BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

OPEN THEORY QUESTIONS FOR THE NEXT SQMS

THE 19TH INTERNATIONAL CONFERENCE ON STRANGENESS IN QUARK MATTER - 05/22/2021

THEORY SUMMARY OF THIS (AND FUTURE) SQMS:

FOCUS ON PARALLEL TALKS AND WHAT WE DO NOT UNDERSTAND

OPEN QUESTIONS IN THIS COLOR

PHASE DIAGRAM AND EQUATION OF STATE

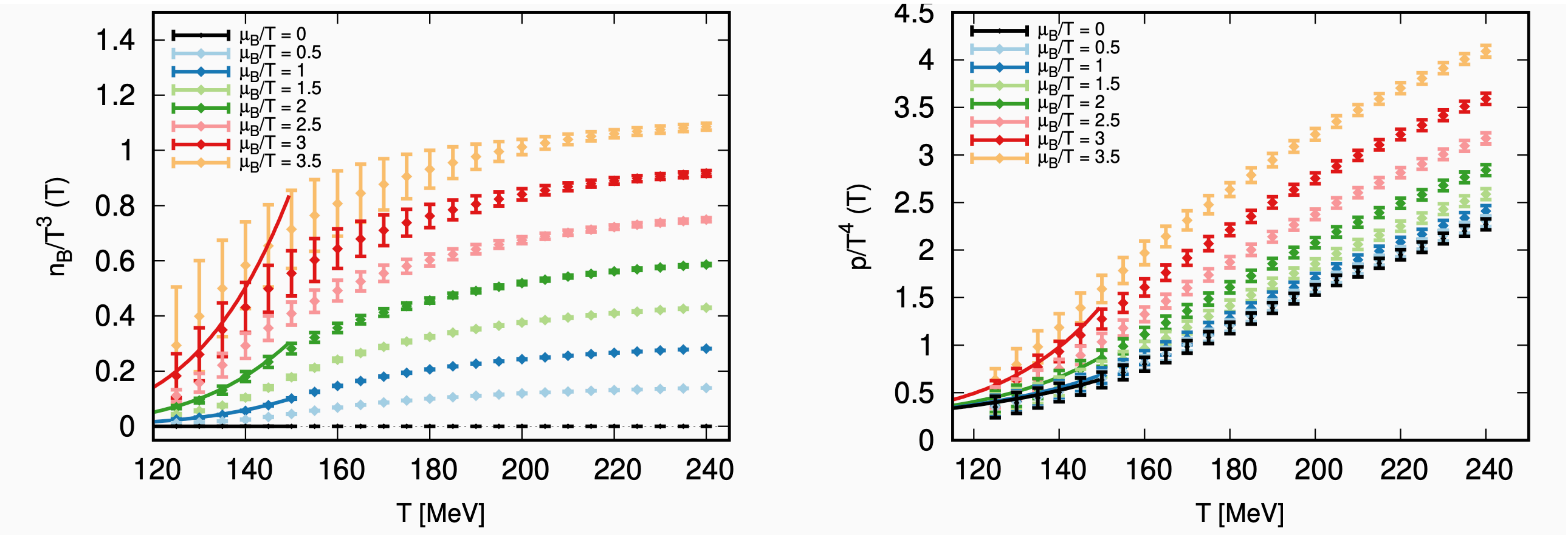
EQUATION OF STATE AT FINITE μ_B

- Lattice QCD: **How do we get to larger μ_B efficiently? How can we work around the sign problem?**
  - Taylor expansion has problems for $\mu_B > 2T$ (slow convergence, higher order coefficients have bad signal to noise ratio)
  - New expansion scheme: Reorganize the expansion via an expansion in the shift

$$\frac{\chi_1^B(T,\hat{\mu}_B)}{\hat{\mu}_B} = \chi_2^B(T',0)\ , \quad T' = T\left(1+\kappa_2(T)\,\hat{\mu}_B^2+\kappa_4(T)\,\hat{\mu}_B^4+\mathcal{O}(\hat{\mu}_B^6)\right)$$

PAROTTO, THU 9:30 EDT

  - Determine coefficients using simulations at imaginary μ_B, then reconstruct thermodynamic quantities up to $\mu_B/T \approx 3.5$

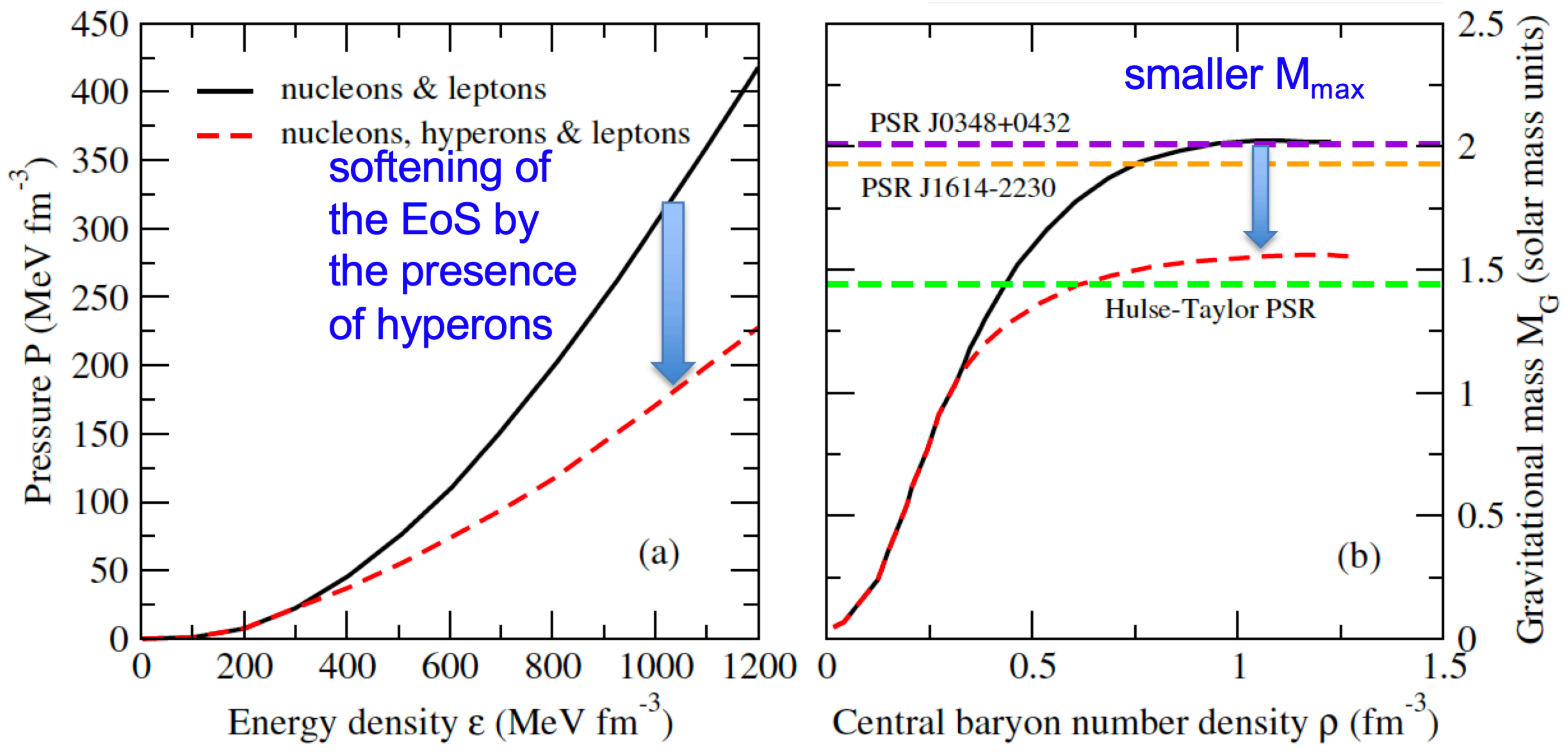


- **Can Taylor expansion around $\mu_B = 0$ produce reliable results beyond $\mu_B/T > \pi$?**

EQUATION OF STATE AT FINITE μ_B

- Can go to larger μ_B in a model (constrained by LQCD) **MOTORNENKO, THU 10:30 EDT**
- Chiral mean field model with species dependent excluded volumes
  - Smaller excluded volumes for strange hadrons than for non-strange
  - Leads to hyperons melting into quarks at higher densities than non-strange hadrons. Effects on neutron star properties are small

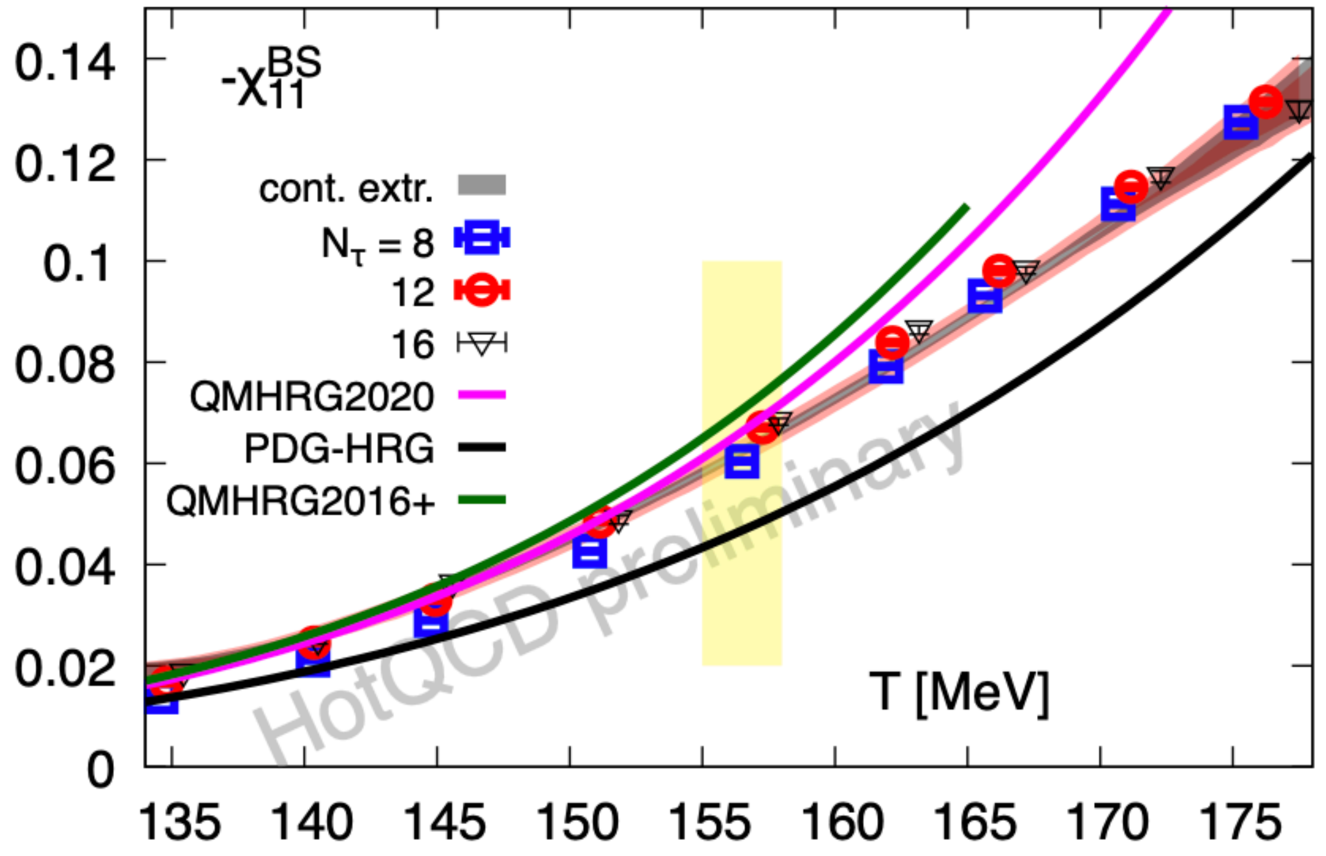
- Neutron star properties are affected by presence of hyperons ($\mu_s = 0$) **TOLOS, THU 10:10 EDT**



- Can we solve this hyperon puzzle?
  - Options: stiffer YN and YY interactions, hyperonic 3-body forces, push of Y onset by Δ-isobars or meson condensates, quark matter below Y onset, dark matter, modified gravity theories…

ALSO FUKUSHIMA, THU 11:40 EDT, DEXHEIMER, THU 12:40 EDT

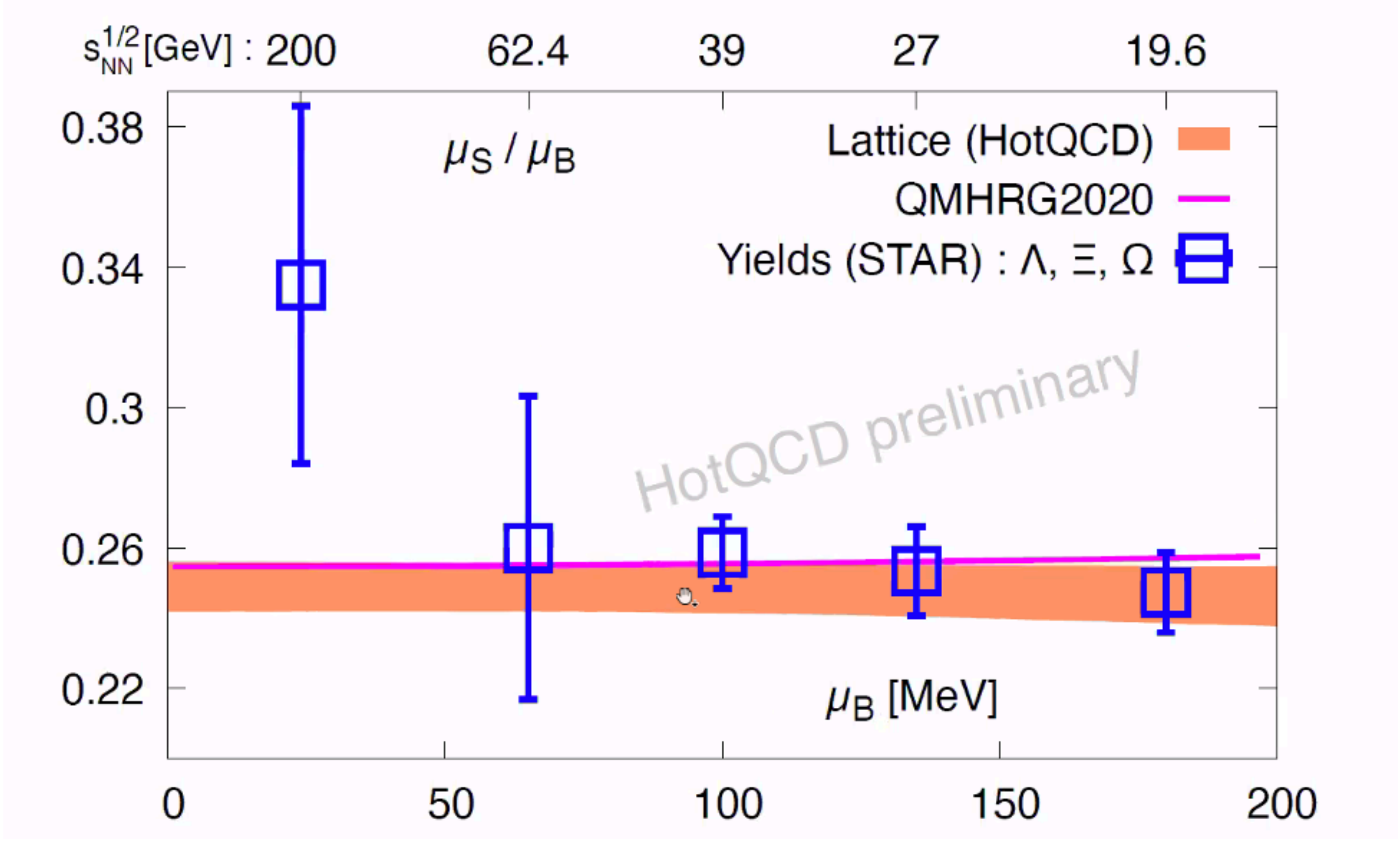
EQUATION OF STATE - FLUCTUATIONS



GOSWAMI, TUE 11:50 EDT

- New continuum extrapolation for second order cumulants of (2+1)-flavor QCD
- Detailed Comparison of Lattice QCD calculations with HRG models at vanishing chemical potentials
- Particle content in the HRG matters
- Excluded volume can improve agreement with LQCD (single parameter not enough to describe all 2nd order cumulants)

- Can extract freeze-out parameters from continuum extrapolated fluctuation measures. Here strangeness fluctuations: **BOLLWEG, THU 9:50 EDT**
- Can differences of some fluctuation measures in the strangeness sector between LQCD and HRG (even at $T \lesssim 130$ MeV) be understood?

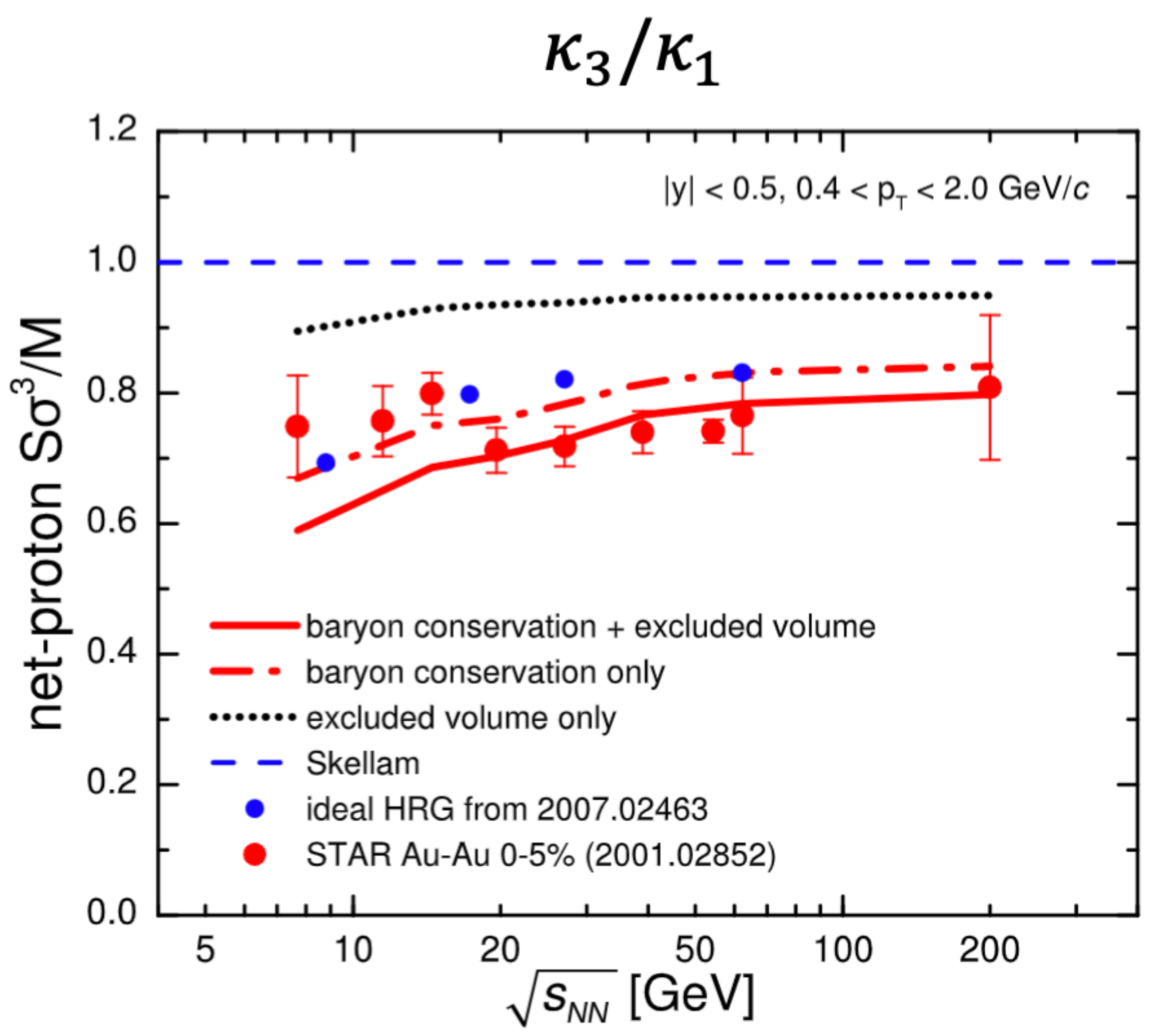


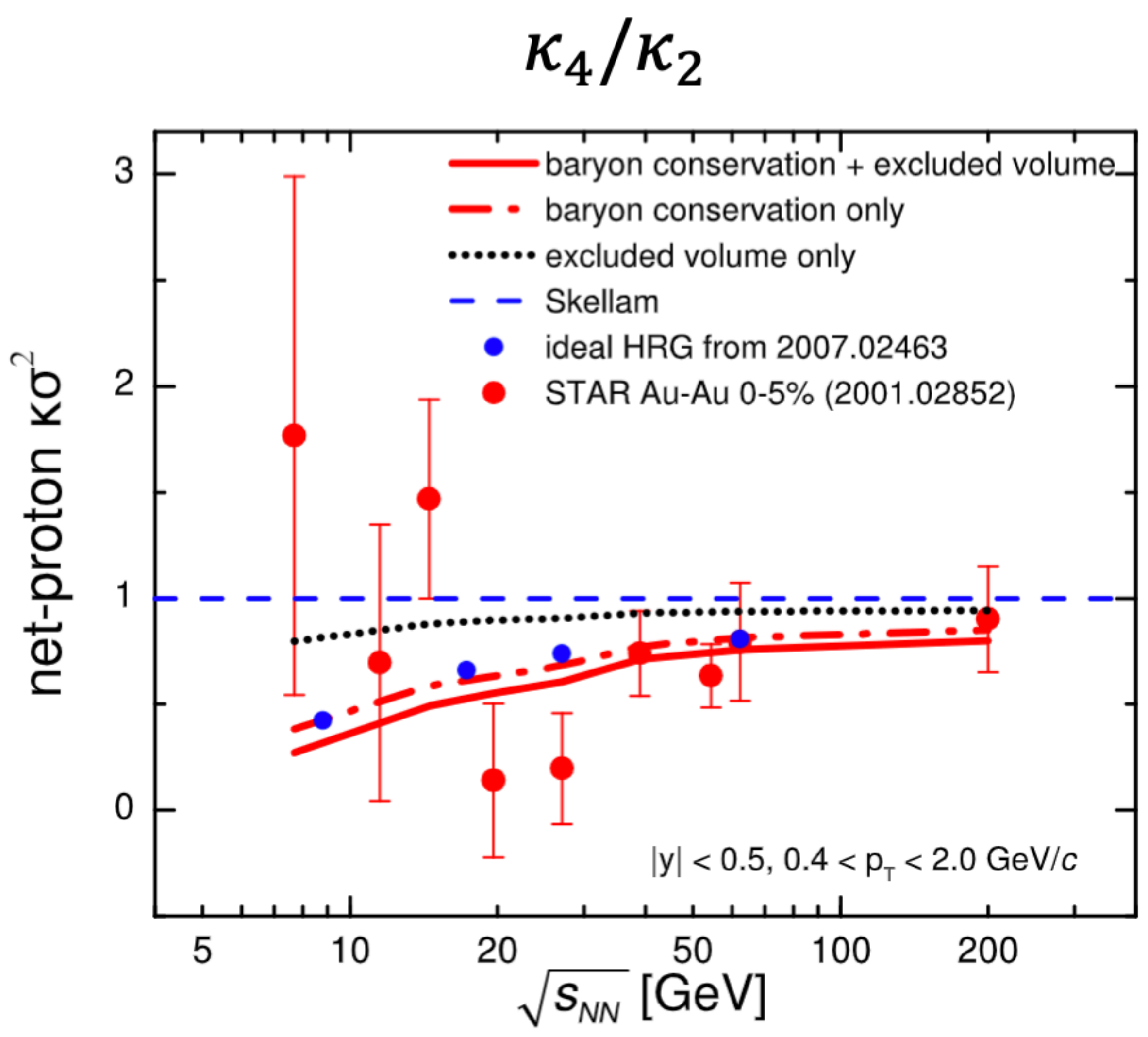
μ_S/μ_B along $T_{pc}(\mu_B)$ vs. μ_S/μ_B extracted from STAR

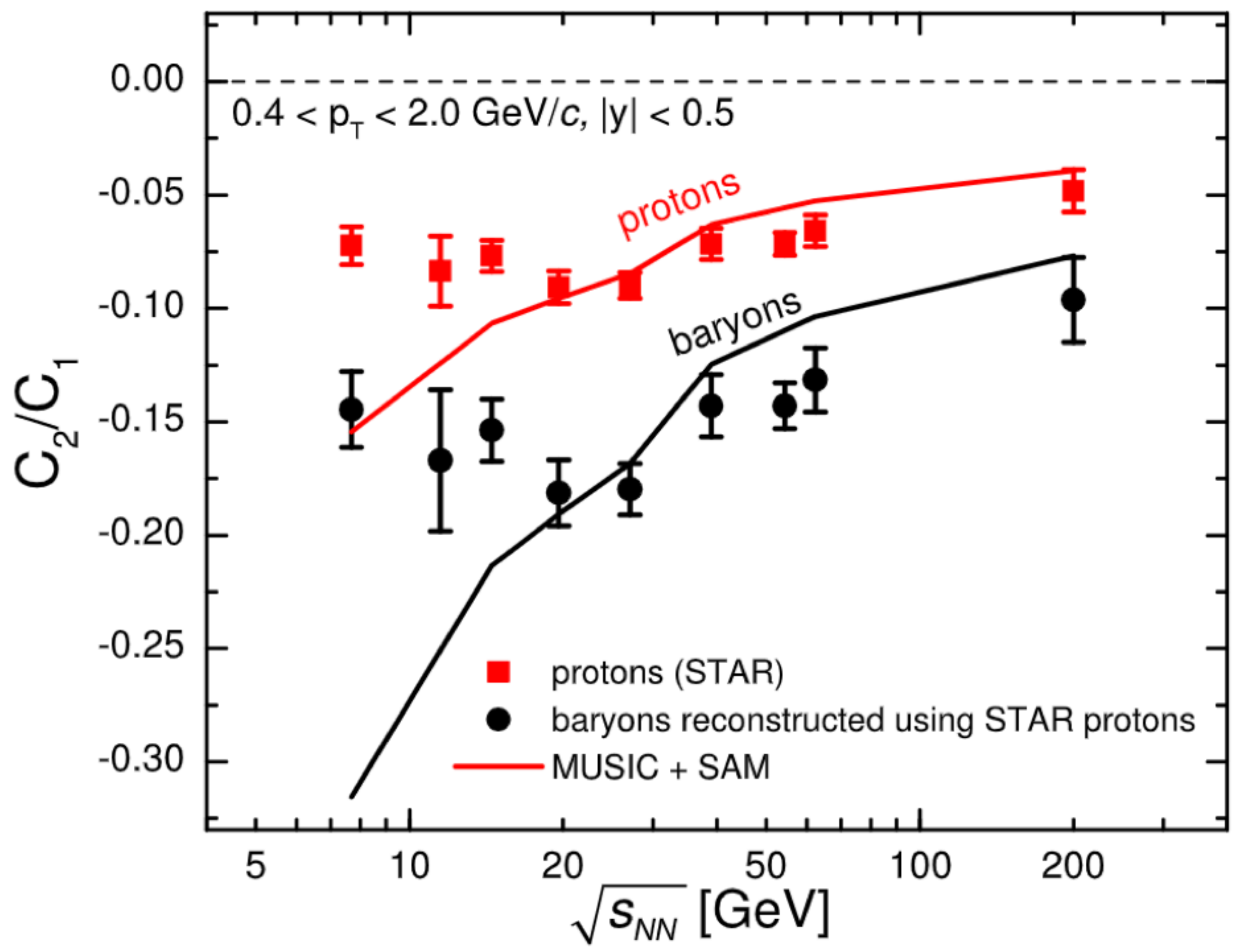
FLUCTUATIONS - MOVING CLOSER TO EXPERIMENT

VOVCHENKO, TUE 11:10 EDT

- Hydrodynamics + an excluded volume hadron resonance gas model matched to lattice QCD susceptibilities. Calculate proton cumulants in experimental acceptance in the grand-canonical limit and apply correction for exact baryon number conservation
- Differences between net baryons (computed on lattice) vs. net protons (measured)





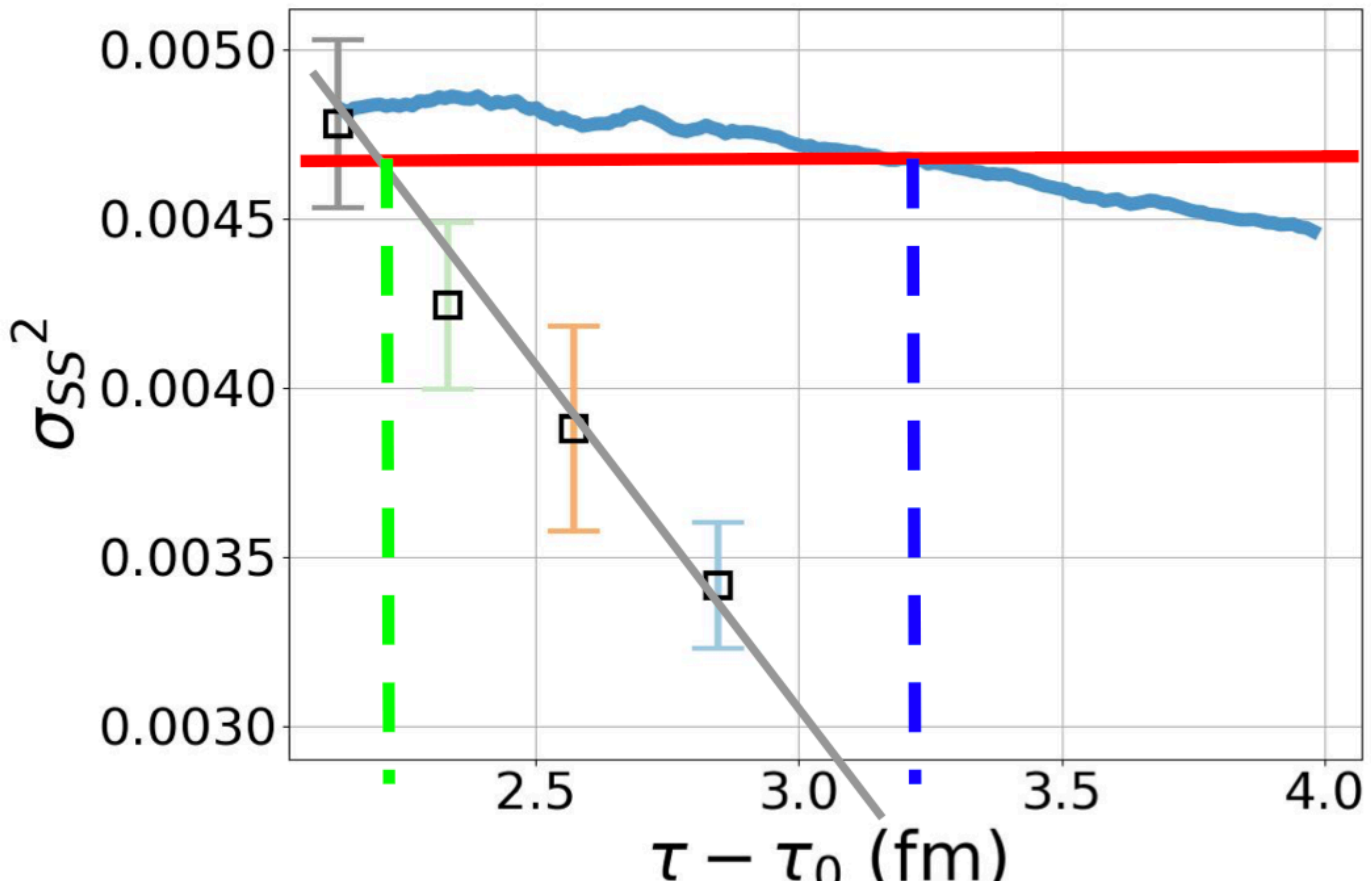


$$\frac{\hat{C}_2^B}{\hat{C}_1^B} \approx 2\,\frac{\hat{C}_2^p}{\hat{C}_1^p}$$

- Do the non-monotonicities in the fluctuation measures indicate any critical behavior?
- Can this study be done with an EOS that has a critical point put in by hand, like BEST-EOS?

FLUCTUATIONS - OFF EQUILIBRIUM

- Can freeze-out conditions be reliably determined from fluctuation observables?
- Compute coupled diffusion of BQS **PIHANI, TUE 12:10 EDT**
- Expansion/cooling drives fluctuations out of equilibrium
- Find: FO temperatures obtained from the comparison of equilibrium HRG vs. experiment are over-estimated compared to dynamically expanding systems



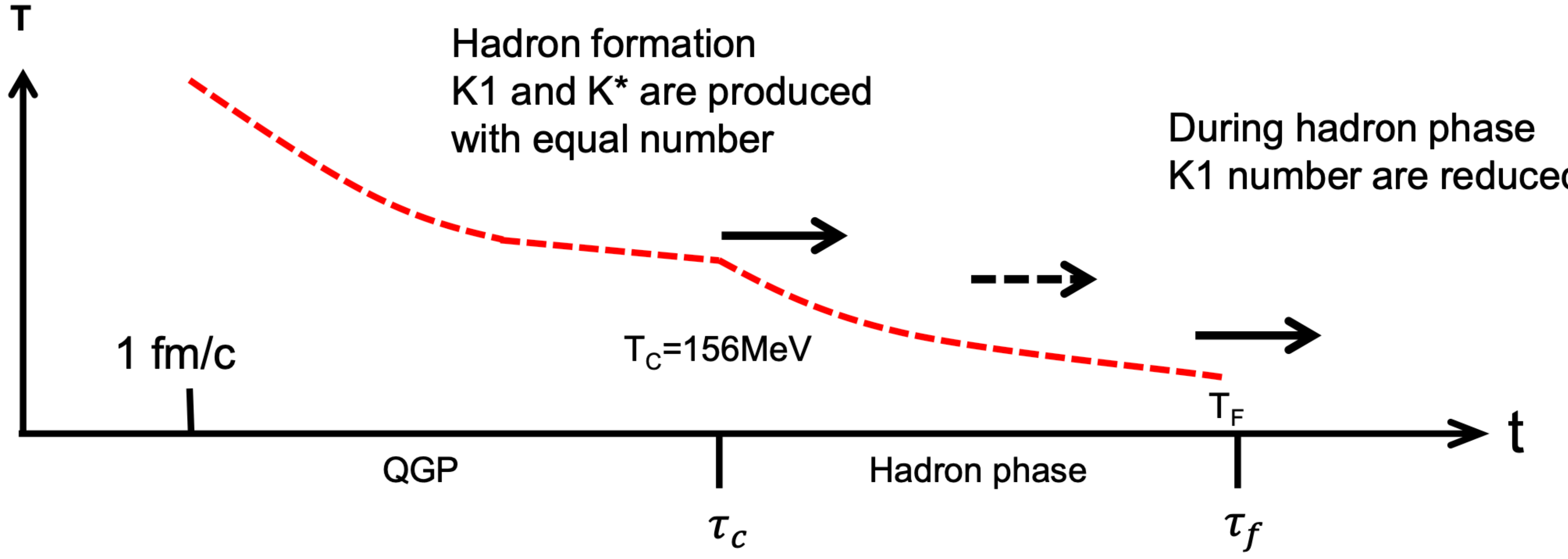
- Also: Initial off-equilibrium effects (initial stress tensor) affect the evolution through the phase diagram

DORE, TUE 12:30 EDT

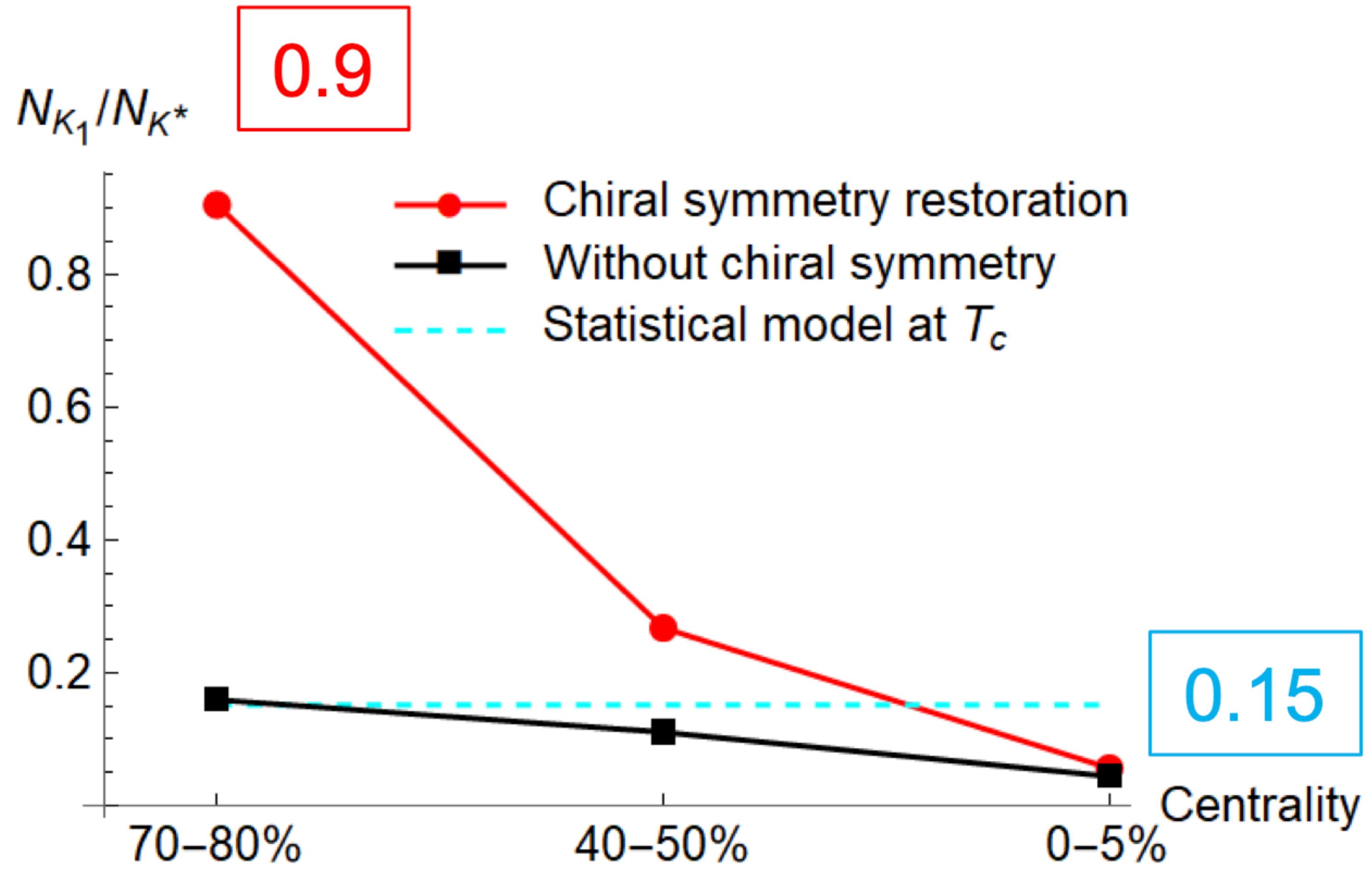
MORE ON THE PHASE TRANSITION

- **Can we learn about chiral symmetry restoration with strange particles?**
- K_1/K^* is enhanced if chiral symmetry is restored
  K_1 has $\sim$2 times the decay width, solve rate equation

SUNG, TUE 10:50



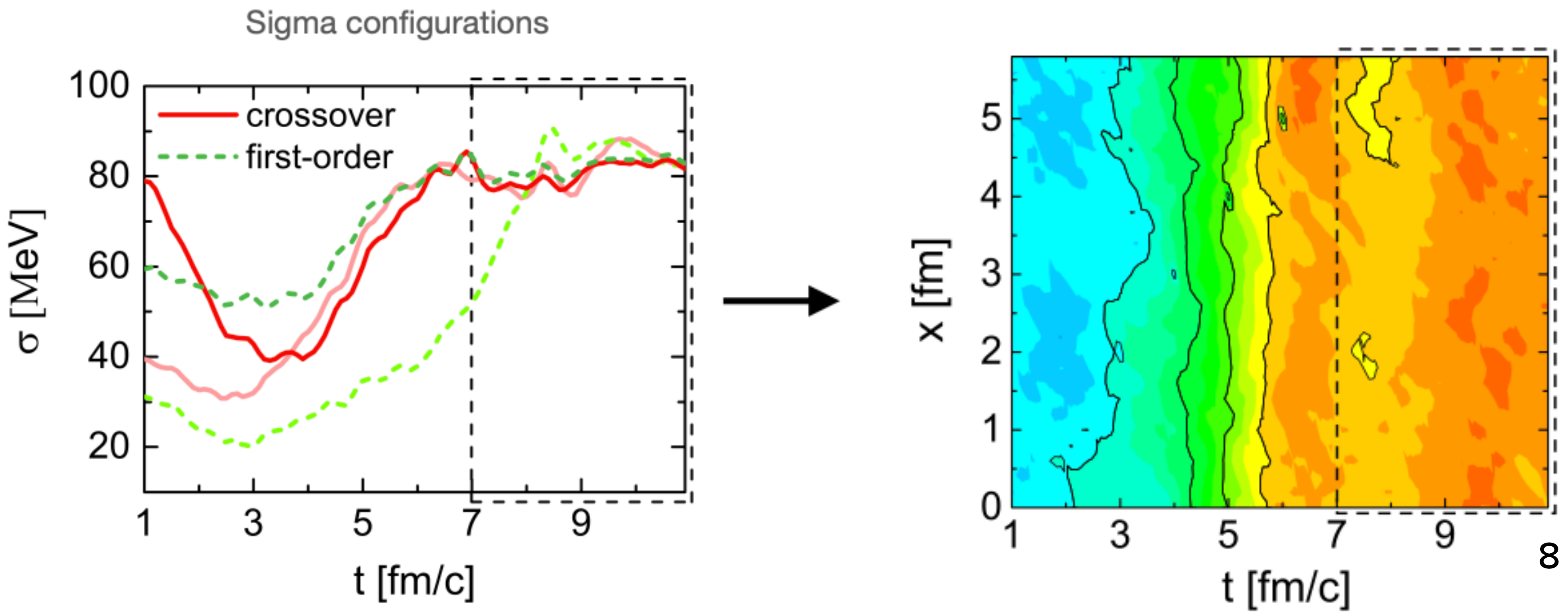
H. Sung et al, arXiv:2102.11665 [nucl-th] (2021)



- **Will deep learning help us?**
- Linear sigma model, fluctuations, Langevin process

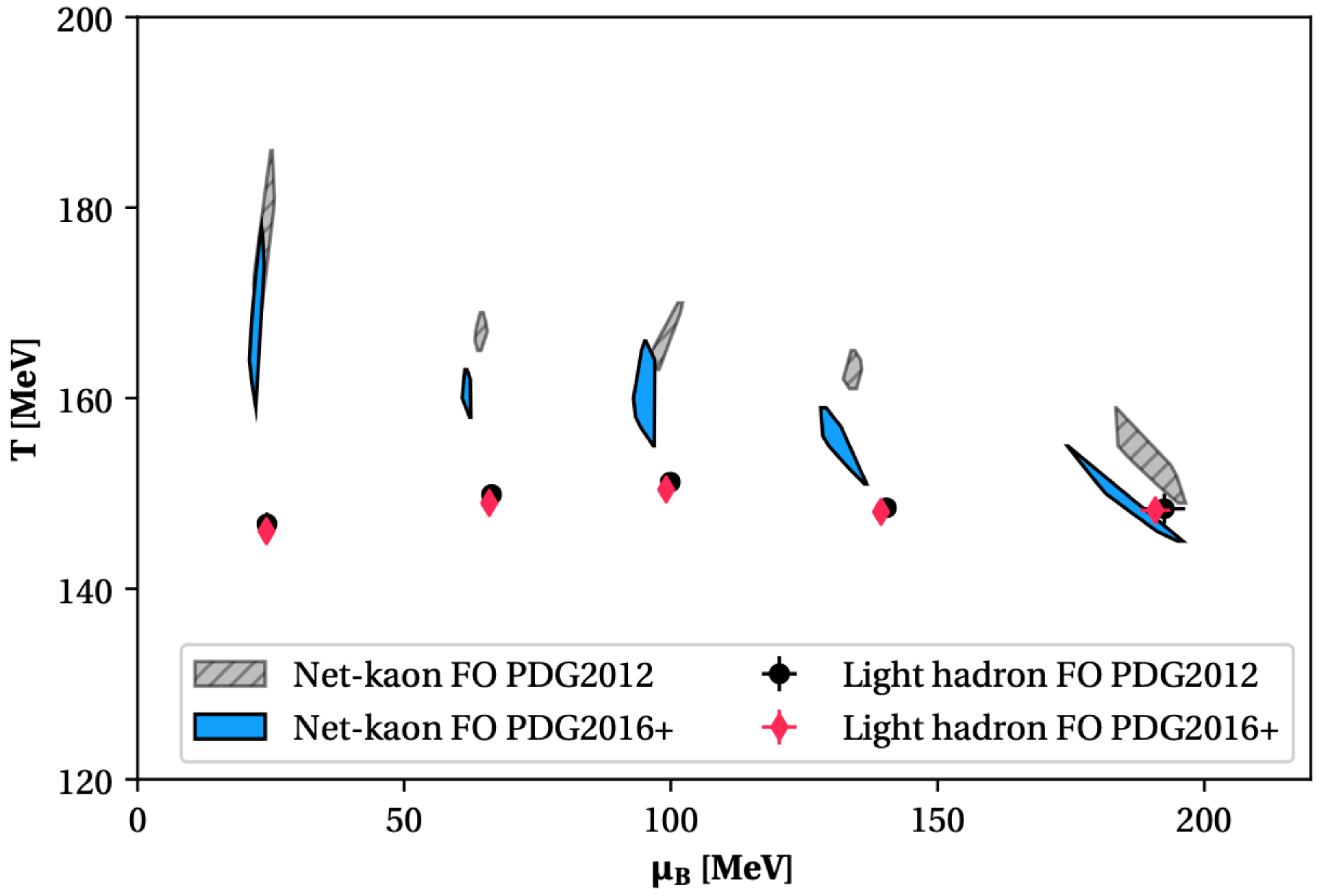
WANG, TUE 10:50

- Make 2D images
- Accuracy of recognition of phase transition order depends on strength of fluctuations



MORE ON FREEZE OUT

- Thermal model / hadron resonance gas model
- Separate light and strange freeze-out temperatures improves particle yield agreement with data



- Λ freezes out at kaon FO temperature

KARTHEIN, TUE 11:30 EDT

- Again, particle content in the HRG matters
- Next, go beyond ideal HRG (include repulsive interactions)

- Chemical freeze-out in UrQMD is driven directly by the scattering dynamics
- Determine chemical freeze out microscopically in UrQMD, determine chemical freeze out hyper surface via coarse graining
- Kaons freeze out at higher T (and slightly lower μ_B)
- T and μ_B from transport consistent with statistical model fits

REICHERT, WED 9:30 EDT

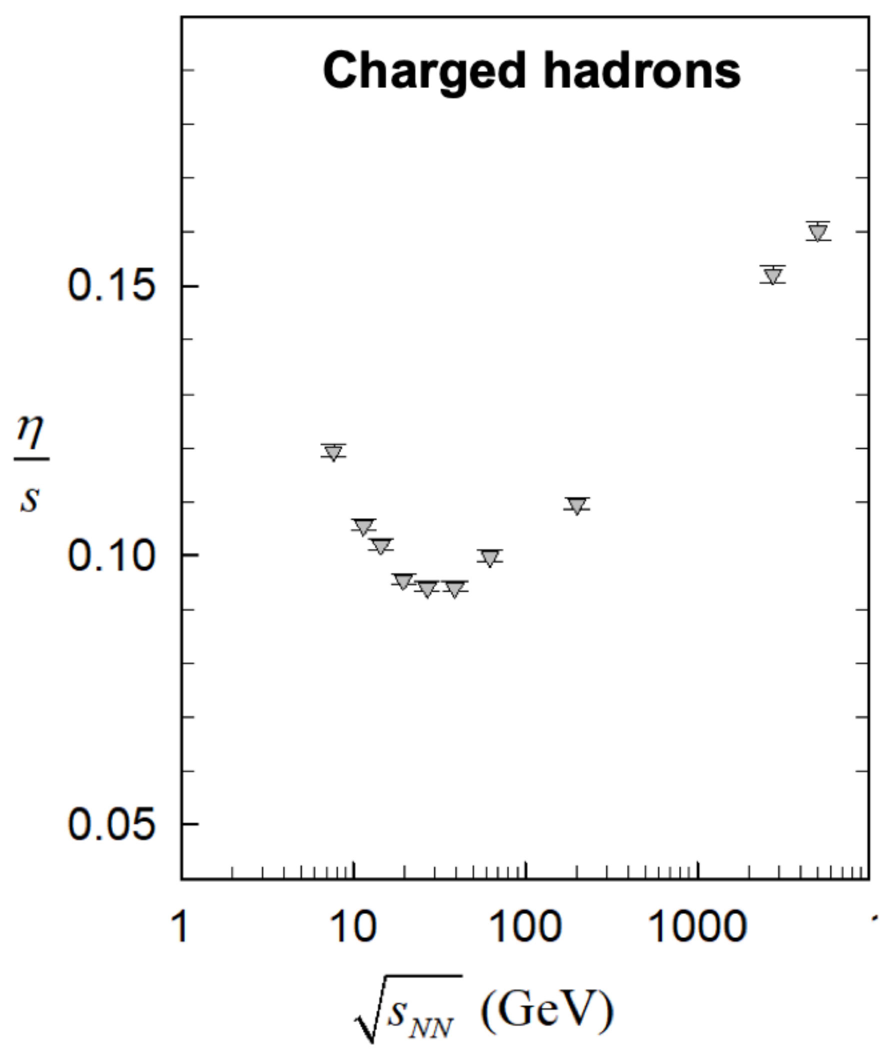
- Higher freeze-out temperature for strangeness also found in a Tsallis Blast Wave model

CHEN, TUE 11:50 EDT

TRANSPORT COEFFICIENTS

TRANSPORT COEFFICIENTS: $(\eta/s)(T,\mu_B)$

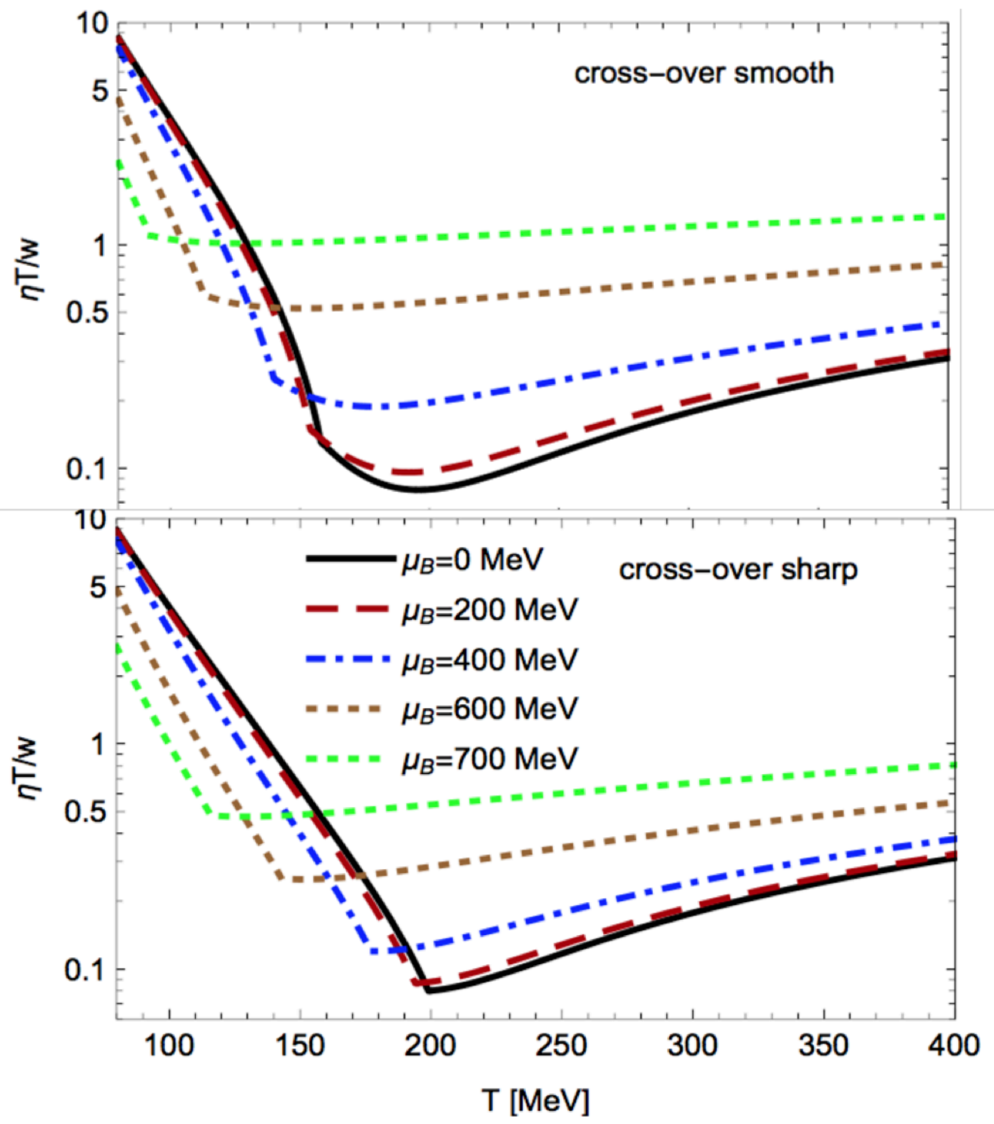
LACEY, TUE 11:10 EDT

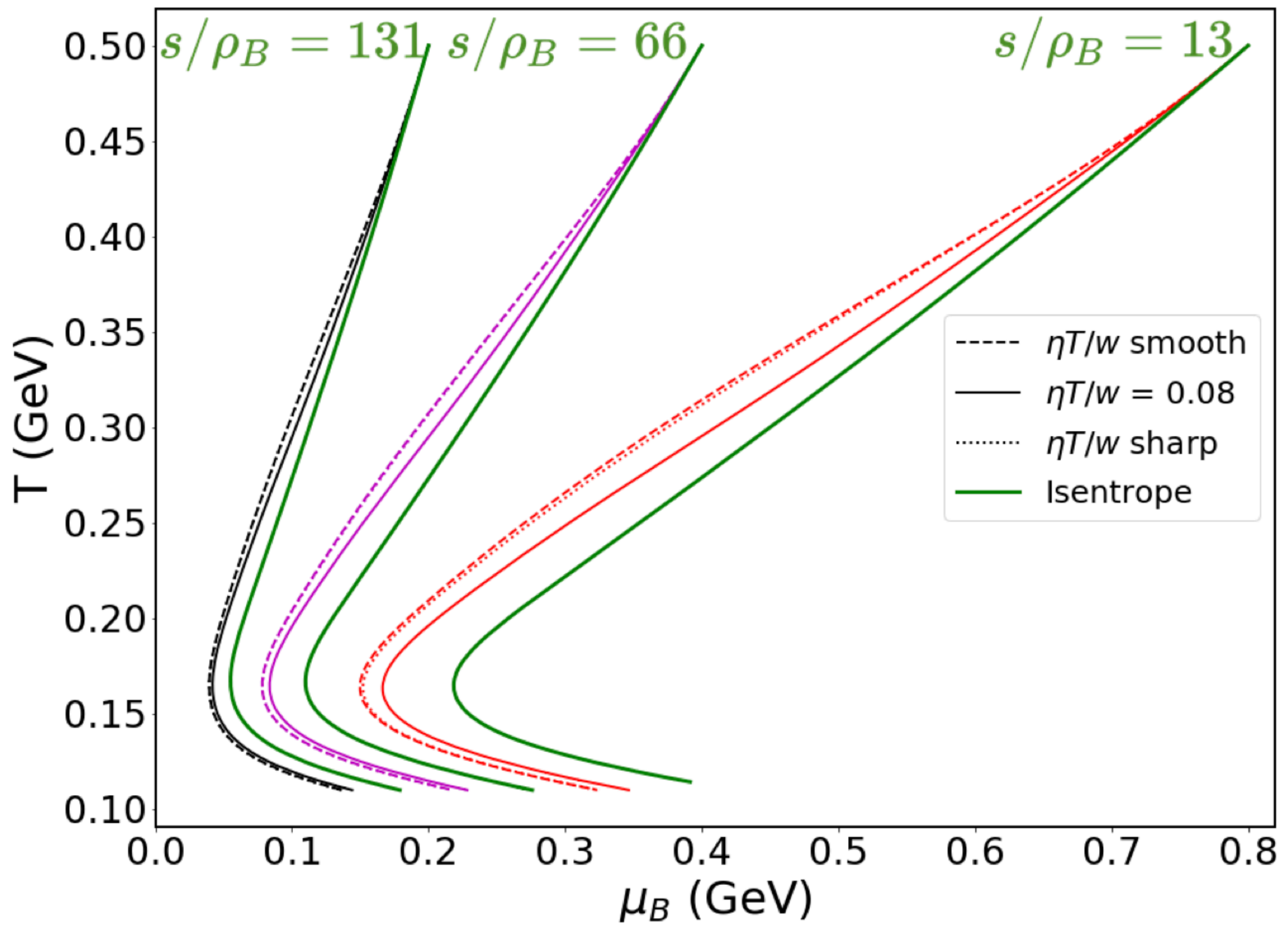


- **How do transport coefficients depend on chemical potentials and T?**
- **Analyze experimental data using anisotropic scaling function**

$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^2\right]\frac{1}{RT}}, \; RT \propto \langle N_{chg} \rangle^{1/3}$$

- **Excluded volume HRG model: Compute $\eta T/(\epsilon + p)$ (also parametrized QGP value) for cross-over and with critical point**

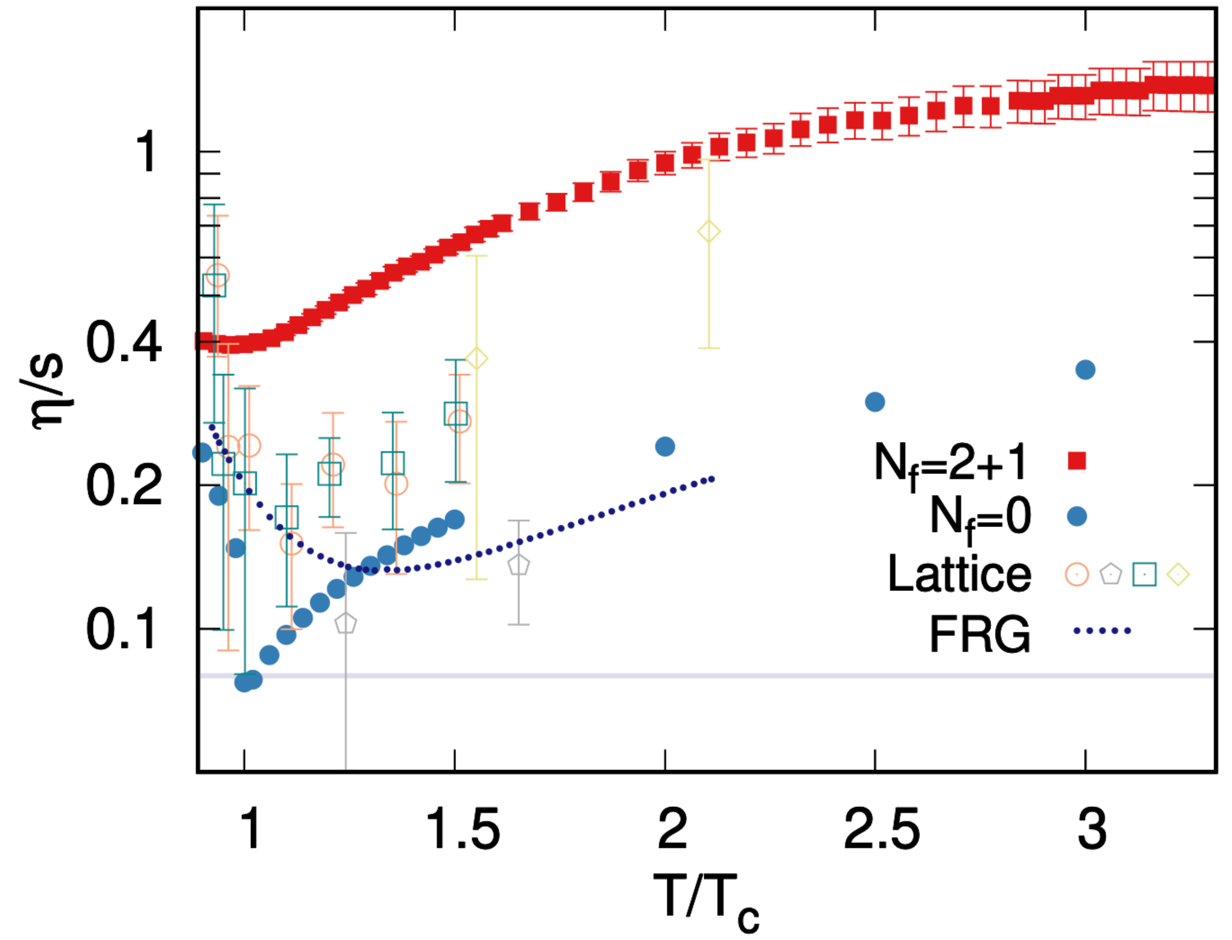




- **$\eta T/(\epsilon + p)$ affects trajectories**

MCLAUGHLIN , TUE 11:50 EDT

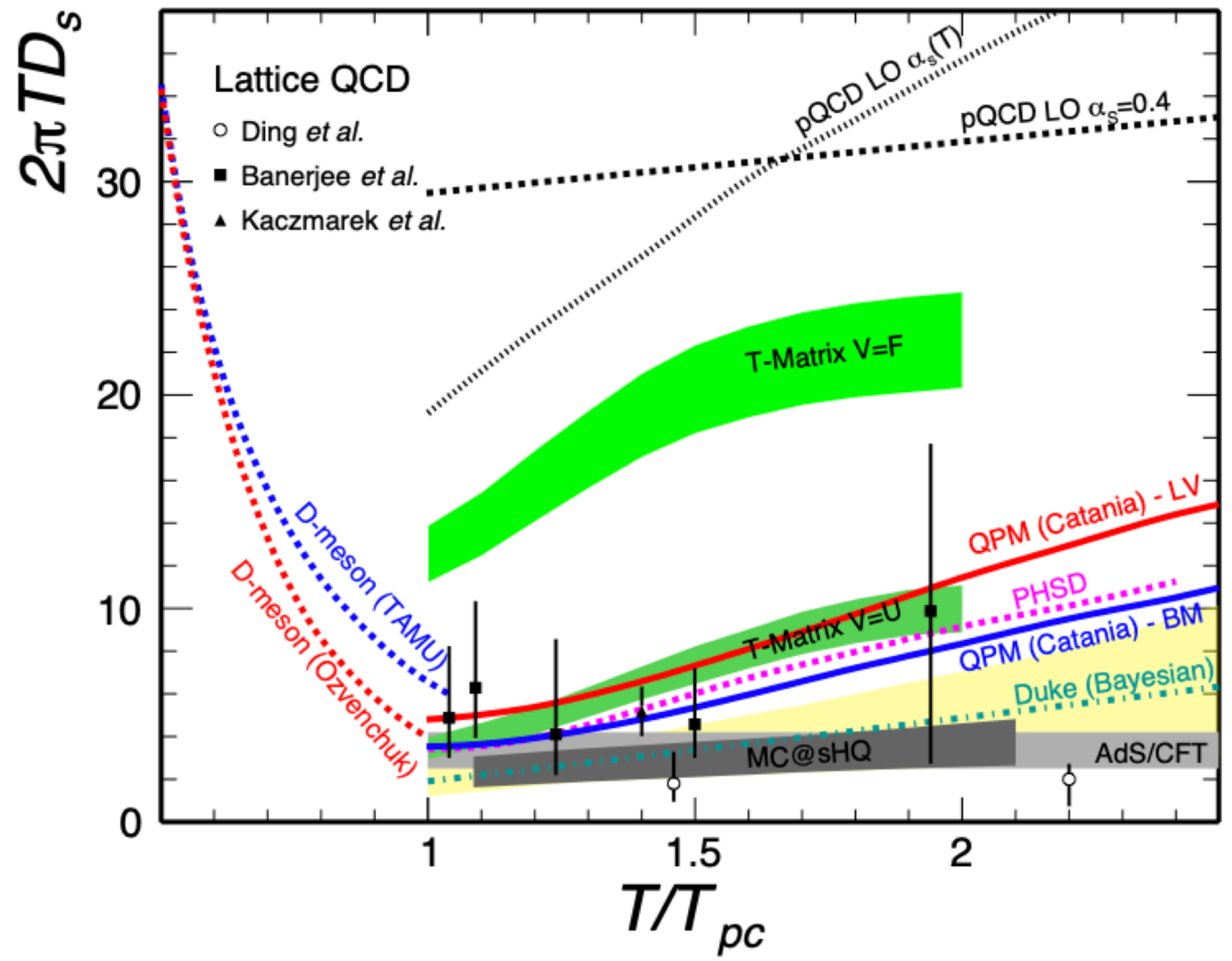
- **Also quasiparticle model can provide η/s and ζ/s**

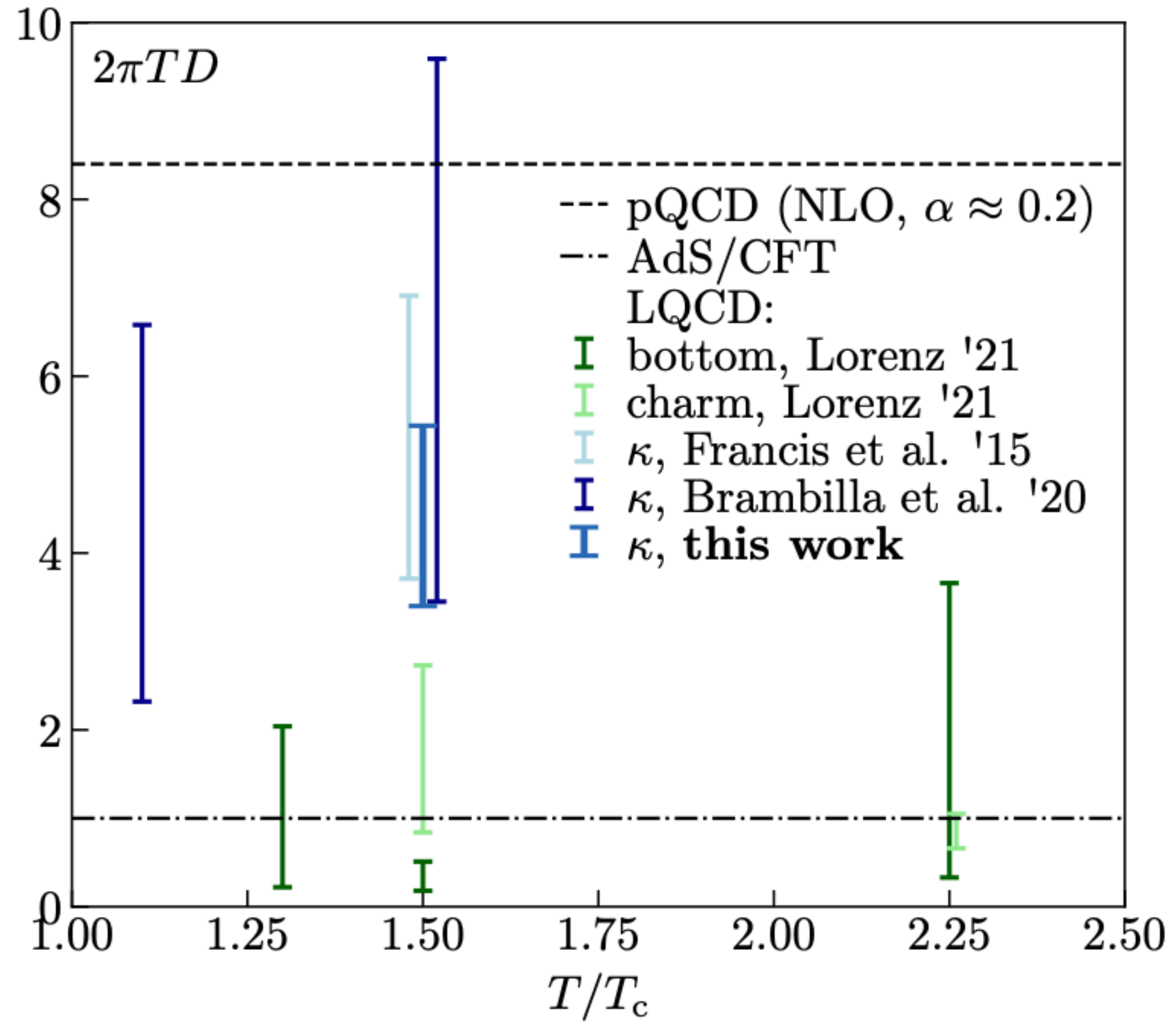


MYKHAYLOVA , WED 10:50 EDT

TRANSPORT COEFFICIENTS

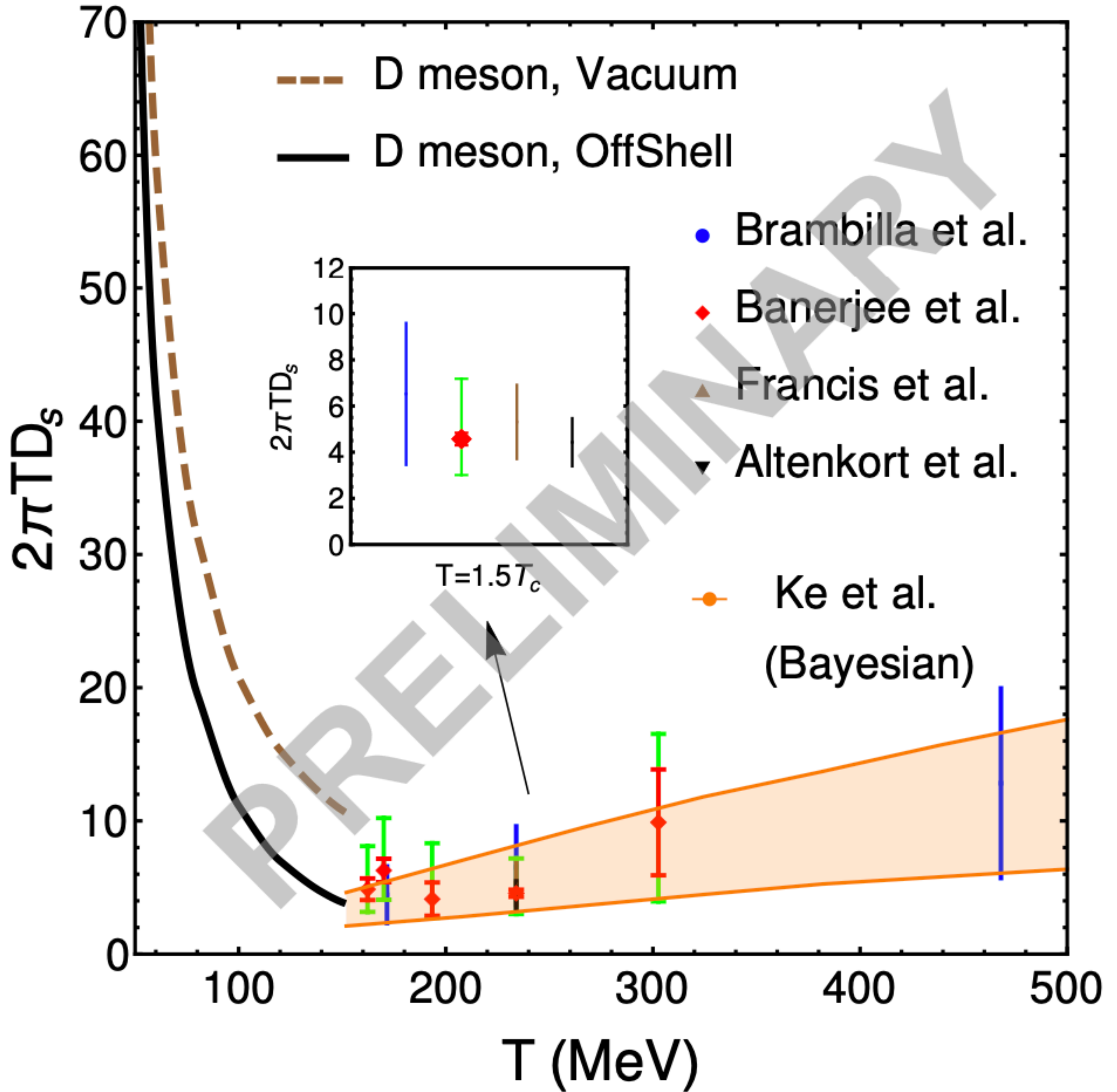
- Can we determine the full T dependence of diffusion of charm quarks in medium?
- Lattice QCD: Heavy quark diffusion coefficients
  - Spatial diffusion from hadronic correlators
    SHU, WED 10:30 EDT – at physical masses
  - Momentum diffusion from gluonic correlators
    ALTENKORT, THU 10:50 EDT – non-relativistic limit





- Effective theory starting from Lagrangian at NLO in the chiral expansion and LO in the heavy quark expansion; Compute scattering in coupled channels and introduce thermal (self energy) corrections

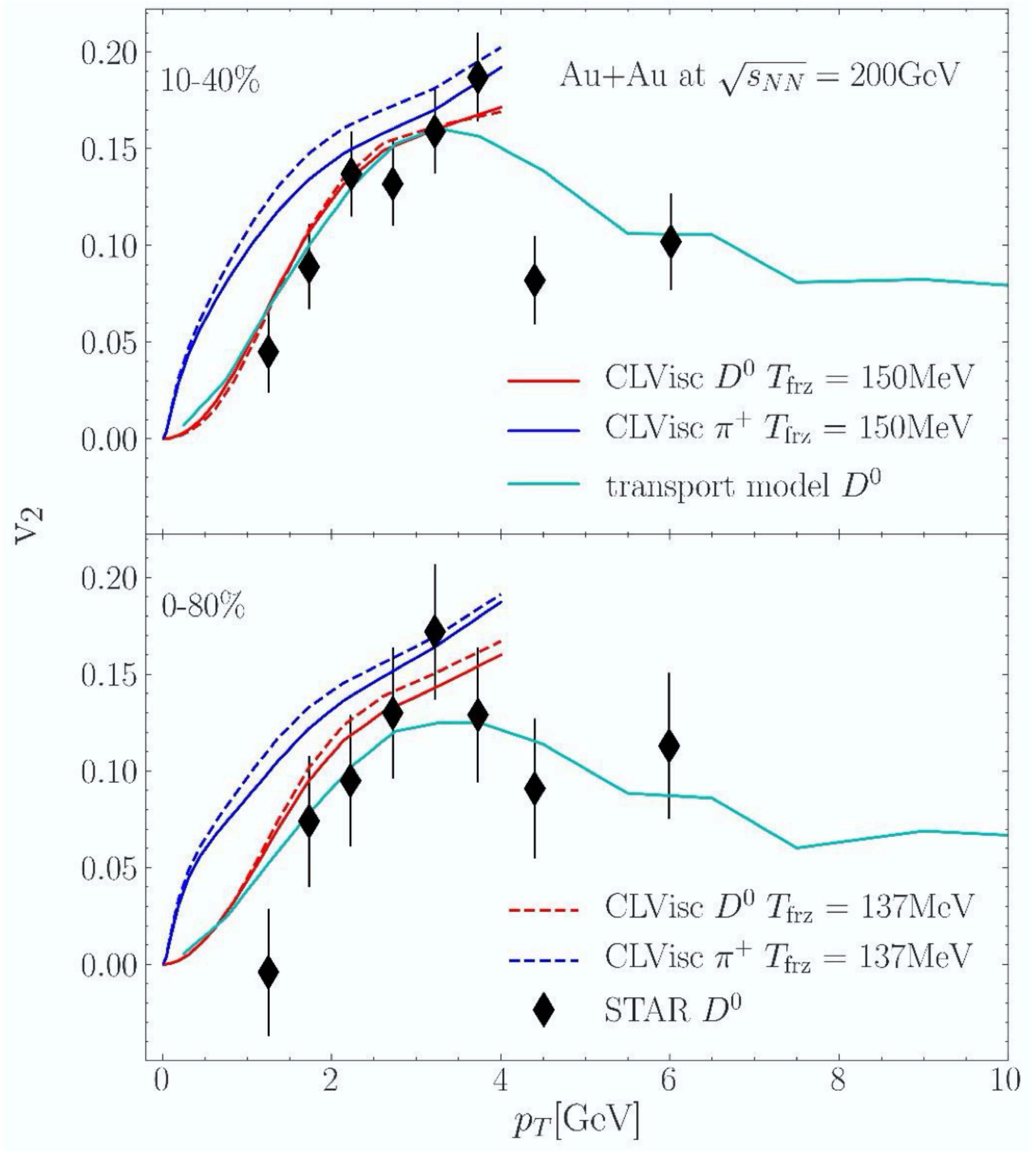
MONTAÑA, WED 10:10 EDT

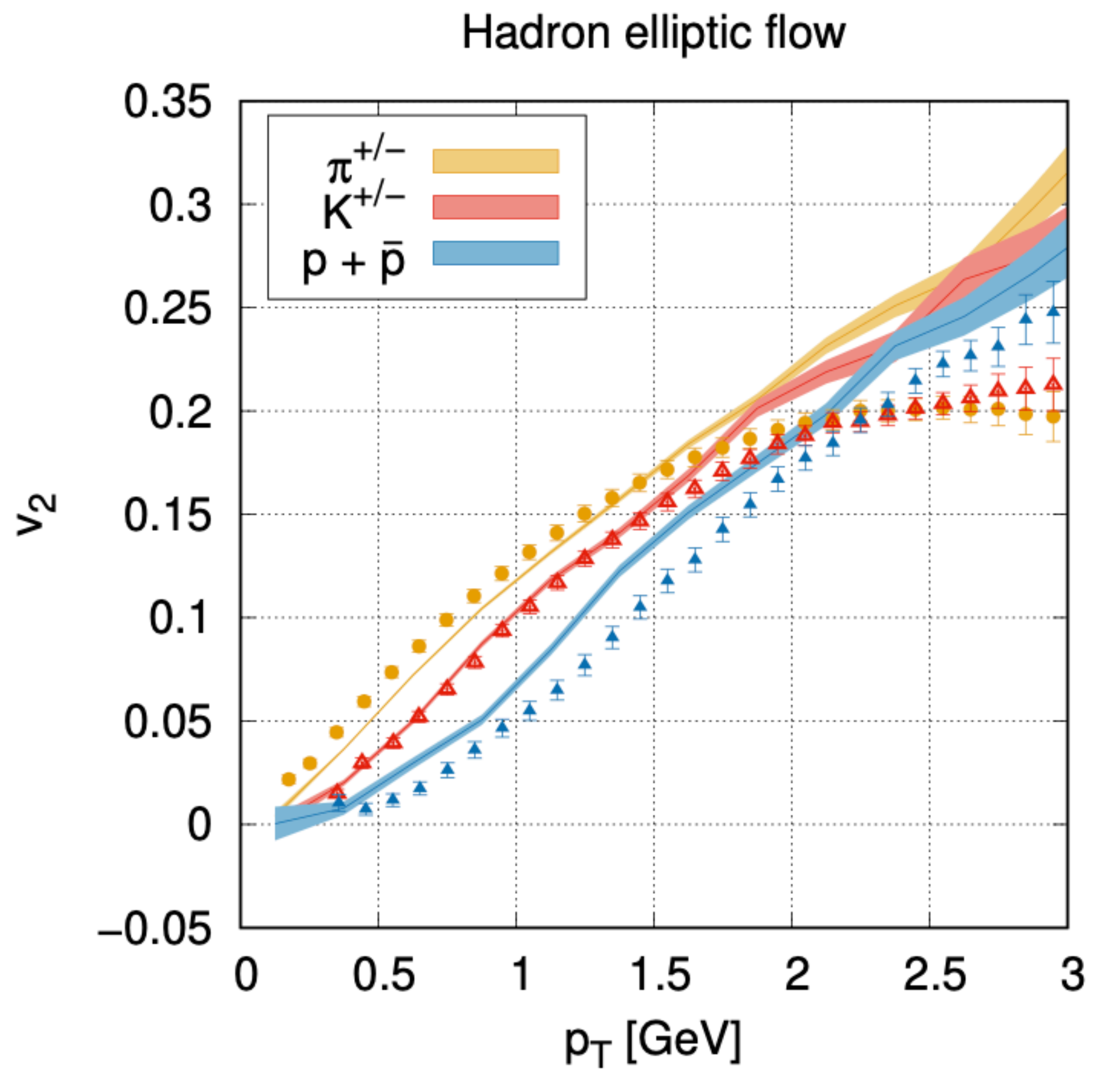


MEDIUM EFFECTS

TRANSPORT AND HYDRODYNAMICS

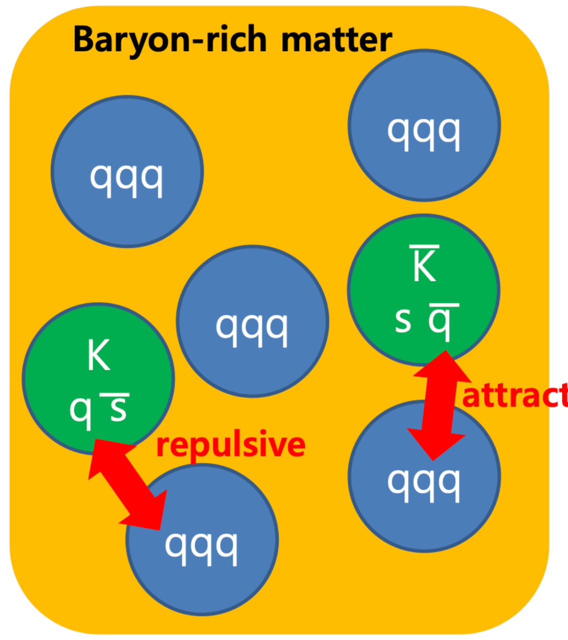
- Comparison of hydrodynamics to transport description **DING, TUE 12:10**
  - At low p_T D^0 spectra are well described by hydro, underestimated in transport, at higher p_T (>4 GeV), transport describes spectra well. v_2 is well described by both models at low p_T
- Transport theory can be done at fixed η/s **GALESI, TUE 10:50**
  - Kind of like hydro. Can be compared to hydrodynamics and can be pushed to large stress tensors
  - Uses quasiparticle model with thermal masses to also reproduce the LQCD EOS
  - Will be able to compare different hadronization prescriptions - microscopic vs. Cooper Frye type
- Can also include large initial vorticity and EM fields **PLUMARI, WED 9:50**
  - D meson v_1 sensitive to initial tilt, transport coefficients, EM fields
- Can we understand all systematics of directed flow of all particles?

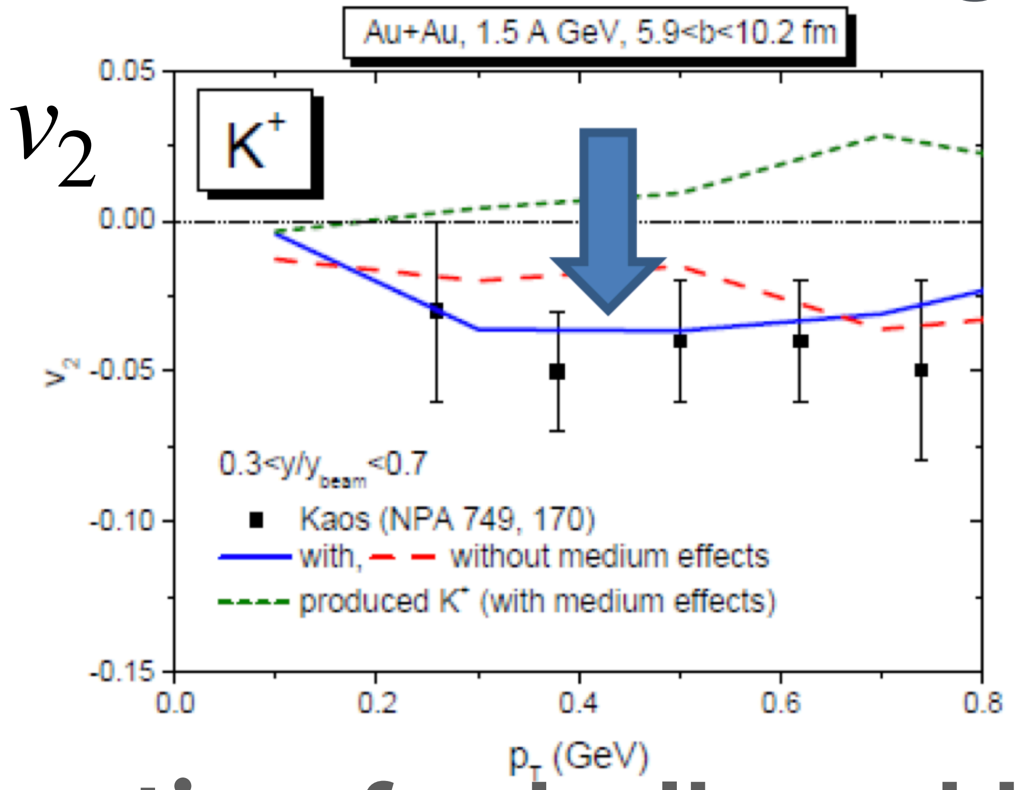


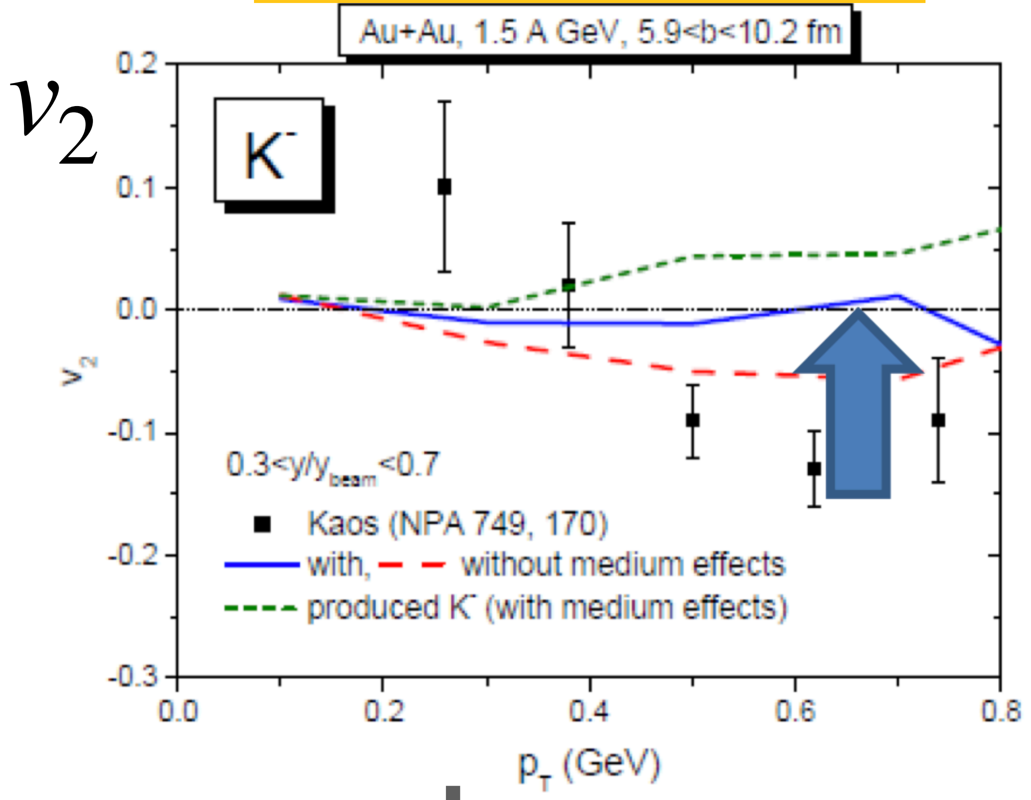


STRANGE AND HEAVY QUARKS IN MEDIUM

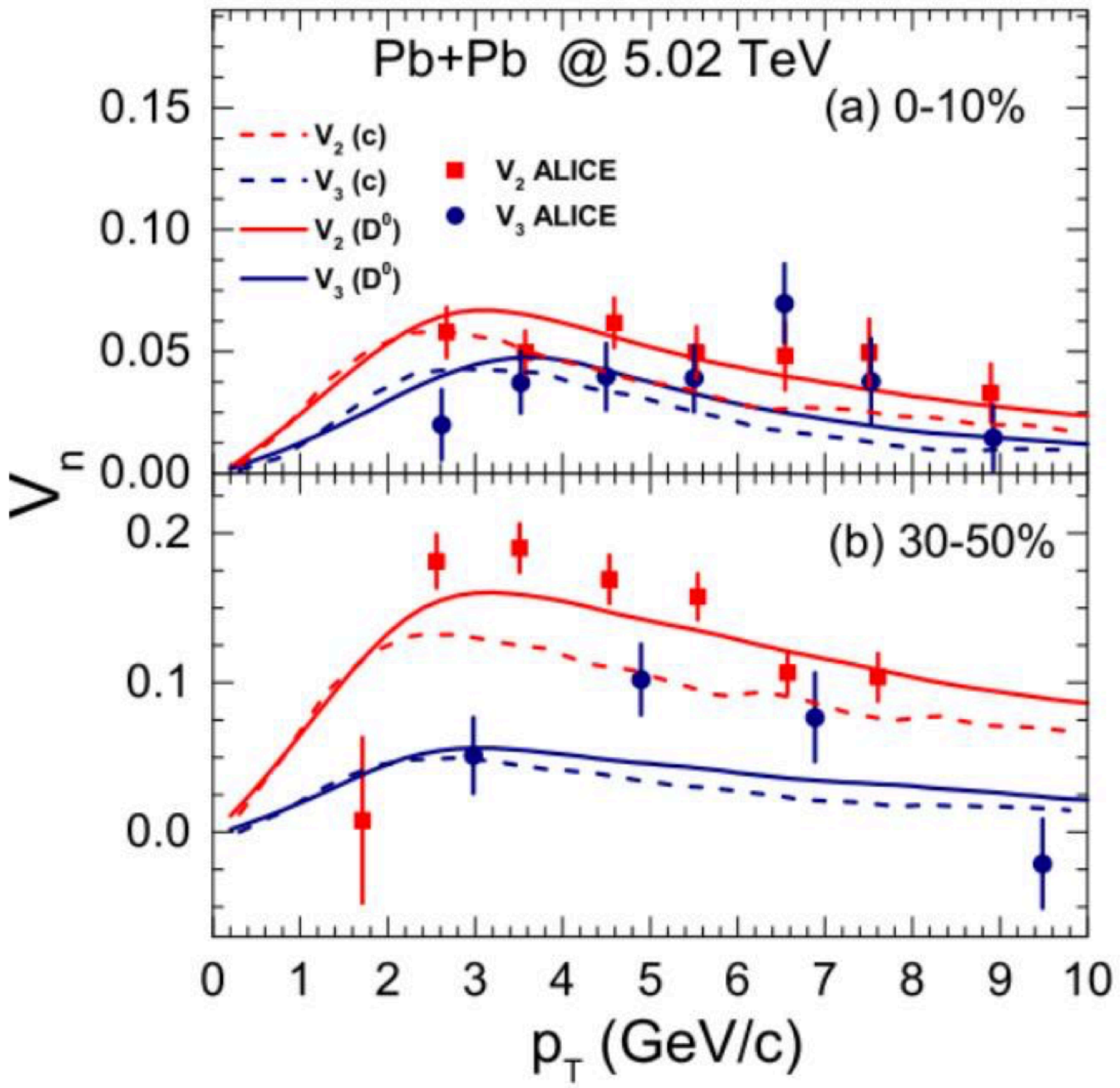
- (Anti-)kaon production with in-medium modifications of the antikaon properties described via coupled-channel unitarized scheme based on a SU(3) chiral Lagrangian and propagation in medium using PHSD **SONG, TUE 10:30**







- Boltzmann equation for bulk and heavy quarks + coalescence and fragmentation hadronization
- Include fluctuations, compute v_n and their correlations for charm and bottom quarks and mesons: Can be used to constrain charm and bottom $D_s(T)$ from experiment (consistent with lattice data) **SAMBATARO, TUE 9:50**



- What are the effects of the strong magnetic field?
  - Magnetic field induces anisotropy in the heavy quark transport **KURIAN, TUE 9:50**

QUARKONIUM IN THE MEDIUM

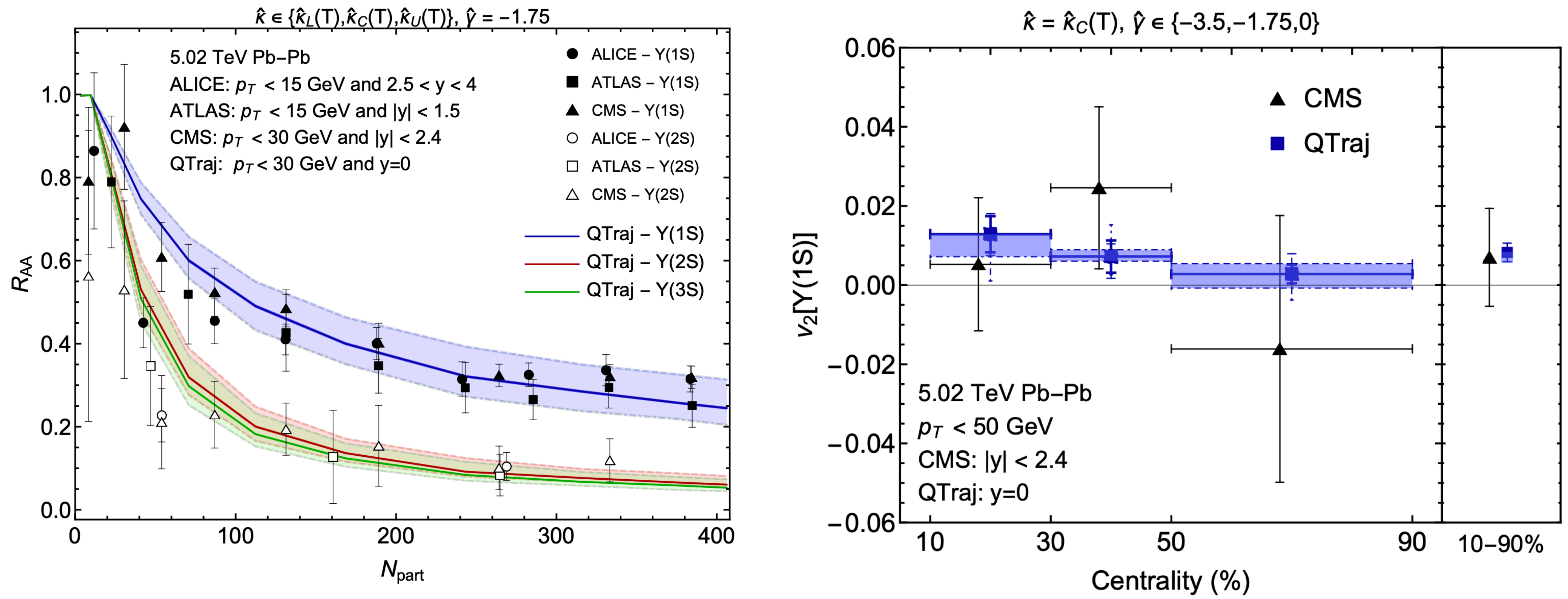
- Static screening, dynamic suppression, recombination
- Theory: Statistical recombination, transport, open quantum system **DELORME, TUE 9:30**
  Open quantum system: Quantum master equation describing transition between color states and dissipation, solution for 1D case.

Total density matrix

$$\rho_{\rm tot} = \sum_j p_j |\psi_j\rangle\langle\psi_j| \longrightarrow \frac{d}{dt}\rho_{\rm tot} = -i[H_{\rm tot}, \rho_{\rm tot}]$$

Reduced density matrix

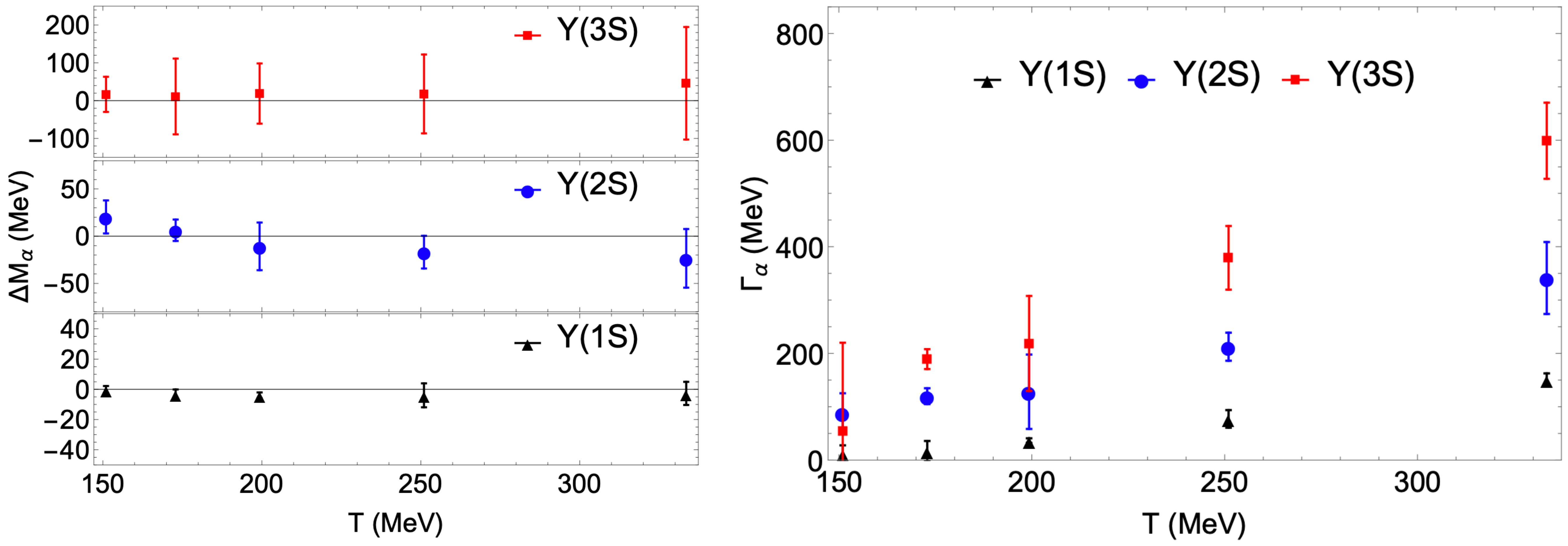
$$\rho_{\rm probe} = {\rm Tr}_{\rm medium}[\rho_{\rm tot}] \longrightarrow$$ **Evolution equation?**



- Can we solve the quantum system in 3D?
- Yes **STRICKLAND, WED 12:55**
  OQS+pNRQCD
  Solve Lindblad equation
  with temperature from aHydro
  that enters transport coefficient from lattice
- Can we go from bottomonium to charmonium?

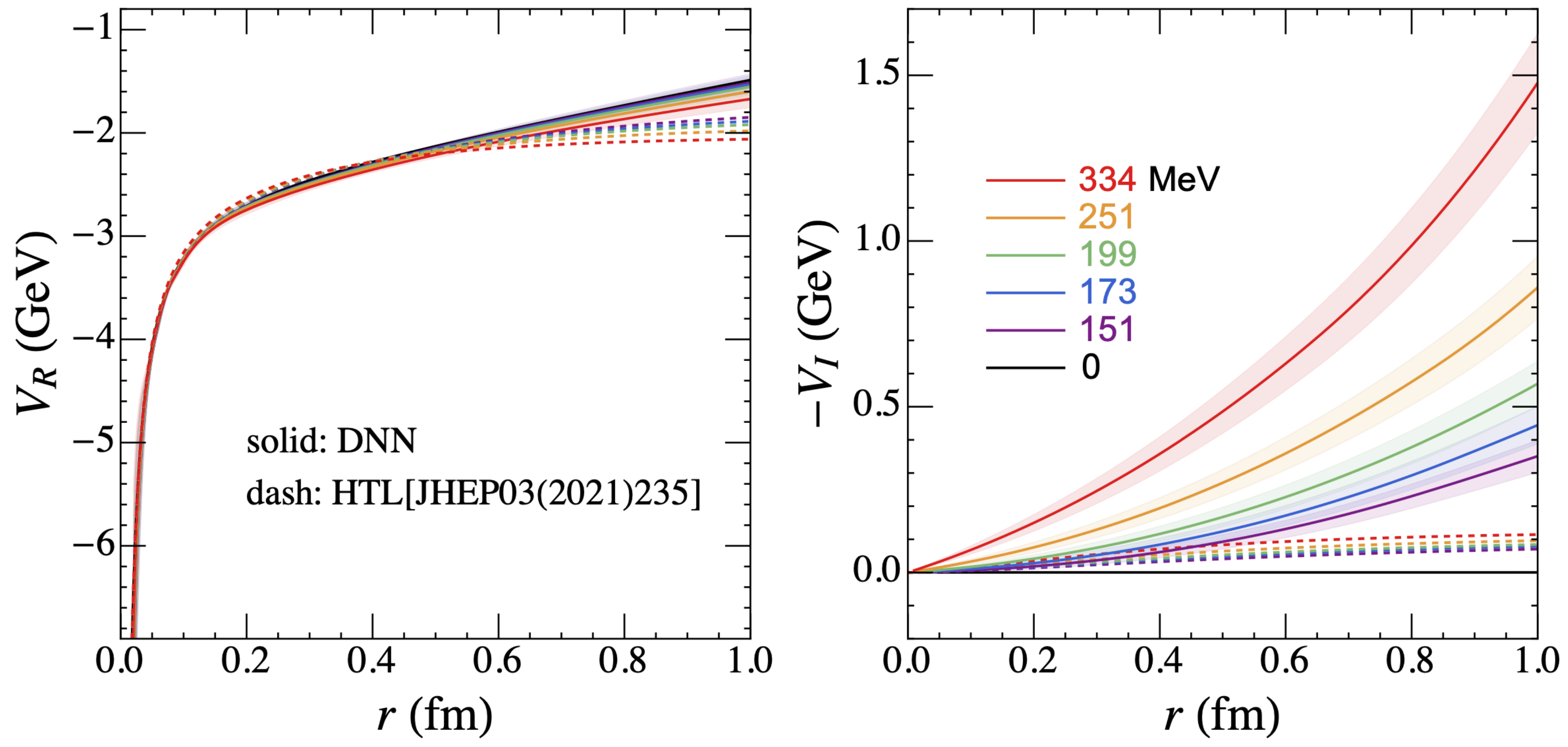
QUARKONIUM IN THE MEDIUM

- NRQCD on the Lattice, explore Υ and χ_b via correlation functions (obtain spectral functions) using extended (instead of point) sources **LARSEN, THU 10:10**



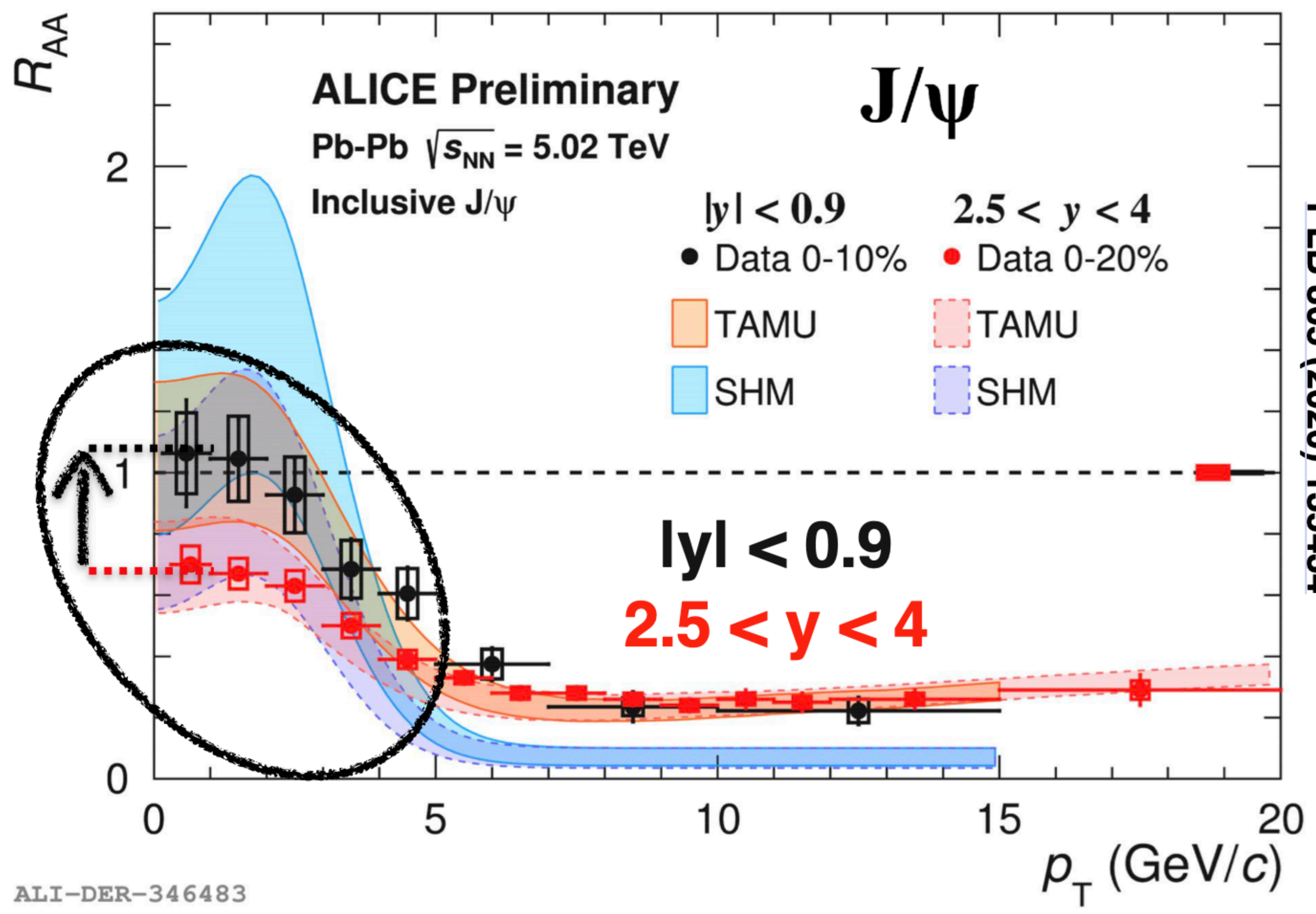
- Also, width of Wilson line correlator shows the same behavior as the bottomonium results

- These LQCD results seem incompatible with HTL potential **SHI, WED 12:25**
- Use deep learning to extract potential in model independent way



QUARKONIUM IN THE MEDIUM

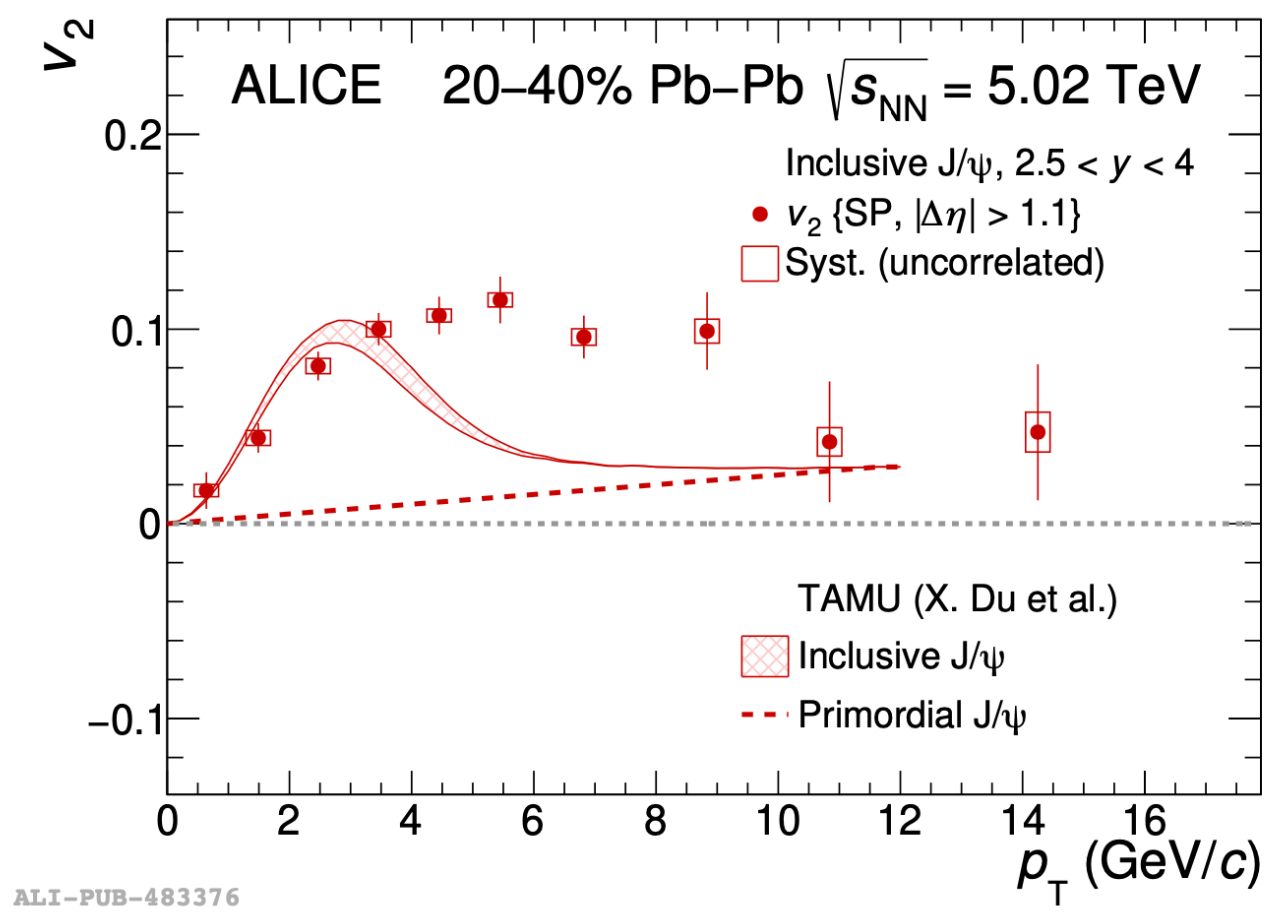
- **How do we understand the R_{AA} and v_2 of J/ψ and Υ over the entire p_T range?**



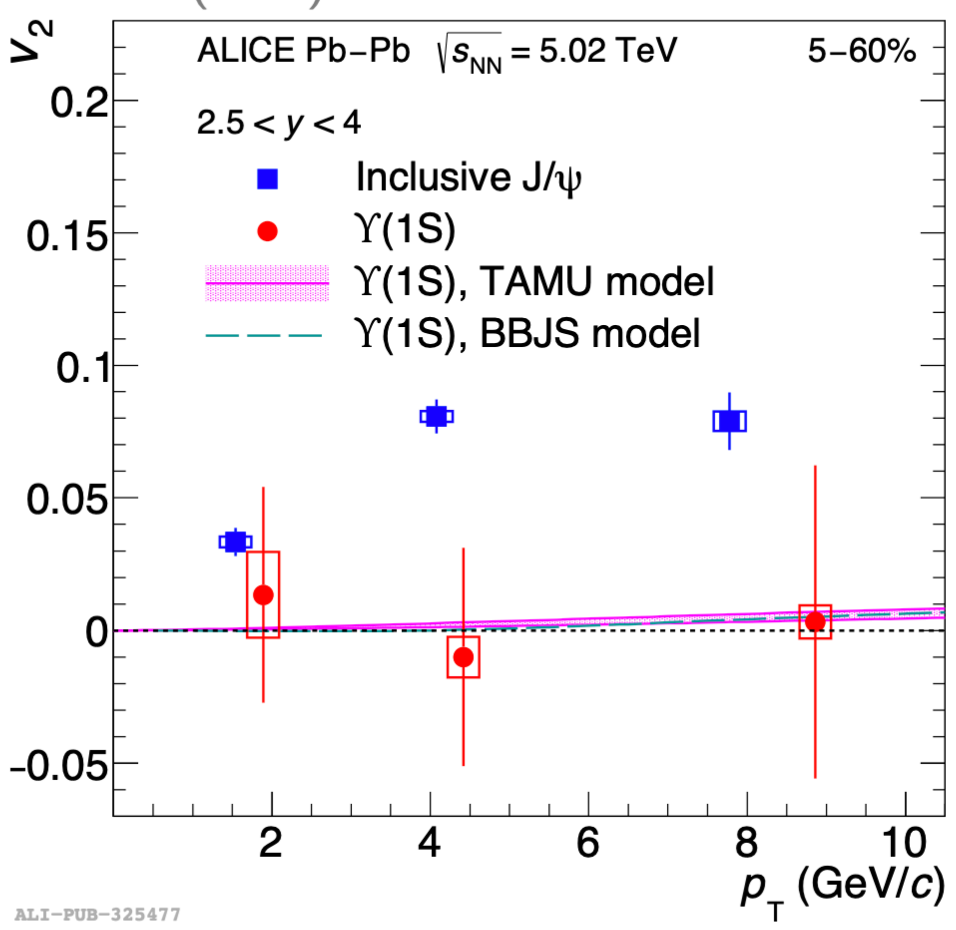
PLB 805 (2020) 135434

JHEP 02 (2020) 041

JHEP10 (2020) 141



PRL123 (2019) 192301



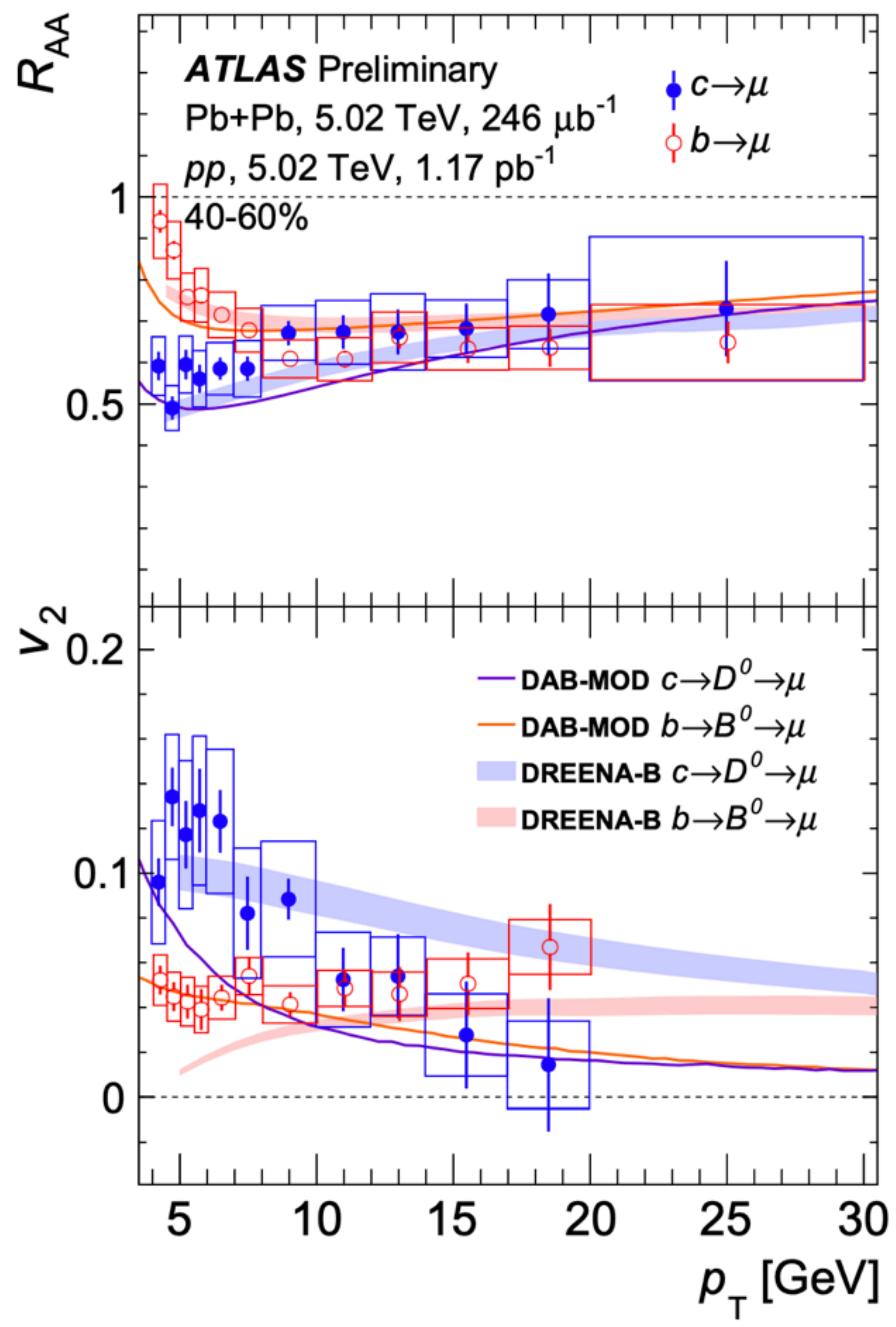
FROM STÅHL'S TALK, THU 14:25

- Models with regeneration can describe the low p_T R_{AA} and v_2

- **What are the effects of magnetic field and vorticity on charmonium states?**
  - Solve two body Schroedinger equation in EM and vorticity fields
  - Mass and shape are both significantly changed **ZHAO, FRI 9:30**

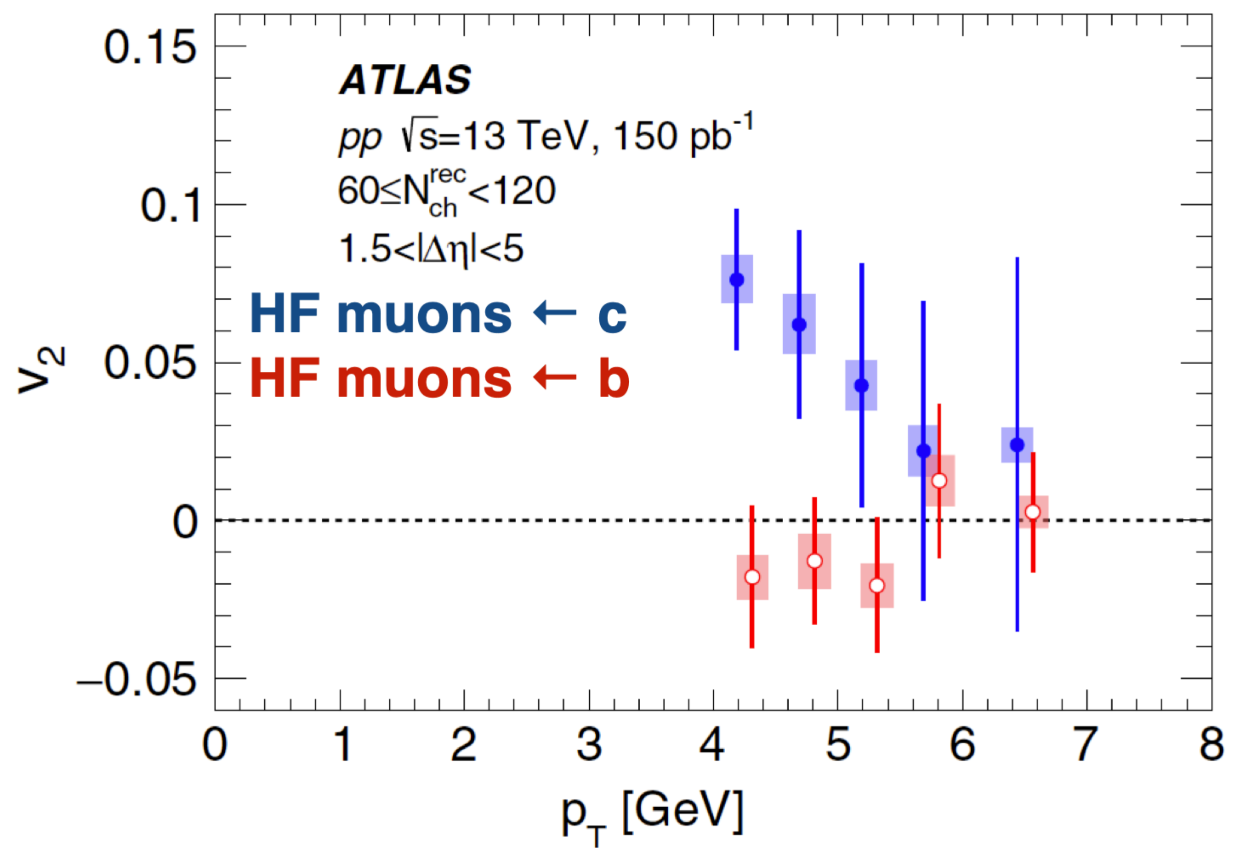
IN MEDIUM ENERGY LOSS

- Is there still an R_{AA} - v_2 puzzle at higher p_T (both for $h^{+/-}$ and heavy particles)?
  - Proper description of parton-medium interaction is (most?) important to get both R_{AA} and v_2 right (DREENA-B) **ZIGIC, FRI 10:30**
  - DREENA-A also includes a realistic 3D hydro medium evolution Let's test both models on the right (DREENA-A and DAB-MOD) with the same background medium **NAGLE, TUE 10:30**
- If there is no more R_{AA} - v_2 puzzle, why?
  - DREENA-B: Because one needs a sophisticated energy loss description. Medium details not so important
  - Others: Fluctuations are important (*Phys.Rev.Lett.* 116 (2016) 25, 252301) What will DREENA get when fluctuations are included?
- Infer QGP properties (e.g. thermalization time) from high p_T probes using DREENA-A **STOJKU, FRI 10:10**

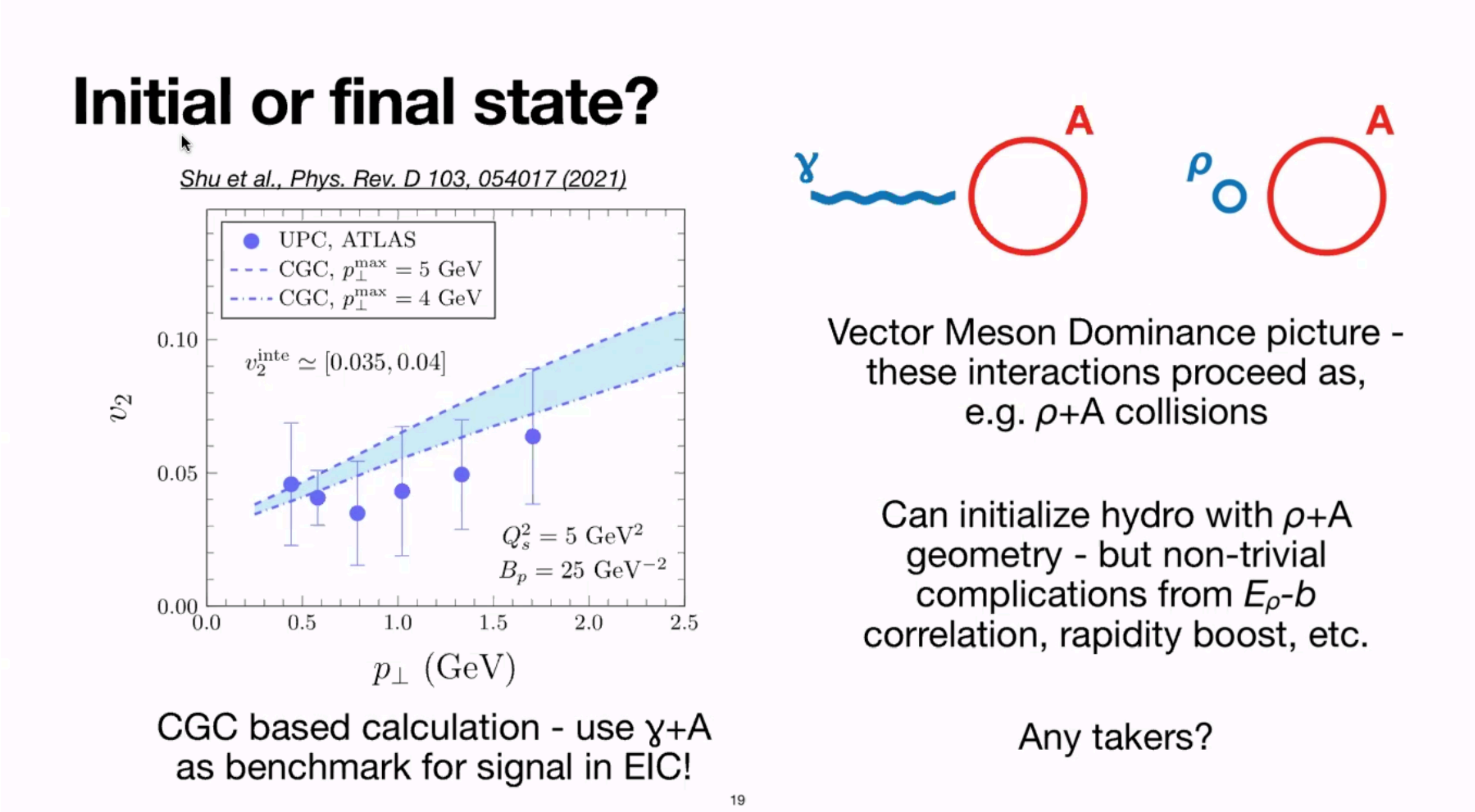


SMALL SYSTEMS

- Are there final state interactions for charm in pp and pPb collisions? None for bottom?



- What is the origin of the anisotropy in $\gamma + A$ collisions (UPCs)?



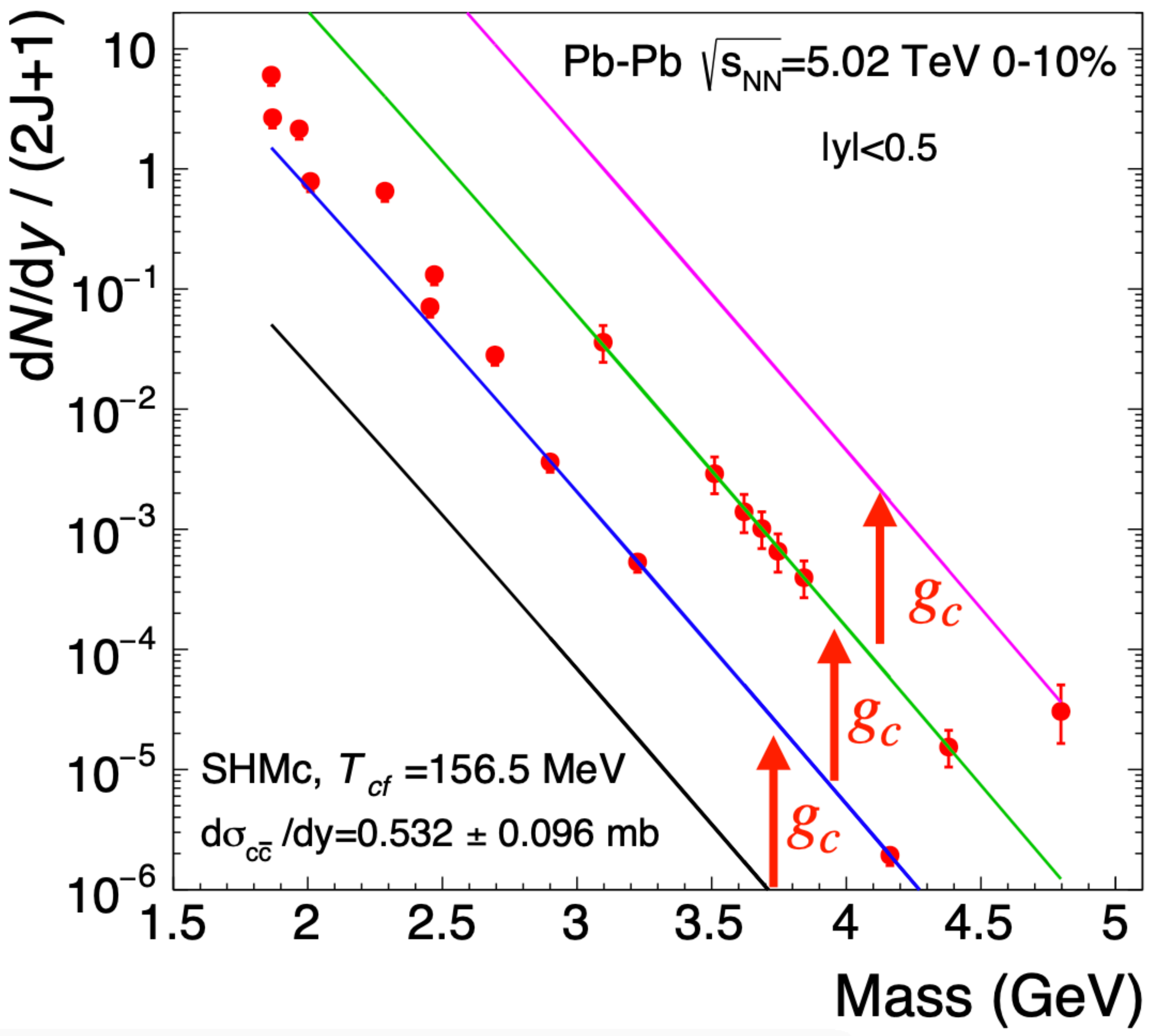
SLIDE FROM D. PEREPELITSA

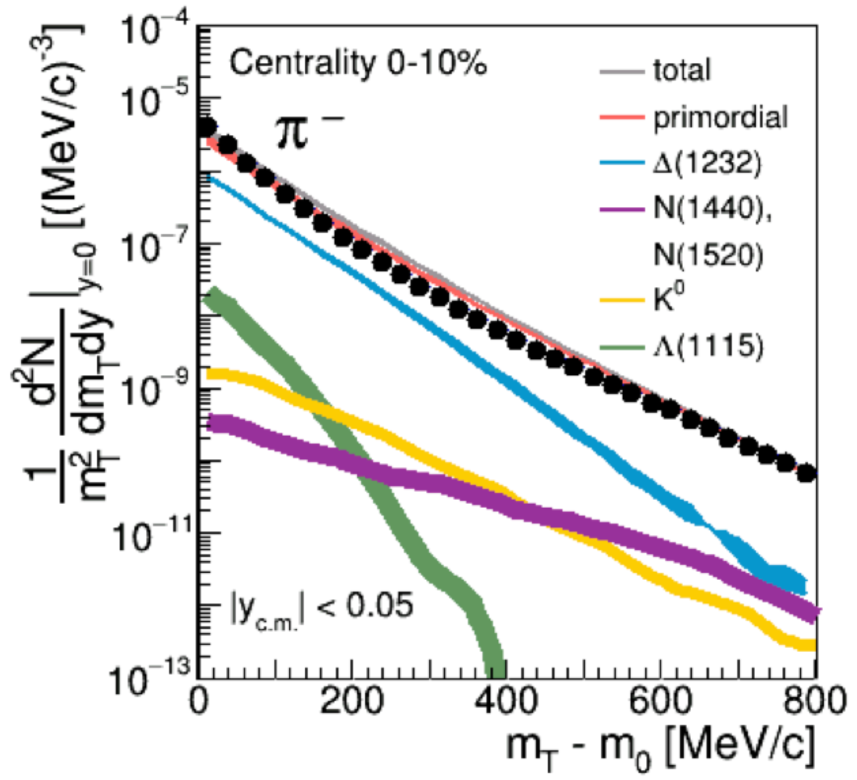
HADRONIZATION

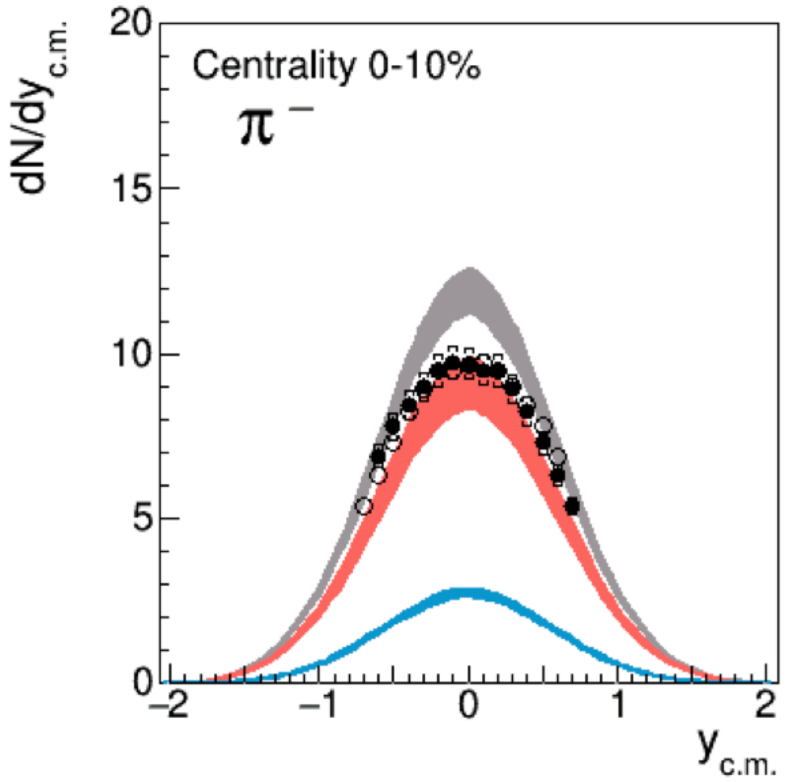
HADRONIZATION

- Extending the Statistical Hadronization Model to include charm (SHMc) - from initial hard scattering
  Charm survives and thermalizes (implement with fugacity g_c)
- Find “charm hadron hierarchy” due to enhancement compared to purely thermal production
- Compute spectra in statistical hadronization model using spherically symmetric hypersurface (Siemens-Rasmussen blast-wave model)

VISLAVICIUS, TUE 10:50 EDT







Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV, 0-10%

HARABASZ , TUE 12:10 EDT

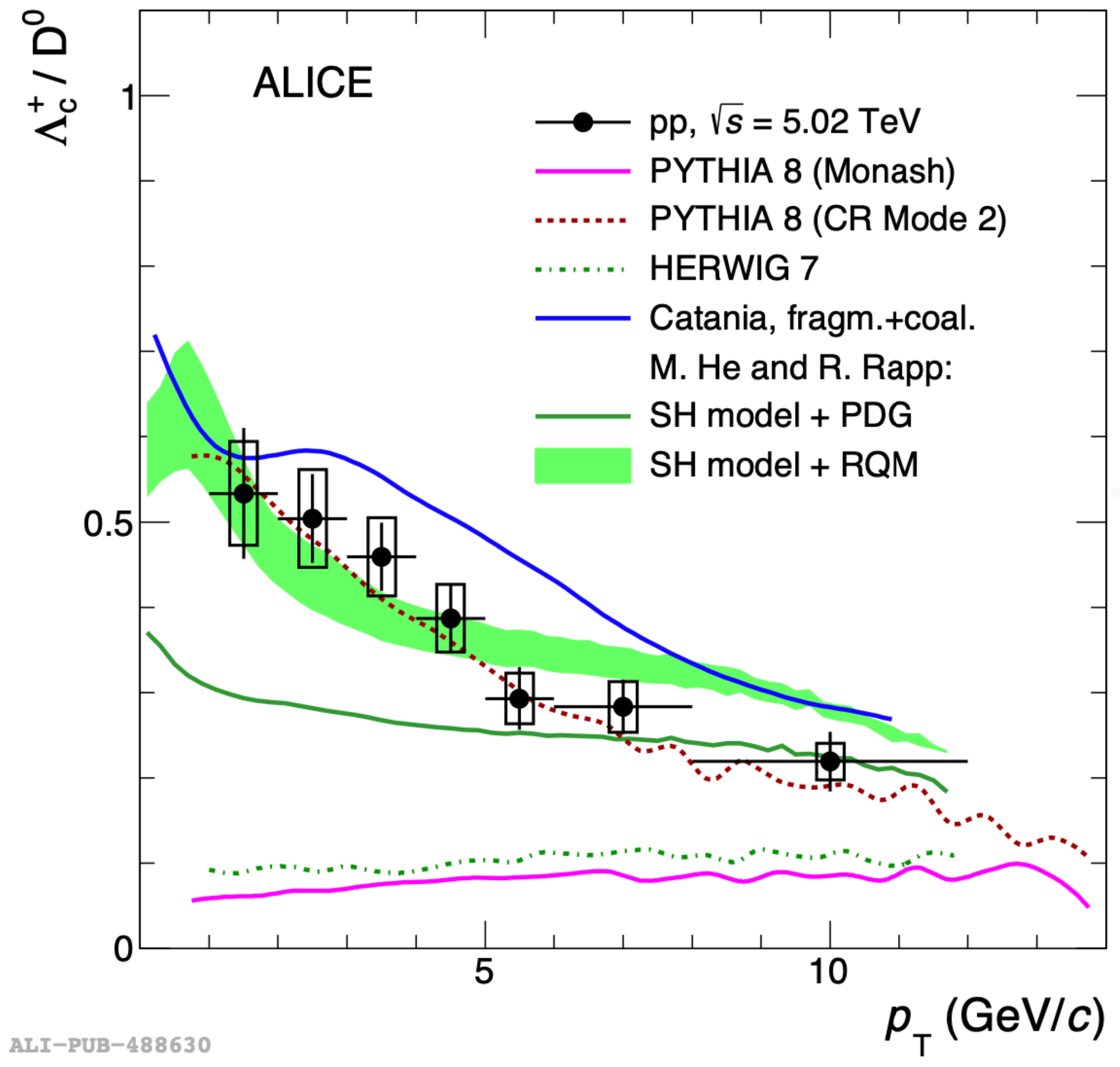
HADRONIZATION UNIVERSALITY

INNOCENTI, WED 13:35 EDT

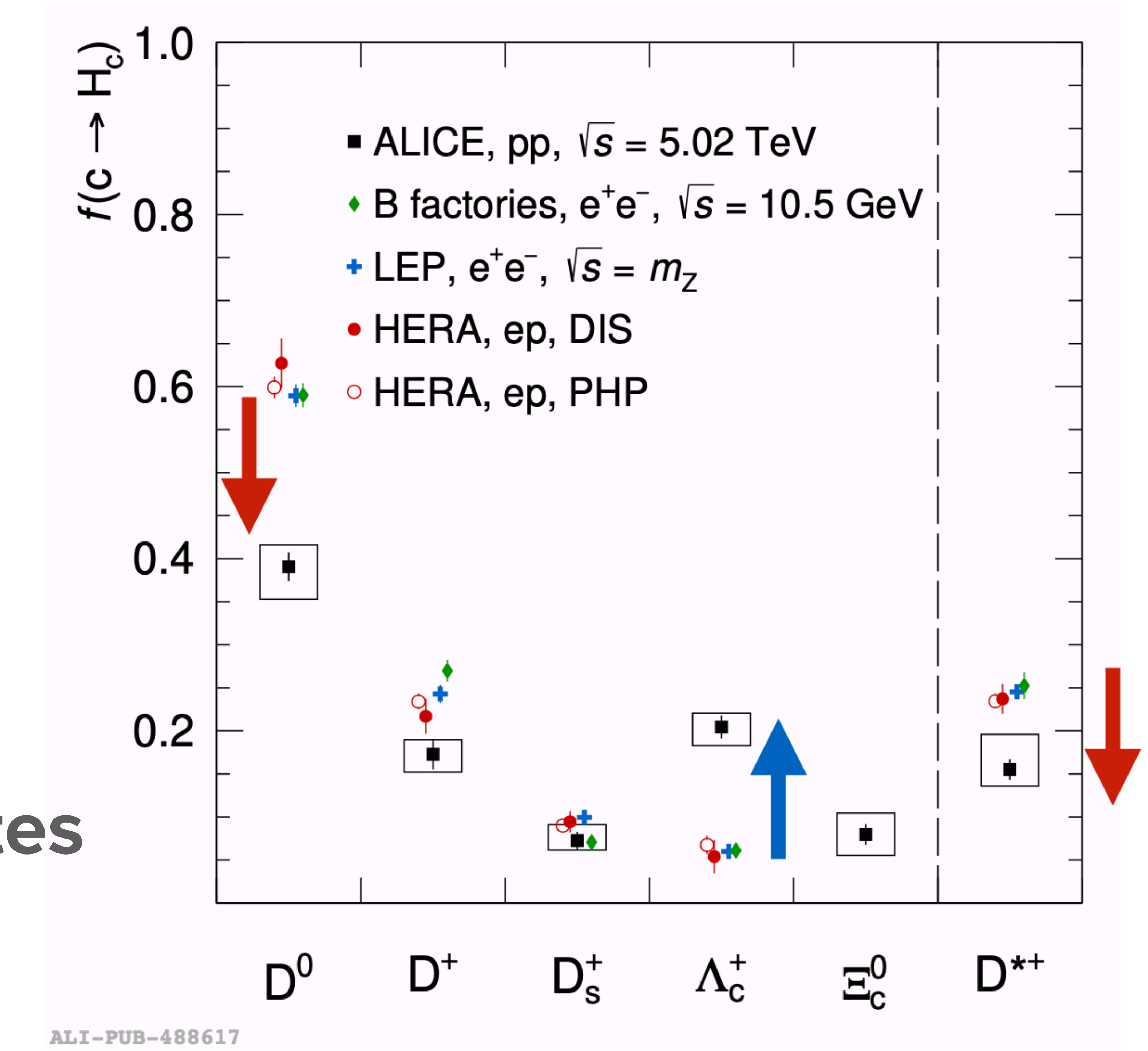
- How can we understand the “redistribution of charm quarks” from meson to baryons as we move from e+e- to pp?

$\sigma(pp \rightarrow H_Q X)$ = PDF ⊗ σ(pQCD) ⊗ $D^{vacuum}(z,Q^2)$ modifications to this?

- Various models can produce such a trend:



- PYTHIA8 + enhanced color reconnection (CR Mode 2)
- Additional excited baryon states in SHM (SHM+RQM)
- Coalescence+fragmentation (Catania)
- Quark Recombination model



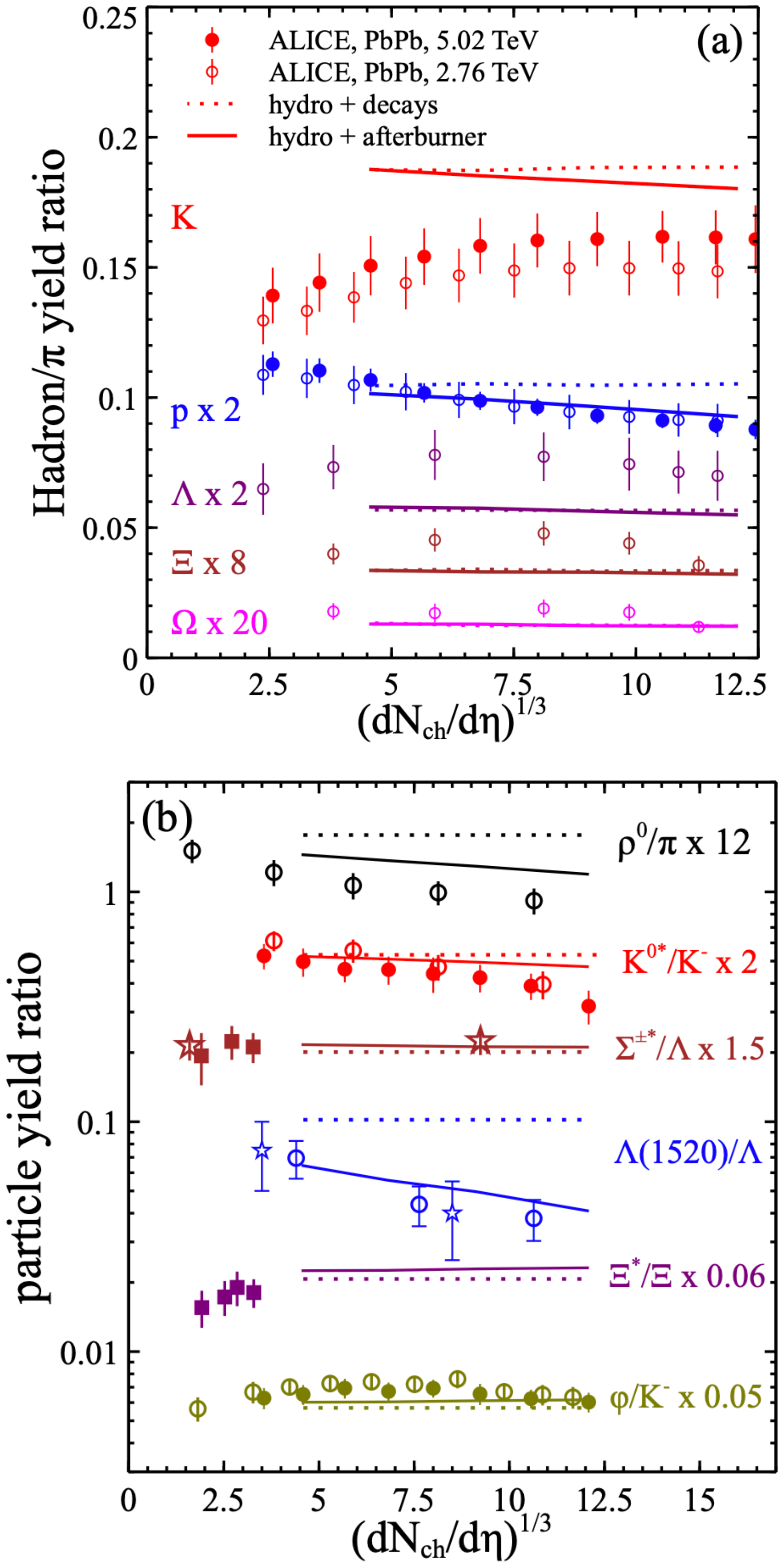
- Can we understand heavier baryon states like Ξ_c^0, Ξ_c^+, and Ω_c^0?

LUPARELLO, WED 13:55 EDT

RESONANCE PRODUCTION

- What is the role of hadronic afterburners on resonance production?
- Afterburner suppresses some resonances in central collisions, increases $\langle p_T \rangle$, decreases v_2
  - Afterburner effects could help constrain unknowns, like certain branching ratios
  - What matters: • resonance mean free path • decay products mean free path • tendency of decay products to regenerate to the same resonance **OLIINYCHENKO, WED 10:10**
- Similar results seen with EPOS and EPOS+UrQMD

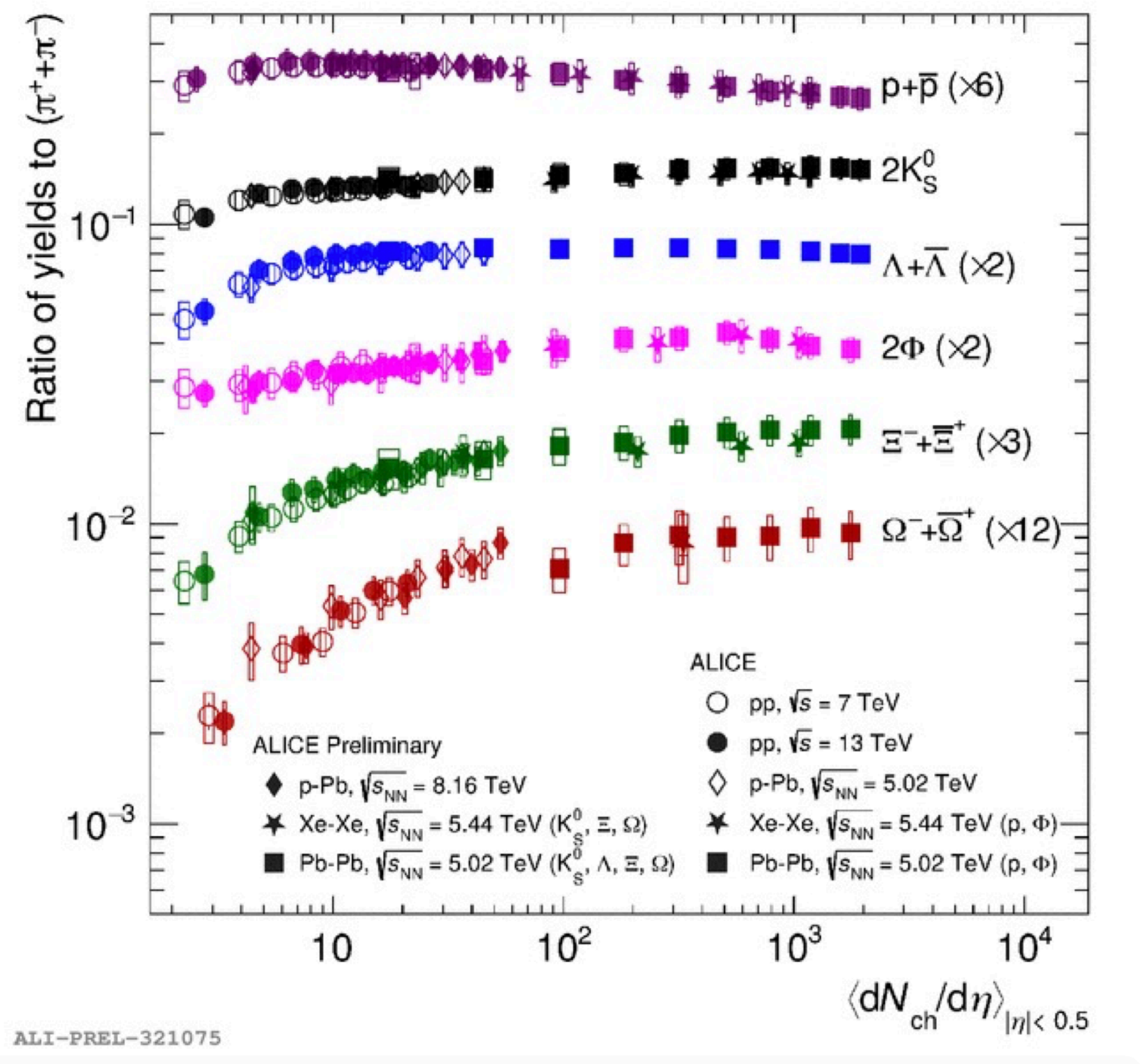
SONG, FRI 13:40



STRANGENESS ENHANCEMENT

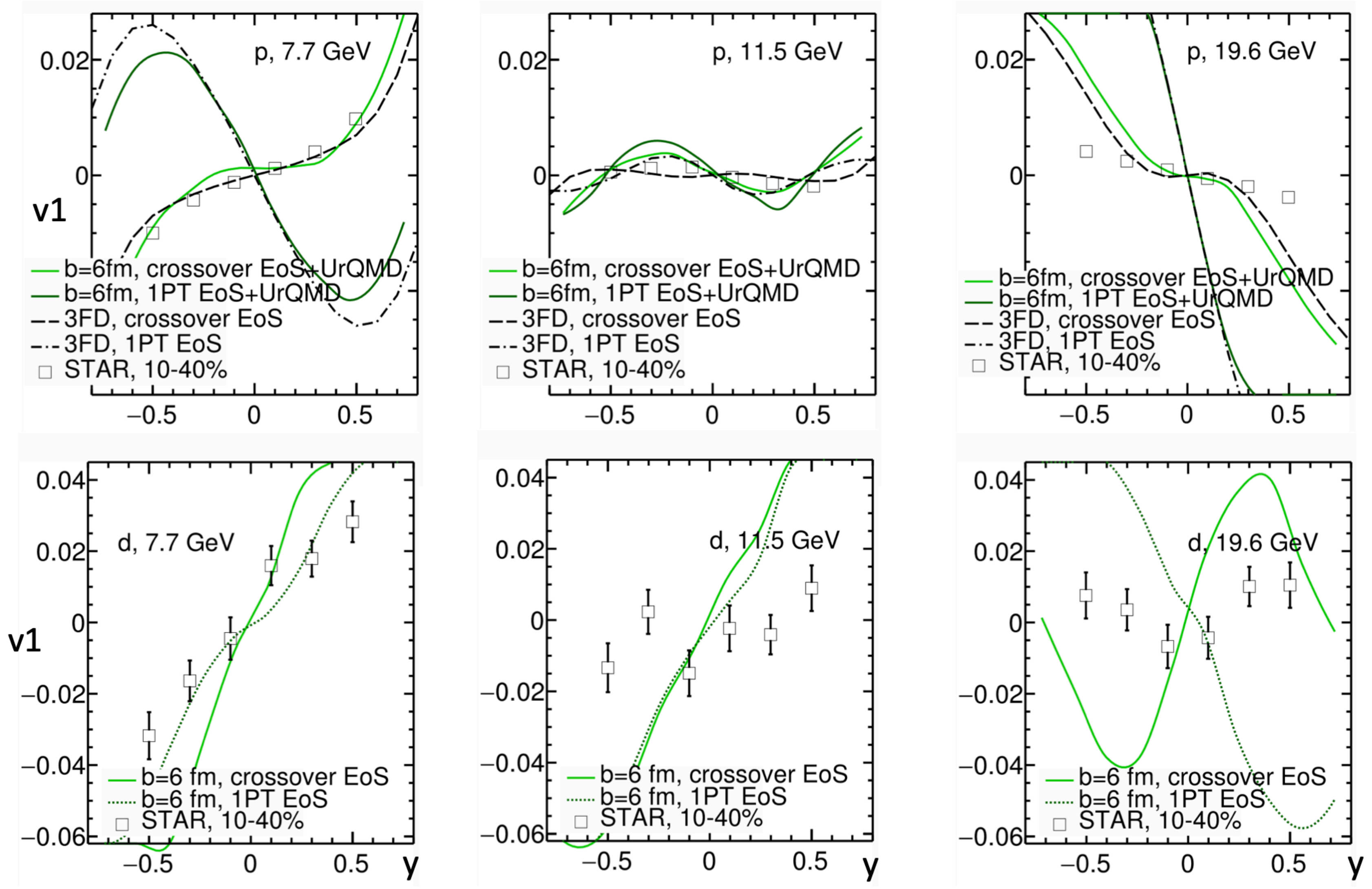
- **PYTHIA with rope hadronization describes pp data**
  Nayak, Pal, Dash, Phys.Rev.D 100 (2019) 7, 074023
- **Cora+Corona model gets enhancement right**
  Kanakubo, Tachibana, Hirano, PRC 101 (2020) 2, 024912
- **Thermal system with canonical suppression also works**
  ALICE, PRC 99 (2019) 2, 024906 (using THERMUS)

- **3 different pictures, 3 different physics interpretations**
- **Which one is right? Will additional observables help?**



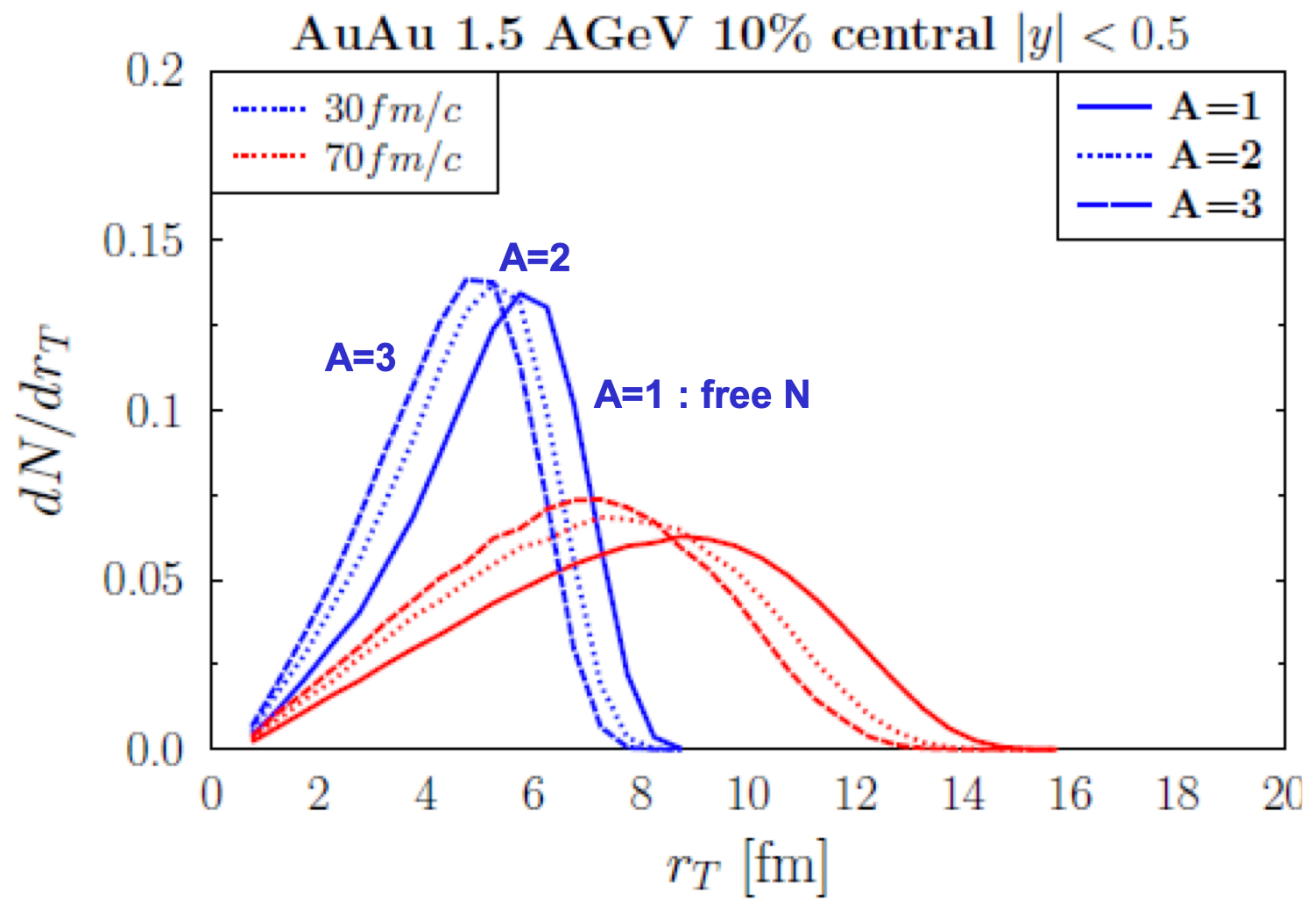
LIGHT NUCLEI PRODUCTION

KOZHEVNIKOVA, WED 10:50 EDT



- Light nuclei can be computed using coalescence
  - Done for example in three fluid dynamics + UrQMD
  - Can we understand v_1 of light nuclei?
- How can weekly bound objects be formed and survive in a hot environment? (ice in a fire puzzle)
  - Study dynamically in transport model: Parton-Hadron-Quantum-Molecular Dynamics

BRATKOVSKAYA, FRI 10:10 EDT



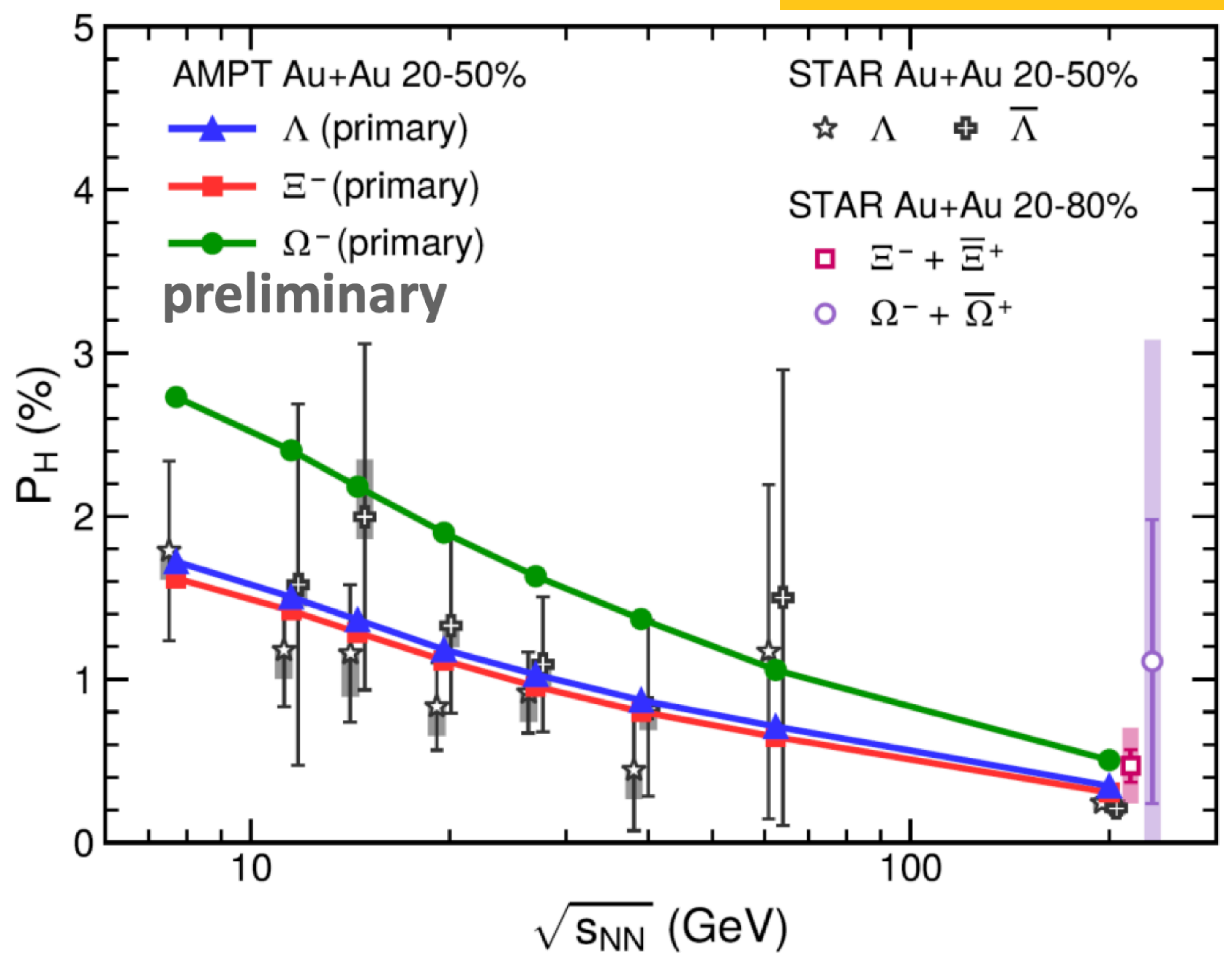
- Data is well described. Clusters are formed …
  - shortly after elastic and inelastic collisions have ceased
  - behind the front of the expanding energetic hadrons
  - since the ‘fire’ is not at the same place as the ‘ice’, cluster can survive.

POLARIZATION AND SPIN

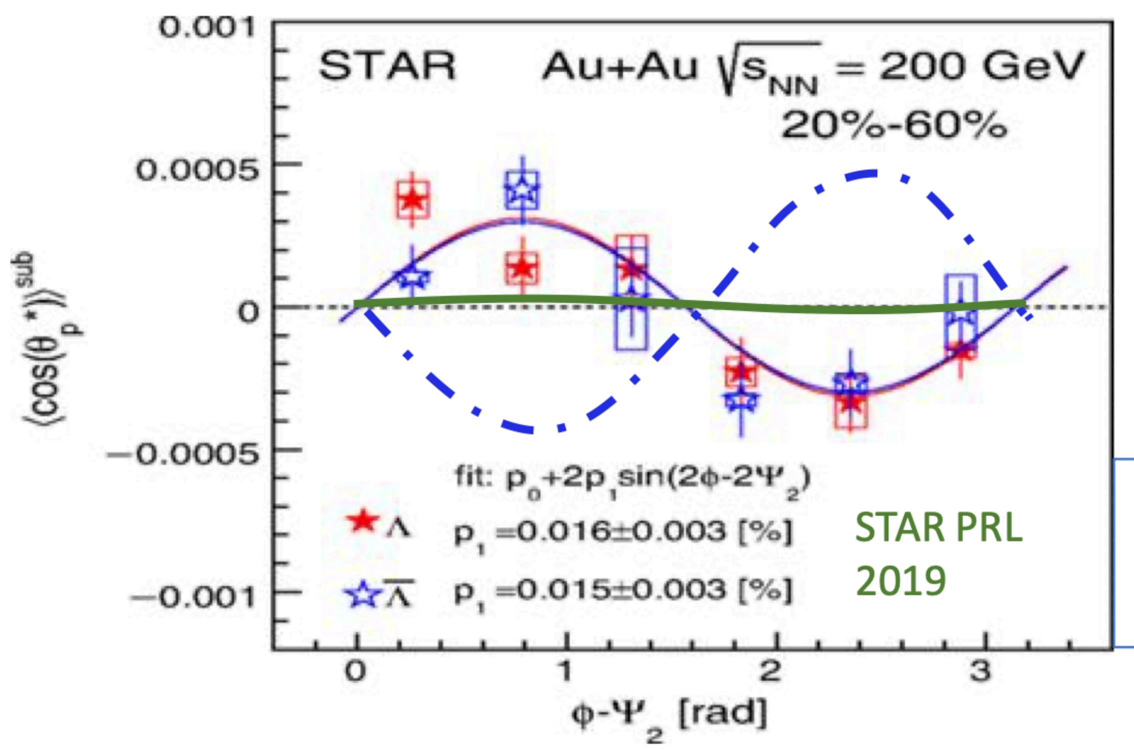
HYPERON POLARIZATION

- Global angular momentum
  RHIC: $L = 10^5\ \hbar$ @ 200 GeV & 7 fm
  LHC: $L = 10^7\ \hbar$ @ 2760 GeV & 7 fm
- Vorticity $\omega \sim \frac{\Delta v}{2\Delta x} \sim 10^{-2} \mathrm{c/fm} \sim 10^{21} \mathrm{s}^{-1}$

LI, WED 10:10



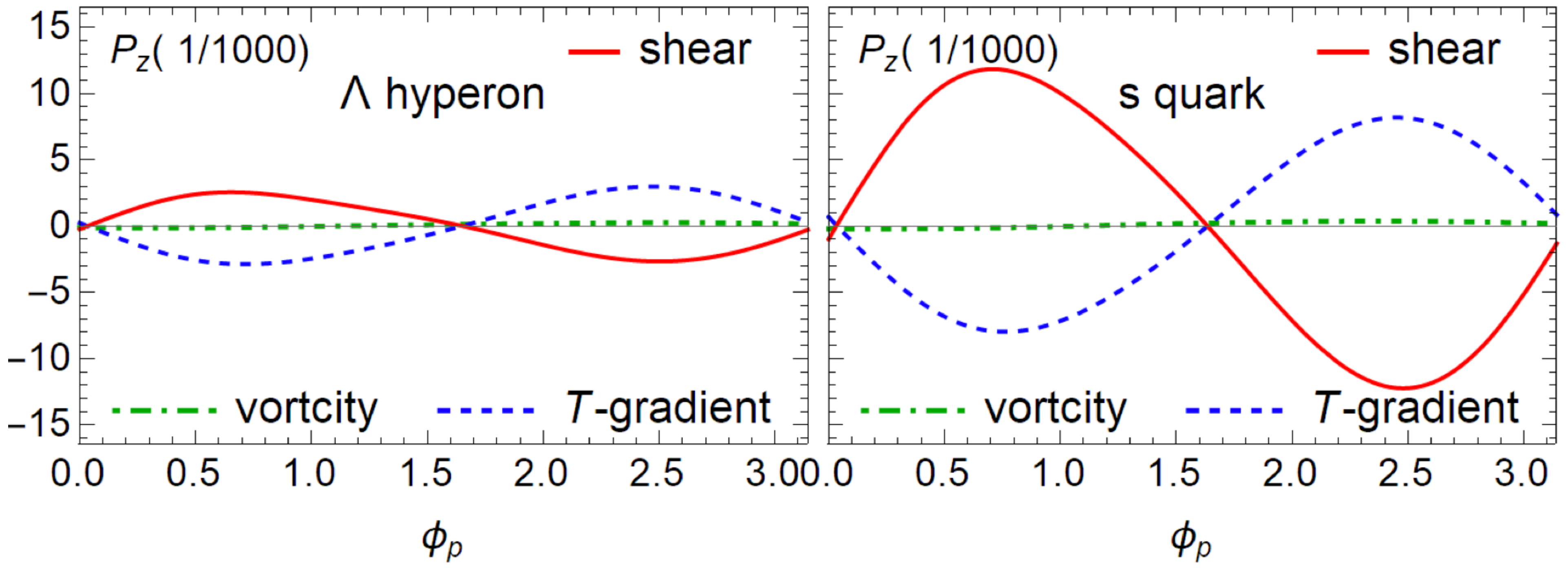
- Polarization because of spin orbit coupling
- Angular distribution of hyperon decay products (weak decay) carry information on the hyperon's spin
- Phase space averaged polarization well described in models, but differential result has opposite sign
- Can we get the right sign of the differential polarization?
  - Shear can induce polarization **LIU, WED 10:50**
  - Need good description of hadronization and hadronic evolution of spin



Sketches of theoretical curves

Lambda equilibrium
Assuming P_Λ in equilibrium

Strange memory
Assuming $P_\Lambda = P_s$



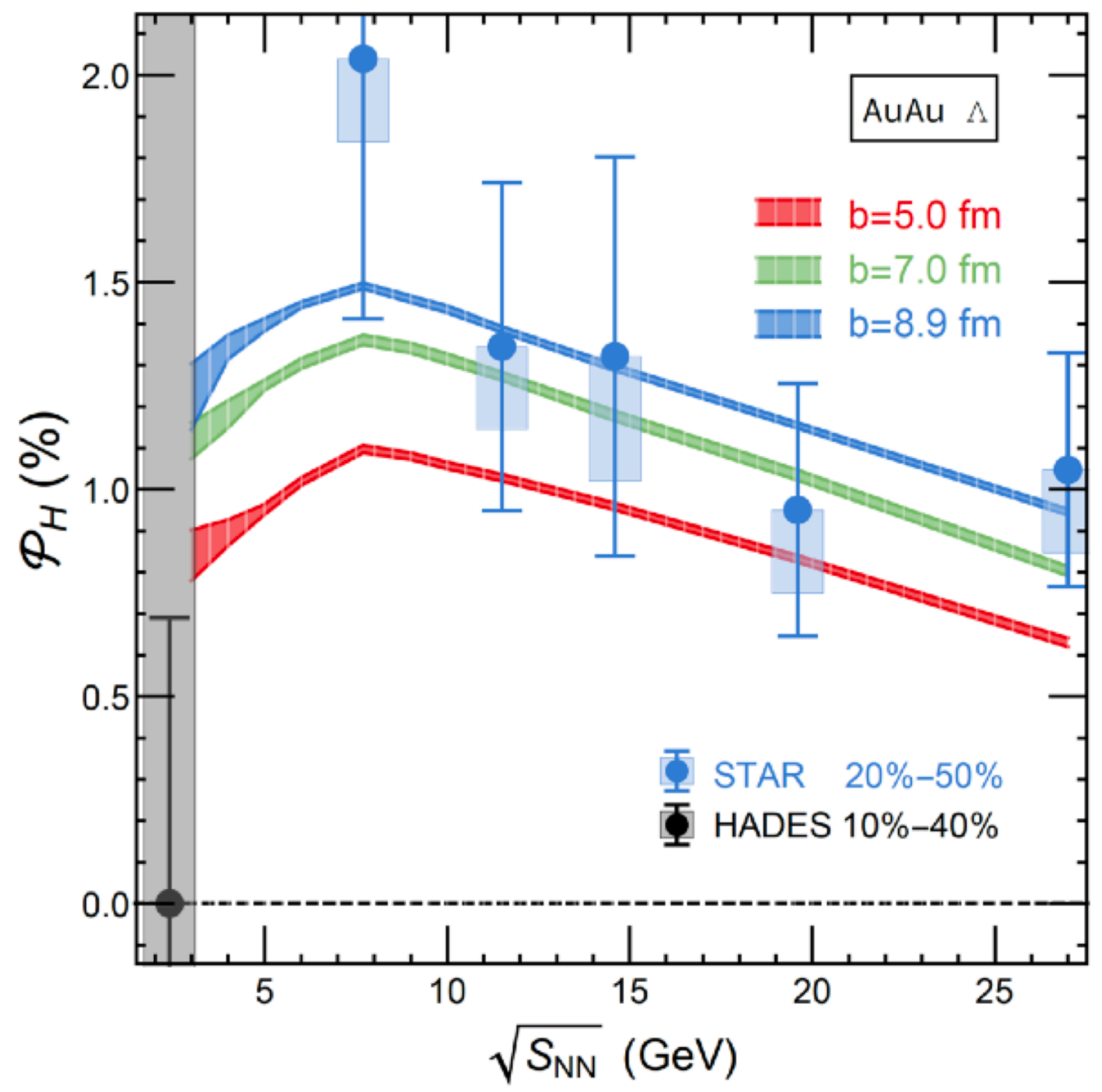
- Does not work with statistical hadronization
- May need stronger memory of strange quark spin

POLARIZATION AND SPIN ALIGNMENT

- Spin direction is measured in hyperon rest frame (direction of angular momentum needs to be boosted from COM frame to the hyperon rest frame to get the right relation

RYBLEWSKI, THU 9:50

- Lower collision energies: Calculations predict non-monotonic behavior. LIAO, THU 10:30
  Most vortical fluid around 7.7 GeV
  Questions about strongly Interacting Matter under Rotation
  Phase structure change? Equation of state change?
  Global and local polarization? Vector mesons?
  Spin transport theory? Spin hydrodynamics?
  Novel transport processes?



- Spin alignment of vector mesons needs to be better understood (experimentally much larger than simple estimate)
  - Effect of vorticity on spin alignment of vector mesons studied in a quark coalescence model SHENG, WED 9:50
- Can we fully understand spin in HICs (e.g. via spin hydro/spin kinetic theory)?

- We have learned a lot
- But many fascinating questions remain
- See you at the next SQM with (some of) the answers!

? = fill in your own question

- Can we fully understand spin in HICs (e.g. via spin hydro/spin kinetic theory)?
- Can we learn about chiral symmetry restoration with strange particles?
- Are there final state interactions for charm in pp and pPb collisions? None for bottom?
- Can we understand v_1 of light nuclei?
- Can we determine the full T dependence of diffusion of charm quarks in medium?
- Will deep learning help us?
- Do the non-monotonicities in the fluctuation measures indicate any critical behavior?
- Can this study be done with an EOS that has a critical point put in by hand, like BEST-EOS?
- Which explanation of strangeness enhancement is right? Will additional observables help?
- Is there still an R_{AA} - v_2 puzzle at higher p_T (both for $h^{+/-}$ and heavy particles)?
- How do we get to larger μ_B efficiently? How can we work around the sign problem?
- Can we get the right sign of the differential polarization?
- Can differences of some fluctuation measures in the strangeness sector between LQCD and HRG (even at $T \lesssim 130$ MeV) be understood?
- How can weekly bound objects be formed and survive in a hot environment? (ice in a fire puzzle)
- Can Taylor expansion around $\mu_B = 0$ produce reliable results beyond $\mu_B/T > \pi$?
- Can we solve the hyperon puzzle?
- Can freeze-out conditions be reliably determined from fluctuation observables?
- If there is no more R_{AA} - v_2 puzzle, why?
- Can we go from bottomonium to charmonium in the OQS?
- What will DREENA get when fluctuations are included?
- Can we understand heavier baryon states like Ξ_c^0, Ξ_c^+, and Ω_c^0?
- How can we understand the “redistribution of charm quarks” from meson to baryons as we move from e+e- to pp?
- Questions about strongly Interacting Matter under Rotation: Phase structure change? Equation of state change? Global and local polarization? Vector mesons? Spin transport theory? Spin hydrodynamics? Novel transport processes?
- Can we understand all systematics of directed flow of all particles?
- What is the origin of the anisotropy in $\gamma + A$ collisions (UPCs)?
- What are the effects of the strong magnetic field?
- How do we understand the R_{AA} and v_2 of J/ψ and Υ over the entire p_T range?
- What are the effects of magnetic field and vorticity on charmonium states?
- How do transport coefficients depend on chemical potentials and T?

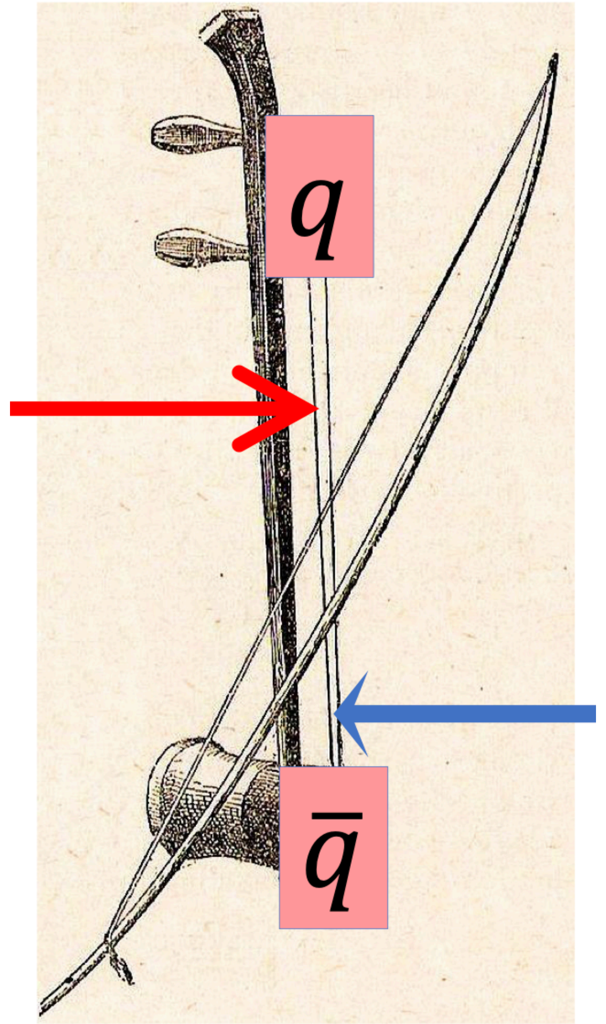
BACKUP

QED

- QED mesons

WONG, TUE 10:10 EDT

QCD string



QED string

$$\frac{(QCD\ boson\ mass)}{(QED\ boson\ mass)} = \sqrt{\frac{\alpha_s}{\alpha_c}} \approx \sqrt{\frac{0.7}{1/137}} \approx 10 \approx \frac{(hundreds\ MeV)}{(tens\ MeV)}$$

anomalous soft photons, X17, E38,…
also QED d-u-d neutron (stable, dark matter candidate)