Heavy flavor, Quarkonia and Exotic hadrons in Hot QCD

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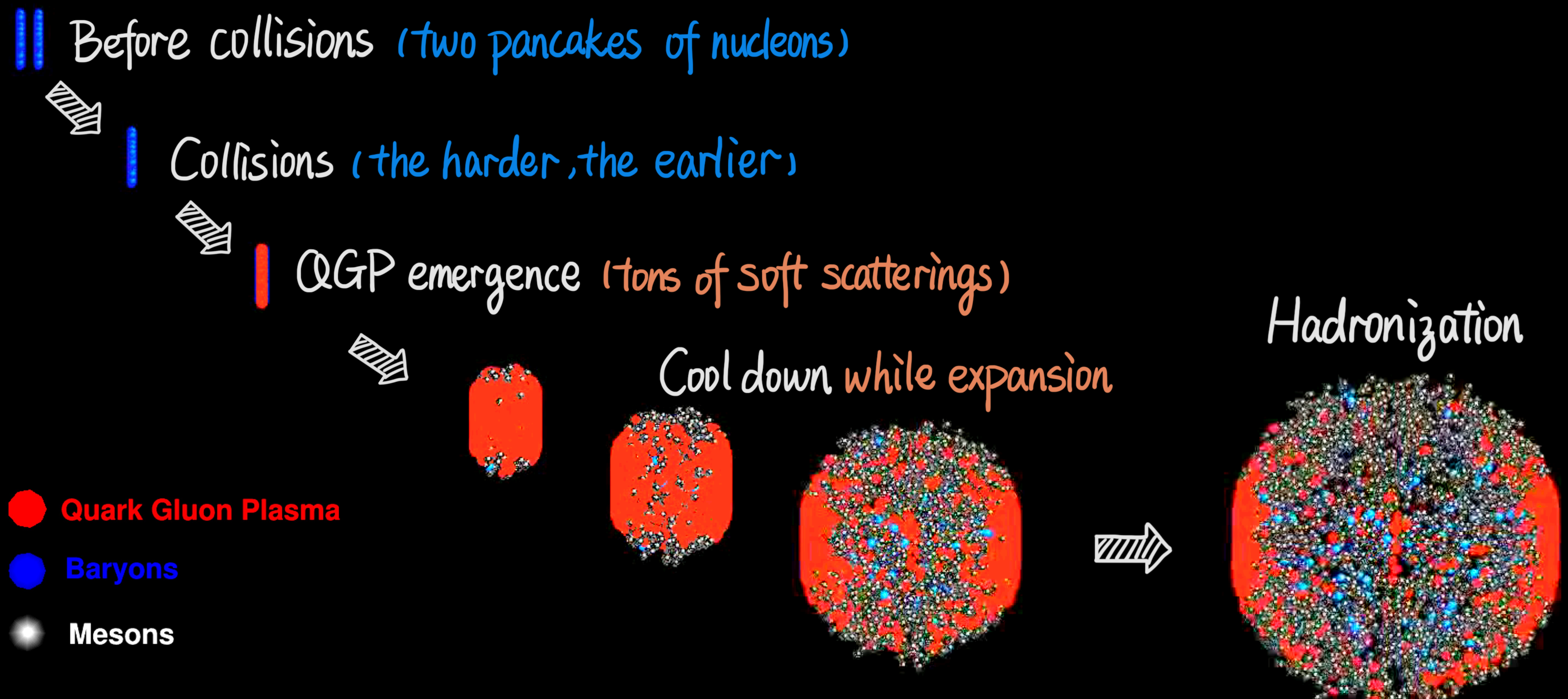
10th Workshop of the APS Topical Group on Hadronic Physics

April 13, 2023

I gratefully acknowledge financial support from The Gordon and Betty Moore Foundation and the American Physical Society to present this work at the GHP 2023 workshop.

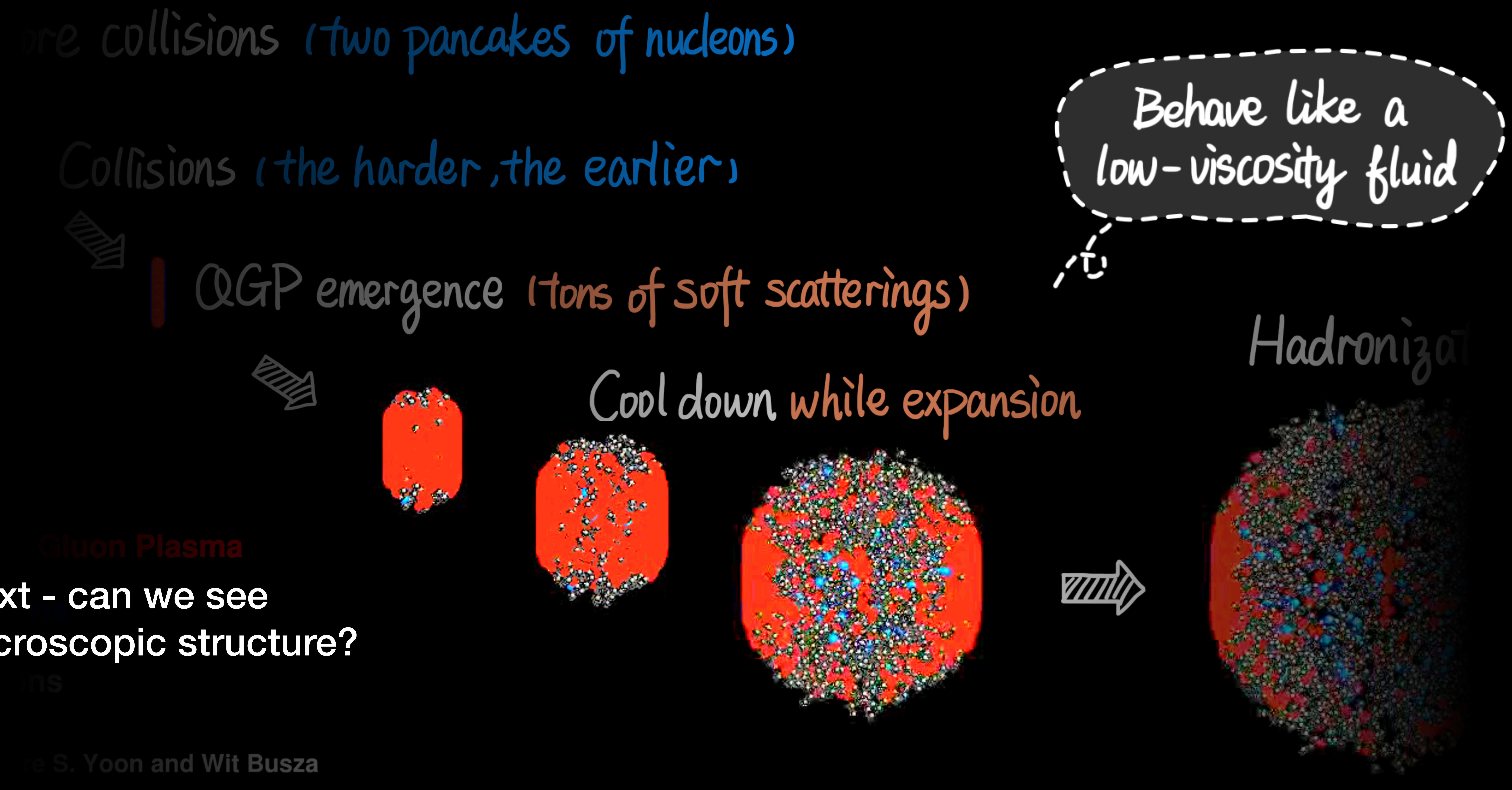
Being Hot Matters

Relativistic Heavy Ion Collisions



Yen-Jie Lee, Andre S. Yoon and Wit Busza

Understand Quark Gluon Plasma



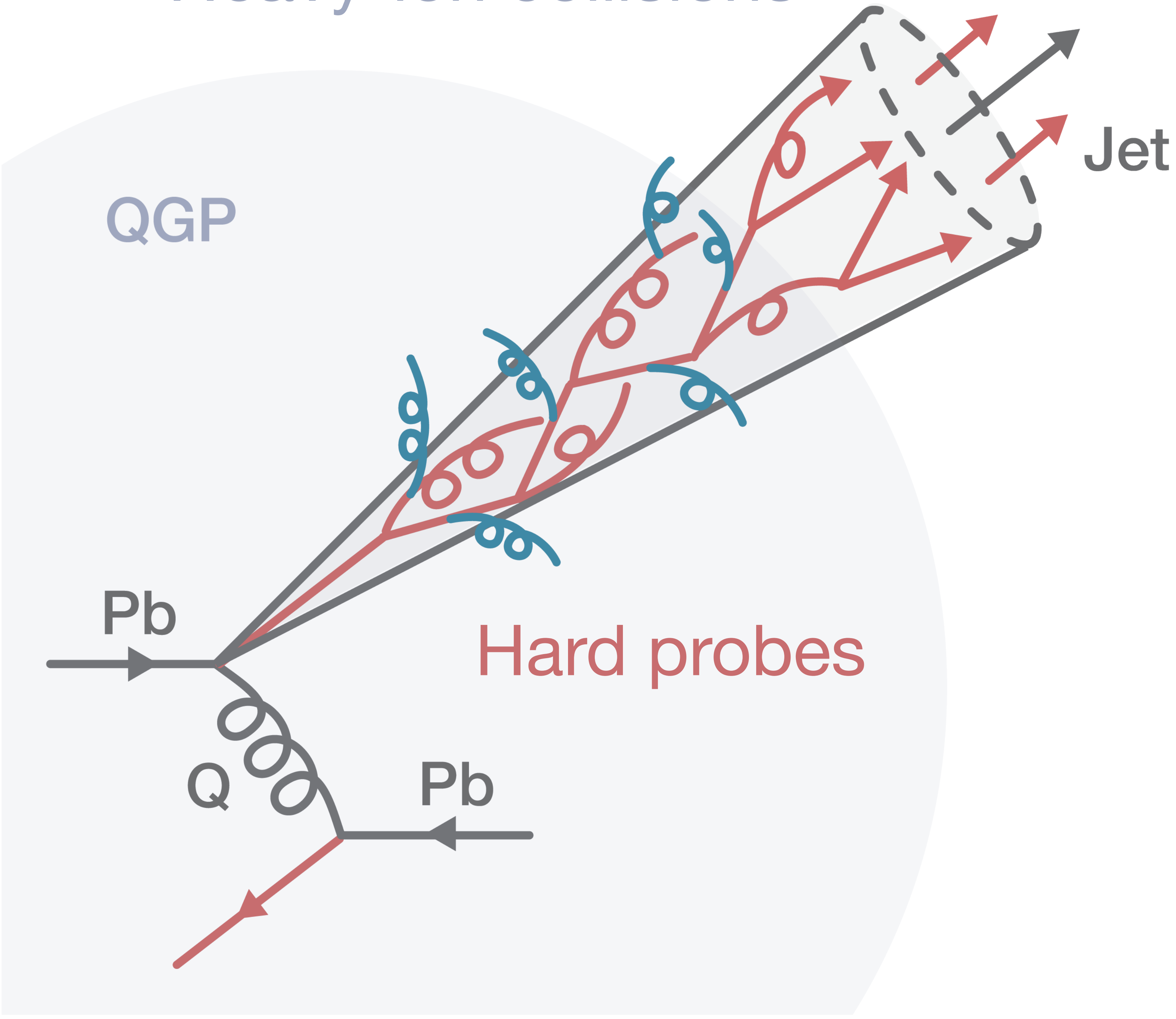
Next - can we see microscopic structure?

Hard Probes

Hard (large Q) ➜ High p_T energetic particles

- Q ~ 1/τ
  - Produced early → Unique process, high T
- Q ≫ Λ_{QCD}
  - Initial production with pQCD
- Q ≫ T_{QGP}
  - Seldom produced in QGP
- With color charge
  - Interact with QGP

Heavy-ion collisions



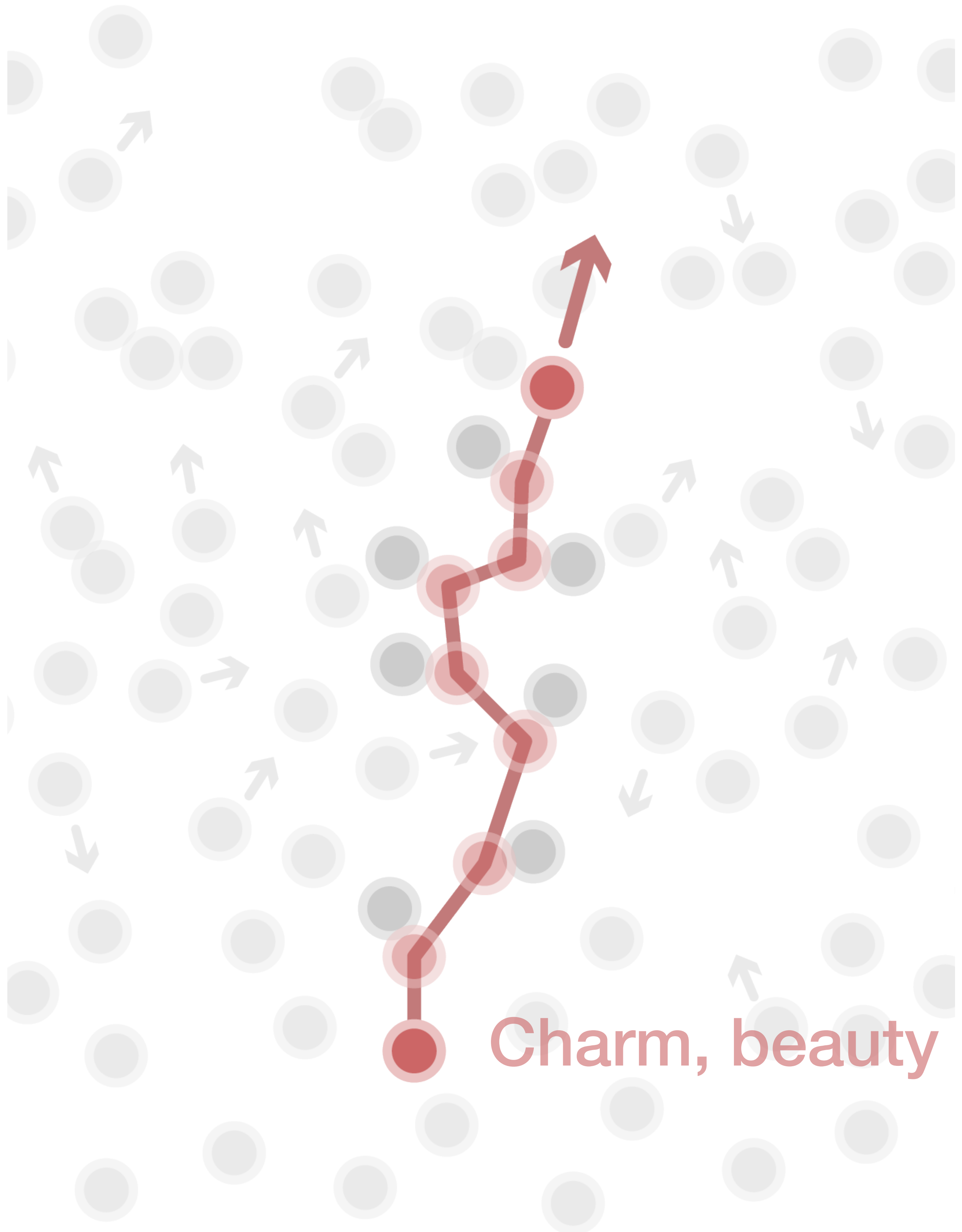
Hard probes "X-ray" QGP

How to probe different length scale structures?

Special Hard Probe: Heavy Flavors

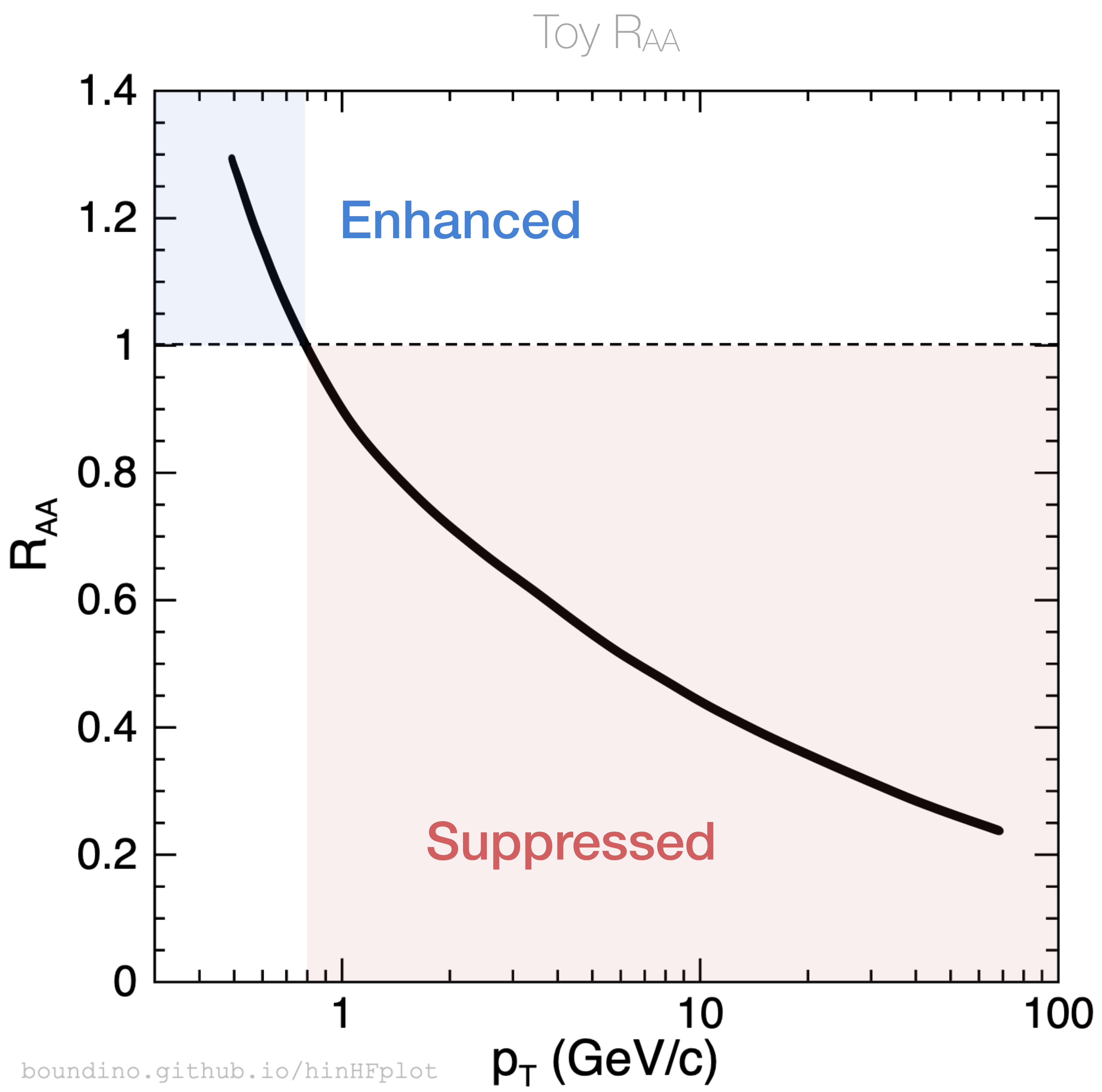
Large mass m_{HQ} ➜ Unique slow HP

- $m_{HQ} \sim 1/\tau$
  - Produced early
- $m_{HQ} \gg \Lambda_{QCD}$
  - Initial production with pQCD even at low p_T
  - Different length scale structure by varying p_T
- $m_{HQ} \gg T_{QGP}$
  - Seldom produced in QGP → Keep identity
  - Brownian motion → Diffusion coefficient D_s
- $m_{HQ} \gg m_q$
  - Interact with QGP differently from light quark



Heavy quark diffusion in QGP

Modification of Particle Spectra



Nuclear modification factor R_{AA}

R_{AA} =1: superposition of nucleon-nucleon collisions

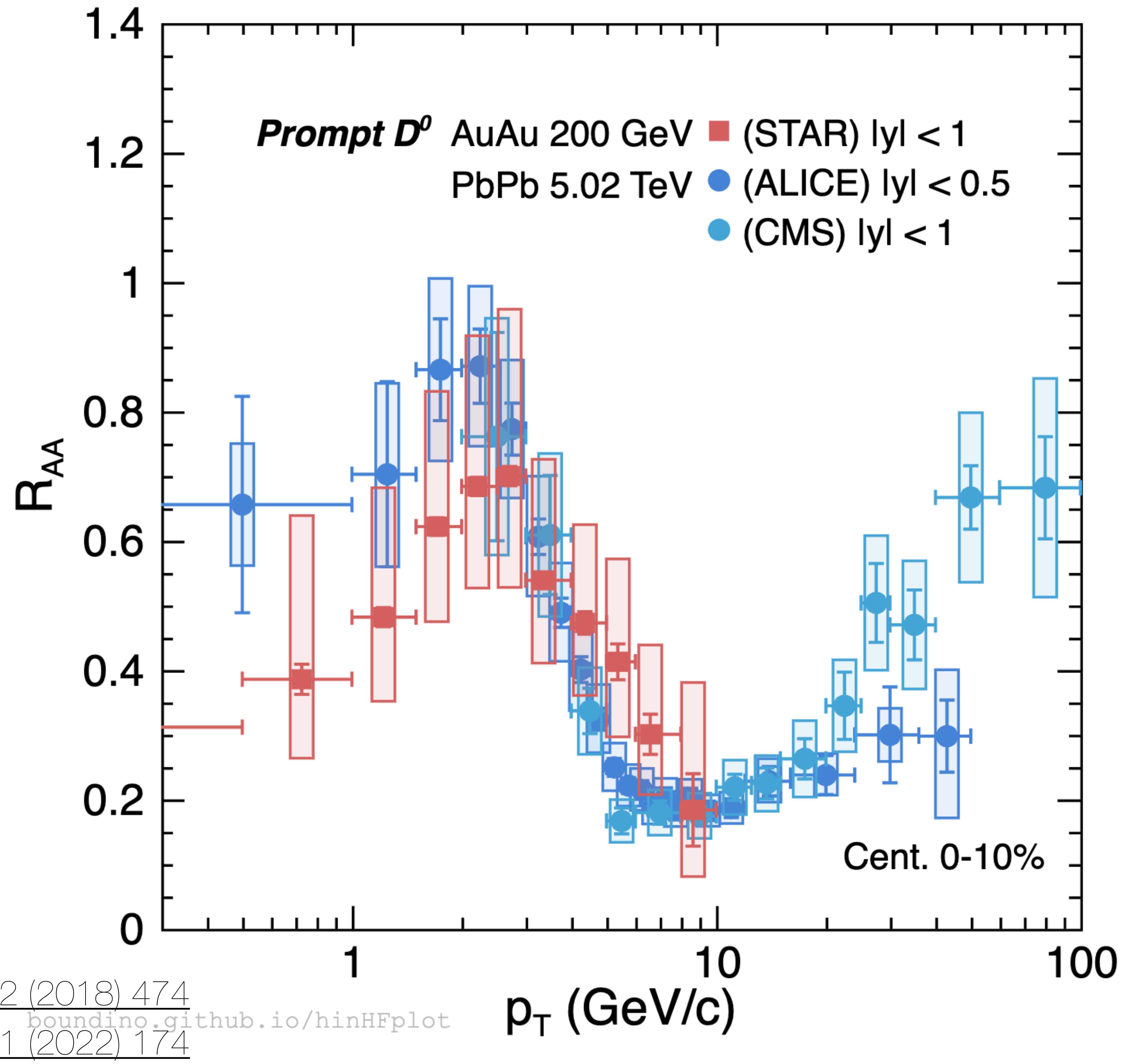
$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA} d\sigma_{pp}/dp_T}$$

← Heavy-ion

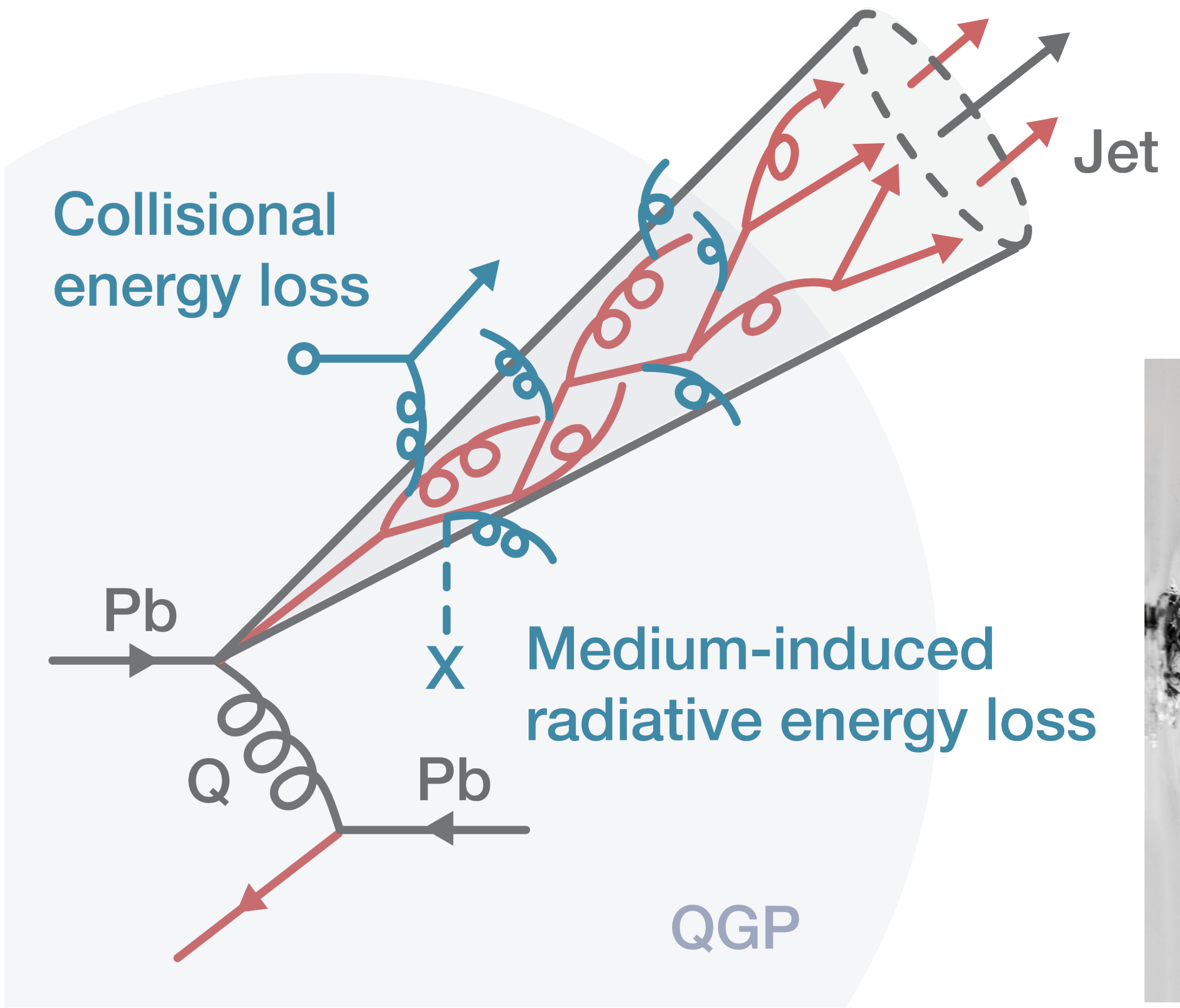
← pp

Suppression of Charm Meson D^0

D^0 R_{AA} in PbPb and AuAu



- D^0 $R_{AA} < 1$ in wide kinematics
  - Lose energy in QGP via collisions (low p_T) and radiations (high p_T)
  - Unique info from low p_T



Hard parton in QGP

Bullet in gelatin block

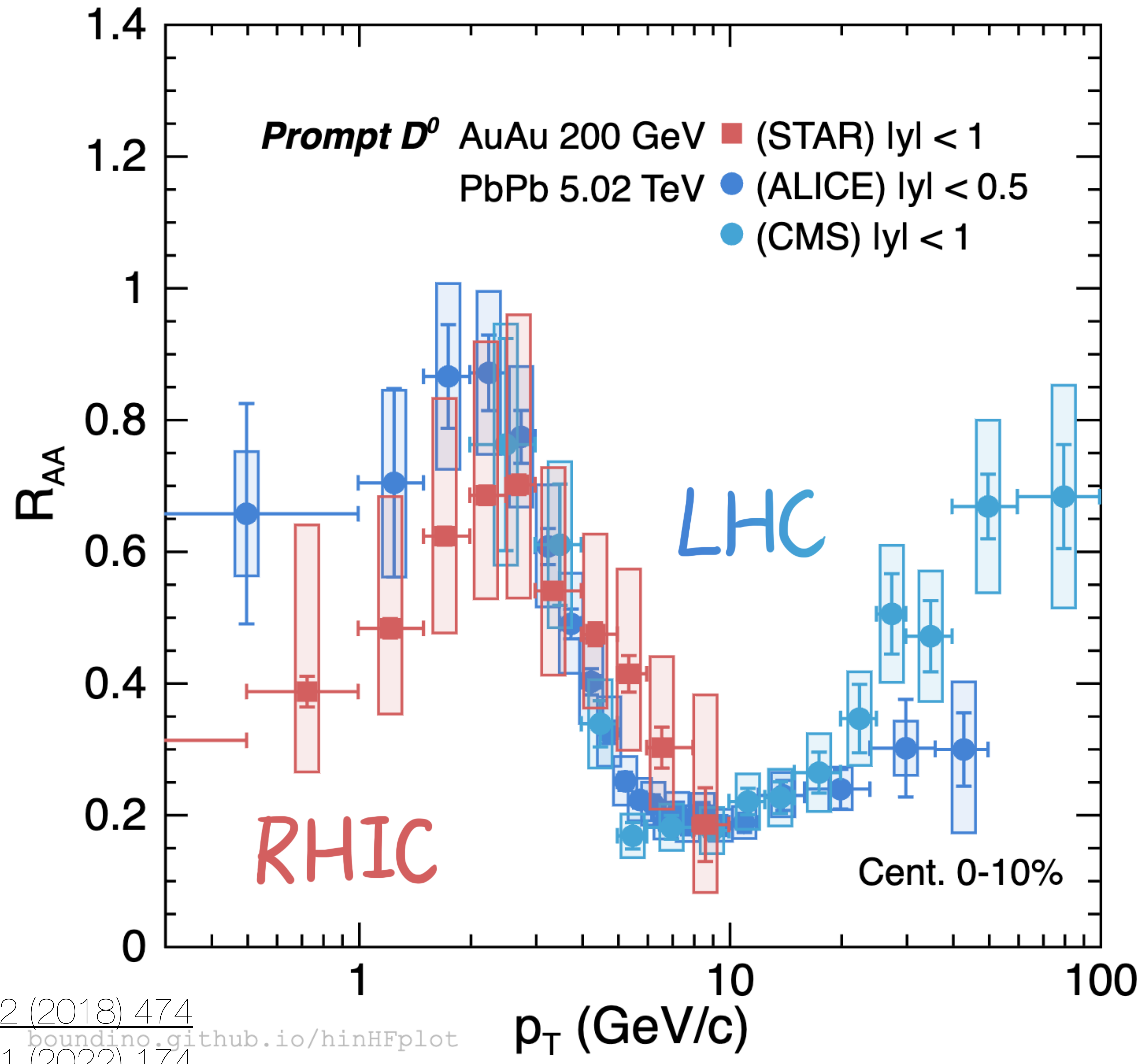
PLB 782 (2018) 474

JHEP 01 (2022) 174

PRC 99 (2019) 034908

Suppression of Charm Meson D^0

D^0 R_{AA} in PbPb and AuAu



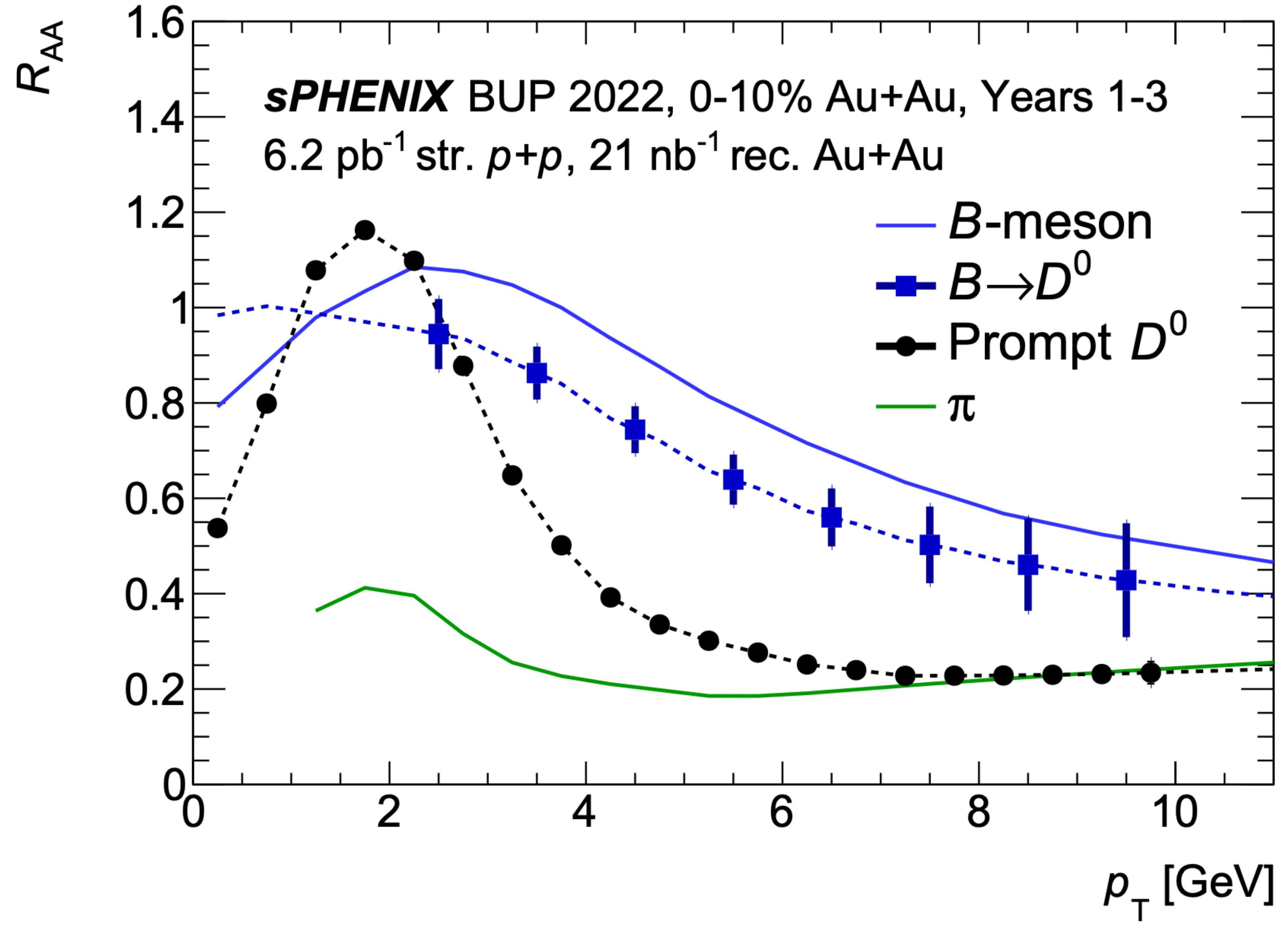
PLB 782 (2018) 474

JHEP 01 (2022) 174

PRC 99 (2019) 034908

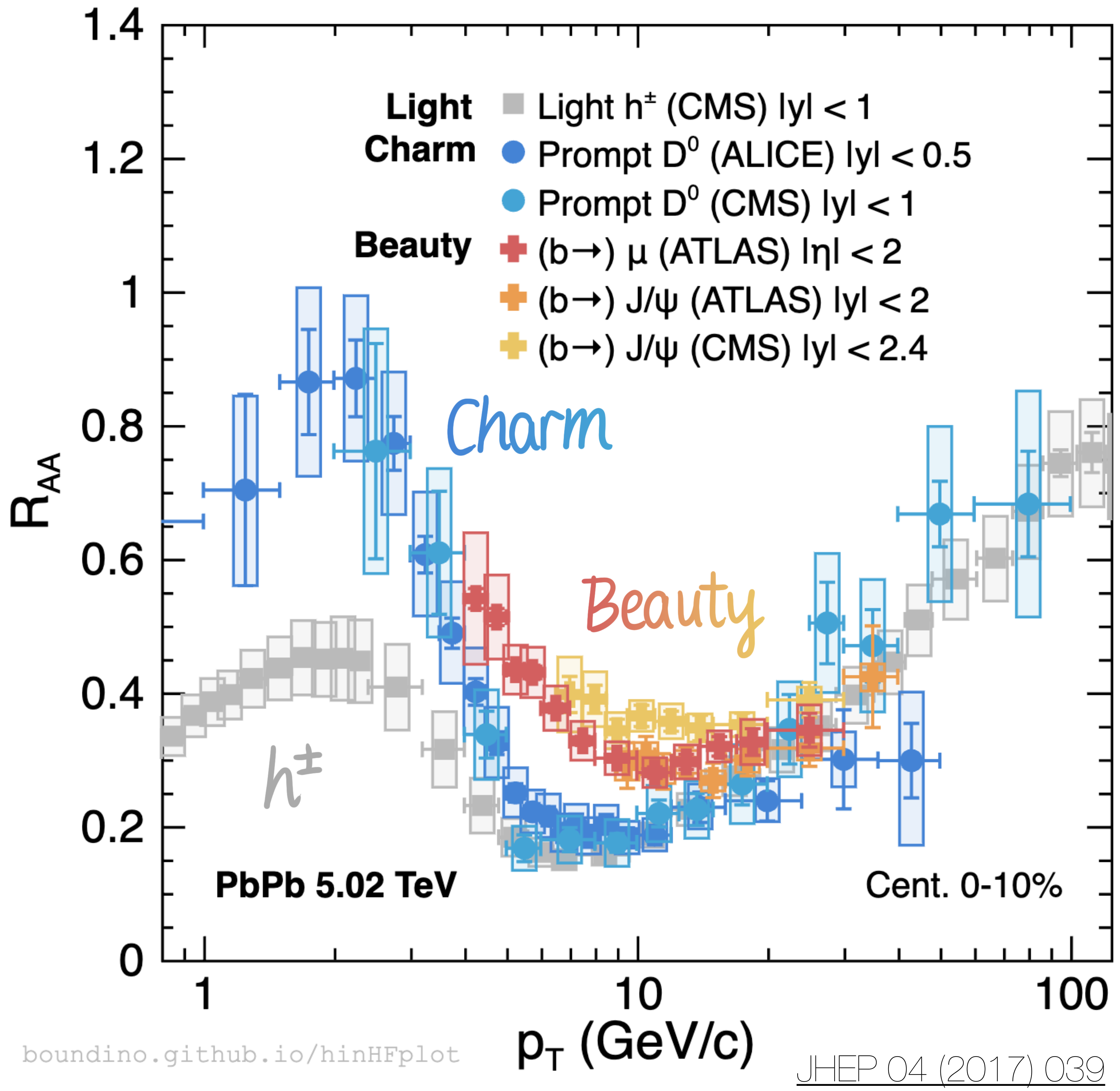
- Similar D^0 R_{AA} in LHC & RHIC in overlap region?
  - Despite different temperature & size

High-precision at sPHENIX



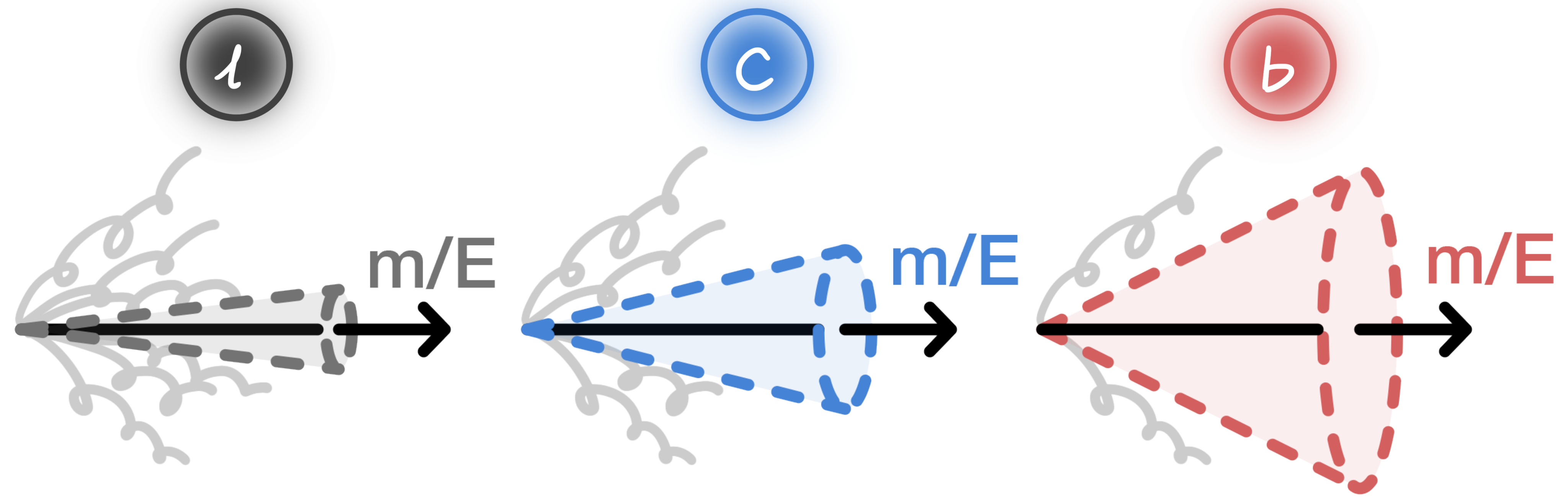
Flavor Dependence of Energy Loss

RAA vs. Flavors



boundino.github.io/hinHFplot

- Dead cone effect
  - Radiation is suppressed inside $\theta < m/E$
  - Energy loss $\Delta E_l > \Delta E_c > \Delta E_b$

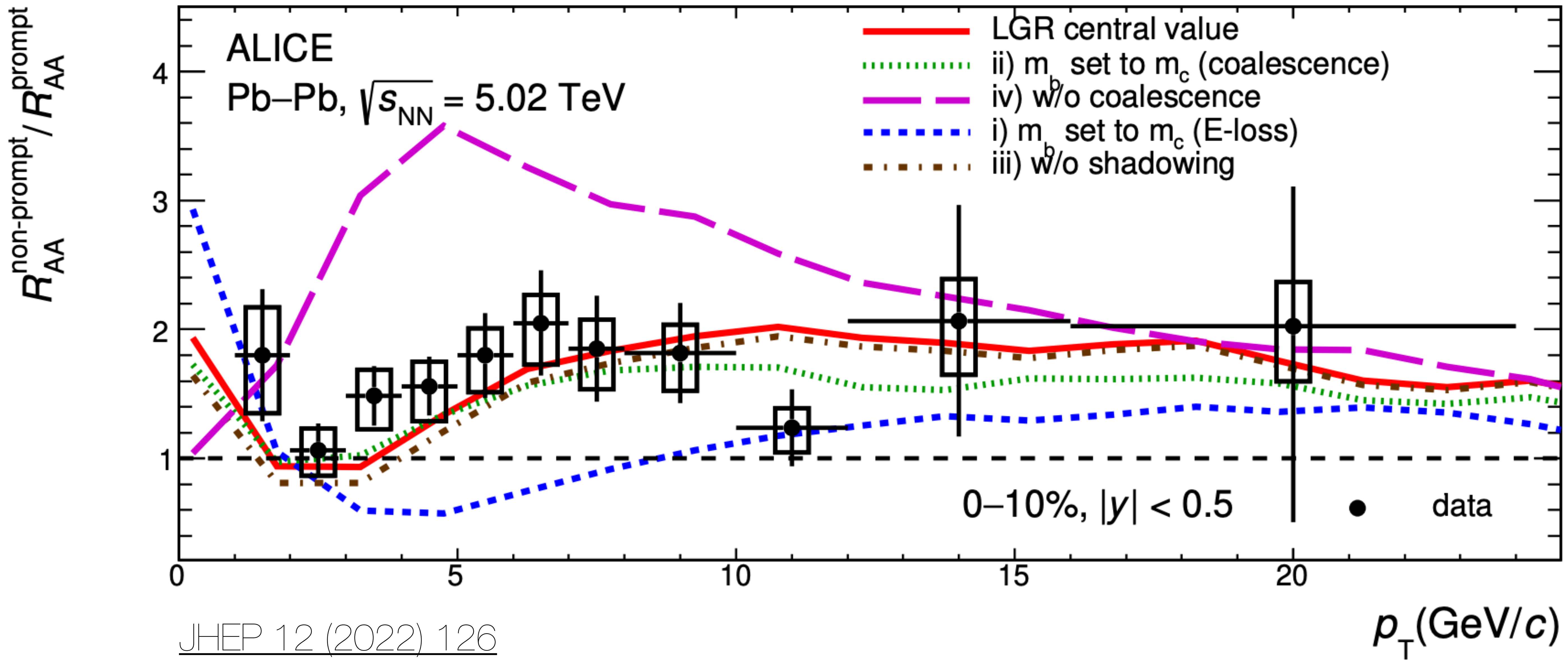


Larger energy loss ➔ Smaller energy loss

JHEP 04 (2017) 039 EPJC 78 (2018) 509
PLB 829 (2022) 137077 EPJC 78 (2018) 762

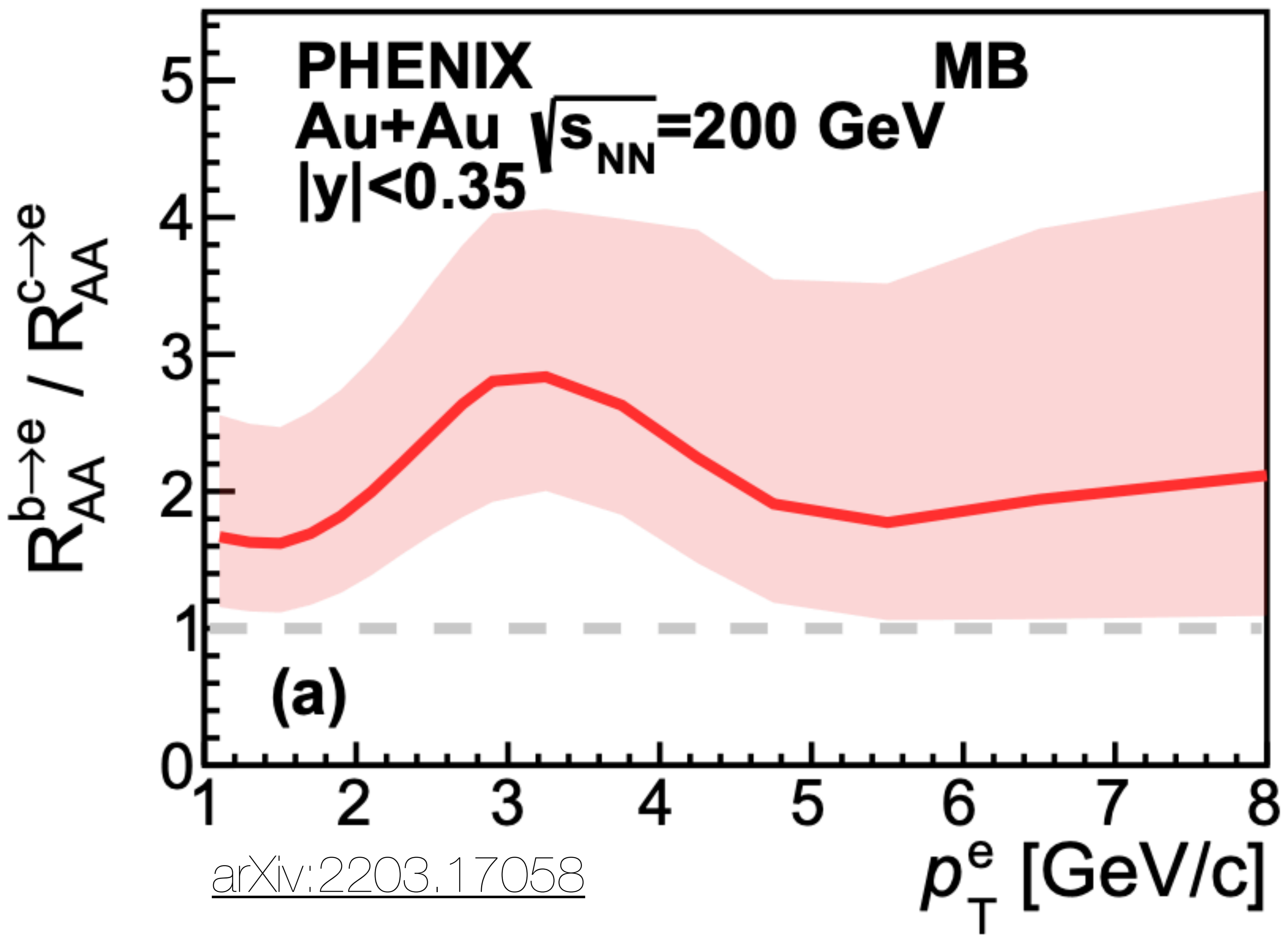
Flavor Dependence of R_{AA}

$b \to D^0$ / $c \to D^0$ R_{AA} in PbPb



JHEP 12 (2022) 126

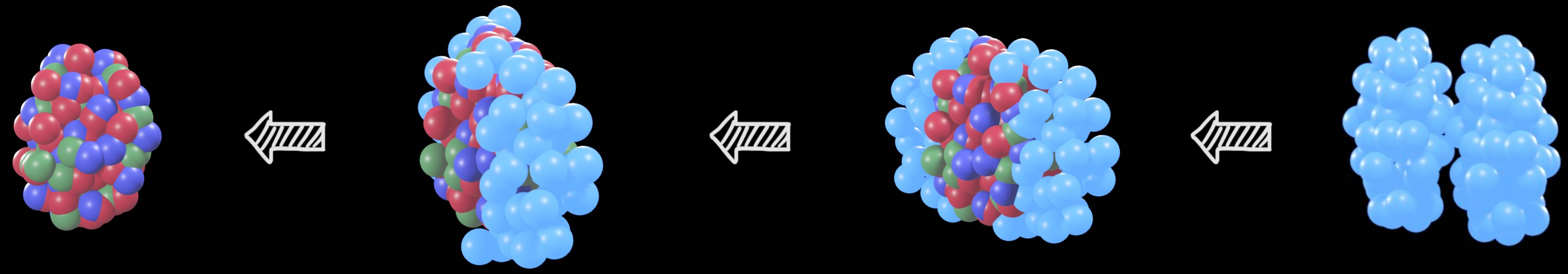
$b \to e$ / $c \to e$ R_{AA} in AuAu



arXiv:2203.17058

- Interplay of energy loss, shadowing, flow, coalescence, spectrum shape, nPDF
  - Model suggests difference at intermediate p_T results from energy loss
- Test transport models over all flavors and collision systems simultaneously

Initial Spatial Anisotropy of Medium

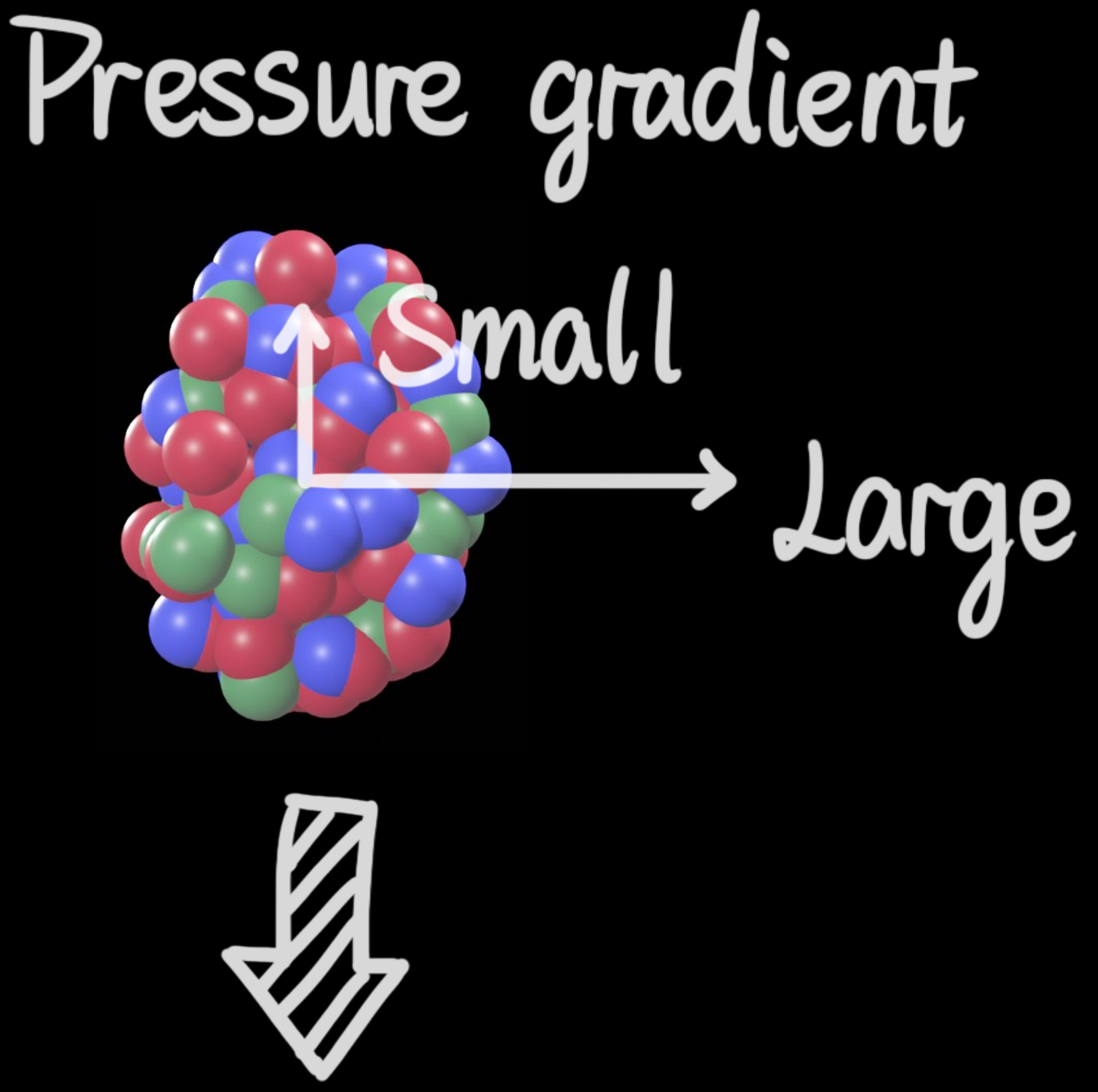


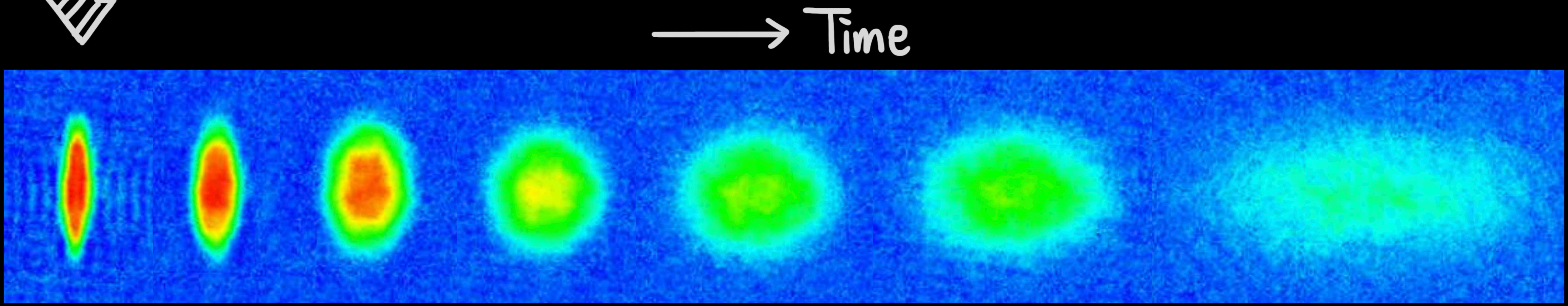
Azimuthal anisotropic Initial shape in peripheral* events

*Peripheral: relatively large impact parameter

Animation

Collective Flow

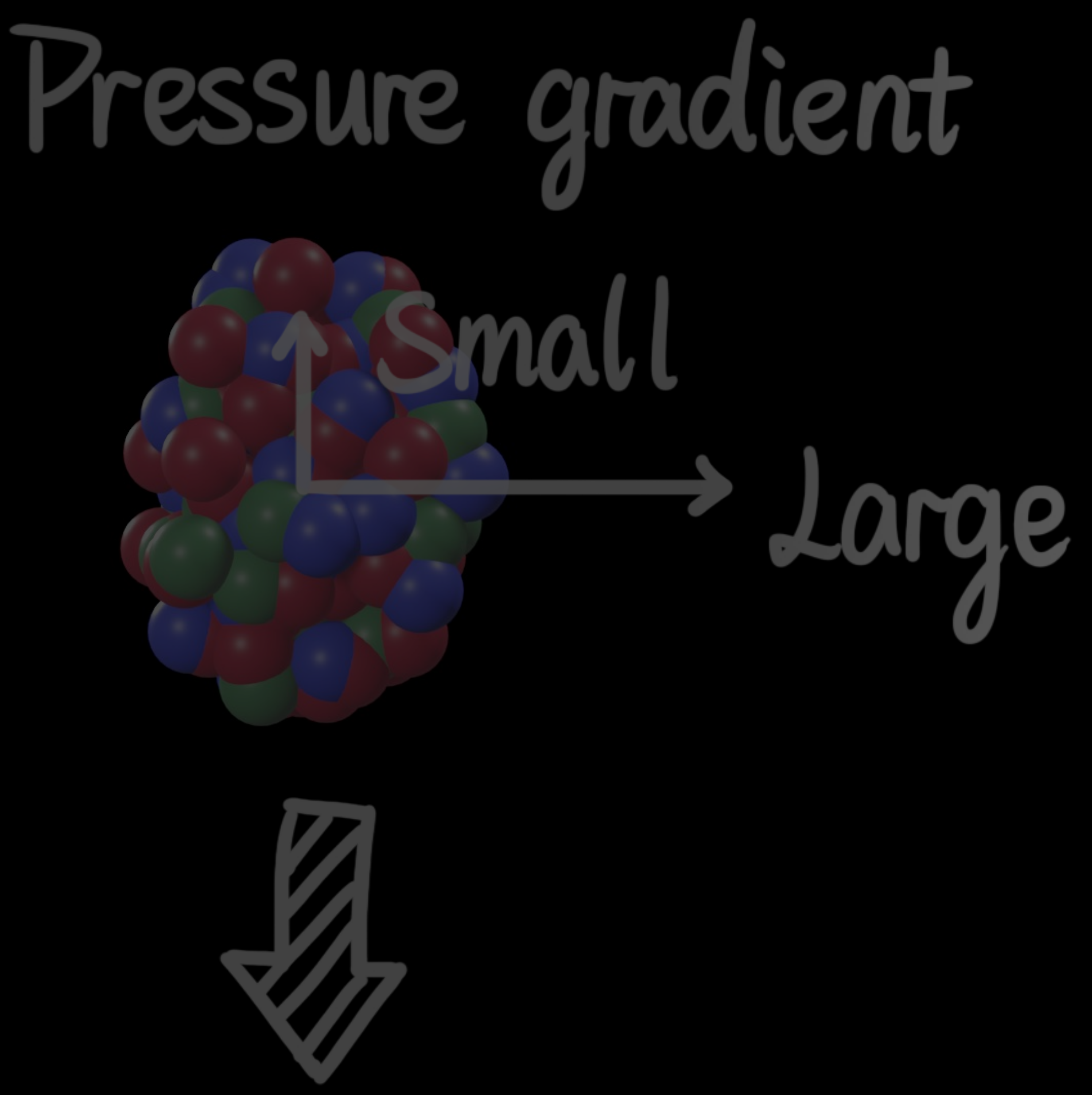




Pressure driven expansion

Science 298 (2002) 2179

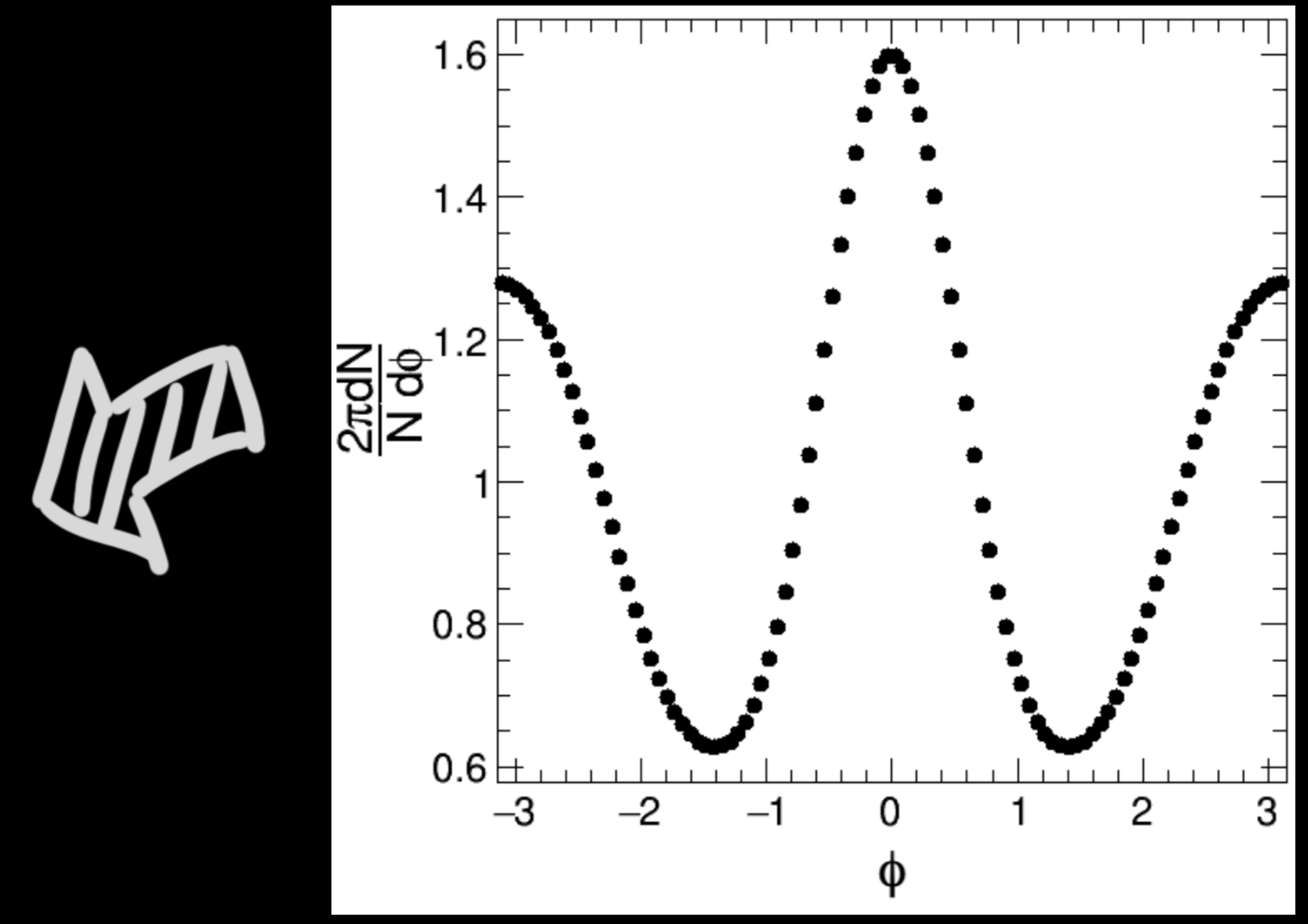
Collective Flow

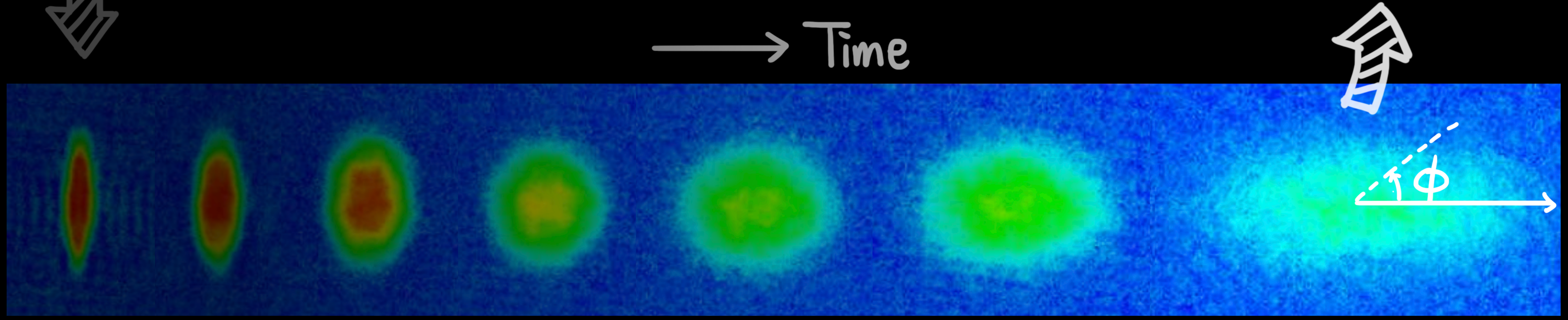


Existence of QGP ➜ Final-state particle azimuthal anisotropy

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

➜ Elliptic $v_2 \neq 0$



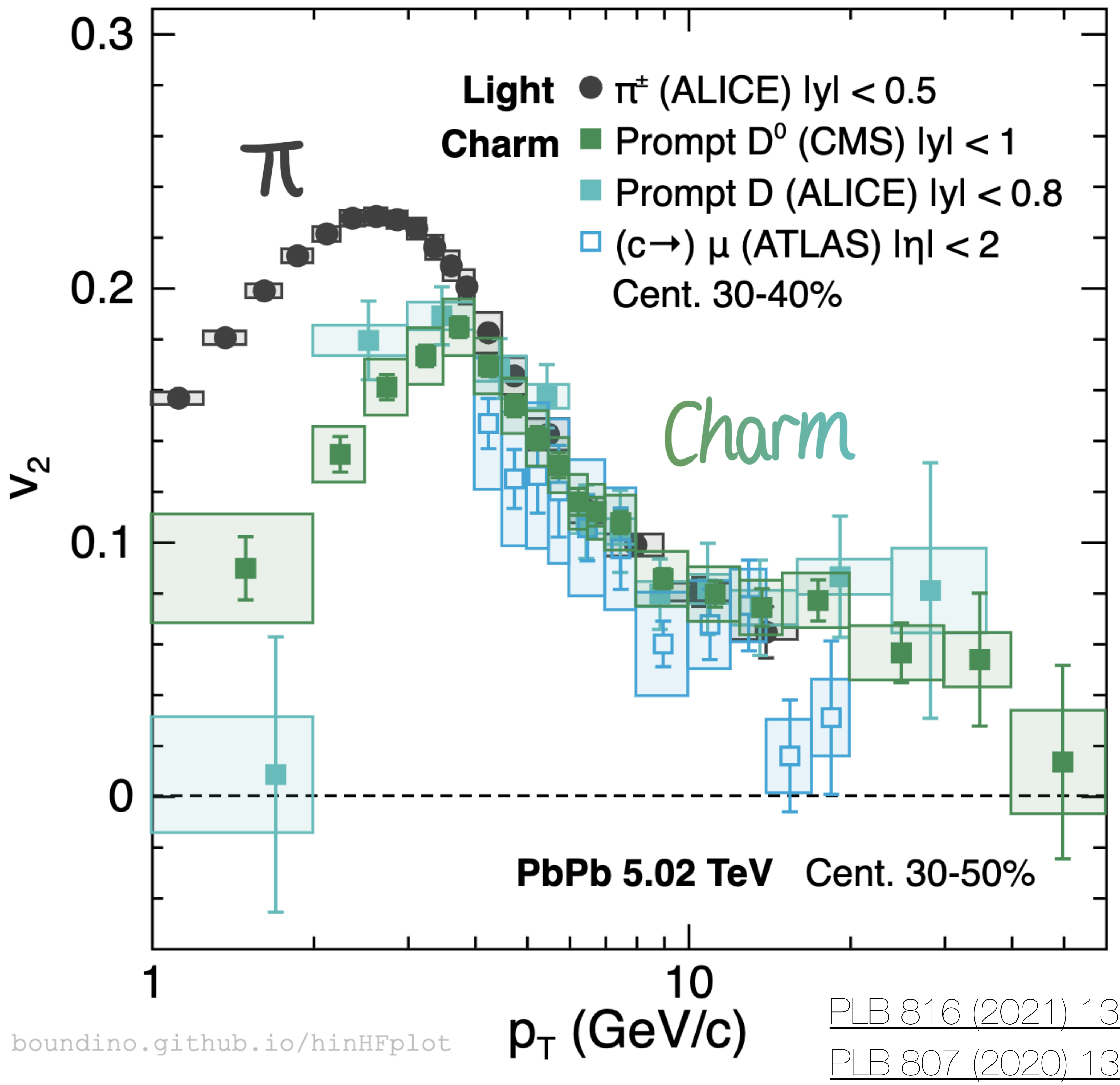


Pressure driven expansion

Science 298 (2002) 2179

Charm Flow Signal in PbPb

Open charm v_2 in PbPb



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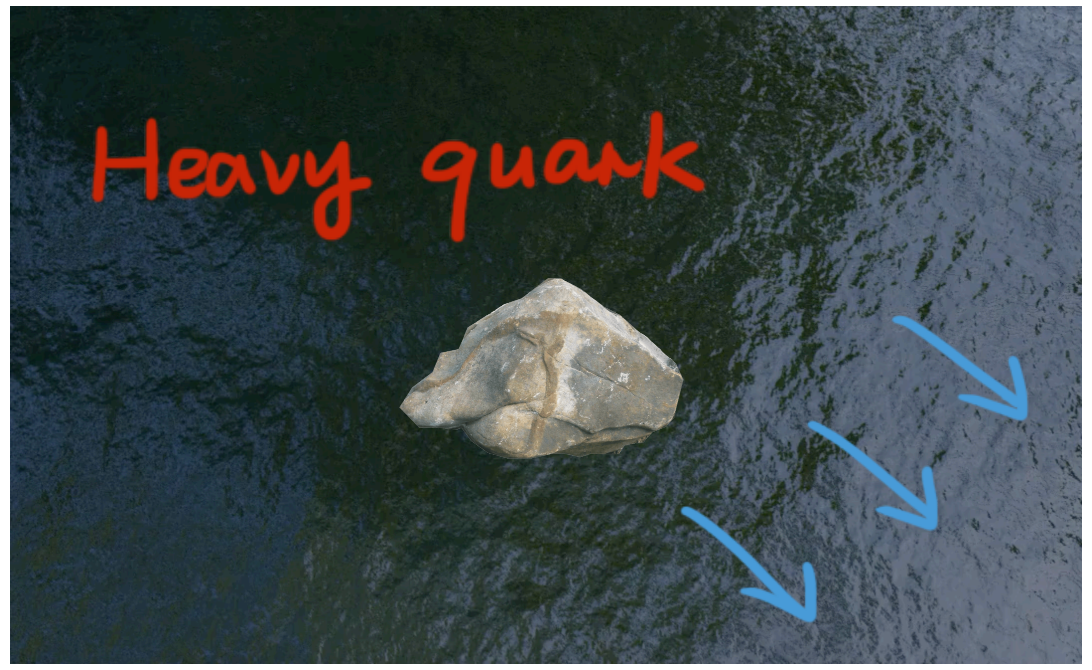
PLB 816 (2021) 136253
PLB 807 (2020) 135595
PLB 813 (2021) 136054

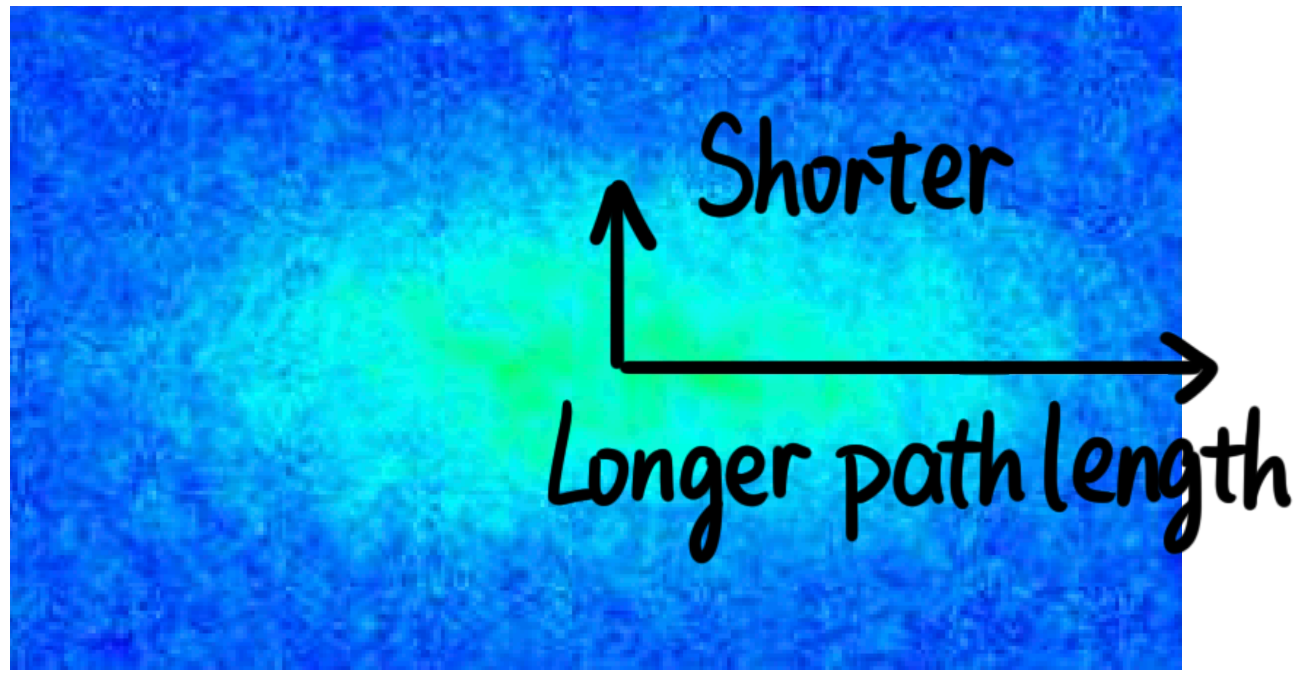
- Heavy flavor flow signal well-established
  - Flavor hierarchy at low p_T
  - Magnitude reflects thermalization degree

- Non-zero v_2 up to high p_T ~40 GeV
  - Path-length dependence of energy loss

Flow

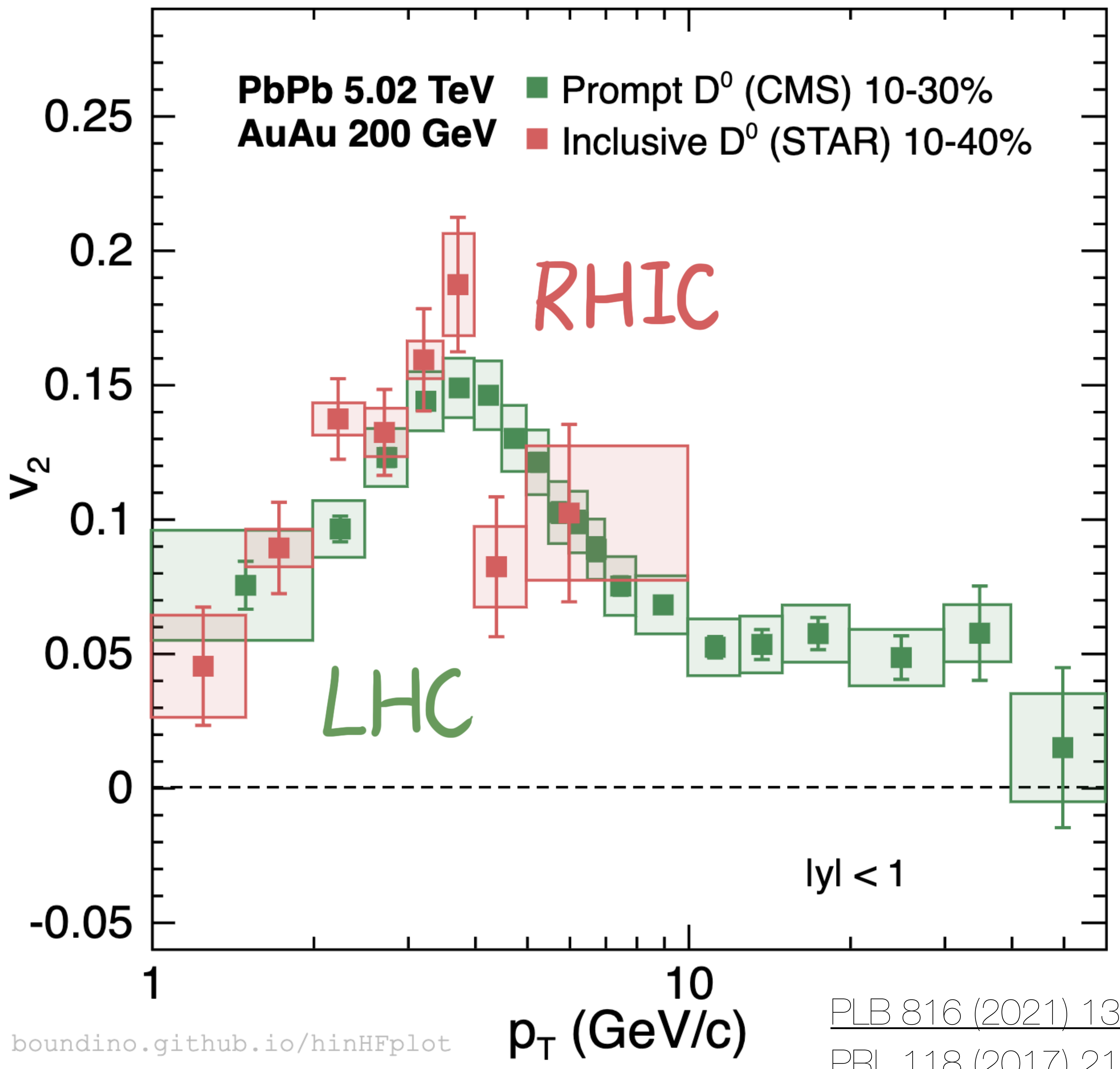


Path-length anisotropy



Charm Flow Signal: LHC vs. RHIC

D^0 v_2 in PbPb vs. AuAu

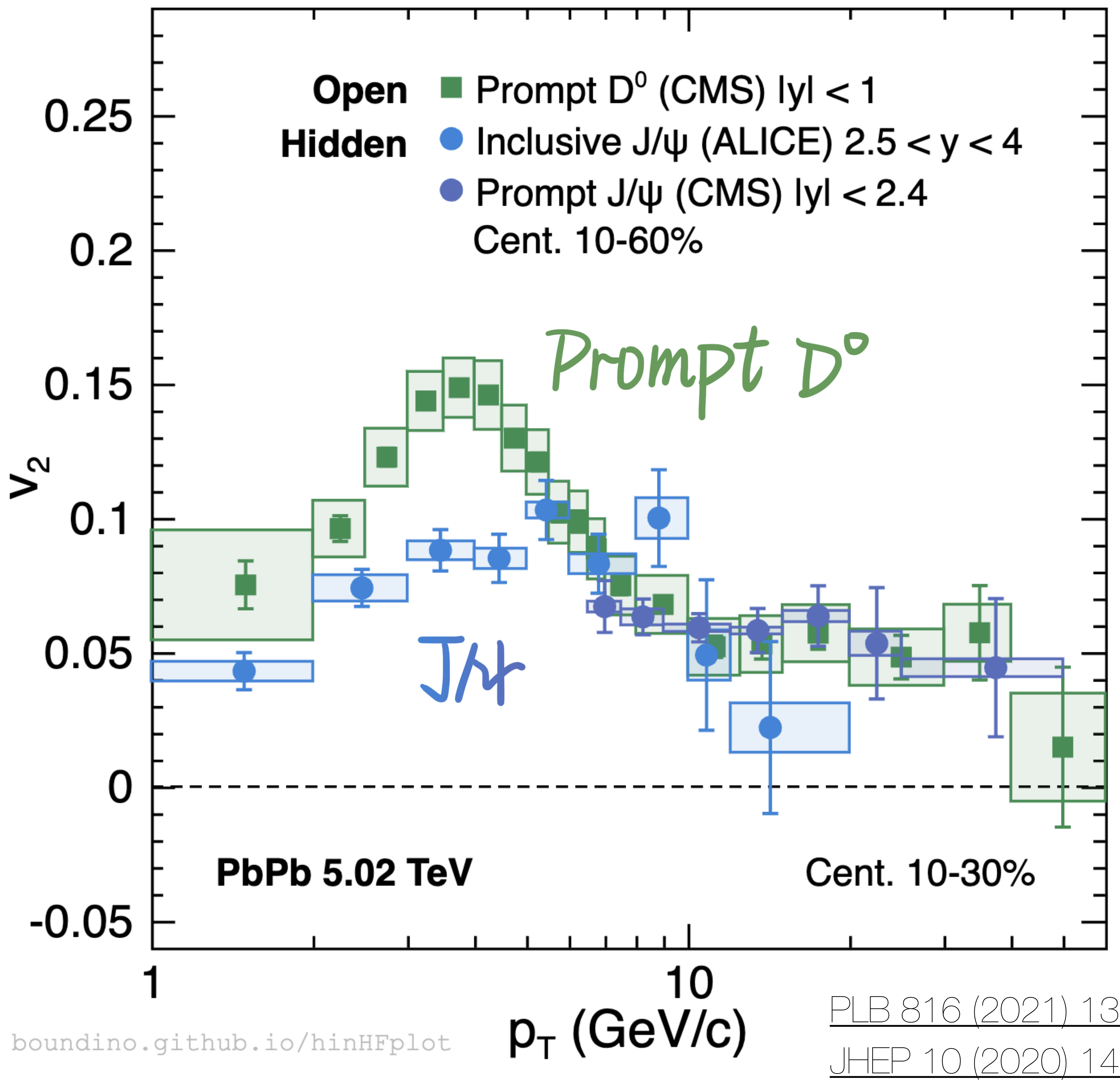


PLB 816 (2021) 136253
PRL 118 (2017) 212301

- Heavy flavor flow signal well-established
  - Flavor hierarchy at low p_T
  - Magnitude reflects thermalization degree
- Non-zero v_2 up to high p_T ~40 GeV
  - Path-length dependence of energy loss
- LHC vs. RHIC
  - Similar D v_2 → despite different T & size?
  - Decisive precision at sPHENIX

J/ψ Flow Signal at LHC

D^0 v_2 vs. J/ψ v_2



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PLB 816 (2021) 136253
JHEP 10 (2020) 141
CMS-PAS-HIN-21-008

- Heavy flavor flow signal well-established
  - Flavor hierarchy at low p_T
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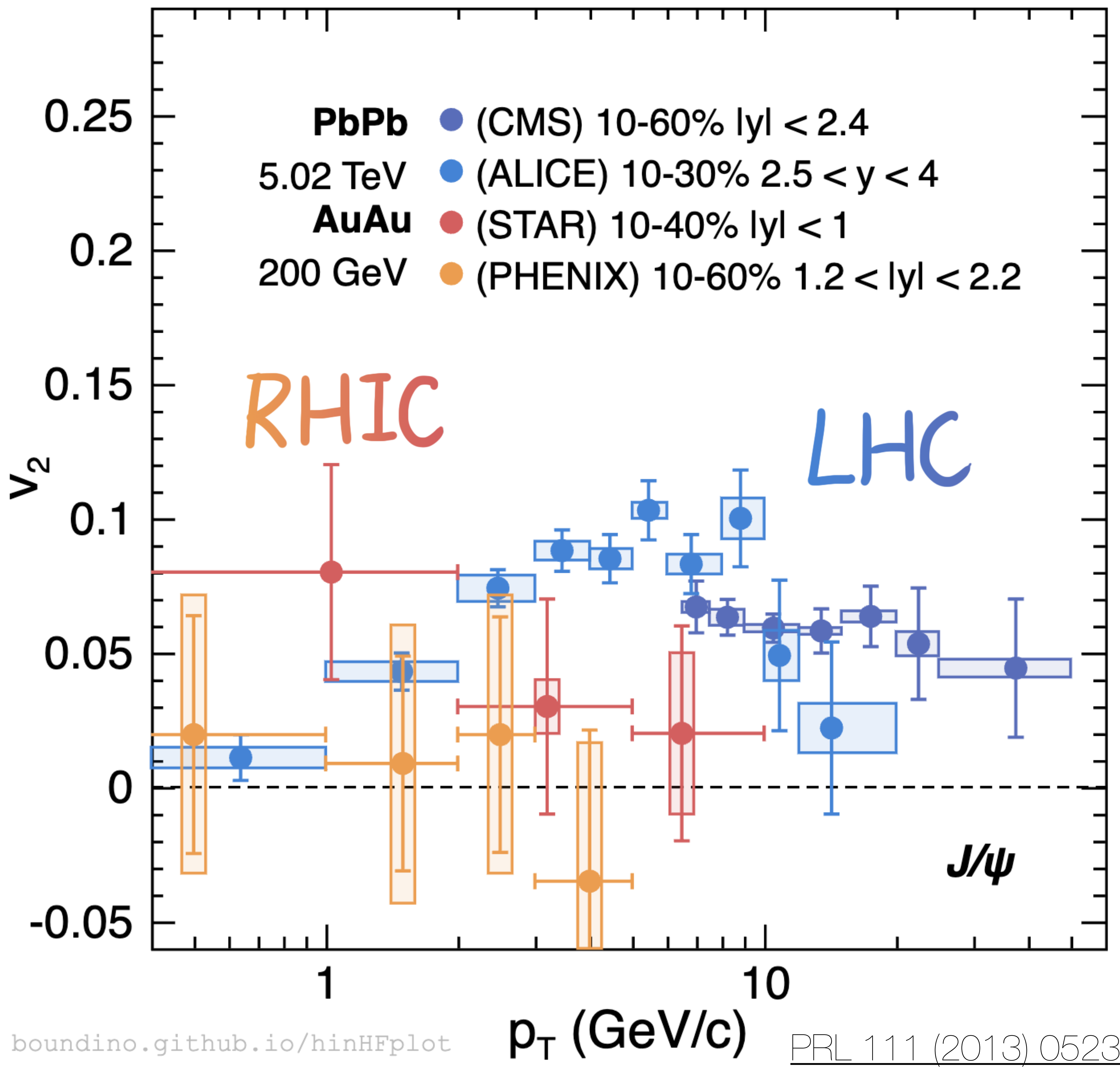
- Non-zero v_2 up to high p_T ~40 GeV
  - Path-length dependence of energy loss
  - All flavors tend to converge

- LHC vs. RHIC
  - Similar D v_2 → despite different T & size?

J/ψ Flow Signal at RHIC?

J/ψ v_2 in PbPb vs. AuAu



boundino.github.io/hinHFplot

PRL 111 (2013) 052301 JHEP 10 (2020) 141
PHENIX Preliminary CMS-PAS-HIN-21-008

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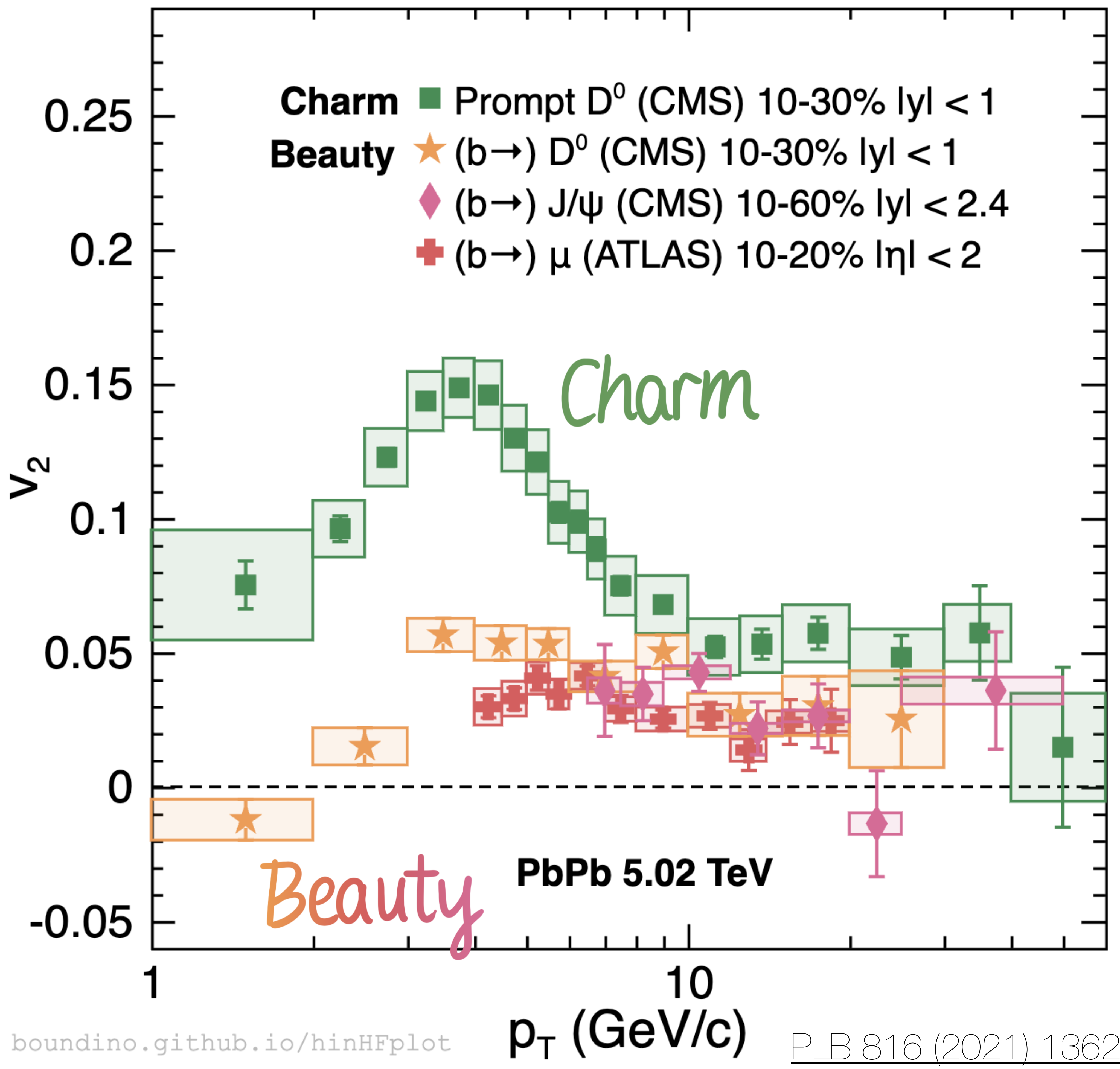
  - Similar D v_2 → despite different T & size?
  - Hint of zero v_2 of J/ψ at RHIC → recombination mainly contributes to v_2?

Beauty Flow Signal

Charm v_2 vs. Beauty v_2



boundino.github.io/hinHFplot

- Heavy flavor flow signal well-established
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  - Magnitude reflects thermalization degree
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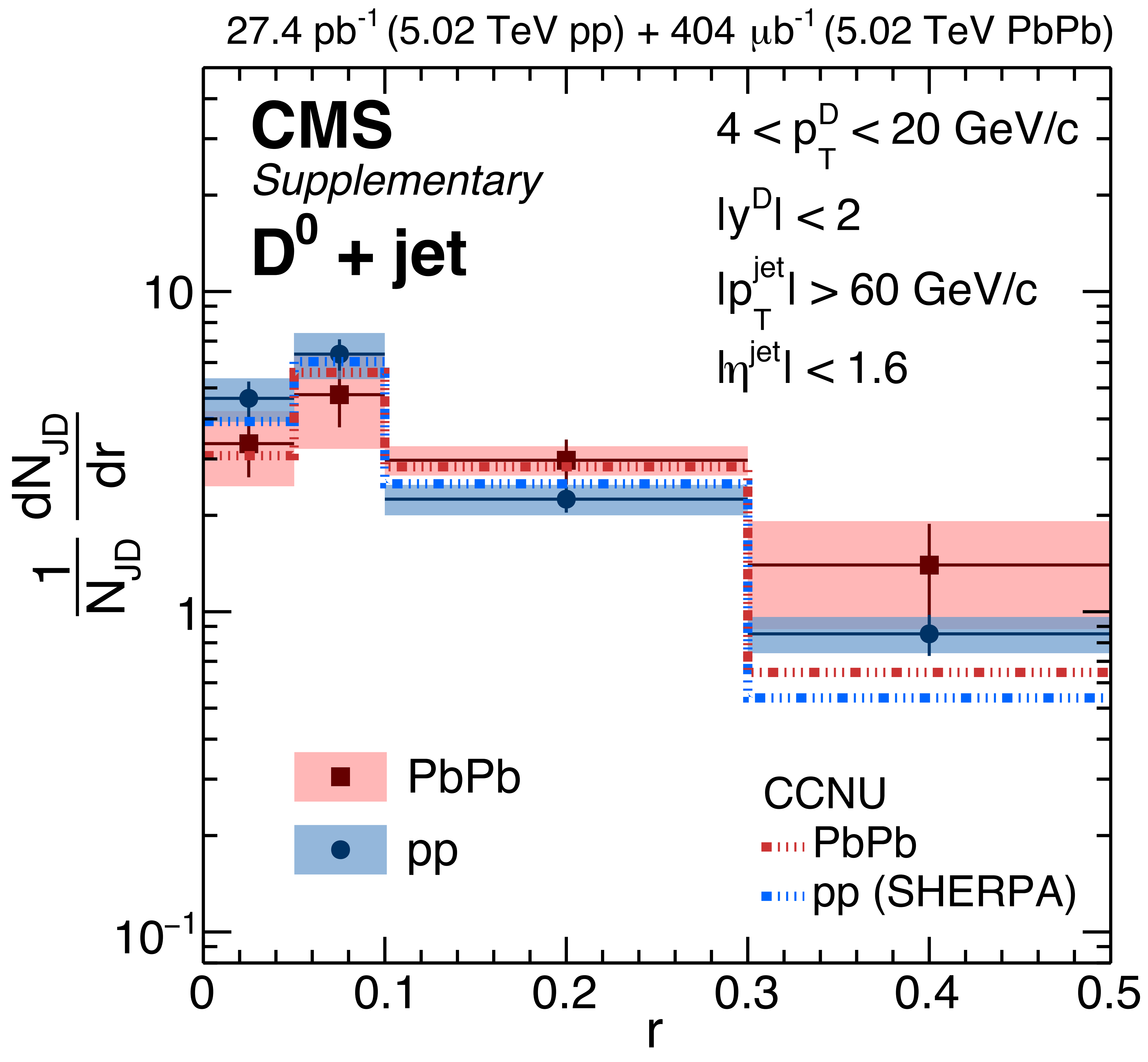
  - Path-length dependence of energy loss
  - All flavors tend to converge
- LHC vs. RHIC
  - Similar D v_2 → despite different T & size?
  - Hint of zero v_2 of J/ψ at RHIC → recombination mainly contributes to v_2?
  - Eager for high precision beauty v_2 at RHIC

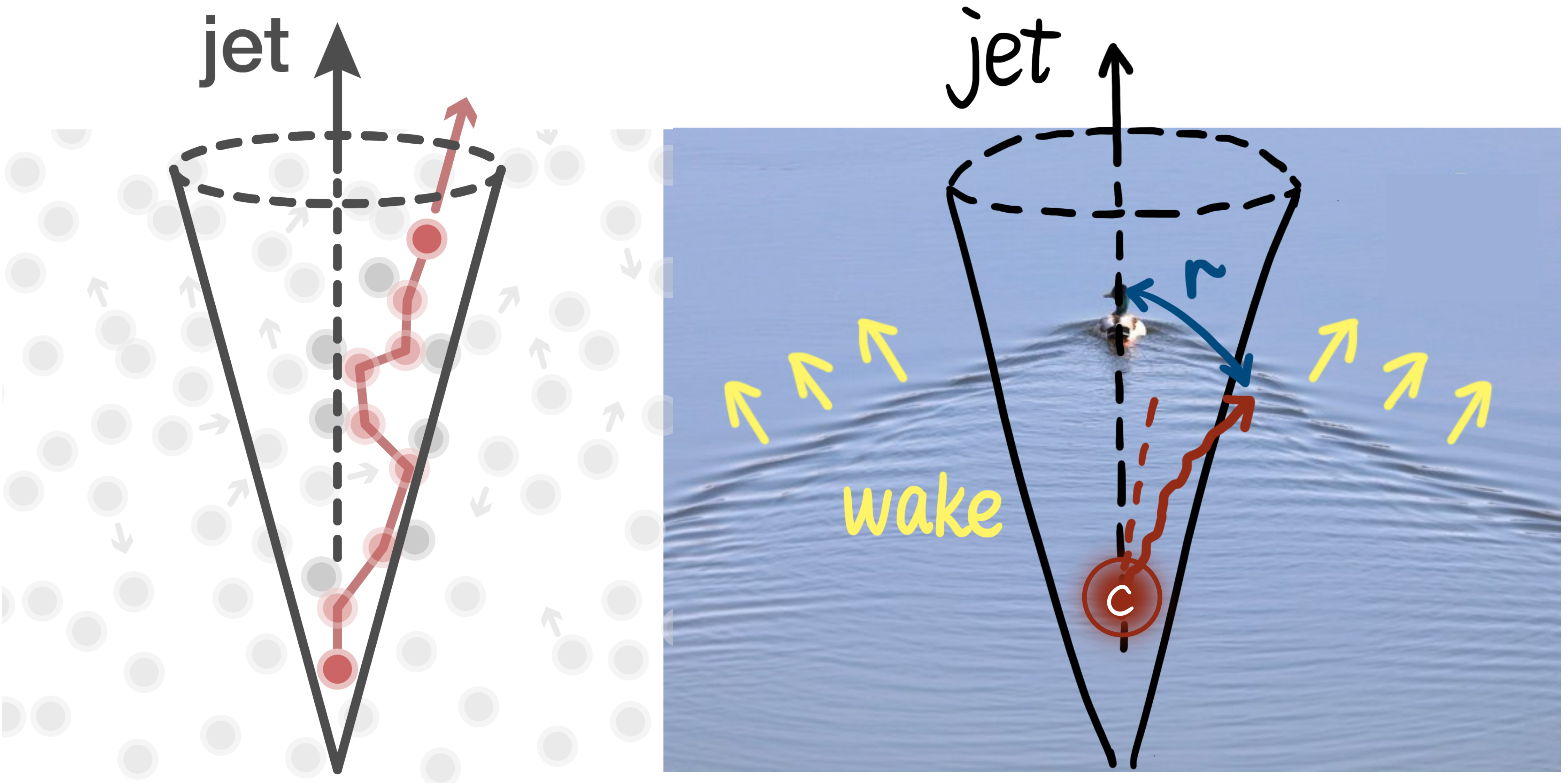
PLB 816 (2021) 136253 arXiv:2212.01636
PLB 807 (2020) 135595 CMS-PAS-HIN-21-008

Diffusion & Medium Response

Angular profile of D wrt jet axis



- Directly see diffusion via the angle between D mesons and jet axis
- Hint of D^0 farther from jet axis in PbPb than pp

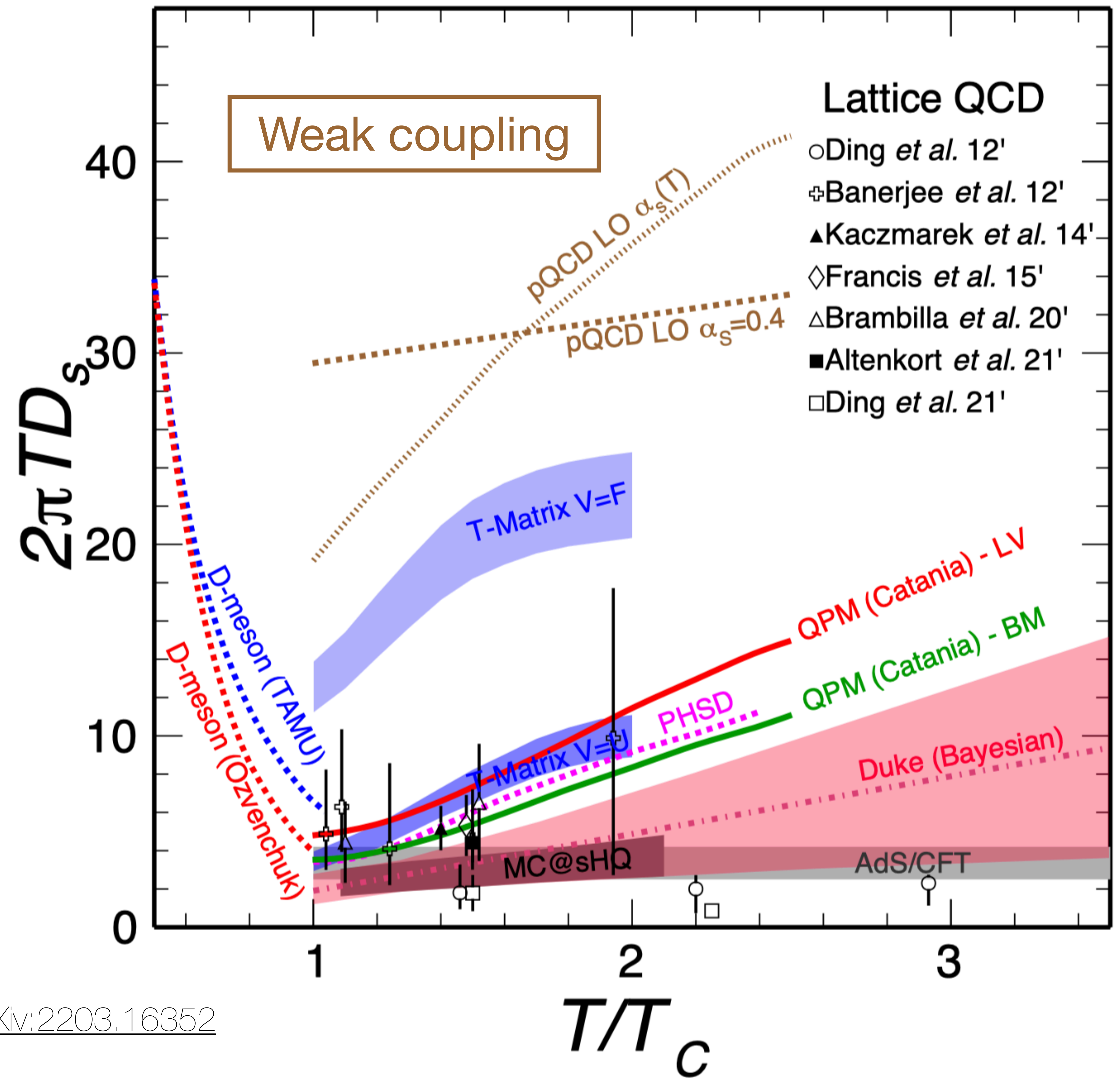


Charm diffusion   Medium response

PRL 125 (2020) 102001

Heavy Quark Probe QGP Transport Property

Diffusion coefficient D_s



arXiv:2203.16352

- Diffusion coefficient D_s directly related with QGP properties, e.g. viscosity
- D_s extracted from data with phenomenological model
  - Compare to first principle calculation
- Data agrees with strong coupling
  - Sensitive to long-range force and non-perturbative structure of QGP

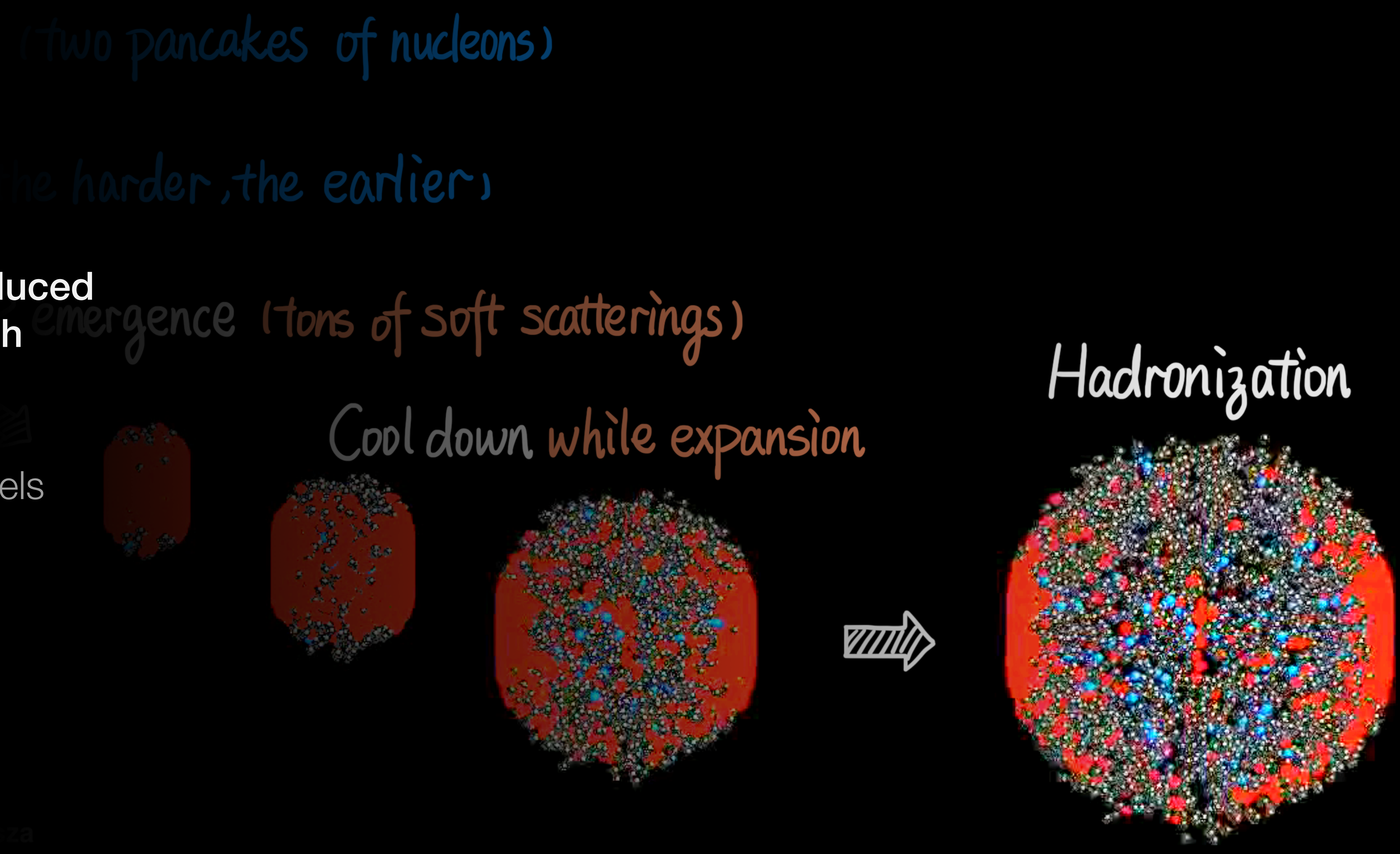
Extracted from data

Strong coupling

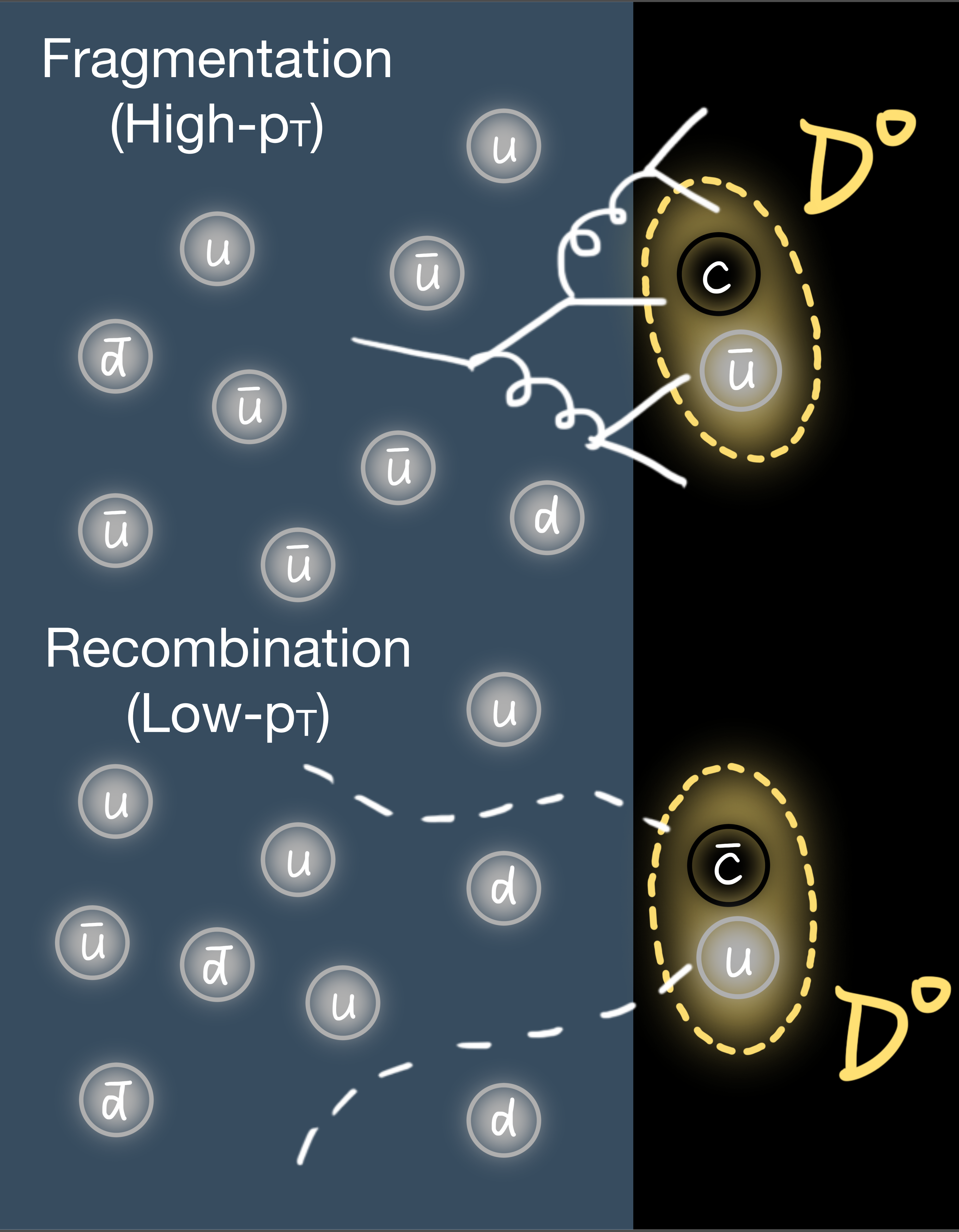
In-Medium Hadronization

How are hadrons produced from heavy quarks with medium existence?

Major uncertainty in phenomenological models

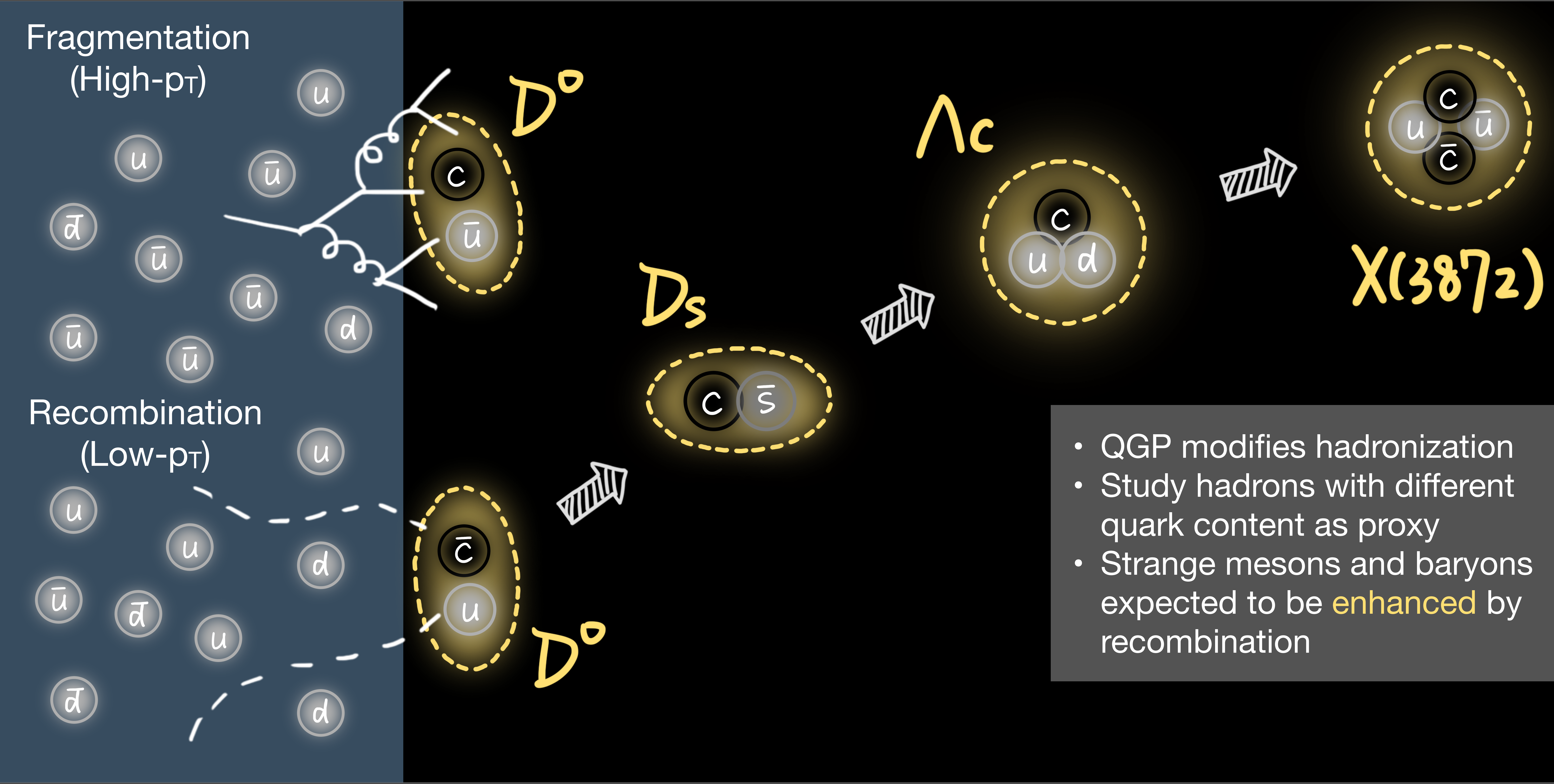


In-Medium Hadronization



- QGP modifies hadronization
  - Recombination in addition to fragmentation

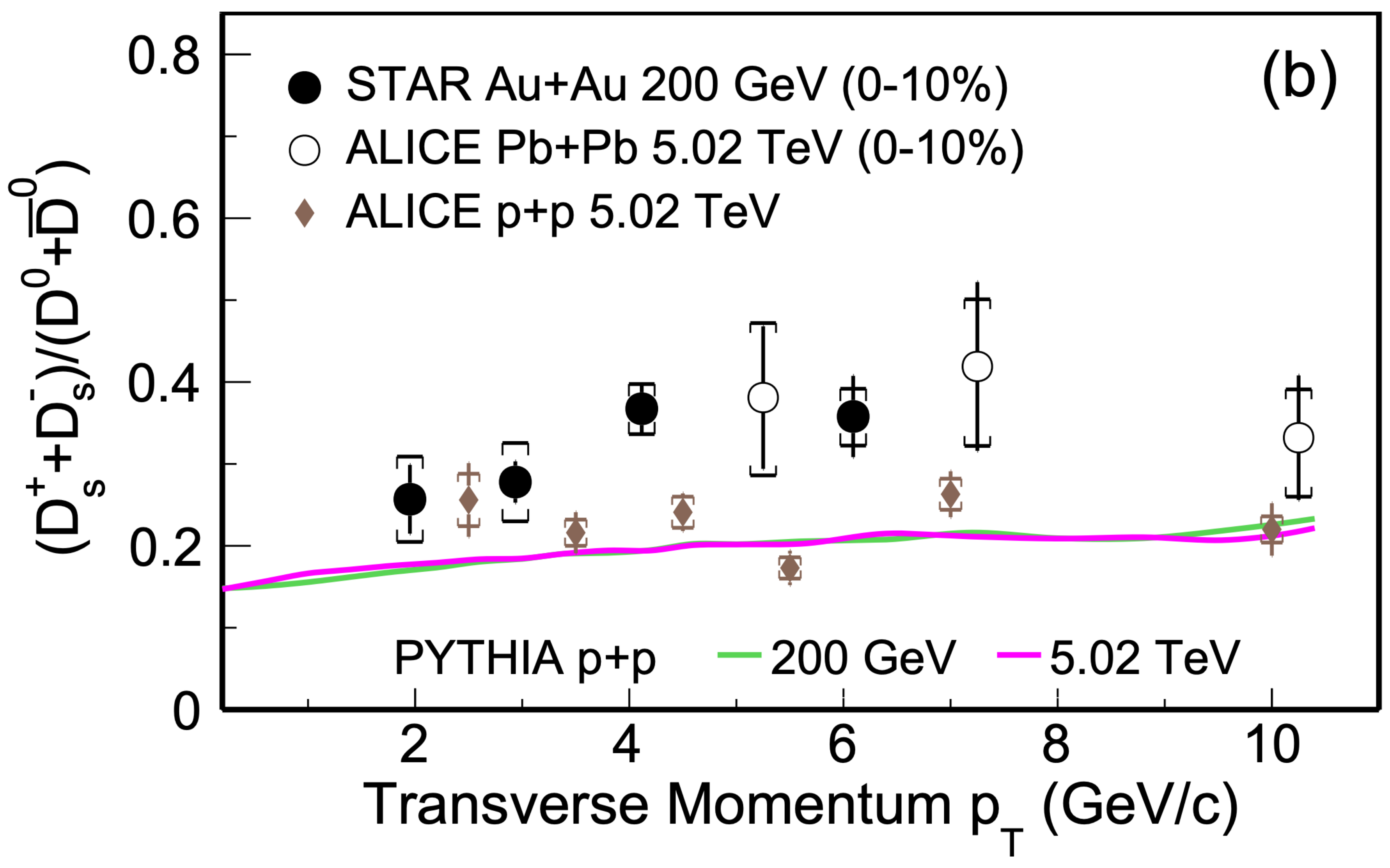
In-Medium Hadronization



- QGP modifies hadronization
- Study hadrons with different quark content as proxy
- Strange mesons and baryons expected to be enhanced by recombination

Hadronization: Strange- & Charm-Meson

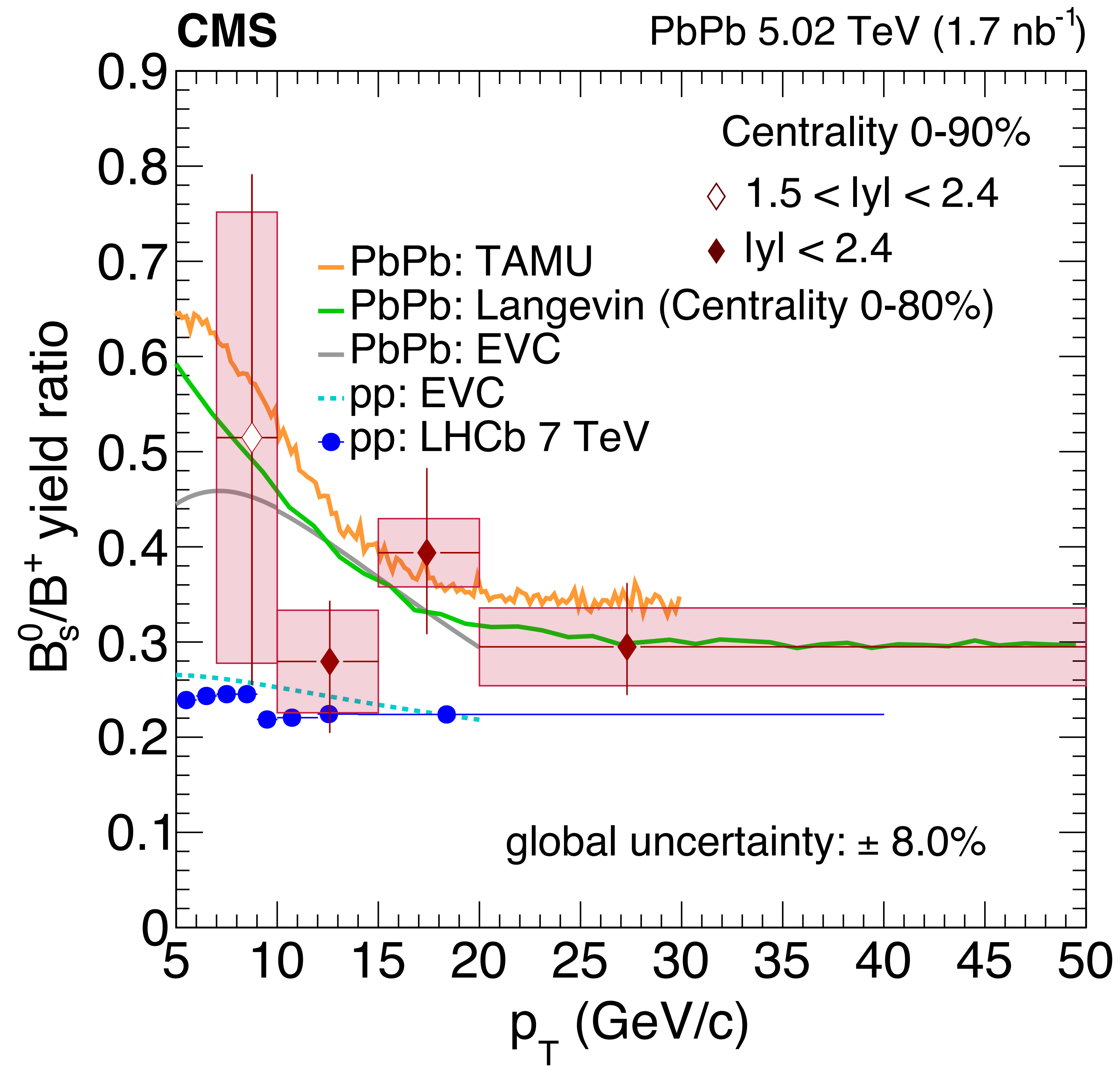
D_s/D^0 ratio



- Indication of larger D_s/D^0 in PbPb and AuAu than pp

PRL 127 (2021) 092301

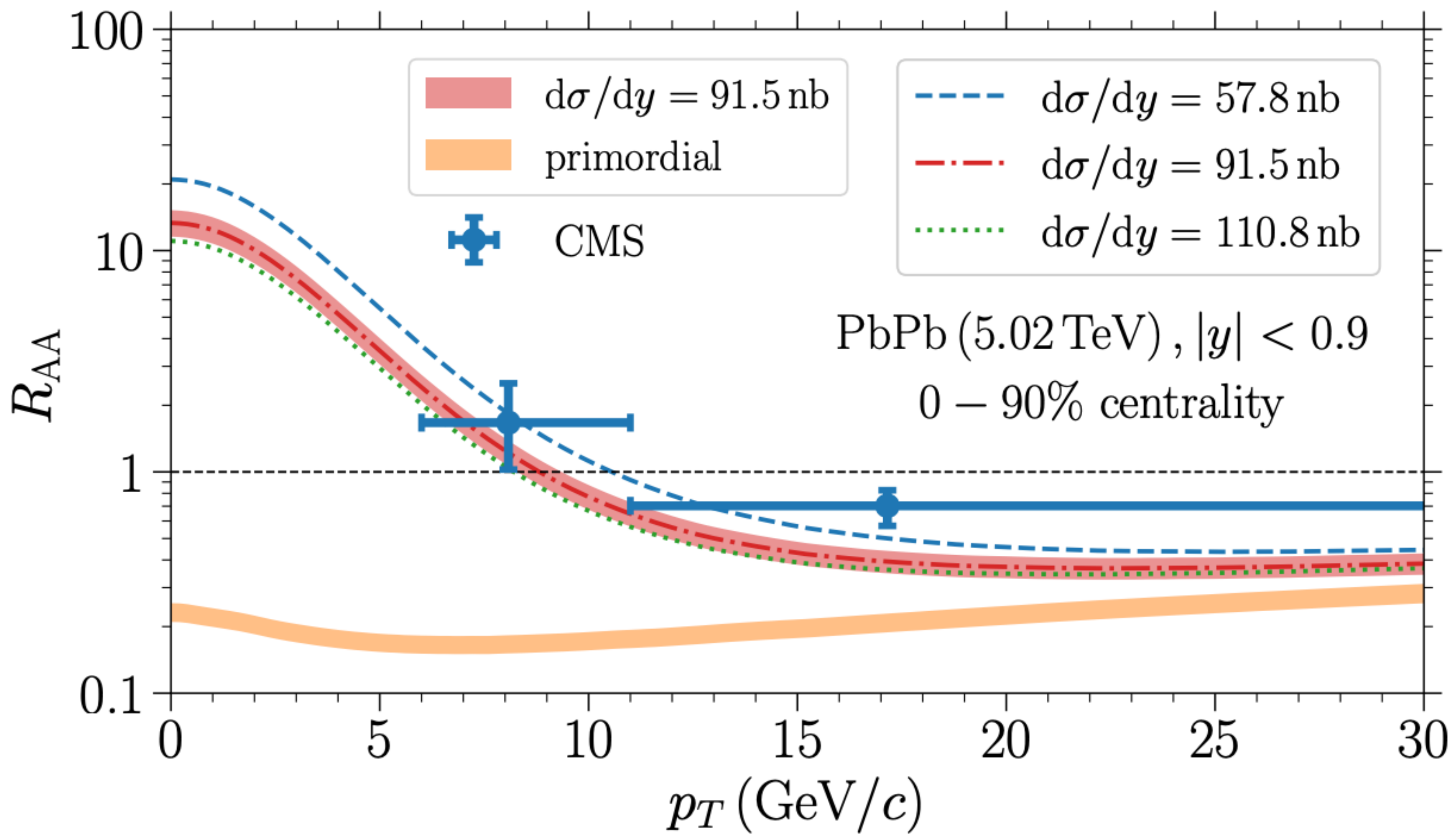
B_s/B^+ ratio



- Statistically compatible b/w PbPb and pp

PLB 829 (2022) 137062

B_c R_{AA}

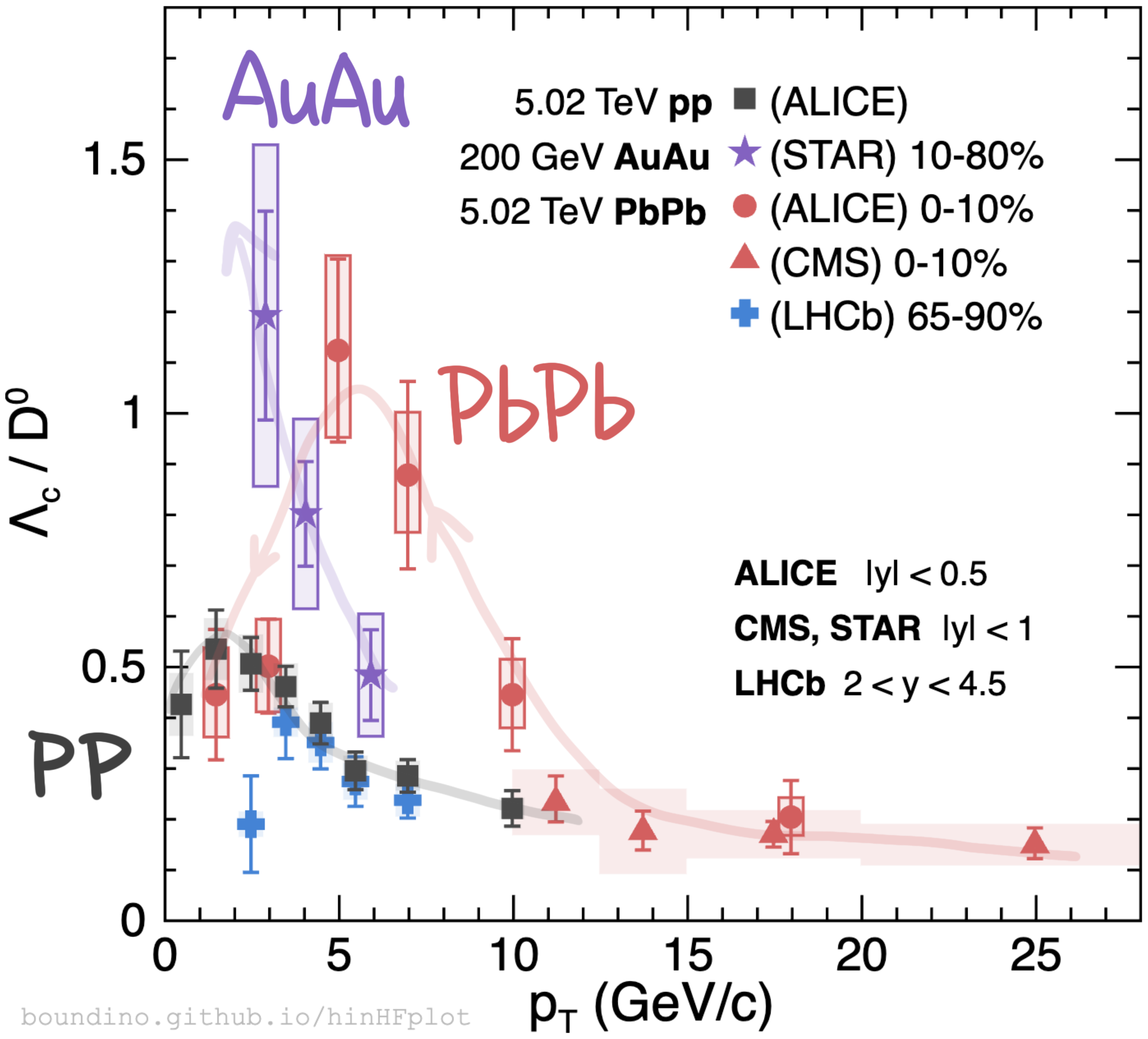


- B_c enhancement expected due to recombination

PRL 128 (2022) 252301 arXiv:2302.11511

Hadronization: Λ_c Production

Λ_c/D^0 in pp vs. AA



boundino.github.io/hinHFplot

- Enhanced Λ_c/D^0 ratio in AA collisions
  ➜ Hint of recombination
  - Only at intermediate p_T
  - Stronger in central events
  - Effect of rapidity under study

arXiv:2112.08156

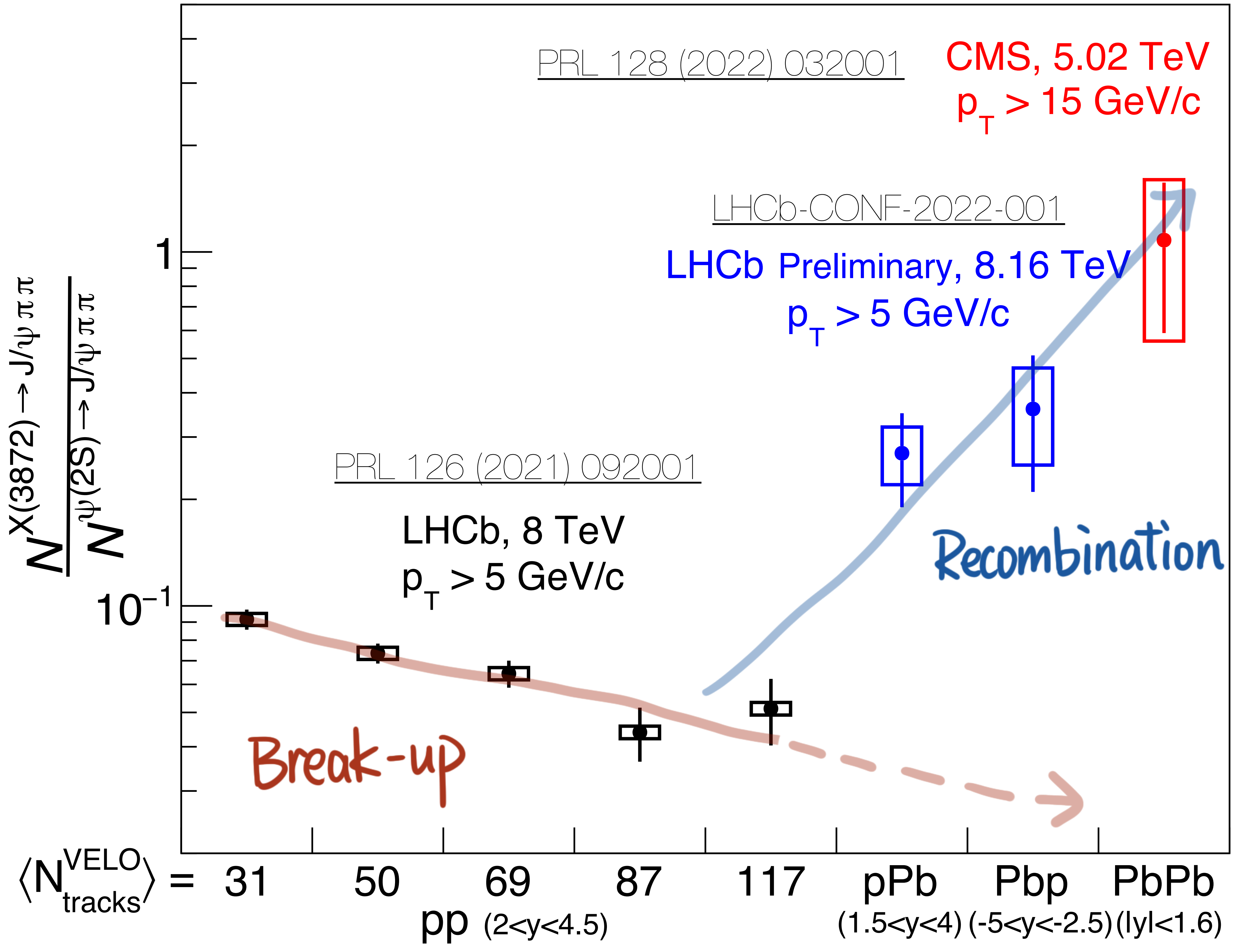
arXiv:2210.06939

PRL 124 (2020) 172301

CMS-PAS-HIN-21-004

Hadronization New Frontier: X(3872)

X(3872)/ψ(2S) vs. collision system size



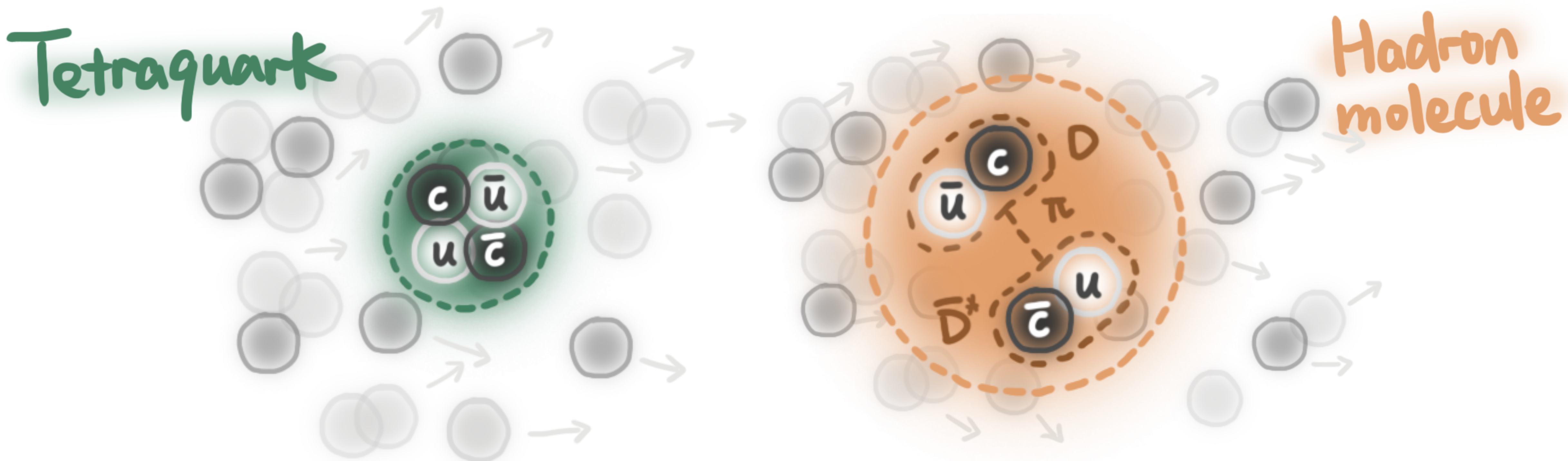
Low multiplicity
Small system

High multiplicity
Large system

- Broken up by interactions with comovers
  - Stronger in high-multiplicity environment
- Production via recombination
  - Stronger than baryons ← more quark content
- Both effects depend on inner structure
  - Potential discrimination in heavy-ion collisions

Tightly bound, small radius

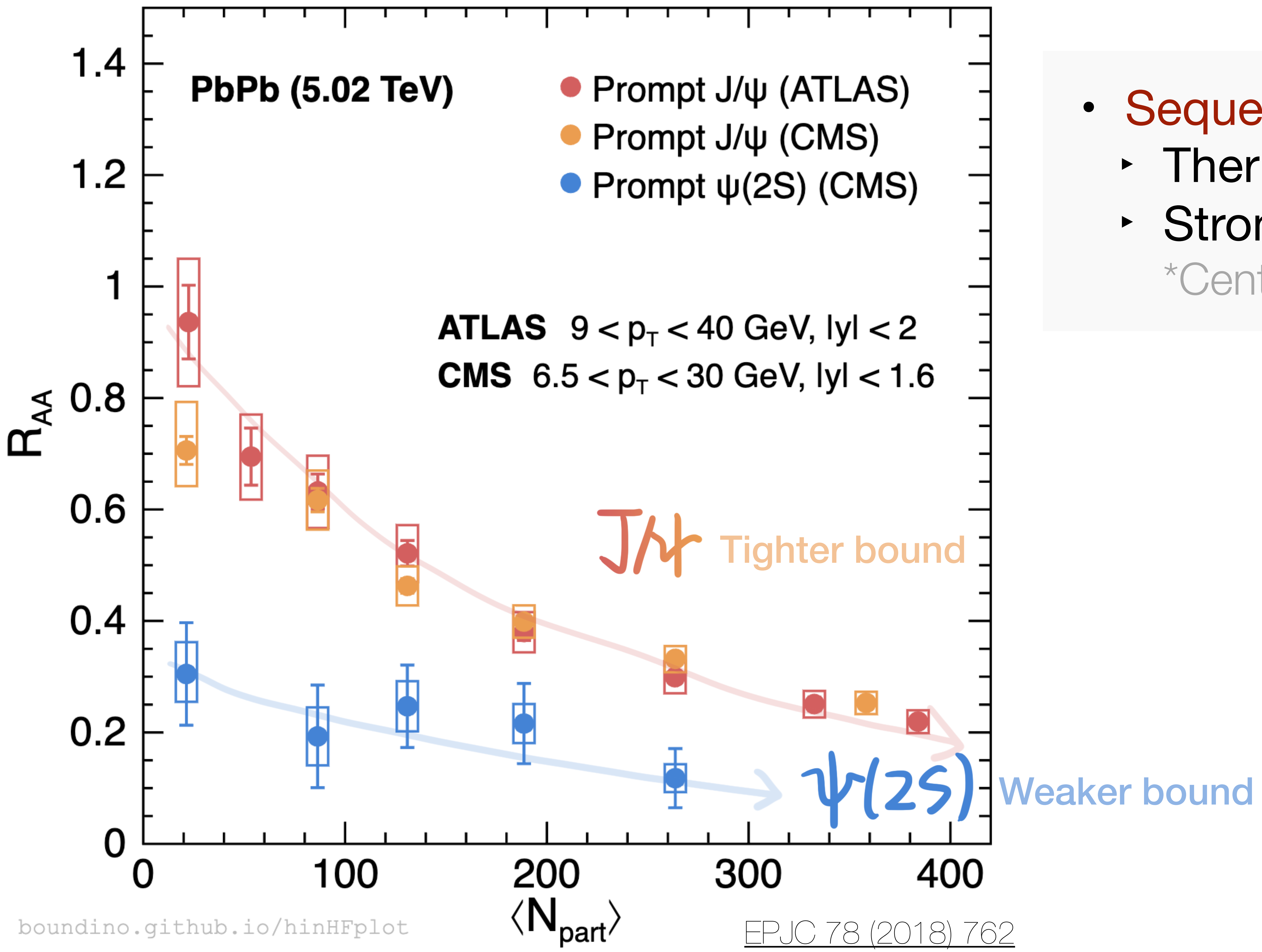
Weakly bound, large radius



20-year debate of X(3872) nature

Charmonium Production: Sequential Melting

J/ψ, ψ(2S) vs. centrality

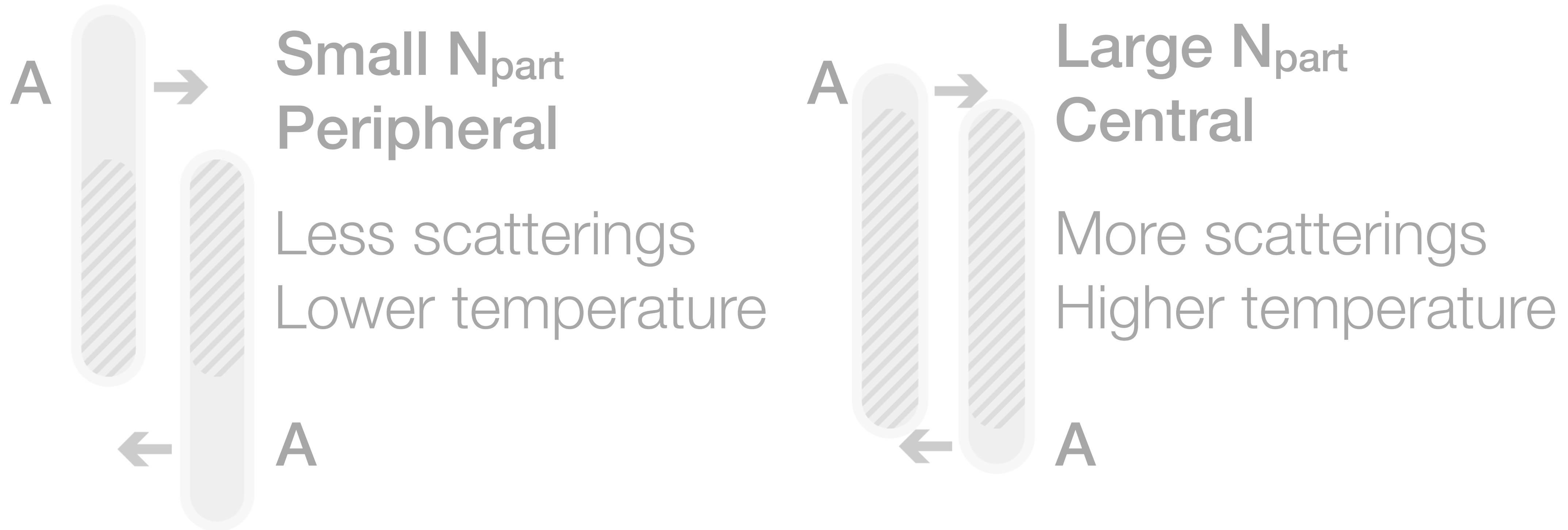


EPJC 78 (2018) 762
EPJC 78 (2018) 509

$Q\bar{Q}$ → Bound states of quark and its anti-quark

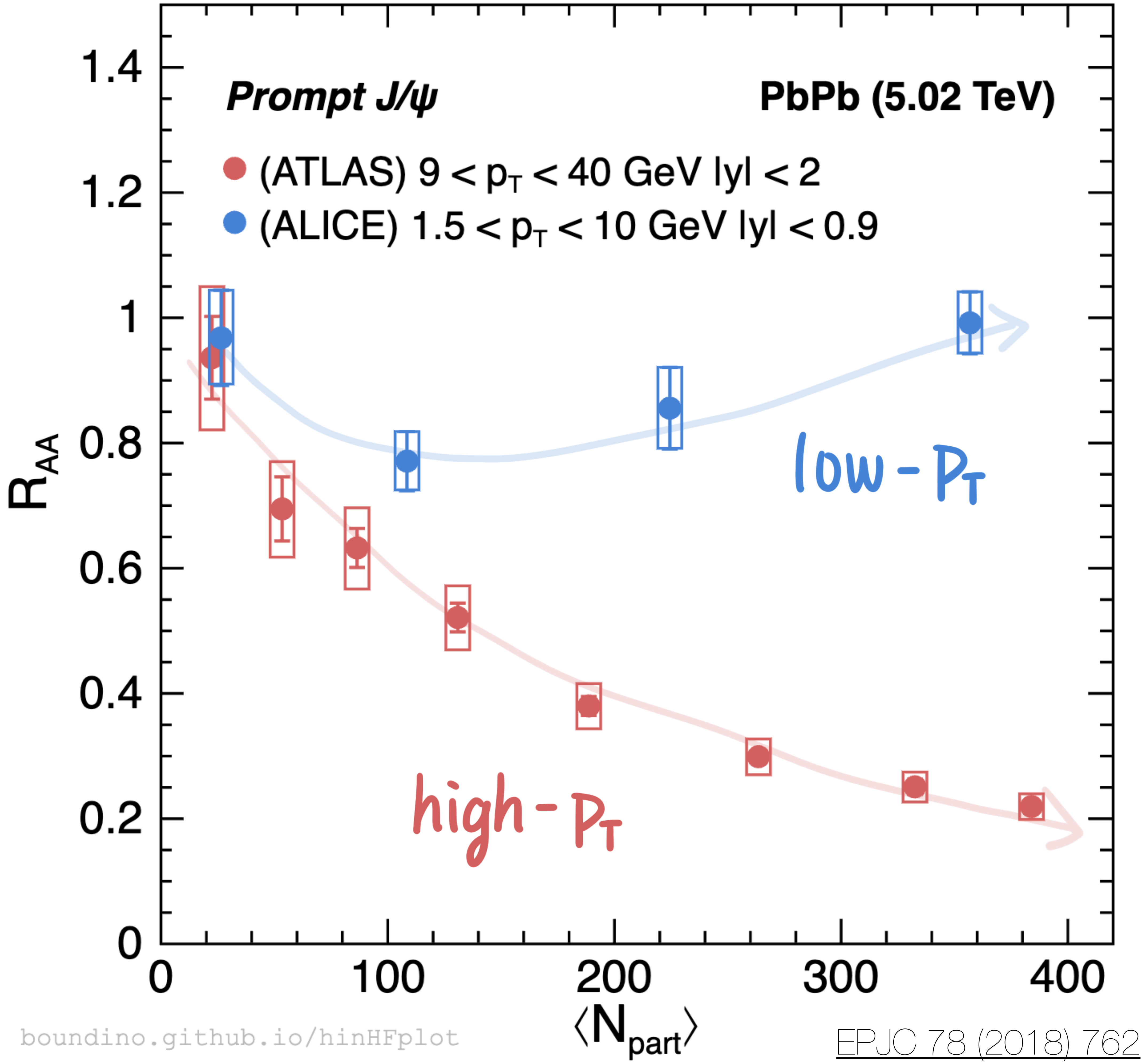
- Sequential melting → binding energy hierarchy
  - Thermometer of QGP
  - Stronger suppression in central events → higher T

  *Central: large N_{part}



Charmonium Production: Recombination

Low p_T vs. High p_T



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EPJC 78 (2018) 762
ALICE Preliminary

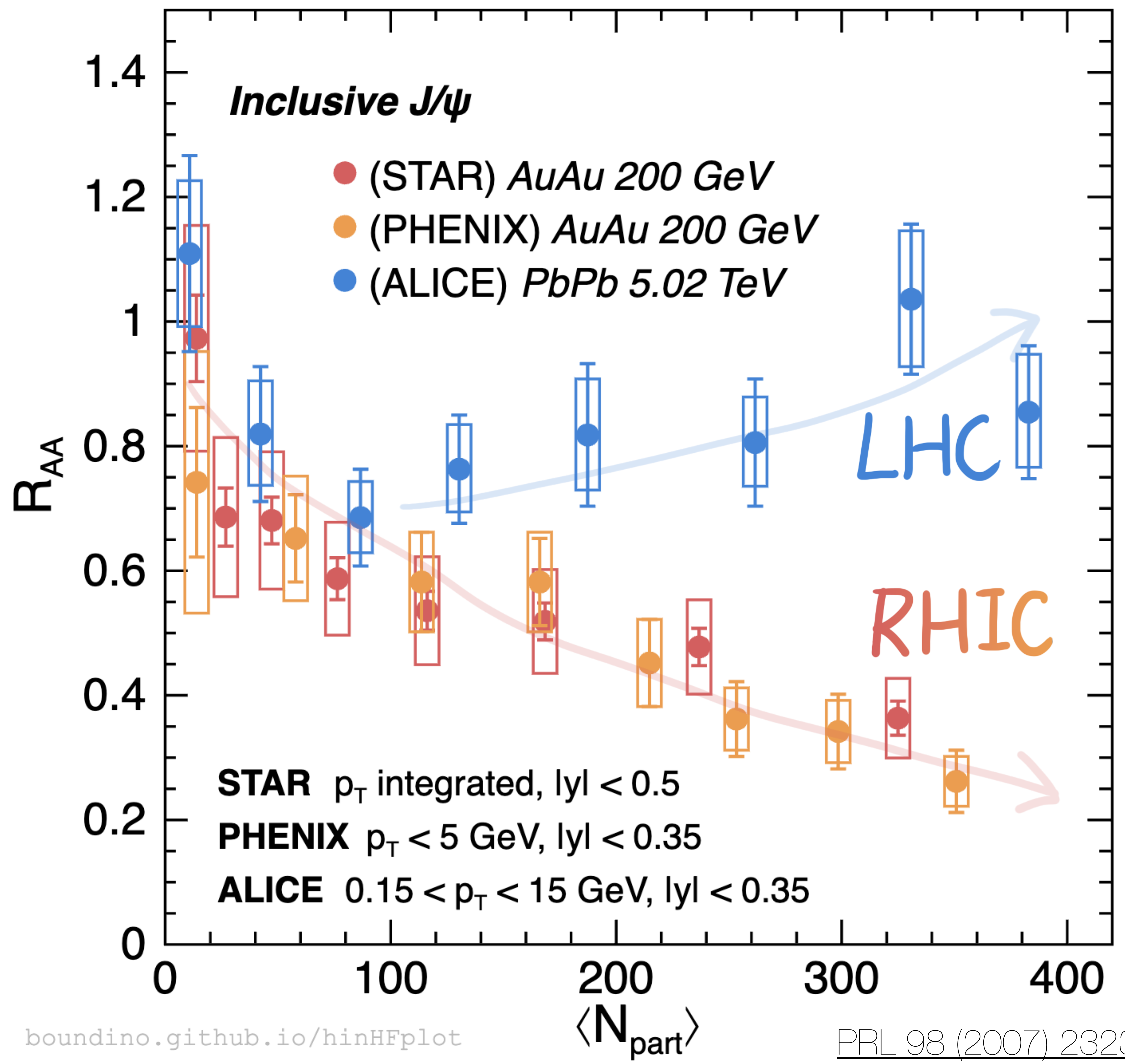
$Q\bar{Q}$ → Bound states of quark and its anti-quark

- Sequential melting → binding energy hierarchy
  - Thermometer of QGP
  - Stronger suppression in central events → higher T

- Recombination
  - Enhancement at low p_T in central events → larger $\sigma_{c\bar{c}}$

Charmonium Production: Recombination

LHC vs. RHIC



PRL 98 (2007) 232301
PLB 797 (2019) 134917 arXiv:2303.13361

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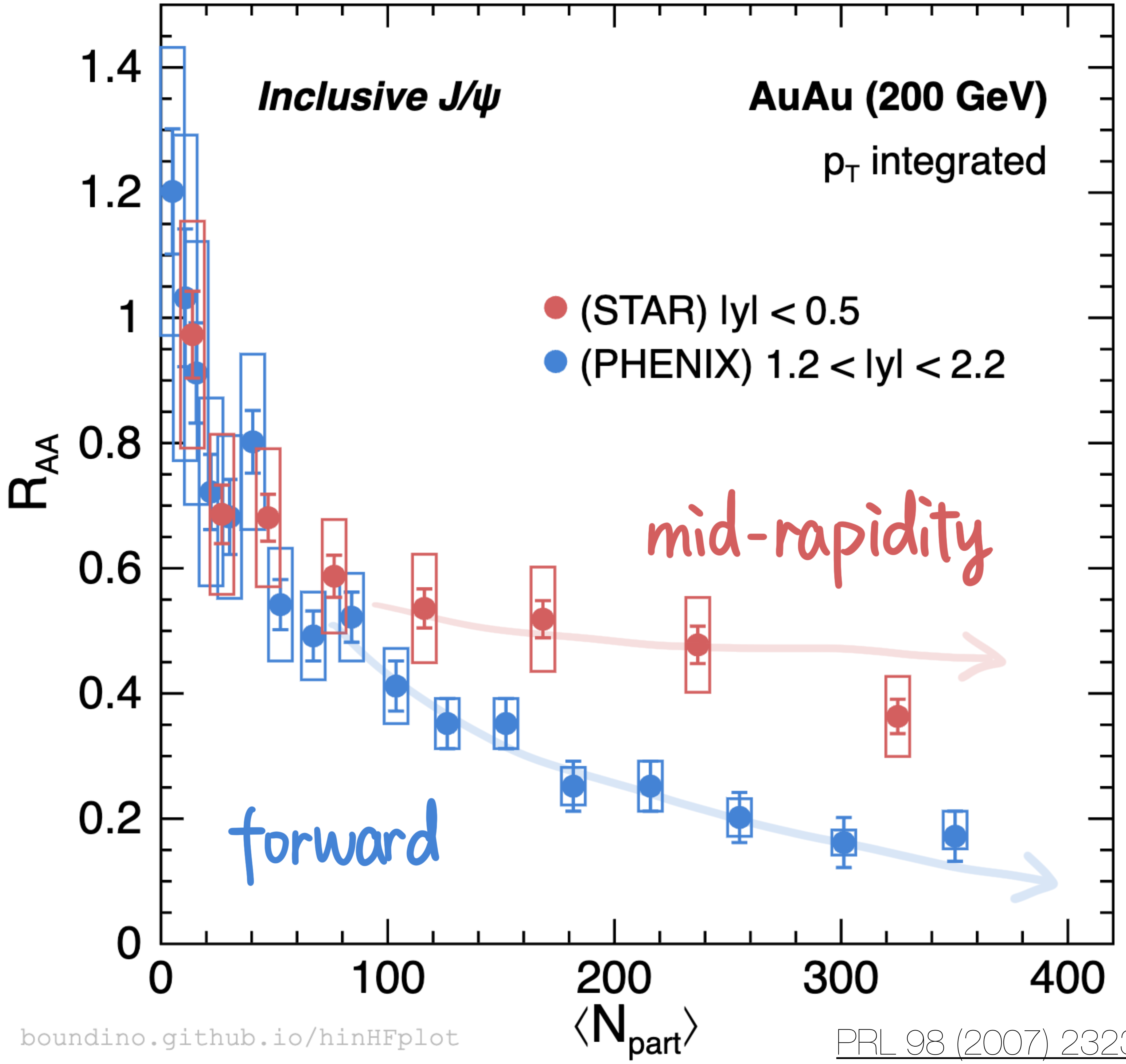
  - Stronger suppression in central events → higher T

- Recombination
  - Enhancement at low p_T in central events → larger $\sigma_{c\bar{c}}$
  - Significant in LHC not RHIC → larger $\sigma_{c\bar{c}}$

Charmonium Production: Cold Nuclear Matter Effects

Mid-rapidity vs. Forward



boundino.github.io/hinHFplot

PRL 98 (2007) 232301
PLB 797 (2019) 134917

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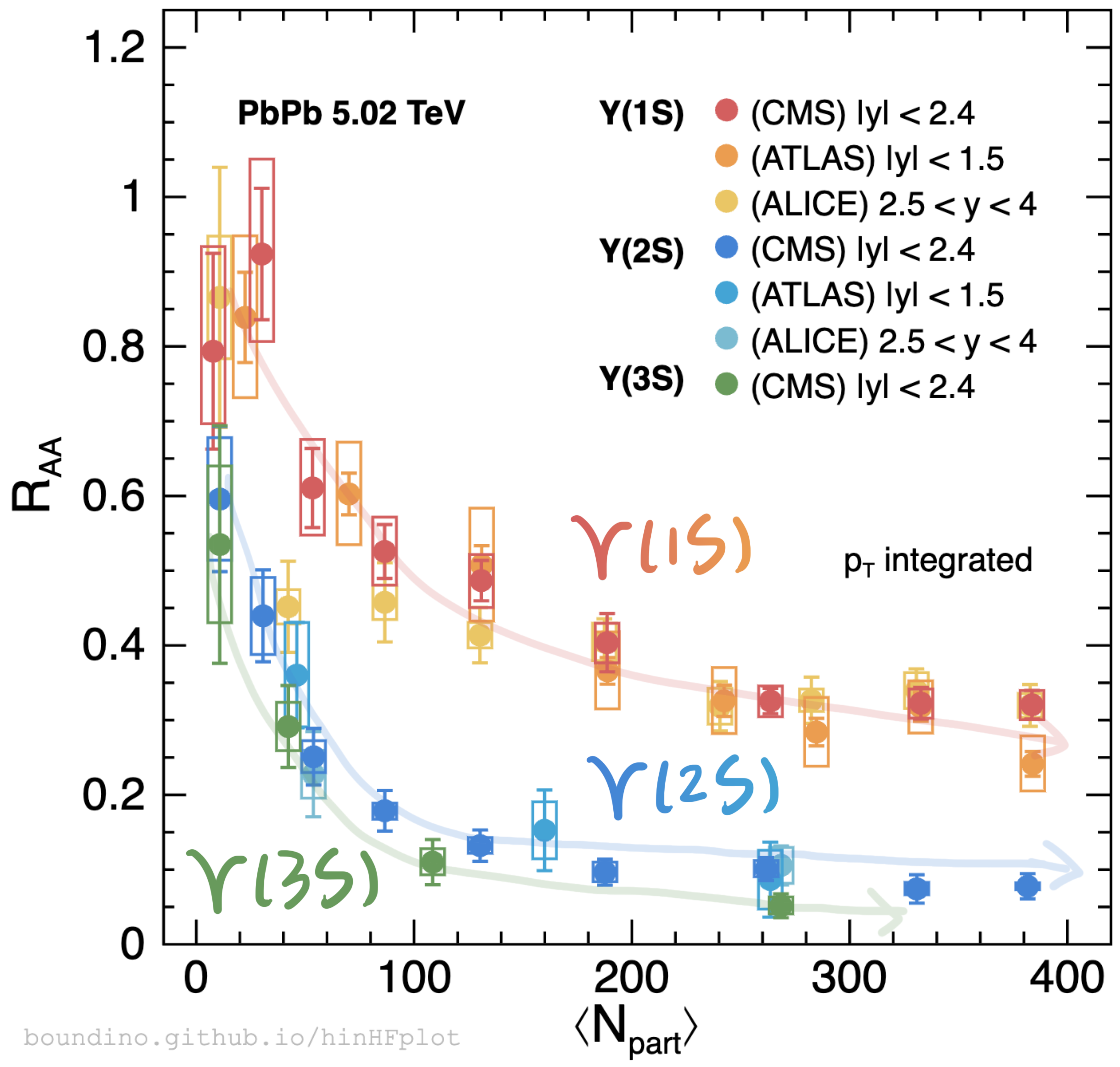
- Sequential melting → binding energy hierarchy
  - Thermometer of QGP
  - Stronger suppression in central events → higher T
- Recombination
  - Enhancement at low p_T in central events → larger $\sigma_{c\bar{c}}$
  - Significant in LHC not RHIC → larger $\sigma_{c\bar{c}}$
- Cold nuclear matter effects
  - Nuclear/comover absorption
    - Destroyed by interactions with nucleus remnants
  - Nuclear PDF

Bottomium Production: Sequential Melting

Y(nS) vs. centrality

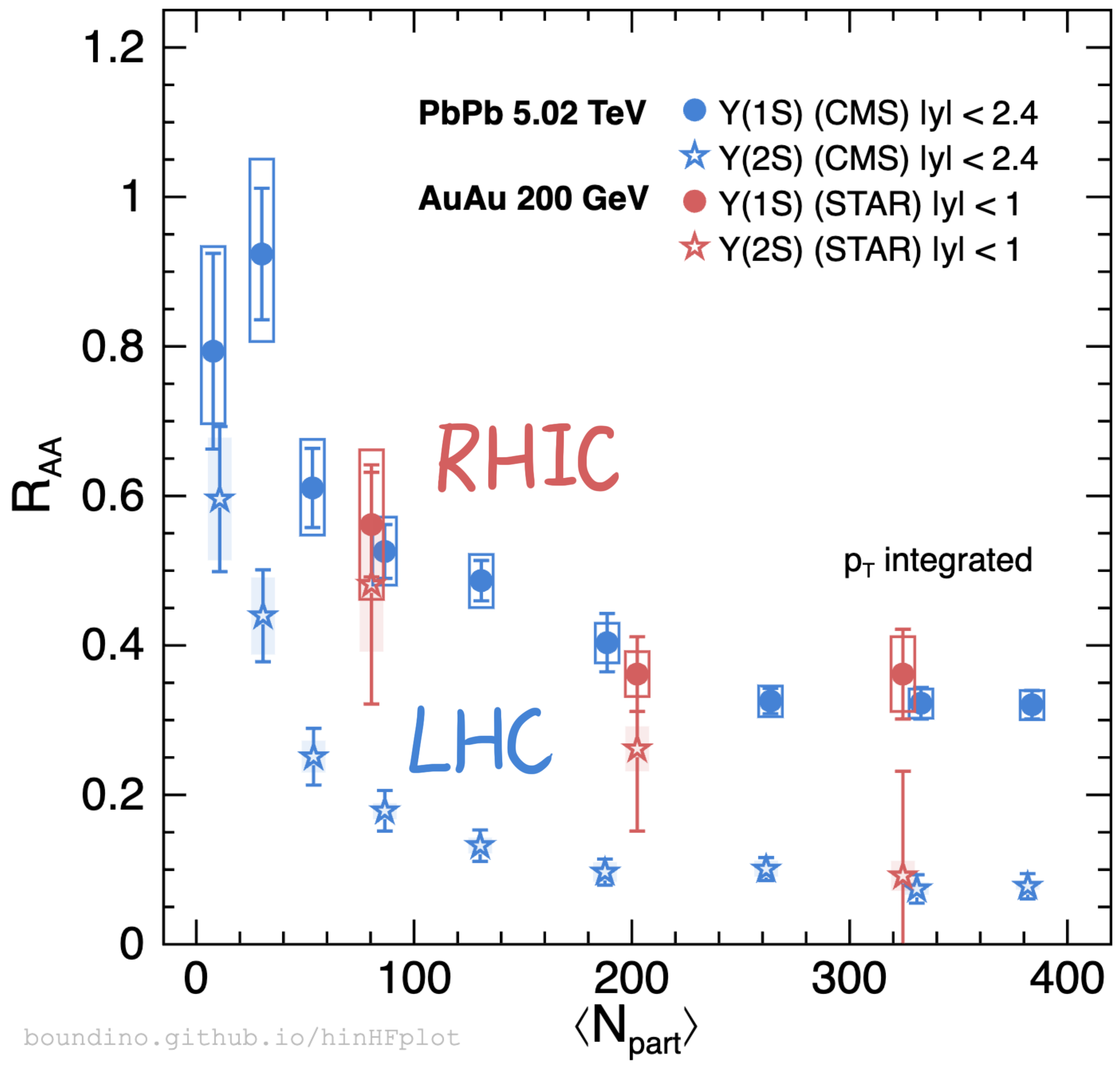


- Sequential suppression for Υ(nS)
  - Υ(1S) > Υ(2S) > Υ(3S)
  - Much weaker recombination for beauty

PLB 822 (2021) 136579
arXiv:2205.03042
arXiv:2303.17026

Bottomium Production: LHC vs. RHIC

Υ(nS) R_{AA} in PbPb vs. AuAu

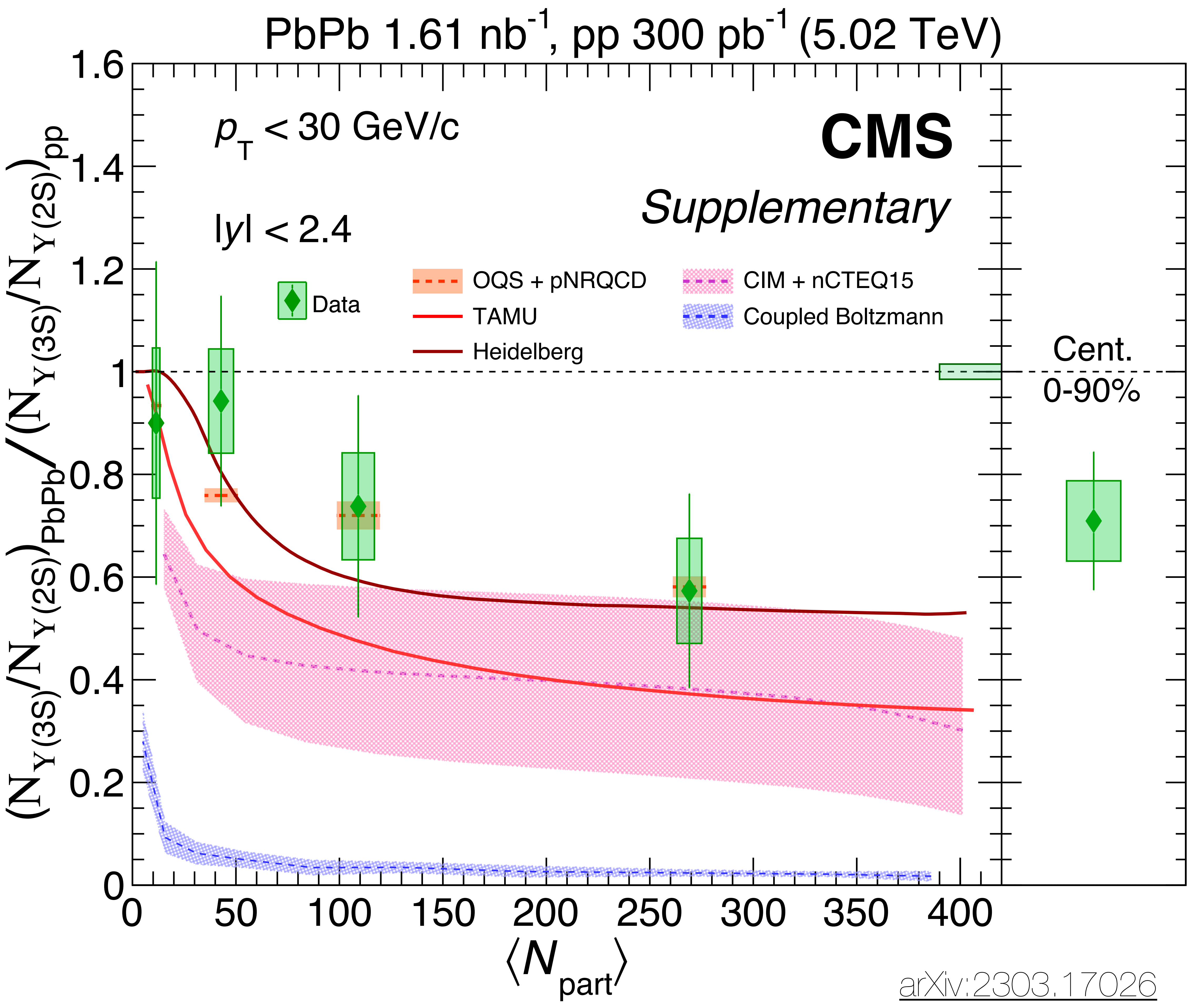


- Sequential suppression for Υ(nS)
  - Υ(1S) > Υ(2S) > Υ(3S)
  - Much weaker recombination for beauty
  - Why similar Υ(1S) R_{AA} in LHC & RHIC?
  - High precision at sPHENIX

PRL 130 (2023) 112301
arXiv:2303.17026

First observation of Υ(3S) in AA

RAA(Υ(3S)) / RAA(Υ(2S))

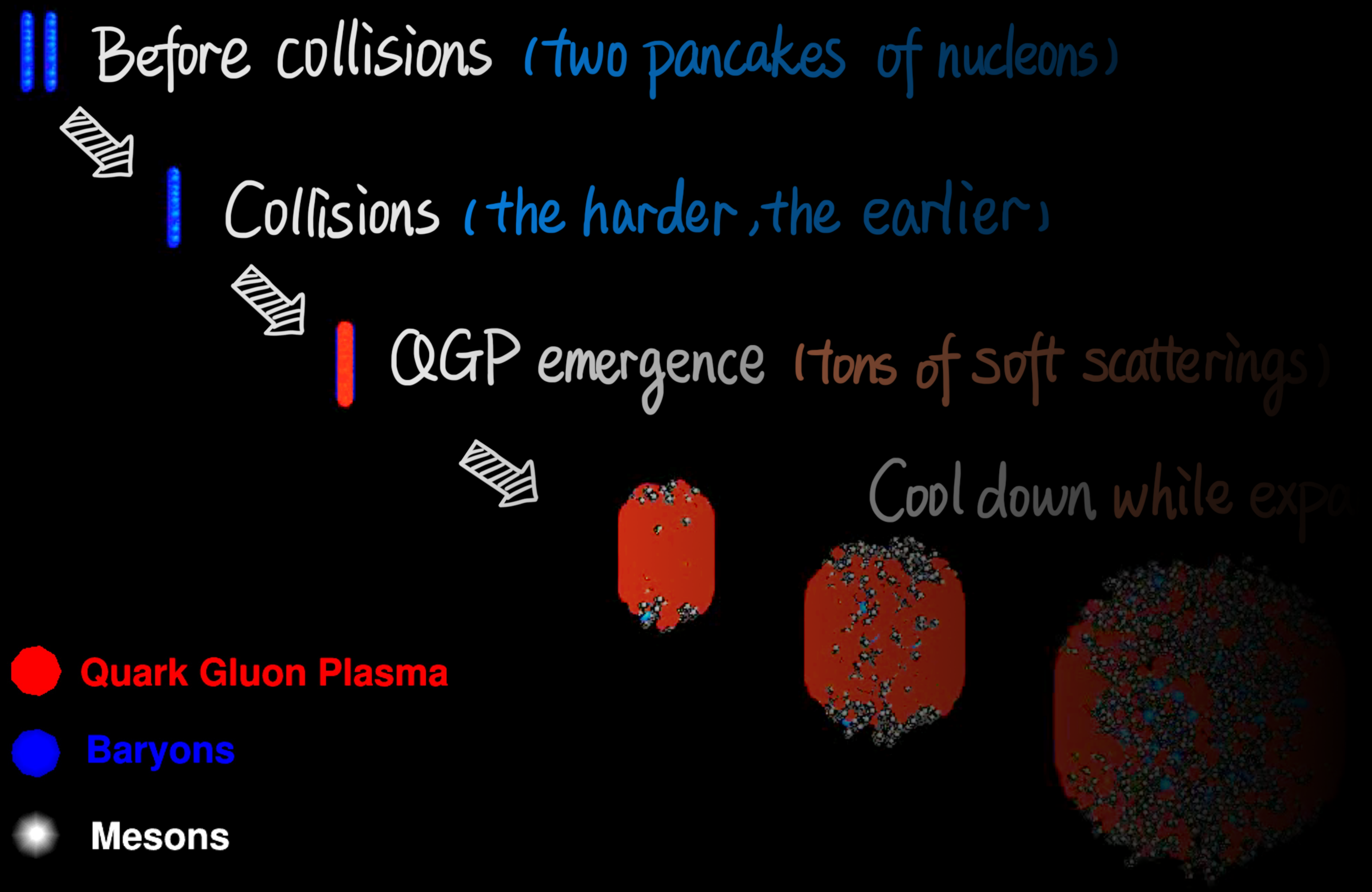


arXiv:2303.17026

- Sequential suppression for Υ(nS)
  - Υ(1S) > Υ(2S) > Υ(3S)
  - Much weaker recombination for beauty
  - Why similar Υ(1S) R_{AA} in LHC & RHIC?
  - High precision at sPHENIX

- Υ(3S) first observed in AA collisions
  - Crucial to constrain feed-down contribution
  - Particle ratio cancels nPDF effect
  - Challenging for theoretical models

Initial State



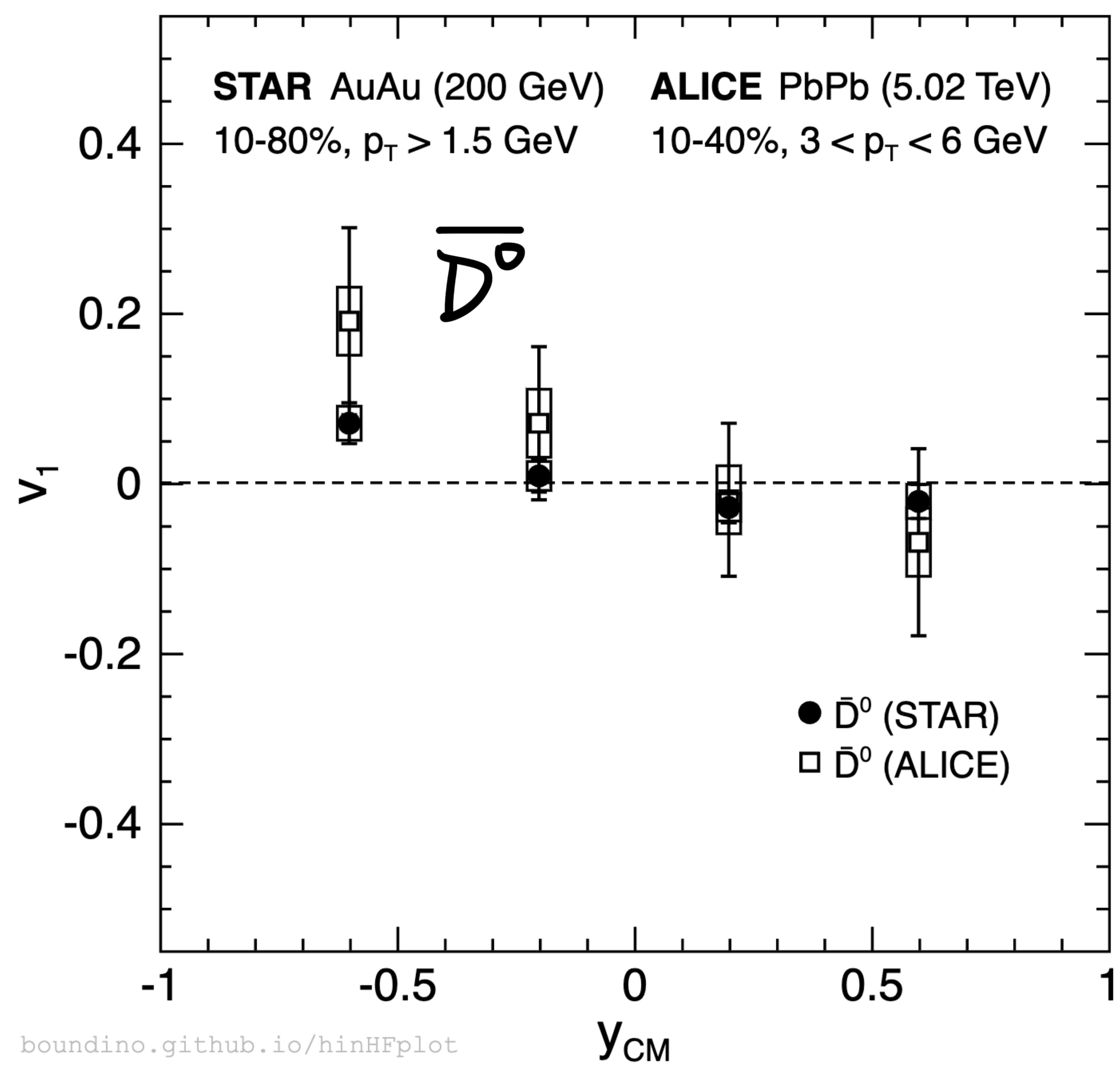
Yen-Jie Lee, Andre S. Yoon and Wit Busza

How is energy distributed before expansion?

Important input to models

Directed Flow v_1: Tilt of Medium

v_1 vs. y in PbPb, AuAu

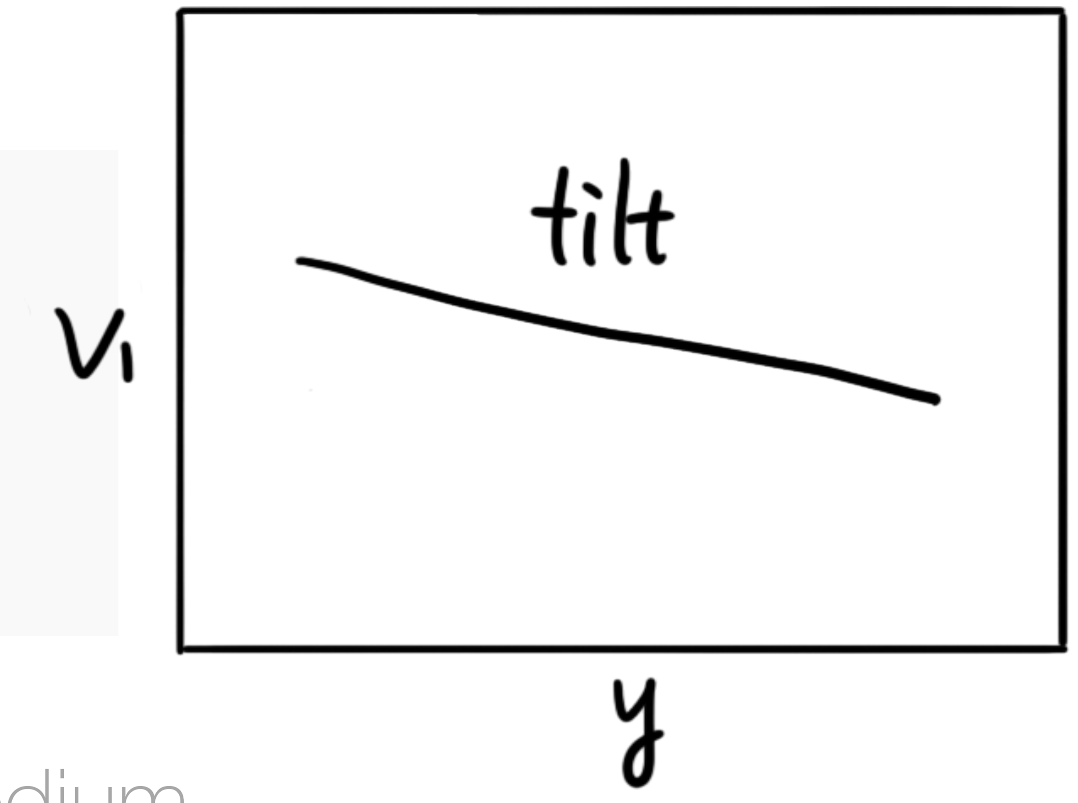


boundino.github.io/hinHFplot

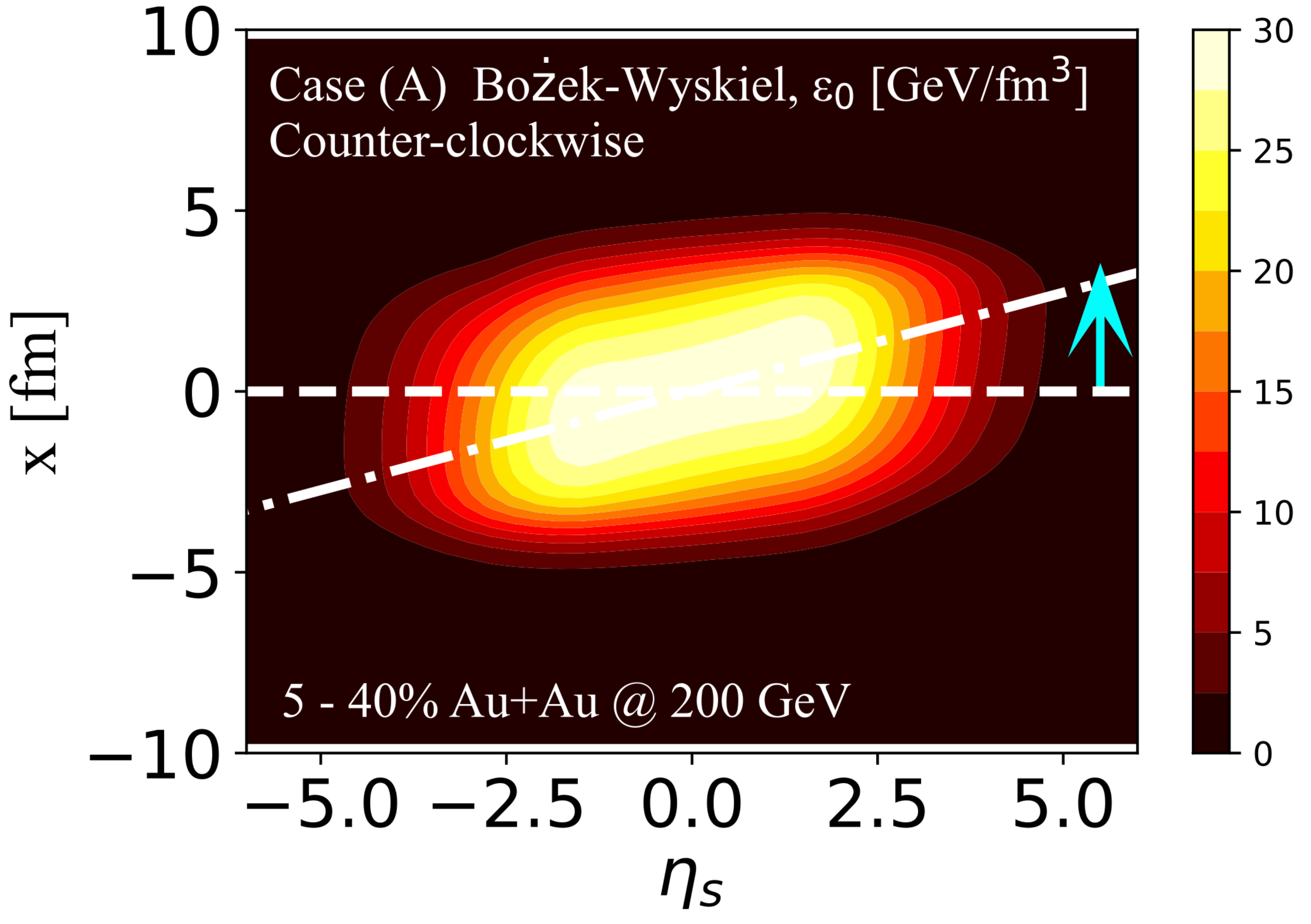
PRL 125 (2020) 022301

PRL 123 (2019) 162301

- Tilt → Longitudinal structure of initial energy density distribution
  ➡ Non-zero (rapidity-dependent) v_1



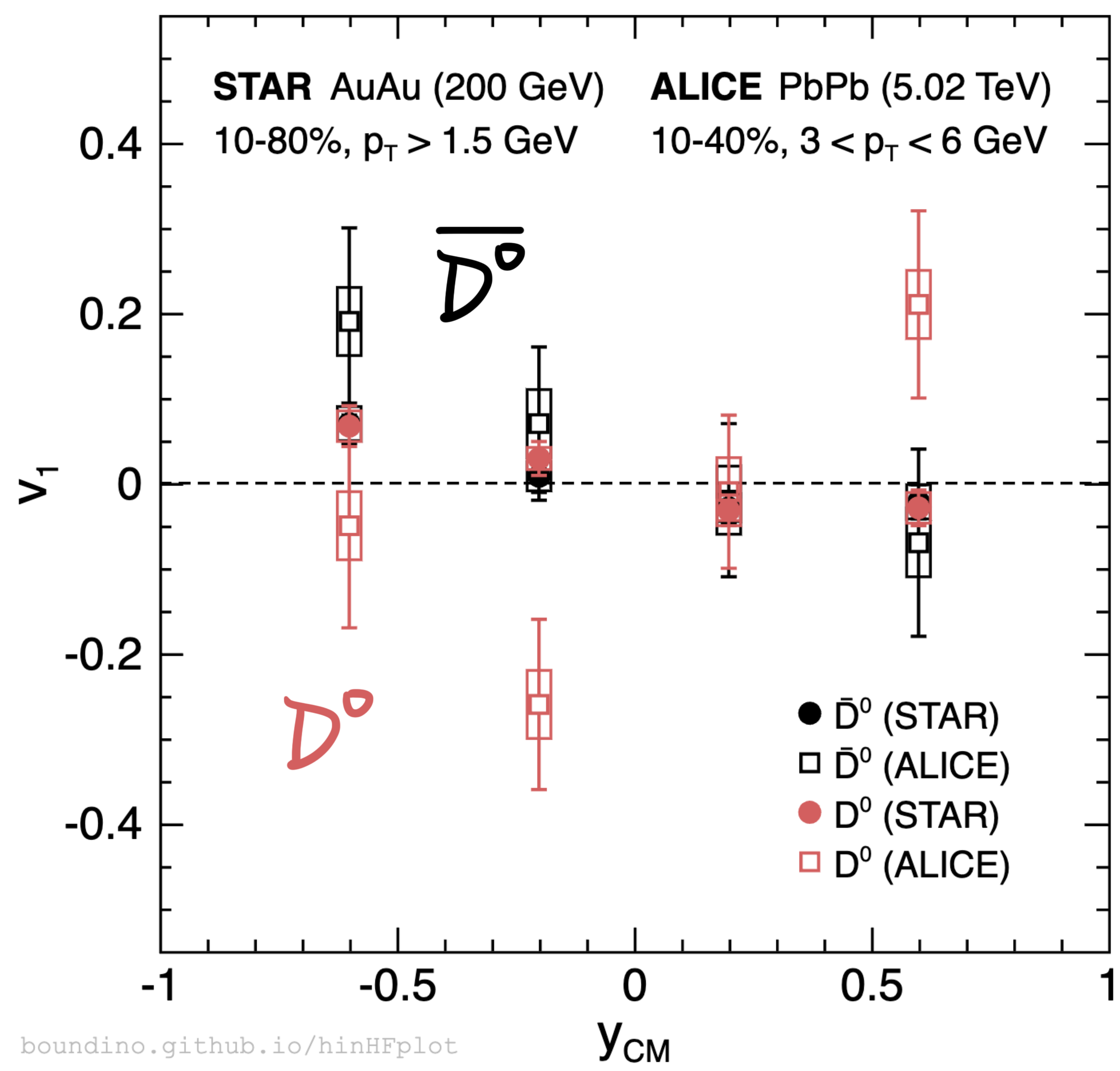
Counter clockwise tilt of the medium



PRC 105 (2022) 034901

Directed Flow v_1: Strong EM Field

v_1 vs. y in PbPb, AuAu



PRL 125 (2020) 022301

PRL 123 (2019) 162301

- Tilt → Longitudinal structure of initial energy density distribution
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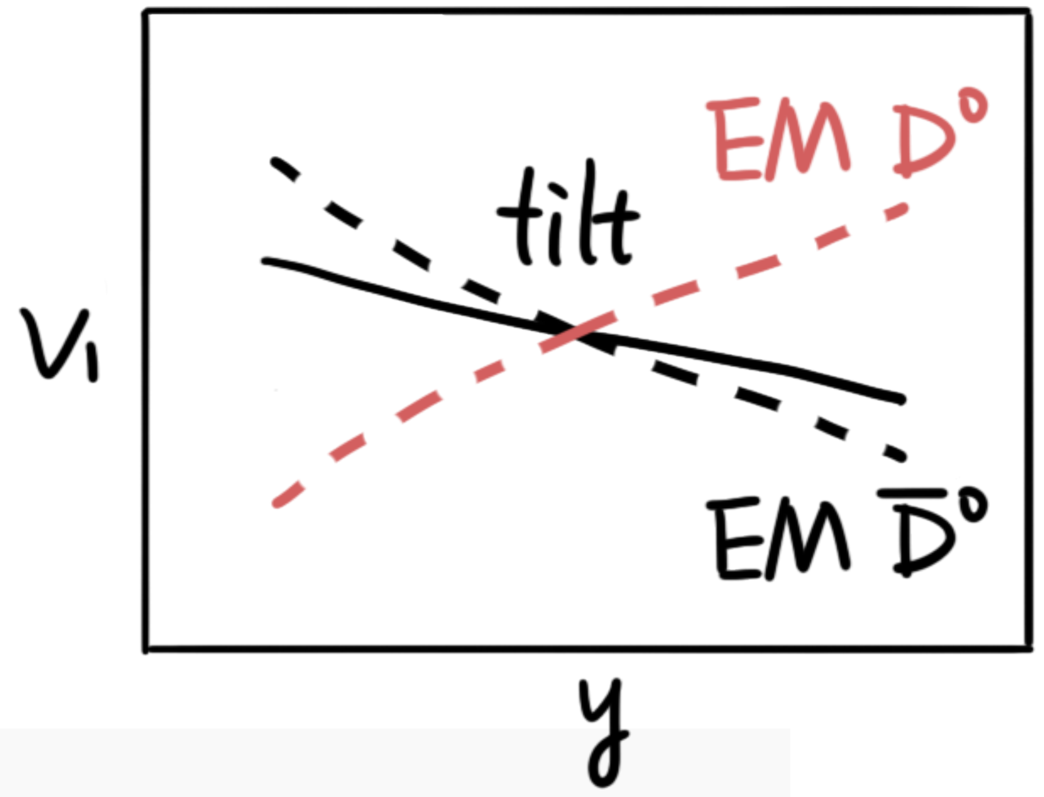
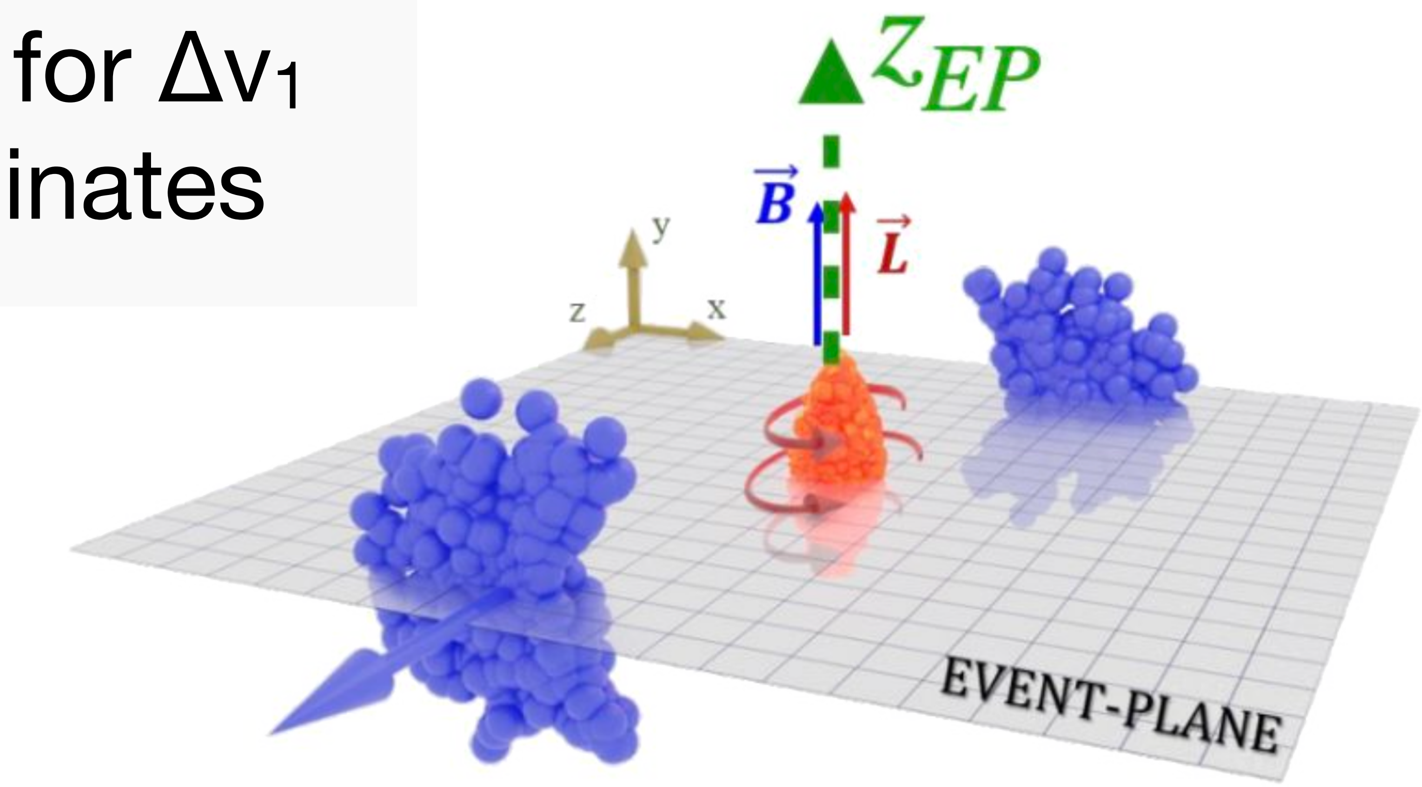


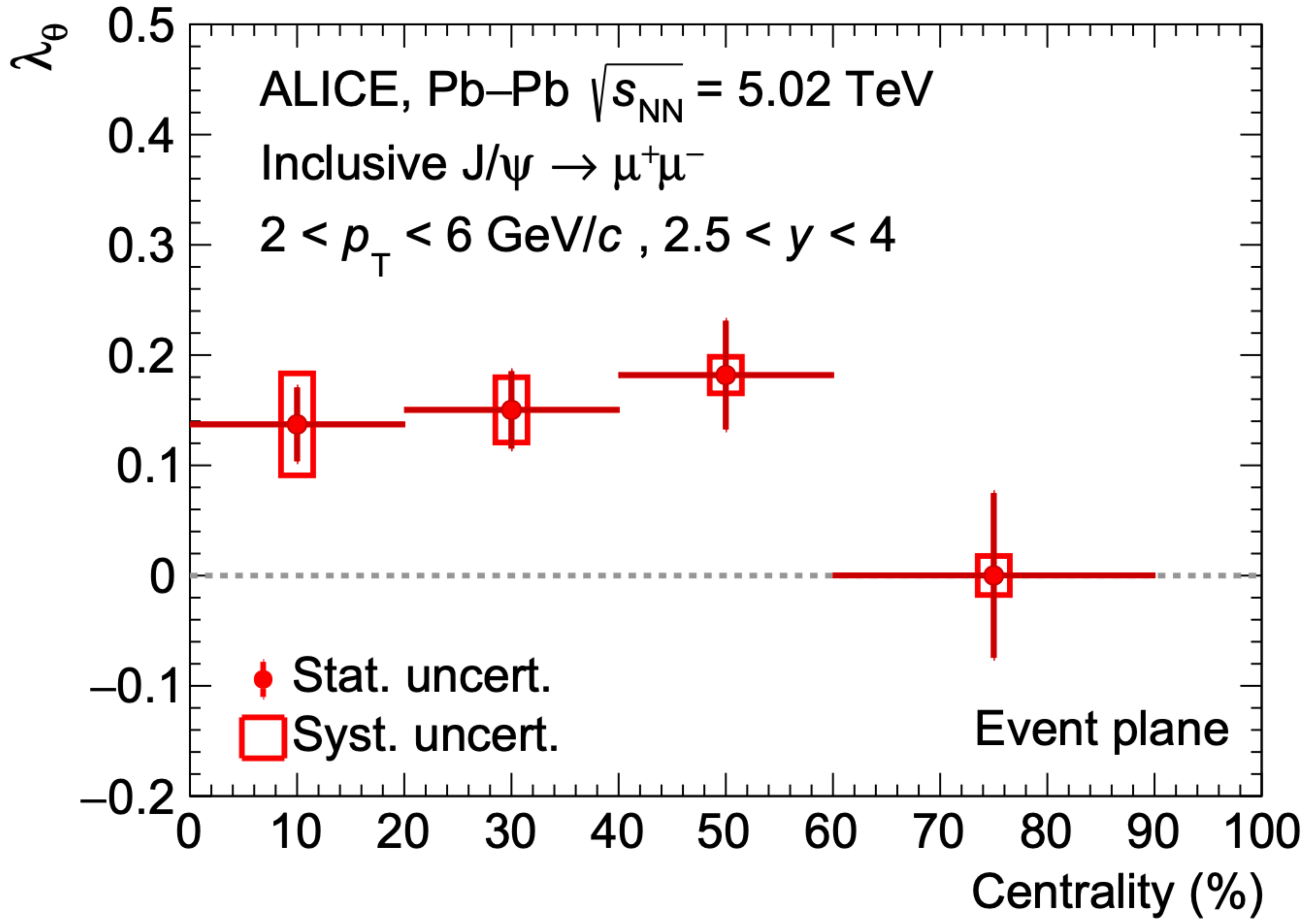
- Strong EM field emerges at early stage
  - Decays quickly → unique chance for heavy flavors
  ➡ Split v_1 of c and $\bar{c}$ → non-zero (rapidity-dep) Δv_1

- Difference b/w LHC and RHIC for Δv_1
  - Possibly different effect dominates



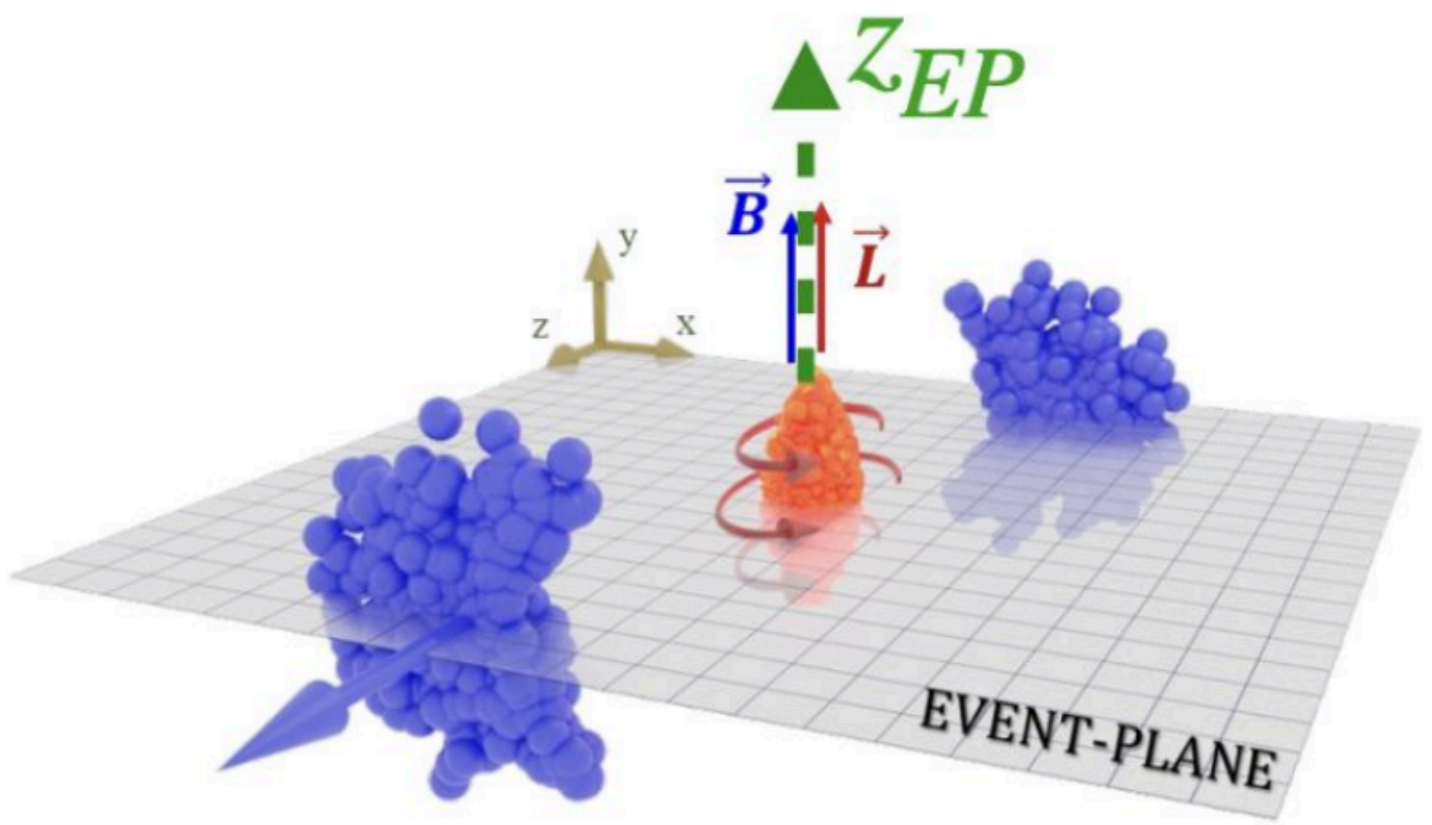
J/ψ Polarization: Initial B Field & Rotation

J/ψ Polarization



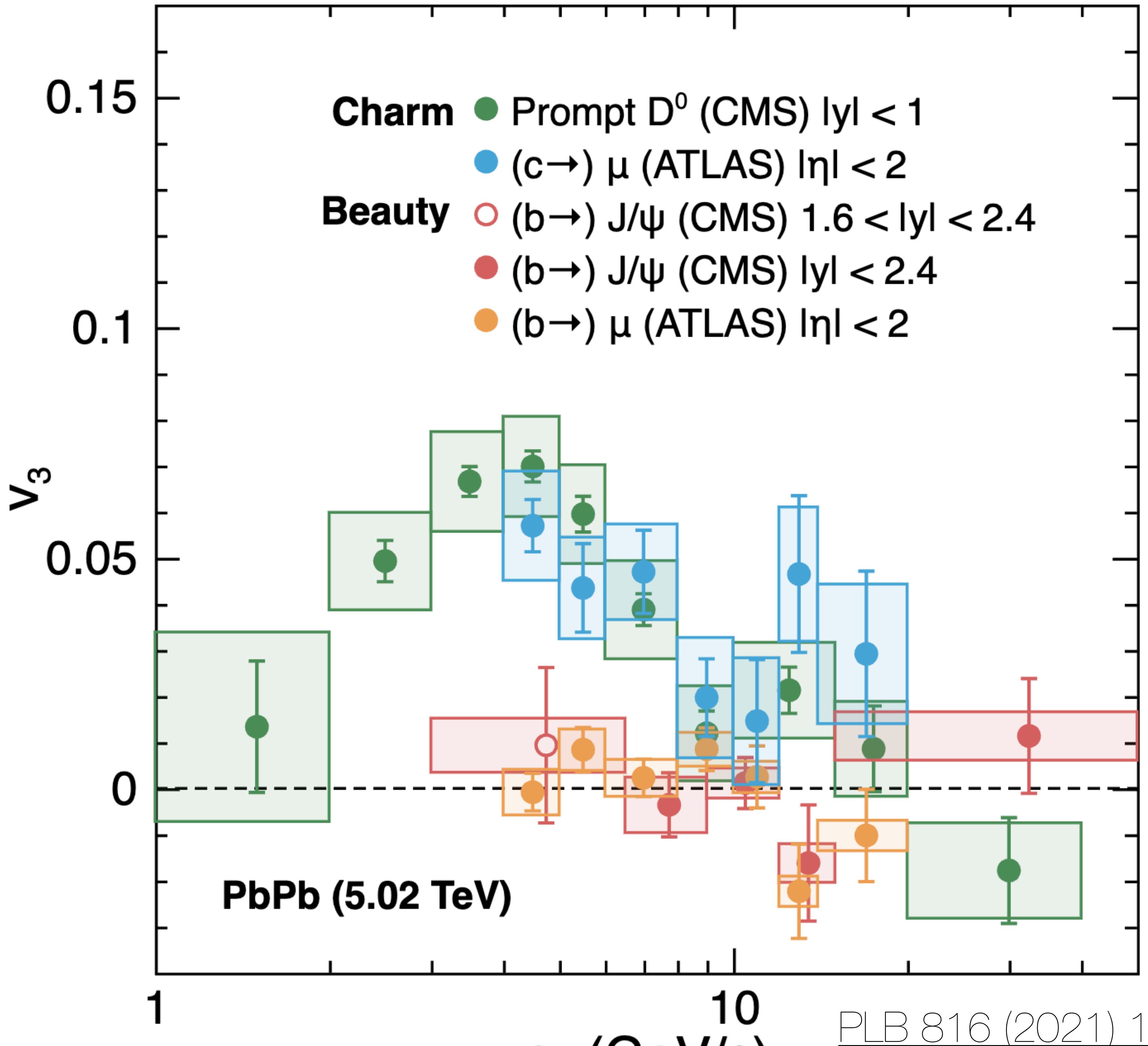
arXiv:2204.10171

- $\lambda_\theta > 0$ → Transverse polarization in the direction perpendicular to the reaction plane
  ➜ connected with
  - Strong magnetic field
  - Rotation at early stage via spin-orbit coupling



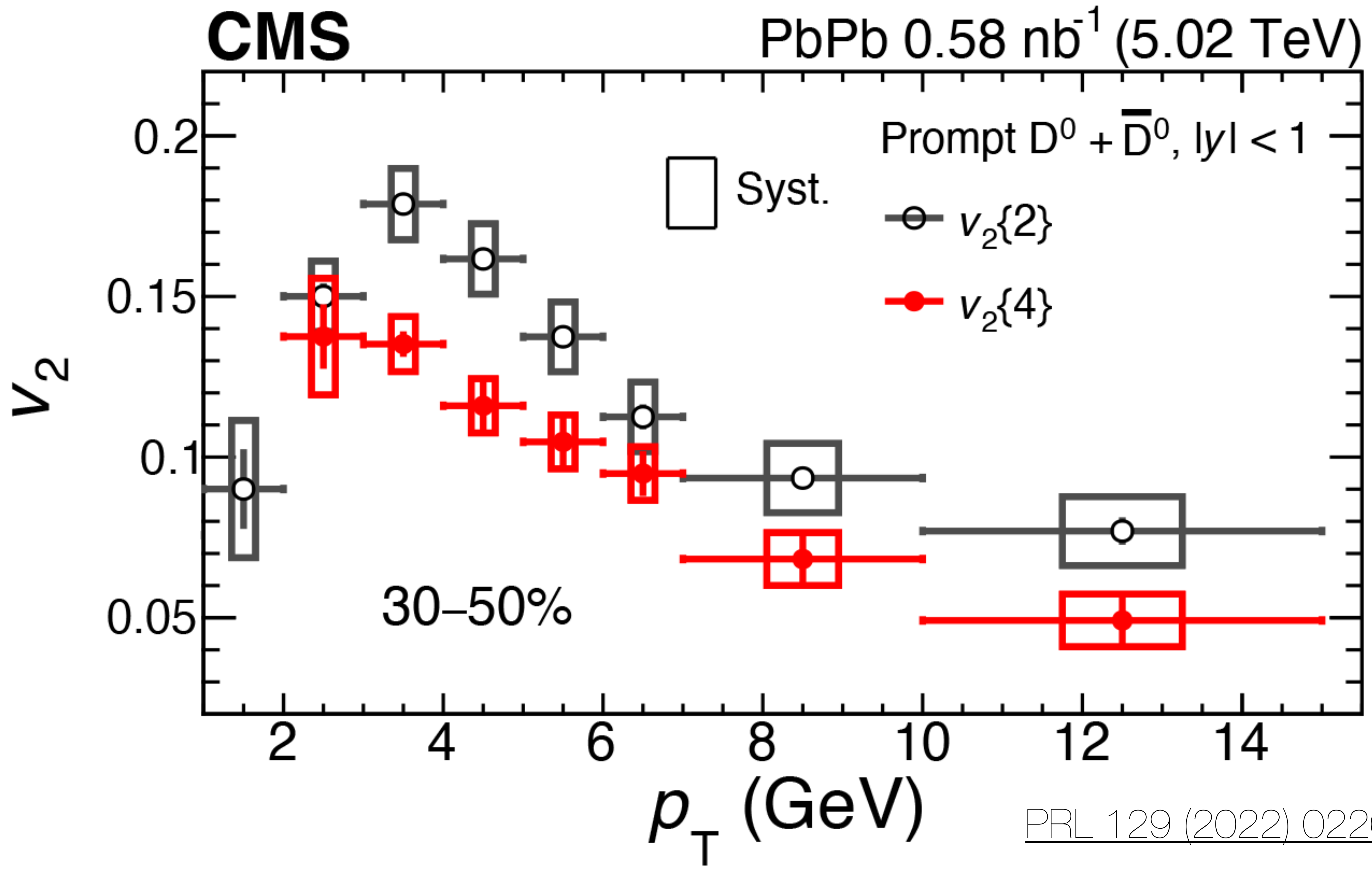
Initial Geometry Fluctuations

Heavy flavor v_3



boundino.github.io/hinHFplot

D0 4-particle correlation $v_2\{4\}$



PRL 129 (2022) 022001

PLB 816 (2021) 136253 CMS-PAS-HIN-21-008
PLB 807 (2020) 135595 PLB 807 (2020) 135595

- Study event-by-event initial shape fluctuation via higher-order v_n and multi-particle correlation

Summary: Being Hot Matters

Many interesting heavy flavor behaviors driven by existence of QGP

- Energy loss
- Collective flow
  - Directed flow
- $Q\bar{Q}$ sequential suppression
  - $Q\bar{Q}$ Polarization
- Enhancement of baryon production
  - X(3872) production modification

Summary: Being Hot Really Matters?

Most of them also observed in small systems

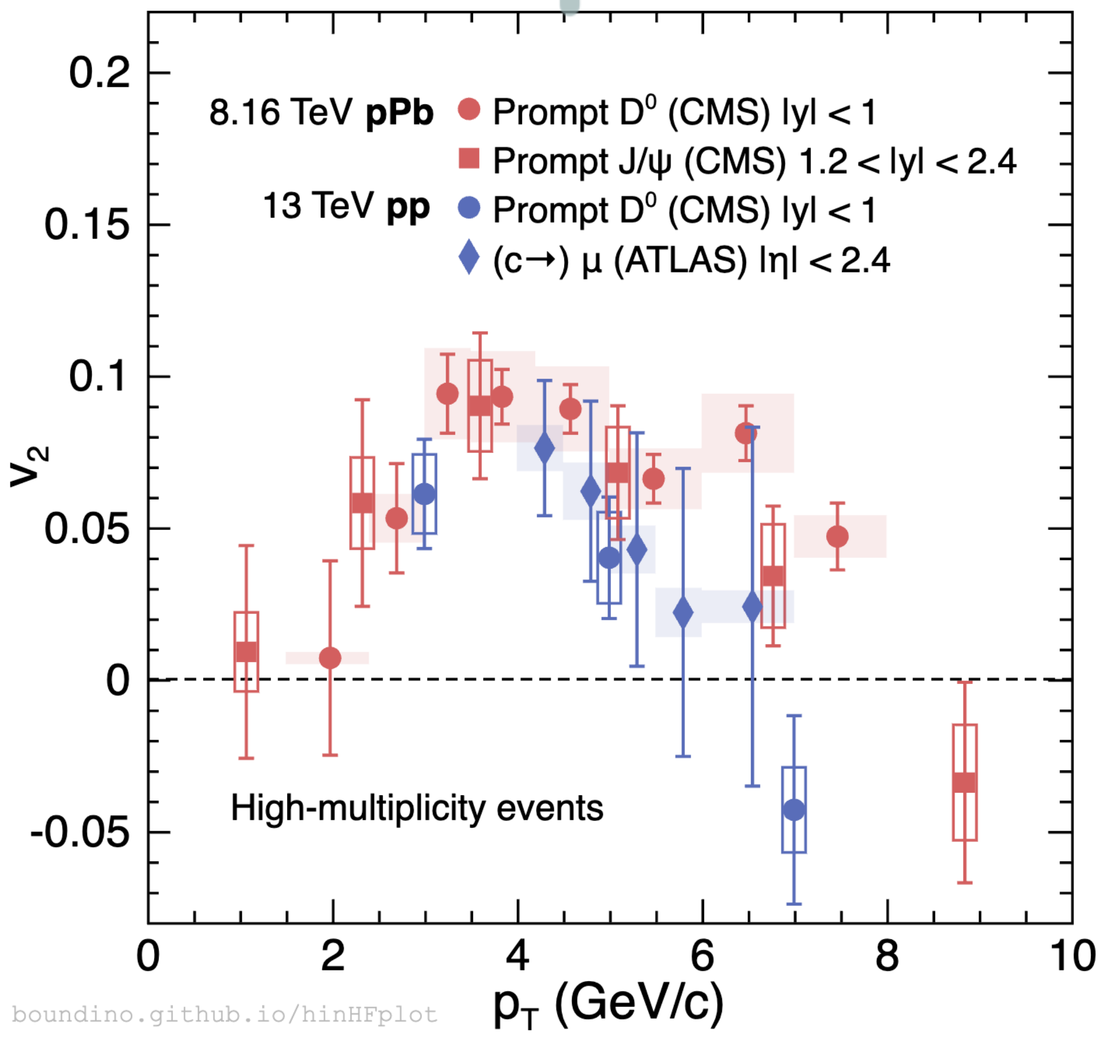
~~Energy loss~~

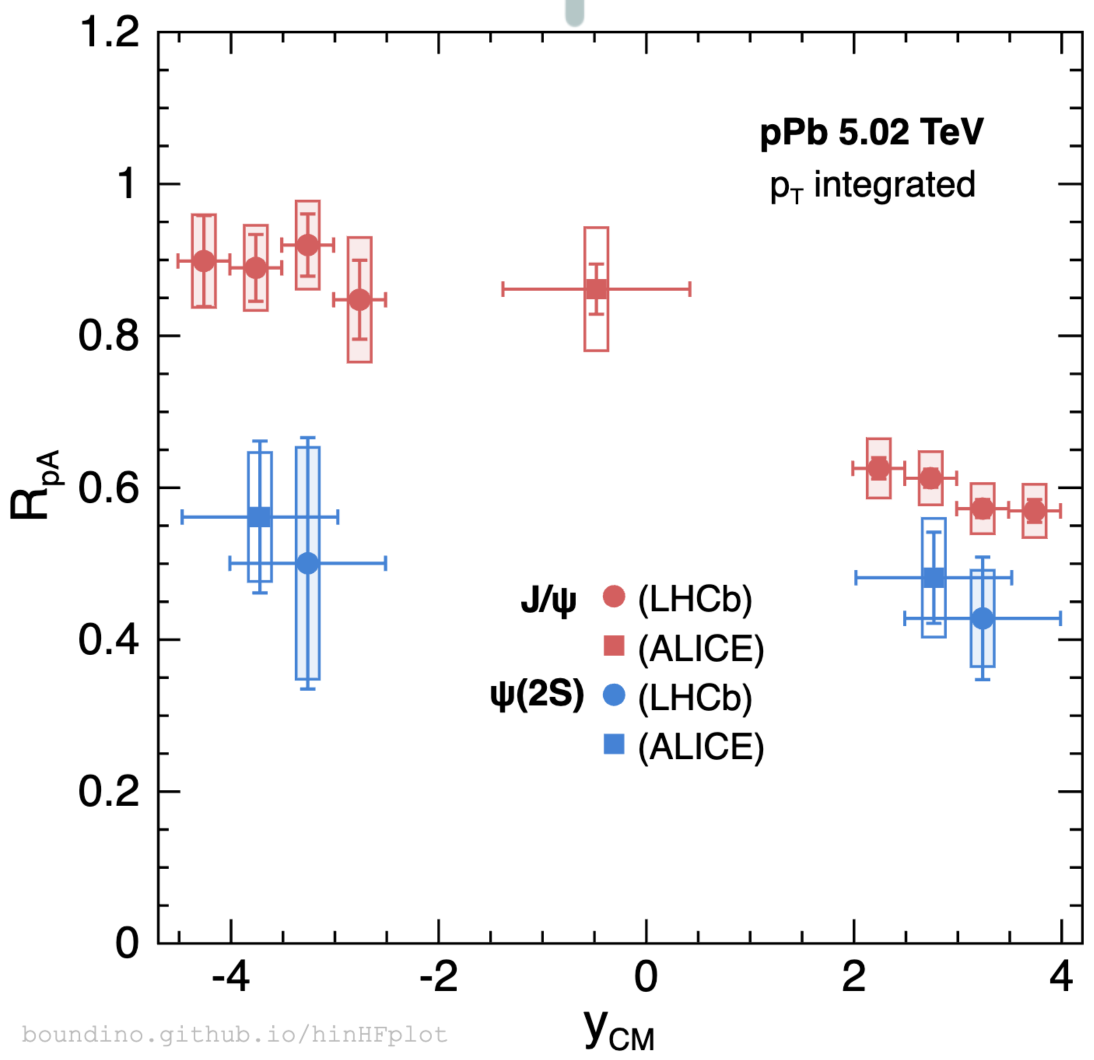
~~QQ̄ Polarization~~

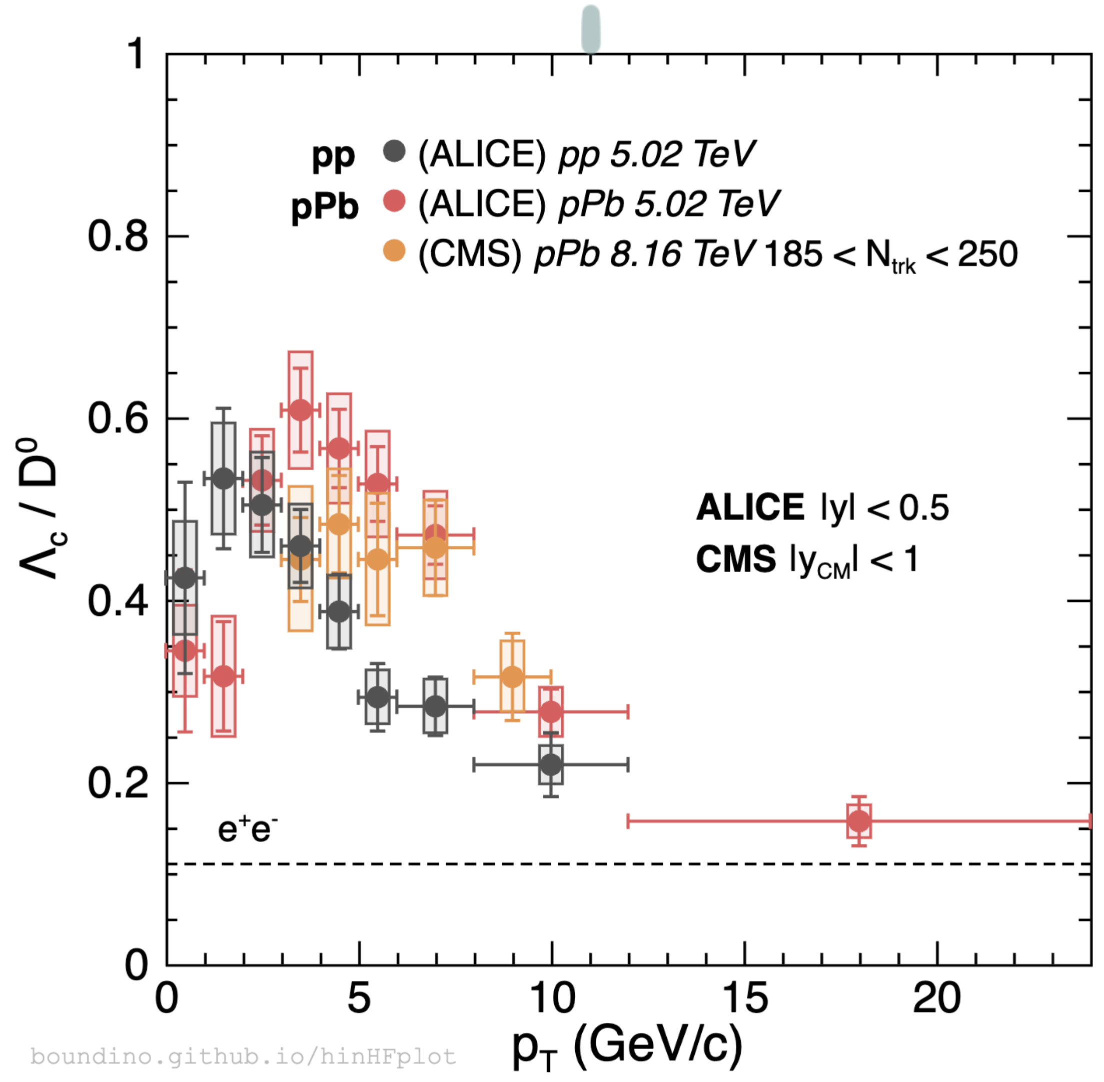
Collective flow

QQ̄ sequential suppression

Enhancement of baryon production



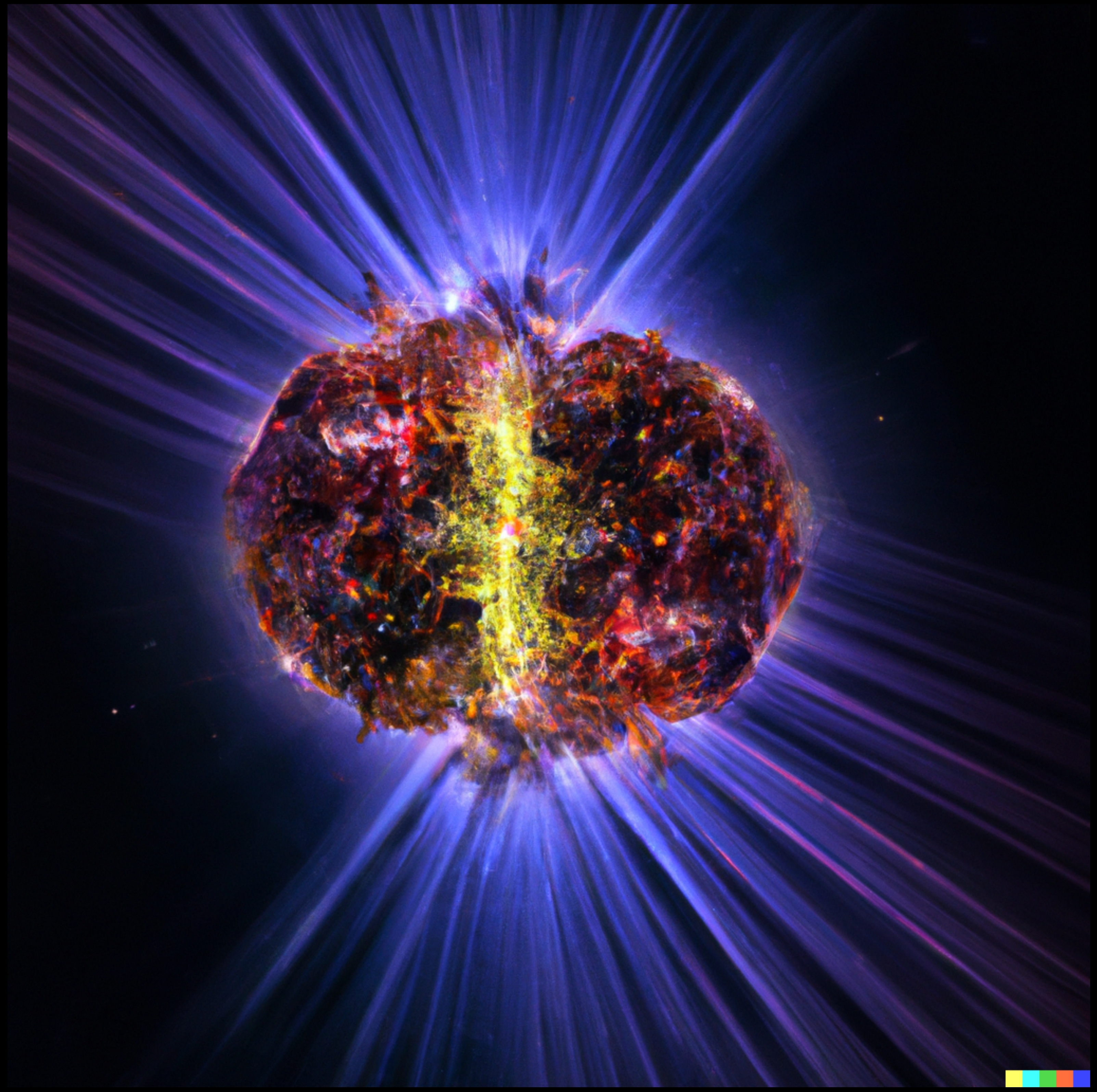




Challenge & opportunity ➜ Stress collision system scan of EIC→RHIC→LHC to understand the onset of QGP

I Asked AI to Imagine…

Heavy-ion collisions



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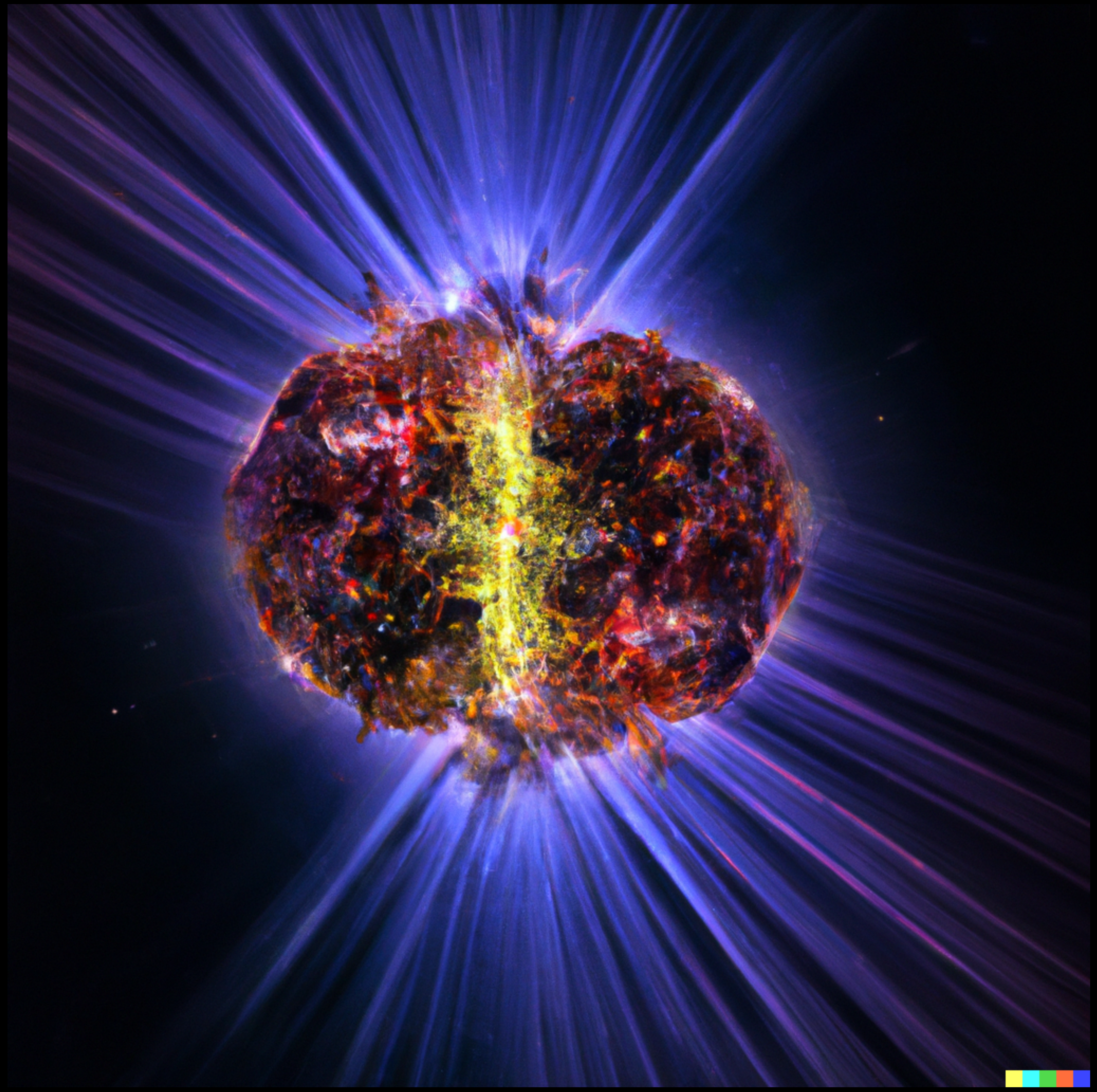
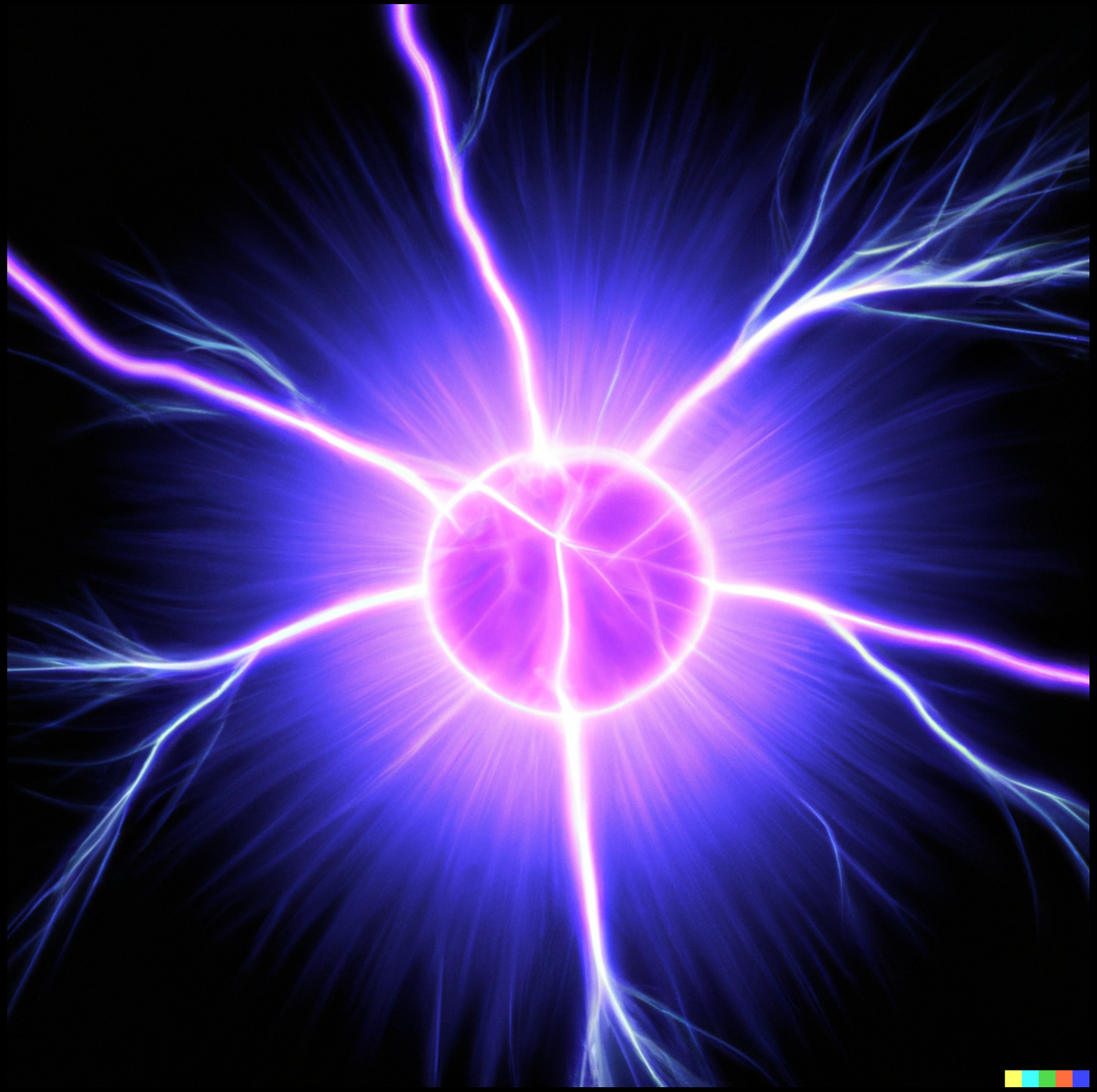


A long way to go to understand quarks and gluons

Quark-gluon plasma




Isabelle
Thanks for your attention!

Back up

MITHIG group's work was supported by US DOE-NP

Future Data and Experiments

Run 1	Run 2	Long Shutdown 2	Run 3	LS 3	Run 4	LS 4
	PbPb (2.2 nb^{-1}) **pPb** (0.18 pb^{-1})	5 TeV	**PbPb** (6 nb^{-1}) **pPb** (0.5 pb^{-1}) pO/OO	CMS/ATLAS Phase-2 upgrades	**PbPb** (7 nb^{-1}) **pPb** (0.5 pb^{-1})	

2015 - 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032

We are here!

sPHENIX 23-35

200 GeV

AuAu (32 nb^{-1}) **pAu** (0.11 pb^{-1})

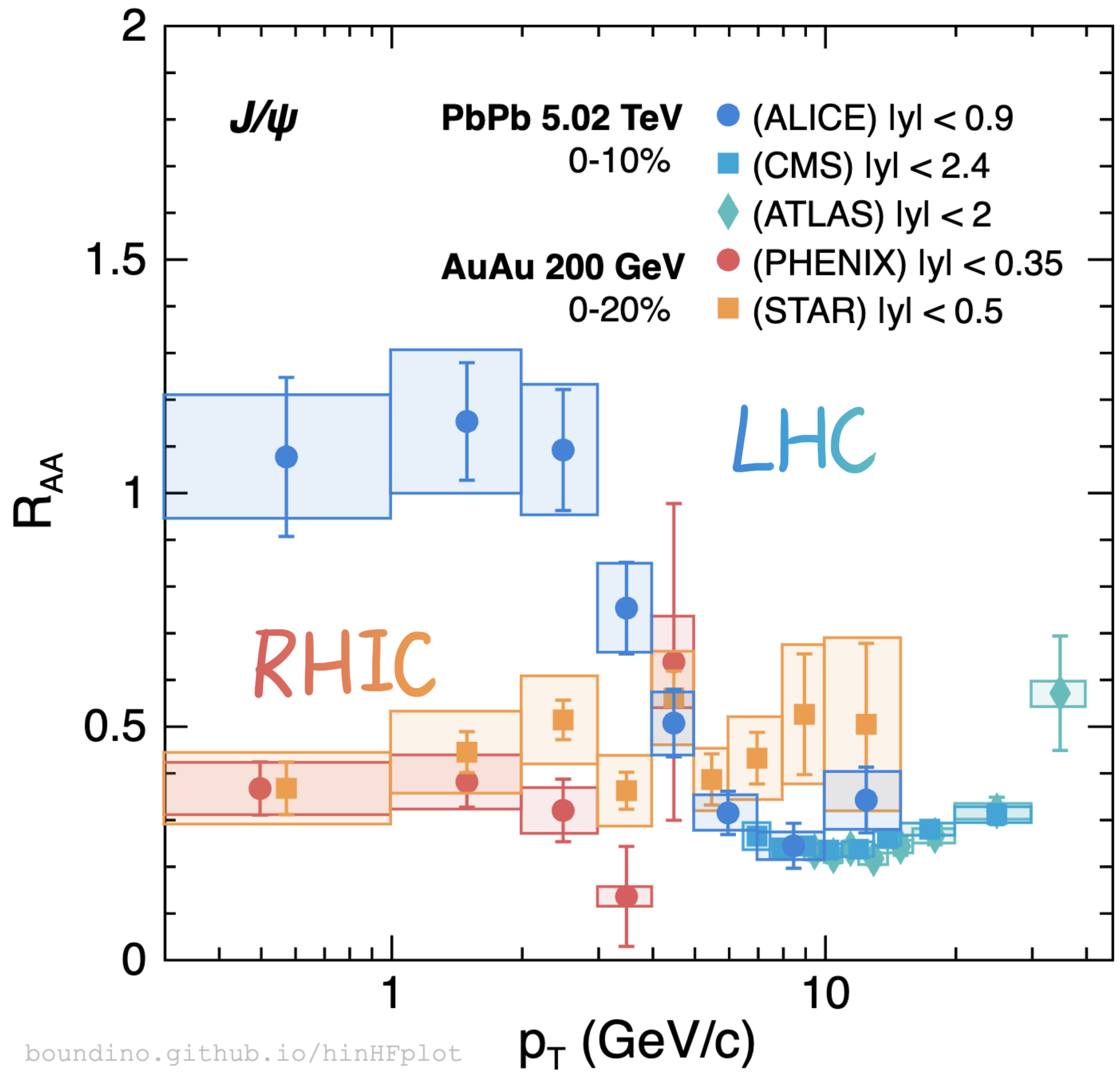
EIC

28-140 GeV

ep (100-1000x HERA) **eA (d→Pb)**

Charmonium Production: Summary

R_{AA} vs. p_T

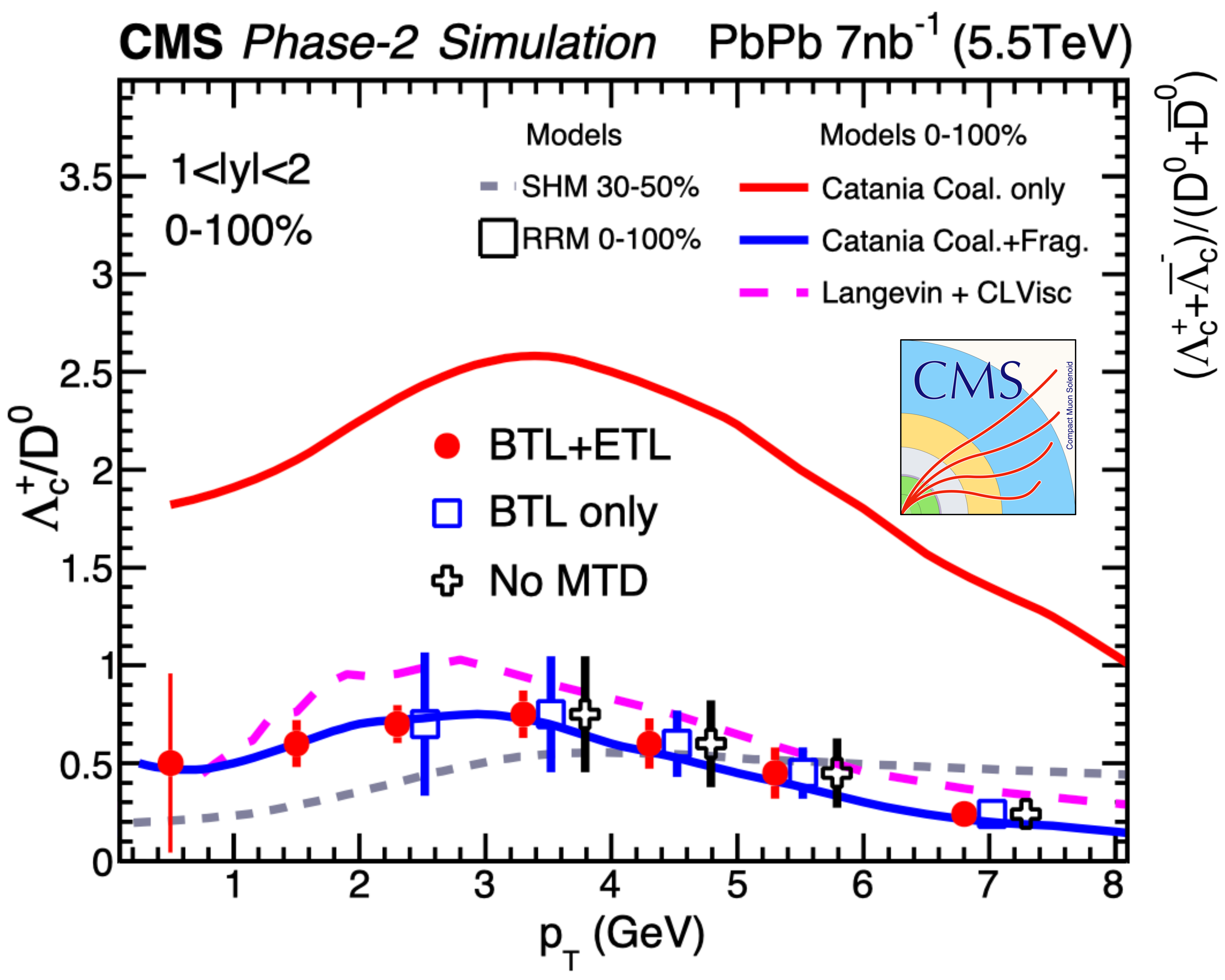


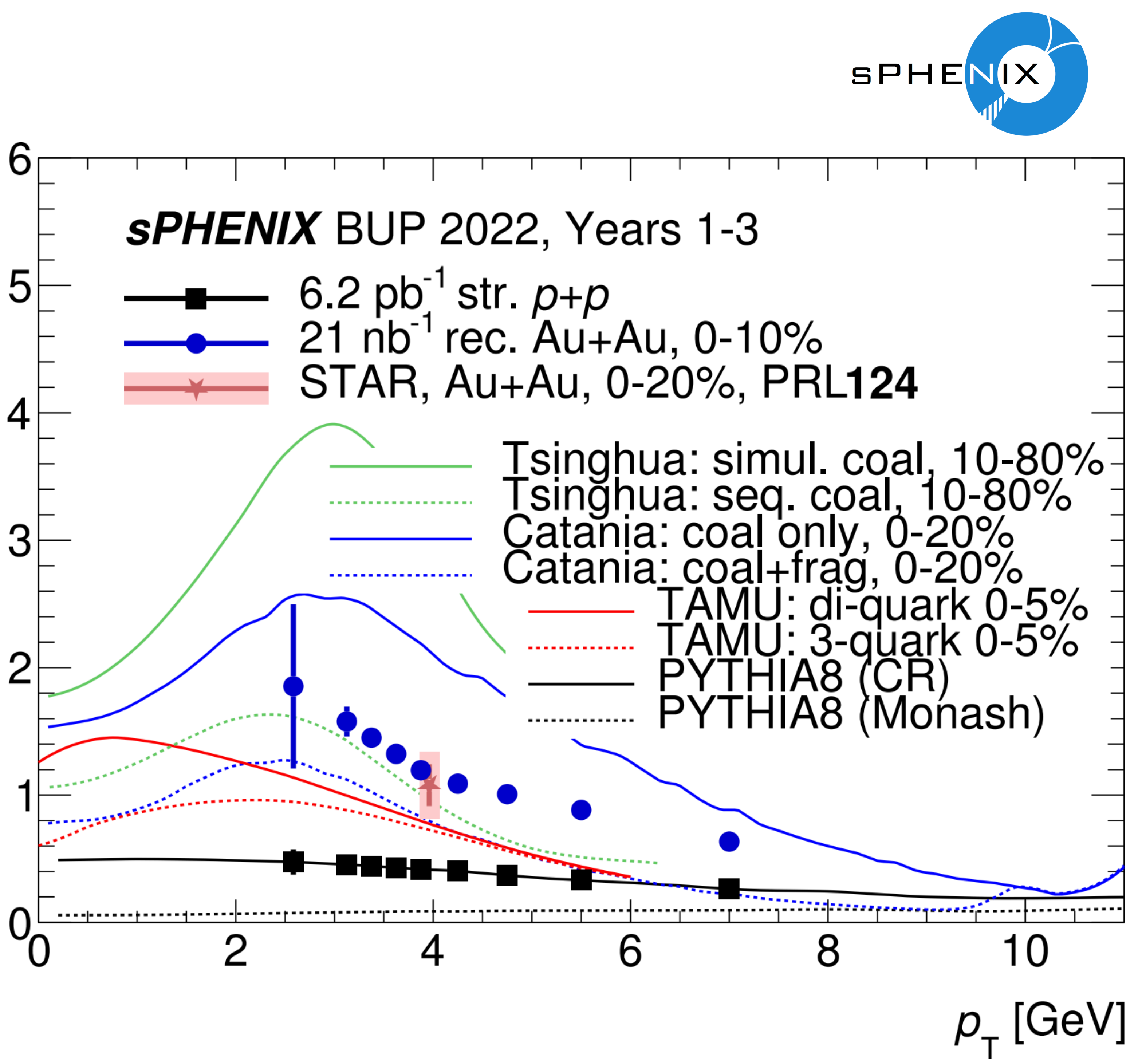
$Q\bar{Q}$ → Bound states of quark and its anti-quark

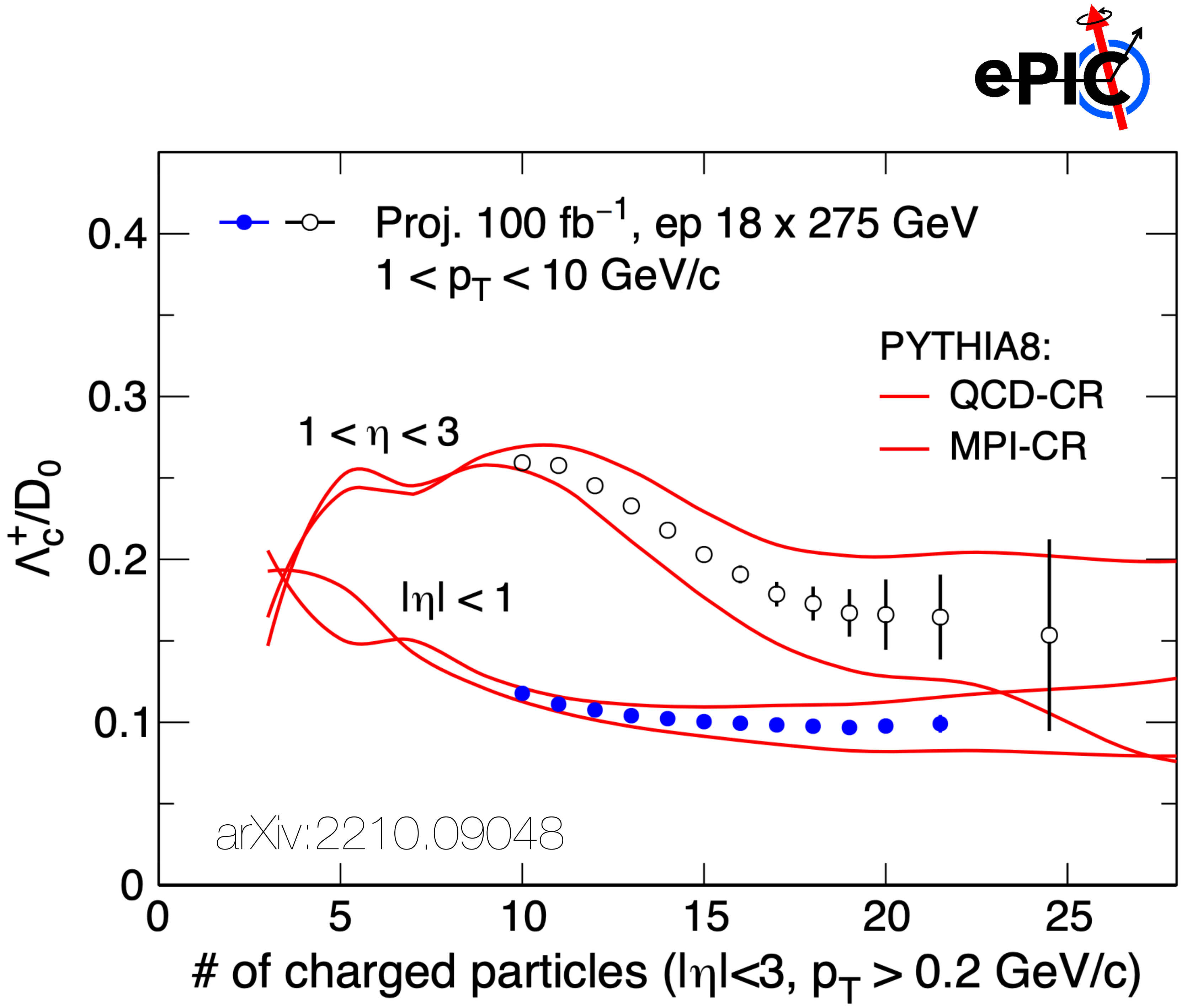
- Sequential melting (binding energy hierarchy)
  - Thermometer of QGP
  - Stronger suppression in central events → higher T
  - Smaller R_{AA} in LHC than RHIC at high p_T → higher T
- Recombination
  - Enhancement at low p_T in central events → larger $\sigma_{c\bar{c}}$
  - Significant in LHC not RHIC → larger $\sigma_{c\bar{c}}$
- Cold nuclear matter effects
  - Nuclear/comover absorption
    - Destroyed by interactions with nucleus remnants
  - Nuclear PDF

Heavy Quark Hadronization: Baryons

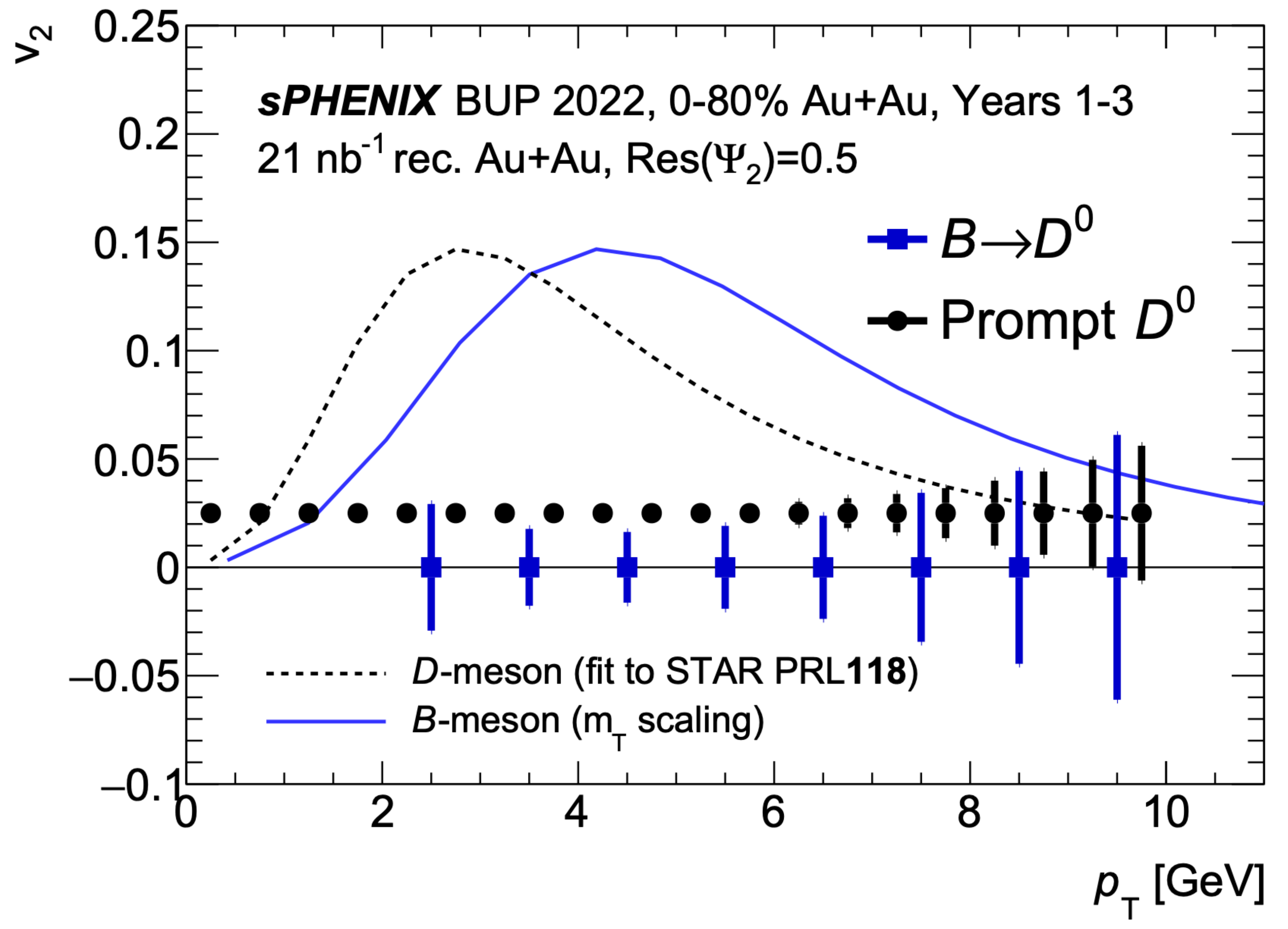
- High precision Λ_c/D^0 expected from CMS, sPHENIX and EIC with different environments

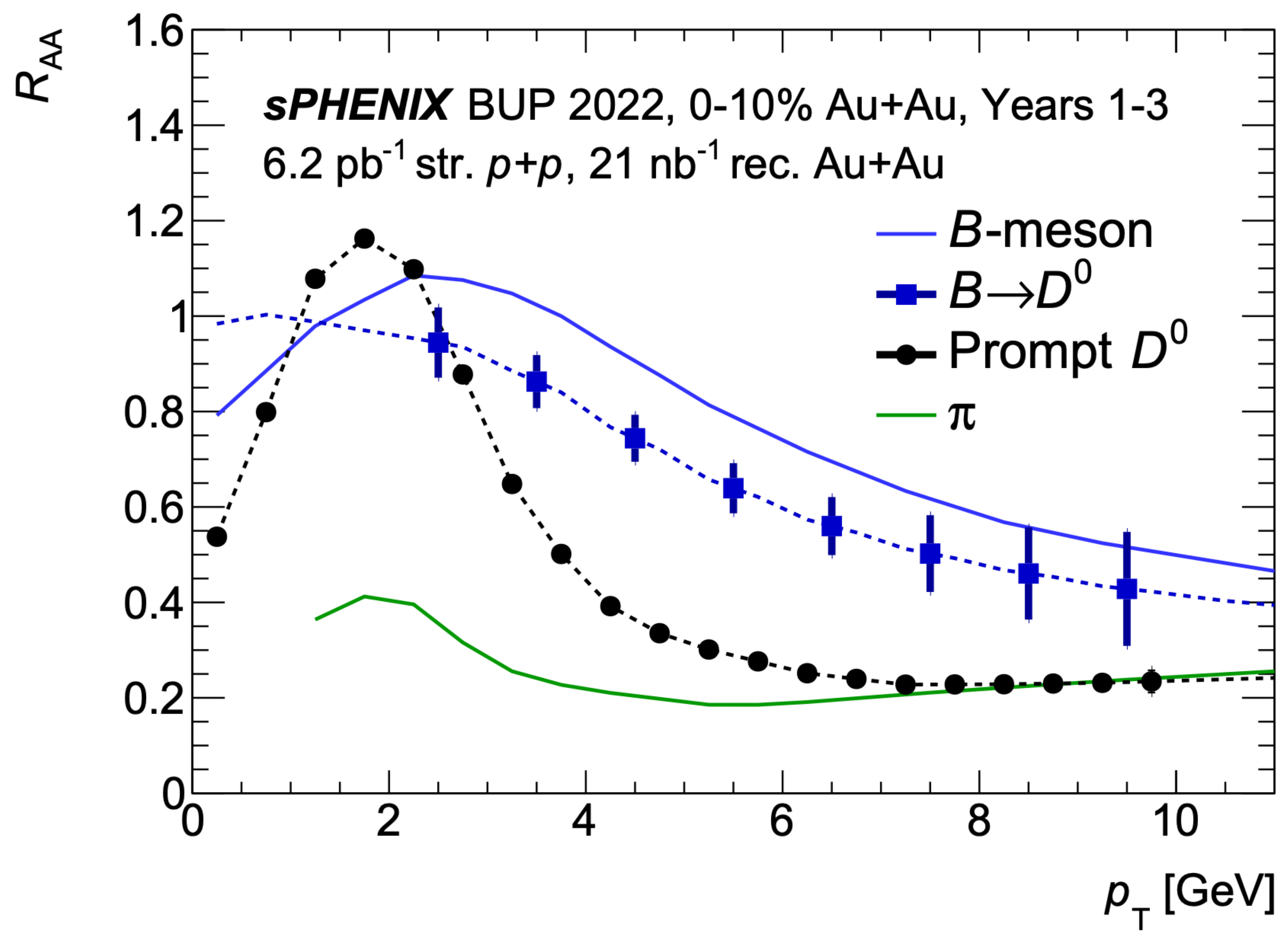


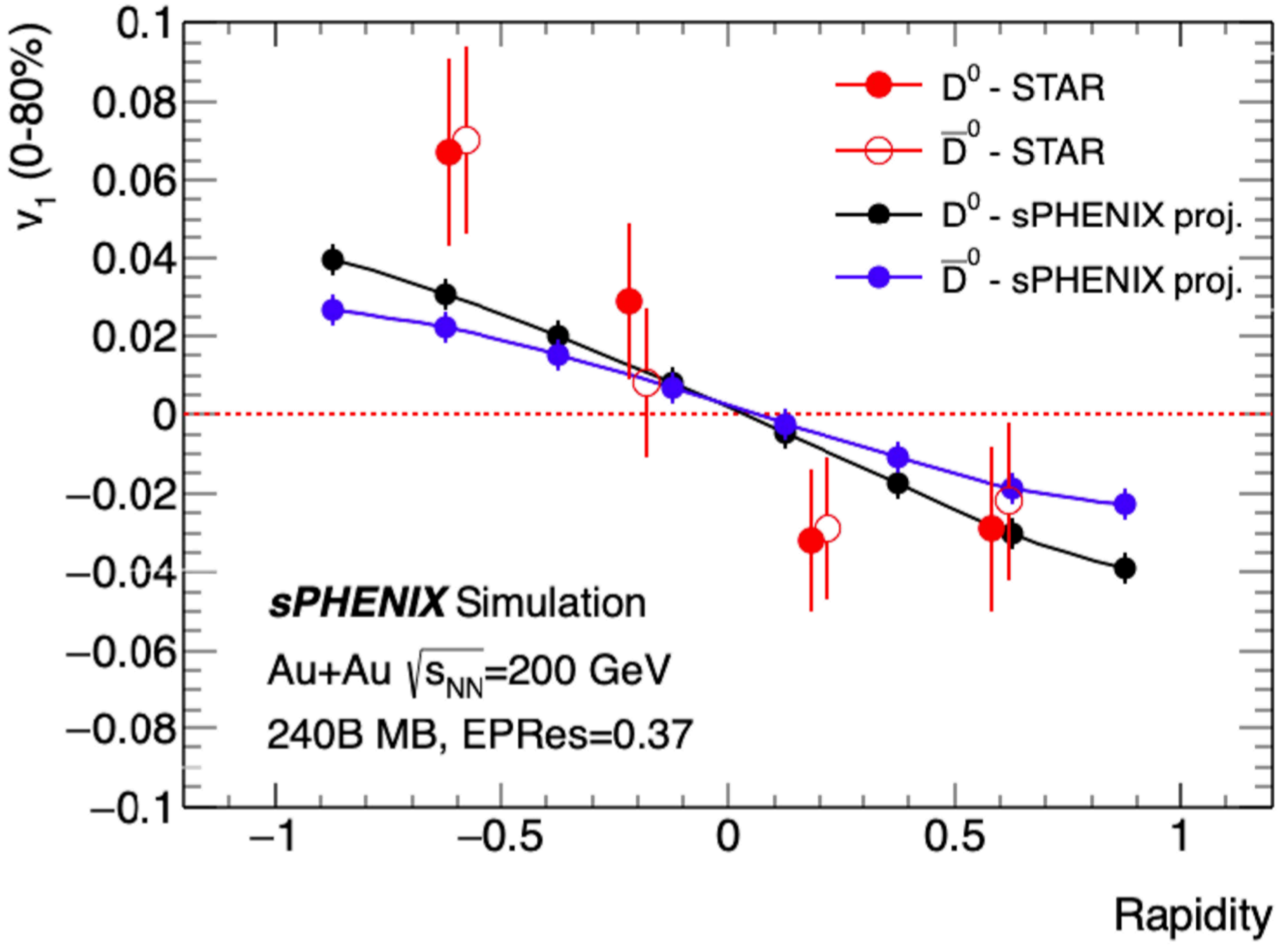




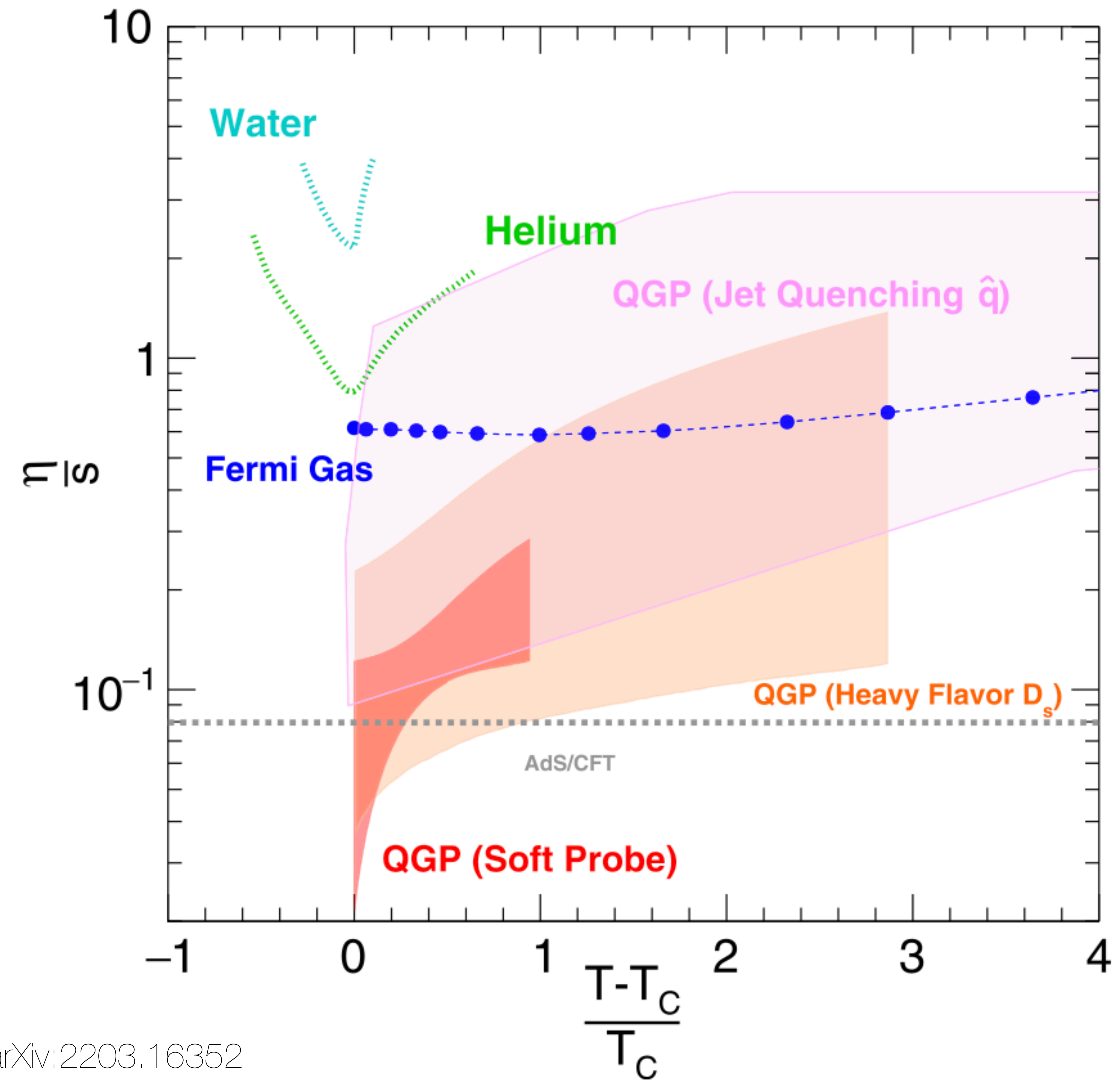
sPHENIX Projection







HF Probe QGP Transport Property



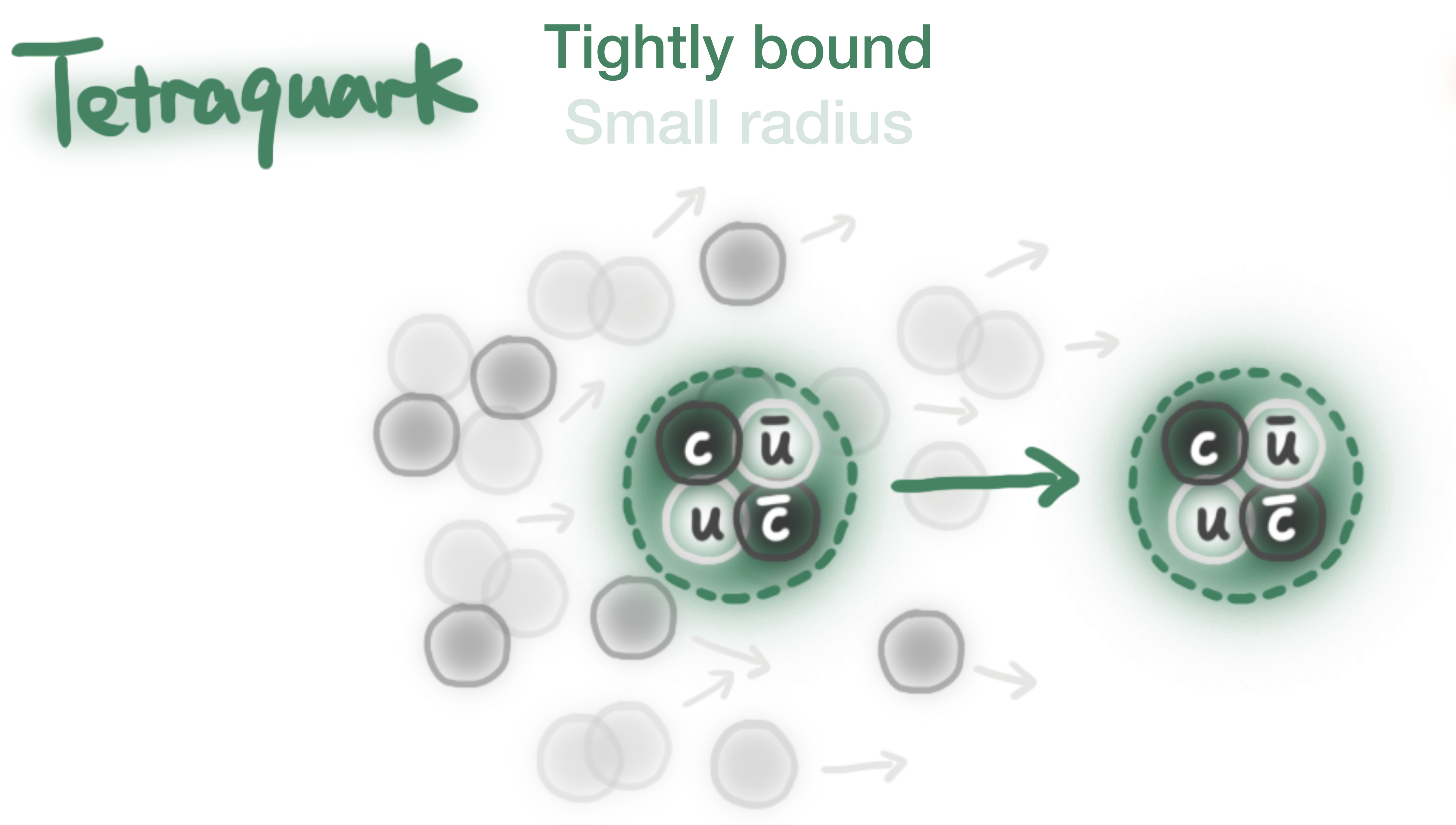
arXiv:2203.16352

- Small specific shear viscosity η/s
  - Consistent from soft probe and heavy flavors
  - Heavy quarks produced earlier than soft probes ➜ unique at higher temperature
- Hadronization is critical to suppress uncertainty

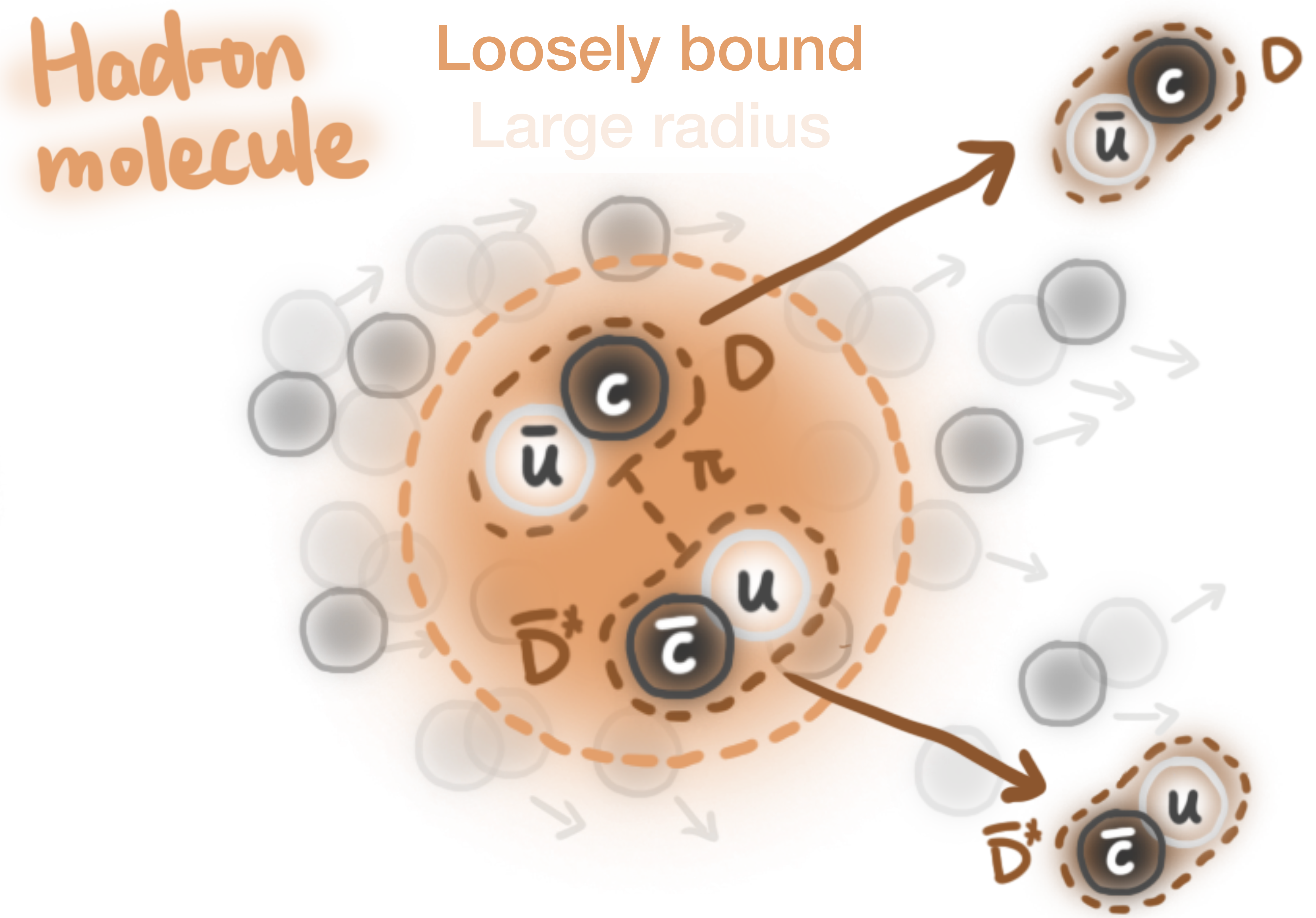
New Window to X(3872) Structure

- Breakup by comoving particles ➜ Suppress X(3872)

➡ Reflect the nature of X(3872)



Lower dissociation probability



Higher dissociation probability

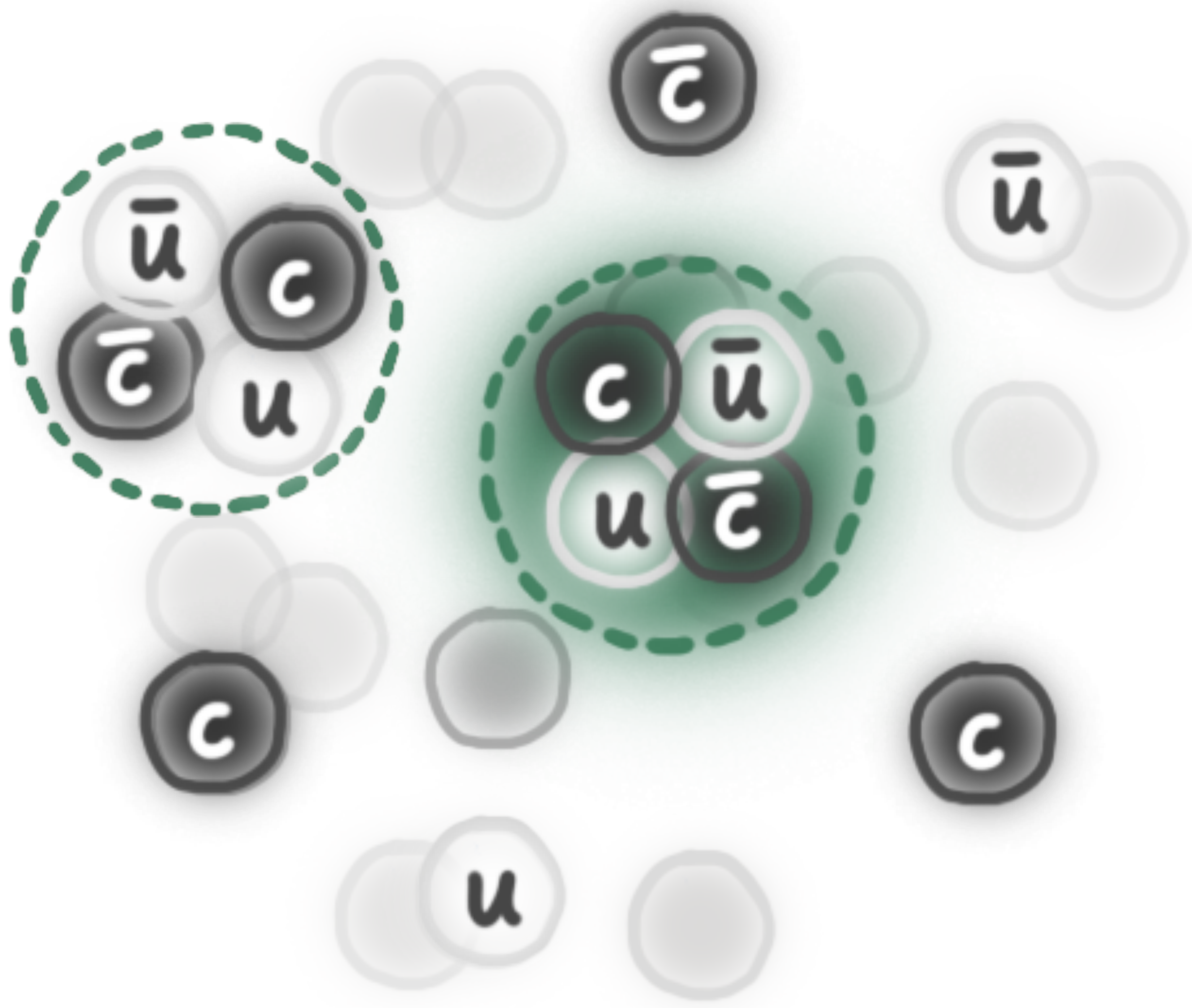
New Window to X(3872) Structure

- Breakup by comoving particles ➜ Suppress X(3872)
- Coalescence with diffusing particles ➜ Enhance X(3872)

Tetraquark

Tightly bound

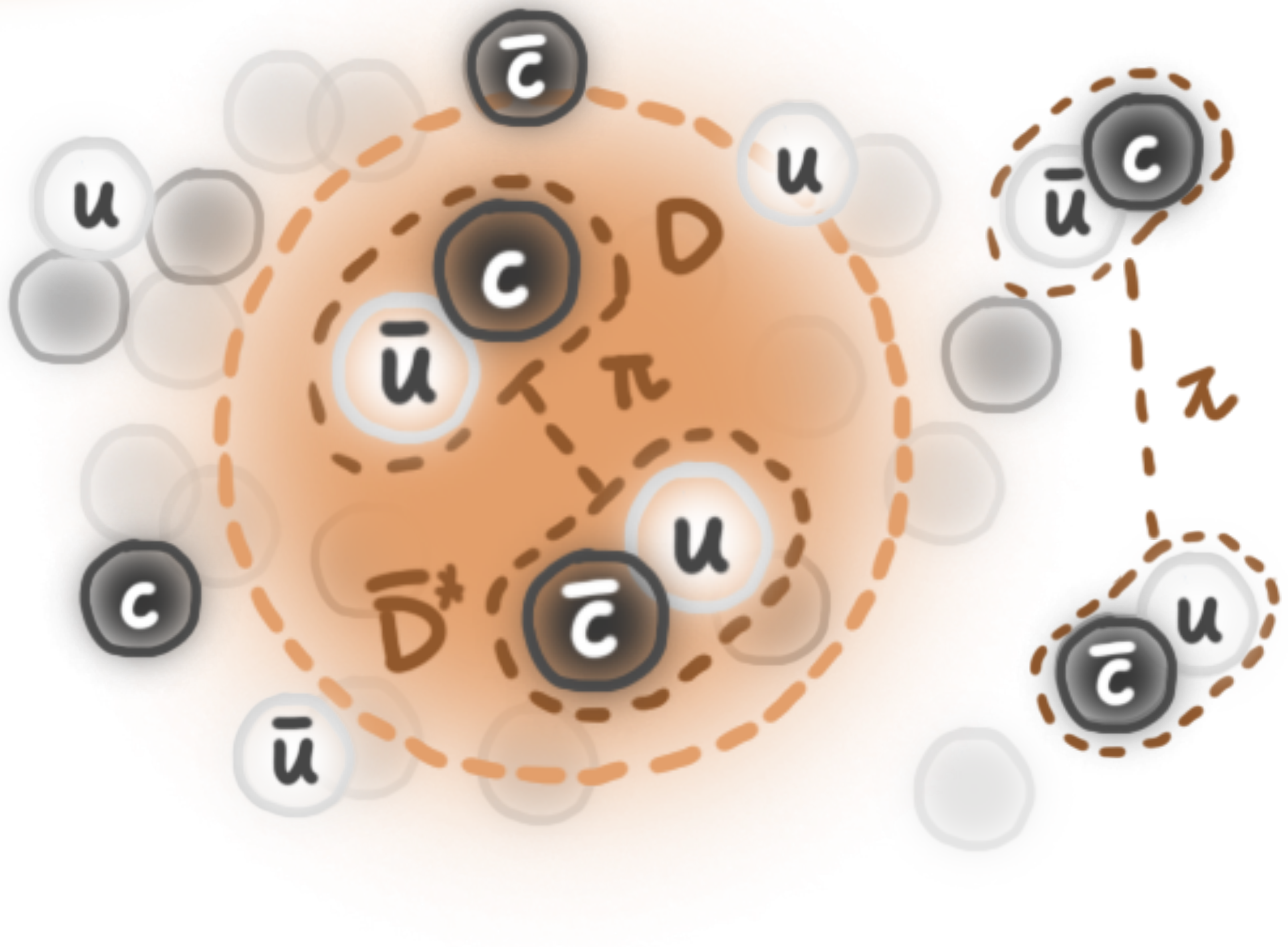
Small radius



Hadron molecule

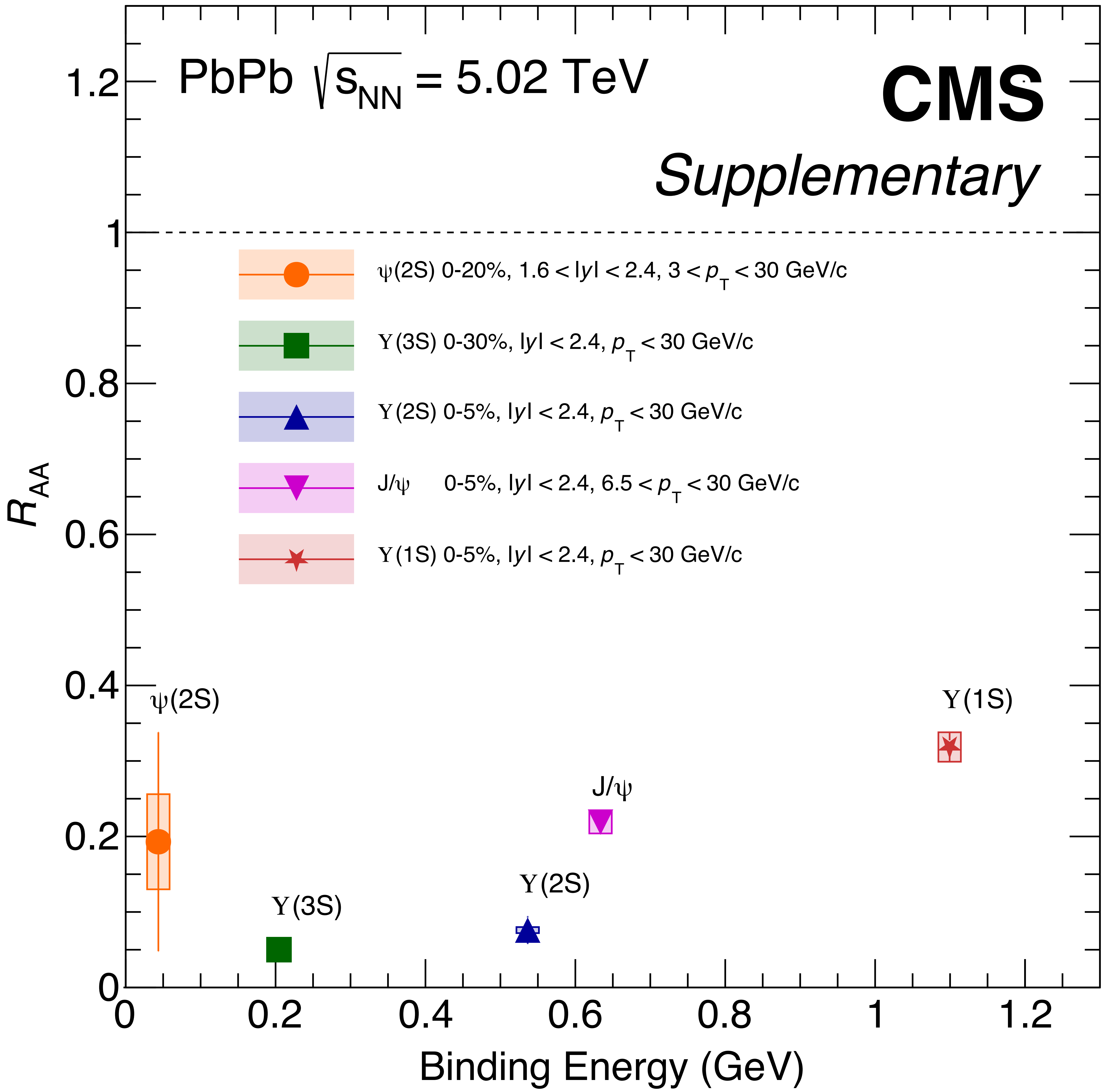
Loosely bound

Large radius

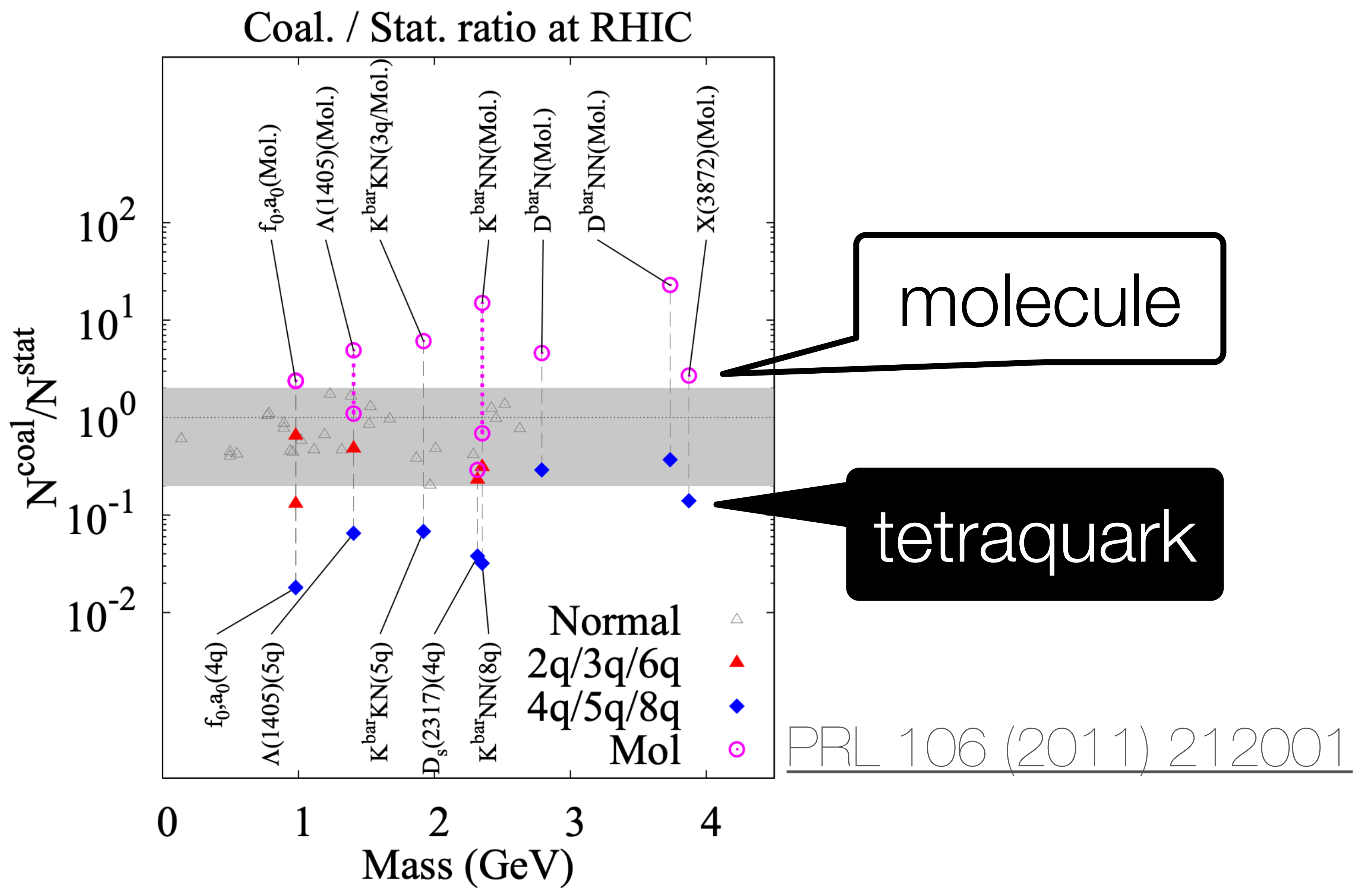


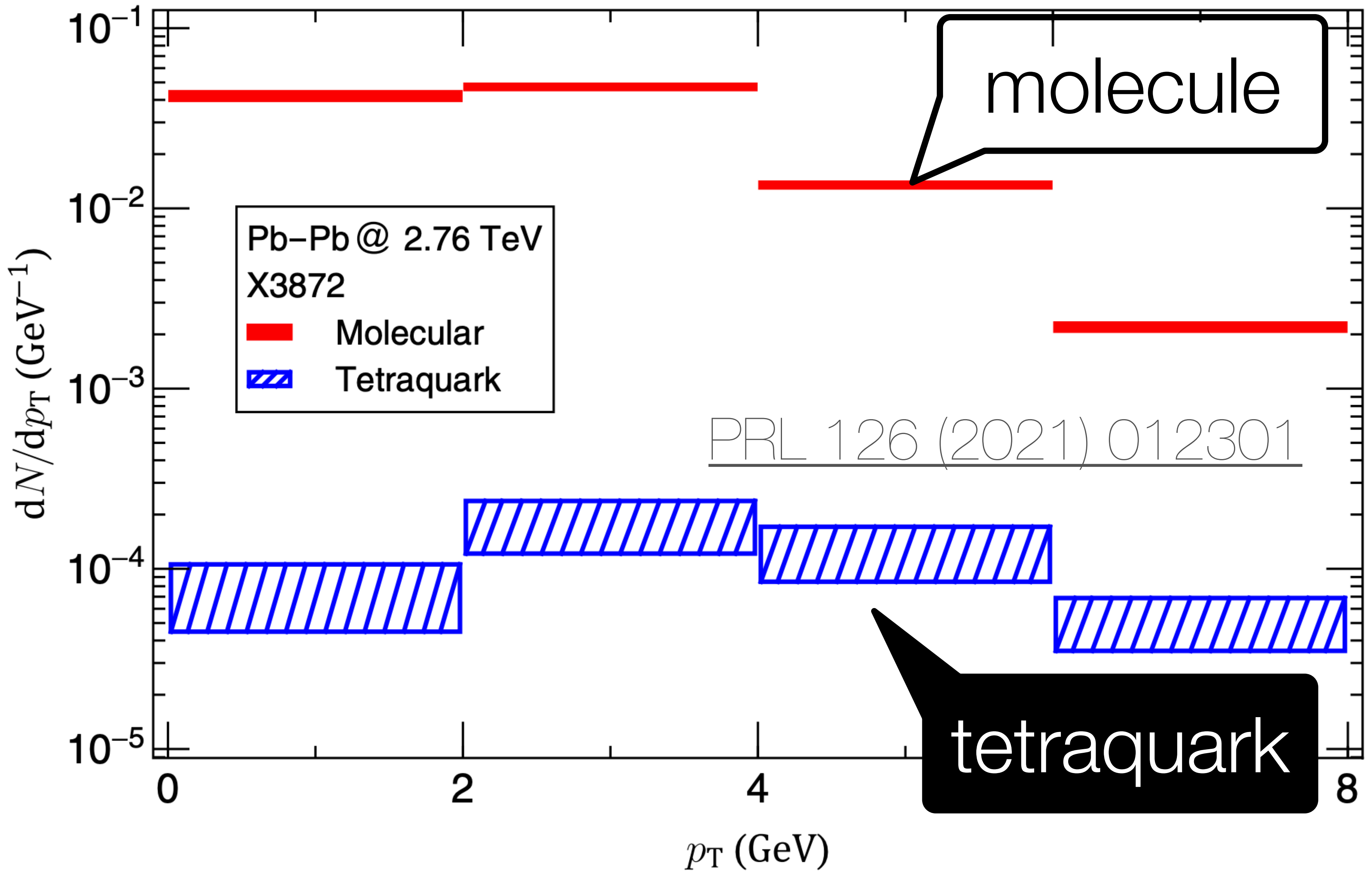
Coalescence probability depends on X(3872) inner structure and particle distribution

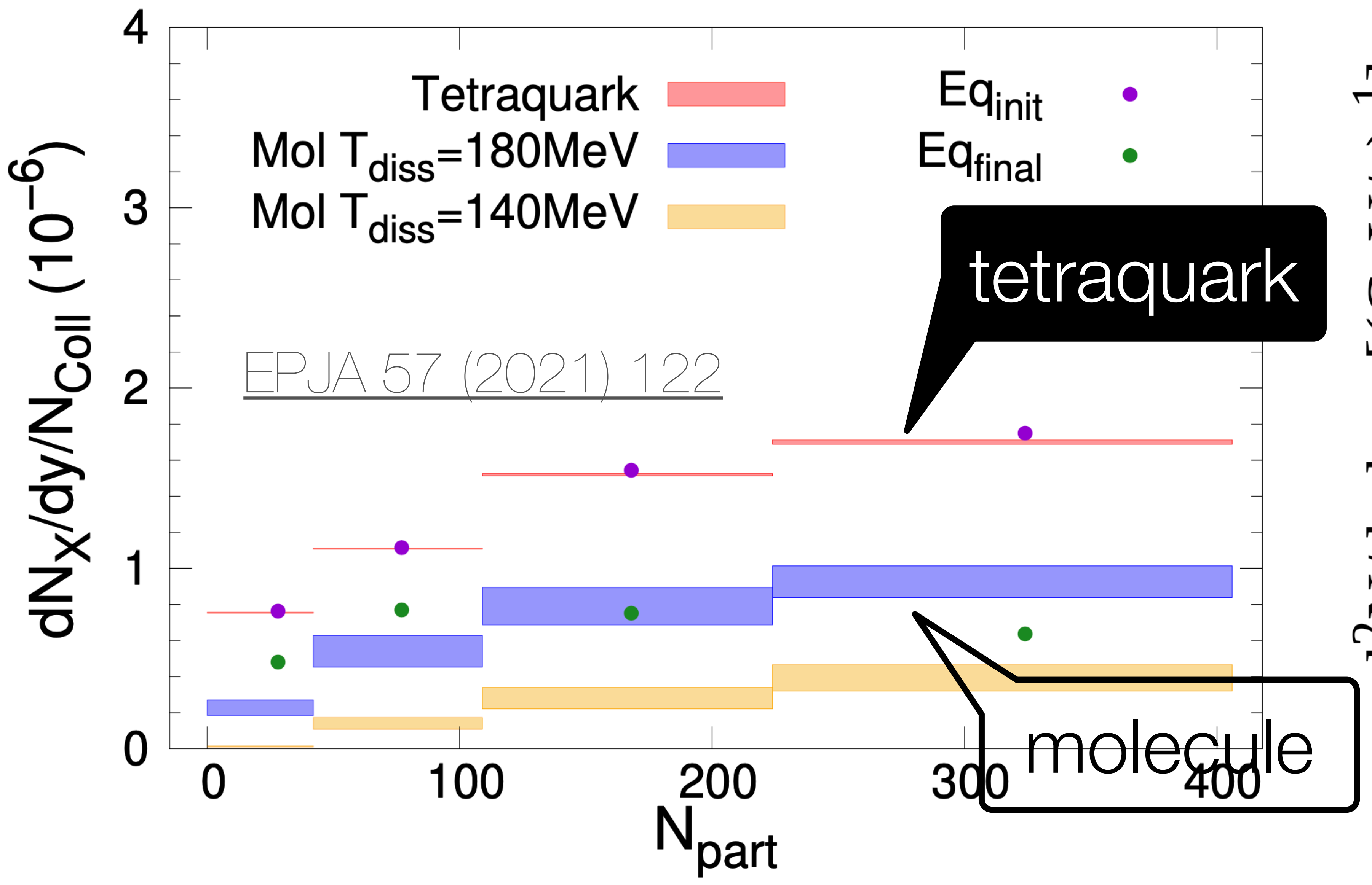
Quarkonium Binding Energy

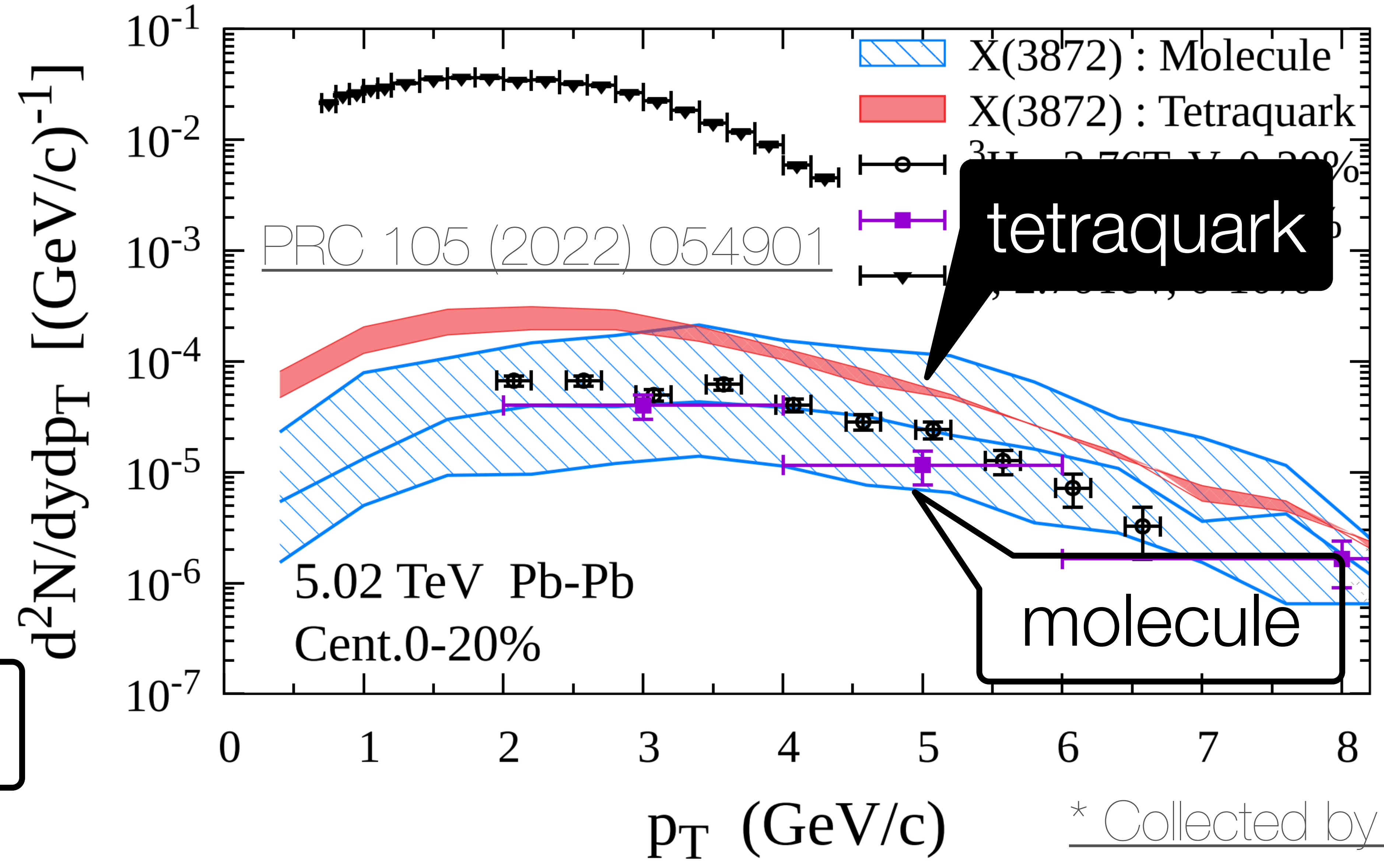


Tetra-quark or Molecule: Theory









- Many theoretical efforts!
- Divergence in theoretical calculations
- Different recombination and dissociation implementation

* Collected by J. Zhao