Workshop on Heavy Ion Physics in the EIC Era, August 19-23

Overview of hadron production measurements in relativistic ion collisions

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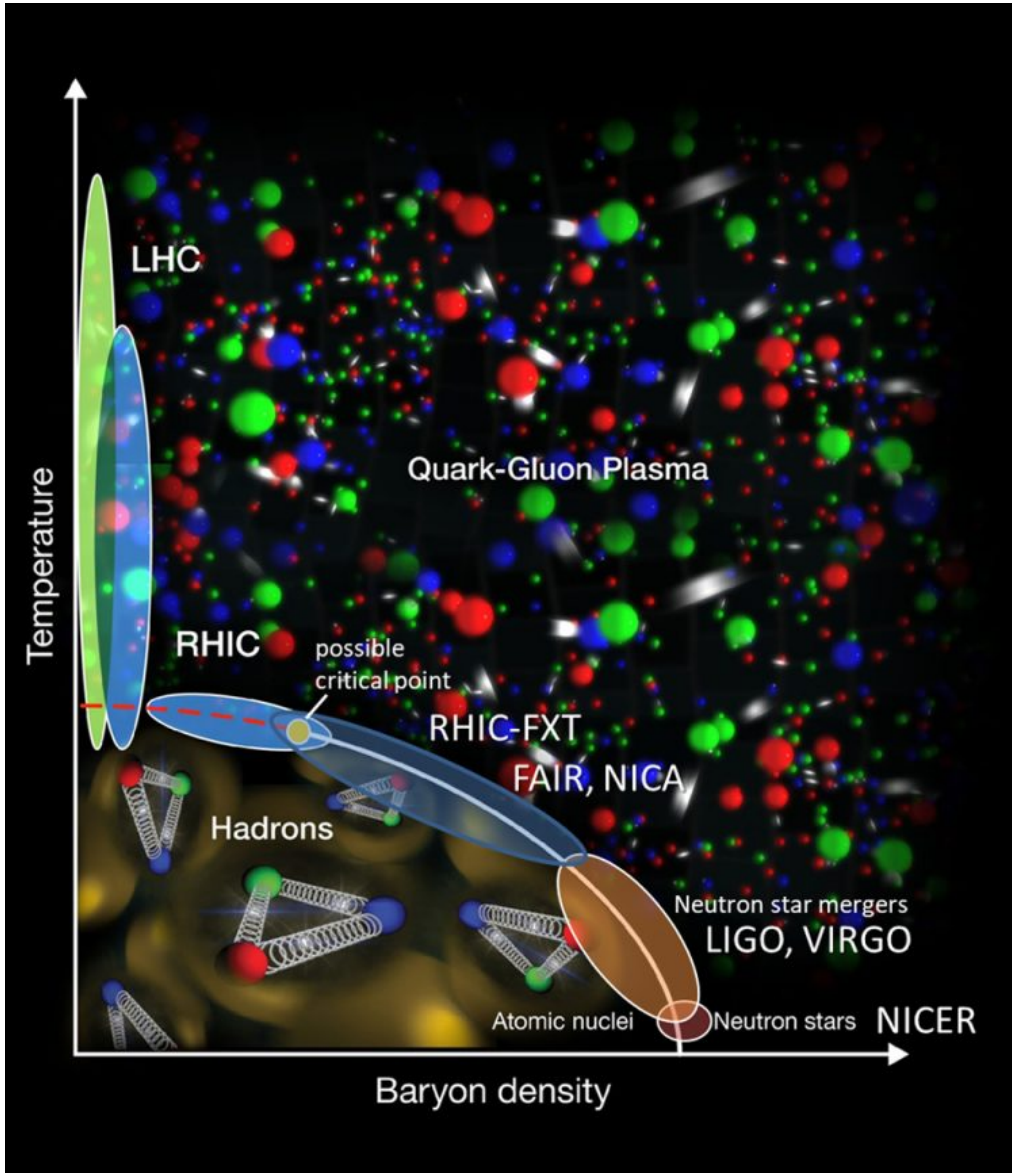
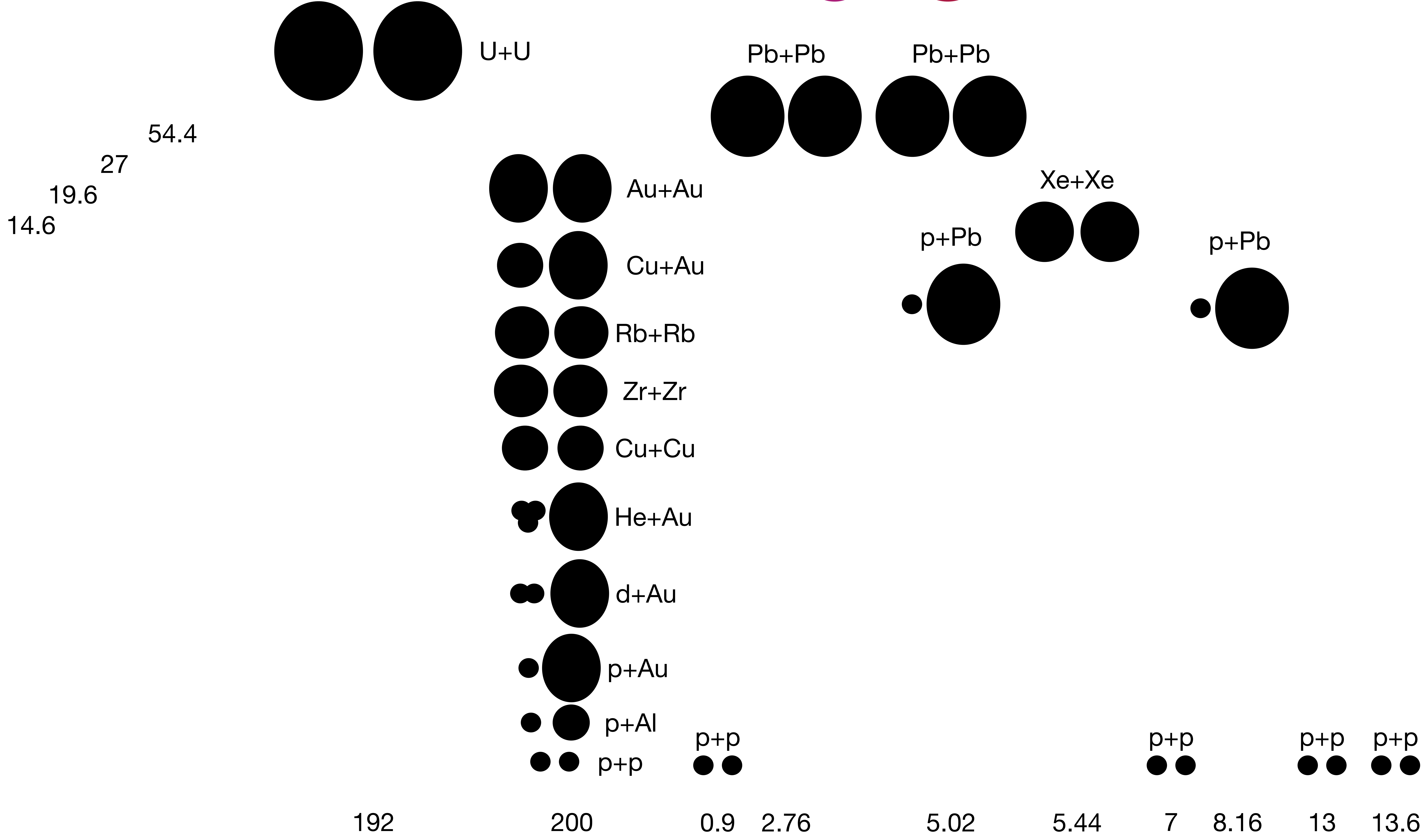
Stony Brook University

QCD phase diagram

How do we transition from point like to non-point like physics. How do arrive at a perfect liquid?
How do the confined hadronic states emerge from these quarks and gluons.

EIC will provide a reference for studies of hadron production in relativistic ion collisions





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54.4
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19.6
14.6
Au+Au
Xe+Xe
p+Pb
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Cu+Au
Rb+Rb
Zr+Zr
Cu+Cu
He+Au
d+Au
p+Au
p+Al
p+p
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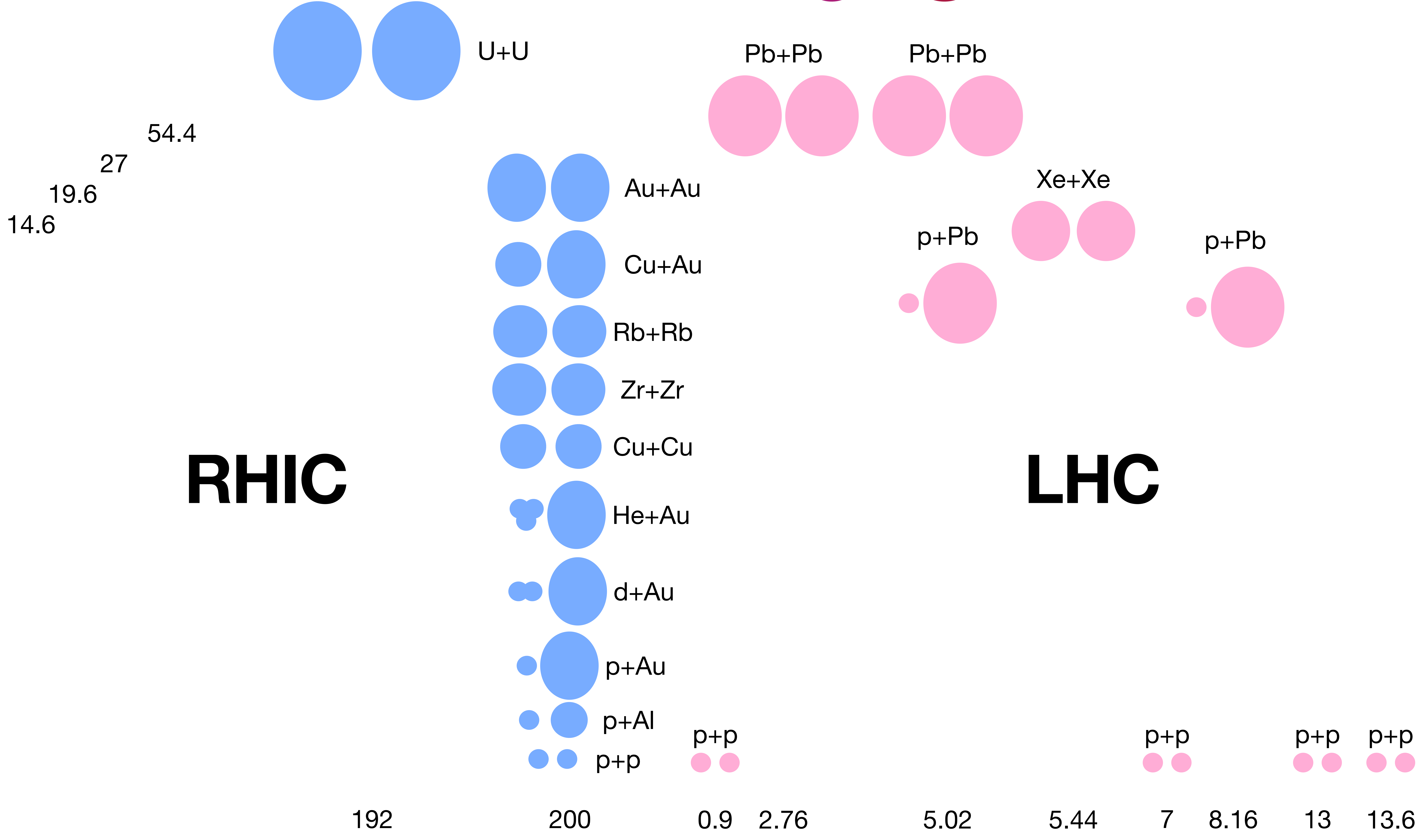

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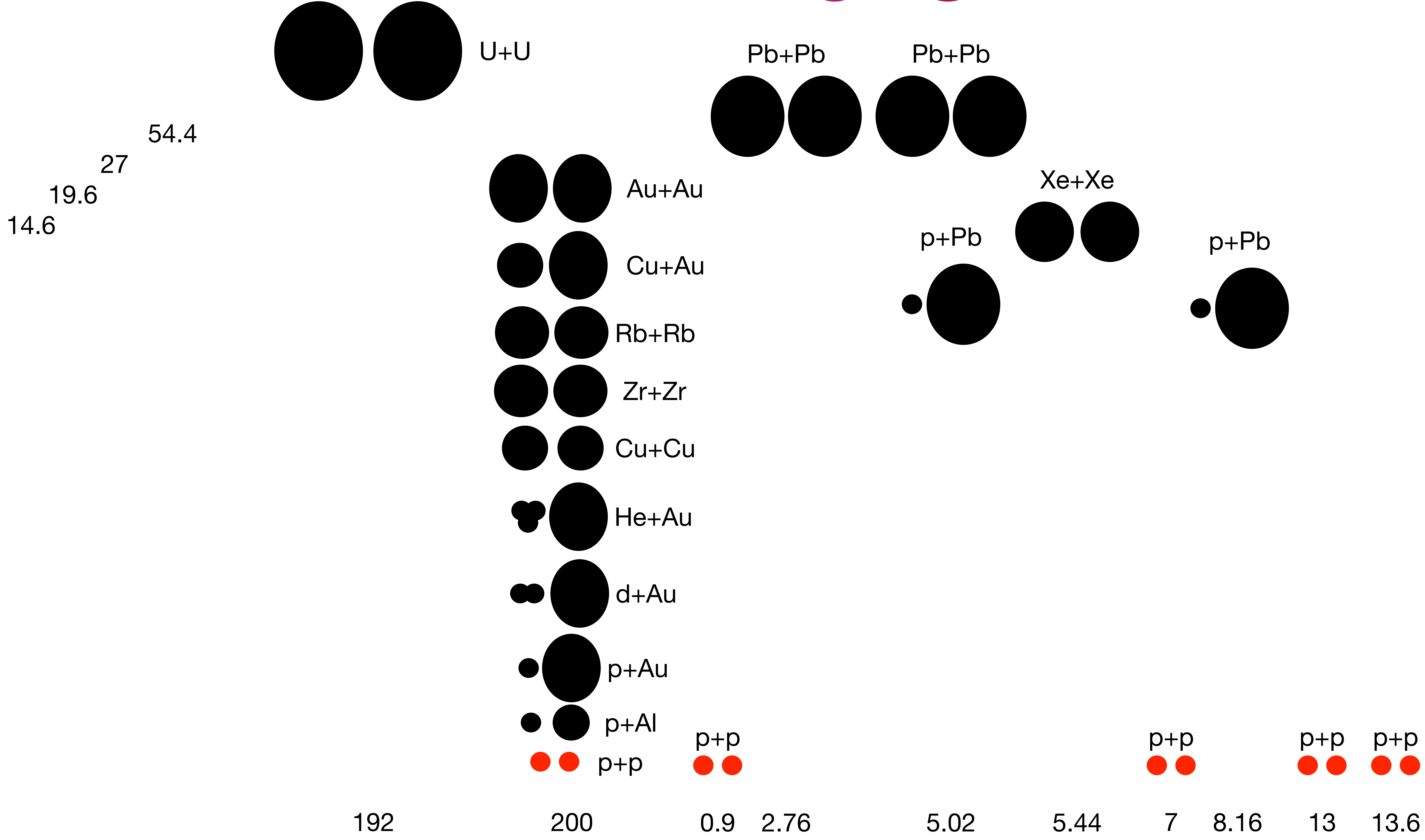
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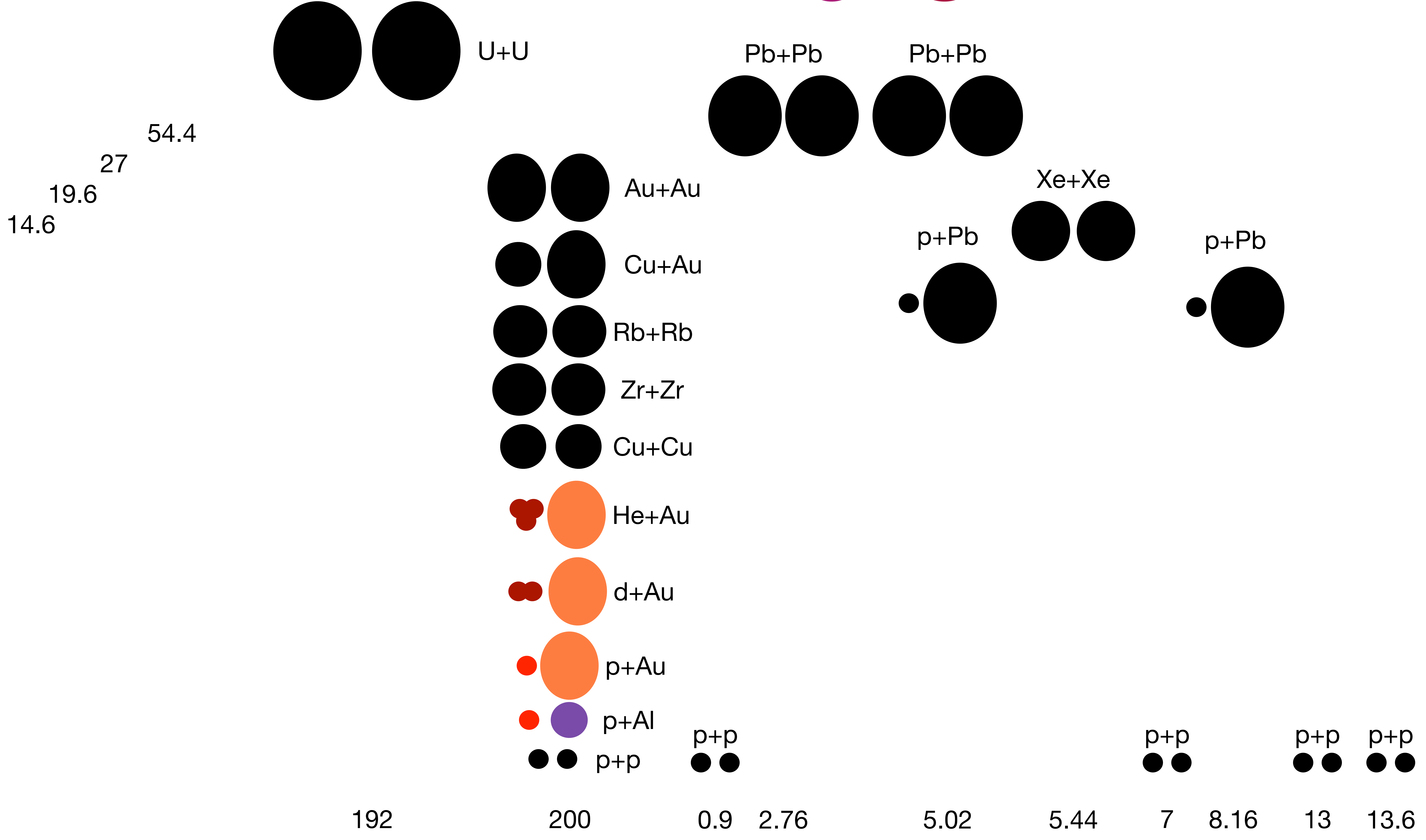

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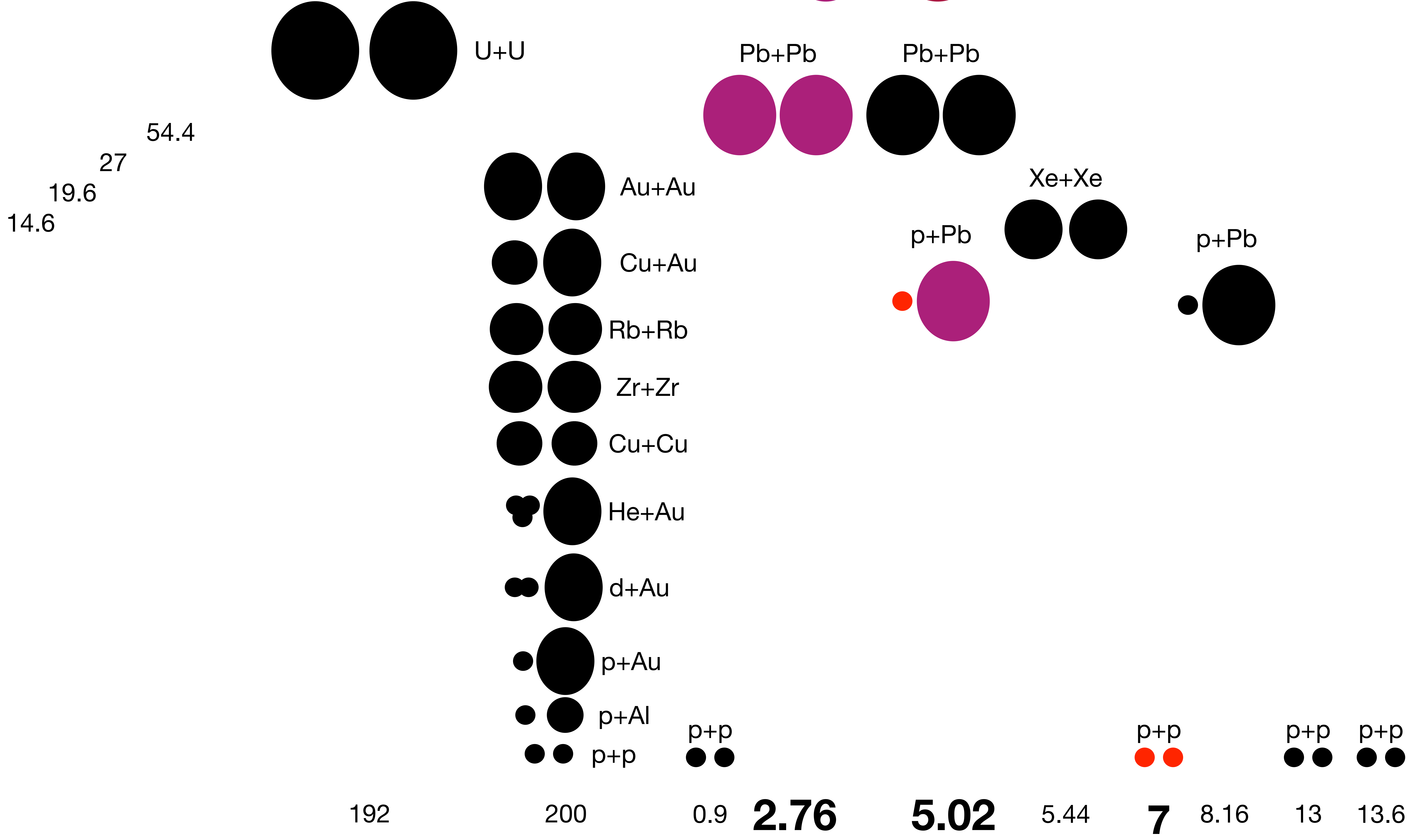
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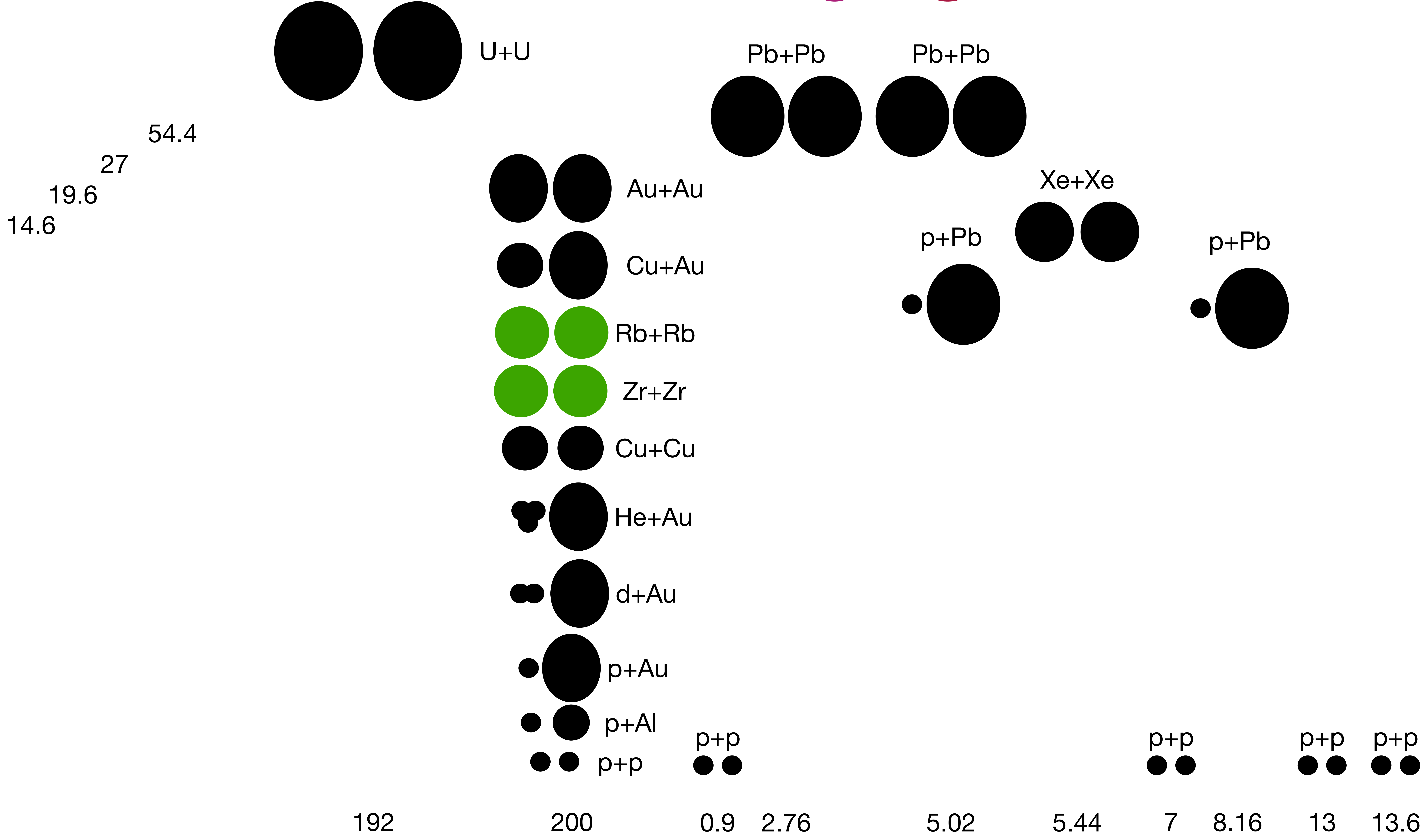

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Light flavored and Strange particles

uud — p — 938.27 MeV/c

$u s$ — $K^{\pm}$ — 493.67 MeV/c

$u d$ — $\pi^{\pm}$ — 139.57 MeV/c

$s \bar{s}$ — ϕ — 1019.46 MeV/c

$u \bar{u}$, $d \bar{d}$ — π^{0} — 134.98 MeV/c

$d \bar{s}$ — K_{s}^{0} — 497.61 MeV/c

$d \bar{s}$ — K^{*0} — 891.66 MeV/c

uds — Λ — 1115.68 MeV/c

dss — Ξ — 1321 MeV/c

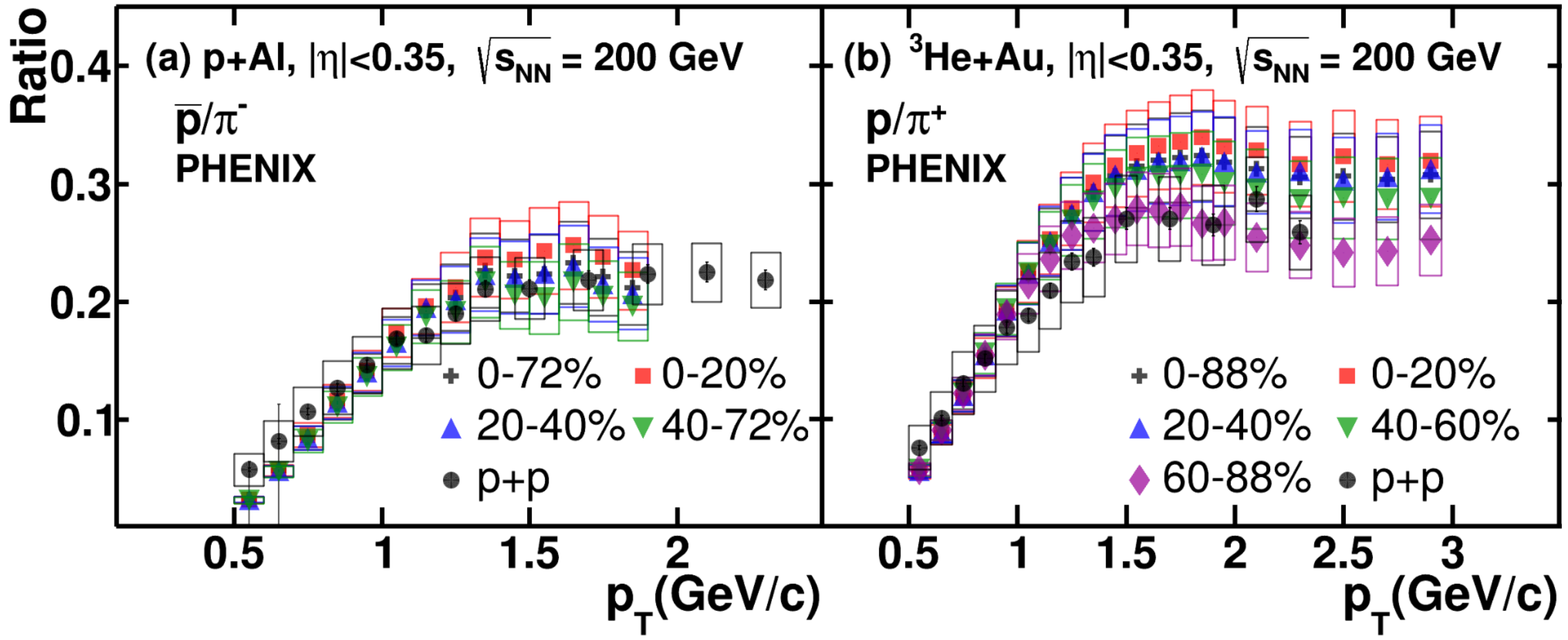
sss — Ω — 1672 MeV/c

Identified charged-hadron production

PHENIX. The ratios of p/π as a function of p_T

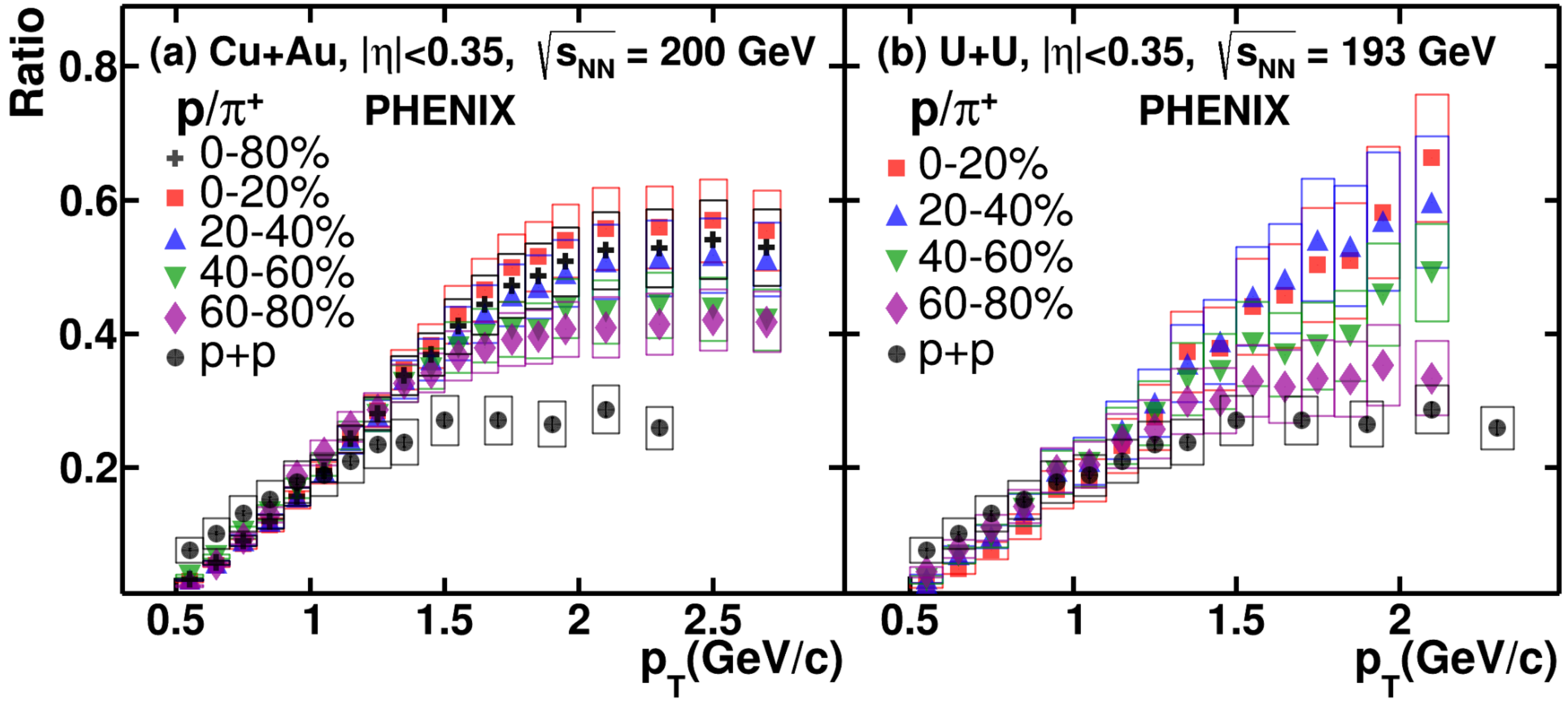
Stony Brook University

PRC 109, 054910 (2024)



Small collision systems

- p/π ratios are similar to ones in $p+p$ collisions
- **3He+Au collisions**
- Modest centrality dependence can be seen



Large collision systems

- **In central collisions**
- p/π ratios reach the values of ≈ 0.6
- **In peripheral collisions**
- p/π ratios < 0.4 in the whole p_T range
- can be qualitatively described using recombination models

Identified charged-hadron production

PHENIX. Nuclear-modification factors

PRC 109, 054910 (2024)

In large collision systems

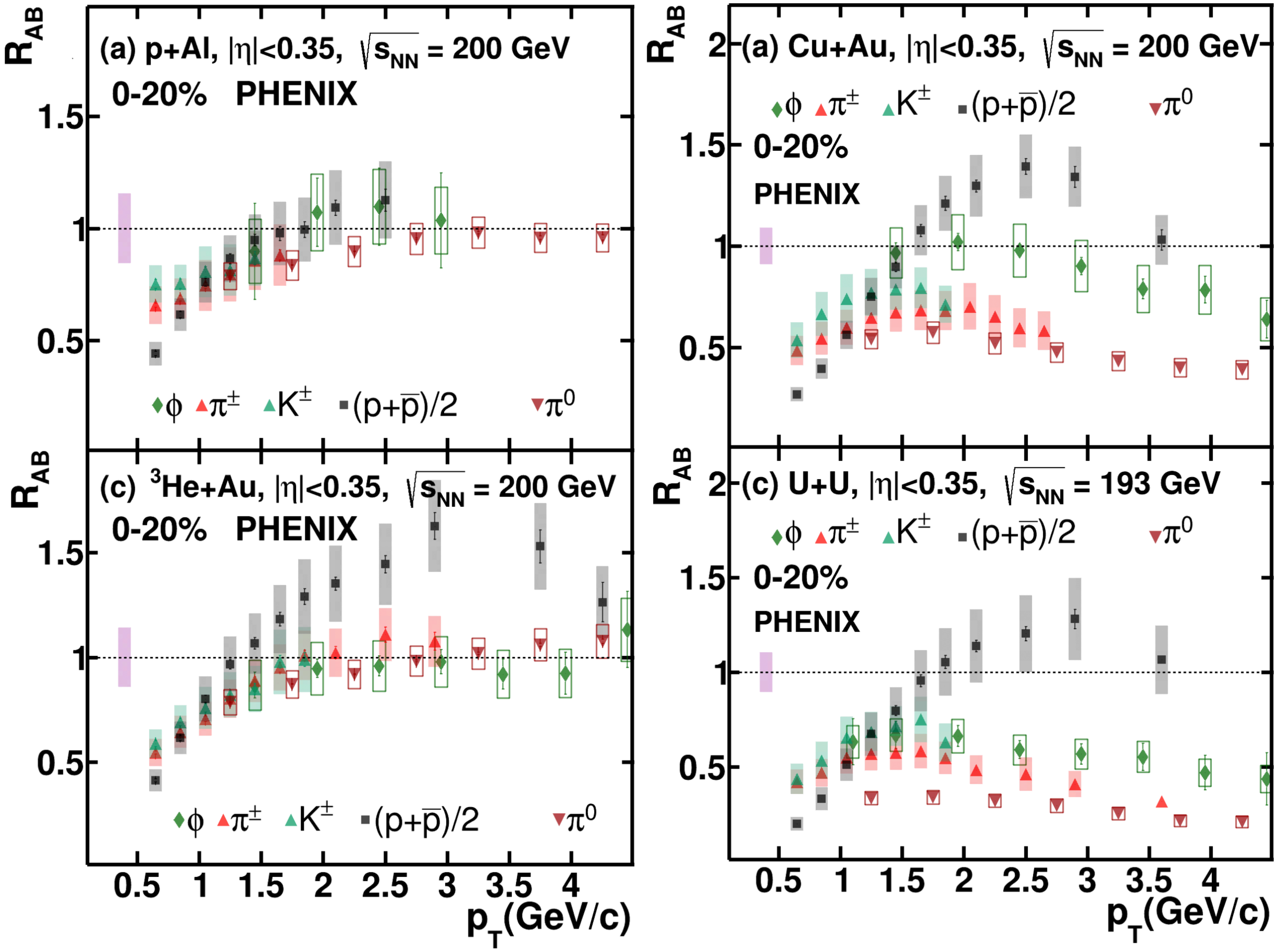
- ϕ meson R_{AB} > other mesons R_{AB}
  - Strangeness enhancement

In large collision systems and in the ^{3}He+Au collisions

- proton R_{AB} > all meson R_{AB}
  - $m_\phi = 1019 \approx m_p = 938$ [MeV/c^2]
    - Differences in baryon versus meson production

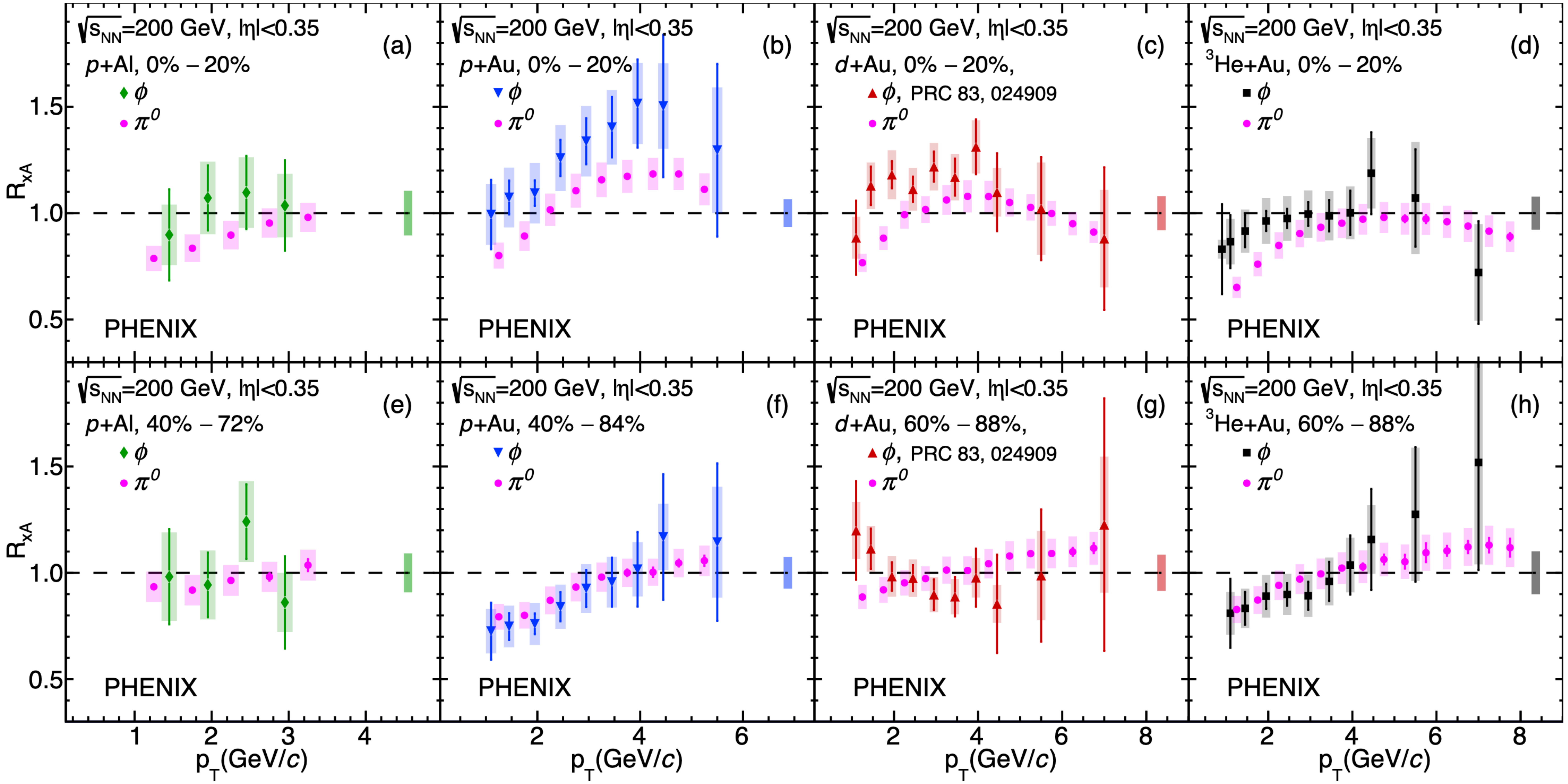
In *p*+Al collisions

- proton $R_{AB} \sim$ all measured mesons R_{AB} within uncertainties



Identified charged-hadron production

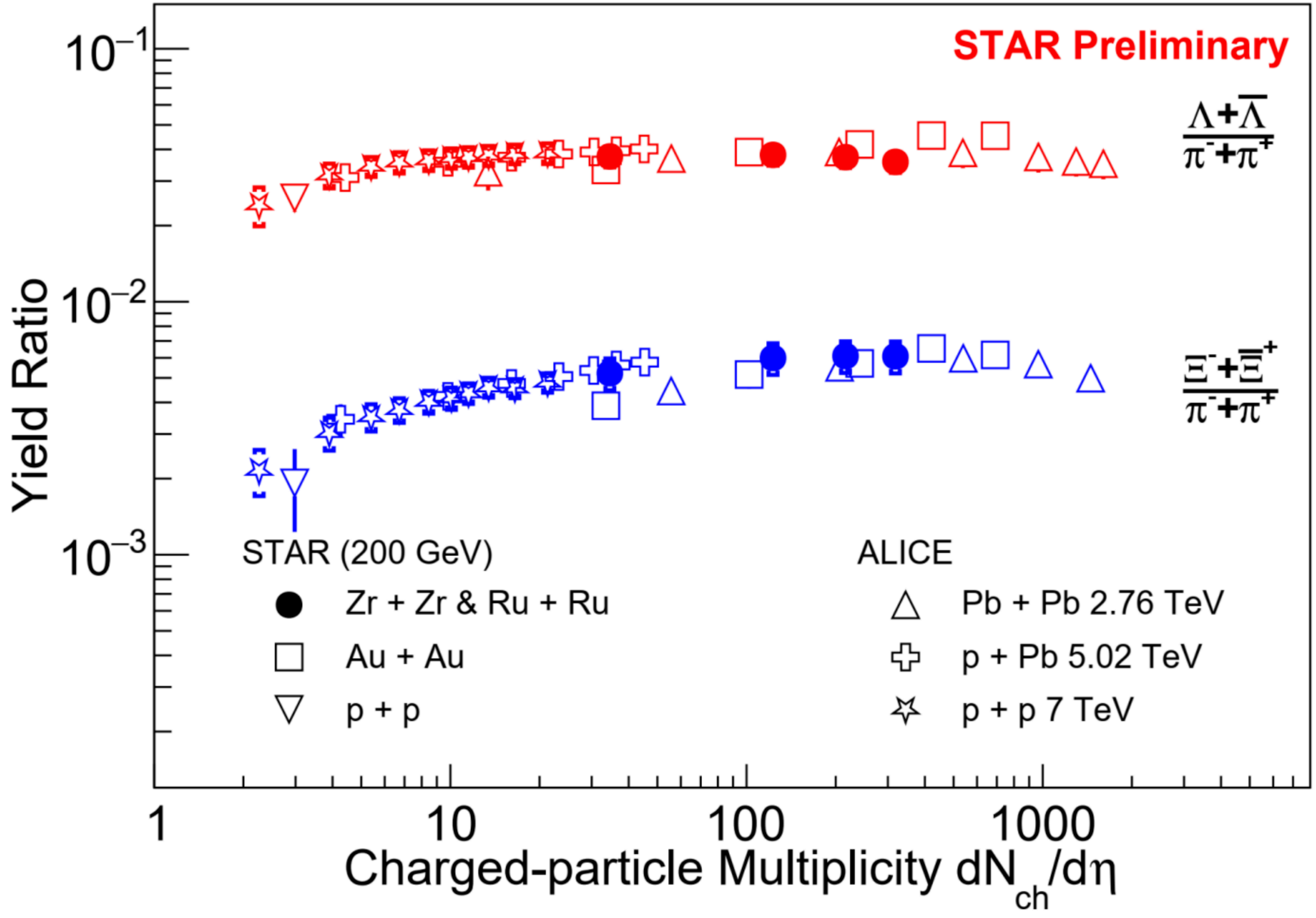
PHENIX. Nuclear-modification factors



- Nuclear modification factors of both π^0 and ϕ mesons are consistent with each other and unity within large systematic uncertainties
- In Au target collisions there ϕ meson R_{xA} tend to be larger then π^0 meson R_{xA}

Hyperon production

STAR and ALICE



- Hyperon-to-pion ratios follow the same trend as a function of $dN_{ch}/d\eta$ for different collision systems
- Similar hyperon production mechanism for systems with same multiplicity despite differences in collision energy or system

STAR:
PRL 98, 062301 (2007)
PRC 75, 064901 (2007)
PRC 79, 034909 (2009)

ALICE:
PLB 728, 216–227 (2014)
PLB 728, 25–38 (2014)
PLB 758, 389–401 (2016)
Nature Phys 13, 535–539 (2017)

Hadron production

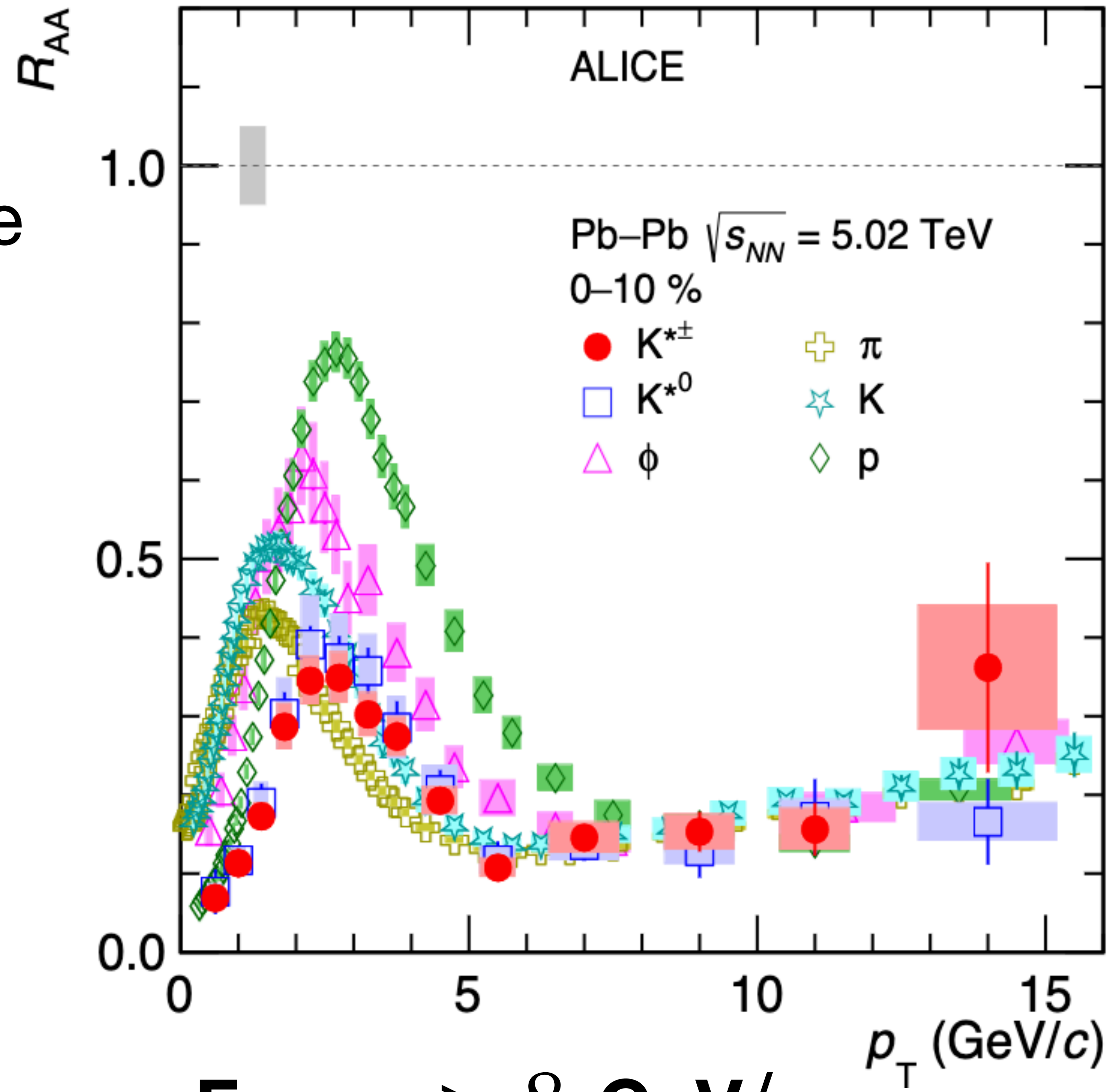
ALICE. Nuclear-modification factors

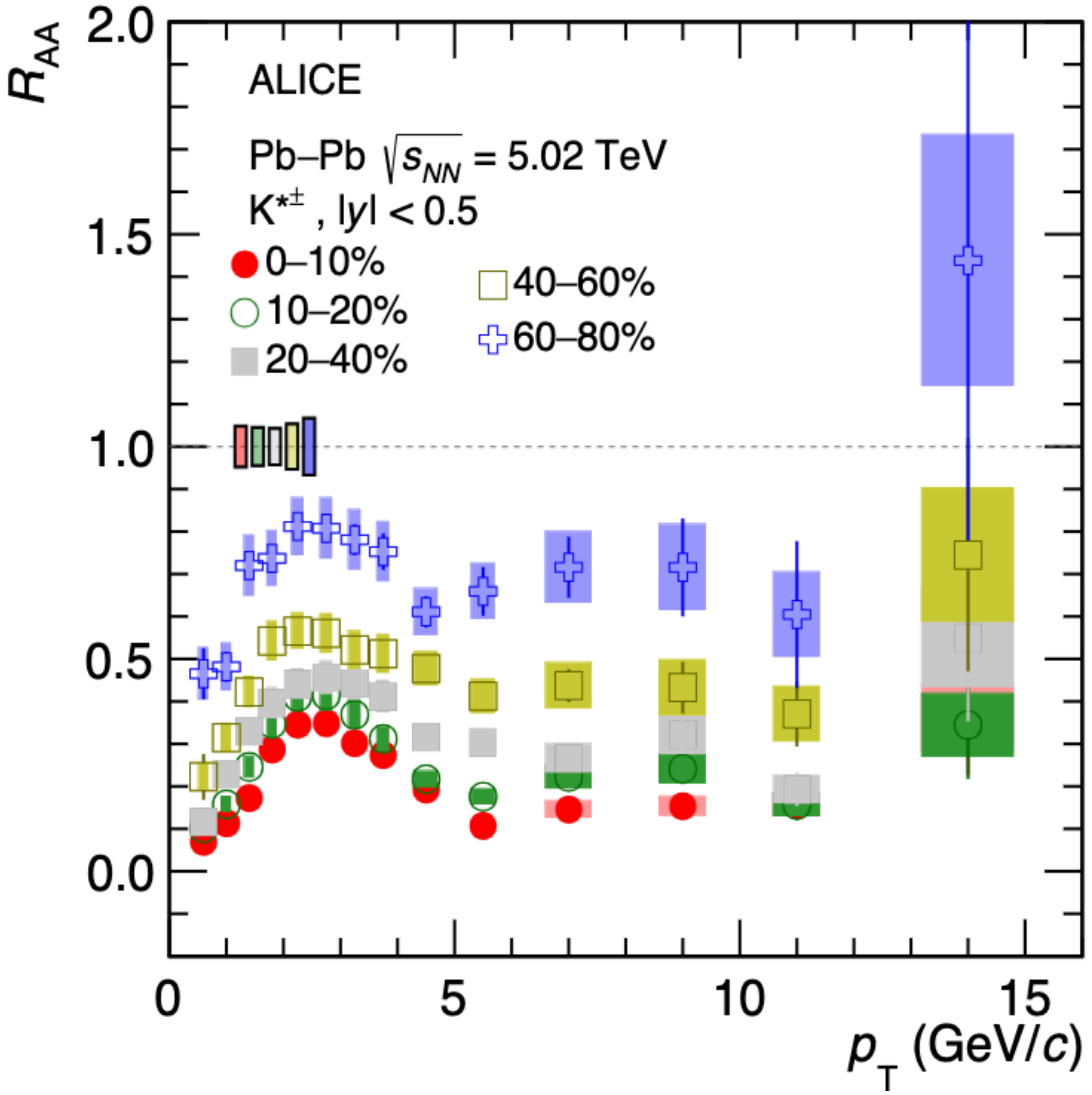
Low p_T (< 2 GeV/c)

- $K^{*\pm}$ and K^0 R_{AA} values are the smallest among the listed hadrons
  - ‣ Rescattering effect

Intermediate p_T range

- Species dependence with evidence of baryon–meson splitting
  - ‣ Influenced by a combination of effects like radial flow, parton recombination, enhanced strangeness production, steepness of particle p_T spectra in reference $p+p$ collisions, etc





ALICE https://arxiv.org/pdf/2308.16119

For $p_T > 8$ GeV/c

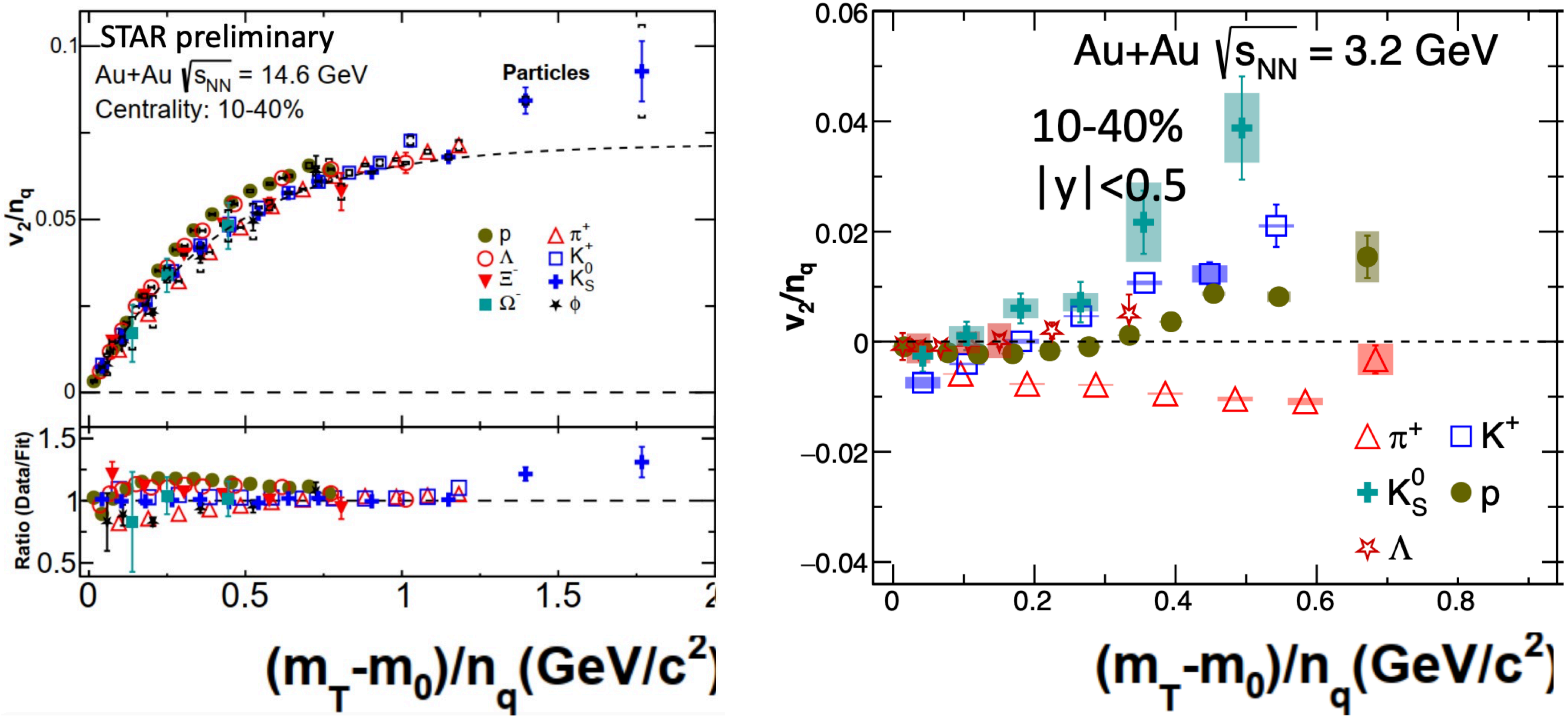
- All the particle species show similar R_{AA} within the uncertainties, including the $K^{*\pm}$
  - ‣ Suppression of various light flavored hadrons is independent of their quark content and mass

Elliptic flow NCQ scaling

STAR. Search for breakdowns

STAR BES observation: NCQ scaling of v_2

- is followed in Au+Au at 14.6 GeV
- but breaks down at 3.2 GeV: hadronic vs partonic regime

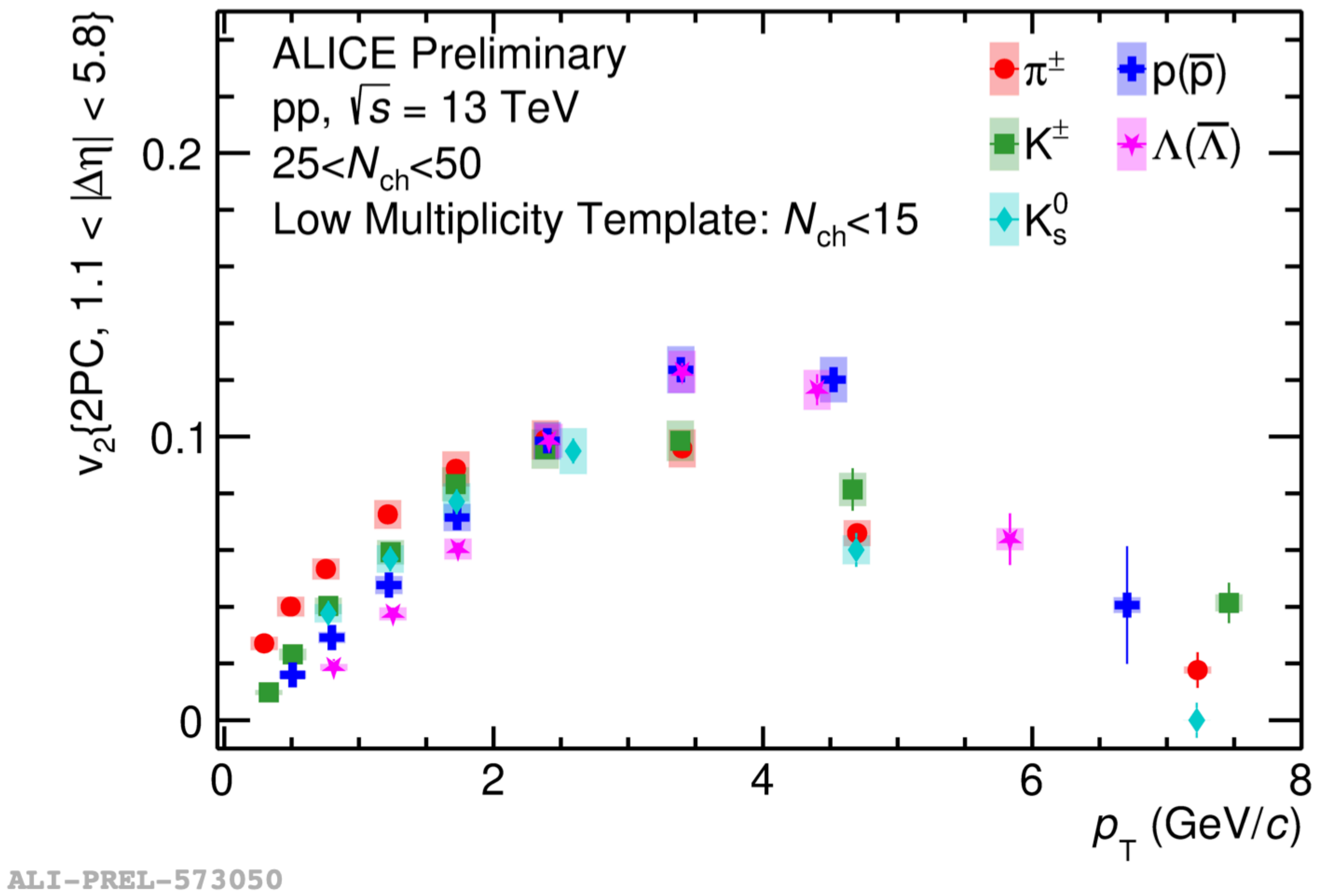


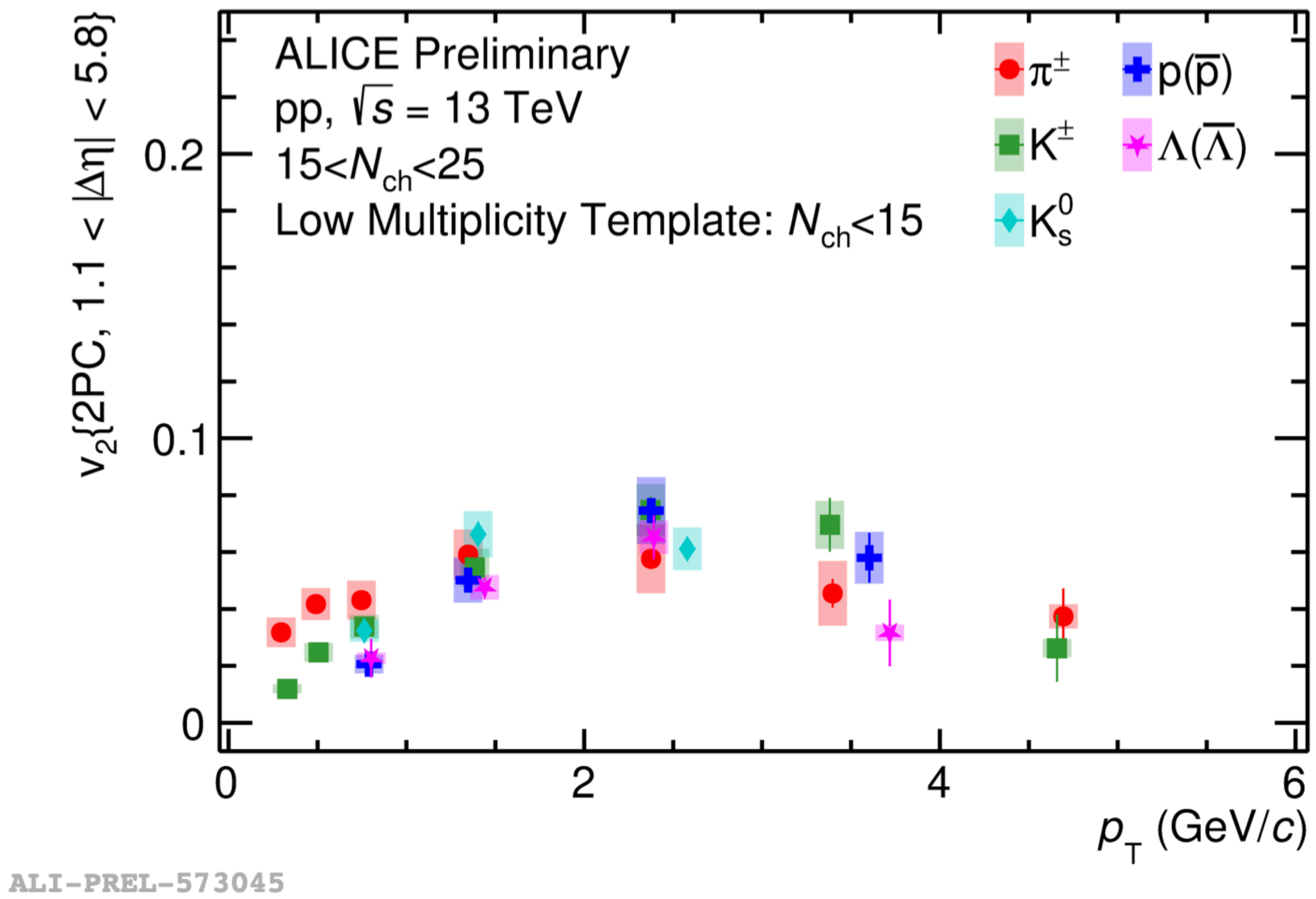
Collectivity in small systems

ALICE

- Mass ordering observed at low p_T
  - Consistent with hydro-like behavior
- Baryon/meson grouping at intermediate p_T

- Bryon to meson grouping and splitting (within 1σ confidence) disappears
  - Hint of an onset



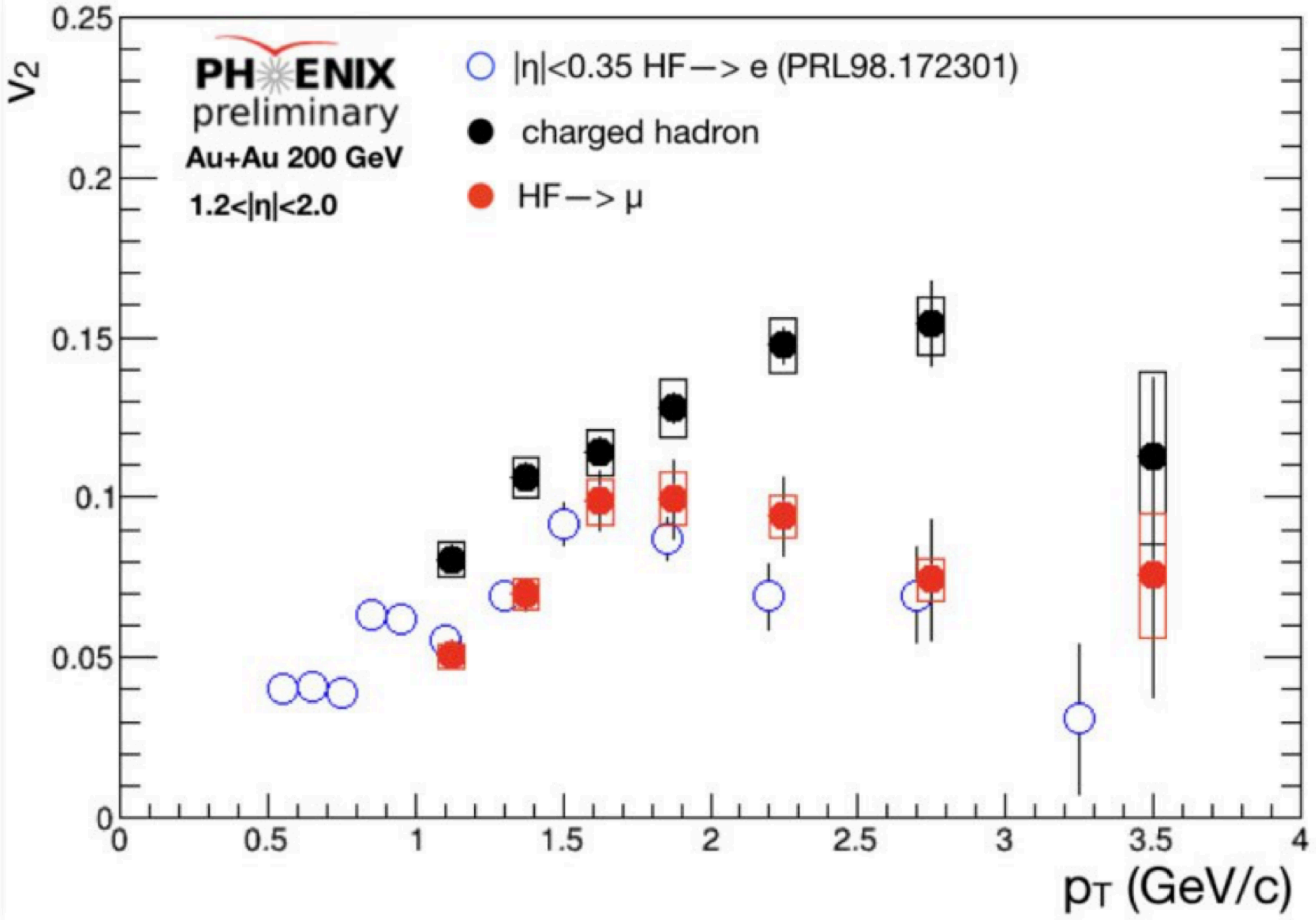


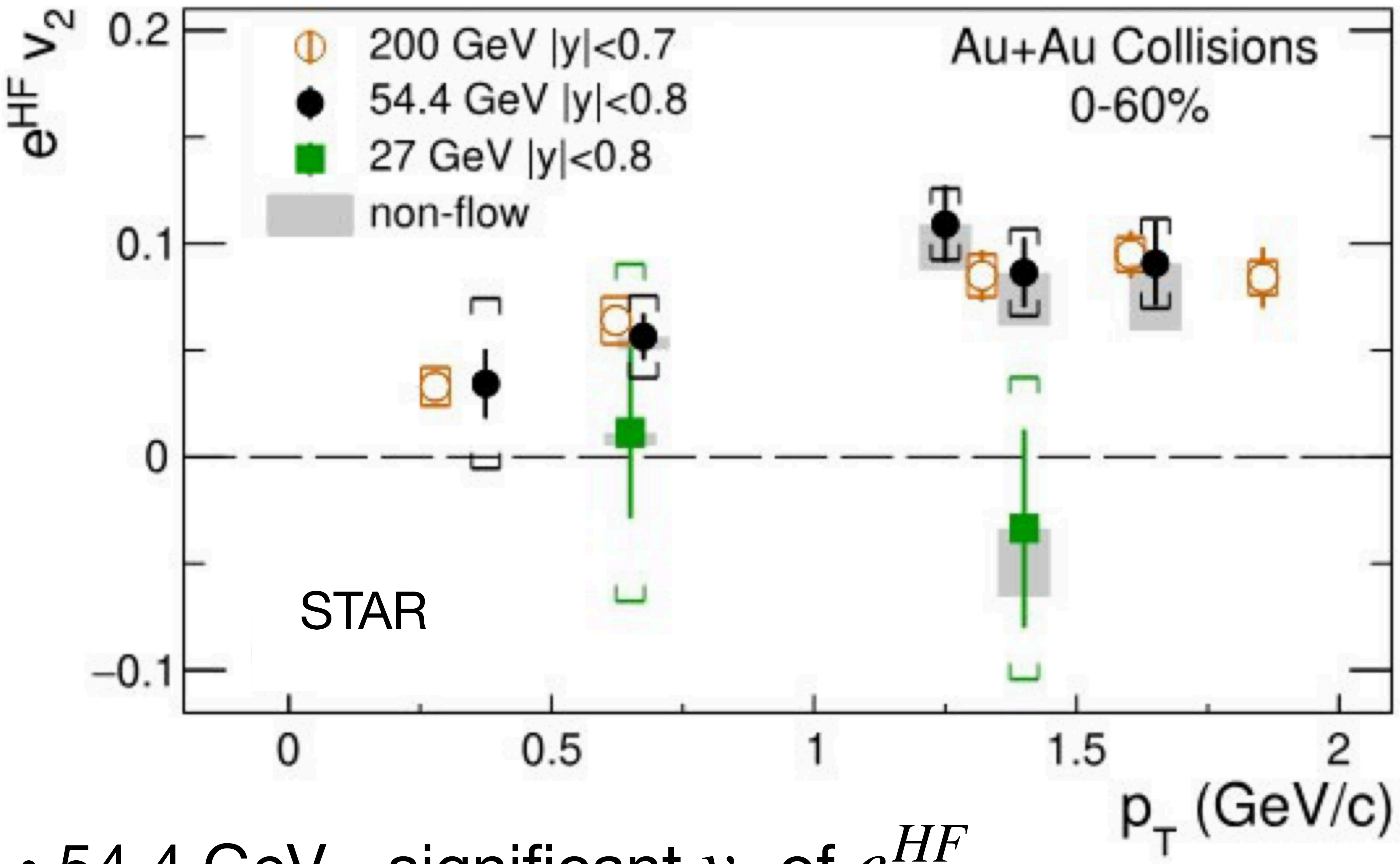
Open heavy flavor

Quarks	Particle	Mass
c d	D^+	1869.62±0.20 MeV/c^2
c u	D^0	1968.47±0.33 MeV/c^2
c s	D_s^+	1968.47±0.33 MeV/c^2
u d c	Λ_c^+	2286.46±0.14 MeV/c^2
d b	B^0	5279.65±0.12 MeV/c^2
u d b	Λ_b^0	5619.60±0.17 MeV/c^2

Open heavy-flavor v_2 measurements

RHIC





- Open HF v_2 is consistent with previous PHENIX results at mid rapidity
- HF particles flow with the QGP, but less then charged hadrons

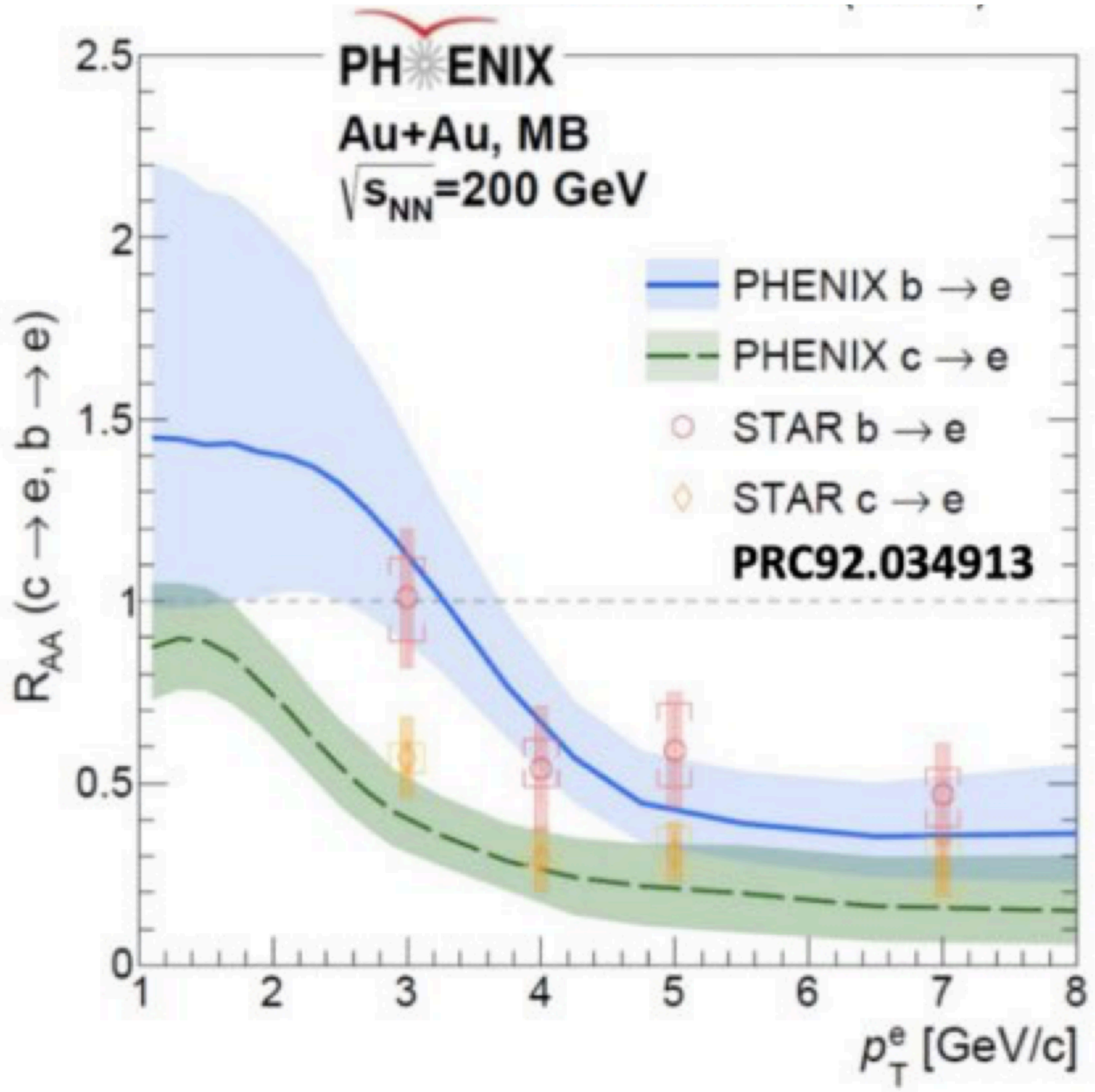
- 54.4 GeV - significant v_2 of e^{HF}
- Strong interaction of c quarks with QGP
- Hints of close to thermal equilibrium with the medium
- 27 GeV - $v_2 \sim 0$ within uncertainties

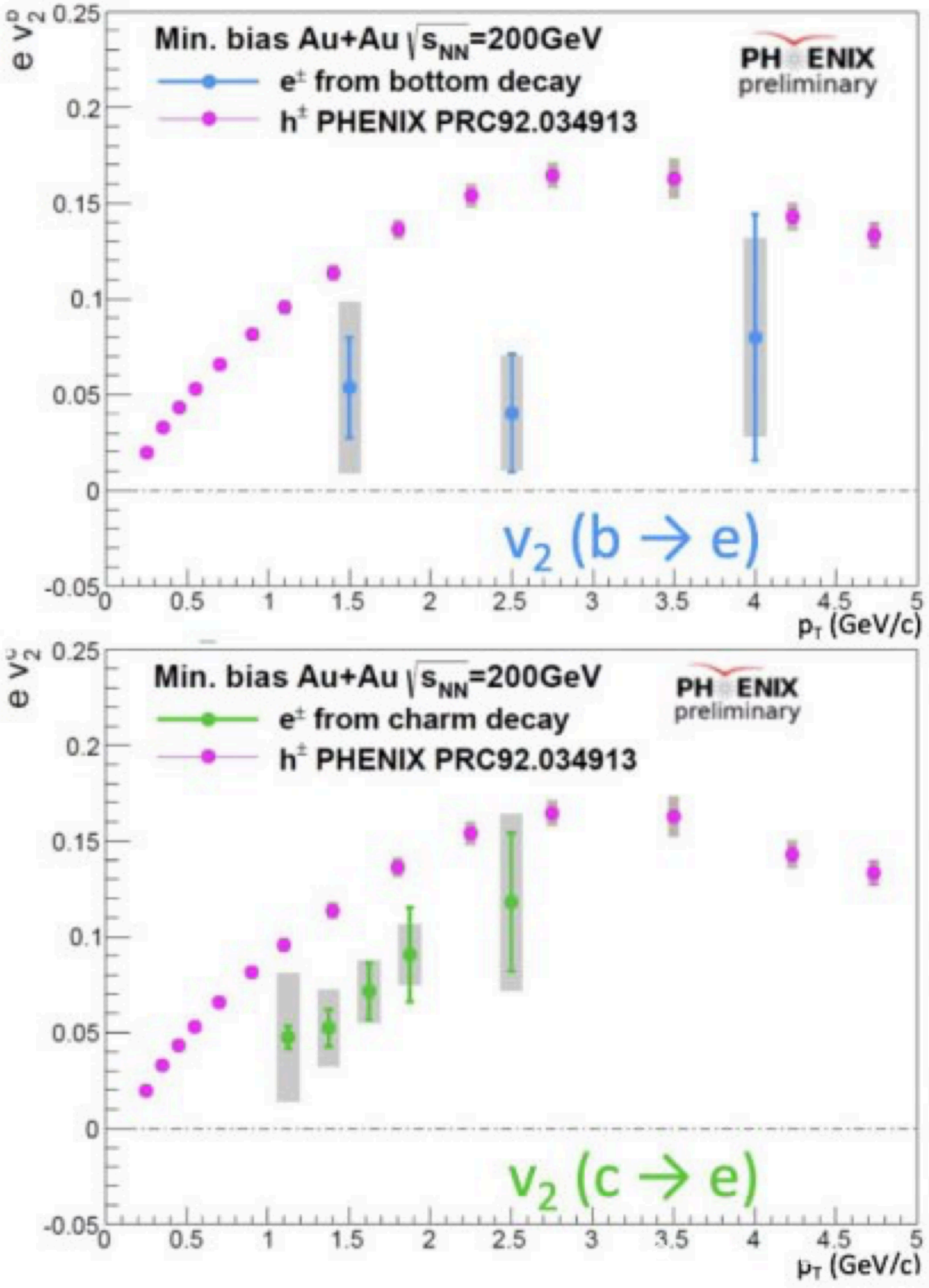
Hint of deviations of c quarks from local thermal equilibrium?

Separated Charm and Beauty

PHENIX. Nuclear modification factors and elliptic flow

PRC 109 044907 (2024)

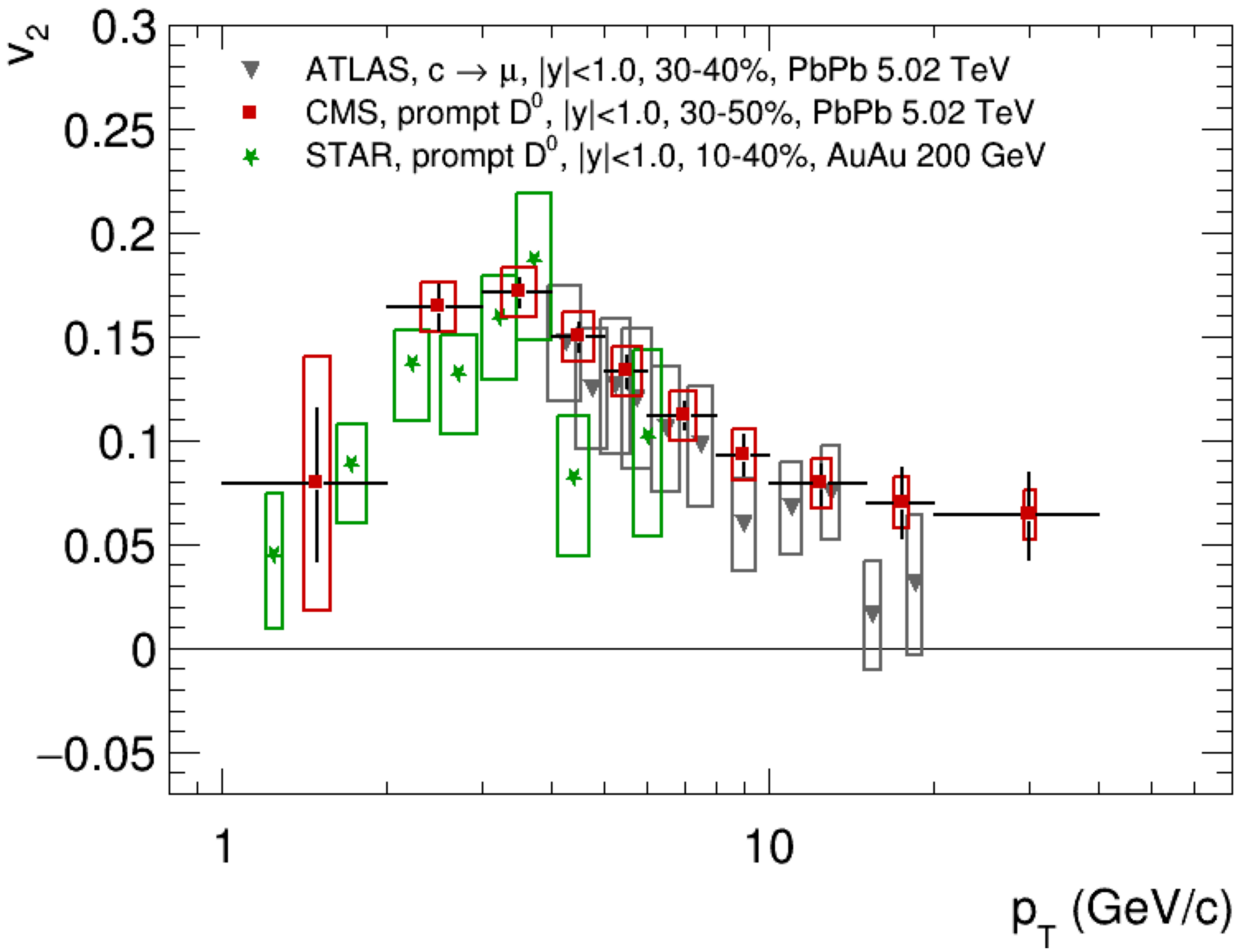


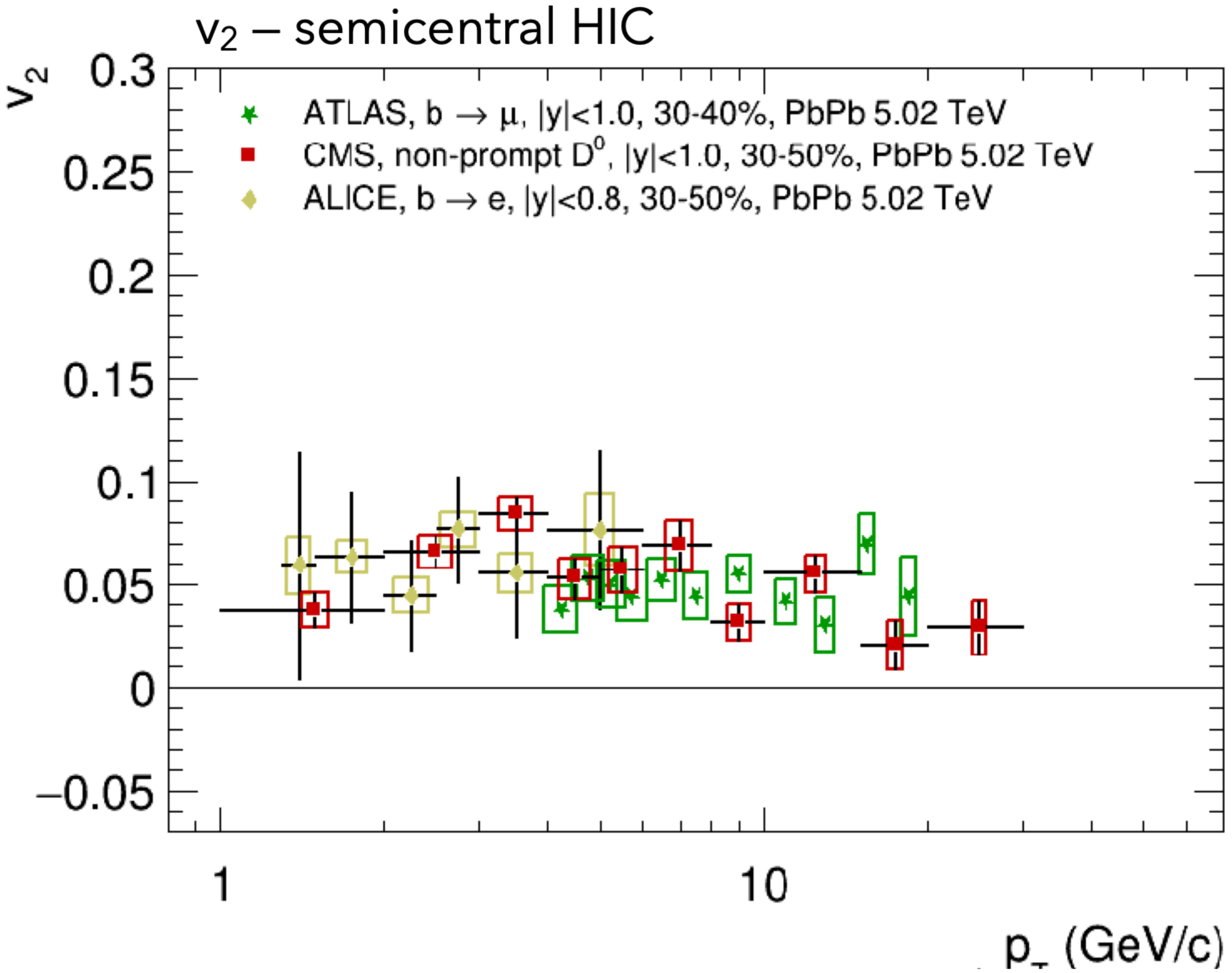


- Clear mass ordering observed between $(b \to l)$ and $(c \to l)$ at RHIC for both R_{AA} and v_2
- Interplay of energy loss and hydro at mid-p_T?

Charm and Beauty hadrons in medium

ALICE, CMS, ATLAS, and STAR. Elliptic flow





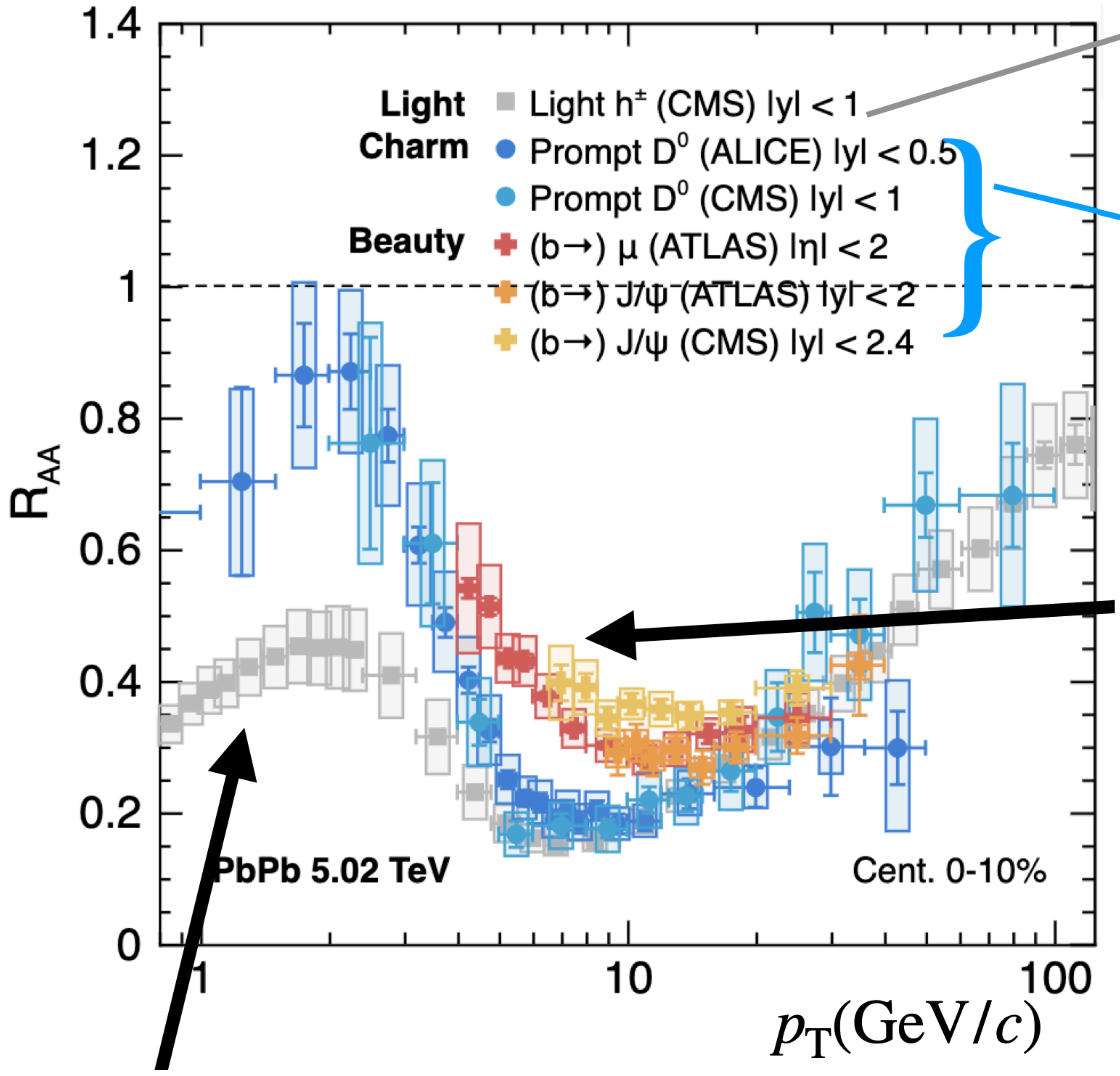
ALICE, v_2, PLB 813 (2021) 136054
CMS, v_2, PRL 120 (2018) 202301
ATLAS, v_2, PLB 807 (2020) 135595
STAR, v_2, PRL 118 (2017) 21

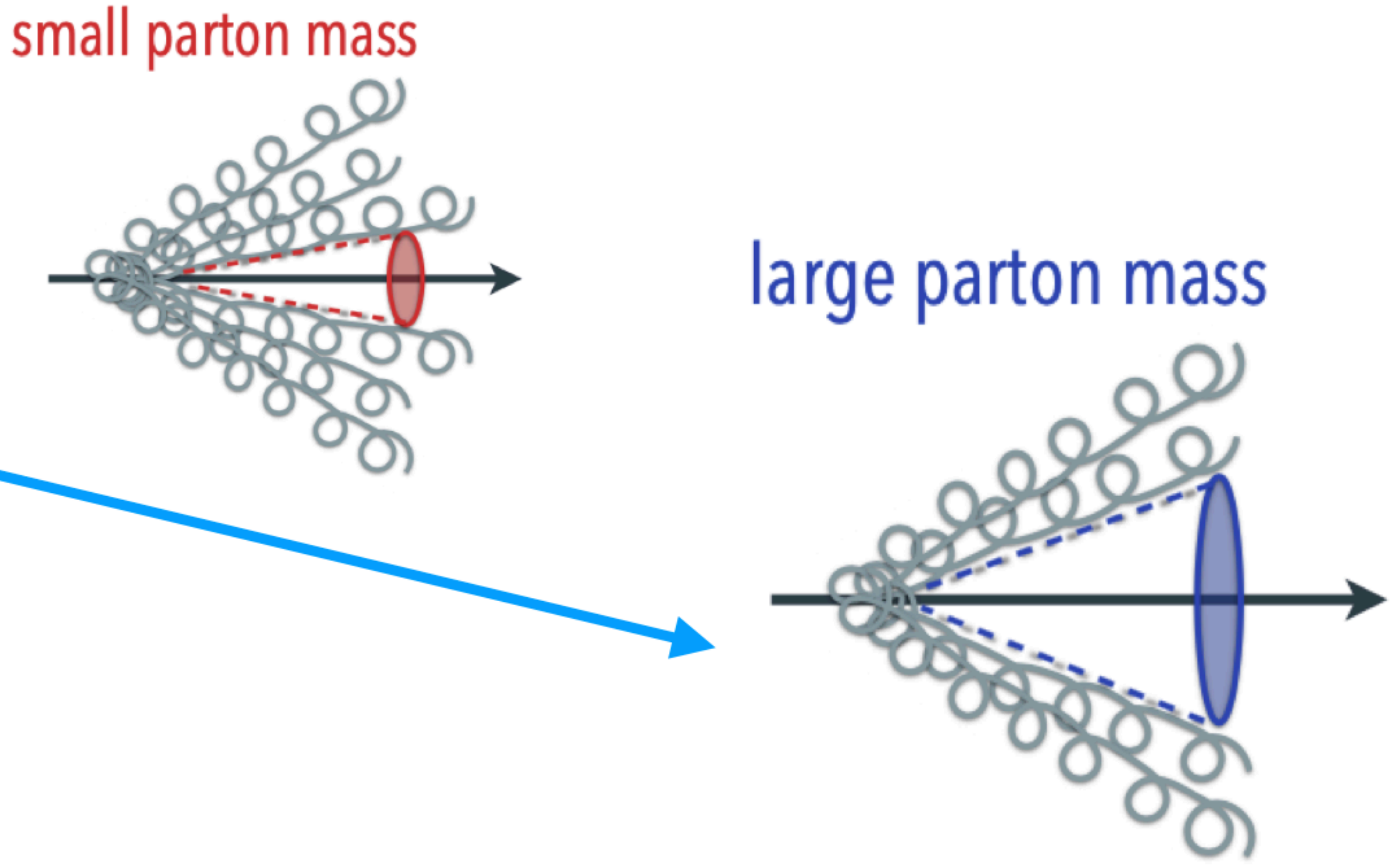
ATLAS, v_2, b to μ, Phys.Lett.B 807 (2020) 135595
ALICE, non-prompt D v_2, EPJ.C 83 (2023) 1123
ALICE, v_2, b to e, Phys.Rev.Lett. 126 (2021) 16, 16200
CMS, v_2, non-prompt D^0, arXiv: 2212.01636

- Positive v_2: participation to the collective motion
- Positive v_2 for $p_T > 2 - 3$ GeV, lower values for beauty than for charm hadrons

Charm and Beauty hadrons in medium

ALICE, CMS, ATLAS. Nuclear modification factors





Dead cone effect: gluon radiation suppressed at angles smaller than θ < m/E

$$R_{AA}(q/g) < R_{AA}(c) < R_{AA}(b)$$

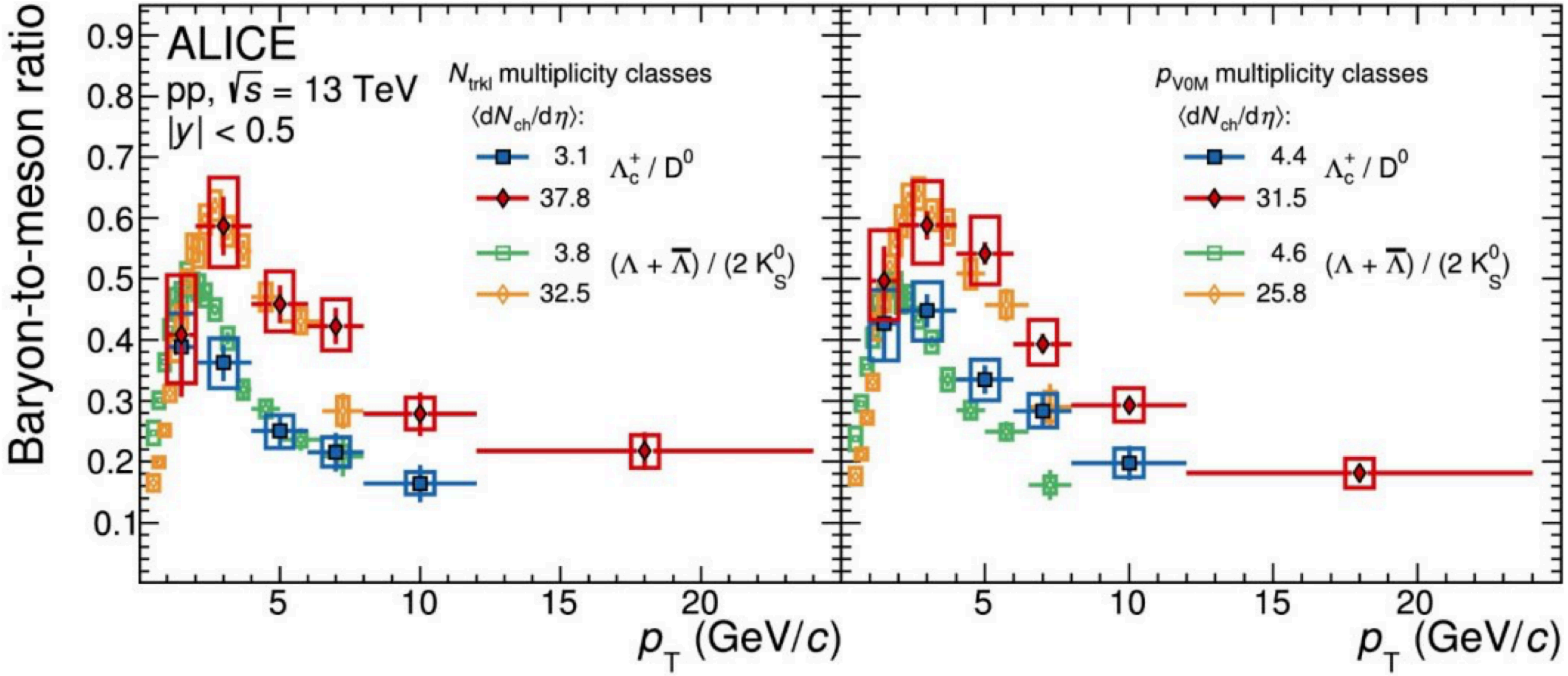
Consistent with mass dependent hierarchy

"Flow bump" due to (radial) flow of medium and coupling at small p_T

Baryon-to-meson ratio

ALICE. Radial flow

ALICE. PLB 829, 137065 (2022)



- Charm baryons/meson like for strangeness

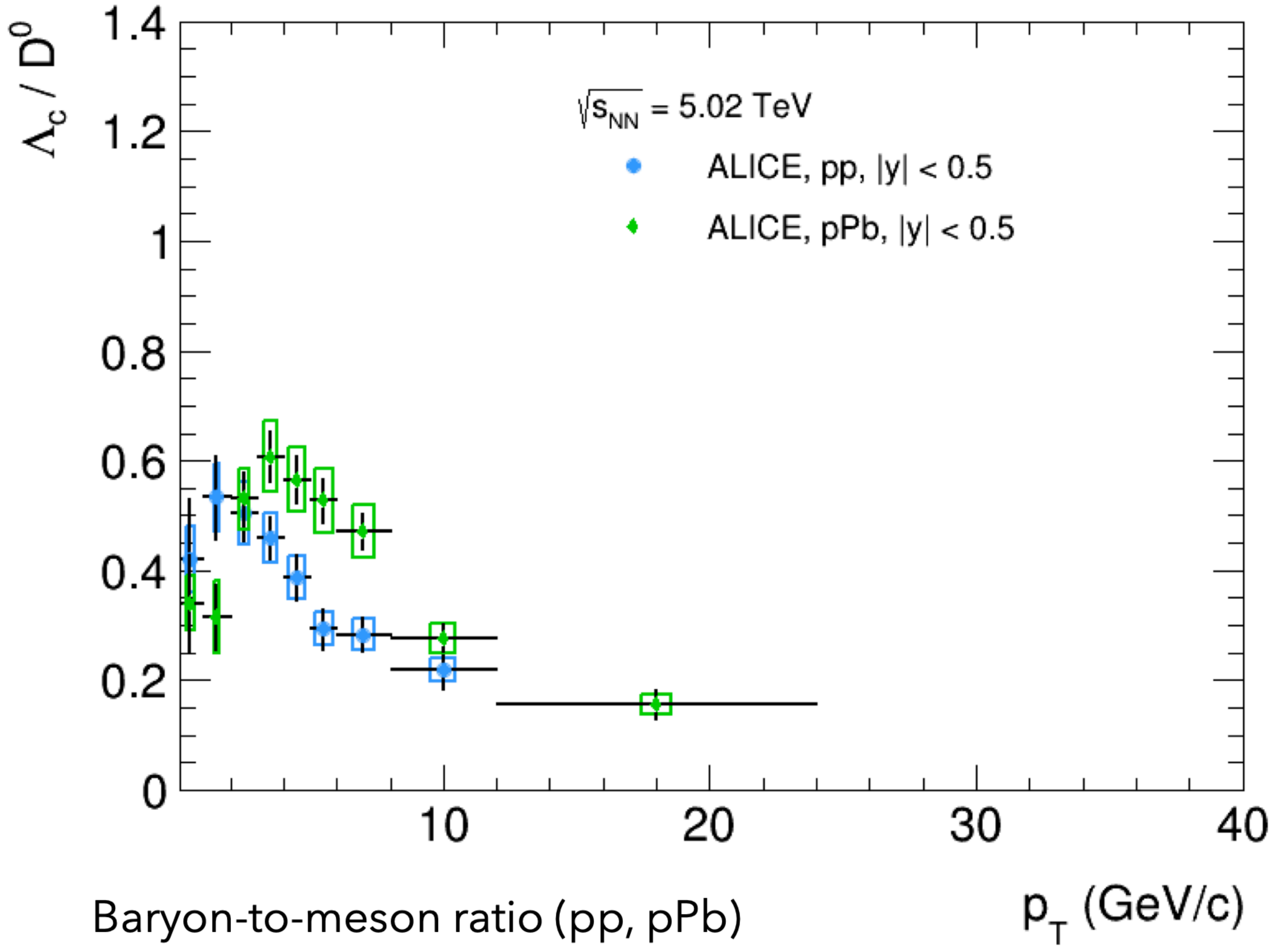
in ee these ratios are flat in p_T, in $p+p$ at low p_T peak

peak of the ratio → quark coalescence

peak pushed to higher p_T at high multiplicity

Baryons vs. mesons

ALICE. Charm hadron results. *p*+Pb



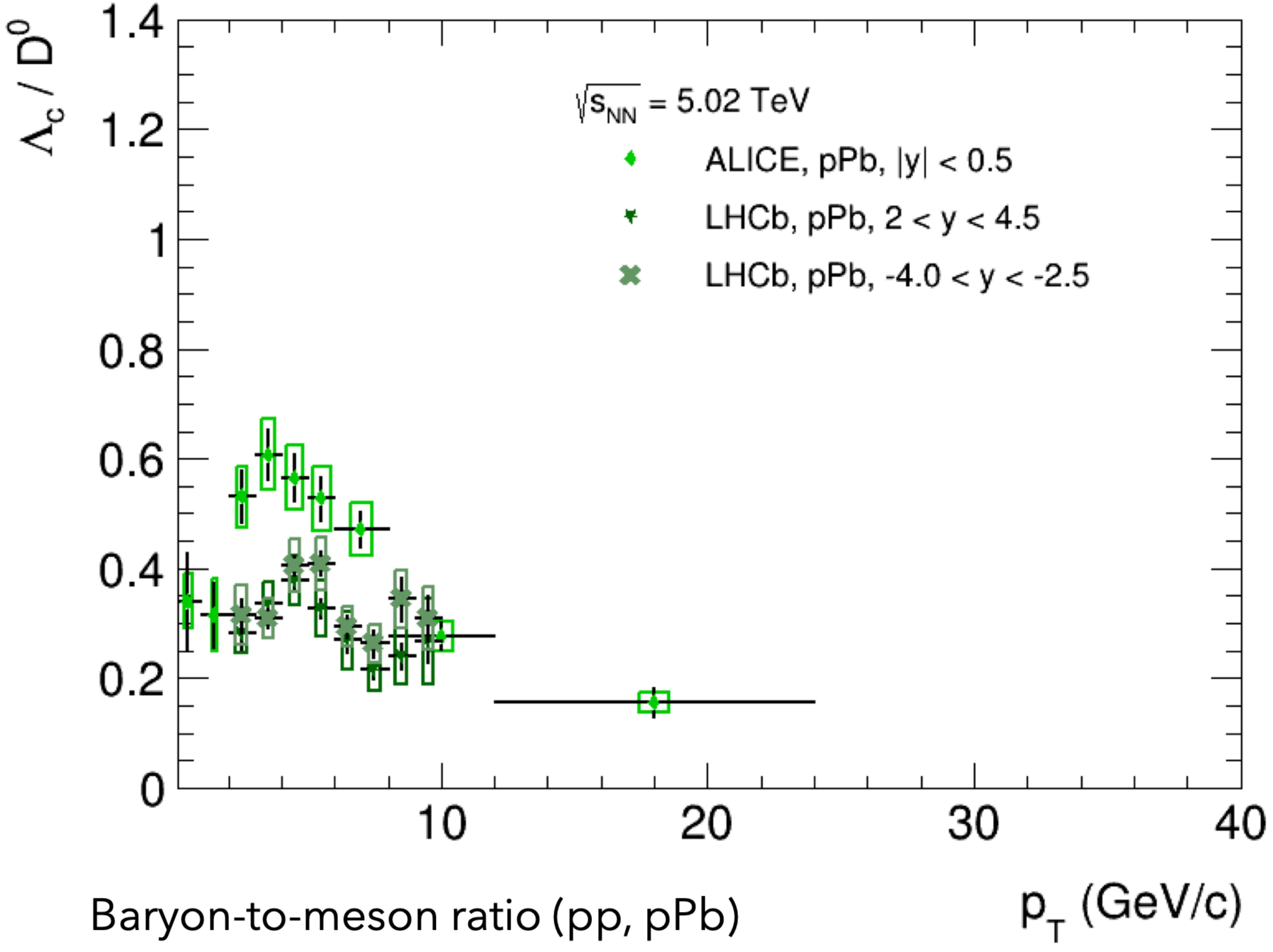
Baryon-to-meson ratio (pp, pPb)

- Observed a strong p_T dependence of the baryon-to-meson ratios in the charm sector, similar to that observed in the light-flavour sector
- Ratio modified in p+Pb w.r.t. $p + p$ (intermediate p_T)
- Possible influence of recombination or radial flow?
- No significant p_T dependence observed at large rapidity in p+Pb
- Possible rapidity dependence?

ALICE, pp, pPb, PRC 107 (2023) 064901
CMS, pp, PbPb, JHEP 01 (2024) 128
LHCb, pPb, JHEP 02 (2019) 102
LHCb, PbPb, JHEP06 (2023) 132

Baryons vs. mesons

ALICE. Charm hadron results. *p*+Pb



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LHCb, PbPb, JHEP06 (2023) 132

Baryons vs. mesons

ALICE. Charm hadron results. Pb+Pb

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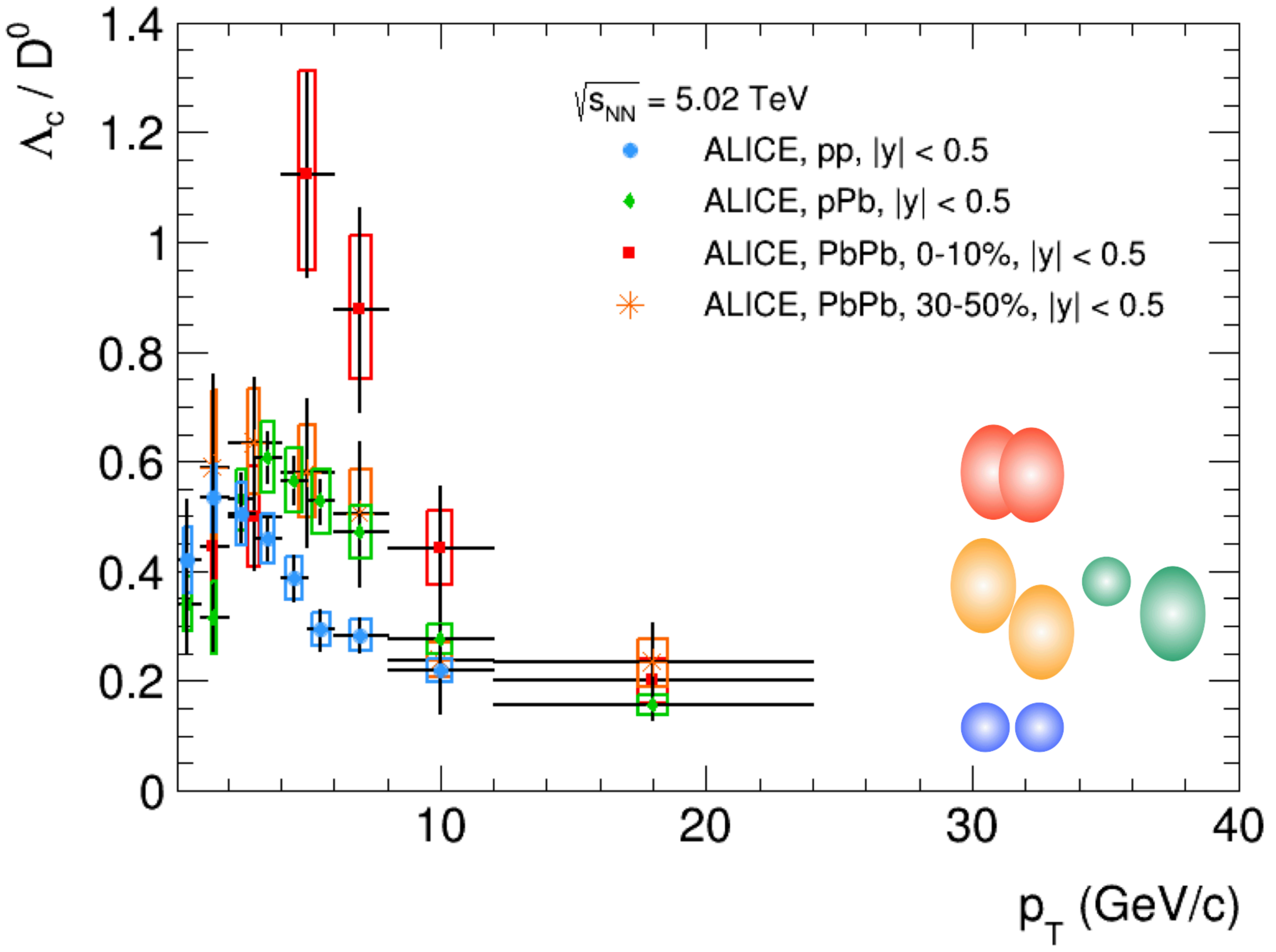
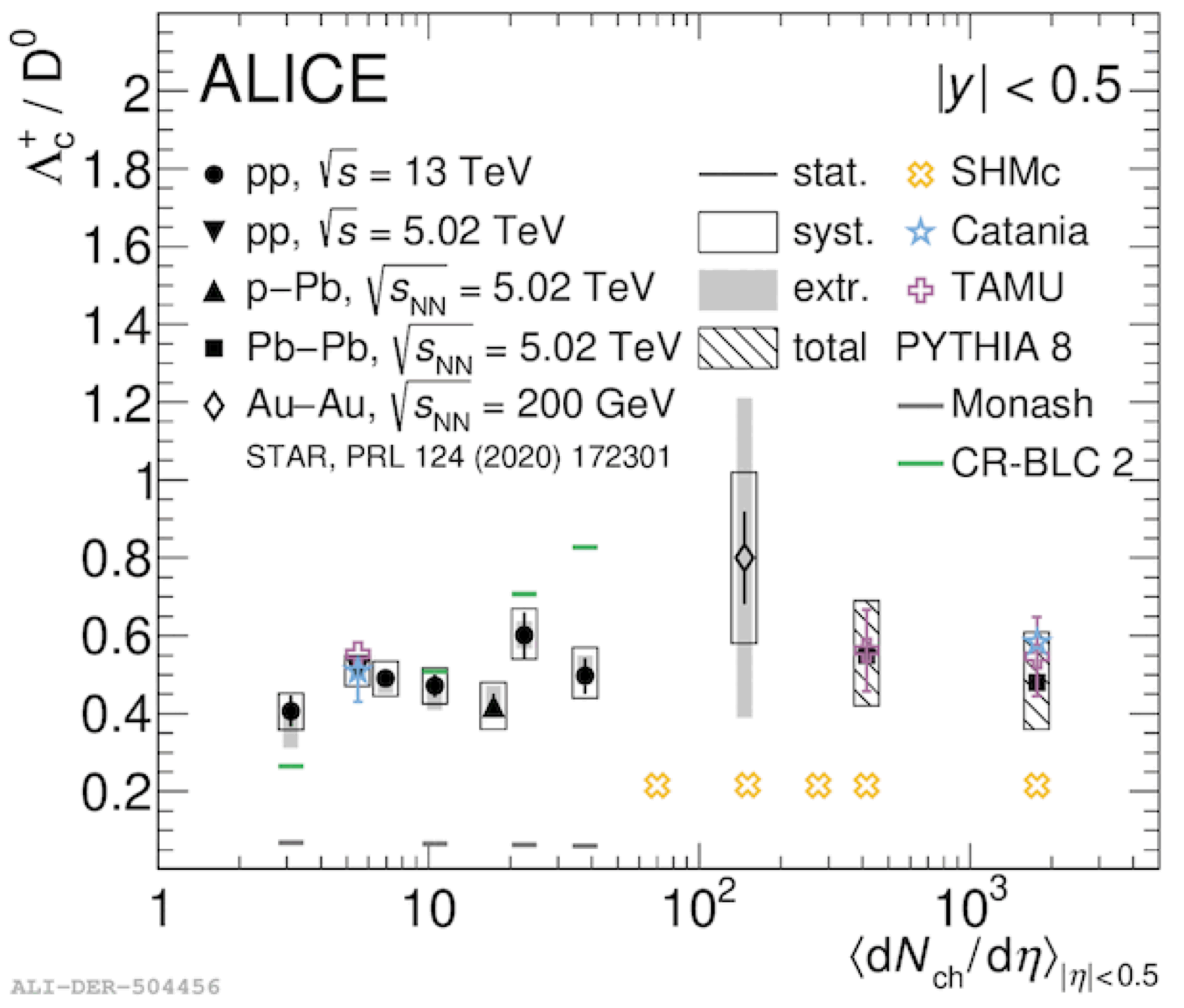


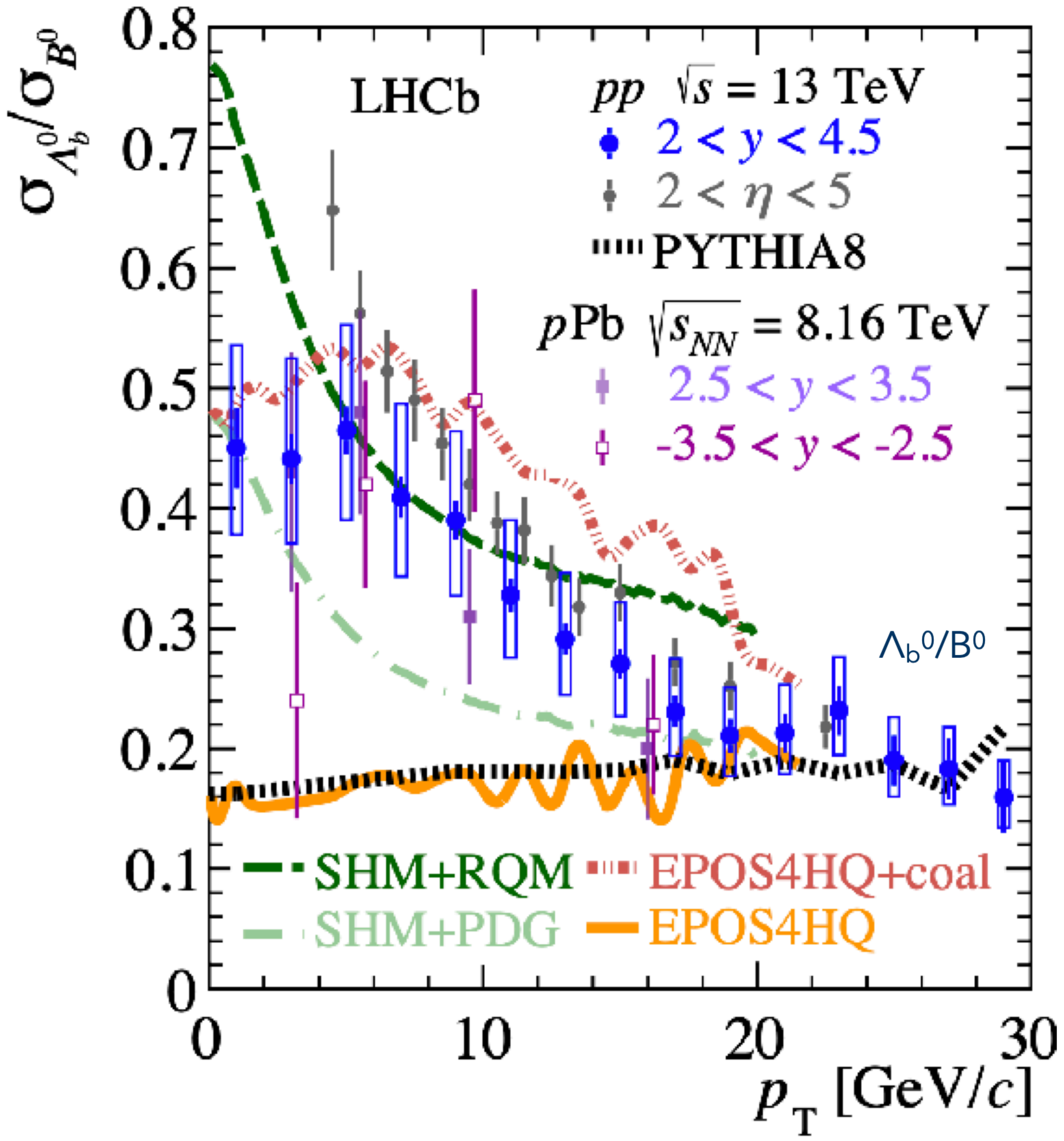


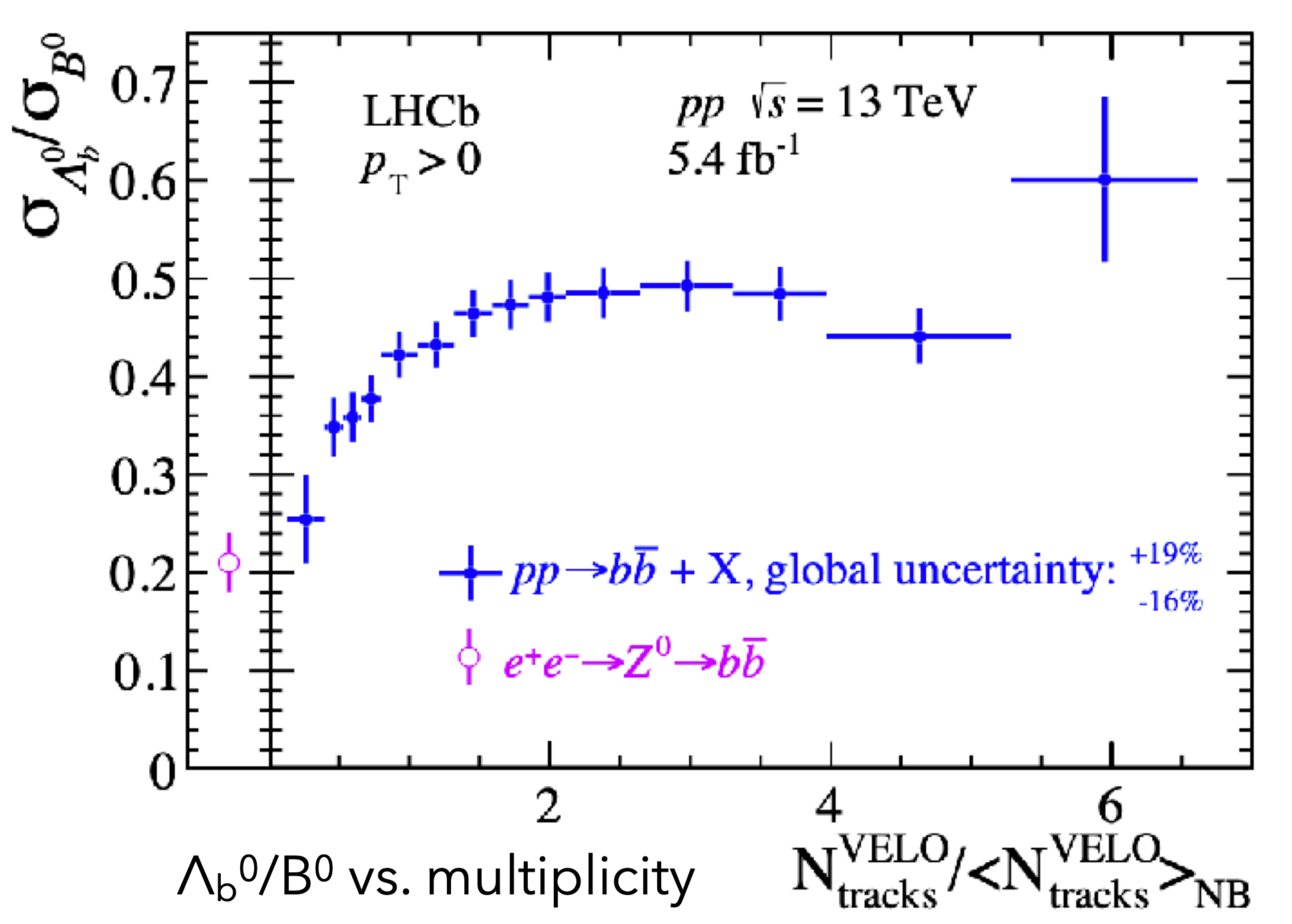
- Larger modification of the p_T distribution for the most central collisions
- Qualitative agreement with model calculation

ALICE, pp, pPb, PRC 107 (2023) 064901
ALICE, PbPb, PLB 839 (2023) 137796
CMS, pp, PbPb, JHEP 01 (2024) 128
LHCb, pPb, JHEP 02 (2019) 102
LHCb, PbPb, JHEP06 (2023) 132
TAMU: He et al, PRL 124 (2020) 042301

Baryons vs. mesons

LHCb. Beauty sector. *p+p*





Λ_b^0/B^0 vs. multiplicity

- Results described by models considering additional effects to the independent fragmentation picture, e.g. coalescence or colour-reconnection mechanisms
- Evolution of the ratios with charged-particle multiplicity

c $\bar{c}$

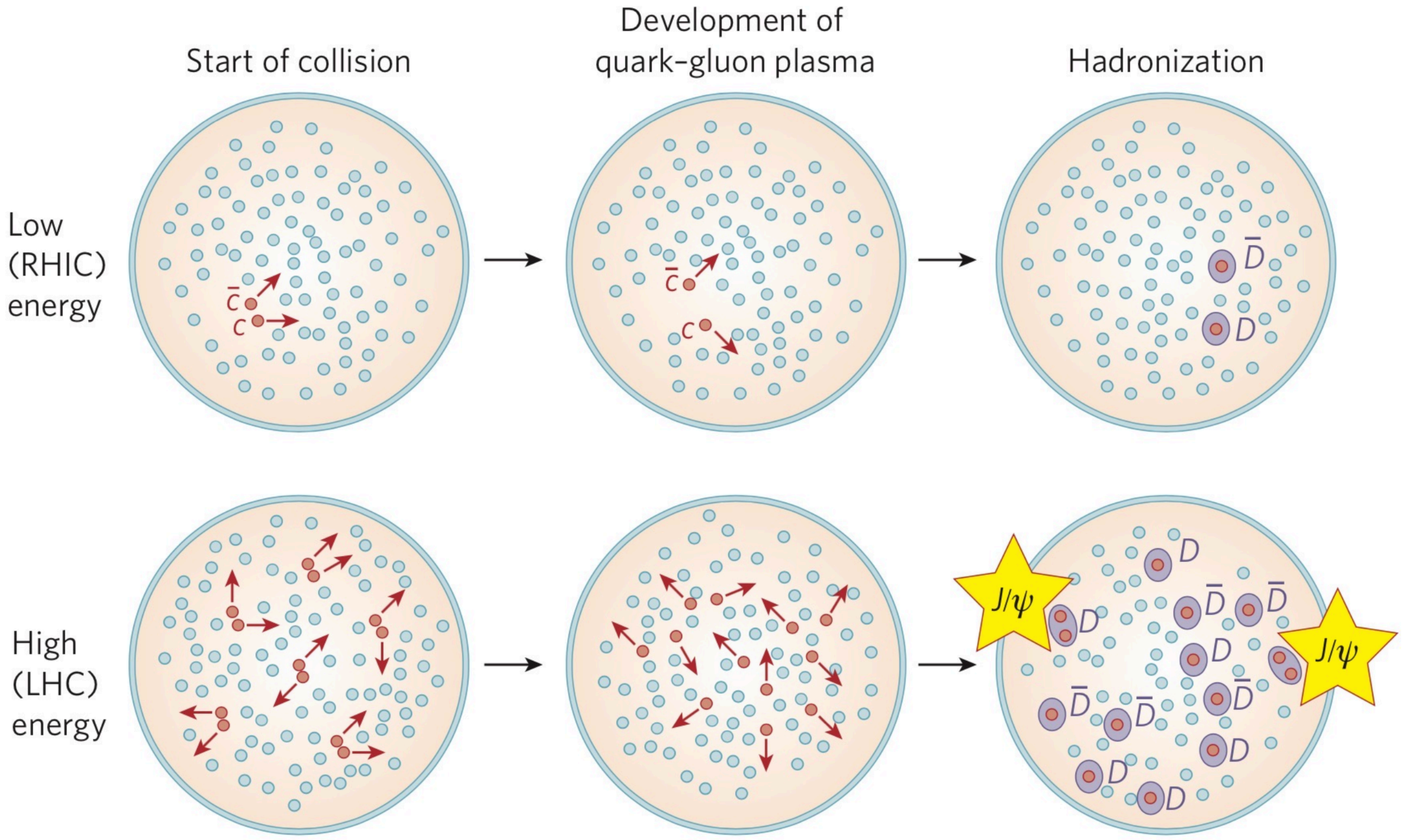
J/ψ

3096.916 MeV/c

c $\bar{c}$

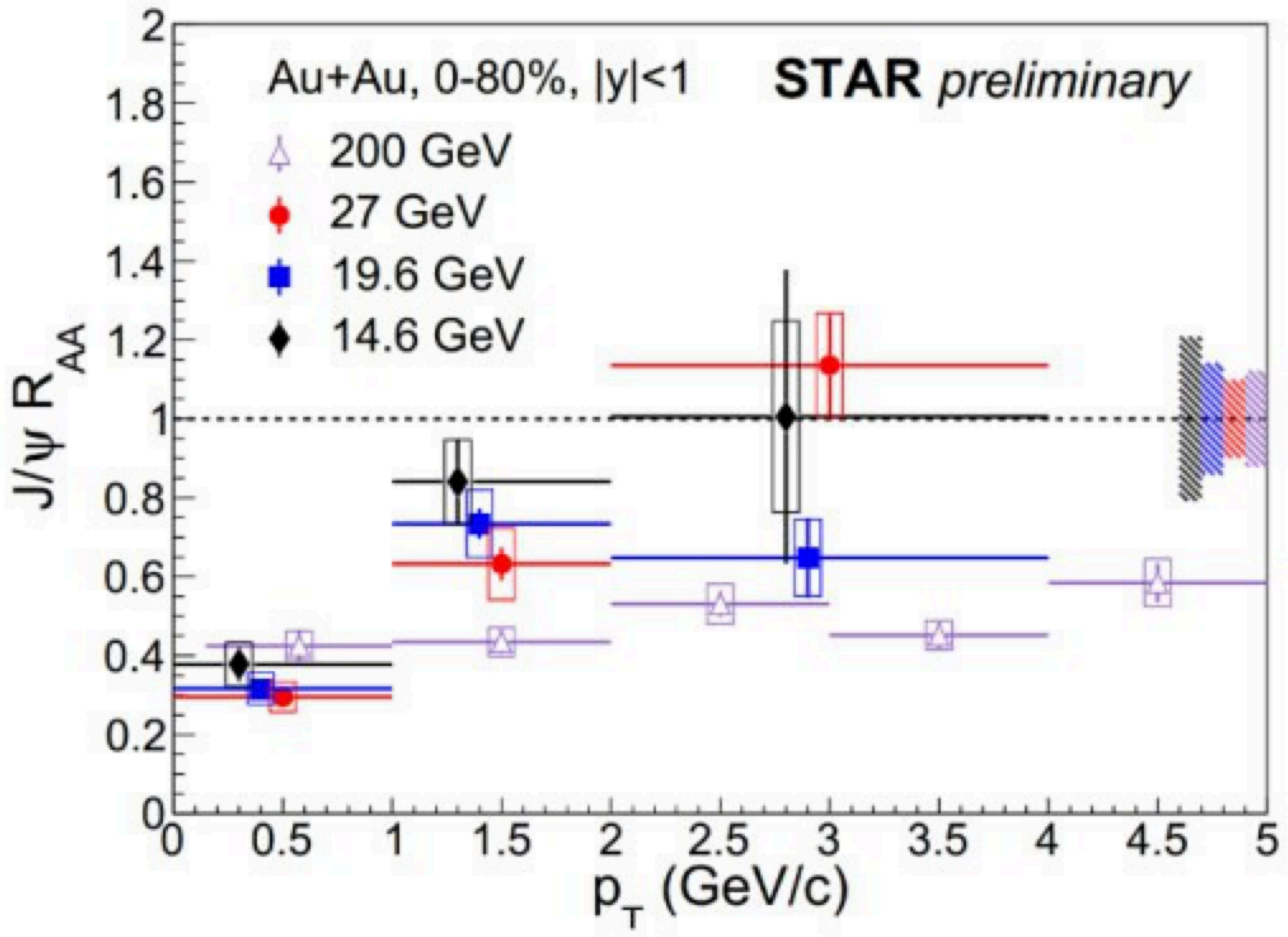
$\psi(2S)$

3686.09 ±0.04 MeV/c



Charmonium

$J/\psi\ R_{AA}$ vs. p_T
STAR. Au+Au collisions

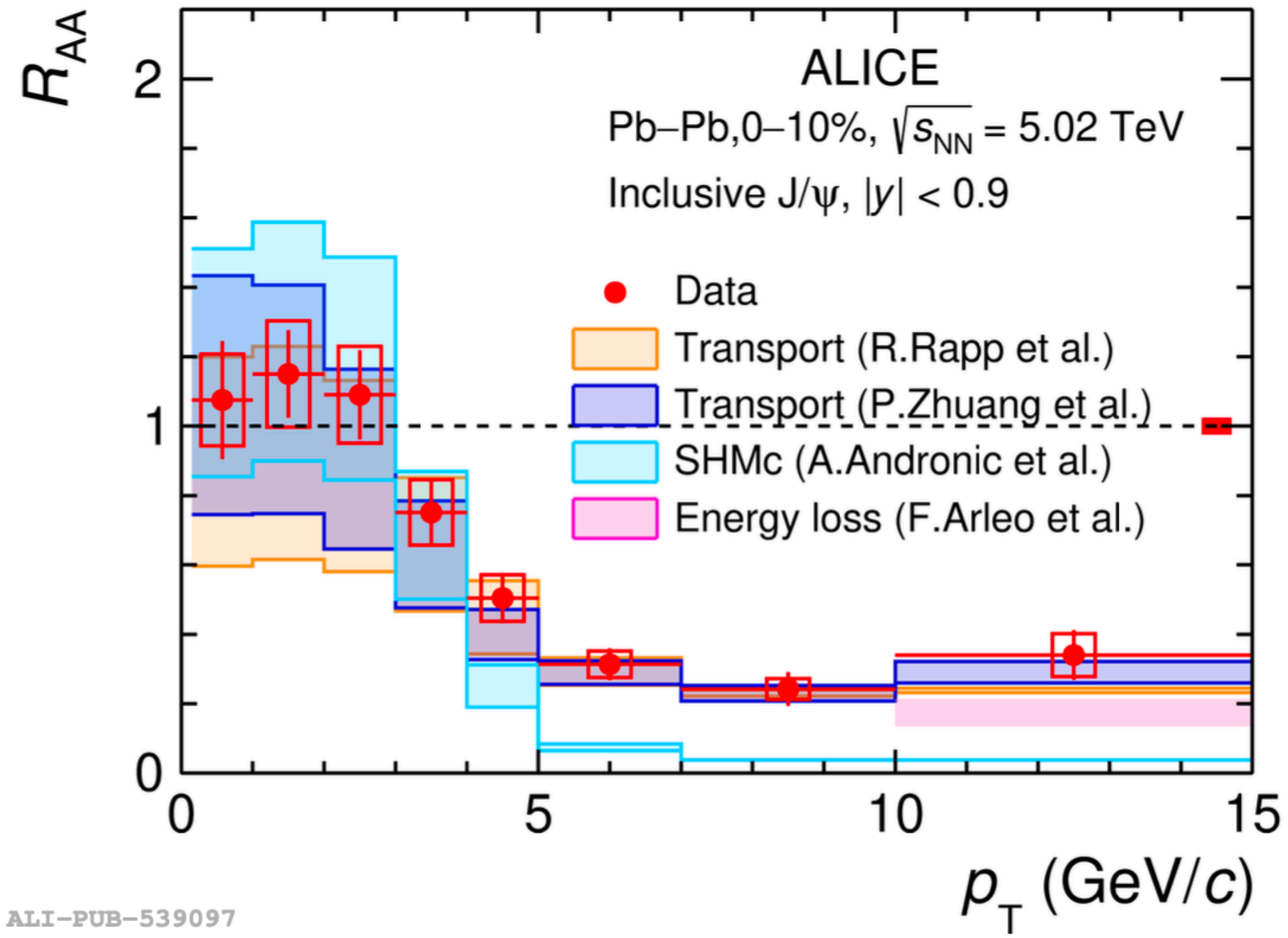


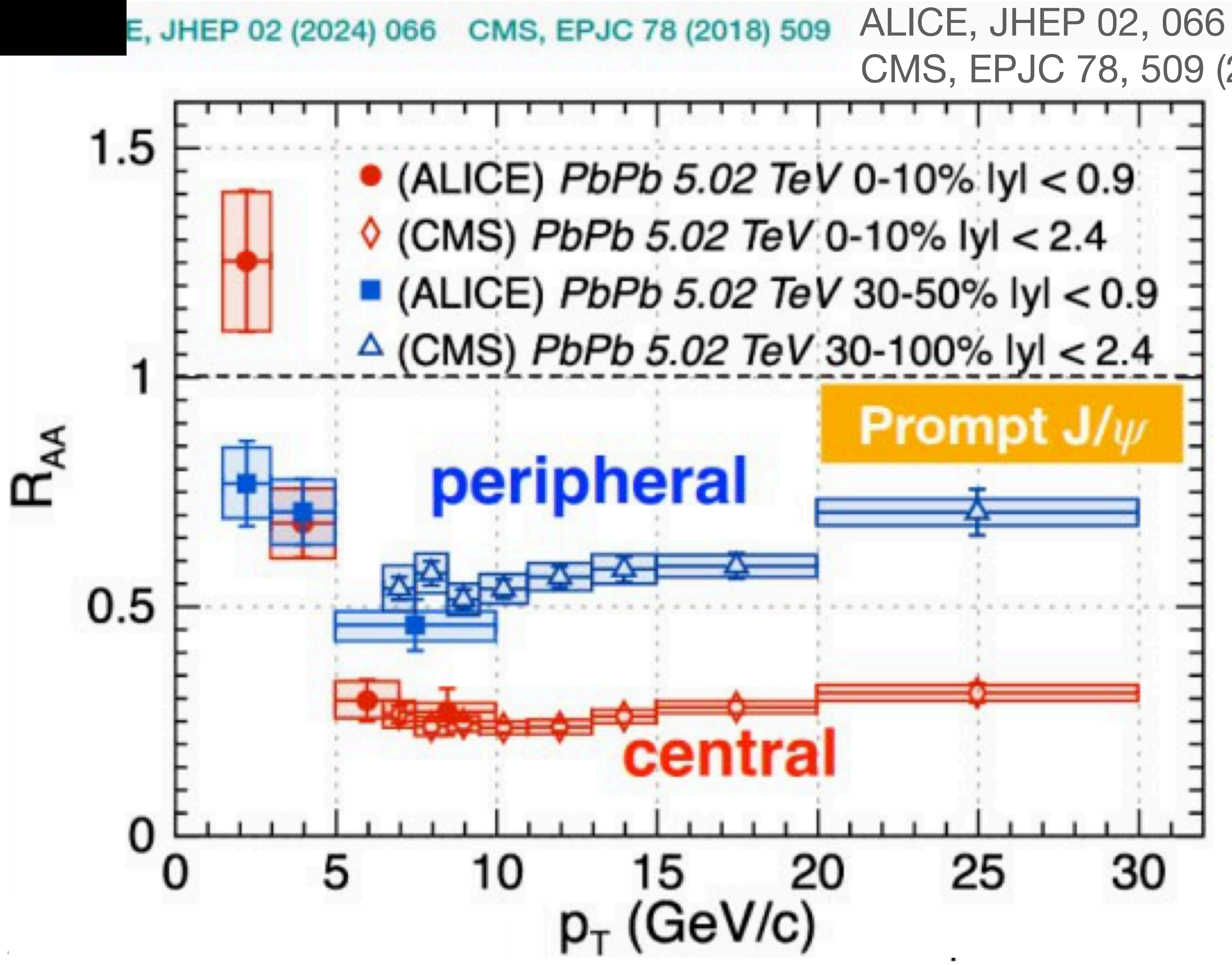
- Low p_T suppression,
- R_{AA} increases with p_T for $\sqrt{s_{NN}} = 14.6,\ 19.6$ and 27 GeV
- No significant p_T dependence at 200 GeV

$J/\psi\ R_{AA}$

ALICE. CMS. Interplay between [redacted]eneration and suppression

ALICE, JHEP 02, 066 (2024
CMS, EPJC 78, 509 (2018))



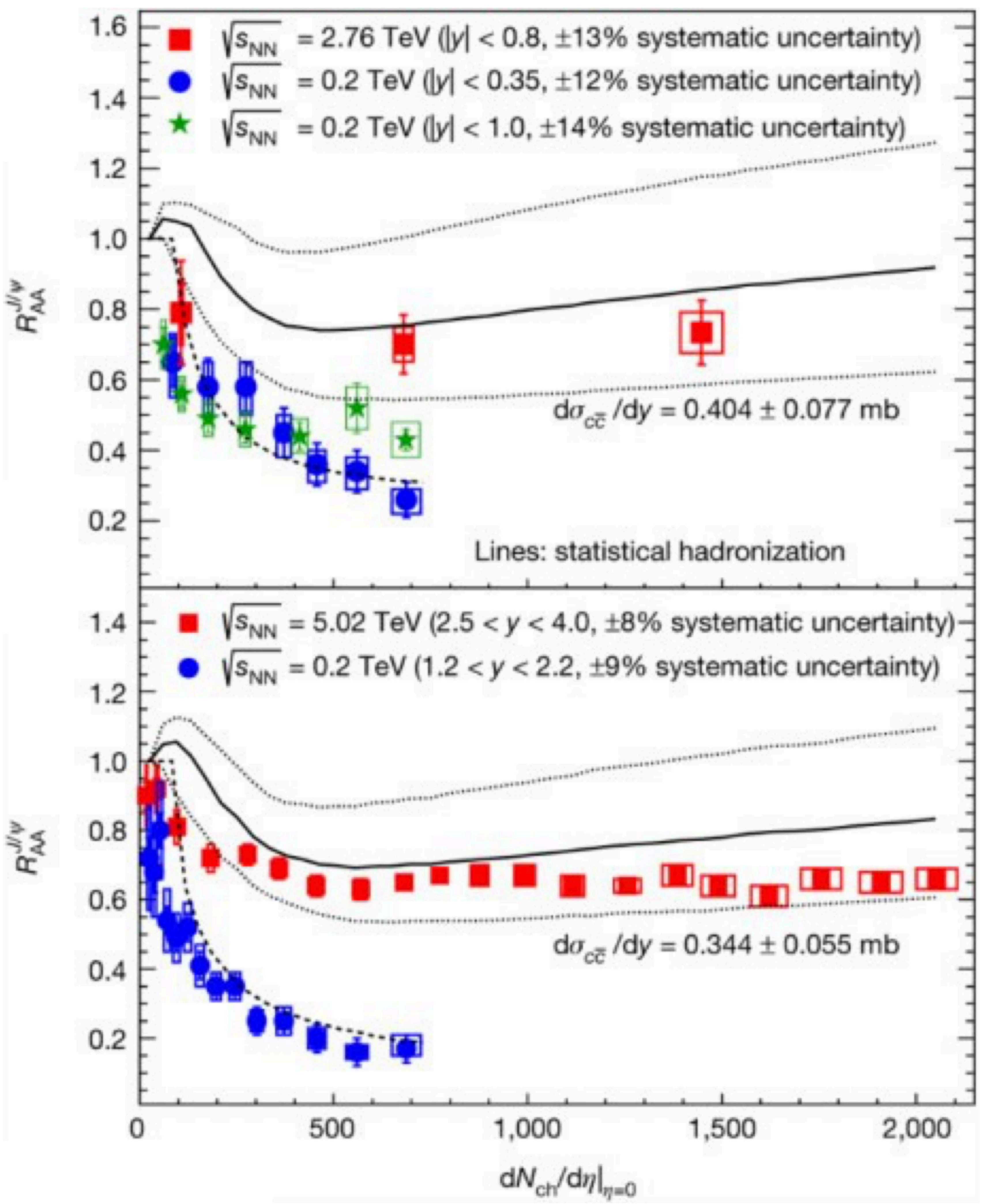


- Stronger R_{AA} increase towards lower p_T in midrapidity, exhibiting comparable suppression at high p_T
- Stronger R_{AA} increase towards lower p_T in central events, exhibiting larger suppression at high p_T
- Theoretical predictions support (re)generated J/ψ concentrated at low p_T at midrapidity with larger $c\bar{c}$ cross section

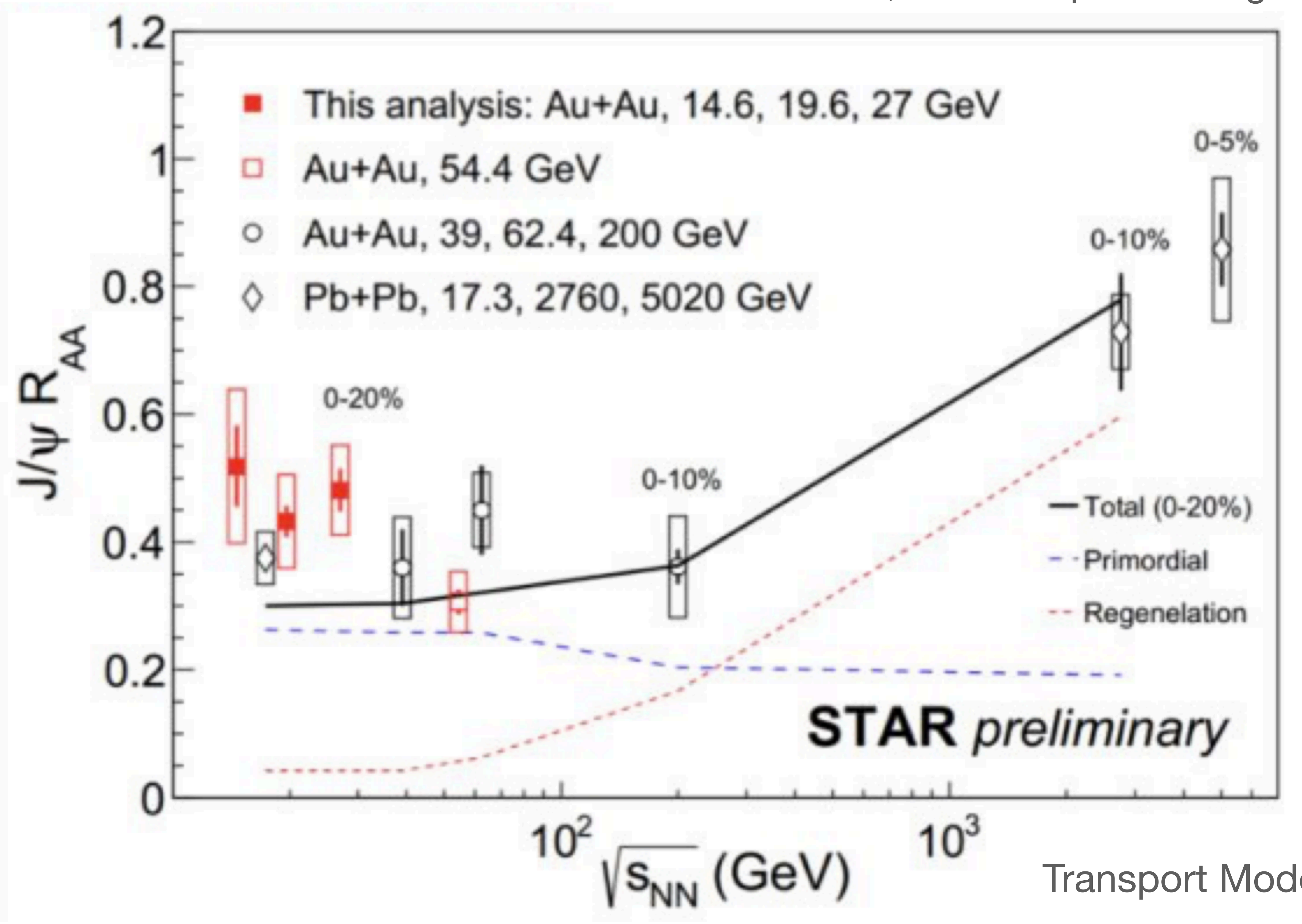
J/ψ in different system energies

RHIC and LHC

SHM: Nature 561 321-330 (2018)



STAR, QM2023 proceedings



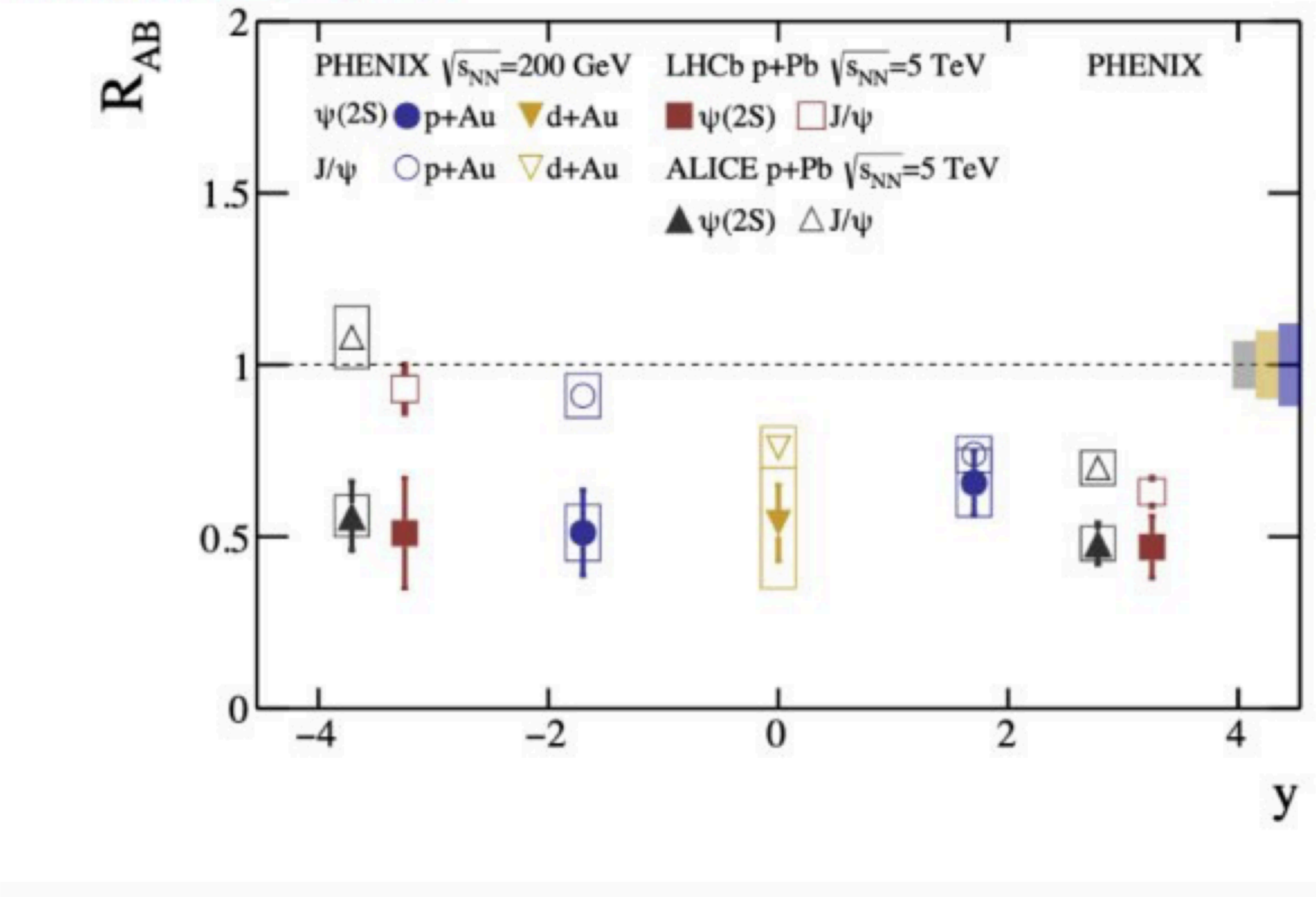
Transport Model. PRC 82, 064905 (2010)

- Strong rise of the $J/\psi\ R_{AA}$ from RHIC to LHC energies:
  - Interplay between regeneration and suppression
- Both SHM and Transport model simultaneously describe RHIC/LHC data

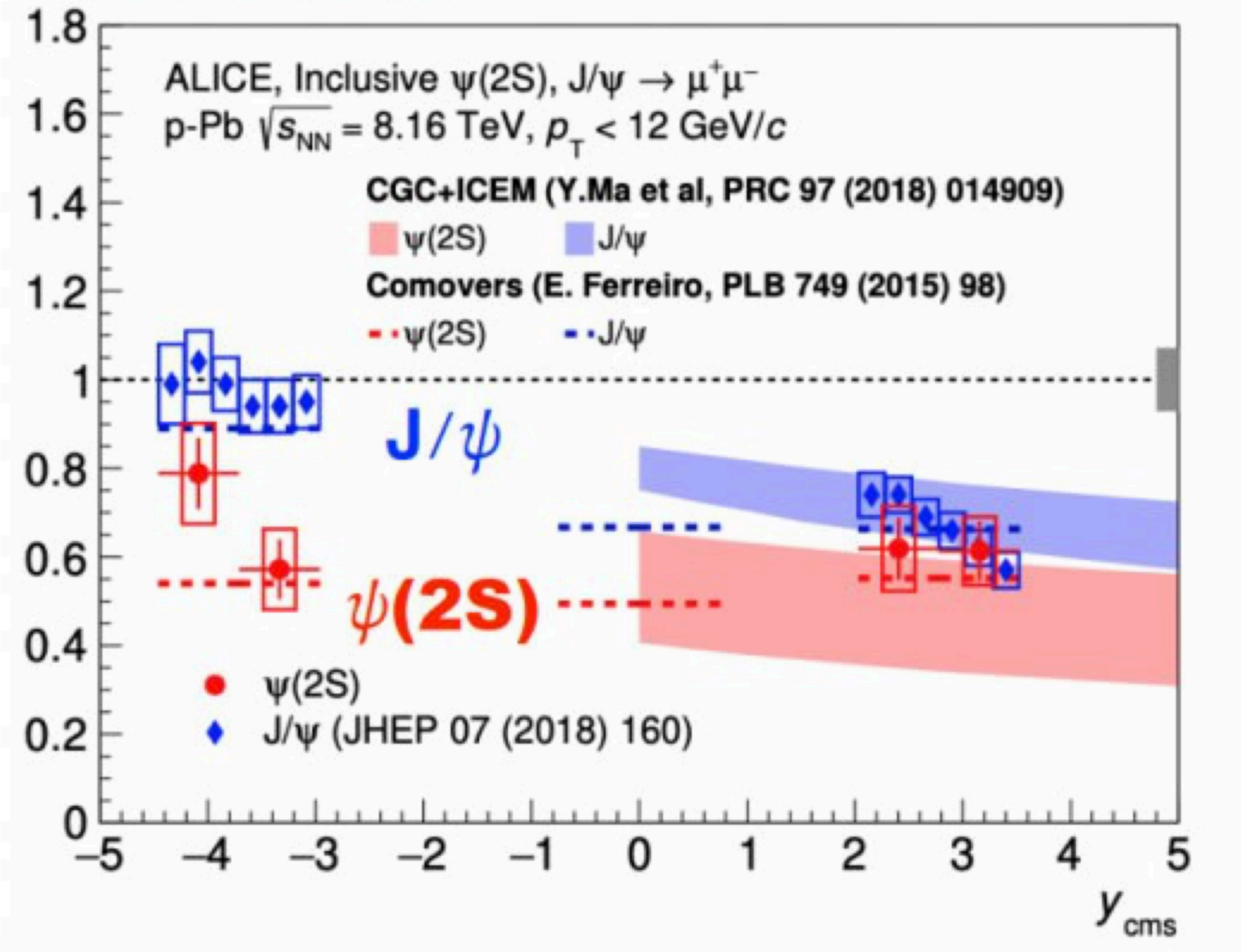
Excited charmonium states

LHC and RHIC

PHENIX, PRC 105, 064912 (2022)



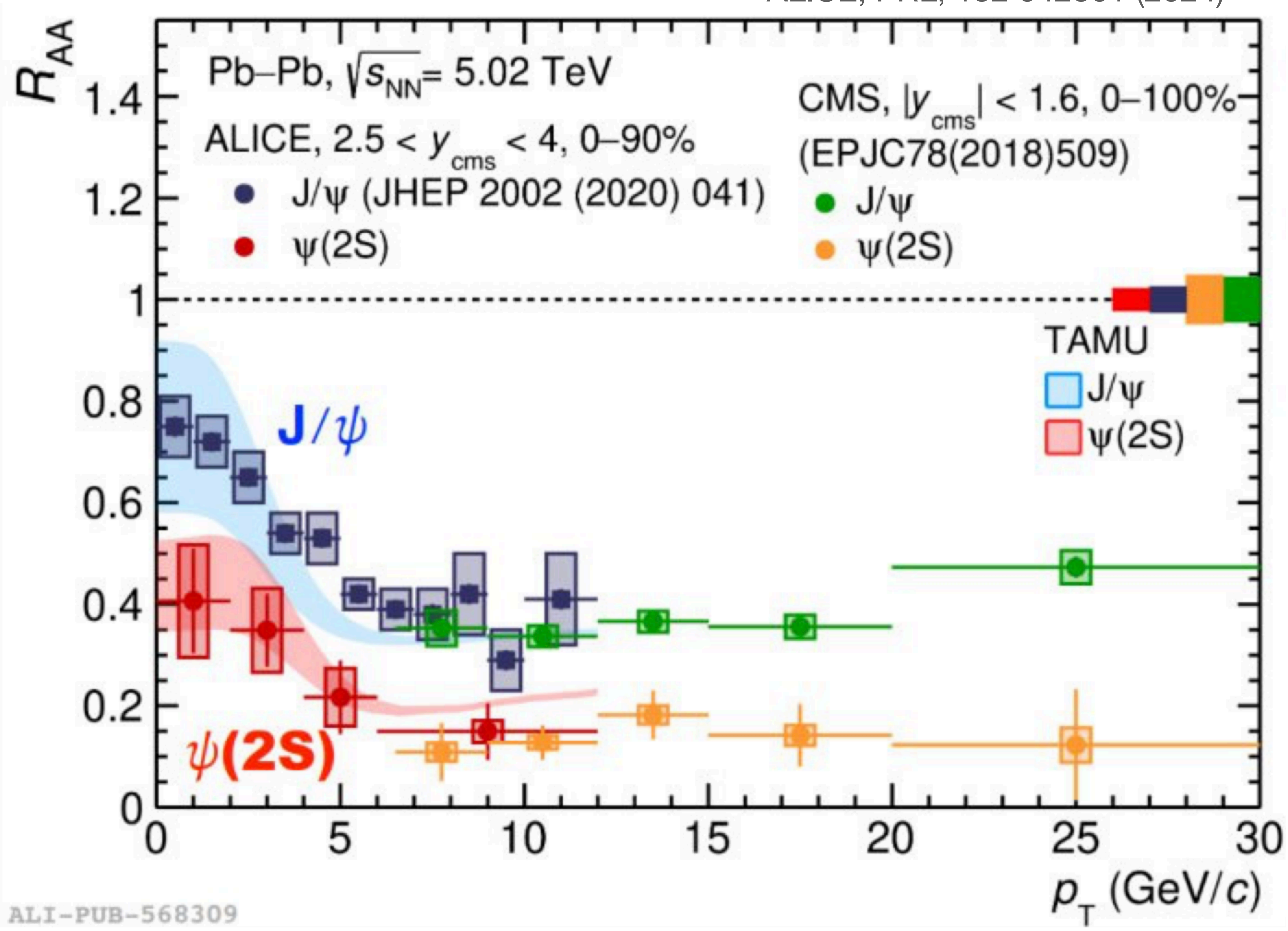
ALICE, JHEP 07 237 (2020)



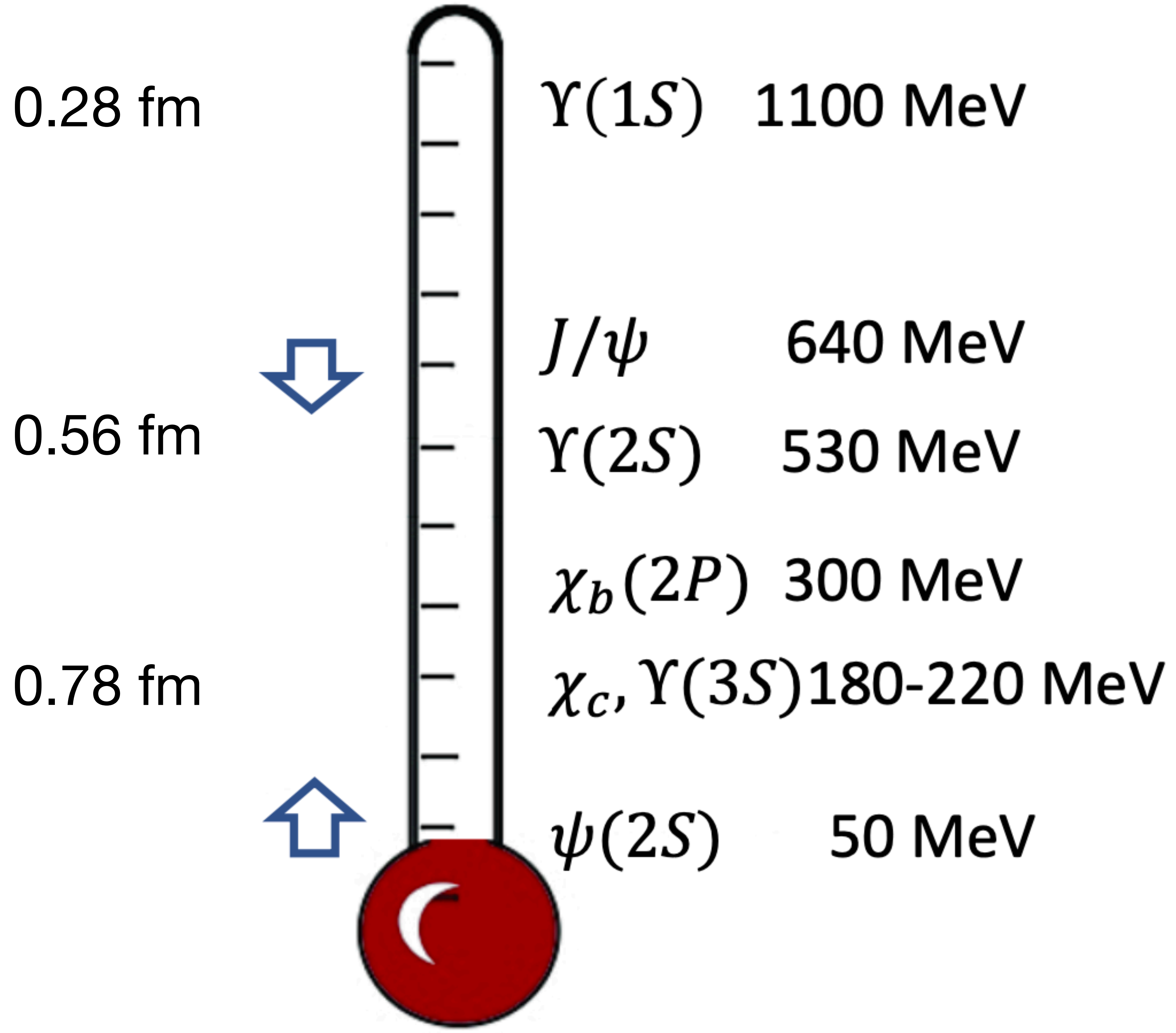
- Stronger suppression of $\psi(2S)$ in backward-y both at RHIC/LHC
- Initial-state effects or coherent energy loss, largely independent on the specific charmonium resonance → final-state effects?
- Comover model agrees with the measurement within uncertainty

$\psi(2S)$ production
ALICE. CMS. Pb+Pb

ALICE, PRL, 132 042301 (2024)



- Larger suppression for $\psi(2S)$ than J/ψ in measured p_T range
- Increasing trend at low p_T also in $\psi(2S)$ → hint of $\psi(2S)$ regeneration
- More differential and improved precision measurements required → Run 3 + Run 4



$b\ \bar{b}$

$\Upsilon(1S)$ 9460.30±0.26 MeV/c

$\Upsilon(2S)$ 10023.26±0.31 MeV/c

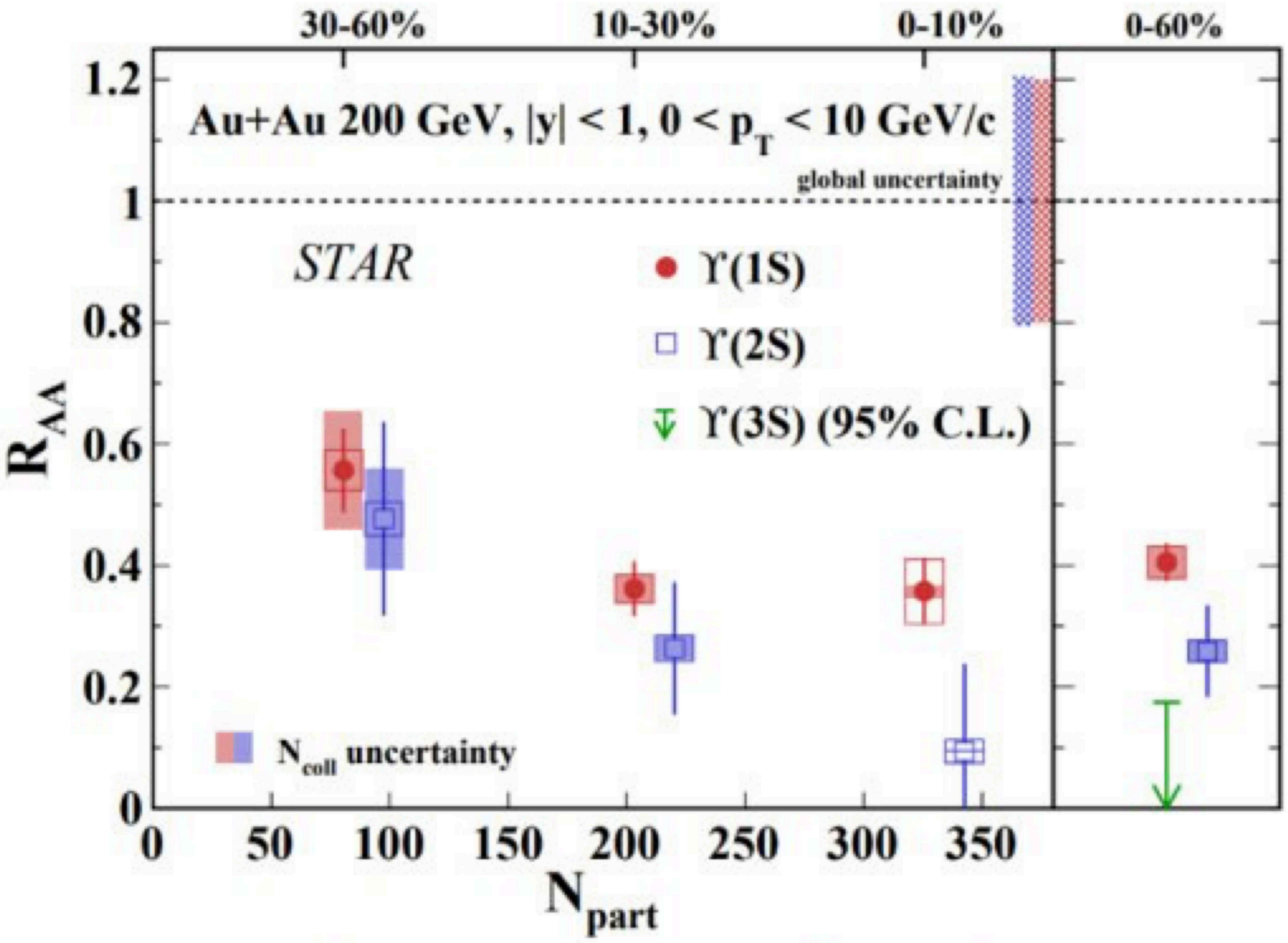
$\Upsilon(3S)$ 10355.2±0.5 MeV/c

Botomonium

Υ R_{AA} vs $\langle N_{part} \rangle$

STAR. Au+Au

STAR, Phys. Rev. Lett. 130 (2023) 112301



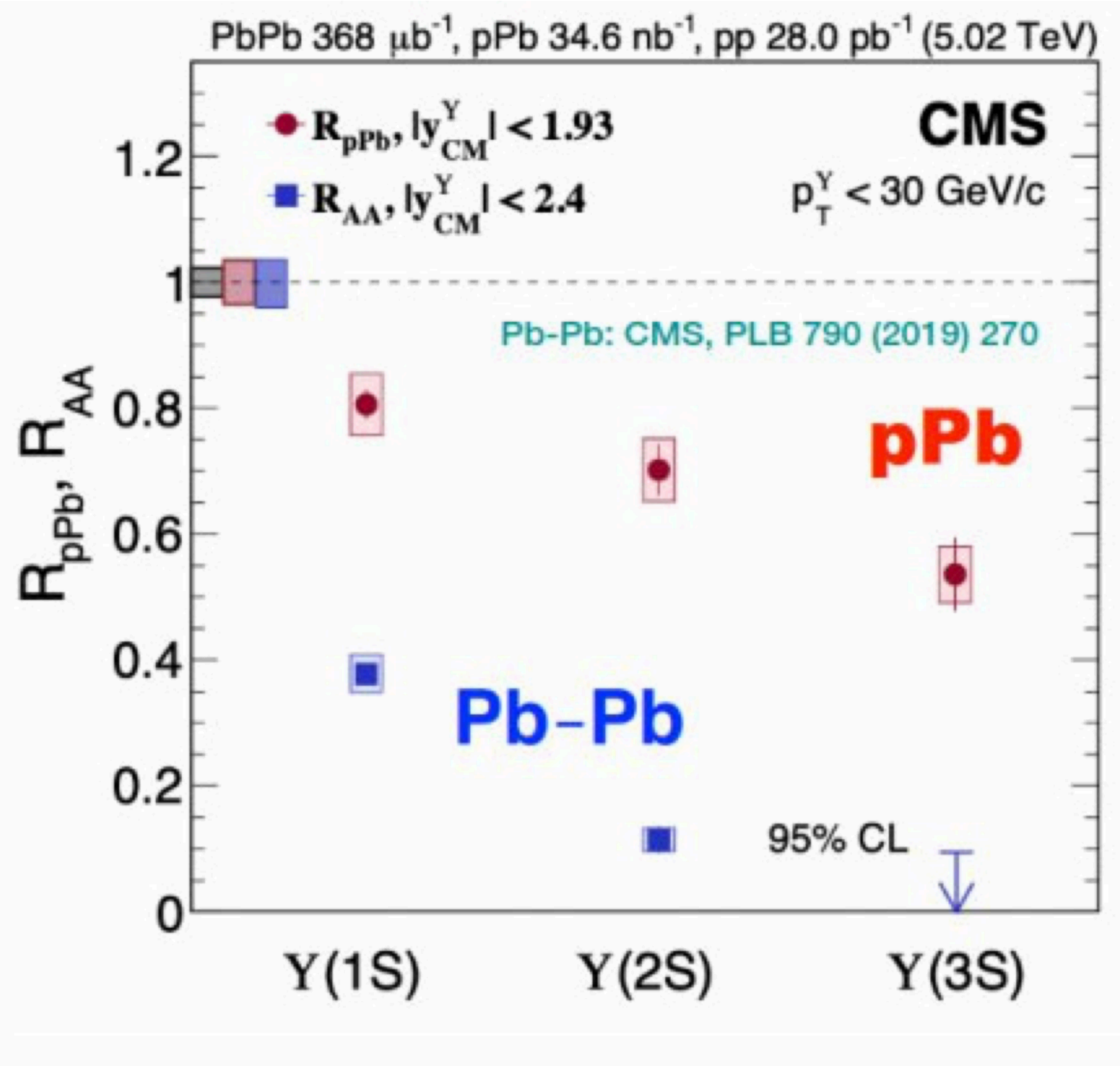
- Different sensitivity to the medium:
  $\Upsilon(1S)$: 1100 MeV;
  $\Upsilon(2S)$: 500 MeV
  $\Upsilon(3S)$: 200 MeV

- First measurement of suppression of three Υ states separately at RHIC
- $> 3\sigma$ difference for $\Upsilon(1S)$ and $\Upsilon(3S)$

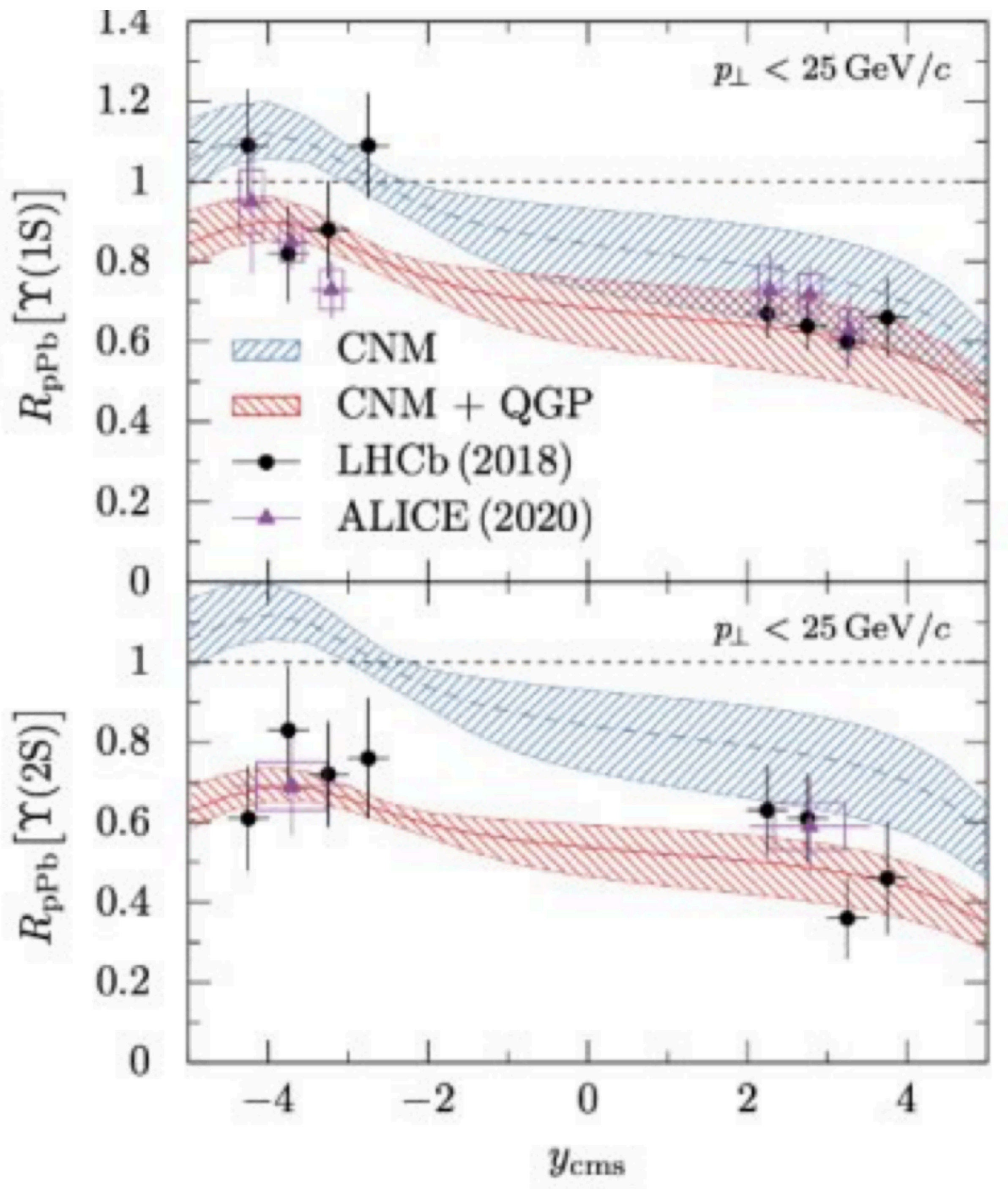
Bottomonium

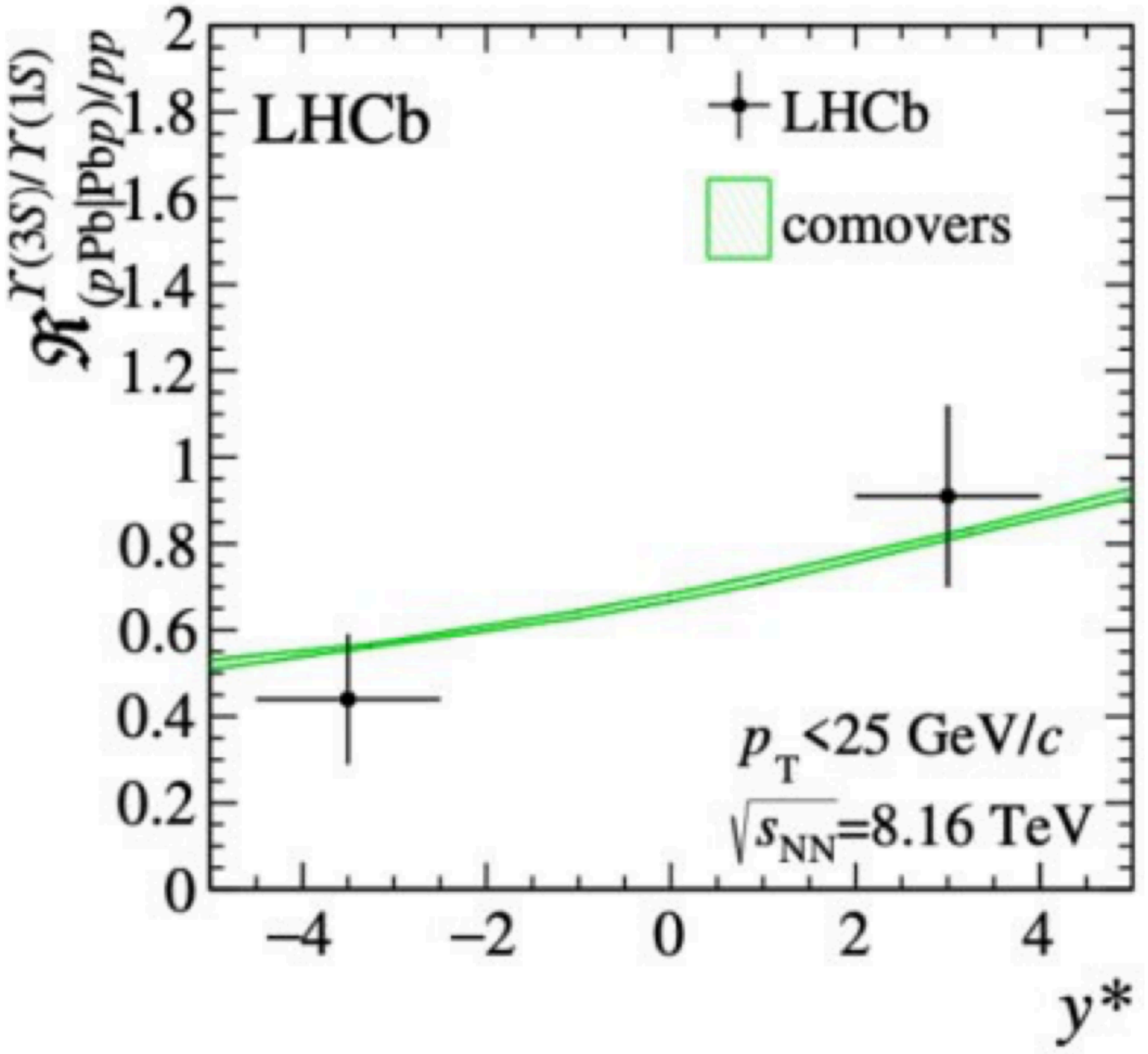
CMS. ALICE. LHCb

CMS. PLB 835, 137397 (2022)



Int.J.Mod.Phys.A, 35, 29, 2030016 (2020)

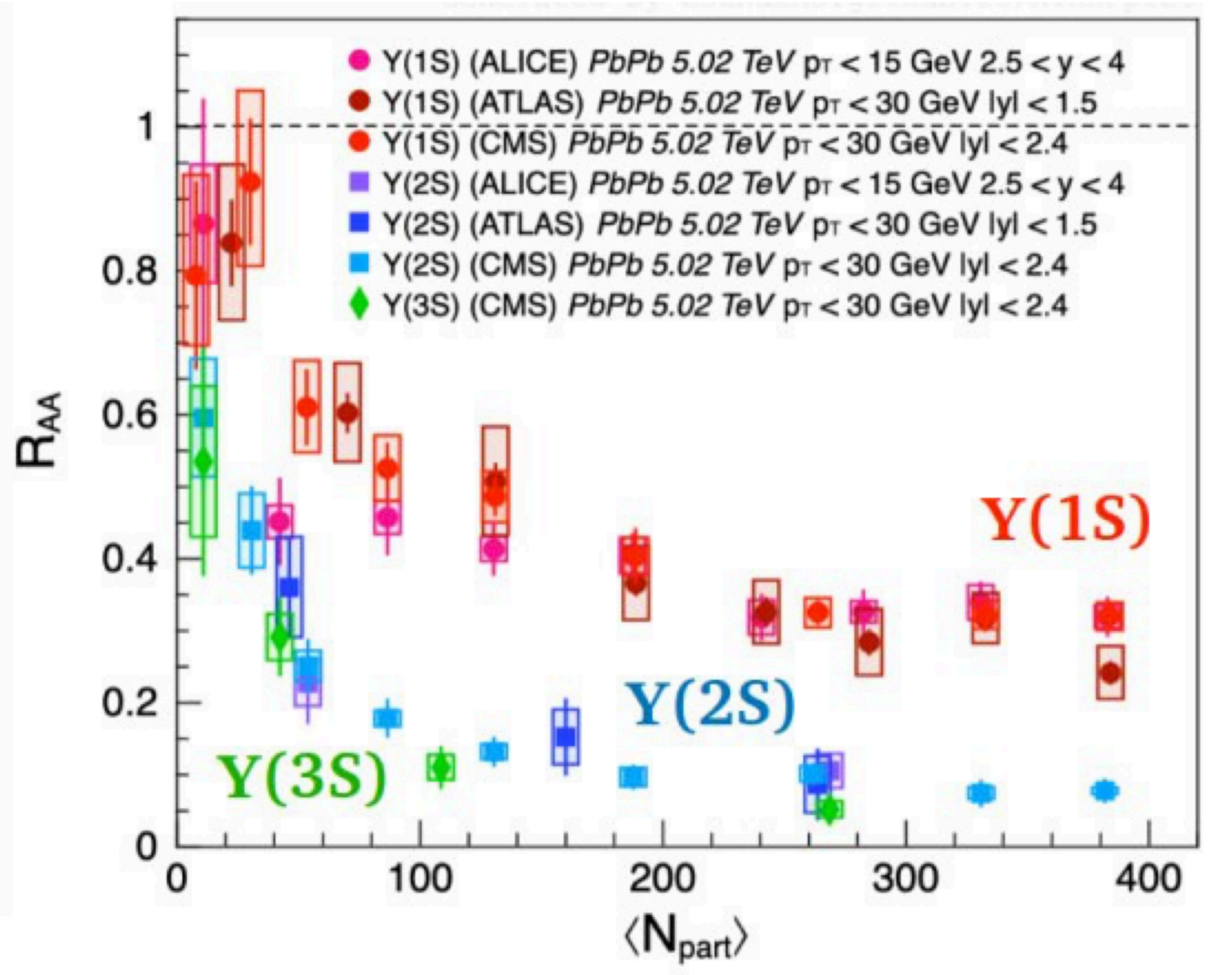




- Sequential suppression observed in p-Pb collisions with improved precision for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$
  → yet much less than in Pb+Pb collisions
- Suppression trend reproduced by PDF + comover breakup Model
- Hot-medium effects describe Υ suppression in p+Pb collisions as well

Bottomonium production

LHC. Pb+Pb



ALICE, PLB 822 (2021) 136579
ATALAS, PRC 107 (2023) 054912
CMS, arXiv:2303.17026

- Strong suppression vs centrality with sequential melting pattern:

$$R_{AA}\left(\Upsilon(1S)\right) > R_{AA}\left(\Upsilon(2S)\right) > R_{AA}\left(\Upsilon(3S)\right)$$

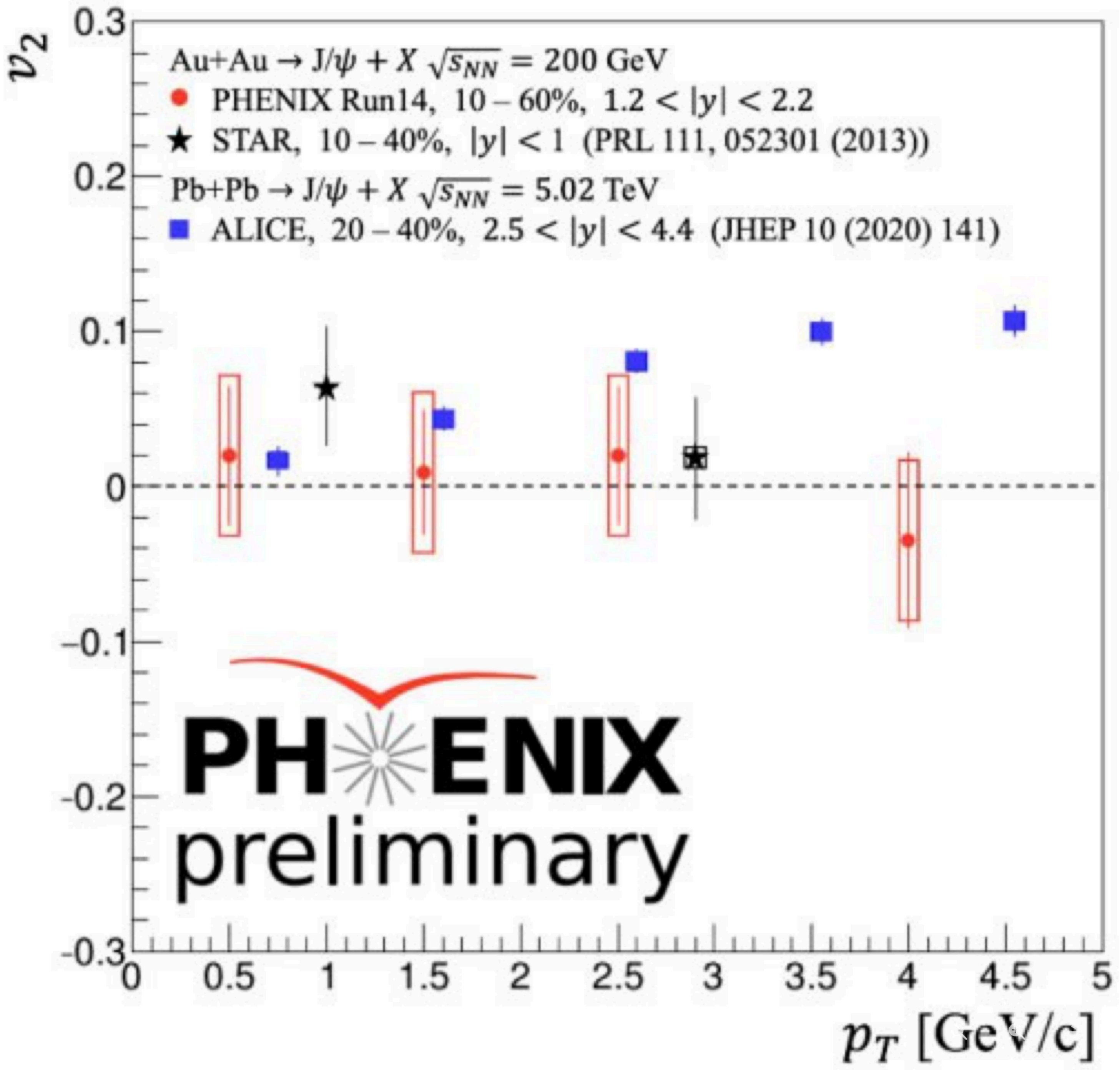
- Is bottomonium genuine thermometer of QGP?
  - Feed-down contribution (i.e. P-wave states → excited ϒ not measured)
  - Regeneration contribution
  - Cold nuclear matter effects?

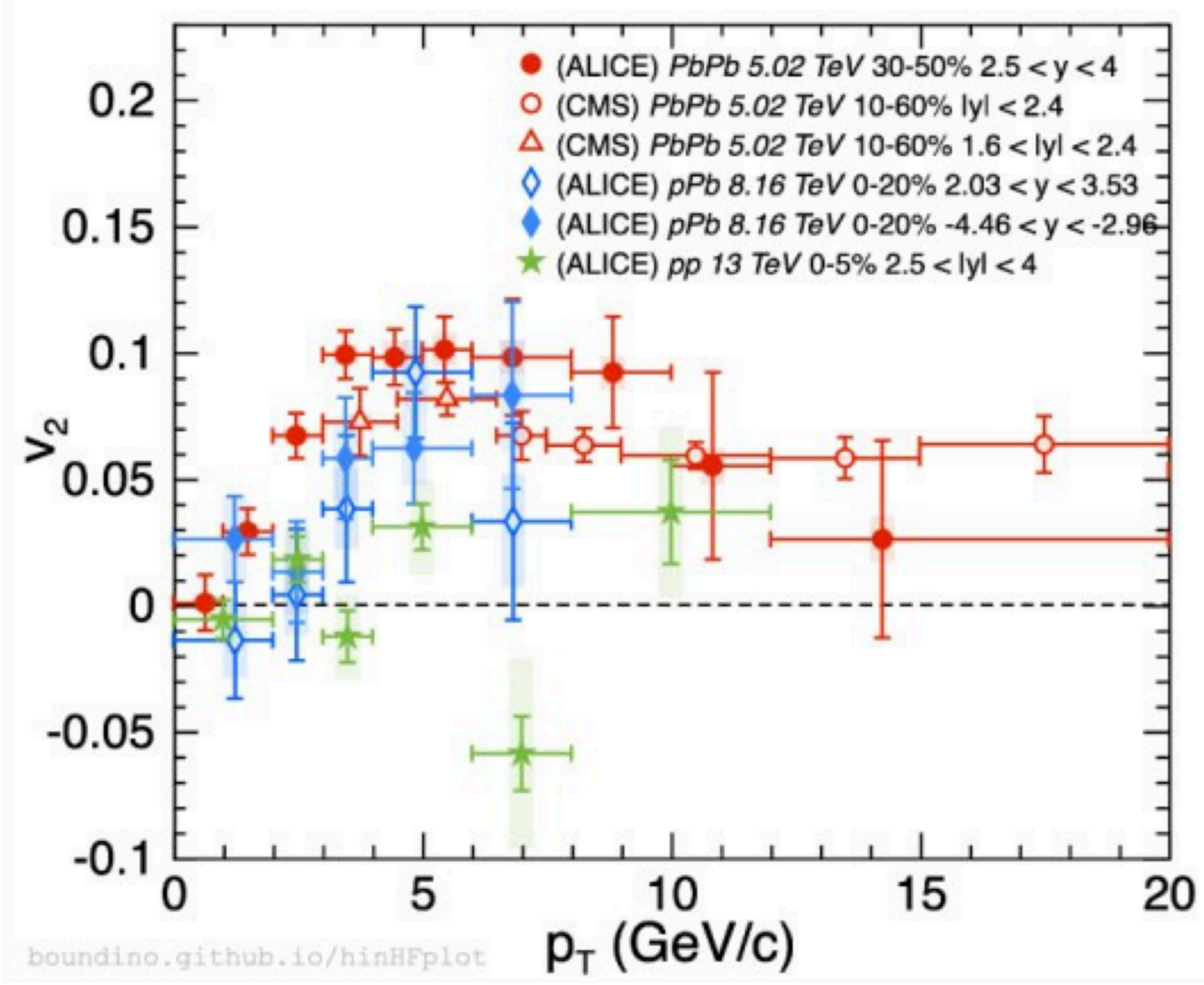
Quarkonium

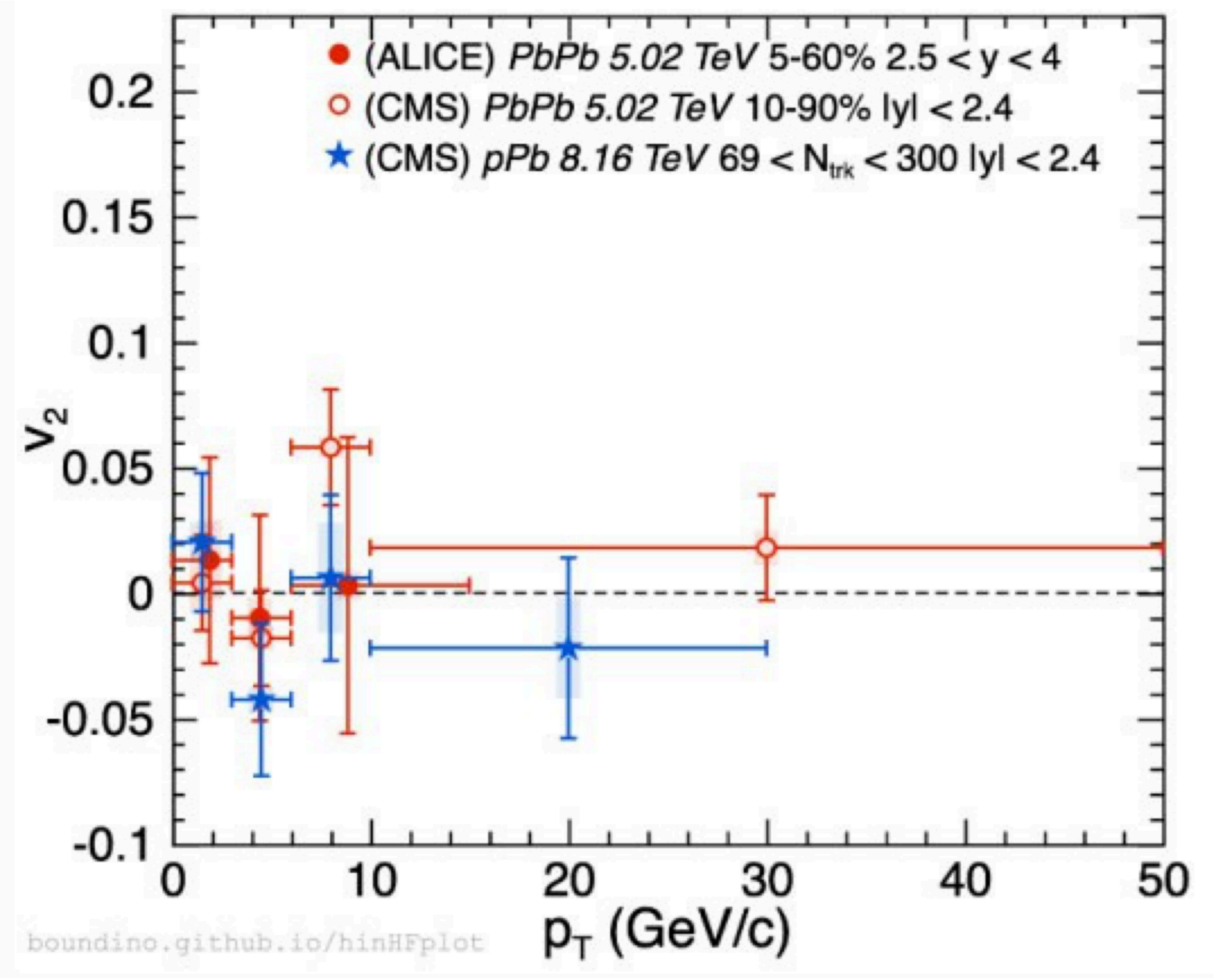
Elliptic flow measurements

INSTITUTE for NUCLEAR THEORY

Stony Brook University







STAR (central) and ALICE (forward) none-zero v_2, much smaller v_2 in the forward rapidity, ~ 0

- Open charm, none-zero v_2
- Final State Interactions
- J/ψ formation
  - lack of "recombination" in the forward rapidity?

- Good agreement in CMS and ALICE in various systems; without strong rapidity dependendence found in current precision
- J/ψ : Pb+Pb $v_2 \geq p$+Pb $v_2 > p + p$ $v_2 \sim 0$
- $\Upsilon(1S)$: Pb+Pb$v_2 \sim p +$ Pb $v_2 \sim 0$

SUMMARY

- Baryon enhancement effect is seen even in small collision systems at RHIC
- Strangeness enhancement is observed at RHIC in large system collisions and strangeness production increases with particle $dN_{ch}/d\eta$ at LHC (even in charm sector)
- In heavy ion collisions clear mass ordering of suppression and flow of open charm leptons is observed at both RHIC and LHC
- Baryon enhancement is observed at LHC in charm sector?
- For J/ψ production - interplay of regeneration and suppression at LHC
- $\psi(2S)$ tends to be suppressed even in small system collisions at RHIC and at LHC
- Sequential dissociation of $\Upsilon(nS)$ states in medium at RHIC and LHC with similar pattern

SUMMARY

“Heavy Ion Physics in the EIC Era”

- LHC Run 3 program started and smoothly ongoing
  → much larger data sample expected with upgrade detectors
- sPHENIX is collecting data in *p*+*p* collisions - future Au+Au
- STAR recorded large sample of isobar collisions $\sqrt{s_{NN}} = 200$ GeV in 2018
  → great opportunity to study the systemsize dependence

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THANK YOU FOR YOUR ATTENTION!