Duke
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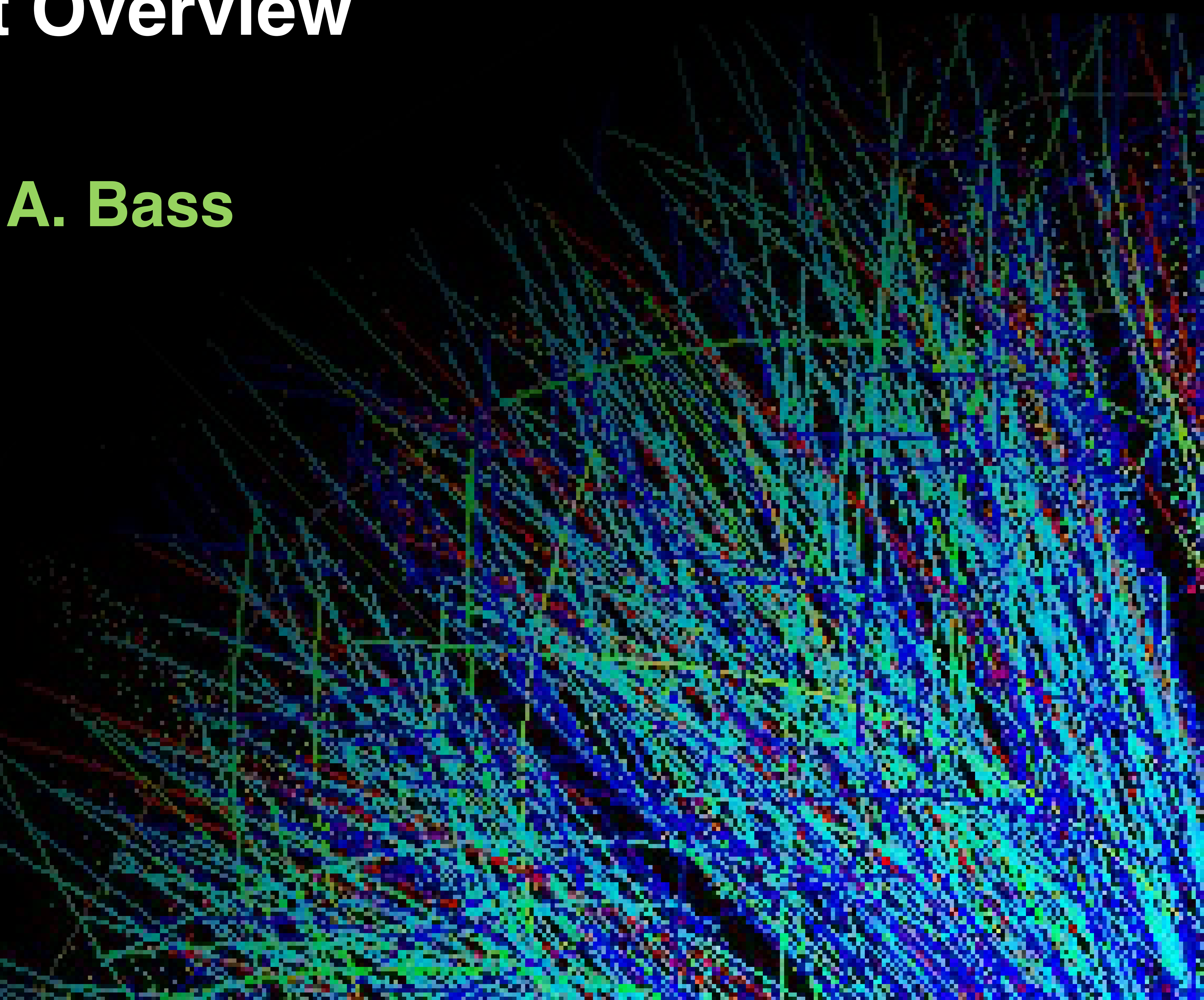
Transport Overview

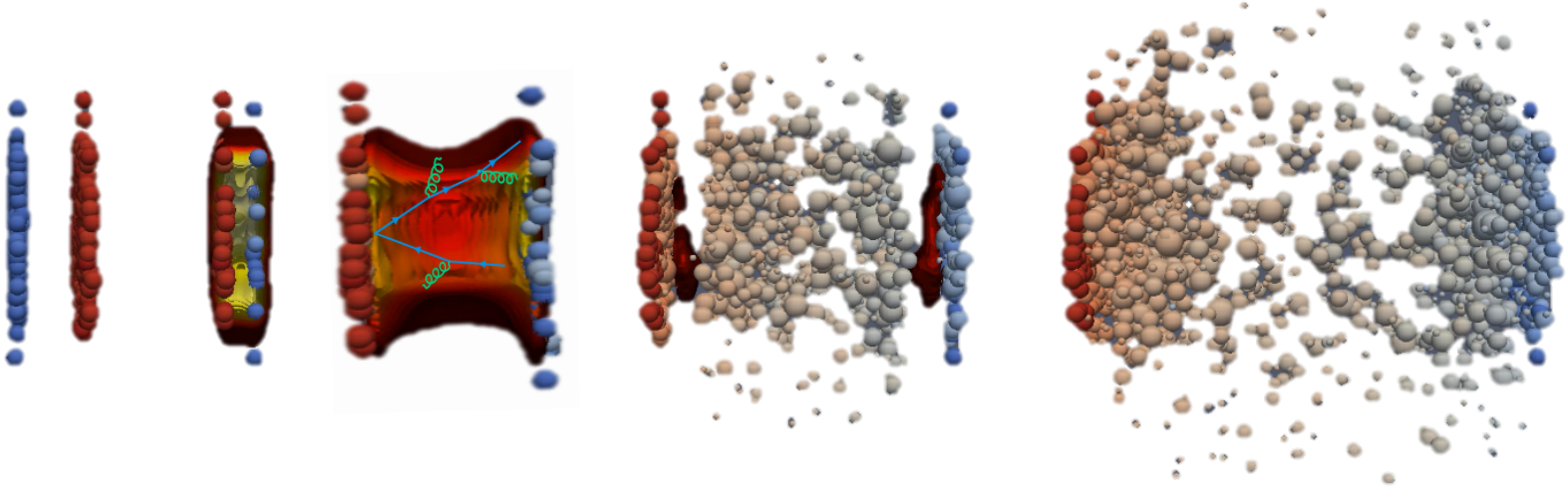
Steffen A. Bass



emphasis on:
- transport relevant to strangeness and open heavy flavor

not covered:
- transport for (heavy flavor) jets, quarkonia, photons & leptons
- initial state phenomena & spin degrees of freedom
- general soft matter transport w/o flavor applications

What is a transport model?



- A transport model describes the time-evolution of the collision, utilizing a set of physics processes that can be derived or approximated from some underlying theory.

- The model is capable of predicting quantities that can be measured in experiments, thus allowing for the testing of its underlying assumptions via a comparison to data and gaining physics insight from such a comparison

- Transport models are also utilized to gain understanding on processes not directly accessible to experimental observation

Flavors of Transport Models:

microscopic transport models based on the **Boltzmann Equation**:

- transport of a system of microscopic particles
- all interactions are based on binary scattering

$$\left[\frac{\partial}{\partial t} + \frac{\vec{p}}{E} \times \frac{\partial}{\partial \vec{r}}\right] f_1(\vec{p}, \vec{r}, t) = \sum_{processes} C(\vec{p}, \vec{r}, t)$$

diffusive transport models based on the **Langevin Equation**:

- transport of a system of microscopic particles in a thermal medium
- interactions contain a drag term related to the properties of the medium and a noise term representing random collisions

$$\vec{p}(t + \Delta t) = \vec{p}(t) - \frac{\kappa}{2T}\vec{v} \cdot \Delta t + \vec{\xi}(t)\Delta t$$

(viscous) relativistic fluid dynamics:

- transport of macroscopic degrees of freedom
- based on conservation laws:

$$\partial_\mu T^{\mu\nu} = 0$$

$$\begin{aligned} T_{ik} &= \varepsilon u_i u_k + P\left(\delta_{ik} + u_i u_k\right) \\ &- \eta\left(\nabla_i u_k + \nabla_k u_i - \frac{2}{3}\delta_{ik}\nabla \cdot u\right) \\ &+ \varsigma\,\delta_{ik}\nabla \cdot u \end{aligned}$$

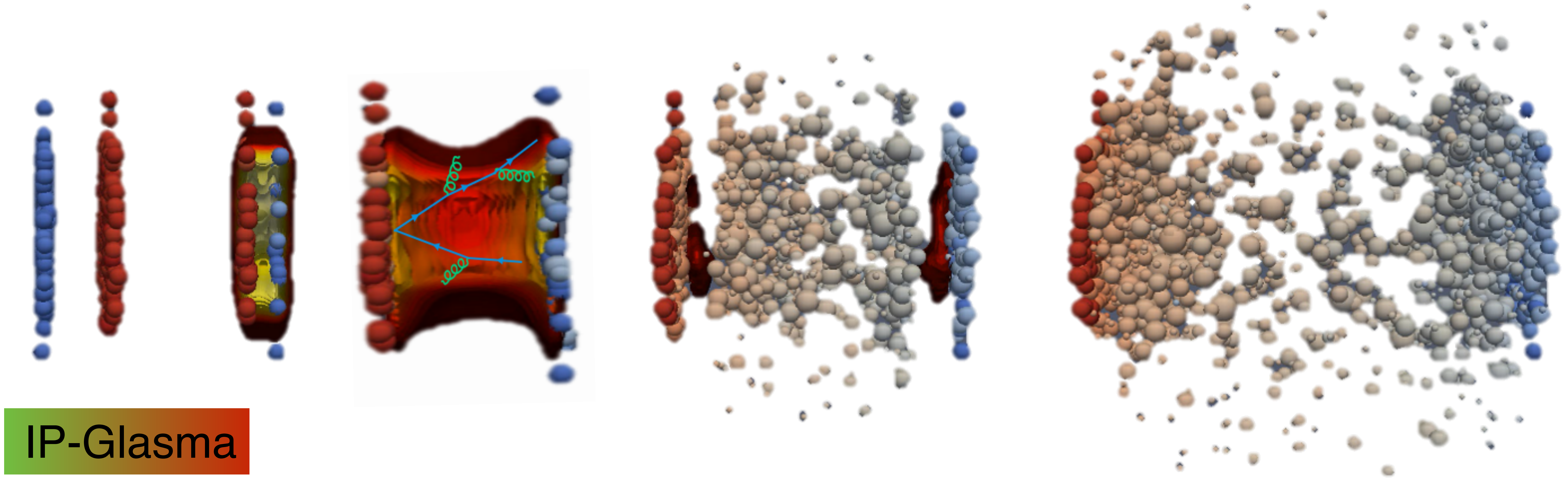
(plus an additional 9 eqns. for dissipative flows)

hybrid transport models:

- combine microscopic & macroscopic degrees of freedom
- current state of the art for RHIC modeling

Each transport model relies on roughly a dozen physics parameters to describe the time-evolution of the collision and its final state. These physics parameters act as a representation of the information we wish to extract from experiment.

Applicability ranges for transport @ high energy



IP-Glasma

kinetic theory

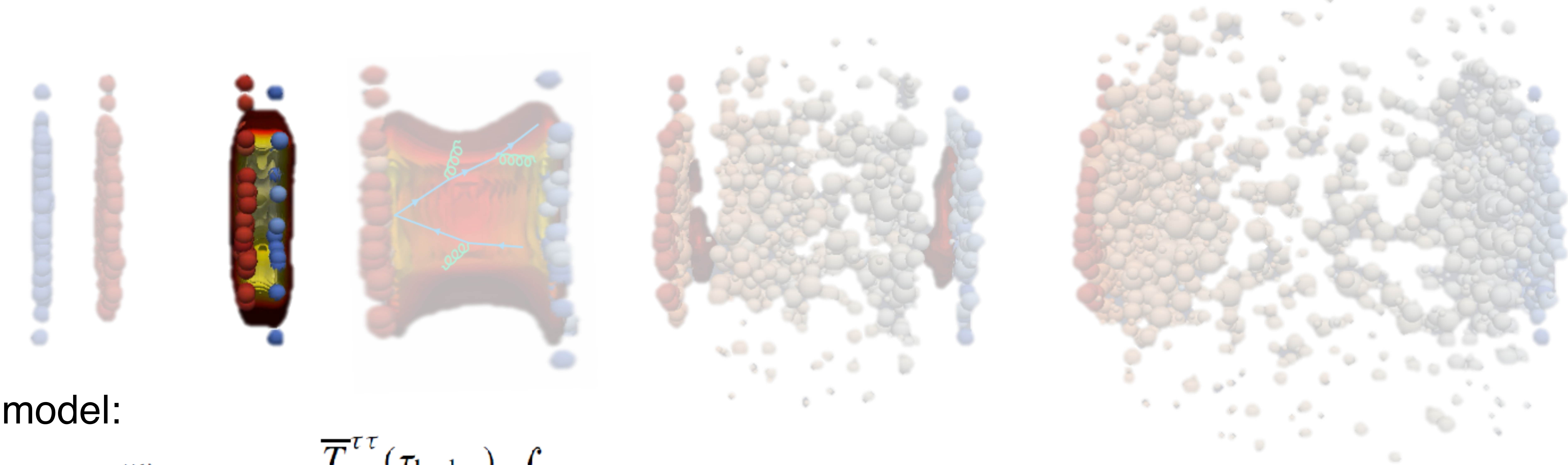
anisotropic viscous RFD

viscous RFD

Boltzmann transport

viscous RFD + hadronic afterburner (hybrid models)

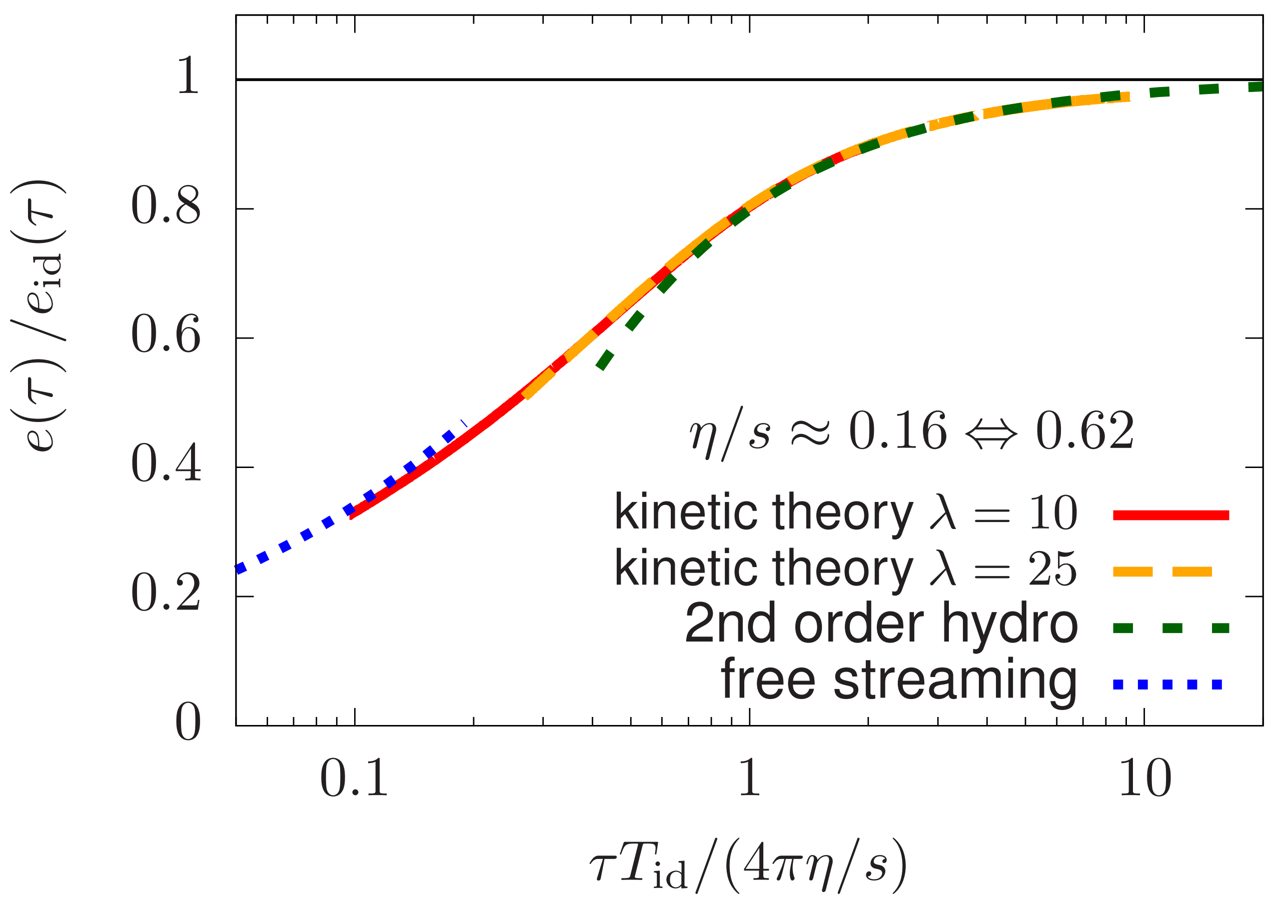
Kinetic theory: from initial state to hydrodynamic evolution

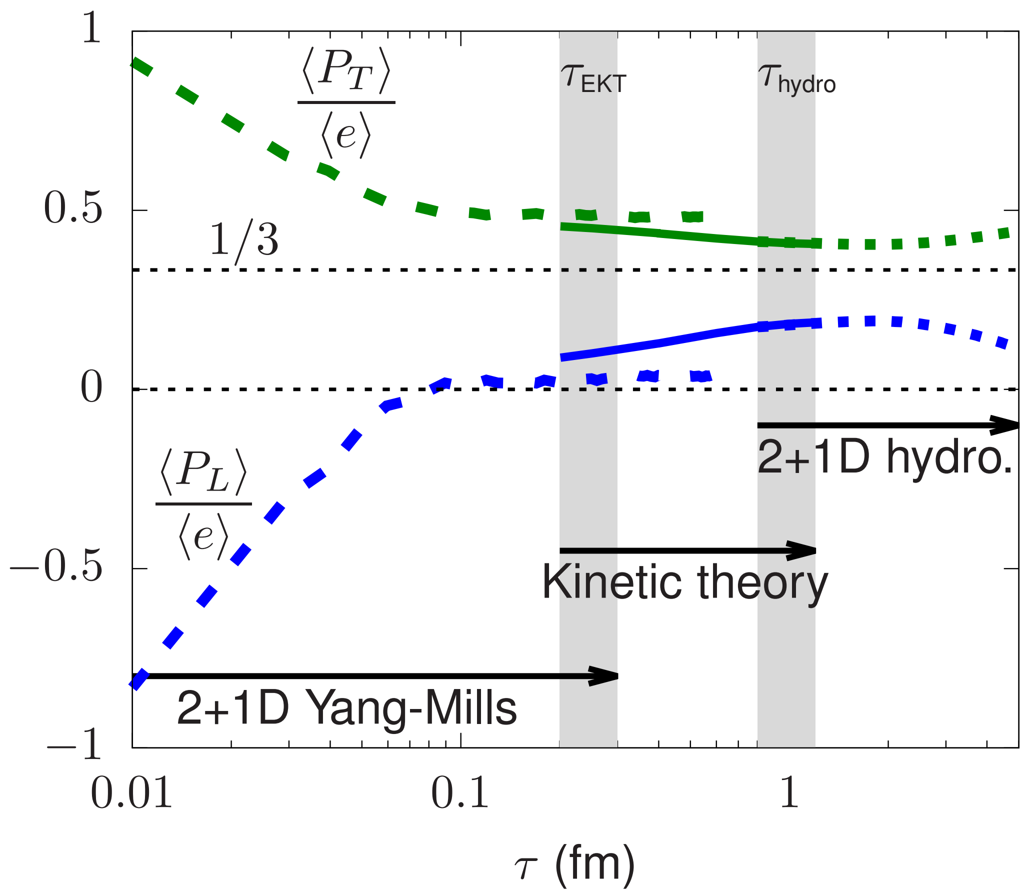


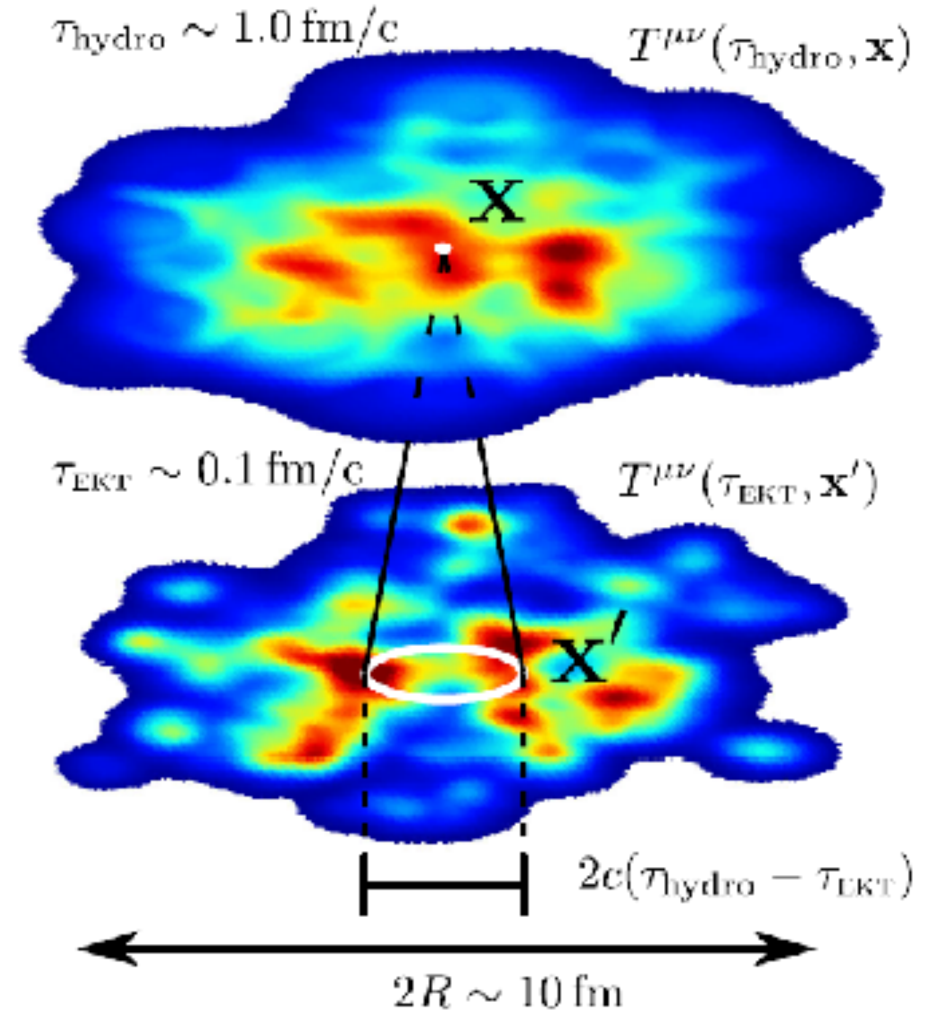
KøMPøST model:

$$T^{\mu\nu}(\tau_{\rm hydro}, \mathbf{x}) = \overline{T}^{\mu\nu}_{\mathbf{x}}(\tau_{\rm hydro}) + \frac{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau_{\rm hydro})}{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau_{\rm EKT})} \int d^2\mathbf{x}'\, G^{\mu\nu}_{\alpha\beta}(\mathbf{x}, \mathbf{x}', \tau_{\rm hydro}, \tau_{\rm EKT})\, \delta T^{\alpha\beta}_{\mathbf{x}}(\tau_{\rm EKT}, \mathbf{x}')$$

- non-equilibrium linear response formalism: evolve energy-momentum tensor from its non-equilibrium form at $\tau_{\rm EKT}$ up to $\tau_{\rm hydro}$
- decompose energy-momentum tensor into a local average and linearized perturbations δT
- response functions G describe evolution of perturbations calculated via kinetic theory







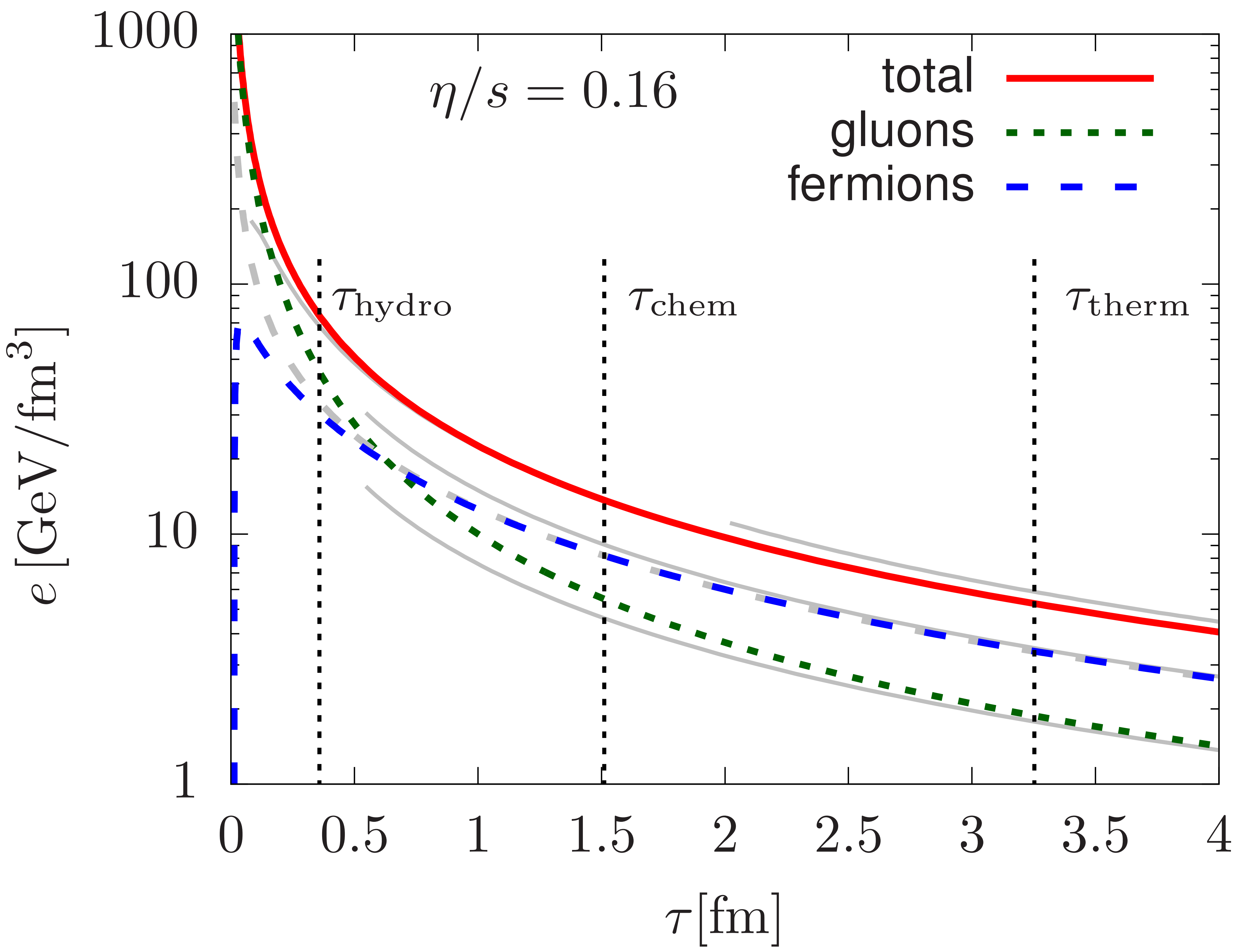
- Kurkela, Mazeliauskas, Paquet, Schlichting & Teaney: Phys. Rev. Lett. 122 (2019) 122302

Kinetic theory: chemical equilibration

Numerically solve Boltzmann equation for homogenous boost invariant q and g distribution functions:

$$\partial_\tau f_s(\mathbf{p},\tau) - \frac{p^z}{\tau}\partial_{p^z} f_s(\mathbf{p},\tau) = -\mathcal{C}^s_{2\leftrightarrow 2}[f] - \mathcal{C}^s_{1\leftrightarrow 2}[f]$$

with scattering rates for gg↔gg, gq↔gq, qq↔qq, gg↔qqbar, g↔gg, q↔qg,g↔qqbar



- ordering of equilibration time scales:

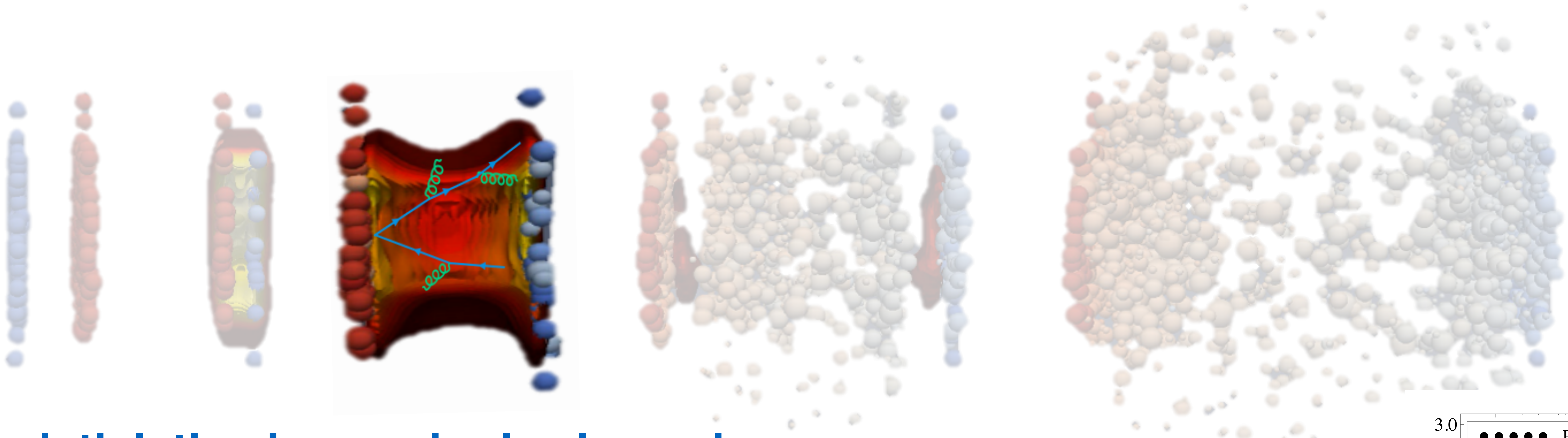
  $$\tau_{\rm hydro} < \tau_{\rm chem} < \tau_{\rm therm}$$

- for reasonable values of the coupling (in terms of η/s) one obtains the following time scale estimates
  - hydrodynamization: ~ 0.5 fm/c
  - chemical equilibration: ~ 1.5 fm/c
  - thermalization: ~ 3.3 fm/c

- validates application of hydrodynamics at times $\tau_0 \sim 0.6$ fm/c
- use of Lattice EoS in full chemical equilibrium at early times is questionable

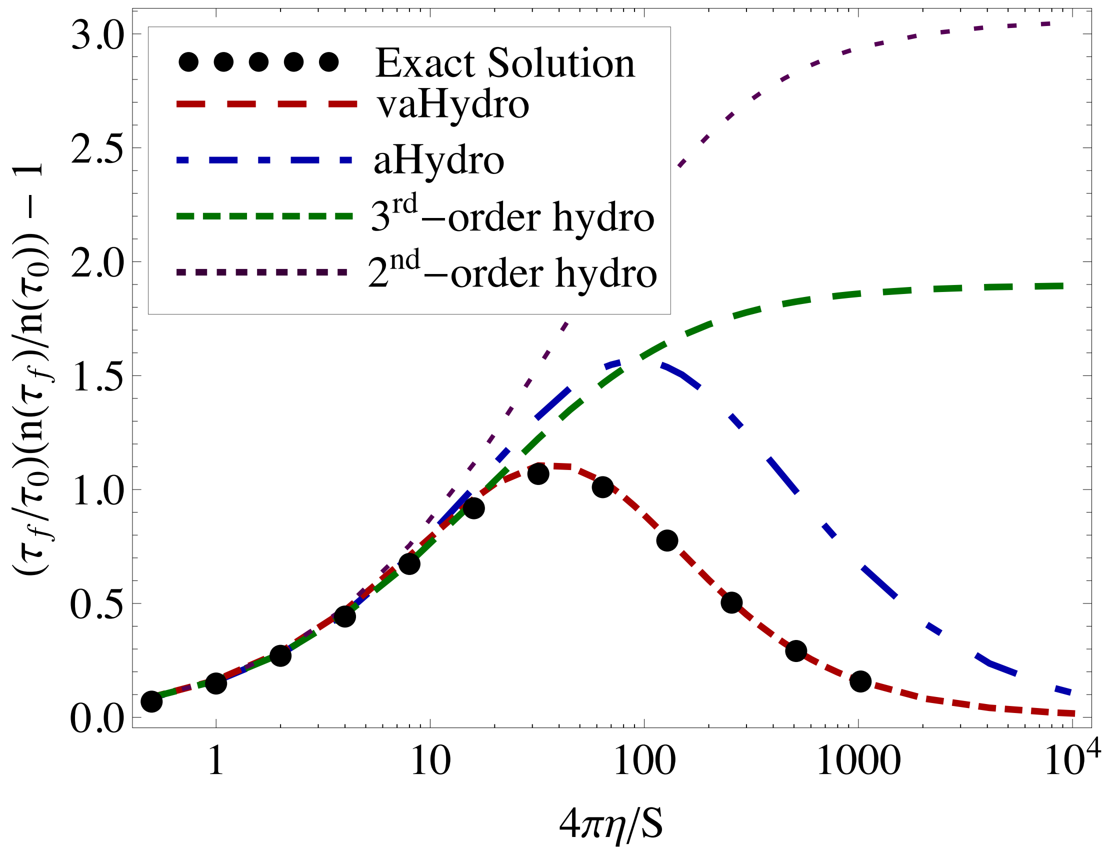
- Kurkela & Mazeliauskas: Phys. Rev. Lett. 122 (2019) 142301

State of the Art: viscous relativistic fluid dynamics



standard relativistic viscous hydrodynamics:

- based on 2nd order Israel-Stewart theory
- (Lattice) Equation of State & (temperature dependent) shear & bulk viscosities as input
- several extensively validated codes are publicly available: MUSIC, VISHNU, vHLLE

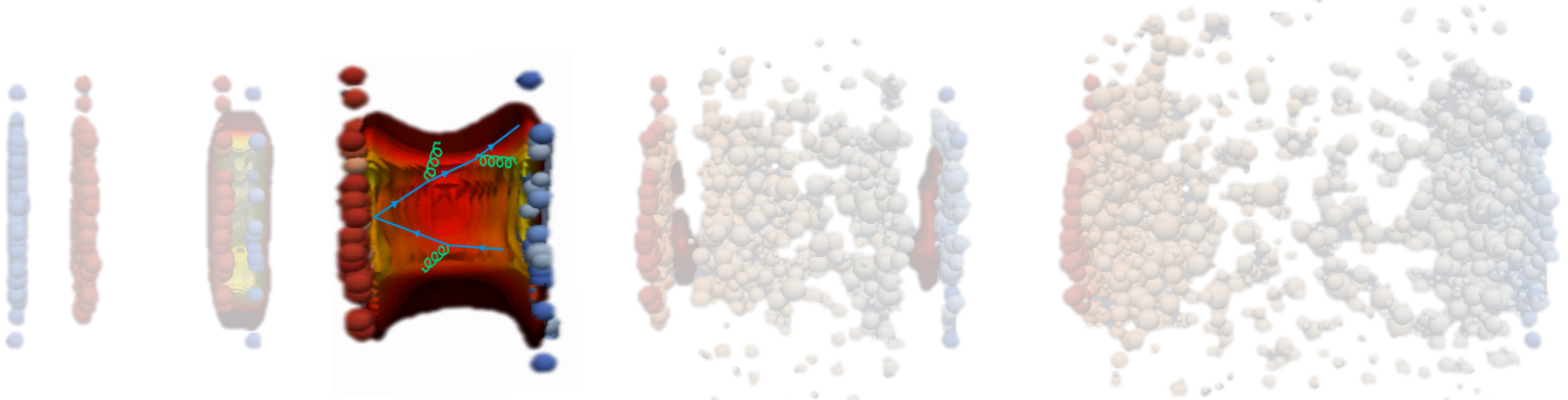


anisotropic hydro:

- allows to describe systems far from isotropy (equilibrium)
- aHydroQP: QCD EoS via a temperature-dependent quasi-particle mass, includes shear & bulk viscosities

- VISH: Song & Heinz; Phys. Rev. C77 (2008) 064901
- MUSIC: Schenke, Jeon & Gale; Phys. Rev. C82 (2010) 014903
- vHLLE: Karpenko, Huovinen & Bleicher; Computer Phys. Comm. 185 (2014) 3016-3027
- VISHNU: Chen, Song, Bernhard, Bass & Heinz; Computer Phys. Comm. 199 (2016) 61-65
- aHydroQP: M. Alqahtani, M. Nopoush & M. Strickland: Phys. Rev. C92 (2015) 054910

New developments: hydro with conserved charges

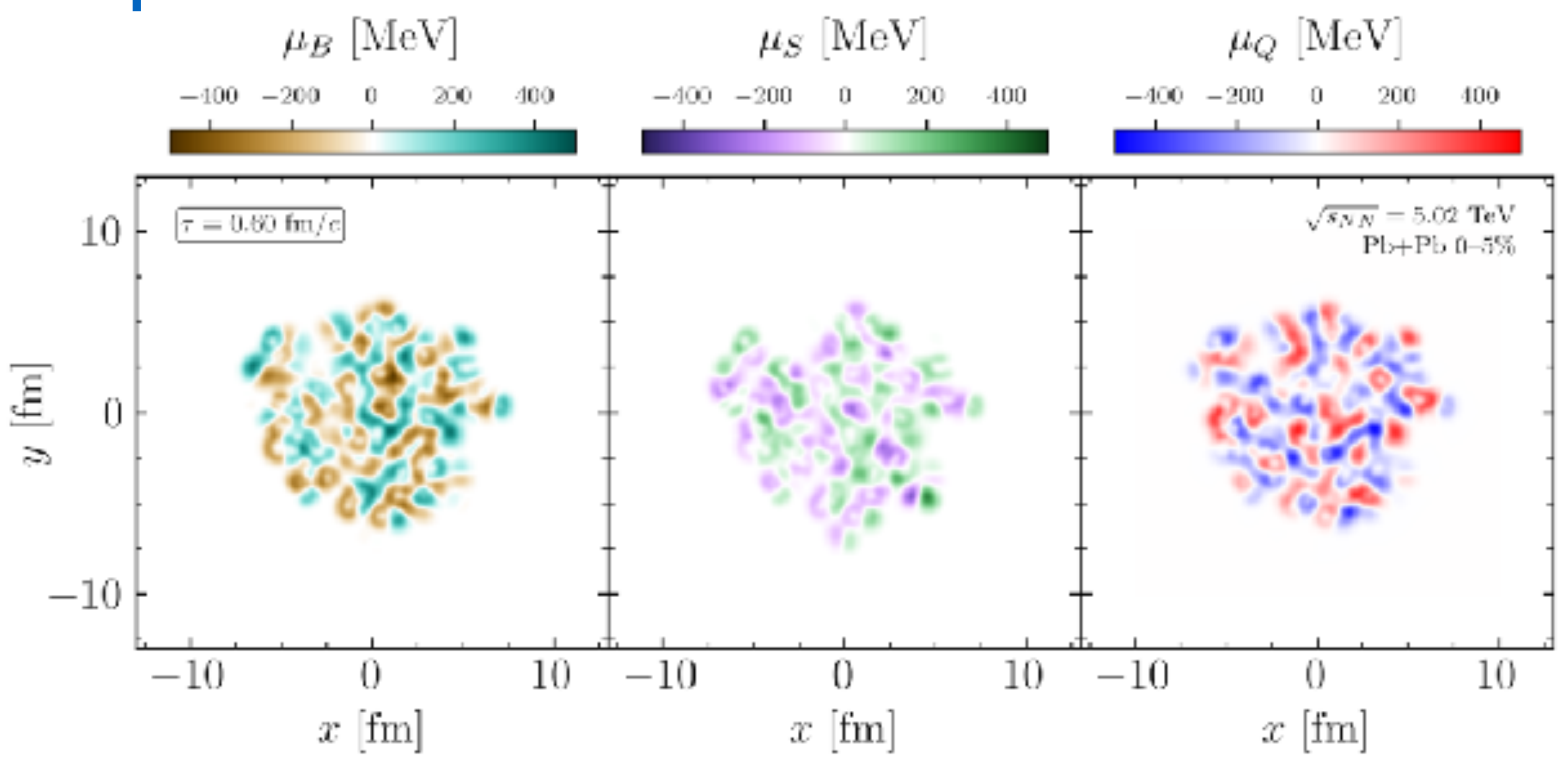


Dynamics of conserved charges (BQS) provide additional insights:

- impact of gluon splitting (charge creation) in the initial state
- formation and dynamics of multi-strange hadrons
- proper modeling of conserved charge fluctuations as probes of the QCD critical point

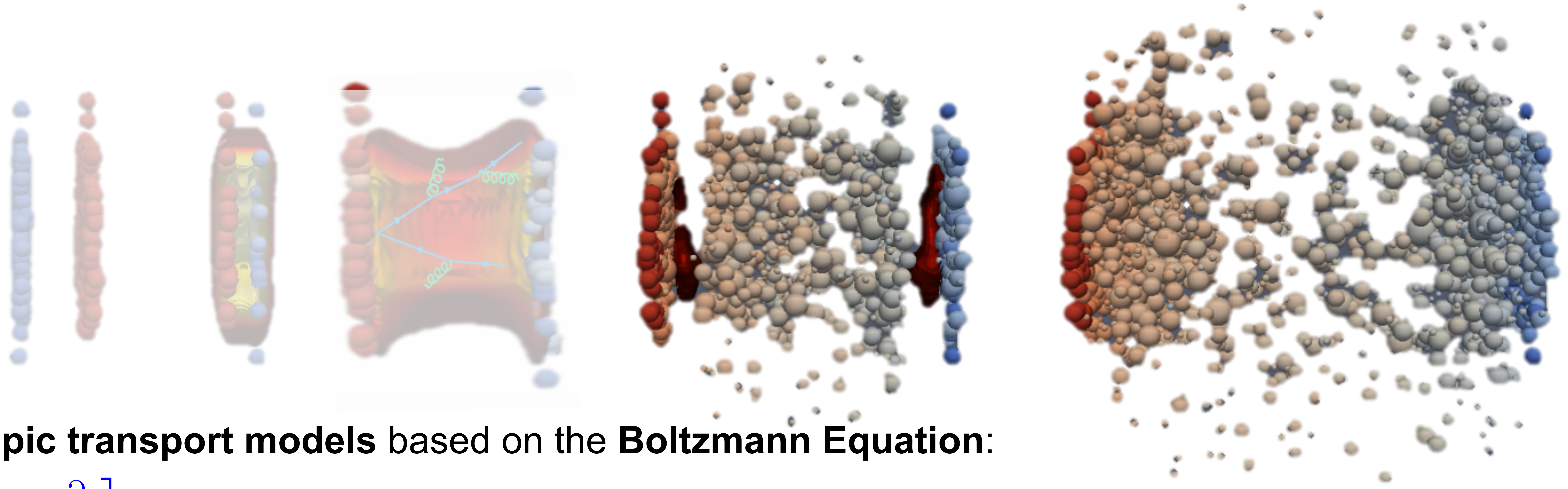
Hydro with BSQ conserved charges:

- conservation of Baryon-#, Strangeness and Charge (vHLLE)
- 4D Equation of State, EoM with a 3x3 diffusion matrix for conserved charges
- coupling terms between shear & bulk viscosities and BSQ currents
- available codes: `CCAKE` w/ `ICCING` initial condition (SPH), MUSIC



- C. Plumberg et al.: e-Print: 2405.09648 [nucl-th]

(Mostly) hadronic transport: UrQMD and SMASH



microscopic transport models based on the **Boltzmann Equation**:

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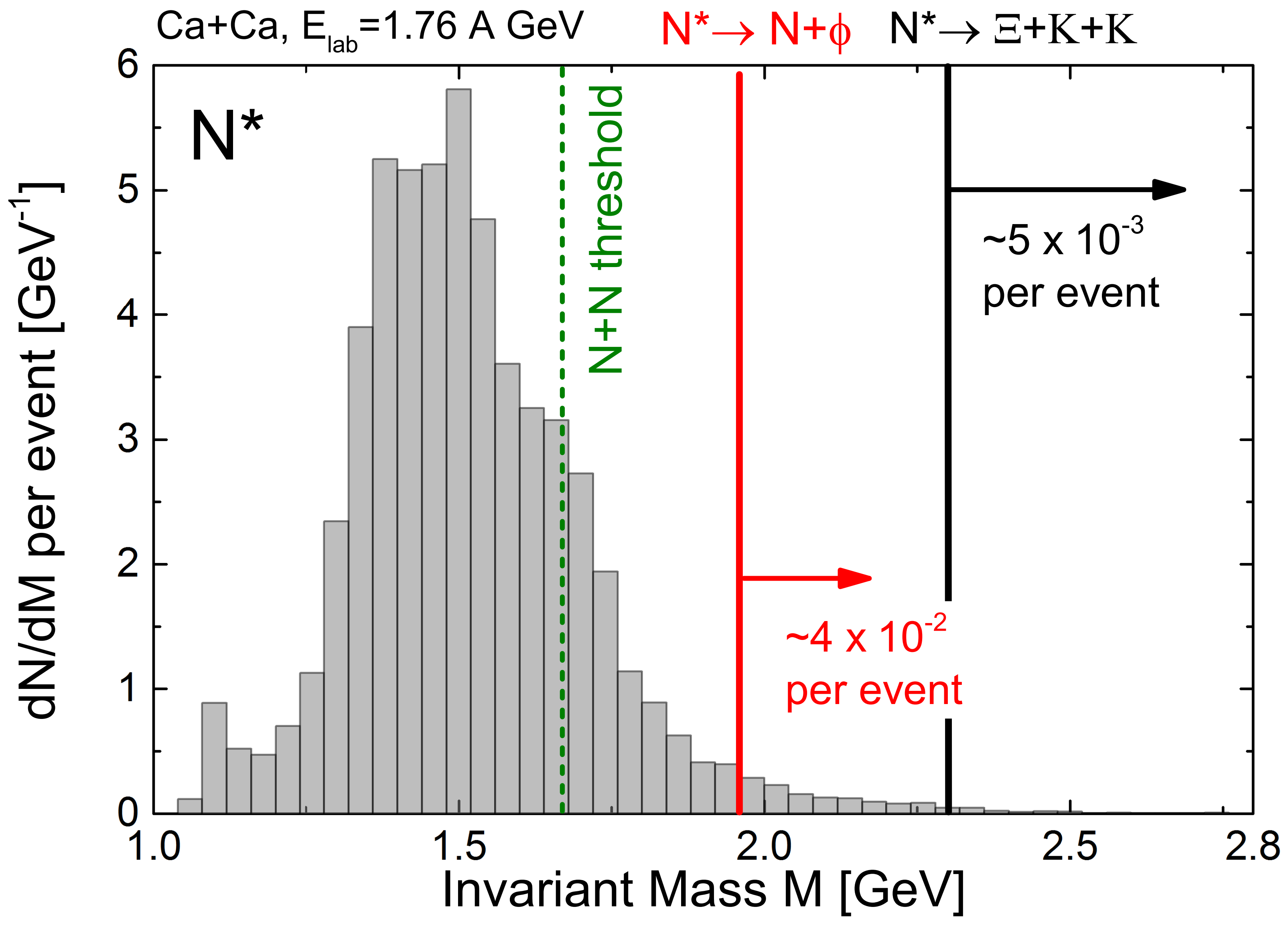
- transport of a system of hadrons (all well-established hadrons & resonances listed by PDG up to mass of M ≈ 2.4 GeV
- interactions are based on binary scattering using a geometric collision criterion: $d_{\mathrm{min}} \leq \sqrt{\frac{\sigma_{\mathrm{tot}}}{\pi}}$
- multi-particle decays via formation of intermediate resonance states
- string fragmentation via PYTHIA for initial particle production in high-energy collisions
- Potentials modeled via QMD type sum over two-particle interactions (UrQMD) or test particle method (SMASH)

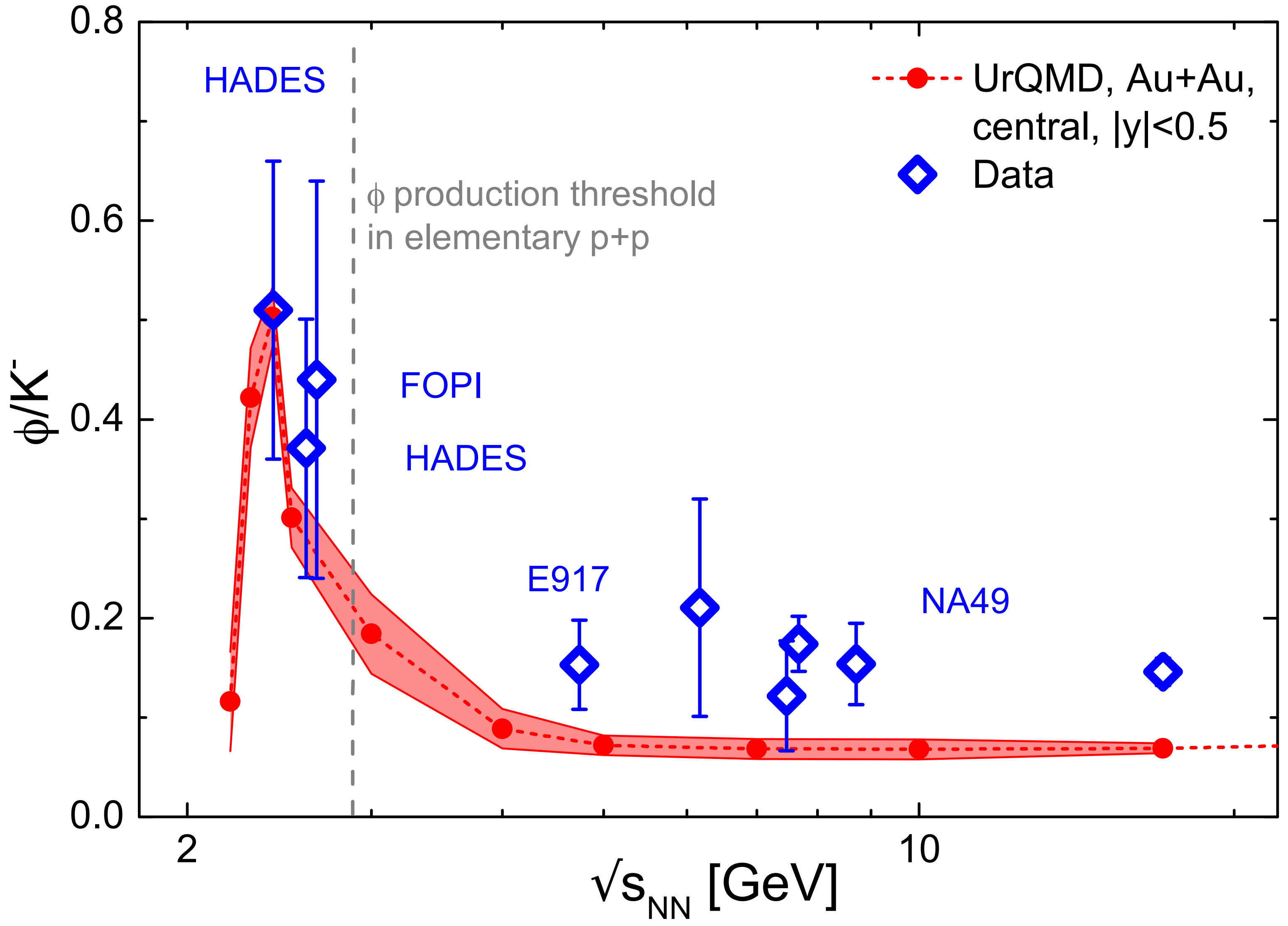
- S. A. Bass et al.: Prog.Part.Nucl.Phys. 41 (1998) 255-369
- M. Bleicher et al.: J.Phys.G 25 (1999) 1859-1896
- J. Weil et al.: Phys. Rev. C 94 (2016) 054905

Phi meson production: resonances & rescattering

UrQMD:

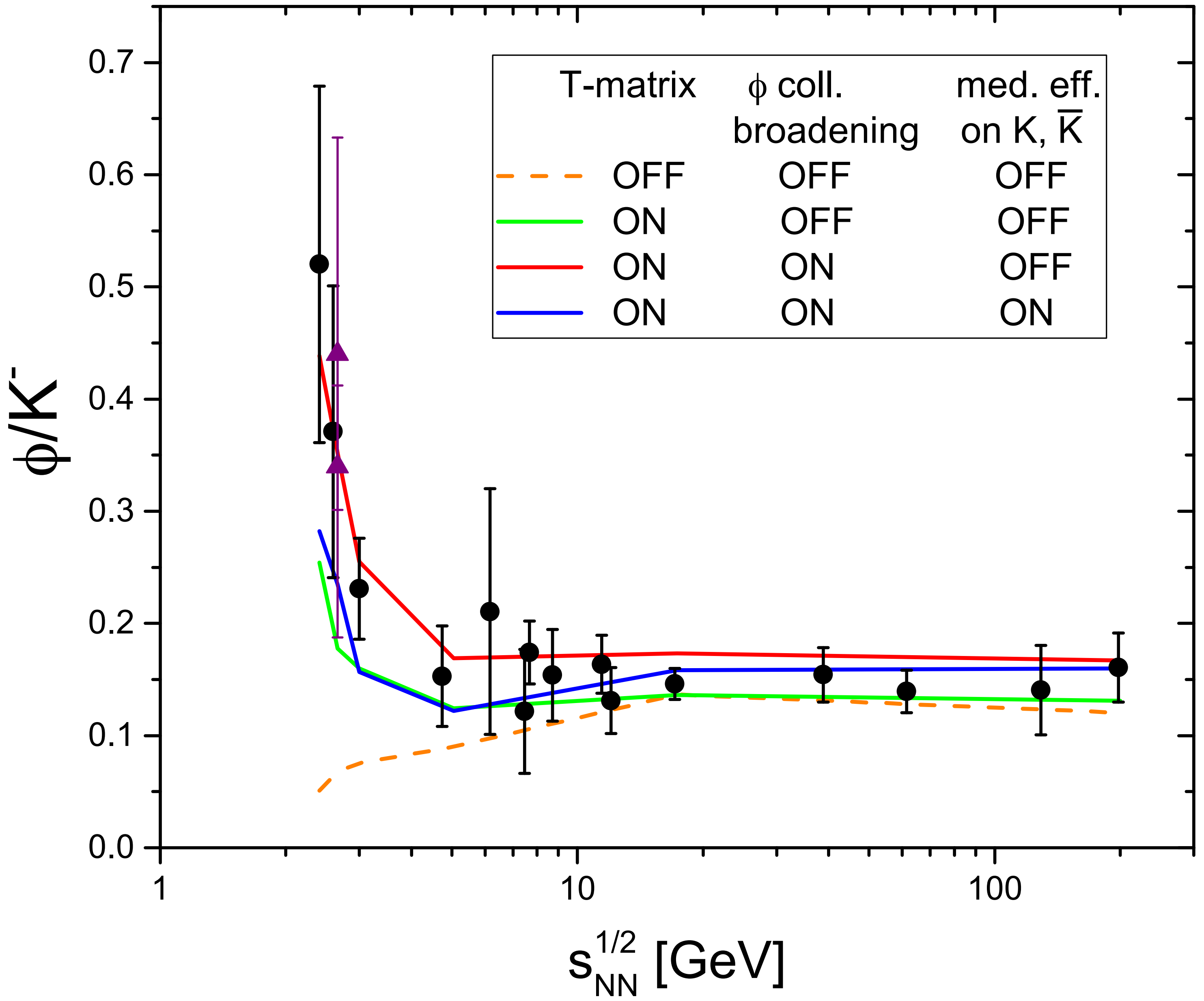
- at SIS energies, ϕ meson production is strongly suppressed since only the highest mass tails of the spectral function of high mass N* resonances allow for an on-shell decay into a ϕ meson final state
- BB scattering with subsequent BB and mB rescattering allows for the excitation of heavy resonances w/ a branching ratio to ϕ mesons N*↔ ϕB at beam energies below the pp threshold





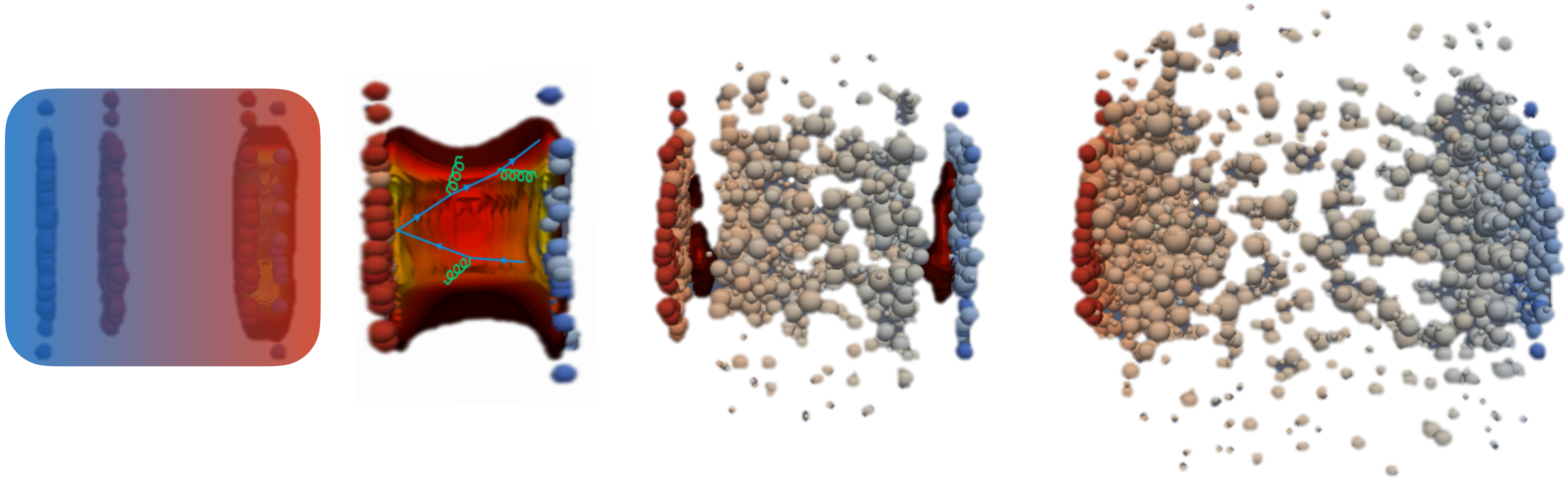
PHSD:

- introduce mB ↔ ϕB channels via SU(6) based T-matrix approach
- include potentials that modify kaon mass as function of baryon-density: enhances anti-K yield and suppresses K yield near threshold



- J. Steinheimer & M. Bleicher: J. Phys. G 43 (2016) 015104
- T. Song, J. Aichelin & E. Bratkovskaya: Phys. Rev. C 106 (2022) 024903

State of the Art @ High Energy: Macro + Micro Hybrid



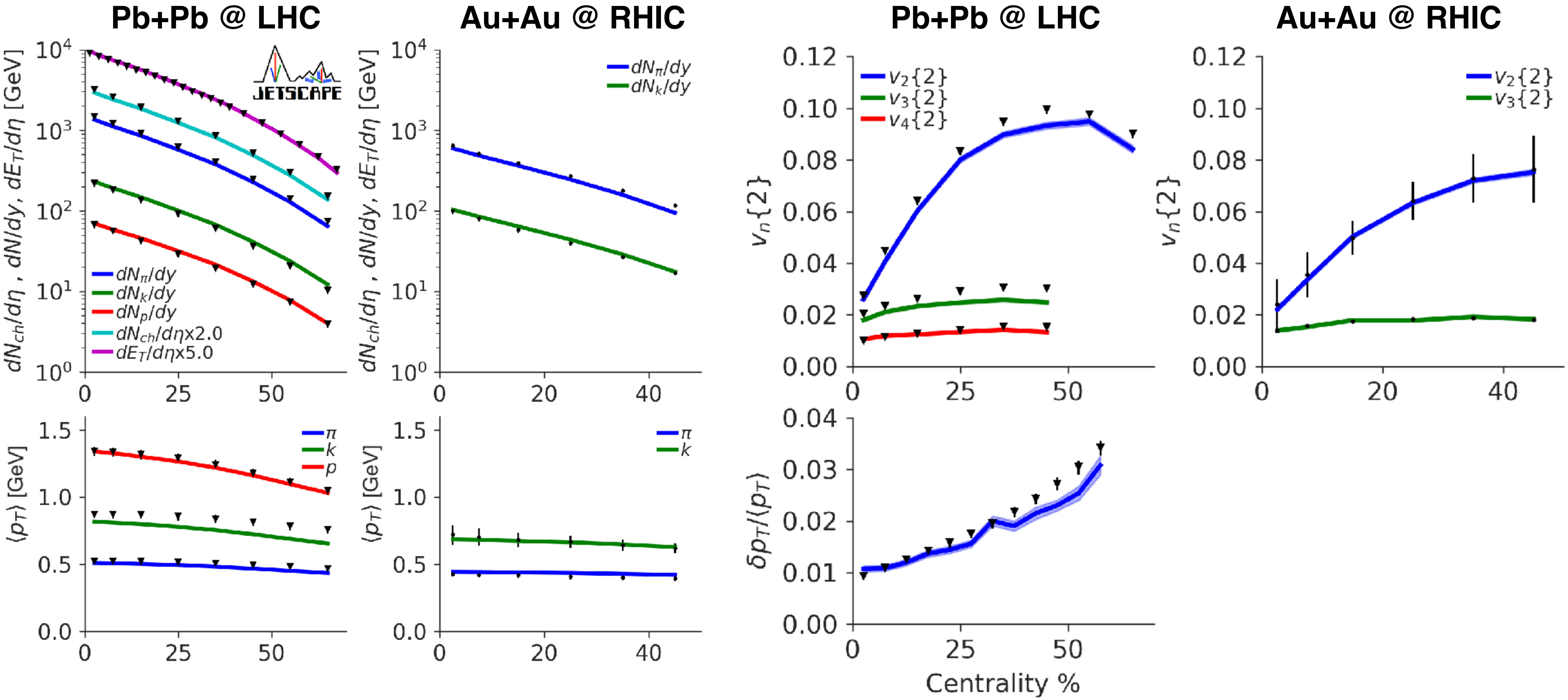
Initial condition:
- calculated on the basis of gluon saturation physics or pomeron exchange
- alternatively: phenomenological scheme for entropy deposition & constrained by global model to data fit
- examples: IP-Glasma, Trento

viscous hydrodynamics
- EbE 3+1D viscous RFD
- describes QGP dynamics & hadronization
- Lattice QCD EoS
- examples: MUSIC, VISHNU, vHLLE

Hadronic afterburner:
- non-equilibrium evolution of an interacting hadron gas
- separation of chemical and kinetic freeze-out
- hadron gas shear & bulk viscosities are implicitly contained in calculation
- Examples: UrQMD, SMASH

Similar Macro + Micro Hybrids: EPOS 4 & Trajectum

Macro + Micro Hybrid: comprehensive description of data



- Macro + Micro hybrid models are capable of describing a comprehensive set of bulk observables across RHIC & LHC

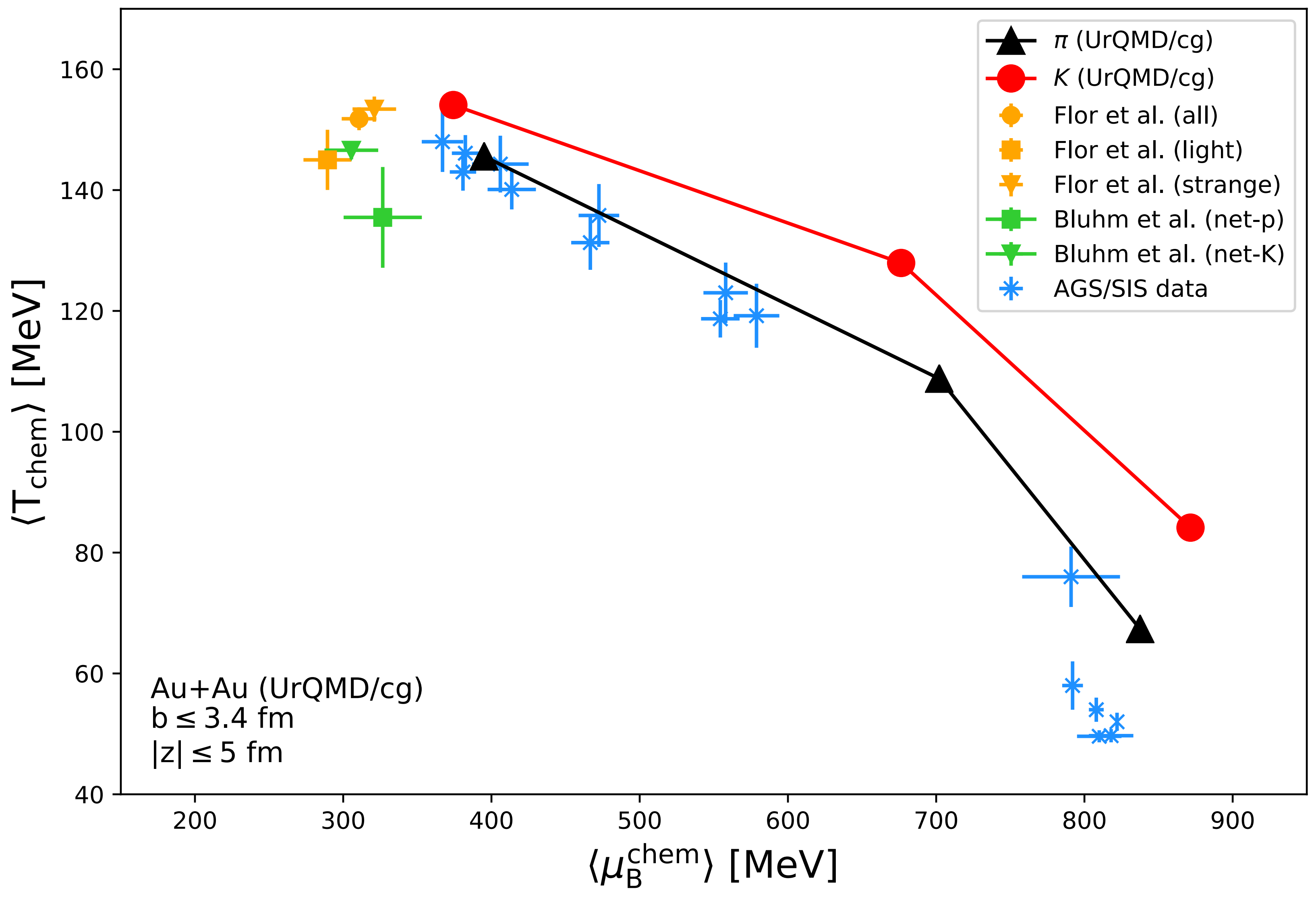
- D. Everett et al.: Phys Rev C103 (2021) 054904

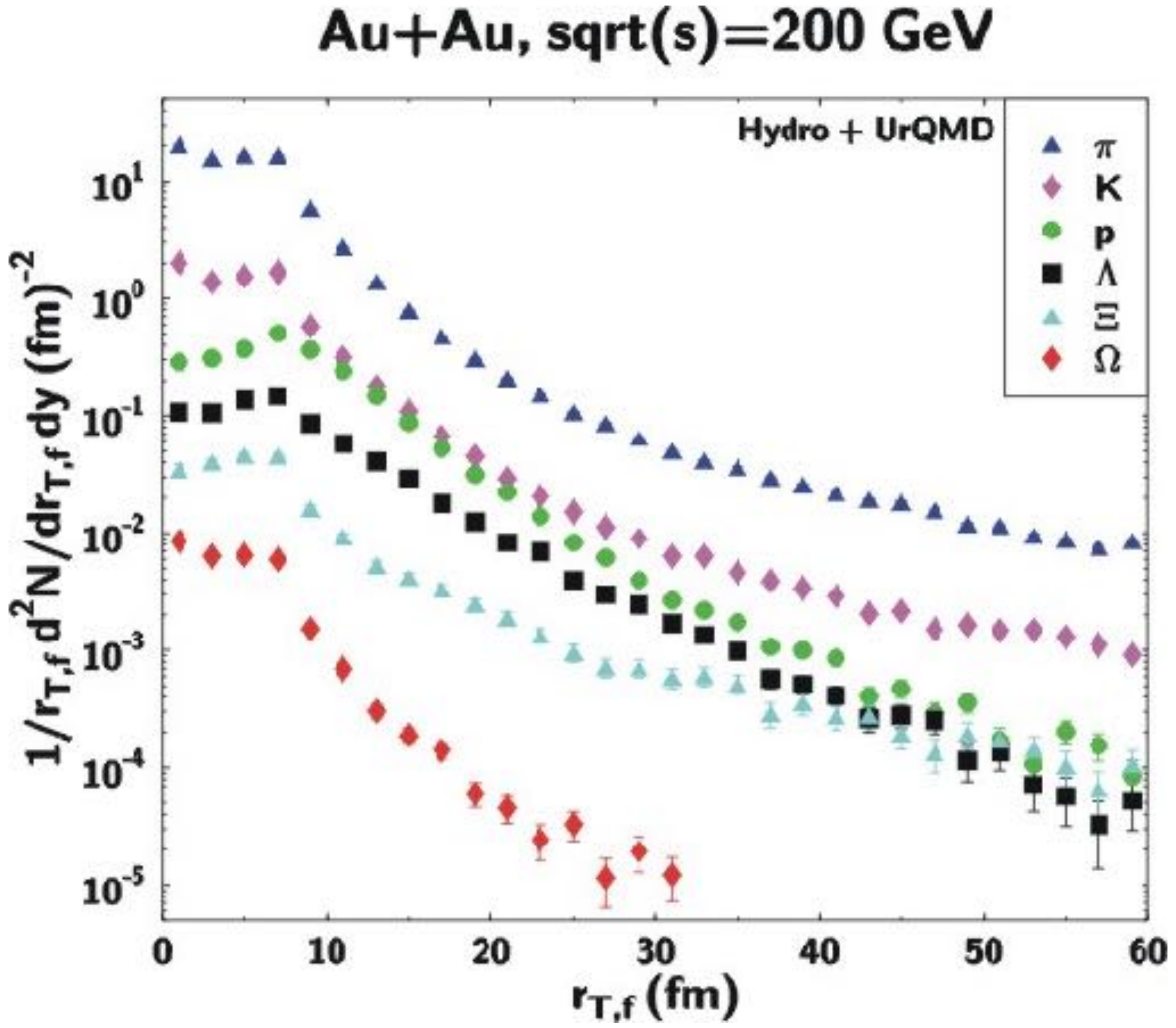
Transport and strangeness: mapping freeze-out

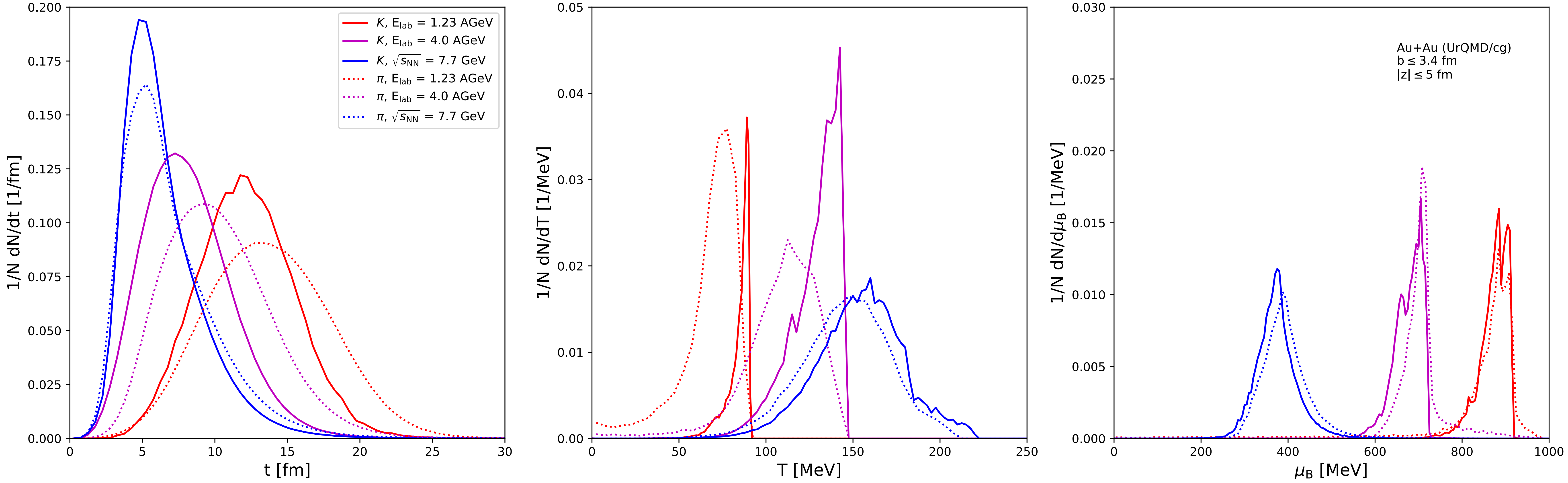
Chemical Freeze-Out: flavor composition fixed

Kinetic Freeze-Out: cessation of elastic scattering

- freeze-out times/radii/temperatures are broad distributions with long tails
- freeze-out is species-dependent: cross sections drive the process
- strangeness suppresses magnitude of cross section: hierarchy of freeze-out times, temperatures and radii
- multi-strange baryons are emitted closest to the phase-boundary

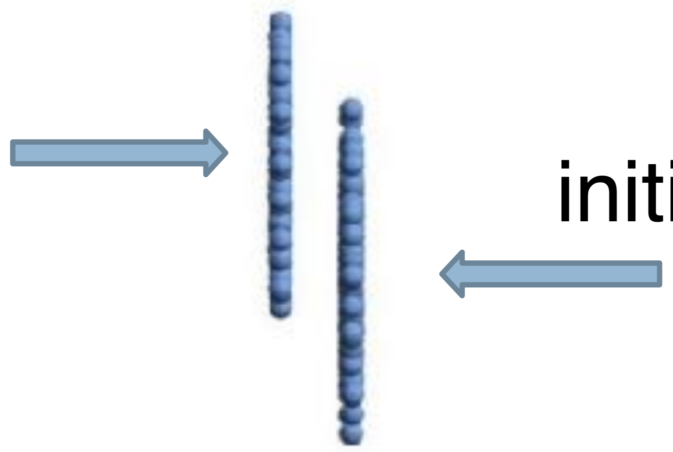






- S.A. Bass & A. Dumitru: Phys. Rev. C 61 (2000) 064909
- T. Reichert, G. Inghirami & M. Bleicher: European Physics Journal Web Conf. 259 (2022) 10005 [SQM 2021]

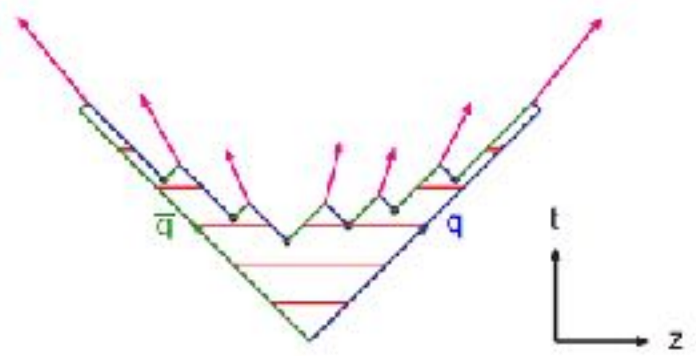
Microscopic transport: PHSD



initial A+A collision

- String formation in primary NN collisions
  → decays to pre-hadrons (baryons and mesons)

LUND string model



partonic stage

- Formation of a QGP state if $\varepsilon > \varepsilon_{critical}$:

  Dissolution of pre-hadrons → DQPM

  → massive quarks/gluons and mean-field energy

  (quasi-)elastic collisions :

  $g+q \to g+q \quad g+q \to g+q$

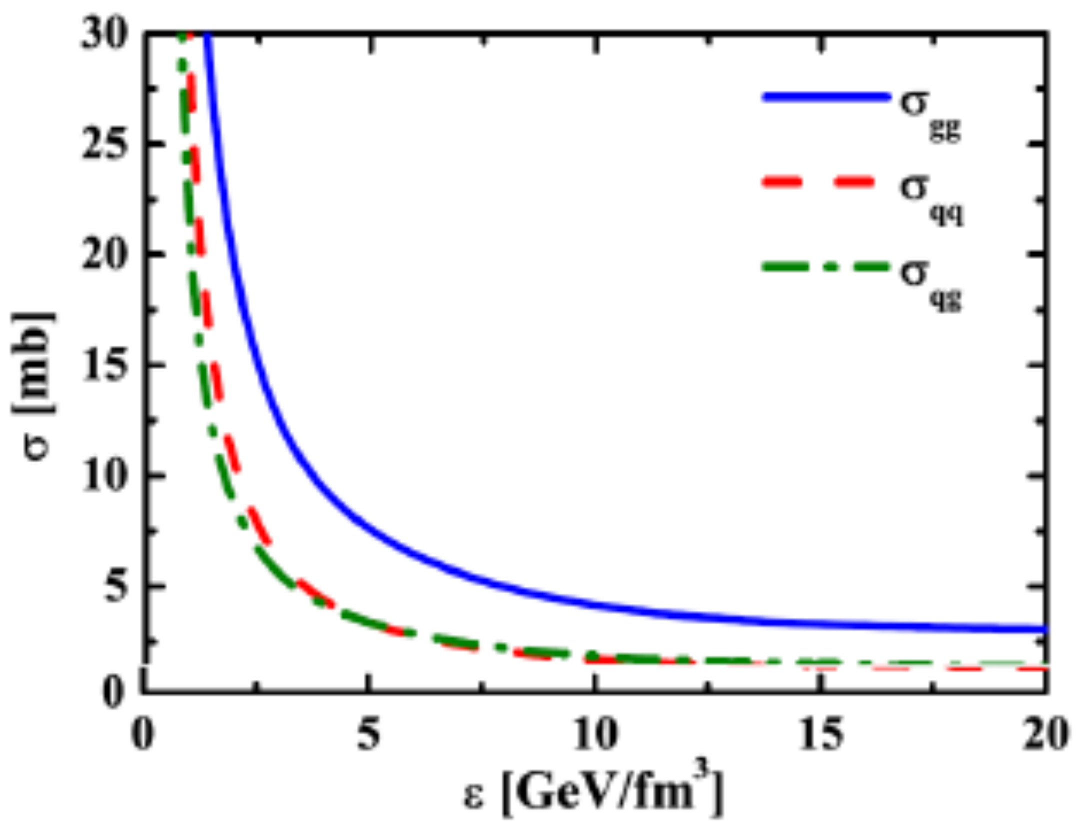
  $g+\bar{q} \to g+\bar{q} \quad g+\bar{q} \to g+\bar{q}$

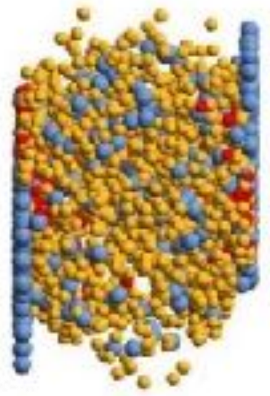
  $g+g \to g+g \quad g+g \to g+g$

  inelastic collisions :

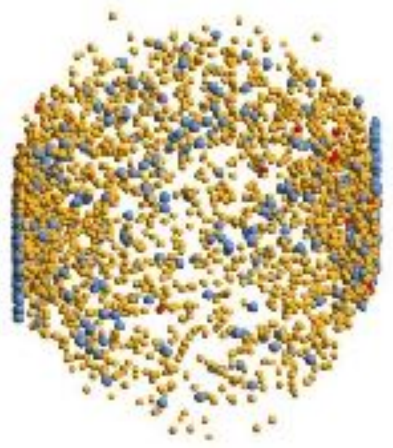
  $q+\bar{q} \to g+g \quad q+\bar{q} \to g+g$

  $g \to g+g \quad g \to g+g$





hadronization



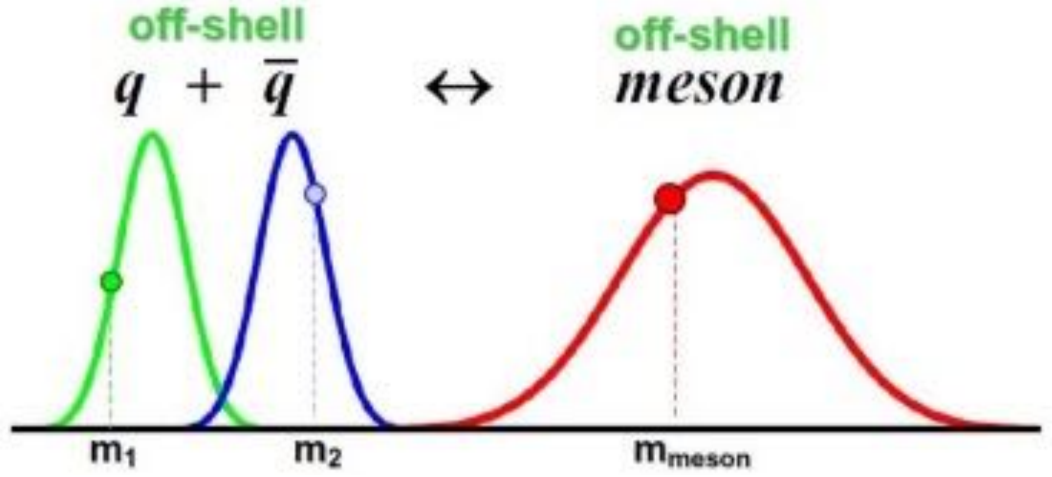
hadronic stage

- Hadronization to colorless off-shell mesons and baryons

  $g \to q+\bar{q}, \quad q+\bar{q} \leftrightarrow meson \ ('string')$

  $q+q+q \leftrightarrow baryon \ ('string')$

  Strict 4-momentum and quantum number conservation

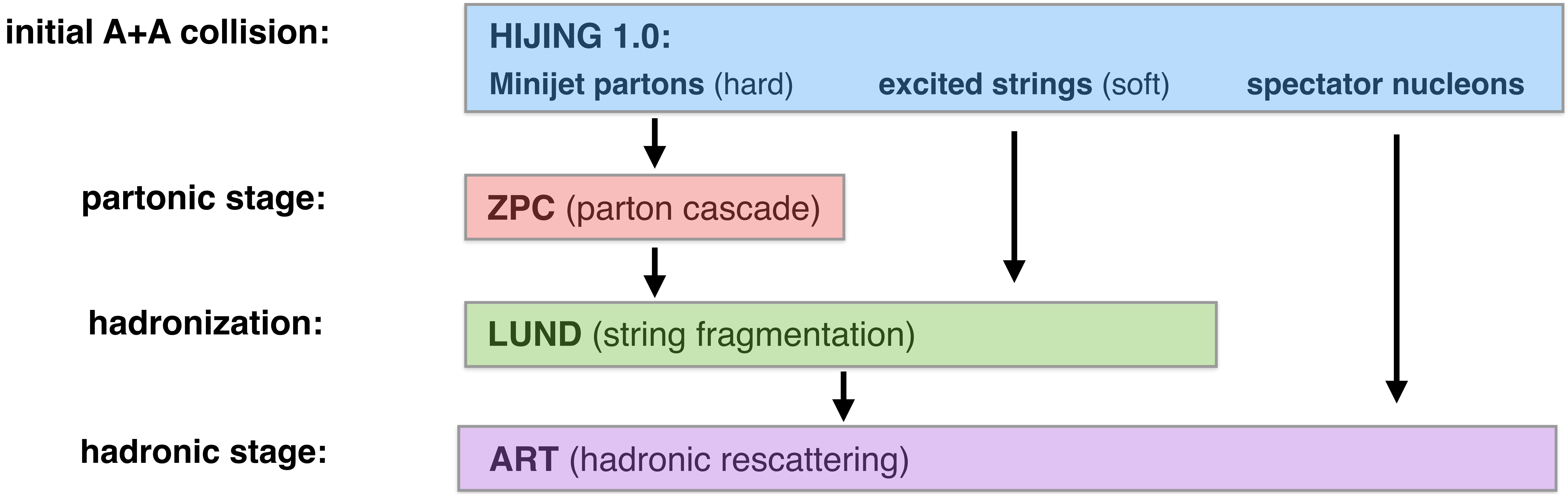


- Hadron-string interactions – off-shell HSD

- W. Cassing & E.L. Bratkovskaya: Phys. Rev. C78 (2008) 034919
- W. Cassing & E.L. Bratkovskaya: Nucl. Phys. A831 (2009) 215-242

Microscopic transport: AMPT 1.X

- **A m**ulti-**p**hase **t**ransport (AMPT) model: constructed as a self-contained kinetic description of heavy ion collisions based on microscopic transport (Boltzmann eqn)
- evolves the system from initial condition to final observables via a changing set of microscopic degrees of freedom
- includes productions of all flavours, 3D, conserved charges
- non-equilibrium initial condition & dynamics/evolution



- Z. Lin, C. Ko, B. Zhang & S. Pal: Phys. Rev. C72 (2005) 064901
- Z. Lin & L. Zheng: Nucl.Sci.Tech. 32 (2021) 113
- https://myweb.ecu.edu/linz/ampt/

Microscopic transport: AMPT 2.X

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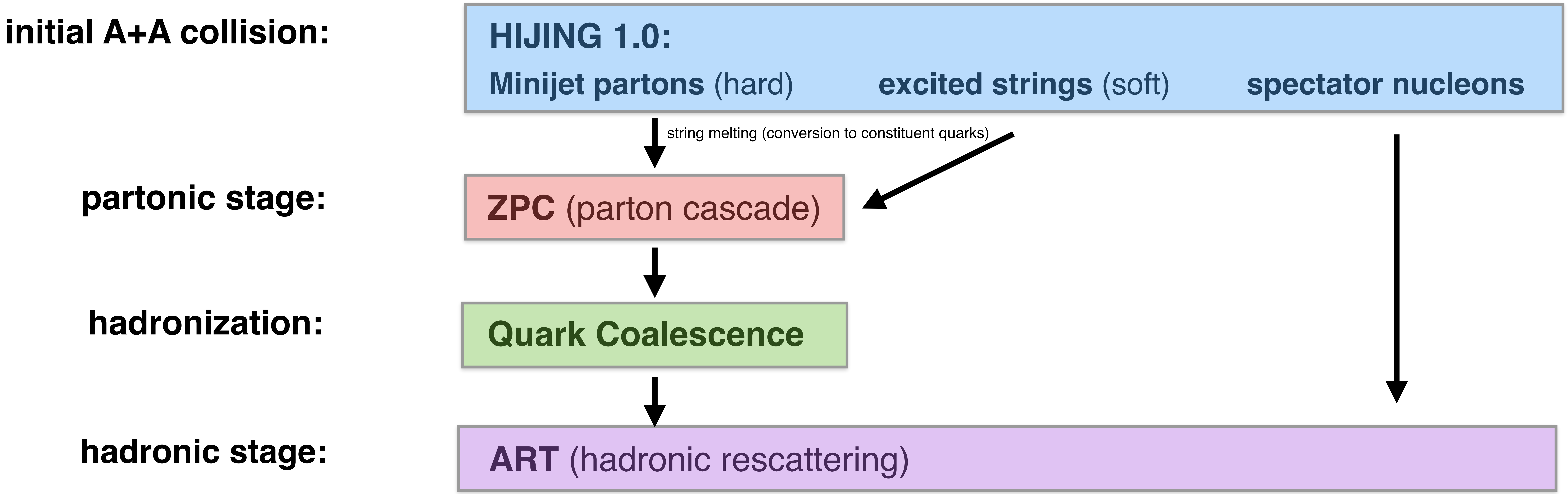

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Low/Medium Energy: Quantum Molecular Dynamics

The Boltzmann Equation does not contain many-body correlations needed to describe cluster formation: use a many-body approach instead: **Quantum Molecular Dynamics (QMD)**

generalized Ritz variational principle:

$$\delta \int_{t_1}^{t_2} \left\langle \Phi \left| i\hbar \frac{d}{dt} - H \right| \Phi \right\rangle dt = 0$$

with $\Phi = \prod_i \phi_i(\vec{x}, \vec{q}_i, \vec{p}_i, t)$ (N-body wave function w/o anti-symmetrization)

and $\phi_i(\vec{x}; \vec{q}_i, \vec{p}_i, t) = \left(\frac{2}{L\pi}\right)^{3/4} \exp\left\{-\frac{2}{L}(\vec{x} - \vec{q}_i(t))^2 + \frac{1}{\hbar} i\vec{p}_i(t)\vec{x}\right\}$

for a Hamiltonian of the form:

$$H = \sum_i T_i + \frac{1}{2}\sum_{ij} V_{ij}$$

the variational principle yields EoM for the centers of the Gaussians:

$$\dot{\vec{p}}_i = -\frac{\partial\langle H\rangle}{\partial\vec{q}_i} \quad \text{and} \quad \dot{\vec{q}}_i = \frac{\partial\langle H\rangle}{\partial\vec{p}_i}$$

- inclusion of potentials / a realistic equation of state is crucial for cluster formation
- current models include: UrQMD, PHQMD, IQMD

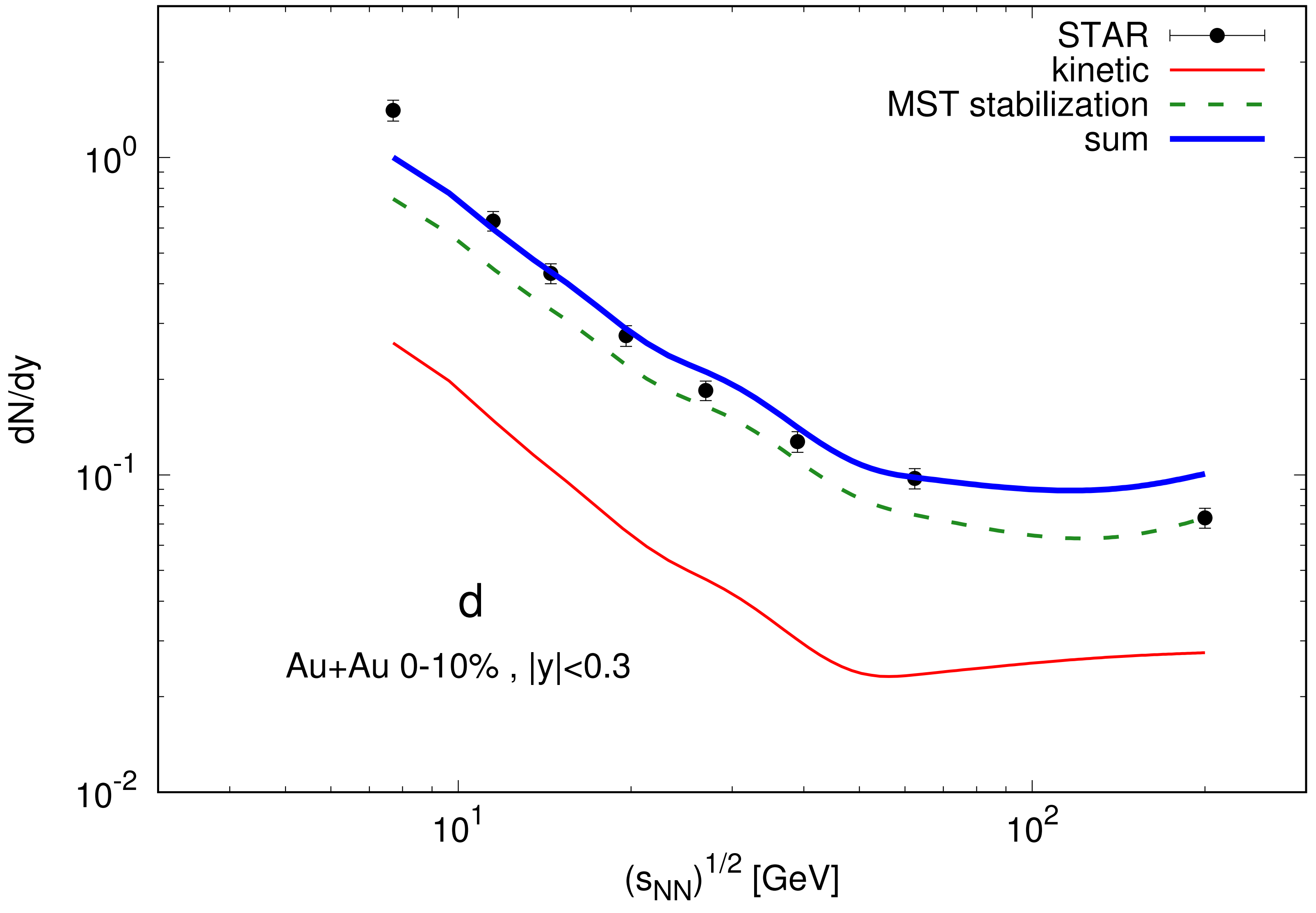
- J. Aichelin: Phys. Rept. 202 (1991) 233-360
- S. A. Bass et al.: Prog.Part.Nucl.Phys. 41 (1998) 255-369
- J. Aichelin, E. Bratkovskaya, A. Le Fevre, V. Kireyeu & V. Kolesnikov: Phys. Rev. C101 (2020) 044905

Cluster formation at low/medium energies:

Transport is a powerful tool for the study of the non-equilibrium dynamics of cluster formation:

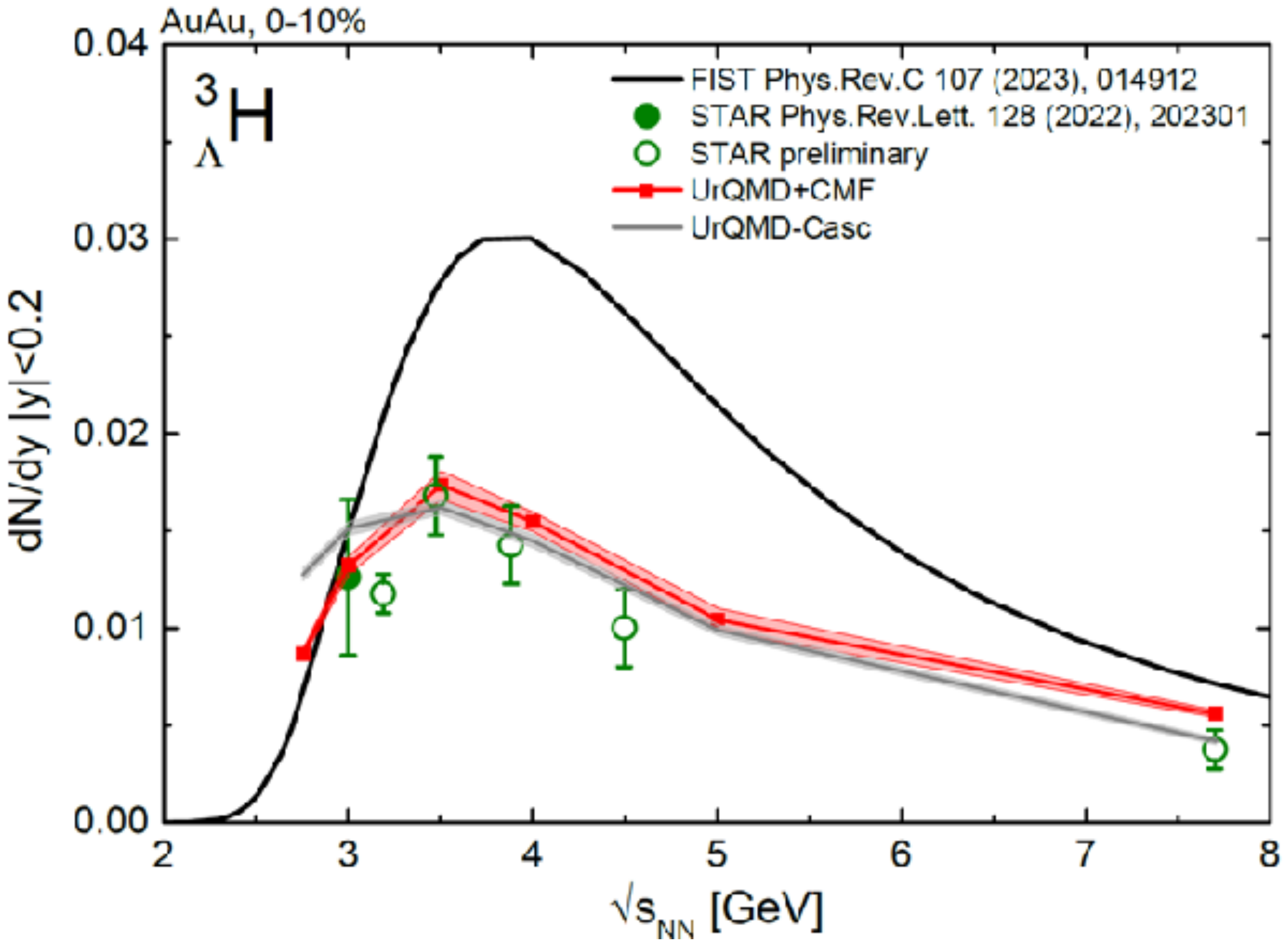
Deuteron formation (RHIC-BES):

- PHQMD w/ realistic EoS & MST cluster algorithm
- Calculation shows the need to include correlations and binding energy effects



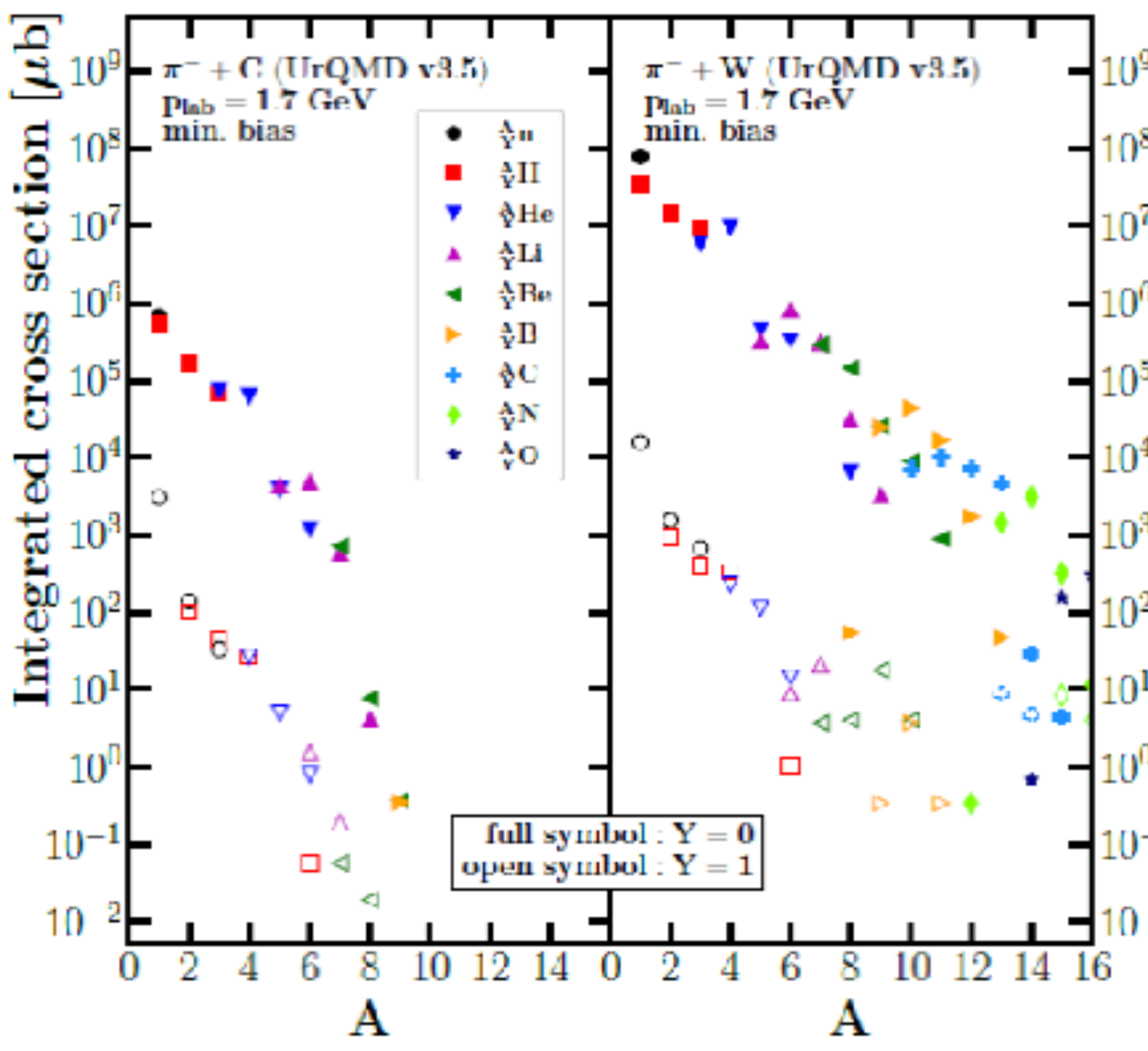
Hyper-triton formation (RHIC-BES):

- UrQMD w/ coalescence
- Transport dynamics provide more robust description of data than a thermal model approach



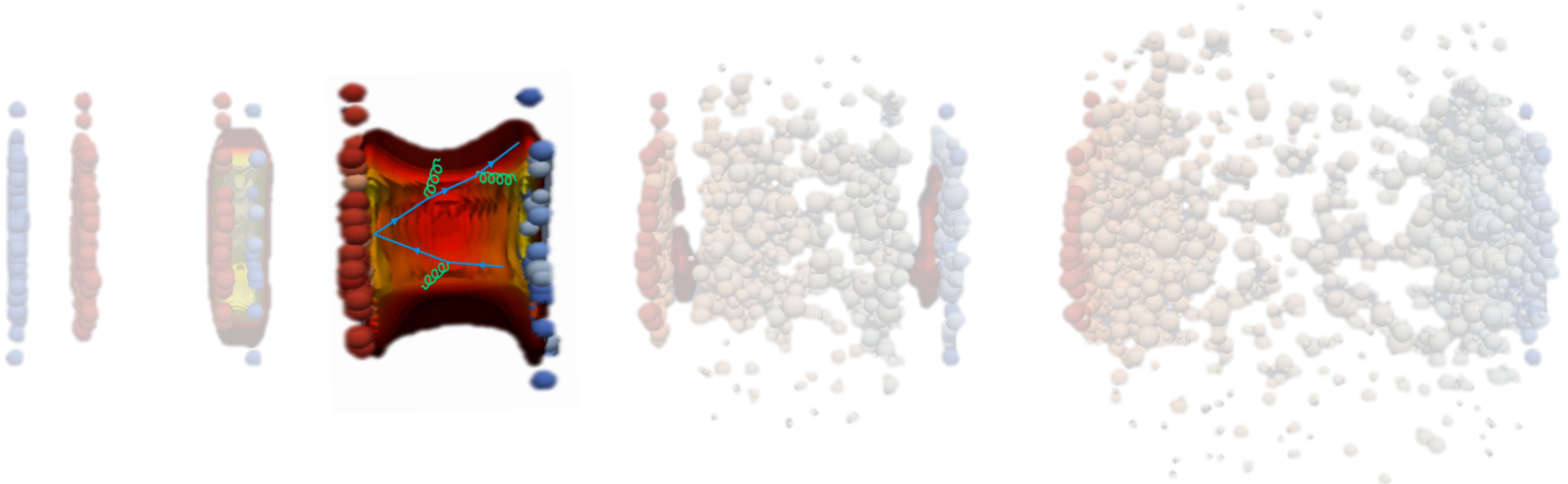
Hyper-nuclei in π+A at SIS:

- UrQMD predicts π+A collisions may produce a large variety of hyper-nuclei at SIS
- allows for study of the strange matter EoS



- G. Coci, S. Glaessel, V. Kireyeu, J. Aichelin, C. Blume, E. Bratkovskaya, V. Kolesnikov & V. Voronyuk: Phys. Rev. C108 (2023) 014902
- T. Reichert, J. Steinheimer, V. Vovchenko, B. Doenigus & M. Bleicher: Phys. Rev. C 107 (2023) 014912
- A. Kittiratpattana, T. Reichert, N. Buyukcizmeci, A. Botvina, A. Limphirat, C. Herold, J. Steinheimer & M. Bleicher: Phys. Rev. C 109 (2024) 044913

Heavy Quark Transport



RFD with conserved charm current:

- fluid-dynamical description of charm evolution
- heavy quarks are treated as a conserved current after initial production in hard processes

Boltzmann dynamics:

- medium constituents: thermal light partons
- heavy quarks scatter with medium partons & radiate gluons based on pQCD matrix elements

Langevin dynamics:

- no assumptions on medium constituents
- heavy quarks get frequent kicks from the medium → transport coefficients

Hybrid models

- Improved Langevin (with radiative energy loss)
- Lido - **Li**nearized Boltzmann with **d**iffusion m**o**del
- MATTER/LBT: multi-scale energy-loss

Langevin with Radiative Processes

modify Langevin Eqn. with force term due to gluon radiation:

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\,\vec{p} + \vec{\xi} + \vec{f}_g$$

radiation force defined through rate of radiated gluon momenta:

$$\vec{f}_g = \frac{d\vec{p}}{dt}$$

- same noise correlator and fluctuation-dissipation relation still hold:

$$\eta_D(p) = \frac{\kappa}{2TE} \quad \text{and} \quad \langle \xi^i(t)\,\xi^j(t')\rangle = \kappa\,\delta^{ij}\,\delta(t-t')$$

- gluon radiation calculated in Higher Twist formalism:

$$\frac{dN_g}{dx\,dk_\perp^2\,dt} = \frac{2\alpha_s(k_\perp)}{\pi} P(x)\,\frac{\hat{q}}{k_\perp^4}\sin^2\left(\frac{t-t_i}{2\,\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4$$

Guo & Wang: *PRL 85, 3591*
Majumder: *PRD 85, 014023*
Zhang, Wang & Wang: *PRL 93, 072301*

- relevant transport coefficients are now:

$$D = \frac{t}{M\eta_D(0)} = \frac{2T^2}{\kappa} \quad \text{and} \quad \hat{q} = 2\,\kappa\, C_A/C_F$$

- S. Cao, G-Y. Qin & S.A. Bass: Phys. Rev. C88 (2013) 044907

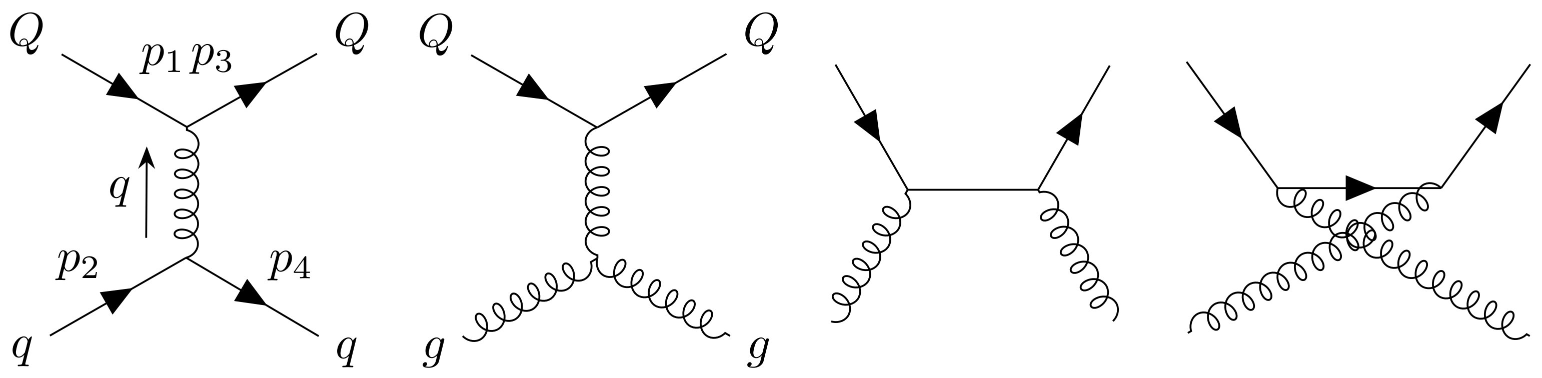
Lido: Boltzmann + Langevin Hybrid

Combine the strength of the linearized-Boltzmann and Langevin approaches:

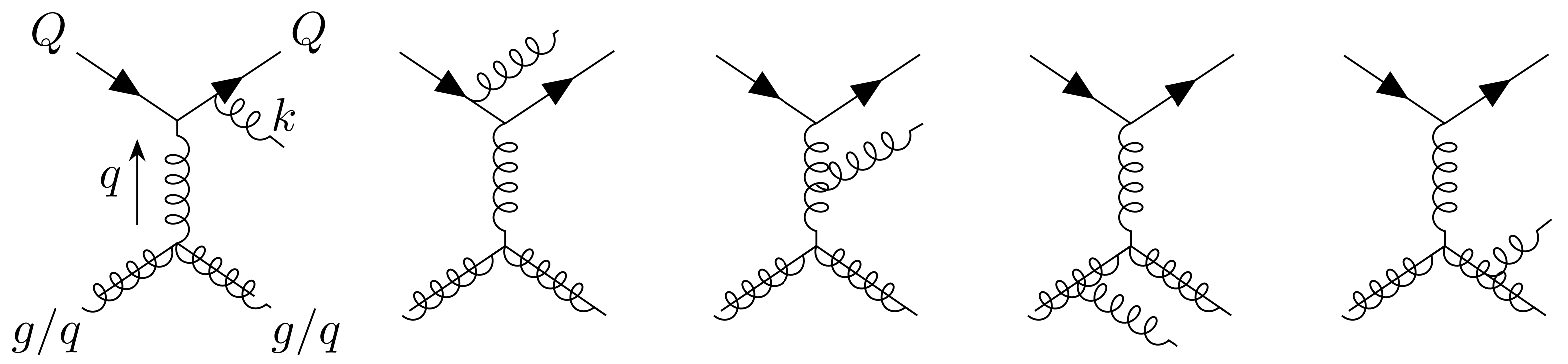
$$\frac{p\cdot\partial f_Q}{E} = \mathcal{C}[f_Q] - \frac{\partial}{\partial p_i}\left(A_i - \frac{1}{2}\frac{\partial}{\partial p_j}B_{ij}\right) f_Q = \left(\hat{\mathcal{C}} + \hat{\mathcal{D}}\right) f_Q$$

perturbative processes:

- elastic scattering:



- inelastic: improved Gunion Bertsch



Fochler et al. PRD88 014018

- gluon radiation **and** absorption implemented to conserve detailed balance

non-perturbative processes:

- treated in a Langevin equation with isotropic random force

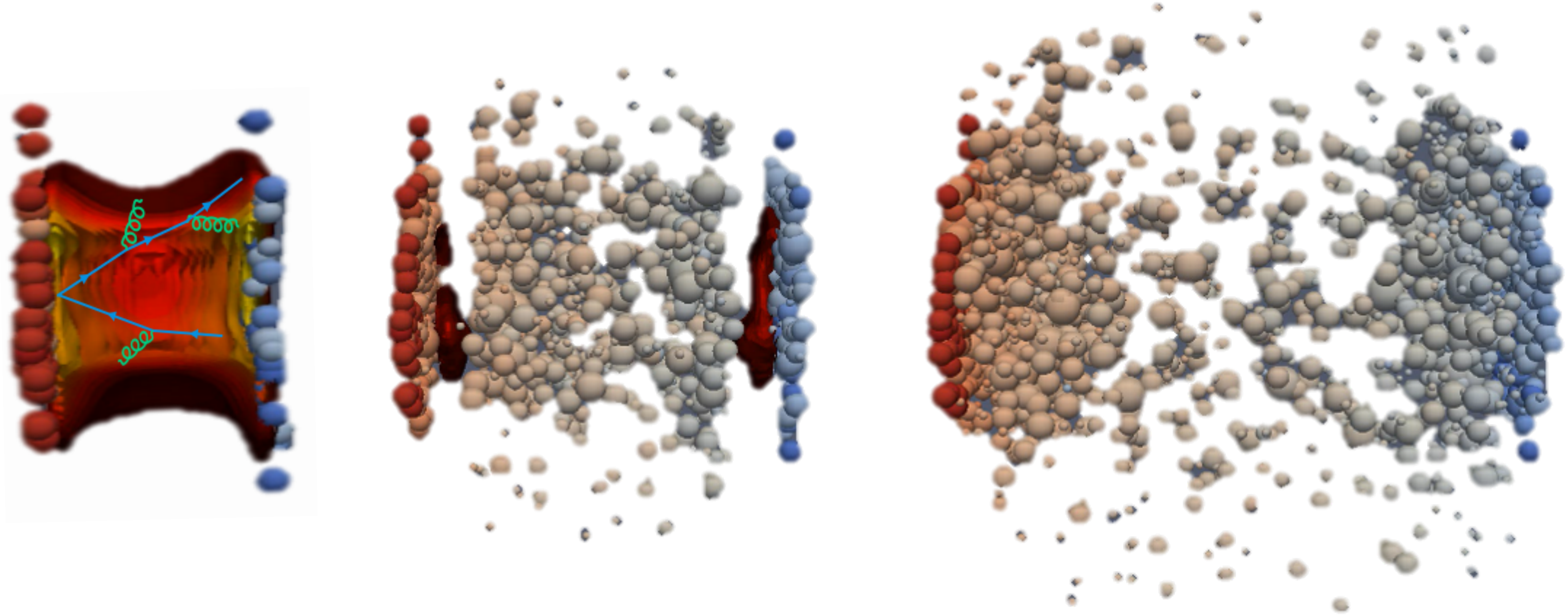
$$\Delta\vec{x_i} = \frac{\vec{p_i}}{E}\Delta t \qquad \Delta\vec{p_i} = -\eta_D\,\vec{p_i}\,\Delta t + \Delta t\,\vec{\xi_i}(t)$$

- Einstein relation connects random force to drag coefficient to ensure proper equilibrium

- W. Ke, Y. Xu & S.A. Bass: Phys. Rev. C98 (2018) 064901

Heavy Quark Transport: full collision dynamics

parameterized initial QGP state
+
initial HQ production



Trento:

- based on simple phenomenological ideas for entropy deposition
- constrained by global model to data fit

Heavy Quarks:

- PYTHIA to generate initial HQ ensemble

viscous hydrodynamics

- EbE 2+1D viscous RFD
- describes QGP dynamics & hadronization
- Lattice QCD EoS

HQ interaction & transport:

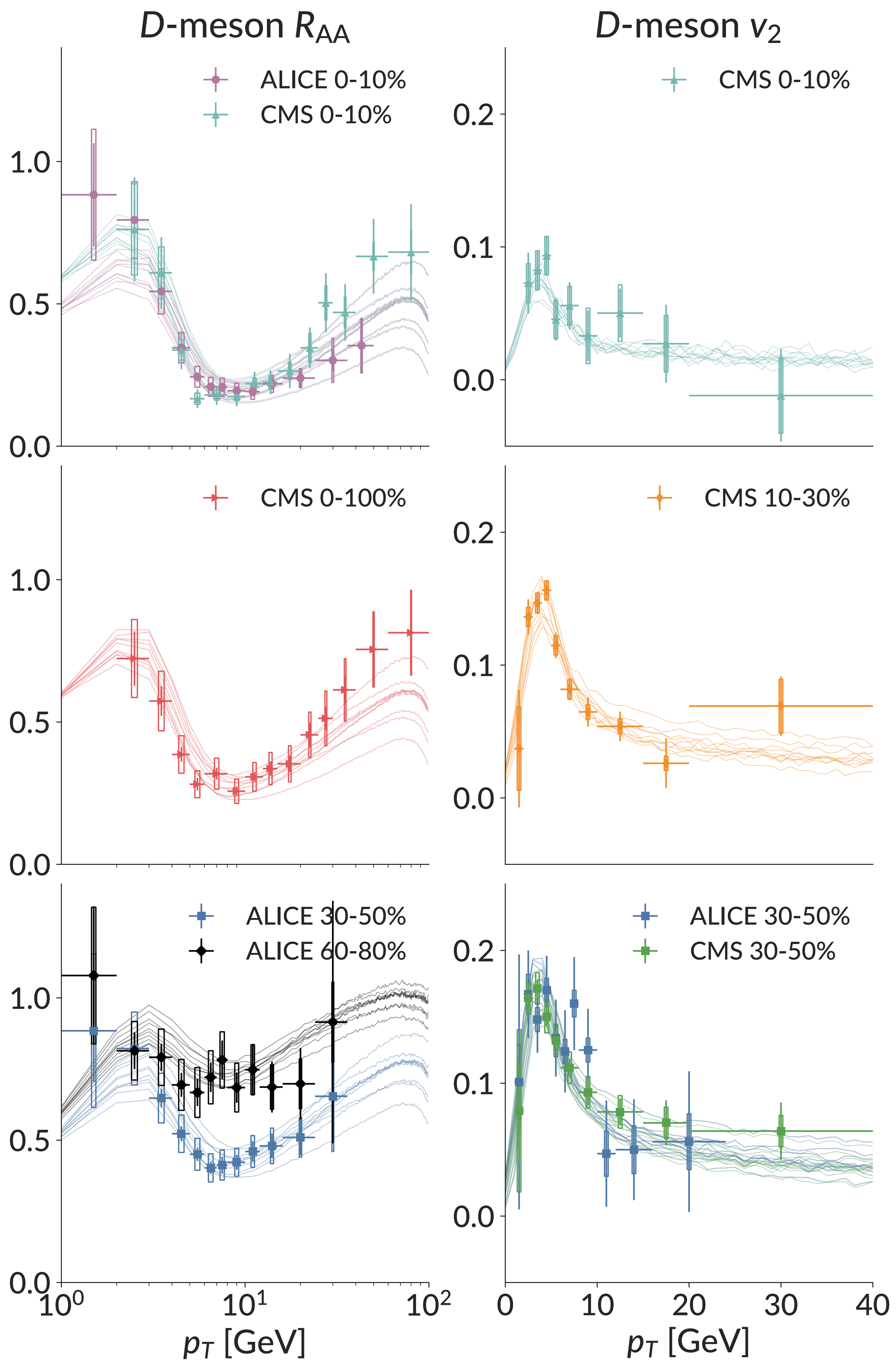
1. D_s from Lattice QCD
2. T-Matrix approach
3. Bayesian calibration

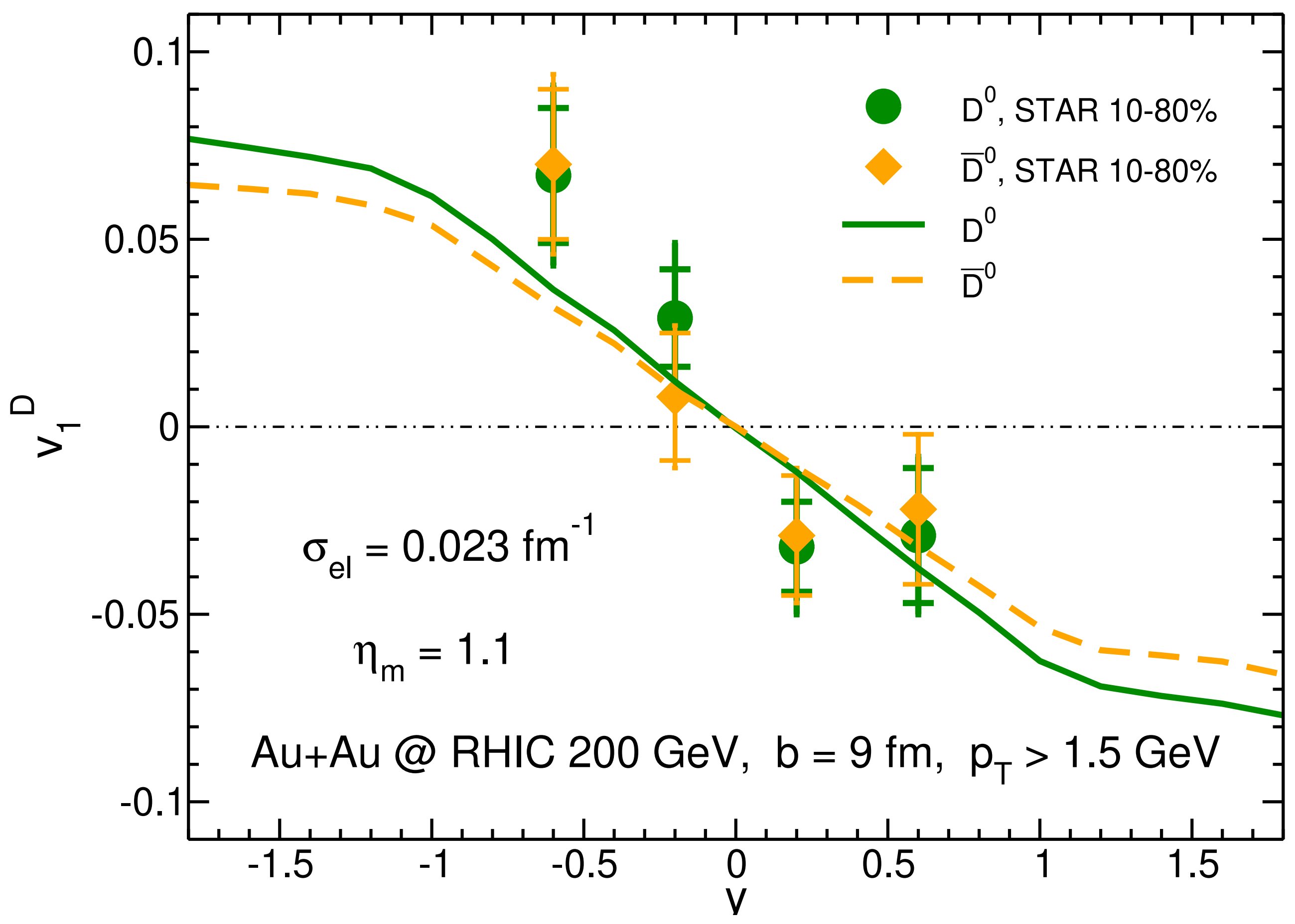
1. Langevin dynamics
2. Boltzmann dynamics
3. Hybrid approaches

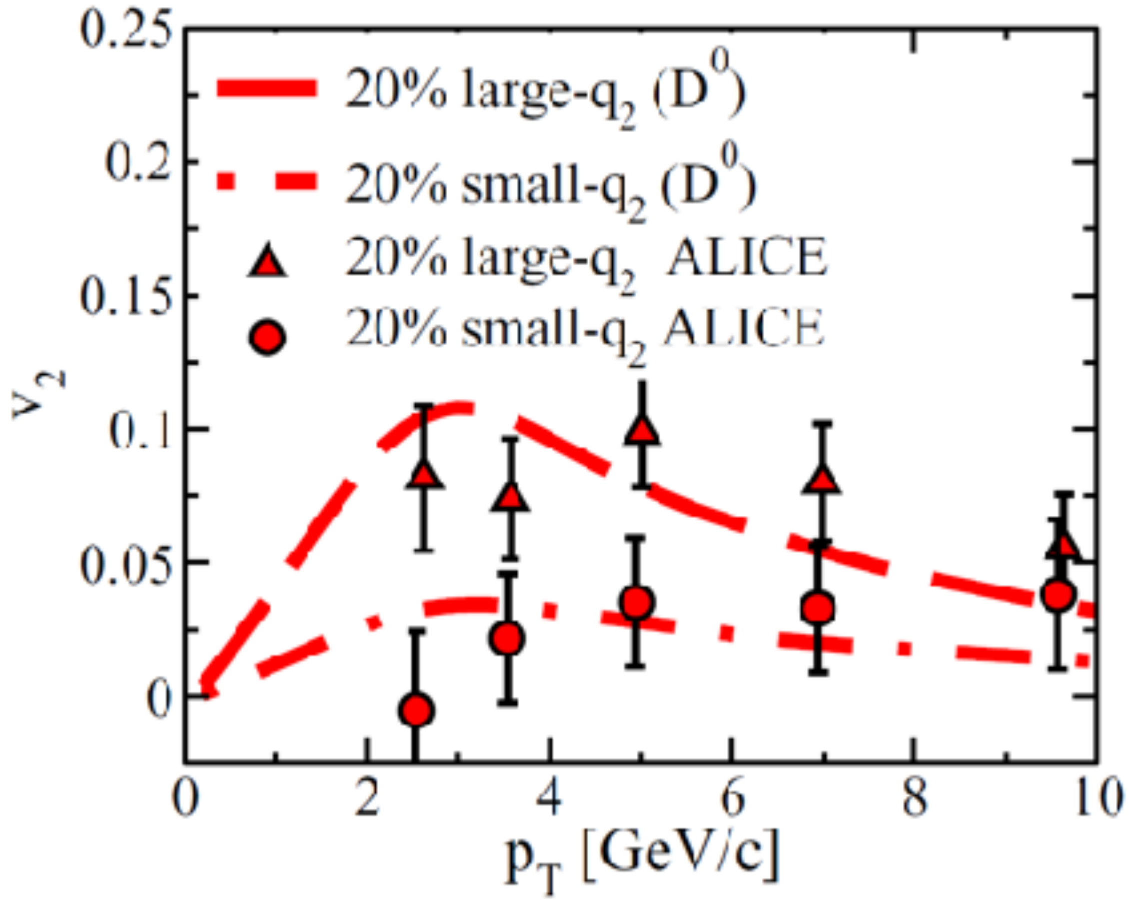
Hadronic afterburner:

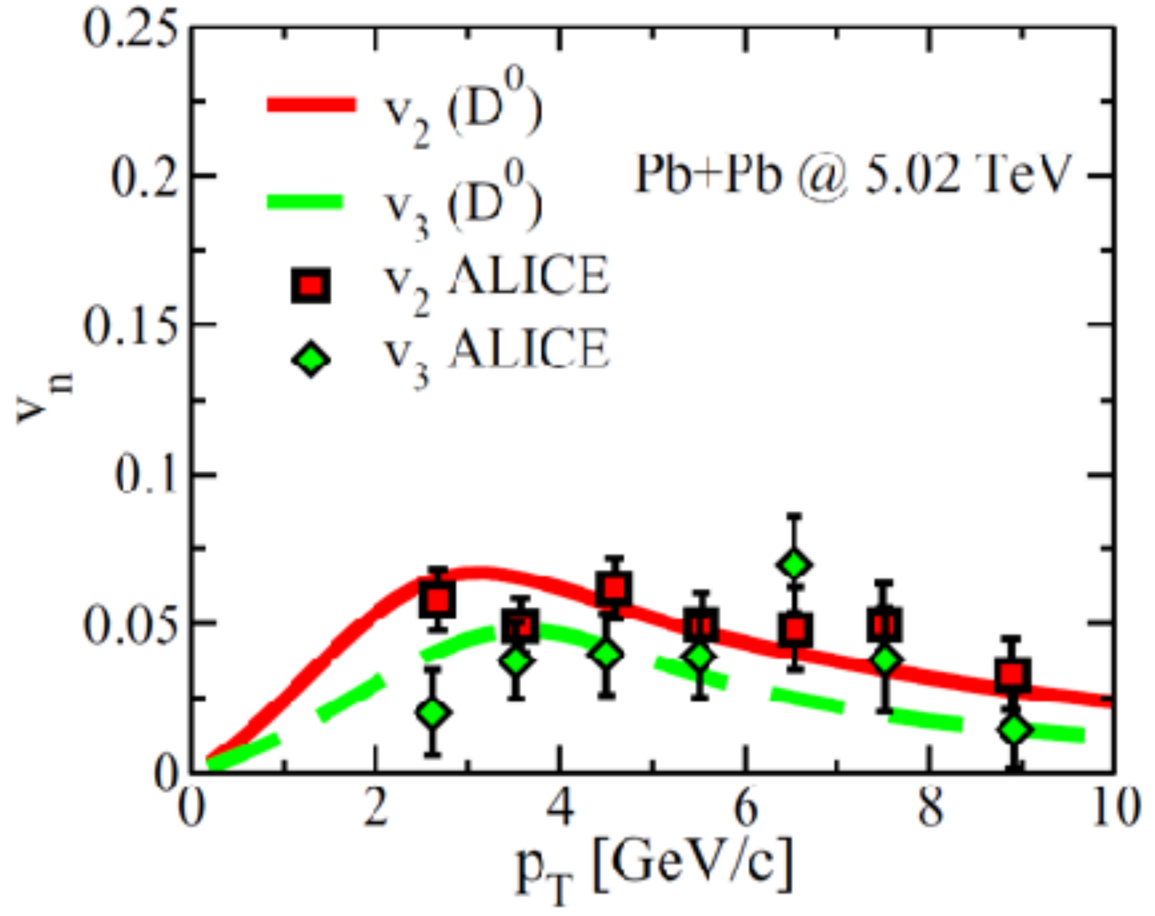
- non-equilibrium evolution of an interacting hadron gas
- separation of chemical and kinetic freeze-out
- hadron gas shear & bulk viscosities are implicitly contained in calculation

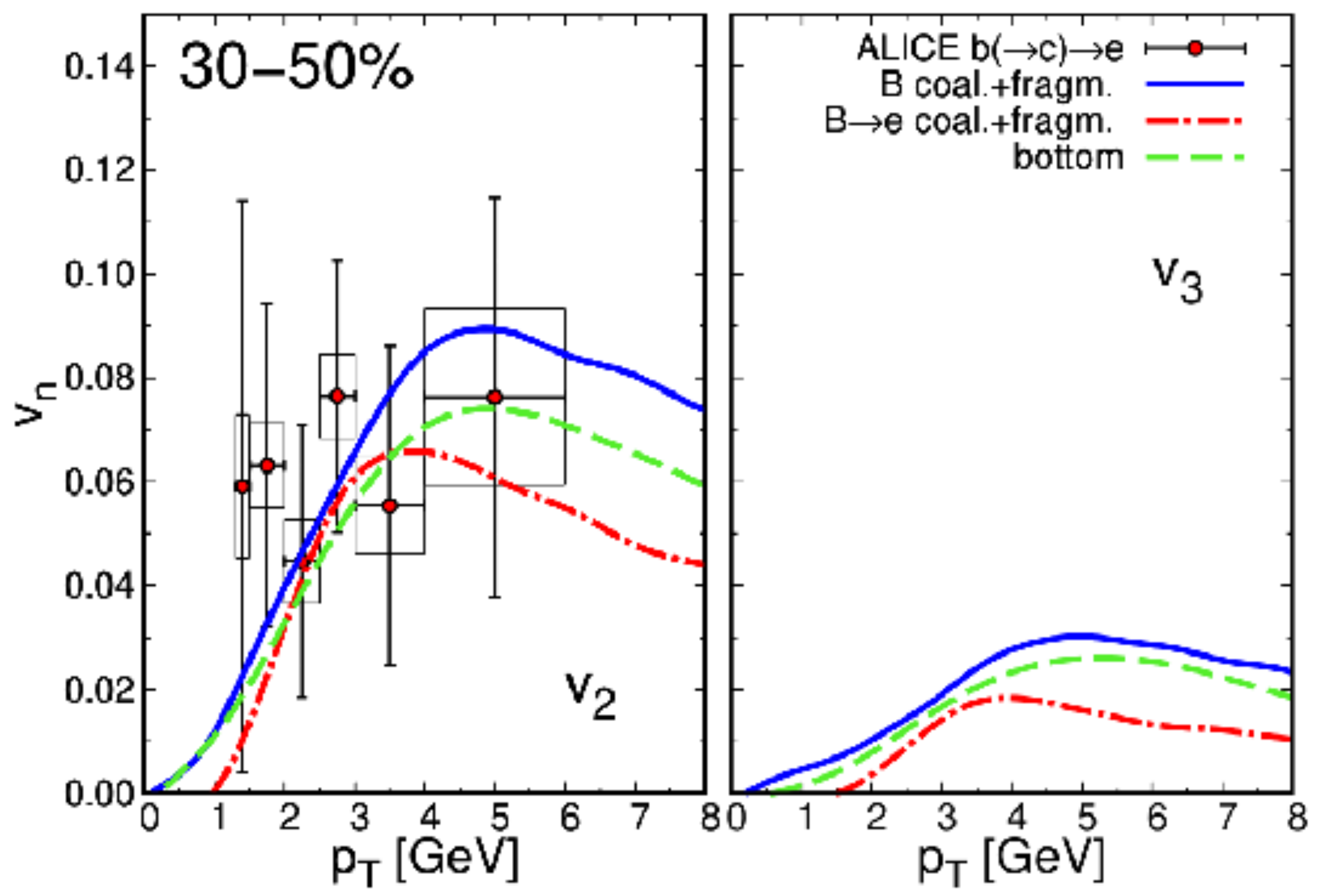
Heavy Quark Transport: comparison to data

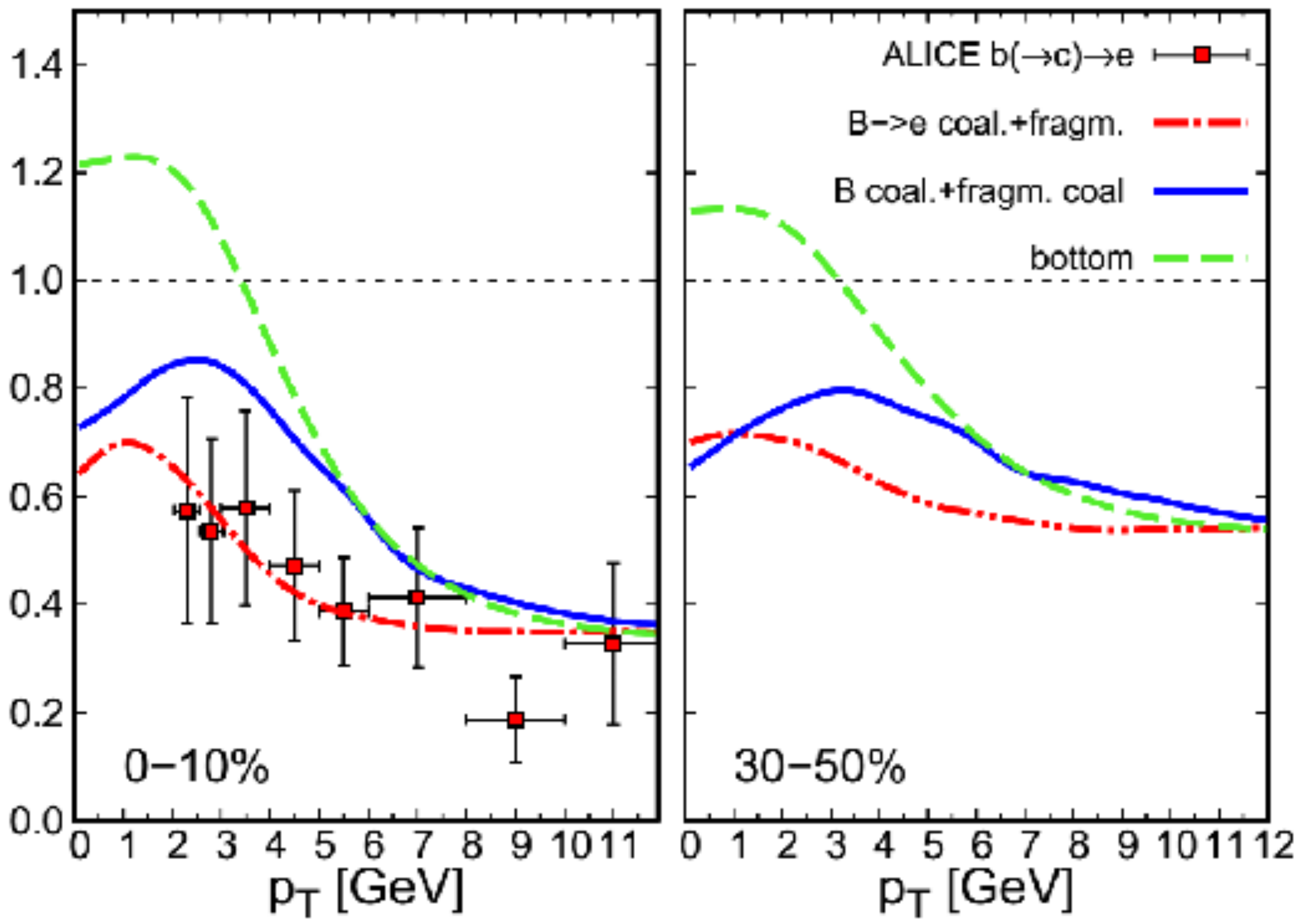












- Y. Xu, J.E. Bernhard, S.A. Bass, M. Nahrgang & G-Y. Qin: Phys. Rev. C97 (2018) 014907
- L. Oliva, S. Plumari and V. Greco, JHEP 05 (2021) 034
- M.L. Sambataro, V. Minissale, S.Plumari, V.Greco, Phys.Lett.B 849 (2024) 138480
- M.L. Sambataro, Y. Sun, V. Minissale, S. Plumari, V.Greco, Eur.Phys.J.C 82 (2022) 9, 833

Collaborative research: key to advancement

PHYSICAL REVIEW C **99**, 054907 (2019)

Toward the determination of heavy-quark transport coefficients in quark-gluon plasma

Shanshan Cao,[1] Gabriele Coci,[2,3] Santosh Kumar Das,[4,2] Weiyao Ke,[5] Shuai Y. F. Liu,[6] Salvatore Plumari,[2] Taesoo Song,[7] Yingru Xu,[5] Jörg Aichelin,[8] Steffen Bass,[5] Elena Bratkovskaya,[9,10] Xin Dong,[11] Pol Bernard Gossiaux,[8] Vincenzo Greco,[2,3] Min He,[12] Marlene Nahrgang,[8] Ralf Rapp,[6] Francesco Scardina,[2,3] and Xin-Nian Wang[13,11,*]

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[3]*Laboratori Nazionali del Sud, INFN-LNS, Via Santa Sofia 62, I-95123 Catania, Italy*
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[5]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*
[6]*Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*
[7]*Institut für Theoretische Physik, Universität Gießen, Germany*
[8]*SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France*
[9]*Institute for Theoretical Physics, Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany*
[10]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
[11]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94740, USA*
[12]*Department of Applied Physics, Nanjing University of Science and Technology, Nanjing 210094, China*
[13]*Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China*

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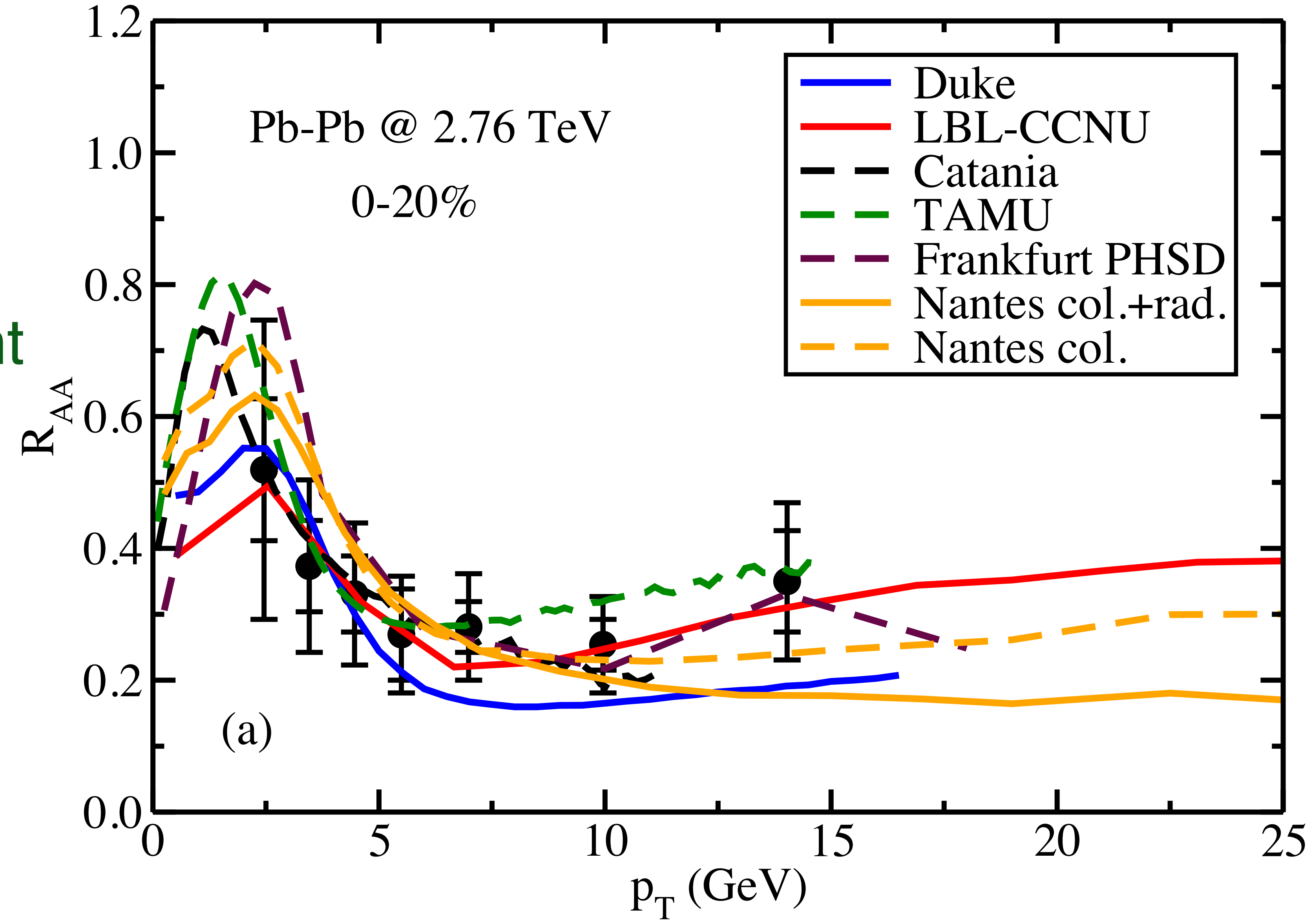
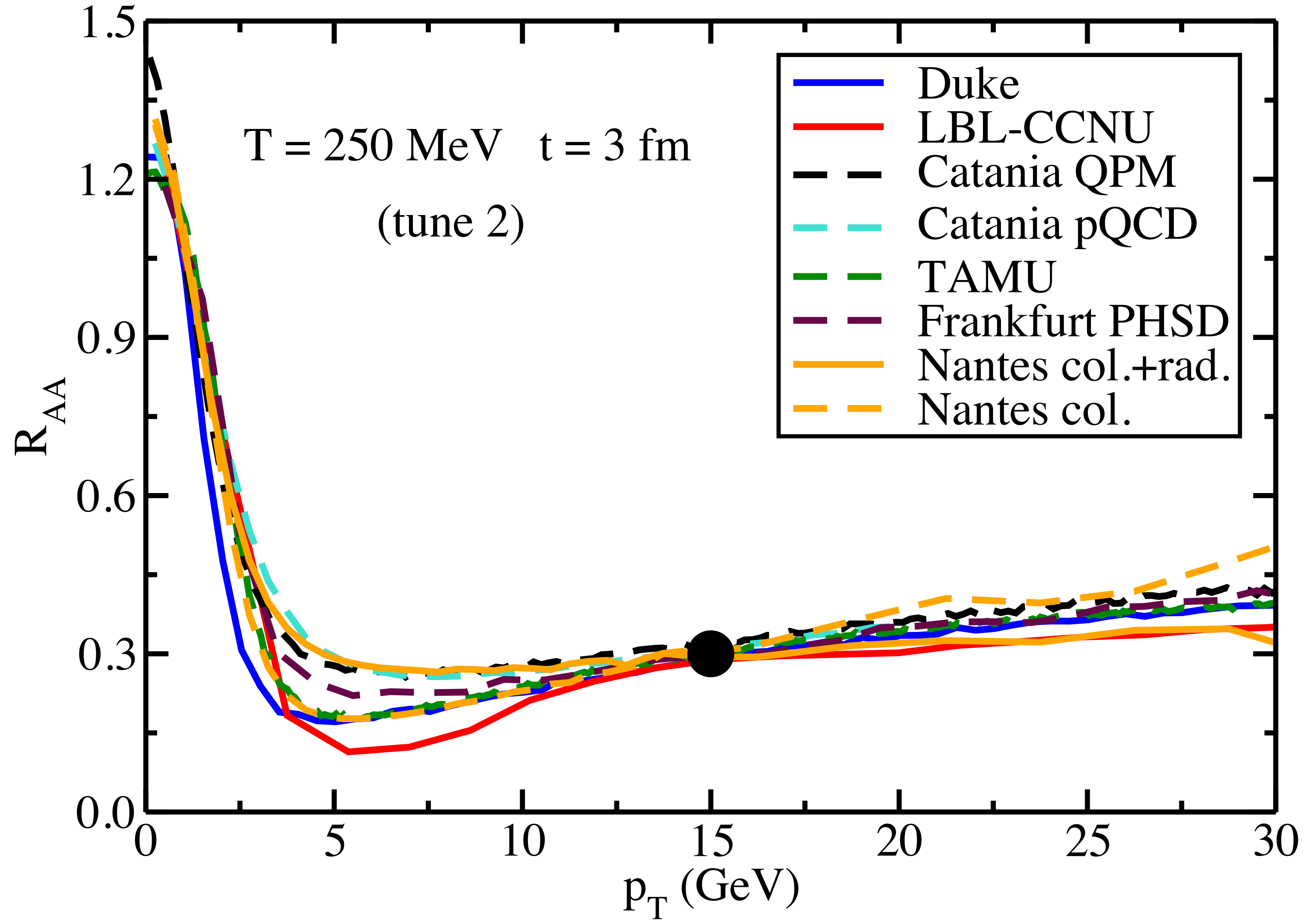
Several transport models have been employed in recent years to analyze heavy-flavor meson spectra in high-energy heavy-ion collisions. Heavy-quark transport coefficients extracted from these models with their default parameters vary, however, by up to a factor of 5 at high momenta. To investigate the origin of this large theoretical uncertainty, a systematic comparison of heavy-quark transport coefficients is carried out between various transport models. Within a common scheme devised for the nuclear modification factor of charm quarks in a brick medium of a quark-gluon plasma, the systematic uncertainty of the extracted drag coefficient among these models is shown to be reduced to a factor of 2, which can be viewed as the smallest intrinsic systematical error band achievable at present time. This indicates the importance of a realistic hydrodynamic evolution constrained by bulk hadron spectra and of heavy-quark hadronization for understanding the final heavy-flavor hadron spectra and extracting heavy-quark drag coefficient. The transverse transport coefficient is less constrained due to the influence of the underlying mechanism for heavy-quark medium interaction. Additional constraints on transport models such as energy loss fluctuation and transverse-momentum broadening can further reduce theoretical uncertainties in the extracted transport coefficients.

DOI: 10.1103/PhysRevC.99.054907

- models show reasonable agreement to D-meson RAA data, but with significant variations

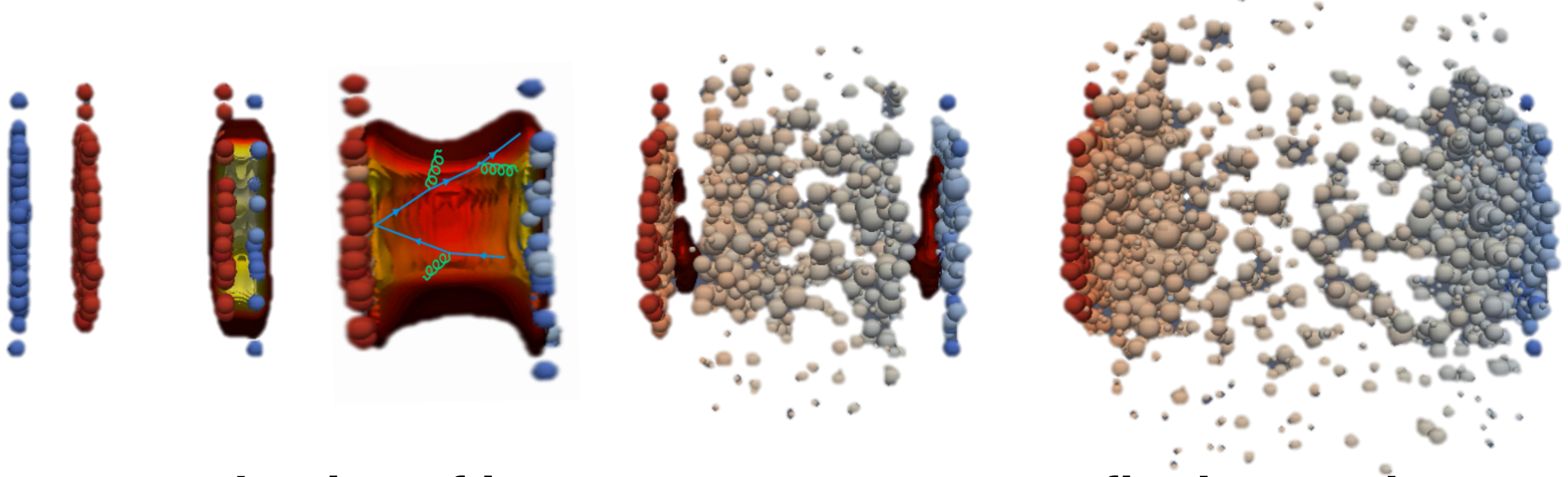




- reduce calculation to quark level with same transport coefficient at fixed temperature & fix normalization: very good agreement!
- details (different medium evolution, ICs etc.) can lead to significant variation!

Transport as discovery tool:

- The goal of constructing a transport model is to test its underlying assumptions via a comparison to data and gaining physics insight from such a comparison



physics of interest ⟷ **final state data**
transport model

- provides access to quantities that are not directly accessible by experiment:
  - QCD transport coefficients (viscosities, diffusion coefficients etc.) & relaxation times
  - structure of the initial state
- probe the underlying physics of observed phenomena
  - jet energy-loss
  - dynamics of thermalization & hadronization

Model to Data Comparison: Parametric Nightmare

Transport Models have multiple parameters encoding its underlying physics that are sensitive to experimental data

Model Parameter:

eqn. of state

shear viscosity

initial state

pre-equilibrium dynamics

thermalization time

quark/hadron chemistry

particlization/freeze-out

experimental data:

π/K/P spectra

yields vs. centrality & beam

elliptic flow

HBT

charge correlations & BFs

density correlations

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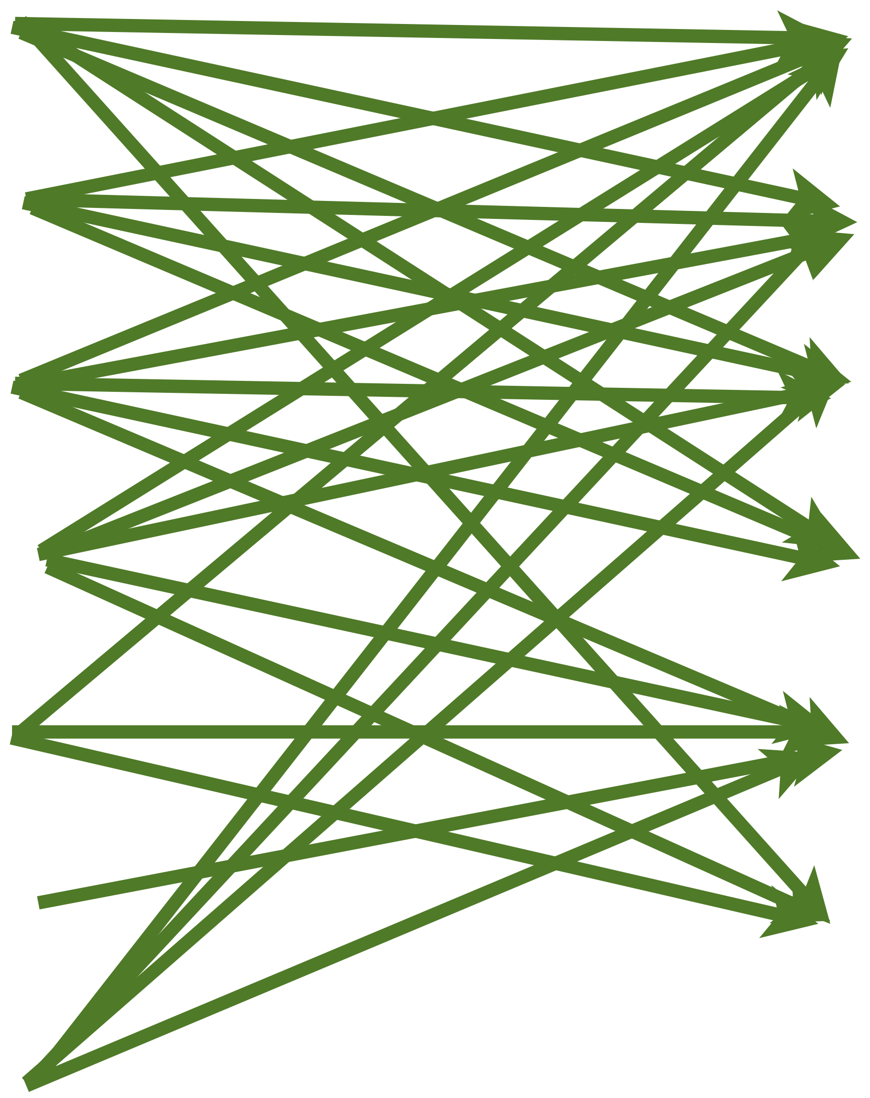

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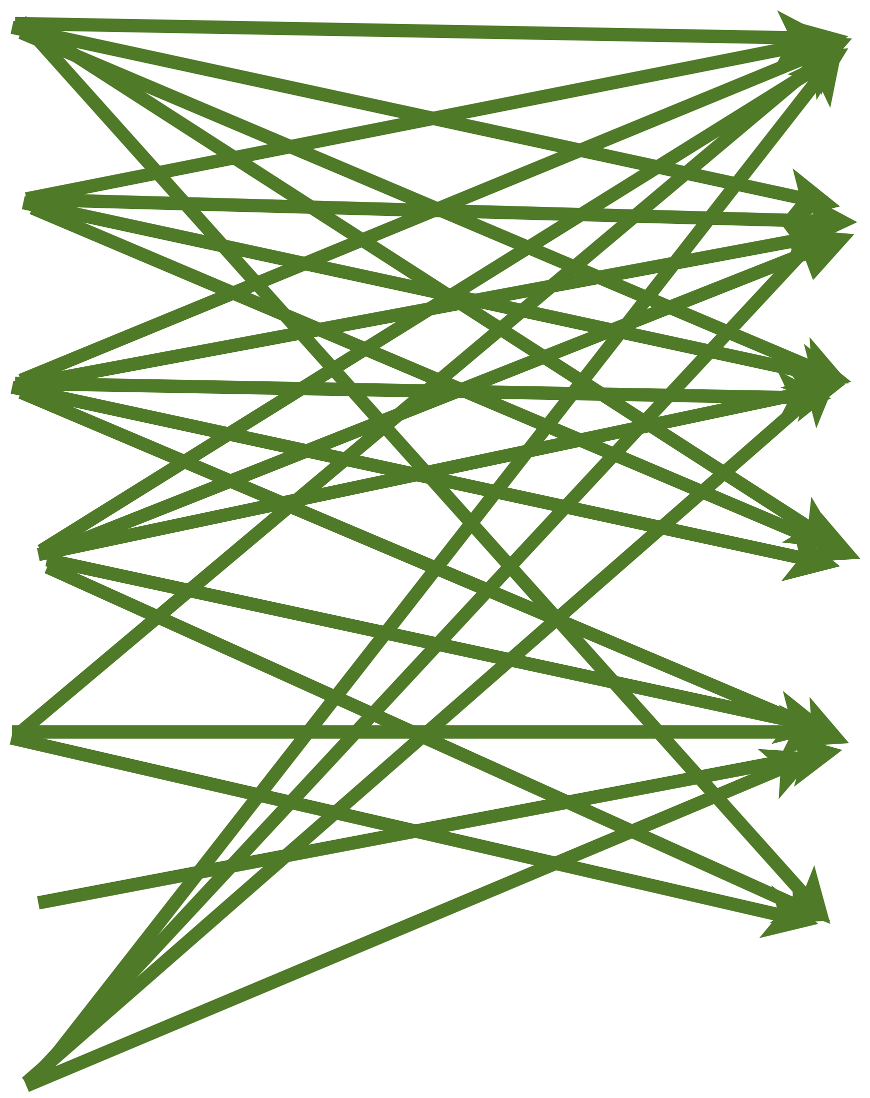


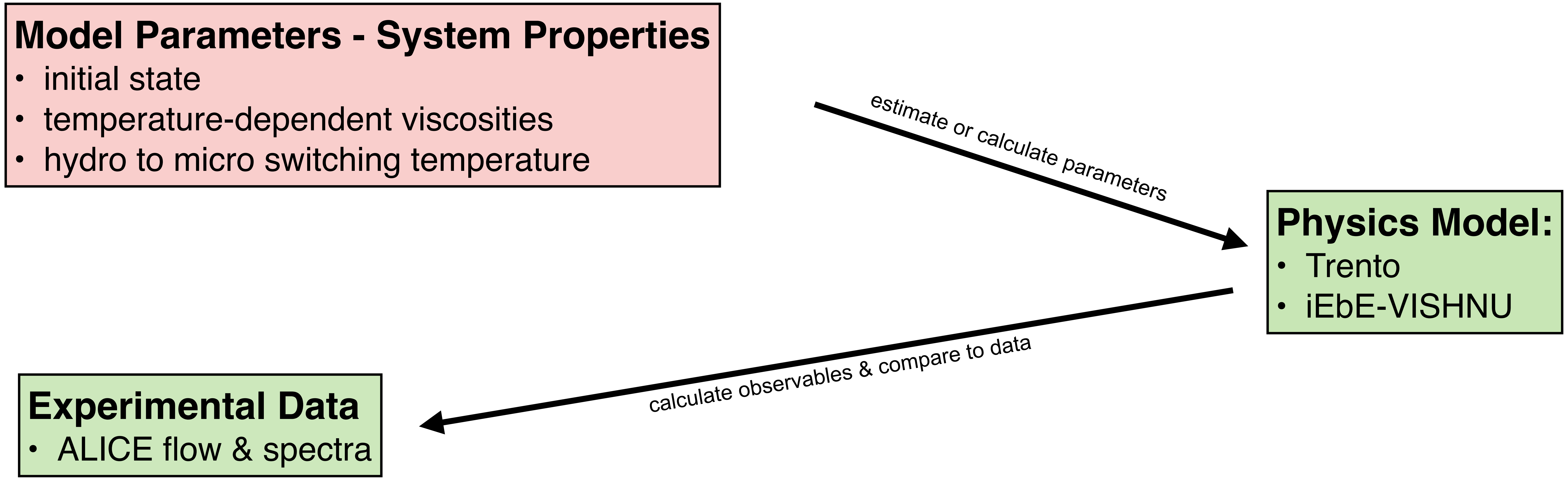
experimental data:

π/K/P spectra
yields vs. centrality & beam
elliptic flow
HBT
charge correlations & BFs
density correlations

- large number of interconnected parameters w/ non-factorizable data dependencies
- data have correlated uncertainties
- develop novel optimization techniques: Bayesian Statistics and MCMC methods
- transport models require too much CPU: need new techniques based on emulators
- general problem, not restricted to RHIC Physics →**collaboration with Statistical Sciences**

State of the Art for model to data comparisons: Bayesian inference

Each computational model relies on a set of physics parameters to describe the dynamics and properties of the system. These physics parameters act as a representation of the information we wish to extract from comparison to data.



State of the Art for model to data comparisons: Bayesian inference

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Model Parameters - System Properties
- initial state
- temperature-dependent viscosities
- hydro to micro switching temperature

Physics Model:
- Trento
- iEbE-VISHNU

Bayesian analysis

Experimental Data
- ALICE flow & spectra

State of the Art for model to data comparisons: Bayesian inference

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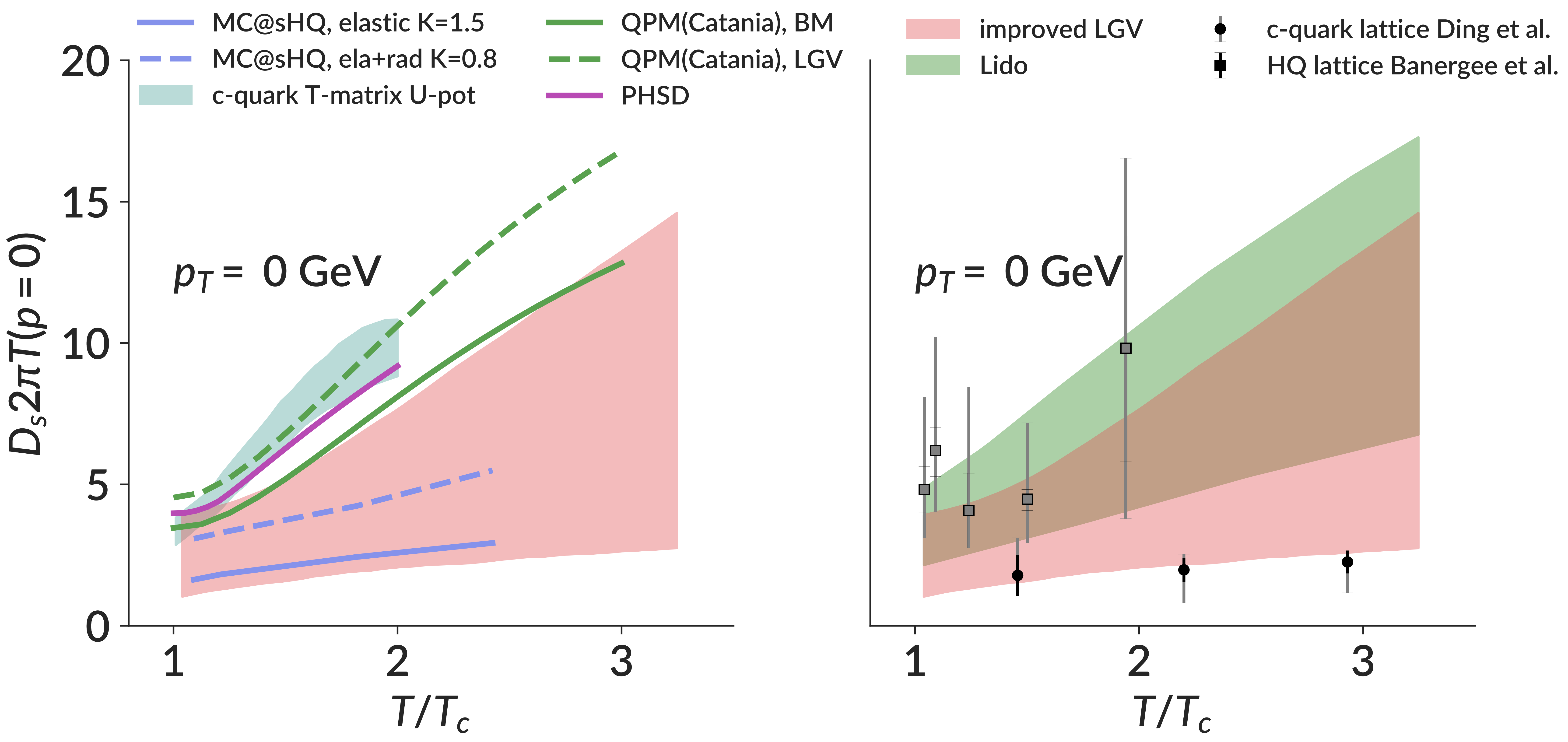
Bayesian analysis

Experimental Data

- ALICE flow & spectra

- Bayesian analysis allows us to simultaneously calibrate all model parameters via a model-to-data comparison
- determine parameter values such that the model best describes experimental observables
- extract the probability distributions of all parameters

Bayesian analysis: heavy flavor transport coefficient

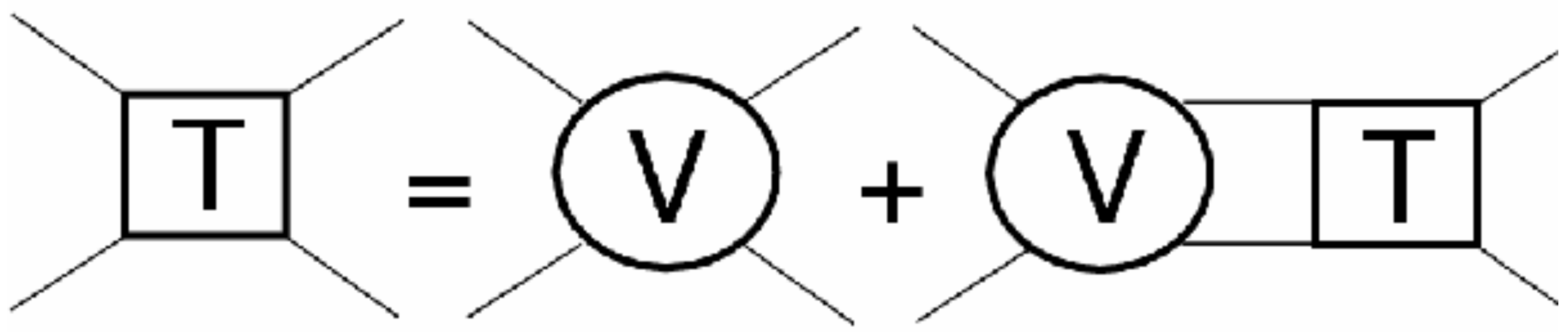


- comparison shows large variability in D_s between different heavy quark transport/interaction models
- Lattice results favor data-driven extraction (within large uncertainties)
- Lido vs. radiation improved Langevin:
  - large overlap in extracted D_s band
  - Lido trends to larger D_s values (influence of pQCD contribution in model)

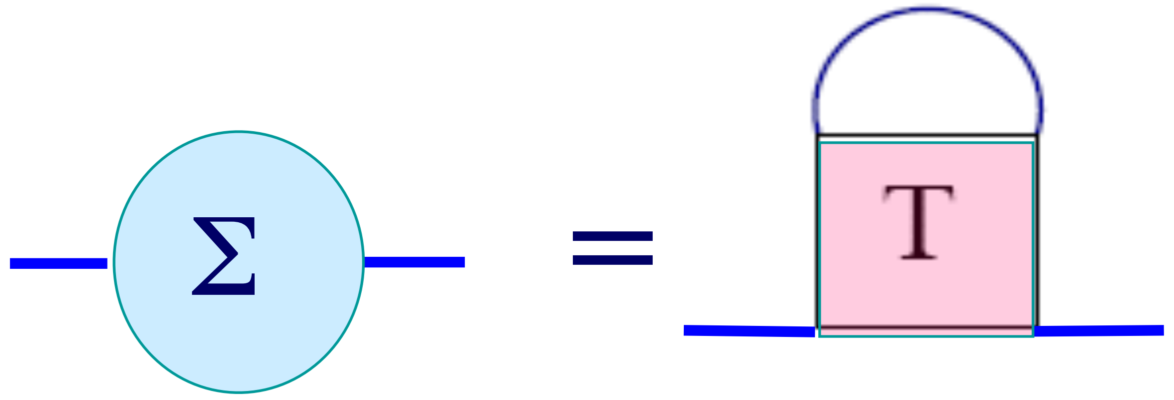
- Y. Xu, J.E. Bernhard, S.A. Bass, M. Nahrgang & G-Y. Qin: Phys. Rev. C97 (2018) 014907
- W. Ke, Y. Xu & S.A. Bass: Phys. Rev. C98 (2018) 064901

T-Matrix formalism for heavy quark interactions (TAMU)

Q



i=q,g

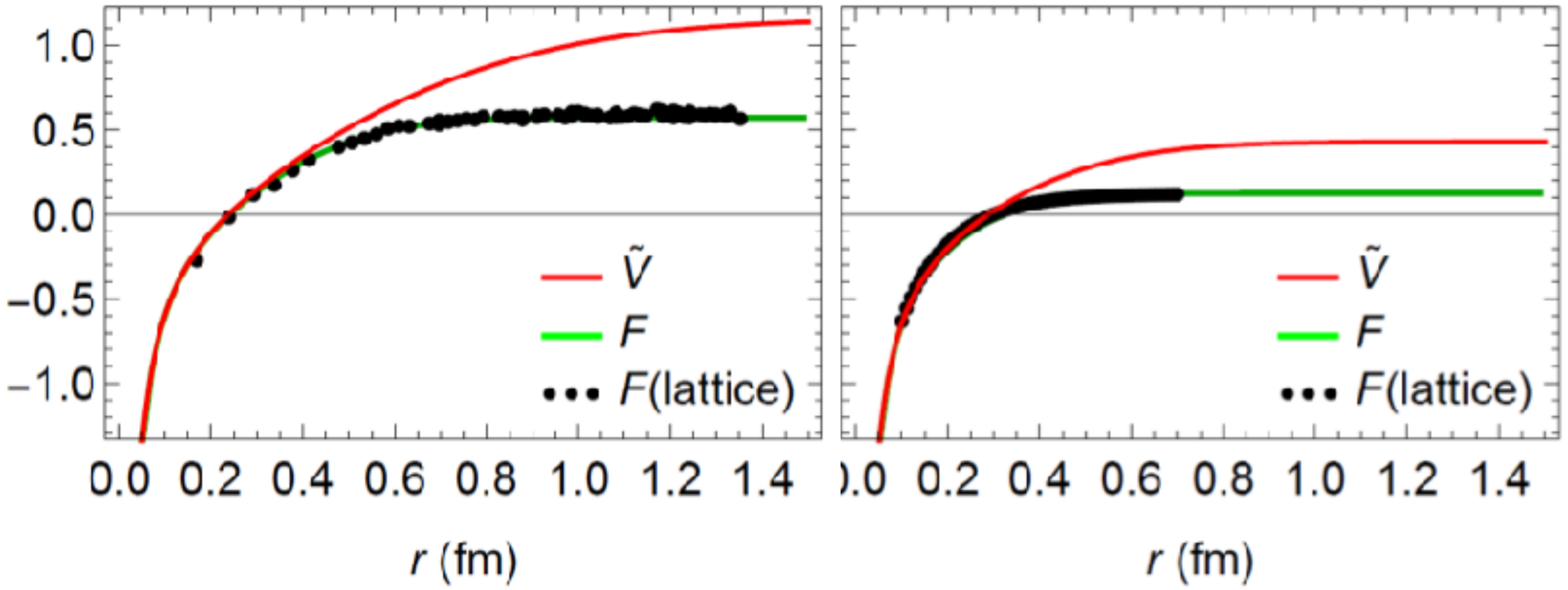


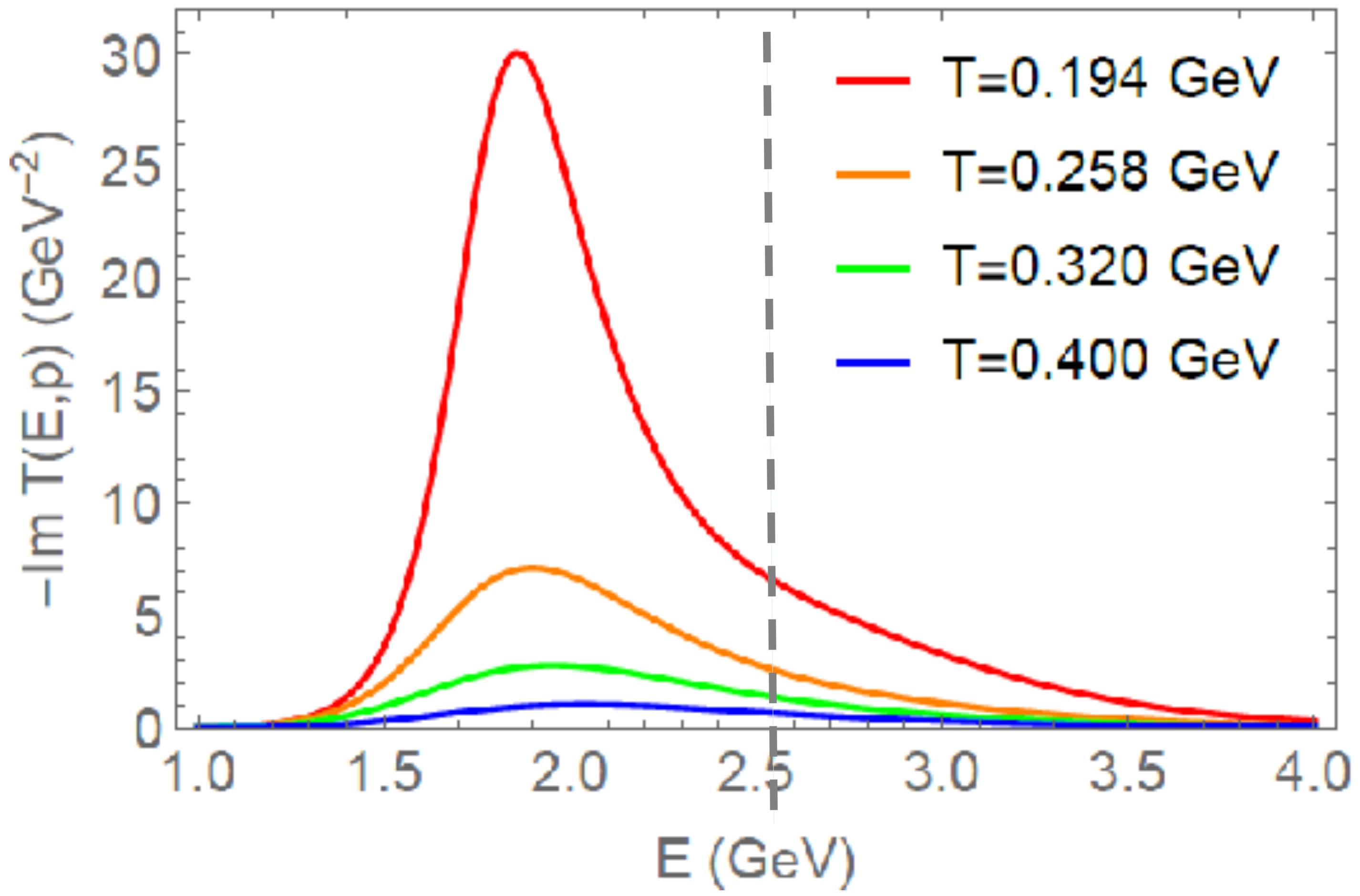
- **strong** coupling → resummation: $T_{Qi} = V_{Qi} + \int V_{Qi}\, D_Q\, D_i\, T_{Qi}$

- **key input**: in-med **potential** V_{Qi} ,

  constrained by lattice QCD

  → "string" force above T_c





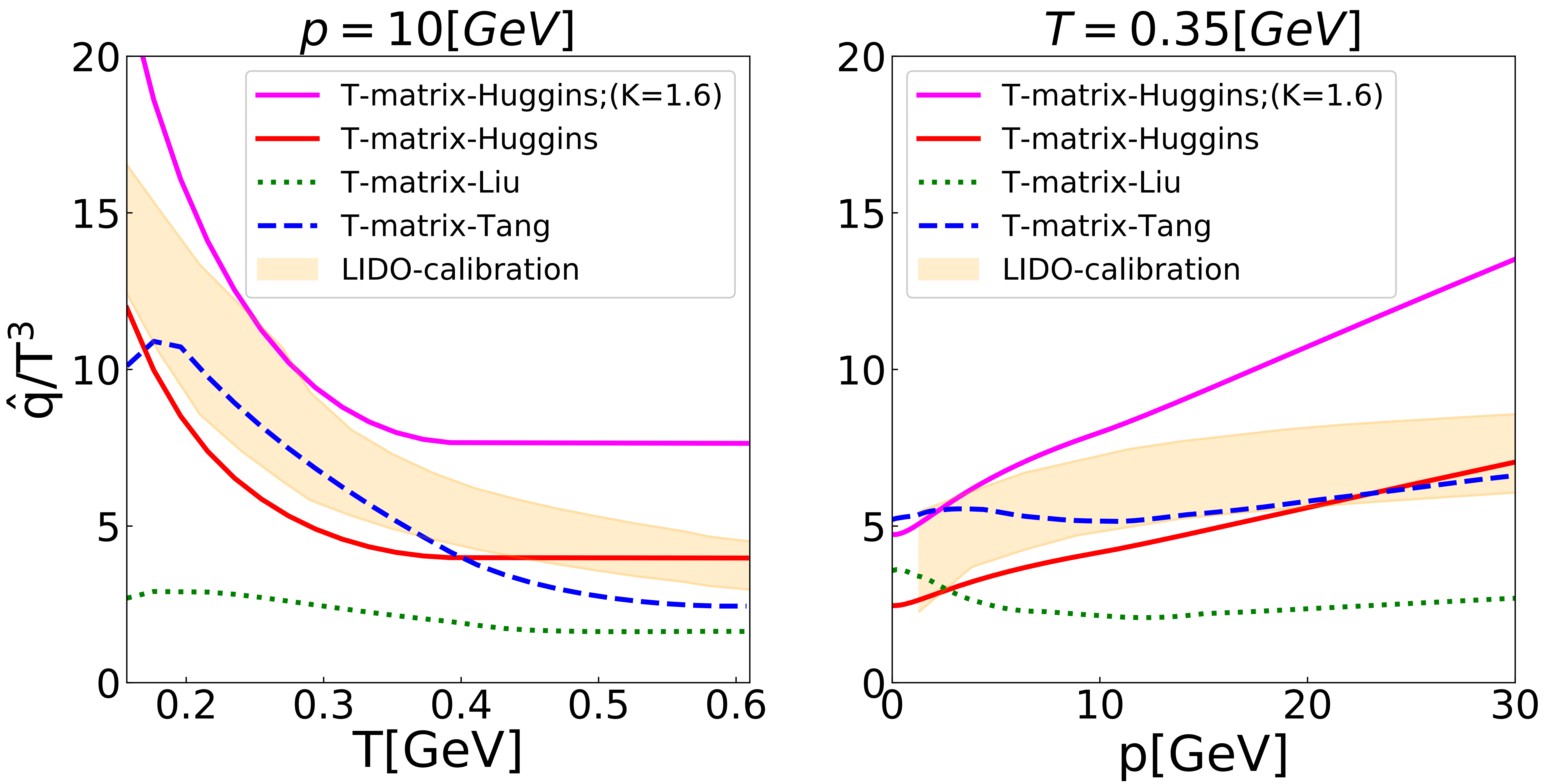
- Non-perturbative effects:
  - thermalization time $\tau_c \approx$ **3-4 fm/c**
  - **hadronization**

- K. Huggins & R. Rapp: Nucl. Phys. A896 (2012) 24-45
- S.Y.F. Liu & R. Rapp: Phys. Rev. C106 (2022) 055201
- Z. Tang, S. Mukherjee, P. Petreczky & R. Rapp: Eur. Phys. Journal A60 (2024) 92

Transport as bridge between theory and data

Two methods for establishing a connection between theory and experiment:

1. Theory to Data: calculate transport coefficients, run evolution model, compare prediction to data
2. Data to Theory: parametrize transport coefficient, perform Bayesian calibration on data



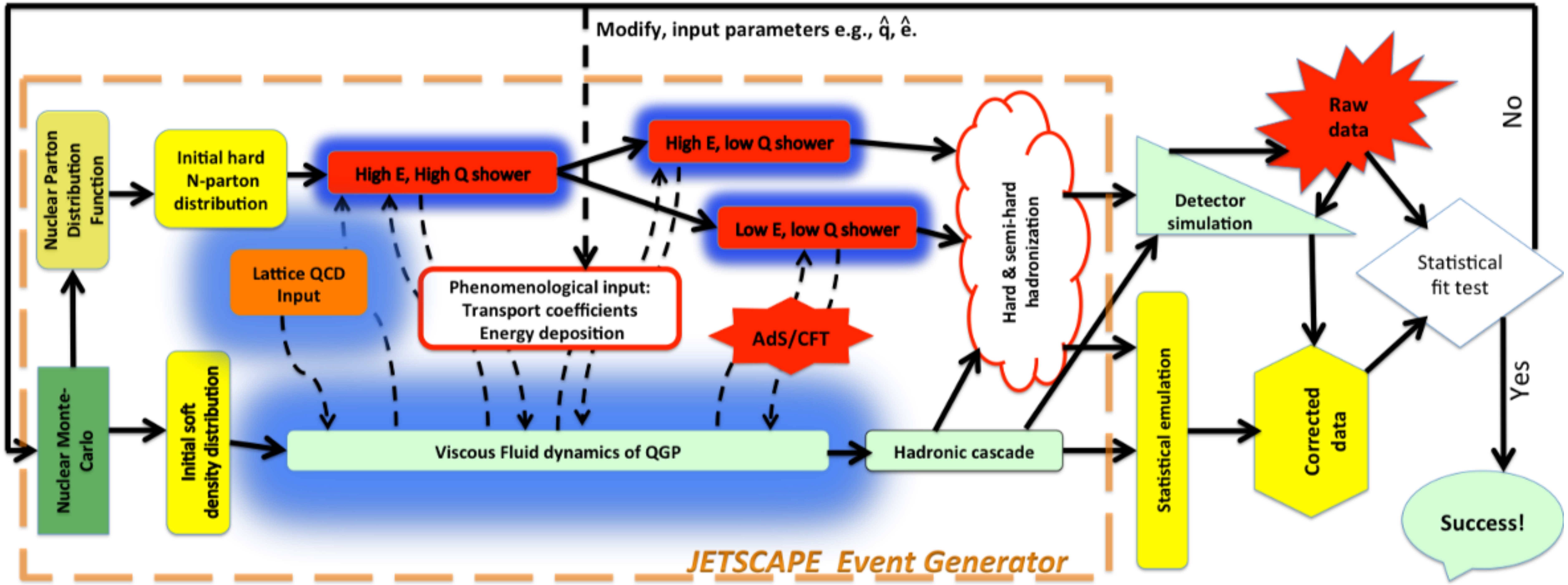
- comparison of theory-calculated transport coefficient to the calibration extraction allows for a quick assessment on whether the theory will be able to describe the data

- HEFTY collaboration: manuscript in preparation

The Jetscape framework

JETSCAPE: **J**et **E**nergy Loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvolope

- provide a tool (modular software library) to study the physics of energy-loss
- large area of research, many different approaches exist, no single group or PI has the capability to do them all
- collaboration of theoretical and experimental physicists, computer scientists and statisticians



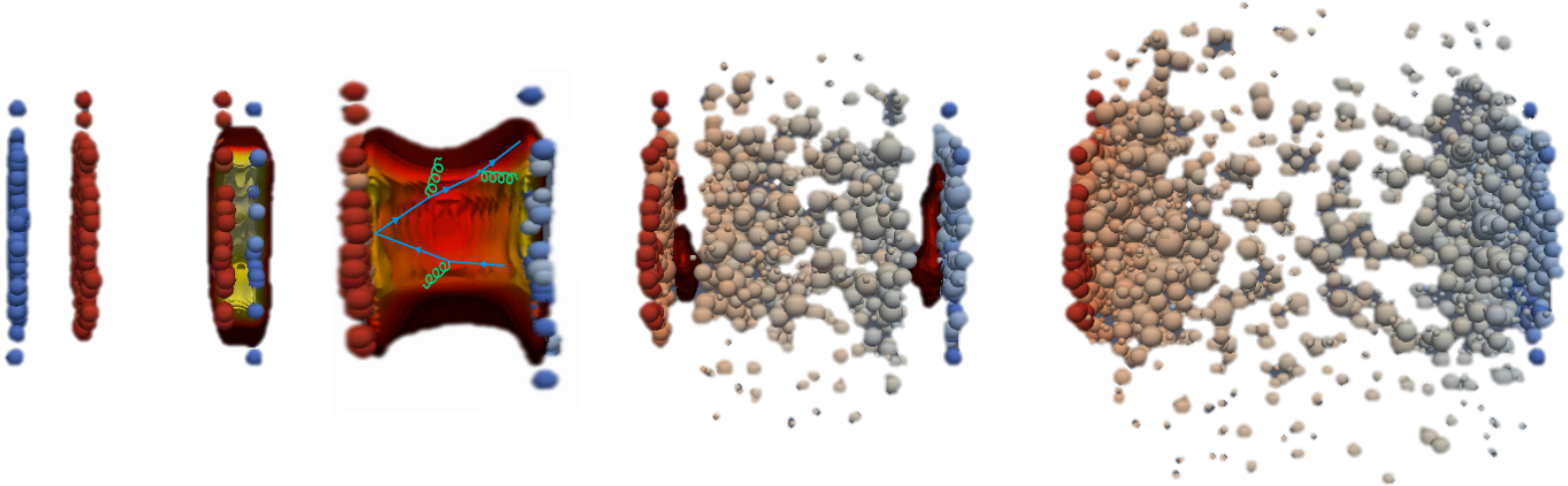
- Trento (2+1) + free Streaming
- Medium evolution:
  - MUSIC (2+1, 3+1),
  - external reader
  - brick
  - Gubser
- Pythia8 (parton gun, string fragmentation)
- MATTER
- Martini
- AdS/CFT
- LBT
- Cooper Frye
- SMASH
- Custom and HepMC output

- JETSCAPE package interfaces with leading community tools that are publicly available and well-tested
- additional functions and codes can be linked as external modules (e.g. Lido) or utilize the framework for their own energy-loss kernel (e.g. Tequila)

Heavy-Flavor Theory for QCD Matter (HEFTY)

Ralf Rapp, Steffen A. Bass, Thomas Mehen, Swagato Mukherjee, Peter Petreczky, Jianwei Qiu, Mike Strickland, Ivan Vitev, Ramona Vogt, Yen-Jie Lee, Xin Dong and Anthony Frawley

Concluding remarks



- Transport models are versatile tools to connect final state data to underlying physics phenomena and to extract physical quantities not directly accessible via measurements
- Transport theory provides a rich set of concepts to design models for the different epochs and regimes of excited QCD matter created in (relativistic) heavy-ion collisions
- Statistical tools (Bayesian analysis, ML) are crucial for model calibration and uncertainty quantification
- The future is bright - many more exciting applications, analyses and results to come!

The End

Transport Model vs. Monte-Carlo:

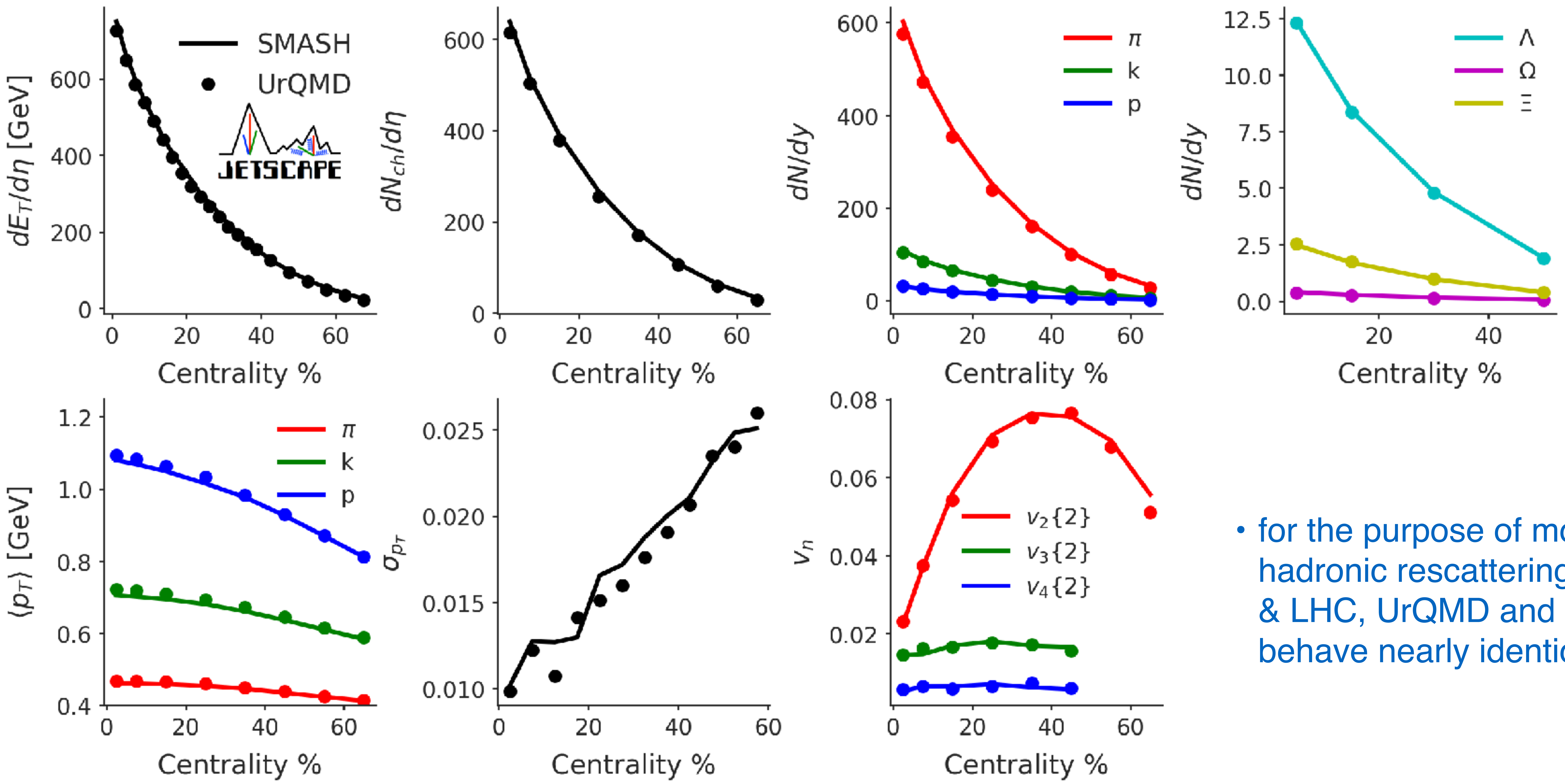
- A transport model is based on some underlying physics model - this is not necessarily the case for a Monte-Carlo

- A Monte-Carlo is designed to describe data under some specific contraints/assumptions. The way it accomplishes this does not necessarily rely on an underlying physics model, instead it can directly parametrize the desired output and/or generate it from sampling some pre-determined distribution.

- The goal of constructing a transport model is to test its underlying assumptions via a comparison to data and gaining physics insight from such a comparison whereas a Monte-Carlo often is utilized as a stand-in for real data.

- A transport model may utilize monte-carlo techniques for sampling of its physics processes.

Macro + Micro Hybrid: hadronic afterburner comparison



- for the purpose of modeling hadronic rescattering at RHIC & LHC, UrQMD and SMASH behave nearly identical

- D. Everett et al.: Phys Rev C103 (2021) 054904

Energy-Loss in Matter/LBT

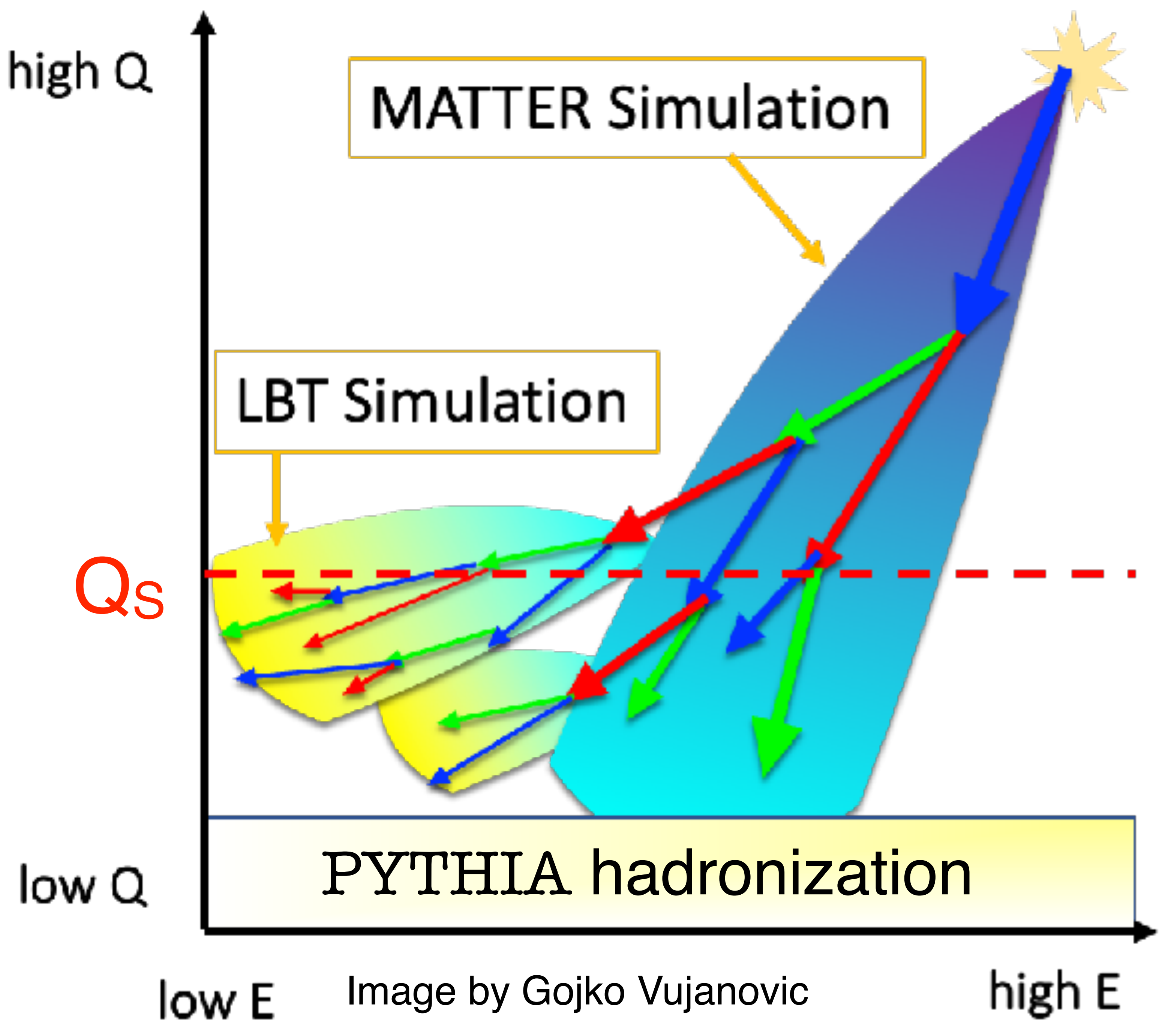
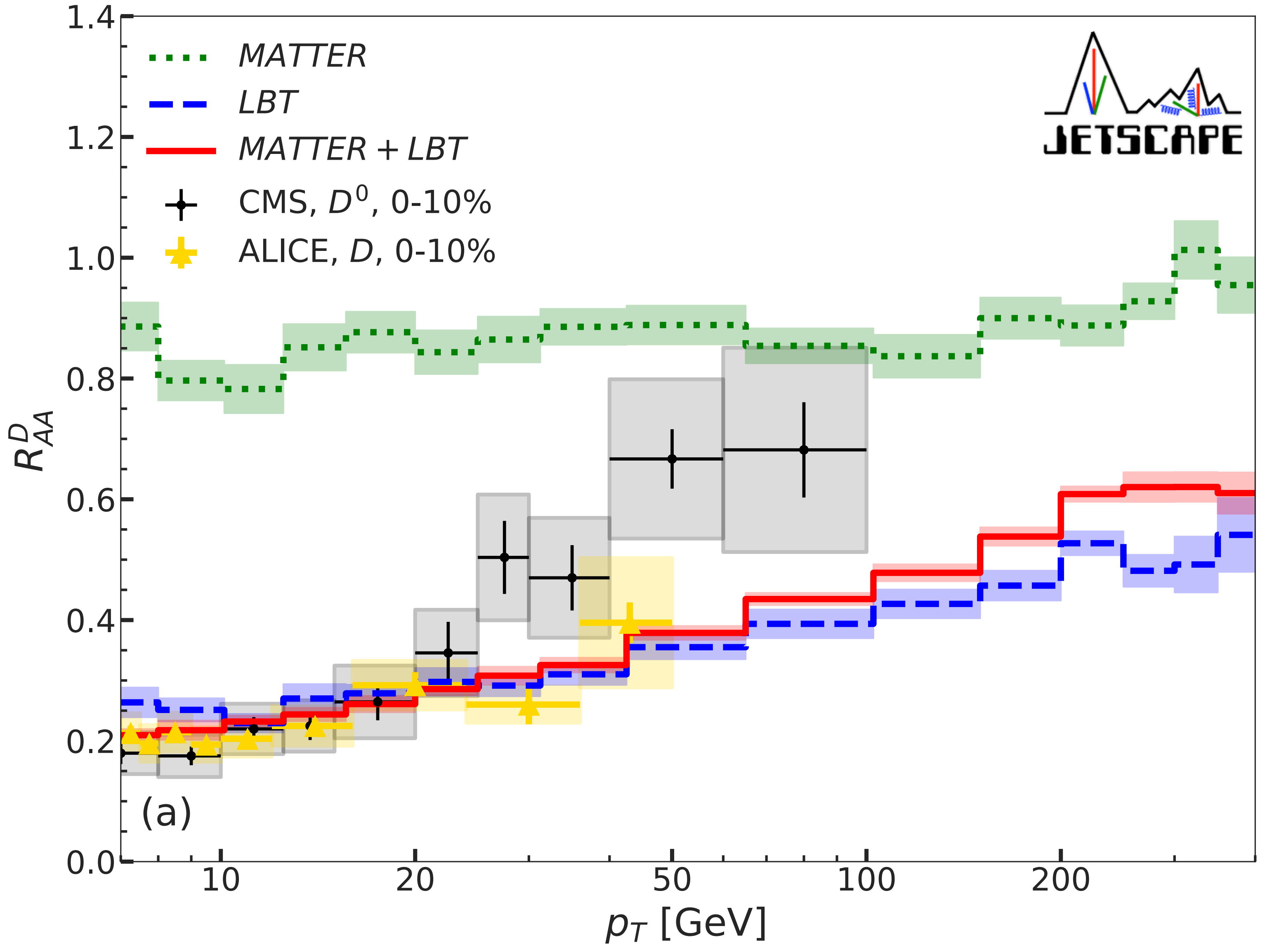


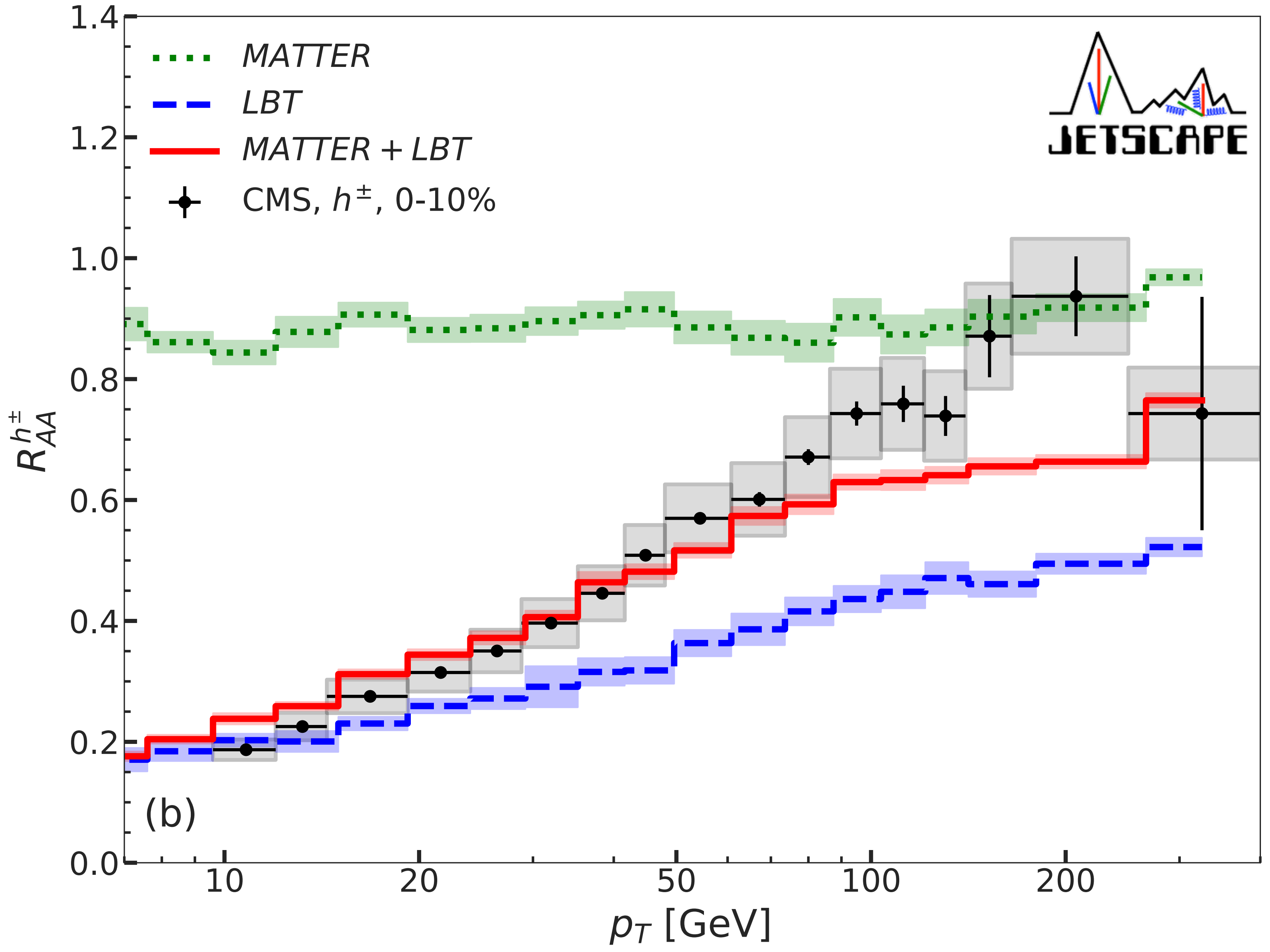
Image by Gojko Vujanovic

- Matter/LBT is embedded into the Jetscape framework that provides a calibrated hydro evolution and initial state
- LBT on-shell parton evolution dominates for D-mesons while Matter evolution is necessary for a good description of charged hadron data

- high virtuality **in medium** parton showering is solved by the Matter model which employs the Higher Twist formalism. It generates a virtuality ordered shower with splittings above Q ≫ Q_0
- low virtuality parton showering is solved via a Linearized Boltzmann Transport (LBT model):

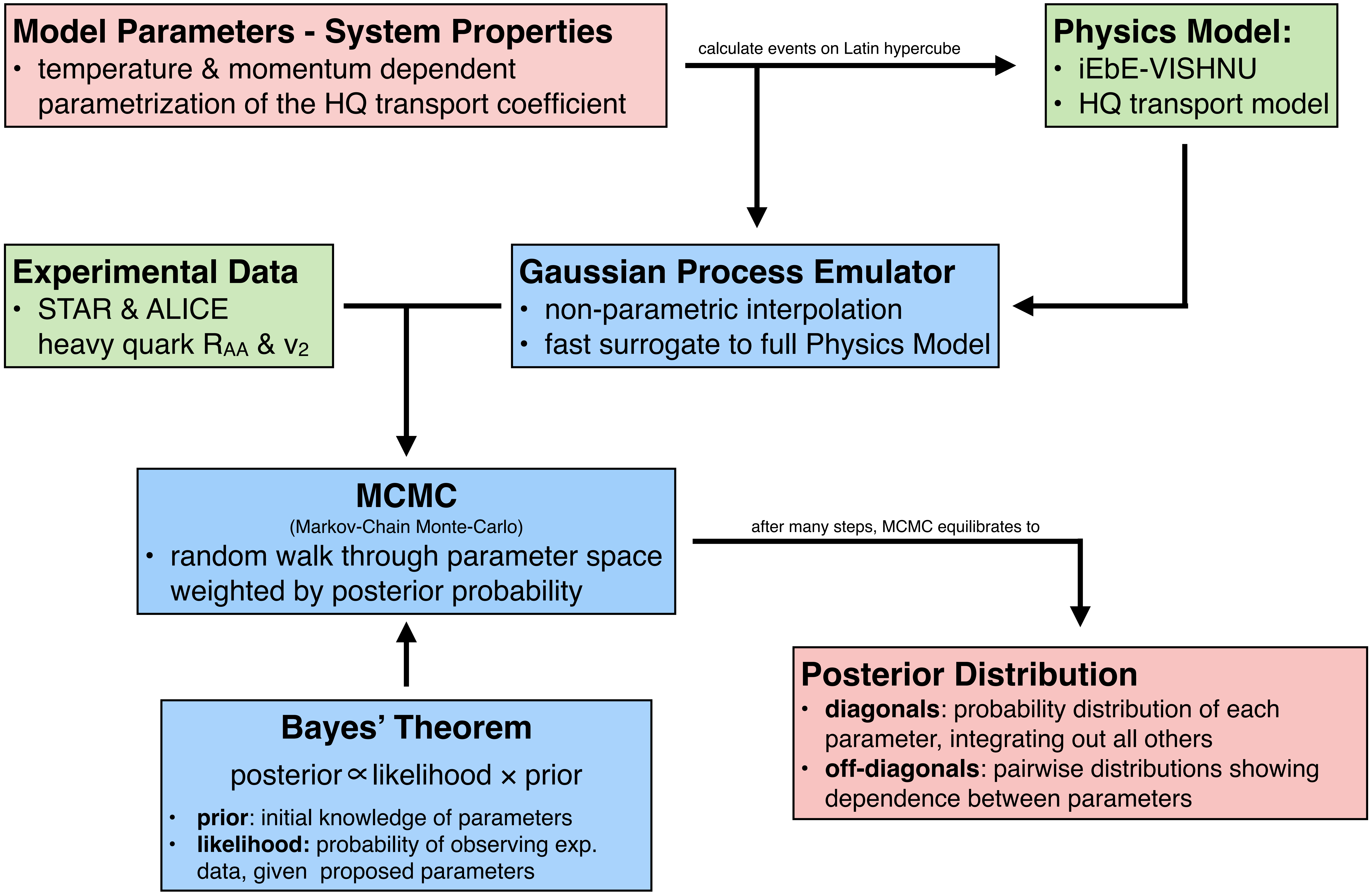
$$p_1^\mu \partial_\mu f_1(x_1, p_1) = \mathcal{C}_{\rm el}[f_1] + \mathcal{C}_{\rm inel}[f_1]$$





- W. Fan et al.: Phys. Rev. C107 (2023) 054901

Setup of a Baysian Statistical Analysis:



Calibration

Vector of input parameters: $\mathbf{x}=[p,k,w,(\eta/s)_{min},(\eta/s)_{slope},(\zeta/s)_{norm},T_{sw}]$

- assume true parameters $\mathbf{x}_\star$ exist ⇒ find probability distribution for $\mathbf{x}_\star$

Bayes' Theorem: $P(\mathbf{x}_\star | X,Y,\mathbf{y}_{exp}) \propto P(X,Y,\mathbf{y}_{exp} | \mathbf{x}_\star)P(\mathbf{x}_\star)$

- X: training data design points
- Y: model output on X
- $P(\mathbf{x}_\star)$ = prior
  ⇒ initial knowledge of $\mathbf{x}_\star$
- $P(X,Y,\mathbf{y}_{exp} | \mathbf{x}_\star)$ = likelihood
  ⇒ probability of observing $(X,Y,\mathbf{y}_{exp})$ given proposed $\mathbf{x}_\star$
- $P(\mathbf{x}_\star | X,Y,\mathbf{y}_{exp})$ = posterior
  ⇒ probability of $\mathbf{x}_\star$ given observations $(X,Y,\mathbf{y}_{exp})$

Calibration

Vector of input parameters: $\mathbf{x}=[p,k,w,(\eta/s)_{min},(\eta/s)_{slope},(\zeta/s)_{norm},T_{sw}]$

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  ⇒ probability of $\mathbf{x}_\star$ given observations $(X,Y,\mathbf{y}_{exp})$

Markov-Chain Monte-Carlo:

- random walk through parameter space weighted by posterior
- large number of samples ⇒ chain equilibrates to posterior distribution
- flat prior within design range, zero outside
- likelihood: $\log[P(X,Y,\mathbf{y}_{exp}| \mathbf{x}_\star)] \sim -(\mathbf{y}(\mathbf{x}_\star) - \mathbf{y}_{exp})^2/(2\sigma^2)$
  - σ=0.1 on principal components (includes correlations)
- posterior ~ likelihood within design range, zero outside

Initial Conditions: Soft - Hard Correlations

QGP medium: Trento

- effective, parametric, description of entropy production prior to thermalization
- entropy deposition *dS/dy* parmeterized in terms of T_A, T_B:

$$dS/dy\,|_{\tau=\tau_0} \propto T_R(p; T_A, T_B) \equiv \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$

- choose p=0: EKRT & IP-Glasma scaling

Heavy Quarks:

- initial spatial production probability: $\propto T_A T_B$, consistent with soft QGP medium
- momentum space: use PYTHIA to generate HQ momenta