Recent results on hard and soft probes at RHIC

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RHIC and BES-II

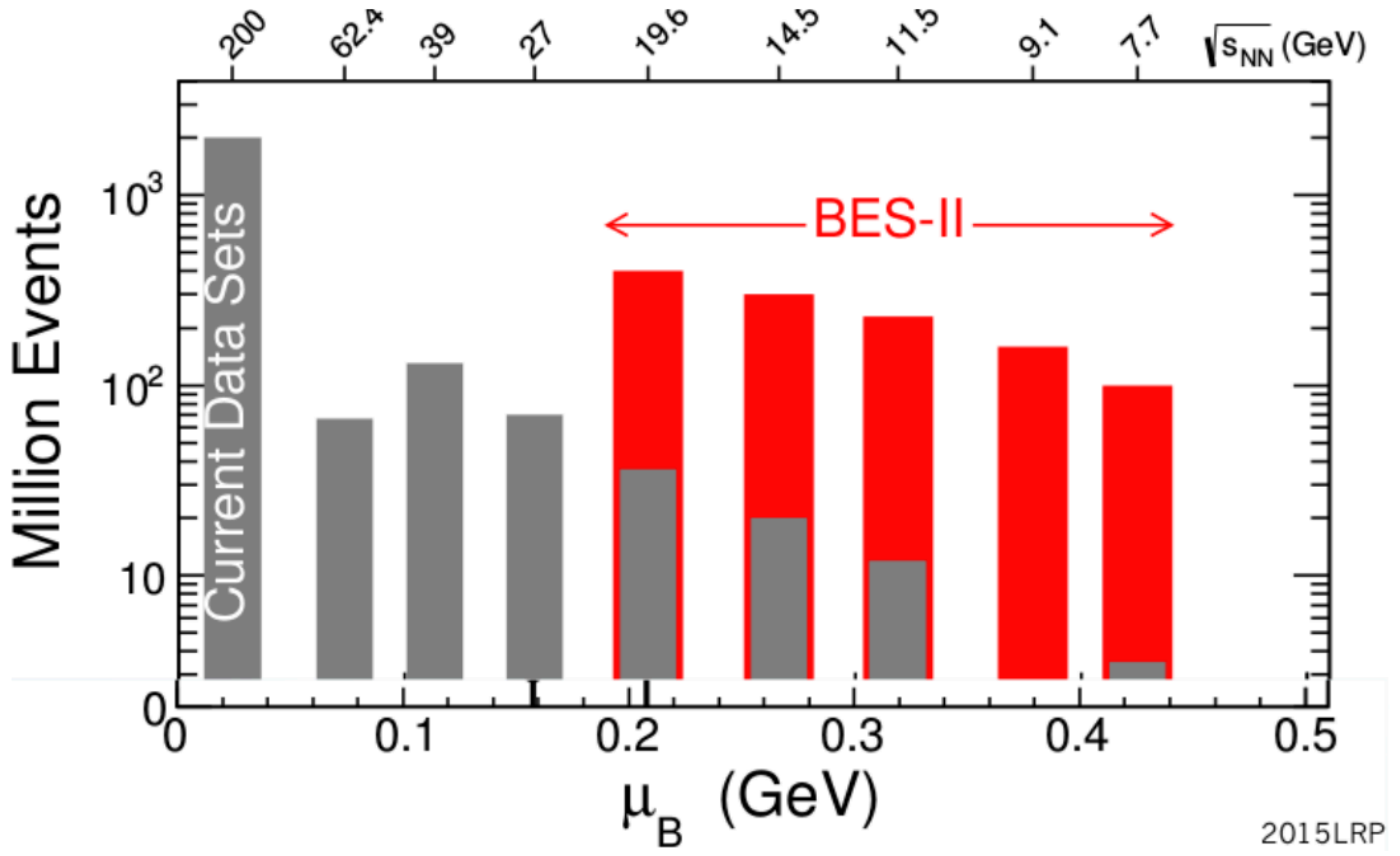
- **PHENIX completed data taking in 2016**
  - Ongoing analysis efforts

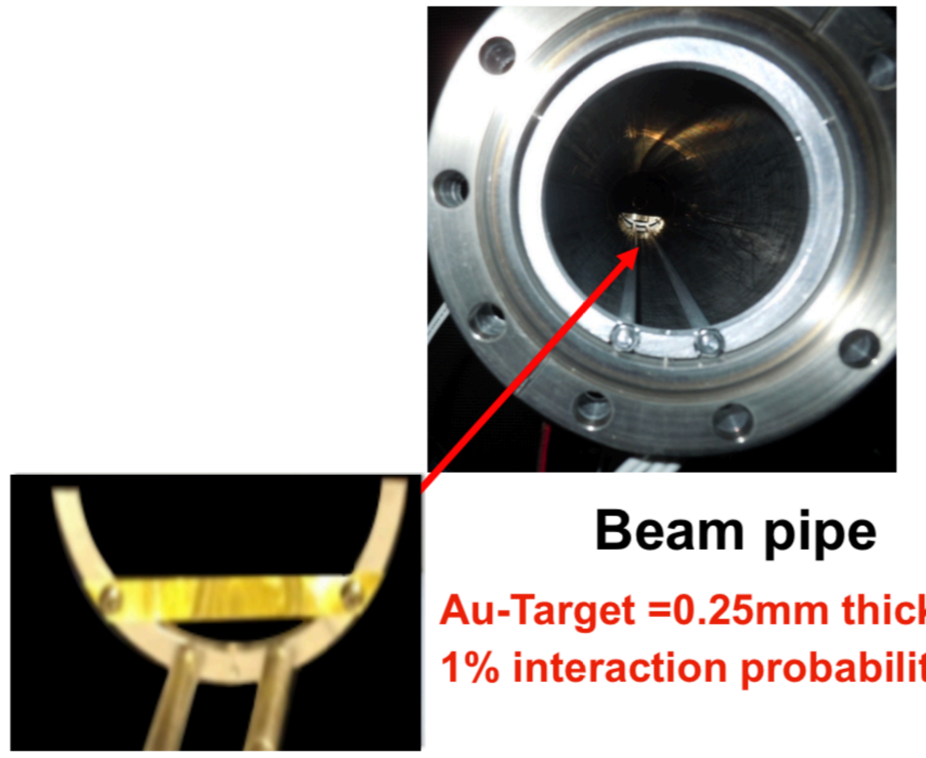
- **STAR BES-II (2018-2021)**
  - Collider mode: $\sqrt{s_{NN}}$ = 7.7-19.6 GeV

    μ_B = 420 - 200 MeV

  - Fixed-target mode: $\sqrt{s_{NN}}$ = 3.0-13.7 GeV

    μ_B = 750 - 280 MeV

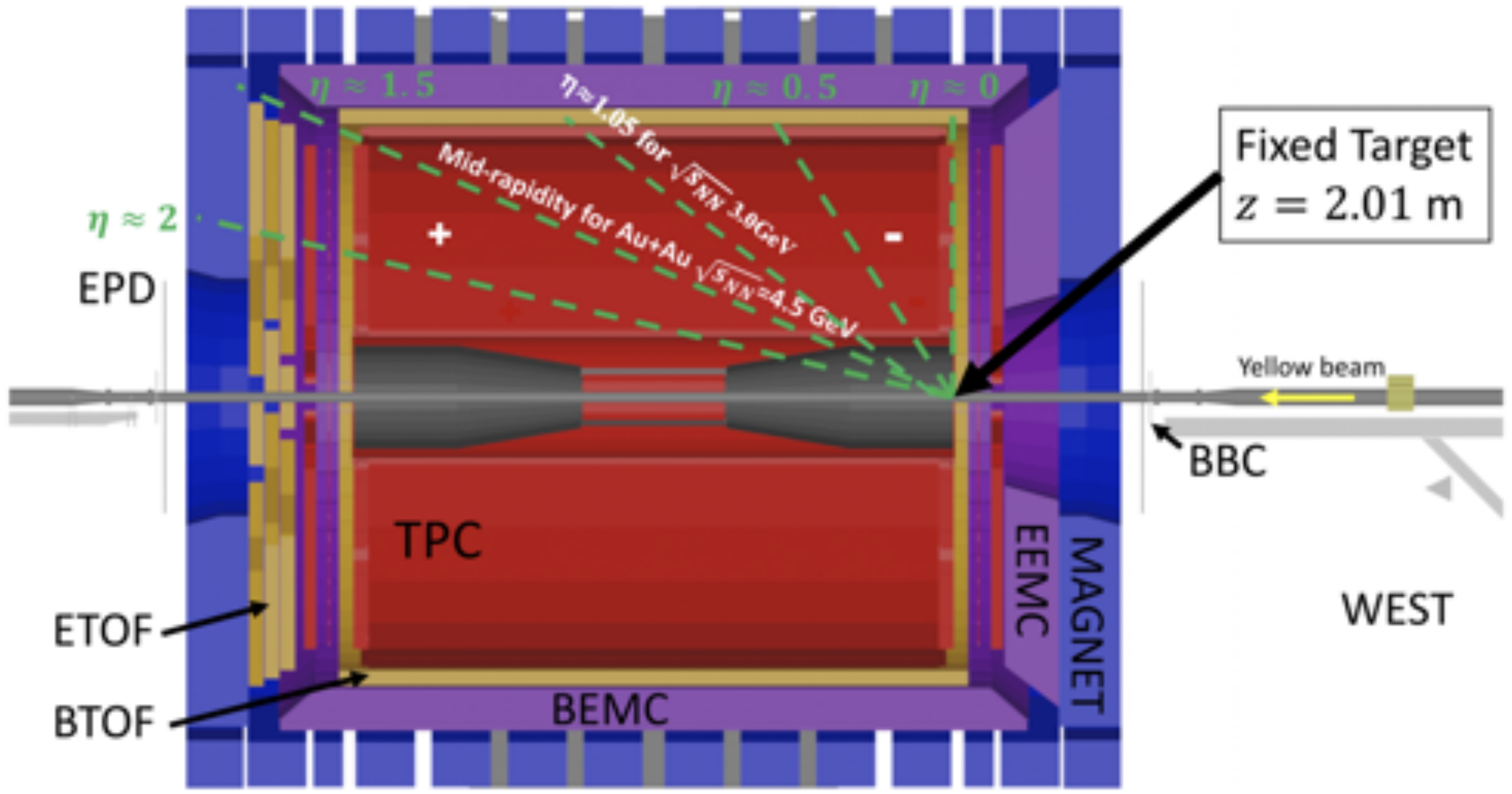




Beam pipe

Au-Target =0.25mm thickness

1% interaction probability



Probing the QCD Phase Diagram

- **QGP formation at top RHIC energies**

  $\sqrt{s_{NN}}$ = 200 GeV, μ_B = 20 MeV

  - Probe characteristics with heavy flavor, strangeness, jets etc.

- **Finite μ_B region: Beam Energy Scan (BES)**

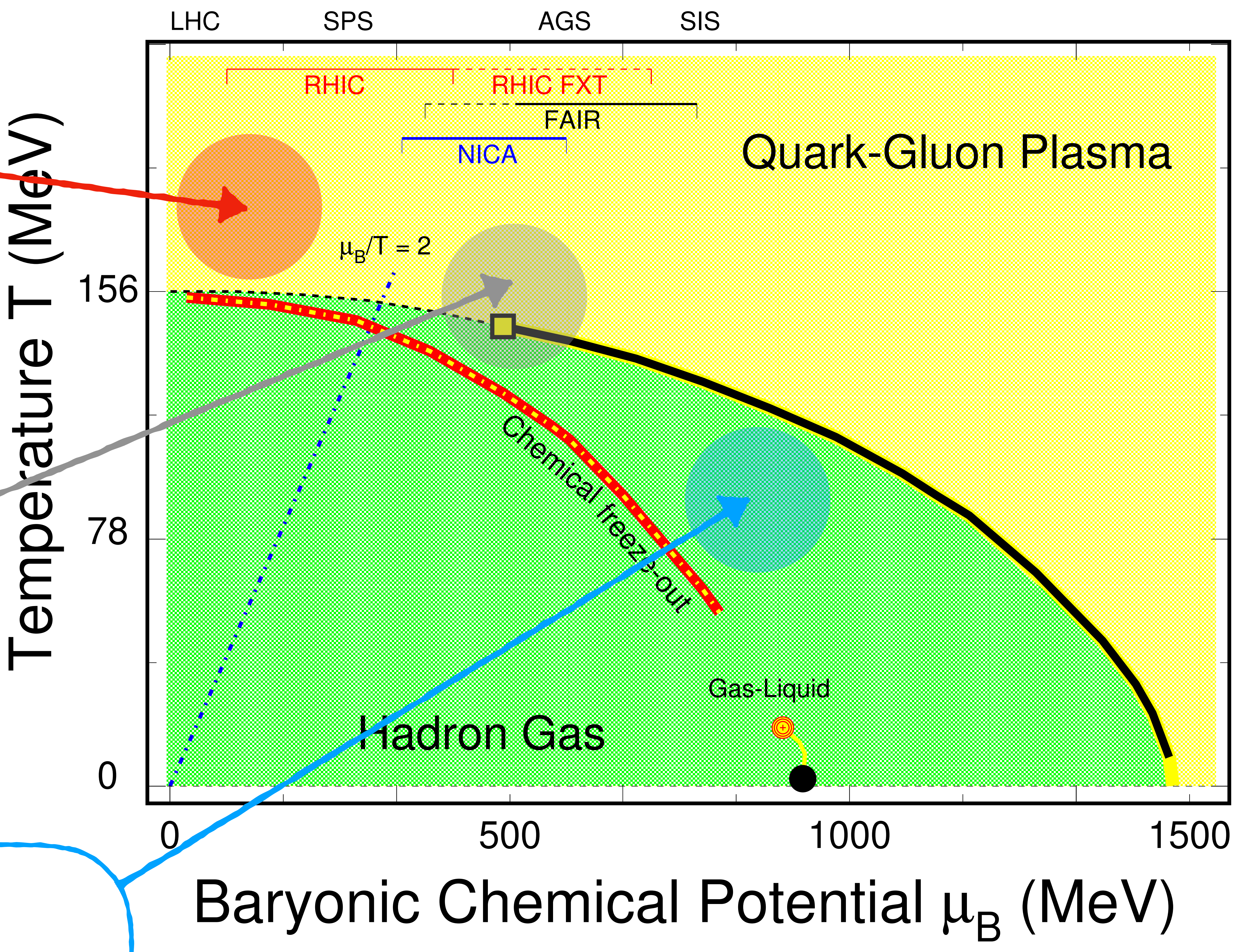
  $\sqrt{s_{NN}}$ = 7.7-27 GeV, μ_B = 420 - 200 MeV

  - Probe onset of deconfinement
  - Search for critical phenomena

- **High μ_B region: STAR fixed-target**

  $\sqrt{s_{NN}}$ = 3.0-13.7 GeV, μ_B = 750 - 280 MeV

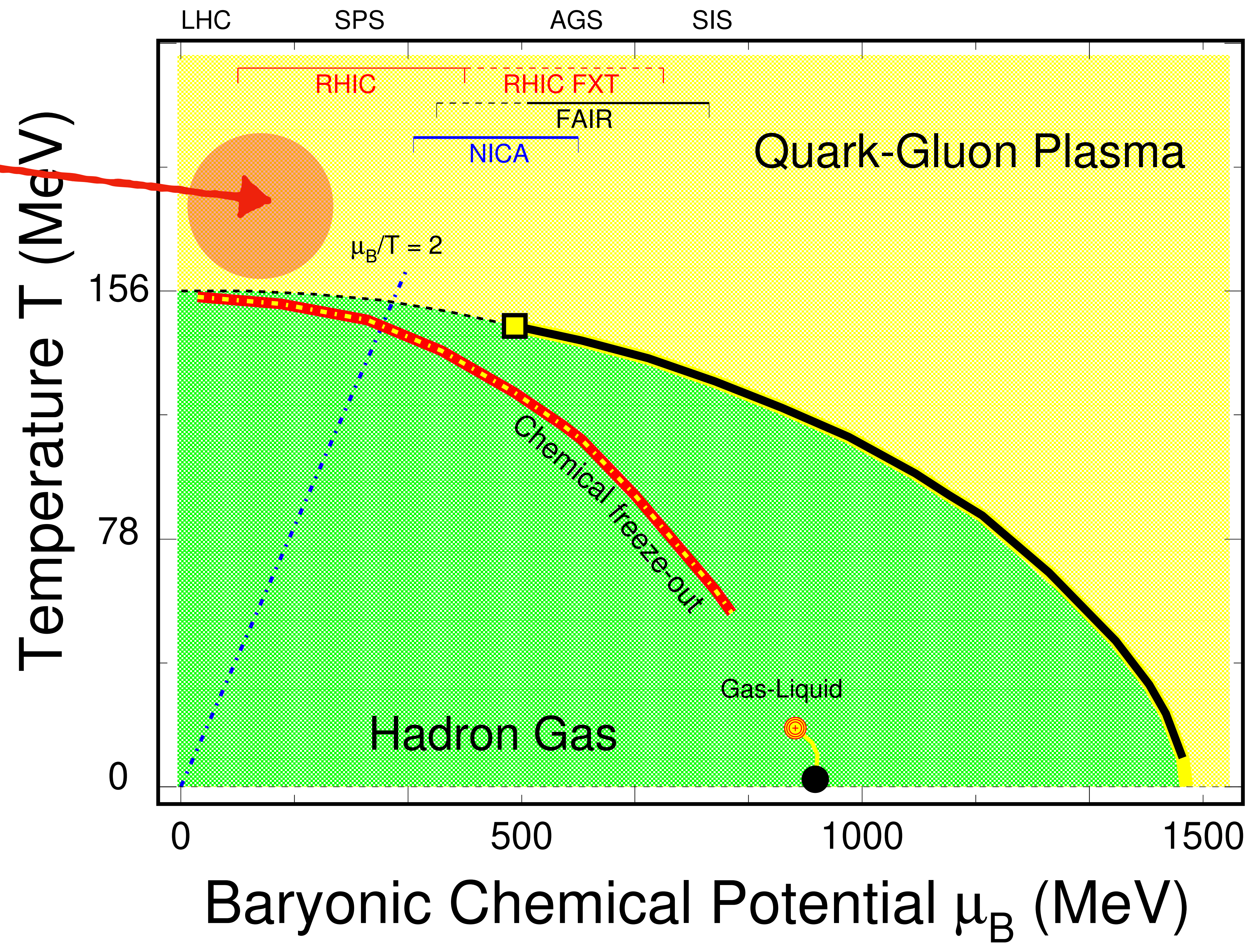
  - Nature of produced medium (hadronic vs partonic?)
  - Hyperon contribution to EOS via hypernuclei



STAR, PRL126,9,092301(2021)

1. Top RHIC energies: $\sqrt{s_{NN}}$ = 200 GeV

($\sqrt{s_{NN}}$ = 54.4, 27 GeV)

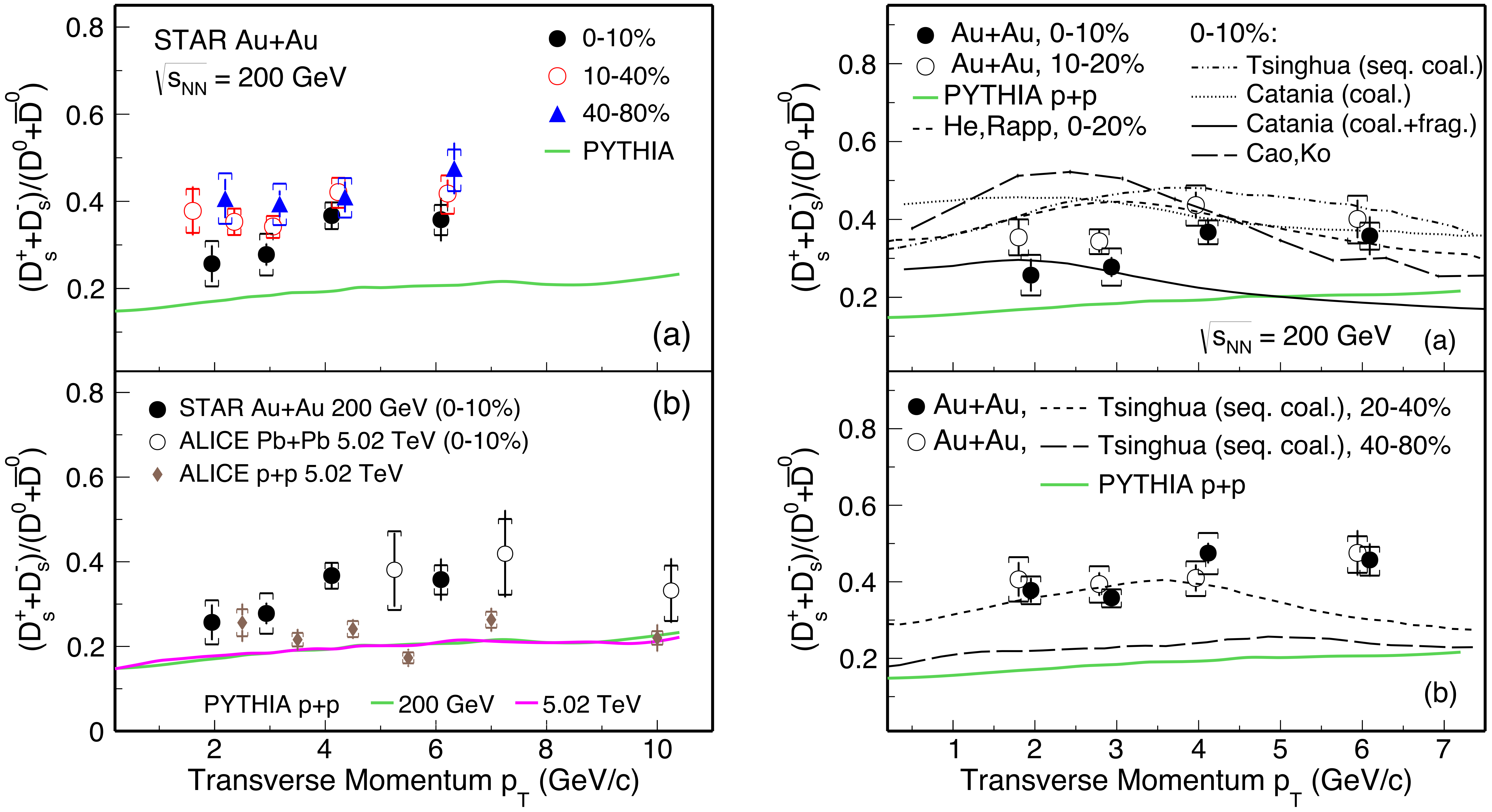


Selected results on

- Heavy flavor
- Photons
- Strangeness
- Global polarization
- Net-proton cumulants

D_s Production in Au+Au Collisions at 200 GeV

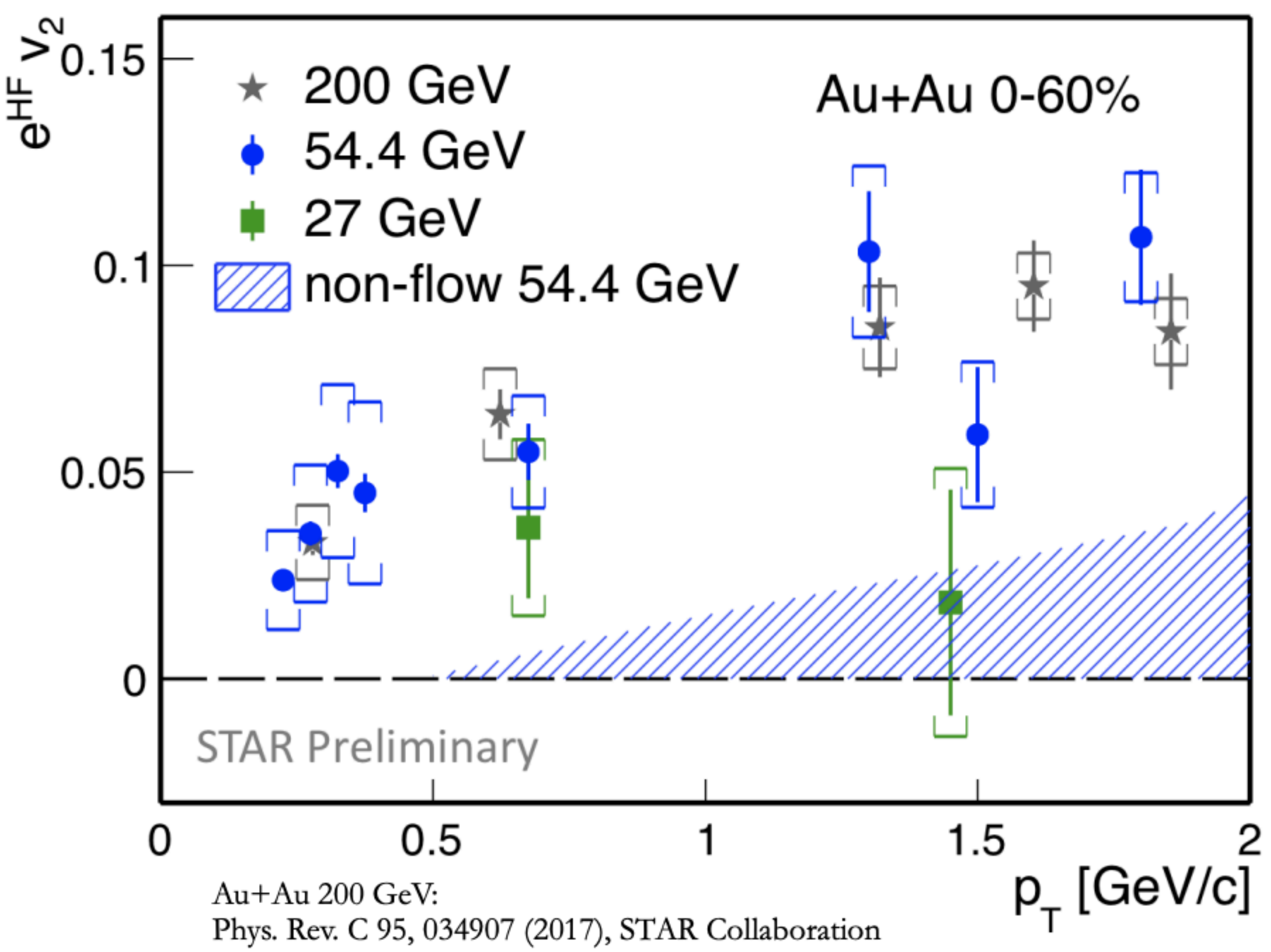
- $D_s^{\pm}/D^0$ in Au+Au 200 GeV
  - Significant enhancement compared to p+p 5.02 TeV and PYTHIA
  - Comparable to Pb+Pb at 5.02 TeV
  - No strong centrality dependence



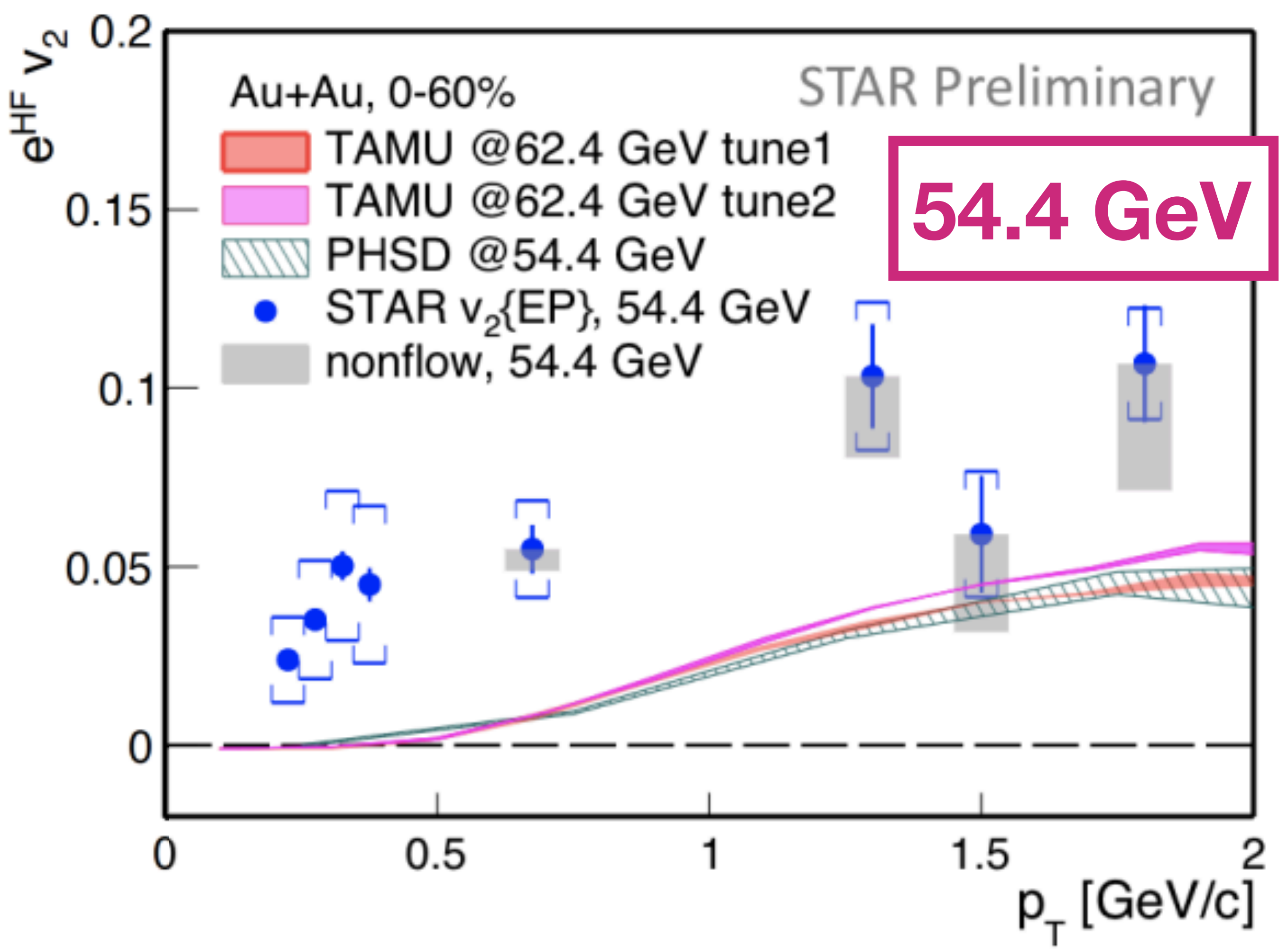
STAR, PRL 127, 092301 (2021)

Models incorporating **coalescence** and **thermal abundance of strange quarks** qualitatively describe data

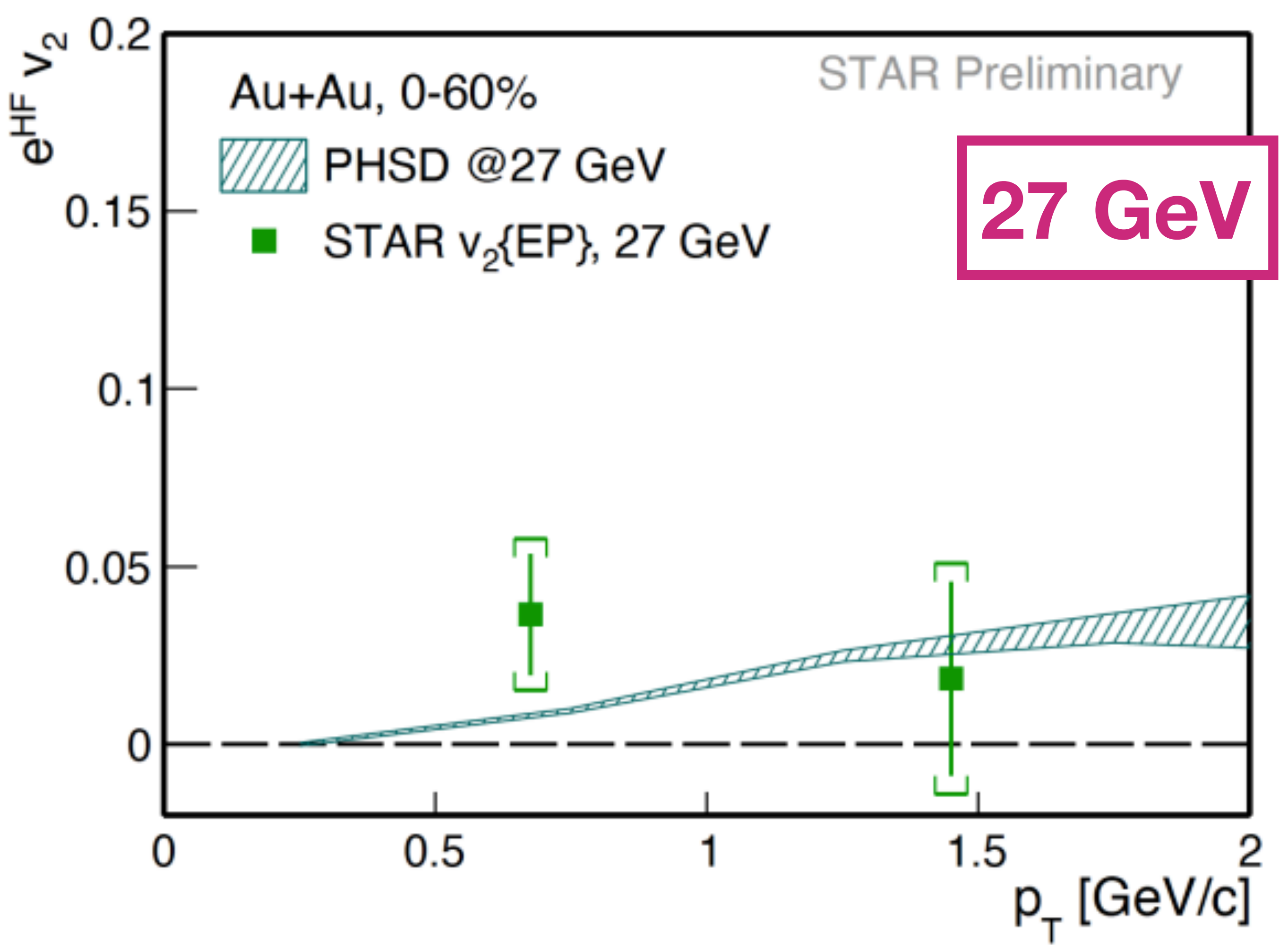
Energy Dependence of HF Electron v_2



Au+Au 200 GeV:
Phys. Rev. C 95, 034907 (2017), STAR Collaboration



- Model calculations lower than data at 54.4 GeV



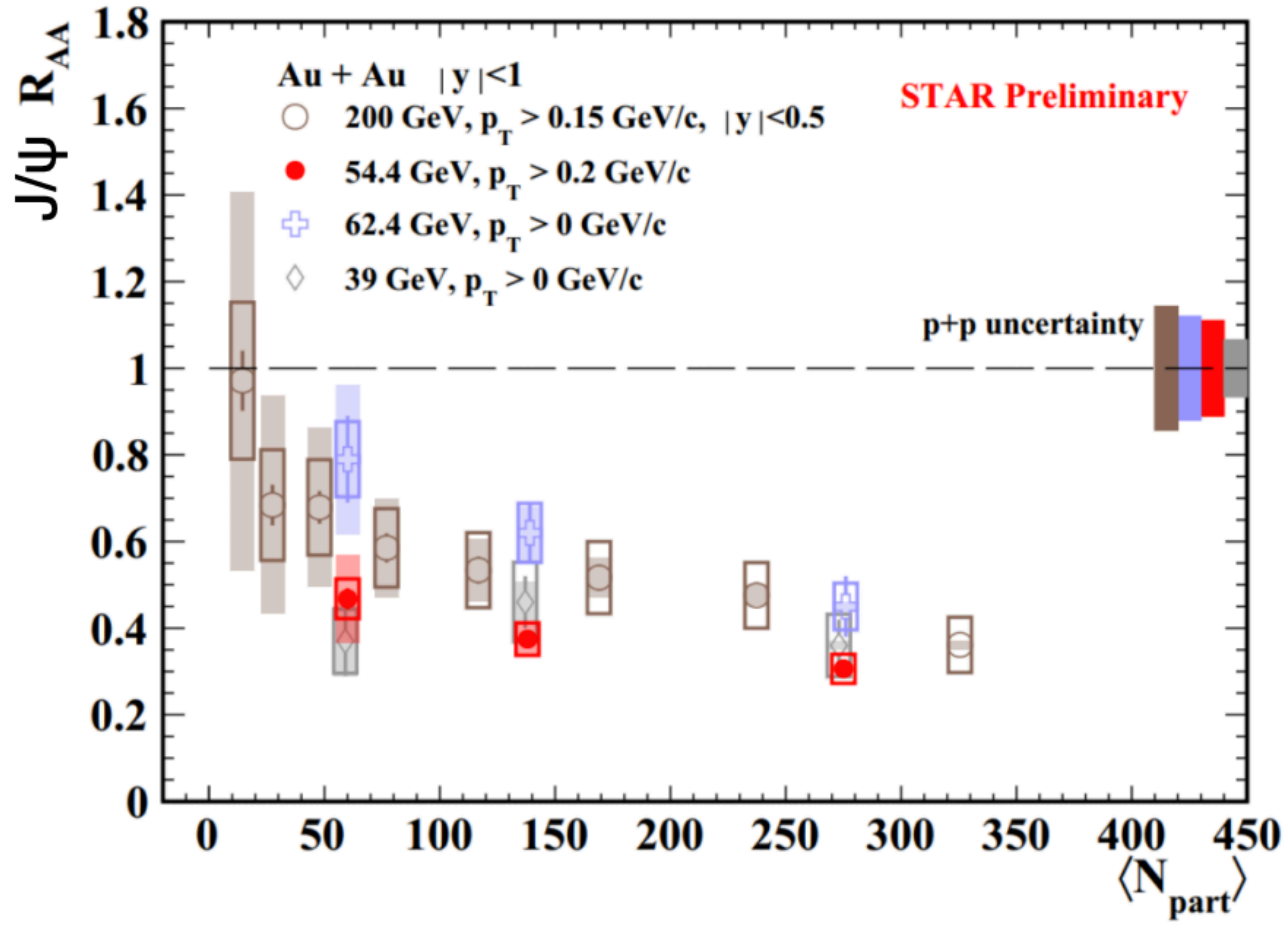
- PHSD calculation comparable to data at 27 GeV

M. He et al., PRC 91,024904 (2015)
T. Song et al., PRC 92, 014910 (2015)
T. Song et al., PRC 96, 014905 (2017)

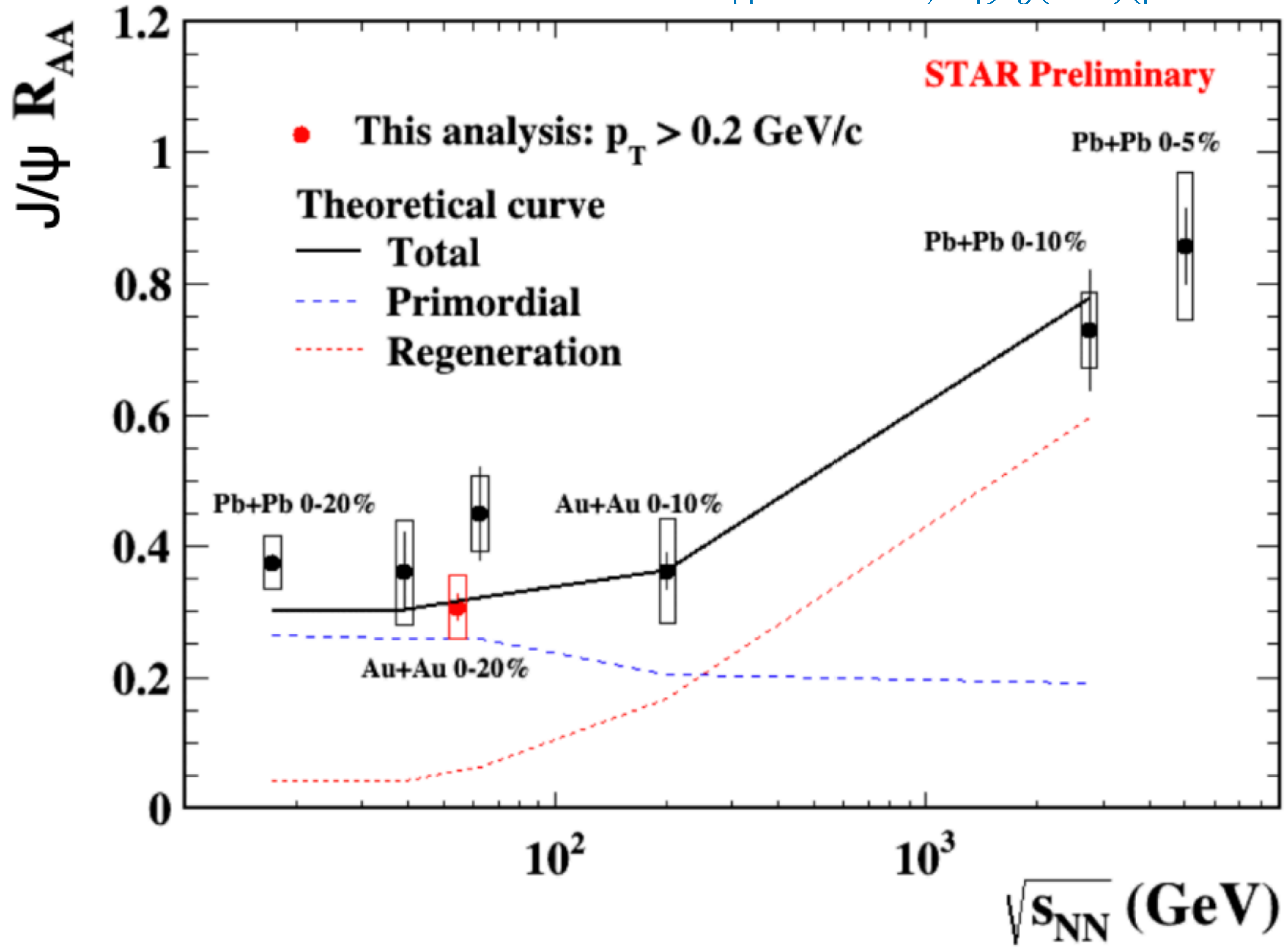
- HF e v_2 at 54.4 GeV comparable to that at 200 GeV
- Hint of lower HF e v_2 at 27 GeV

Charm quark interacts strongly with the medium at 54.4 GeV

Energy Dependence of J/ψ Suppression



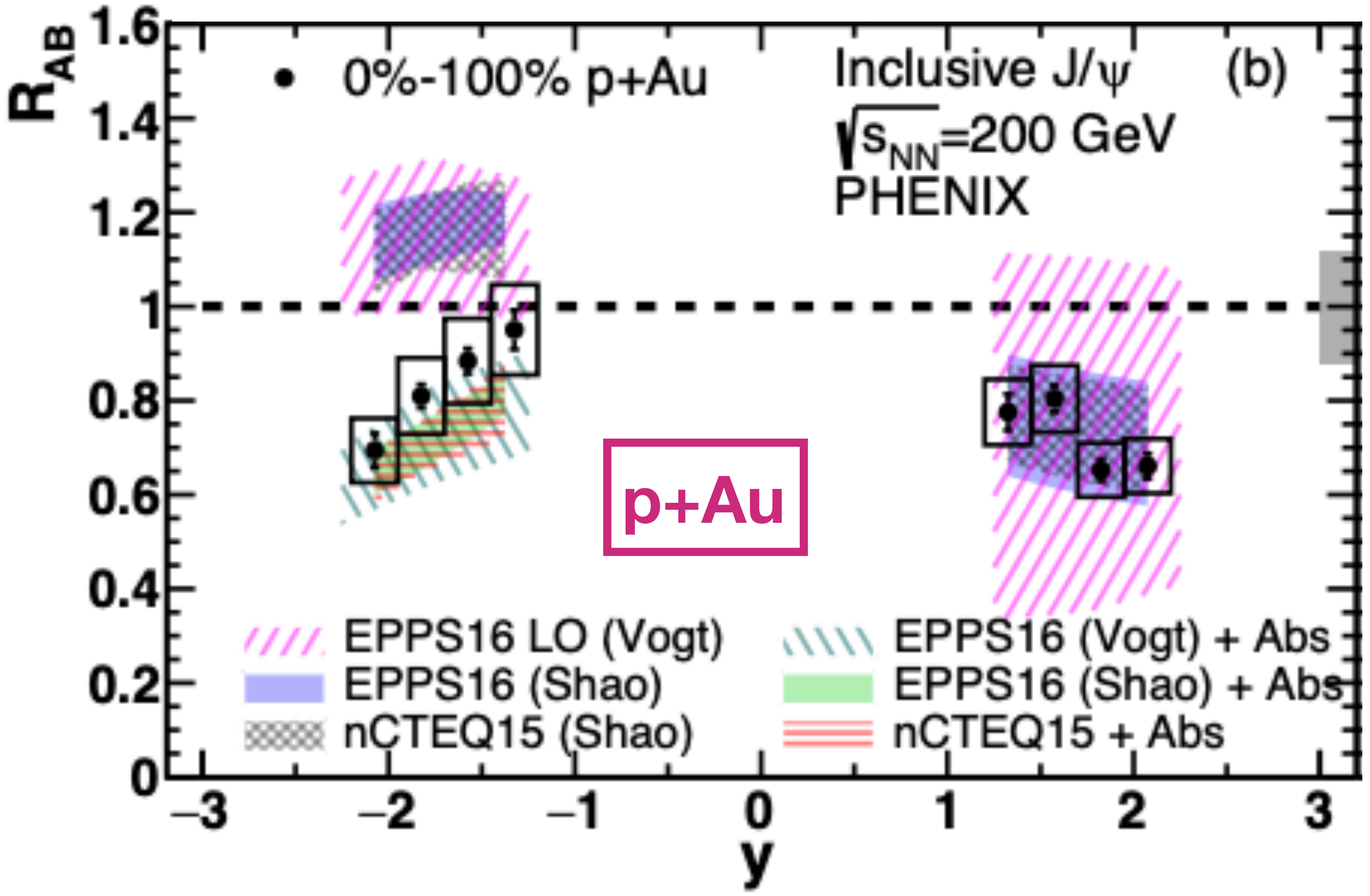
R.Rapp et al PRC 82,064905 (2010) (private comm.)



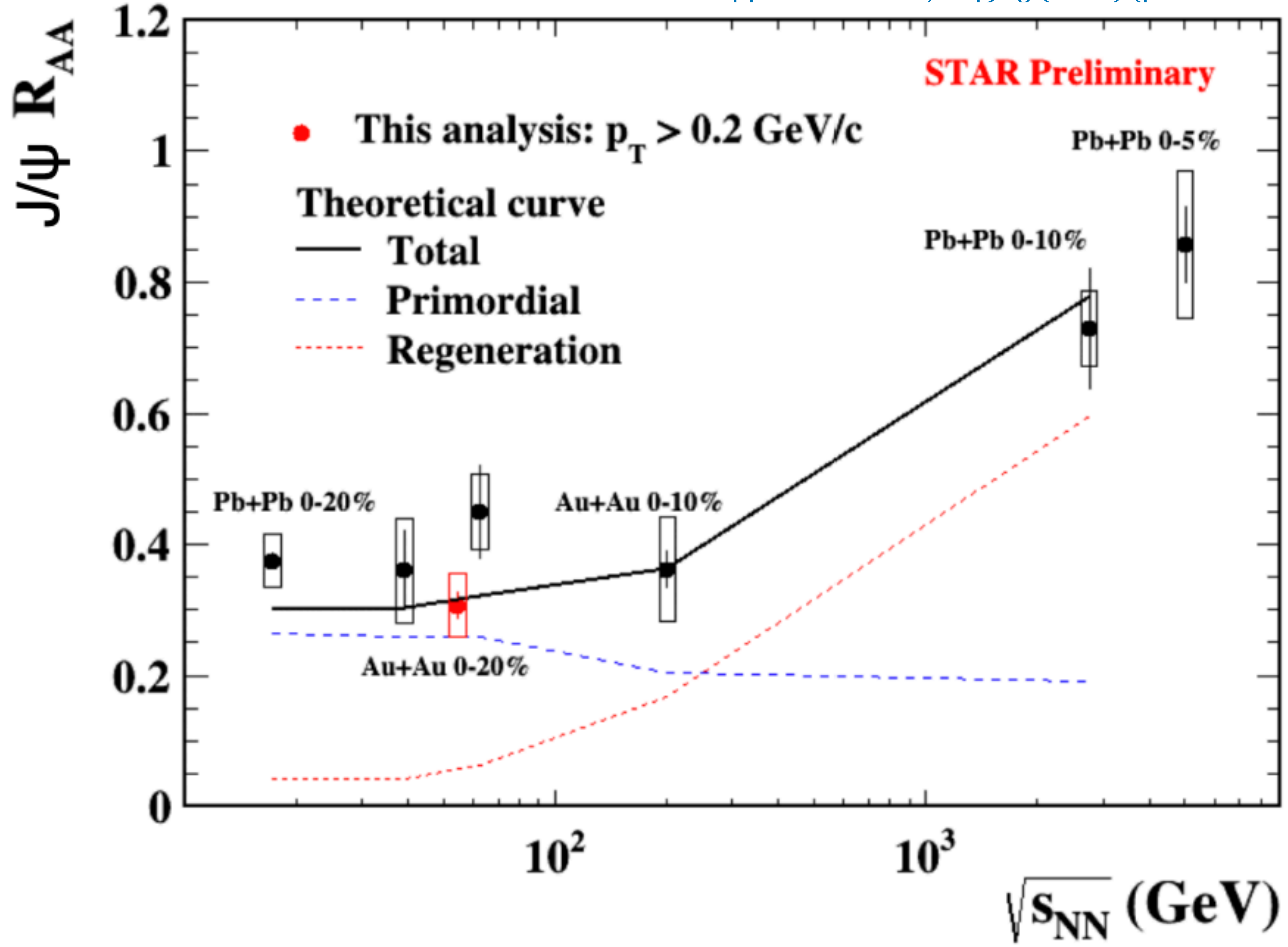
- Suppression of J/ψ in Au + Au collisions at 54.4 GeV observed with high precision

- No significant energy dependence of J/ψ R_{AA} in central collisions from 17.2 to 200 GeV
- At LHC energies, J/ψ R_{AA} increases due to regeneration
    - **Interplay among dissociation, regeneration**

Energy Dependence of J/ψ Suppression



R.Rapp et al PRC 82,064905 (2010) (private comm.)



- Effects beyond nPDF modification alone are required to describe quarkonia production in **p+Au** at backward rapidity

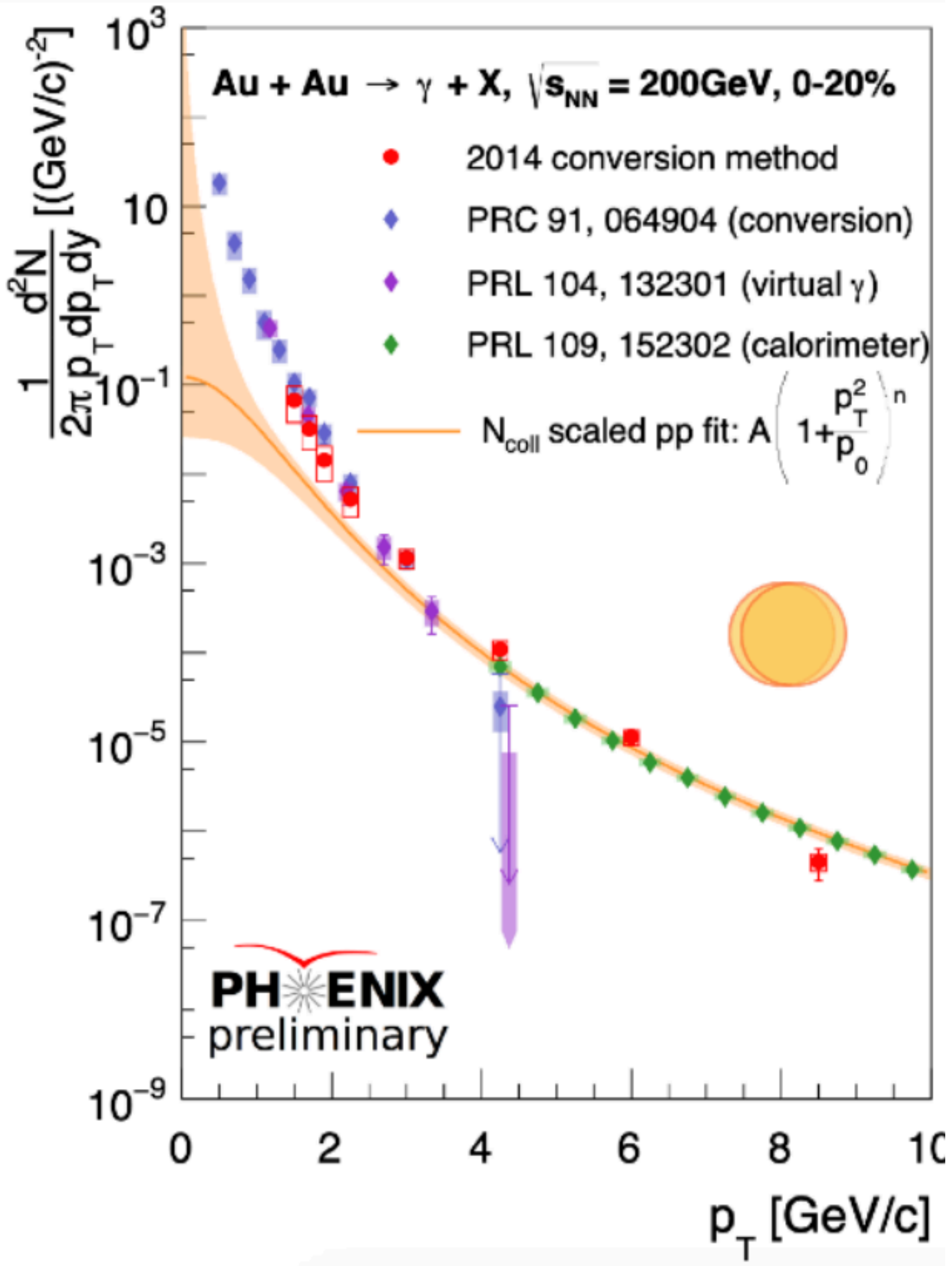
- No significant energy dependence of J/ψ R_{AA} in central collisions from 17.2 to 200 GeV
- At LHC energies, J/ψ R_{AA} increases due to regeneration
  - **Interplay among dissociation, regeneration, cold nuclear matter effects**

Direct Photons in 200 GeV Au+Au Collisions

- Photons do not experience strong interaction
  -> probes space-time evolution of matter produced

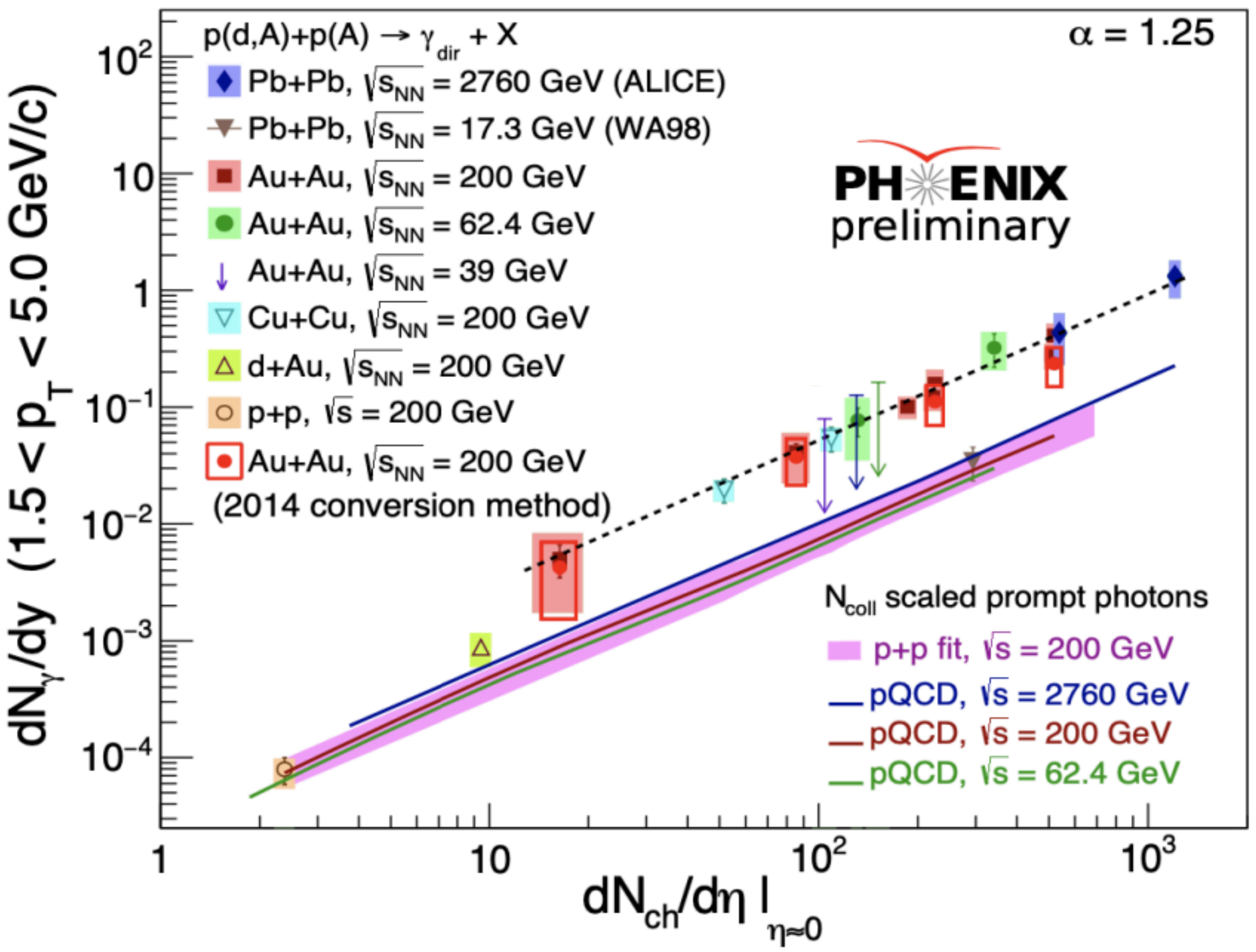
Direct photons = Inclusive photons - decay photons

- New PHENIX measurement from 2014 Au+Au 200 GeV
  - high statistical precision
  - consistent with published results



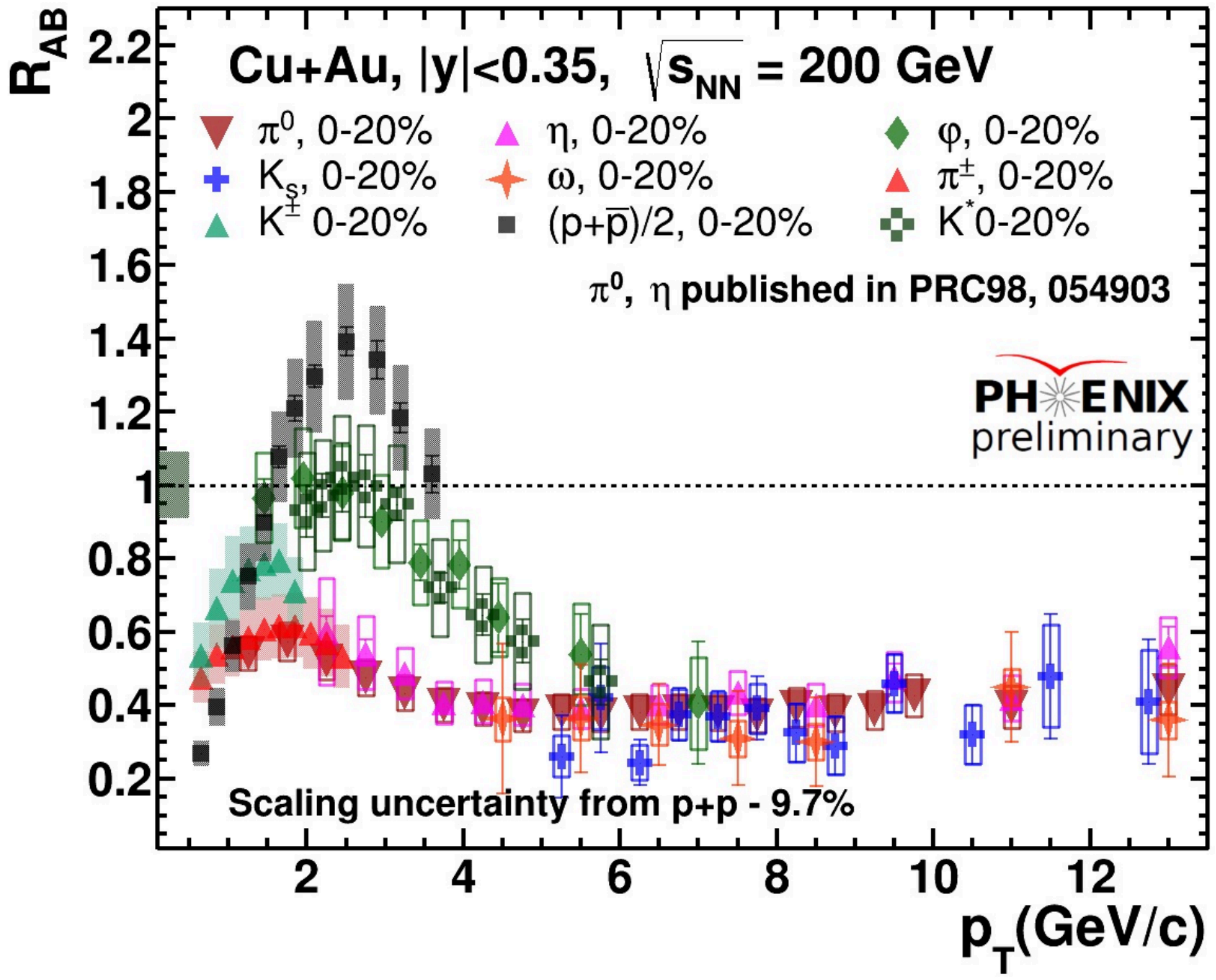
- At low p_T, Au+Au data show an enhancement compared to prompt contribution

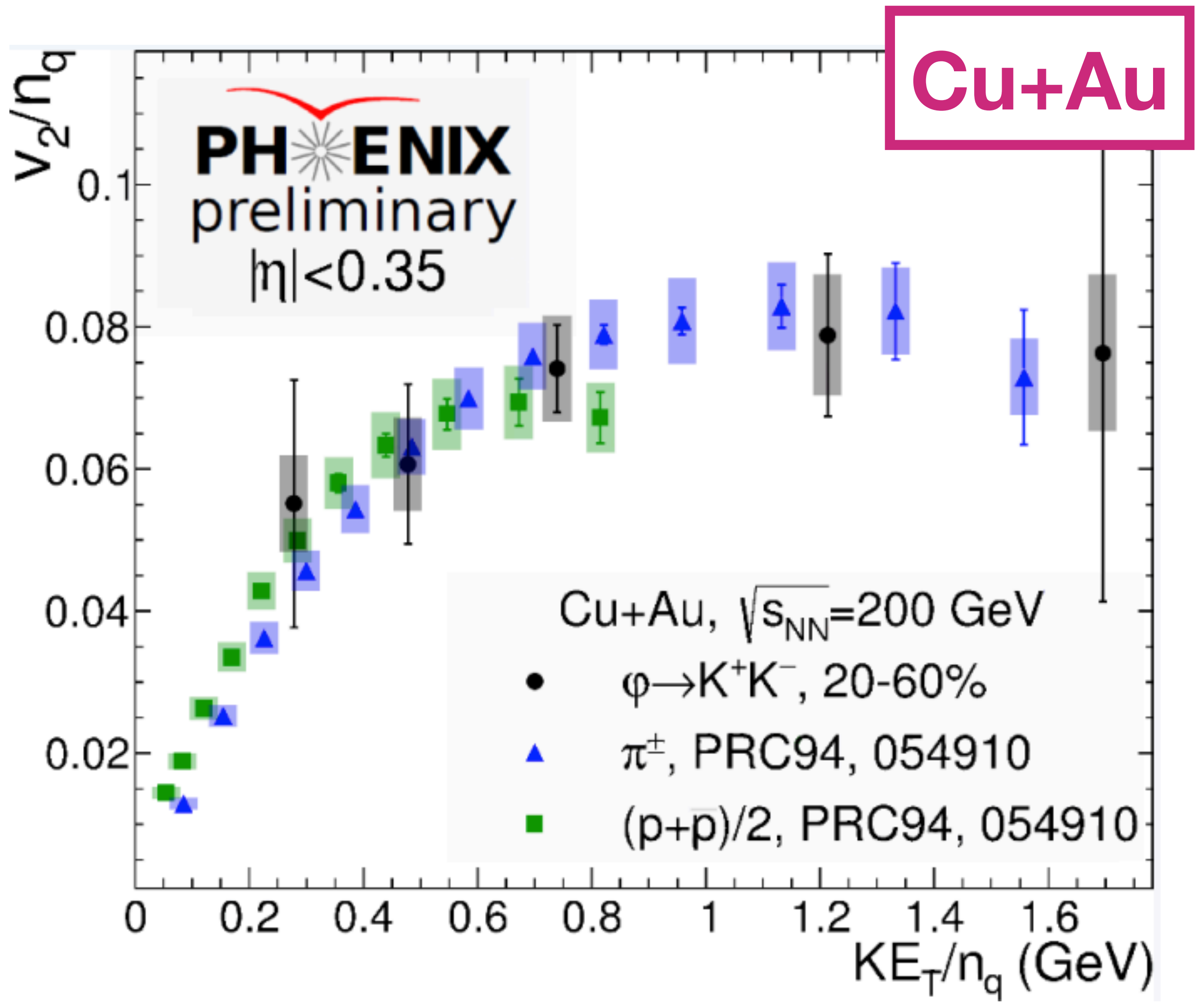
PRL 123, 022301 (2019)

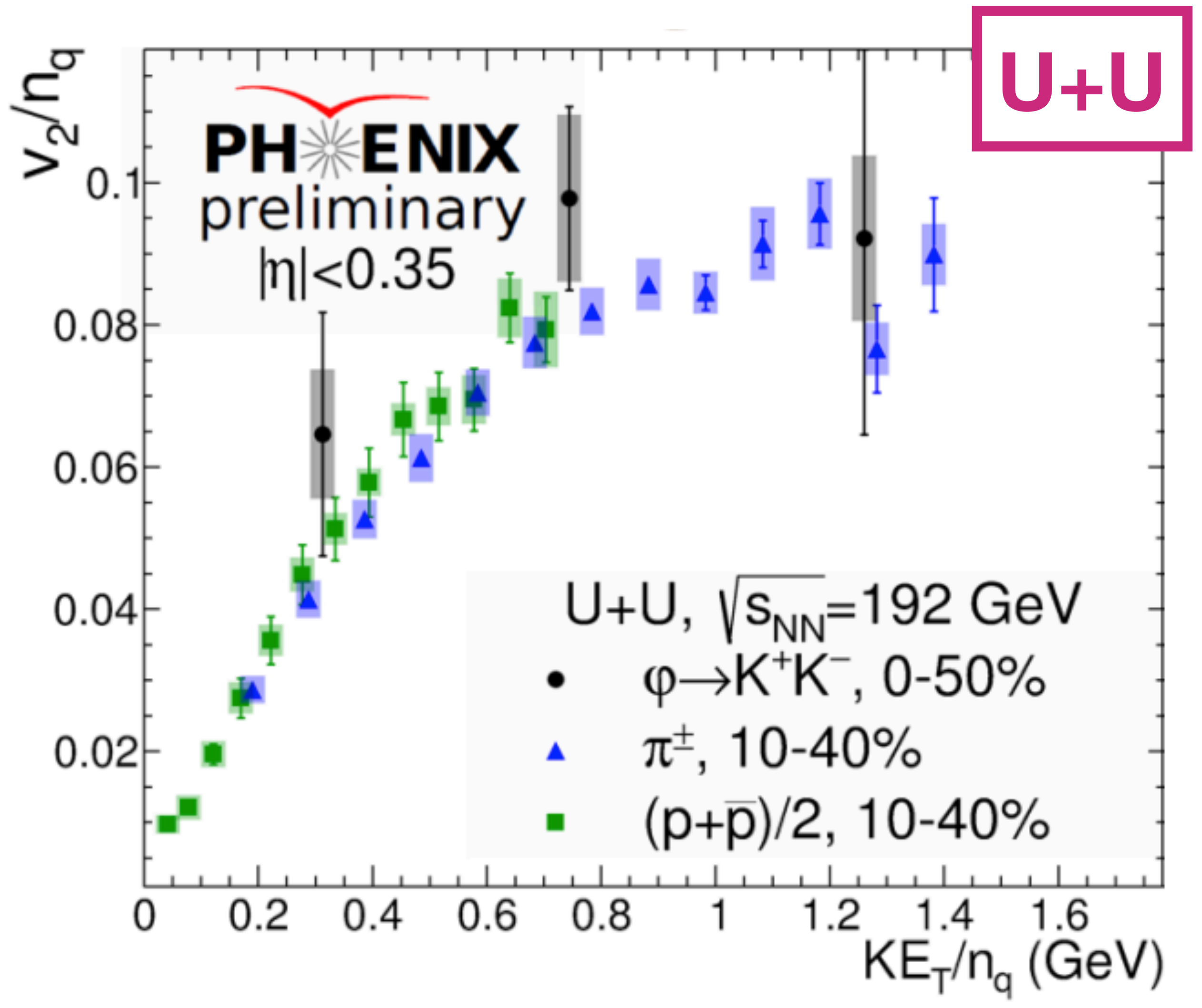


Observed scaling behavior in A+A collisions suggests that emission source of low p_T direct photons are similar from $\sqrt{s_{NN}}$ = 39 - 2760 GeV

ϕ Production in Cu+Au and U+U Collisions at 200 GeV



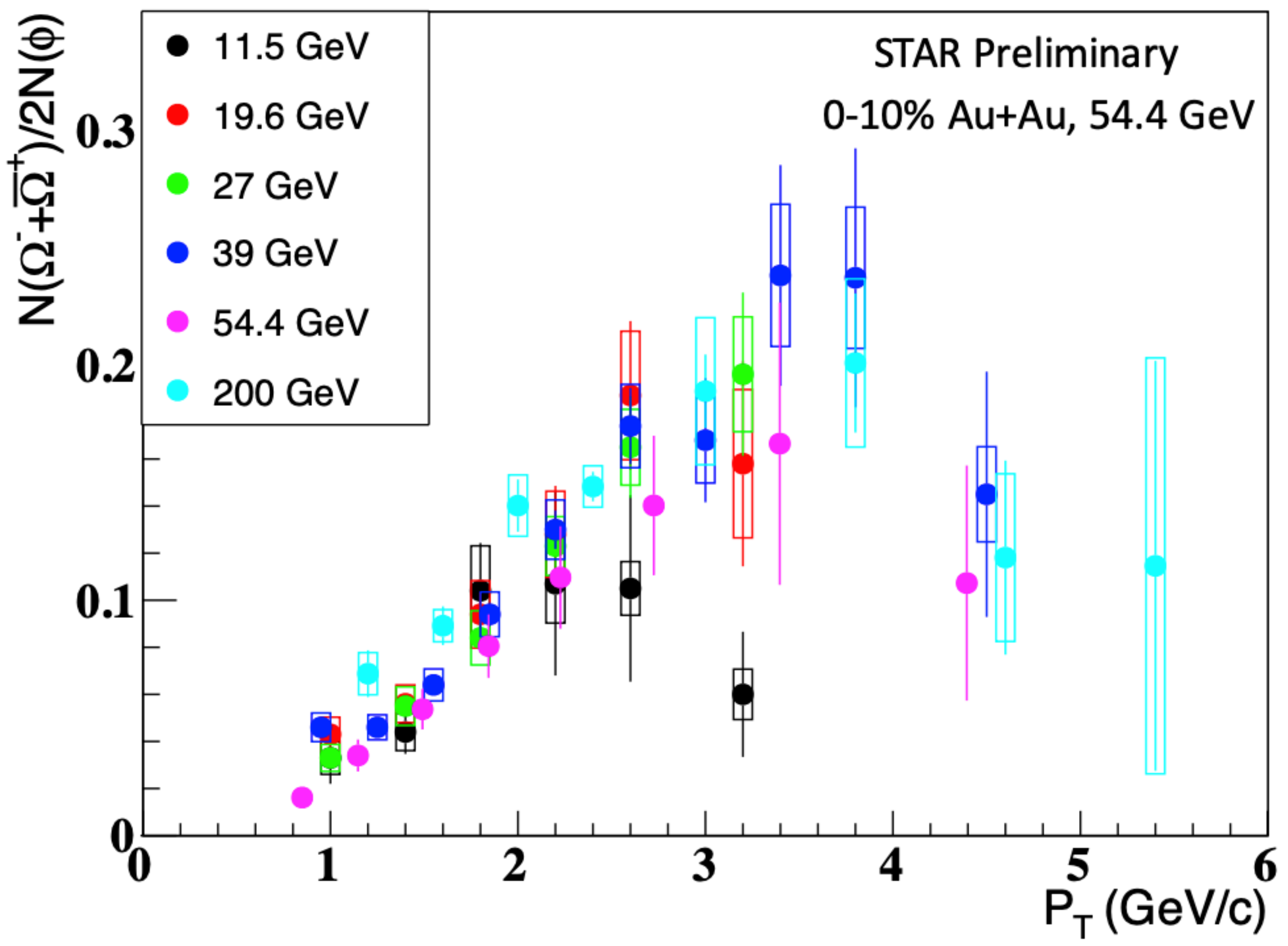


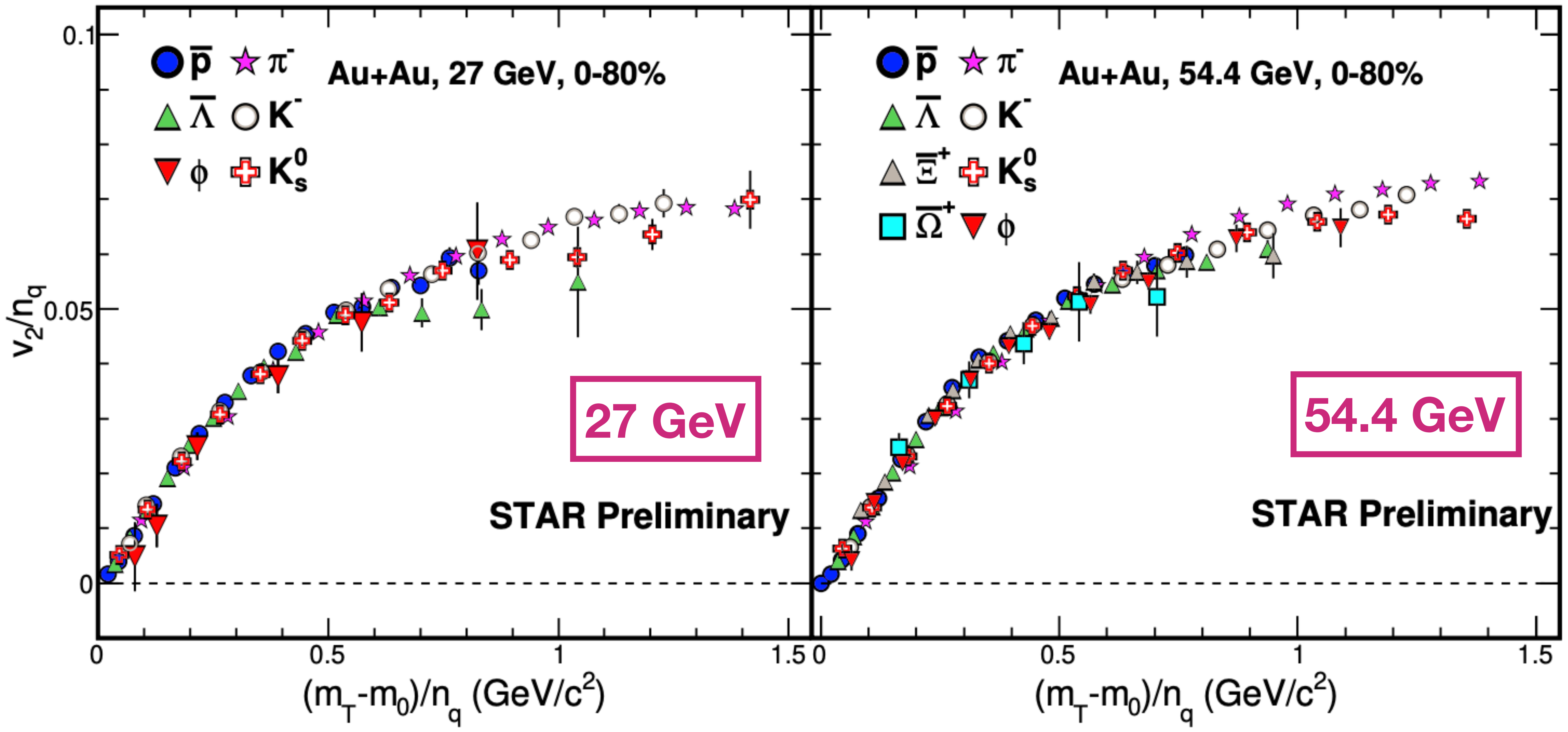


- At high p_T, similar suppression for all species: parton energy loss
- At intermediate p_T, $R_{AB}(p) \geq R_{AB}$ (ϕ, K*) $\geq R_{AB}$ (π^0, η)
  - Interplay of radial flow, strangeness enhancement, coalescence hadronization

- ϕ follows NCQ scaling in Cu+Au, U+U 200 GeV
  - Consistent with ϕ production via coalescence, similar to HF

Strangeness Production at 27 and 54.4 GeV





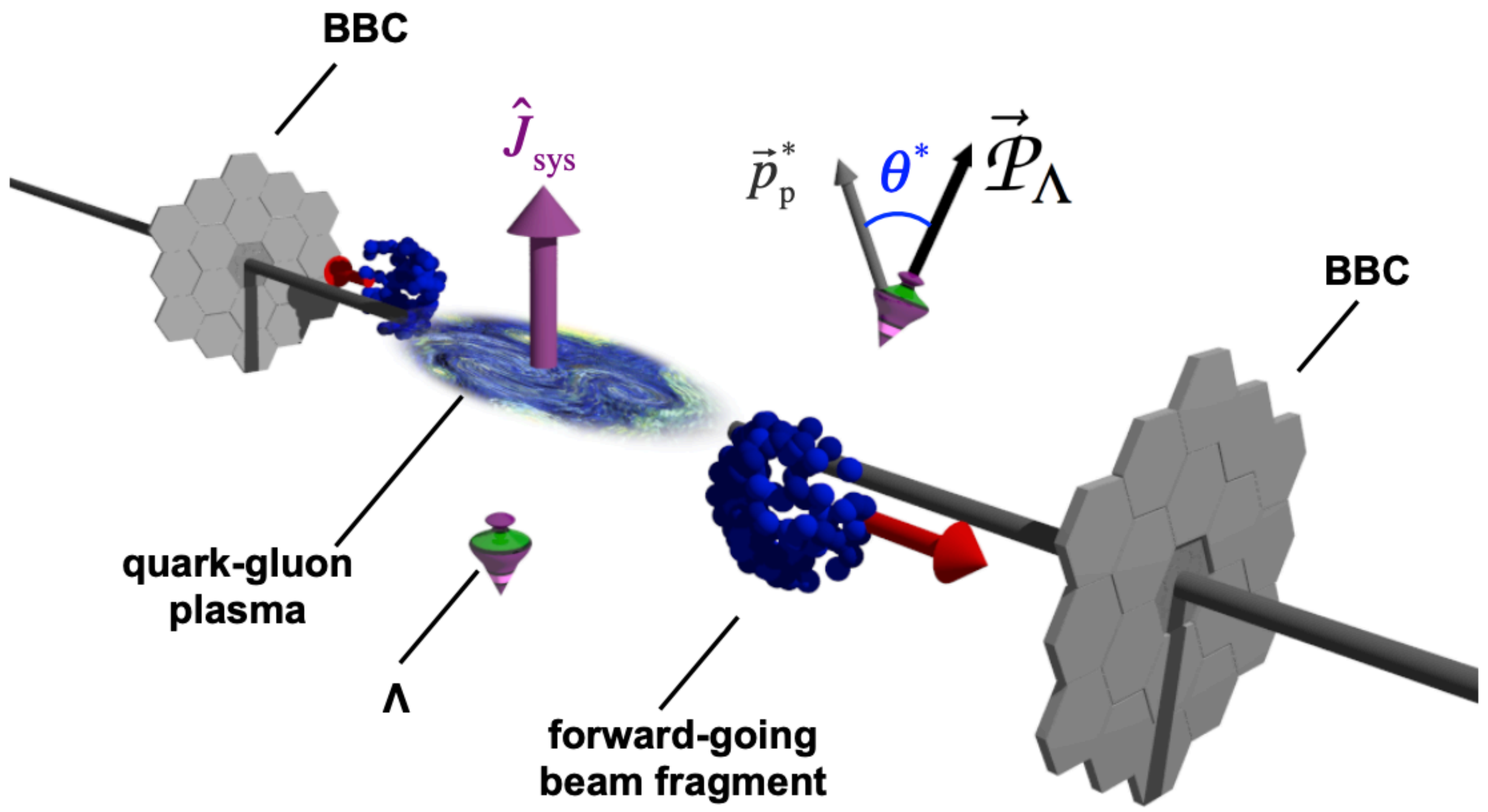
- Ω/ϕ ratio enhanced at intermediate p_T for $\sqrt{s_{NN}}$ = 19.6 - 200 GeV

- NCQ scaling holds for multi-strange baryons at 54.4 GeV

ϕ, Ξ, Ω coalescence hadronization as dominant production mechanism at 54.4 GeV

First Measurement of Ξ and Ω Global Polarization

- Λ global polarization: evidence for the most vortical fluid



STAR, Nature 548, 62 (2017)

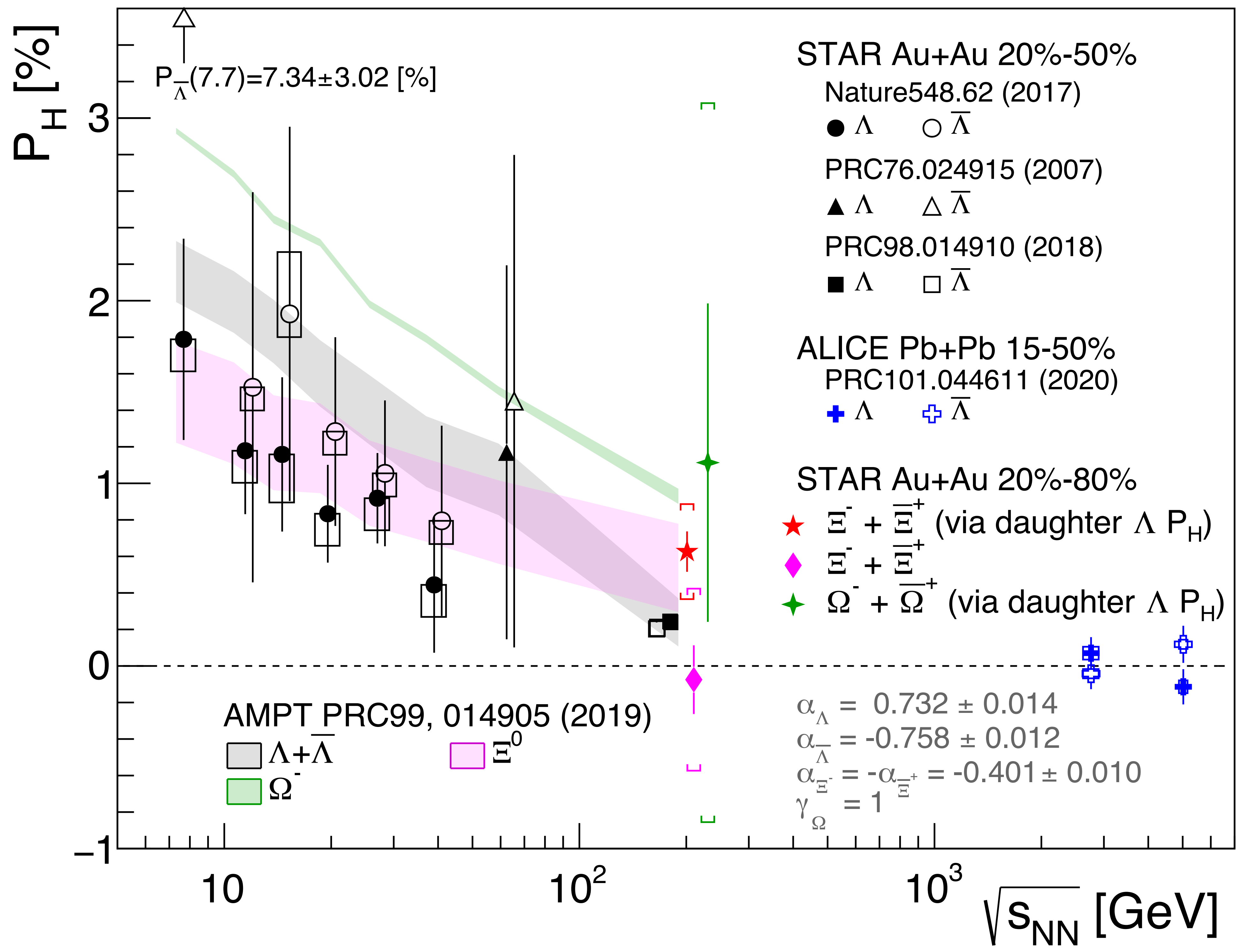
- Global polarization is the alignment between:

spin of emitted particles

angular momentum of a non-central collision

Decay proton tends to be emitted along the spin direction of the parent Λ

$$\overline{\mathcal{P}}_{\mathrm{H}} \equiv \langle \vec{\mathcal{P}}_{\mathrm{H}} \cdot \hat{J}_{\mathrm{sys}} \rangle = \frac{8}{\pi \alpha_{\mathrm{H}}} \frac{\left\langle \cos\left(\phi_{p}^{*} - \phi_{\hat{J}_{\mathrm{sys}}}\right)\right\rangle}{R_{\mathrm{EP}}^{(1)}}$$



STAR, PRL126, 162301 (2021)

- positive Ξ global polarization observed

Results confirm the global polarization picture based on the system fluid vorticity

6th-Order Cumulant of Net-Proton Multiplicity in 27-200 GeV Au+Au Collisions

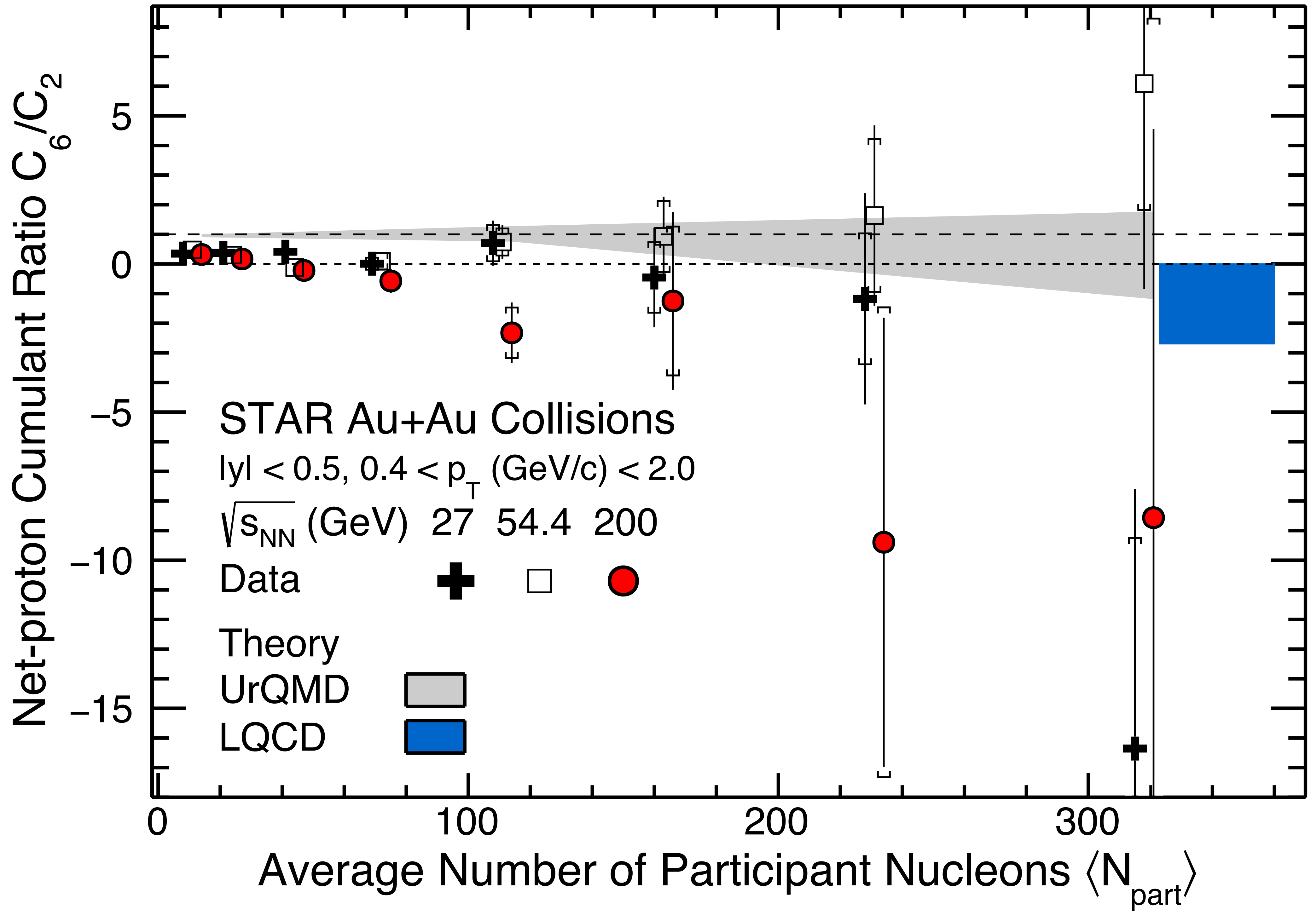
- Cumulants characterize event-by-event fluctuations

$$C_1 = <N> \qquad \delta N = N - <N>$$
$$C_2 = <(\delta N)^2>$$
$$C_3 = <(\delta N)^3>$$
$$C_4 = <(\delta N)^4> - 3<(\delta N)^2>^2$$
$$C_5 = <(\delta N)^5> - 5<(\delta N)^3><(\delta N)^2>$$
$$C_6 = <(\delta N)^6> - 15<(\delta N)^4><(\delta N)^2> - 10<(\delta N)^3>^2 + 30<(\delta N)^2>^3$$

- Higher order cumulants of net-proton multiplicity probe the nature of phase transition

Ratios of cumulants cancel system size to first order

- $C_6/C_2 < 0$ predicted as a signature of cross-over transition (Lattice QCD)
- $C_6/C_2 > 0$ from UrQMD (no QCD transition)



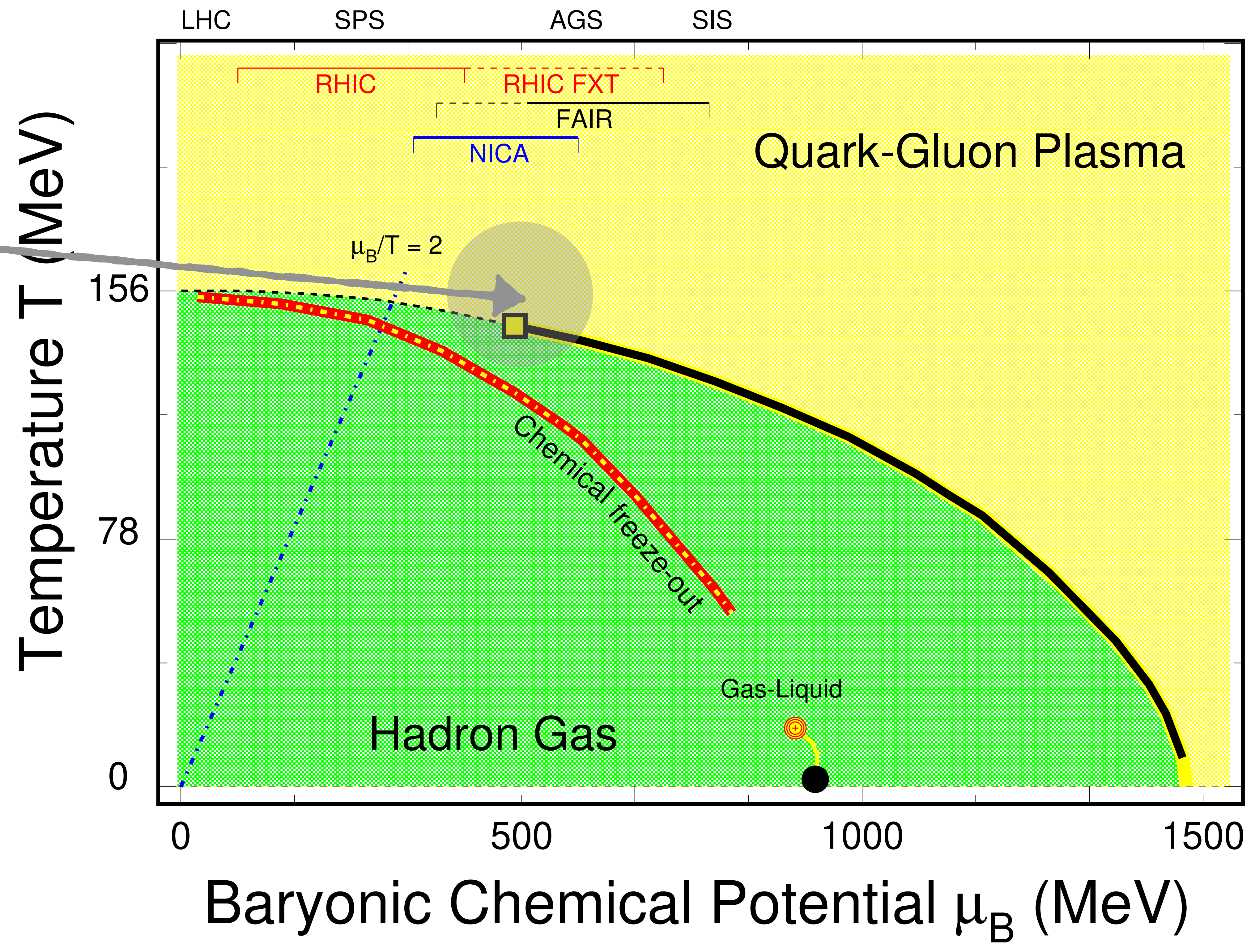
STAR, arxiv:2105.14698

- **Data, albeit with large uncertainties, favor smooth cross-over at Au+Au 200 GeV**
- **If confirmed with higher statistics, this will be the first direct comparison between data and LQCD calculations**

2. Finite μ_B region: $\sqrt{s_{NN}}$ = 7.7 - 27 GeV

Selected results on

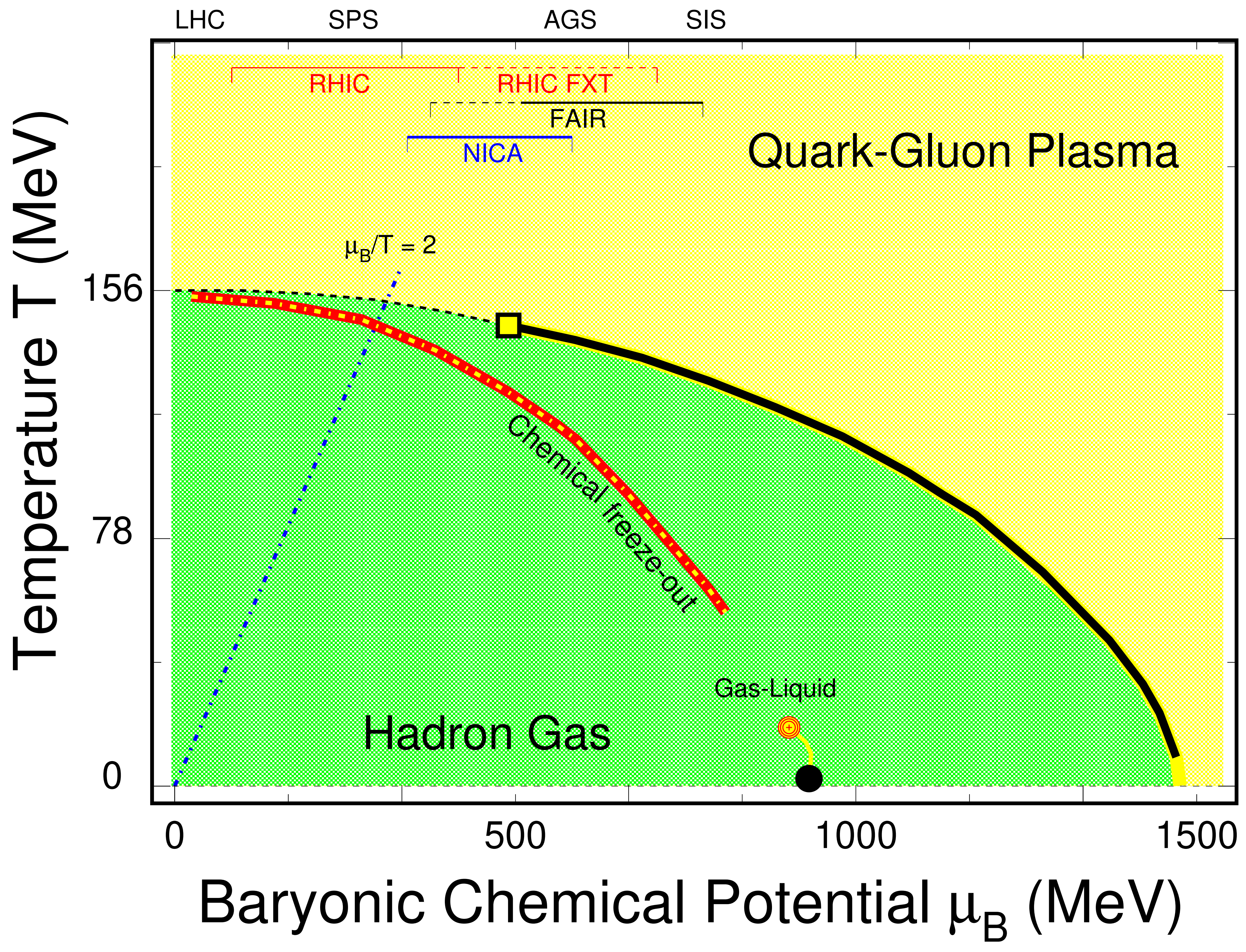
- Net proton cumulants



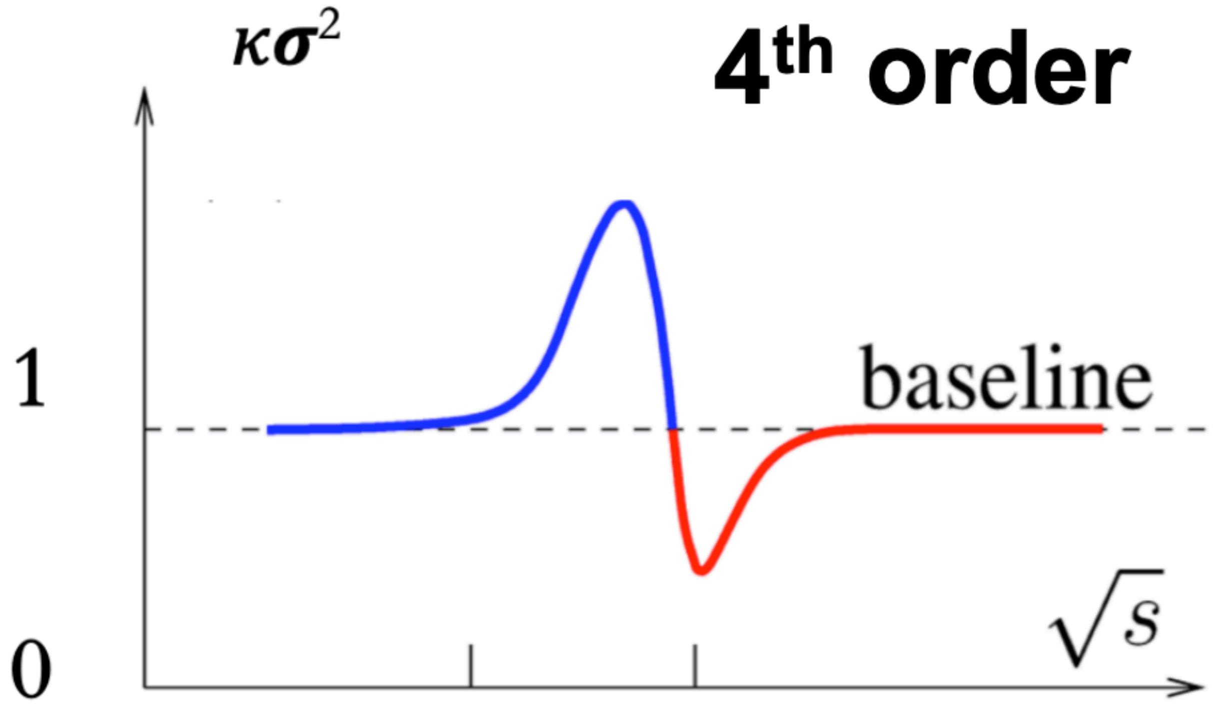
Search for Critical Fluctuations

- Finding conjectured critical point (CP) is one of the main goals of the BES program
- Cumulants of conserved quantities (Q, B, S) are sensitive to the correlation length, which diverges at CP
- Non-monotonic behavior of $\kappa\sigma^2$ proposed as signature of CP

$$\kappa\sigma^2 = \frac{C_4}{C_2}$$

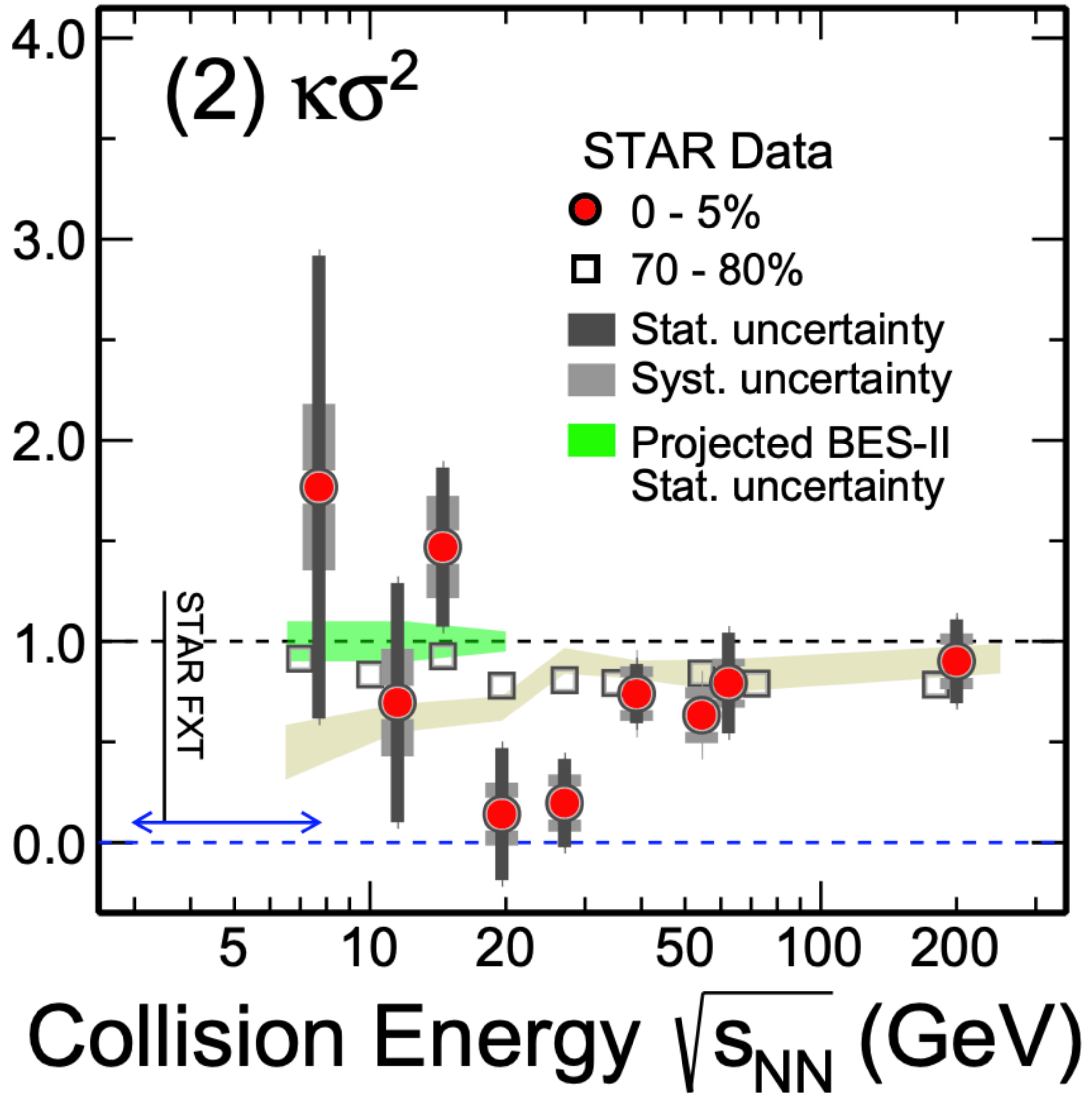


STAR, PRL126,9,092301(2021)



M. A. Stephanov, PRL 102,032301(2009)
M. A. Stephanov, PRL 107,052301(2011)

Search for Critical Fluctuations



STAR, PRL 126 (2021) 092301

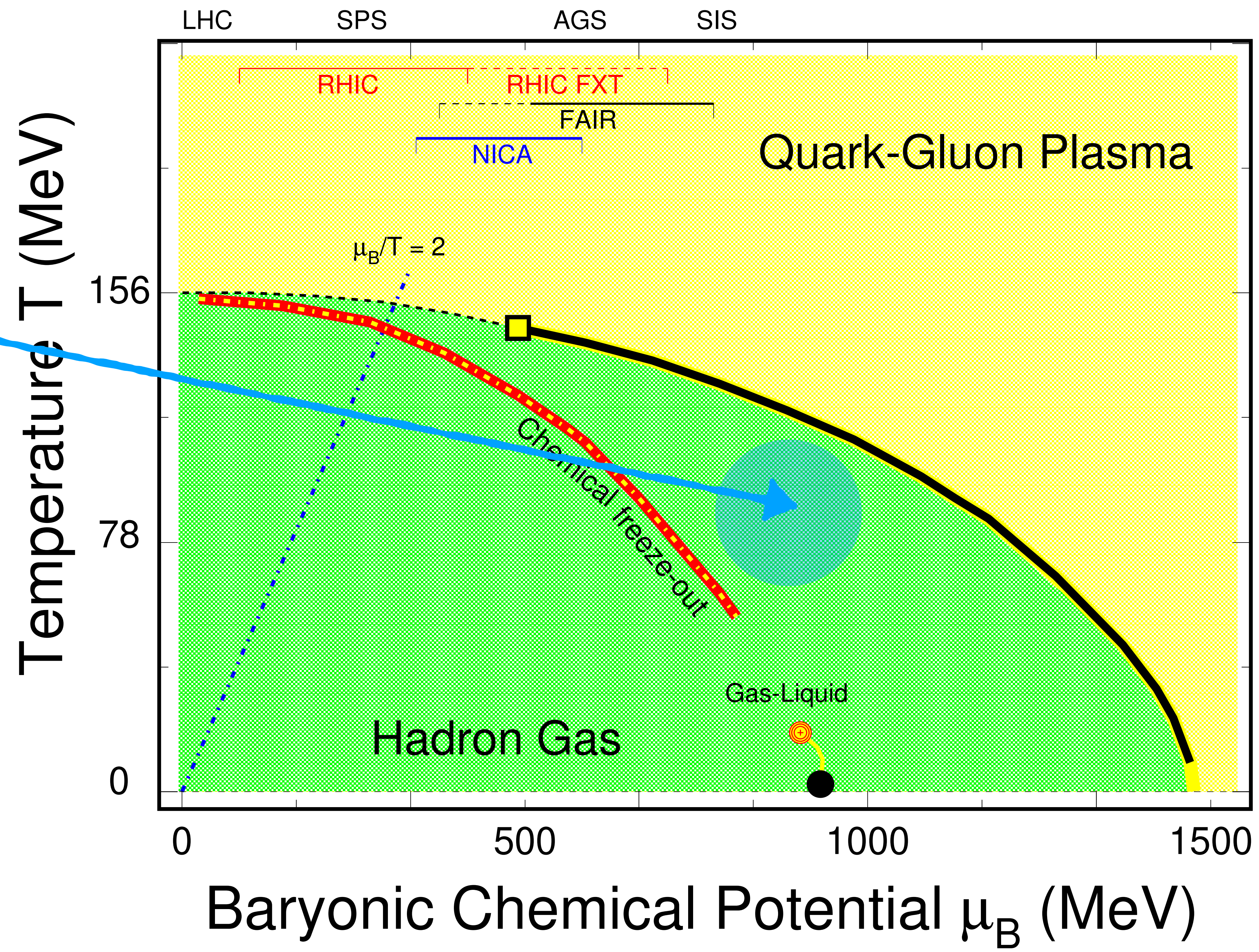
- Non-monotonic behavior of $\kappa\sigma^2$ vs. $\sqrt{s_{NN}}$ in 0-5% central collisions observed at 3.1σ

Hint of critical fluctuations, look forward to BES-II data

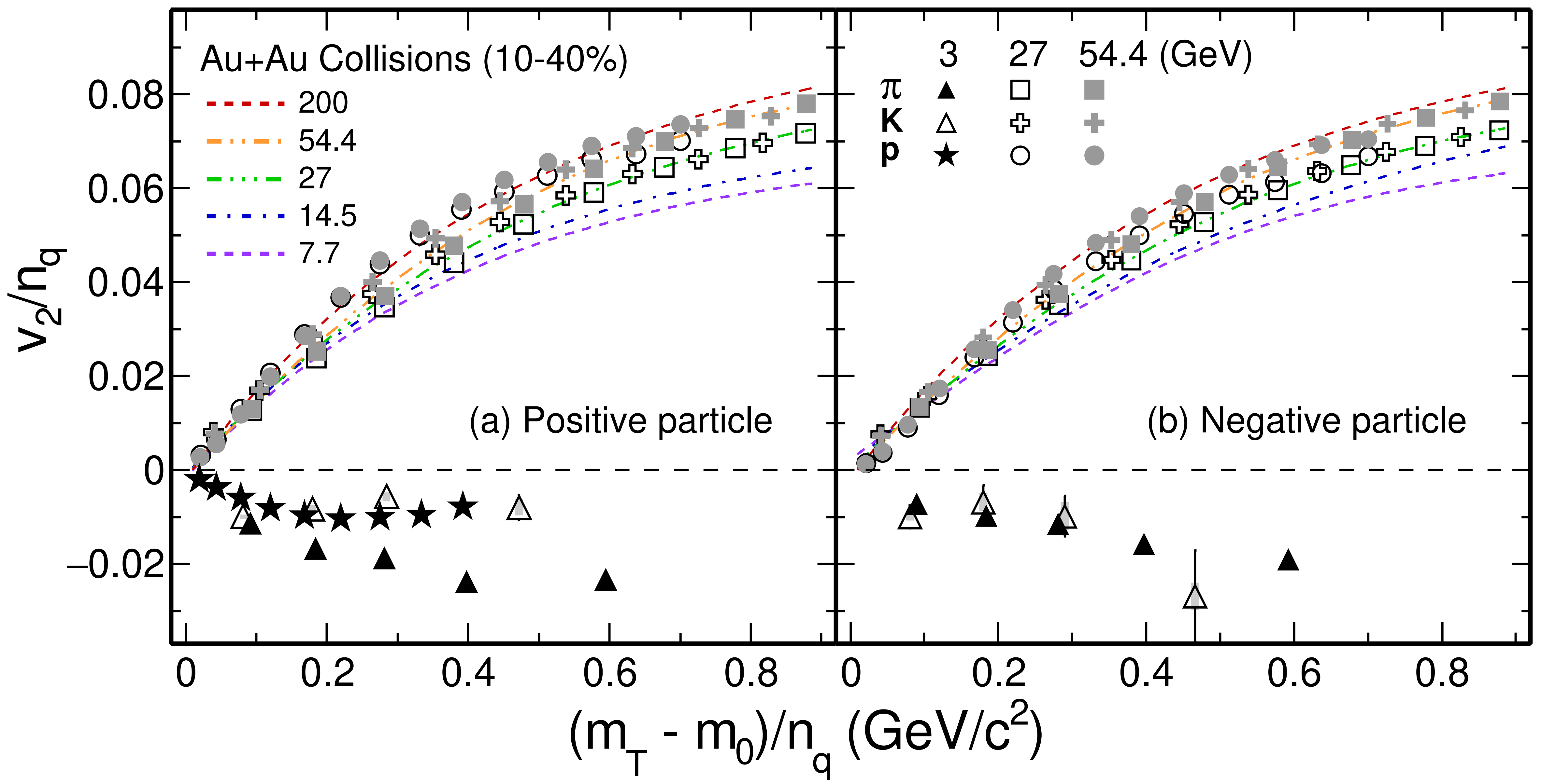
3. High μ_B region: $\sqrt{s_{NN}}$ = 3 GeV

Selected results on

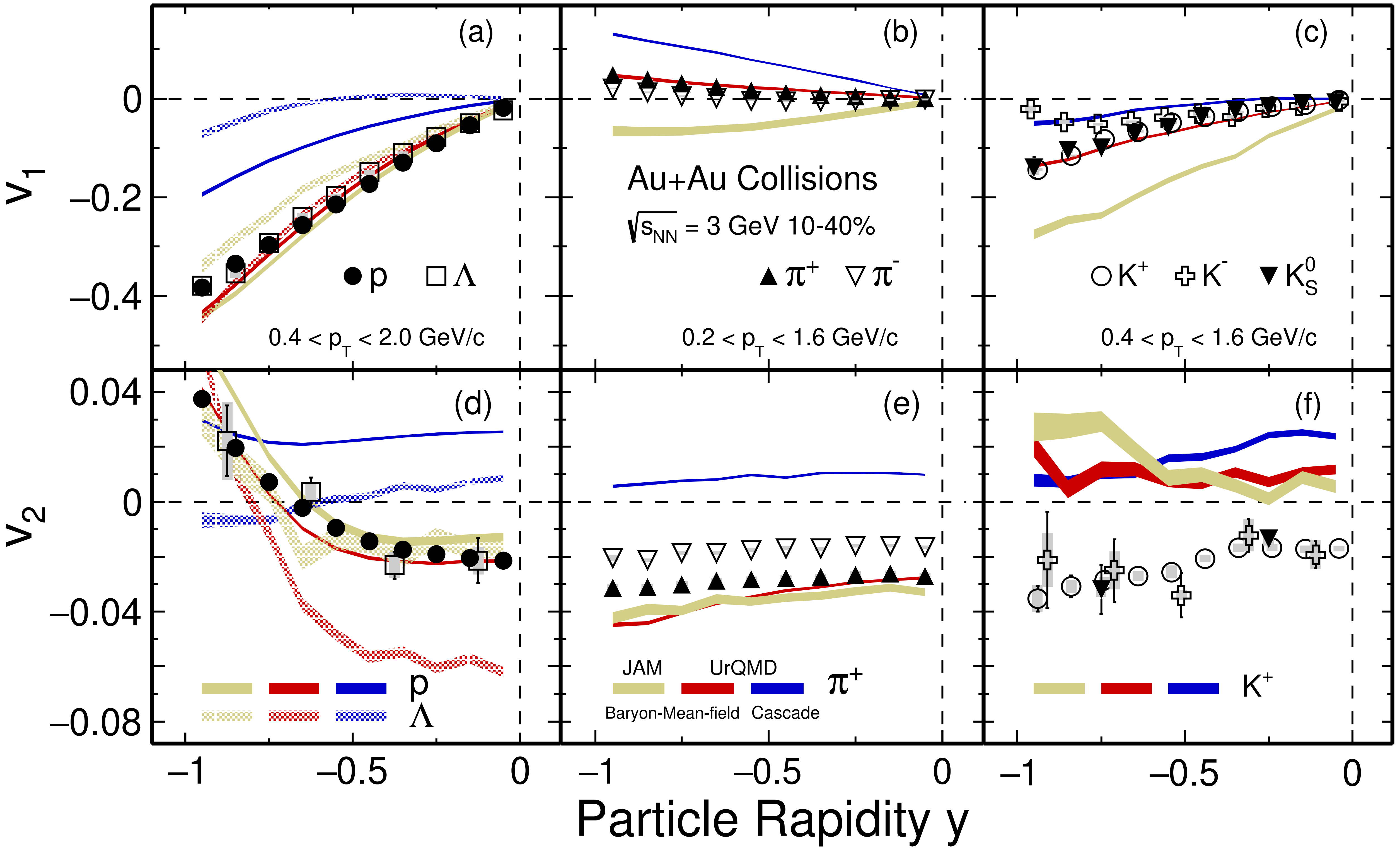
- Light flavor
- Strangeness
- Global polarization
- Hypernuclei



Collectivity at 3 GeV



STAR, arXiv:2108.00908

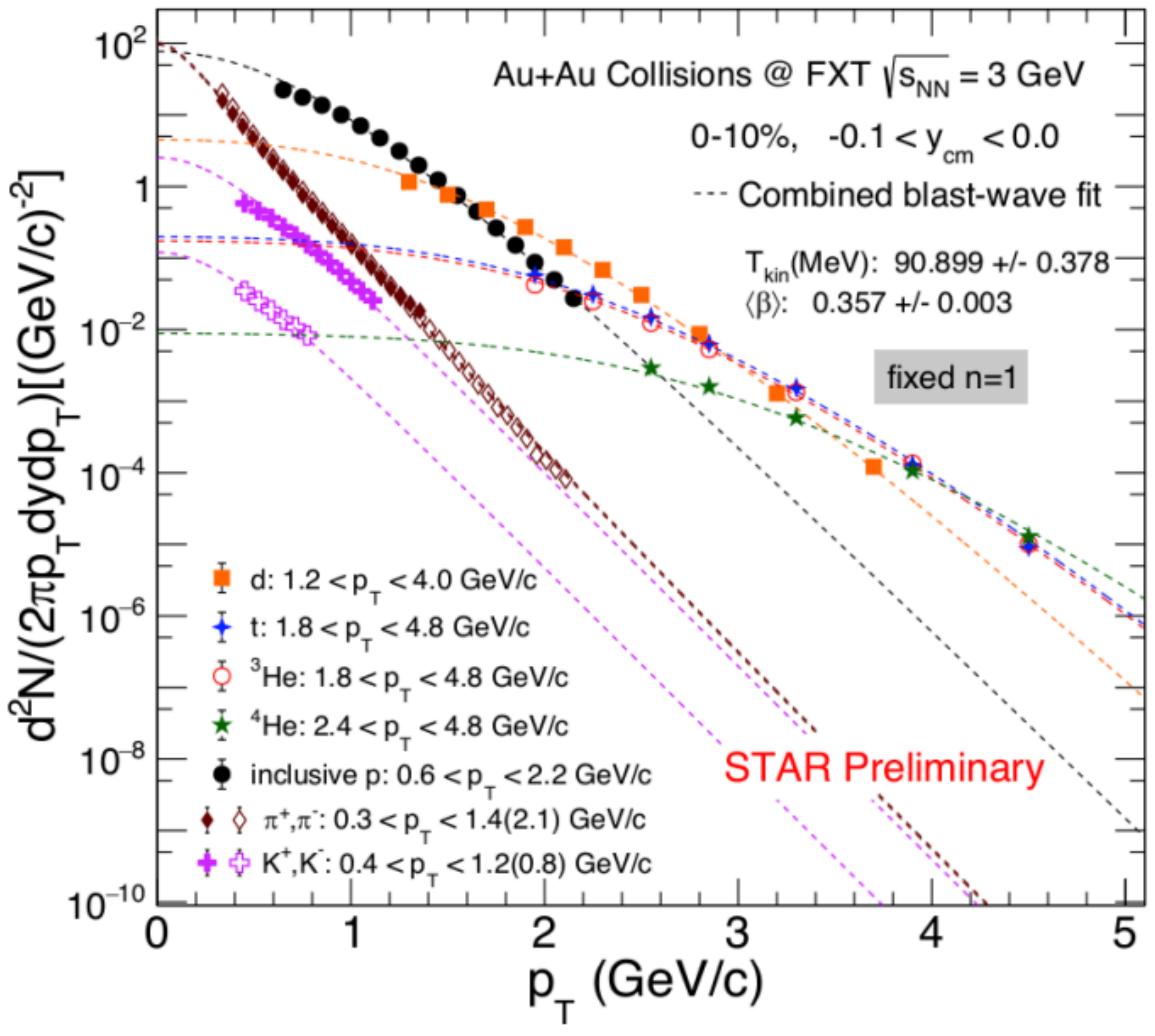


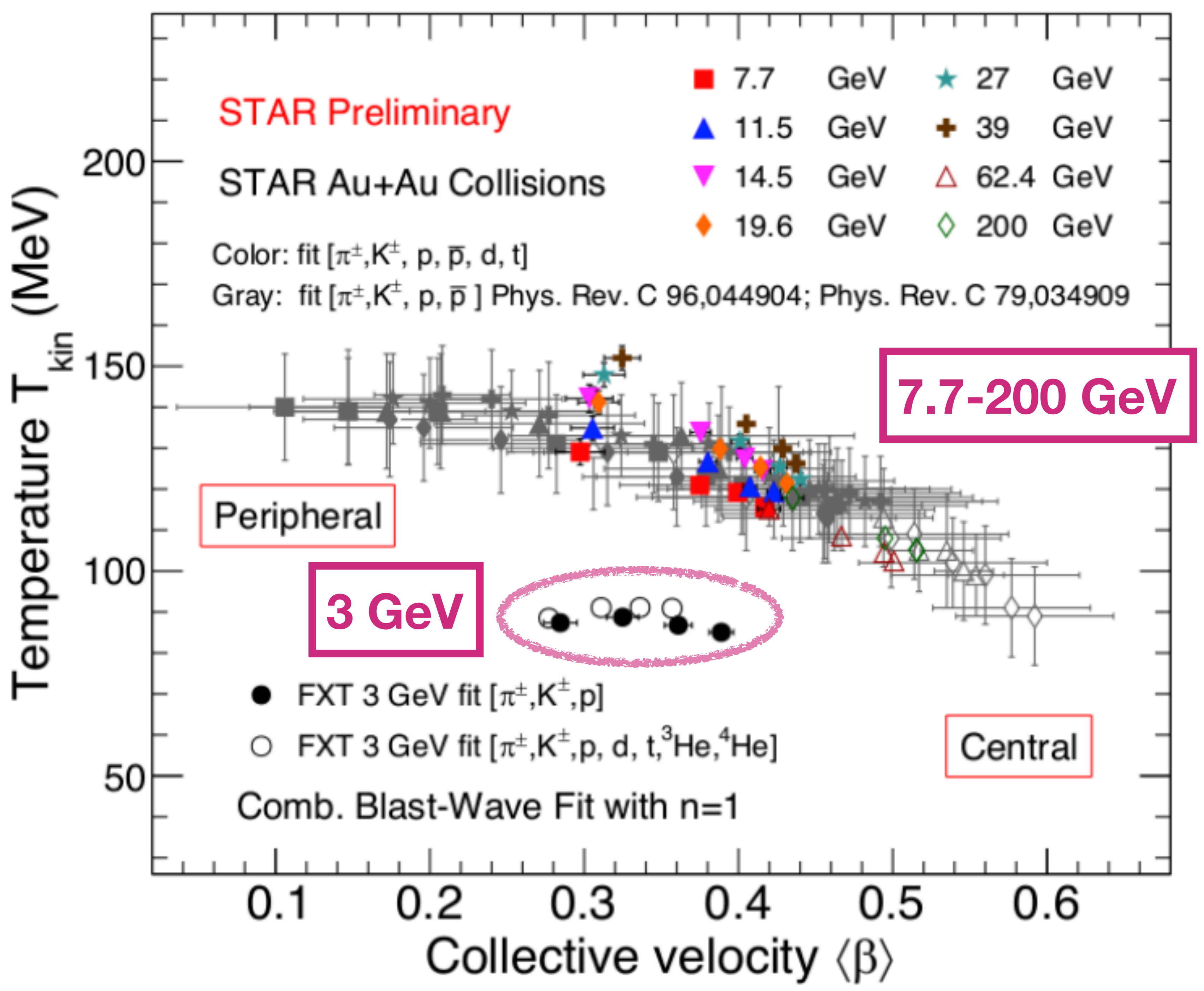
- v_2 values are negative and NCQ scaling violated at 3 GeV
- Disappearance of partonic collectivity at 3 GeV

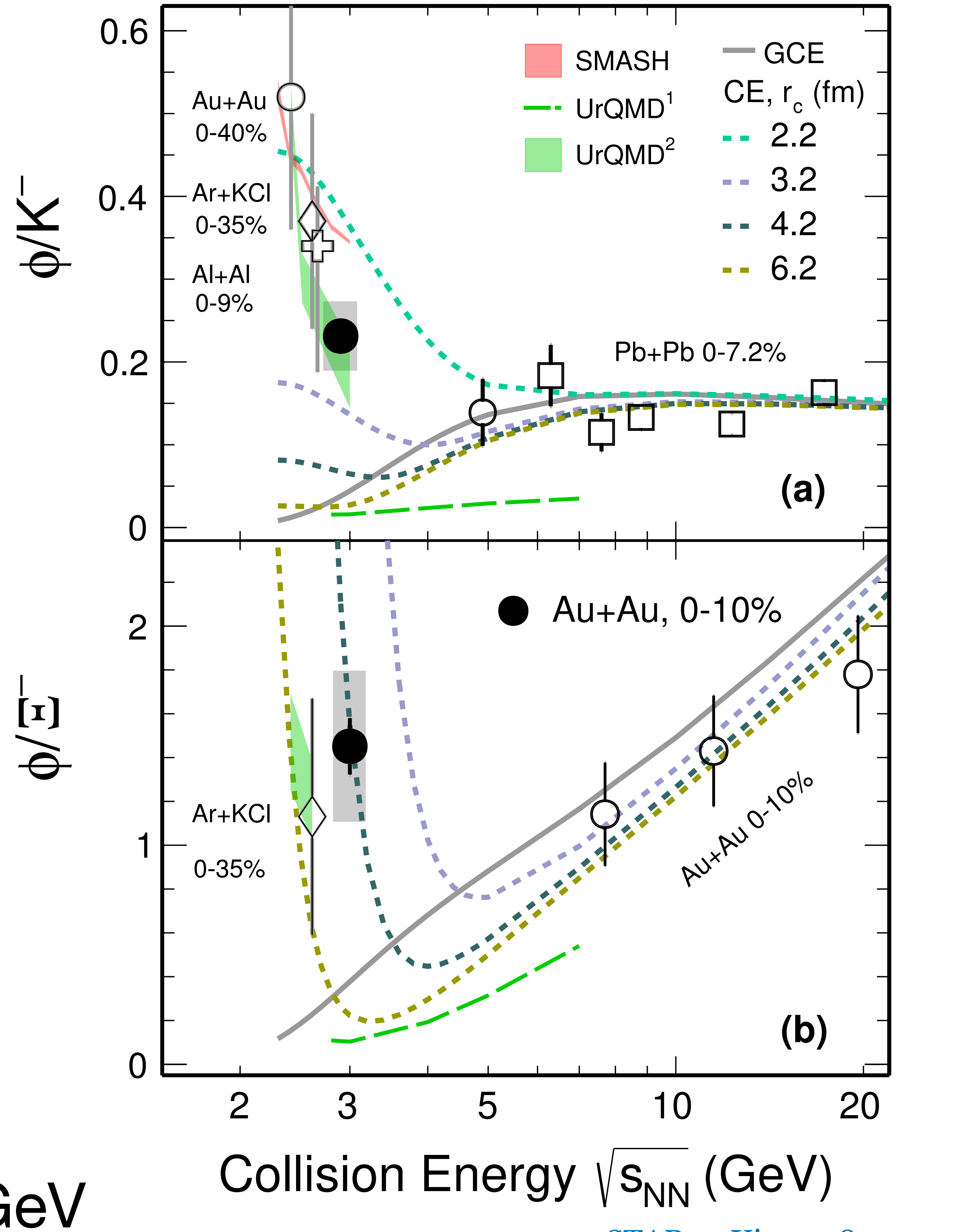
- UrQMD cascade model fails to describe data
- Including baryonic mean field generates trends seen in data

Medium created in 3 GeV Au+Au collisions dominated by baryonic interactions

Particle Yields at 3 GeV







STAR, arXiv:2108.00924

- π, K, p, light nuclei mid-rapidity p_T spectra fitted with blast-wave function
  - Simultaneous fit gives good description to all particles considered
  - Different trend in in kinetic freeze-out temperature compared to $\sqrt{s_{NN}}$ > 7.7 GeV

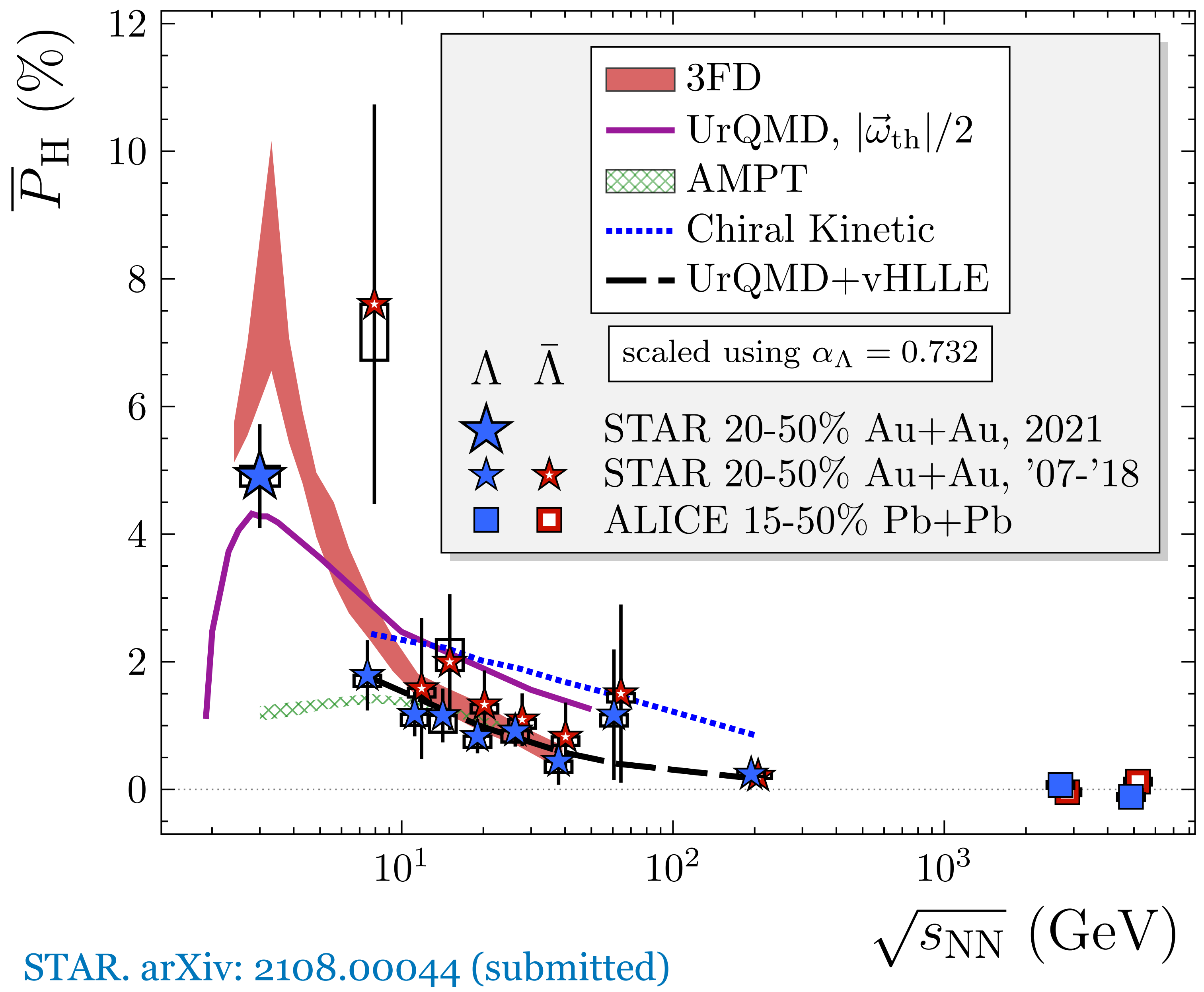
Different EOS at 3 GeV compared to that at higher collision energies

Canonical ensemble (CE) statistics is mandatory to describe strange particle yields at 3 GeV

Λ Global Polarization at 3 GeV

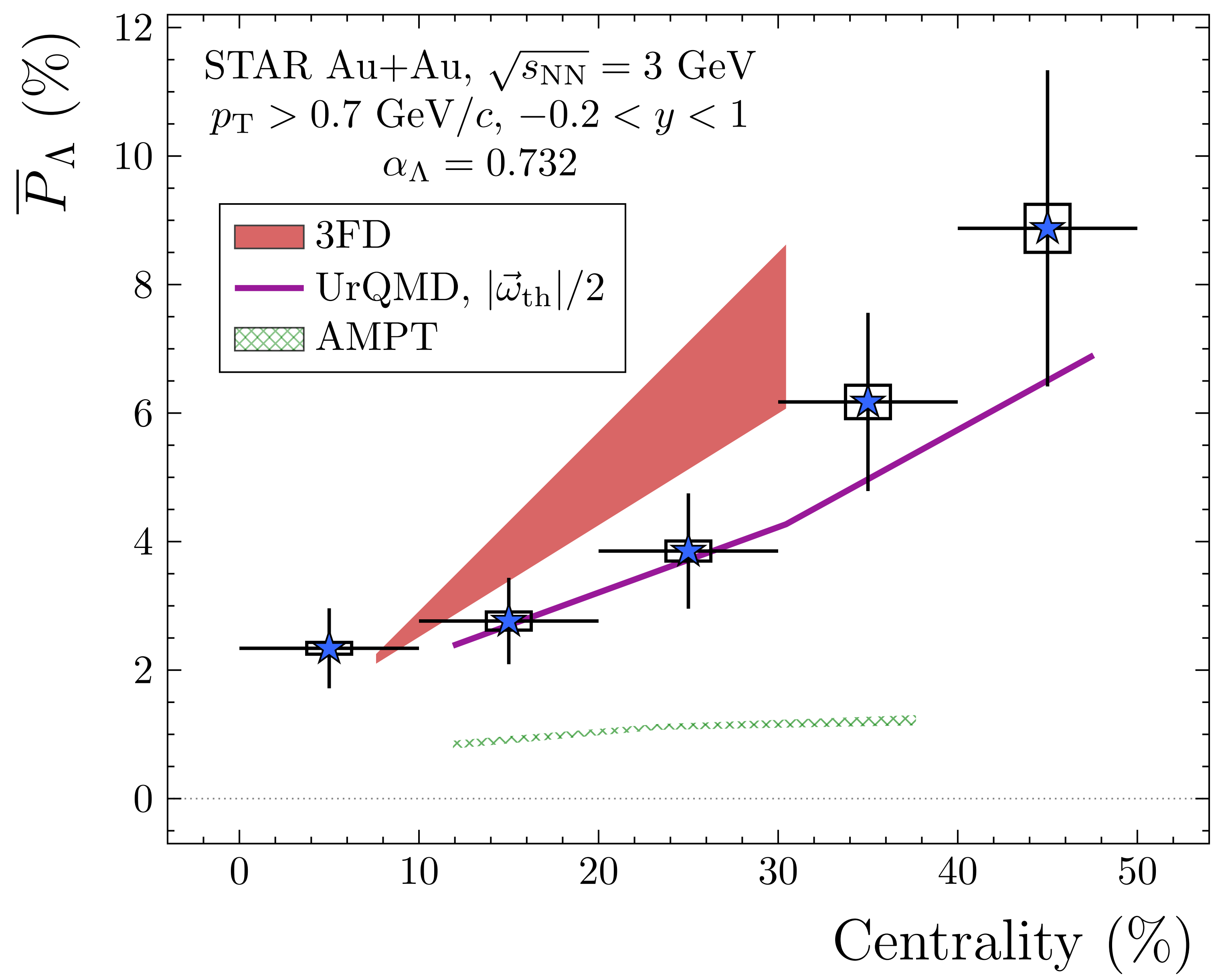
- 3 GeV: Largest Λ global polarization yet observed

$$\bar{P}_{\Lambda} = 4.91 \pm 0.81(stat) \pm 0.15(syst)\,\%$$



STAR. arXiv: 2108.00044 (submitted)

- $\overline{P}_{\Lambda}$ at 3 GeV consistent with:
  - 3FD (hydro-model)
  - URQMD (hadronic transport)
- Inconsistent with:
  - AMPT (partonic transport)
- URQMD overestimates $\overline{P}_{\Lambda}$ at $\sqrt{s_{NN}}$>7.7GeV



STAR. arXiv: 2108.00044 (submitted)

- Larger P_{Λ} for more peripheral collisions,
  - consistent with the increased initial global angular momentum in the system

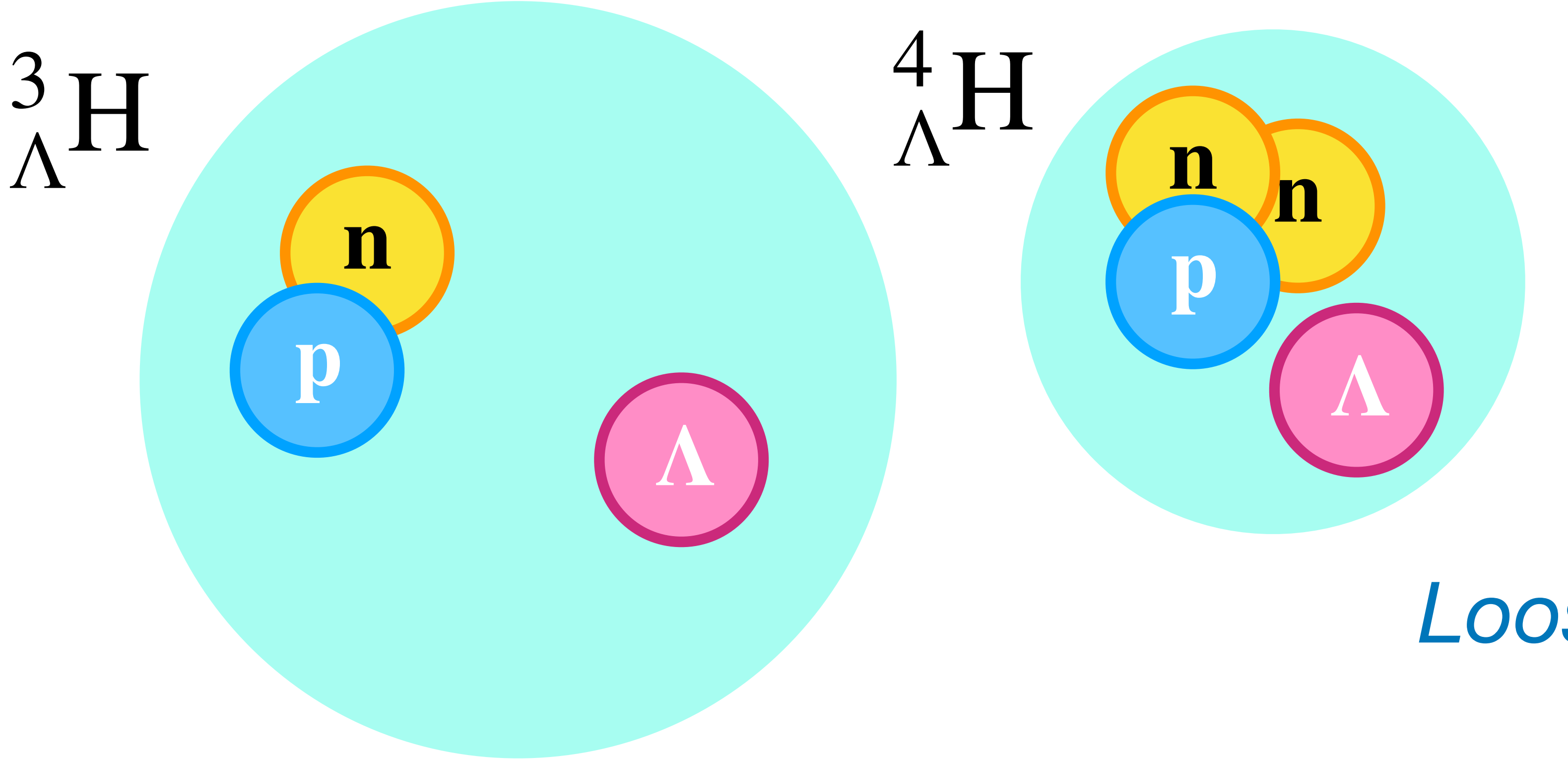
Comparisons to URQMD and AMPT seem to suggest that vorticity is affected strongly by the state of the system

Hypernuclei Lifetime and Binding energy

Hypernuclei are nuclei containing at least one hyperon

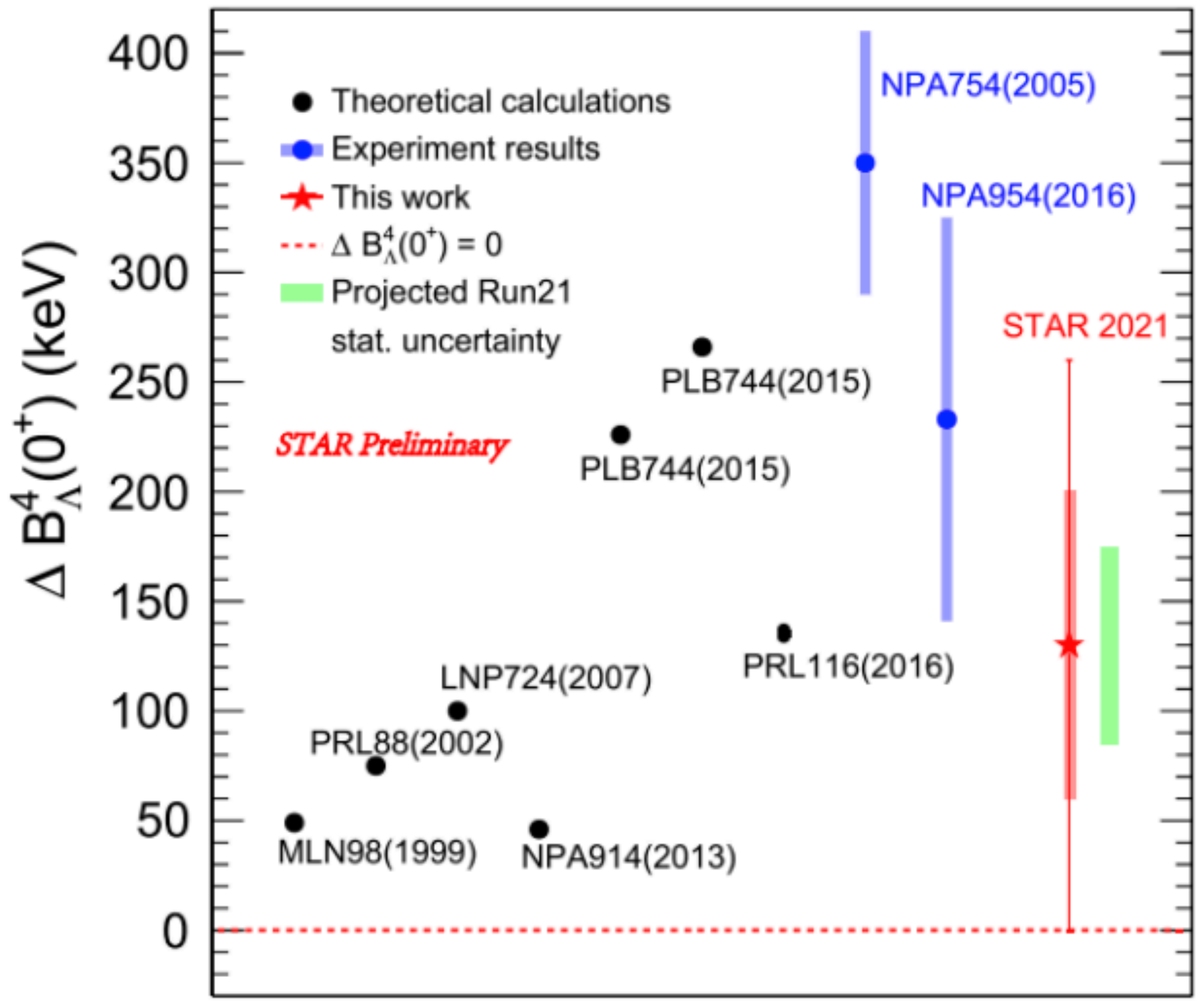
- STAR measured hypernuclei lifetime and binding energy using 3 GeV data

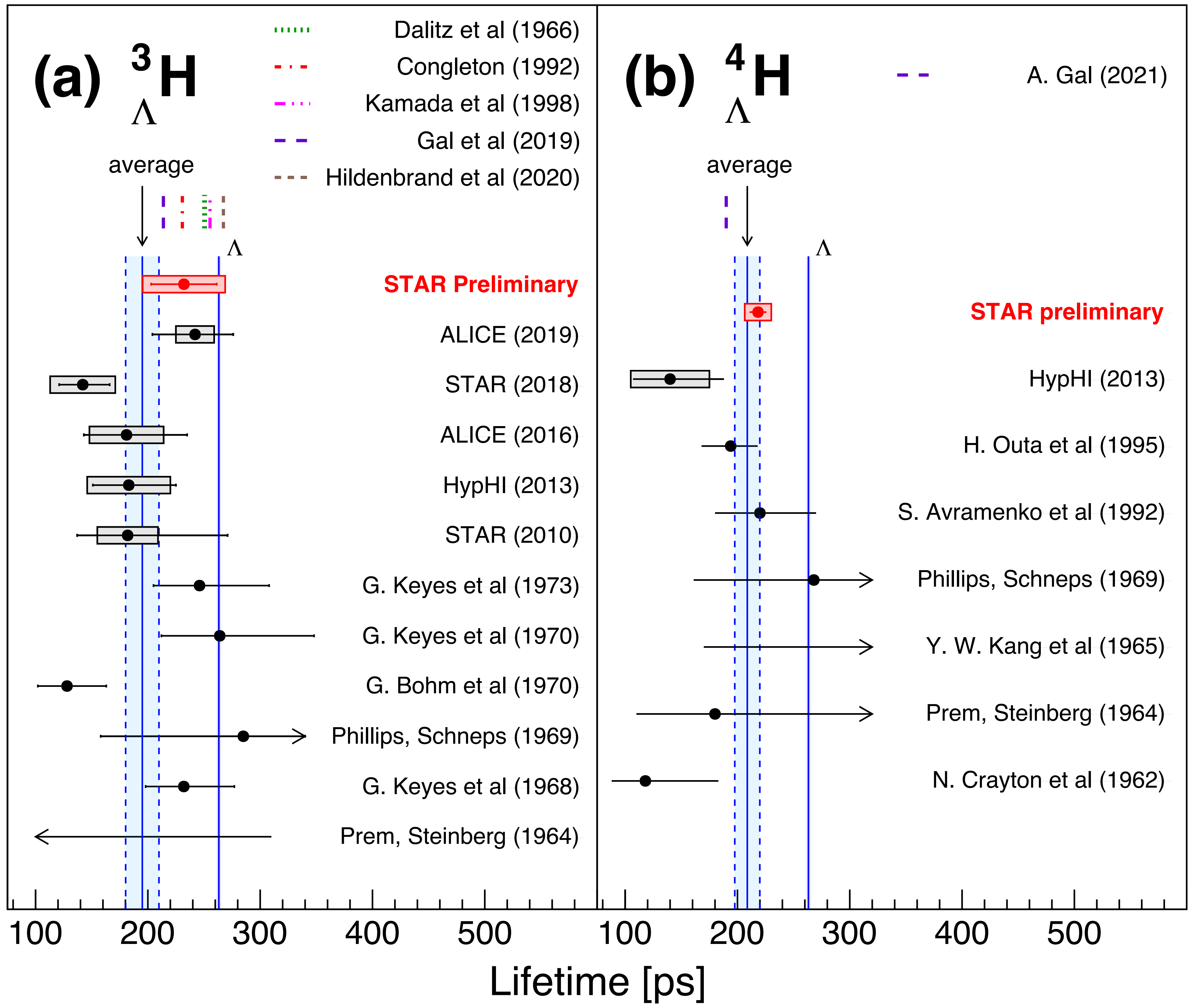
  Provide information on the Y-N interaction and hypernuclear structure



- $^{3}_{\Lambda}H$: ~0.2 MeV
- $^{4}_{\Lambda}H$: ~2.2 MeV

Loosely bound objects





$\tau(^{3}_{\Lambda}H) = 232 \pm 29(stat) \pm 37(syst)[ps]$

$\tau(^{4}_{\Lambda}H) = 217 \pm 8(stat) \pm 12(syst)[ps]$

$B_{\Lambda}(^{4}_{\Lambda}H) = 2.24 \pm 0.06(stat) \pm 0.18(syst)[MeV]$

$B_{\Lambda}(^{4}_{\Lambda}He) = 2.37 \pm 0.12(stat) \pm 0.14(syst)[MeV]$

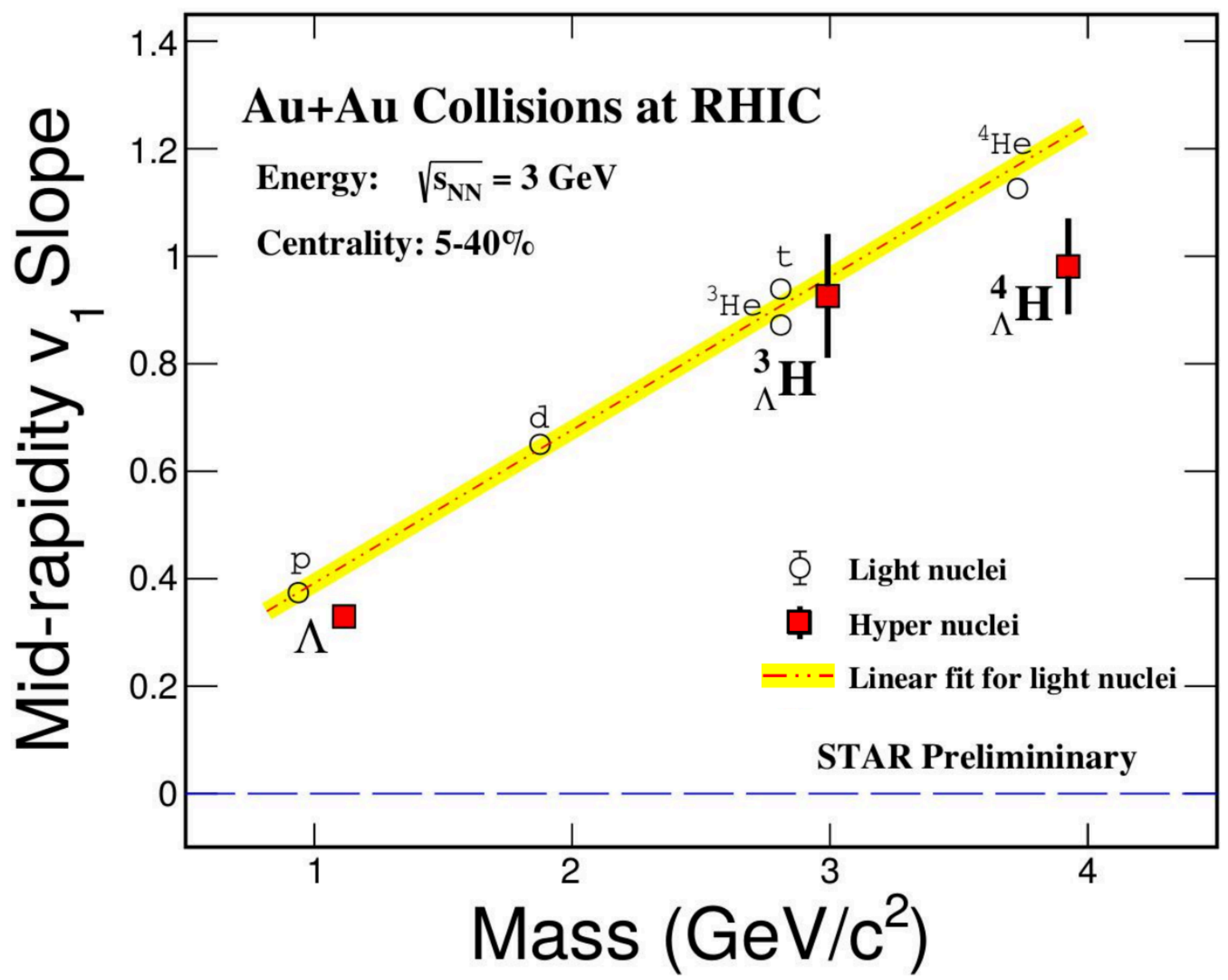
Hypertriton lifetime puzzle:

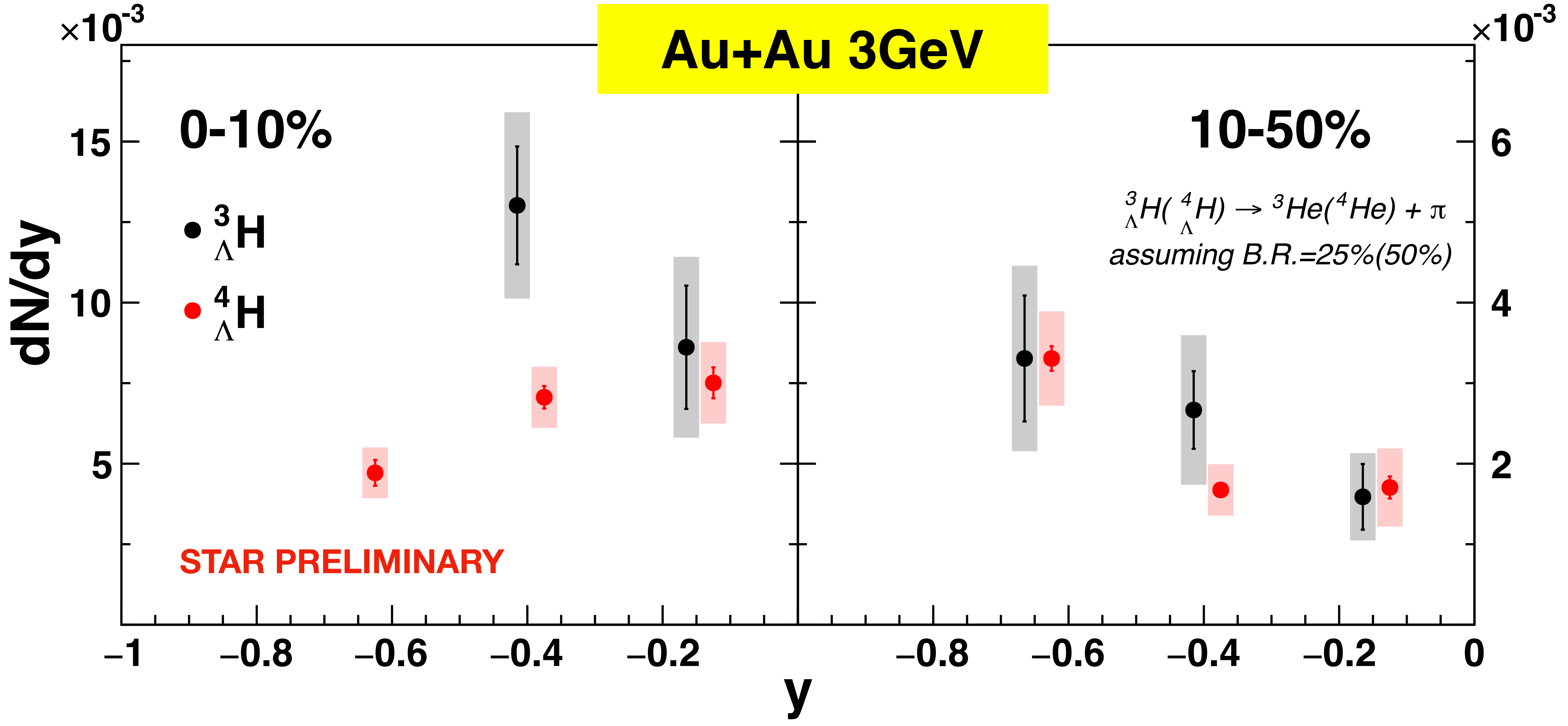
$^{3}_{\Lambda}H$ lifetime observed to be smaller than Λ, with tension between different experiments

Combine with other BES-II data to improve statistical precision

-> Help resolve the $^{3}_{\Lambda}H$ lifetime puzzle

First Measurement of Hypernuclei v_1 and dN/dy at 3 GeV





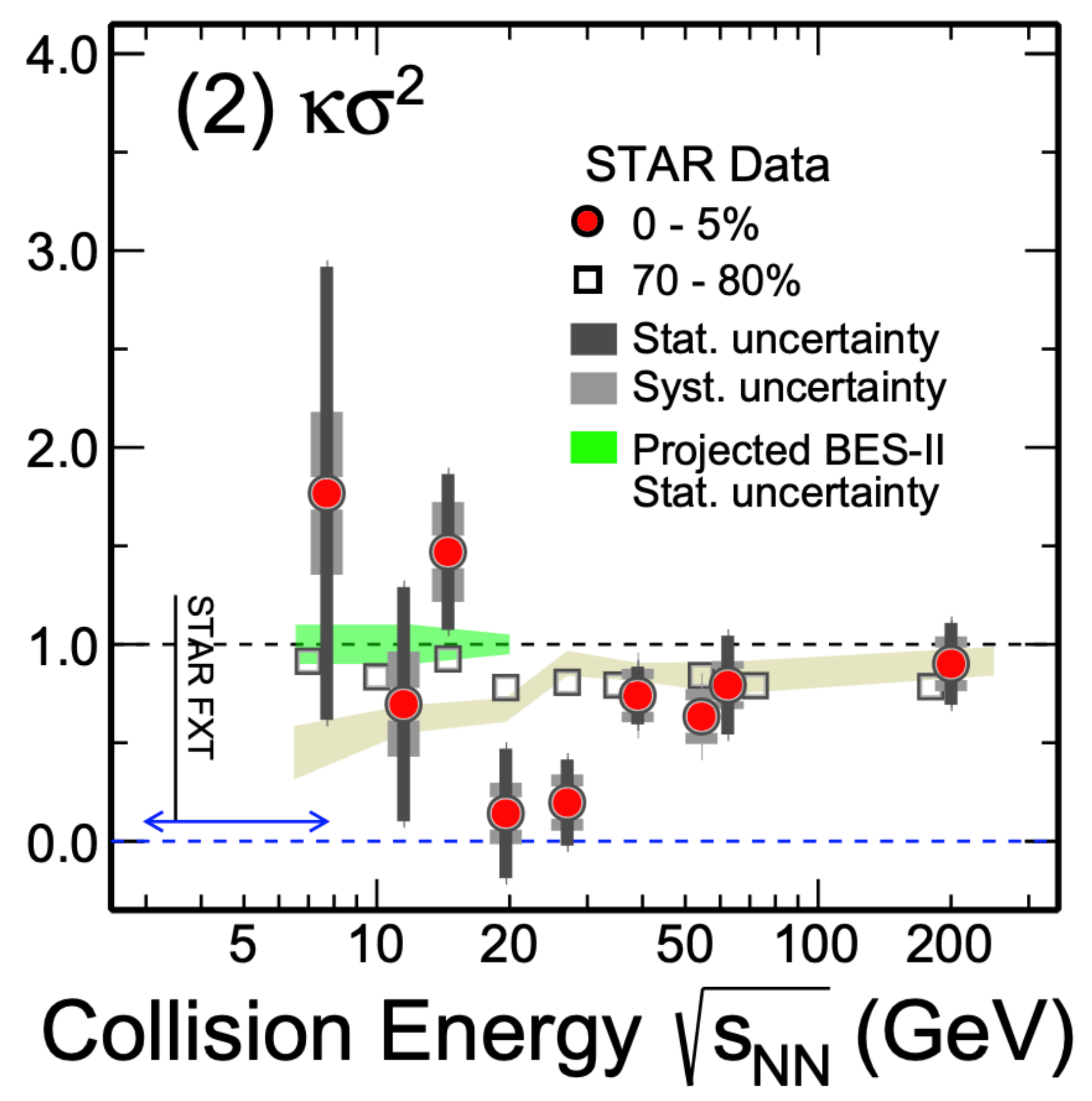
- Light nuclei v_1 slopes follow baryon number scaling in 5-40% 3 GeV Au+Au collisions
- First observation of hypernuclei collectivity in HI collisions
- Hypernuclei v_1 similar to light nuclei with similar mass

Consistent with hypernuclei production from coalescence of hyperons and nucleons

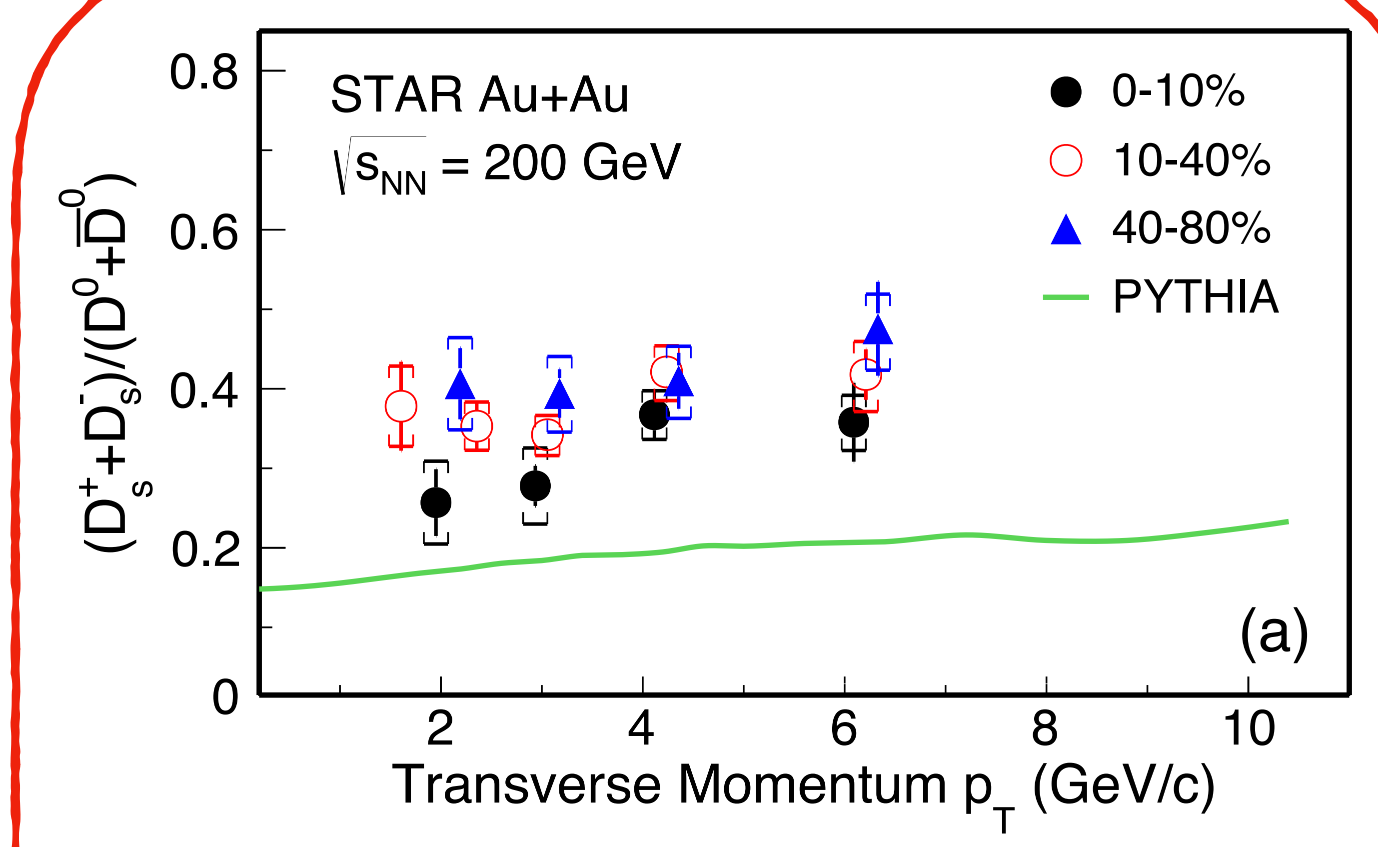
- Different trends in rapidity distribution in central (0-10%) and mid-central (10-50%) collisions for $^4_\Lambda$H
- Likely driven by collision geometry, e.g. spectators in non-central collisions

Summary

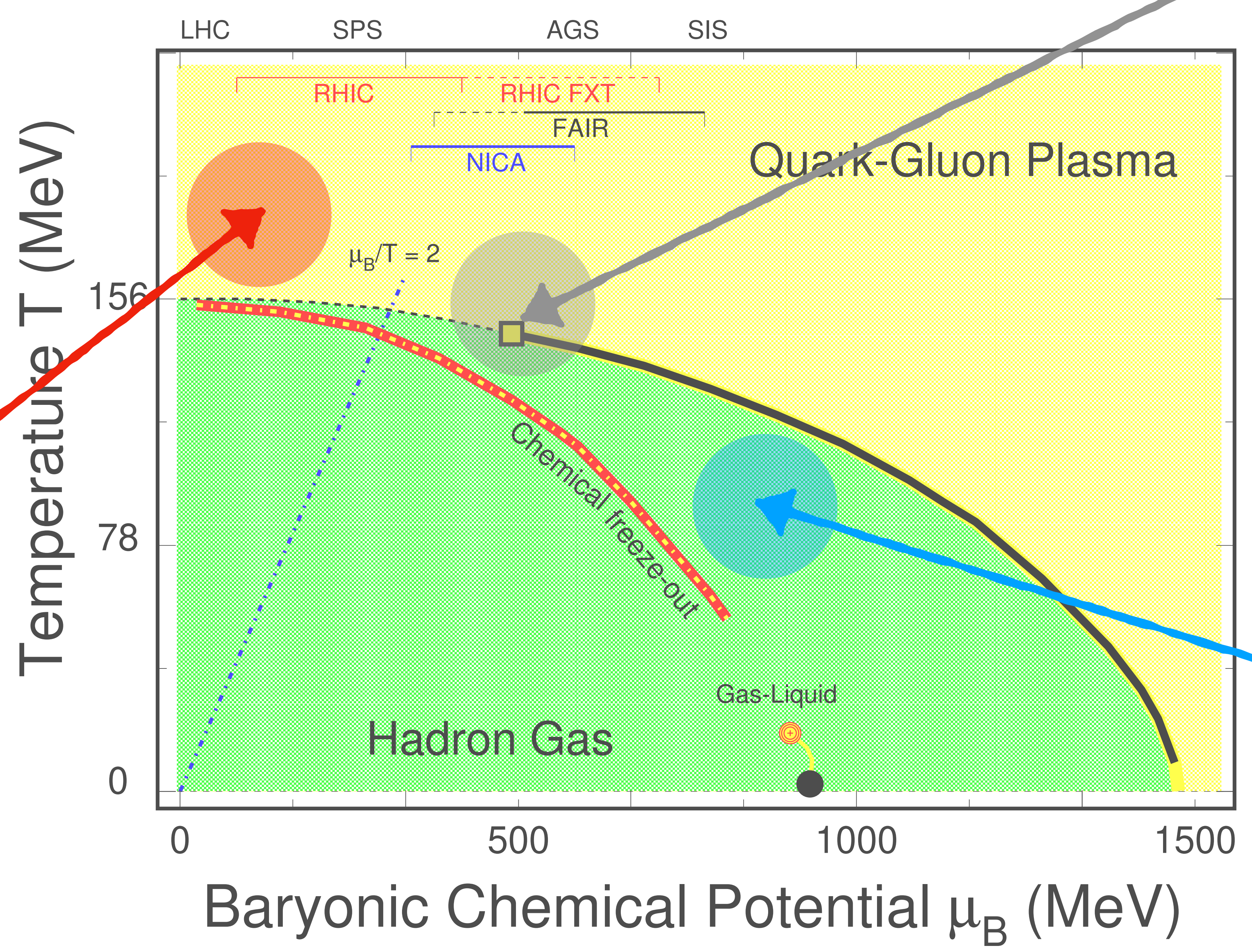
- **Variety of probes** employed at **different collision energies** at RHIC to map the QCD phase diagram
  - **Partonic interactions** dominant at **top RHIC energies**, open heavy flavor and strange hadron formation via **quark coalescence**
    - Interplay of dissociation, recombination and cold nuclear matter effects for J/ψ production in QGP
    - Main sources contributing to low p_T direct photons in large systems are similar from 39 GeV to 2.76 TeV
  - Hints of smooth cross-over at $\sqrt{s_{NN}}$ = 200 GeV and critical fluctuations $\sqrt{s_{NN}} \sim$ 20 GeV
  - **Hadronic interactions** dominant at $\sqrt{s_{NN}}$ = 3 GeV, light and hyper-nuclei formation via **coalescence of baryons**

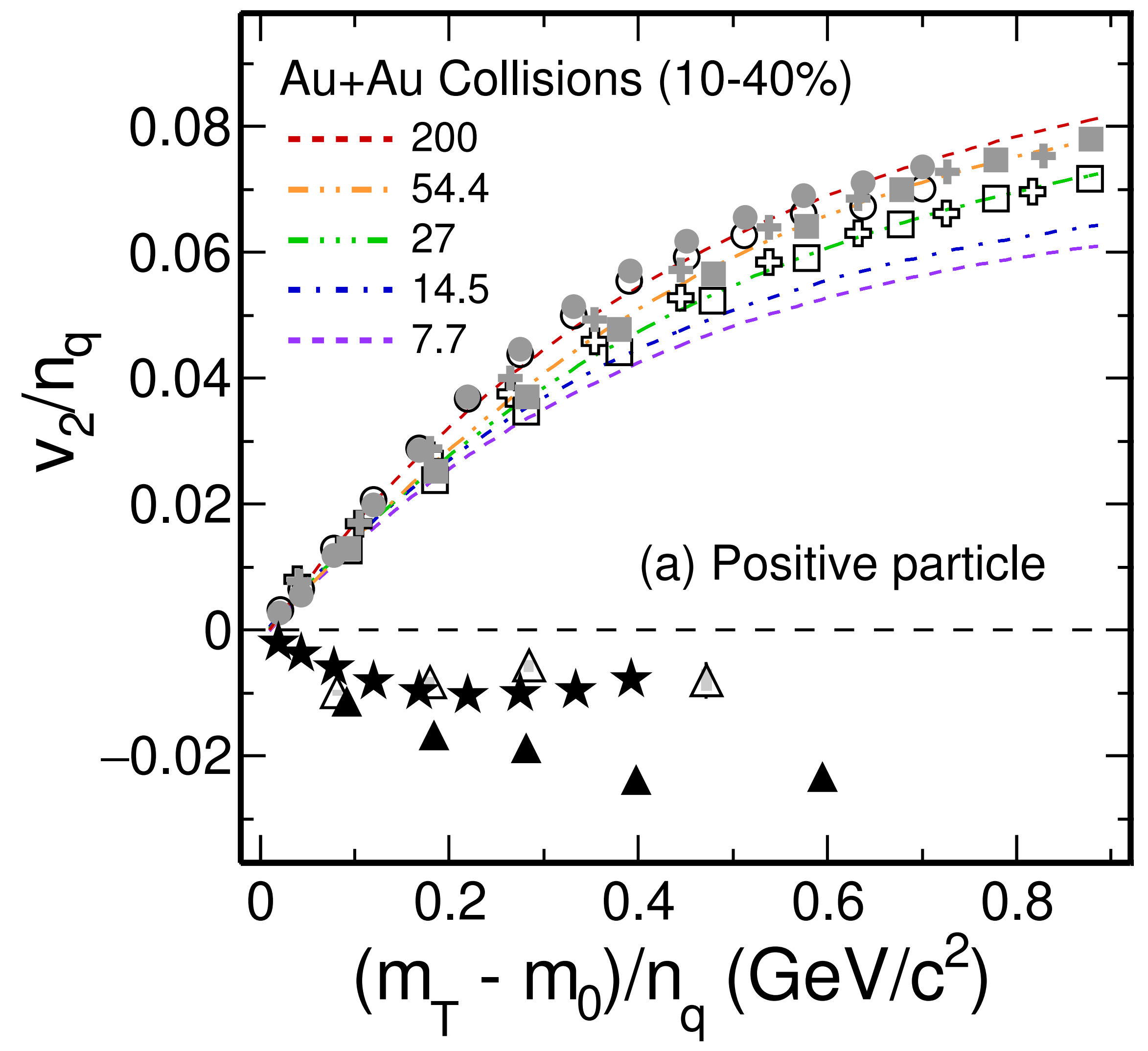


- Hint of **critical fluctuations**



- Data suggests **coalescence** of charm quarks with strange quarks in QGP dominate D_s production





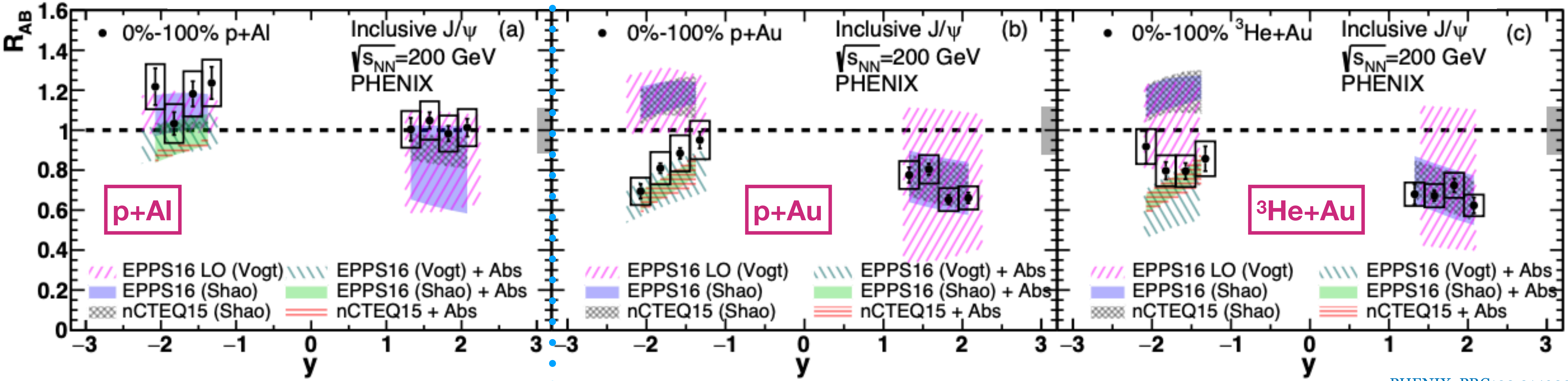
- **Disappearance of partonic collectivity** at $\sqrt{s_{NN}}$ =3 GeV

Thank you for listening!

Look forward to BES-II data and high statistics Au+Au 200 GeV data from sPHENIX and STAR!

Backup slides follow

Quarkonia production in small systems



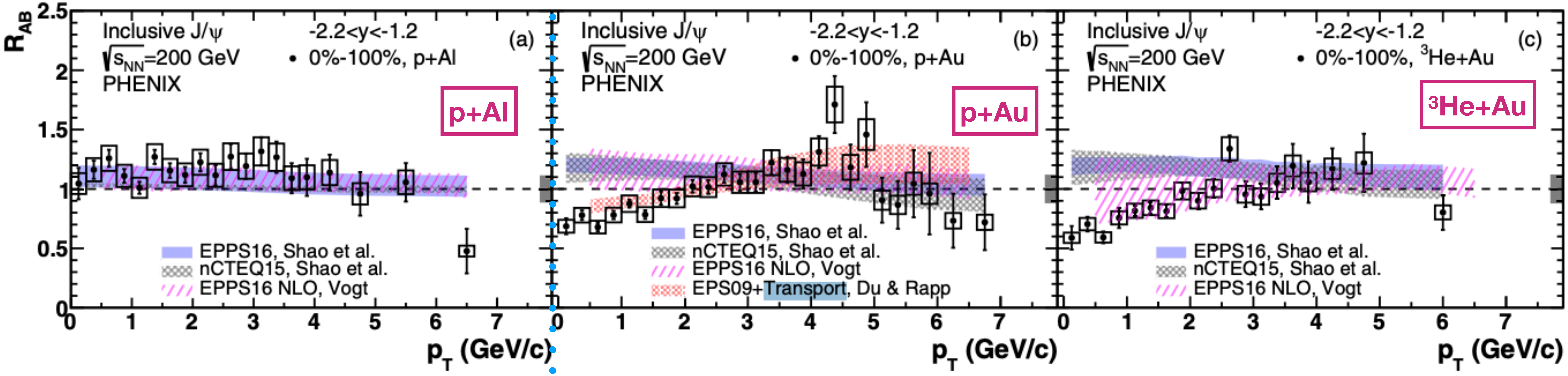
PHENIX, PRC102,014902(2020)

- p+Al: consistent with no modification

- p- or ^{3}He-going: consistent with nPDF
- Au-going: consistent with nPDF + **nuclear absorption**
  - nuclear crossing time comparable formation time at backward rapidity

Effects beyond nPDF modification alone are required to describe quarkonia production in p(^{3}He)+Au

Quarkonia production in small systems



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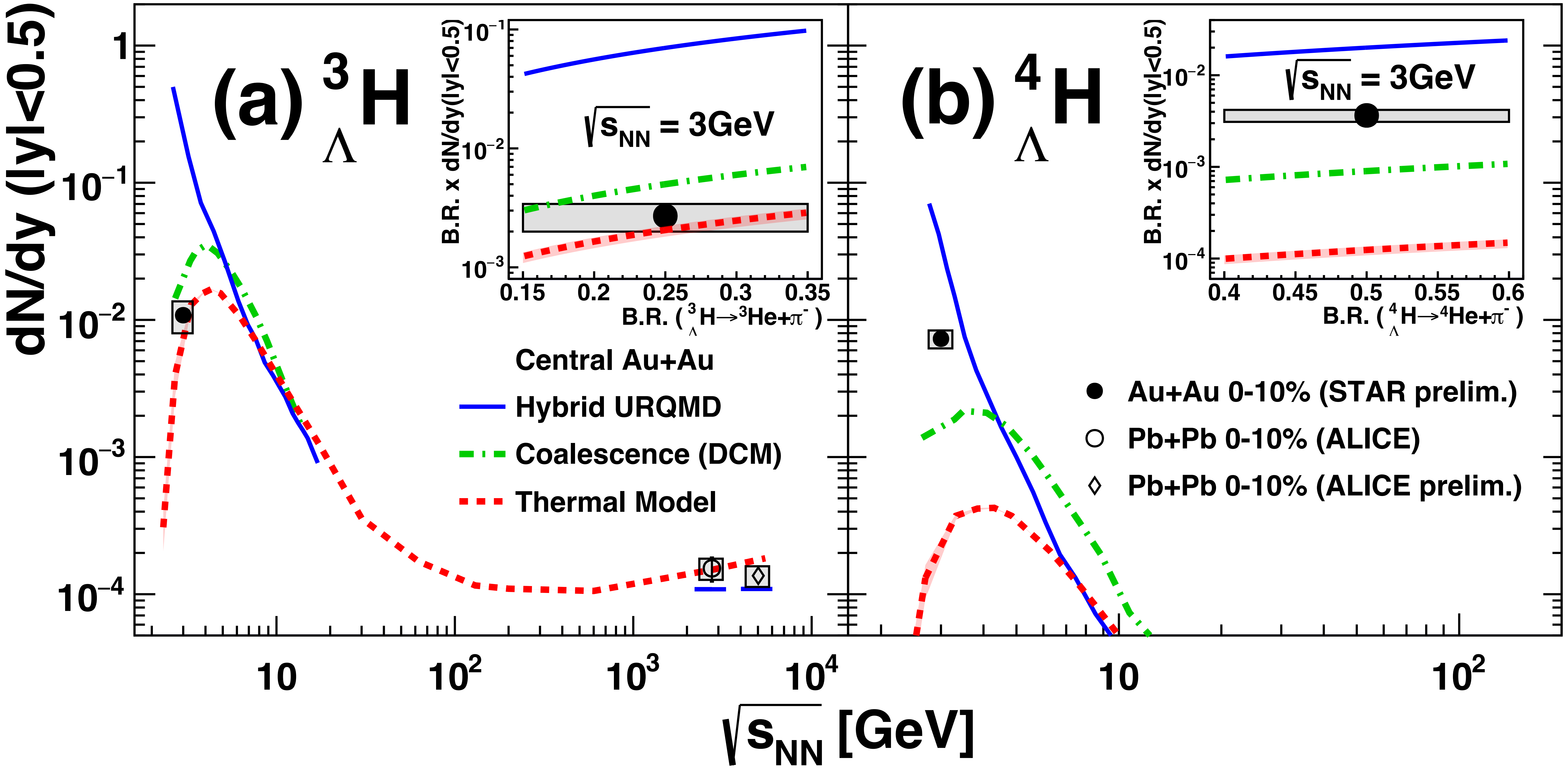
- p+Al: consistent with no modification

- Discrepancy between nPDF calculation and data is at low p_T
- Transport calculation with nPDF + p_T broadening + nuclear absorption describes p+Au data

Effects beyond nPDF modification alone are required to describe quarkonia production in p(^{3}He)+Au

Energy dependence of Hypernuclei Mid-Rapidity Yield



- Thermal model which adopts the canonical ensemble and coalescence (DCM) model describes $^{3}_{\Lambda}H$ yield at 3 GeV

- Yield of $^{4}_{\Lambda}H$ not described by models