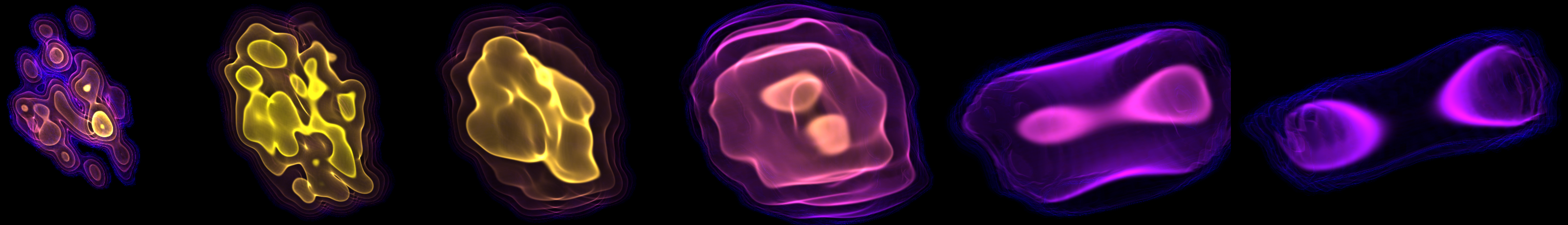
RBRC
RIKEN BNL Research Center

3D MODELING FOR THE RHIC ISOBAR COLLISIONS

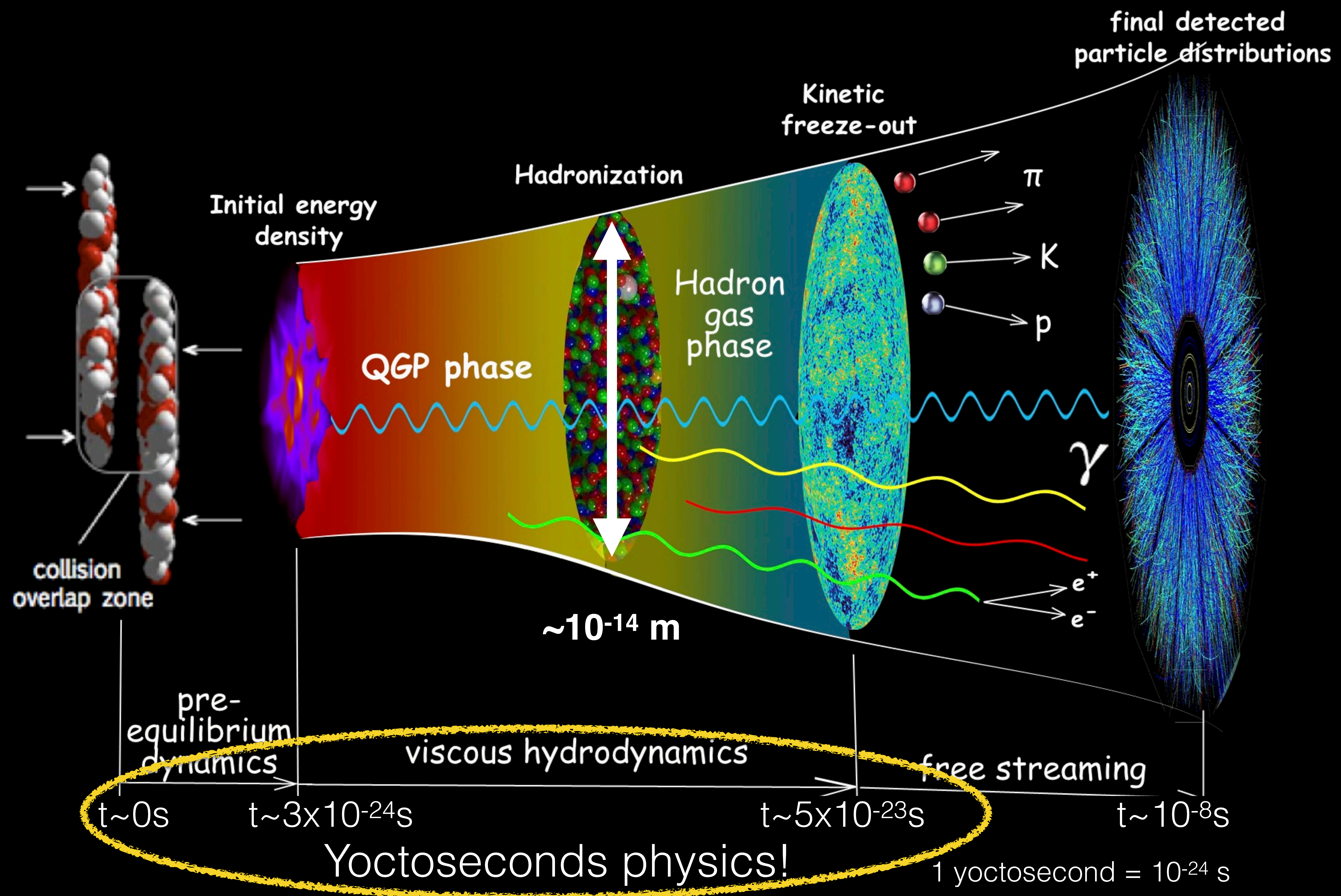
CHUN SHEN



Intersection of nuclear structure and high-energy nuclear collisions

Feb. 17, 2023

NUCLEAR MATTER UNDER EXTREME CONDITIONS

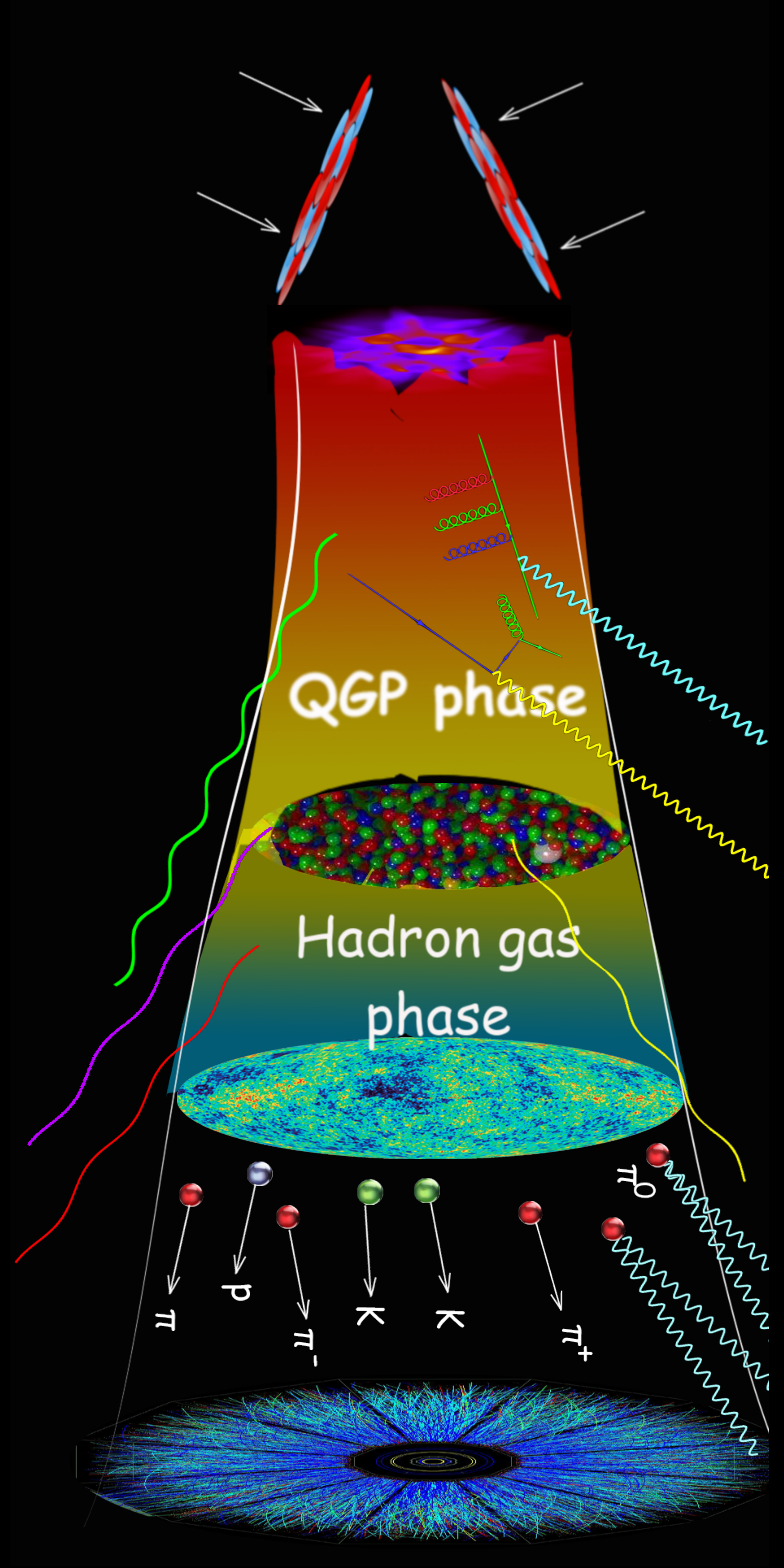


Heavy-ion collisions are tiny and have ultra-fast dynamics

A variety of particles are emitted from the collisions

Multi-messenger nature of heavy-ion physics

DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$

$$c_s^2 = \partial P / \partial e|_{s/n}$$

Shear and bulk viscosities $\eta/s(T, \mu_B), \zeta/s(T, \mu_B)$

Charge diffusion D_B, D_Q, D_S

Electromagnetic emissivity

Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$

Spectra, collective flow, femtoscopy

Anisotropic flow v_n
Flow correlations

Balance functions

Photons and dileptons

Jets and heavy-quarks

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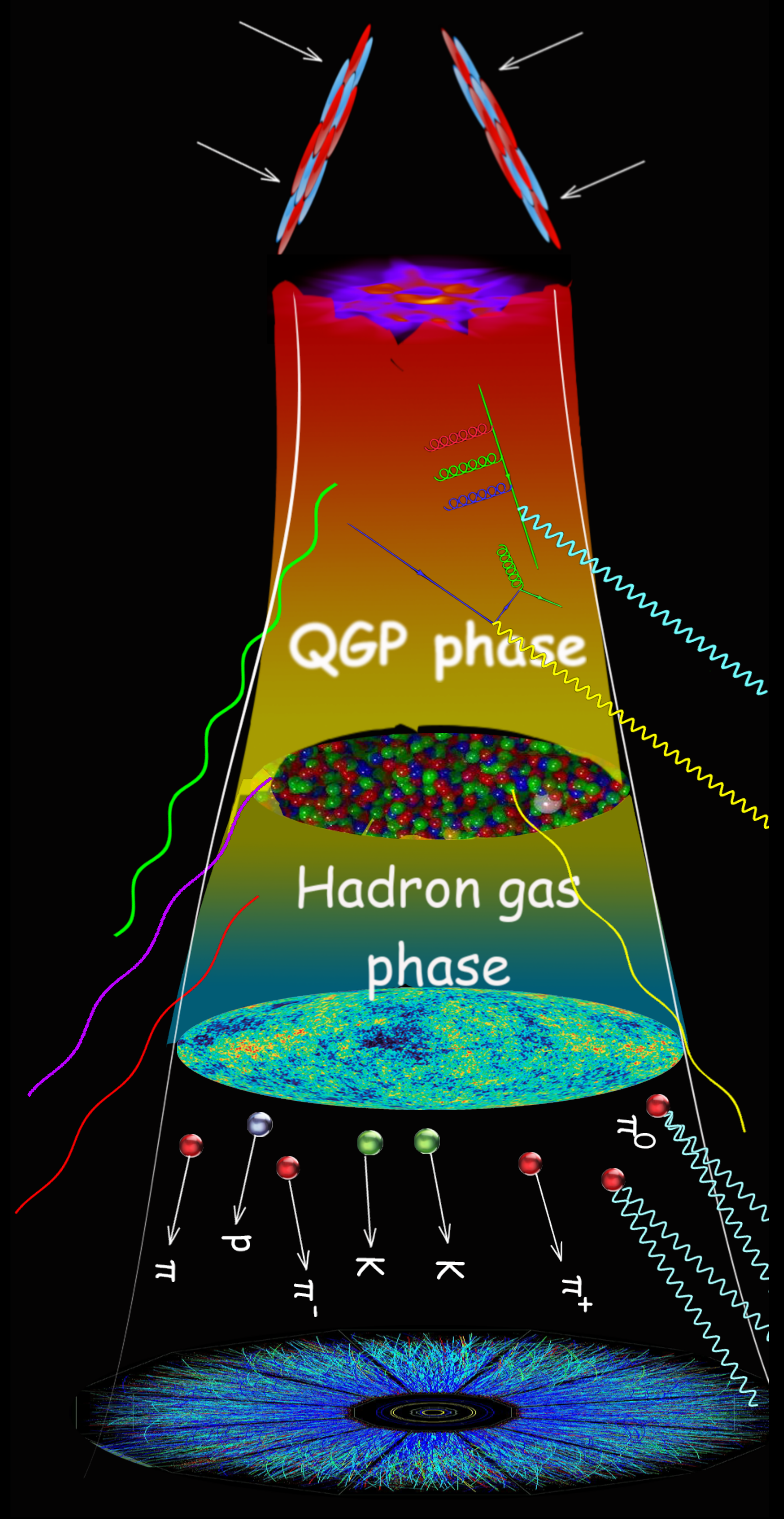

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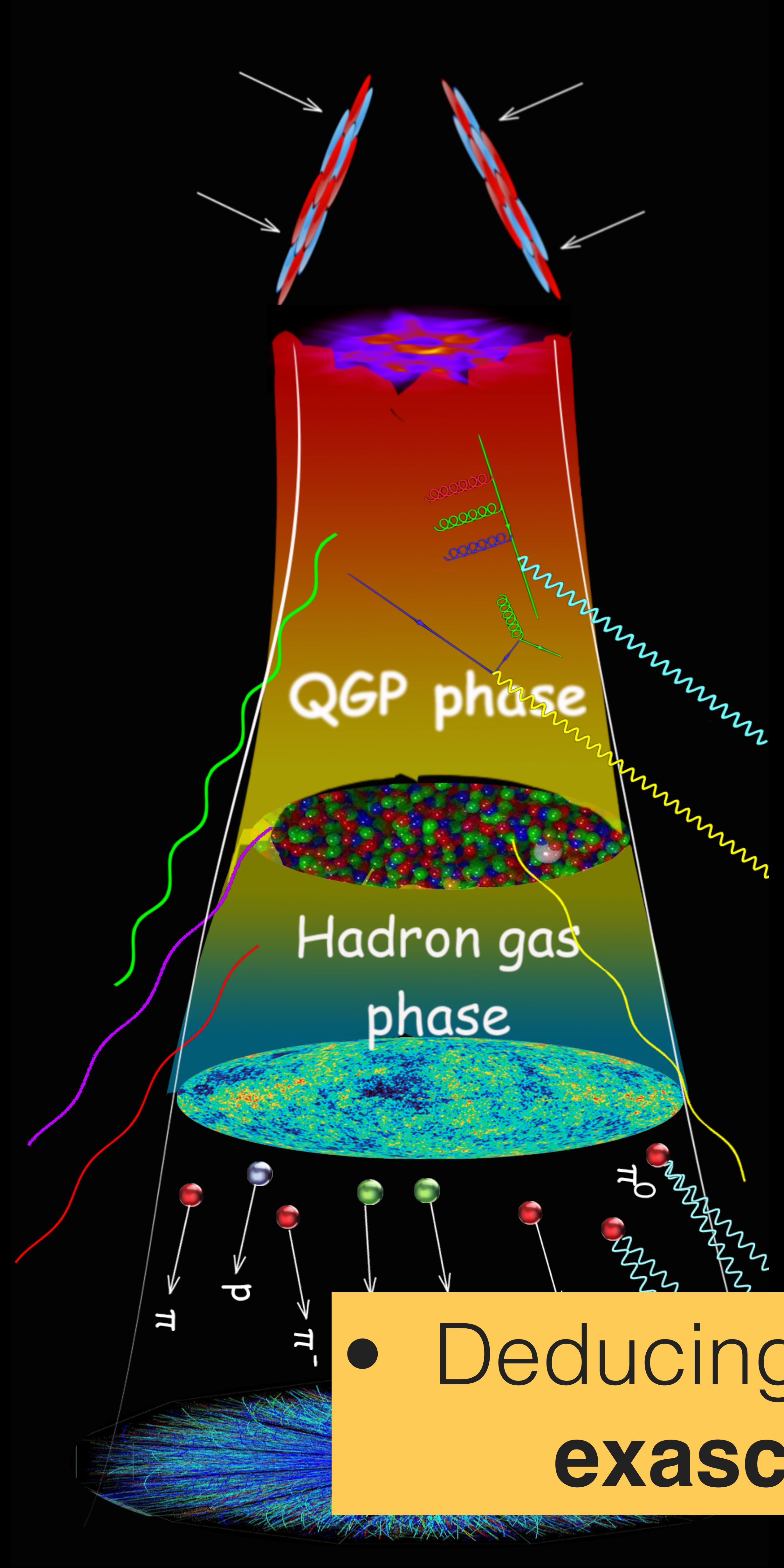

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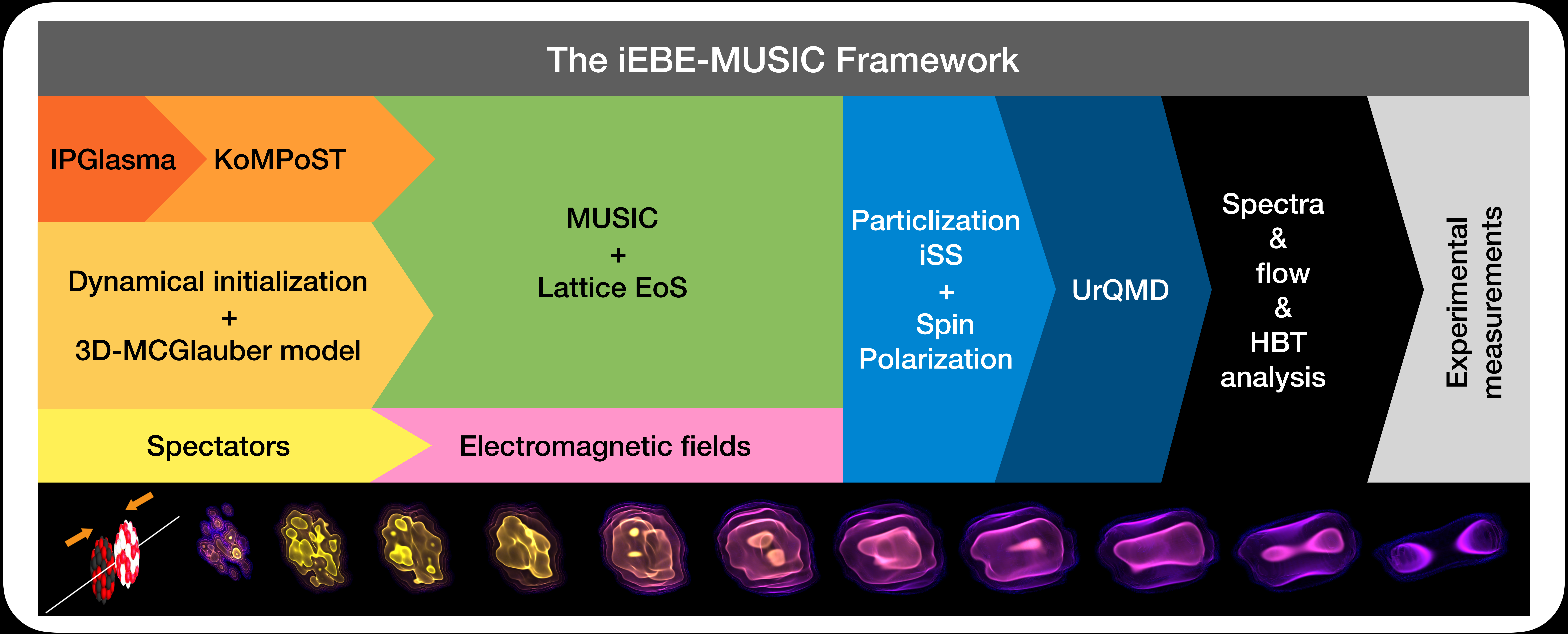
Photons and dileptons

quarks

- Deducing the QGP properties from experimental data requires **exascale computing** with advanced statistical methods

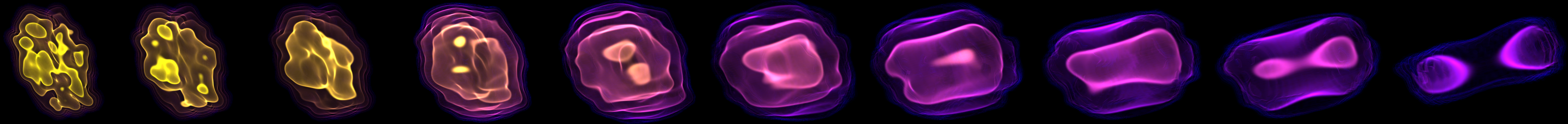
AN OPEN SOURCE HYBRID FRAMEWORK—IEBE-MUSIC

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



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

THE MULTI-STAGE THEORETICAL FRAMEWORK



$T^{\mu\nu}$ 0^+ 0.5-1 → τ (fm)

Initial State +
Pre-equilibrium dynamics

Hydrodynamics

Hadronic Transport

$$T^{\mu\nu}_{\rm pre.\,eq} = T^{\mu\nu}_{\rm hydro}$$

+ Landau Matching
with lattice EoS

Cooper-Frye
particlization

- Continuously connect the system's energy-momentum tensor $T^{\mu\nu}$ between different stages

WHERE WE ARE AND WHERE WE ARE GOING

- Quark-Gluon Plasma is the hottest, smallest, and the most perfect fluid ever created in the laboratory

- A fluid has “close” to the fundamental degrees of freedom

How does the strongly coupled liquid emerge from fundamental QCD interactions?

- Probes the inner working of QGP at multi-resolution scales with jets and heavy-quarks

- What is the smallest possible droplet of QGP?

- What is the structure of QCD phase diagram?

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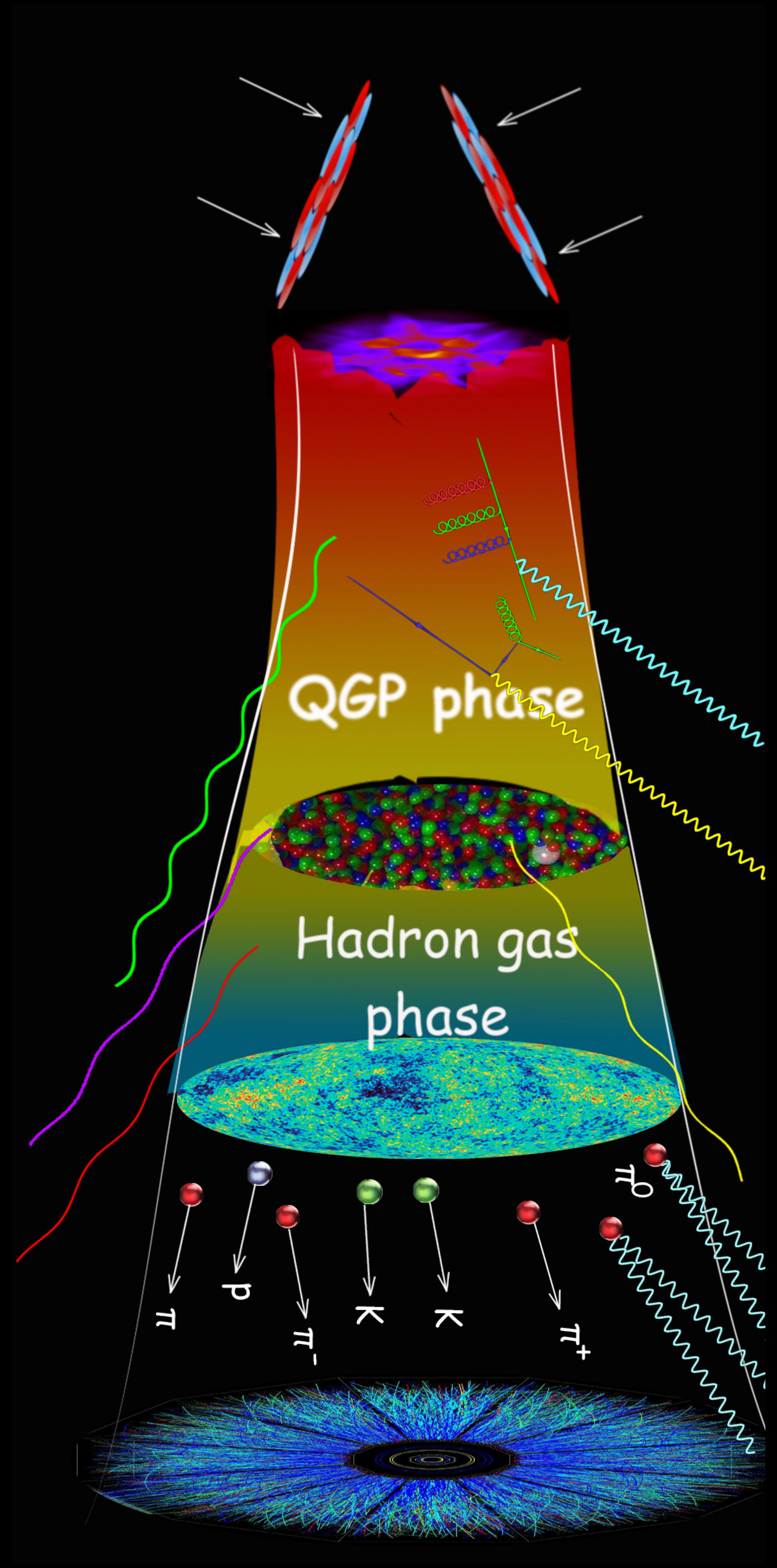
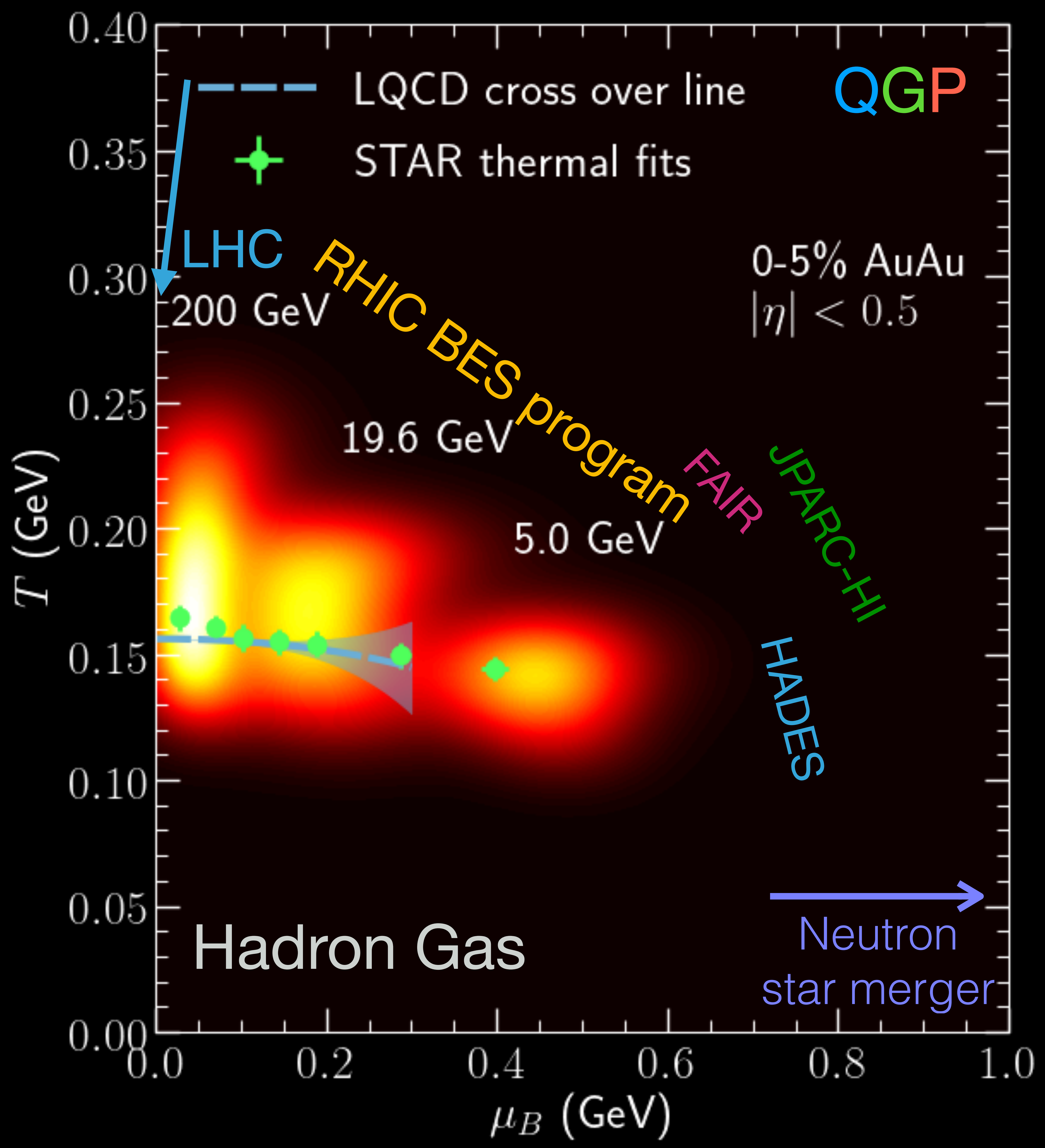
3D simulations are essential!

PROBING THE NUCLEAR MATTER PHASE DIAGRAM





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

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

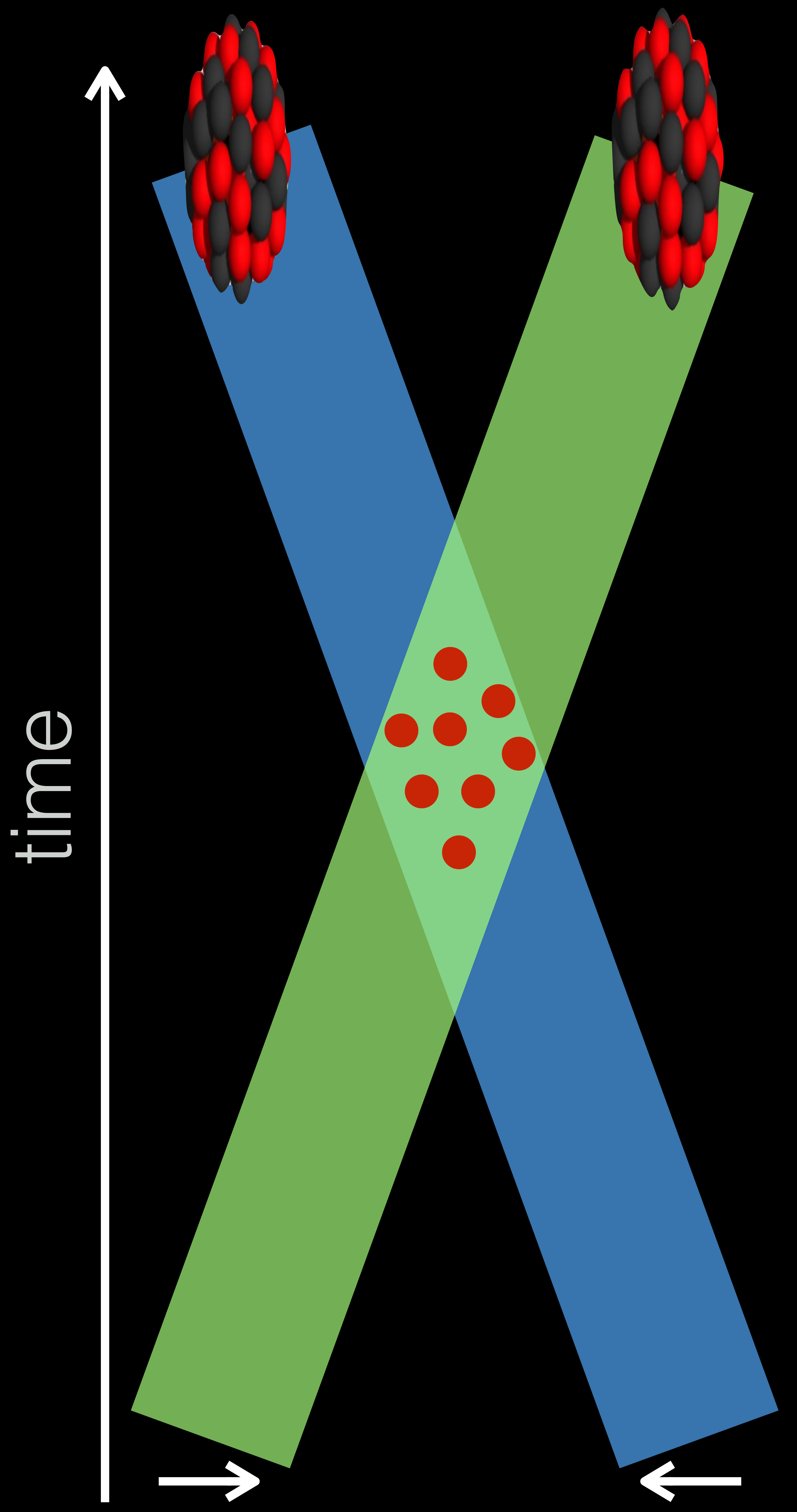
- How do the QGP transport properties change with baryon doping?

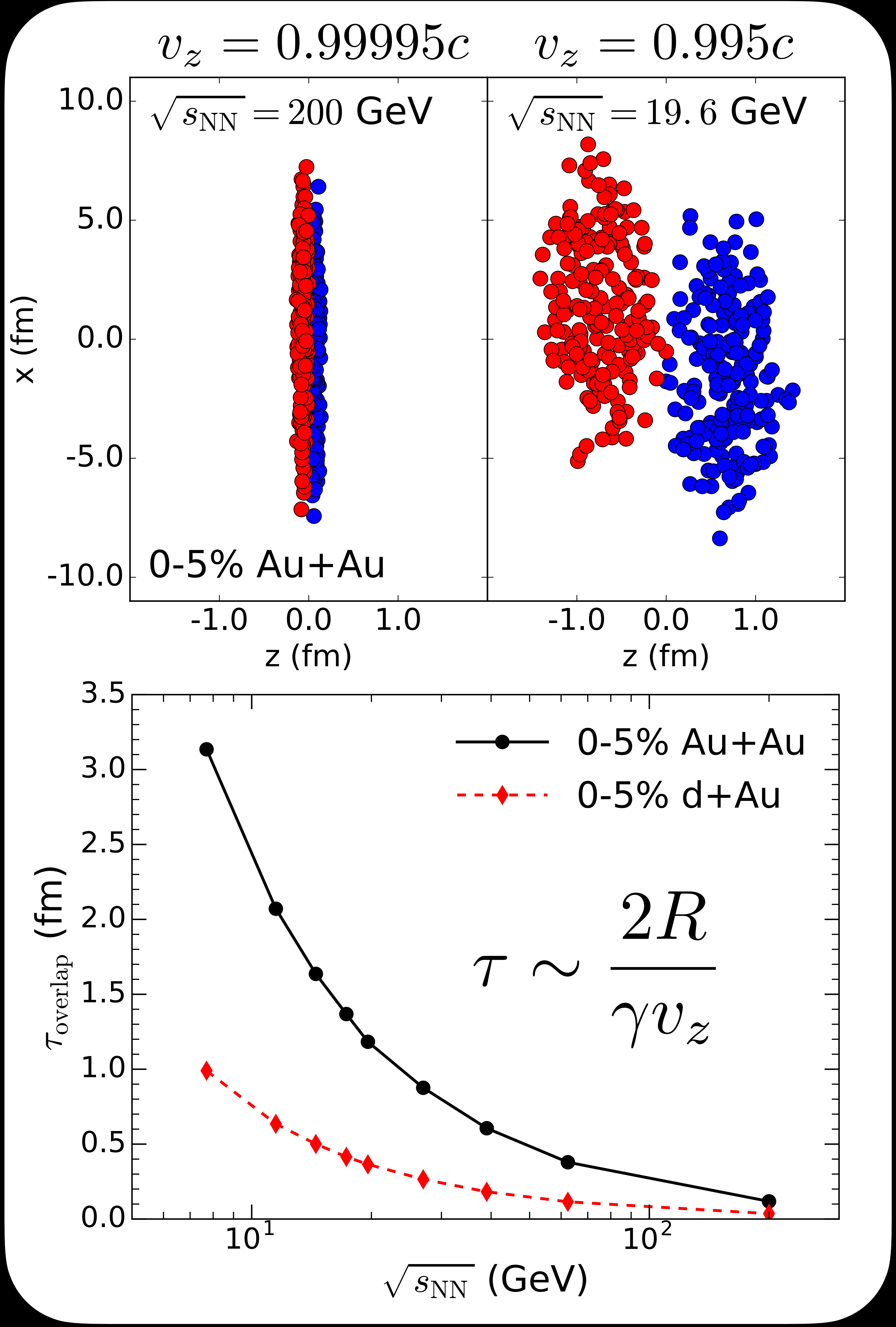
  $(\eta/s)(T, \{\mu_q\})$, $(\zeta/s)(T, \{\mu_q\})$

- Access to new transport phenomena

  Charge diffusion

3D DYNAMICS BEYOND THE BJORKEN PARADIGM

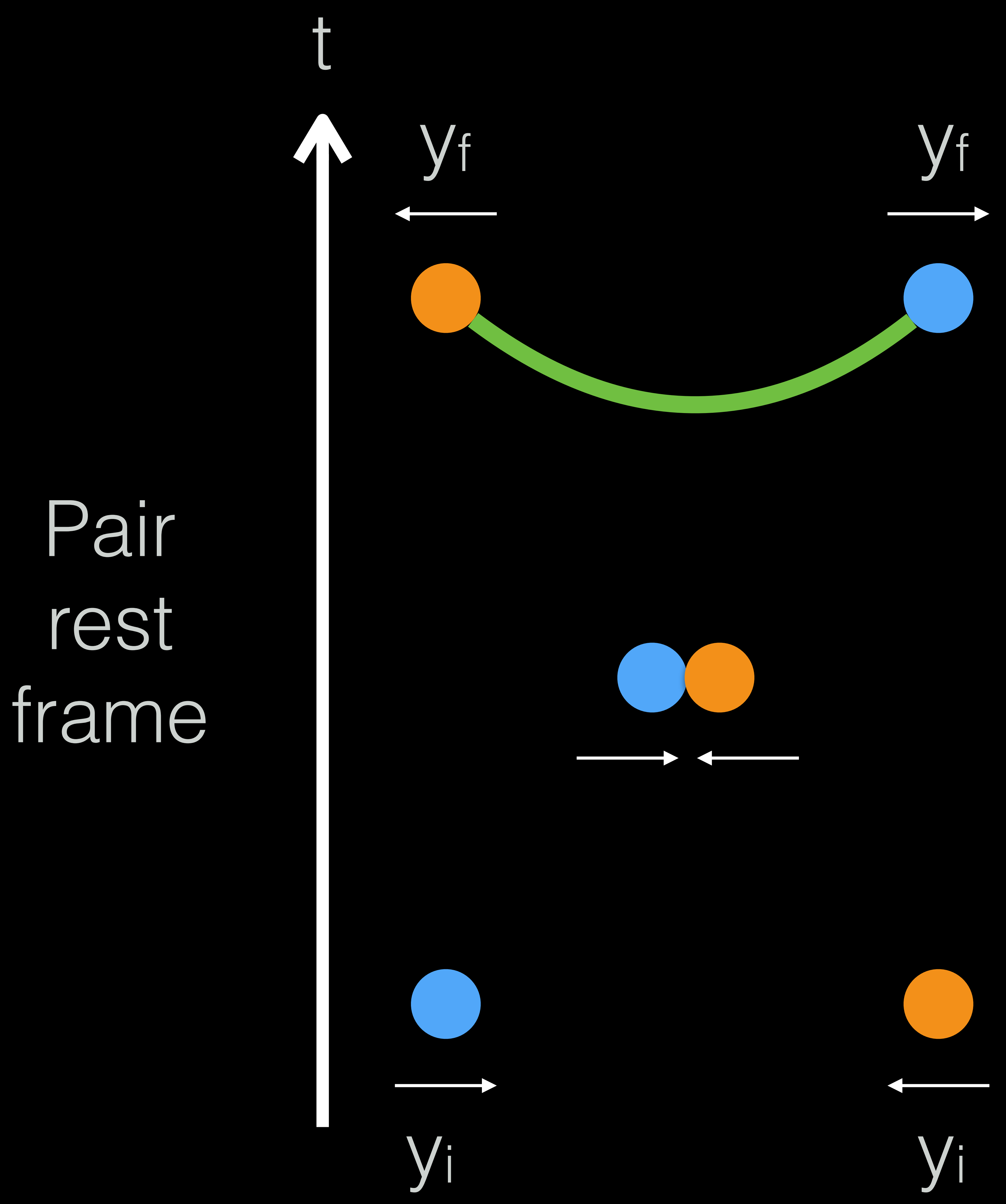




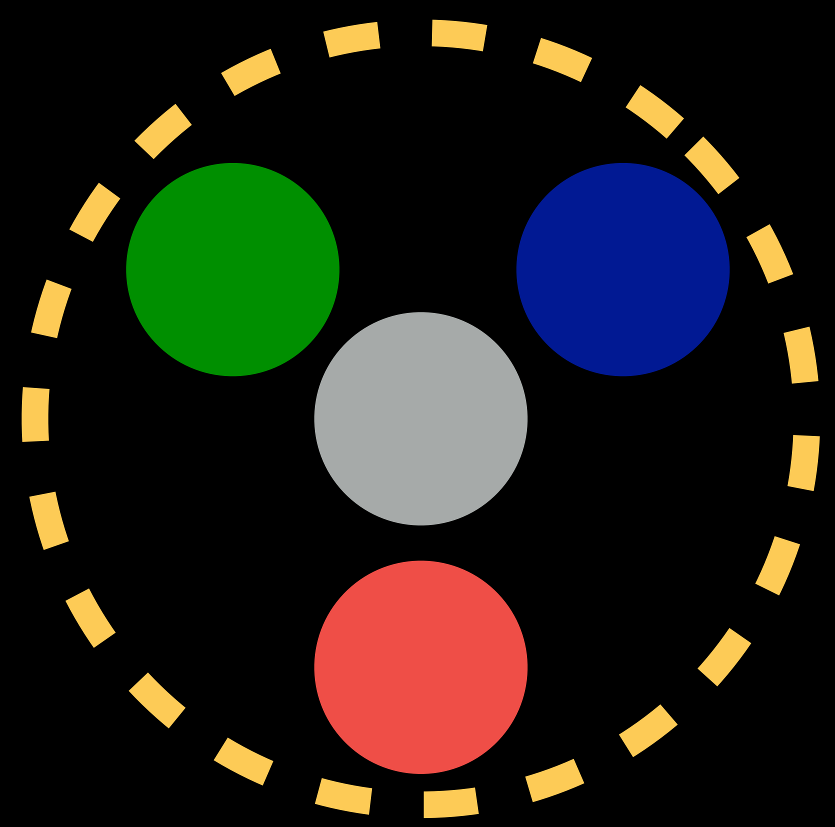
- Geometry-Based initial conditions
  - C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)
- Classical string-based initial conditions
  - A. Bialas, A. Bzdak and V. Koch, Acta Phys. Polon. B49 (2018)
  - C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907
- Transport model based initial conditions
  - Phys. Rev. C91 (2015) 064901
  - Nucl. Phys. A982 (2019) 407-410
  - Eur. Phys. J. A 58, no.11, 230 (2022)
  - arXiv:2301.11894 [nucl-th]
- 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, Phys. Rev. C105, 034908 (2022)
- Holographic approach at intermediate coupling
  - M. Attems, et al., Phys.Rev.Lett. 121 (2018), 261601

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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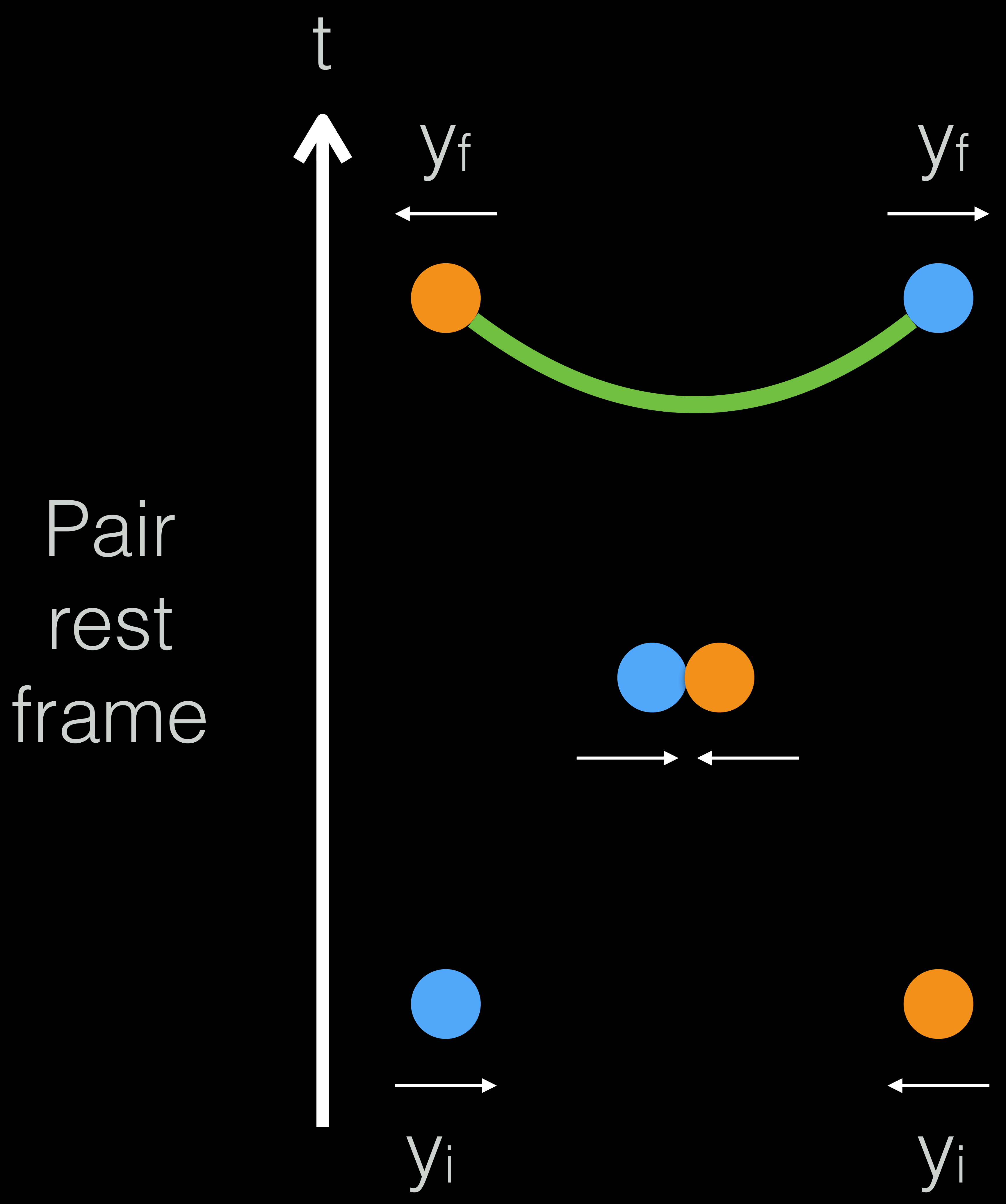

- Collision geometry is determined by MC-Glauber model
- Hot spots are sampled and randomly picked to lose energy during a collision
- Incoming quarks are decelerated with a classical string tension,

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

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

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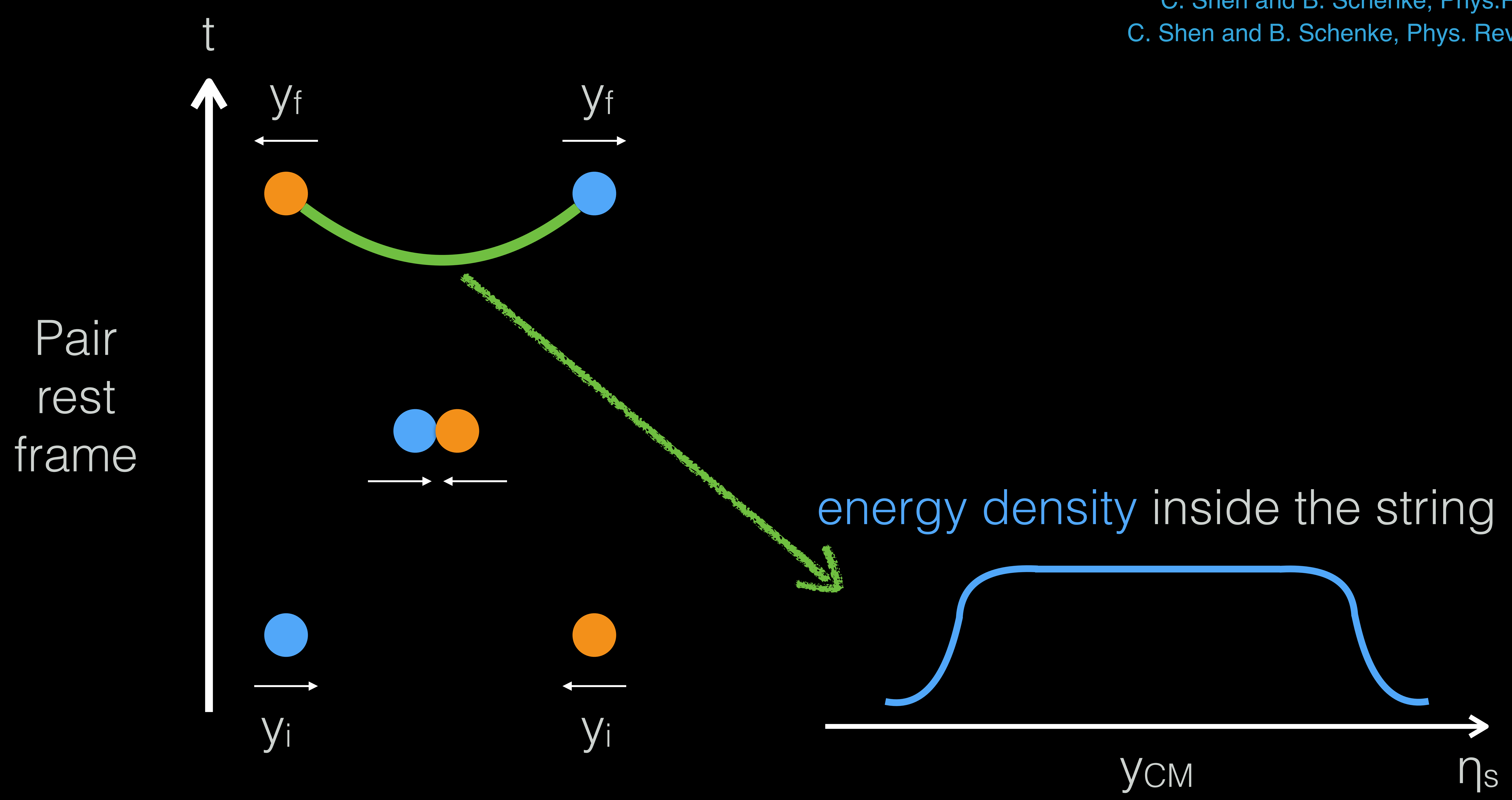

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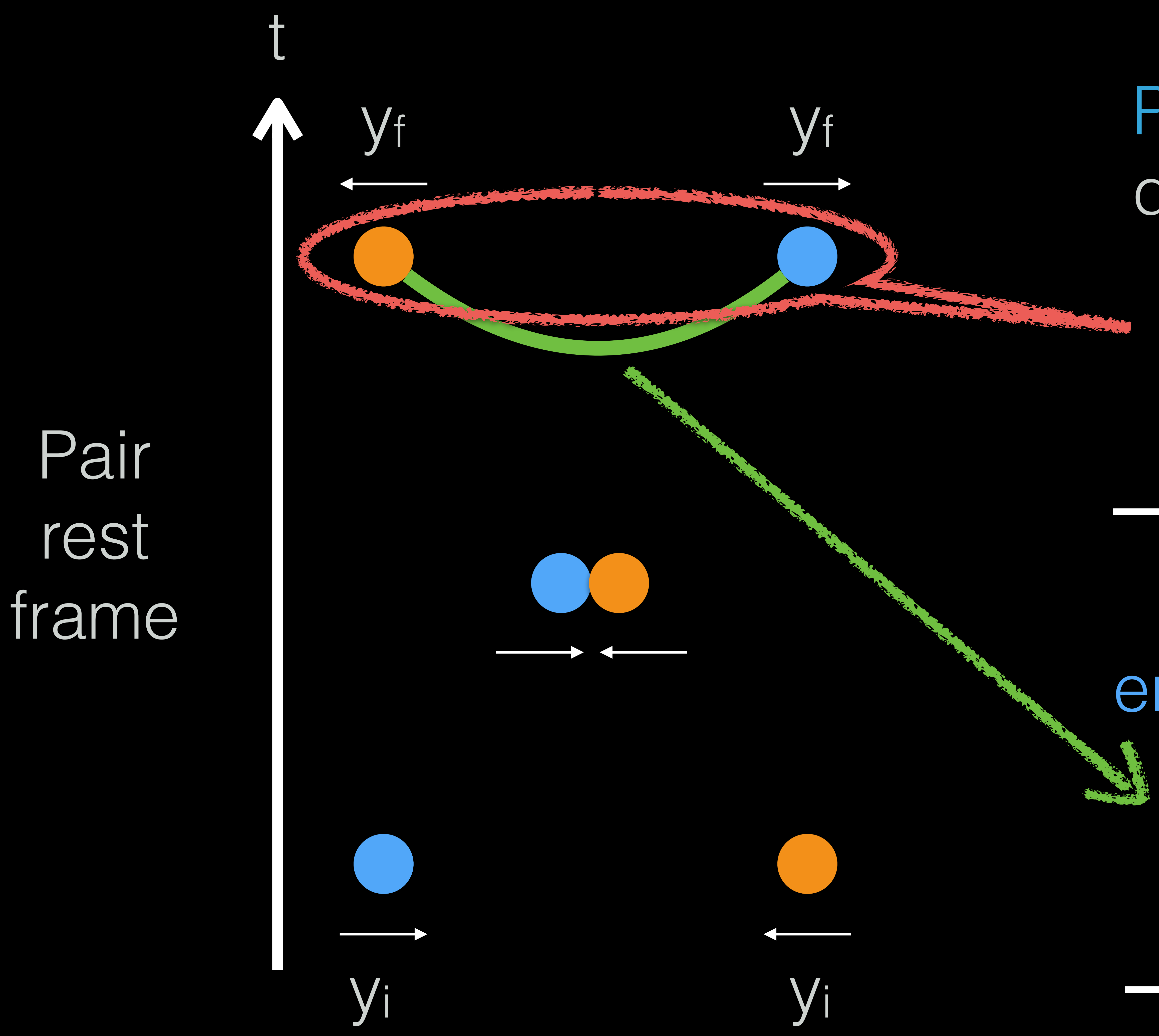
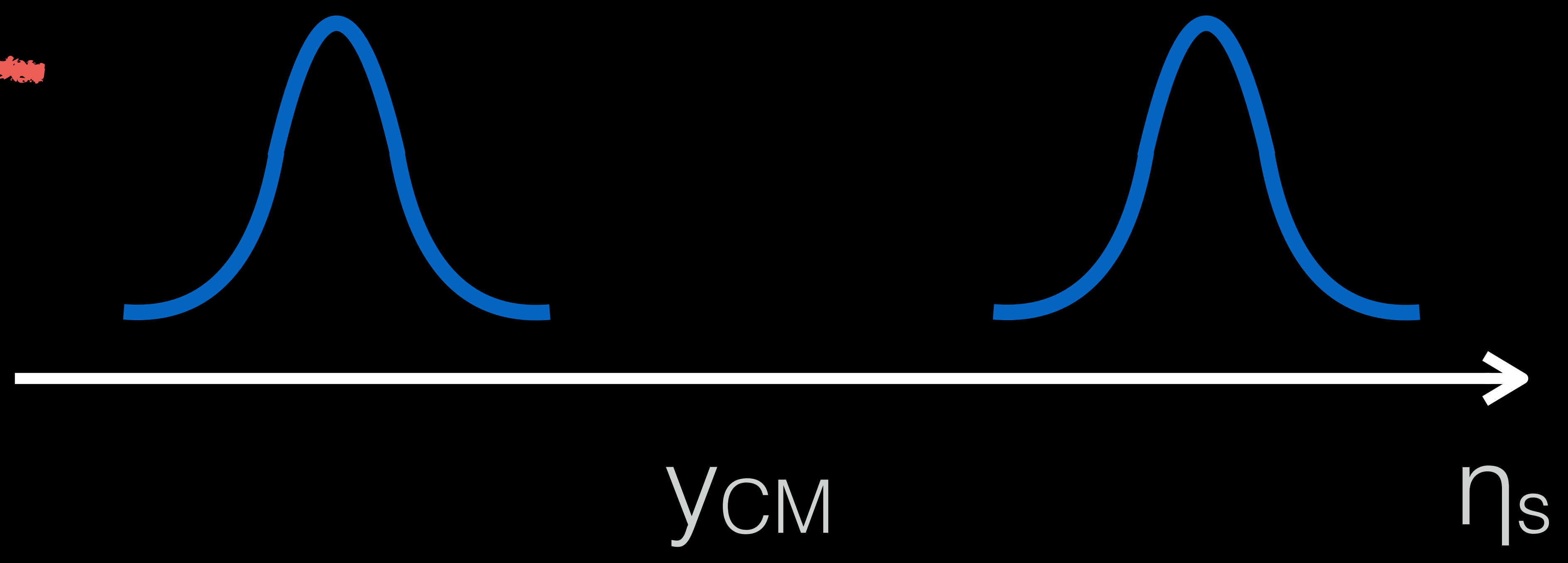
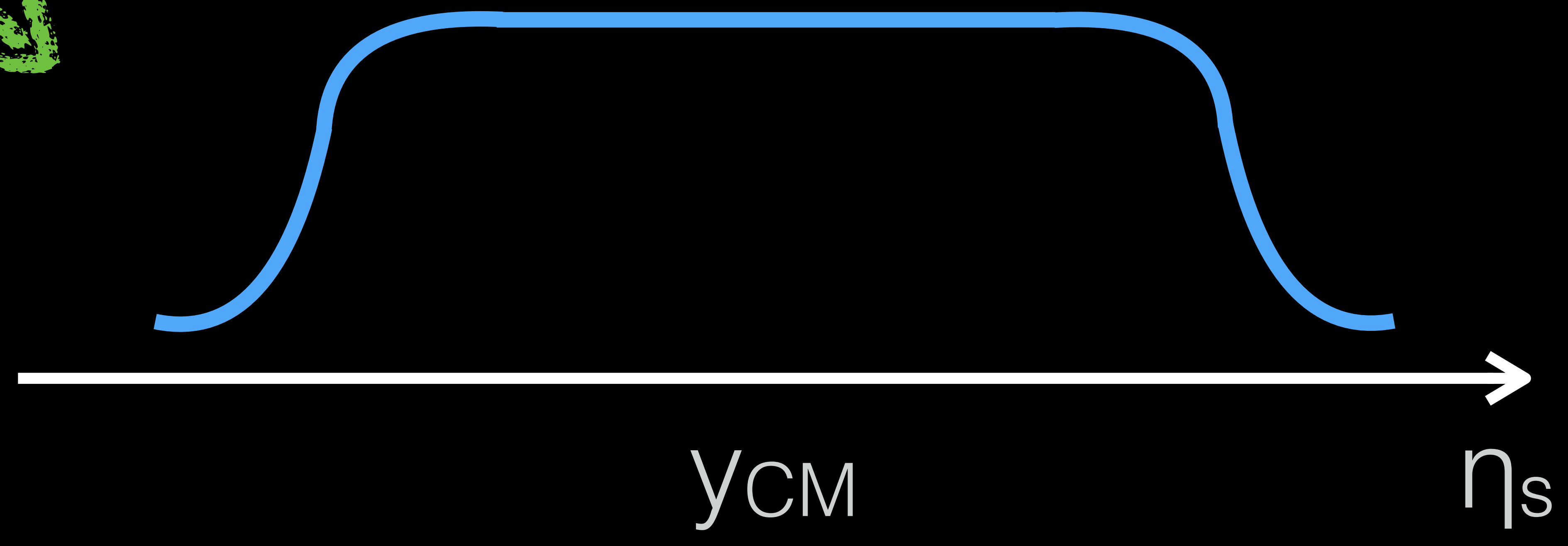


Partons' remaining energies are deposited at the string ends



energy density inside the string



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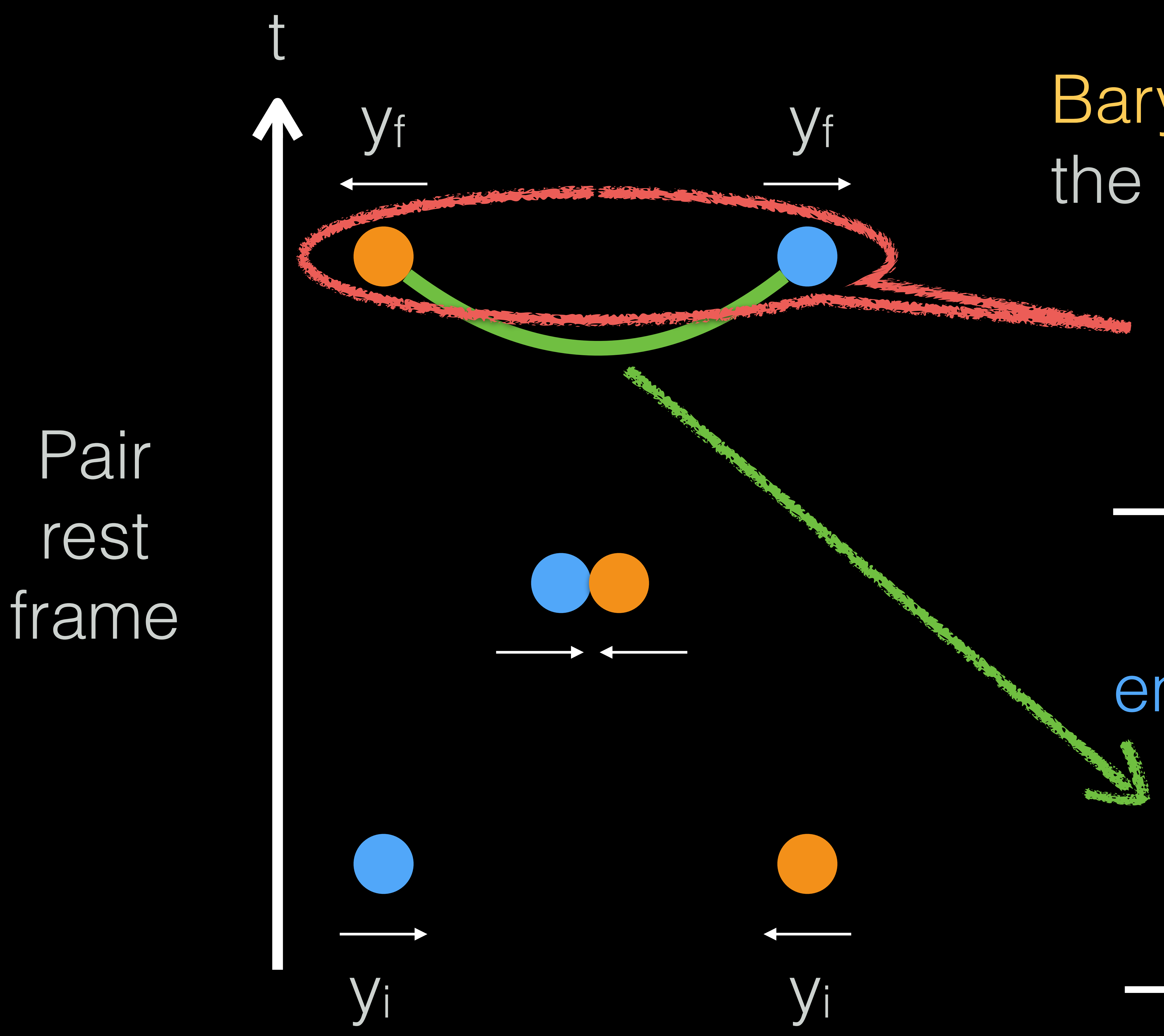
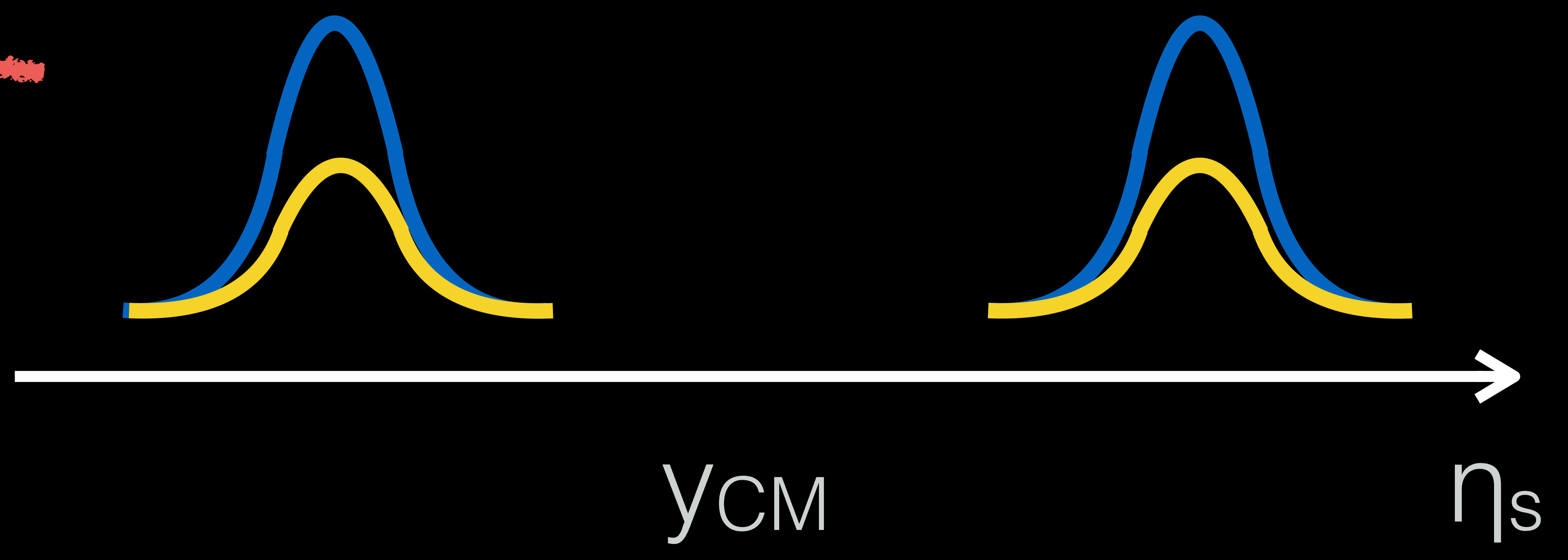
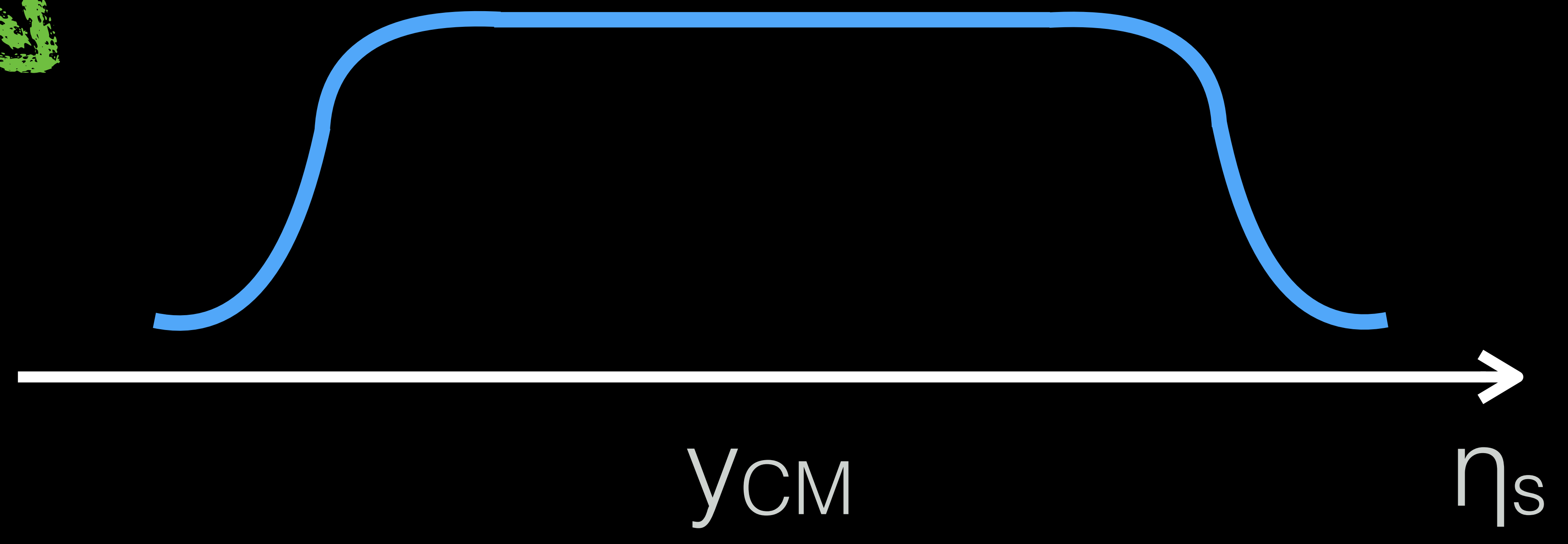


Baryon densities are deposited at the string ends or string junctions

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



energy density inside the string



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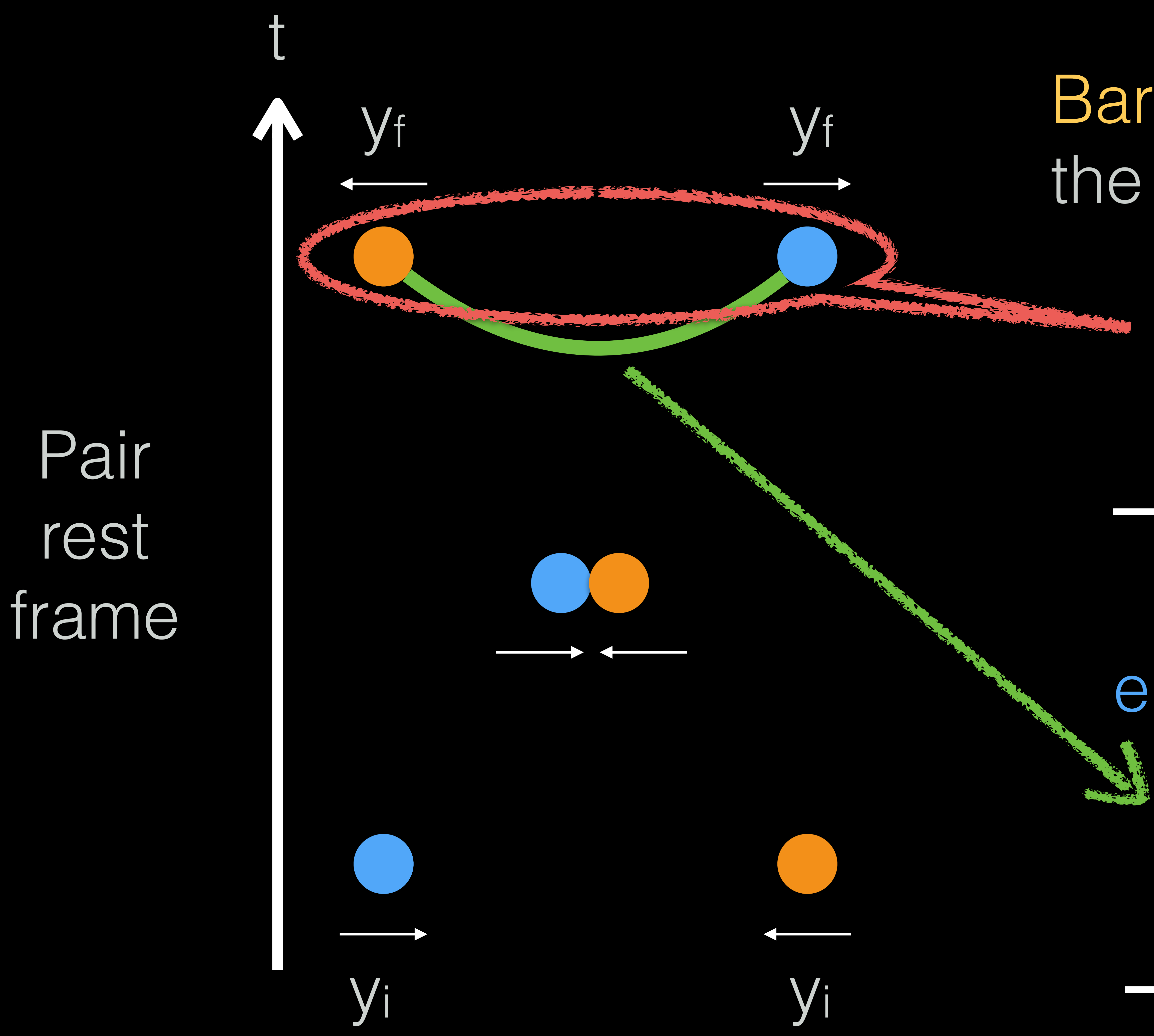

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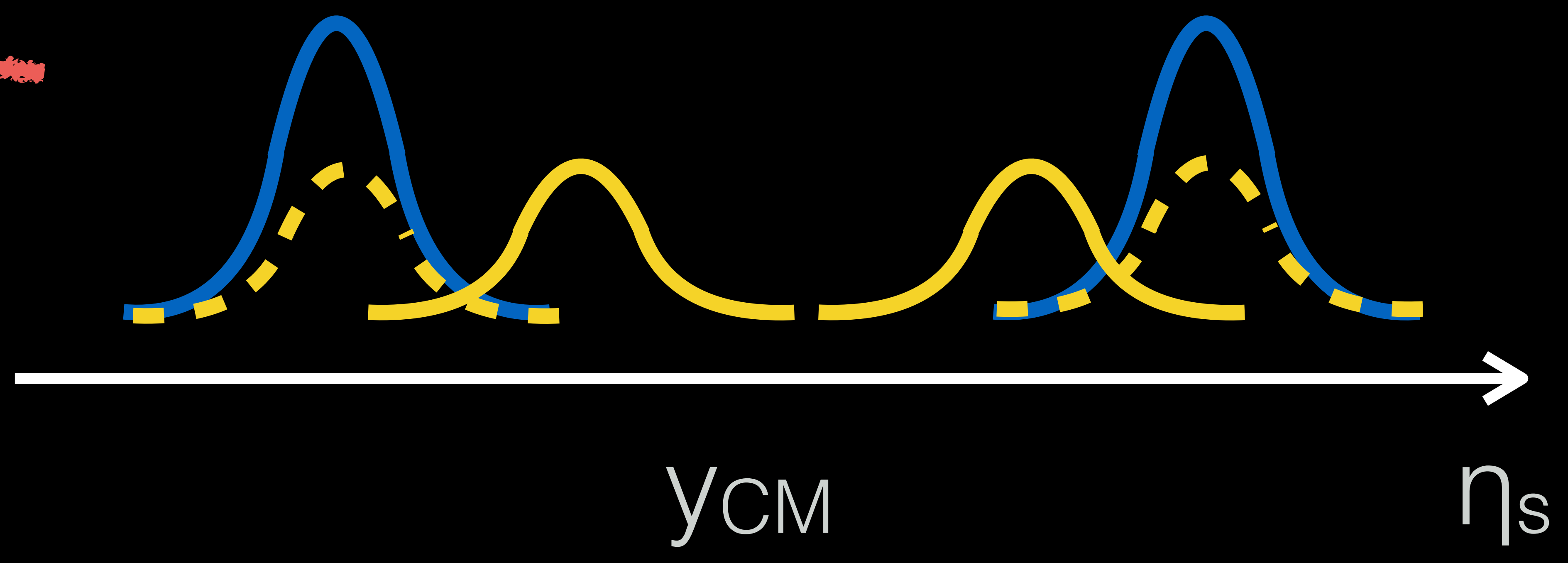

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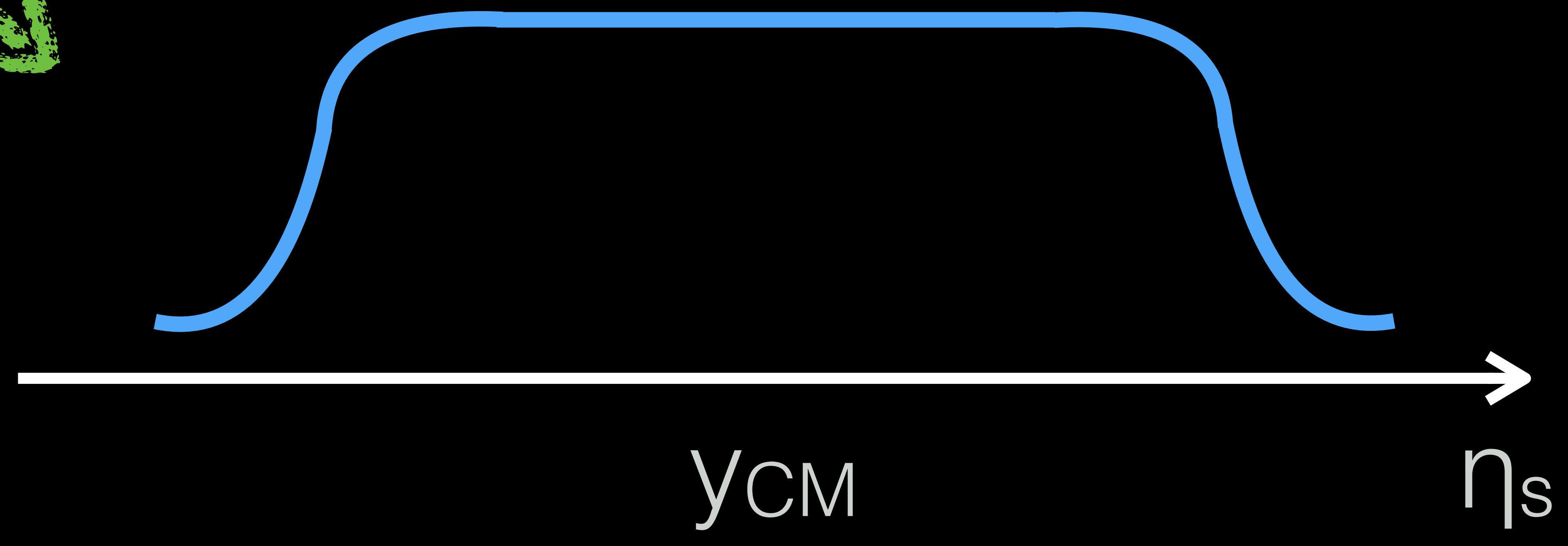

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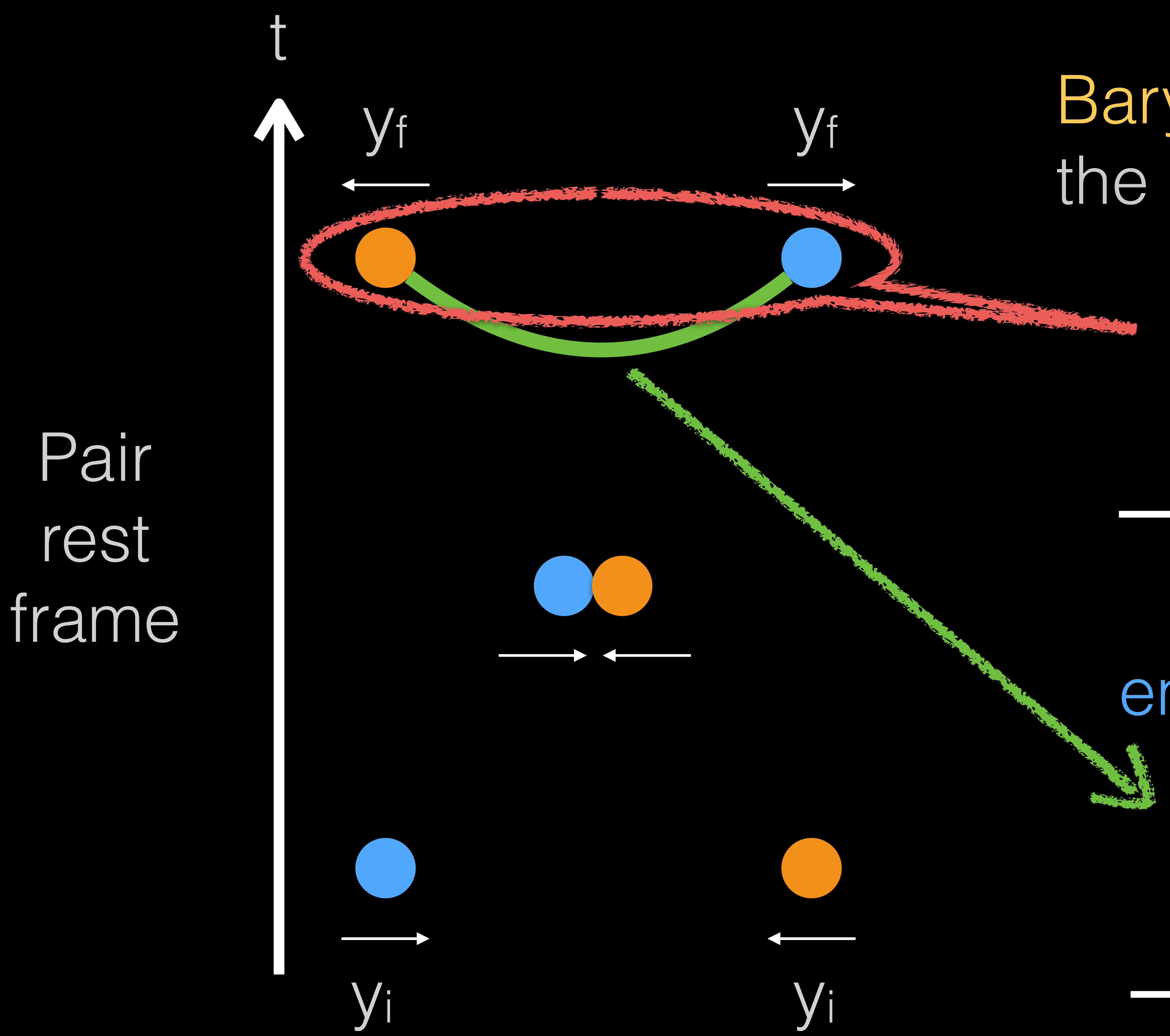

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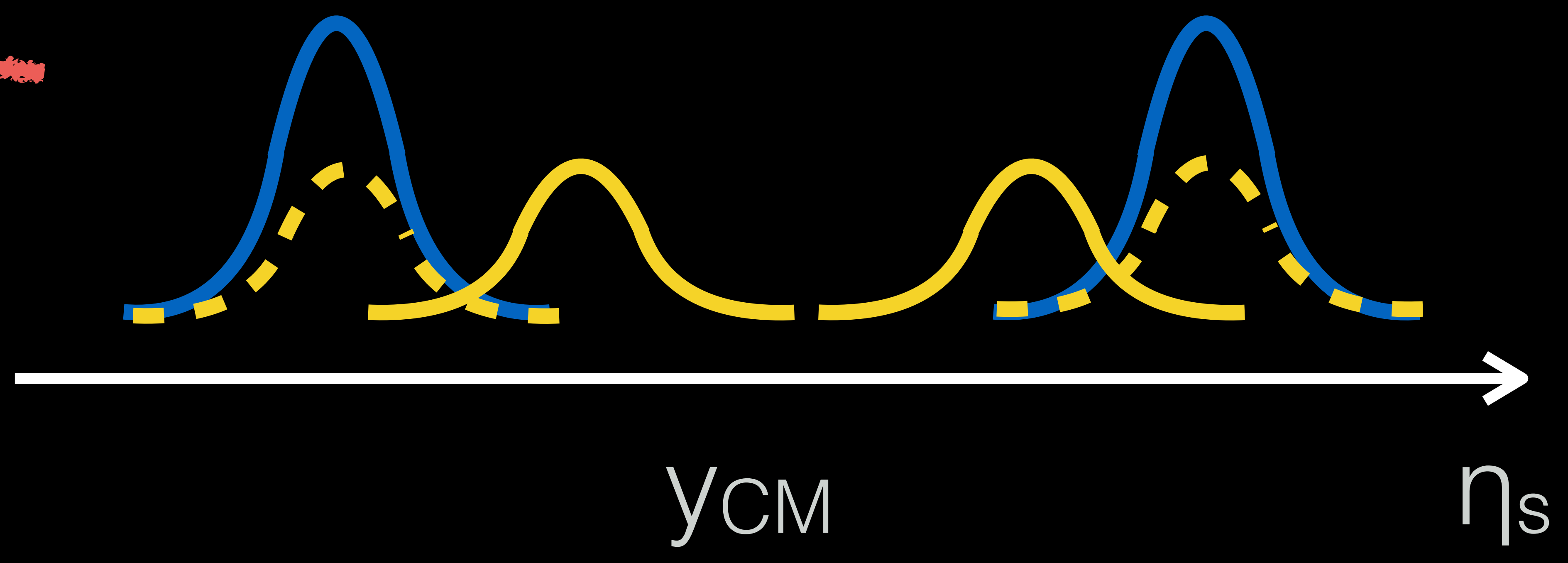

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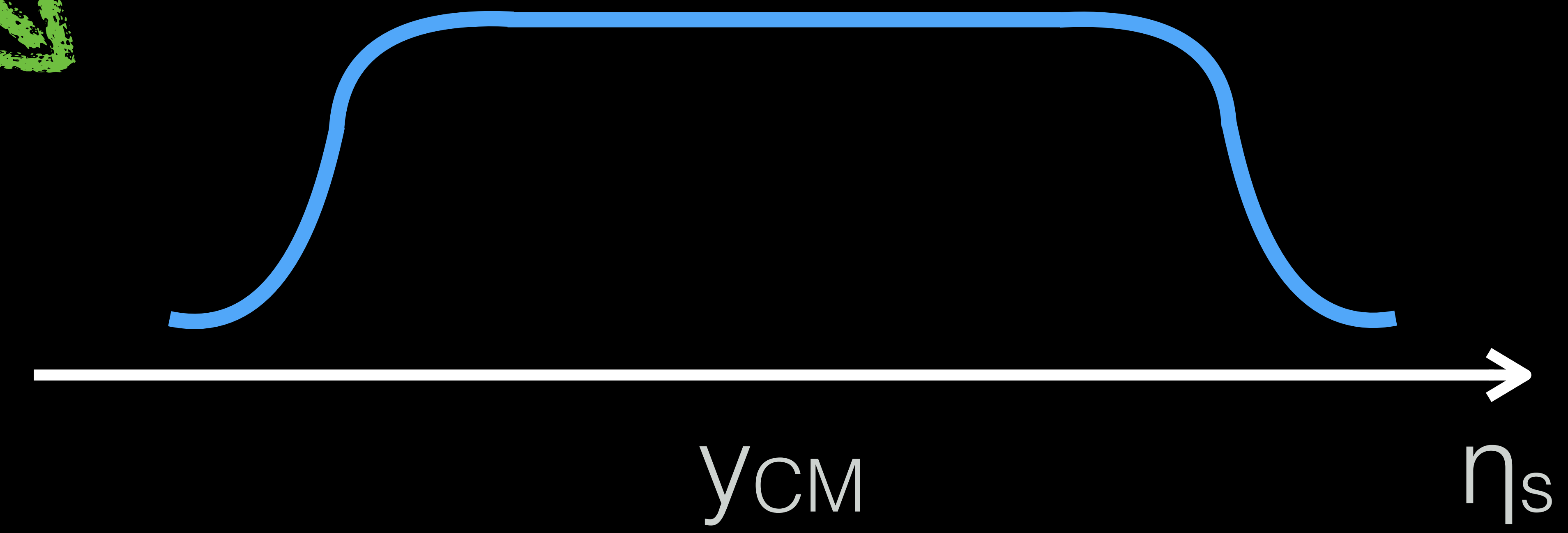
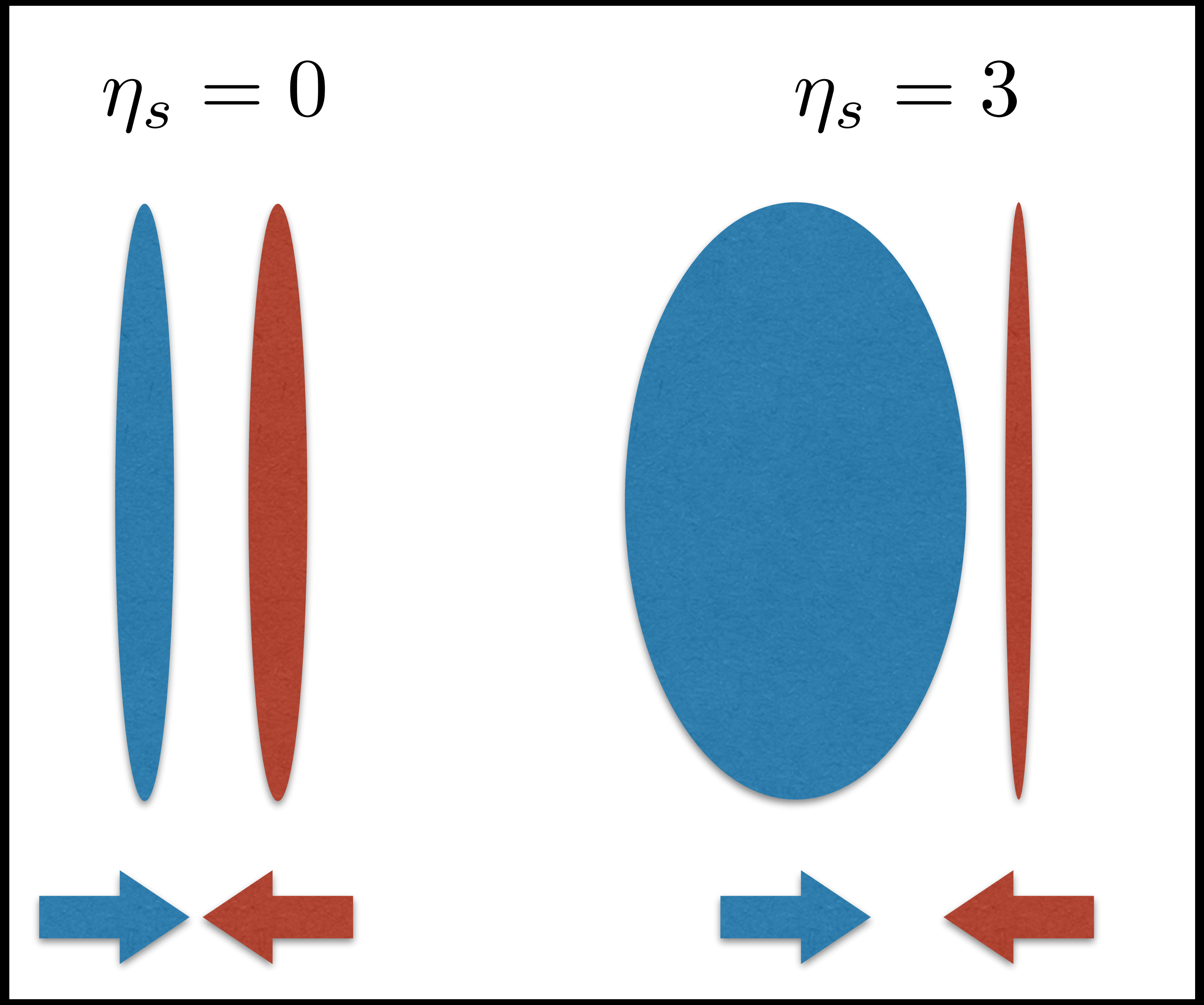
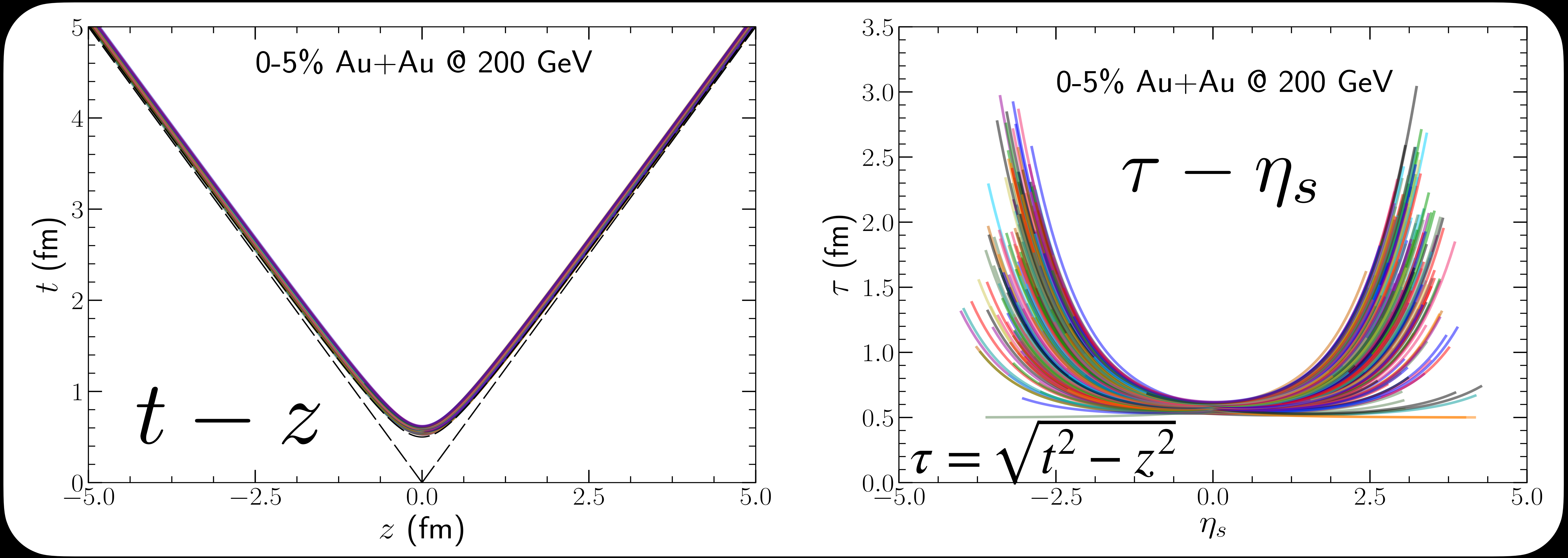
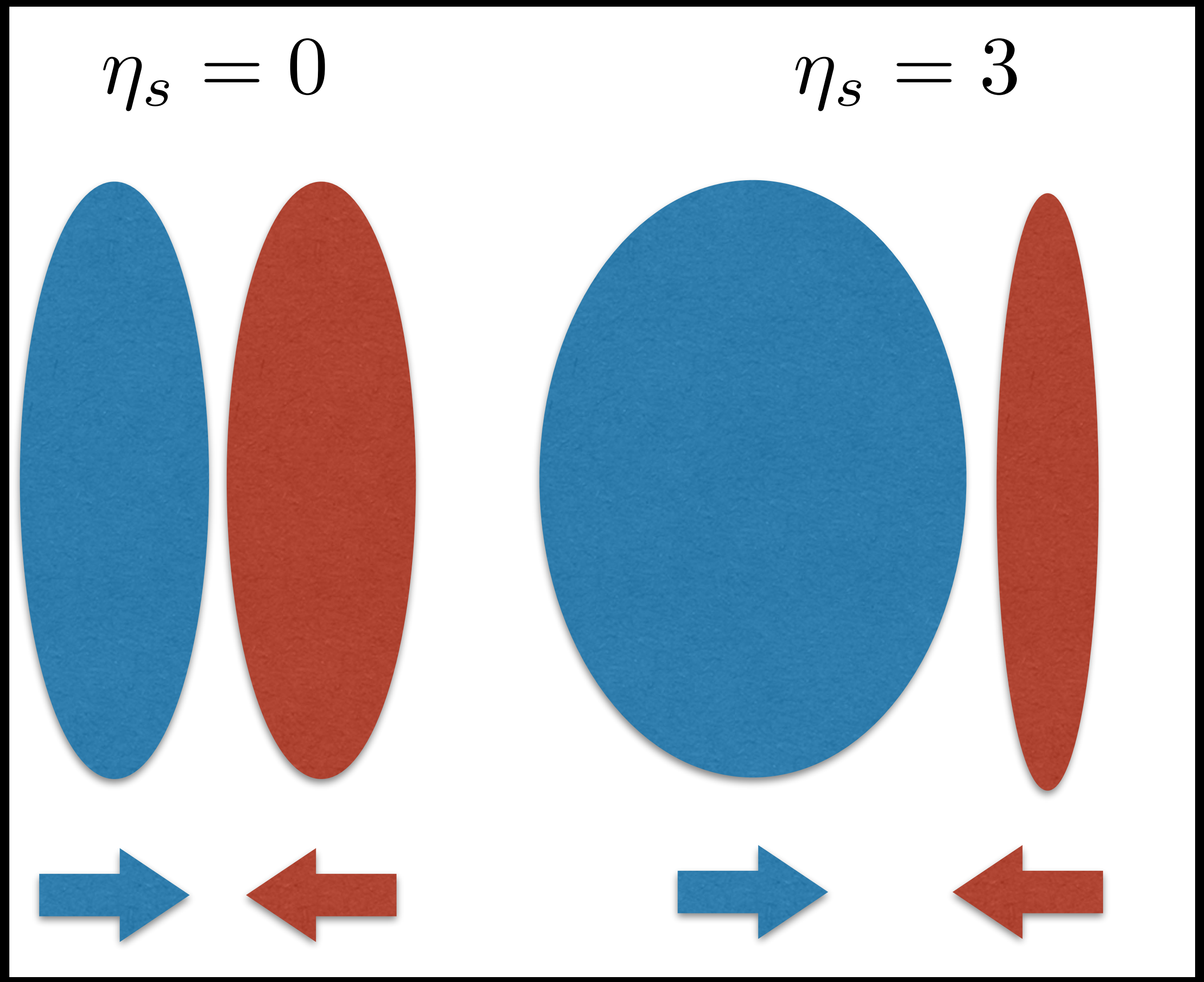


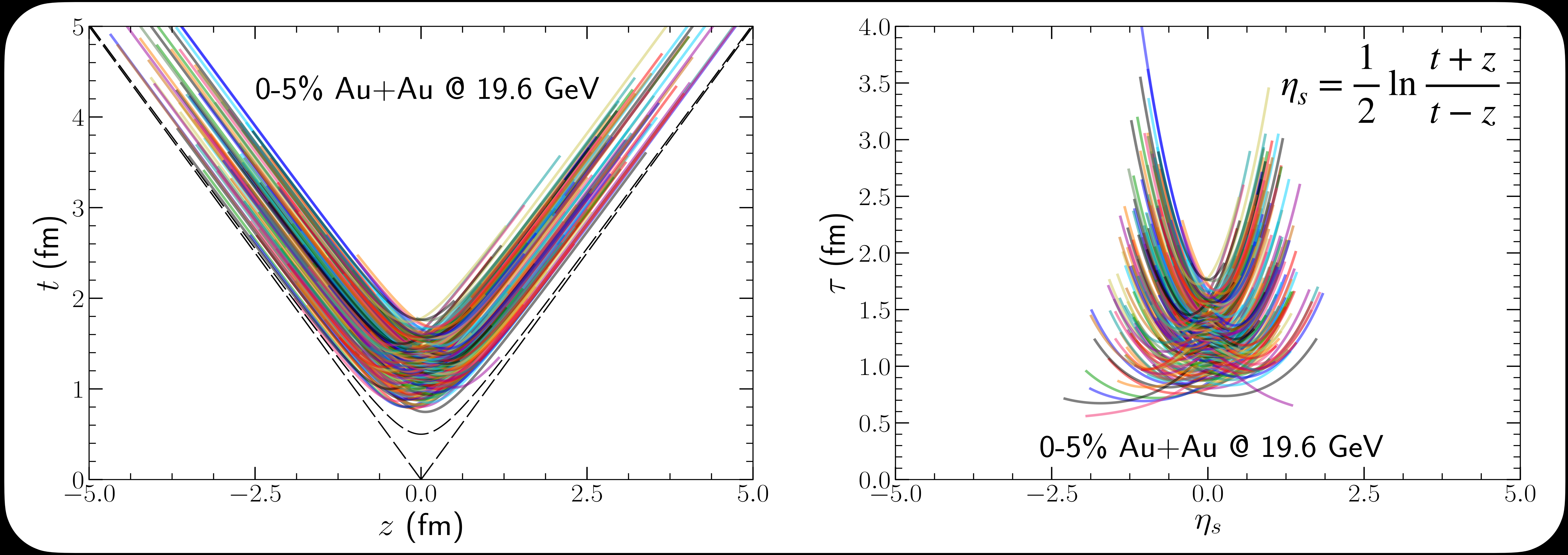
Imposed conservation for energy, momentum, and net baryon density

STRINGS' SPACE-TIME DISTRIBUTION



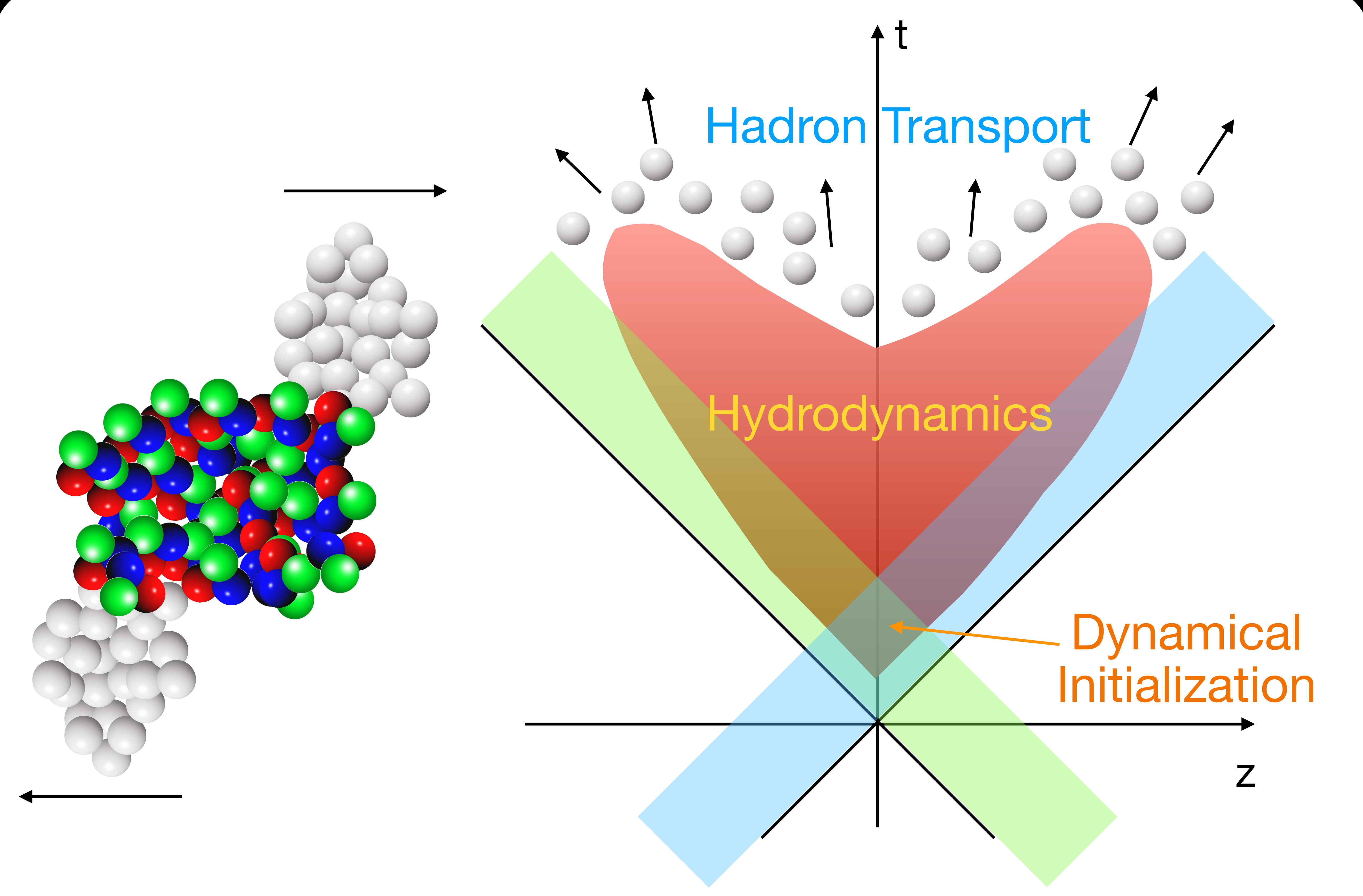






HYDRODYNAMICS WITH SOURCES

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)

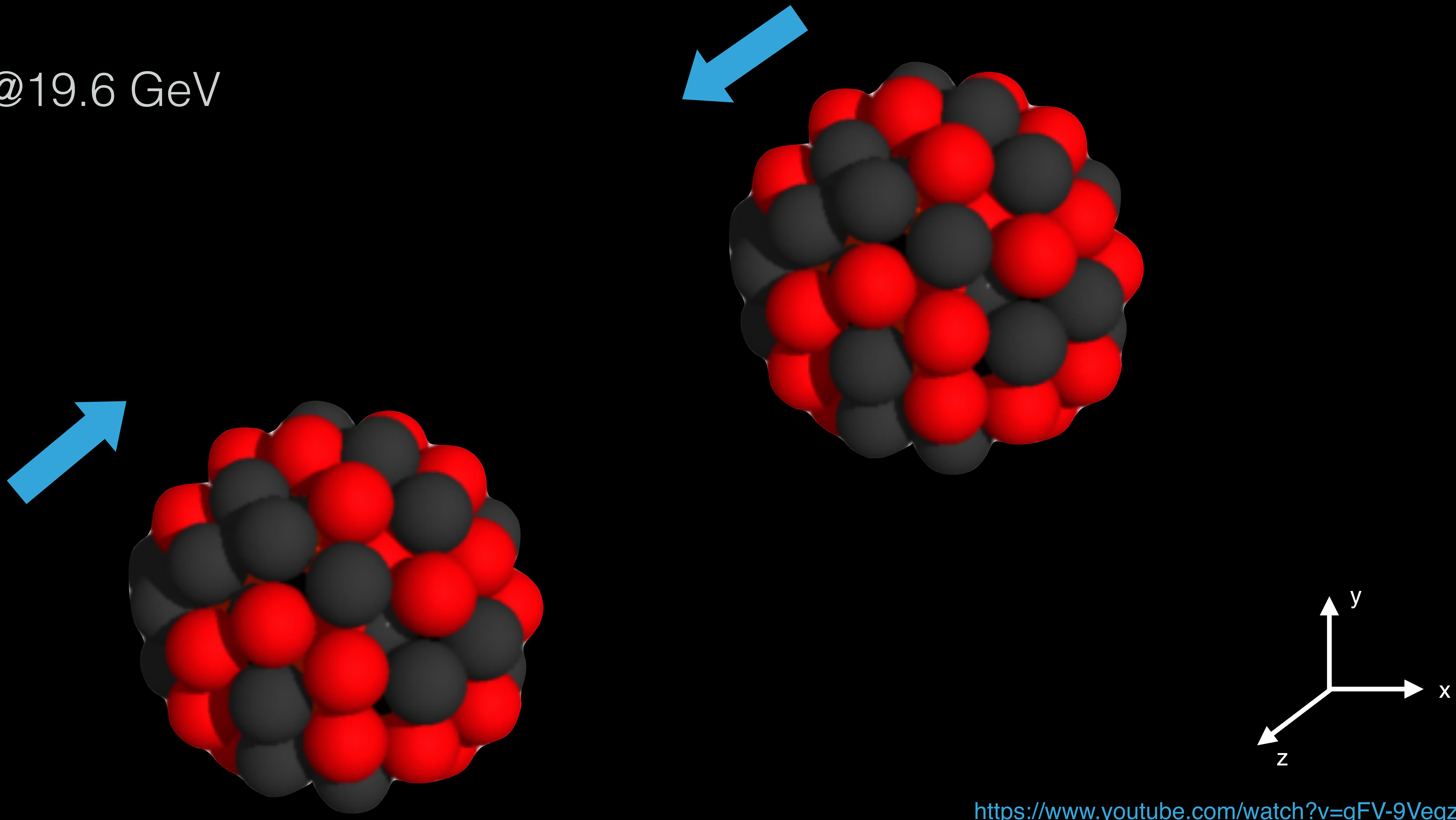
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907

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)

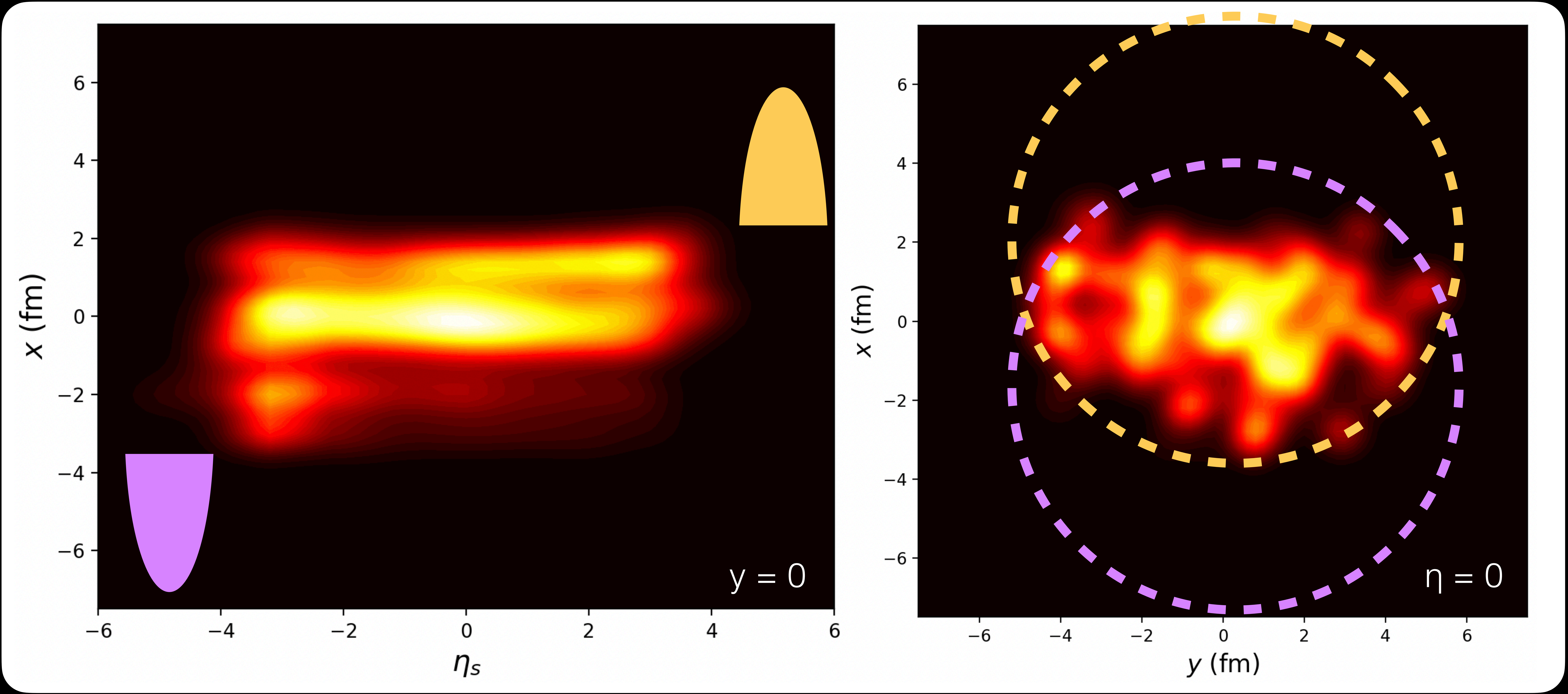
RELATIVISTIC HEAVY-ION COLLISIONS

0-5% AuAu@19.6 GeV



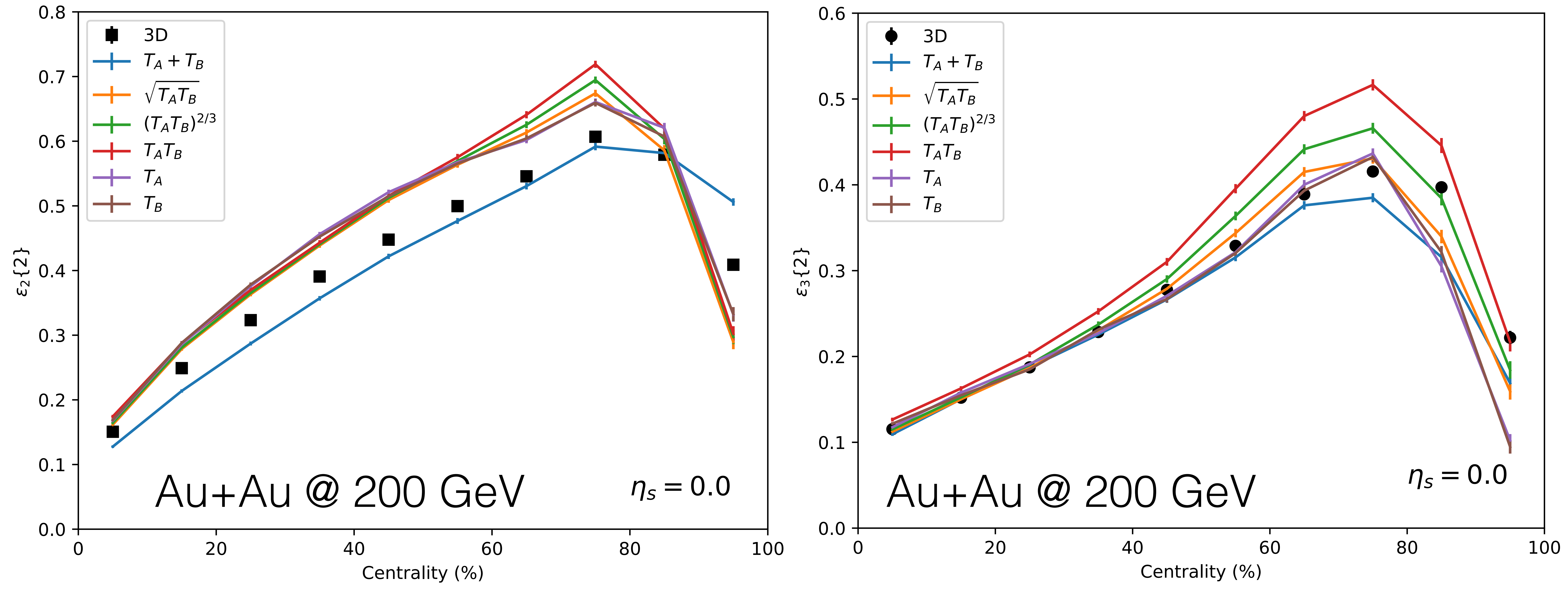
https://www.youtube.com/watch?v=gFV-9VeqzkE

UNDERSTAND THE 3D ENERGY DENSITY PROFILE



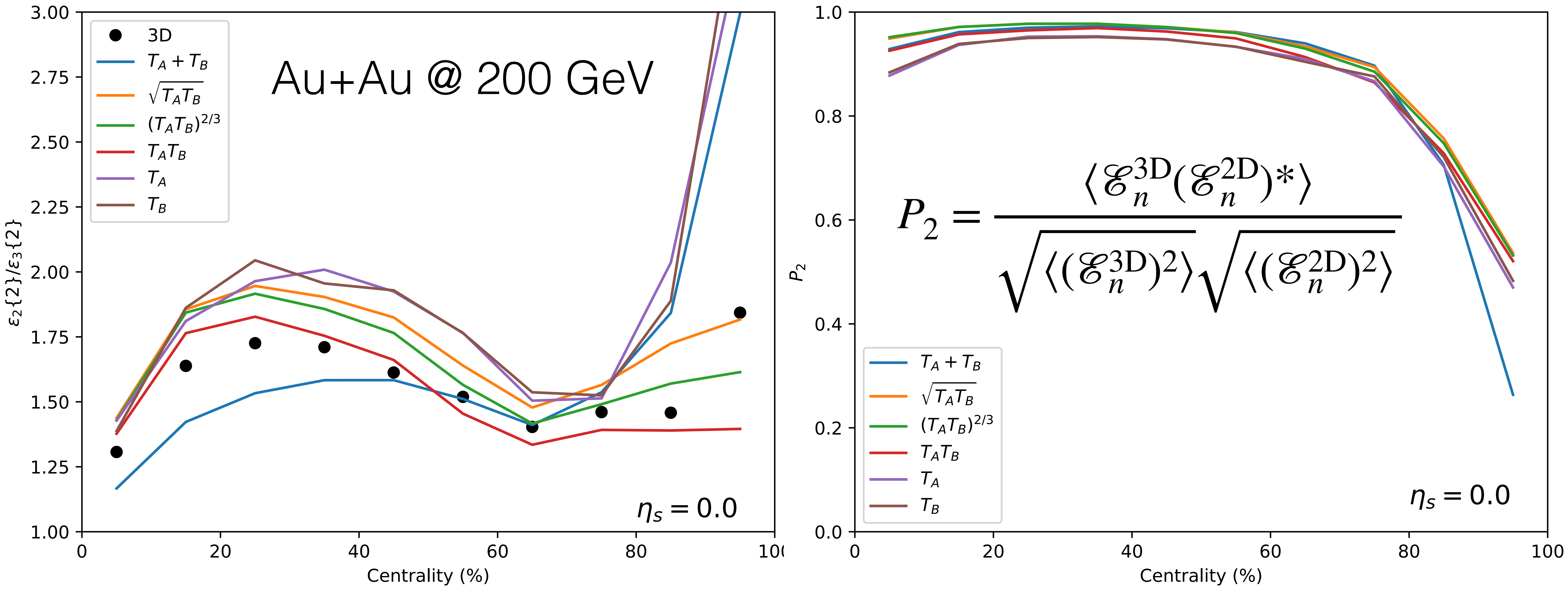
Au+Au@200 GeV b = 7 fm

MID-RAPIDITY SPATIAL ECCENTRICITY



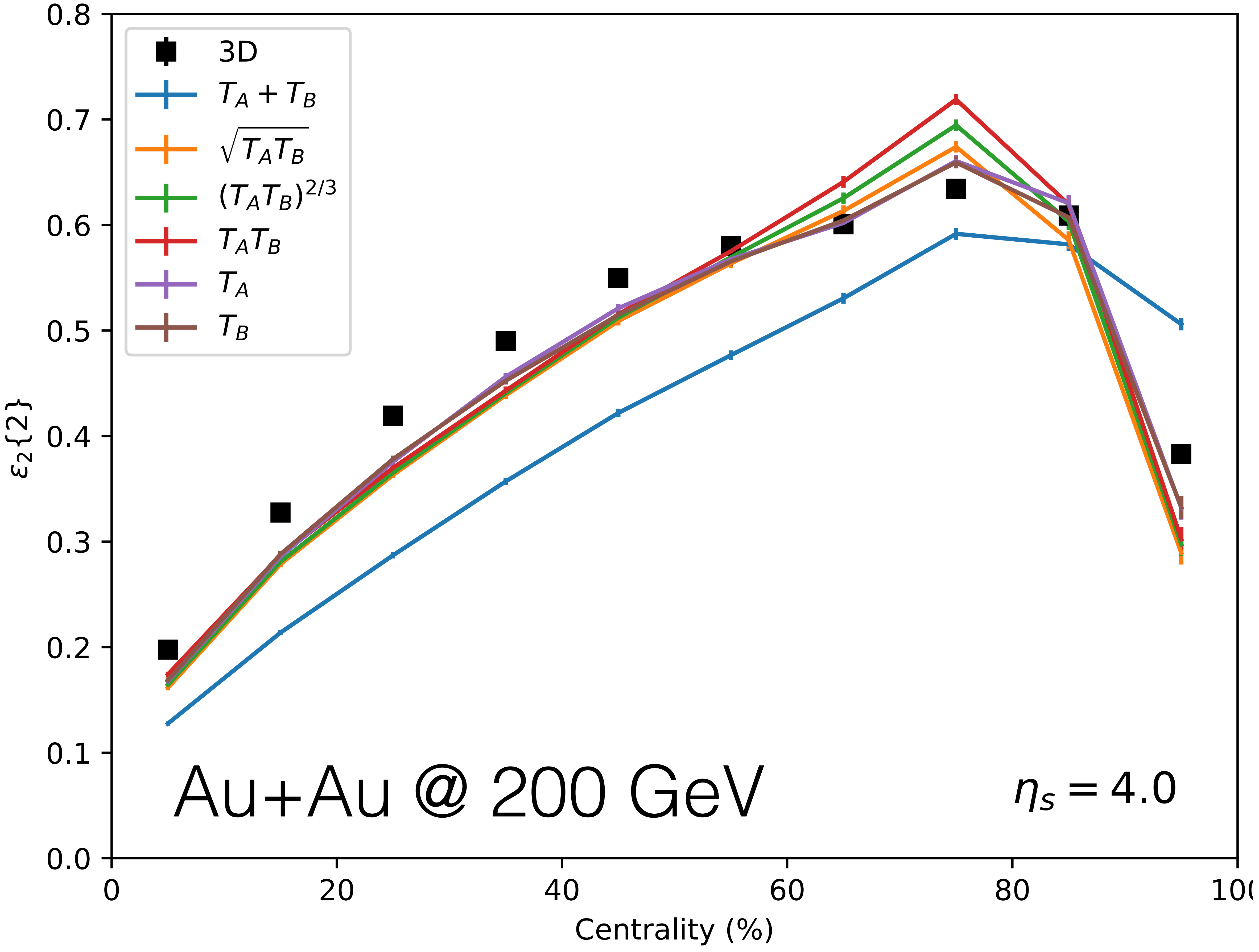
- No clear 2D estimators with nuclear thickness functions for the eccentricities of the 3D MC-Glauber model

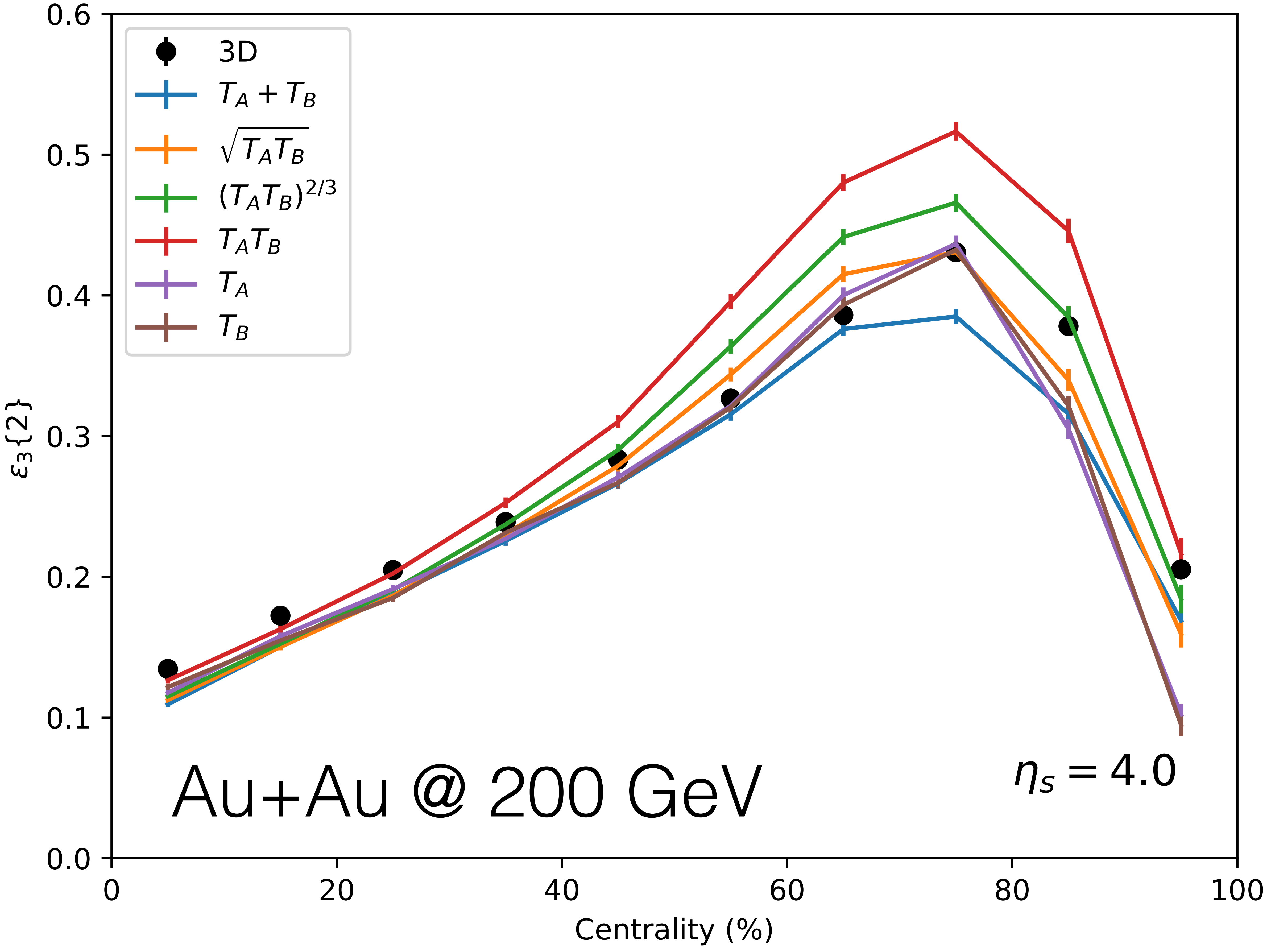
UNDERSTAND SPATIAL ECCENTRICITY



- At mid-rapidity, the ratio of ϵ_2/ϵ_3 is close to the $T_A T_B$ scaling; The Pearson correlation slightly favors $(T_A T_B)^{1/2}$ and $(T_A T_B)^{2/3}$

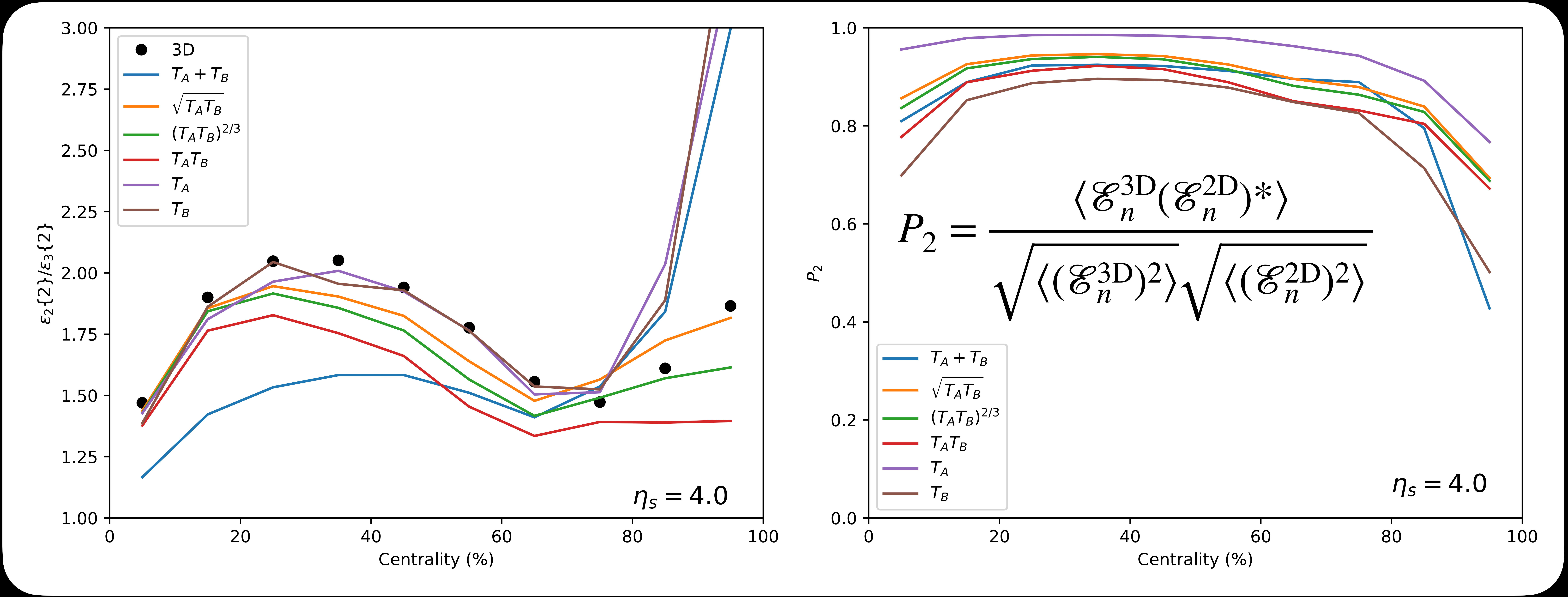
FORWARD SPATIAL ECCENTRICITY





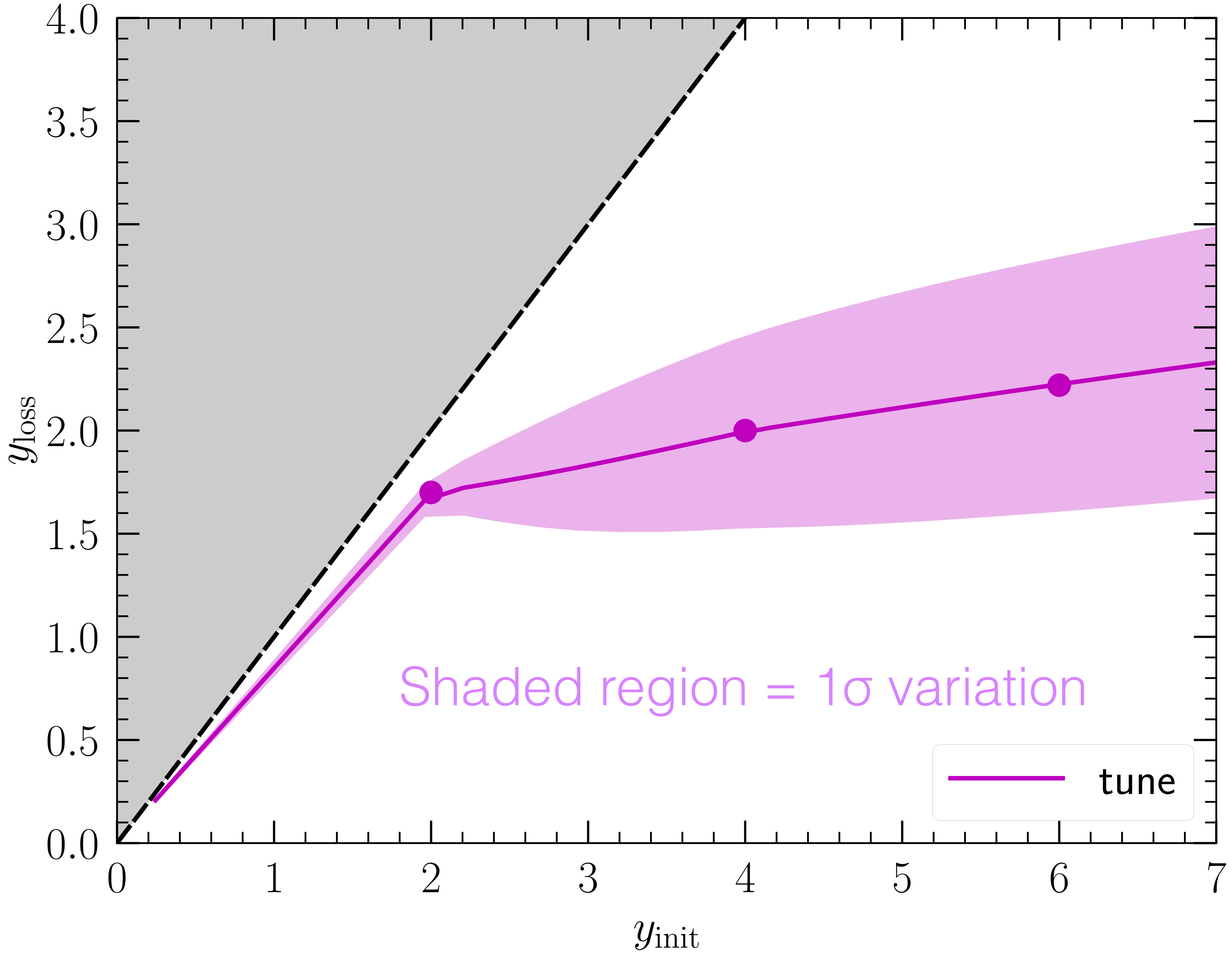
- Ellipticity increases in the forward rapidity compared to those at mid-rapidity

UNDERSTAND SPATIAL ECCENTRICITY



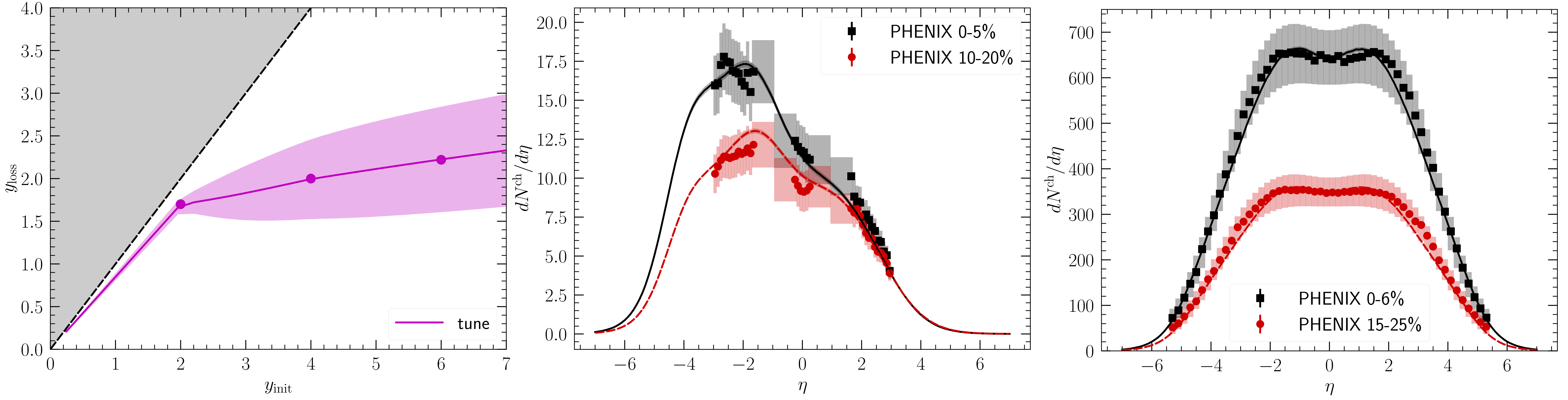
- At forward rapidity, the spatial eccentricity is correlated with T_A
- Similarly, the spatial eccentricity in the backward rapidity is correlated with T_B

PARAMETERIZE THE CONSTITUENTS ENERGY LOSS



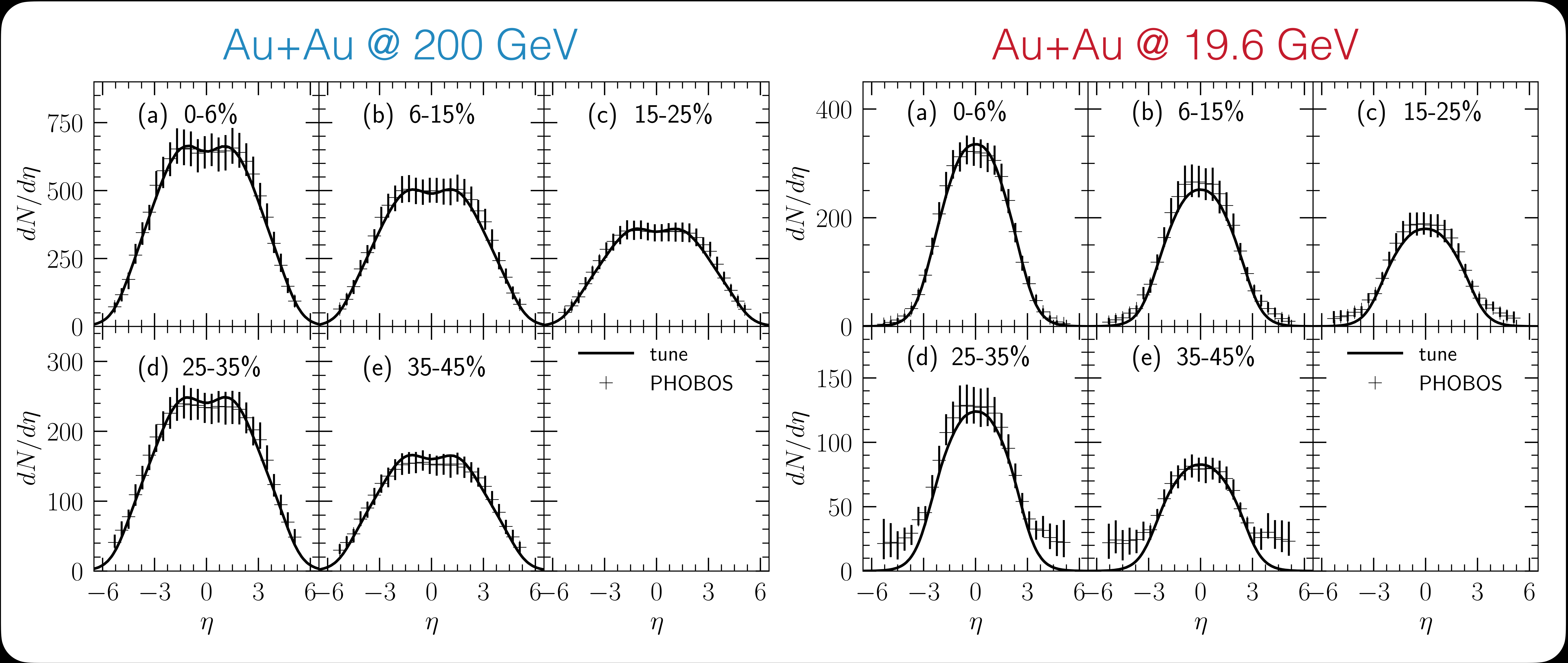
- Piece-wise parameterization of the averaged rapidity loss
- Std of $y_{\rm loss}$ fluctuations: σ_y bounded between ($y_{\rm loss} \in [0, y_{\rm init}]$)

CALIBRATION OF RAPIDITY LOSS



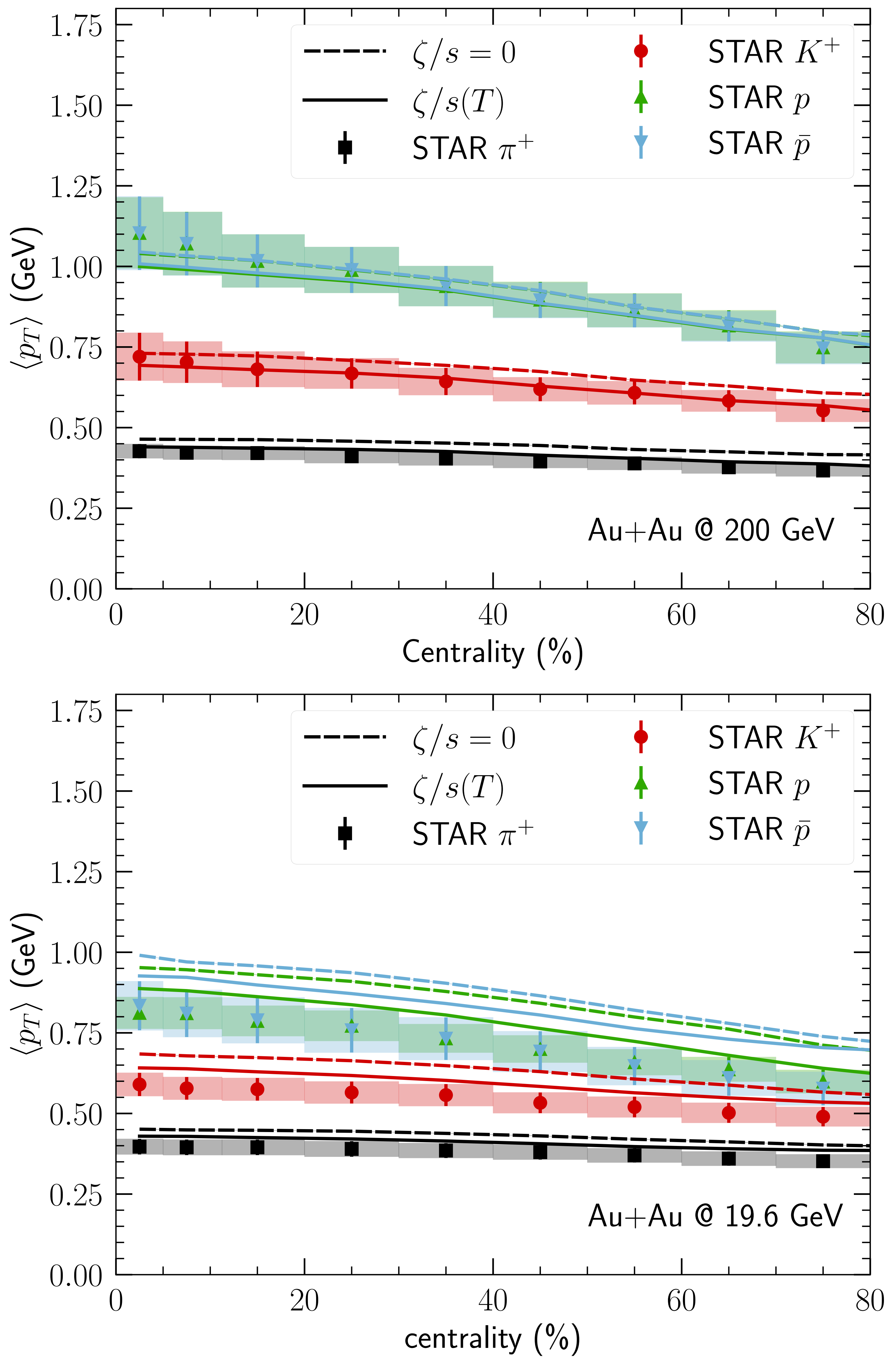
- Calibrated with charged particle pseudo-rapidity distribution in p+Au and Au+Au collisions at 200 GeV

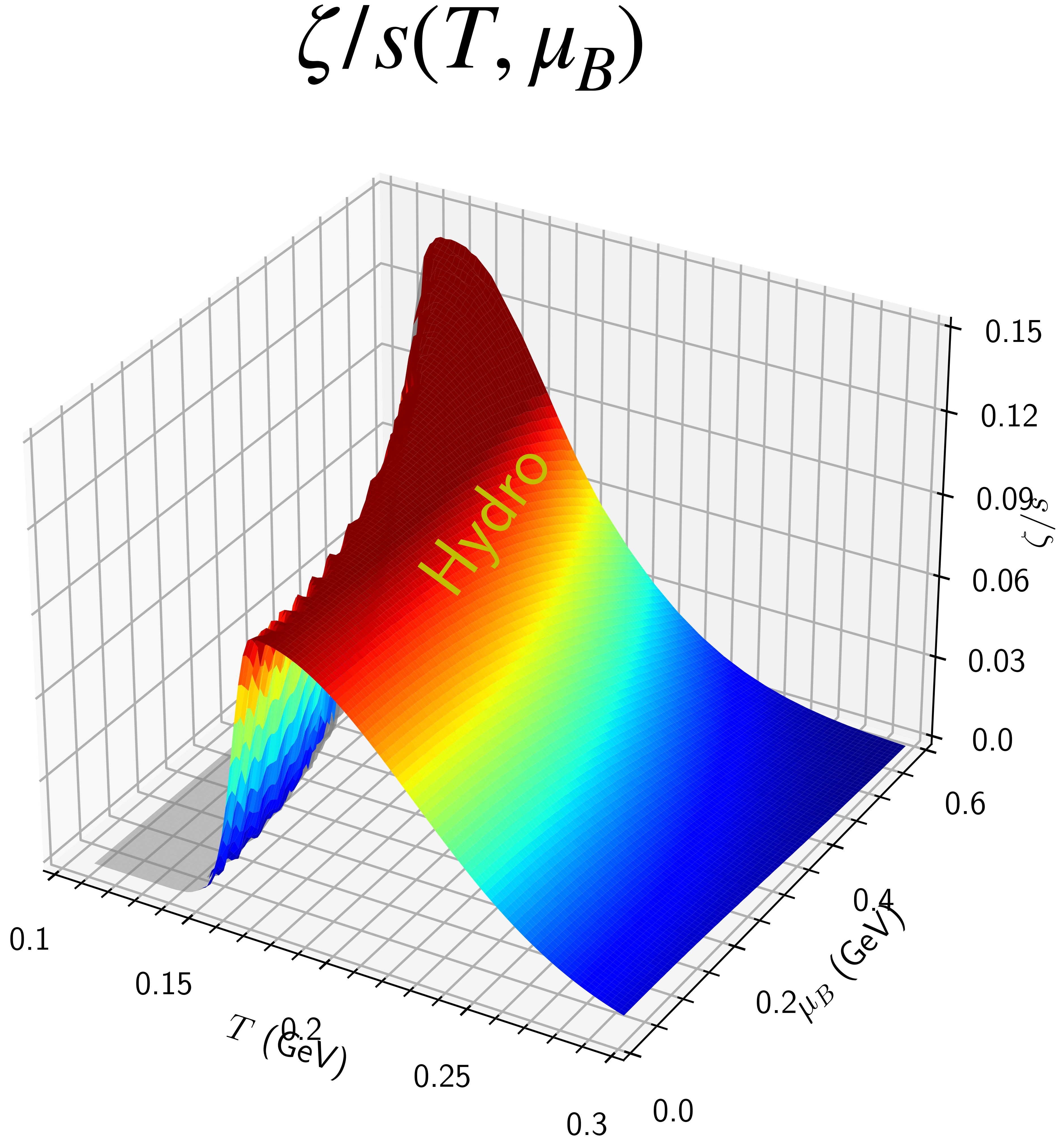
PARTICLE PRODUCTION IN AA COLLISIONS



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

CONSTRAINING QGP VISCOSITY AT FINITE μ_B

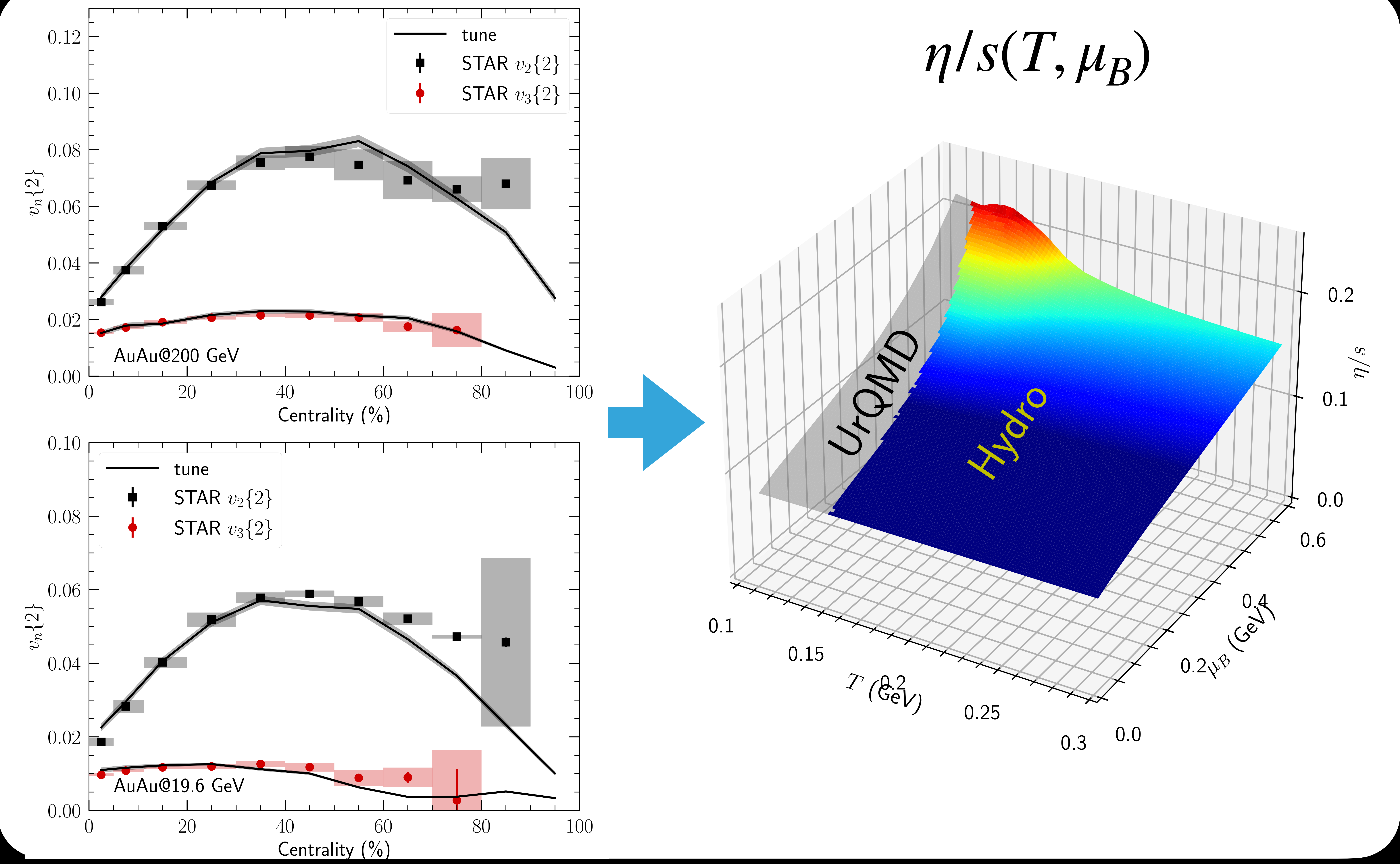




Sangwook Ryu et al., in preparation

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



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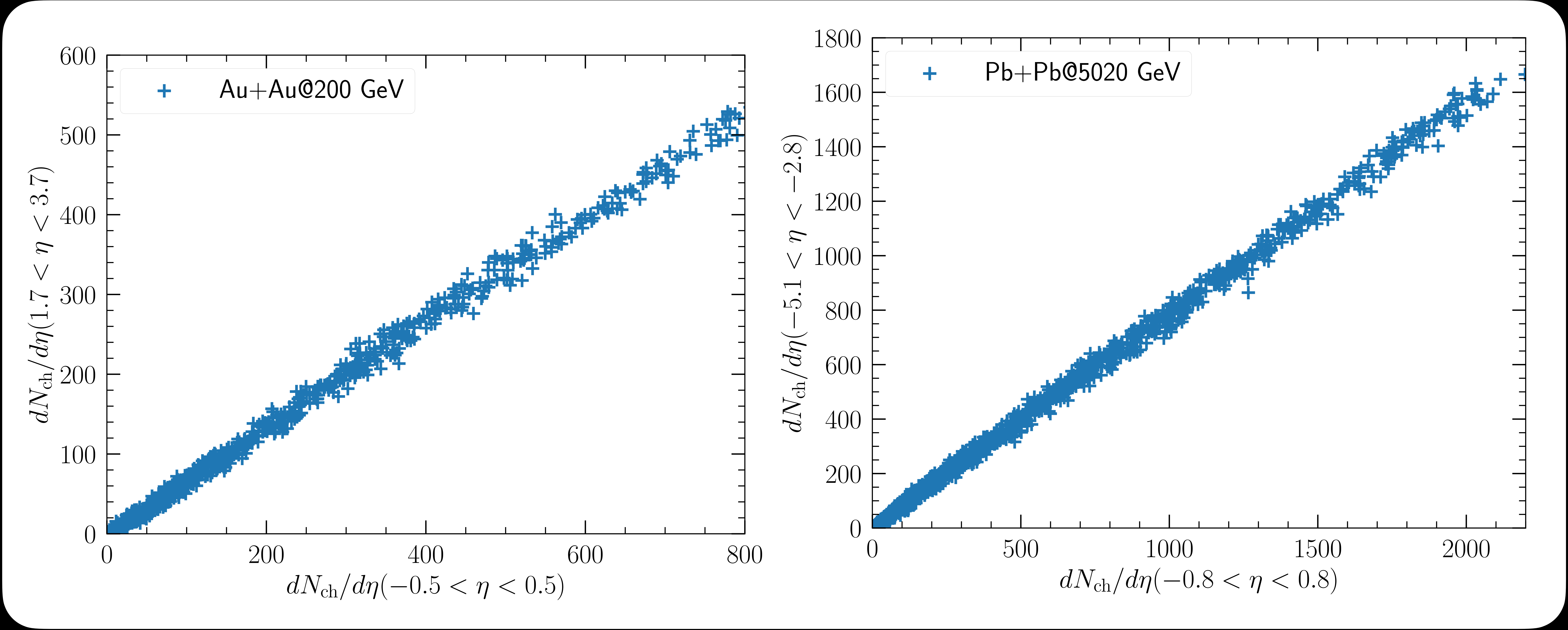
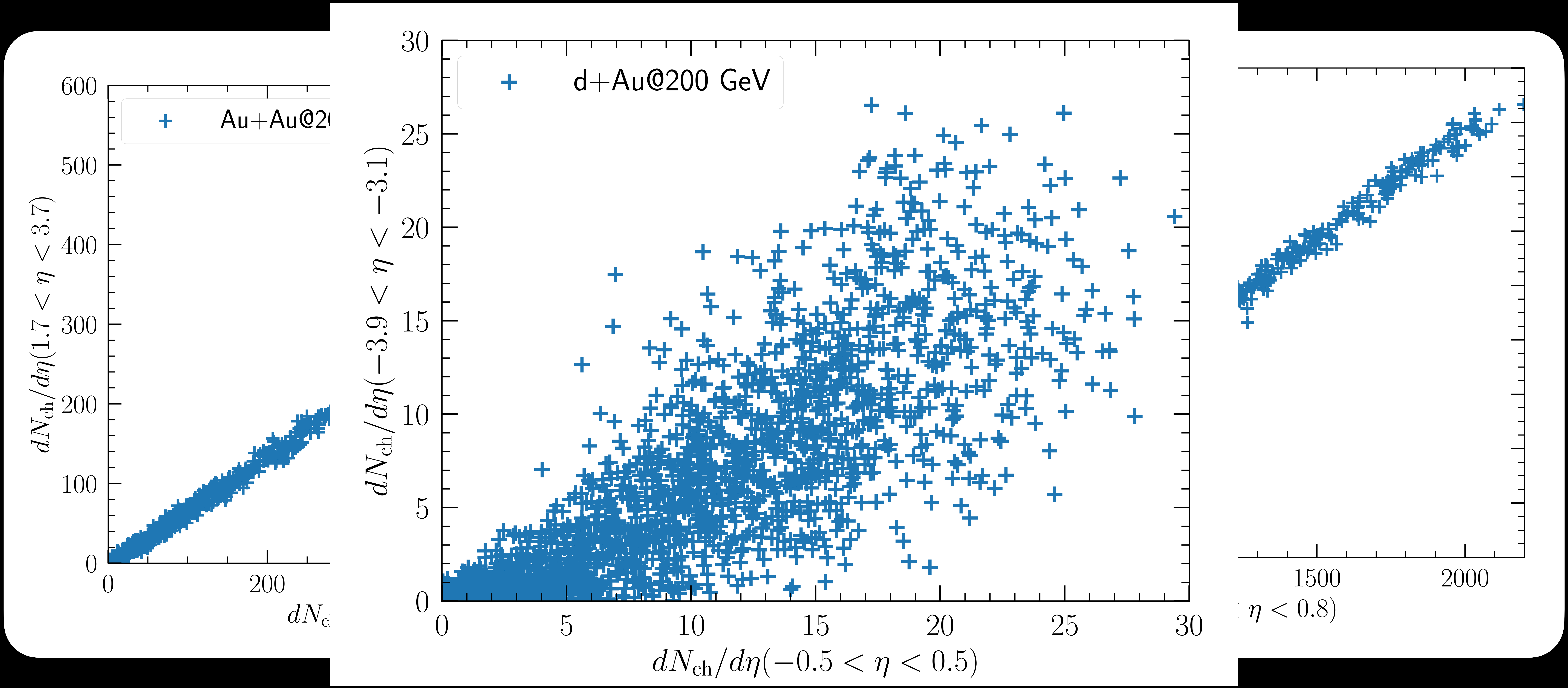
PARTICLE YIELD CORRELATION



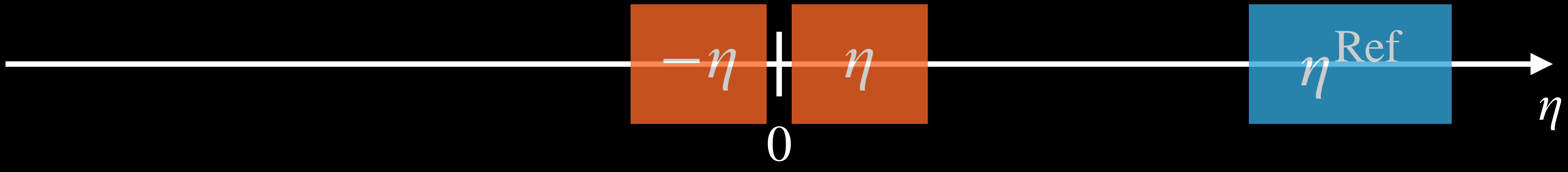
- In symmetric heavy-ion collisions, particle production in the forward rapidity is strongly correlated with those at mid-rapidity

PARTICLE YIELD CORRELATION



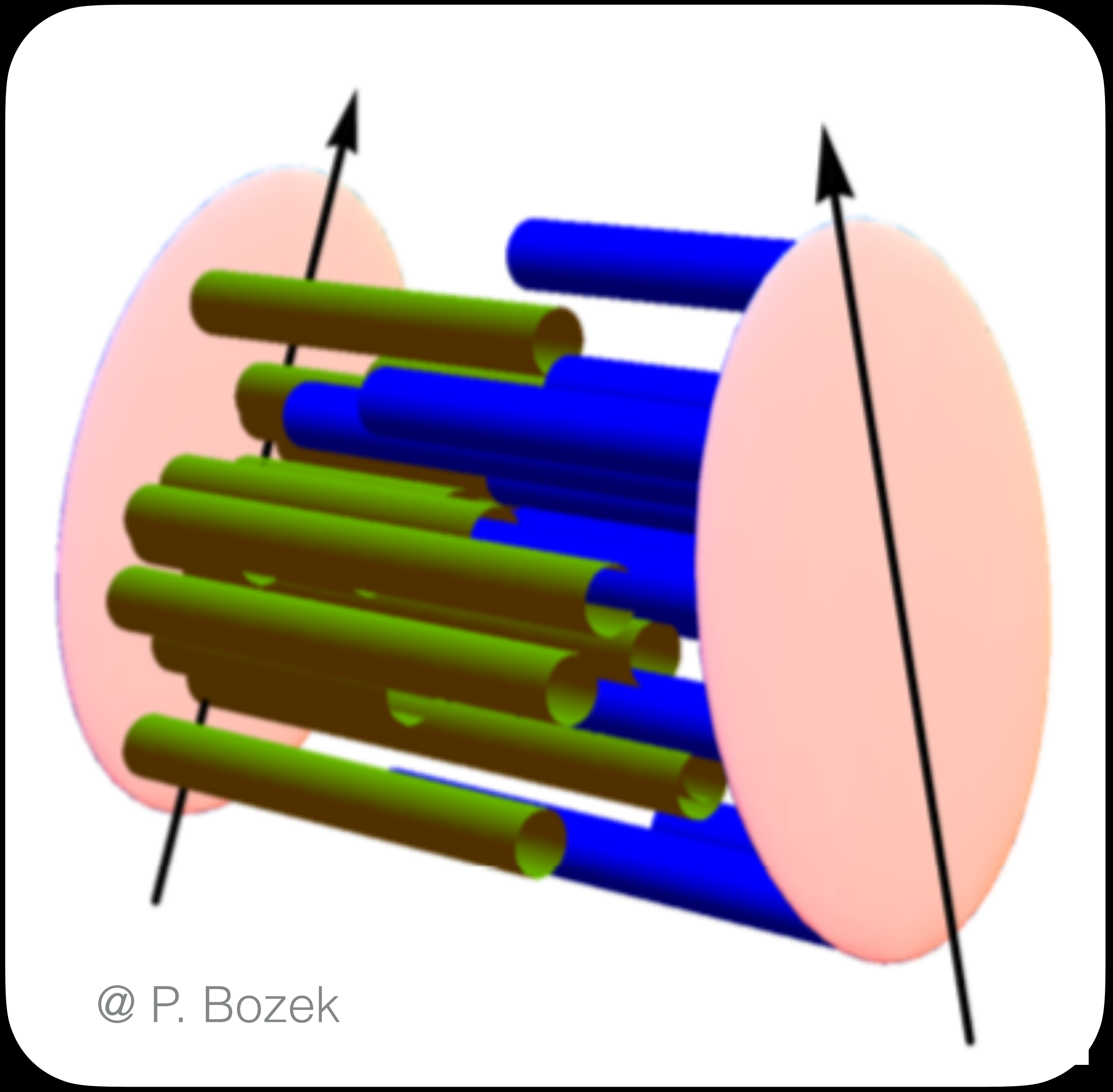
- In symmetric heavy-ion collisions, particle production in the forward rapidity is strongly correlated with those at mid-rapidity

LONGITUDINAL FLOW DECORRELATION

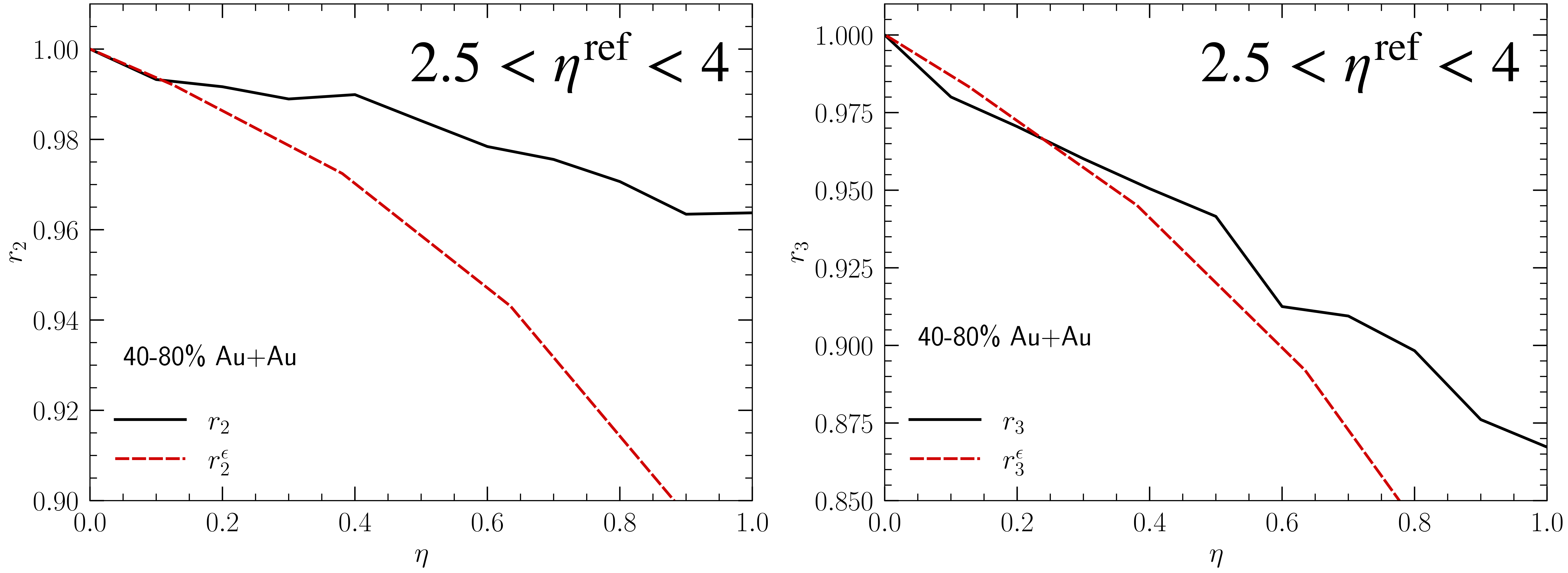


$$r_n = \frac{\langle Q_n(-\eta) Q_n(\eta^{\mathrm{ref}})^* \rangle}{\langle Q_n(\eta) Q_n(\eta^{\mathrm{ref}})^* \rangle}$$

$$r_n^{\epsilon} = \frac{\langle \mathcal{E}_n(-\eta_s) \mathcal{E}_n(\eta_s^{\mathrm{ref}})^* \rangle}{\langle \mathcal{E}_n(\eta_s) \mathcal{E}_n(\eta_s^{\mathrm{ref}})^* \rangle}$$

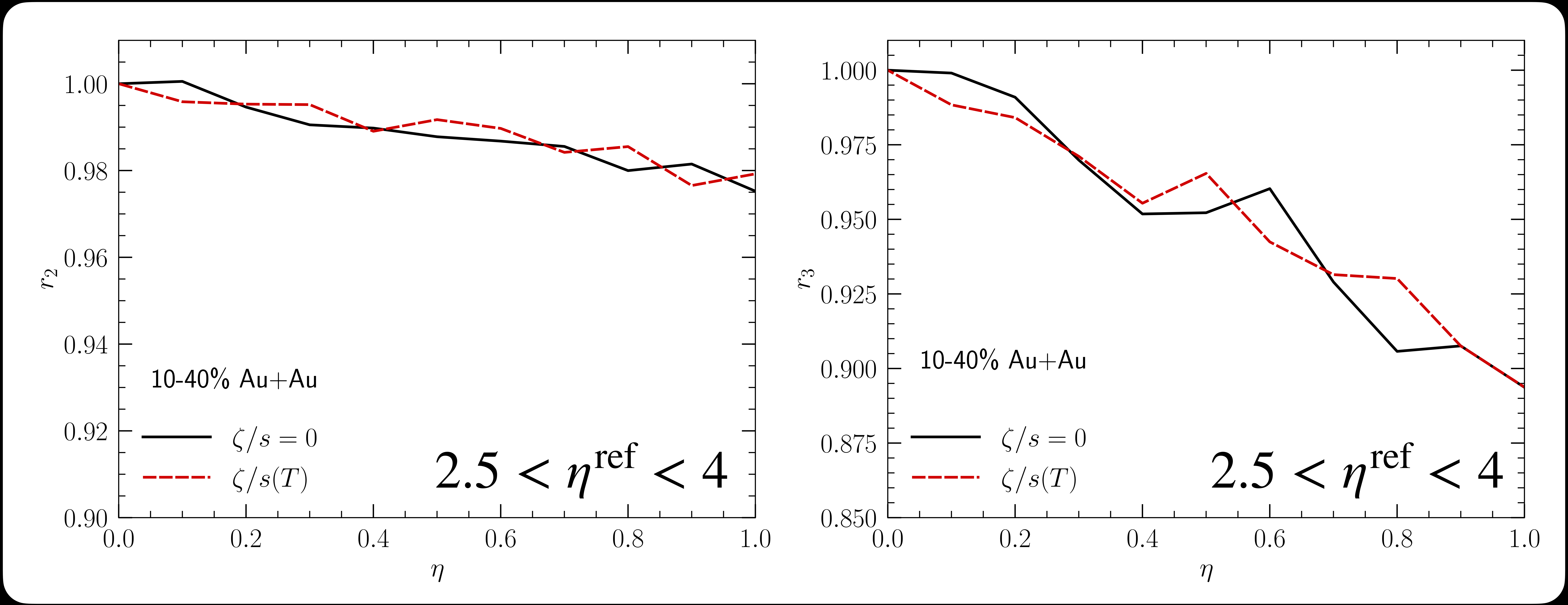


INITIAL STATE r_n^ϵ VS. FINAL STATE r_n



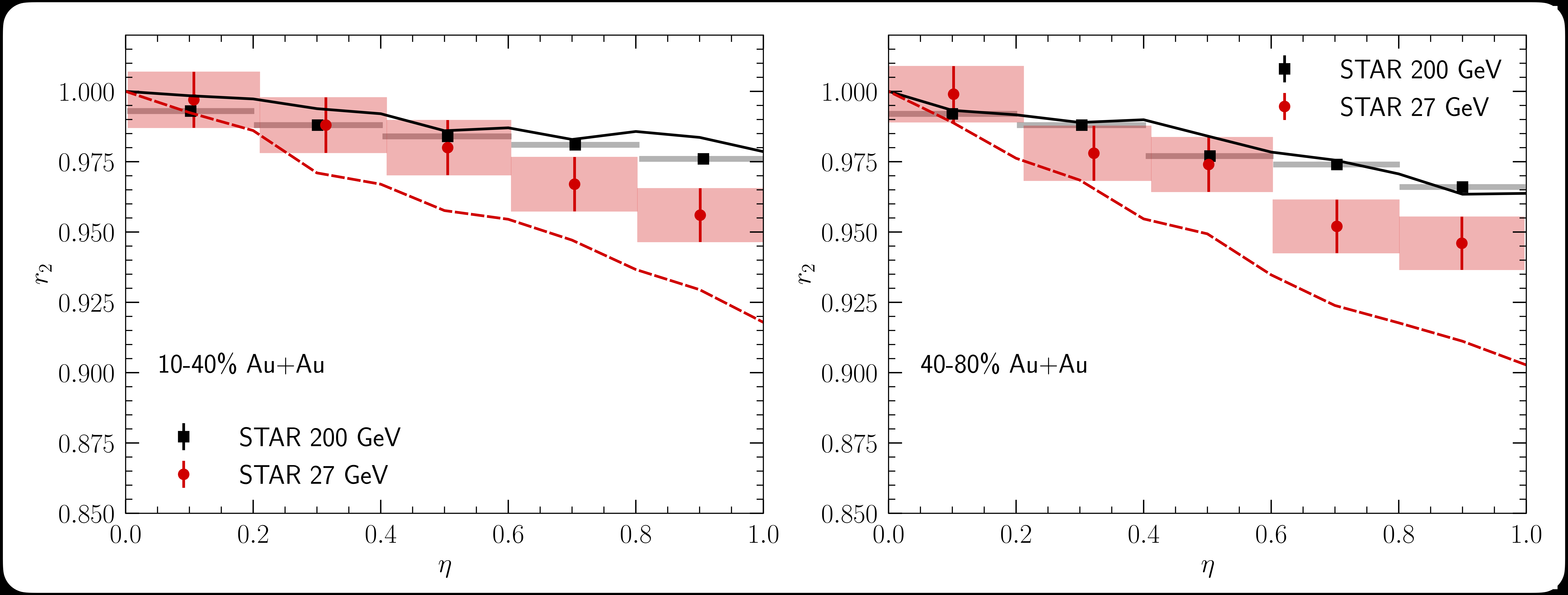
- The initial-state estimator overestimates the rapidity decorrelation

BULK VISCOUS EFFECTS ON r_n



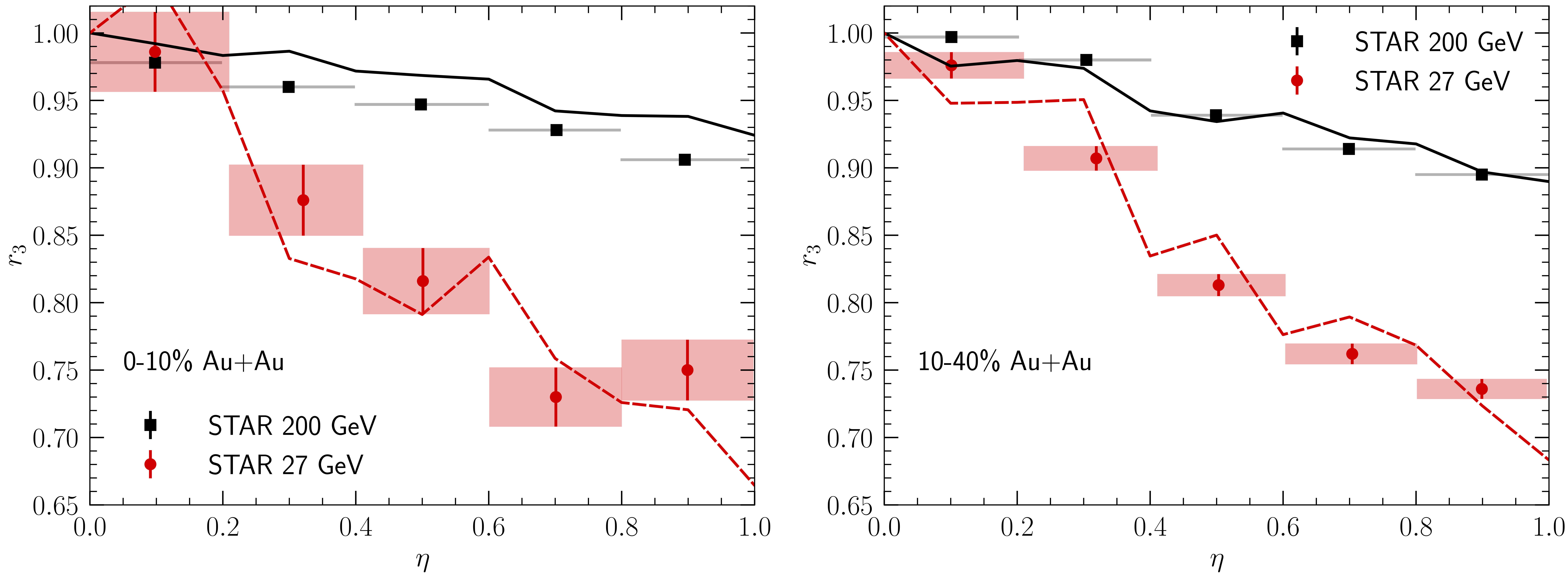
- Bulk viscosity does not have sizable effects on r_n

COLLISION ENERGY DEPENDENCE OF r_n



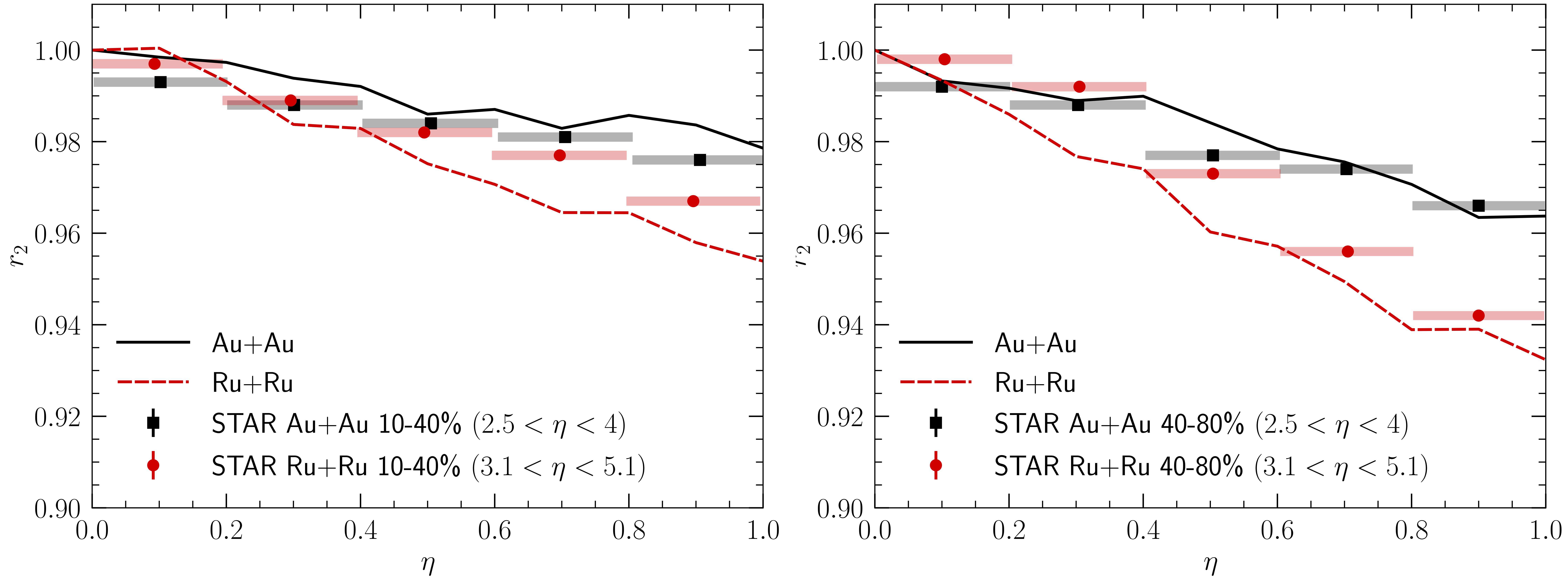
- Our model overestimated the elliptic flow decorrelation at 27 GeV

COLLISION ENERGY DEPENDENCE OF r_n



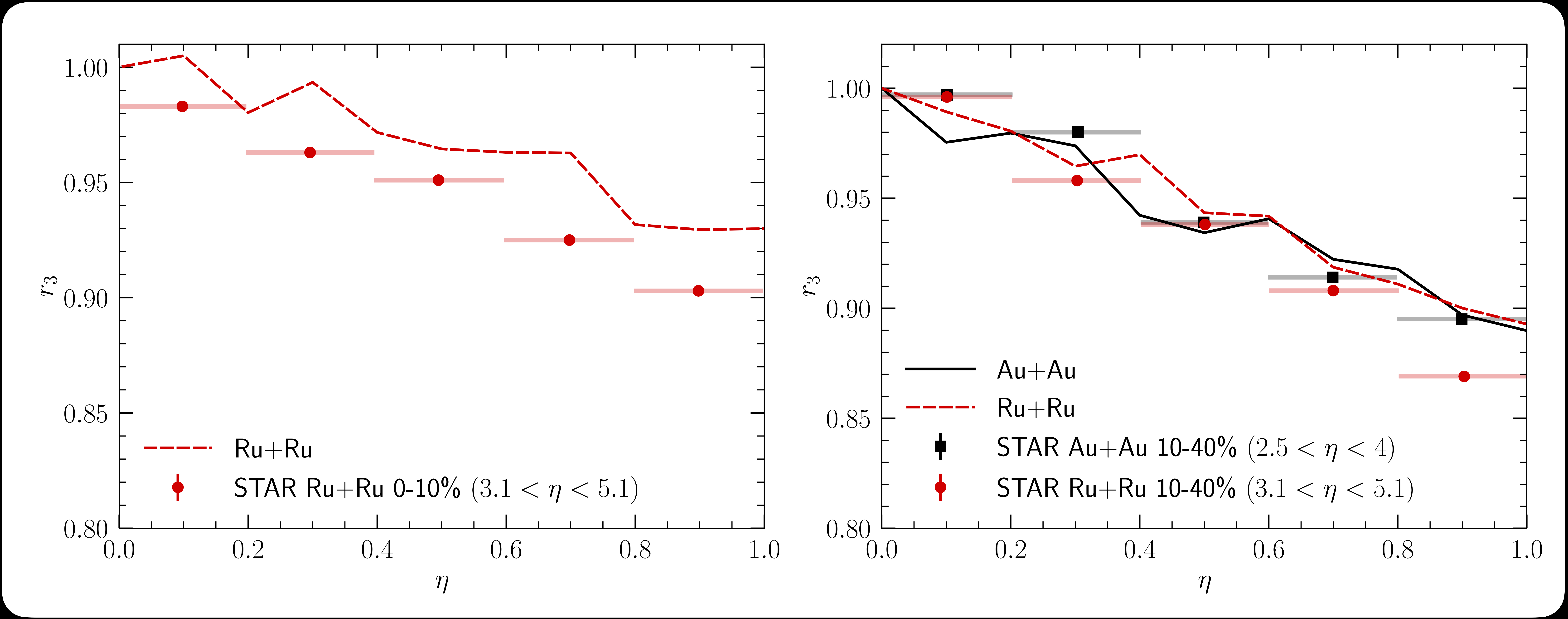
- Our model reproduces the triangluar flow decorrelation at 200 and 27 GeV

SYSTEM SIZE DEPENDENCE OF r_n



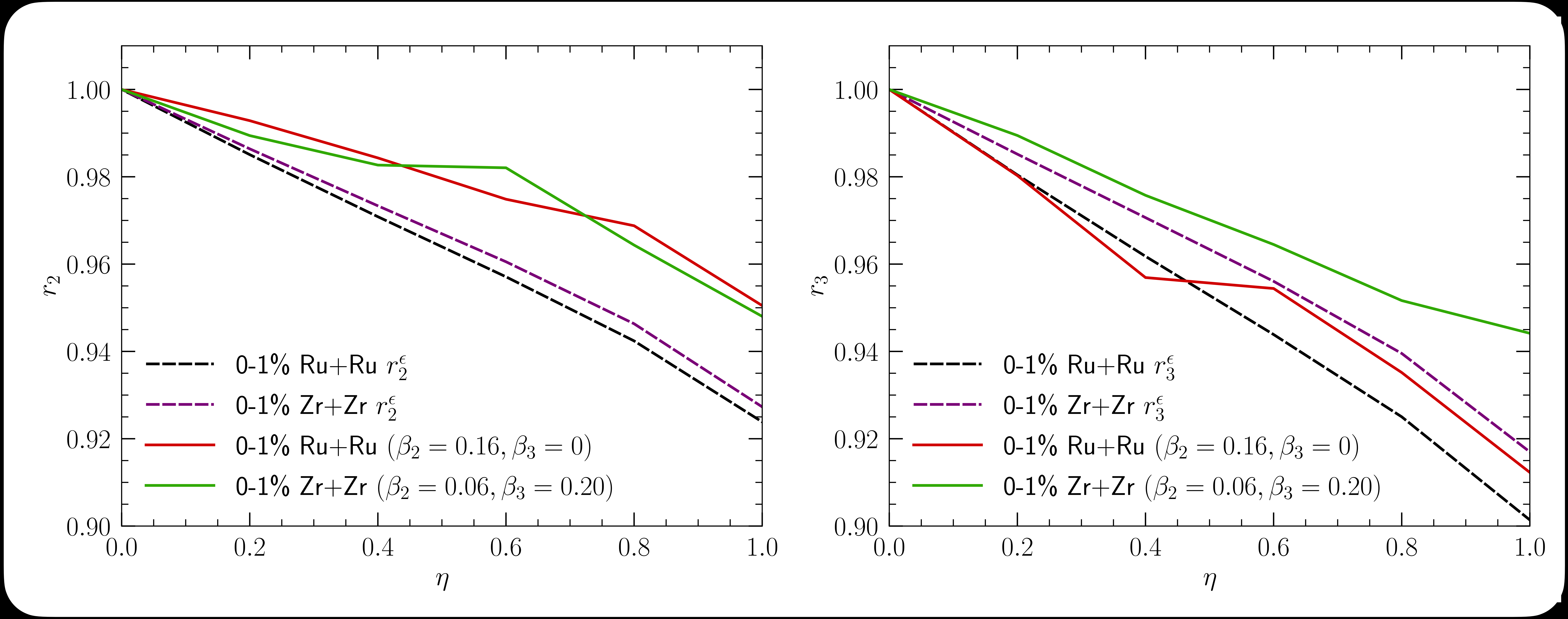
- The smaller Ru+Ru collisions have larger flow decorrelation with those in Au+Au collisions

SYSTEM SIZE DEPENDENCE OF r_n



- Our model underestimated the r_3 compared to the STAR measurements

NUCLEAR STRUCTURE EFFECTS ON r_n AT RHIC ISOBAR



- The non-zero β_3 in Zr+Zr collisions results in a larger r_3 than those in Ru+Ru collisions in central isobar collisions

SUMMARY

- We developed an effective (3+1)D dynamical framework to understand particle production and flow in relativistic heavy-ion collisions for the RHIC beam energy scan program
    - First principle inputs from lattice QCD for EoS
    - Systematically study the phase structure (critical point) of hot QCD matter
    - Elucidating the initial baryon stopping, charge diffusion, and transport properties of QGP in a baryon rich environment
- The 3D MC-Glauber model qualitatively captures the system size and collision energy dependence of flow rapidity decorrelation in Au+Au and Isobar collisions at RHIC
- **We predict a smaller r_3 in central Zr+Zr than Ru+Ru collisions as a consequence of the non-zero β_3 deformation in Zr**