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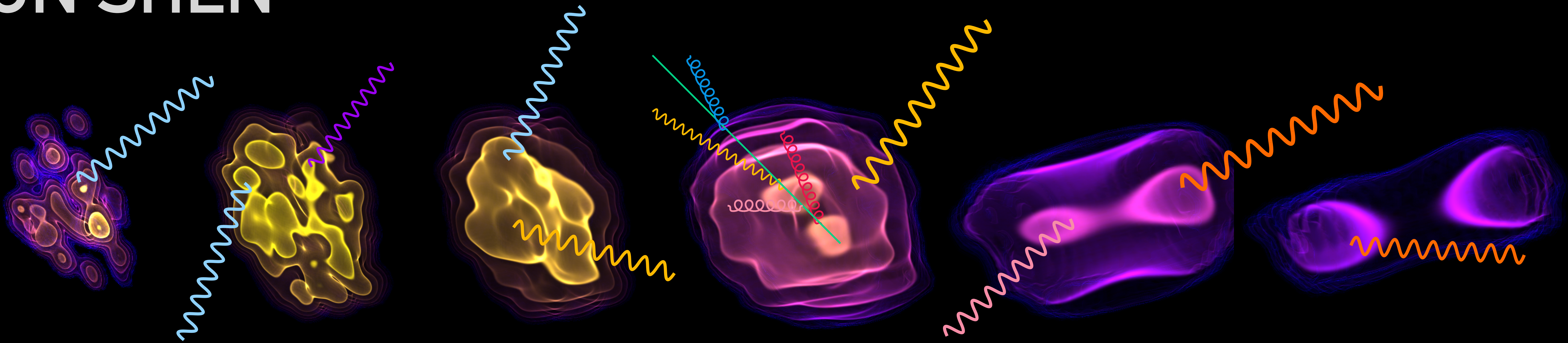
ILLUMINATING EARLY-STAGE DYNAMICS OF HEAVY-ION COLLISIONS THROUGH PHOTONS AT RHIC BES ENERGIES

CHUN SHEN



In collaboration with Abel Noble, Jean-Francois Paquet, Björn Schenke, and Charles Gale

The 11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

March 29, 2023

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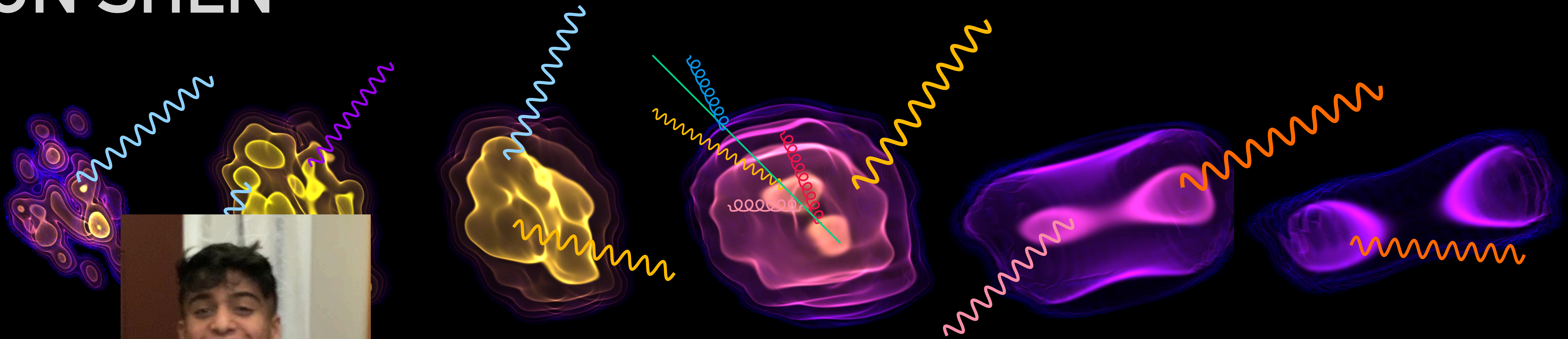

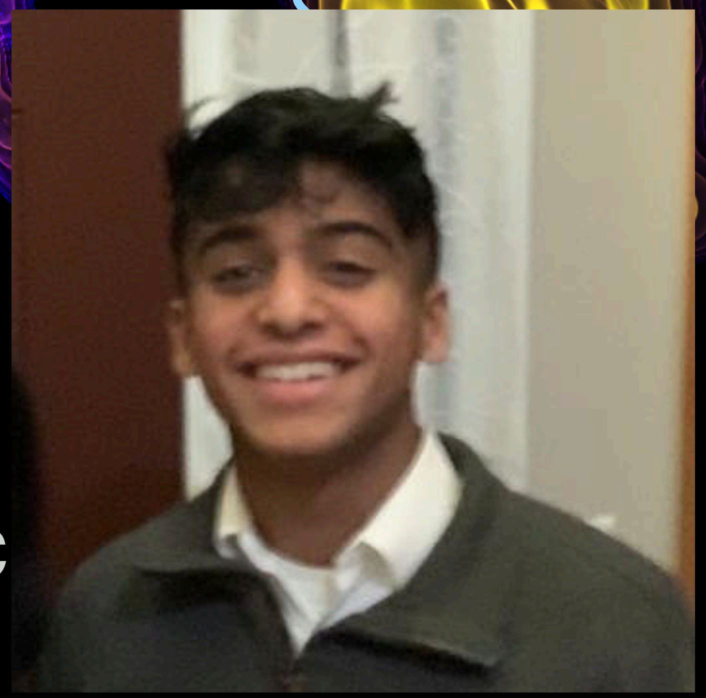

In c Abel Noble, Jean-Francois Paquet, Björn Schenke, and Charles Gale

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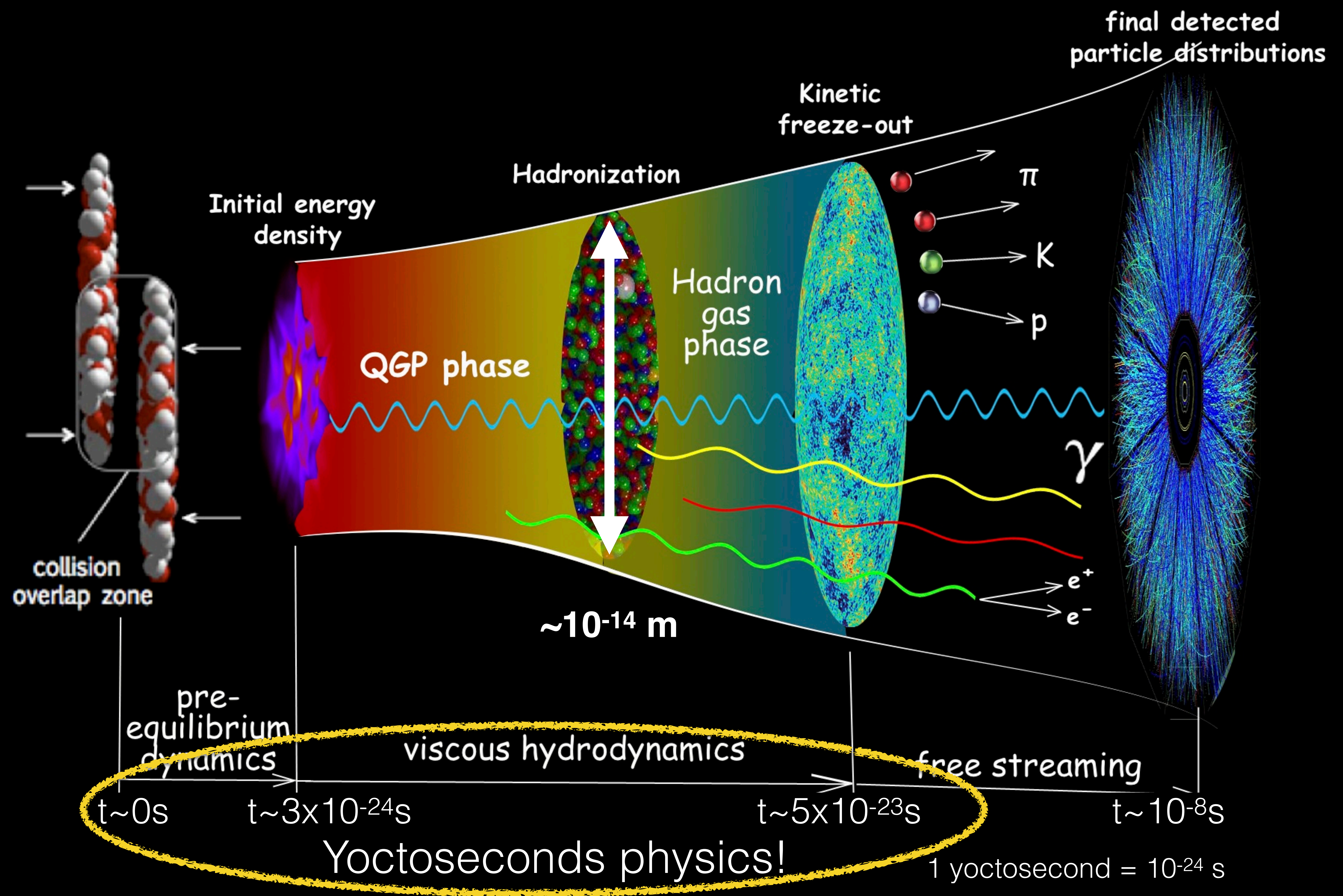
NUCLEAR MATTER UNDER EXTREME CONDITIONS



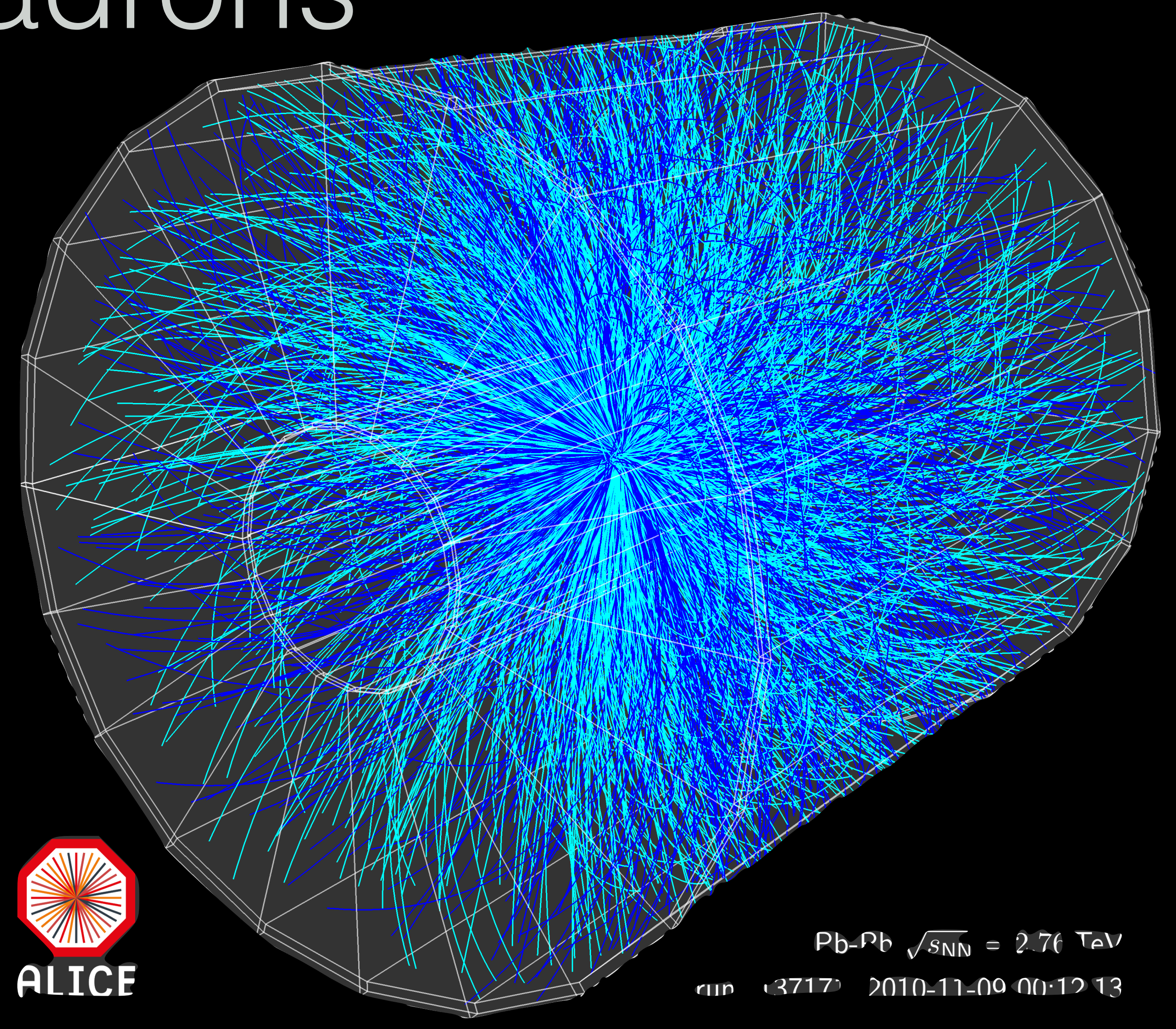
Heavy-ion collisions are tiny and have ultra-fast dynamics

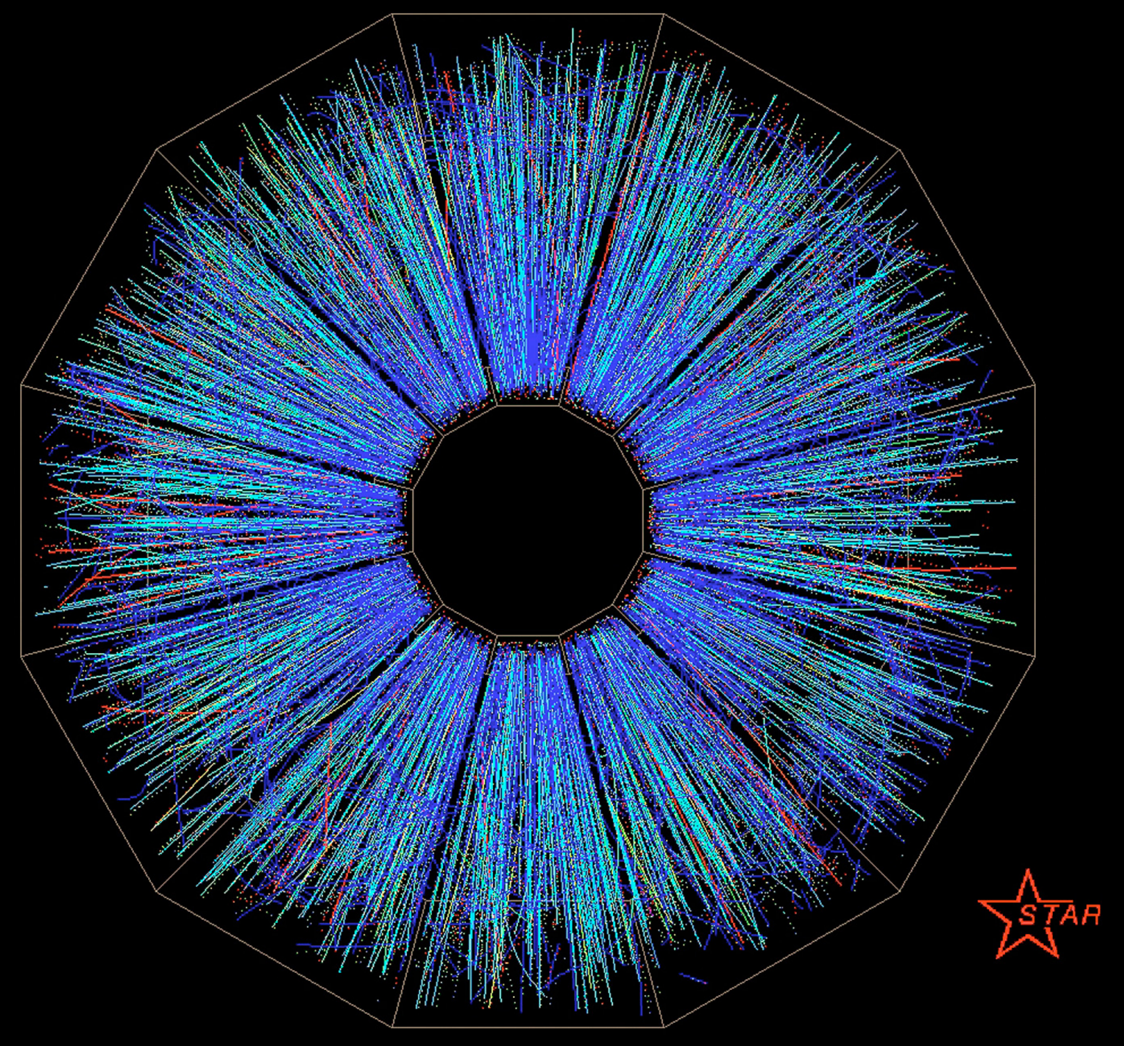
A variety of particles are emitted from the collisions

Multi-messenger nature of heavy-ion physics

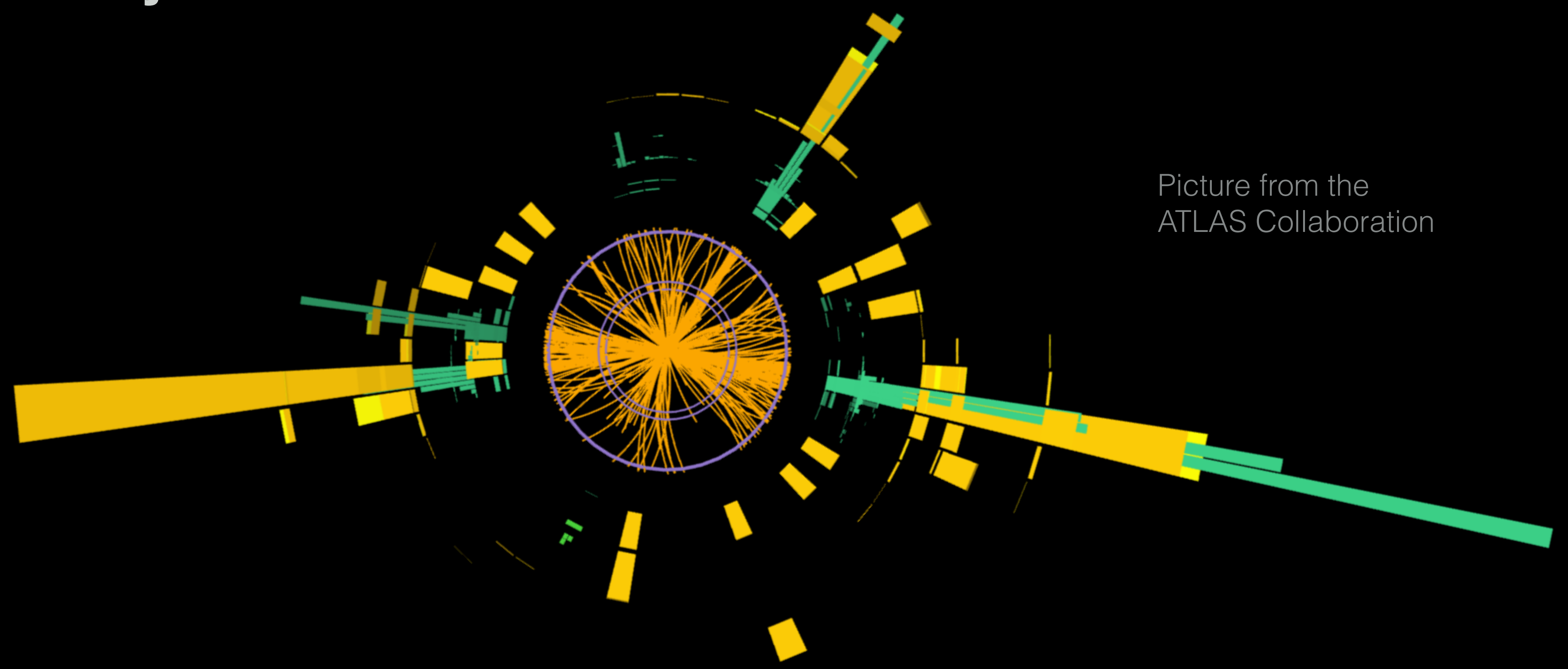
MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons



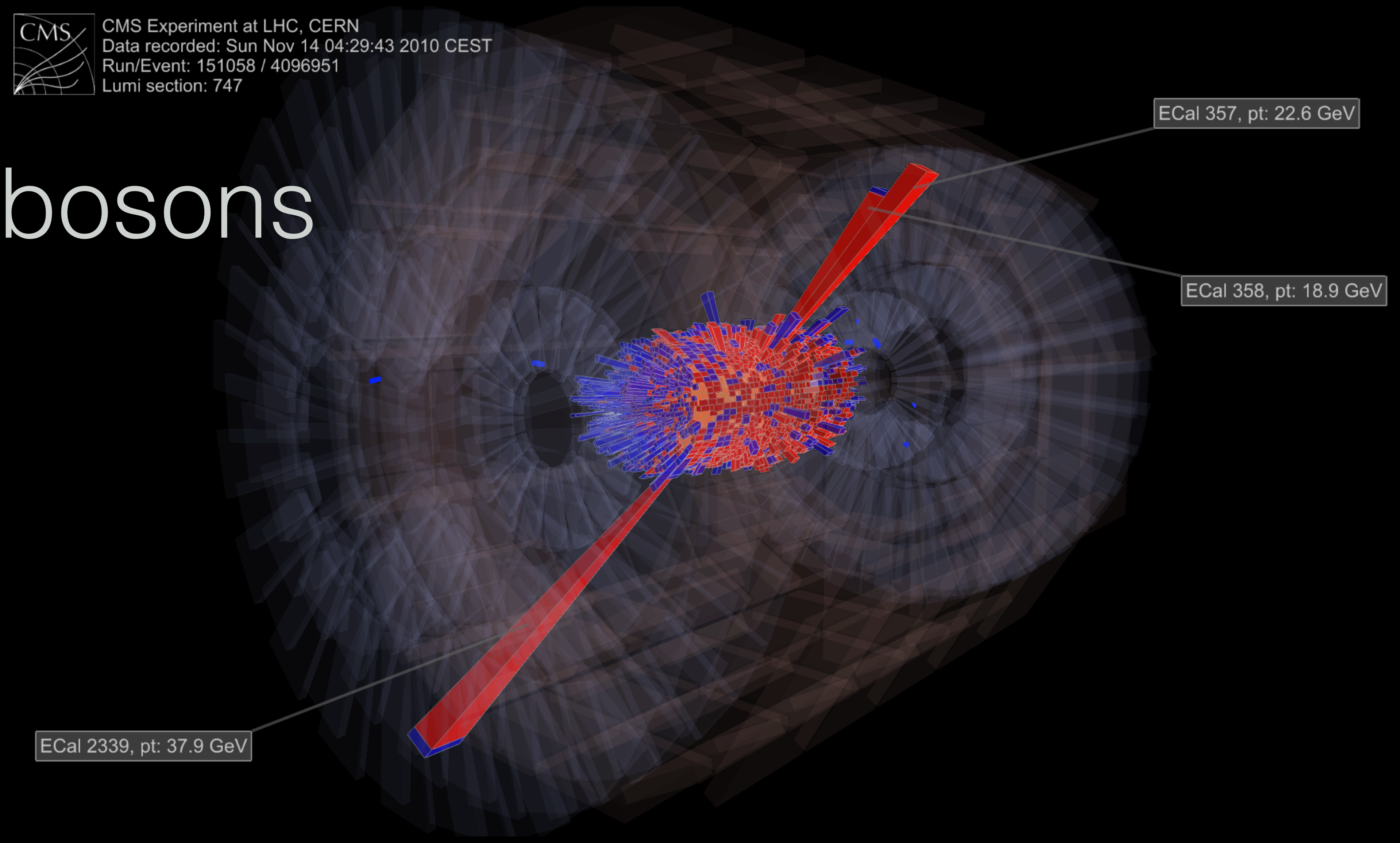


QCD jets

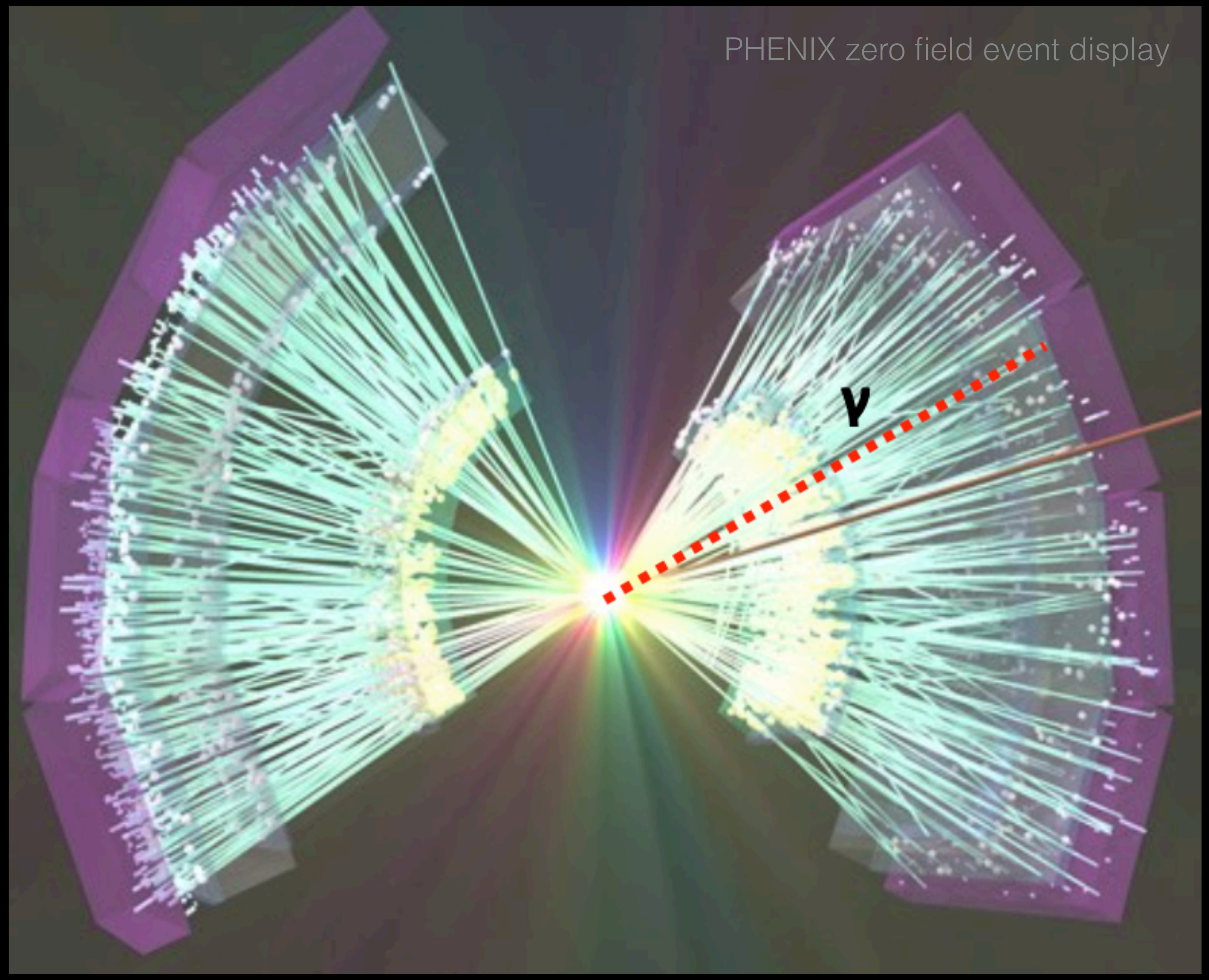


Picture from the ATLAS Collaboration

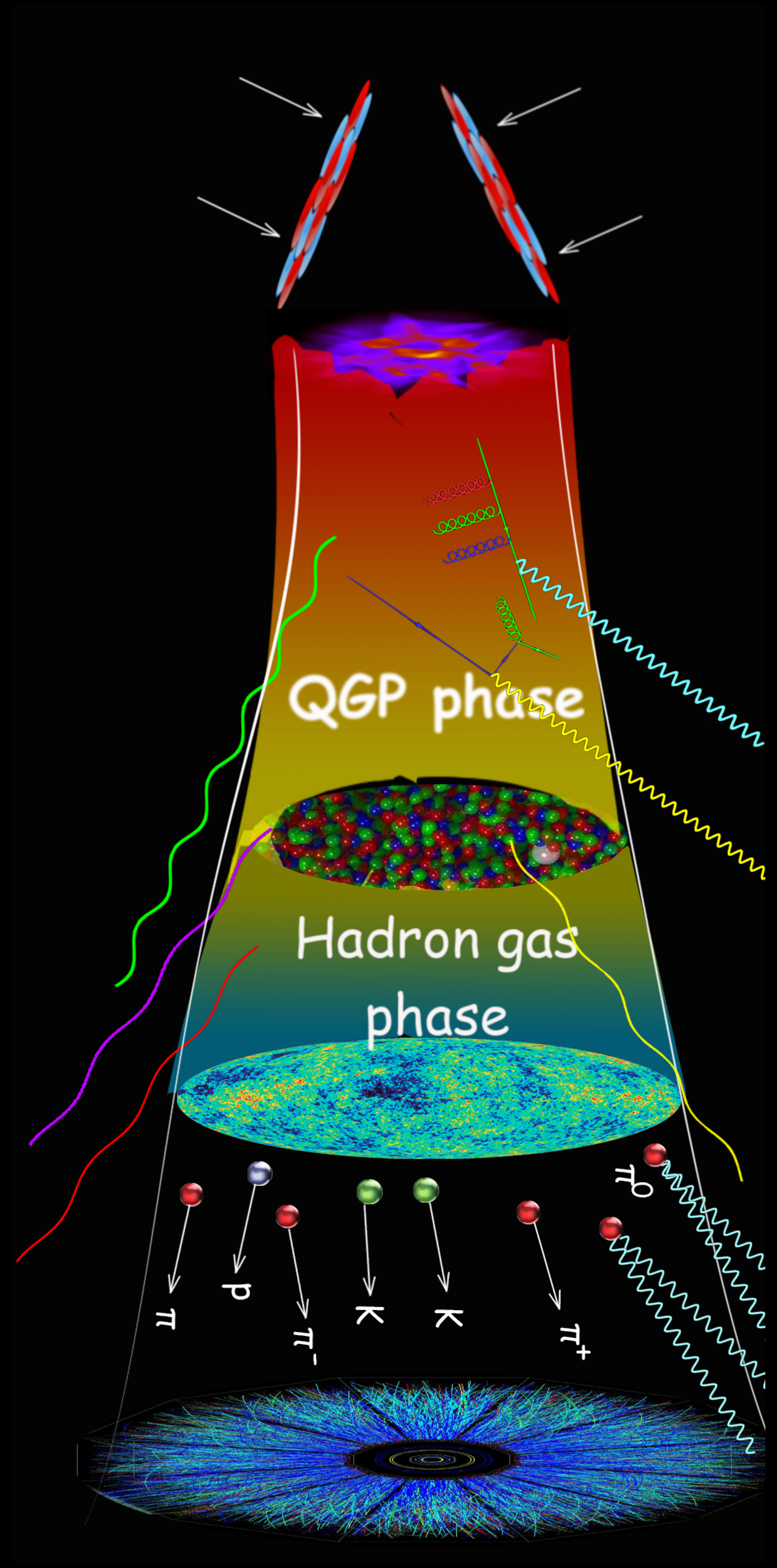
EW bosons

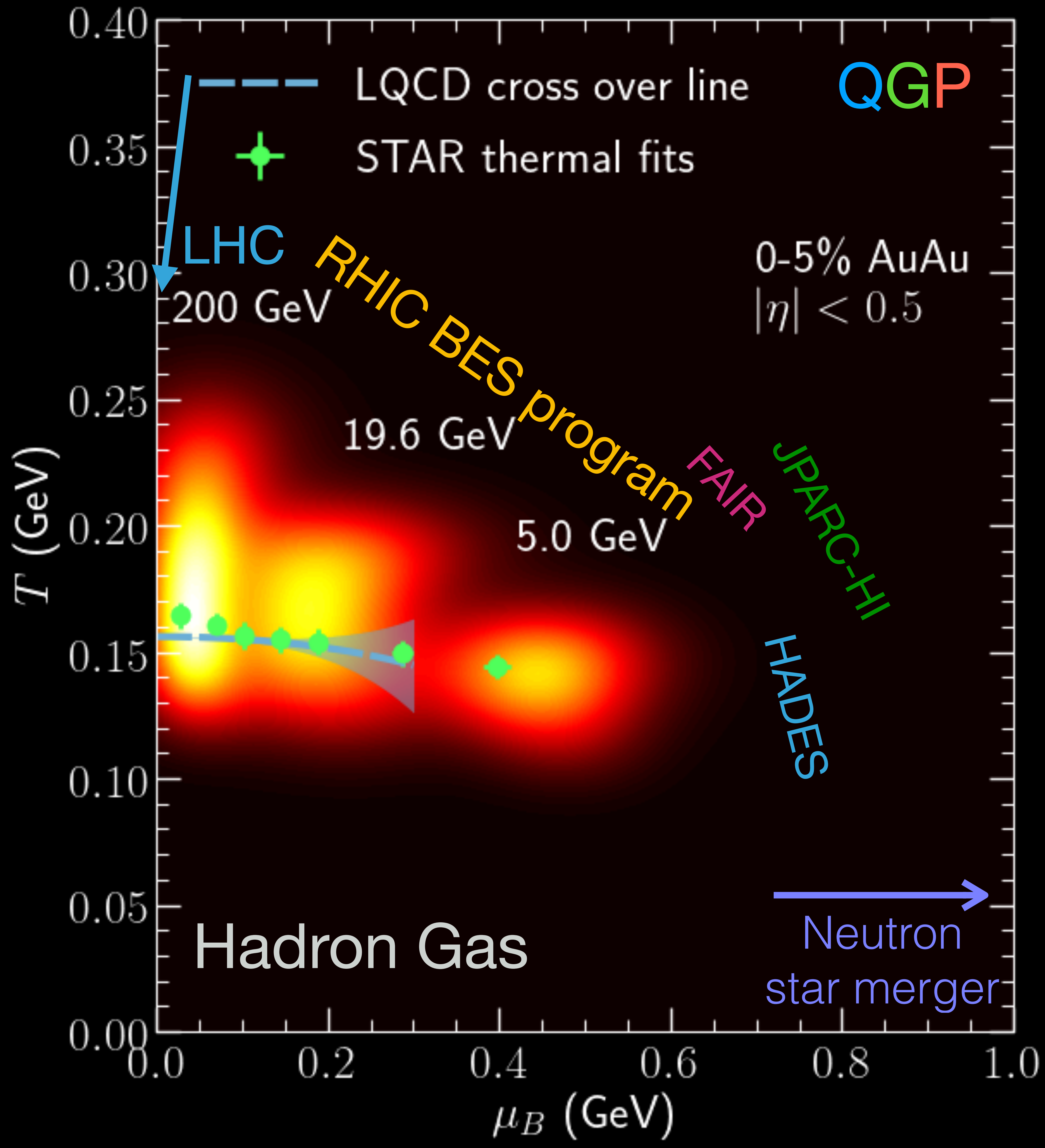


EM radiations



PROBING THE NUCLEAR MATTER PHASE DIAGRAM





- Search for a critical point & 1st order phase transition

$c_s^2(T, \{\mu_q\})$

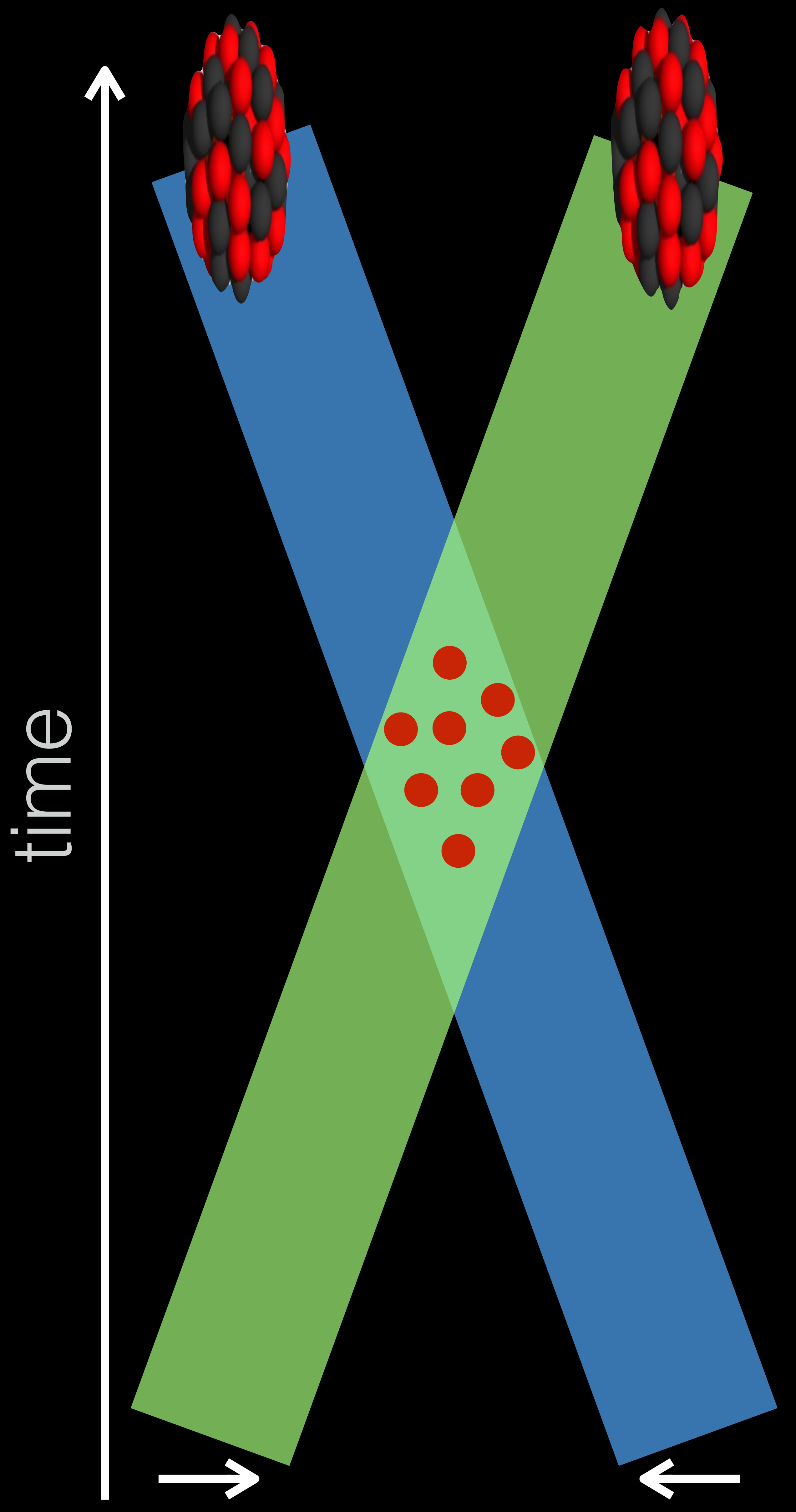
- How do the QGP transport properties change with baryon doping?

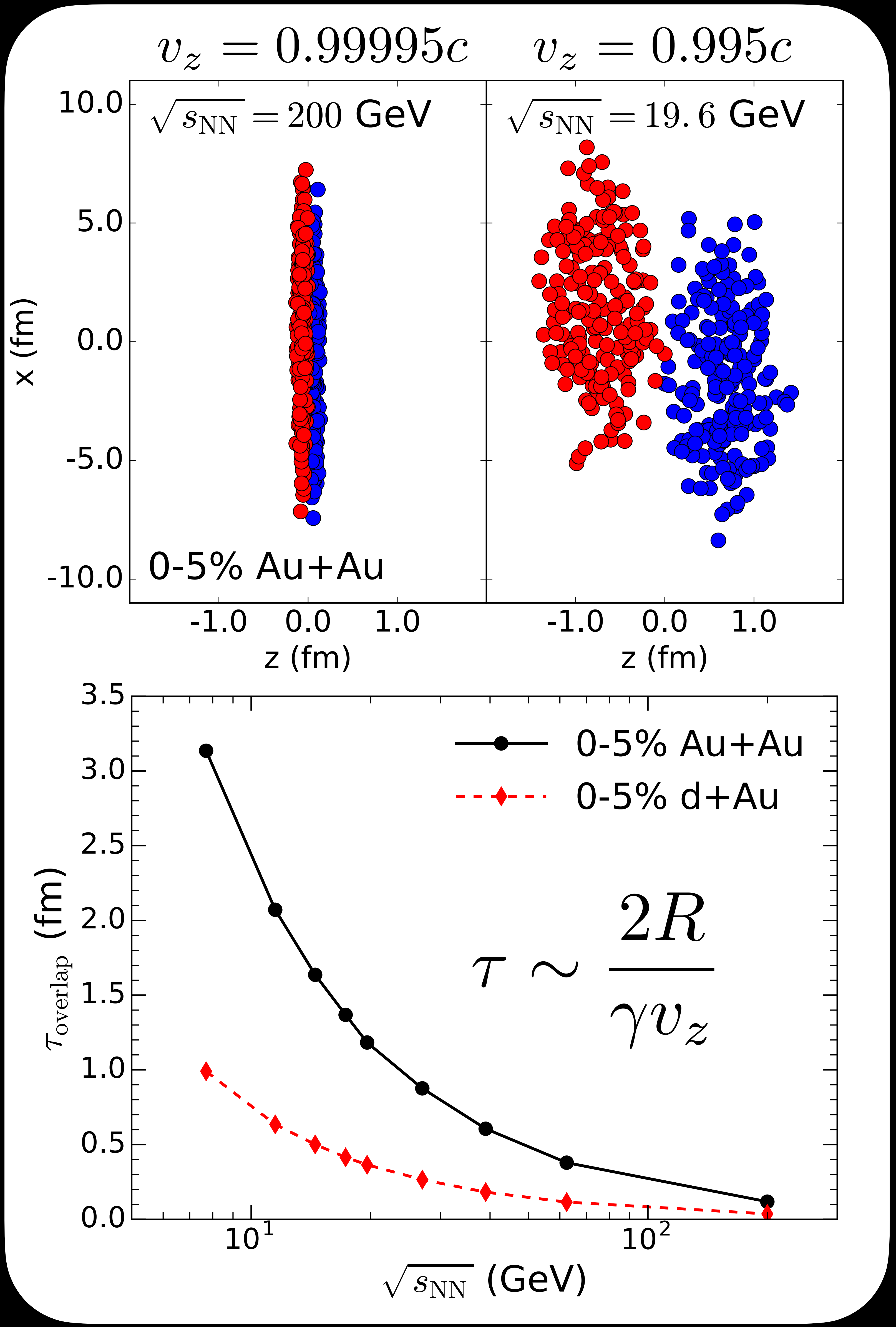
$(\eta/s)(T, \{\mu_q\})$, $(\zeta/s)(T, \{\mu_q\})$

- Access to new transport phenomena

Charge diffusion

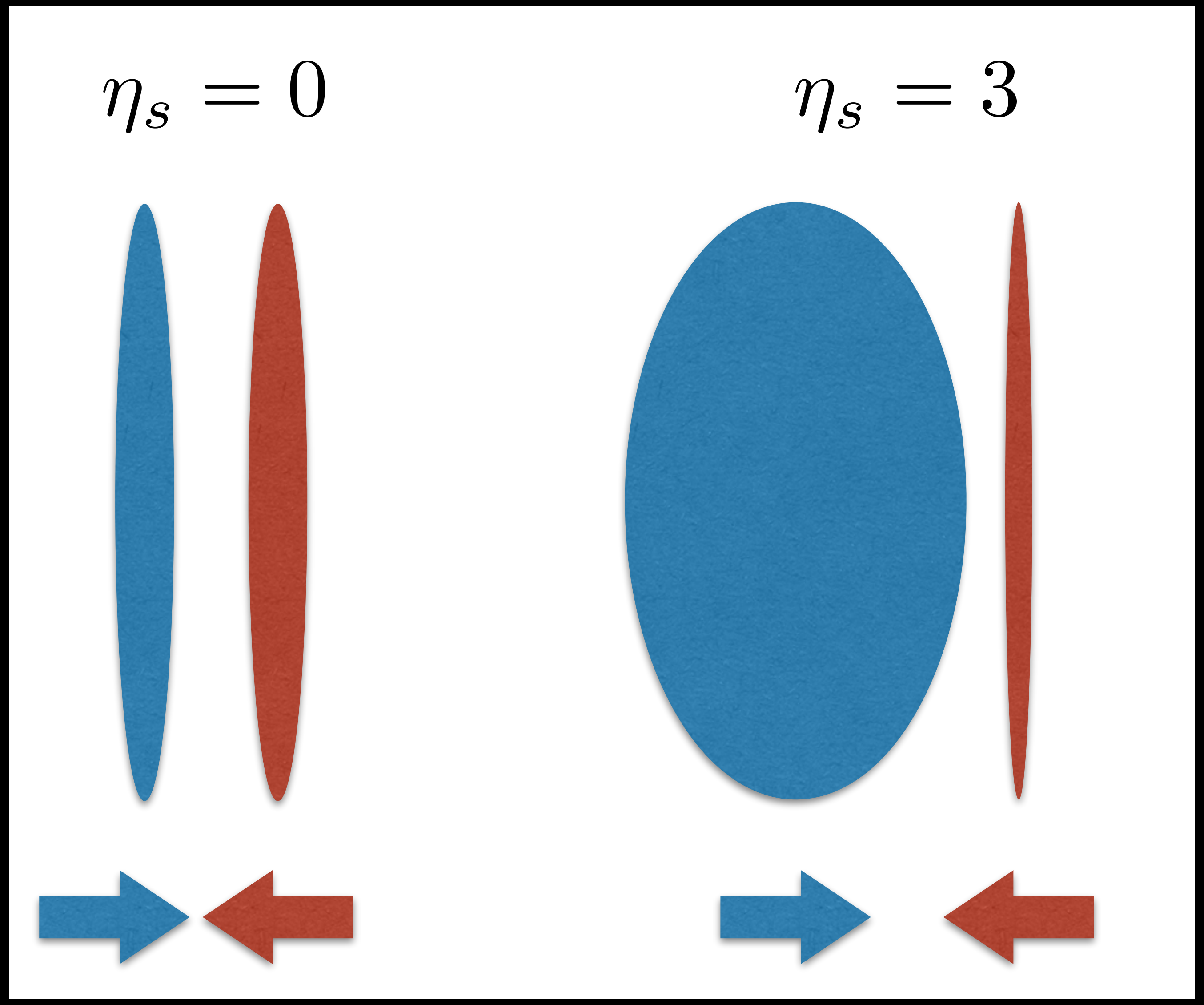
3D DYNAMICS BEYOND THE BJORKEN PARADIGM

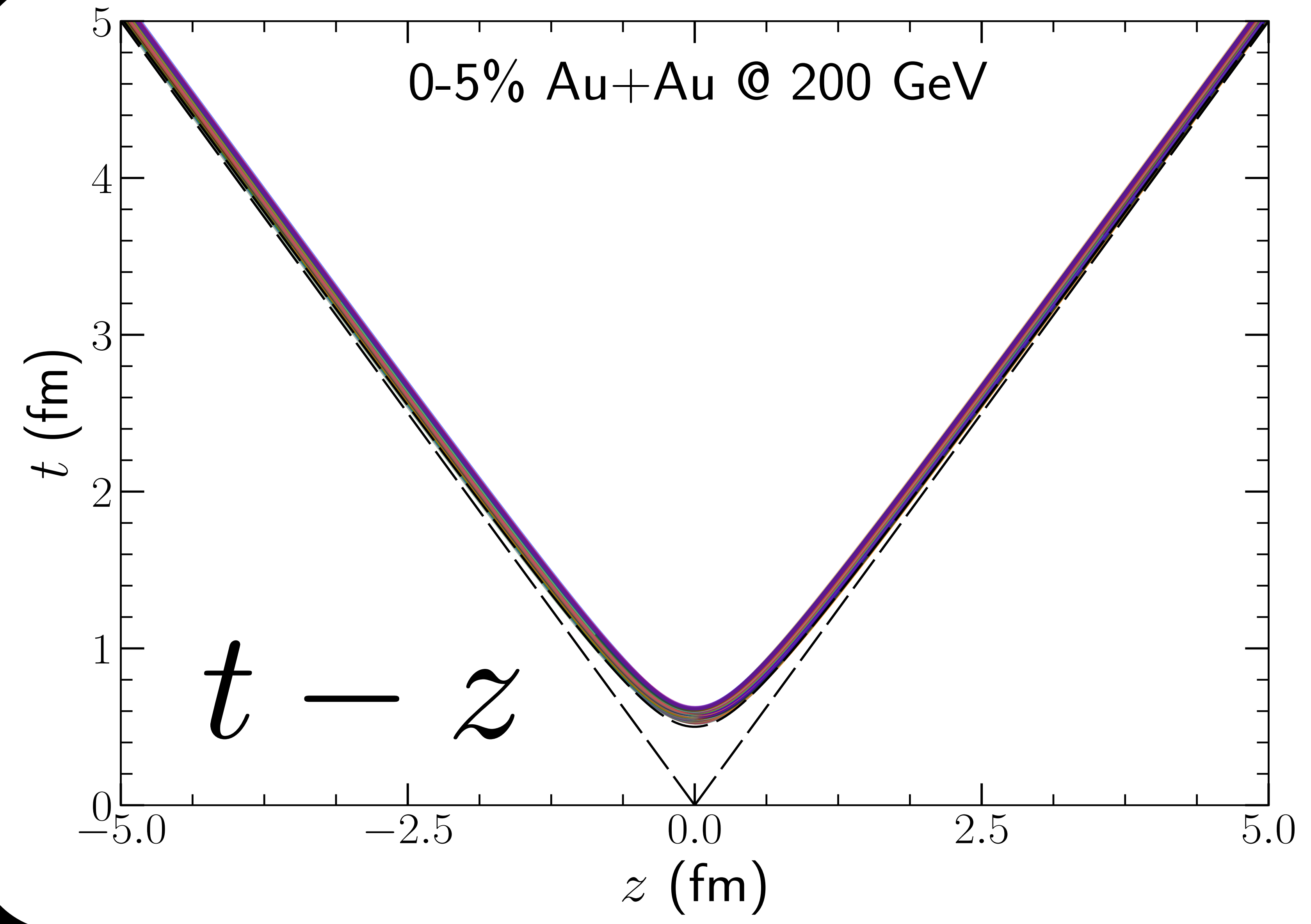


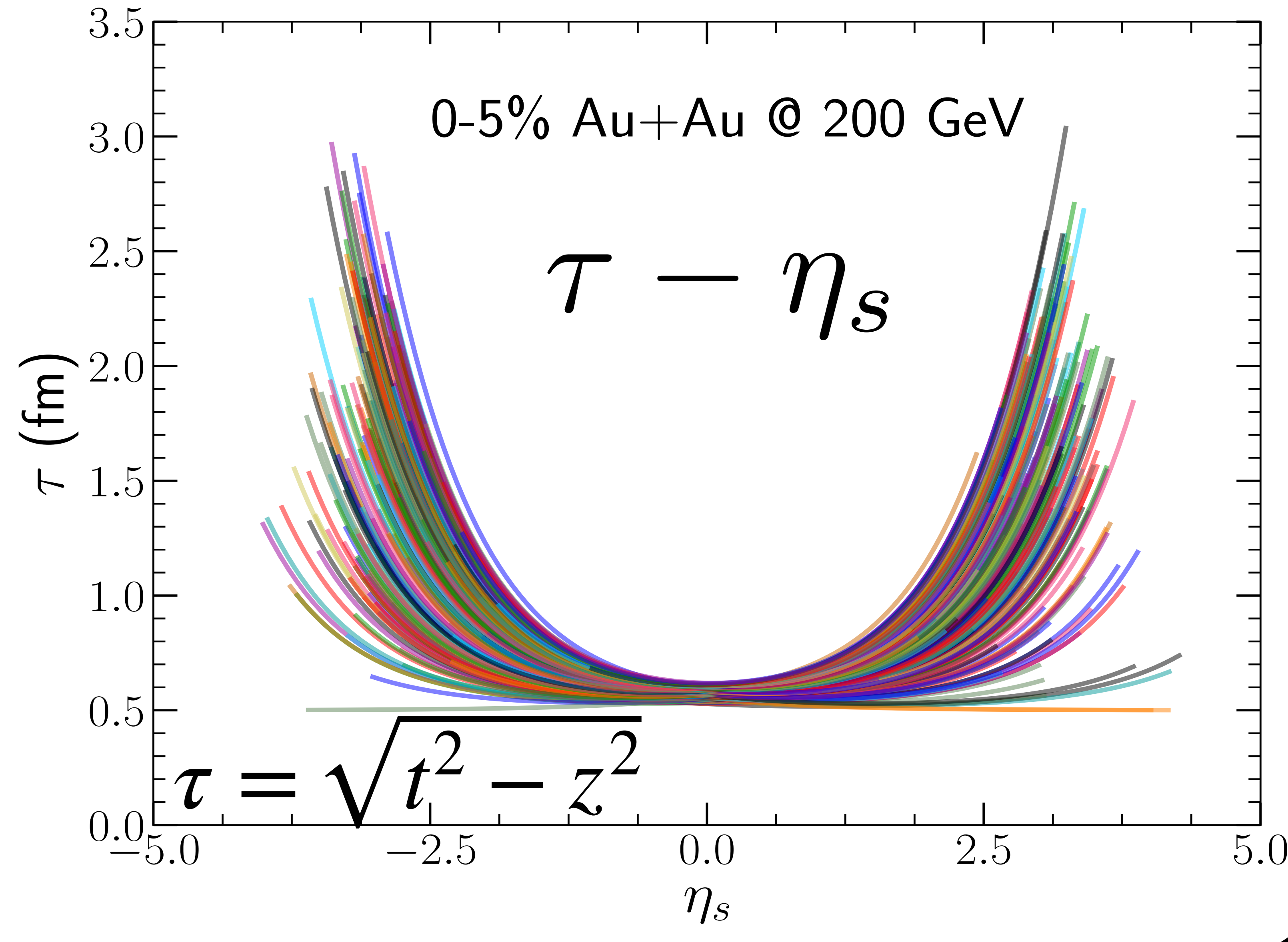


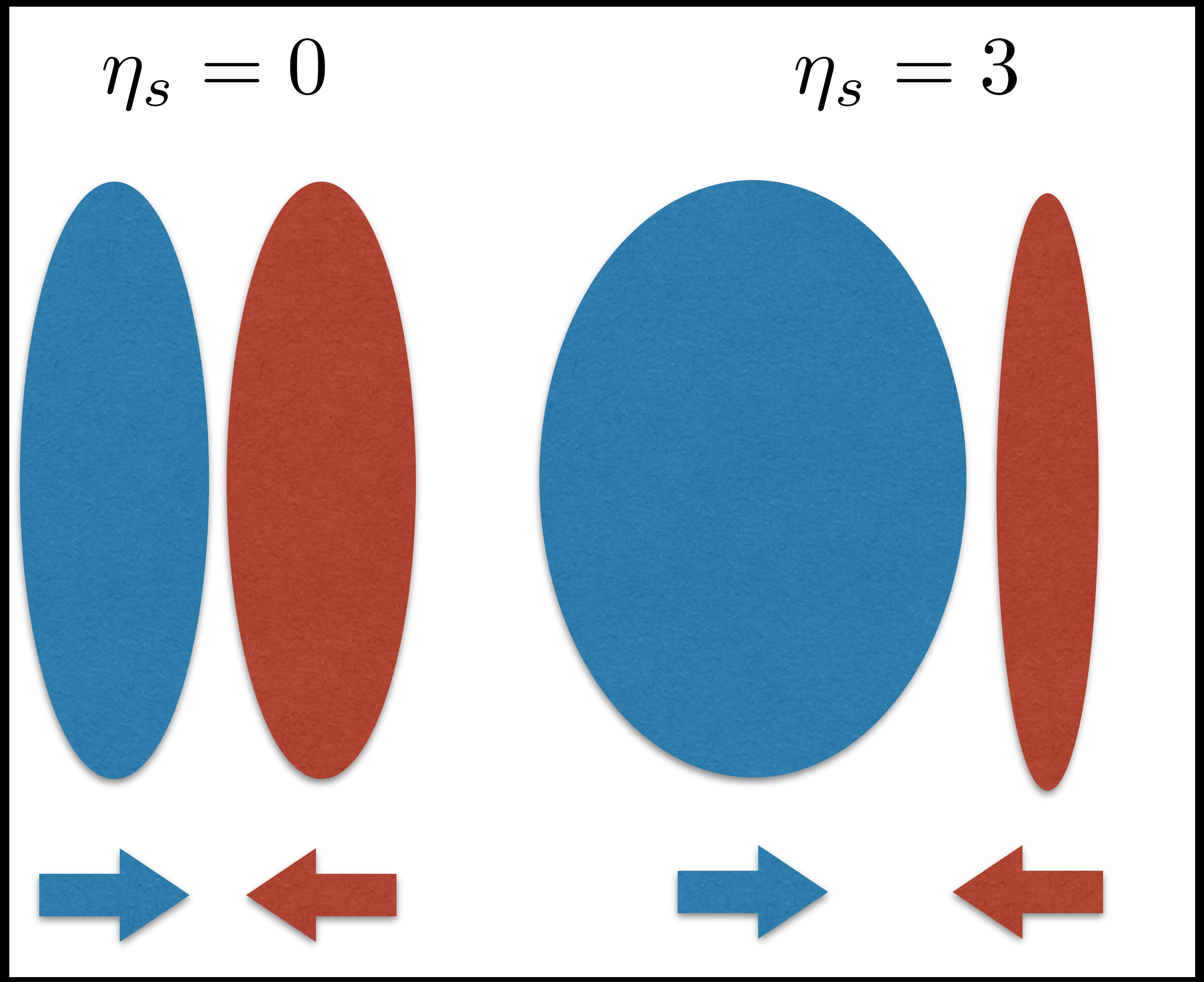
- Geometry-Based initial conditions
  - C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)
- Classical string-based initial conditions
  - A. Bialas, A. Bzdak and V. Koch, Acta Phys. Polon. B49 (2018)
  - C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907
- Transport model based initial conditions
  - I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
  - L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410
- Color Glass Condensate based models
  - M. Li and J. Kapusta, Phys. Rev. C 99, 014906 (2019)
  - L. D. McLerran, S. Schlichting and S. Sen, Phys. Rev. D 99, 074009 (2019)
  - M. Martinez, M. D. Sievert, D. E. Wertepny and J. Noronha-Hostler, arXiv:1911.10272 + arXiv:1911.12454 [nucl-th]
- Holographic approach at intermediate coupling
  - M. Attems, et al., Phys.Rev.Lett. 121 (2018), 261601

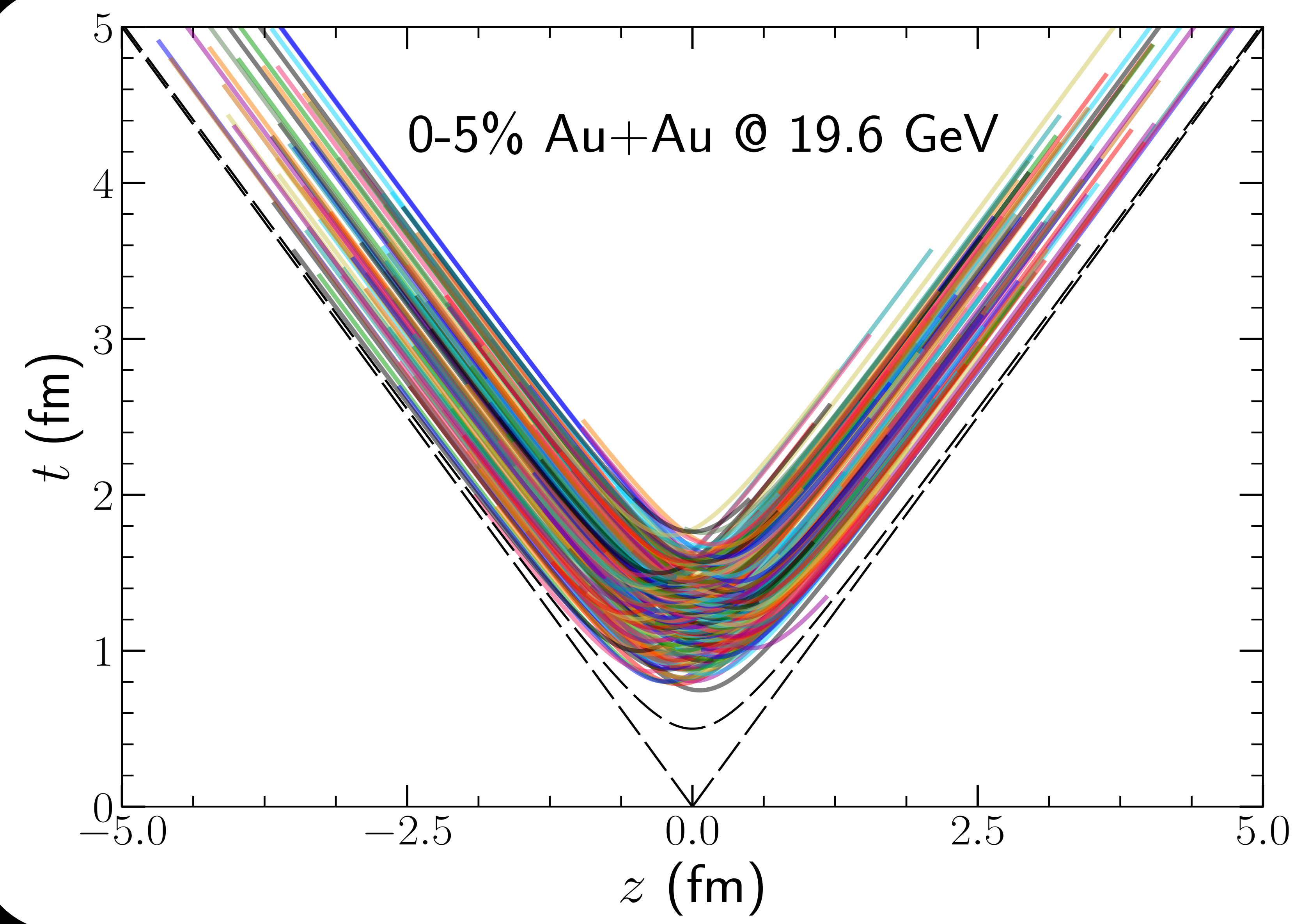
STRINGS' SPACE-TIME DISTRIBUTION

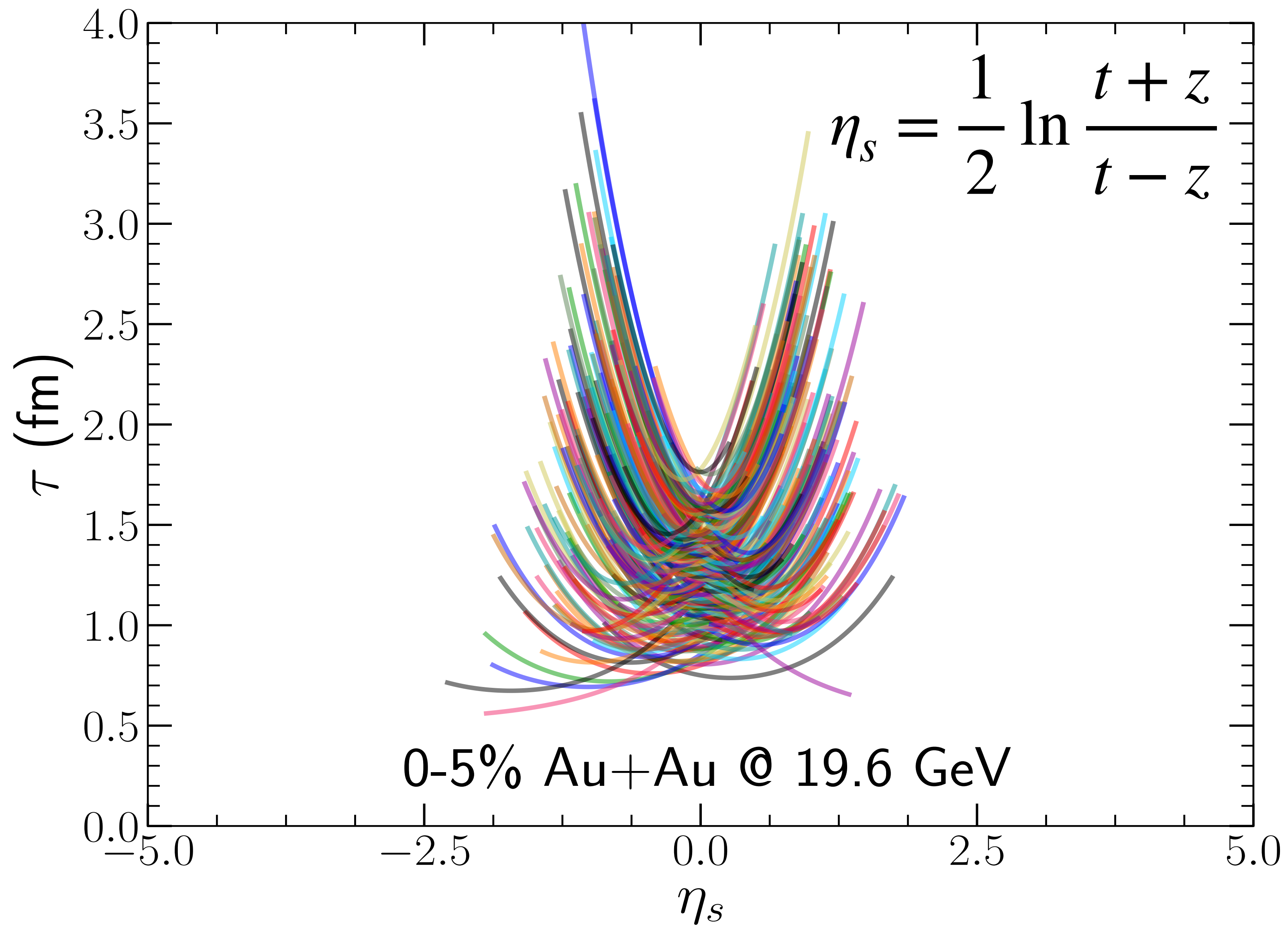






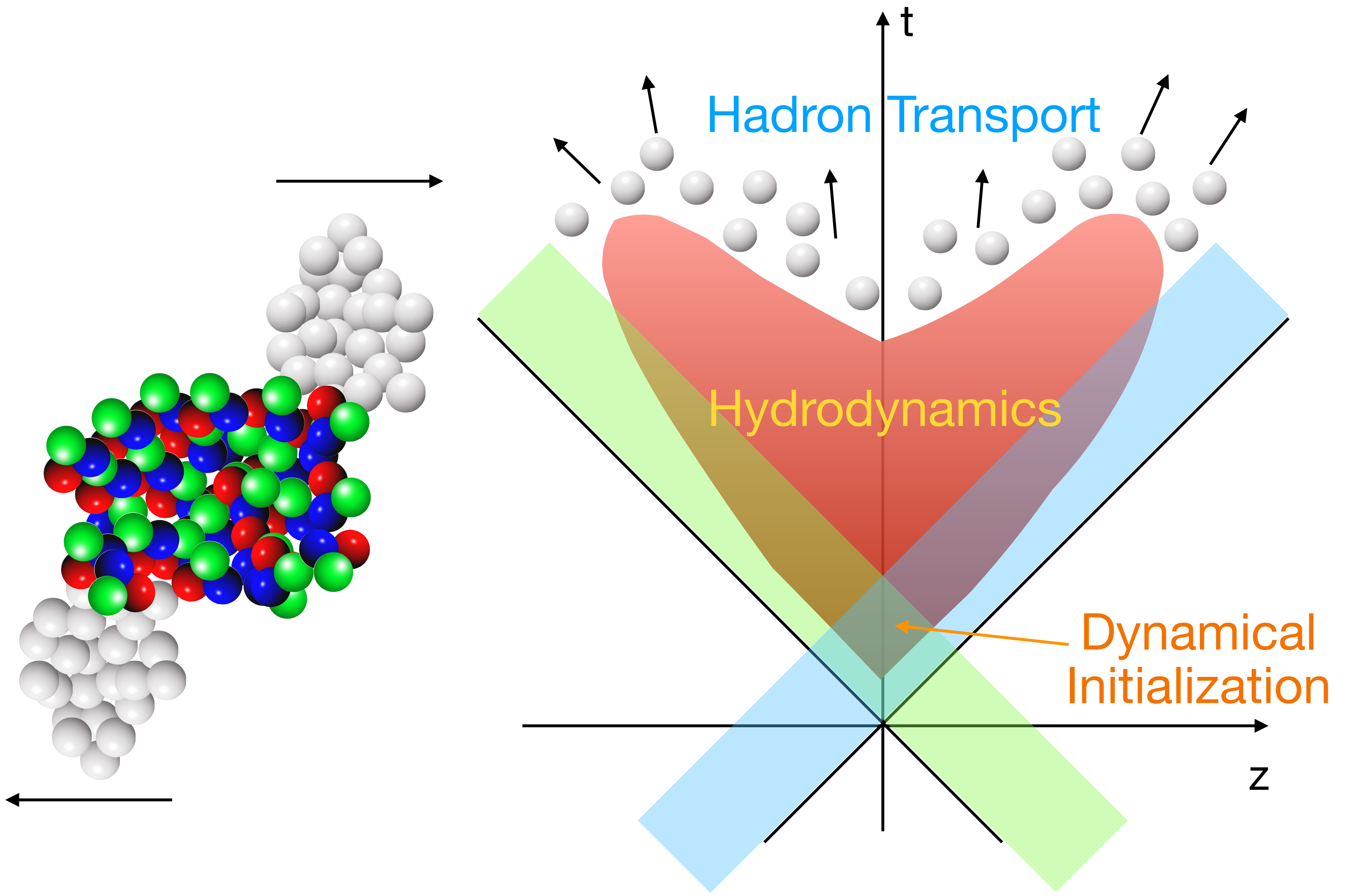






HYDRODYNAMICS WITH SOURCES

Energy-momentum current and net baryon density are fed into hydrodynamic simulations as source terms



C. Shen and L. Yan, Nucl. Sci. Tech. 31, no.12, 122

$$\partial_\mu T^{\mu\nu} = J^\nu_{\mathrm{source}}$$

$$\partial_\mu J^\mu = \rho_{\mathrm{source}}$$

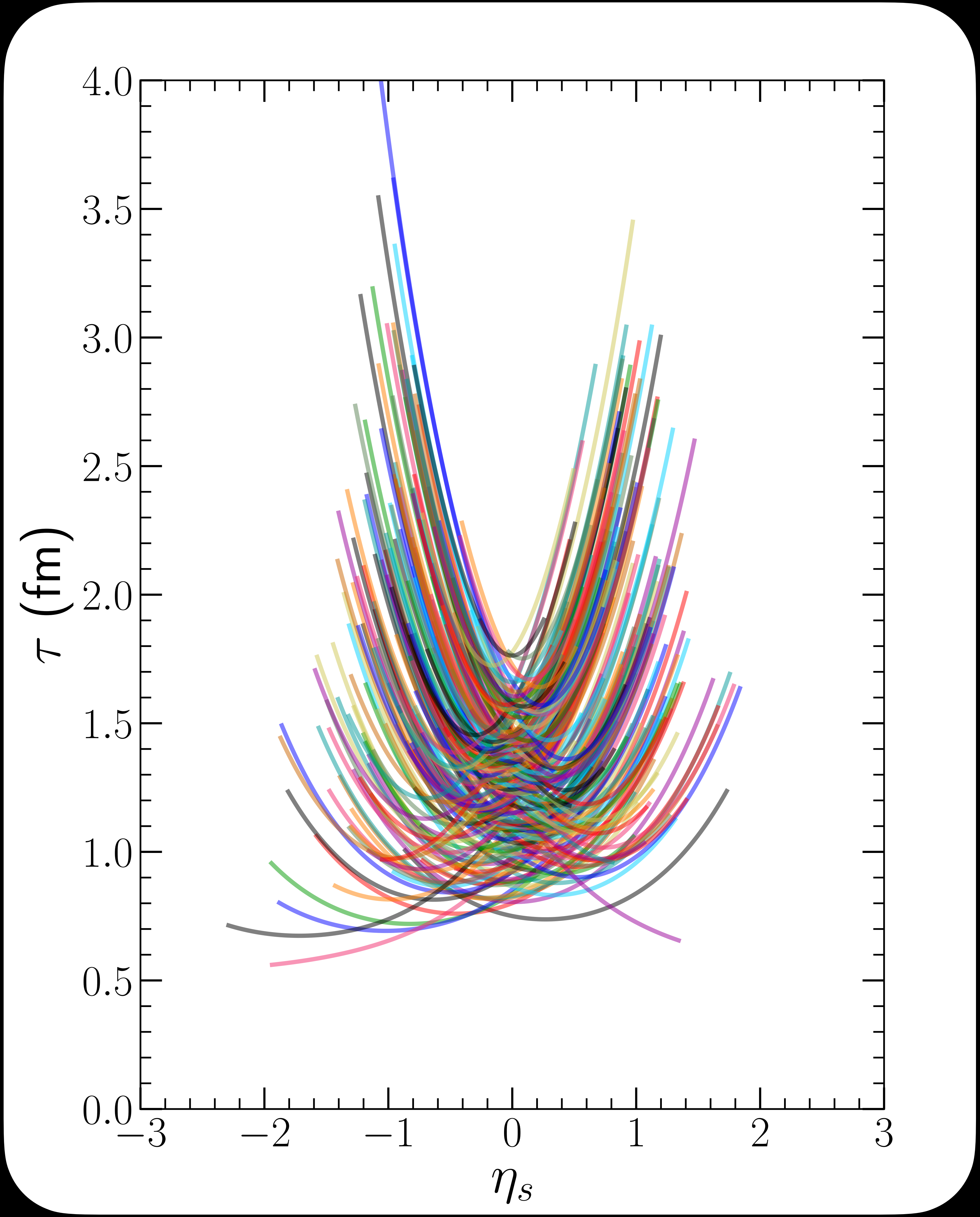
M. Okai, K. Kawaguchi, Y. Tachibana, and T. Hirano, Phys. Rev. C95, 054914 (2017)

C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907

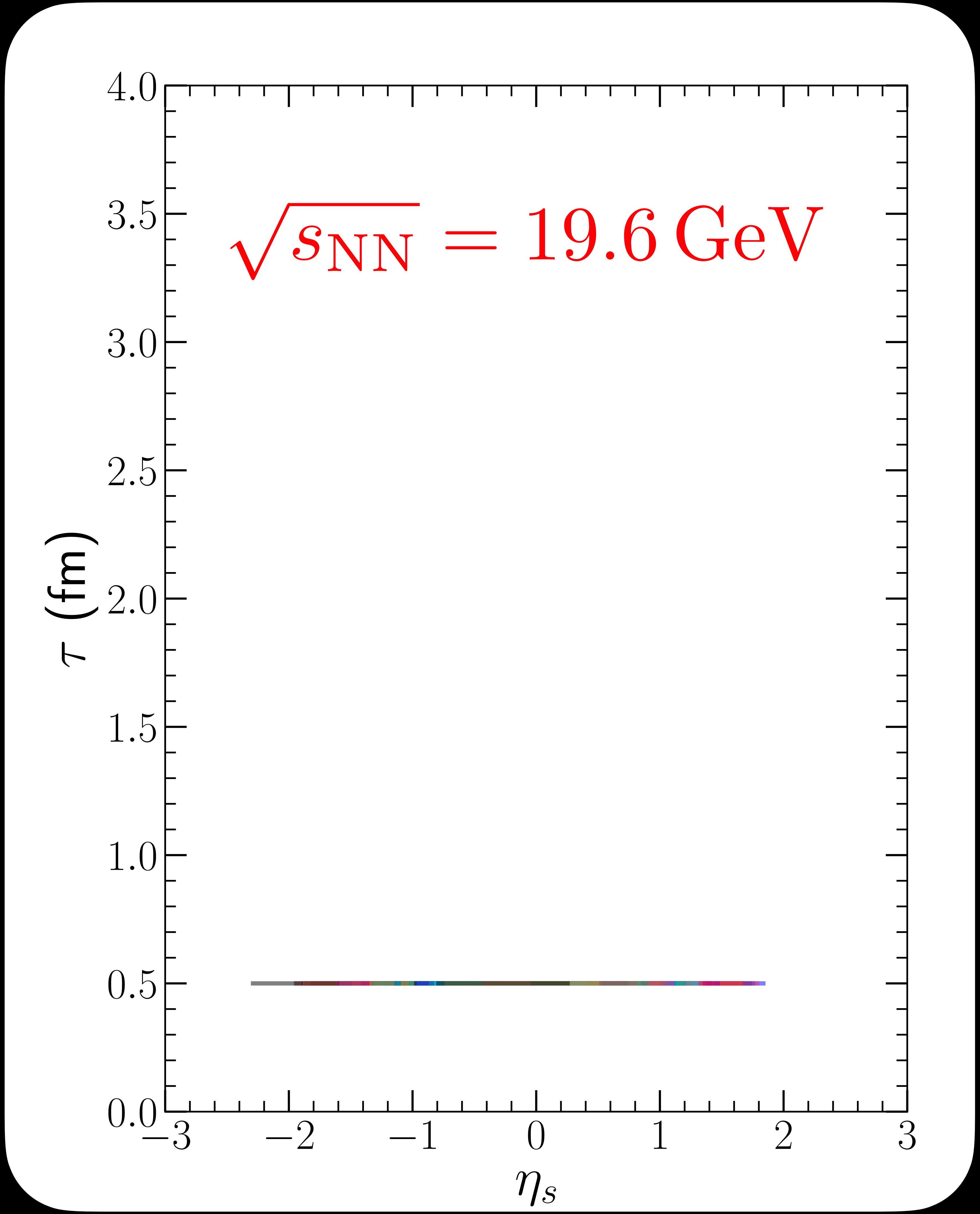
L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

Y. Akamatsu, M. Asakawa, T. Hirano, M. Kitazawa, K. Morita, K. Murase, Y. Nara, C. Nonaka and A. Ohnishi, Phys. Rev. C98, 024909 (2018)

CAN WE SEE DYNAMICAL INITIALIZATION IN DATA?

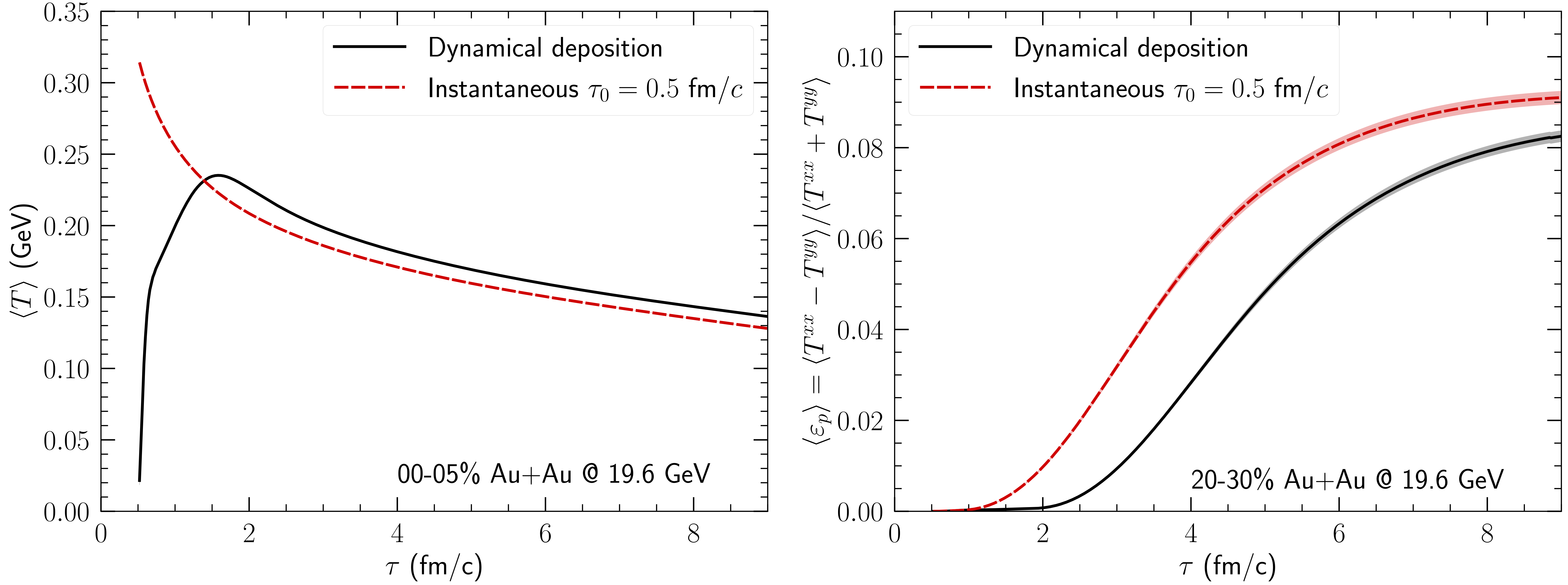


vs.



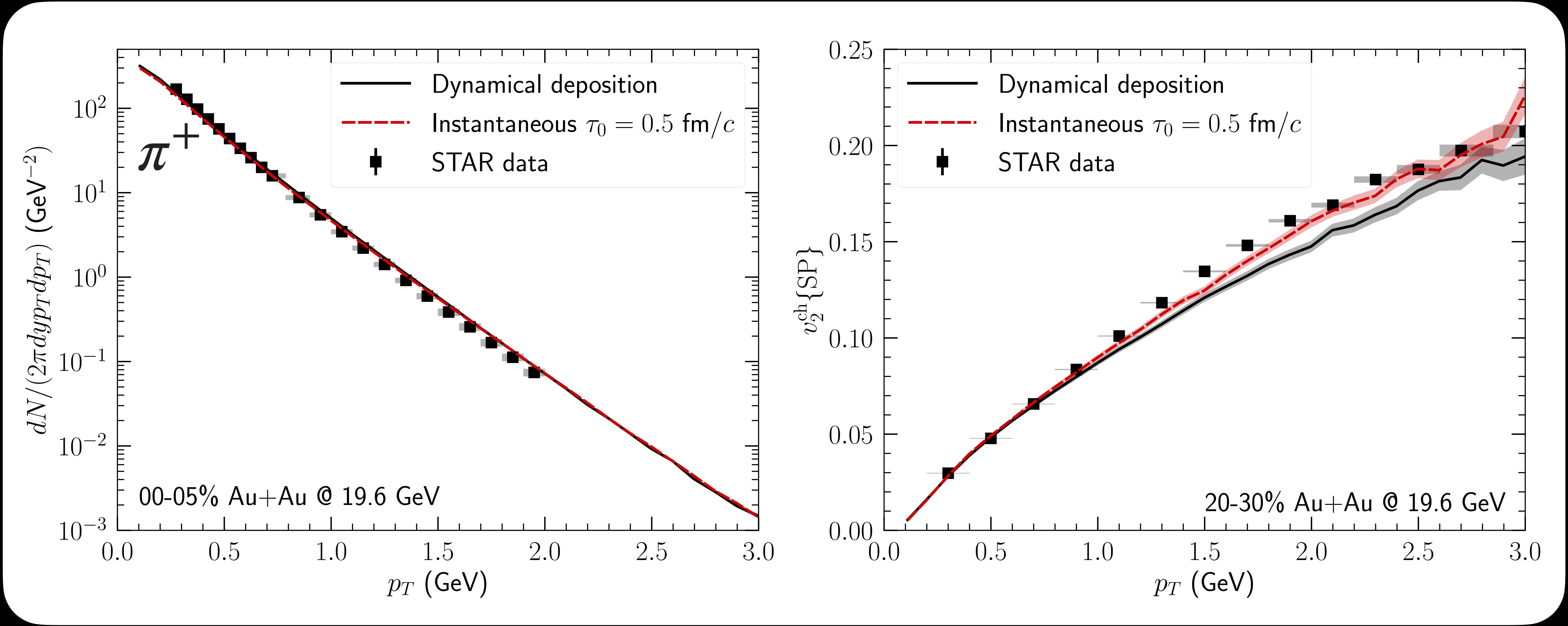
TRANSVERSE DYNAMICS WITH DYNAMIC SOURCES

C. Shen and B. Schenke, arXiv:1807.05141 [nucl-th]



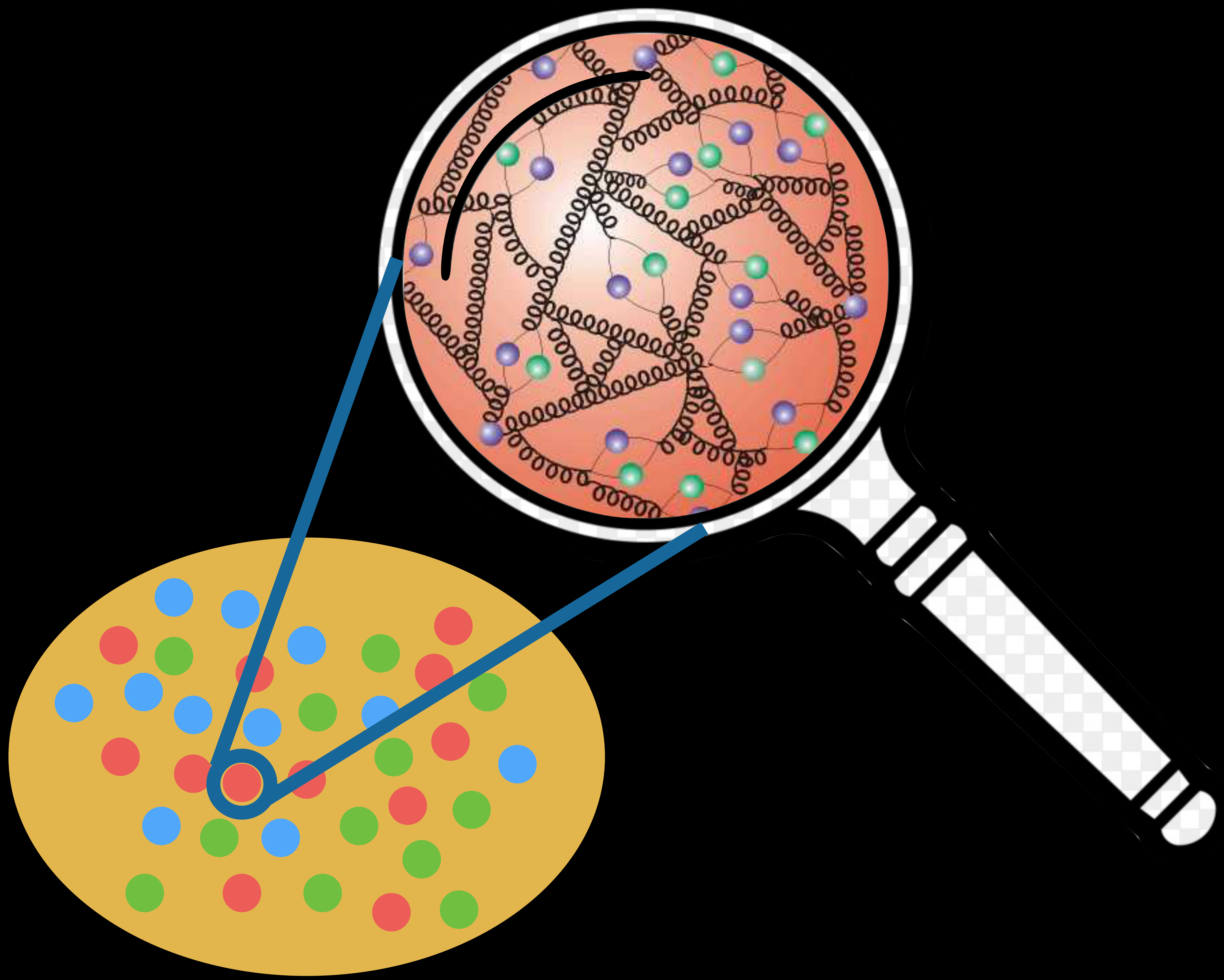
- The fireball average temperature heats up during the first 2 fm/c when the two nuclei pass through each other in the dynamical initialization setup
- Hydrodynamic flow and its anisotropy develop slower with dynamical sources

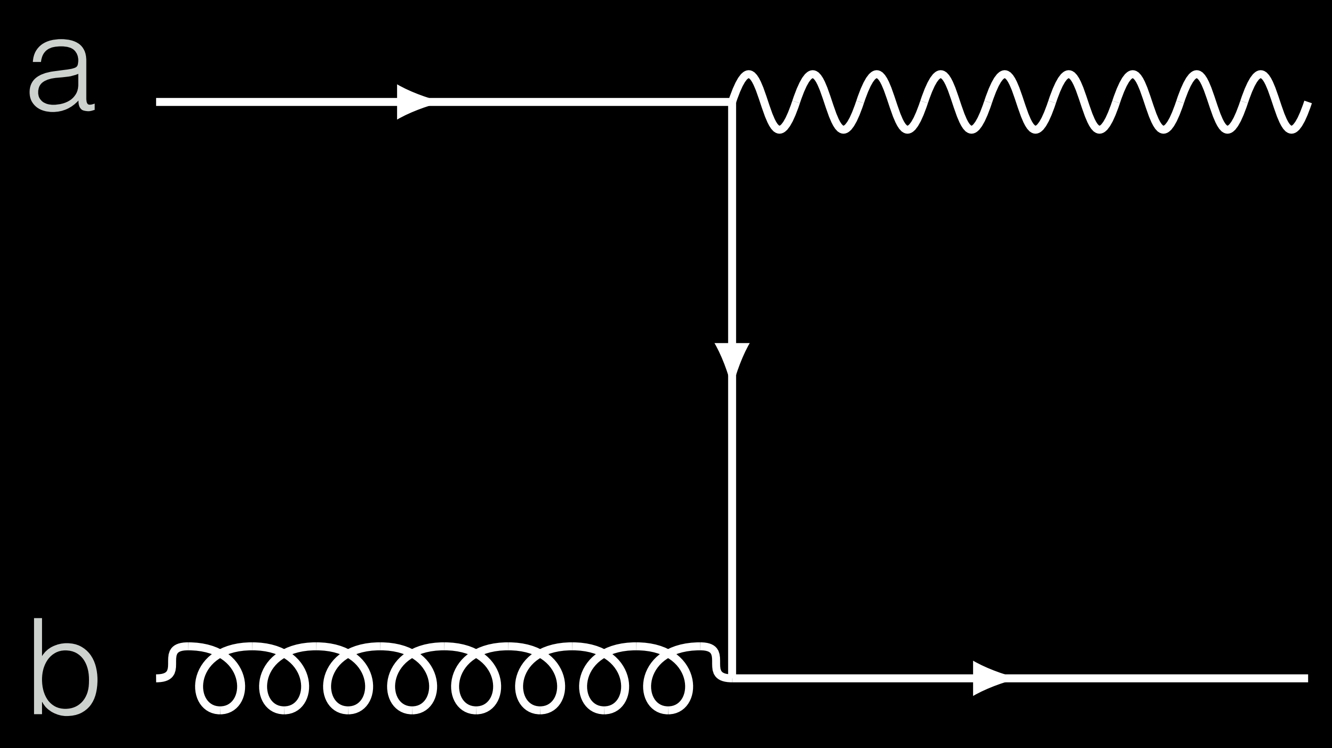
DO HADRONIC OBSERVABLES REMEMBER?



- Particles' p_T-spectra show little sensitivity to the dynamical source terms at 19.6 GeV
- Charged hadron elliptic flow is slightly smaller with dynamical sources

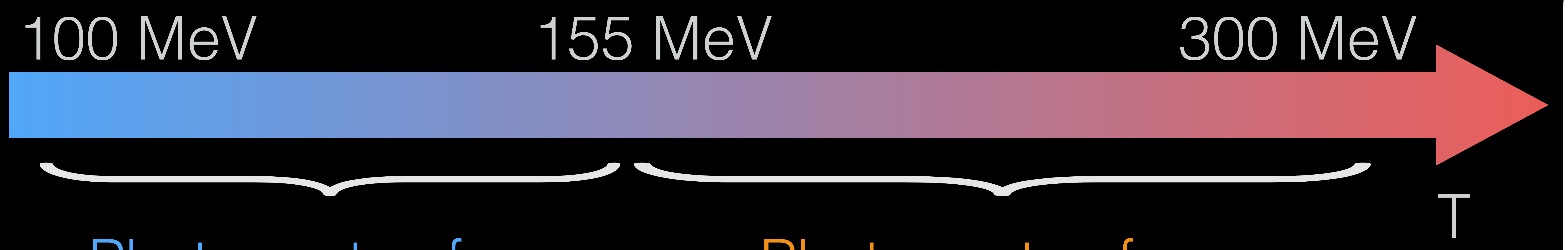
PHOTON AS A MICROSCOPE FOR THE QCD MATTER





$$E_p \frac{dN^\gamma}{d^3p} \propto f_a(p)$$

THERMAL PHOTON RATES AT FINITE μ_B



Photon rates from hadronic degrees of freedom

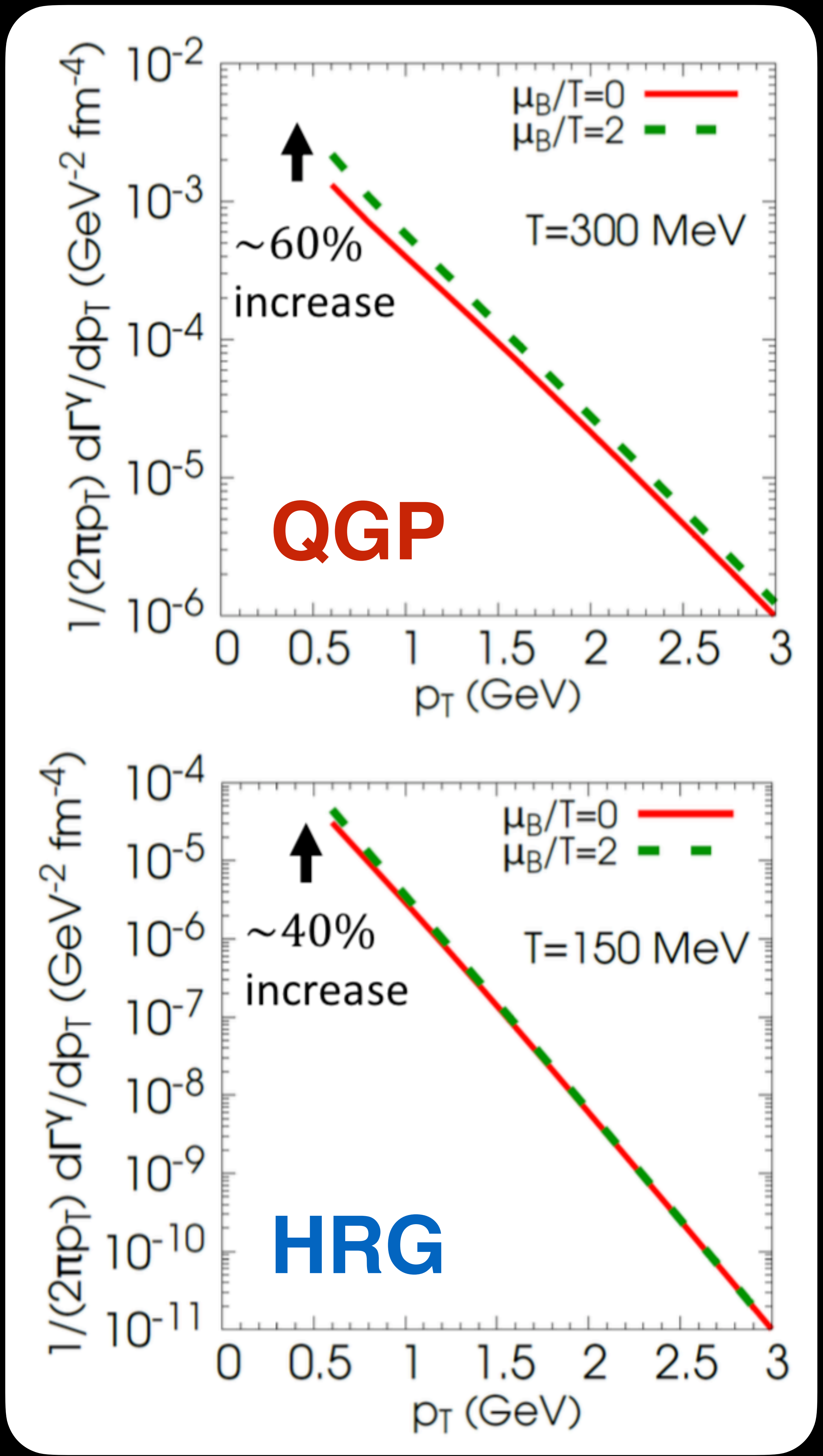
Photon rates from QGP degrees of freedom

QGP rates: Compton scatterings, $q\bar{q}$ annihilation & bremsstrahlung (with LPM) at finite μ_B

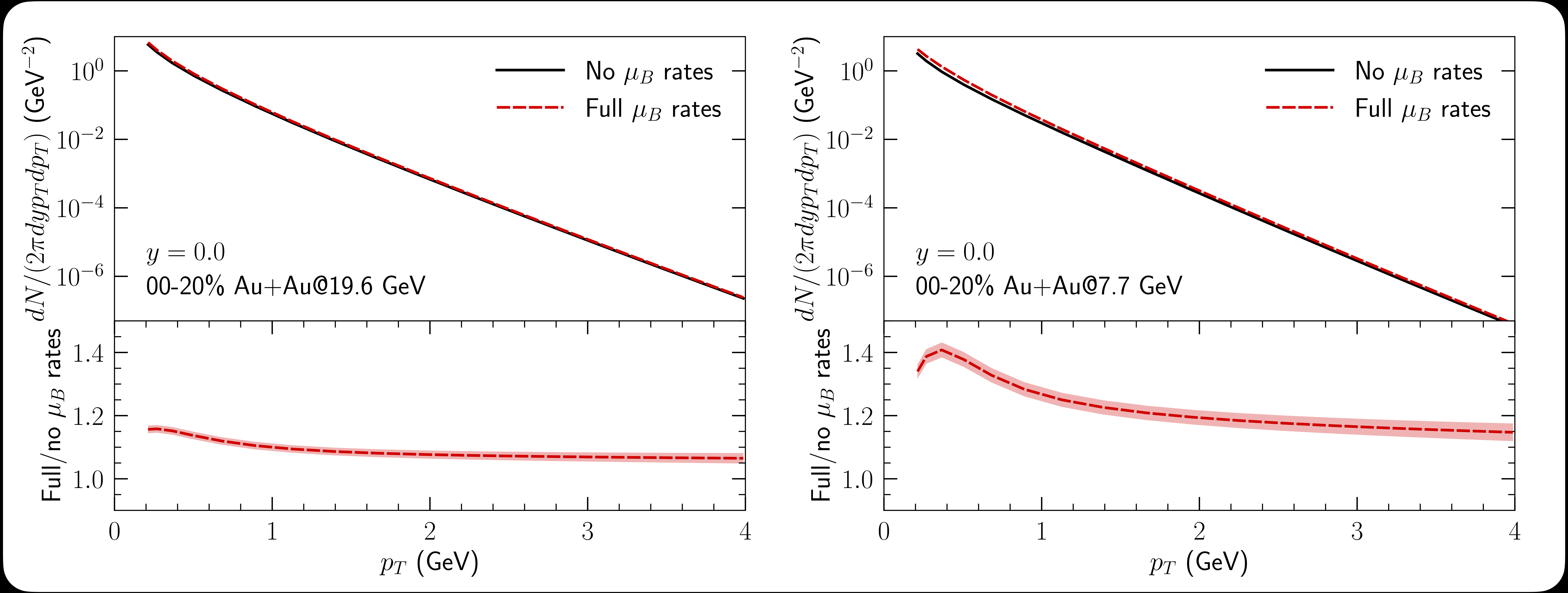
Traxler, Vija, Thoma (1995); Gervais, Jeon (2012); + this work

Hadronic rates: meson scatterings & baryon interactions (at finite μ_B)

Turbide, Rapp, Gale (2004); Heffernan, Hohler, Rapp (2014); Holt, Hohler, Rapp (2016)



ENHANCEMENT OF PHOTON EMISSION AT FINITE μ_B



- Baryon chemical potential increases thermal photon yield by 20-40% at low collision energies

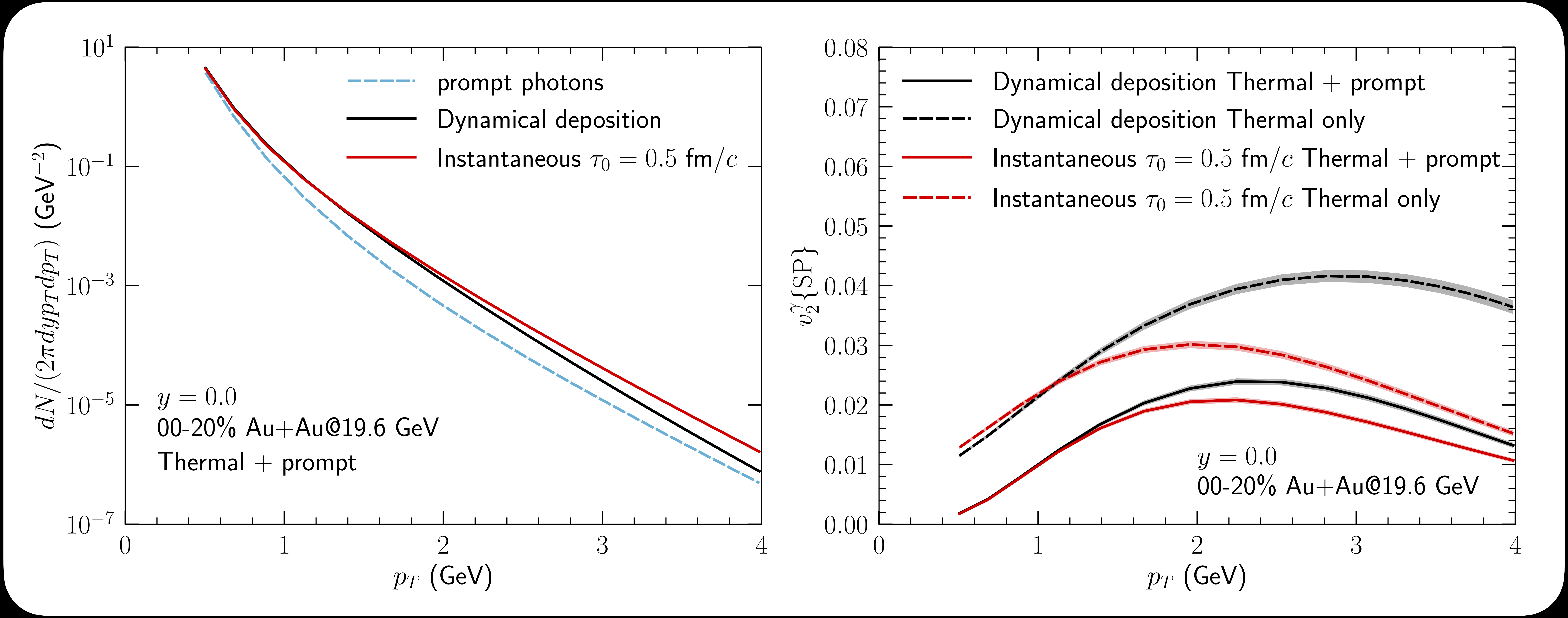
DYNAMICAL INITIALIZATION EFFECT ON EM PROBES

- The early-stage dynamical Initialization results in fewer high p_T thermal photons than those in the instantaneous simulations at low collision energies

DYNAMICAL INITIALIZATION EFFECT ON EM PROBES

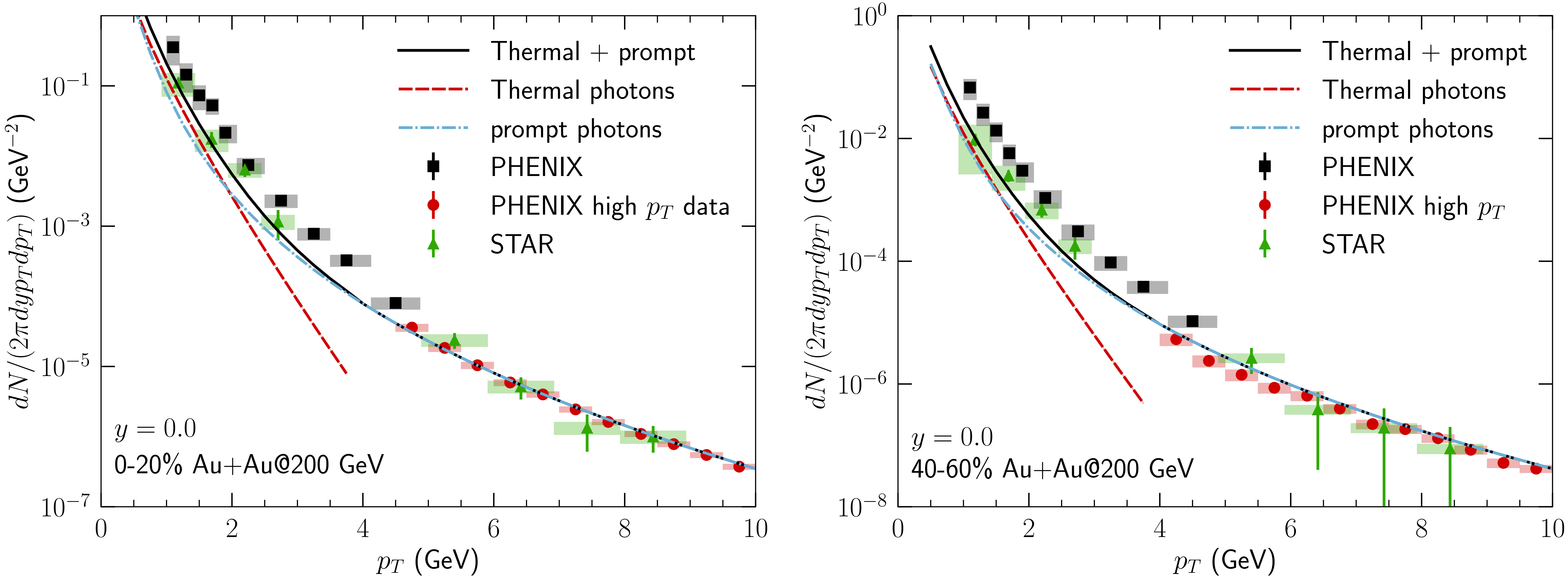
- The dynamical initialization gives a smaller elliptic flow for low p_T thermal photons than those from Instantaneous simulations because of the slow development of system's momentum anisotropy
- The enhancement of high p_T elliptic flow is a results of fewer early-stage emission in the dynamical initialization

DYNAMICAL INITIALIZATION EFFECT ON EM PROBES



- The prompt photons dilute the difference between the results from the two initialization setups
- The dynamical initialization effects are still significant in the direct photon observables for $p_T \in [2,4]$ GeV

PHOTON RADIATION AT RHIC



- The $N_{\rm coll}$-scaled prompt photon spectra give good agreement with PHENIX and STAR measurements for $p_T > 4$ GeV
- Thermal radiation shines out for $p_T < 3$ GeV

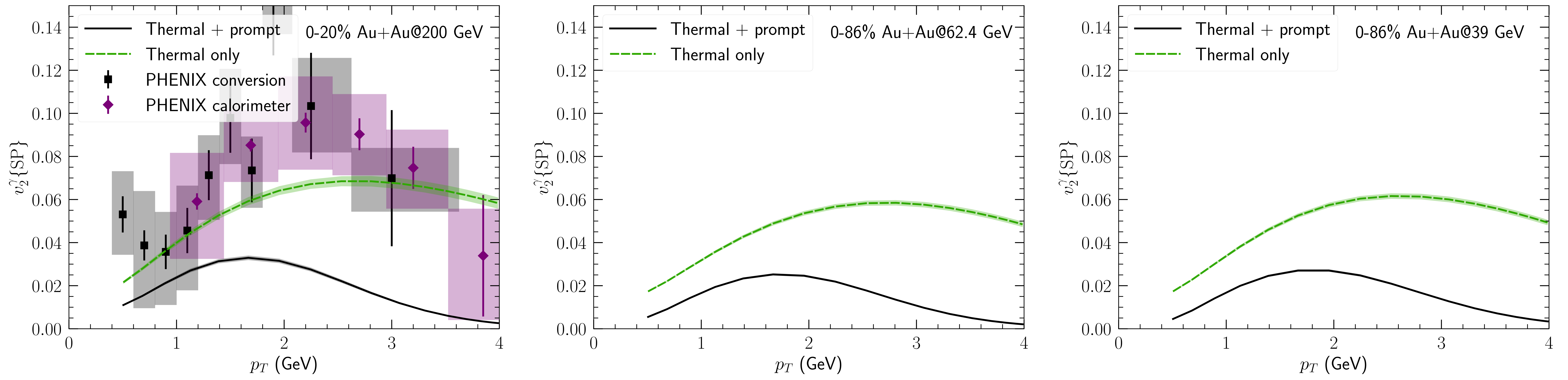
ENERGY SCAN OF PHOTON RADIATION AT RHIC

- The direct photon spectra get steeper at lower collision energies
- Our calculations underestimated the PHENIX measurements by a factor of 2-3 across all collision energies
- Agreement with the STAR measurements in 0-20% Au+Au collisions at 200 GeV

ENERGY SCAN OF PHOTON RADIATION AT RHIC

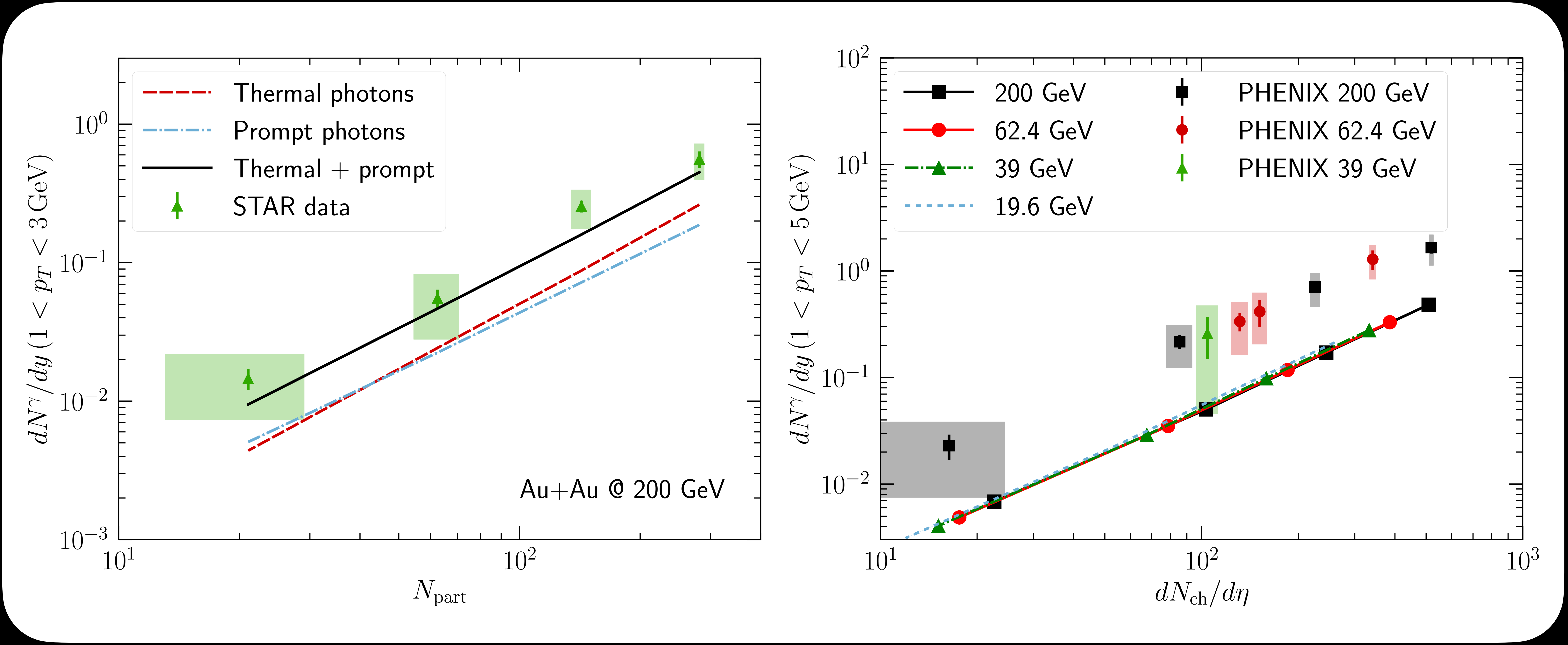
- The high p_T thermal photons fall slower than the prompt photons as the collision energy decreases

ENERGY SCAN OF PHOTON RADIATION AT RHIC



- There are significant thermal and direct photon elliptic flow at 62.4 and 39 GeV, which are comparable with those at 200 GeV
- After the dilution from prompt photons, the elliptic flow of direct photons underestimated the PHENIX measurements at 200 GeV

DIRECT PHOTON YIELD VS CHARGED HADRONS



- Our direct photon yields agree with reasonably the STAR data at 200 GeV
- Despite of underestimating the PHENIX photon yields, our calculation shows that dN^γ/dy scales well with $(dN_{\rm ch}/d\eta)^\alpha$ across all collision energies similar to the scaling in the PHENIX measurements

SUMMARY AND OUTLOOK

- We developed a dynamical initialization framework to study the early time evolution of heavy-ion collisions at the BES energies

  full **(3+1)-d** event-by-event hydro with net baryon current

  Important effect on the fireball evolution

- Photons are **unique** direct probes of this complex dynamics of heavy-ion collisions at RHIC BES

  Significant thermal photon signals

  High sensitivity to the early stage dynamics

  Prompt photons at low energies are challenging

Dileptons will come next …

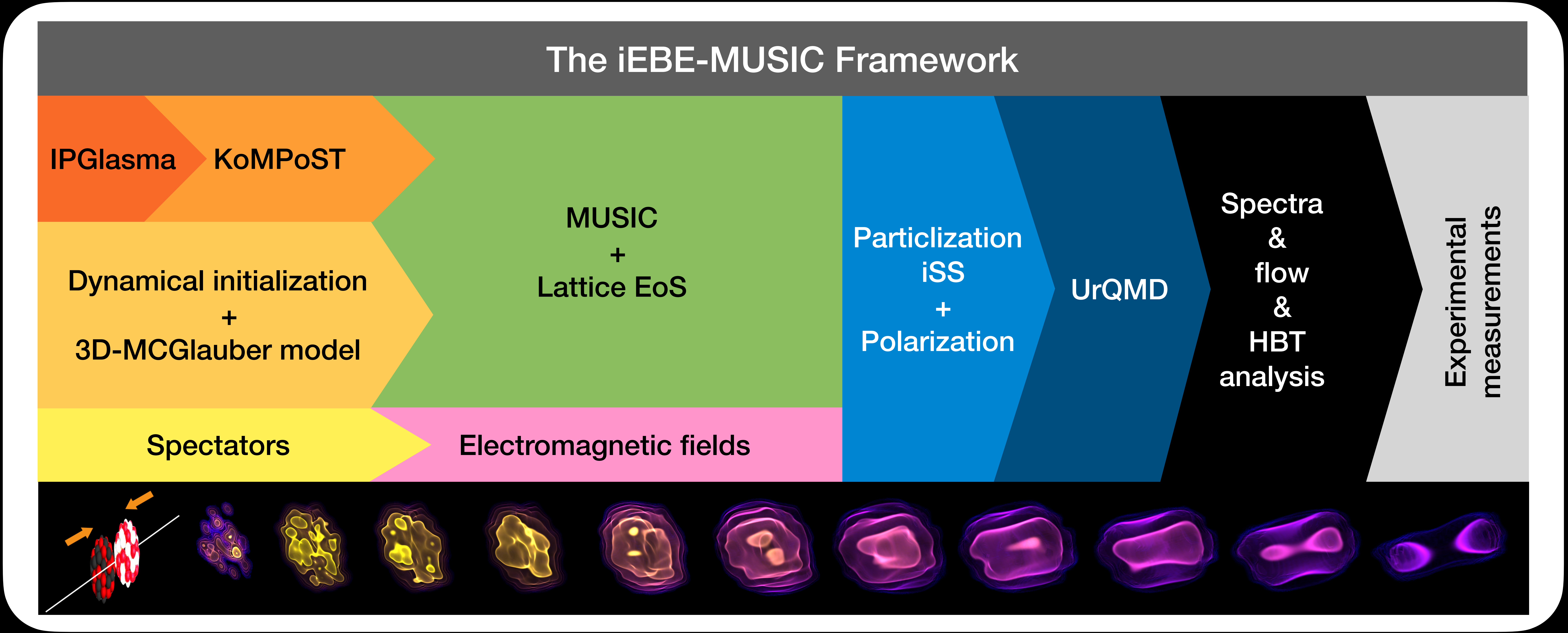

BACKUP

DIRECT PHOTON YIELD VS CHARGED HADRONS

- The scaling across different collision energies is a coincidence by choosing the lower limit of the p_T integration at 1 GeV

AN OPEN SOURCE HYBRID FRAMEWORK—IEBE-MUSIC

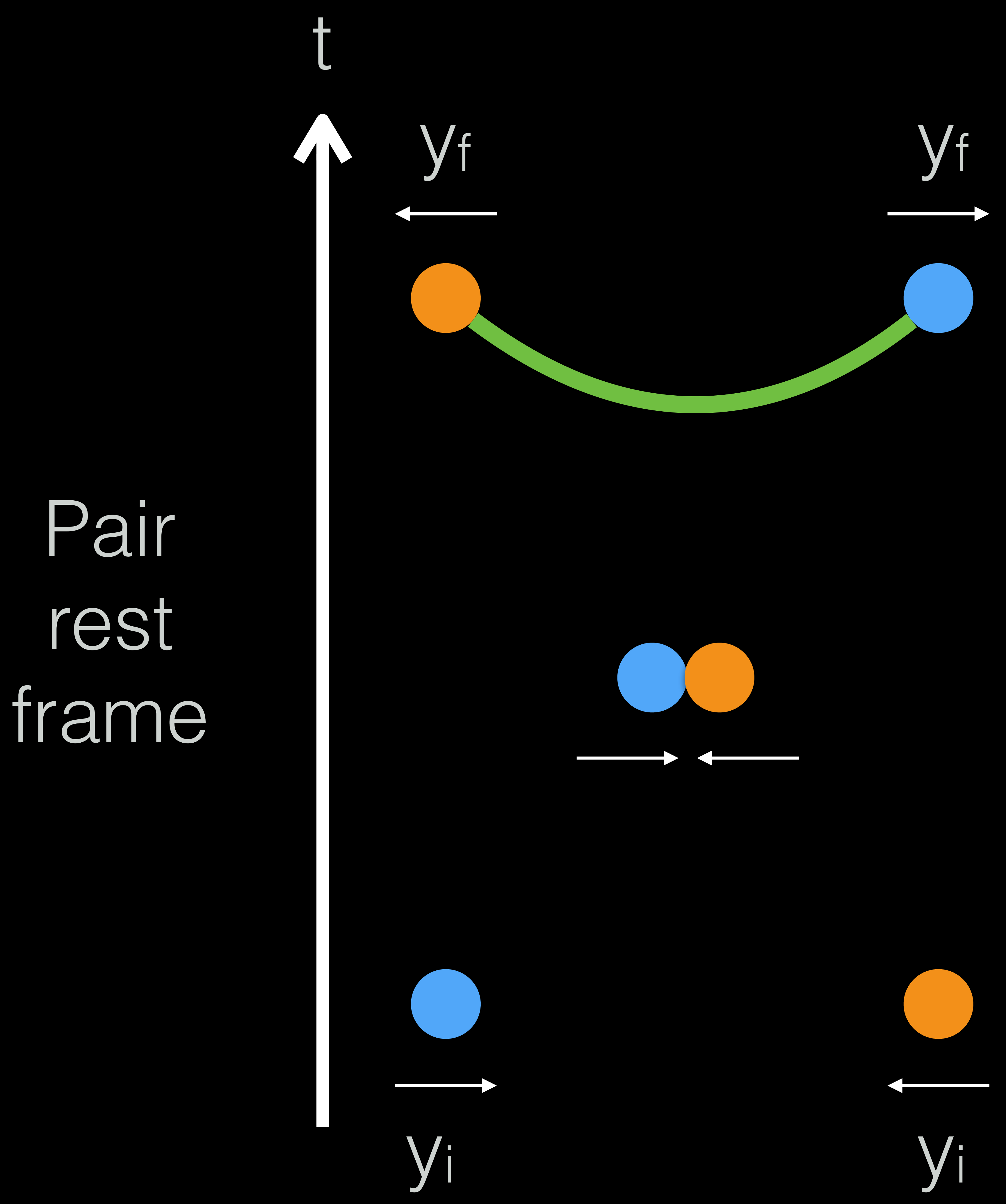
https://github.com/chunshen1987/iEBE-MUSIC



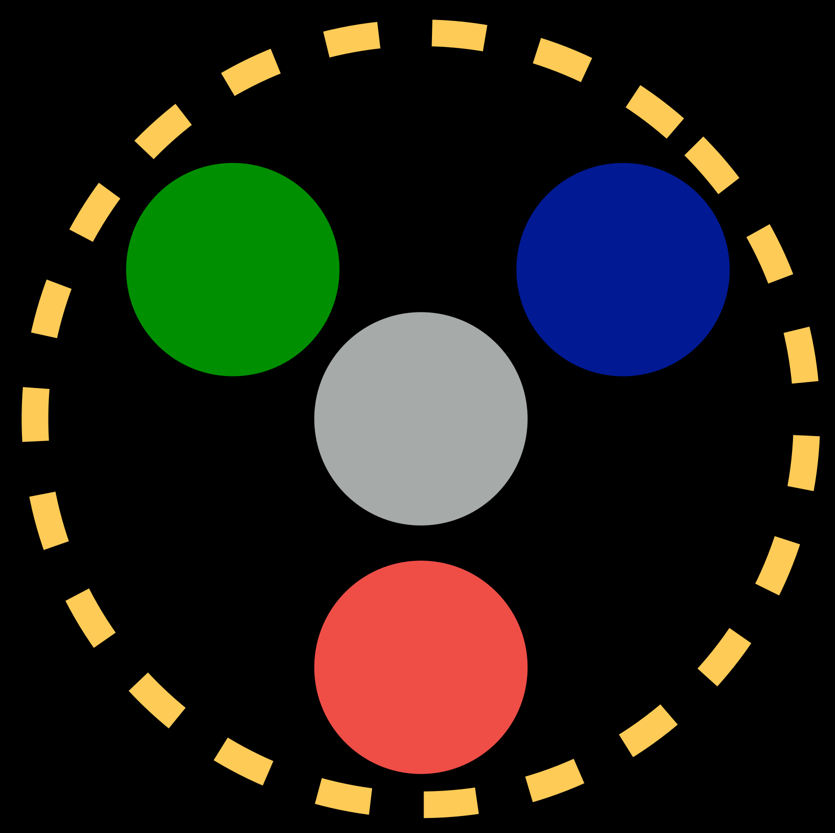
The state-of-the-art event-by-event simulations for relativistic heavy-ion collisions

THE 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 024907 (2018)
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



- Collision geometry is determined by MC-Glauber model
- Hot spots associated with valence quarks are sampled from PDF + a soft partonic cloud carrying the rest small x partons
- Hot spots are randomly picked to lose energy during a collision



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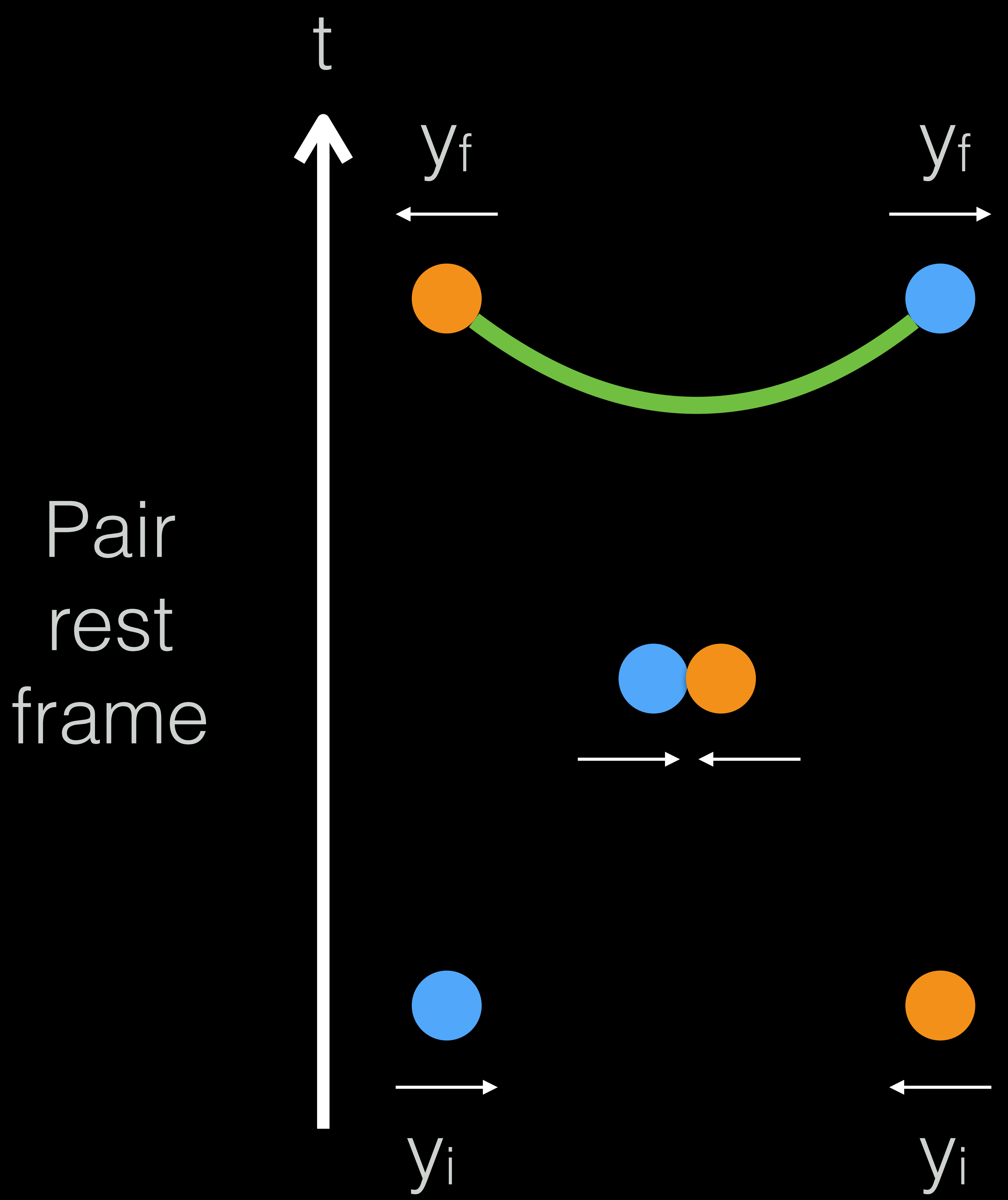


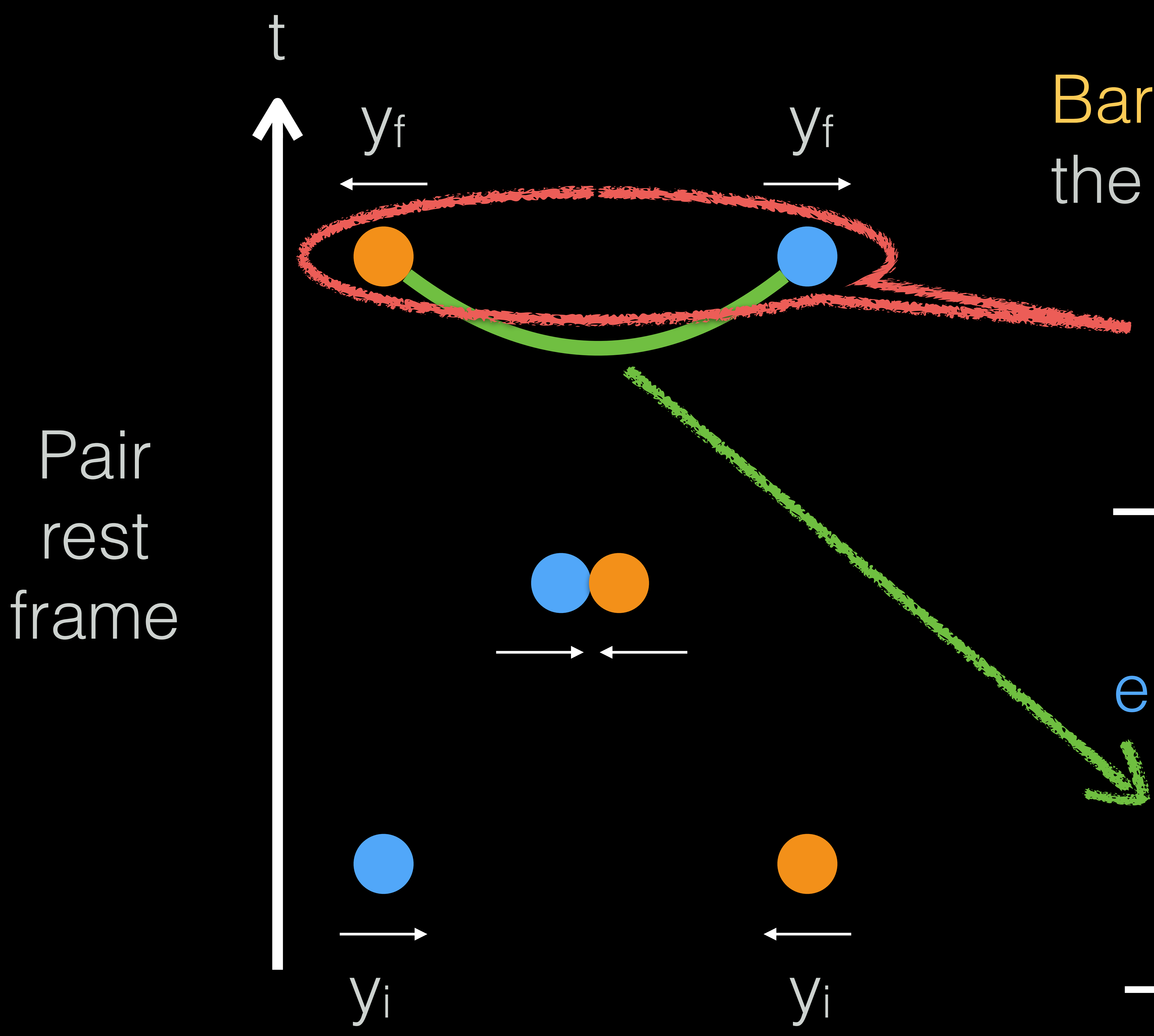
- Collision geometry is determined by MC-Glauber model
- Hot spots are sampled and randomly picked to lose energy during a collision
- Incoming quarks are decelerated with a classical string tension,

$$dp^\mu = -T^{\mu\nu} d\Sigma_\nu$$

$$T^{\mu\nu} = \begin{pmatrix} \sigma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\sigma \end{pmatrix} \qquad d\Sigma_\nu = (dz, 0, 0, -dt)$$

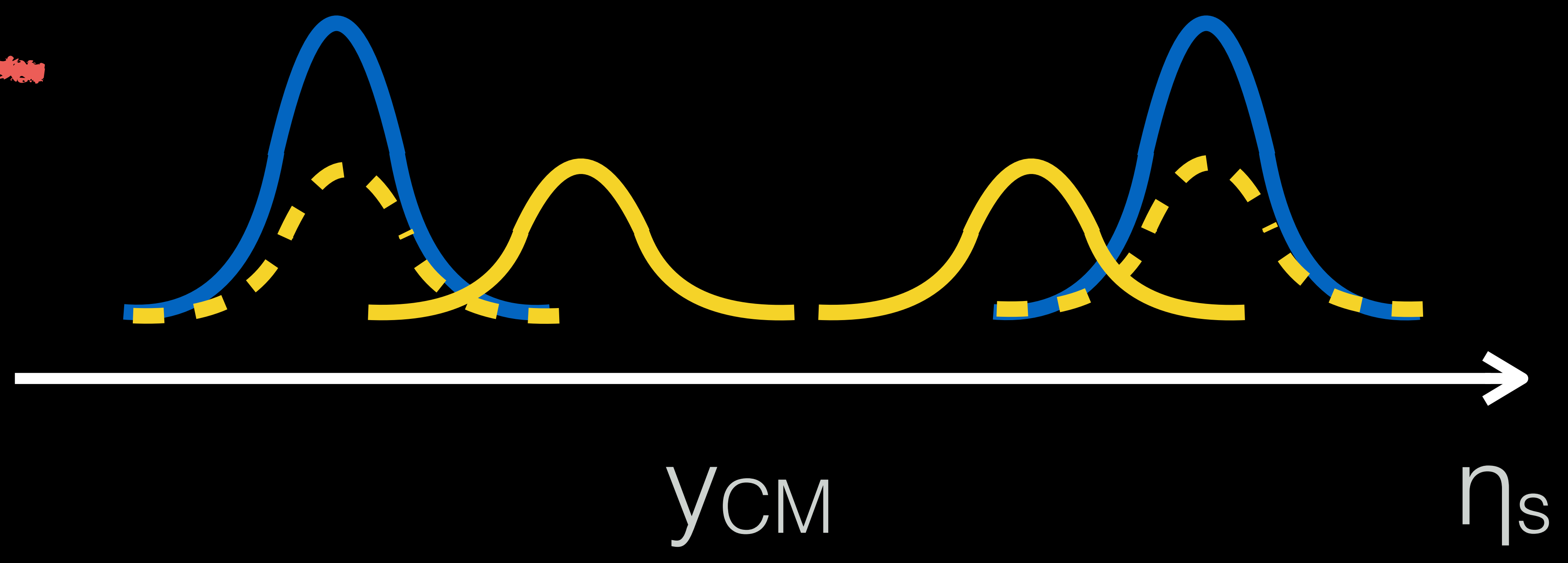
THE 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 024907 (2018)
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



Baryon densities are deposited at the string ends or string junctions

D. Kharzeev, Phys. Lett. B 378, 238 (1996)

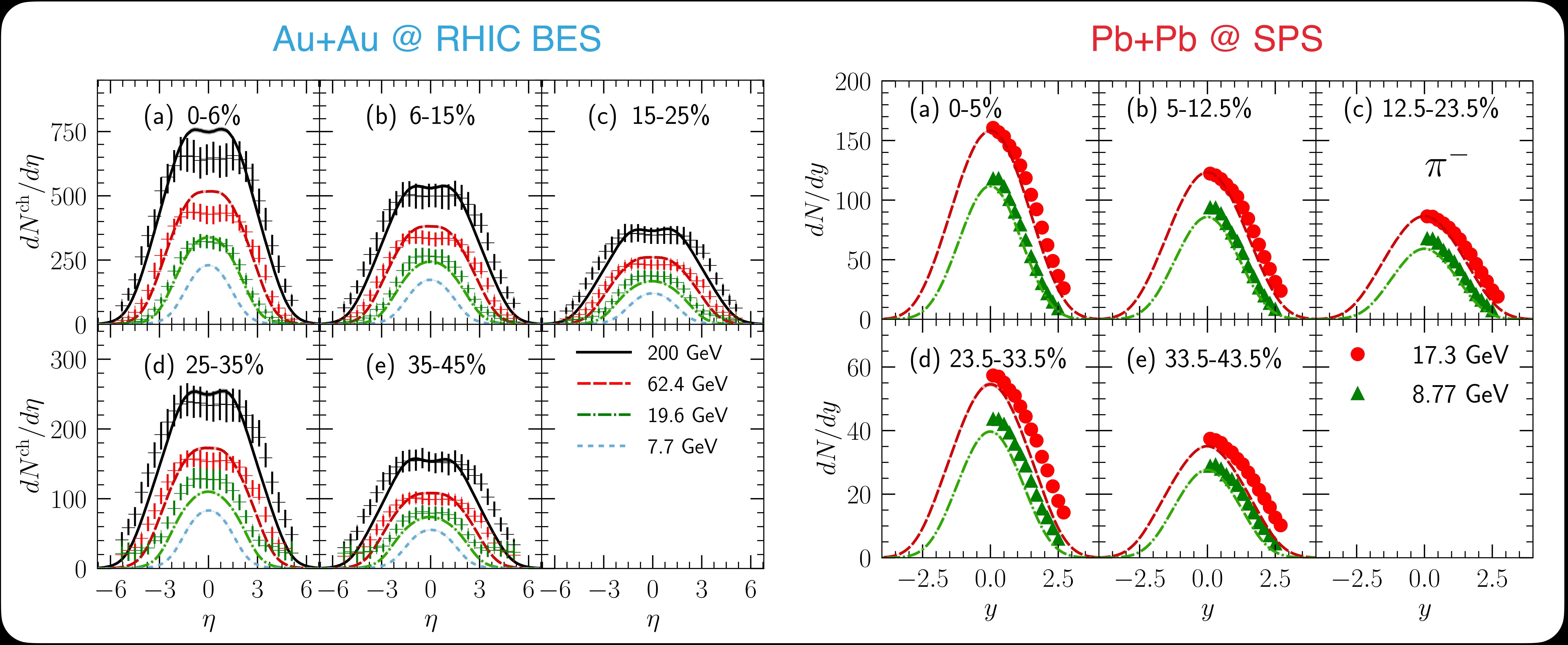


energy density inside the string

Imposed conservation for energy, momentum, and net baryon density

PARTICLE PRODUCTION IN AA COLLISIONS

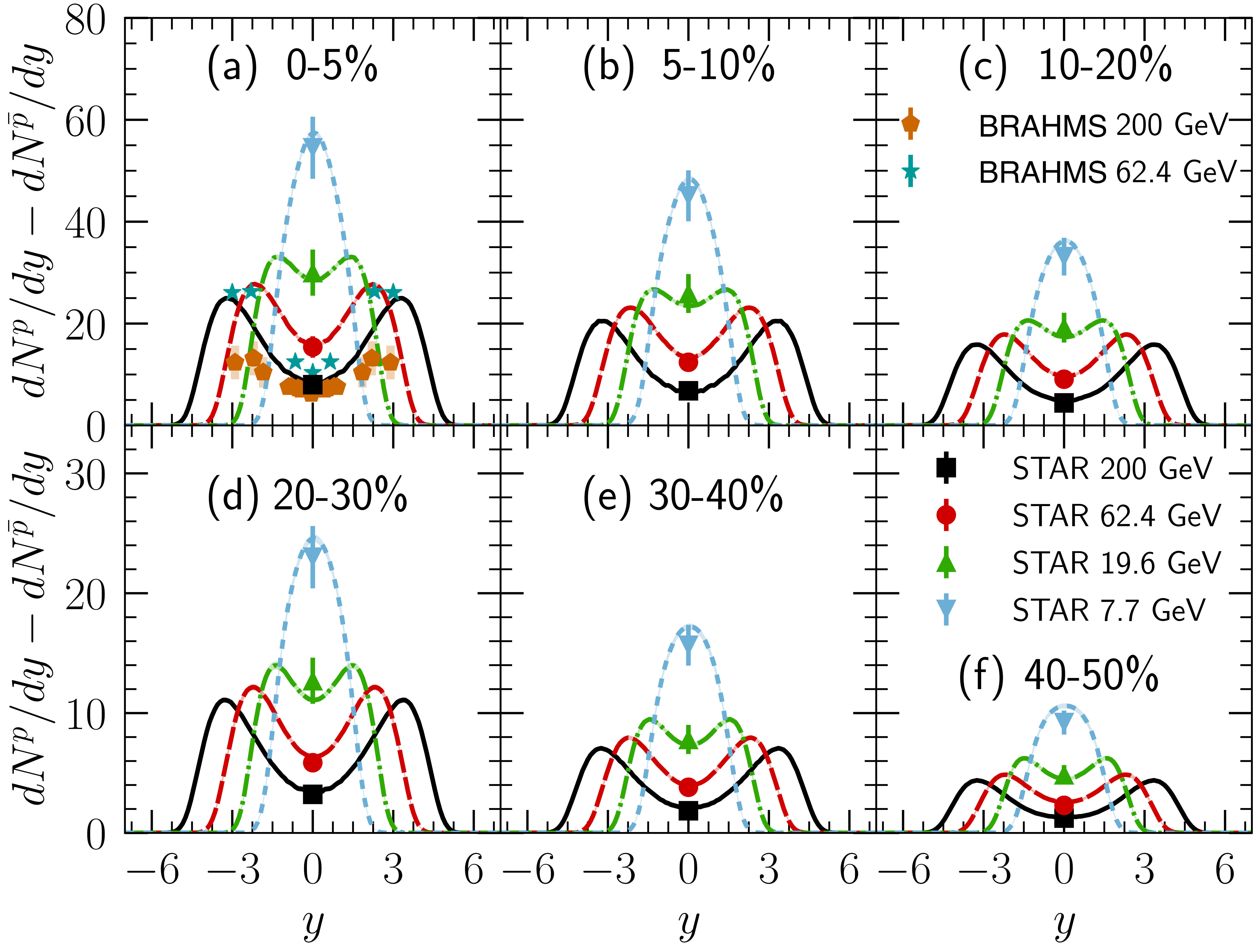
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



- Extension to AA collisions gives a reasonable description of the exp. data

CENTRALITY AND RAPIDITY DEPENDENCE OF NET PROTONS

C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



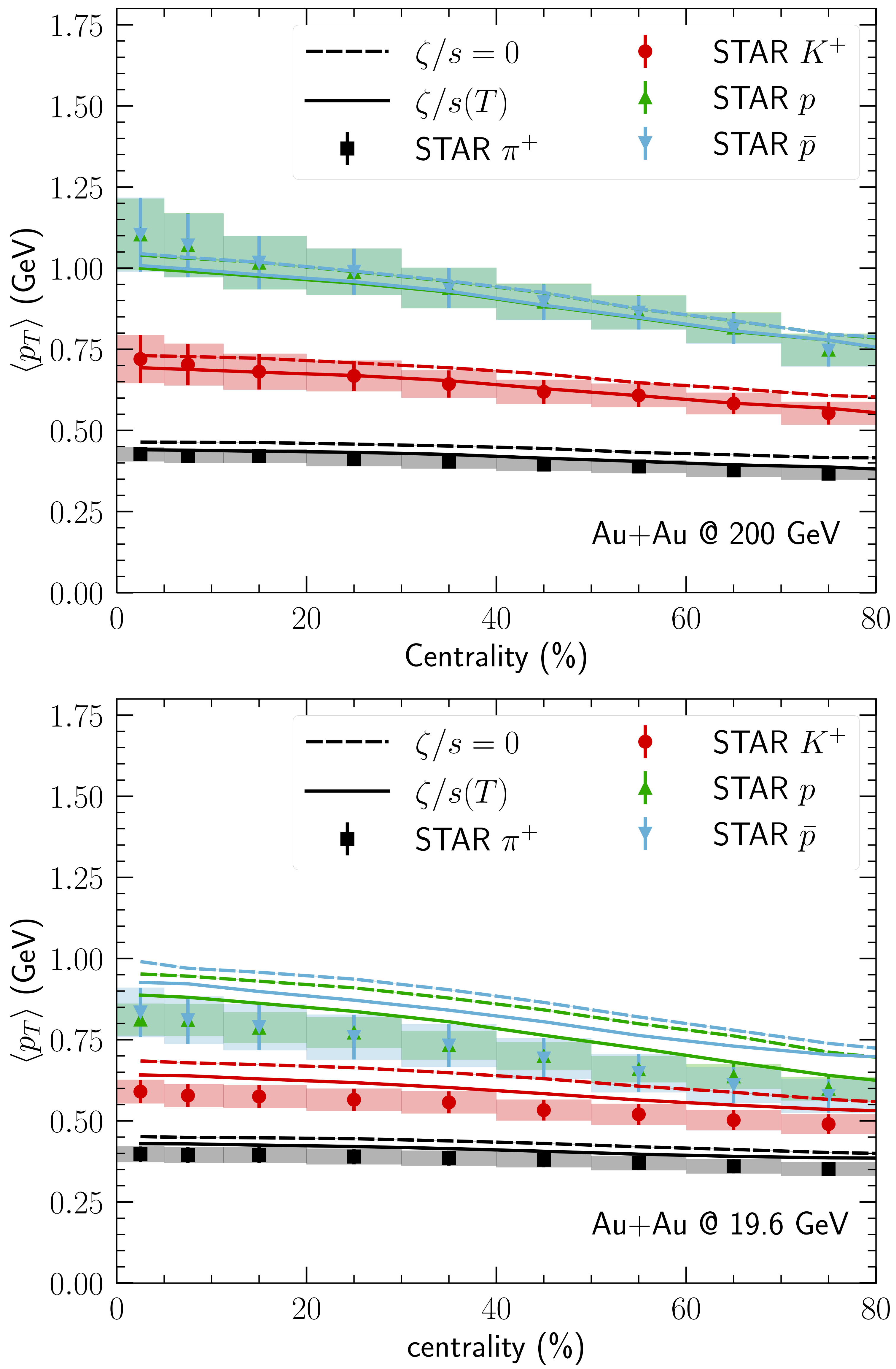
- Predictions for the net proton rapidity and centrality dependence at RHIC BES energies
- Our results at mid-rapidity are consistent with the STAR measurements
- Measurements of the rapidity dependence can further constrain the distributions of initial baryon charges

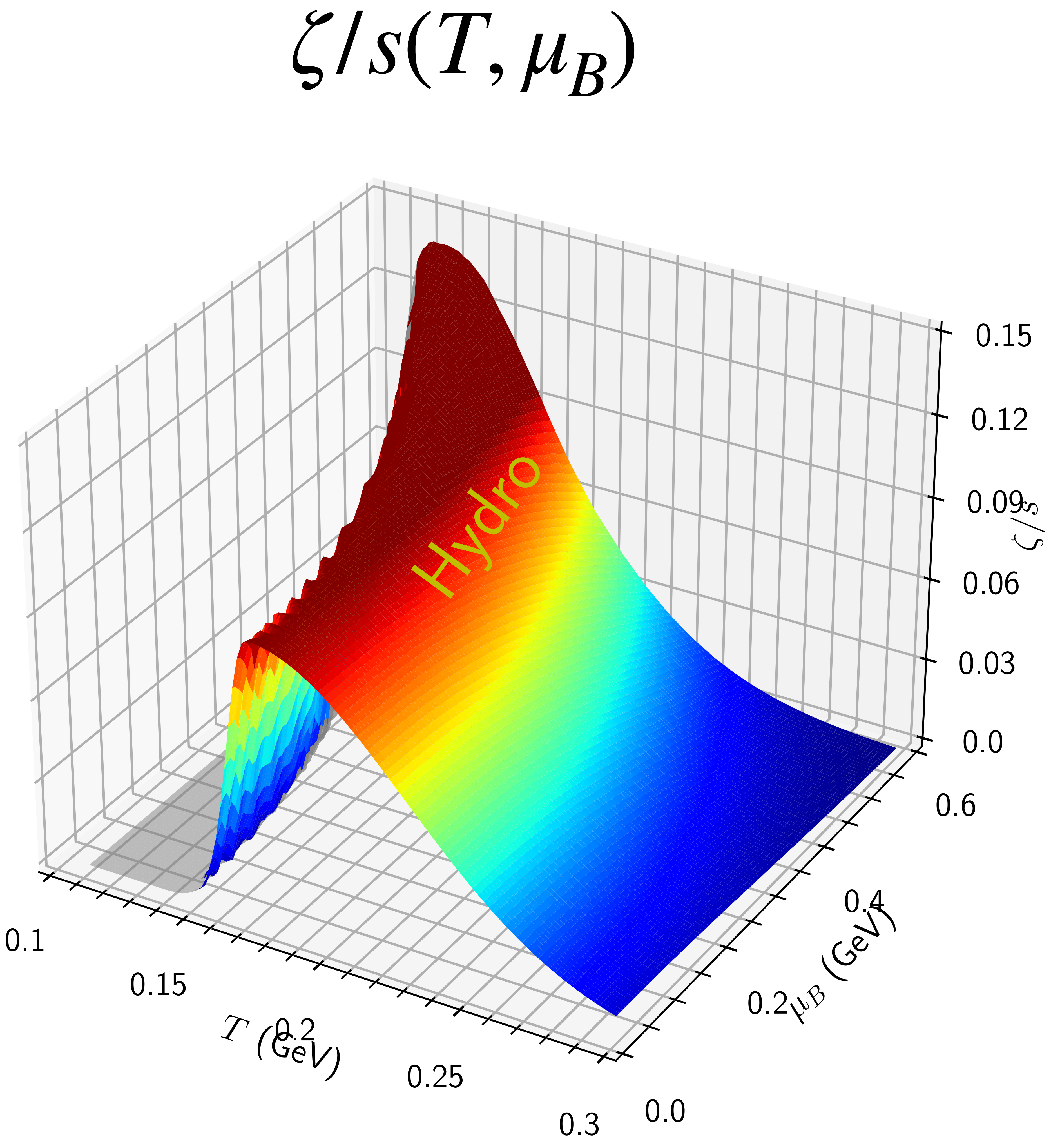
EXTRAPOLATE TO AA COLLISIONS AT LHC

C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)

- Particle productions in Pb+Pb collisions are well reproduced
- The rapidity plateau are slightly wider than the measurements in central Xe+Xe collisions at 5.44 TeV

CONSTRAINING QGP VISCOSITY AT FINITE μ_B

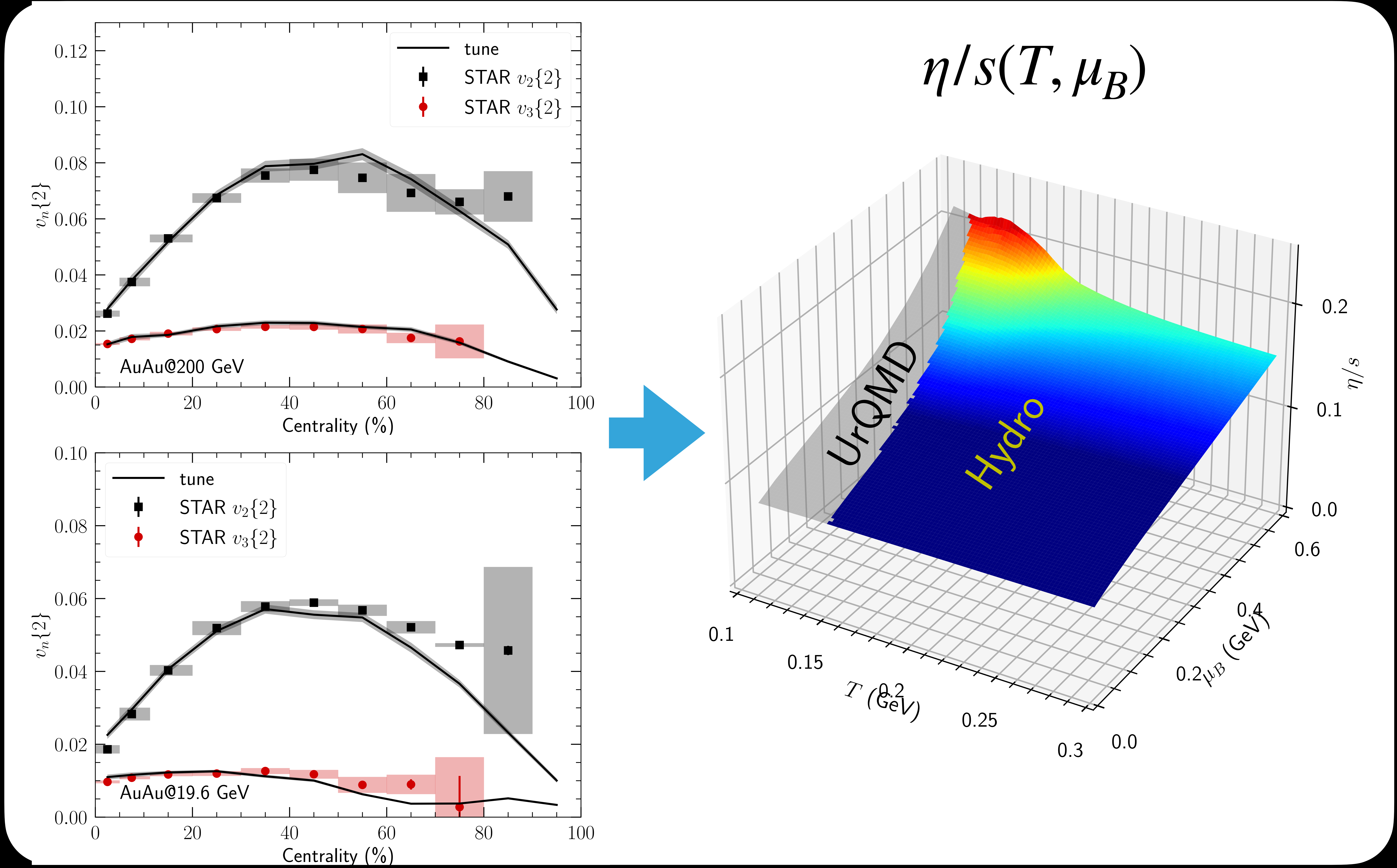




Sangwook Ryu et al., in preparation

By implementing the viscous effects at finite baryon density, we are progressing to constrain the QGP's viscosity with the STAR measurements at Beam Energy Scan program

CONSTRAINING QGP VISCOSITY AT FINITE μ_B



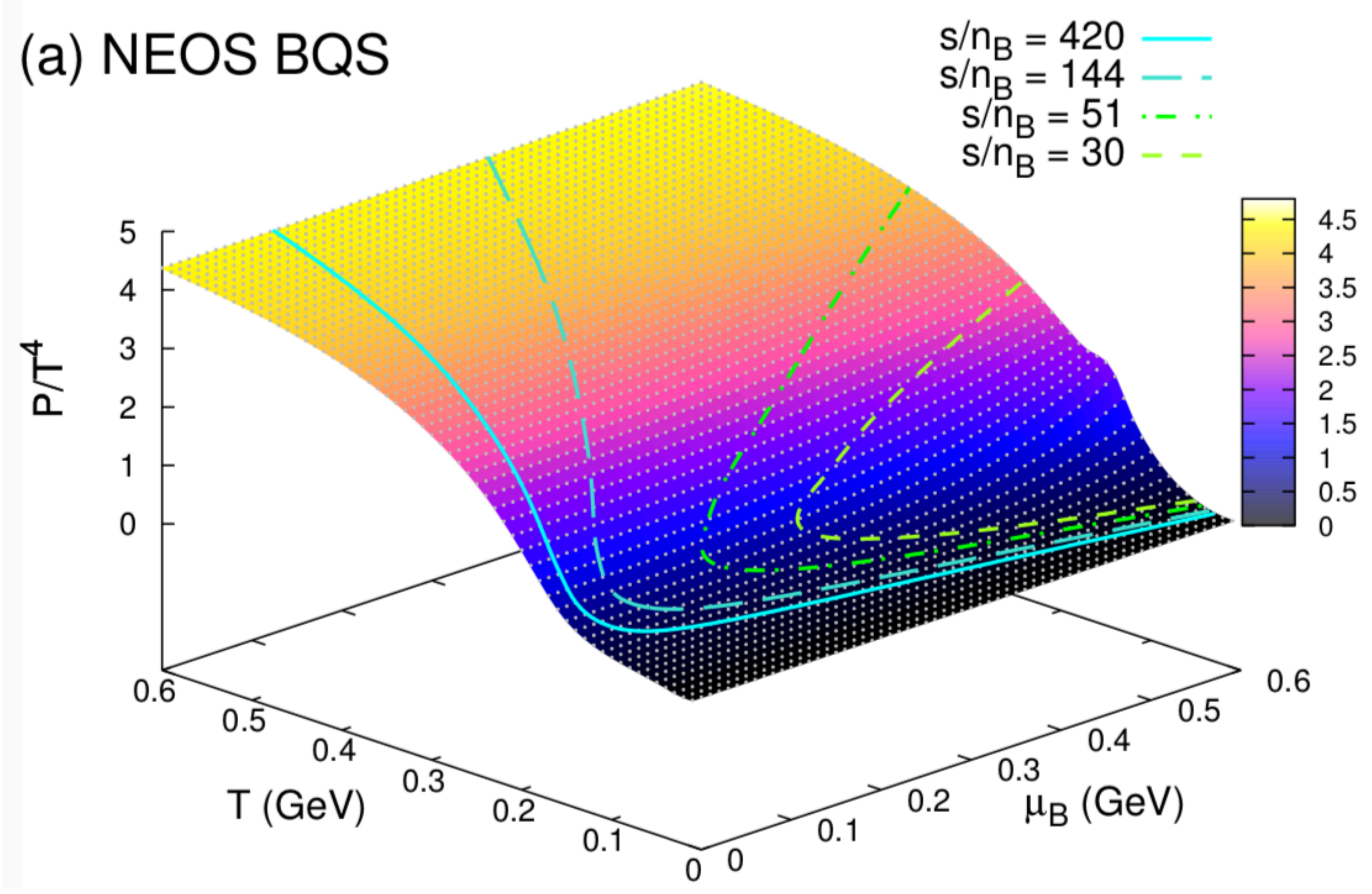
Sangwook Ryu et al., in preparation

By implementing the viscous effects at finite baryon density, we are progressing to constrain the QGP's viscosity with the STAR measurements at Beam Energy Scan program

QCD EQUATION OF STATE AT FINITE DENSITIES

M. Albright, J. Kapusta and C. Young, Phys. Rev. C90, 024915 (2014)
A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)
J. Noronha-Hostler, P. Parotto, C. Ratti and J. M. Stafford, Phys. Rev. C100, 064910 (2019)
J. M. Stafford *et. al*, arXiv:2103.08146 [hep-ph]

$n_s = 0 \quad n_Q = 0.4 n_B$



Lattice QCD: Taylor expansion up to the 4th order

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi^{B,Q,S}_{l,m,n}}{l!m!n!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

Match to Hadron Resonance Gas model at low T

$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T,\mu_J)]\frac{P_{\rm had}(T,\mu_J)}{T^4} + \frac{1}{2}[1 + f(T,\mu_J)]\frac{P_{\rm lat}(T,\mu_J)}{T^4}$$

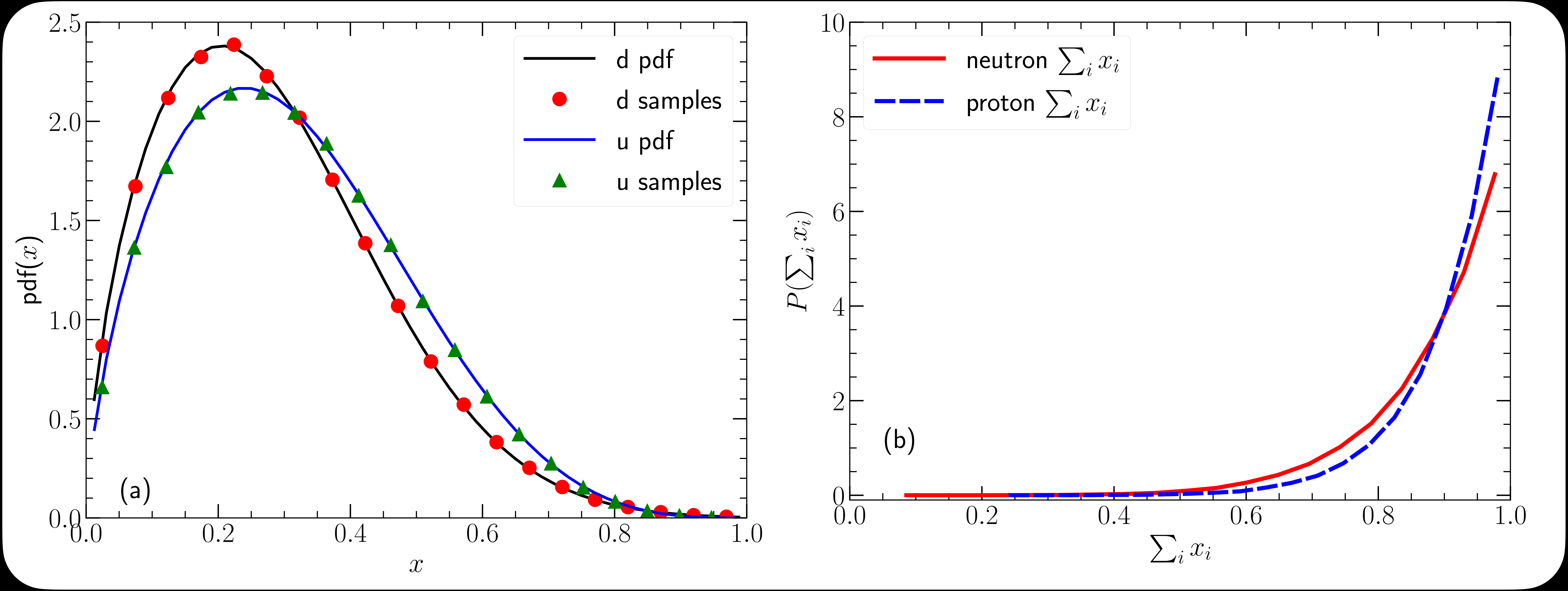
$$f(T,\mu_B) = \tanh[(T - T_c(\mu_B)/\Delta T_c]$$

Enabled hydrodynamic simulations at finite μ

IMPROVED PDF SAMPLING FOR MULTIPLE PARTONS

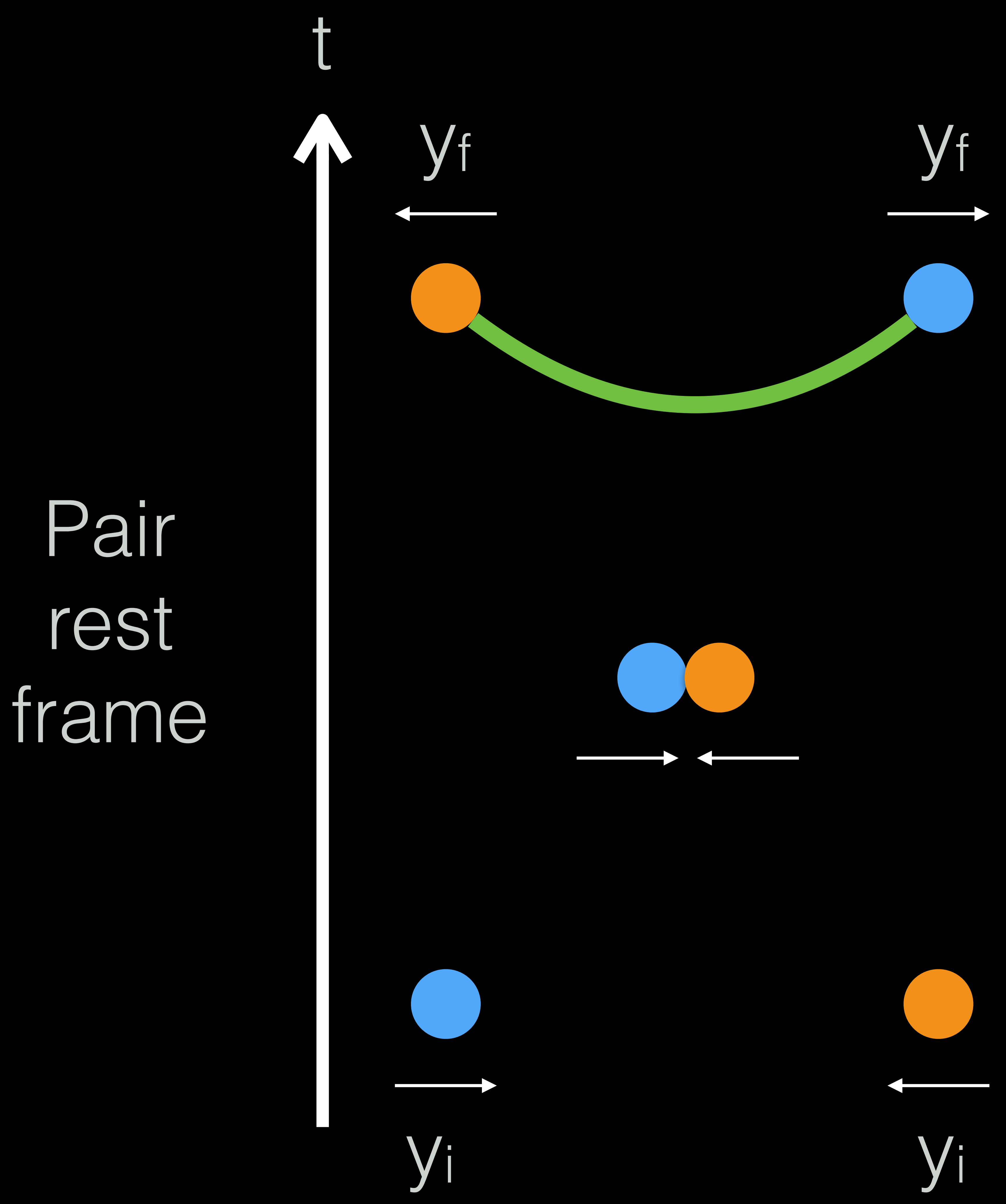
C. Shen and B. Schenke, in preparation

- We develop a Metropolis algorithm to sample multiple partons from PDFs with constraint $\sum_i x_i \leq 1$



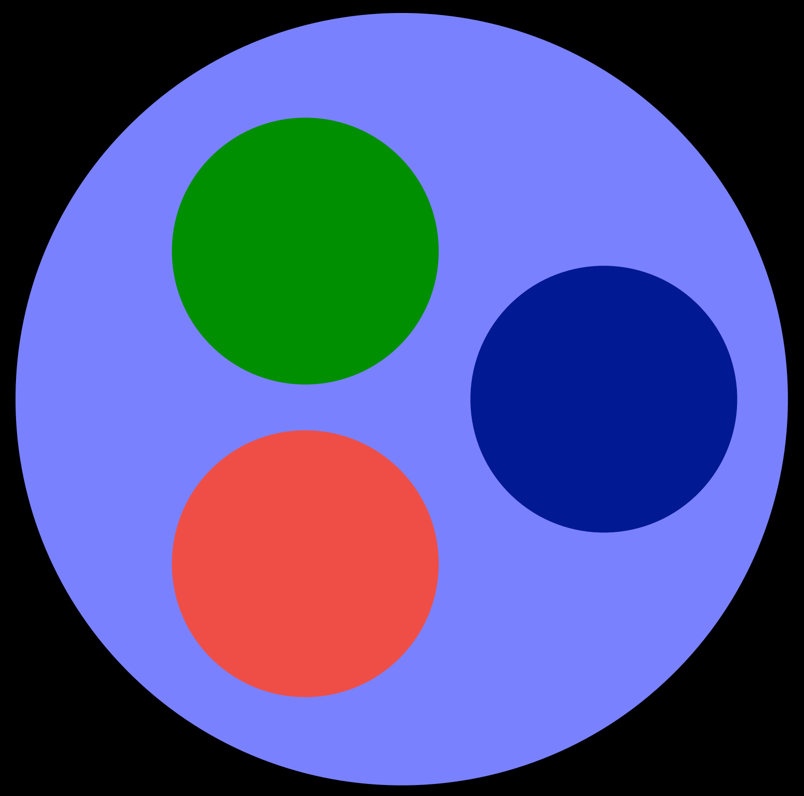
THE 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



- Collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF and randomly picked to lose energy during a collision

$$\sum_i x_i \leq 1$$



3 valence quark
+
soft parton cloud