Mapping the QCD Phase Diagram

The Beam Energy Scan II at RHIC

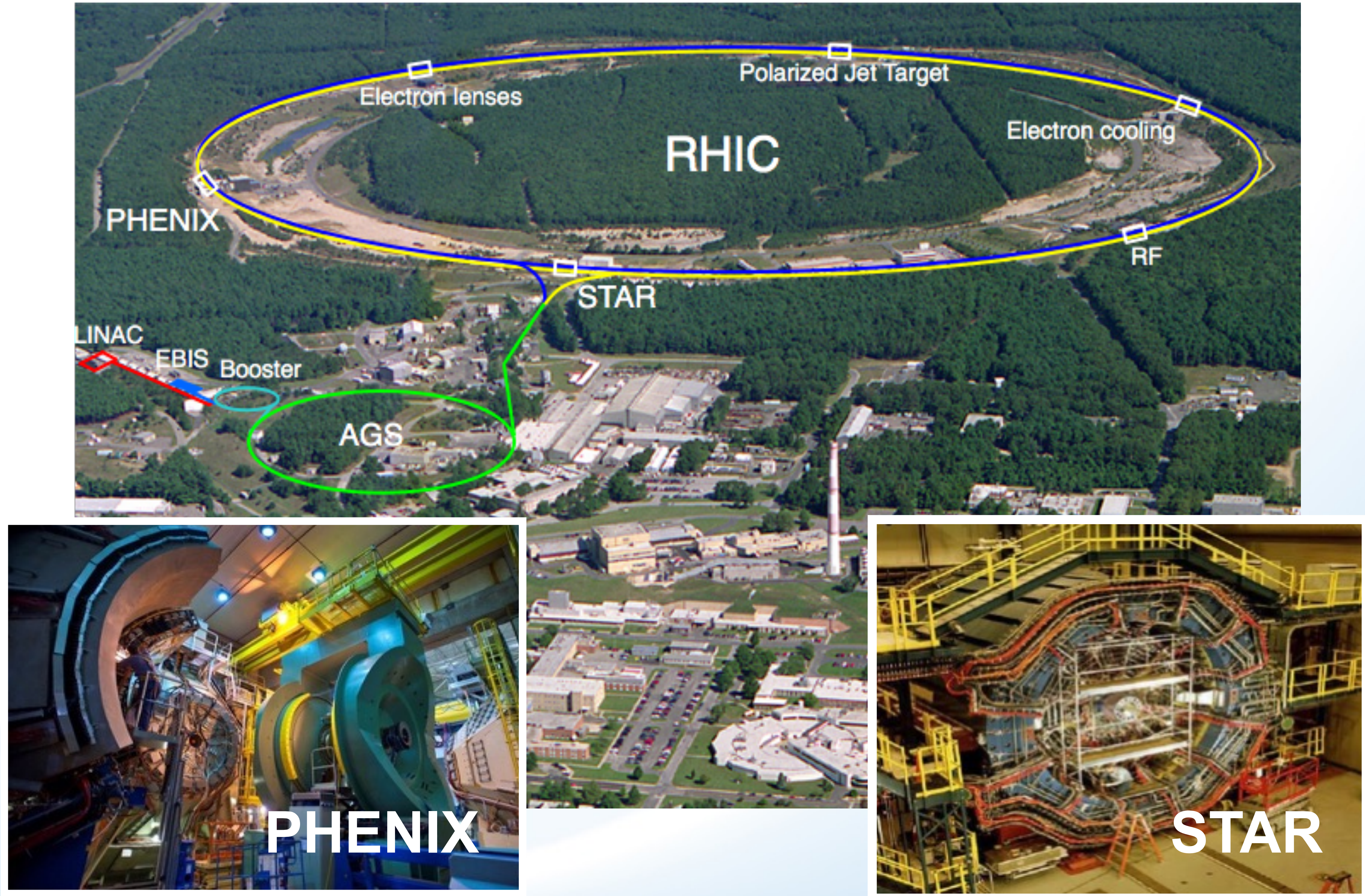
Berndt Mueller
Brookhaven National Laboratory
& Duke University

BEST Collaboration Meeting
Indiana University
9-11 May 2016

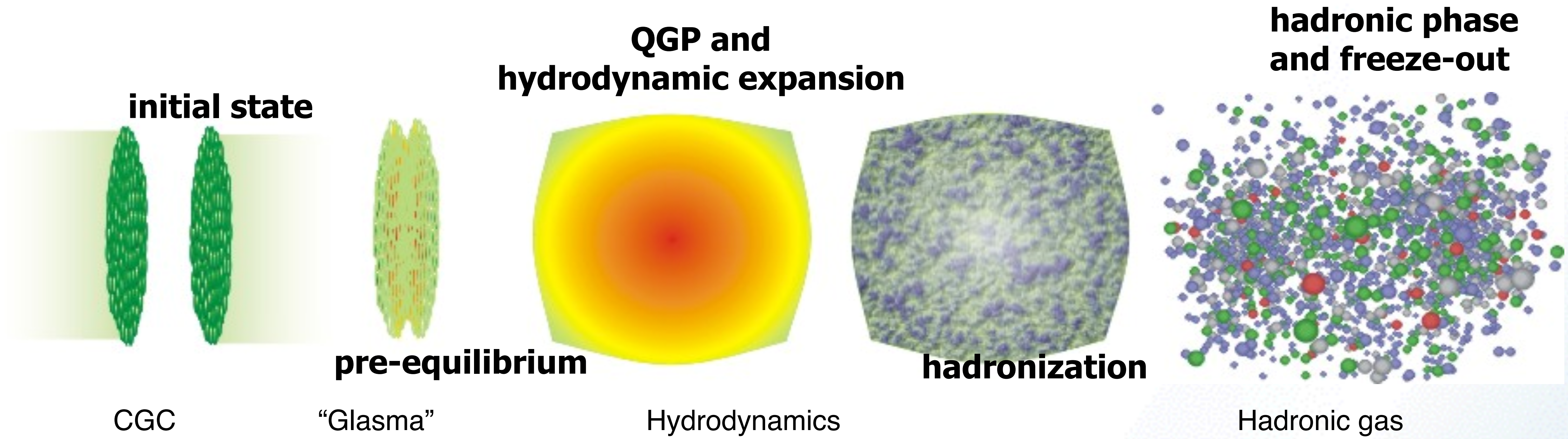
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

The Relativistic Heavy Ion Collider



Recreating QGP on Earth in Little bangs



fast moving nuclei

nuclei collide

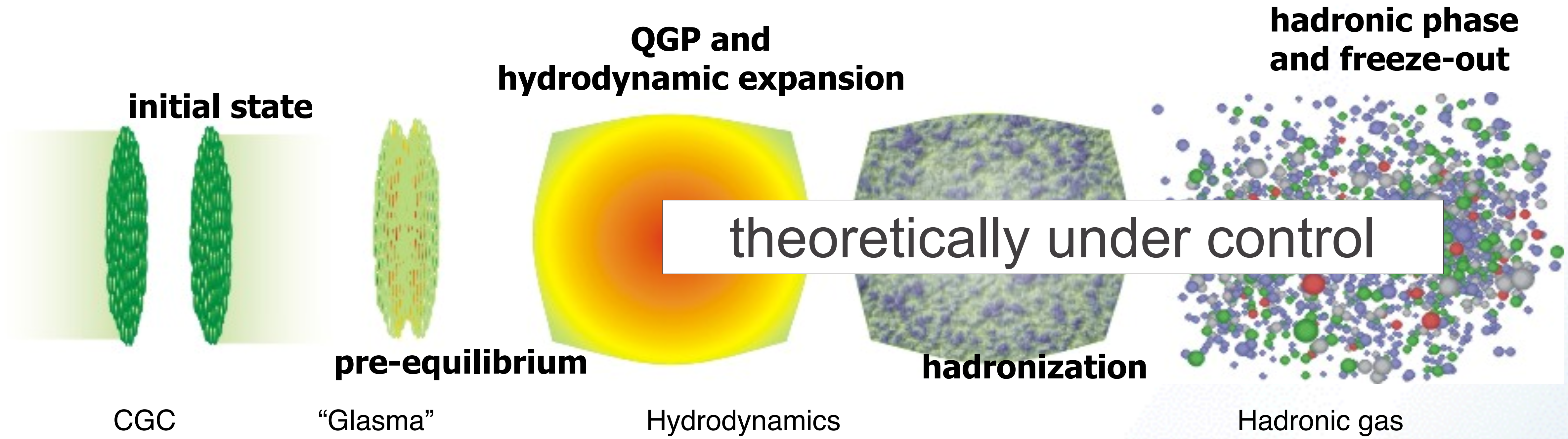
expanding & cooling QGP

hadrons re-formed

observed in experiments

Comprehensive framework based on transport theory provides description of reaction from start to finish

Recreating QGP on Earth in Little bangs



fast moving nuclei

nuclei collide

expanding & cooling QGP

hadrons re-formed

observed in experiments

Comprehensive framework based on transport theory provides description of reaction from start to finish

Equation of State of QCD Matter

Equation of State

EOS of flowing matter has conservative and dissipative contributions:

$$T_{\mu\nu} = T_{\mu\nu}^{(\mathrm{cons})} + T_{\mu\nu}^{(\mathrm{diss})}$$
$$= \varepsilon u_\mu u_\nu + p\left(u_\mu u_\nu - g_{\mu\nu}\right)$$
$$+ \eta\left(\partial_\mu u_\nu + \partial_\nu u_\mu - \tfrac{2}{3} g_{\mu\nu}\partial_\alpha u^\alpha\right) + \zeta\,\partial_\alpha u^\alpha\left(g_{\mu\nu} - u_\mu u_\nu\right)$$

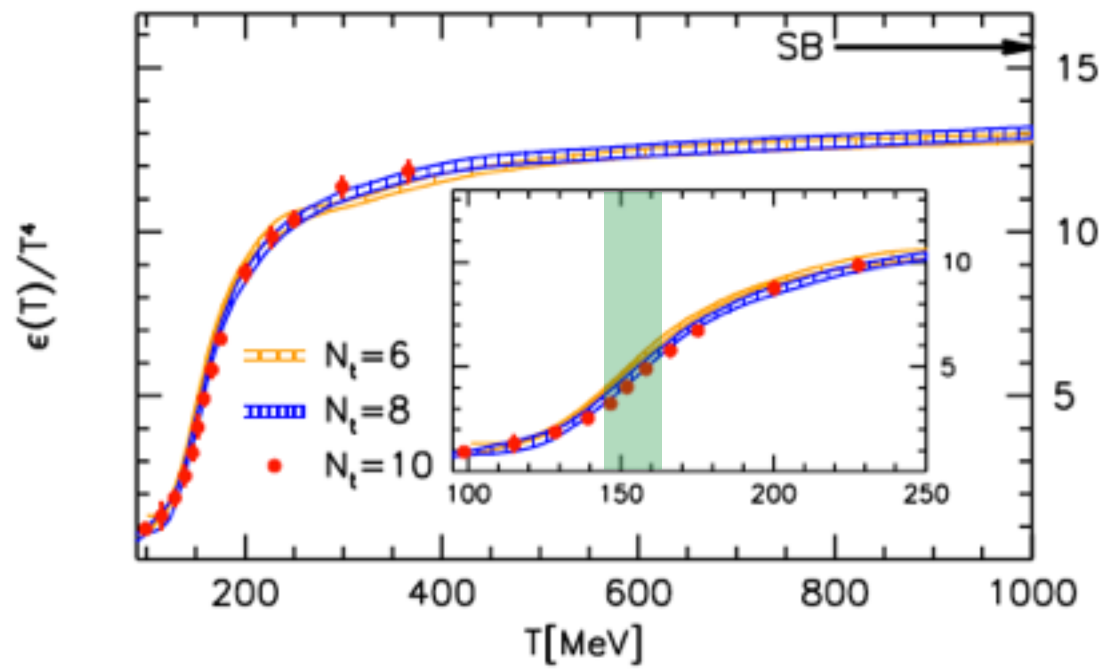
When $\zeta(\partial_\alpha u^\alpha) > p$, the matter becomes unstable and cavitates.

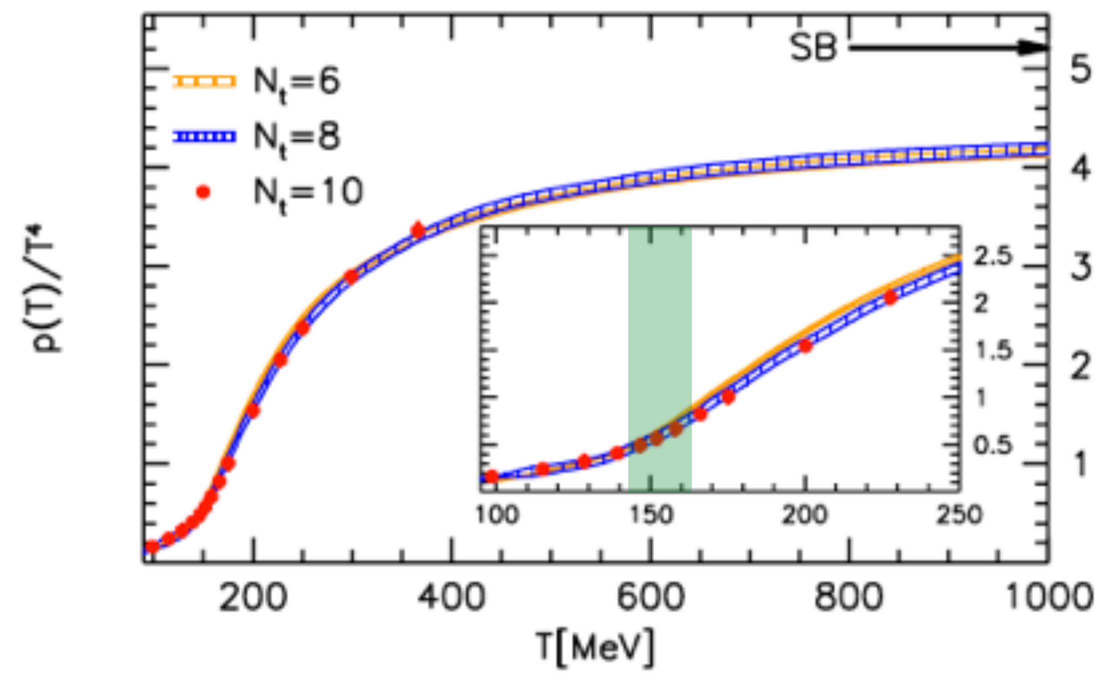
In general, $T_{\mu\nu}$ is a dynamical quantity that relaxes to its equilibrium value on a time scale τ_π that itself is related to the viscosity.

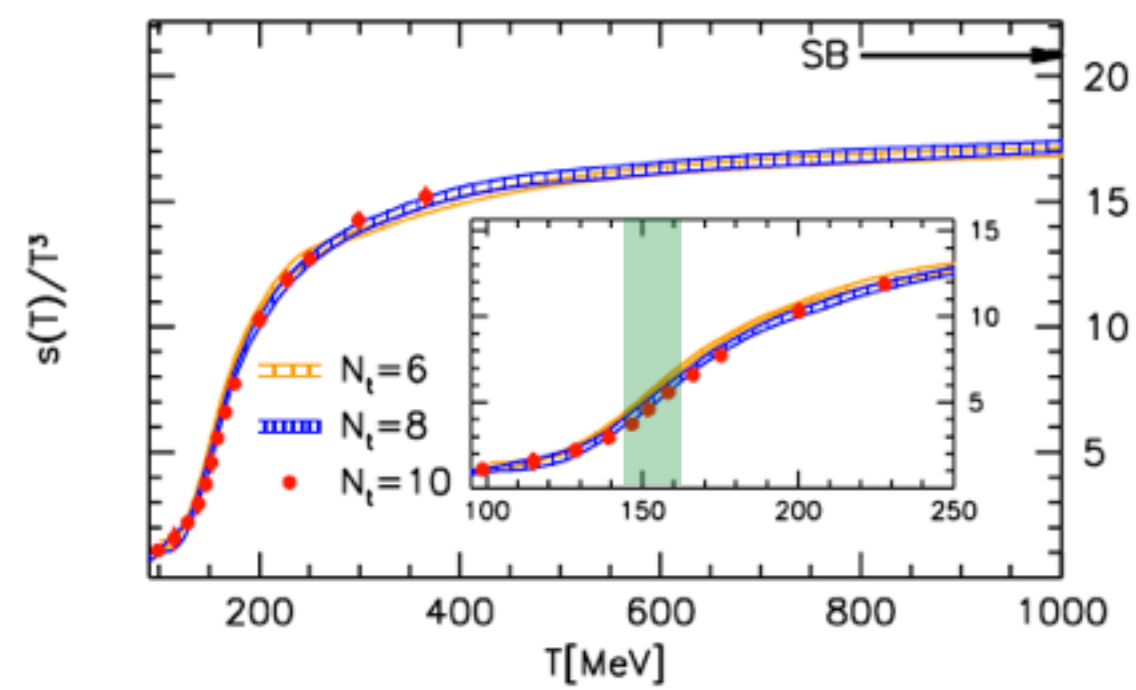
While the shear viscosity η has a lower quantum bound, the bulk viscosity ζ vanishes for conformally invariant matter.

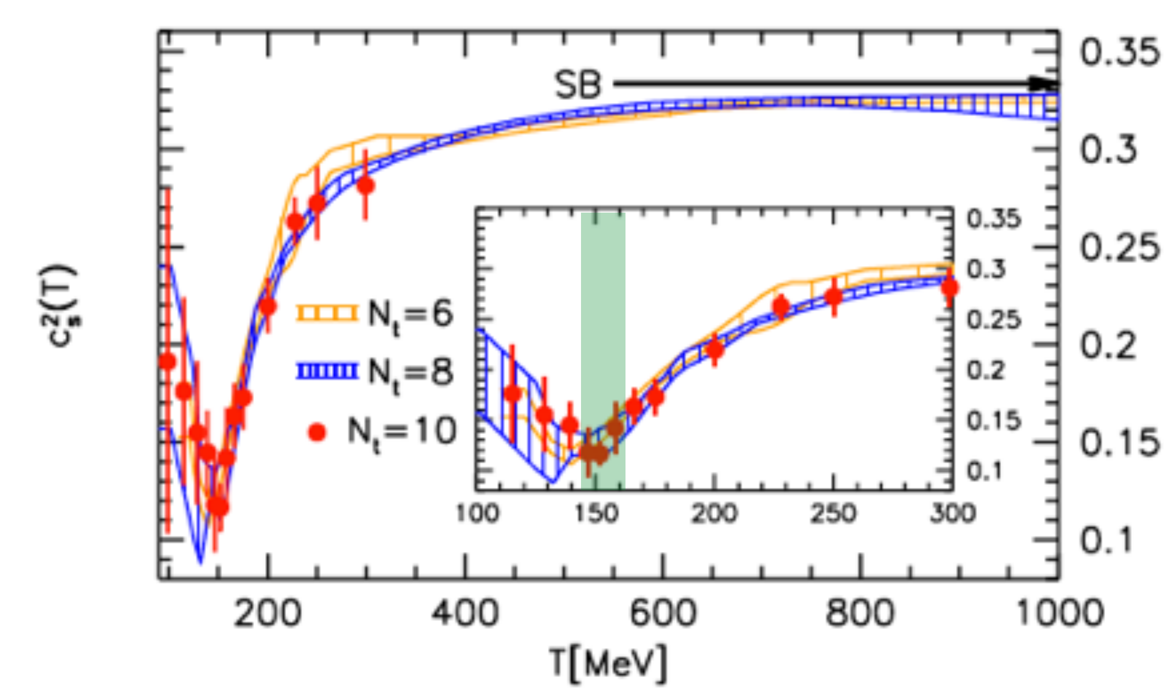
QCD EOS at $\mu_B = 0$

Results (true quark masses, continuum extrapolated) have converged; full agreement found between groups (HotQCD, Wuppertal-Budapest) using different quark actions.



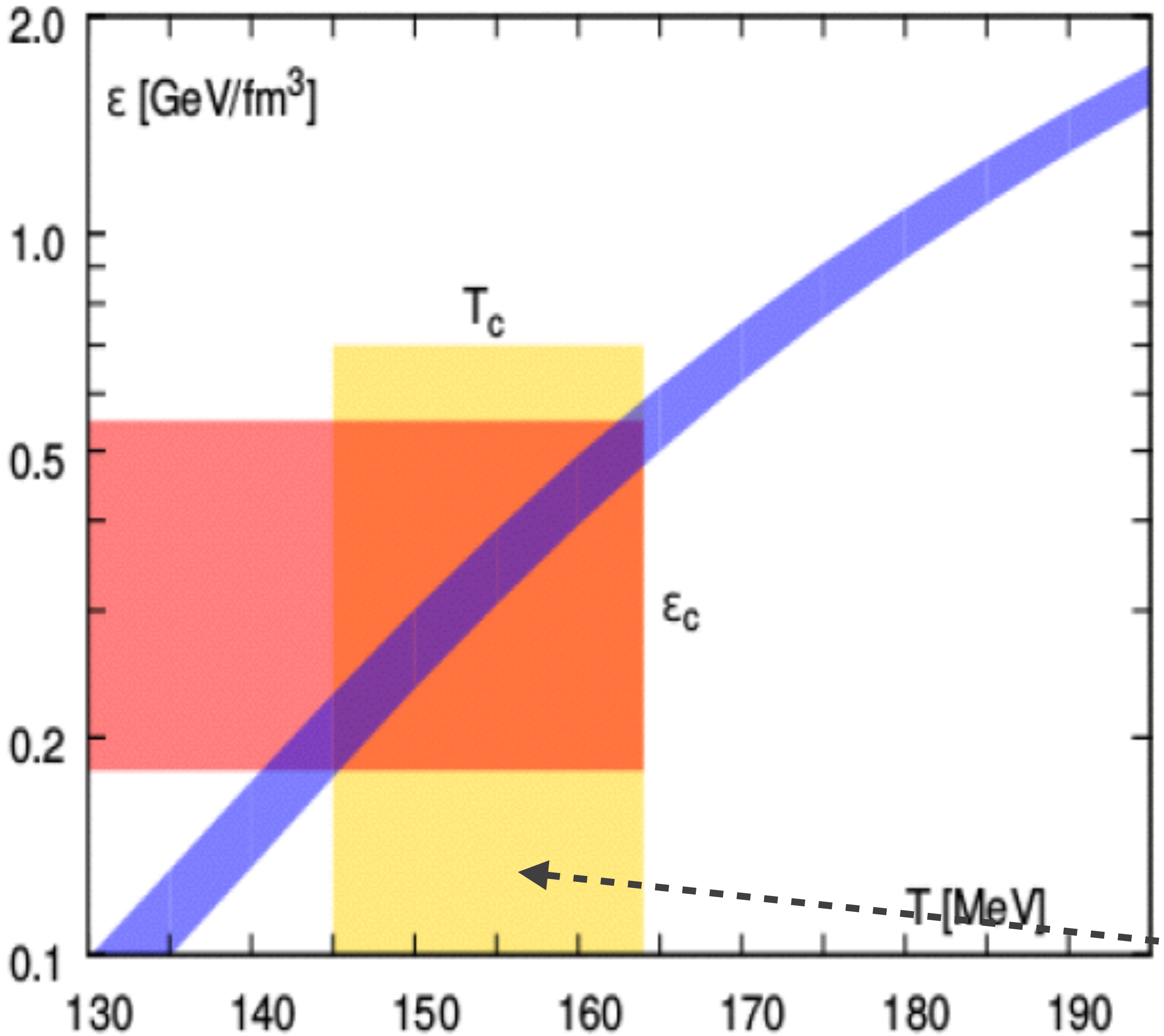






(Pseudo-) Critical temperature

Transition between hadron gas and quark-gluon plasma is a **cross-over** at $\mu_B = 0$ and for small μ_B. Precise value of T_c depends on the quantity used to define it.



HotQCD: arXiv:1407.6387

Pseudo-critical temperature from chiral susceptibility peak:

T_c = 154 ± 9 MeV

critical energy density:

$\epsilon_c = 0.18 - 0.50\ \mathrm{GeV/fm^3}$

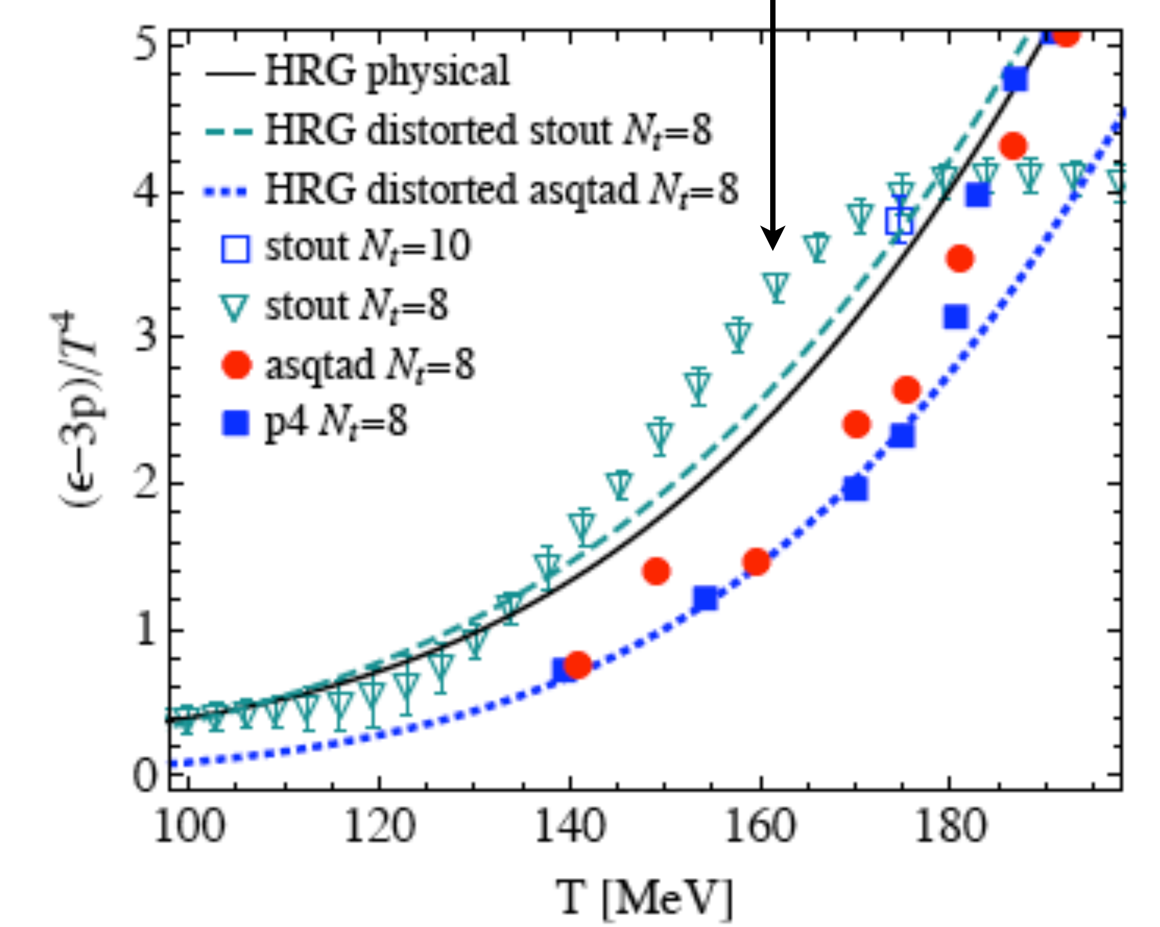
$\epsilon_c = (1.2 - 3.3)\rho_{nuclear}$

Uncertainty in T_c, not width of cross-over region!

Hadron mass spectrum

Below T_c, the quantity $(\varepsilon - 3p)/T^4$ measures the level density of massive hadronic excitations of the QCD vacuum.

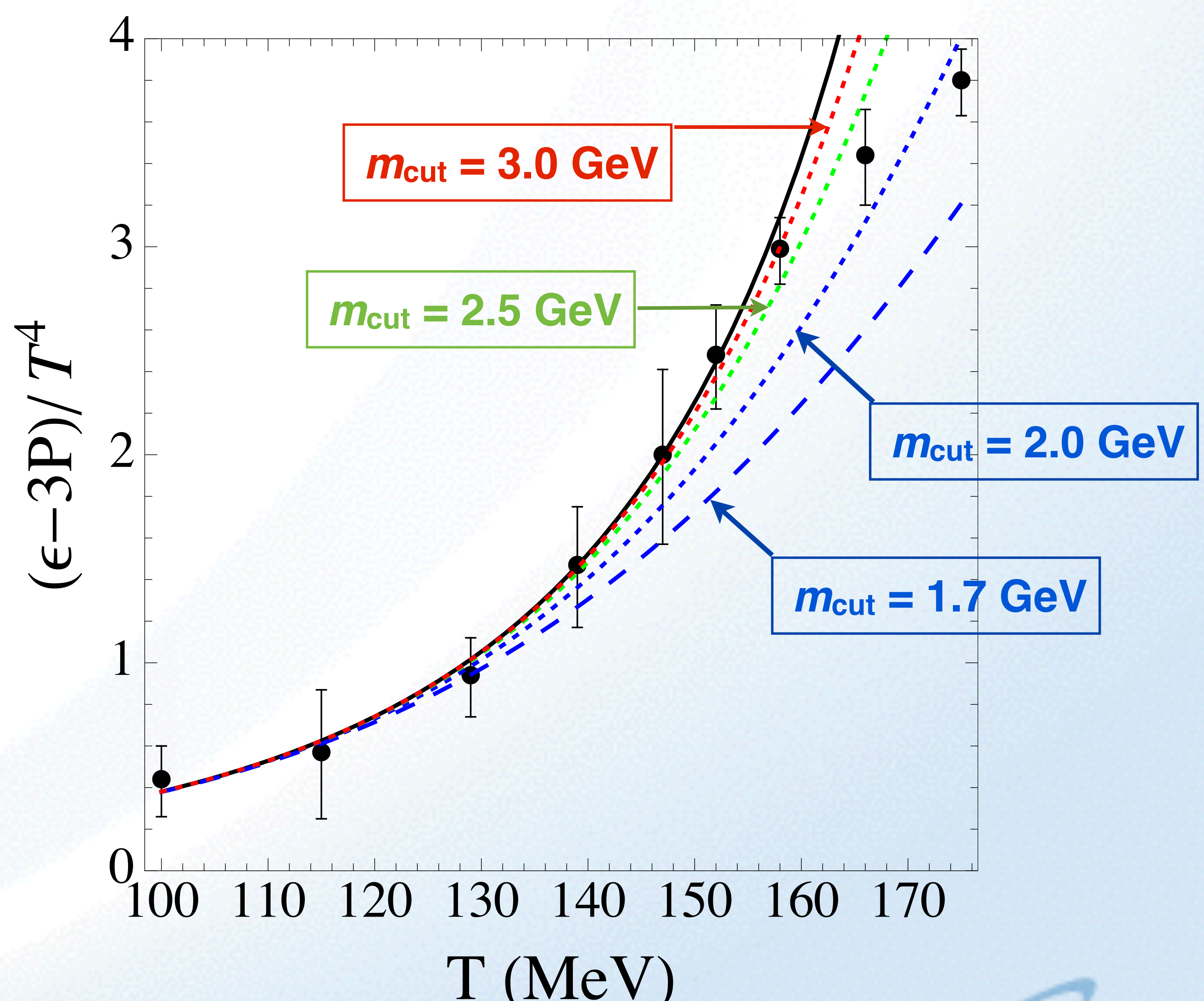
Lines: Hadron resonance gas using only PDG resonances
Data points: Lattice QCD
LQCD lies above HRG for T > 140 MeV
Indicates additional hadron resonances



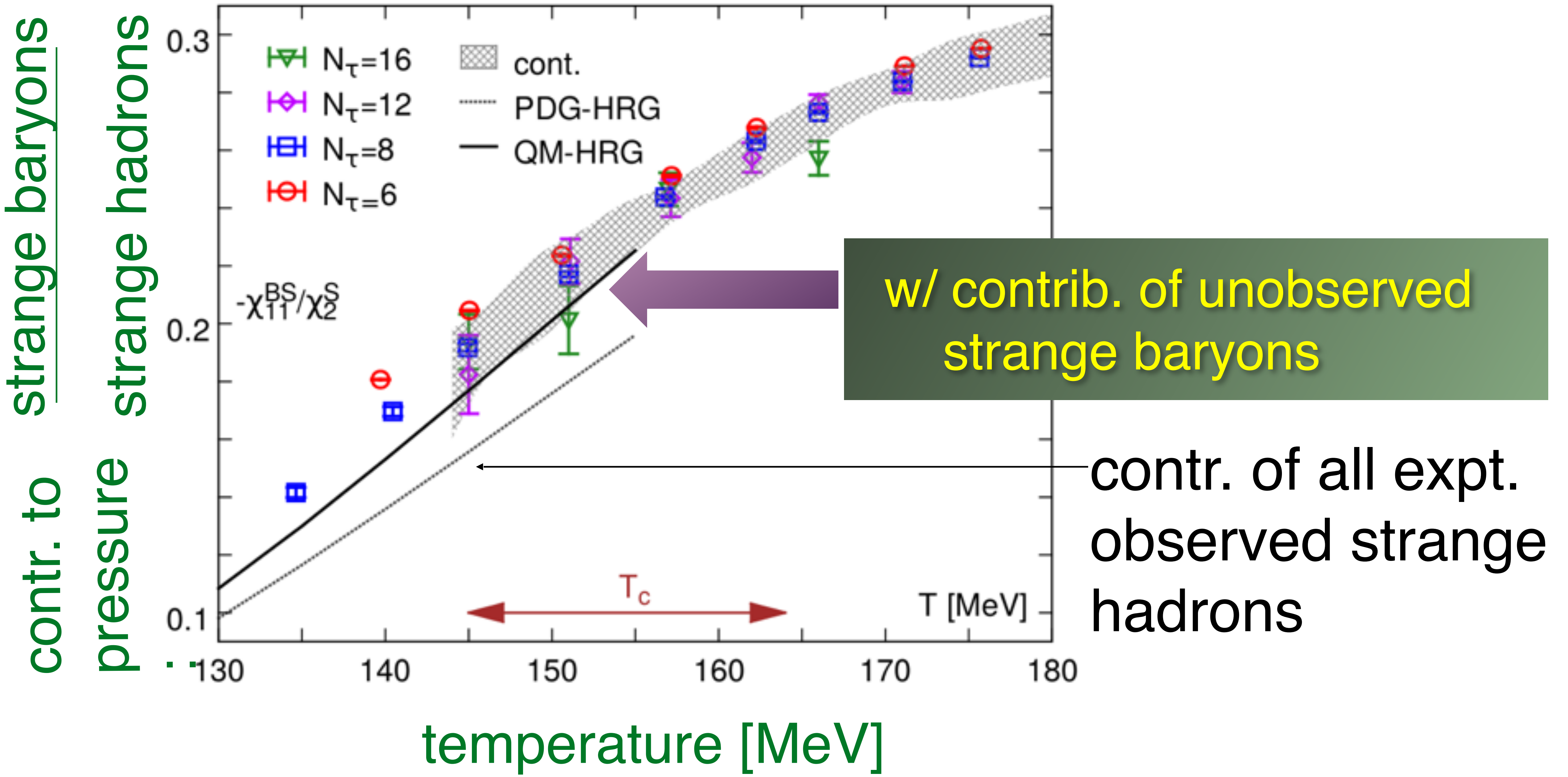
Hagedorn spectrum ($T_H \approx$ 180 MeV):

$$\rho_H(m) = \frac{A\, e^{m/T_H}}{\left(m^2 + m_0^2\right)^{5/4}}$$

In good agreement with lattice results
Hadrons up to 3 GeV mass contribute



Lattice evidence for strange baryons



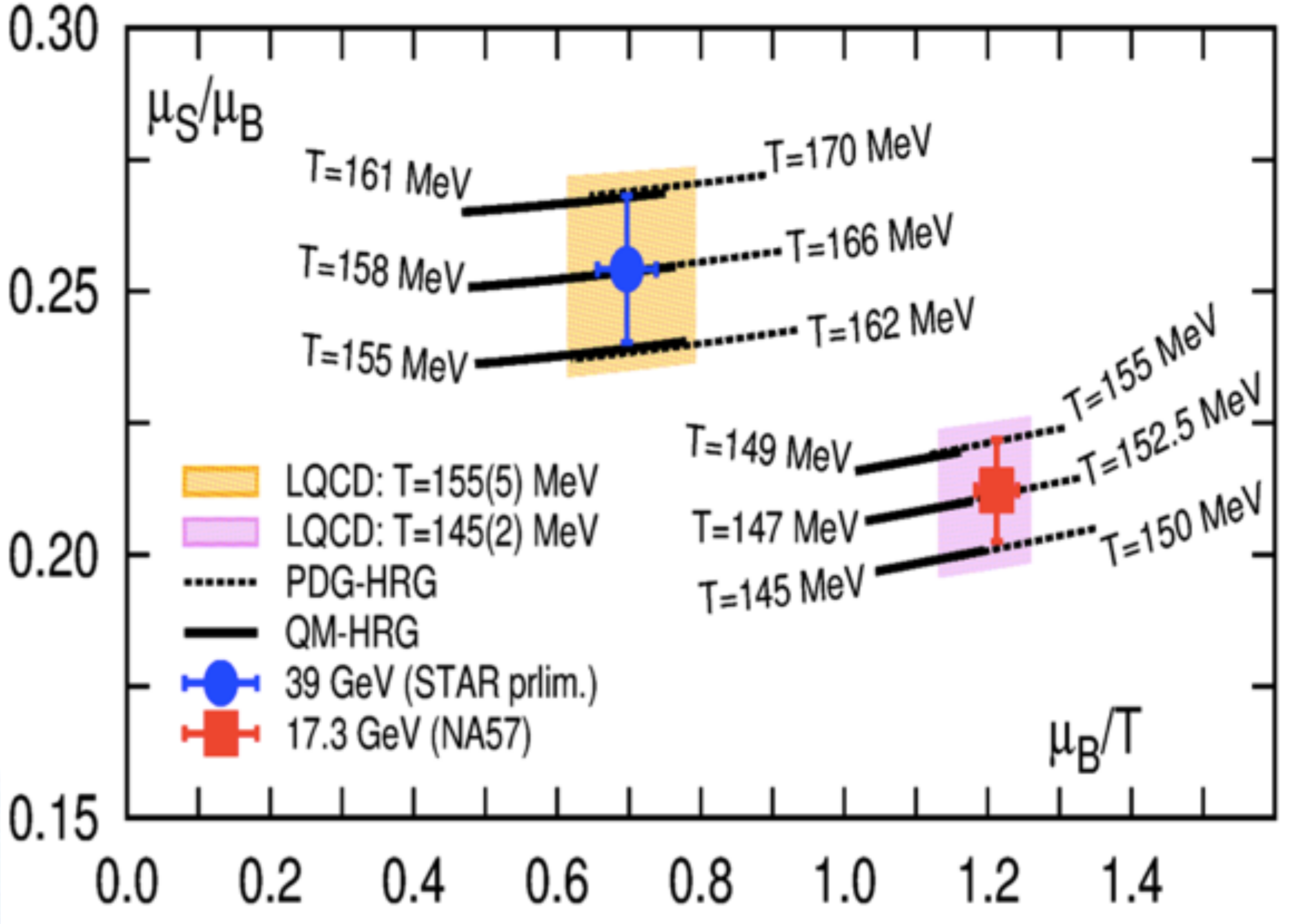
indirect signatures in heavy-ion experiments

BNL-Bielefeld-CCNU: Phys. Rev. Lett. 113, 072001 (2014)

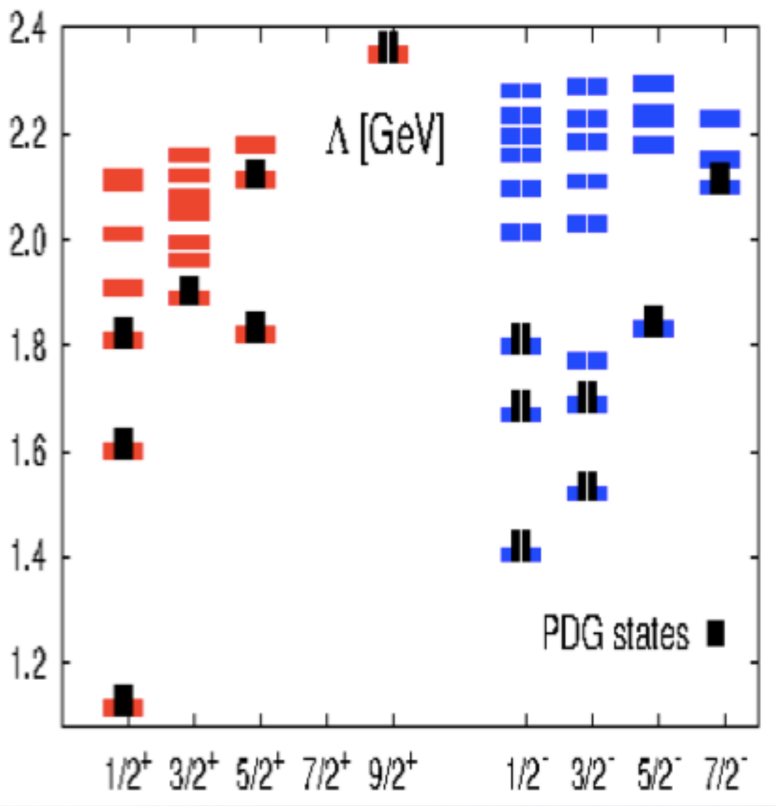
Probing the baryon spectrum

Consistency of μ_S/μ_B and μ_B/T with chemical composition of emitted hadrons and Lattice QCD requires additional strange baryon resonances beyond those in the PDG tables.

BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001

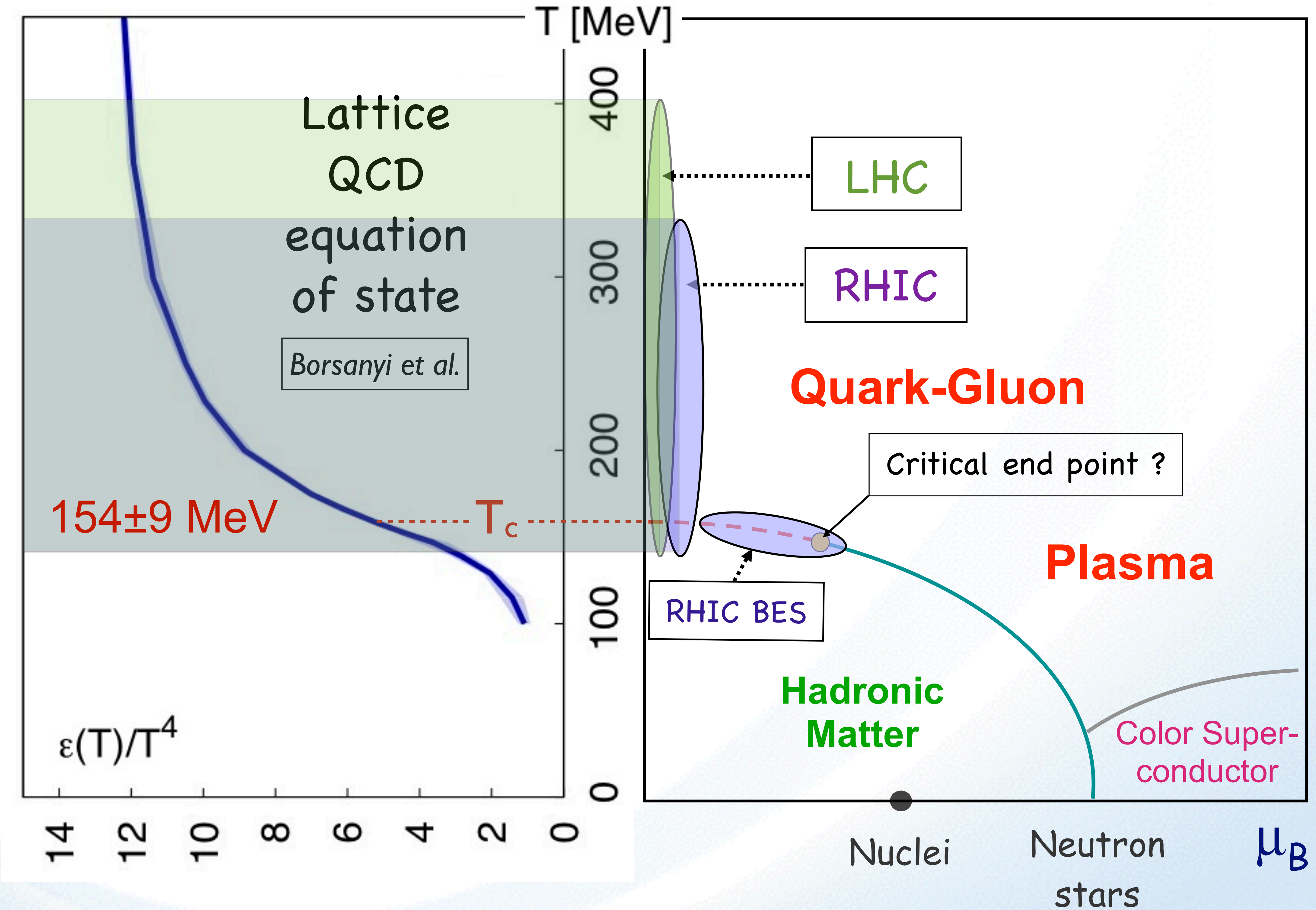


Quark model states of strange baryons



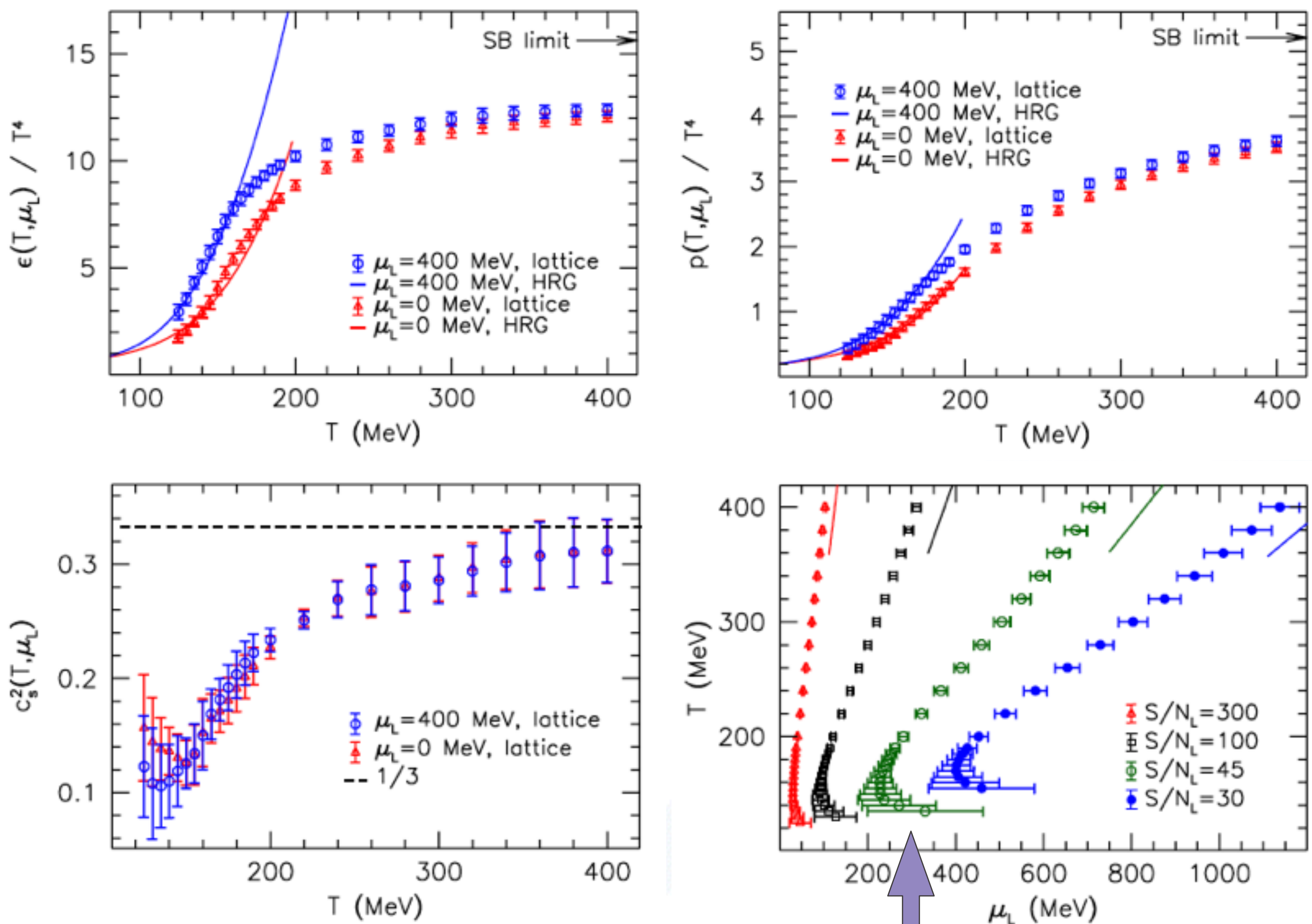
Probing the QCD Phase Boundary

QCD Phase Diagram



QCD EOS at μB ≠ 0

Borszanyi et al., arXiv:1204:6710



Approximate trajectories in QCD phase diagram

Thermodynamic fluctuations

Susceptibilities measure thermodynamic fluctuations.
Interesting because they exhibit singularities at a critical point.
Fluctuations of conserved quantities (charge *Q*, baryon number *B*,…) cannot be changed by local final-state processes.

Expt.: mean: M_Q
variance: σ_Q^2
skewness: S_Q
kurtosis: κ_Q

$$\sqrt{s} \Leftrightarrow (T, \mu_B)$$

Lattice gauge theory:

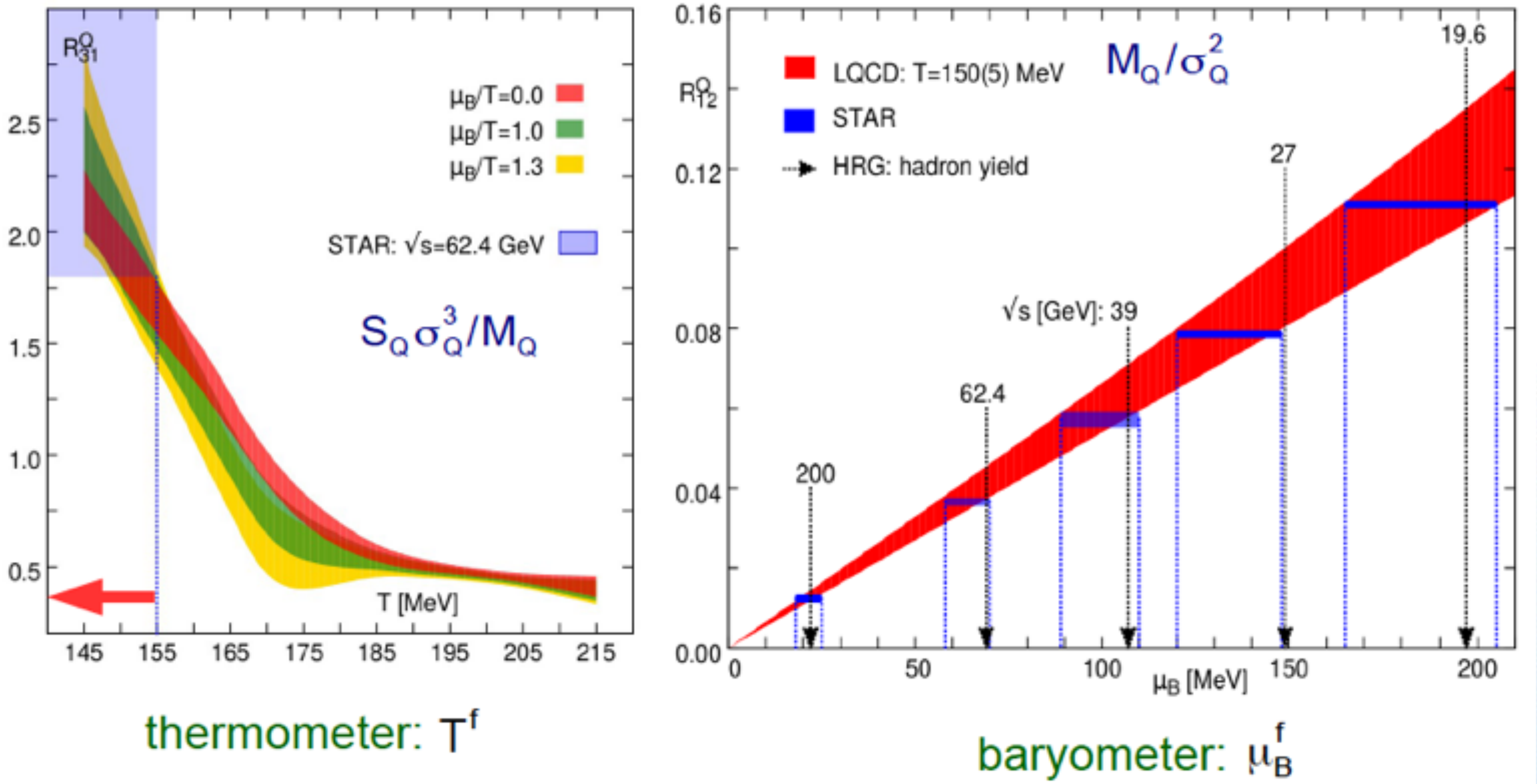
$$\chi_n^X(T, \mu_X) = \frac{\partial^n \left(p(T, \mu_X)/T^4\right)}{\partial(\mu_X/T)^n}$$

Ratios are independent of the (unknown) freeze-out volume:

$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\chi_1^Q(T, \mu_B)}{\chi_2^Q(T, \mu_B)} \qquad \frac{S_Q(\sqrt{s})\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\chi_3^Q(T, \mu_B)}{\chi_1^Q(T, \mu_B)}$$

Chemical freeze-out

… from fluctuations of conserved quantum numbers (here *Q*):



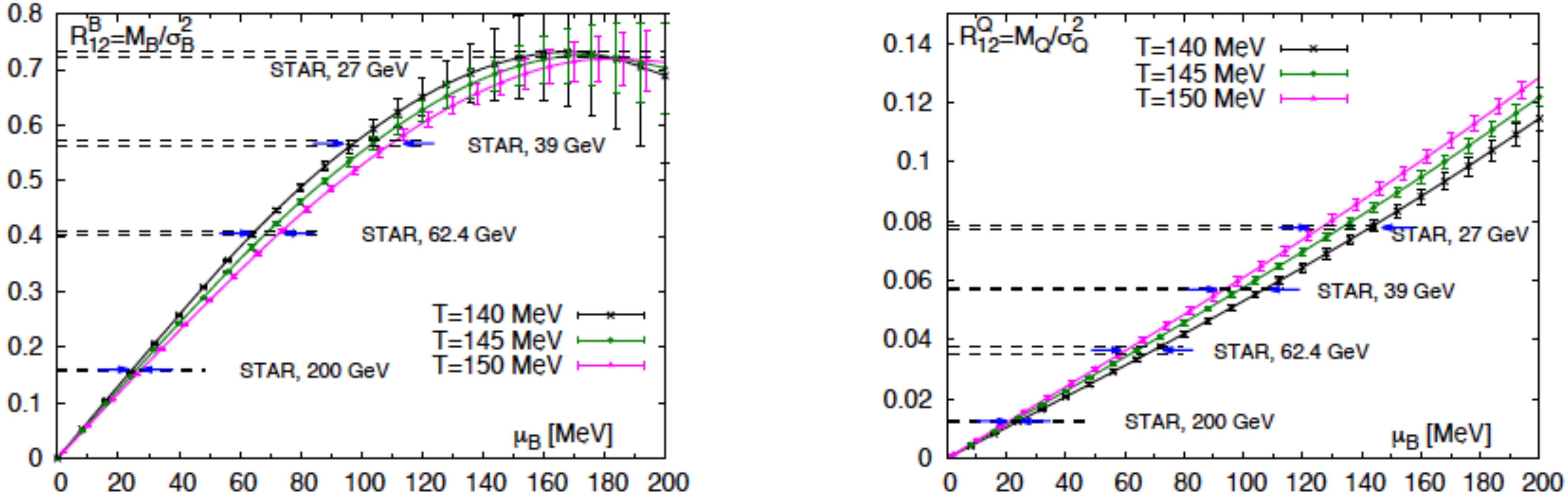
Net charge fluctuations permit independent determination of freeze-out parameters (T^f, μ^f) using both variance and skewness, when additional strange baryon states beyond those in the PDG tables (e.g. in the quark model) are taken into account.

Chemical freeze-out

… from fluctuations of conserved quantum numbers (*Q*, *B*):

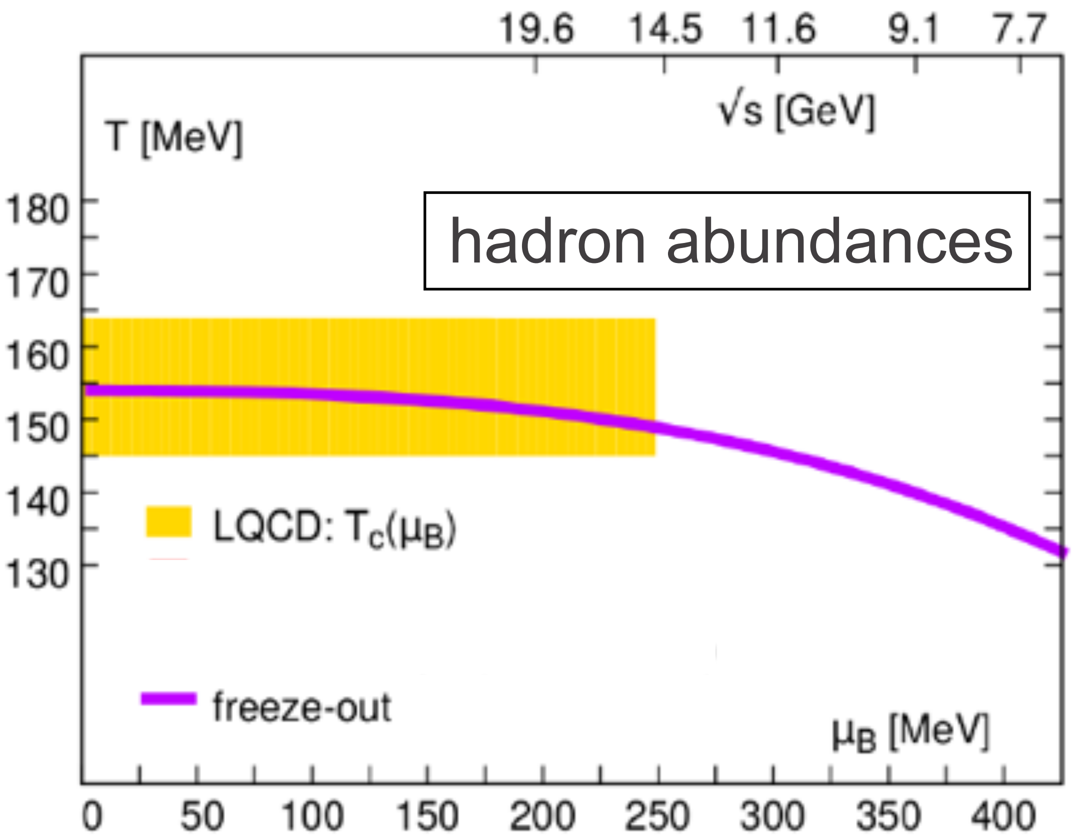
Borsanyi et al. Wuppertal-Budapest Coll. Phys.Rev.Lett. 111, 062005 (2013); Phys.Rev.Lett. 113, 052301 (2014)

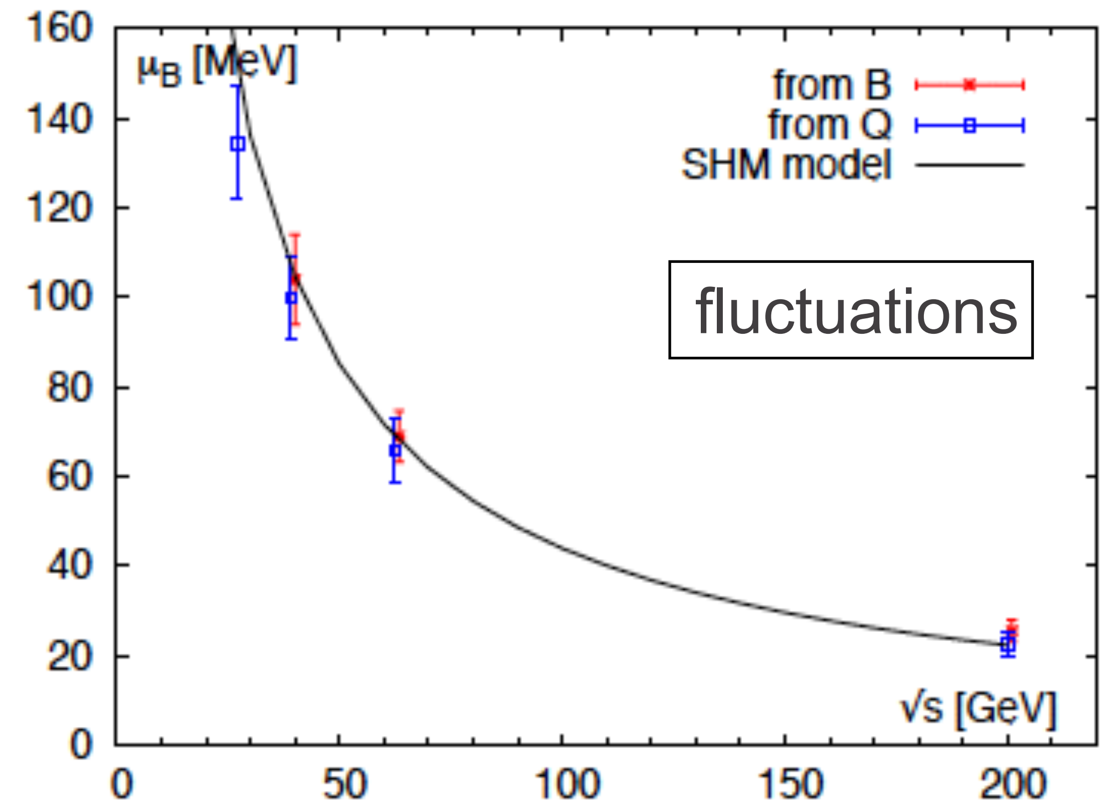
use M/σ^2 both in the baryon and in the charge sector



Comparison of lattice results with the STAR data for the μ_B and *Q* fluctuation ratios in the temperature range 140−150 MeV permits to read off μ_B. Both methods are consistent with each other.

Chemical freeze-out





Consistency of freeze-out parameters from mean hadron abundances and from fluctuations (*Q*, *B*) opens the door to search for a critical point in the QCD phase diagram by looking for enhanced critical fluctuations as function of beam energy.

Probing the Quark-Gluon Plasma

Hot QCD matter properties

Which **properties of hot QCD matter** can we hope to determine and how ?

Easy for LQCD

$$T_{\mu\nu} \Leftrightarrow \varepsilon, p, s$$

Equation of state: spectra, coll. flow, fluctuations

$$\eta = \frac{1}{T}\int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$$

Shear viscosity: anisotropic collective flow

Very Hard for LQCD

$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0) \right\rangle$$

$$\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle i U^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0) \right\rangle$$

$$\kappa = \frac{4\pi \alpha_s}{3N_c}\int d\tau \left\langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b \right\rangle$$

Momentum/energy diffusion: parton energy loss, jet fragmentation

Hard for LQCD

$$\Pi_{\rm em}^{\mu\nu}(k) = \int d^4x\, e^{ikx} \left\langle j^\mu(x) j^\nu(0) \right\rangle$$

QGP Radiance: Lepton pairs, photons

Easy for LQCD

$$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln \left\langle U^\dagger E^a(x) U E^a(0) \right\rangle$$

Color screening: Quarkonium states

Viscous hydrodynamics

Hydrodynamics = effective theory of energy and momentum conservation

energy-momentum tensor = **ideal fluid** + **dissipation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

$$\tau_\Pi \left[\frac{d\Pi^{\mu\nu}}{d\tau} + \left(u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda}\right) \frac{du^\lambda}{d\tau} \right] = \eta\left(\partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace}\right) - \Pi^{\mu\nu}$$

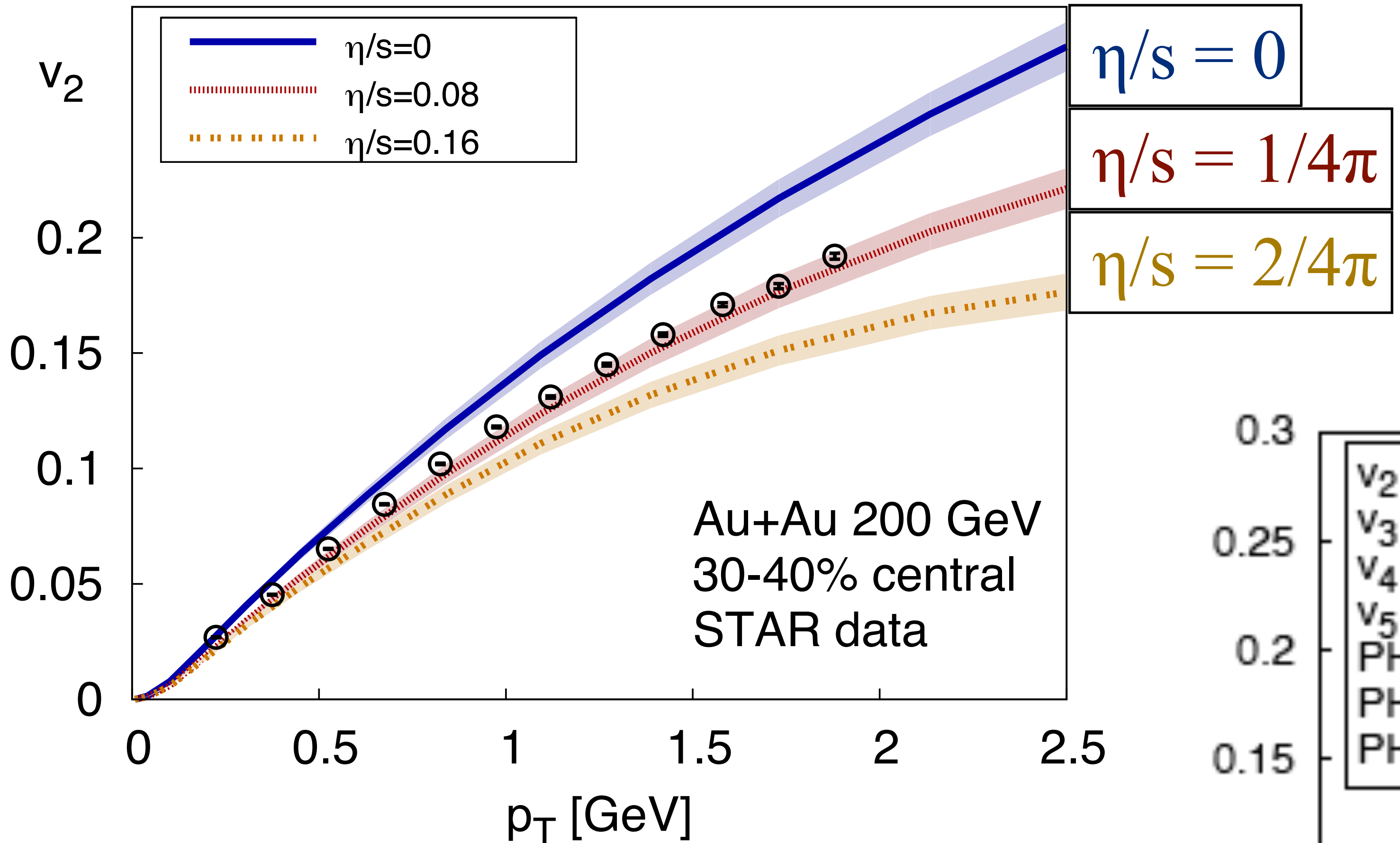
Input: Equation of state P(ε), shear viscosity, initial conditions ε(x,0), u^μ(x,0)

Shear viscosity **η** is normalized by density: **kinematic viscosity η/ρ**.

Relativistically, the appropriate normalization factor is the **entropy density** s = (ε+P)/T, because the particle density is not conserved: **η/s**.

Elliptic flow "measures" η_{QGP}

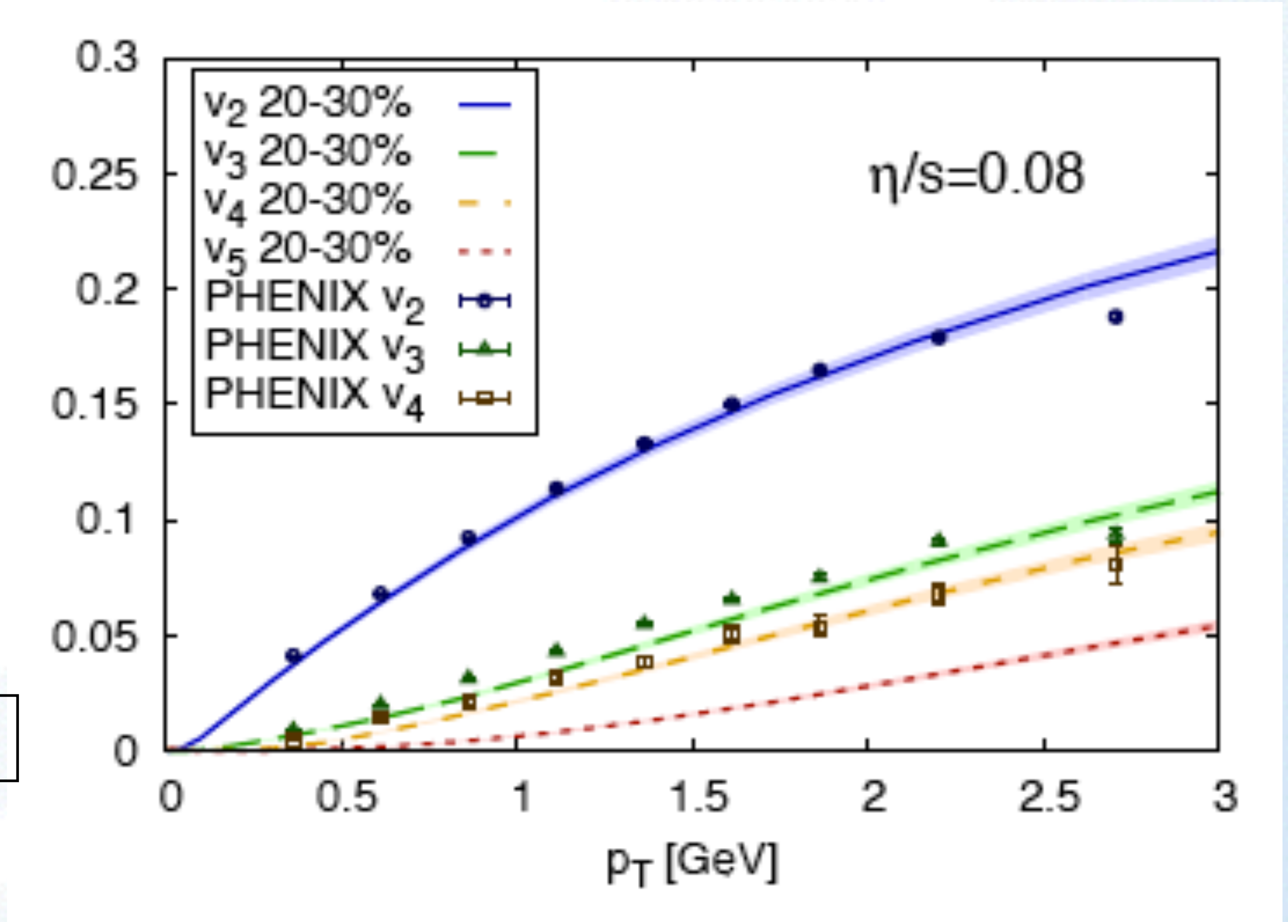
Schenke, Jeon, Gale, PRL 106 (2011) 042301



Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$\eta/s \rightarrow 1/4\pi$

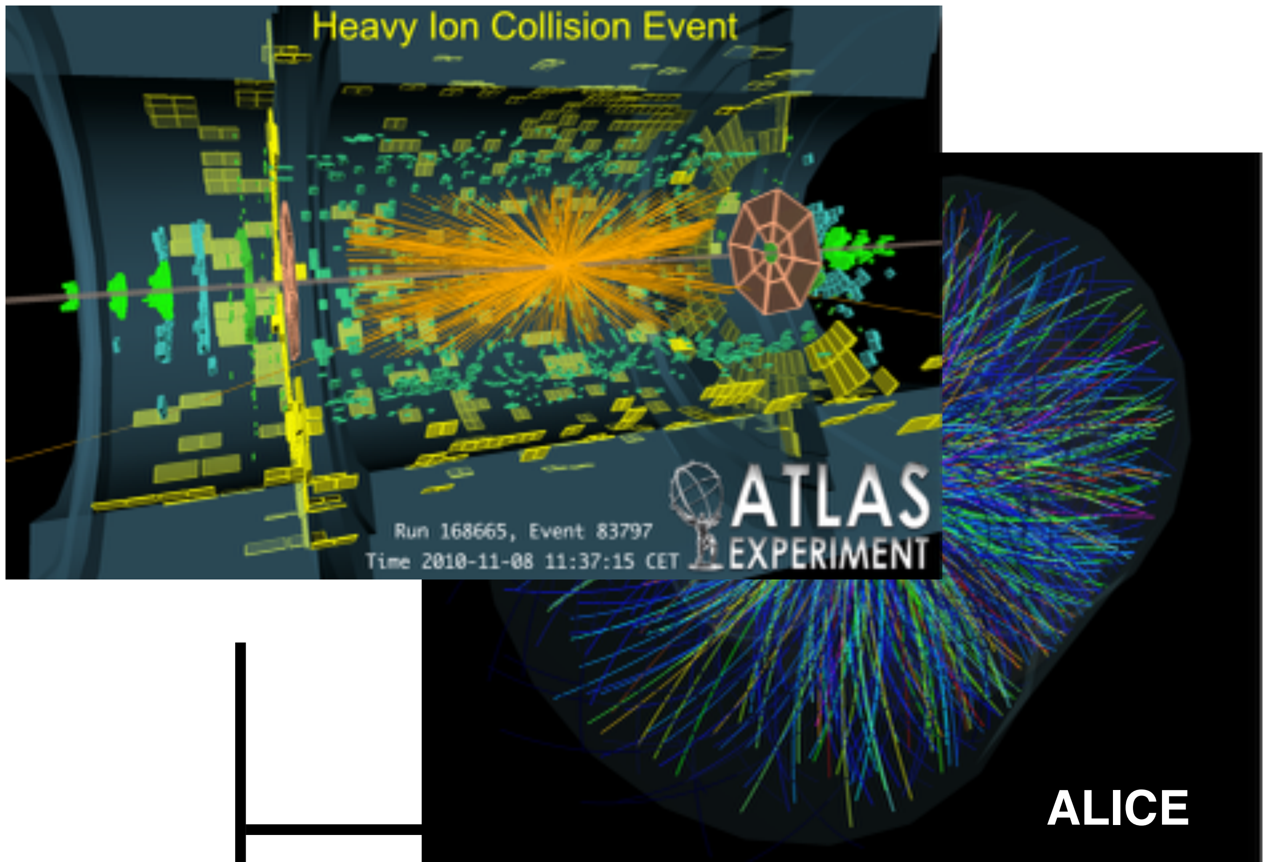
aka: the "perfect" liquid

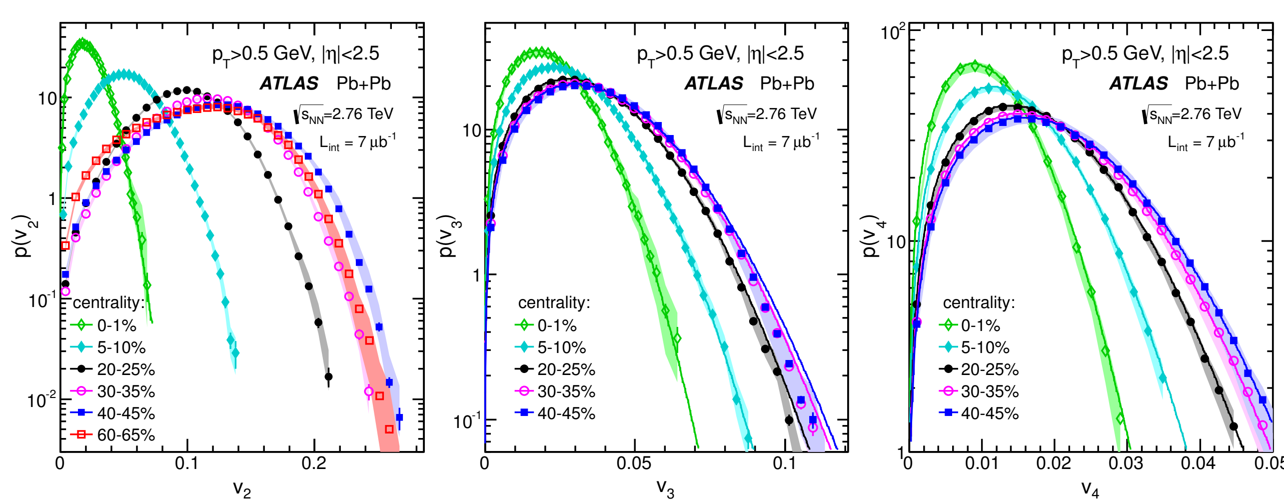


Schenke, Jeon, Gale, PRC 85 (2012) 024901

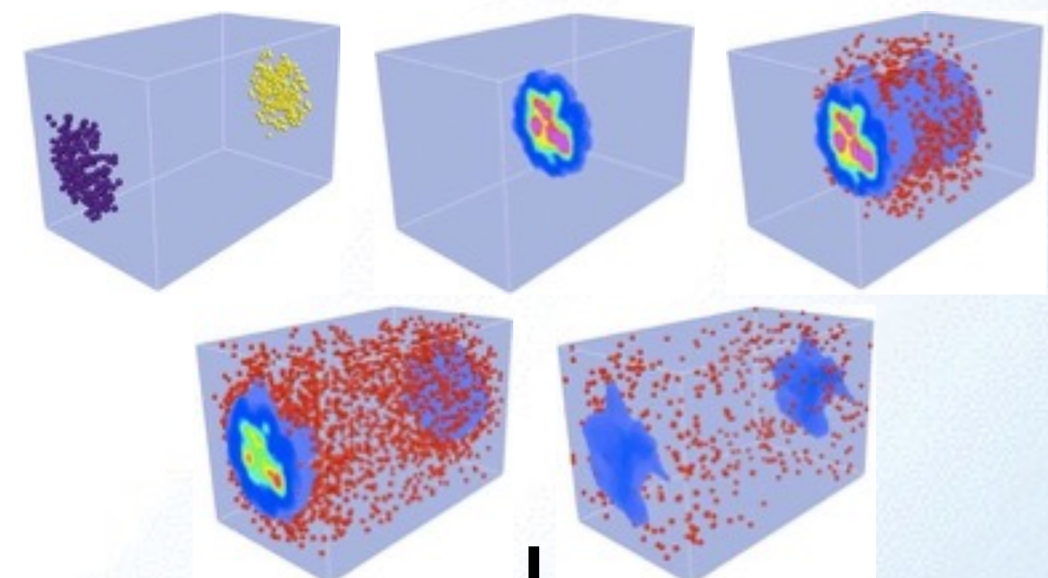
Discovery by model-data comparison

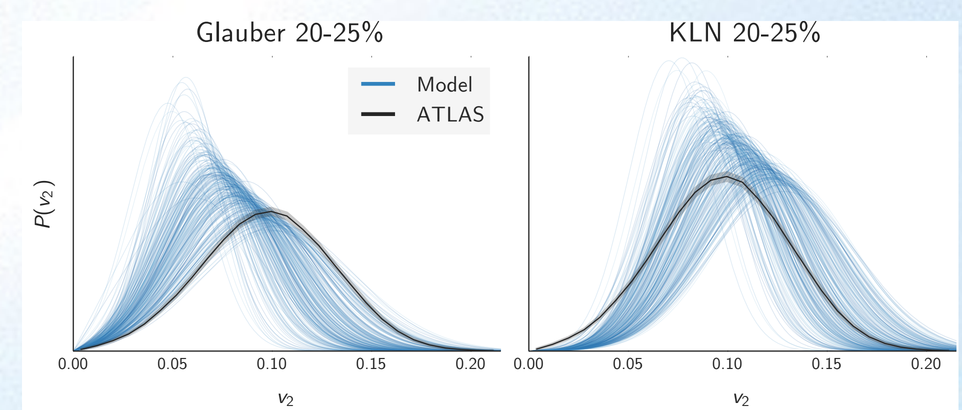
Data:





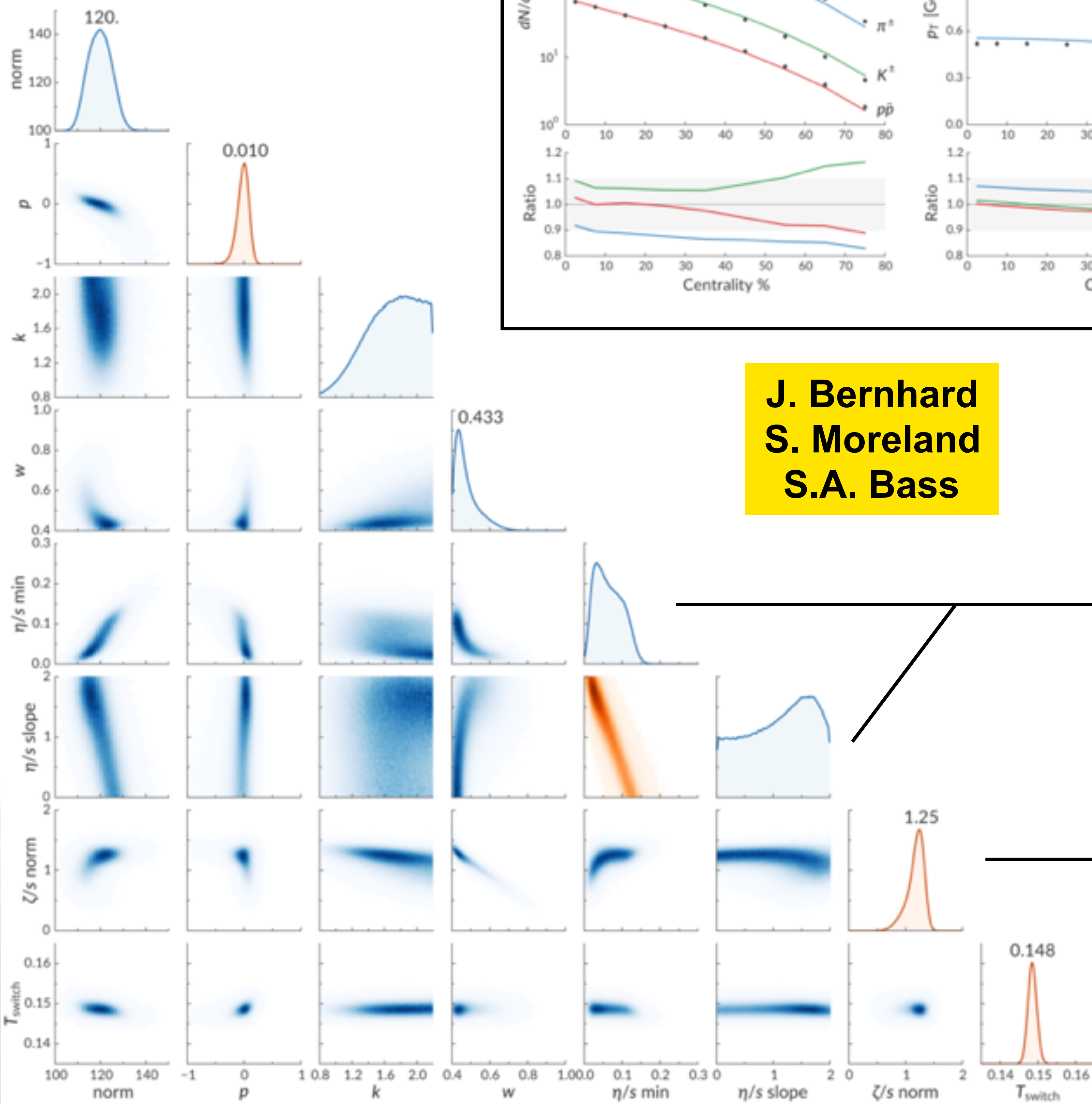
Model:
initial conditions, τ_0, η/s, ζ/s, ….



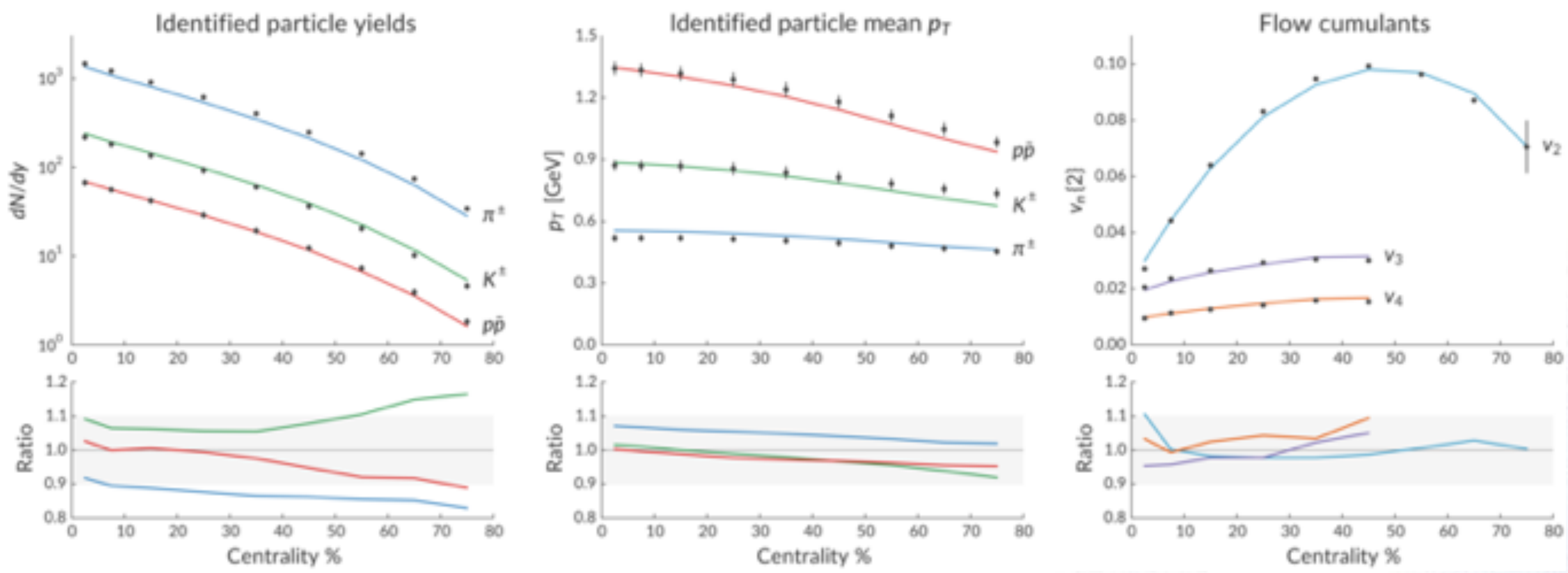


extracted QGP properties: η/s, …

Calibrated posterior distributions:

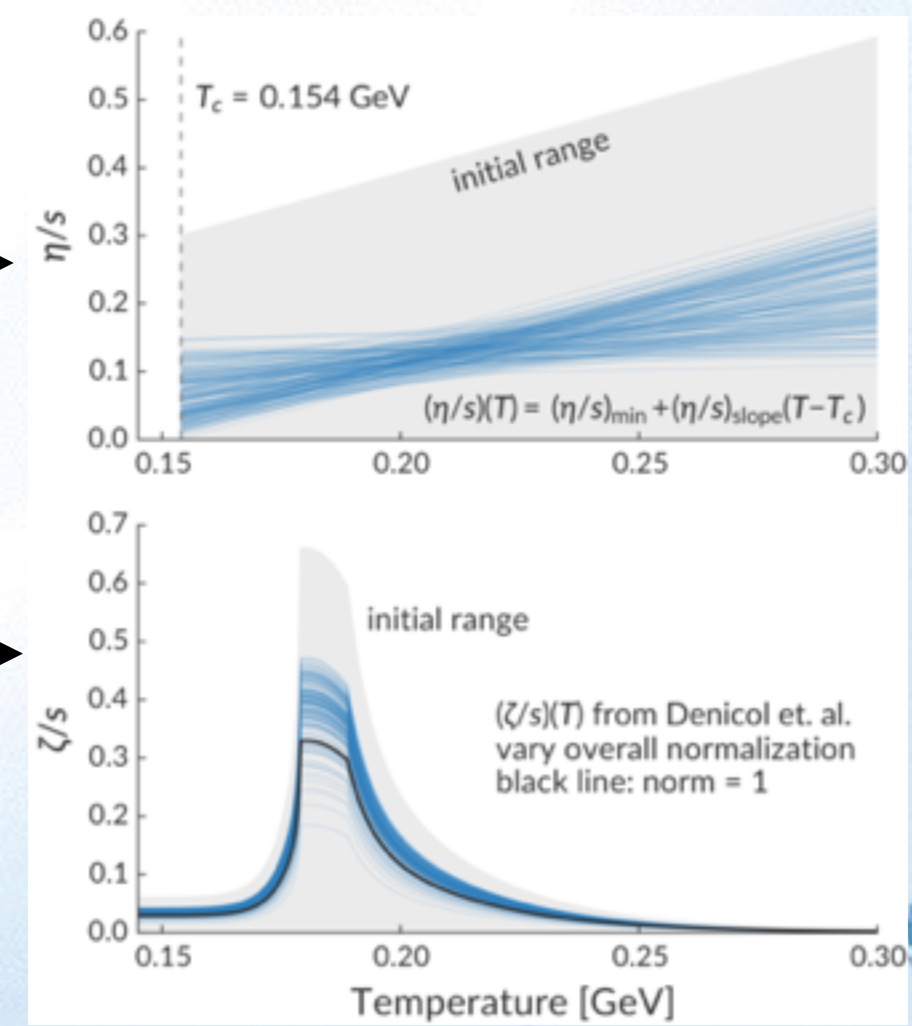


Explicit model calculations (no emulator):



J. Bernhard
S. Moreland
S.A. Bass

Temperature-dependent viscosities from the calibrated posterior:



Future of RHIC

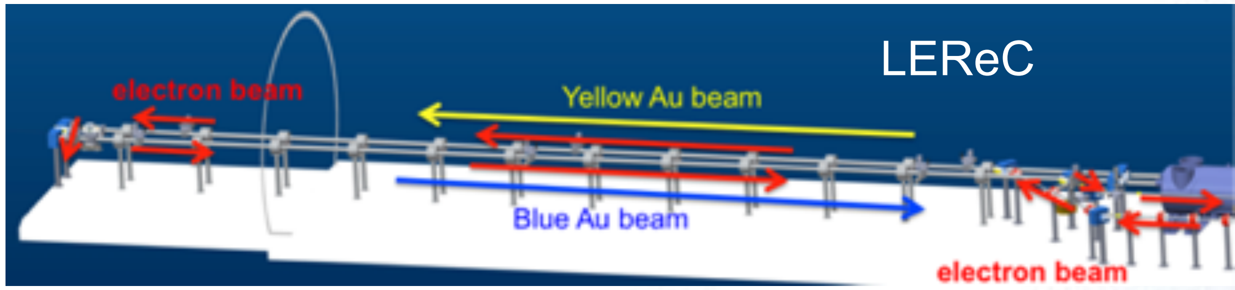
Completing the RHIC science mission

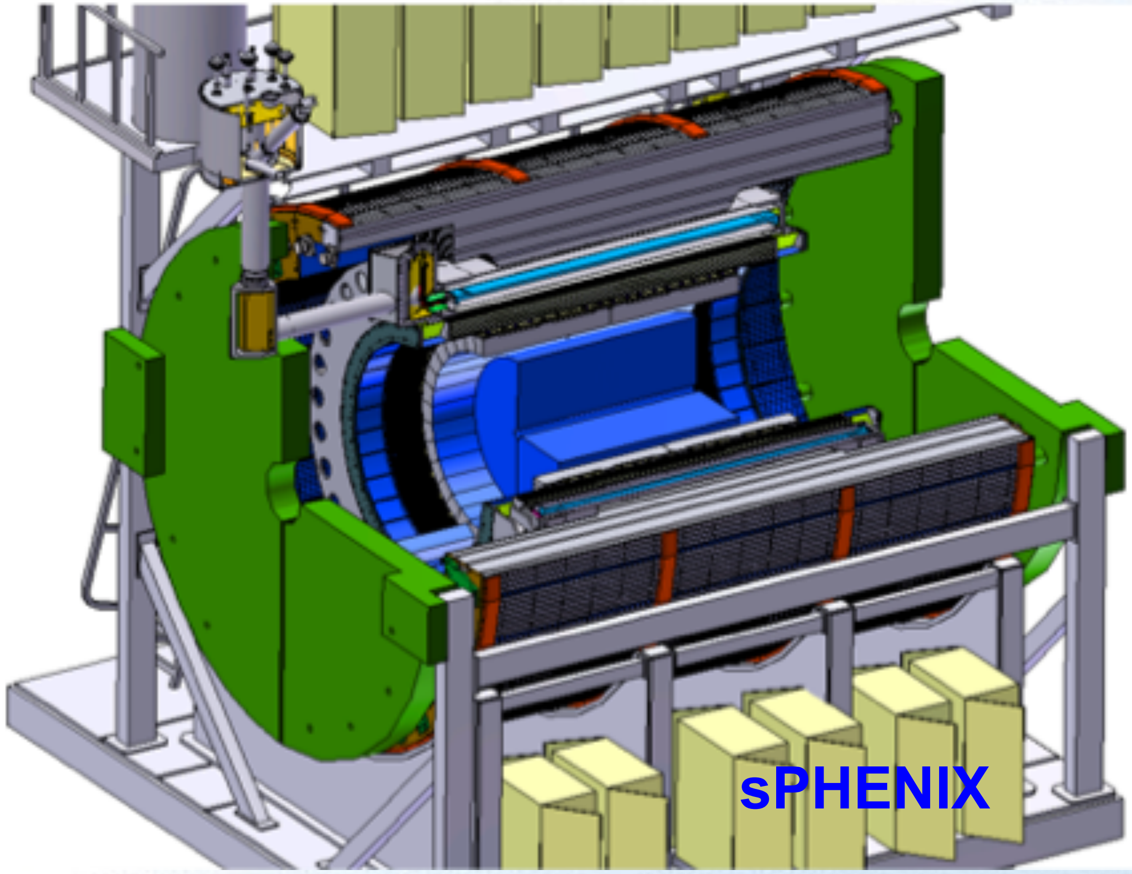
Status: RHIC-II configuration is complete

- Vertex detectors in STAR (HFT) and PHENIX
- Luminosity reaches 25x design luminosity

Plan: Complete RHIC mission in 3 campaigns:

- **2014–18: Heavy flavor probes of the QGP using the micro-vertex detectors;**
  Transverse spin physics;
  Isobar (^{96}Zr-^{96}Ru) run
- *2018: Install low energy e-cooling*
- **2019/20: High precision scan of the QCD phase diagram & search for critical point**
- *2021: Install sPHENIX*
- **2022-23: Probe perfect liquid QGP with precision measurements of jet quenching and Upsilon suppression**
- *Transition to eRHIC?*

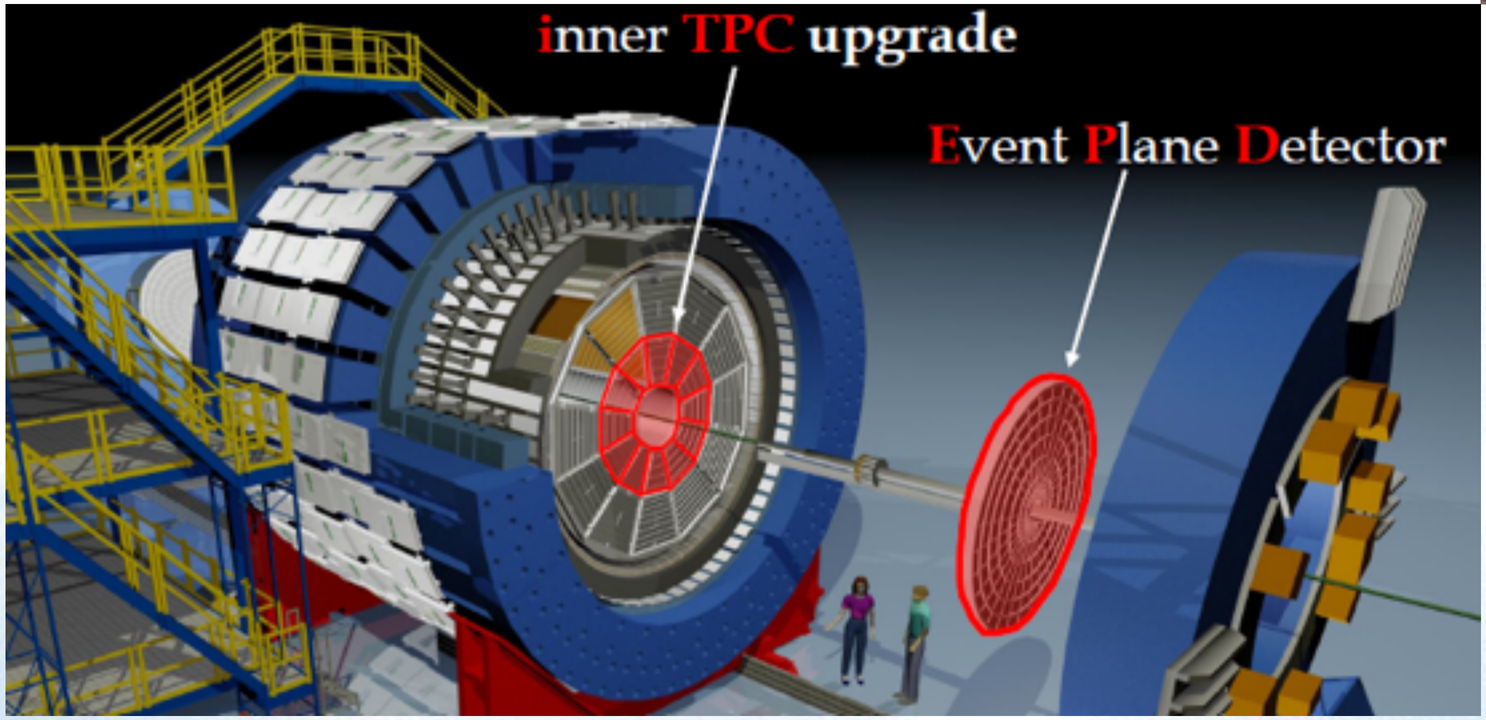




RHIC remains a unique discovery facility

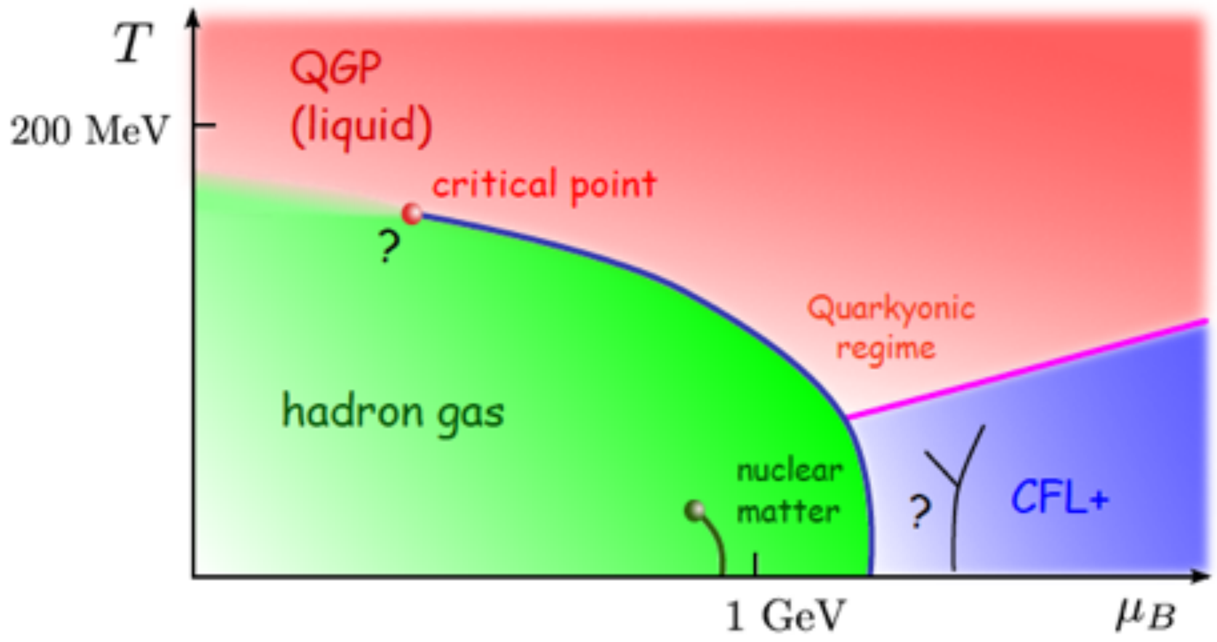
STAR Upgrades for BES II

iTPC upgrade (2018)
Replace inner TPC Sectors
Extend rapidity coverage
Better particle ID
Low p_T coverage

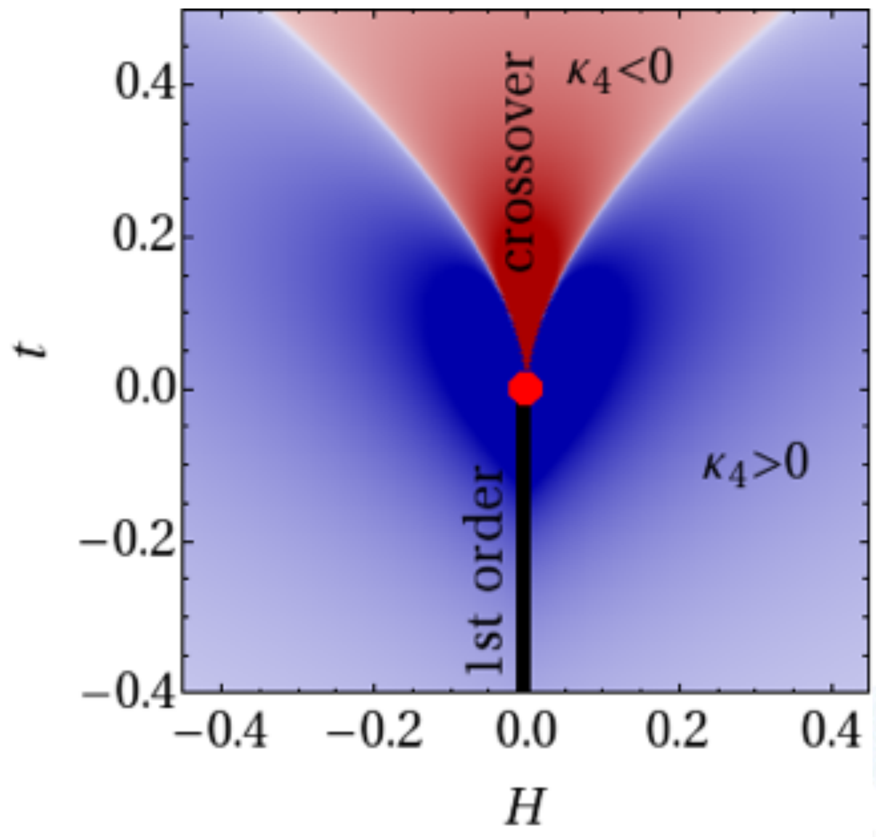


Event Plane Detector (2018)
Improved Event Plane Resolution
Centrality definition
Improved trigger
Background rejection

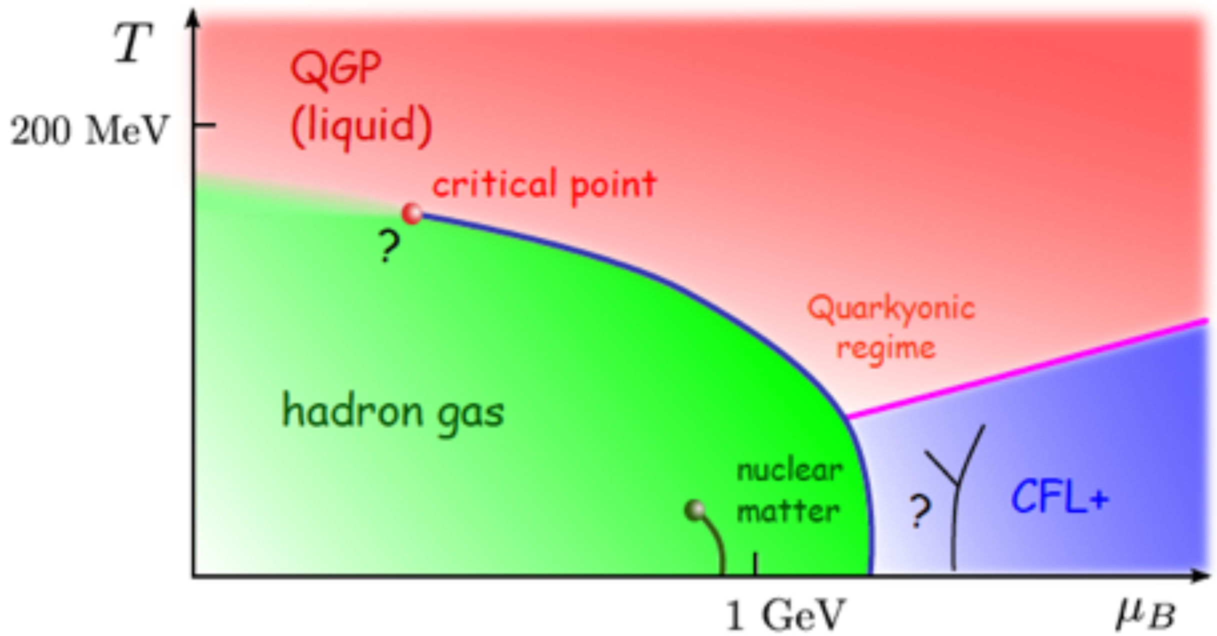
Toward critical fluctuations



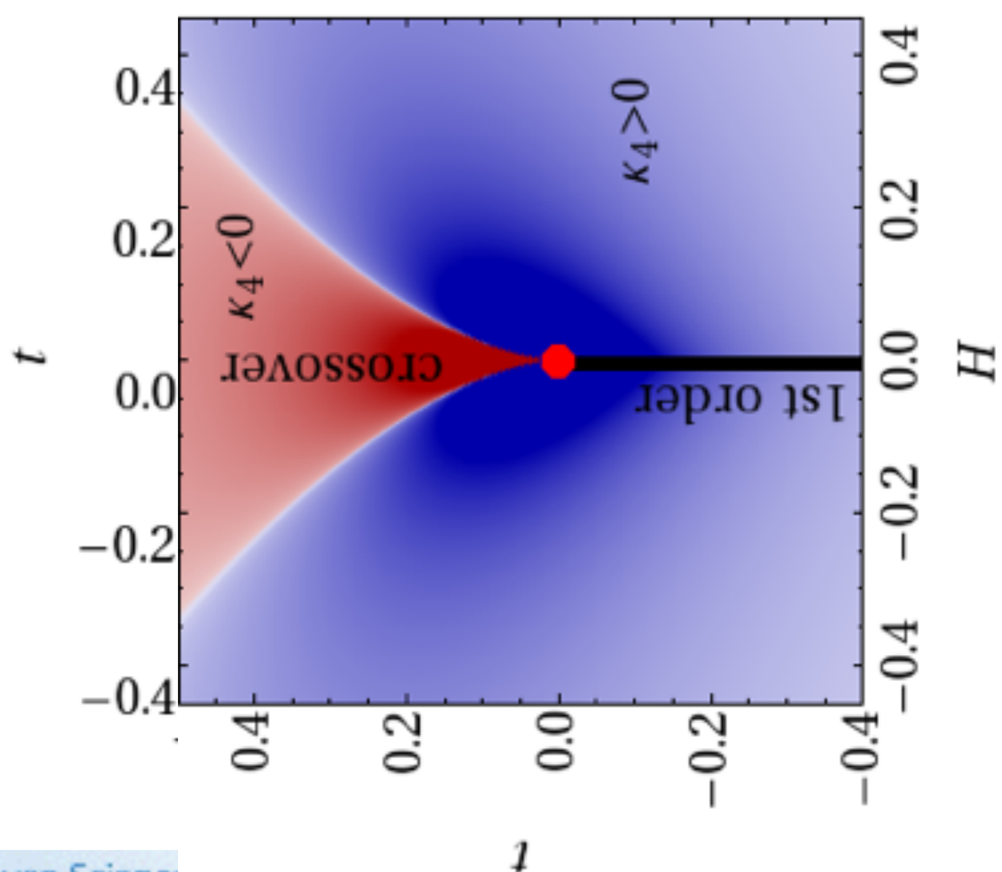
Model independent structure of kurtosis



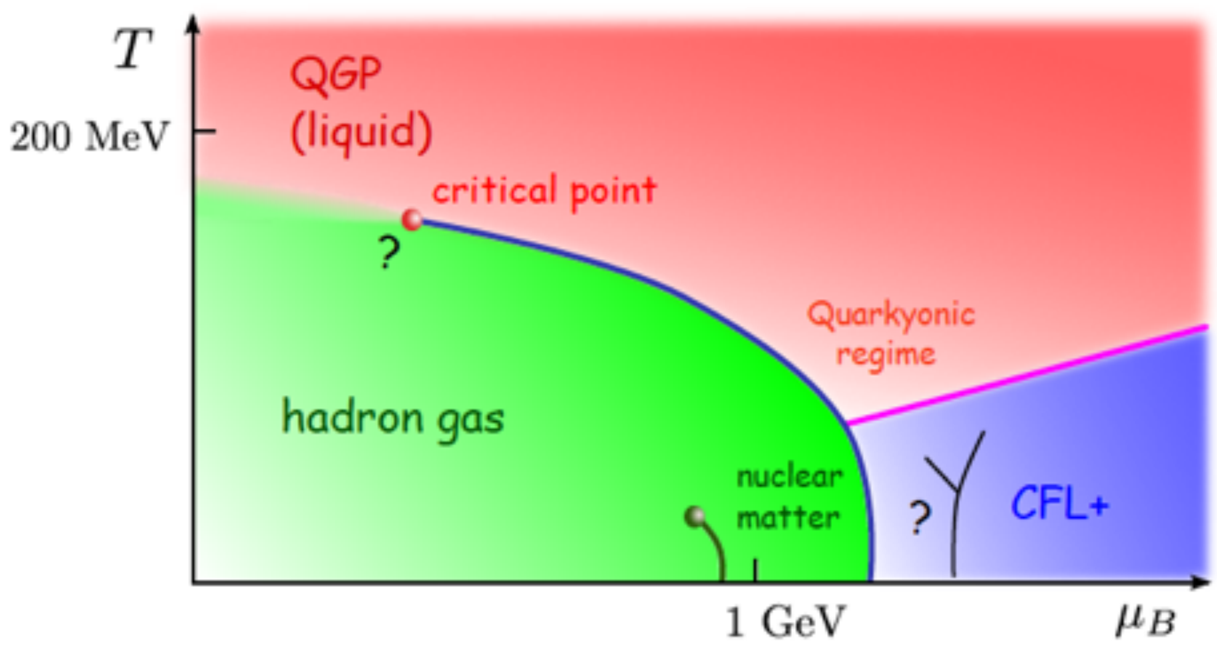
Toward critical fluctuations

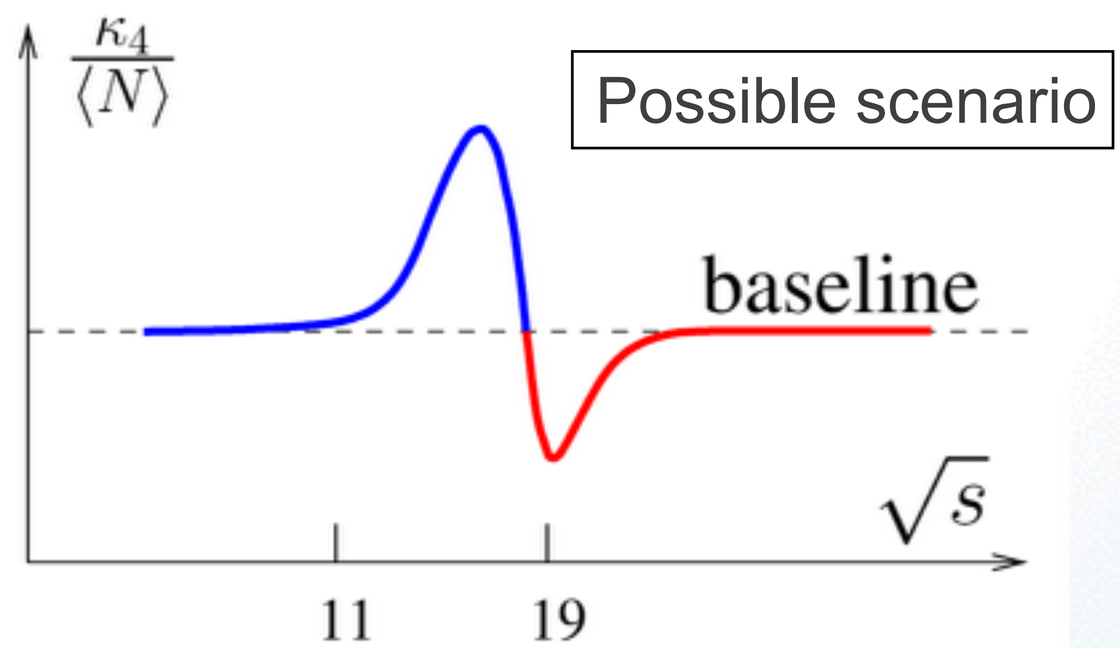


Model independent structure of kurtosis

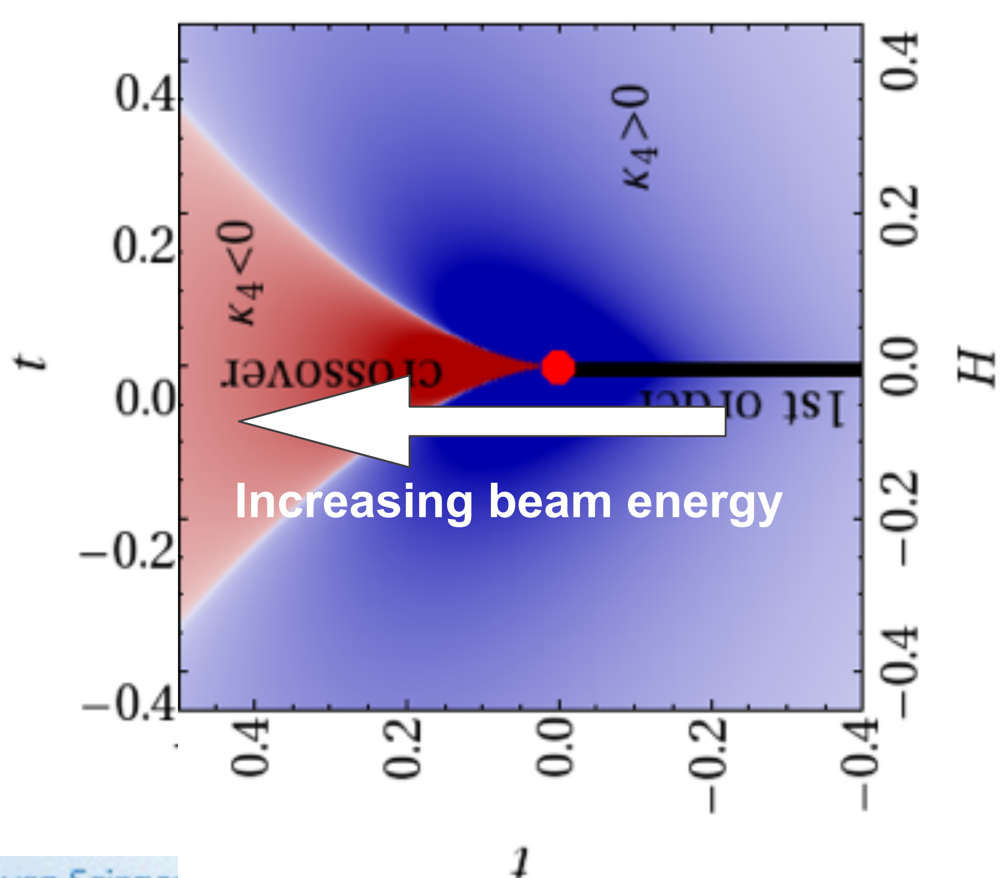


Toward critical fluctuations

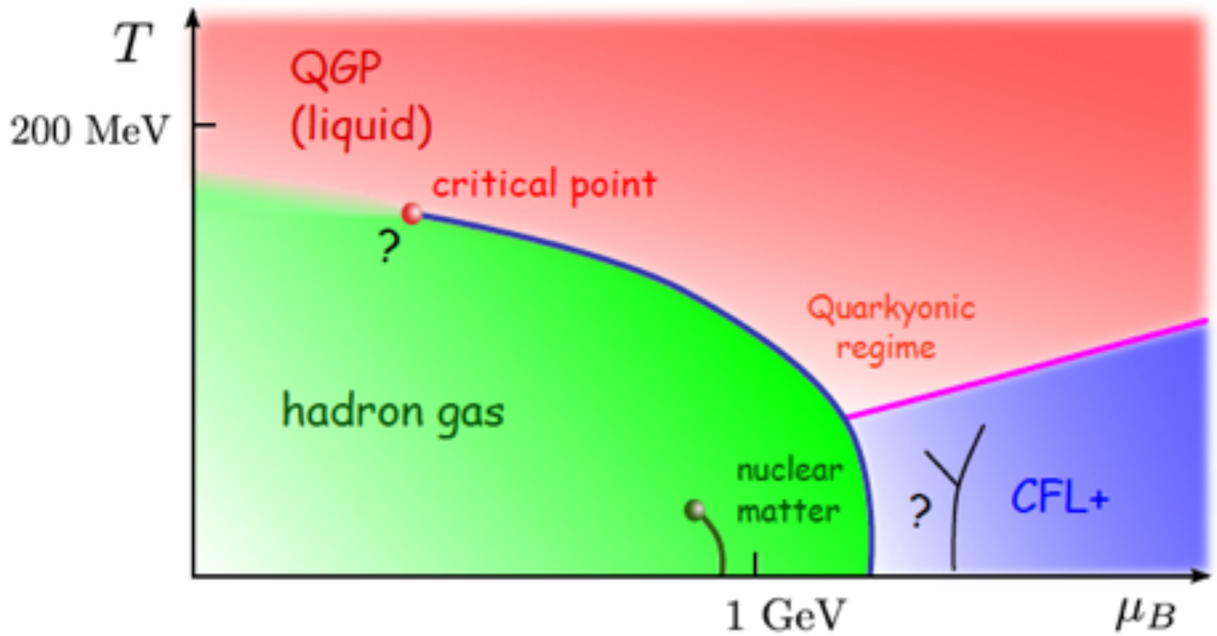


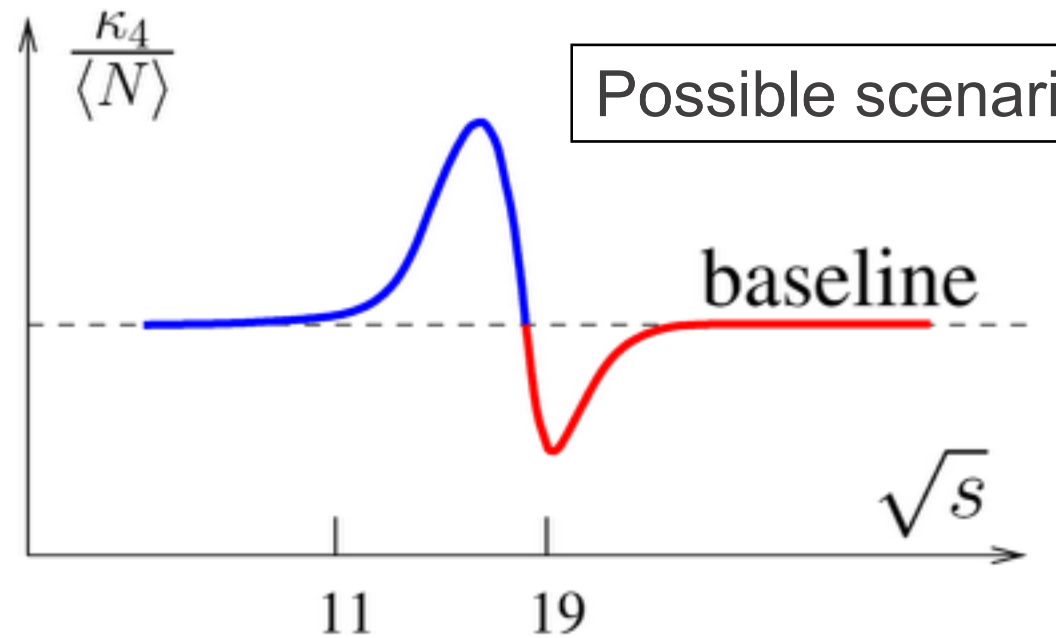


Model independent structure of kurtosis

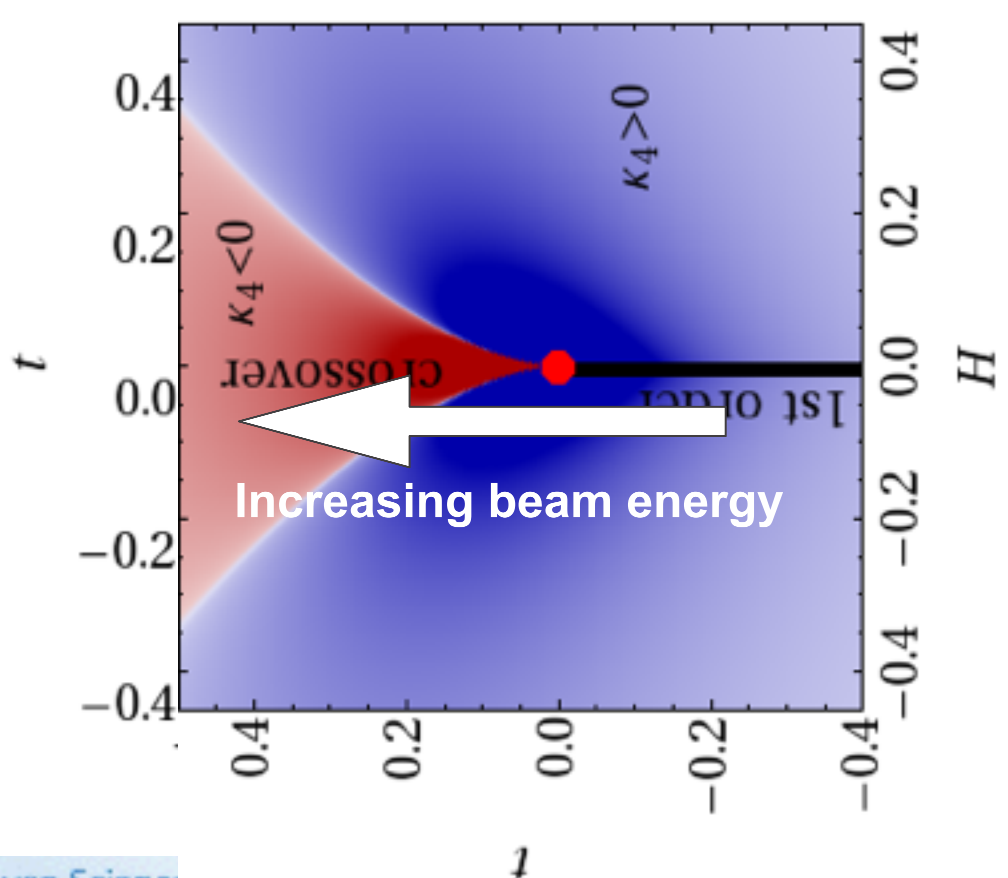


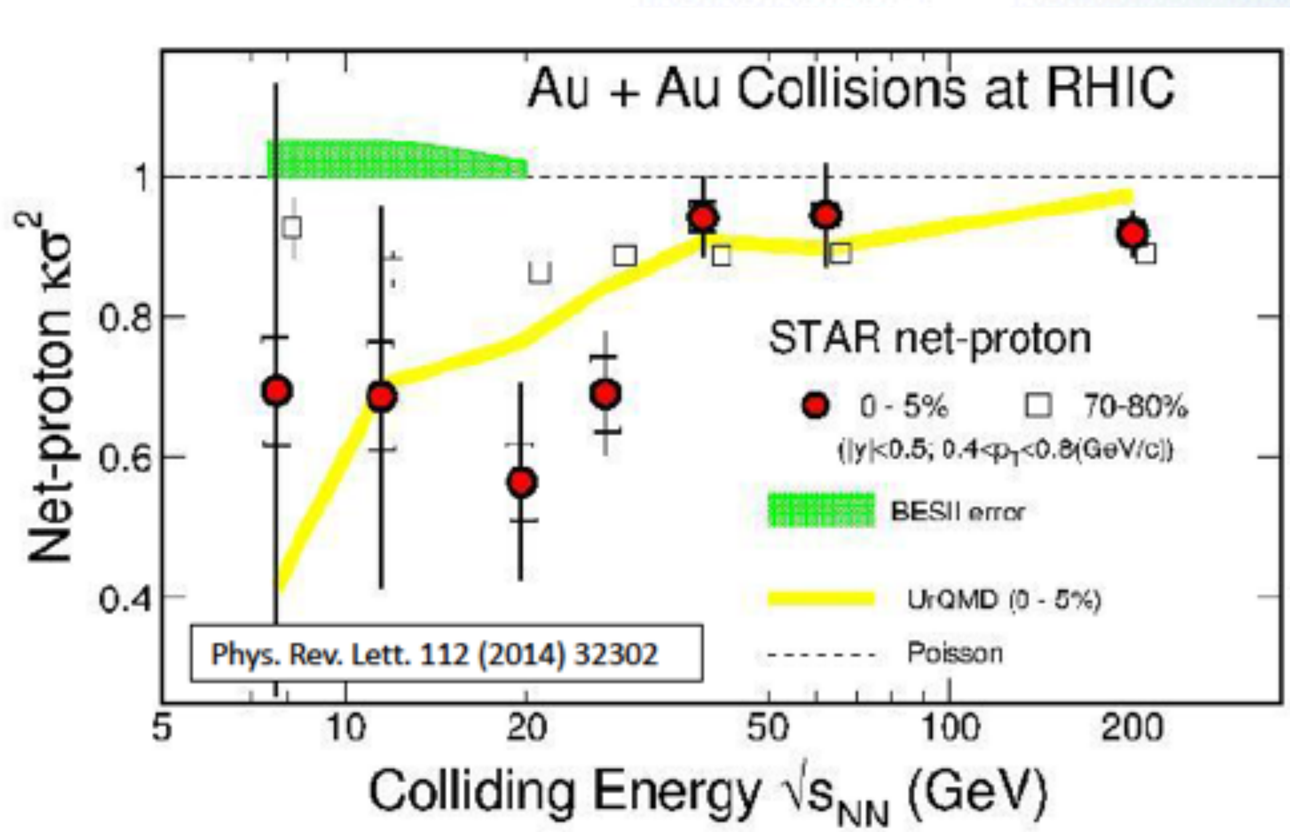
Toward critical fluctuations





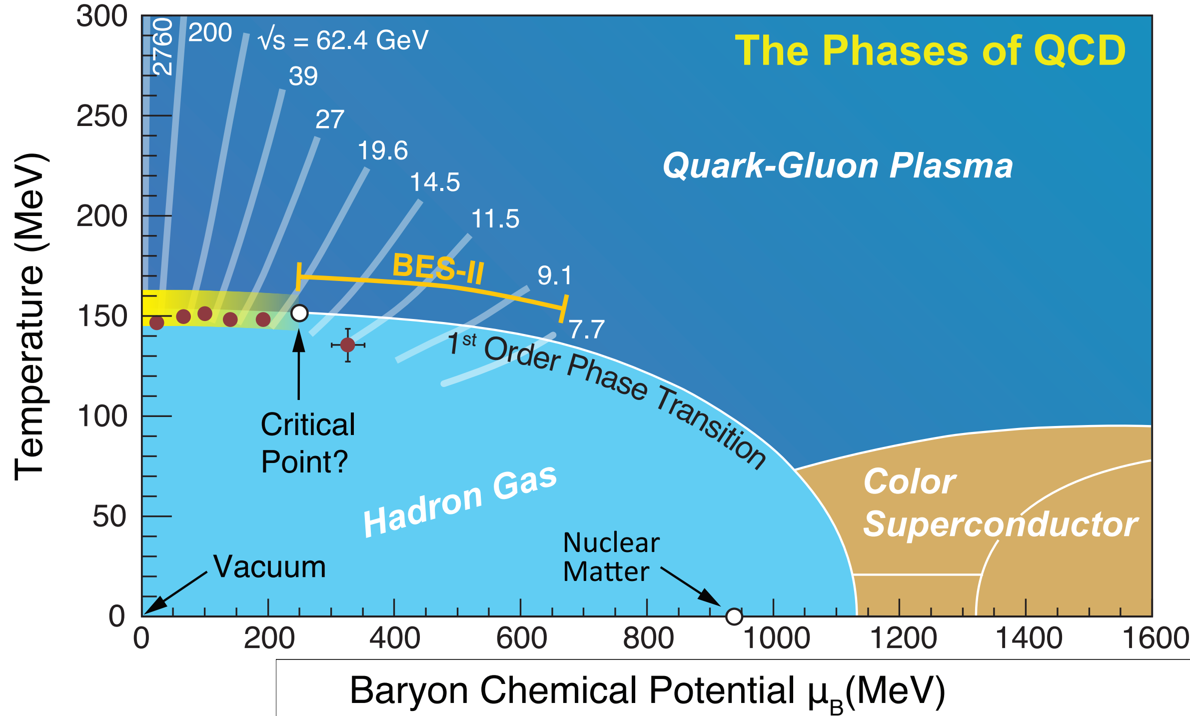
Model independent structure of kurtosis



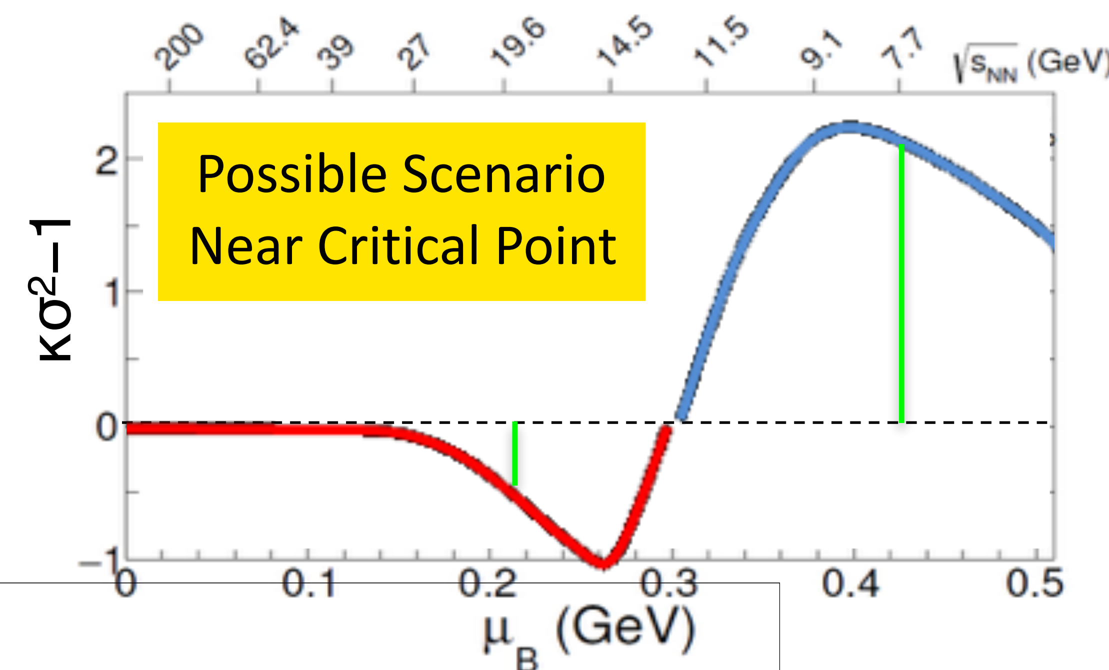


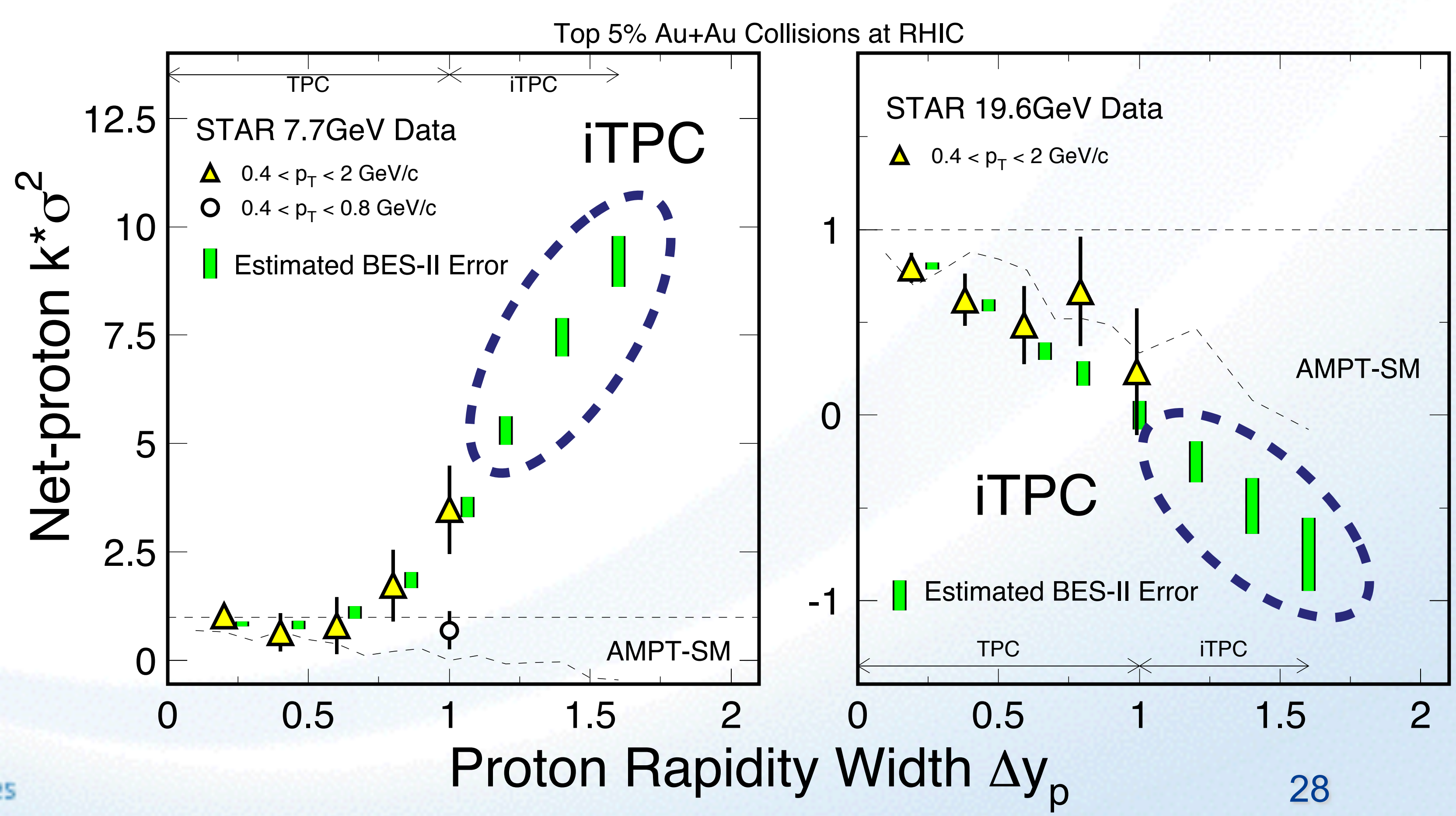
BROOKHAVEN NATIONAL LABORATORY

Critical fluctuations in BES-II

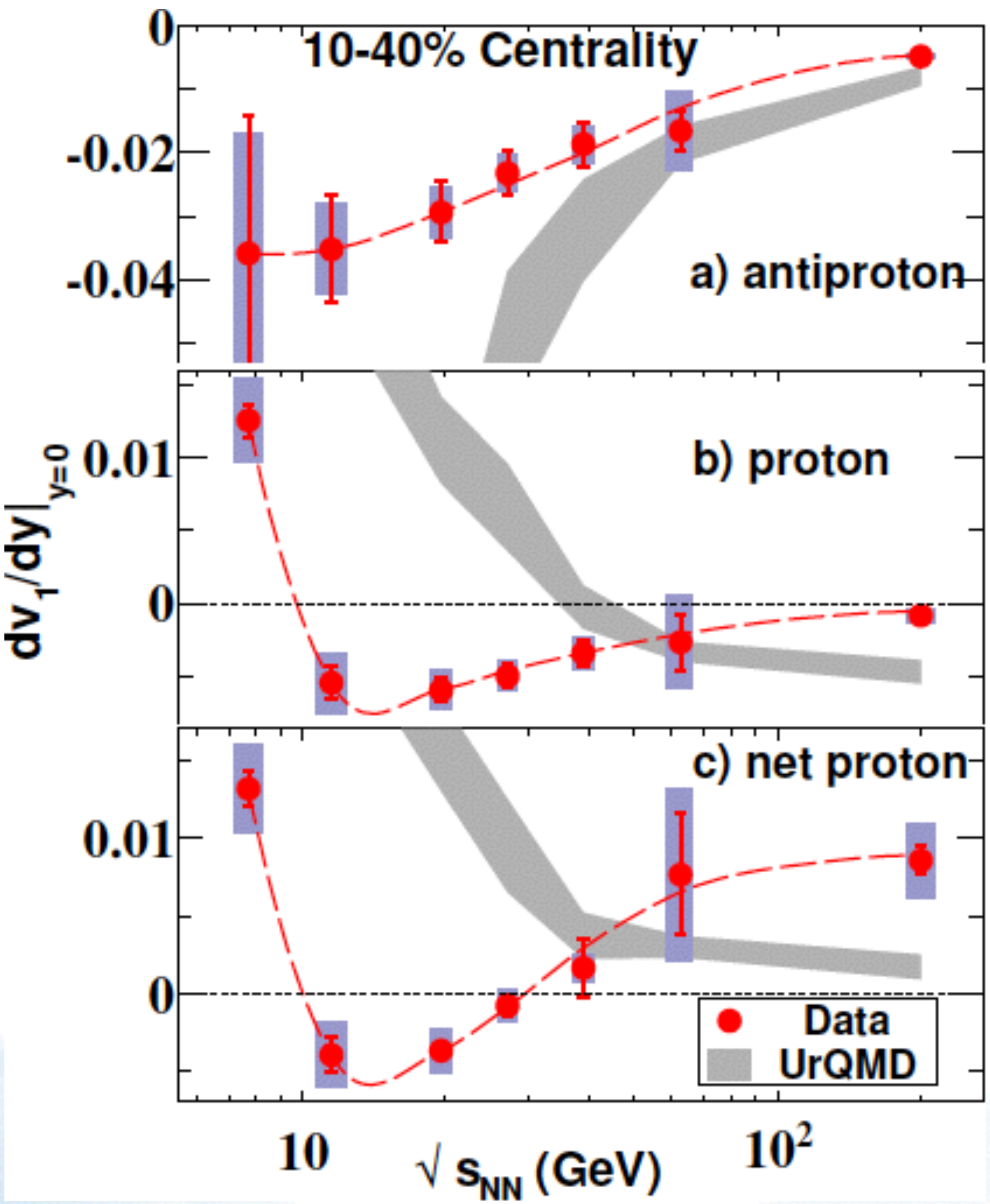


Model independent structure of net baryon number kurtosis

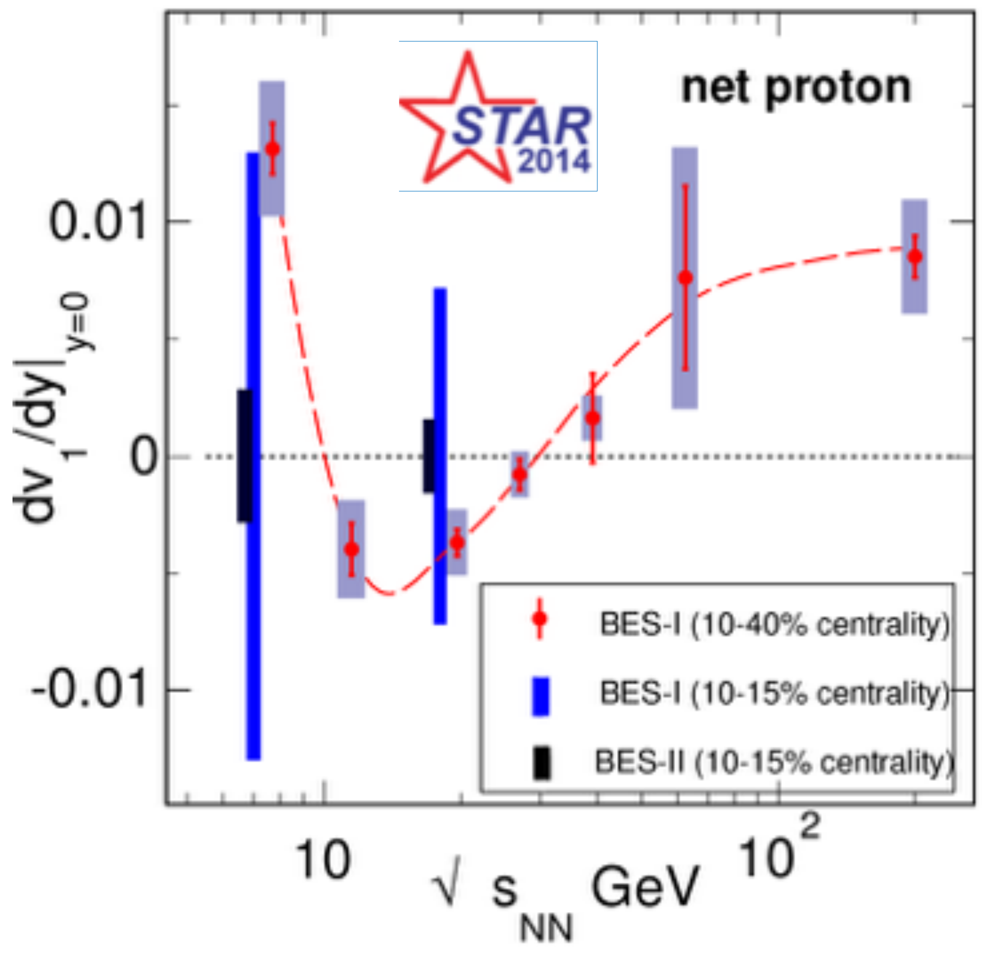




Softening of the Equation of State: v_1



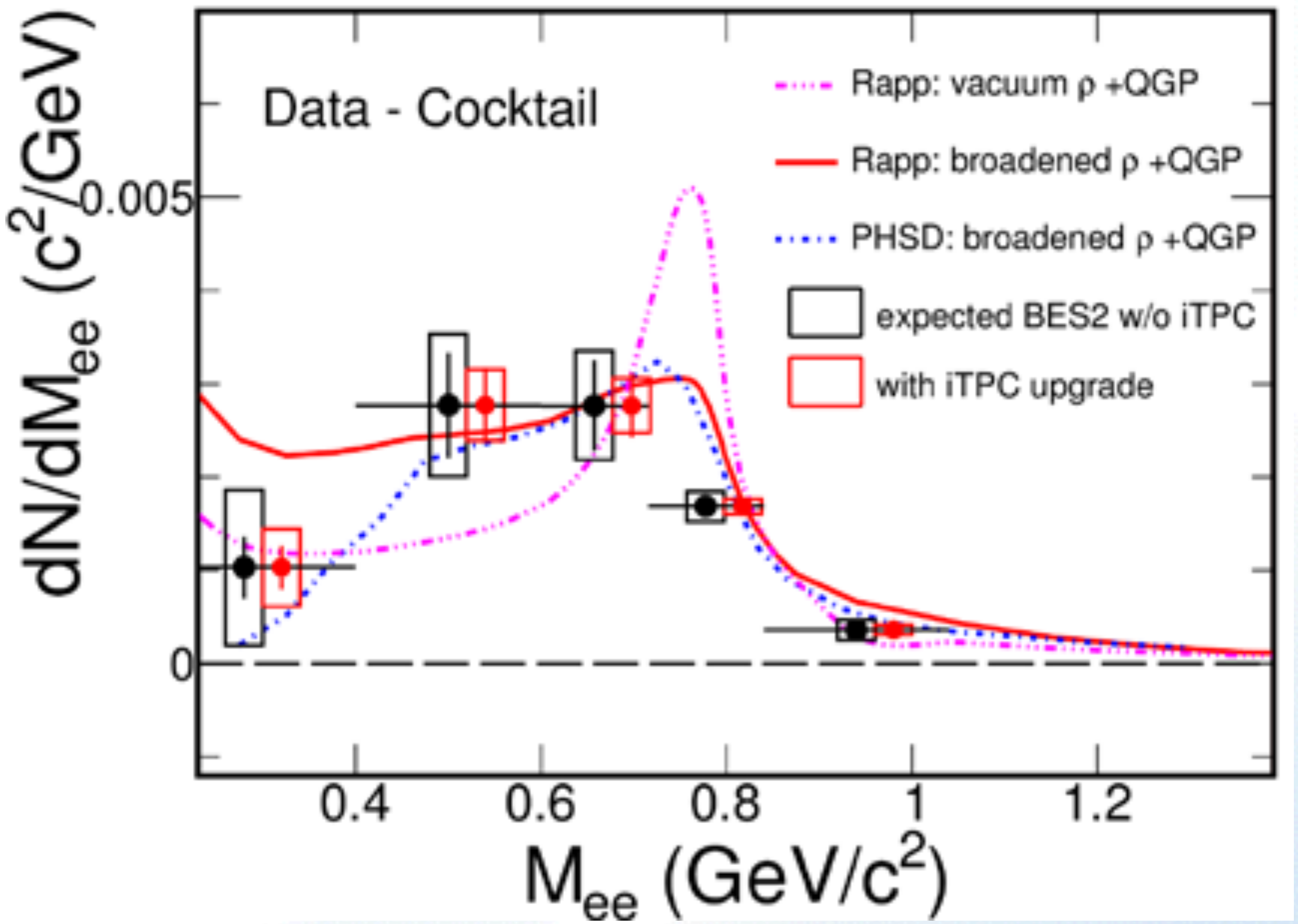
Phys. Rev. Lett, 112 (2014) 162301



- Minimum in v_1 is consequence of the softening of the equation of state in the transition region of the phase diagram.
- Precision measurement requires BES-II data allowing dv_1/dy to be measured with tightly specified centrality.

γ spectral function in BES-II

The iTPC will also enable a more precise measurement of the photon spectral function at masses below 1 GeV



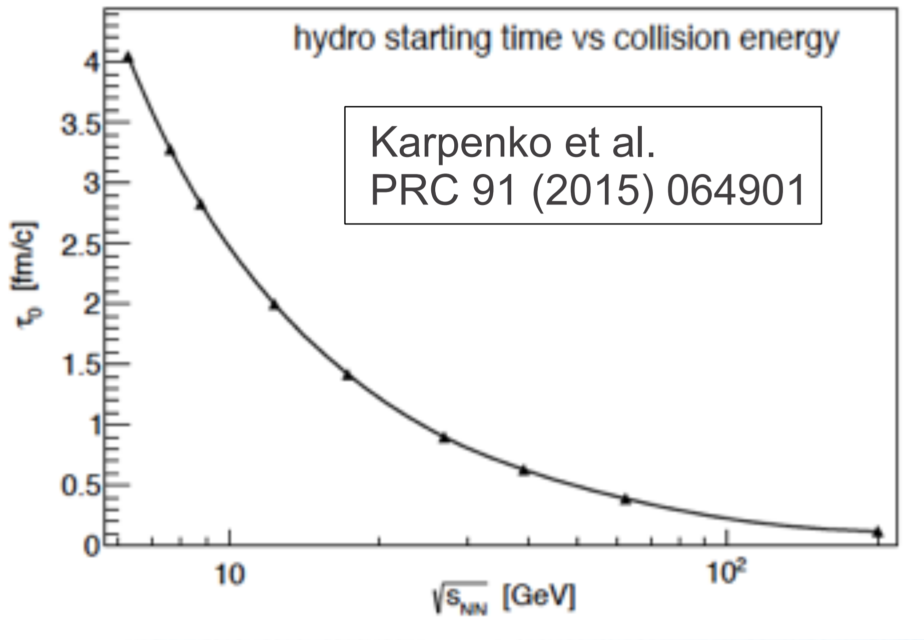
Challenges

Challenges (modeling)

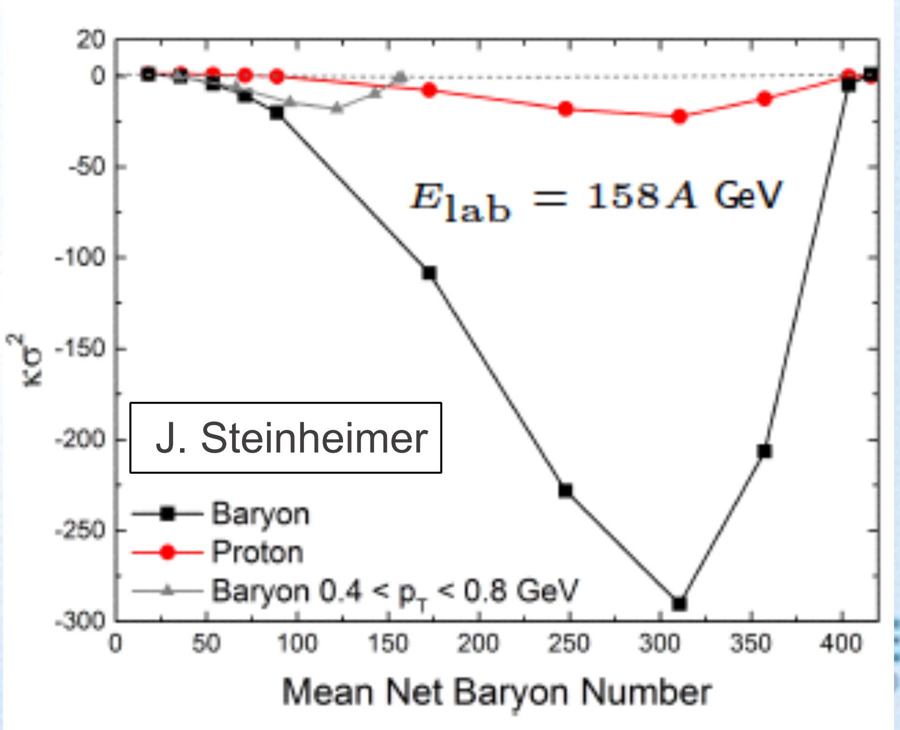
- Dynamical modeling becomes more difficult at lower energy:
  - Hydrodynamical phase starts later

$$\tau_0 \geq 2R\left(\left(\sqrt{s_{NN}}/2m_N\right)^2 - 1\right)^{-1/2}$$

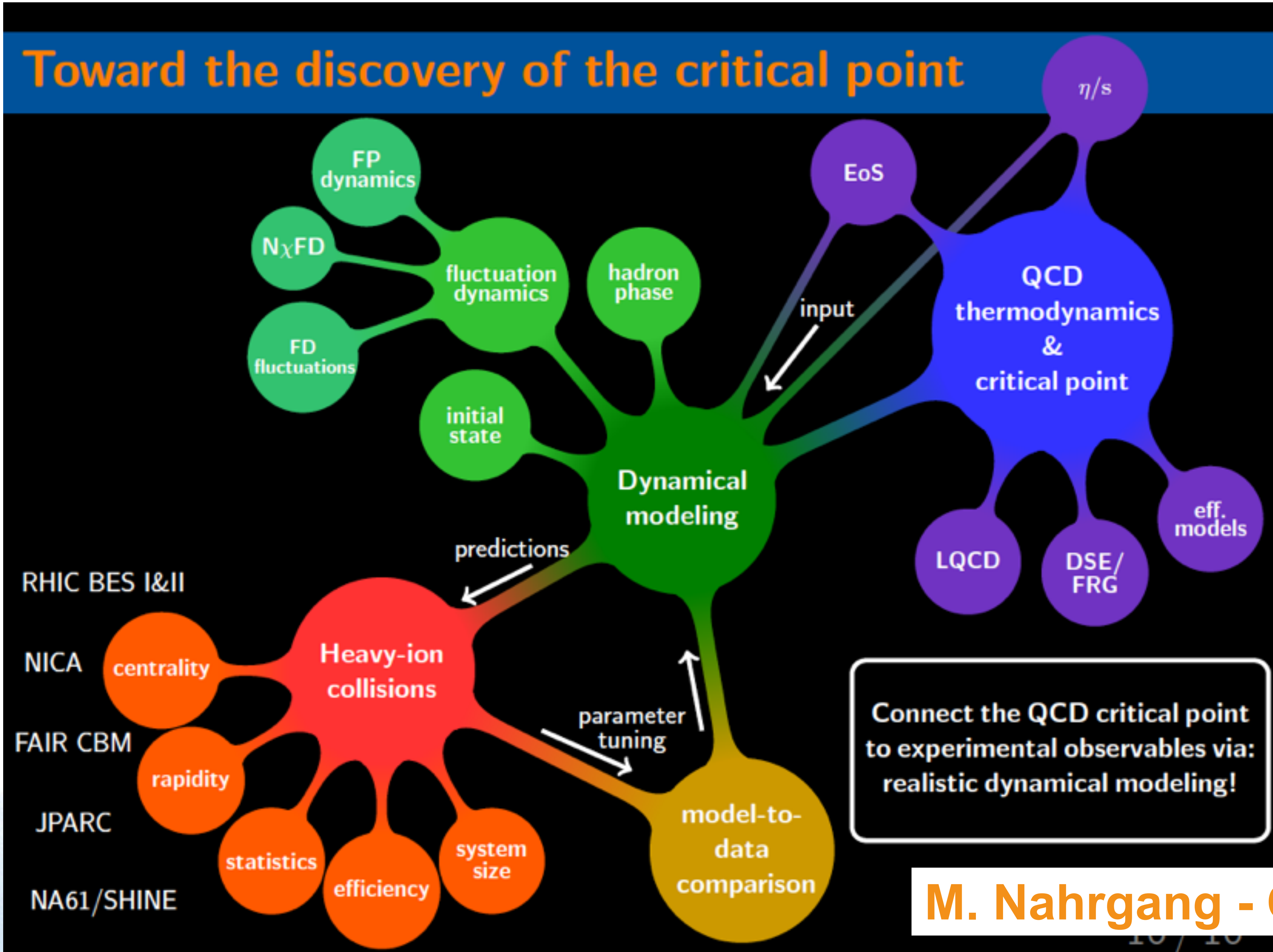
  - Hydrodynamical phase lasts shorter
  - Hadronic final phase more important



  - Energy deposition not dominated by gluons; valence quarks play increasingly important part
  - Threshold effects for particle production
  - Net protons ≠ net baryons
  - Species related flow effects grow
  - More relevant transport parameters!



Fitting it all together



M. Nahrgang - QM2015

Challenges (collaboration)

- Maintain focus on deliverables without becoming rigid or ideological
- Create culture of constructive dialogue between different parts of the collaboration (lattice, thermal QCD, modeling, etc.)
- What worked in JET Collaboration:
  - Topical working groups with convener and bi-weekly video sessions
  - Annual collaboration meetings
  - Active (co-)spokespersons who are leaders in more than science
- Learn from experimental collaborations - they have it all figured out and incorporated into their work culture
- One side benefit: Collaborative work attracts a more diverse community - young scientists feel included, not isolated

Completing the RHIC science mission

- A unique forefront science program with tremendous discovery potential that is ONLY possible with RHIC
- Quantify the transport properties of the QGP using heavy quarks as probes
- Measure gluon and sea quark contributions to proton spin and explore coupled momentum-spin dynamics of QCD
- High statistics map of the QCD phase diagram, including search for a critical point in BES-II and discovery of anomaly induced local symmetry violations in QCD
- Probe internal structure of the *most liquid* QGP using fully reconstructed jets and resolved Upsilon states as probes
- Extend the effective collaboration among theorists and with experimentalists pioneered by the JET Collaboration to the core challenges of mapping the QCD phase diagram and extracting QCD matter properties from the data.