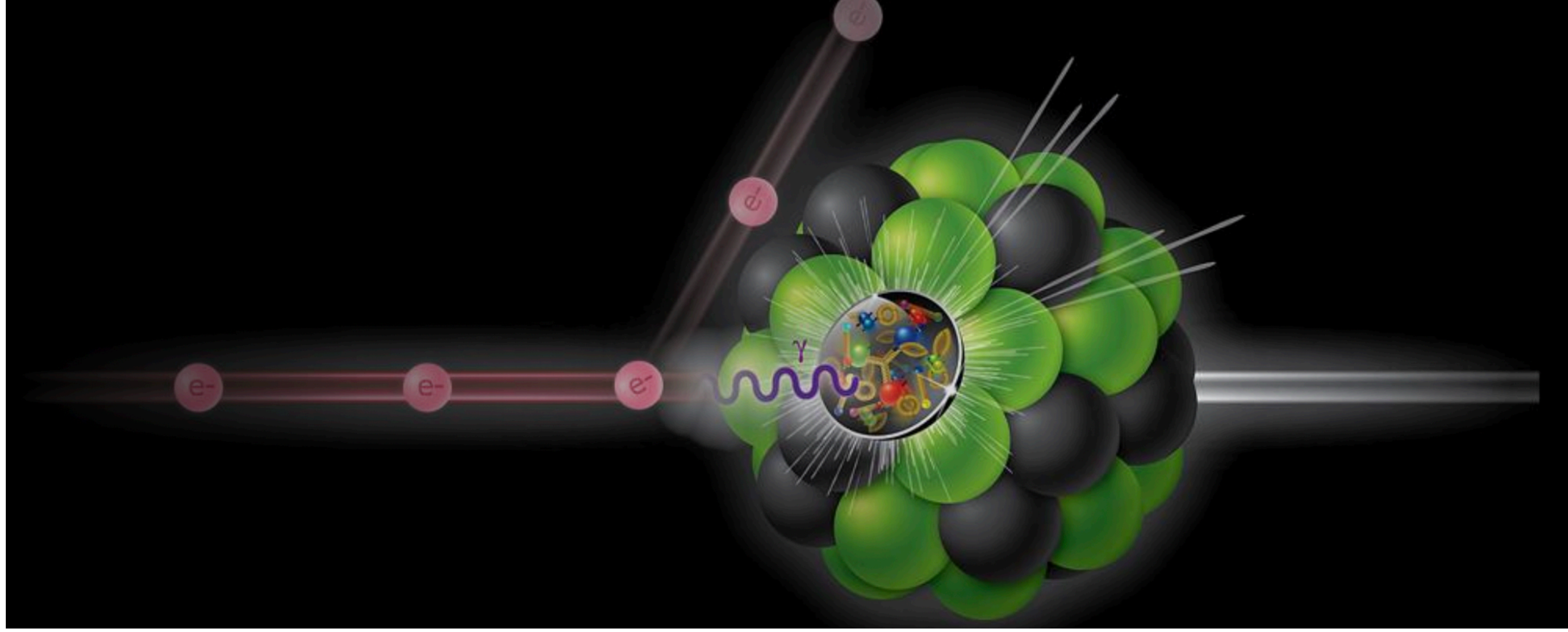
Center for Frontiers in Nuclear Science

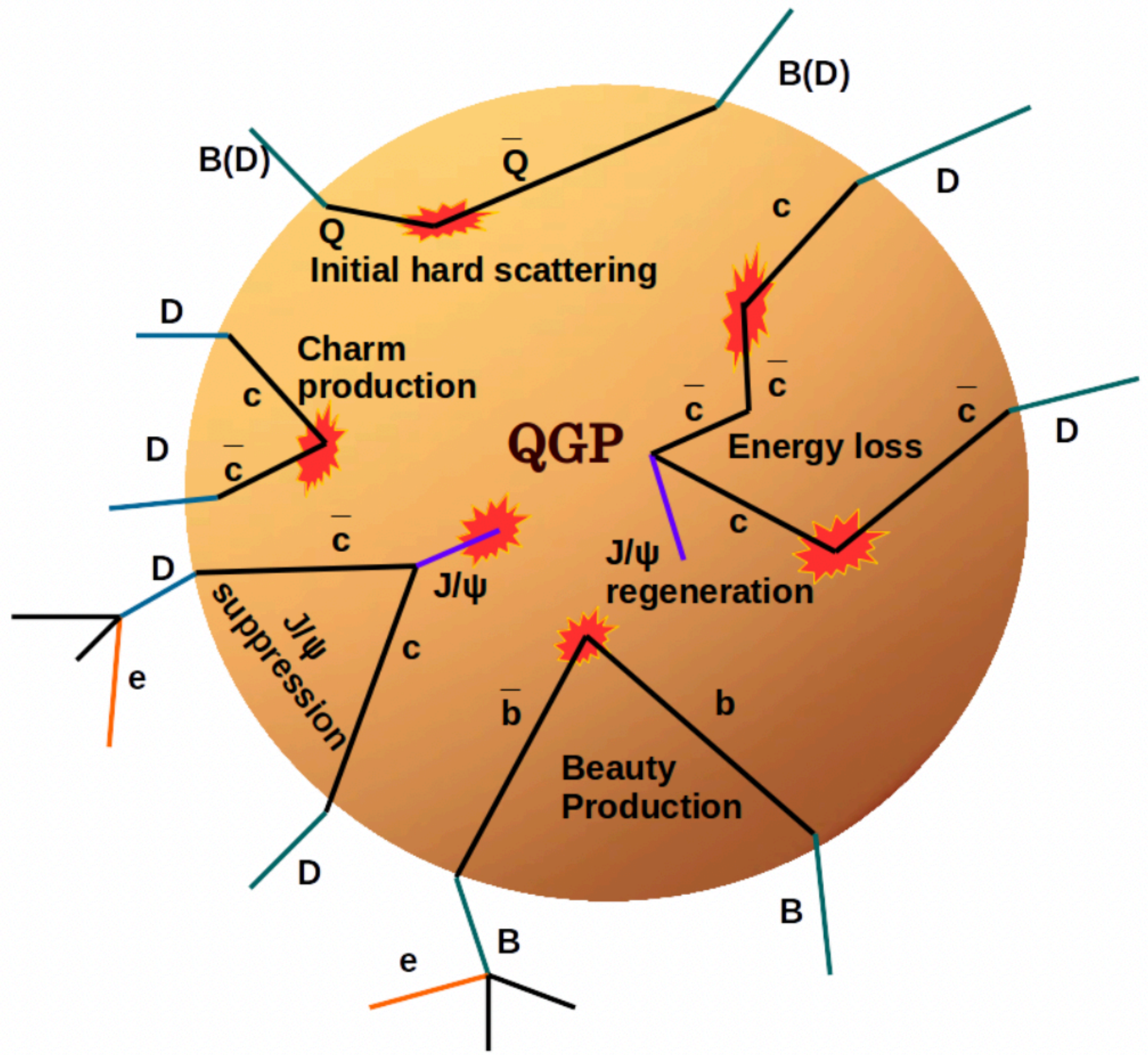


Production of HF hadrons and npQCD at RHIC

Sooraj Radhakrishnan
Kent State University/Lawrence Berkeley National Laboratory
CFNS Workshop, Sep 19-22, 2022

Advancing the Understanding of Non-Perturbative QCD Using Energy Flows

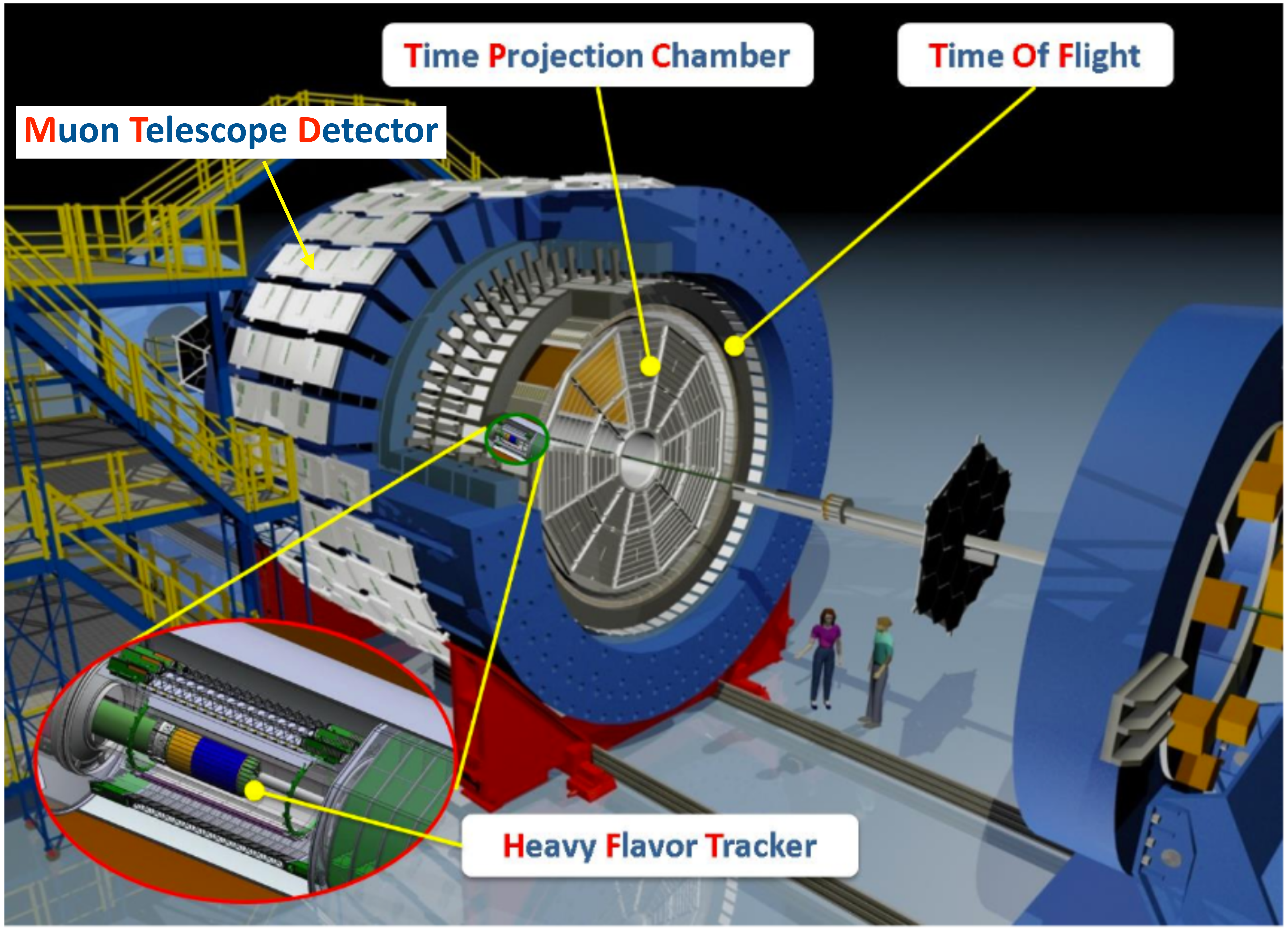
Heavy flavor to study npQCD

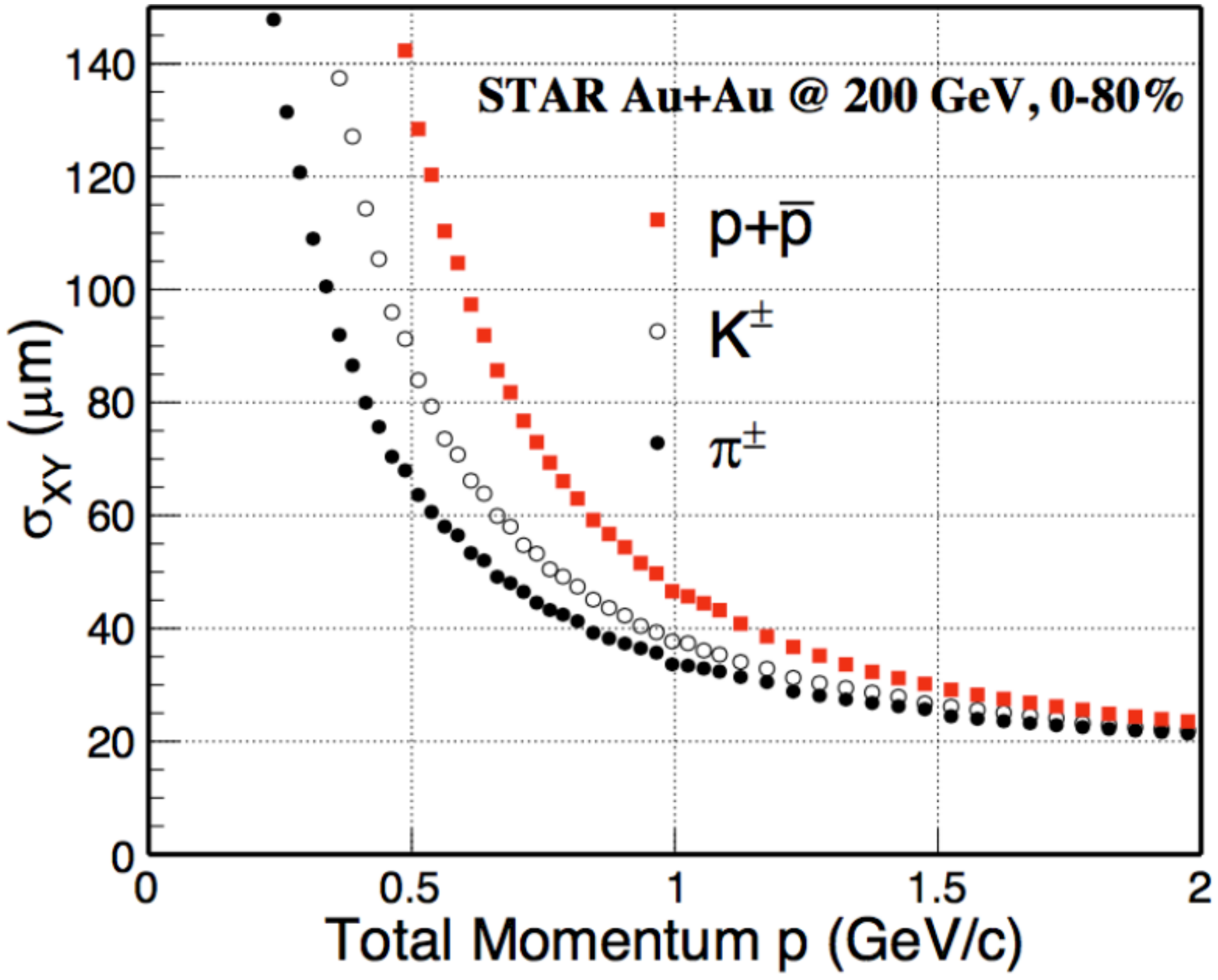


- Probes that cover both low and high momentum ranges, production cross-sections amenable to pQCD calculations
- Ideal probes of a number of npQCD effects
  - QGP transport, energy loss
  - Color screening
  - Hadronization
  - Onia production mechanism in p+p

- Strong experimental focus recently at both RHIC and LHC experiments

Heavy flavor at RHIC

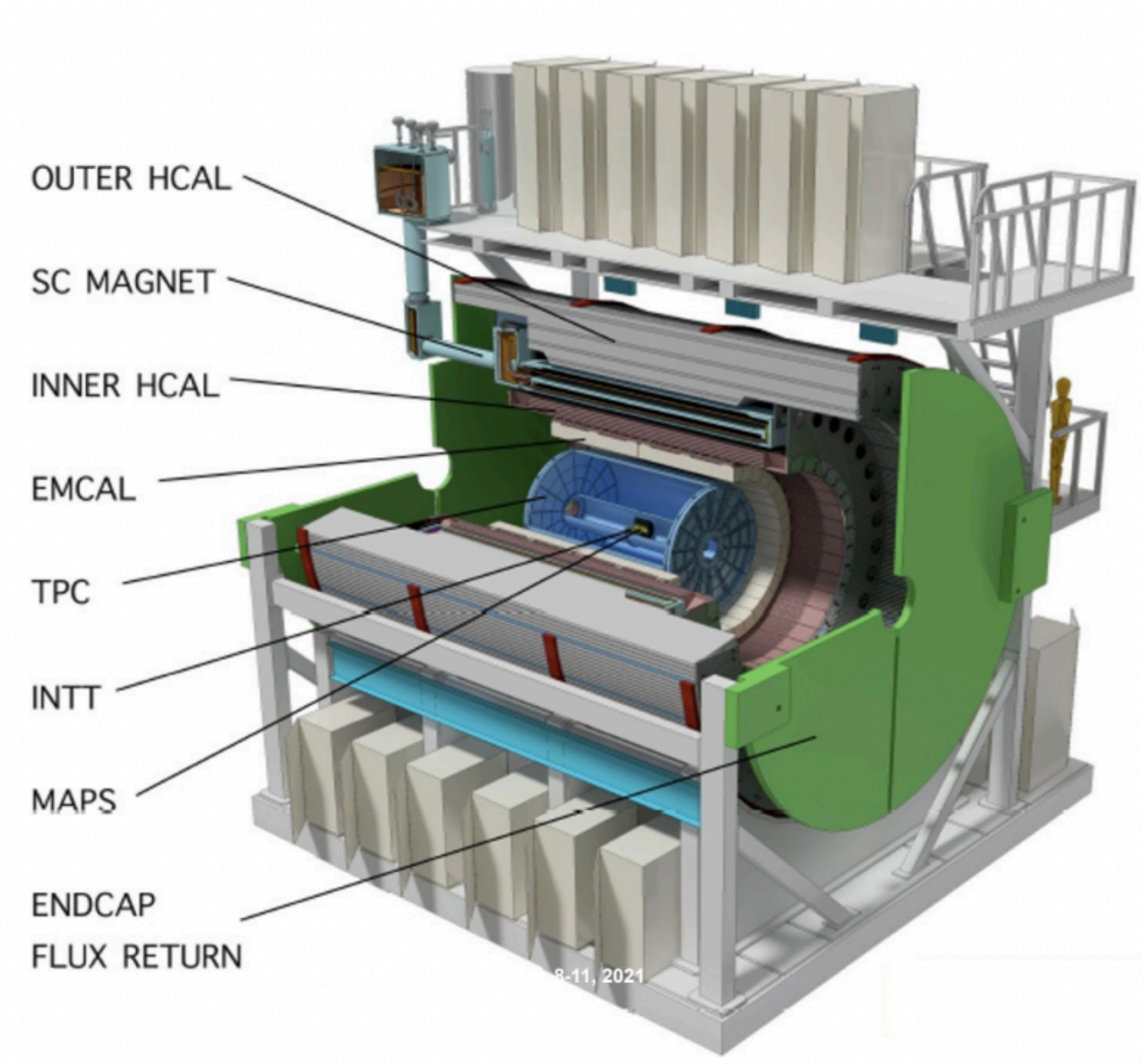


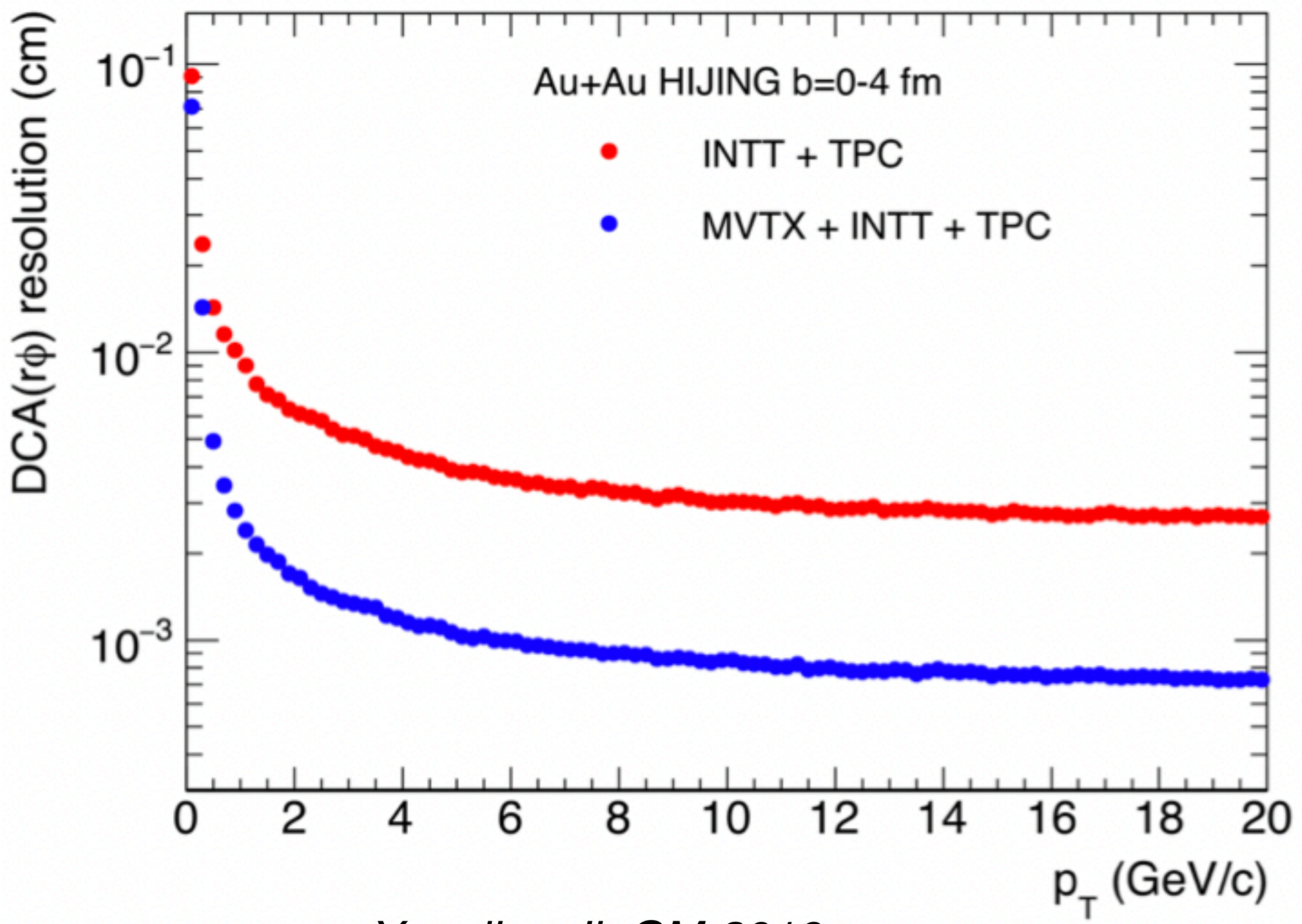


Phys. Rev. Lett 118 212301

- STAR Heavy Flavor Tracker (HFT) with ultra thin MAPS sensors. Provides excellent vertex resolution for HF hadron reconstruction. MTD for muon identification

Heavy flavor at RHIC

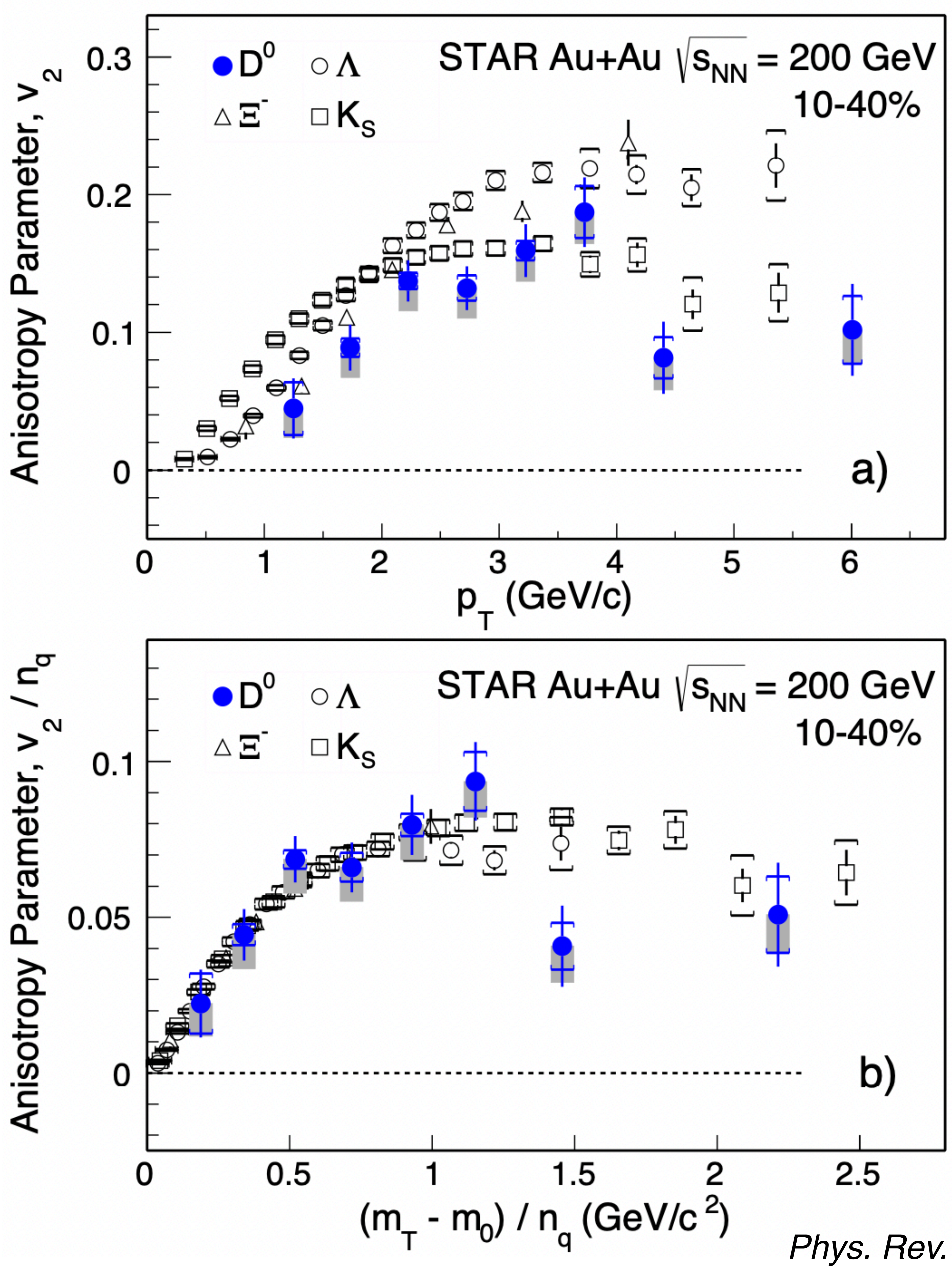


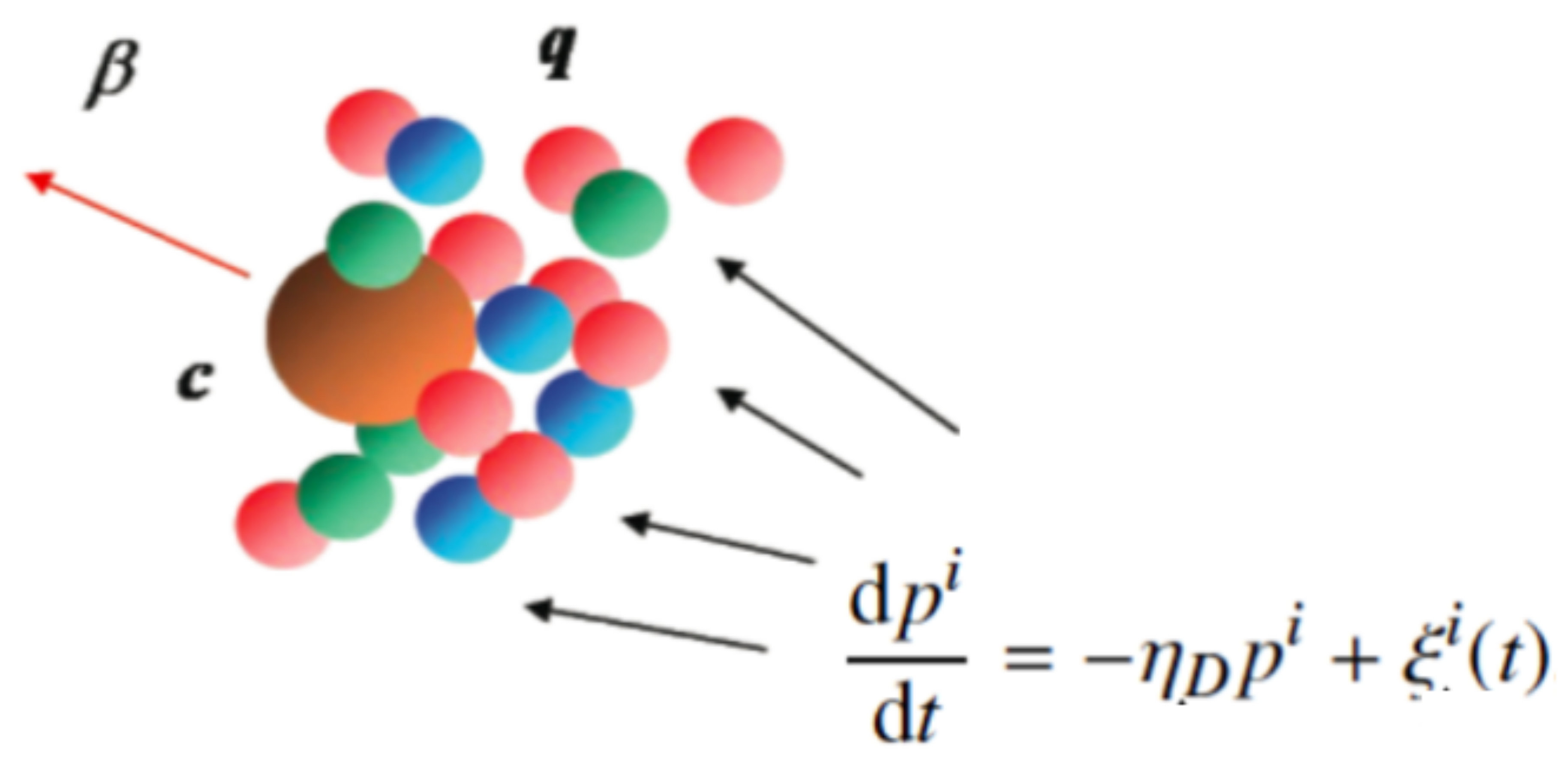


Yuanjing Ji, QM 2019

- MAPS based vertexing system also part of upcoming sPHENIX experiment
- Excellent track pointing resolution and momentum resolution

HQ Diffusion in QGP



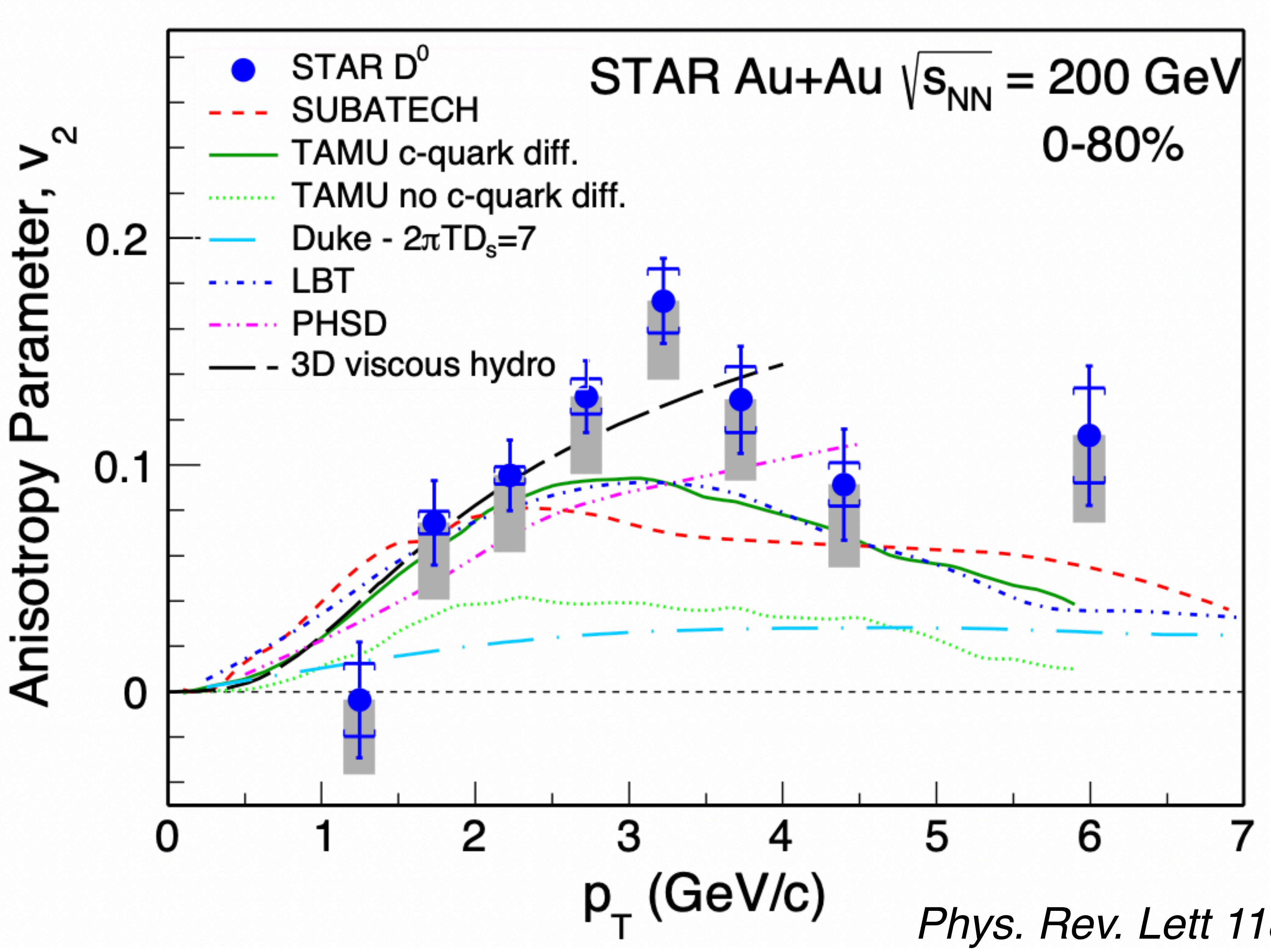


- Thermalization times for heavy quarks delayed, by factor of m_Q/T
- Flow of HF hadrons sensitive to coupling strengths of HQs to the expanding medium
- Probes long wavelength dynamics in the QGP

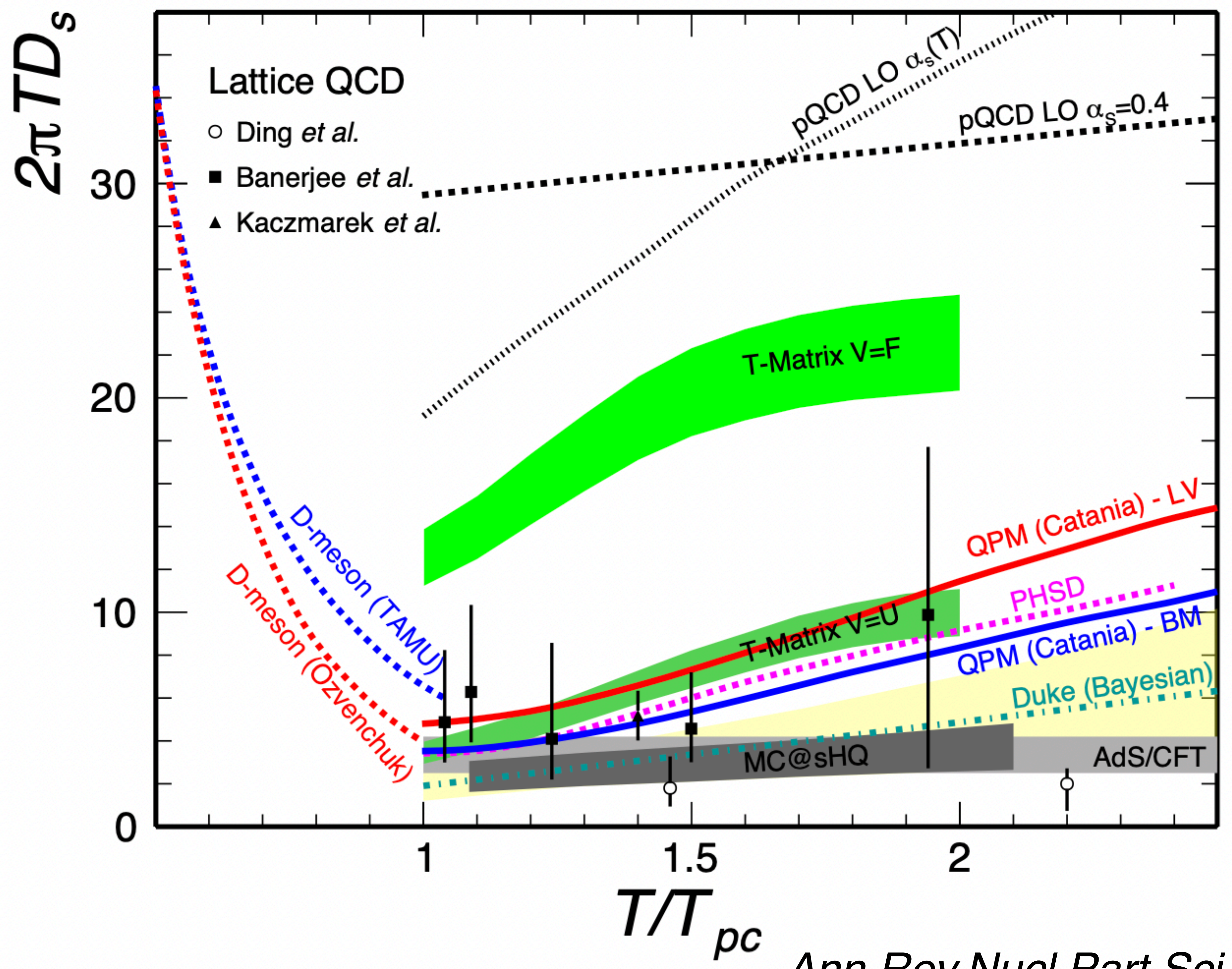
- Large v_2 values measured for D mesons at RHIC
- Consistent values with light quarks for NCQ scaled values

Phys. Rev. Lett 118 212301

HQ Diffusion coefficient



Phys. Rev. Lett 118 212301

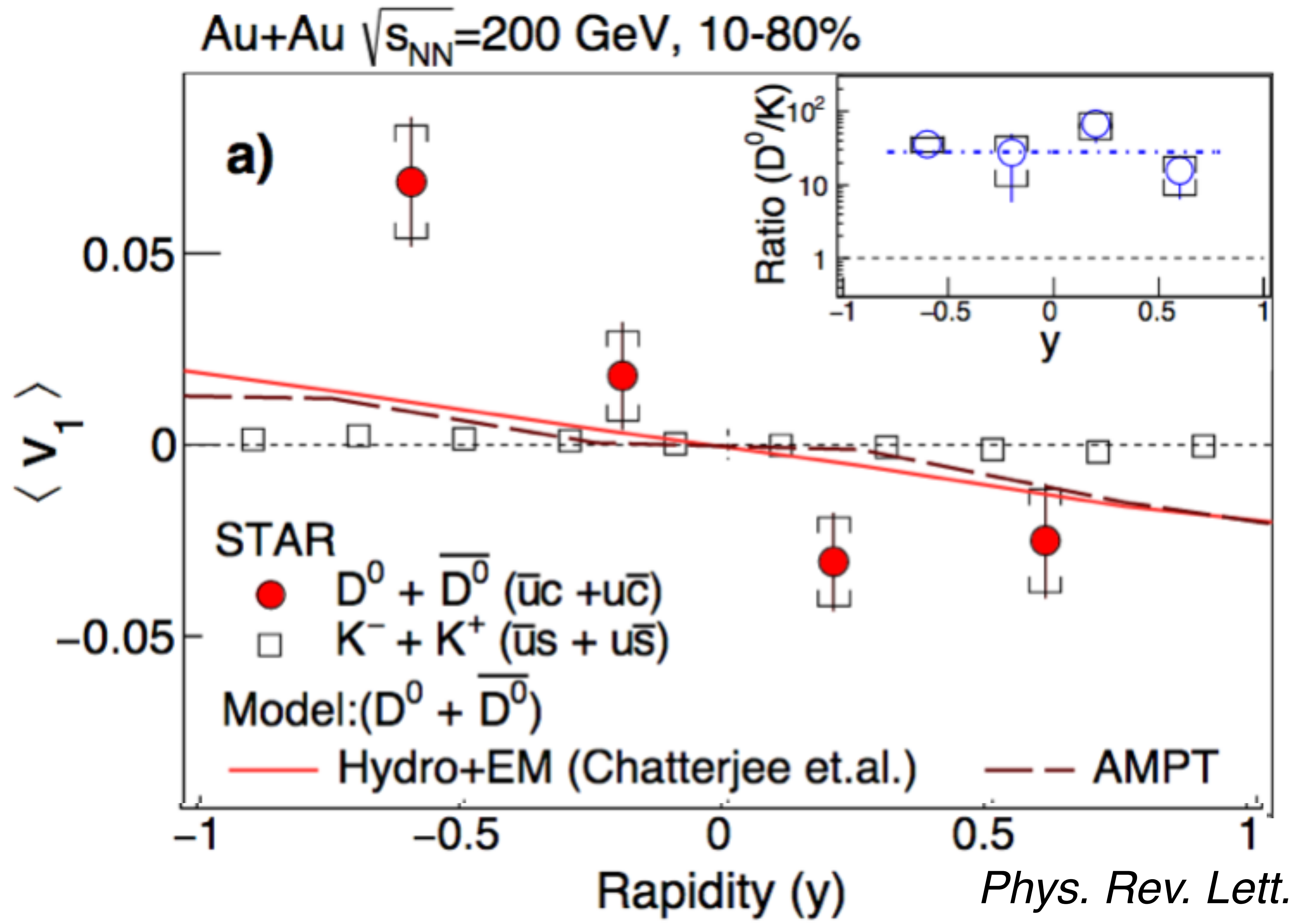


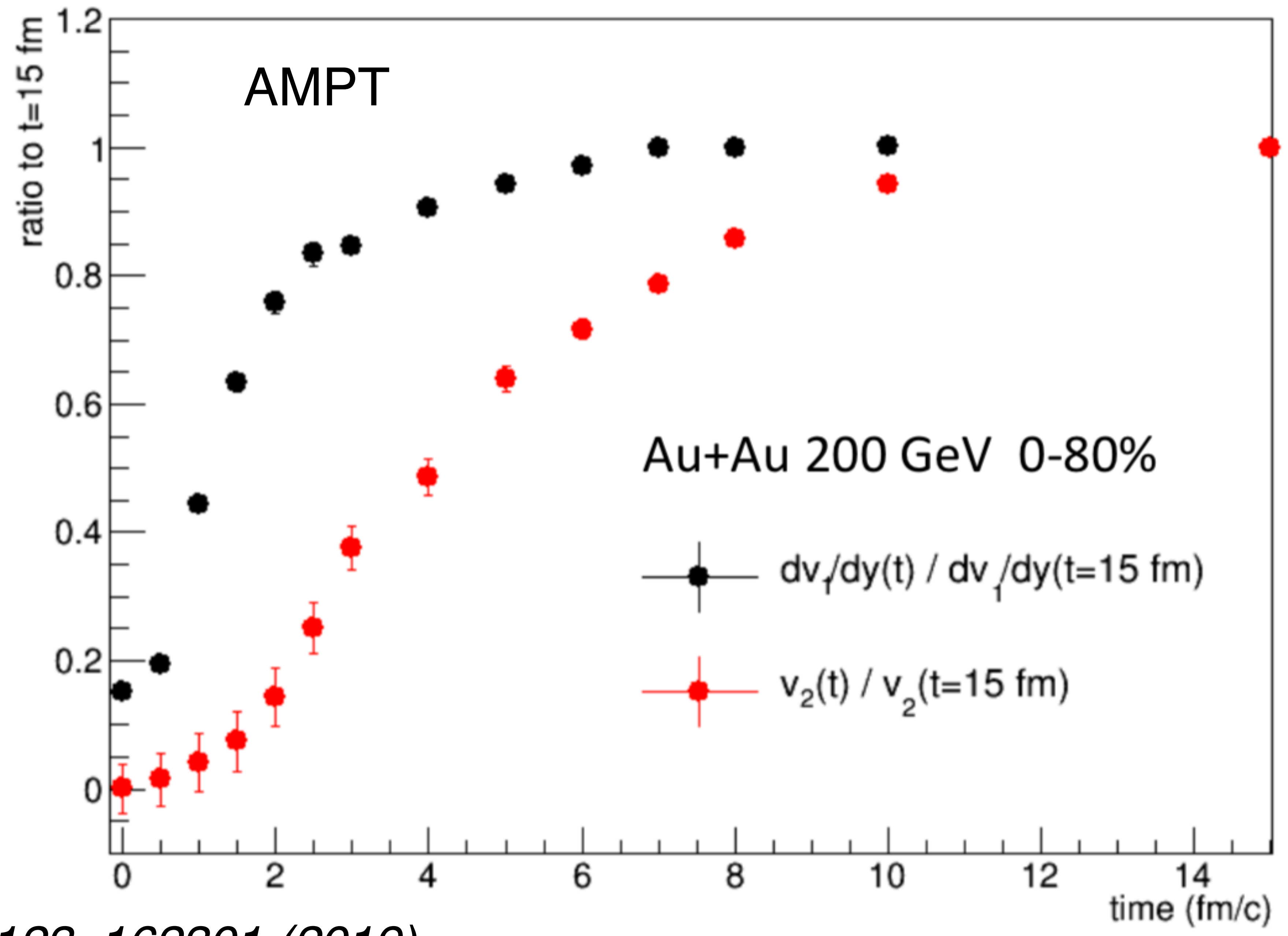
Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

- Spatial diffusion coefficient $2\pi T D_s$ constrained to be ~ 2 - 4 near T_{pc} -> strong coupling
- Diffusion coefficient relates to the long range part of interactions between the HQs and the medium, for eg., the screened confining potential *Ann.Rev.Nucl.Part.Sci.* 69 (2019) 417-445

- Temperature dependence not well constrained
- How about bottom hadron flow? Can there be a consistent description?

Temperature dependence of D_s

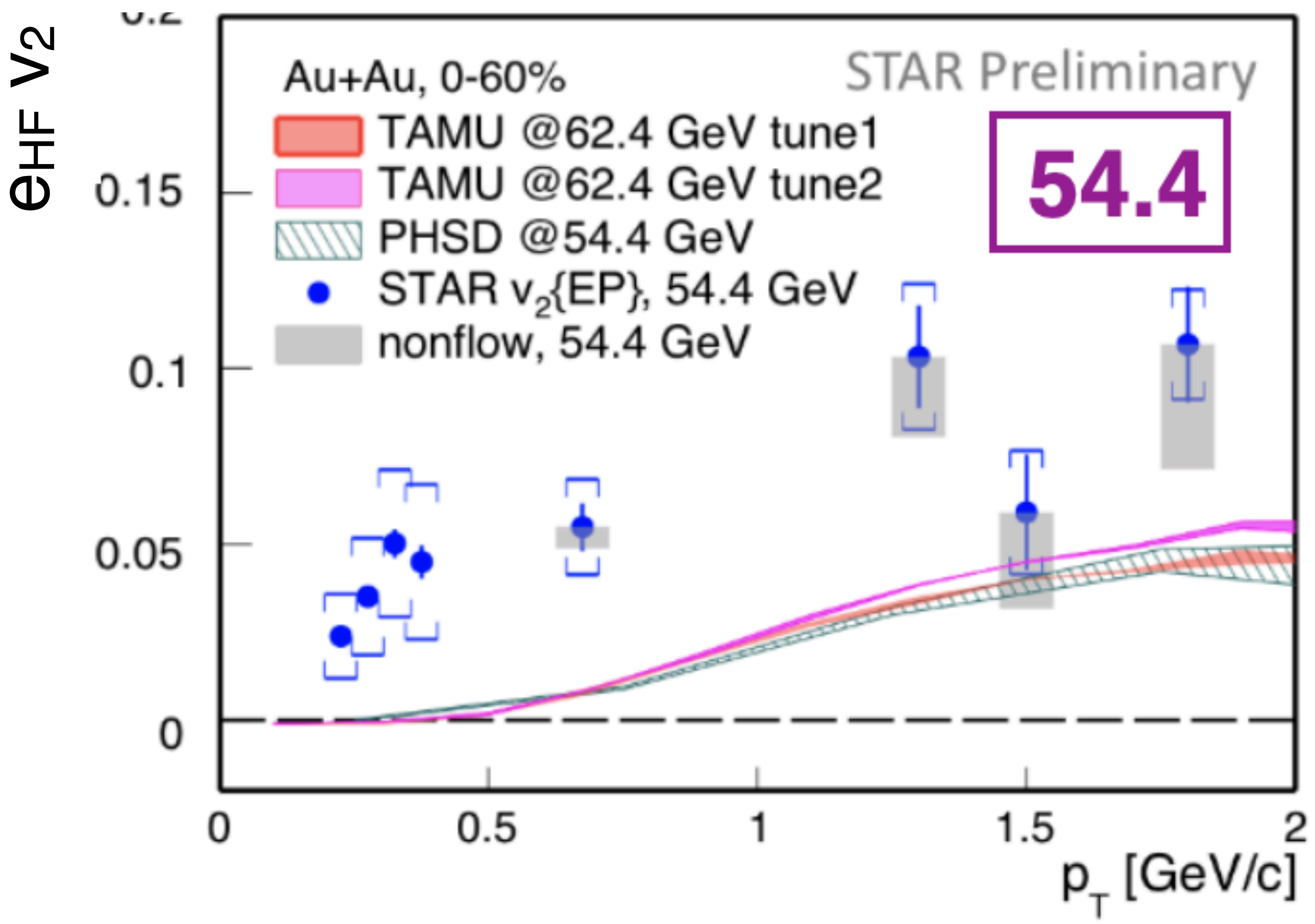




Phys. Rev. Lett. 123, 162301 (2019)

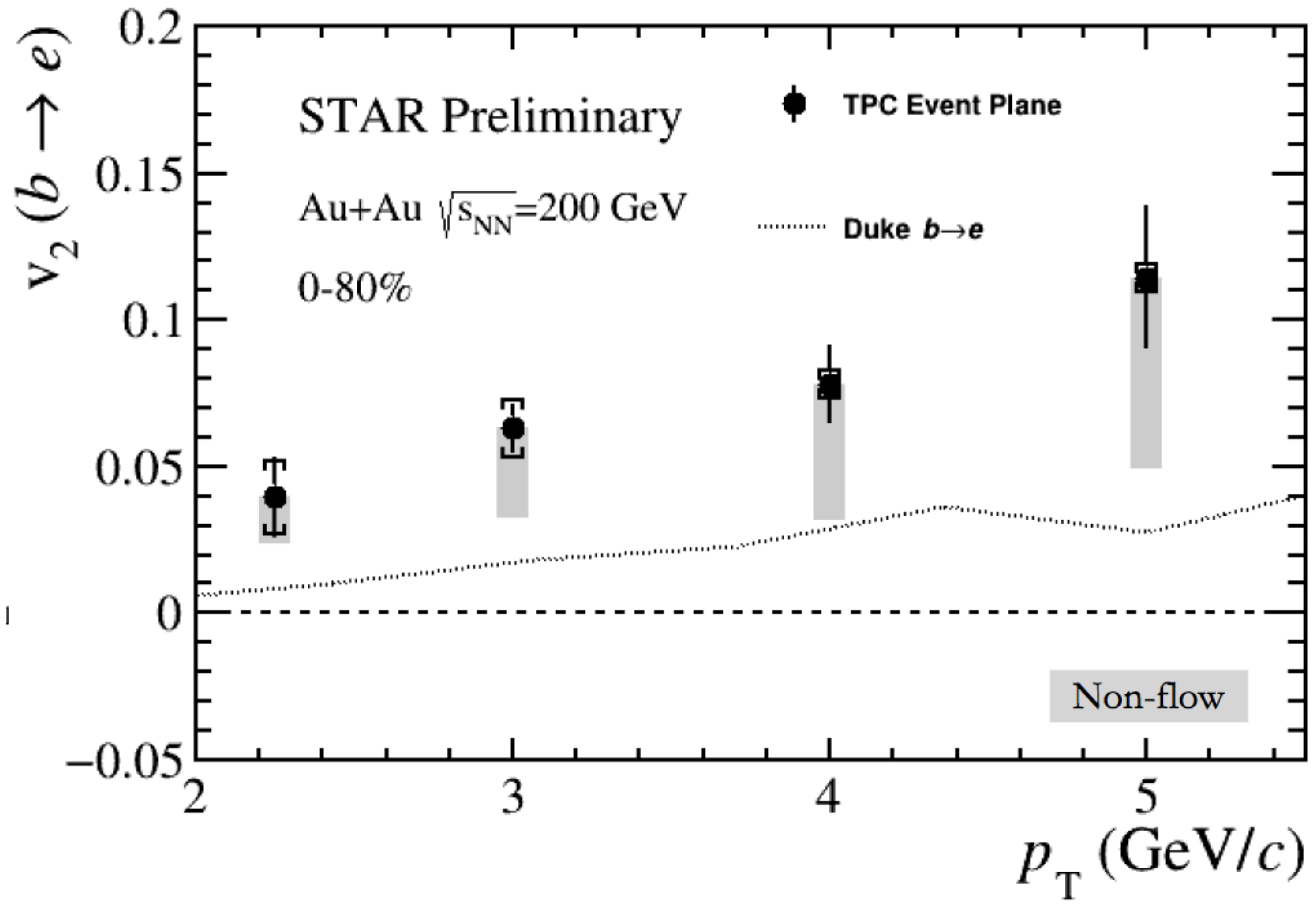
Xinyue Ju, DNP Fall 2019 Meeting

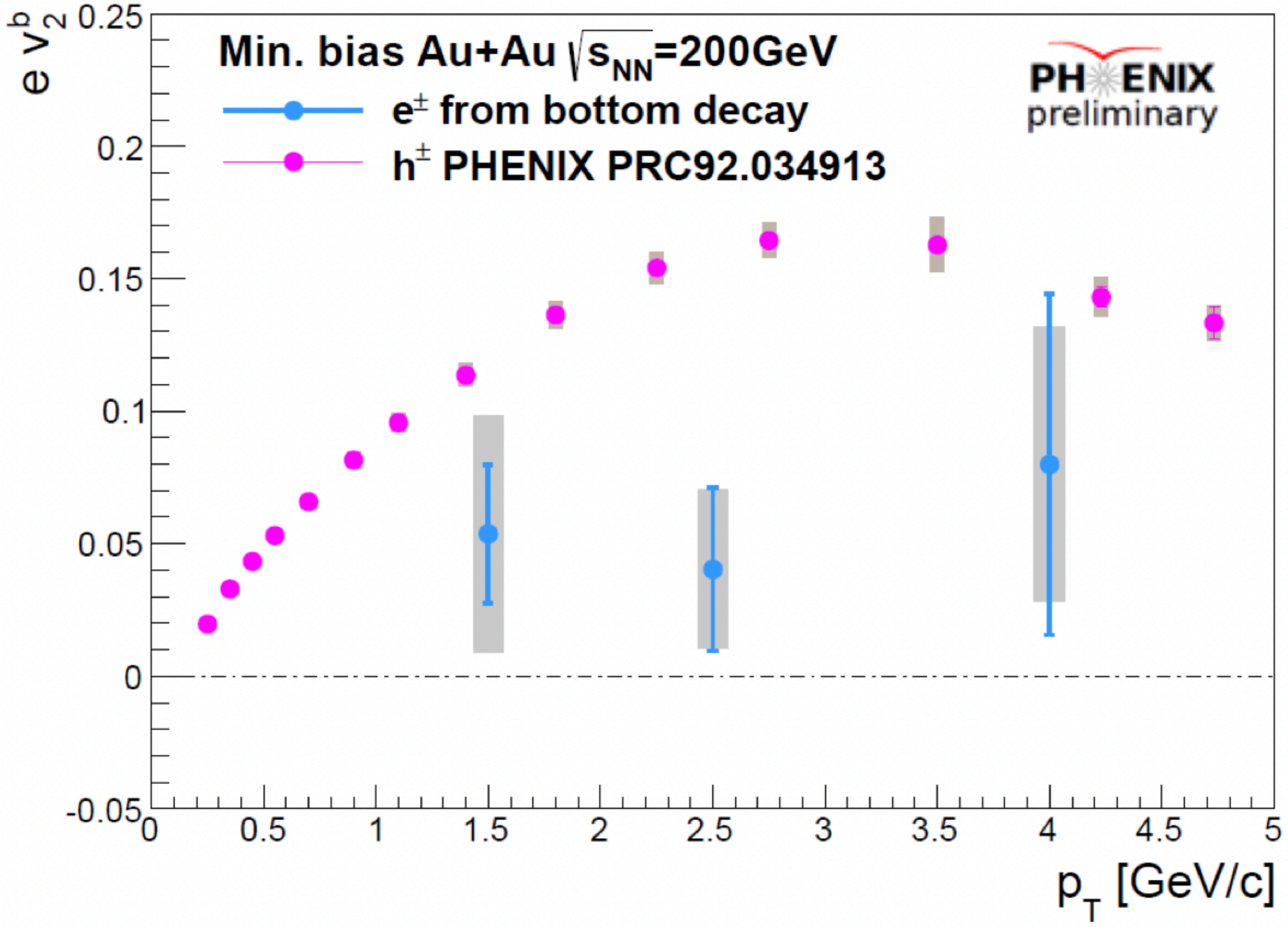
- Large D meson v_1 measured at RHIC
- Develops early compared to v_2, could provide constraints to temperature dependence of D_s



- Different temperature profile for the fireball at lower collision energies
- Could also be an useful probe to study T dependence

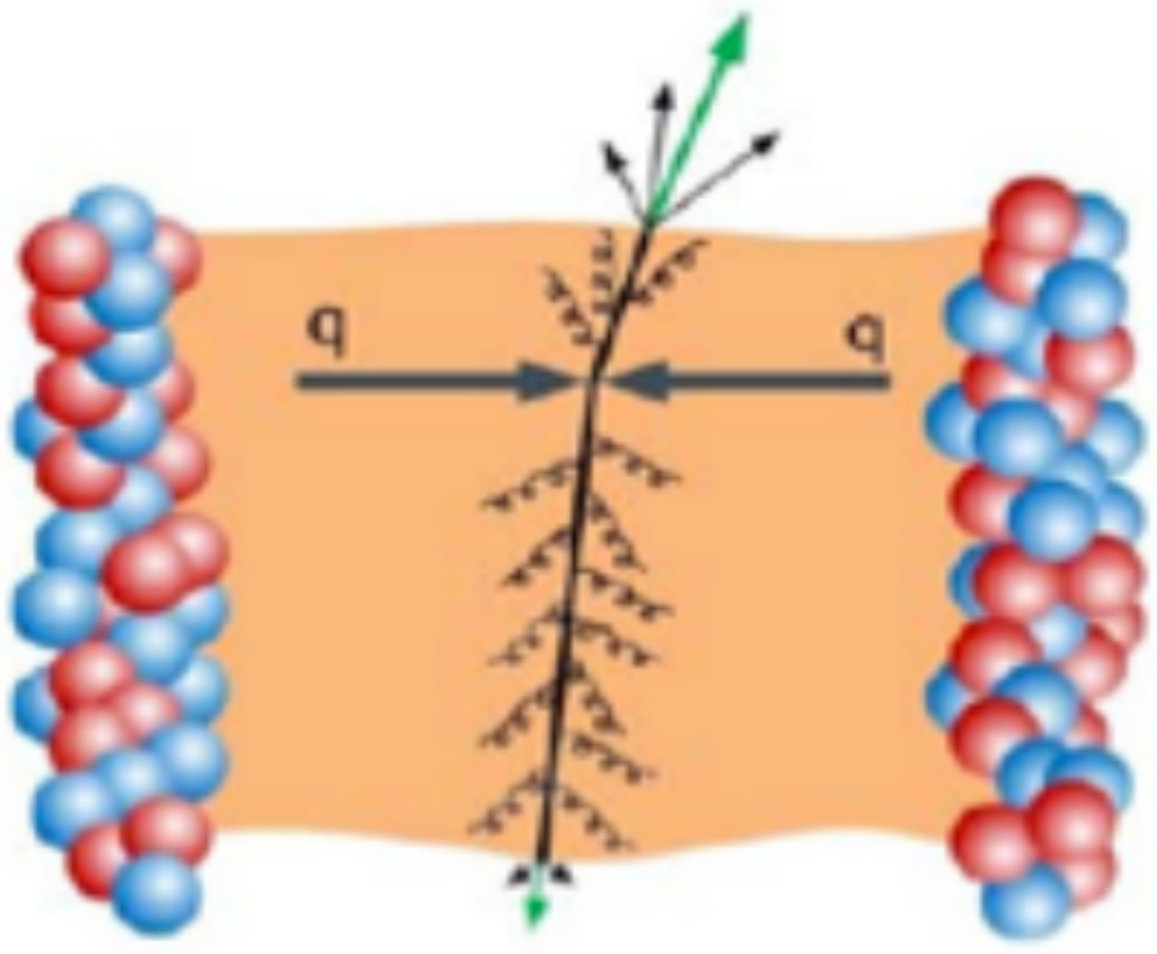
Bottom flow at RHIC

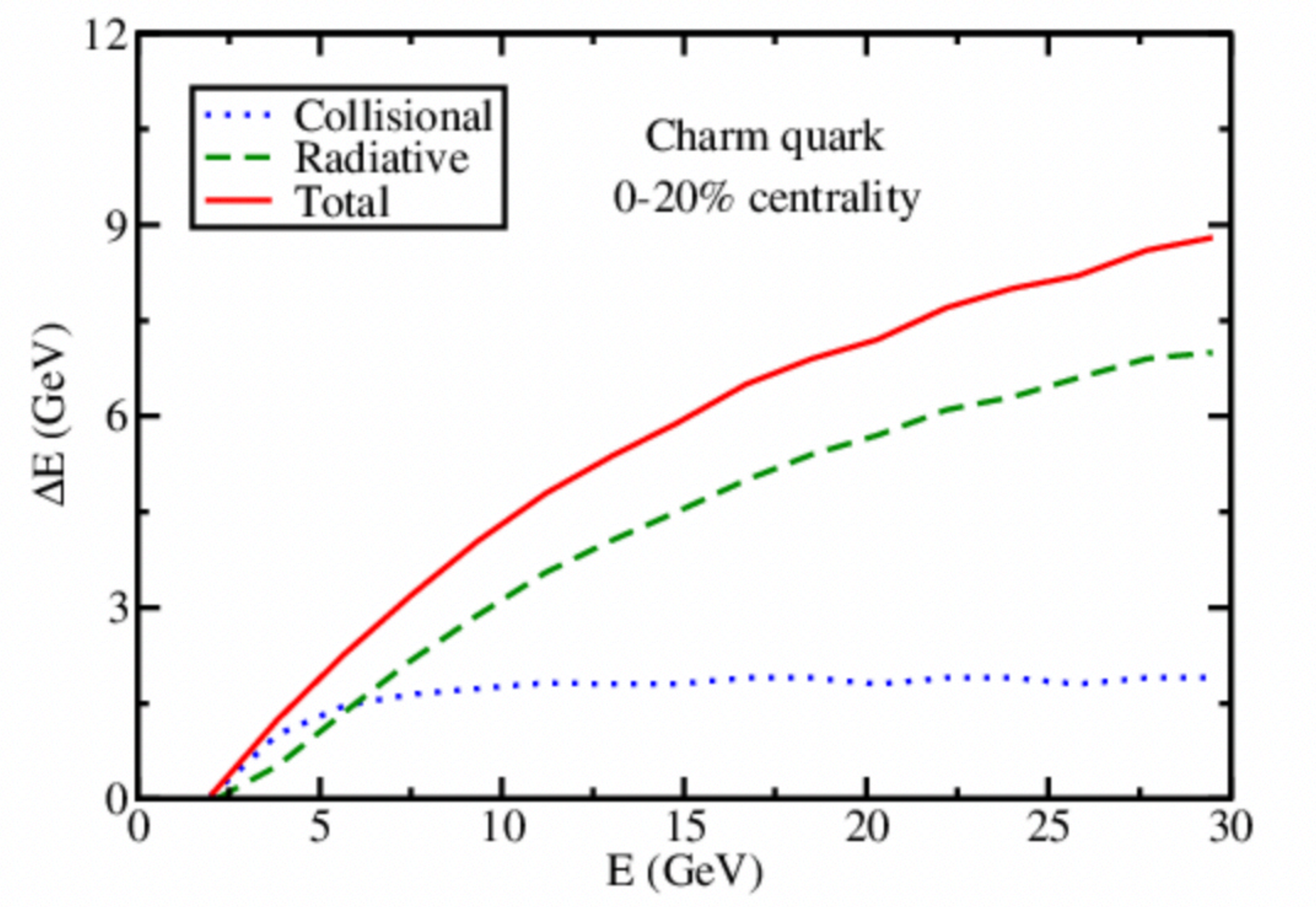




- Smaller values of v_2 for electrons from b hadron decays, experimental precision needs to improve
- b-quarks taking longer to thermalize
- Can provide further understanding to HQ diffusion and interactions in the QGP

Heavy flavor energy loss

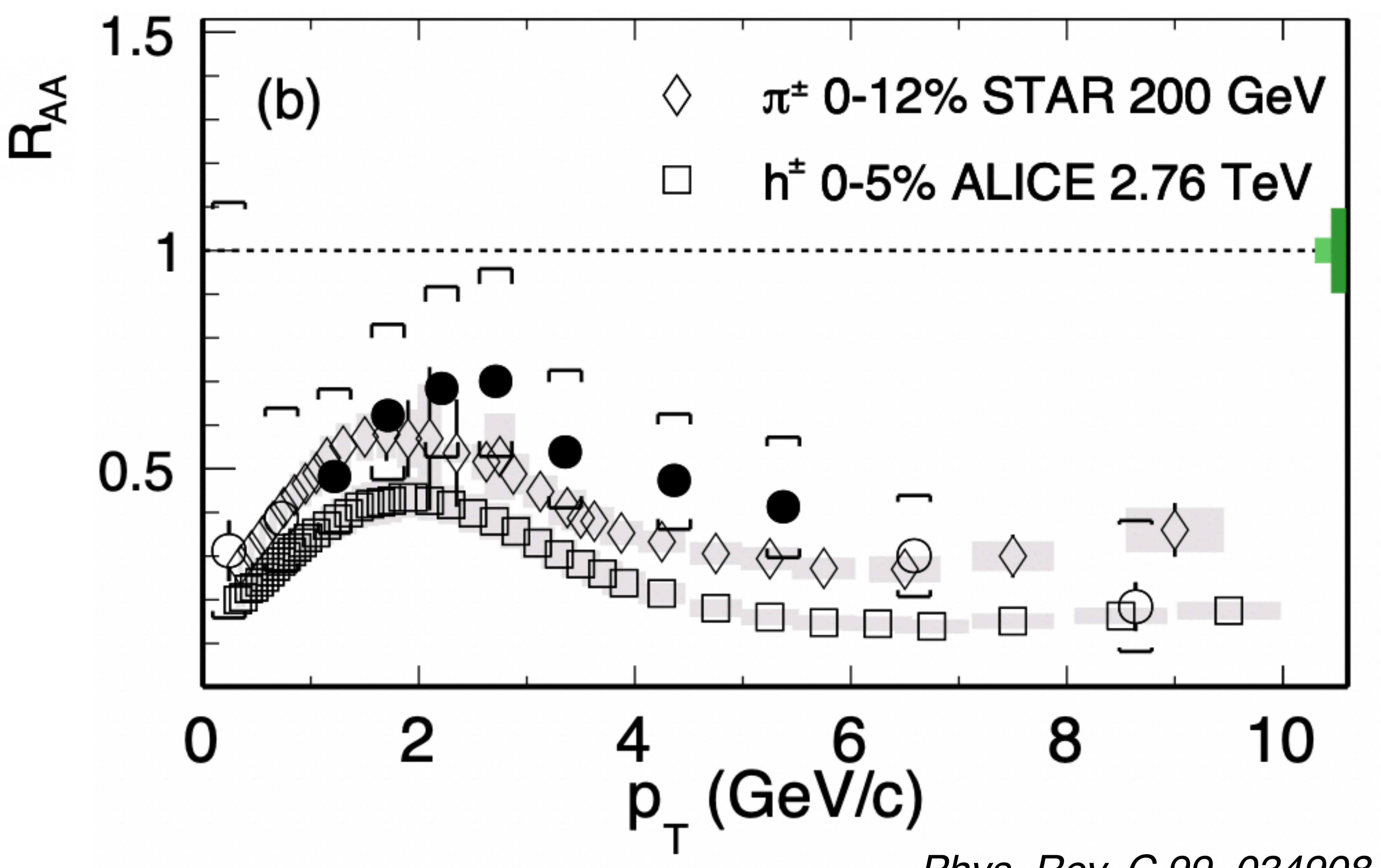


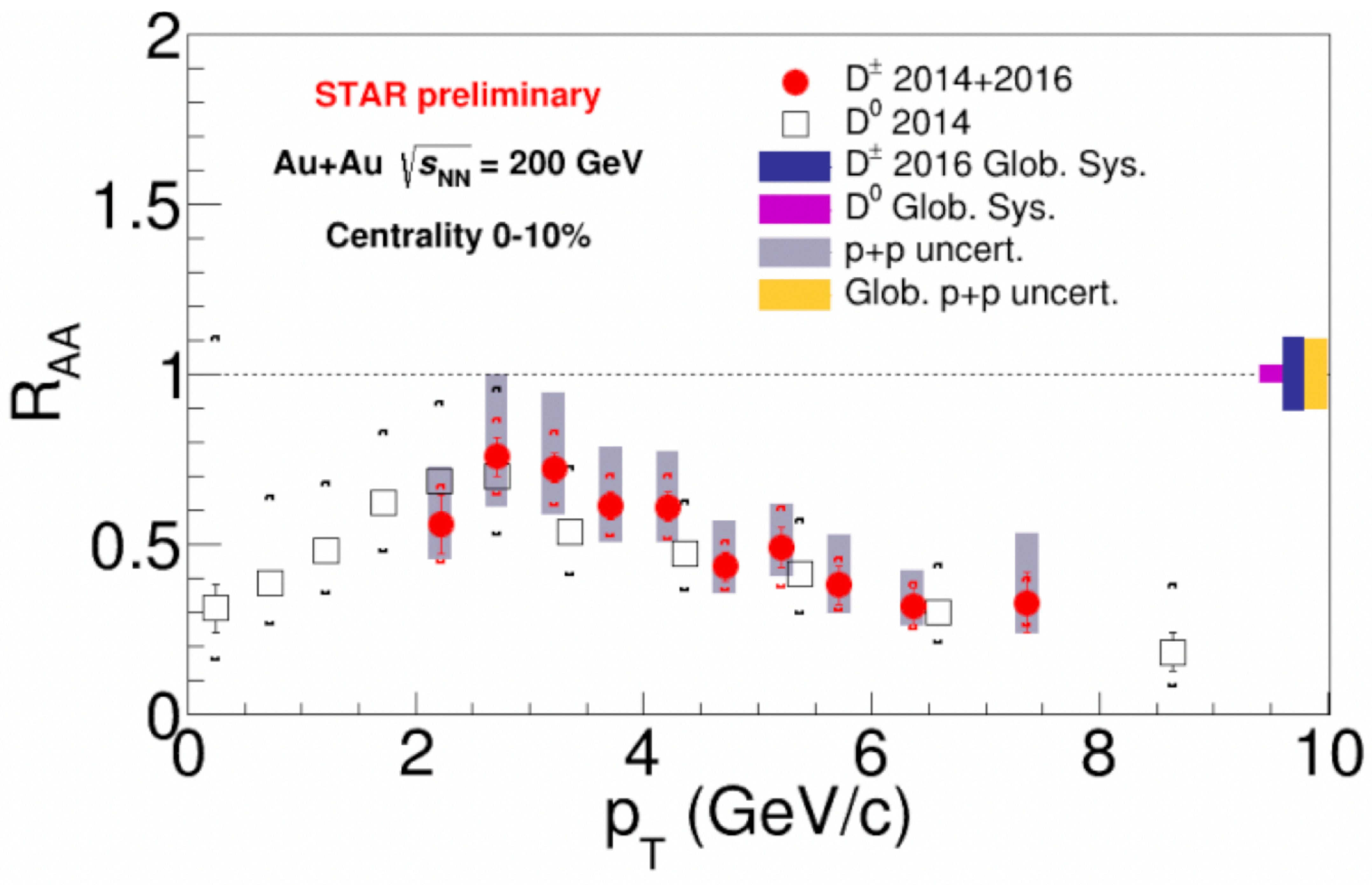


S. Cao, J. Nucl. Phys. A.(2013) 02,100

- At large p_T radiative energy loss dominates and both HF and LF show similar behavior
- Significant collisional energy loss also contributes at lower p_T
- Need precision measurements and differential measurements (along with v_n measurements) to pin down heavy quark interactions in the QGP

Heavy flavor energy loss

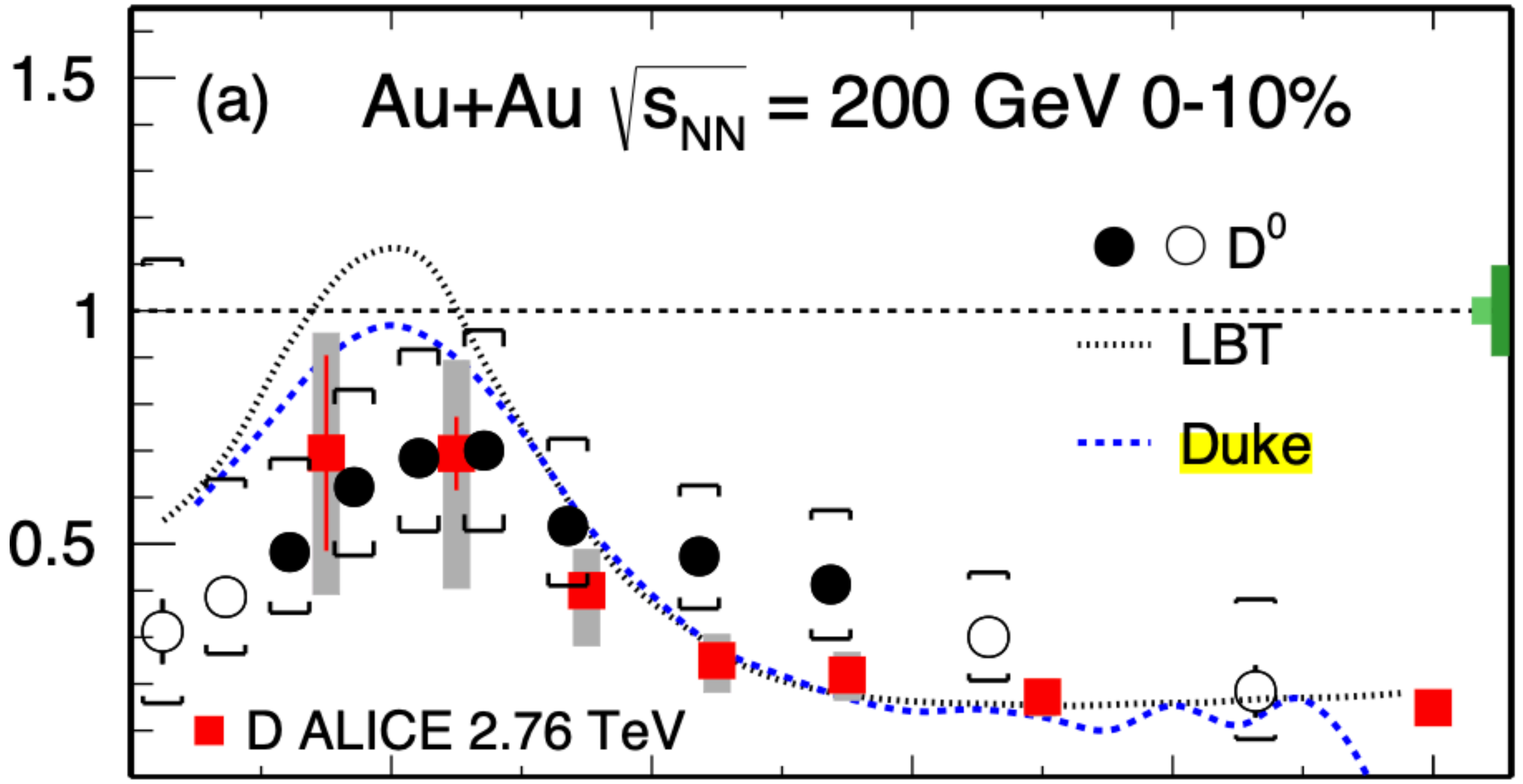




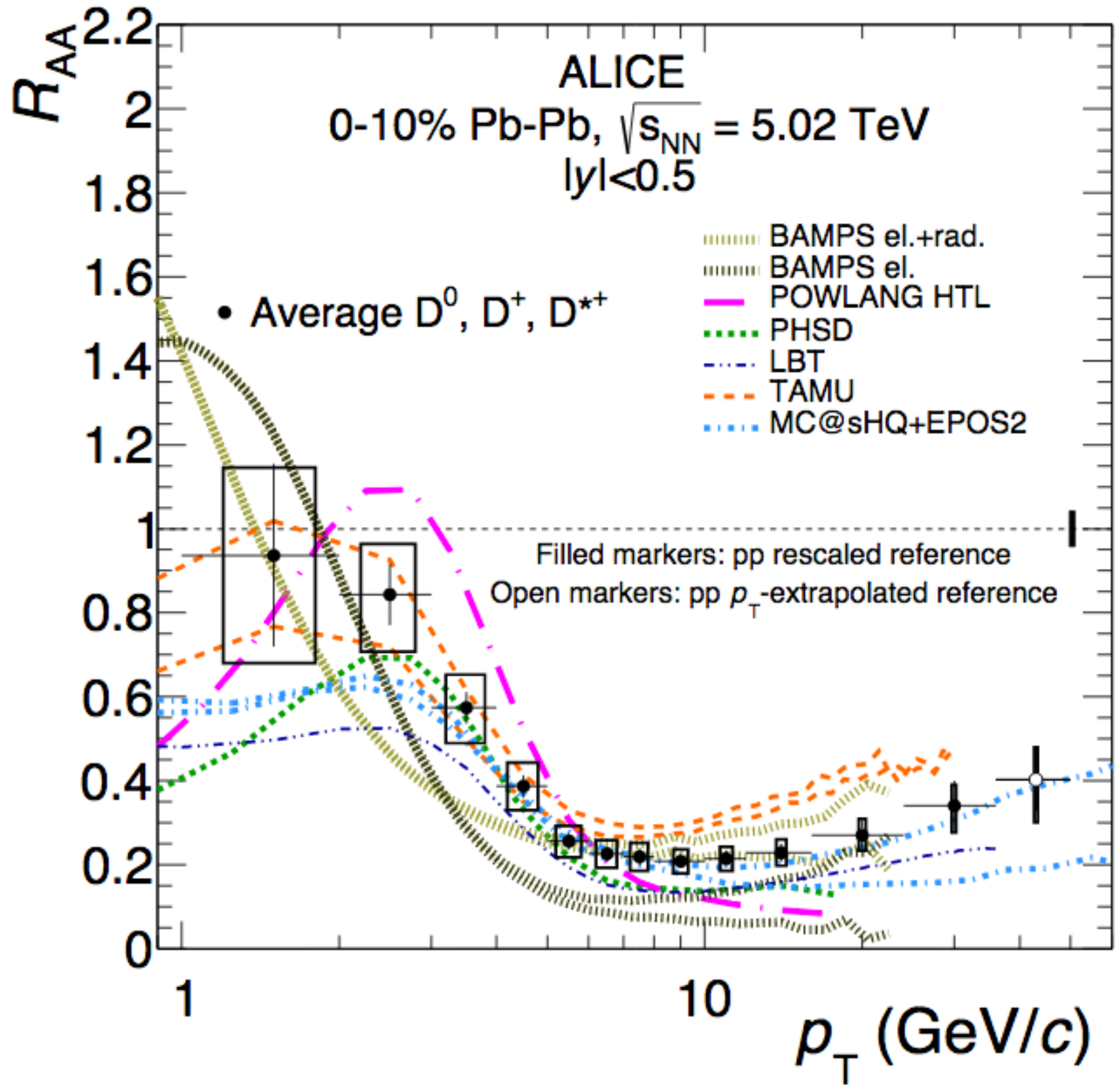
Phys. Rev. C 99, 034908 (2019)

- At large p_T radiative energy loss dominates and both HF and LF R_{AA} show similar behavior
- Significant collisional energy loss also contributes at lower p_T
- Current measurements show consistent R_{AA} with light flavor hadrons
- Systematic uncertainties dominated by p+p reference

Heavy flavor energy loss



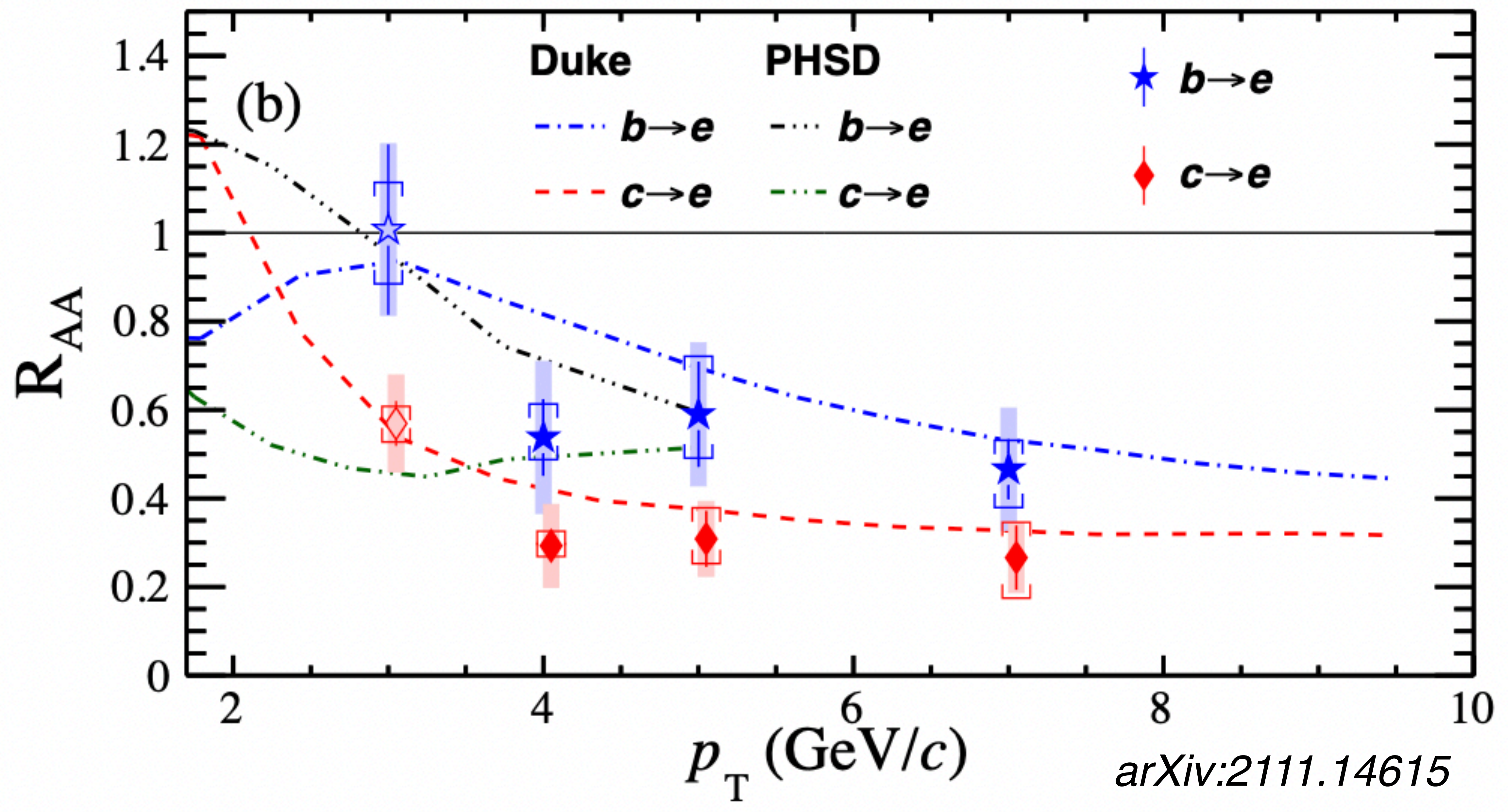
Phys. Rev. C 99, 034908 (2019)



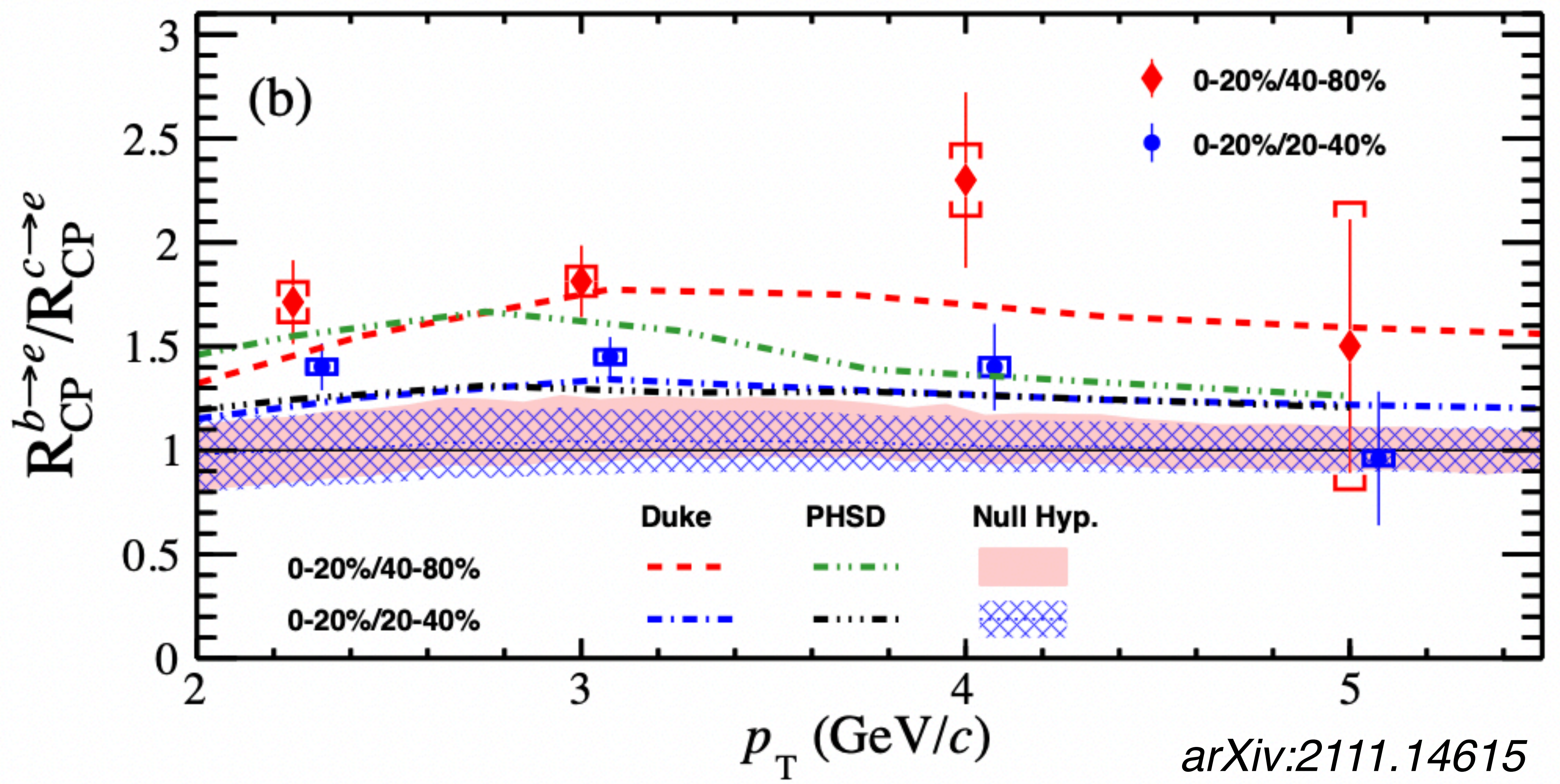
JHEP 1810 (2018) 174

- Models with collisional and radiative energy loss can describe the data
- Large uncertainties in data, models with different prescriptions can describe data
- Need better precision measurements, observables on jet substructure etc

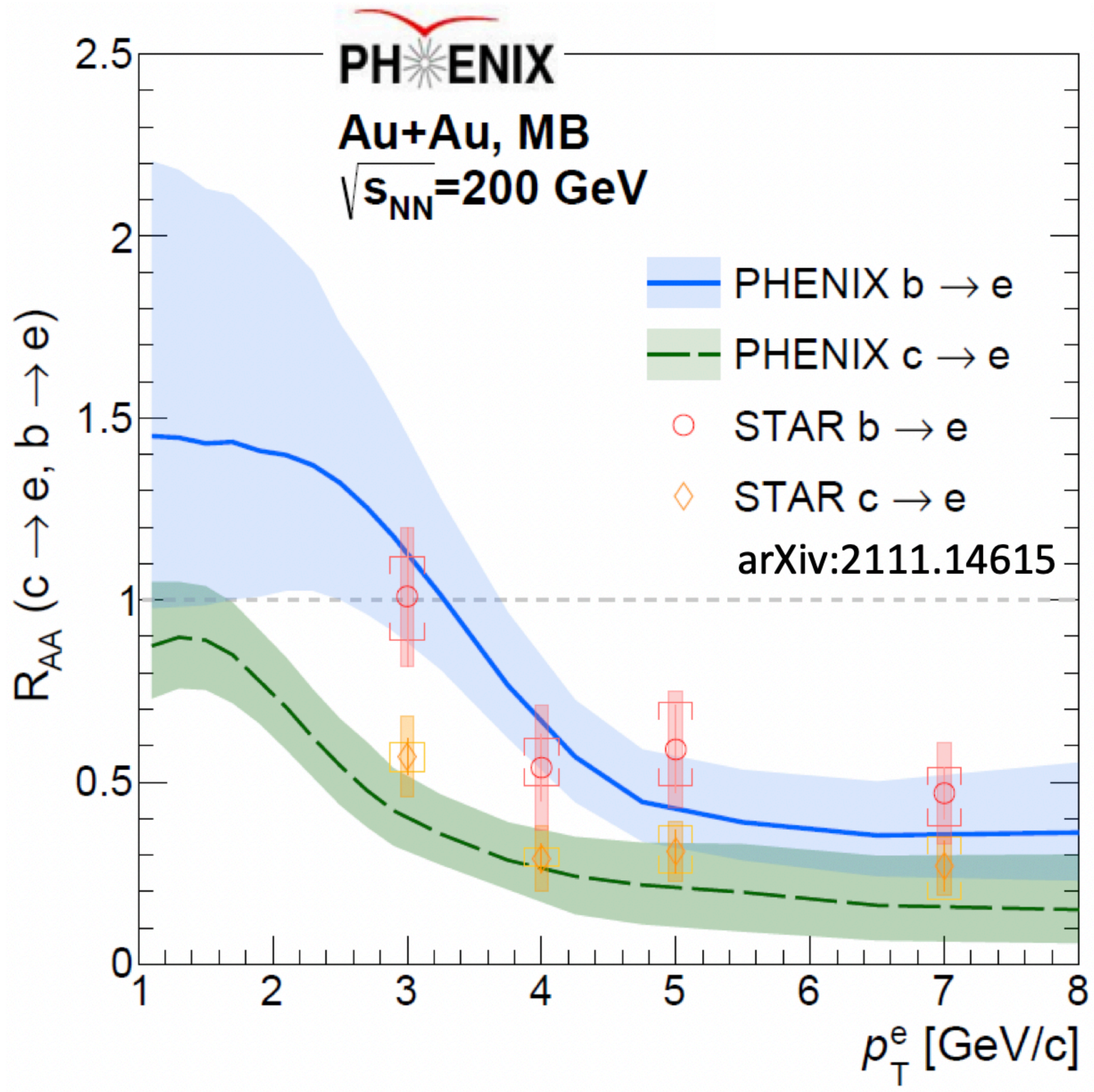
Mass dependence of energy loss



arXiv:2111.14615



arXiv:2111.14615

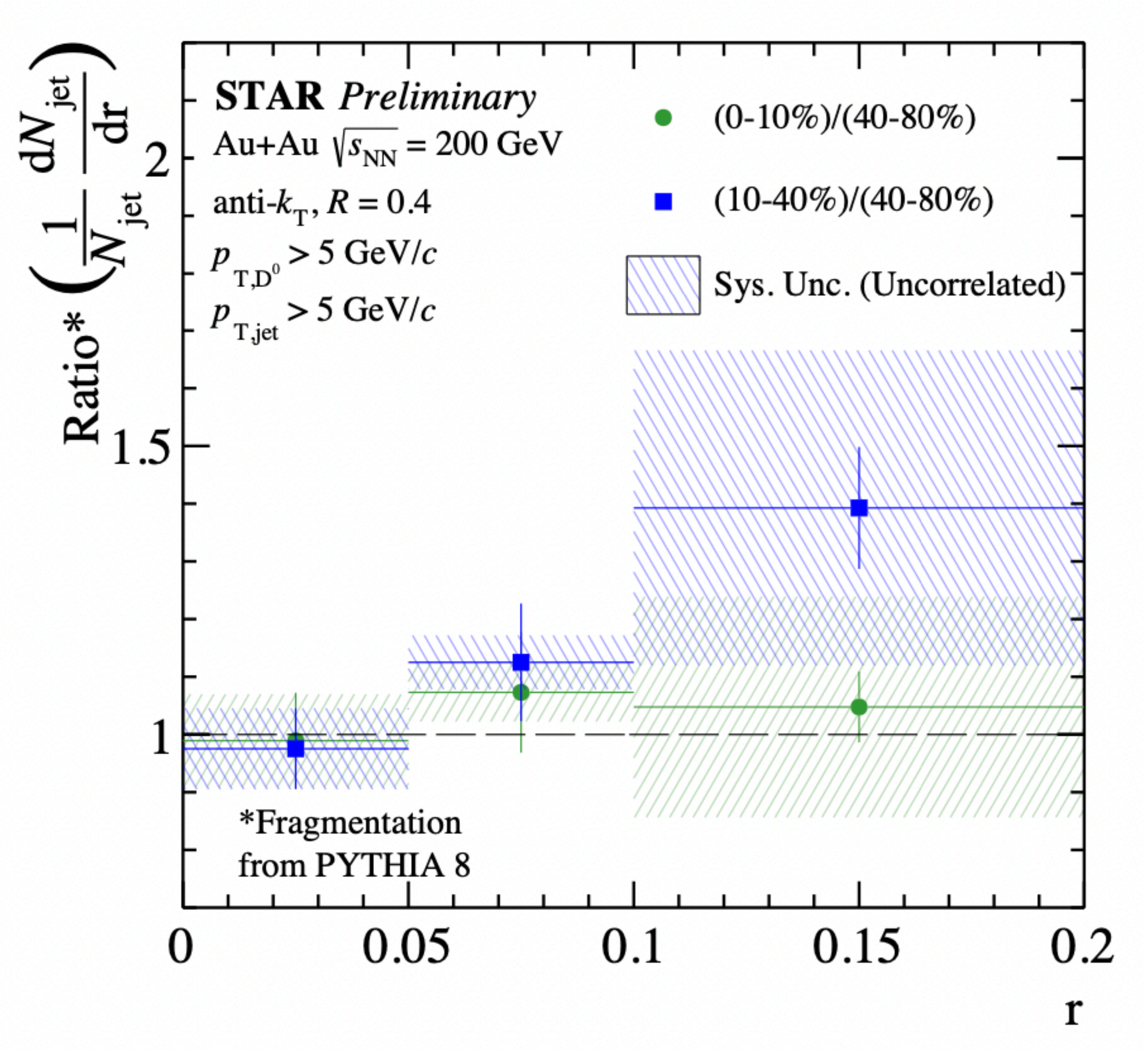


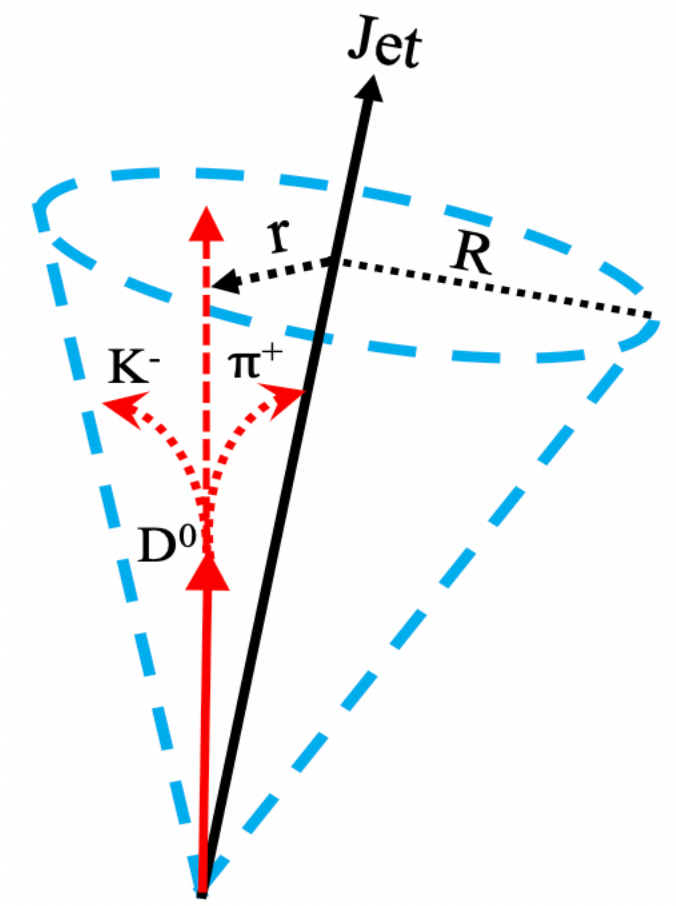
arXiv:2203.17058

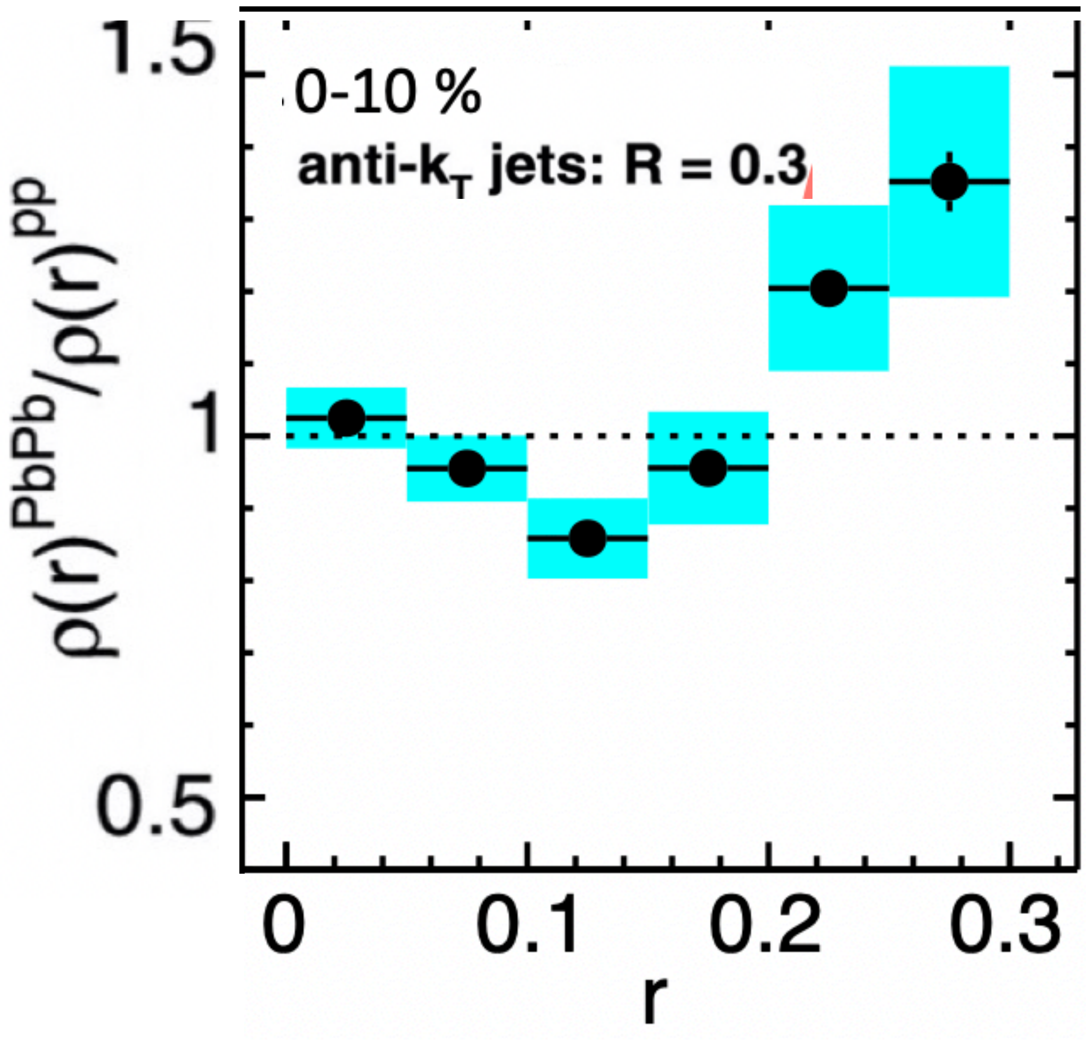
- Clear mass dependence of energy loss: agrees with less energy loss for b quarks in medium
- Expected from less radiative (and collisional) energy loss for bottom quarks

Heavy flavor tagged jets

- Jet substructure with HF hadrons, understand the flavor dependence of redistribution



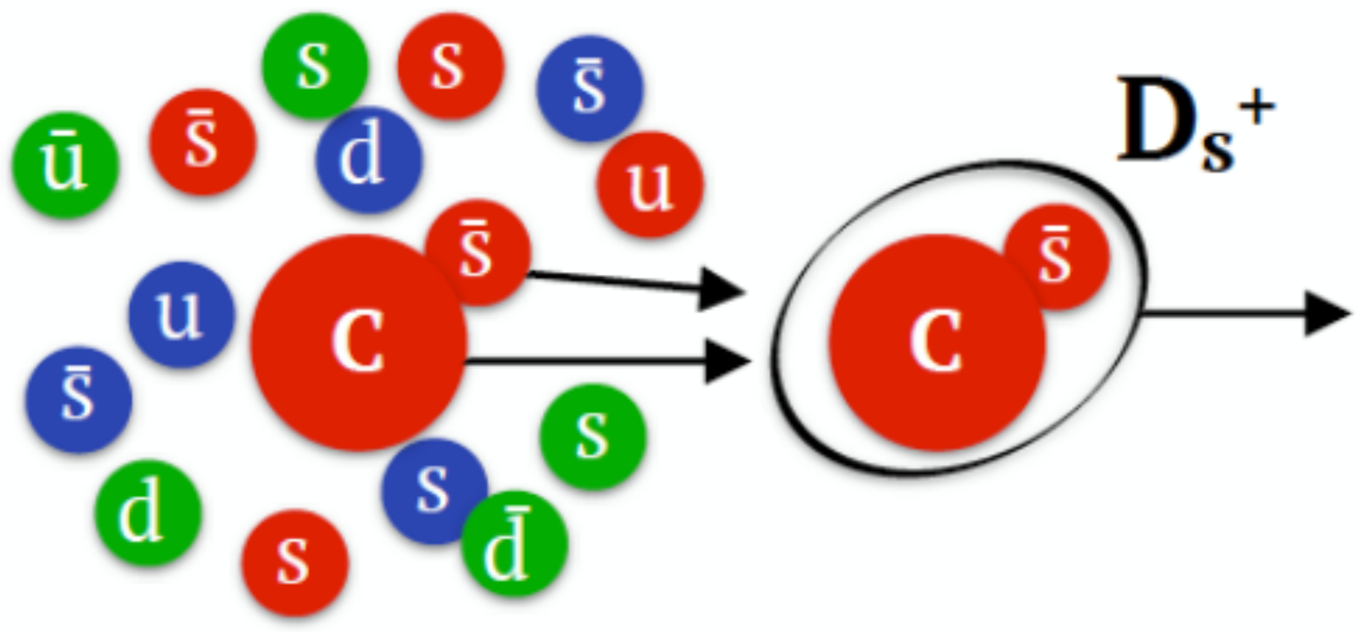


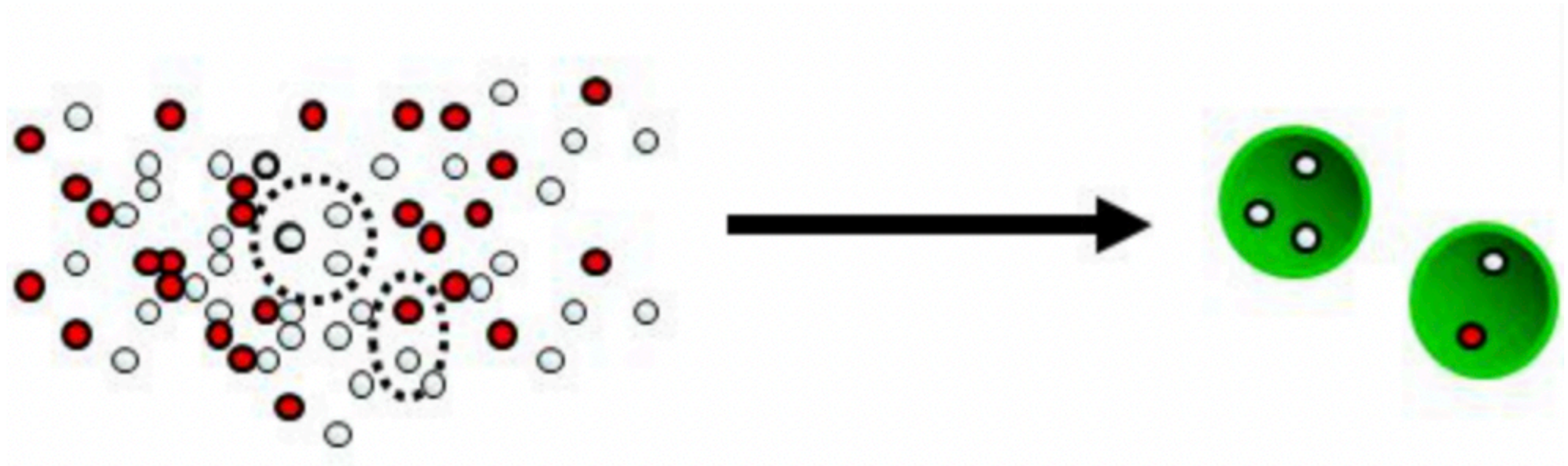


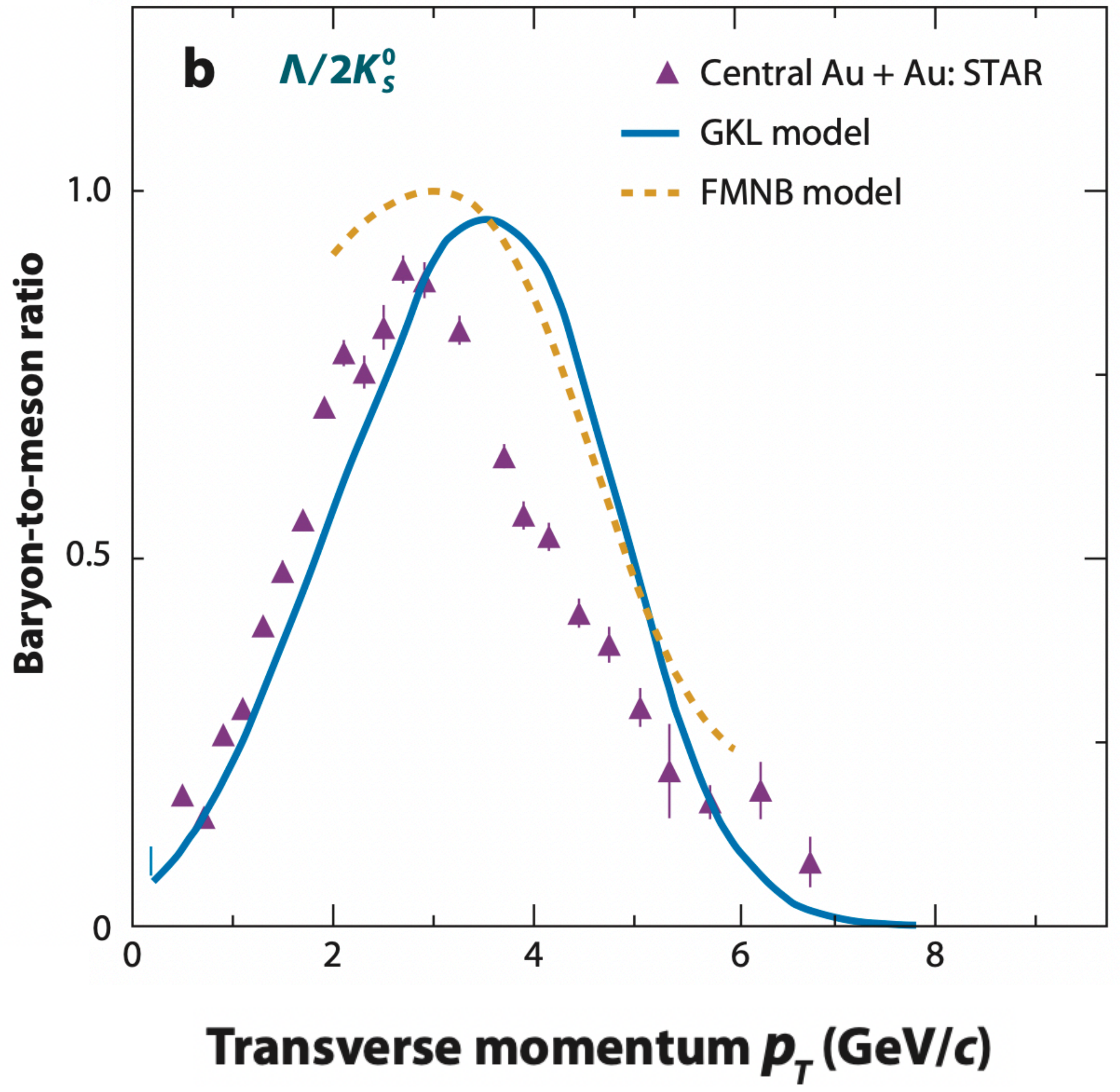
CMS, Phys. Lett. B 730 (2014) 243

- Ratios of radial distributions in central to peripheral collisions consistent with unity for D^0 tagged jets
- Extending the analysis to lower D^0 kinematics is essential to study D^0 diffusion

Heavy flavor as probes to study hadronization



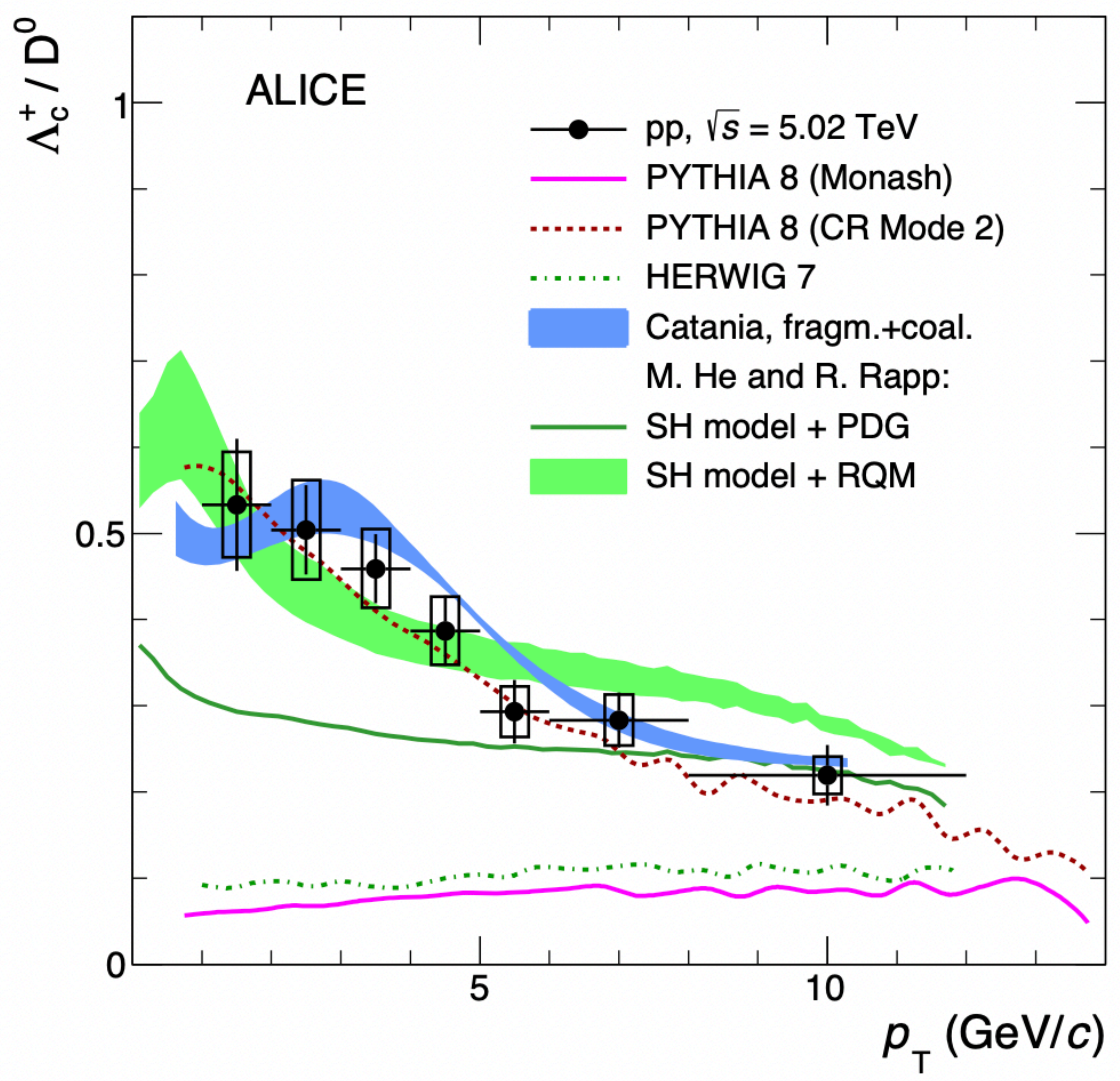




Ann.Rev.Nucl.Part.Sci 58.177-205

- Heavy quarks produced early in collisions and have small thermal production during medium evolution
- Ideal to study modification in particle ratios and hadronization
- Coalescence hadronization used to explain enhanced baryon/meson ratios for light hadrons in heavy-ion collisions
- Will also lead to enhancement of strange hadrons

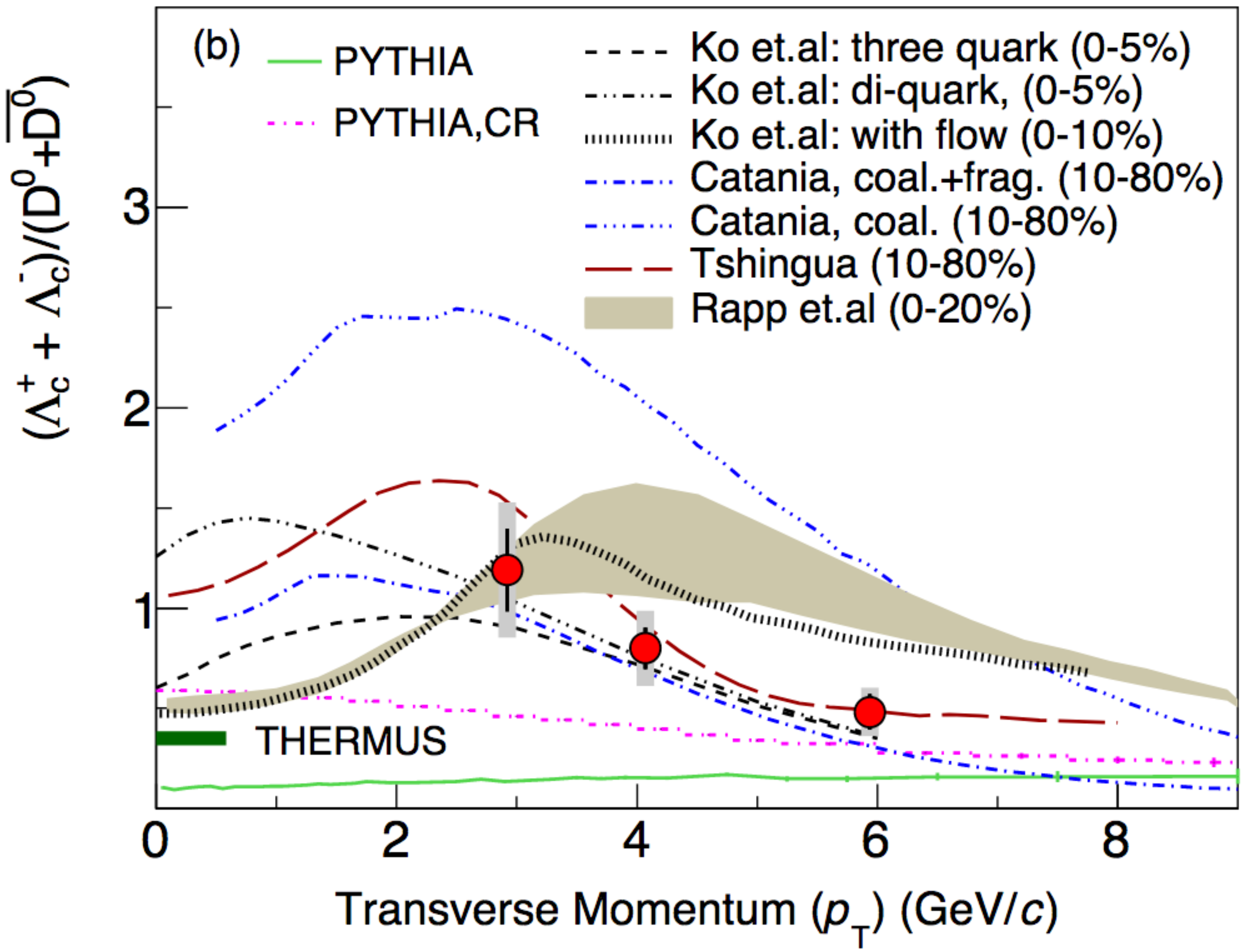
Non-universality of heavy quark FFs

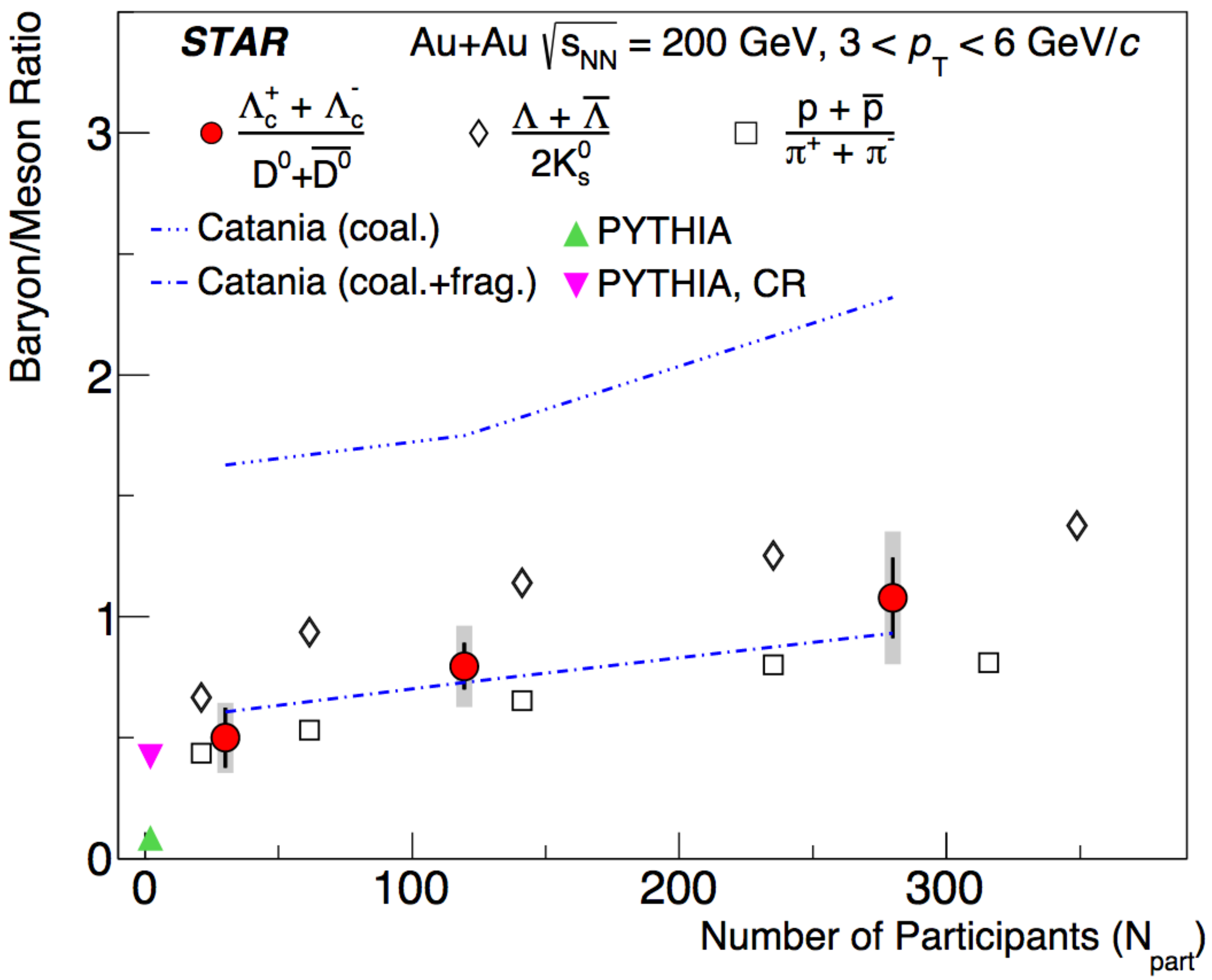


Phys. Rev. Lett. 127 (2021) 202301

- Breaking of universality of charm fragmentation fractions
- Strong enhancement of Λ_c production in p+p and p+Pb collisions for $p_T < 8$ GeV/c compared to fragmentation ratios measured at high p_T
- PYTHIA with color reconnection and thermal model with feed down from excited charm states describe data
- Multiplicity dependence, QGP impact, rapidity, collision energy dependence?

Λ_c enhancement in HIC

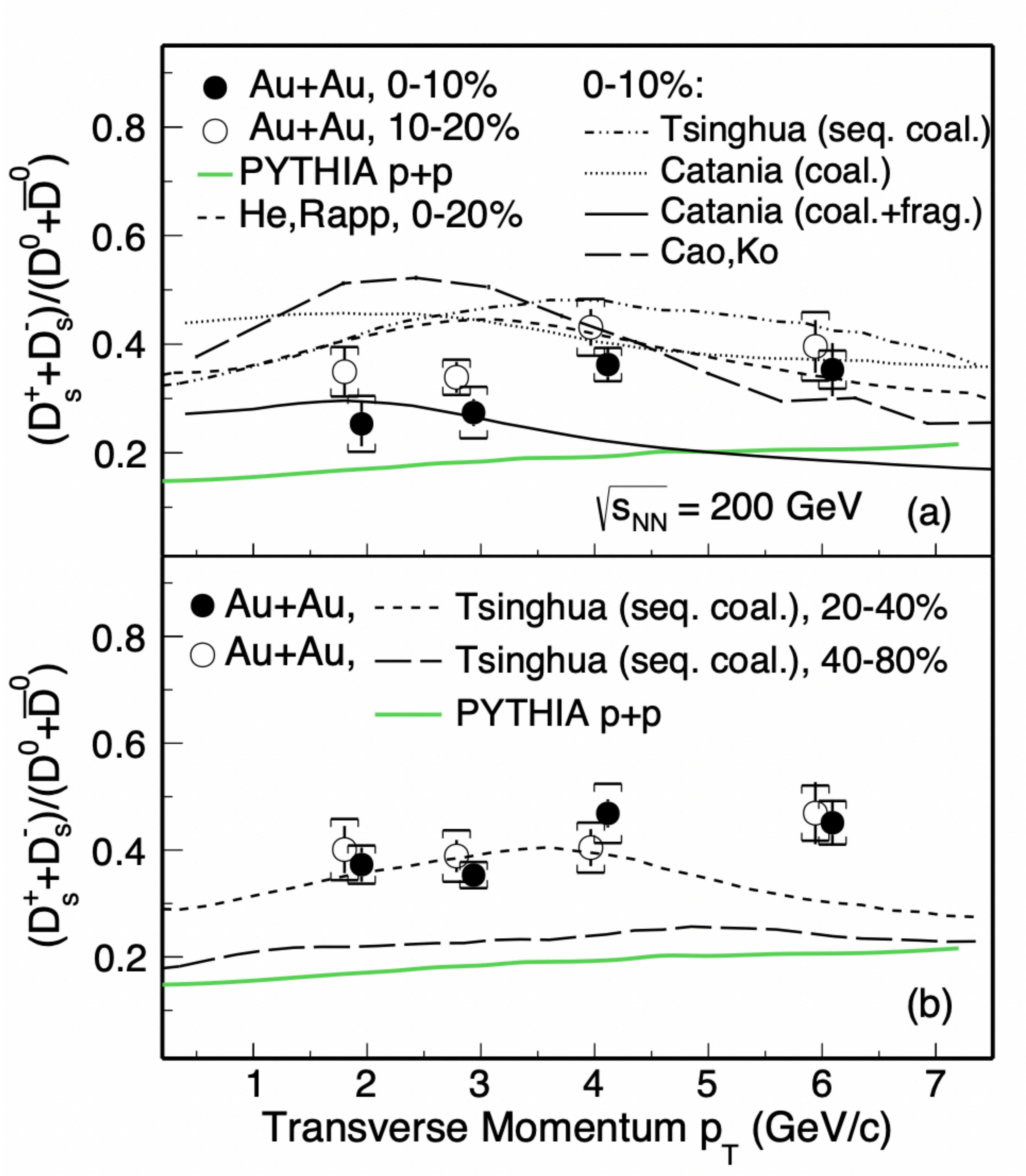


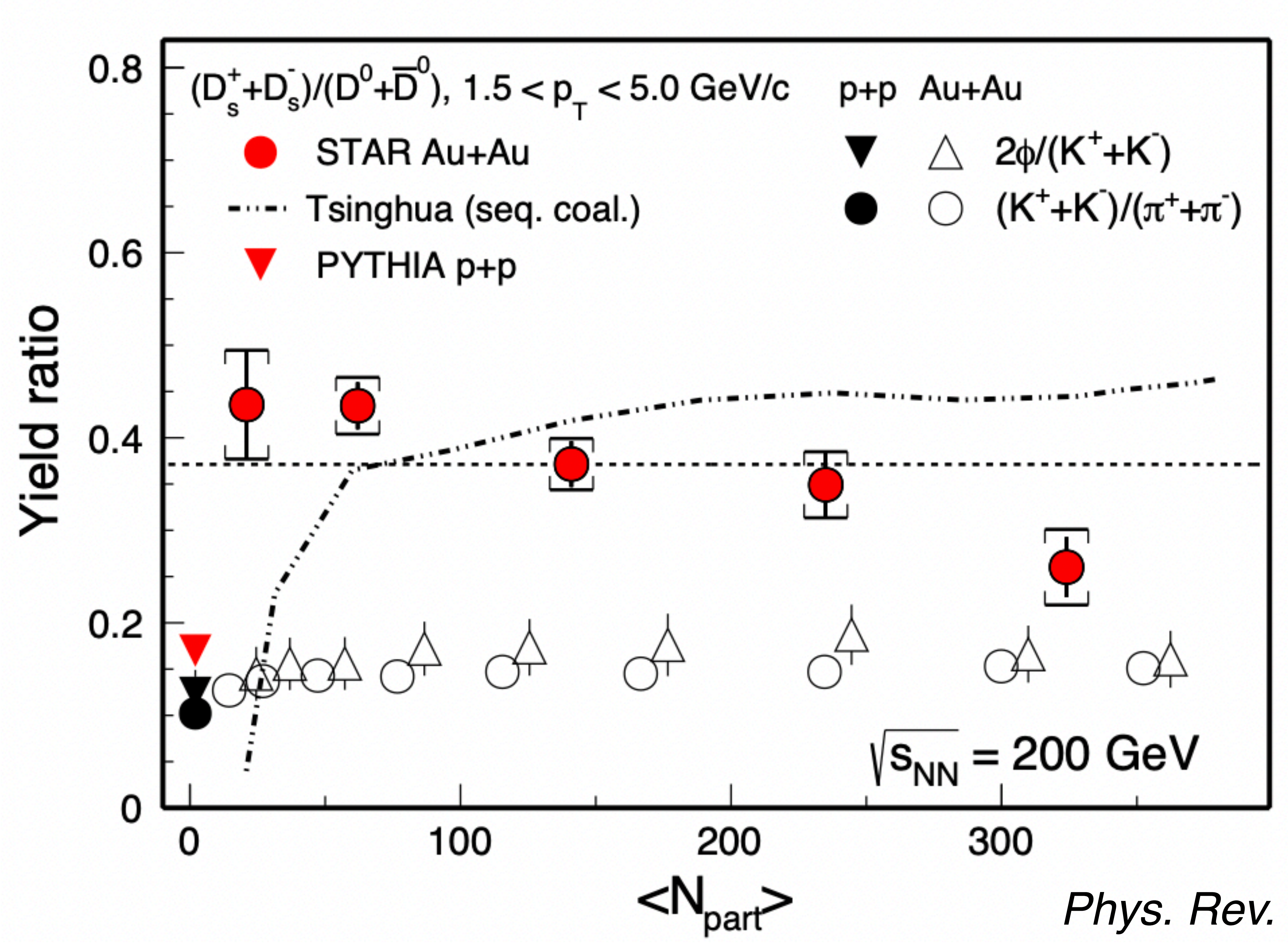


Phys. Rev. Lett. 124, 172301 (2020)

- Strong enhancement relative to PYTHIA in Au+Au collisions at RHIC
- Similar trend as seen for B/M ratio enhancement for light flavor hadrons
- Consistent with coalescence model calculations

Strange D meson production





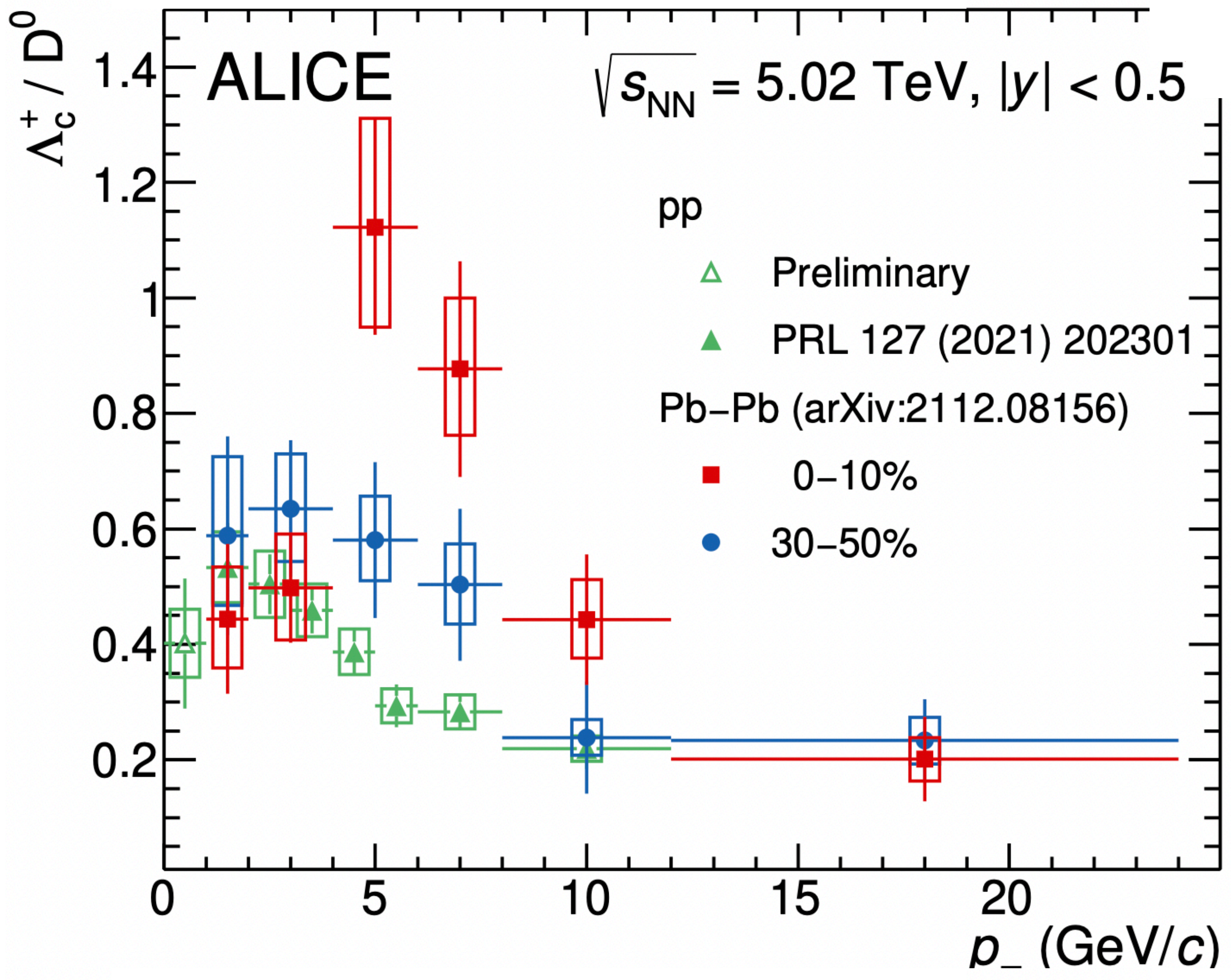
Phys. Rev. Lett. 127, 092301 (2021)

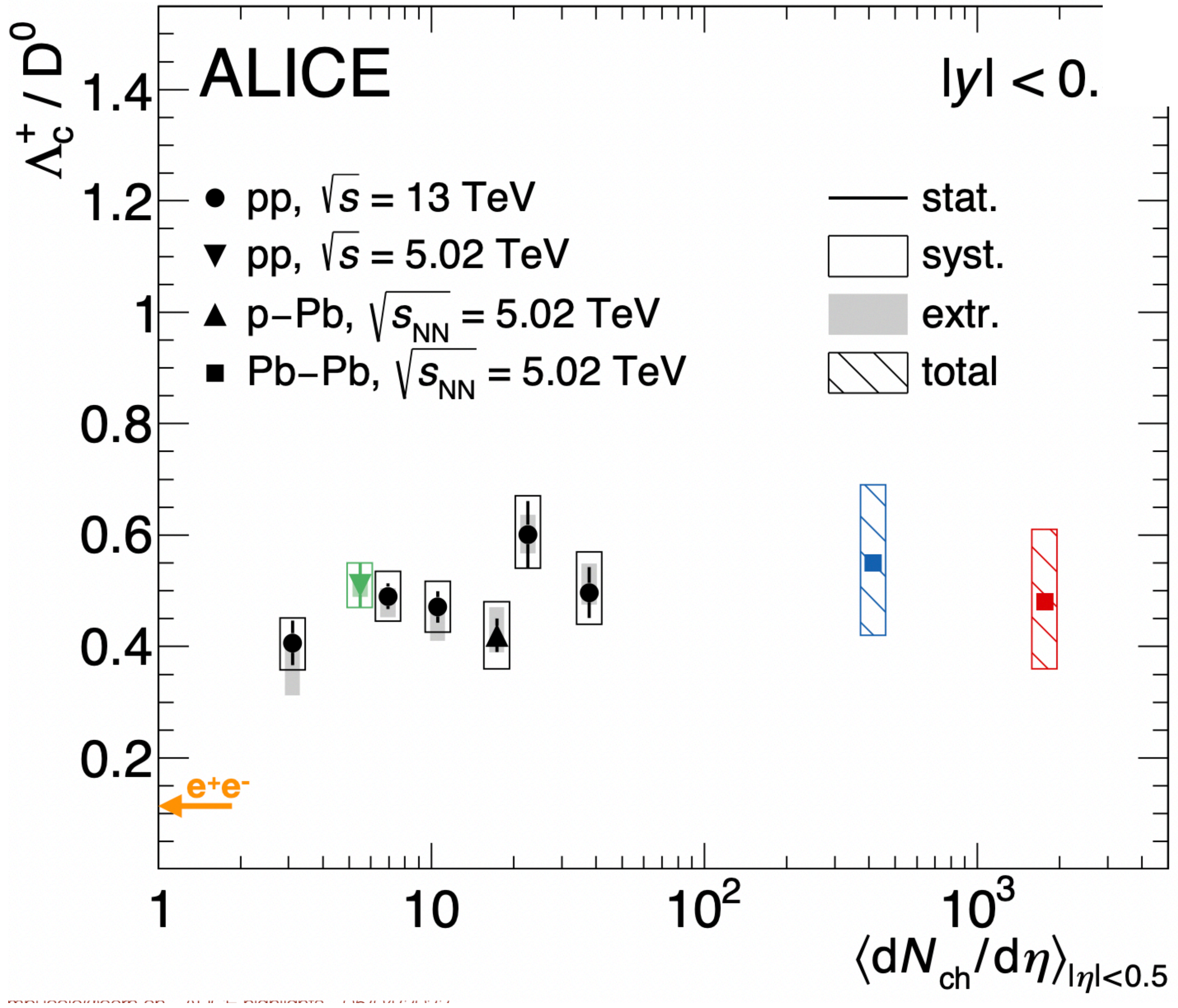
- Clear enhancement relative to p+p values
- CR has no impact for Ds/D^0 ratios
- Indication that coalescence hadronization is relevant in charm sector in heavy-ion collisions at RHIC

Low p_T yields and total charm cross-section

Coll. system	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3
	D_s	15 ± 2 ± 4
	Λ_c	40 ± 6 ± 27*
	Total:	**112 ± 6 ± 27**
p+p at 200 GeV	**Total:**	**130 ± 30 ± 26**

STAR Preliminary

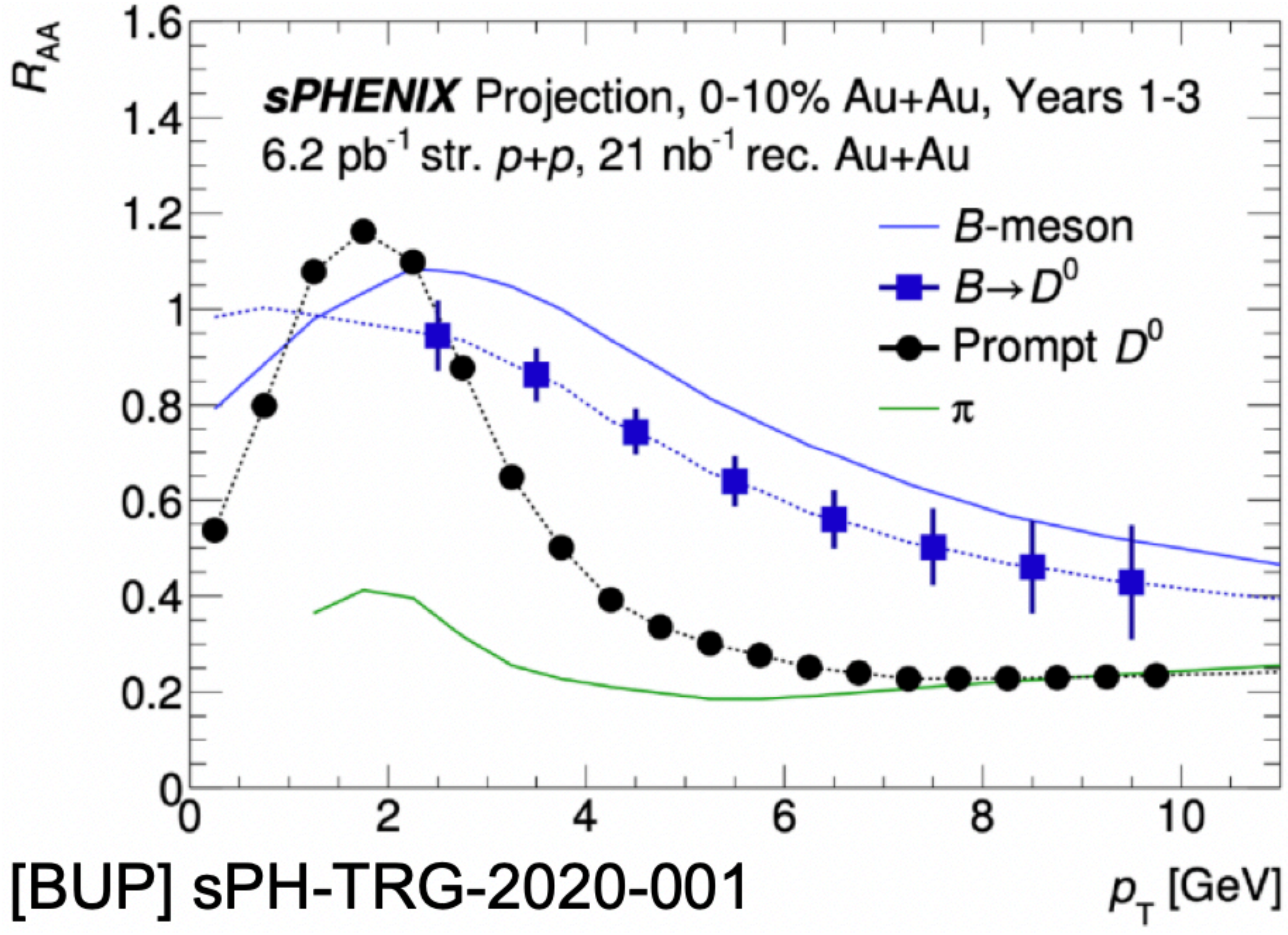


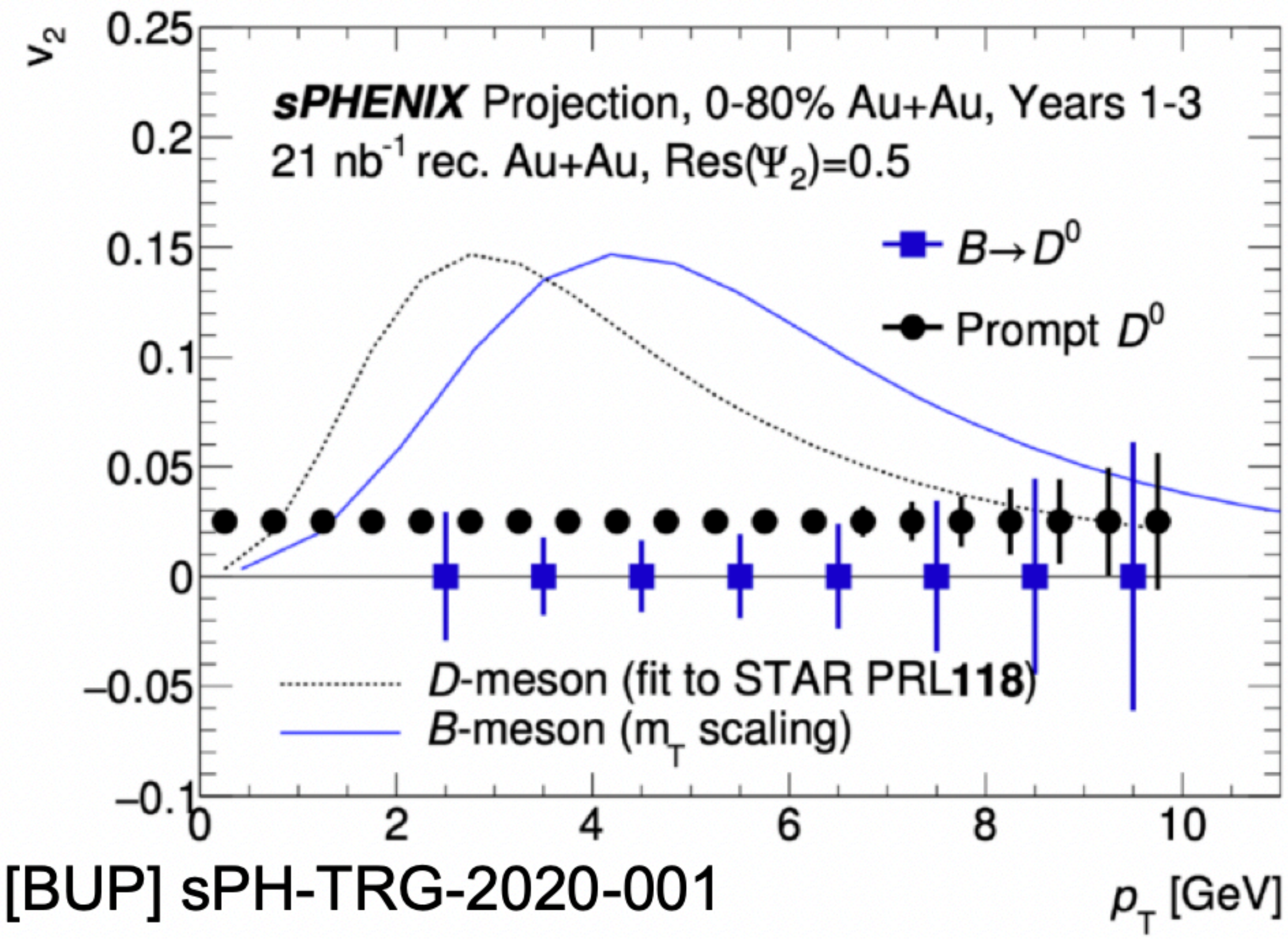


- Extrapolation to zero p_T using coalescence models at RHIC gives different values (with large errors) for Λ_c/D^0 ratios than in p+p
- ALICE observes strong enhancement in A + A at intermediate p_T, but integrated ratios consistent with p+p
- Need low p_T measurements at RHIC for better understanding of enhancement

arXiv:2112.08156

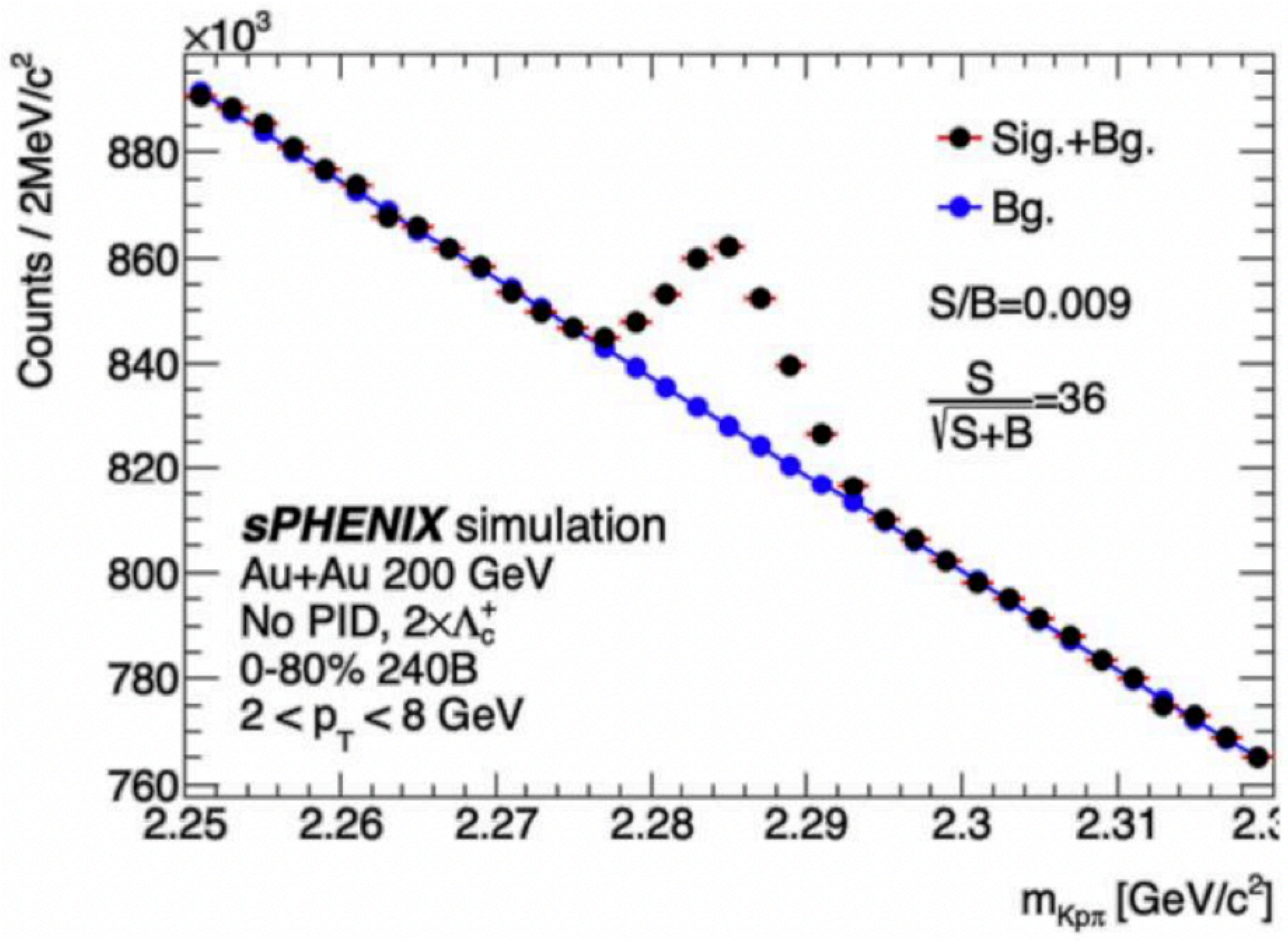
Improvements from sPHENIX

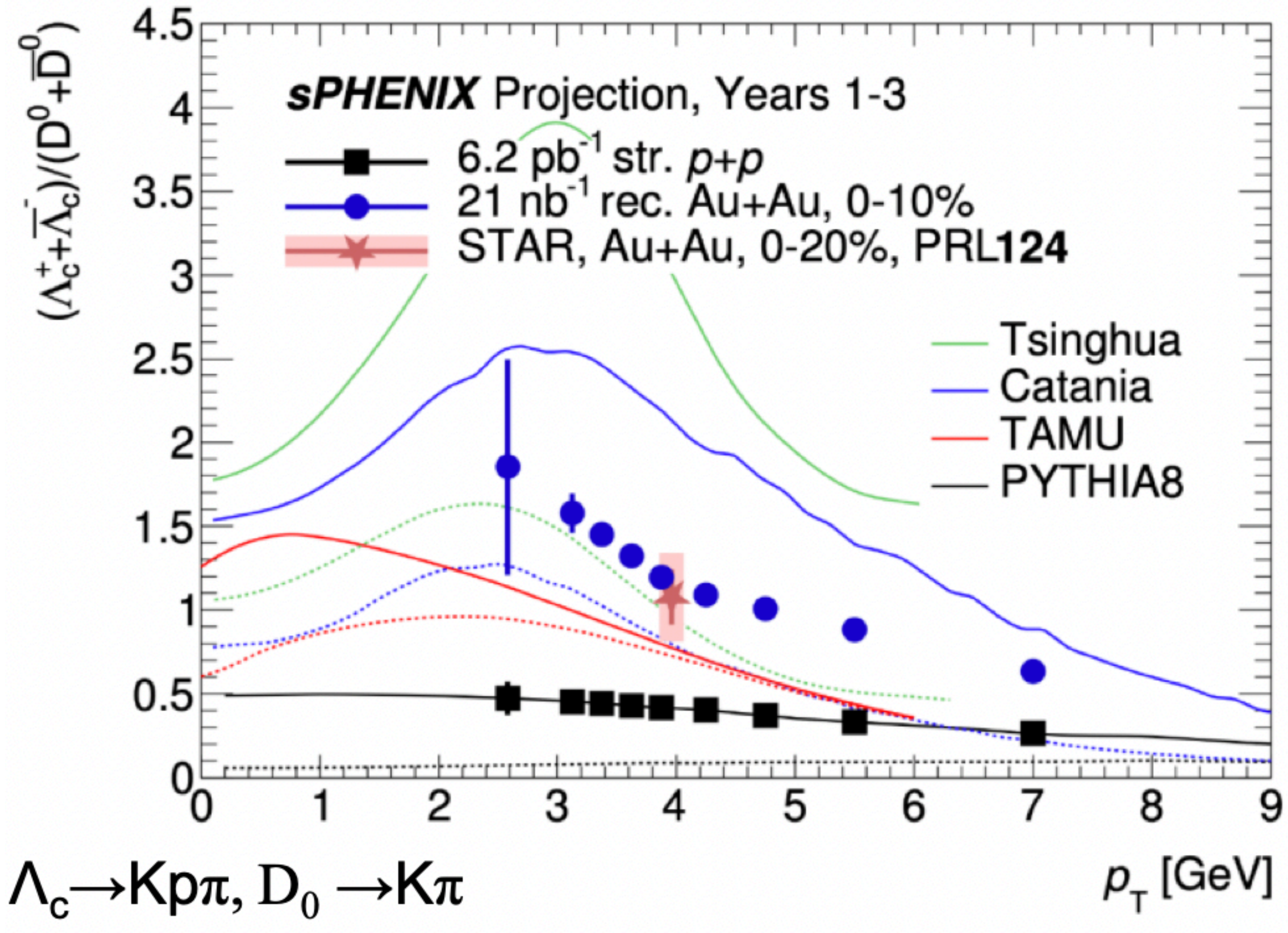




- For most of the open HF measurements sPHENIX expected to give significant enhancement in precision and kinematic reach
- Hight precision measurements both in the charm sector and bottom sector for v_2, v_1, flow fluctuations, R_{AA}, jet fragmentation modifications …

Improvements from sPHENIX

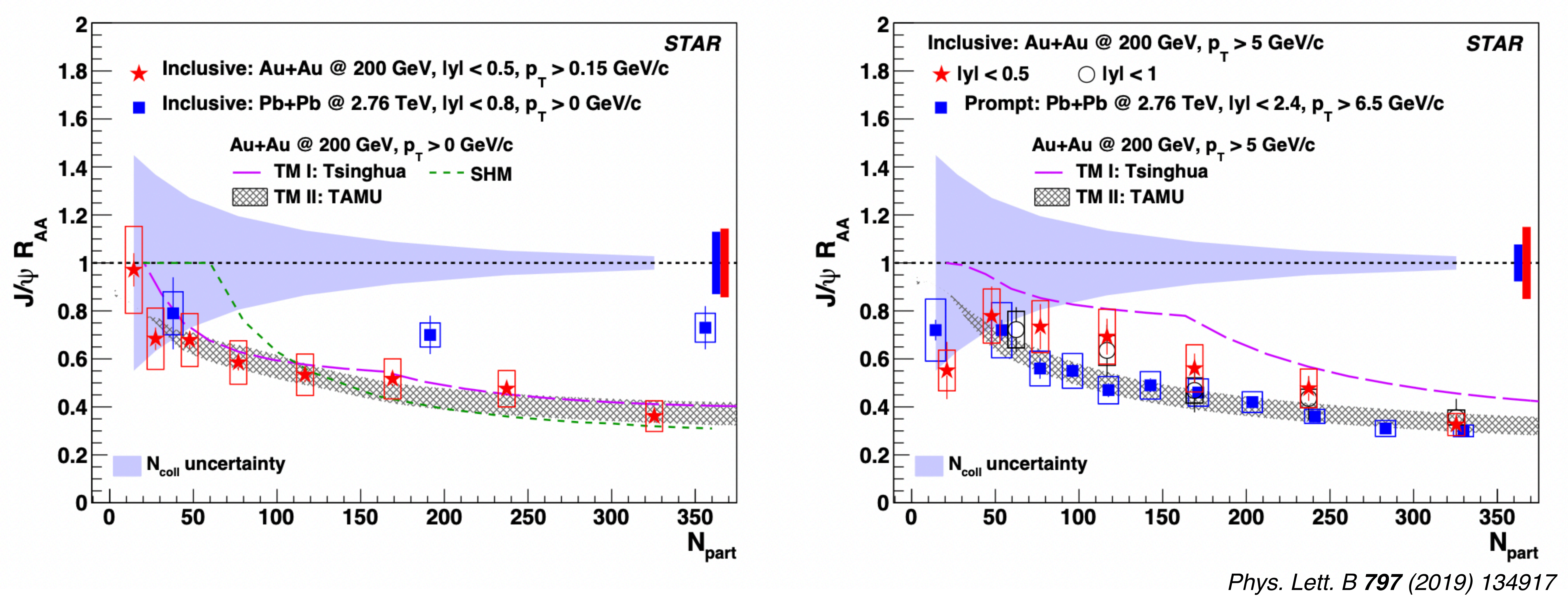




- Better precision and improved kinematic reach for Λ_c measurements in p+p and Au+Au
- Study multiplicity, system size dependences, and also potentially extend to lower p_T

Color screening and quarkonia in A+A

- Quarkonia production: probes color screening and deconfinement

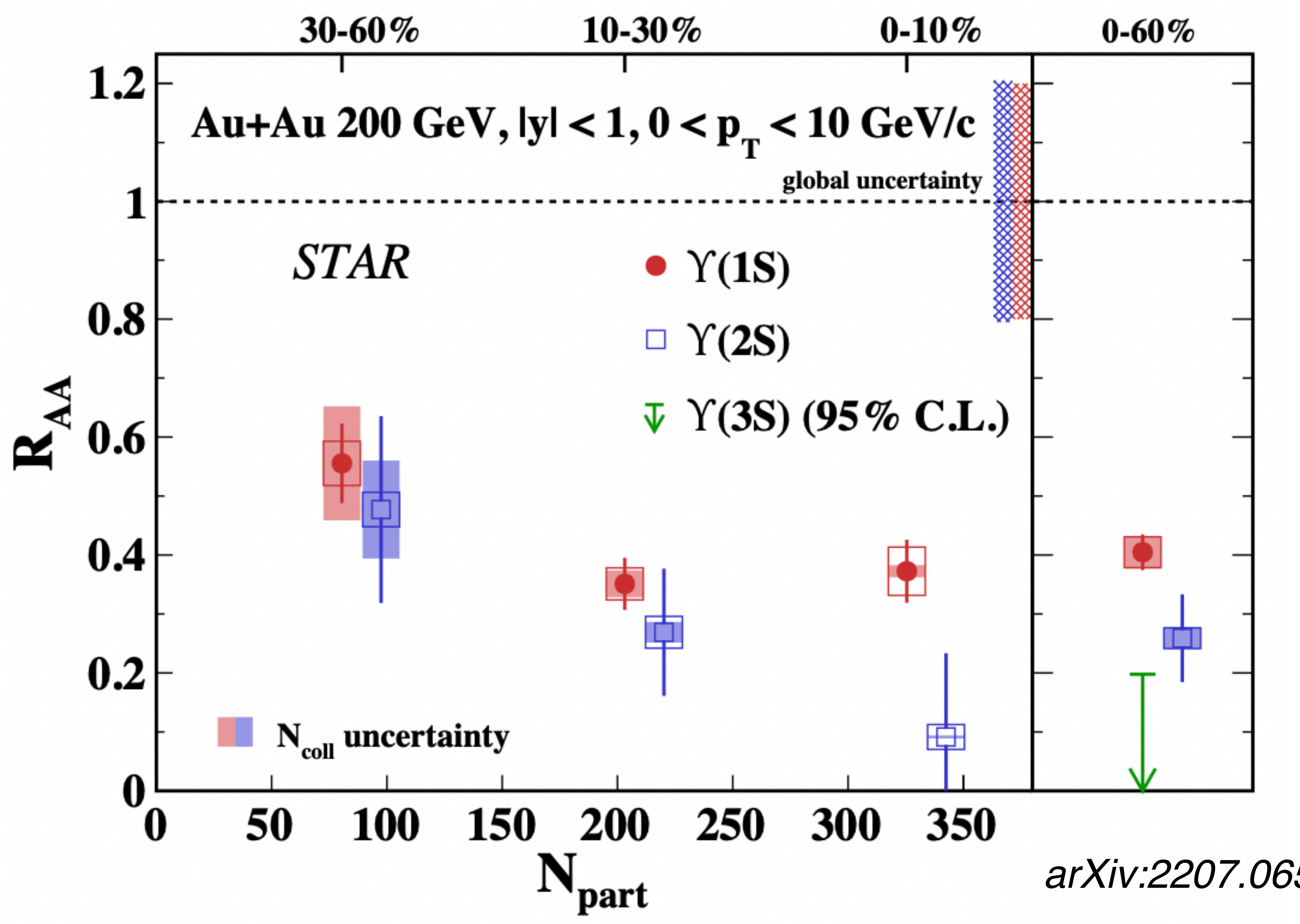


*Phys. Lett. B **797** (2019) 134917*

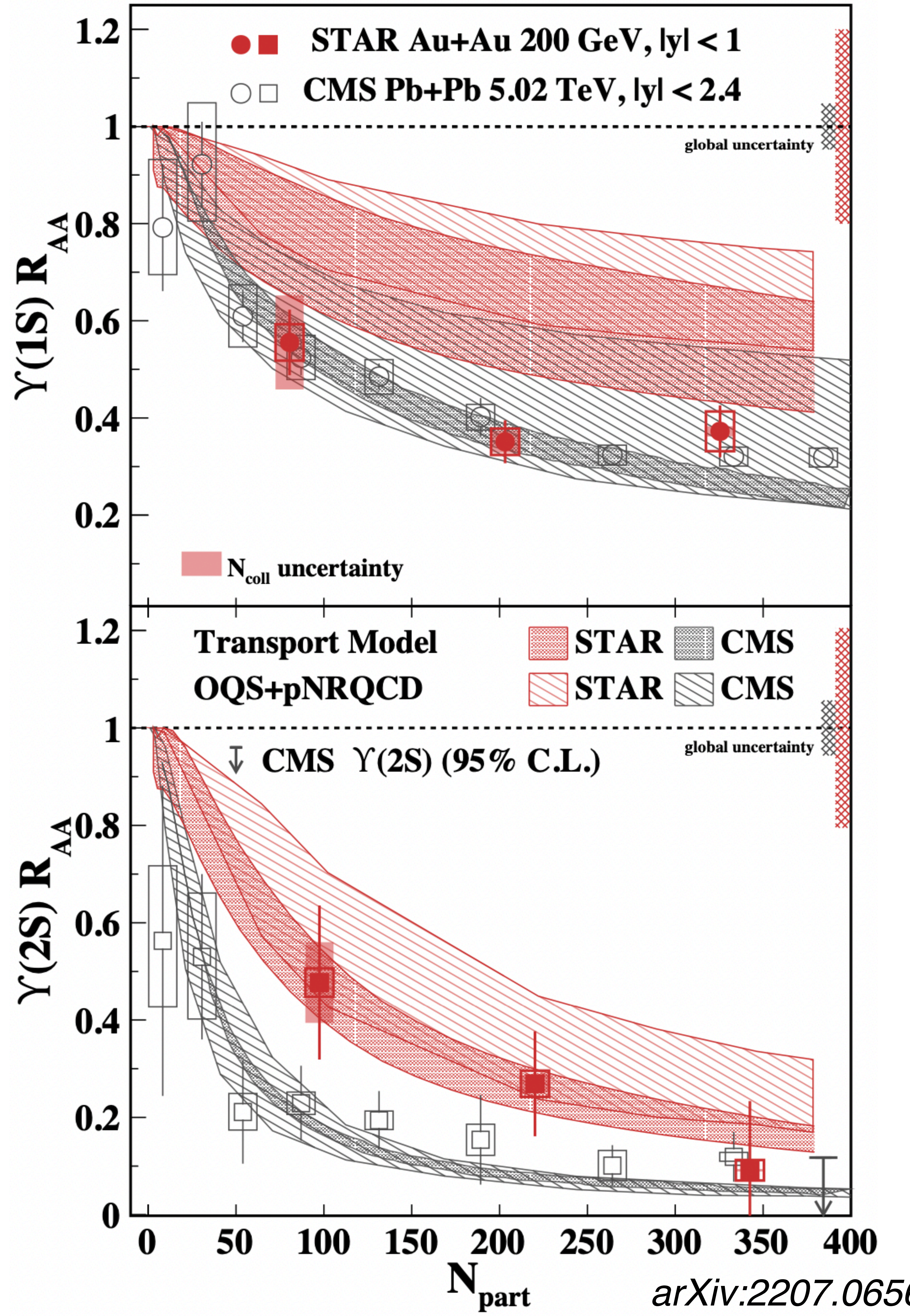
- High p_T suppression similar at RHIC and LHC: dissociation from color screening
- Low p_T suppression less at LHC than at RHIC: larger regeneration component at LHC from larger total charm cross-section

Sequential suppression of Υ

- Less regeneration contribution for Υ at RHIC (lower b cross-section)



arXiv:2207.06568

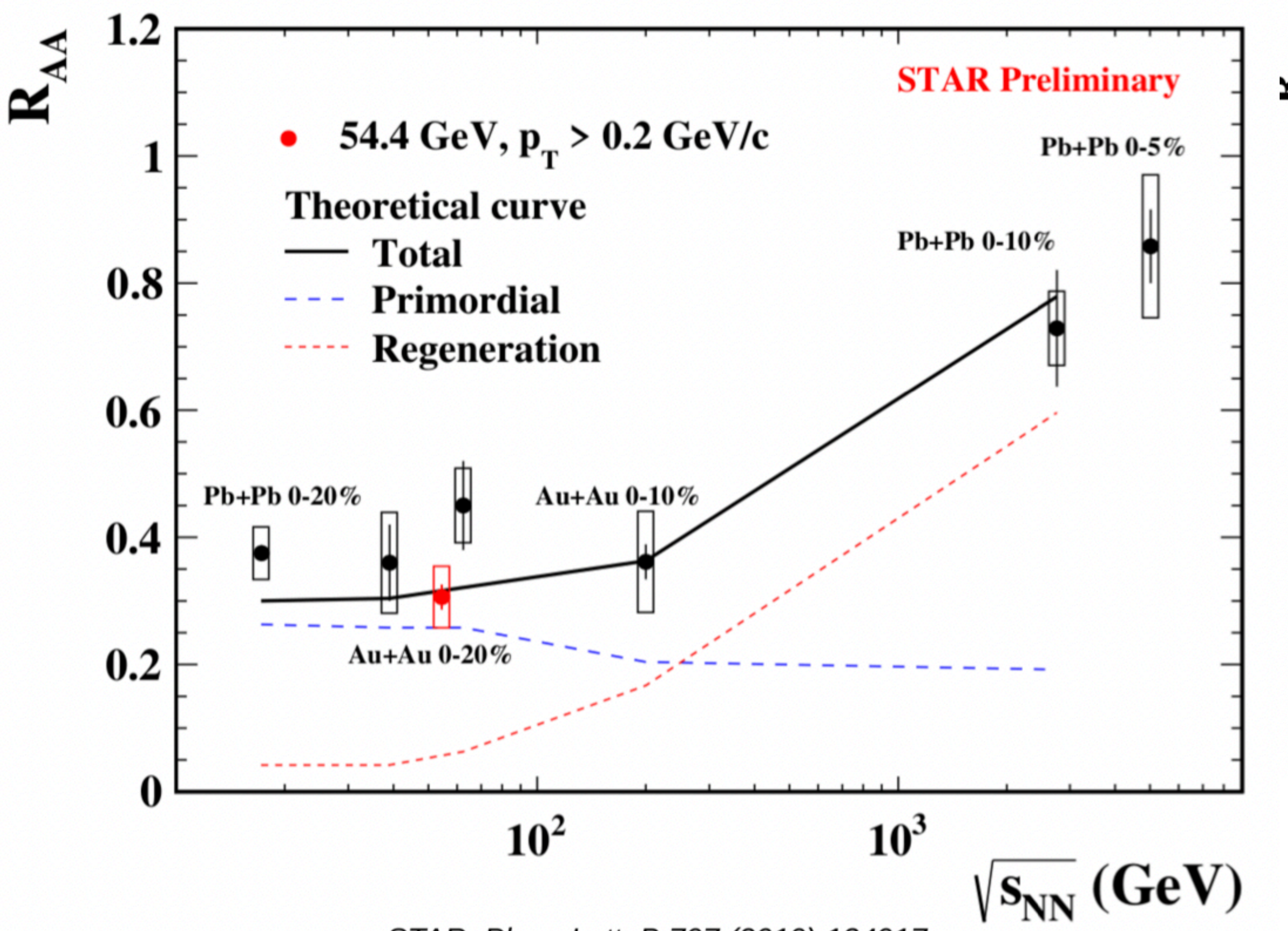


arXiv:2207.06568

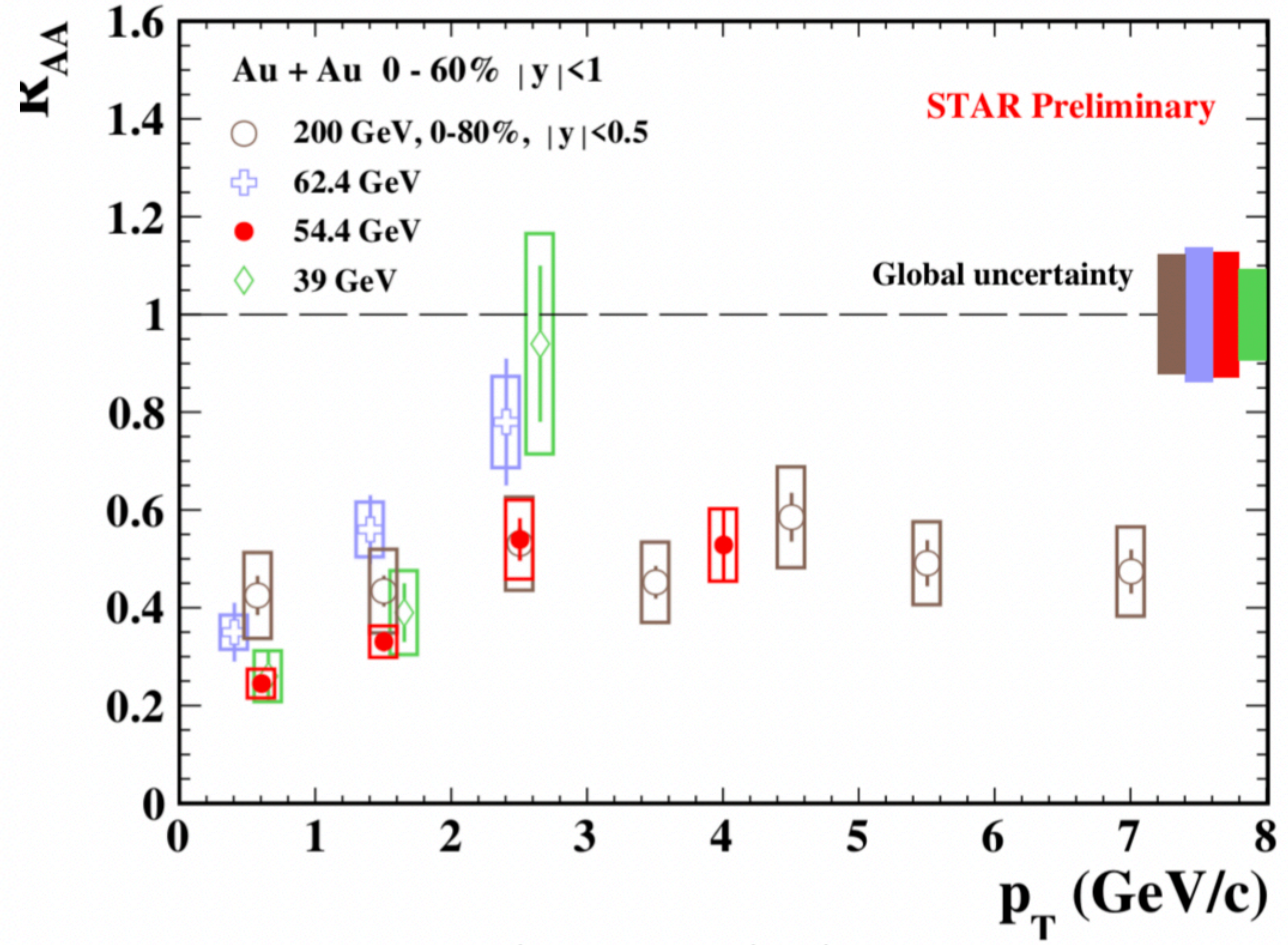
- Observation of sequential suppression of Υ at RHIC
- Similar suppression for Υ(1S) at LHC and RHIC, smaller suppression for Υ(2S) at RHIC
- Models describe data, but large errors too (including from CNM effects)

J/Ψ suppression at lower collision energies

- Collision energy dependence can help constrain the dissociation and regeneration contributions for J/Ψ modification



STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13-20
ALICE, Nucl. Phys. A 1005 (2021) 121769
ALICE, Phys. Lett. B 734 (2014) 314
X. Zhao, R. Rapp, Phys. Rev. C 82, 064905



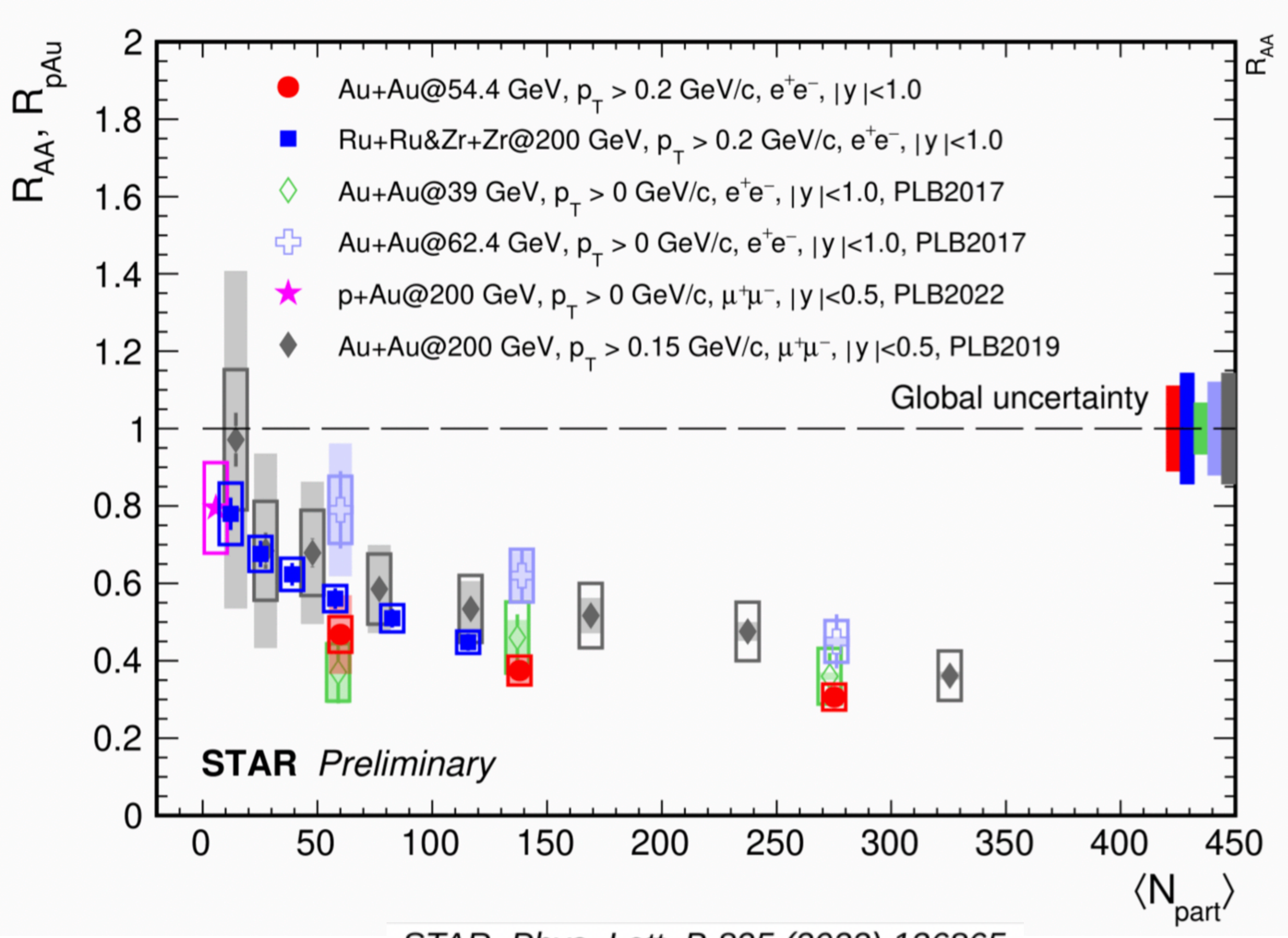
STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13

- Better precision for new measurement at 54.4 GeV compared to BES-I results

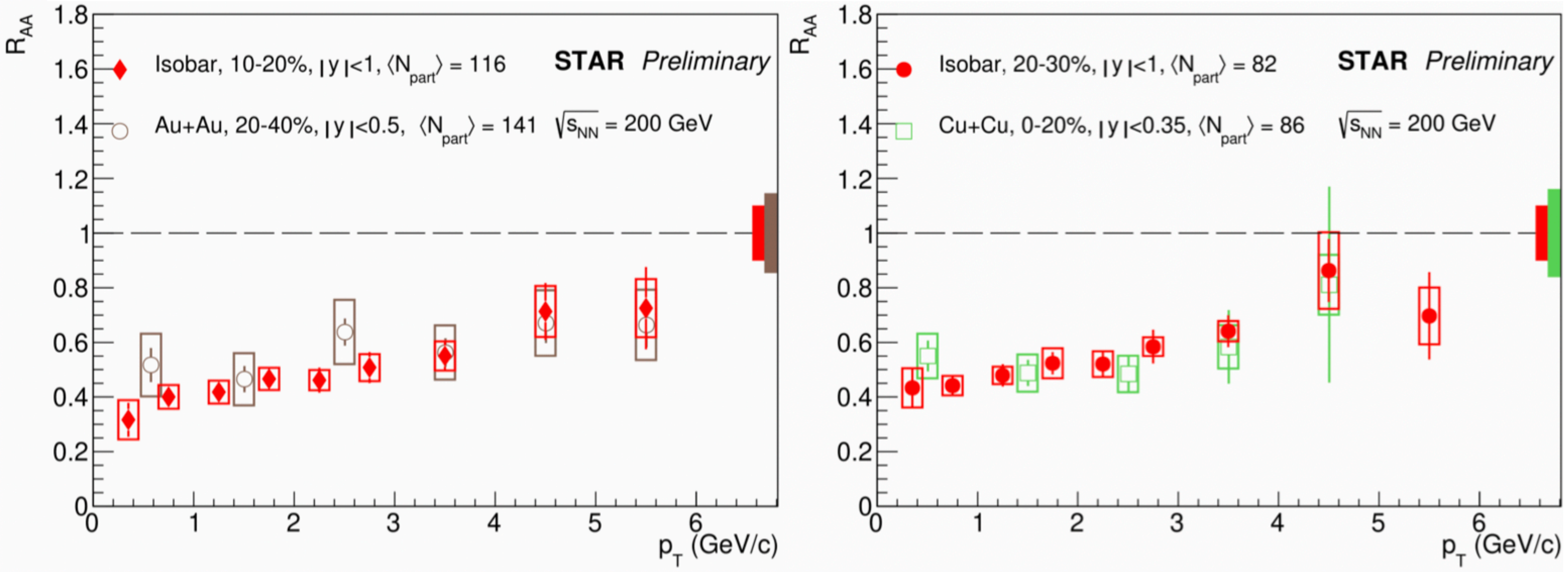
- No significant energy dependence of J/ψ R_{AA} below 200 GeV
- Transport model with both dissociation and regeneration effects describes the data
- Lower BES-II energies could also be measured

Collision system dependence of J/Ψ suppression

- Large isobar dataset, about 4 billion minimum bias events.
- Ideal to study system size and geometry dependence of J/ψ suppression



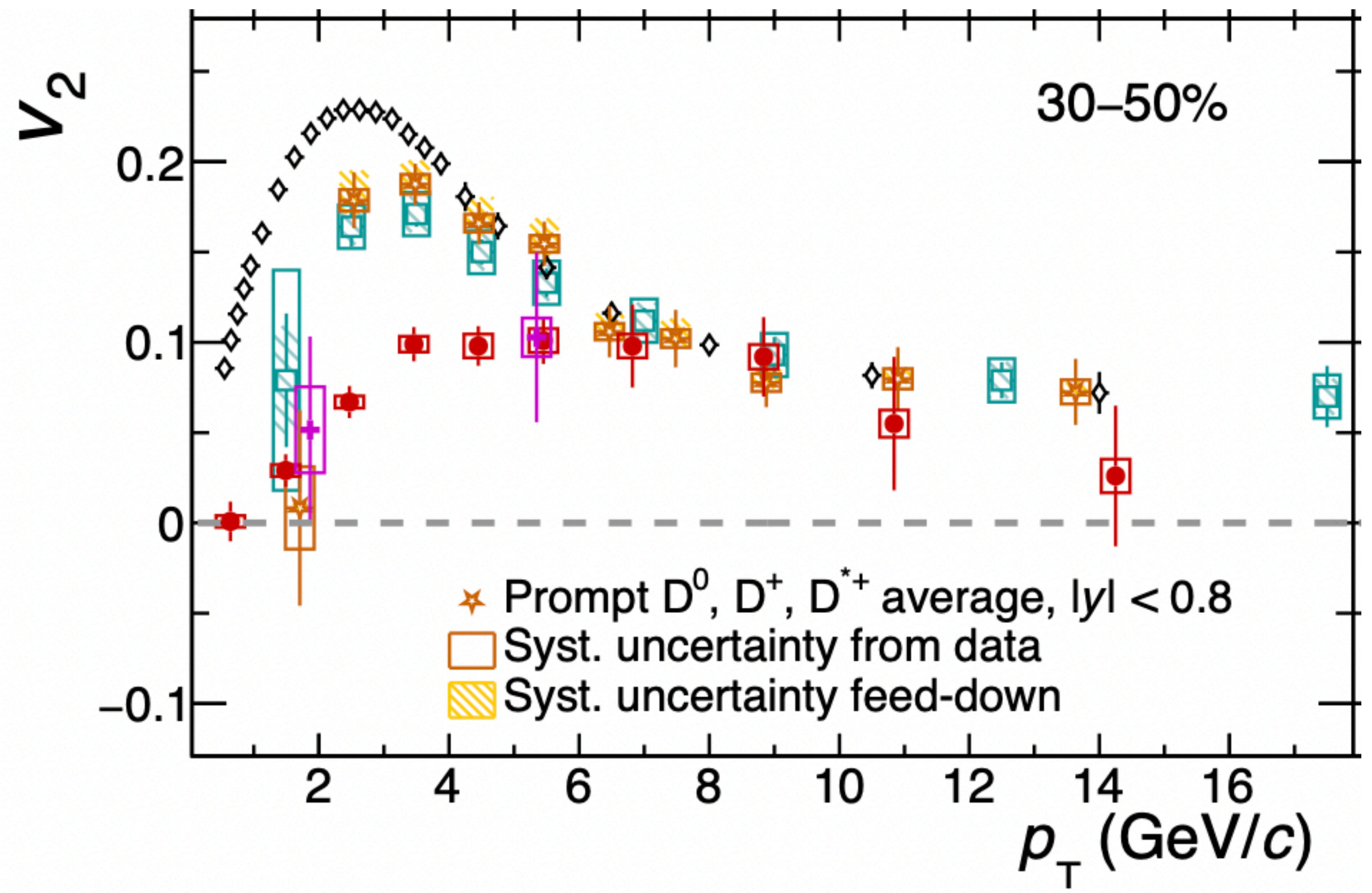
STAR, Phys. Lett. B 825 (2022) 136865
STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13



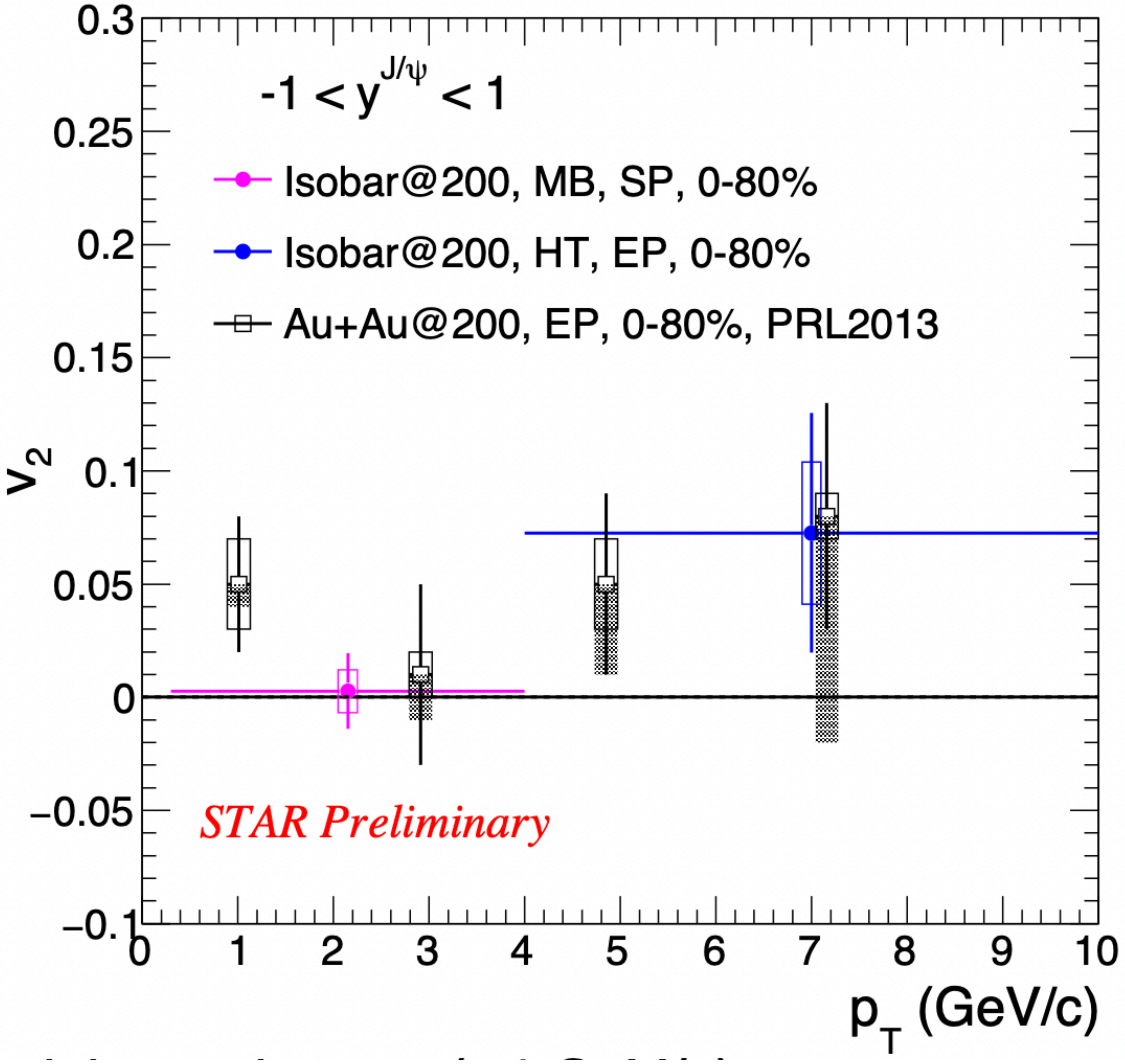
- Good precision data from Isobar collisions
- J/ψ R_{AA} consistent between Au+Au, Cu+Cu and Isobar collisions at similar N_{part}
- J/ψ suppression driven by N_{part}

J/Ψ v_2 as probe of regeneration contribution

- Non zero J/ψ v_2 could arise from medium interactions of deconfined charm quarks
- Can give additional constraints to the regeneration component



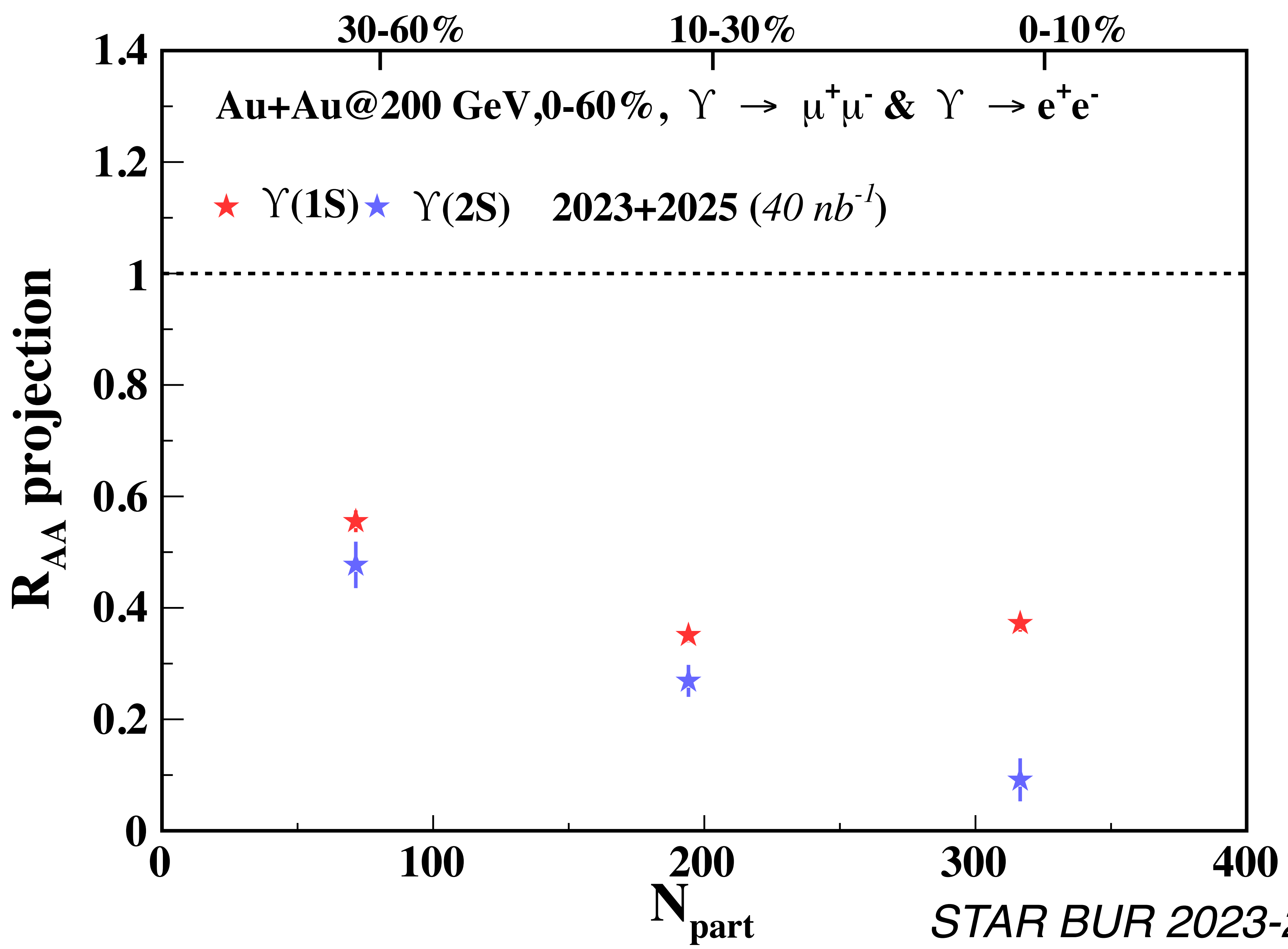
JHEP 141 (2020)



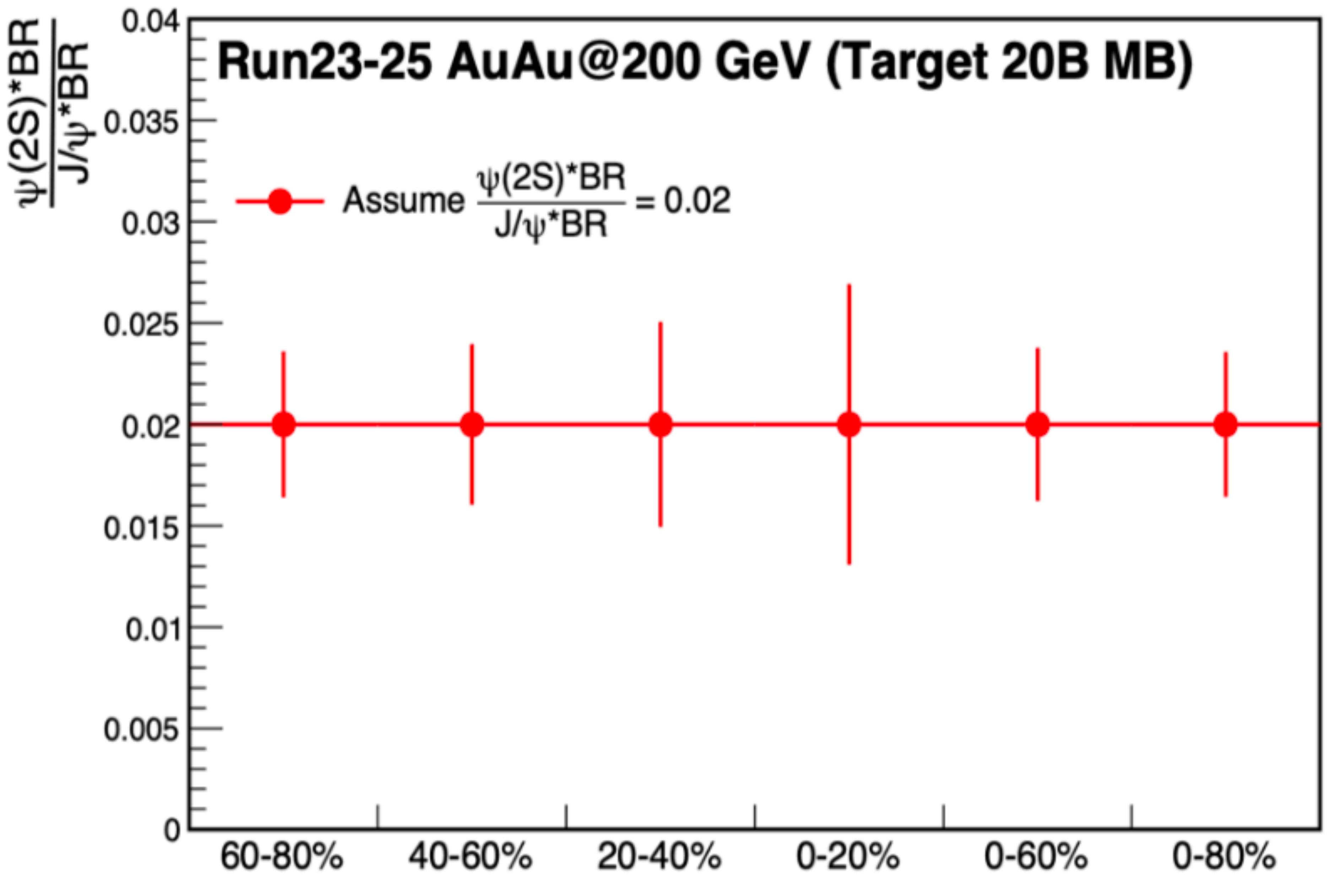
- Non zero J/Ψ v_2 observed at LHC
- STAR measurements at RHIC consistent with zero,
  value = 0.003 ± 0.017 (stat.)±0.010(sys.)
- Precision can be improved with RHIC runs 2023-25

Potential improvements from Run 23 — 25

- Improved precision measurements for quarkonia production and flow possible from high statistics RHIC runs in 2023 - 25



STAR BUR 2023-25

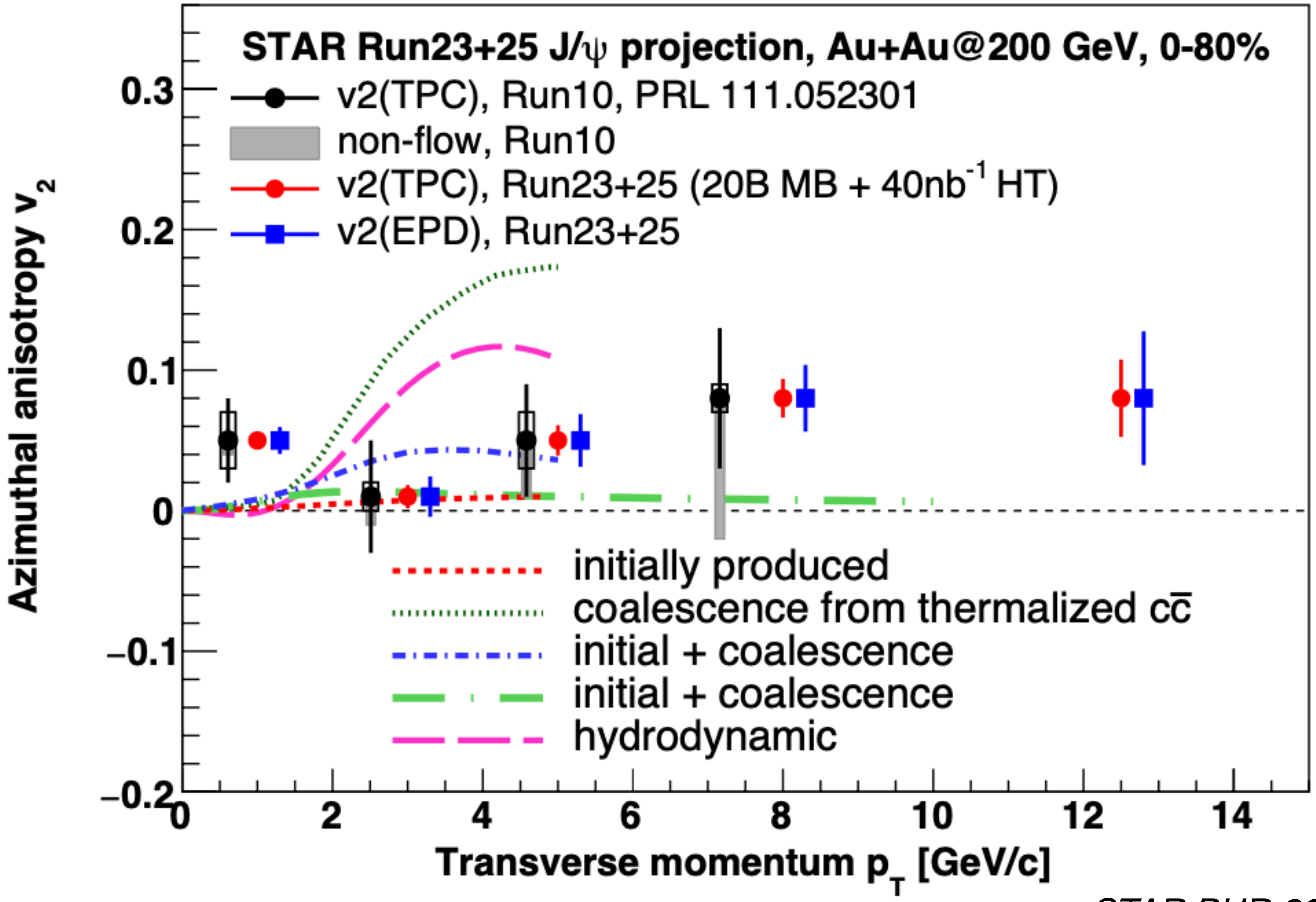


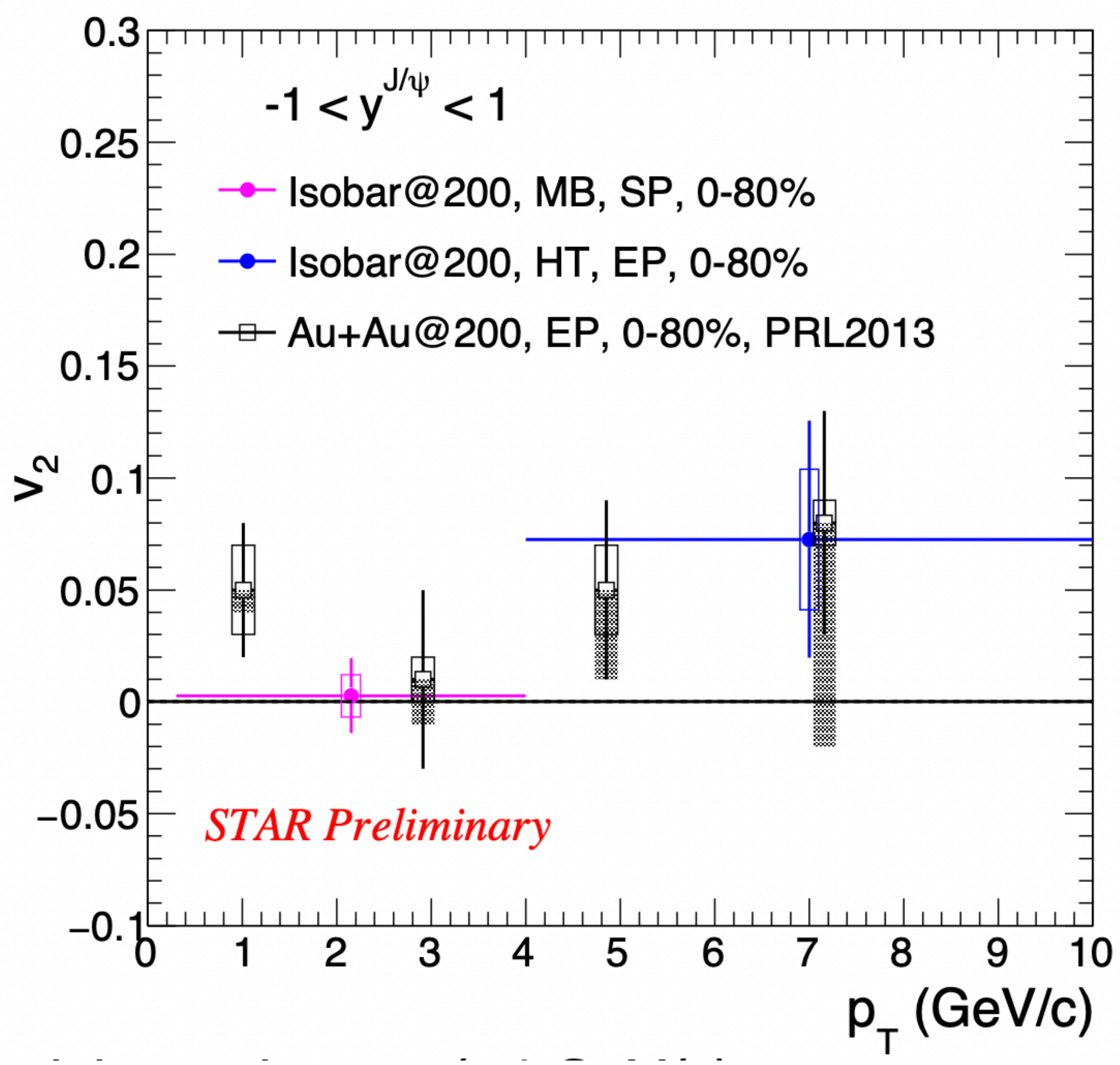
STAR BUR 2023-25

- Factor of 17 (1.5) improvement in statistics compared to existing dielectron (dimuon) measurements with Run 23+25 data from STAR
- Constrain screening dynamics and temperature of the medium

- Lower binding energy for ψ(2S) compared to J/ψ and Y states
- Sensitive to regeneration contribution and temperature profile of QGP

Potential improvements from Run 23 — 25



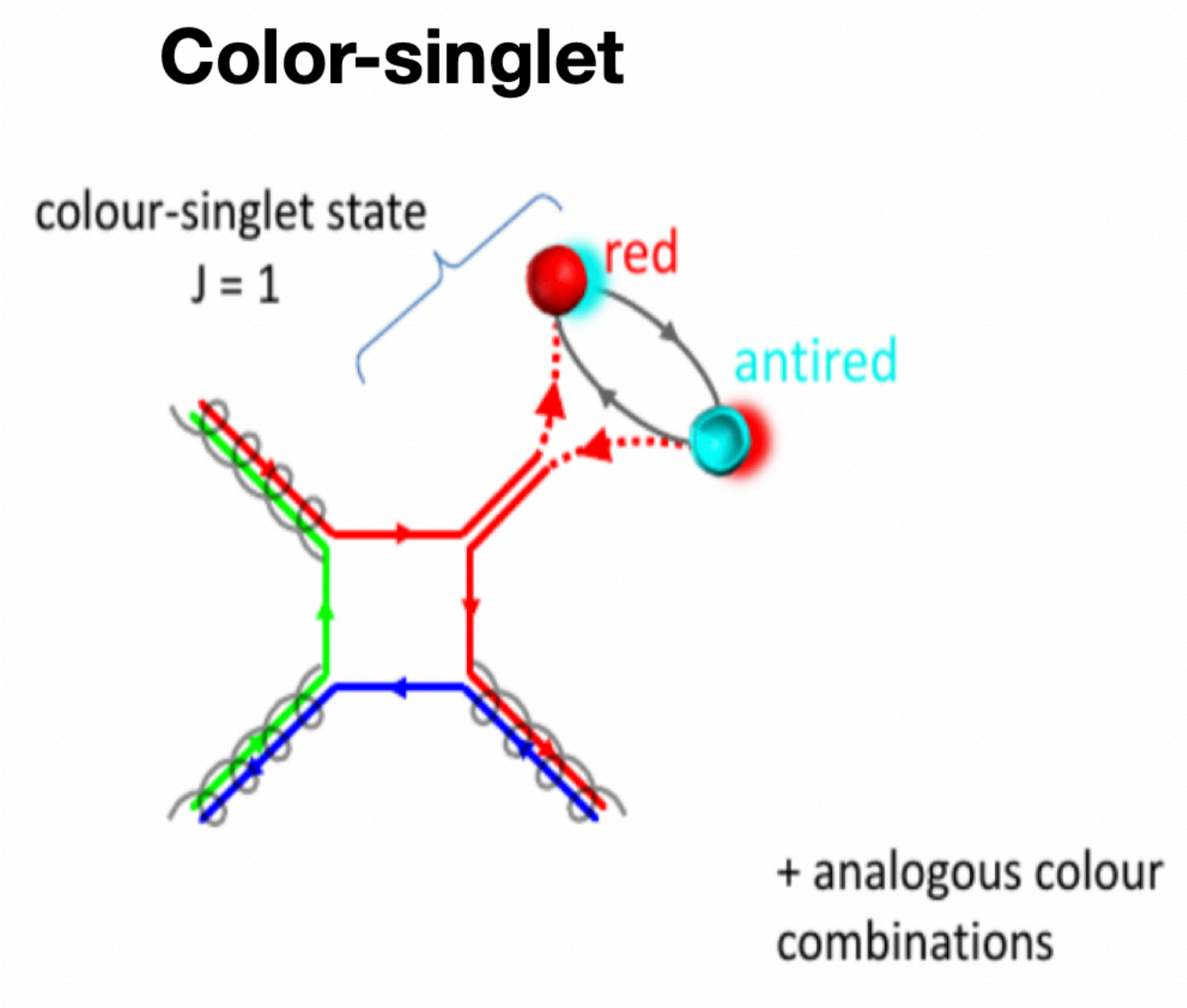


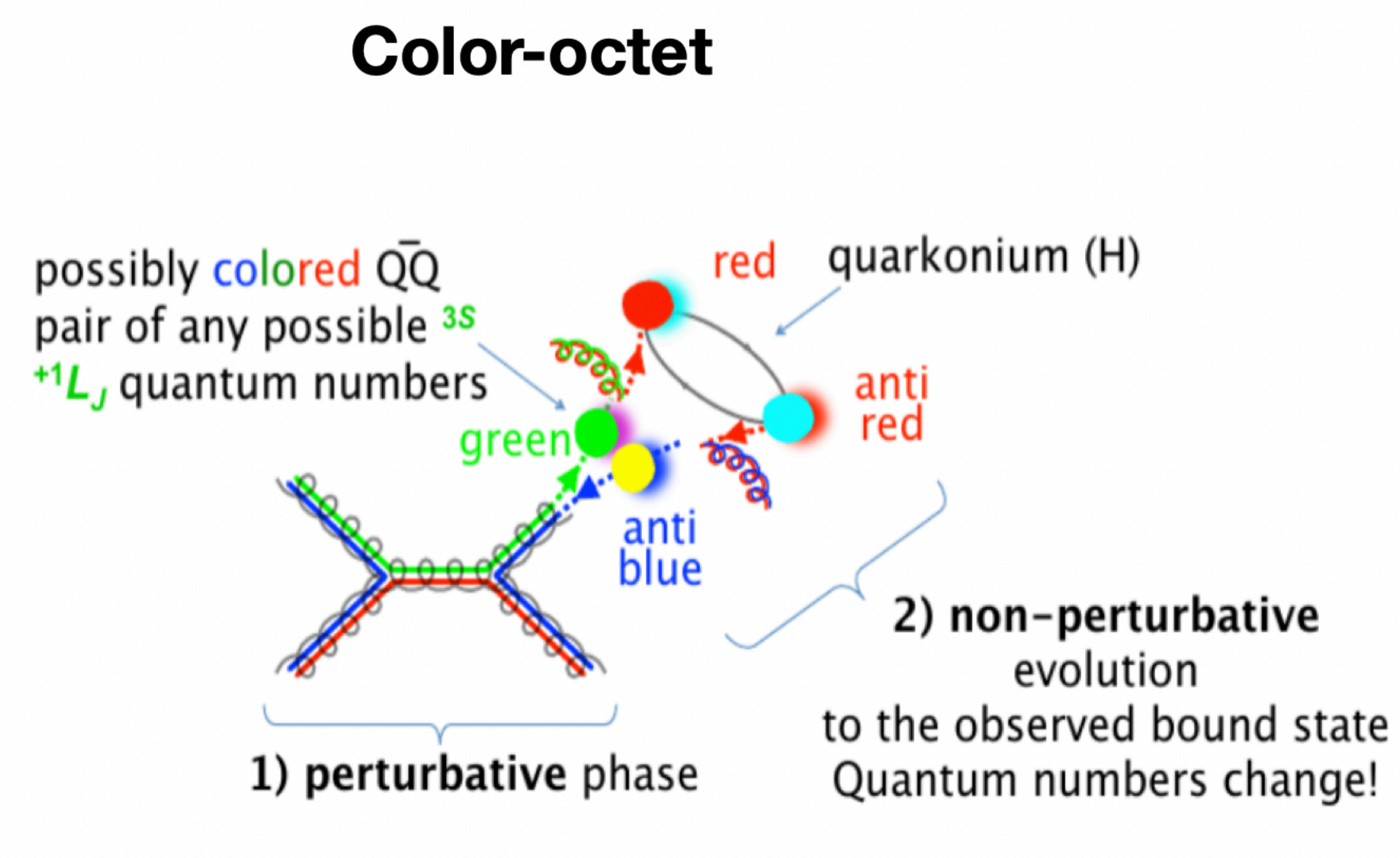
STAR BUR 2023-25

- Precision measurement for J/Ψ v_2 also possible
- Better constraint on the regeneration contribution for J/Ψ at RHIC

Quarkonia production and npQCD

- Quarkonia production in elementary collisions probes both perturbative and non-perturbative regimes of QCD
- Production of $Q\overline{Q}$ pair driven by pQCD, while evolution to quarkonia state is long distance non-perturbative process
- Due to large mass of heavy quarks, a non-relativistic QCD system

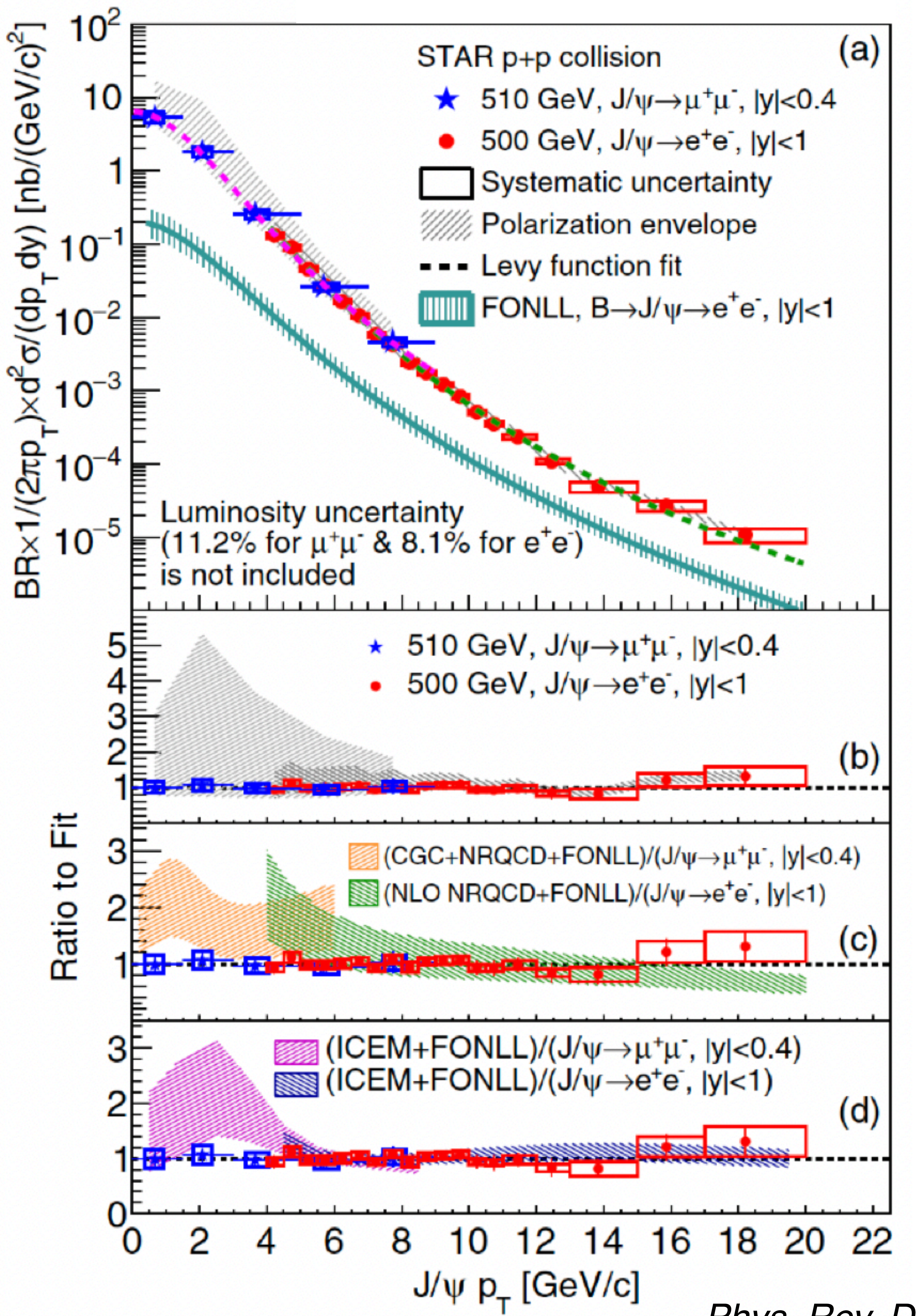




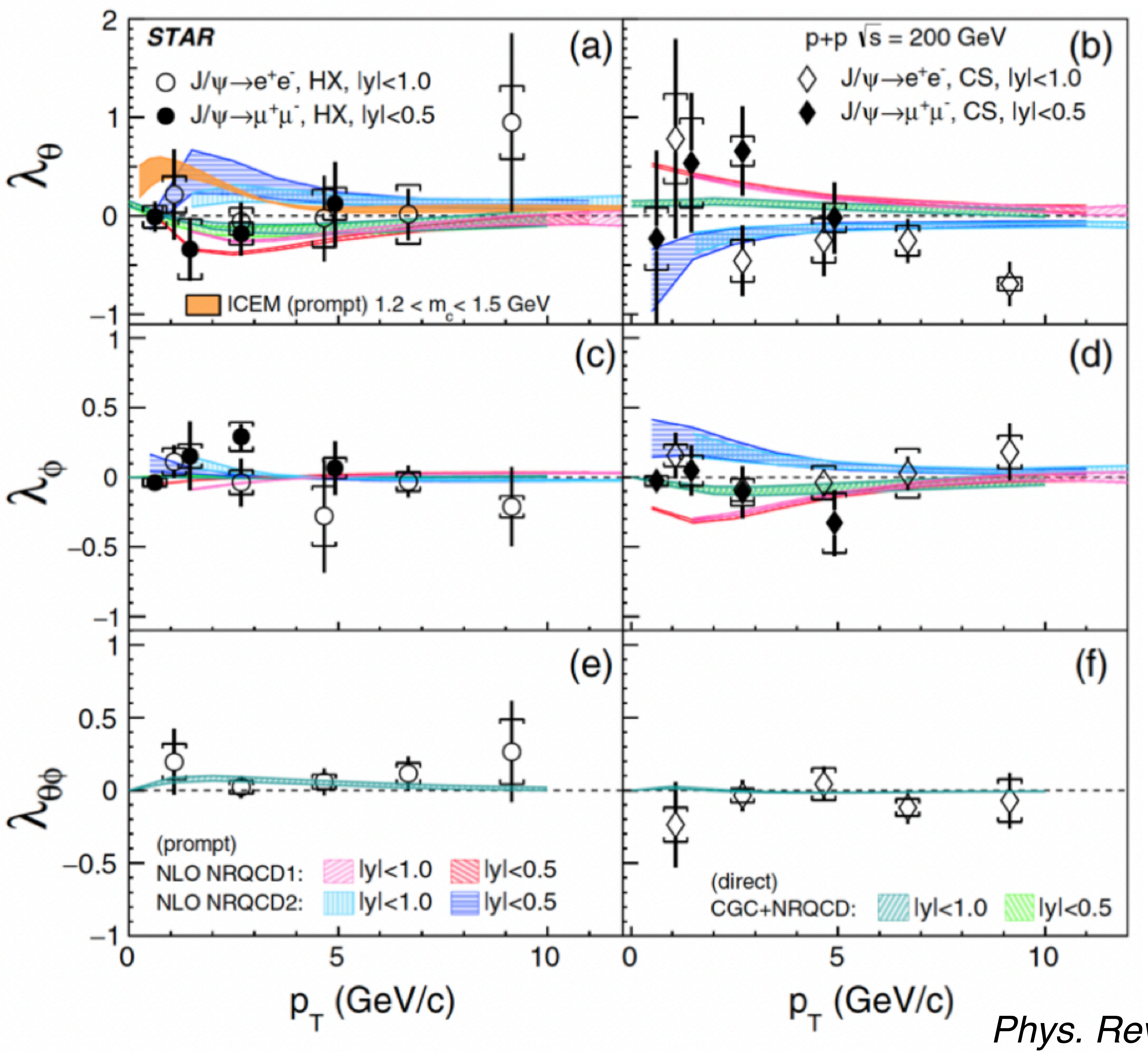
[P. Faccioli, Polarization in LHC physics, Course on Physics at the LHC 2014]

- Several models, production of $Q\overline{Q}$ pairs in color singlet (CSM) or color octet (COM) states, color evaporation model etc

Quarkonia production and npQCD



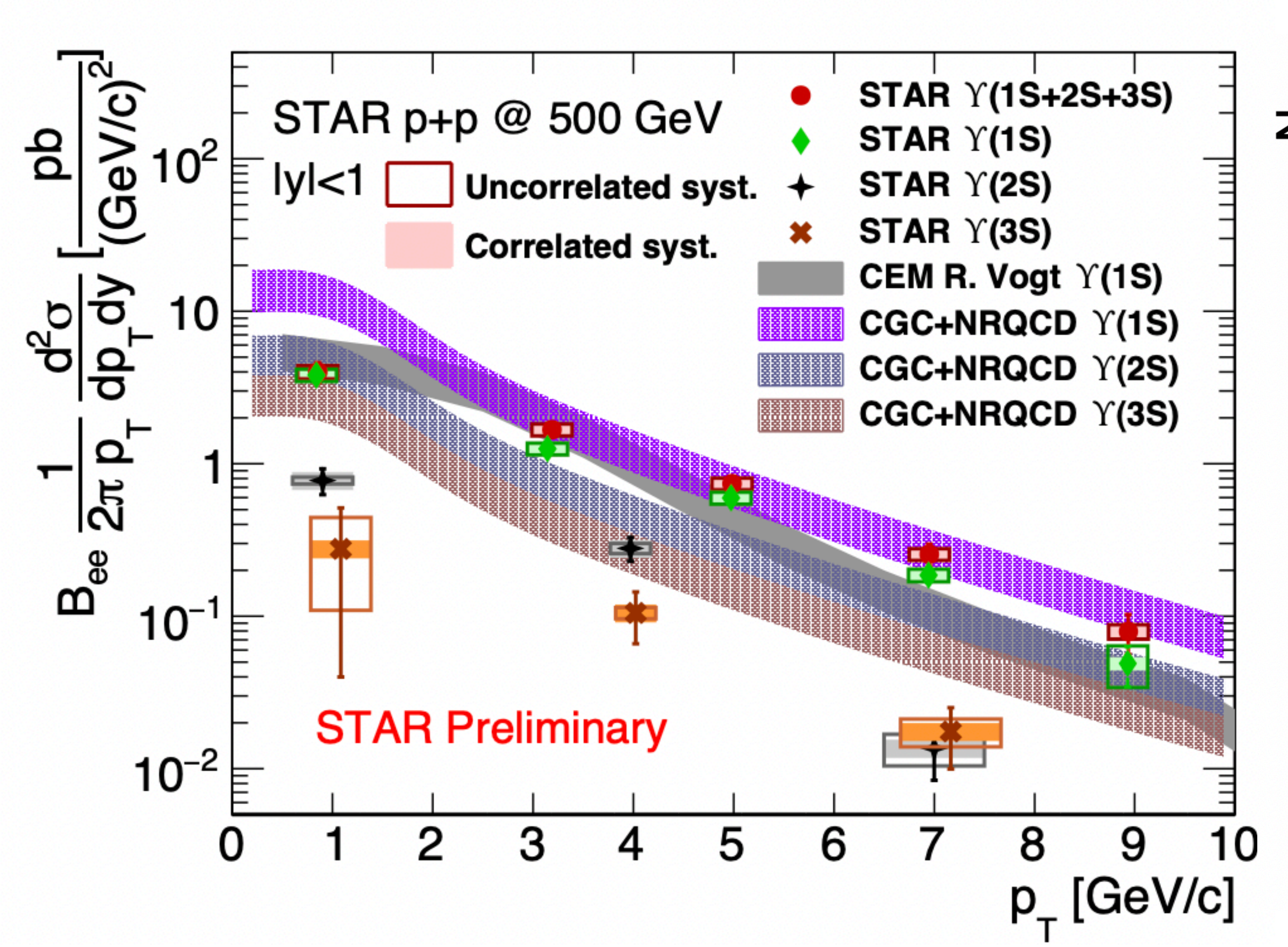
Phys. Rev. D 052009 (2019)

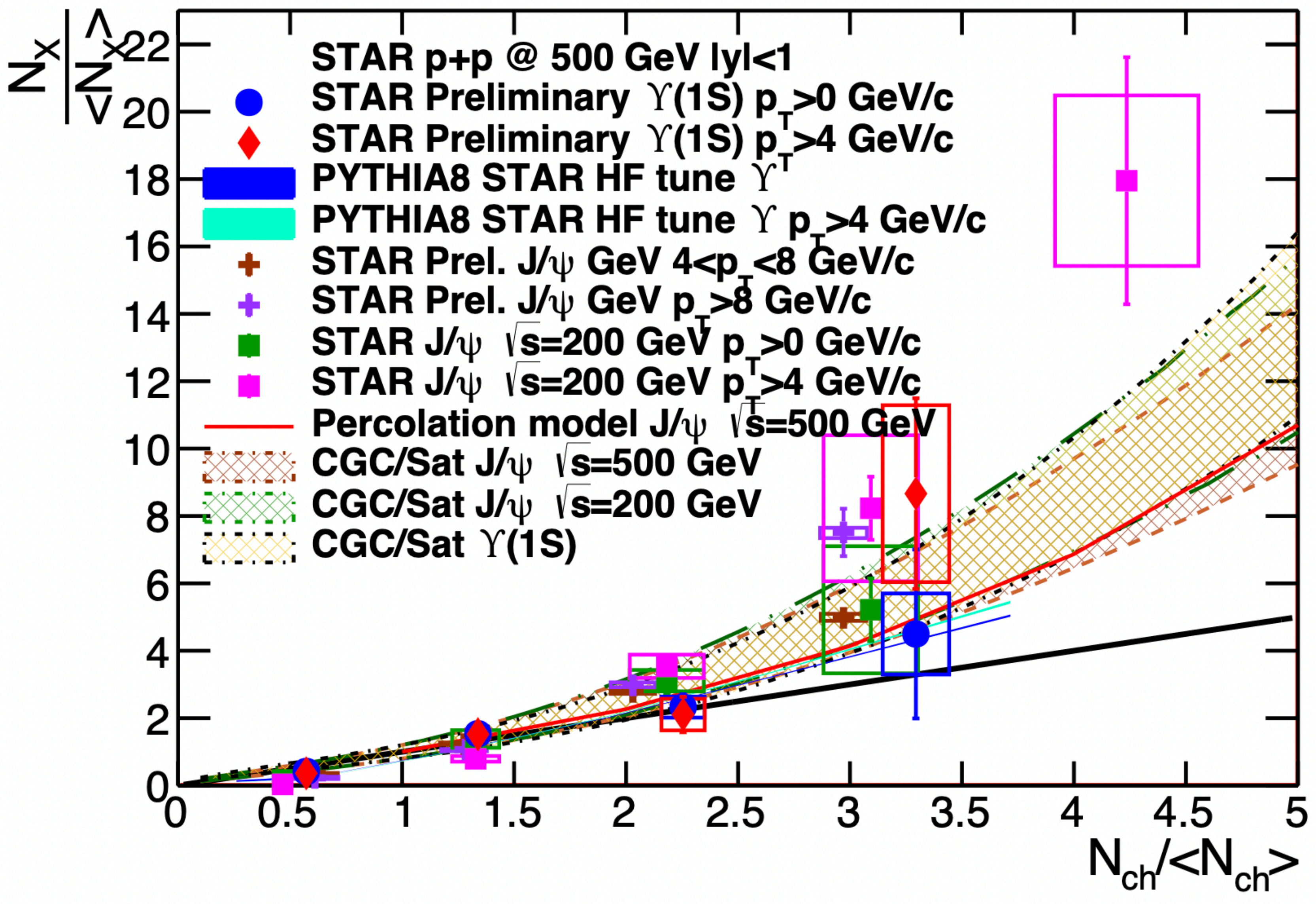


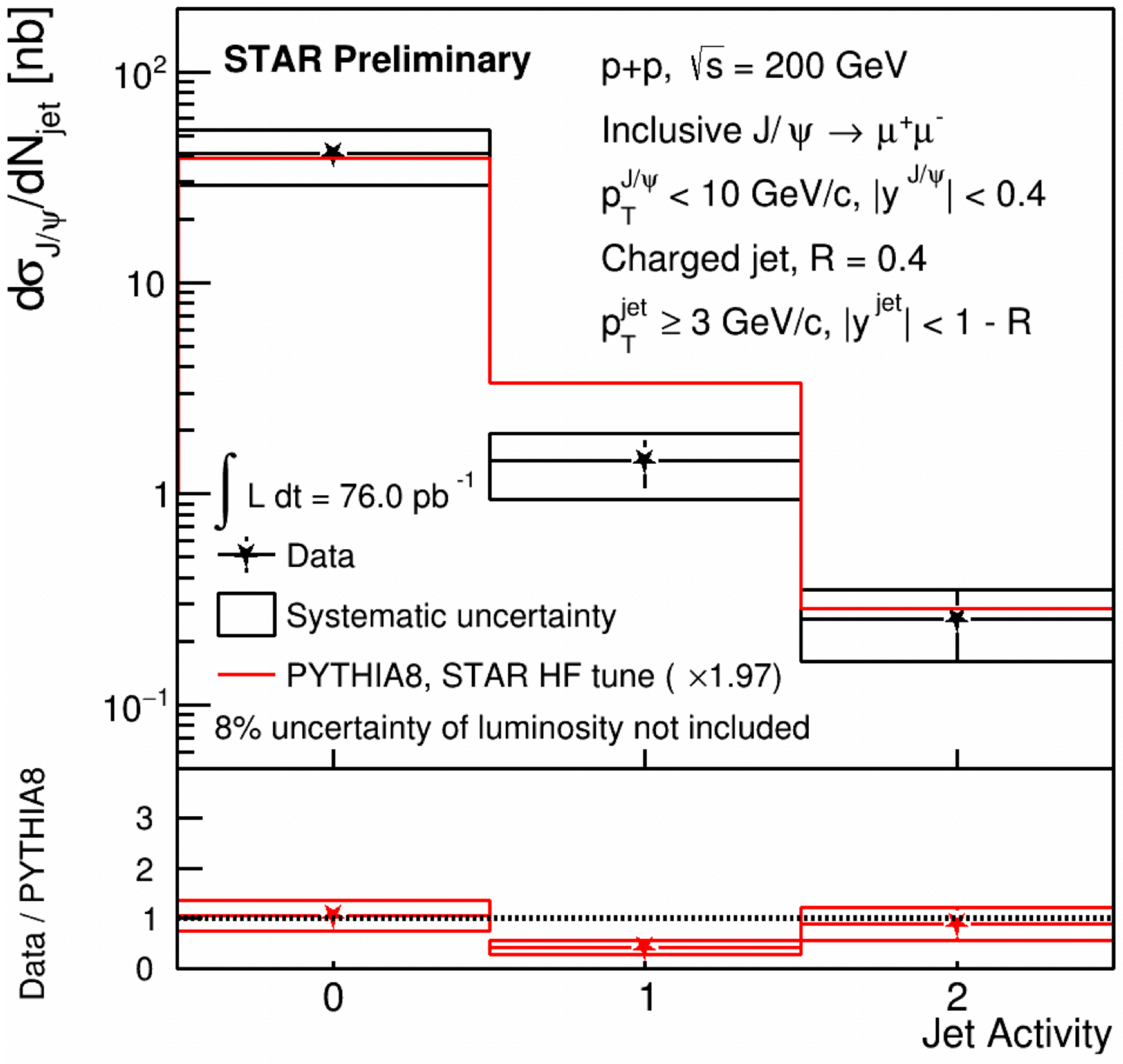
Phys. Rev. D 092009 (2020)

- Need better precision and other observables to distinguish between models and to constrain matrix-elements of NRQCD

Quarkonia production in p+p collisions at RHIC







- Differential measurements of Y production in p+p vs p_T, rapidity and event activity
- New measurements of J/Ψ production vs jet activity
- Help understand quarkonia production mechanism
- Improved precision measurements, including of polarization, possible with data from 2023-25

Summary and Outlook

- Great progress over the years in heavy flavor measurements from RHIC
  - Improved constraint for $2\pi T D_s$ from v_2 and R_{AA} data (between 2 - 4 near T_{pc})
  - Mass hierarchy in energy loss, energy loss of b quarks less than c quarks
  - Modification of hadronization seen in A+A collisions from D_s and Λ_c measurements
  - Sequential suppression of Υ states from color screening in QGP
  - Measurements indicate small regeneration of J/Ψ at RHIC energies
  - Differential and new measurements to understand quarkonia production mechanism in p+p

- High statistics runs in 2023 - 25
  - High precision measurements for charm and bottom hadron R_{AA}, v_2, HF jets … possible with sPHENIX
  - Better understand hadronization through differential measurements
  - Improved precision Υ R_{AA} and J/Ψ v_2 from Runs 23 - 25
  - Quantitatively understand QGP screening potential, mechanism of deconfinement, hadronization mechanism etc