Experimental Overview of Heavy Flavor Physics in HIC - Part I

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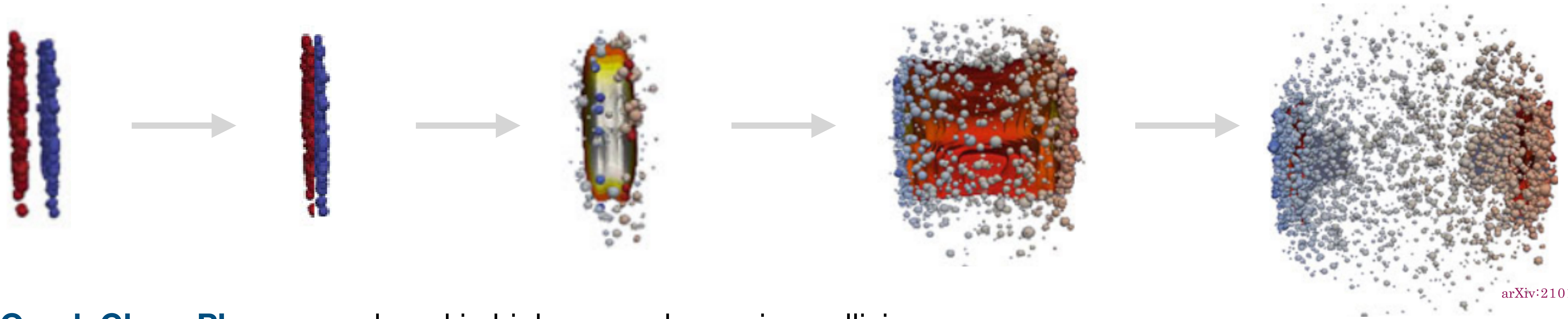
Outline

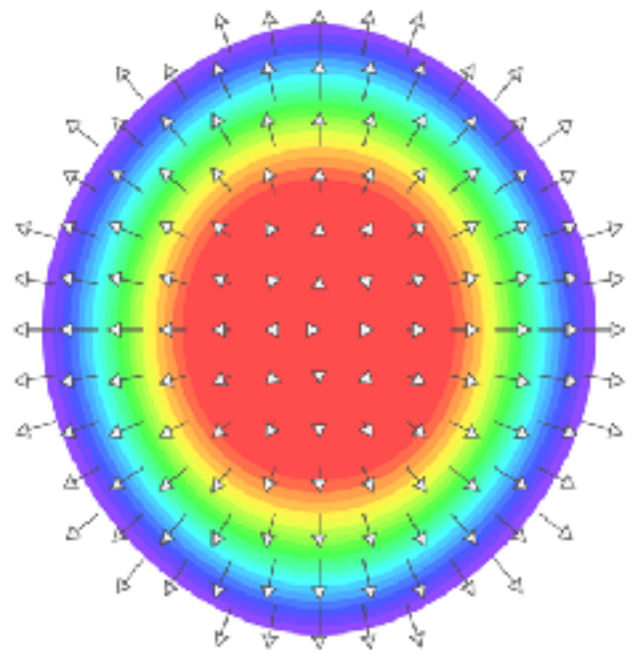
- Experimental overview Part 1
  - Why study heavy-flavor?
  - How HF particles are studied and experimentally measured?
  - Experimental results: R_{AA}, v_2…
- Experimental overview Part 2
  - Techniques for heavy-flavor measurements: strategies, challenges and future direction
- Theoretical description of HF energy loss

Introduction

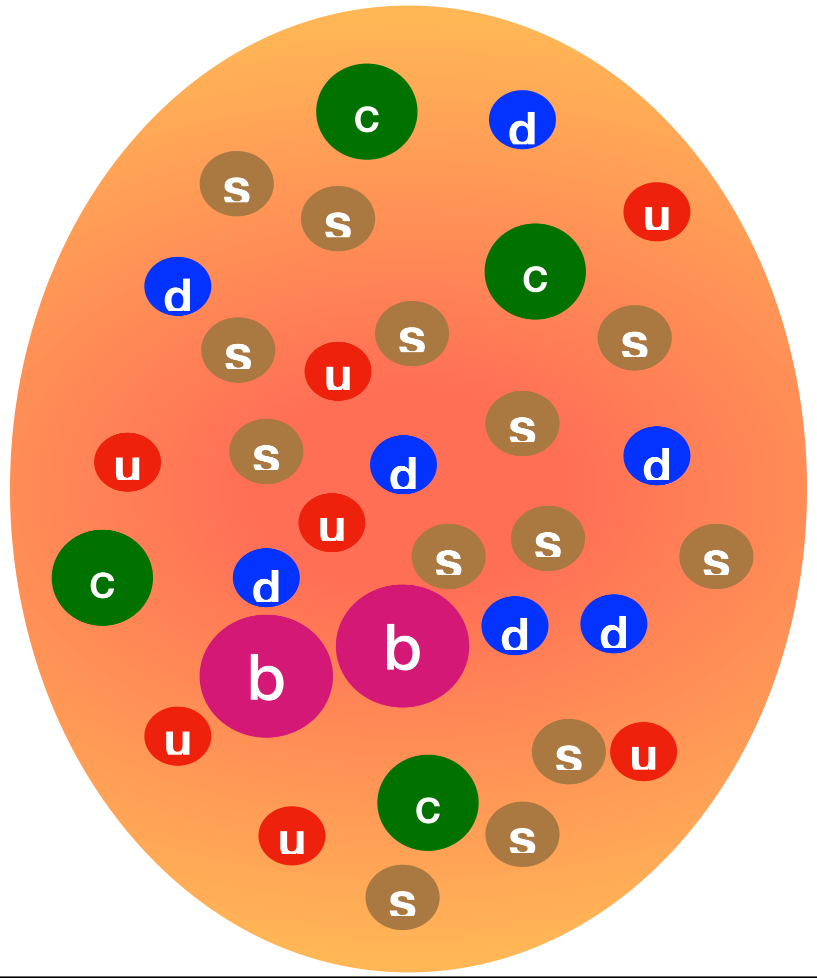


arXiv:2101.04963

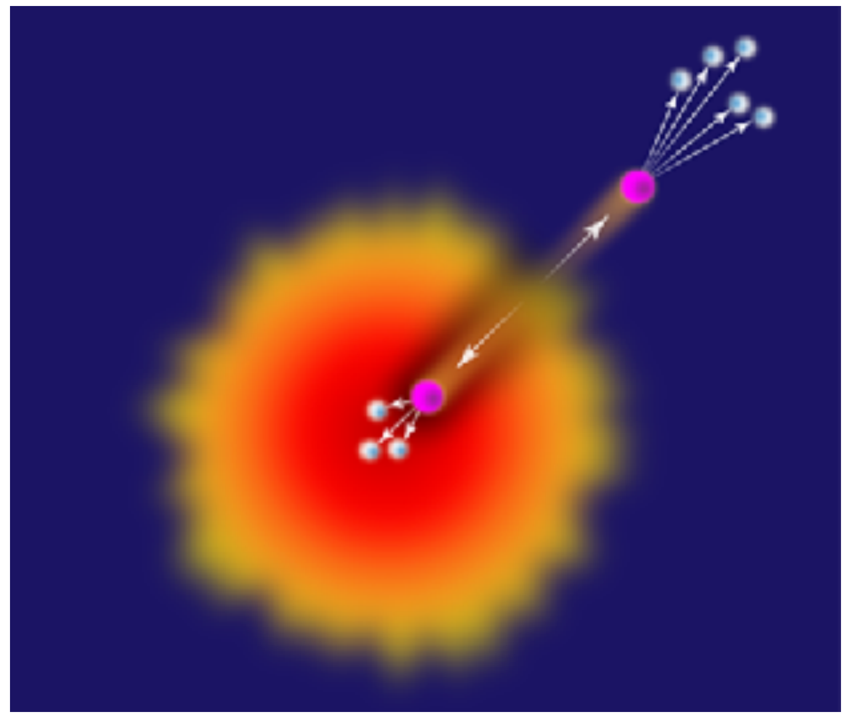
- **Quark Gluon Plasma** produced in high energy heavy-ion collisions.
- Experimental evidence of QGP formation from light hadrons.



Collective flow



Enhanced strange quarks

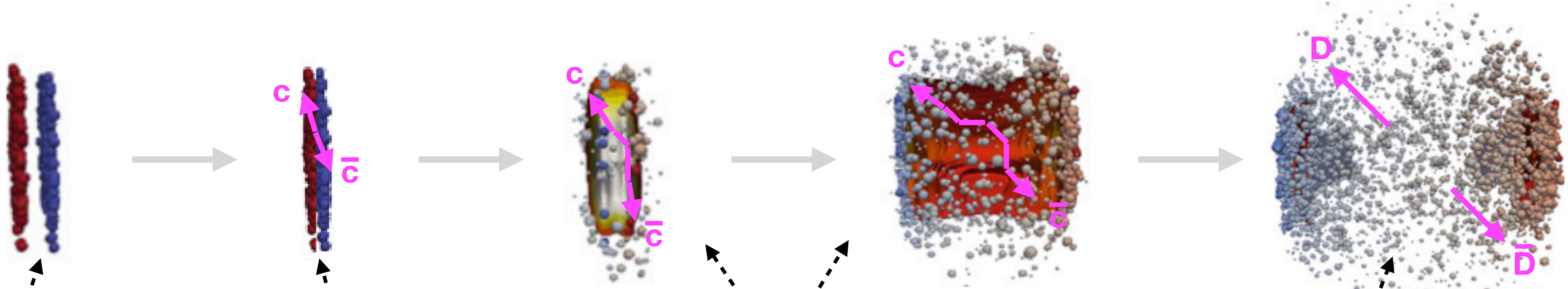


Jet quenching

Heavy quarks in Hot QCD medium

- How does QCD interactions at the microscopic level lead to emergent phenomena in QGP
  -> probe inner workings of QGP by resolving properties at shorter length scales.

Heavy quarks (charm and beauty)



arXiv:2101.04963

- Initial stage

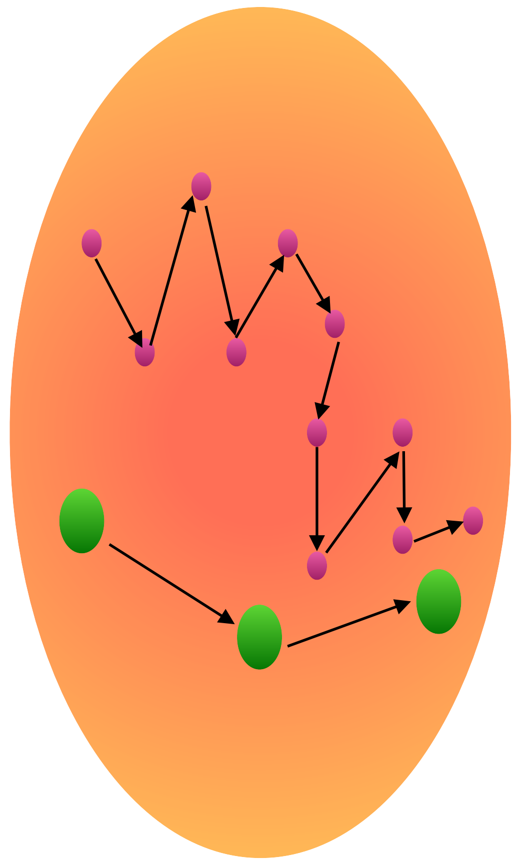
- Production:
  - In hard scattering (< 0.1 fm/c)
  - Calculable with pQCD
    -> calibrated probe

- Energy loss (pQCD):
  - collisional and radiative
  - Low p_T: Brownian motion
    —> spacial diffusion coefficients
- Mass hierarchy
  - Dead cone effect
    —> Less energy loss compared to light quarks

- $m_Q >> T_{QGP}$
- Hadronization:
  - Identify preserved

How to study HF

- Open heavy-flavour
- Quarkonia

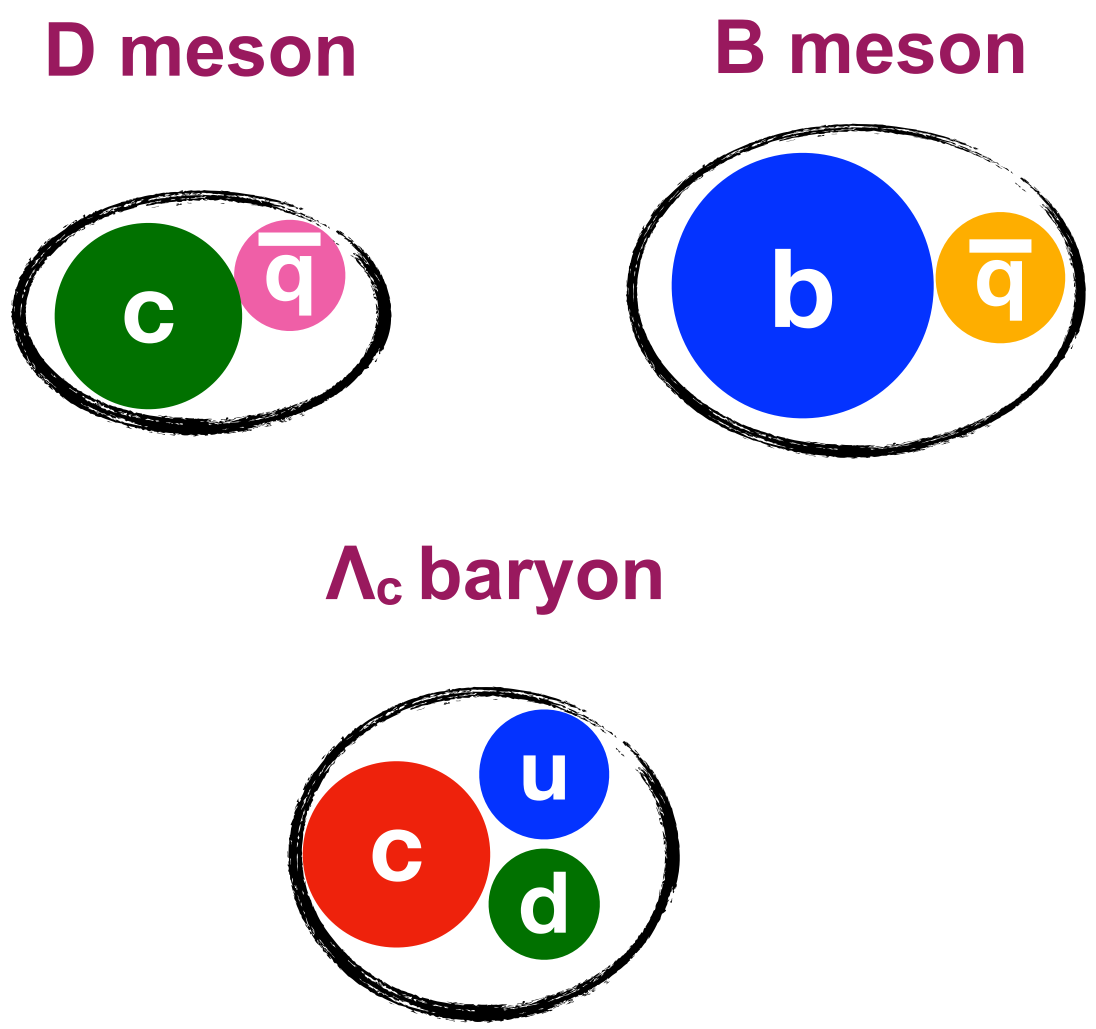


Open heavy-flavour : heavy quark (c/b) hadronise with light quarks (q)

- D mesons(D^0, D^+, D_s, D^{*}_{+}), B meson (B^0, B^+,..)
- Study in-medium interactions
  —> depends on quark mass and color charge

$$\Delta E(g) > \Delta E(u, d, s) > \Delta E(c) > \Delta E(b)$$

- Study fragmentation and hadronisation mechanisms in the presence of the medium

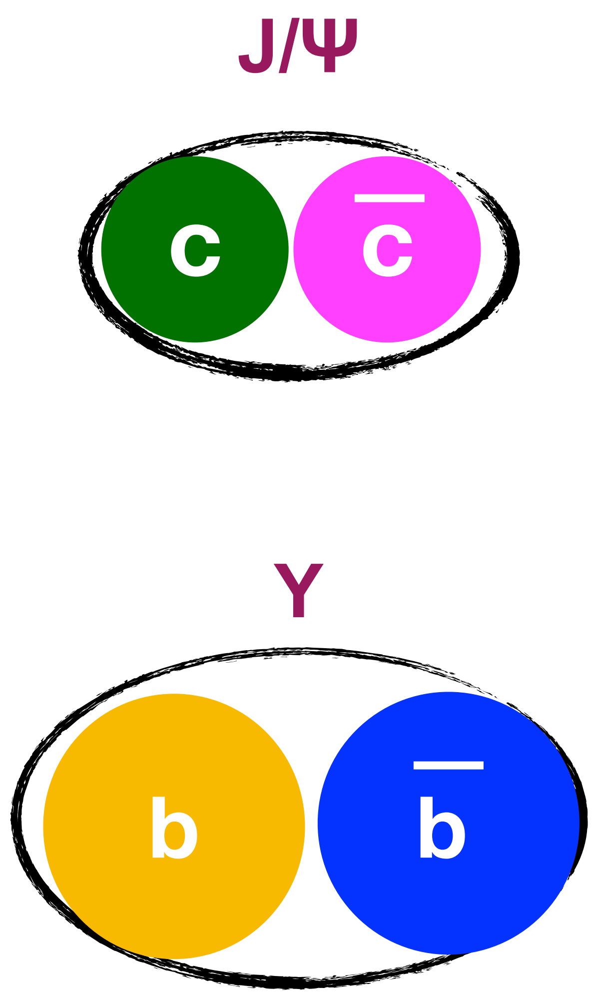


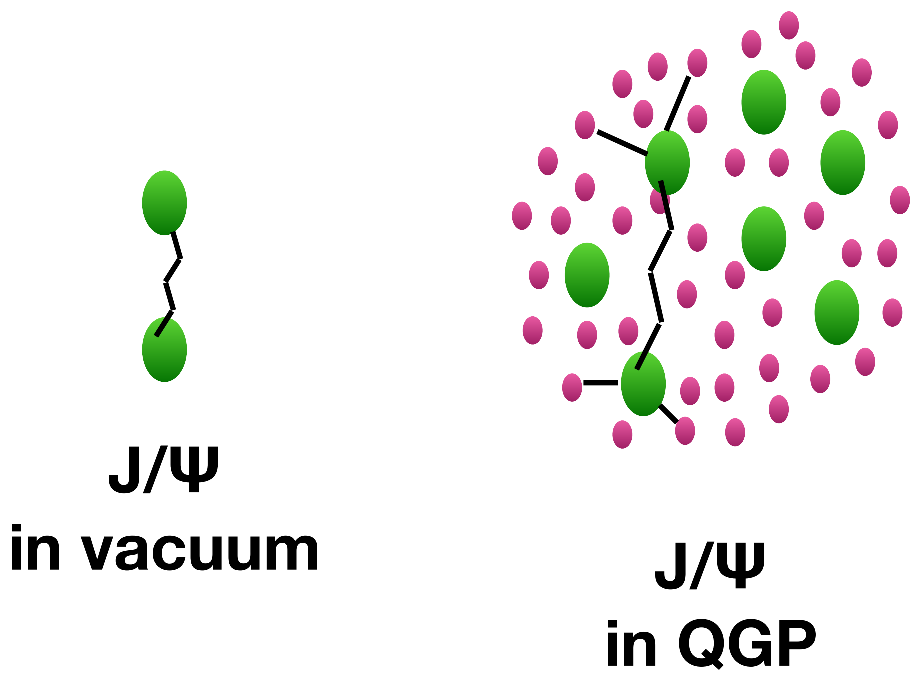
How to study HF

- Open heavy-flavour
- Quarkonia

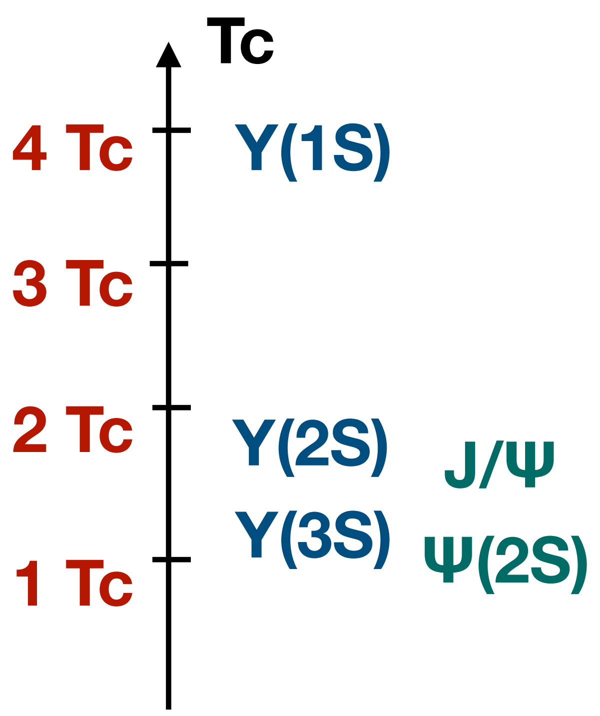
Quarkonia / Hidden heavy-flavor (bound states of $c\bar{c}$ and $b\bar{b}$)

- J/Ψ, Ψ(2S), Υ(1S),…
- Screening of color force in the deconfined medium —> suppression.
- Depends on the binding energy of Quarkonia and the temperature of the medium —> sequential suppression pattern expected.



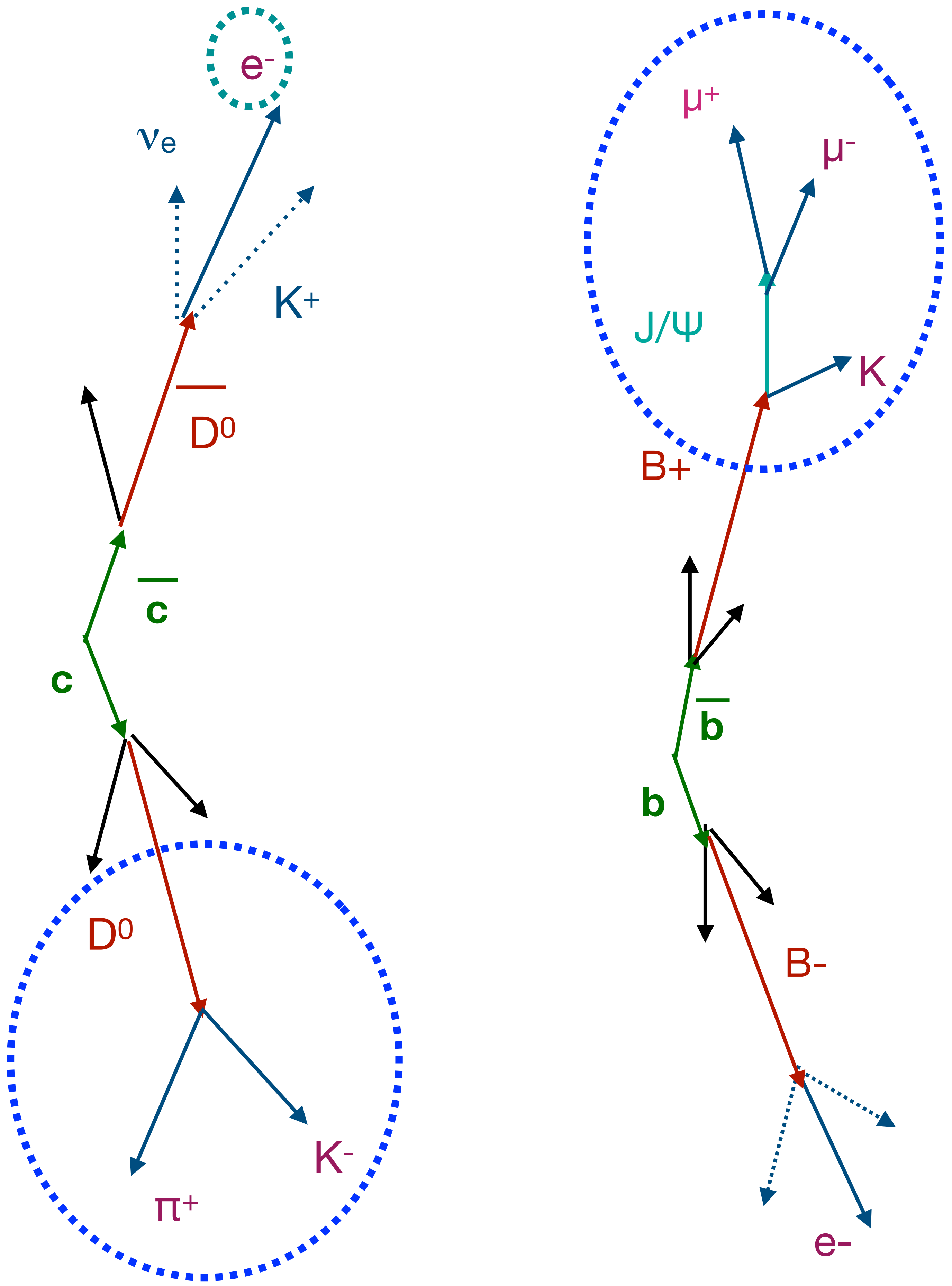


Debye screening of color charge



- Recombination of thermalized heavy quarks in the medium during or at the phase boundary of the deconfined phase —> regeneration

Measuring HF particles



Experimentally heavy-flavour hadrons studied through their decay products:

Inclusive channels:

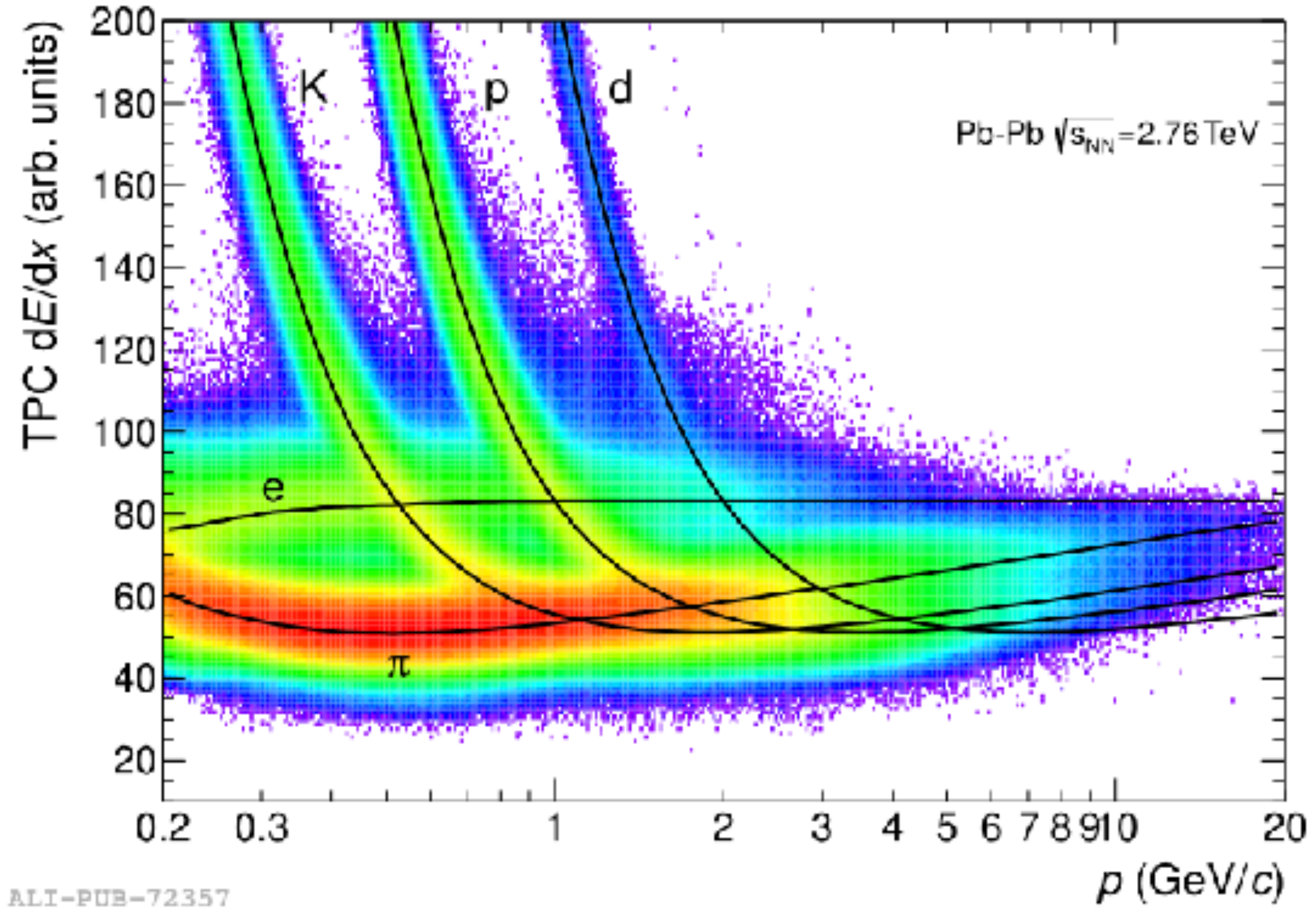
- c,b -> l(e,μ) + X (BR: 10%)
- B^+ -> $\overline{D}^0$ + X (BR: 80%)

Exclusive channels:

- D^0 -> K^- + π^+ (BR: 3.88%)
- D^{*+} -> D^0 + π^+ (BR: 2.62%)
- B^+ -> J/Ψ + K (BR: 6.12 x 10^{-5}%)
- Λ_c -> K+π+p (BR: 6.28%)
- J/Ψ -> e^+e^- (BR: 5.9%)
- Υ(1S) -> $\mu^+\mu^-$ (BR: 2.48%)

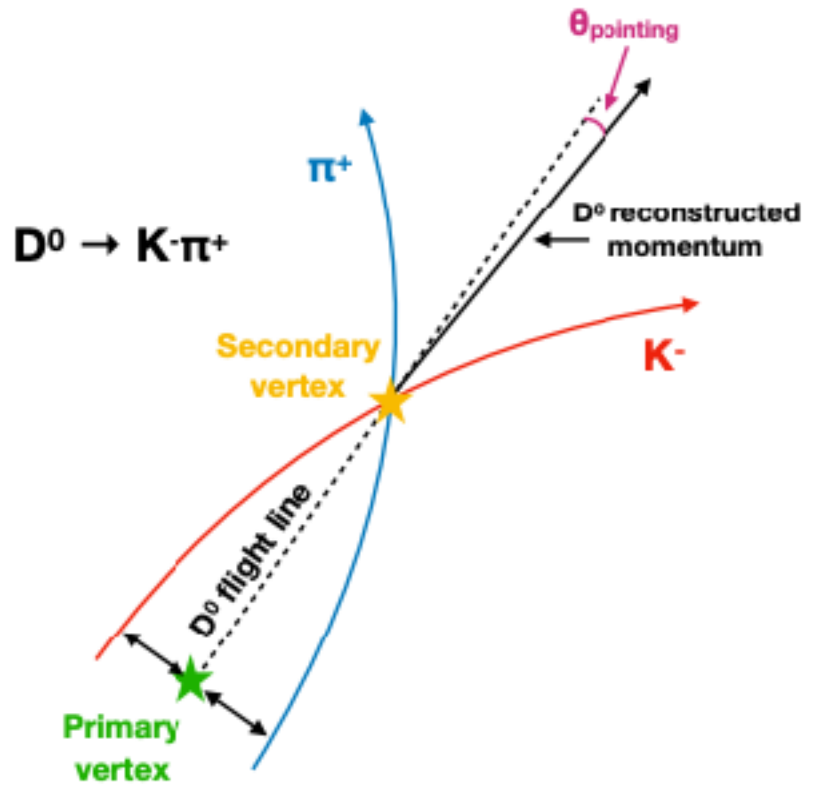
Measuring HF particles

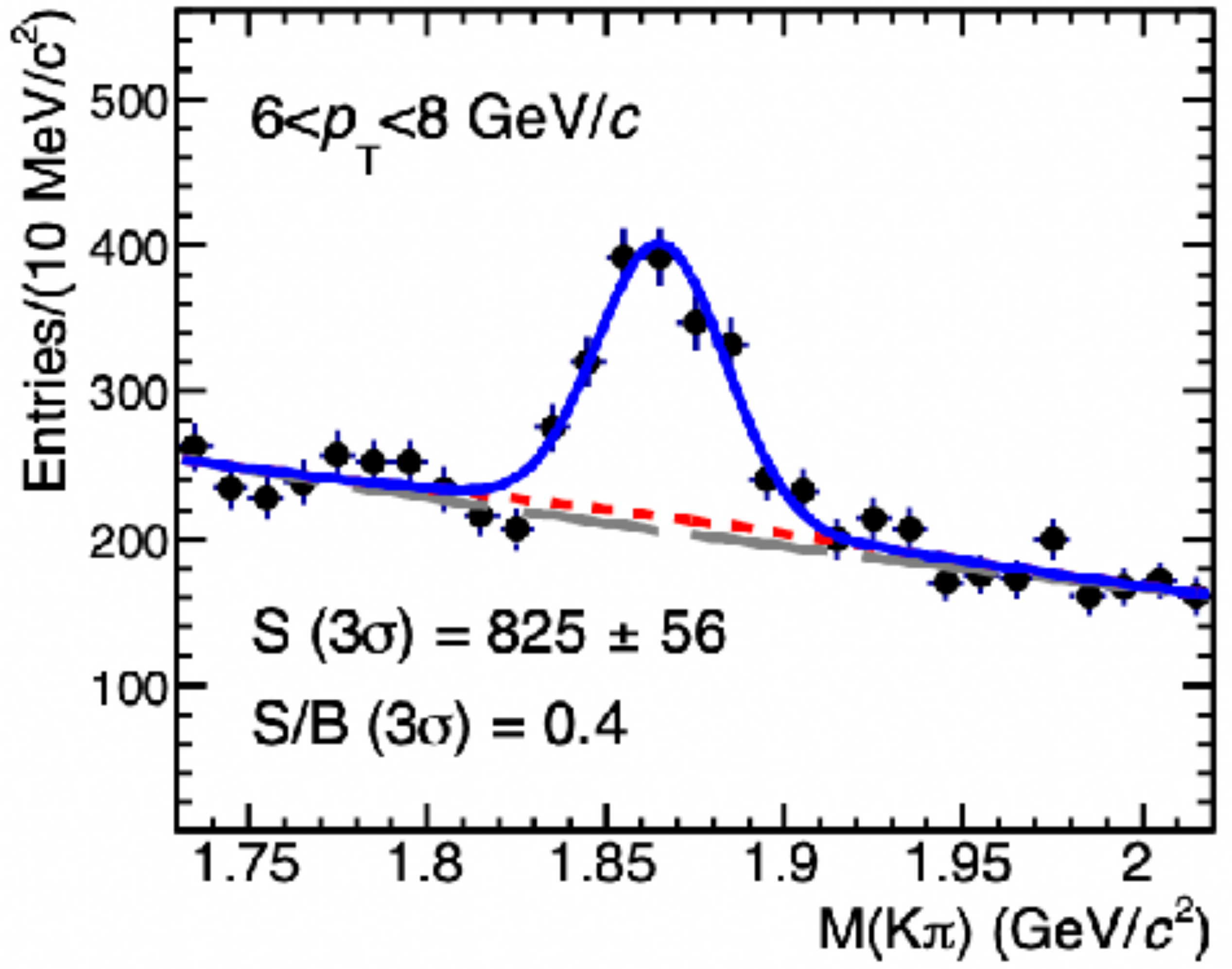
Particle identification of final state particles



D mesons reconstruction

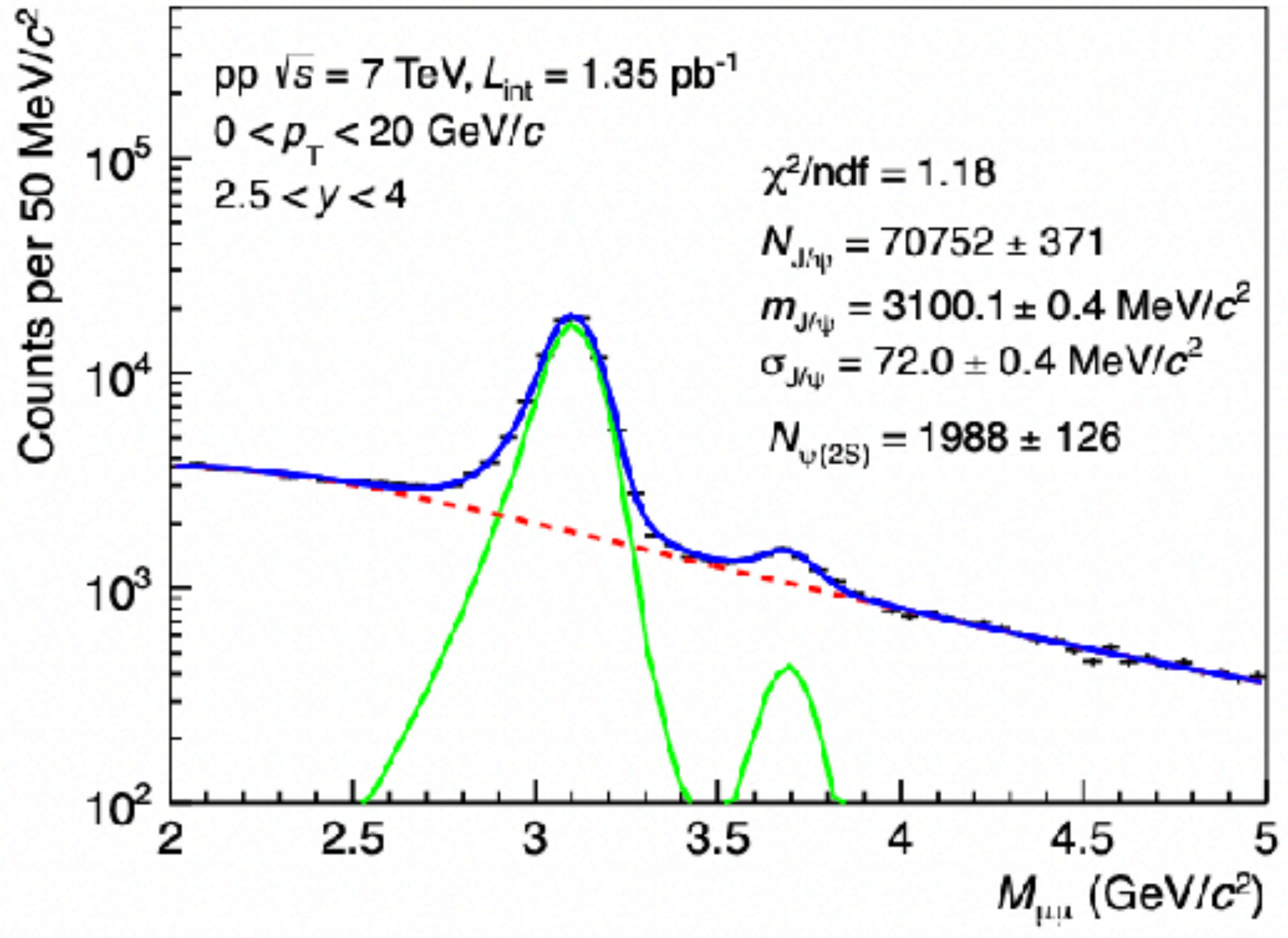
- Secondary vertex displaced from primary vertex
- Apply topological cuts
- Calculate invariant mass of decay particles





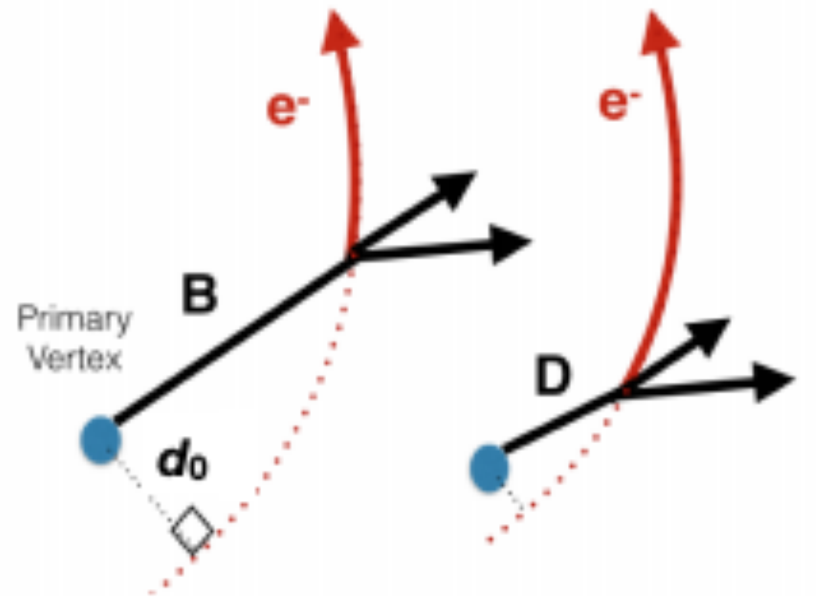
Quarkonia

- Calculate invariant mass of lepton pairs.
- Background subtraction



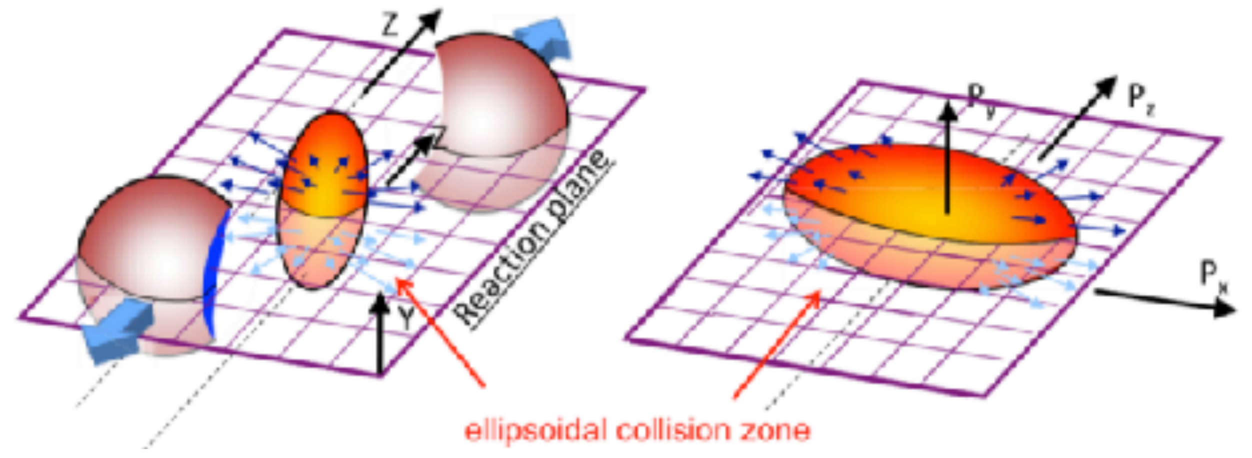
Beauty Measurements

- Uses longer lifetime of beauty than charm
  - beauty hadrons τ ~ 500 μm/*c*
  - charm hadrons τ < 300 μm/*c*
- Larger distance of closest approach

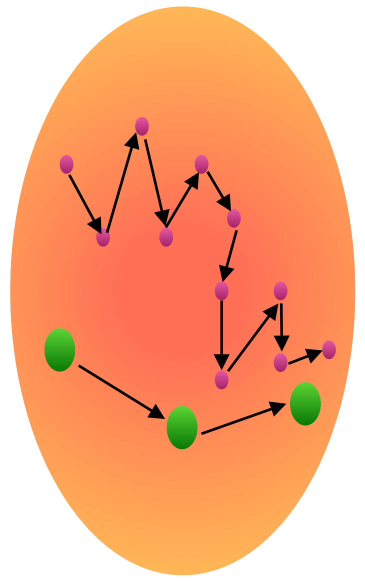


Heavy-flavor measurements in A-A

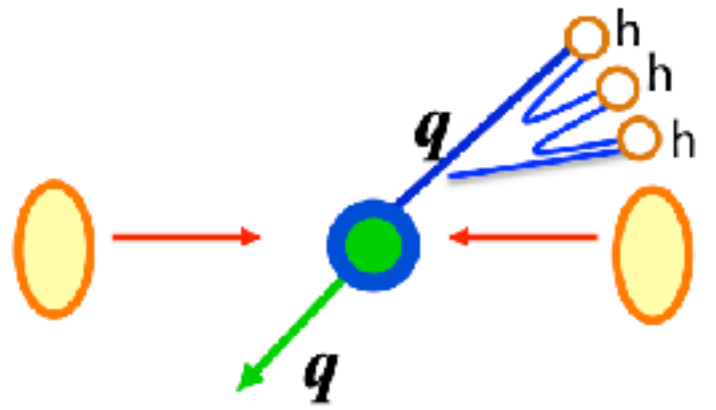
- **Azimuthal anisotropy (v_n)** - information about the initial collision geometry and its fluctuations

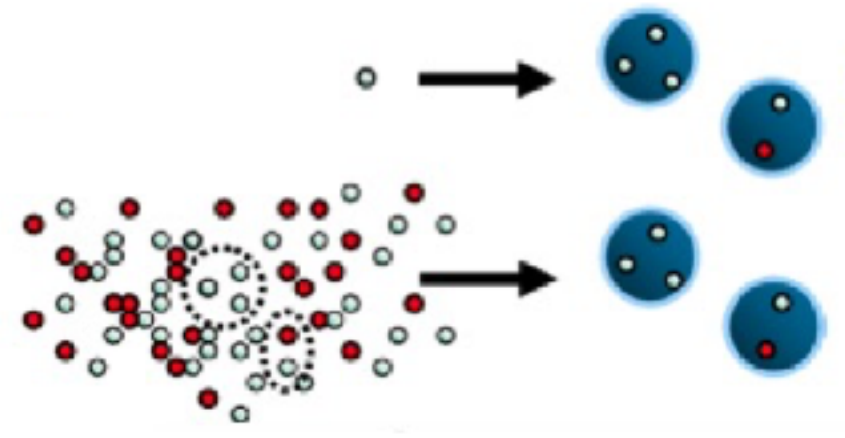


- **Nuclear Modification Factor (R_{AA})** - energy loss in the QGP

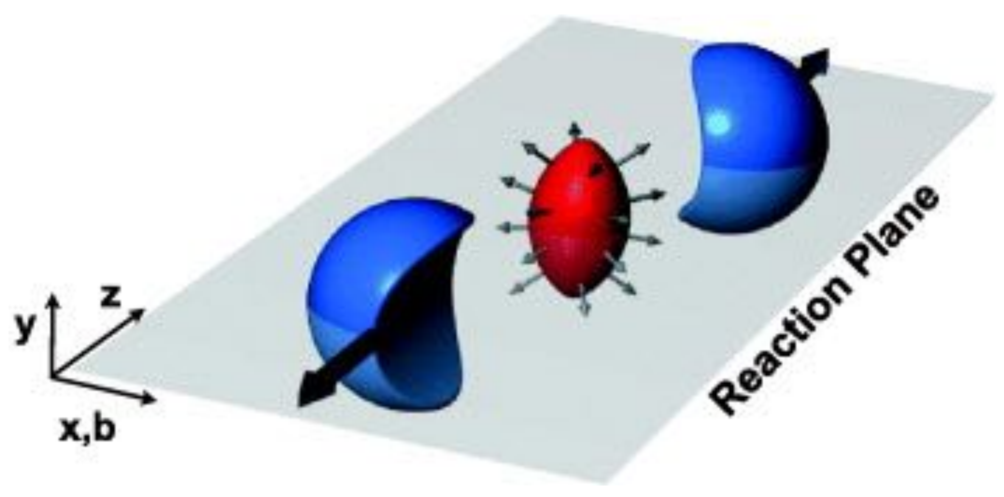


- **Jet fragmentation and hadronisation processes**



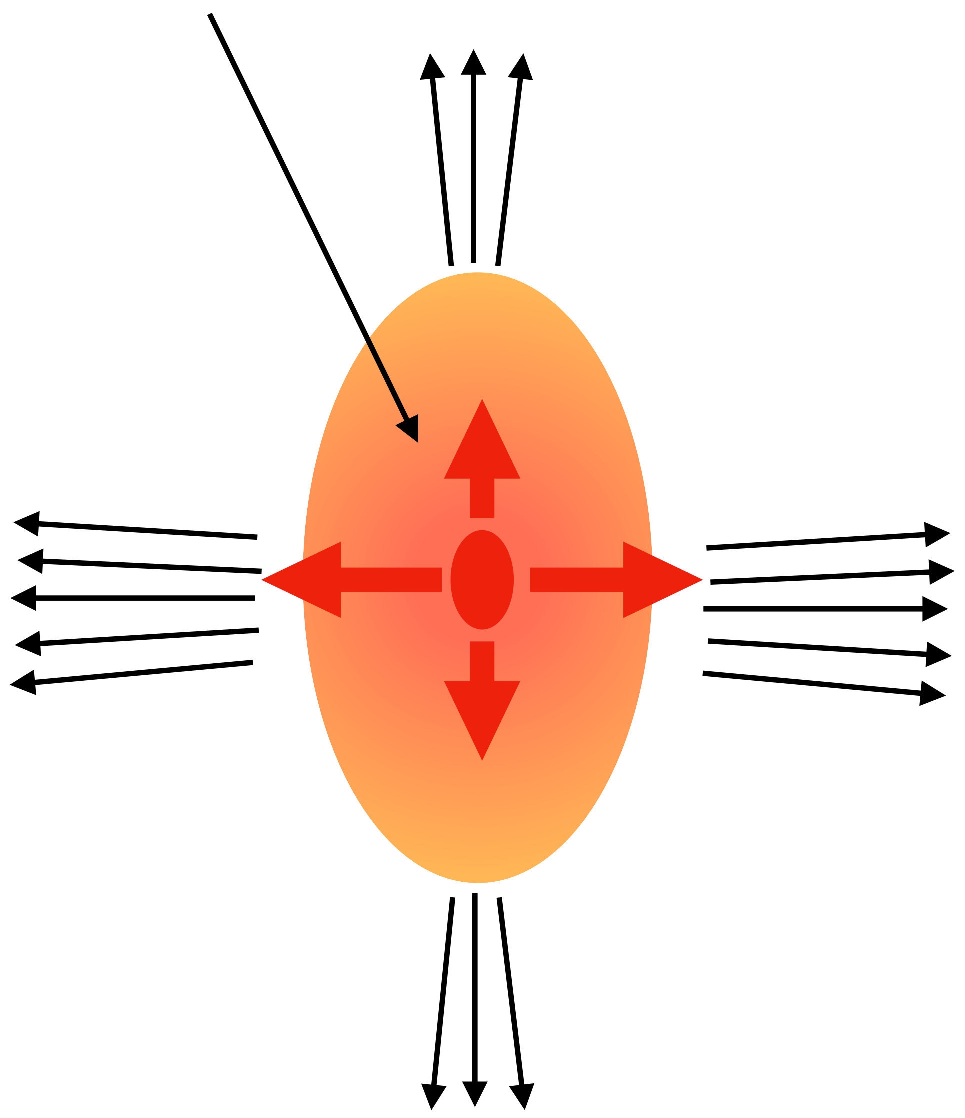


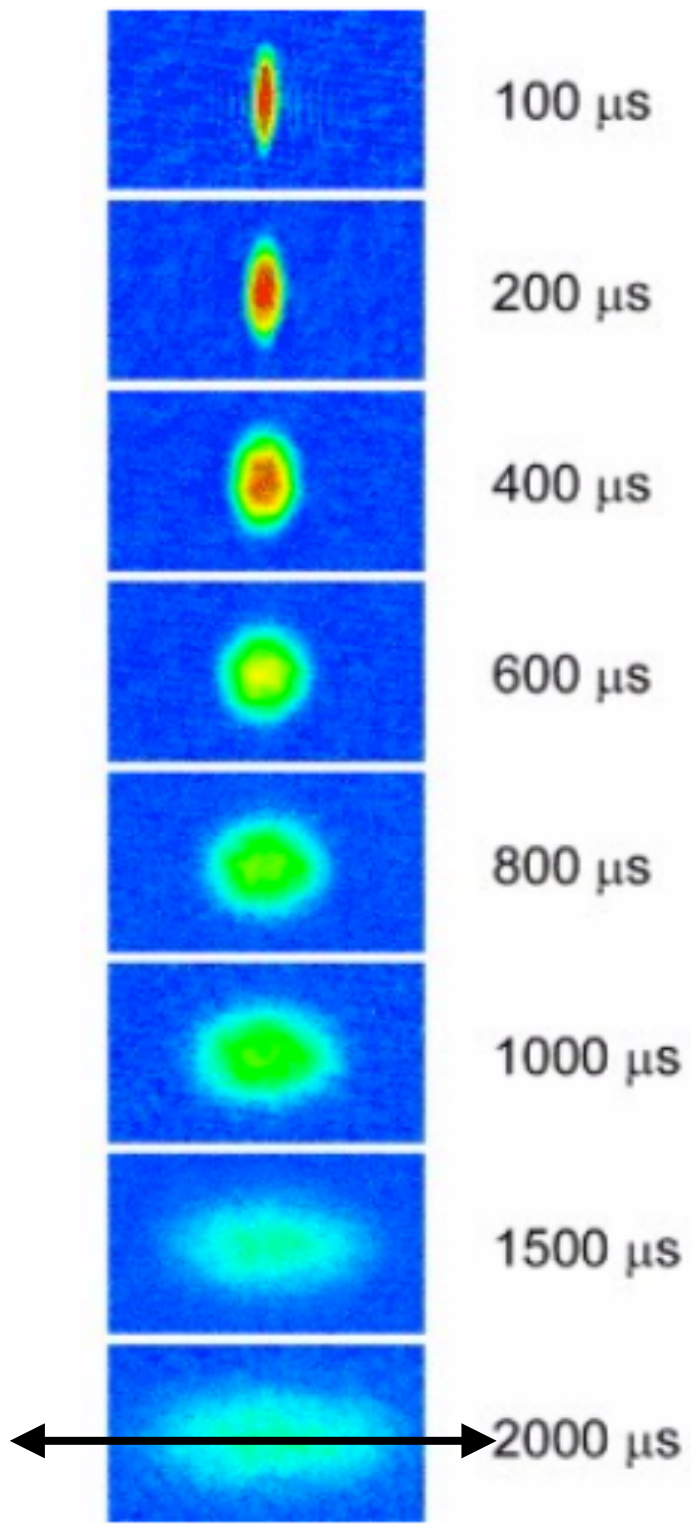
Collective flow



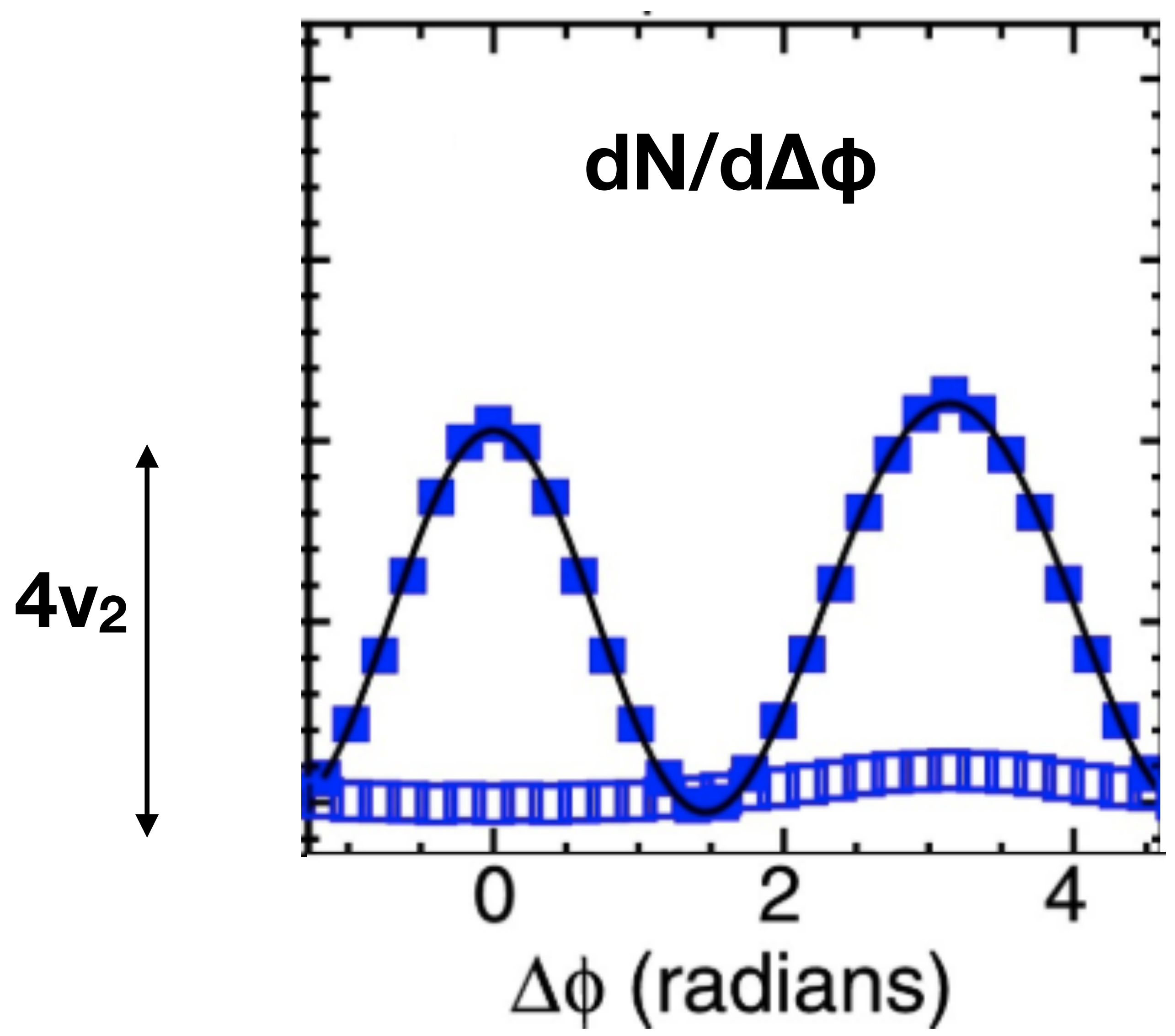
- **Observable**: azimuthal distribution of particles in the plane perpendicular to beam axis -> sensitive to dynamics at the early stages of collision.
- In semi-central A-A collisions:
  - Overlap region is anisotropic - almond shape.

high density at the center





Pressure driven expansion
Demonstration by ultra-cold atom gas system



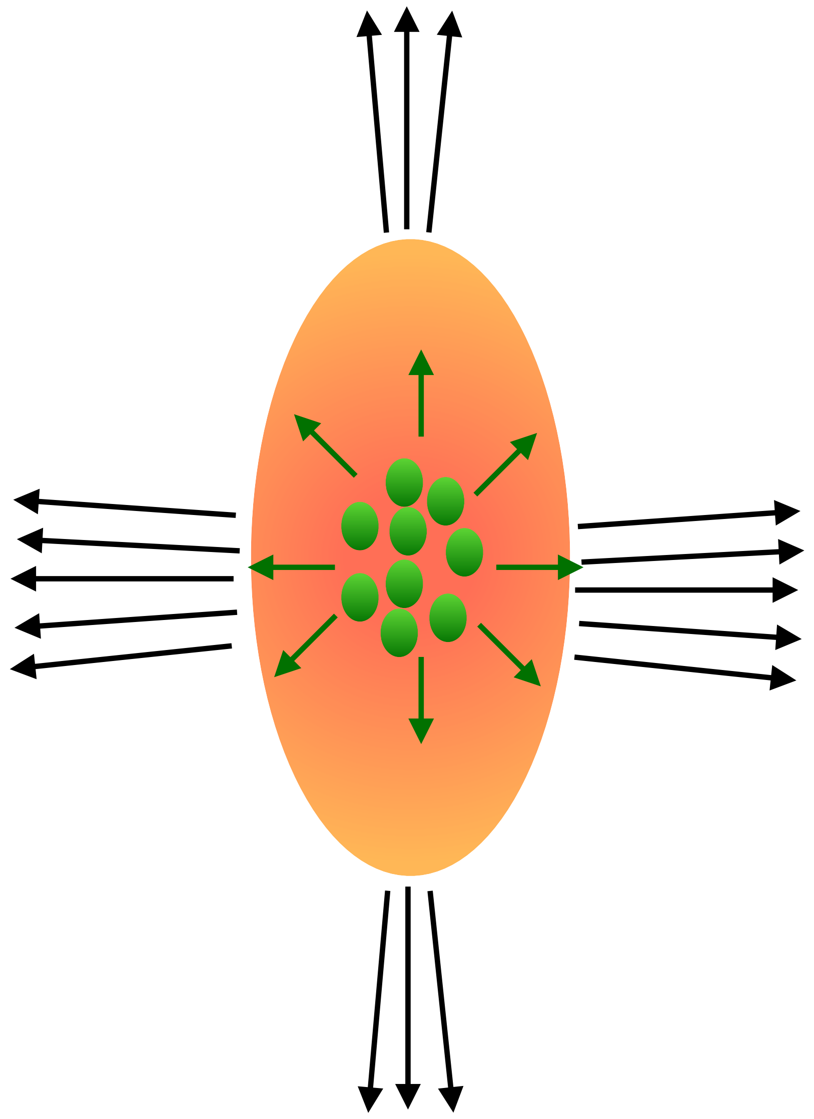
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos(\Delta\varphi) + 2v_2\cos(2\Delta\varphi) + 2v_3\cos(3\Delta\varphi) + \ldots$$

Elliptic flow

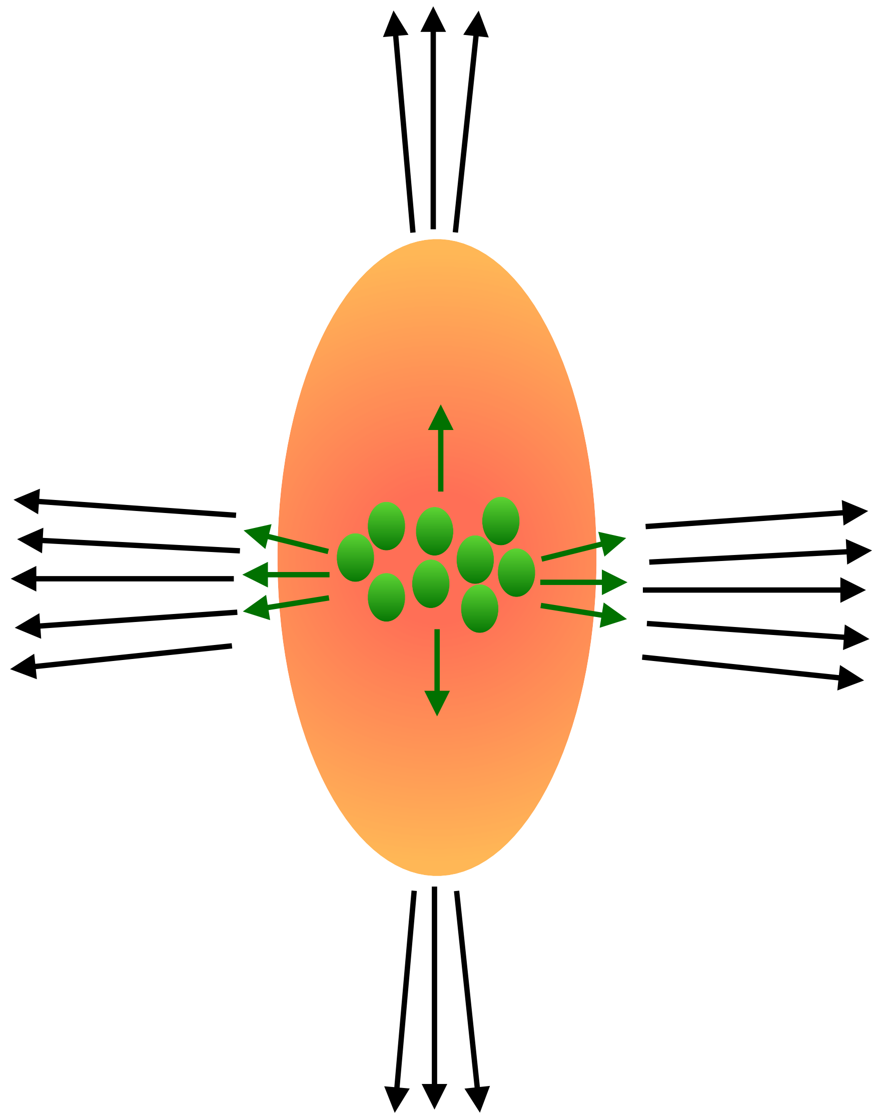
Heavy-quark collective flow

- Elliptic flow (v_2) of light flavour hadrons at low p_T (< 2-3 GeV/c) explained by hydrodynamical models.
- Heavy quarks with large mass interact enough that they thermalize (equilibrate)?
  - Expected to take longer than light quarks

HQ production is isotropic
(***v*₂ = 0**) ??



HQ production is
anisotropic (***v*₂ != 0**) ??

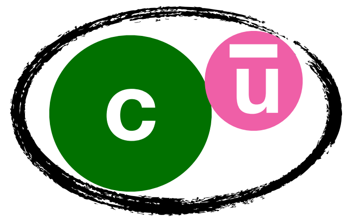


v_2 of charm quarks

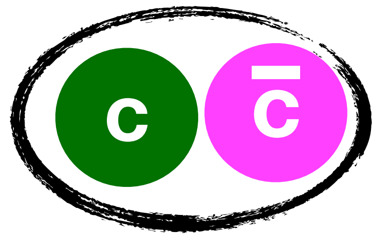
Quantify HQ interaction strength at low p_T and constraint its path length dependent energy loss at high p_T

π^{+-}

D mesons

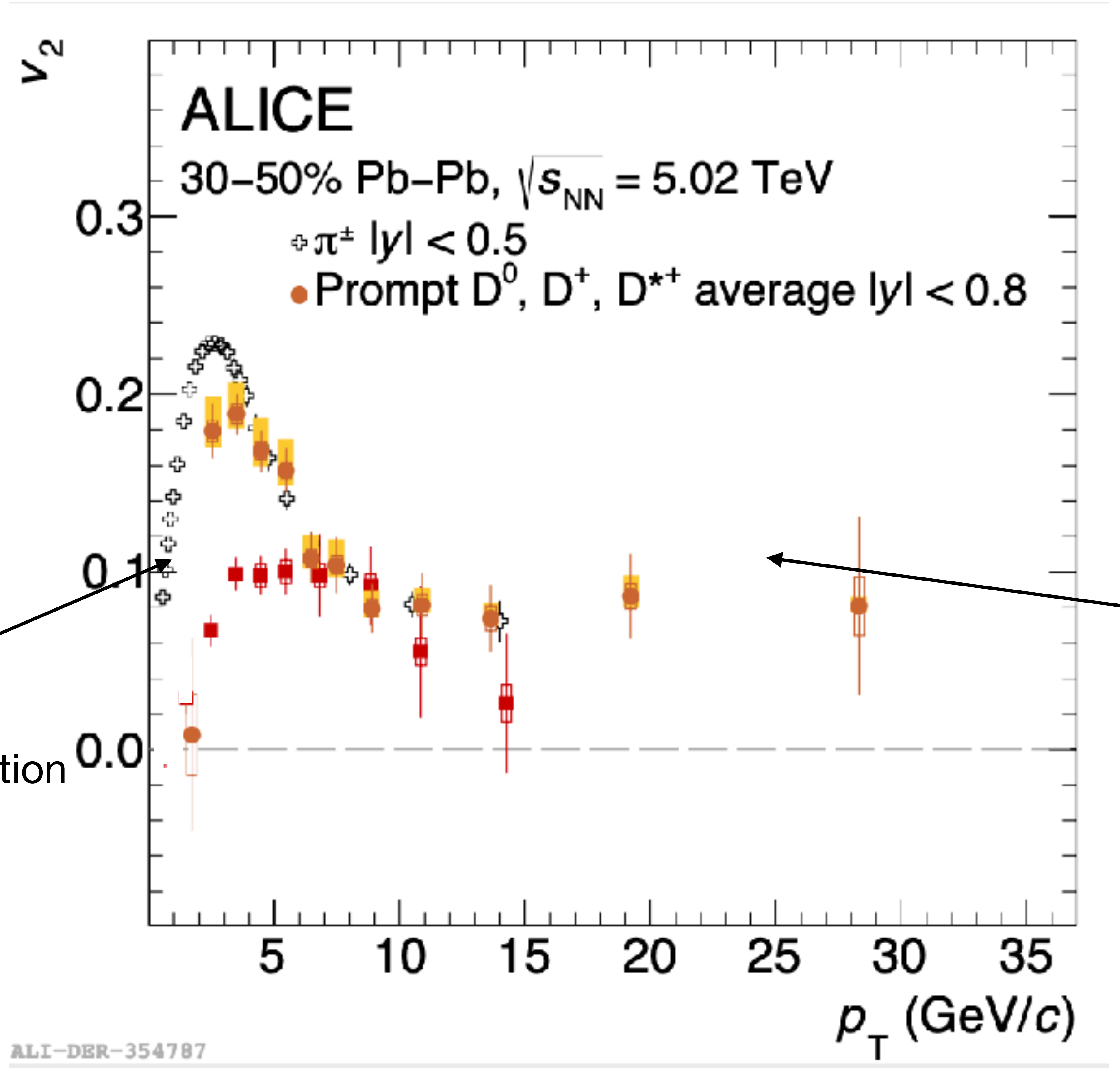


J/Ψ



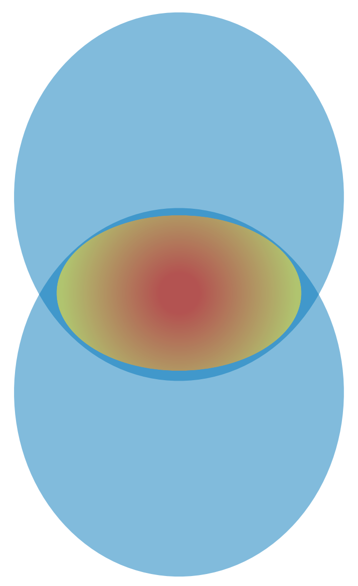
$$v_2 = < \cos[2(\phi - \Psi_2)] >$$

Low p_T:
Collective flow and hadronization



π^{+-}
D mesons
J/Ψ

JHEP 09 (2018) 006
PRL 123 (2019) 192301
arXiv:2005.11130
arXiv:2005.11131
arXiv:2005.14518

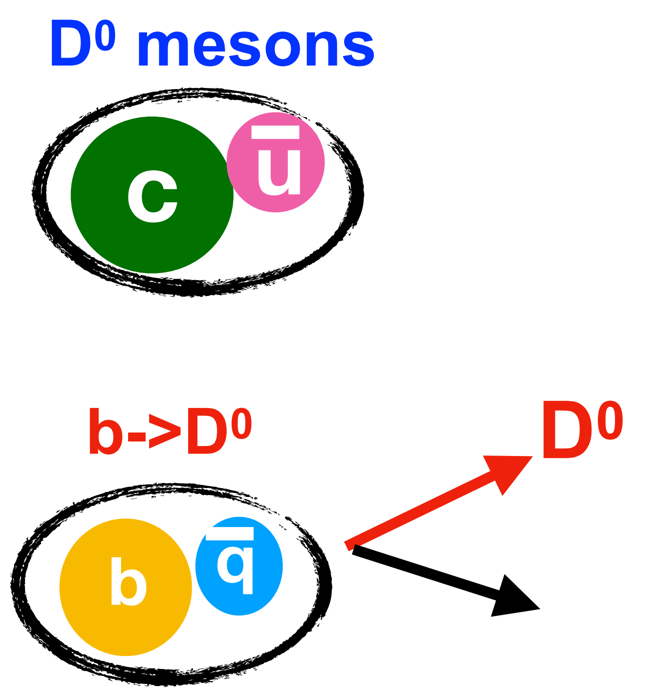


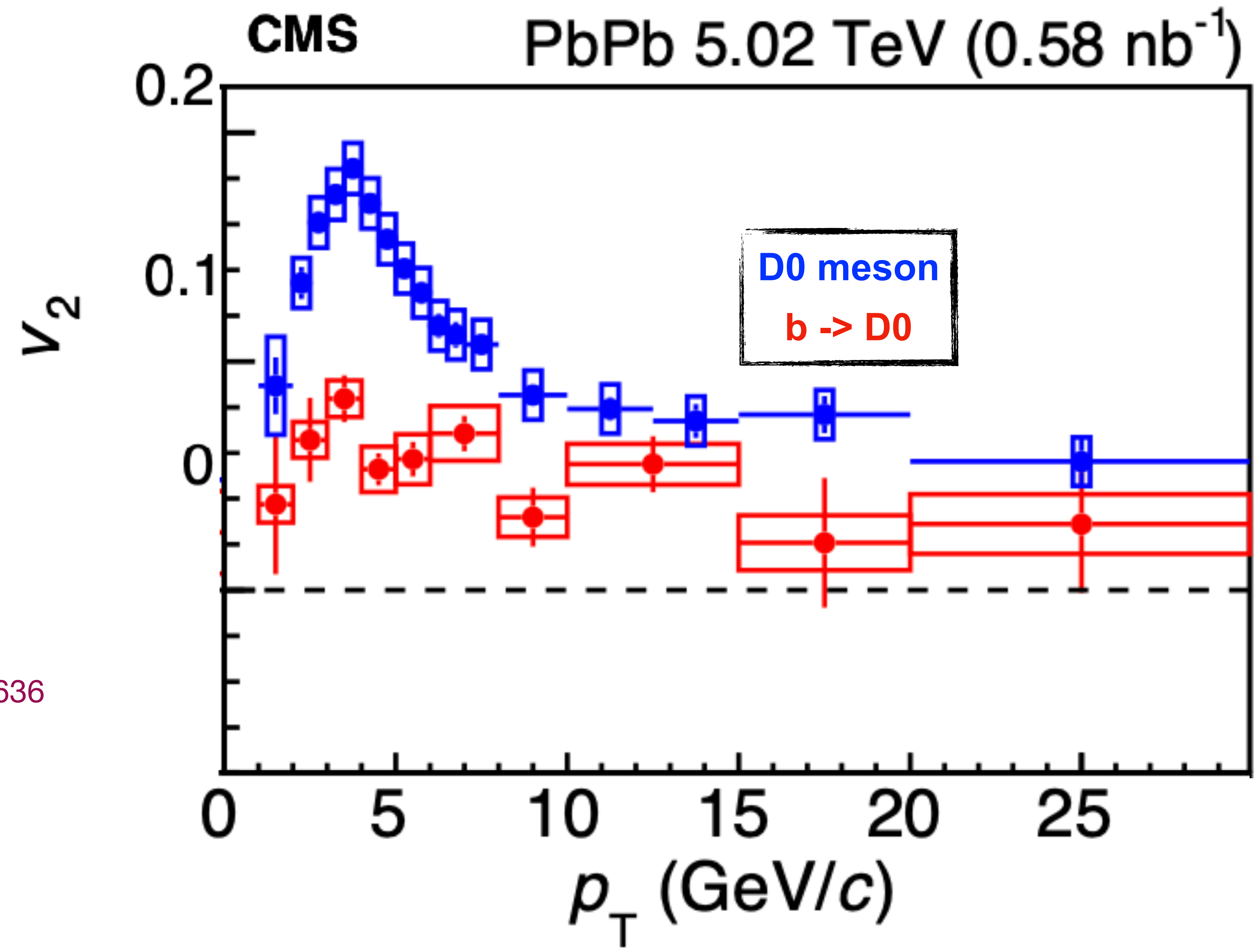
Semi-central

High p_T:
Path-length dependent energy loss

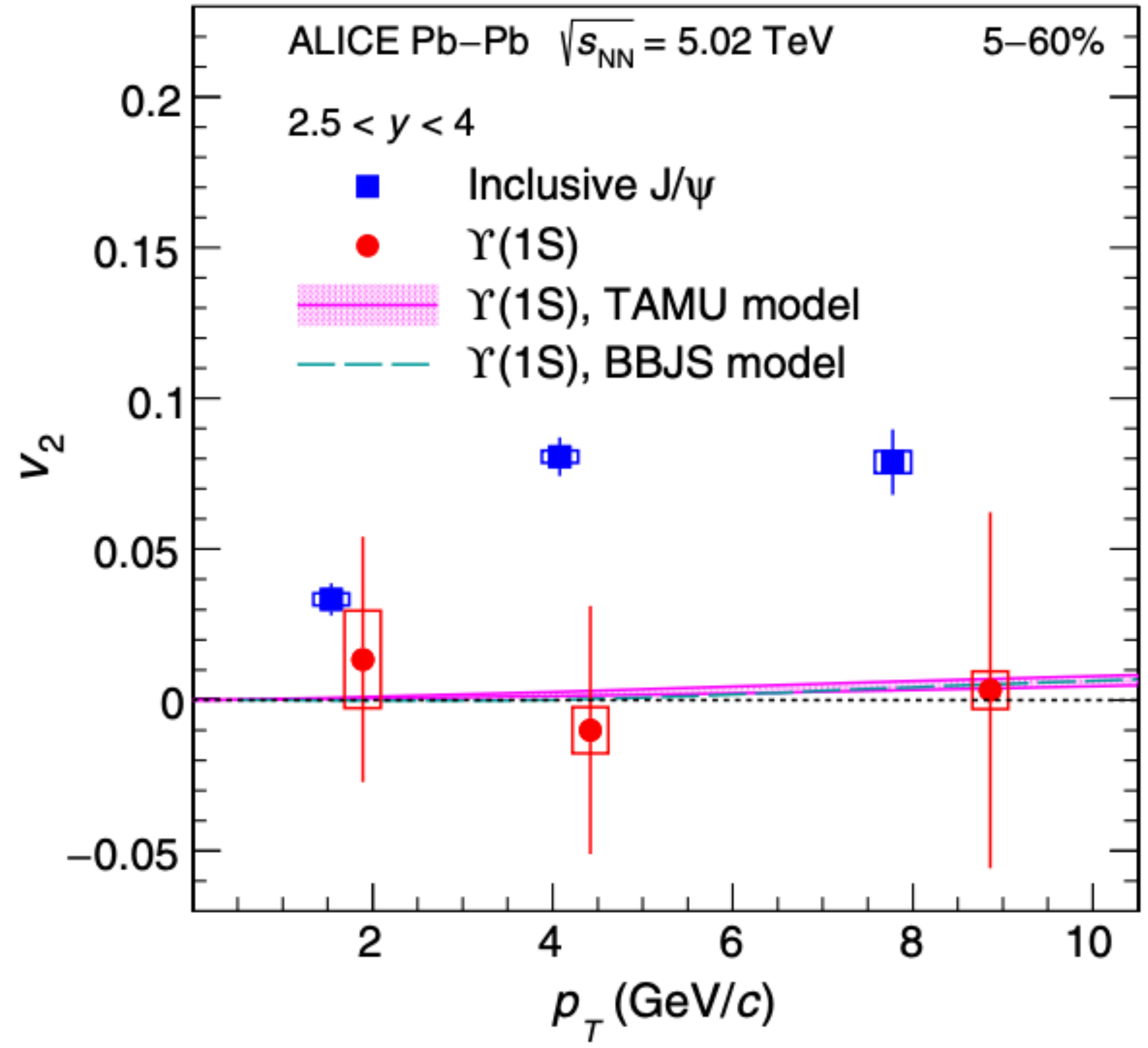
- Low p_T: $v_2(\pi^{+-}) > v_2(D) > v_2(J/\Psi)$
  - v_2 possibly from charm quark flow + recombination with the light-flavor quark
- **Charm quarks interact strongly with the medium and participate in its collective expansion**

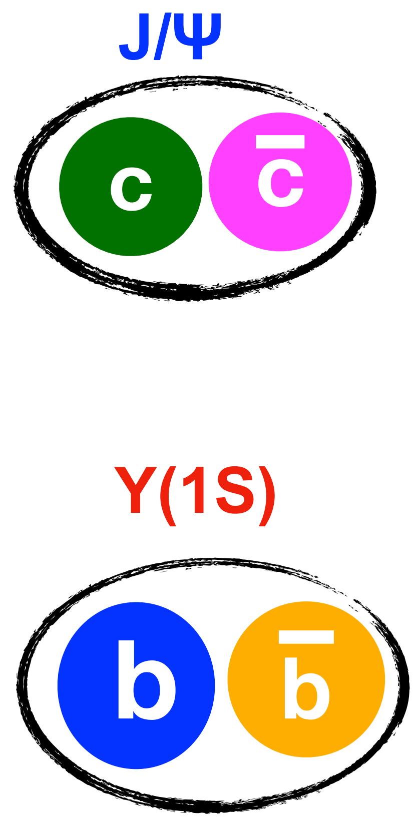
v_2 of beauty quarks





arXiv:2212.01636



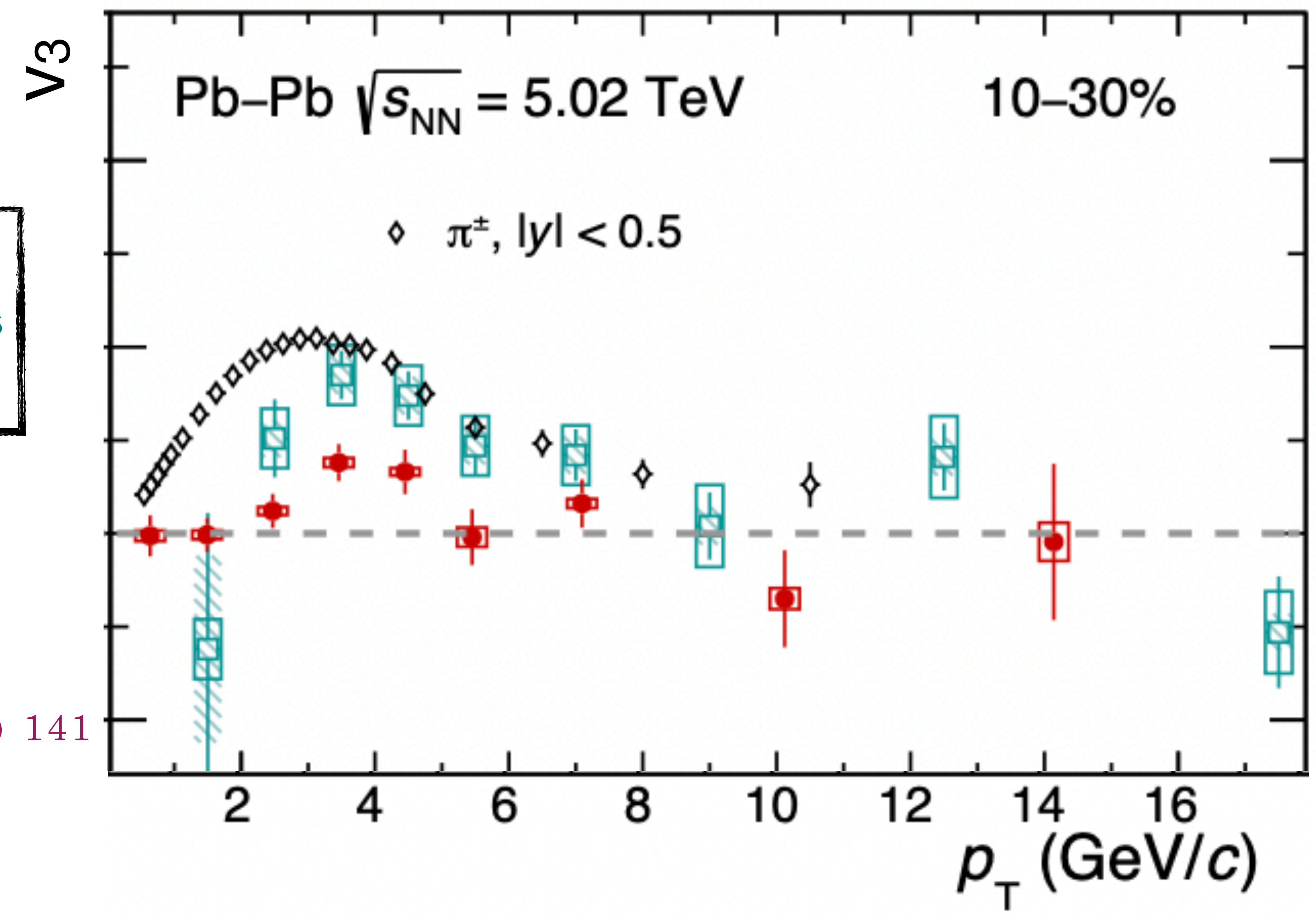


PRL 123 (2019) 192301

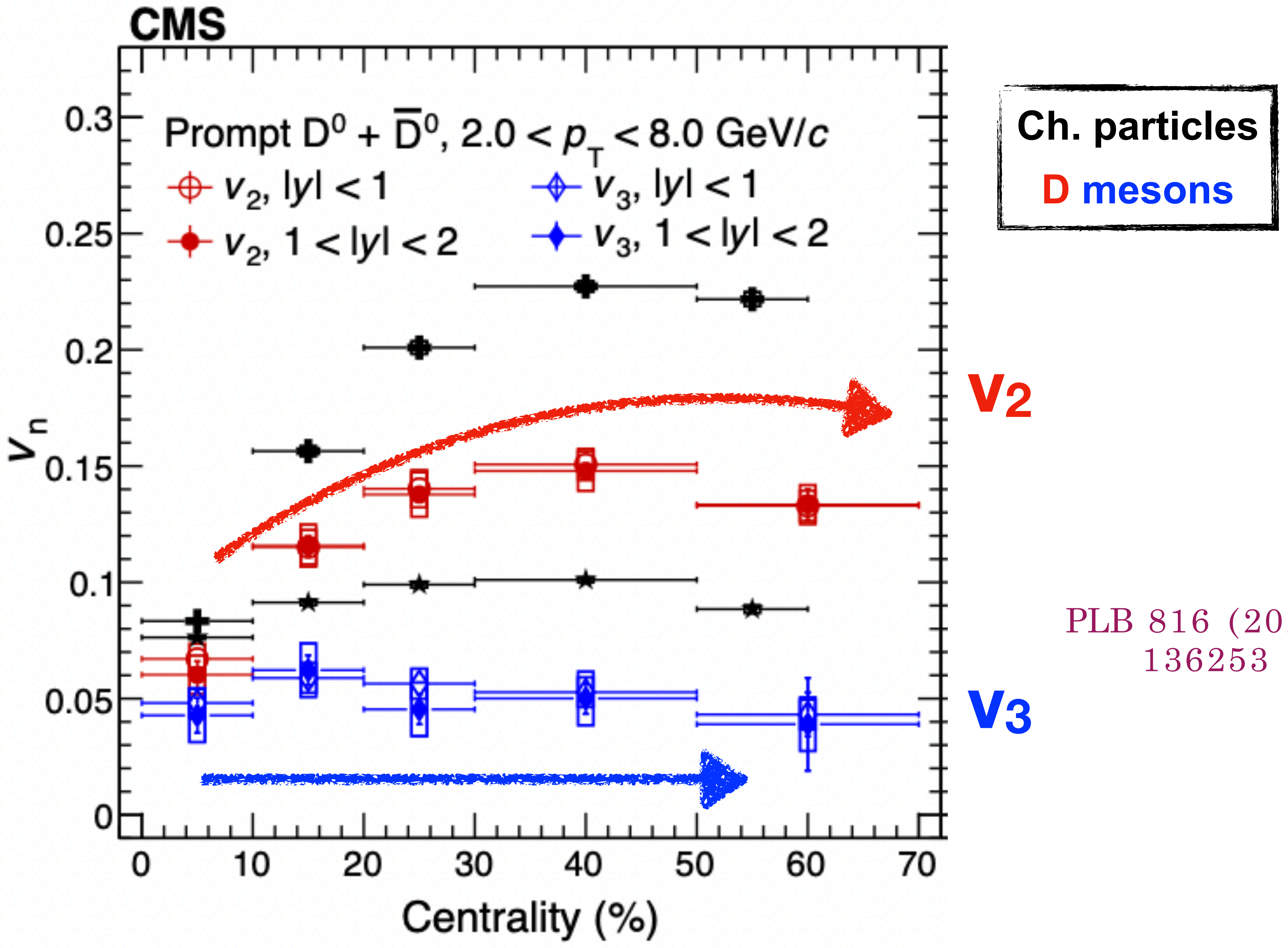
- Low p_T: $v_2(D) > v_2(B)$
- High p_T: $v_2(D) \sim v_2(B)$
- **Open-beauty $v_2 > 0$; bottomonia $v_2 \sim 0$**
  - Impact of path-length dependent energy loss and recombination of open beauty?

v_3 of charm quarks

Sensitive to the fluctuations in the initial energy-density within the overlap region



JHEP 10 (2020) 141

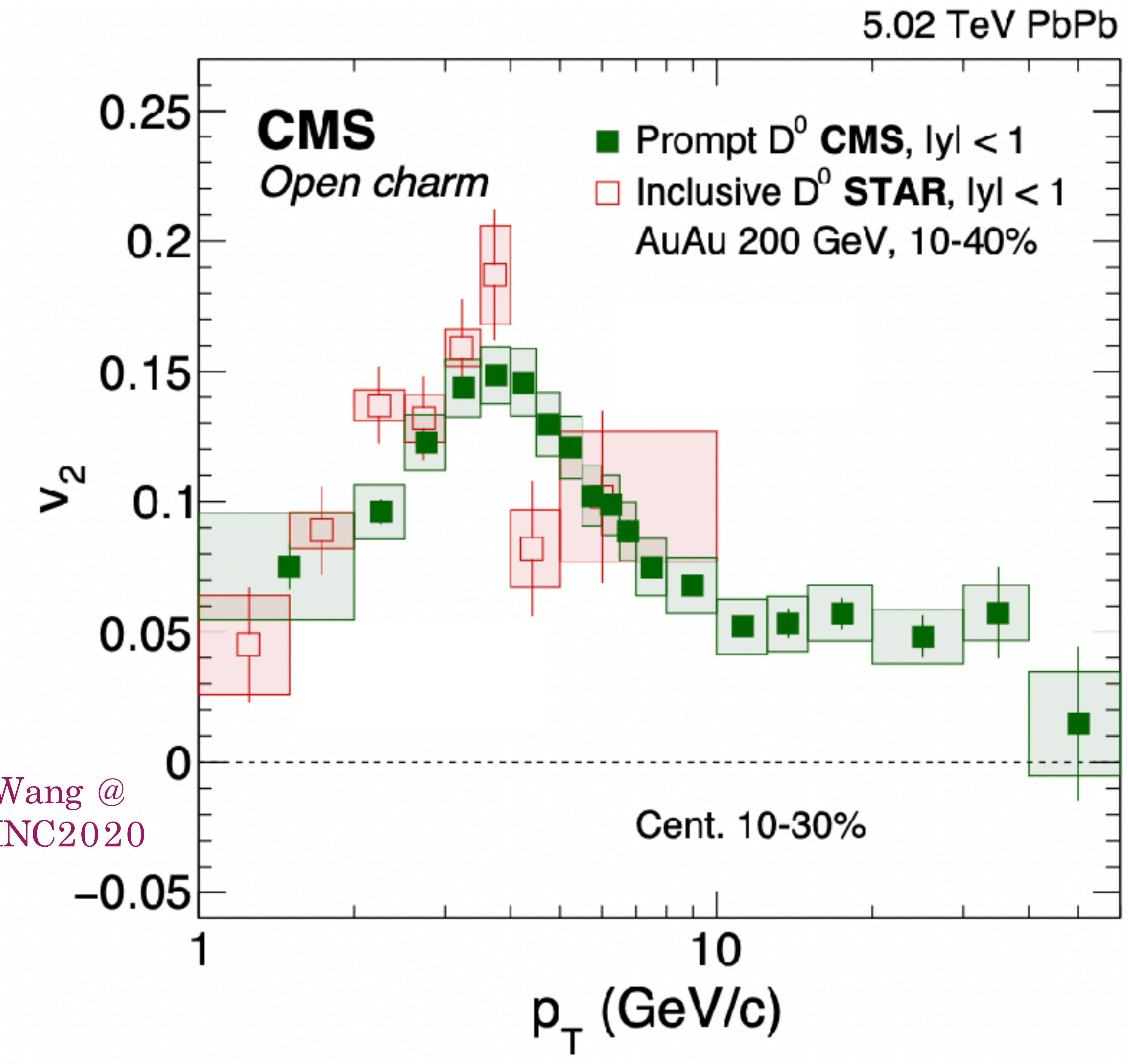


PLB 816 (2021) 136253

- $v_3(\pi^{+-})$ > v_3(D) > v_3(J/Ψ) —> mass hierarchy observed in v_3 as well.
- **Confirms charm quark being kinetically equilibrated in the QGP medium.**

- Centrality trend similar for D mesons and charged particles
- v_2: **strong centrality dependence** —> collision geometry and viscosity effects.
- v_3: **weak centrality dependence** —> expected from fluctuations in collision geometry.

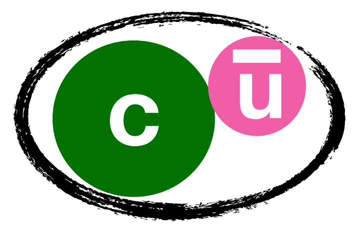
v_2 at LHC and RHIC



Jing Wang @ HF-WINC2020

LHC
RHIC

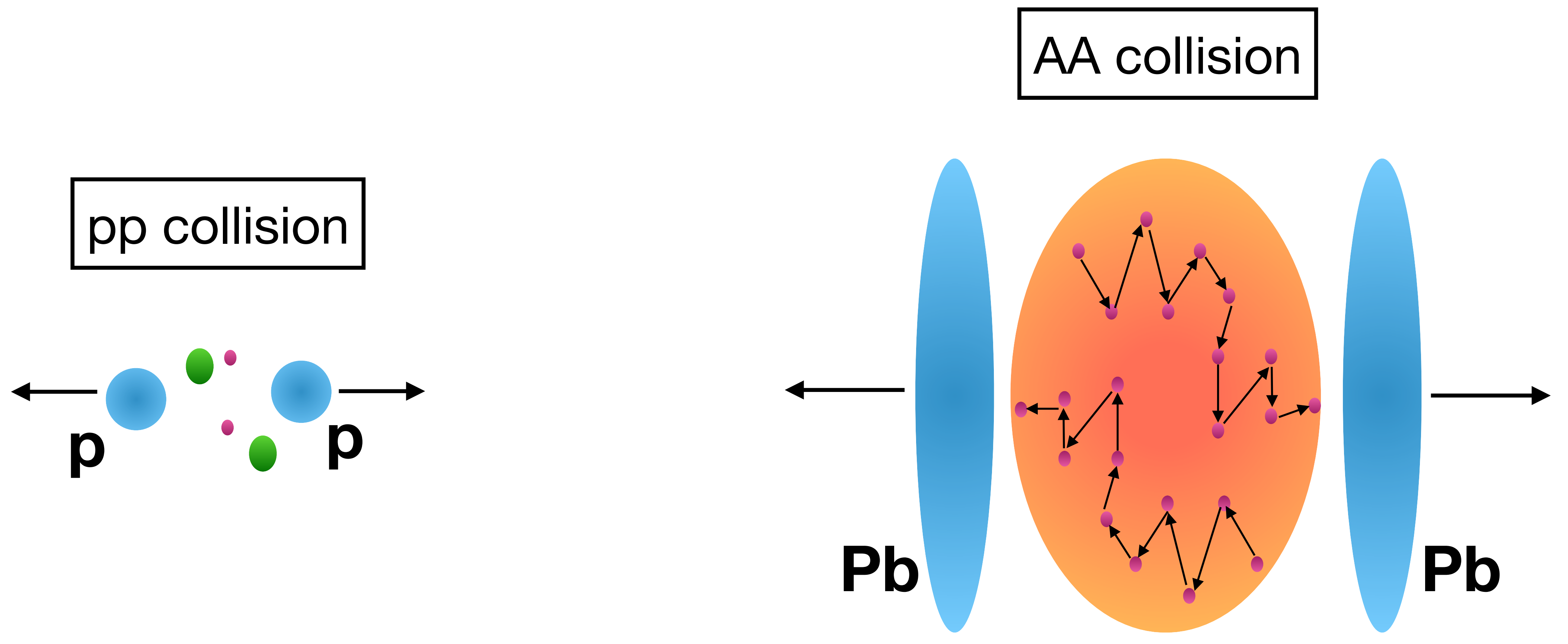
D mesons

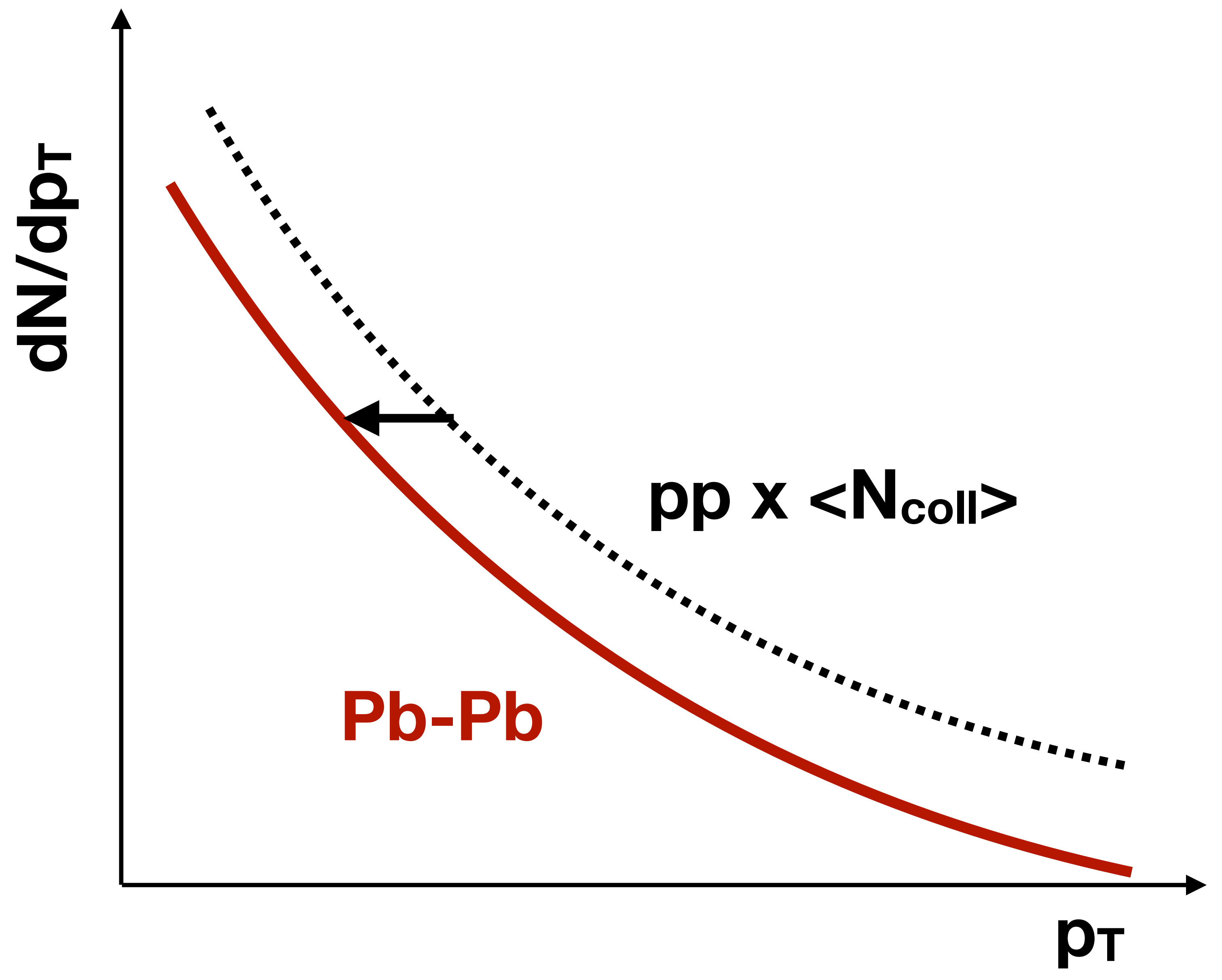


v_2 of D mesons at different collision energies at LHC and RHIC show similar p_T dependence.

Nuclear Modification factor

Measuring energy loss: **Nuclear Modification Factor (R_{AA})**





$$R_{AA} = \frac{1}{< N_{coll} >} \frac{Y_{AA}}{Y_{pp}}$$

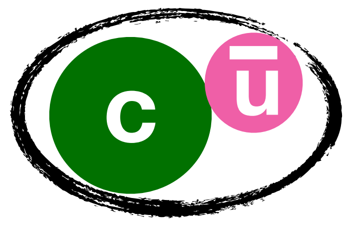
R_{AA} = 1 -> No medium
R_{AA} < 1 -> Energy loss

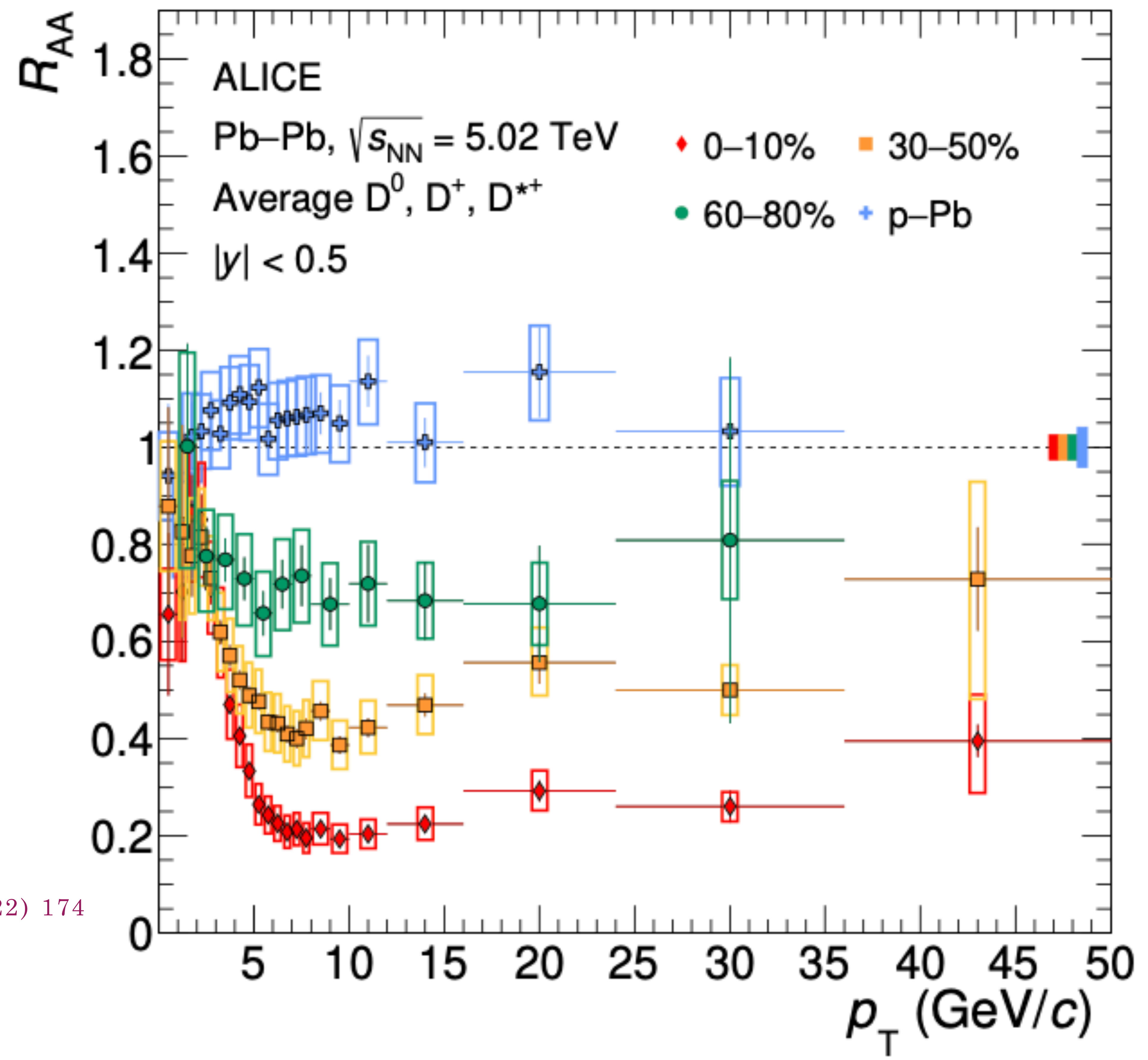
$\langle N_{coll} \rangle$: Average number of binary nucleon-nucleon collisions
Y_{pp} : Yield of a particle in proton-proton collisions
Y_{AA} : Yield of a particle in nucleus-nucleus collisions

R_{AA} of D mesons

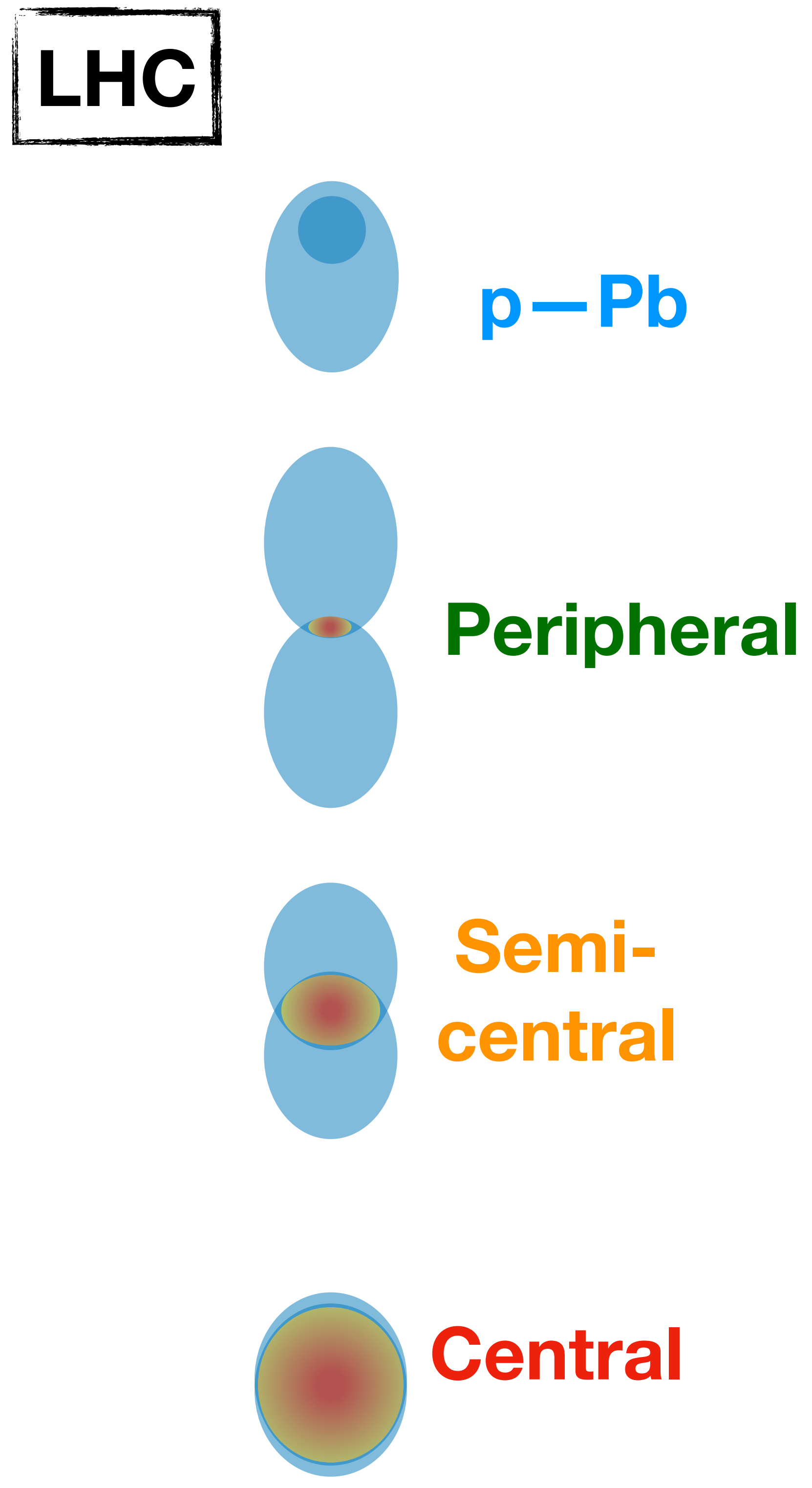
$$R_{AA} = \frac{1}{< N_{coll} >} \frac{Y_{AA}}{Y_{pp}}$$

D mesons





JHEP 01 (2022) 174



$R_{AA} < 1$ -> charm undergoes energy loss in GQP

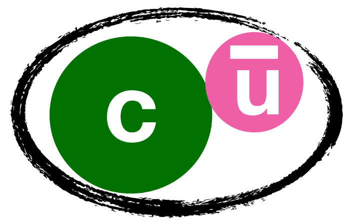
R_{AA} (0-10%) < R_{AA} (30-50%) < R_{AA} (60-80%) at intermediate and high p_T

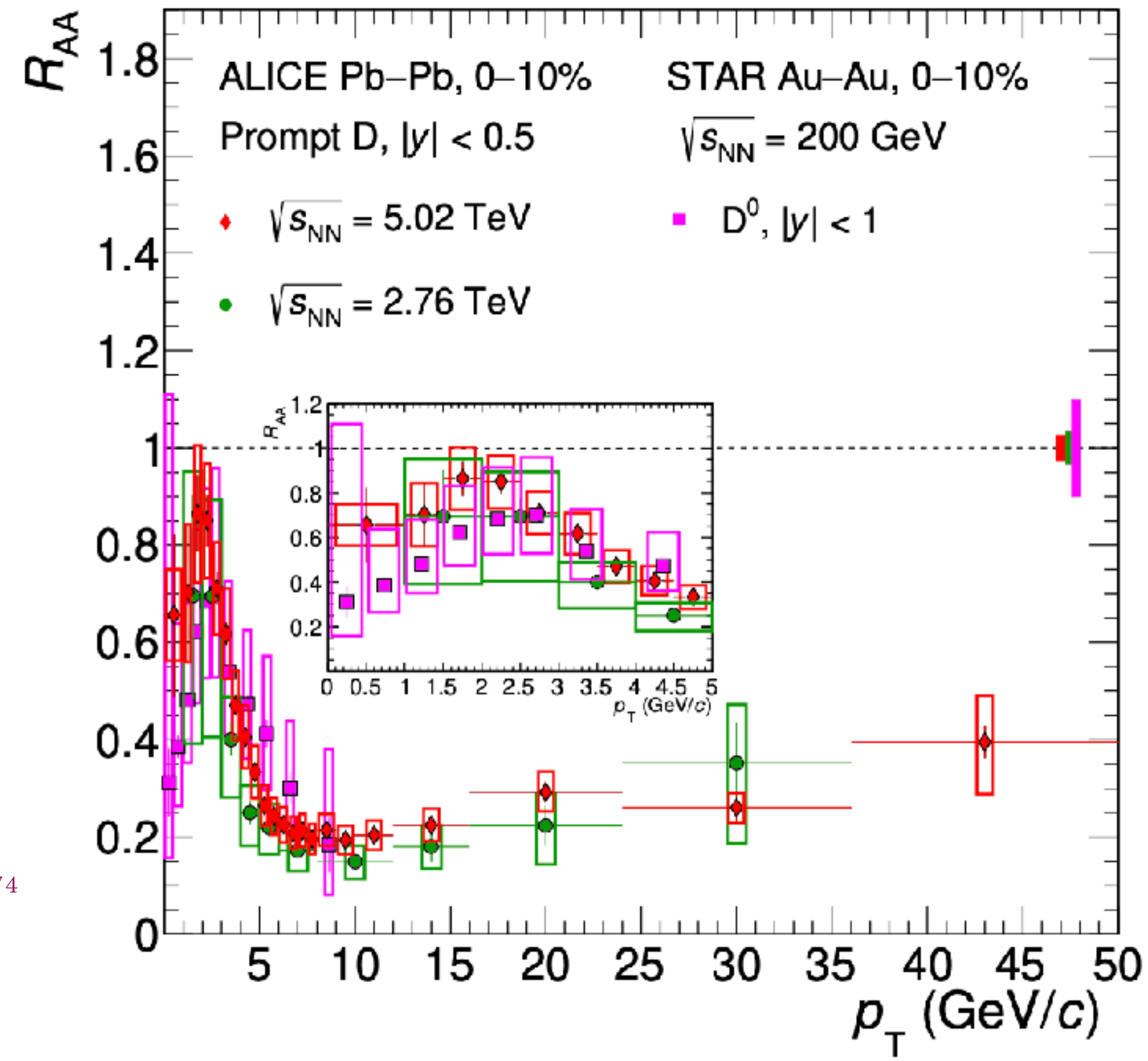
Hotter and denser medium in central Pb-Pb collisions compared to peripheral collisions.

R_{AA} of D mesons

$$R_{AA} = \frac{1}{< N_{coll} >} \frac{Y_{AA}}{Y_{pp}}$$

D mesons





JHEP 01 (2022) 174

ALICE
5.02 TeV
2.76 TeV

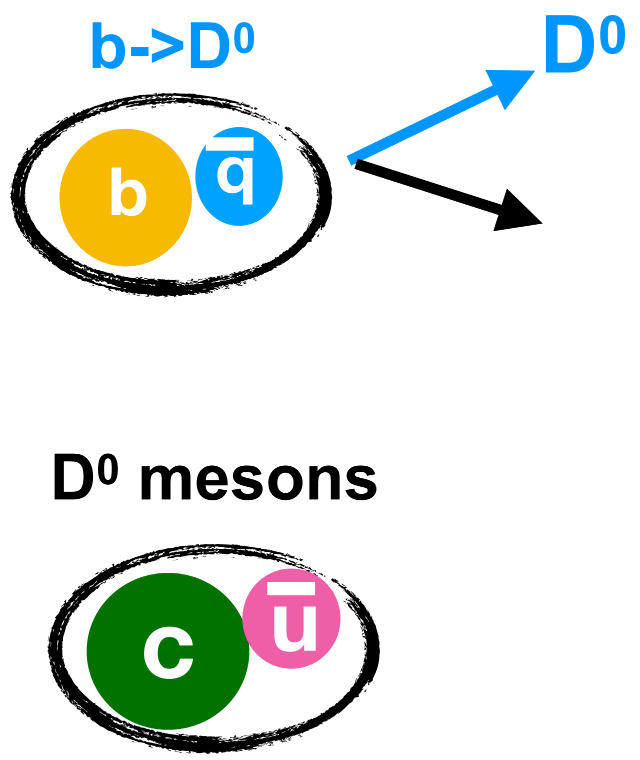
STAR
200 GeV

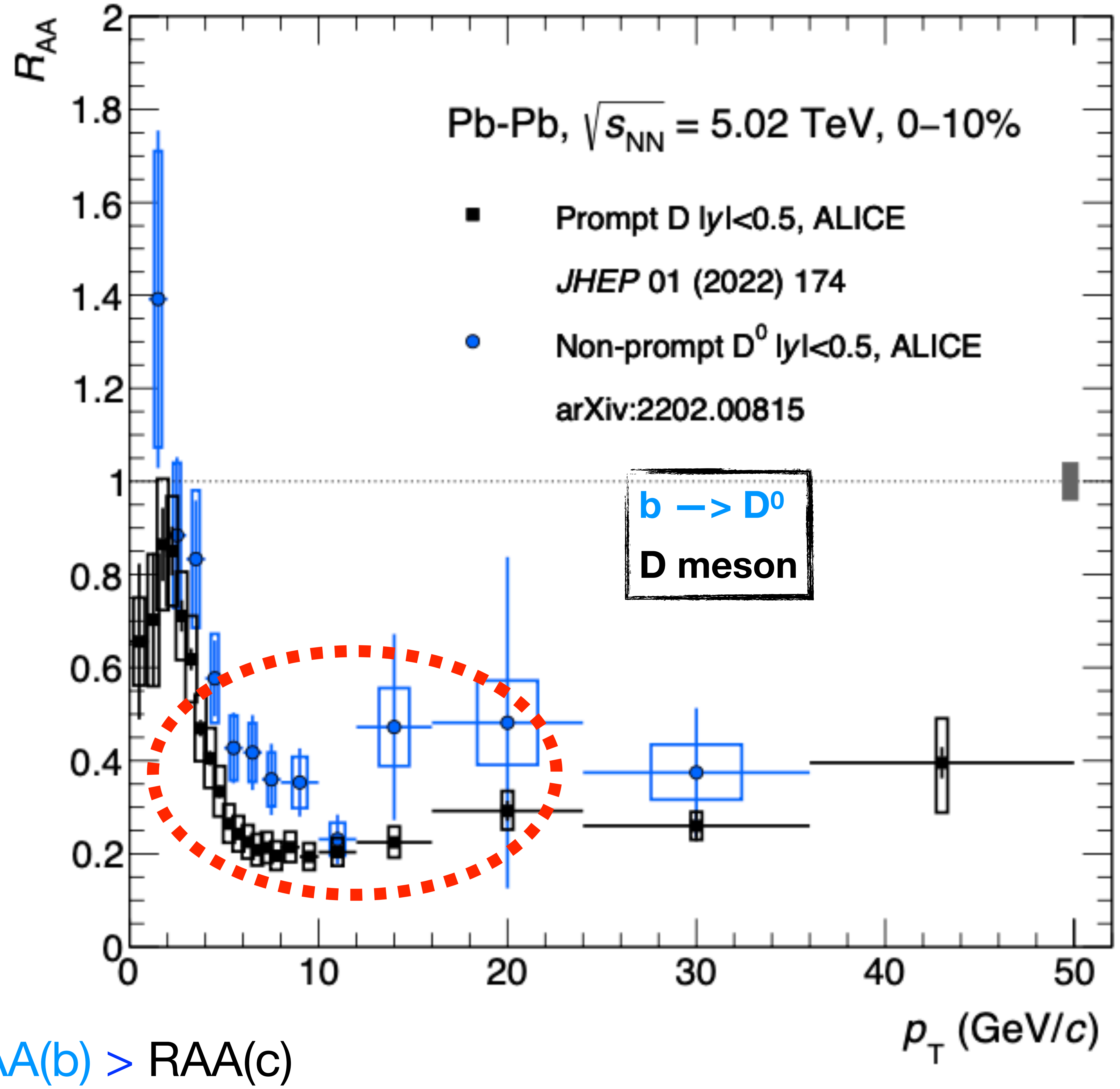
R_{AA} of D mesons at different collision energies at LHC and RHIC show similar p_T dependence.

—> interplay of p_T spectra shape and collision energy/initial temperature.

Mass hierarchy of energy loss

$$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) => R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$





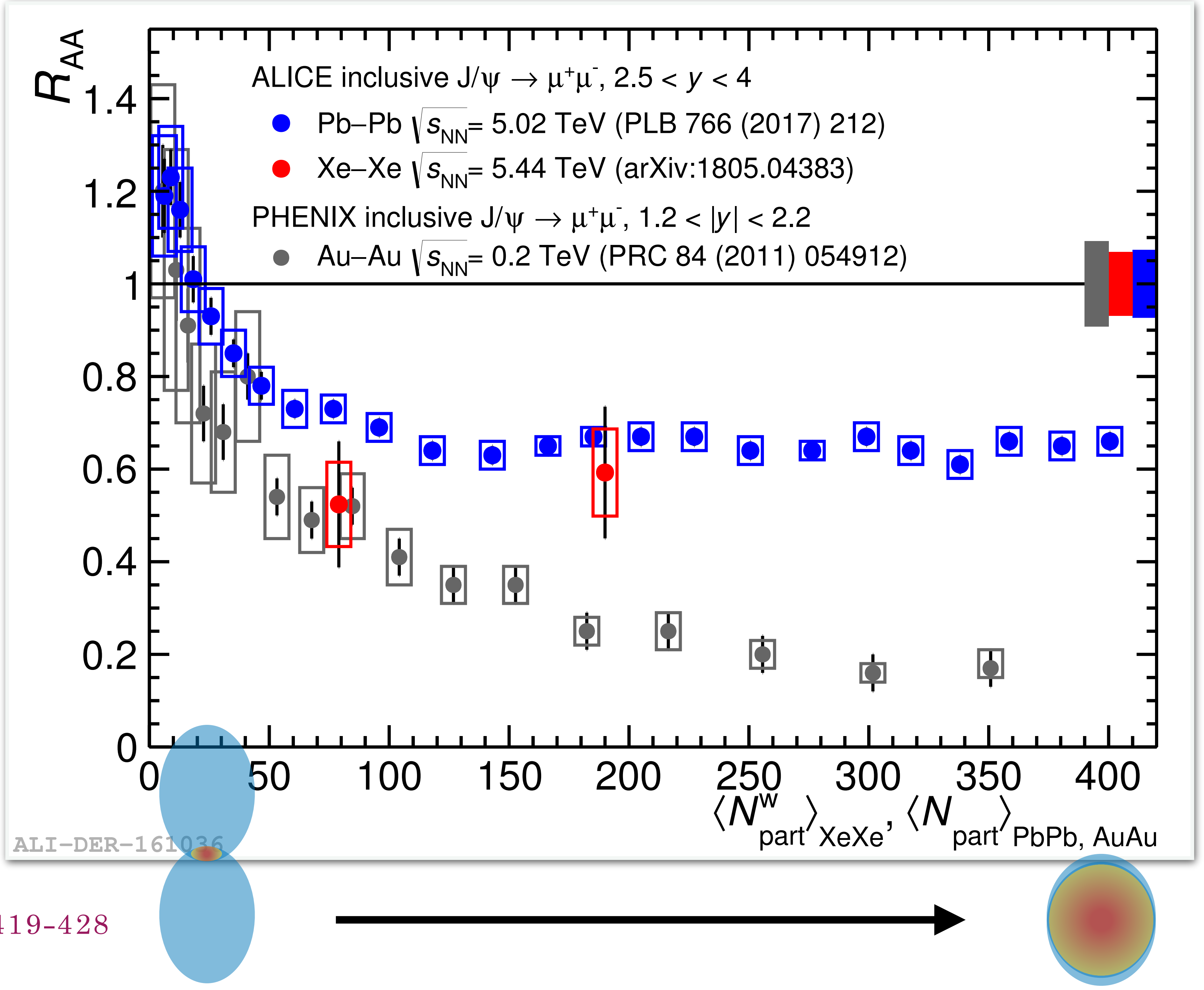
JHEP 01 (2022) 174
arXiv: 2202.00815

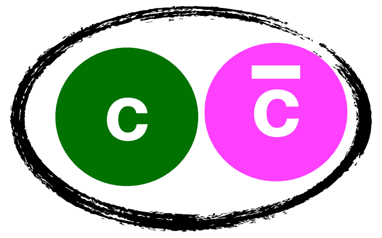
Intermediate p_T (5-20 GeV/c): RAA(b) > RAA(c)

High p_T: RAA(b) ~ RAA(c)

R_{AA} of Charmonia

J/Ψ





LHC

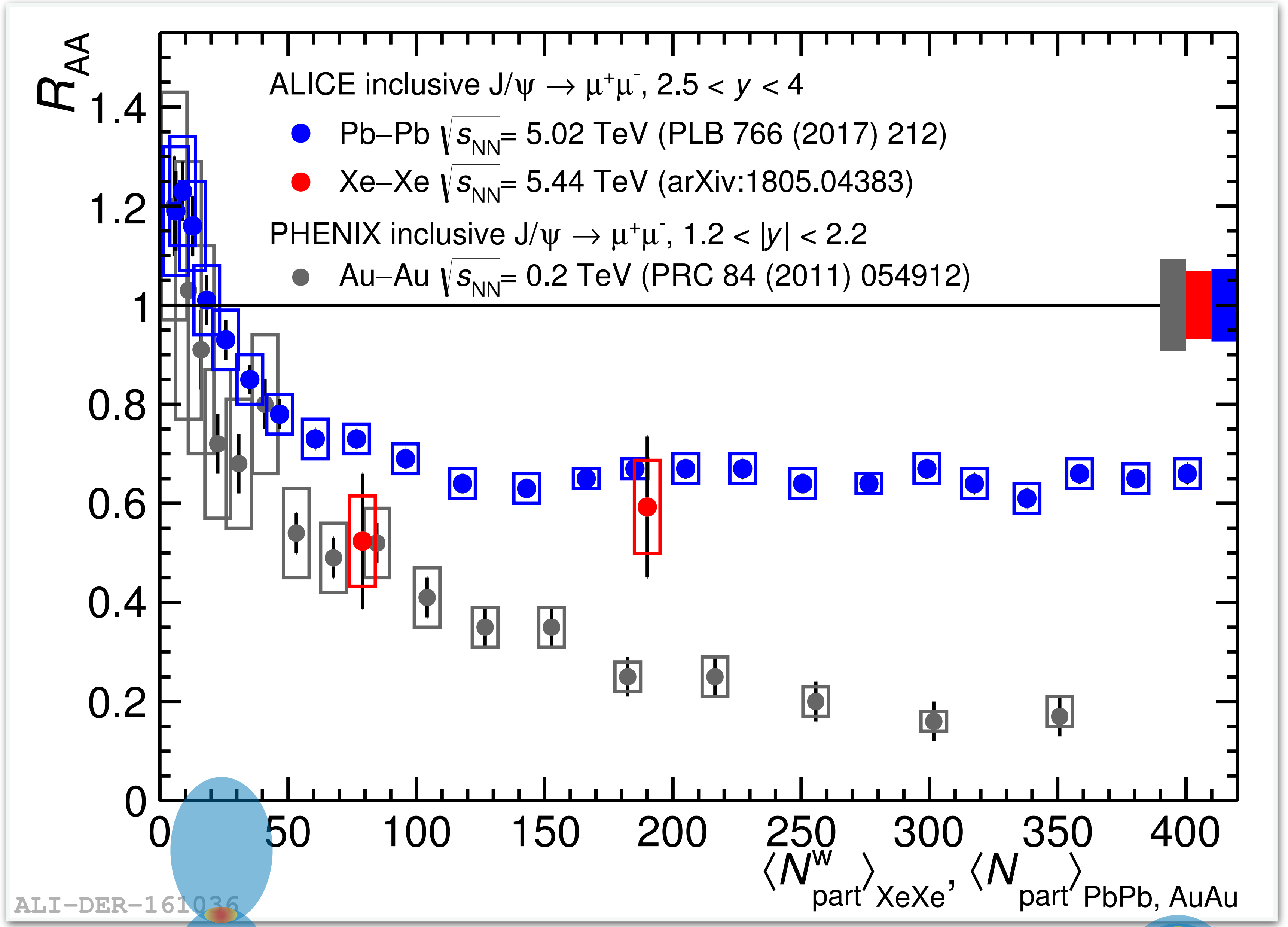
RHIC

PLB785 (2018) 419-428

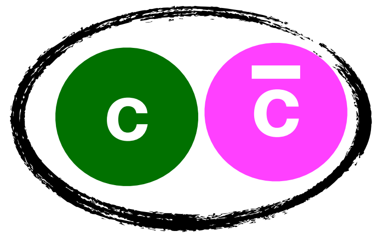
- **LHC**: **increasing suppression with centrality** up to N_{part}~100, followed by a **constant R_{AA} due to regeneration effects**.
- **RHIC**: increasing suppression with centrality; **smaller effects of regeneration.**

R_{AA} of Charmonia

J/Ψ

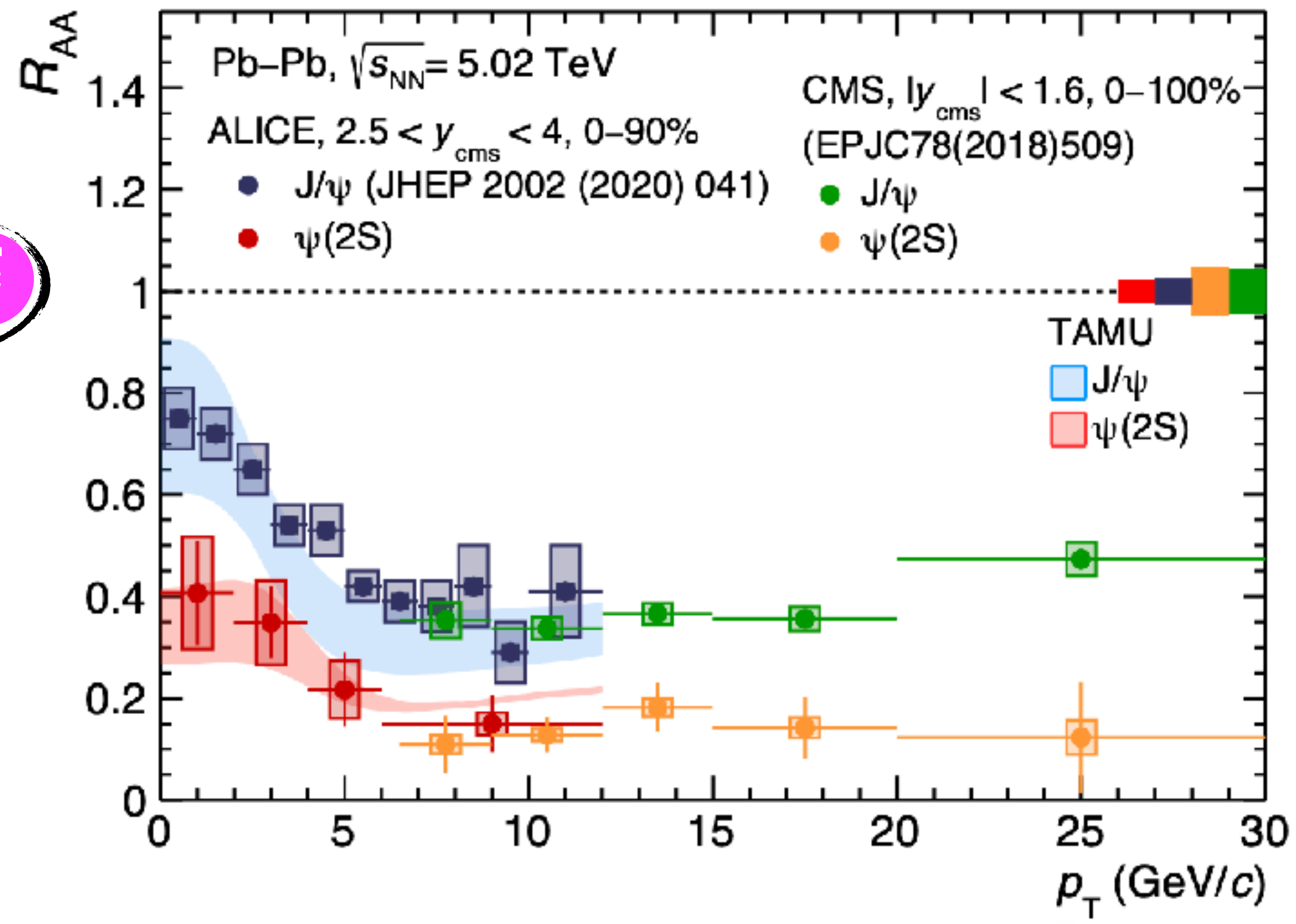


PLB785 (2018) 419-428



LHC

RHIC



J/Ψ
Ψ(2S)

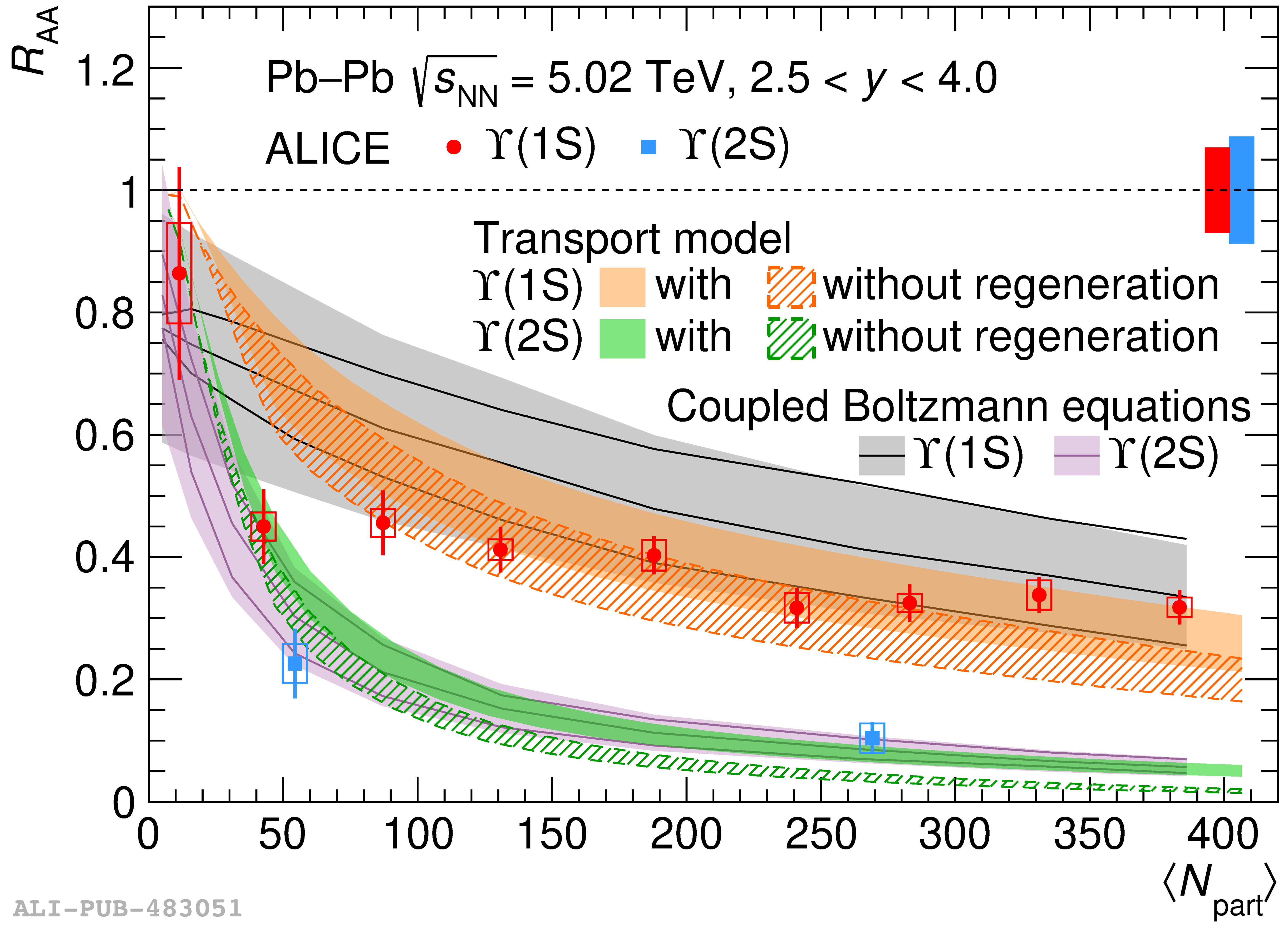
arXiv:2210.08893v2

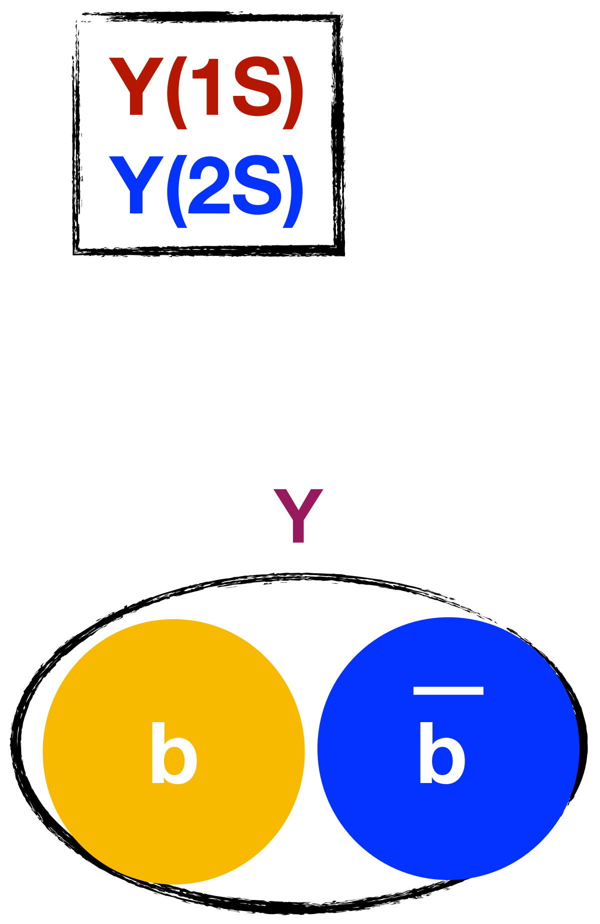
	J/Ψ	Ψ(2S)
Binding Energy (MeV):	640	50
Size (fm):	0.5	0.9

- **LHC**: **increasing suppression with centrality** up to N_{part}~100, followed by a **constant R_{AA} due to regeneration effects**.
- **RHIC**: increasing suppression with centrality; **smaller effects of regeneration.**

- **Larger suppression for Ψ(2S) compared to J/Ψ -> factor of 2**
- Similar p_T dependence
- Models including recombination describe data.

R_{AA} of Bottomonium



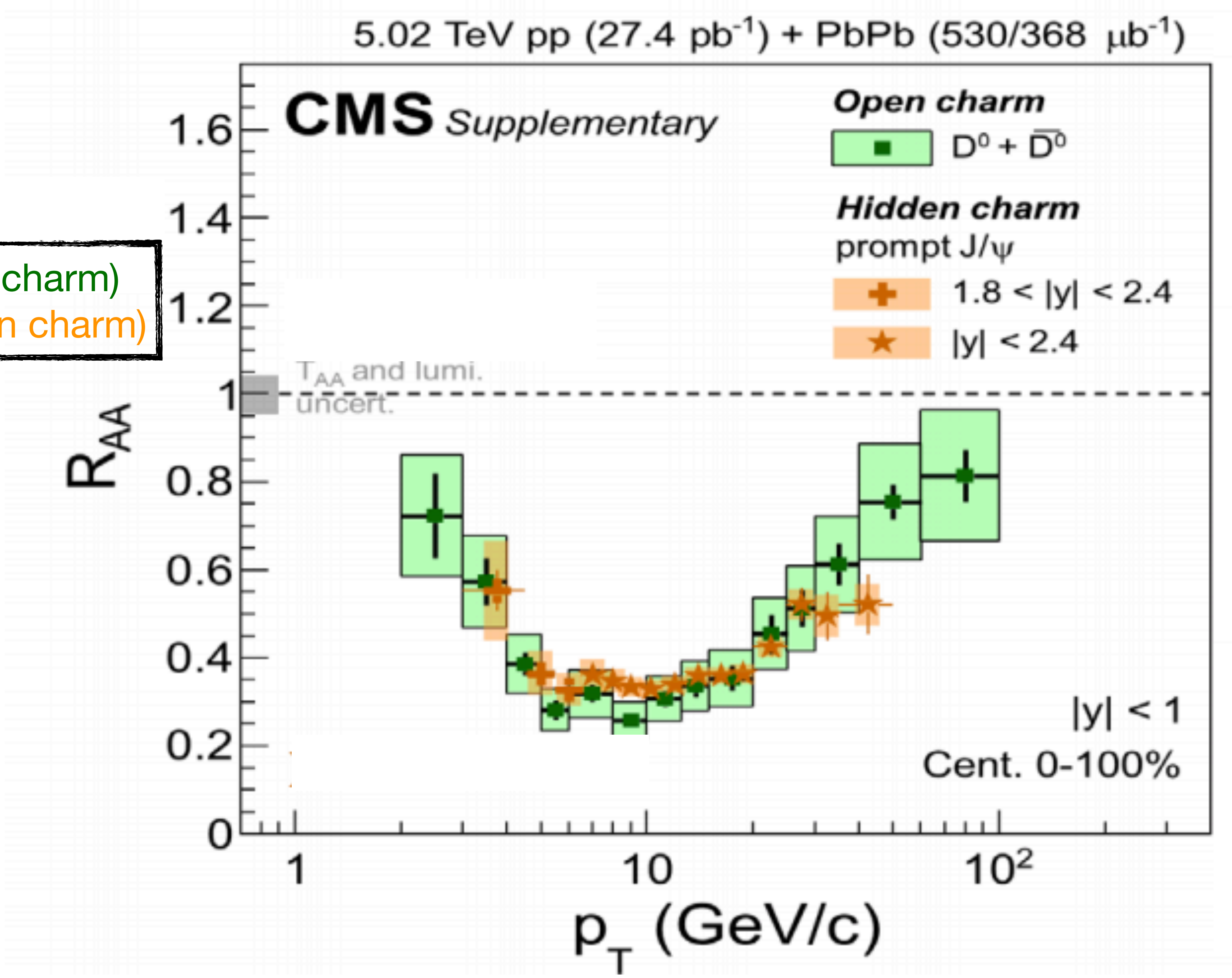


- **Strong suppression of Y(1S) and Y(2S)** observed in central Pb-Pb collisions.
- Transport models **without regeneration** compatible with data.

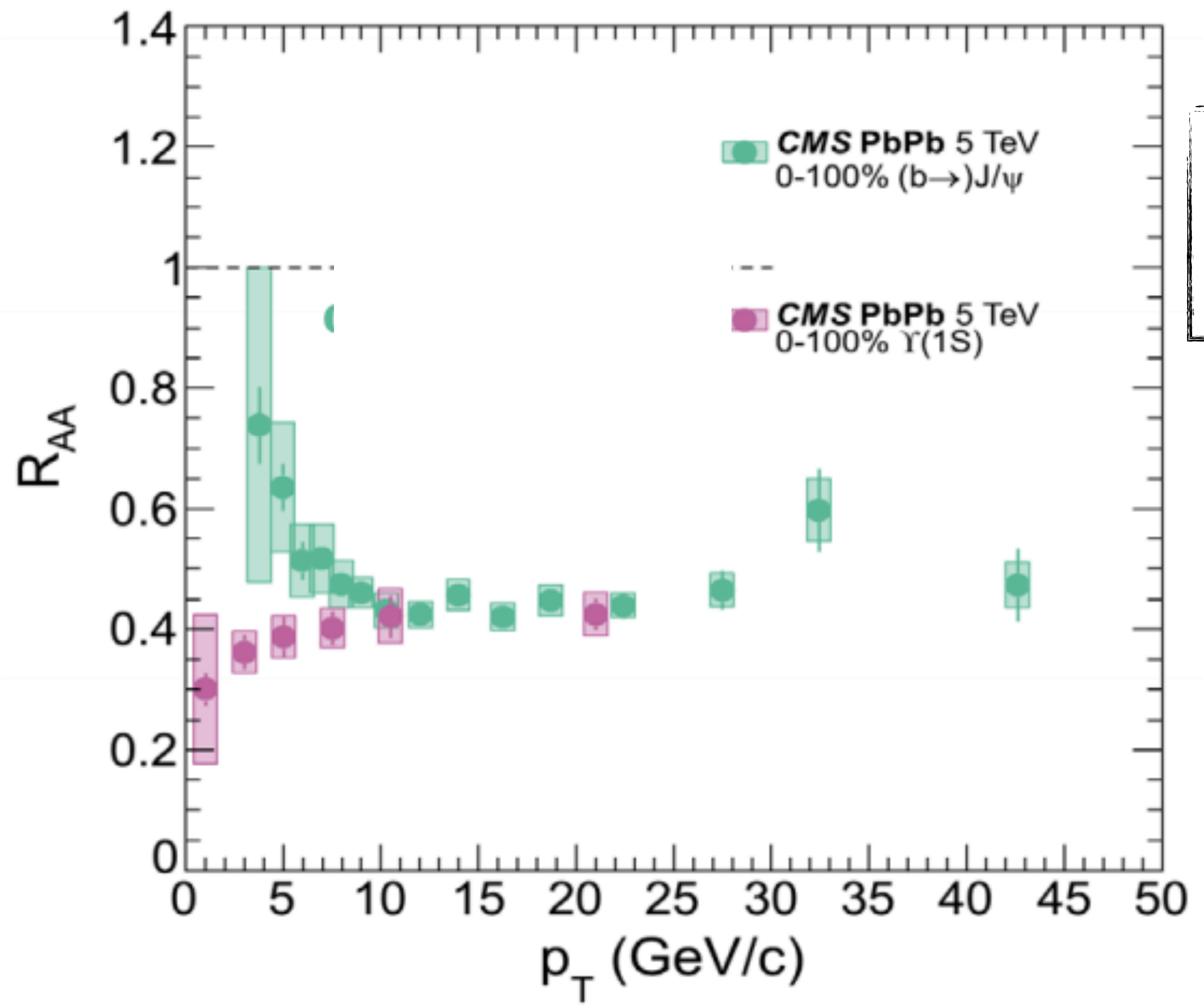
R_{AA} of open and hidden HF

Charm

D⁰ (open charm)
J/Ψ (hidden charm)



Beauty



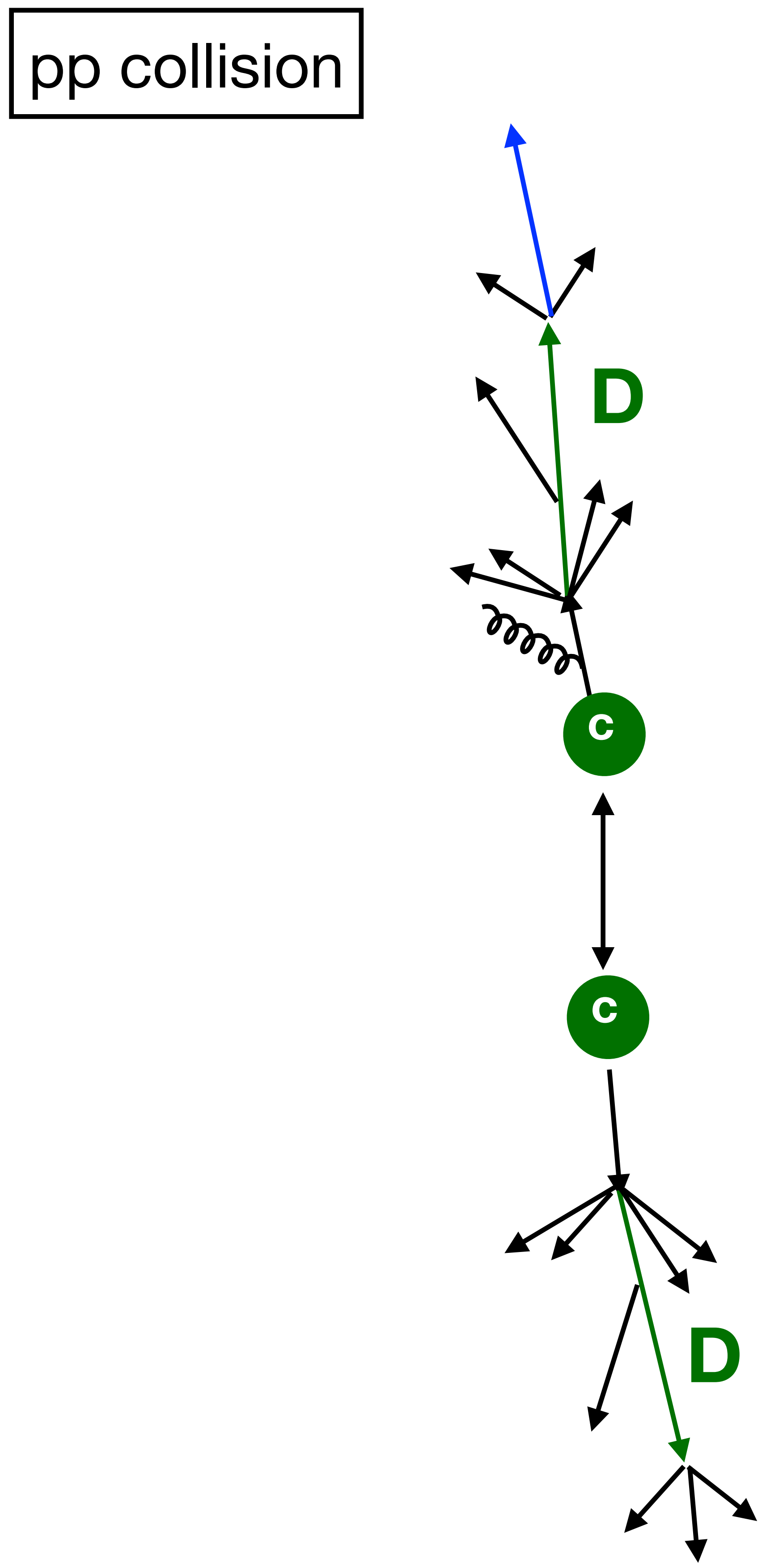
b-> J/Ψ (open beauty)
Υ(1S) (hidden beauty)

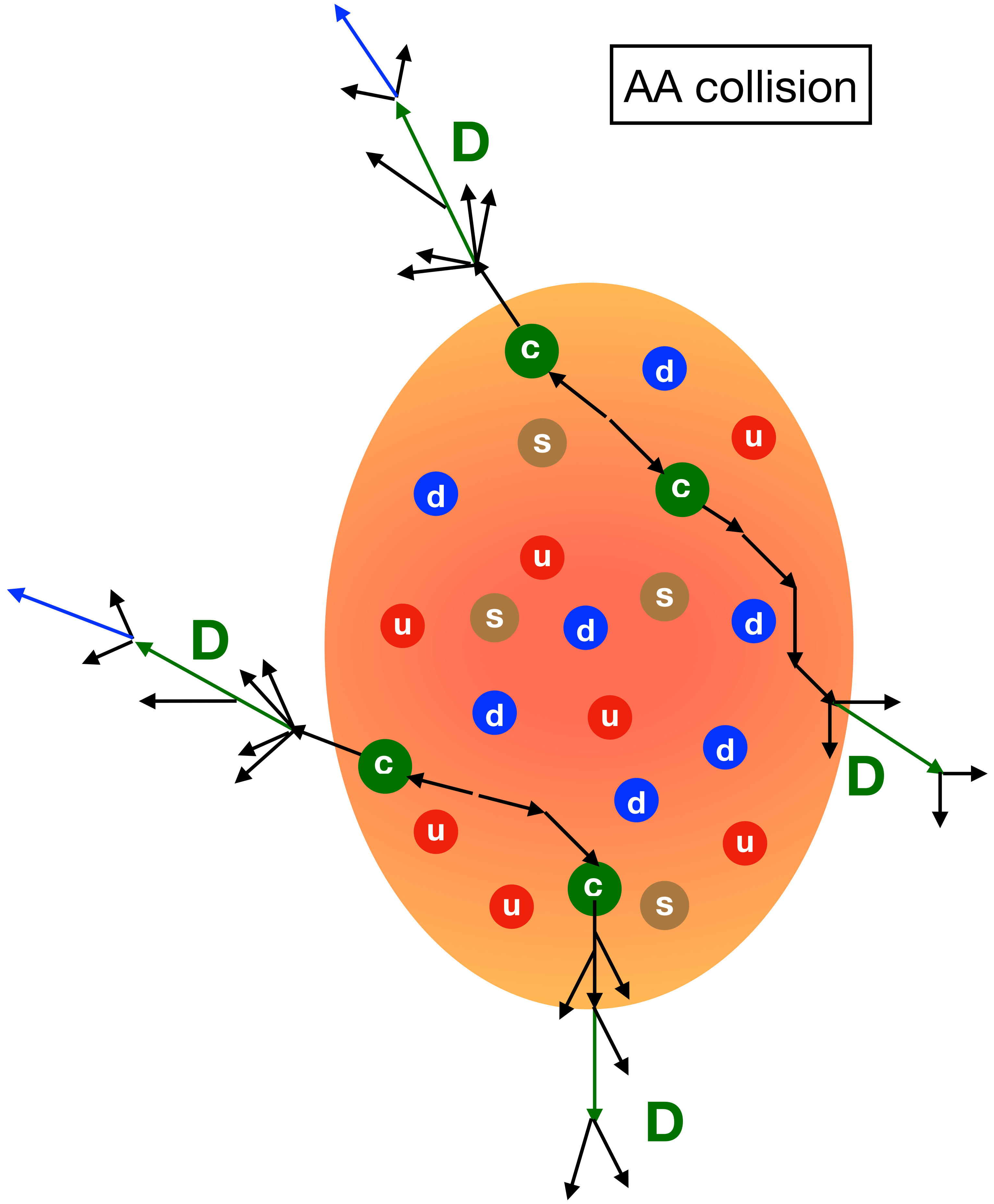
Camelia Mironov @ HP2020

- **Charm: same trend in the full p_T range.**
- **Beauty: difference at low p_T; same trend at high p_T.**

Jet structure and fragmentation

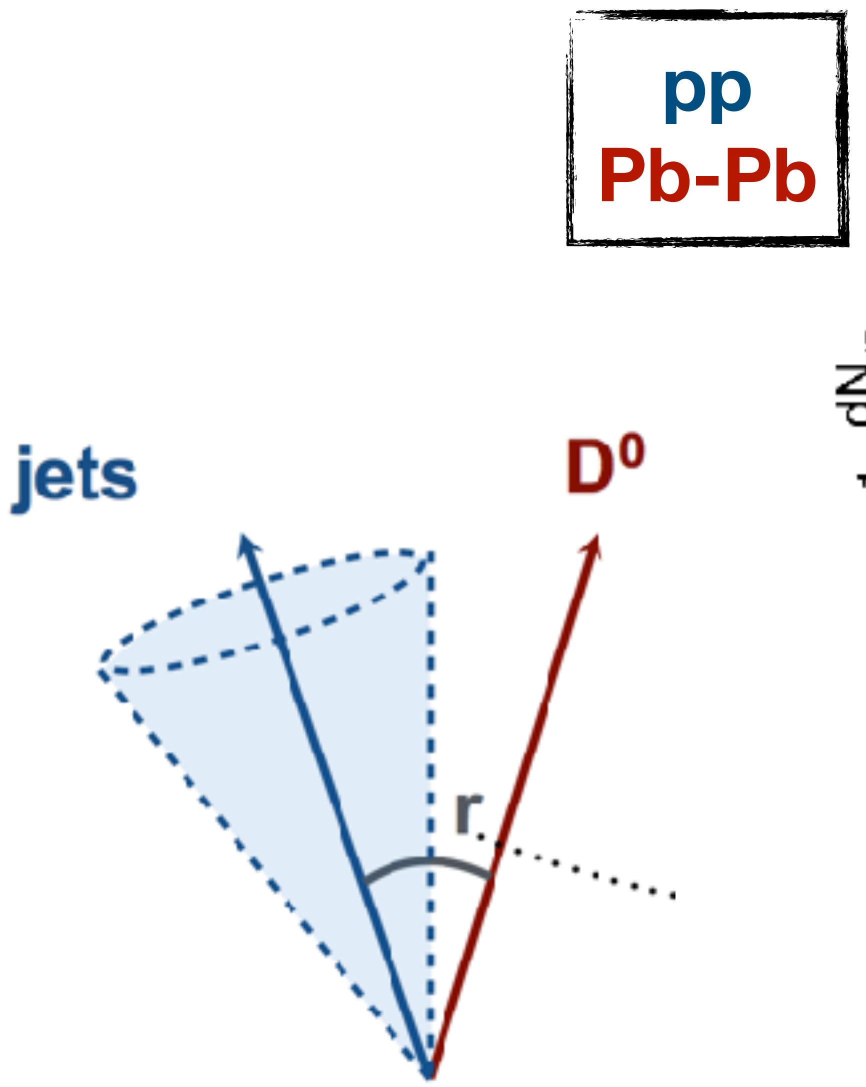
The hard scattered partons propagates through the QGP —> jet shower itself evolves; jet constituents interact with the medium modifying the shower.

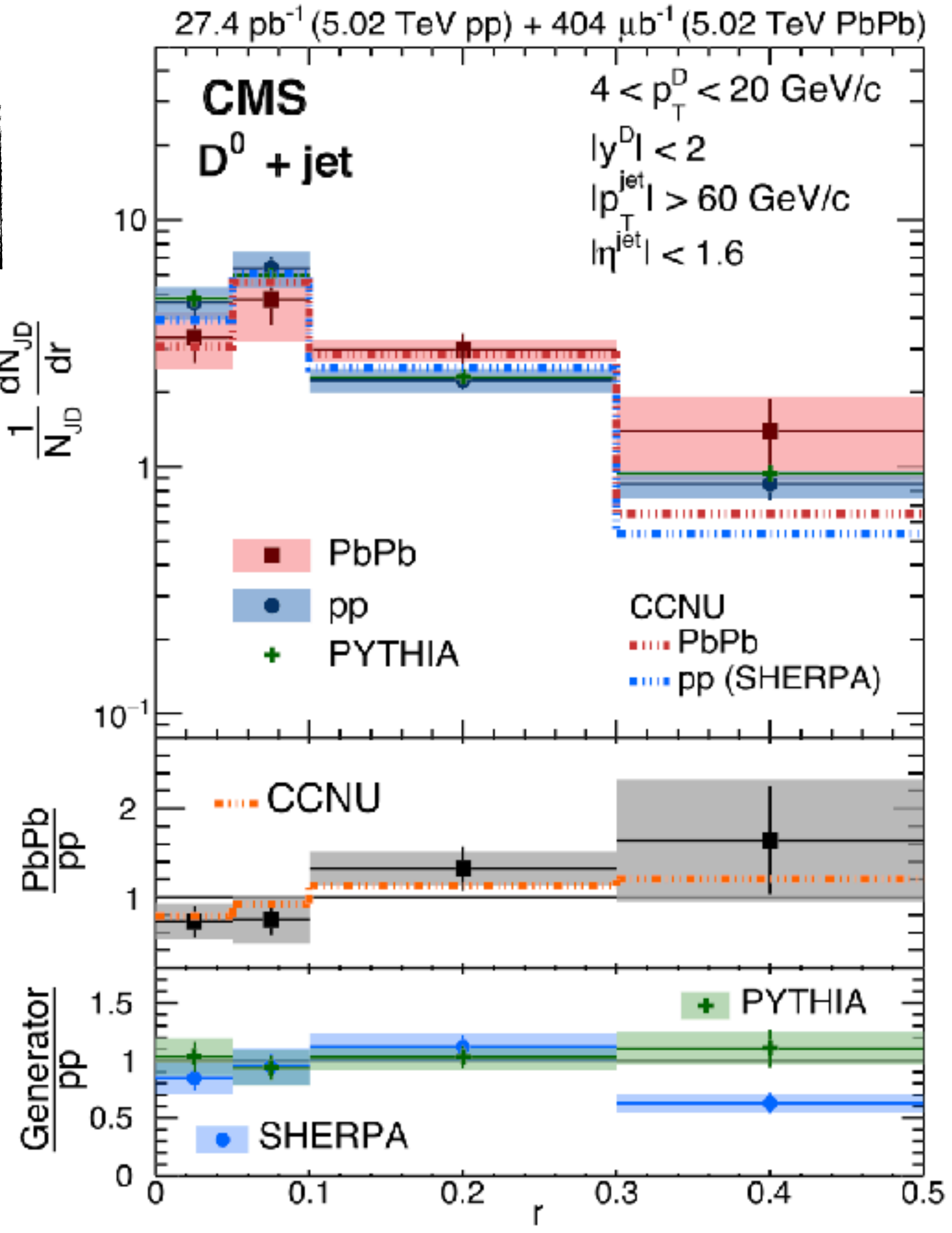




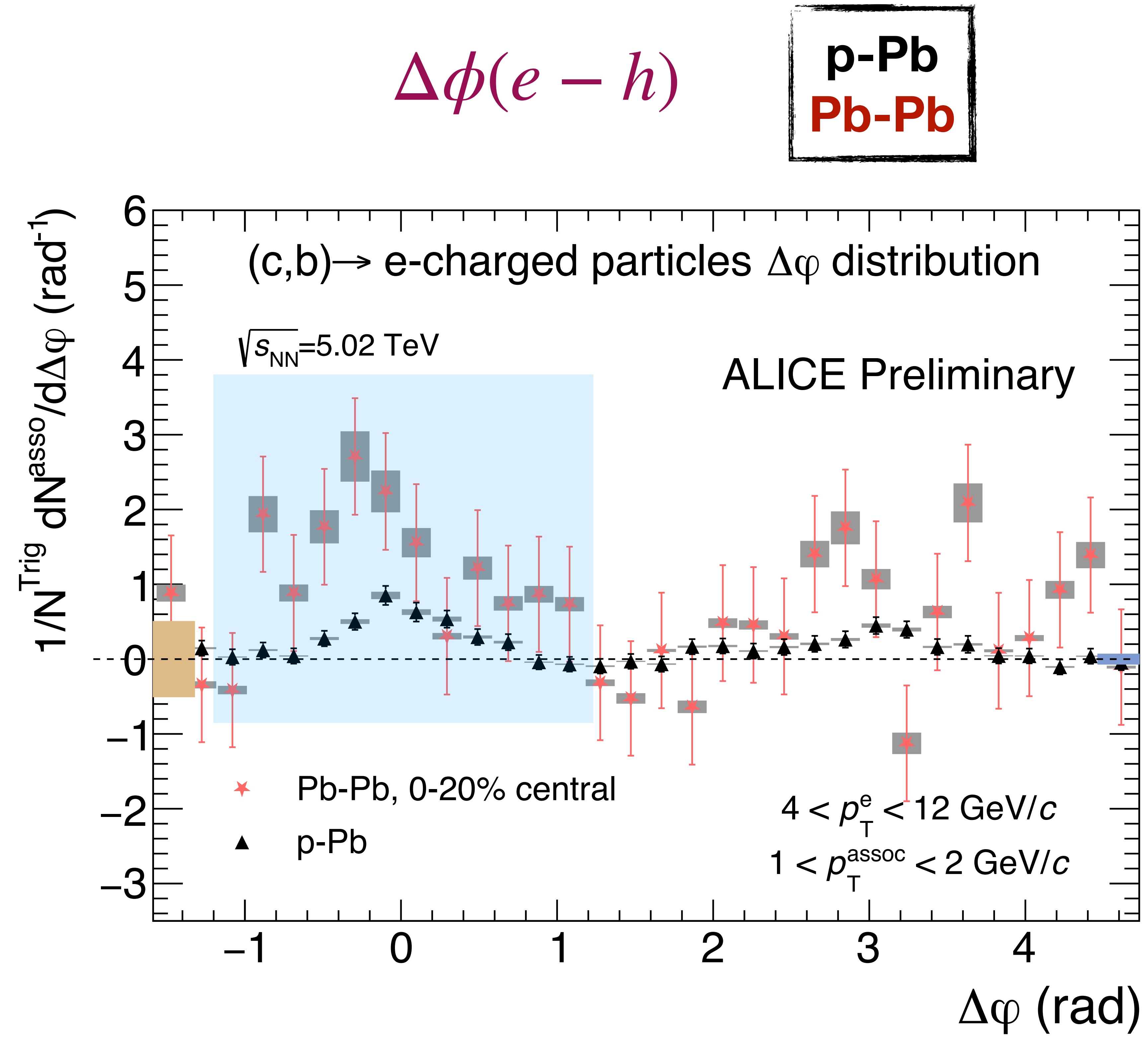
Jet fragmentation in AA

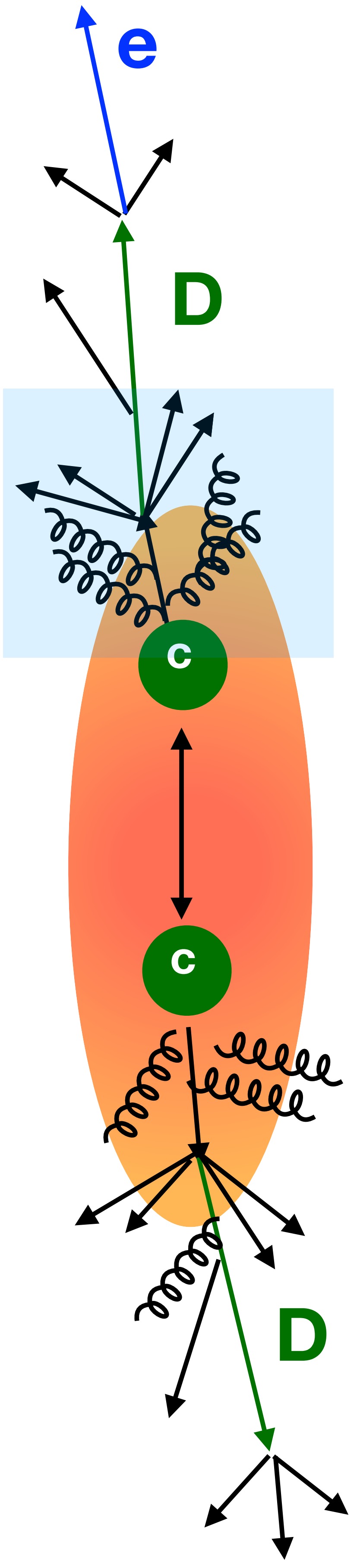
Study the modification of jet fragmentation in QGP





PRL 125 (2020) 102001





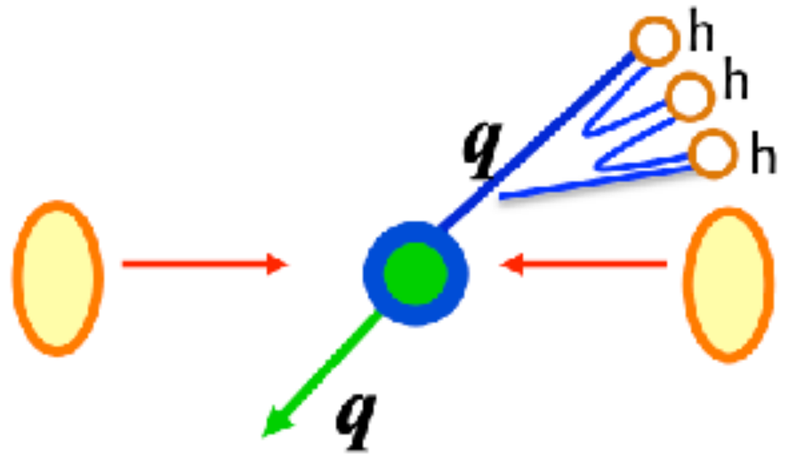
- Radial distribution of D^0 in jets - D^0 further away from jet-axis in Pb-Pb compared to pp.

- HF electron - hadron correlations - Enhancement of yield on near-side in Pb-Pb compared to p-Pb

—> Energy loss goes into low p_T particles

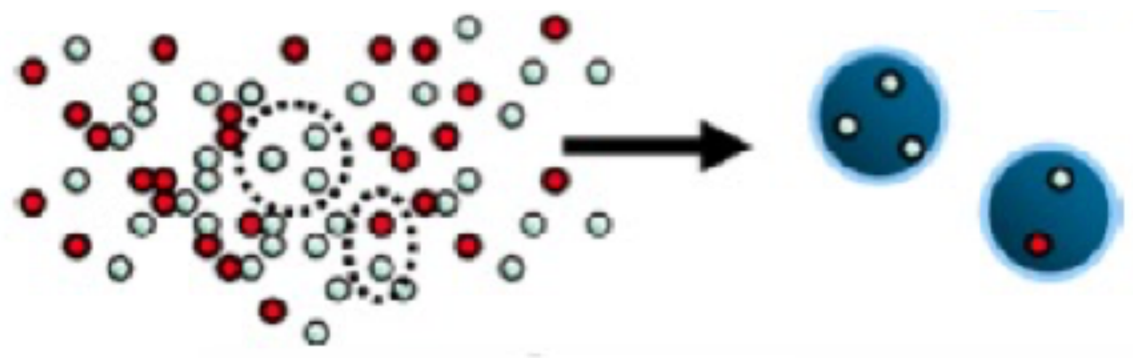
Hadronization

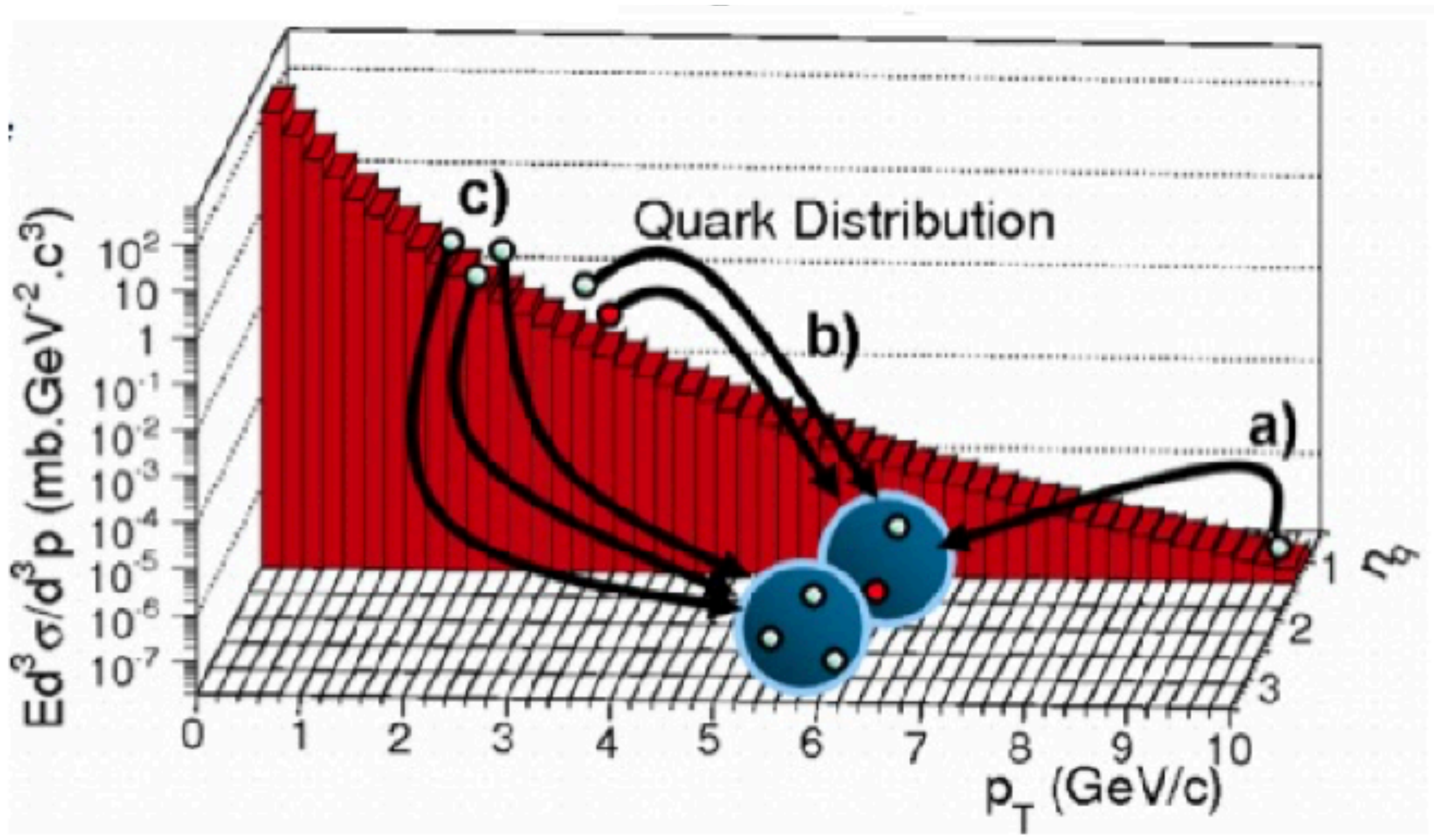
e+ e- like fragmentation



- Phenomenological models (cluster and string model) based on parametrization using e+ e- data

Recombination / Coalescence





a) 6 GeV/c pion from 1x 10 GeV/c quark fragmentation
b) 6 GeV/c pion from 2x 3 GeV/c quark recombination
c) 6 GeV/c proton from 3x 2 GeV/c quark recombination

- High parton density in QGP favors hadronization by recombination of quarks
  - dominant at low momentum

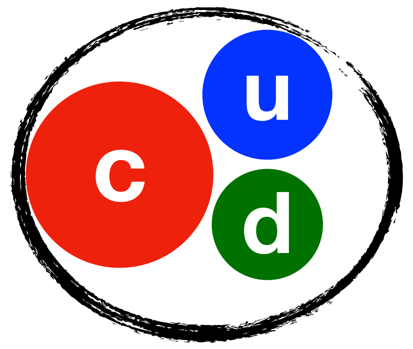
- Affects momentum distribution and azimuthal anisotropy of hadrons, and enhances baryon/meson ratios

$$\vec{p} = \sum \vec{p}_{quark} \qquad v_n^{hadron} = \sum v_n^{quark}$$

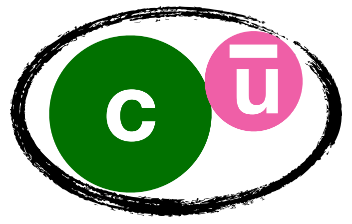
Hadronization using baryons

Studying heavy-flavour hadronization mechanism using Λ_c

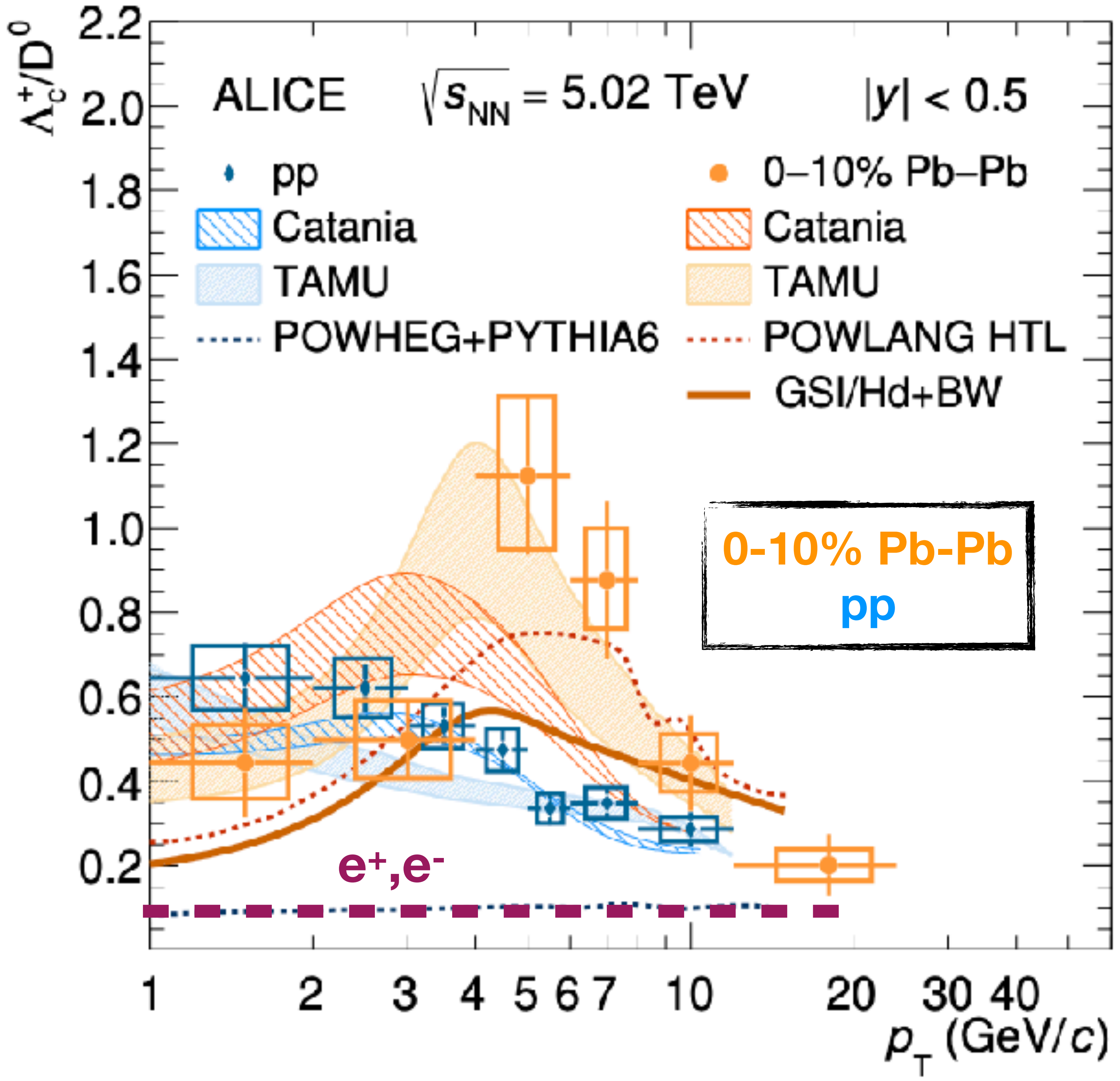
Λ_c baryon



D^0 meson



arXiv:2112.08156



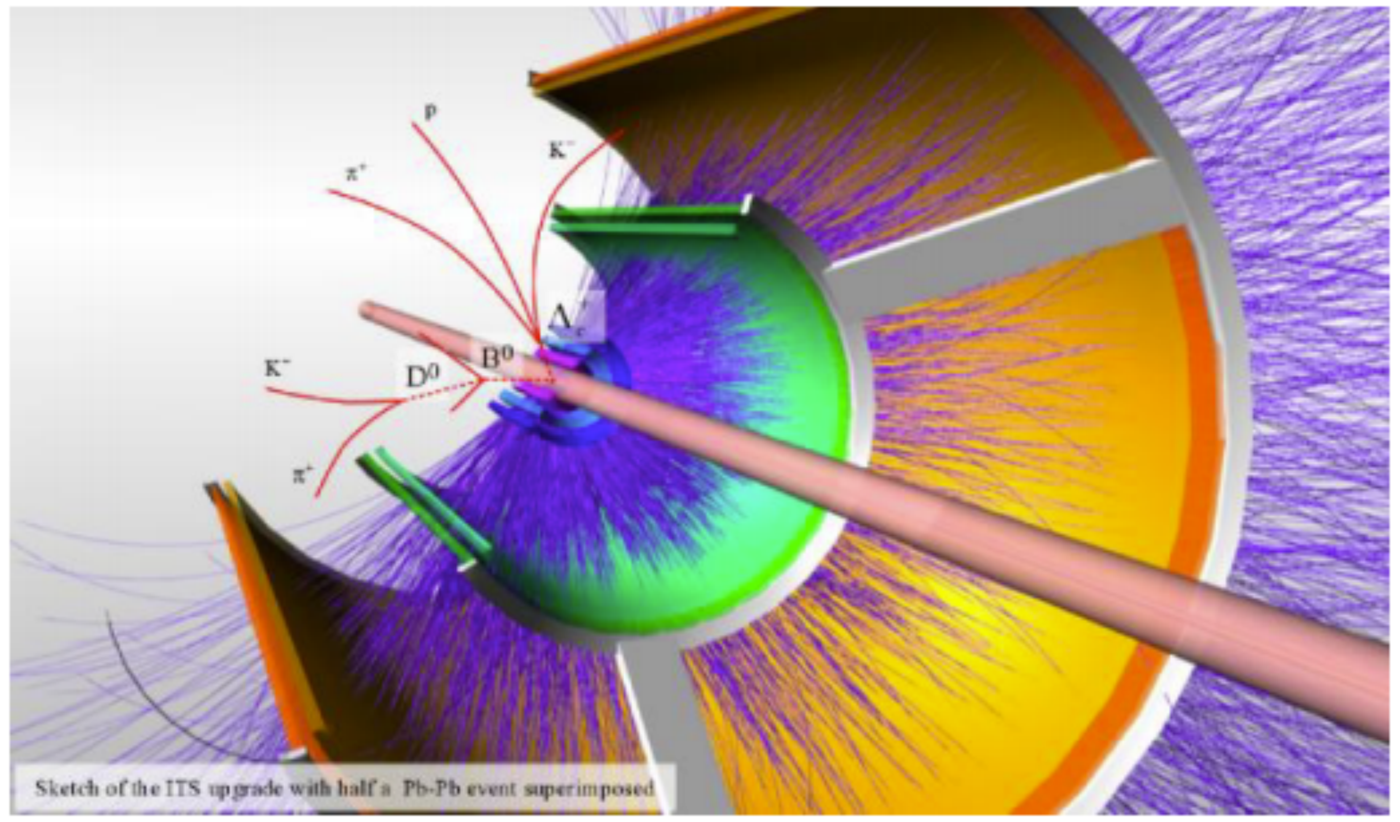
- Λ^+_c/D^0 in Pb-Pb collisions higher than in pp

-> model calculations with fragmentation and coalescence favors data.

Summary

- **Heavy quarks** are excellent probes to study the properties of QGP.
- Heavy quark interaction and energy loss studies using charm and beauty hadrons.
  - In-medium energy loss —> mass hierarchy seen
  - Charm quarks participate in the collective expansion of the medium
- Study of jet-fragmentation and hadronization.
  - Indication of modification in the QGP.
- Several new heavy-flavor measurements anticipated in Run3&4 at the LHC and at RHIC
  —> exciting times ahead.

Future prospects



LHC:

Run3

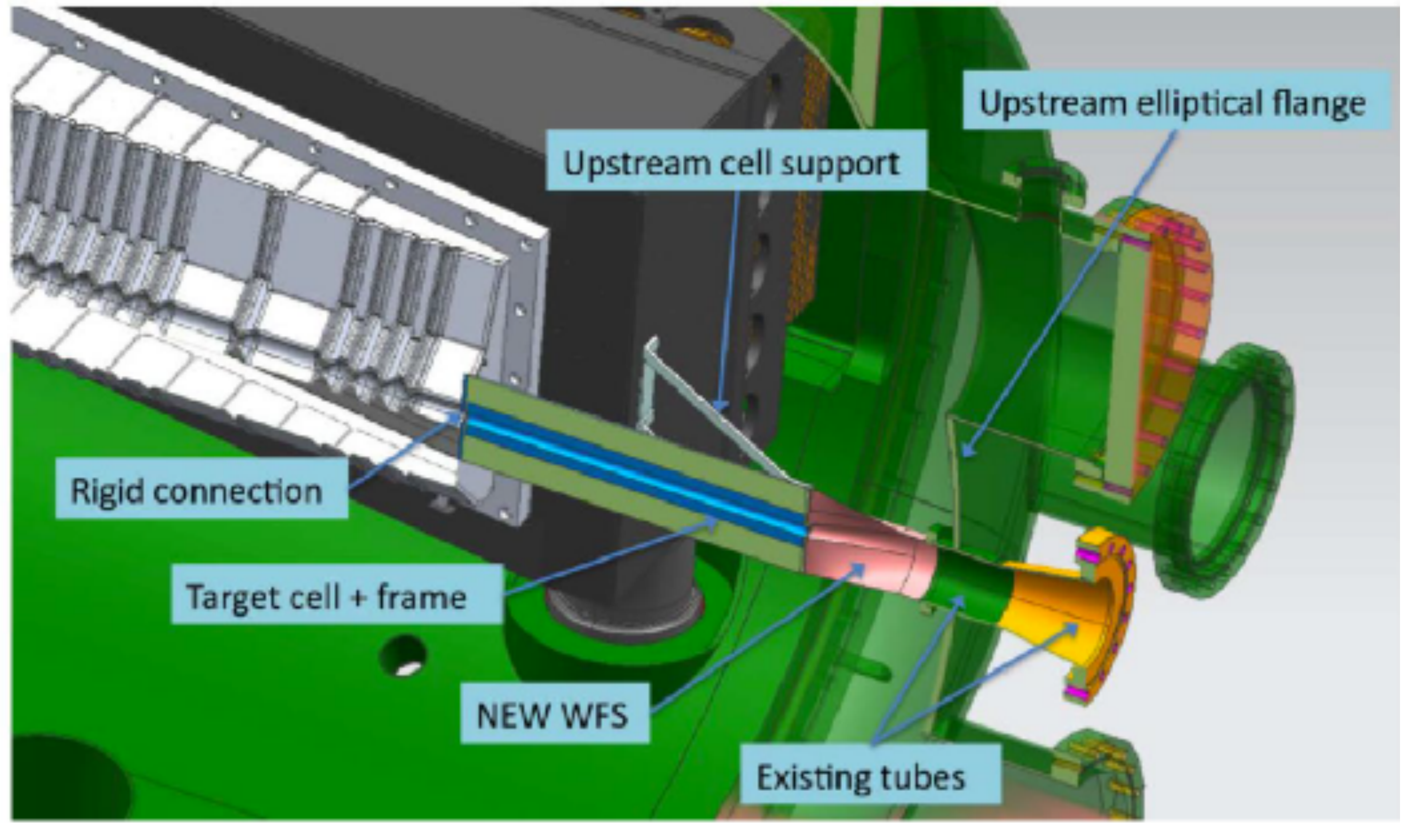
ALICE: New ITS, MFT, TPC readout chambers and fast interaction trigger
—> high precision measurements including beauty hadrons possible.

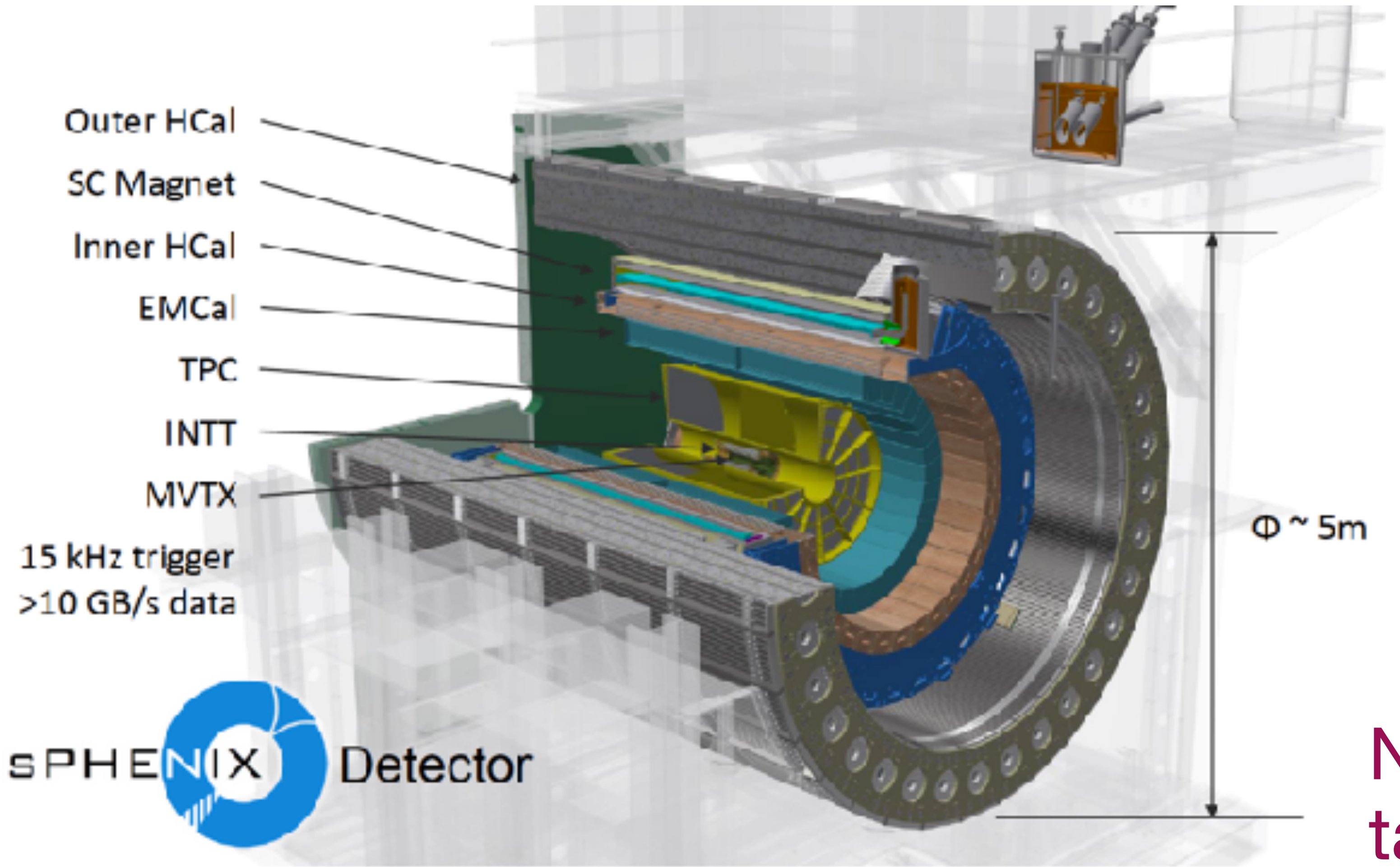
LHCb: SMOG upgrade
—> high precision charm measurements at different $\sqrt{s_{NN}}$.

LS3 for Run 4

ATLAS: New ITK —> Heavy-flavor jet measurements

CMS: Upgrade Inner tracker —> Heavy-flavor measurements at low p_T





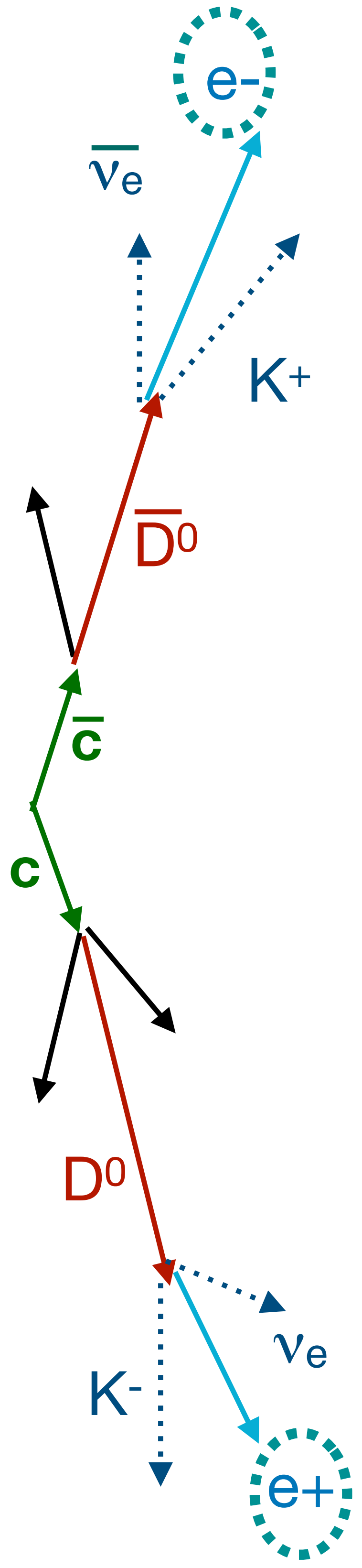
RHIC:
sPHENIX: extensive heavy-flavor physics including measurements of b-jets and full B meson reconstruction

New measurements and techniques in the next talk by **Gian Michele Innocenti**

Backup

How to study HF

- Open heavy-flavour
- Quarkonia
- Di-leptopns



Di-lepton pairs (electron-positron pairs)

- From correlated semi-leptonic decays of heavy-flavor hadrons.
- Probe full p_T range of heavy-quark pairs and contain complementary information about the initial correlation of heavy quarks.
- HF decays dominate in the intermediate mass range ($1.03 < m_{ee} < 2.86$ GeV/c^2).