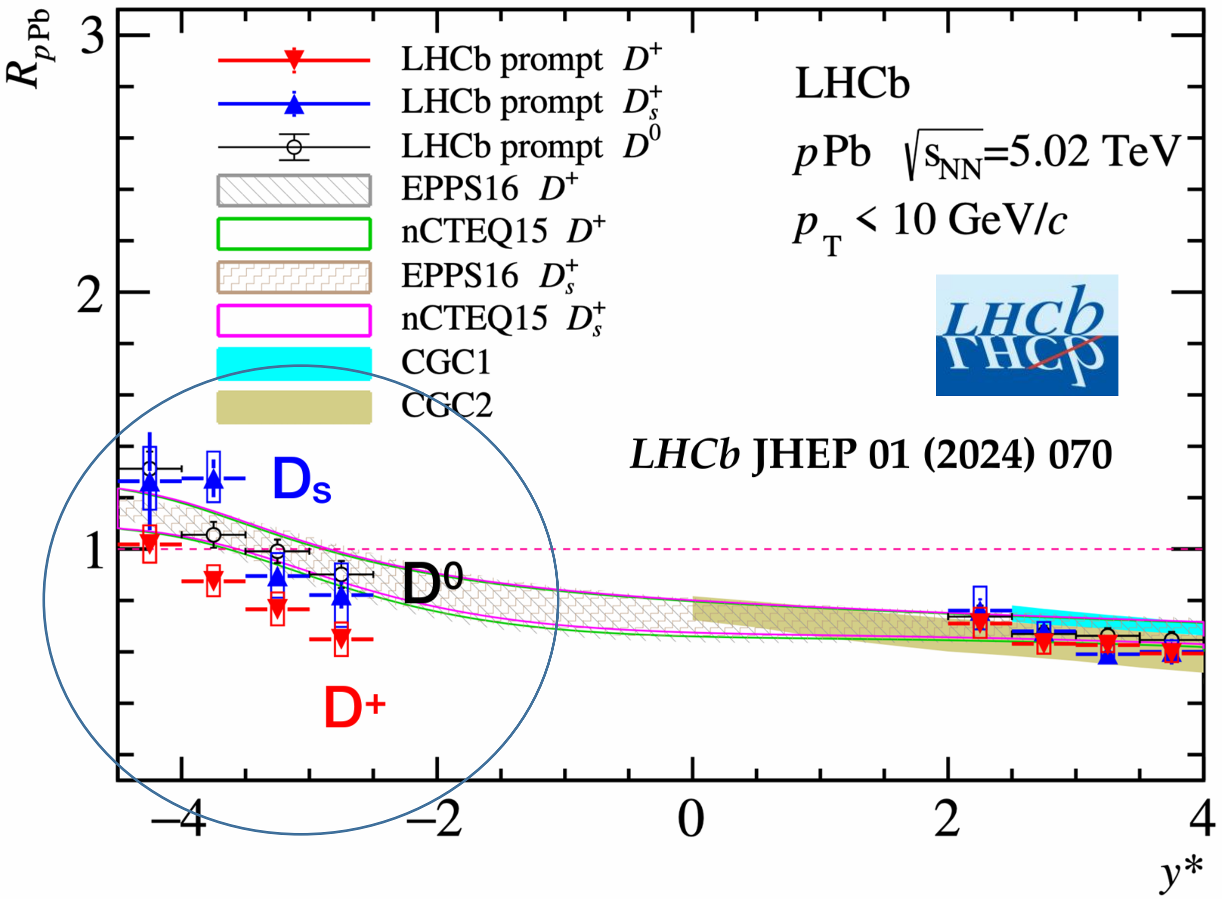
- Can be described by **Nuclear PDF**
- Nucleons in ions have different PDF from free protons

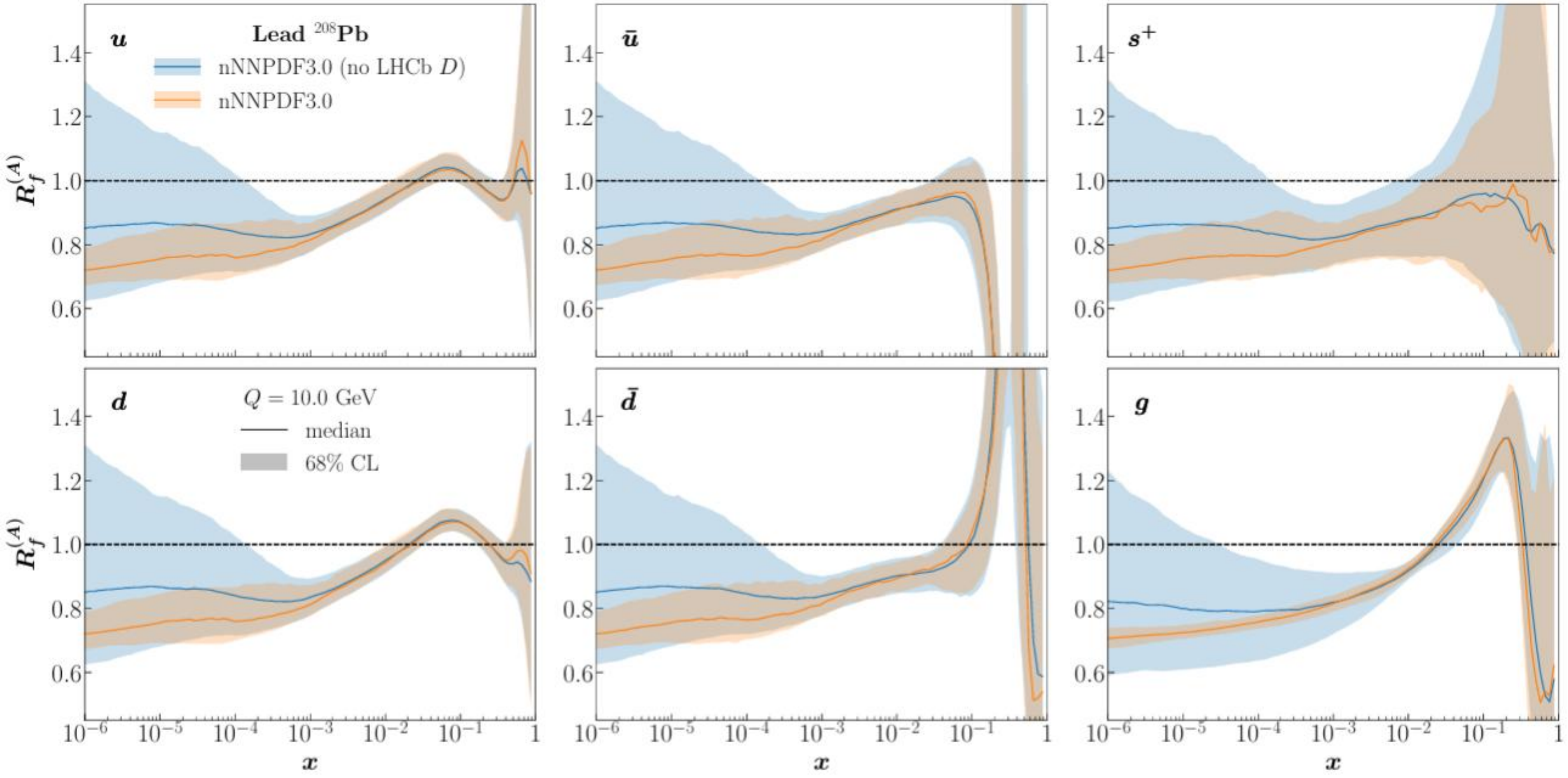
Strong constraints on gluon PDF at **low x** from **LHCb D^0** and CMS dijet at intermediate to high x in pPb collisions in NNPDF3.0 (shown), EPPS21 and nCTEQ25



Low x gluons are strongly suppressed in heavy ion!

Initial Production Nuclear PDF with D^0 R_{pPb}





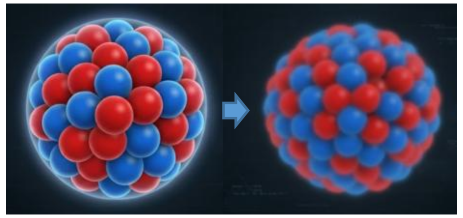
Significant **hadronization effect** may present in the experimental data

Strong constraints on gluon PDF at **low x** from **LHCb D^0** and CMS dijet at intermediate to high x in pPb collisions in NNPDF3.0 (shown), EPPS21 and nCTEQ25

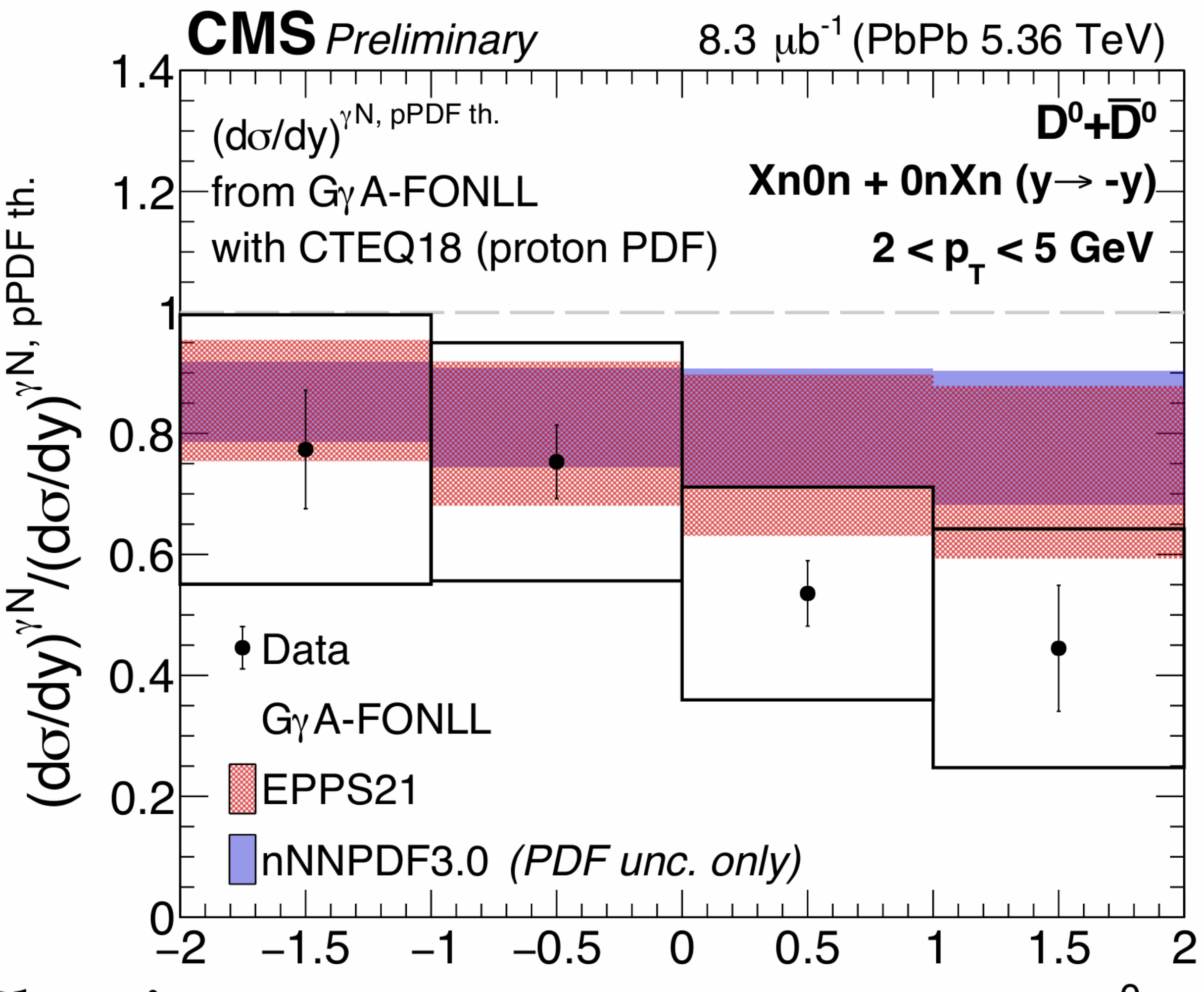
Backward region R_{pPb}: (**high x** region)

$$D_s \geq D^0 \geq D^+$$

nPDF analyzers needs to proceed with caution!



Photonuclear D^0 Production in PbPb UPC

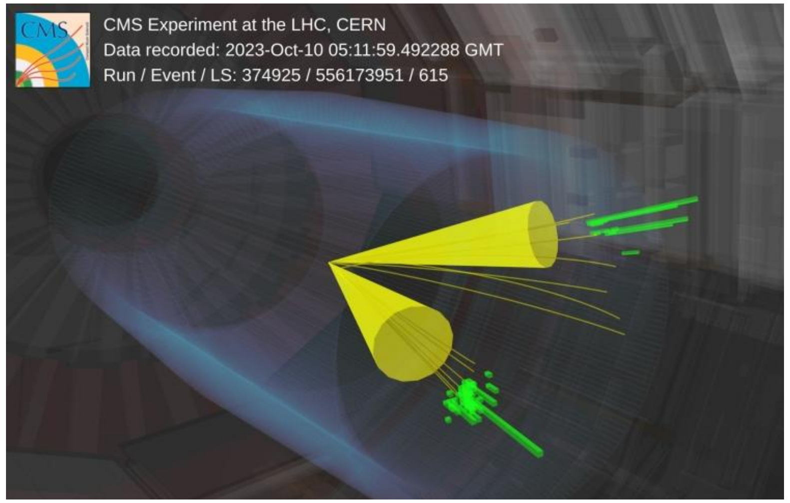


Pb-going **γ-going**

large-x small-x

- First photonuclear production of D° in PbPb UPCs
- Large suppression compared to pQCD calculations with no nuclear PDF effect:
  - $G_{\gamma A}$-FONLL[1] with CTEQ18 + 0nXn EMD
- Sensitive to gluon nPDF to small x
- **Negligible hadronization effects** expected in the vacuum like UPC environment

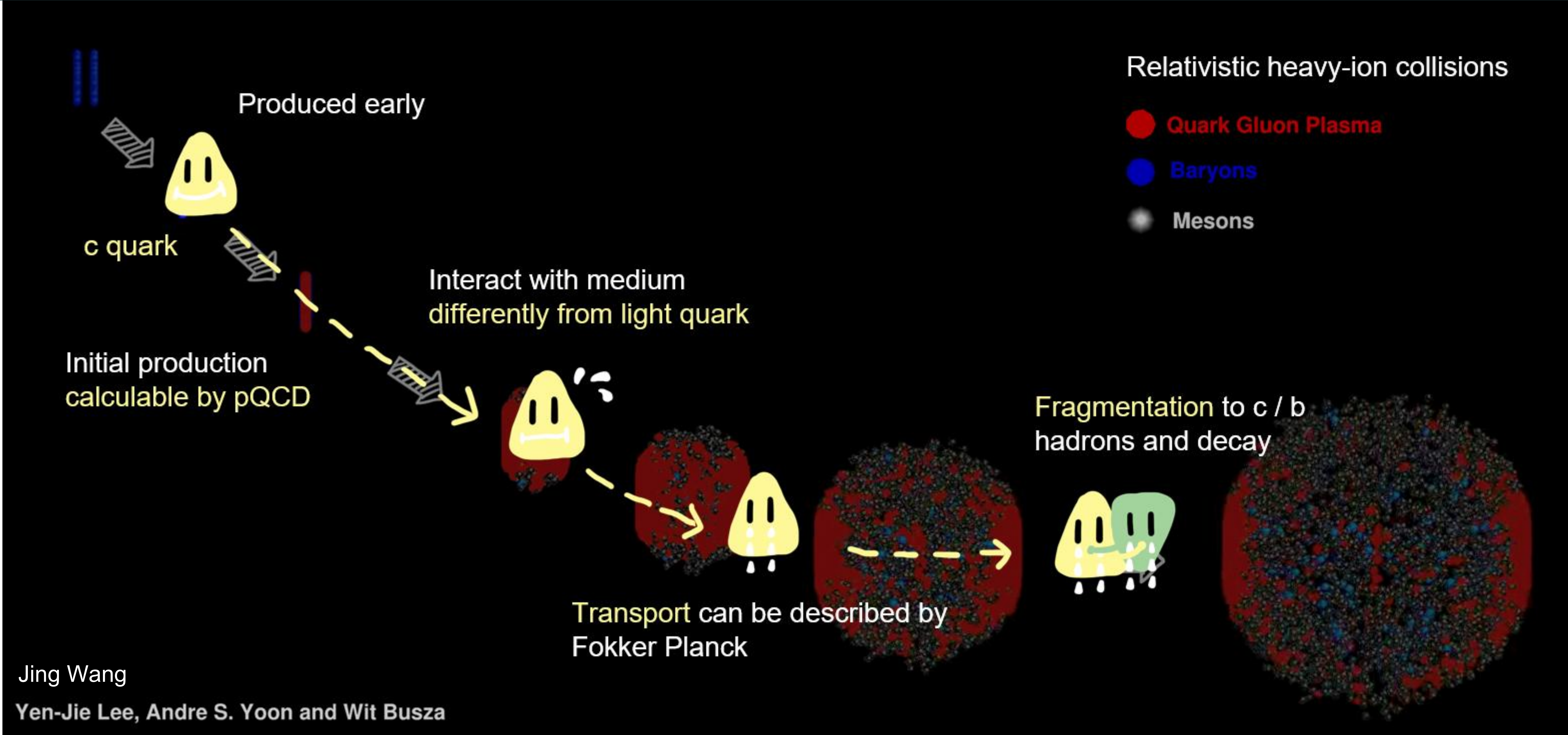
→ **Opens a large program of open heavy flavors in UPC at LHC**



CMS-PAS-HIN-25-002

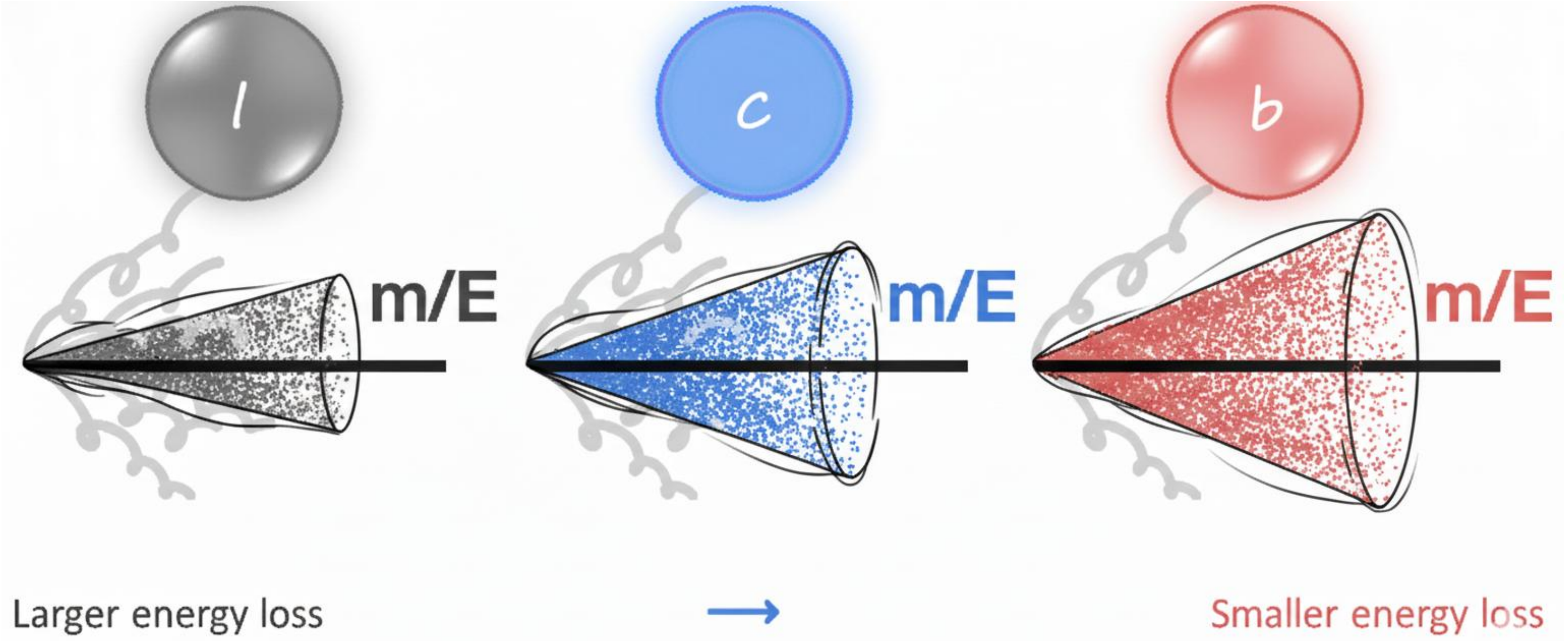
[1] A. M. Stasto, G.M. Innocenti, M. Cacciari paper in preparation

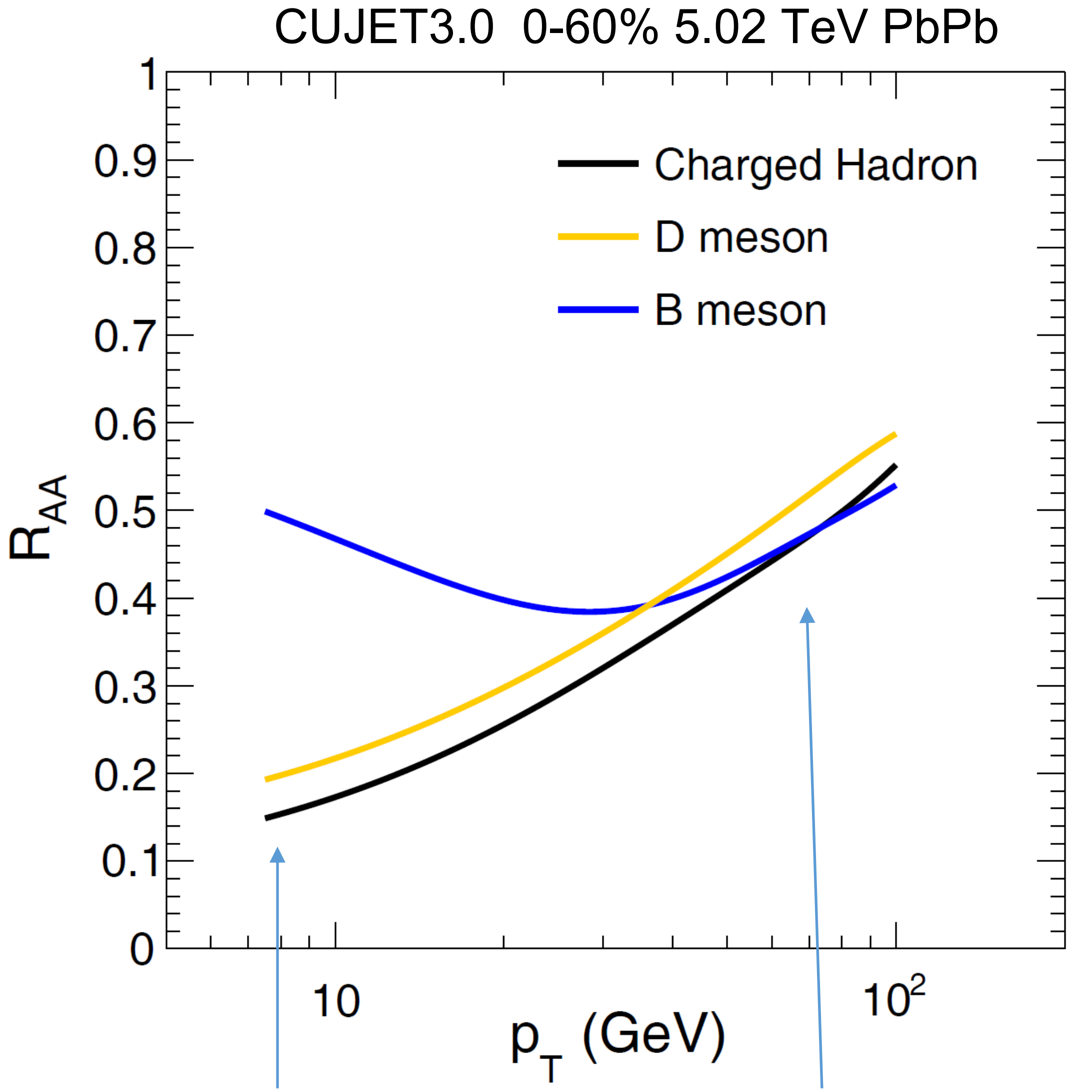
Life of a Heavy Quark in HIC



Quark Mass Dependence of the Hadron Suppression

Radiation is suppressed inside θ < m/E

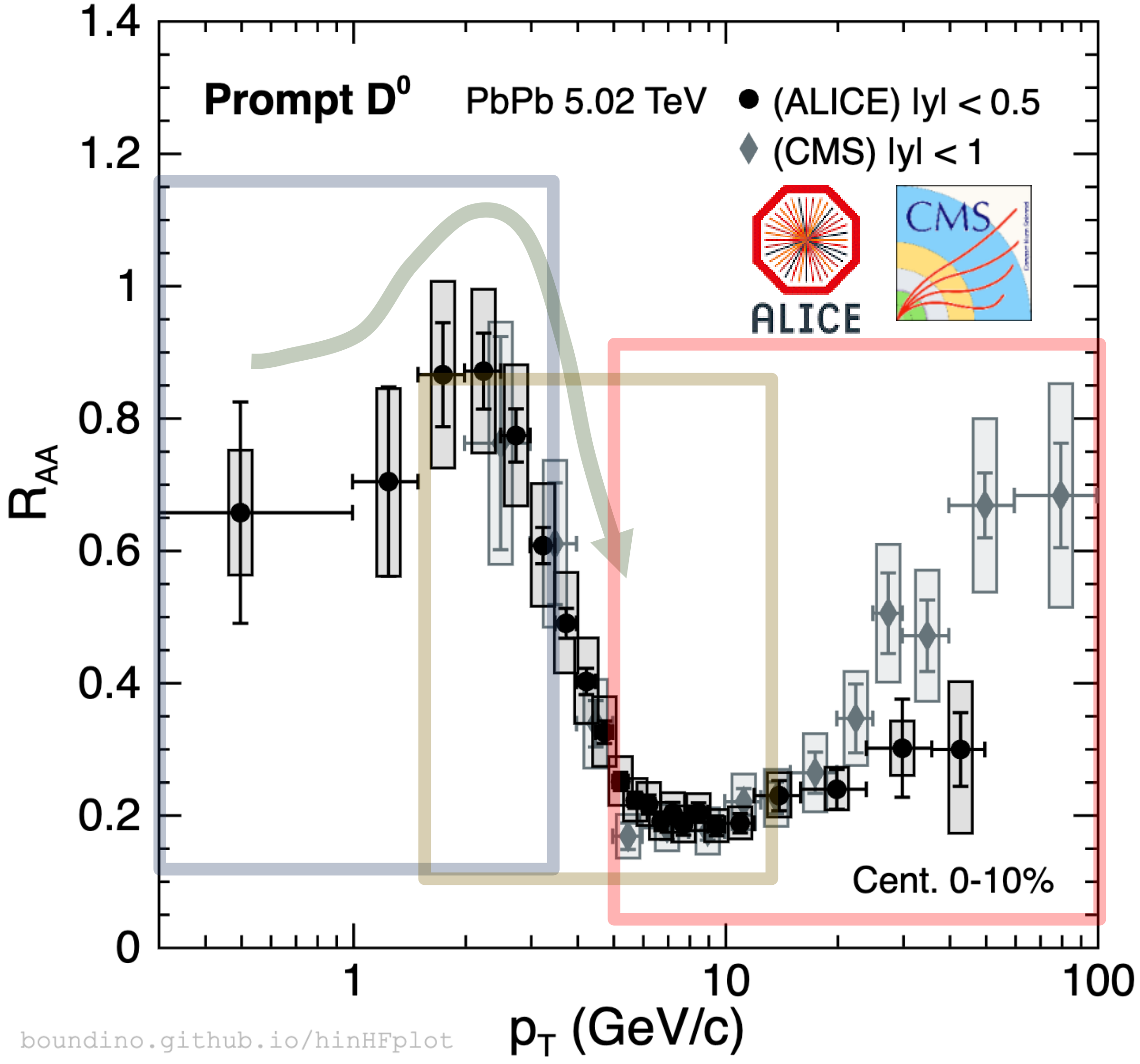




Mass effect
(Dead cone)

Dead cone
goes away

D^0 R_{AA} Understanding the Shape



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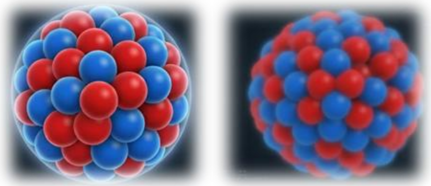
Good agreement between experiments at low D^0 p_T,
Some difference at high D^0 p_T

Multiple effects at play:

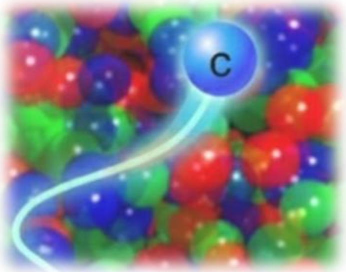
nPDF shadowing:

- Suppression at low p_T



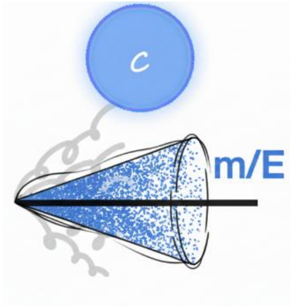
Collective flow + hadronization:

- Medium pushes very low-p_T charm quarks to higher p_T
- Receive momentum from light quark, creating a "flow bump"



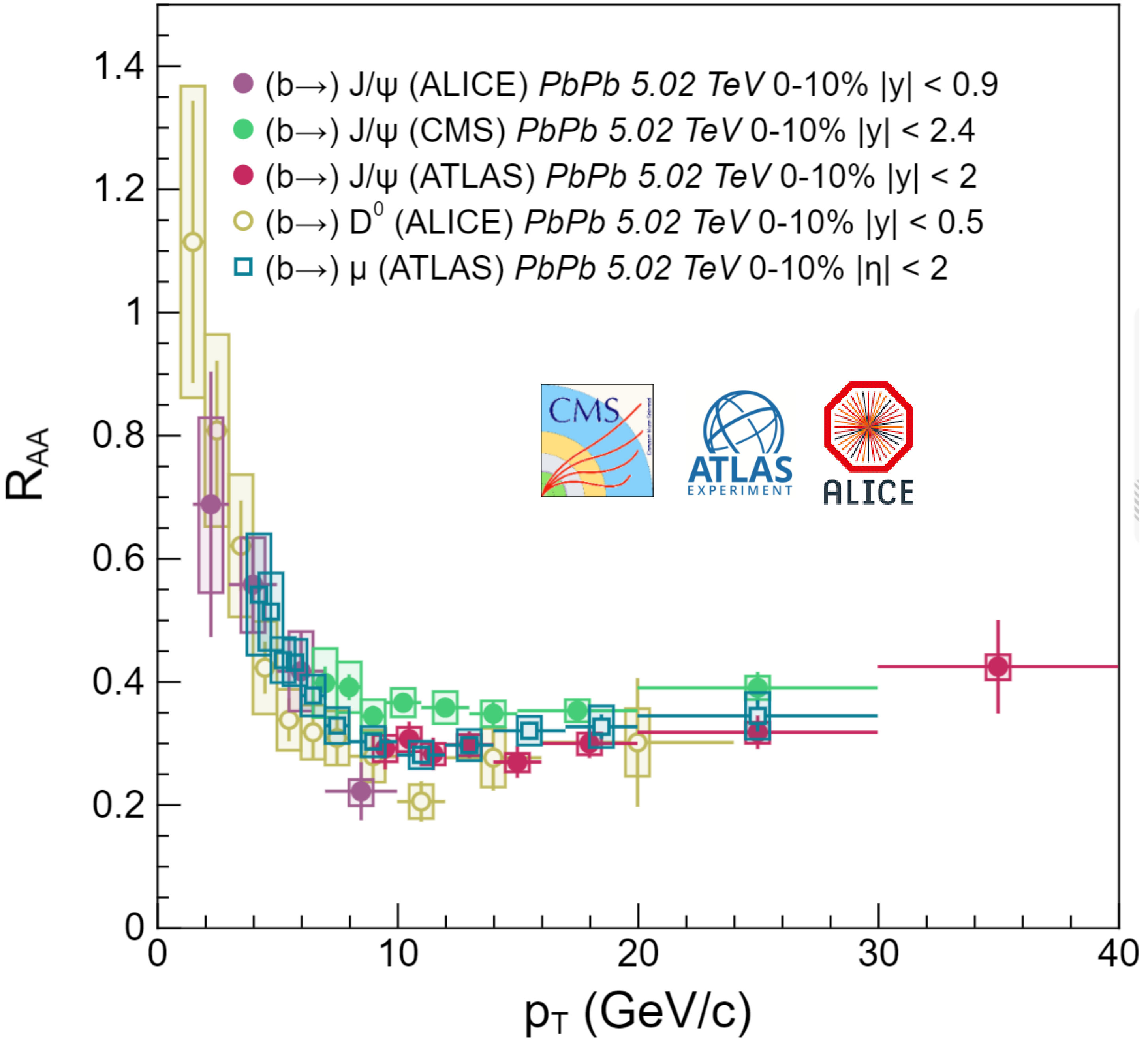
Jet quenching:

- Collisional (in the intermediate p_T) and radiative energy loss
- Sensitive to p_T shape before modification (lower slope at high p_T)



Beauty R_{AA} in 0-10% PbPb at 5 TeV

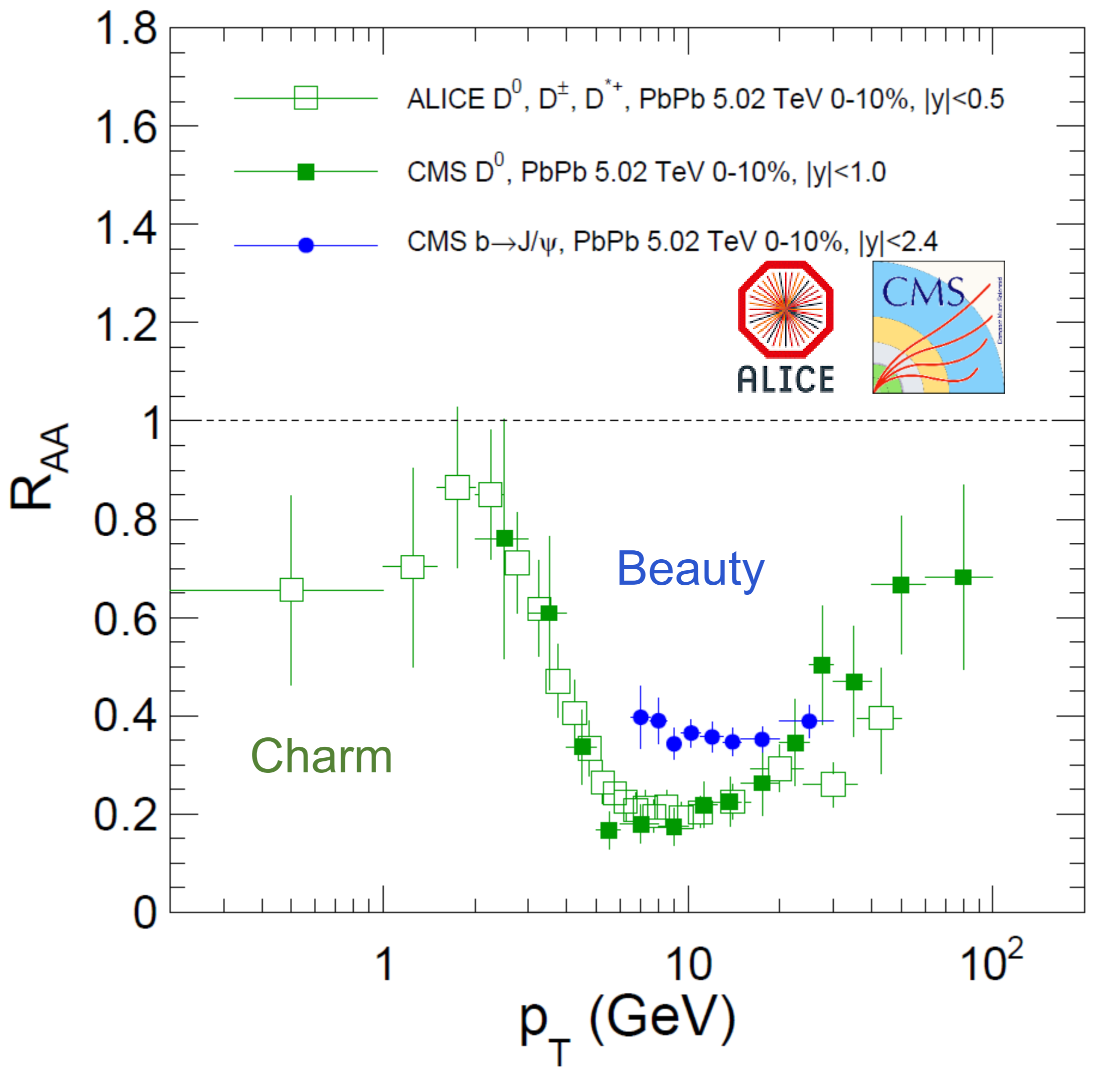
- Precise measurement of beauty suppression from **non-prompt J/ψ**, **D⁰** and **μ** from b decay in **0-10% PbPb**
- R_{AA} results are close to each other at high p_T (although J/ψ, D^0 and μ carry different fraction of beauty momentum)
- Some difference between non-prompt J/ψ from **ATLAS** and **CMS**, to be followed up with Run 3+4 data

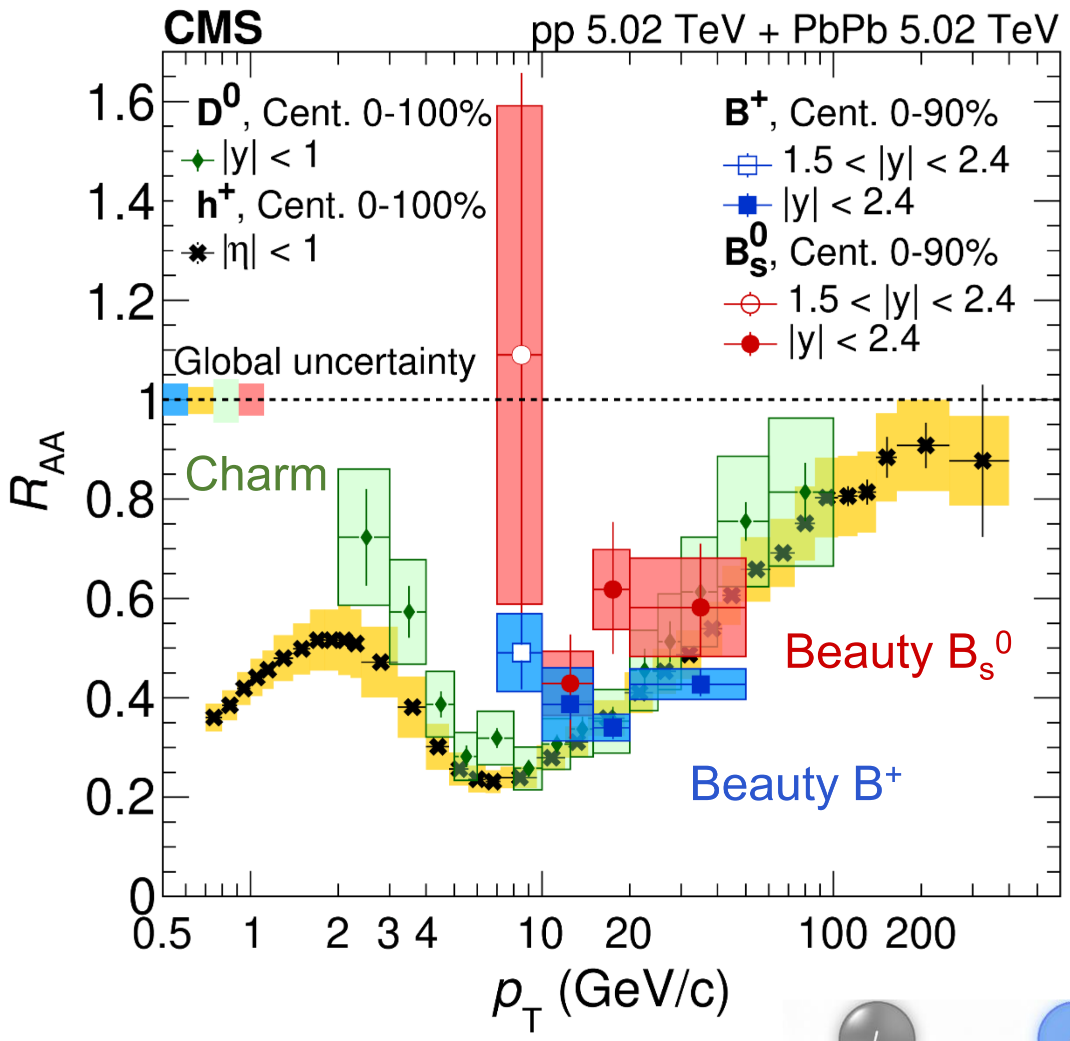


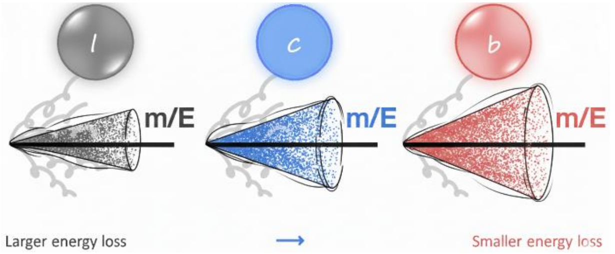
NP J/ψ ALICE Preliminary
NP J/ψ CMS EPJC 78 (2018) 509
NP D ALICE arXiv 2202.00815

NP μ ATLAS PLB 829 (2022) 137077
NP J/ψ ATLAS EPJC 78 (2018) 762

Beauty vs. Charm R_{AA}

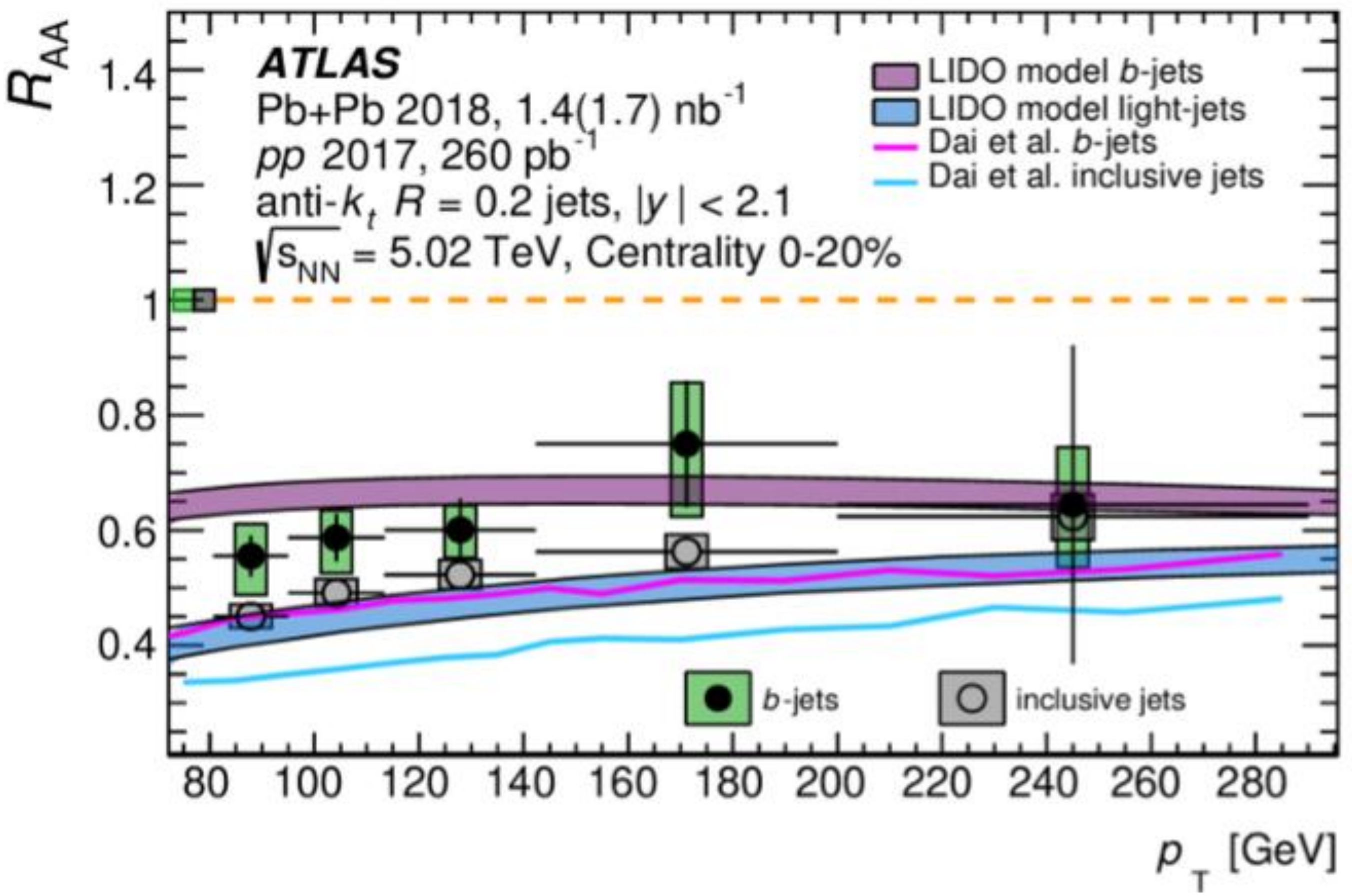


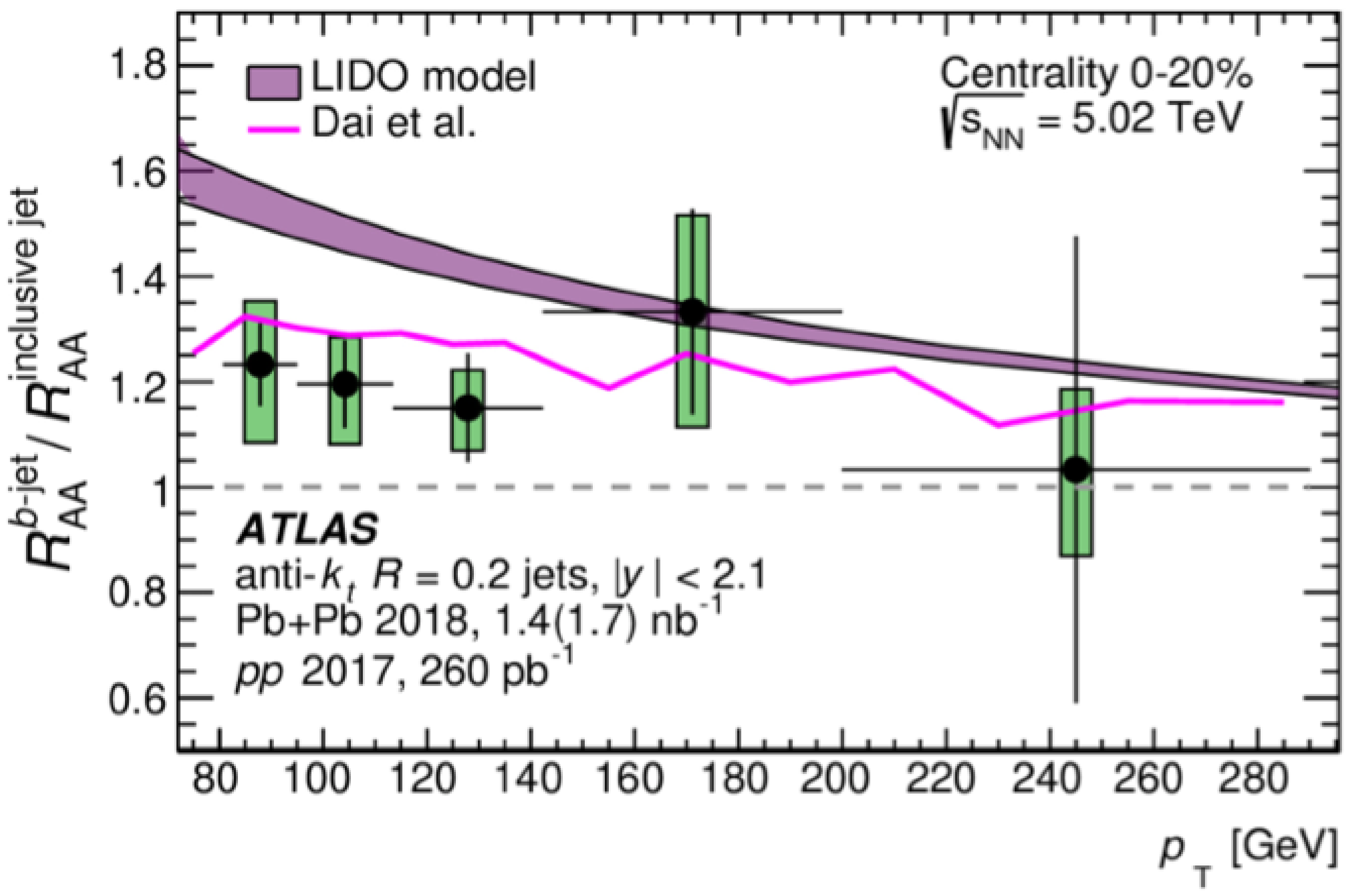




- Important input to diffusion coefficient D_s and $\hat{q}$
- HF hadron R_{AA} depends on quark mass:
    - Significance mass dependence at low p_T and disappearance at high p_T

Color Charge Dependence of Energy Loss





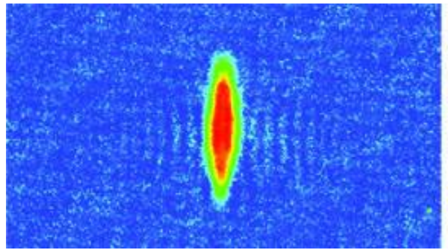
Comparison between **quark-enriched** jets and **inclusive (quark & gluon)** jets

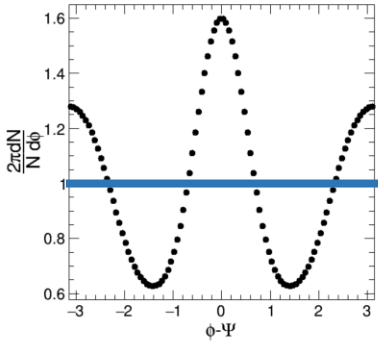
R_{AA} larger for b-jets: smaller b-jet suppression as compared to inclusive jets

Double ratios show that b-jets are about 20% less suppressed than inclusive jet in central collisions

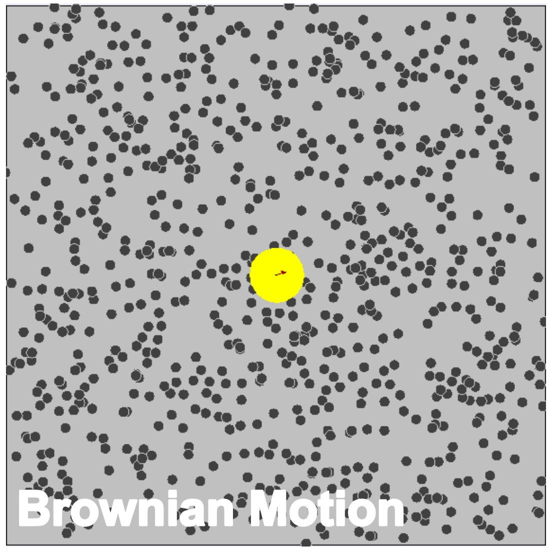
Gluons lose more energy than (beauty-) quarks

Heavy Quark (Charm and Beauty) Diffusion

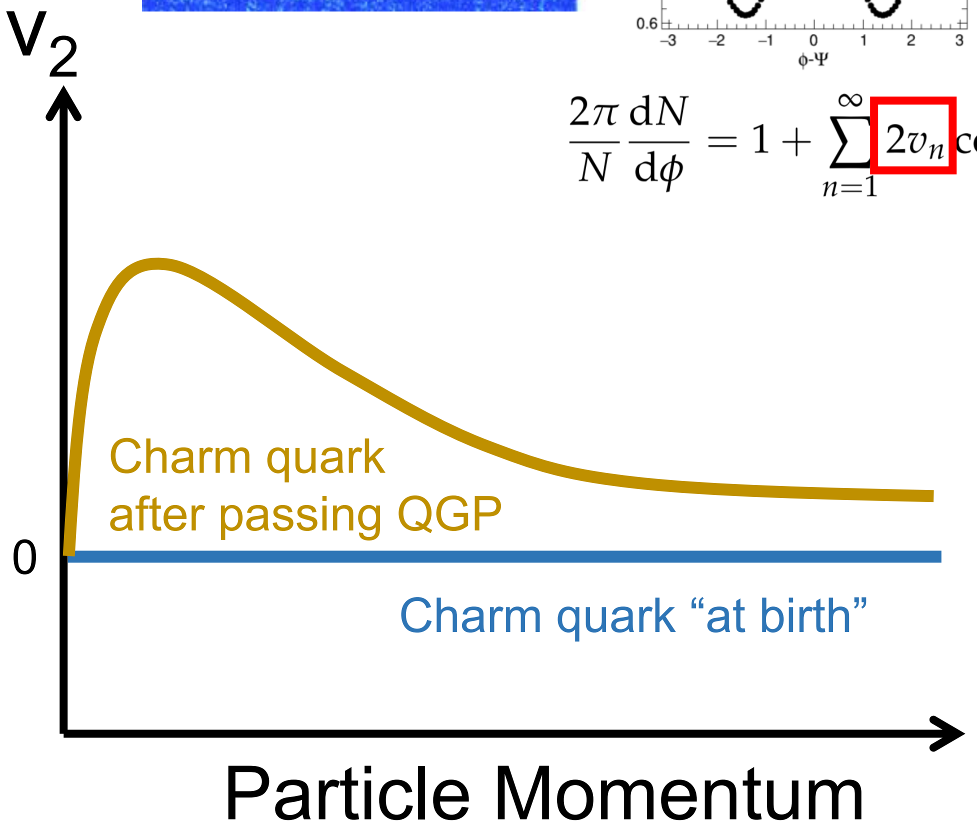




$$\frac{2\pi}{N}\frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \sum_{n=1}^{\infty} \boxed{2v_n} \cos[n(\phi - \Psi_n)]$$



Artist's impression



Fokker-Planck equation

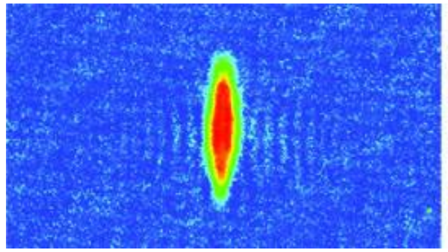
$$\frac{\partial}{\partial t} f_Q(t,p) = \frac{\partial}{\partial p} pA(p) f_Q(t,p) + \frac{\partial^2}{\partial^2 \vec{p}} B(p) f_Q(t,p)$$

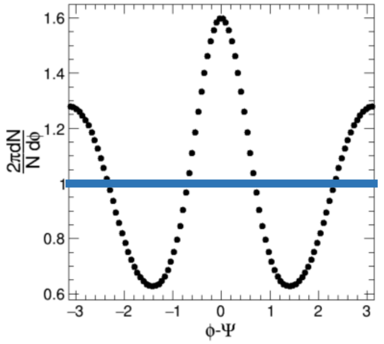
A and B are transport coefficients

$$\mathcal{D}_s = \frac{T}{m_Q A(p=0)}$$

- Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the azimuthal anisotropy (v_2) of the charm quarks in the QGP bath!!

Heavy Quark (Charm and Beauty) Diffusion





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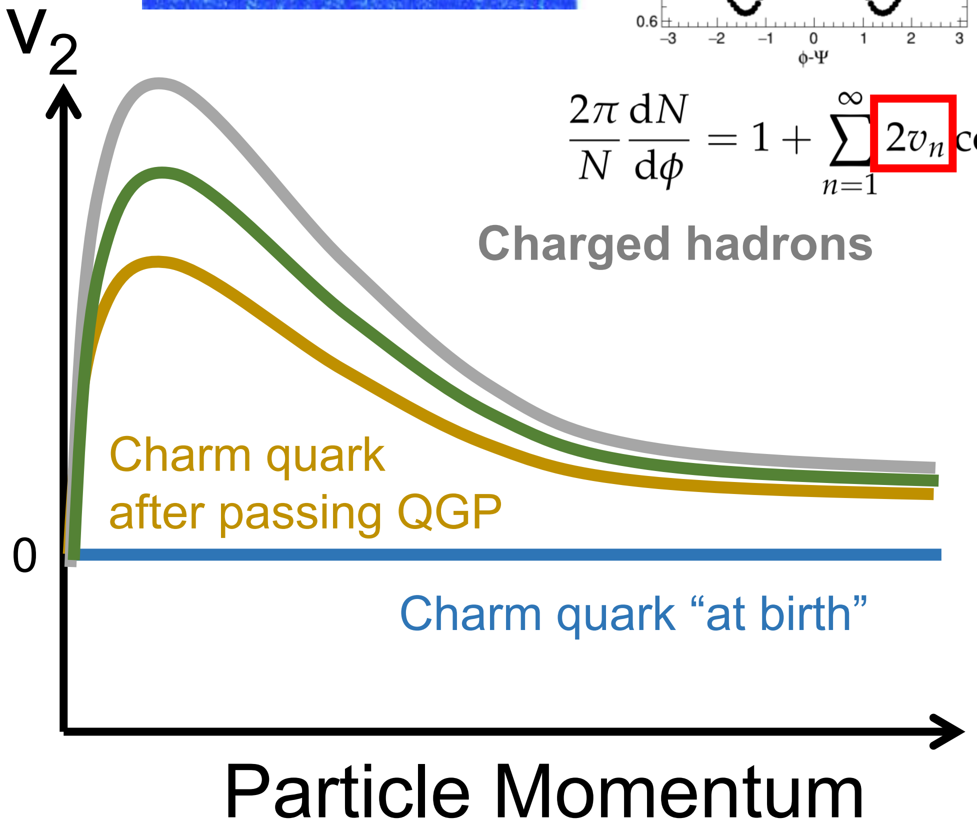
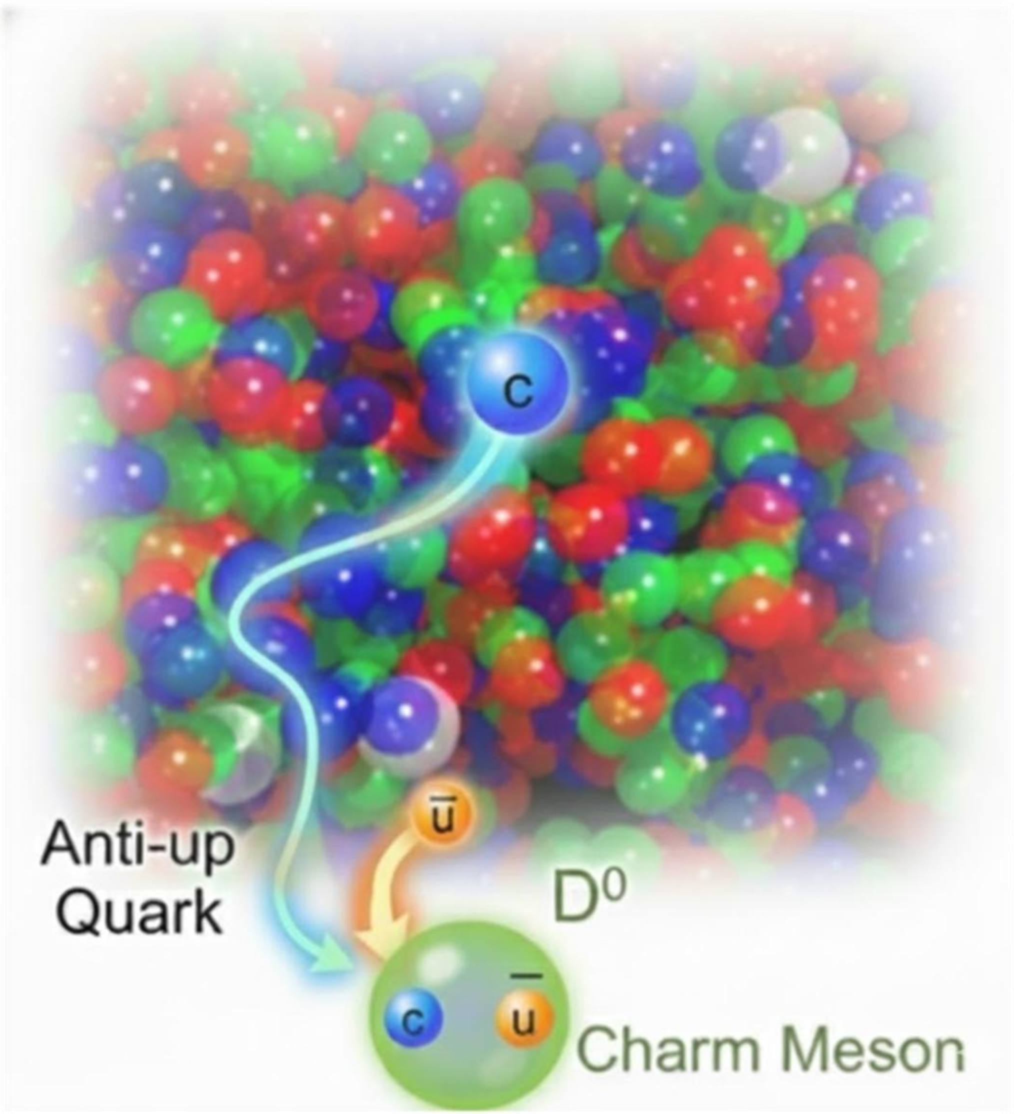


Artist's impression



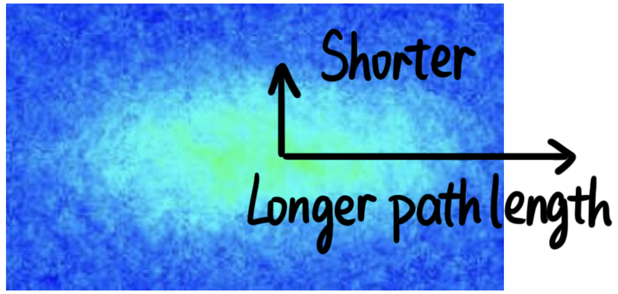
- Since the **QGP is expanding radially**, QCD force (like '**wind**') increases the azimuthal anisotropy (v_2) of the charm quarks in the QGP bath!!
- Hadronization effect could change the v_2 of the heavy flavor hadron further

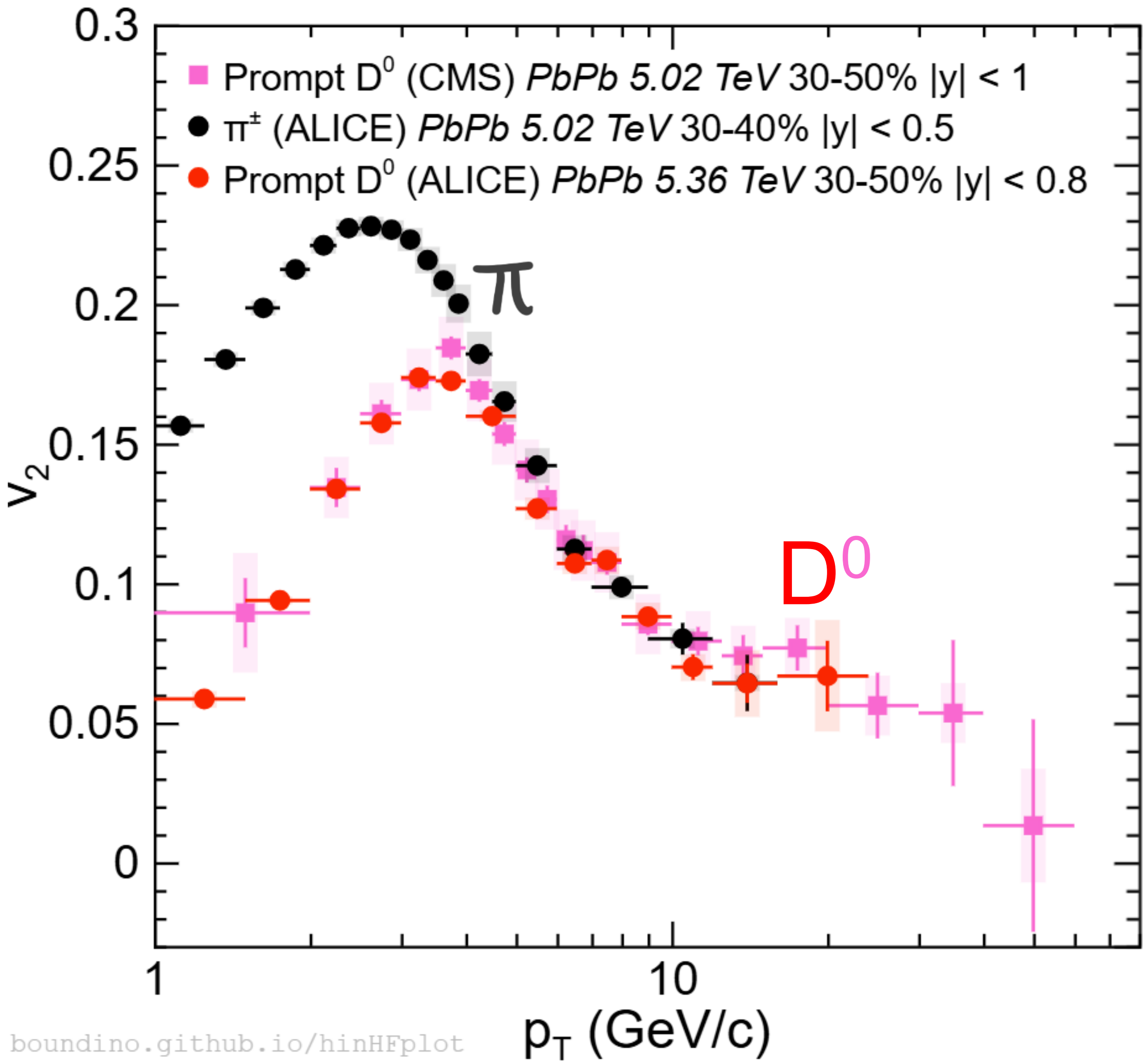
D^0 v_2 vs. Charged Hadron v_2

Charm quarks flow with the medium!

Non-zero D^0 meson v_2 up to high p_T

- Mass ordering at low p_T, expected from hydrodynamic flow (heavier particles get smaller v_2 at the same p_T)
- Same magnitude between **π** and D^0 in p_T> 4~5 GeV, a regime where the anisotropy may come mainly from path-length dependence of energy loss?





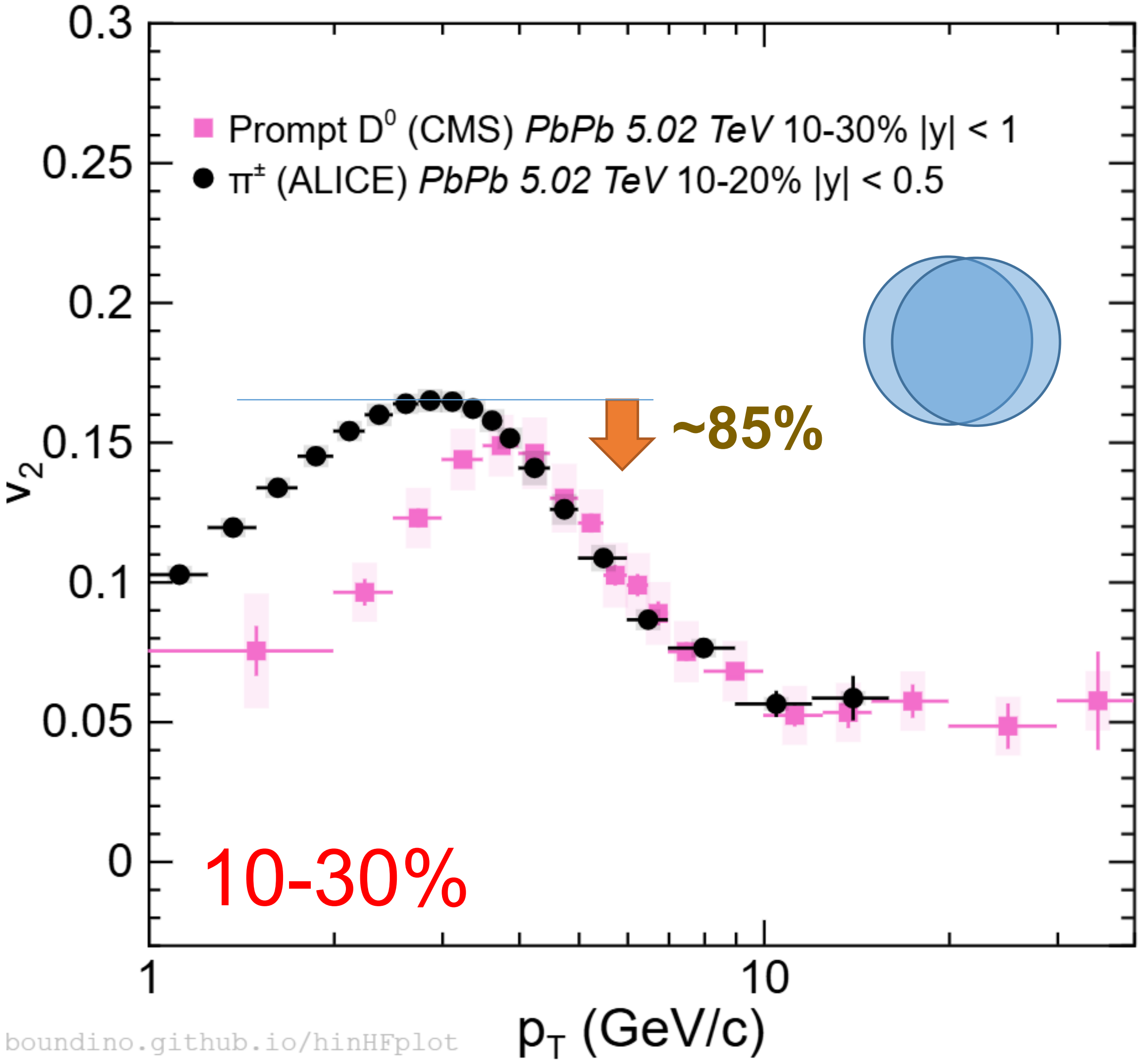
→ PLB 816 (2021) 136253 → JHEP 09 (2018) 006
→ ALICE Preliminary

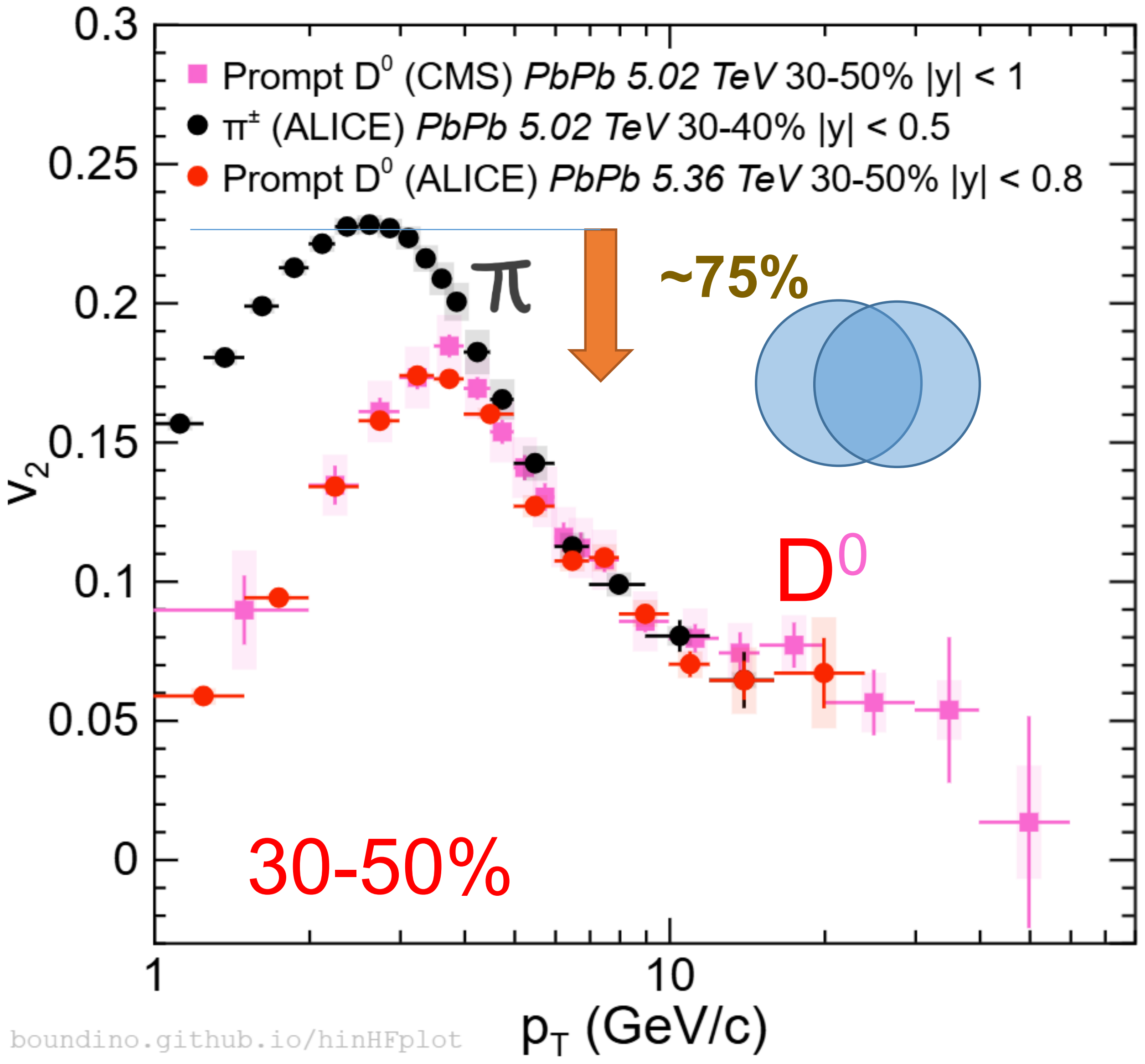
D^0 v_2 vs. Charged Hadron v_2: Degree of Charm Hydrodynamization

~95%

0-10%

(not shown)



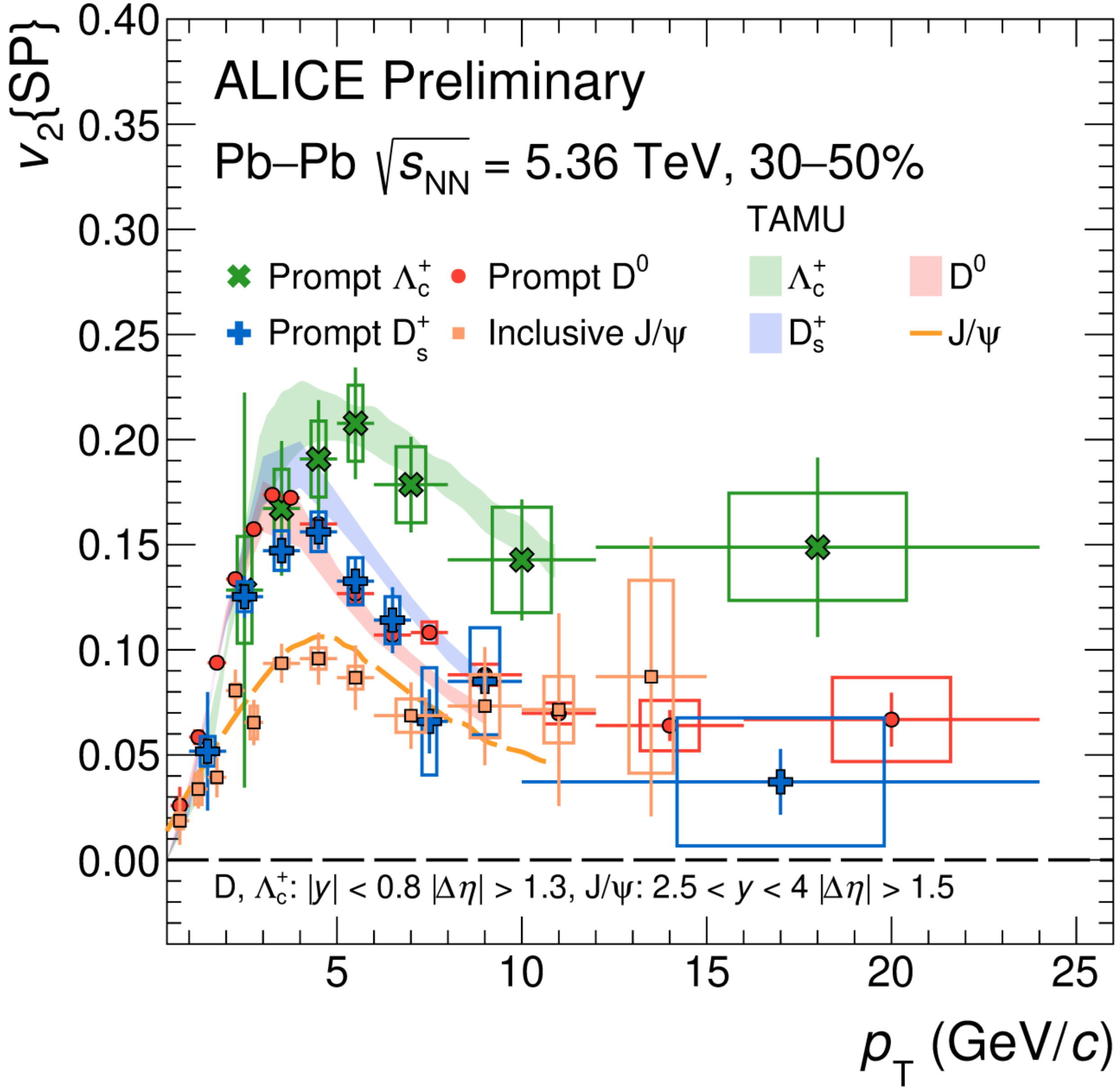


In central collision (10-30%), the max D^0 v_2 is closer to π^+ v_2
In 0-10%, max D^0 v_2 is very similar to π^+ v_2 (~95%)
(not shown, if average 0-5% and 5-10% π^+ results)

→ Indication that D^0 is closer to hydrodynamization in 0-10% than 30-50%!

HEFTY COLLABORATION

Charm Hadron v_2 in PbPb at 5.36 TeV



- All measured charm hadrons exhibit flow.

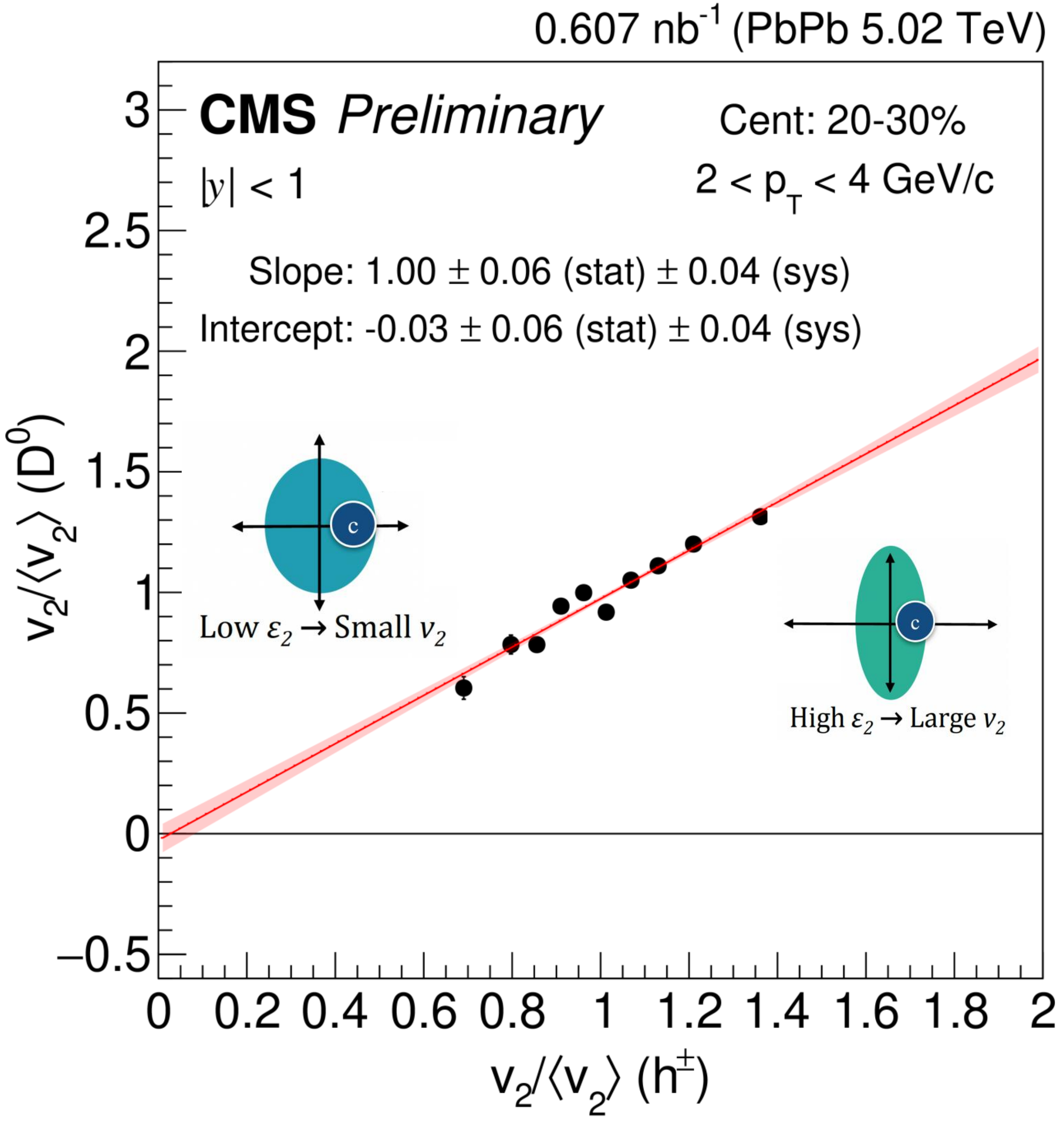
- Observed ordering Λ_c v_2 > D^0 v_2:

It probably suggest **hadronization via sequential heavy-light quark combination** rather than charm-diquark coalescence

- Data show D_s v_2 ≤ D^0 v_2, opposite to TAMU prediction D_s v_2 > D^0 v_2.

- This data shows charm hadron v_2 is not a simple linear combination of constituent-quark v_2.

Charm Quark v_2 vs. Light Flavor v_2

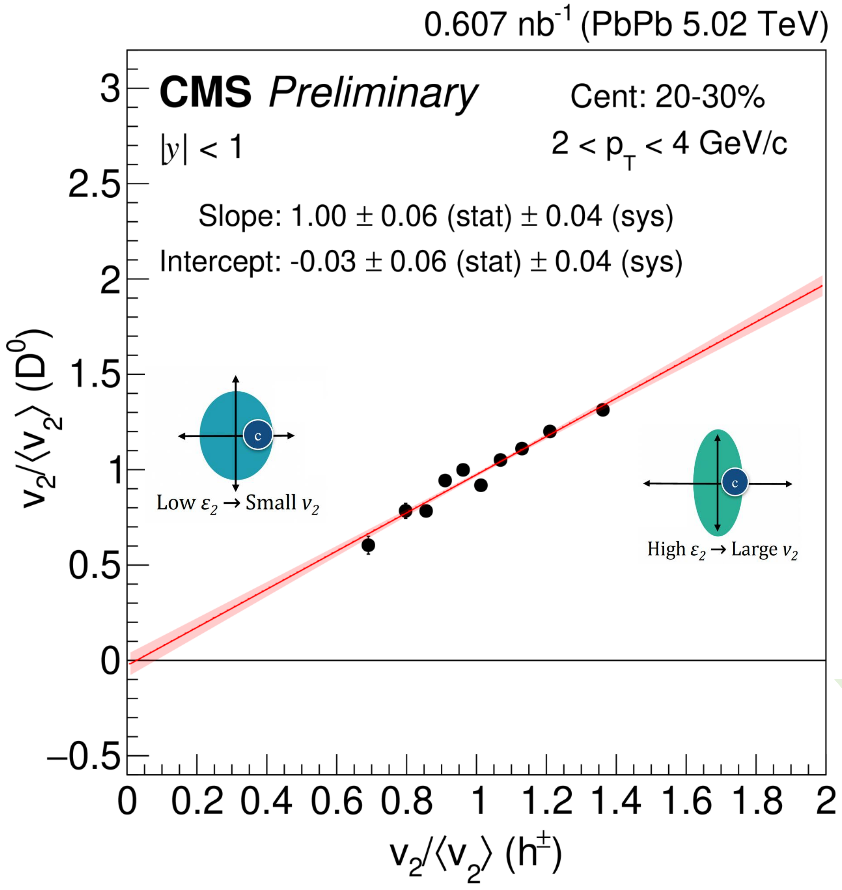


Do charm quarks develop elliptic flow (v2) through interactions with the light partons in the QGP?

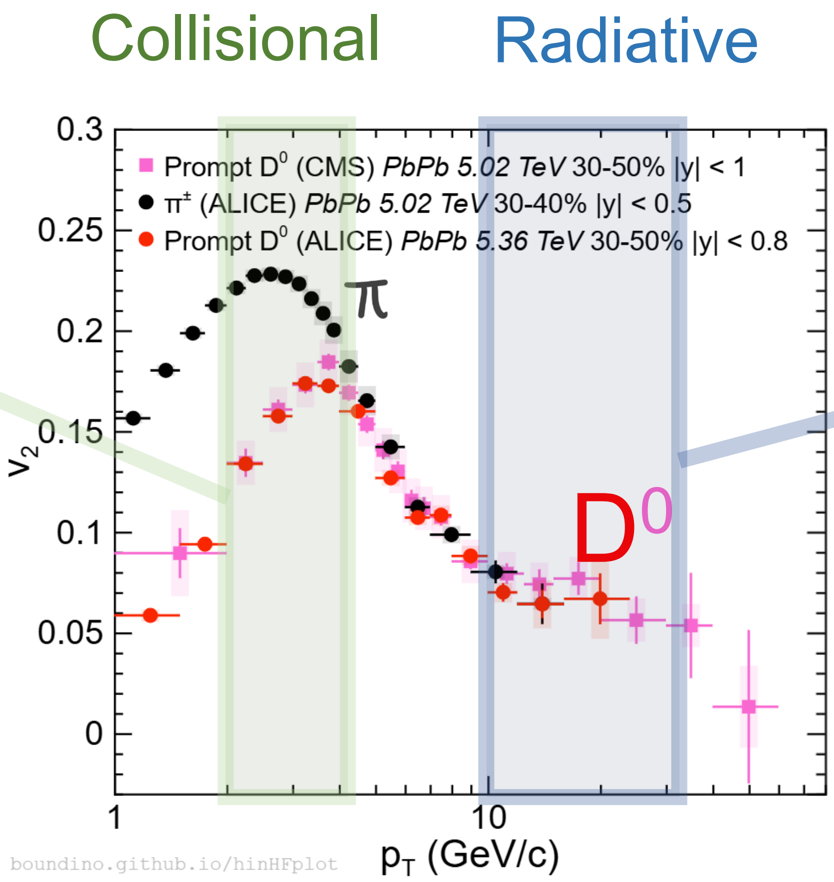
Vary initial eccentricity by Event Shape Engineering q_2 while **keeping the same centrality**

- D^0 v_2 significantly increases with q_2
- **Linear correlation** between D^0 v_2 and light hadron v_2
- Slope is consistent with 1
- This shows D^0 v_2 is driven by initial shape, similar to light flavors

Charm Quark v_2 vs. Light Flavor v_2

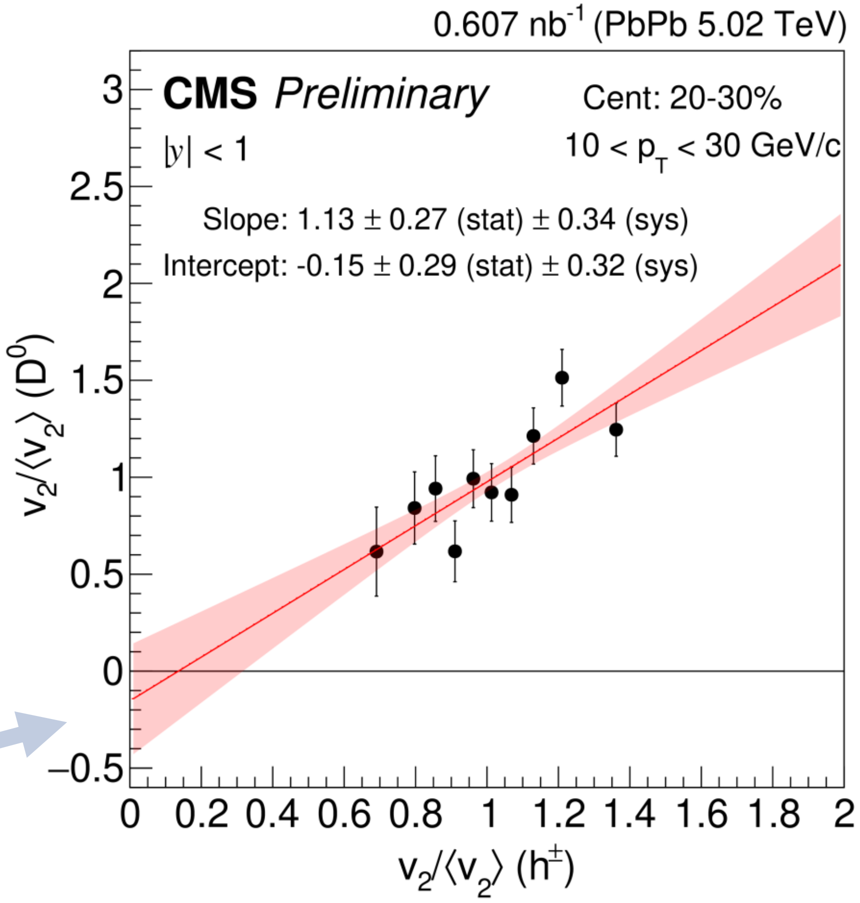


Insensitive to the underlying mechanism!!!



→ PLB 816 (2021) 136253 → JHEP 09 (2018) 006

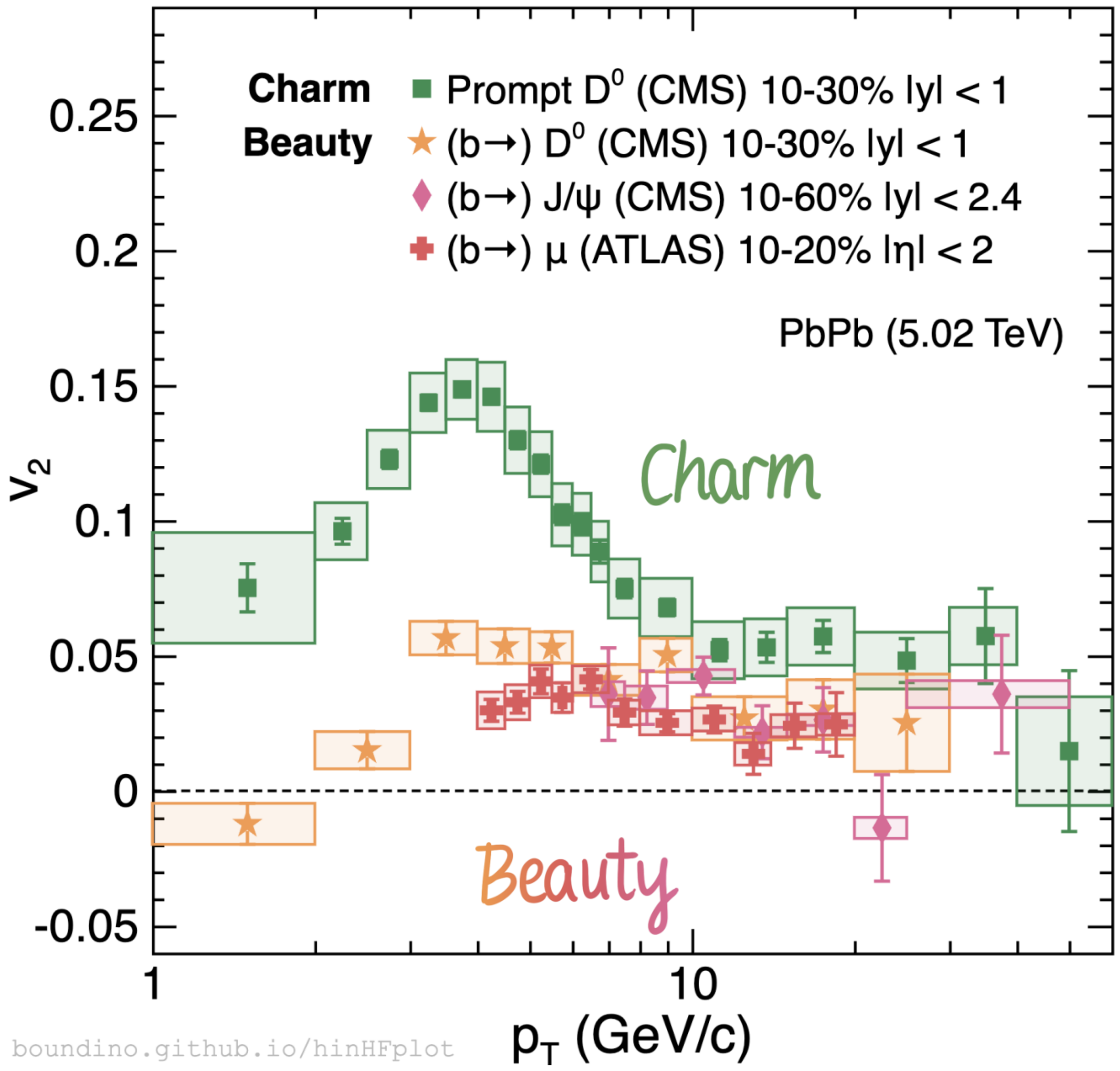
→ ALICE Preliminary



D^0 v_2 is driven by initial shape, similar to light flavors at low p_T

Also true at high p_T, regardless of the underlying mechanism

Collective Flow: Charm vs Beauty



Significant open beauty flow signal!

- Smaller v_2 than charm hadrons at low p_T
- Weaker collective flow behavior

→Beauty remembers more about their initial state (v_2=0) than charm due to the expected longer relaxation time

Important input to diffusion constant

However, there are significant uncertainties associated with hadronization that translate **charm** and **beauty** quark spectra to hadron spectra

PLB 850 (2024) 138389 JHEP 10 (2023) 115 PLB 807 (2020) 135595

Experimental and Theoretical Extraction

Experimentally, we usually use two particle correlation, cumulant or scalar product method to extract $v_2\{2\}$

$$v_2\{2\}^2 \approx \bar{v}_2^2 + \sigma_{v_2}^2 + \delta,$$

It has been shown experimentally feasible to extract $v_2\{4\}$ using four particle correlation:

$$v_2\{4\}^2 \approx \bar{v}_2^2 - \sigma_{v_2}^2$$

* In the Gaussian limit and assuming D v_2 is proportional to light flavor v_2

Theoretical calculations usually extract directly the $\bar{v}_2$

$$v_2^{(i)} \equiv \left\langle \cos 2(\phi - \Psi_{2,\mathrm{PP}}^{(i)}) \right\rangle_{\text{particles in event } i}.$$

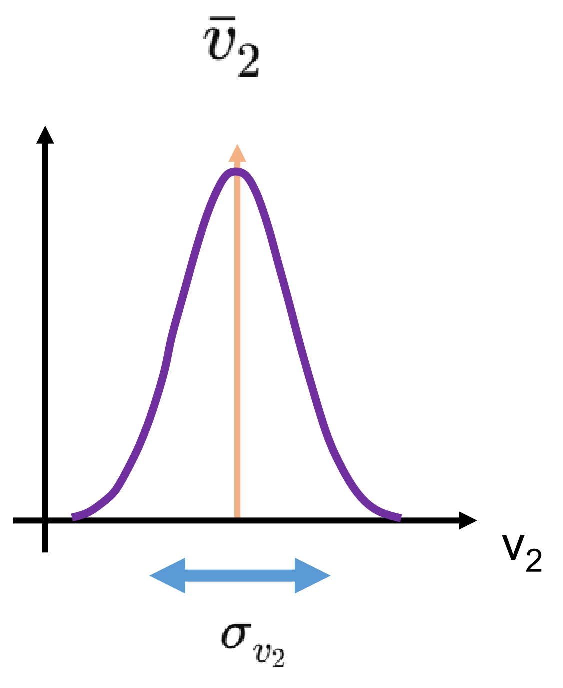
Not apple to apple comparison!

- the event-by-event mean

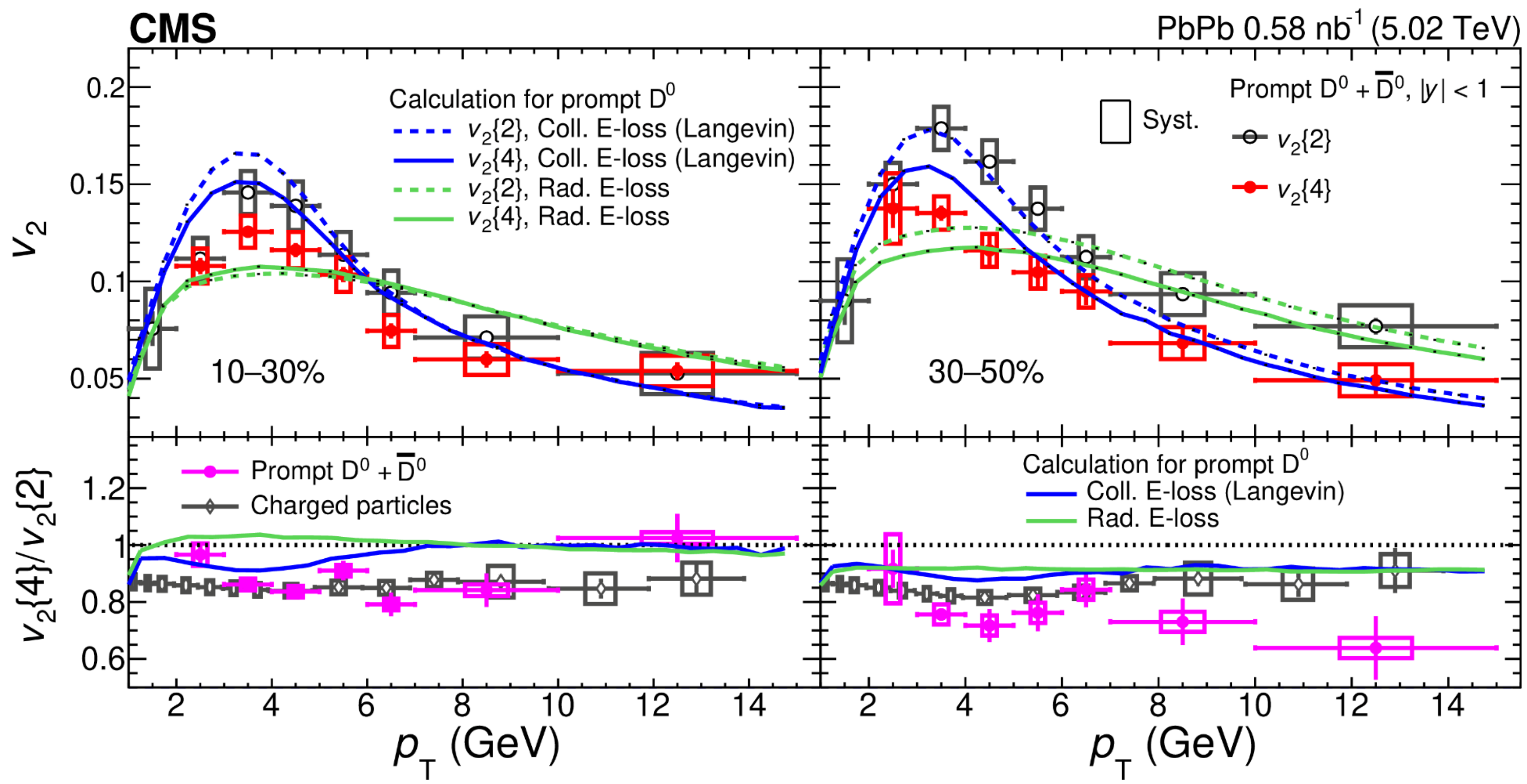
$$\bar{v}_2 = \langle v_2^{(i)} \rangle,$$

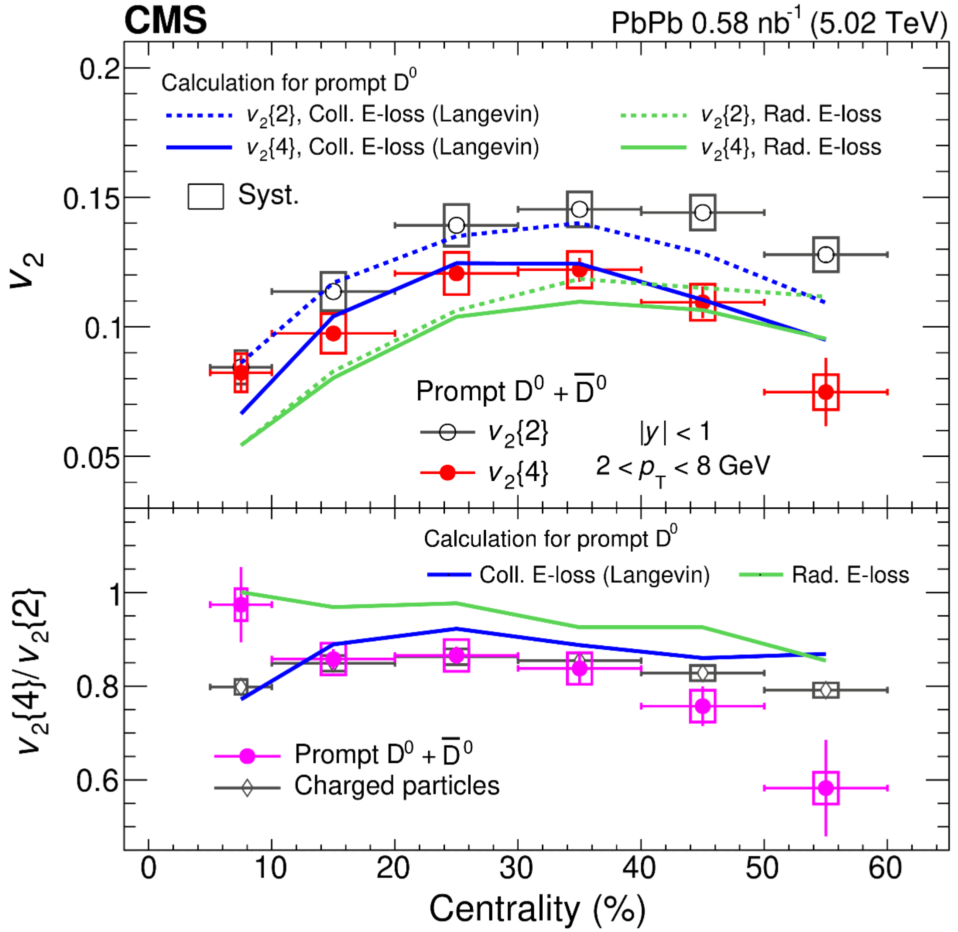
- the variance

$$\sigma_{v_2}^2 = \langle (v_2^{(i)})^2 \rangle - \bar{v}_2^2.$$



Prompt D^0 $v_2\{2\}$ vs. $v_2\{4\}$





Multiparticle correlation measurement with D^0 is possible at LHC!

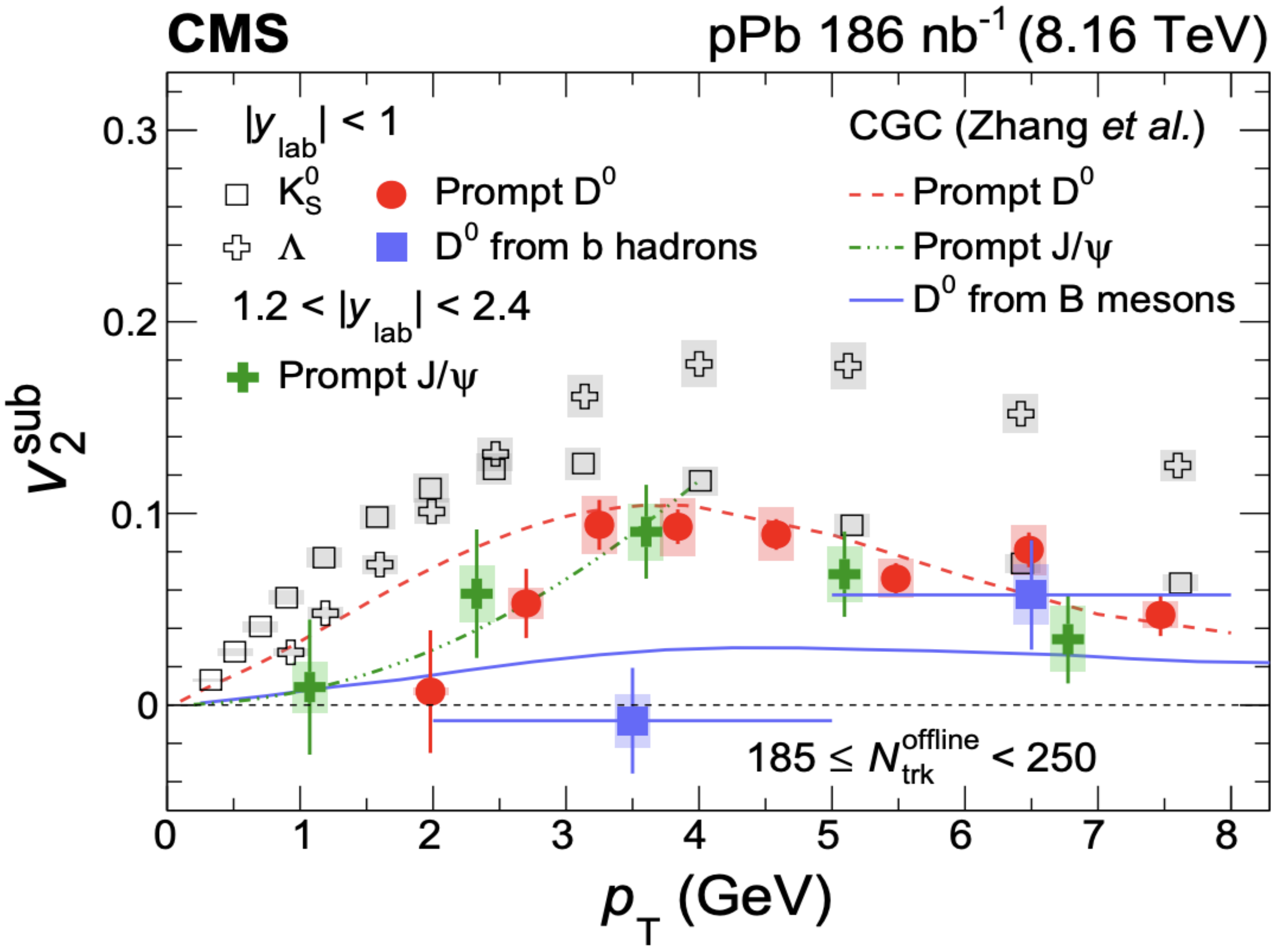
- Sensitive to D^0 flow fluctuation and suppression of nonflow contribution.

$v_2\{2\}$ and $v_2\{4\}$ can differ by up to 30-40%!!

Phys. Rev. Lett. 129 (2022) 022001

- Similar or slightly larger than that in light flavor
- Hinting significant contribution from flow fluctuation in v2{2}! (and possibly residual nonflow)

Heavy Flavor Hadron v_2 in pPb



At high multiplicity, significant prompt **D^0** and **J/ψ** v_2 were observed (with nonflow subtraction)

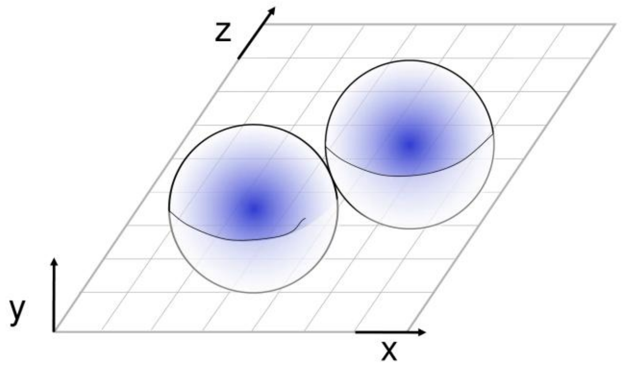
→Charm diffusion in pPb?

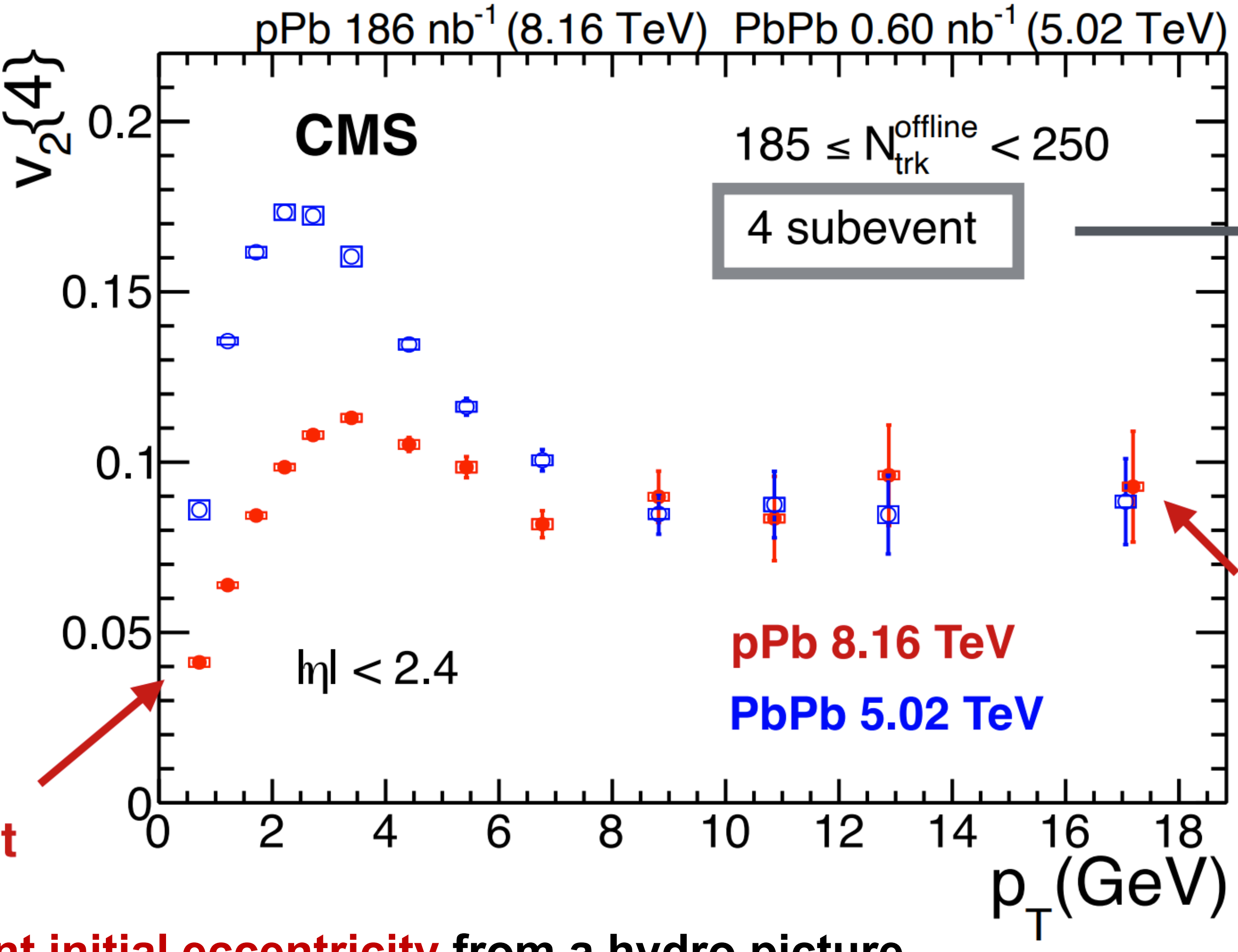
The v_2 values are sizable (as large as 0.09) and remain non-zero up to high p_T (p_T~ 8 GeV)!

→Is this pathlength dependent parton energy loss?

High multiplicity selection:
What kind of events are we studying?

Charged Hadron v_2 in pPb and PbPb





suppression of non-flow

Same $v_2\{4\}$ in pPb and PbPb collisions

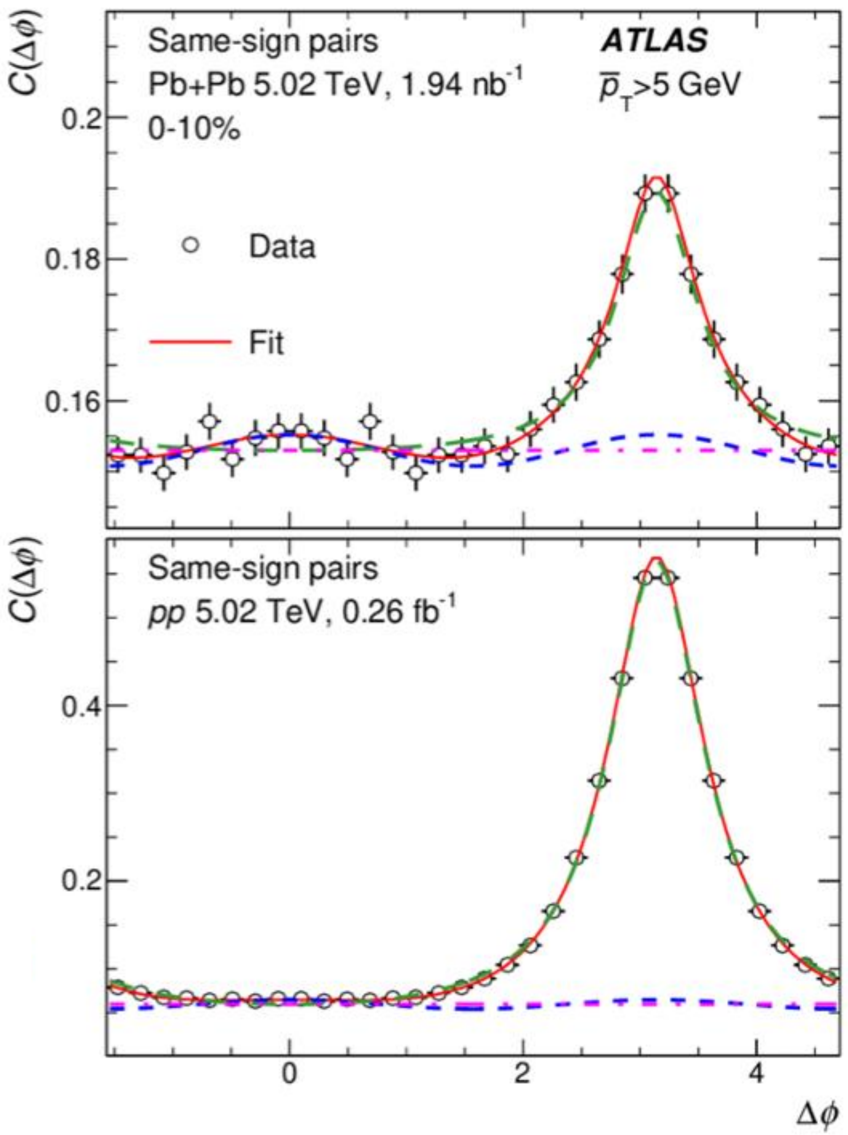
???

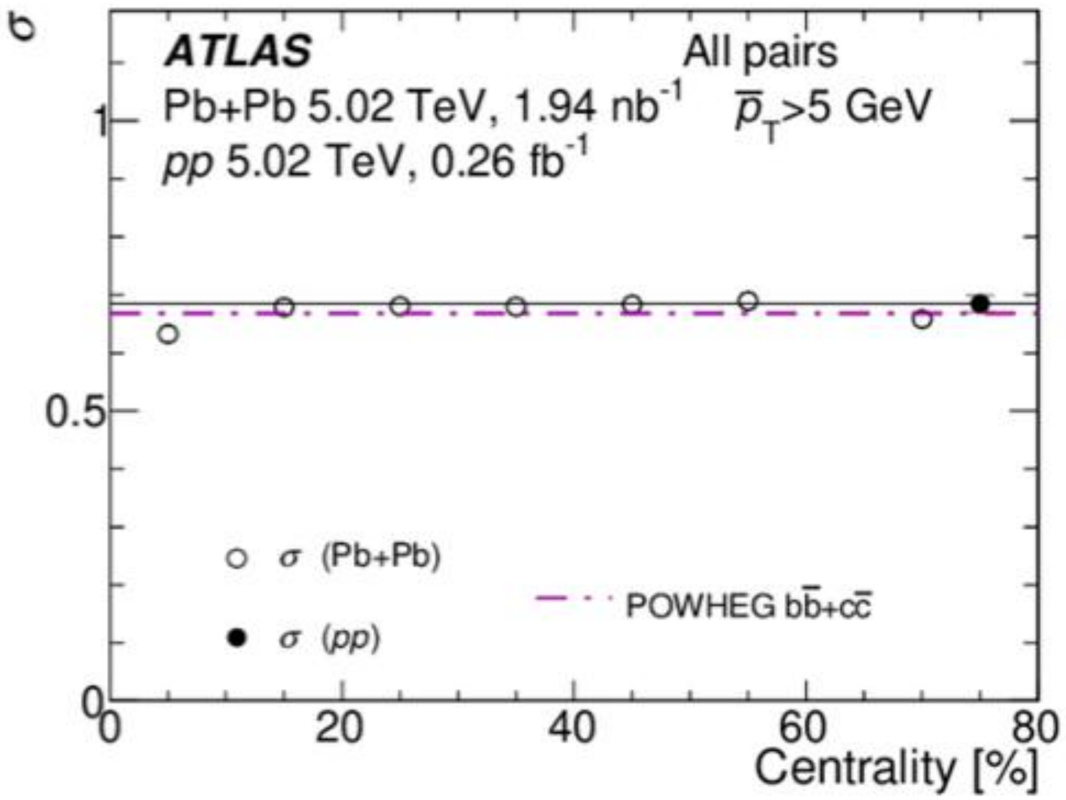
Sizable differences at low p_T

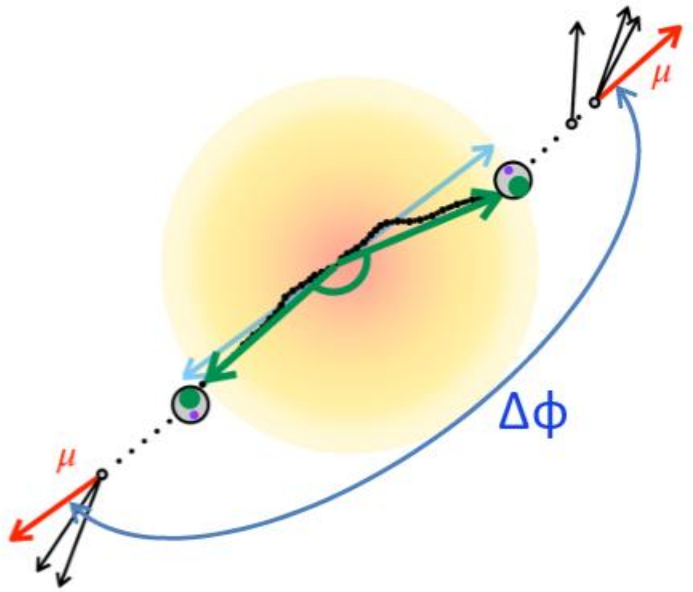
➔**Point to very different initial eccentricity from a hydro picture**

- High p_T v_2 highly depends on the analysis method
- May not be explained by simply pathlength dependence of parton energy loss

Beyond v_2: Heavy Flavor Muon Angular Correlation







Strong suppression of HF muon in PbPb has been observed

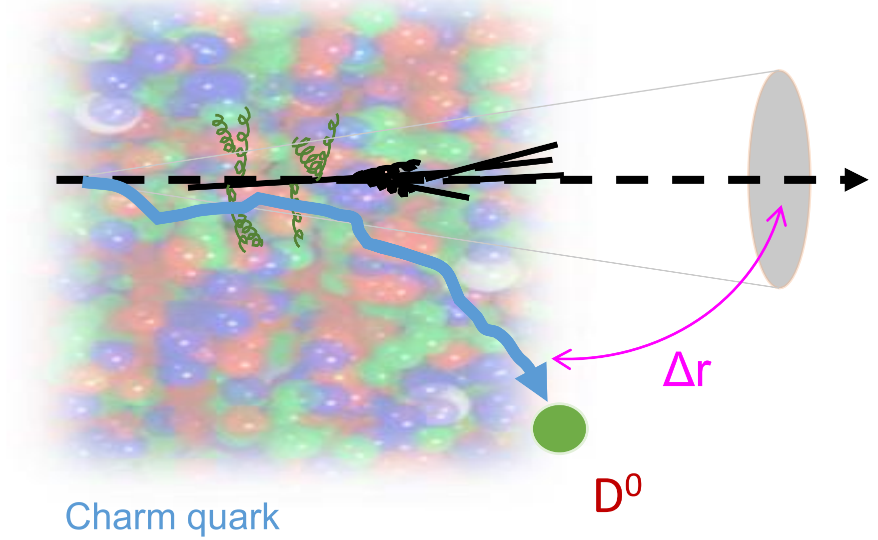
μ+μ angular correlation: An attempt to study charm diffusion with respect to **another hard probe (axis)!**

No significant modification of the width in the two HF-muon correlation function was observed

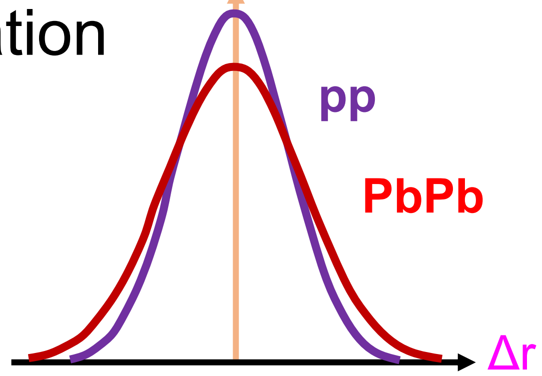
→Competing effect from jet selection bias?

Beyond v_2: Direct Detection of Charm Diffusion

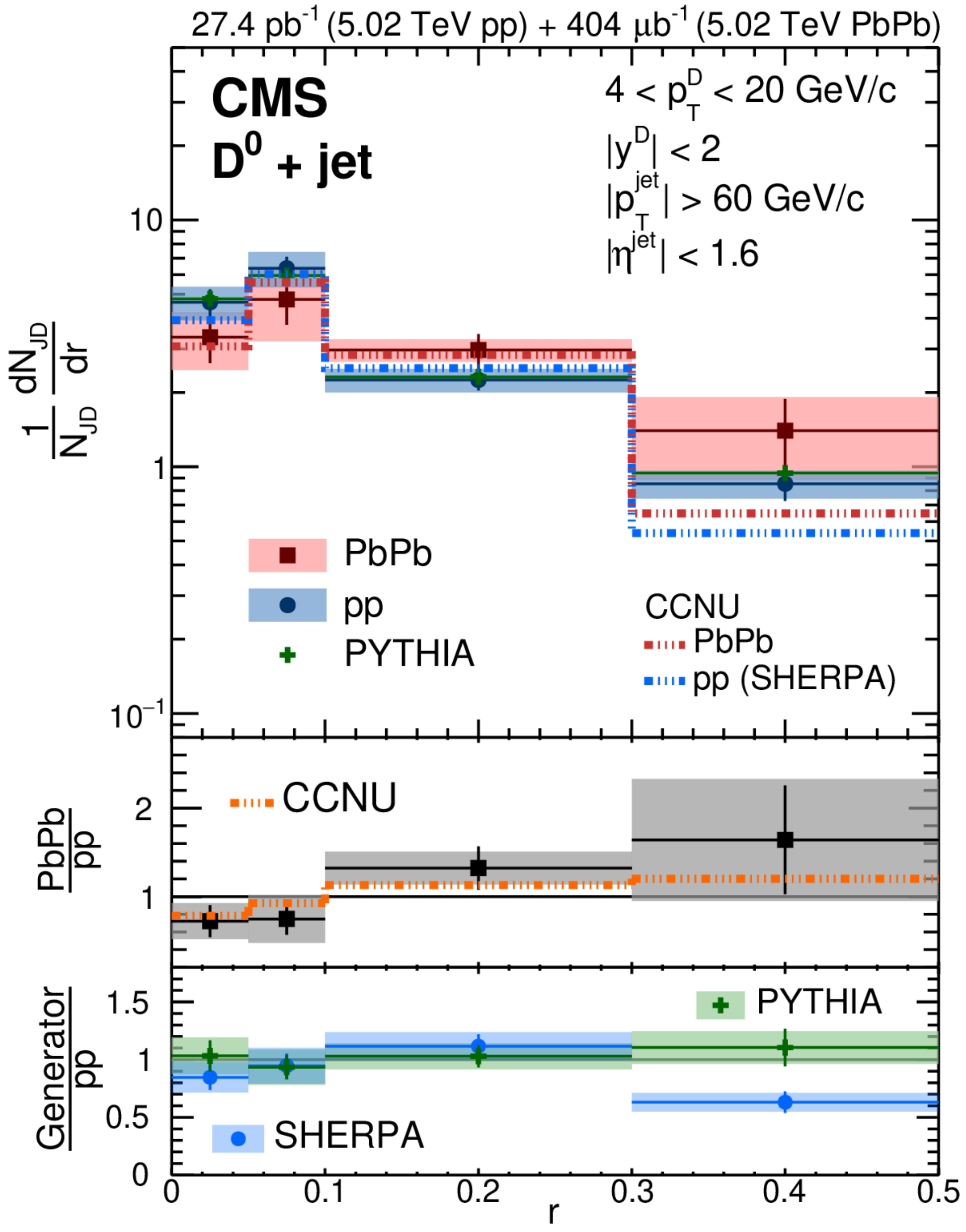
PRL 125 (2020) 102001



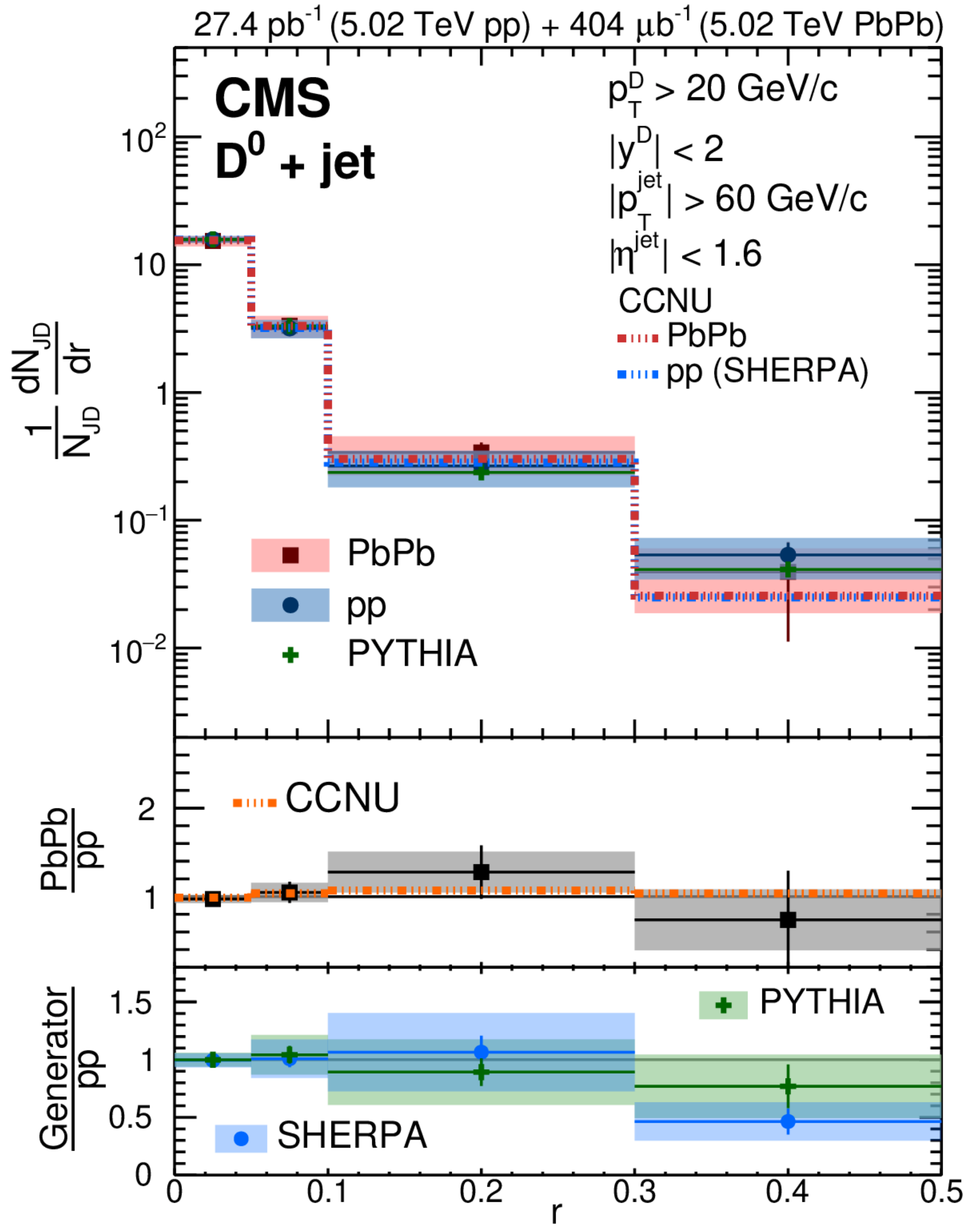
- Indication of charm diffusion with **low p_T D^0**, but not yet significant
- **High p_T D^0:** small or no modification



Low p_T D^0



High p_T D^0

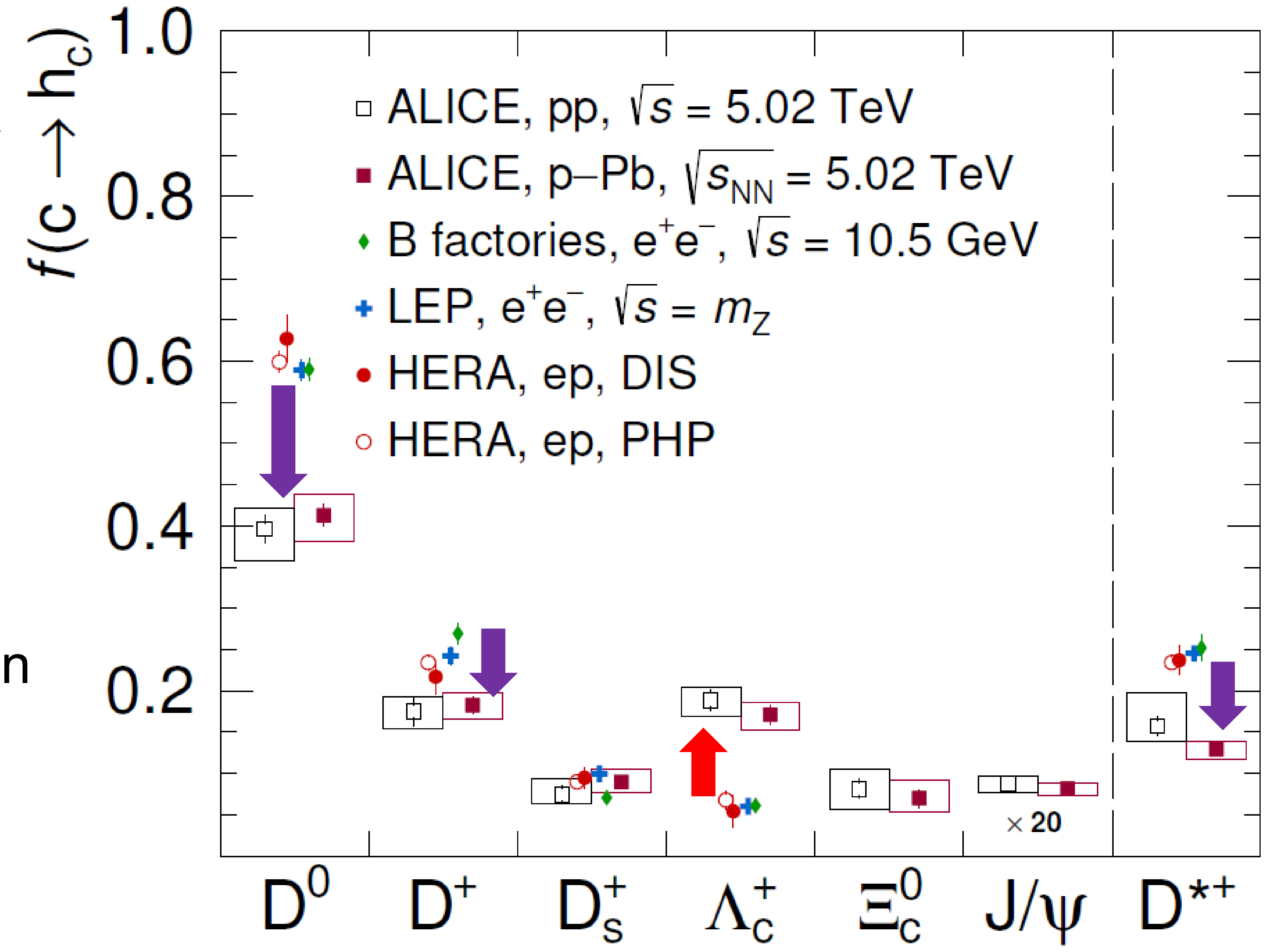


Heavy Quark Hadronization

Necessary for the interpretation of experimental data

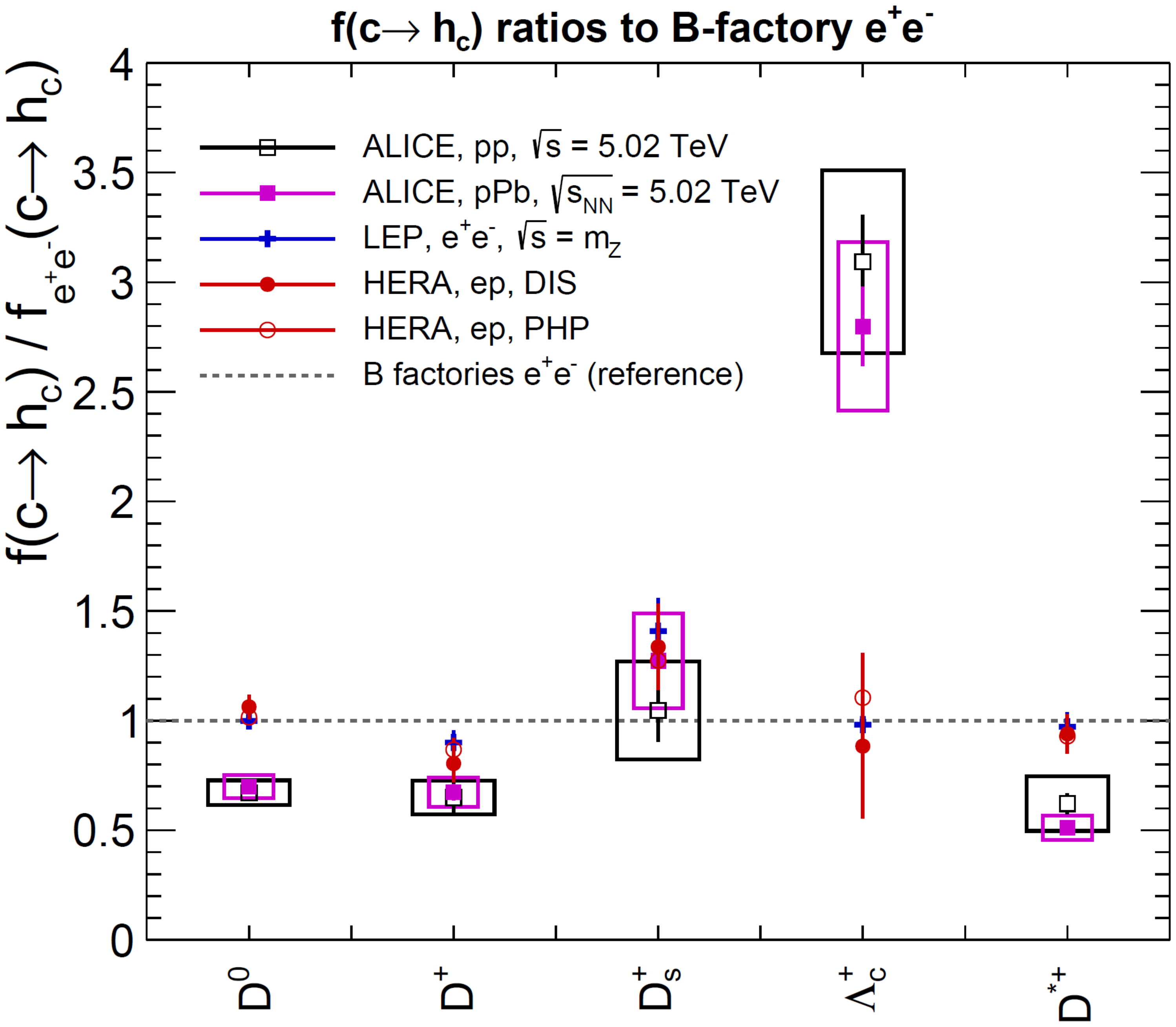
Charm Hadronization in ee, ep, pp and pPb

- Charm hadronization is already modified in pp collisions!
- Suppression of D^0, D^+, and D^{*+}
- Enhancement of Λ_c
- Challenge to the **"universal" fragmentation function** used in theoretical calculations

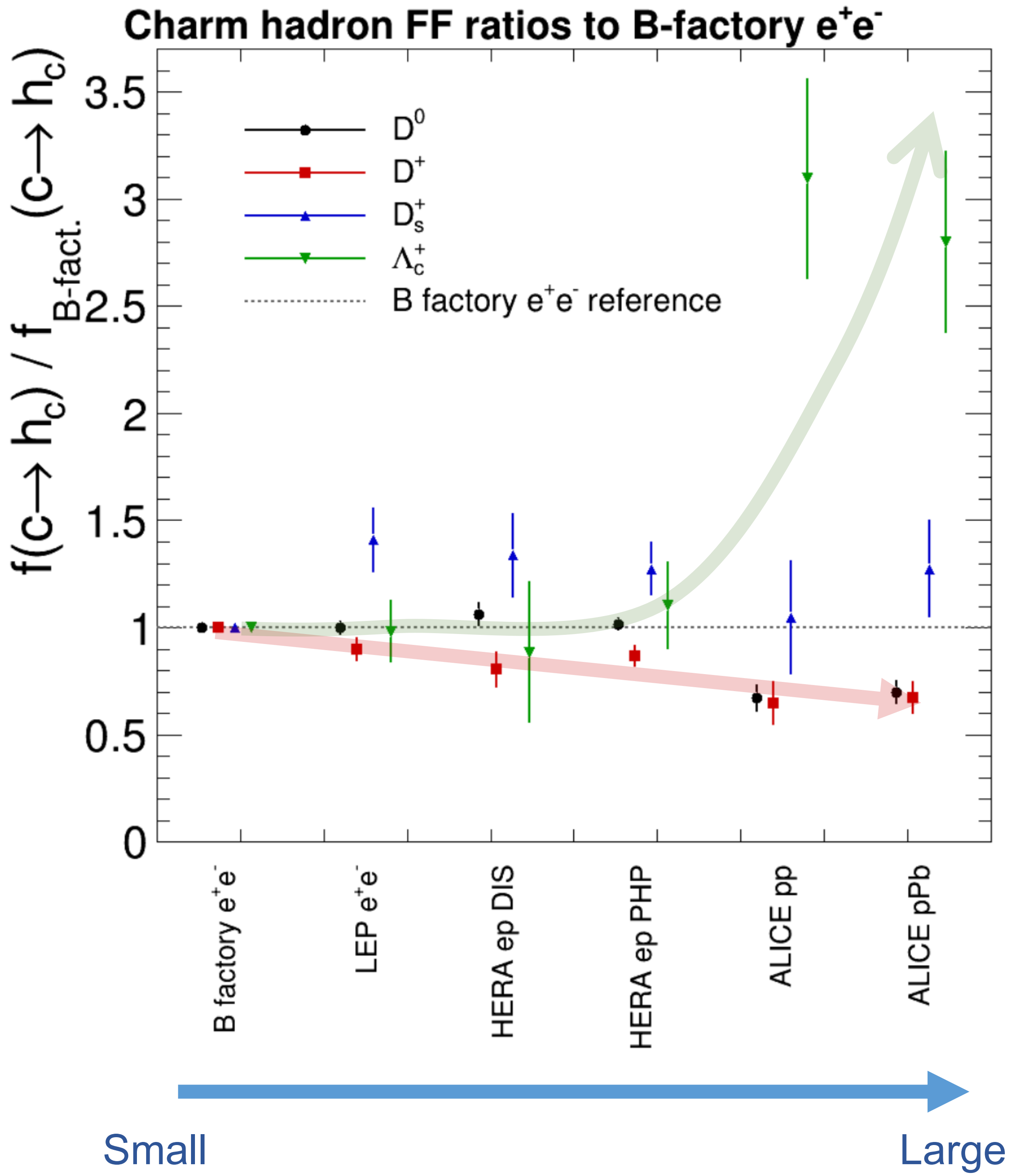


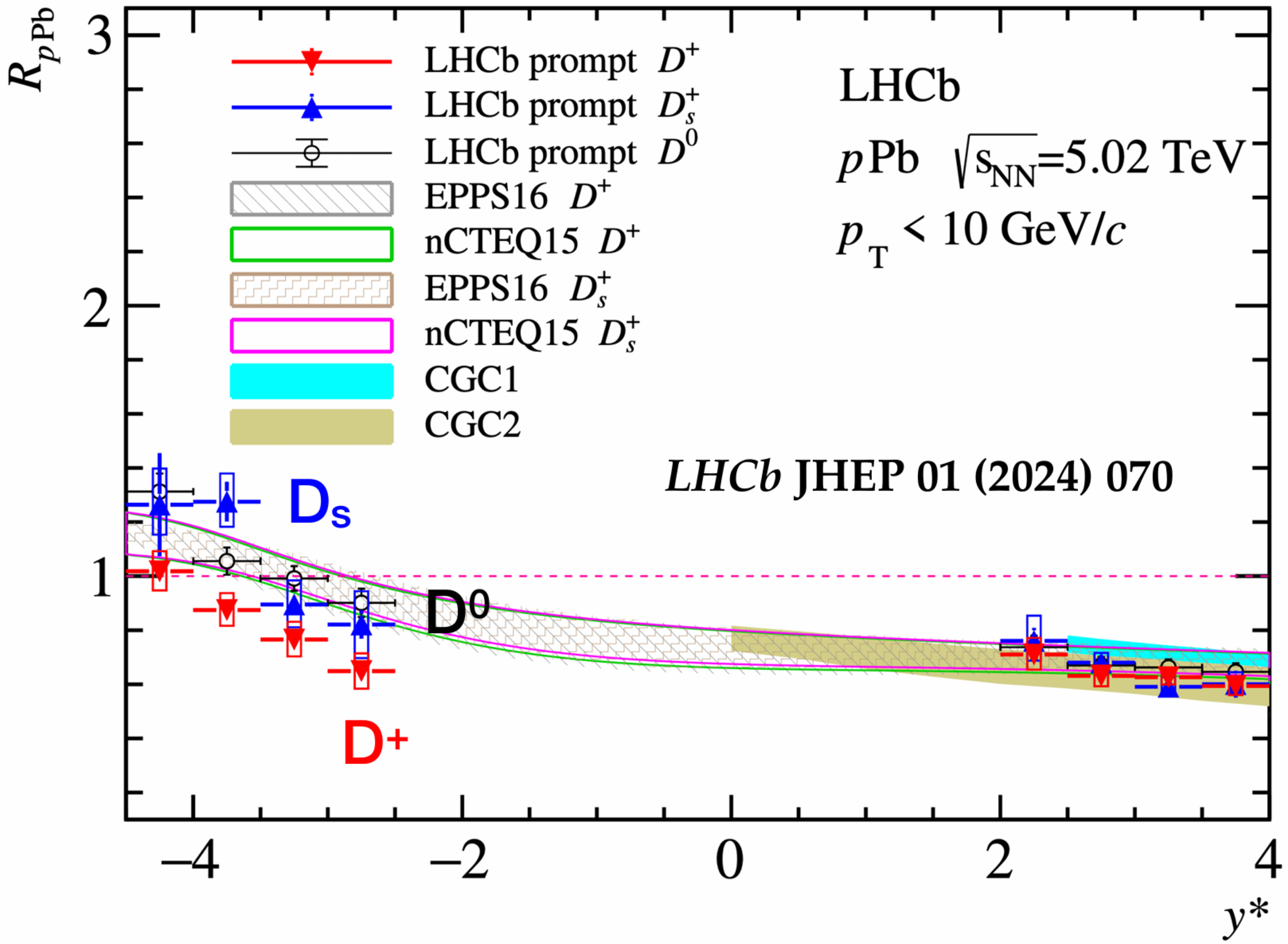
Charm Hadronization in ee, ep, pp and pPb

- Charm hadronization is already modified in pp collisions!
- Suppression of D^0, D^+, and D^{*+} **(30%)**
- Enhancement of Λ_c (up to 3x)
- Challenge to the **"universal" fragmentation function** used in theoretical calculations



Charm Hadron FF Ratios from ee, ep, pp to pPb



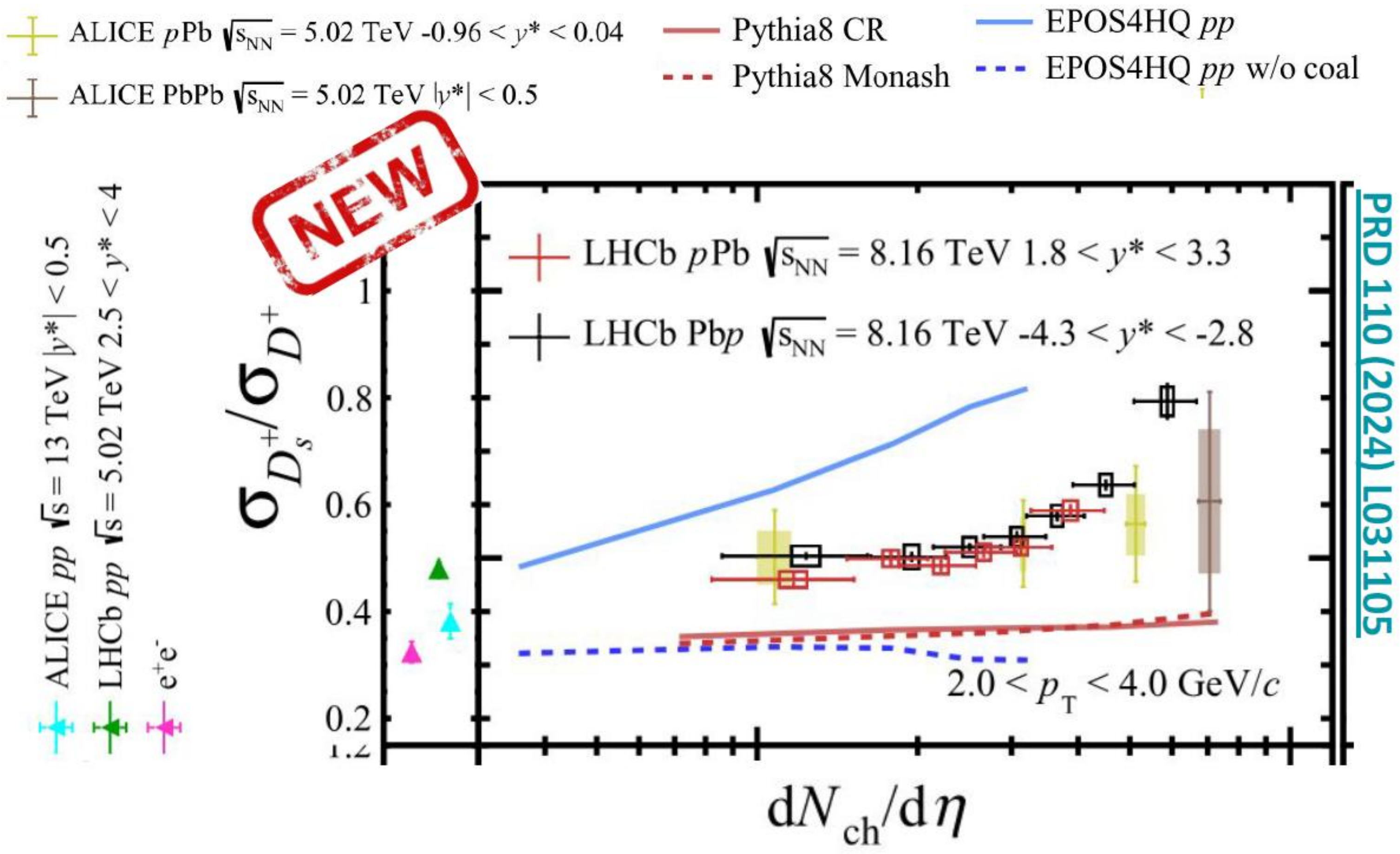


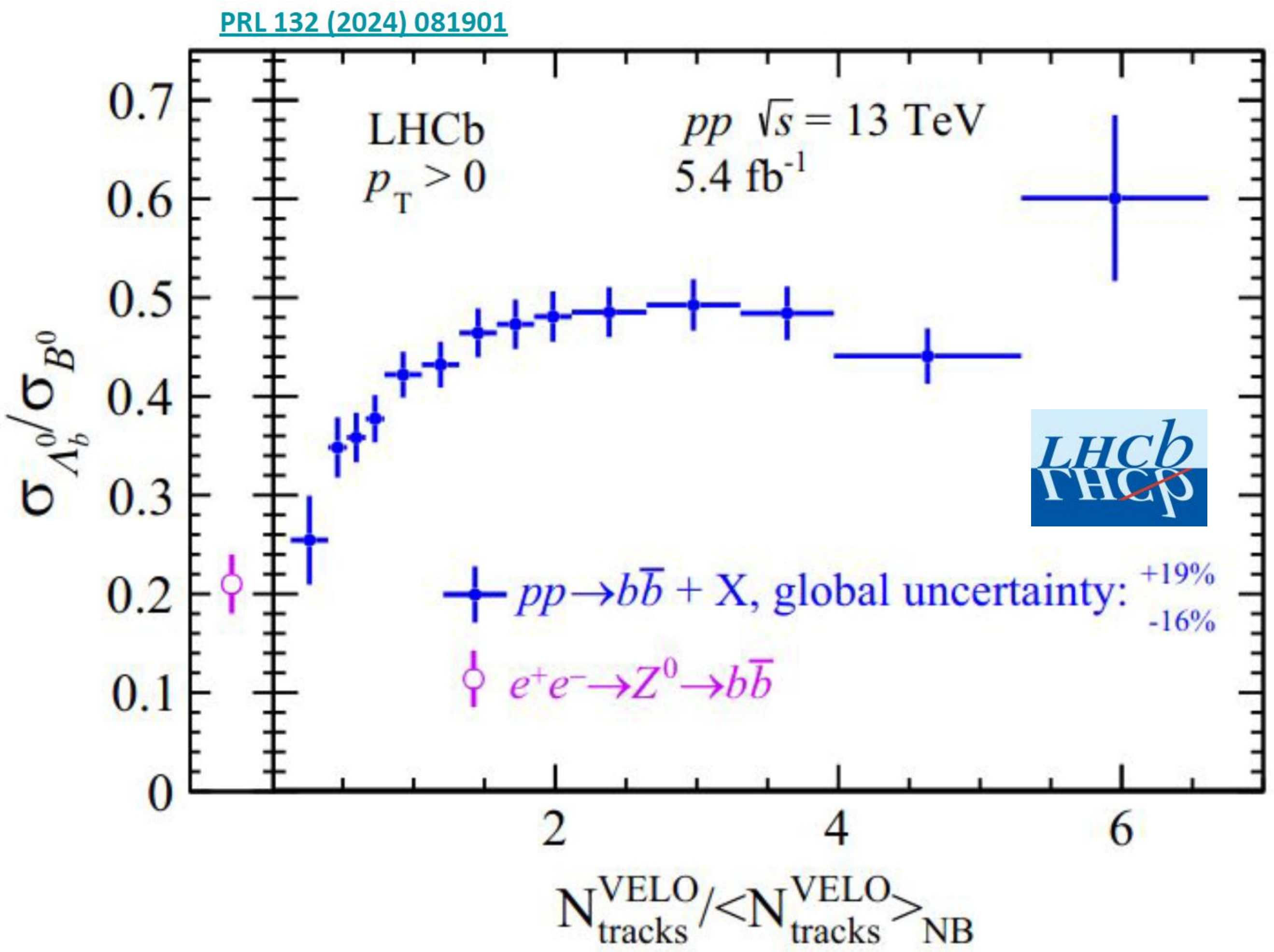
The universality already broken in ee and ep?

→What is the proper baseline?

Motivate particle ratio measurements in ee, pp and pPb as a function of event size

D_s^+/D^0 and Λ_b/B^0 Ratios vs. Event Size



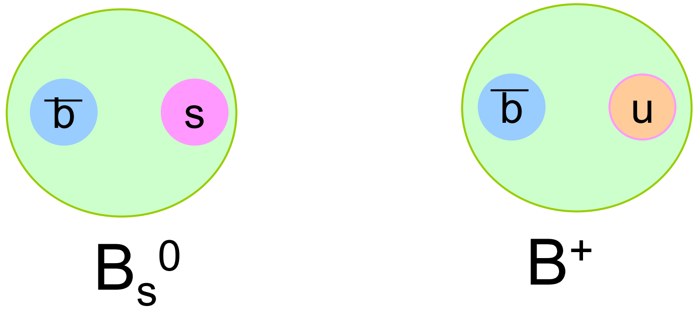


Larger D_s^+/D^0 ratio at high multiplicity in pPb
Can not be described by event generators

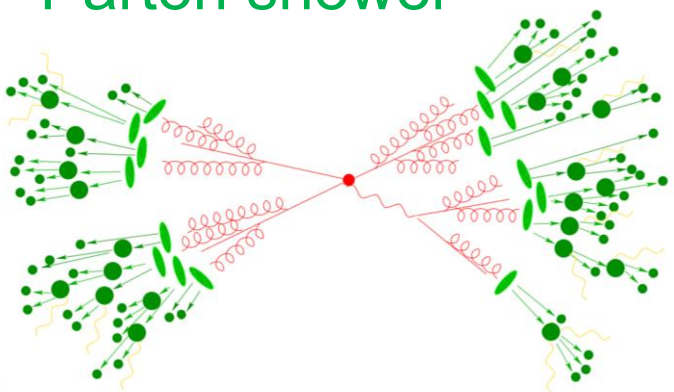
Larger Λ_b/B^0 ratio at high multiplicity in pp
Extrapolate nicely to Z pole e^+e^- data at low multiplicity limit

Is this hadronization effect or selection bias?

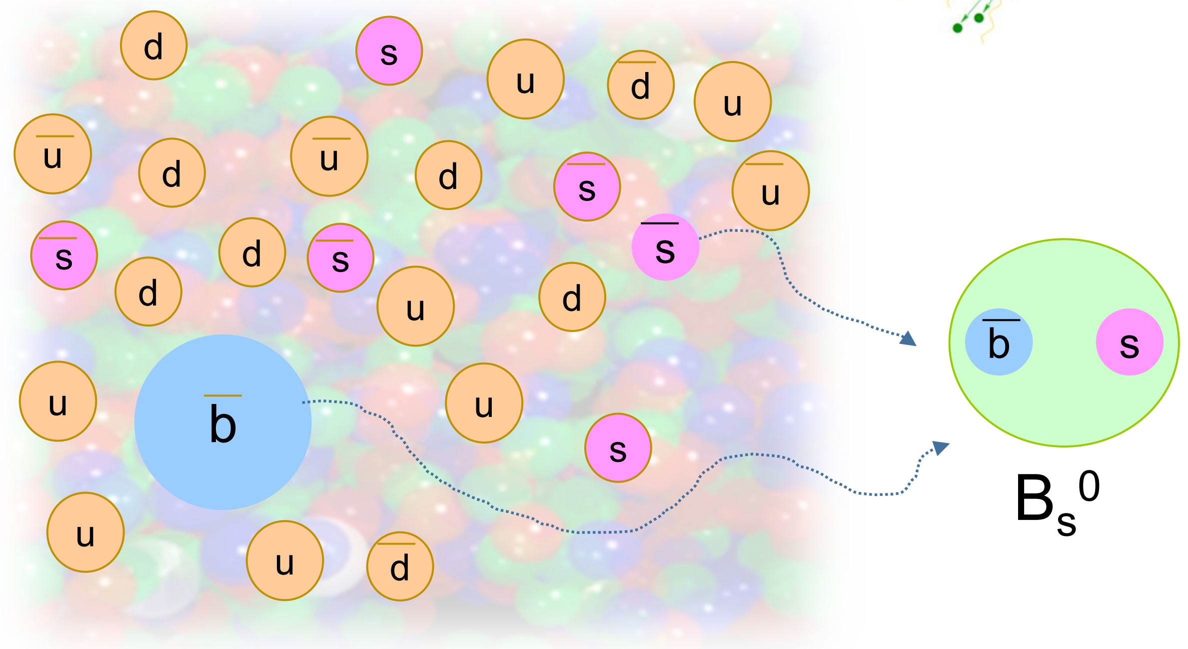
Beauty Quark Hadronization in PbPb

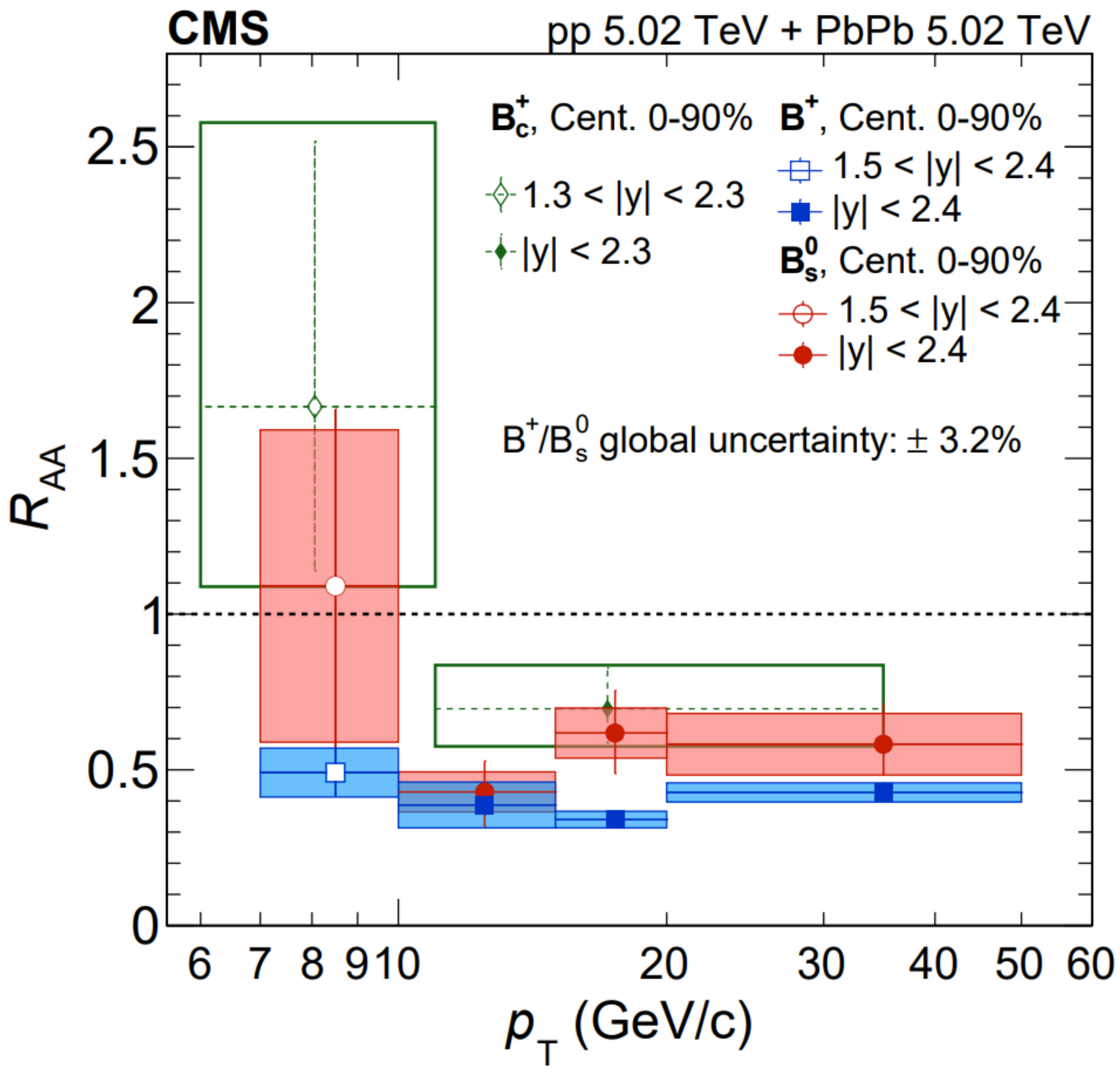


Parton shower



Parton Coalescence



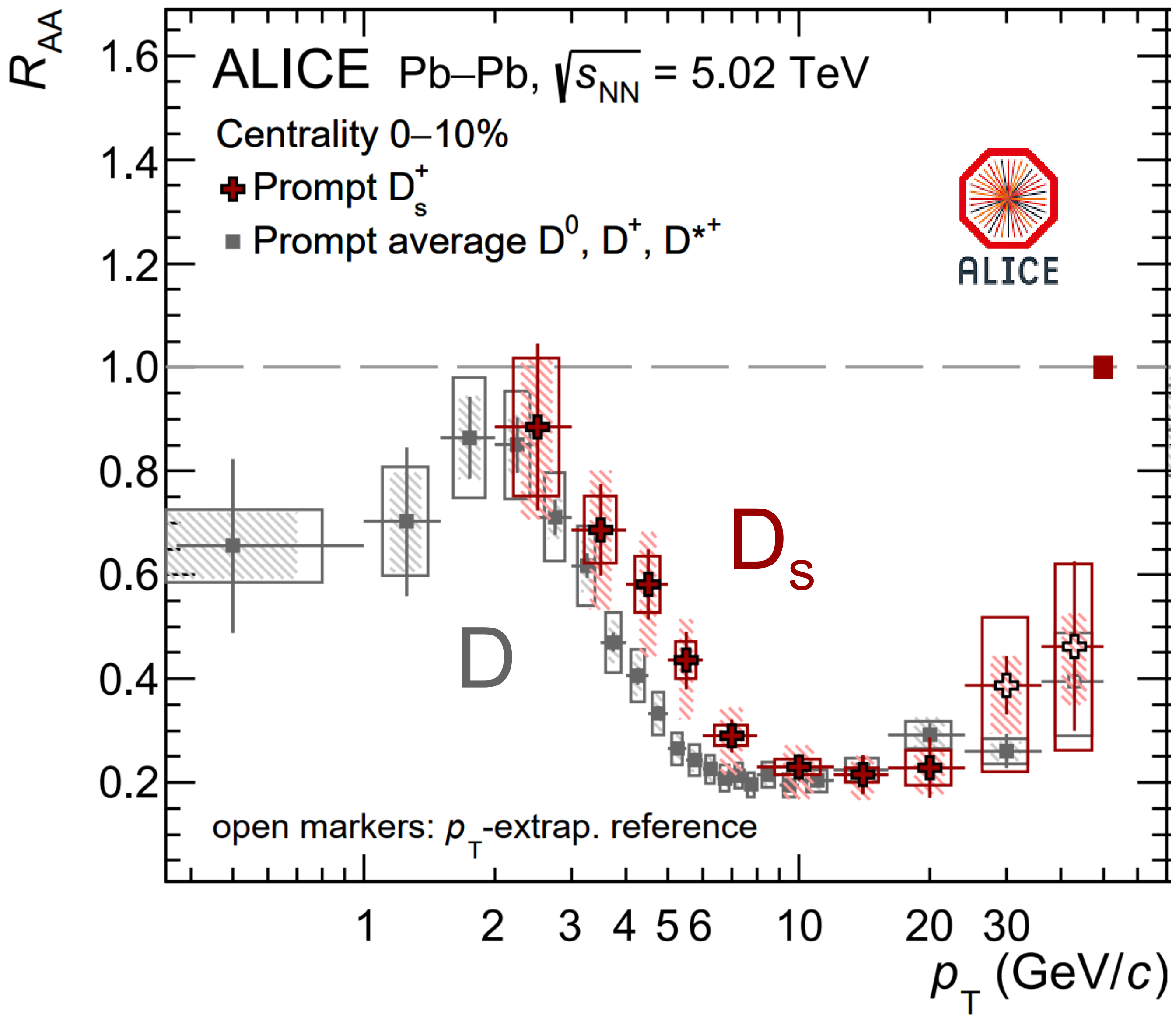


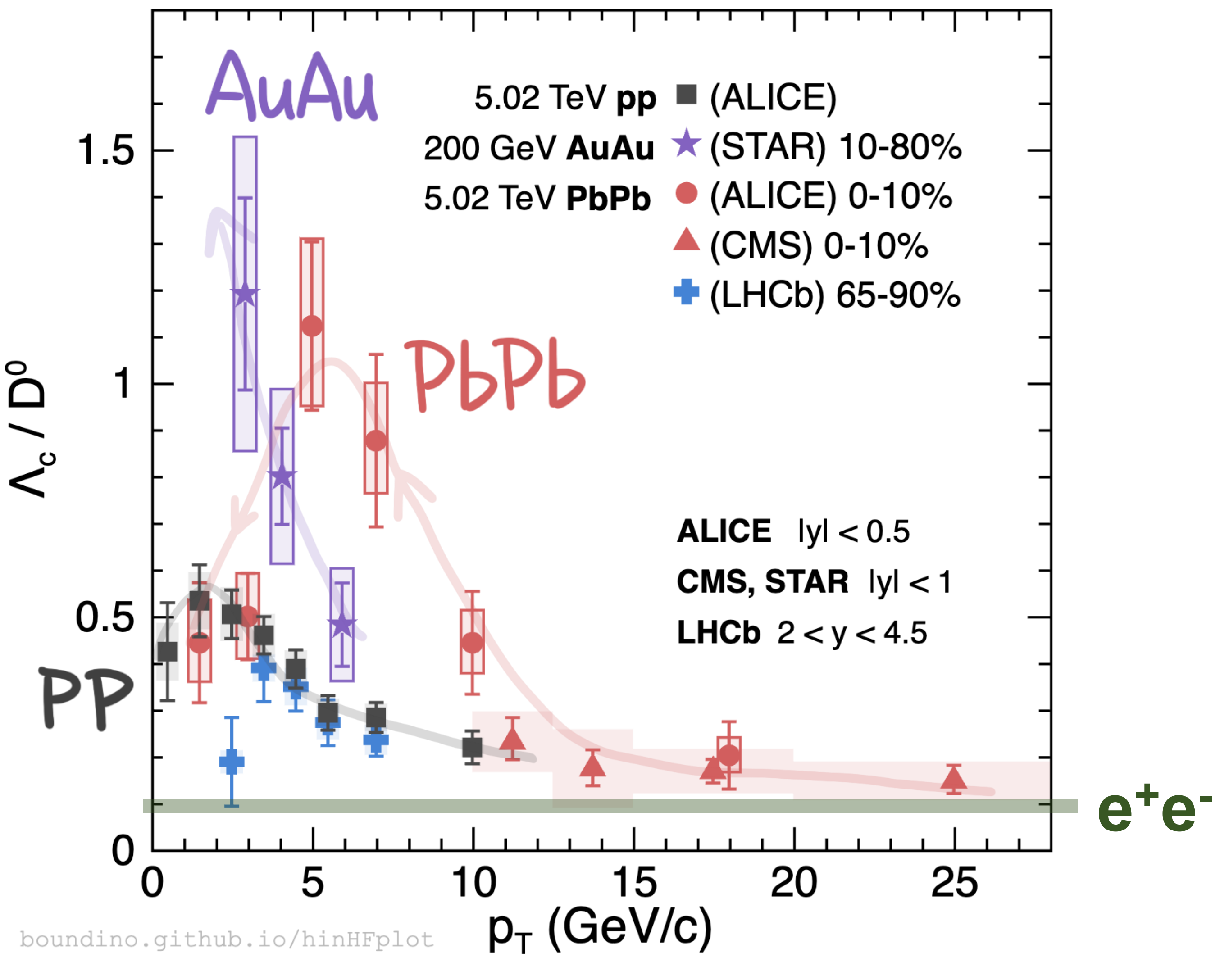
In PbPb, there are **additional modifications** beyond pp collisions:

$B_c^+ R_{AA} \geq$ **B_s** $\geq$ **B^+**

PRL 128 (2022) 25, 252301
JHEP 02 (2025) 195

Charm Quark Hadronization



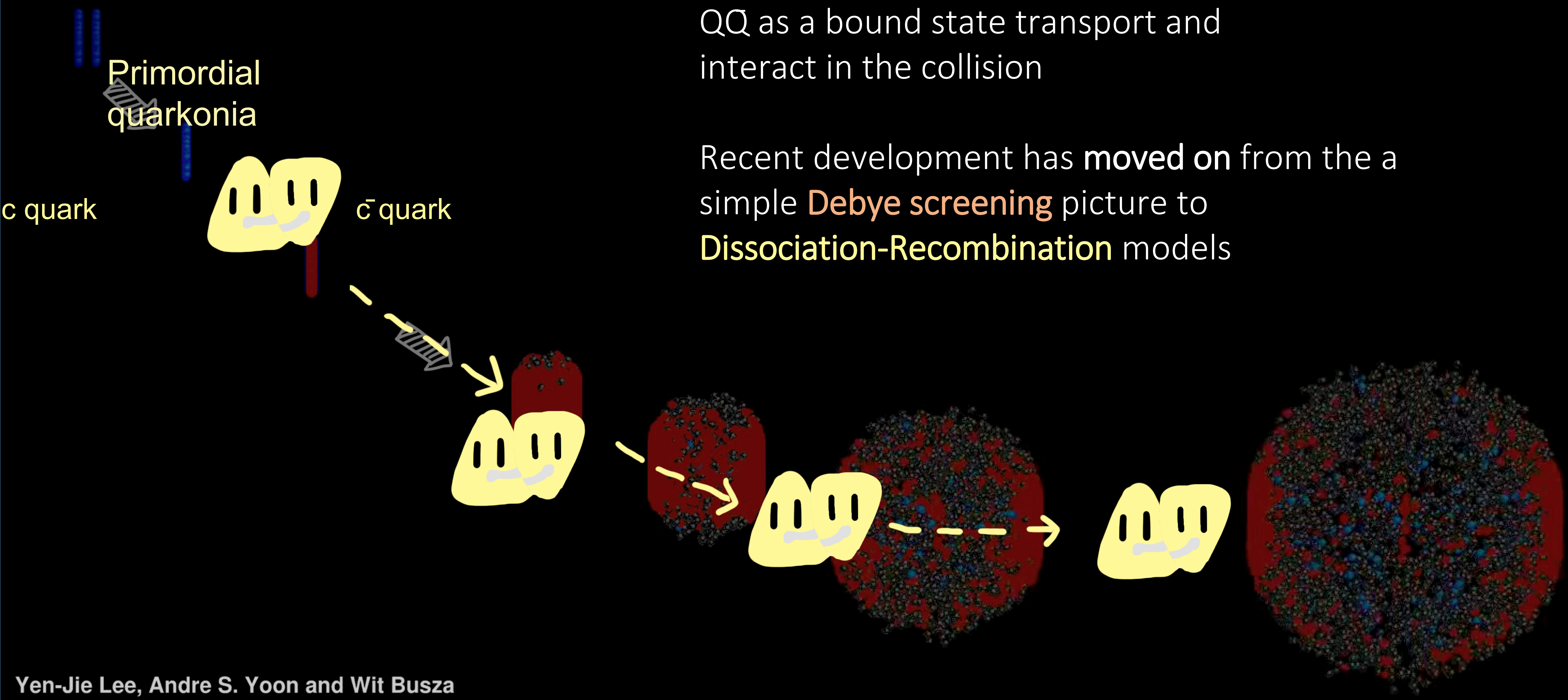


EPJC 78 (2018) 762 JHEP 02 (2024) 066

Indication of enhanced production of D_s (2.3σ) in PbPb collisions

Significant enhancement of charm baryon in AuAu and PbPb compared to pp at intermediate p_T

Life of a Quarkonium in HIC



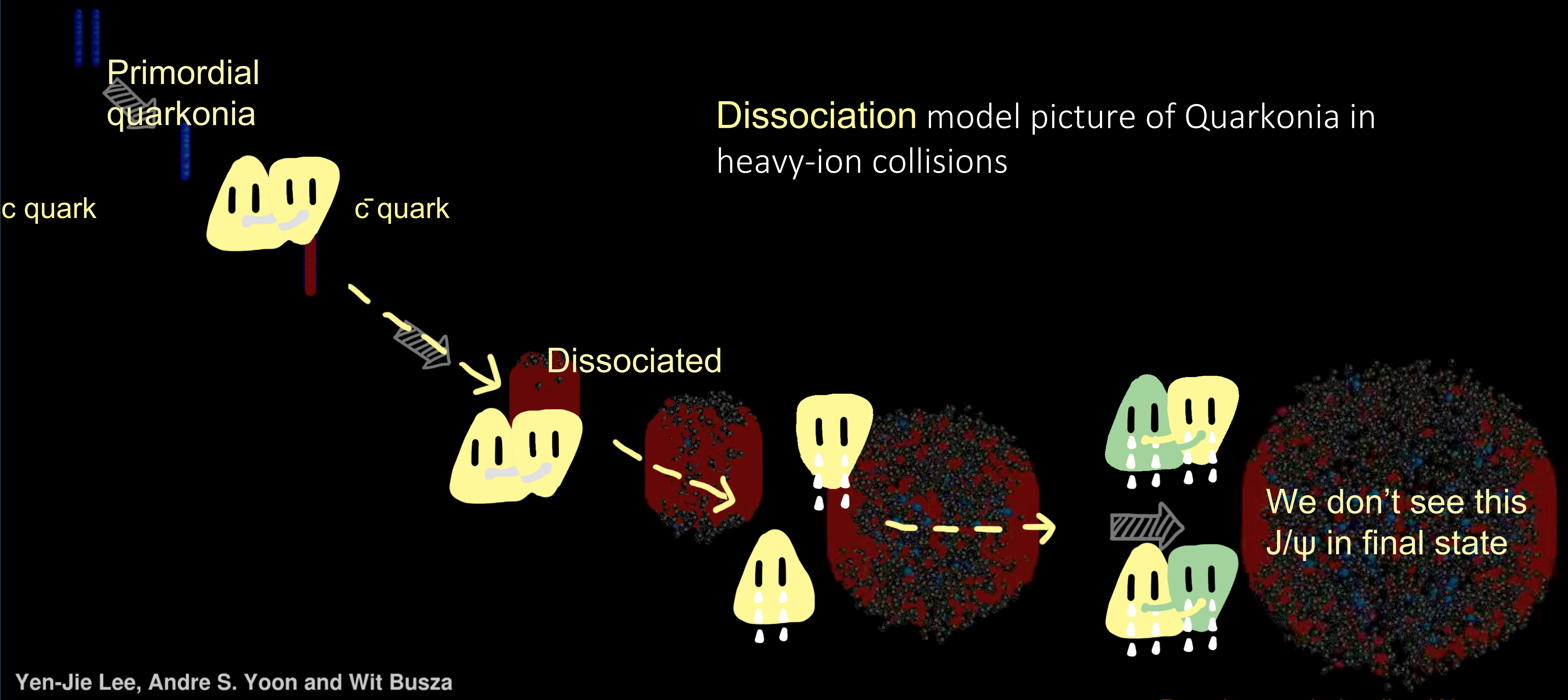
$Q\bar{Q}$ as a bound state transport and interact in the collision

Recent development has **moved on** from the a simple Debye screening picture to Dissociation-Recombination models

Drawing made by Jing Wang

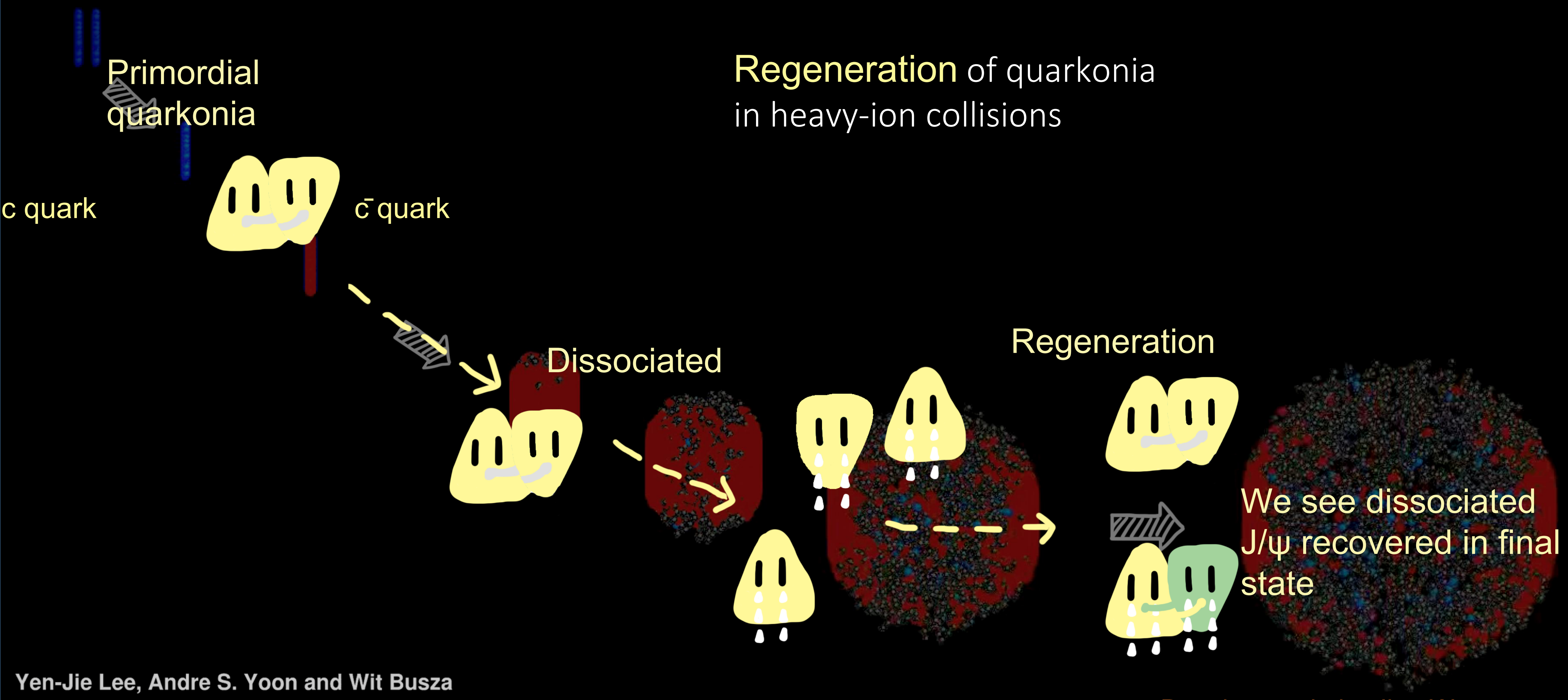
Life of a Quarkonium in HIC

Dissociation model picture of Quarkonia in heavy-ion collisions



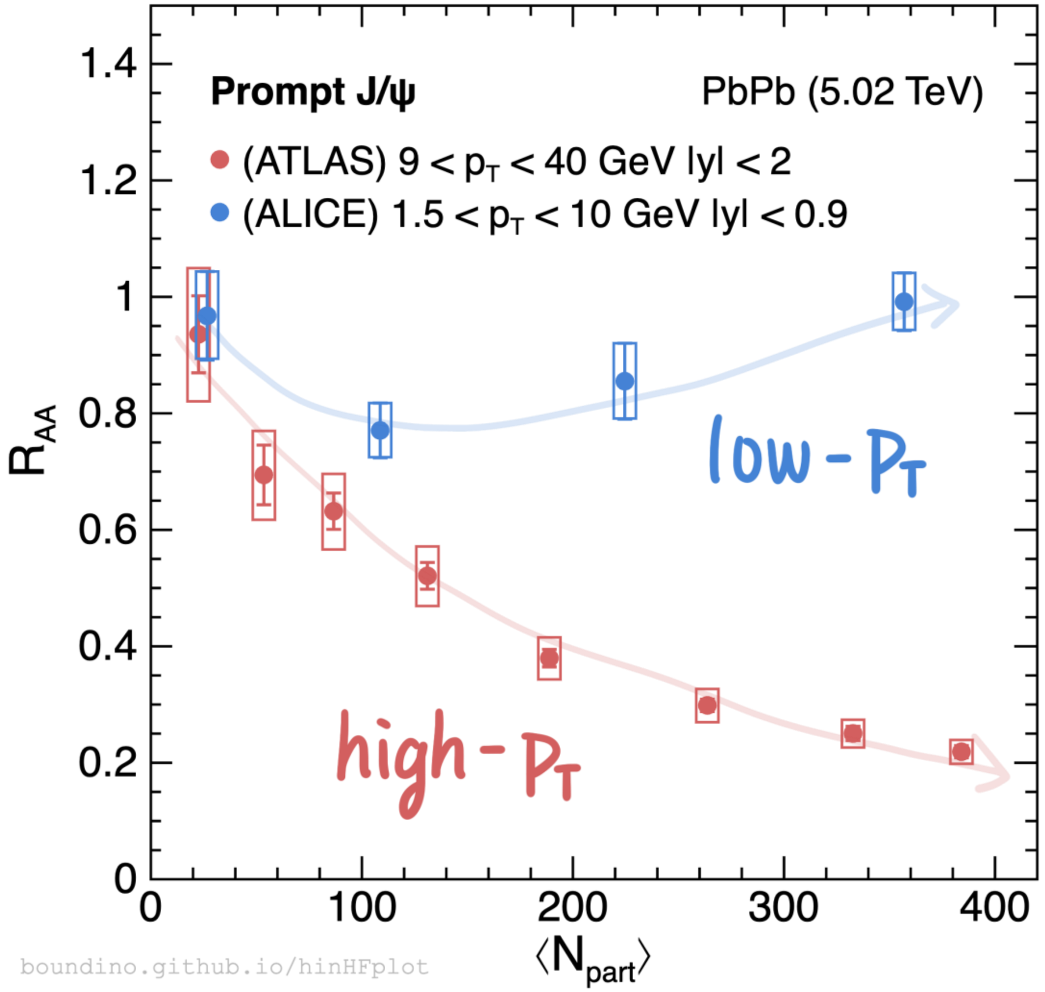
Drawing made by Jing Wang

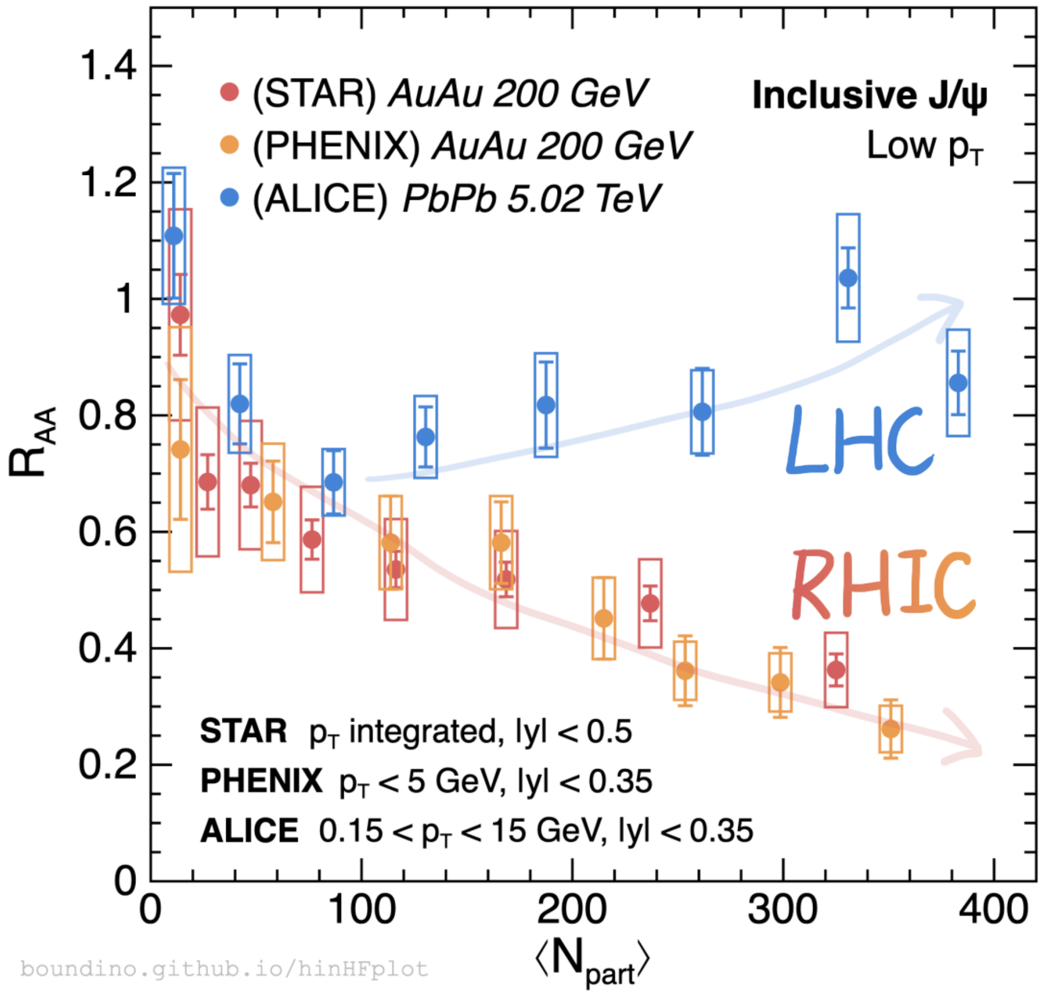
Life of a Quarkonium in HIC



Drawing made by Jing Wang

Charmonia in QGP Regeneration



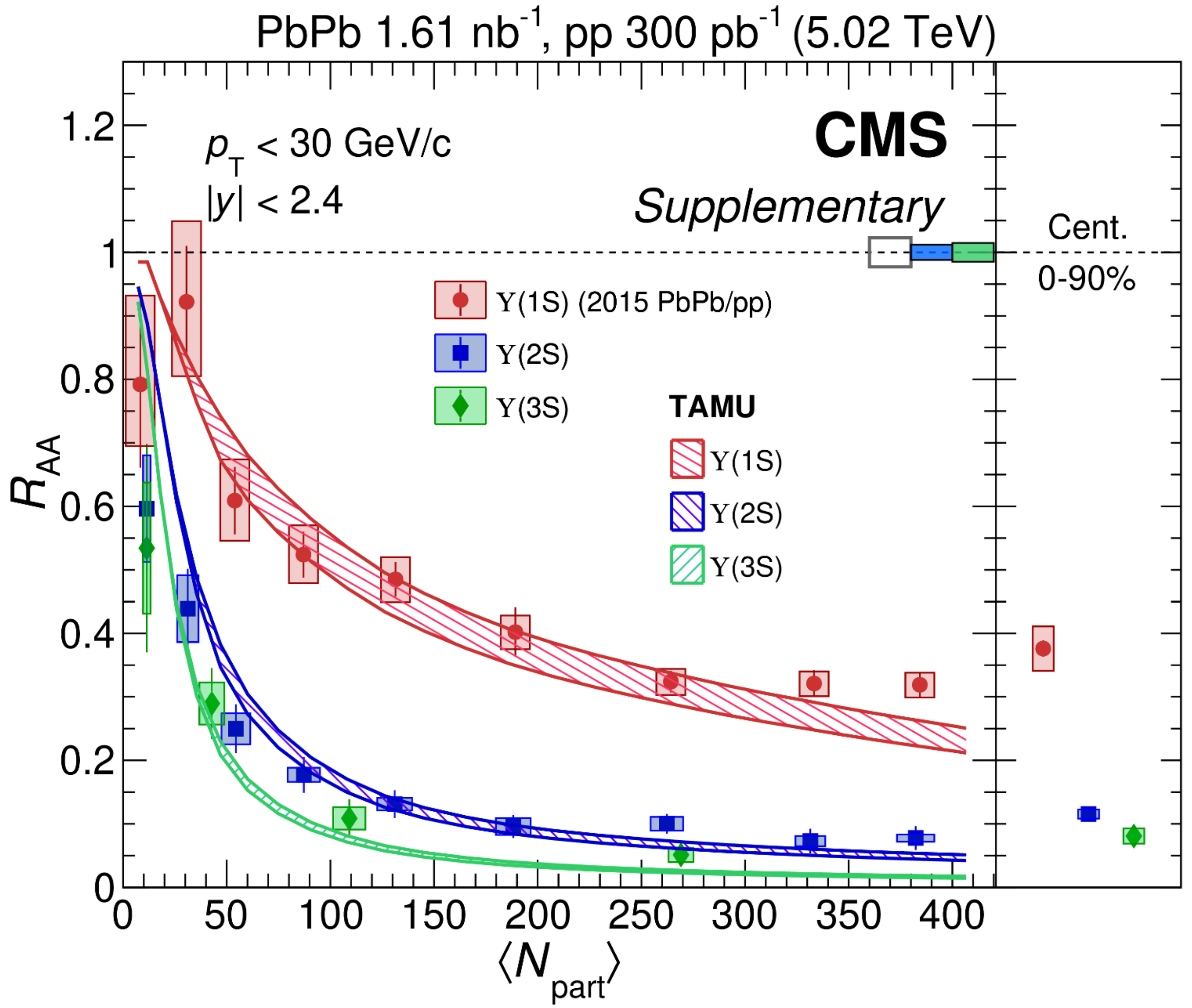


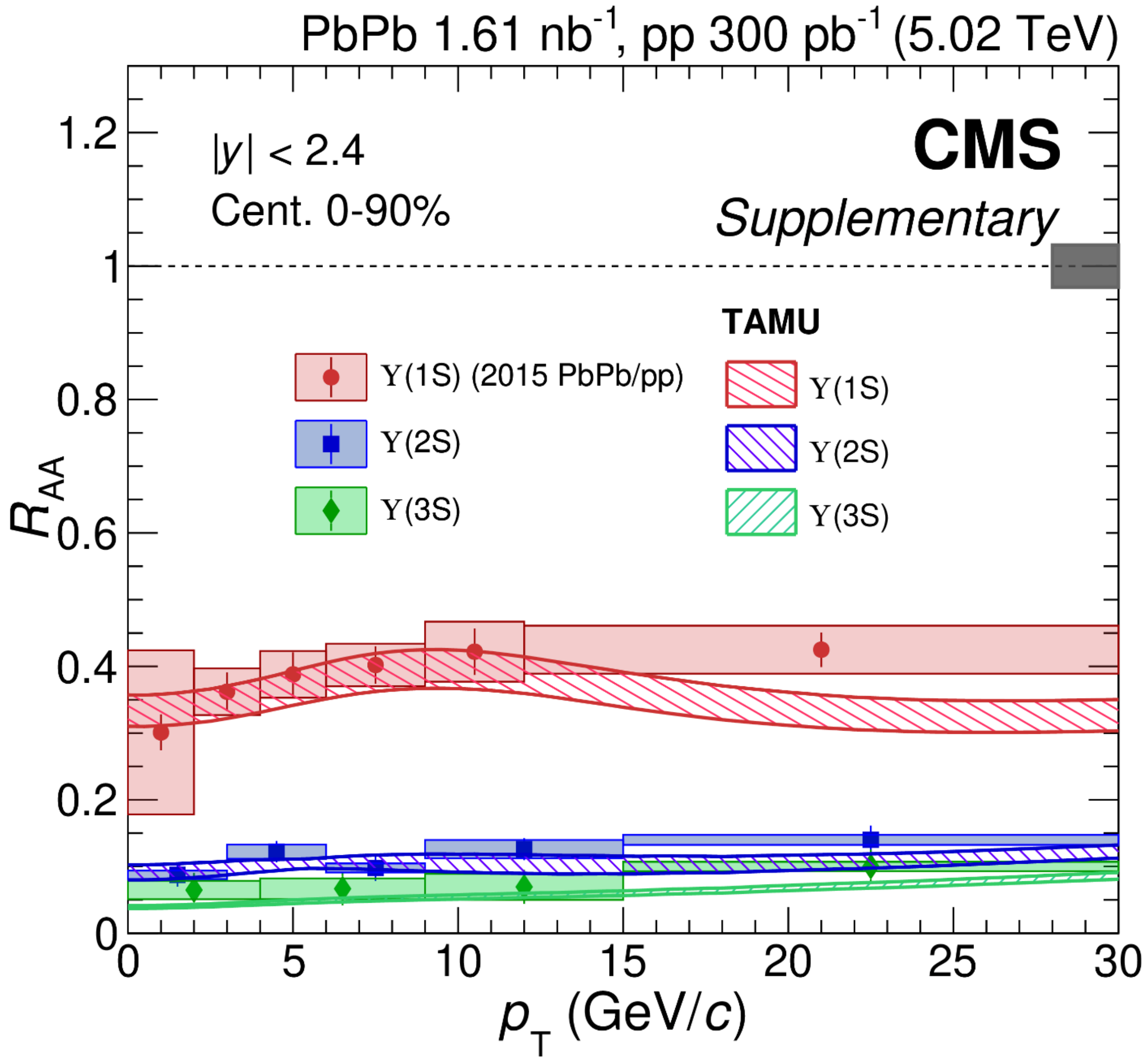
Regeneration

- (Un-)correlated $Q\bar{Q}$ in QGP regenerate Quarkonia
- Increasing R_{AA} at low p_T towards central events
  - Central events have larger $\sigma_{c\bar{c}}$

- Significant in LHC but not in RHIC
  - Higher collision energy: **larger** $\sigma_{c\bar{c}}$

Υ(nS) R_{AA} in PbPb

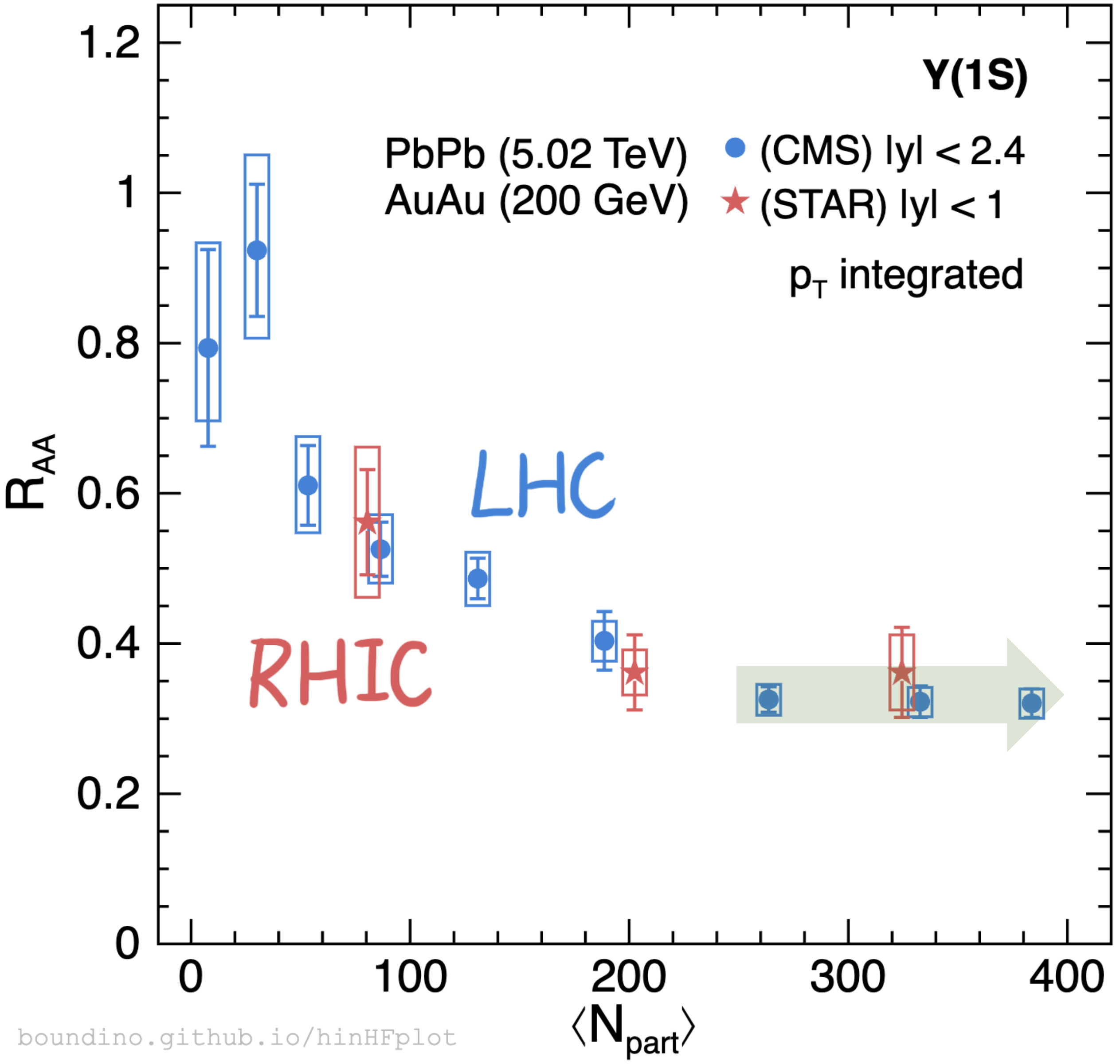




- Following the sequential suppression pattern well
- Reasonable but not perfect description from **TAMU**, tends to overpredict the suppression in central PbPb

- Is there a “flow bump”?
- Do we have room for regeneration?

Dissociation + Regeneration Picture: Challenge



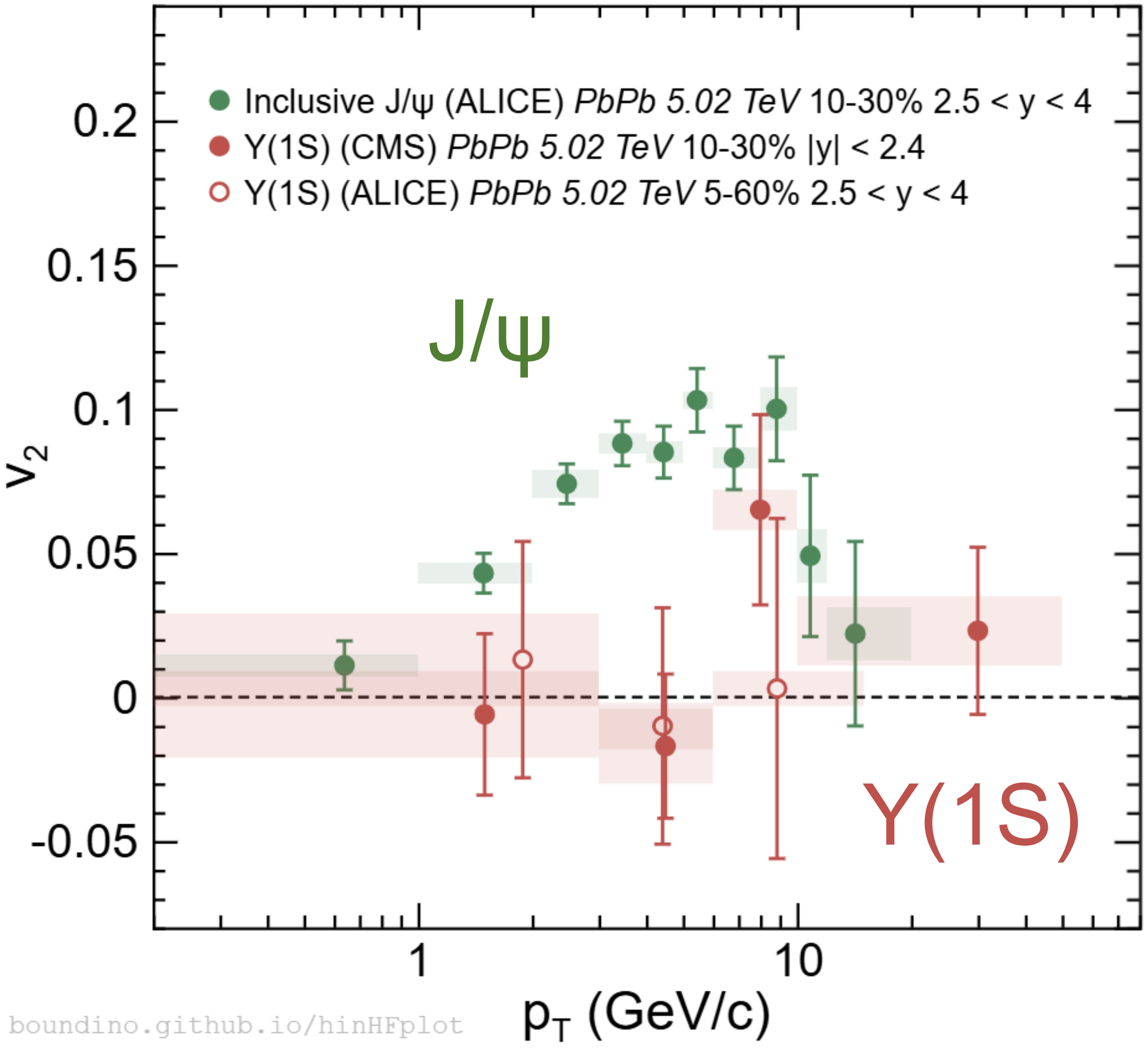
- Why is Υ(1S) suppression so similar between **LHC** and **RHIC**?
  - Regeneration in LHC compensated the effect from higher initial temperature?

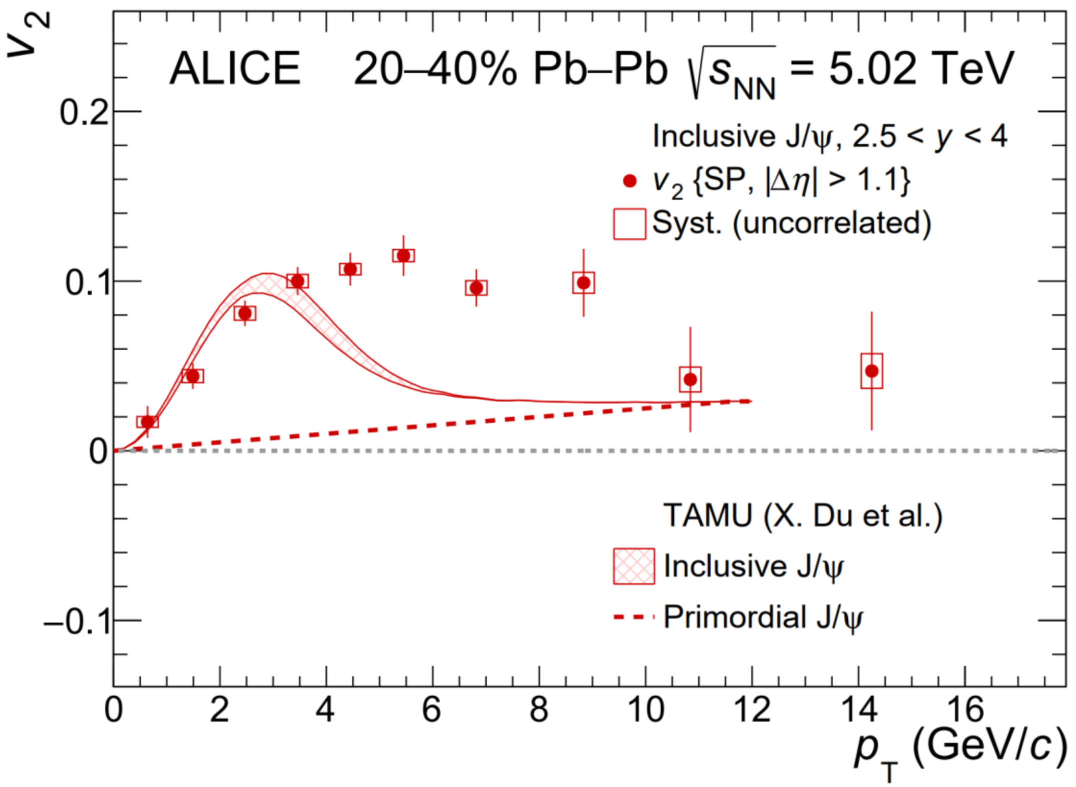
- Why does Υ(1S) not continue decreasing in most central events?
  - Models with regeneration don't describe it perfectly

PLB 790 (2019) 270 PRL 130 (2023) 112301

Collective Flow Mass Hierarchy in Quarkonia

JHEP 10 (2020) 141 PLB 819 (2021) 136385
PRL 123 (2019) 192301

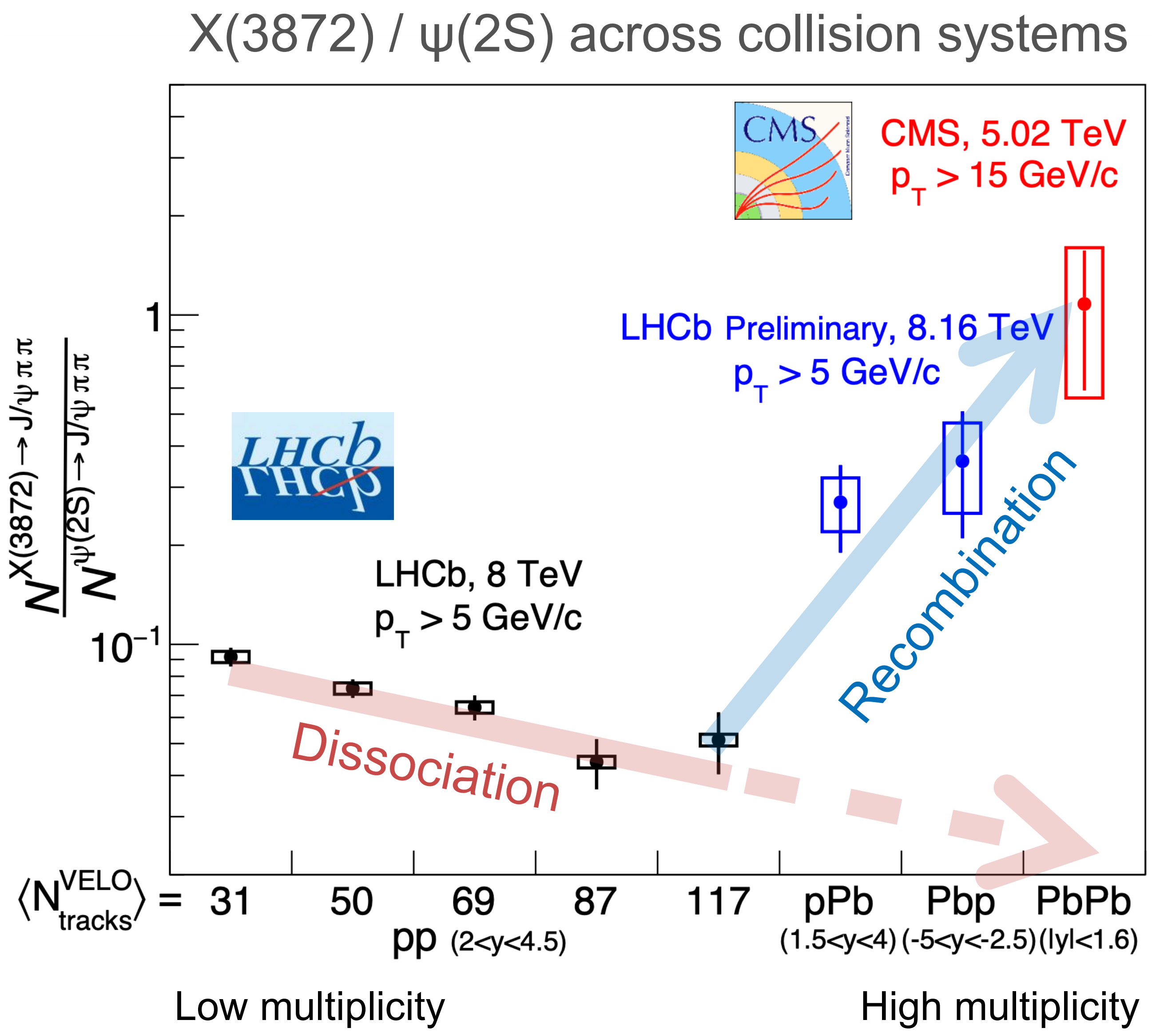




- Significant J/ψ v_2: contribution from regeneration effect, can not be described by pure melting picture
- Υ(1S) v_2 consistent with 0
  - Leave only small room for regeneration

→Generally b quarks are less hydrodynamized than charm

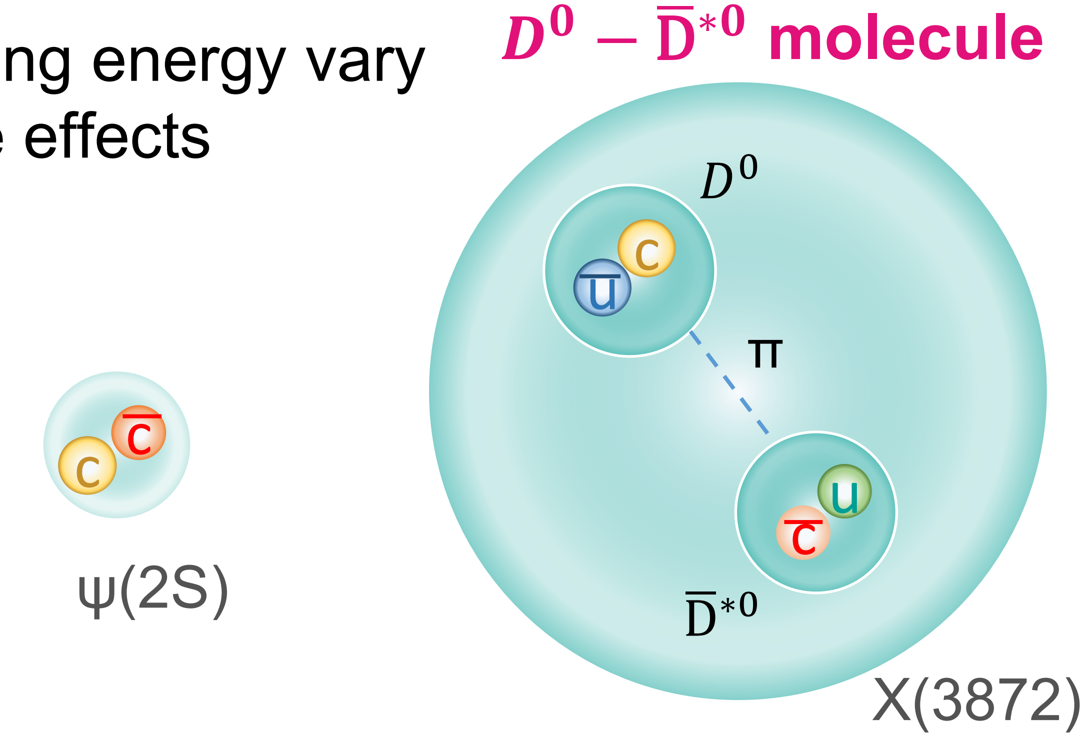
Dissociation-Recombination: Exotic Hadron X(3872)



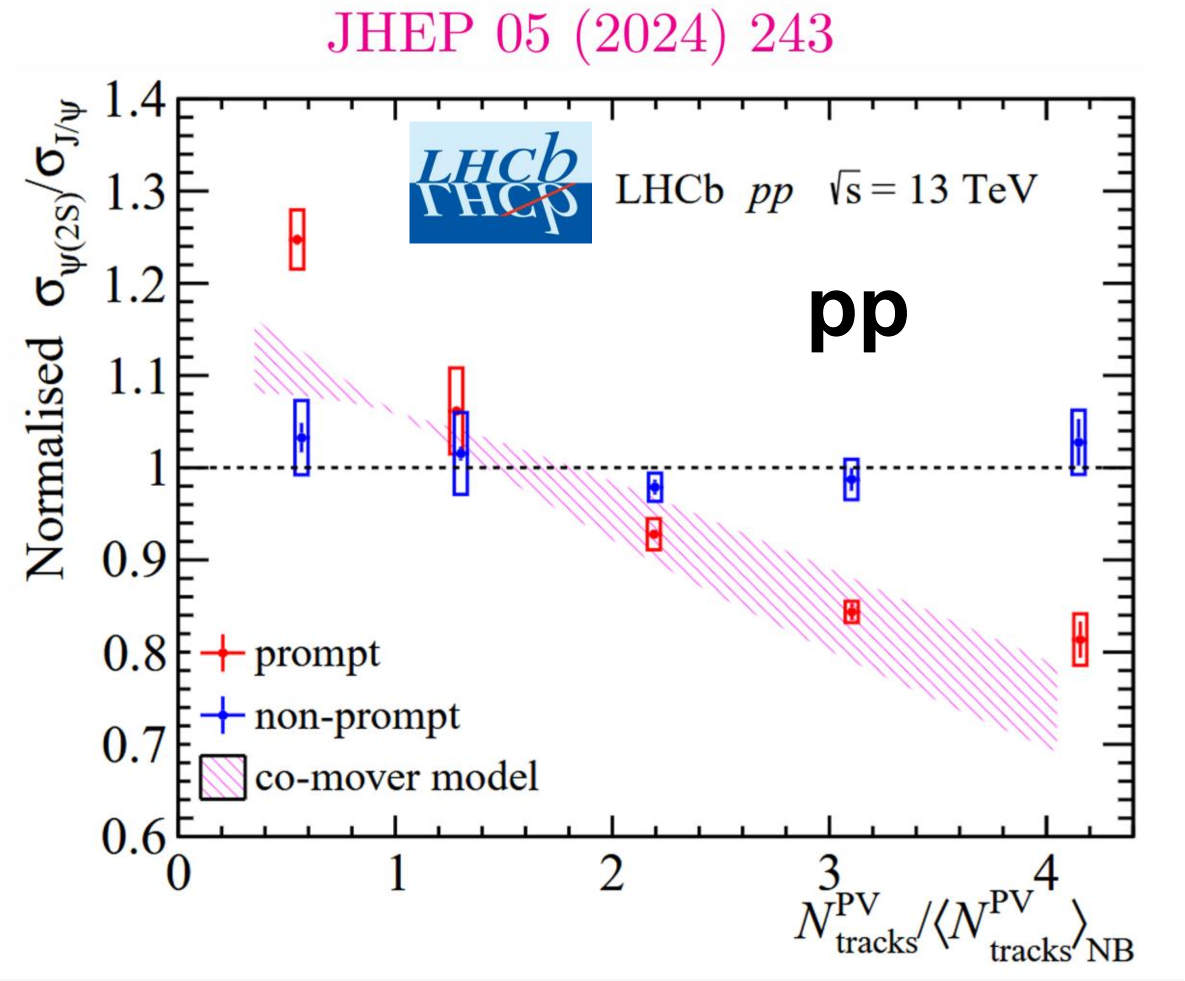
[2402.14975]

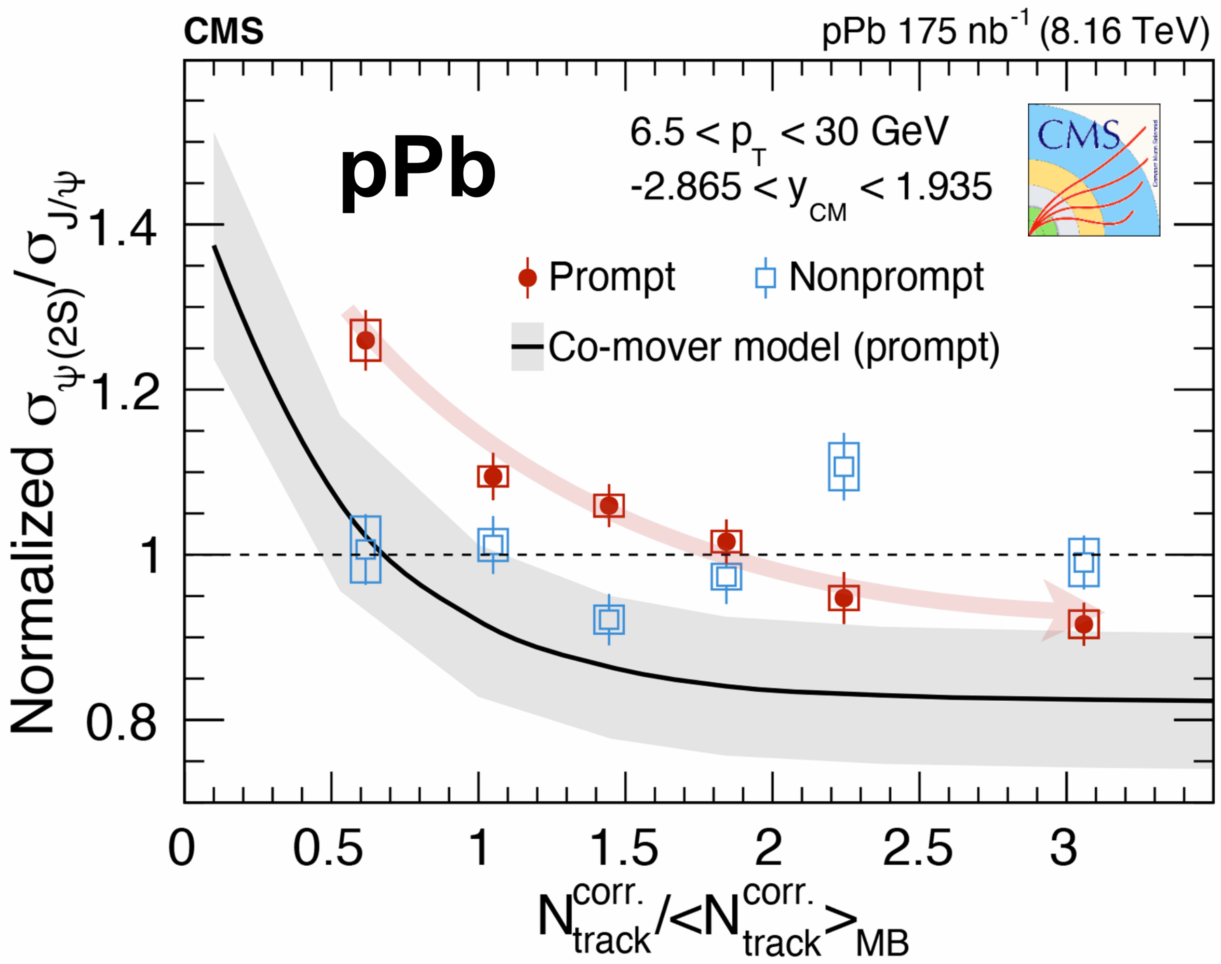
X(3872) to ψ(2S) yield ratio across collision systems:

- Dissociated by interactions with comovers (pp/pPb) or medium (PbPb)
- Enhanced via recombination
- Different binding energy vary the size of the effects



Final State Effects in pPb ψ(2S)/J/ψ vs. Multiplicity

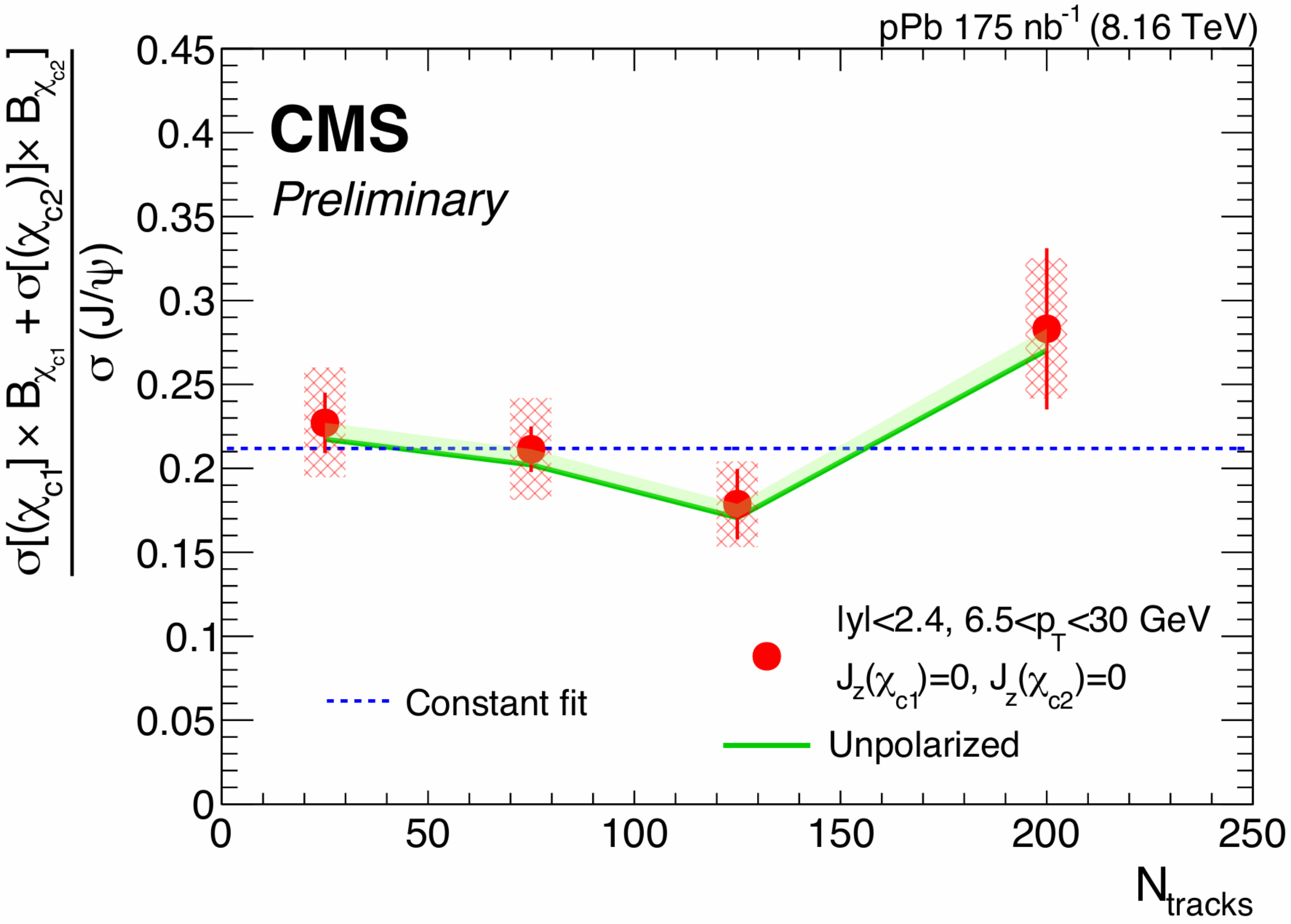




Significant **multiplicity dependence** of prompt ψ(2S)/J/ψ in **pp** and **pPb**

- Can't be due to initial state effects alone
- **Weaker bound state** ψ(2S) easier to be destroyed
  - Predicted by **comover models** but can't describe data qualitatively

Final State Effects in pPb X_c/J/ψ vs Multiplicity



X_{c1}, X_{c2}

- Binding energy between J/ψ and ψ(2S)
- Different orbital angular momentum

X_c/J/ψ **does not** have significant multiplicity dependence in pPb

- Comover / dissociation picture doesn't hold?
- Angular momenta change final state interactions?

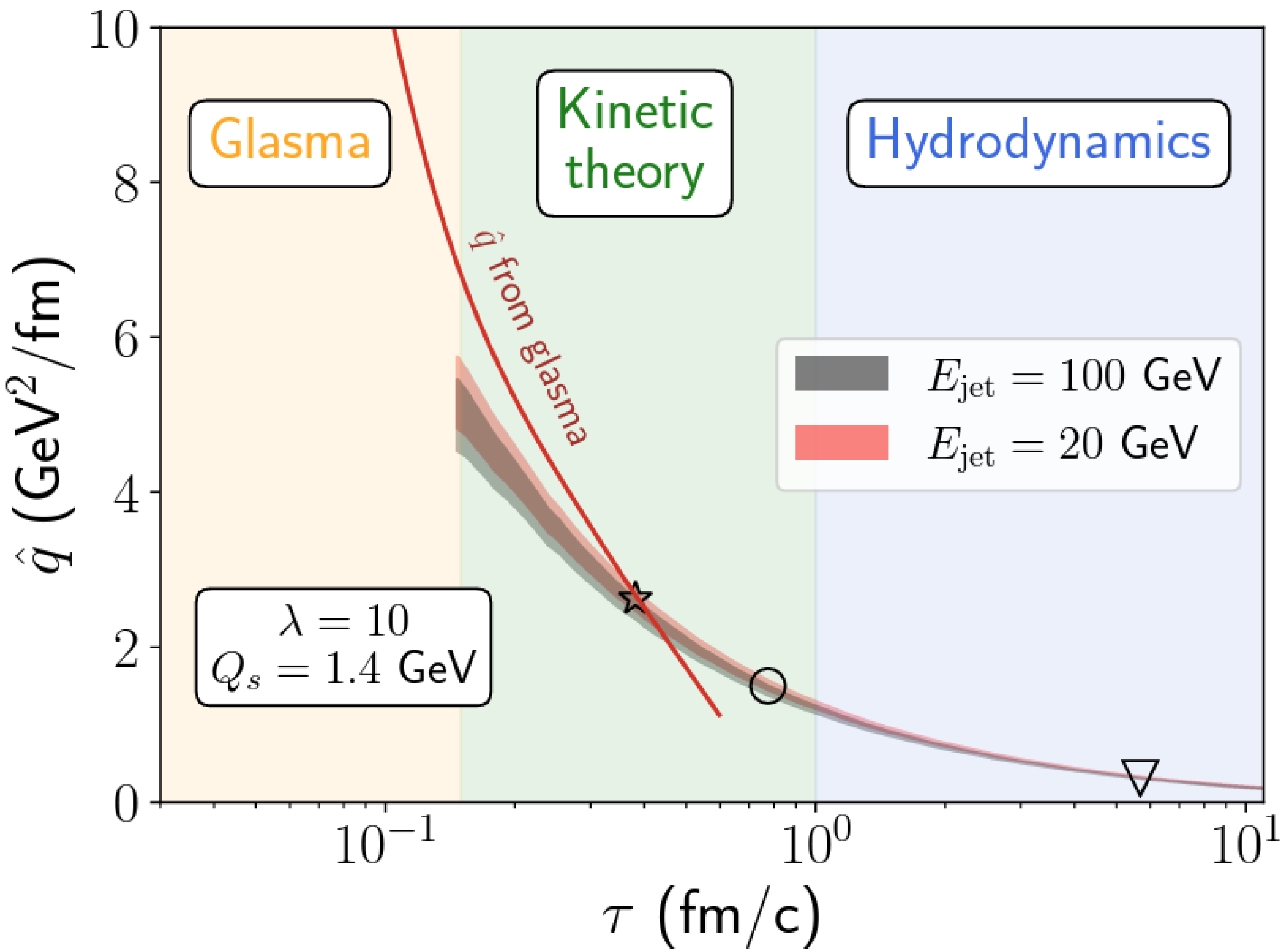
Medium Properties

Time Dependence of Jet Quenching (and Diffusion?)

- We know really little about time dependence
- Jet quenching parameter extracted from data mostly **only in hydrodynamics phase**
- To describe high p_T hadron **v_2** and **R_{AA}**, later **quenching start time** τ_0 is preferred in models:
  - Carlota Andres et al. (R_{AA} and v_2, PLB 803 (2020) 135318) : τ_0 ~ 0.6 fm/c
  - JETSCAPE (R_{AA}): τ_0 ~ 0-1 fm/c
- What is the role of the **Glasma** phase?

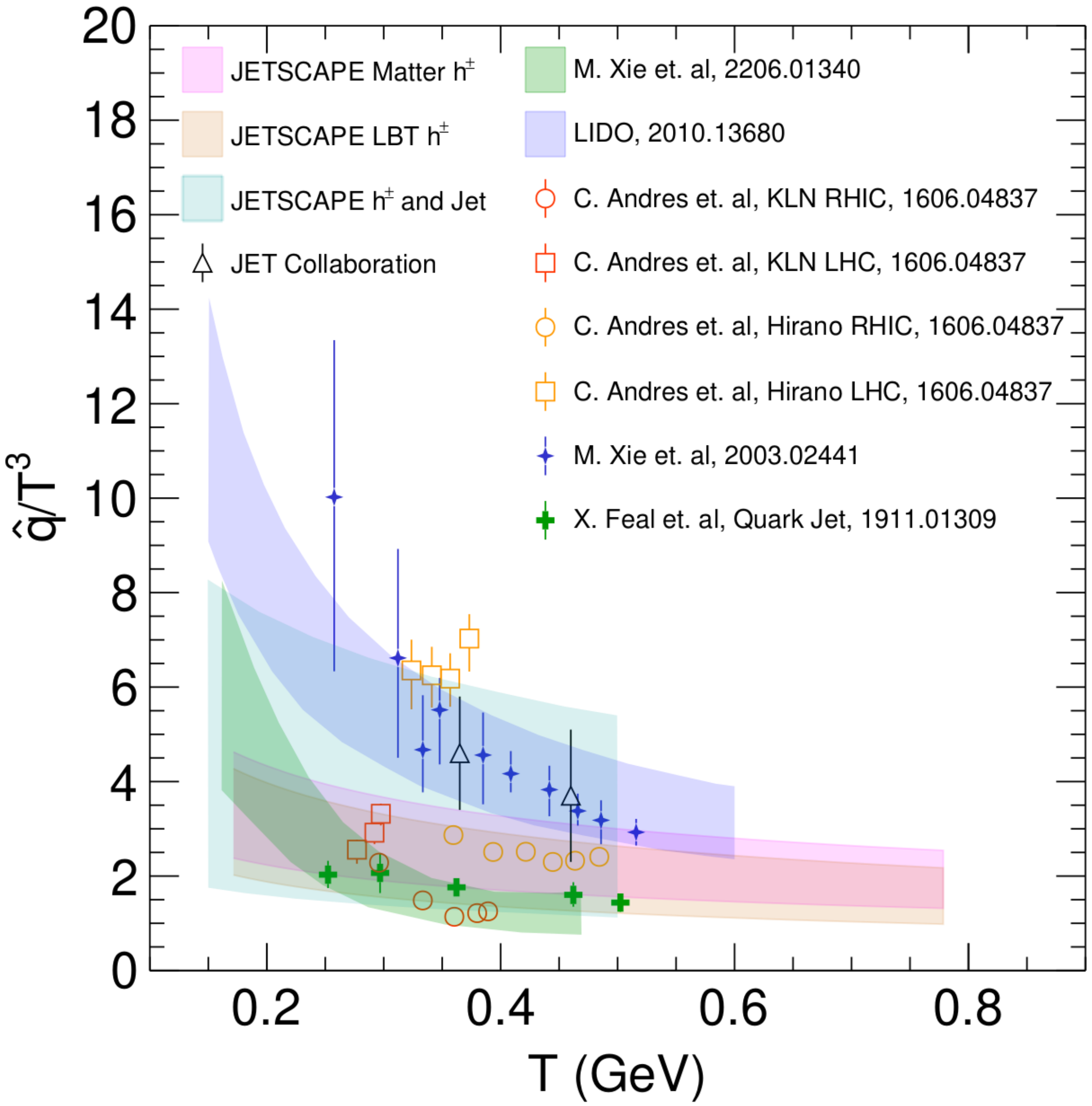
→ Need to measure **hadronic W/Z jets** which Skip jet Quenching in the first O(0.1 fm)

What can we measure in the HF sector?



[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

QGP Transport Properties with RHIC and LHC Run 2 Data



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022), plot updated for 2025 DNP meeting

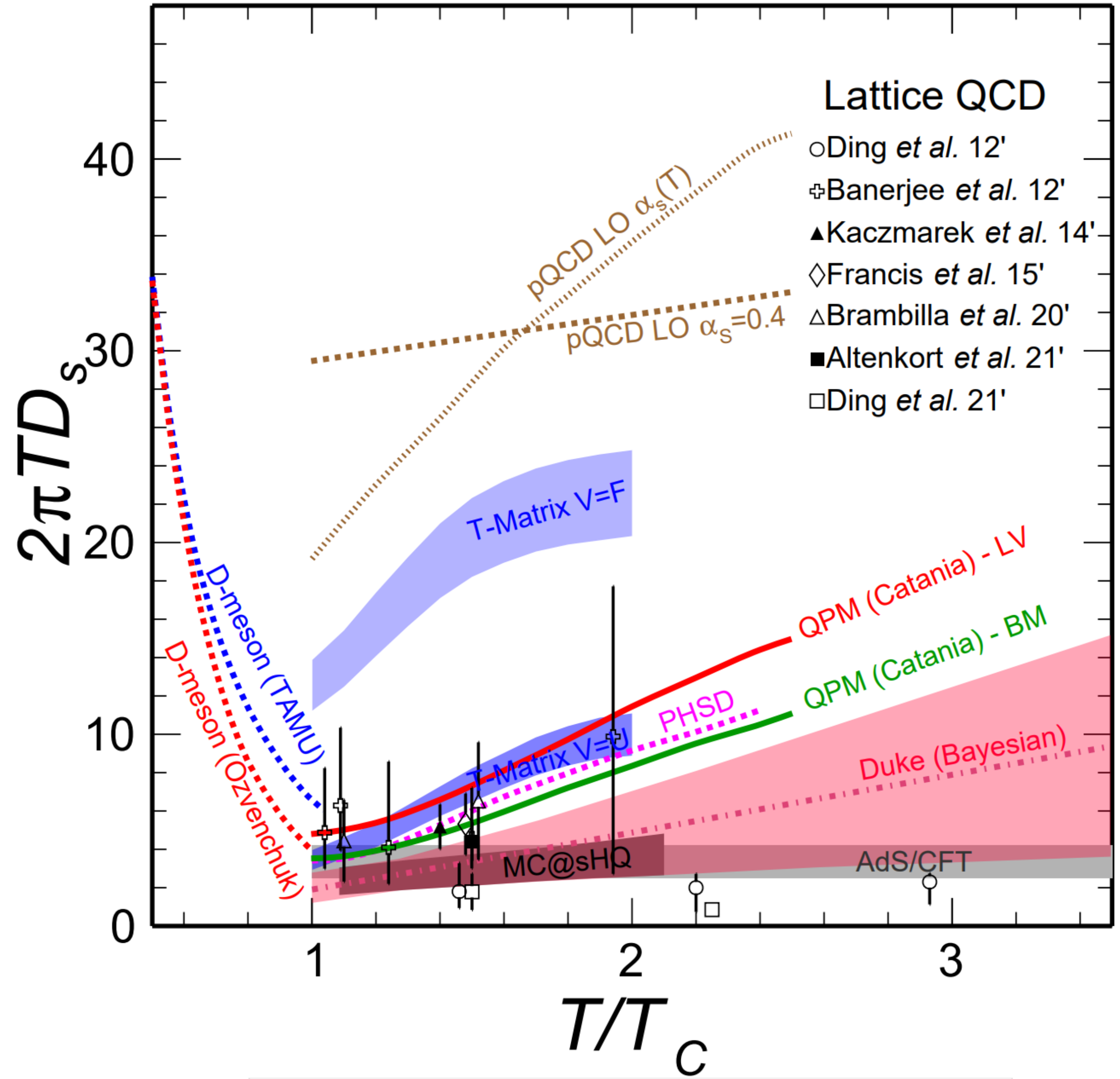
Jet Quenching Parameter $\hat{q}$

- Extracted mainly from charged hadron spectra R_{AA} data
  - Some analyses included γ-hadron and di-hadron data
  - Expansion to include jet observables has started (for instance, **JETSCAPE h± and Jet**)
- $\hat{q}/T^3$: decreasing trend vs. T
- Extracted values differ by up to a factor of 7 (!)

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- Different QGP media used in calculations
- Hadron re-scattering in the hadron gas phase
- Hadronization of fast moving partons
- Role of initial stages

QGP Transport Properties with RHIC and LHC Run 2 Data



Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

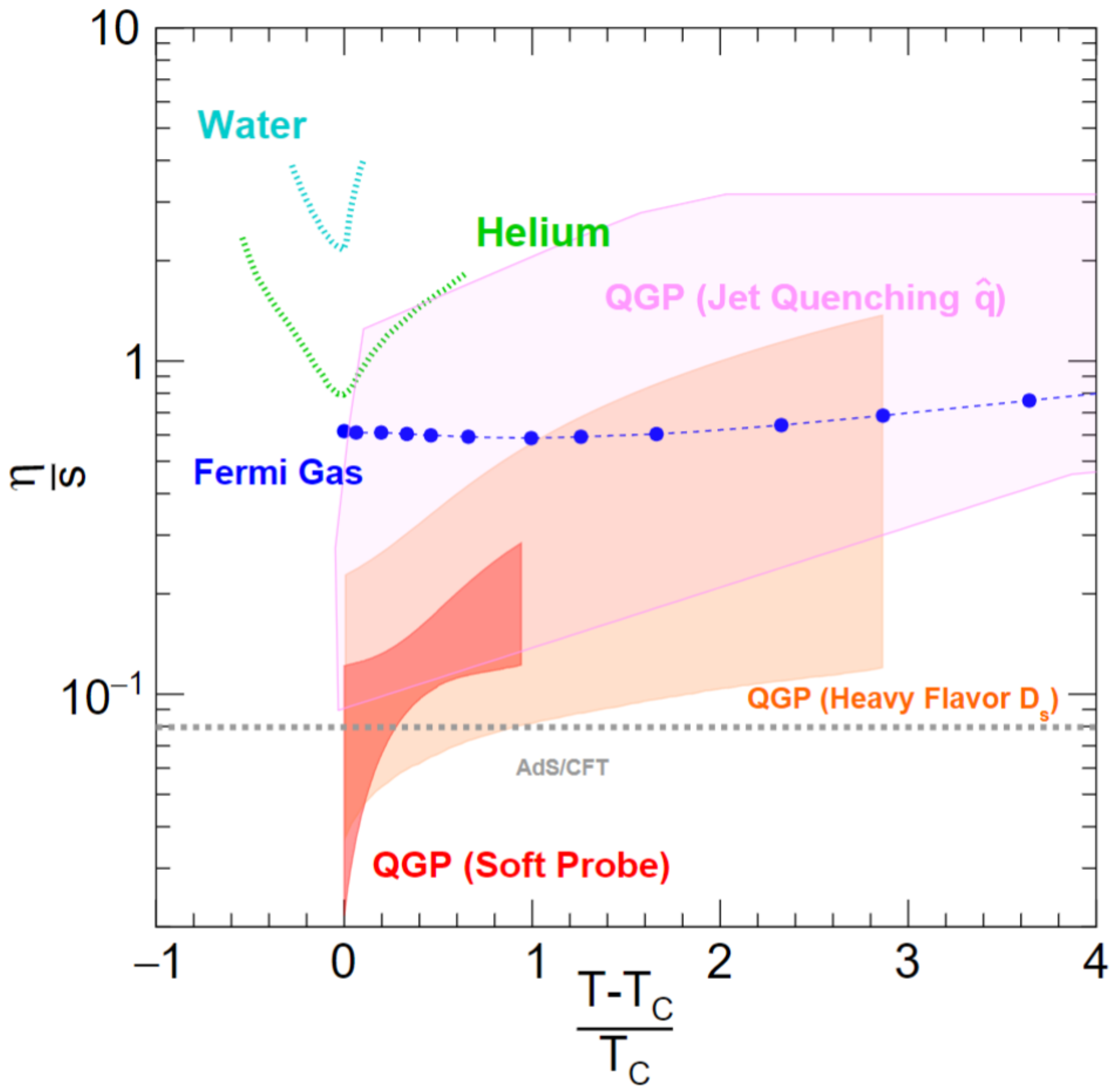
Charm diffusion coefficient D_s

- Bayesian analysis from D meson R_{AA} and v_2
- pQCD calculations at LO are ruled out by the data
- Non-perturbative calculations with a potential close to the HQ free energy from LQCD are not viable
- Increasing trend of $2\pi TD_s$ vs. T in various models

Remaining Issues:

- Hadronization of charm quarks
- Charm diffusion mechanism
- Different QGP media used in various calculations
- Role of initial stages

Medium Properties from Soft and Hard Probes



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

Specific viscosity has been extracted from **soft probes**

- Via identified hadron dN/dη, $<p_T>$, v_2, v_3 and v_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with LHC + RHIC data, one could compare the inputs from soft and hard probes:

- **HQ D_s** could be related to specific viscosity by

$$\frac{\eta}{s} = \frac{D_s(2\pi T)}{4\pi k}$$

R. Rapp, H. van Hees, 0903.1096
X. Dong, YJL, R. Rapp, 1903.07709

Where the scale factor k ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- **Jet quenching parameter $\hat{q}$** could be related to specific viscosity in the limit of multiple soft scattering by

$$\frac{\eta}{s} = C\frac{T^3}{\hat{q}}$$

Where the scale factor C is varied between 1.25 and 2.5

A. Majumder, B. Muller, Xin-Nian Wang PRL 99 (207) 192301
B. Muller PRD 104 (2021) 7, L071501

Medium properties extracted from **Jet Quenching** and **Open Heavy Flavor** are consistent with the results from **Soft Probes**, but within rather large uncertainties

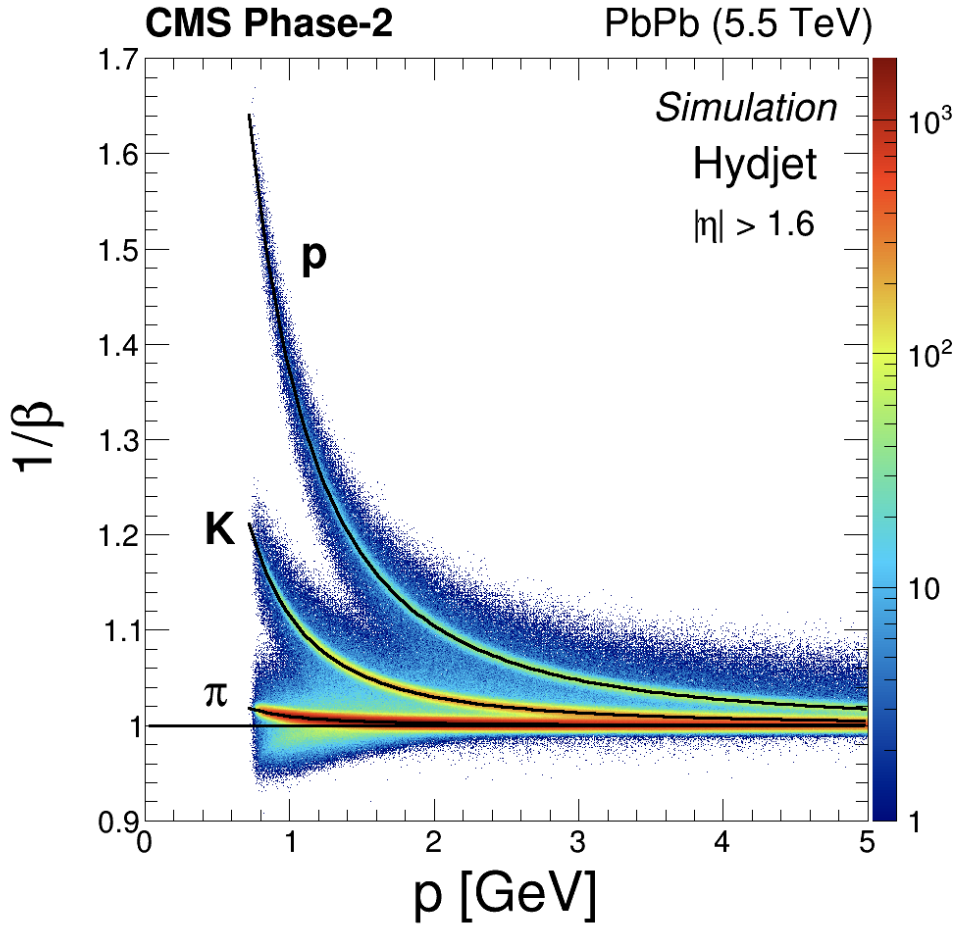
Future Performance in Run 4 Focusing on CMS

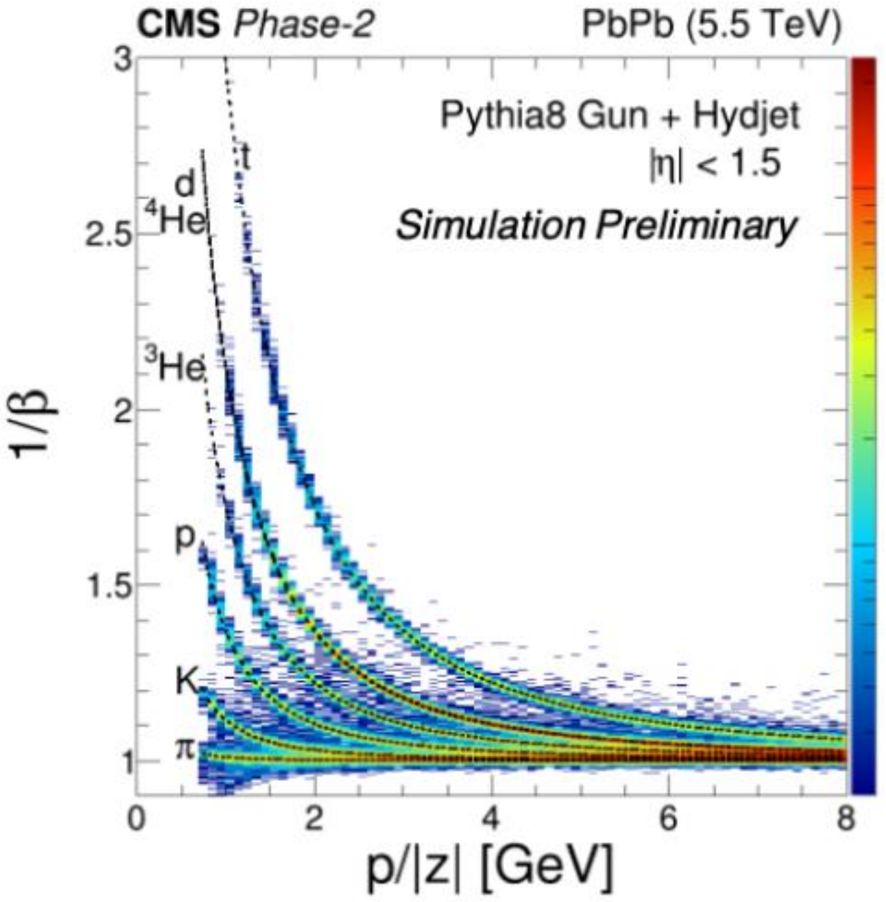
CMS MIP Timing Detector (MTD)

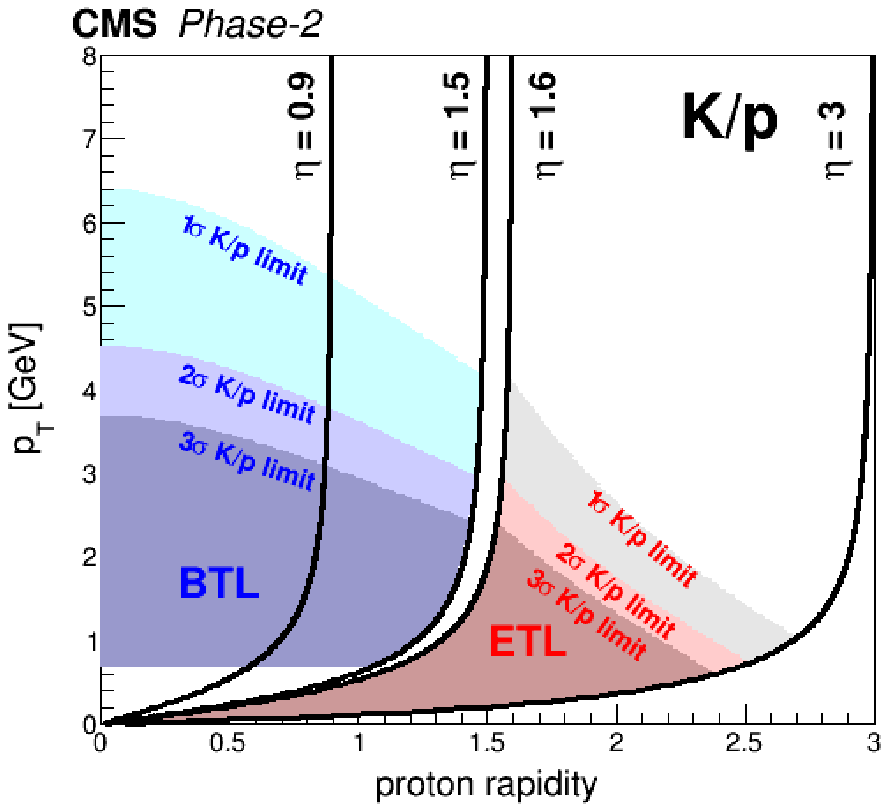
p / K / π separation

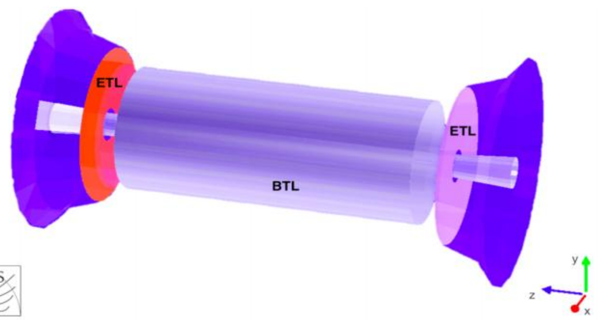
Light ion identification

CMS DP_2021_037



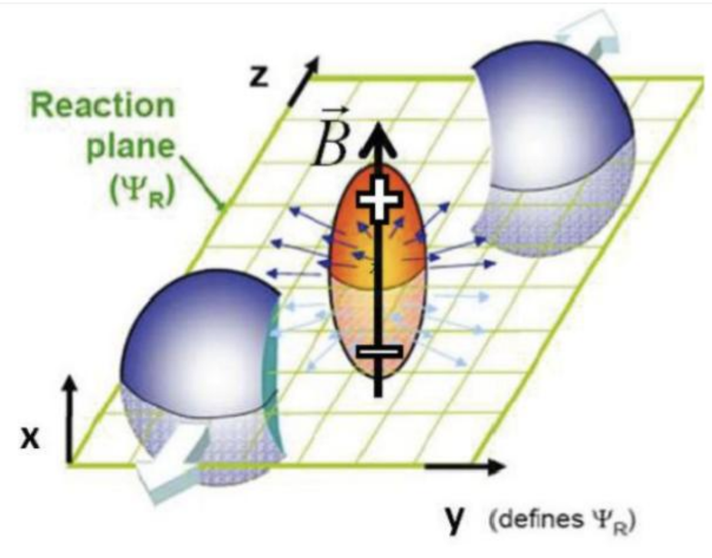




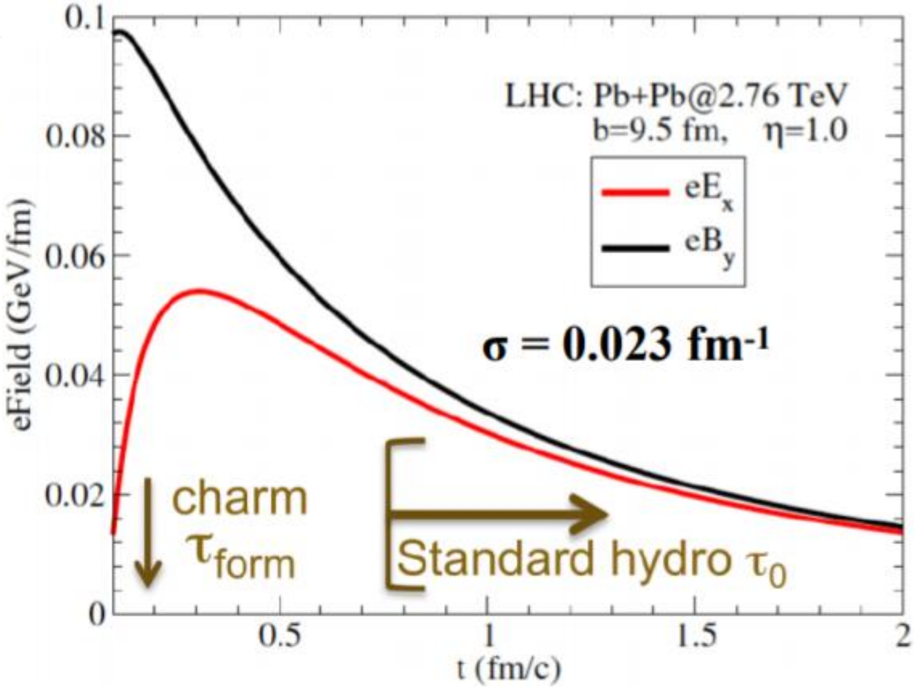


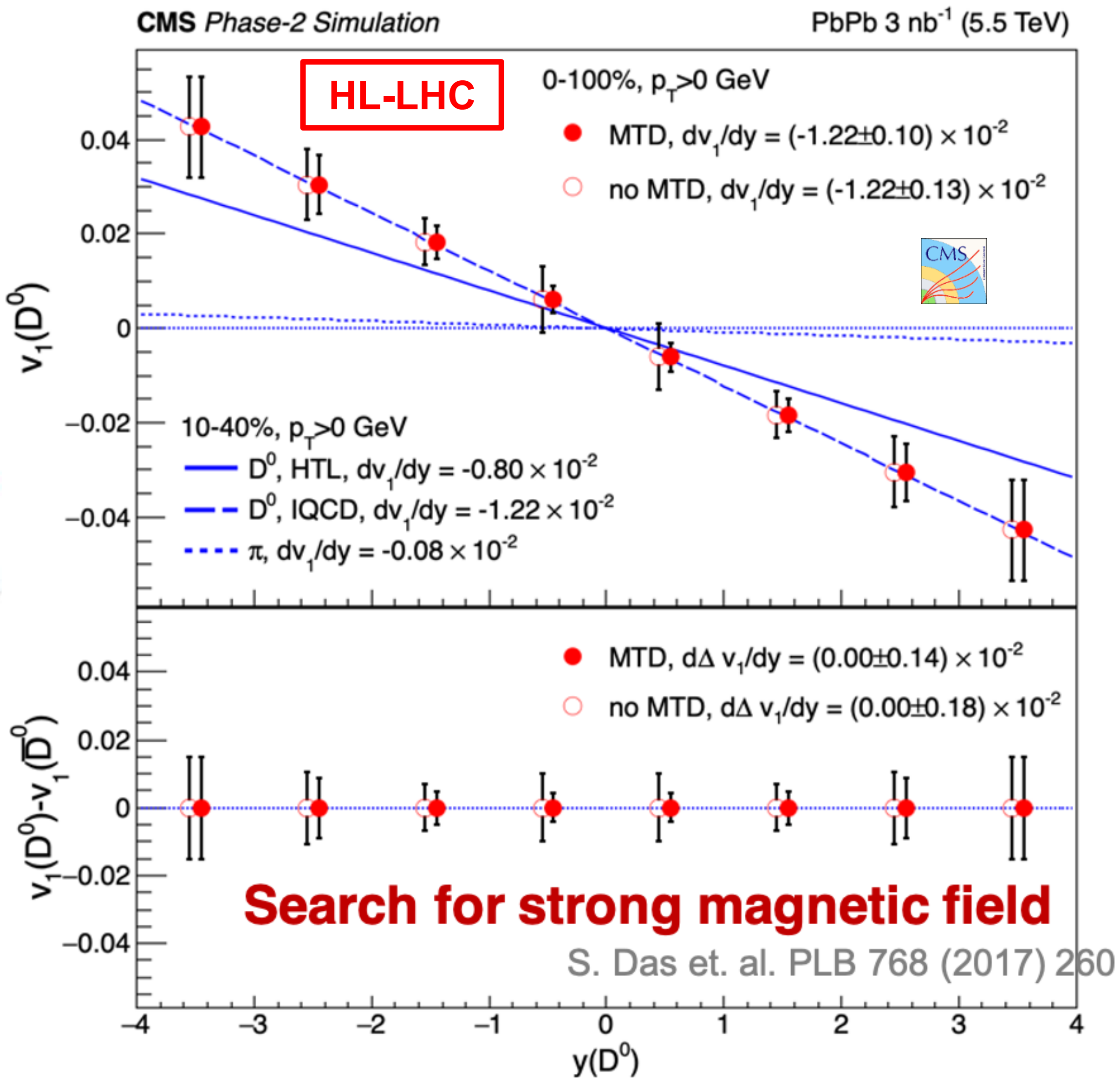
- Unique hermetic particle identification coverage by CMS MTD
- **Crucial Upgrade** for CMS Heavy Flavor Program with heavy ion collision

Initial Magnetic Field with D^0 Directed Flow v_1



CMS DP_2021_037

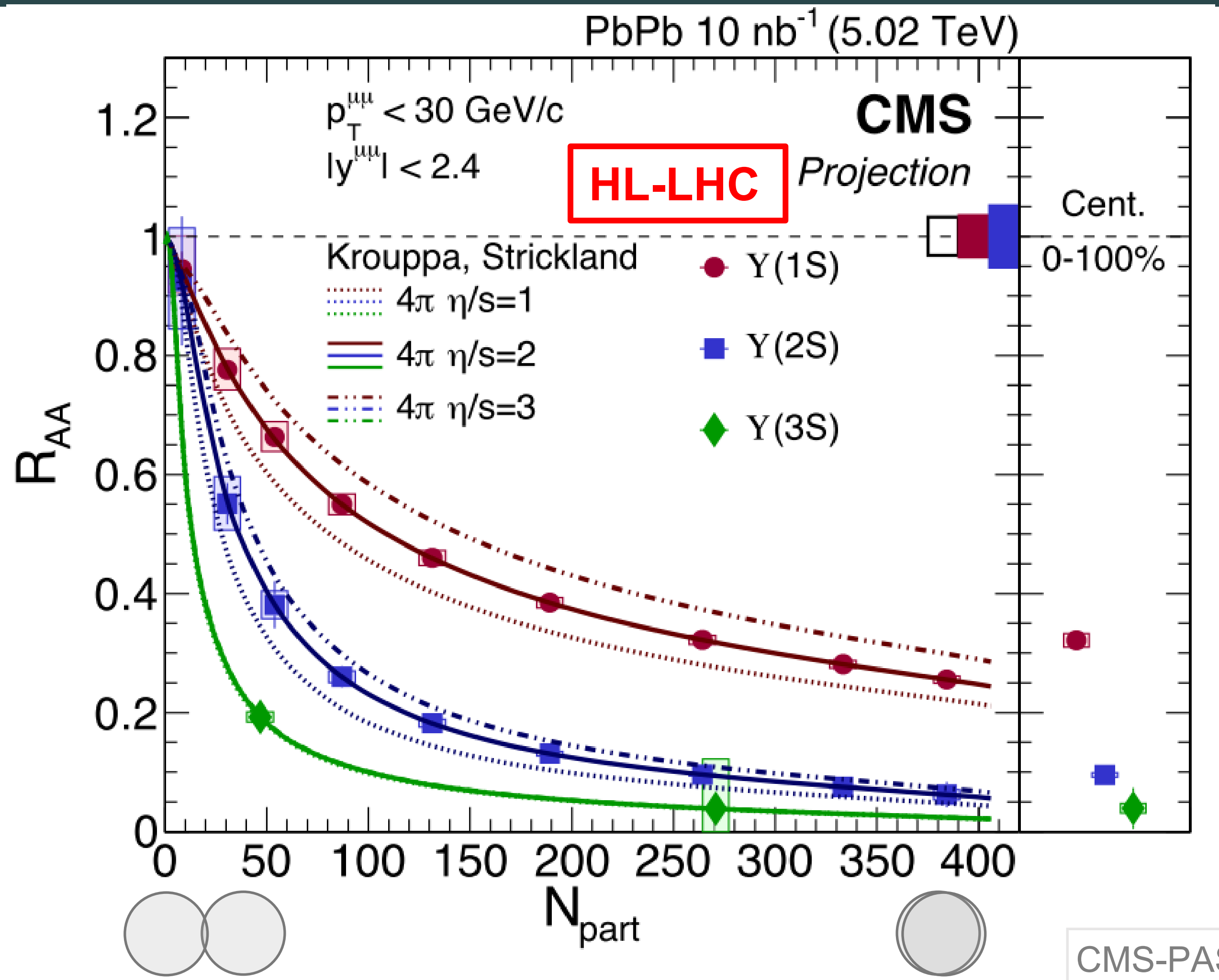




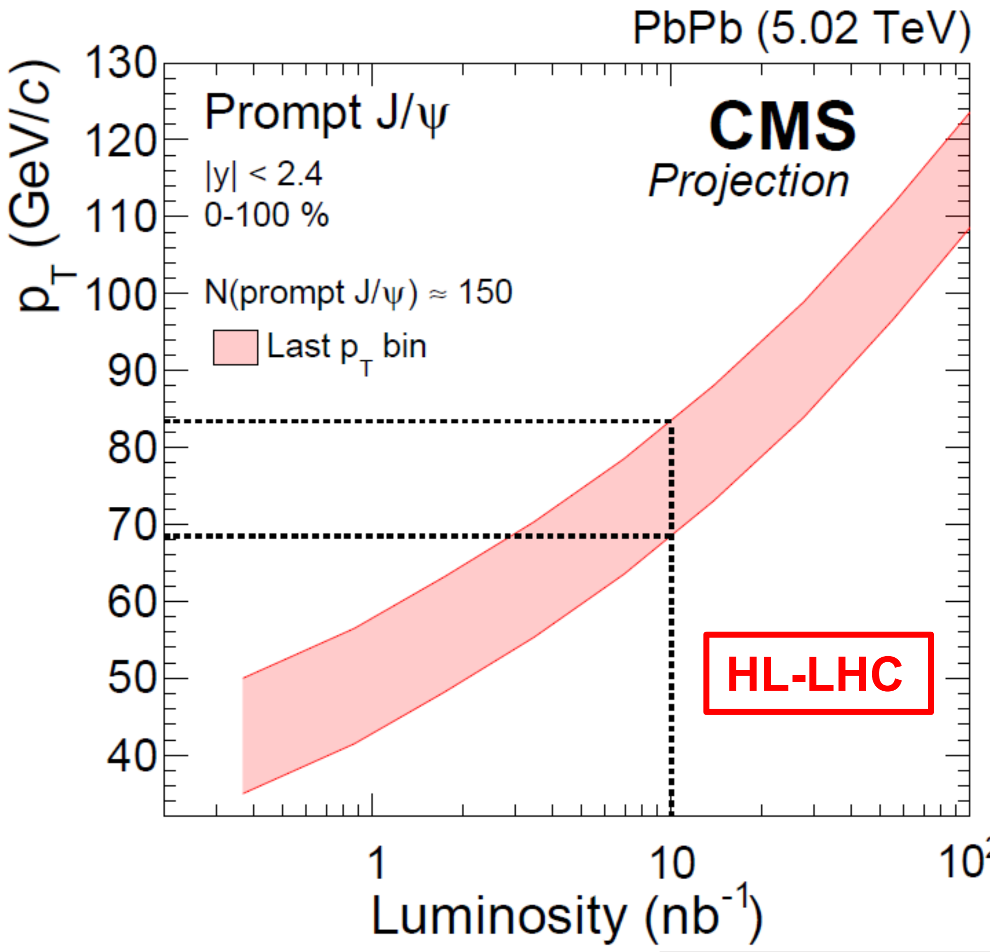
- Strong initial electromagnetic field in heavy ion collisions inducing a vorticity in the reaction plane.
- The resultant effects entails a significant directed flow (v_1) and the effects increase vs. D^0 rapidity
- MTD and the large acceptance CMS tracker could provide high precision measurement of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

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

Quarkonia Production in PbPb Collisions



CMS-PAS-FTR-17-002

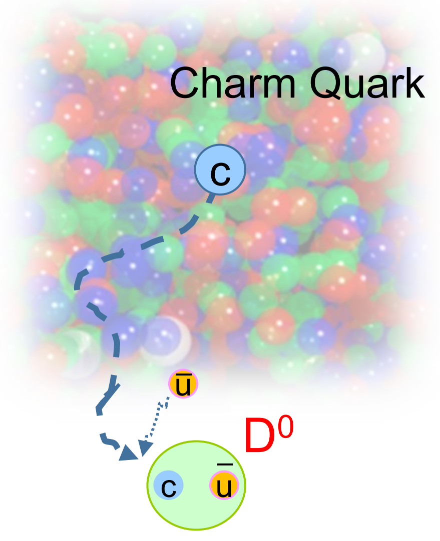


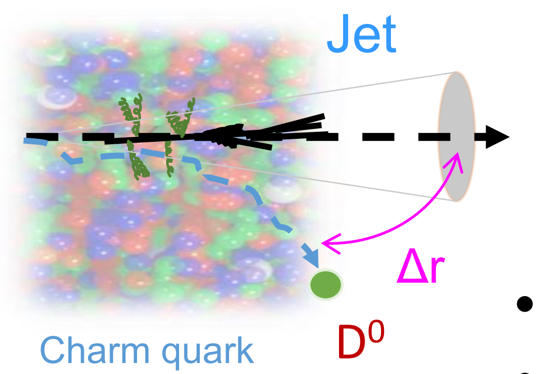
CMS-PAS-FTR-18-024

- 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.

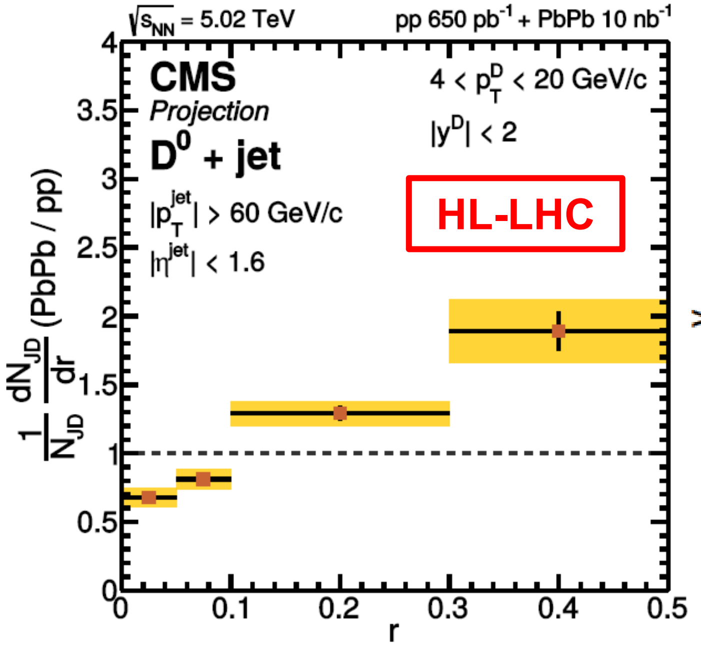
- High p_T reach of prompt J/ψ up to ~ 80 GeV
- Hadronic decays of Quarkonia enabled by CMS MTD such as J/ψ, ψ(2S) and $\eta_c \rightarrow p\bar{p}$

High Precision Measurement of HQ Diffusion



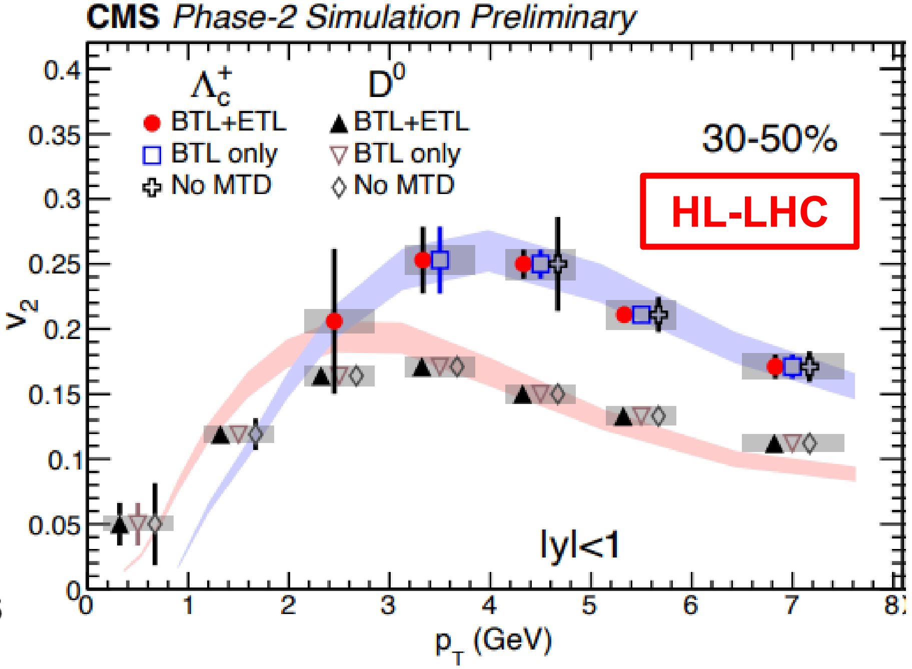


Jet-D^0 Correlation



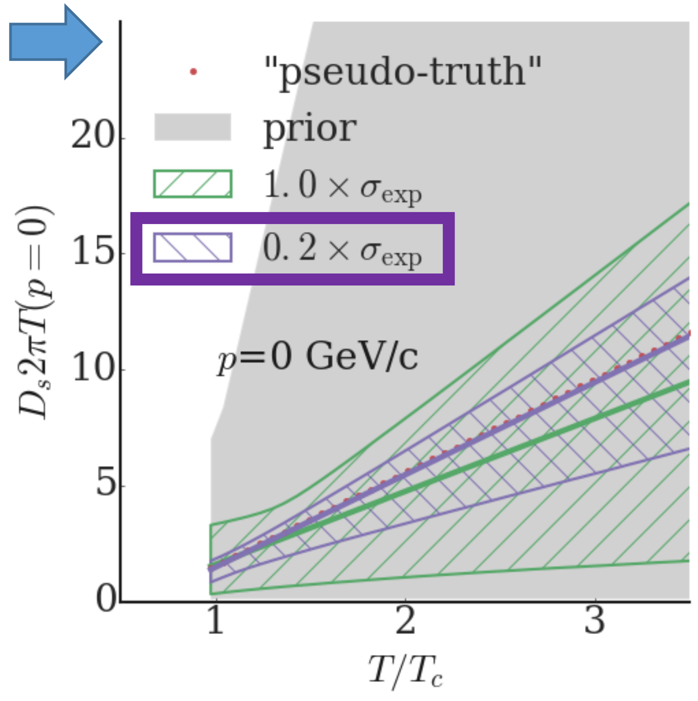
CMS PAS-FTR-18-025

D^0 and Λ_c v_2



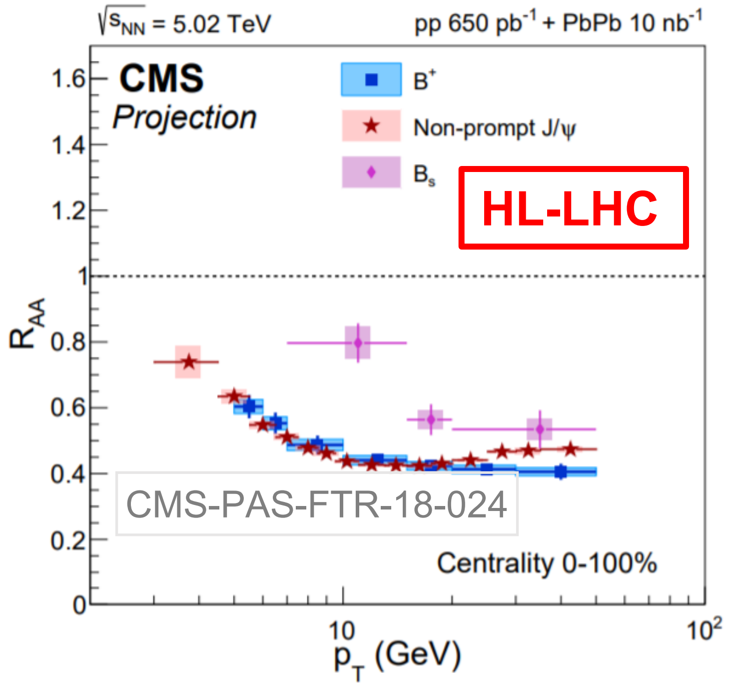
CMS DP_2021_037

D_s vs. T



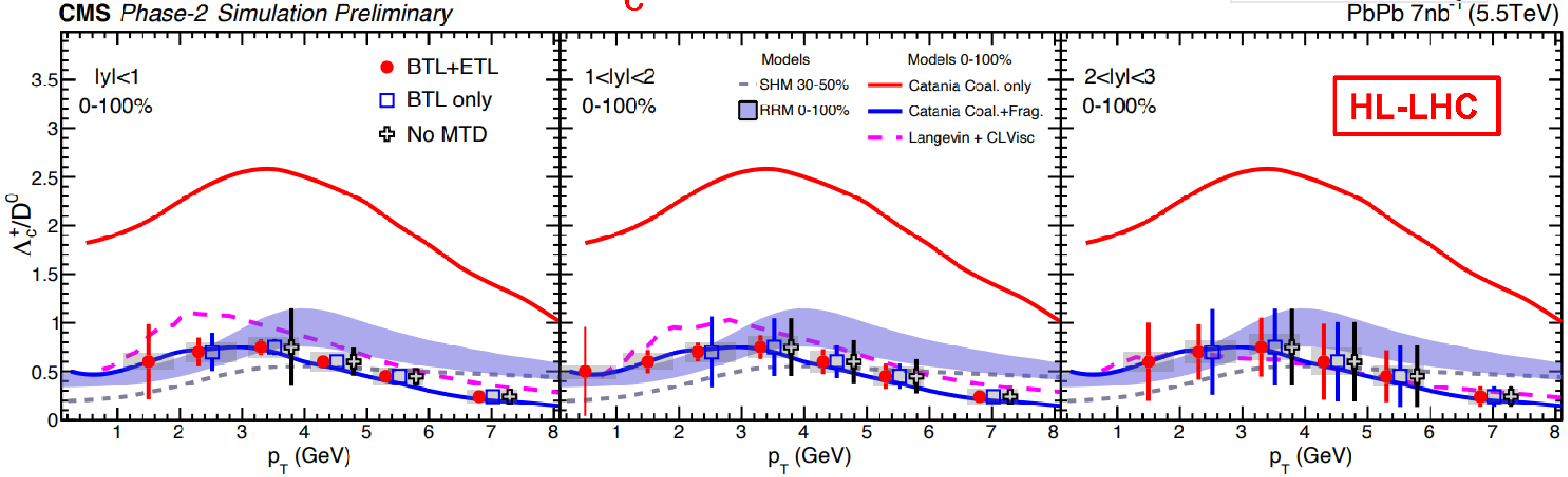
- Large improvement on the Λ_c and D^0 v_2 measurements with CMS MTD
- Direct observation of charm diffusion with D^0-Jet and D^0-Photon correlation
- Strong constraint on the HQ diffusion coefficient $\mathbf{D_s}$

Heavy Quark Hadronization

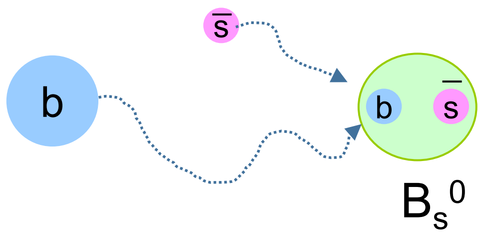


Λ_c^+/D^0 ratio

CMS DP_2021_037

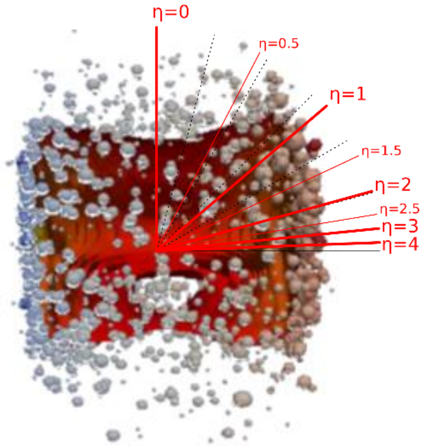


|y|<1 1<|y|<2 2<|y|<3



- 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 $p_T \sim 0$: 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.

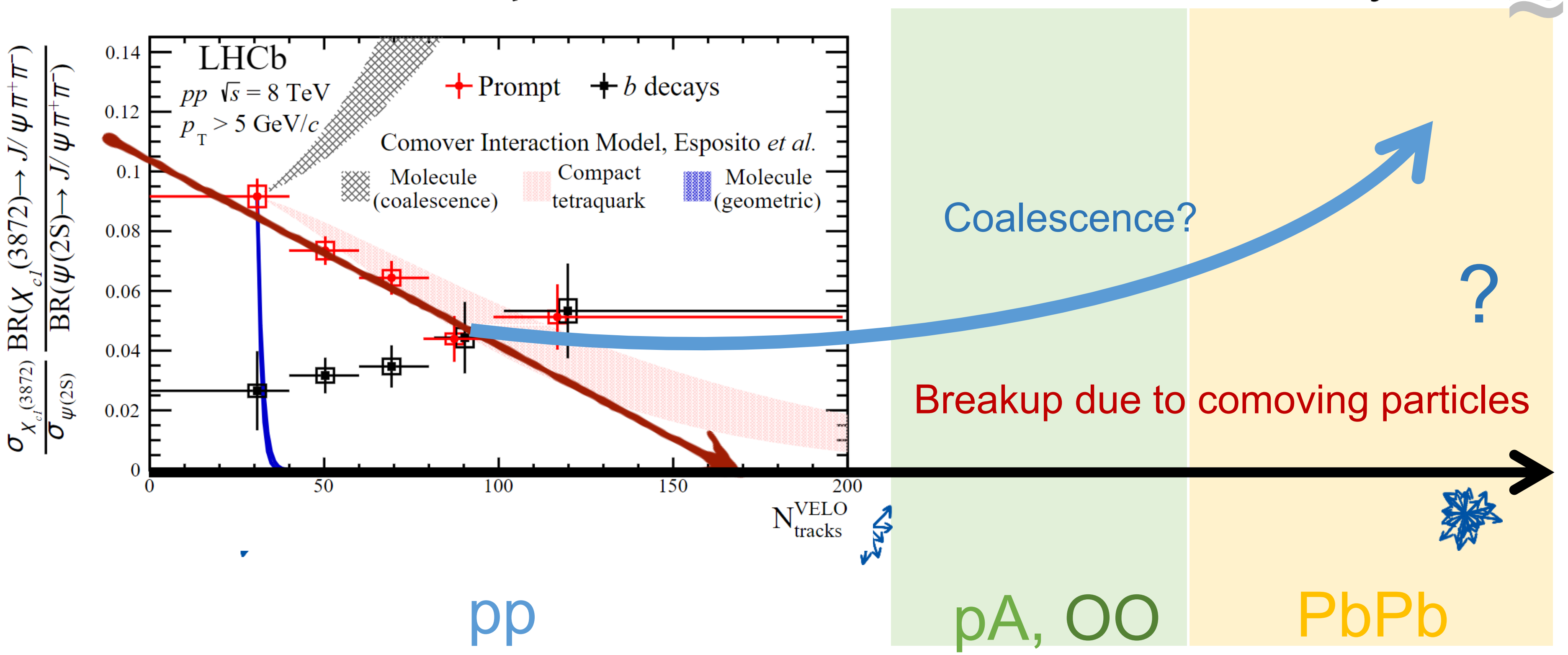
New Frontier of Hadronization Study: Exotic Hadron

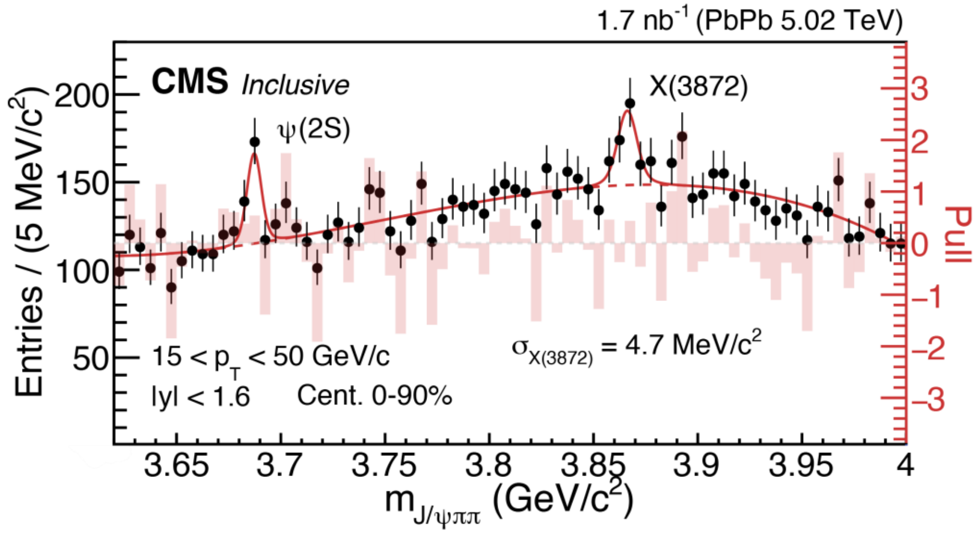
LHCb
PRL 126 (2021) 9, 092001

CMS PbPb

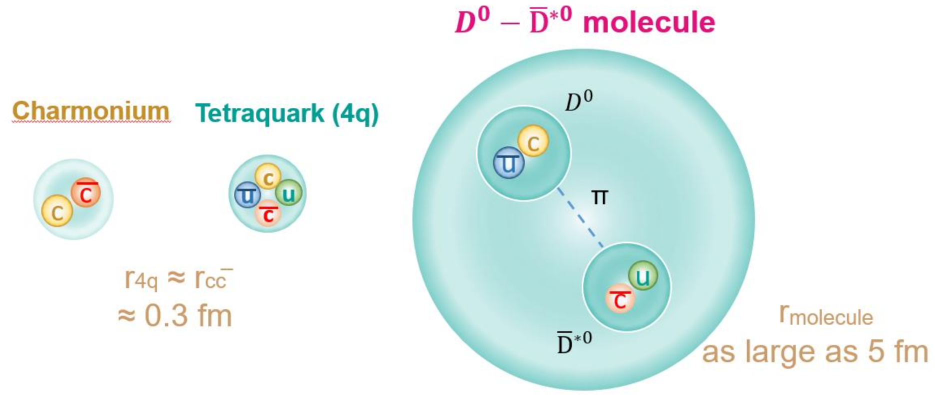
$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$

CMS
PRL 128 (2022) 032001





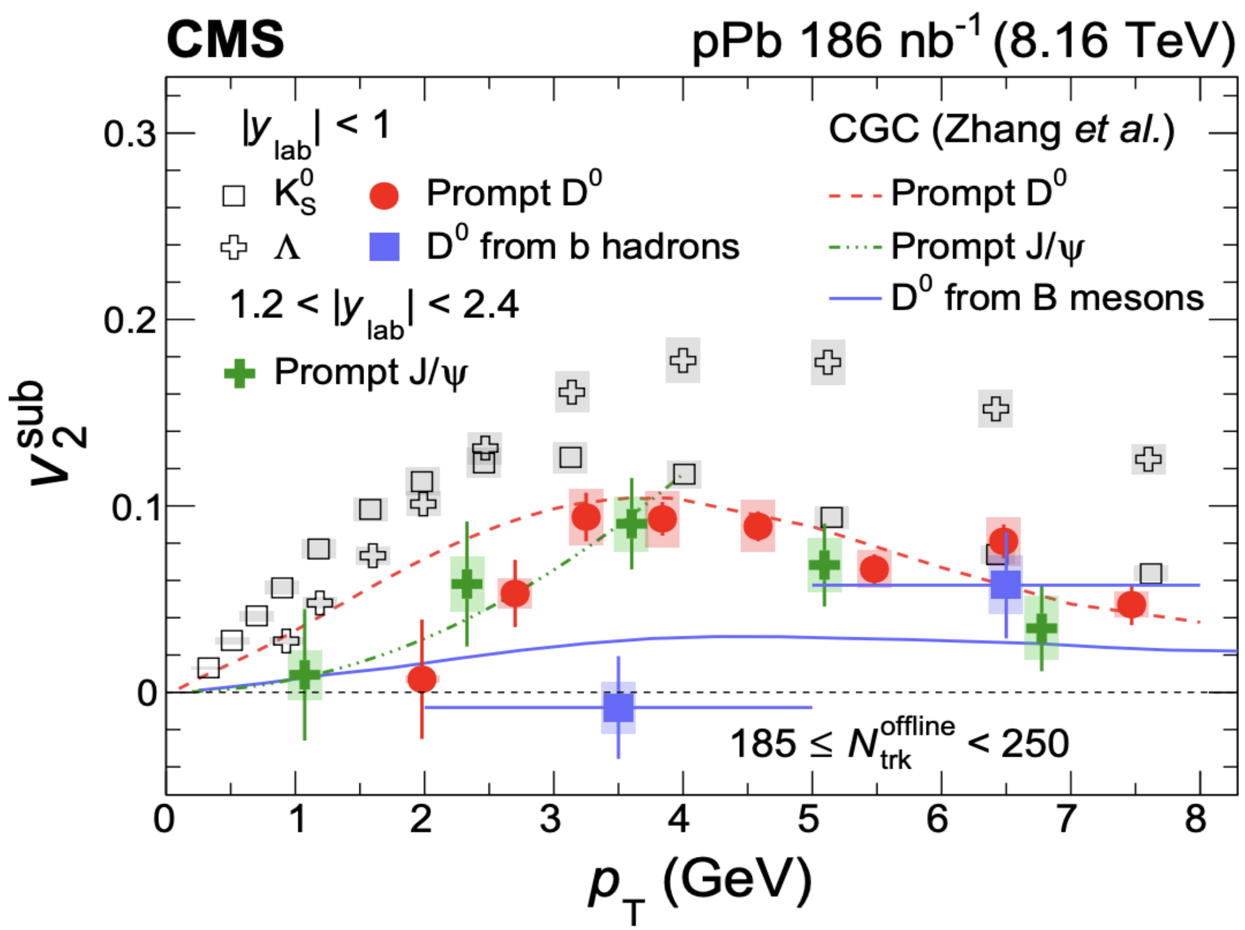
The first evidence of X(3872) in HI



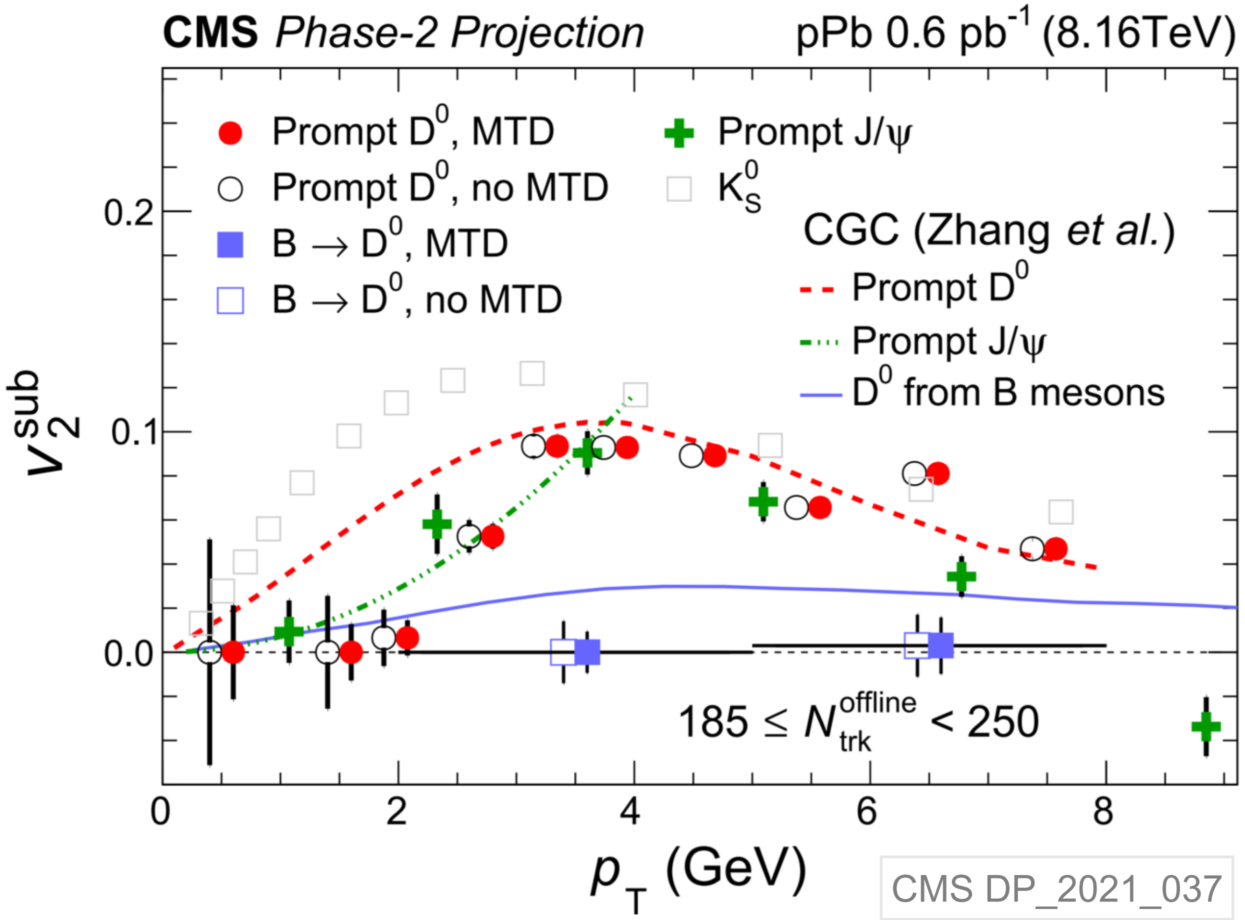
- Observation **of X(3872) in PbPb is expected (>5 σ) in Run3**
- Run3+4: Differential studies
  - Centrality dependence: Probe the structure of X(3872) with QGP
- Search for other exotic hadrons such as T_{cc}
- Exotic hadron production in UPC events

Collectivity in Small System

CMS Run 2



CMS 1-year with MTD



CMS DP_2021_037

- 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 and access to **multiparticle correlation**

Summary: Answers with Hard Probes

- What are the properties of QGP?
  - QGP properties in the long wavelength limit from **slow** (diffusion) and **fast** moving hard probes are consistent with soft probes.
  - Significant room for improvement from both theory and experimental side
  - Novel HF observables needed to be sensitive to QGP properties at short distance scale
- How does the hydrodynamization happen and how QGP is created?
  - Evidence that charm and beauty are moving toward hydrodynamization
  - Beauty is less hydrodynamized than charm
  - Parton energy loss is mass and color charge dependent
- How does hadronization happen in low and high parton density environment?
  - Modification of hadronization already in pp (or even in ee and ep!)
  - Strong modification of heavy quark hadronization beyond parton shower
  - Deconfinement: Recombination signal from J/ψ and B_c

Thank you!

Credit: Nano Banana