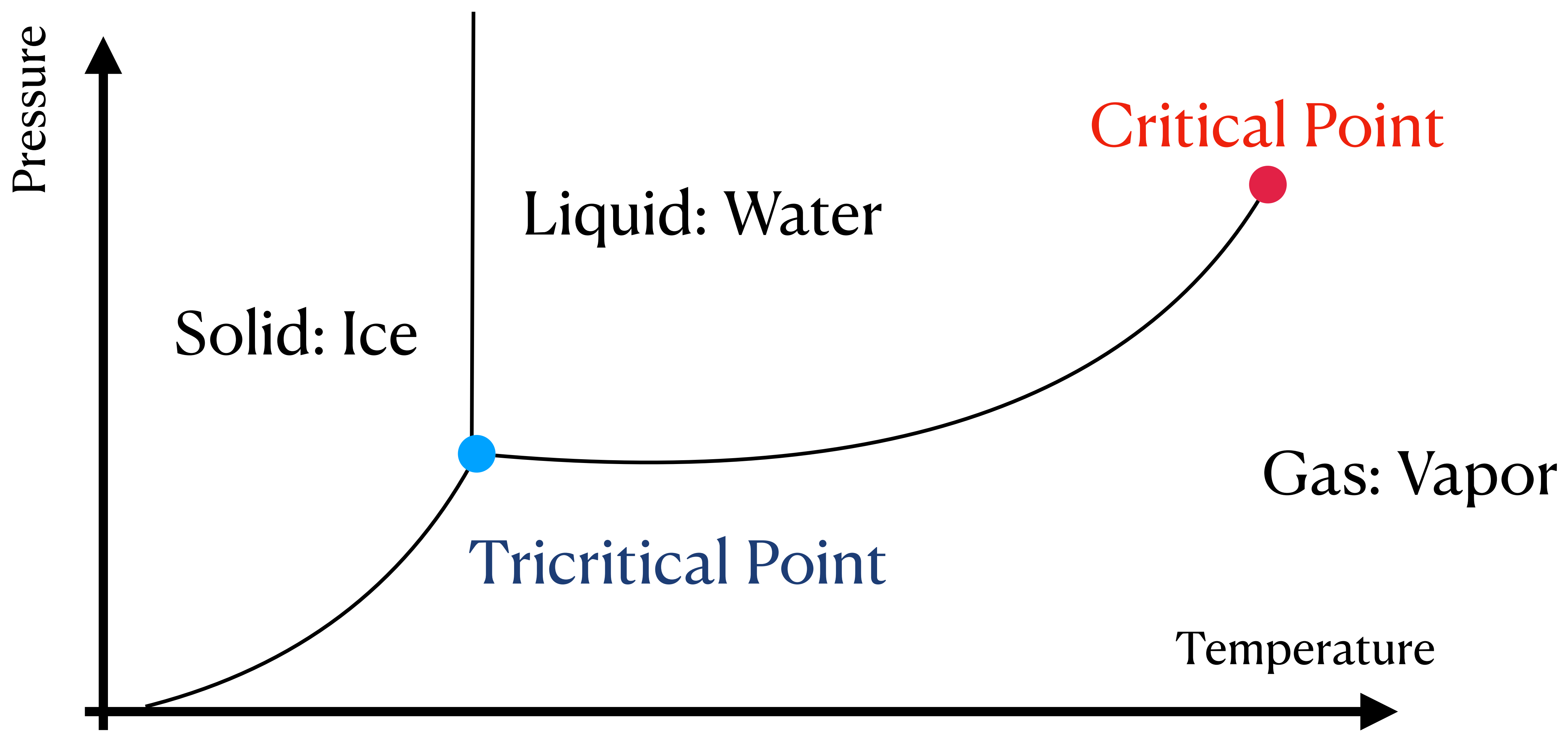
Deconfinement effects in net-proton fluctuations

FRIB

Oleh Savchuk, June 10th 2025, CIPANP2025

Introduction: Thermodynamic properties



The most basic knowledge we have about water is when it boils or when it freezes

Thermodynamics describes relation between the pressure, bulk volume, density/chemical potential and temperature.

$$\Omega(\mu, T, V) = -VP(\mu, T)$$
$$F(T, V, N) = U - TS$$

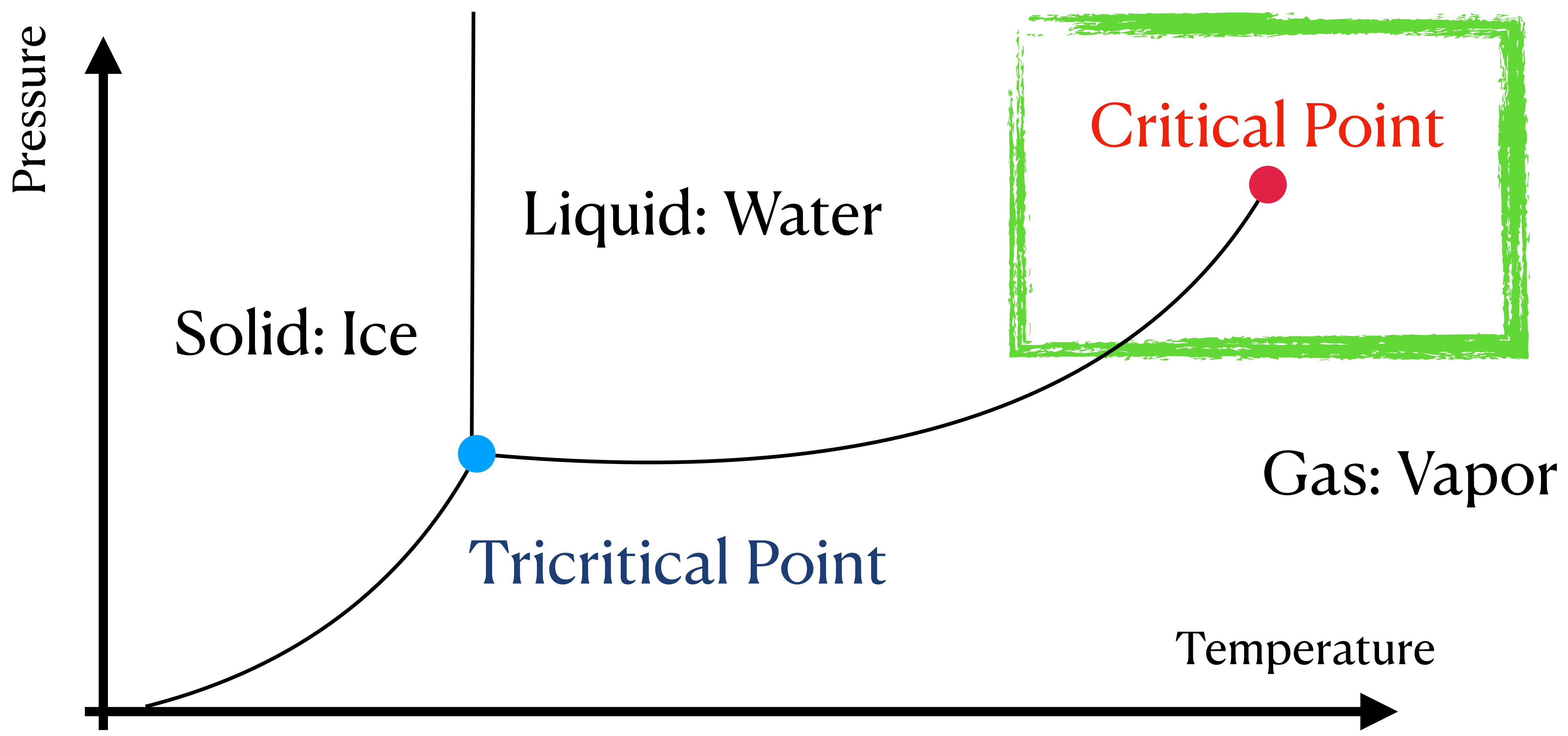
Transition from liquid to gaseous phase happens with a jump in density.
This is a case of the first order phase transition with density being first derivative of pressure:

$$n = \frac{\partial P(\mu, T)}{\partial \mu}$$

There is also a second order phase transition when the jump happens in second derivative:

$$\frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle} = \frac{\mu}{T} \frac{\partial^2 P}{\partial \mu^2}$$

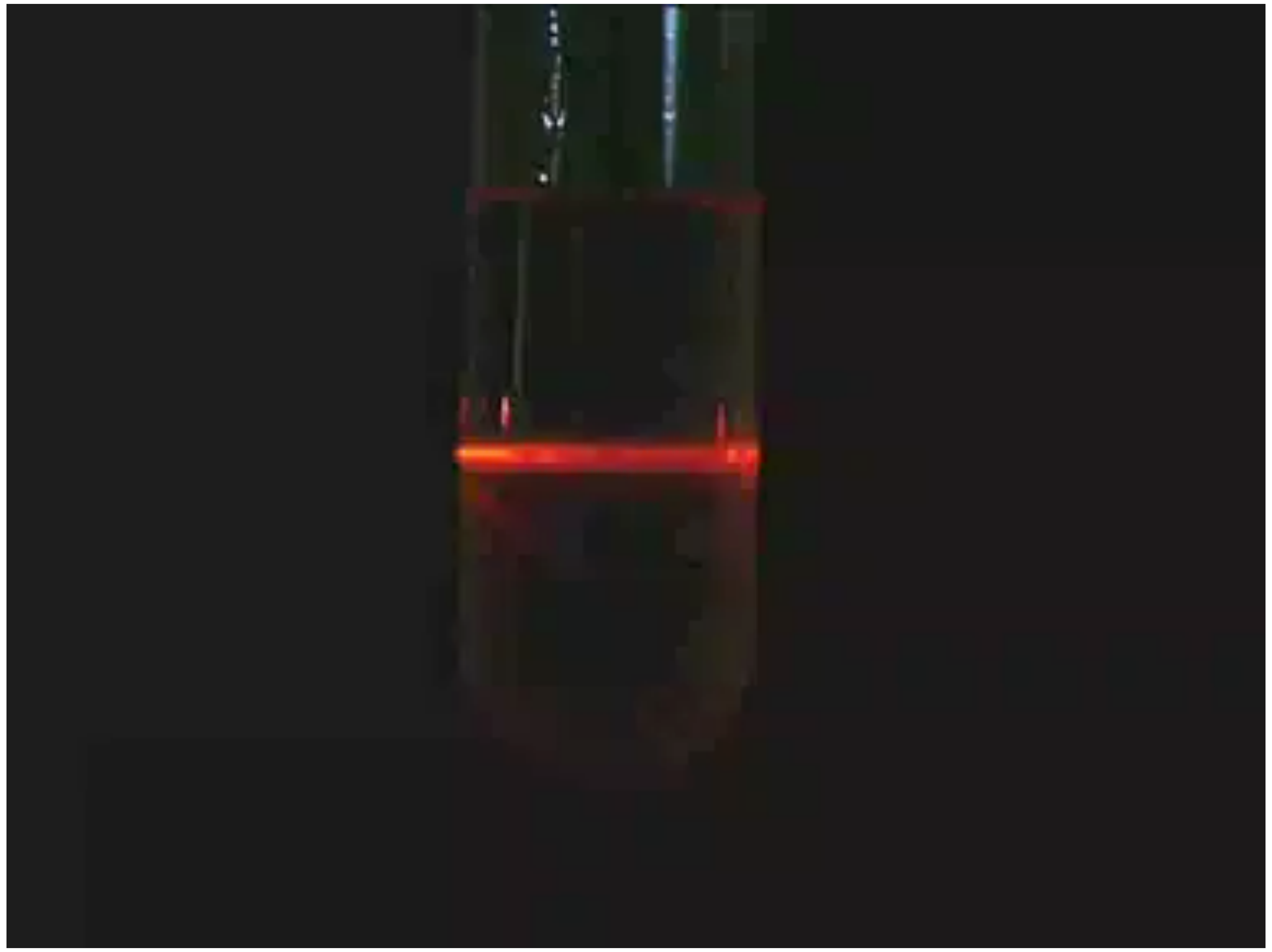
Introduction: Thermodynamic properties



Above critical point the transition between liquid and gas is smooth/continious. At the critical point interesting physics occurs.

Large fluctuations and infinite correlation length!

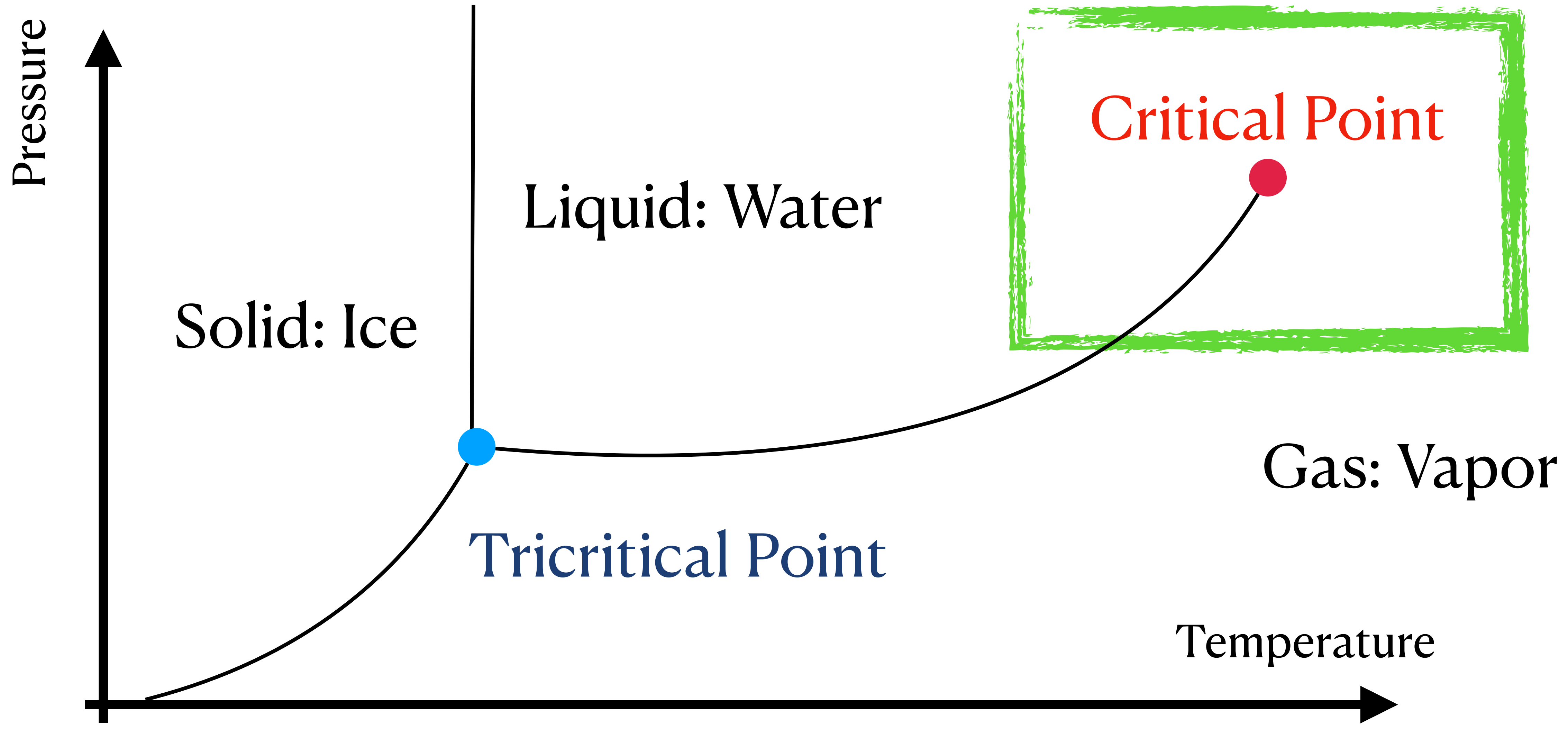
One observes critical fluctuations through critical opalescence:



[https://www.doitpoms.ac.uk/]

Scattering of light on density fluctuations of the size of the wavelength of light.

Introduction: Thermodynamic properties



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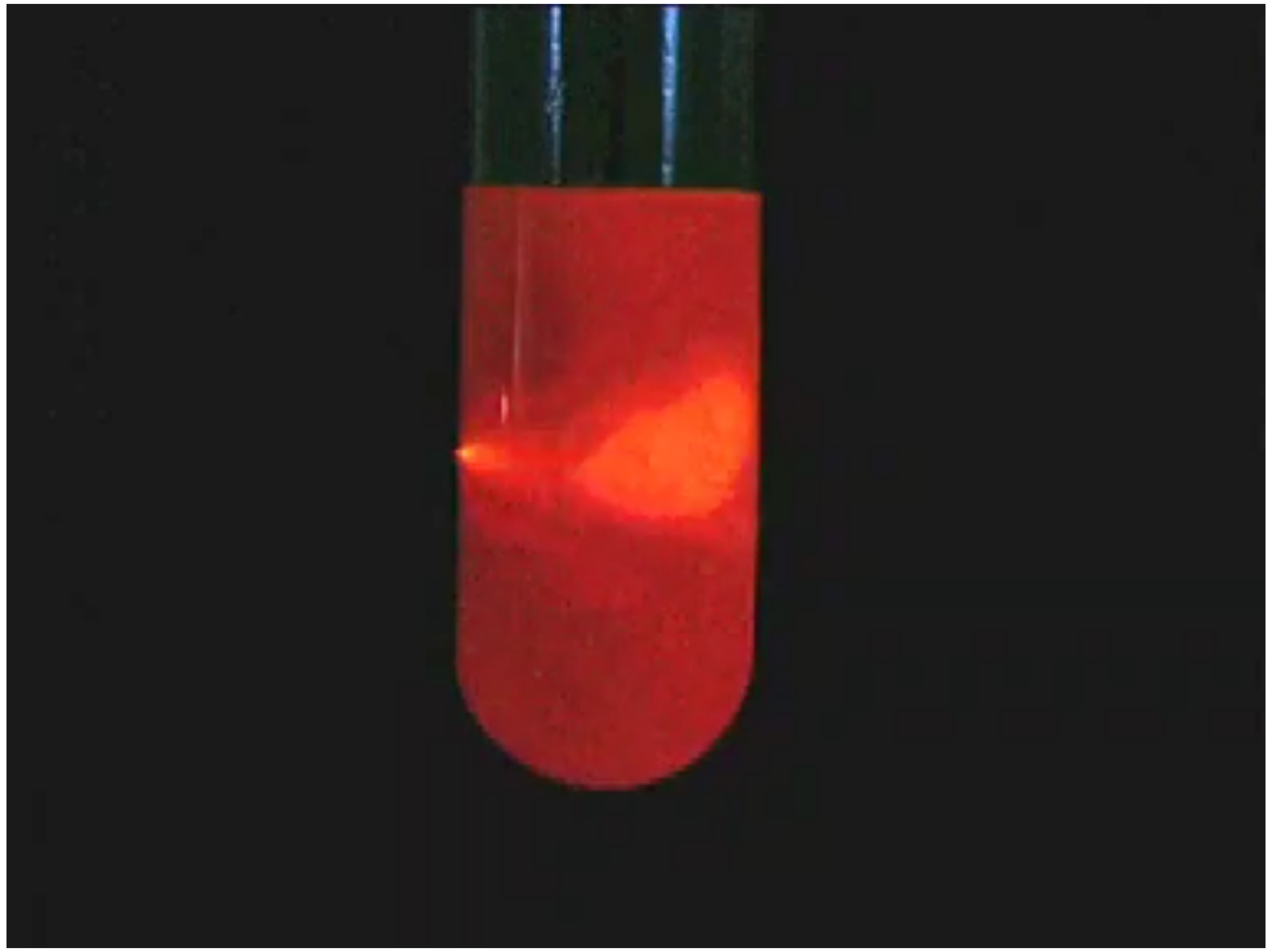

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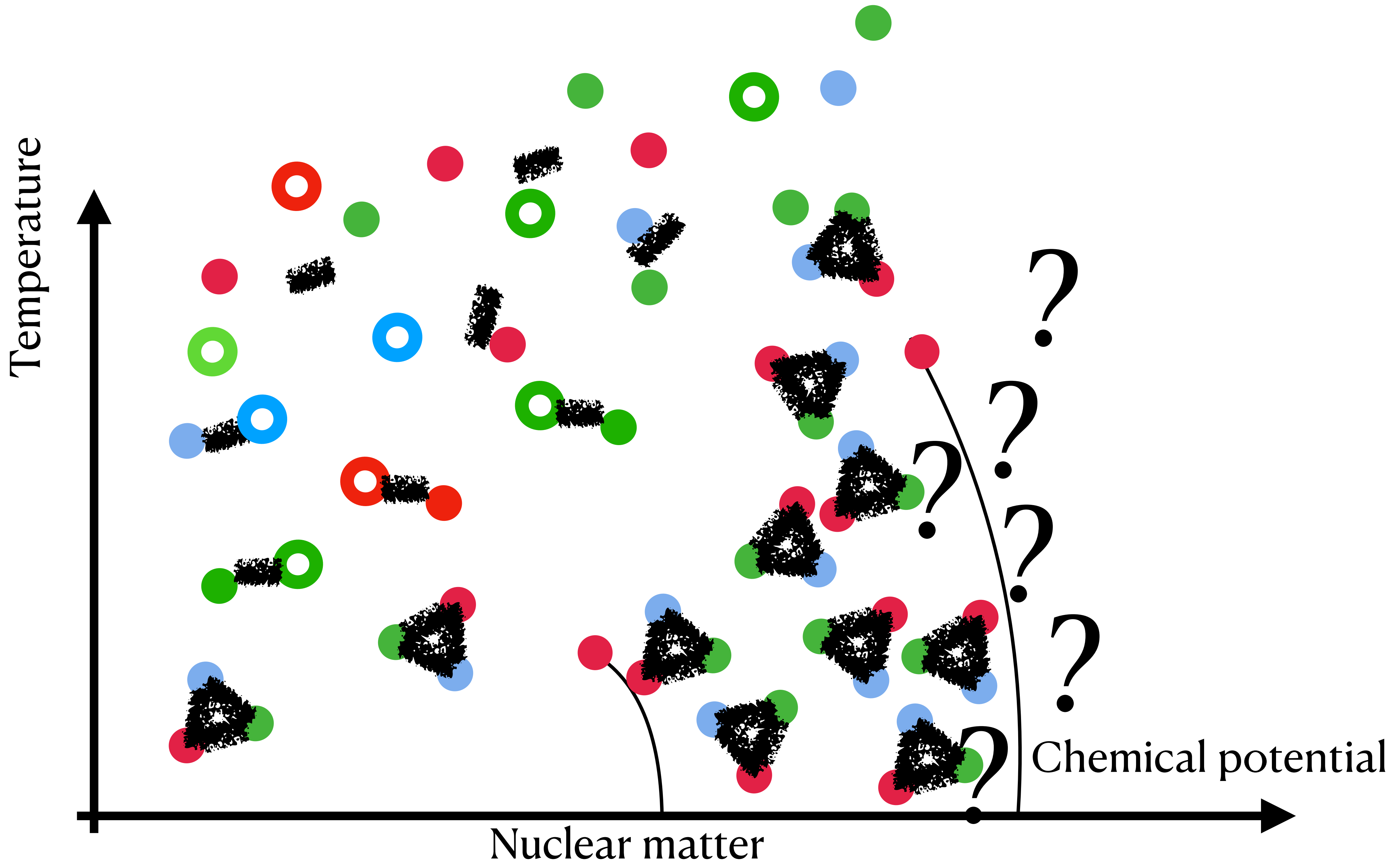
Scattering of light on density fluctuations of the size of the wavelength of light.

Introduction: QCD Critical Point



Strongly interacting matter is poorly understood.
We know that it has deconfined and confined phases.
But we know little of when and how they occur.

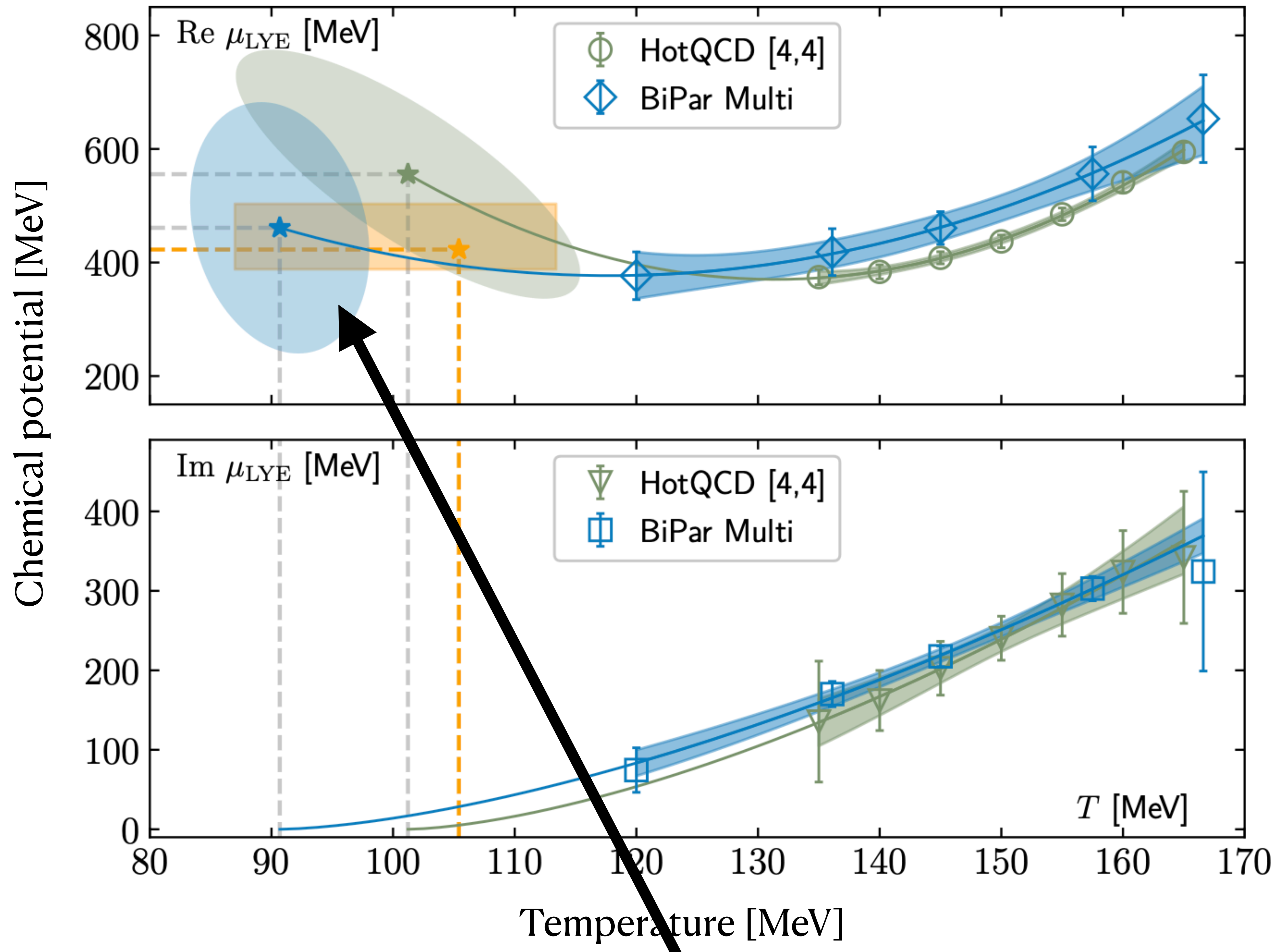
Finding Critical Point would imply existence of the first order phase transition

At the same time it is possible that critical point is easier to find by looking at signatures of criticality in a system.

Such signals might include fluctuations and correlations of conserved charges.

Introduction: QCD Critical Point

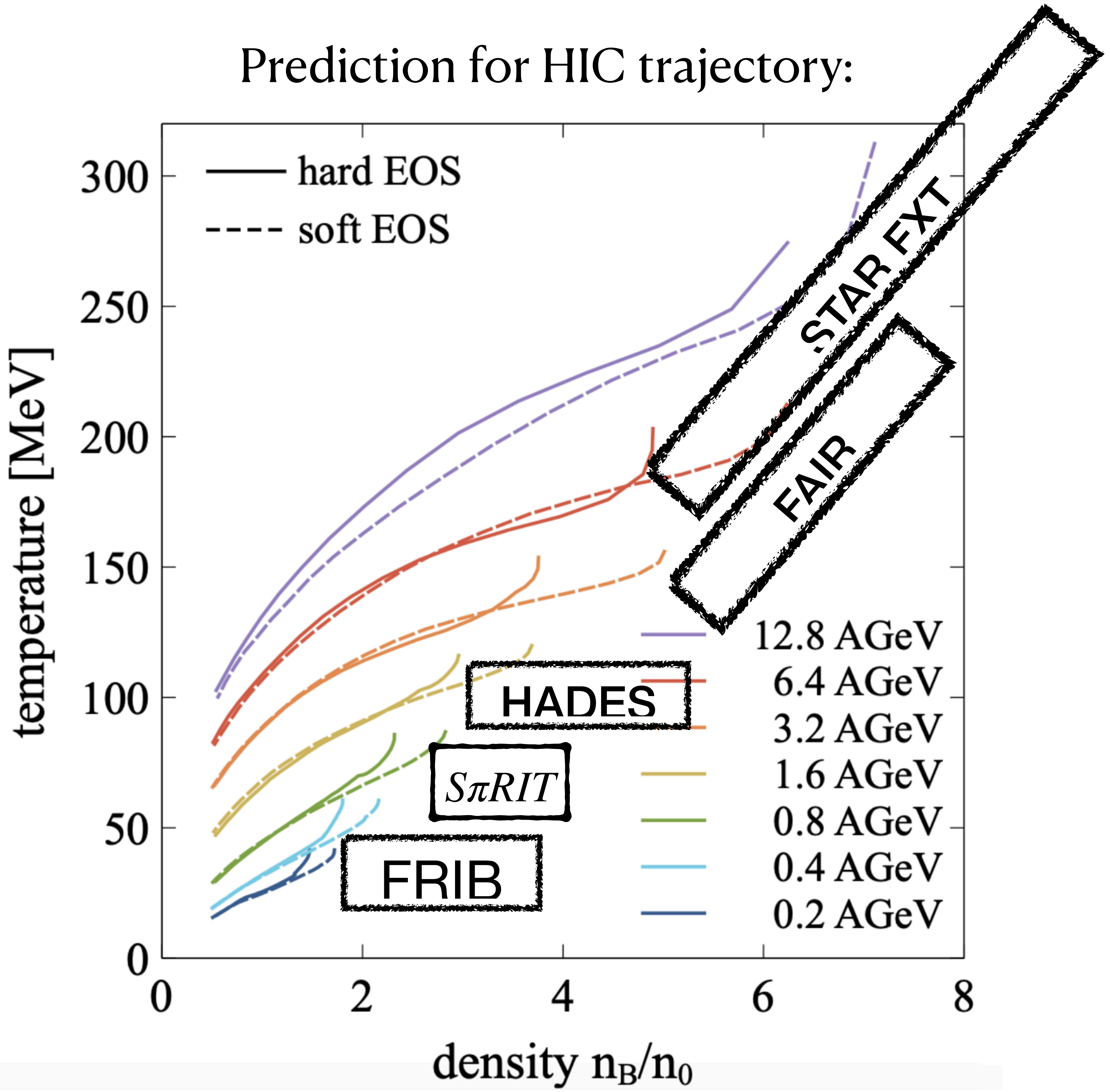
Extrapolations from lattice simulations at zero density:



[D.A. Clarke et al. (Bielefeld-Parma), arXiv:2405.10196]
also [Gokce Basar, arXiv:2312.06952]

Critical point is expected at $\frac{\mu_B}{T} = 4 - 6$

Prediction for HIC trajectory:

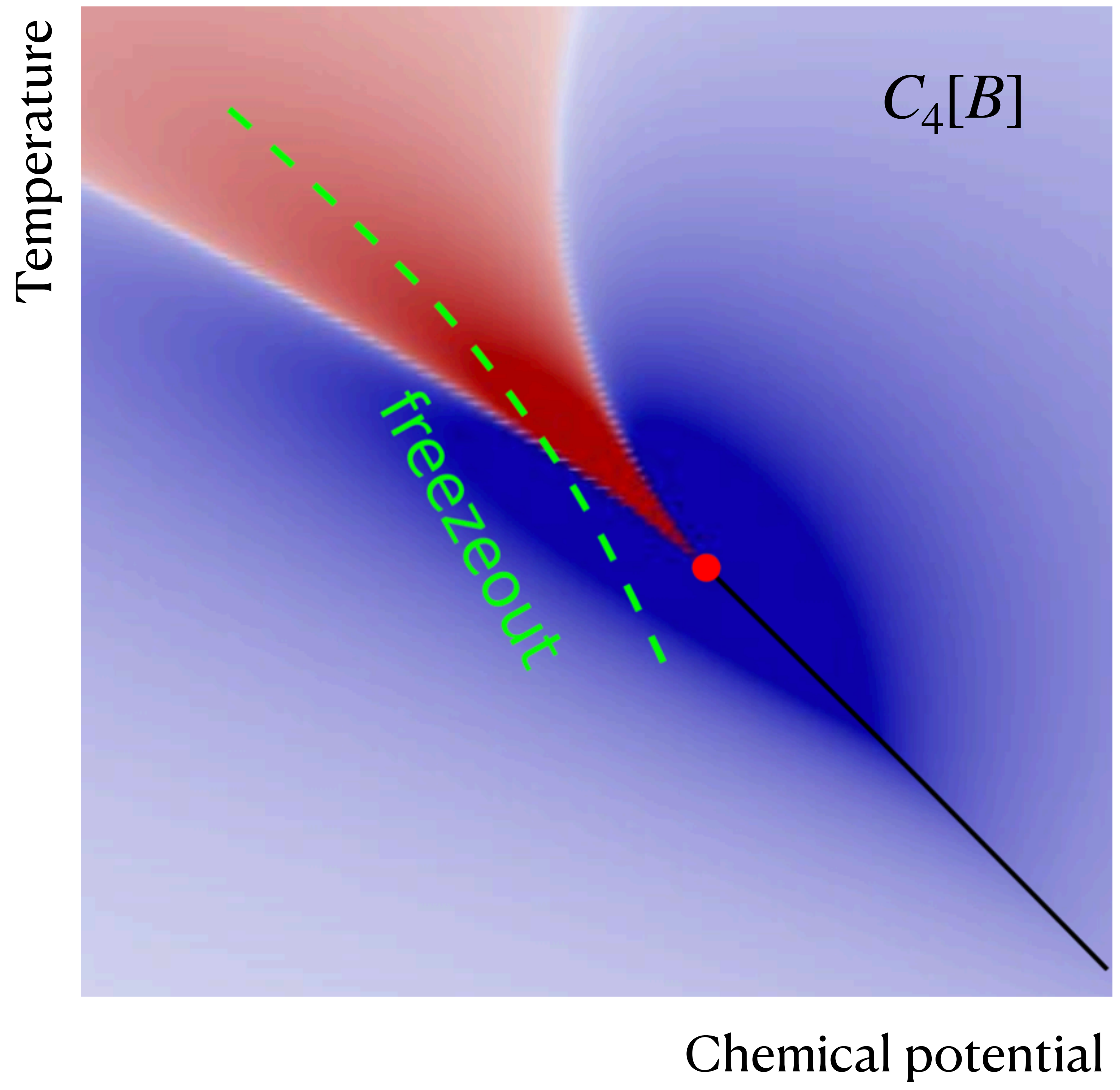


This corresponds to $E_{lab} = 6 - 14\ AGeV$

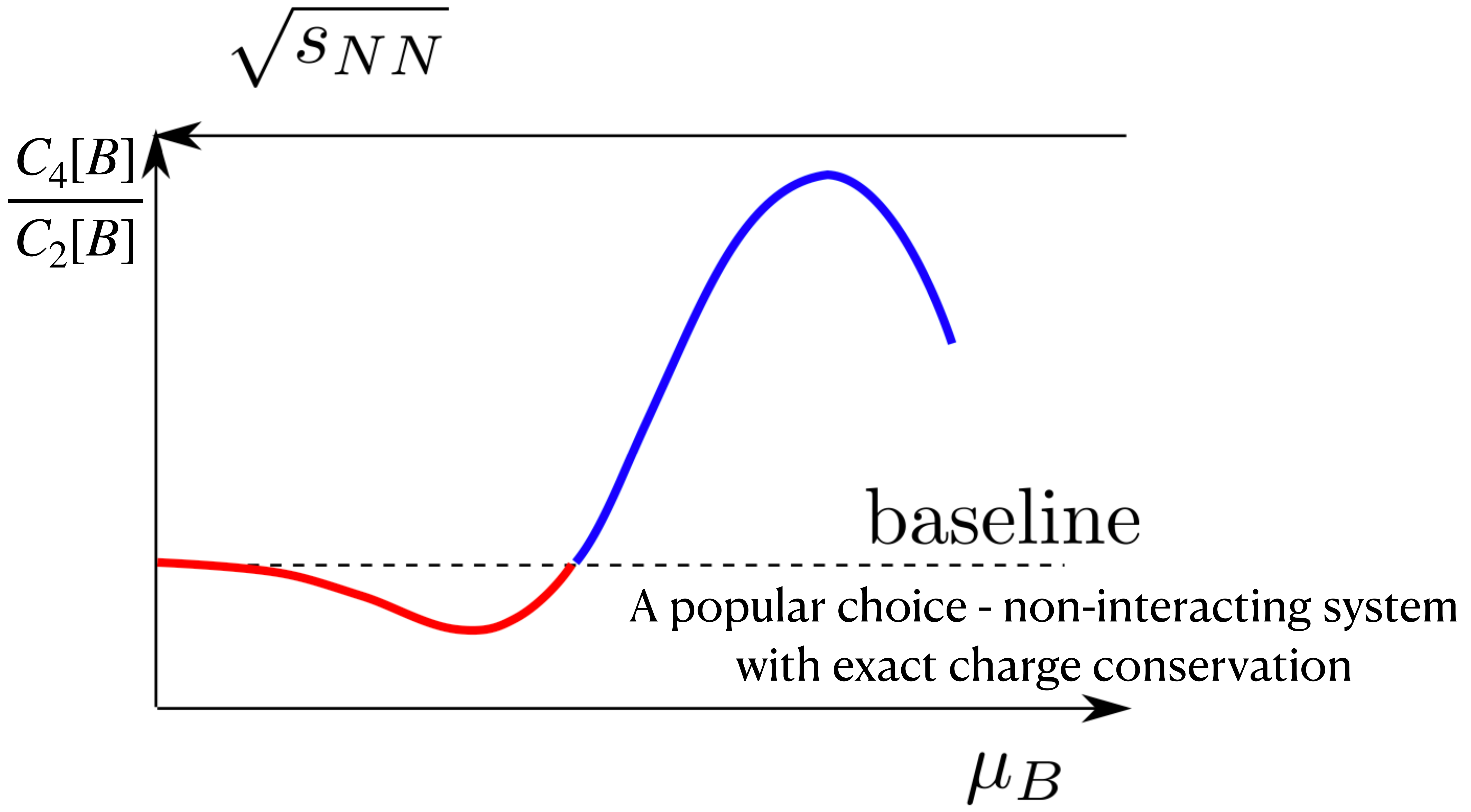
Search for CP with fluctuations

- Fluctuations of baryon charge are connected to the equation of state as cumulants:

$$C_n[B] = \frac{\partial^n \ln Z(\mu_B, T, V)}{\partial \left(\frac{\mu_B}{T}\right)^n} = VT^{n-1}\frac{\partial^n P(\mu_B, T)}{\partial \mu_B^n}$$



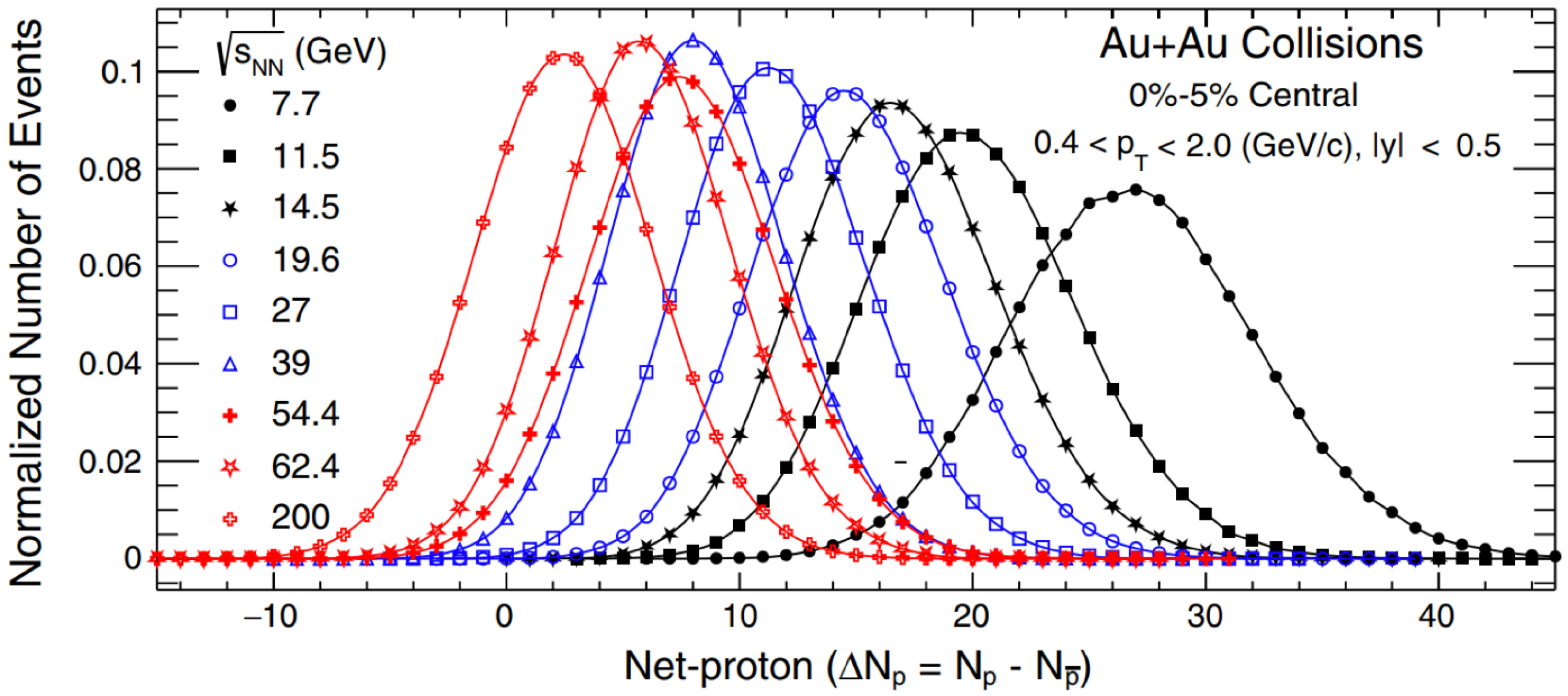
In order to add background effects one compares against baselines:

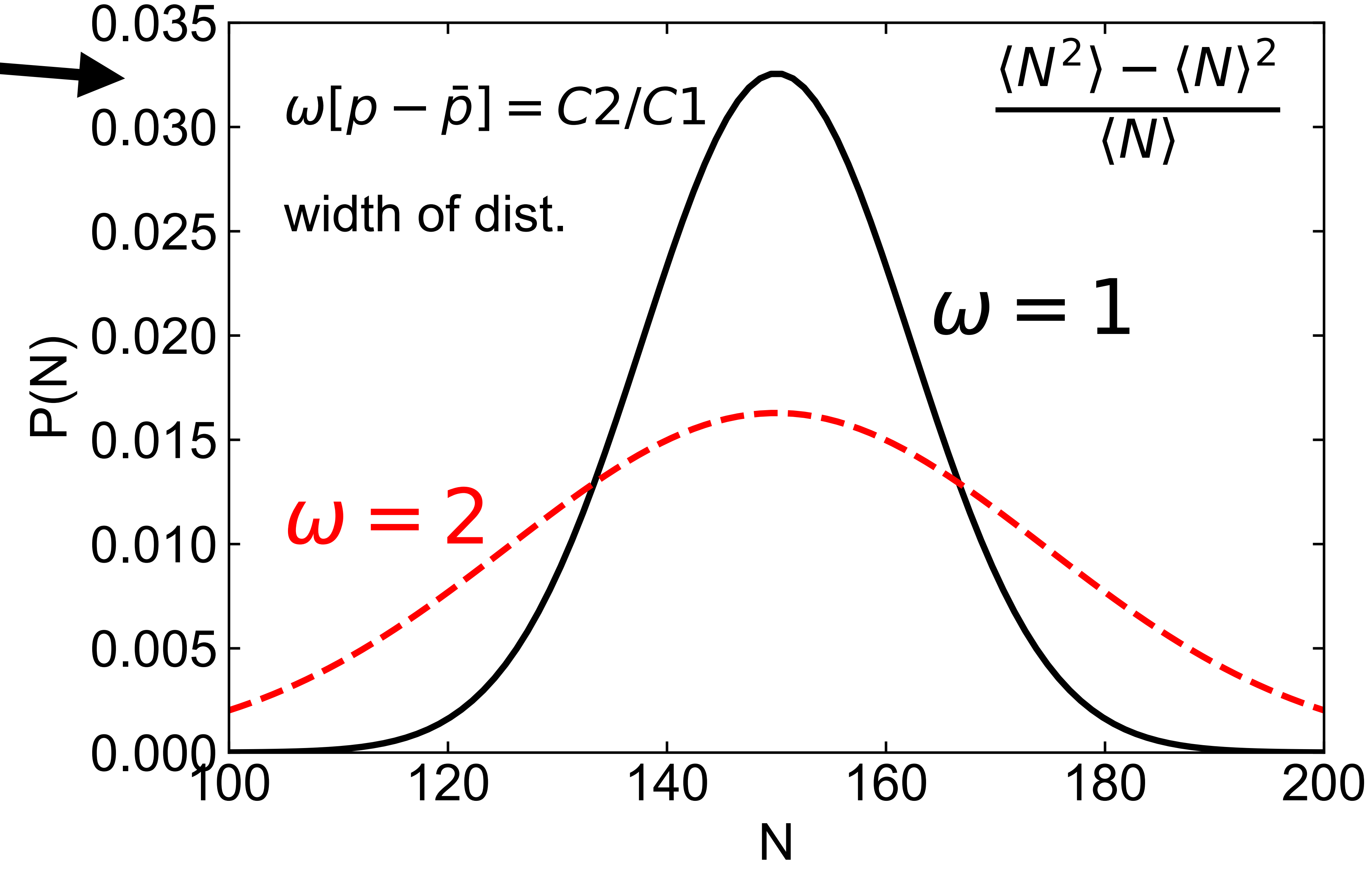


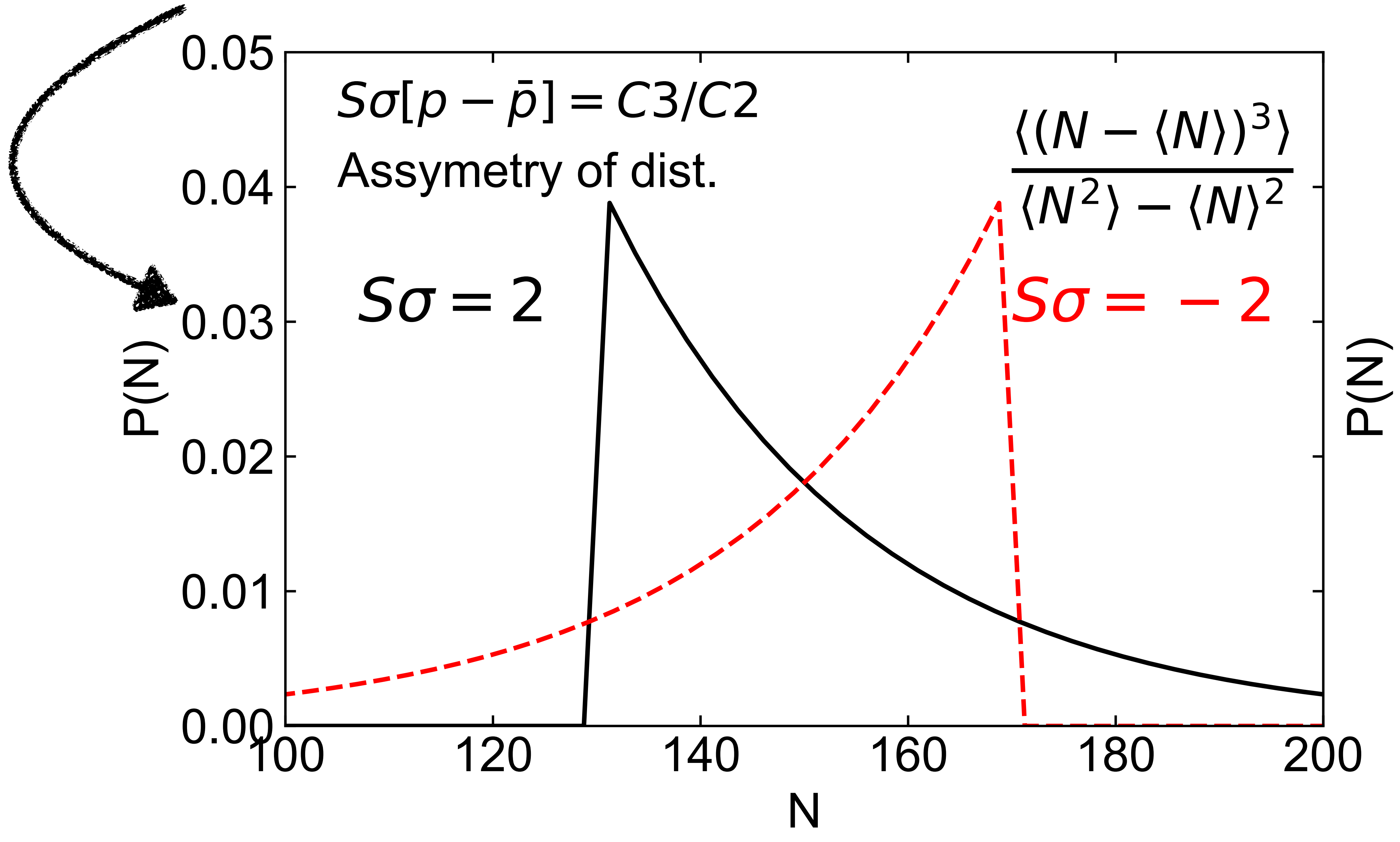
[M. Stephanov, Phys. Rev. Lett. **102**, 032301]
[Adam Bzdak, ShinIchi Esumi, Volker Koch, Jinfeng Liao, Mikhail Stephanov, Nu Xu, Physics Reports 853 (2020) pp. 1–87]

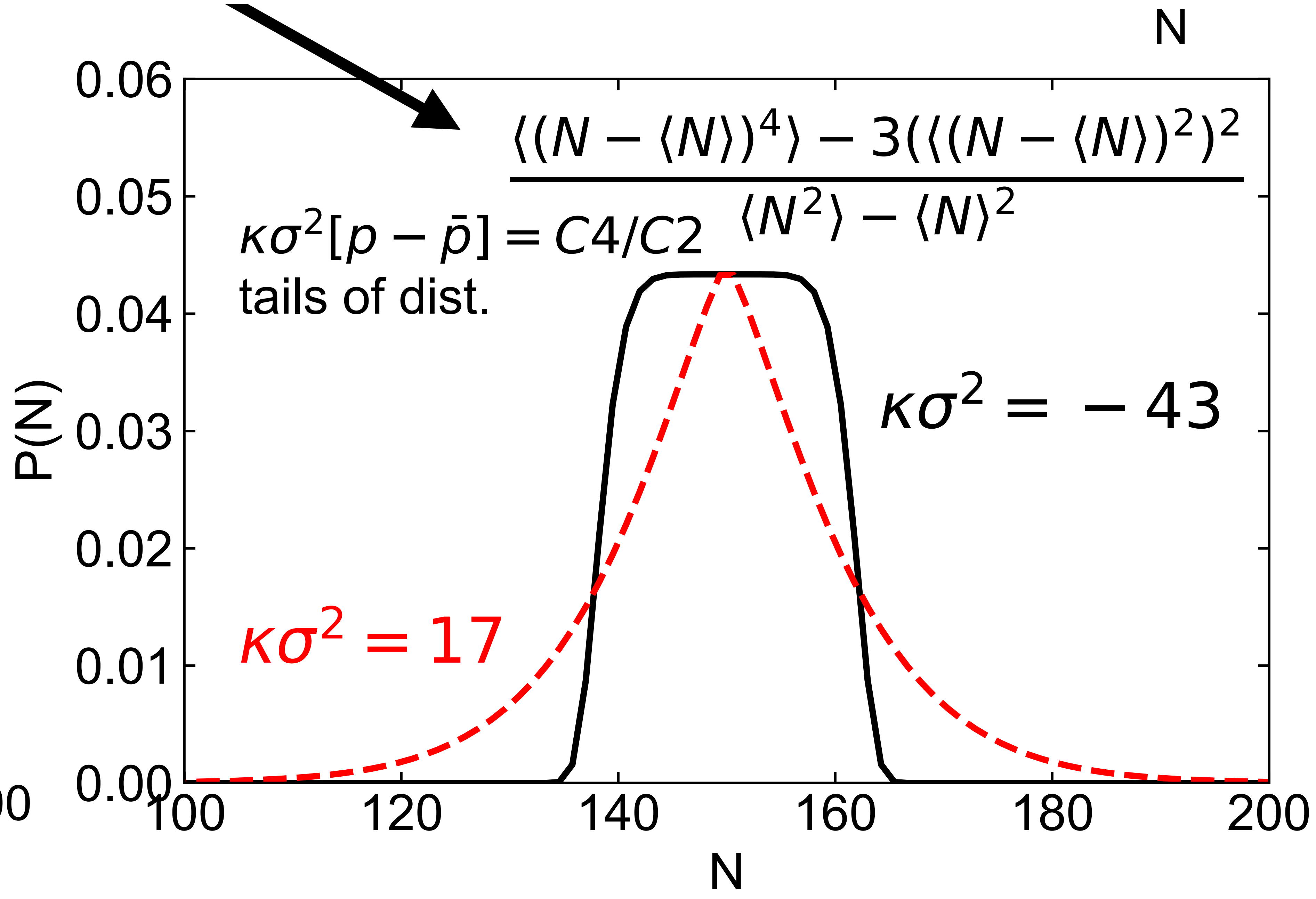
Cumulants of net-proton number

STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021)

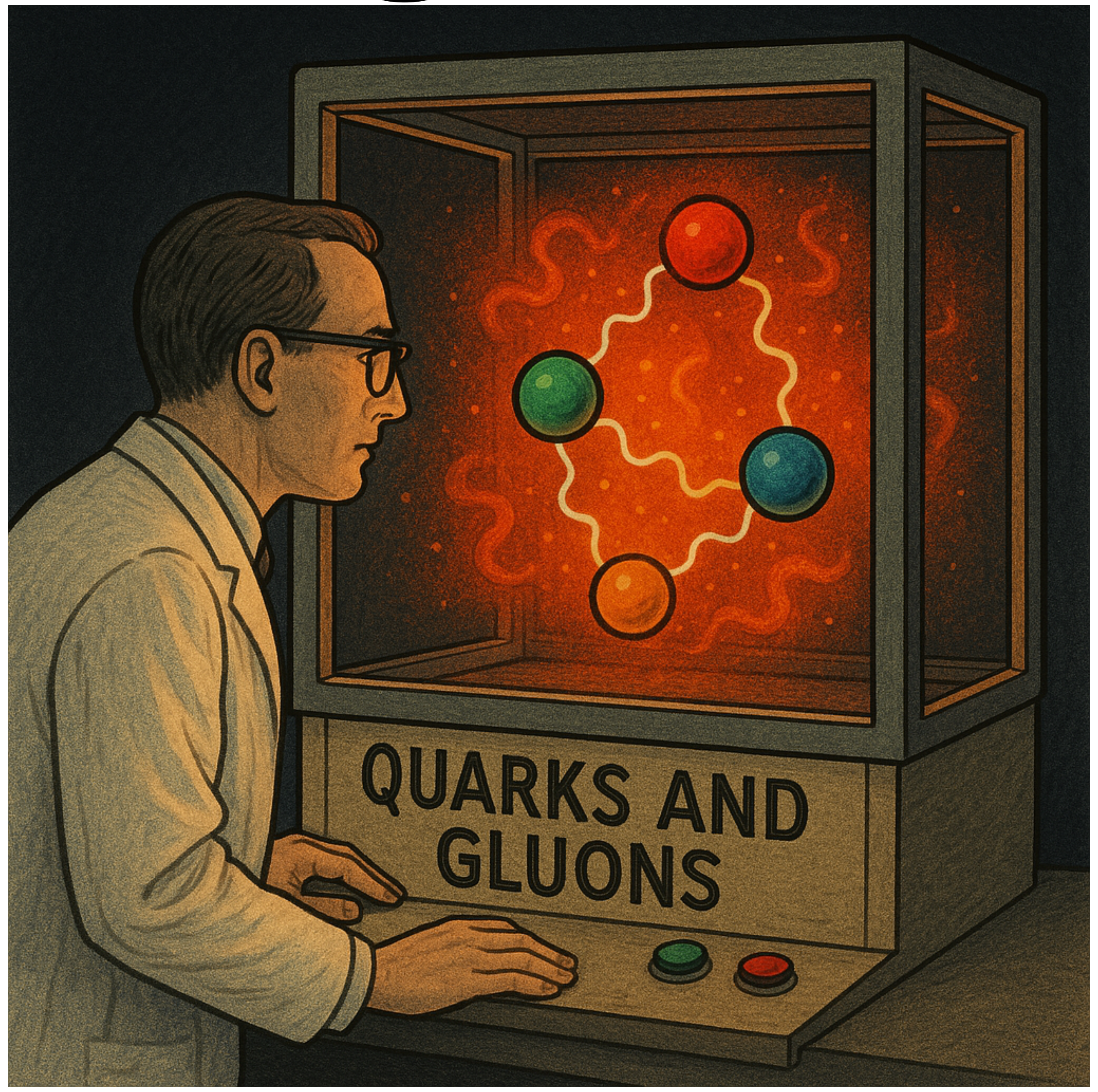


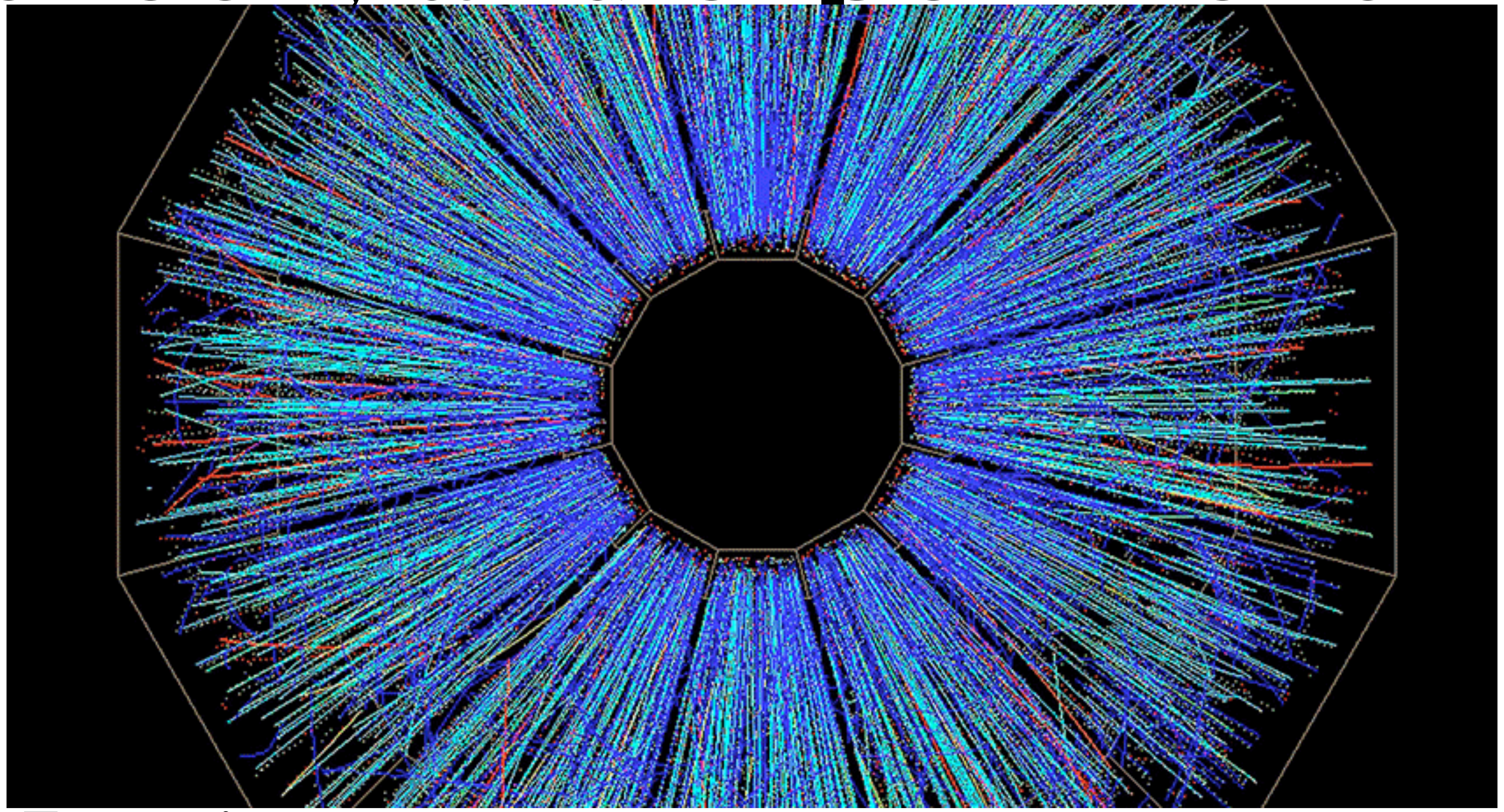






Challenges in comparing theory and experiment





[star.bnl.gov]

Theory:

- Coordinate space
- Energy-momentum and baryon, electric, strange charges are conserved on average
- Matter at stationary equilibrium
- Ensemble is well controlled

Experiment:

- Momentum distribution of charged particles
- Energy-momentum and baryon, electric, strange charges are conserved exactly
- Dynamic evolution
- Mixture of different event classes over various initial conditions

Stages of Heavy-Ion Collisions

Every stage of collision is important. Multi-messenger study.

Profiles of conserved charges: Energy-momentum, baryon, electric, strange

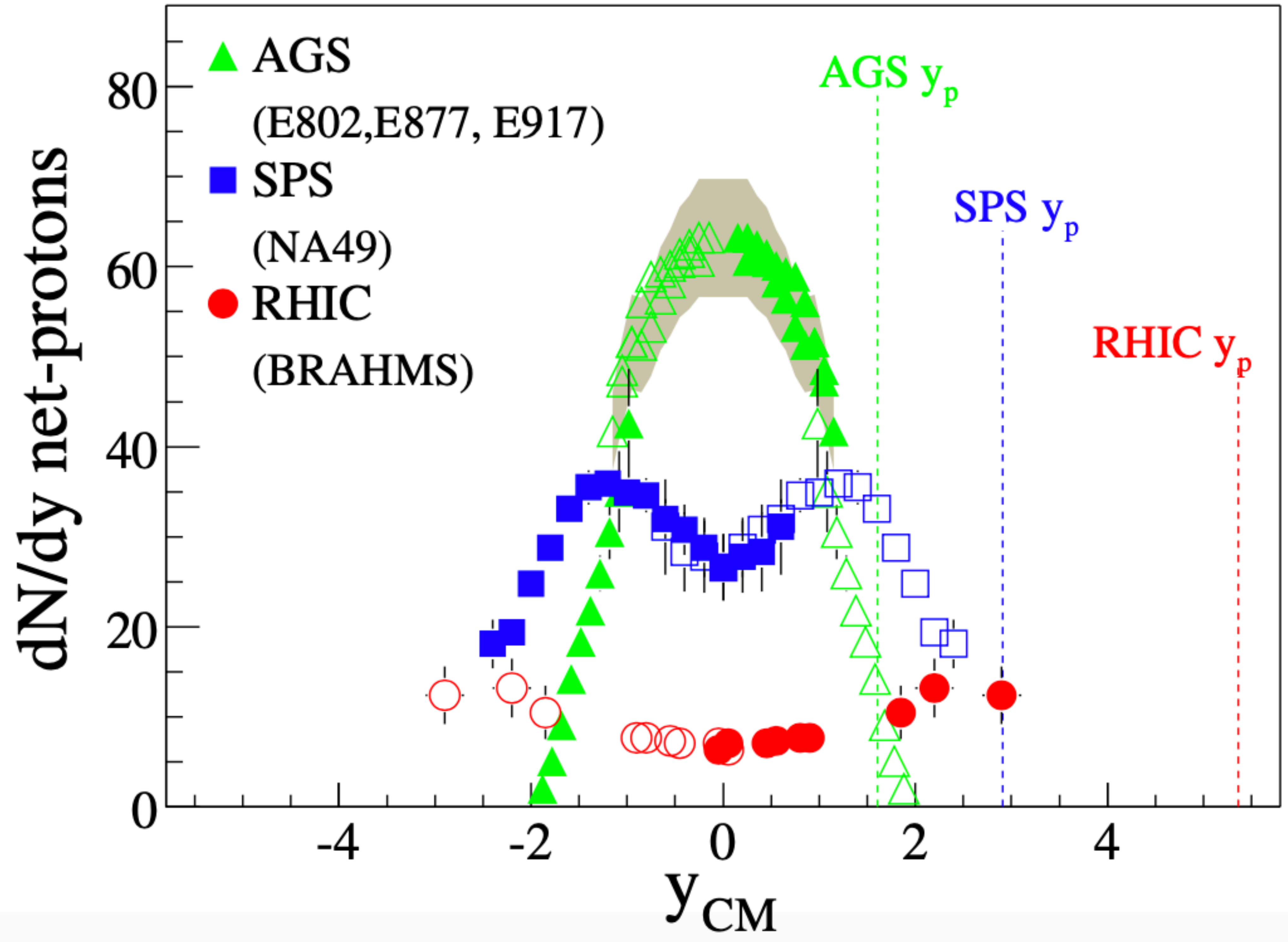
Collective expansion and fluctuations of thermal medium. Out-of-equilibrium/memory effects.

Quarks form hadrons. Correlations and fluctuations of charges.

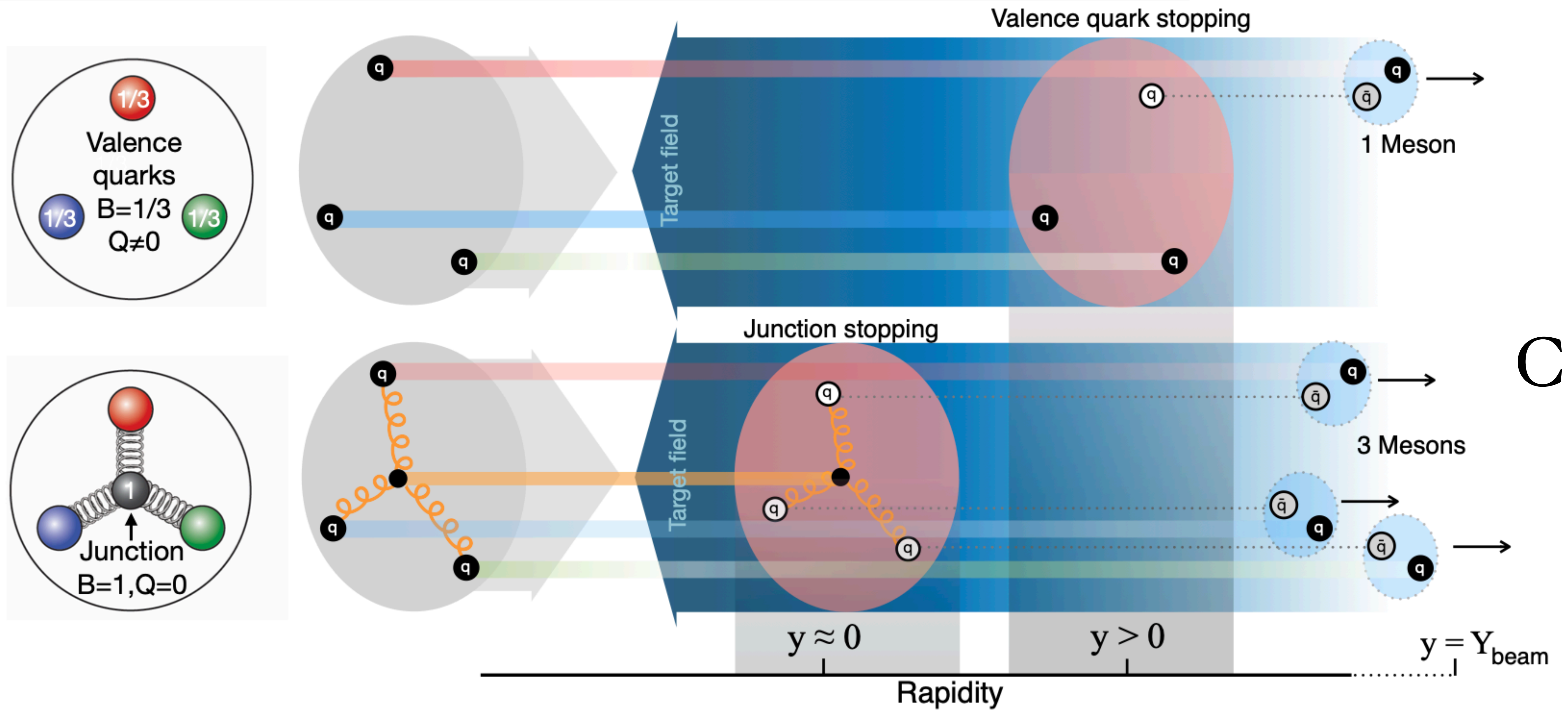
Modeling of each stage requires finesse.

Baryon Stopping

[BRAHMS Collaboration]



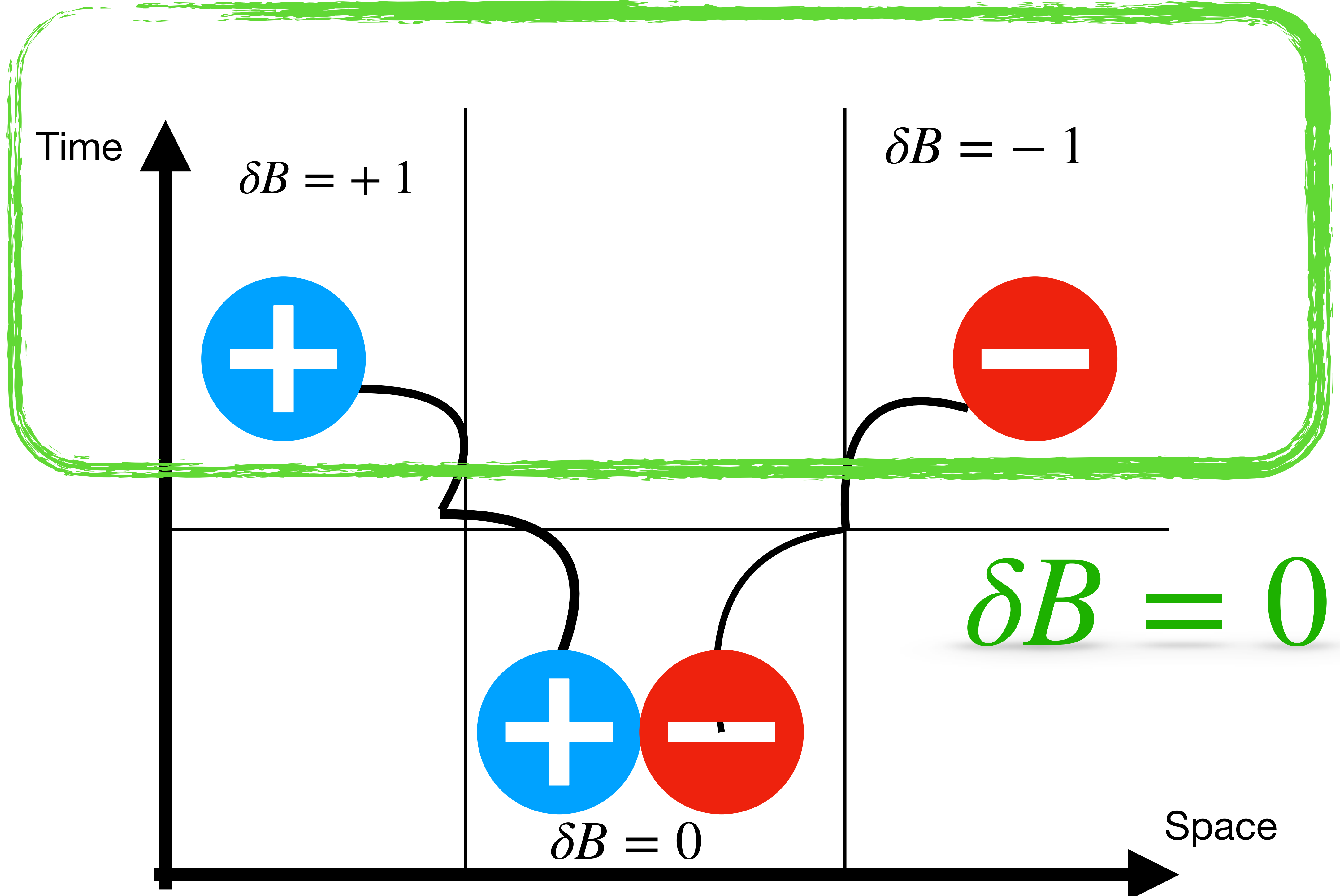
- At the very beginning baryon charge fluctuations are from stopping of proton and neutron, charge is transferred from beam rapidity to the mid-rapidity.
- Stopped charge is well approximated with net-protons.
- Qualitative change of rapidity spectra with energy - different physics!
- Important at low energy!
- Less important at high energy - charge produced in pairs from vacuum.



[STAR Collaboration, Do quarks or gluons carry baryon number?]

Can fluctuations be used to tell the difference?

Local charge conservation



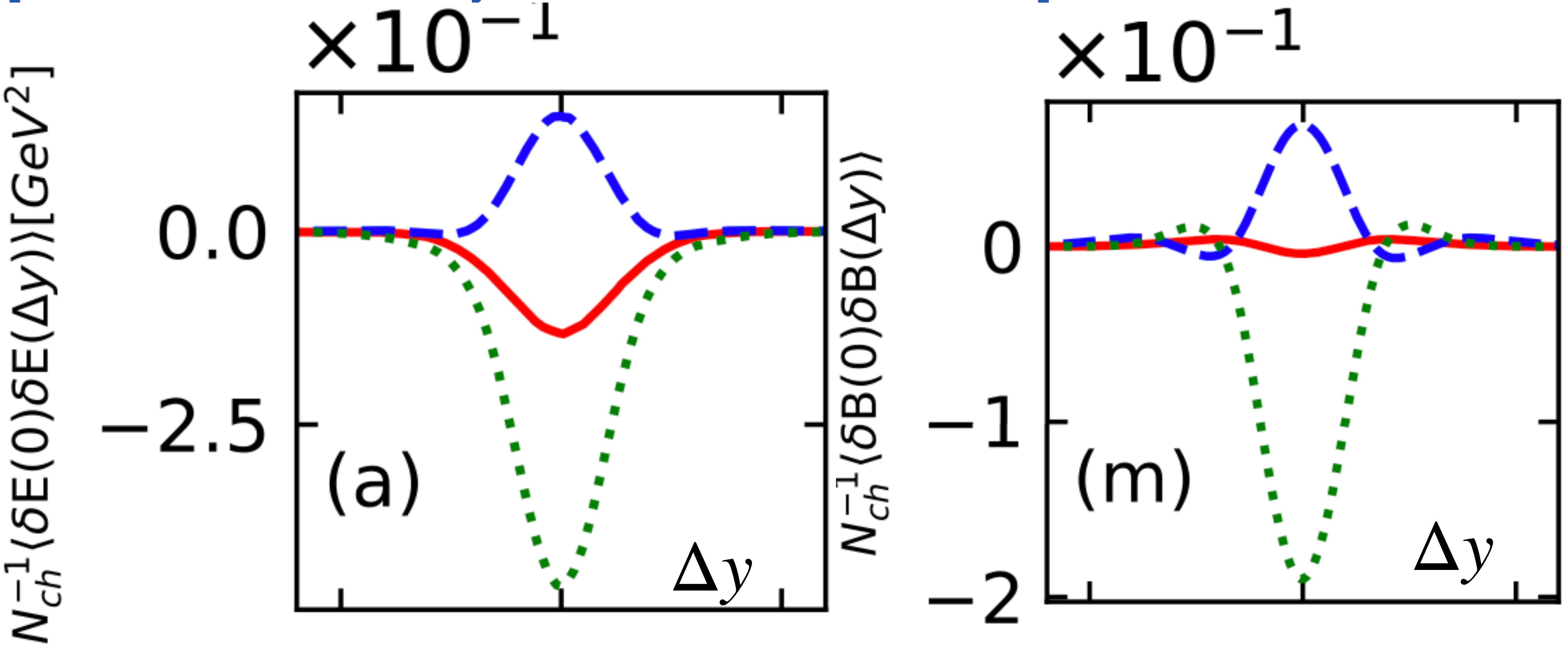
[Scott Pratt, Rachel Steinhorst Phys. Rev. C **102**, 064906]

[OS, J. Phys. G: Nucl. Part. Phys. 52 035106]

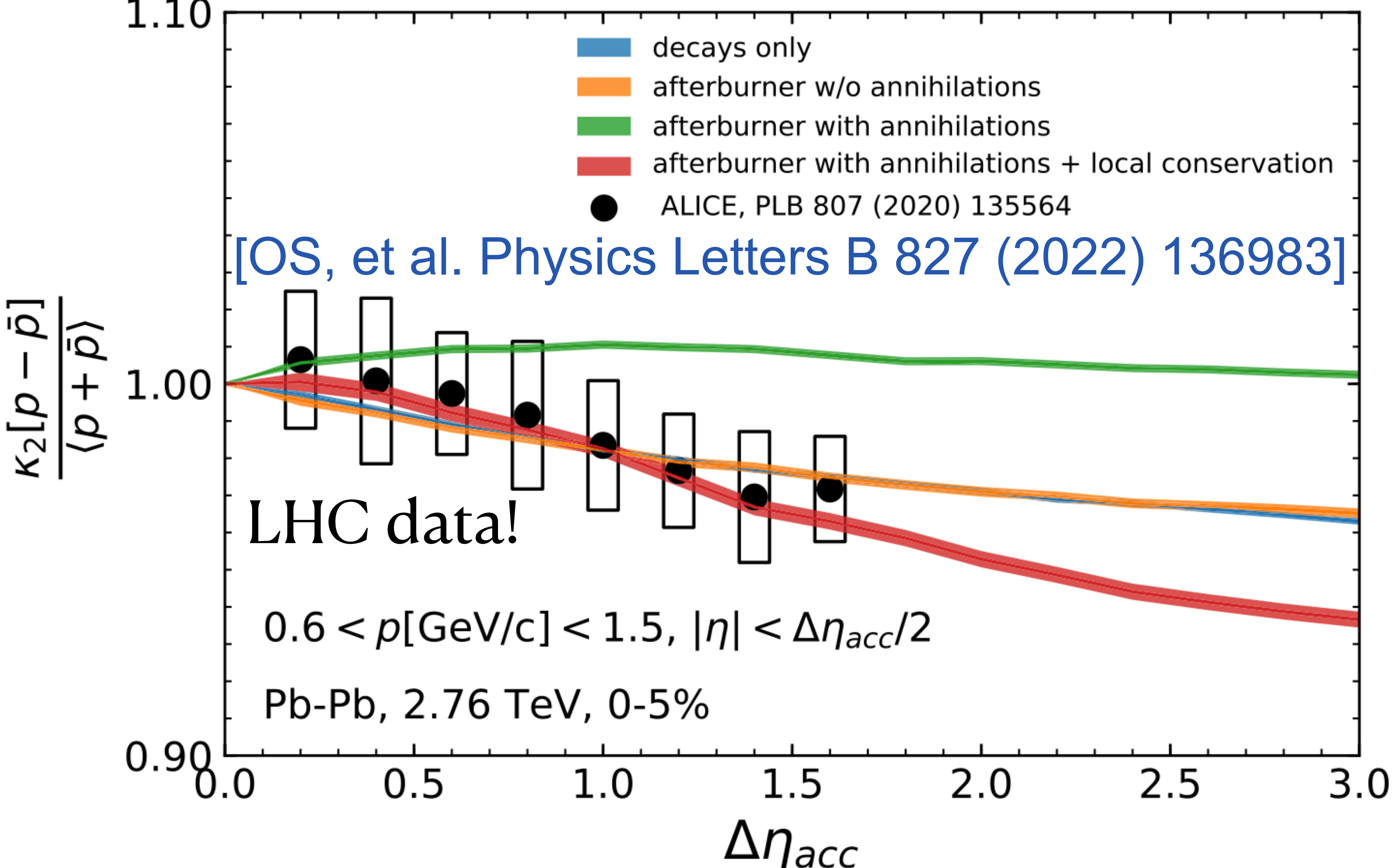
- Apart from stopped charge, particle anti-particle pairs can be produced dynamically in a collision.
- To affect fluctuations in a given bin only one of the particles must enter acceptance.
- Maximal spread of pairs depends on the properties of the medium and time.

Appears in Energy and Baryon charge correlations!

[OS, Scott Pratt Phys. Rev. C **109**, 024910]

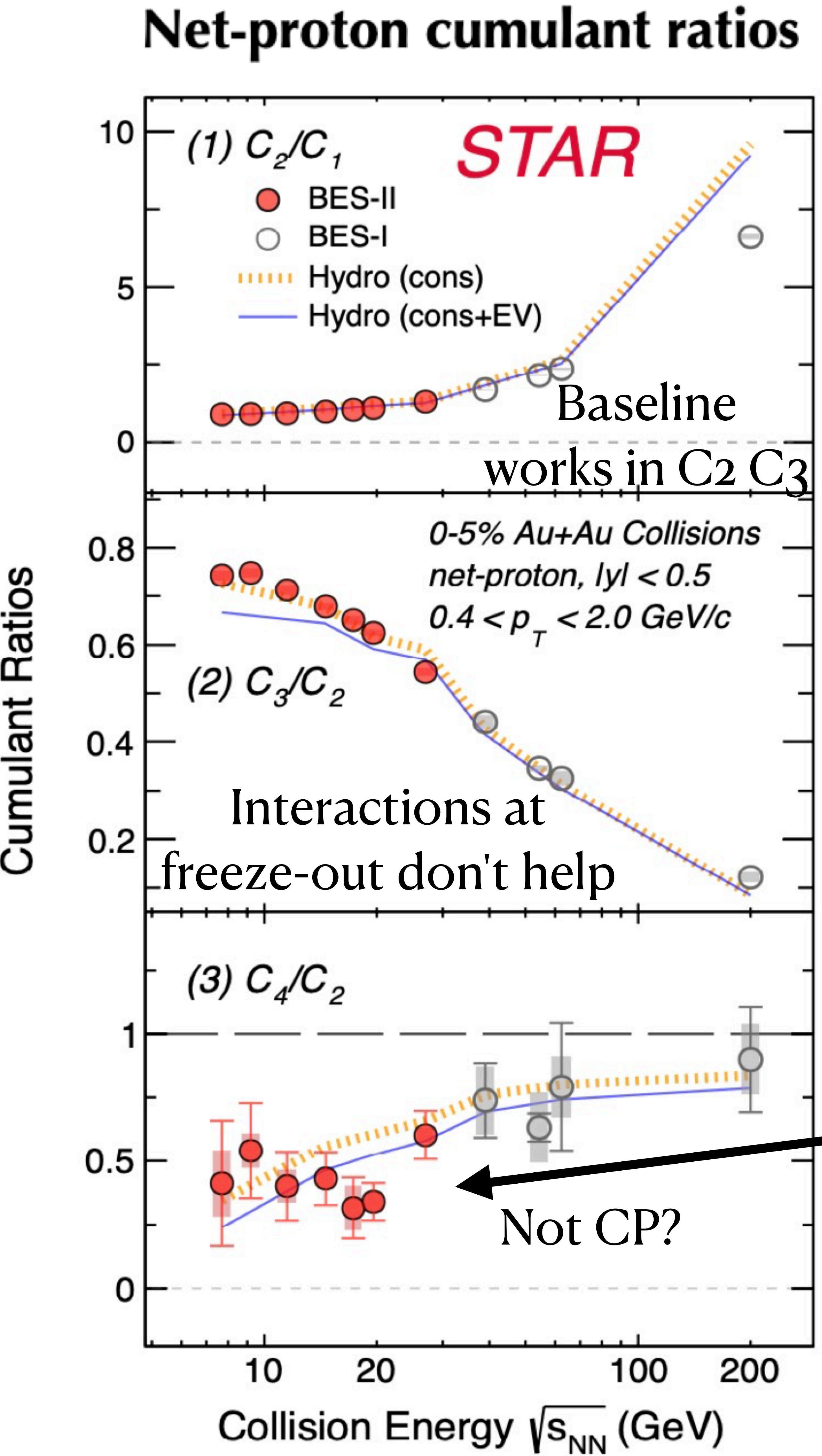


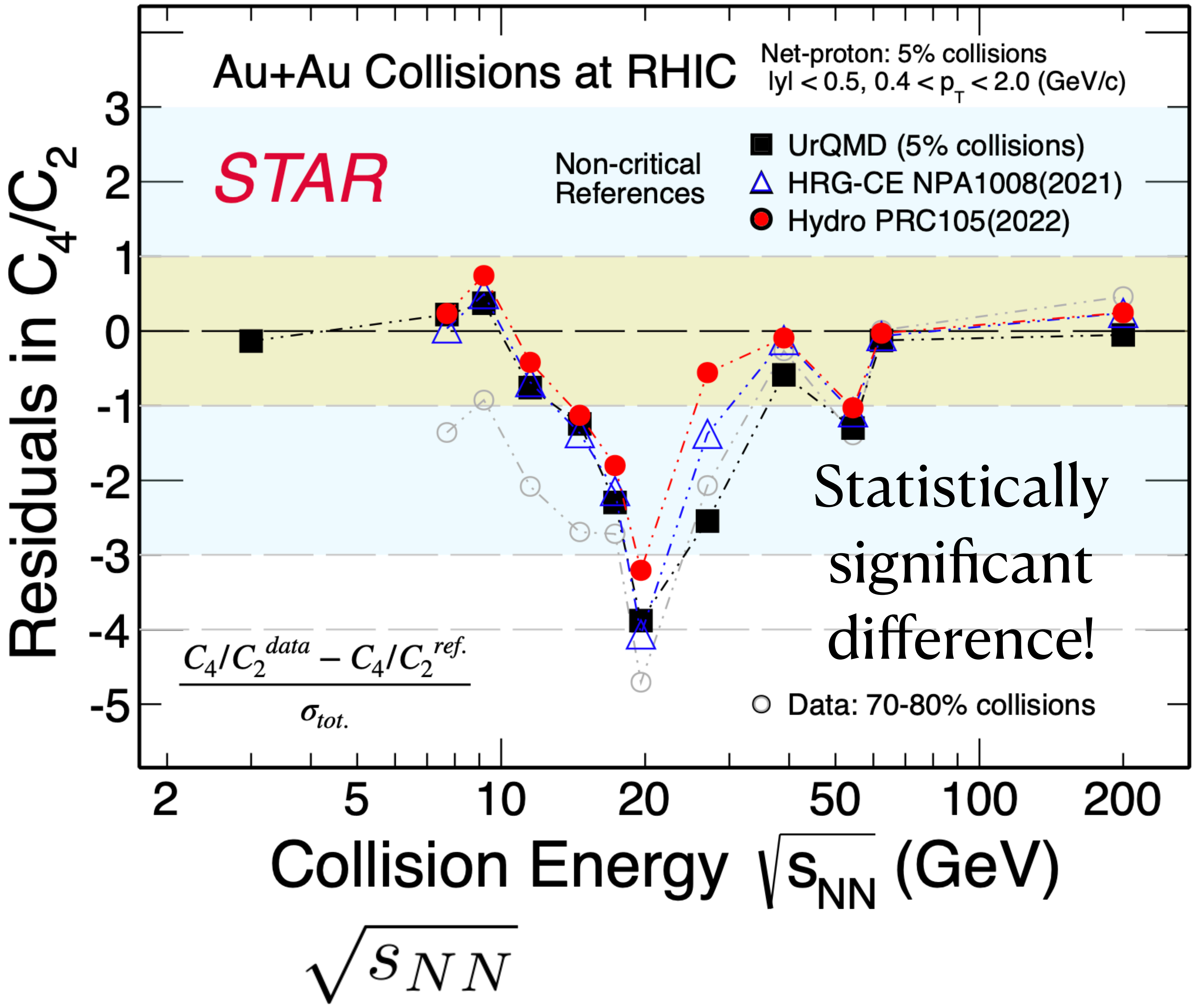
Local conservation important at high energies!

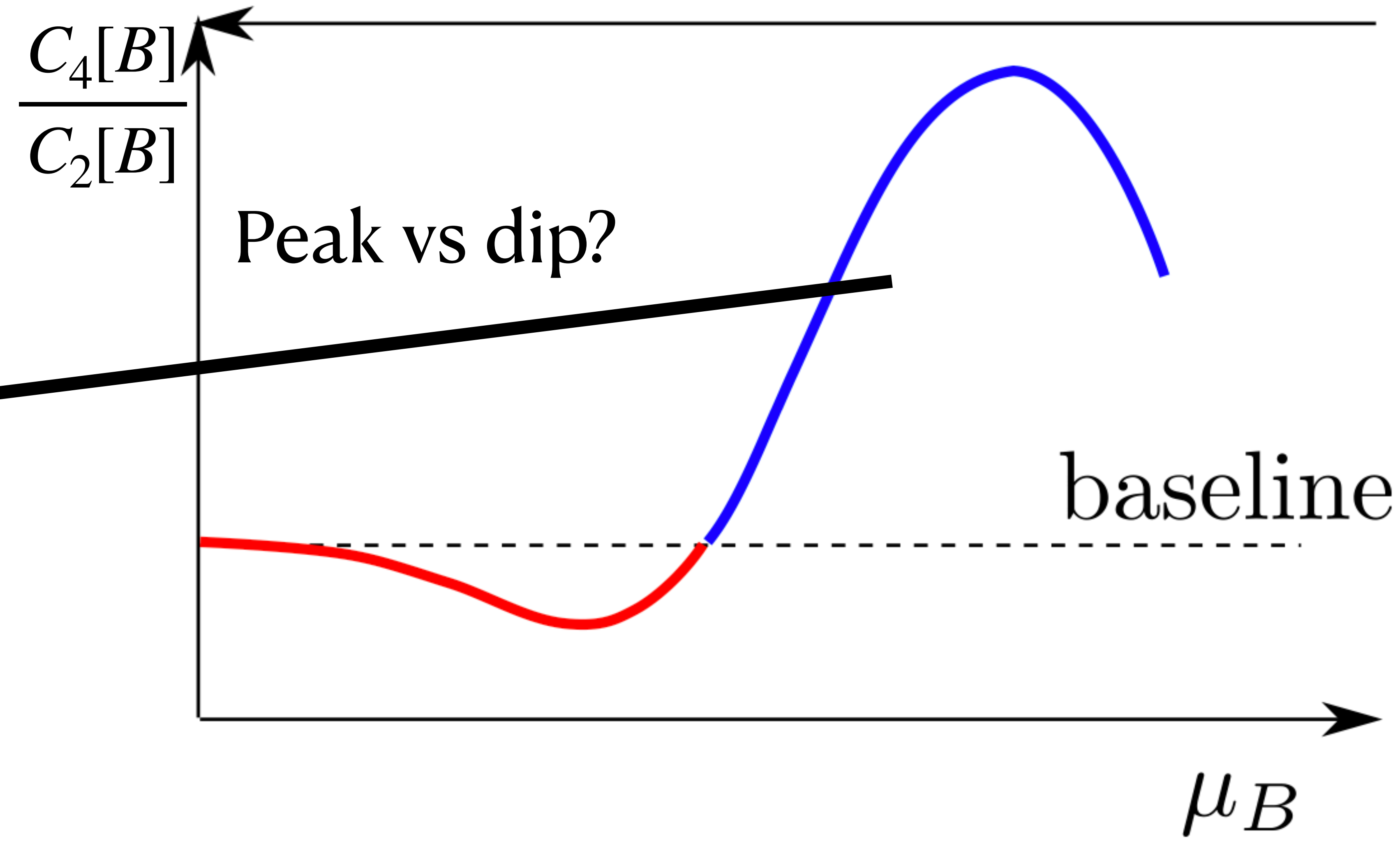


Models vs Experiment

[A. Pandav, CPOD2024]





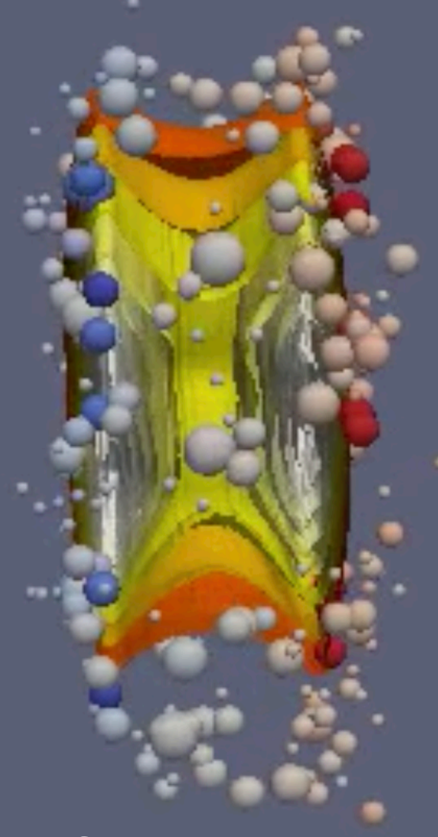


- Non-interacting baselines fail in 20 GeV range.
- This difference is seen only in kurtosis.
- Hard to include interactions.
- Not $E_{lab} = 6 - 14\ A\text{GeV}$.

History of each event is important!

Initial stage is ignored in baseline.

Non-trivial behaviour

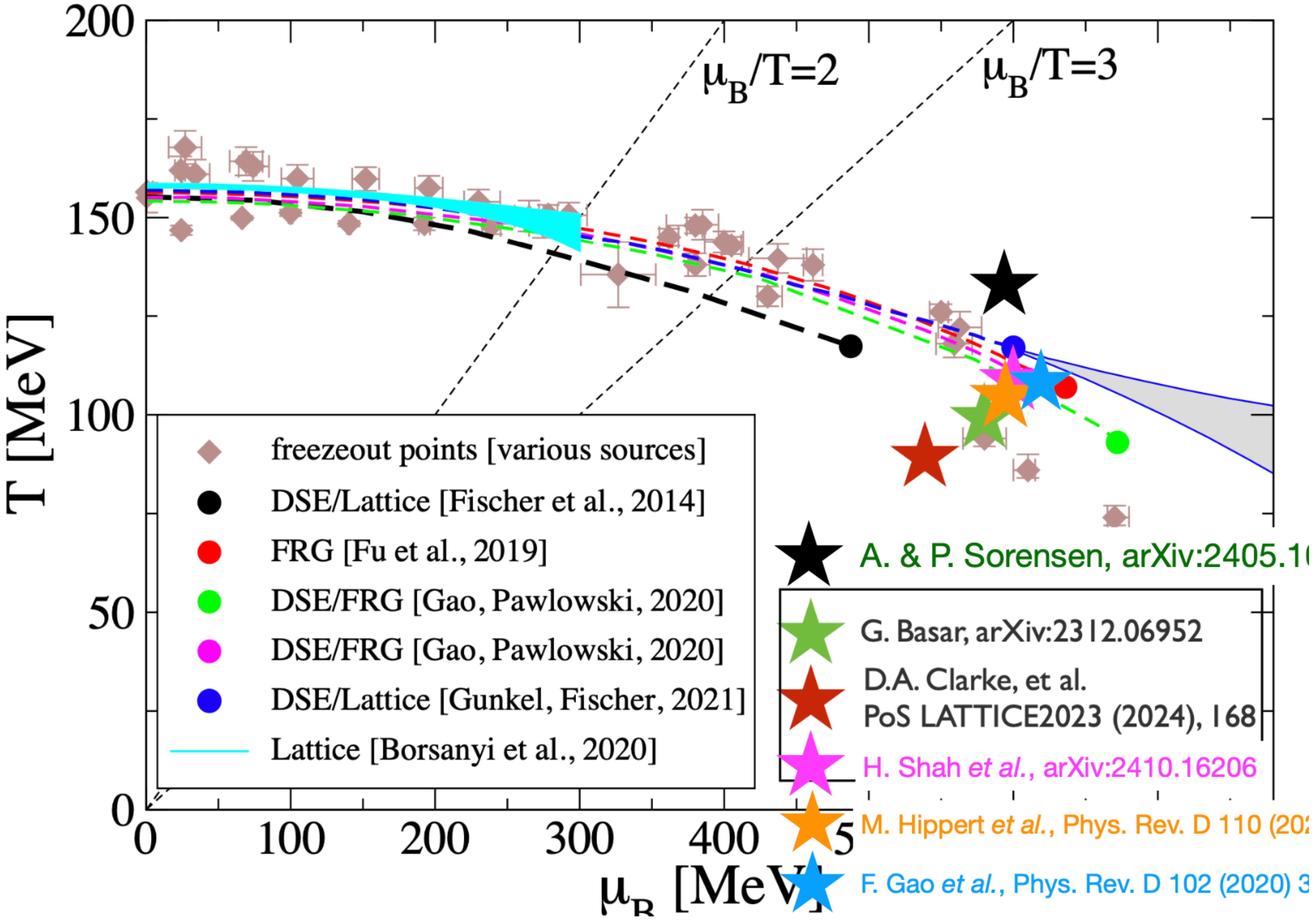


Local conservation is not accounted for!

Onset of QGP formation.
String melting / recombination.

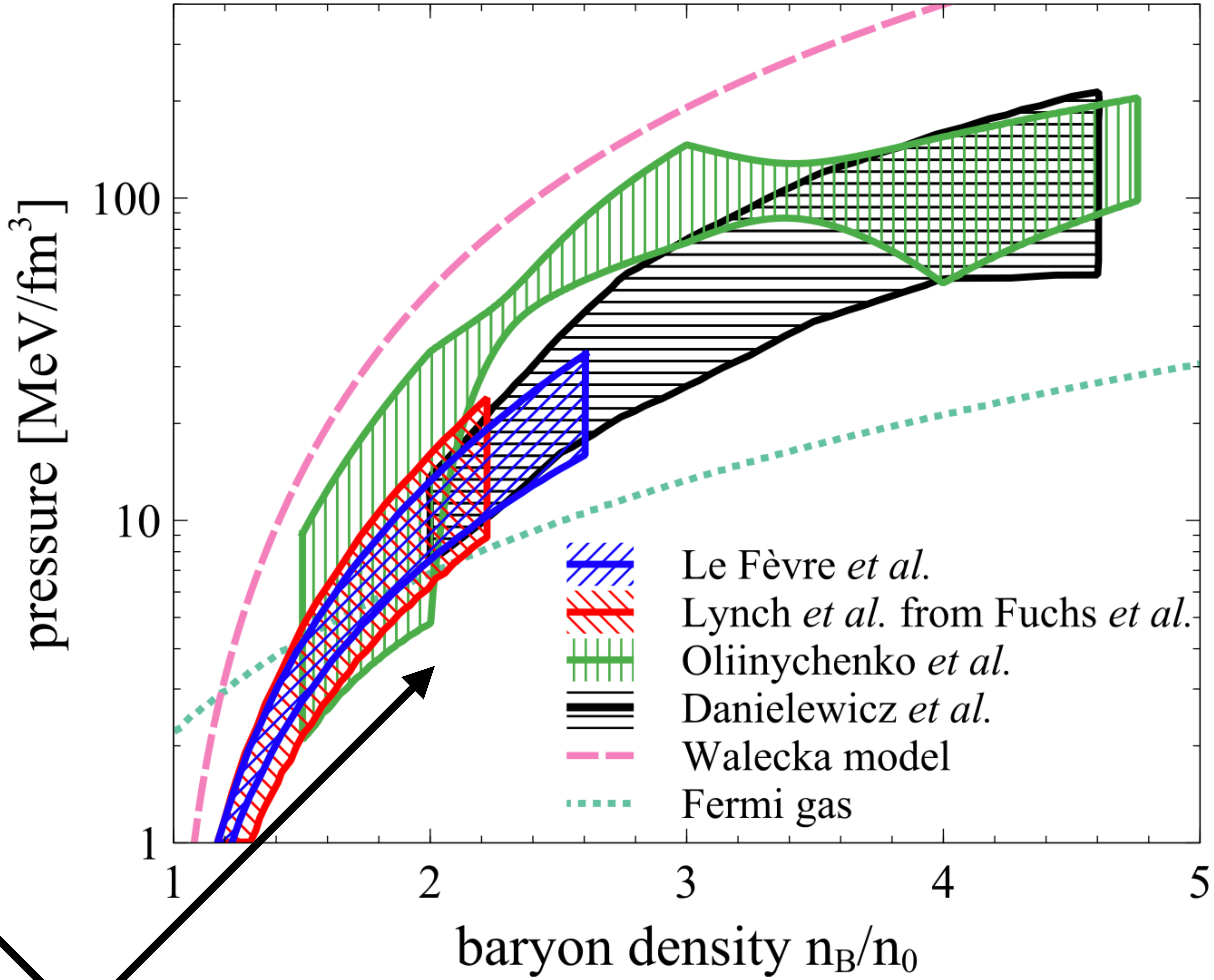
Running from problems back to lower energies

You can get a Critical Point.
Third Time the Charm.



[adapted from Christian Fischer, CPOD 2024]

Equation of state can be constrained using transport simulations
We need more data and better models.

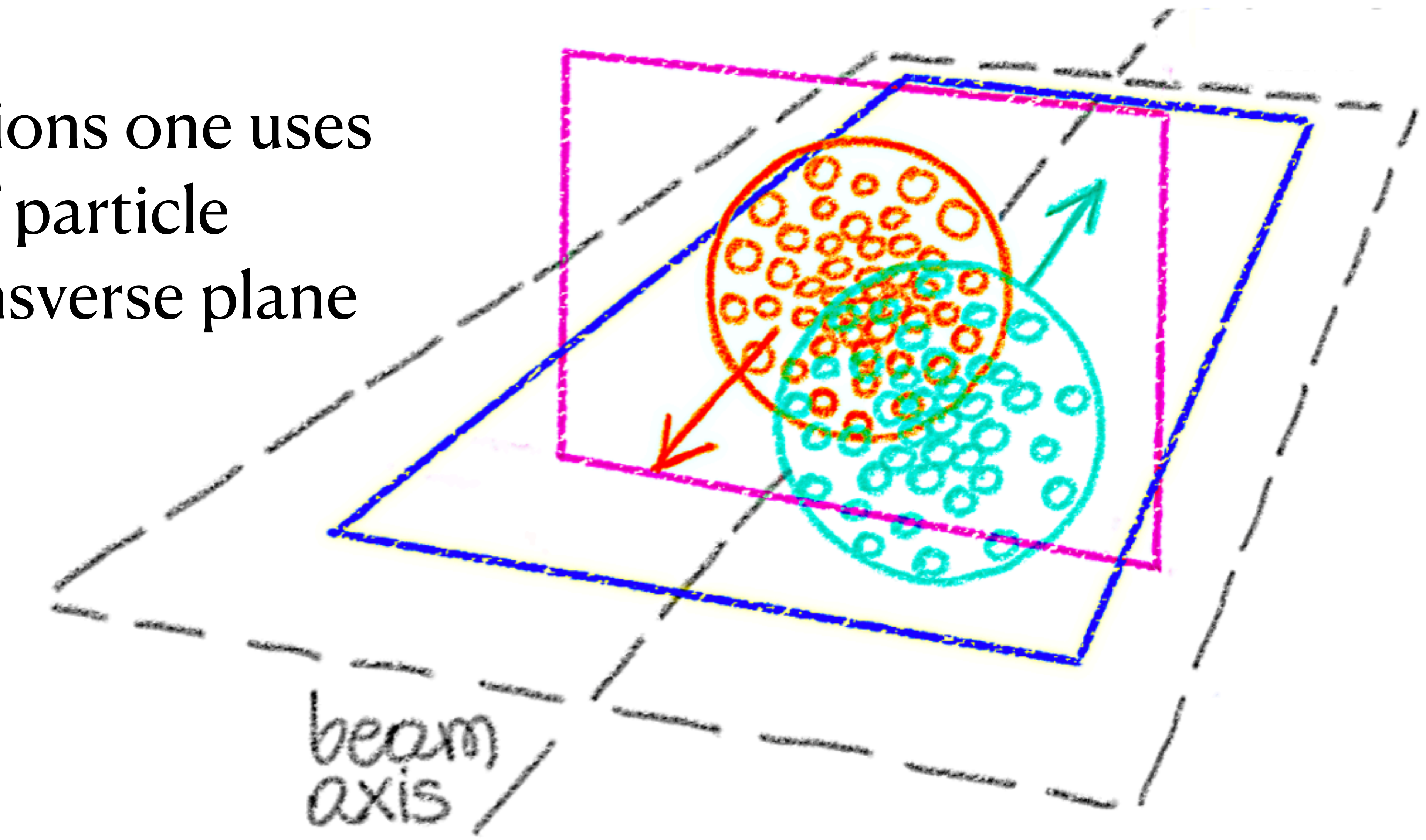


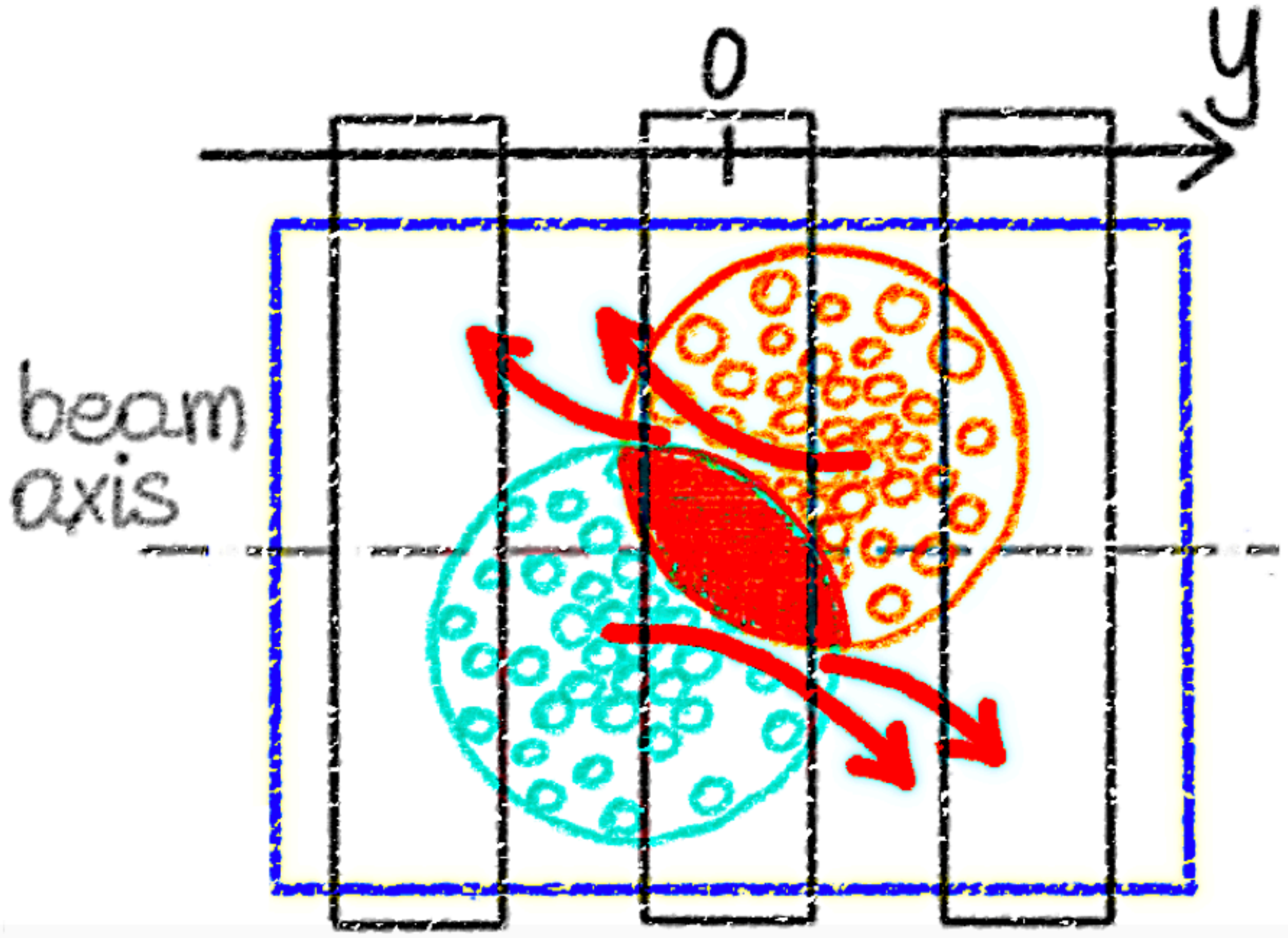
[Prog. Part. Nucl. Phys. **134**, 104080 (2024)]

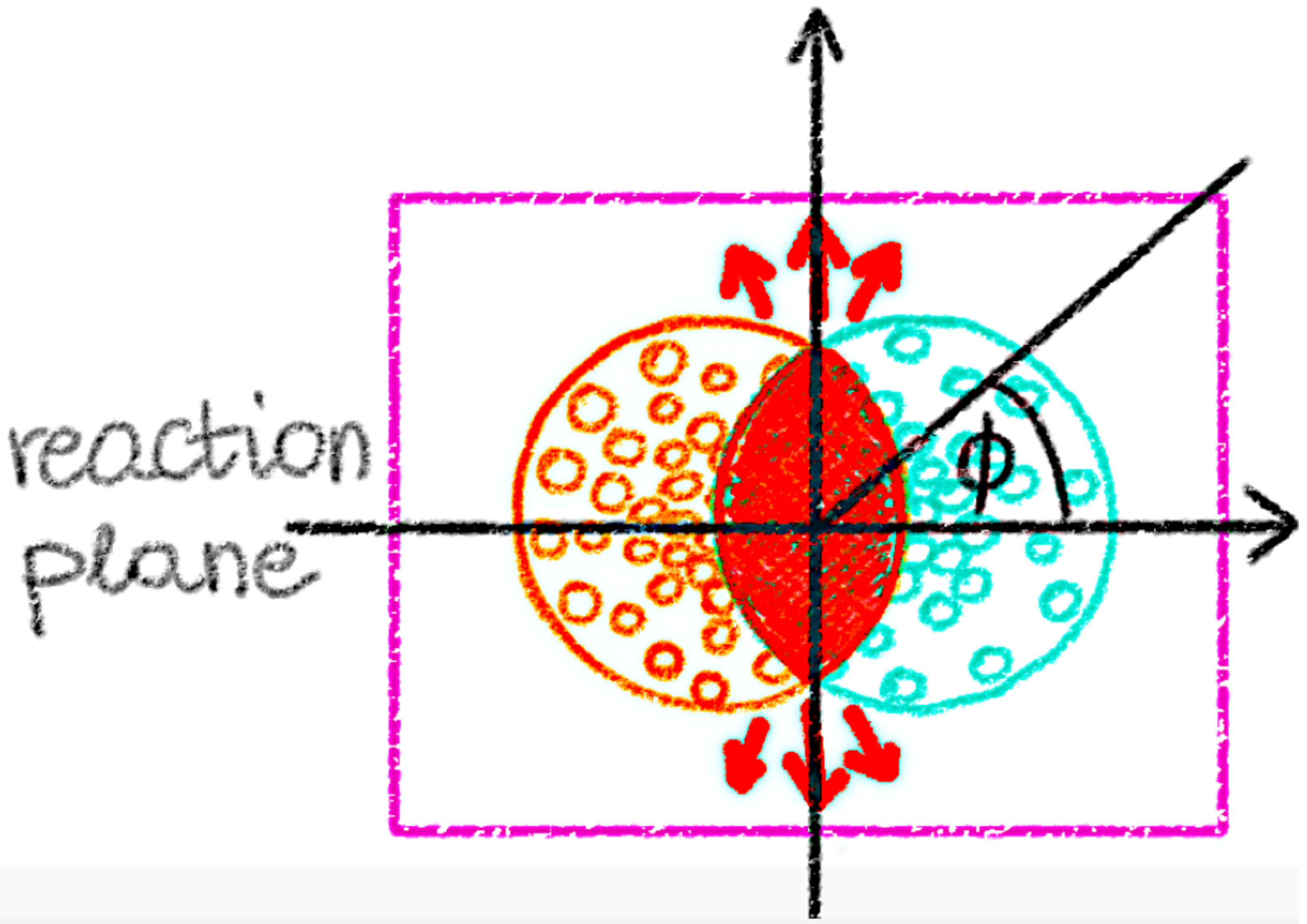
Is there a room for a phase transition?

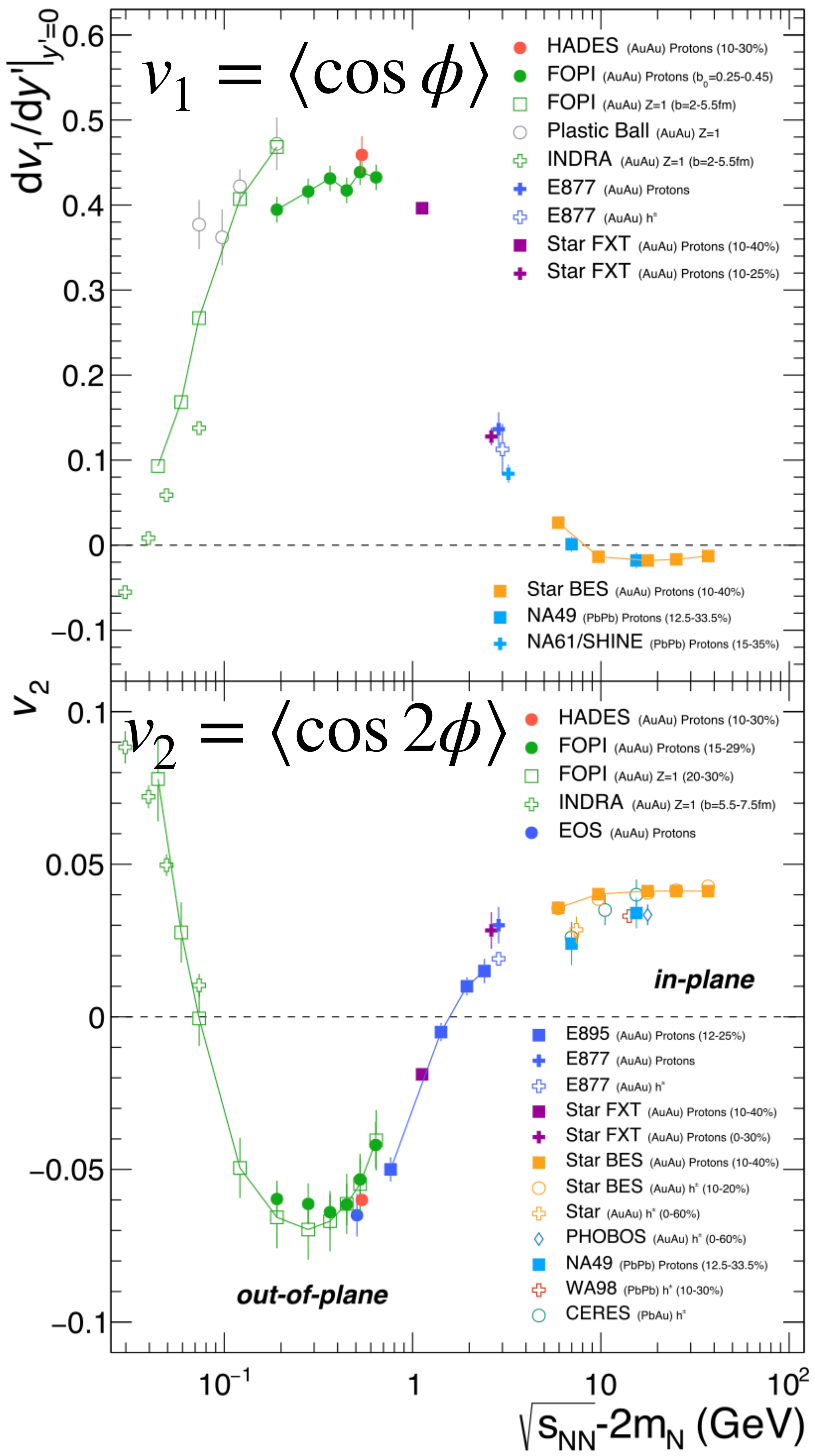
Azimuthal flow as an observable

Instead of fluctuations one uses anisotropy of particle production in transverse plane





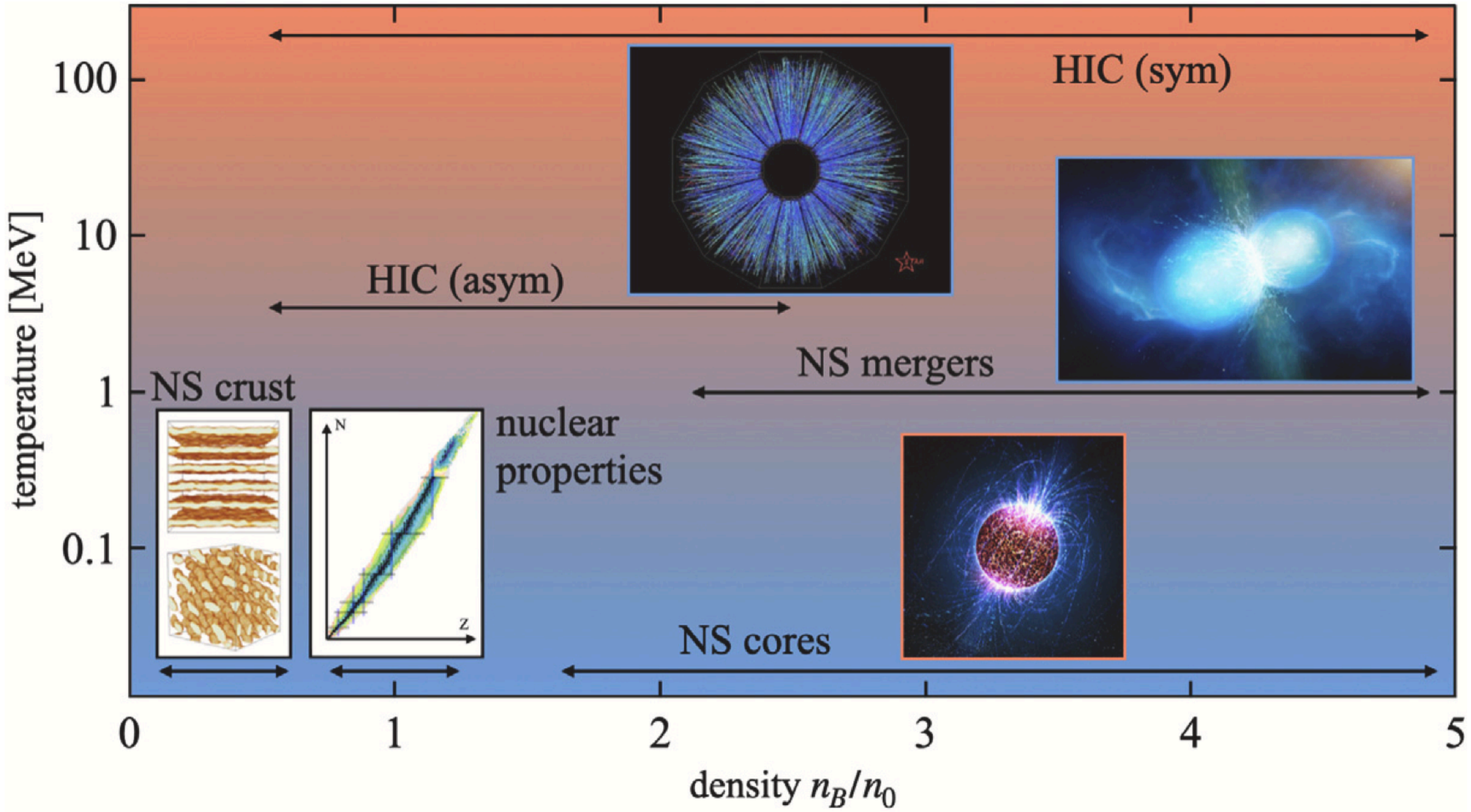




[L.Du, A. Sorensen, M. Stephanov, *Int.J.Mod.Phys.E* 33 (2024) 07, 2430008]

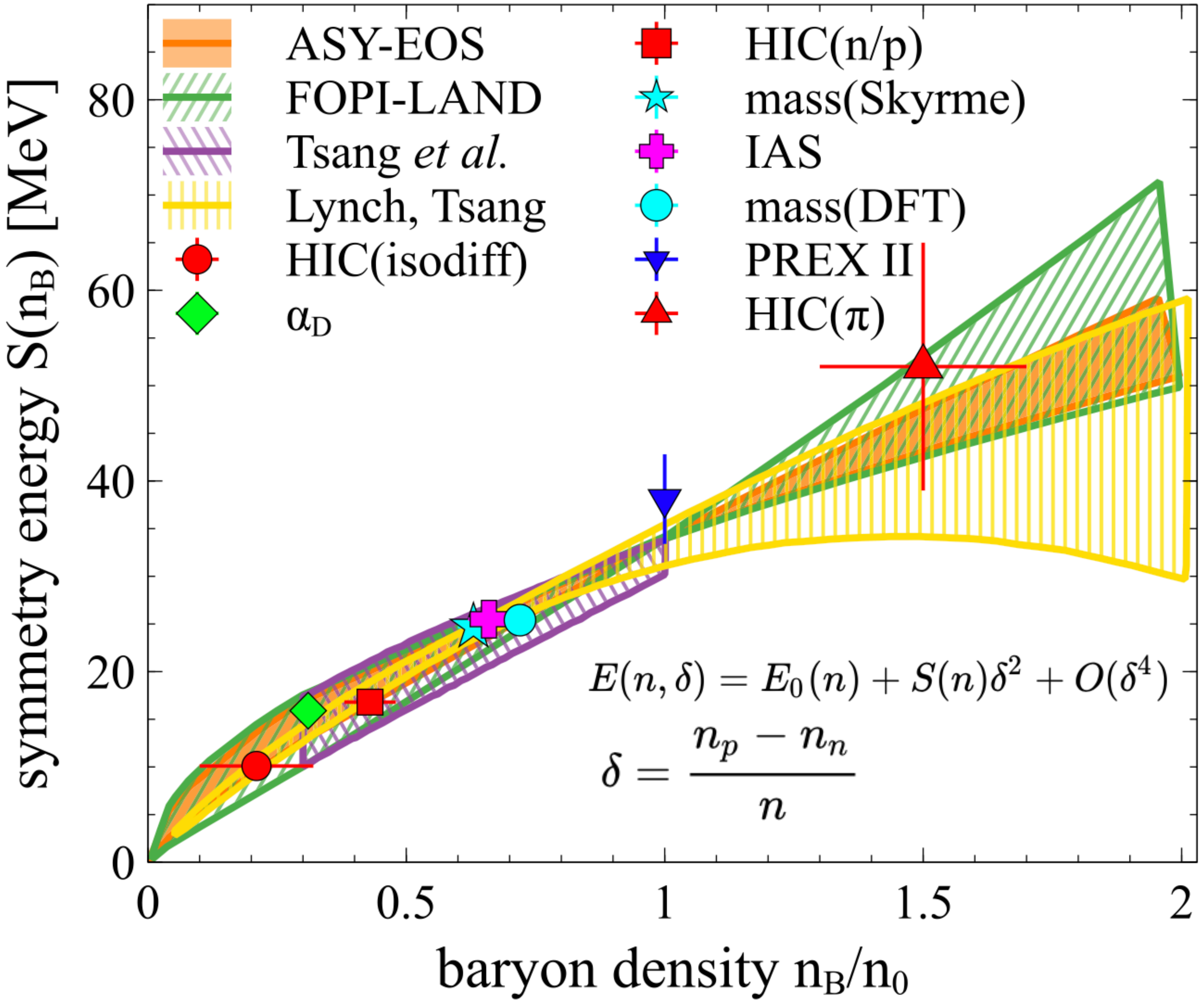
Connections with Neutron Stars

And connection with neutron star EoS



Same density, different fraction of protons.
Obtain symmetry energy from experiment.

Development and tuning of microscopic transport simulations is required to compare theory with the data.

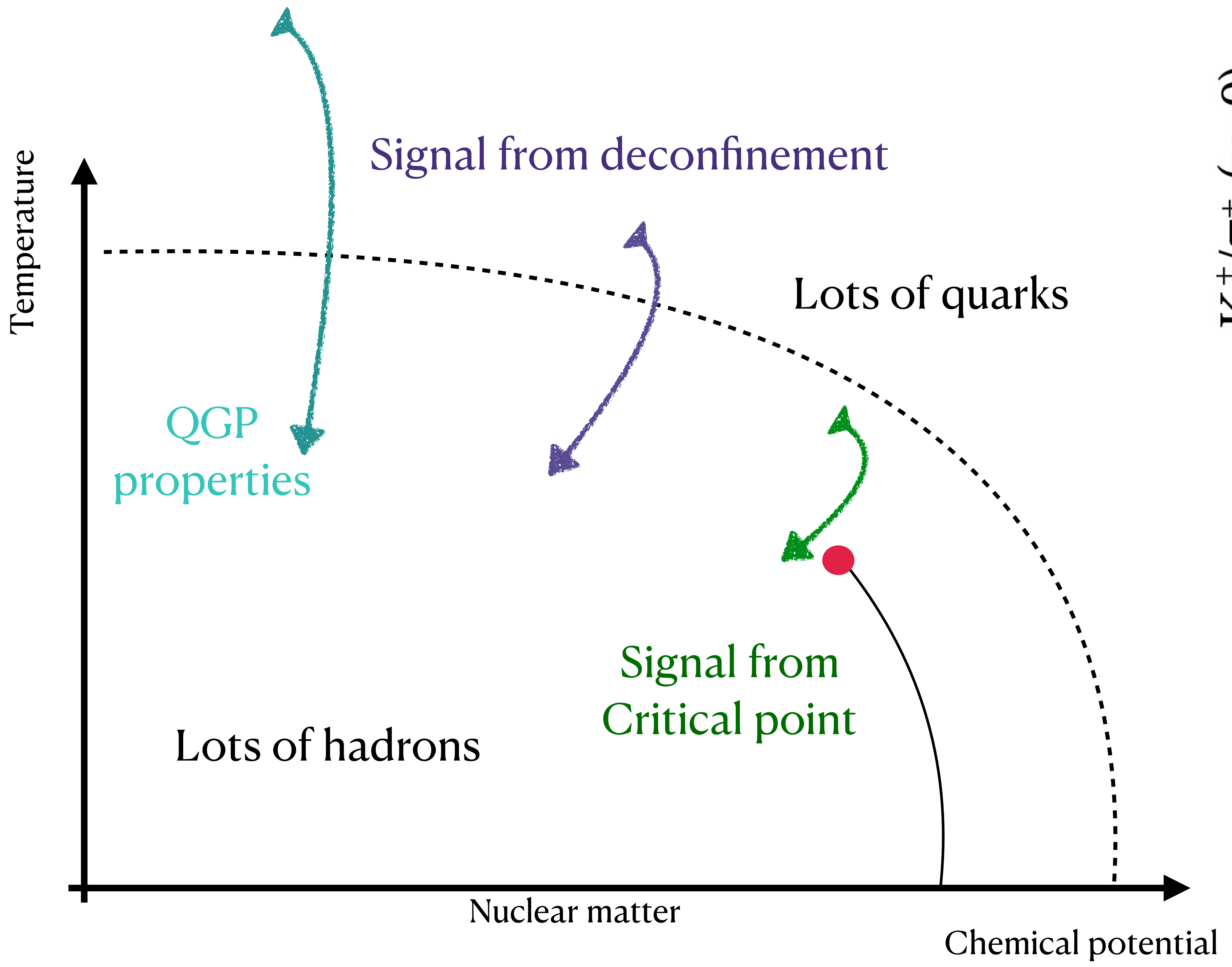


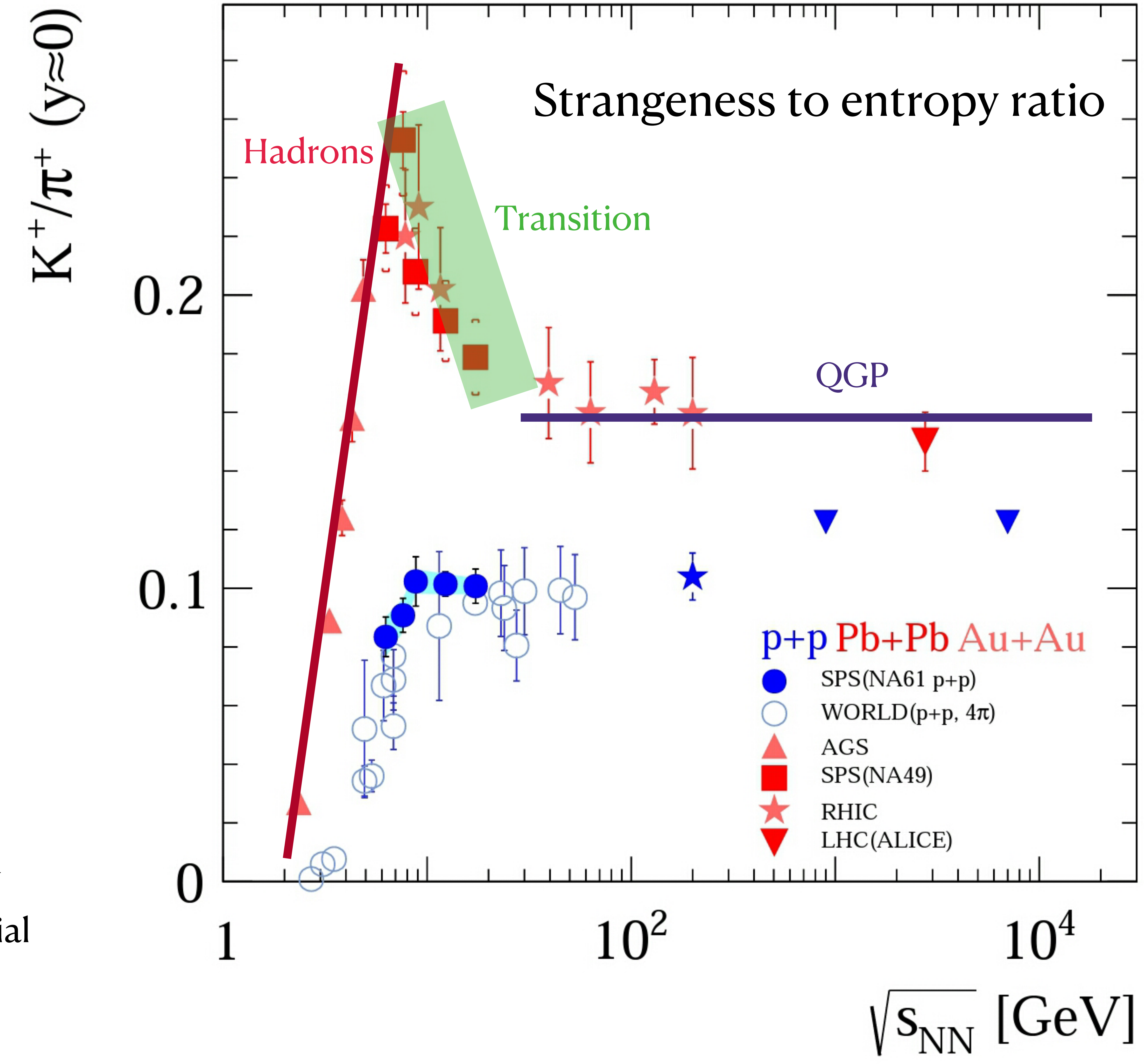
The full potential of Facility for Rare Isotope Beams

[Prog. Part. Nucl. Phys. **134**, 104080 (2024)]

...brings more nuclei into reach, which is important for the r-process during neutron-star mergers and for neutron star crust processes; compresses asymmetric nuclear matter to densities required for experiments relevant to multi-messenger astronomy; enables fast-beam reactions to be done in the optimal energy regime for their interpretation...
Long Range Plan 2023

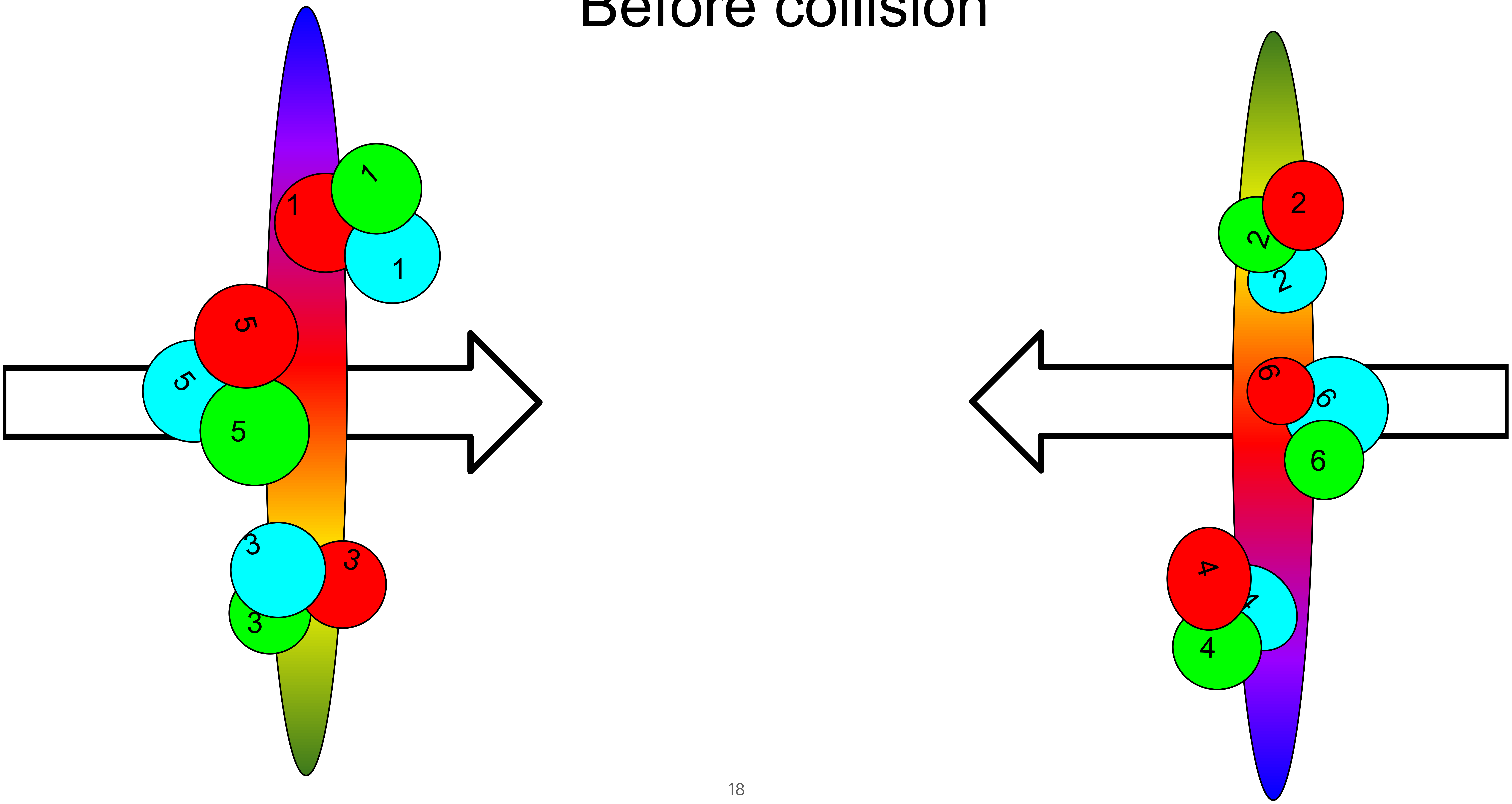
Initial state effects in fluctuations: Onset of deconfinement





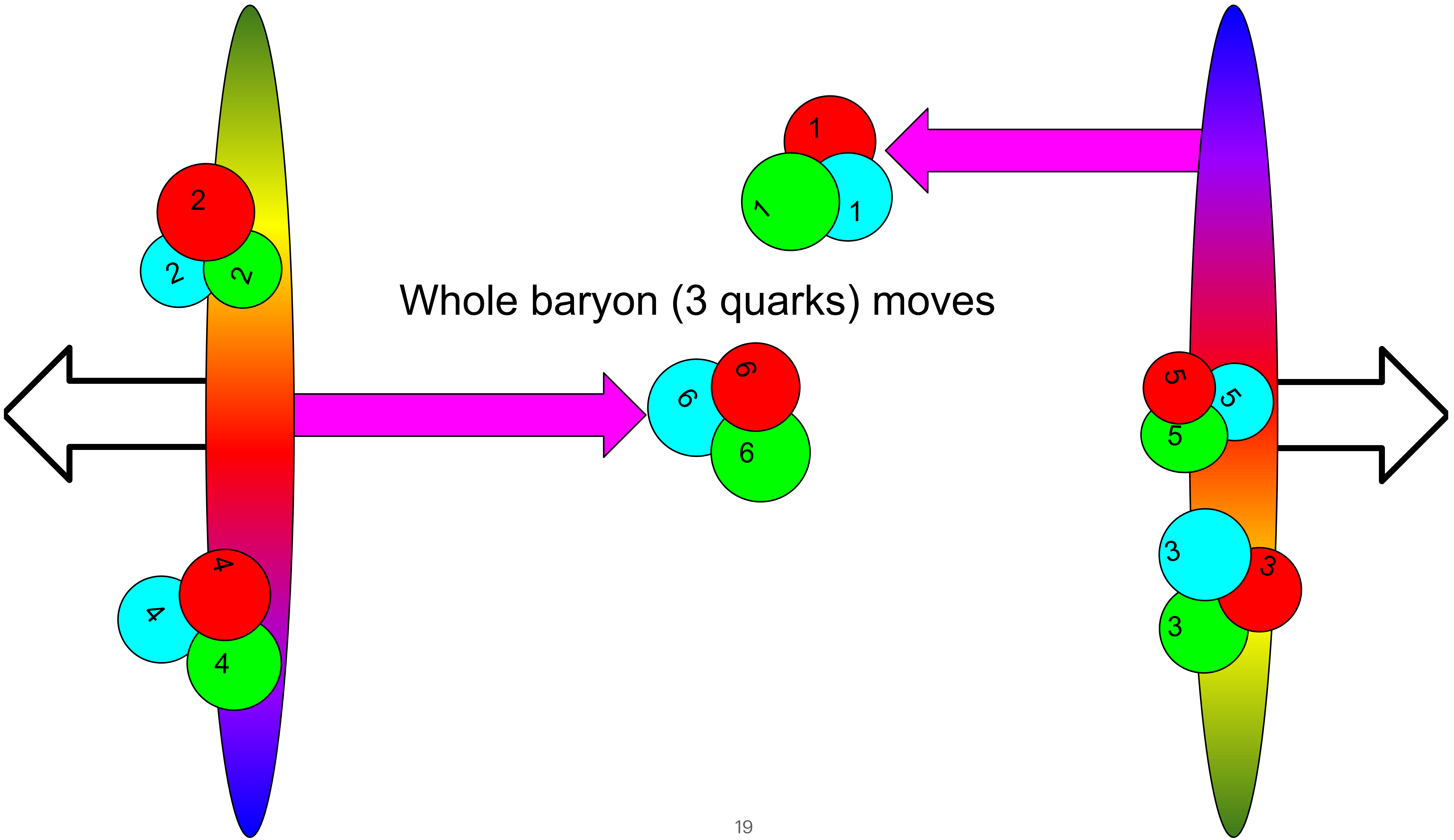
[Marek Gazdzicki, Mark Gorenstein, Peter Seyboth, Acta Phys.Polon.B42:307-351,2011]

Before collision



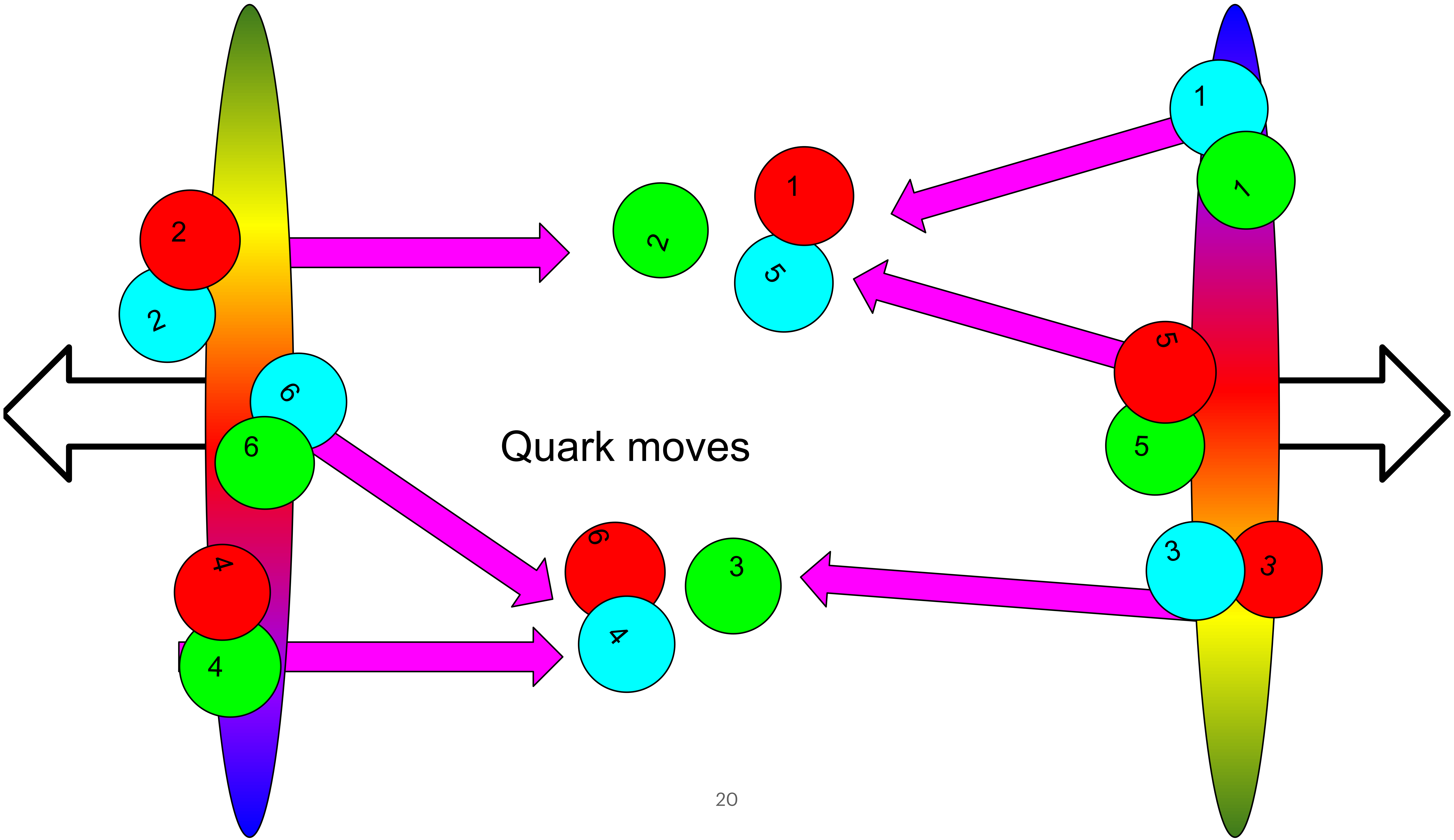
Scenario 1

Baryon stopping

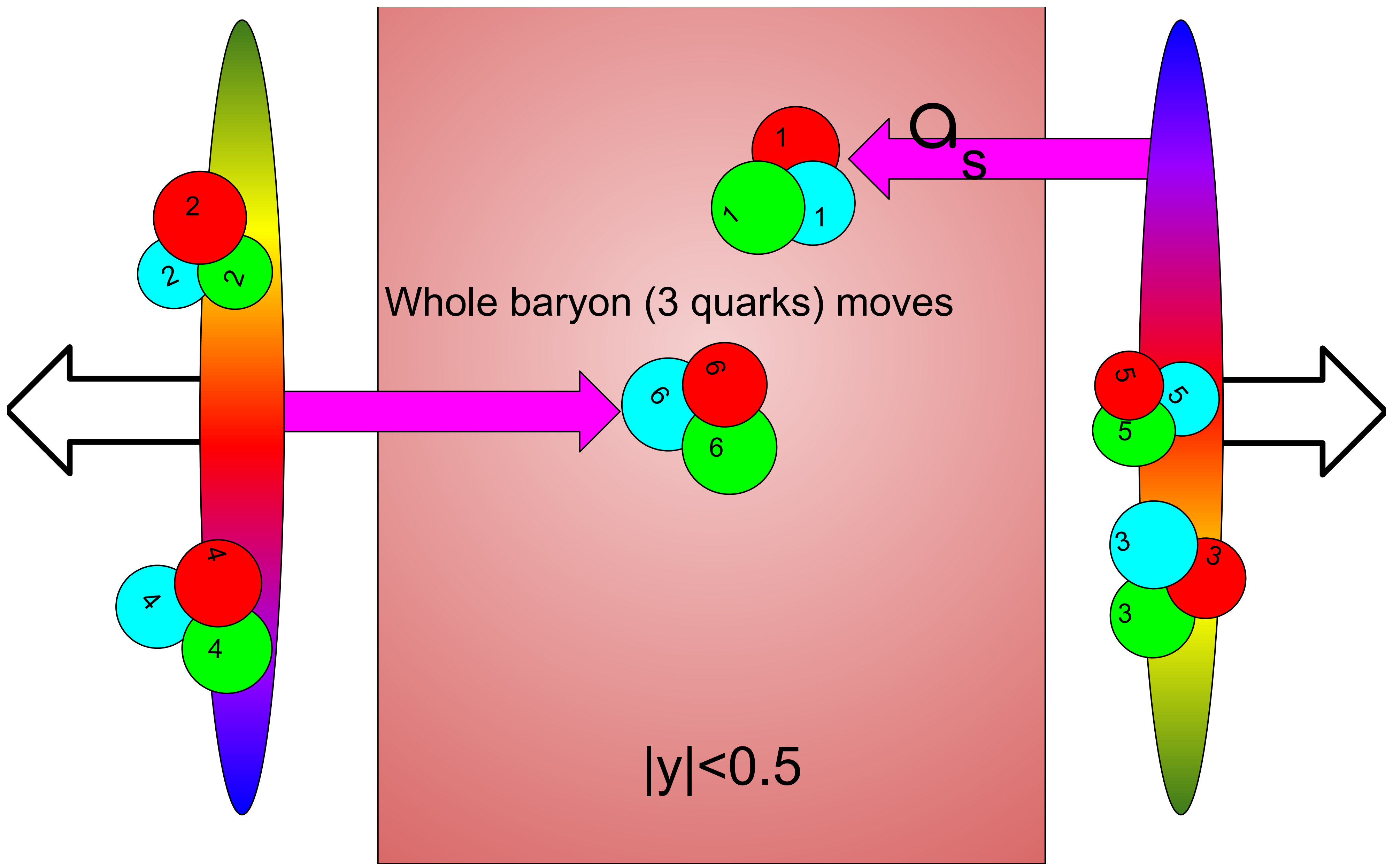


Scenario 2

Quark stopping



Case 1: Baryon stopping



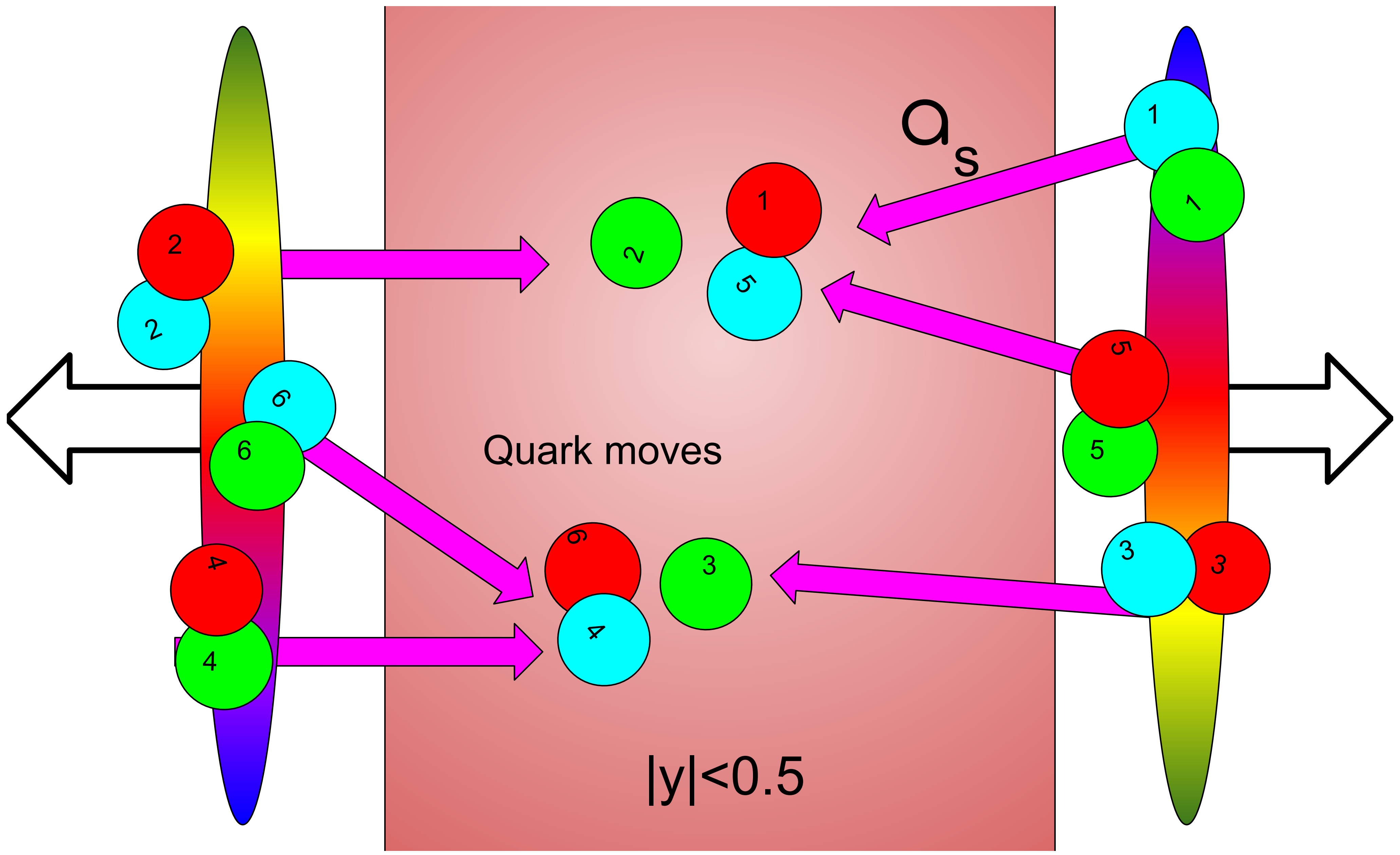
$$C_1^{stopping} = \alpha_s B_s,$$

$$C_2^{stopping} = B_s \alpha_s (1 - \alpha_s),$$

$$C_3^{stopping} = B_s \alpha_s (1 - 2\alpha_s),$$

$$C_4^{stopping} = B_s \alpha_s (1 - \alpha_s)(1 - 6\alpha_s(1 - \alpha_s))$$

Case 2: Quark stopping



$$C_1^{stopping} = \alpha_s B_s,$$

$$C_2^{stopping} = \frac{1}{3} B_s \alpha_s (1 - \alpha_s),$$

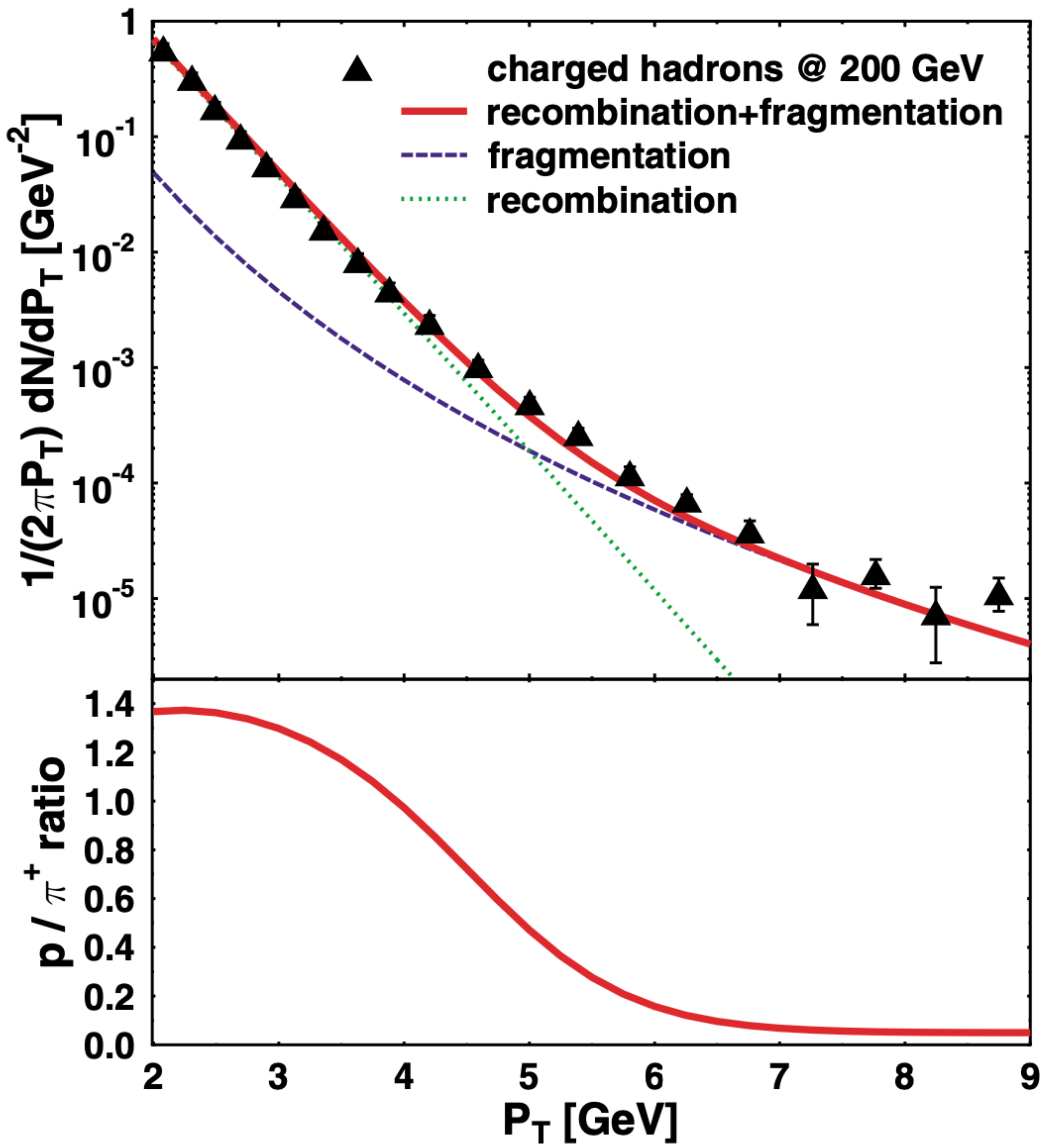
$$C_3^{stopping} = \frac{1}{9} B_s \alpha_s (1 - 2\alpha_s),$$

$$C_4^{stopping} = \frac{1}{27} B_s \alpha_s (1 - \alpha_s)(1 - 6\alpha_s(1 - \alpha_s))$$

Huge suppresion of fluctuations if the transition from baryons to quarks occurs

[OS, Physical Review C 111 (2), 024913]

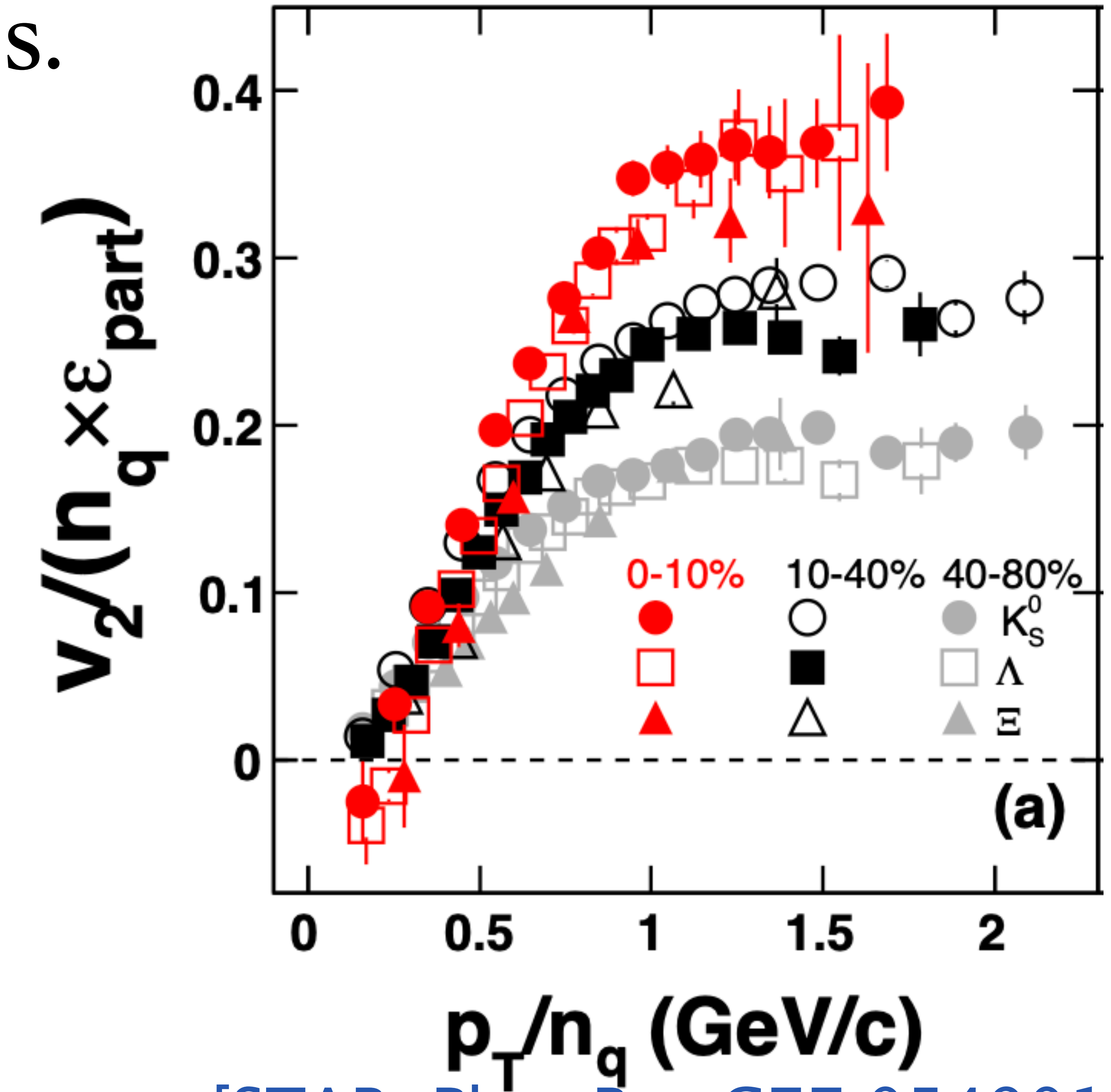
Recombination



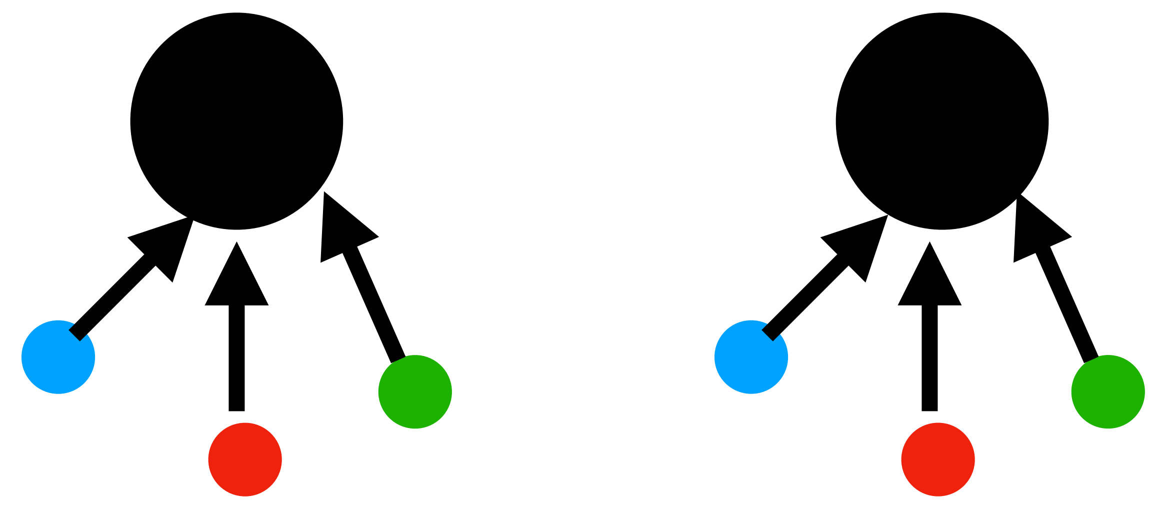
[R. J. Fries, S. A. Bass, B. Muller, C. Nonaka, Phys.Rev.Lett.90:202303,2003]

- Quark coalescence into hadrons.
- Number of constituent quarks scalling supports this picture.
- Alternatively at high transverse momentum one expects fragmentation of partons.

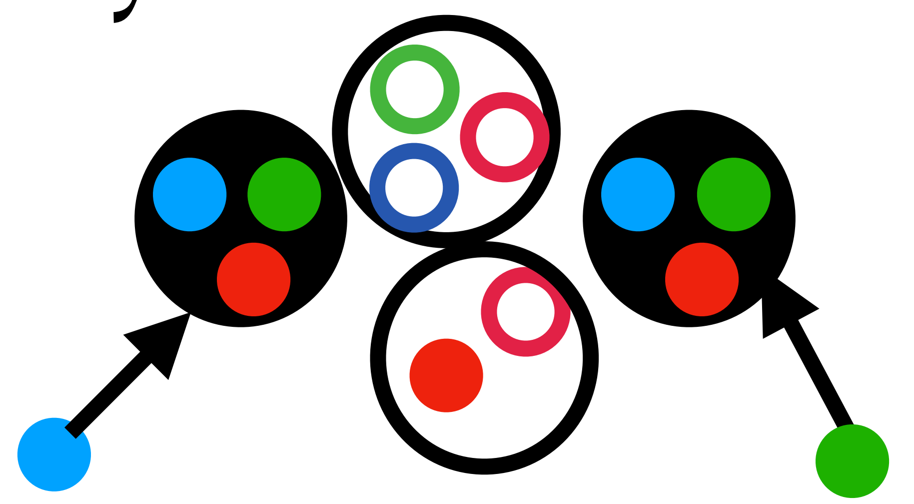
- Net-proton fluctuations originate from fluctuations of stopped quarks/baryons.
- Coalescence does not modify fluctuations.



[STAR, Phys.Rev.C77:054901,2008]



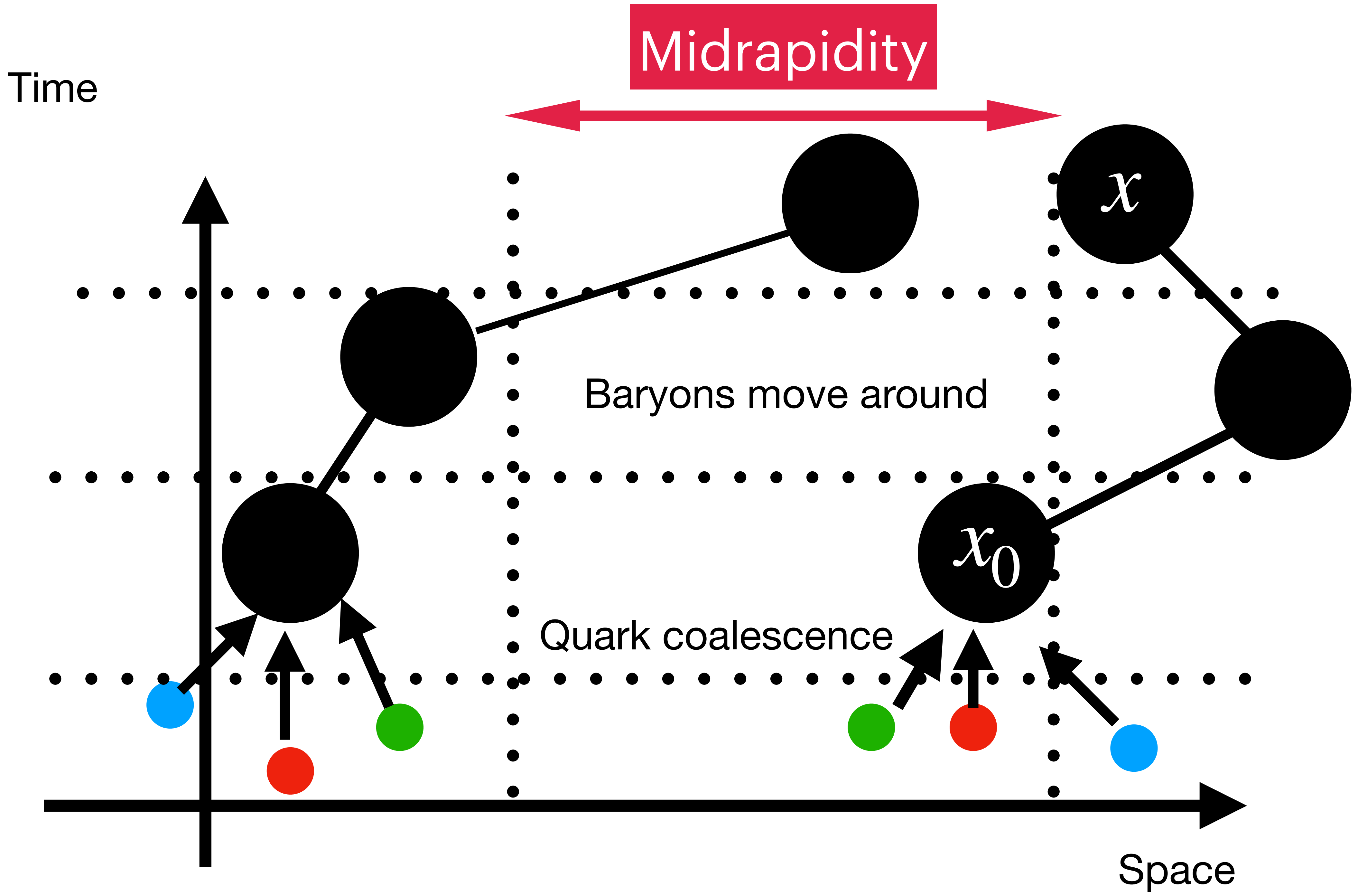
Fluctuations conserved on coalescence scale



Anti-quarks from vacuum

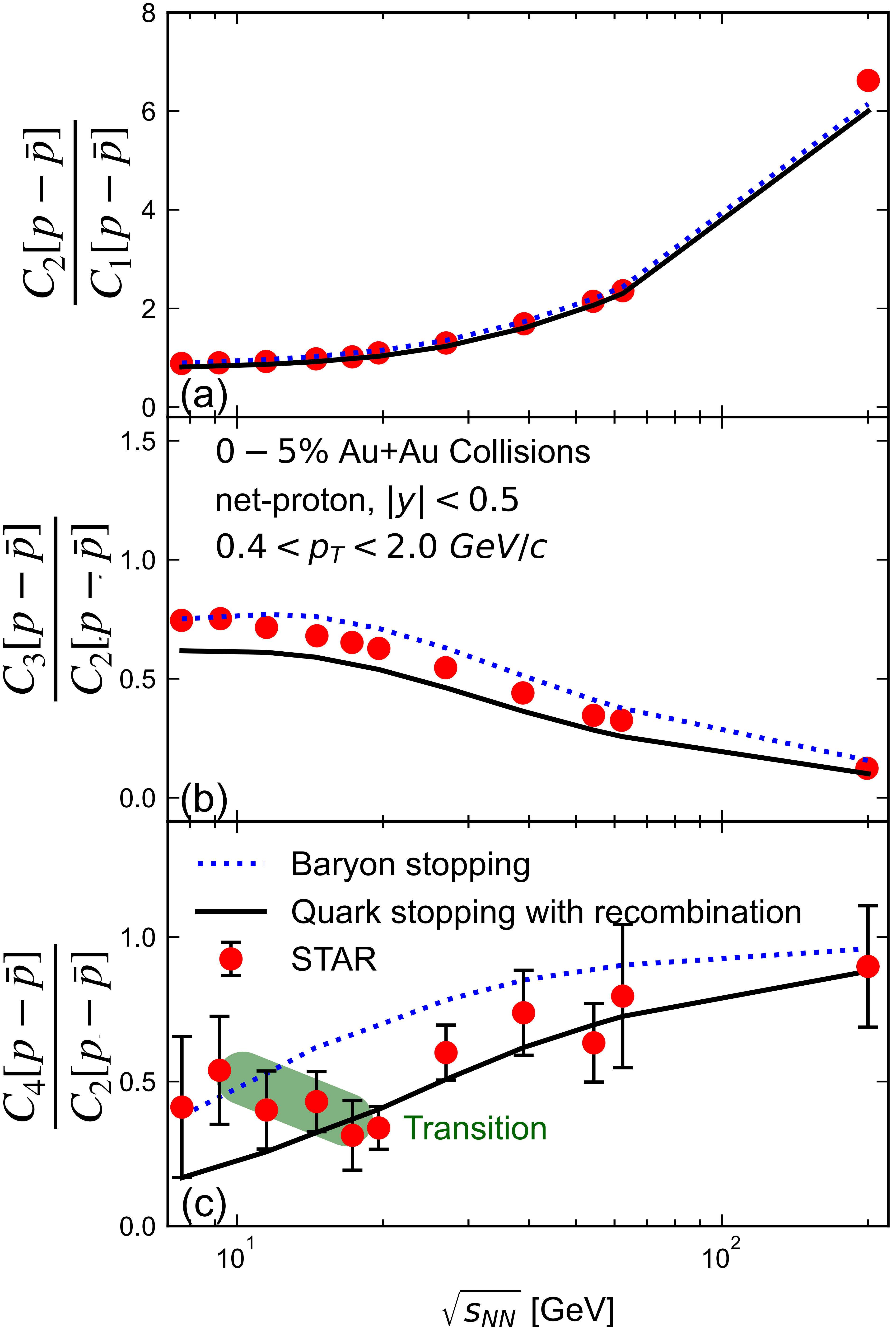
Drastically change baryon charge distribution

Hadronic stage



[OS, Physical Review C 111 (2), 024913]

- After recombination baryons undergo diffusion/scattering/momentum smearing
- Because quarks now move in a group of three fluctuations should recalibrate towards hadron resonance gas values - global conservation baseline



Model vs Data

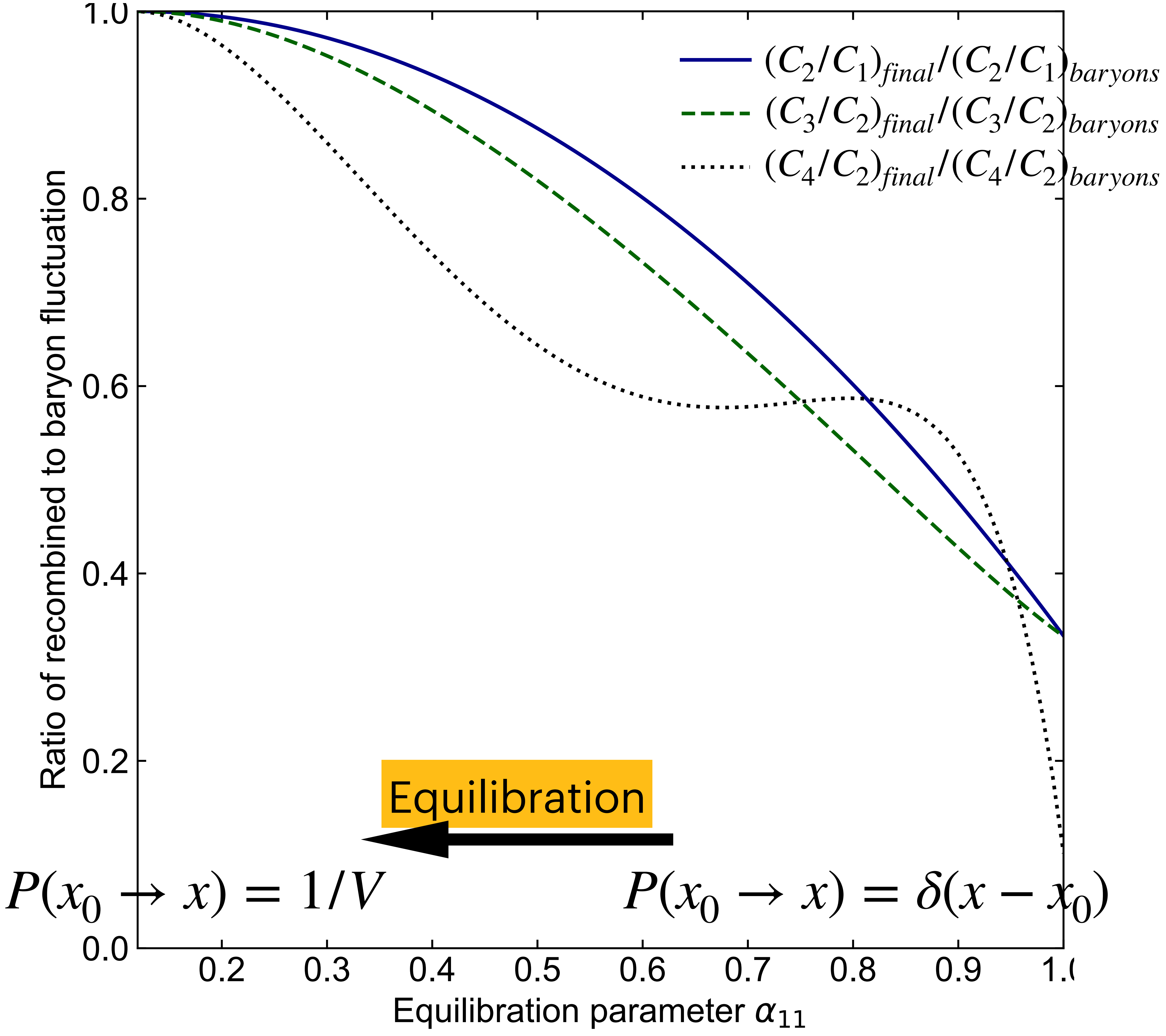
- Global conservation baseline fails to capture trends seen in the data.
- Local conservation and fluctuations at stopping stage improve the description.
- Recombination stage and subsequent hadron phase are crucial for modeling fluctuations following initial stage and hydrodynamic expansion.
- Memory about initial state dissipates faster for low orders of cumulants.
- Signal should survive in kurtosis and higher cumulants.
- At high energies stopping happens on a quark level. Challenge to baryon junction picture?

Highlights

- New data from BESII rises a lot of questions!
- Significant difference with global conservation baseline.
- Critical point from lattice is at STAR-FXT energies.
- New facilities are developed at energies $\sqrt{s_{NN}} < 7.7\ \mathrm{GeV}$, including Facility for Rare Isotope Beams.
- Great potential for discovery, connection with astrophysics and multi-messenger astronomy.
- Non-trivial behavior seen in the BESII can be caused by ignoring memory about initial-state and local charge conservation.
- Transition between baryon and quark charge carriers conveniently matches with energy and captures qualitative (and quantitive) trends seen in the data.

BACKUP

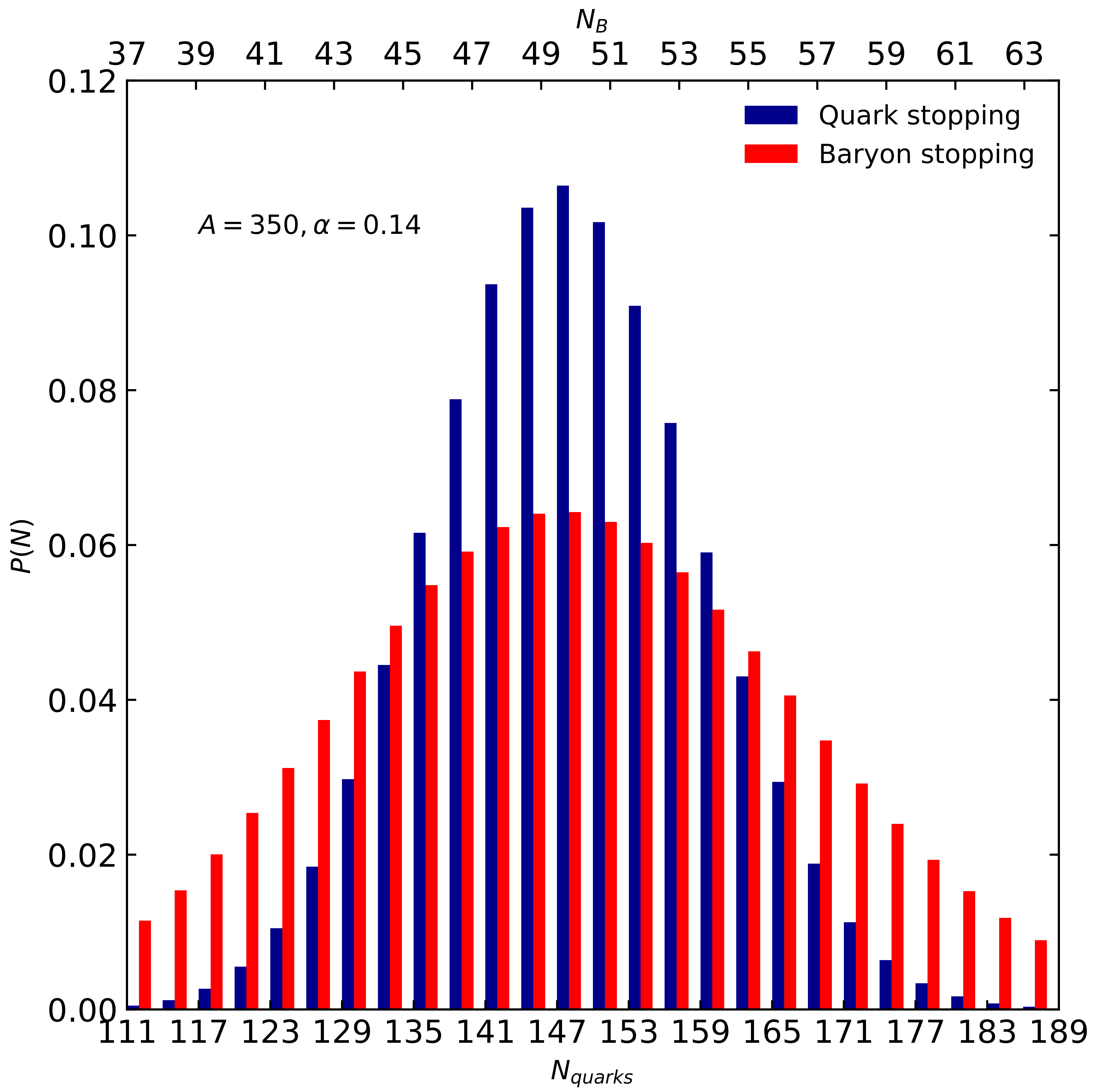
Model: Final stage

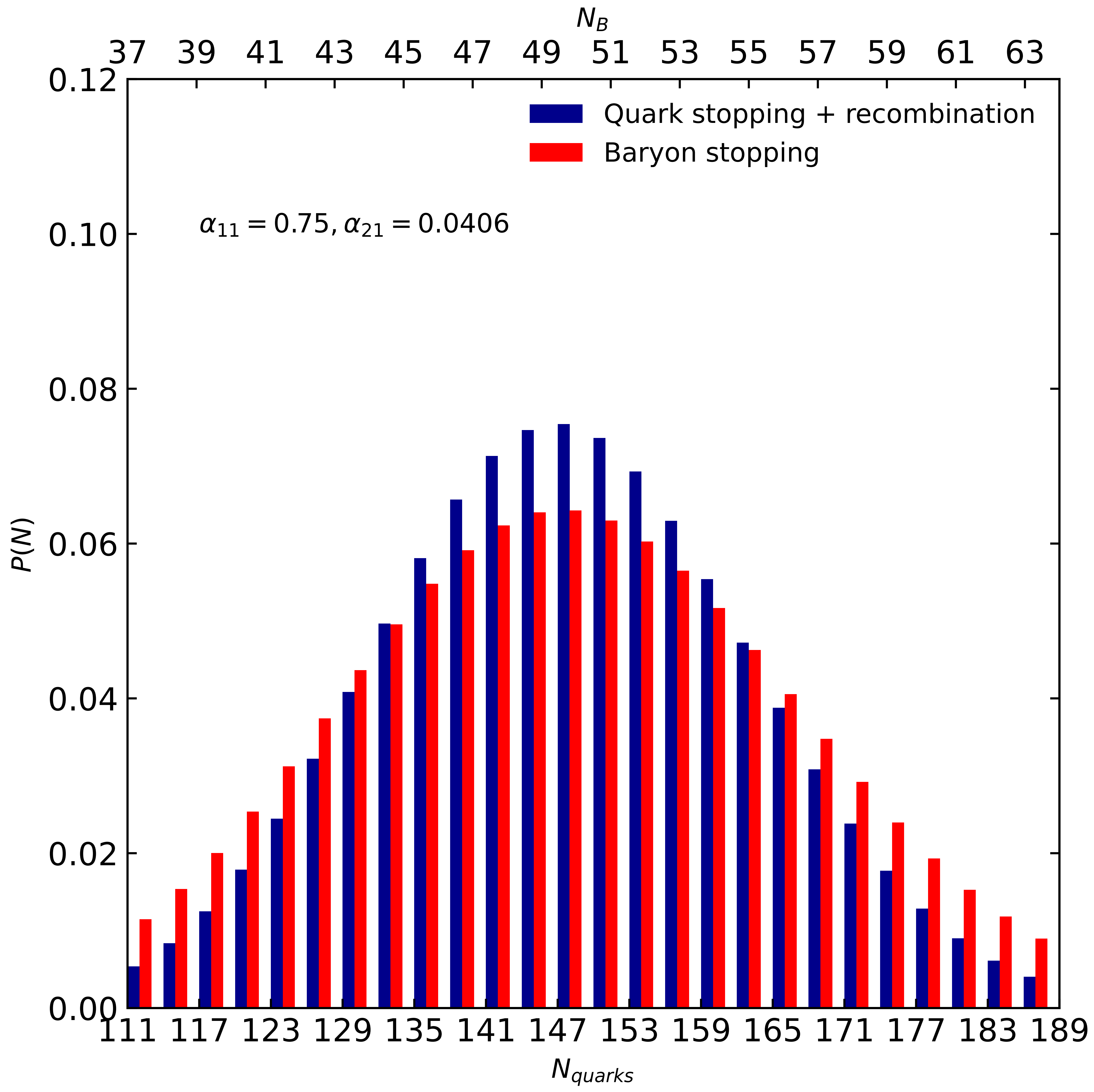


- The equilibration happens faster in lower orders of fluctuations.
- As a consequence scaled variance and skewness can approach baseline values.
- Signal survives in higher cumulants such as kurtosis C_4/C_2.

[OS, Physical Review C 111 (2), 024913]

Impact of final evolution stage





Final evolution reduces differences between stopping variants

Fluctuations: Global conservation baseline

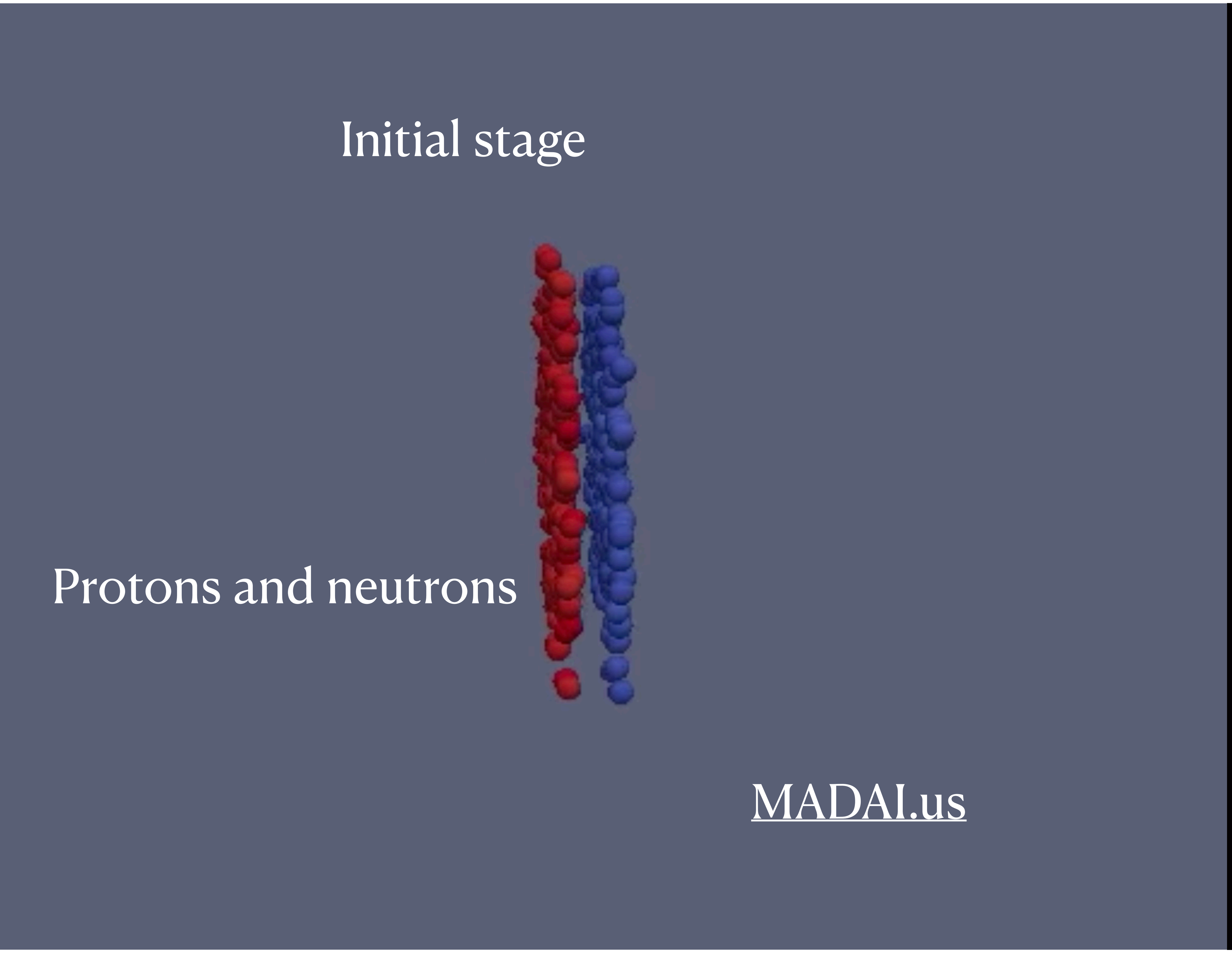
- (3+1)D viscous hydrodynamics
- Cooper-Frye freeze-out
- Exact global baryon number conservation (Baryon charge sampled over freeze-out hypersurface is fixed)

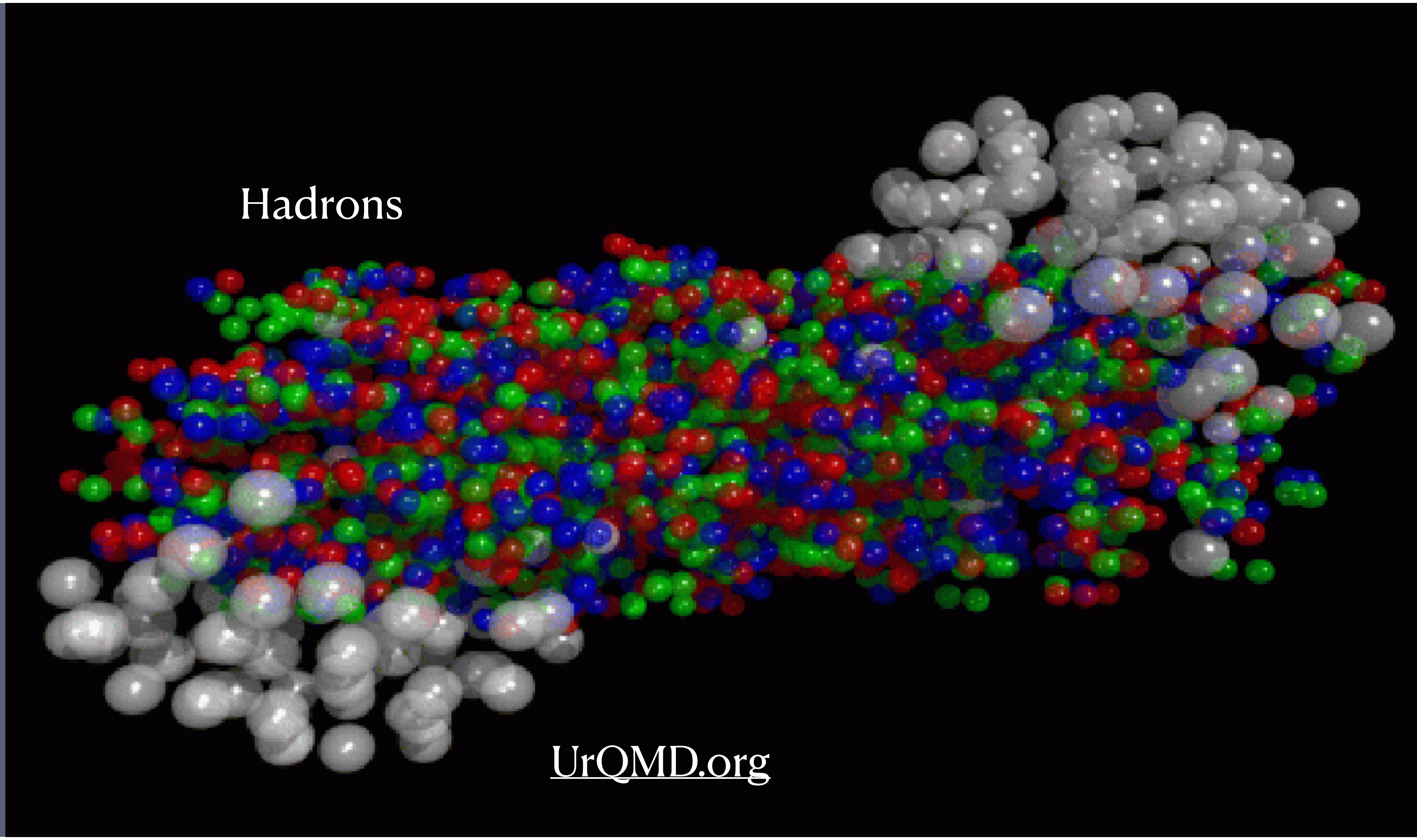
[V. Vovchenko, V. Koch, C. Shen, Phys. Rev. C 105, 014904 (2022)]

Lacks: local conservation, baryon stopping fluctuations

Fluctuations: Stages of Heavy-Ion Collisions

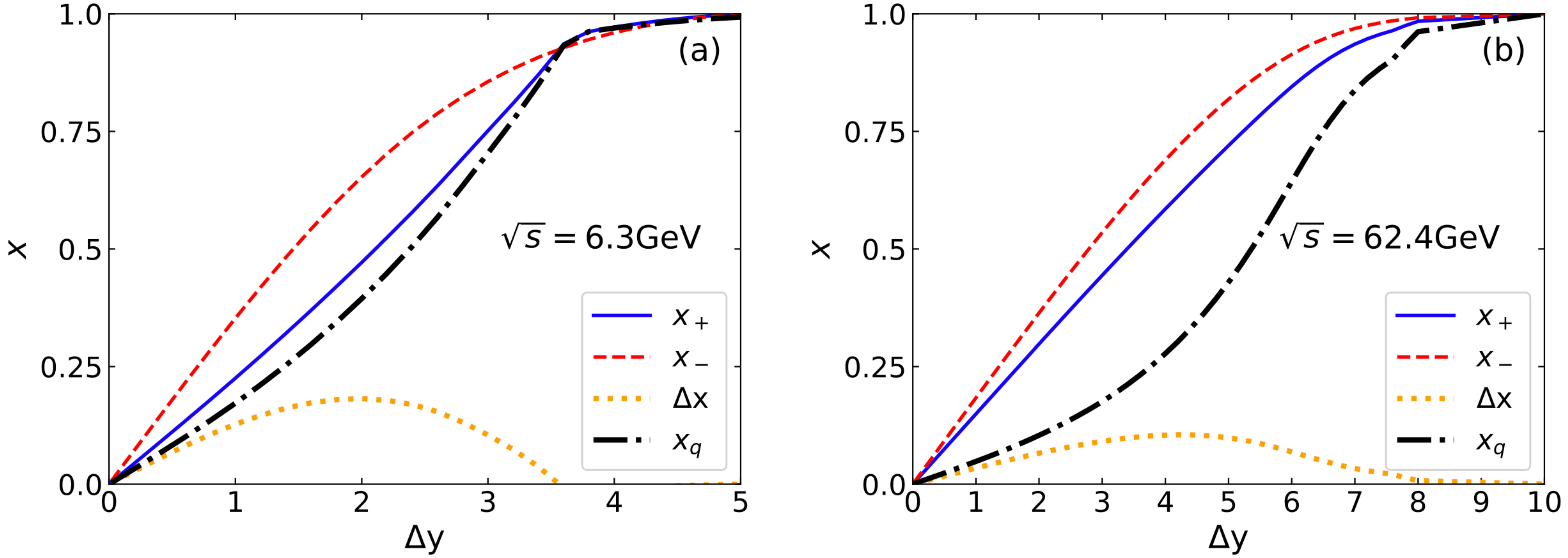
Low energy - Hadrons from initial to final state



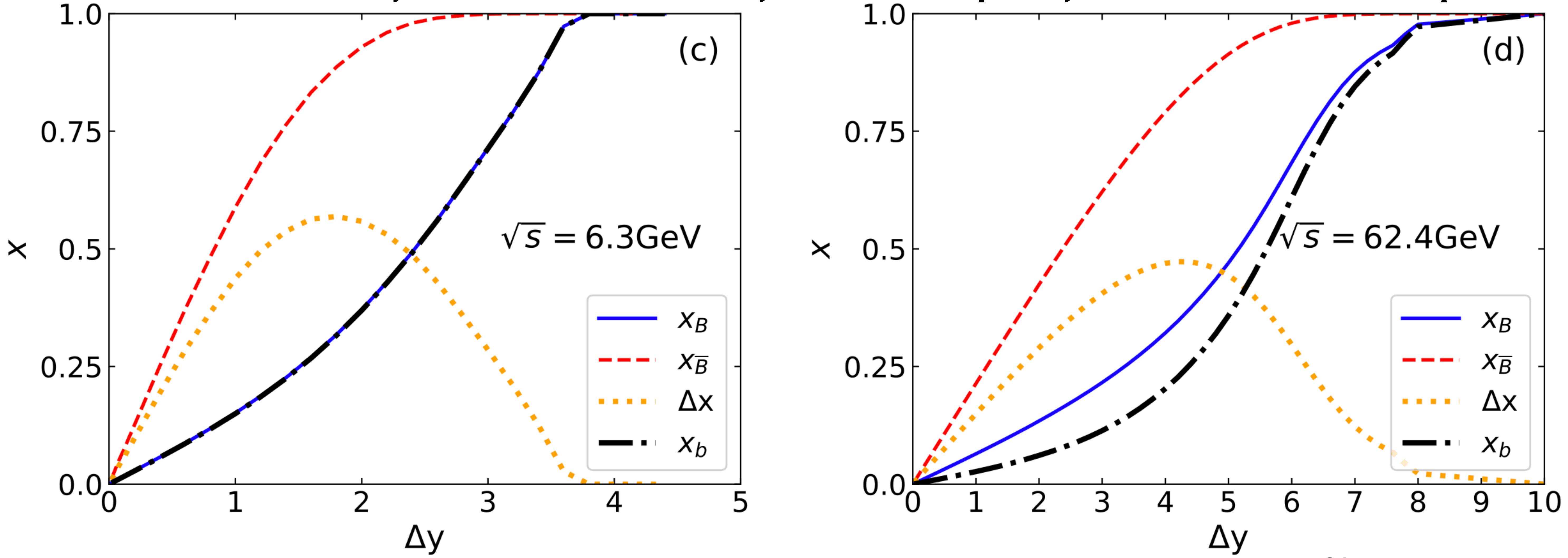


Fluctuations: Local charge conservation

Fraction of positive and negative charge to its value in full space



Fraction of baryons B and anti-baryons $\bar{B}$ in rapidity window to whole space

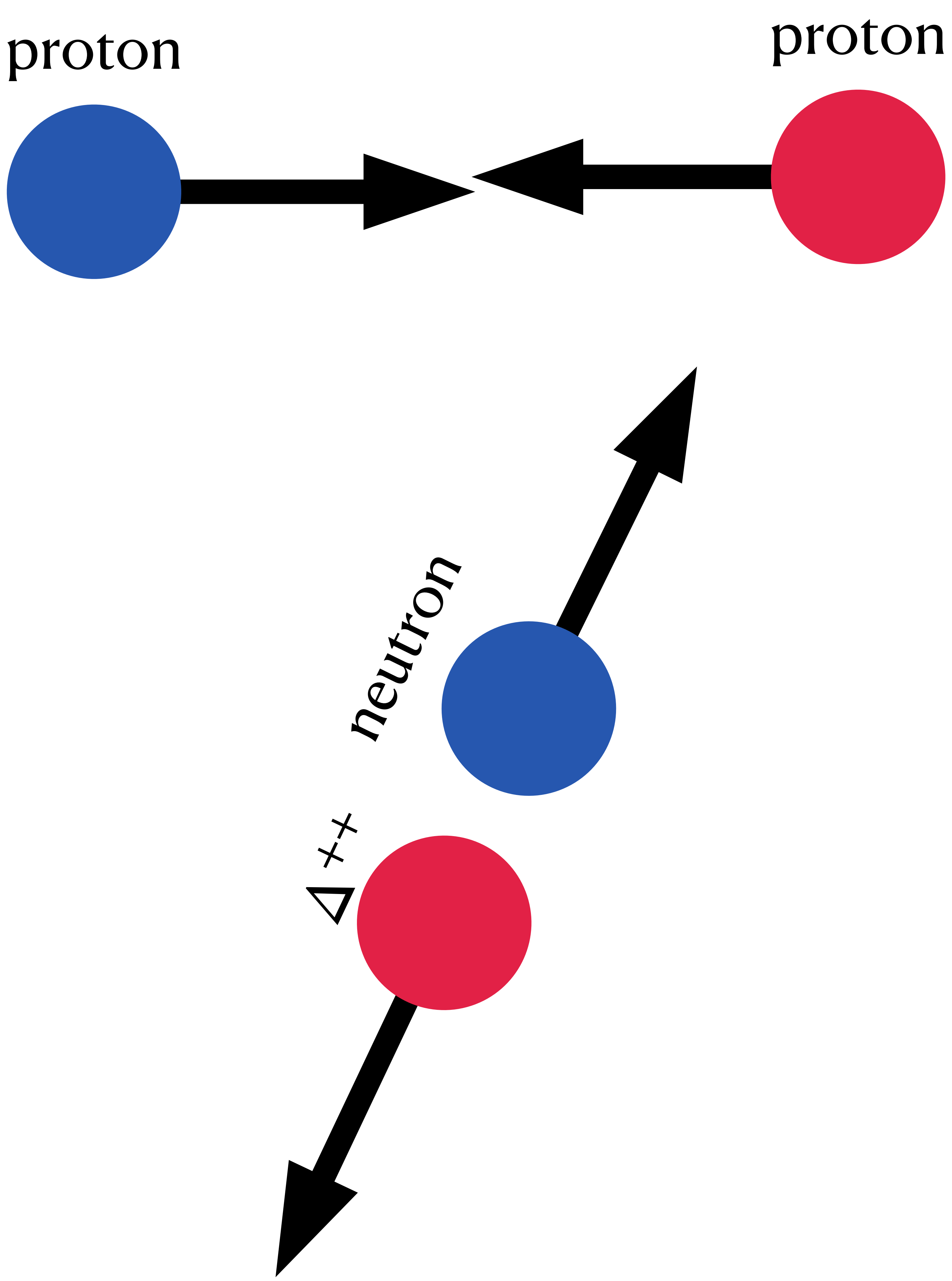


$$x = \frac{\int_{-\Delta y/2}^{\Delta y/2} dy \frac{dN}{dy}}{\int_{-\infty}^{\infty} dy \frac{dN}{dy}}$$

- UrQMD simulations of pp reactions.
- One observes that x for anti-particles is generally higher than for particles.
- Which means that most of them are more localized compared to particles.

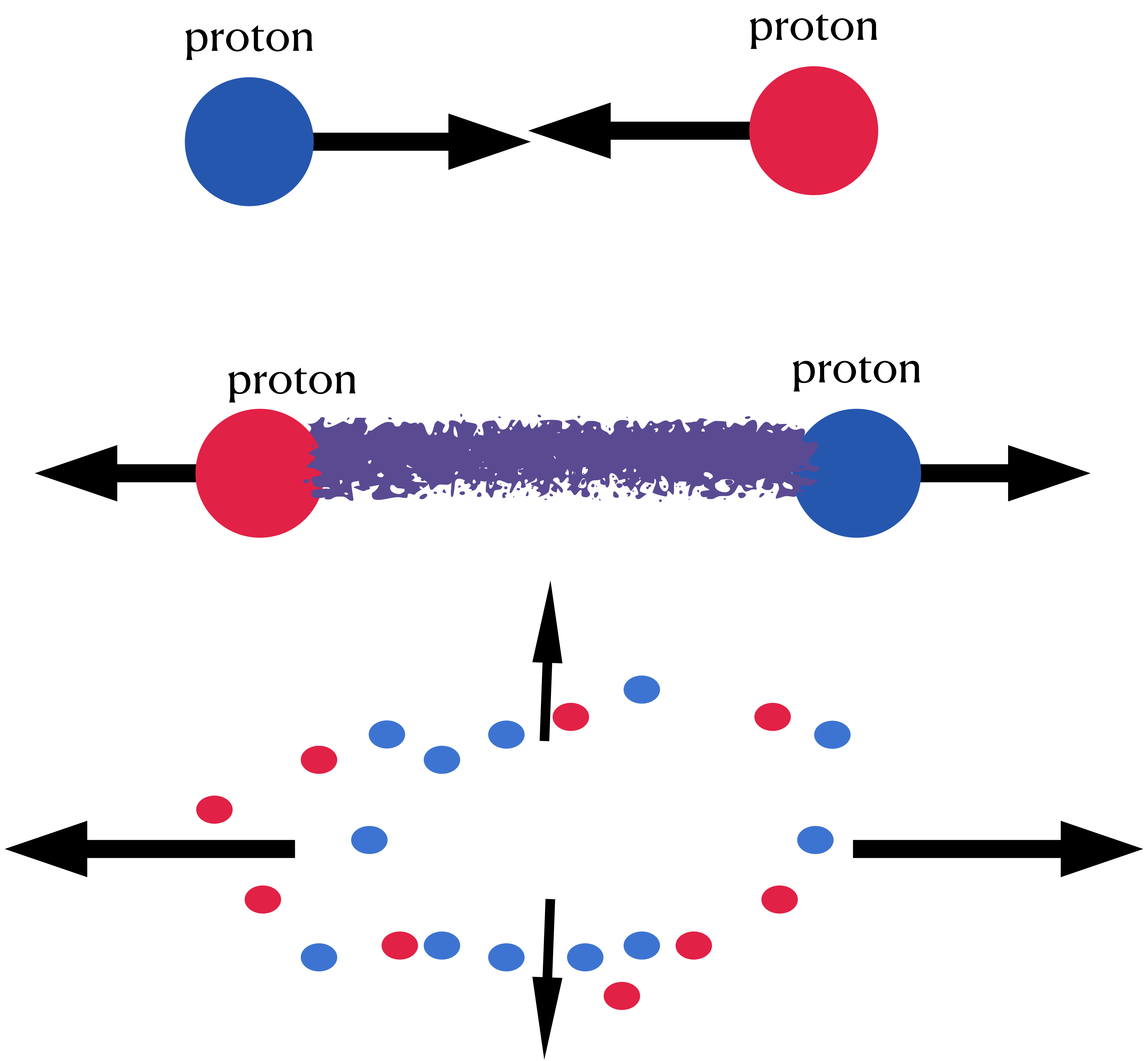
[OS, RV Poberezhnyuk, V Vovchenko, MI Gorenstein, Physical Review C 101 (2), 024917]

Fluctuations: Resonances



- At lower energies incoming nucleons can undergo inelastic $2 \rightarrow 2$ scattering forming baryon resonances.
- This leads to baryon charge distribution peaked around mid-rapidity.
- Baryon charge is carried by hadrons with integer charge.
- Neutral particles decaying into two charged has the effect similar to pair production.
- Cannot describe high multiplicity events at high energies that requires $2 \rightarrow N$ reactions

Fluctuations: Strings

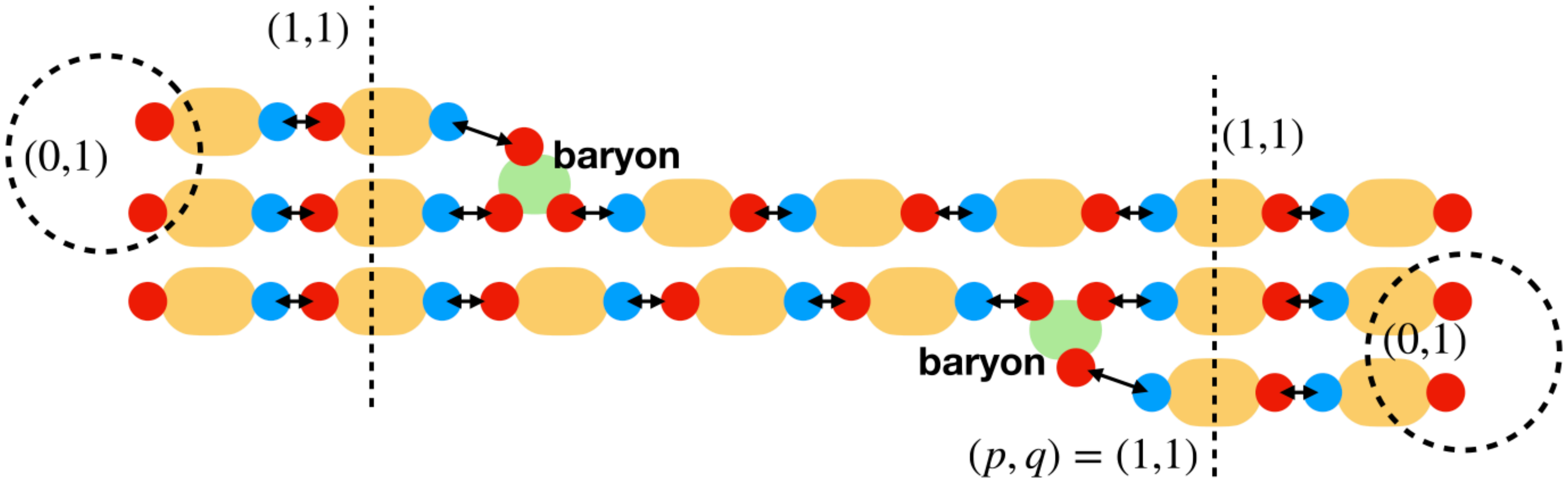


- At higher energies scattering can be described with strings stretched between quarks inside nucleons.
- This leads to baryon charge distribution being significantly wider.
- Baryon charge is carried by hadrons with integer baryon number?
- At very high energies one can consider baryon junction.

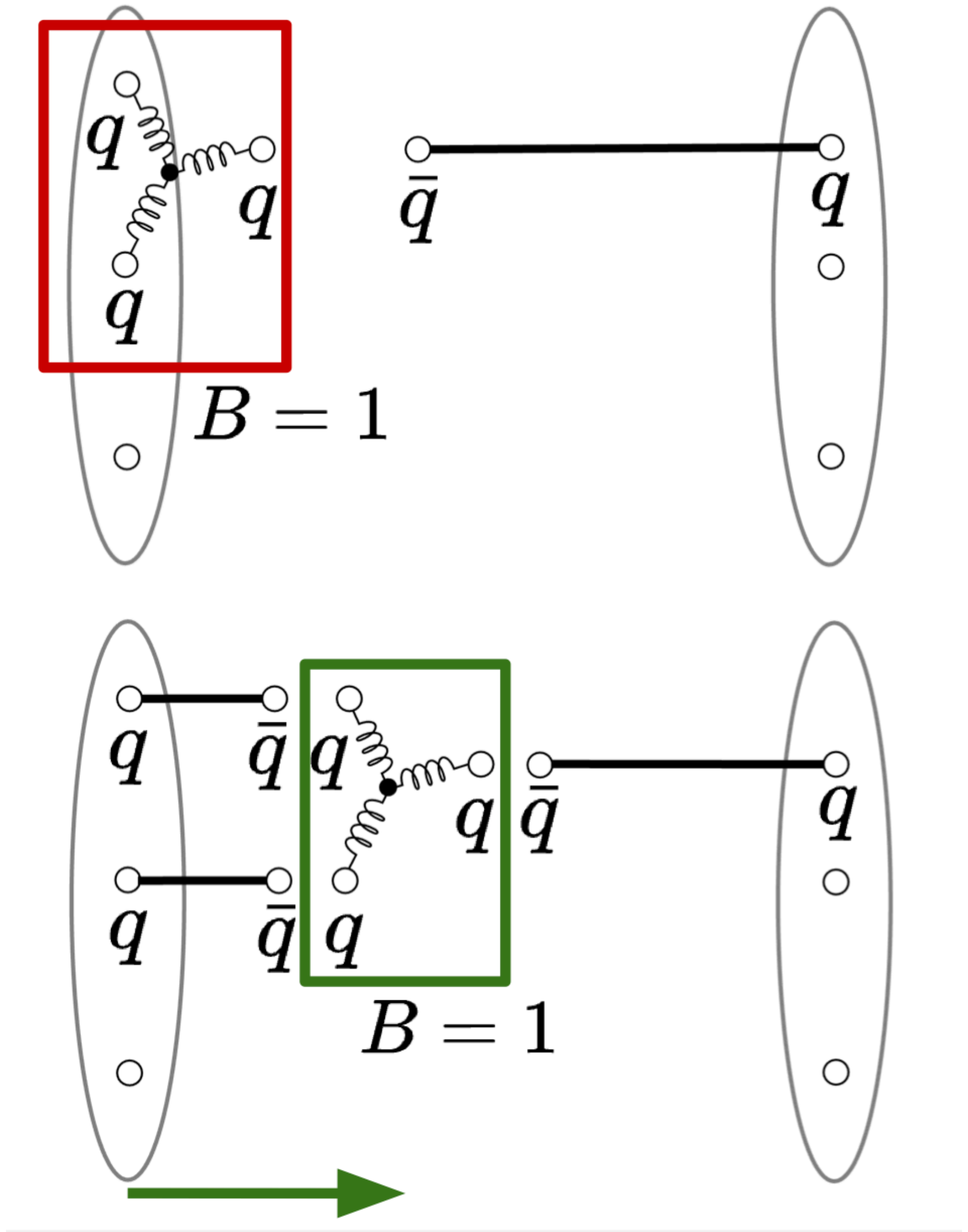
Aside: Baryon junctions vs. String melting

[G. Pihan, QM2024 Talk]

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

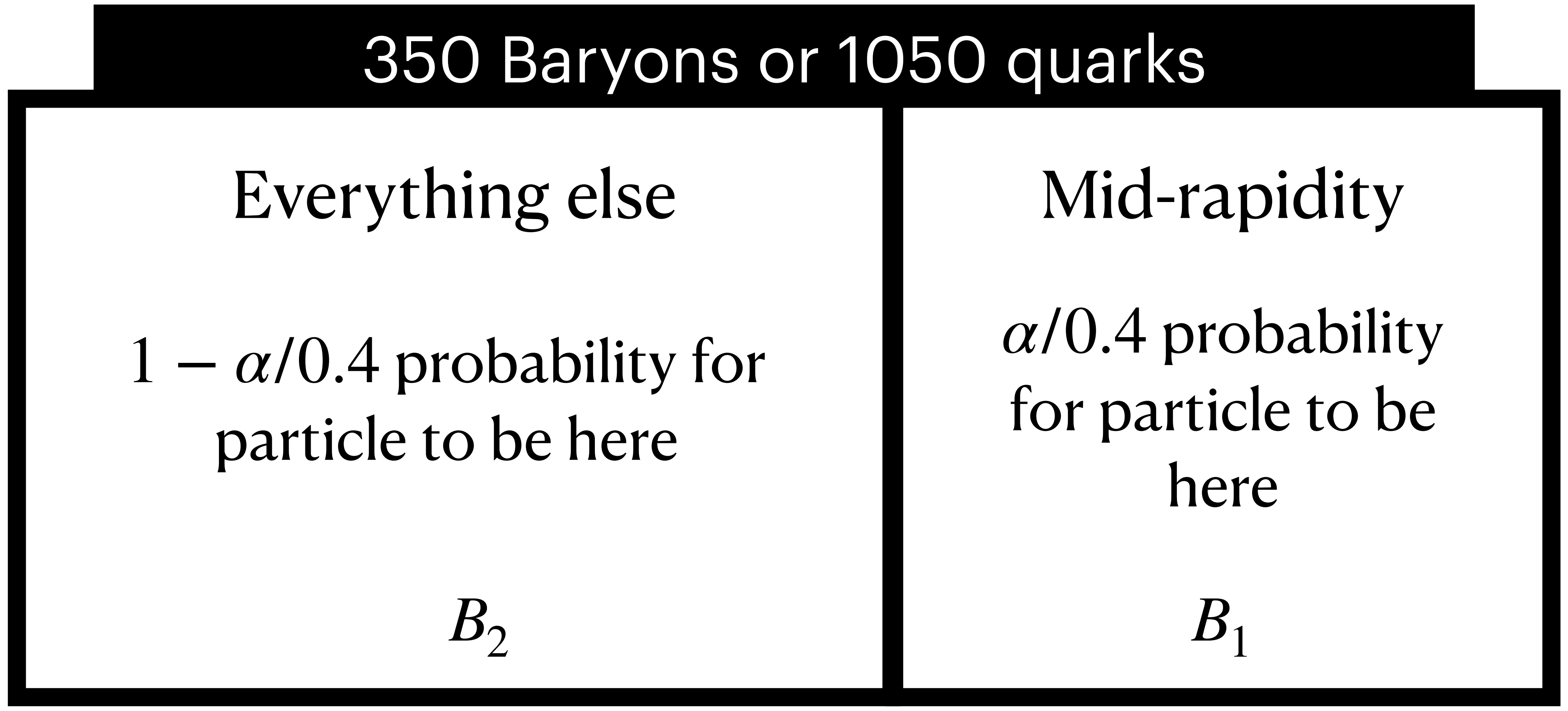


[S.Pratt, Phys. Rev. C **109**, 044910]



- Junctions transfer baryon charge in units of a single baryon.
- Are AuAu collisions different from pp? Are quarks still move as a baryon at very high energy?
- Does string melting introduce individual quarks as charge carriers?

Model: Final stage



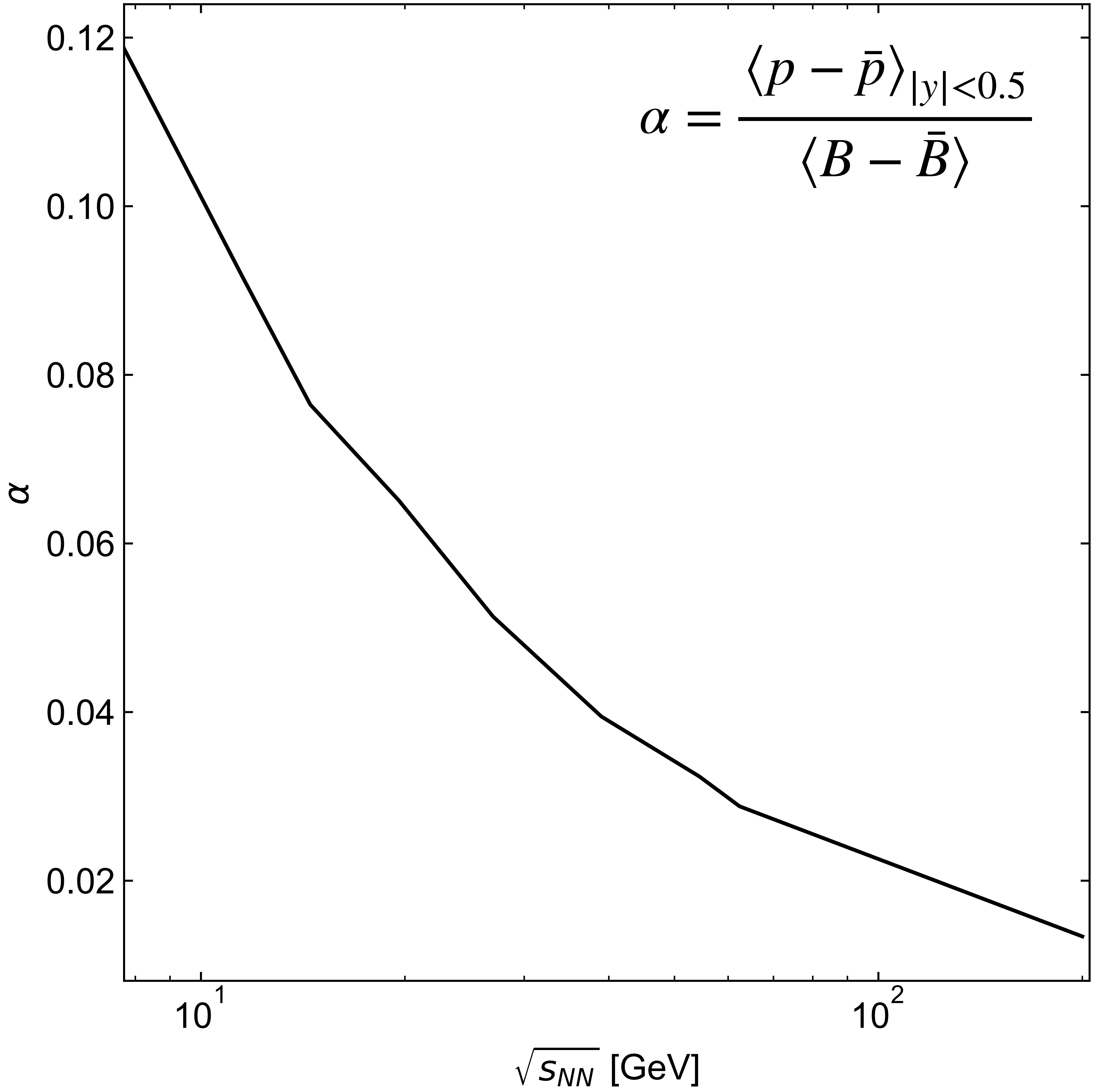
Joint probability distribution: $P^0(B_1, B_2)$

Characteristic function of the distribution:

$$F^0(k_1, k_2) = \langle e^{i(k_1 B_1 + k_2 B_2)} \rangle$$

Cumulants of joint distribution:

$$\kappa^0_{1_1 \ldots 1_n 2_1 \ldots 2_m} = \frac{1}{(n+m)!} \partial^n_{ik_1} \partial^m_{ik_2} \ln F^0(k_1, k_2) \,|_{k_1=0, k_2=0}$$



[OS, Physical Review C 111 (2), 024913]

Hadron stage further evolves cumulants!

Effective mapping between cumulants at recombination $\kappa^0_{1_1 \ldots 1_n 2_1 \ldots 2_m}$ and after hadronic stage $C_1, C_2, \cdots$

$$C_1 = \kappa^0_j \alpha_{j1}$$
$$C_2 = \kappa^0_j \alpha_{j1}(1 - \alpha_{j1}) + \kappa^0_{jk} \alpha_{j1} \alpha_{k1}$$
$$C_3 = \kappa^0_j \alpha_{j1}(1 - \alpha_{j1})(1 - 2\alpha_{j1}) + 3\kappa^0_{jk} \alpha_{j1}(1 - \alpha_{j1})\alpha_{k1} + \kappa^0_{jkl} \alpha_{j1} \alpha_{k1} \alpha_{l1},$$
$$\cdots$$

- α_{11} probability for a baryon to be formed inside acceptance and finish there.
- α_{12} probability for a baryon to be formed inside acceptance but exit at the end.
- α_{22} probability for a baryon to be formed outside acceptance and don't be detected.
- α_{21} probability for a baryon to be formed outside acceptance and be detected.

[OS, Physical Review C 111 (2), 024913]

350 Baryons or 1050 quarks

Everything else

B_2

Mid-rapidity

B_1

350 Baryons

Everything else

Baryons coming from or to mid-rapidity

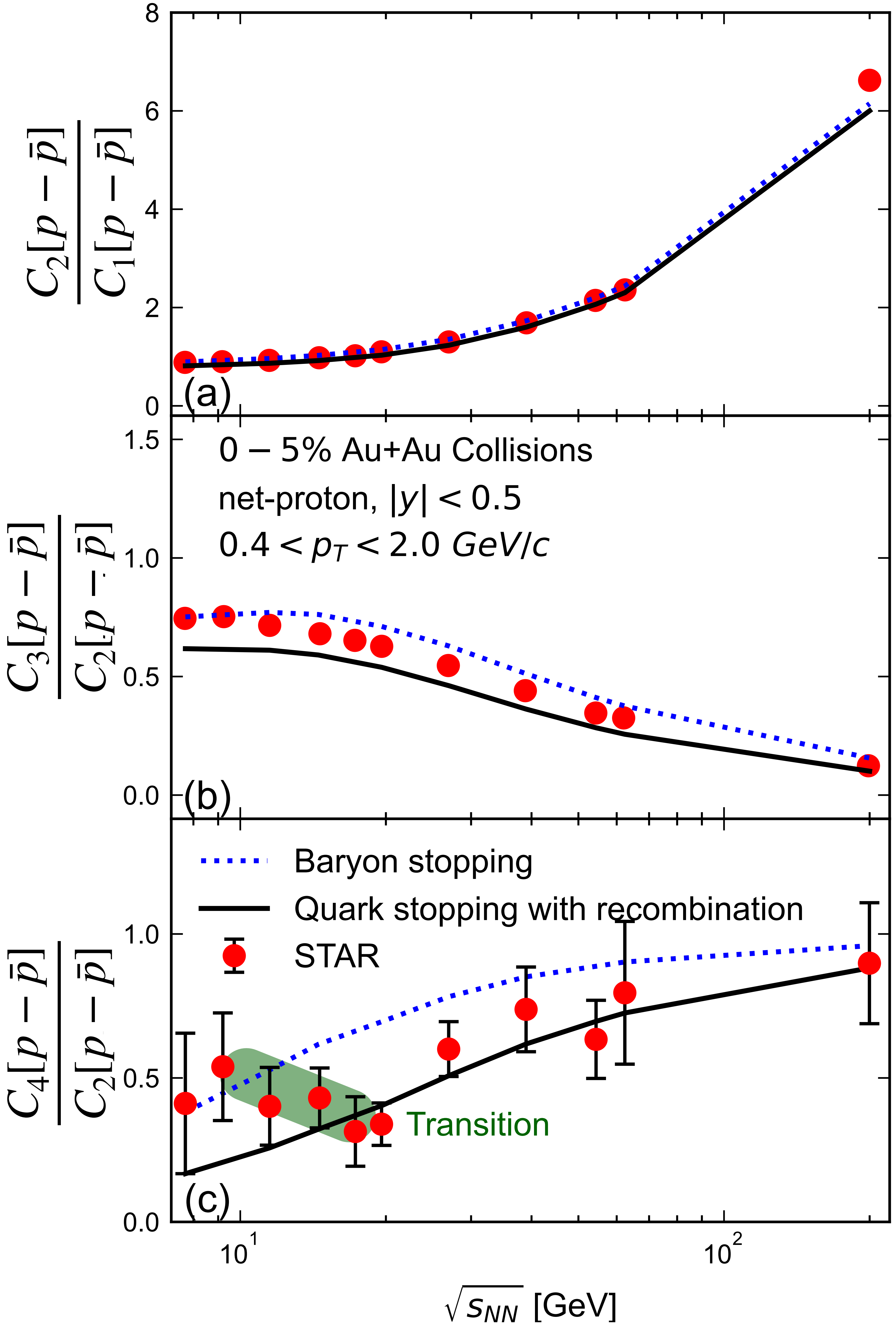
δB_2

Mid-rapidity

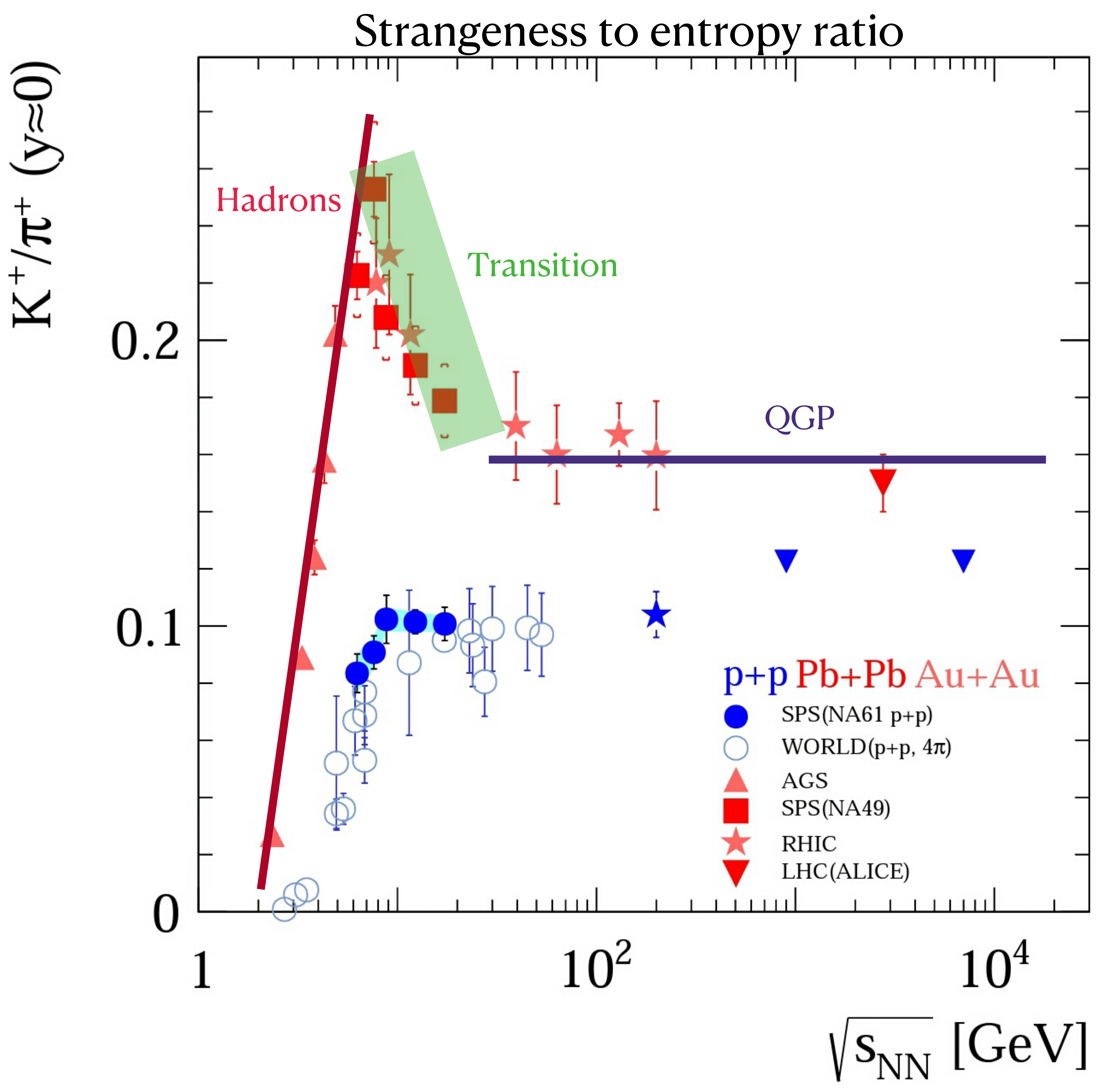
Baryons coming from outside acceptance or leaving it

δB_1

Models vs Experiment



[OS, Physical Review C 111 (2), 024913]



[Marek Gazdzicki, Mark Gorenstein, Peter Seyboth, Acta Phys.Polon.B42:307-351,2011]