A journey through the experimental highlights on heavy-ion physics

QCD@Work - International Workshop on QCD - Theory and Experiment

27 June 2022
Auditorium del Museo Provinciale
"Sigismondo Castromediano" - Lecce (Italy)

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UNIVERSITÀ DEGLI STUDI DI SALERNO

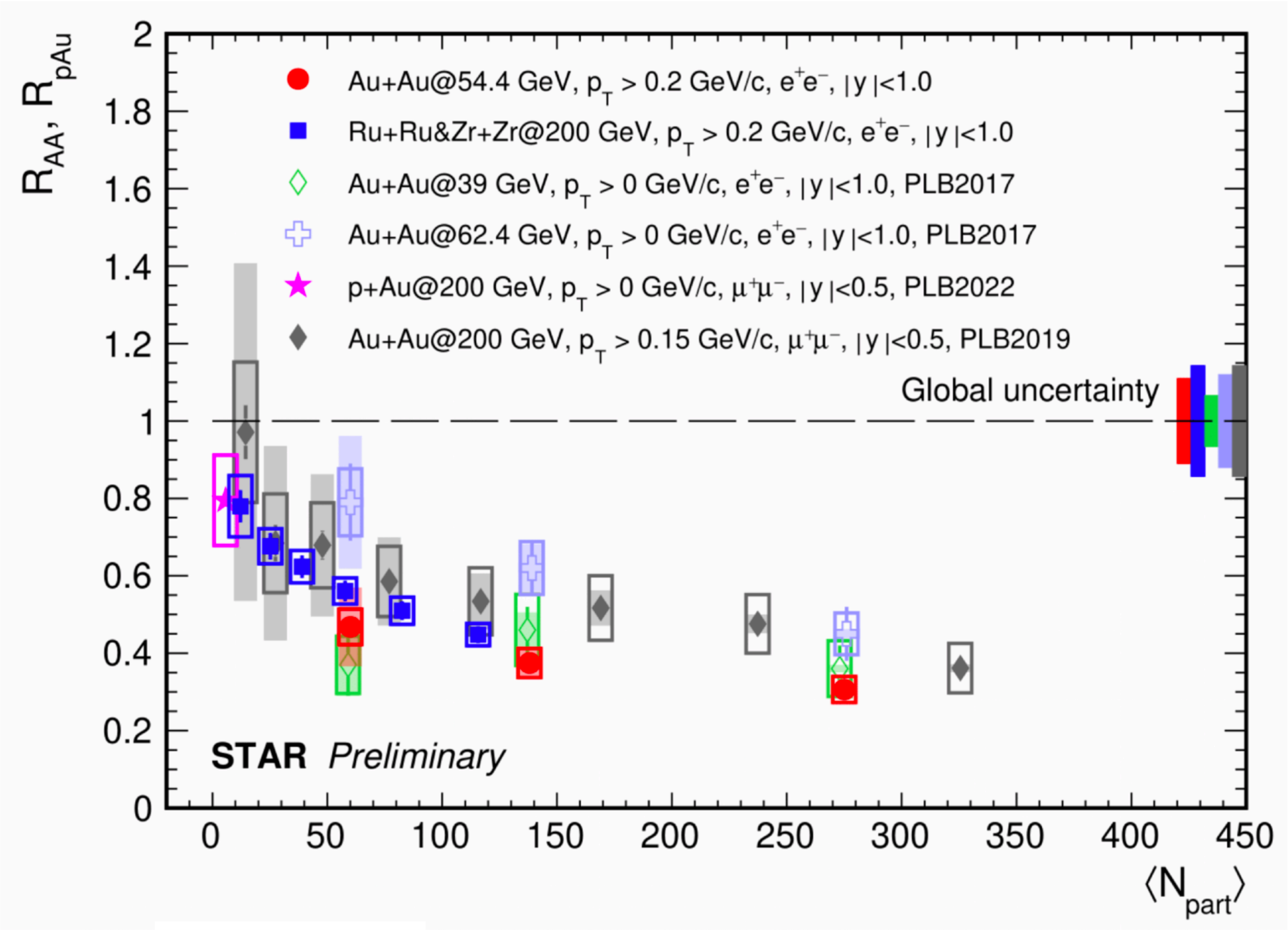
INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI NAPOLI
Gruppo Collegato di Salerno

Outline

- Heavy quarkonia
- Heavy flavor
- Light flavor
- Direct photons and dileptons

Heavy Quarkonia

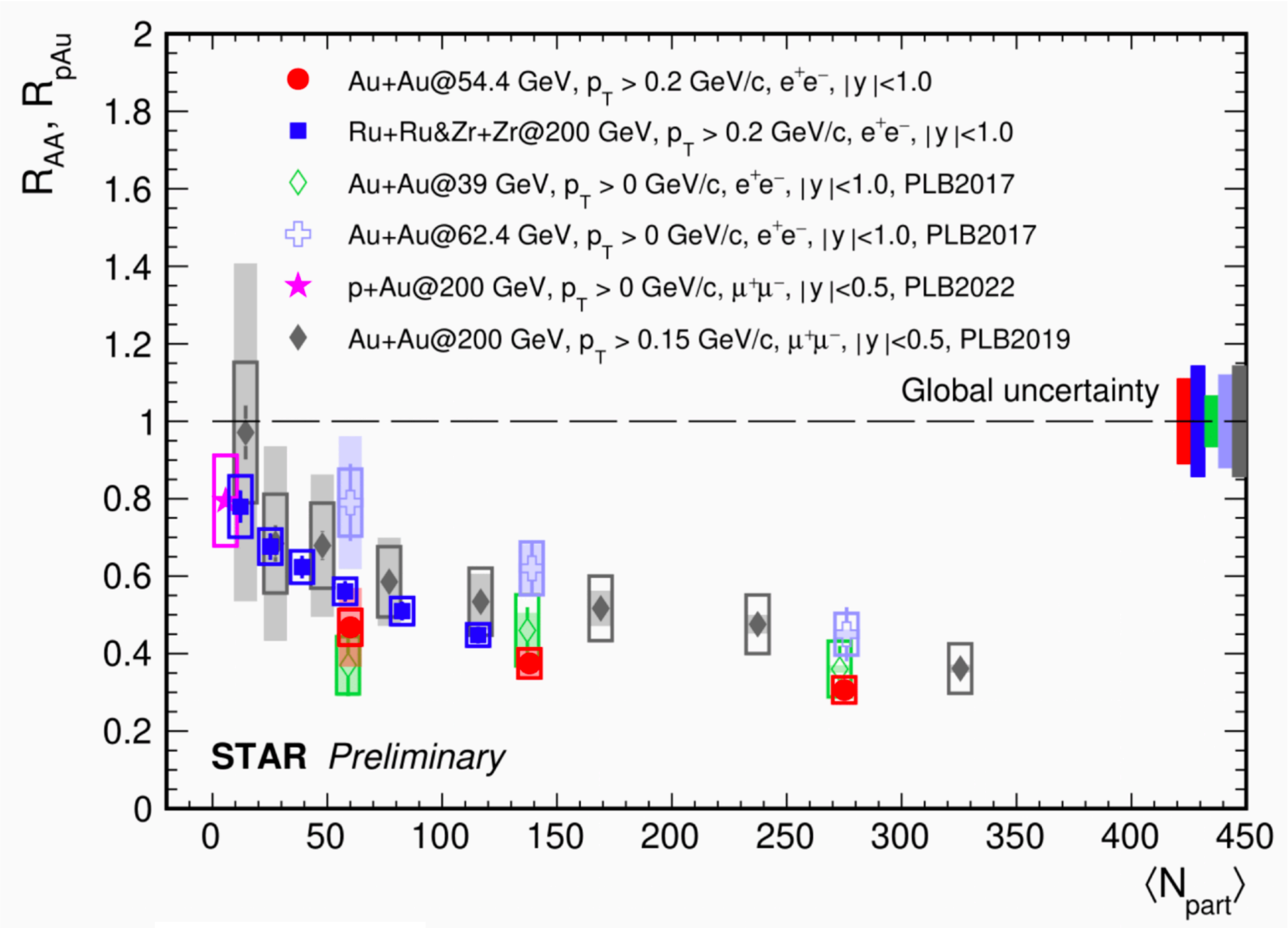
J/ψ R_{AA}: RHIC vs. LHC

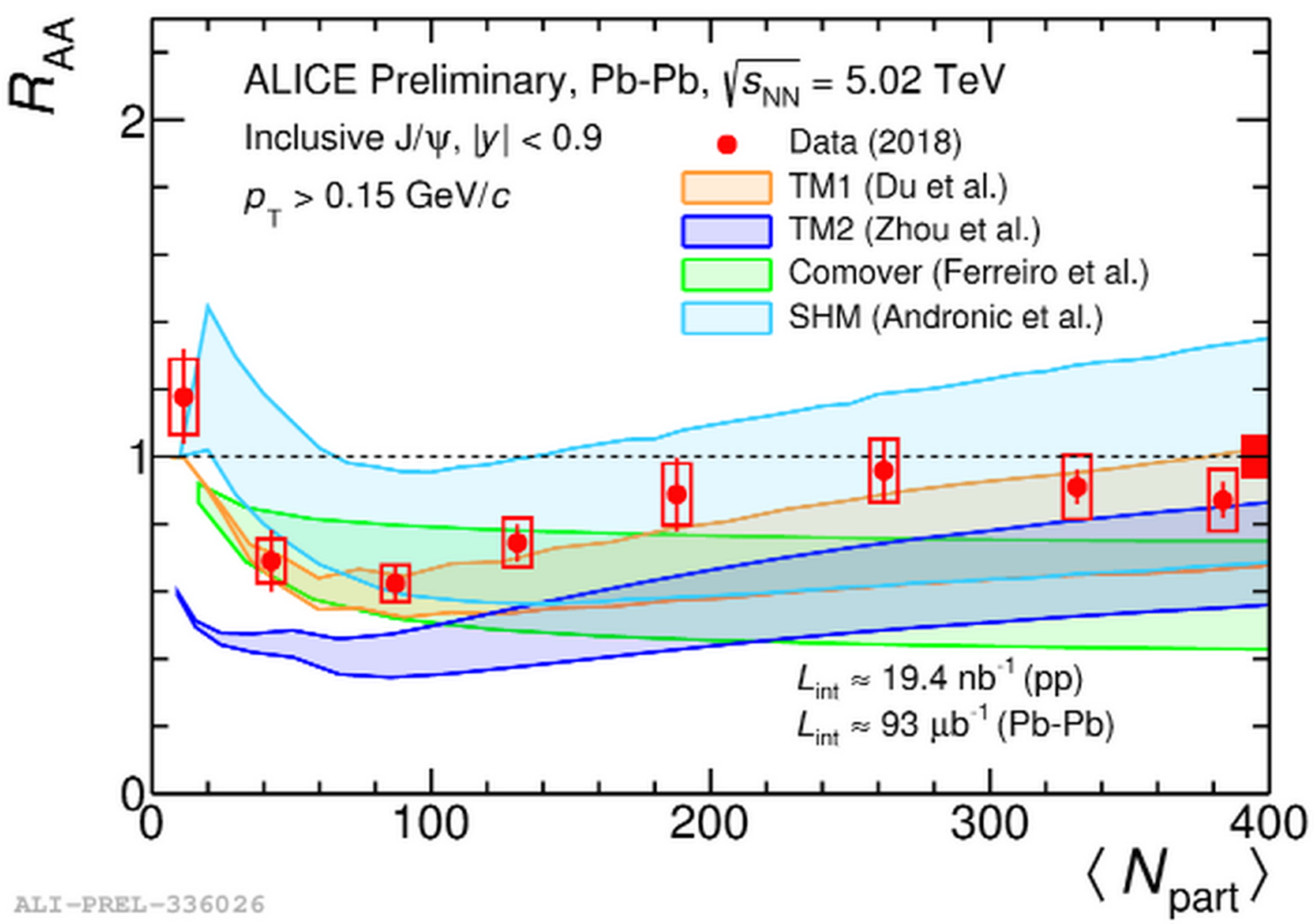


At RHIC:

- R_{AA} of inclusive J/ψ at mid-rapidity decreases with $\langle N_{part} \rangle$ at RHIC energy
- Almost independent of collision system and energy

J/ψ R_{AA}: RHIC vs. LHC





At RHIC:

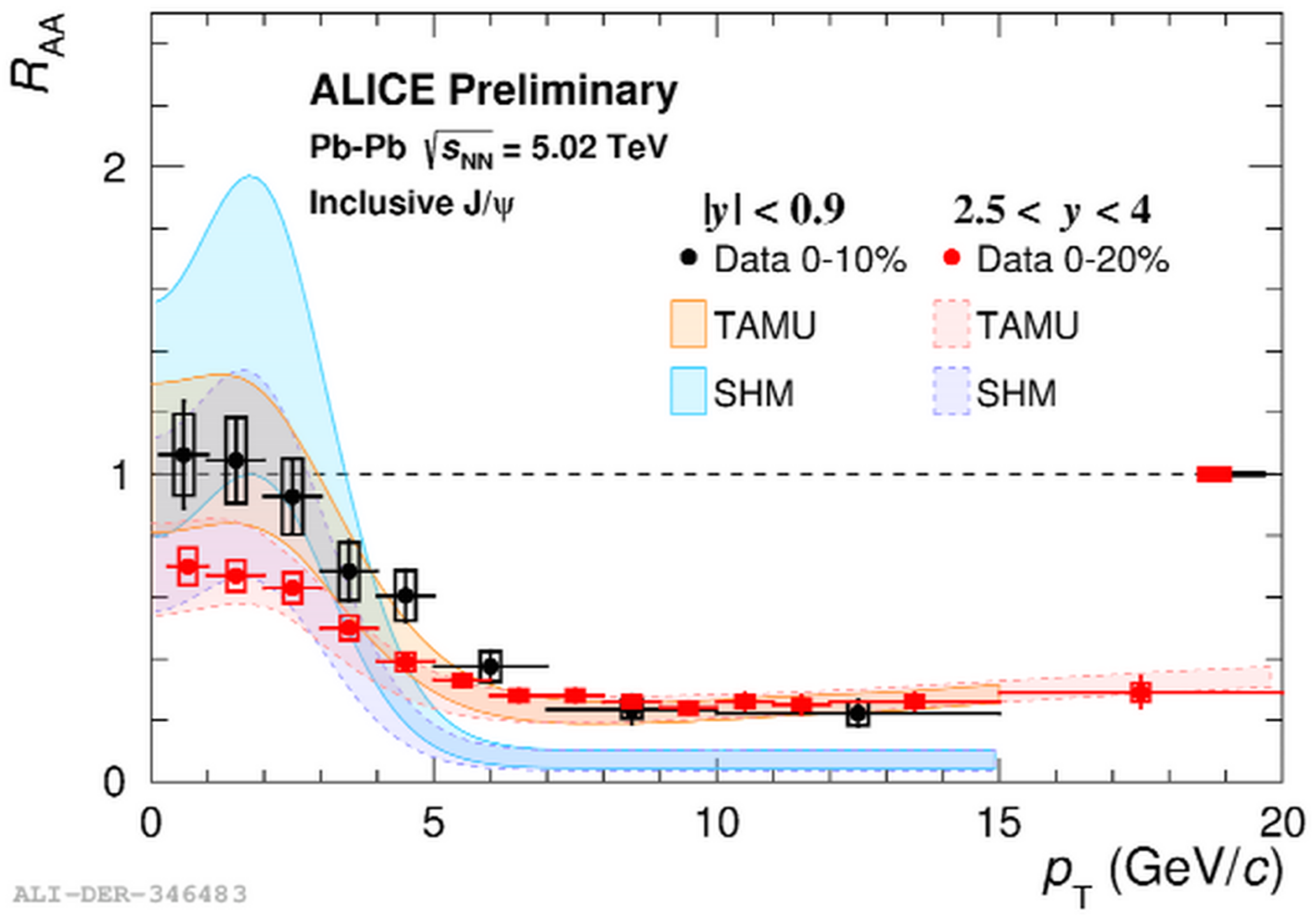
- R_{AA} of inclusive J/ψ at mid-rapidity decreases with $\langle N_{part} \rangle$ at RHIC energy
- Almost independent of collision system and energy

At LHC: in central Pb-Pb collisions ~ 1 $c\bar{c}$ pair per fm^3

→ enhancemnt of the J/ψ R_{AA} with $\langle N_{part} \rangle$ as a sign of $c\bar{c}$ recombination

Svetitsky PRD37 (1988) 2484, PBM & Stachel PLB490 (2000) 196, Thews et al PRC63 (2001) C549005, Andronic et al, PLB 652 2007 259

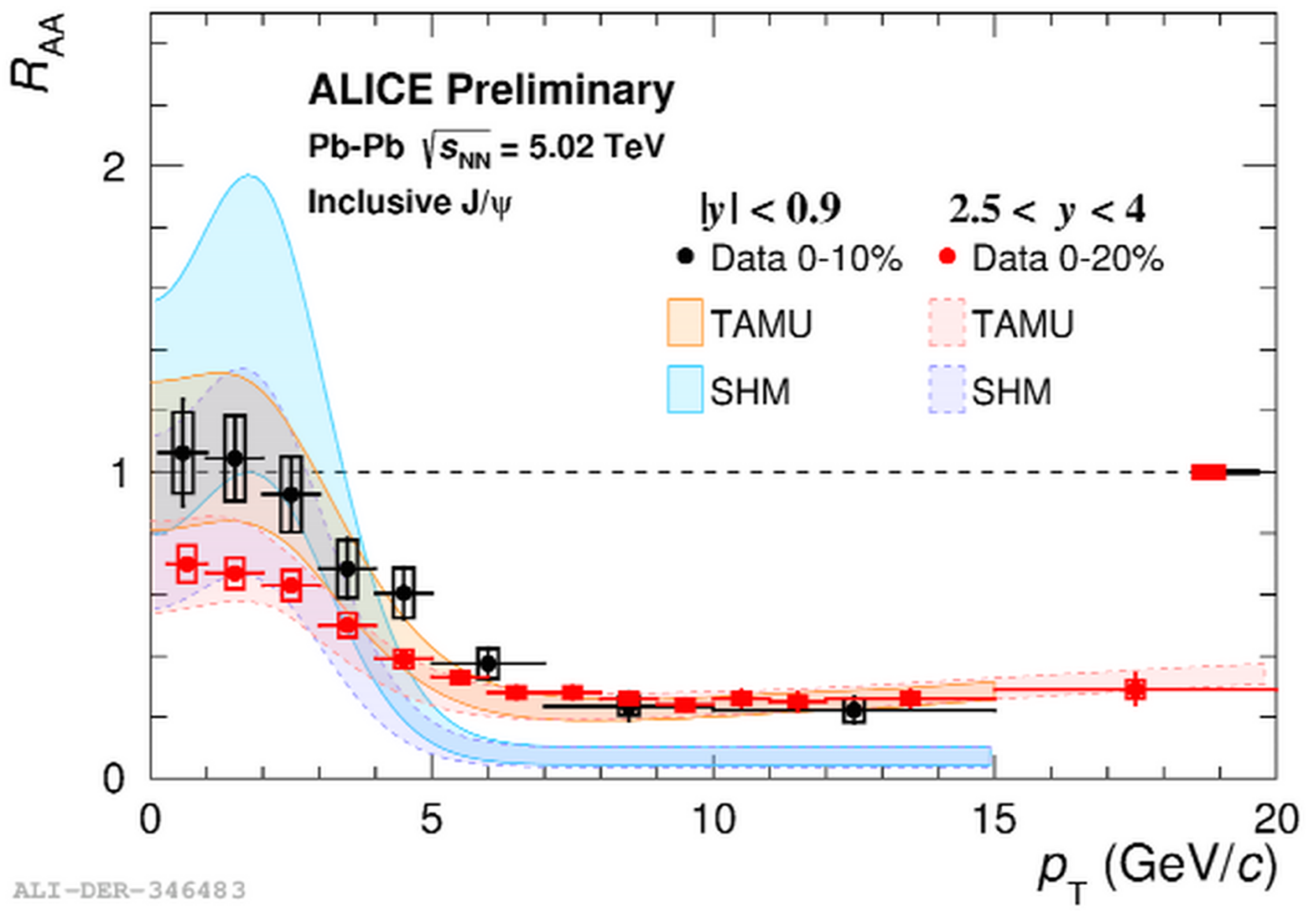
J/ψ R_{AA} vs. p_T

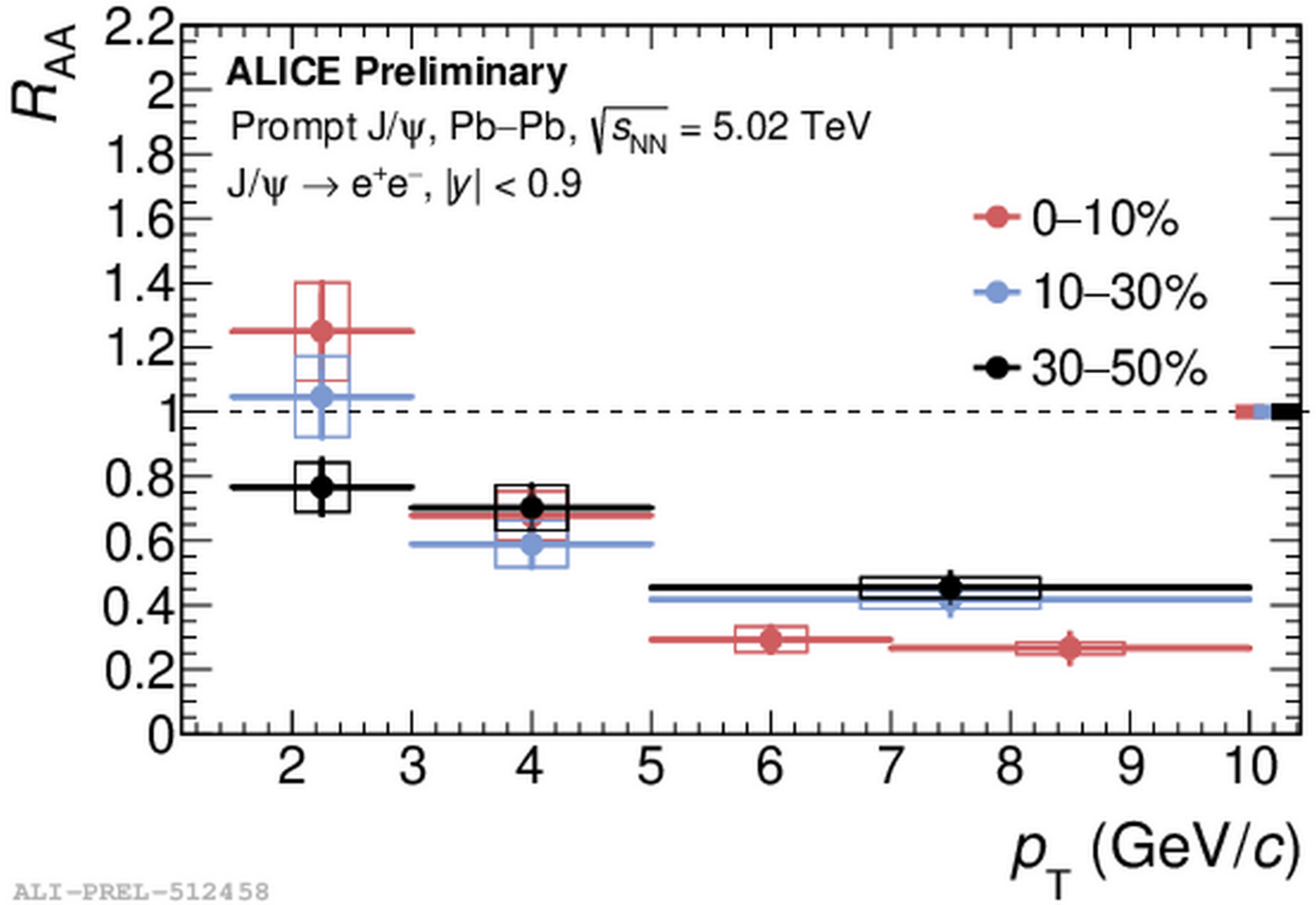


R_{AA} of inclusive J/ψ at LHC:

- Rise at low p_T (stronger effect at midrapidity): **decisive signature of recombination**
- Models that include regeneration (SHMc and TAMU) describe the data at low p_T

J/ψ R_{AA} vs. p_T





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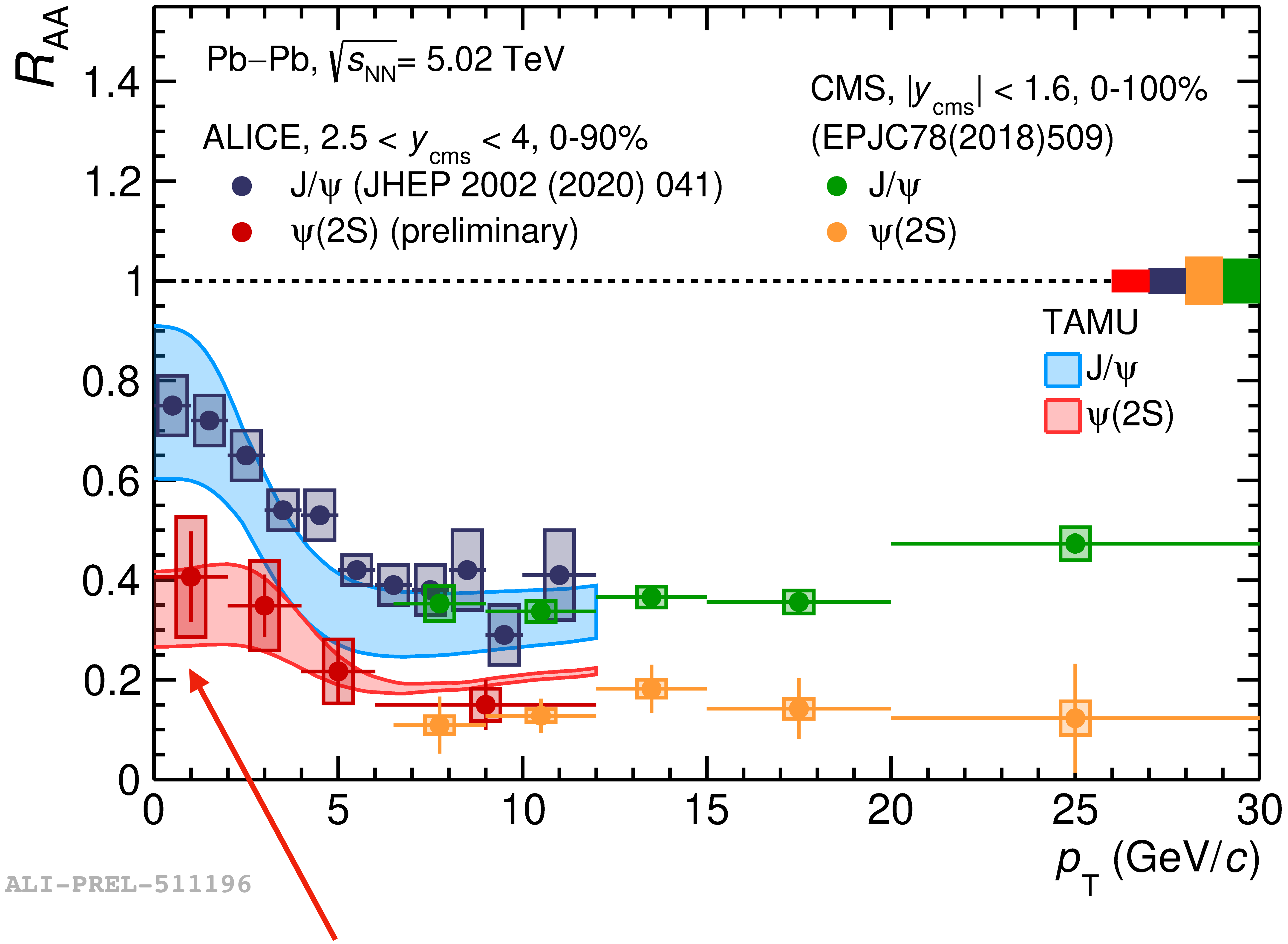
Rise of R_{AA} at low p_T as an effect of recombination confirmed by prompt J/ψ
> clear centrality dependence

Sequential suppression of charmonia



ψ(2S) measurement extended to p_T = 0

Stronger suppression for ψ(2S)
→ sequential suppression of charmonia

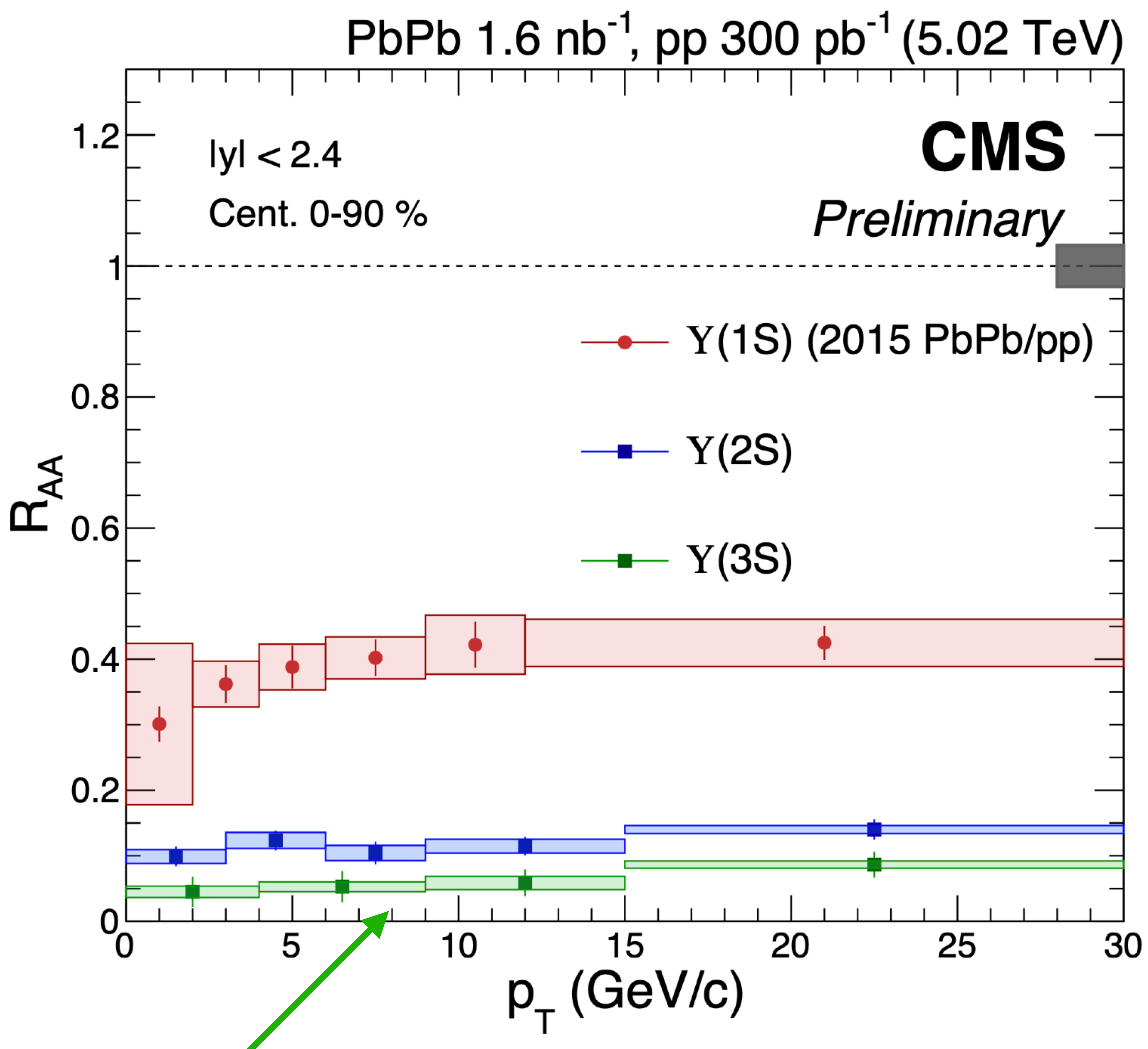
ψ(2S) R_{AA} increases going to lower p_T

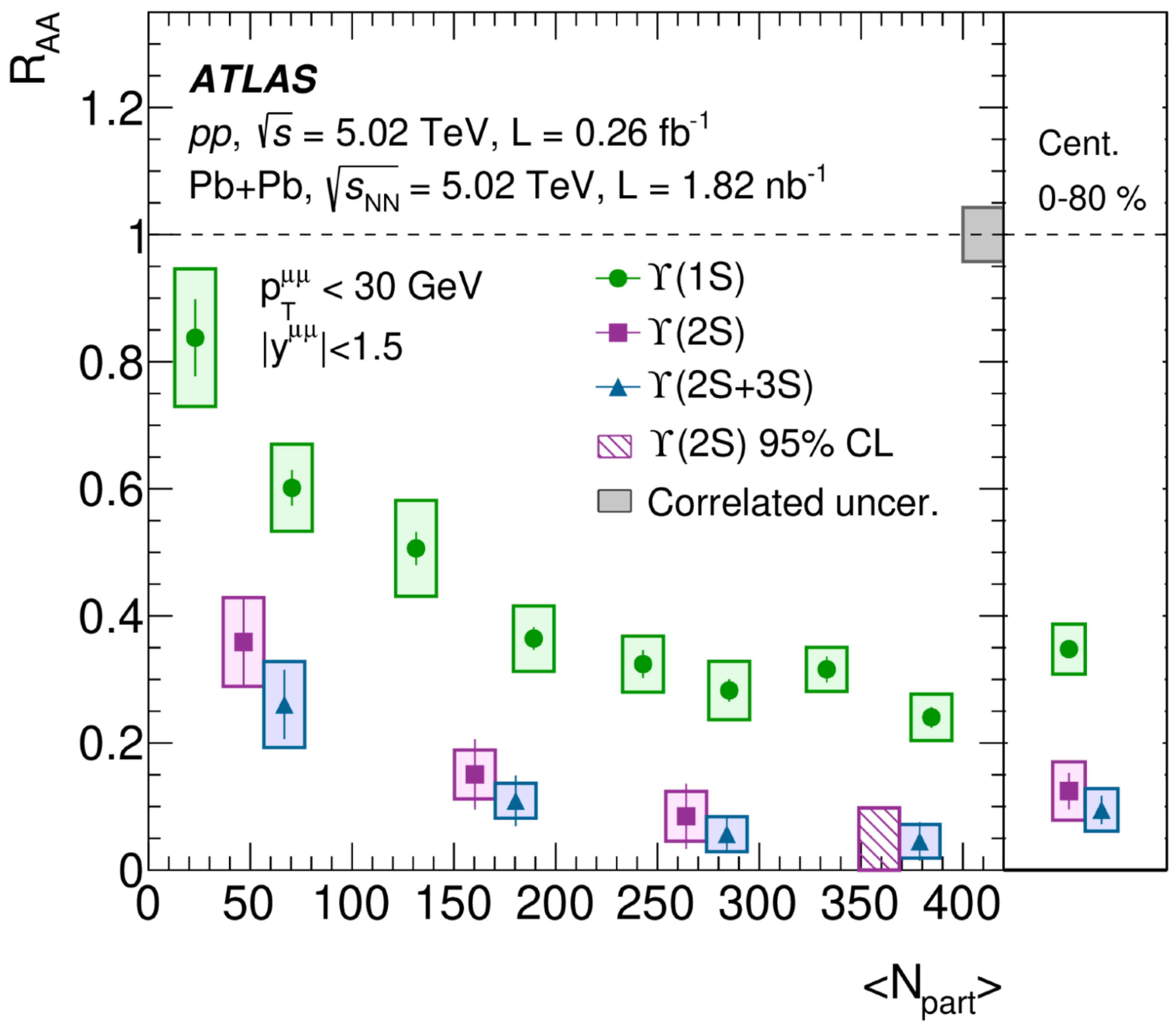
- Qualitatively similar to J/ψ
  → ψ(2S) production via $c\bar{c}$ recombination?

- p_T dependence of R_{AA} reproduced by TAMU

  X. Du and R. Rapp, Nucl. Phys. A943 (2015)

Sequential suppression of bottomonia

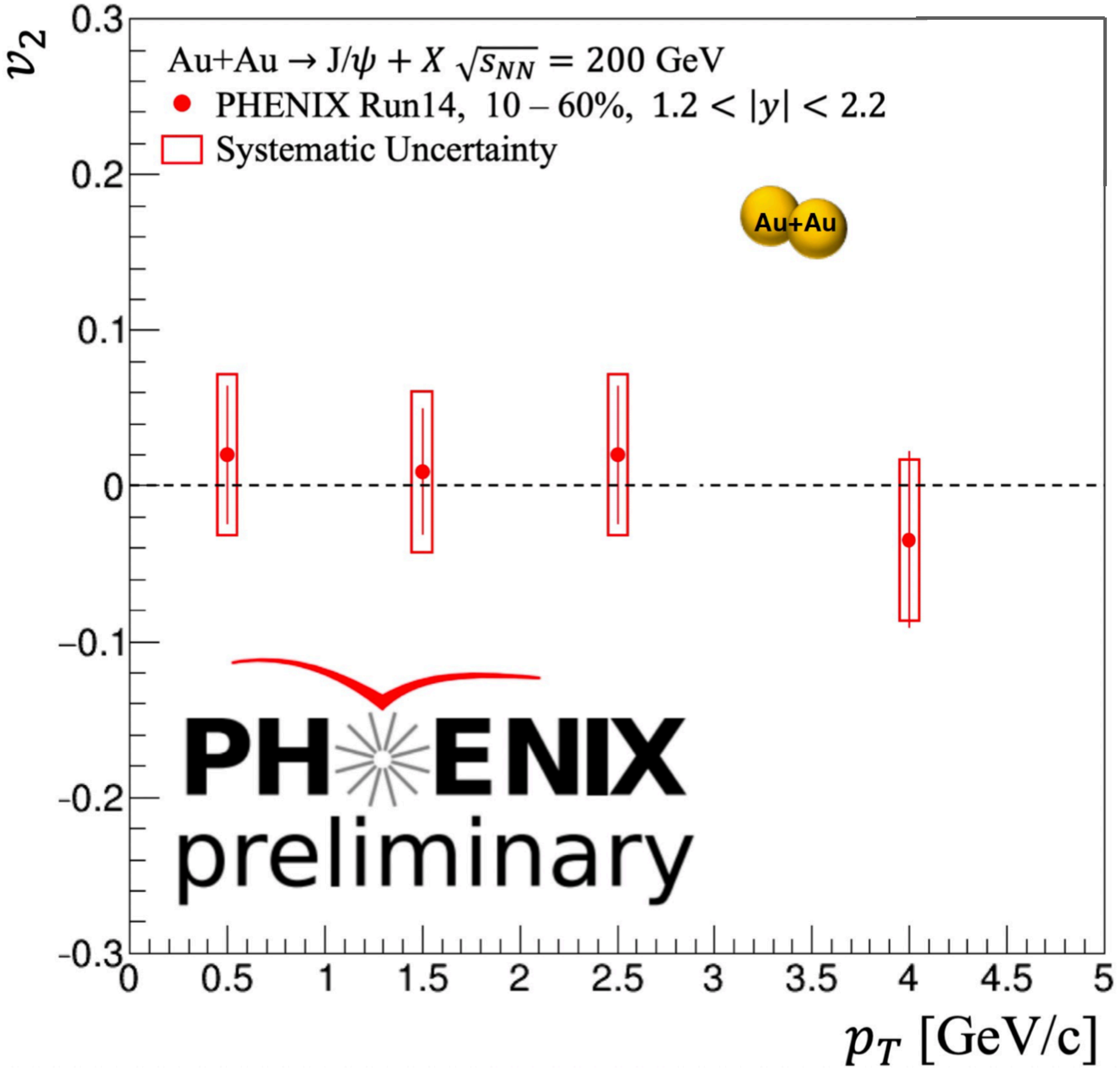


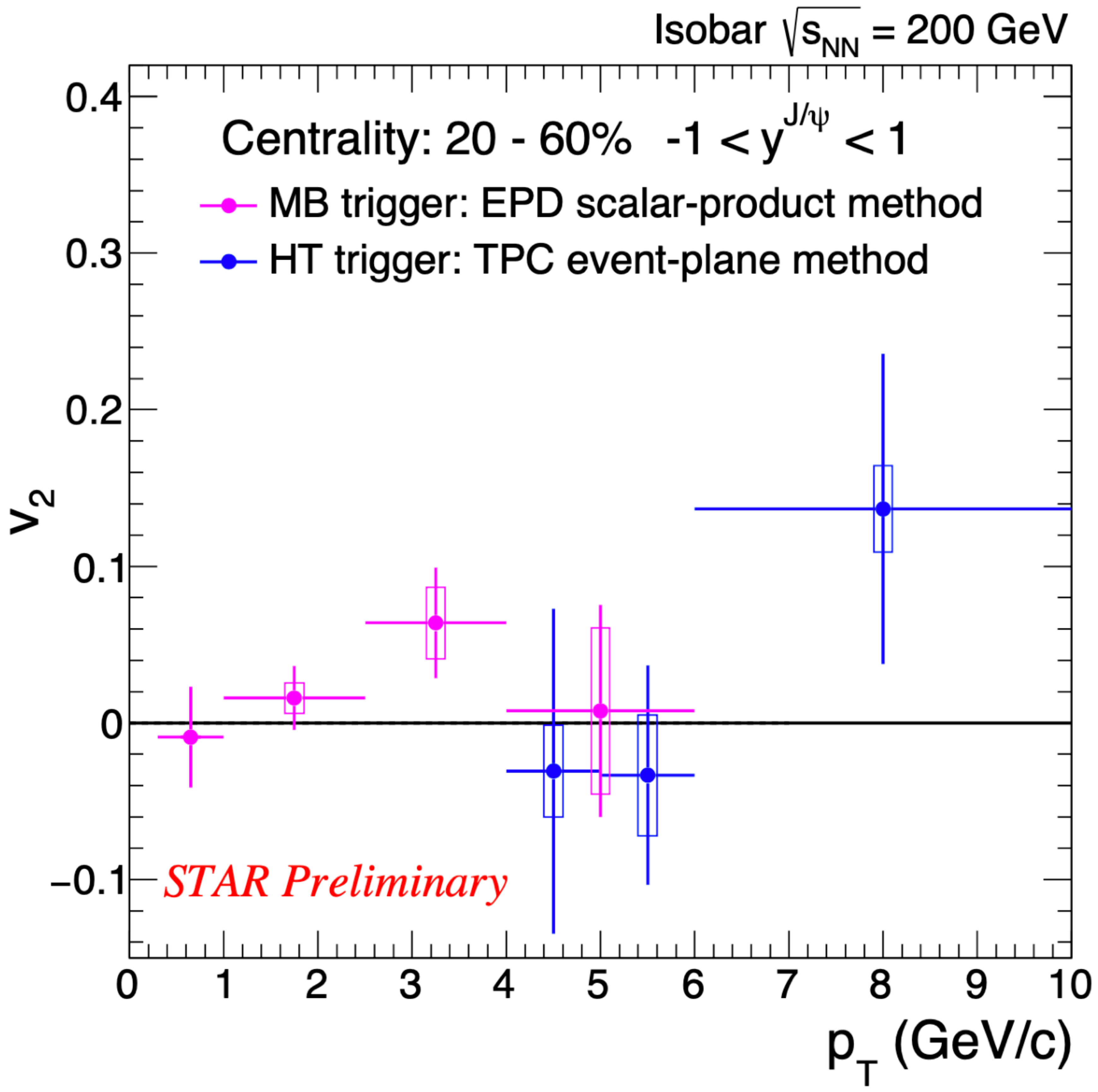


First observation of Y(3s) in Pb-Pb collisions by CMS

- Sequential suppression of $\Upsilon(b\bar{b})$ states
- Stronger suppression in more central collisions (ATLAS)

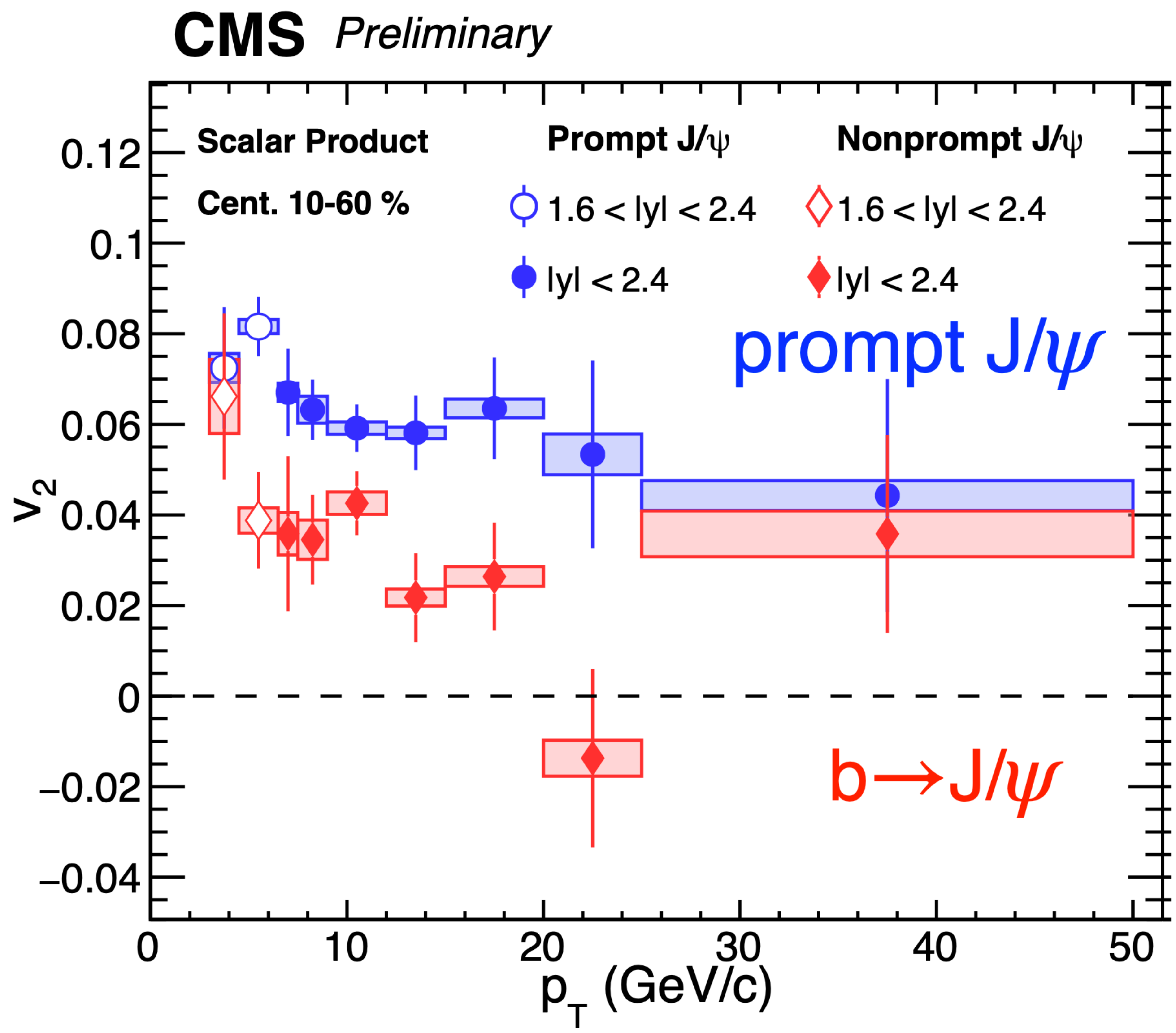
J/ψ elliptic flow at RHIC





- Elliptic flow (v_2) of inclusive J/ψ consistent with zero at "forward" and midrapidity
- Consistent with picture emerged with R_{AA} at RHIC energy
  → absence of significant $c\bar{c}$ recombination effects
  → v_2 of $c\bar{c} \approx 0$ (early production)

Charmonia v_2: prompt vs. non-prompt

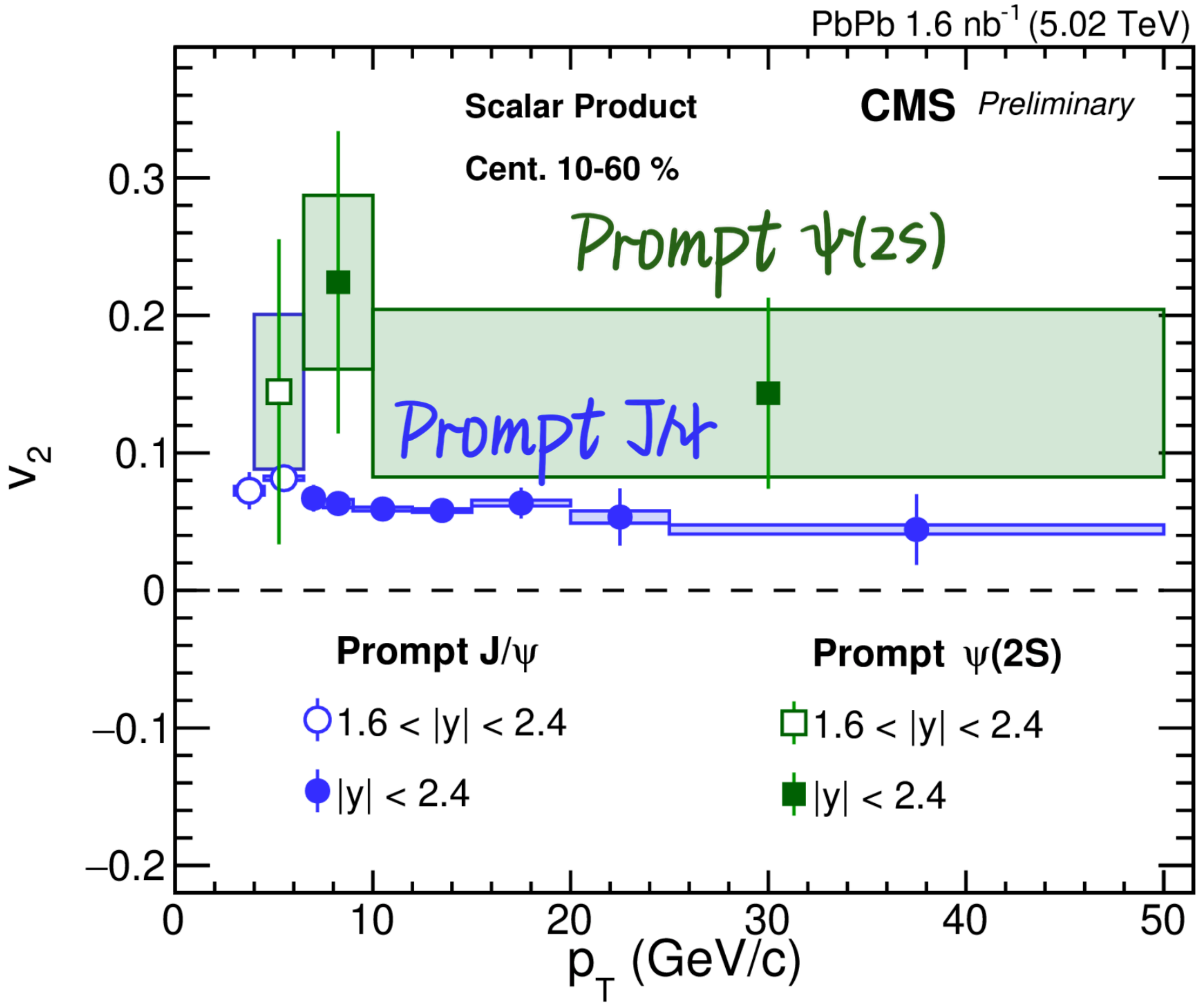


Prompt J/ψ: Significant v_2 up to high p_T

Non-prompt J/ψ:

- lower v_2 than prompt J/ψ
- faster decrease with increasing p_T

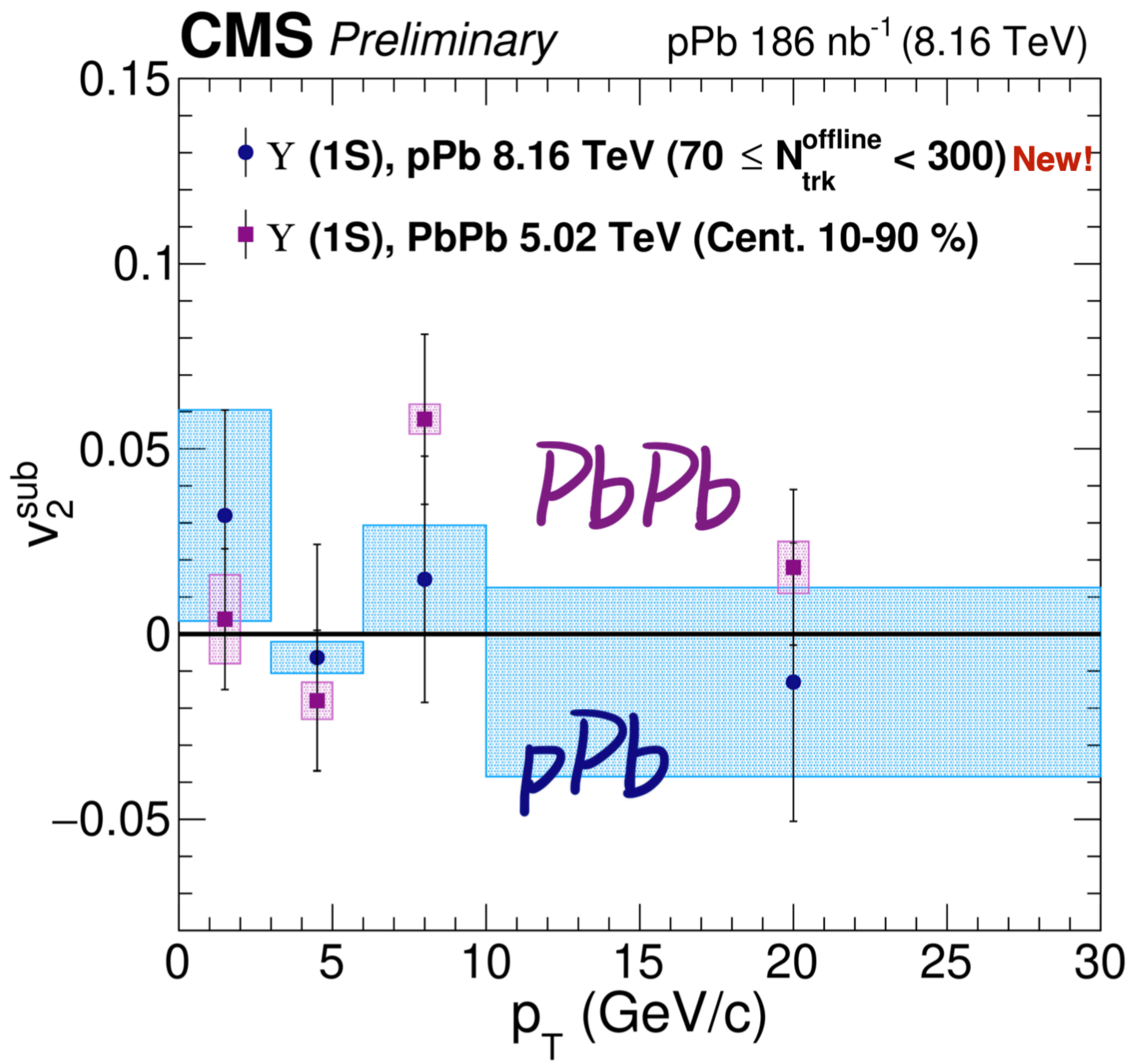
Prompt ψ(2S) v_2 vs. prompt J/ψ v_2



Hint of larger v_2 of prompt ψ(2S) wrt prompt J/ψ

→ Later regeneration of ψ(2S) than J/ψ?
arXiv:1504.00670 [hep-ph]

Bottomonium v_2



Elliptic flow of Υ(1S) measured both in Pb-Pb and high-multiplicity p-Pb collisions by CMS

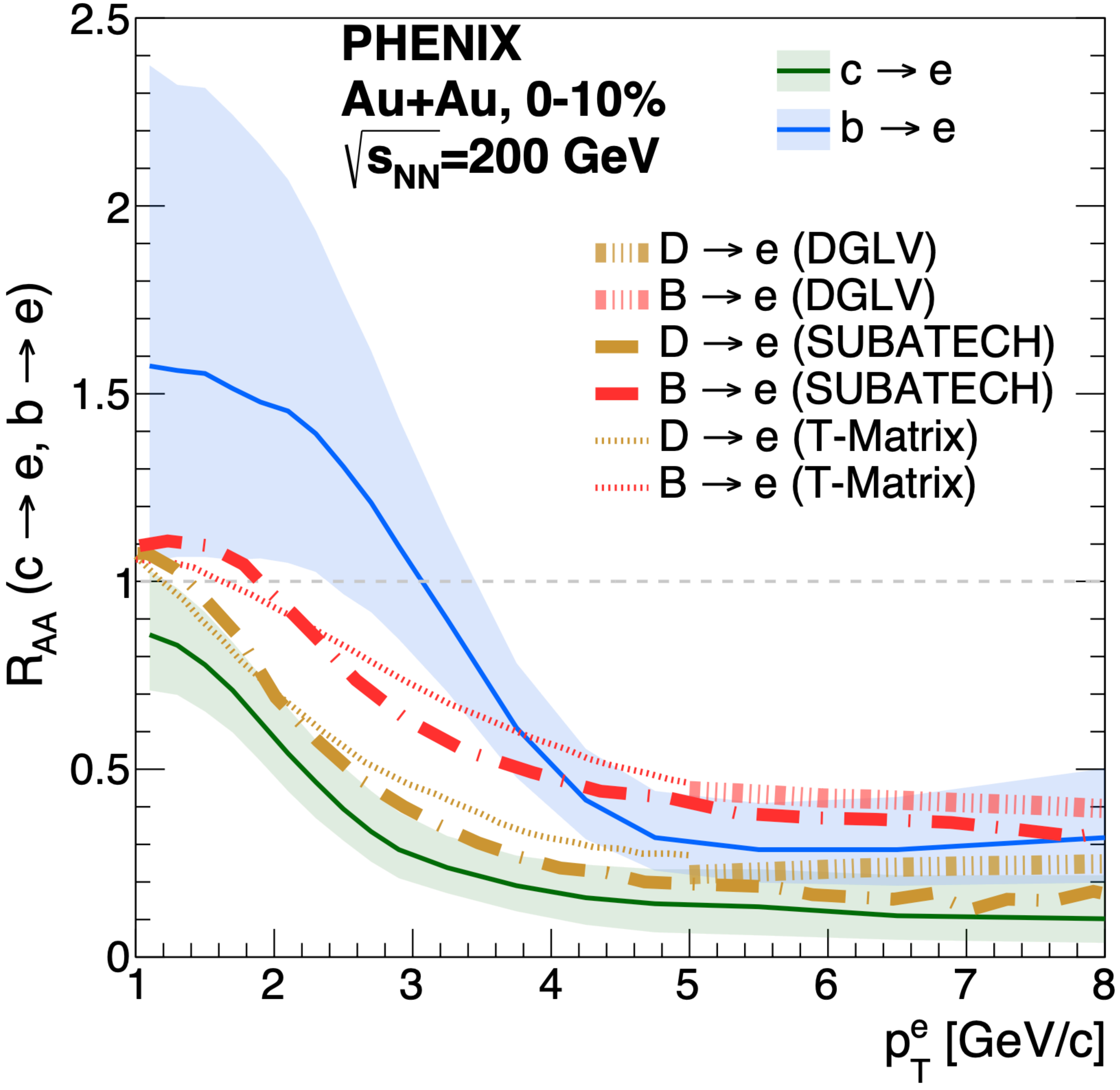
> consistent with zero!

v_2 of b quark ≈ 0 → insufficient thermalization due to large mass?

Heavy Flavor

R_{AA} of charm and bottom

arXiv:2203.17058 [nucl-ex]



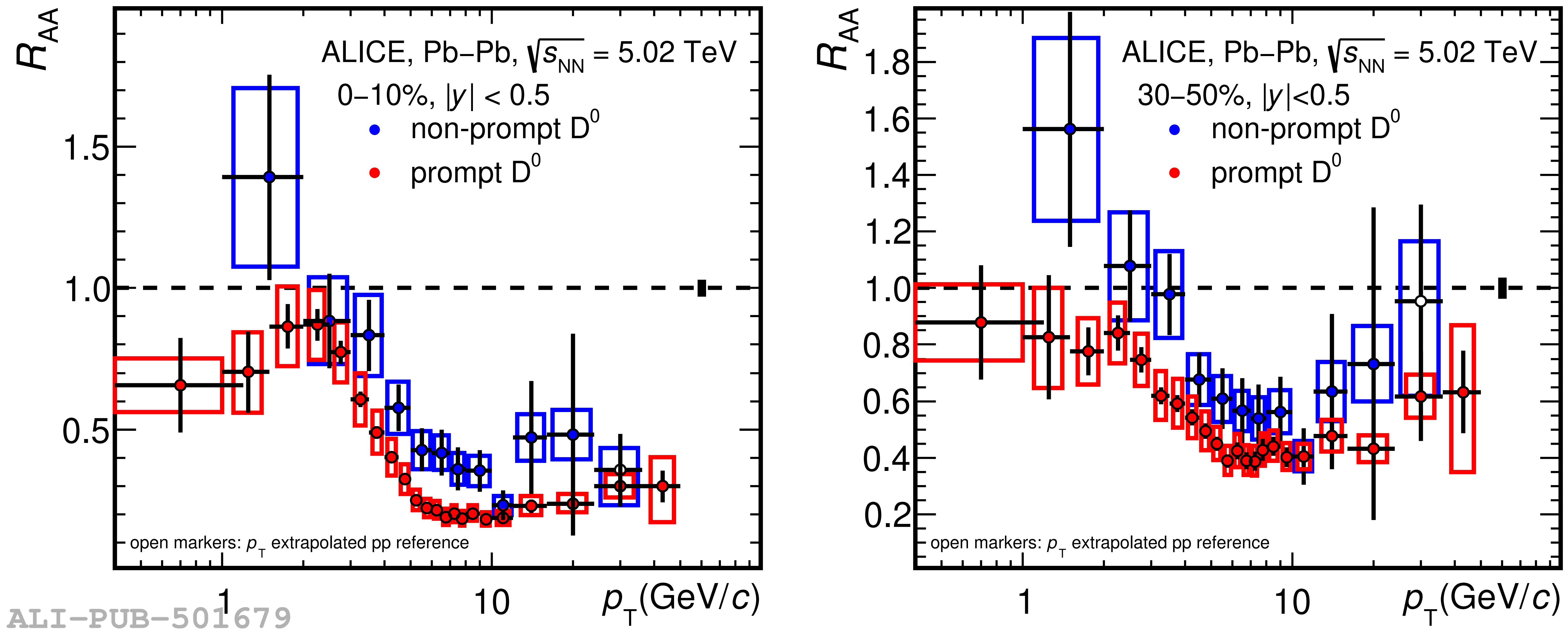
Bottom shows less suppression than charm at RHIC

Models give a fairly good description of the data

- all p_T for **charm**
- p_T > 4 GeV/c for **bottom**

R_{AA} of prompt and non-prompt D^0

arXiv:2202.00815 [nucl-ex]



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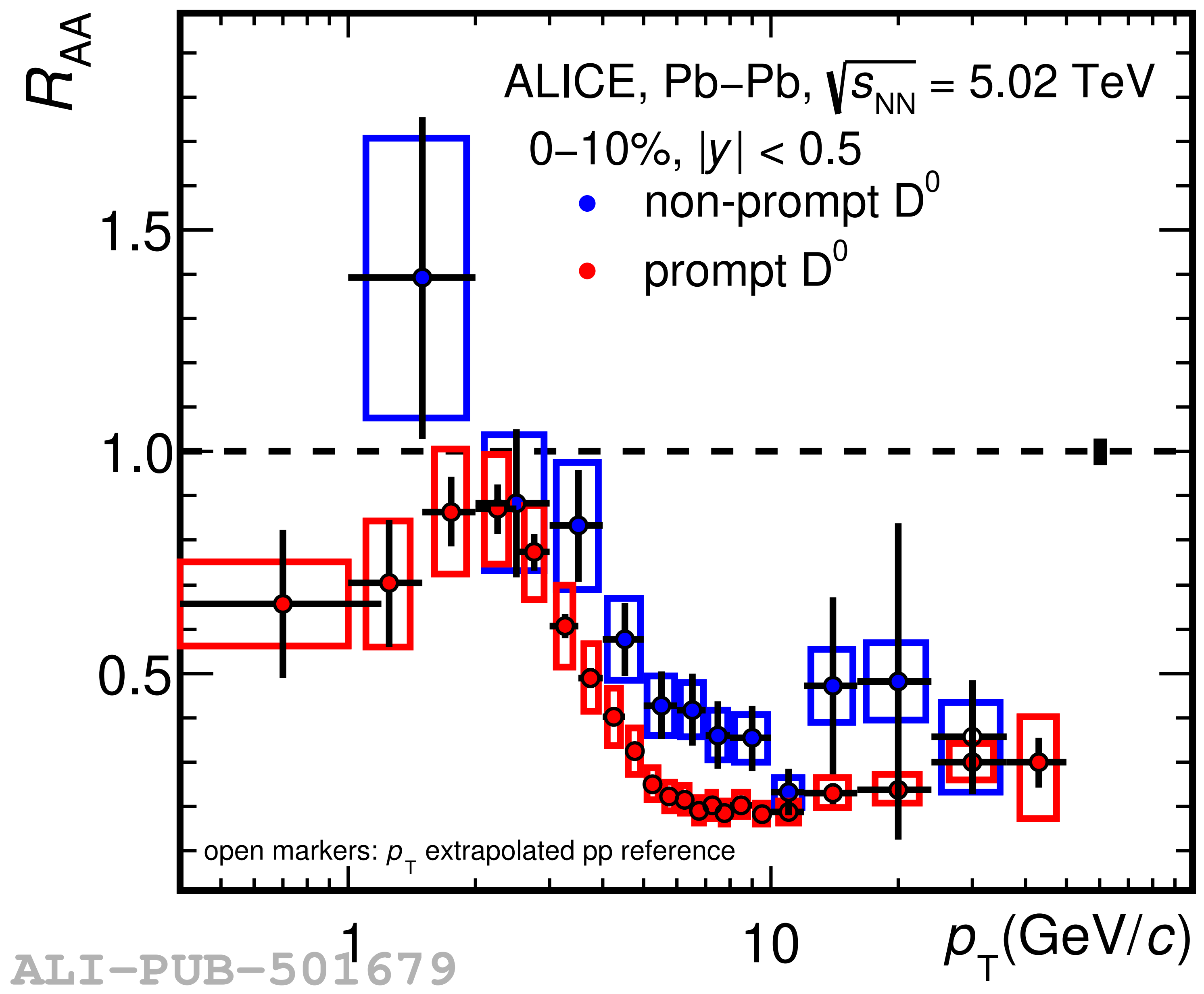
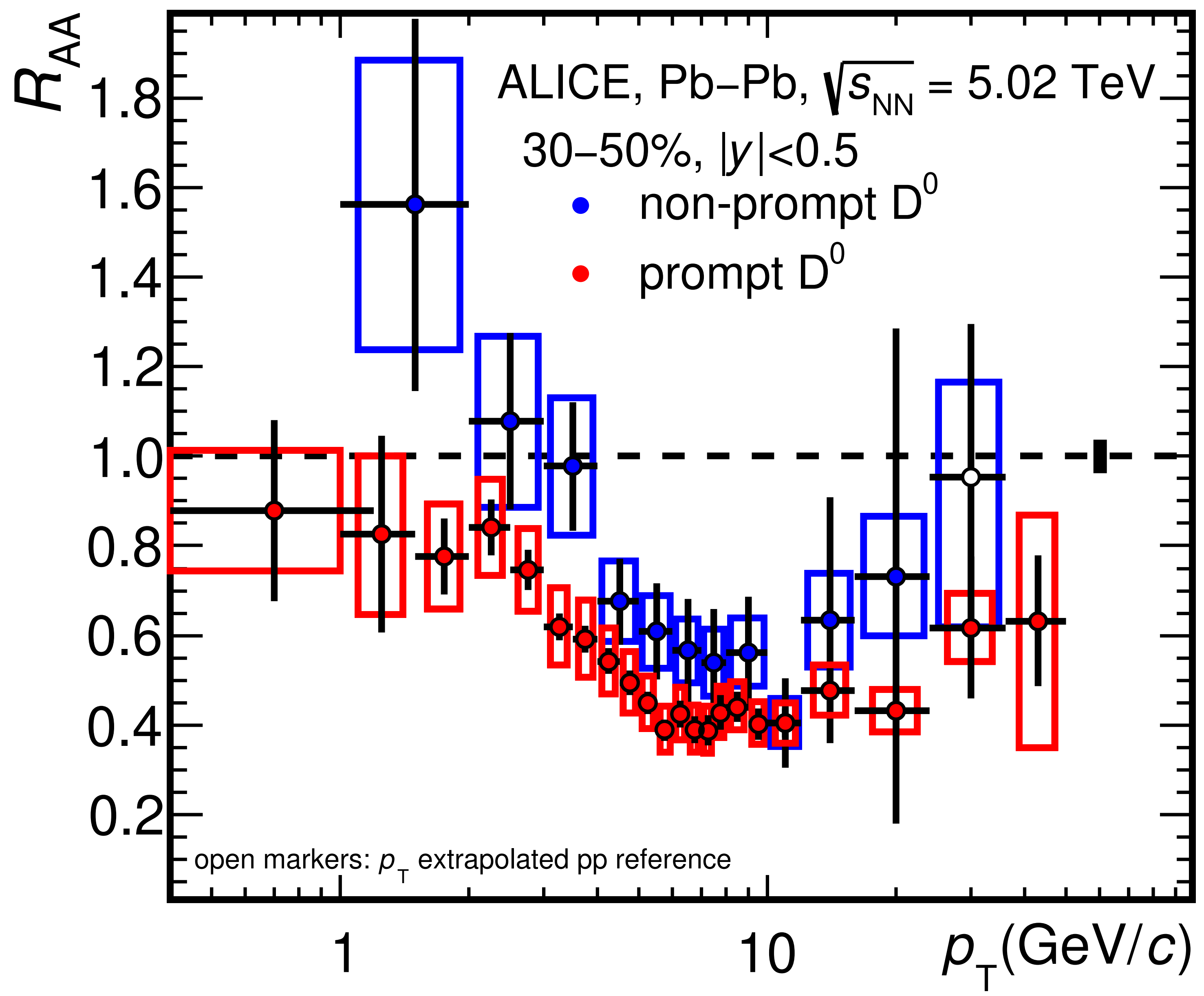
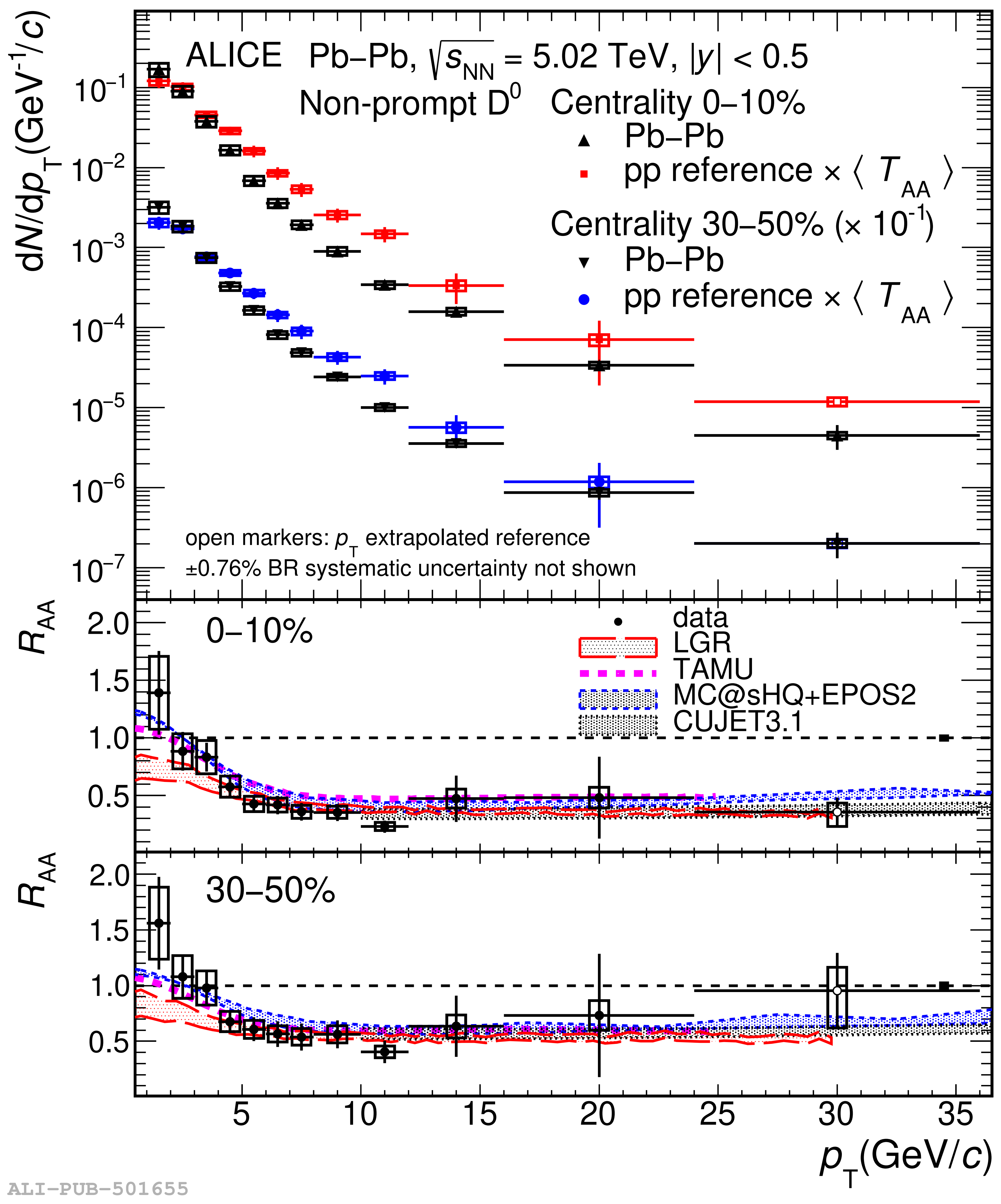






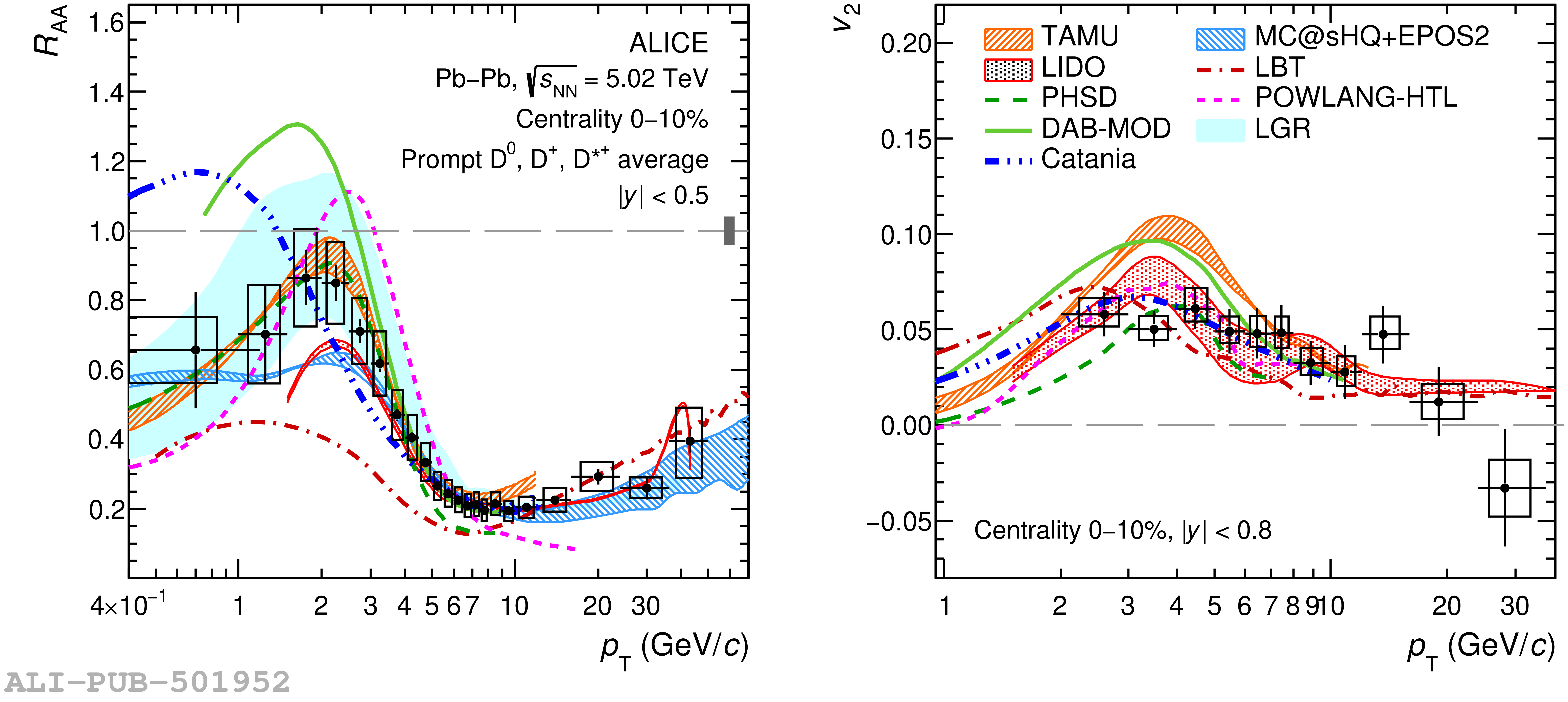
Bottom shows less suppression than charm also at LHC

Theoretical models that include collisional and radiative energy loss describe the data within uncertainties

R_{AA} and v_2 of prompt D-mesons

Prompt D^0, D^+, D^{*+}

JHEP 01 (2022) 174



Most of the transport models describe both R_{AA} and v_2

> constraint on spatial diffusion coefficients

R_{AA} and v_2 of prompt D-mesons

Prompt D^0, D^+, D^{*+}

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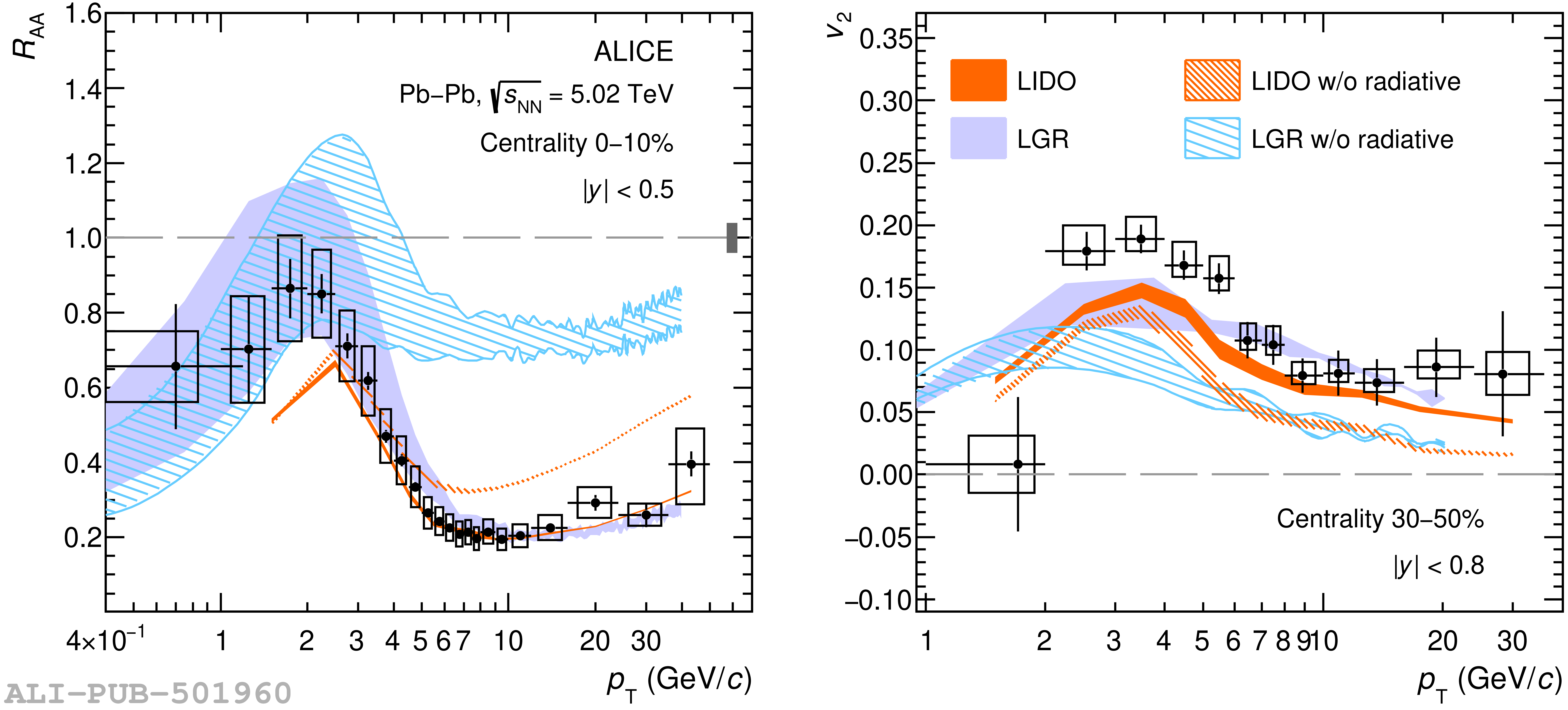
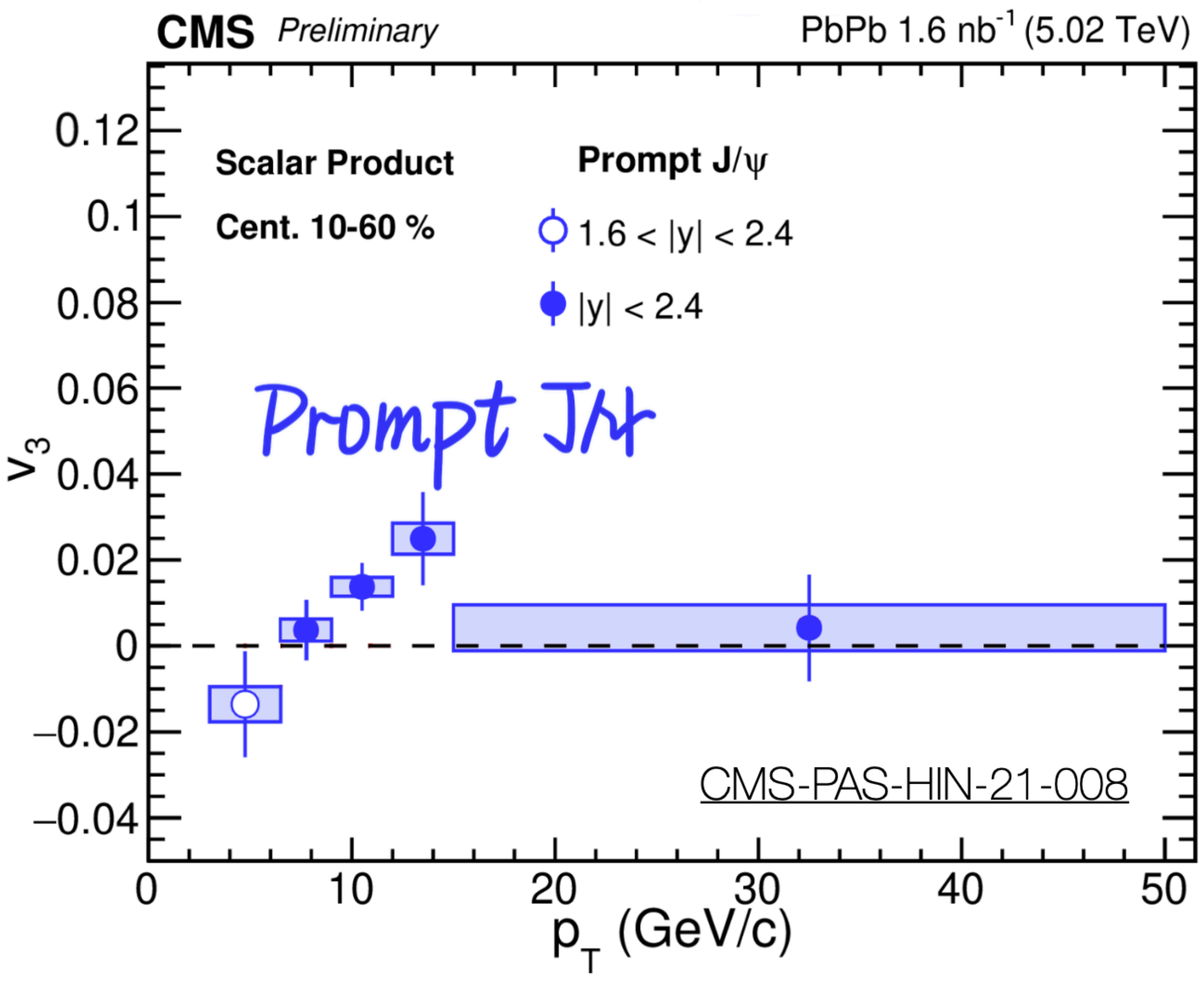
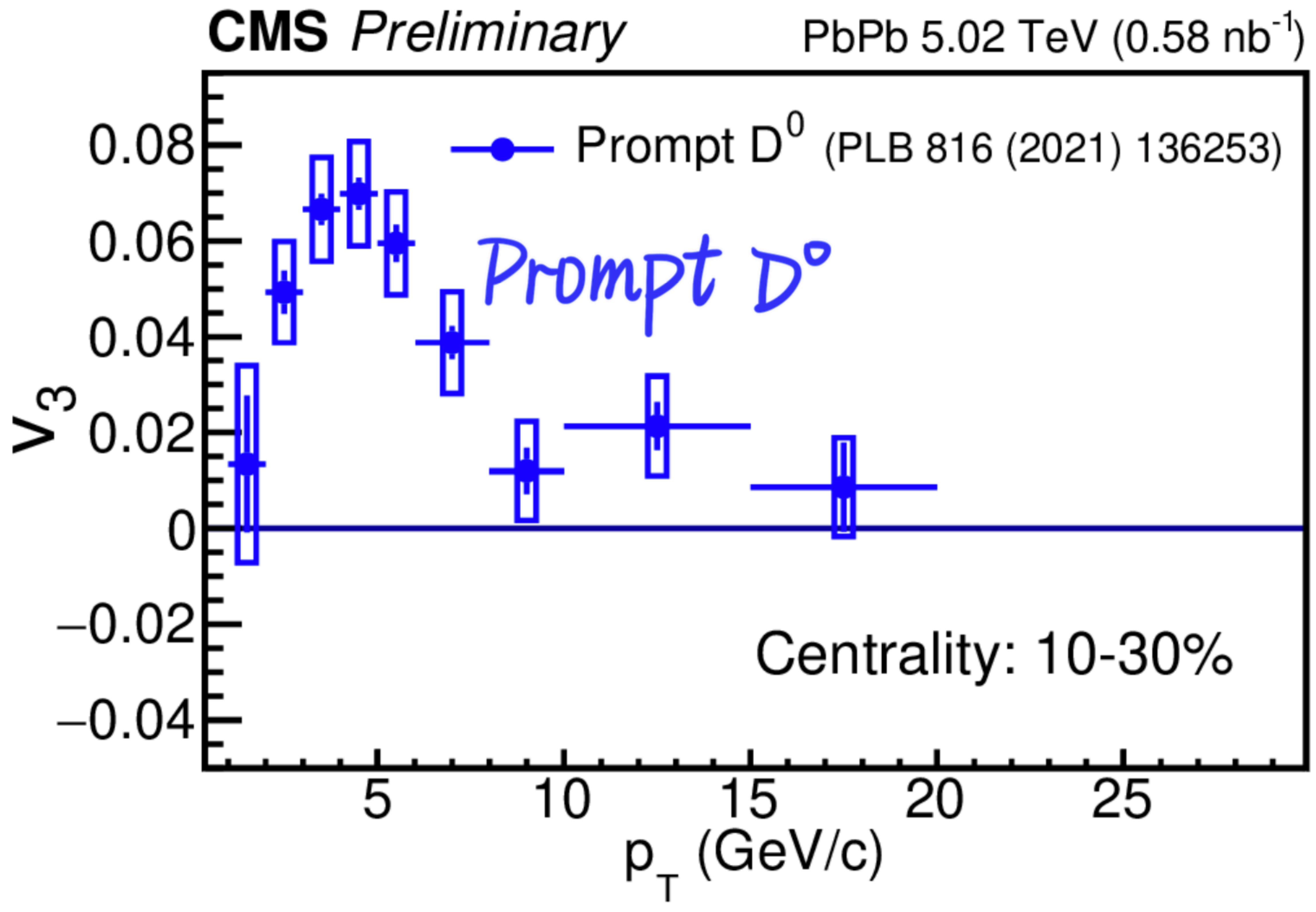


Radiative energy loss important to describe intermediate and high p_T

> small impact on low p_T region

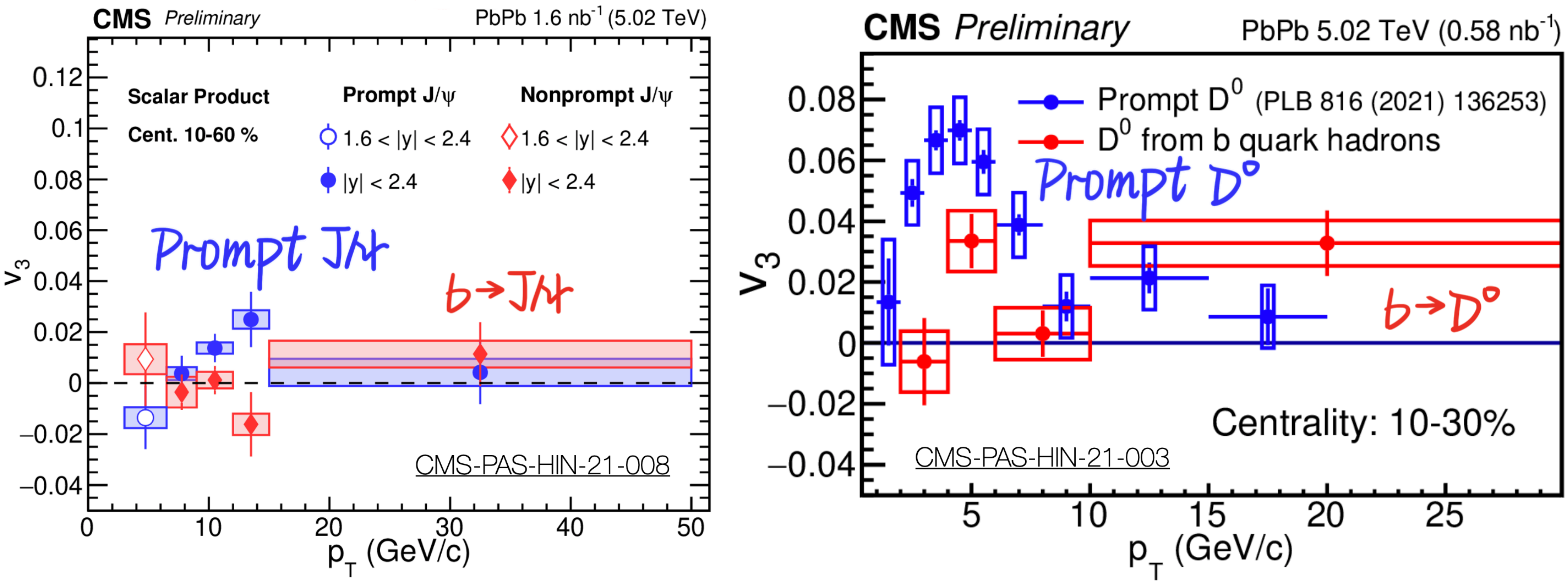
v_3 of charm and bottom





Charm is sensitive to initial state fluctuations (less than light quarks)

v_3 of charm and bottom

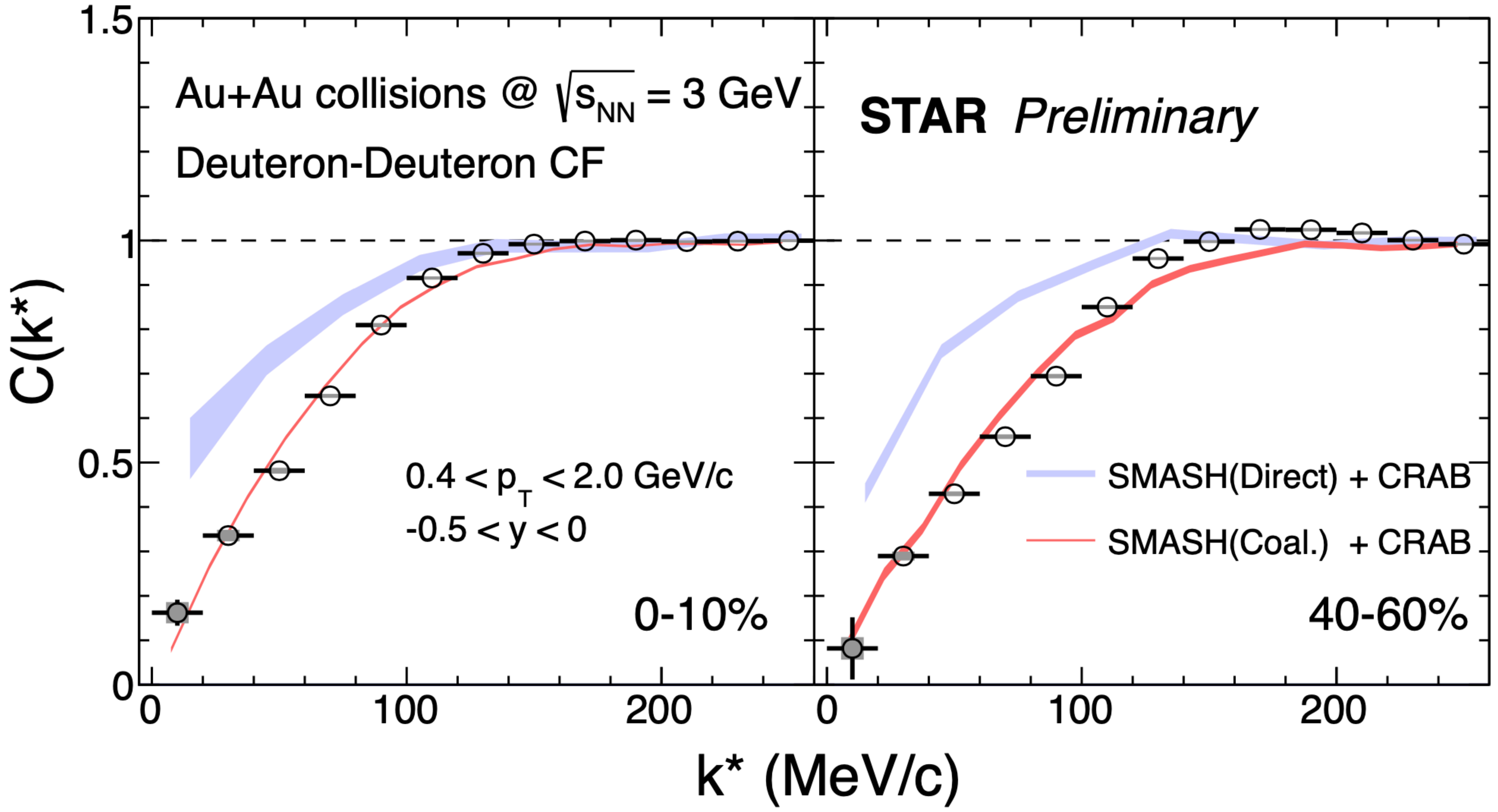


Charm is sensitive to initial state fluctuations (less than light quarks)

Bottom is less sensitive to initial state fluctuations than charm

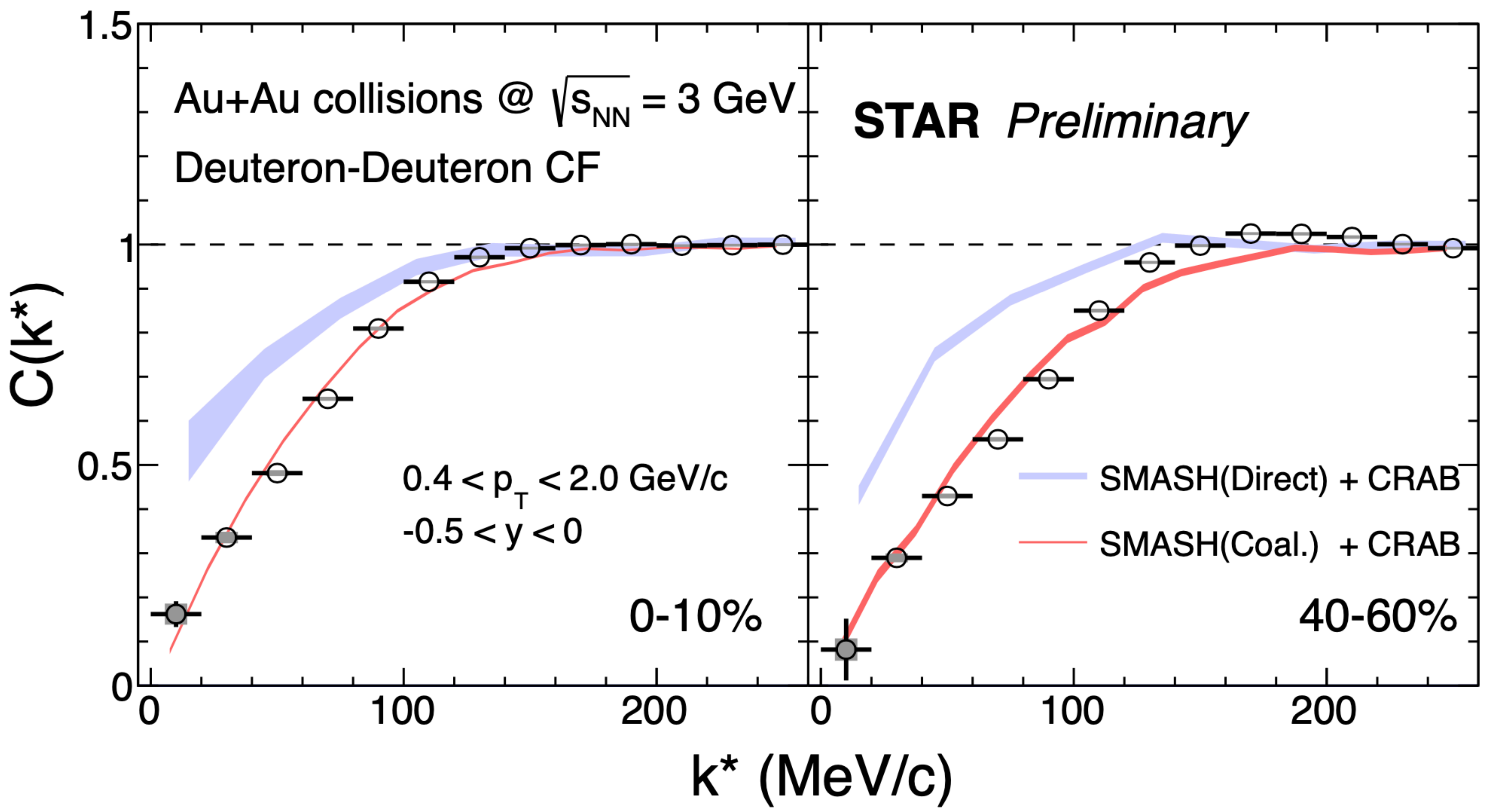
Light Flavor

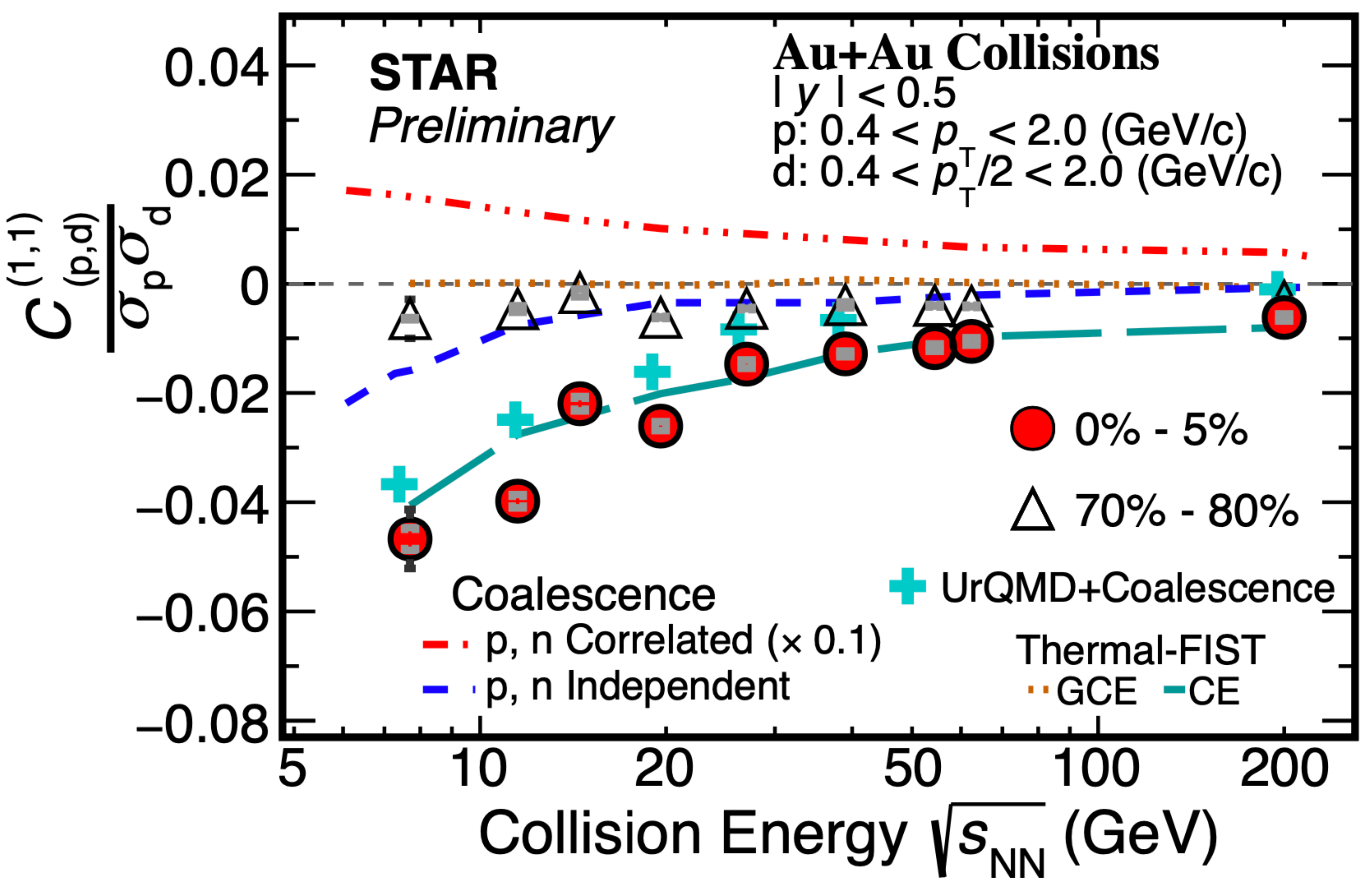
d-d and d-p correlations



- First measurement of deuteron-deuteron femstoscopic correlation
  > consistent with model calculations incorporating nucleon coalescence

d-d and d-p correlations

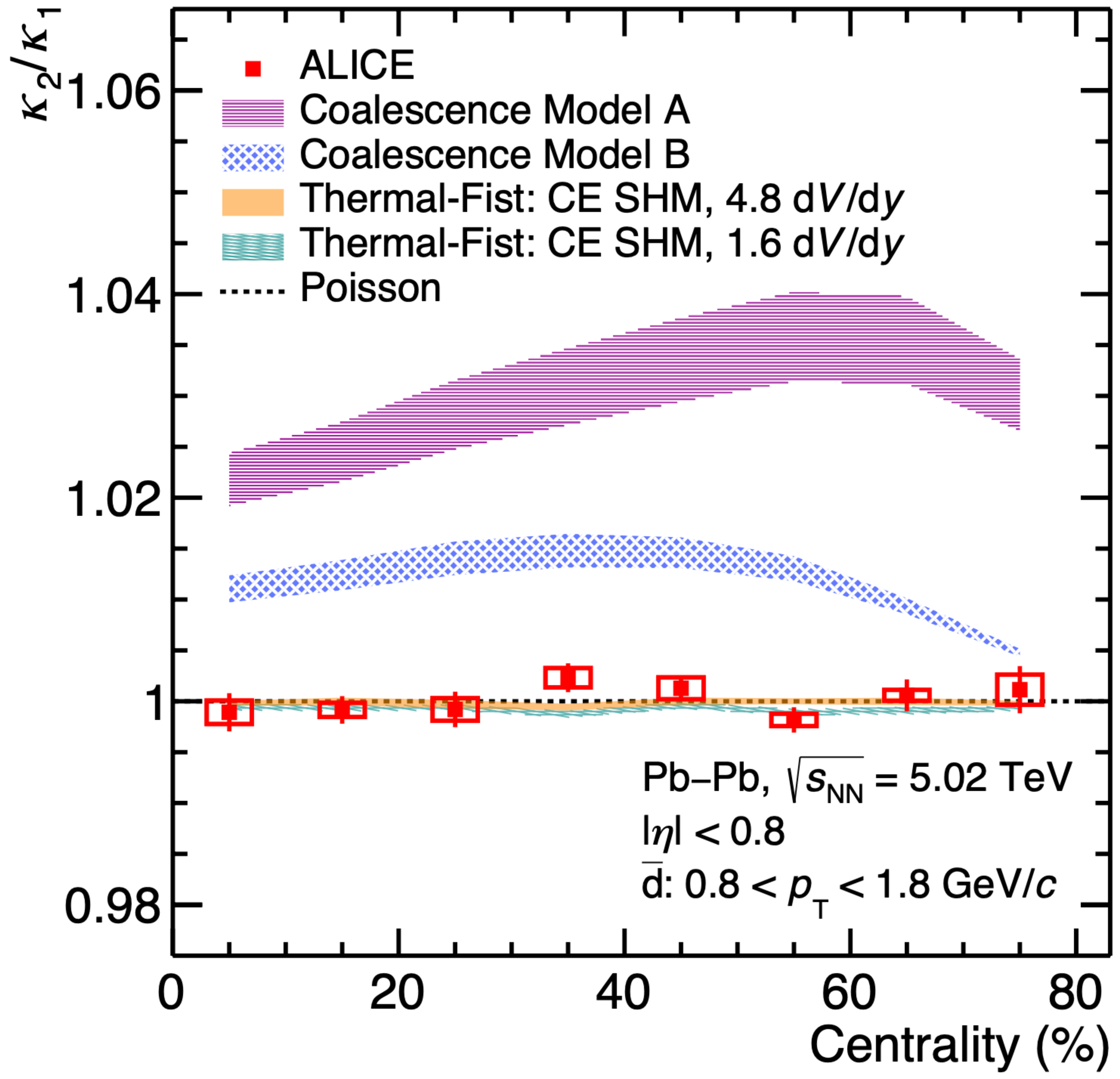




- First measurement of deuteron-deuteron femstoscopic correlation
  > consistent with model calculations incorporating nucleon coalescence
- Pearson coefficient of p-d indicates significant anti-correlation in central Au-Au collisions
  > consistent with afterburner+coalescence and canonical statistical model

Deuteron number fluctuations

arXiv:2204.10166 [nucl-ex]



New observable based on event-by-event (anti)deuteron fluctuations to distinguish SHM and coalescence

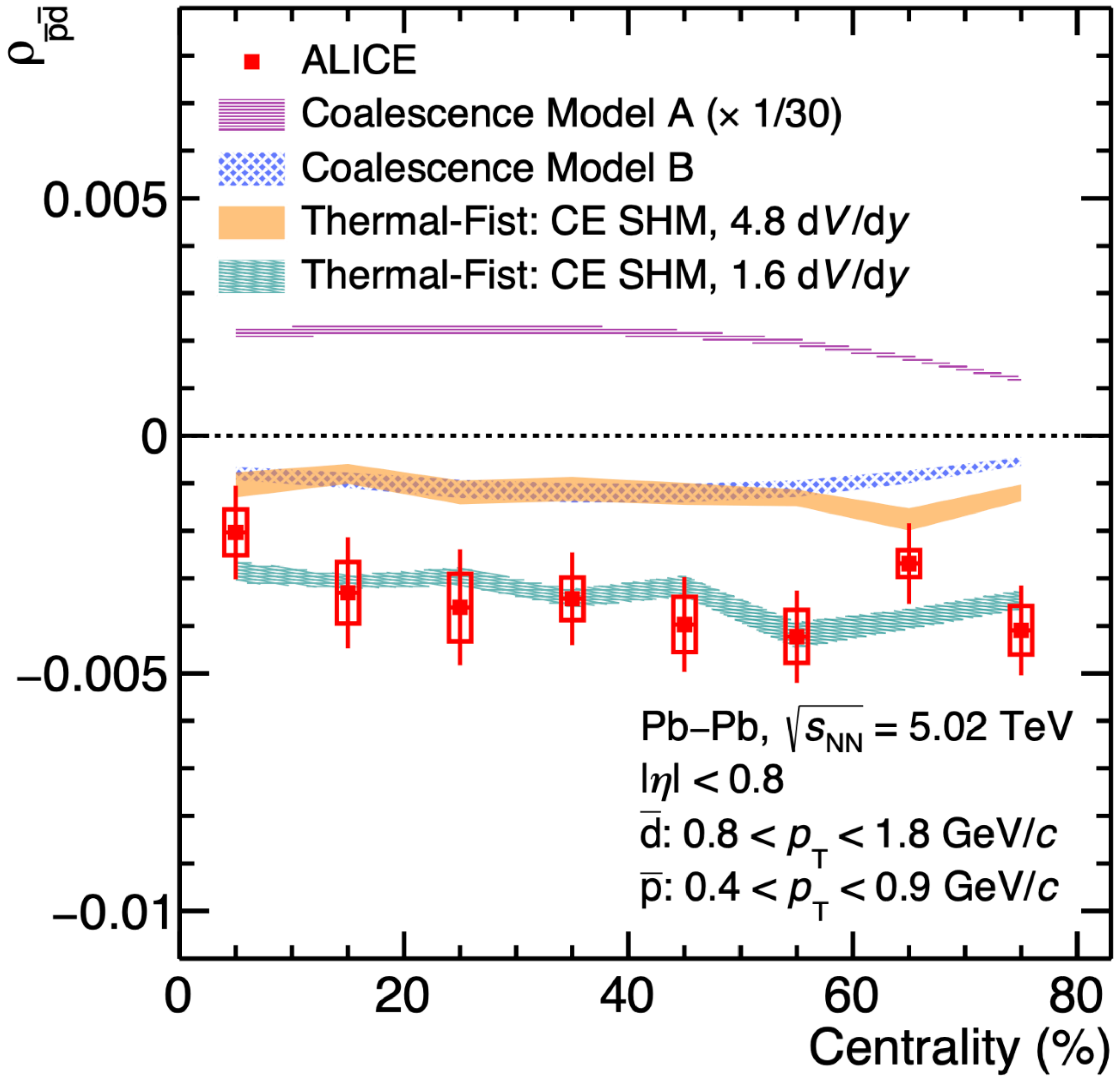
$$\frac{\kappa_2}{\kappa_1} = \frac{\langle (n - \langle n \rangle)^2 \rangle}{\langle n \rangle}$$

Cumulant ratio favors canonical statistical model

Coalescence Model A: full correlation of p and n
Coalescence Model B: independent p and n fluctuations

Correlation volume

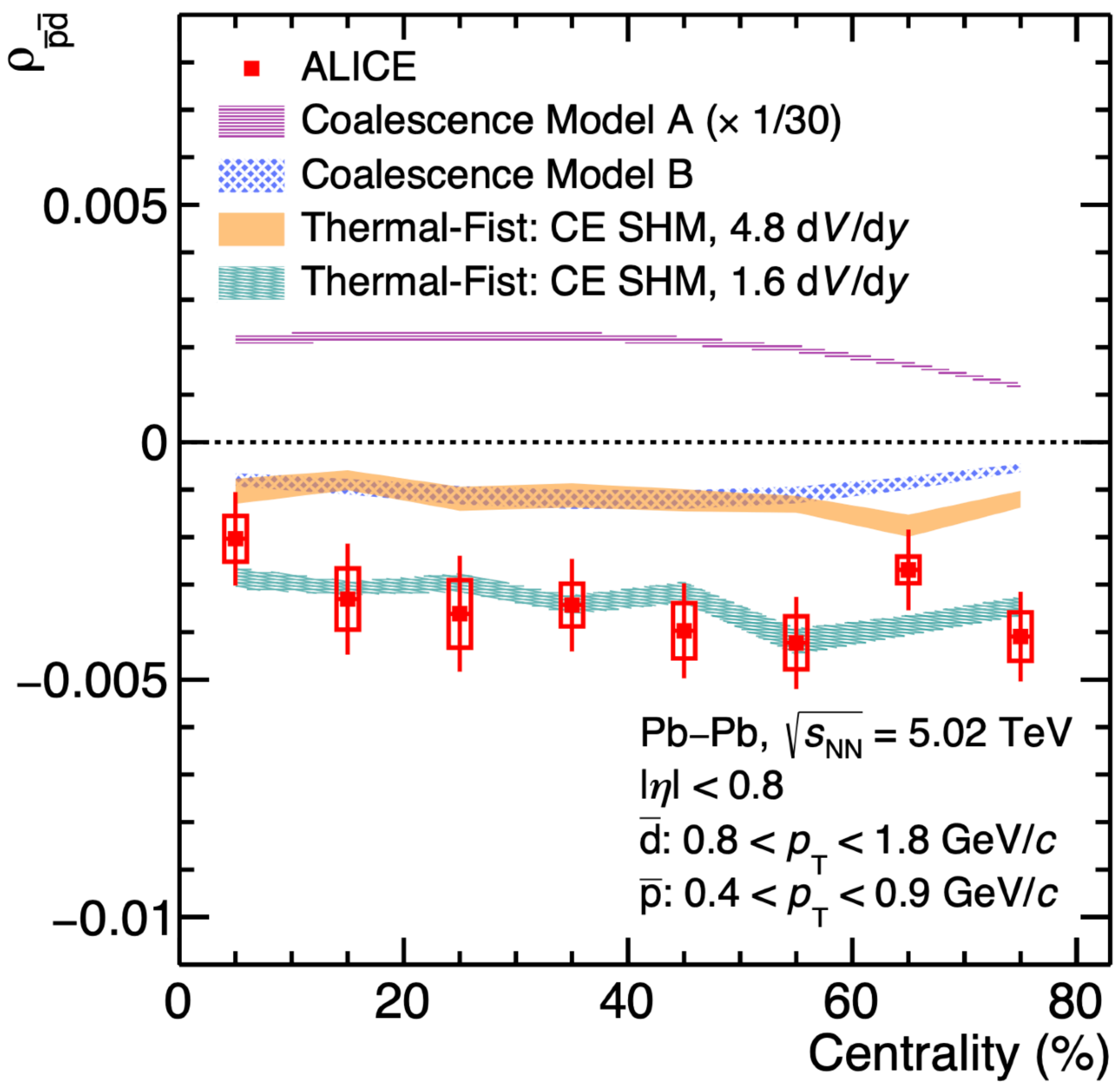
arXiv:2204.10166 [nucl-ex]



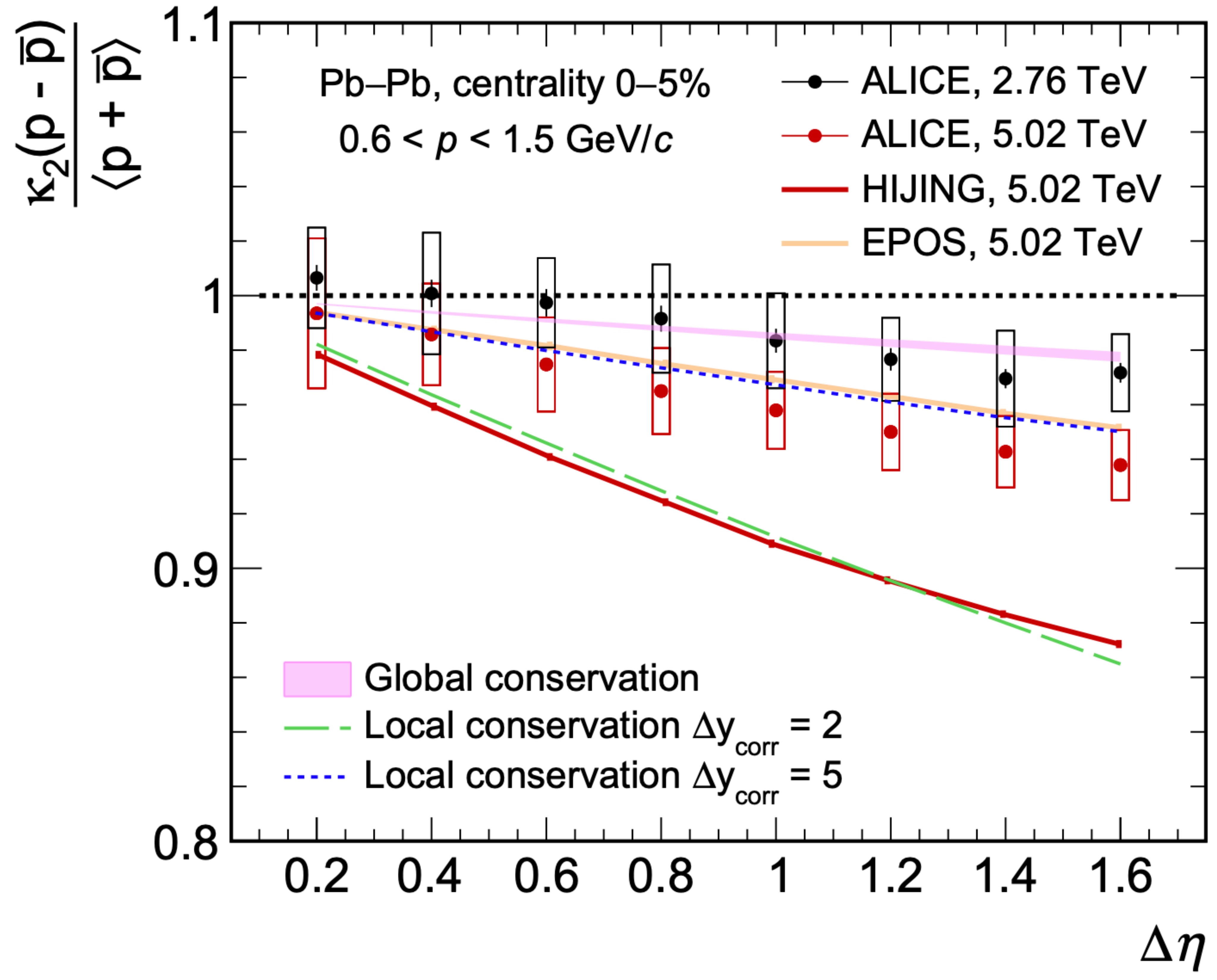
Pearson correlation $\rho_{\bar{p}\bar{d}}$ clearly indicates a correlation volume for baryon number conservation of 1.6 units of rapidity

Correlation volume

arXiv:2204.10166 [nucl-ex]



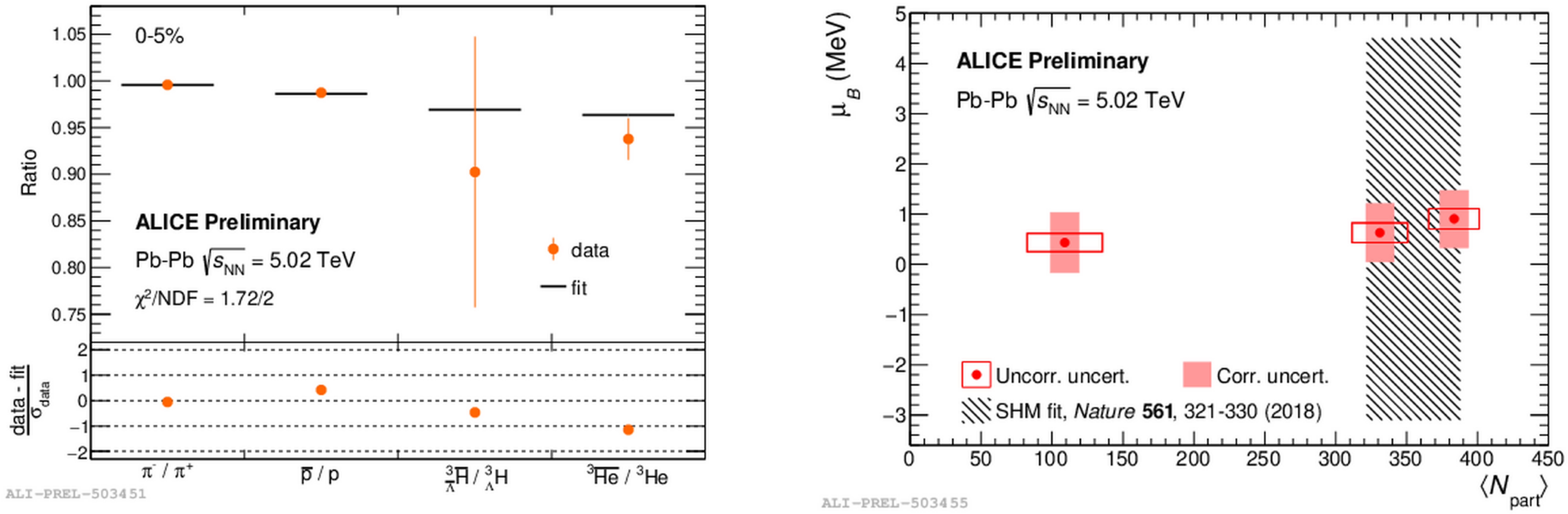
arXiv:2206.03343 [nucl-ex]



Pearson correlation $\rho_{\bar{p}\bar{d}}$ clearly indicates a correlation volume for baryon number conservation of 1.6 units of rapidity

> different from net-proton fluctuation results (Δy_{corr} = 5)

Precise μ_B measurement at LHC



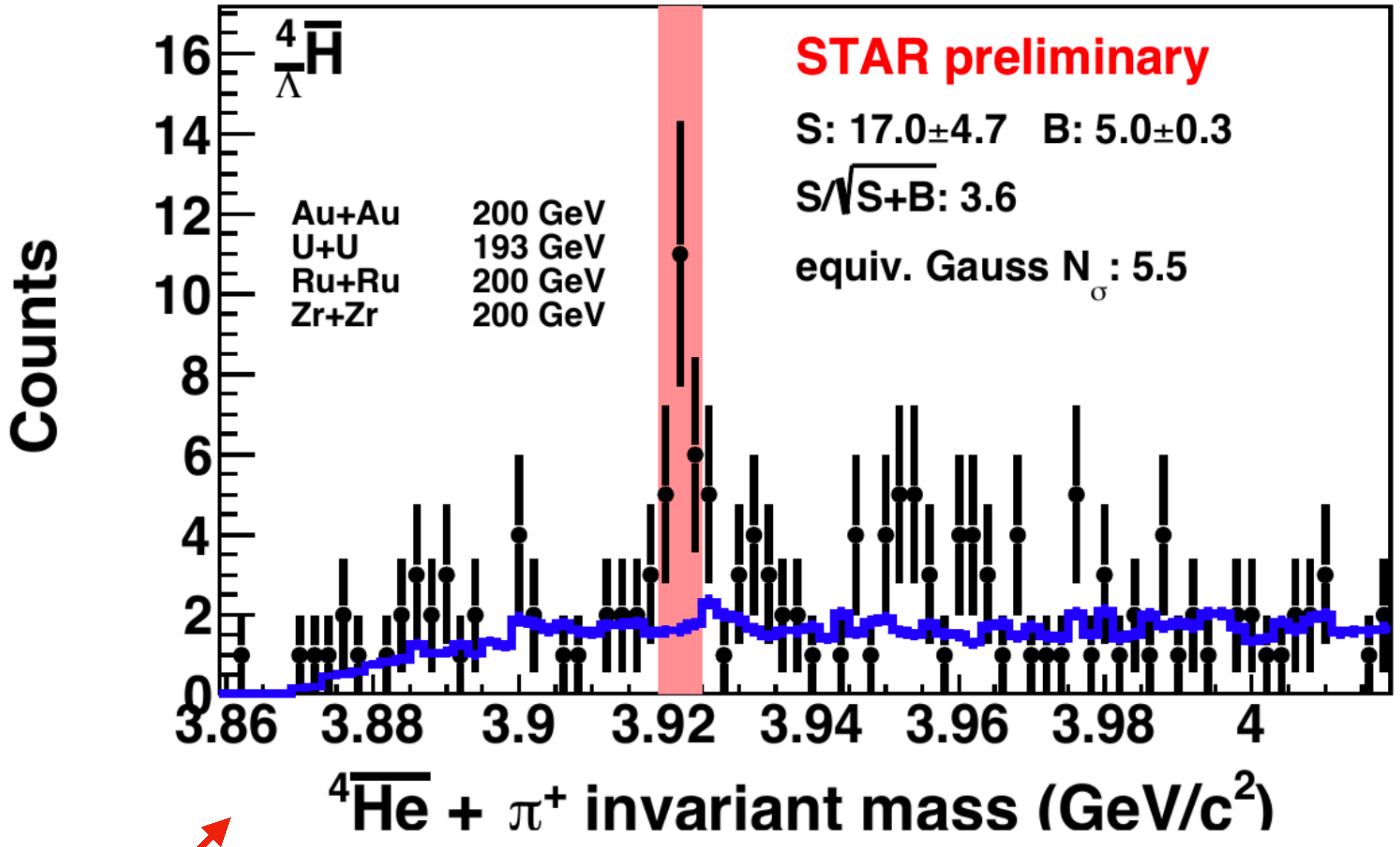
New measurement of antimatter/matter imbalance at the LHC

$$\bar{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T}-2I_3\frac{\mu_{I_3}}{T}\right]$$

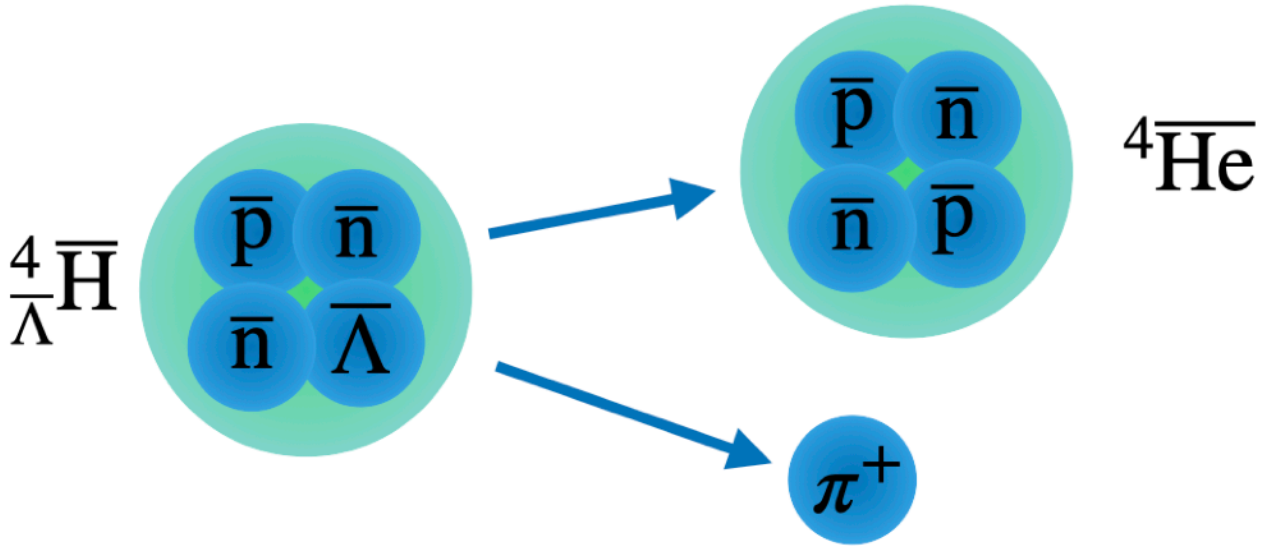
Uncertainties reduced wrt thermal model fit by one order of magnitude

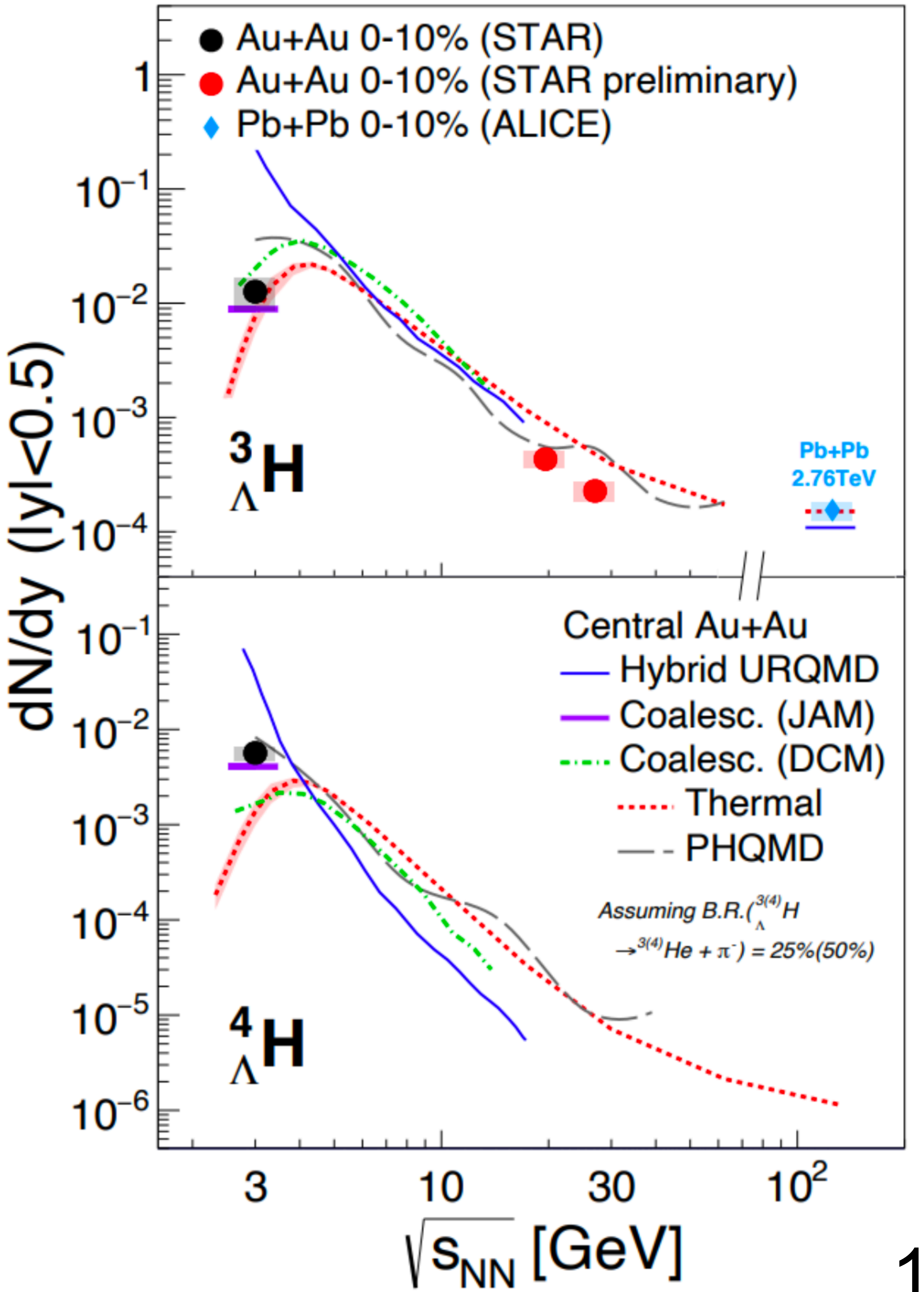
> direct cancellation of correlated uncertainties in antimatter-to-matter ratios

Hypernuclei at high μ_B



First observation of $^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}$

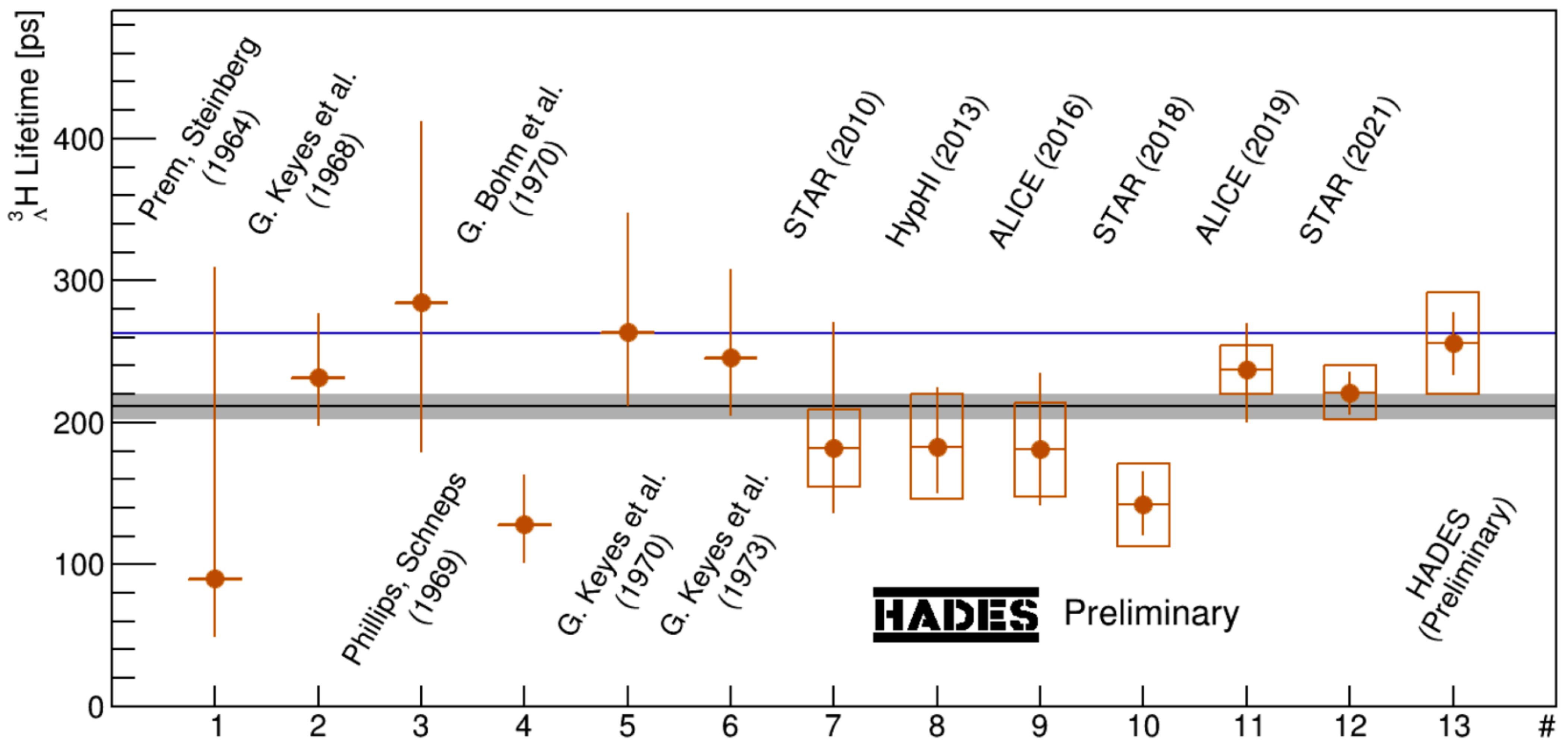




Hypernuclei yields measured at 3, 19.6 and 27 GeV

→ constraints on hypernuclei production models at high μ_B

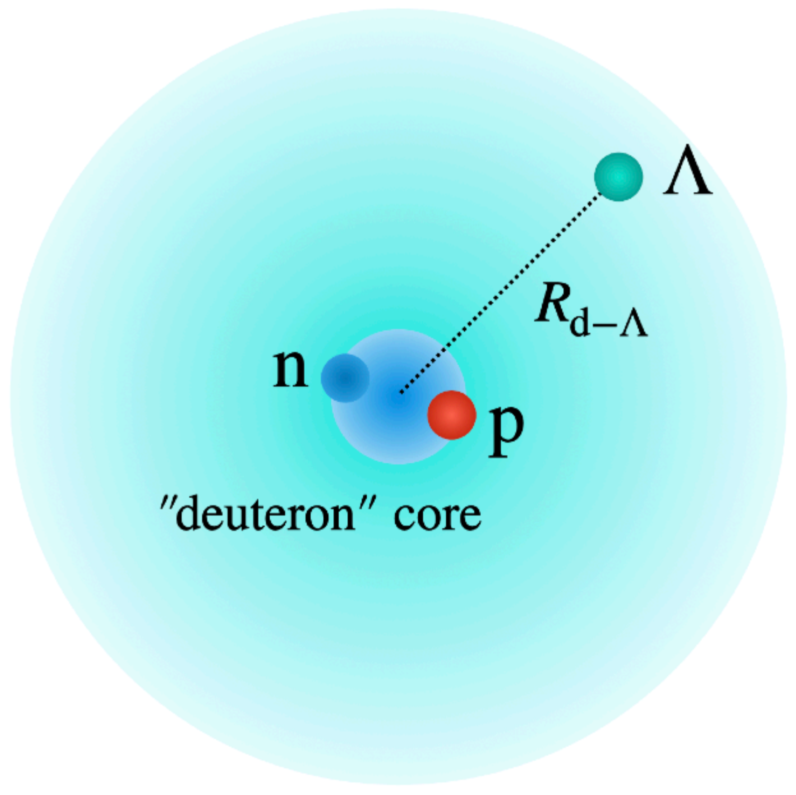
Lifetimes of Hypernuclei

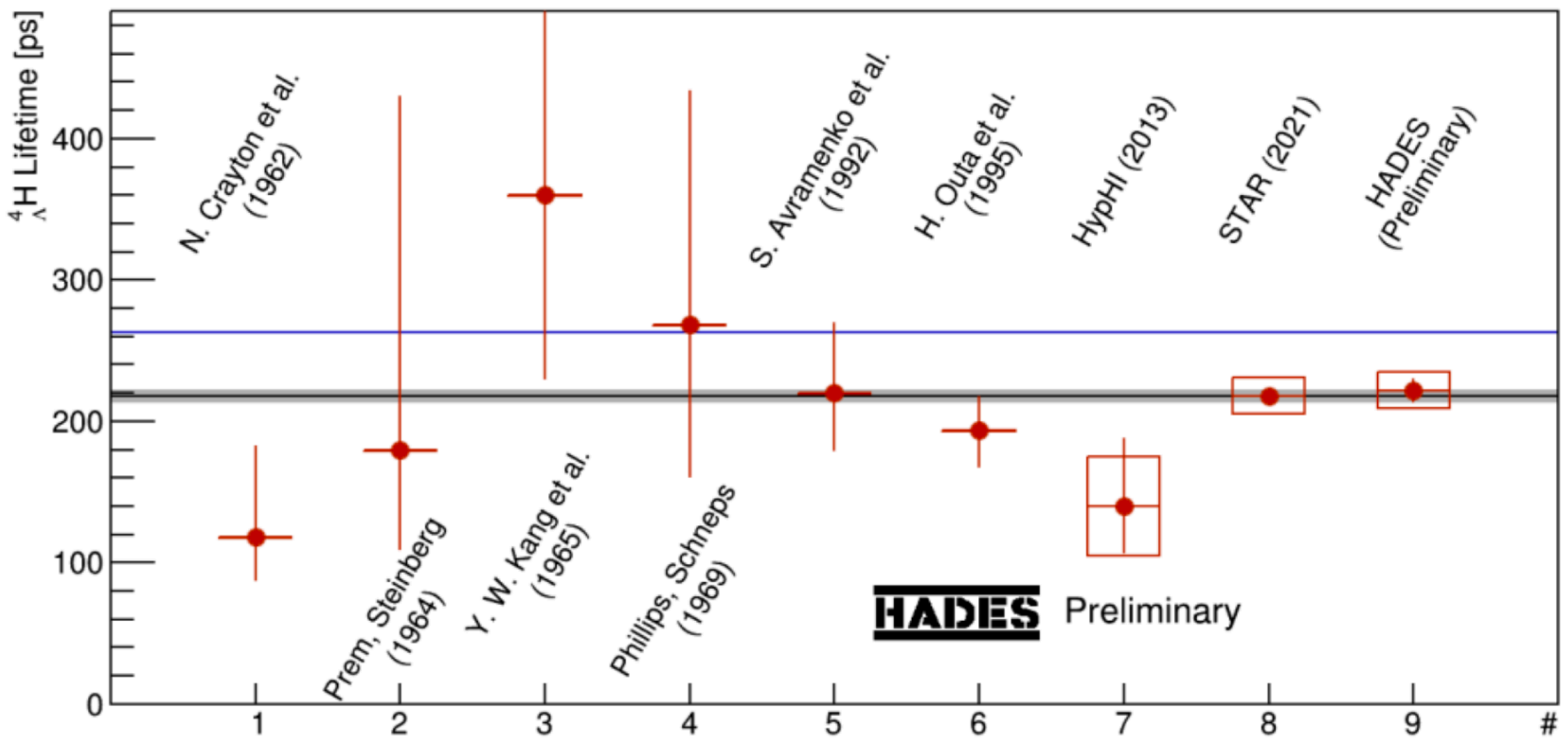


$^{3}_{\Lambda}$H

$^{3}_{\Lambda}$H lifetime = (256 ± 22 ± 36) ps

- compatible with free Λ lifetime
- loosely-bound state

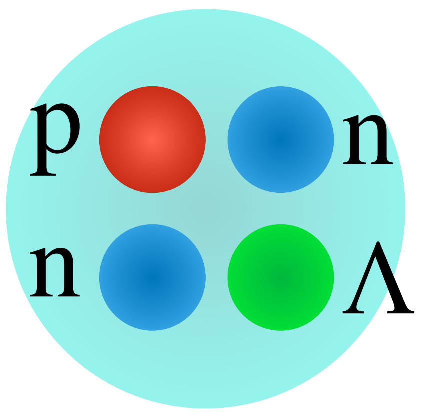




$^{4}_{\Lambda}$H

$^{4}_{\Lambda}$H lifetime = (222 ± 8 ± 13) ps

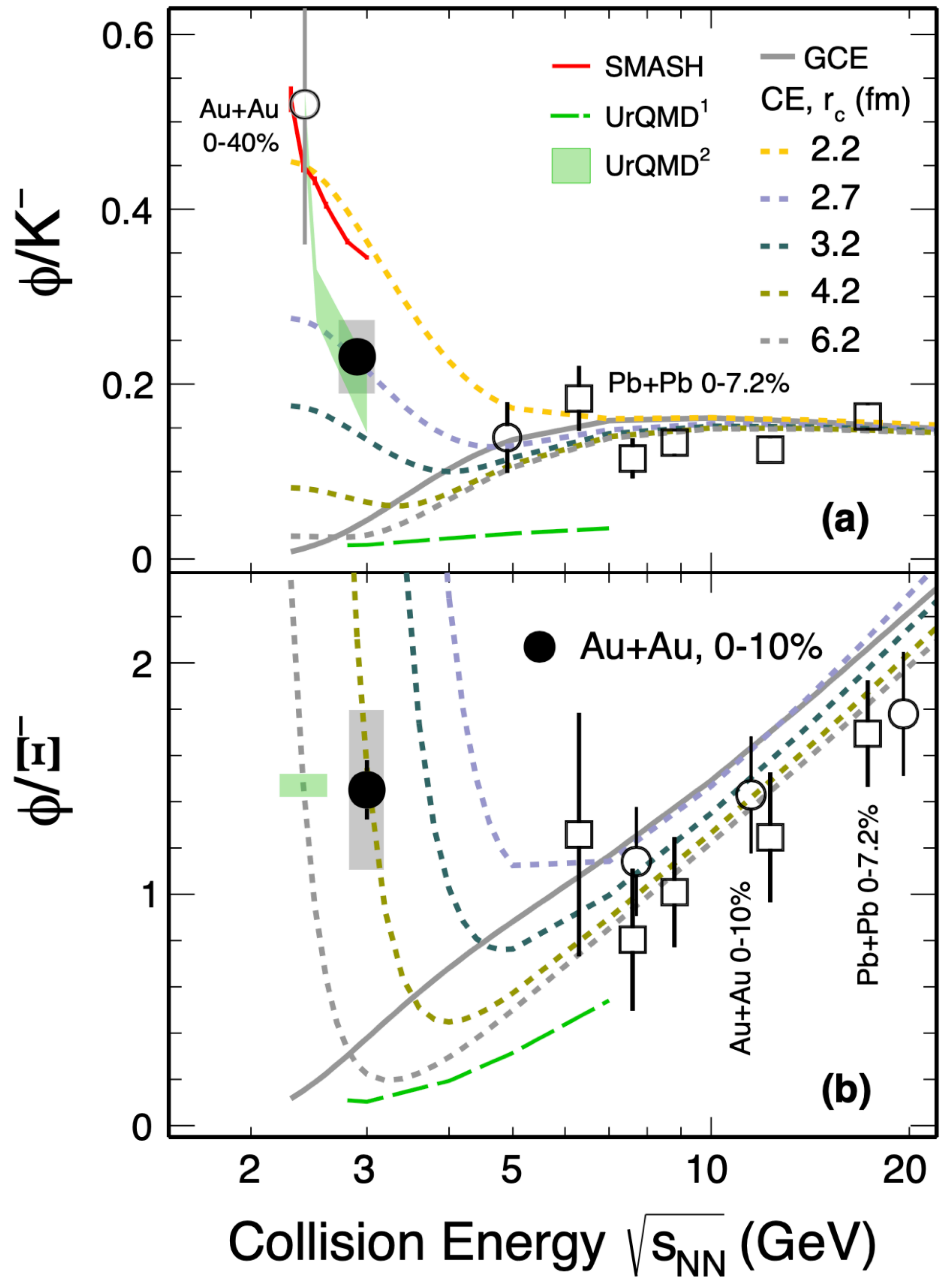
- significantly lower than free Λ
  > higher binding energy than hypertriton
- compatible with other measurements



Lifetime of hypernuclei important to study (low-density limit of) YN interaction

Strangeness and Resonances

PLB 831 (2022) 137152



ϕ/K and ϕ/Ξ: interplay between energy dependence of T and μ_B and canonical suppression

Strangeness and Resonances

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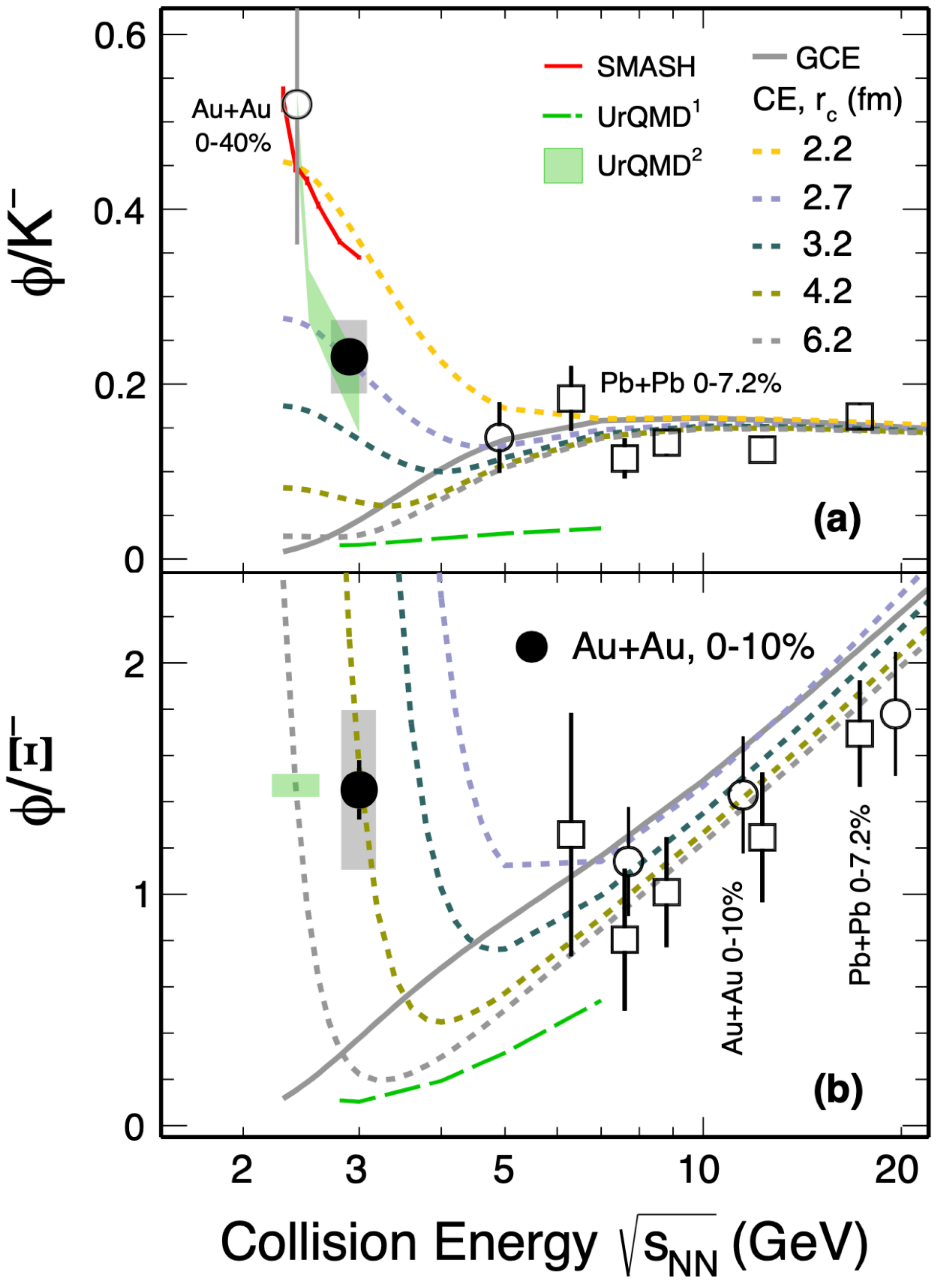
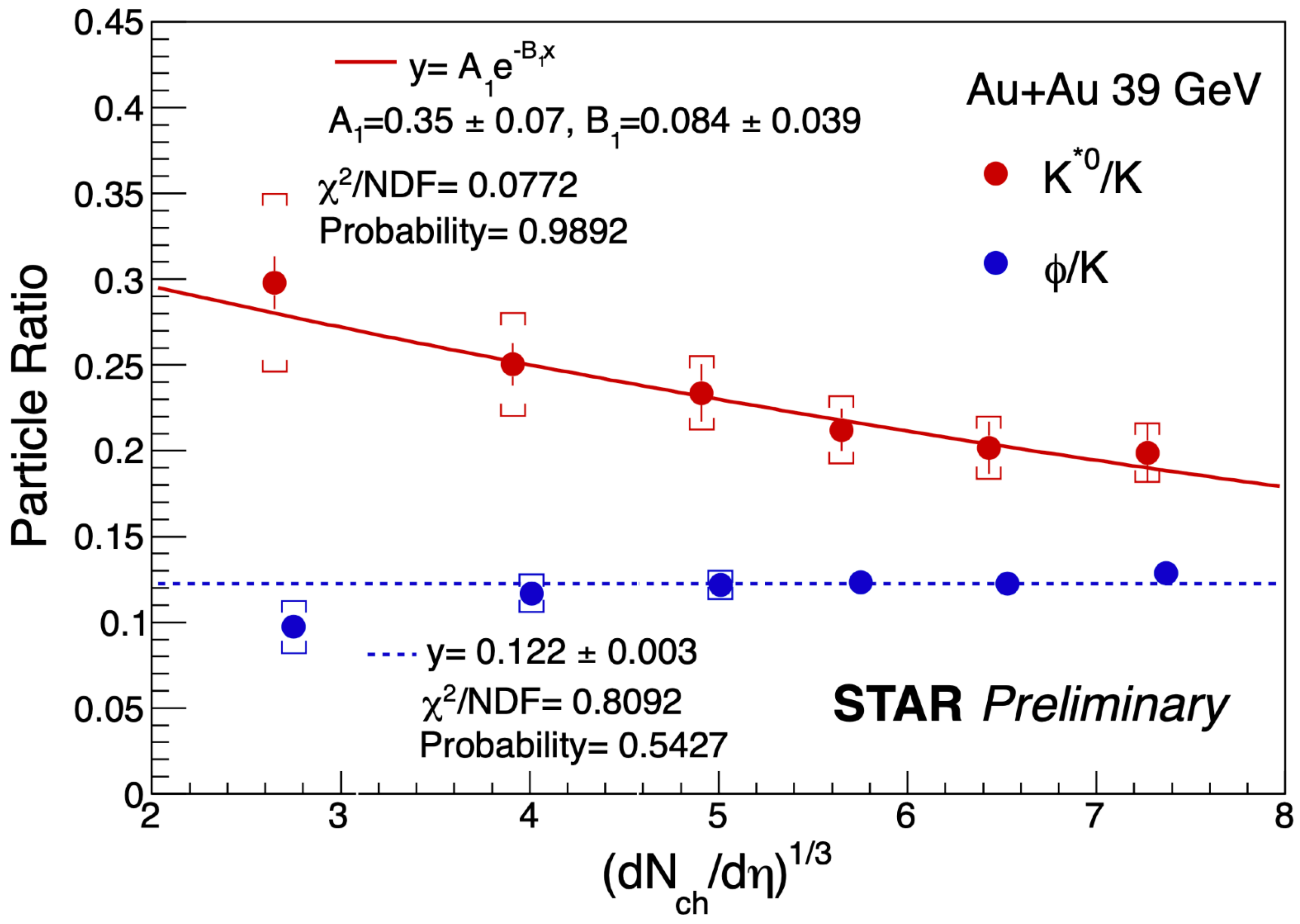


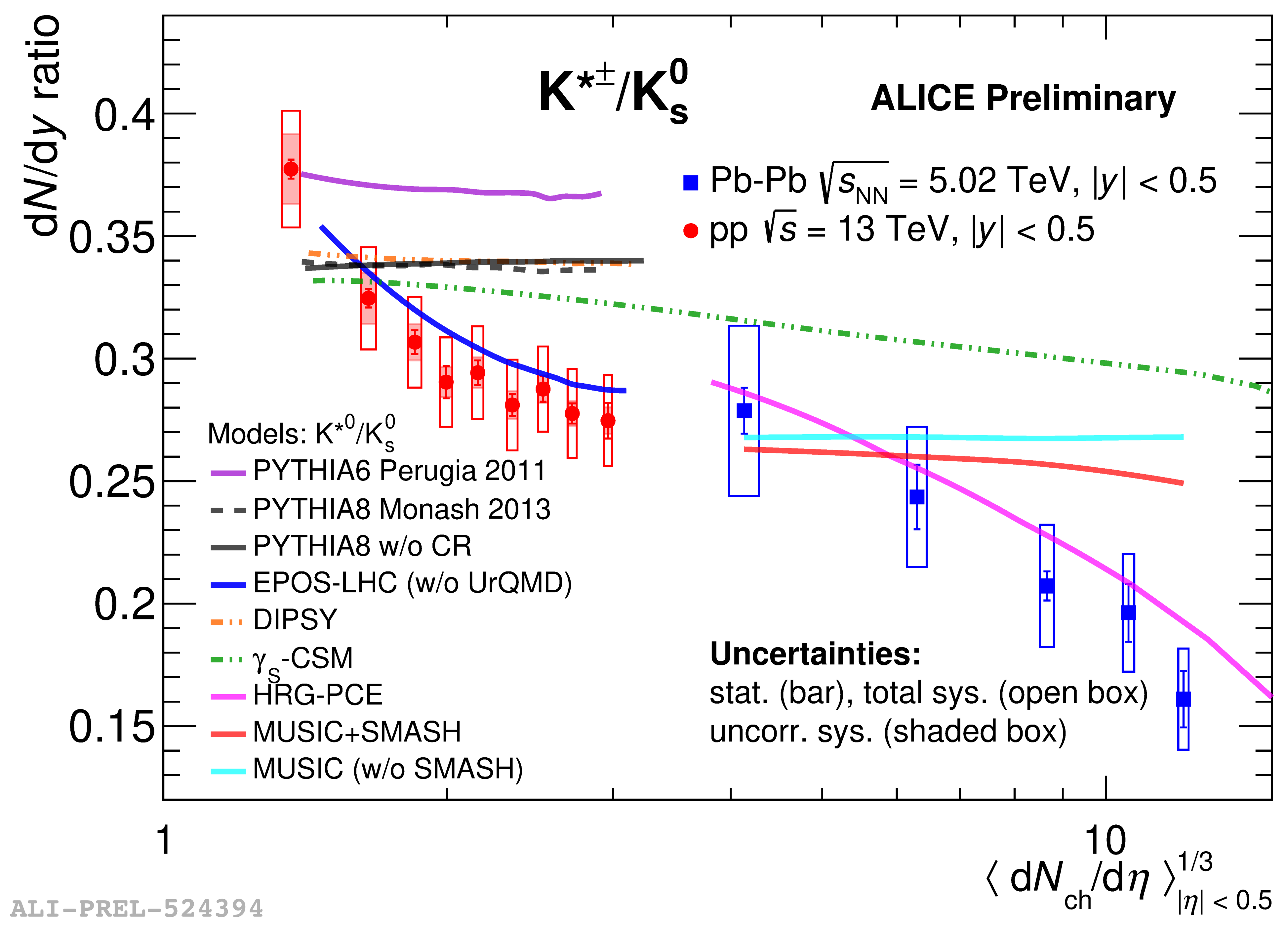


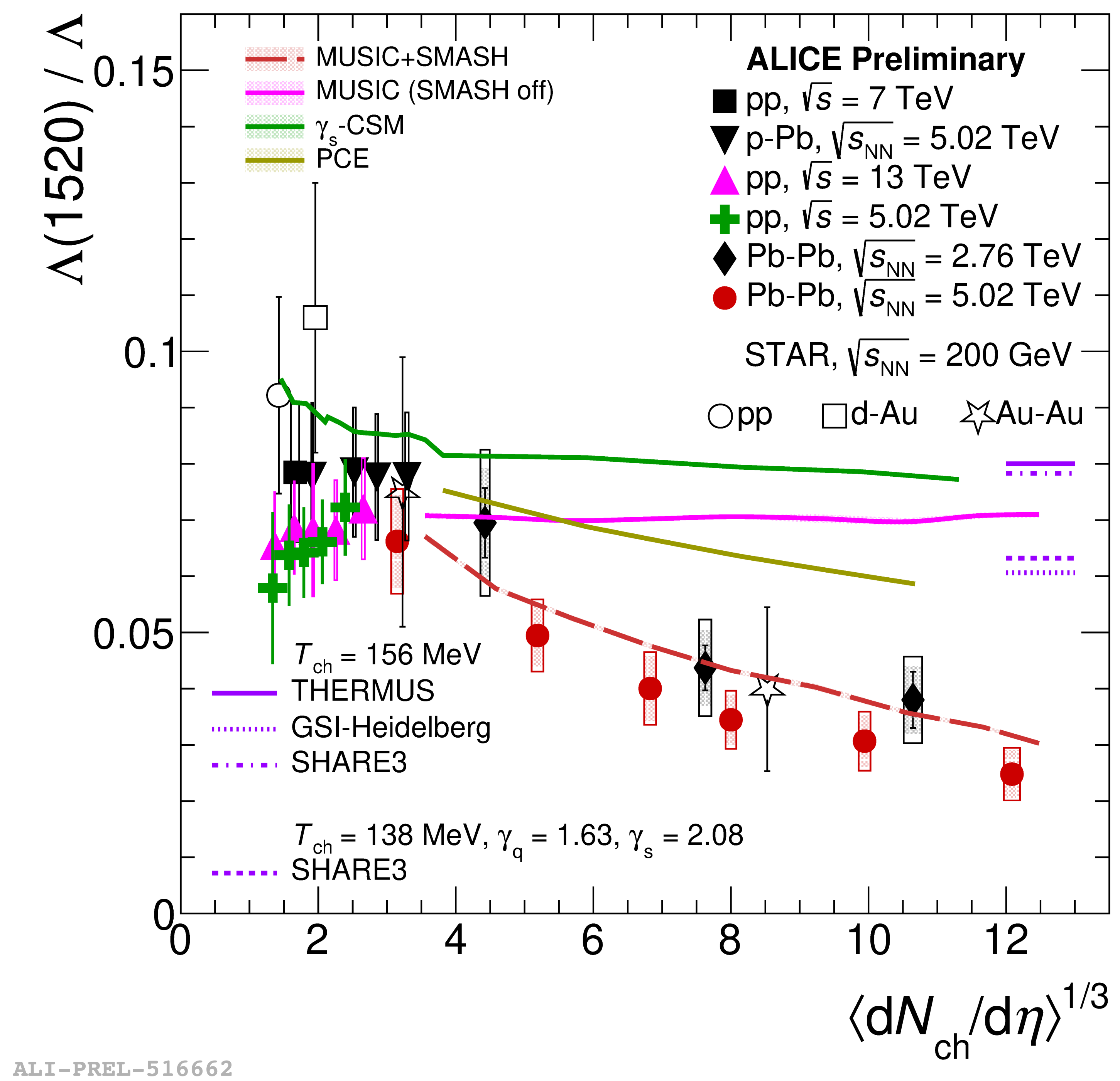
ϕ/K and ϕ/Ξ: interplay between energy dependence of T and μ_B and canonical suppression

Resonance/stable hadron ratios:

- Significant decrease of K*/K vs. multiplicity
- ϕ/K almost flat

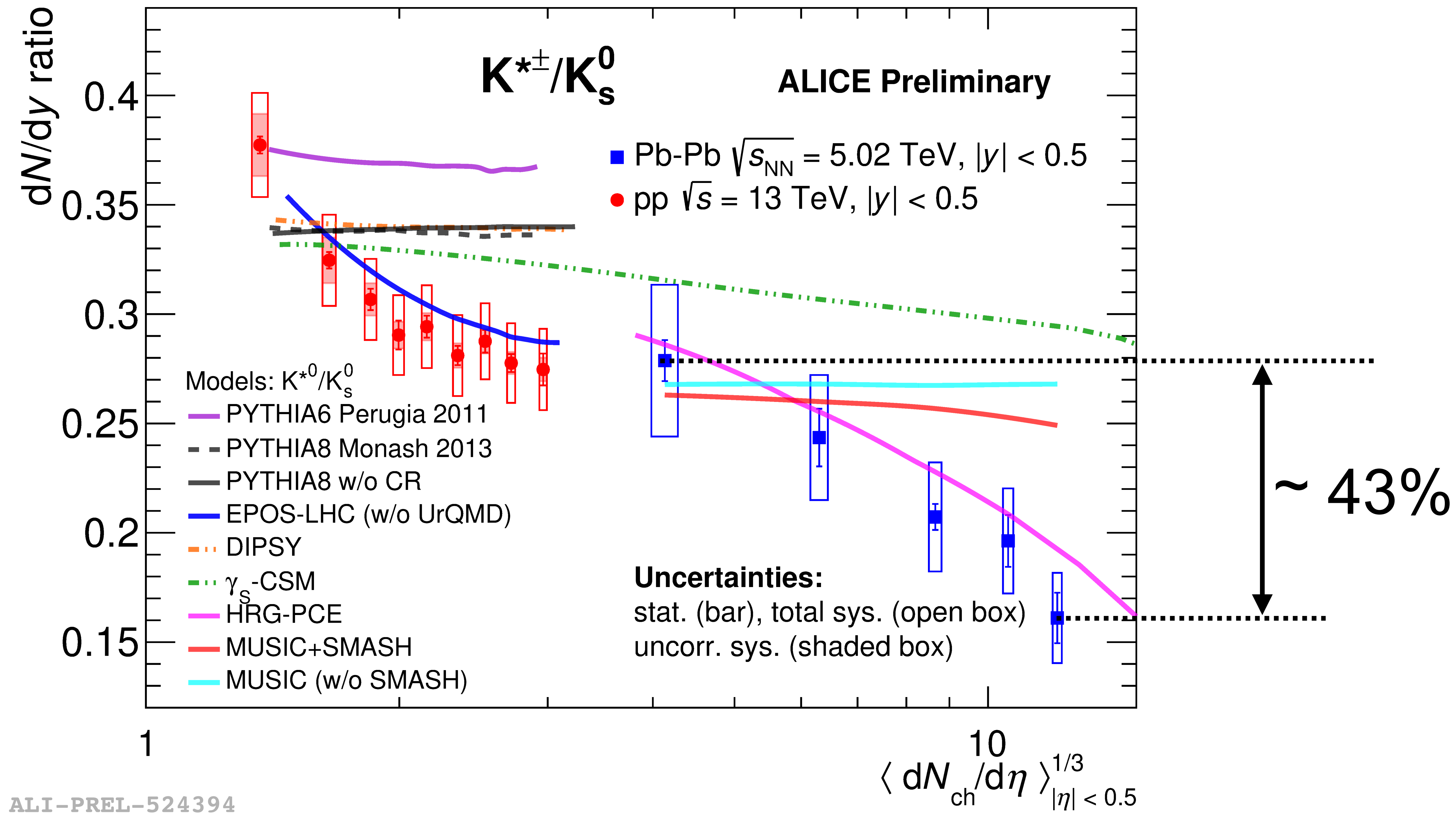
Strangeness and Resonances

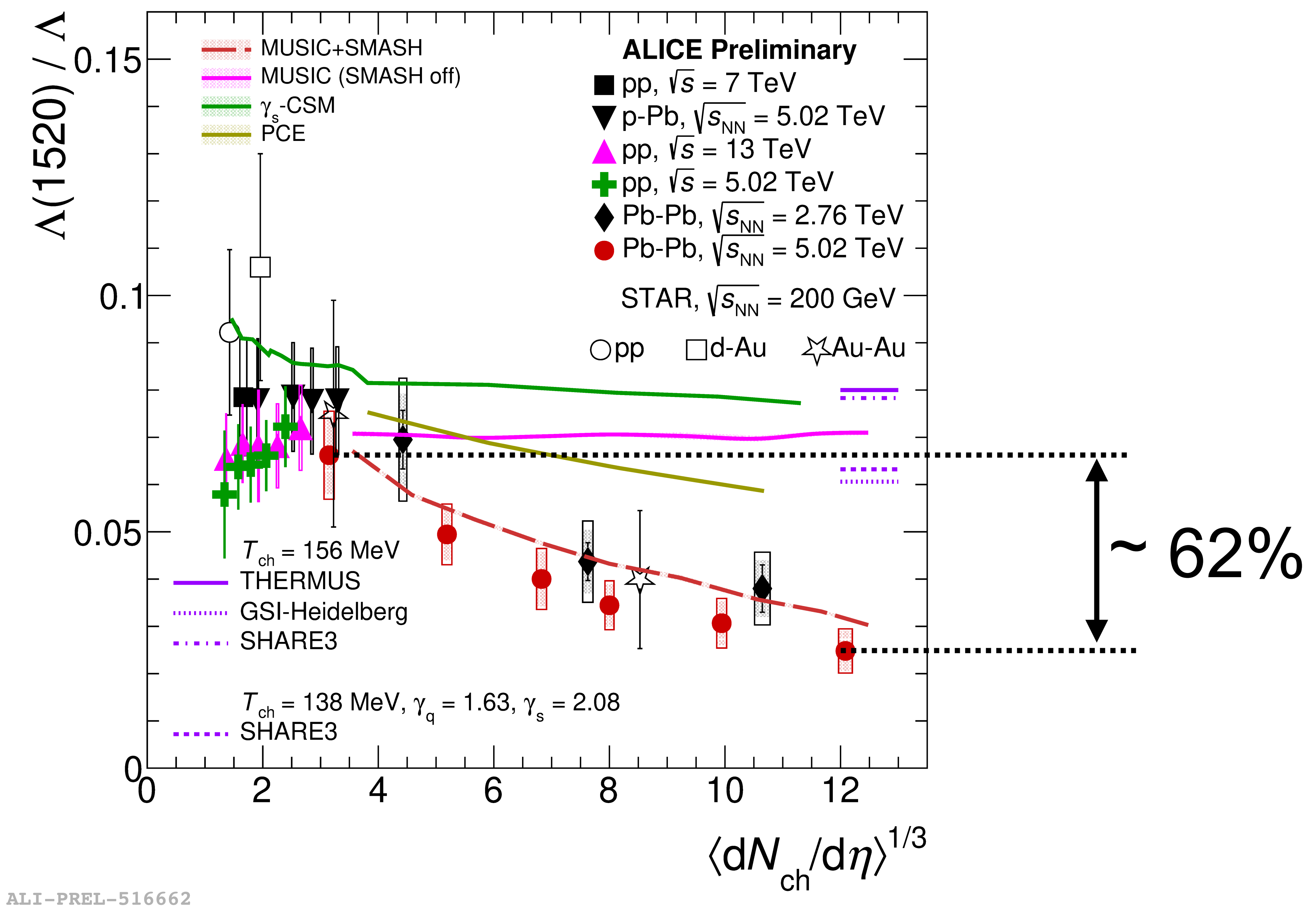




Short-lived resonances are useful tools to study hadron gas phase

Strangeness and Resonances





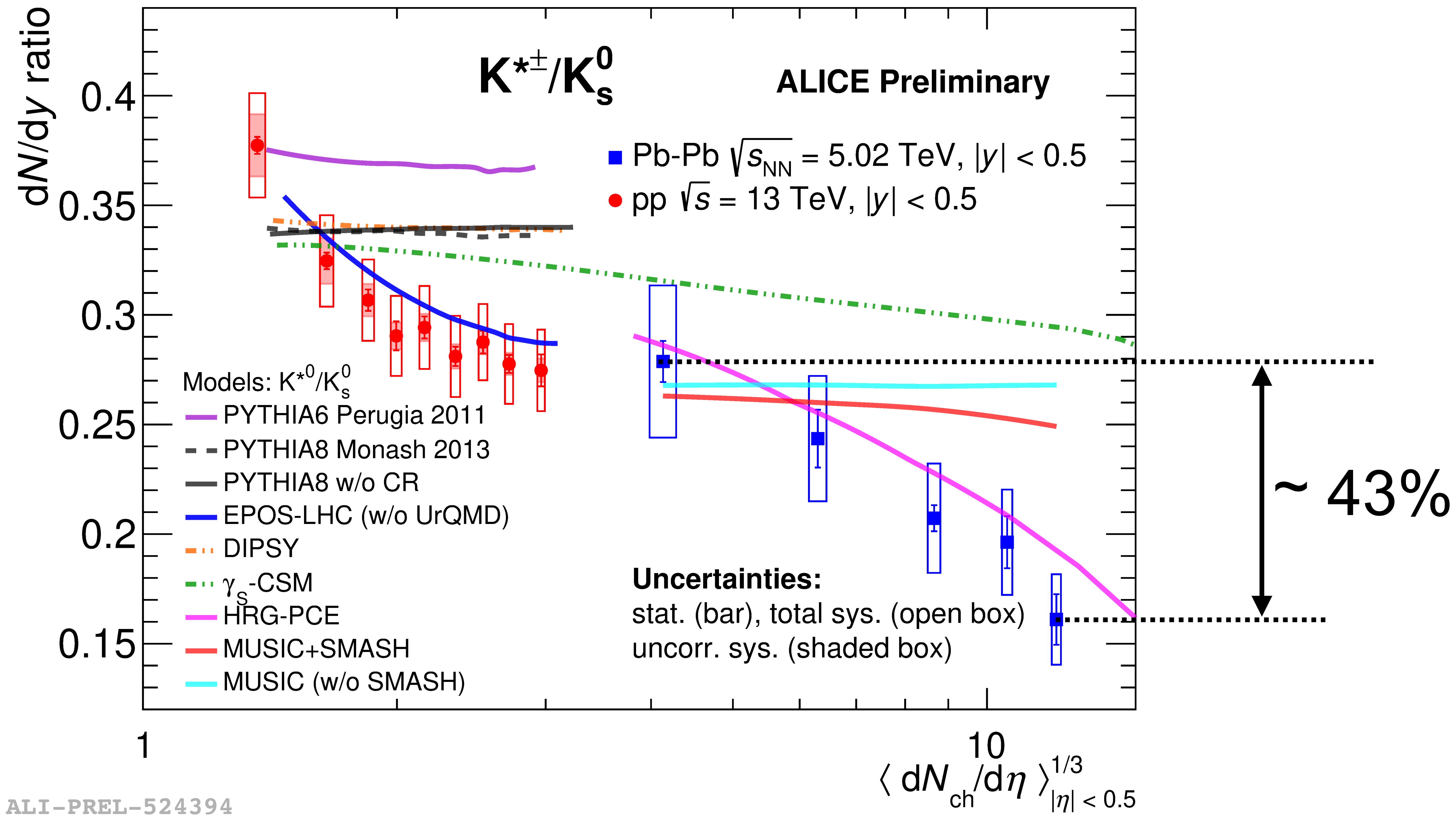
Short-lived resonances are useful tools to study hadron gas phase

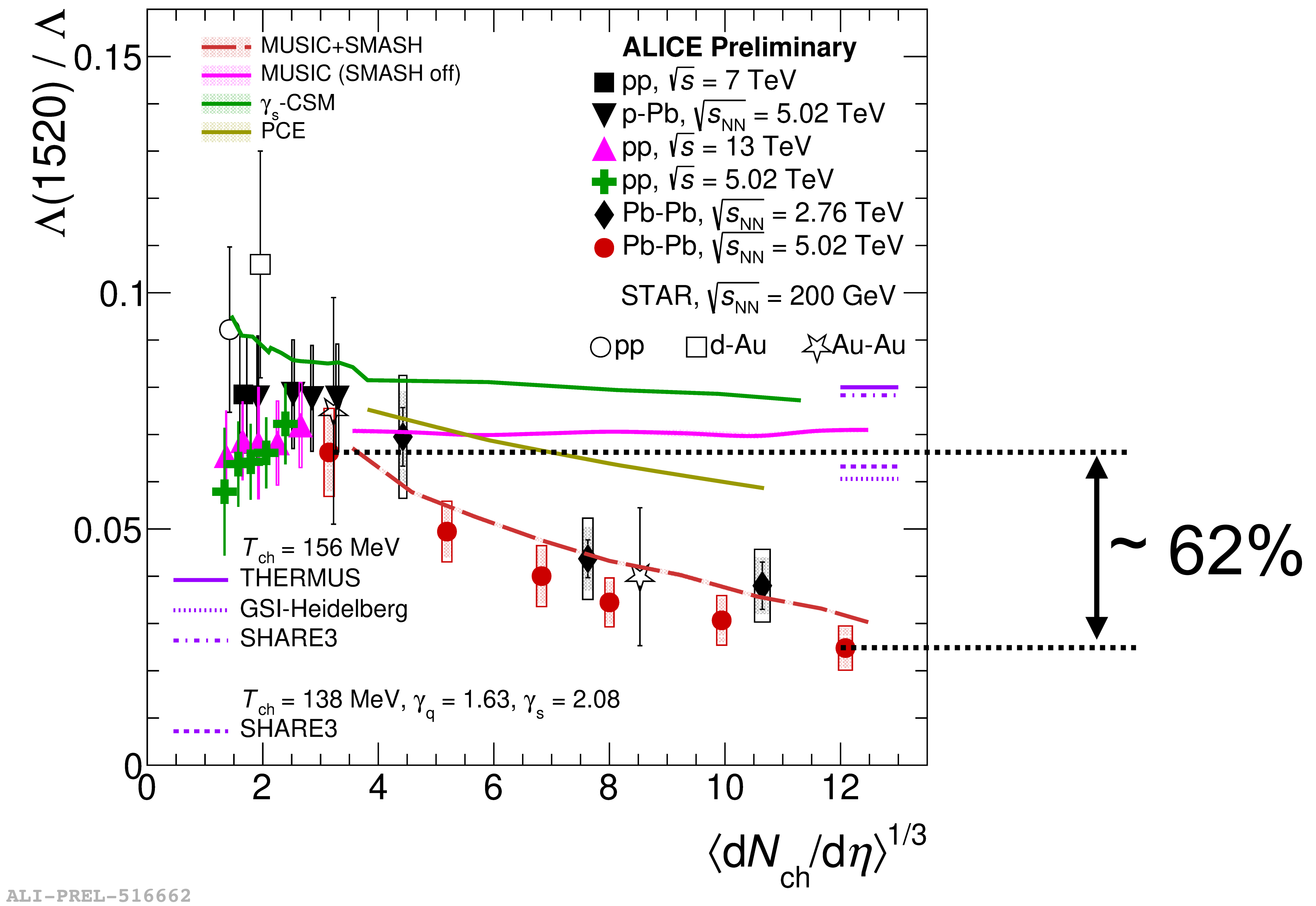
$$\tau_{K^*} = (4.17 \pm 0.04)\ \mathrm{fm/c}$$
$$\tau_{\Lambda^*} = (12.6 \pm 0.8)\ \mathrm{fm/c}$$

Larger suppression for Λ^*/Λ wrt K*/K despite Λ^* has longer lifetime

> lifetime is not a good predictor

Strangeness and Resonances





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Larger suppression for Λ^*/Λ wrt K*/K despite Λ^* has longer lifetime

> lifetime is not a good predictor

Resonances in relative thermodynamic equilibrium with stable hadrons

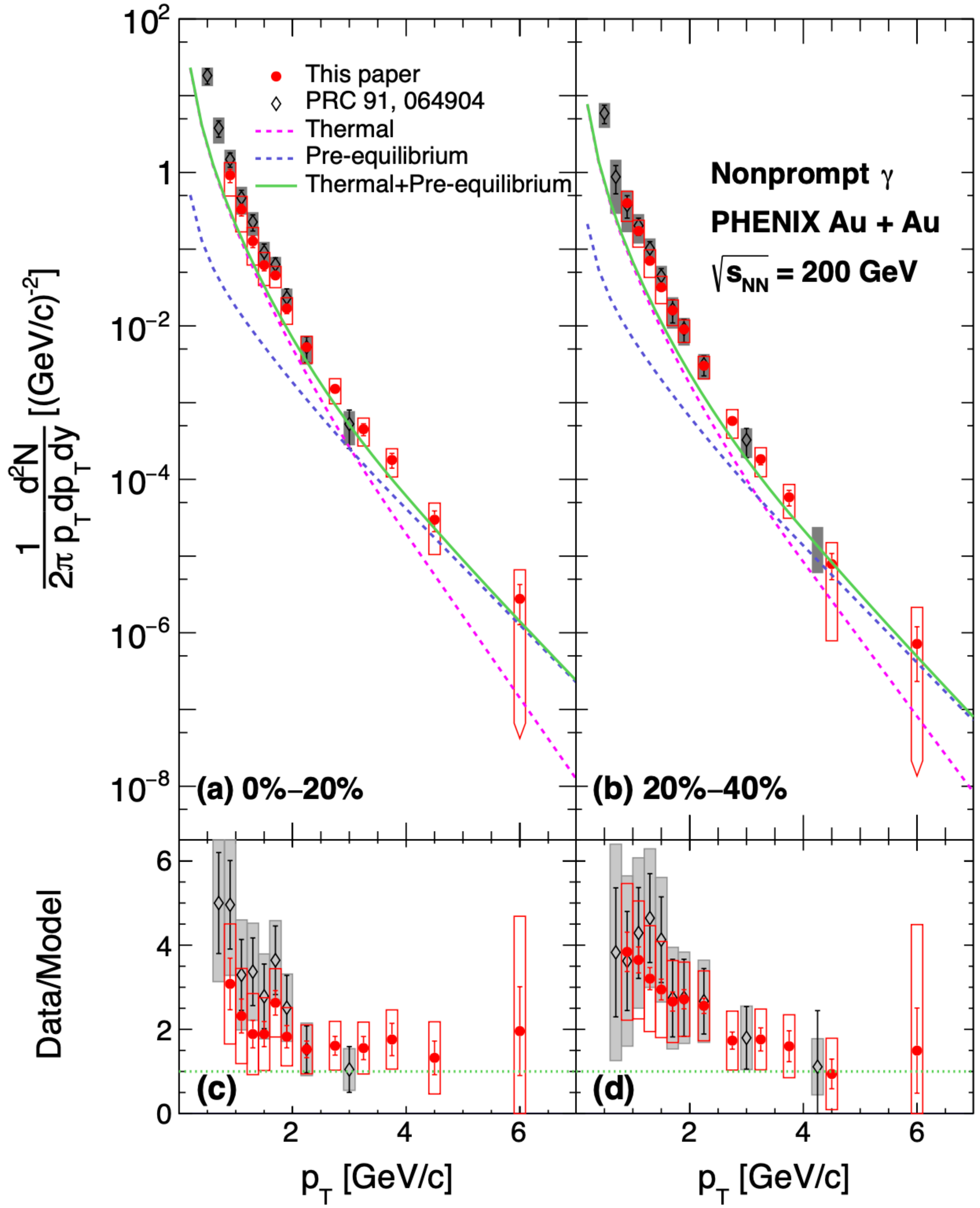
> yields frozen at $T_{kin} < T_{chem}$ → suppression (independent on resonance lifetime)

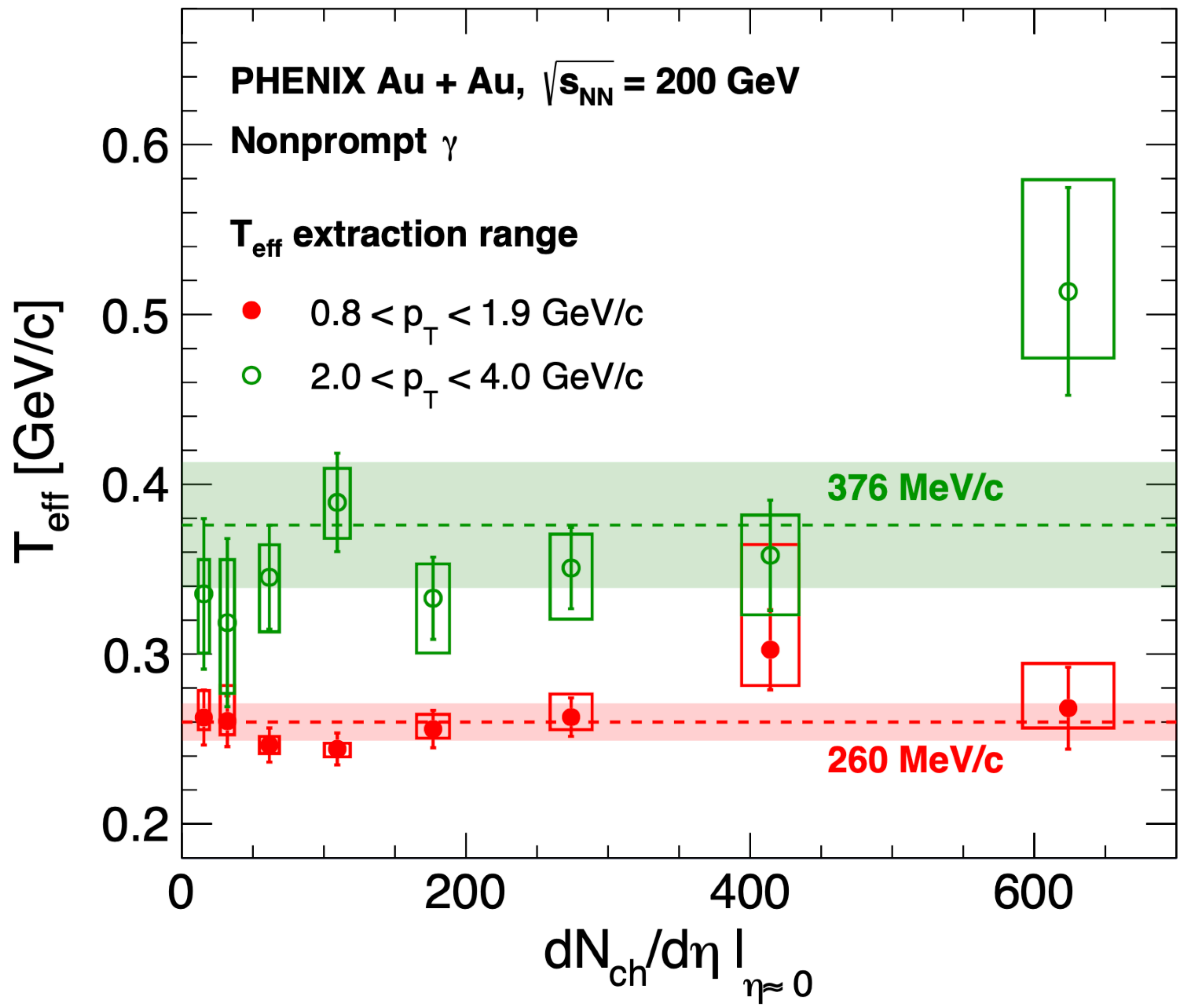
Phys. Rev. C 102, 024909 (2020)

Direct photons and dileptons

Direct photons at RHIC

Non-prompt direct photons: $(N_\gamma^{dir})_{AA} - N_{coll} \cdot (N_\gamma^{dir})_{pp}$ arXiv:2203.17187 [nucl-ex]





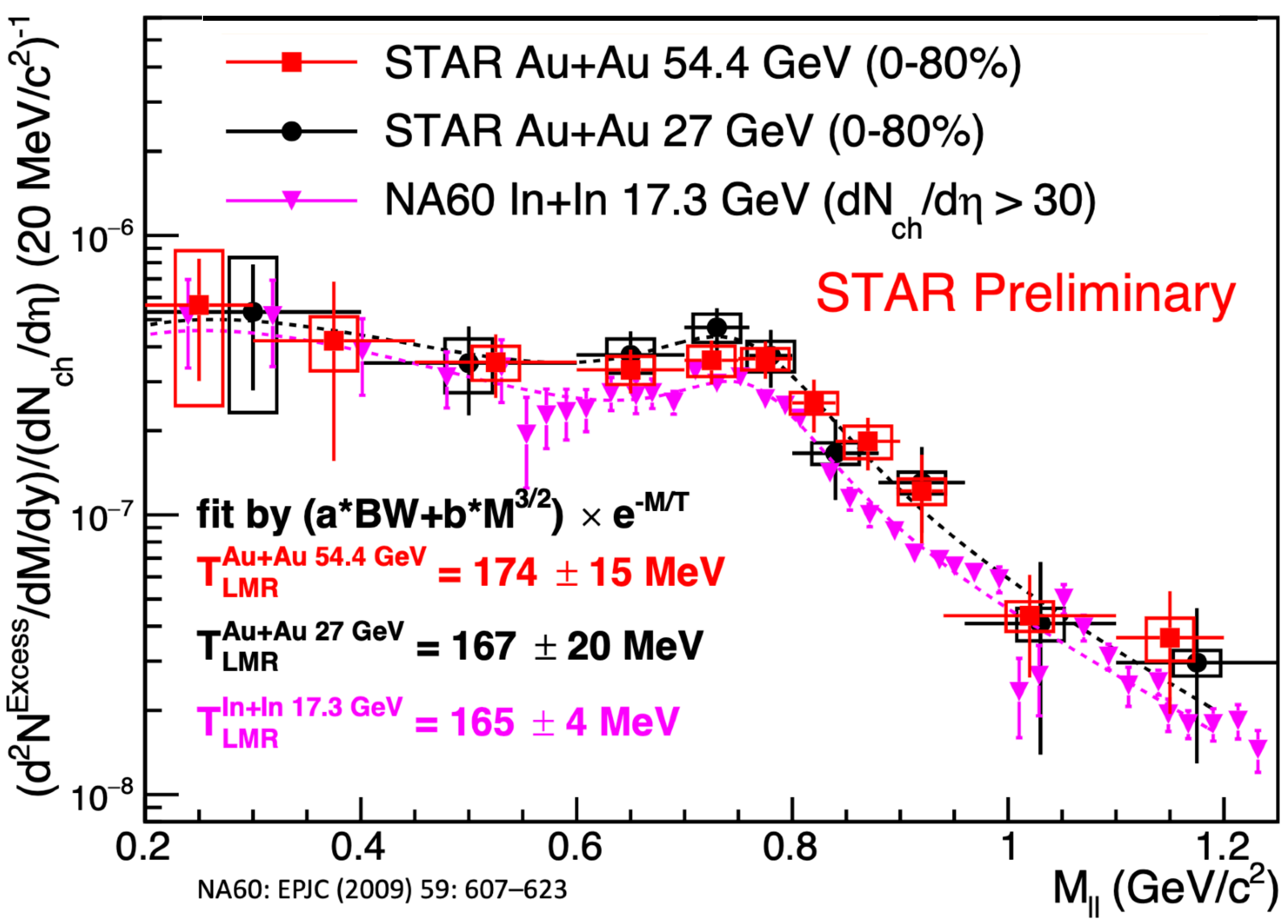
Fit with: $\exp(-p_T/T_{eff})$

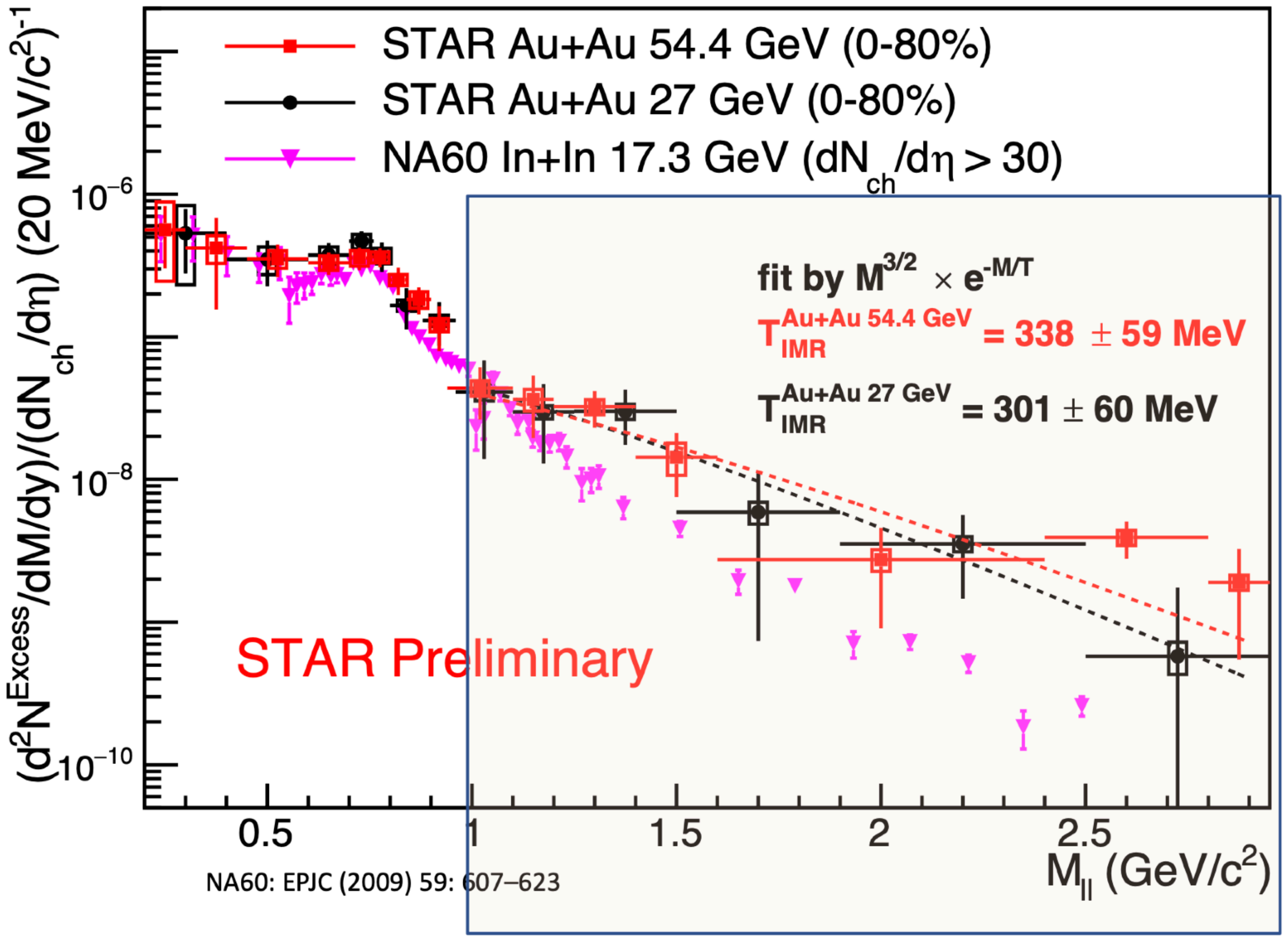
Inverse slope $\langle T_{eff} \rangle$ changes with the p_T

- sensitivity to different stages
- no significant multiplicity dependence

Medium temperature with dileptons

Excess spectrum = $\left(dN/dM_{ll}\right)_{\text{All}} - \left(dN/dM_{ll}\right)_{\text{hadron decays}}$



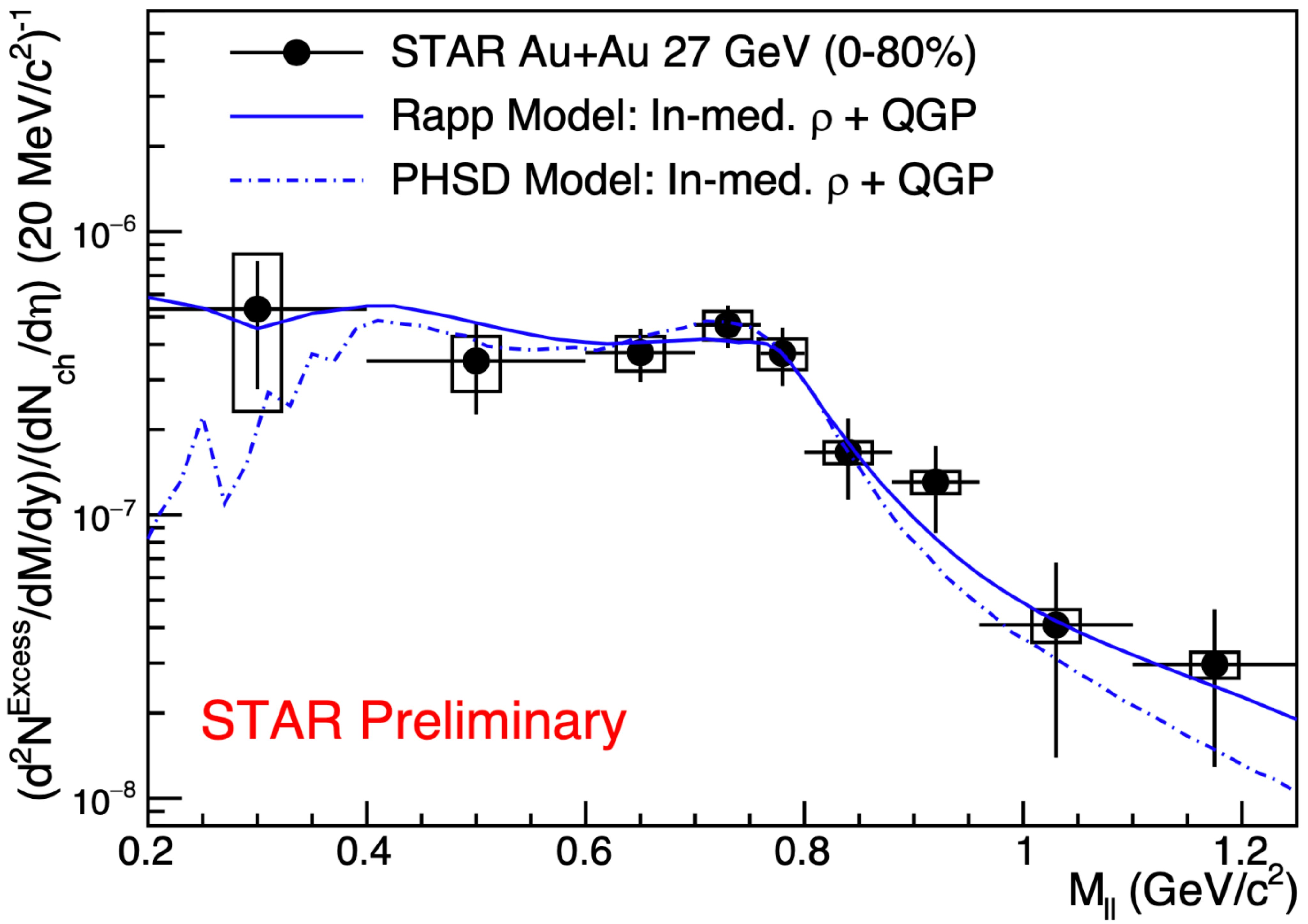


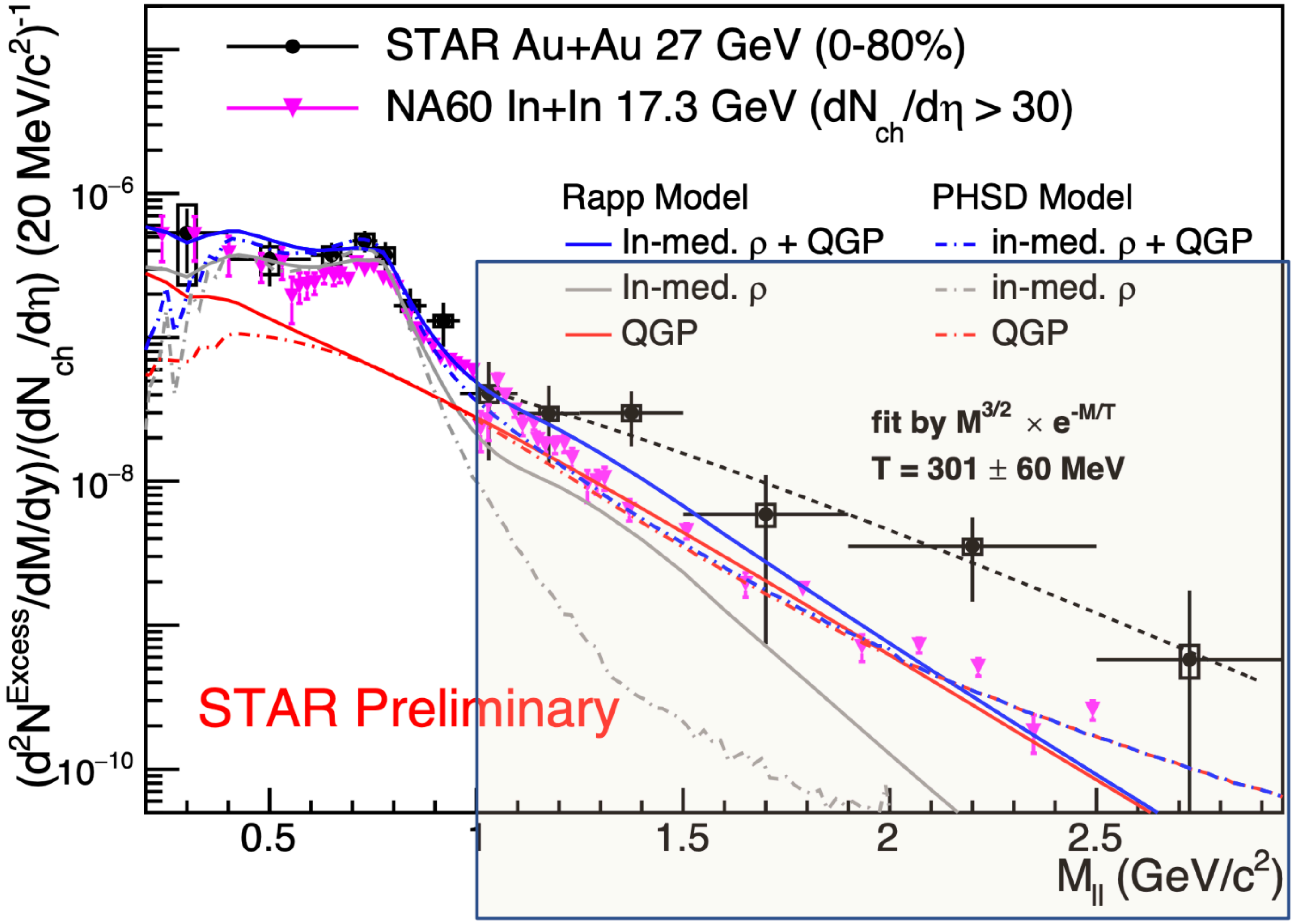
$\langle T \rangle$ extracted (no blue shift) from fit to excess dilepton spectra

- intermediate-mass region ($m > m_\rho$) sensitive to early QGP temperature (~300 MeV)
- QGP at RHIC is hotter and longer-lived than at SPS

Dilepton spectrum vs. models

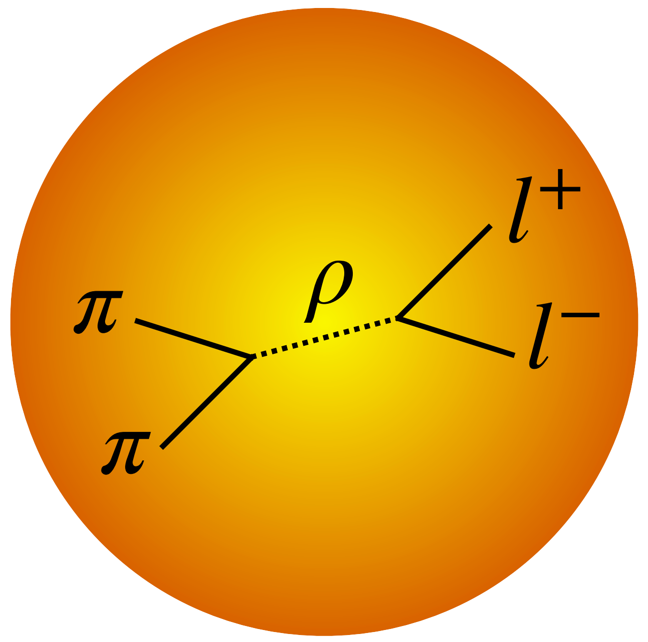
Excess spectrum = $\left(dN/dM_{ll}\right)_{\text{All}} - \left(dN/dM_{ll}\right)_{\text{hadron decays}}$



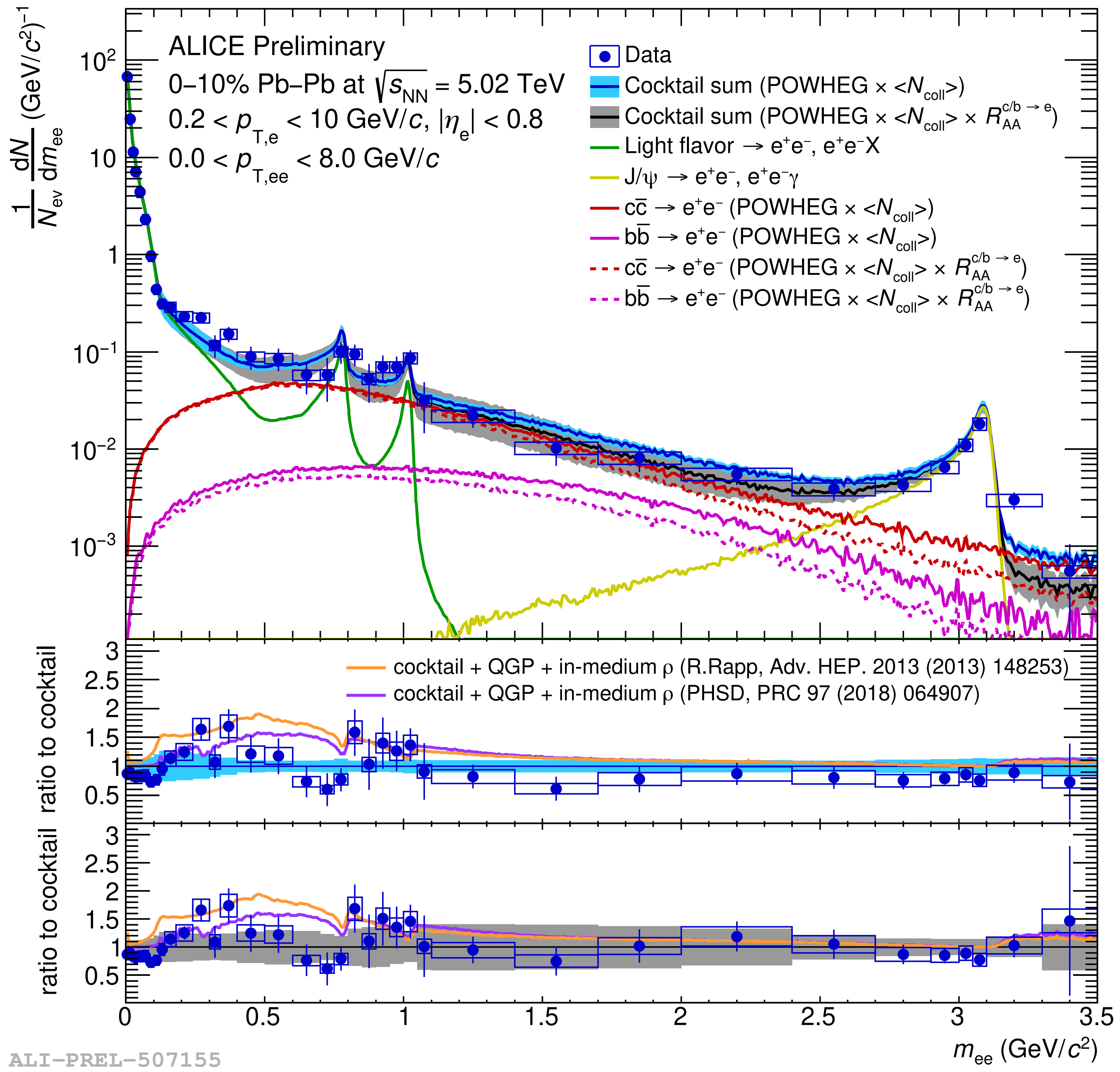


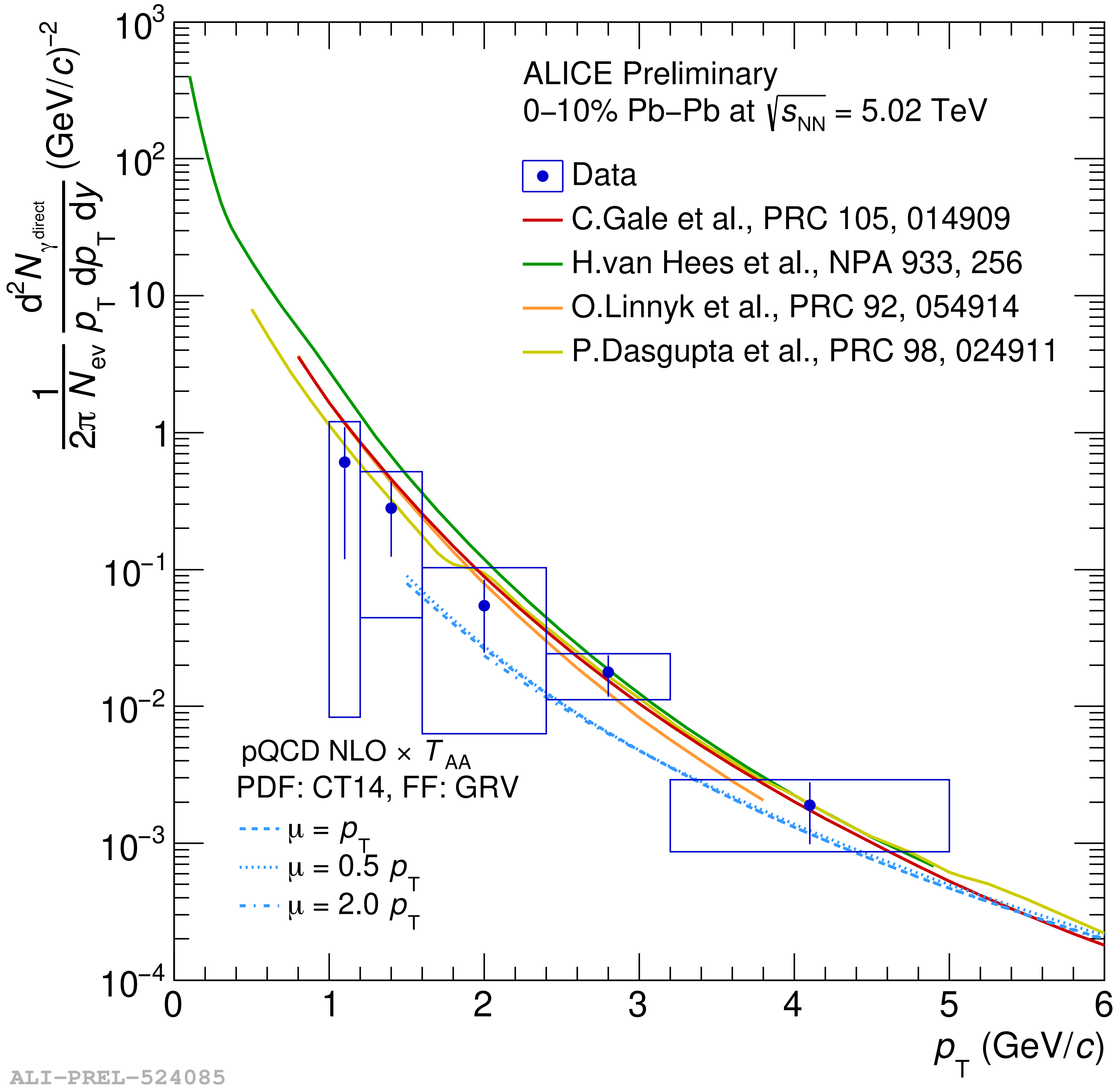
Models with in-medium ρ + QGP

- good description of the low-mass region
- underestimate the intermediate-mass region:
  > QGP is hotter than model expectations



Dileptons at the LHC





Direct photon spectrum:

$$\gamma_{\rm dir} = \frac{\gamma^*_{\rm dir}}{\gamma^*_{\rm incl}} \cdot (\gamma_{\rm incl})_{\rm real}$$

Dilepton spectrum at LHC consistent with hadronic cocktail + QGP with in-medium ρ

First measurement of direct γ in Pb-Pb at 5.02 TeV:

- High p_T: prompt photons consistent with pQCD
- Low p_T: data consistent with models containing in addition pre-eq. + thermal photons

Summary

Detailed characterization of QGP properties

In-depth understanding of a large variety of phenomena have been achieved

Exciting times are ahead

- re-start of LHC
- sPHENIX at RHIC
- future detectors and upgrades
- …

Summary

Detailed characterization of QGP properties

In-depth understanding of a large variety of phenomena have been achieved

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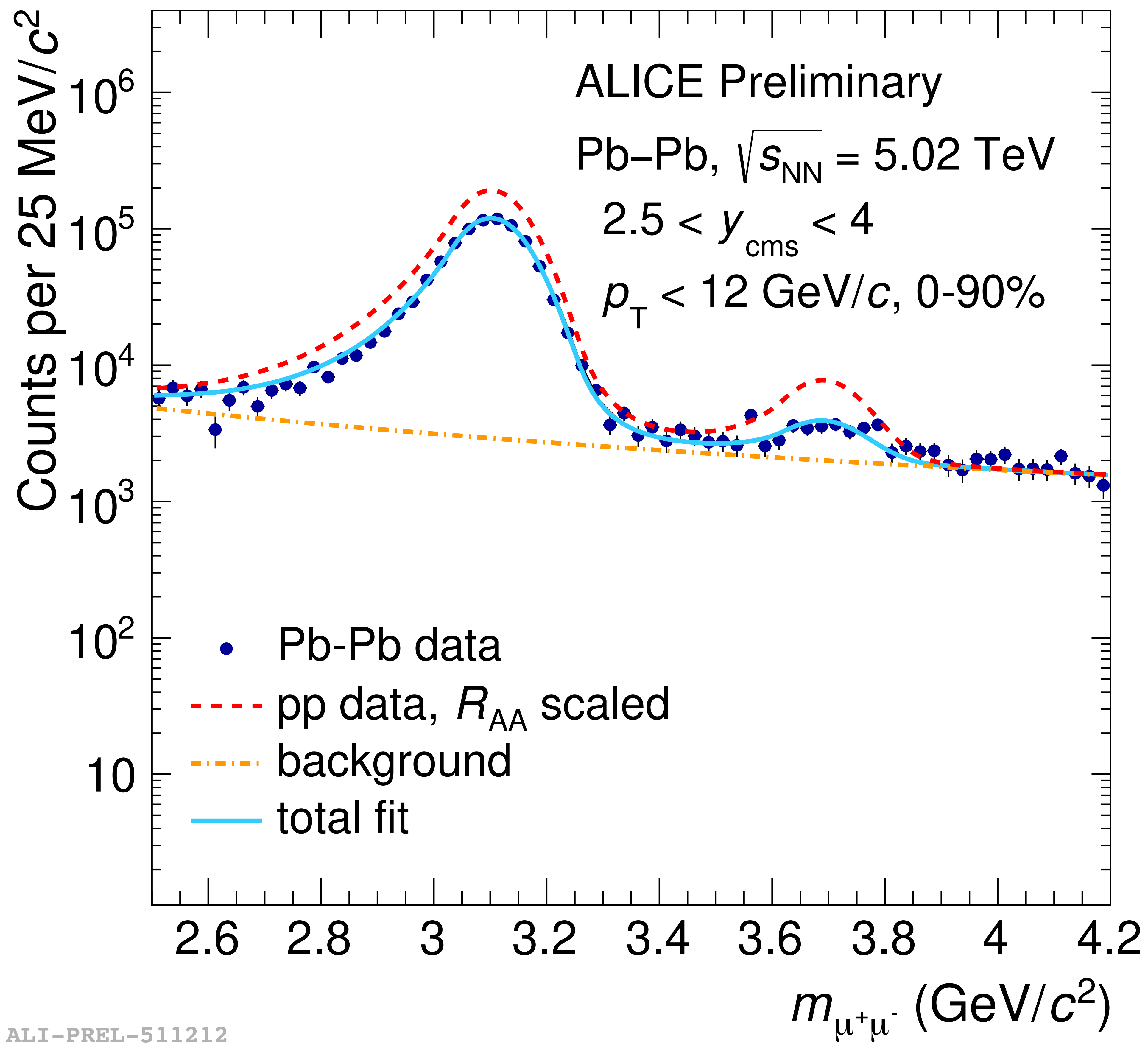
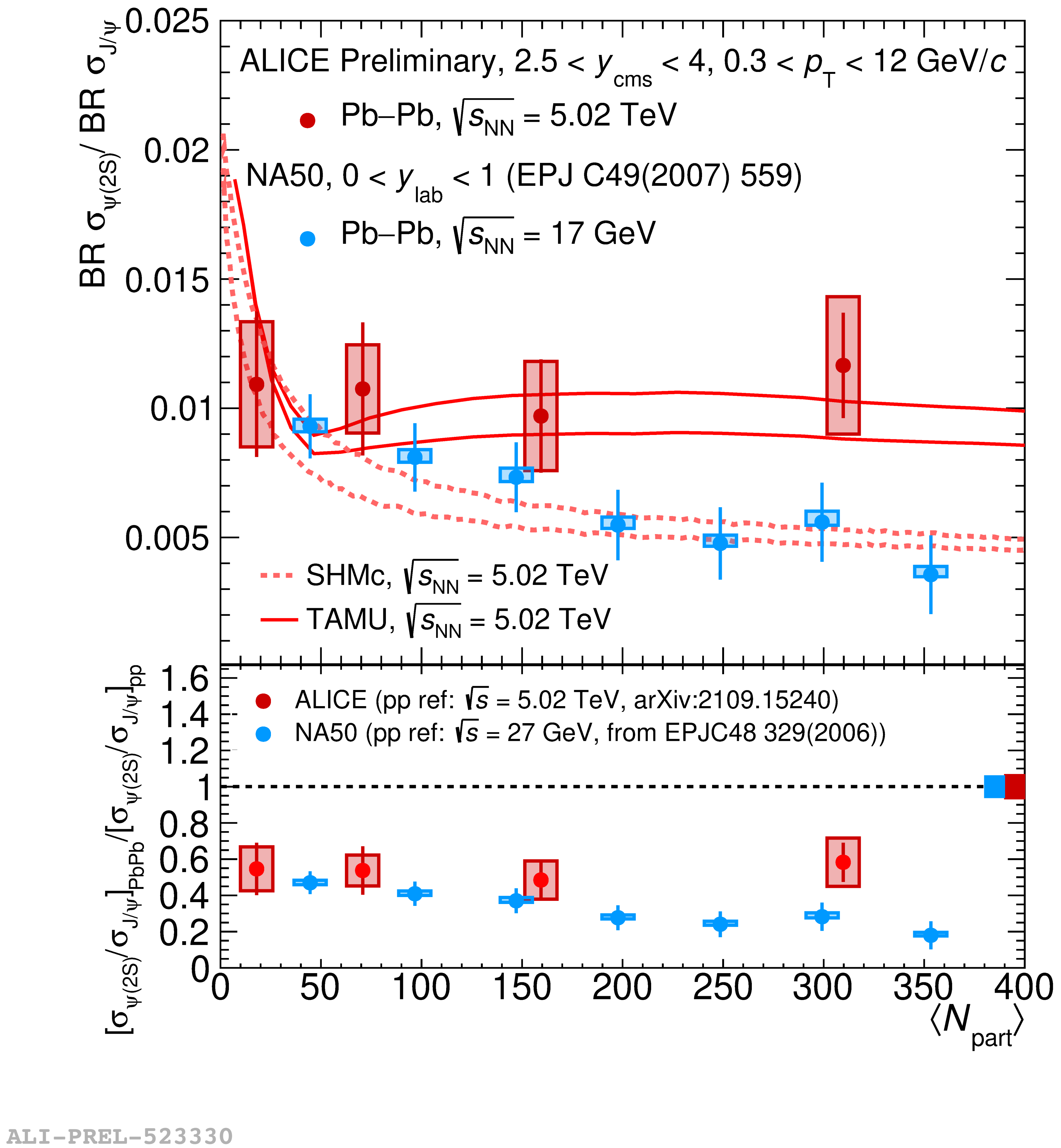
Thank you for your attention!

Backup slides

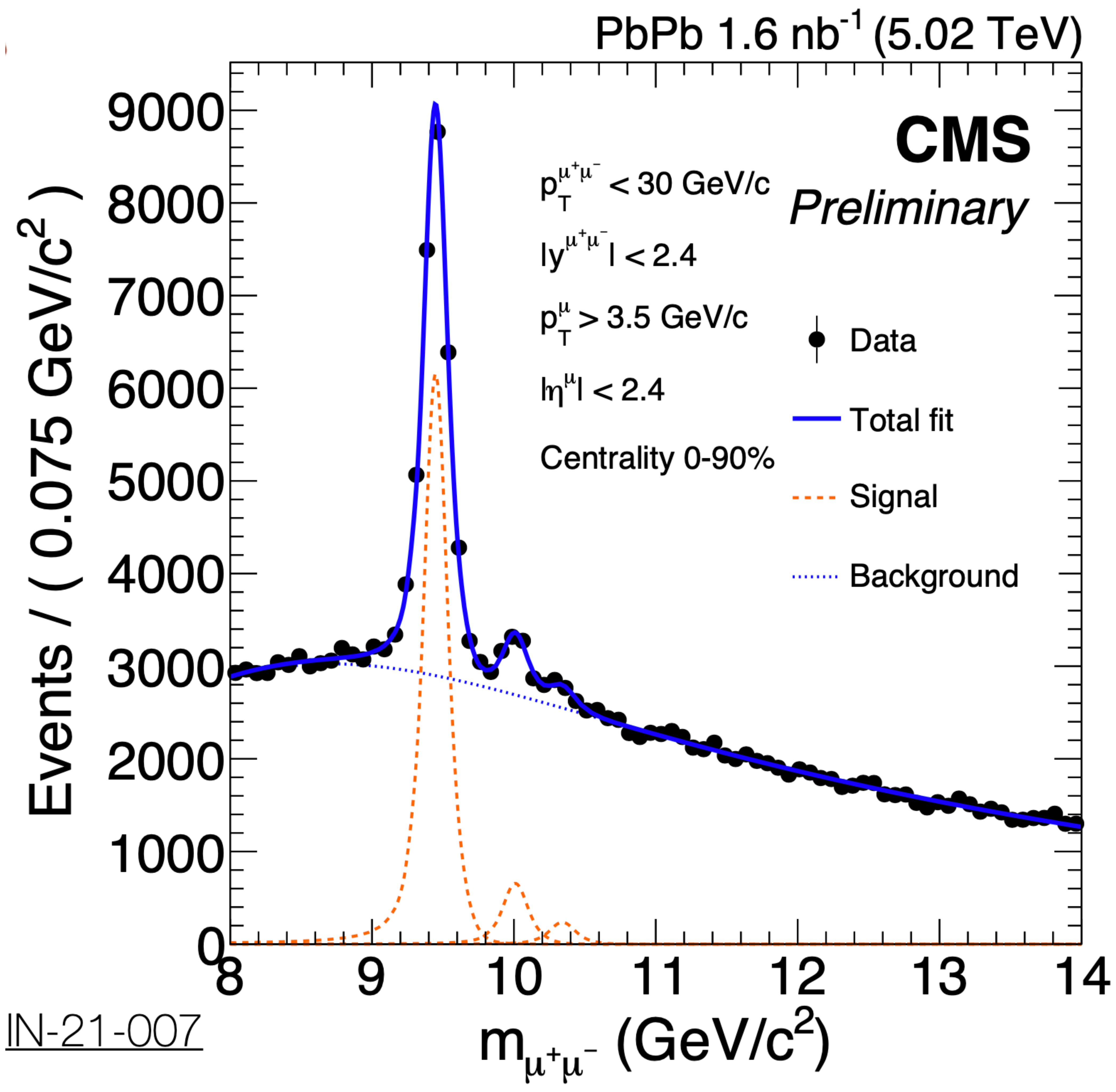
Charmonium suppression





Clear hierarchy of suppression between J/ψ and ψ(2S) for all centralities.

Υ (3S) in Pb-Pb collisions

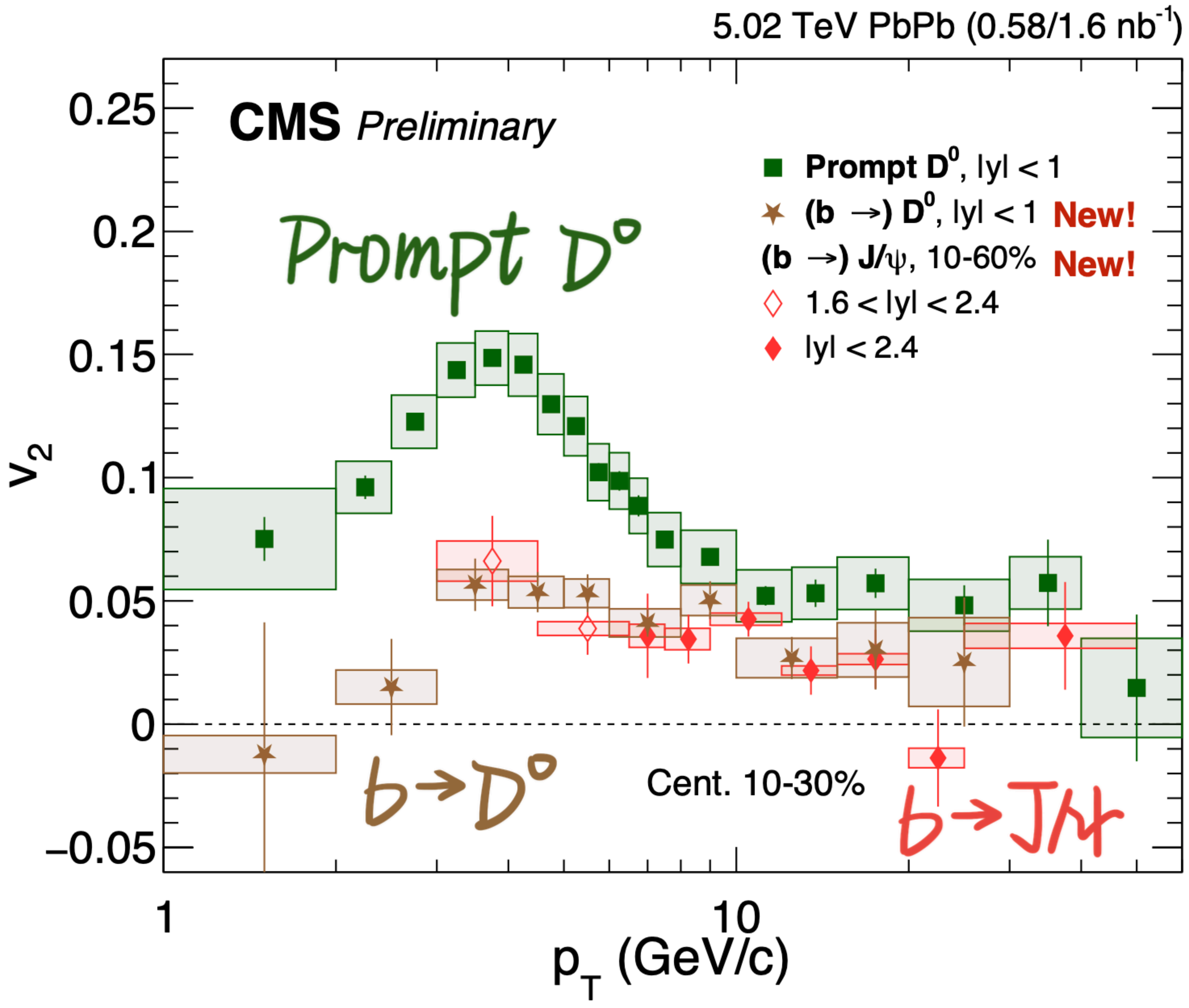


IN-21-007

First observation of Υ(3S) in PbPb collisions

Signal significance > 5σ

Heavy flavor v_2



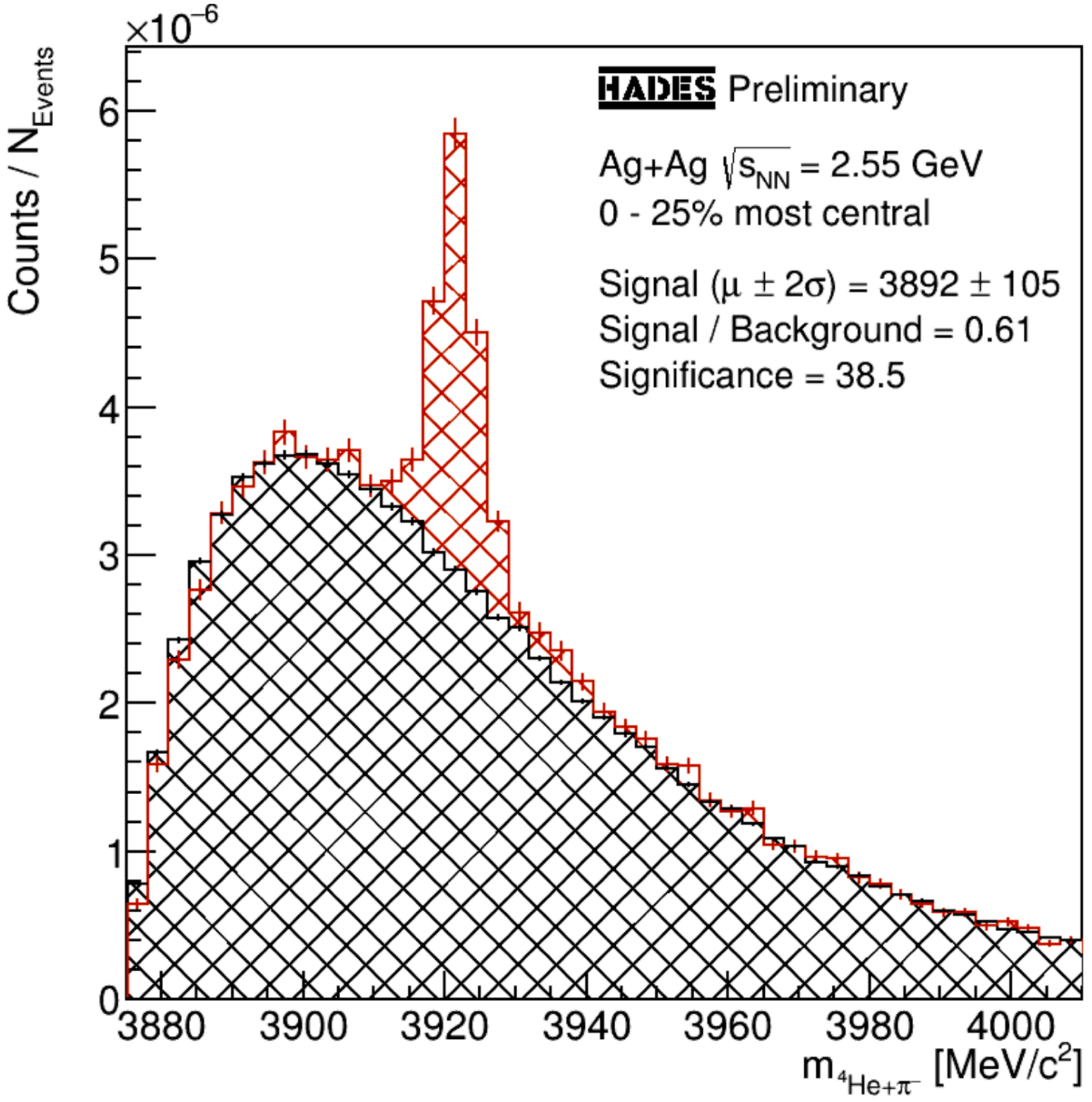
(b→) D^0 v_2 consistent with (b→) J/ψ v_2

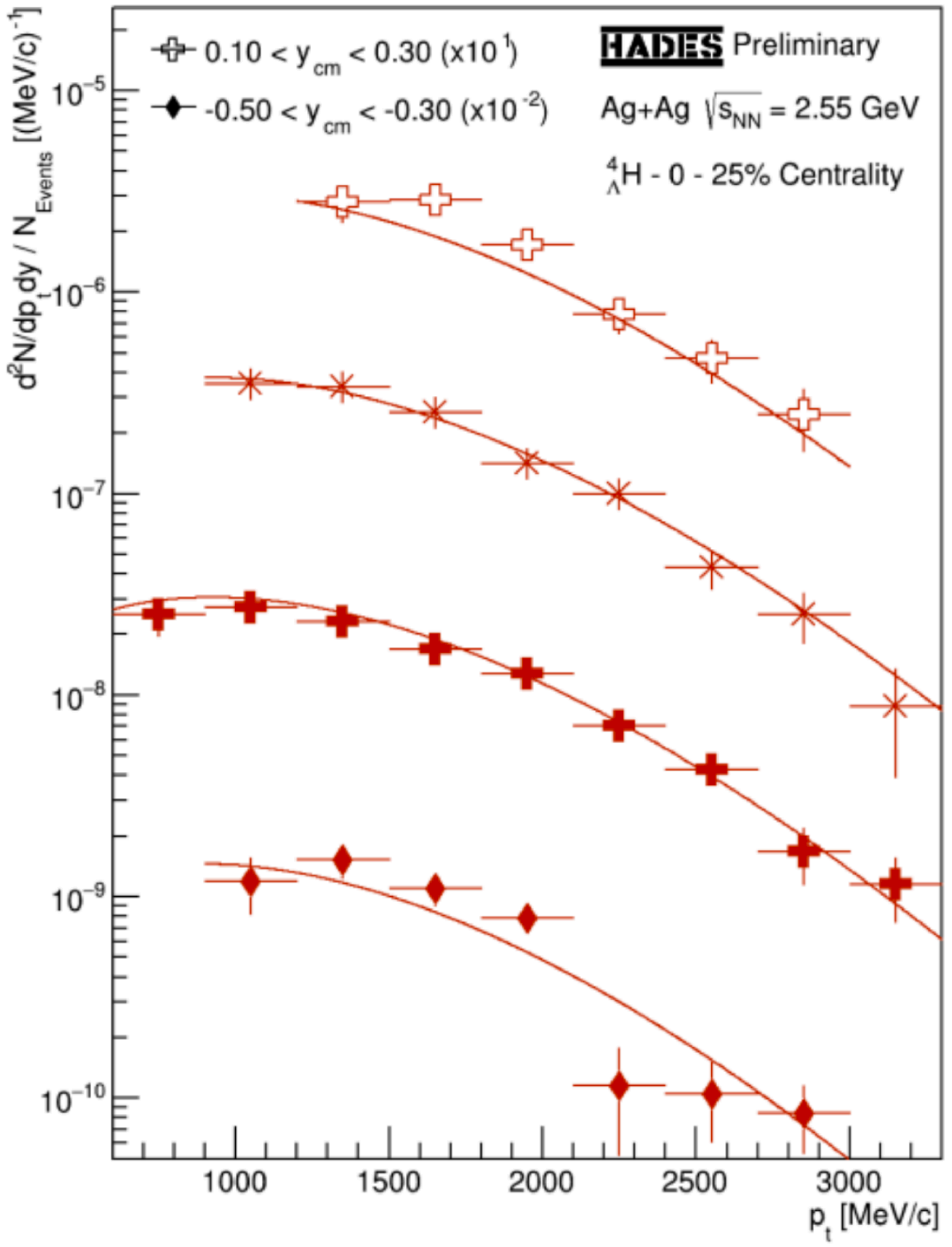
Low p_T: Smaller than prompt D^0 v_2

> Weaker collective motion of bottom than charm

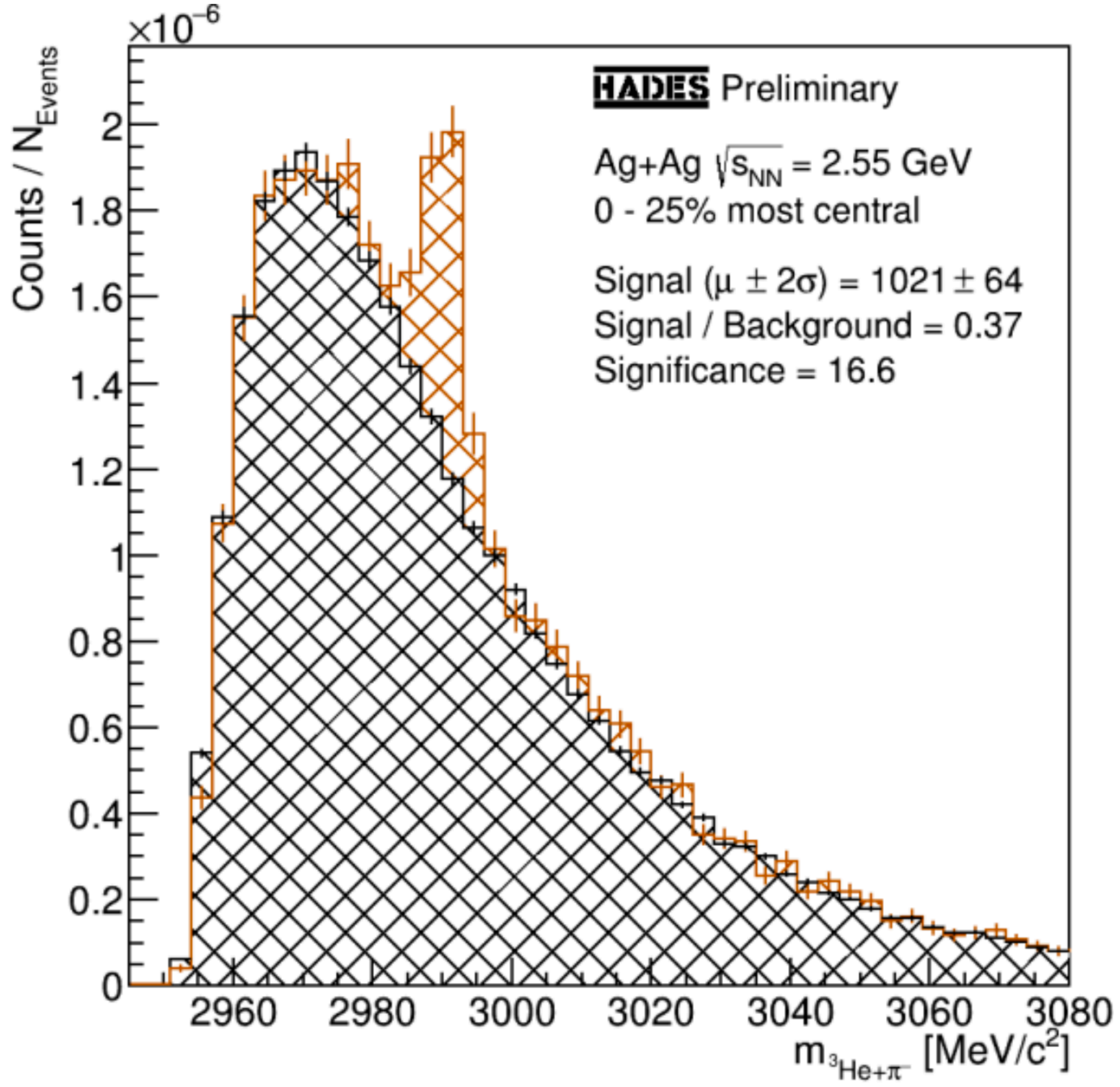
High p_T: v_2 of charm and bottom converge toward similar values

${}^{4}_{\Lambda}H$

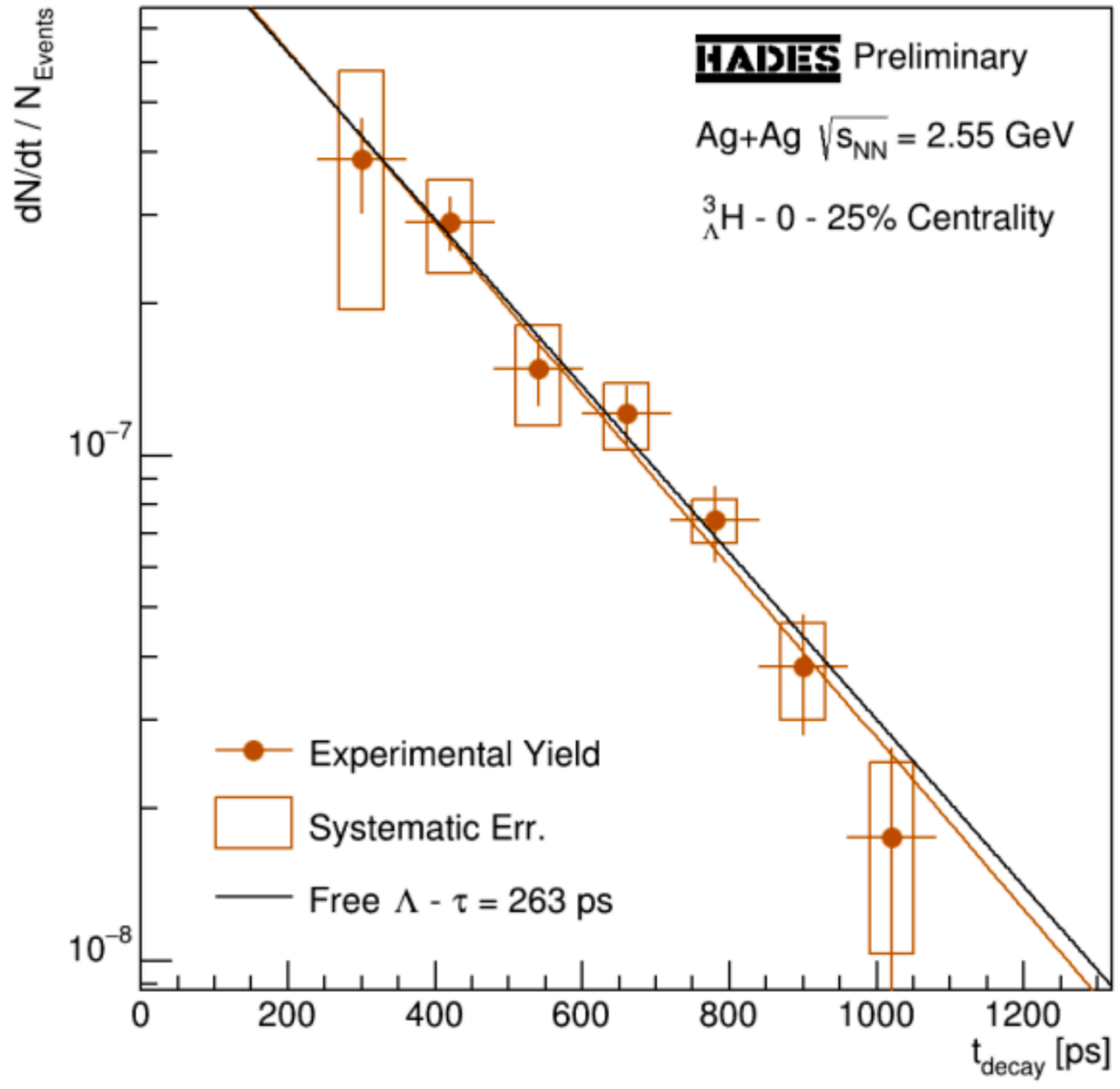

HADES Preliminary
Ag+Ag √sNN = 2.55 GeV
0 - 25% most central
Signal (μ ± 2σ) = 3892 ± 105
Signal / Background = 0.61
Significance = 38.5
Counts / NEvents
×10^-6
m4He+π− [MeV/c2]
3880 3900 3920 3940 3960 3980 4000


0.10 < ycm < 0.30 (x10^1)
-0.50 < ycm < -0.30 (x10^-2)
HADES Preliminary
Ag+Ag √sNN = 2.55 GeV
4ΛH - 0 - 25% Centrality
d2N/dptdy / NEvents [(MeV/c)-1]
pt [MeV/c]
1000 1500 2000 2500 3000

${}^{3}_{\Lambda}H$

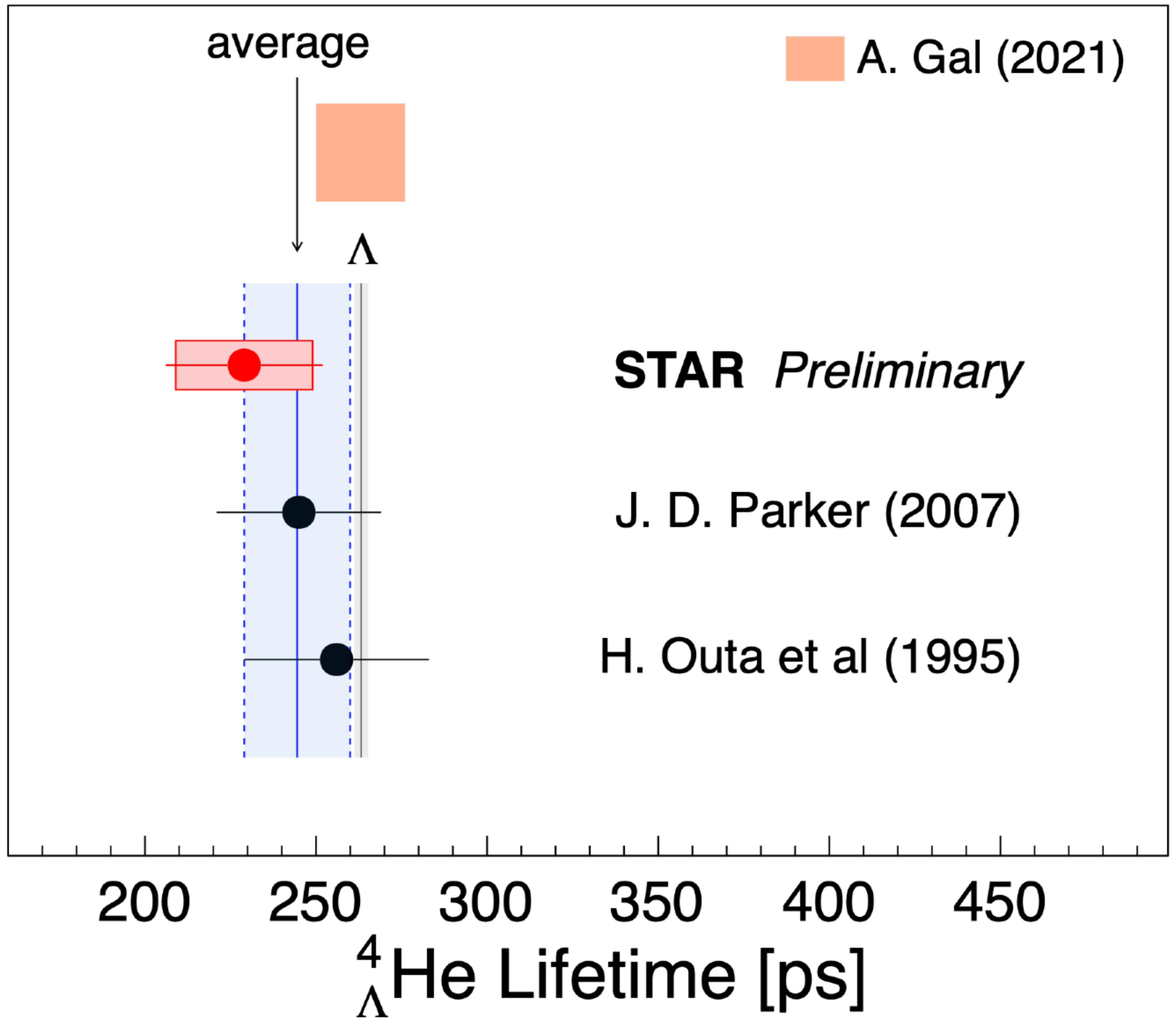


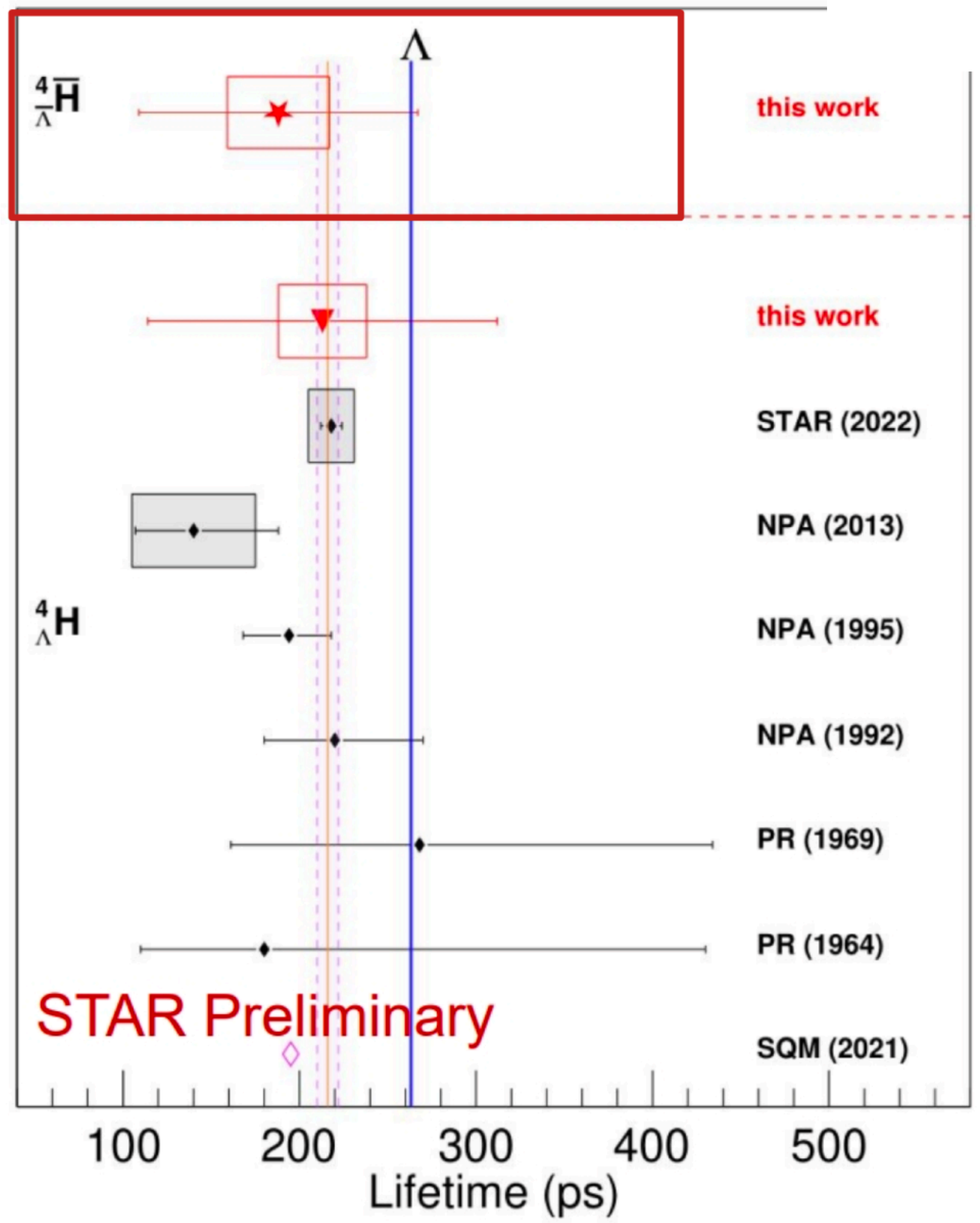
HADES Preliminary
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
0 - 25% most central
Signal ($\mu \pm 2\sigma$) = 1021 ± 64
Signal / Background = 0.37
Significance = 16.6
Counts / N_{Events}
$\times 10^{-6}$
$m_{^3He+\pi^-}$ [MeV/c^2]



HADES Preliminary
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV
${}^{3}_{\Lambda}H$ - 0 - 25% Centrality
Experimental Yield
Systematic Err.
Free Λ - τ = 263 ps
dN/dt / N_{Events}
t_{decay} [ps]

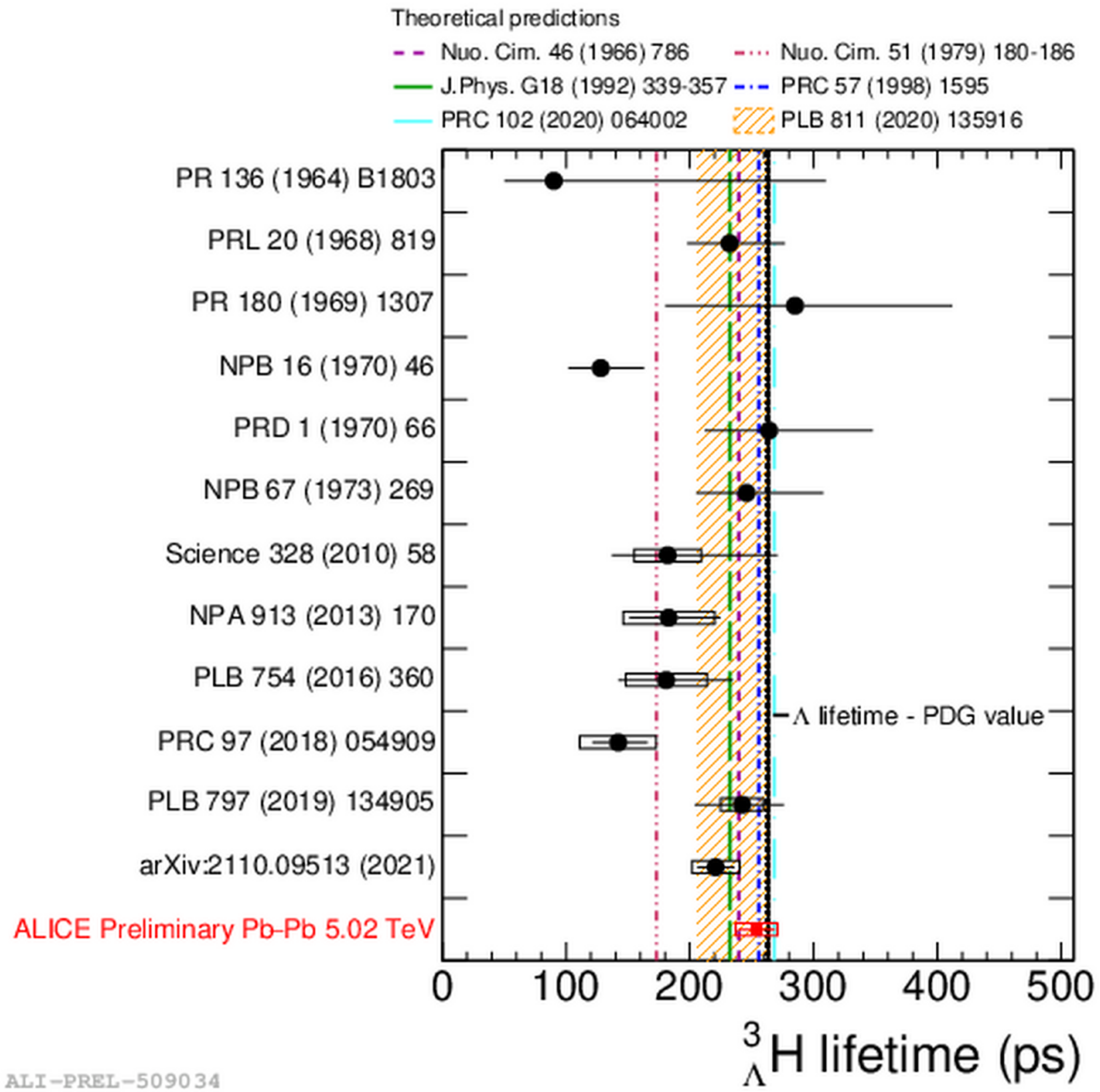
Hypernuclei lifetimes

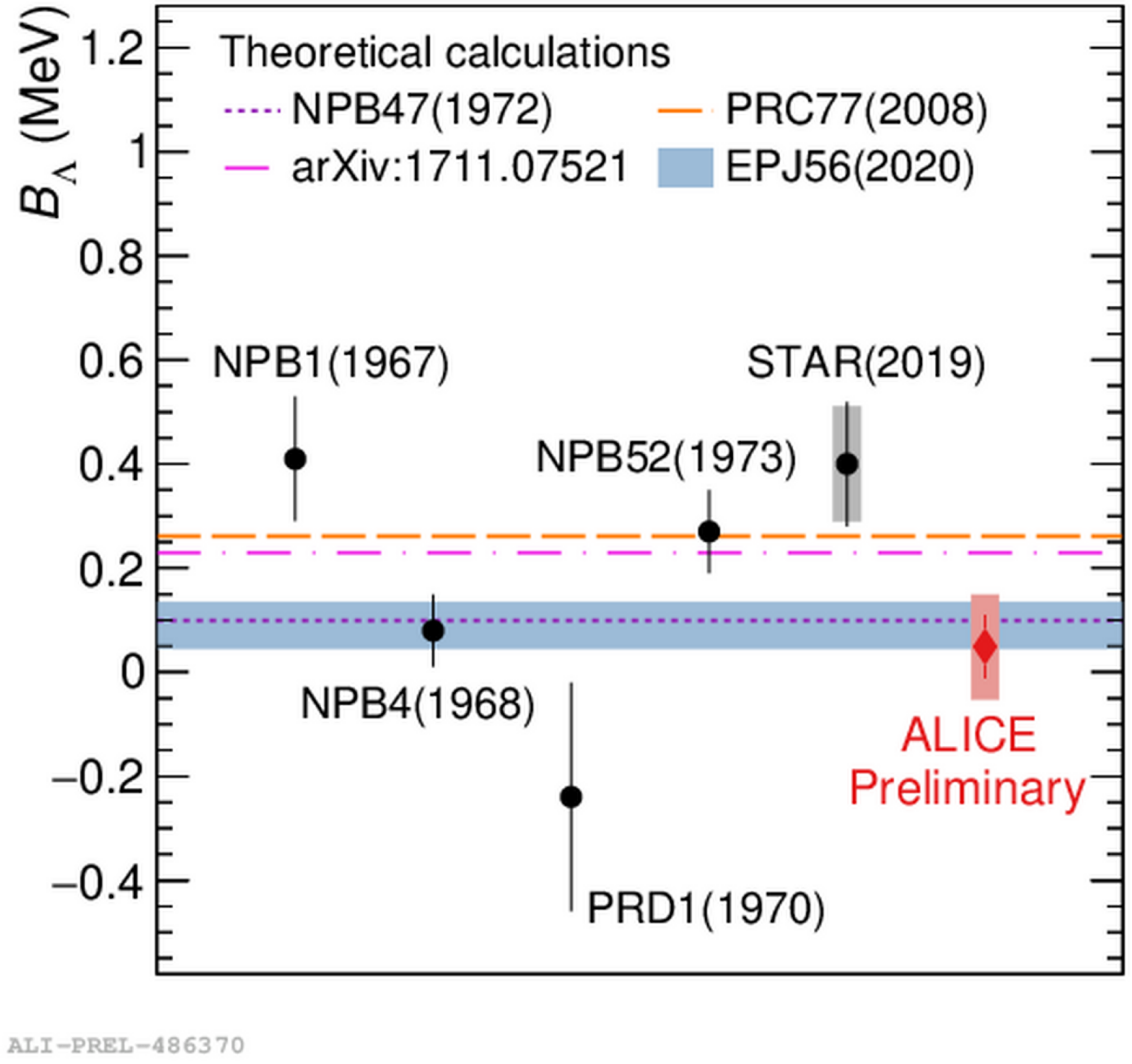




Precision hypernuclei measurements at BES-II (19.6, 27, FXT 3.0, 7.2 GeV) and top RHIC energy (200 GeV)

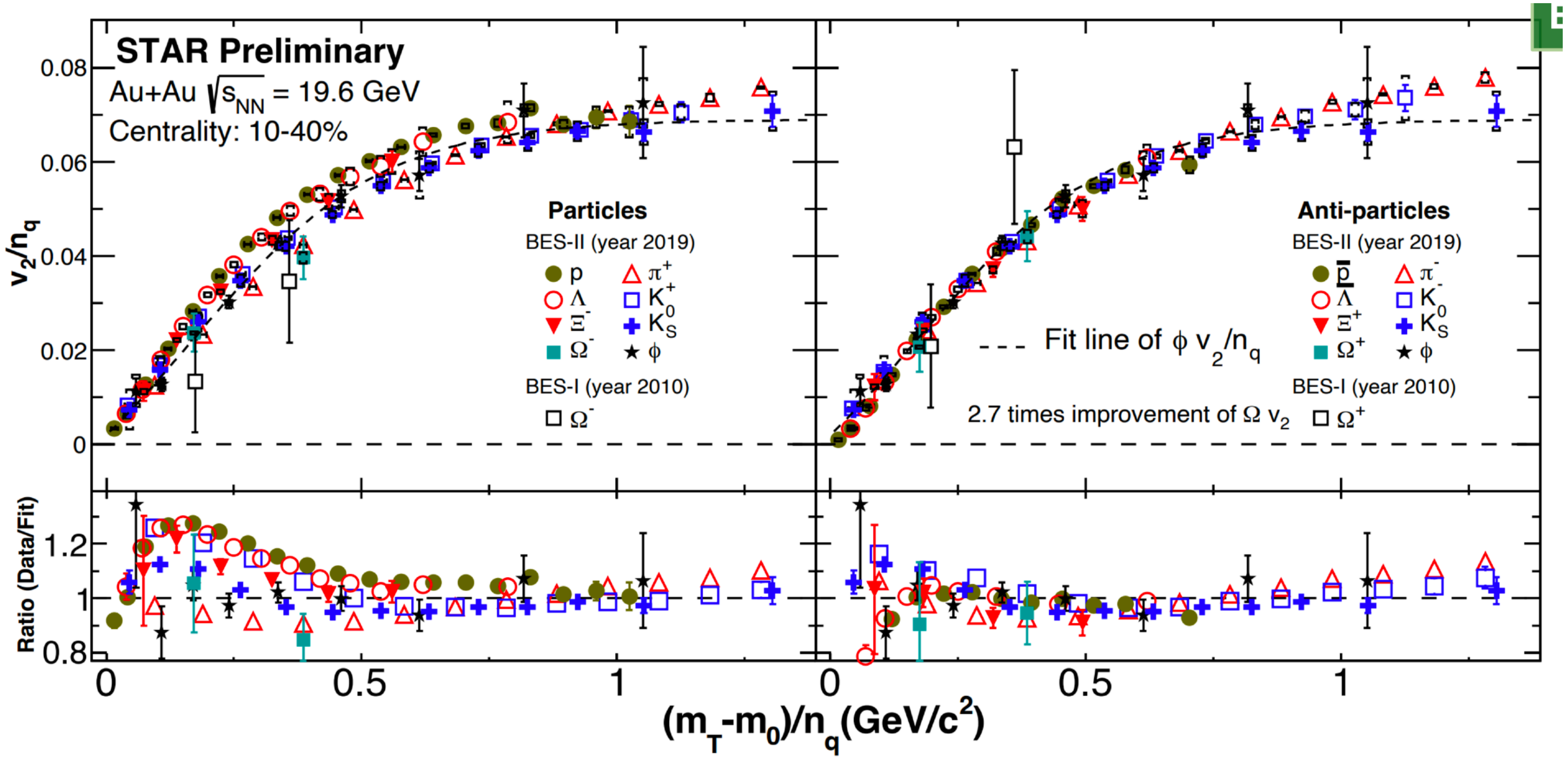
${}^{3}_{\Lambda}H$ Lifetime and B_{Λ}

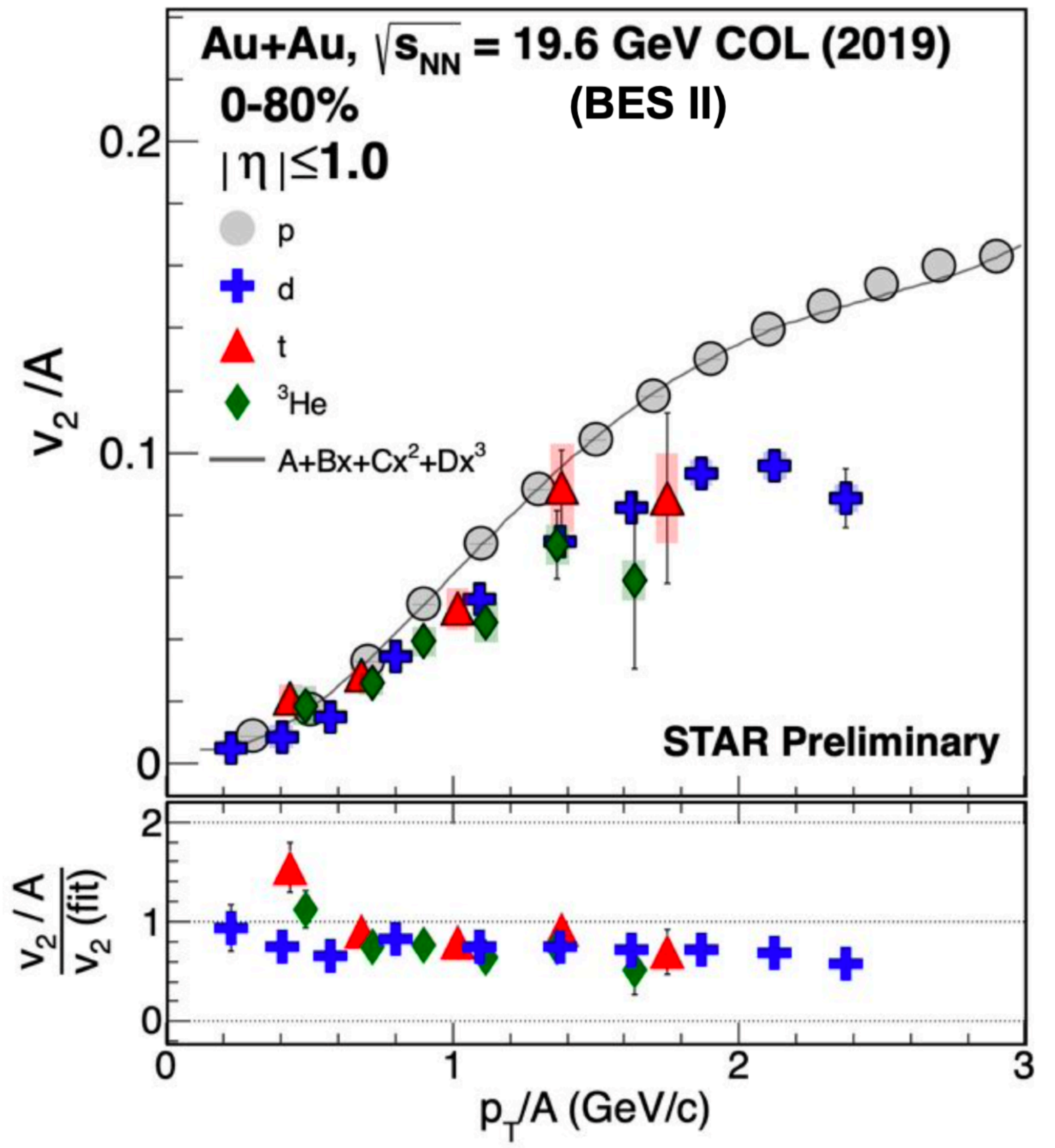




Hypertriton lifetime and Λ separation energy (B_{Λ}) measured by ALICE
> consistent with weakly bound state

v_2 of strange hadrons and nuclei





Mass scaling at low $(m_T-m_0)/n_q$.

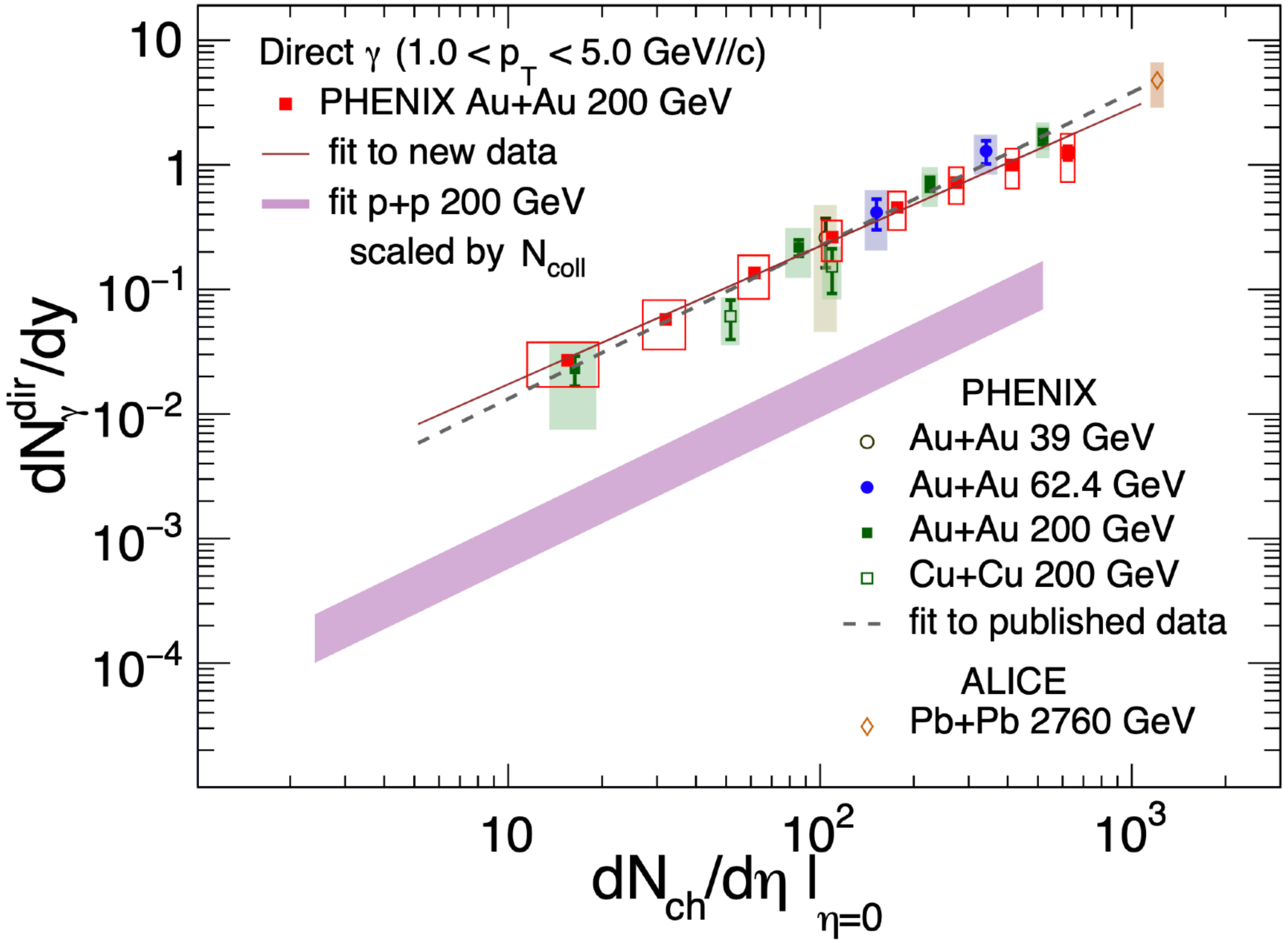
NCQ scaling at higher $(m_T-m_0)/n_q$

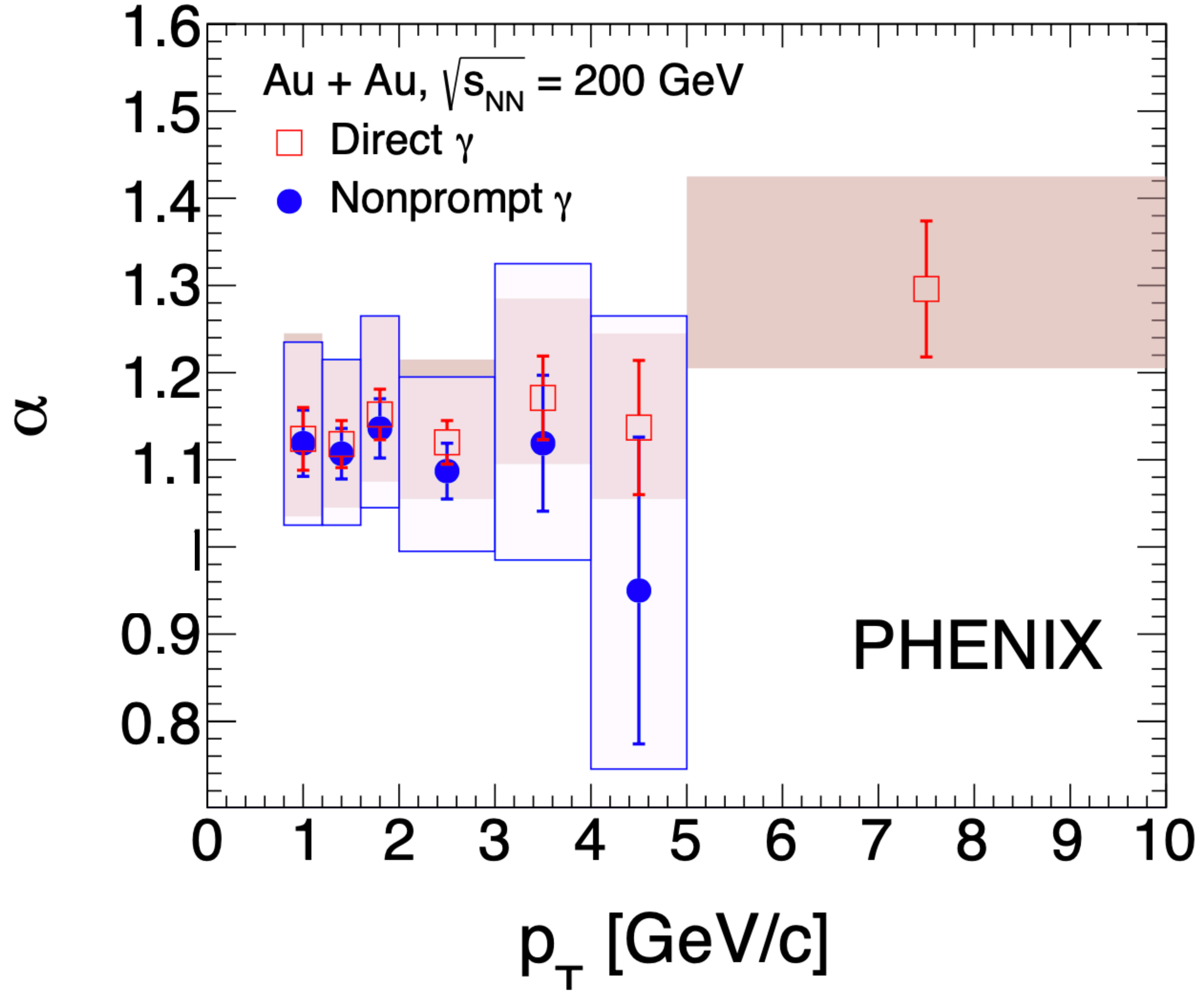
> works better for anti-particles (within 15%) → partonic collectivity

Systematic deviation of around 20-30% from mass number scaling observed for all light nuclei species at all measured energies

Direct photons at RHIC

arXiv:2203.17187 [nucl-ex]

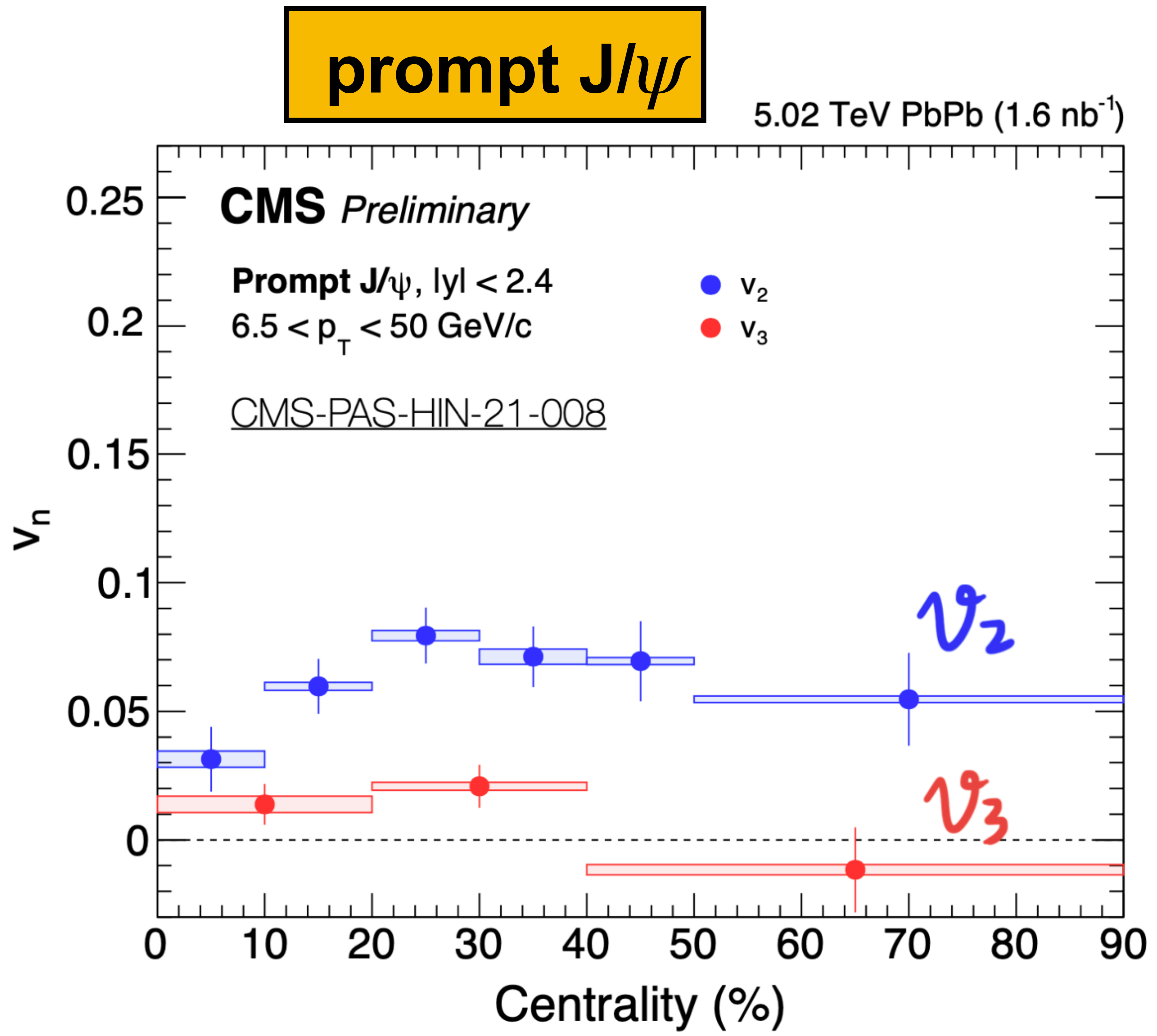


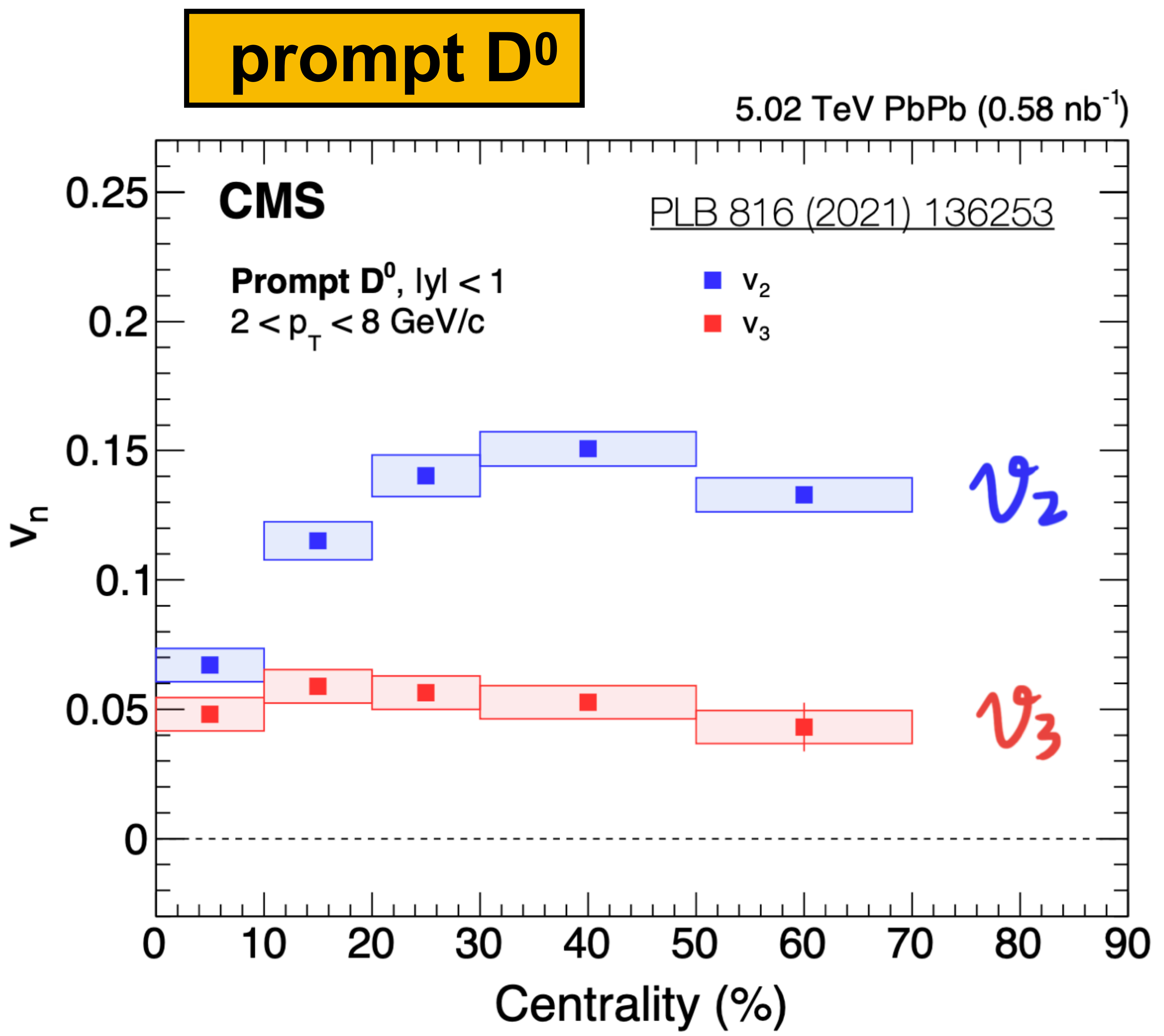


Measurement of direct photons using large data sample of Au-Au collisions of 2014

Scaling with multiplicity: $$\frac{\mathrm{dN}_\gamma^{\mathrm{dir}}}{\mathrm{dy}} = A \left(\frac{\mathrm{dN}_{\mathrm{ch}}}{\mathrm{d}\eta} \right)^{\alpha}$$ α independent of p_T

v_n of J/ψ vs. v_n of D mesons





v_2 of prompt J/ψ < v_2 of prompt D-mesons

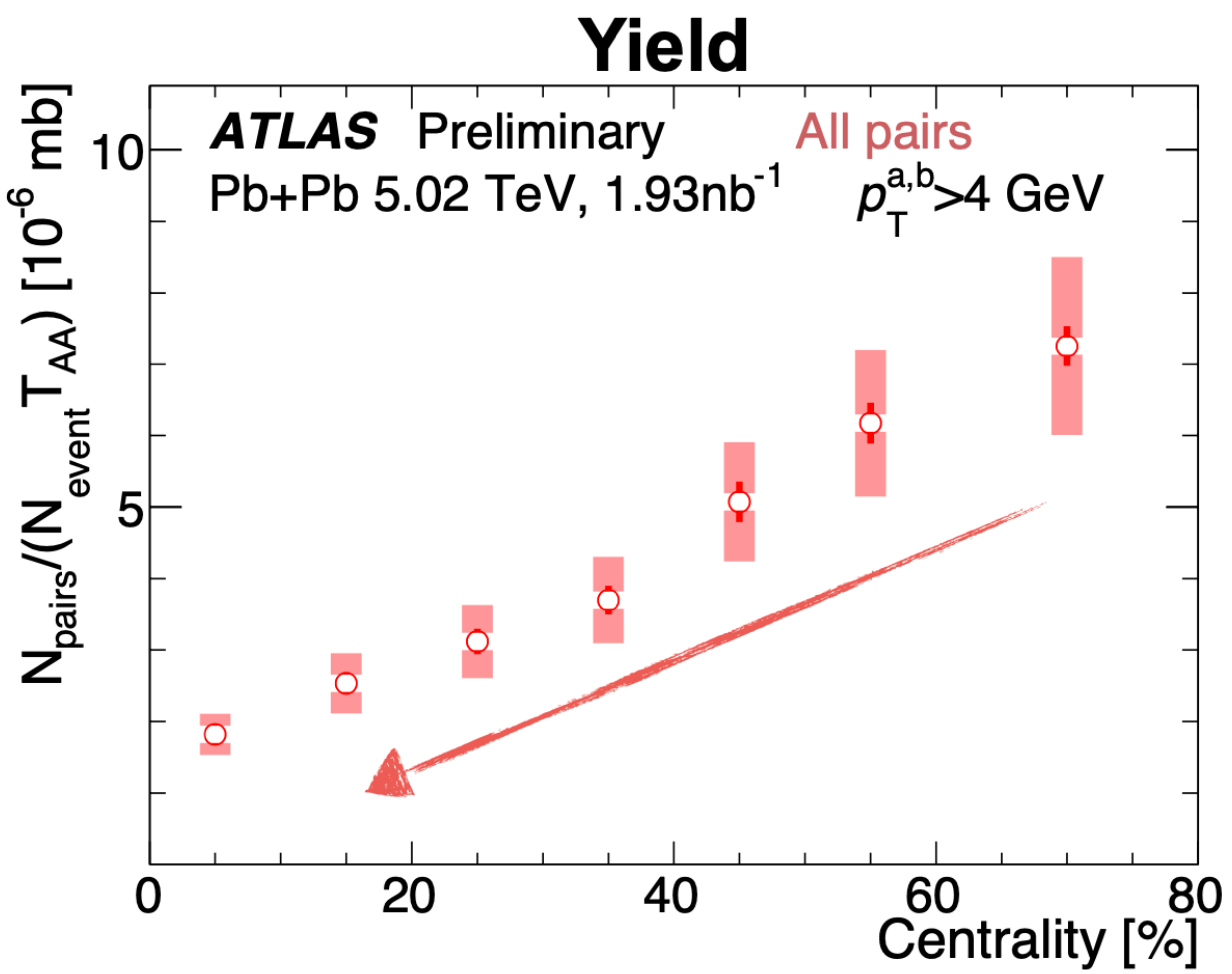
→ larger fraction of v_2 carried by light quarks (v_2: J/ψ < D < light hadrons)

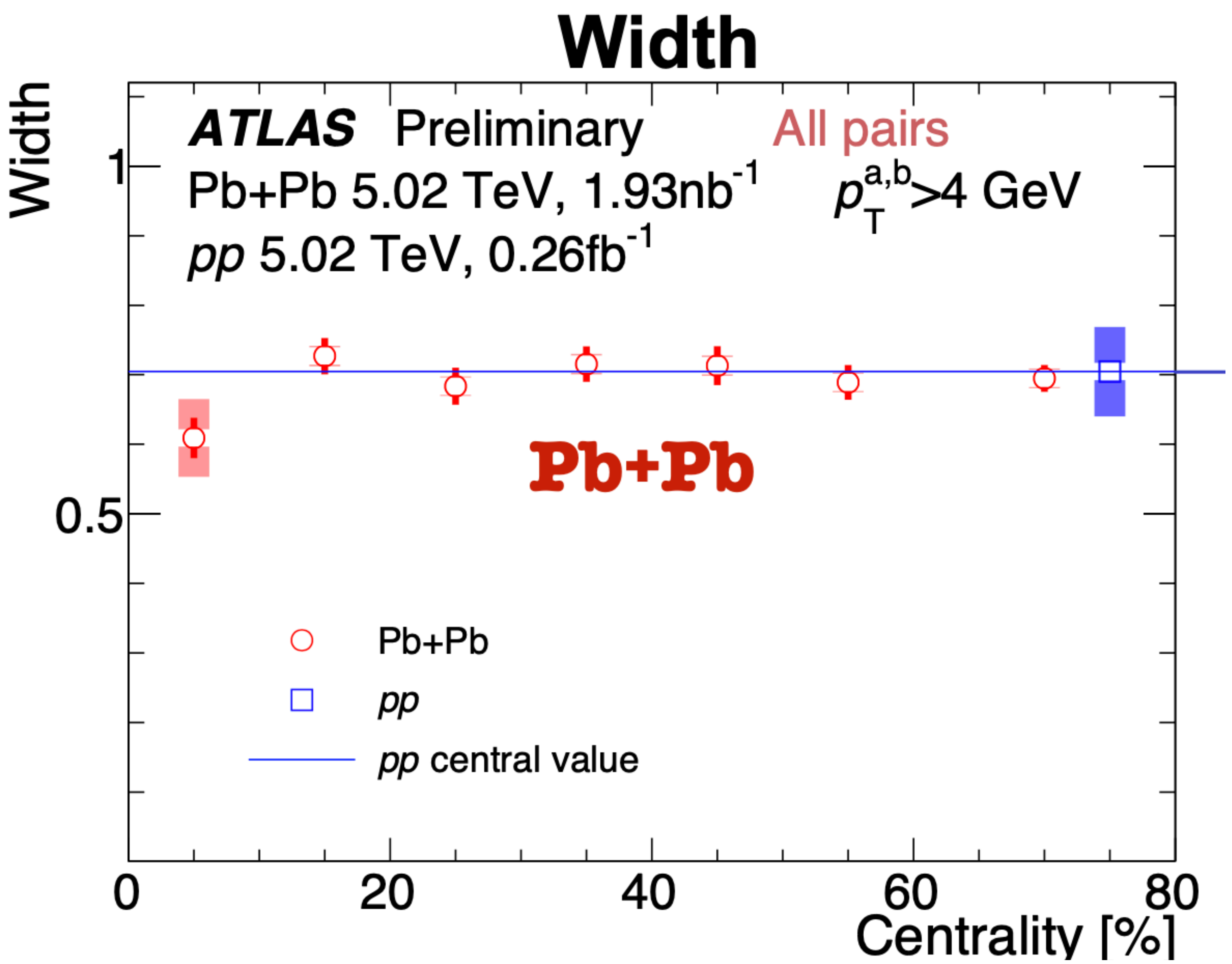
Centrality dependence:

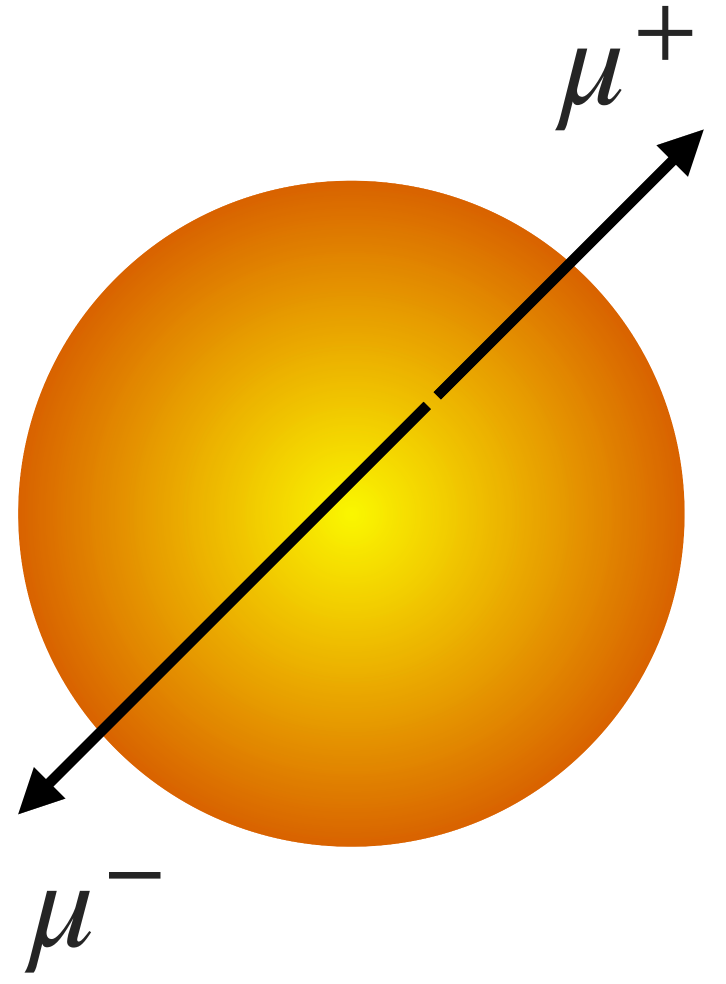
strong for v_2 vs. weak for v_3 for both D and J/ψ (sensitivity to initial state fluctuations)

HF angular correlations

Angular correlation between back-to-back muon pairs from heavy flavor decays





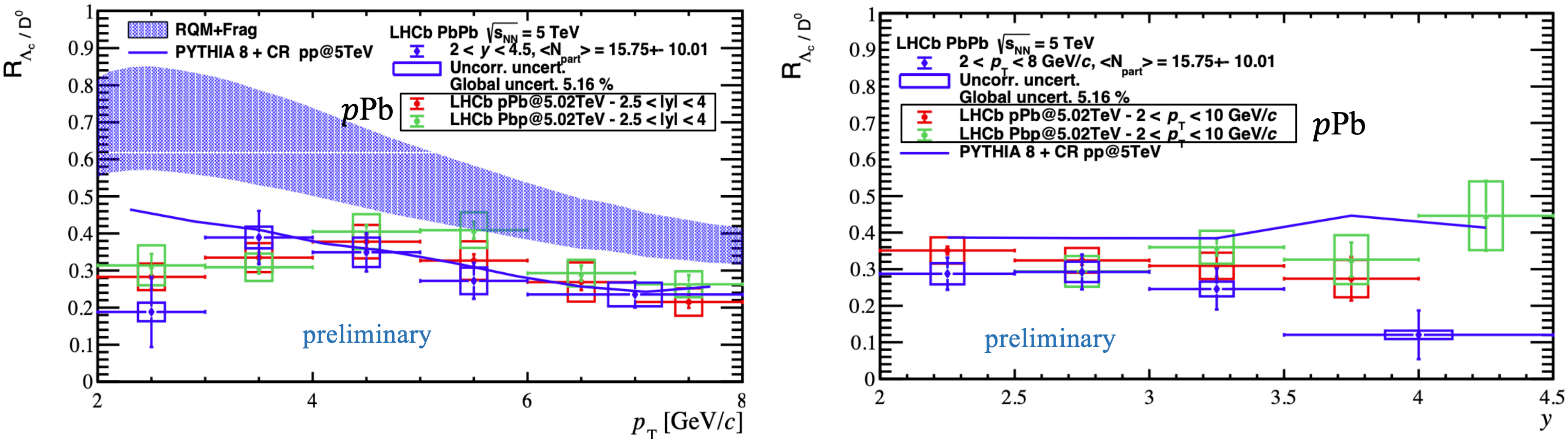


$p_T^\mu > 4$ GeV/c

- More suppression in central than peripheral collisions
- No significant azimuthal correlation broadening observed
  > probably the effect is more pronounced at lower p_T

Λ_c^+/D^0 at forward rapidity

LHCb-PAPER-2021-046



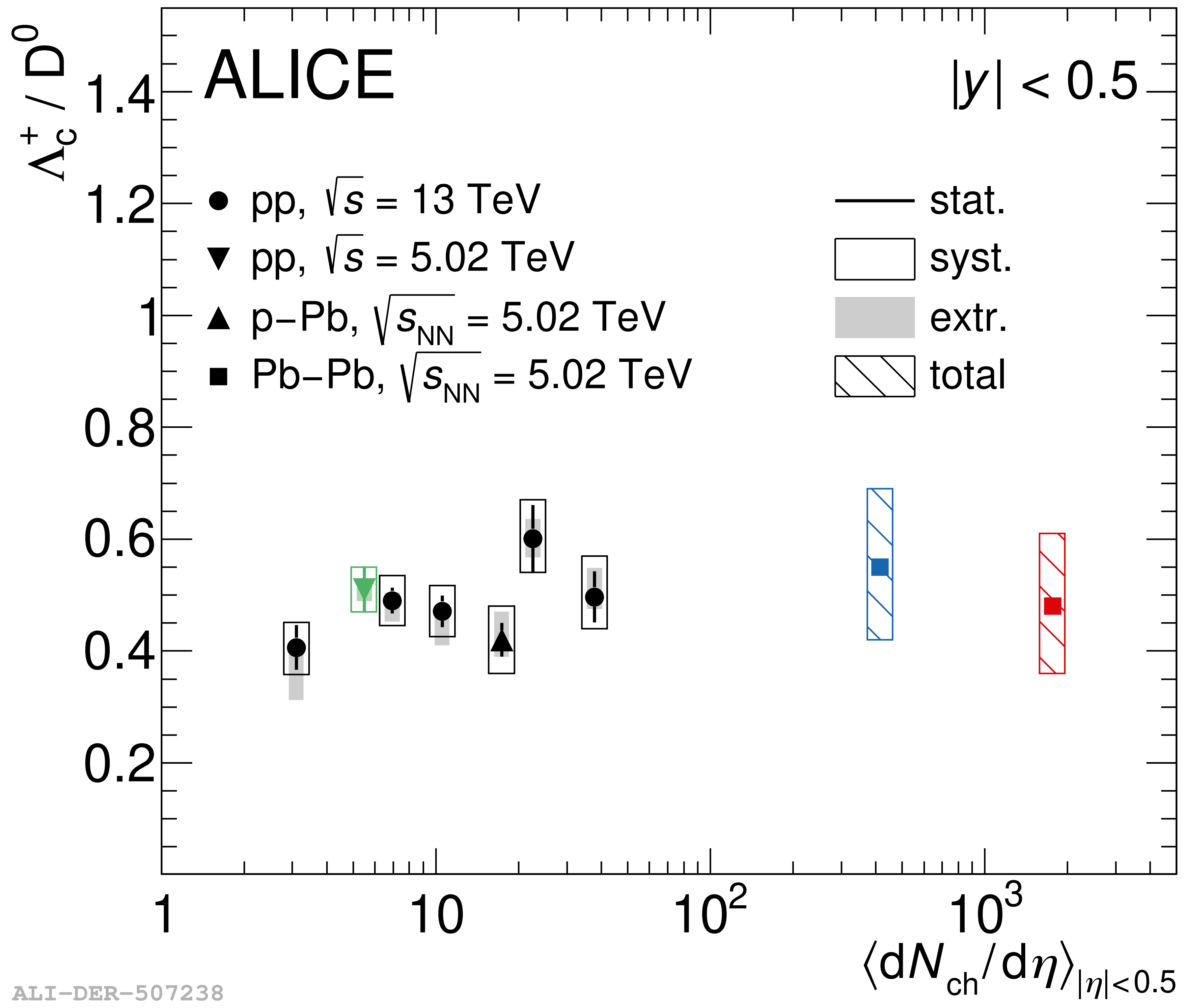
Λ_c^+/D^0 measured in peripheral (60-90%) Pb-Pb collisions at forward rapidity by LHCb

- Compatible with p-Pb measurements and Pythia8 + color reconnection effects
- Overestimated by Statistical Hadronization Model (+ RQM for missing resonances)

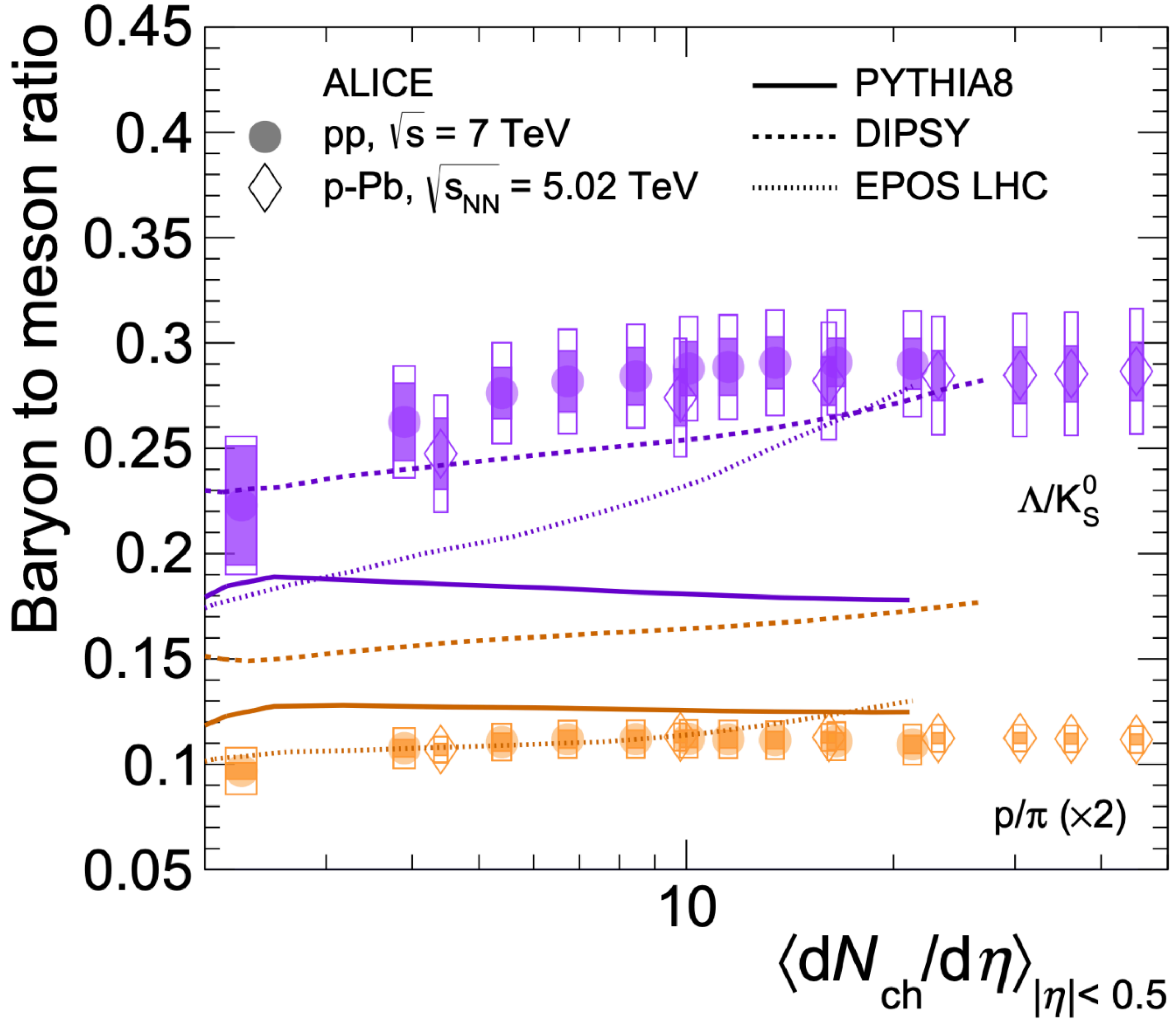
$(\Lambda_c^+/D^0)_{LHCb} < (\Lambda_c^+/D^0)_{ALICE}$

no hint of Λ_c^+ enhancement going to lower rapidities

Λ_c^+/D^0 at mid-rapidity



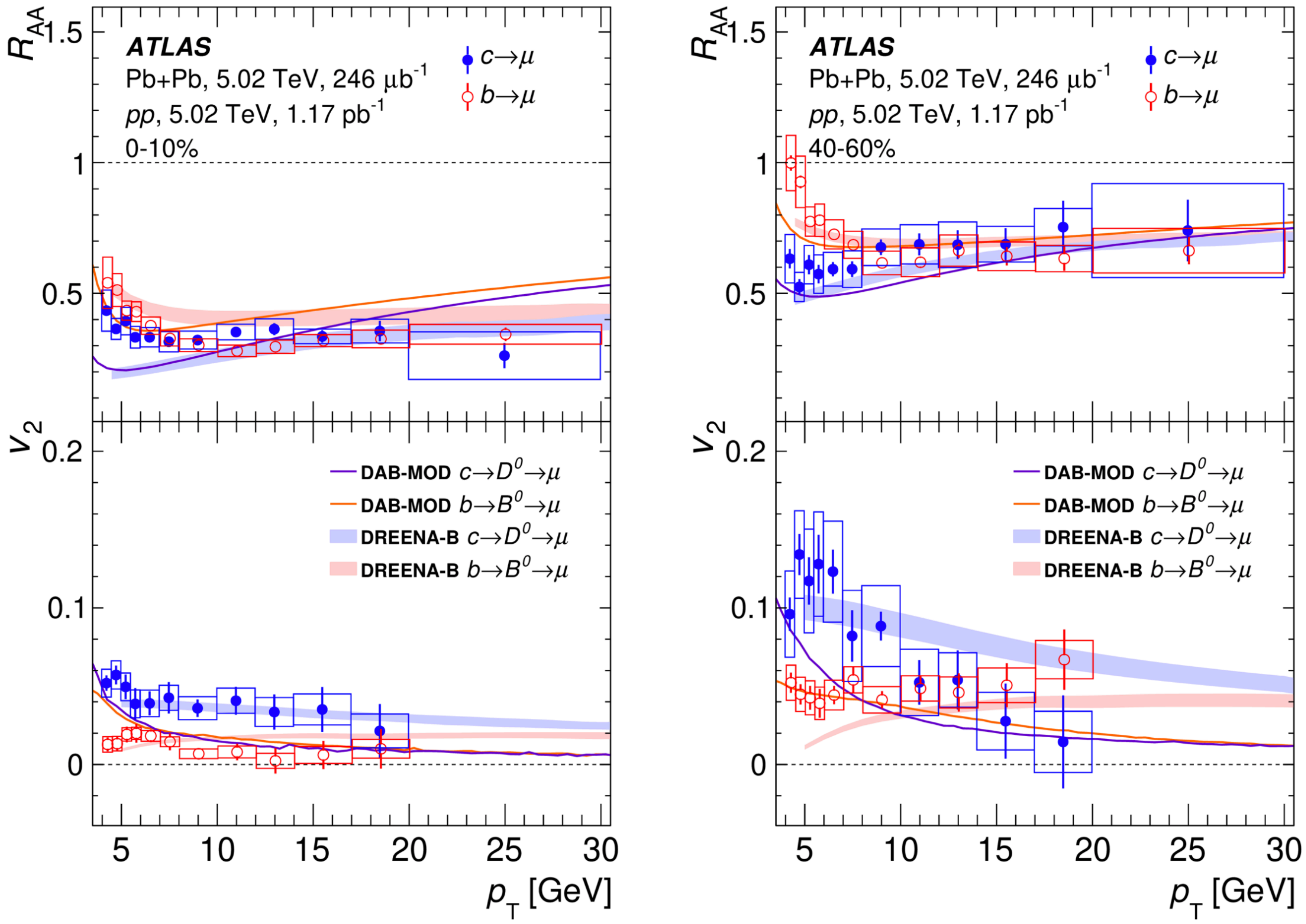
Nature Physics 13 (2017) 535-539



Λ_c^+/D^0 vs. multiplicity: flat and independent on collision system and energy

Qualitatively similar trend of Λ/K^0_S (light-flavor partners)

R_{AA} and v_2 of charm and bottom



RAA and v2 measured at high pT

Low p_T

- R_{AA} of charm < R_{AA} of bottom
- v_2 of charm > v_2 of bottom

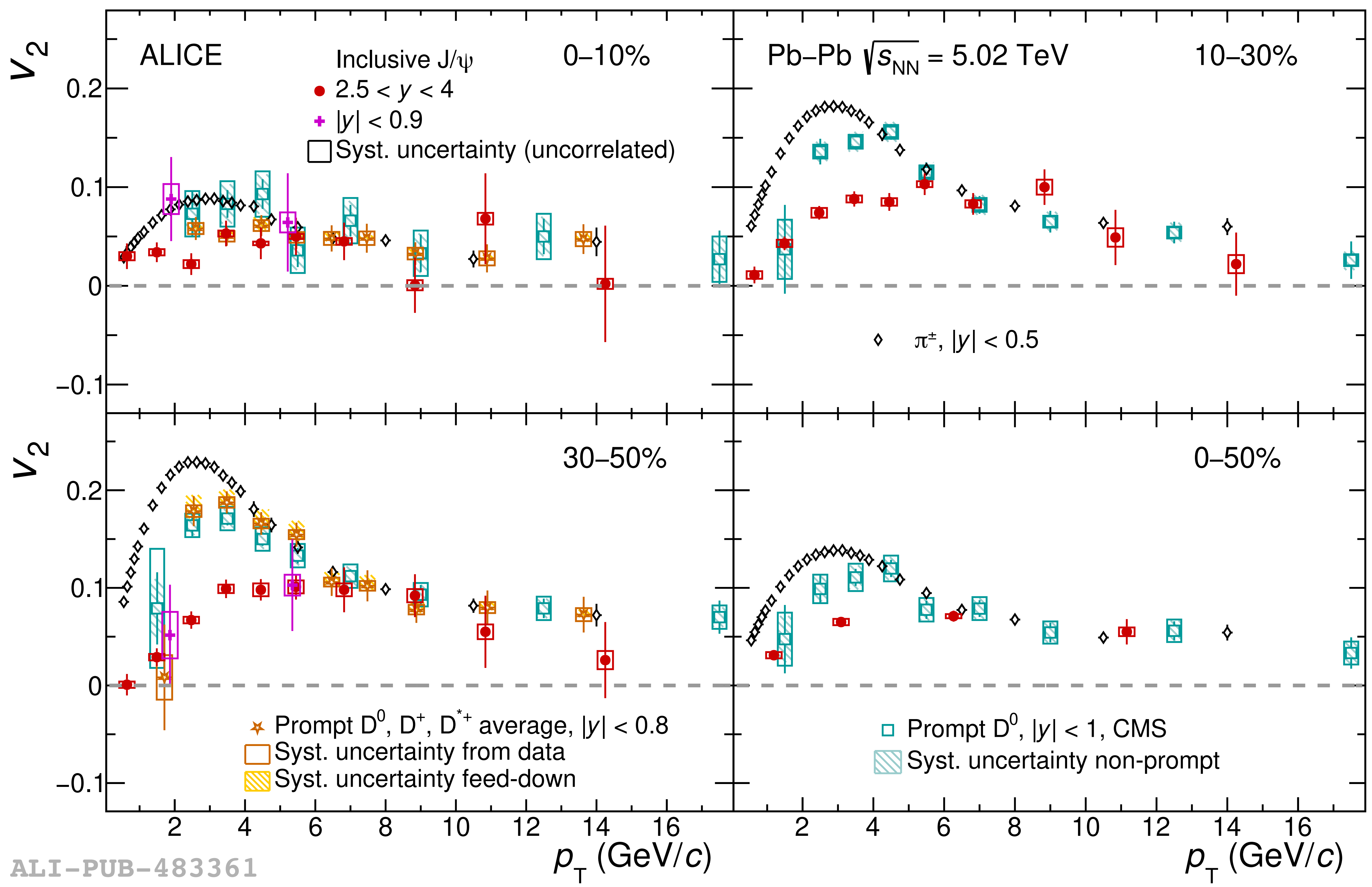
At high p_T both R_{AA} and v_2 converge towards similar values

Smaller v_2 observed for $b \to B^0$ due to larger mass

R_{AA}: PLB 829 (2022) 137077
v_2: PLB 807 (2020) 135595

J/ψ elliptic flow at LHC

JHEP 10 (2020) 141

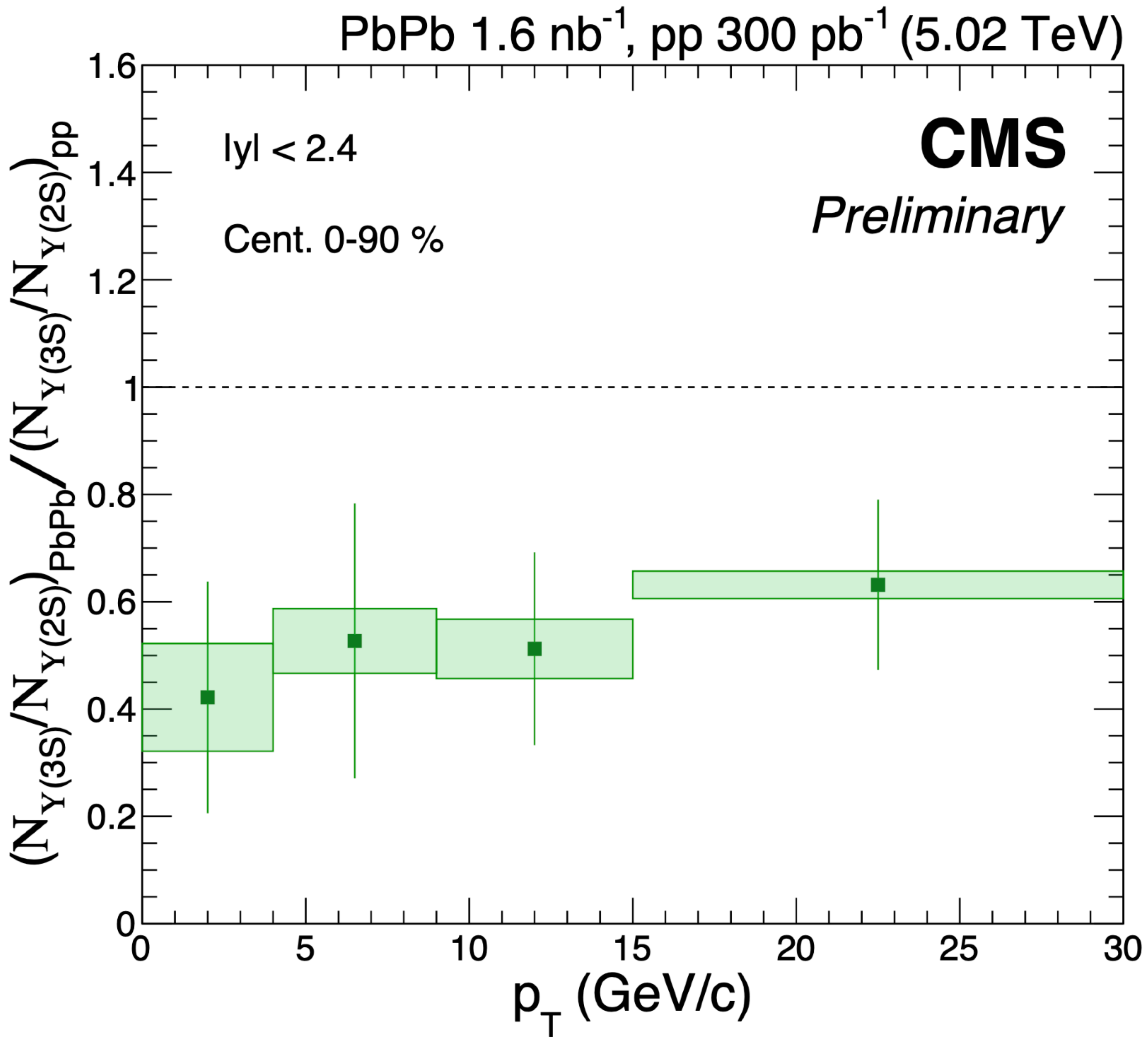


Elliptic flow (v_2) of inclusive J/ψ measured at LHC: significantly > 0 both at forward and midrapidity

v_2 of inclusive J/ψ < v_2 of prompt D mesons

- is feed-down from B responsible?
- larger fraction of v_2 carried by light quarks?
- both?

Suppression of Υ(3s) vs. Υ(2s)



R_{AA} (Υ(3s)) / R_{AA} (Υ(2s)) ≈ 0.5

→ stringent constraint to theoretical models (?)