What heavy-flavor has taught ~~us~~ me about the QGP - What's in store for the future

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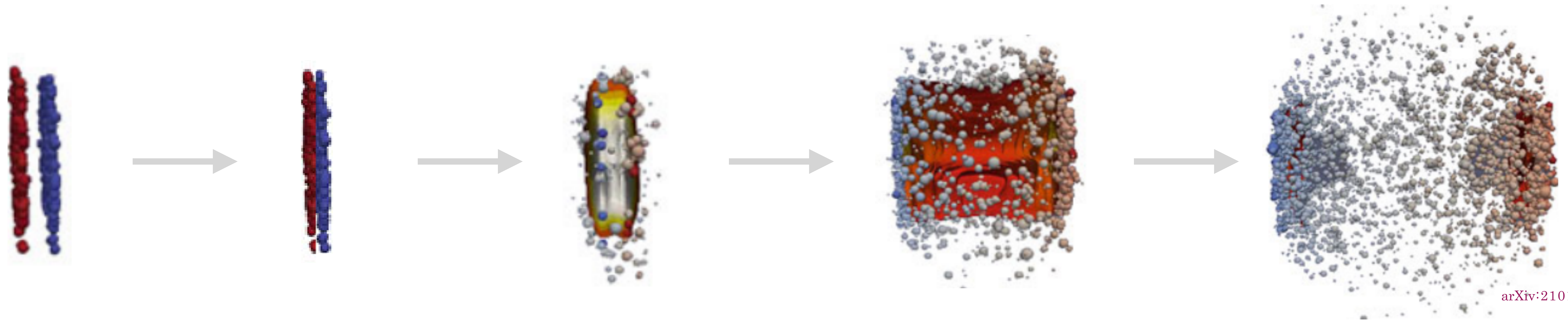
Introduction

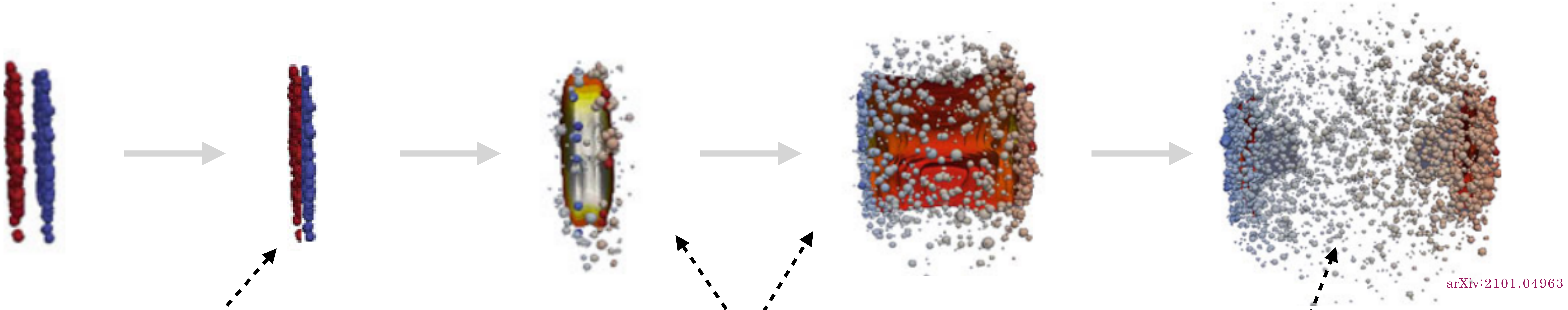


- **Quark Gluon Plasma** produced in high energy heavy-ion collisions.
- Experimentally exploring QGP since 1990s at SPS, RHIC and at the LHC.
- Experimental evidence of QGP formation from light hadrons
  - Initial medium temperature above the critical Temperature Tc
  - Collective flow: system is strongly interacting and the medium evolution can be described by hydrodynamics —> ideal fluid
  - Jet quenching: High energy particles interact with QGP and undergoes energy loss
  - High energy density of QGP allows higher mass particles (strange quarks) to be thermally produced.

Why heavy-quarks?

- Our understanding comes from a macroscopic perspective.
- How does QCD interactions at the microscopic level lead to these emergent phenomena?
  -> probe inner workings of QGP by resolving properties at shorter length scales.

Heavy quarks (charm and beauty)



- 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

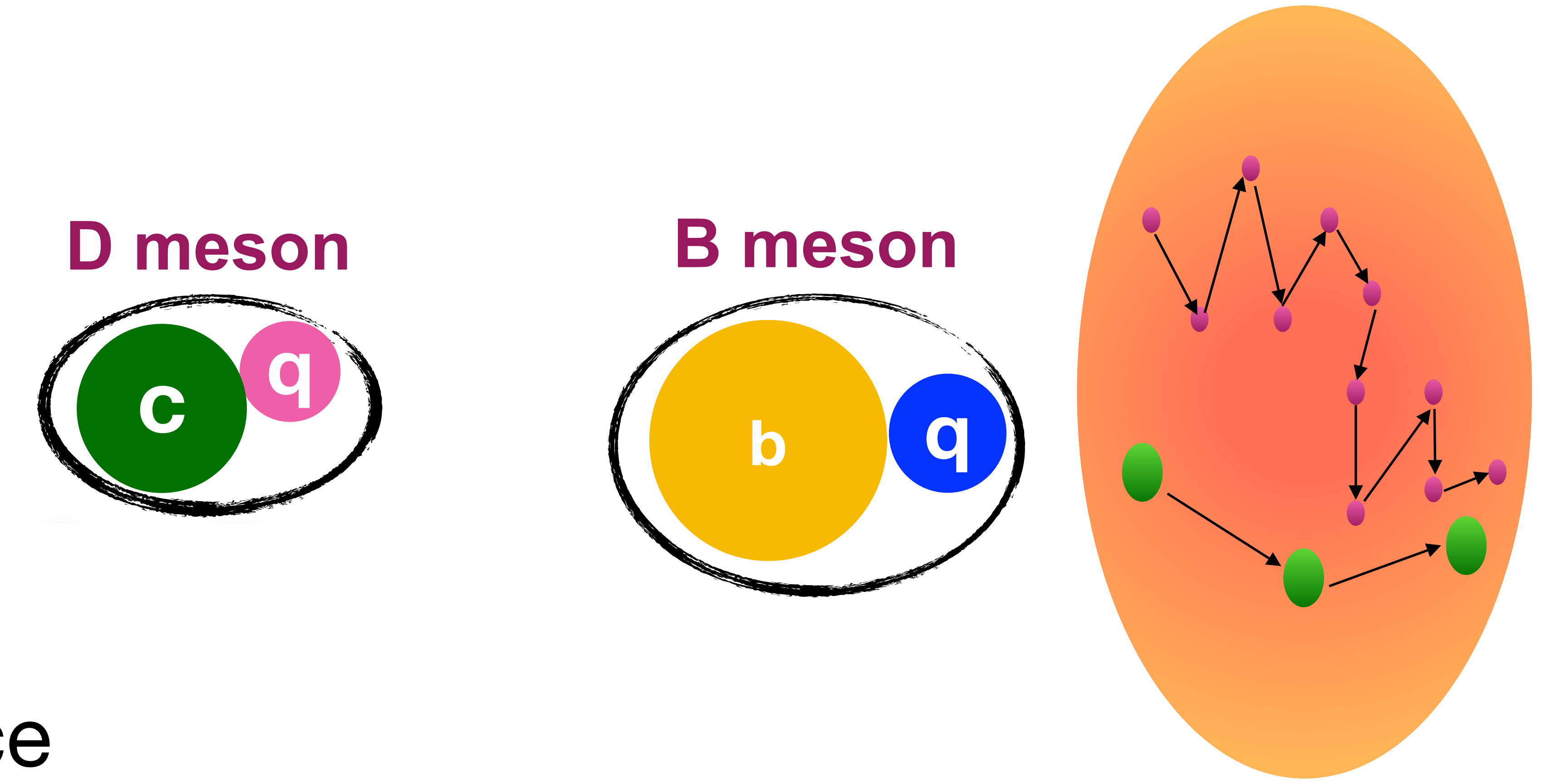
Open HF and Quarkonia

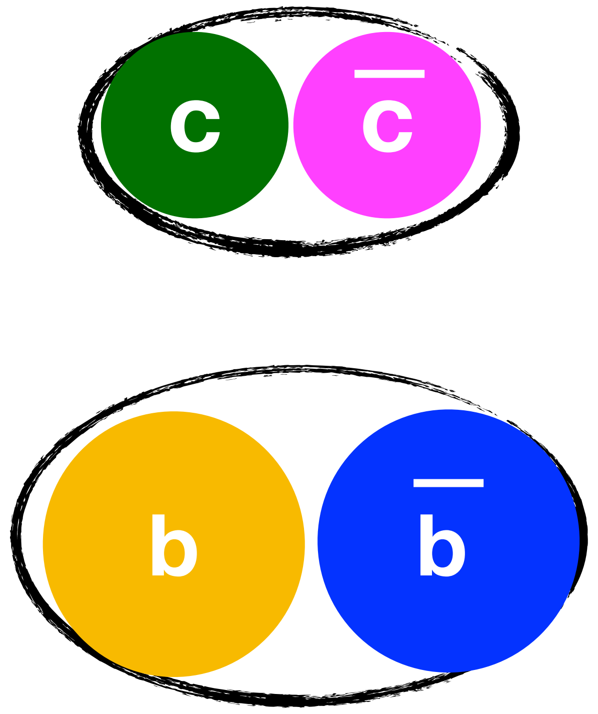
Open heavy-flavour : heavy quark (c/b) hadronise with light quarks (q)

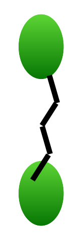
- D mesons(D^0, D^+, D_s, D^*_+), B meson (B^0, B^+,..)
- In-medium energy loss via collisional and radiative processes —> depends on quark mass and color charge

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

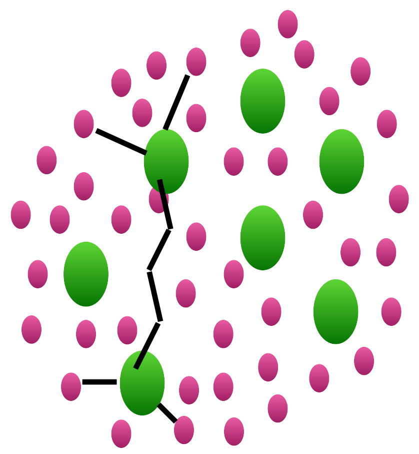
- Study fragmentation and hadronisation mechanisms in the presence of the medium







J/Ψ
in vacuum



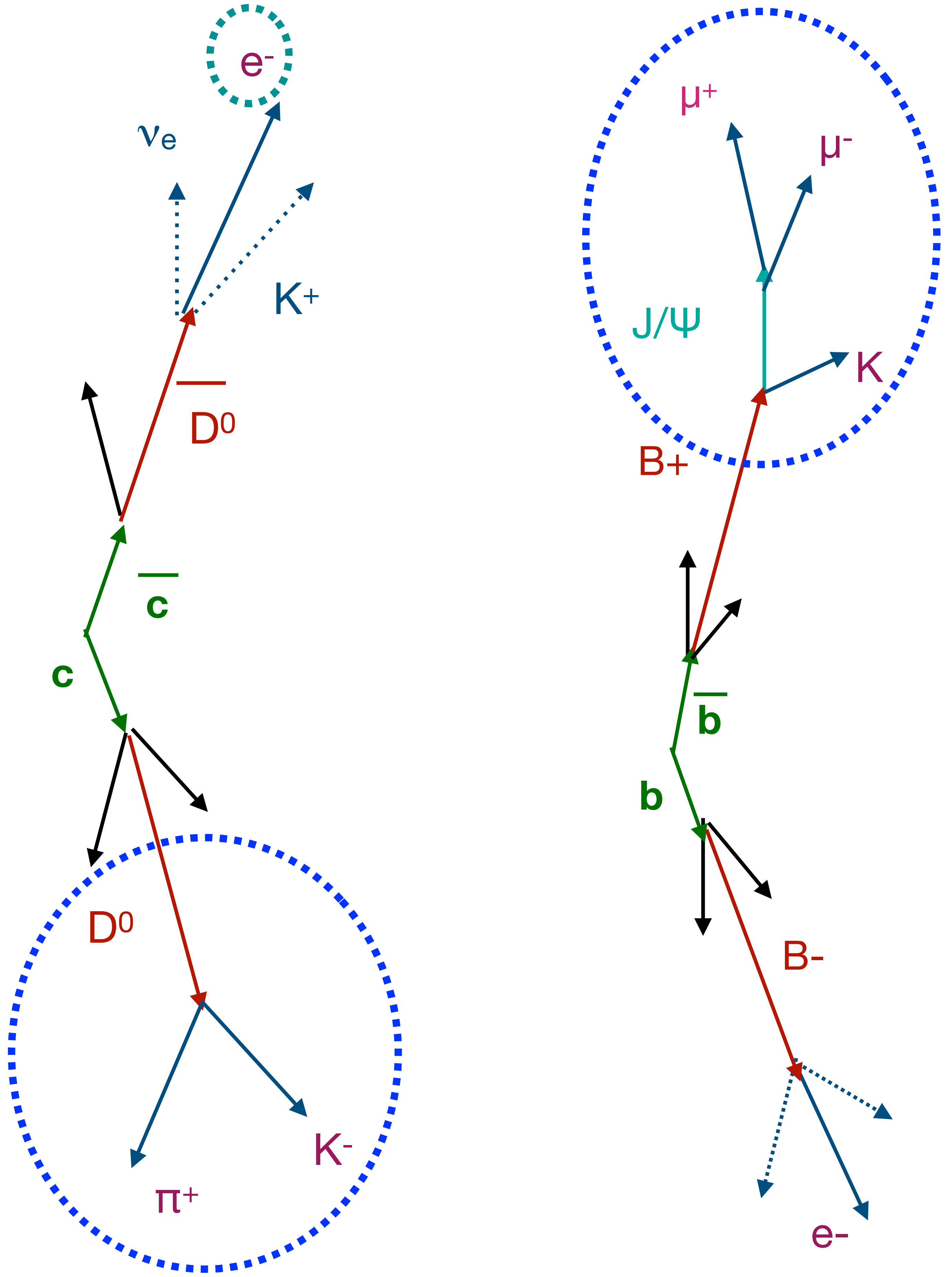
J/Ψ
in QGP

Debye screening of color charge

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

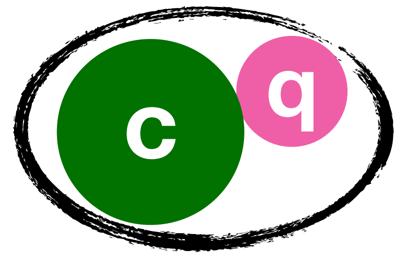
How we measure HF particles



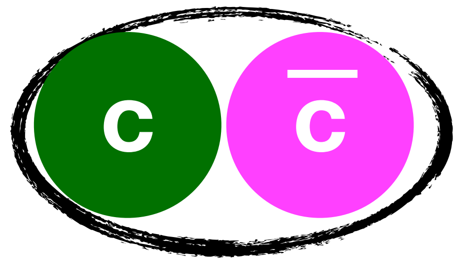
Experimentally heavy-flavour hadrons studied through their decay products:

- c,b -> l(e,μ) + X
- D^0 -> $K^- + \pi^+$
- D^{*+} -> $D^0 + \pi^+$
- Λc -> K+π+p
- J/Ψ -> l^+l^-
- Υ(1S) -> l^+l^-
- B -> D + X
- B^+ -> J/Ψ + K

D meson

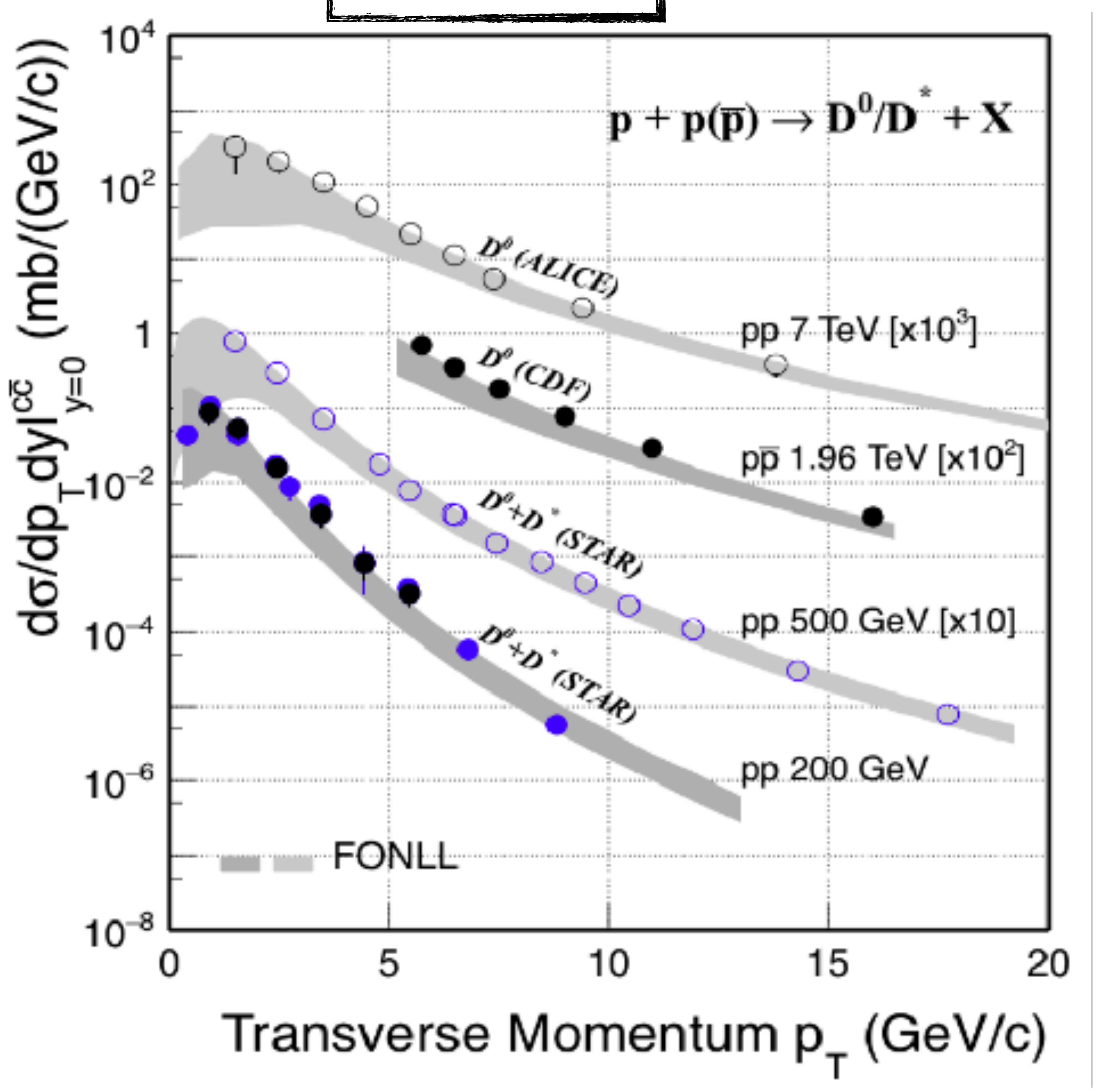


J/Ψ



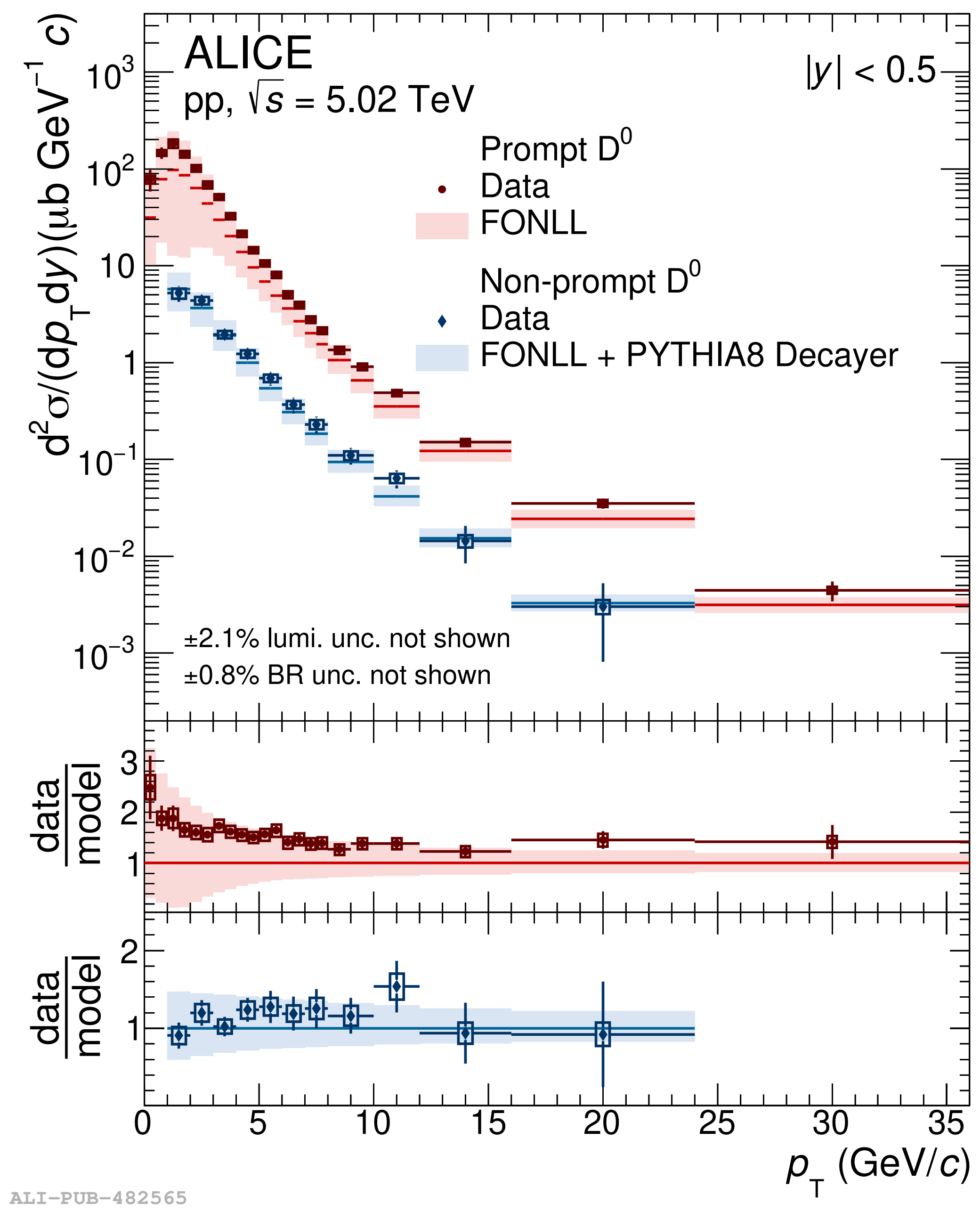
HF production in pp

D meson



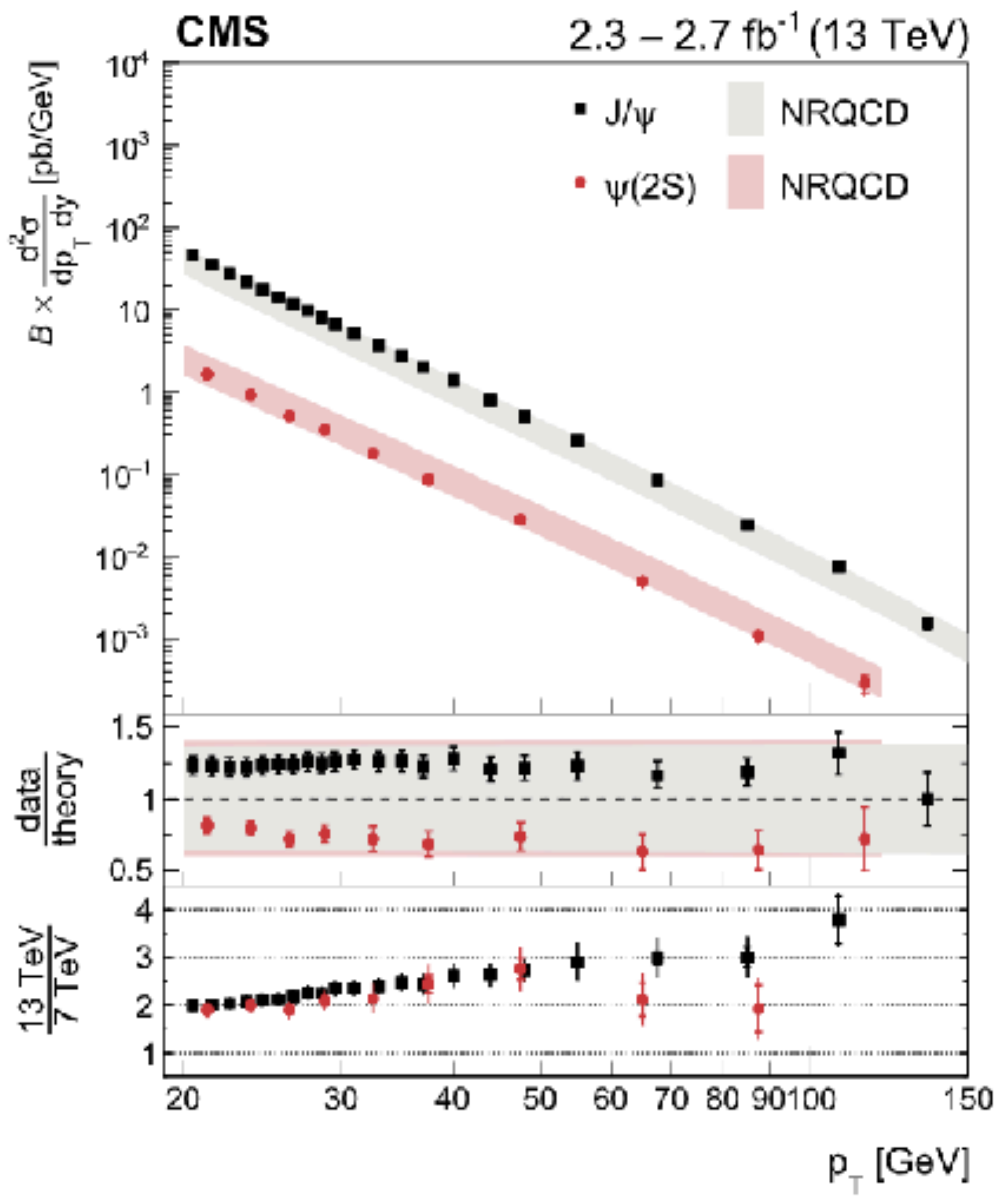
prompt D⁰

b -> D⁰



J/Ψ

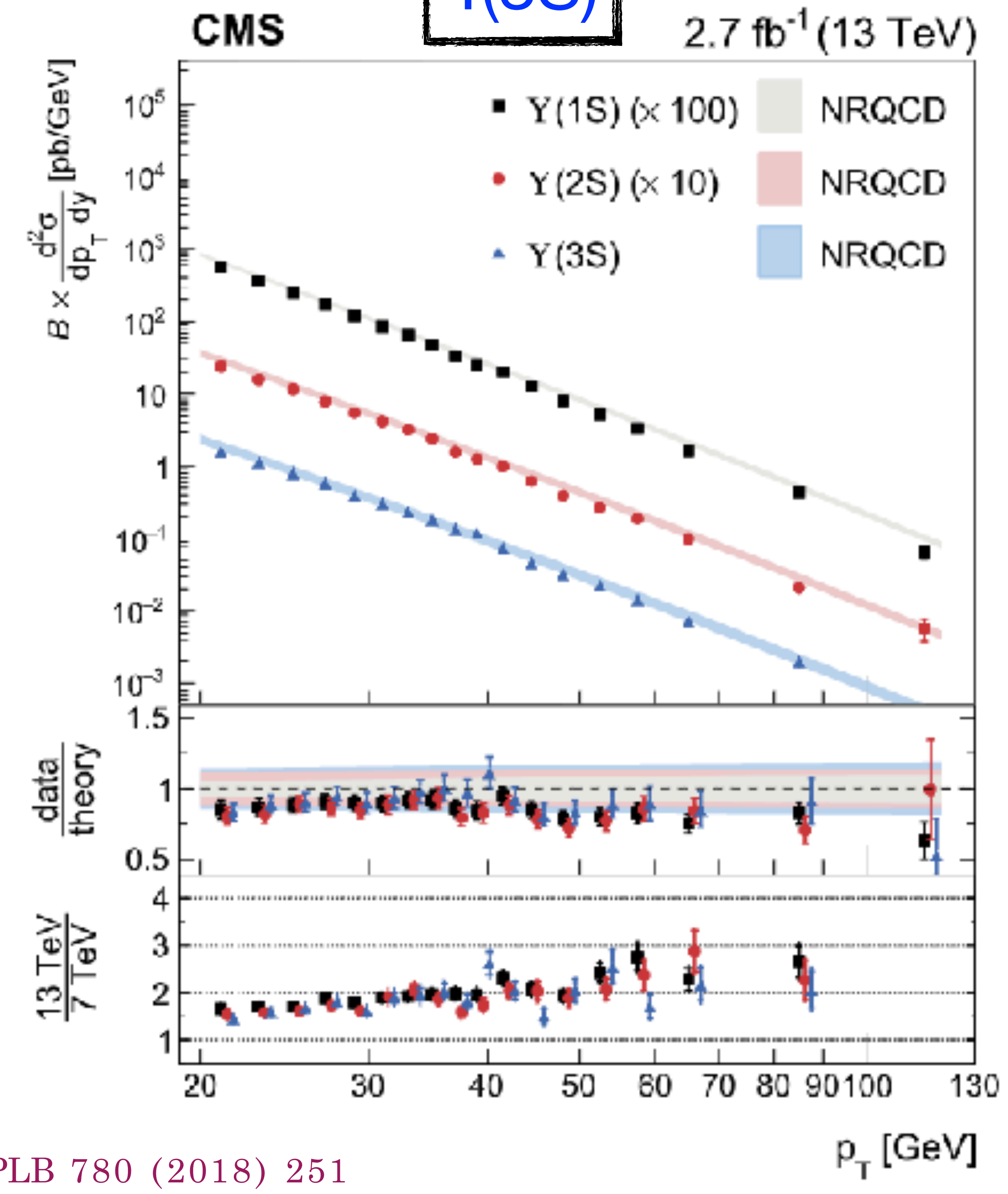
Ψ(2S)



Υ(1S)

Υ(2S)

Υ(3S)

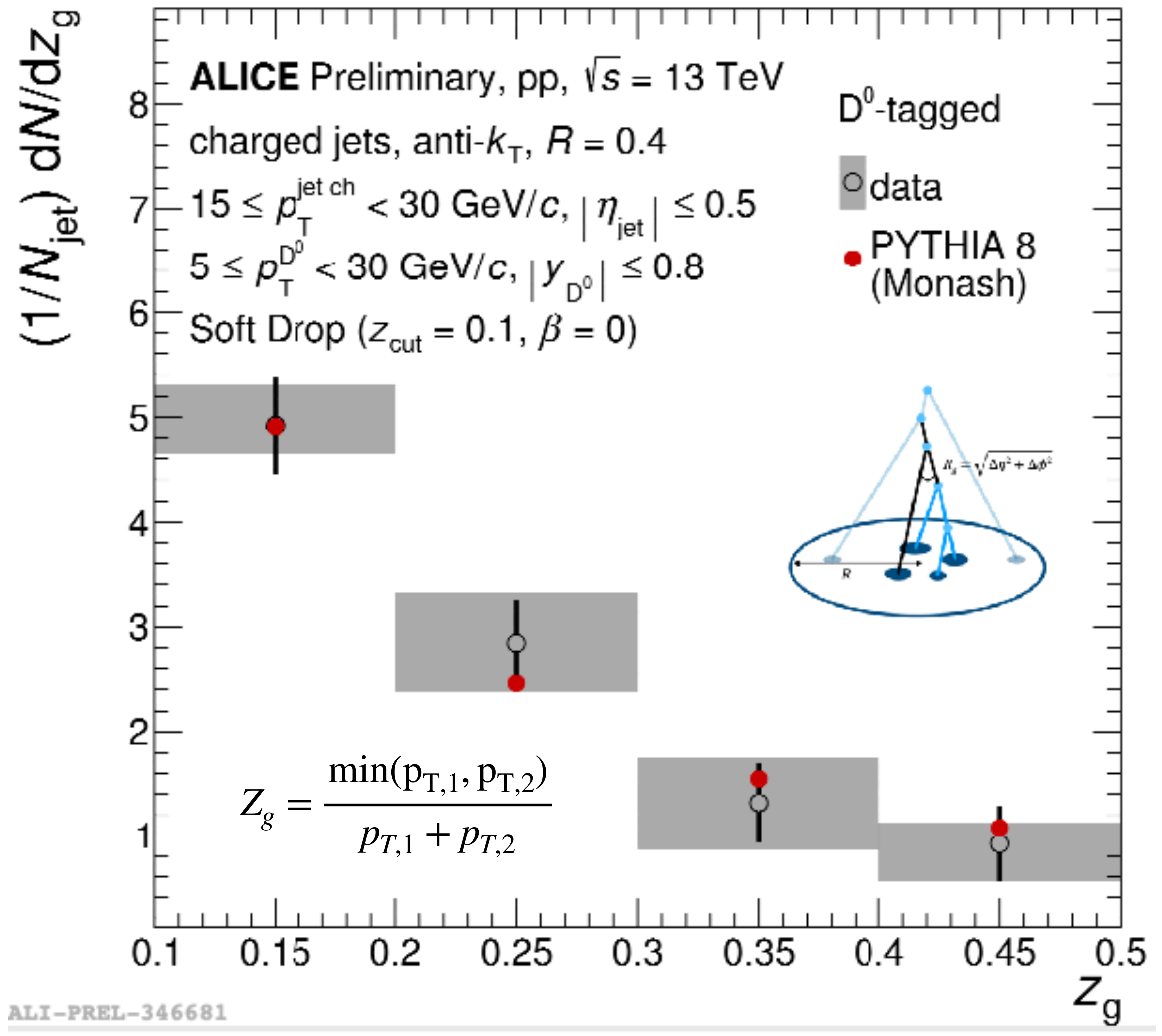


PLB 780 (2018) 251

- p_T and y differential measurements of open heavy-flavour hadrons and quarkonia.
  - ❖ Consistent with pQCD calculations within uncertainties at RHIC and LHC.

Differential HF measurements in pp

Jets with D^0



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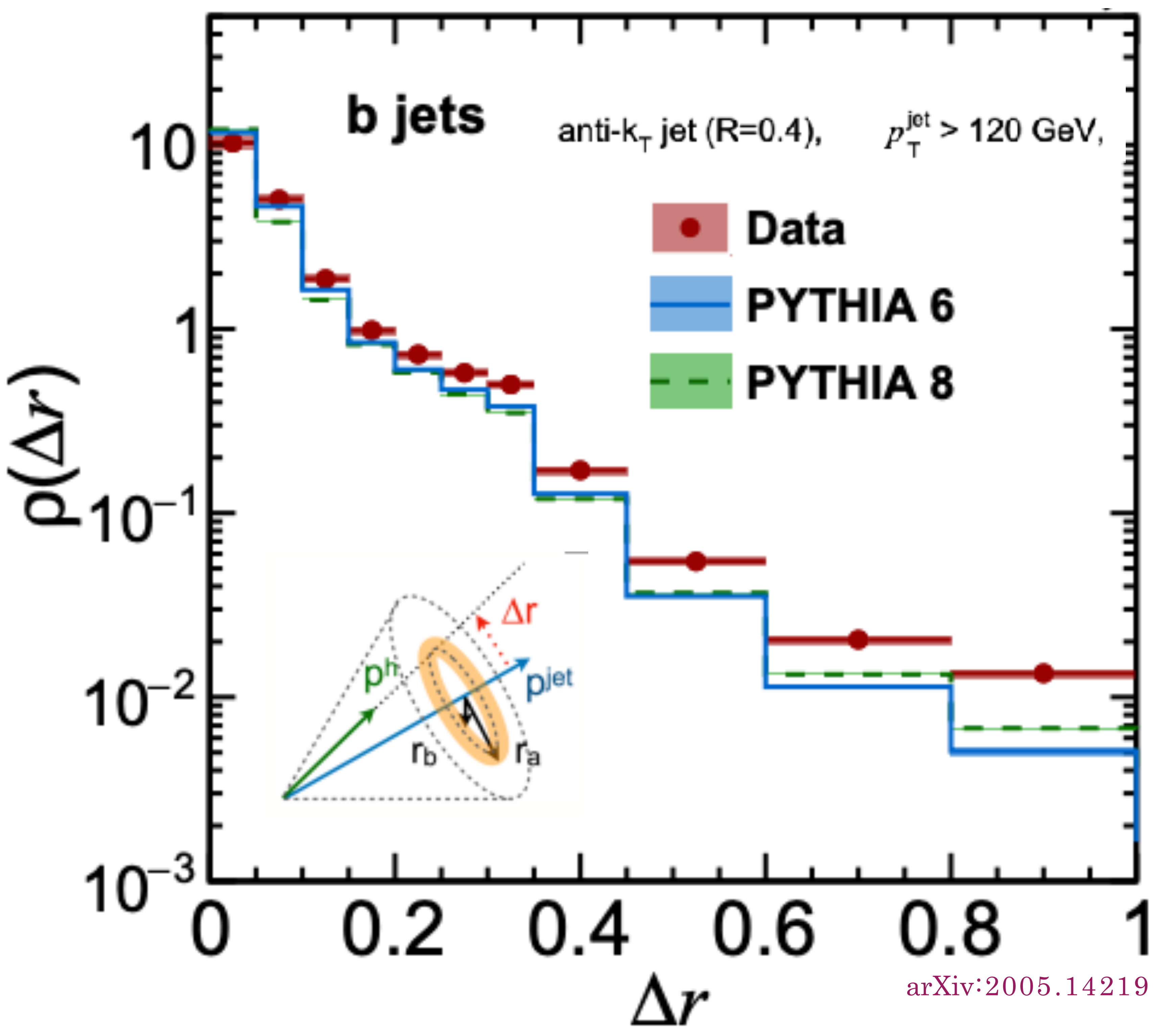
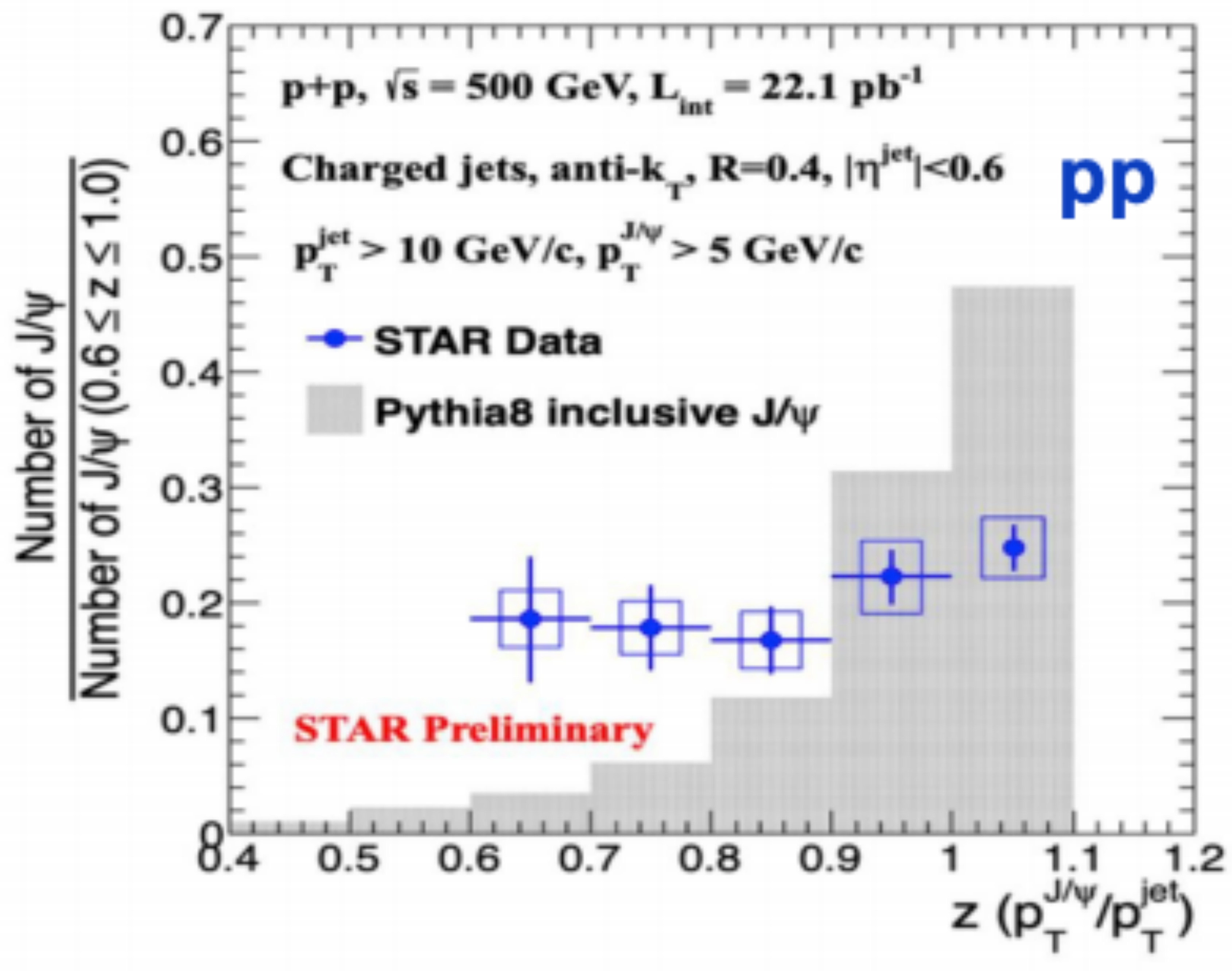
Jets with beauty



arXiv:2005.14219

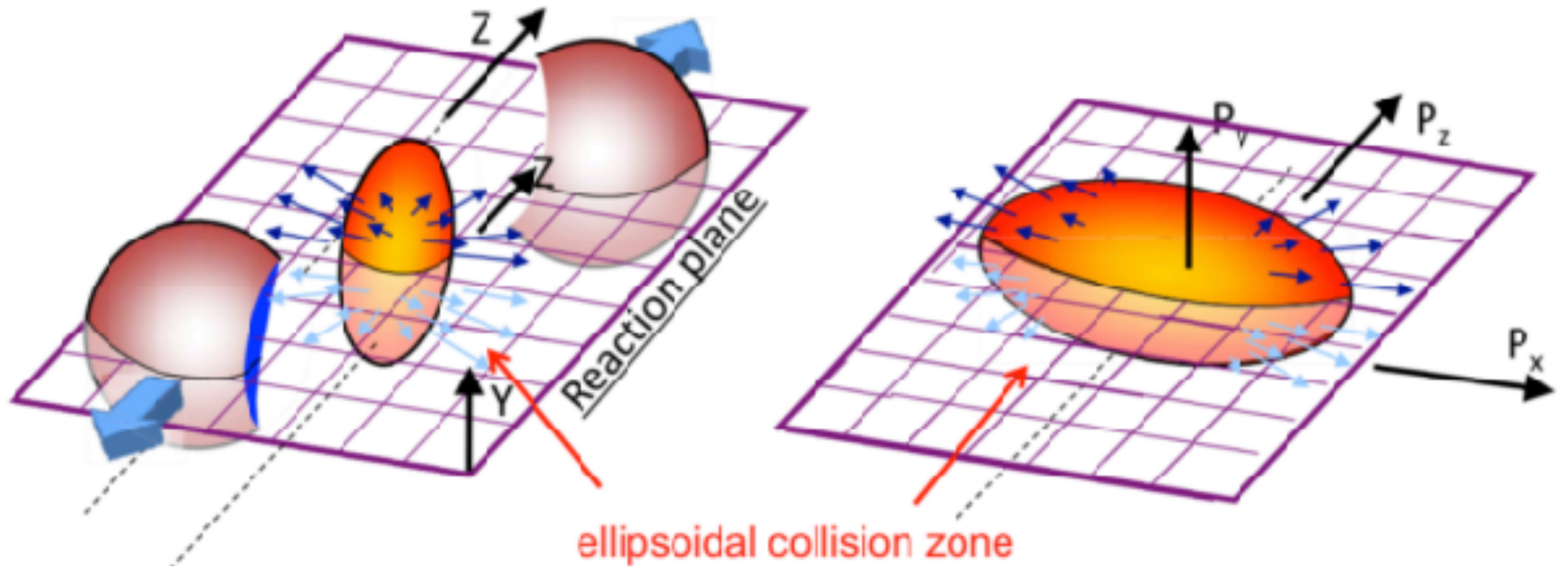
Jets with J/Ψ



- HF jet measurements:
  - D0-jet substructure: groomed momentum fraction - described by PYTHIA.
  - Ch. particle distribution in b-jets: PYTHIA underestimates large Δr contribution.
  - J/Ψ fragmentation function - J/Ψ produced less isolated than predicted by PYTHIA.
- Differential measurements need better understanding

Heavy-flavor measurements in A-A

- **Azimuthal anisotropy (v_n)** - information about the initial collision geometry and its fluctuations
  - Mass dependent v_2 comparing LF, charm and beauty quarks
  - Open HF and quarkonia
  - Mass dependent v_3 comparing LF, charm and beauty quarks
  - v_2 and v_3 vs centrality
  - LHC vs RHIC



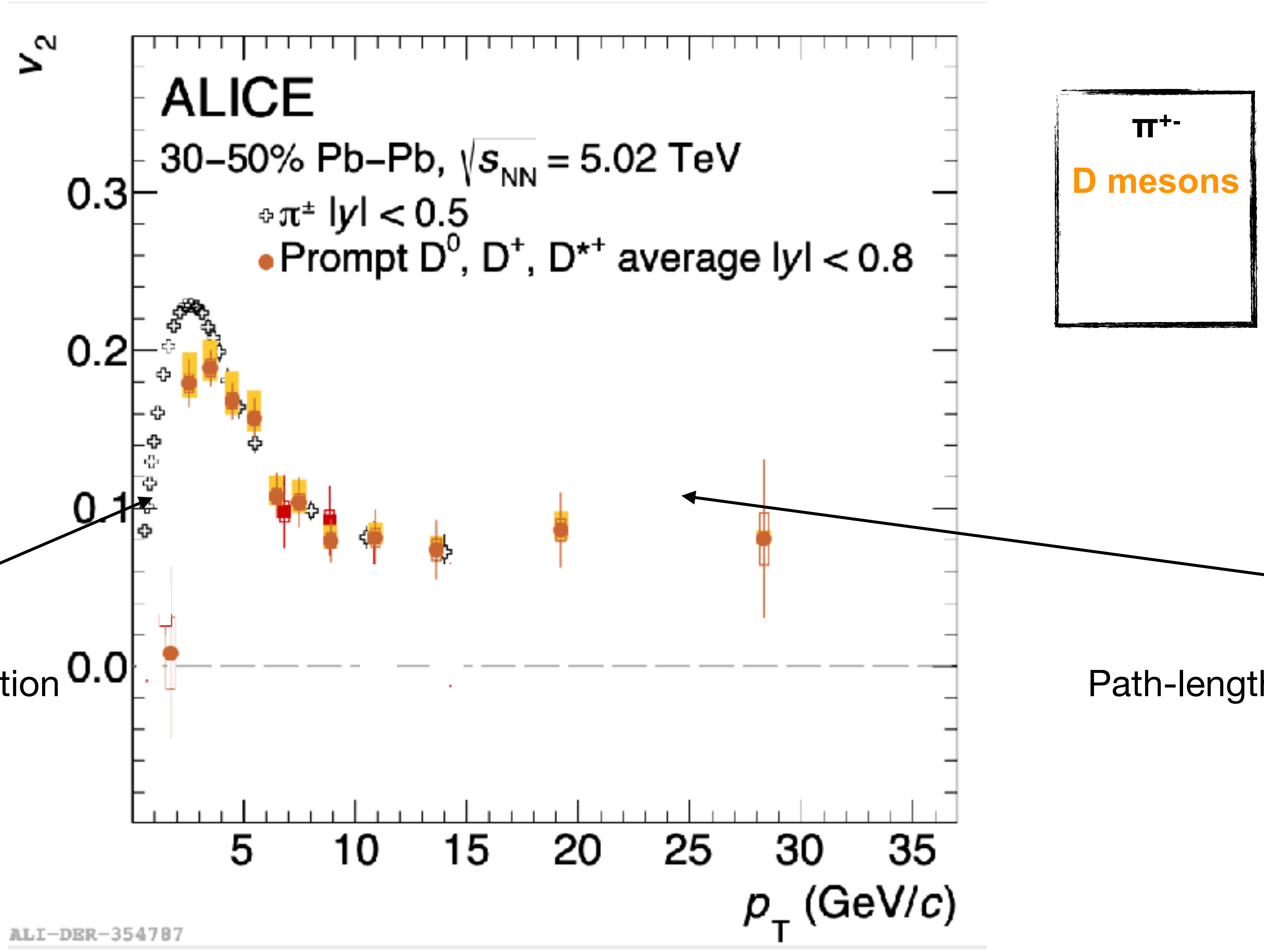
- **Nuclear Modification Factor (R_{AA})** - energy loss in the QGP
- **Jet structure/fragmentation**
- **Hadronisation processes**

v_2 of heavy quarks at LHC

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

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

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



- low p_T: $v_2(\pi^{+-}) > v_2(D)$
  - D-meson v_2 possibly from charm quark flow + recombination with the light-flavor quark

v_2 of heavy quarks at LHC

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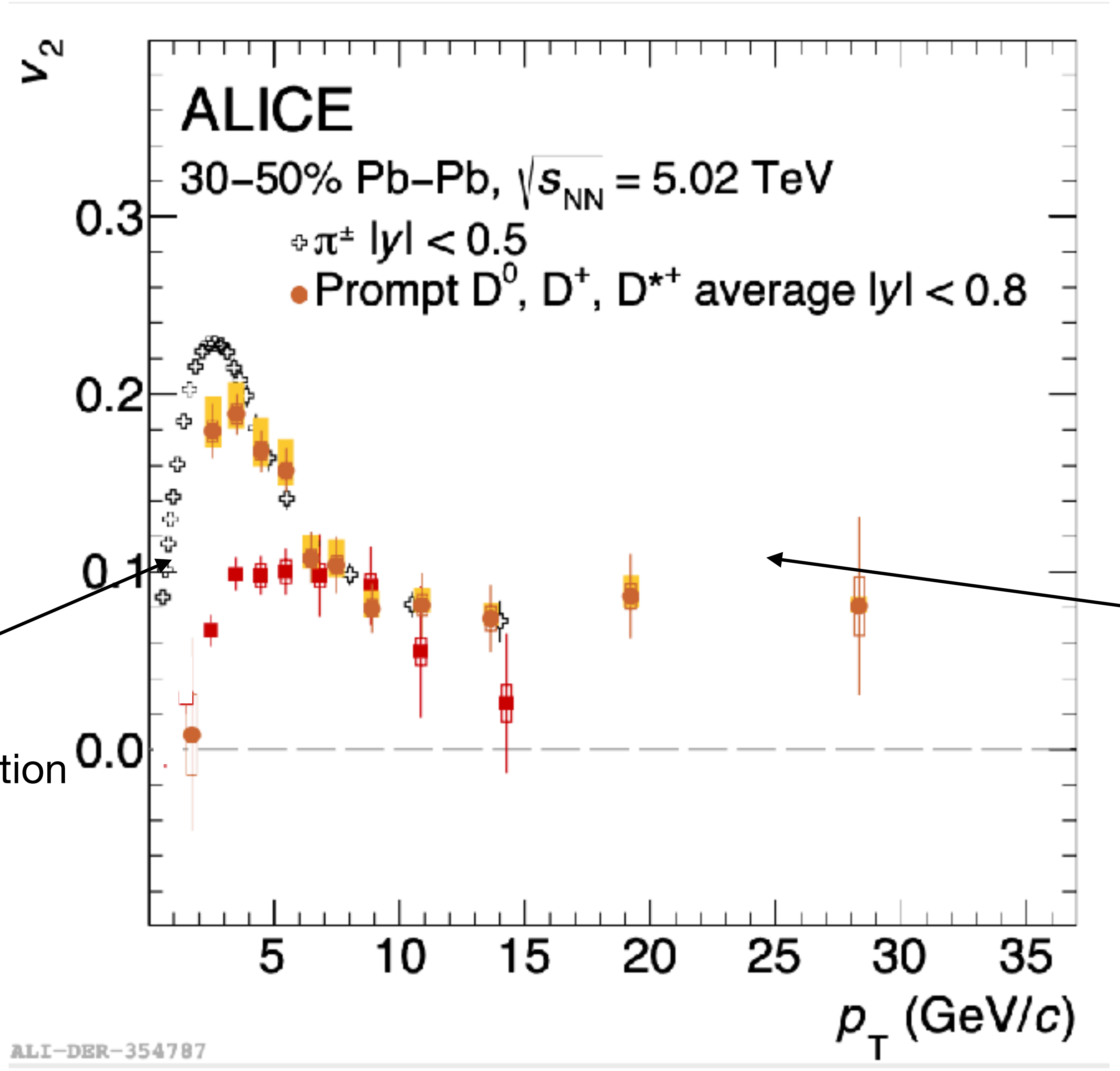


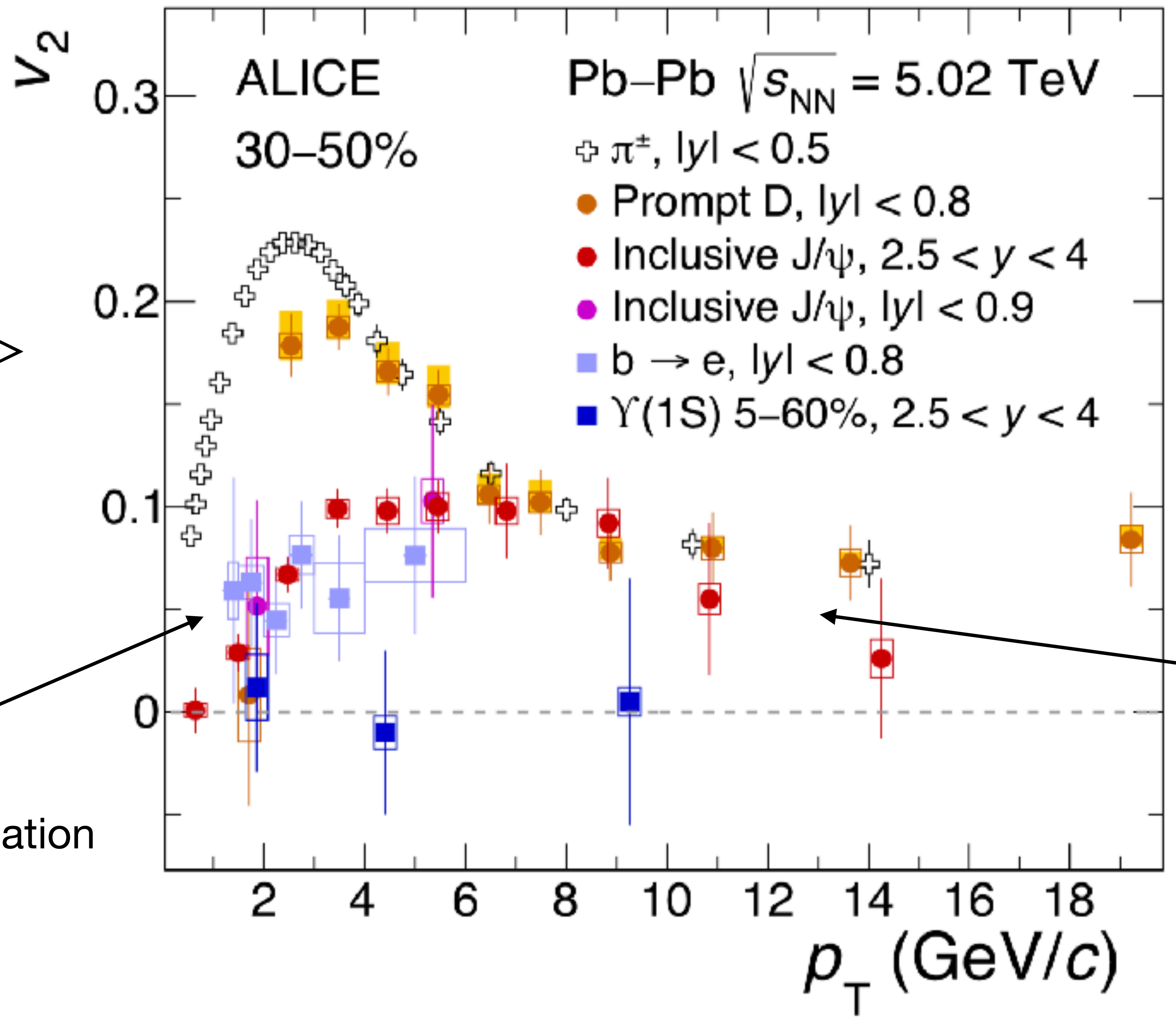
π^{+-}
D mesons
J/Ψ

Low p_T:
Collective flow and hadronisation

High p_T:
Path-length dependent energy loss

- low p_T: $v_2(\pi^{+-}) > v_2(D) > v_2(J/\Psi)$
  - D-meson 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 heavy quarks at LHC



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

Low p_T:
Collective flow and hadronisation

High p_T:
Path-length dependent energy loss

π^{+-}
D mesons
J/Ψ
b->e
Y(1S)

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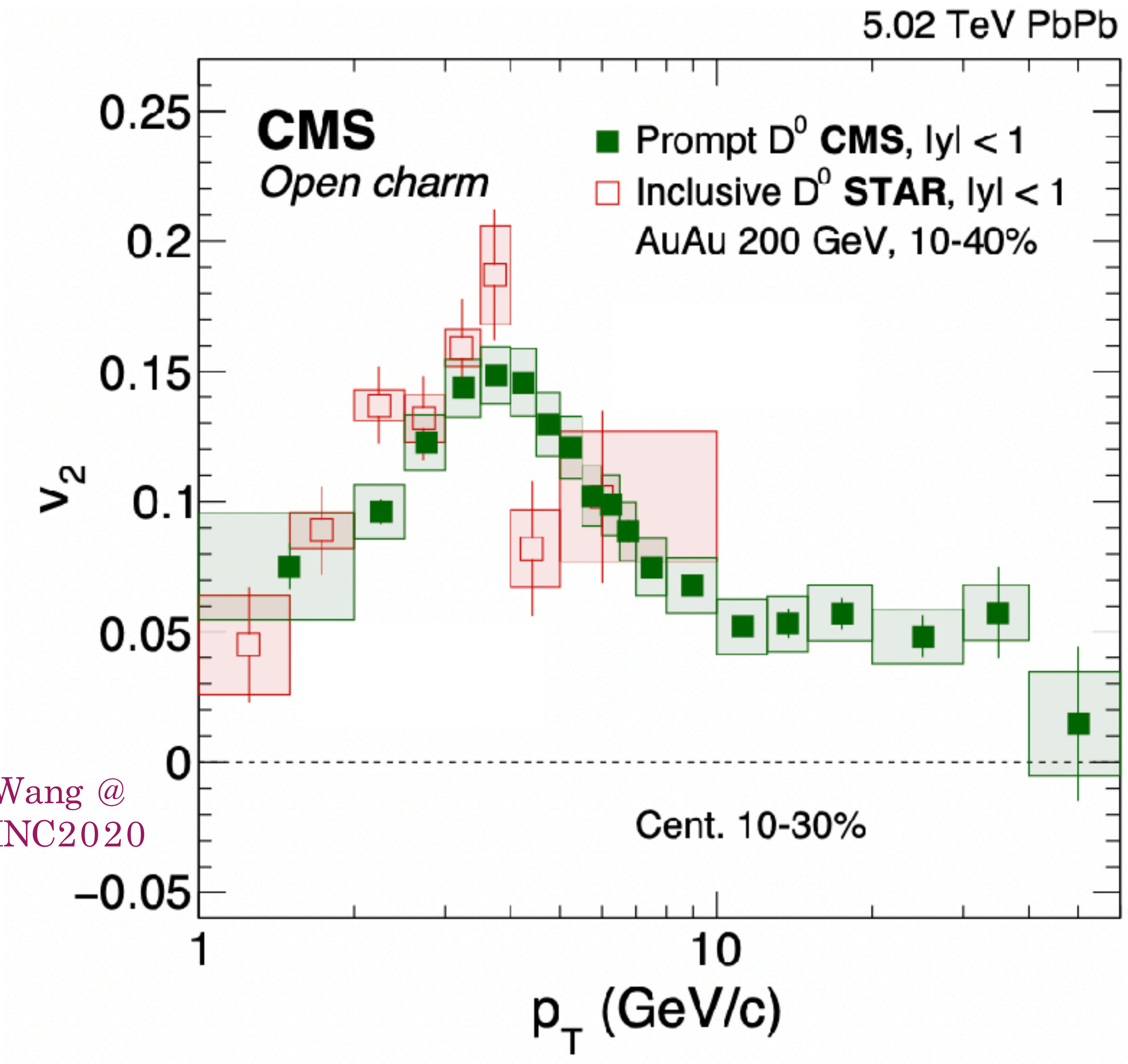
- $v_2(\pi^{+-}) > v_2(D) > v_2(J/\Psi)$
  - D-meson v_2 possibly from charm quark flow + recombination with the light-flavor quark
- Charm quarks interact strongly with the medium and participate in its collective expansion
- Open-beauty $v_2 > 0$, while bottomonia $v_2 \sim 0$
  - Impact of path-length dependent energy loss and recombination of open beauty?
  - Negligible recombination expected for Y(1S)

v_2 at LHC and RHIC



Jing Wang @ HF-WINC2020

LHC
RHIC

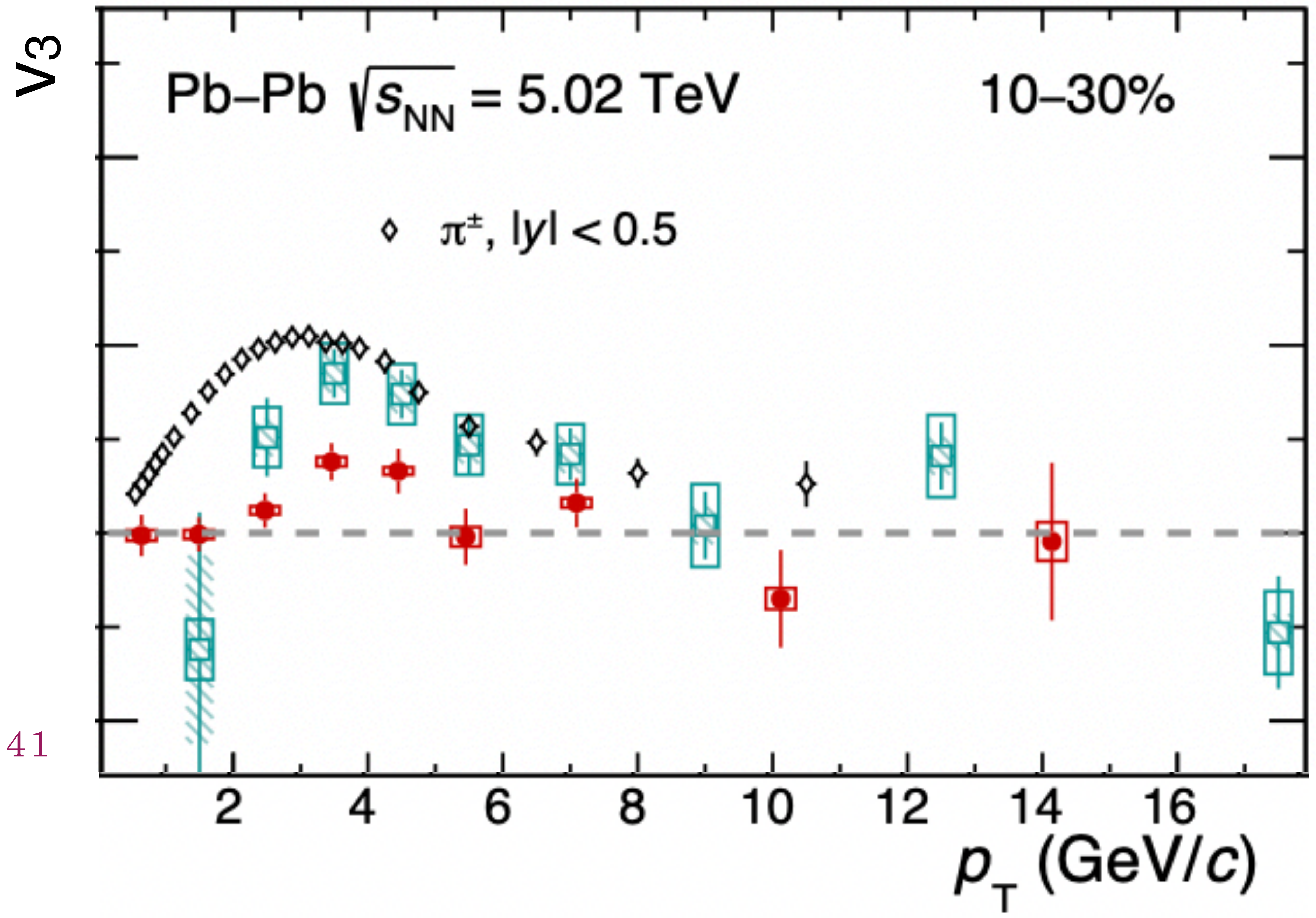
v_2 of D mesons at different collision energies at LHC and RHIC show similar p_T dependence.

v_3 of heavy quarks at LHC

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

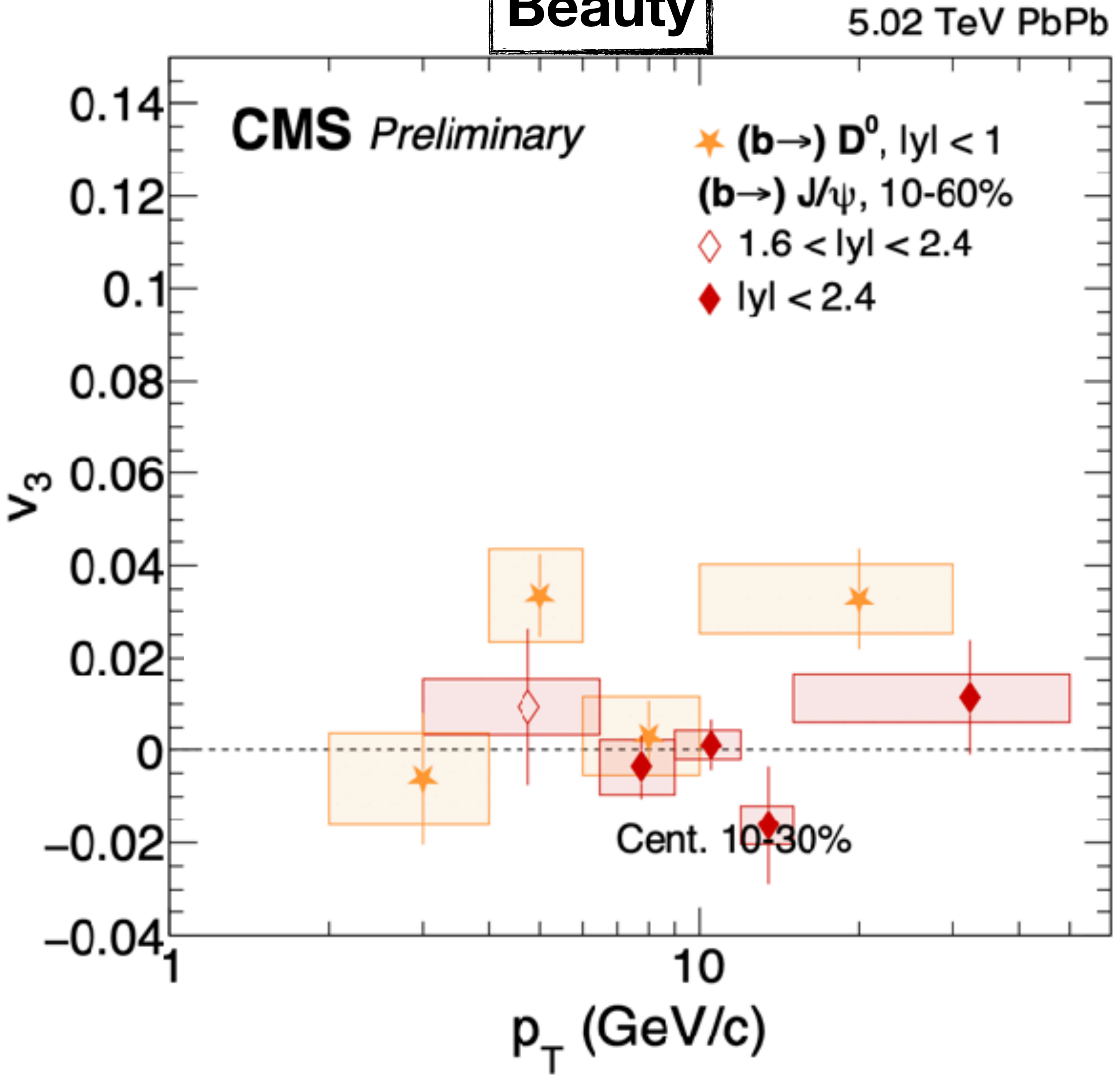
Charm

π+-
D mesons
J/Ψ



JHEP 10 (2020) 141

Beauty

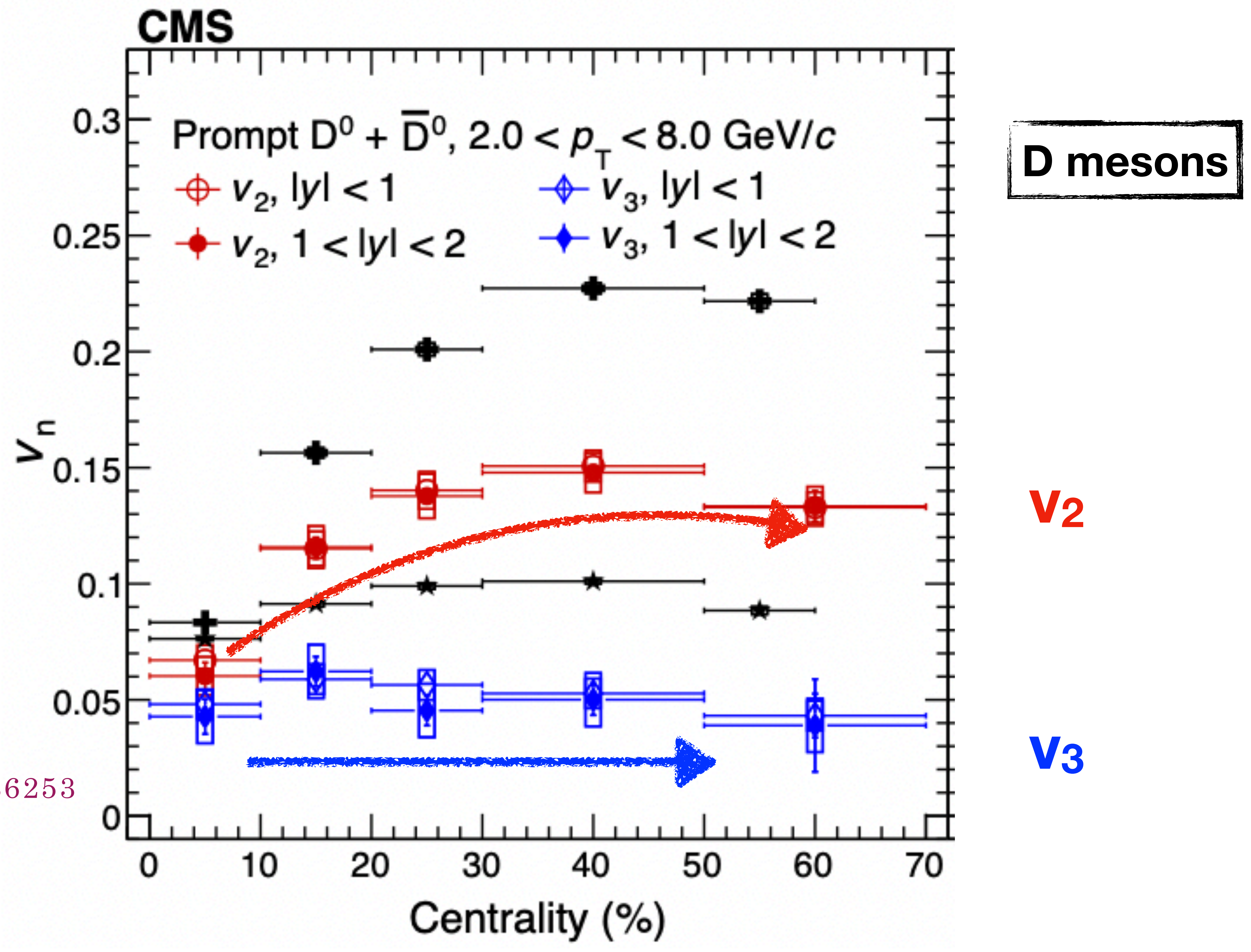


b -> D0
b -> J/Ψ

Jing Wang @ HF-WINC2020

- $v_3(\pi^{+-}) > v_3(D) > v_3(J/\Psi)$ —> mass hierarchy observed in v_3 as well.
- Confirms charm quark being kinetically equilibrated in the QGP medium.
- Beauty quark v_3 ~ 0

Centrality dependence of v_2 and v_3

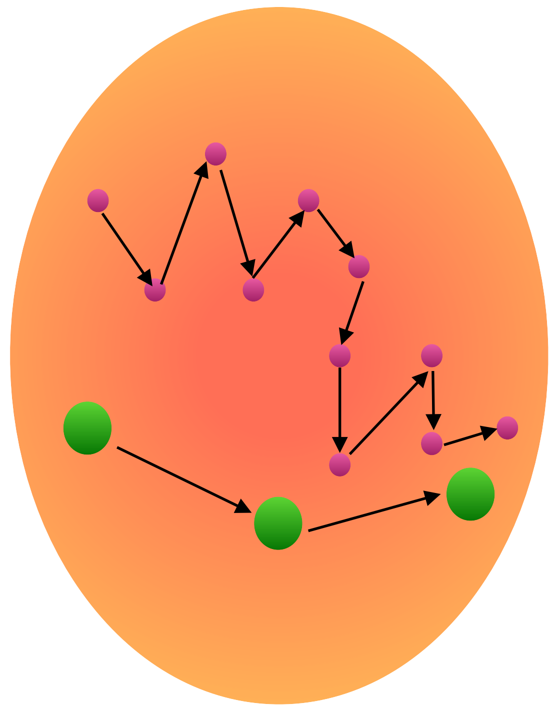


PLB 816 (2021) 136253

- v_n(h) > v_n(D); centrality trend similar for D mesons and charged particles
- v_2: strong centrality dependence —> due to collision geometry and viscosity effects.
- v_3: weak centrality dependence —> expected from fluctuations in collision geometry.

Heavy-flavor measurements in A-A

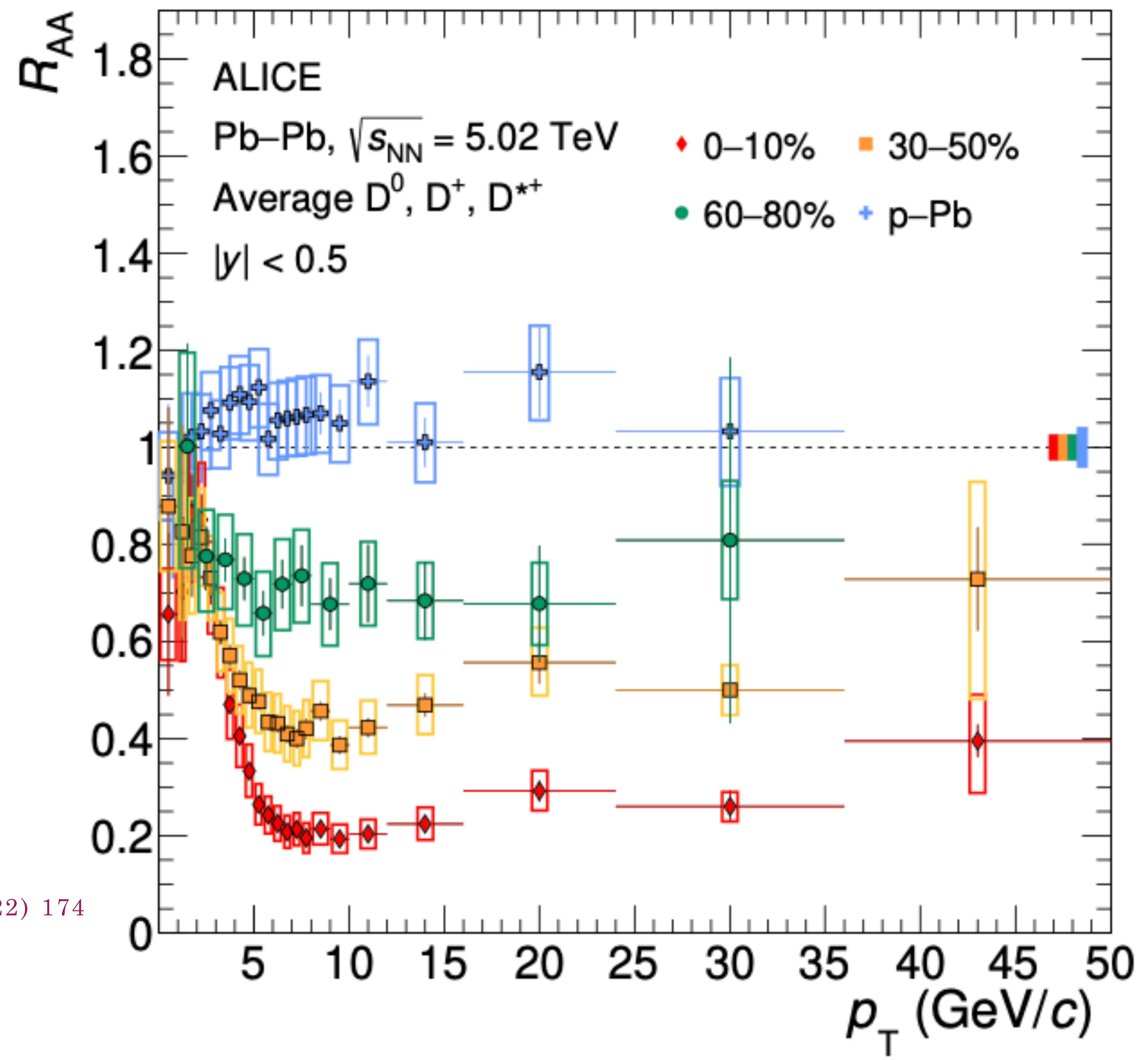
- **Azimuthal anisotropy (v_n)** - information about the initial collision geometry and its fluctuations
- **Nuclear Modification Factor (R_{AA})** - energy loss in the QGP
  - Mass dependent energy loss comparing charm and beauty quarks
  - Compare open HF and quarkonia
  - LHC vs RHIC



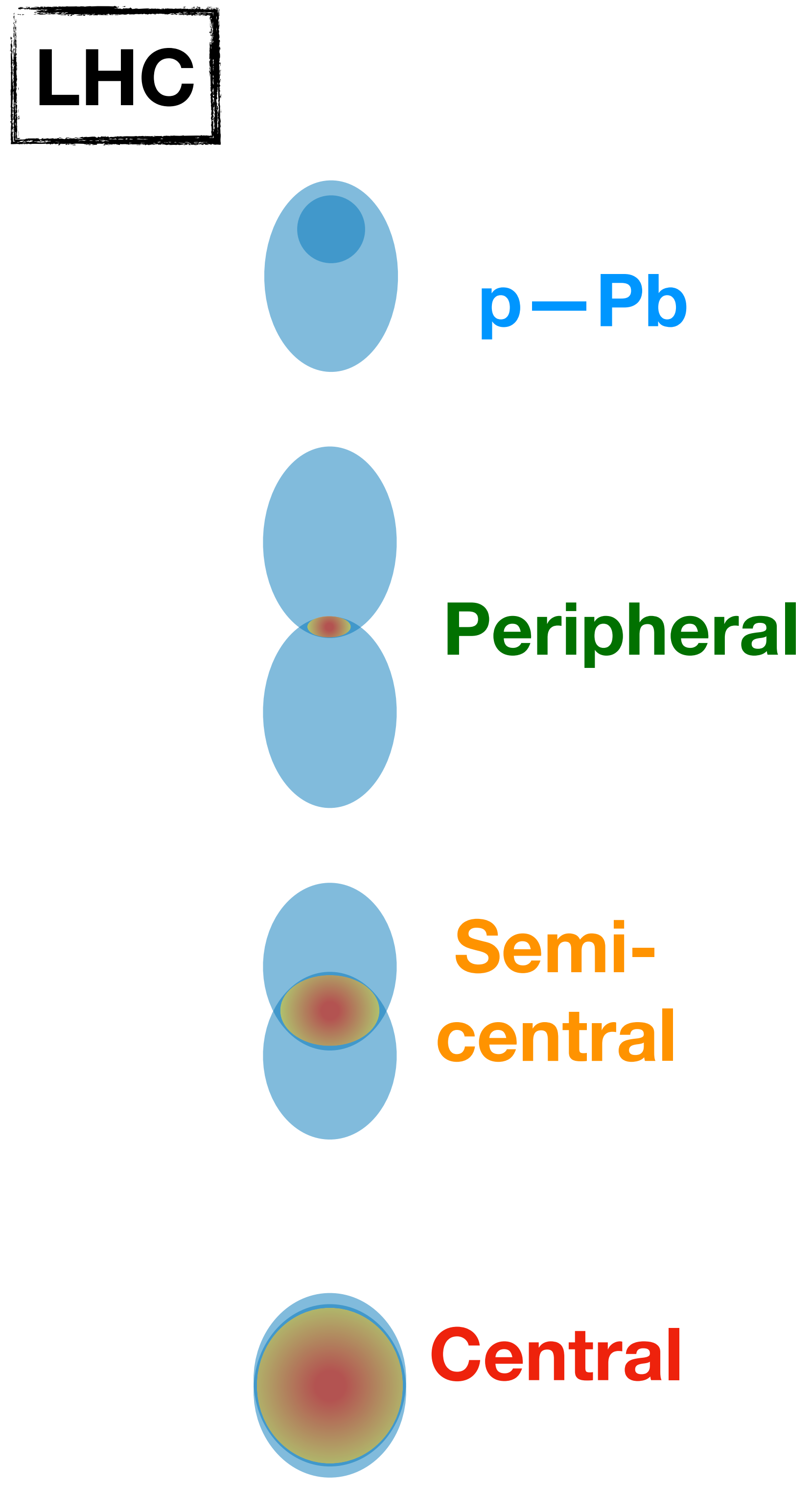
- **Jet structure/fragmentation**
- **Hadronisation processes**

R_{AA} of D mesons

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



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

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

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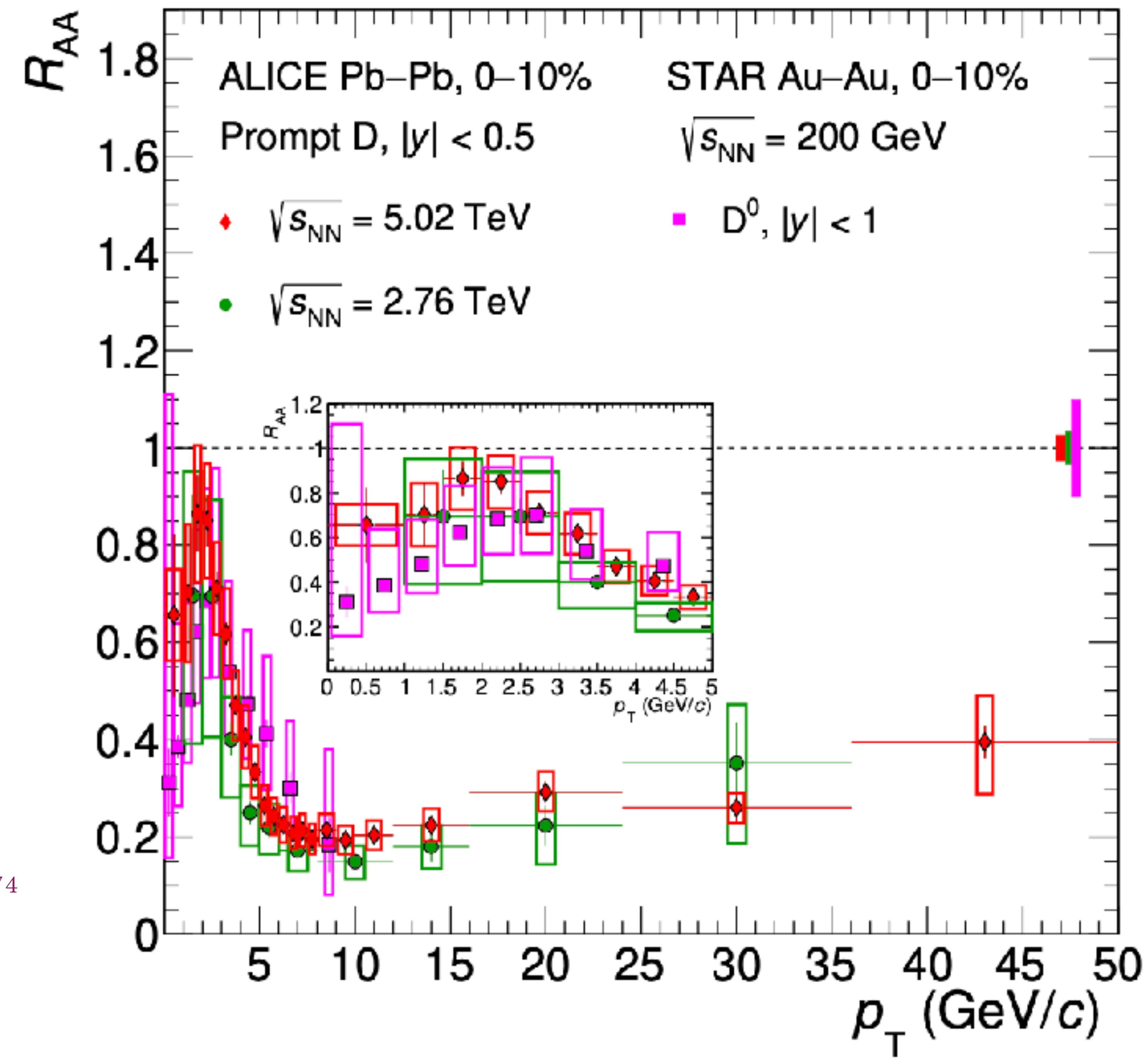


ALICE
5.02 TeV
2.76 TeV

STAR
200 GeV

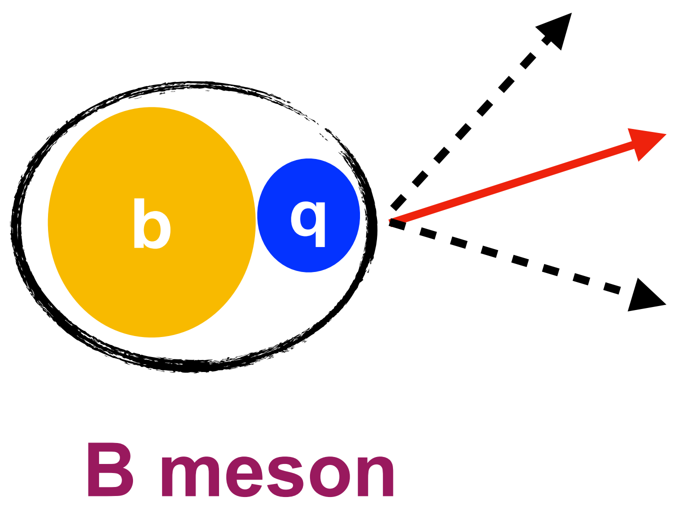
R_{AA} of D mesons at different collision energies at LHC and RHIC show similar p_T dependence.

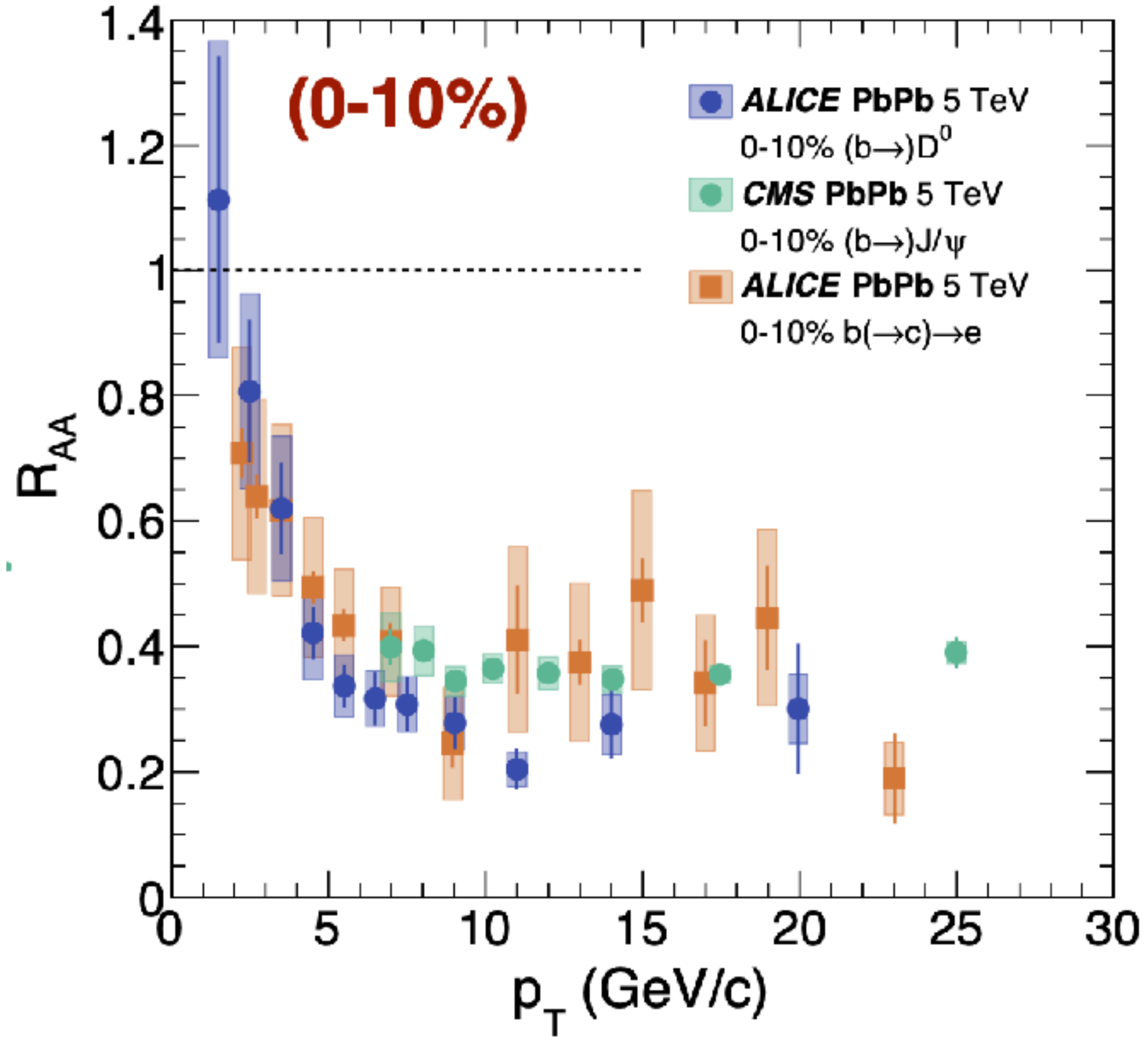
—> interplay of p_T spectra shape and collision energy/initial temperature.

R_{AA} of beauty

Studying mass dependent energy loss

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





b —> D^0 (ALICE)
b —> J/Ψ (CMS)
b —> e (ALICE)

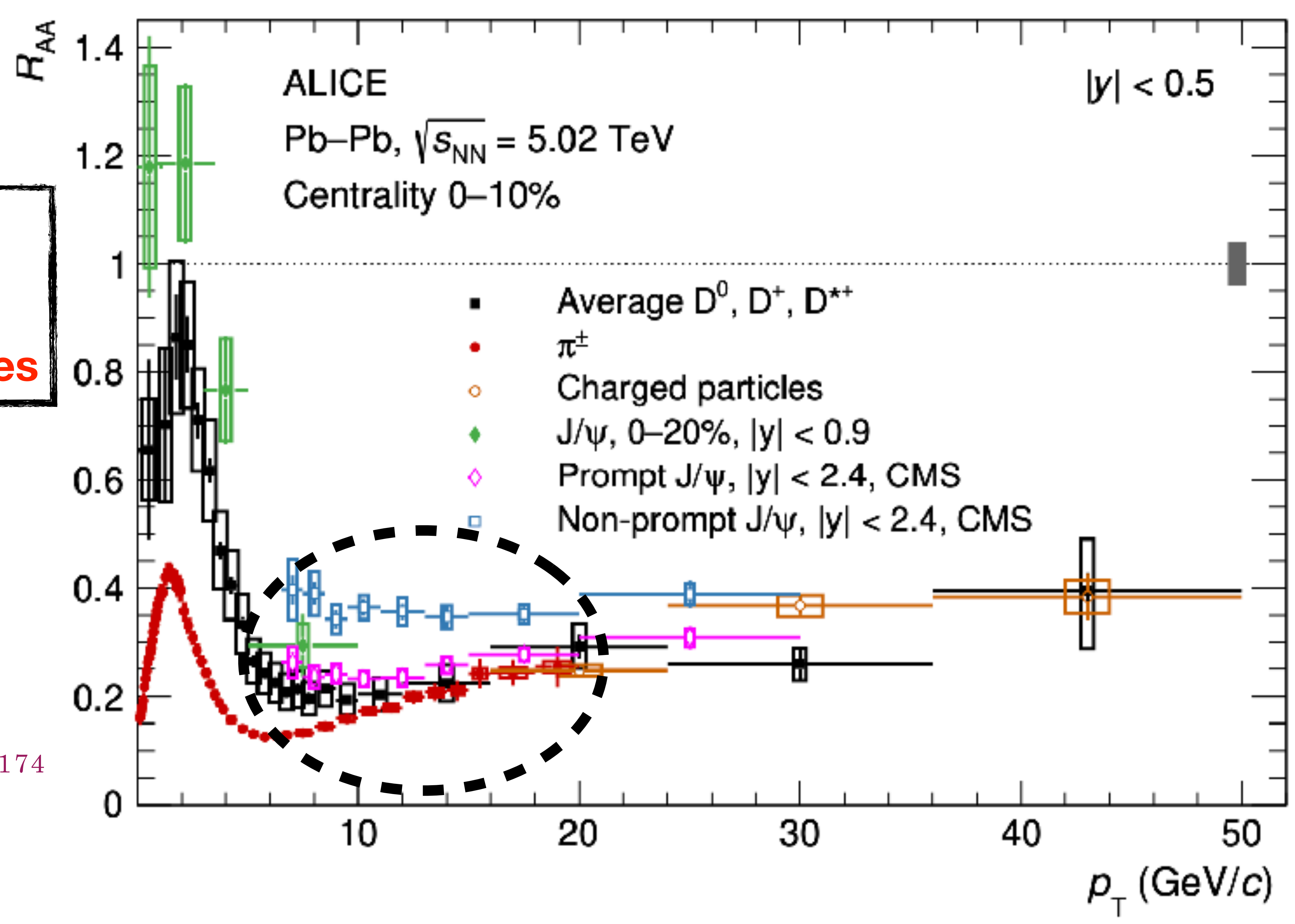
Jing Wang @ QM2019

Beauty quark measurements using different decay channels —> consistent with each other.

Mass hierarchy of energy loss

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

b —> J/Ψ
D meson
Ch. particles



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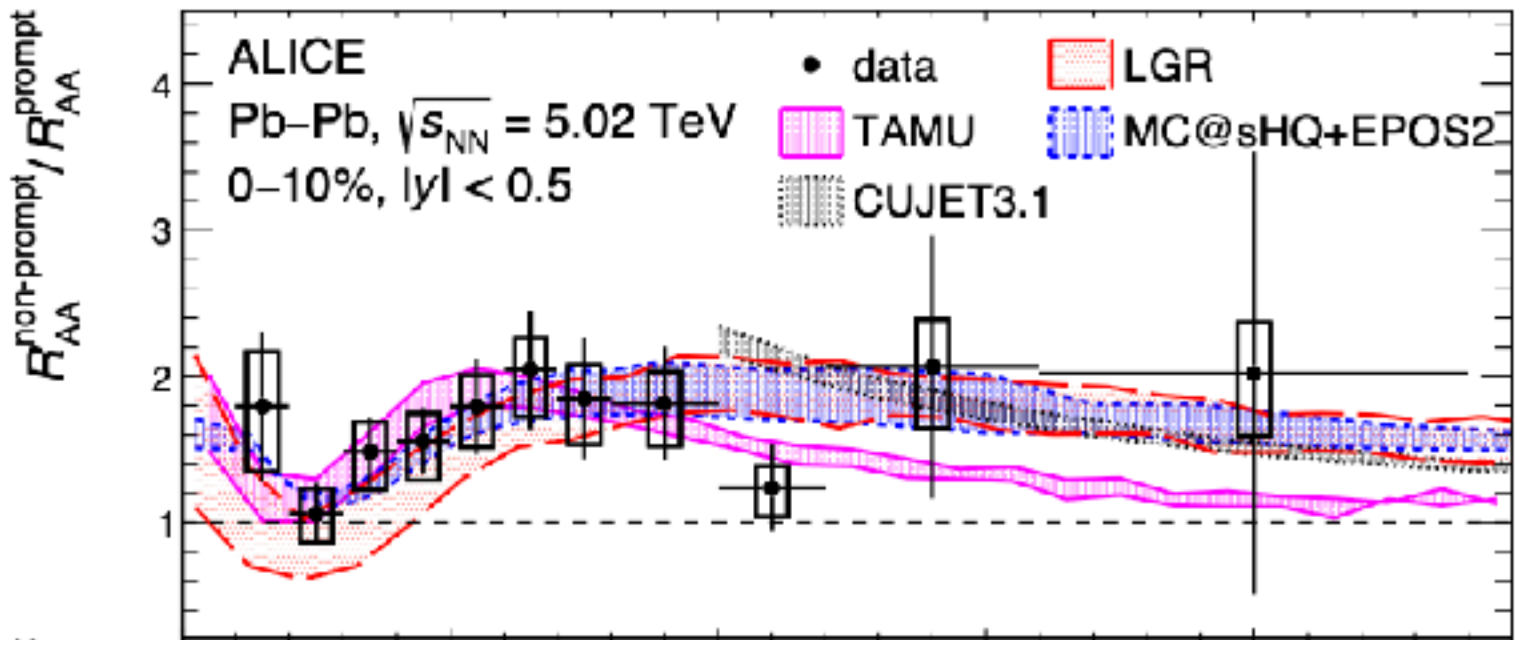


R_{AA}(b->D⁰) / R_{AA}(D⁰)

arXiv: 2202.00815

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

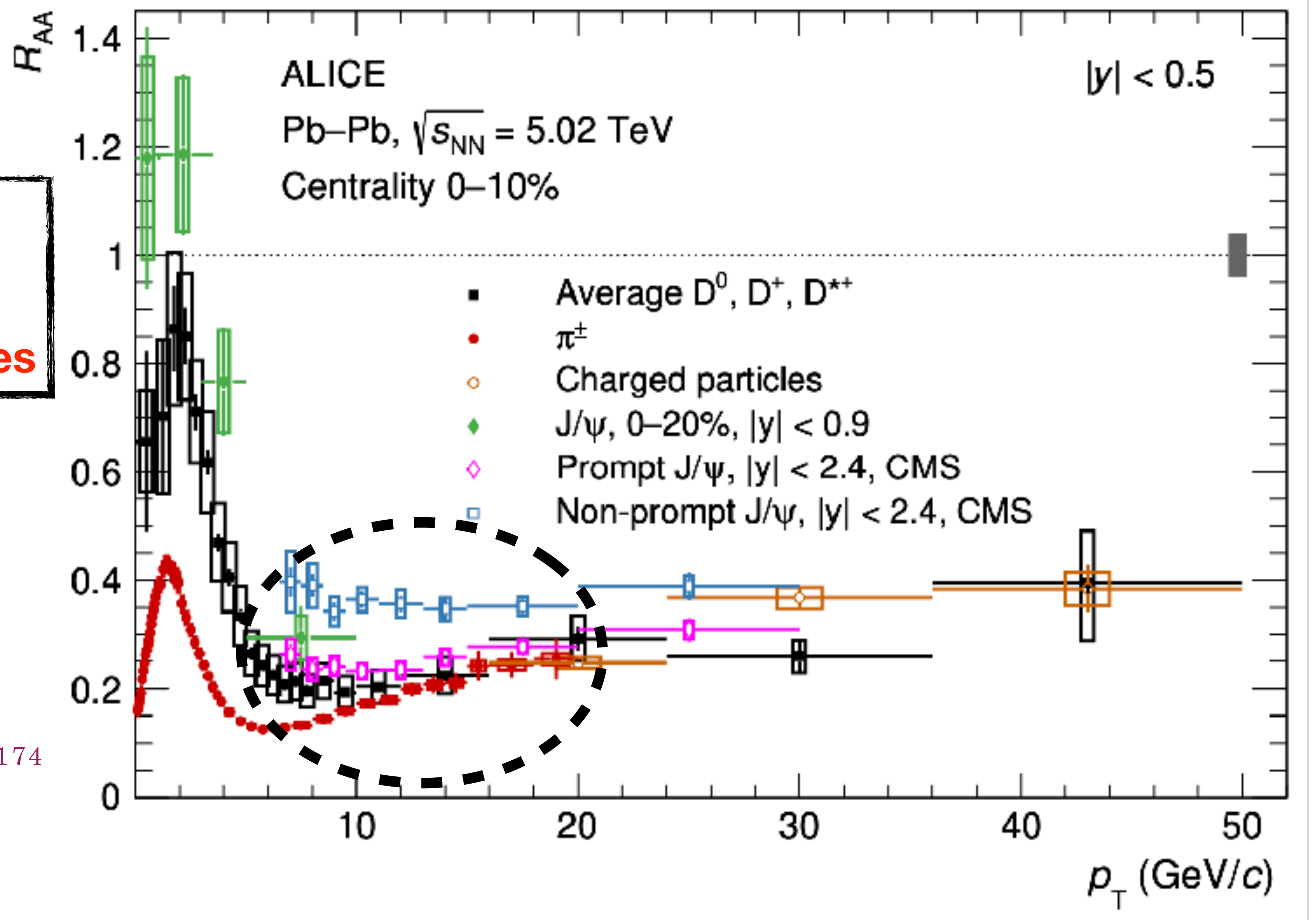
High p_T: RAA(b) ~ RAA(c) ~ RAA (h)

- Qualitatively described by models: smaller b quark energy loss + dead cone for gluon radiation

Mass hierarchy of energy loss

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

b —> J/Ψ
D meson
Ch. particles



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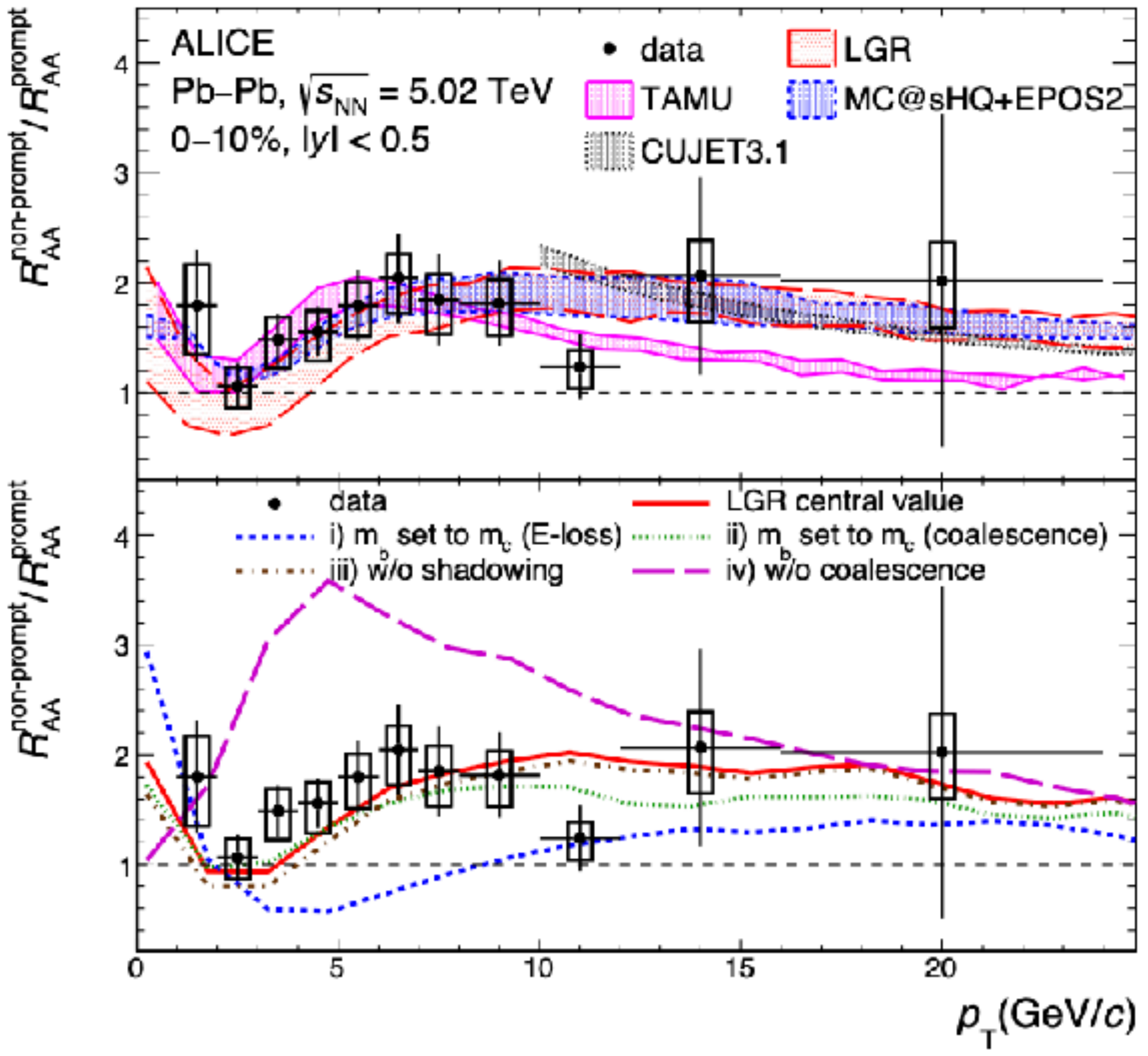


$R_{AA}(b\to D^0)$ / $R_{AA}(D^0)$

arXiv: 2202.00815

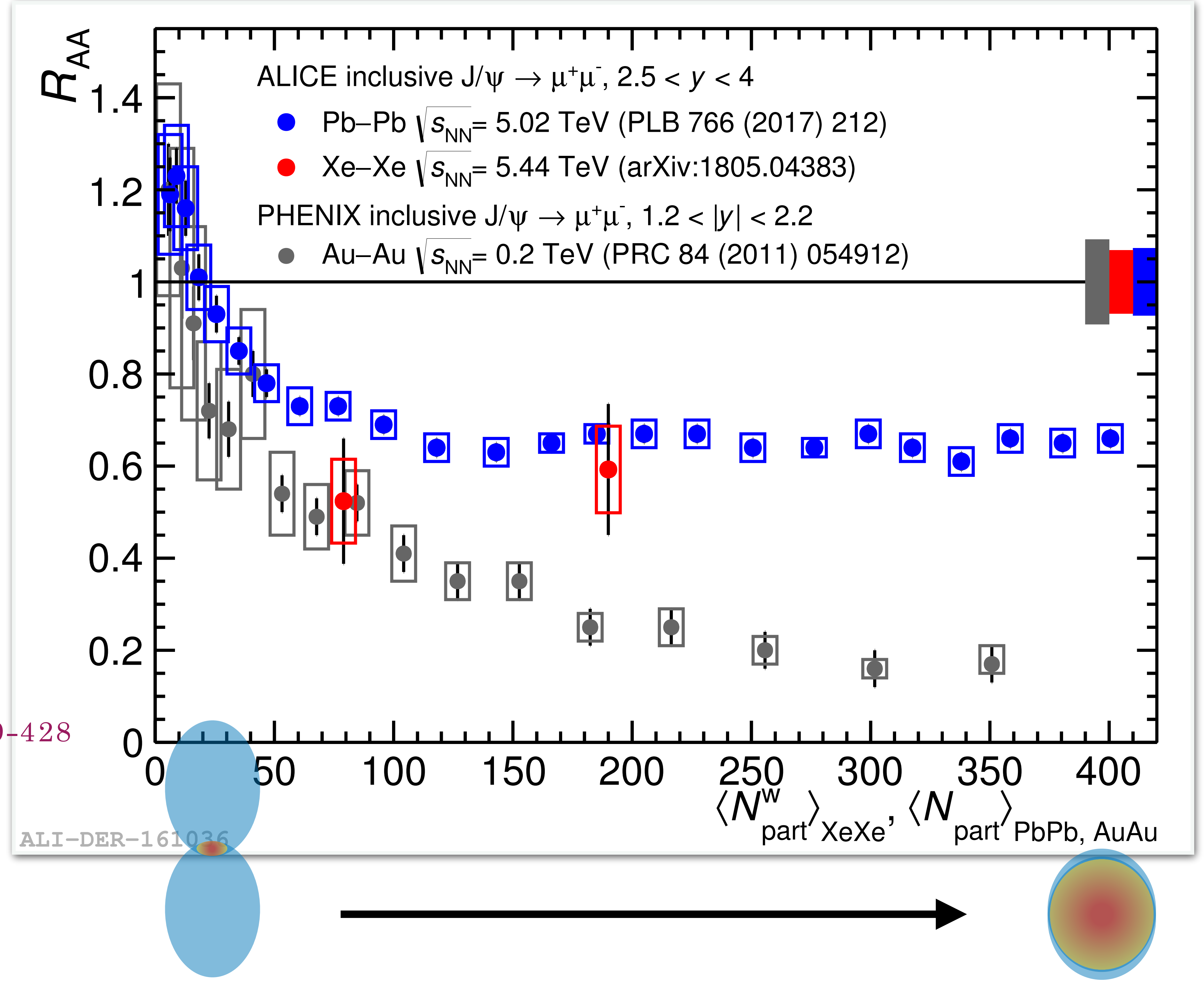
Intermediate p_T (5-20 GeV/c): RAA(b) > RAA(c) ~ RAA (h)

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

- Qualitatively described by models: smaller b quark energy loss + dead cone for gluon radiation
- Dip due to formation of D mesons via coalescence harding the D p_T spectra

R_{AA} of Quarkonia

Charmonium



PLB785 (2018) 419-428

J/Ψ

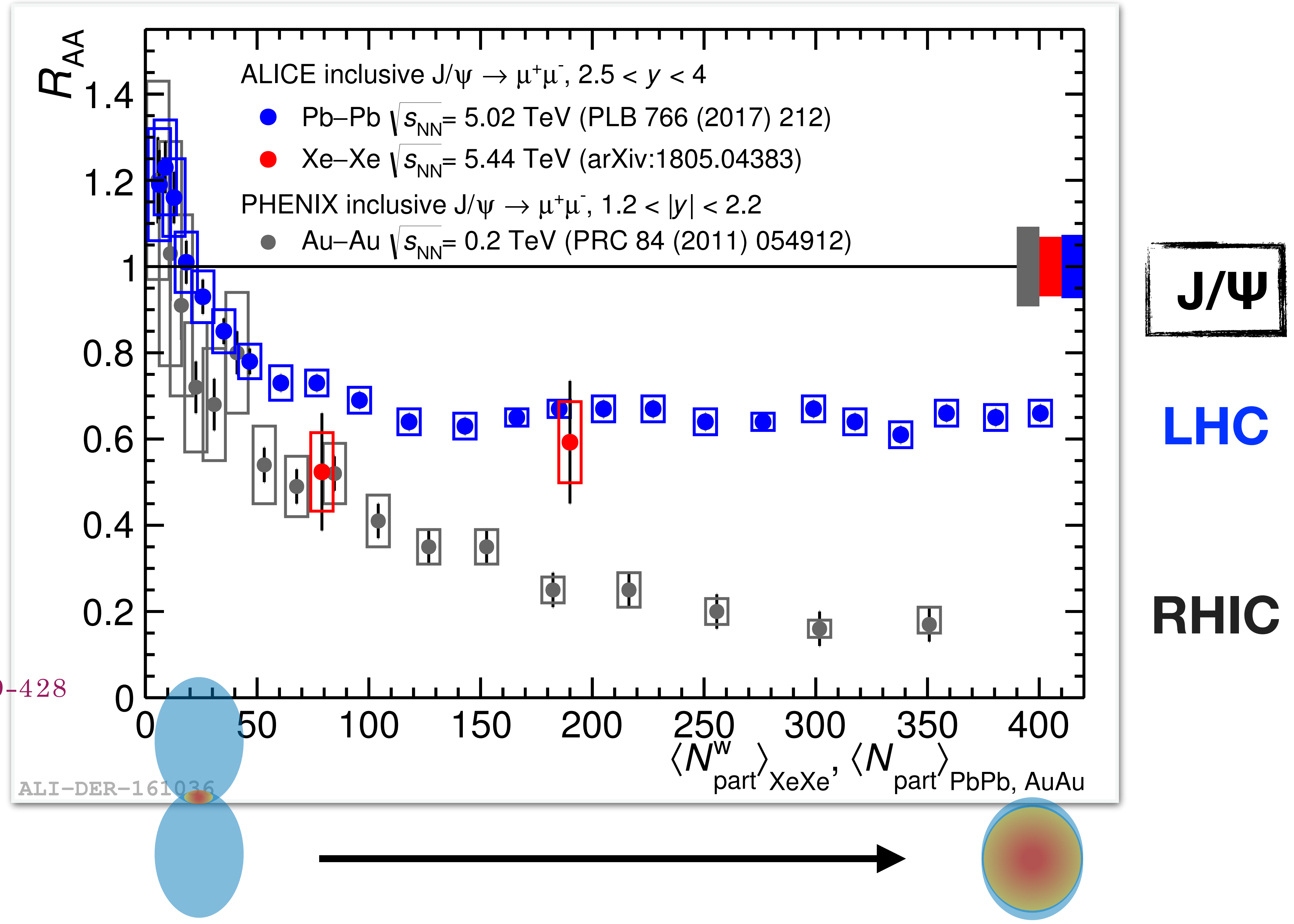
LHC

RHIC

- **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.

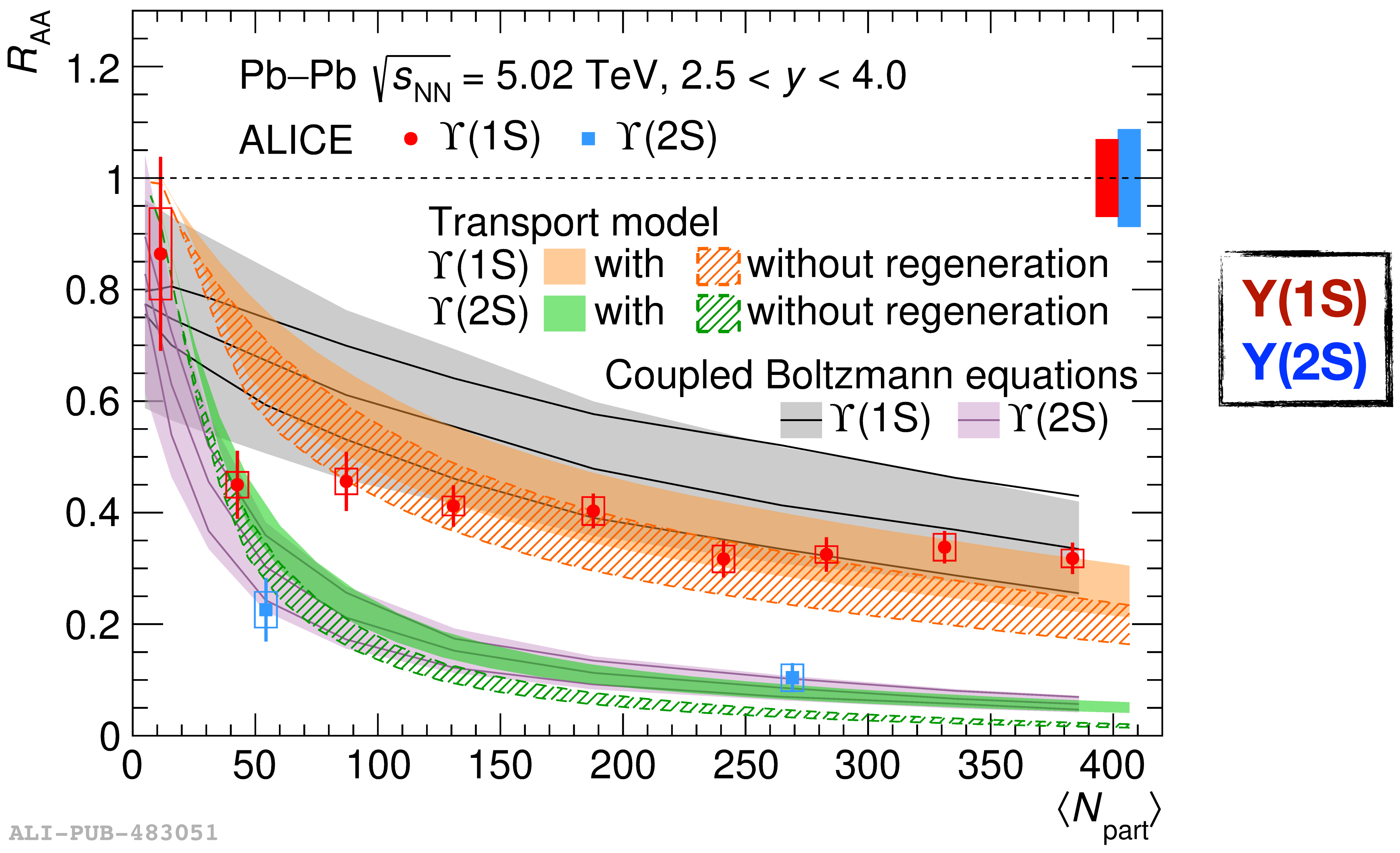
R_{AA} of Quarkonia

Charmonium



PLB785 (2018) 419-428

Bottomonium



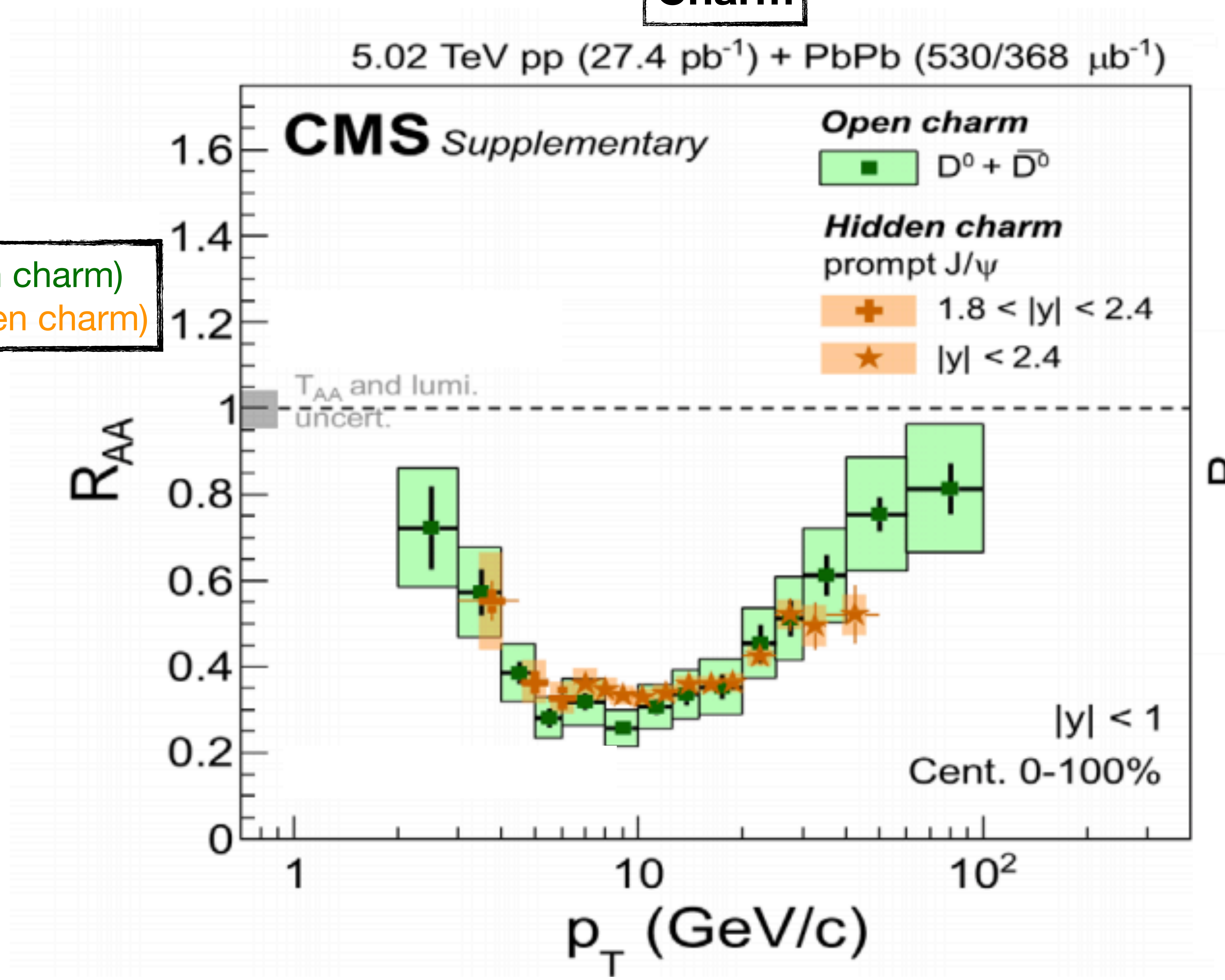
- **LHC**: increasing suppression with centrality up to N_{part}~100, followed by a constant R_{AA} due to regeneration effects.
- **RHIC**: increasing suppression with centrality; smaller effects of regeneration.

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

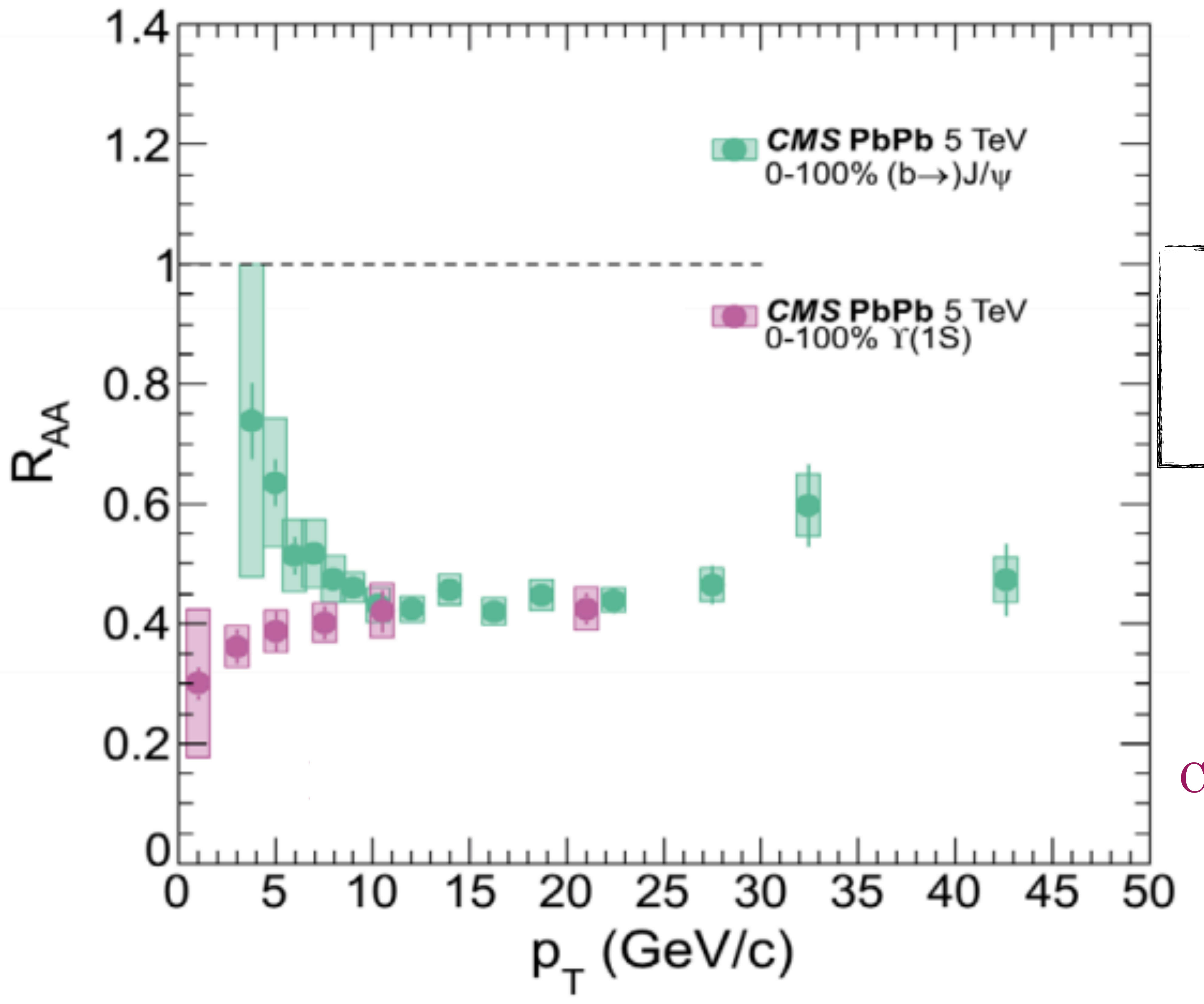
R_{AA} of open and hidden HF

Charm

D^0 (open charm)
J/Ψ (hidden charm)



Beauty



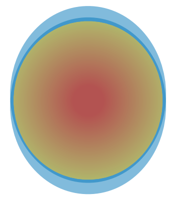
b-> J/Ψ (open beauty)
Υ(1S) (hidden beauty)

Camelia Mironov @ HP2020

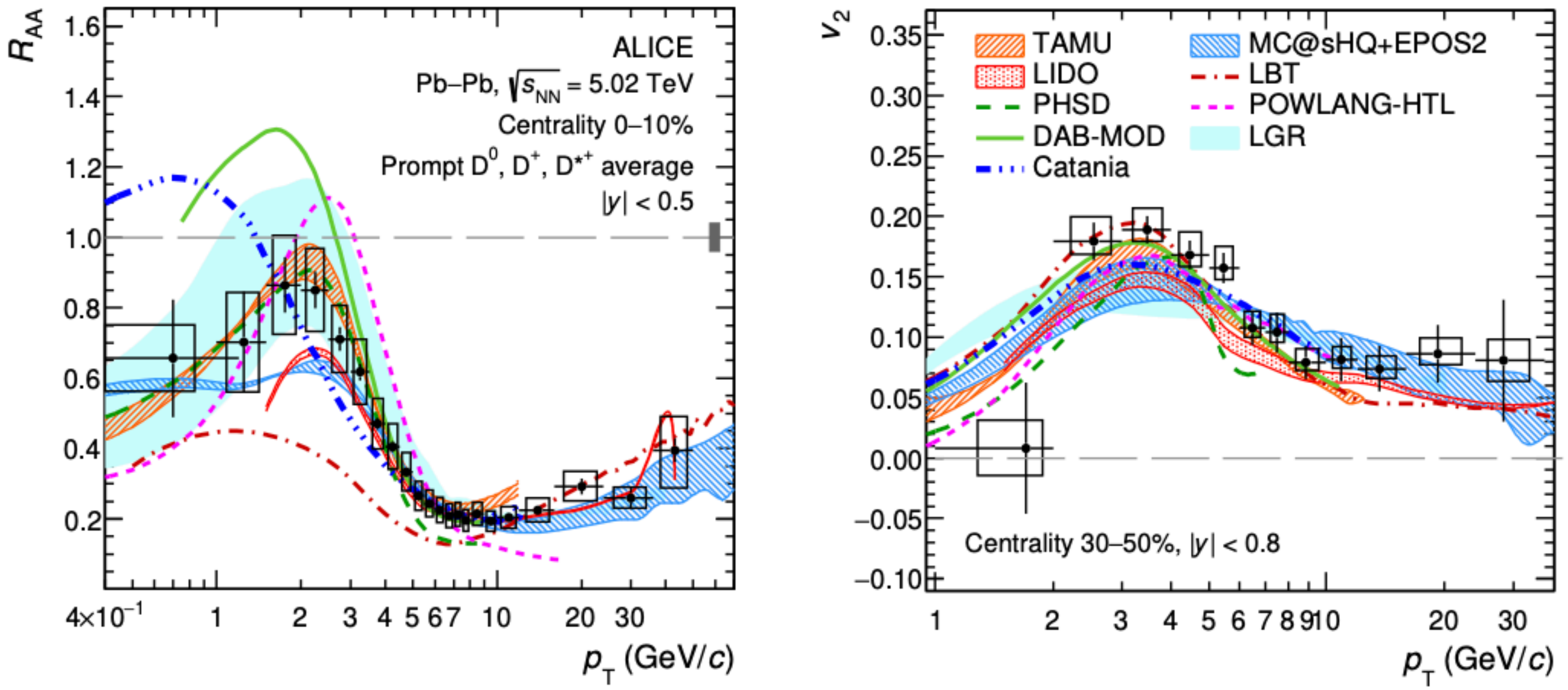
- **Charm**: same trend in the full p_T range.
  - Low p_T: dominated by hadronisation via recombination after interactions of charm quarks with QGP.
  - High p_T: J/Ψ has significant contribution from gluon splitting after in-medium energy loss.
- **Beauty**: difference at low p_T; same trend at high p_T.

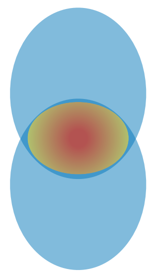
Understanding HQ interaction with QGP

Understanding interaction and energy loss of heavy quarks in the QGP over time —> Simultaneous comparison of D-meson R_{AA} and v_2



Central





Semi-central

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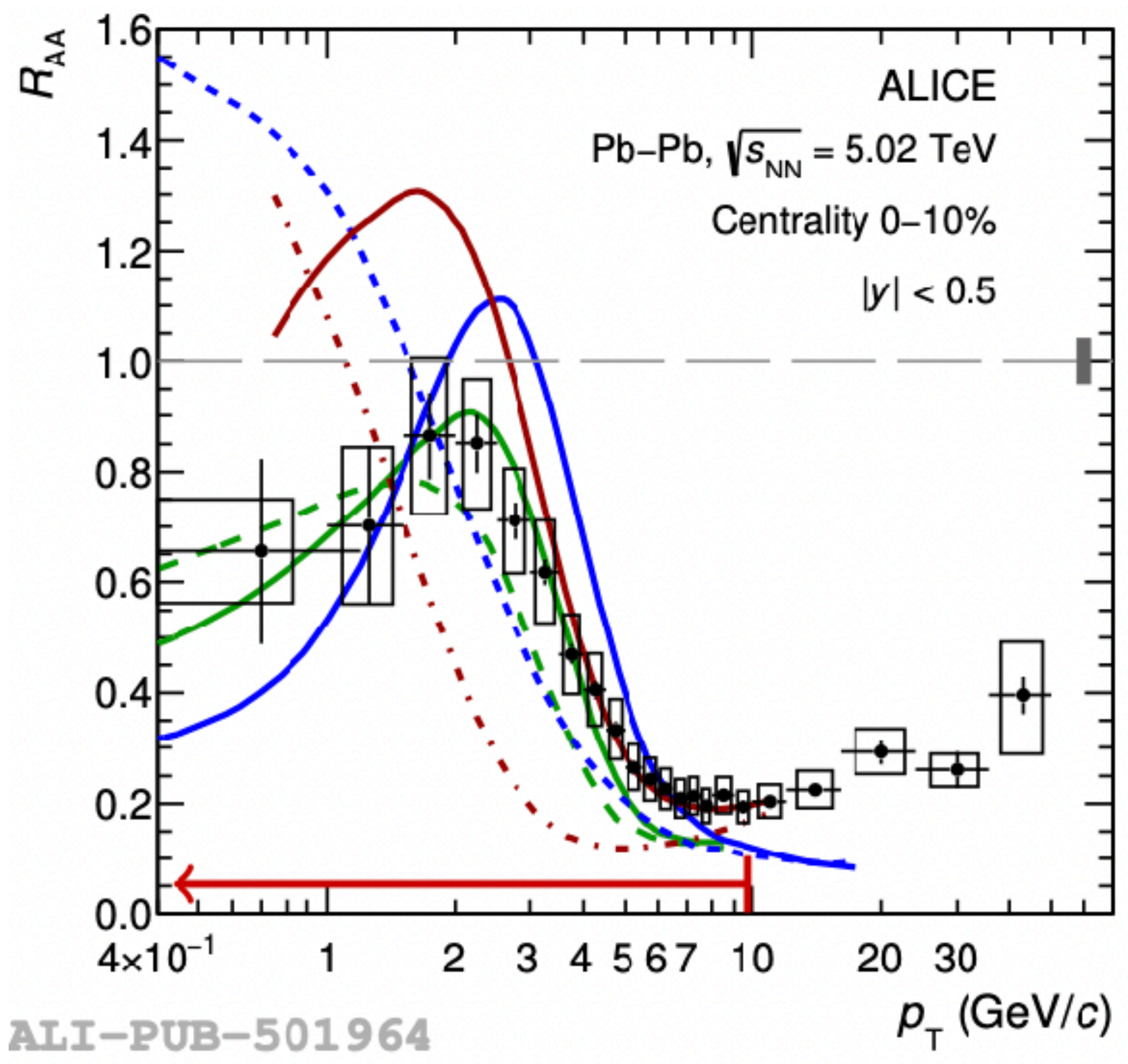
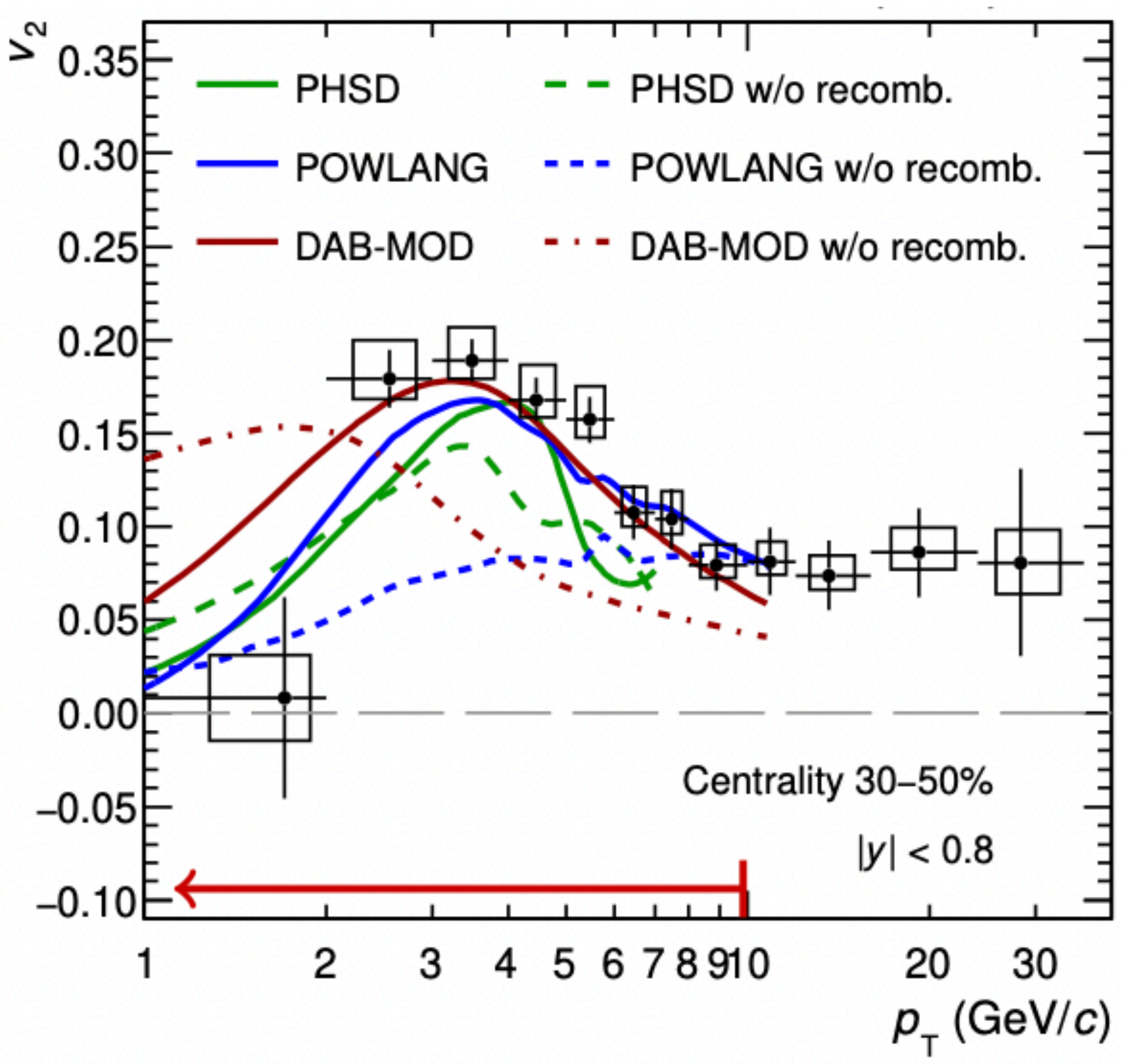
- Interplay of CNM effects, realistic evolution of the QGP, heavy-quark interaction (collisional and radiative) and hadronization via coalescence and/or fragmentation required to describe data.
- Models provide fair description of data —> still challenging for models to describe R_{AA} and v_2 simultaneously in the full p_T range.

Understanding HQ interaction with QGP





PHSD
POWLANG
DAB-MOD

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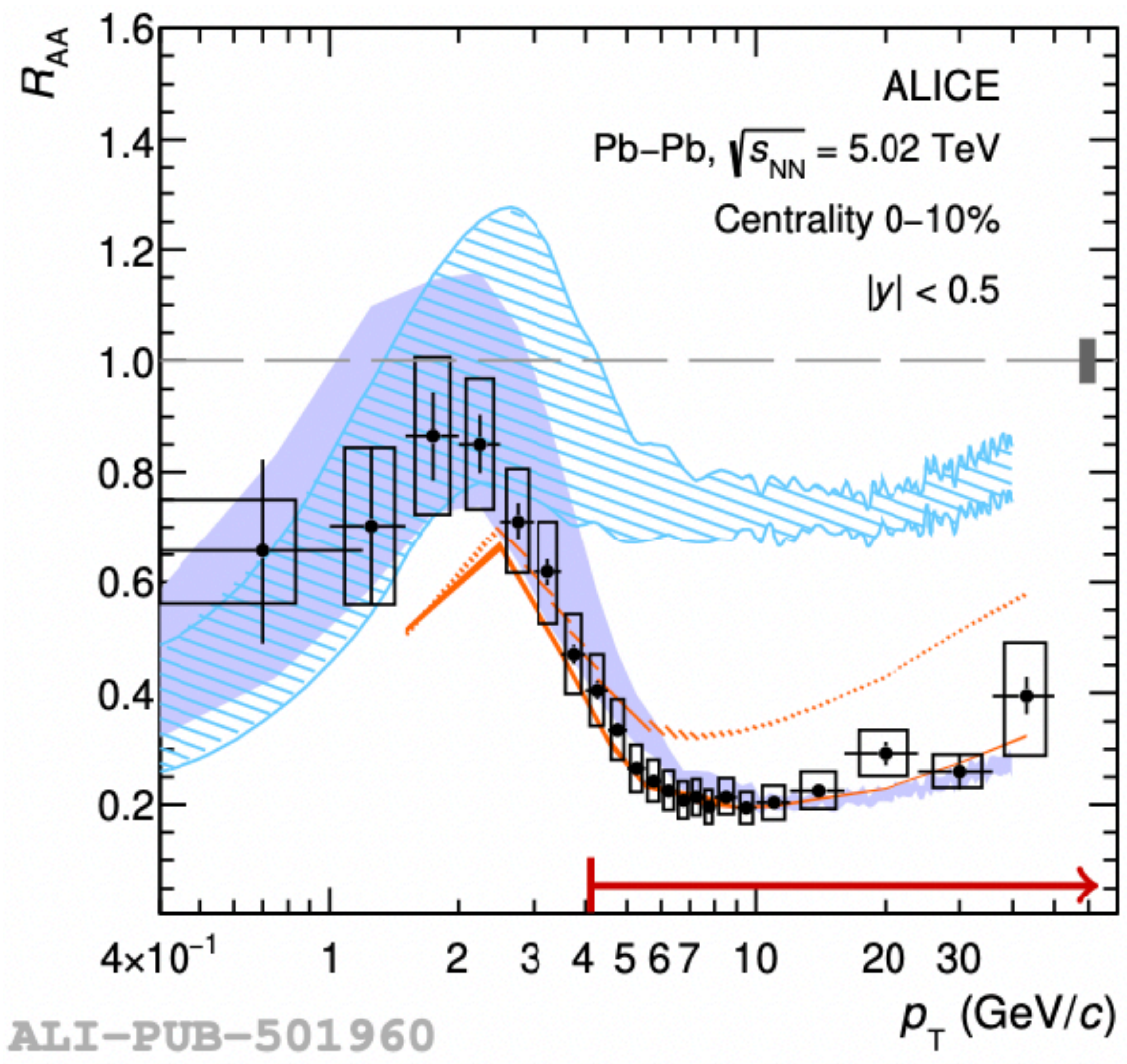
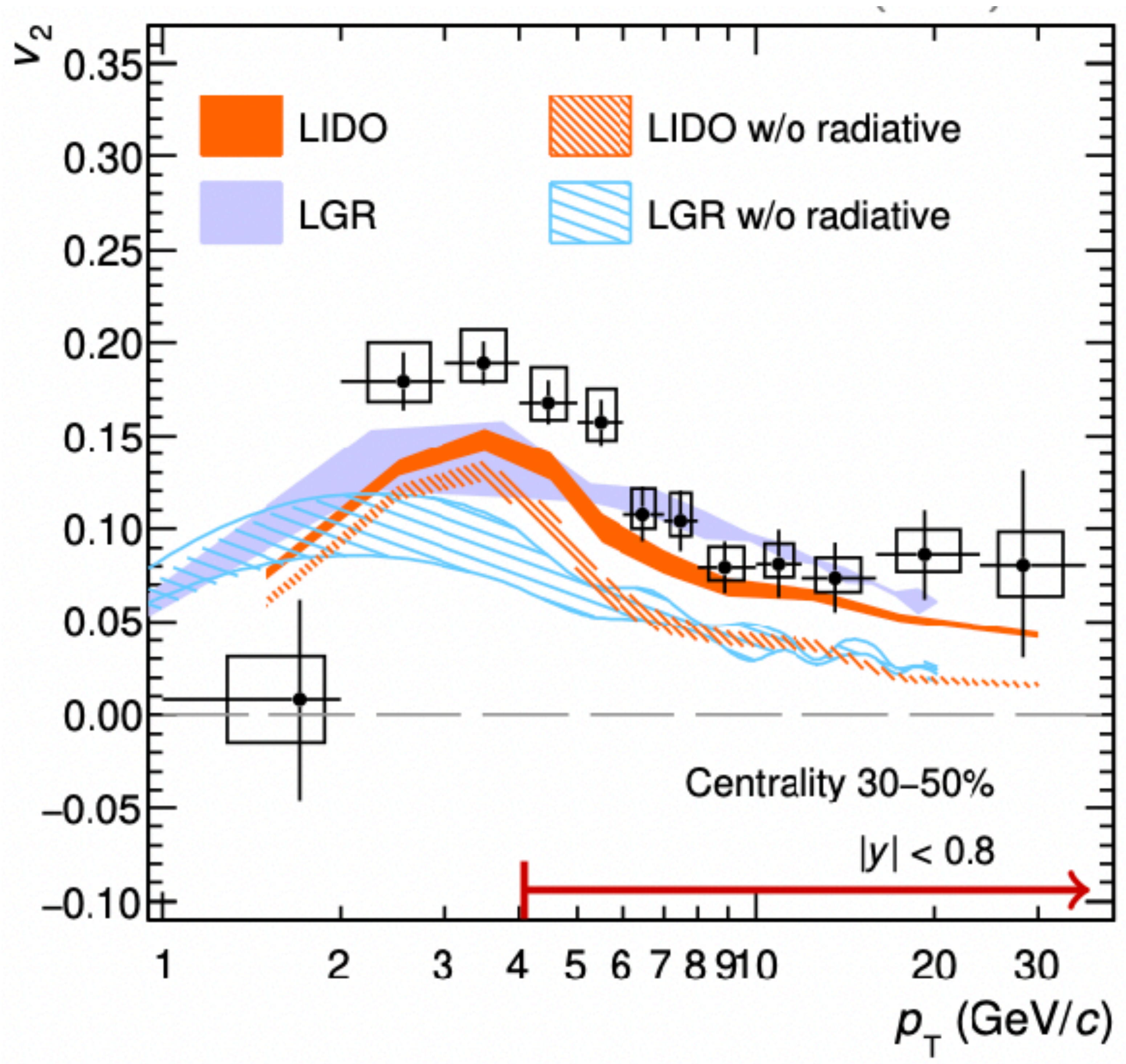
- Hadronization via recombination important to describe low and intermediate p_T.

Understanding HQ interaction with QGP





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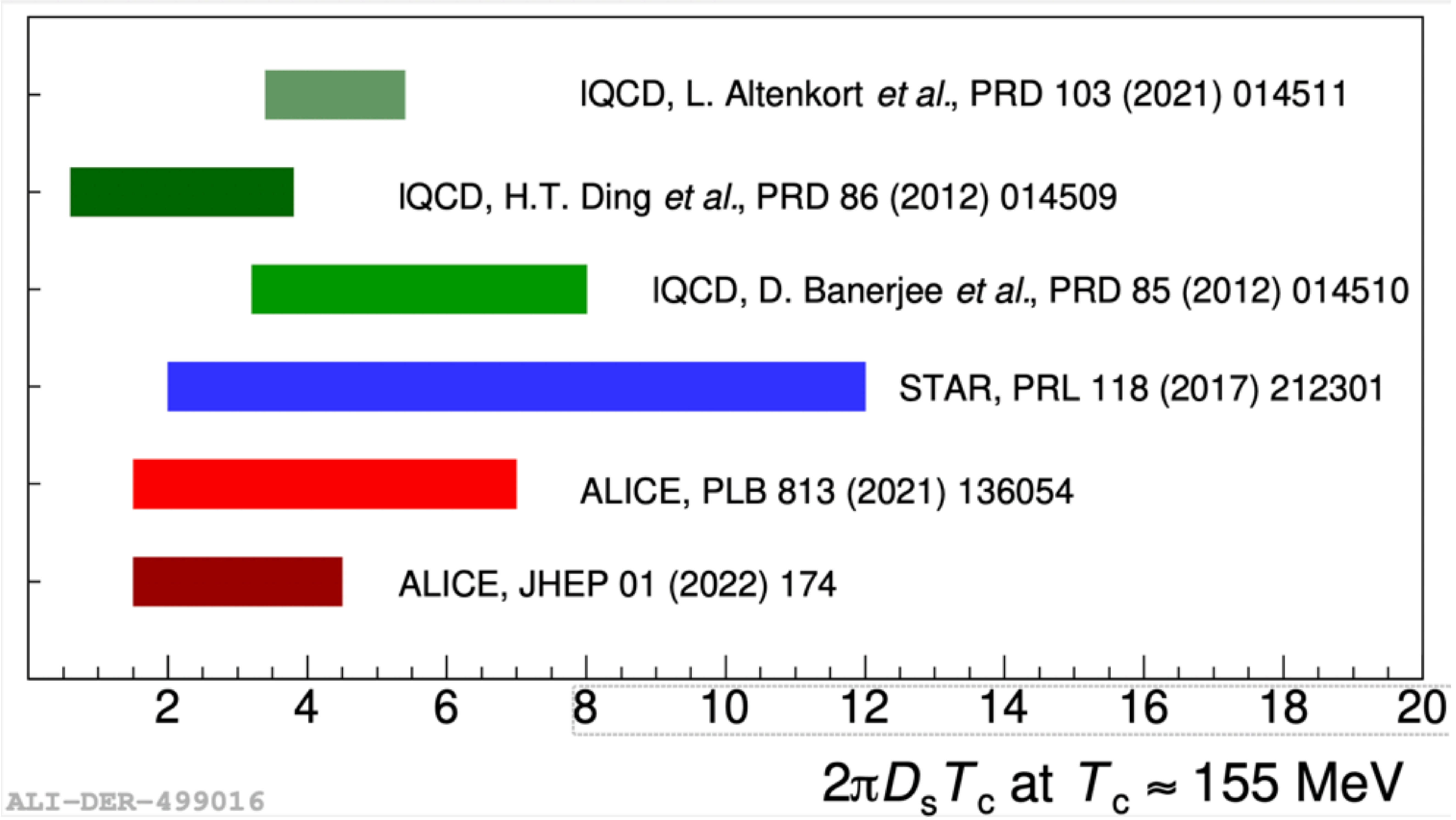
- Radiative energy loss important to describe intermediate and high p_T
  - small impact at low p_T

Heavy-flavor transport coefficients

Using data to constraint model parameters : compute χ^2/ndf between measurements and model predictions



χ^2/ndf < 5

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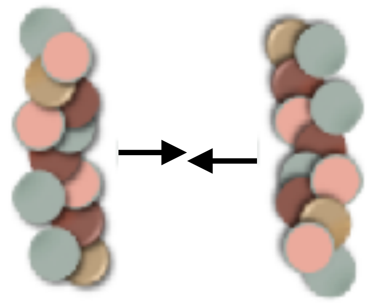
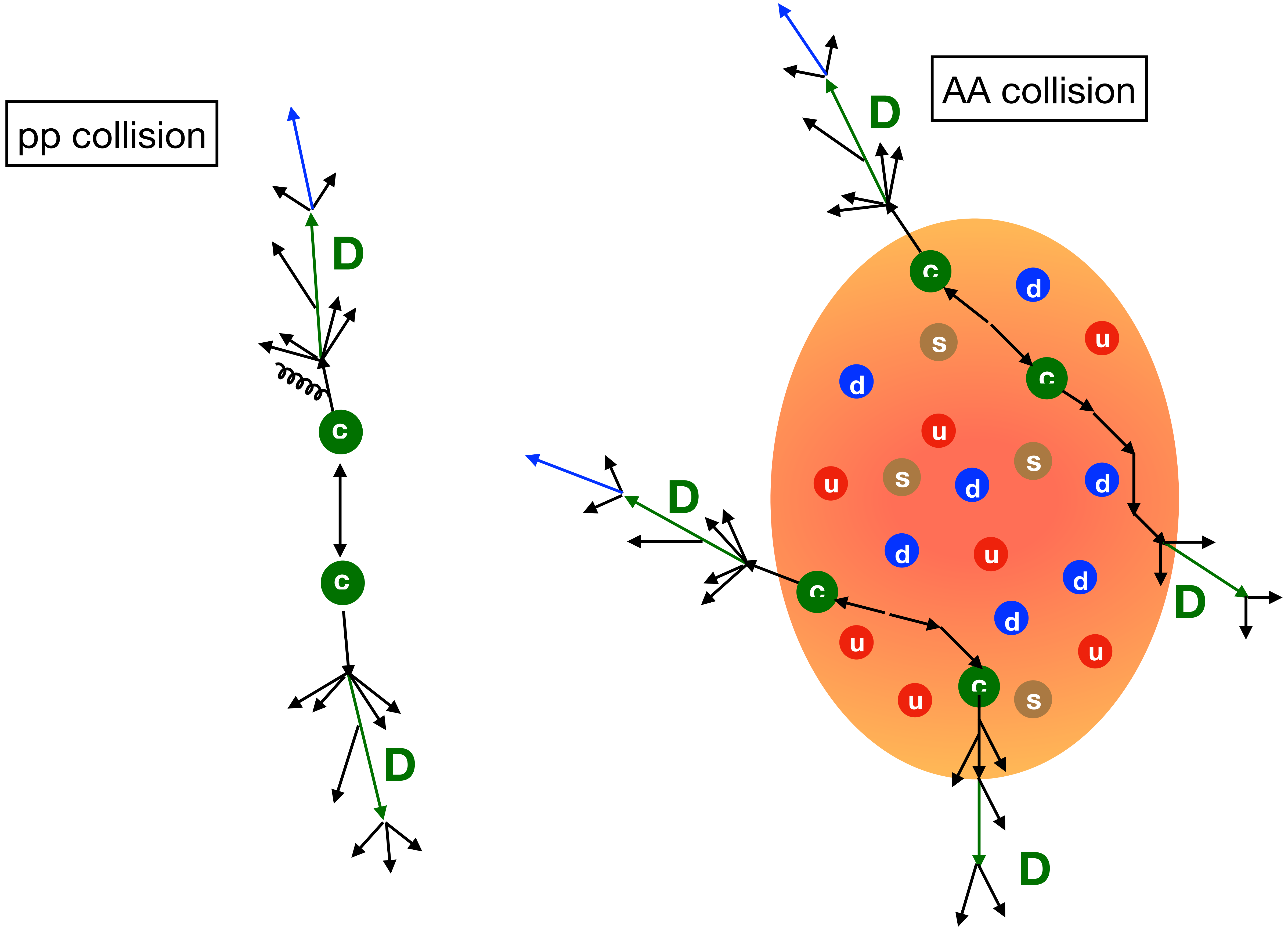
Models use spacial diffusion coefficient at T_c: 1.5-4.5

- More differential measurements could provide more constraints.

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 structure/fragmentation**

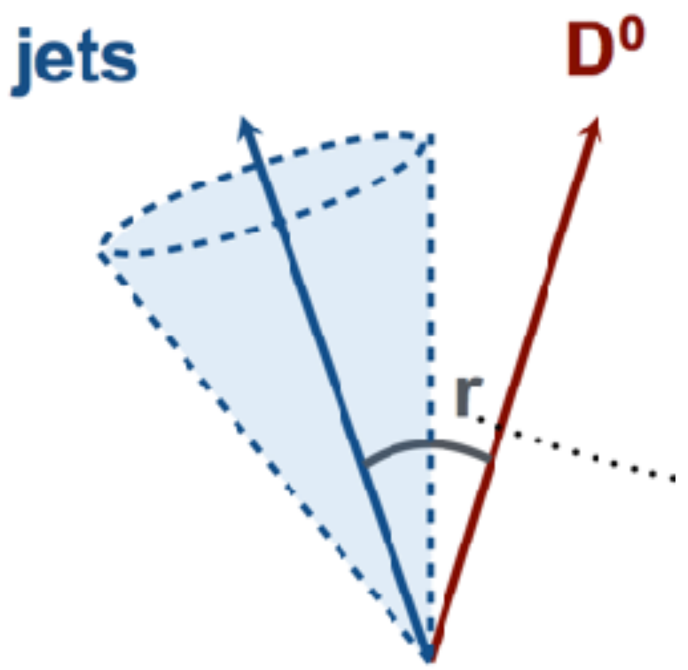


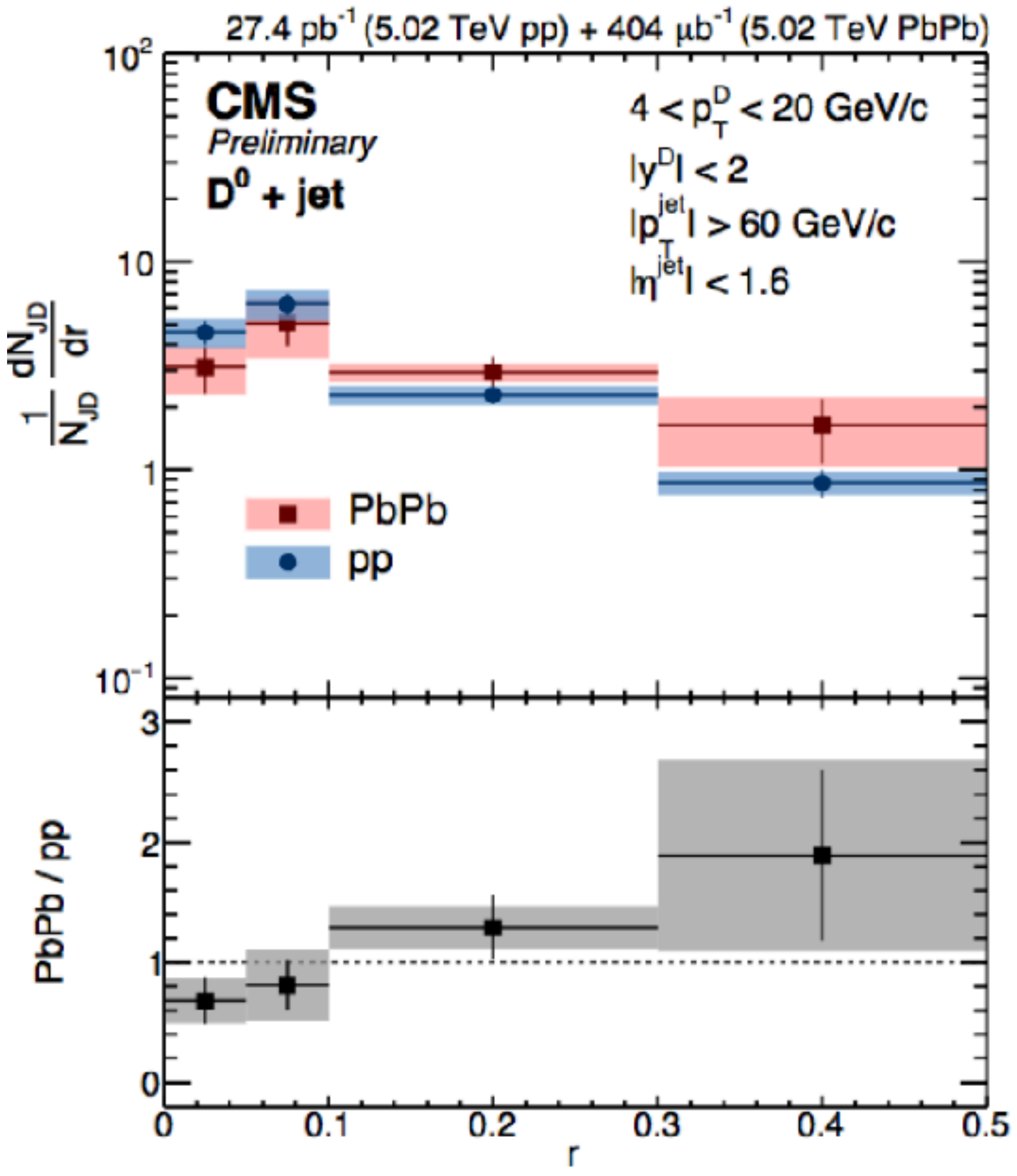
- **Hadronisation processes**

Jet fragmentation in AA

Study the modification of jet fragmentation in QGP

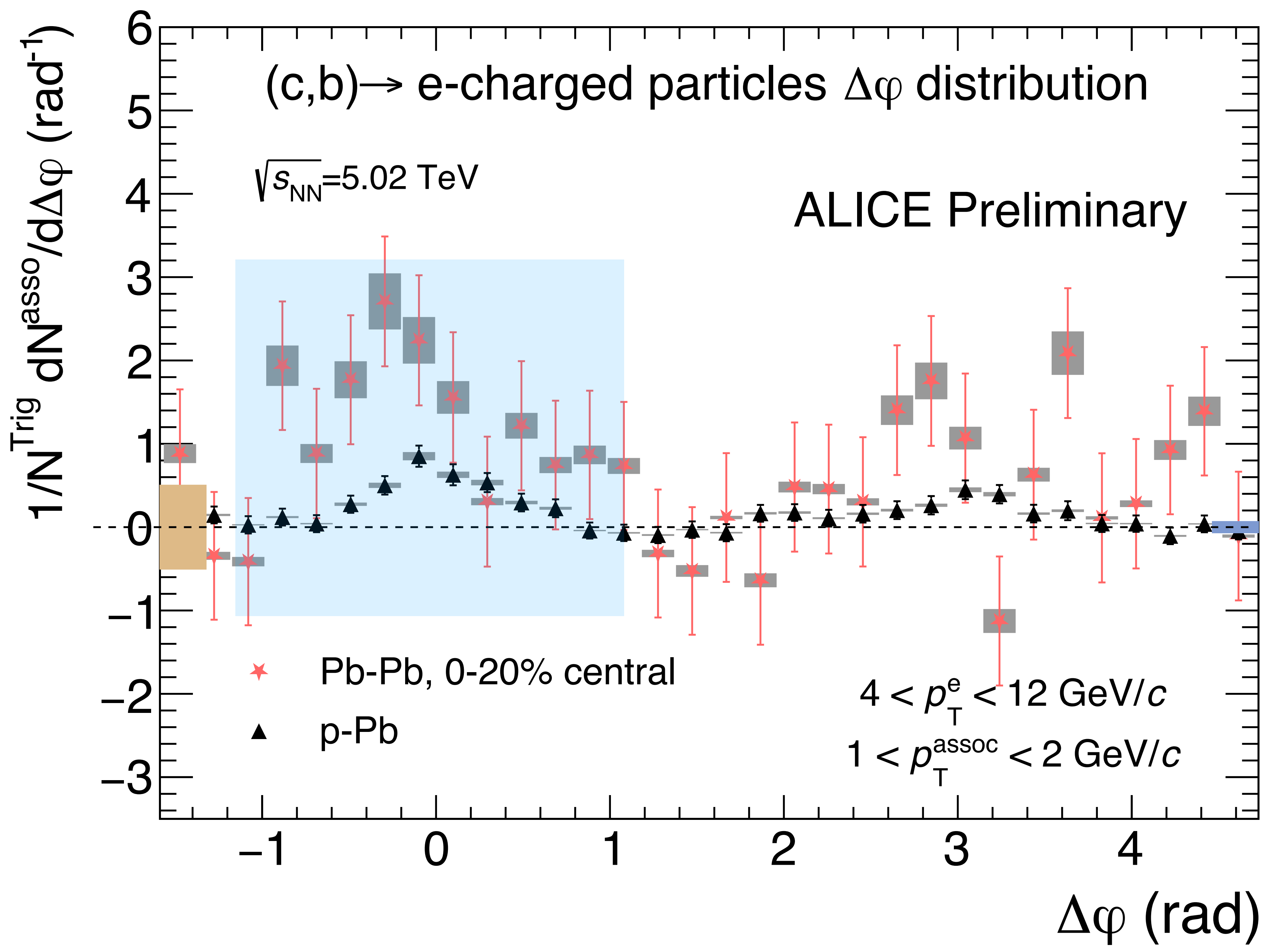
pp
Pb-Pb

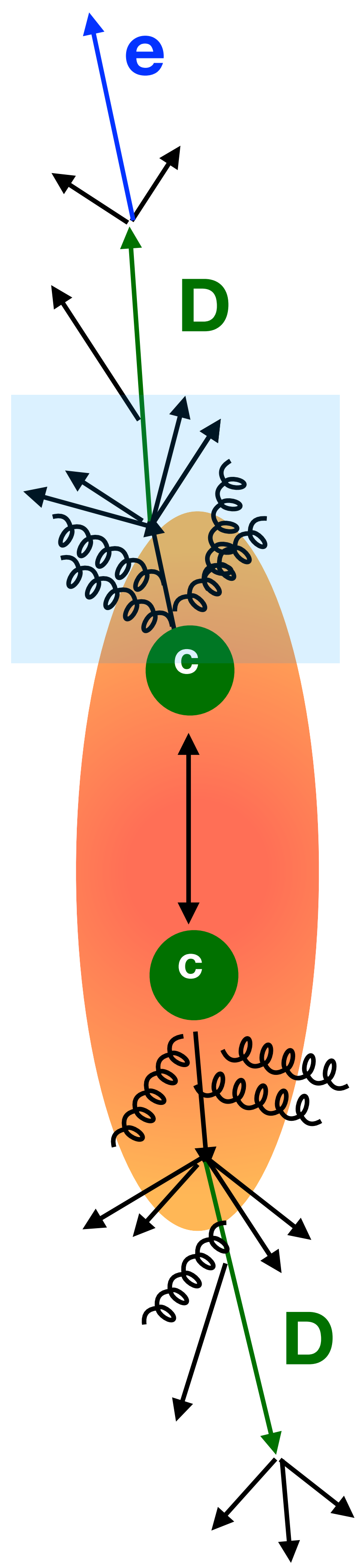




$\Delta\phi(e-h)$

p-Pb
Pb-Pb

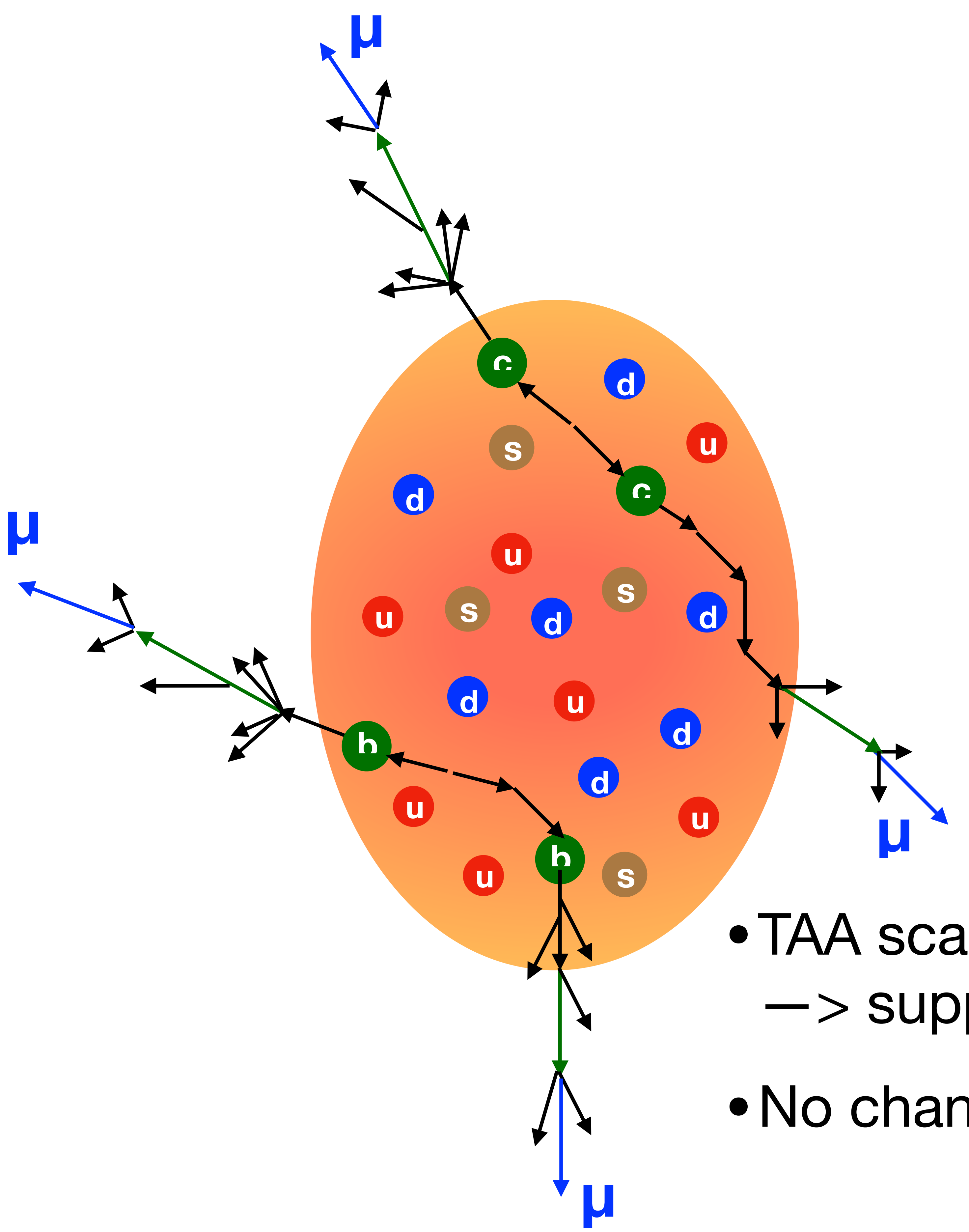


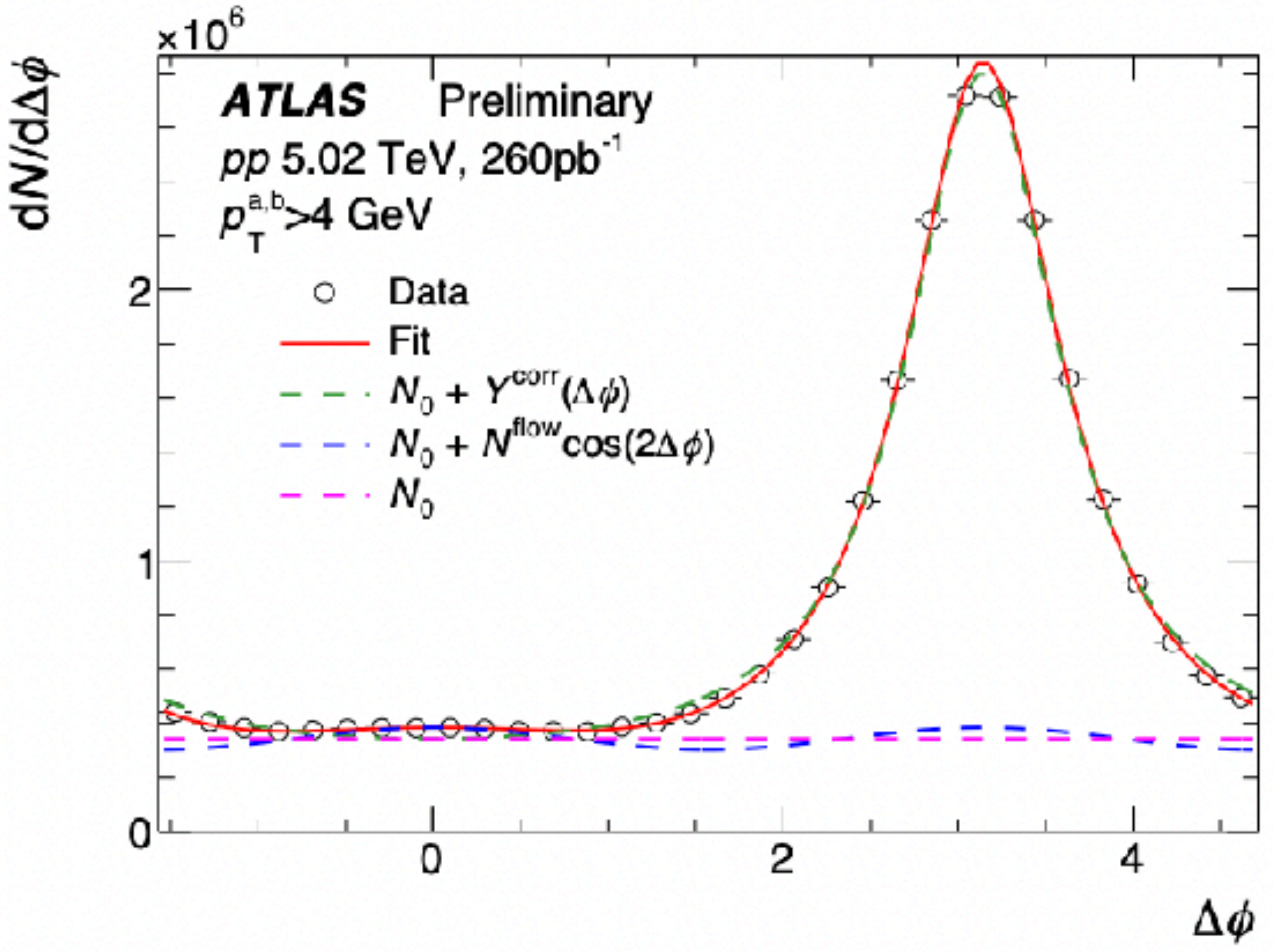


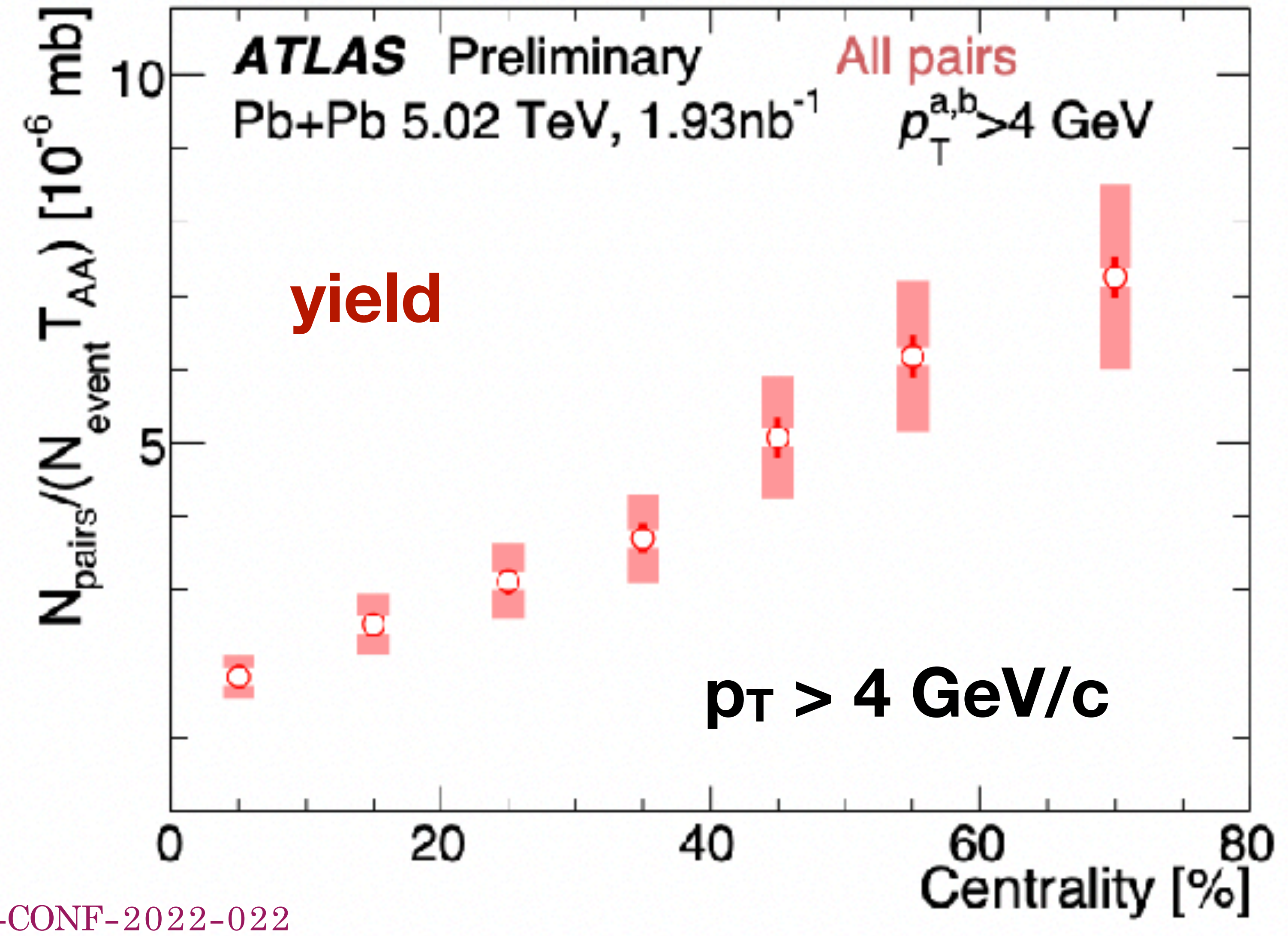
- Radial distribution of D^0 in jets - D^0 further away from jet-axis in Pb-Pb compared to pp.
- HF electron - hadron correlations - Enhancement of yield on near-side in Pb-Pb compared to p-Pb —> Energy loss goes into low p_T particles

HF-HF angular correlations

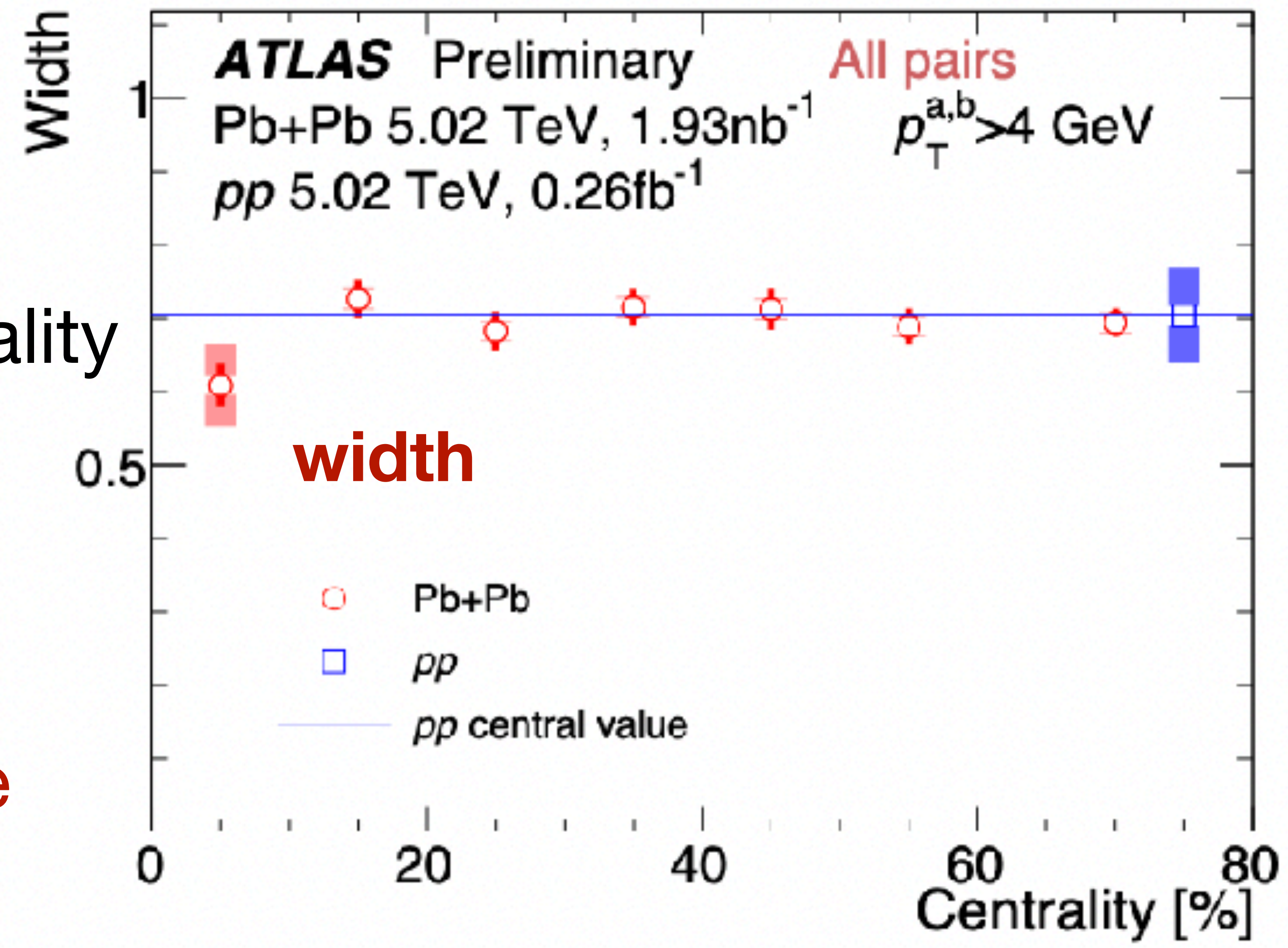
Angular correlations of back to back HF pairs using μ-μ:
- sensitive to relative importance of collisional and radiative scattering







ATLAS-CONF-2022-022

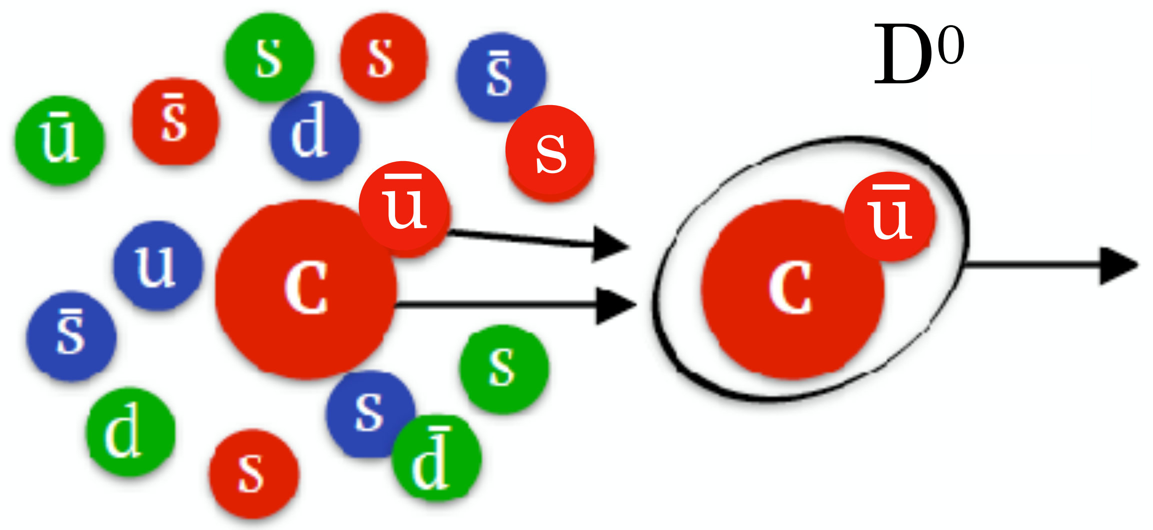


- TAA scaled μ-μ pair yield monotonically decrease with centrality —> suppression of HF pairs.
- No change in the width observed w.r.t. pp

More jet and correlation measurements needed for comprehensive understanding of the mechanisms of HF interaction with the QGP medium.

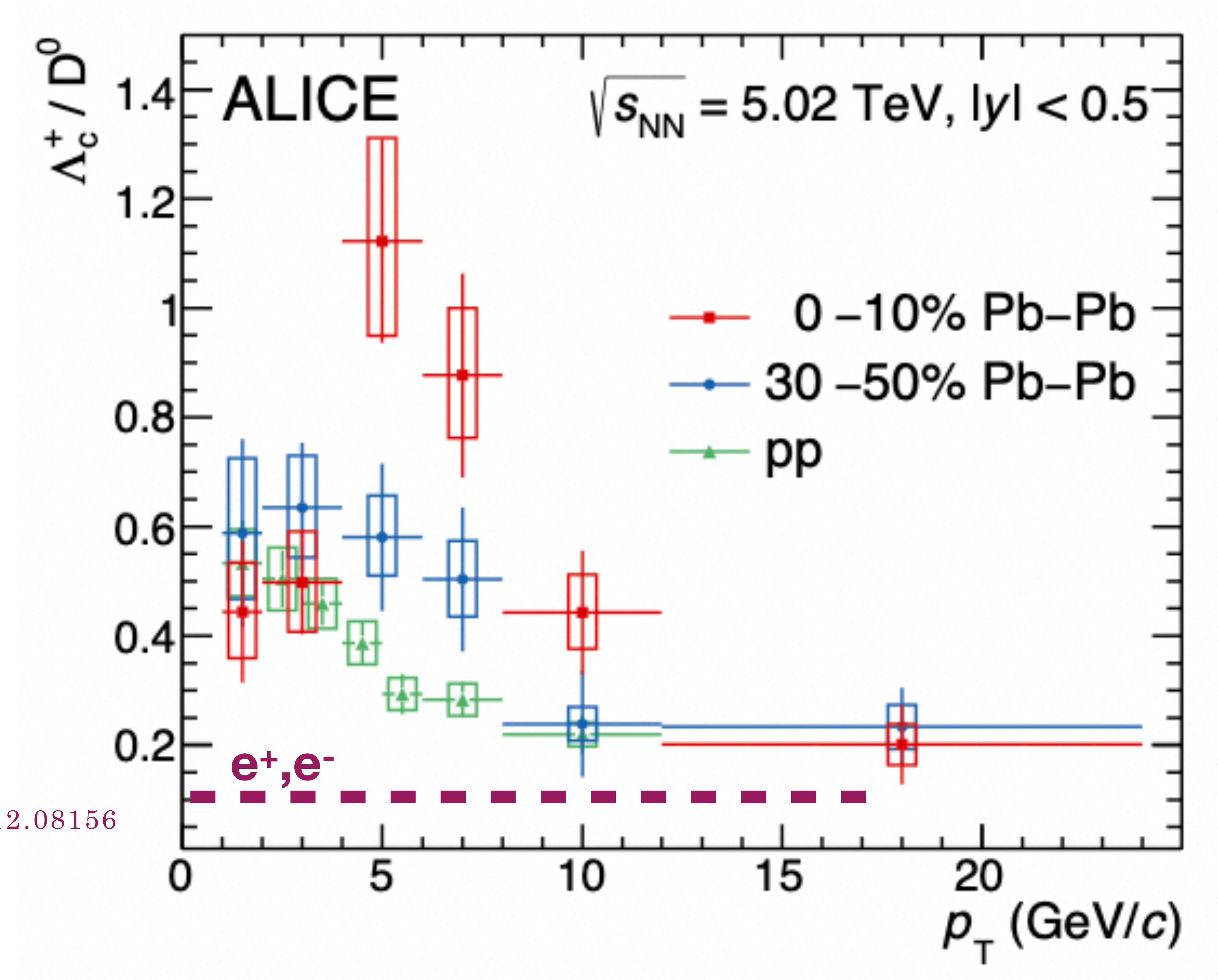
Heavy-flavor measurements in A-A

- **Azimuthal anisotropy (v_n)** - information about the initial collision geometry and its fluctuations
- **Nuclear Modification Factor (R_{AA})** - energy loss in the QGP
- **Jet structure/fragmentation**
- **Hadronisation processes**

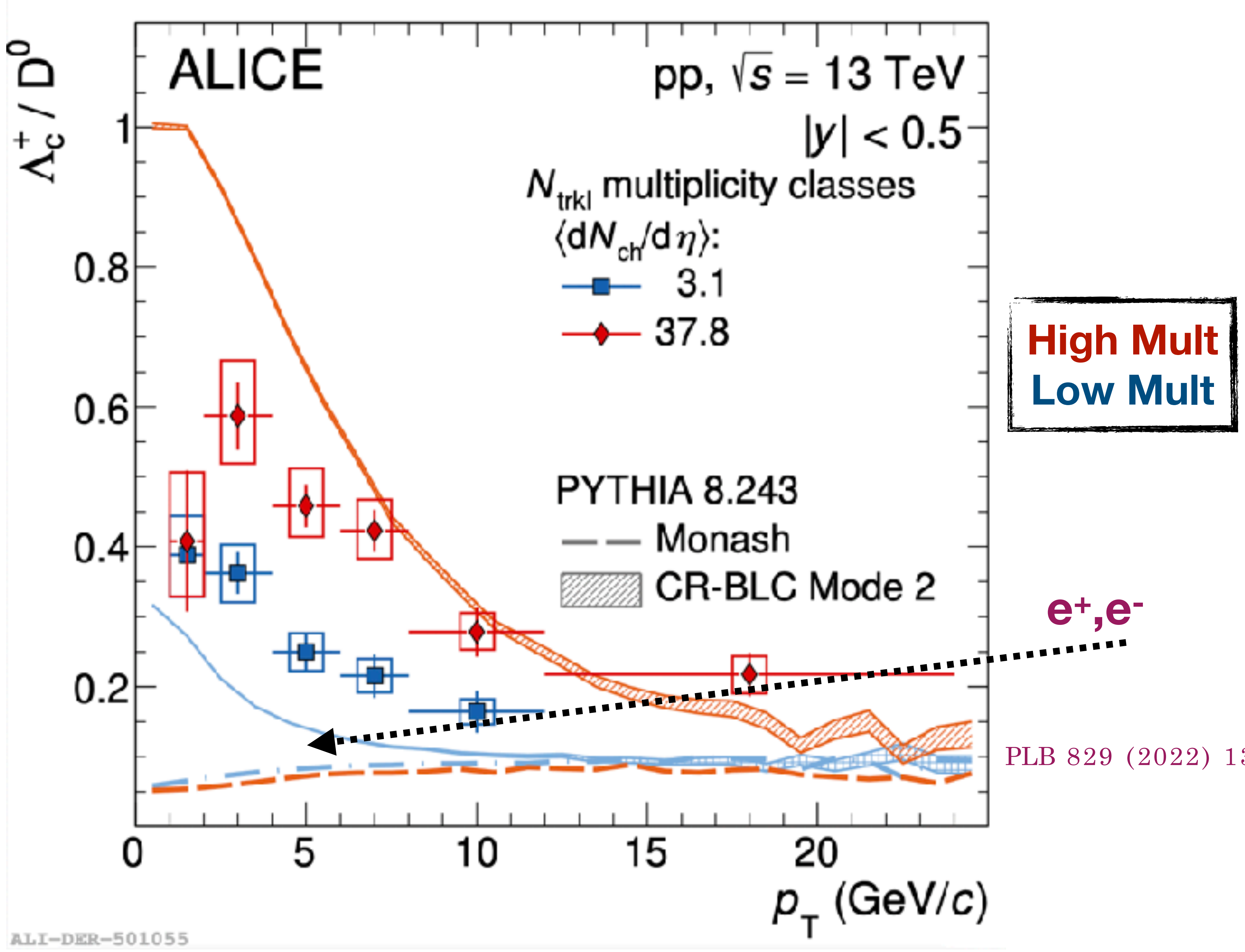


Hadronisation using baryons

Studying heavy-flavour hadronization mechanism using Λc



arXiv:2112.08156



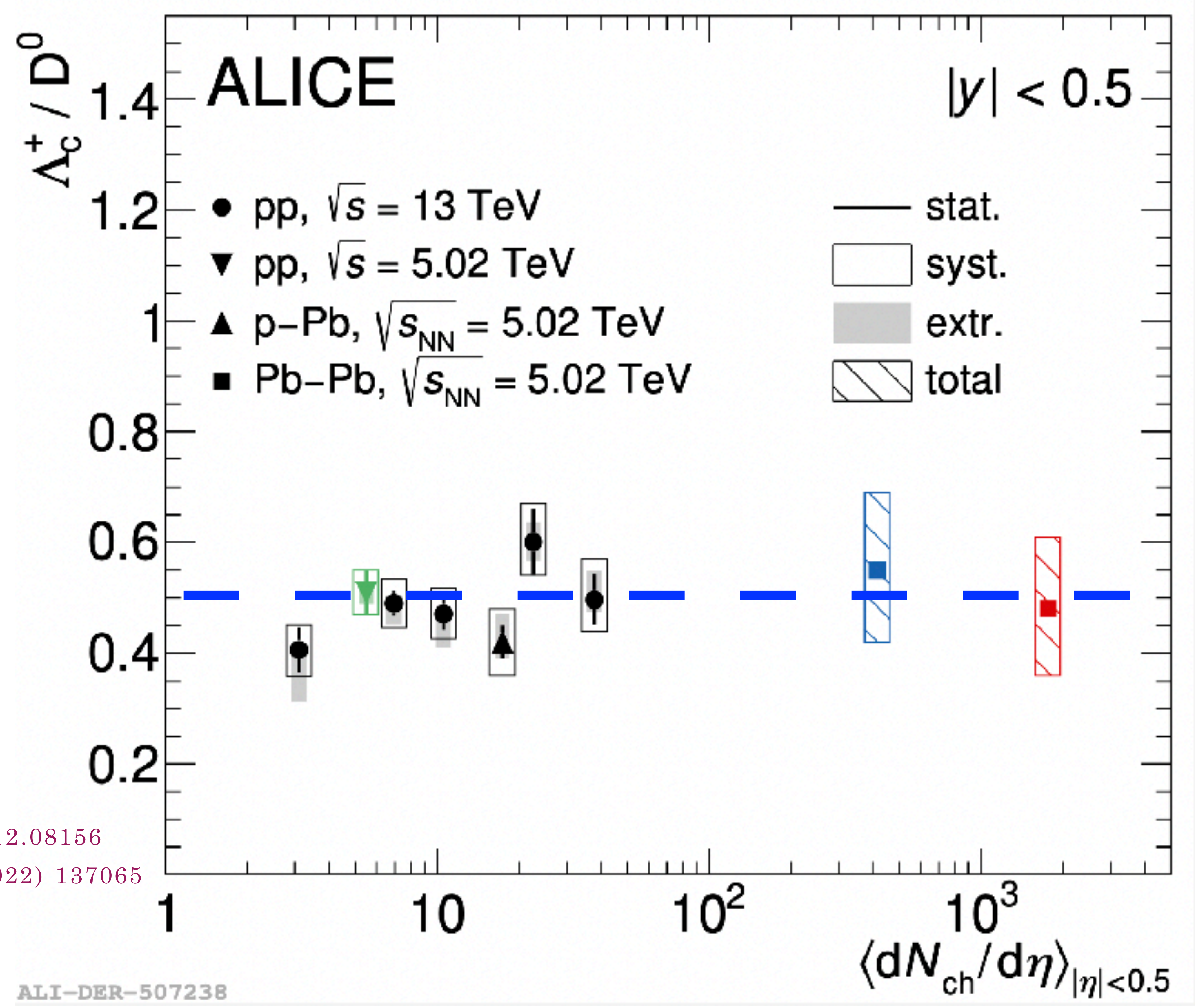
PLB 829 (2022) 137065

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

-> model calculations with fragmentation and coalescence favors data.

- Λ_c/D^0 in pp vs multiplicity:
  - Default PYTHIA tuned on e^+e^- data (Monash), underestimates the measurement
  - PYTHIA with color reconnections describes multiplicity dependent data in pp

Baryon production with Λ^+_c



arXiv:2112.08156

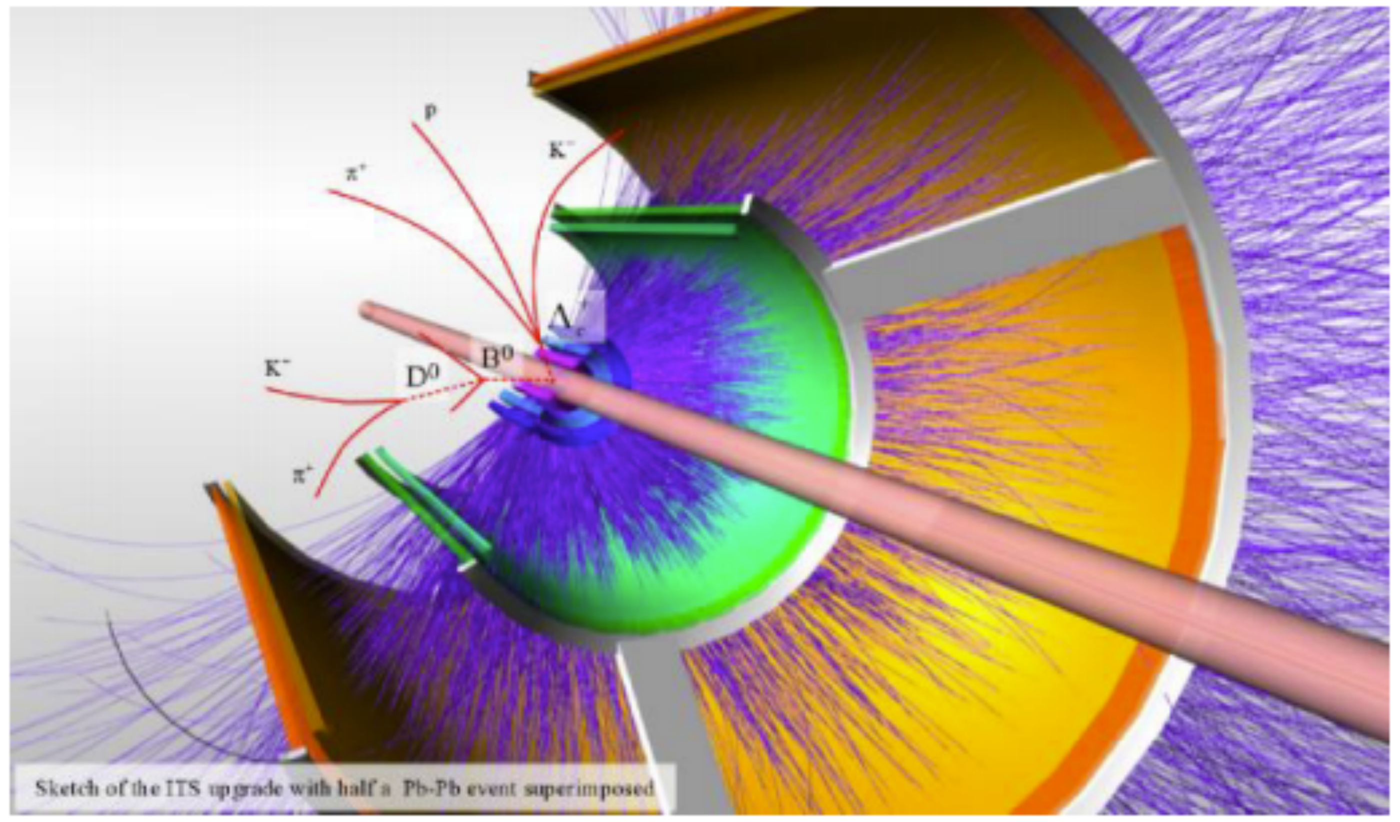
PLB 829 (2022) 137065

- p_T integrated Λ^+_c and D^0 values obtained by extrapolating to p_T = 0 GeV/c.
  - Similar values of Λ^+_c/D^0 ratio for pp, p-Pb and Pb-Pb
- Charm hadronization and Λ^+_c production do not differ significantly from pp to Pb-Pb collisions.
  - Redistribution of p_T due to interactions in the hadronic phase rather than an enhancement in the overall baryon yield??

Need precise measurement down to p_T ~ 0 GeV/c extending to lower multiplicities.

—> More measurements studying hadronization mechanisms needed.

Future prospects



LHC:

Run3

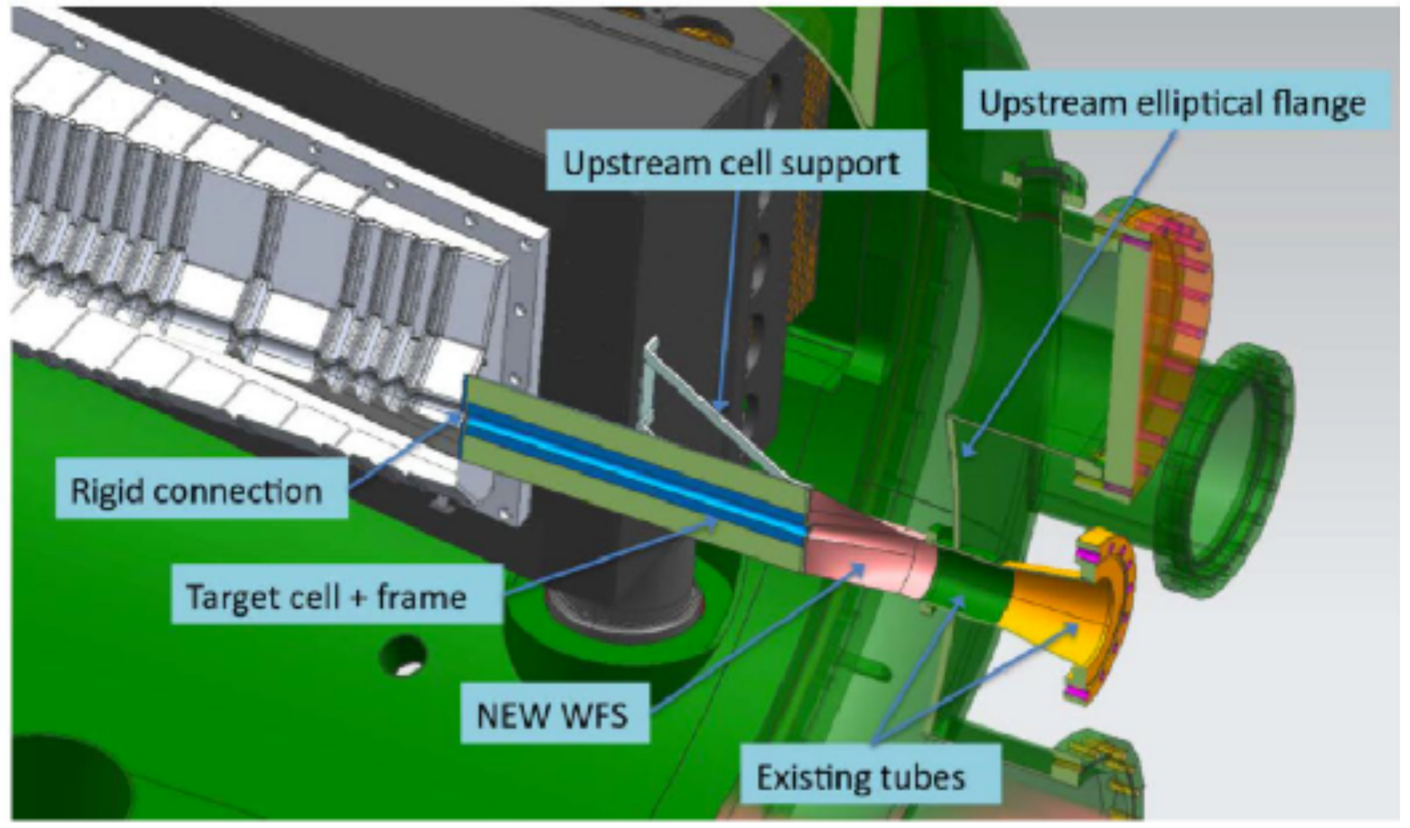
ALICE: New ITS, MFT, TPC readout chambers and fast interaction trigger
—> high precision measurements including beauty hadrons possible.

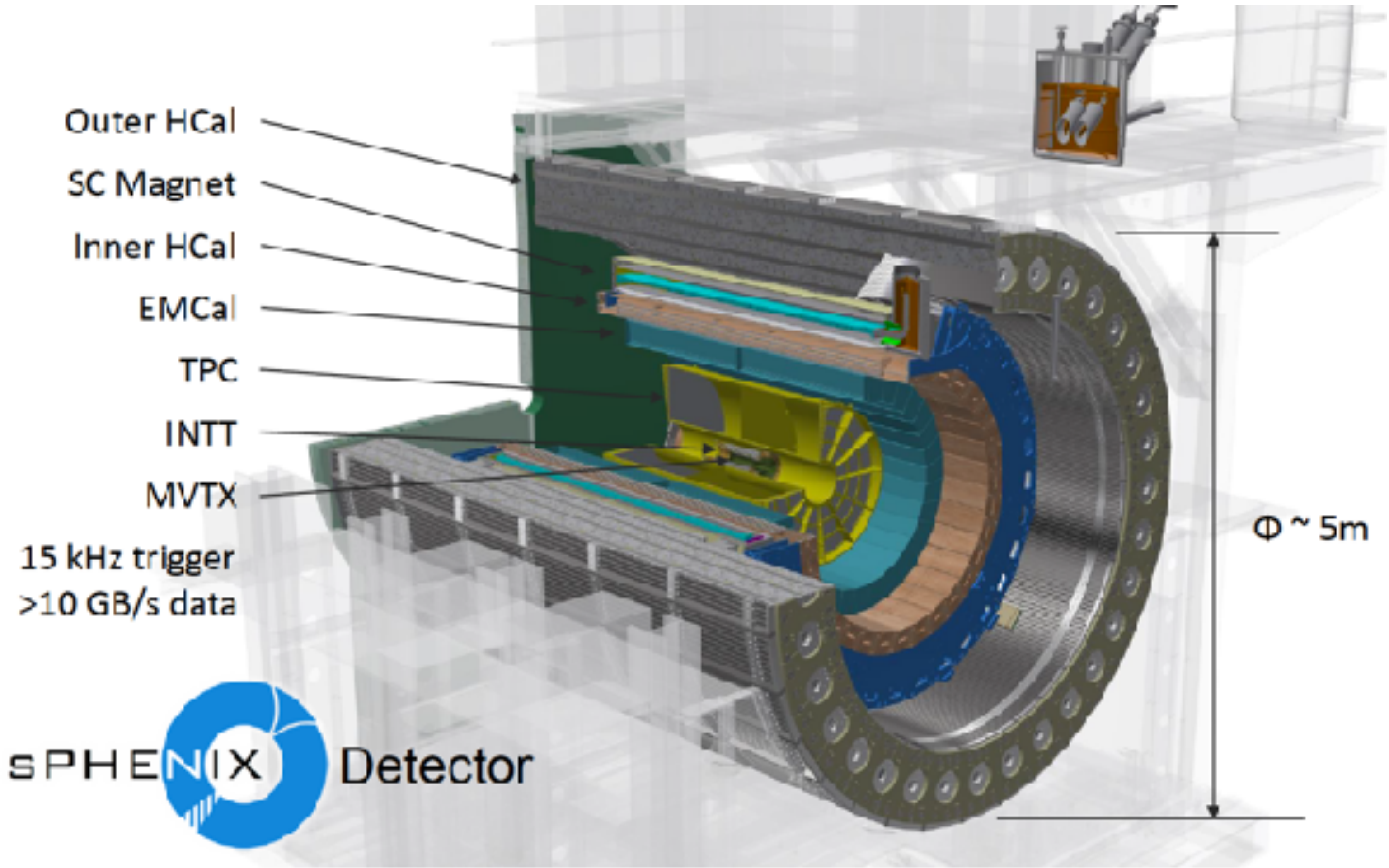
LHCb: SMOG upgrade
—> high precision charm measurements at different $\sqrt{s_{NN}}$.

LS3

ATLAS: New ITK —> Heavy-flavor jet measurements

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



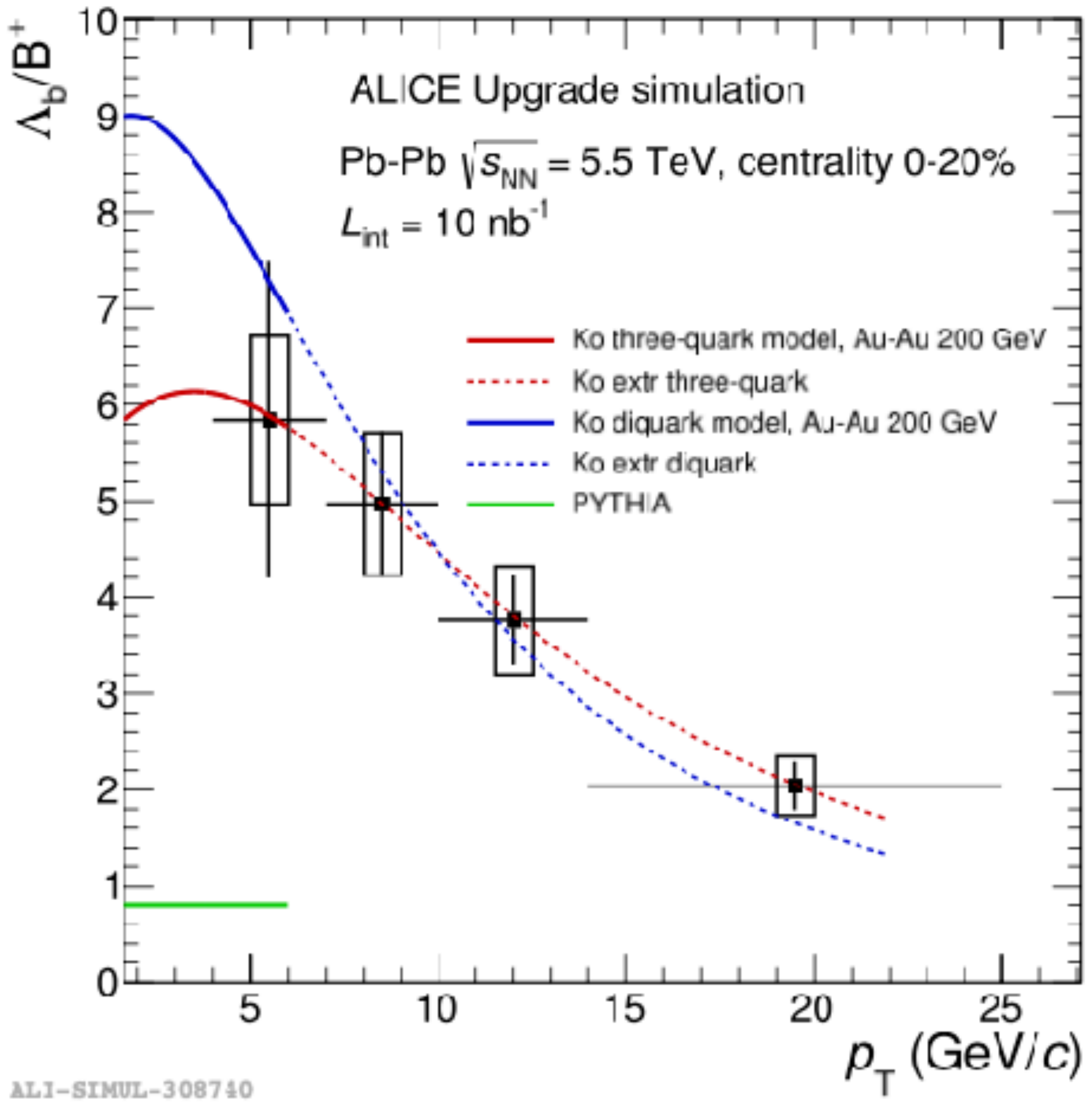


RHIC:

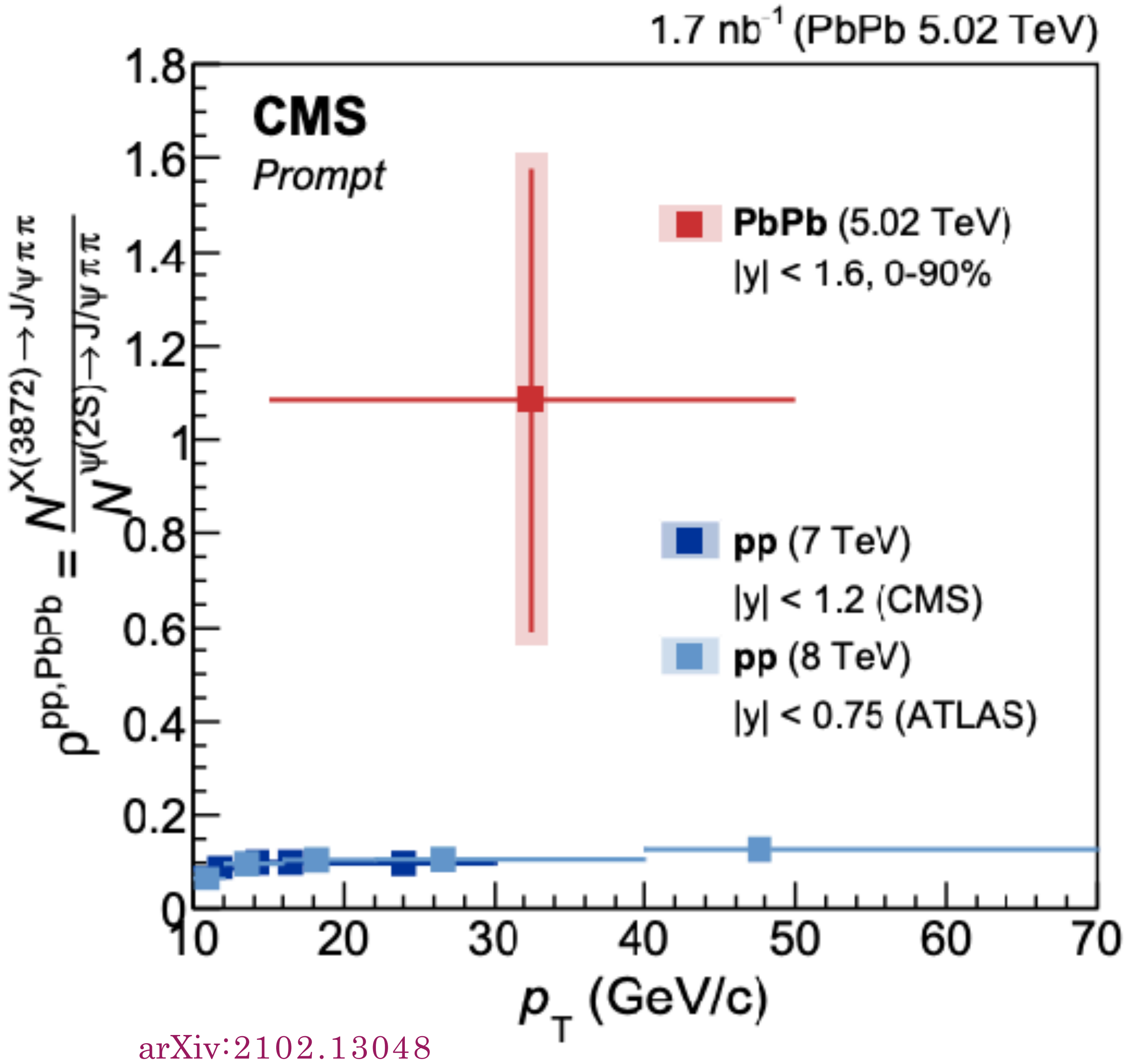
sPHENIX: extensive heavy-flavor physics including measurements of b-jets and full B meson reconstruction

Future prospects

B hadrons

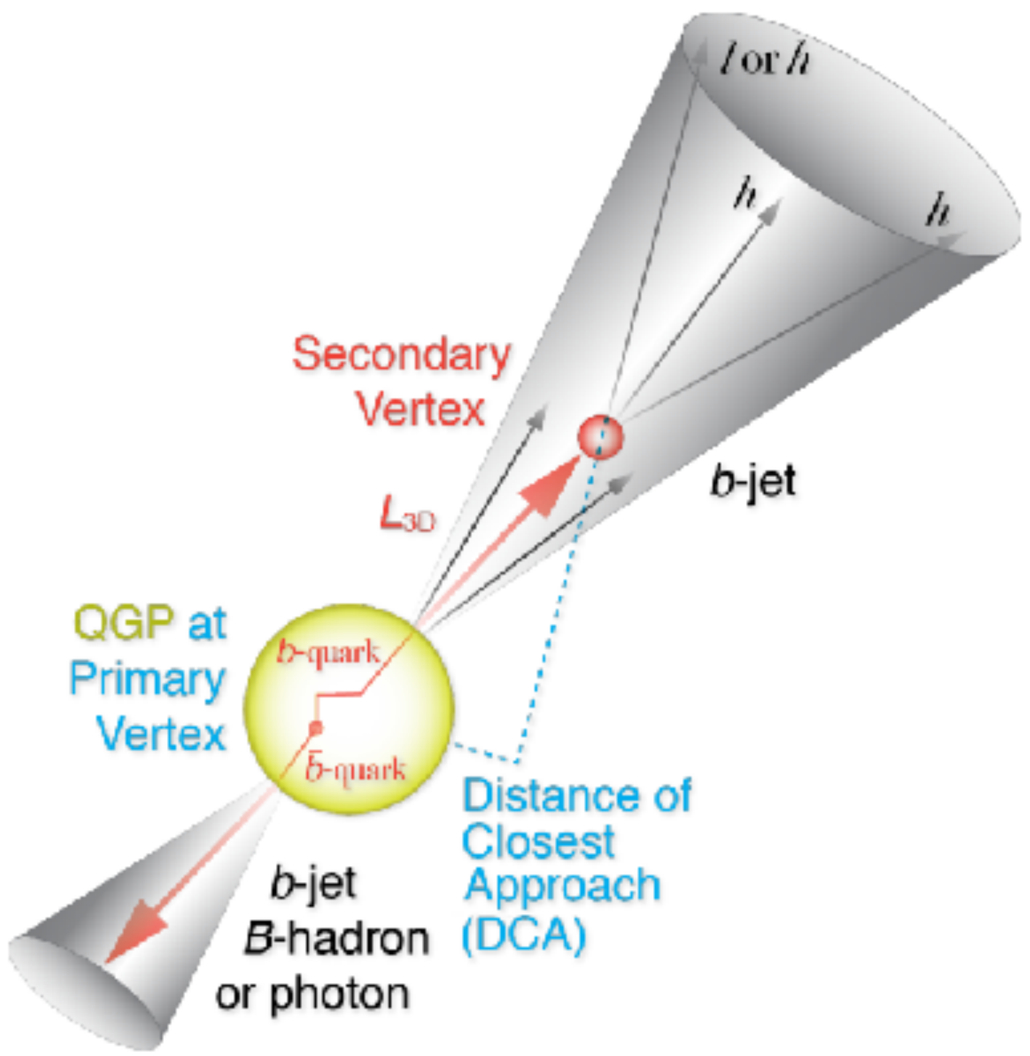


X(3872)

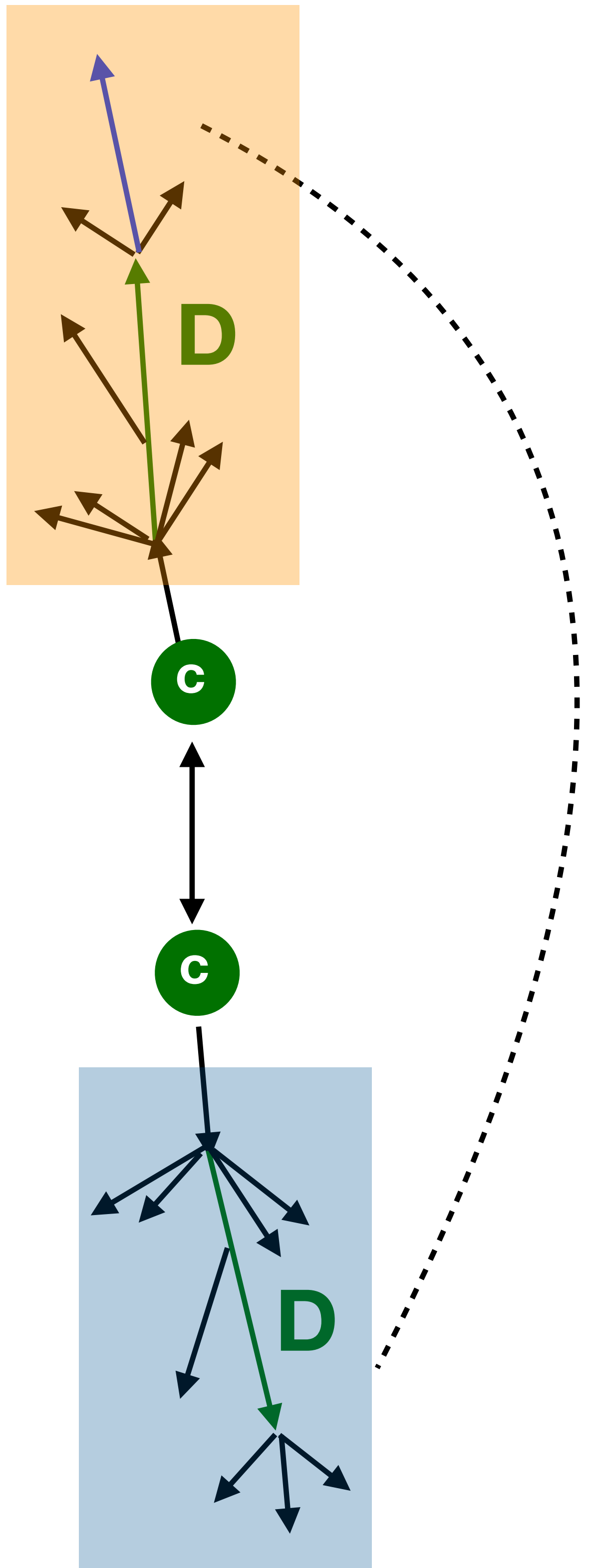


arXiv:2102.13048

HF-jets and substructure



$\Delta\phi(D-D)$



Summary of what we know

- **pp and p-A collisions**
  - Heavy-flavor production measurements in **minimum bias collisions** —> described by **pQCD calculations**.
  - In p-A collisions, measurements in **minimum bias collisions** —> described by **pQCD calculations with cold nuclear matter effects**.
  - Differential and multiplicity dependent measurements —> indicate **need for better understanding** of initial and final state effects.
- **AA collisions**
  - Charm and beauty quarks **undergoes energy loss** -> **mass hierarchy seen for pT~5-10 GeV/c**
  - Charm quarks interact strongly and **participate in the collective expansion** of the medium at RHIC and LHC.
  - Open beauty $v_2 > 0$, hidden beauty $v_2 \sim 0$.
  - Several **theoretical models describe the measurements** well.
  - **Coalescence effects** important at **low p_T**. Fragmentation process takes over at high p_T.

What do we want to learn more?

- Does beauty quark interact strong enough to particle in the collective expansion of QGP?
- Better constraint diffusion coefficients using beauty quarks and differential measurements.
- Modification of jet structure and fragmentation inside the QGP.
- More comprehensive understanding of baryon production and hadronisation processes.
- **Small systems**
  - Origin of the azimuthal anisotropy.
  - Is there a small QGP produced? If so why dont we see energy loss?
- Future is bright for Heavy-flavour studies both at the LHC and at RHIC.

Backup

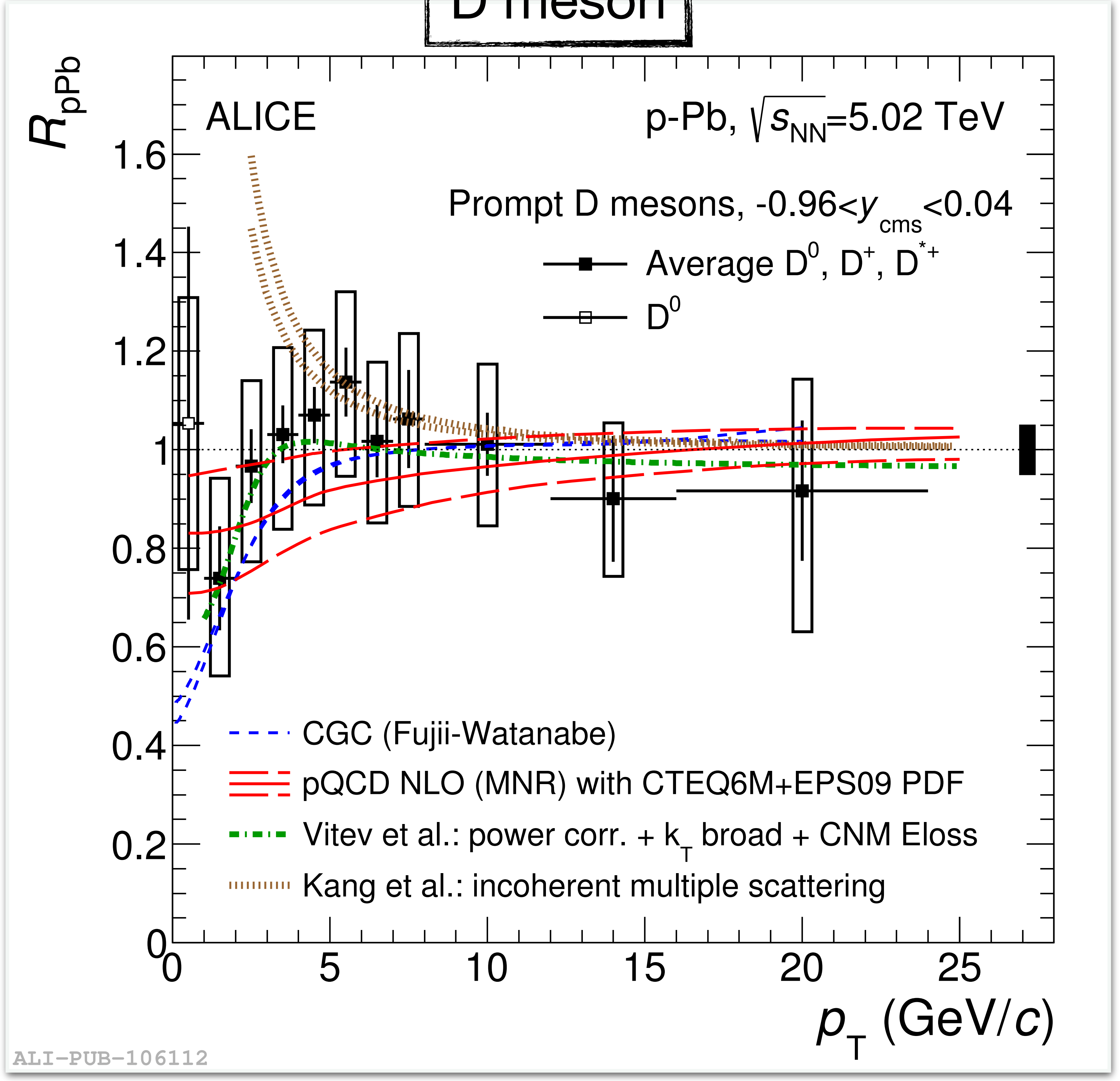
HF production in p-A

Study cold nuclear matter effects:

Nuclear modification factor - R_{pPb}

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

D meson



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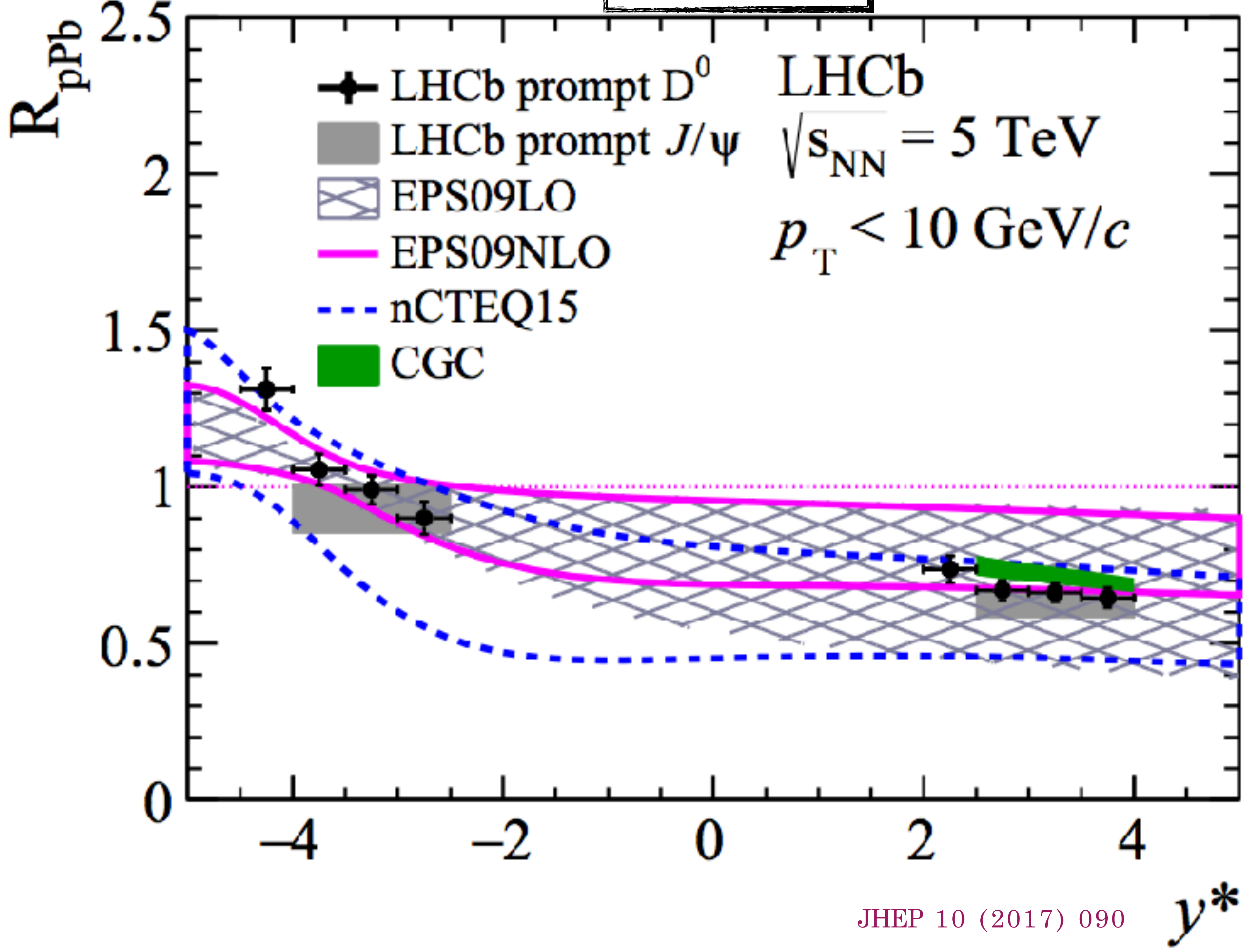
D⁰ meson
J/Ψ



JHEP 10 (2017) 090

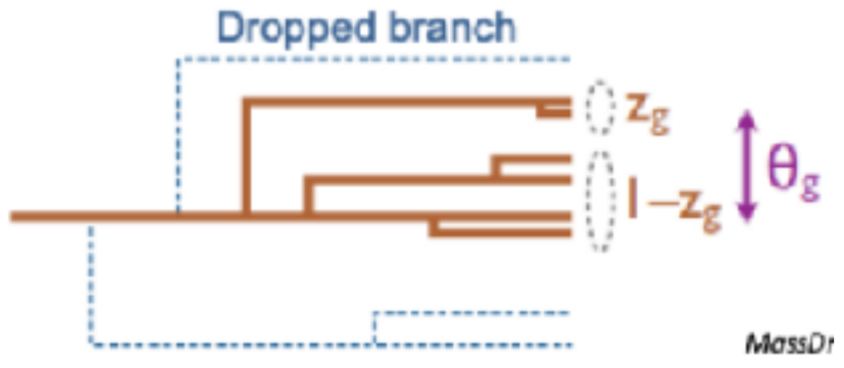
- R_{pA} of open HF hadrons and quarkonia measured in mid- and large- rapidities at RHIC and LHC —> no large suppression of yield observed at high p_T.
  - Models including Cold Nuclear Matter effects describe data within uncertainty for Minimum-Bias collisions.

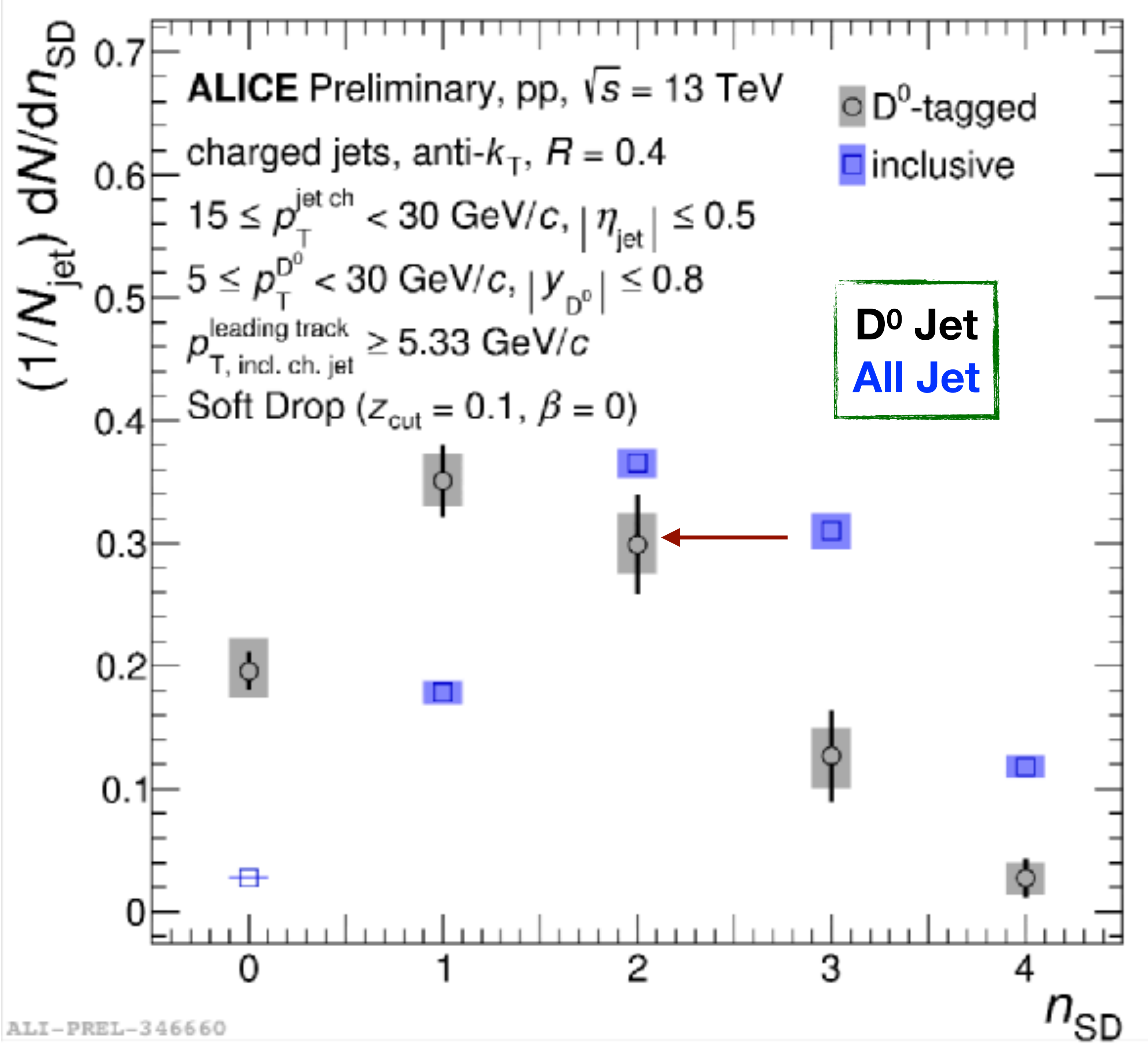
Jet substructure of D^0-tagged jets

Measuring substructure of jets containing D^0 mesons in pp collision

Grooming jets with SoftDrop algorithm:

- Groomed splitting characterized by **N-splitting passing grooming condition(N_{sd})** and **groomed momentum fraction (z_g)**





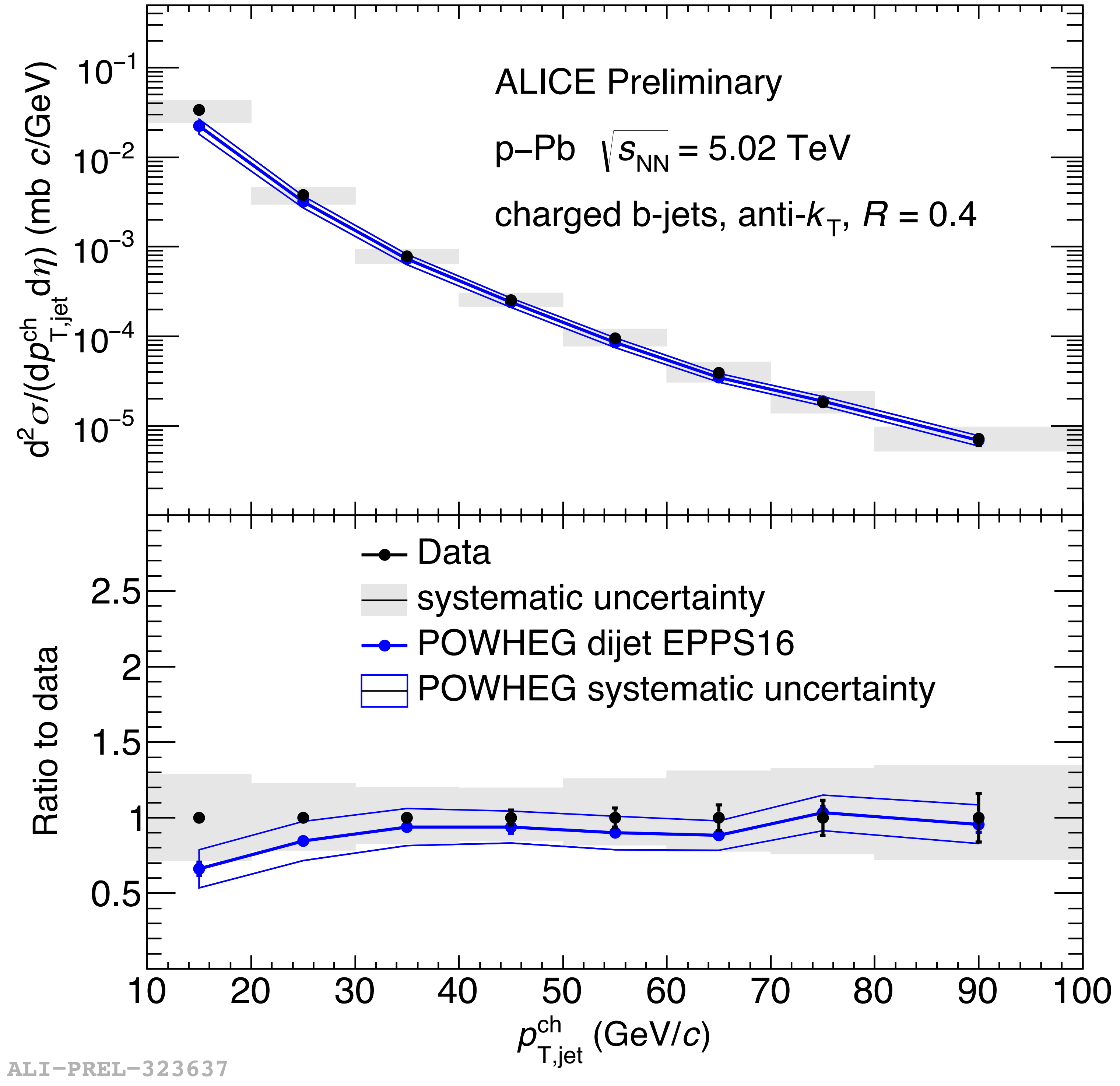
N_{sd} distribution for $Z_g > 0.1$
pp, $\sqrt{s}$=13 TeV

Comparison of inclusive and charm jet using different grooming observables:

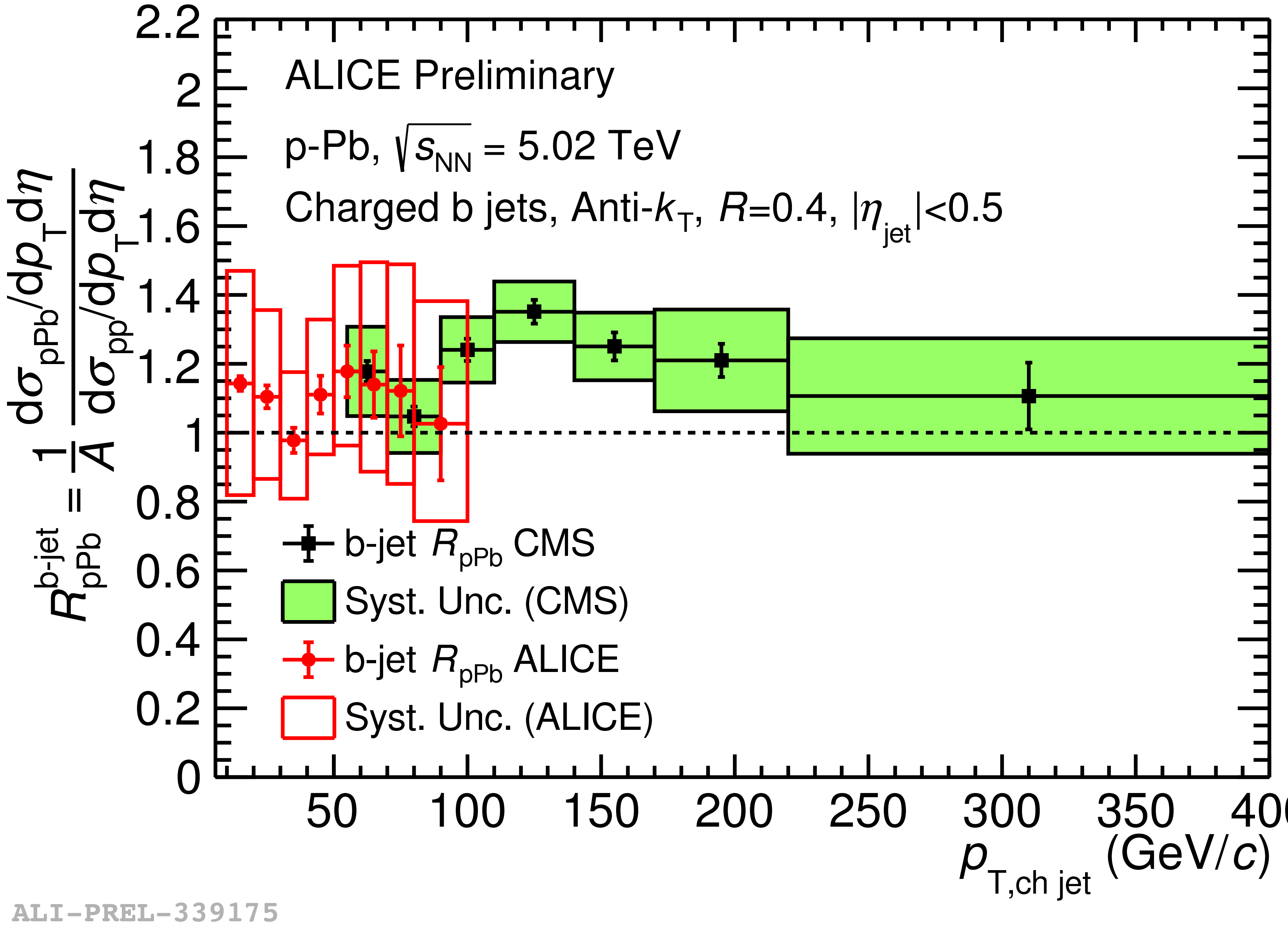
- Groomed momentum fraction similar and well described by Pythia
- **N_{sd} shows significant difference in the behavior**
    - Distribution shifted to smaller values for D-jet —> **fragmentation of HF has less prongs**

Beauty-tagged jet cross-section

b-jet cross-section

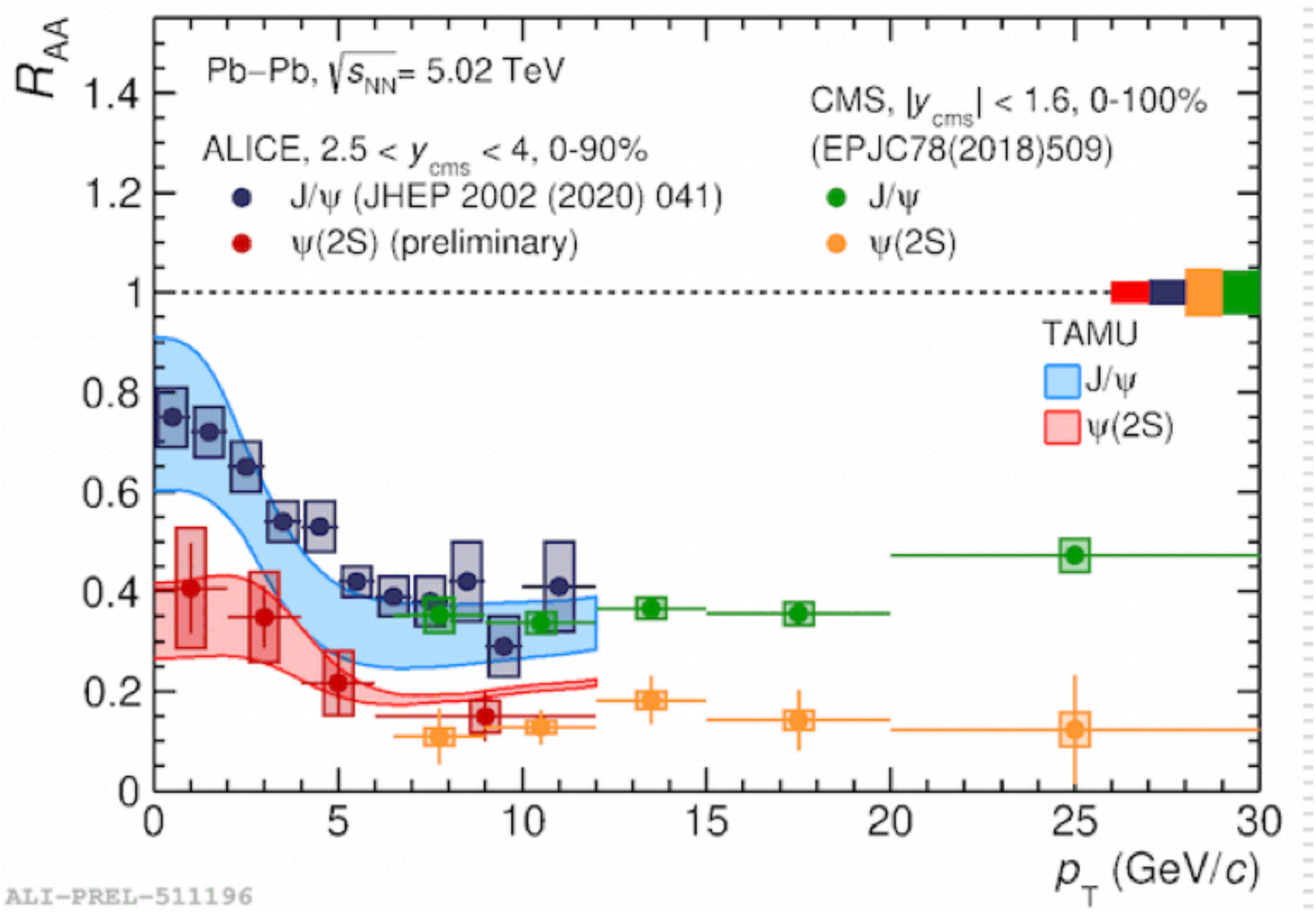


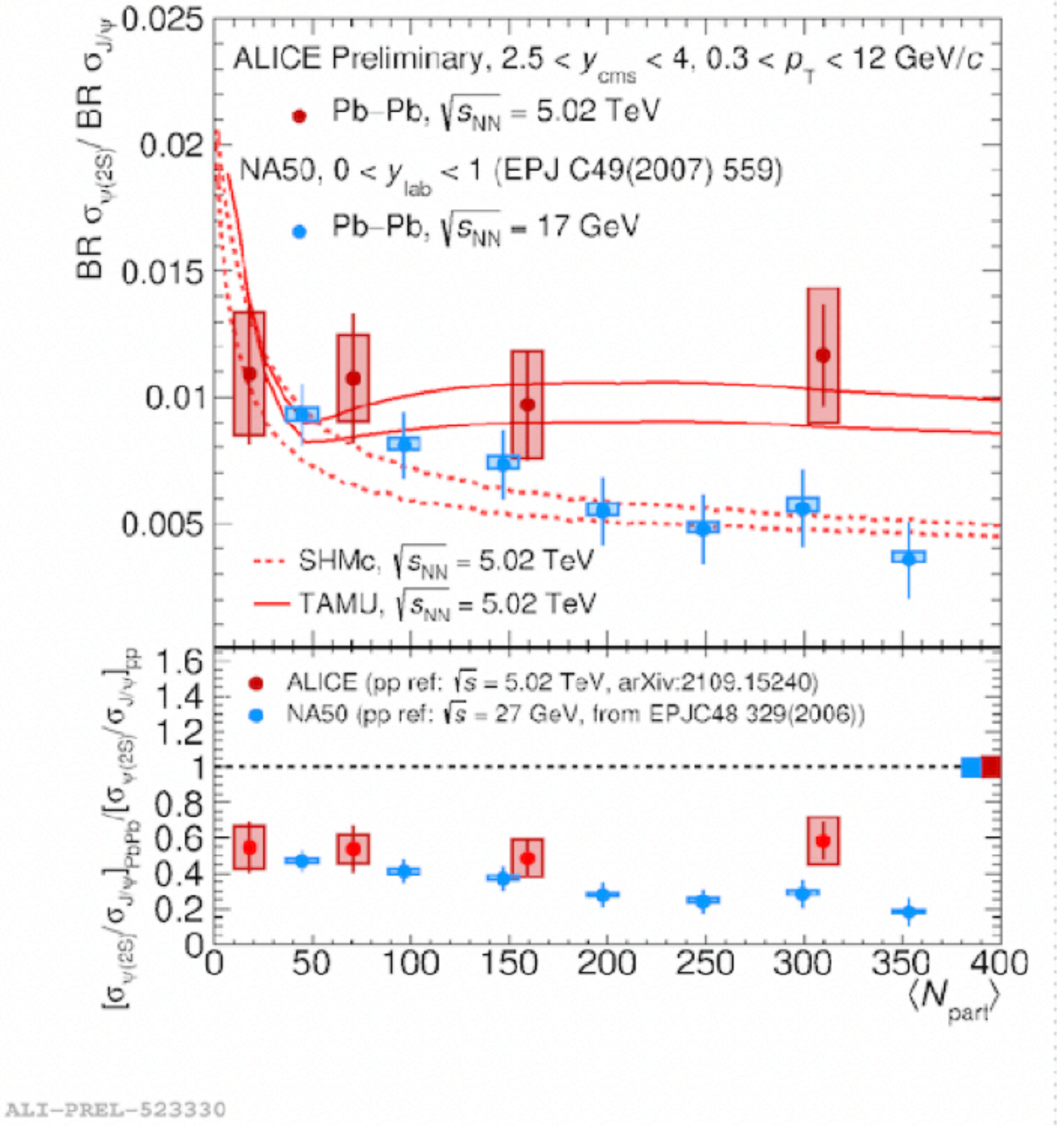
b-jet R_{pPb}



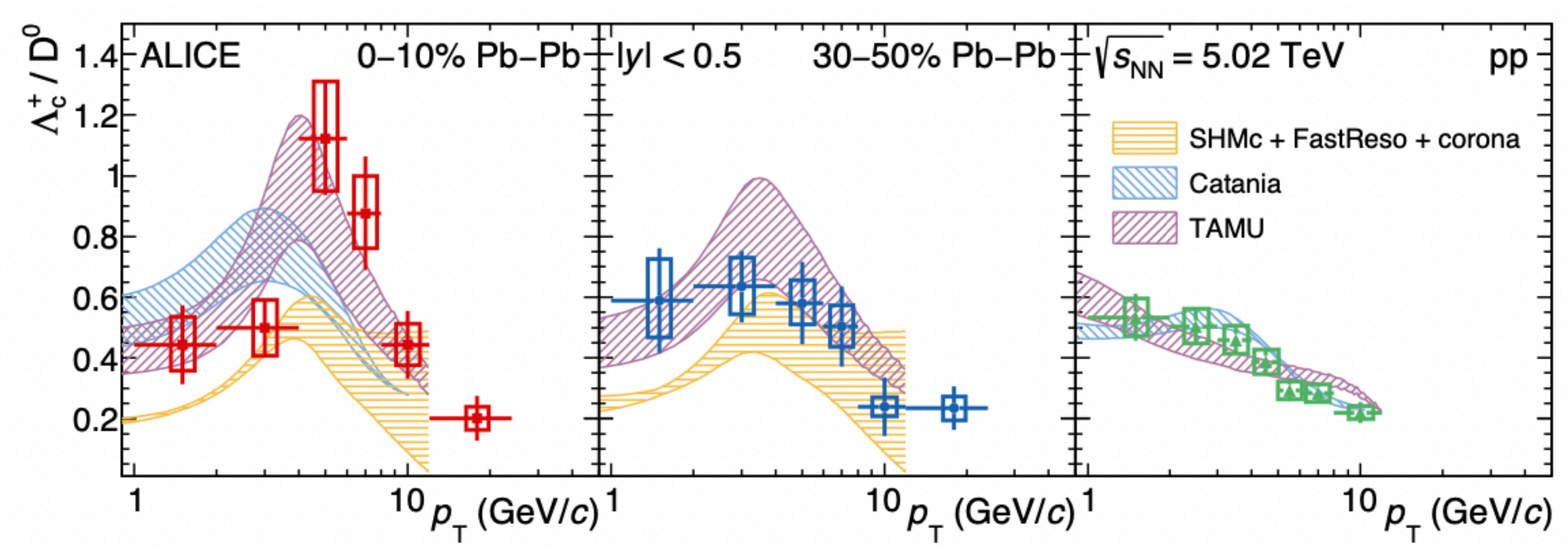
- **b-tagged jet cross-section and R_{pPb} measured in p-Pb collisions** at $\sqrt{s_{NN}} = 5.02$ TeV for $15 < p_T < 90$ GeV/c.
- **Data well described by different POWHEG simulations within uncertainties** (HVQ and Dijet)
- ***R_{pPb}* consistent with unity within uncertainties in the measured p_T range.**
  - ALICE measurement consistent with CMS in the overlapping p_T range of $50 < p_T < 100$ GeV/c.

Quarkonia R_{AA}

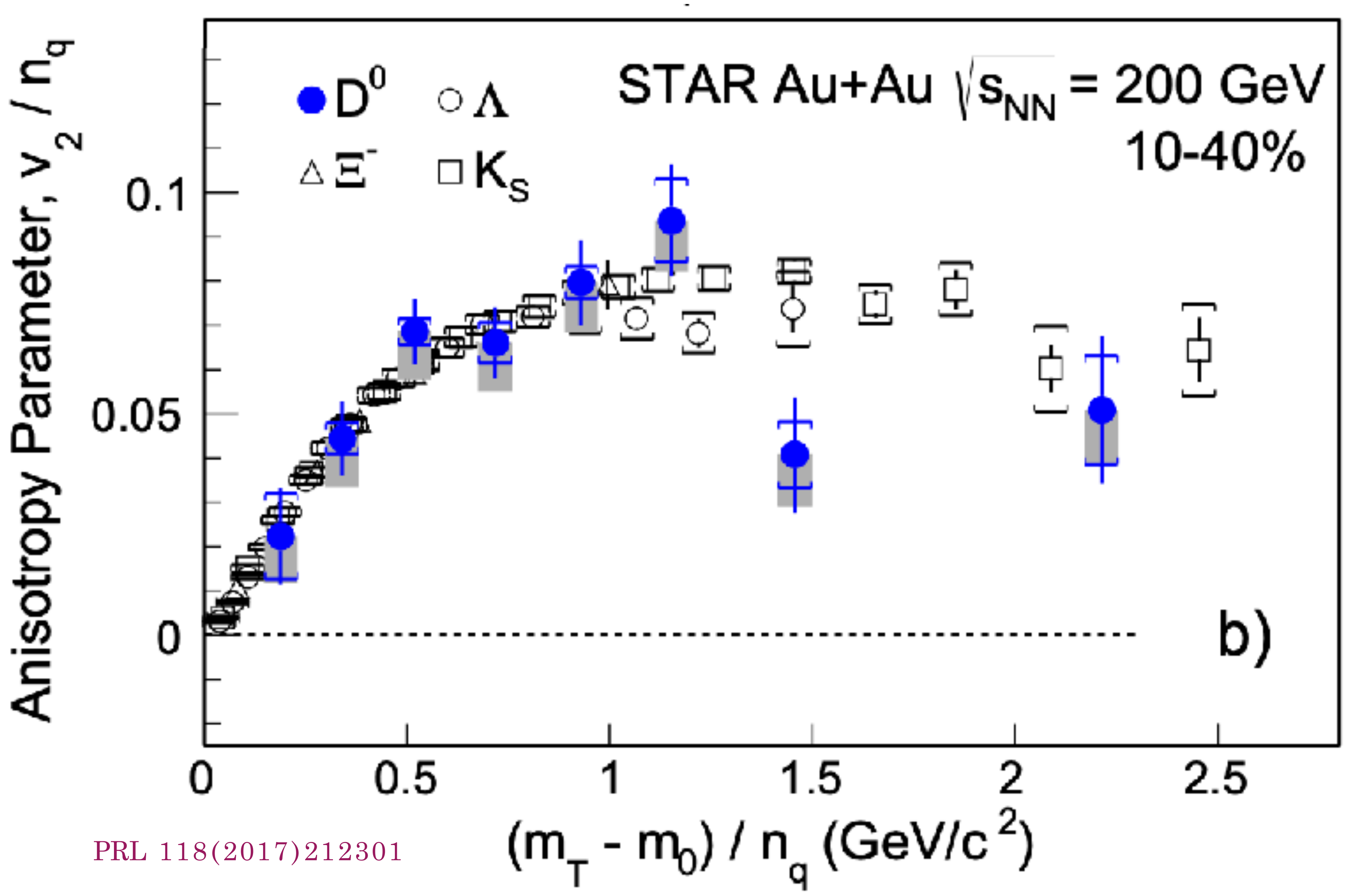




Baryon production with Λ^+_c

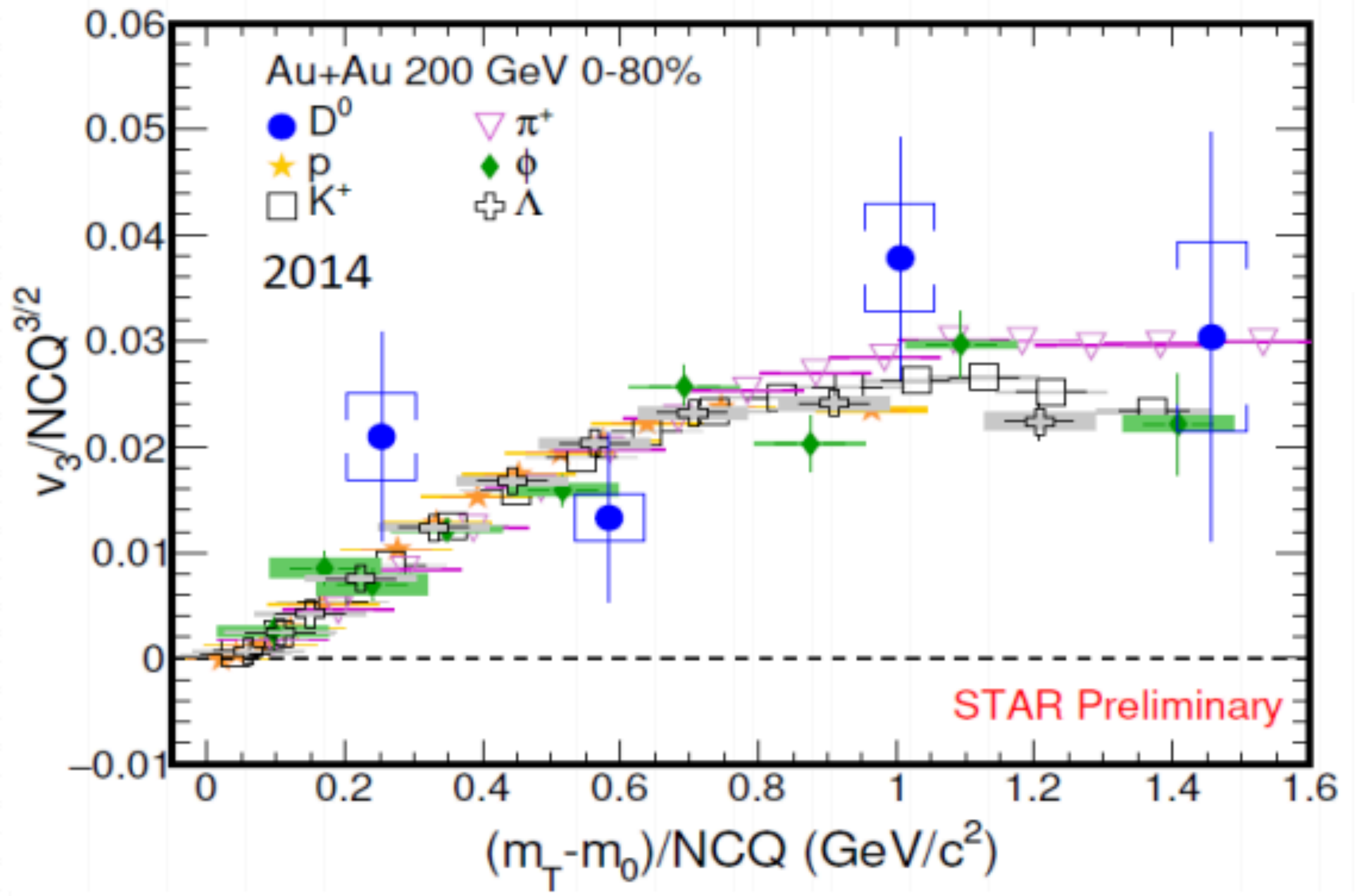


v_2 and v_3 of charm quarks at RHIC



PRL 118(2017)212301

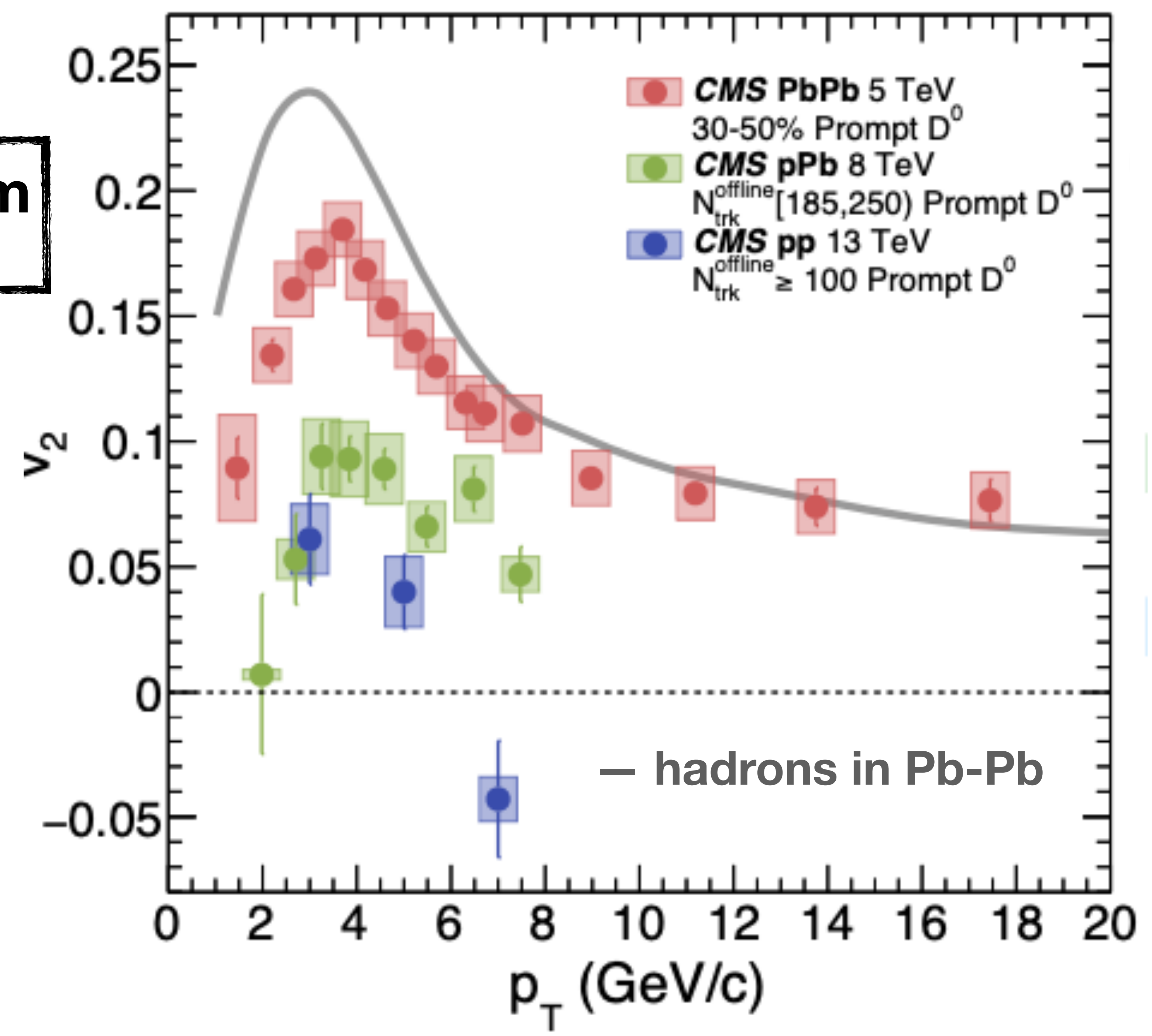
Charm
Light/Strange



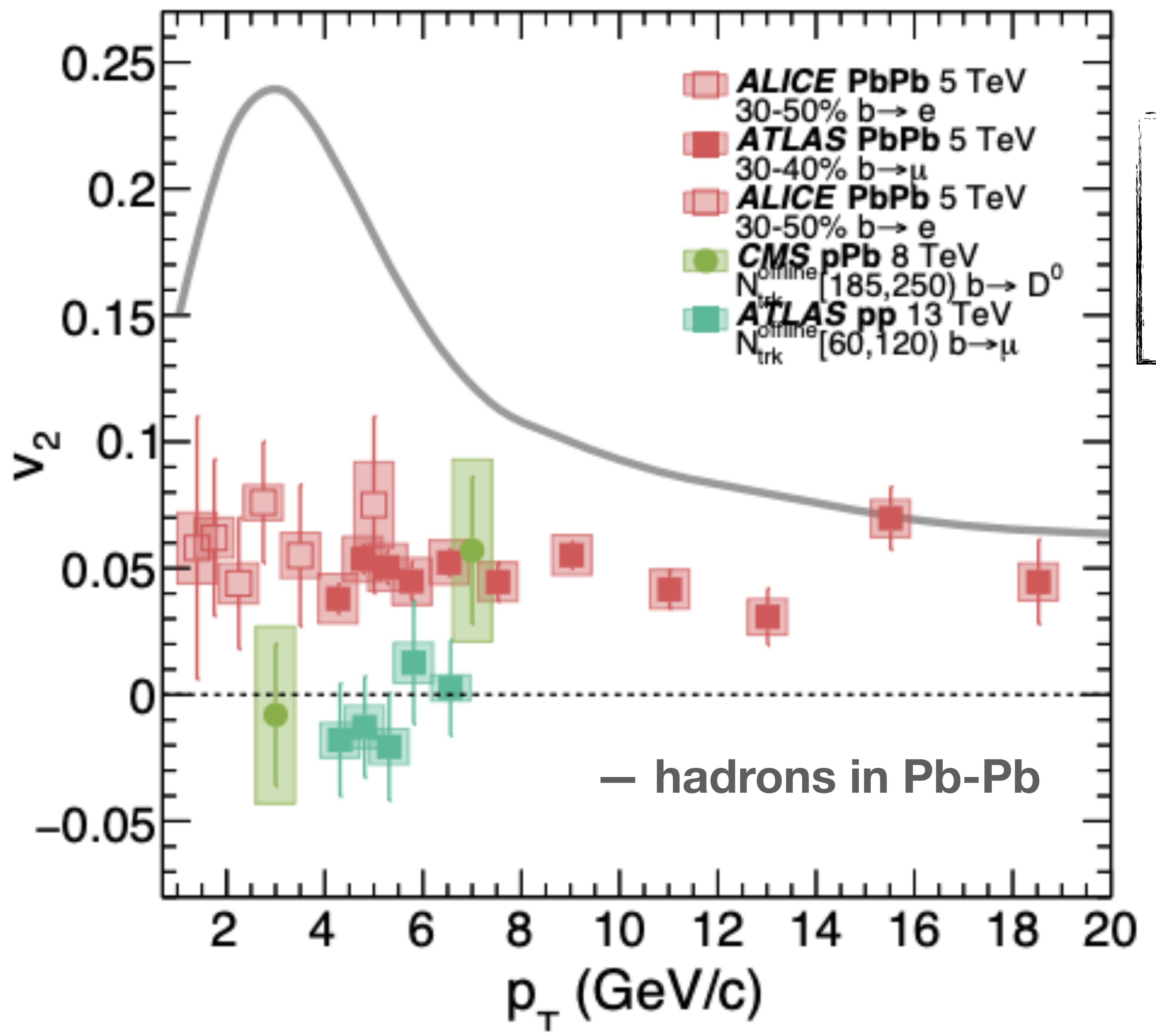
- Significant v_n for charm quarks at low p_T.
- Charm v_2 follows N_{CQ} scaling at low p_T at RHIC.
- Charm quarks interact strongly with the medium and possible thermalization.

v_2 of heavy-flavor in different systems

Open charm
Prompt D⁰



Pb-Pb
p-Pb
pp



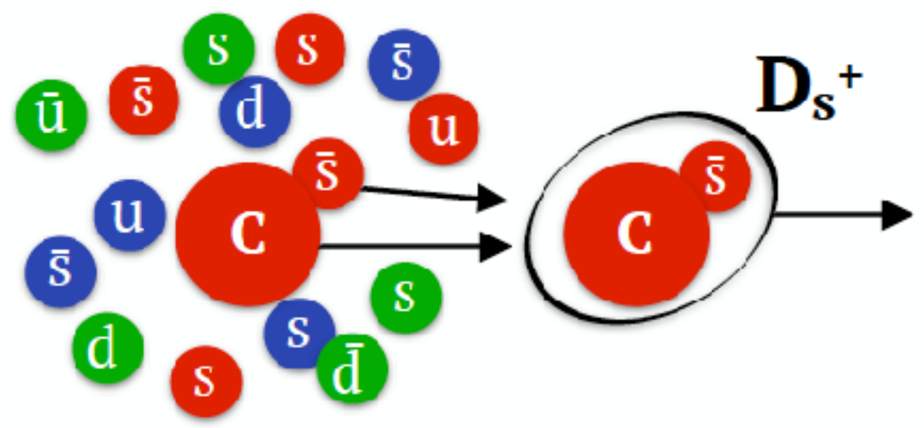
Open beauty
b->e
b->μ
b->D0

Camelia Mironov @ HP2020

- Charm: v_2(Pb-Pb) > v_2(p-Pb) > v_2(pp)
- Beauty: v_2(Pb-Pb) > 0, v_2(p-Pb)~v_2(pp)~0

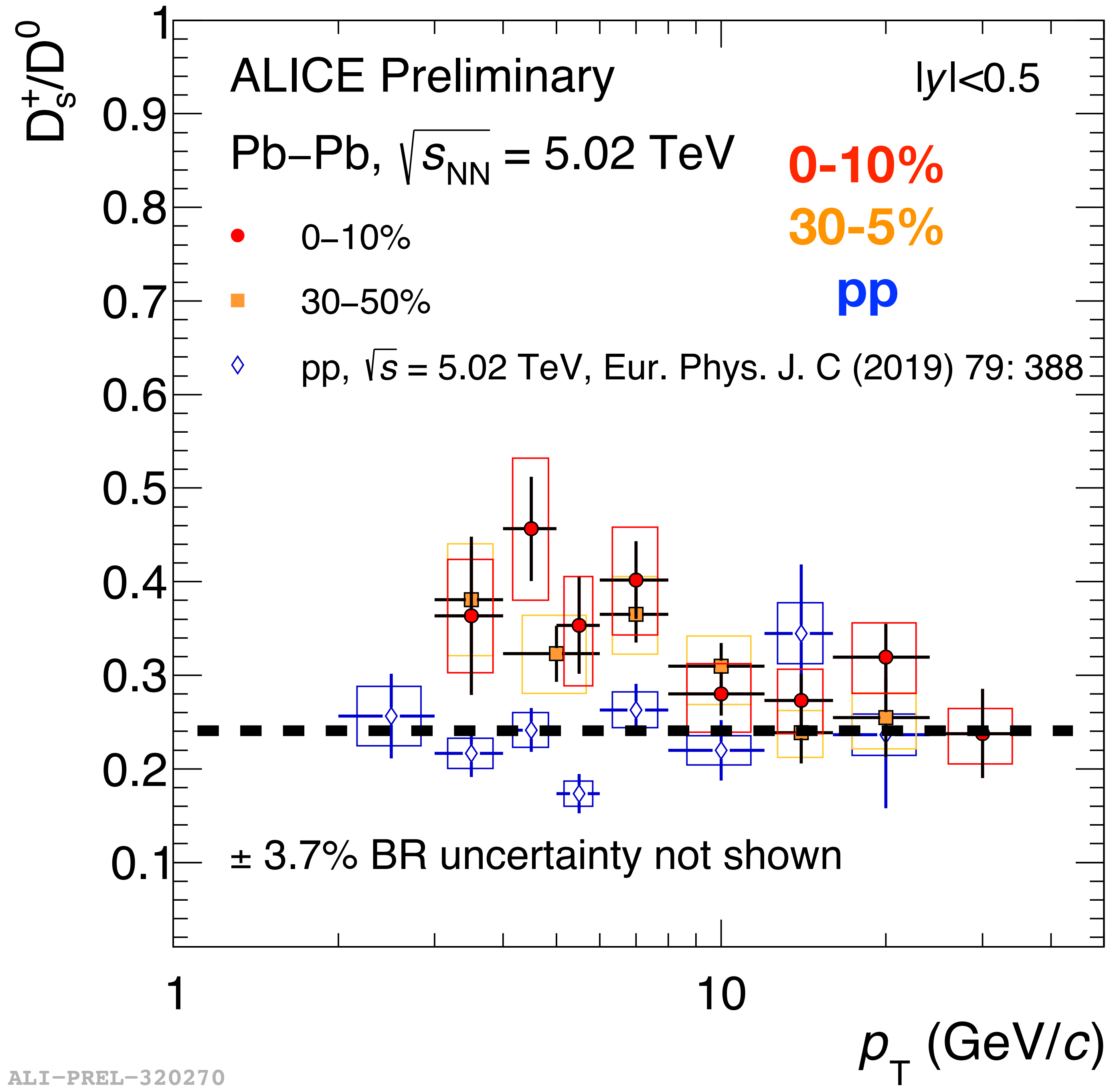
Hadronisation - D_s

Studying heavy-flavour hadronization mechanism

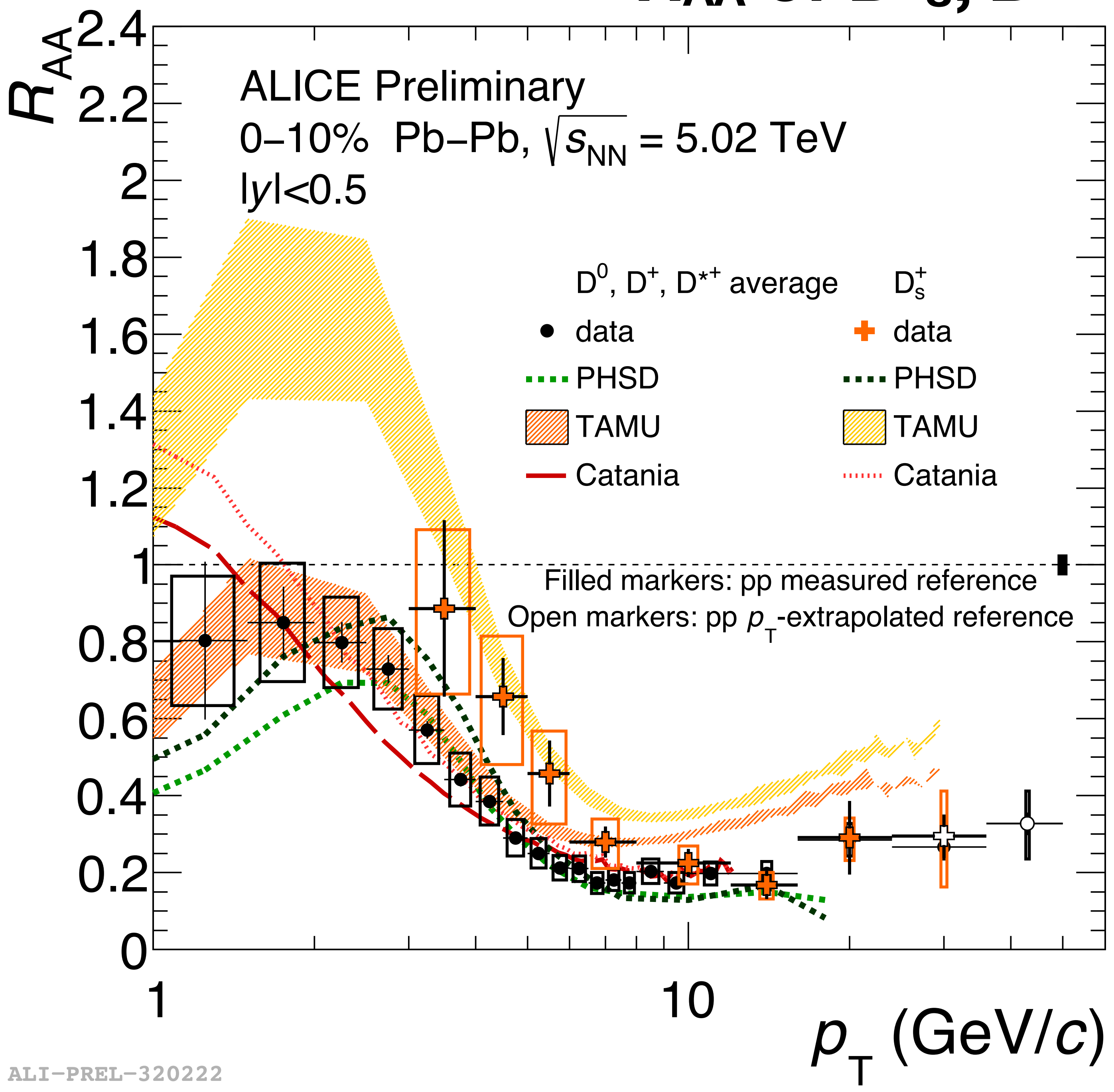


- QGP rich in strange quarks -> expected enhancement of $\mathbf{D^+_s}$ over $\mathbf{D^0}$ yield if hadronization via coalescence.
- D_s/D^0 ~ 0.4 in Pb-Pb while ~ 0.25 in pp —> **hint of enhancement**

D^+_s/D^0

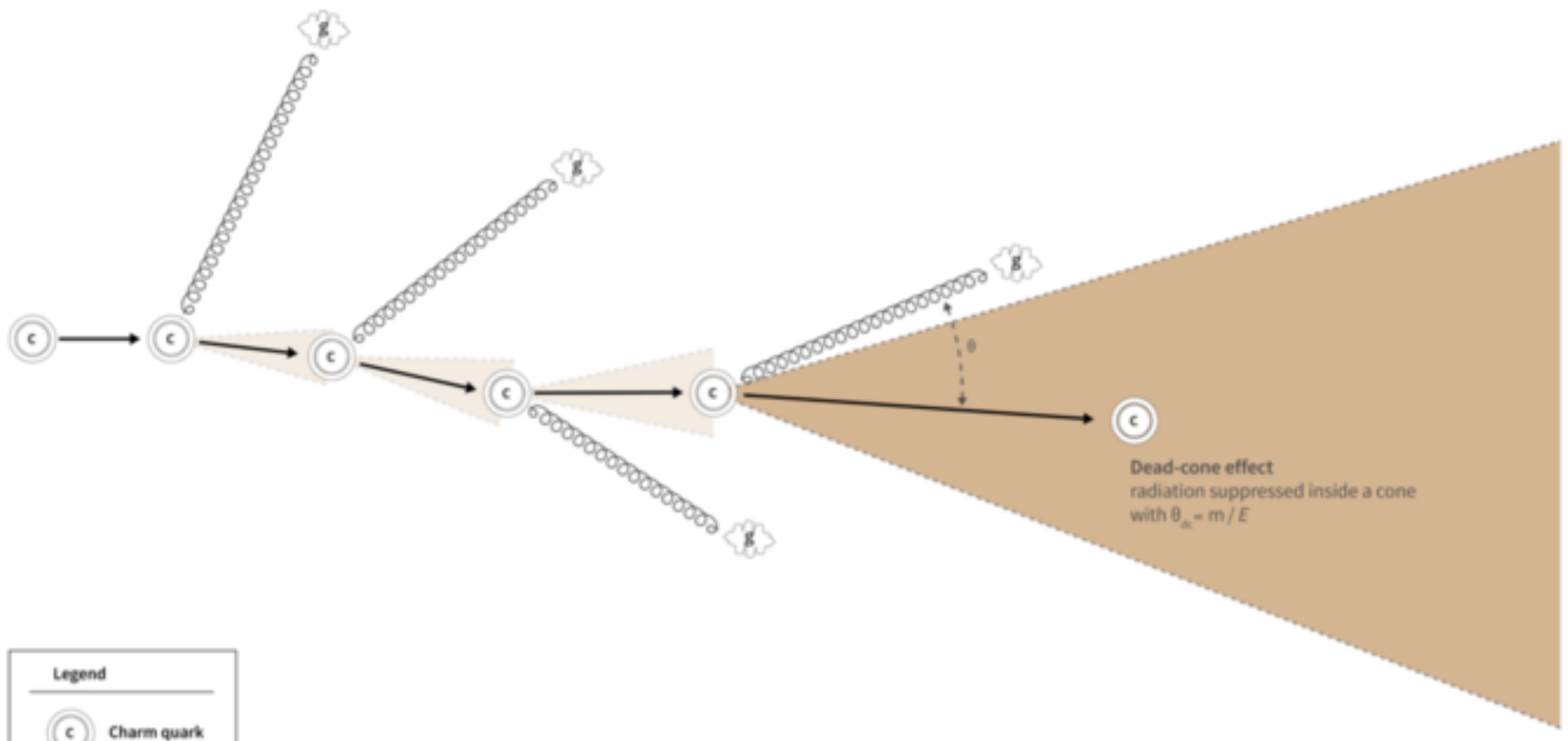


R_{AA} of D^+_s, D^0



D meson
D^+_s

Dead cone effect

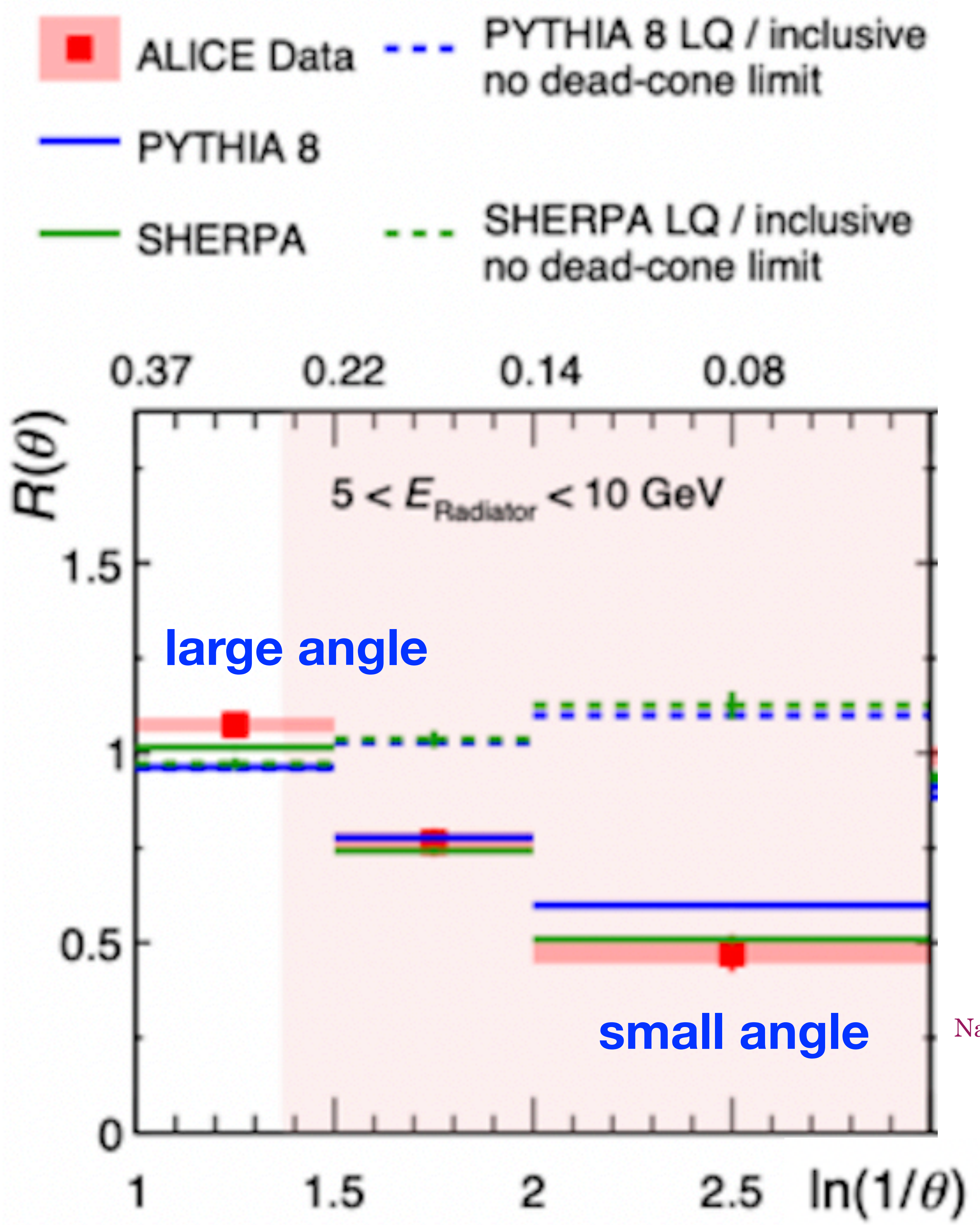


Reduction of gluon radiation from heavy quarks at small angles due to conservation of angular momentum: $\theta \sim m_q/E$

First direct observation using recursive jet-clustering techniques to reconstruct gluon emissions from radiating charm quark

- follows the branch containing the D^0 meson at each de-clustering step —>equivalent to following the emitting charm quark through the shower.

Ratio of splitting angle probability distribution $\frac{D^0\text{-jet}}{\text{Inclusive jets}}$



Nature 605 (2022) 440