Life Above the Hagedorn Temperature

Quark-Gluon Plasma at SPS, RHIC & LHC

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Hagedorn Symposium
CERN
13 November 2015

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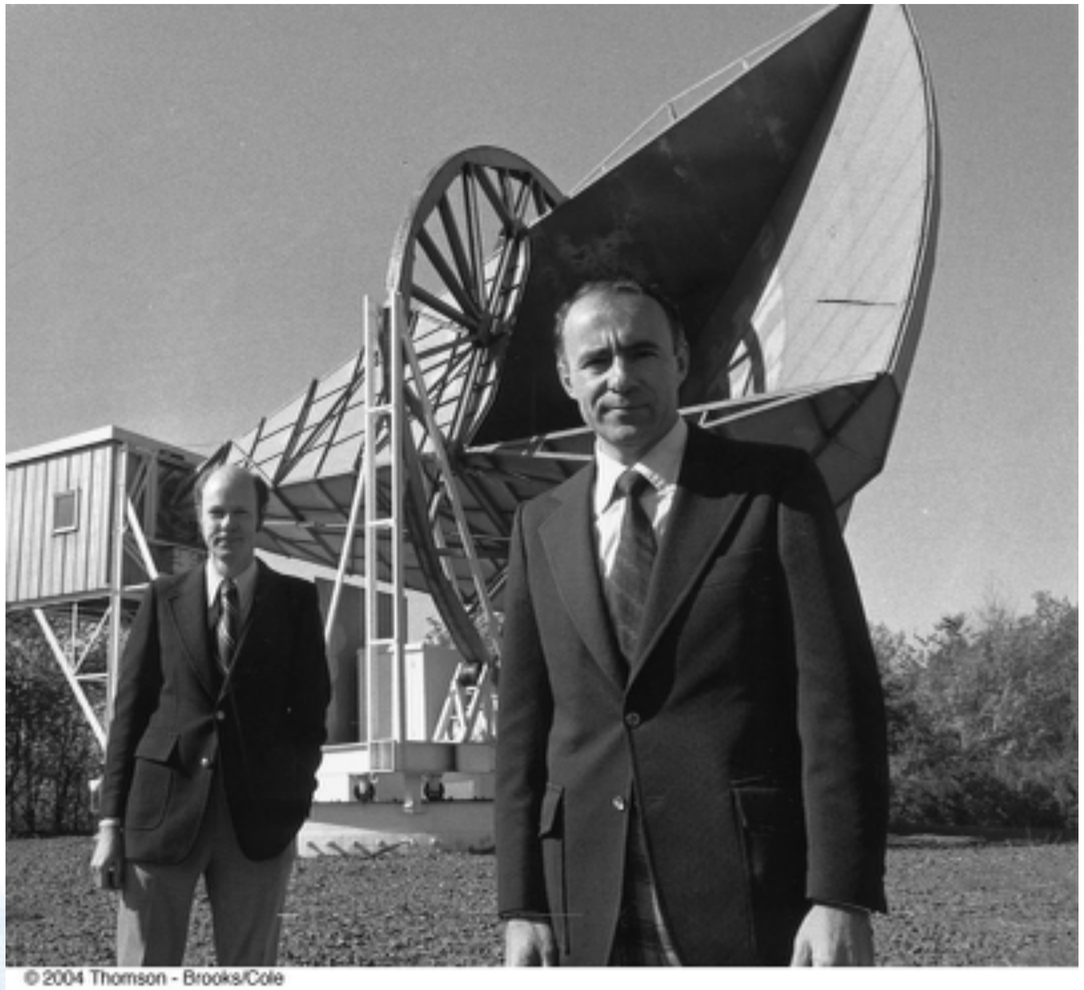
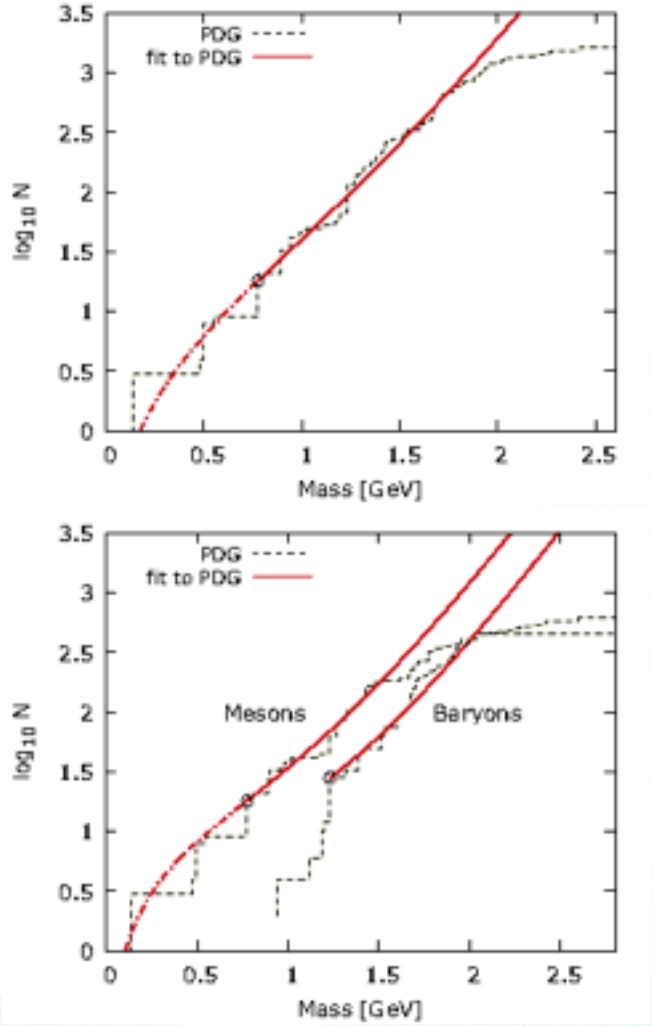
NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

1965

was a momentous year



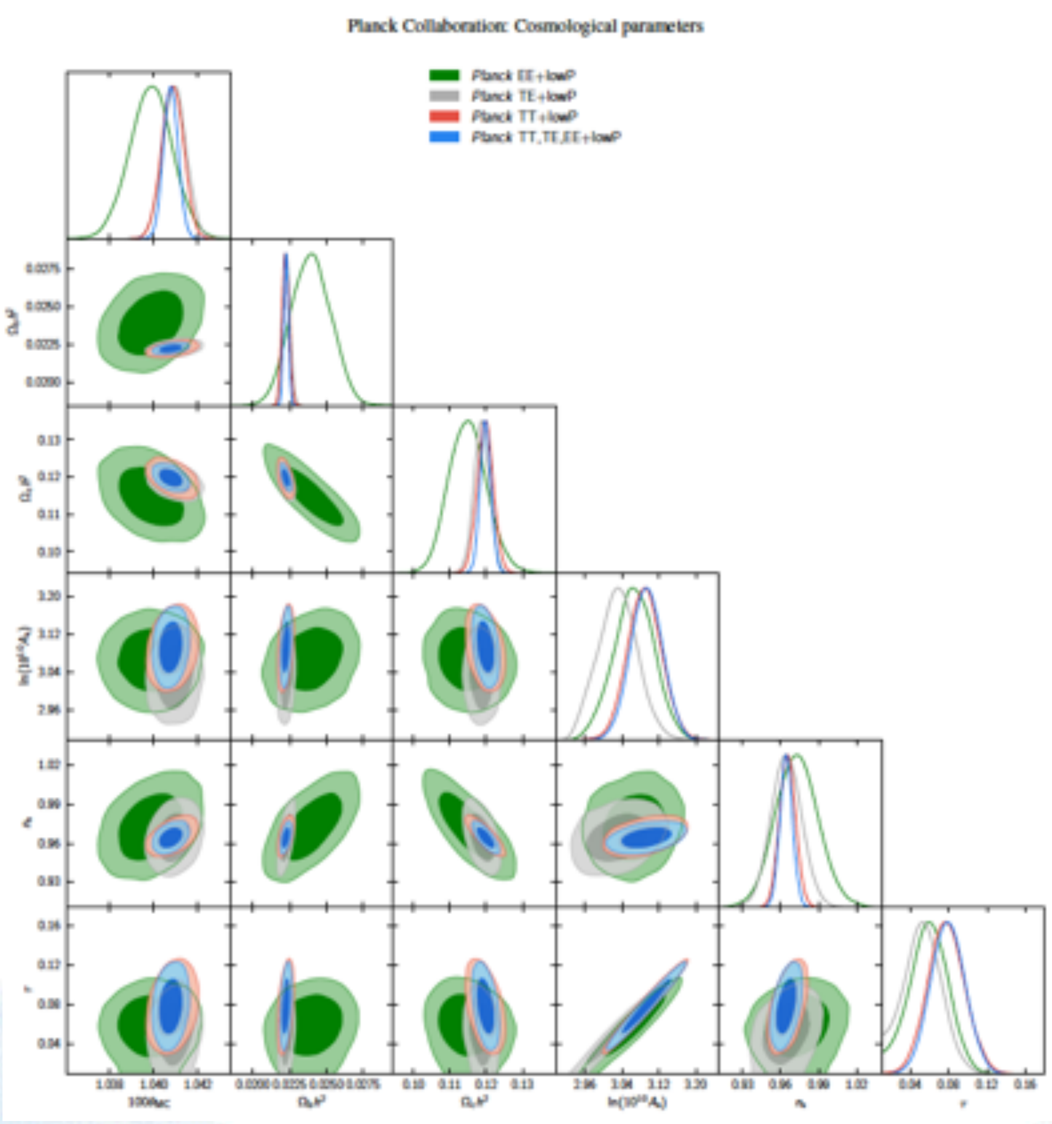


cosmic microwave background

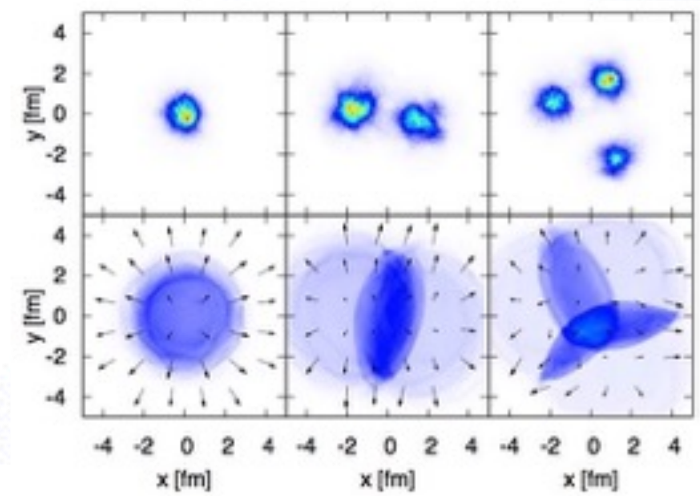
Hagedorn mass spectrum

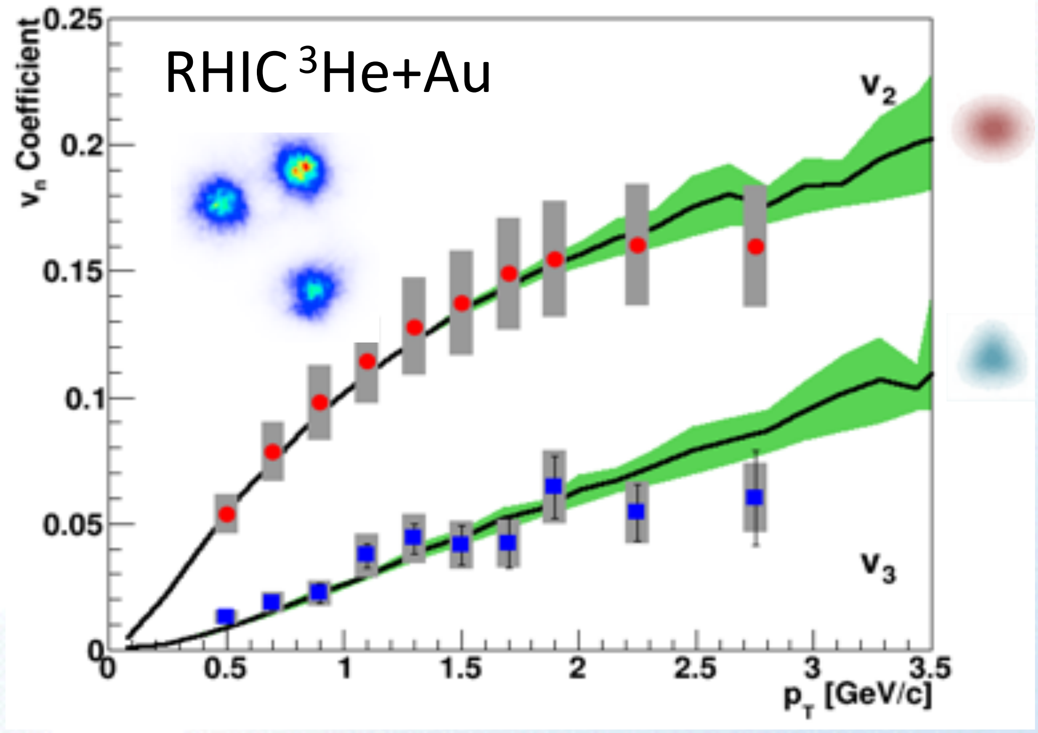
2015

almost unimaginable progress



Planck: cosmological parameters





PHENIX: QGP in p/d/^{3}He+Au

Three things are needed…

…to reach the summit: good equipment, good strategy, determination.

In the study of hot, dense QCD matter this means:

- High luminosity colliders
- Large acceptance, high DAQ rate detectors with good particle ID
- Realistic lattice QCD for thermo-dynamic quantities
- Realistic transport codes
- Weak (pQCD) and strong (AdS/CFT) coupling dynamical models
- Multivariate model-data comparison

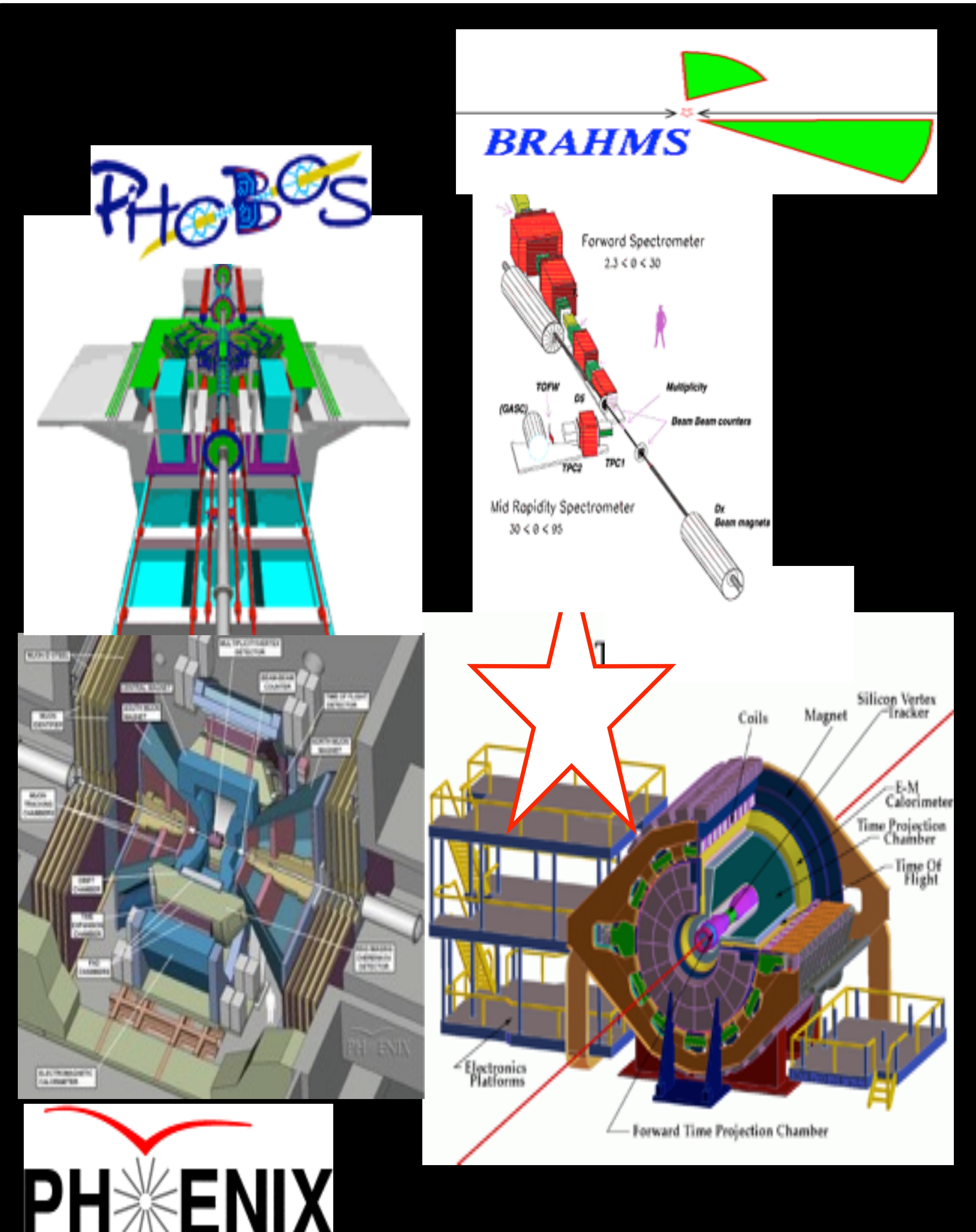
After several decades of experimental and theoretical development, the necessary tools are now all in place.

The Relativistic Heavy Ion Collider

…is hexagonal and 3.8 km long

RHIC-AGS Complex at BNL

The Relativistic Heavy Ion Collider



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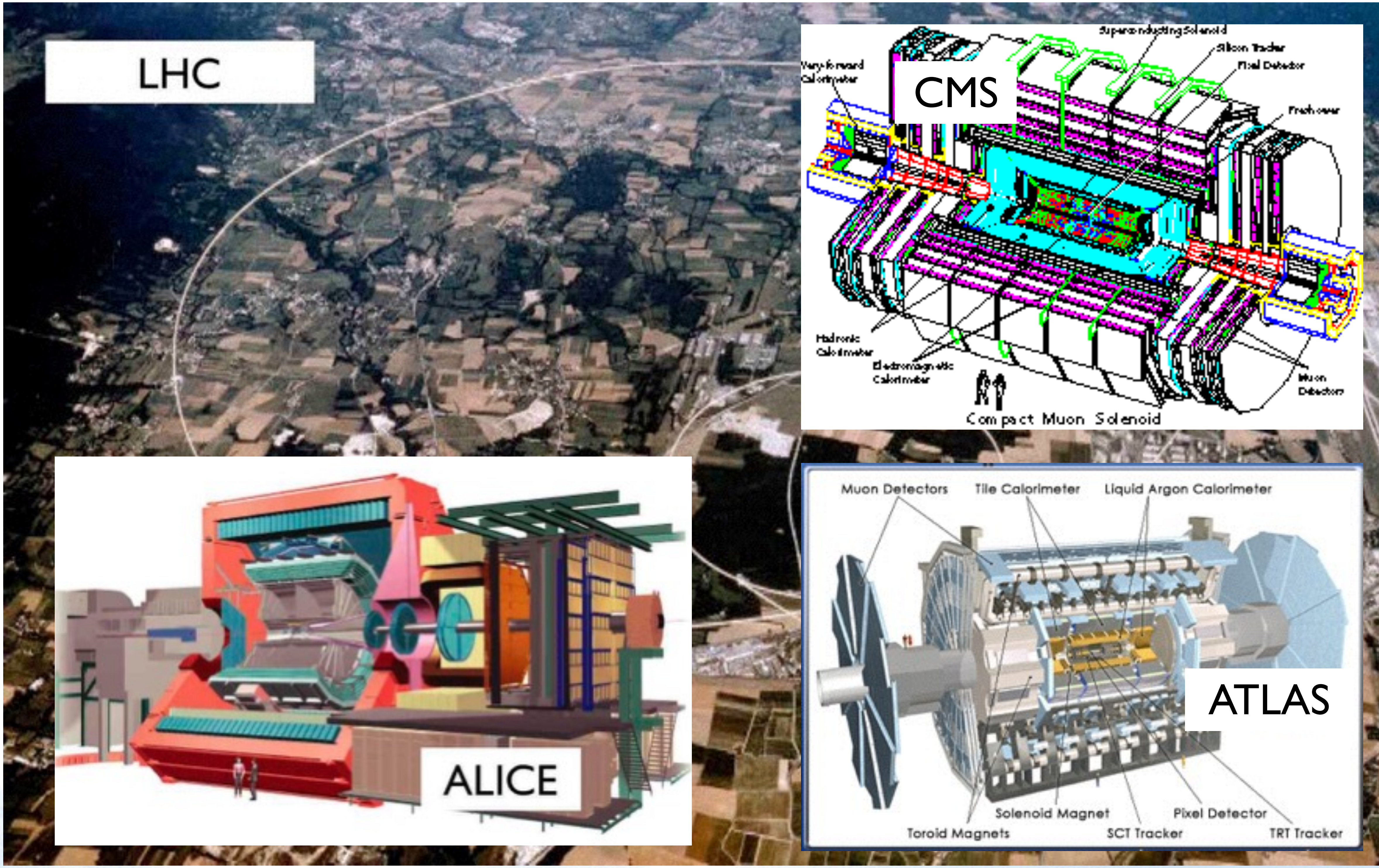
The highest energies…

The highest energies…



Equation of State of QCD Matter

Equation of State

EOS of flowing matter has conservative and dissipative contributions:

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

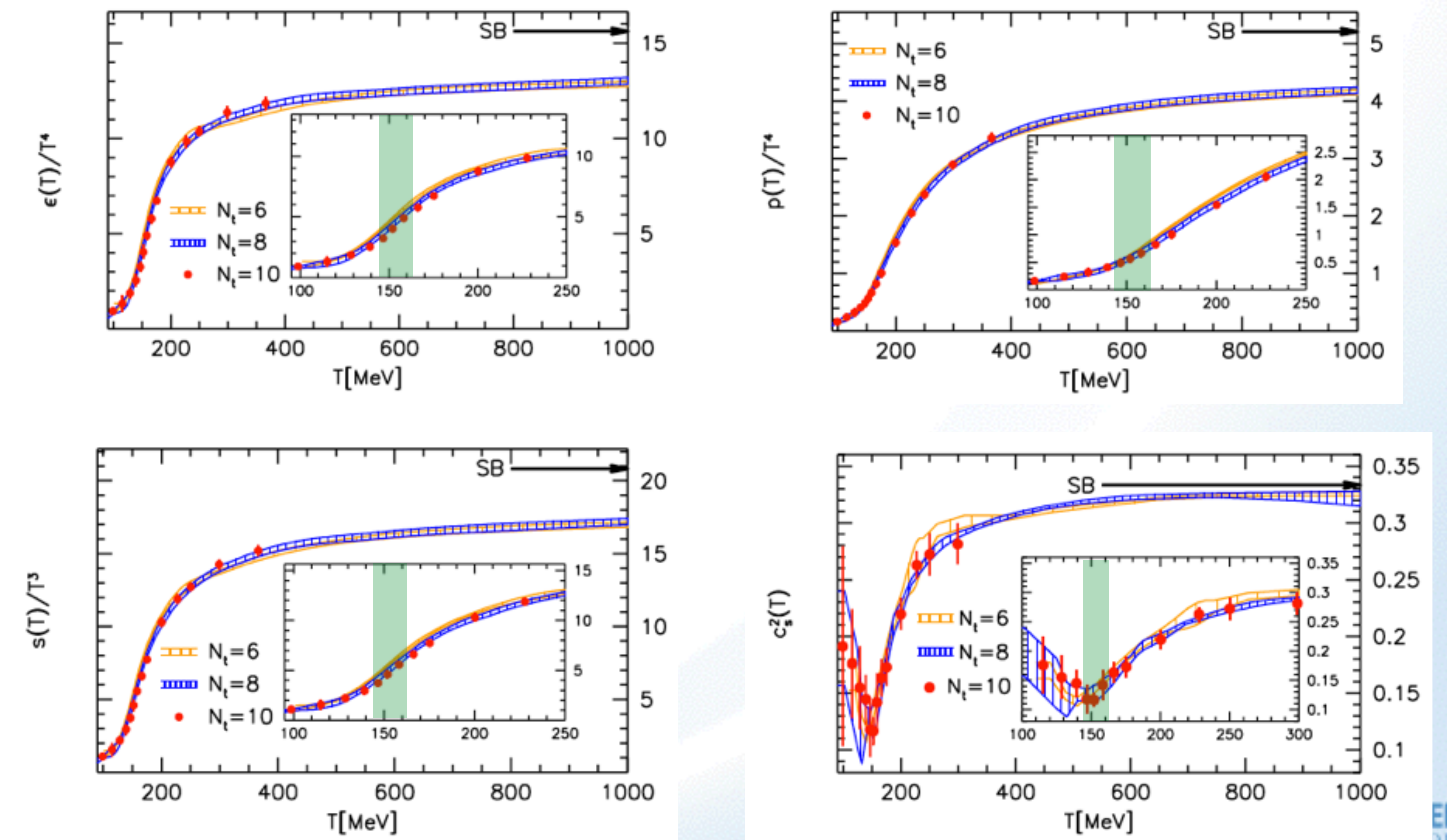
When $\zeta(\partial_\alpha u^\alpha) > p$, the matter becomes unstable and cavitates.

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.

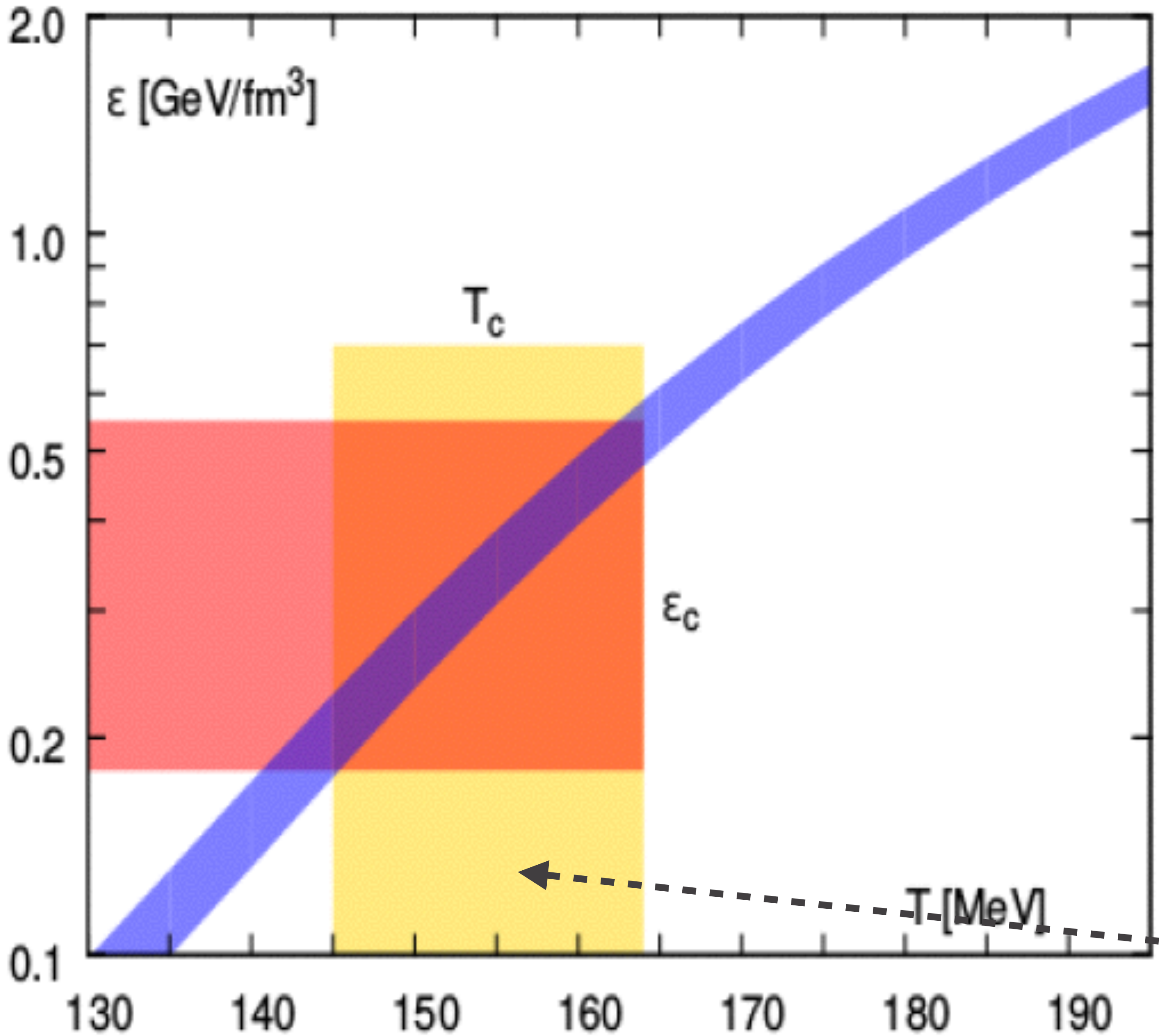
QCD EOS at $\mu_B = 0$

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:

$T_c = 154 \pm 9$ 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!

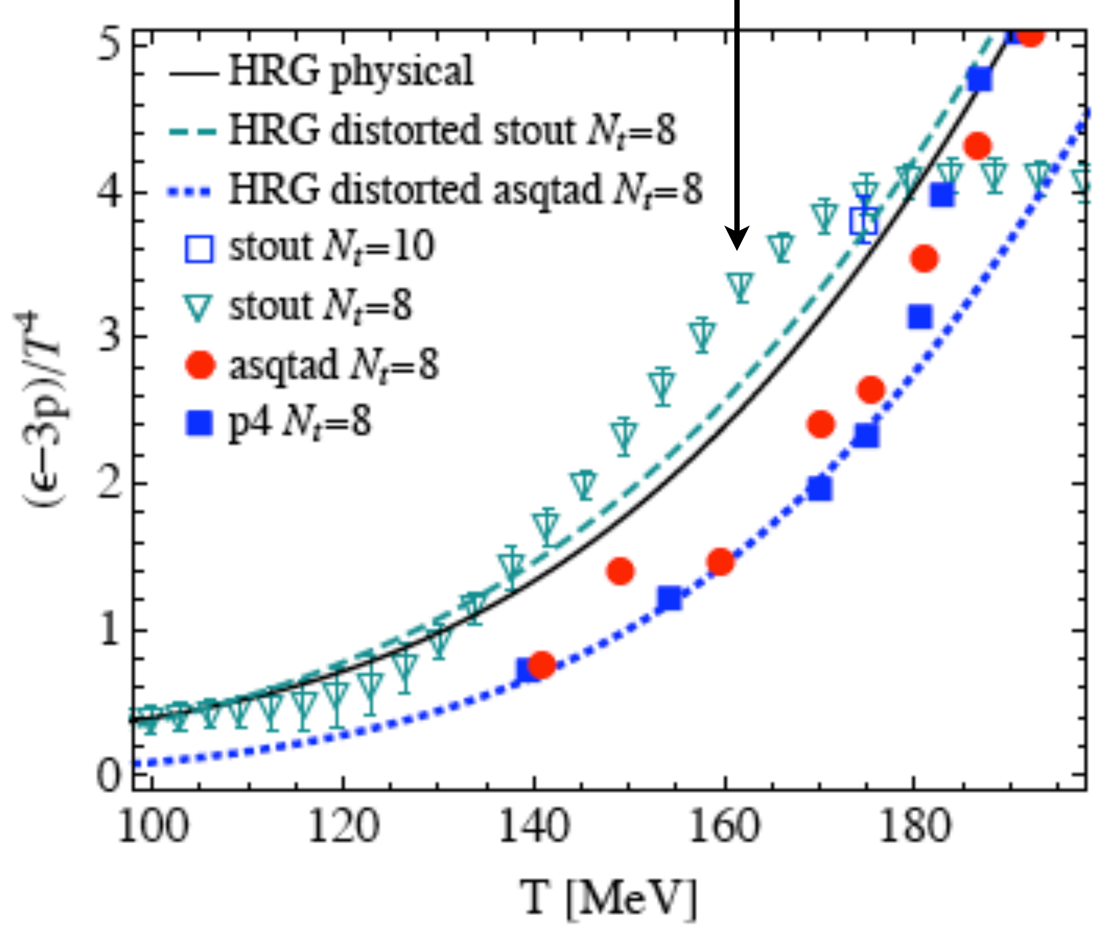
Hadron mass spectrum

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

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

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

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



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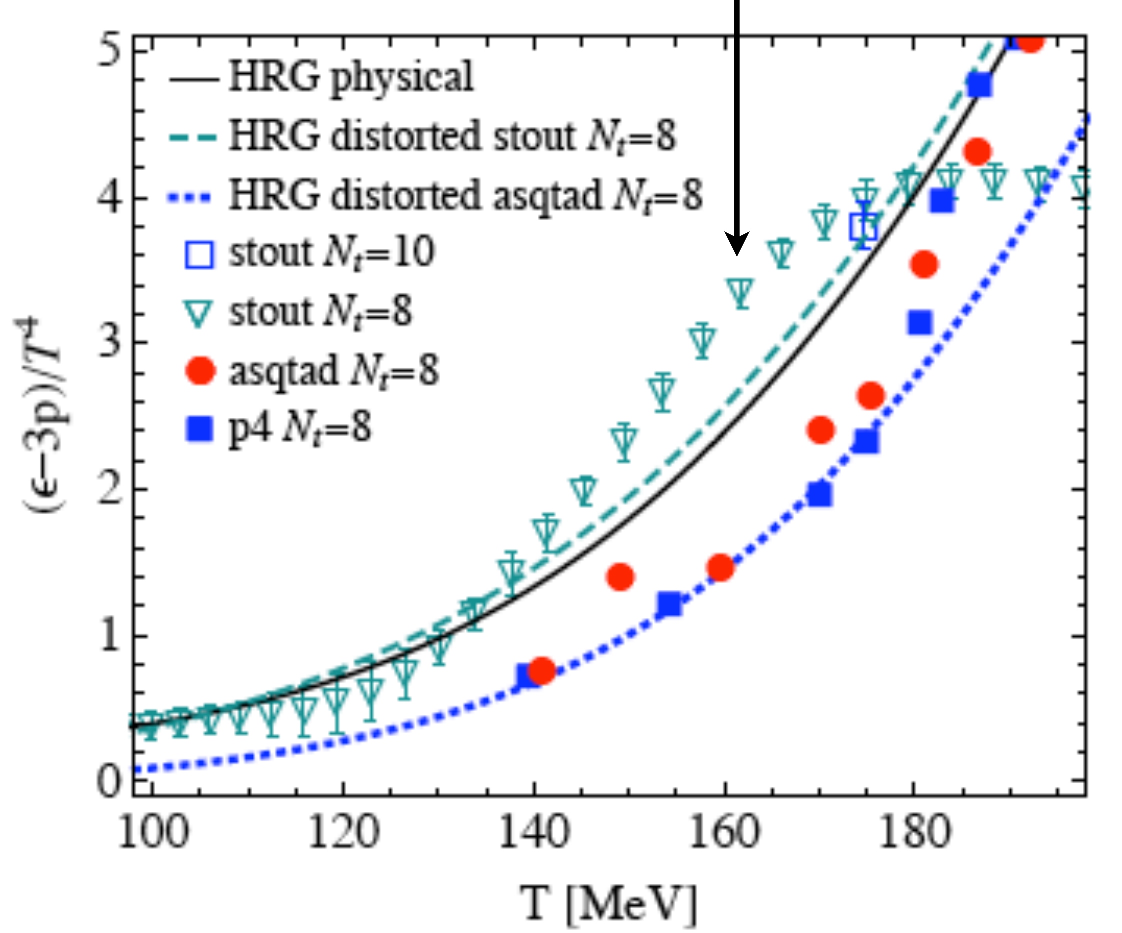
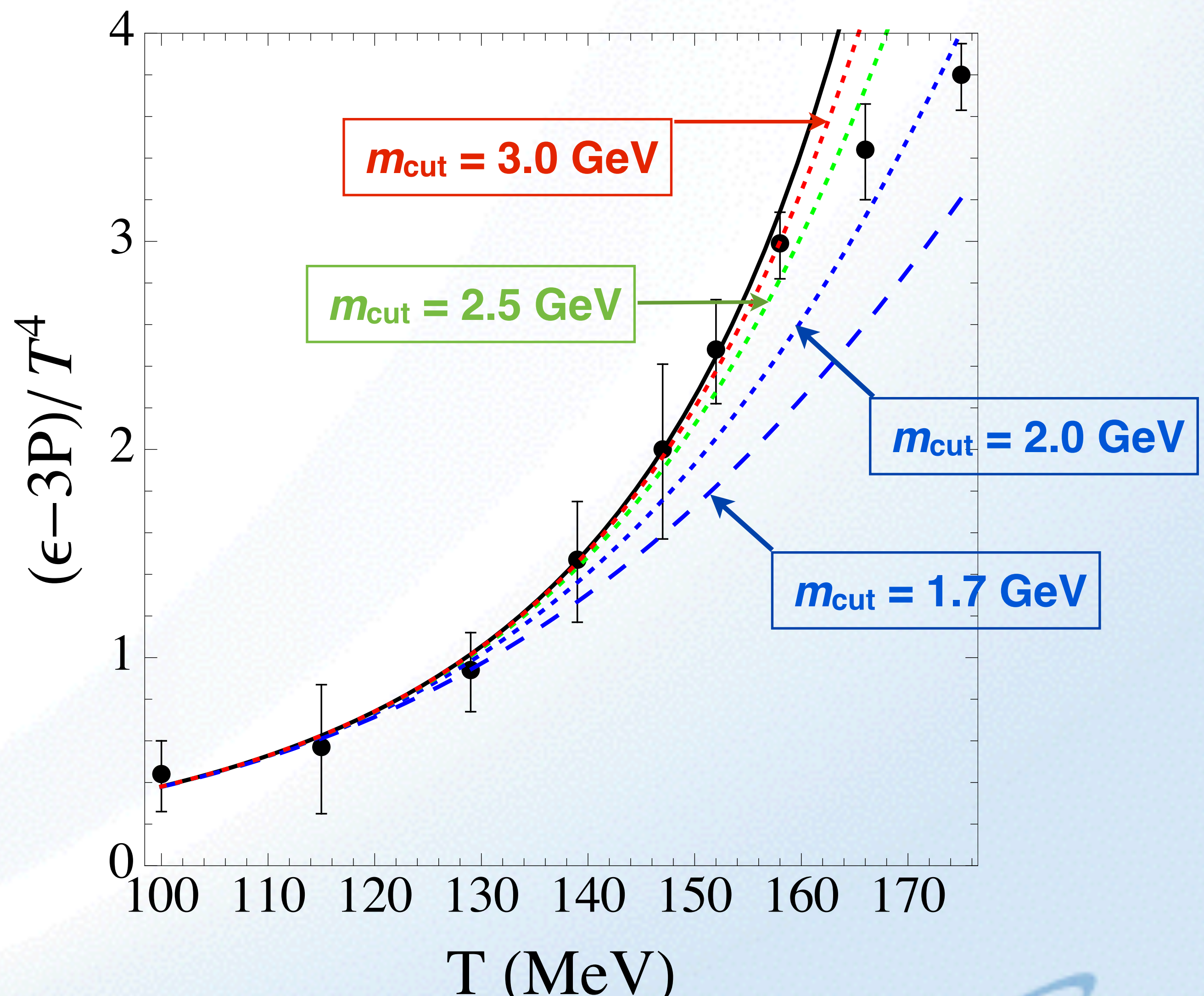


Hagedorn spectrum ($T_H \approx 180$ MeV):

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

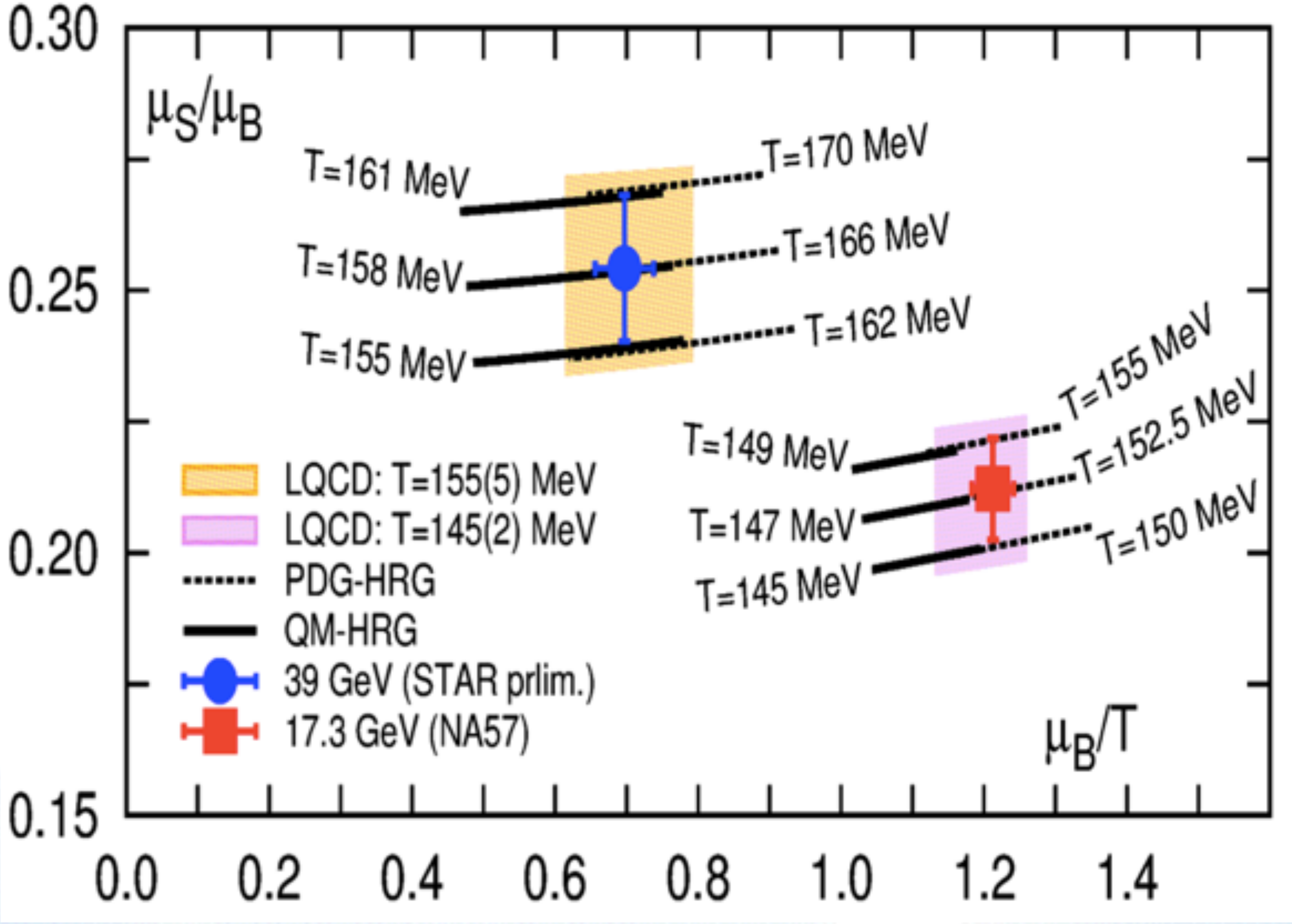
In good agreement with lattice results
Hadrons up to 3 GeV mass contribute



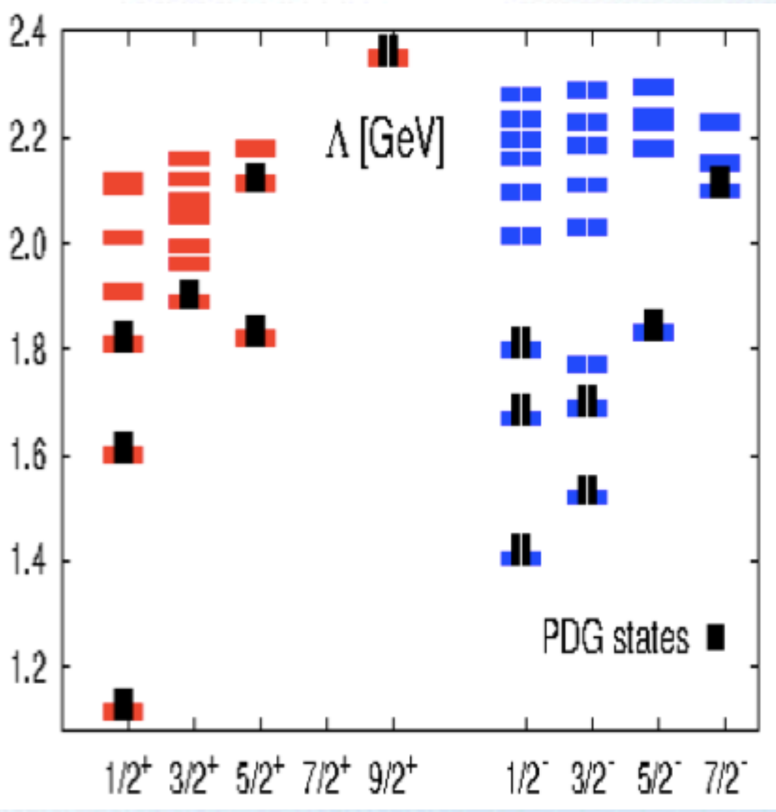
Probing the baryon spectrum

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



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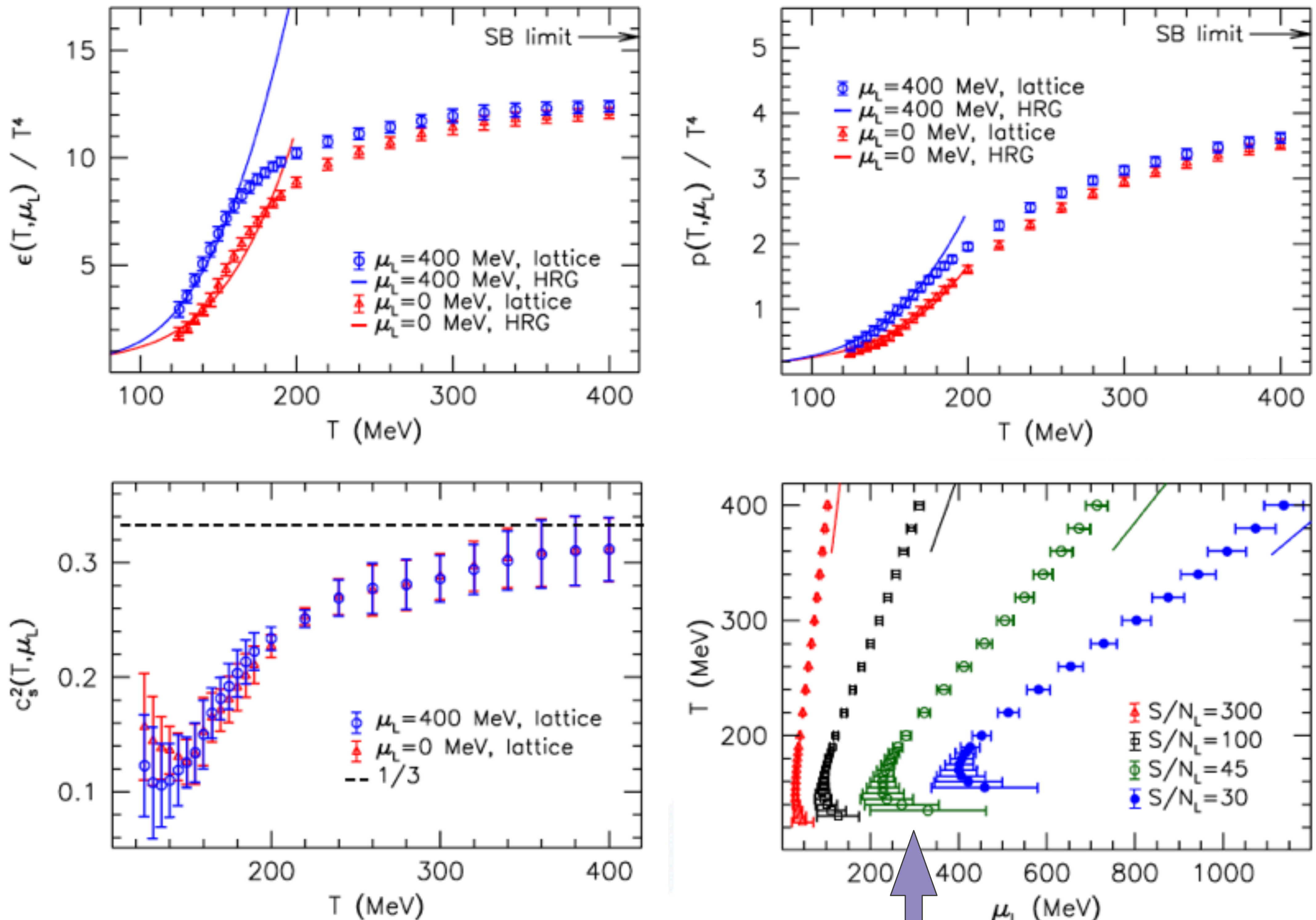
QCD EOS at $\mu_B \neq 0$

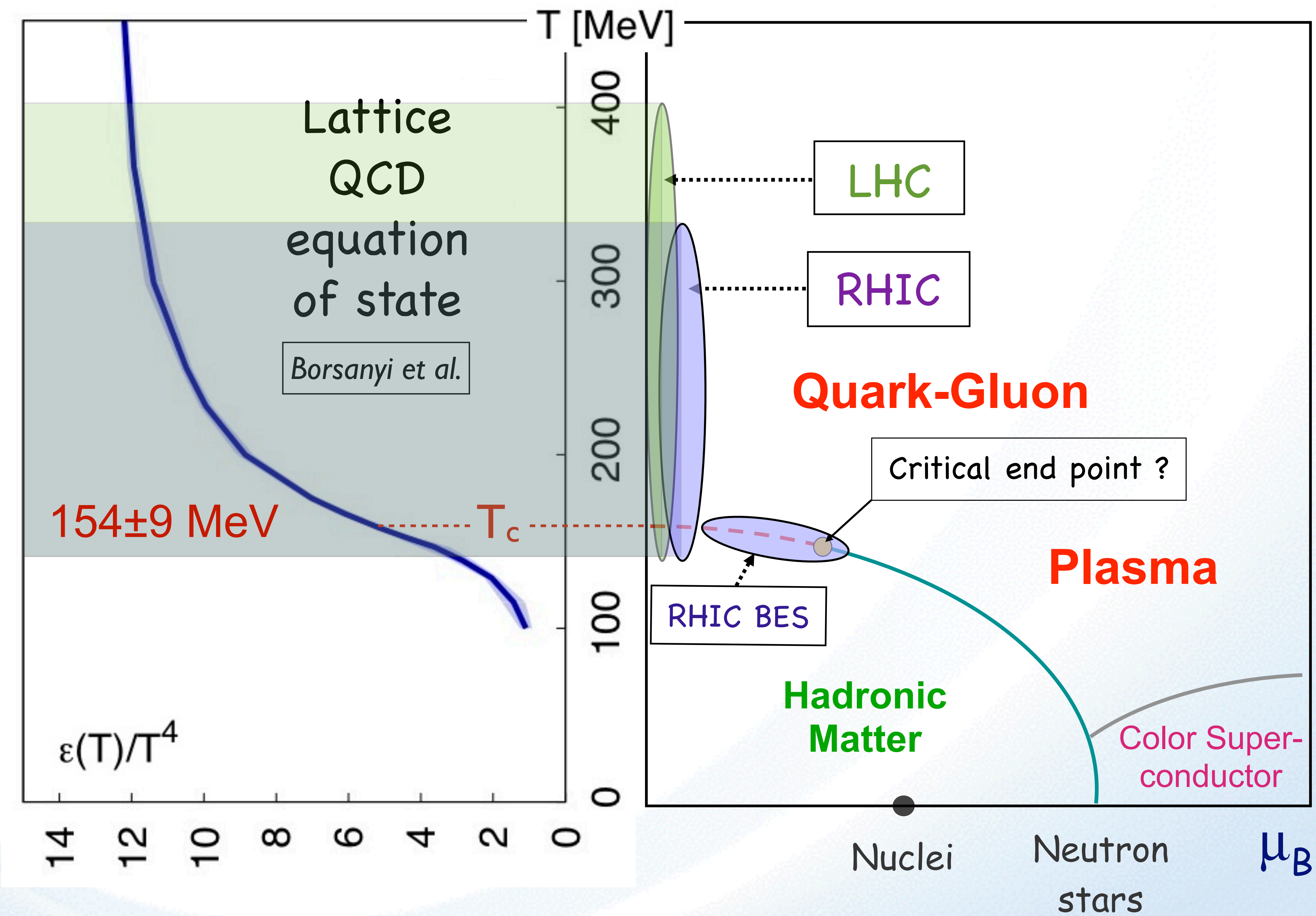
Borszanyi et al., arXiv:1204:6710



Approximate trajectories in QCD phase diagram

Probing the QCD Phase Boundary

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

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

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:

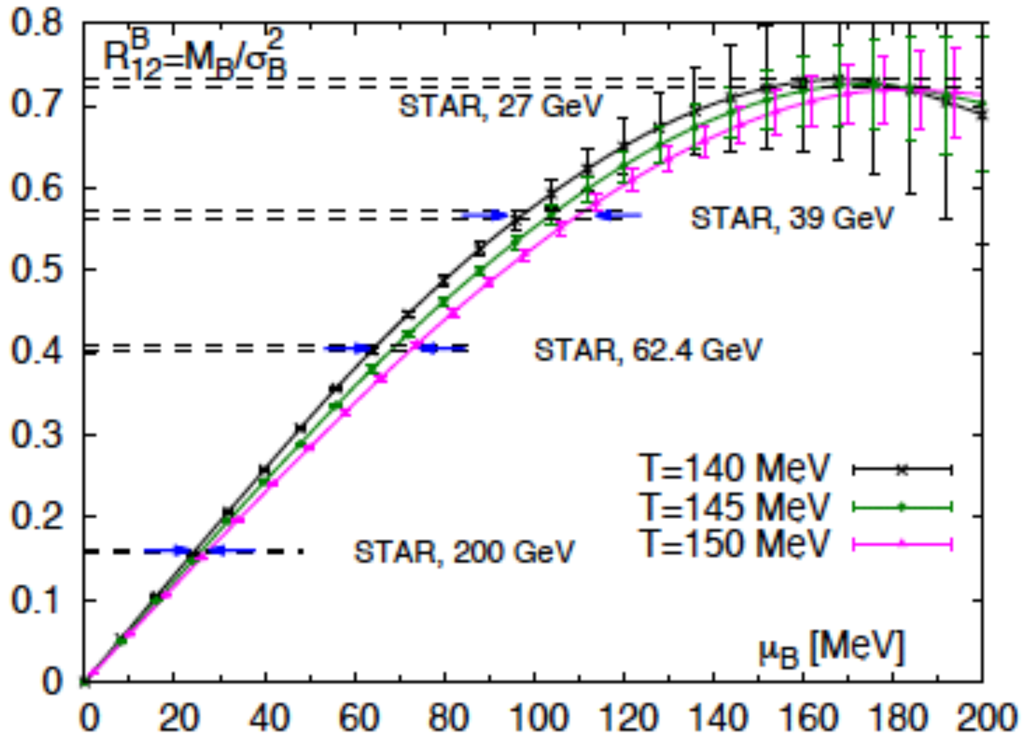
$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\chi_1^Q(T, \mu_B)}{\chi_2^Q(T, \mu_B)} \qquad \frac{S_Q(\sqrt{s})\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\chi_3^Q(T, \mu_B)}{\chi_1^Q(T, \mu_B)}$$

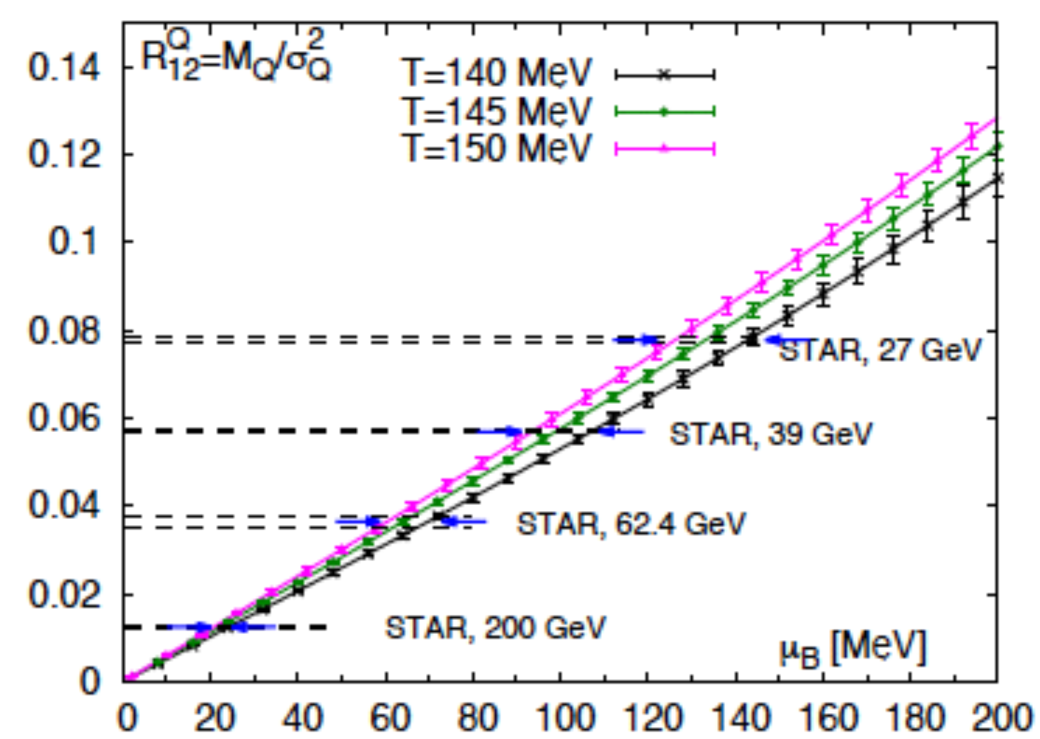
Chemical freeze-out

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

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

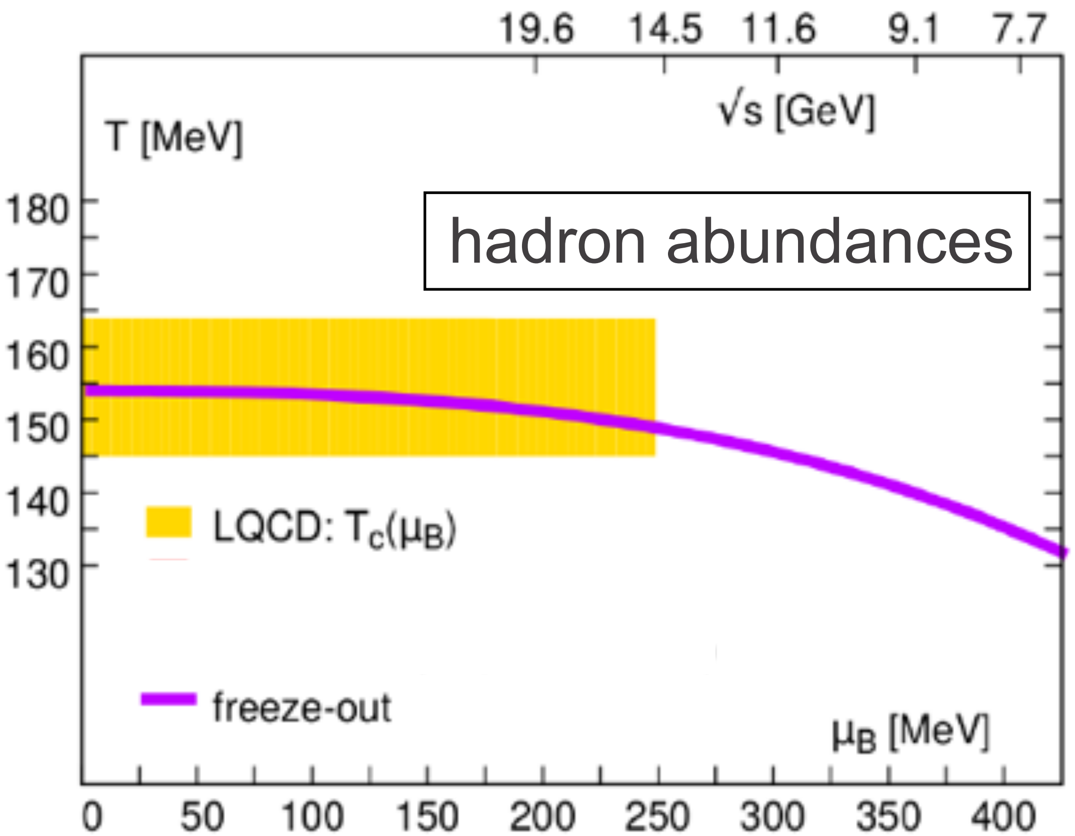
use M/σ^2 both in the baryon and in the charge sector

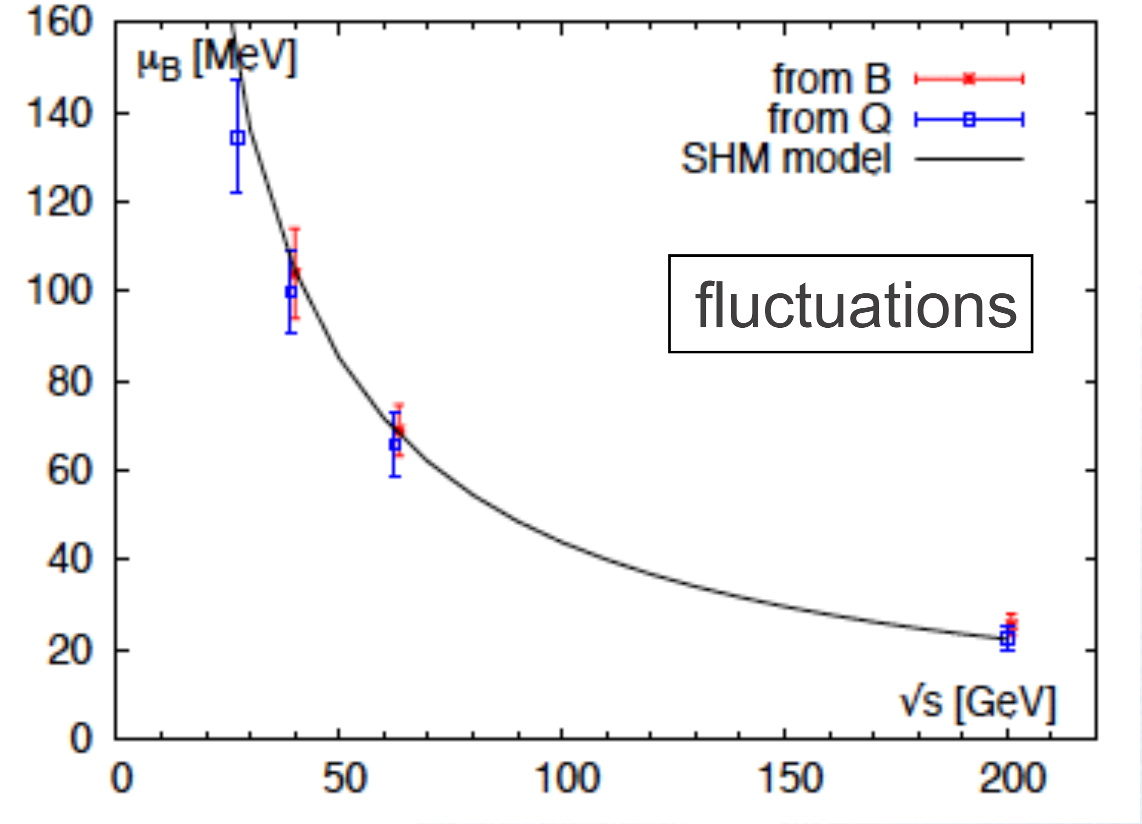




Compare lattice results with the STAR data for the fluctuation ratios in the temperature range 140−150 MeV permits to read off μ_B.
Both methods are consistent with each other and with the measured baryon/antibaryon ratios, if additional strange baryon states beyond those in the PDG tables (e.g. in the quark model) are accounted for.

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 ?

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Easy for LQCD

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

Equation of state: spectra, coll. flow, fluctuations

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

Shear viscosity: anisotropic collective flow

Very Hard for LQCD

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0)\right\rangle \\
\hat{e} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle iU^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0)\right\rangle \\
\kappa &= \frac{4\pi\alpha_s}{3N_c}\int d\tau \left\langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b\right\rangle
\end{aligned}\right\}$$

Momentum/energy diffusion:
parton energy loss, jet fragmentation

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

QGP Radiance: Lepton pairs, photons

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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

The "perfect" fluid

Viscous hydrodynamics

Hydrodynamics = effective theory of energy and momentum conservation

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

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

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

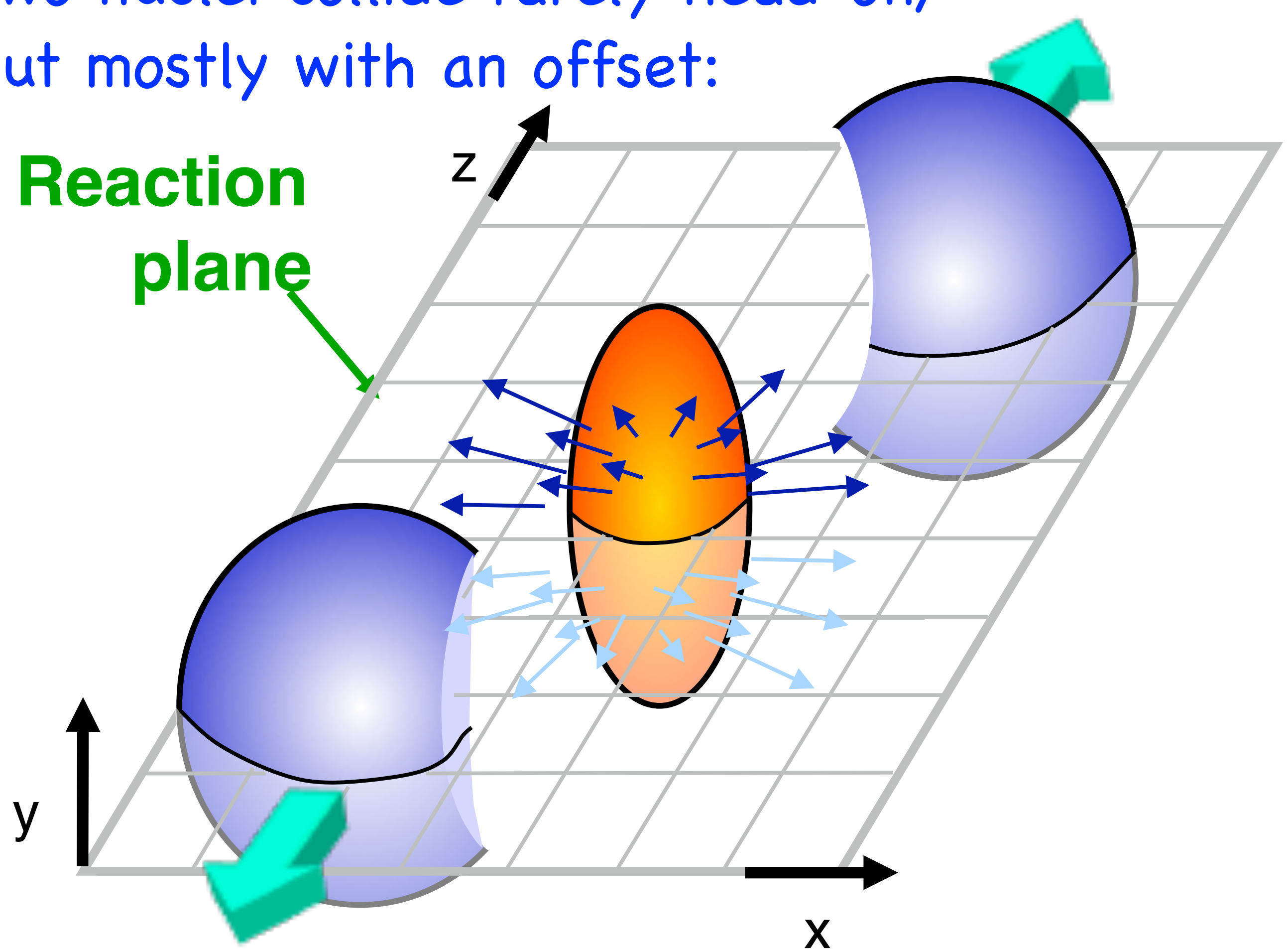
Input: Equation of state P(ε), shear viscosity, initial conditions ε(x,0), $u^\mu(x,0)$

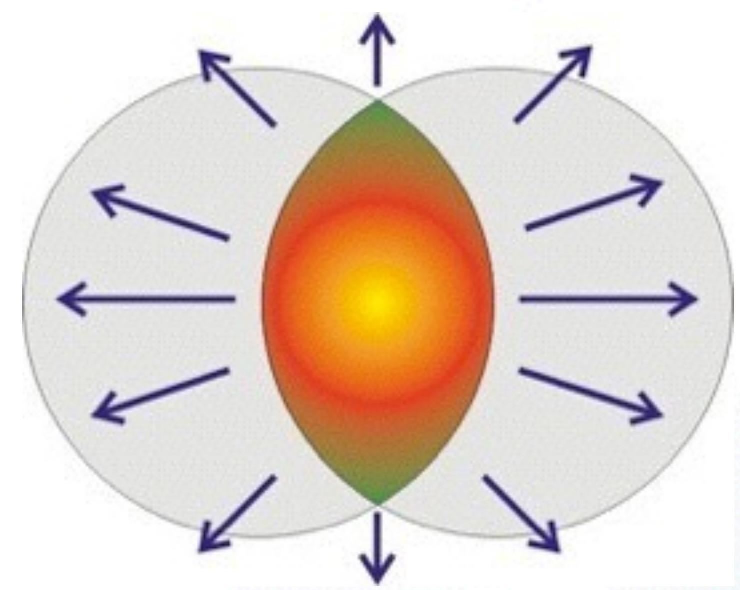
Shear viscosity **η** is normalized by density: **kinematic viscosity η/ρ**.

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

Elliptic flow

- two nuclei collide rarely head-on,
  but mostly with an offset:





only matter in the overlap area
gets compressed and heated

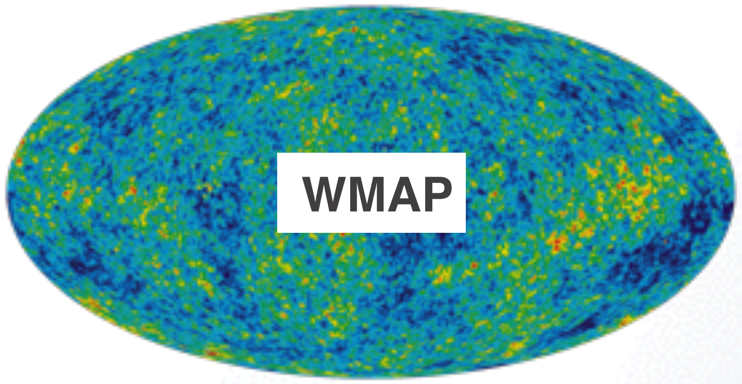
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n \mathrm{v}_n(p_T, \eta) \cos n \left(\phi - \psi_n(p_T, \eta) \right) \right)$$

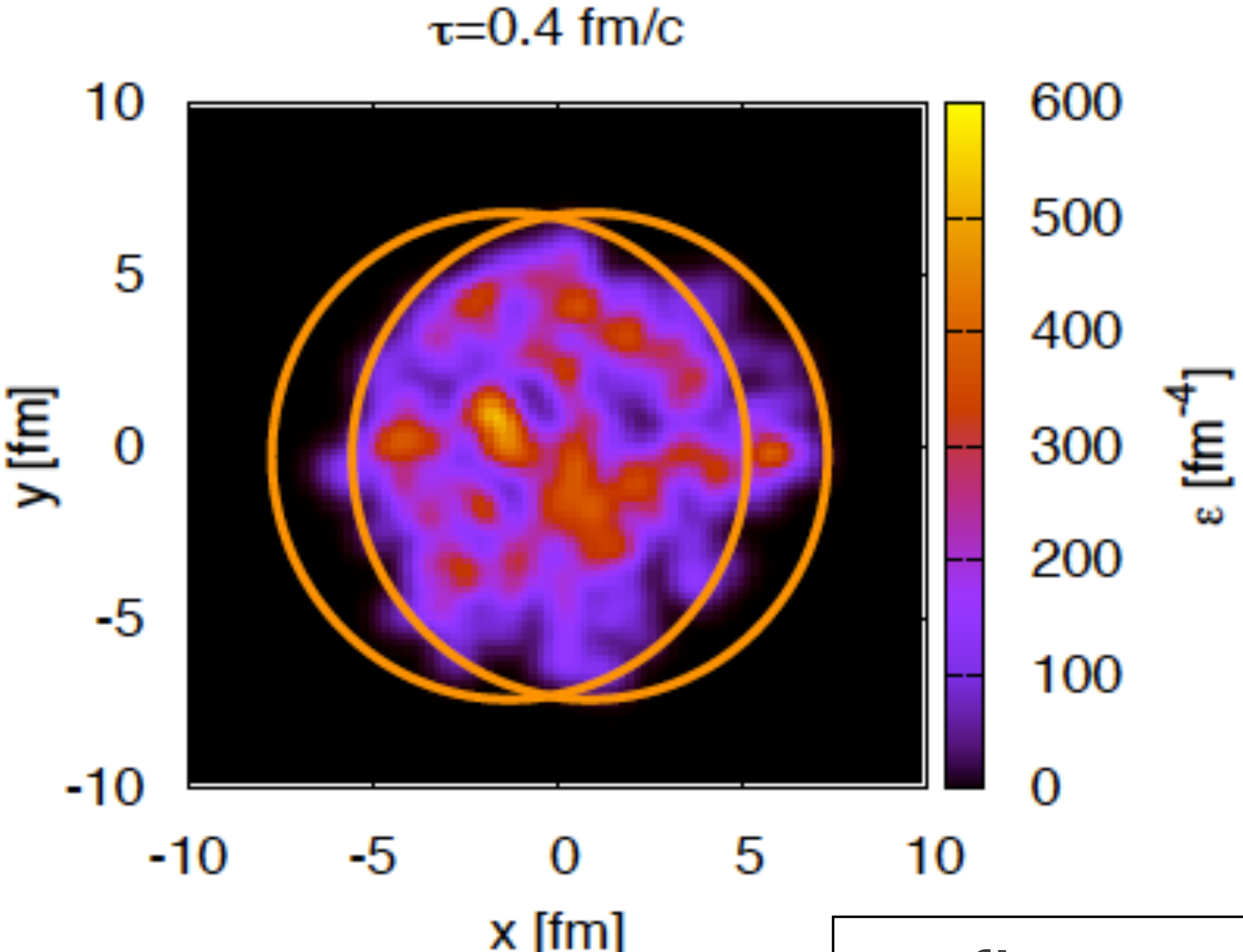
anisotropic flow coefficients

event plane angle

Event-by-event fluctuations

Initial state generated in A+A collision is grainy
event plane ≠ reaction plane
⇒ eccentricities ε_1, ε_2, ε_3, ε_4, etc. ≠ 0



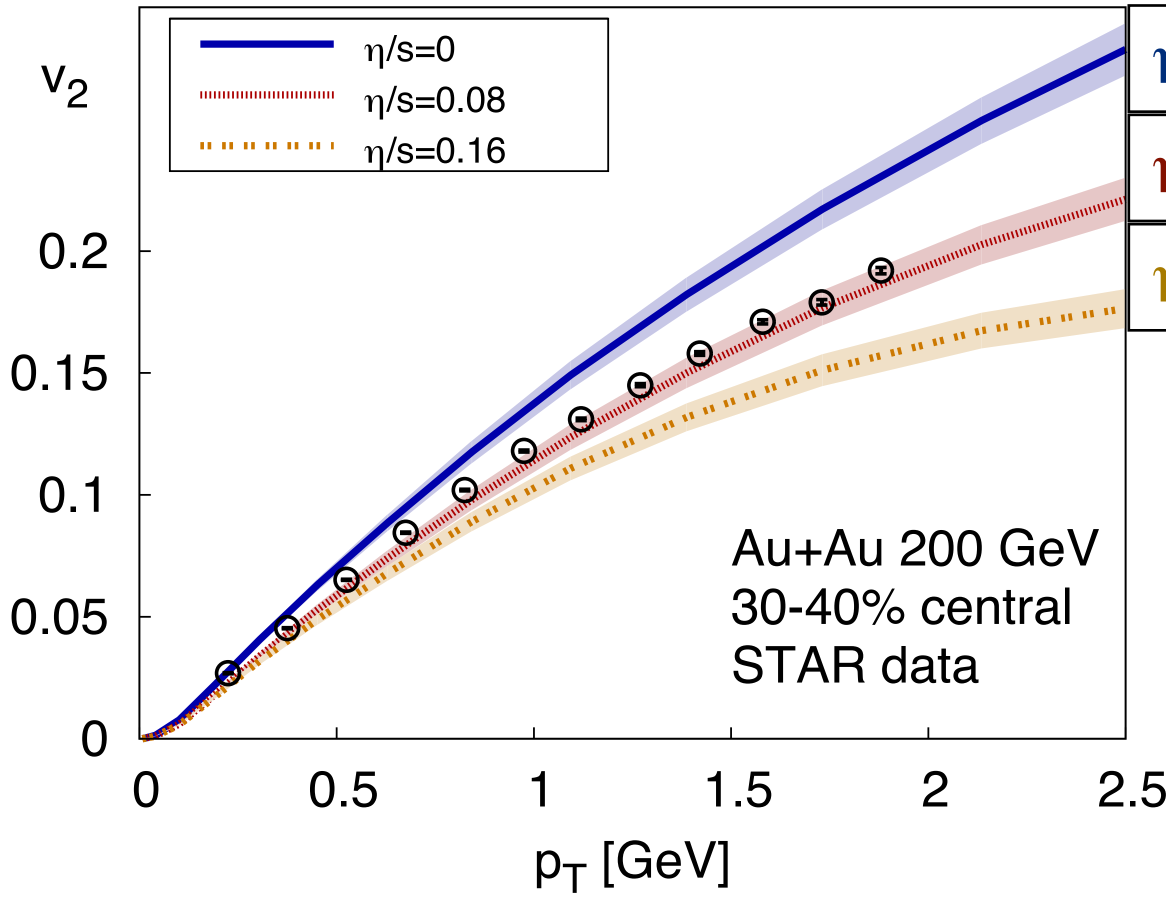


Idea: Energy density fluctuations in transverse plane from initial state quantum fluctuations. These thermalize to different temperatures locally and then propagate hydrodynamically to generate angular flow velocity fluctuations in the final state.

⇒ flows v_1, v_2, v_3, v_4,...

Elliptic flow "measures" η_{QGP}

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



$\eta/s = 0$

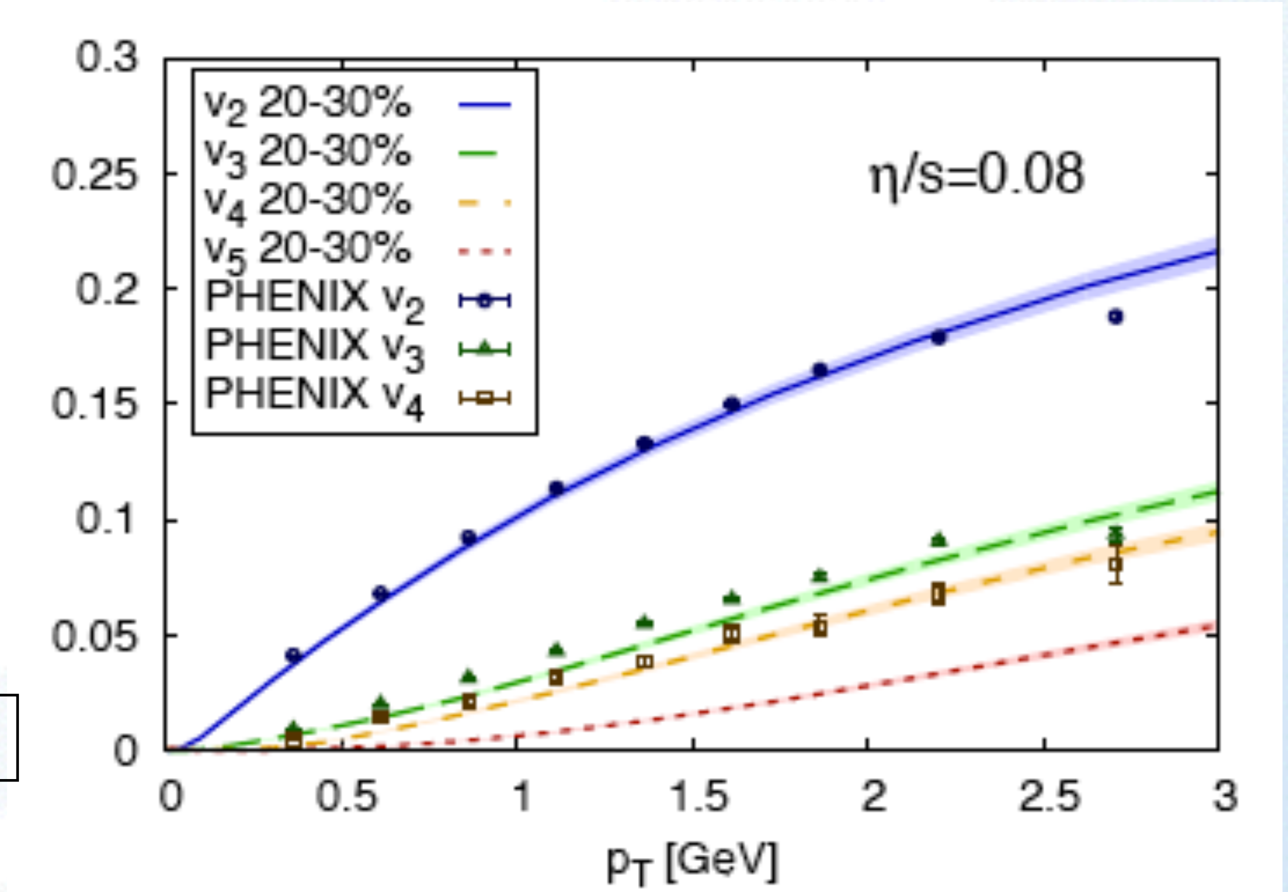
$\eta/s = 1/4\pi$

$\eta/s = 2/4\pi$

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

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

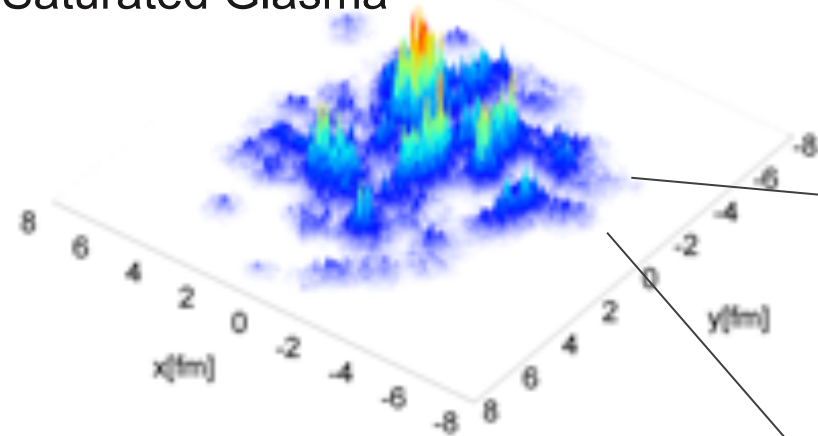
aka: the "perfect" liquid



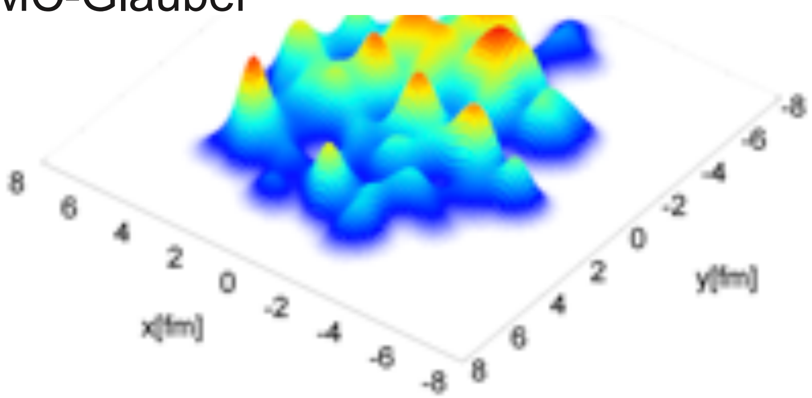
Schenke, Jeon, Gale, PRC 85 (2012) 024901

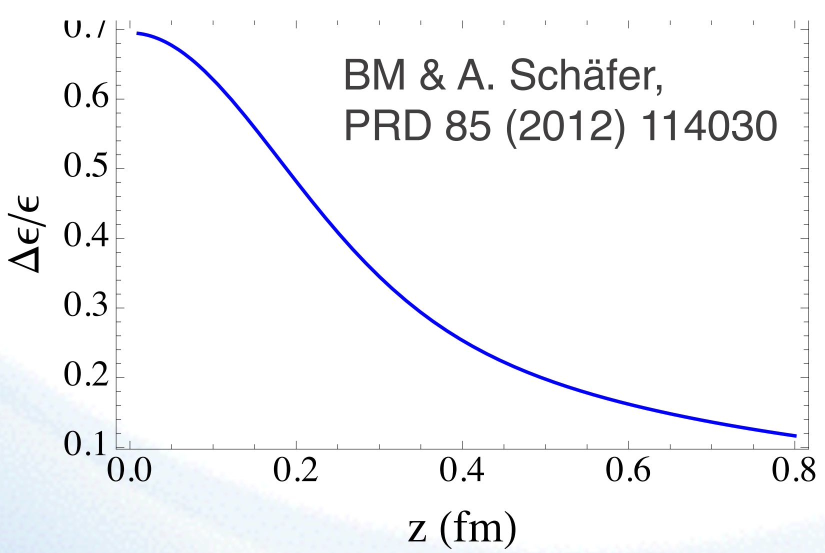
RHIC vs. LHC

Saturated Glasma

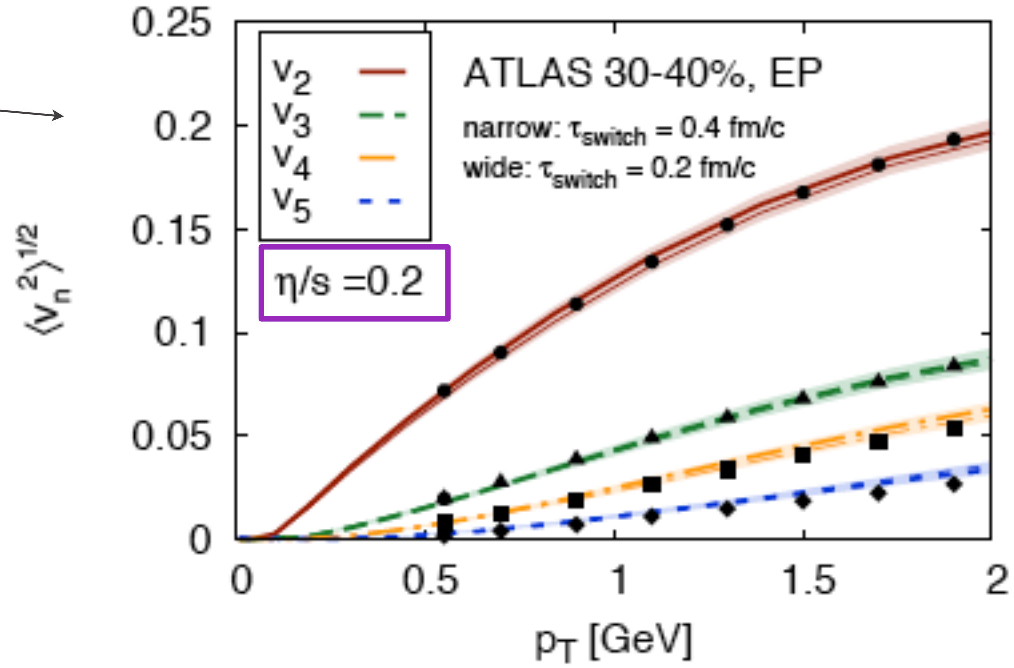


MC-Glauber

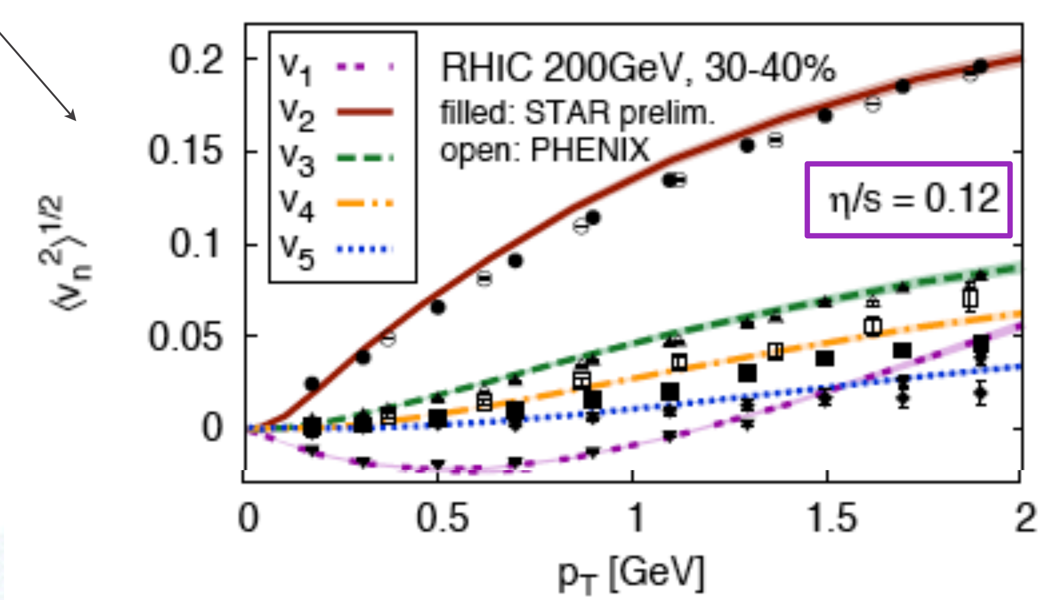




Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330

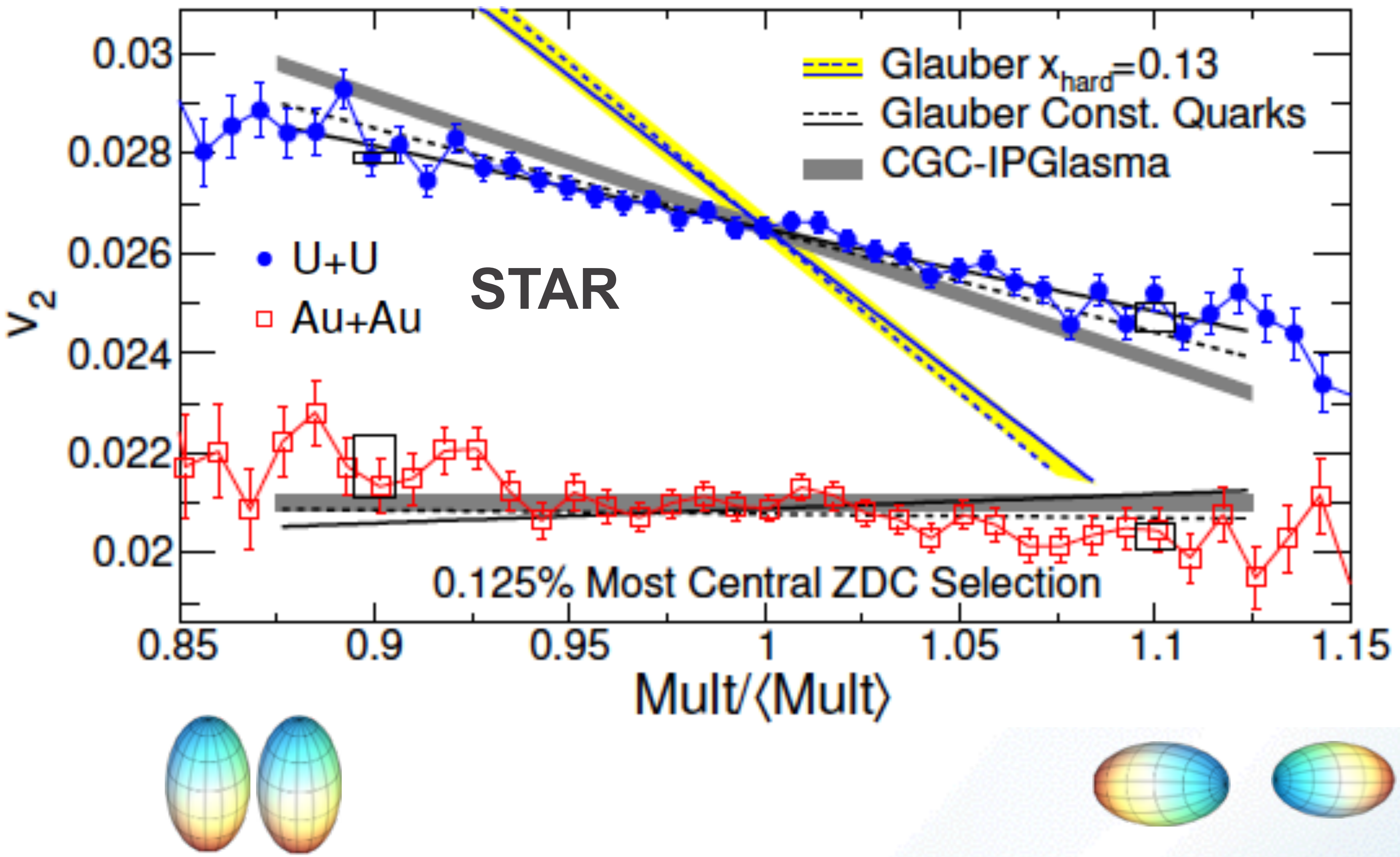


LHC



RHIC

Shape engineering: U+U collisions

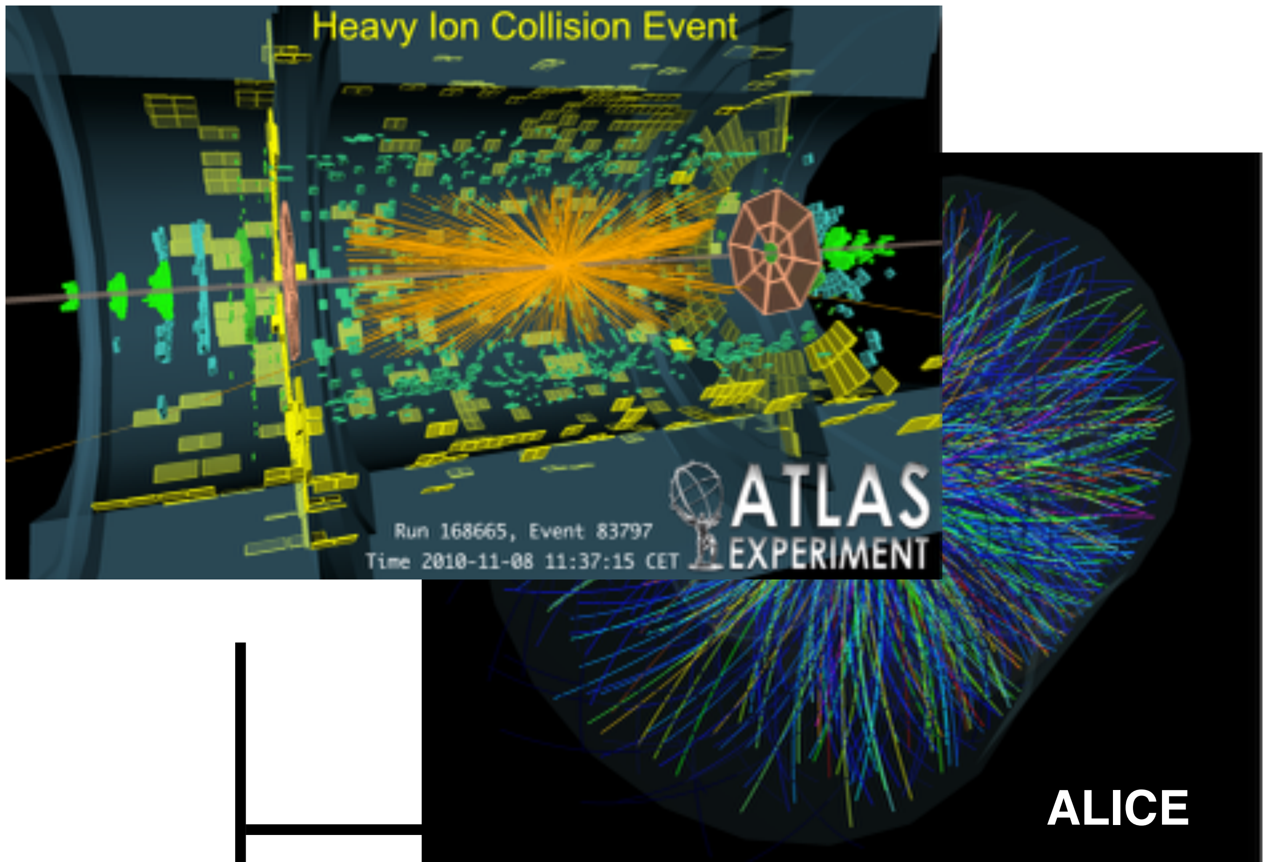


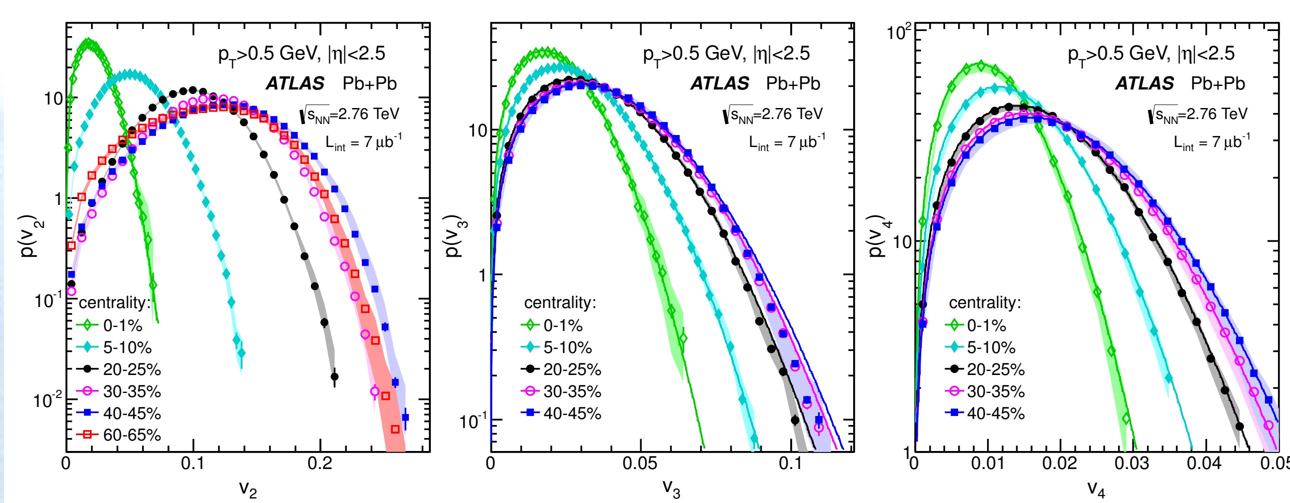
Constituent-quark Glauber model and IP-Glasma model are consistent with the observations, but not the nucleon-nucleon based Glauber model.

→ Initial state fluctuations are driven by interactions at the sub-nucleonic level

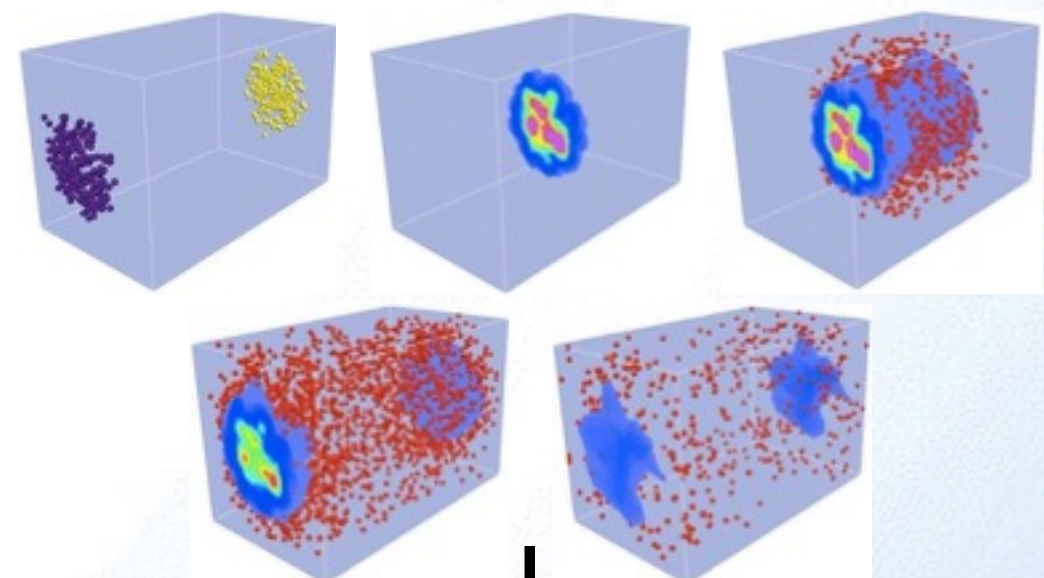
Discovery by model-data comparison

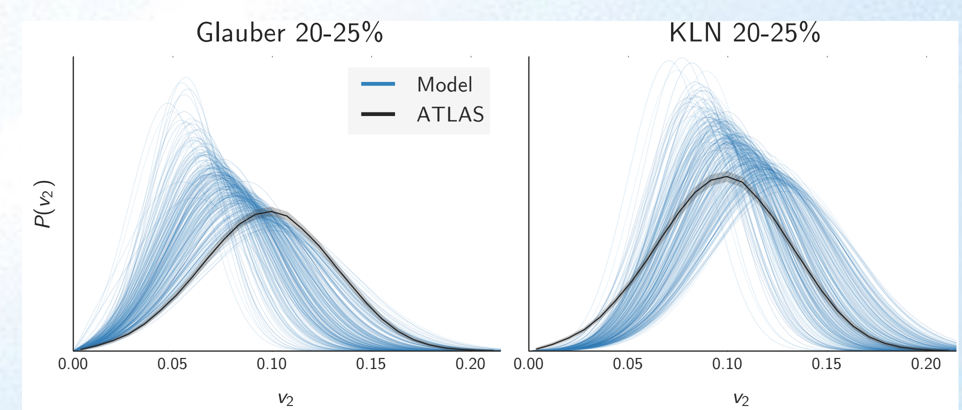
Data:





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





extracted QGP properties: η/s, …

Flow Analysis of QGP Properties at the LHC

Data:
- ALICE v_2, v_3 & v_4 flow cumulants
- identified particle spectra
- identified particle mean p_T

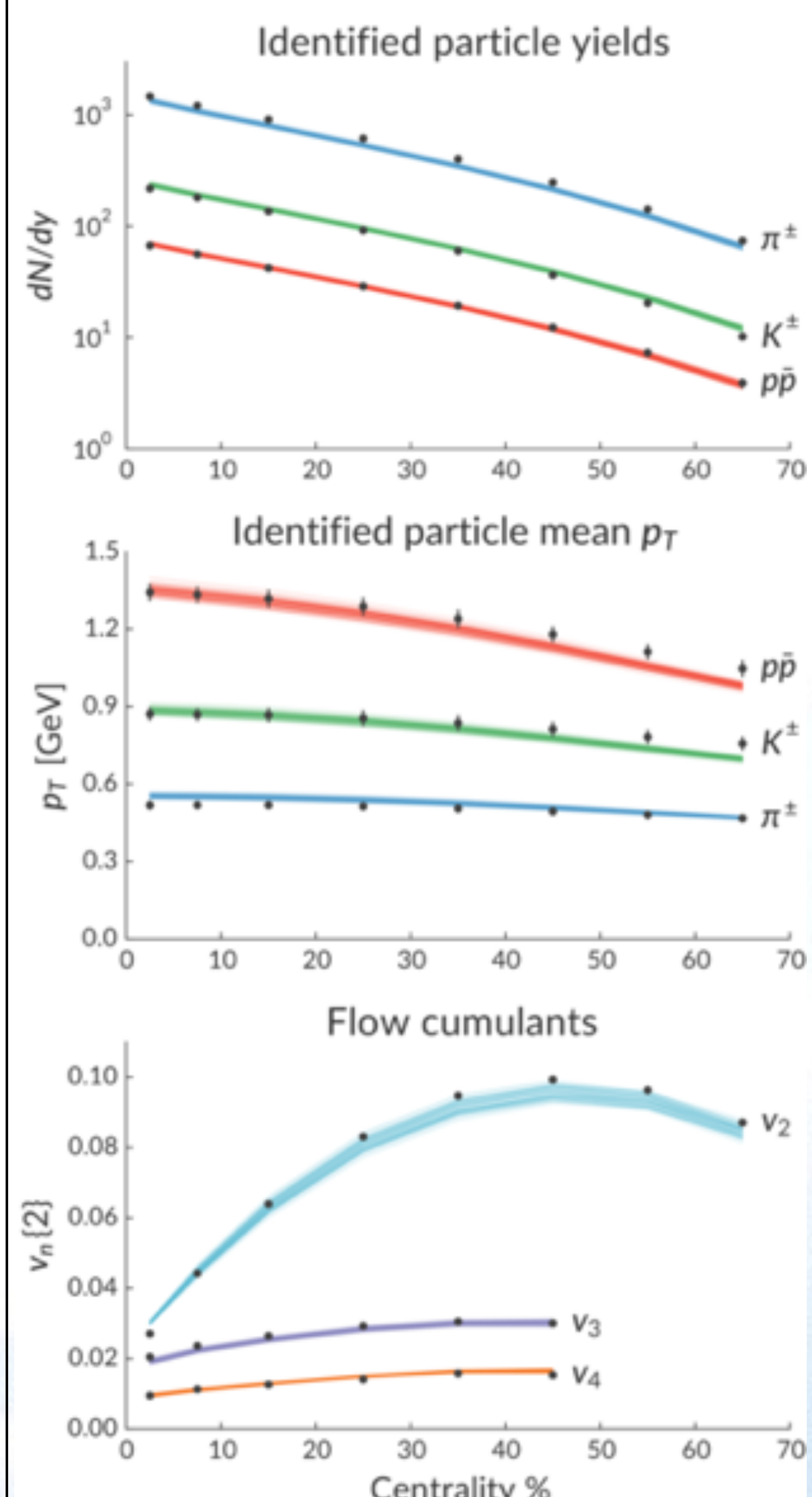
Model:
- EbE VISHNU

Parameter Space:
- Trento initial condition:
  - p: entropy deposition
  - k: nucleon fluctuation
  - w: Gaussian nucleon width
- specific shear viscosity η/s slope and intercept at T_C
- normalization scale for ζ/s
- hydro to micro switching temperature T_{sw}

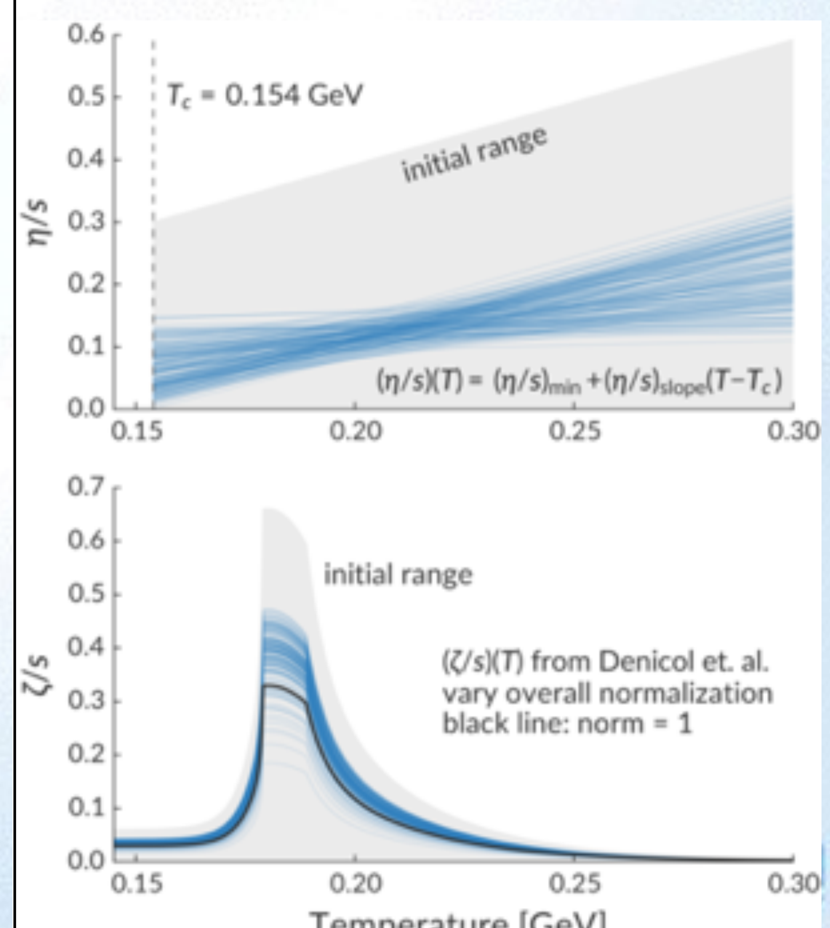
Analysis Design:
- 6 centrality bins
- 300 point Latin Hypercube
- total of 10,000,000 events
- Gaussian Process Emulators for interpolation between LH points

use MCMC for analysis

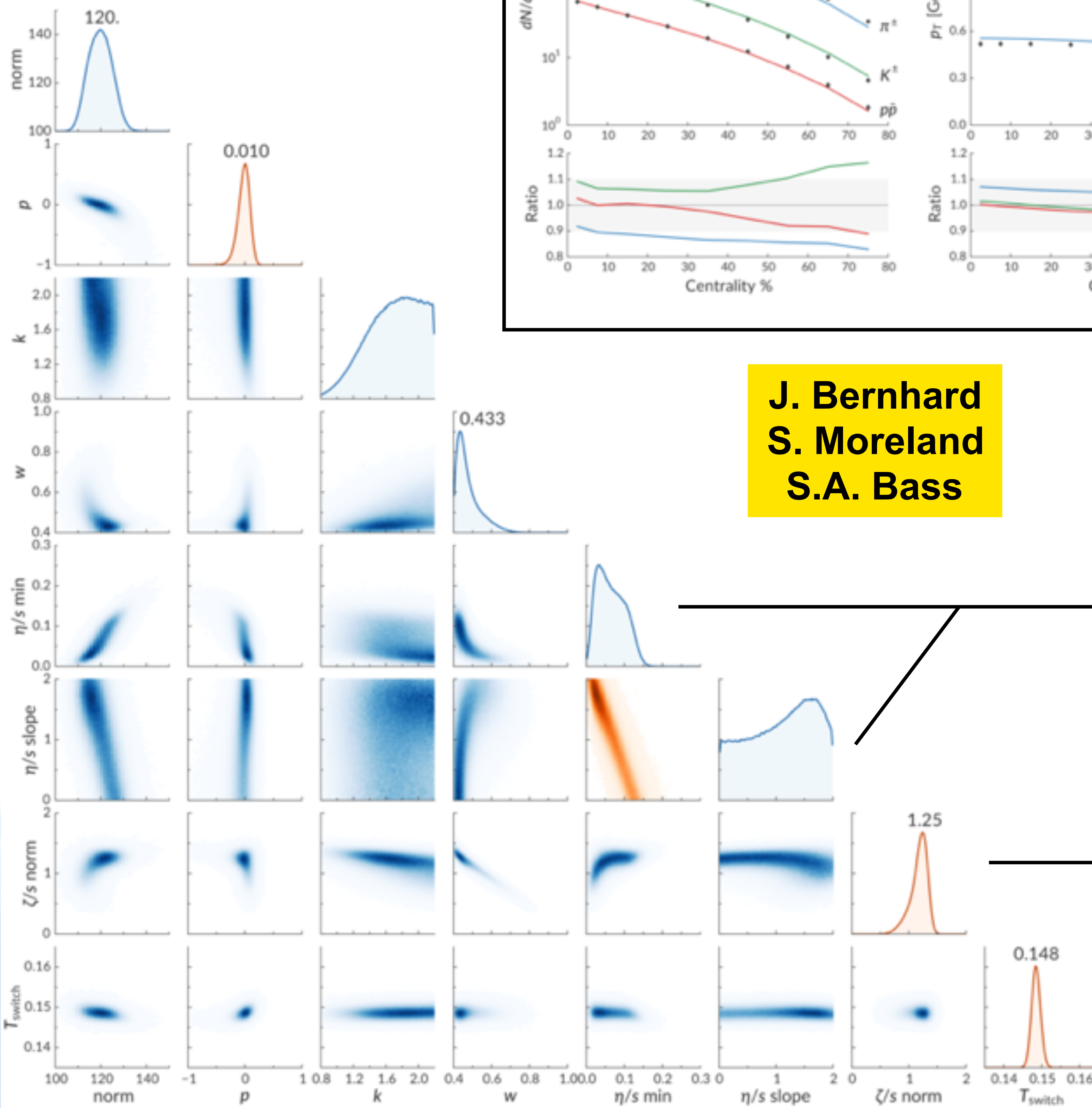
Posterior: emulator predictions for highest likelihood parameter values



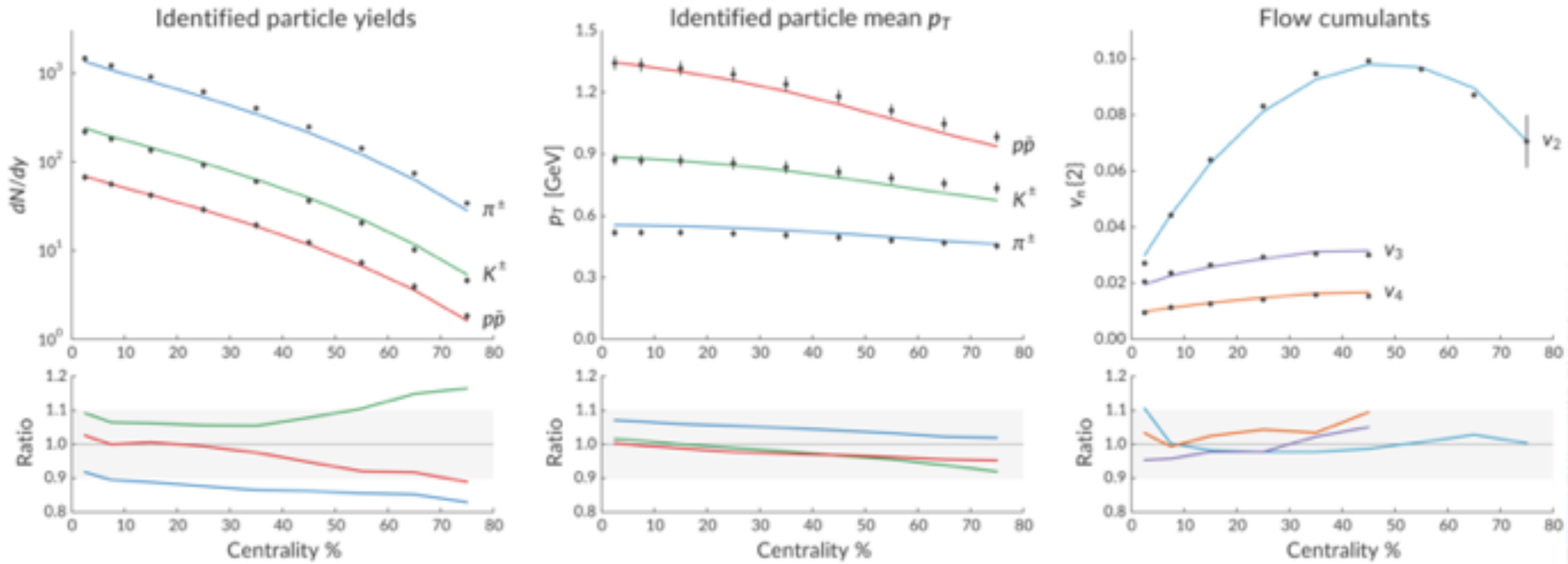
Key Results:
- excellent agreement with data, simultaneous description of v_2, v_3 and v_4 data
- initial condition favors scaling properties of IP-Glasma
- non-zero bulk viscosity
- temperature dependence of η/s requires data at several beam energies to pin down



Calibrated posterior distributions:

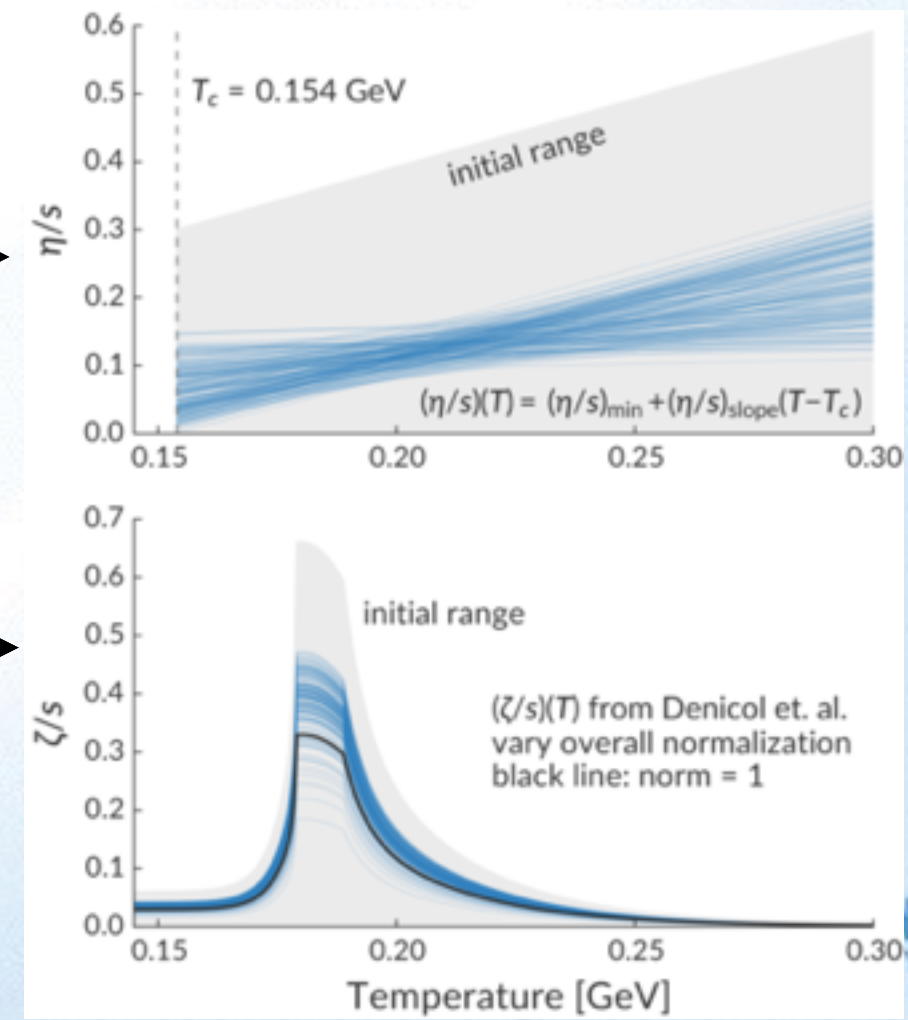


Explicit model calculations (no emulator):

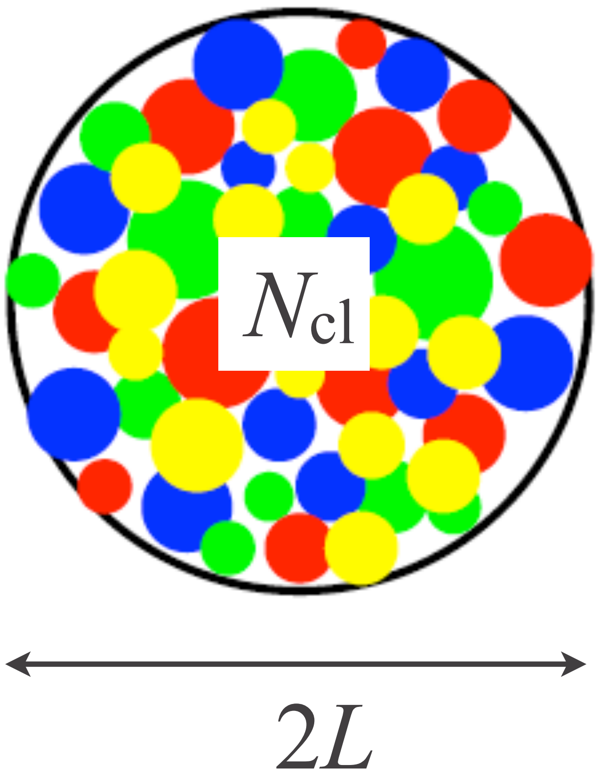


J. Bernhard
S. Moreland
S.A. Bass

Temperature-dependent viscosities from the calibrated posterior:



How small can a QGP be?



saturation scale $$Q_s^2 \propto \frac{N_{cl}}{\pi L^2}$$

mean free path $$\ell_{mfp} \propto Q_s^{-1}$$

final multiplicity $$dN/dy \propto N_{cl}$$

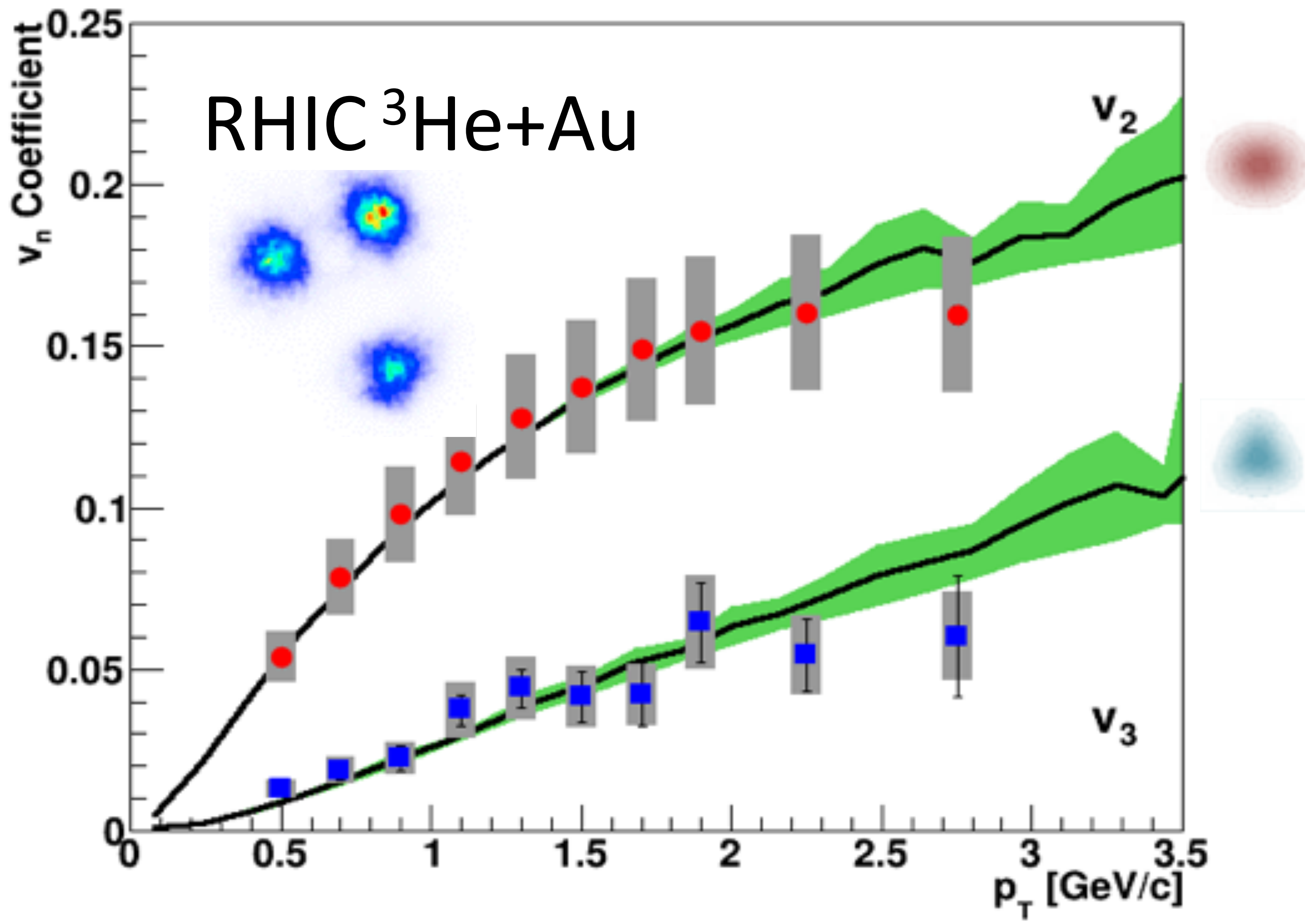
Basar & Teaney, 1312.6770

Size scales out of Reynolds number:

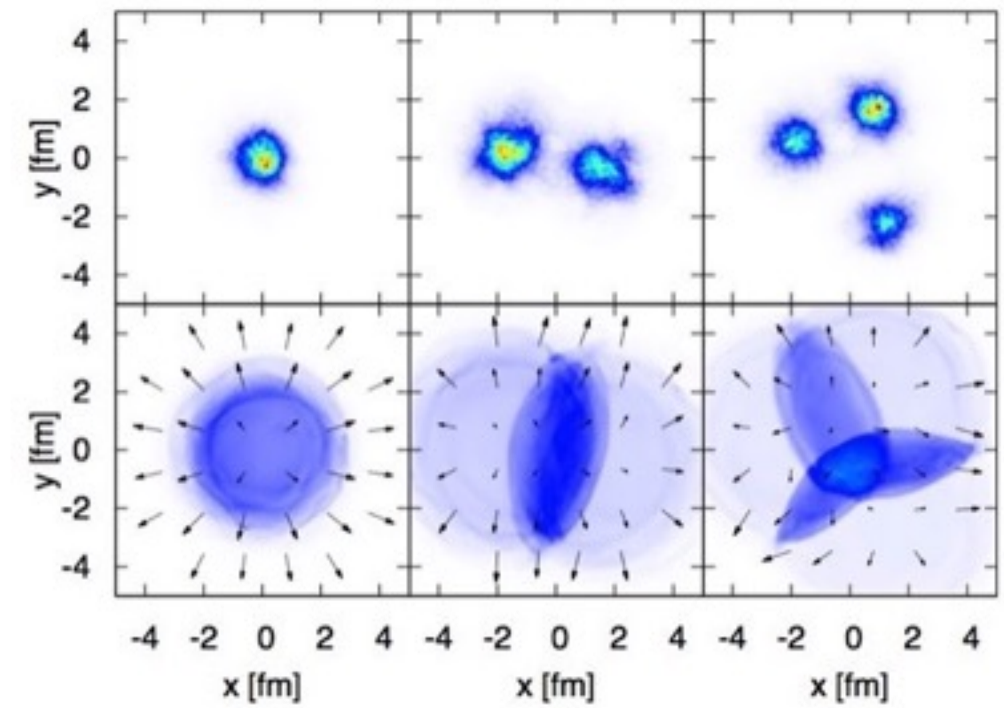
$$\mathrm{Re} = \frac{\ell_{mfp}}{L} \propto \frac{1}{Q_s L} \propto \frac{1}{\sqrt{dN/dy}}$$

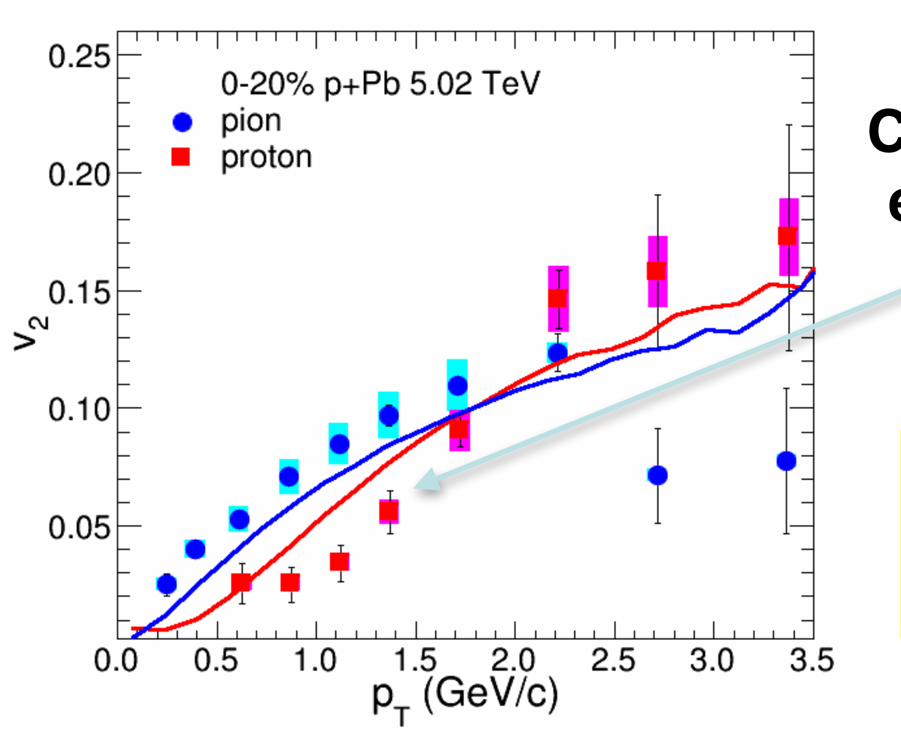
This does not mean that hydrodynamics applies for a given *dN/dy*, but it suggests that the transport is independent of size.

How small can a QGP droplet be?



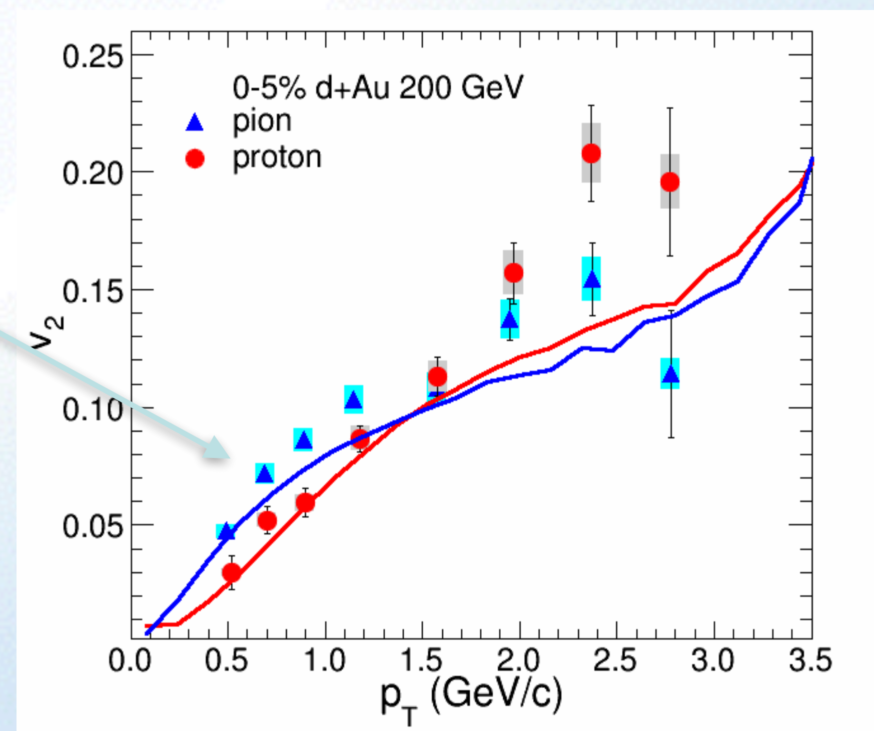
Very successful 3-week run resulted in 2.2 **billion** recorded minimum bias ^{3}**He +Au** collisions (PHENIX)





Characteristic differential elliptic flow for hadrons of different mass

Evidence for strong coupling?



QGP Chemistry

Strangeness enhanced

The original idea (*Rafelski*): $$\frac{N(\bar{s})}{N(\bar{q})} = \frac{1}{2}\left(\frac{m_s}{T}\right)^2 K_2\left(m_s/T\right)e^{\mu_B/(3T)} = 1\cdots 5$$

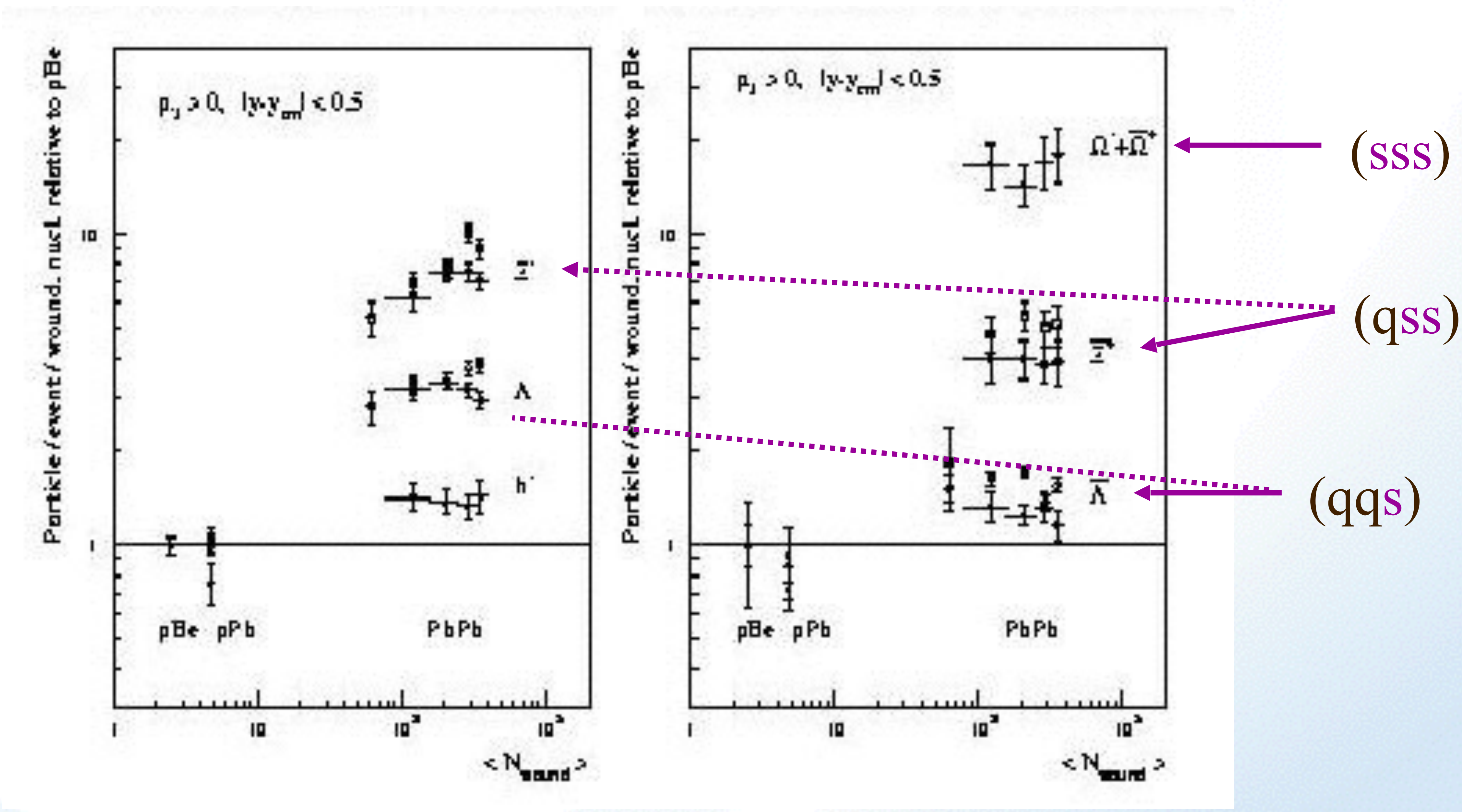
> *"We almost always have more $\bar{s}$ than $\bar{u}$ or $\bar{d}$ quarks. When quark matter reassembles into hadrons, some of the numerous $\bar{s}$ quarks may, instead of being bound into kaons, form multiply strange antibaryons, such as $\bar{\Lambda}$, $\bar{\Xi}$, $\bar{\Omega}$."*

$gg \rightarrow s\bar{s}$ is essential for rapid strangeness equilibration ! (JR & BM)

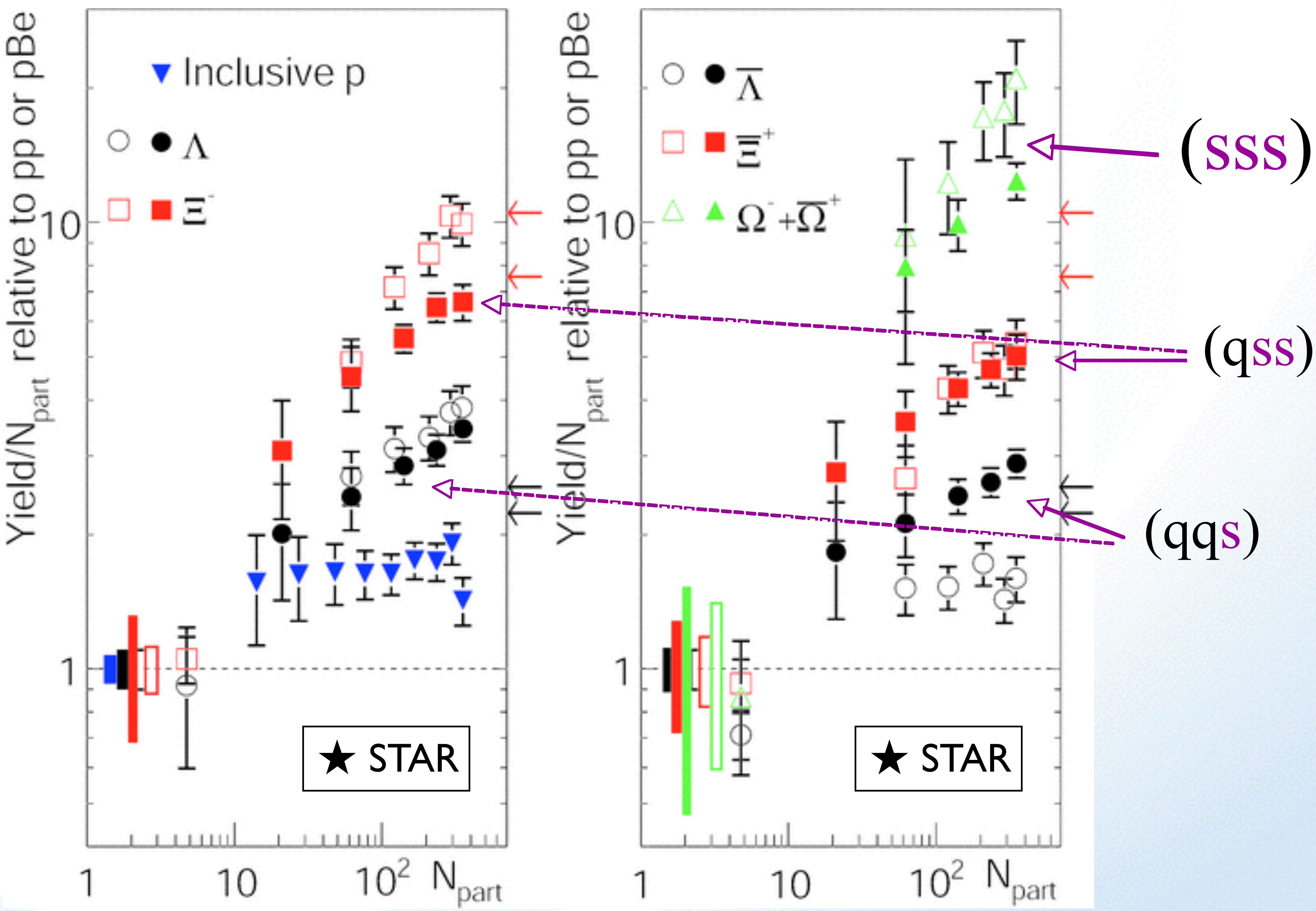
Almost 30 years of investigation: The liberation of quark and gluon degrees of freedom (not necessarily thermalization) is required for strangeness equilibration.

s-enhancement at SPS

NA57 measured enhanced strange baryon yields in Pb+Pb collisions at 158 GeV/c



s-enhancement at RHIC



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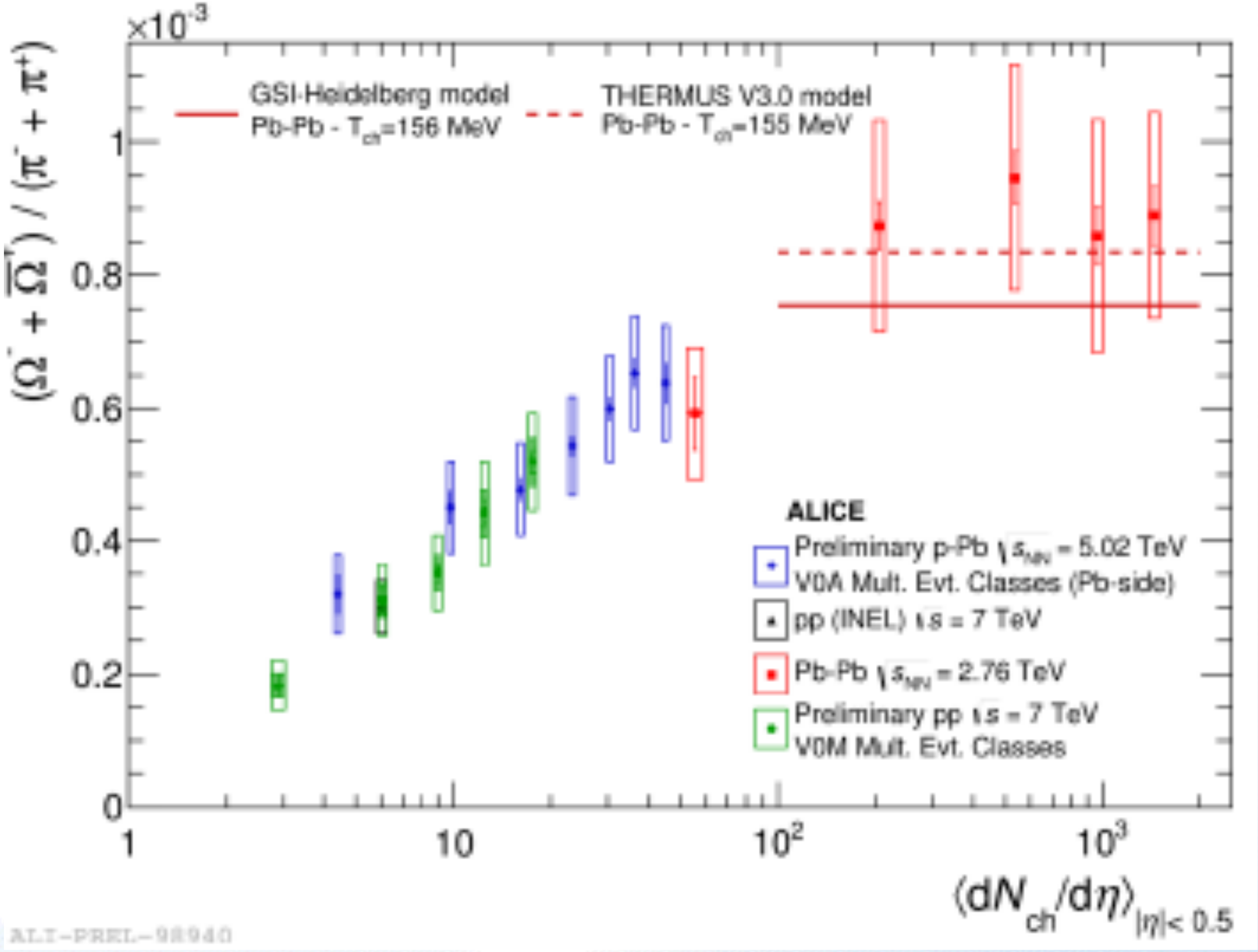
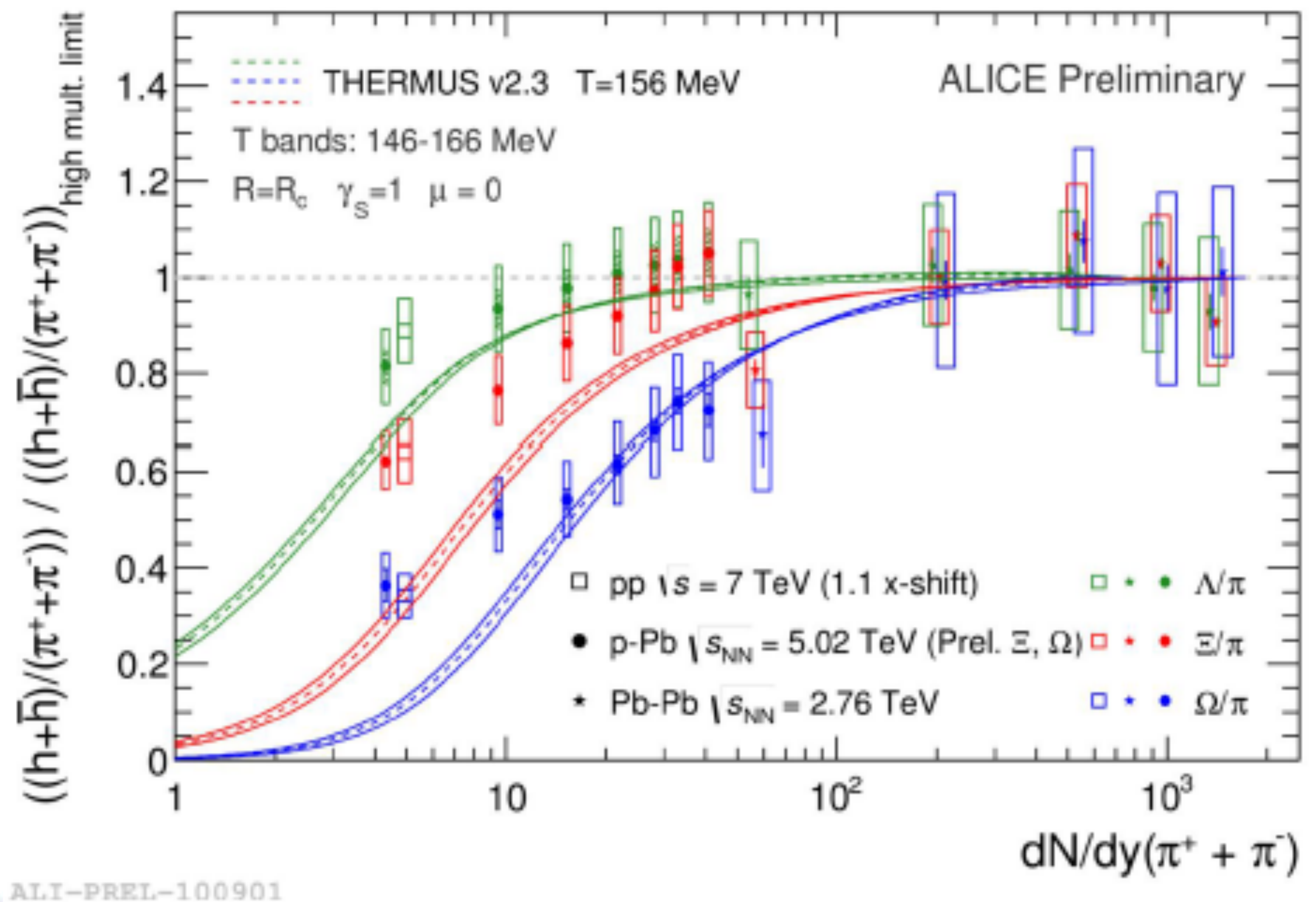
s-enhancement at LHC

Strangeness enhancement grows with fireball size (or life-time) and saturates at grans canonical equilibrium in Pb+Pb collisions



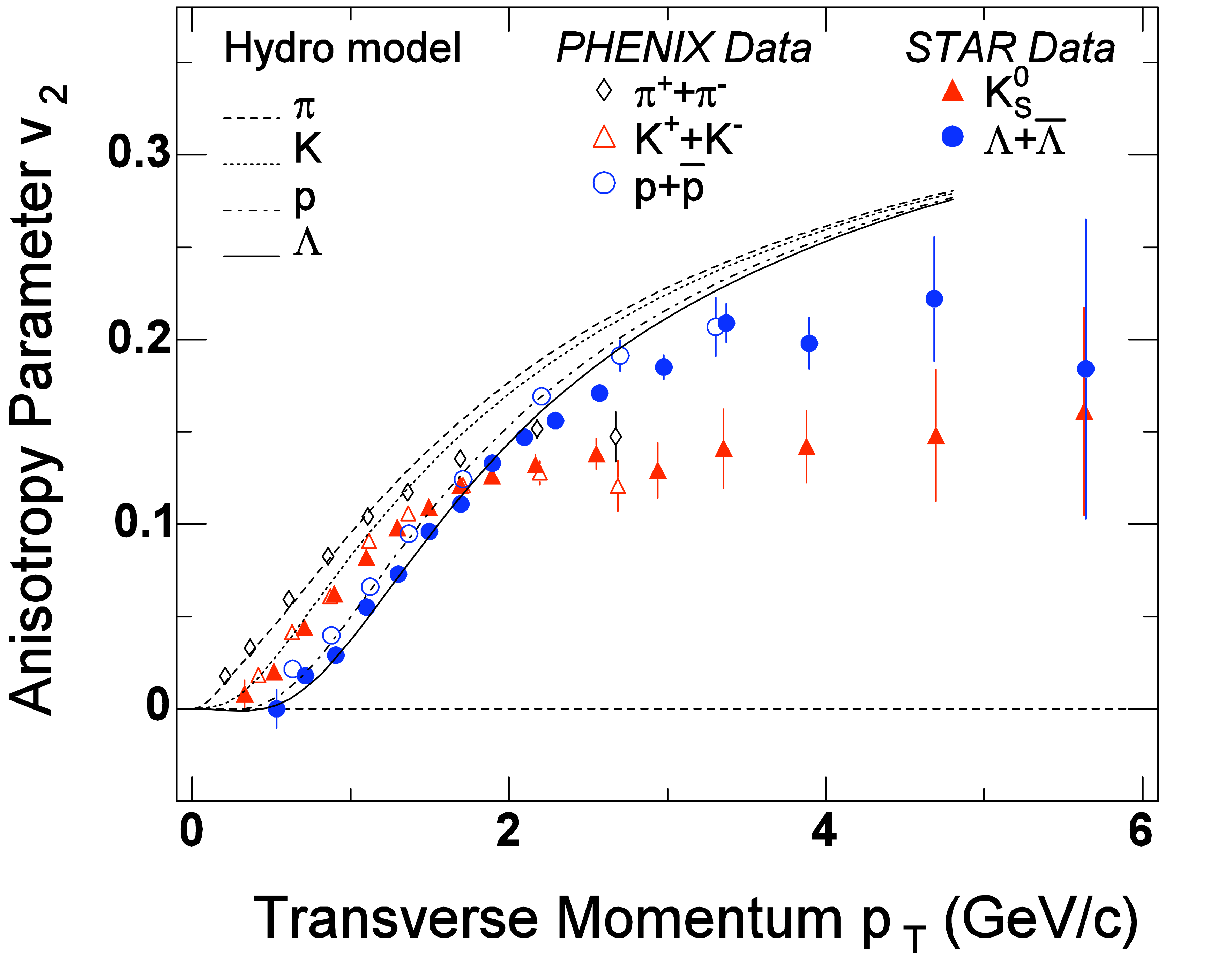
Size dependence of s-enhancement



… together with **THERMUS** curves for the three species (T=156±10MeV, **$R=R_c$, γ_s=1**, $\mu_B=\mu_Q=\mu_S=0$)

Canonical equilibrium gives reasonable fit, but effect of finite life-time of QGP needs to be also explored.

$v_2(p_T)$ vs. hydrodynamics



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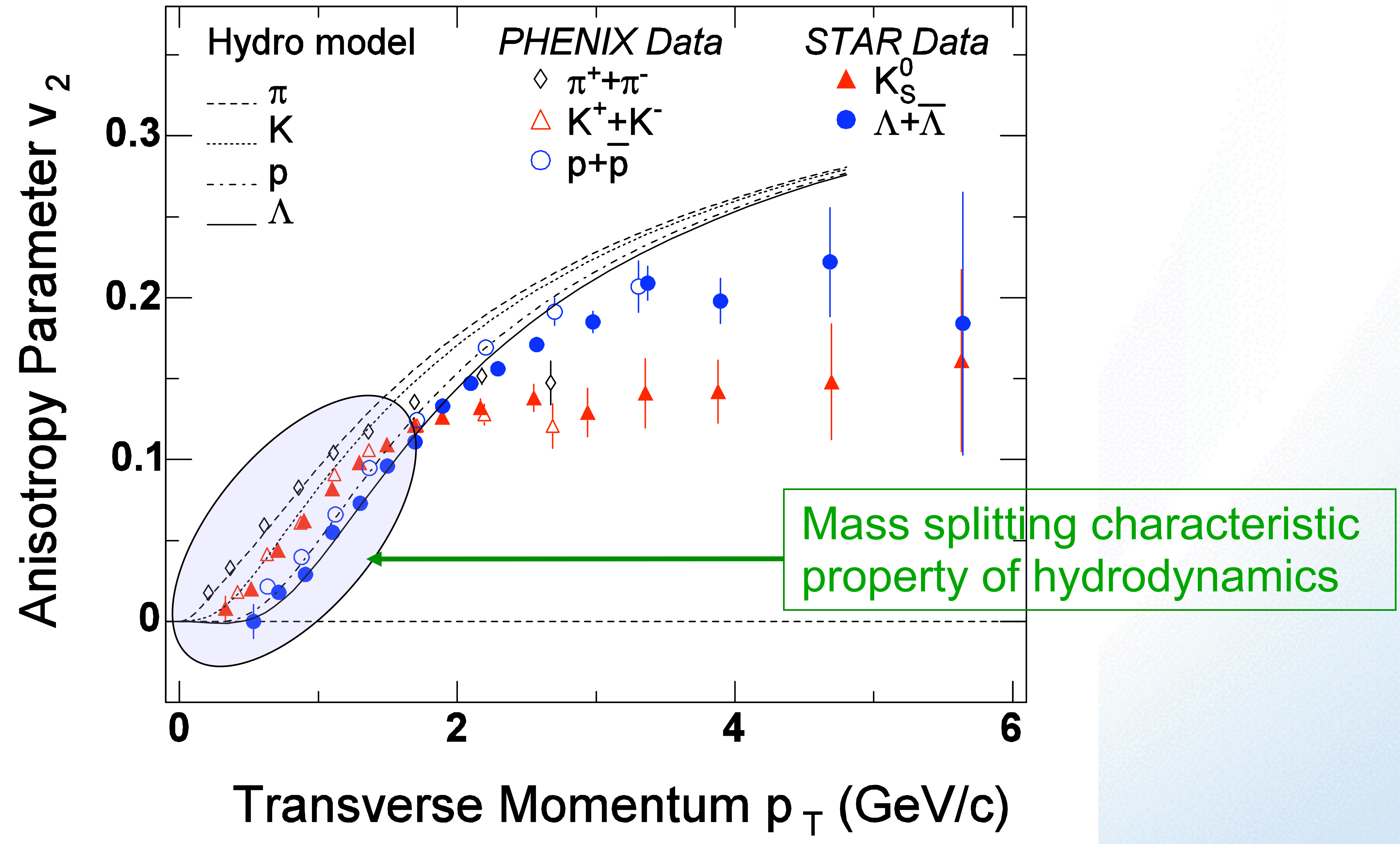
$v_2(p_T)$ vs. hydrodynamics



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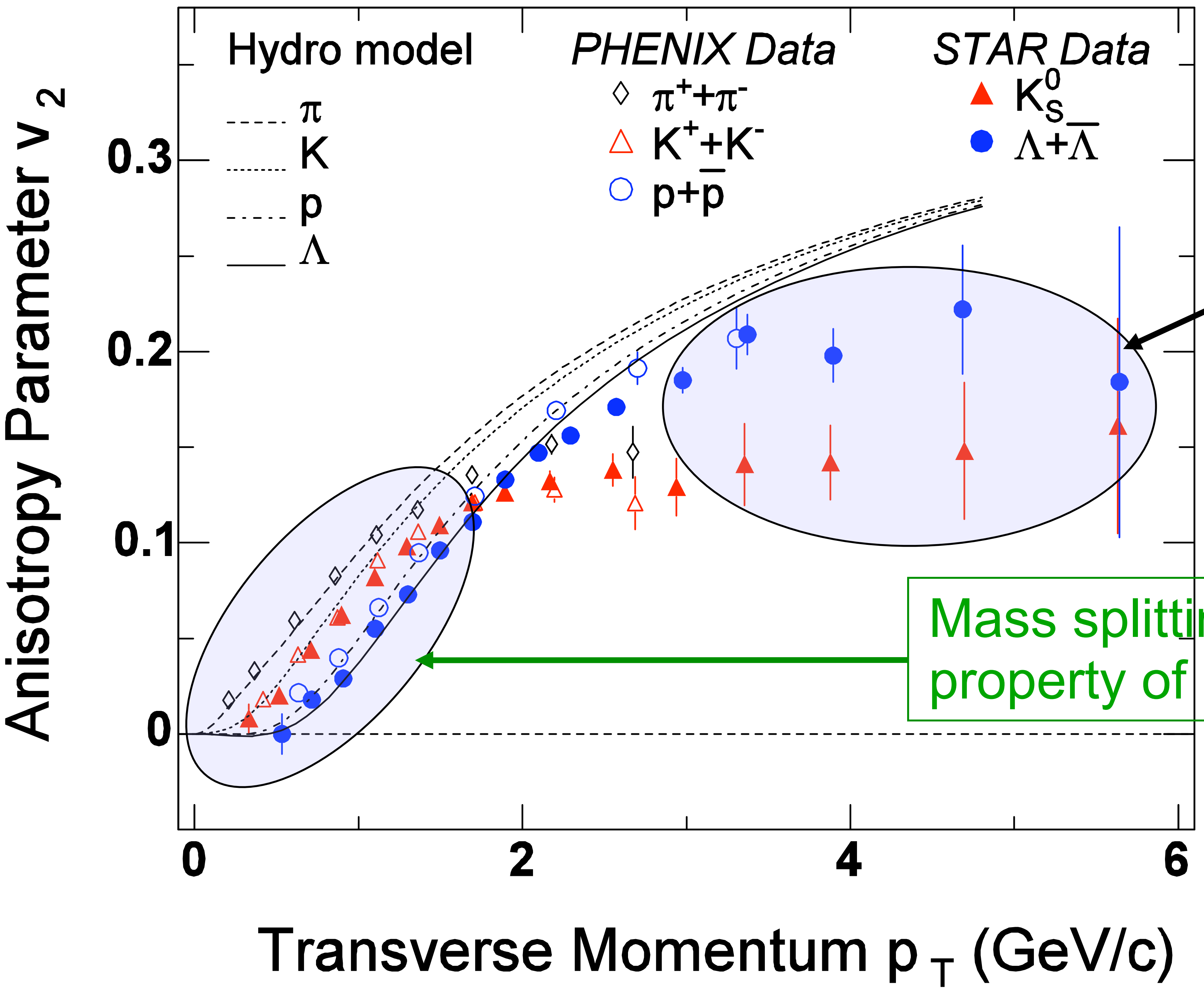
$v_2(p_T)$ vs. hydrodynamics



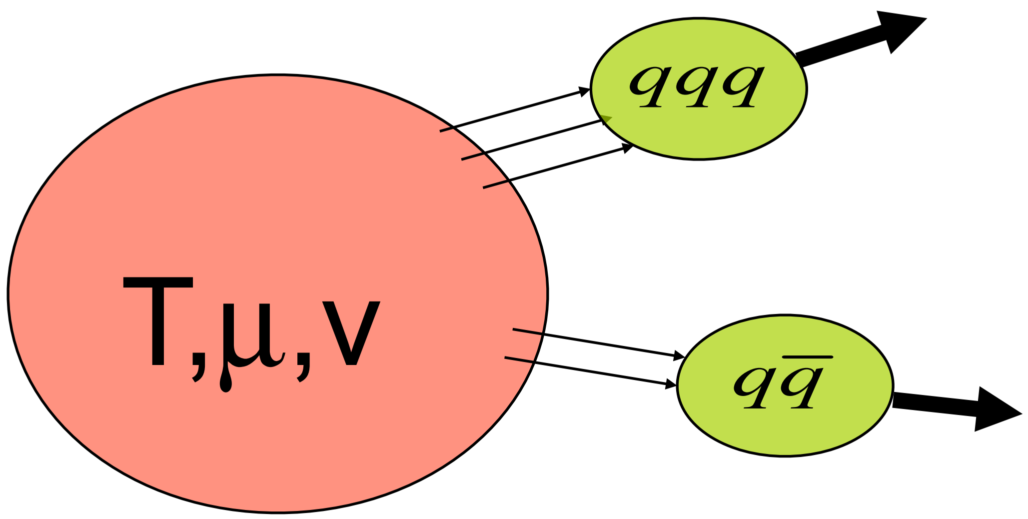
Failure of ideal hydrodynamics tells us how hadrons form

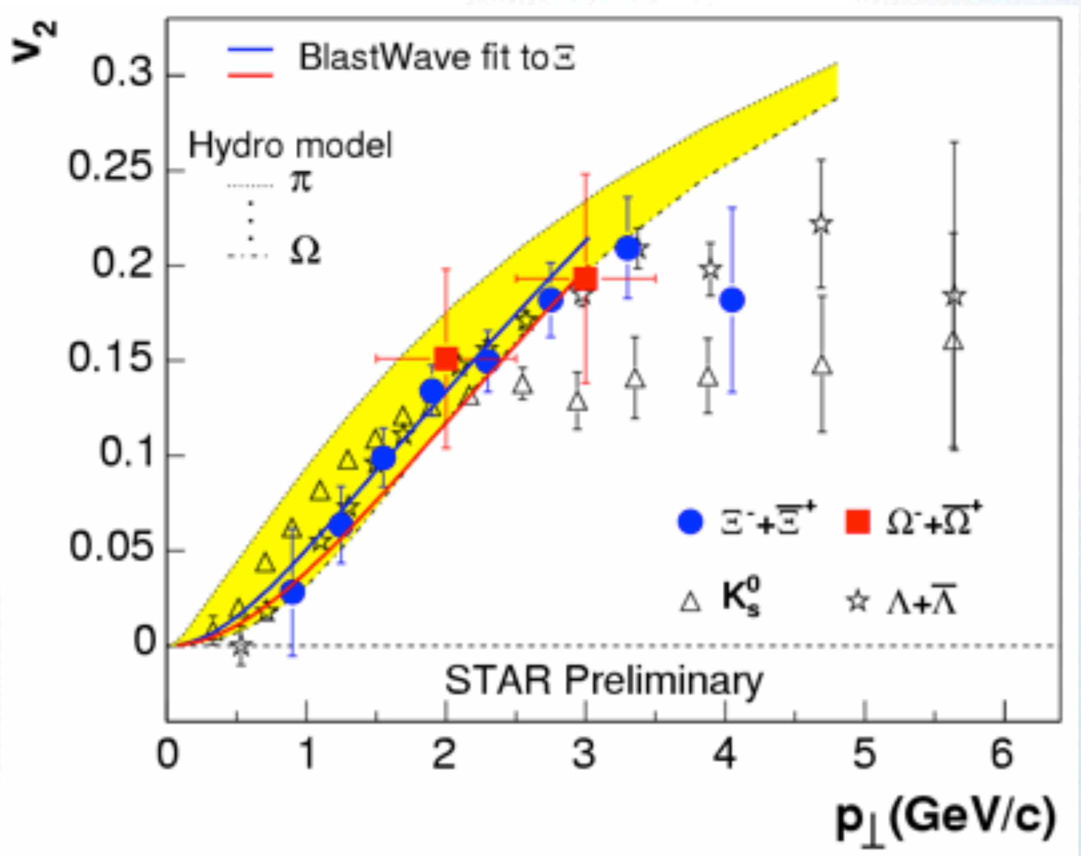
Mass splitting characteristic property of hydrodynamics

Quark number scaling of v_2

In the recombination regime, meson and baryon v_2 can be obtained from the quark v_2 :

$$v_2^M(p_t) = 2v_2^q\left(\frac{p_t}{2}\right) \qquad v_2^B(p_t) = 3v_2^q\left(\frac{p_t}{3}\right)$$





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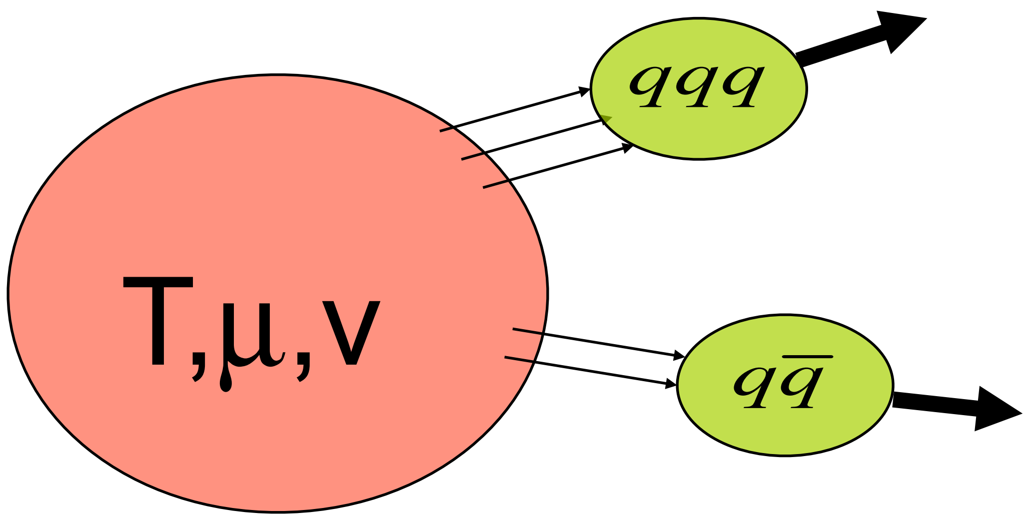
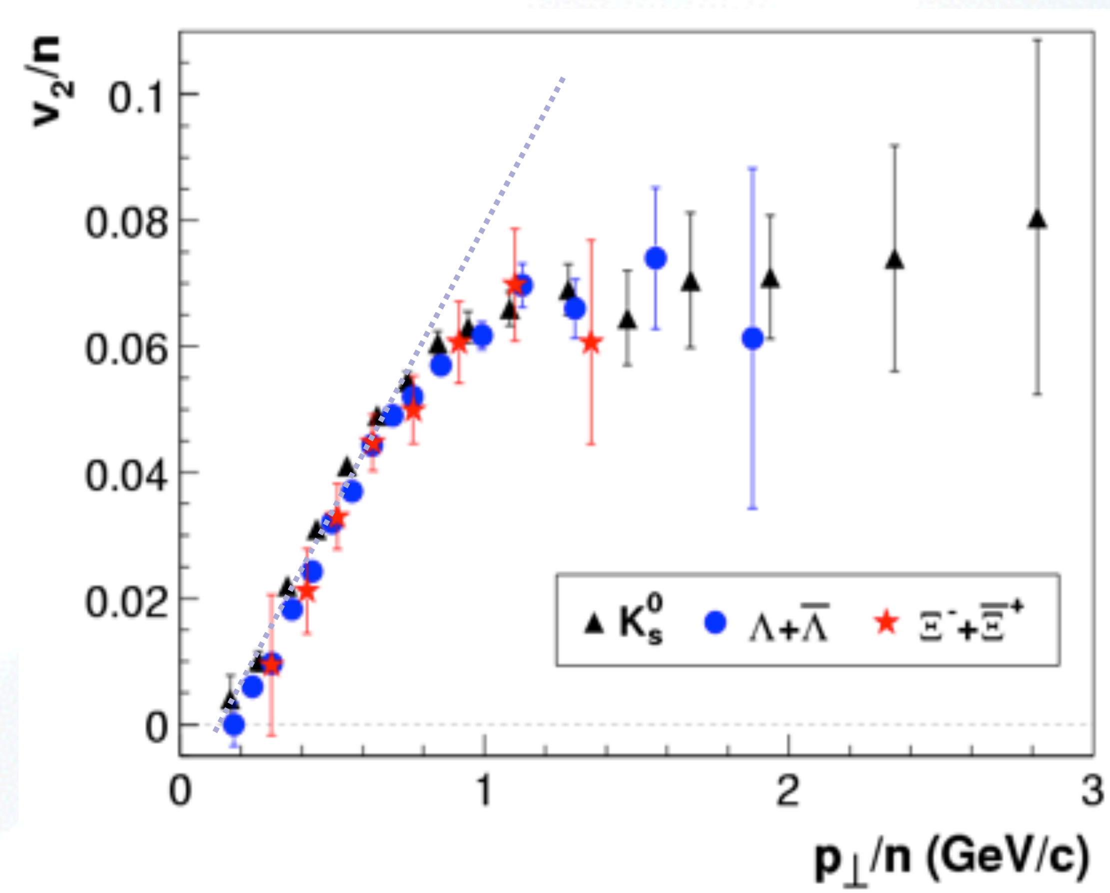
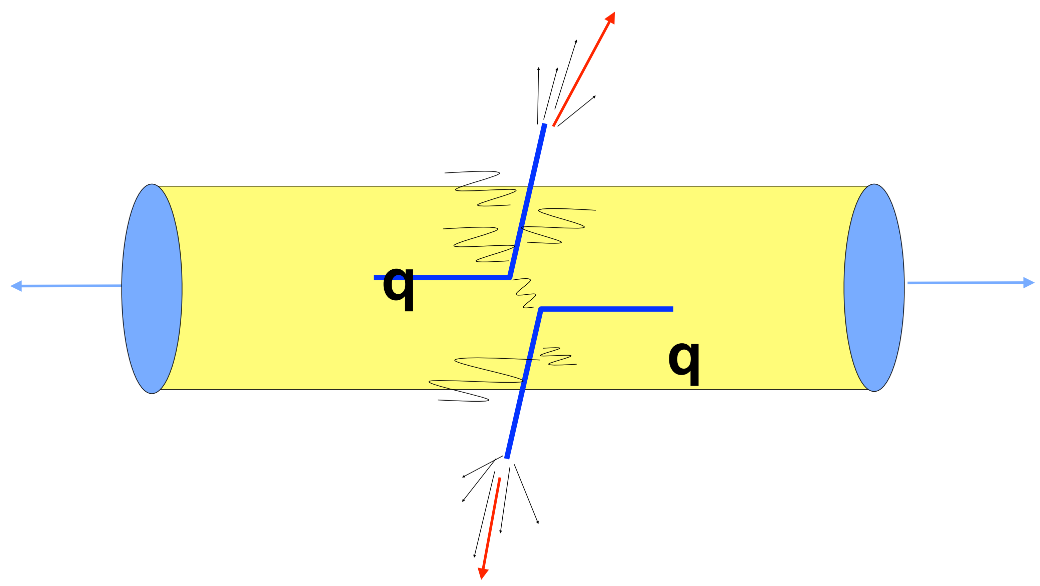


Emitting medium is composed of unconfined, flowing quarks.



Color screening & color opacity

Jet quenching



Toward quantitative measurement of basic medium properties: *q-hat*

$$\frac{dE}{dx} = -C_2 \alpha_s \hat{q} L \qquad \frac{dE}{dx} = -C_2 \hat{e}$$

Radiative Collisional

JET Collaboration

$$\frac{\hat{q}}{T^3} = \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC} \end{cases}$$

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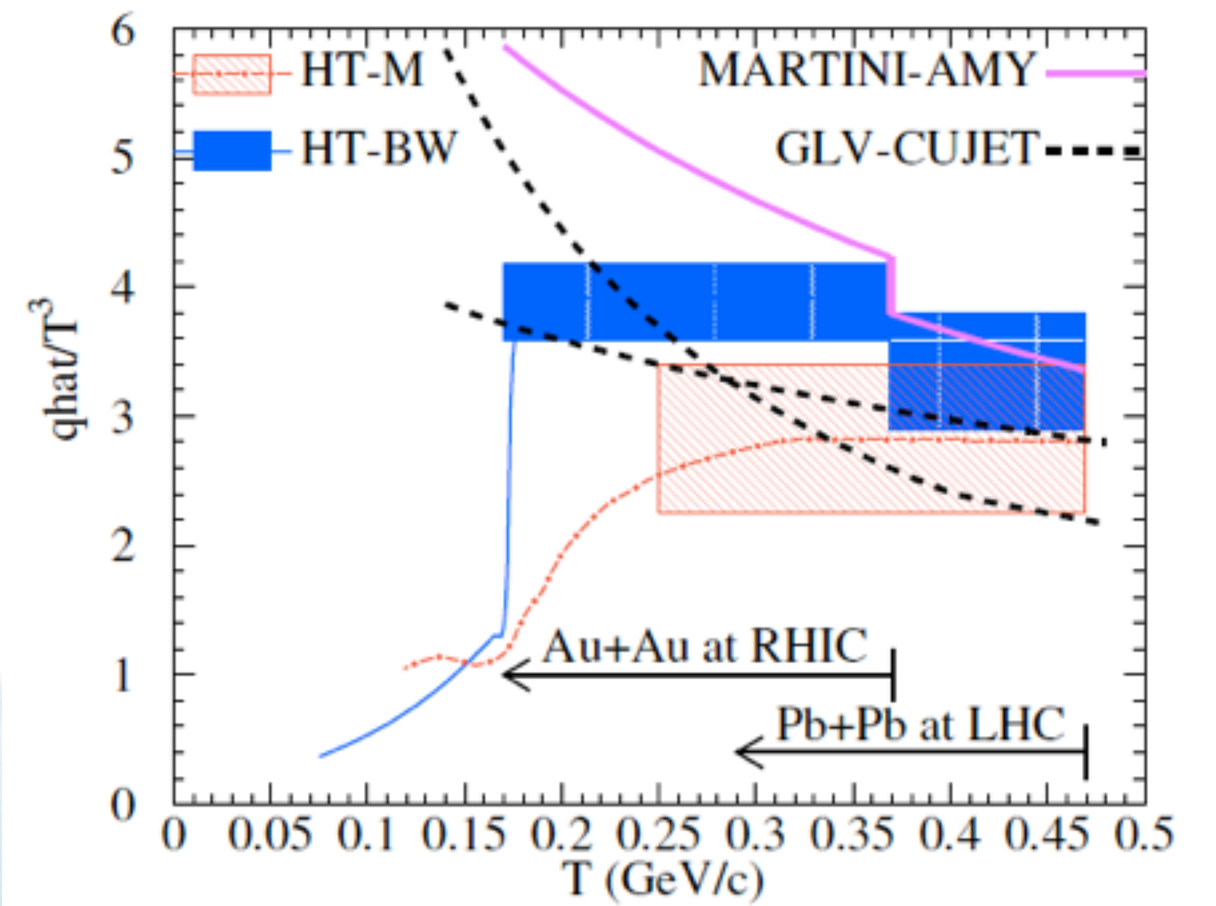
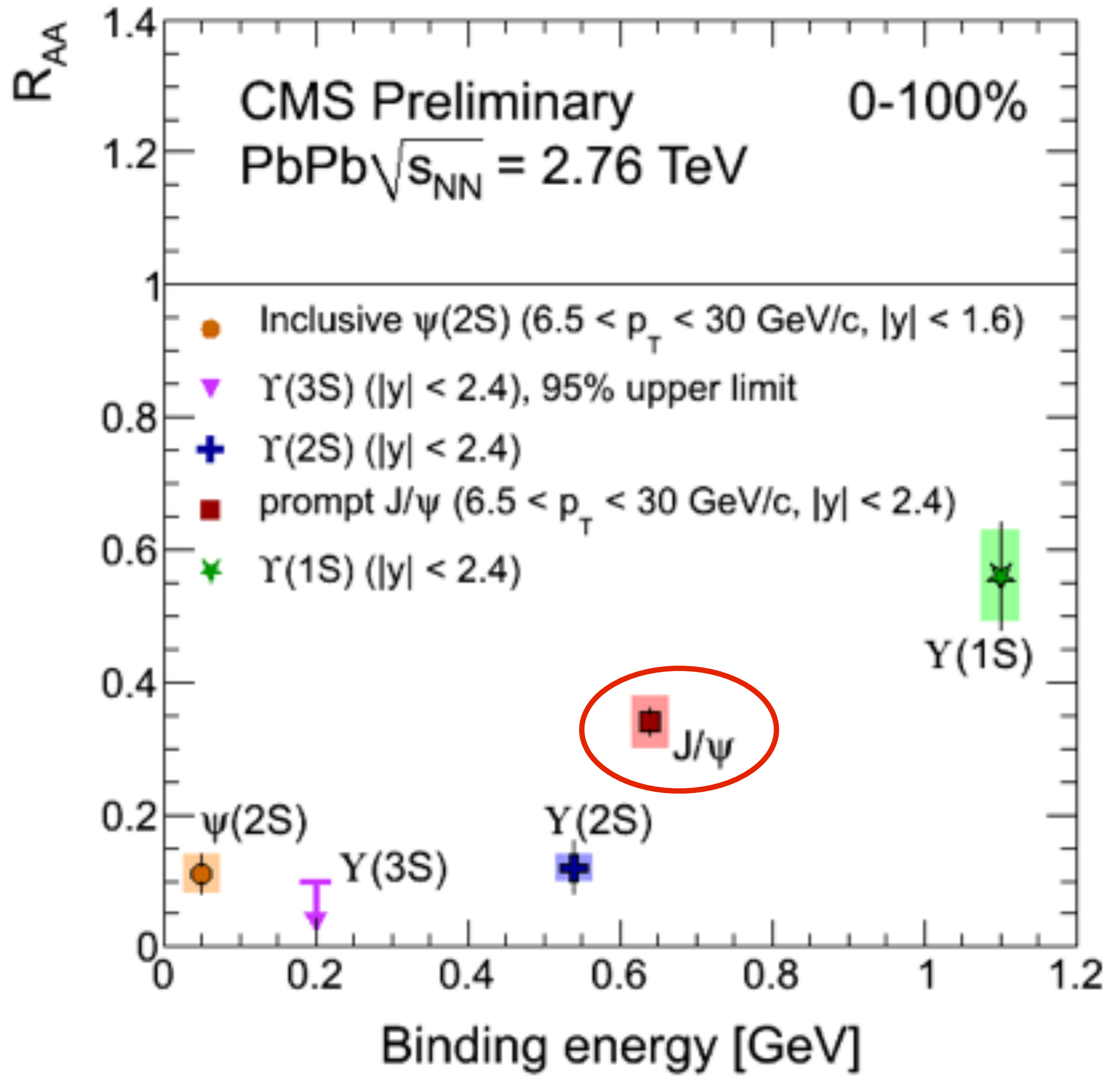
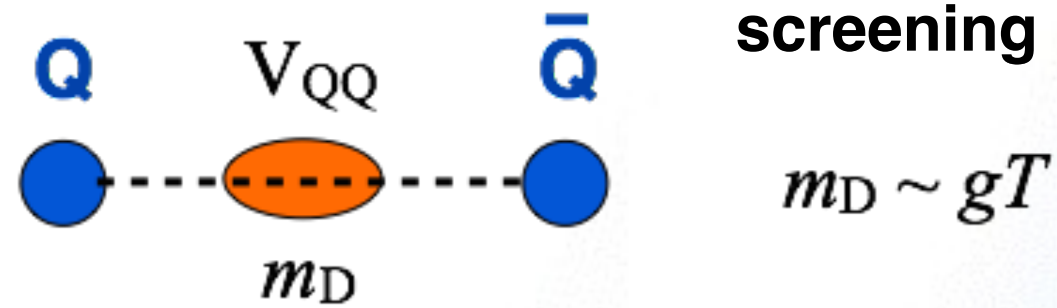


QGP @ RHIC is slightly more strongly coupled than QGP@ LHC.

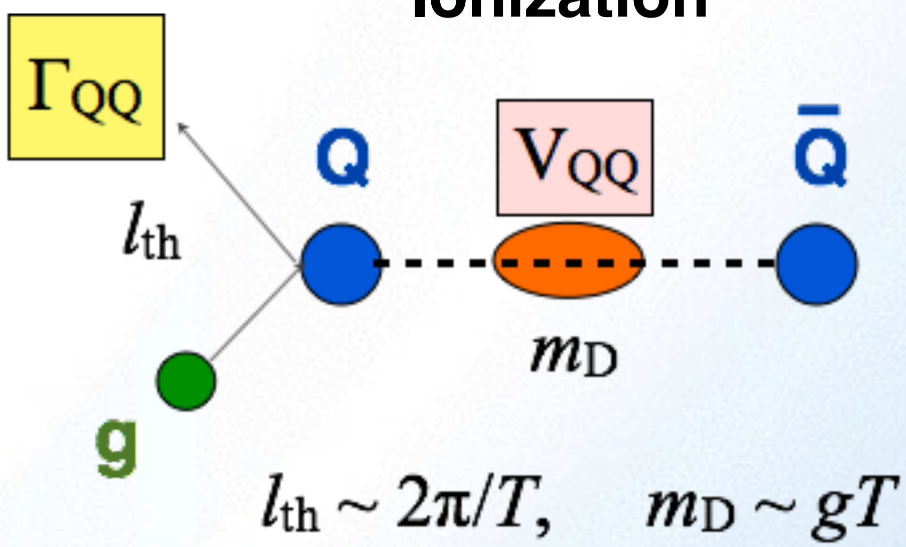
Quarkonium "melting"



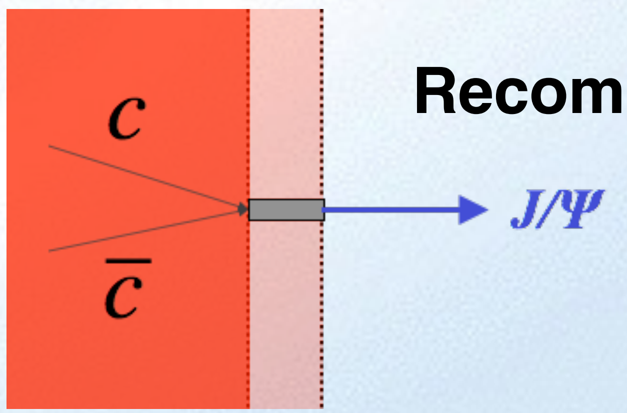
Color screening



Ionization



Recombination



Charmonium states "melt" in the QGP but can be regenerated by recombination when the charm quark density is high (at LHC).

Resolved measurement of Upsilon states required at RHIC.

Future of RHIC

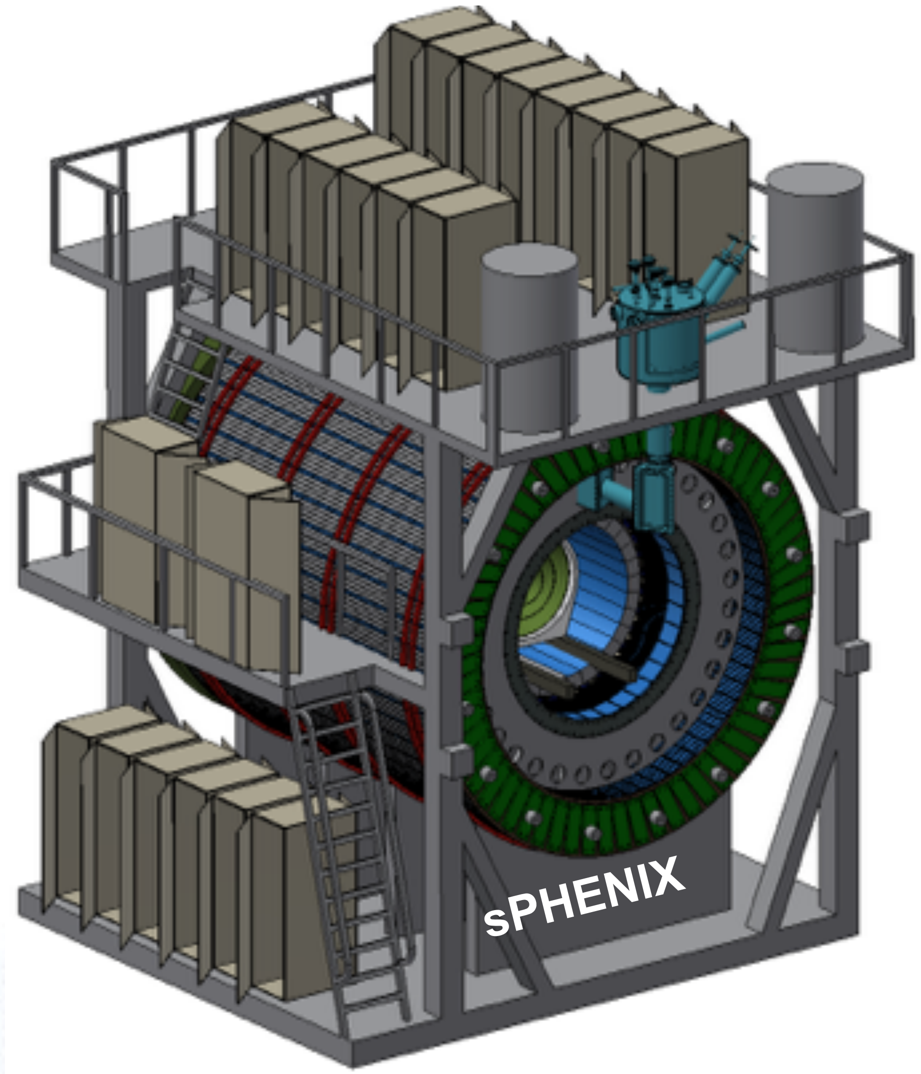
Completing the RHIC science mission

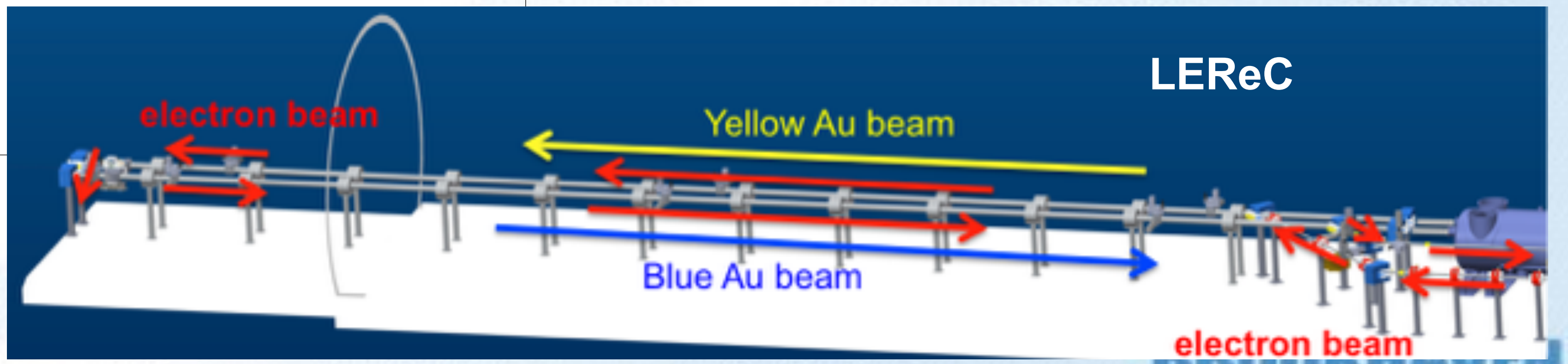
Status: RHIC-II configuration is complete

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

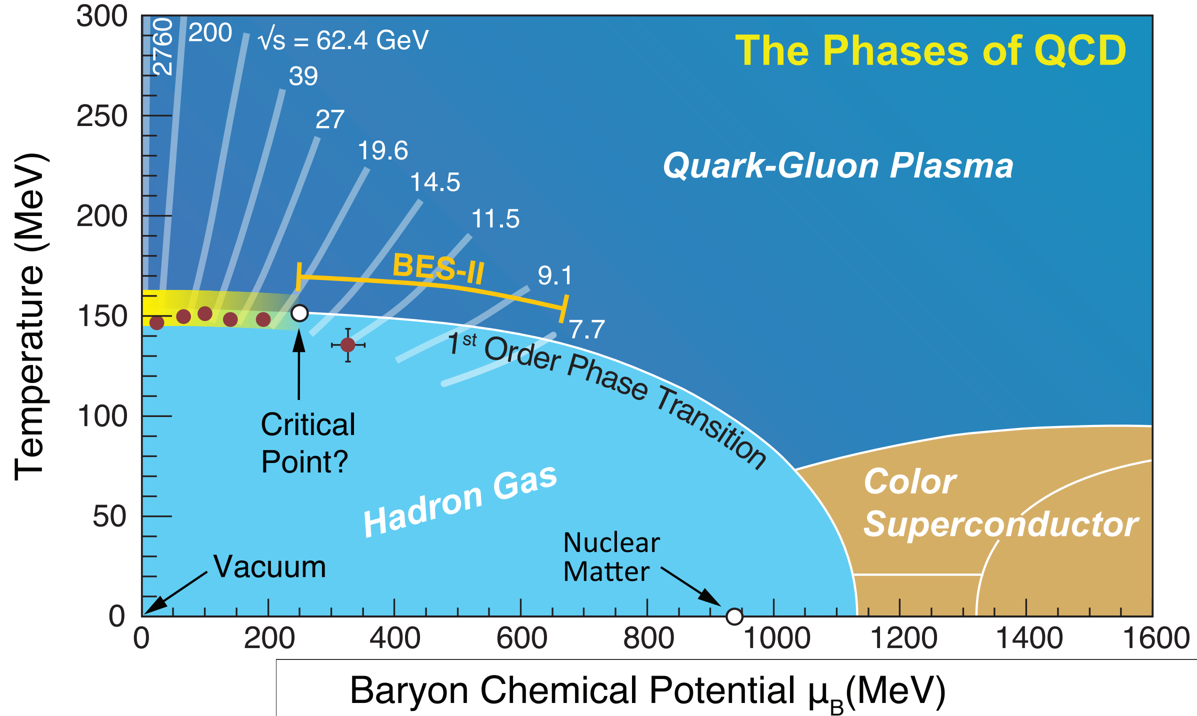
Plan: Complete the RHIC mission in 3 campaigns:

- **2014–17: Heavy flavor probes of the QGP using the micro-vertex detectors;**
  Transverse spin physics
- *2018: Install low energy e-cooling* (LEReC)
- **2019/20: High precision scan of the QCD phase diagram & search for critical point**
- *Install sPHENIX*
- **Probe QGP with precision measurements of jet quenching and Upsilon suppression**
- **Spin physics and initial conditions at forward rapidities with p+p and p+A collisions ?**
- *Transition to eRHIC ?*

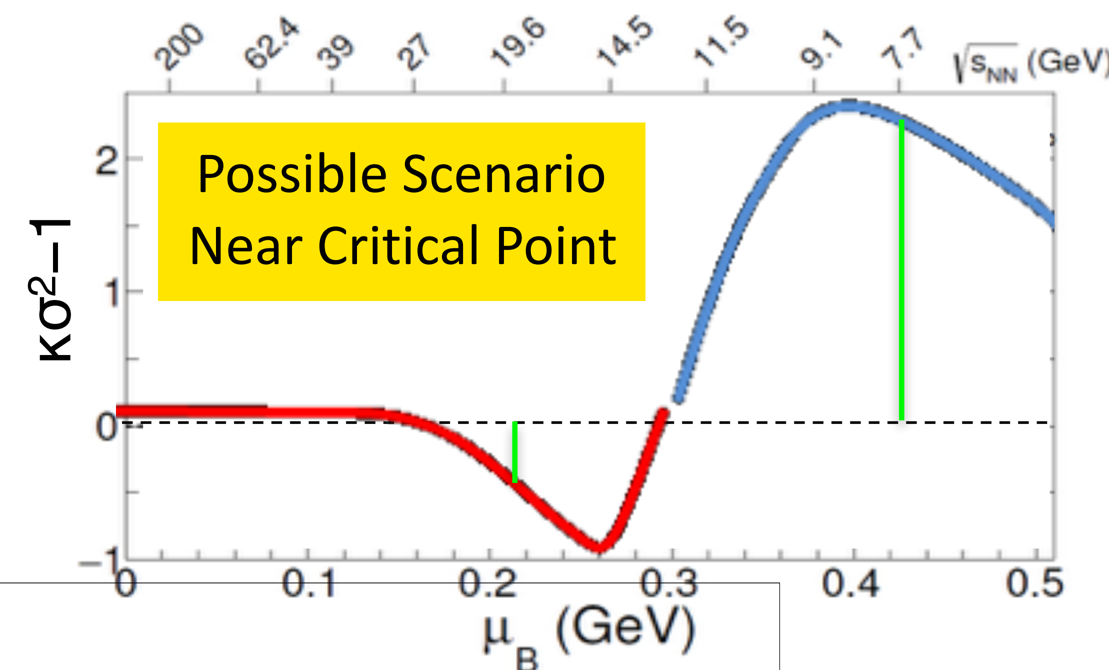


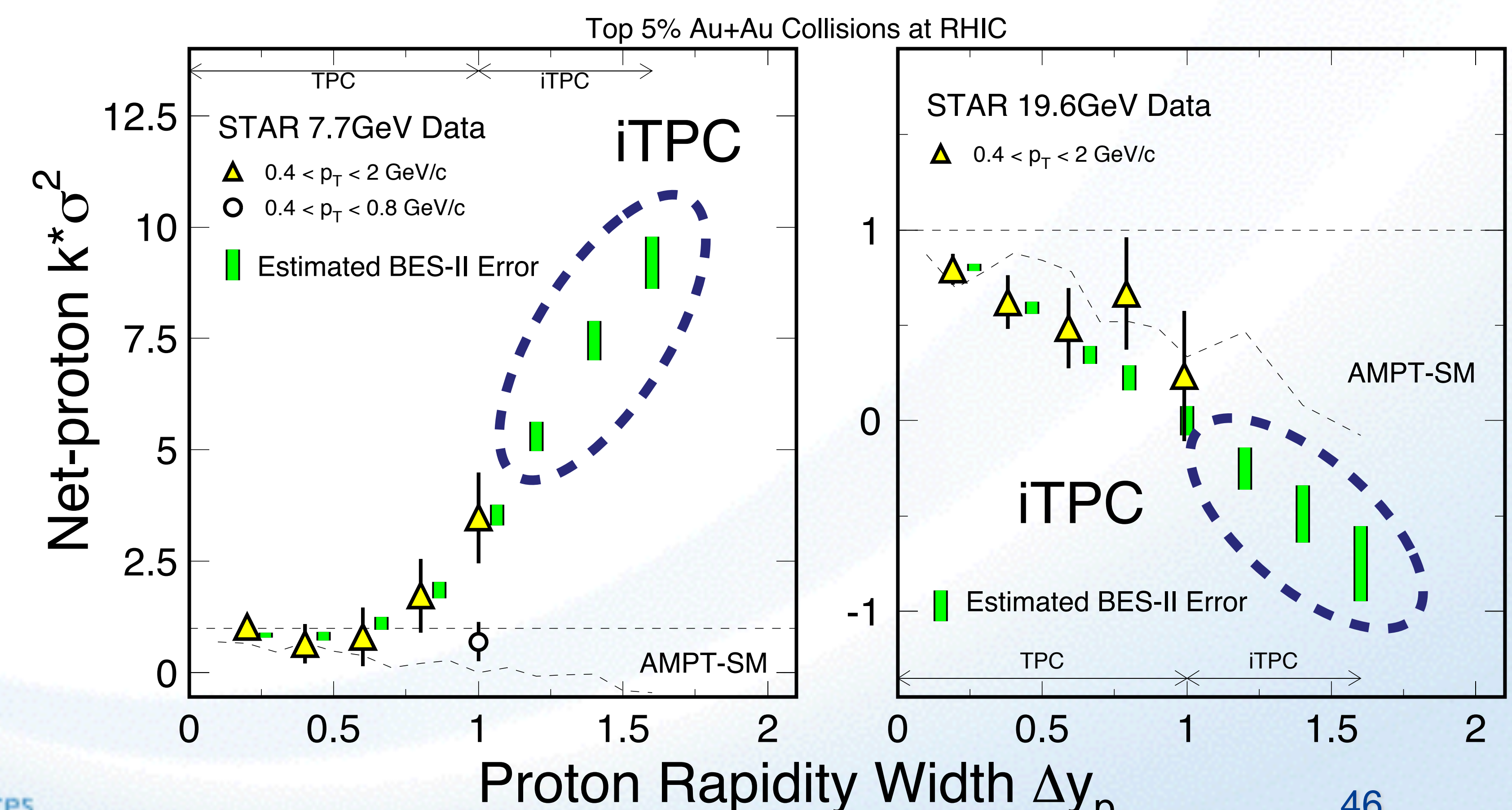


Critical fluctuations in BES-II

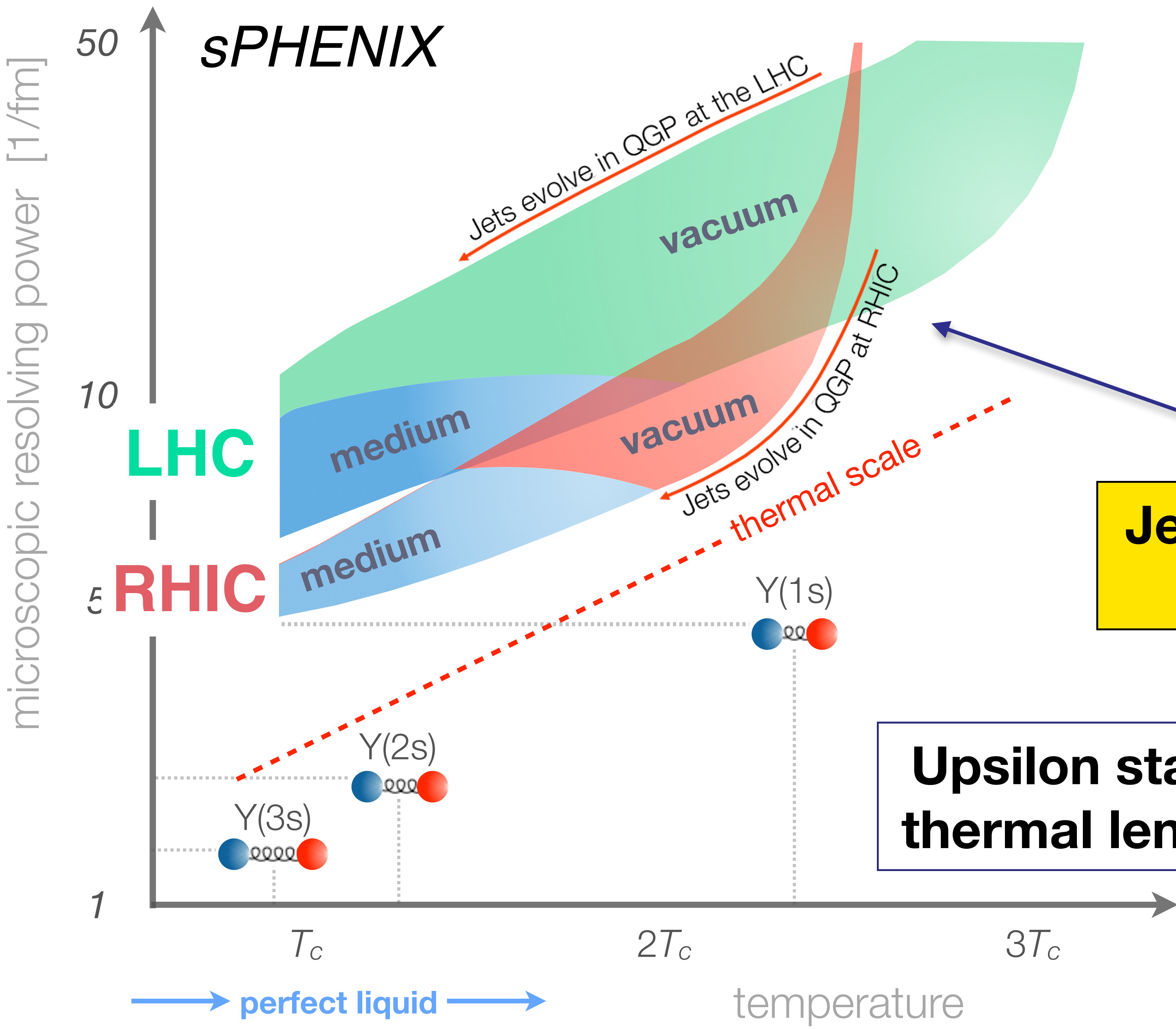


Model independent structure of net baryon number kurtosis





Probing scales in the medium



How does the perfect fluidity of the QGP emerge from the asymptotically free theory of QCD?

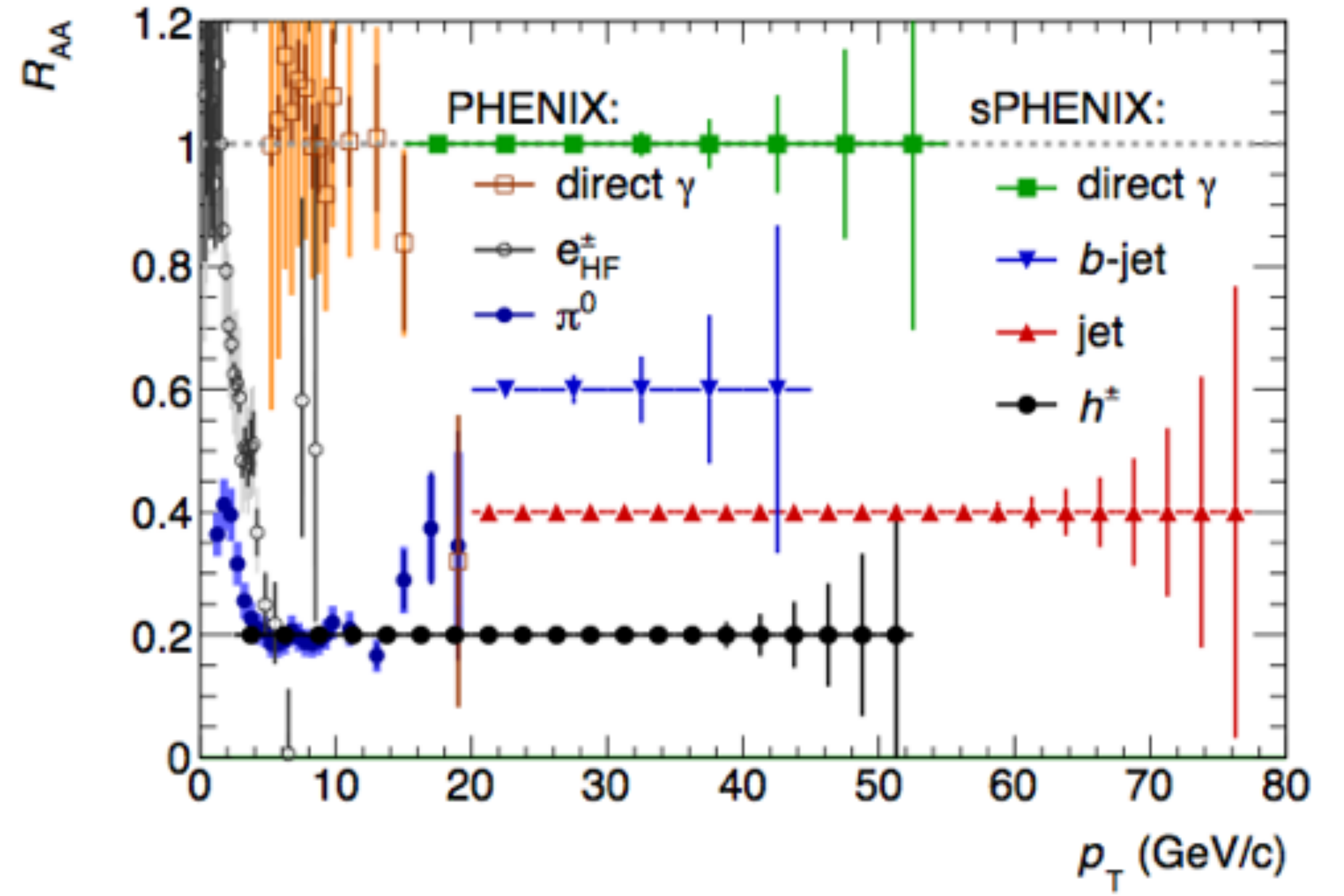
Jets probe sub-thermal length scales

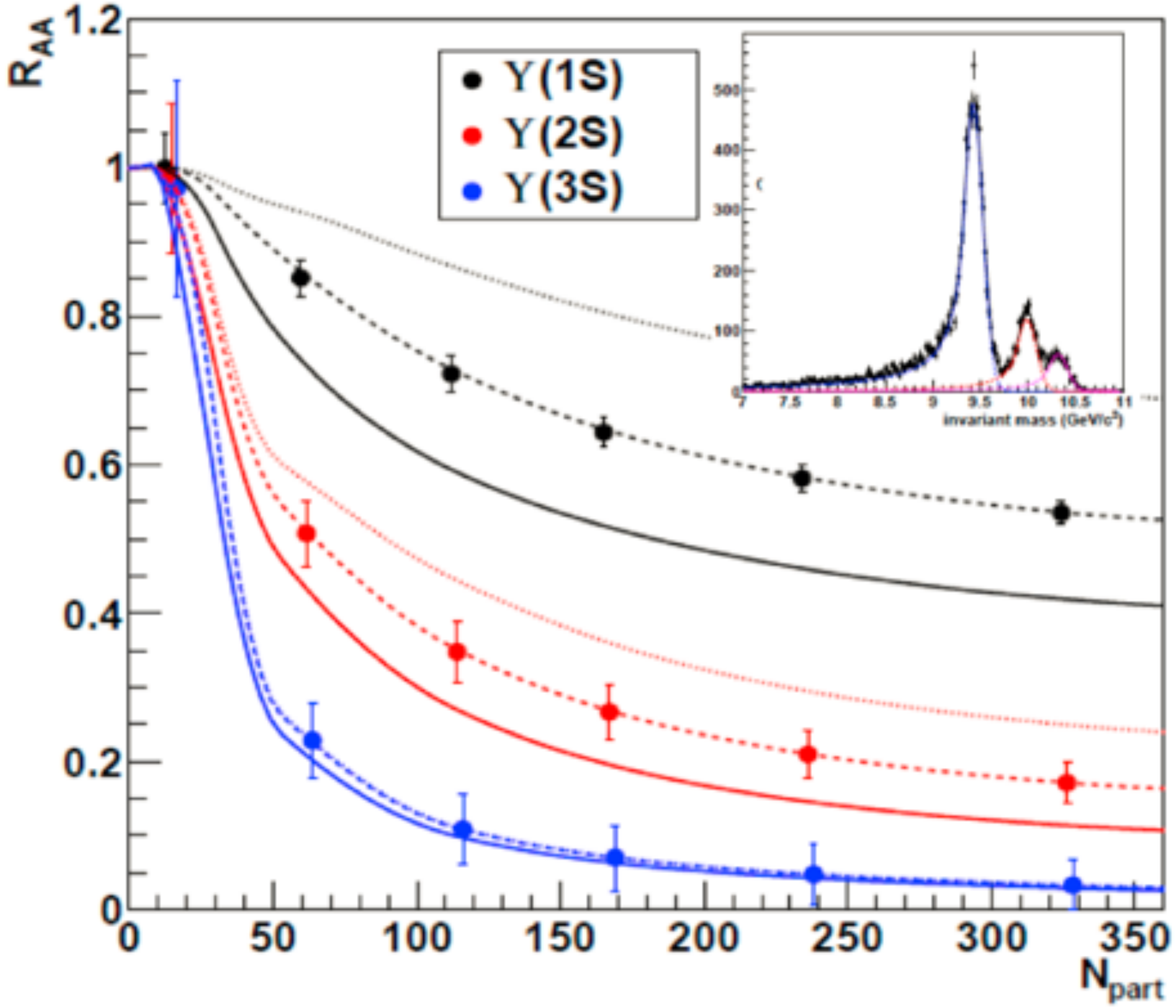
Upsilon states probe thermal length scales

Jets & Upsilon states

sPHENIX capabilities

Complete calorimetric jet spectroscopy





Completely resolved Upsilon spectroscopy

Beyond the Hagedorn temperature…

… lies the **liquid QGP** - a remarkable discovery by any measure.

Imagine: Heating a liquid (nuclear matter) turns it into vapor, i.e. a nucleon/hadron gas, at approximately 100 billion degrees.

But when we heat it to 20 times this temperature (2 trillion degrees) we find that it suddenly turns into a **liquid** again, in fact, into the **most perfect liquid** ever observed.

How is this possible?

It is still a mystery, but precise study of hard probes of various scales at RHIC and LHC, combined with comparative model-data analysis, will resolve the mystery within the next decade.

Rolf Hagedorn would surely be pleased!