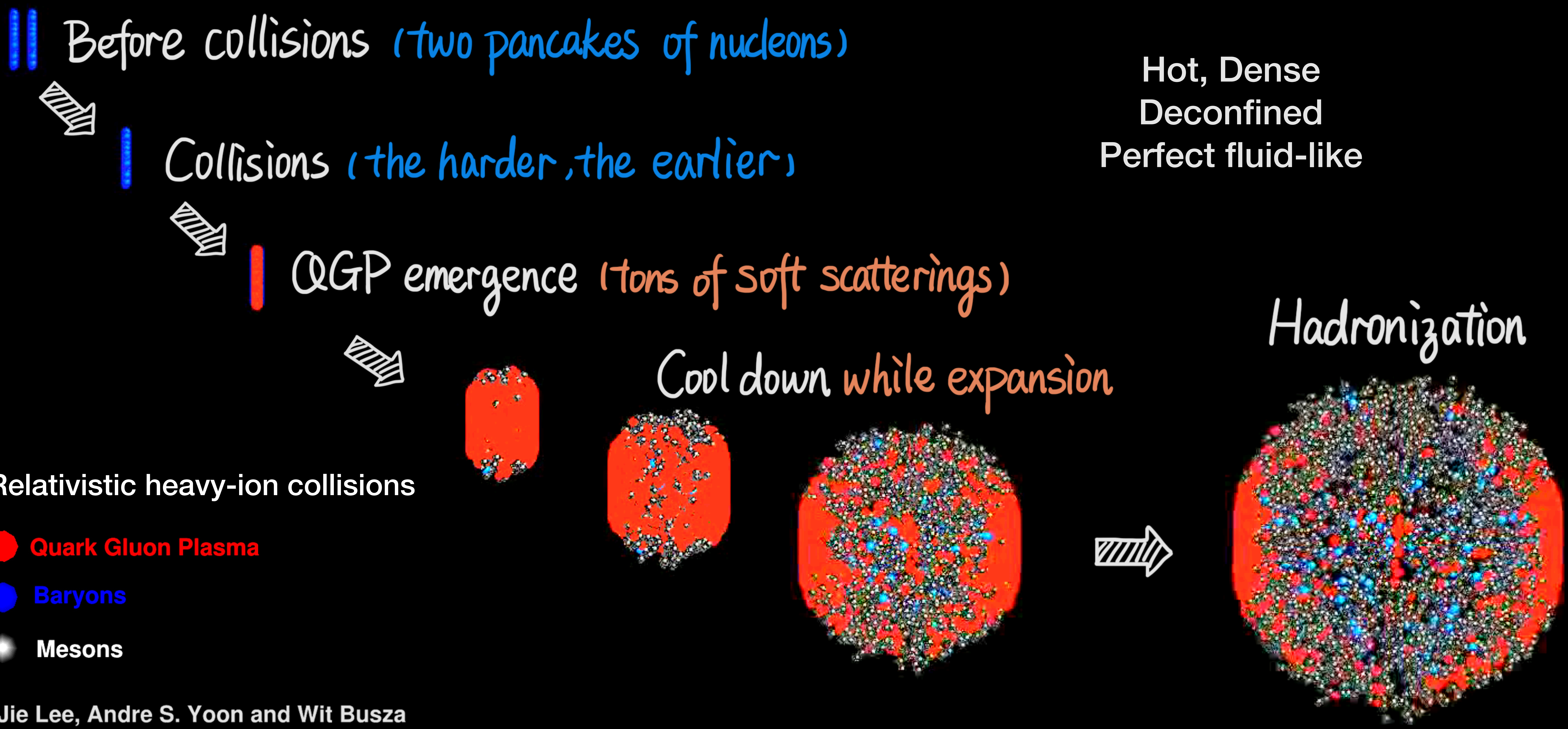
Heavy-flavor Production from pp to Nucleus-nucleus Collisions

Jing Wang (CERN)

HADRON’23 - *Hadrons in hot and nuclear environment*
June 8, 2023
Genoa, Italy

Unique Nuclear Matter: Quark Gluon Plasma

Hot, Dense
Deconfined
Perfect fluid-like



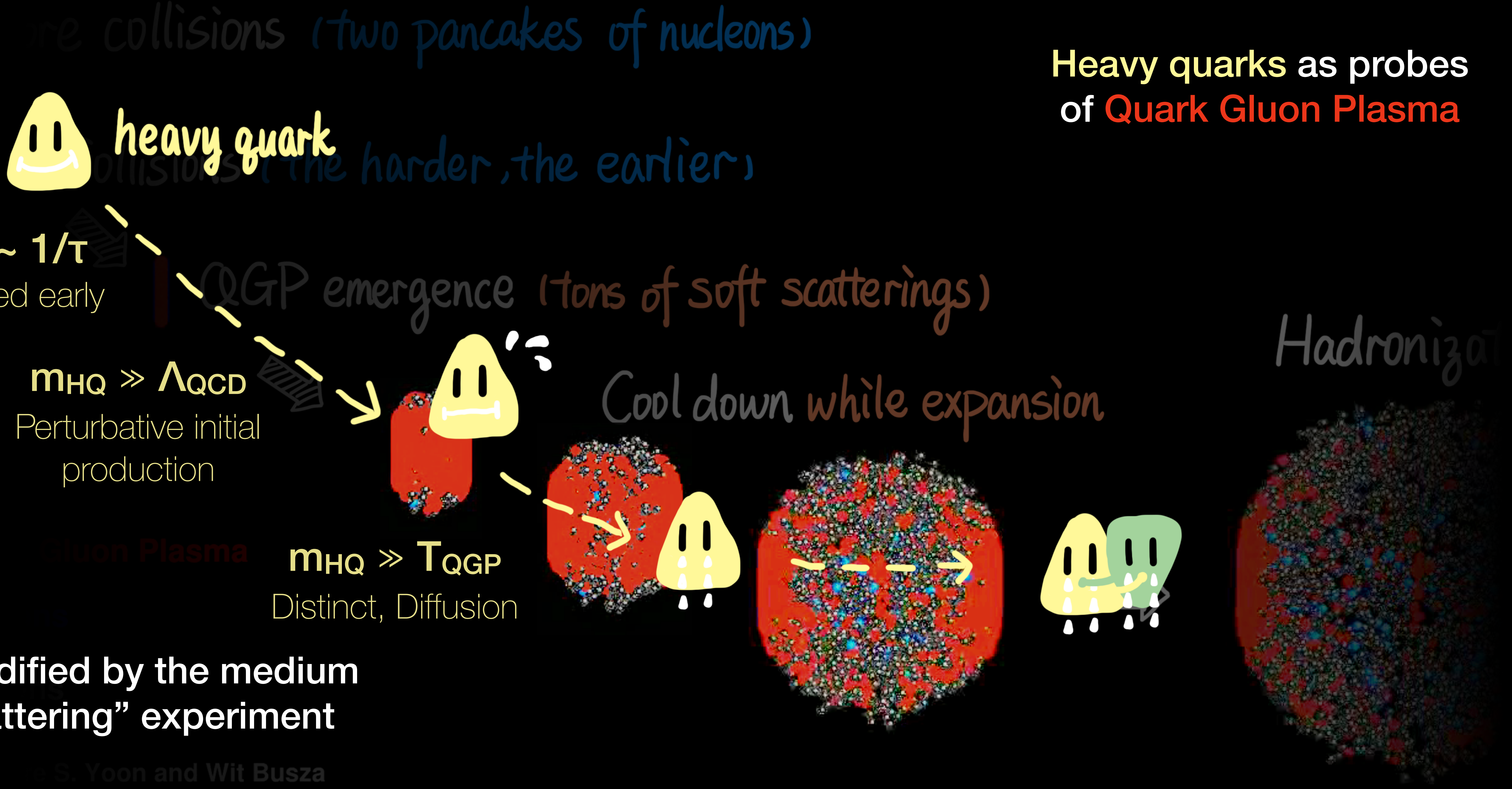
Relativistic heavy-ion collisions

Quark Gluon Plasma
Baryons
Mesons

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

Heavy Flavors in Heavy Ion Collisions

Heavy quarks as probes of Quark Gluon Plasma



$m_{HQ} \sim 1/\tau$
Produced early

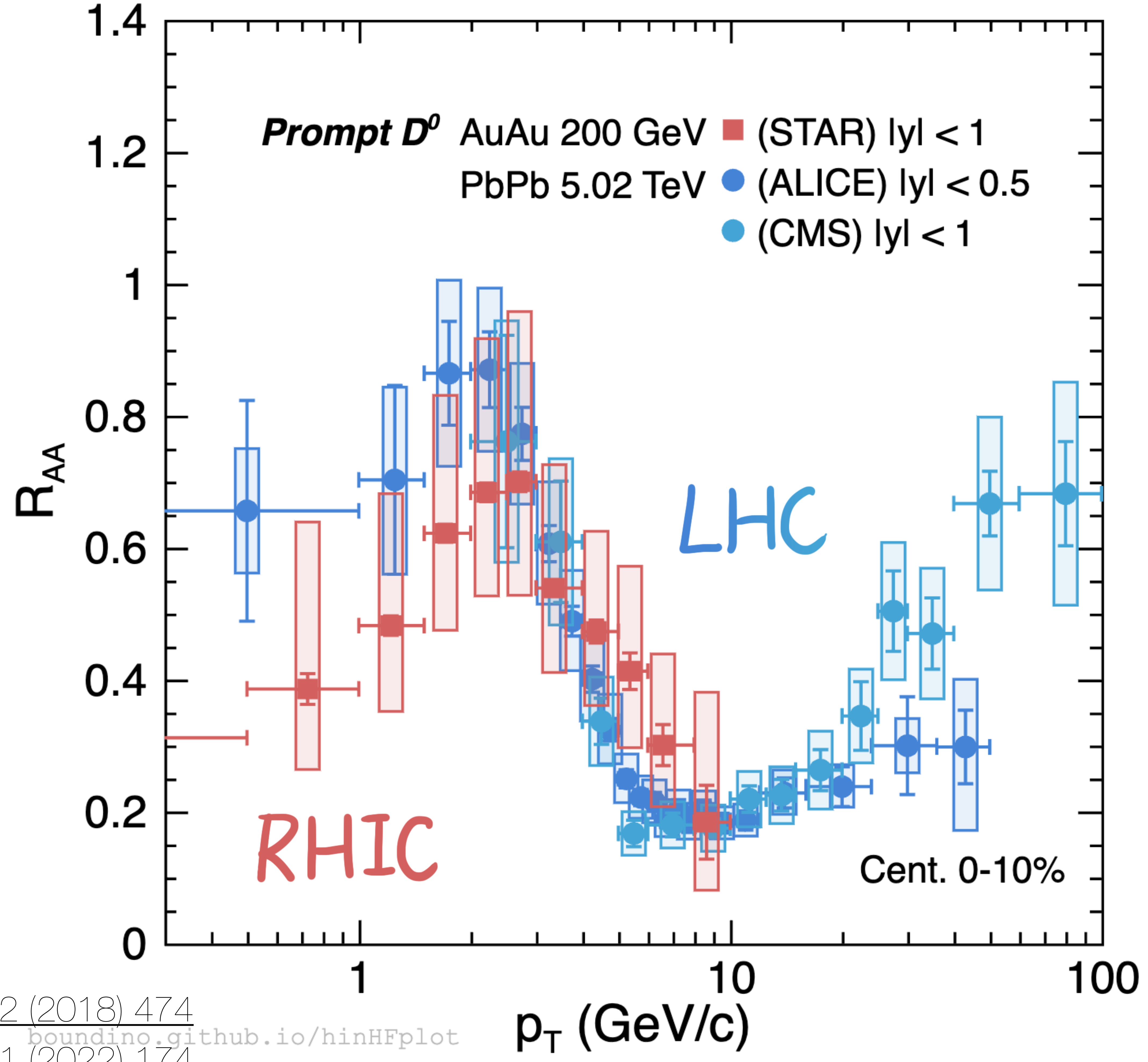
$m_{HQ} \gg \Lambda_{QCD}$
Perturbative initial production

$m_{HQ} \gg T_{QGP}$
Distinct, Diffusion

HQ modified by the medium
➜ "Scattering" experiment

Suppression of D Mesons

D0 R_{AA} in PbPb and AuAu



PLB 782 (2018) 474
JHEP 01 (2022) 174
PRC 99 (2019) 034908

How are particle spectra changed in AA?

Nuclear modification factor R_{AA}

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

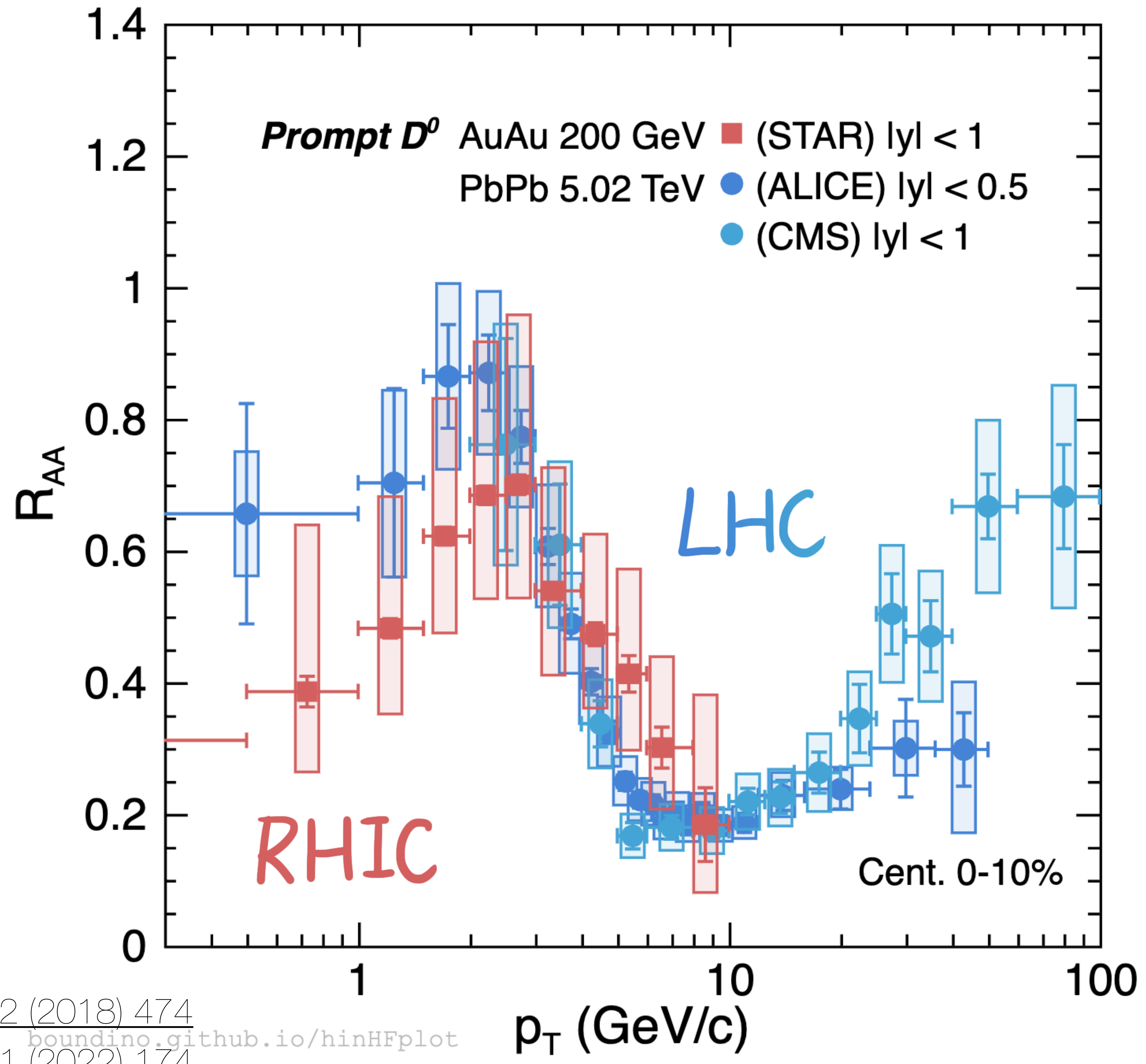
$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA} d\sigma_{pp}/dp_T}$$

← Heavy-ion

← pp

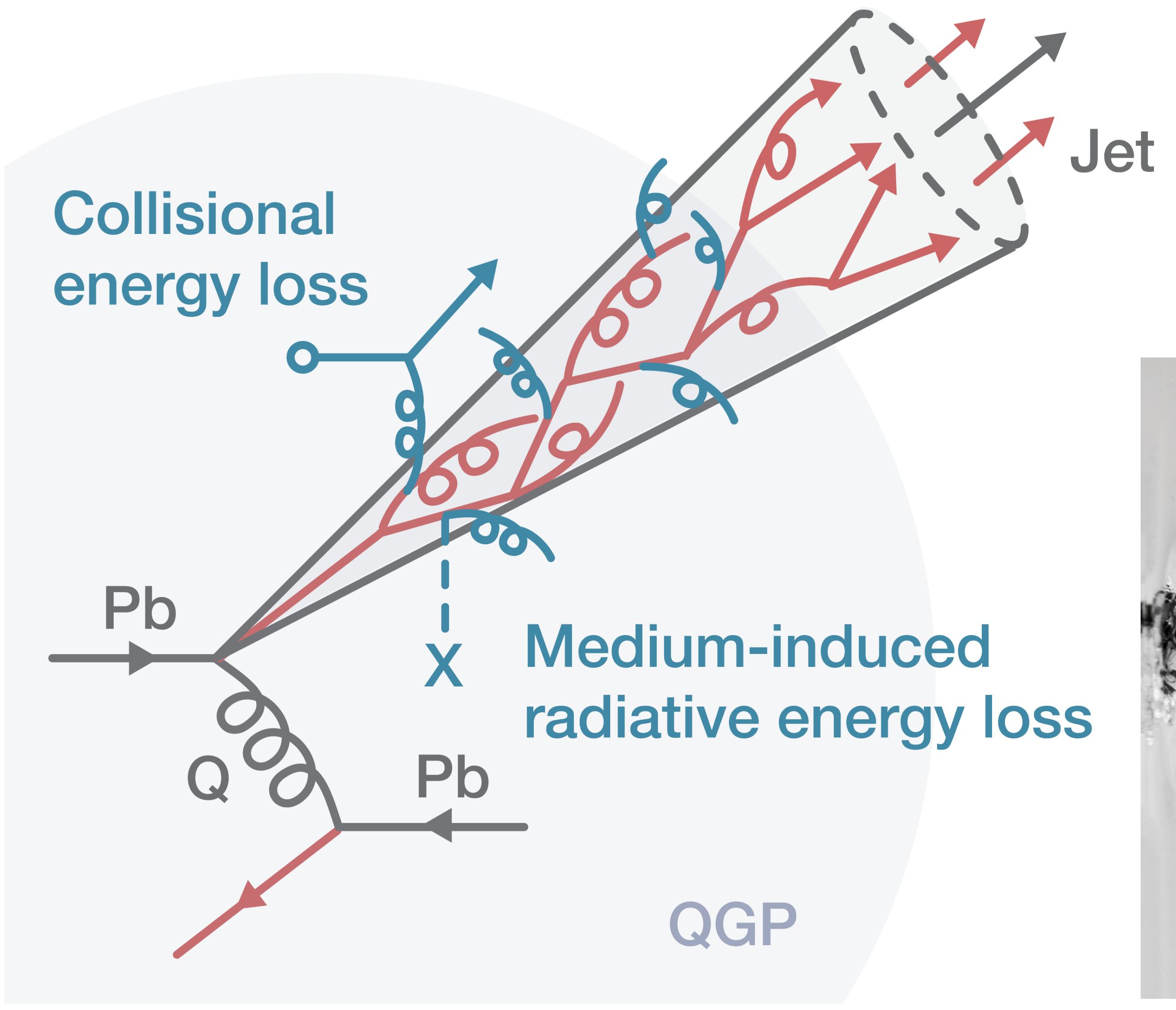
Charm Quarks Lose Energy in QGP

D^0 R_{AA} in PbPb and AuAu



PLB 782 (2018) 474
JHEP 01 (2022) 174
PRC 99 (2019) 034908

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

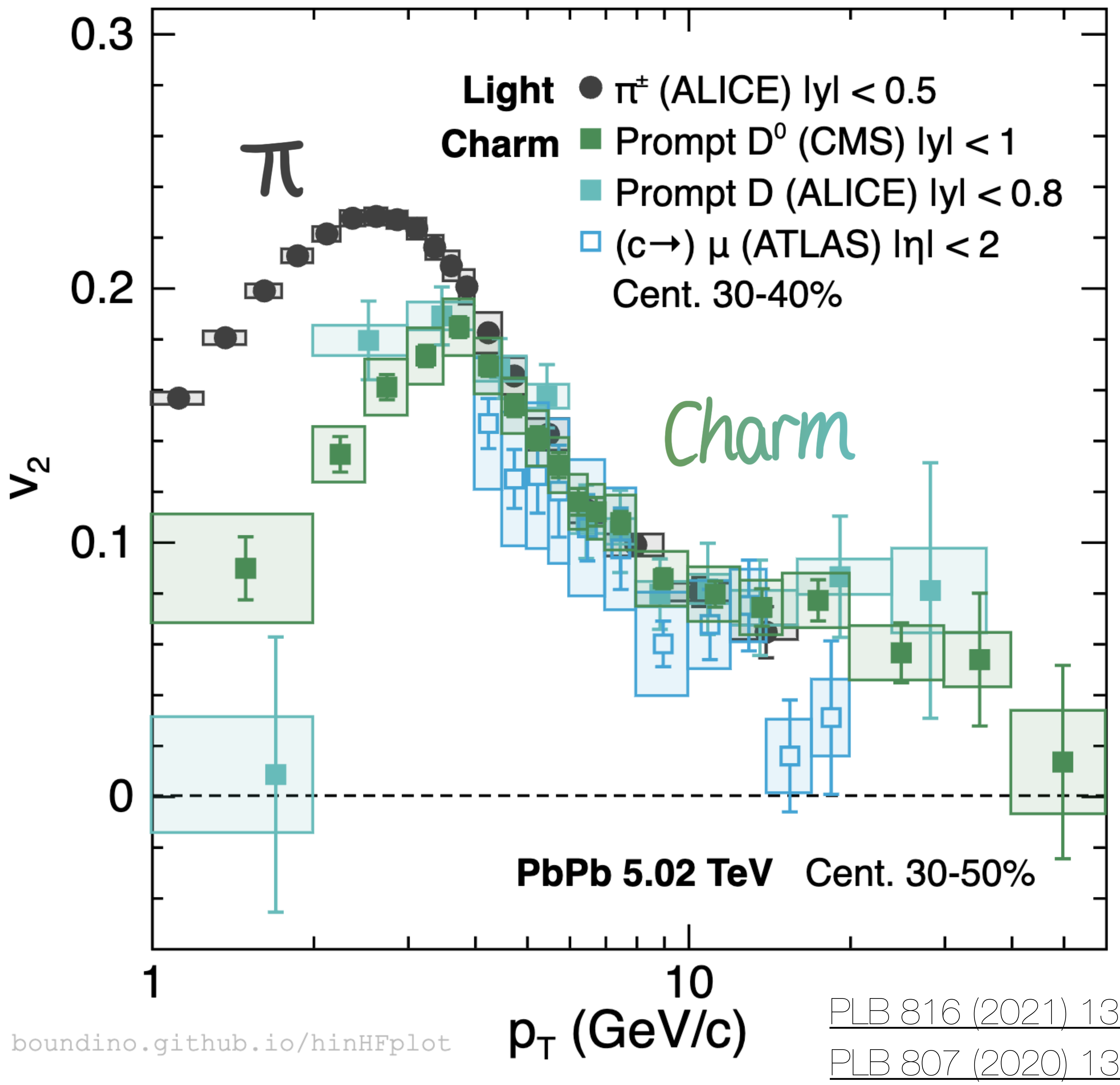


Hard parton in QGP

Bullet in gelatin block

Charm Flow Signal in PbPb

Open charm v_2 in PbPb



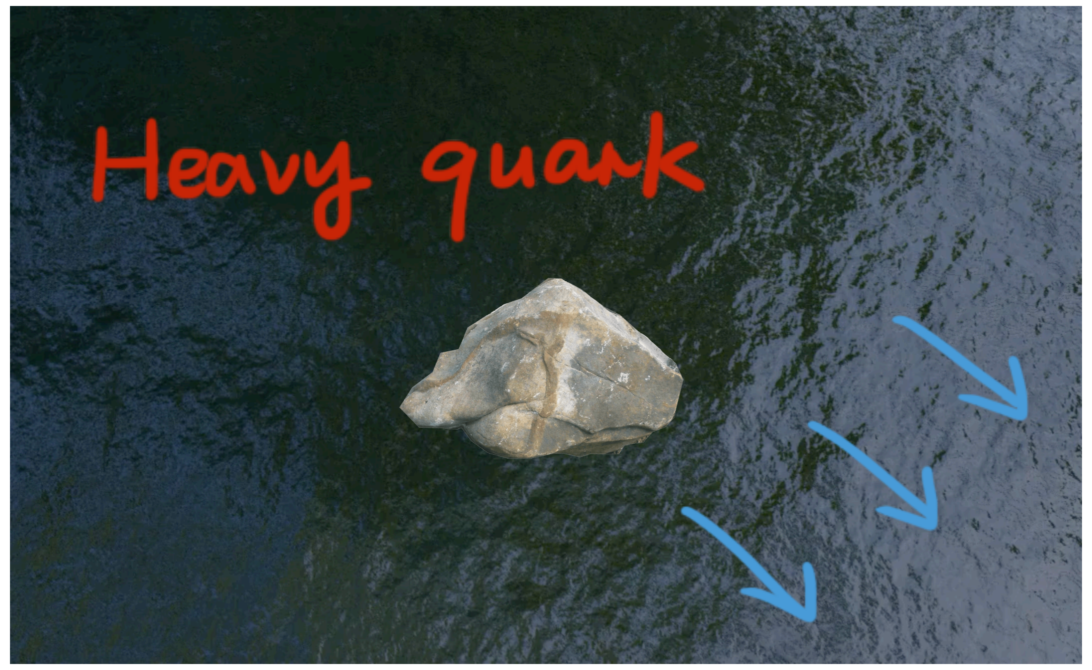
boundino.github.io/hinHFplot

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

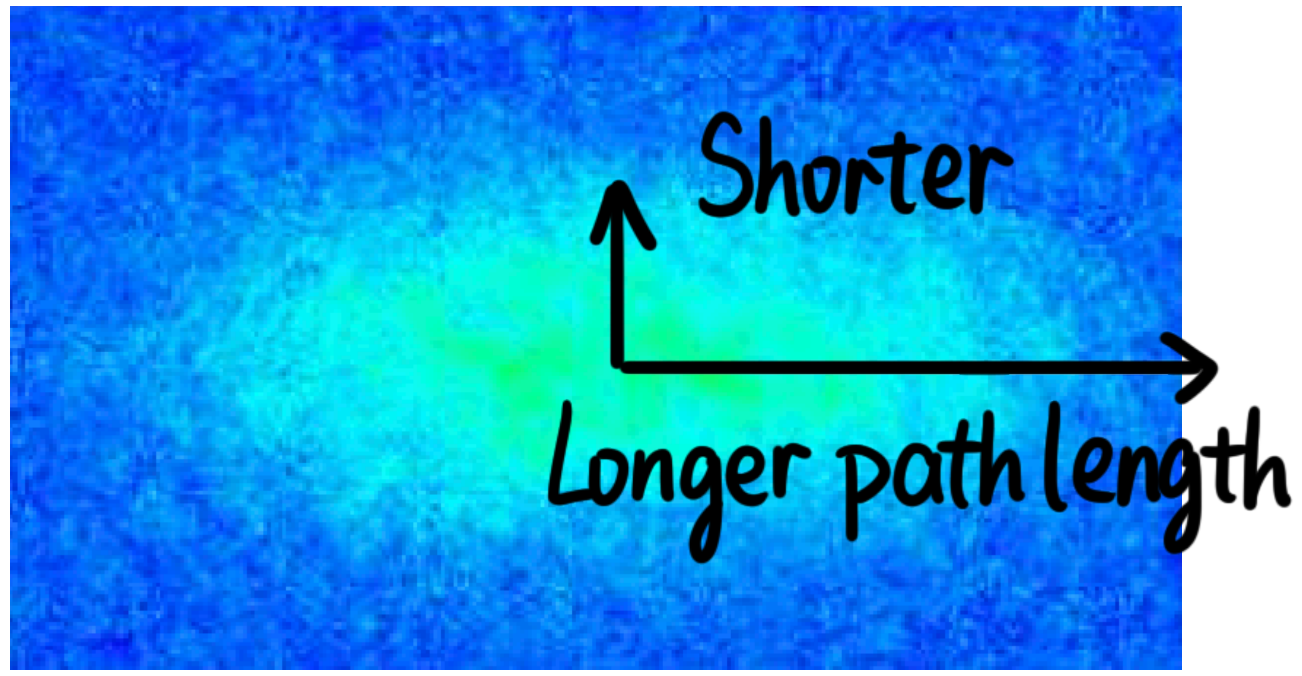
- Heavy flavor flow signal well-established
  - Flavor hierarchy at low p_T
  - Magnitude reflects thermalization degree

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

Flow

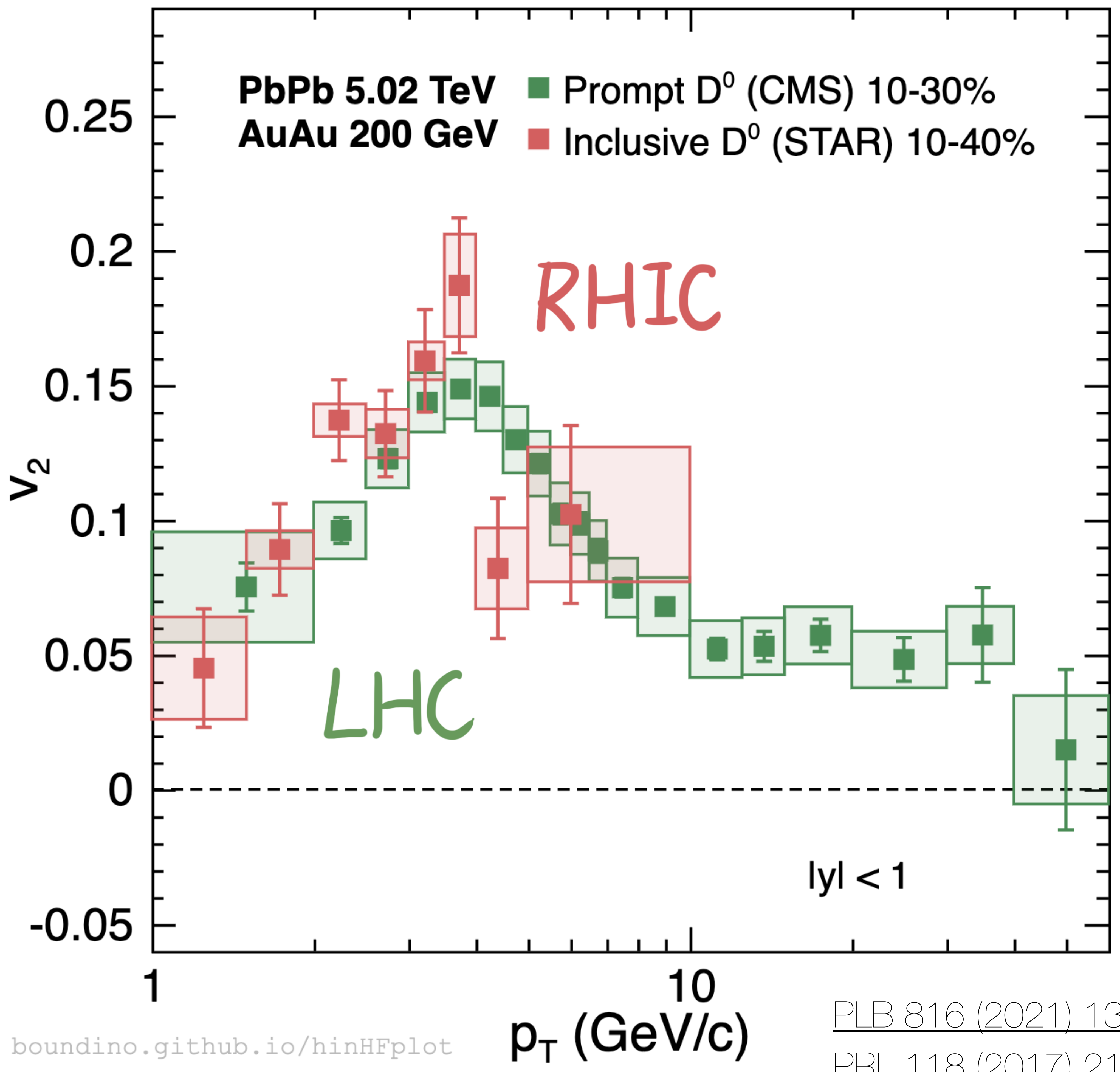


Path-length anisotropy



Vary Medium: LHC vs. RHIC

D^0 v_2 in PbPb vs. AuAu



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PLB 816 (2021) 136253

PRL 118 (2017) 212301

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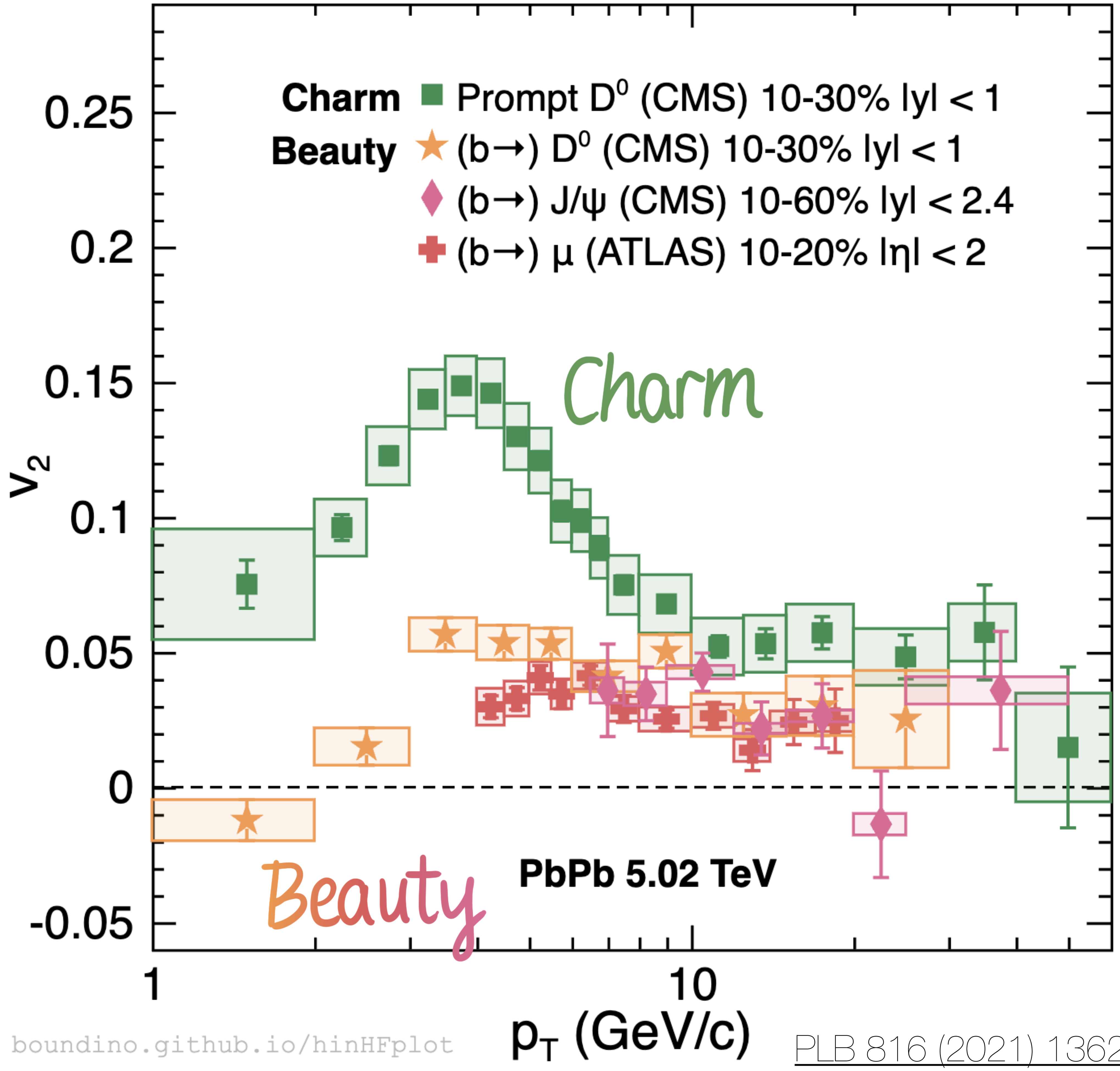
- Non-zero v_2 up to high p_T ~40 GeV
  - Path-length dependence of energy loss
- LHC vs. RHIC
  - Similar D v_2 → despite different T & size?
  - Decisive precision at sPHENIX

Beauty Flow Signal

Charm v_2 vs. Beauty v_2



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

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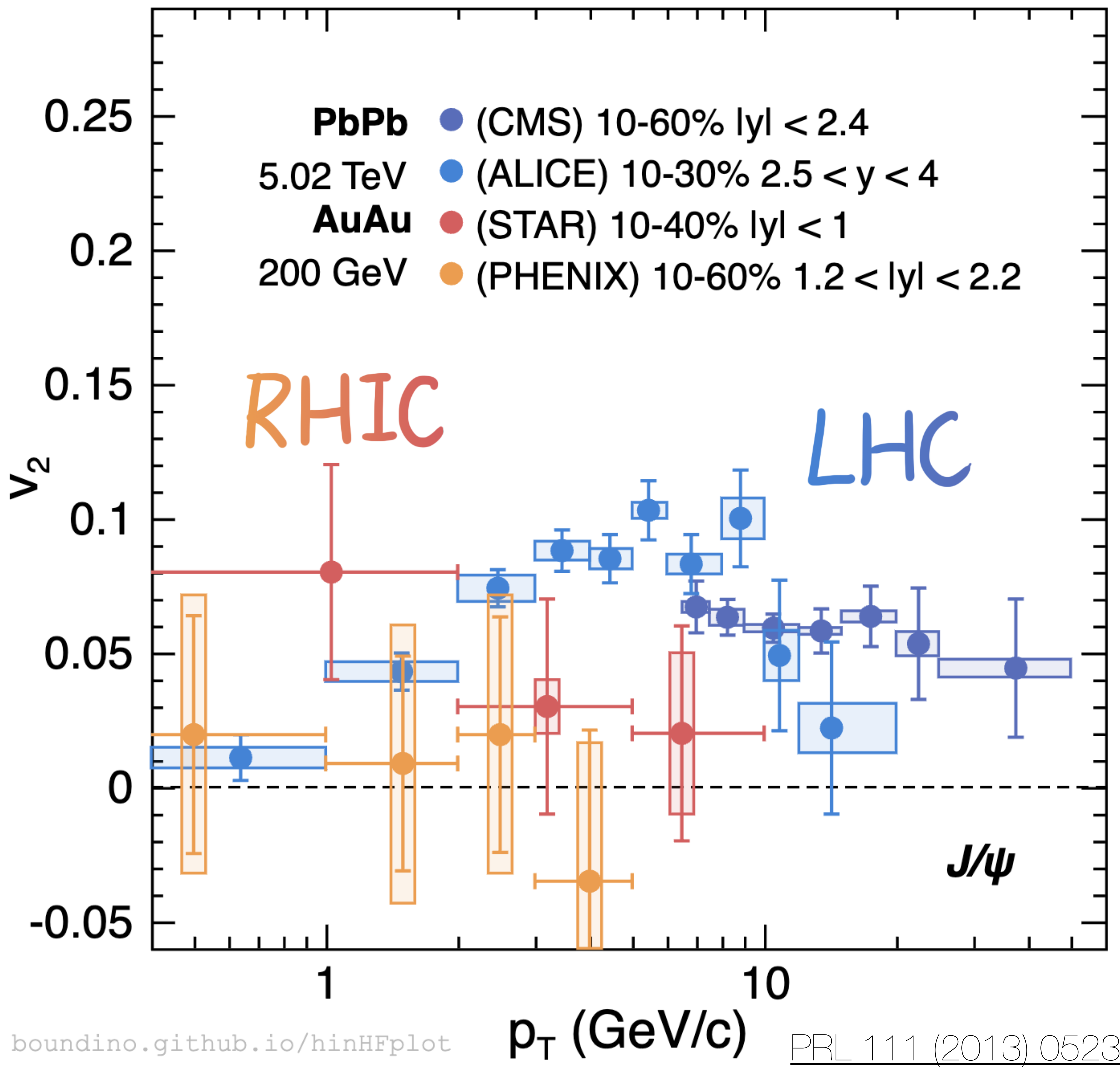
J/ψ Flow Signal

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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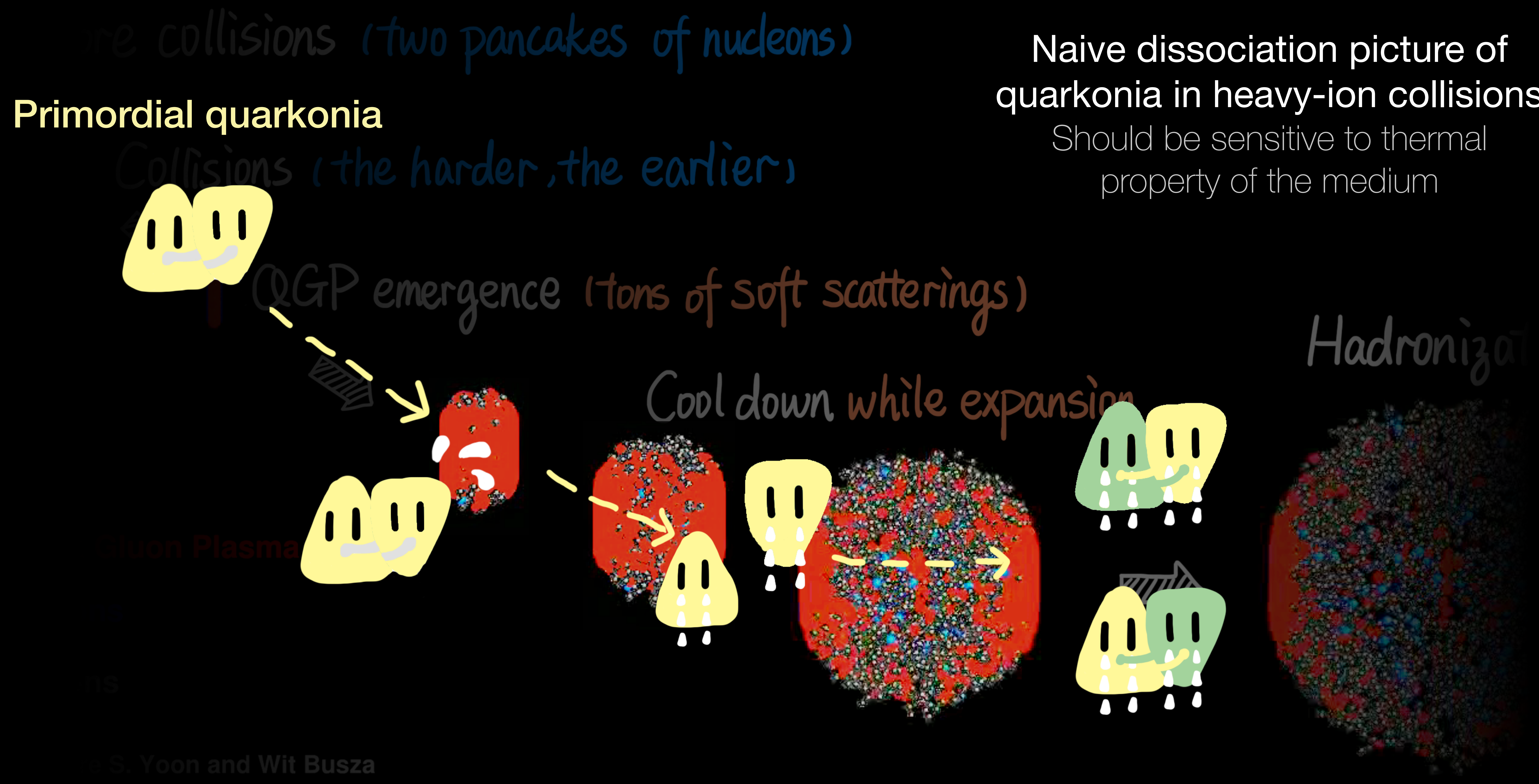
- LHC vs. RHIC
  - Similar D v_2 → despite different T & size?
  - Eager for high precision beauty v_2 at RHIC
  - Hint of zero v_2 of J/ψ at RHIC

Quarkonia is a slightly different story…

Quarkonia: Bound States in Hot Medium

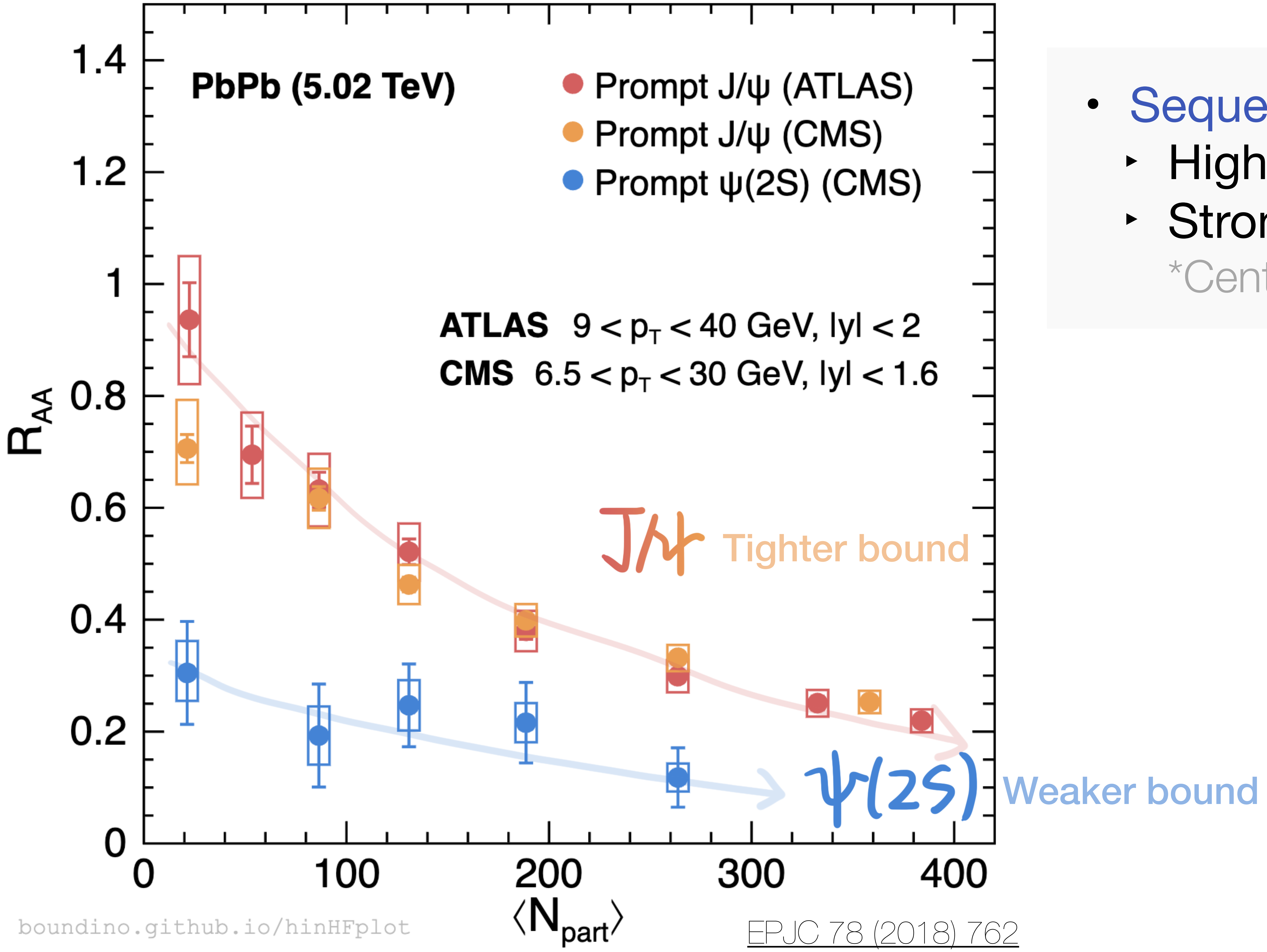


Naive dissociation picture of quarkonia in heavy-ion collisions

Should be sensitive to thermal property of the medium

Charmonia in QGP: Sequential Melting

J/ψ, ψ(2S) vs. centrality



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

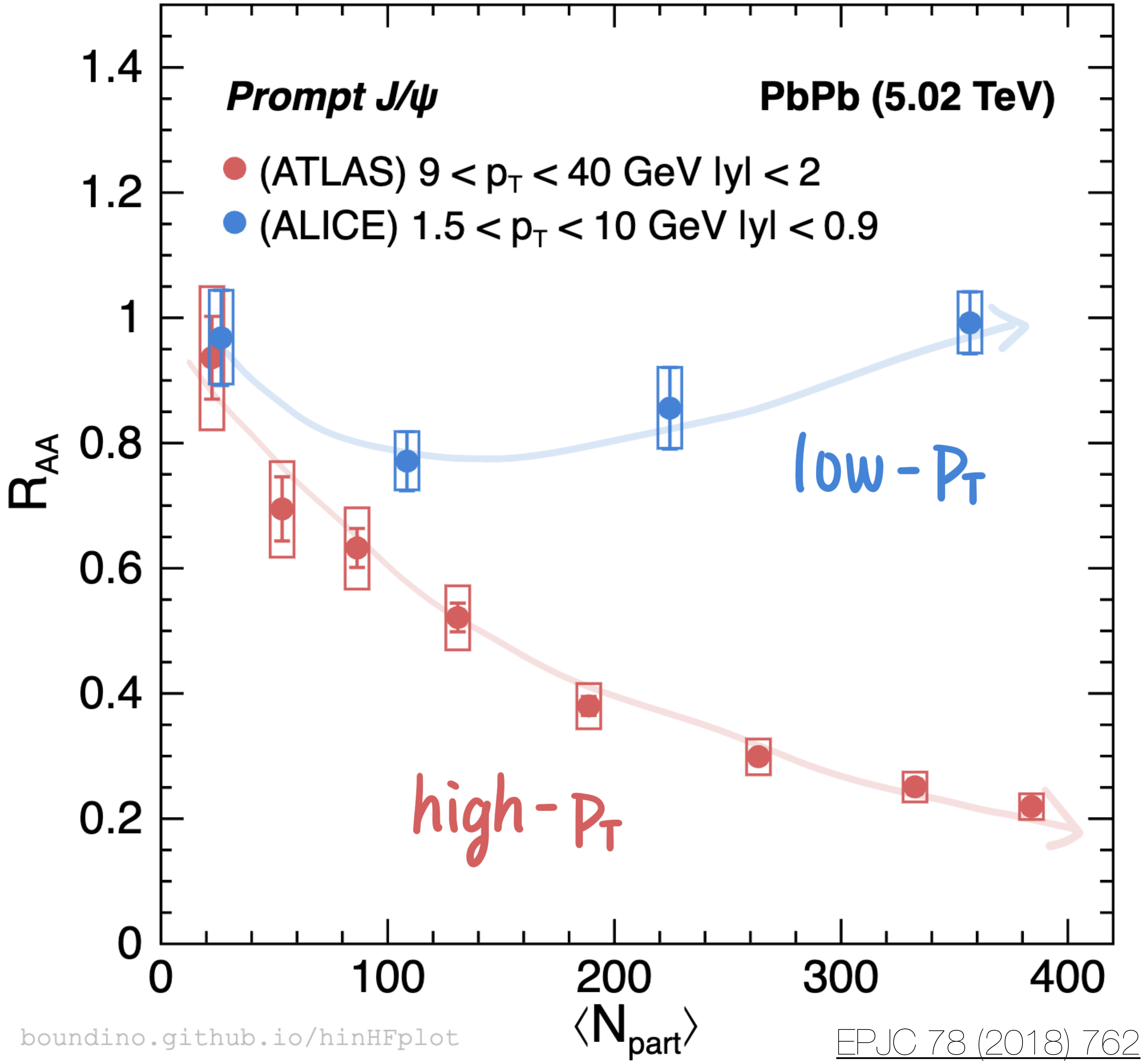
$Q\bar{Q}$ → Bound states of quark and its anti-quark

- Sequential melting → binding energy hierarchy
  - Higher temperature leads to smaller R_{AA}
  - Stronger suppression in central events → higher T

    *Central: large N_{part}

Charmonia in QGP: Recombination

Low p_T vs. High p_T



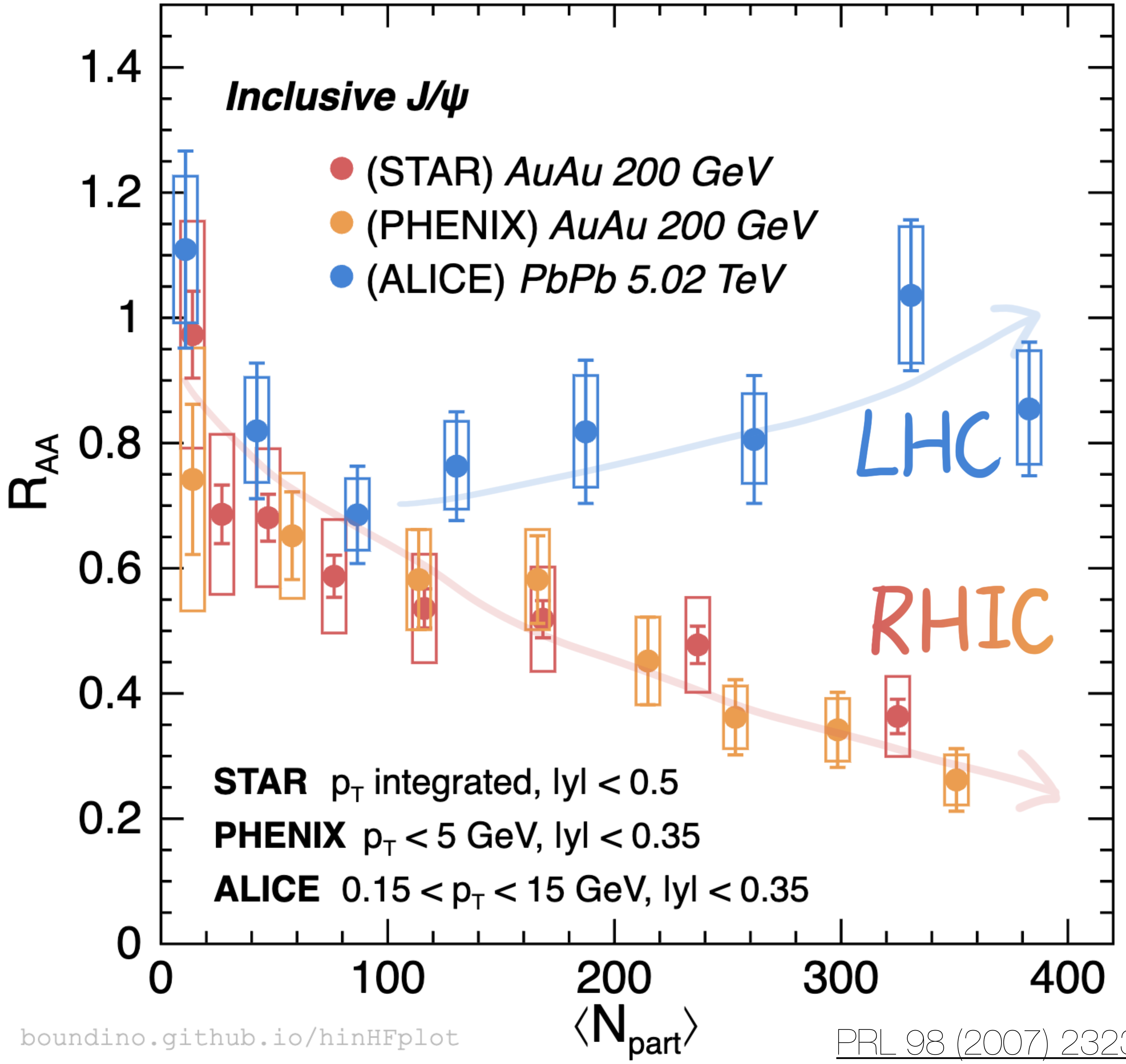
EPJC 78 (2018) 762
ALICE Preliminary

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

- Sequential melting → binding energy hierarchy
  - Higher temperature leads to smaller R_{AA}
  - Stronger suppression in central events → higher T
- Recombination
  - Enhancement at low p_T in central events → larger $\sigma_{c\bar{c}}$
  - Uncorrelated $Q\bar{Q}$ in QGP regenerate quarkonia

Charmonia in QGP: Recombination

LHC vs. RHIC



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

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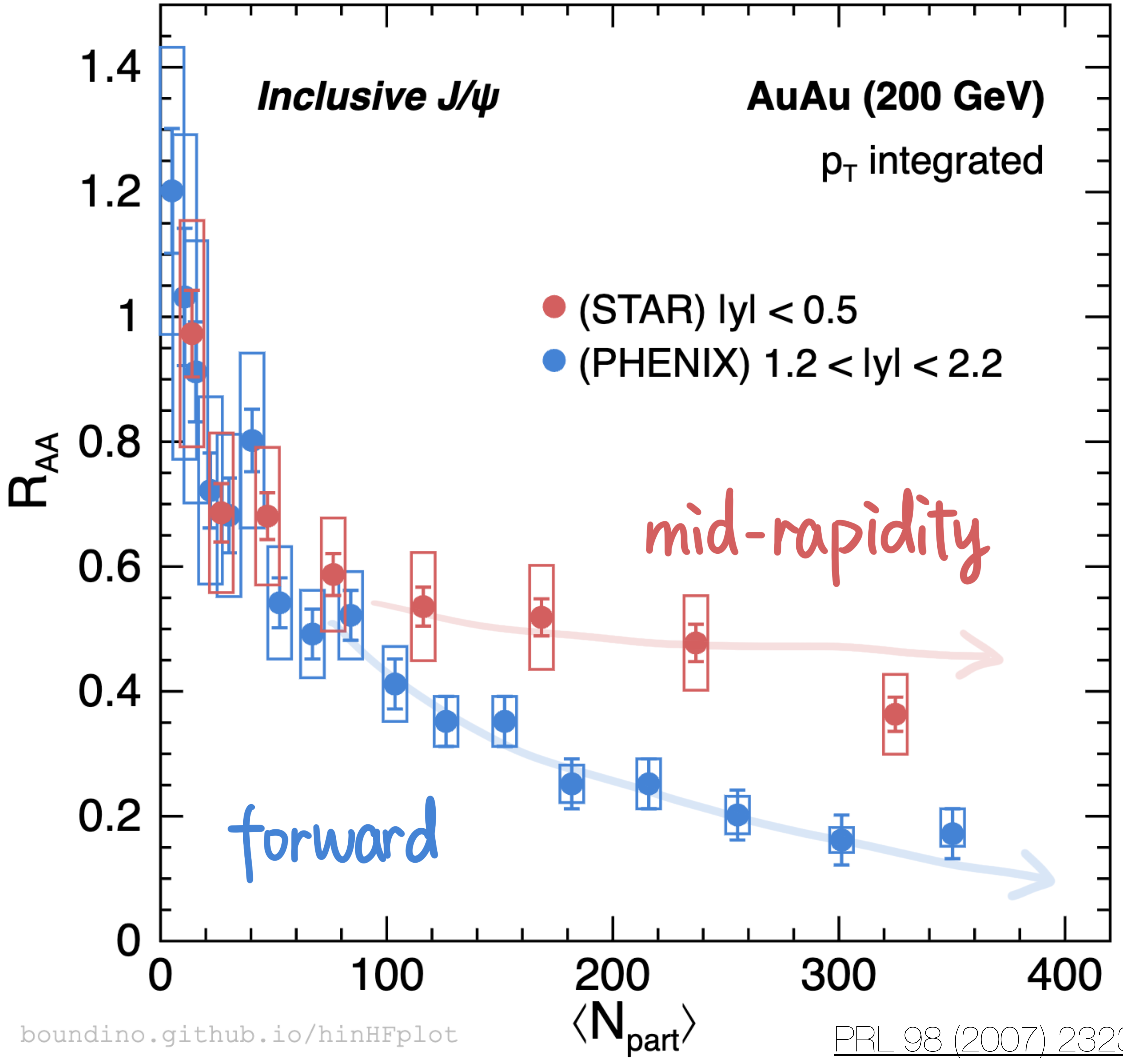
  - Enhancement at low p_T in central events → larger $\sigma_{c\bar{c}}$
  - Significant in LHC not RHIC → larger $\sigma_{c\bar{c}}$

Cold Nuclear Matter Effects

Mid-rapidity vs. Forward



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

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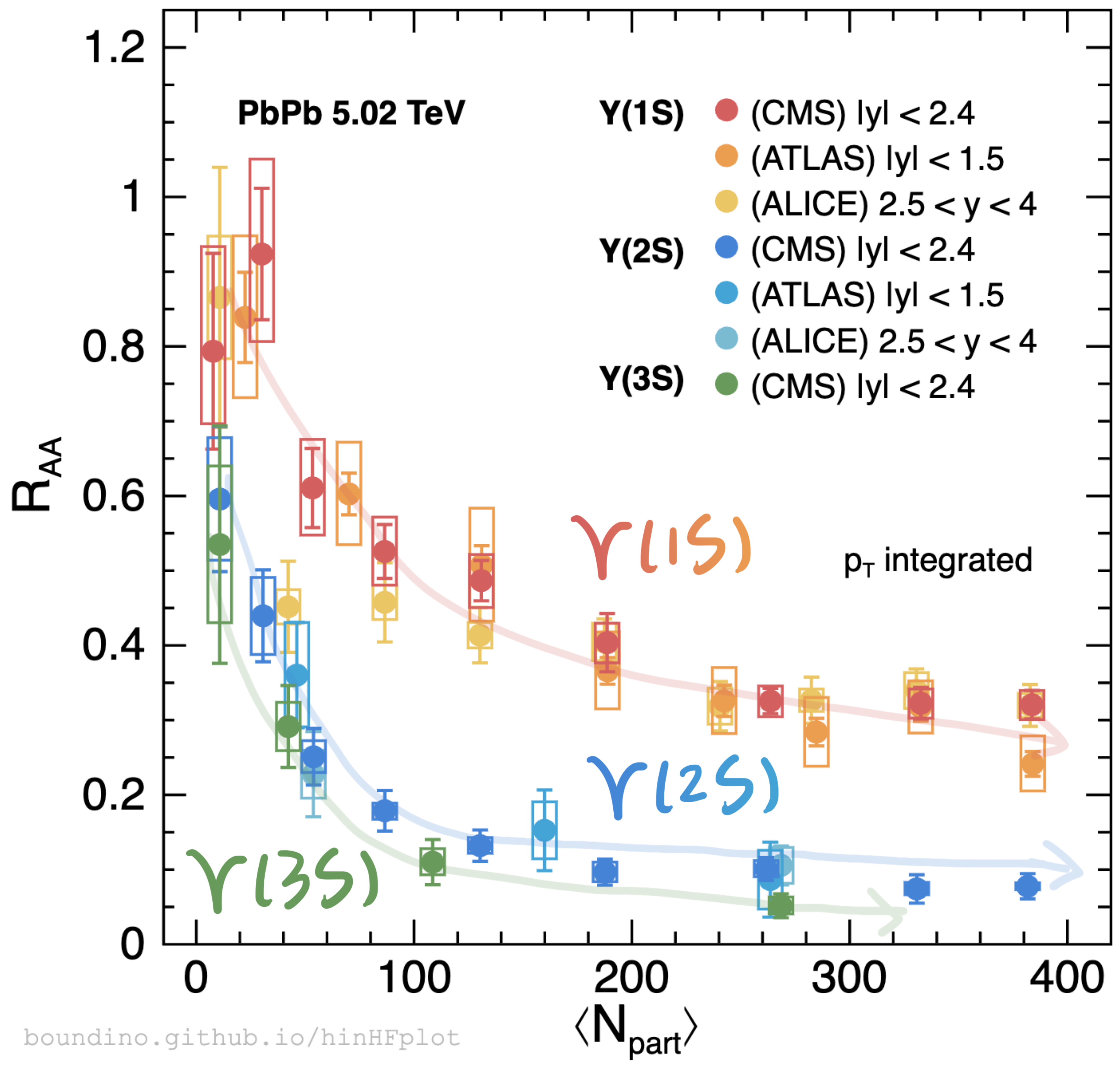
- Recombination
  - Enhancement at low p_T in central events → larger $\sigma_{c\bar{c}}$
  - Significant in LHC not RHIC → larger $\sigma_{c\bar{c}}$
- Cold nuclear matter effects
  - Comover breakup, nuclear absorption
  - Nuclear PDF
  - Initial coherent energy loss

*Not saying rapidity dependence is due to CNM

Bottomonia in QGP

Υ(nS) vs. centrality

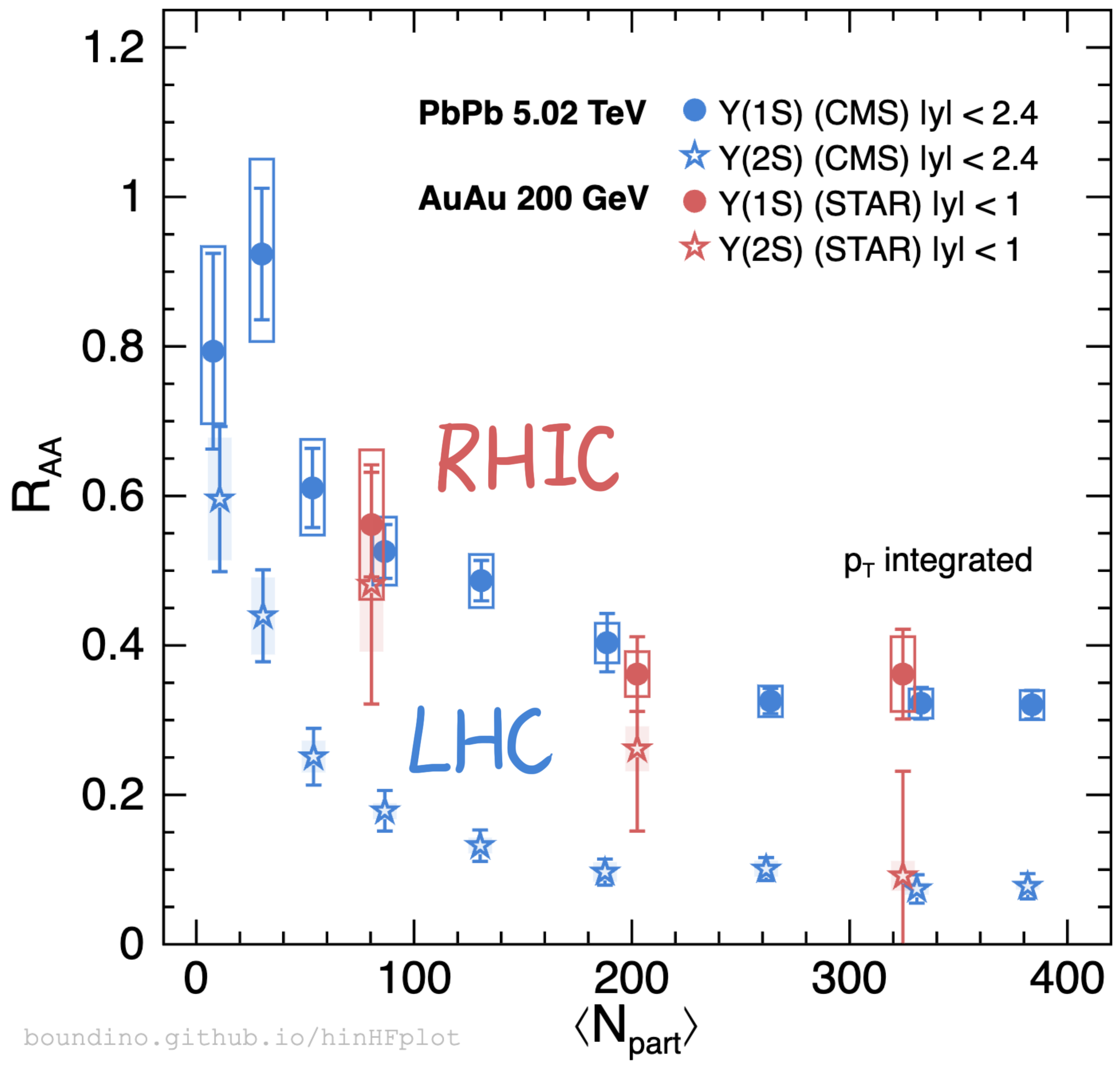


- First Υ(3S) observation in heavy-ion collisions!
- Sequential suppression for Υ(nS)
  - Υ(1S) > Υ(2S) > Υ(3S)
  - Much weaker recombination for beauty

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

Are We Happy With The Picture?

Υ(nS) R_{AA} in PbPb vs. AuAu



boundino.github.io/hinHFplot

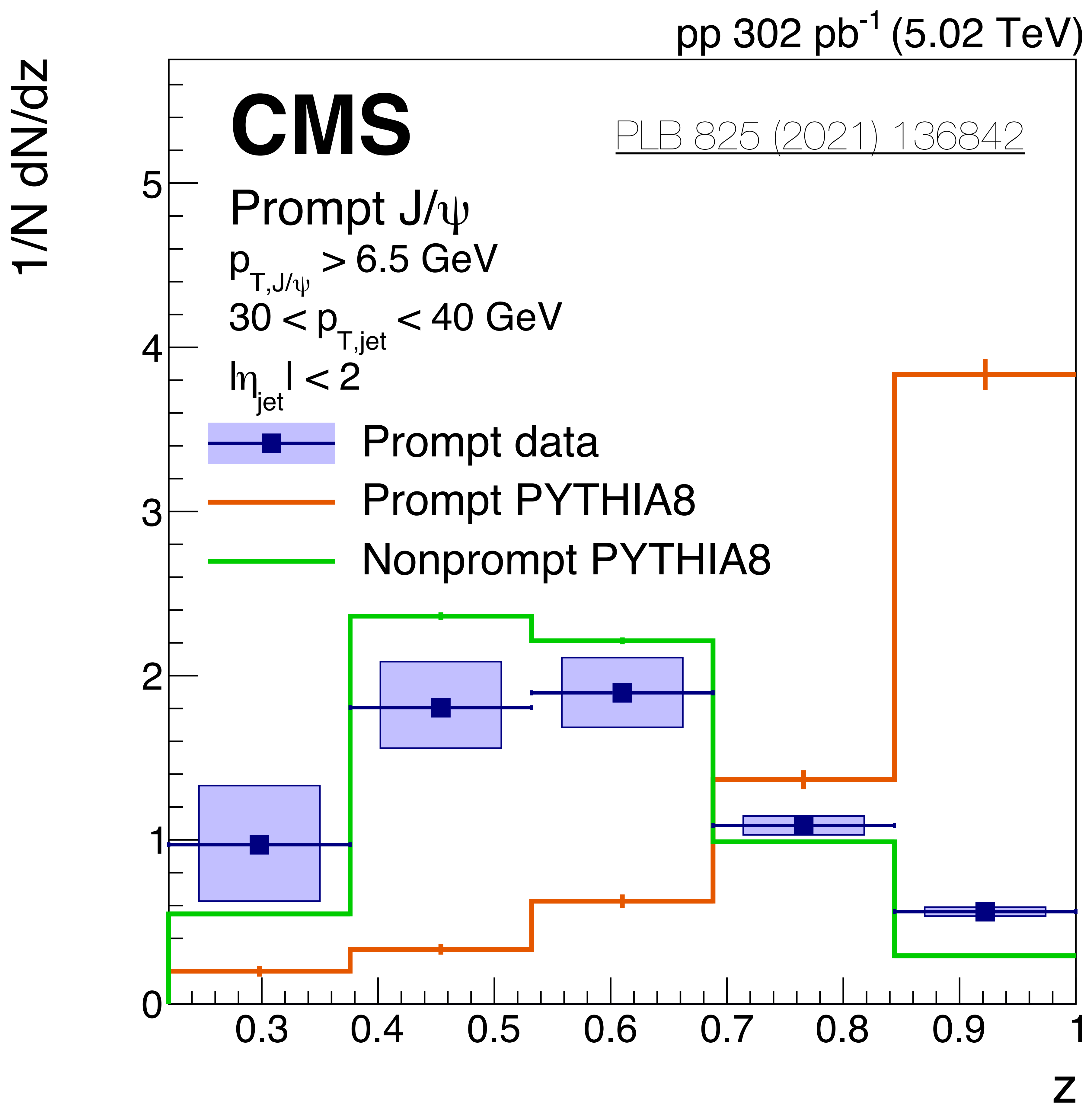
- Why are so similar Υ(1S) R_{AA} at RHIC and LHC
  - Broken thermometer?
- Why R_{AA} doesn't decrease at most central events
  - Models with regeneration still don't describe that
- Feed-down contribution not well constrained

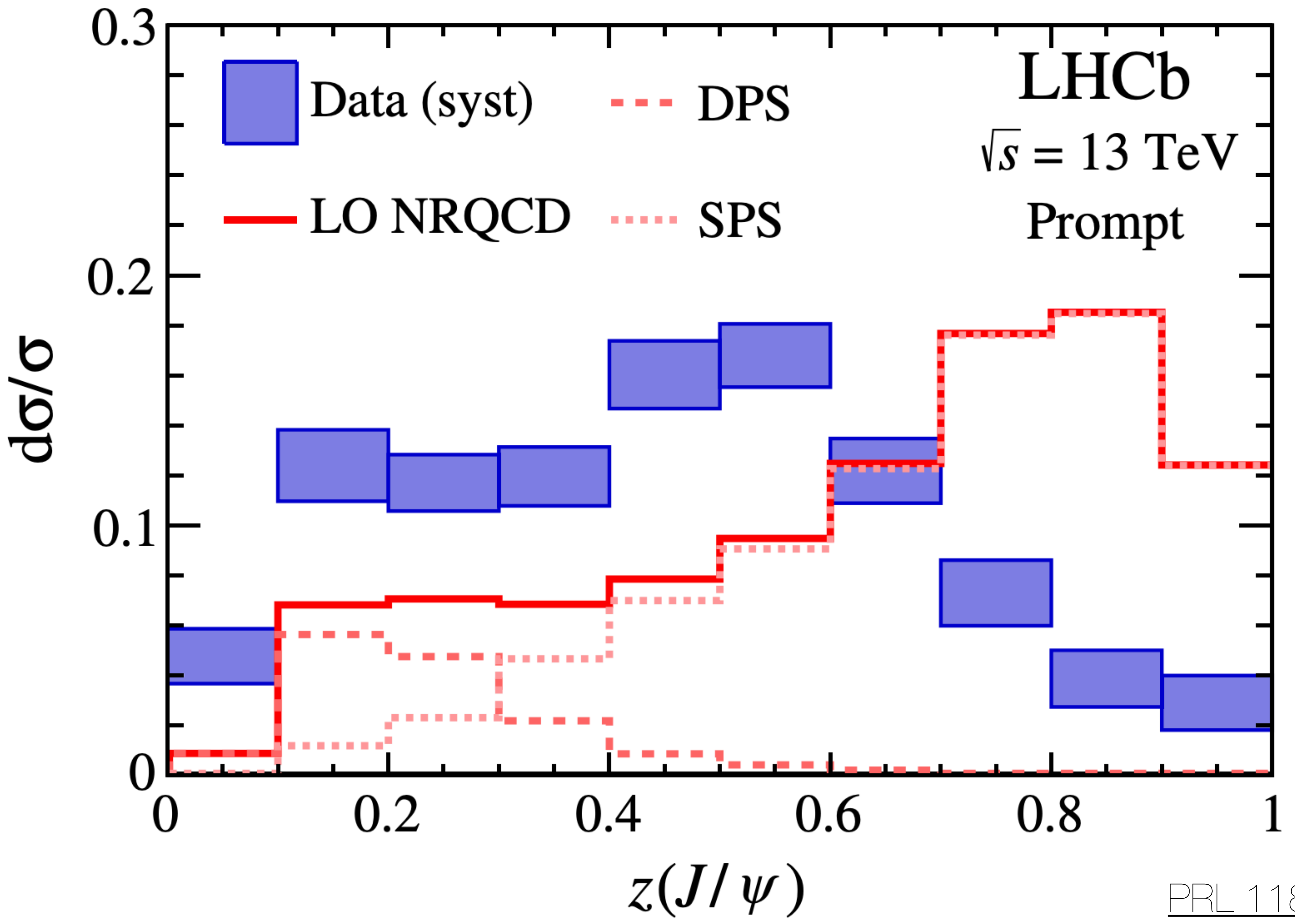
PRL 130 (2023) 112301

arXiv:2303.17026

Revisit J/ψ Believed to be Primordial

- J/ψ have more surrounding jet activities than (model) expected in pp





PRL 118 (2017) 192001

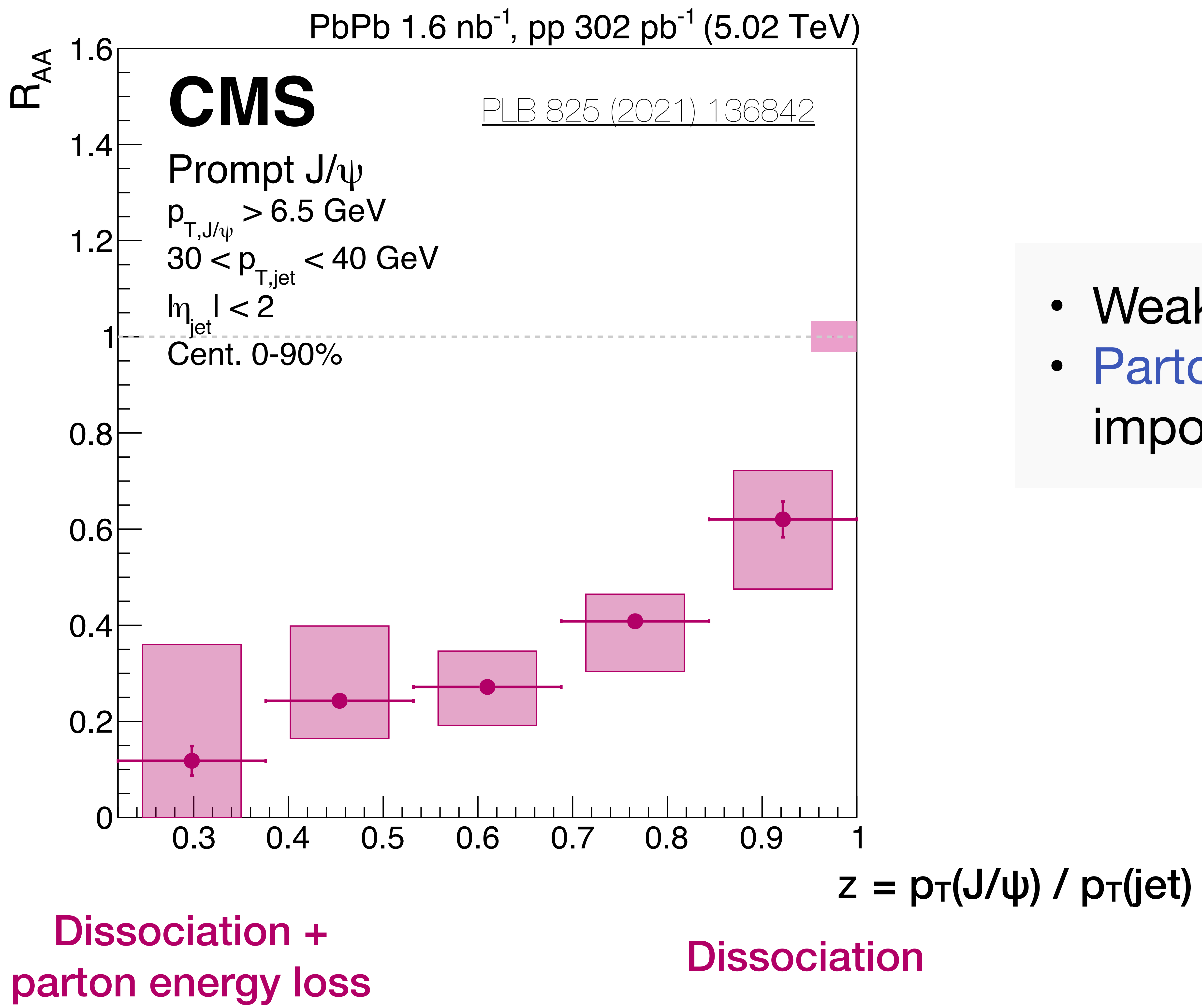
$z = p_T(J/\psi) / p_T(jet)$

Production from jet shower

Early production in dissociation picture

Revisit J/ψ Believed to be Primordial

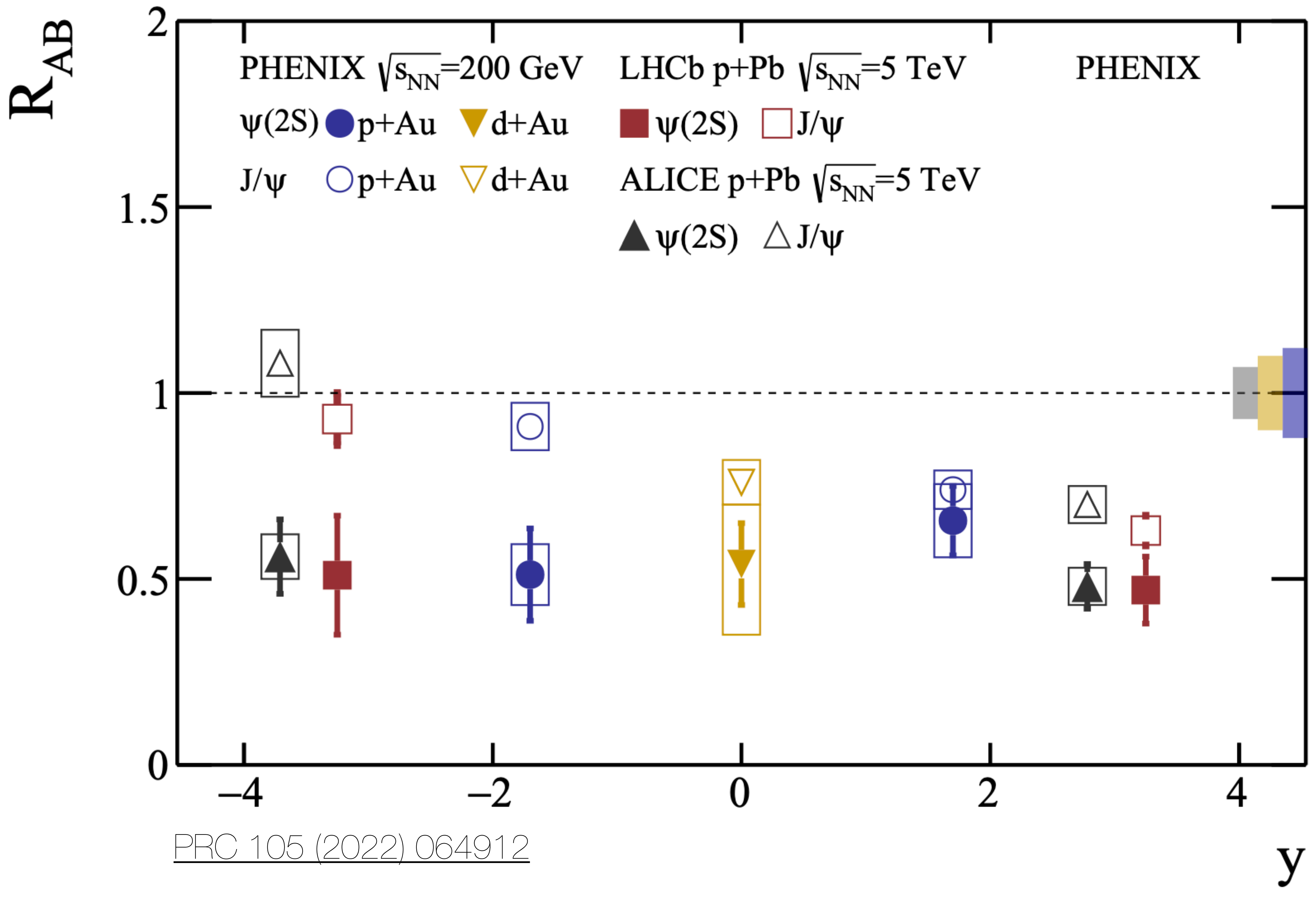
J/ψ suppression in PbPb vs. z



- Weaker suppression for isolated J/ψ
- Parton energy loss may play a more important role than expected

Charmonium Sequential Suppression in pA

R_{pA} vs. rapidity: J/ψ vs. ψ(2S)

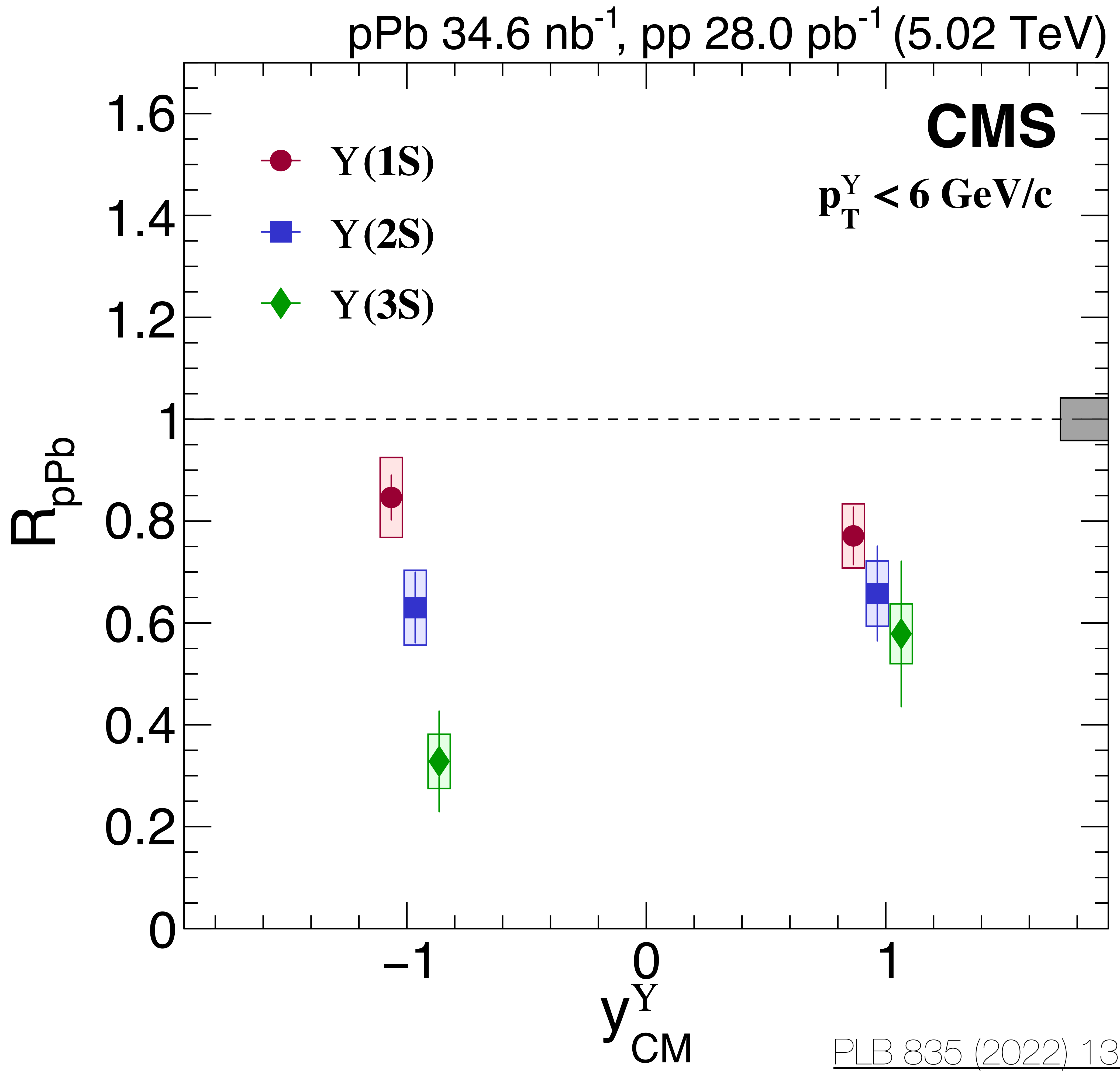


PRC 105 (2022) 064912

- Initial state effects
  ➜ Suppression of J/ψ
  - Nuclear PDF
  - Initial coherent energy loss
- Final state effects
  ➜ Stronger suppression of ψ(2S)
  - Comover breakup
  - Nuclear absorption
  - Medium?

Υ(nS) Sequential Suppression in pA

Υ(nS) R_{pA} vs. rapidity

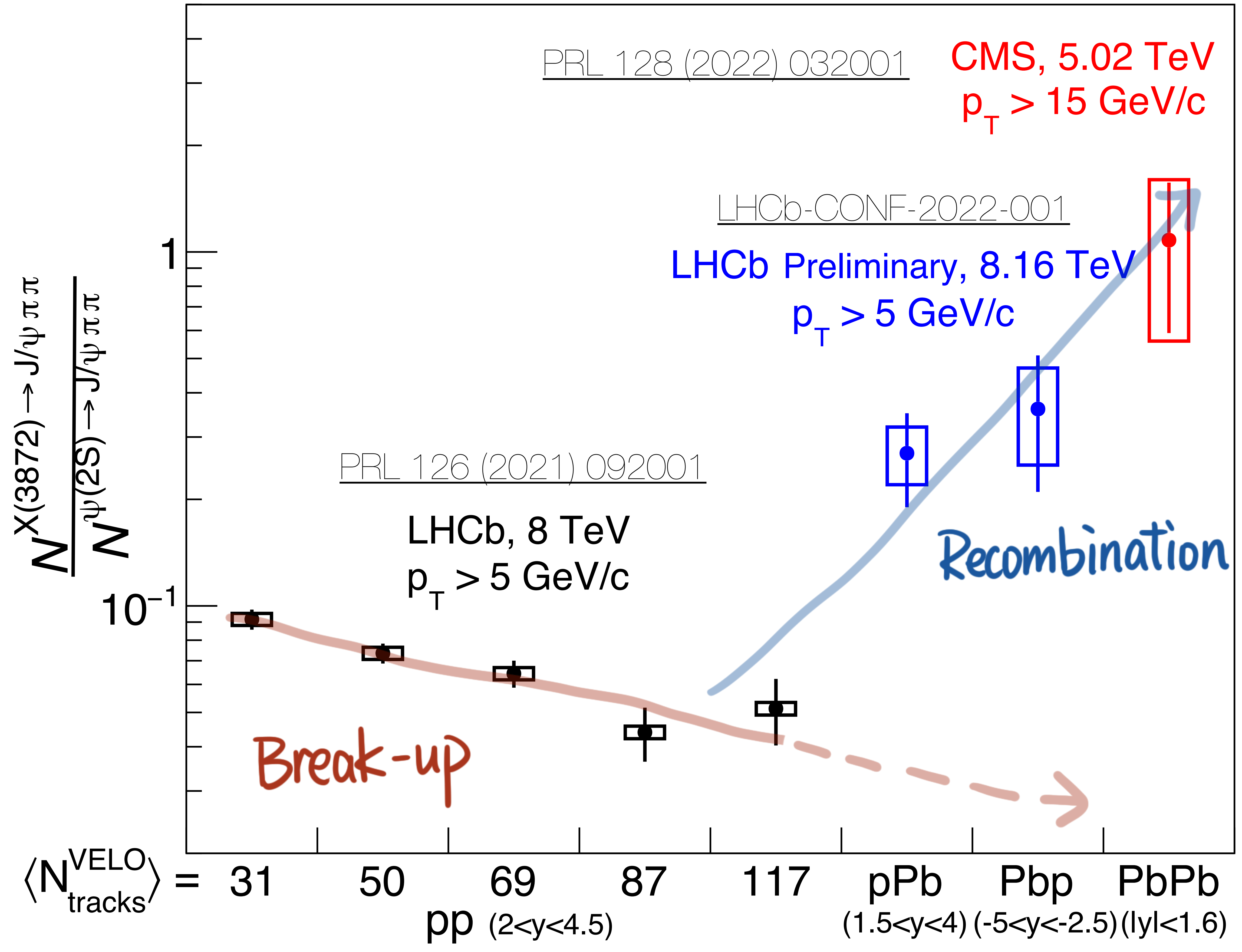


PLB 835 (2022) 137397

- Initial state effects
  ➜ Suppression of Υ(nS)
  - Nuclear PDF
  - Initial coherent energy loss
- Final state effects
  ➜ Sequential suppression
  - Comover breakup
  - Nuclear absorption
  - Medium?

An Application: Probe Structure of X(3872)

X(3872)/ψ(2S) in Different color density environment



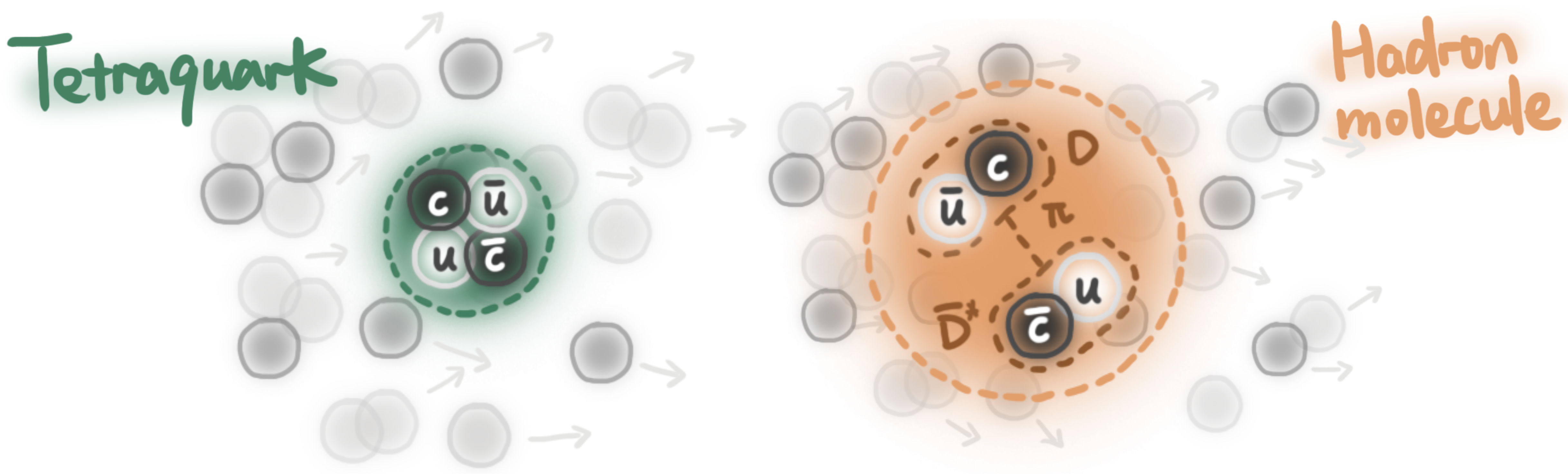
Low multiplicity
Small system

High multiplicity
Large system

- Destroyed by interactions with comovers
- Production via recombination
- Its response in color dense environment tells the inner structures

Tightly bound, small radius

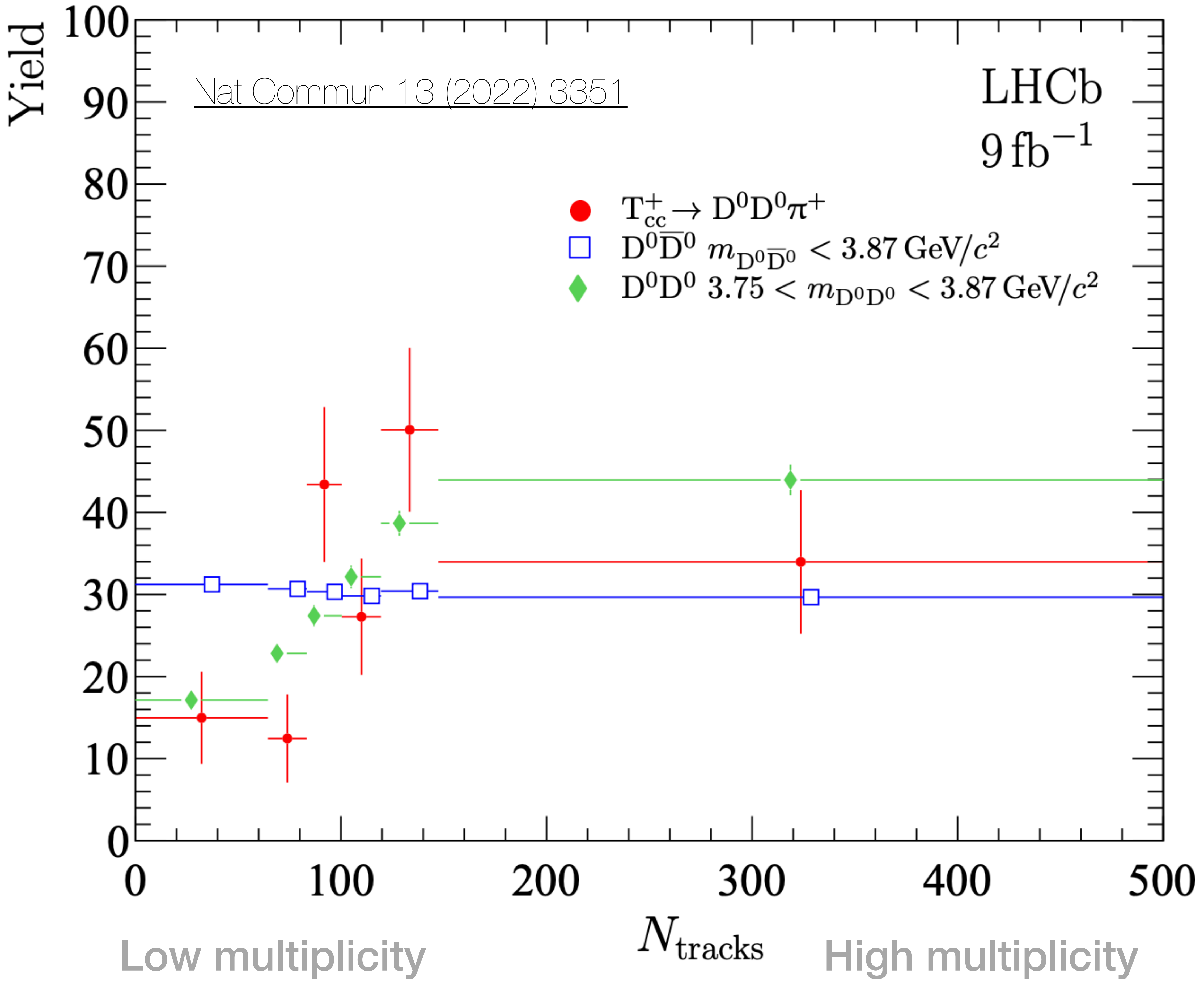
Weakly bound, large radius



20-year debate of X(3872) nature

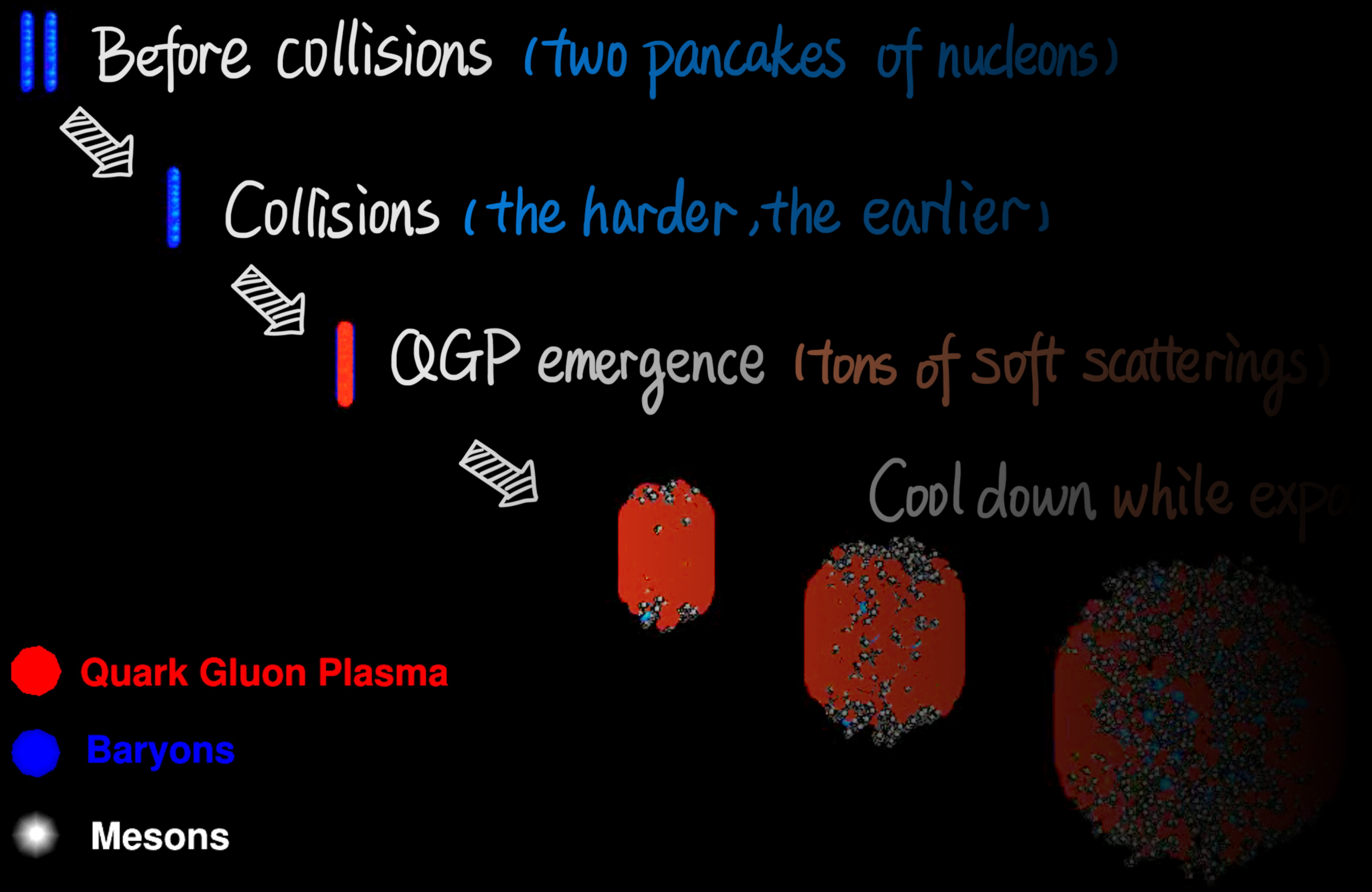
T_{cc} in High Color Density Environment

Tcc yield vs. multiplicity in pp



- Similar idea applied on another exotic T_{cc}
- No suppression in high multiplicity
  - Different response as X(3872) to the color dense environment

Medium is Dynamic: Initial State



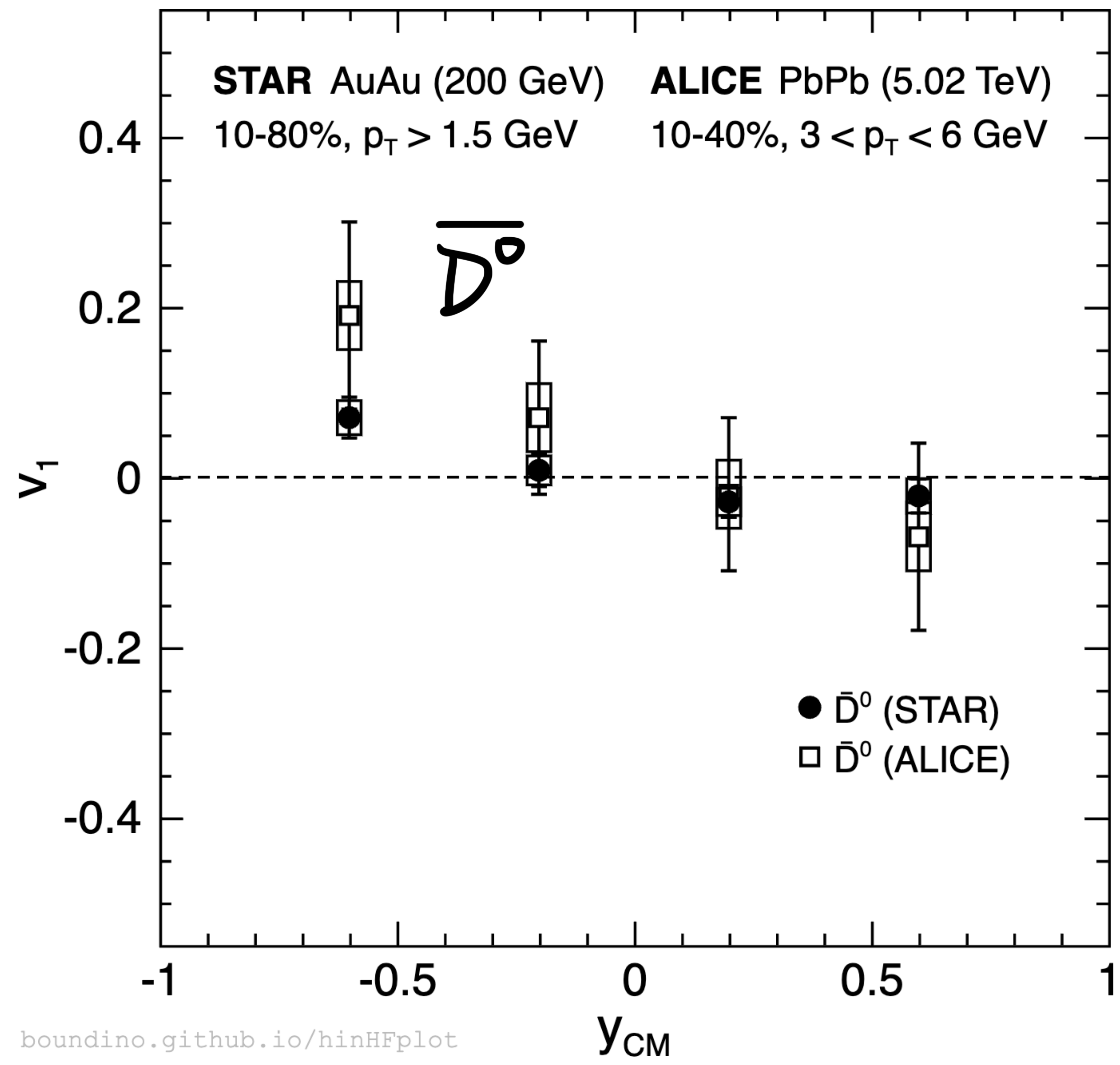
Yen-Jie Lee, Andre S. Yoon and Wit Busza

What is the nuclear matter like before expansion?

Important input to models

Directed Flow v_1: Tilt of Medium

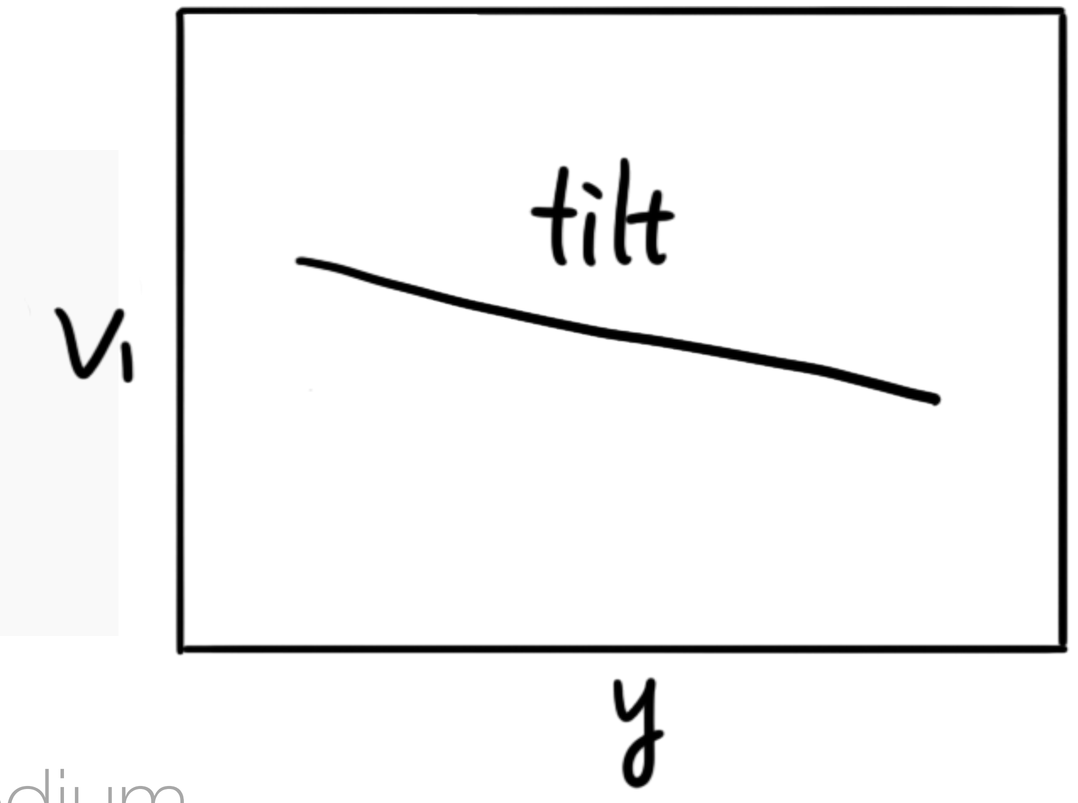
v_1 vs. y in PbPb, AuAu



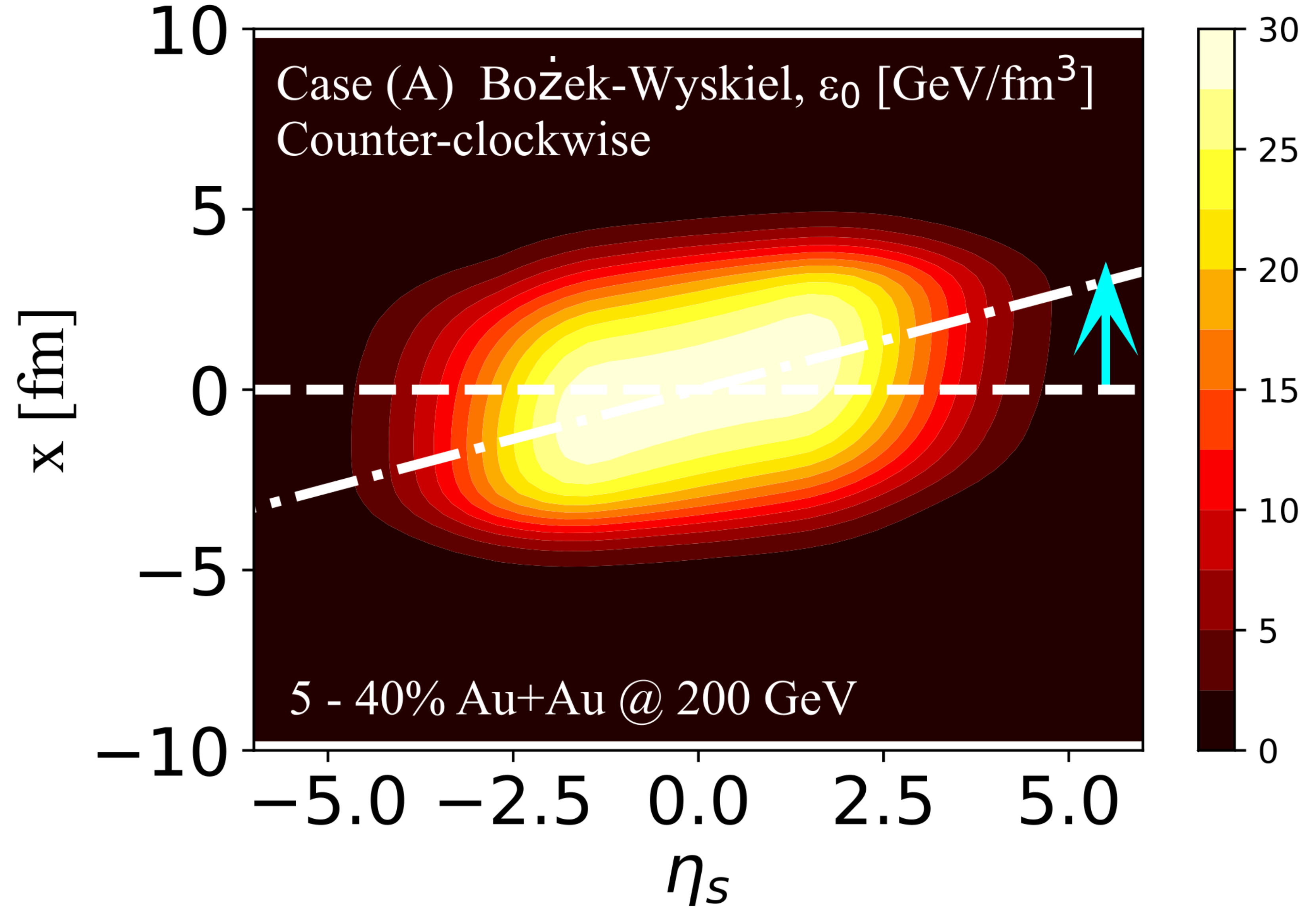
PRL 125 (2020) 022301

PRL 123 (2019) 162301

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



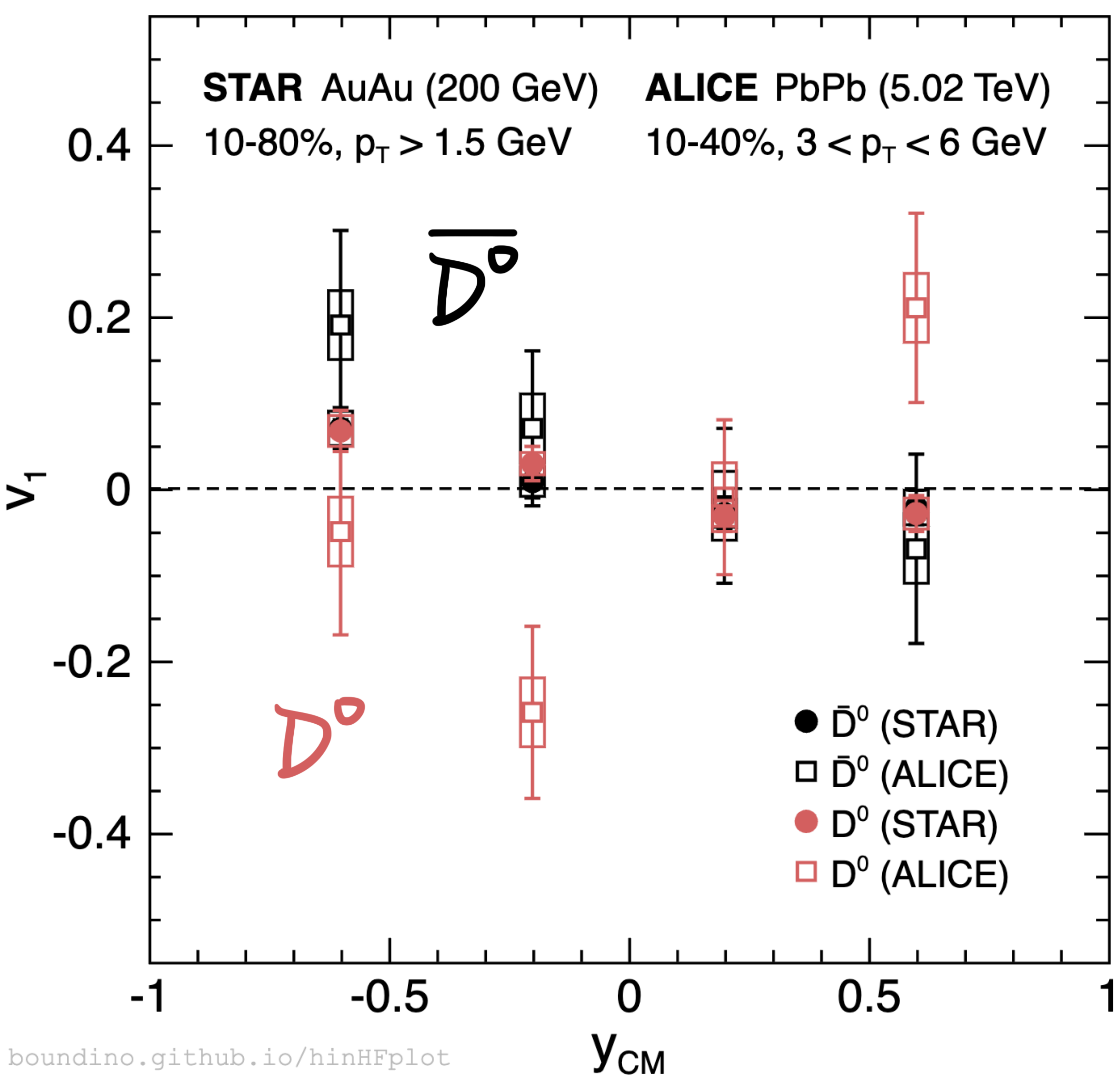
Counter clockwise tilt of the medium



PRC 105 (2022) 034901

Directed Flow v_1: Strong EM Field

v₁ vs. y in PbPb, AuAu



PRL 125 (2020) 022301

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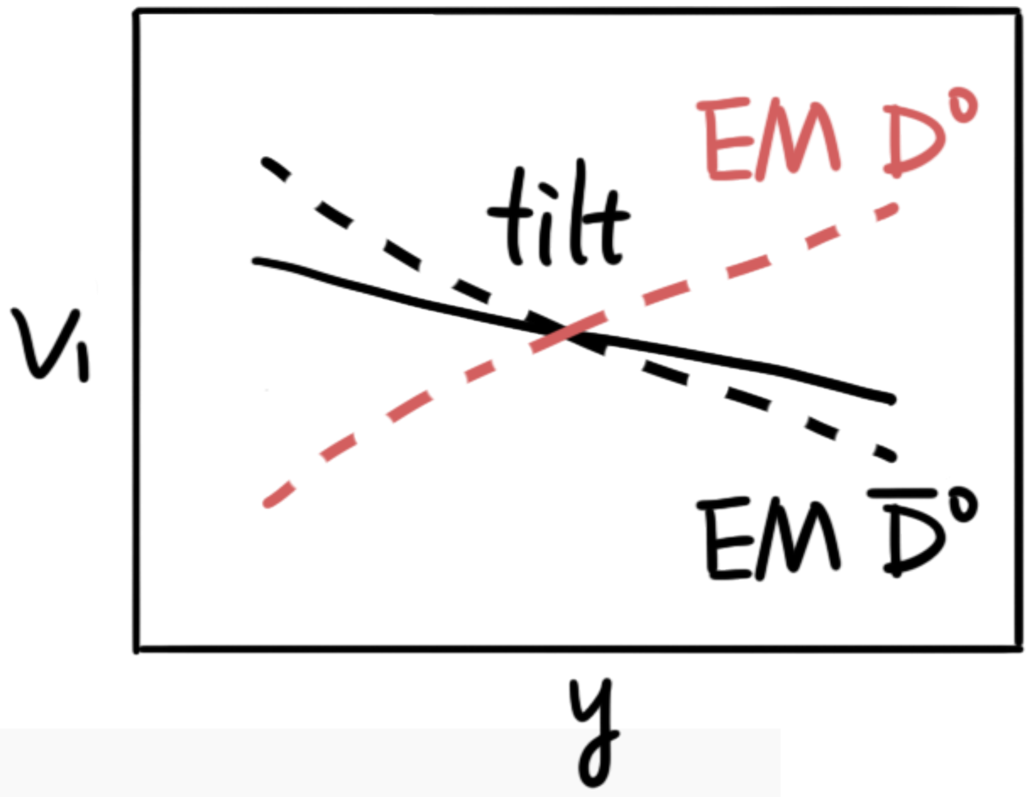
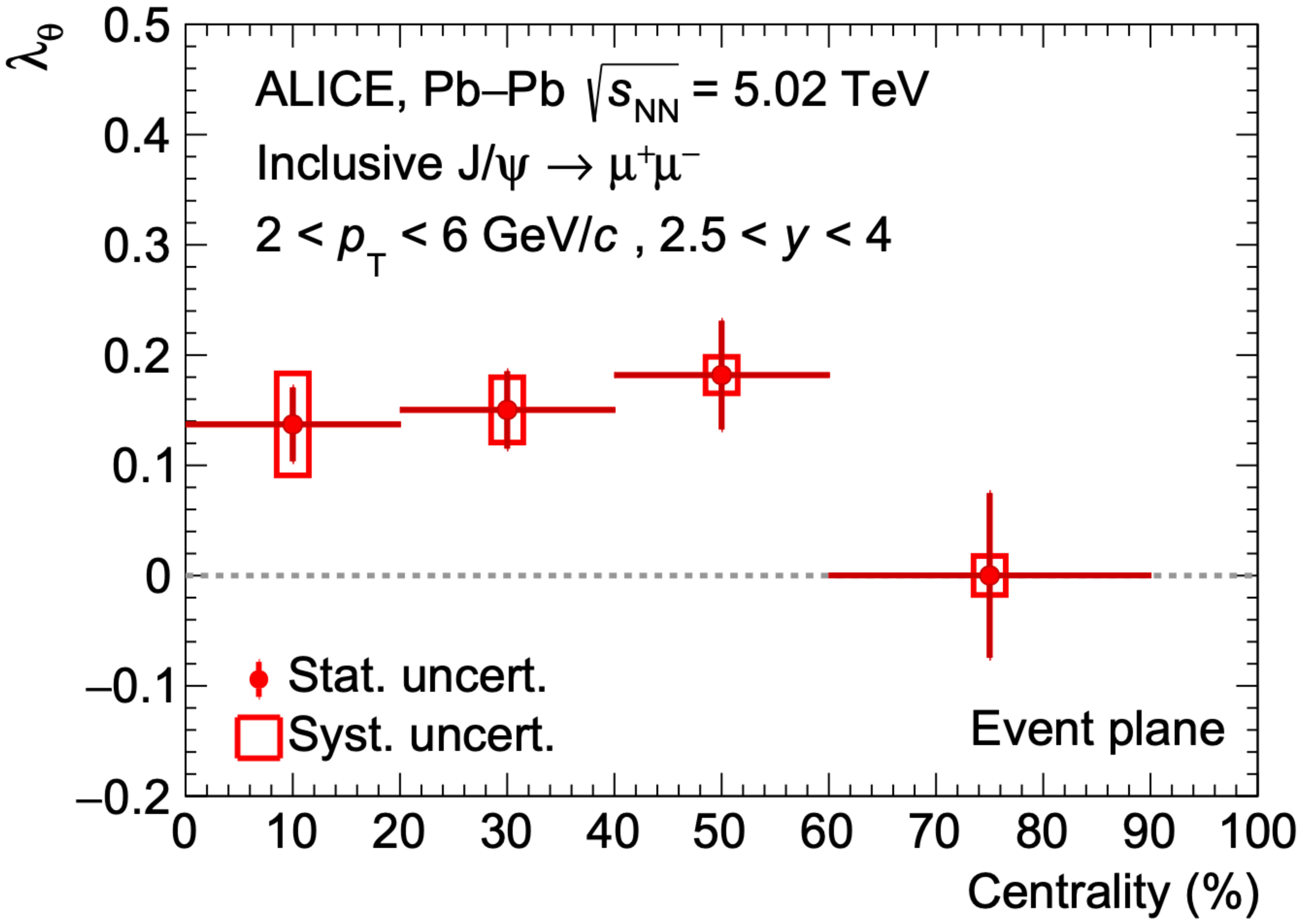


- Strong EM field emerges at early stage
  - Decays quickly → unique chance for heavy flavors
  ➡ Split v_1 of c and $\bar{c}$ → non-zero (rapidity-dep) Δv_1

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

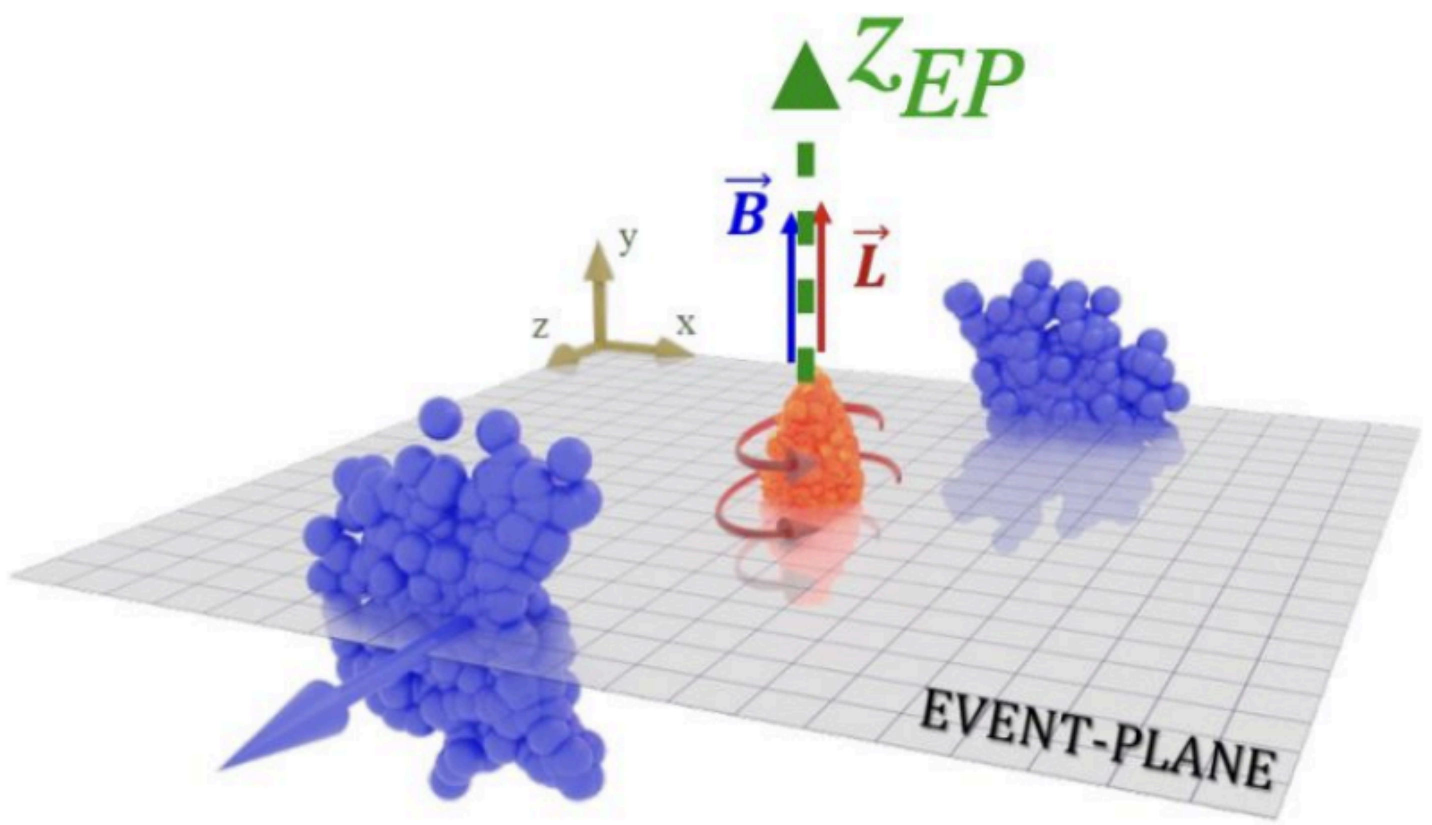
J/ψ Polarization: Initial B Field & Rotation

J/ψ Polarization



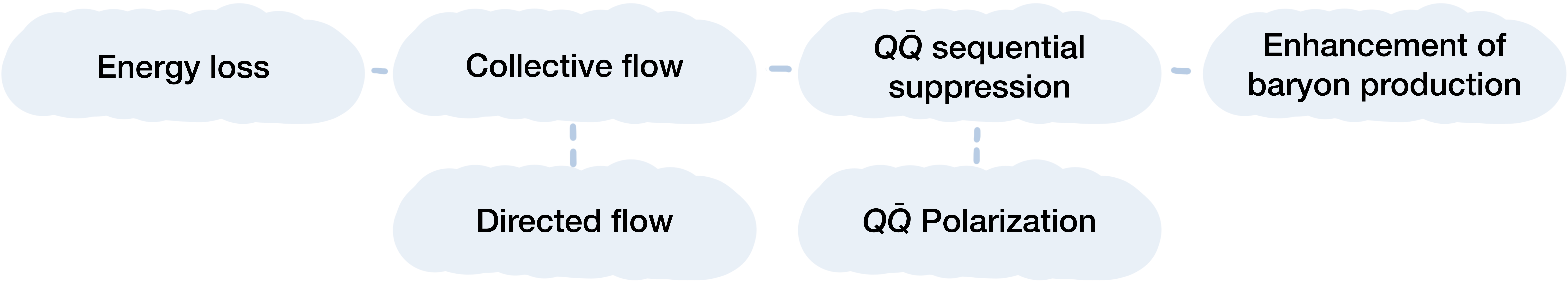
arXiv:2204.10171

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



Being Hot Matters

Many interesting heavy flavor behaviors driven by existence of QGP!



Being Hot Really Matters?

However, many of them also observed in *small* systems

where no medium existence expected

~~Energy loss~~

Collective flow

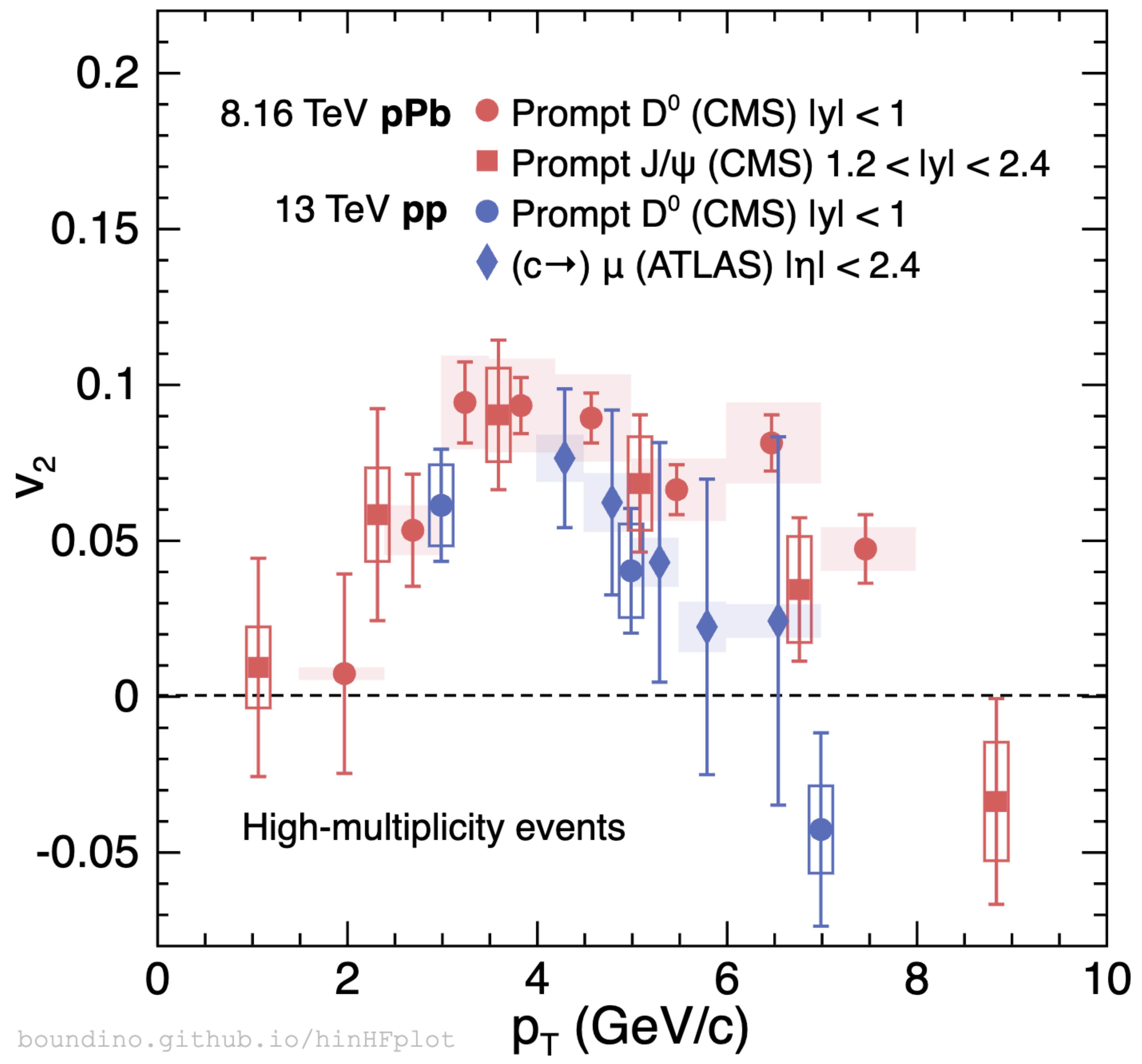
$Q\bar{Q}$ sequential suppression

Enhancement of baryon production

Directed flow

~~$Q\bar{Q}$ Polarization~~

Azimuthal Anisotropy in Small Systems



PRL 121 (2018) 082301

PLB 791 (2019) 172

PLB 813 (2021) 136036

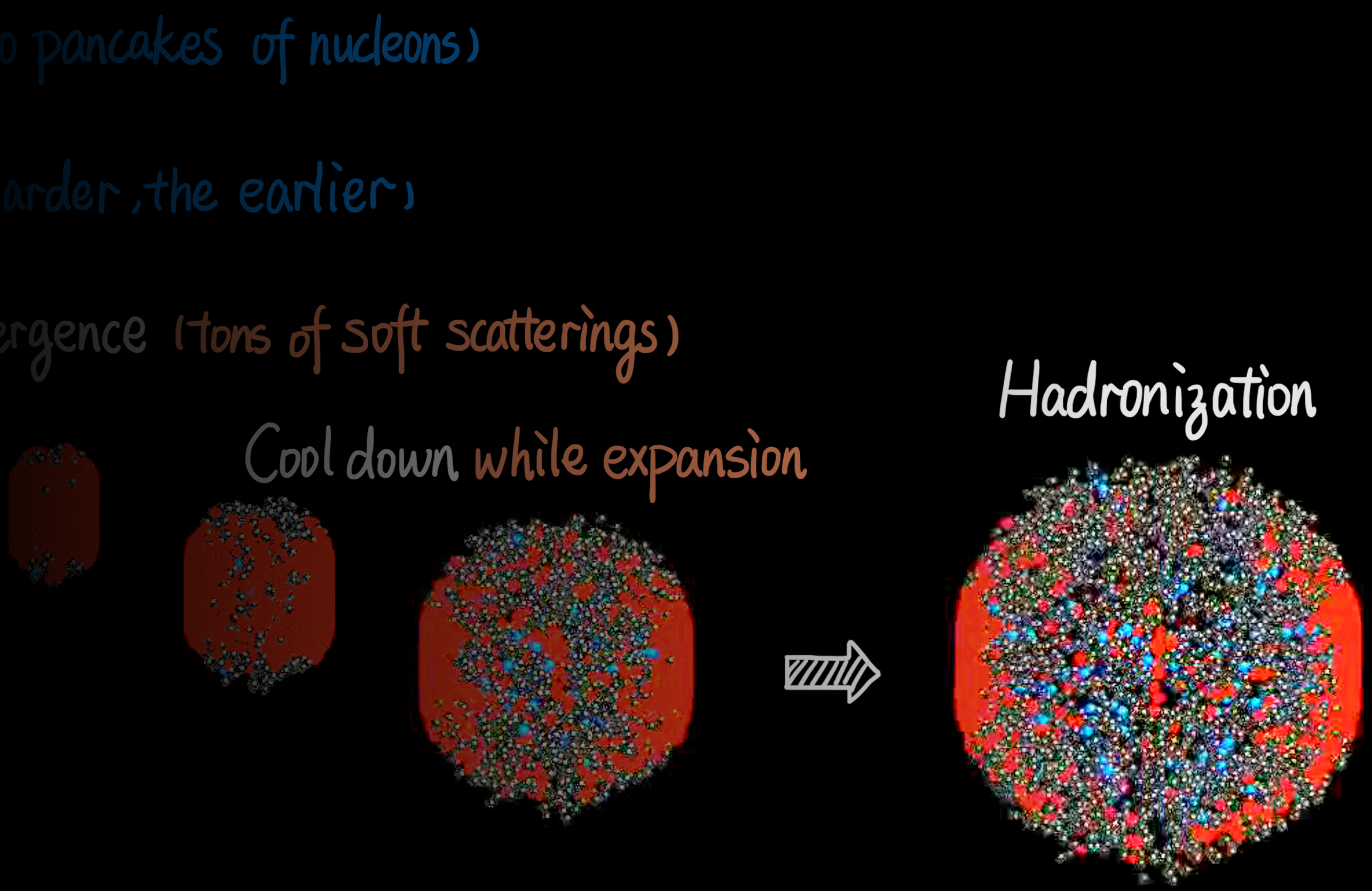
PRL 124 (2020) 082301

- Do we fully understand what nuclear matter environment we are looking at?
- Non-zero v_2 of charm hadrons in high-multiplicity pp and pPb collisions
  - (Maybe) Initial transverse momentum correlation in CGC framework
  - (Maybe) Small QGP medium in small systems

Story Continues in the Next Talk

How are hadrons produced from heavy quarks with medium existence?

Major uncertainty in phenomenological models

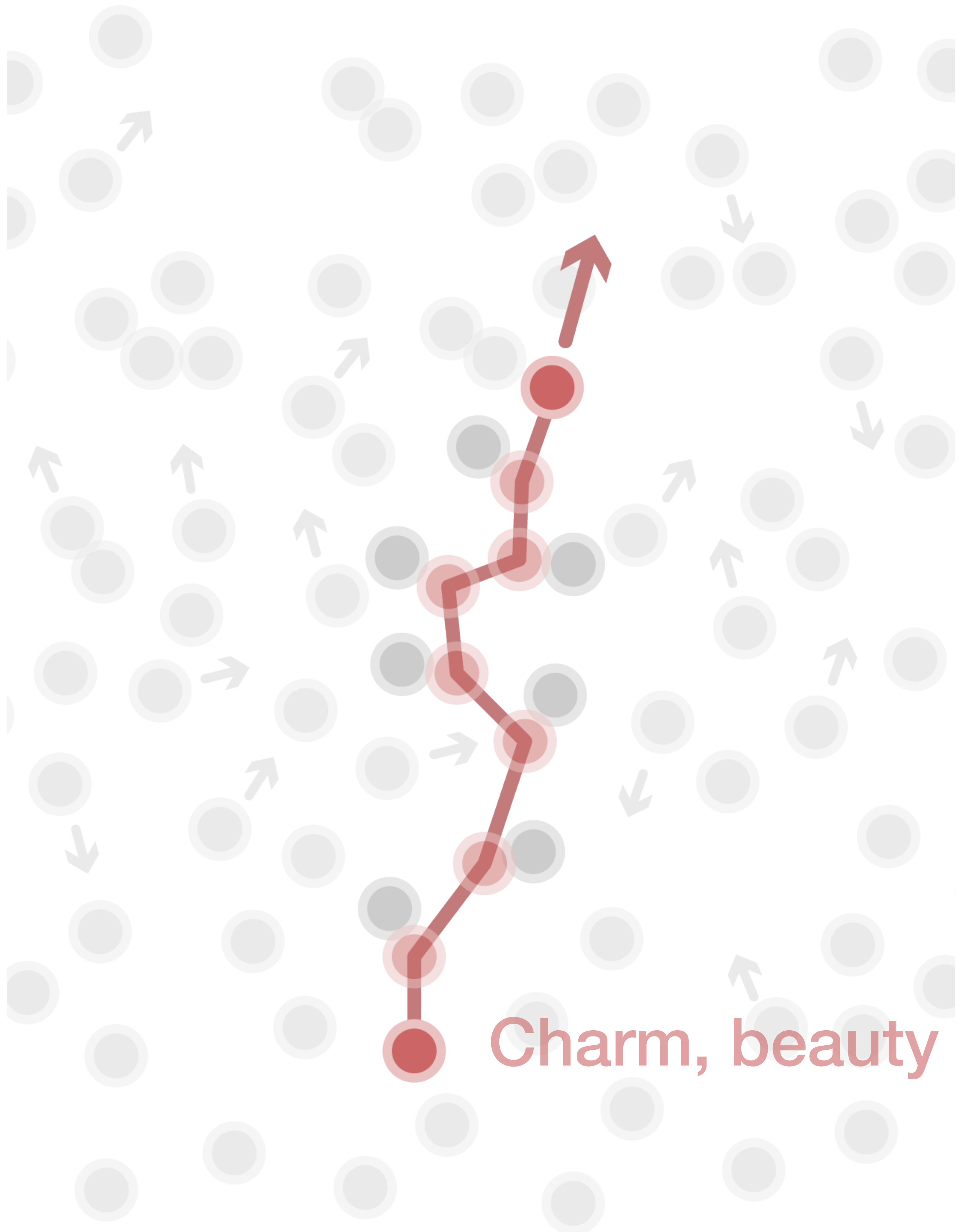



Isabelle
Thanks for your attention!

Heavy Flavors in Heavy Ion Collisions

Large mass m_{HQ} ➜ Unique slow HP

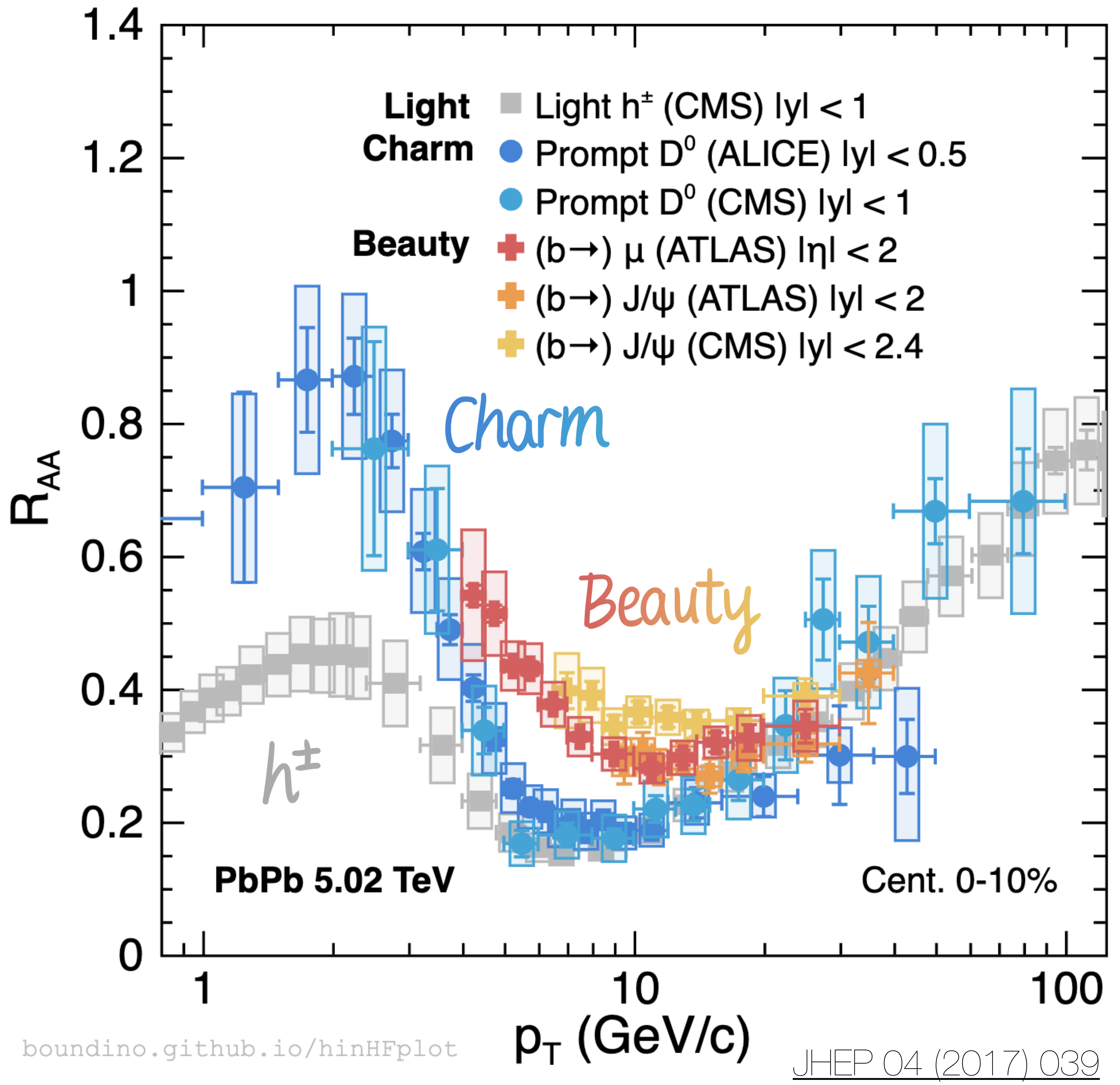
- $m_{HQ} \sim 1/\tau$
  - Produced early
- $m_{HQ} \gg \Lambda_{QCD}$
  - Initial production with pQCD even at low p_T
  - Different length scale structure by varying p_T
- $m_{HQ} \gg T_{QGP}$
  - Seldom produced in QGP
  - Brownian motion at low p_T
- $m_{HQ} \gg m_q$
  - Interact with QGP differently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



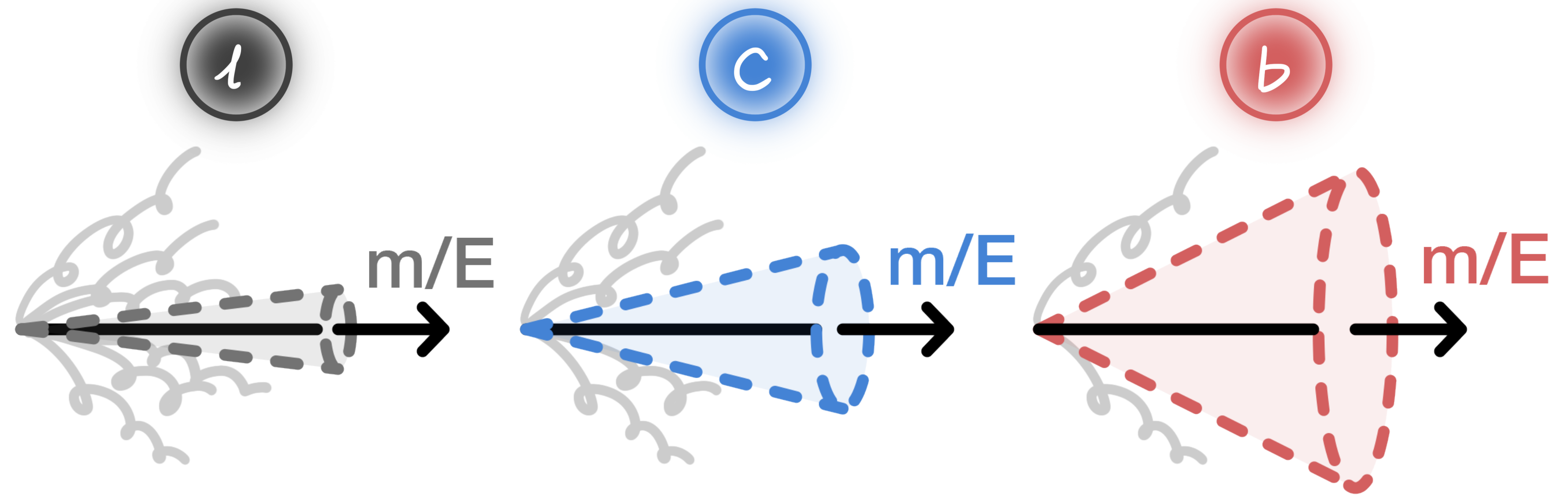
Heavy quark diffusion in QGP

Flavor Dependence of Energy Loss

R_{AA} vs. Flavors



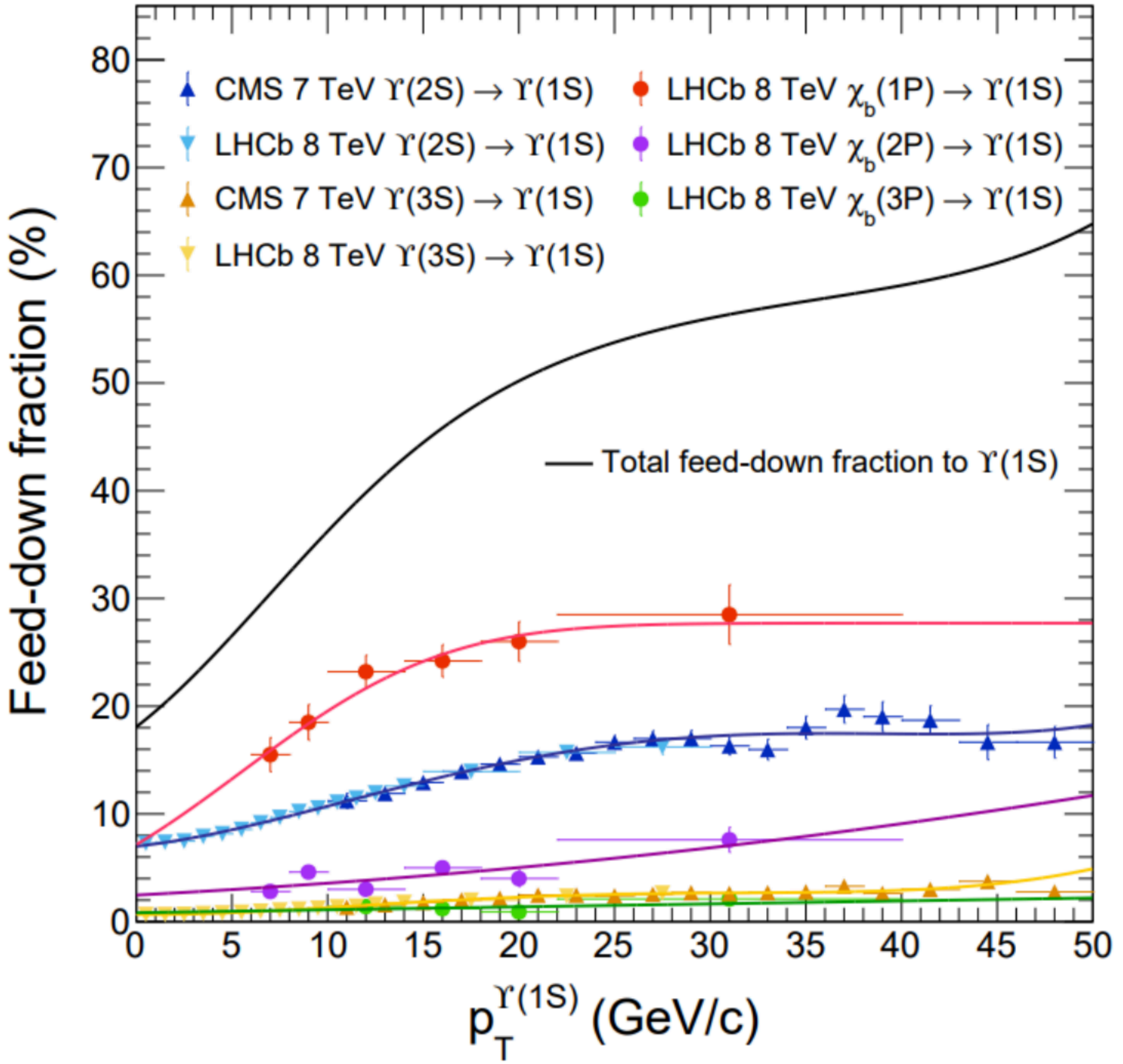
- Interplay of multiple effects
- (One is) Dead cone effect
  - Radiation is suppressed inside $\theta < m/E$
  - Energy loss $\Delta E_l > \Delta E_c > \Delta E_b$



Larger energy loss ➜ Smaller energy loss

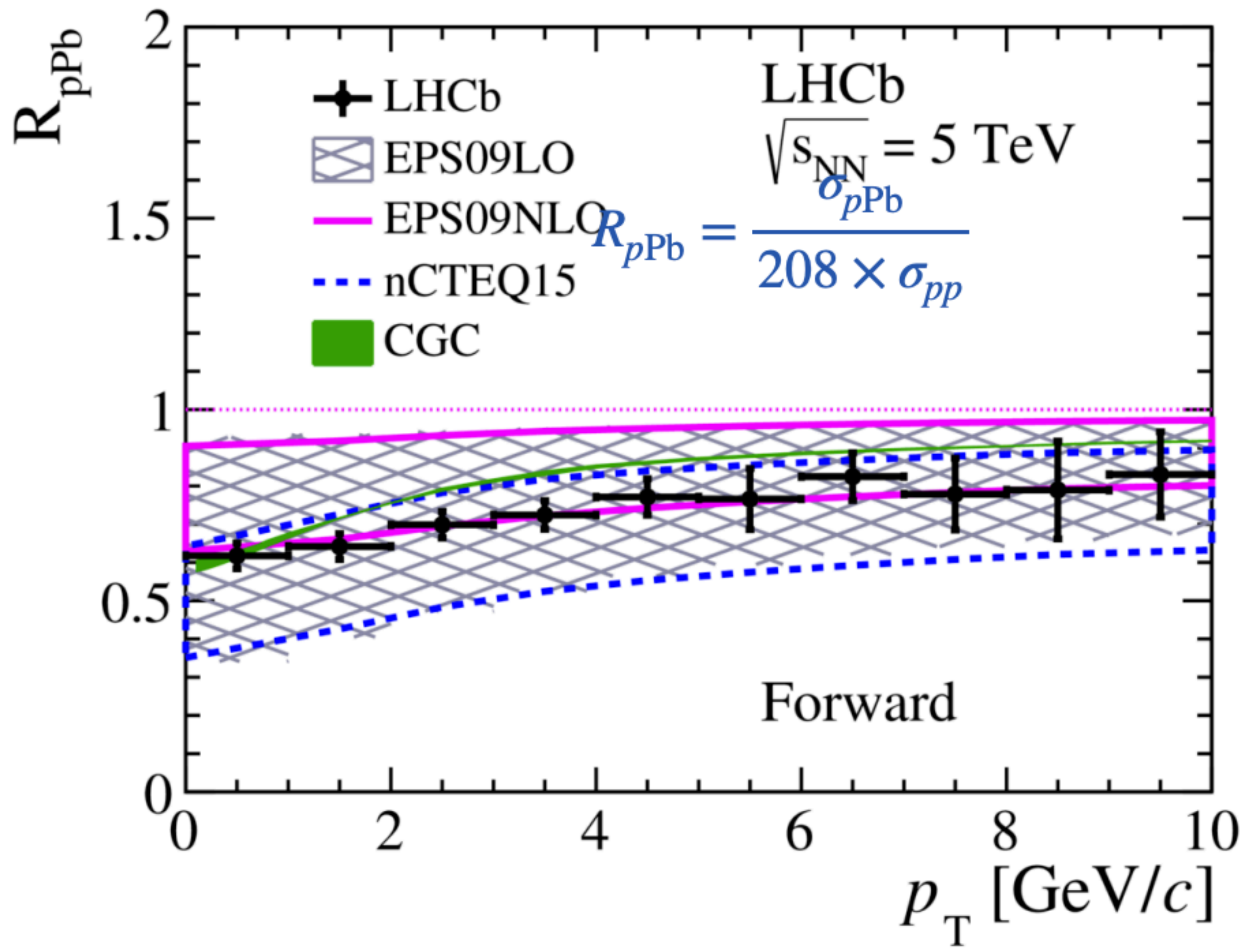
JHEP 04 (2017) 039
EPJC 78 (2018) 509
PLB 829 (2022) 137077
EPJC 78 (2018) 762

Feed-Down Effect on Υ(1S)



Nuclear PDF: D & B Mesons in pPb

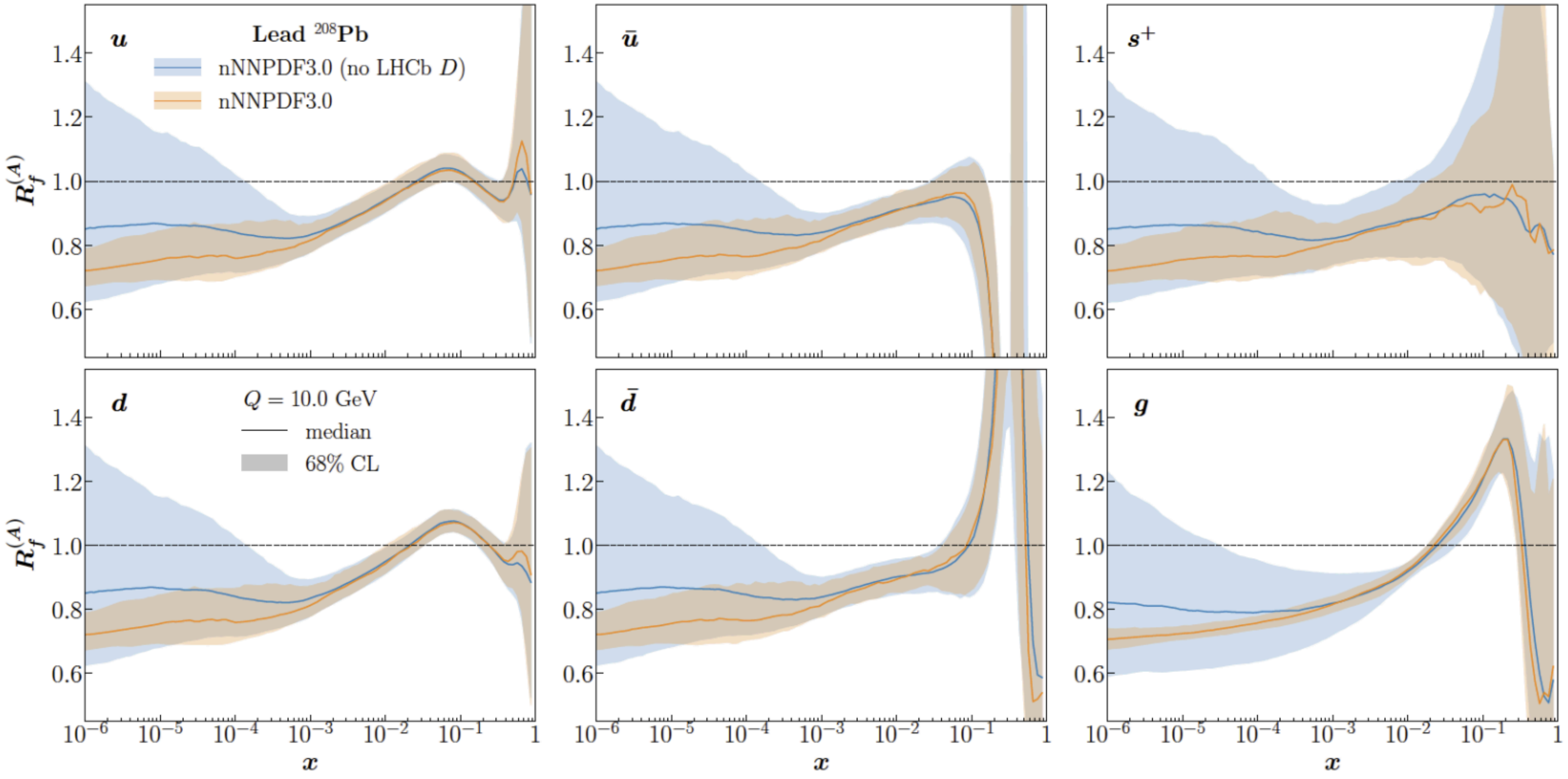
JHEP 10 (2017) 090



- Data included in EPPS21 and nNNPDF3.0

- nNNPDF3.0
- LHCb measurement of prompt D^0 production in pPb collisions at 5TeV makes an impressive impact on reducing nPDF uncertainty down to $x \sim 10^{-6}$

Eur. Phys. J. C 82, 507 (2022)

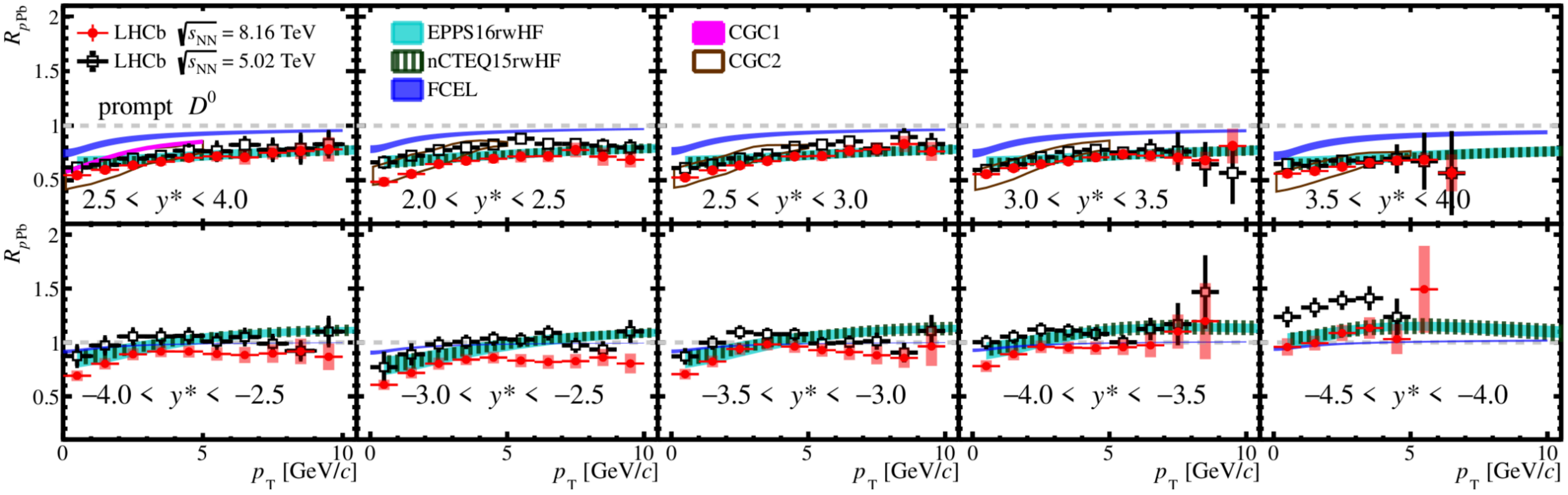


11

Nuclear PDF: D & B Mesons in pPb

- Forward:
  - Suppression consistent with 5TeV D^0 result
  - Consistent with nPDF and CGC
- Backward:
  - Data lower than nPDF at high p_T
  - Room for additional effects in the backward rapidity

arXiv:2205.03936

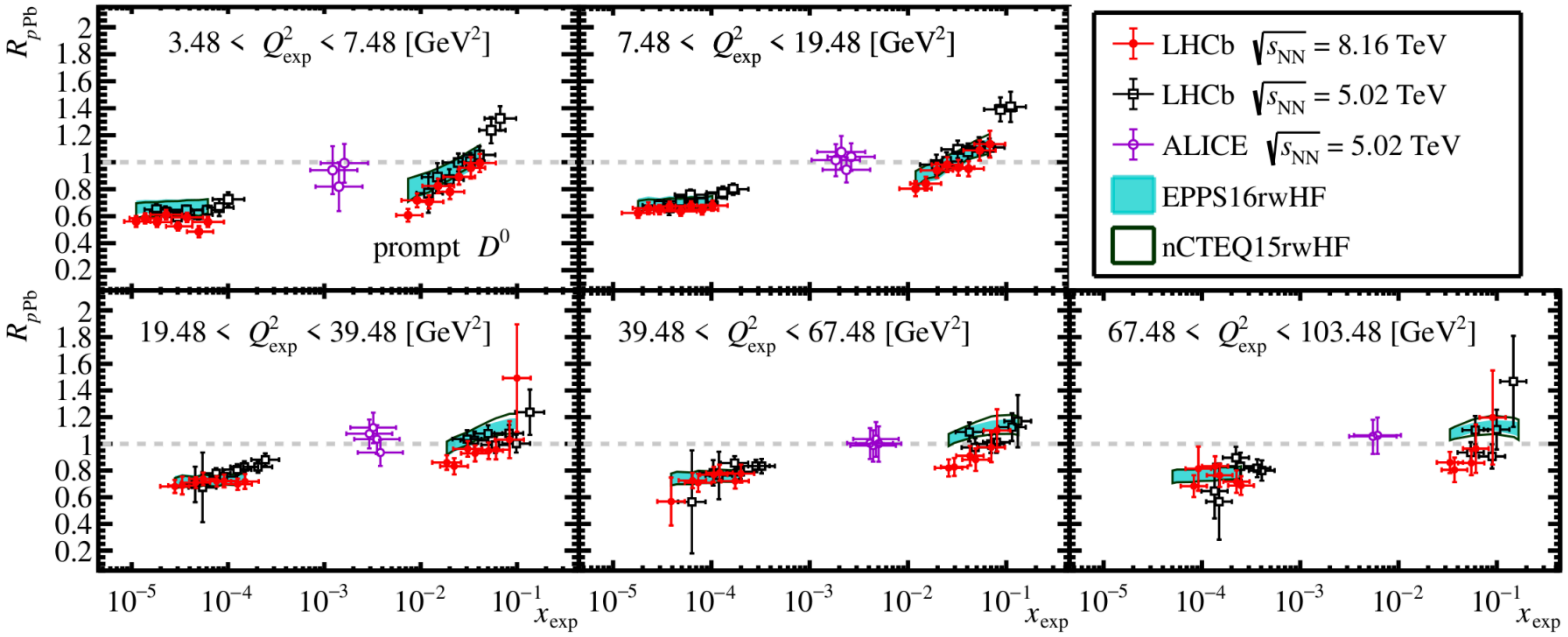


12

Nuclear PDF: D & B Mesons in pPb

- Experimental proxies for x and Q^2
- Forms a continuous trend over wide x coverage
- Lower than nPDF at large x_{exp} and large Q^2_{exp}

arXiv:2205.03936

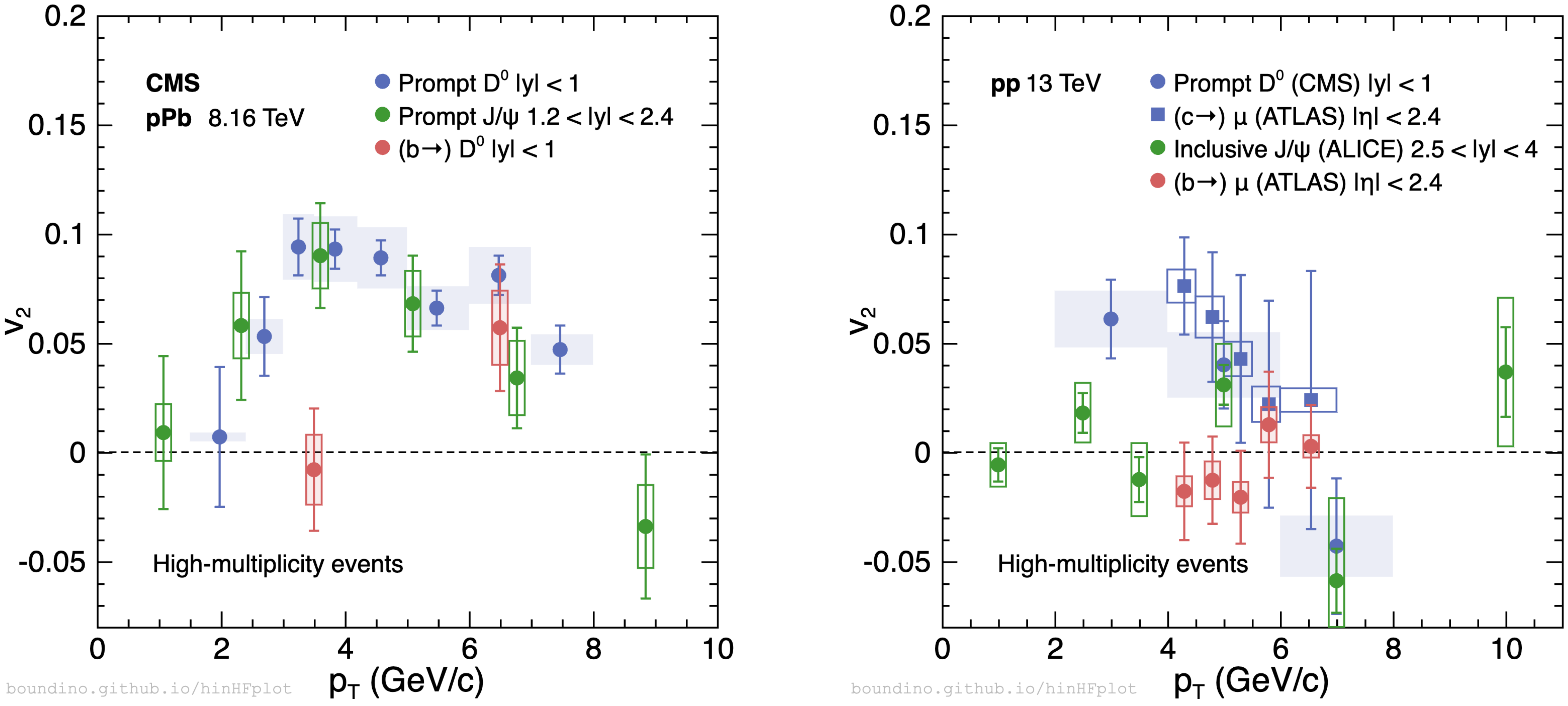


13

$$Q^2_{exp} \equiv m^2_{D^0} + p^2_{T}$$

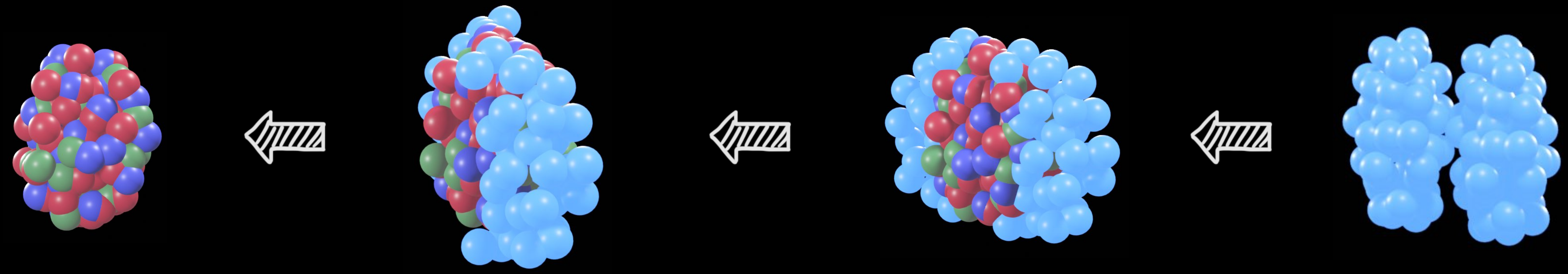
$$x_{exp} \equiv 2\frac{Q_{exp}}{\sqrt{s_{NN}}}e^{-y^*}$$

Azimuthal Anisotropy in pp and pA



Quark Gluon Plasma: Being Hot Matters

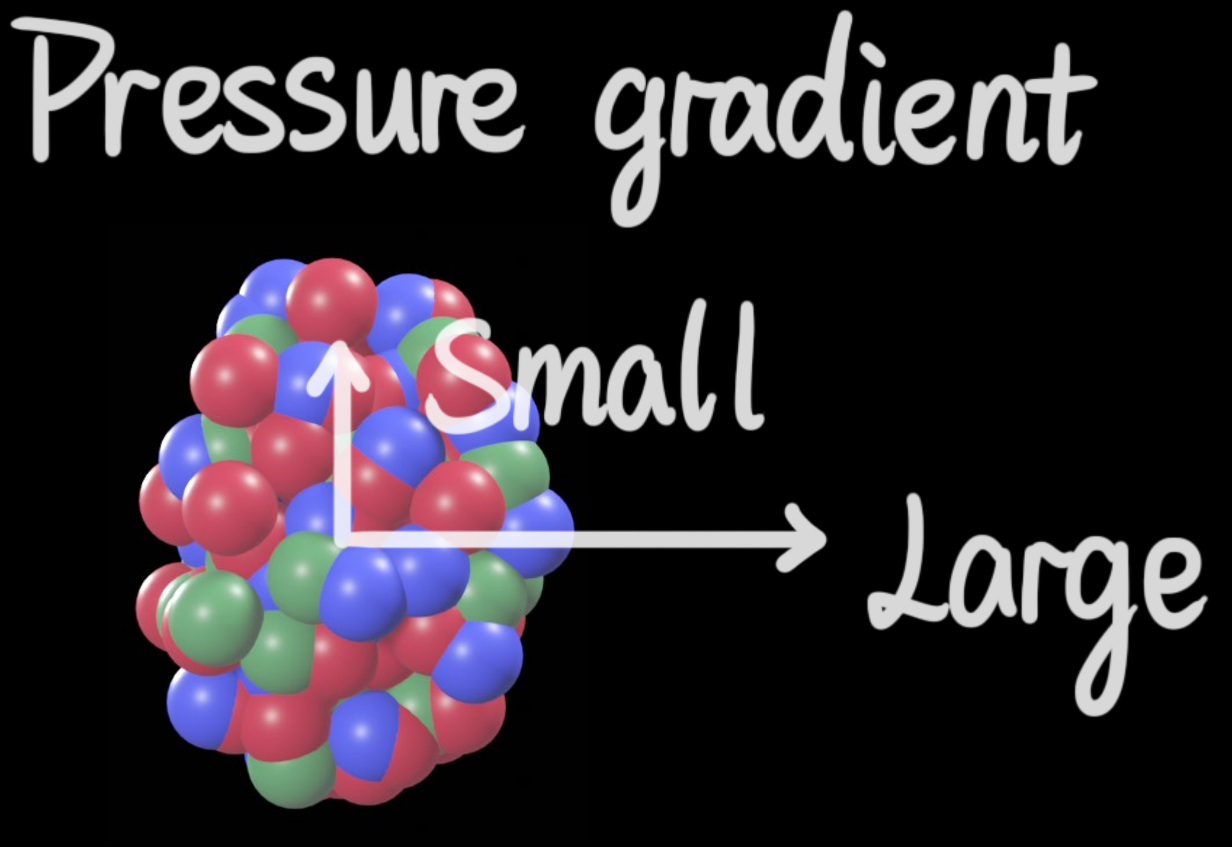
Collective Flow in QGP



Almond shape before expansion

Animation

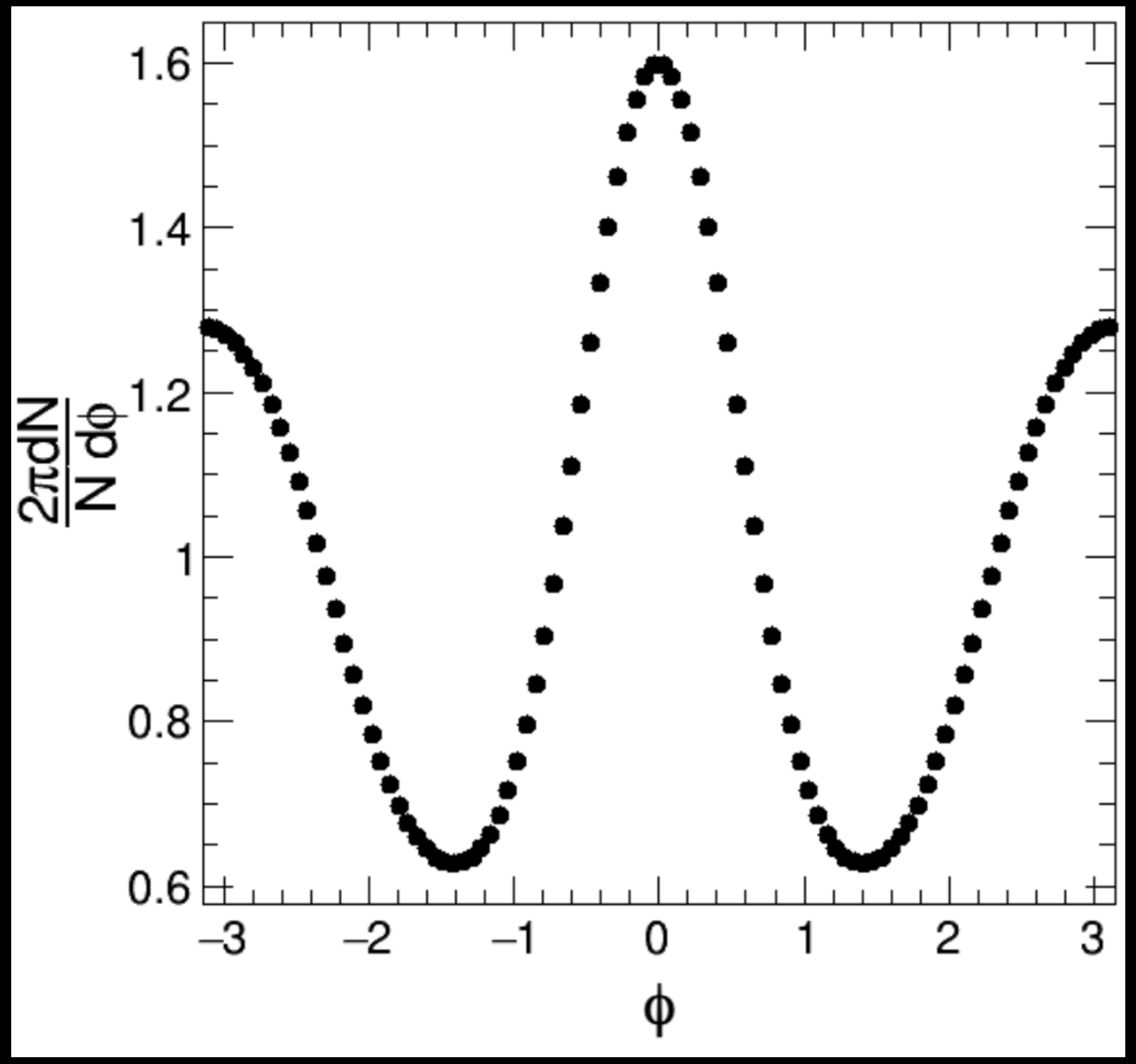
Collective Flow in QGP



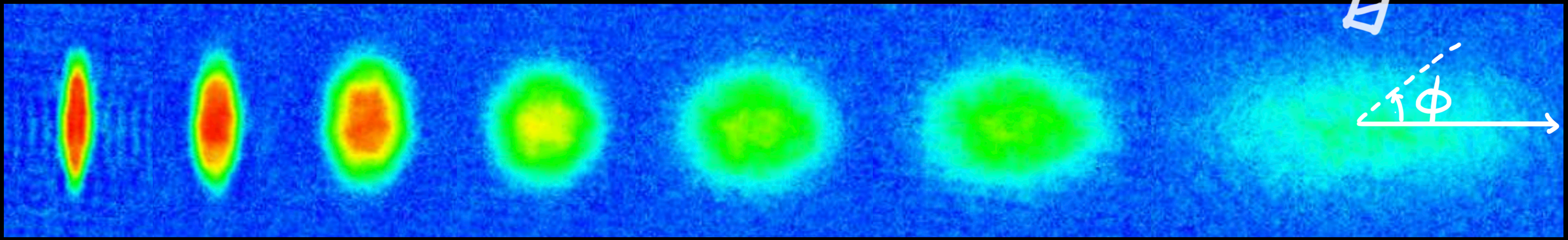
Existence of QGP ➜ Final-state particle azimuthal anisotropy

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

➜ Elliptic $v_2 \neq 0$



⟶ Time



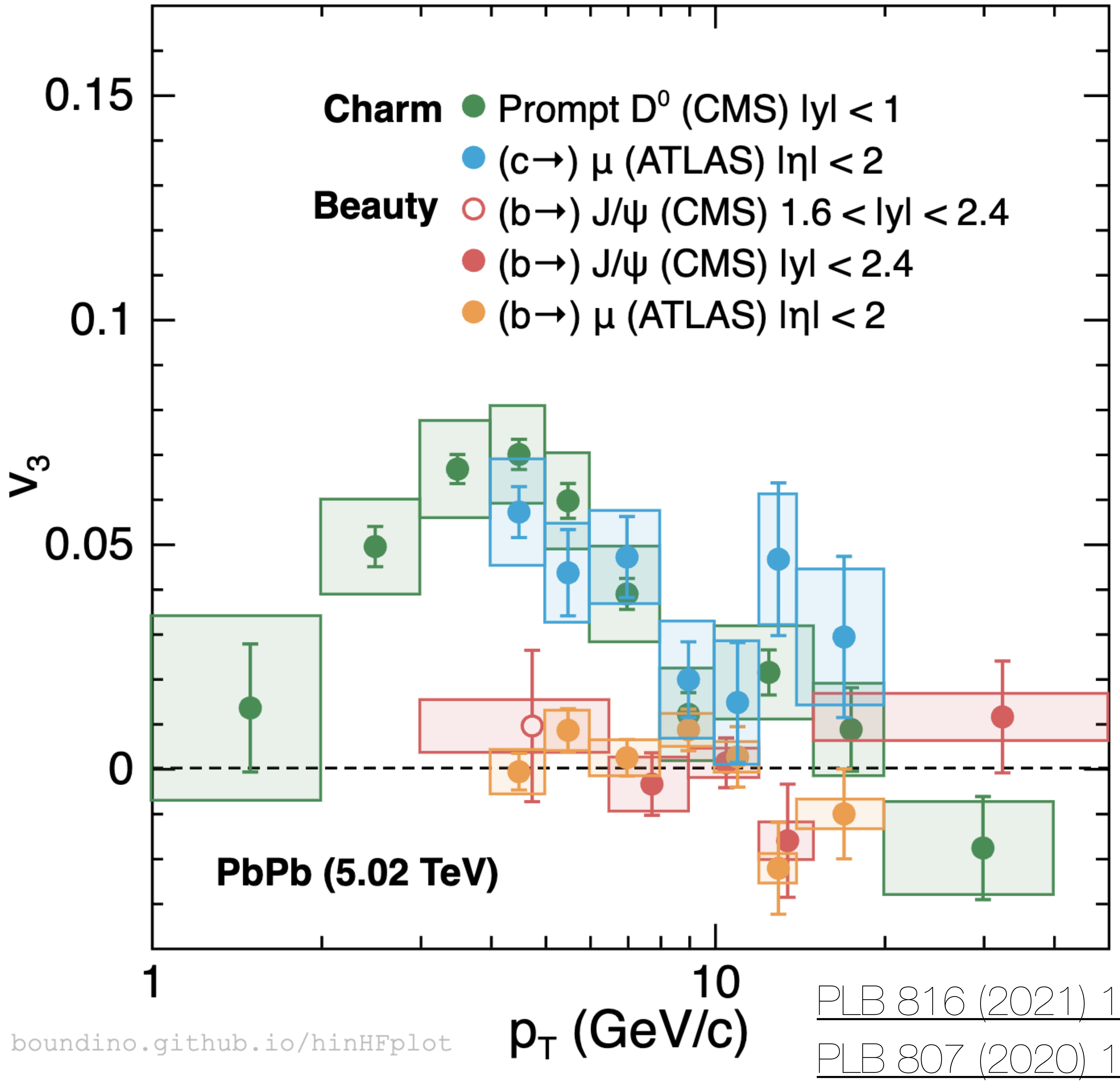
Pressure driven expansion

Science 298 (2002) 2179

Animation

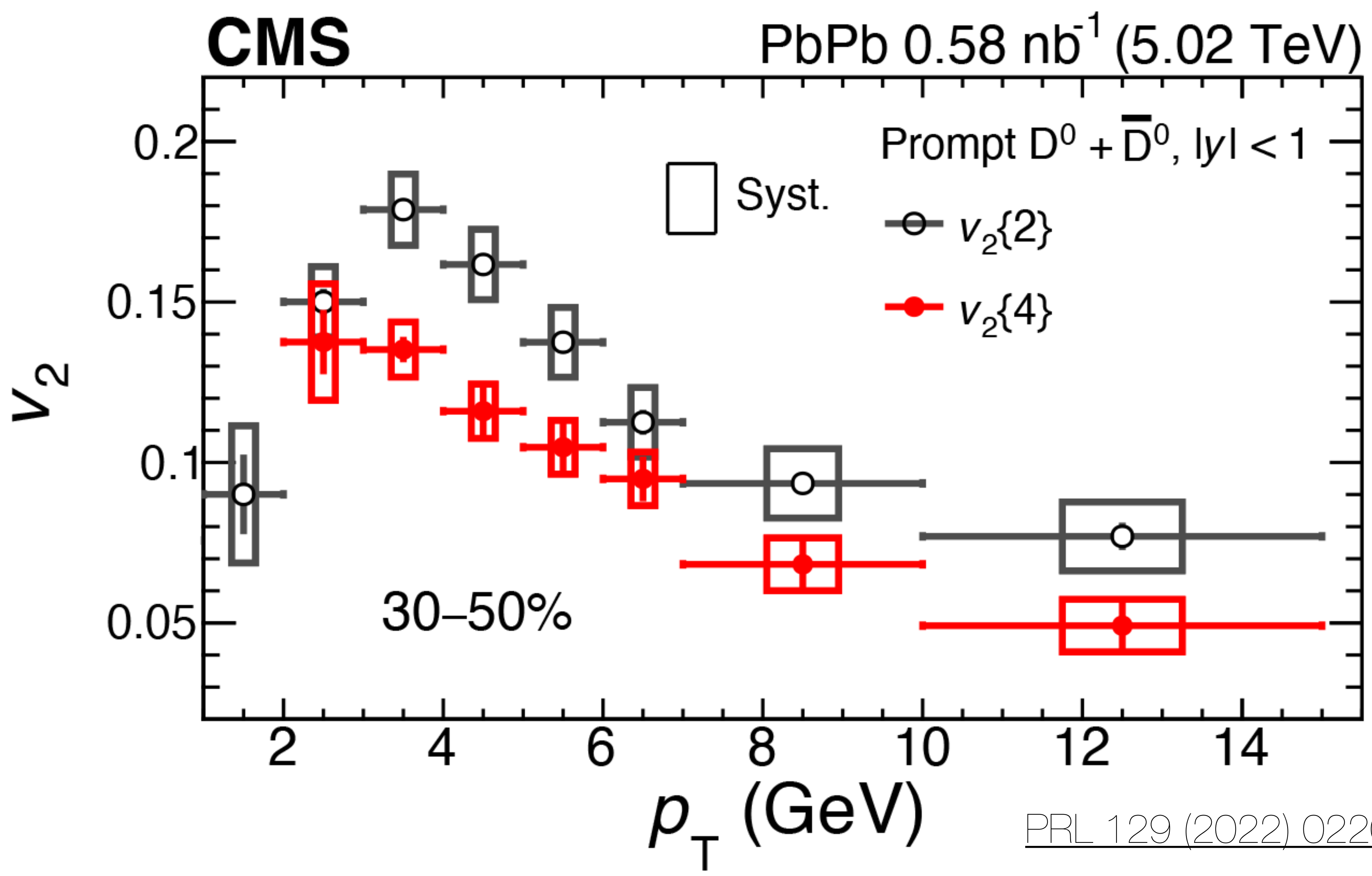
Initial Geometry Fluctuations

Heavy flavor v_3



boundino.github.io/hinHFplot

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



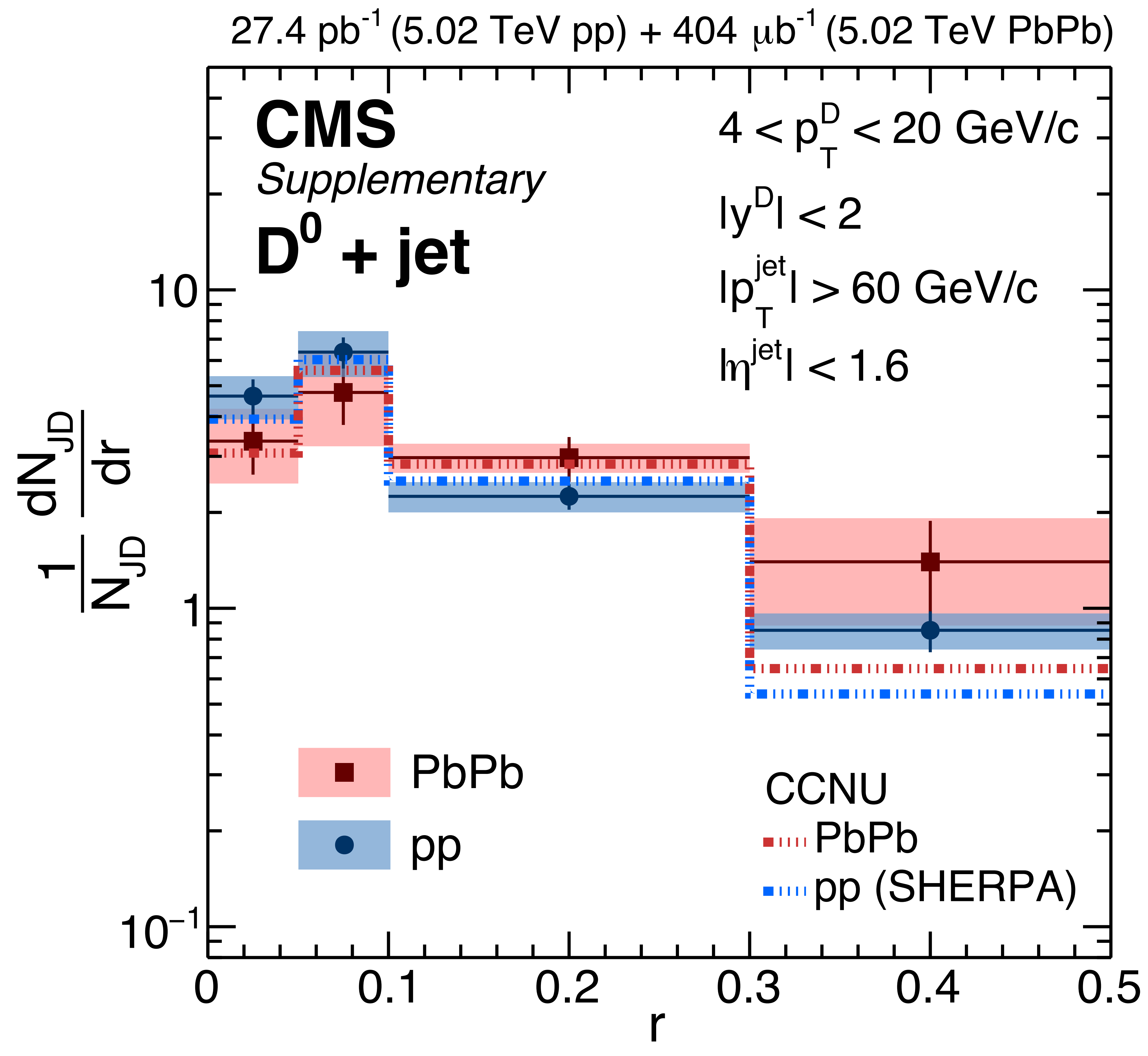
PRL 129 (2022) 022001

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

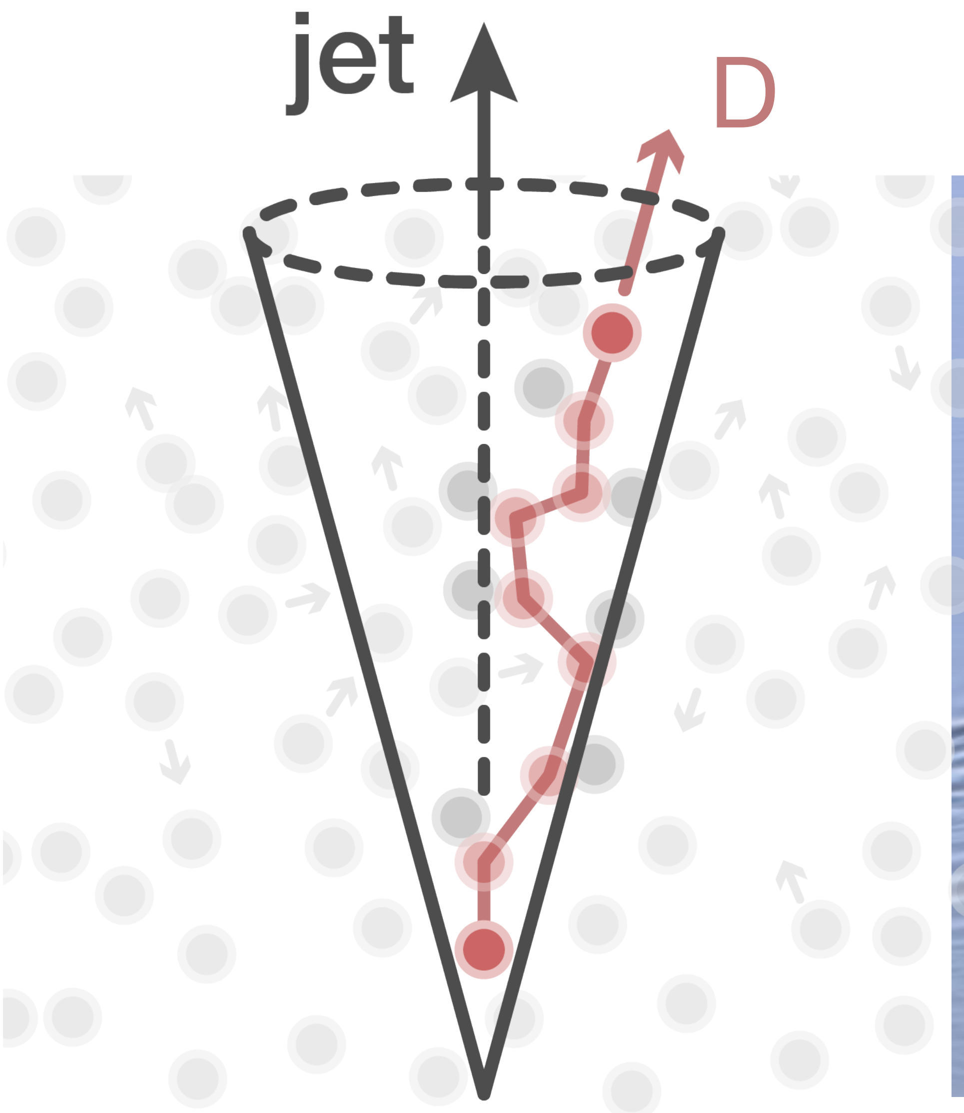
PLB 807 (2020) 135595 PLB 807 (2020) 135595

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

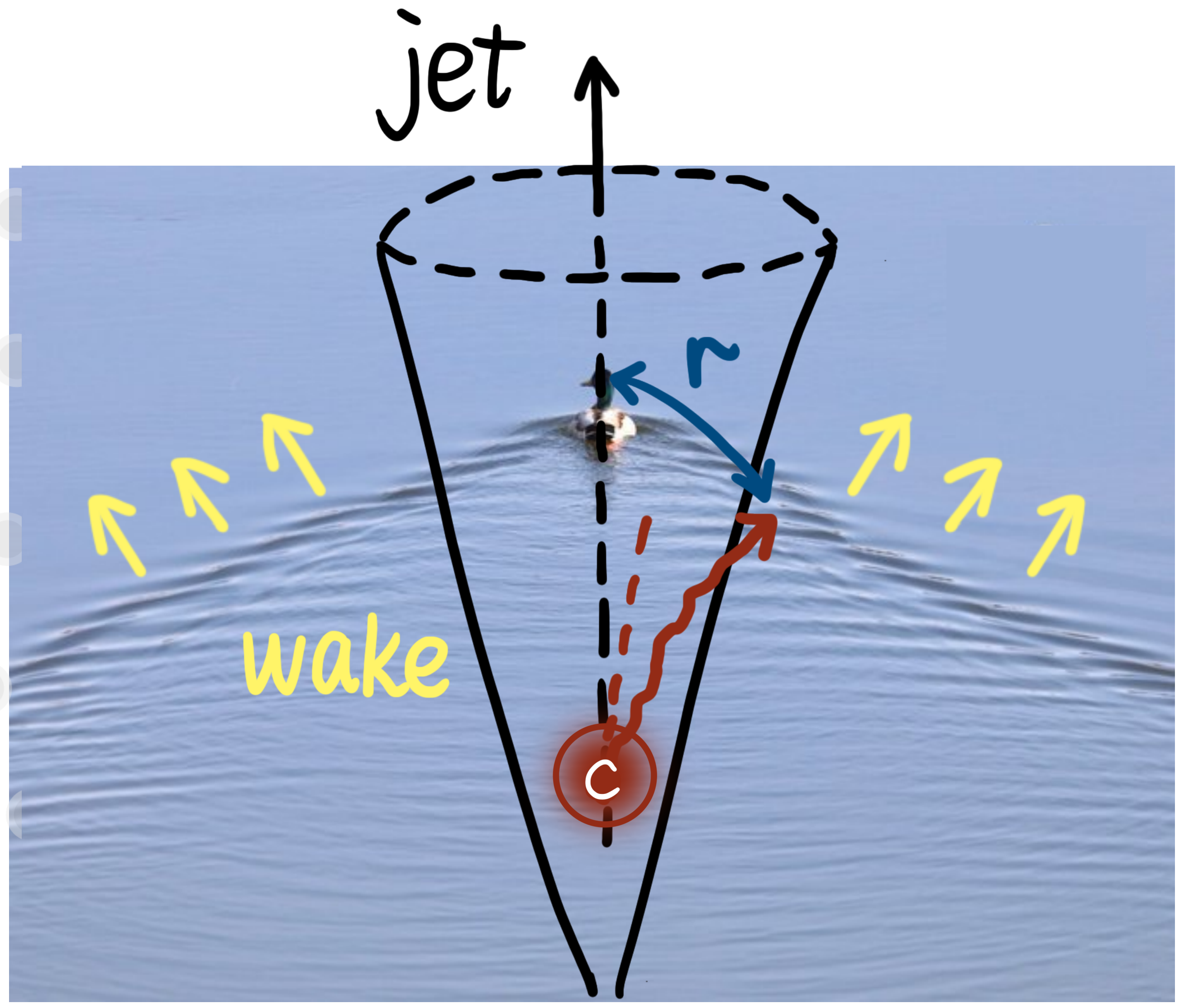
Angular profile of D wrt jet axis



- 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

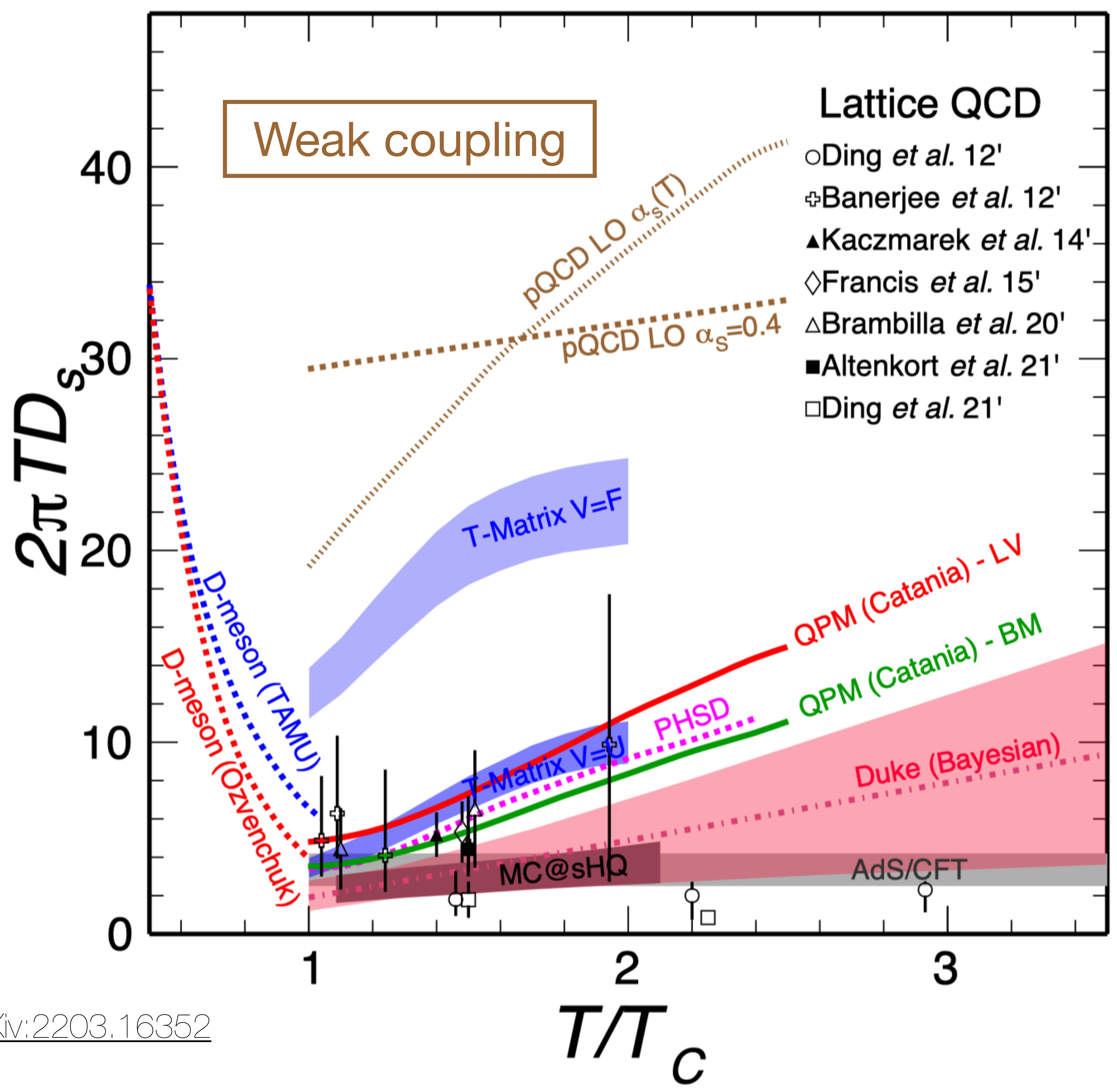


Medium response

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