

Diagnosing the Quark-Gluon Plasma

Dedicated to my collaborators
over 40 years who made this
research possible.

Berndt Müller
APS April Meeting
Feshbach Prize Lecture
19 April 2021

Quark-Gluon Plasma

- 1965: Discovery of the cosmic background radiation: The Universe was exceedingly hot in its infancy.
- This raised the question about the state of matter at the highest temperatures.
- 1965: Hagedorn showed that the highest temperature at which matter can exist as hadrons is $T_H \approx 160 \text{ MeV}$.
- In the late 1970s it became clear that the most likely form of matter at $T > T_H$ must contain “free” quarks and gluons; in other words, be a “quark-gluon plasma” (QGP).
- The two predominant challenges were:
 - How could a QGP be produced in the laboratory?
 - How could a QGP, once formed, be detected and investigated?

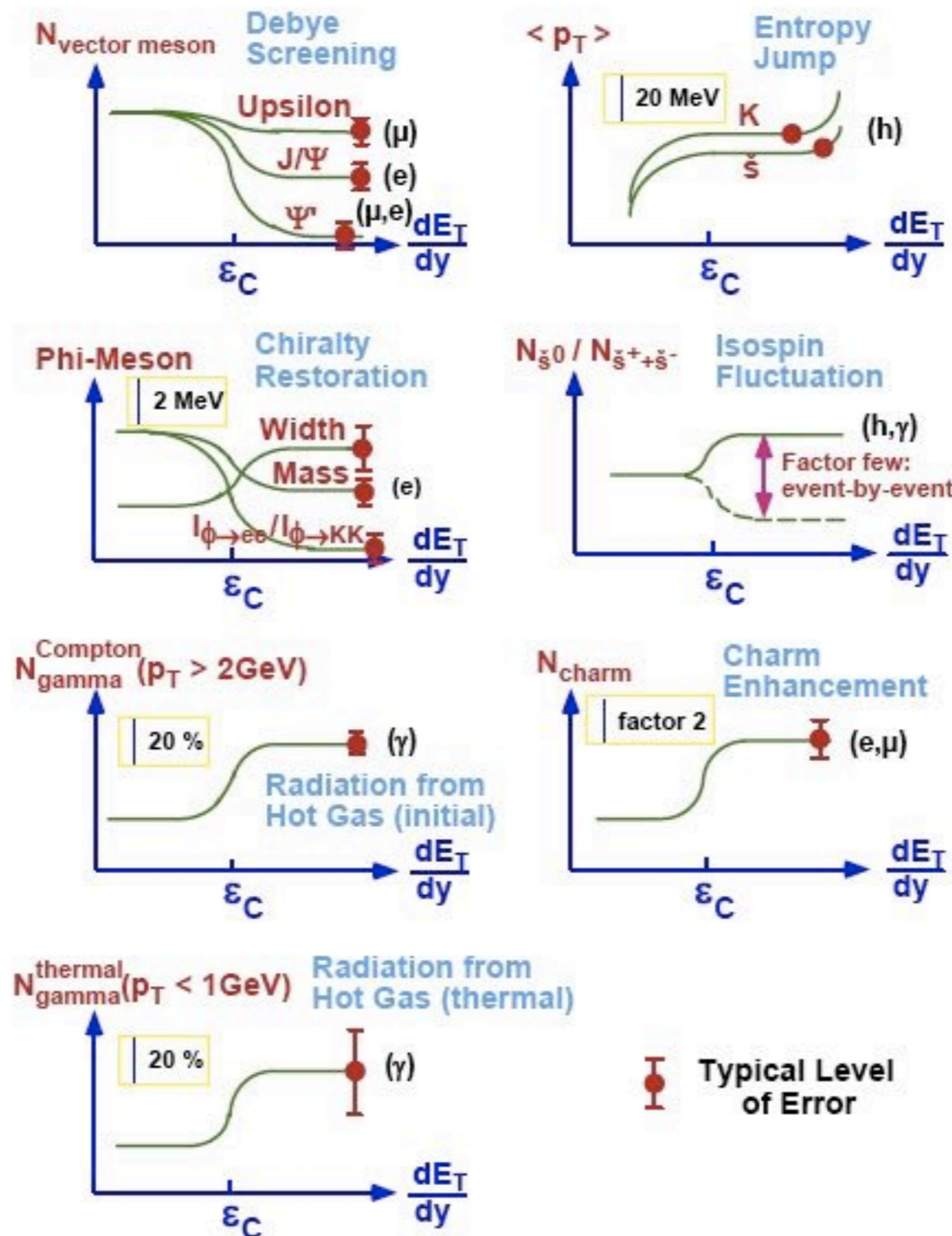
The Quest for the QGP

- Nuclear collisions were seen as the only viable path to create a QGP in the lab, but it was unclear how much CM energy was needed
 - European scientists embarked on using the existing CERN-SPS
 - U.S. scientists embarked on building a dedicated facility (RHIC)
- Theorists went on wild speculations (as usual) proposing a multitude of QGP “signatures.”
- Most nuclear physicists were extremely skeptical that any of the proposed signatures would be compelling.
- As the SPS experiments progressed and RHIC was under construction, NSAC was asked in 1995 to provide a list of “smoking gun” observables that could tell whether a QGP was formed and how it behaved.

Smoking guns - NSAC style



Smoking Guns



Glaring Omissions:

- Strangeness equilibration
- Valence quark recombination
- Anisotropic collective flow
- Jet quenching
- Critical fluctuations

QGP Diagnostics I: Bulk & Quarks

- Equation of state $\varepsilon(T)$, $P(T)$, $s(T)$: Collective flow
 - Speed of sound $c_s^2 = \partial P / \partial \varepsilon$ controls propagation of initial density perturbations
- Flavor equilibration
 - Enhancement of strange and multi-strange baryons sensitive to the flavor equilibration rate
- Hadronization at the phase boundary: quark recombination
 - Baryon/meson enhancement at intermediate momenta
 - J/ψ enhancement
- Fluctuations and correlations of conserved quantities
 - Sensitive to susceptibilities
 - Sensitive to critical fluctuations

Strangeness Enhanced

The original idea (J. *Rafelski* - 1980) of strangeness enhancement was tailored for the baryon-rich QGP expected to be formed in heavy ion collisions at the CERN-SPS:

$$\frac{N(\bar{s})}{N(\bar{q})} = \frac{1}{2} \left(\frac{m_s}{T} \right)^2 K_2(m_s / T) e^{\mu_B / (3T)} = 1 \dots 5$$

“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 $\bar{\Lambda}$, $\bar{\Xi}$, $\bar{\Omega}$.”

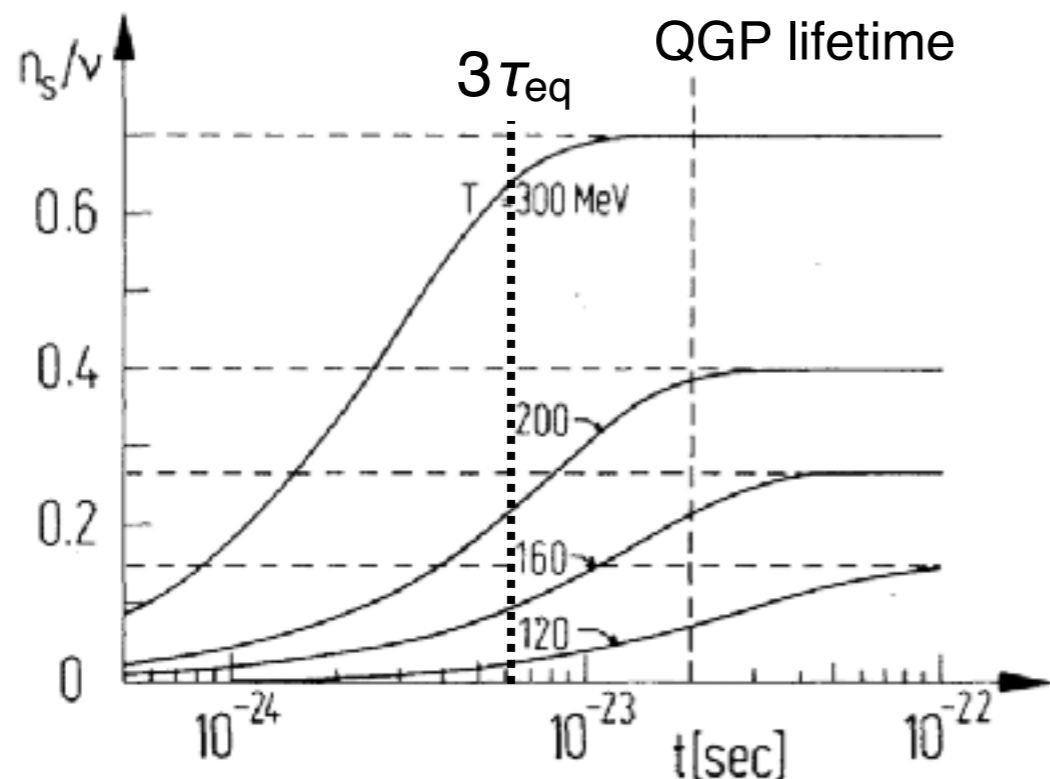
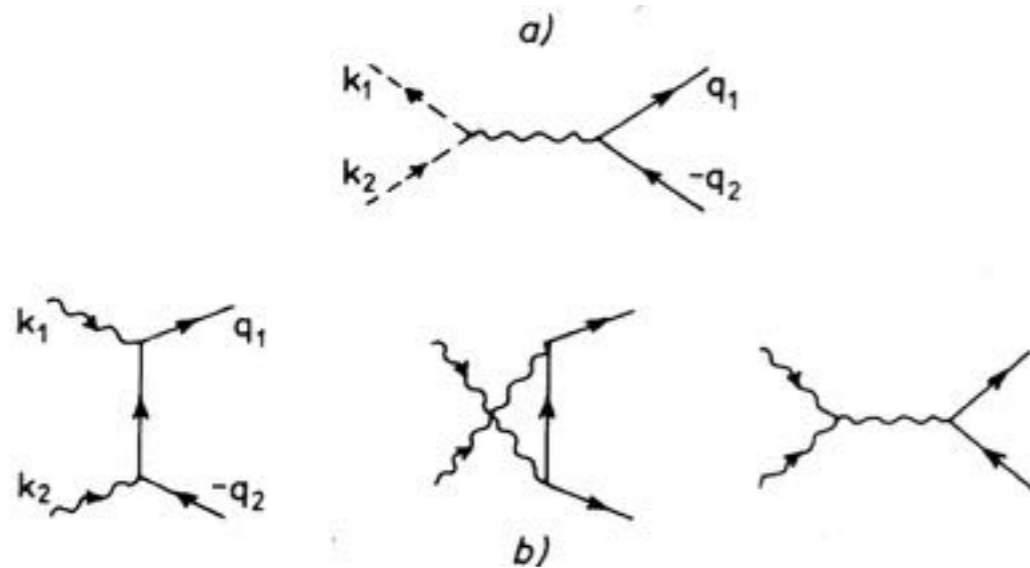


Johann Rafelski

This bold prediction has been quantitatively verified by experiments at SPS (WA85/94/97, NA57), RHIC (STAR), and LHC (ALICE) over more than 2 orders of magnitude in collision energy!

Strangeness Equilibration

J. Rafelski, BM, *PRL* 48 (1982) 1066



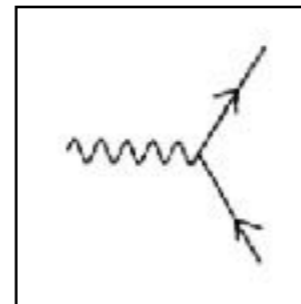
$gg \rightarrow s\bar{s}$ process is essential for rapid strangeness equilibration.

Equilibrated strange quark population survives final-state hadron interactions and leads to enhancement of multi-strange baryons.

[P. Koch, BM, J. Rafelski, *Phys. Rep.* 142 (1986) 167]



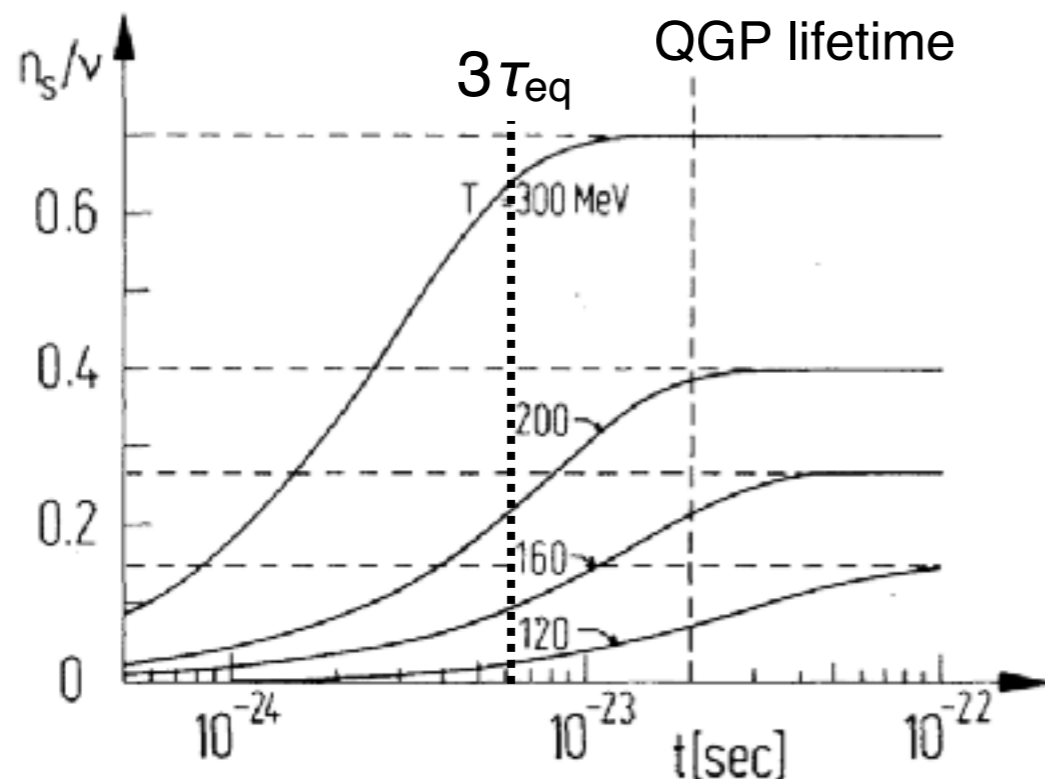
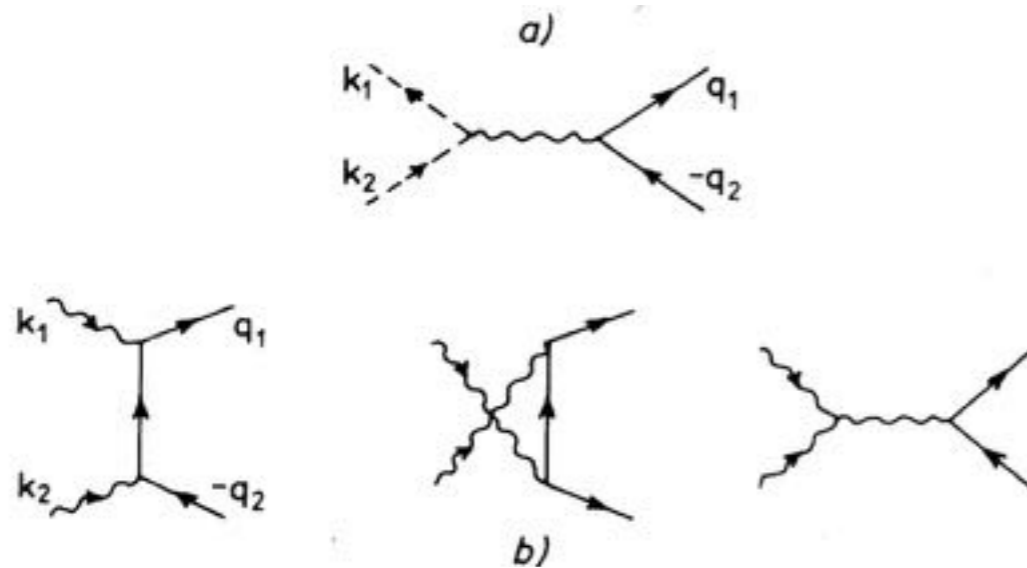
$g \rightarrow s\bar{s}$ becomes relevant for off-shell or "massive" gluons in the QGP:



T.S. Biro, P. Levai, BM, *Phys. Rev. D* 42 (1990) 3078

Strangeness Equilibration

J. Rafelski, BM, *PRL* 48 (1982) 1066



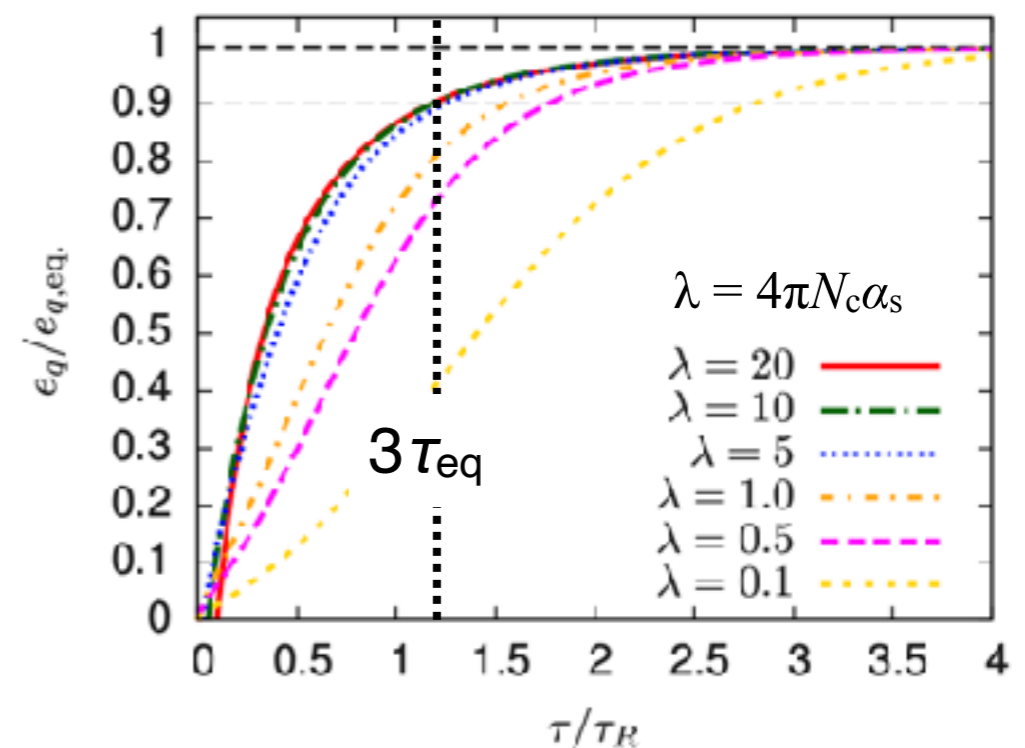
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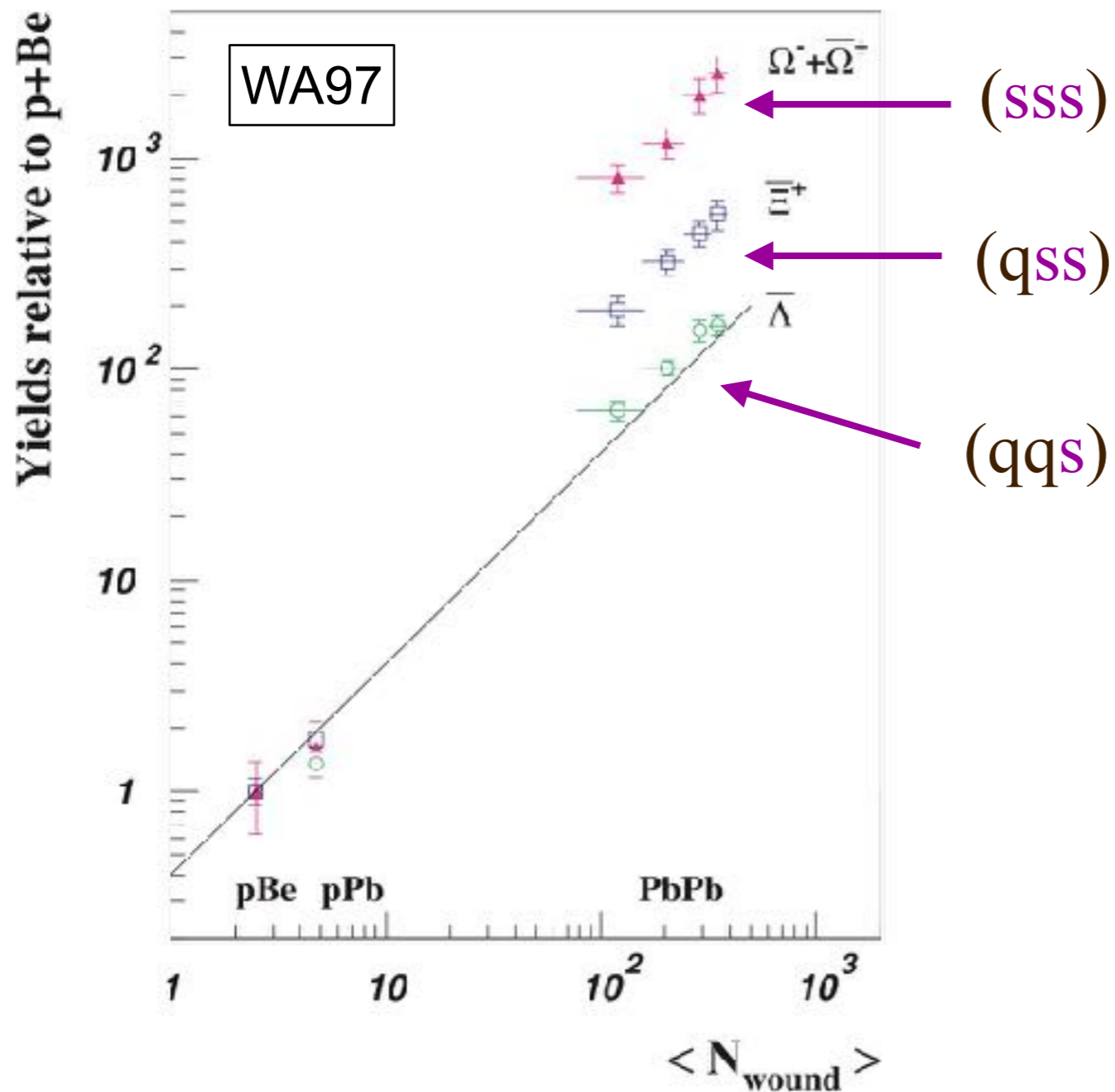
A. Kurkela, A. Mazeliauskas (2019)



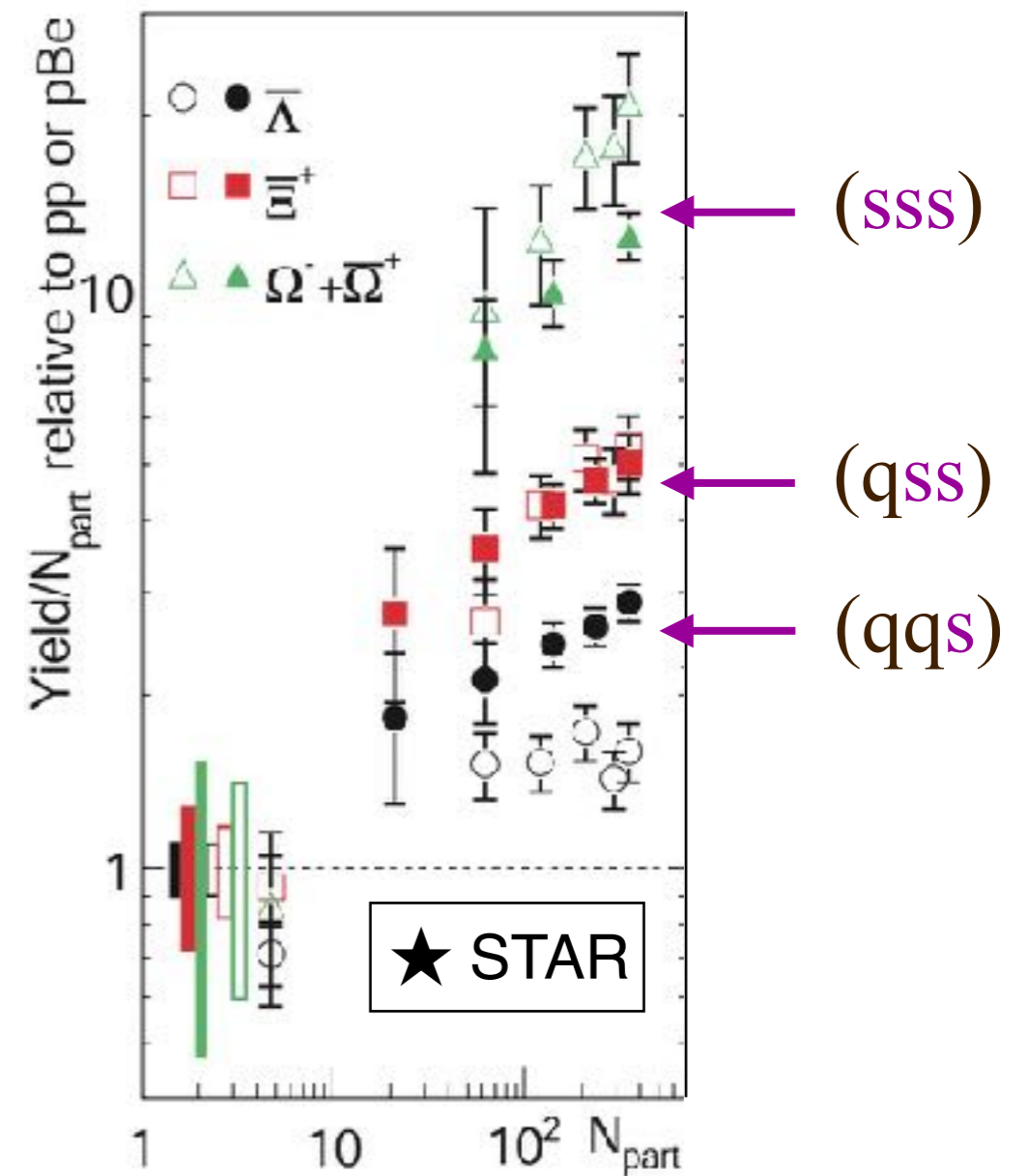
s-Enhancement at SPS & RHIC

Strange anti-baryon yields in Pb+Pb (17.3 GeV) and Au+Au (200 GeV)

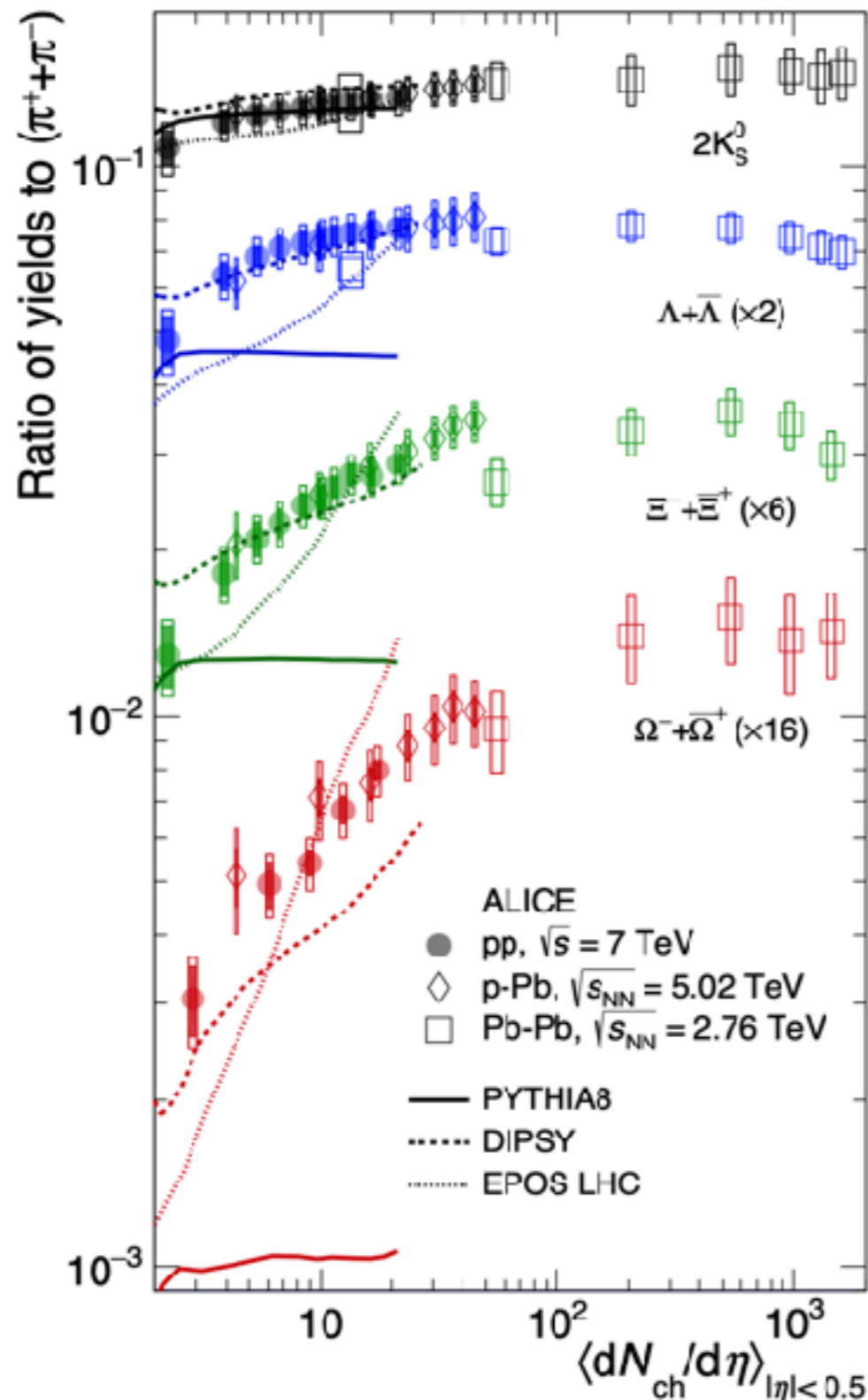
J. Phys. G 27 (2001) 375



Phys. Rev. C 77 (2008) 044908



s-Enhancement at LHC



Strangeness enhancement grows with fireball size / life-time and **saturates at the grand canonical equilibrium** in Pb+Pb collisions

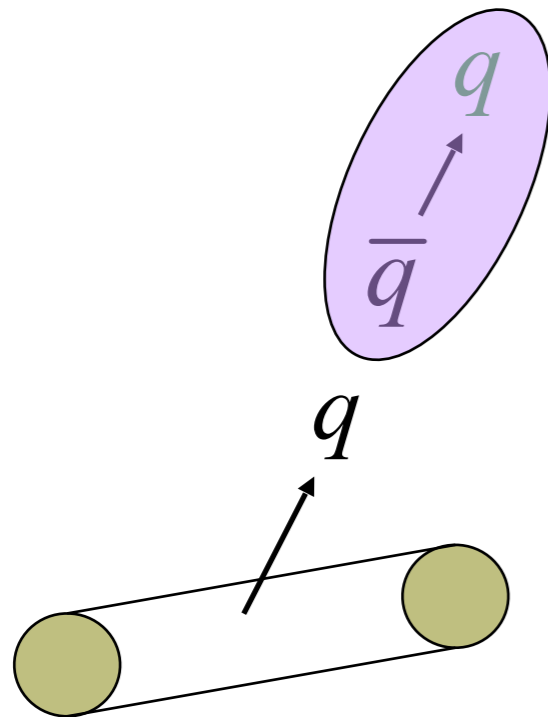
Two separate effects contribute:

- *Net strangeness conservation* in small systems (canonical equilibrium)
- *Incomplete equilibration* due to limited lifetime of small systems

Experimental determination of the strange quark equilibration time τ_{eq} is within reach.

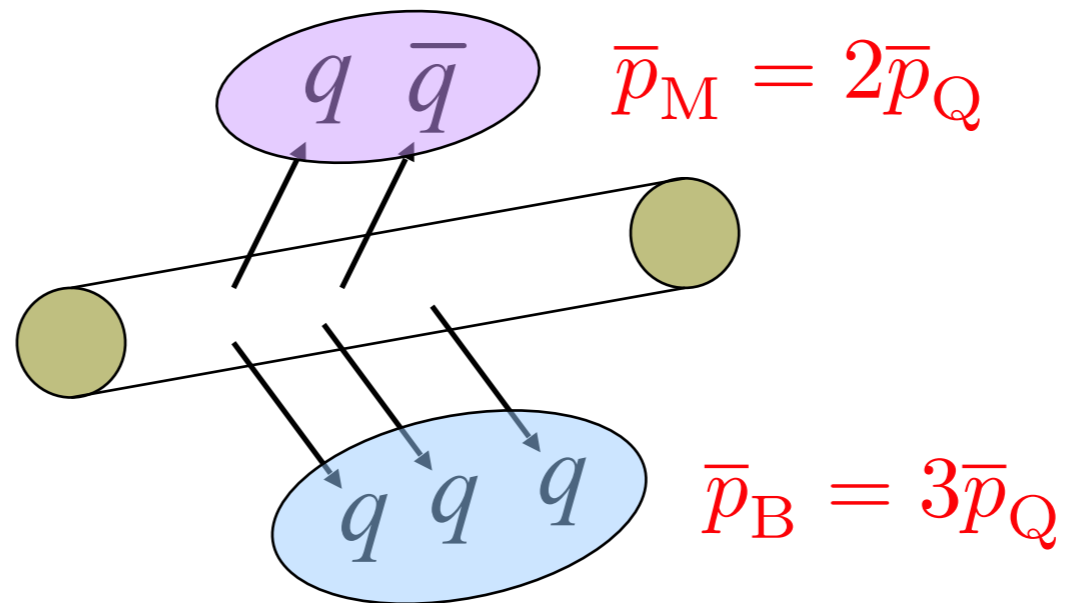
Hadronization Mechanisms

R. Fries, B.M., C. Nonaka, S.A. Bass, PRL 90 (2003) 202303
Phys. Rev. C 68 (2003) 044902



Fragmentation

$$\frac{\text{Baryon}}{\text{Meson}} \ll 1$$



Recombination

$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$



Rainer Fries



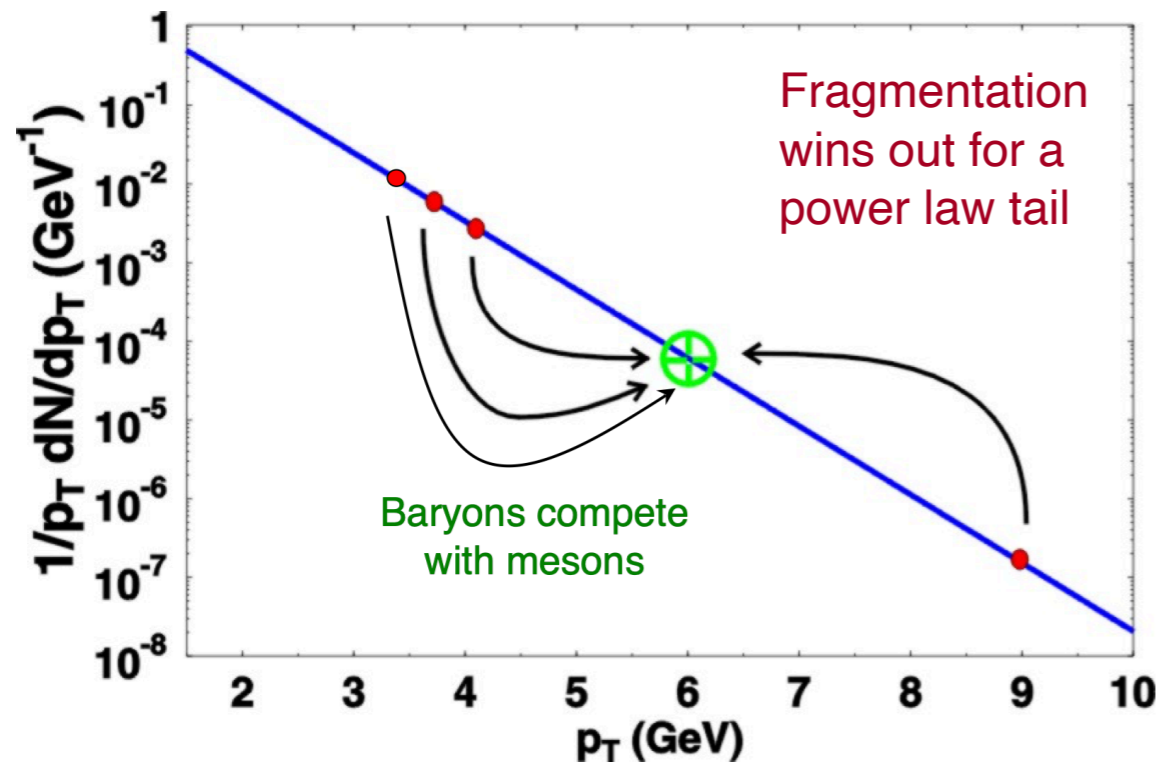
Chiho Nonaka



Steffen Bass

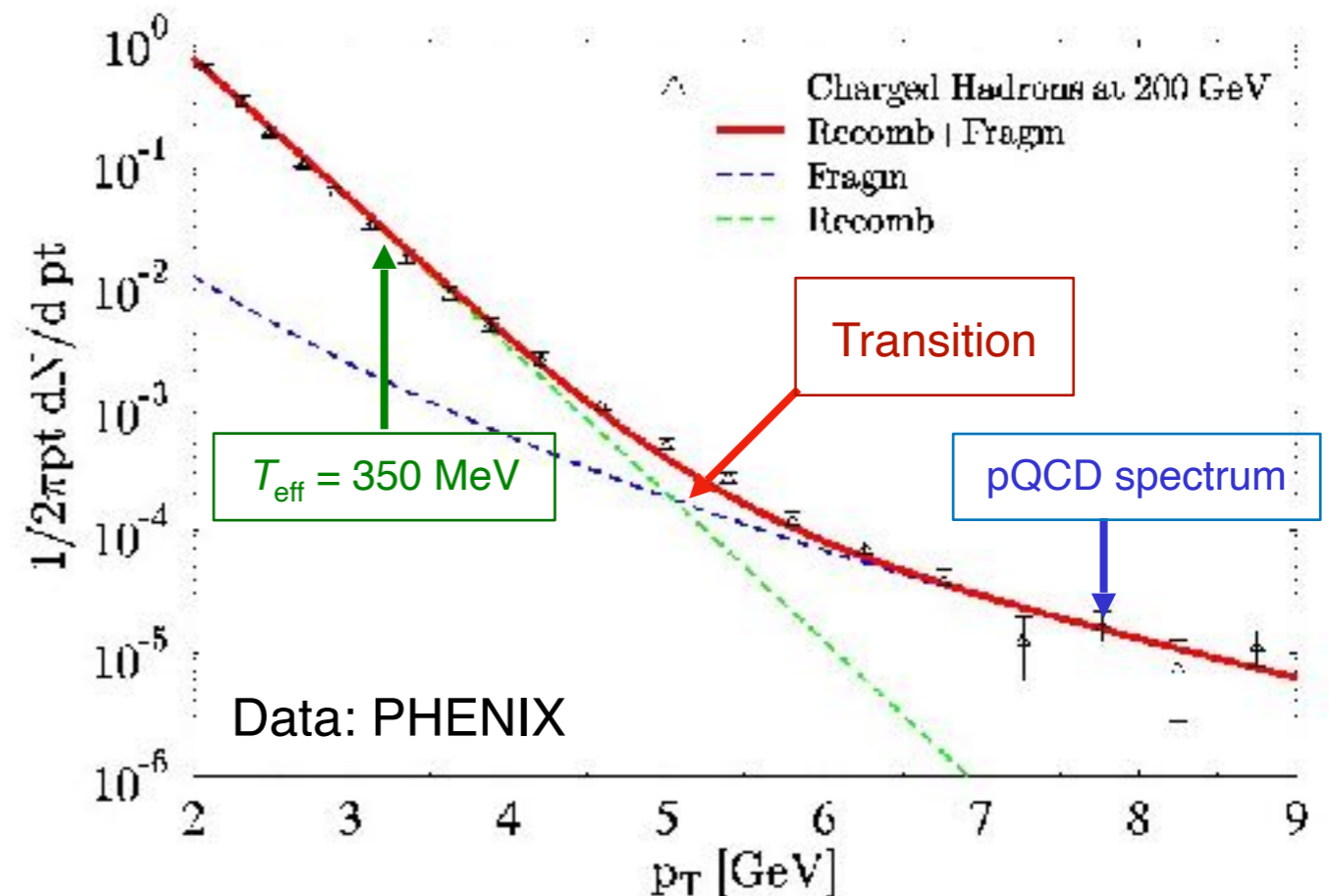
Recombination vs. fragmentation

Recombination dominates over fragmentation for a thermal (exponential) source



Transition happens later for baryons than for mesons: Baryon enhancement at intermediate p_T

R. Fries, BM, C. Nonaka, S.A. Bass, *PRL* 90 (2003) 202303

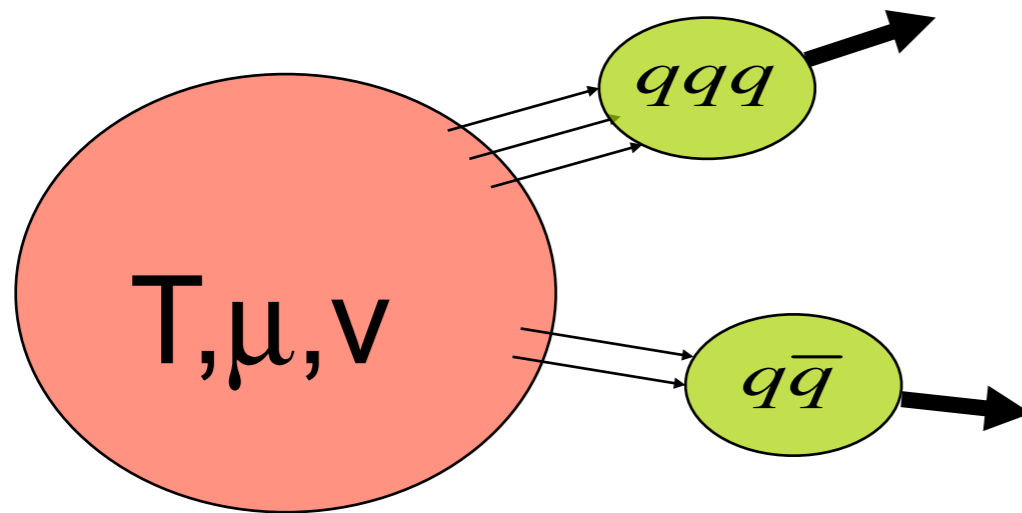


Quark number scaling

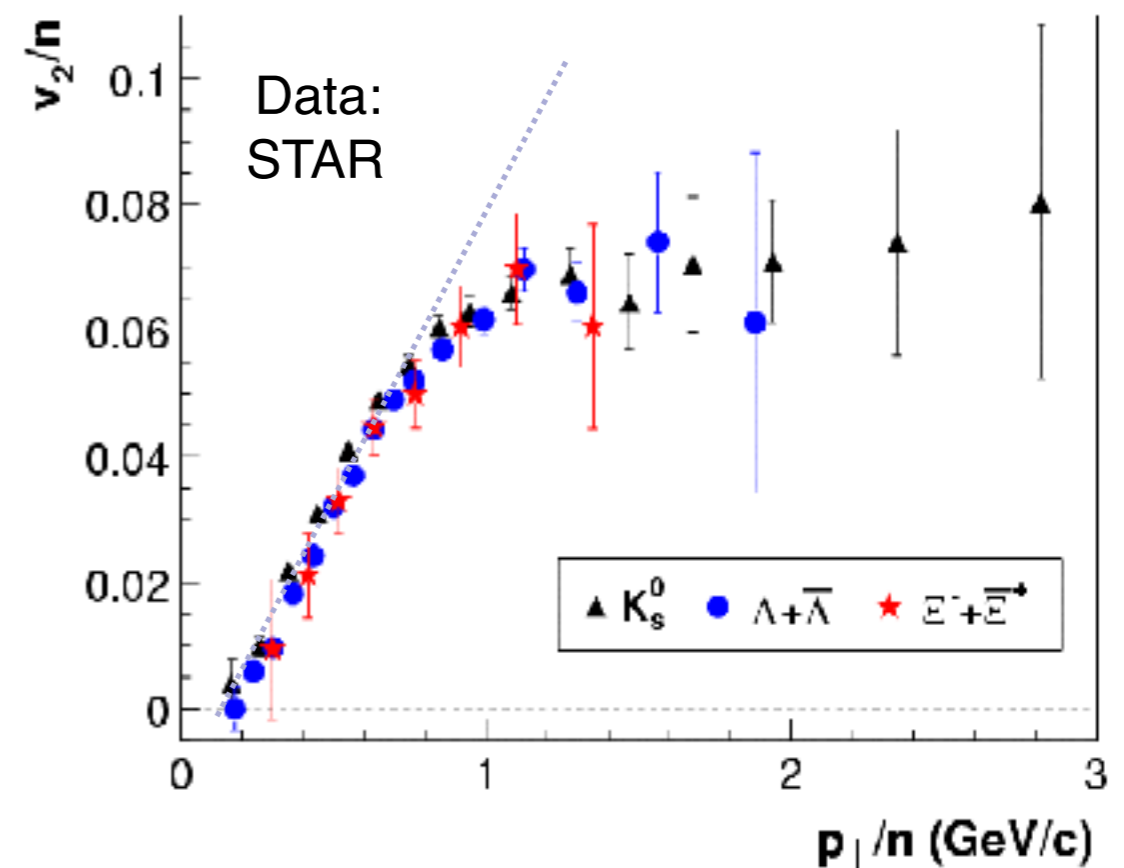
In the recombination regime, **meson** and **baryon** $v_2(p_T)$ can be obtained from the **quark** $v_2(p_T)$ [D. Molnar, S. Voloshin, *PRL* 91 (2003) 092301]:

$$v_2^M(p_T) = 2 v_2^q(p_T/2)$$

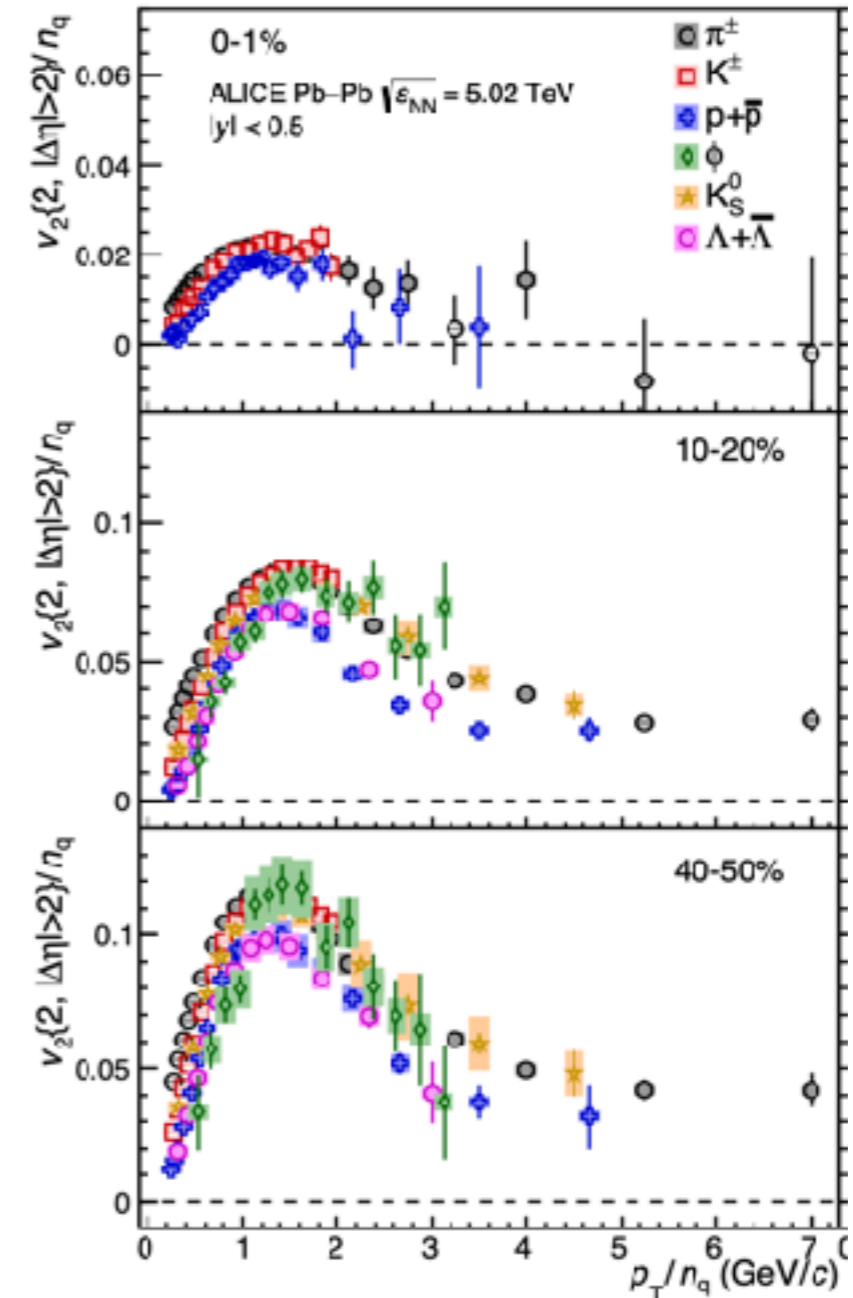
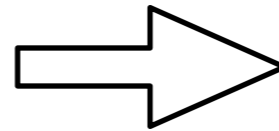
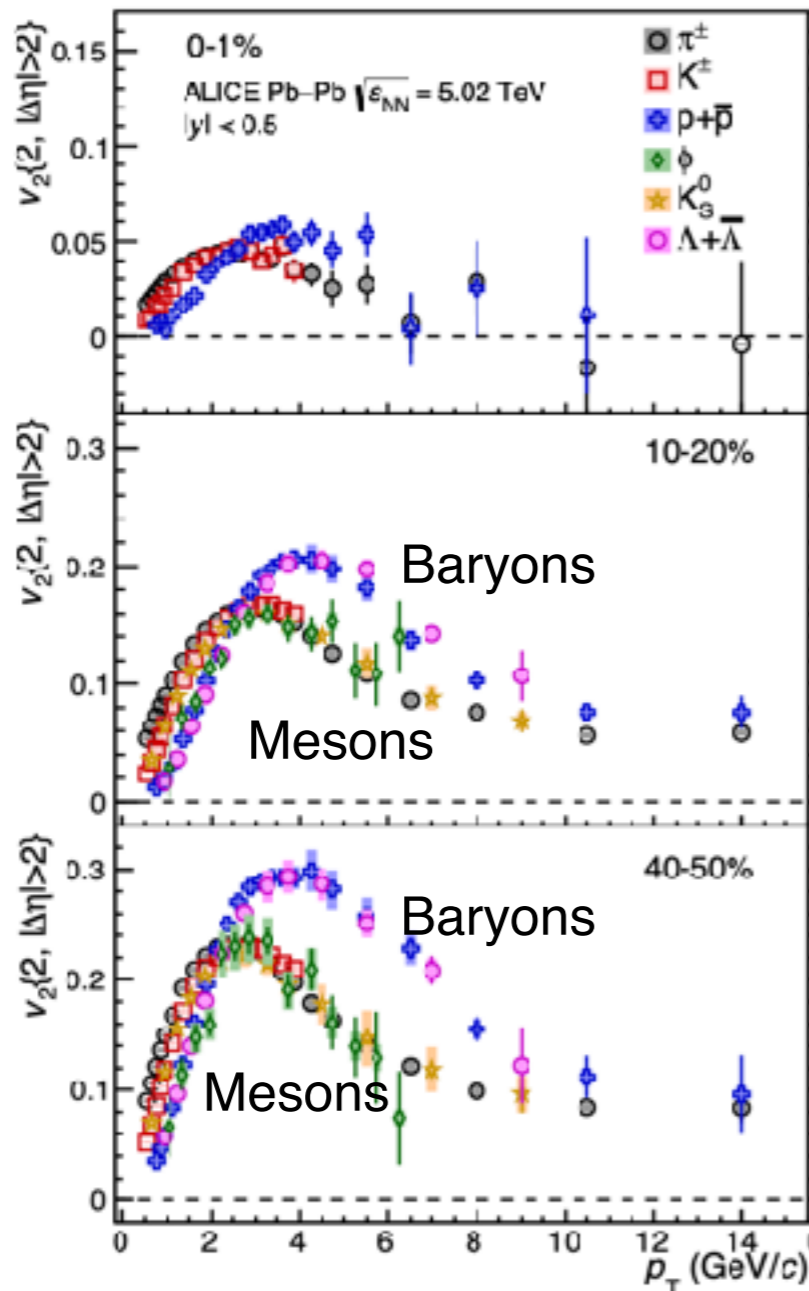
$$v_2^B(p_T) = 3 v_2^q(p_T/3)$$



Emitting medium is composed of unconfined, flowing quarks.



Quark scaling at LHC



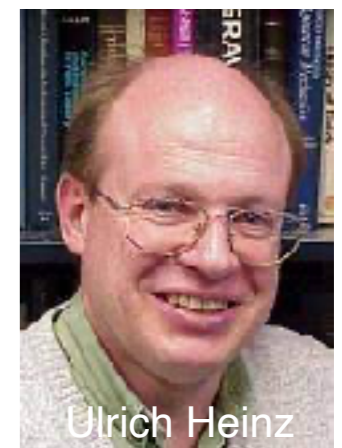
All data from RHIC and LHC are consistent with the interpretation that collective flow is established at the quark level and imprinted on the flow pattern of hadrons.

Fluctuations

- **Fluctuations of conserved quantities** (charge, baryon number, strangeness) can survive final-state interactions, because they cannot be changed by local processes in the hot fireball, only by much slower diffusion.
- They change drastically during the transition from hadron gas to the QGP, because quarks carry non-integral charge and baryon number

M. Asakawa, U. Heinz, BM, *PRL* 85 (2000) 2072

S. Jeon, V. Koch, *PRL* 85 (2000) 2076.



Net baryon number fluctuations will play a central role in the search for a QCD critical point using the data from the high-statistics RHIC beam energy scan.

QGP Diagnostics II: Gluons

Fundamental properties of the QGP, mostly of gluons, that are accessible by measurements in relativistic heavy ion collisions:

Mainly
Gluons

$$\langle T^{xy}(x, t) T^{xy}(0, 0) \rangle$$

$$\langle T_i^i(x, t) T_i^i(0, 0) \rangle$$

Shear viscosity η : anisotropic collective flow

Bulk viscosity ζ : transverse collective flow

Gluons

$$\langle F_a^{i+}(x^-) F_{ai}^+(0) \rangle$$

$$\langle F_a^{i0}(0, t) F_{ai}^0(0, 0) \rangle$$

Momentum diffusion along light-cone:
fast parton energy loss / jet quenching

Heavy quark diffusion: c quark energy loss

Gluons

$$\langle F_a^{i0}(x, 0) F_{ai}^0(0, 0) \rangle$$

Color screening: J/ Ψ , Y suppression

Quarks

$$\langle j^\mu(x, t) j^\nu(0, 0) \rangle$$

Lepton pairs: photon spectral function

Direct photons: spectra, coll. flow, fluctuations

QGP Viscosities

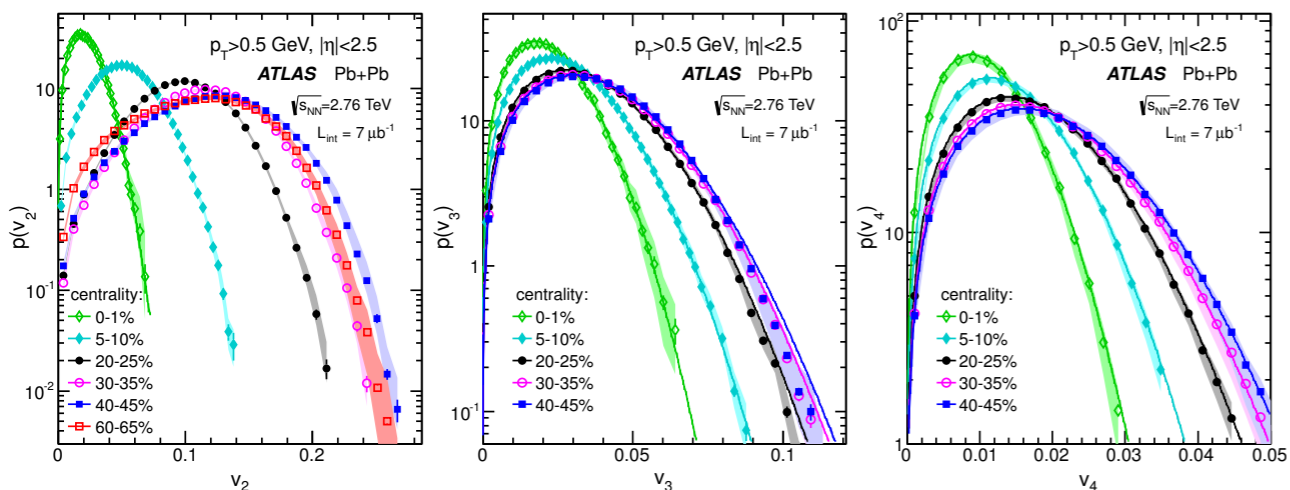
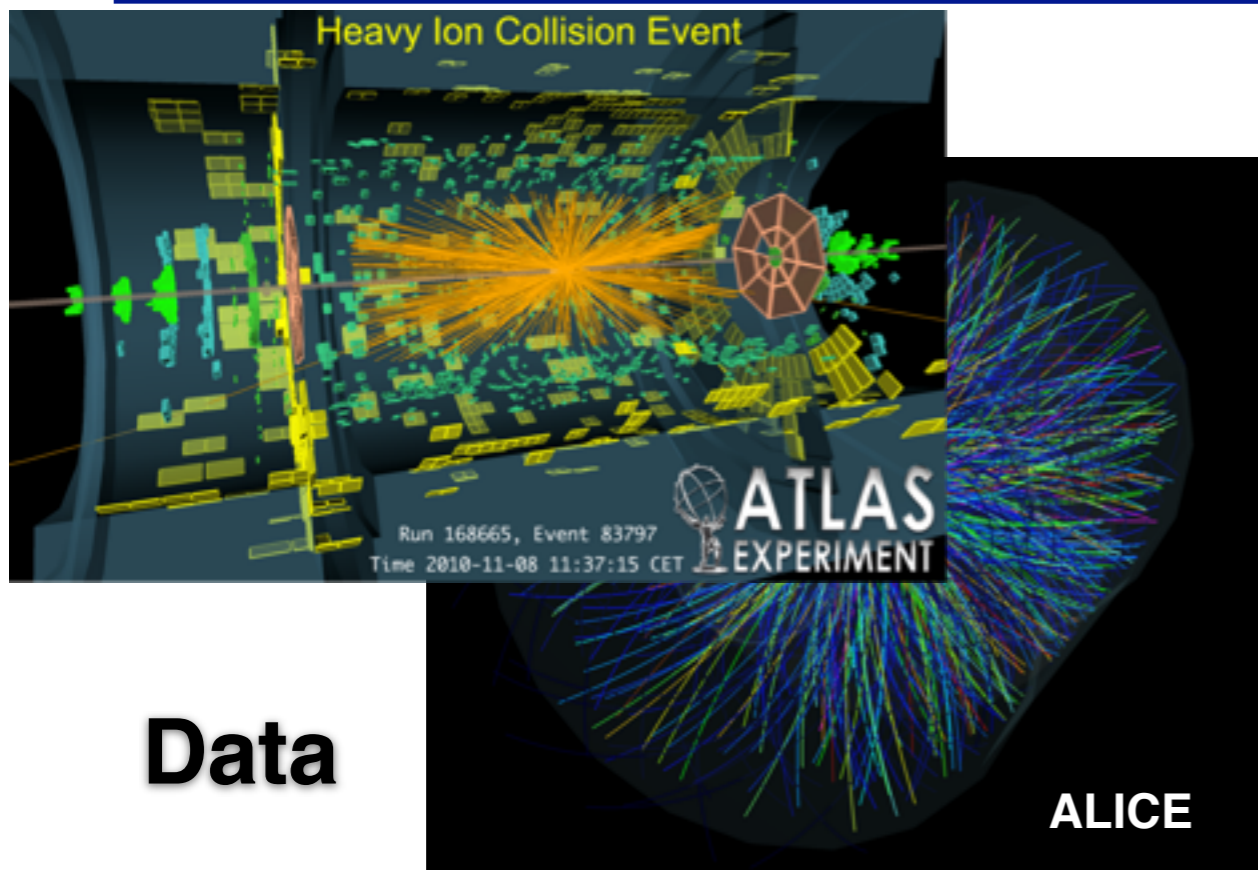
- **Shear viscosity** η is a measure of the ease of momentum transport in the QGP. Since the mean-free path decreases with increasing coupling, it **is a measure of the strength of the interaction among quarks and gluons**. In the strong-coupling limit one expects $4\pi \eta/s \approx 1$.

$$\eta = \lim_{\omega \rightarrow 0} \frac{1}{\omega} \int \frac{dt}{2\pi} e^{i\omega t} \int \frac{d^3x}{(2\pi)^3} \langle T^{xy}(x, t) T_{xy}(0, 0) \rangle \sim \frac{1}{3} \bar{p} n \lambda_{\text{tr}}$$

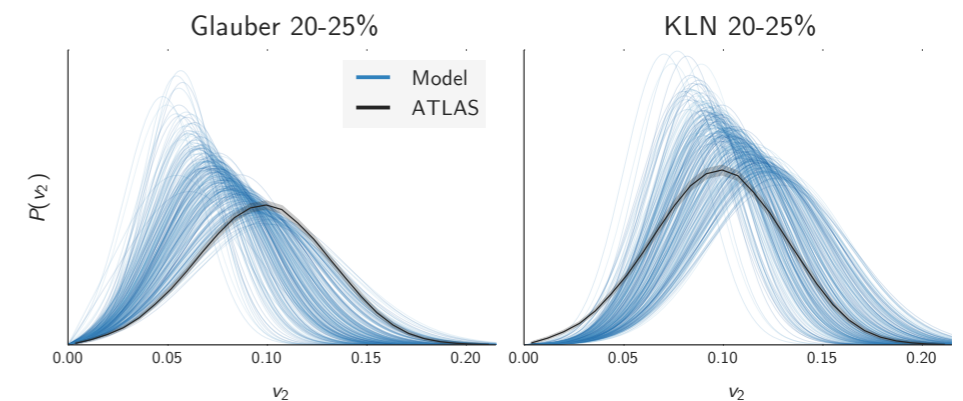
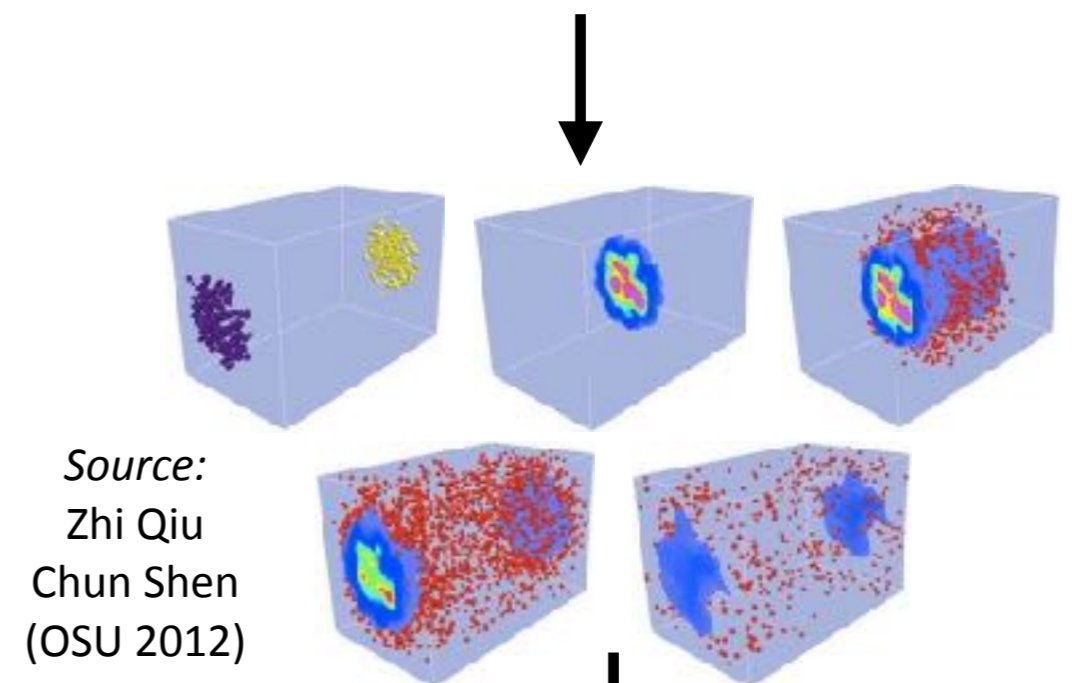
- **Bulk viscosity** ζ is a measure of the deviation from scale invariance in the QGP. Scale invariance of QCD is broken at the quantum level by the $T_{\mu\nu}$ trace anomaly. One expects ζ to be large in the transition region, where $(\varepsilon - 3P)$ is large.

$$\zeta = \lim_{\omega \rightarrow 0} \frac{1}{9\omega} \int \frac{dt}{2\pi} e^{i\omega t} \int \frac{d^3x}{(2\pi)^3} \langle T_i^i(x, t) T_i^i(0, 0) \rangle$$

Model-Data Comparison



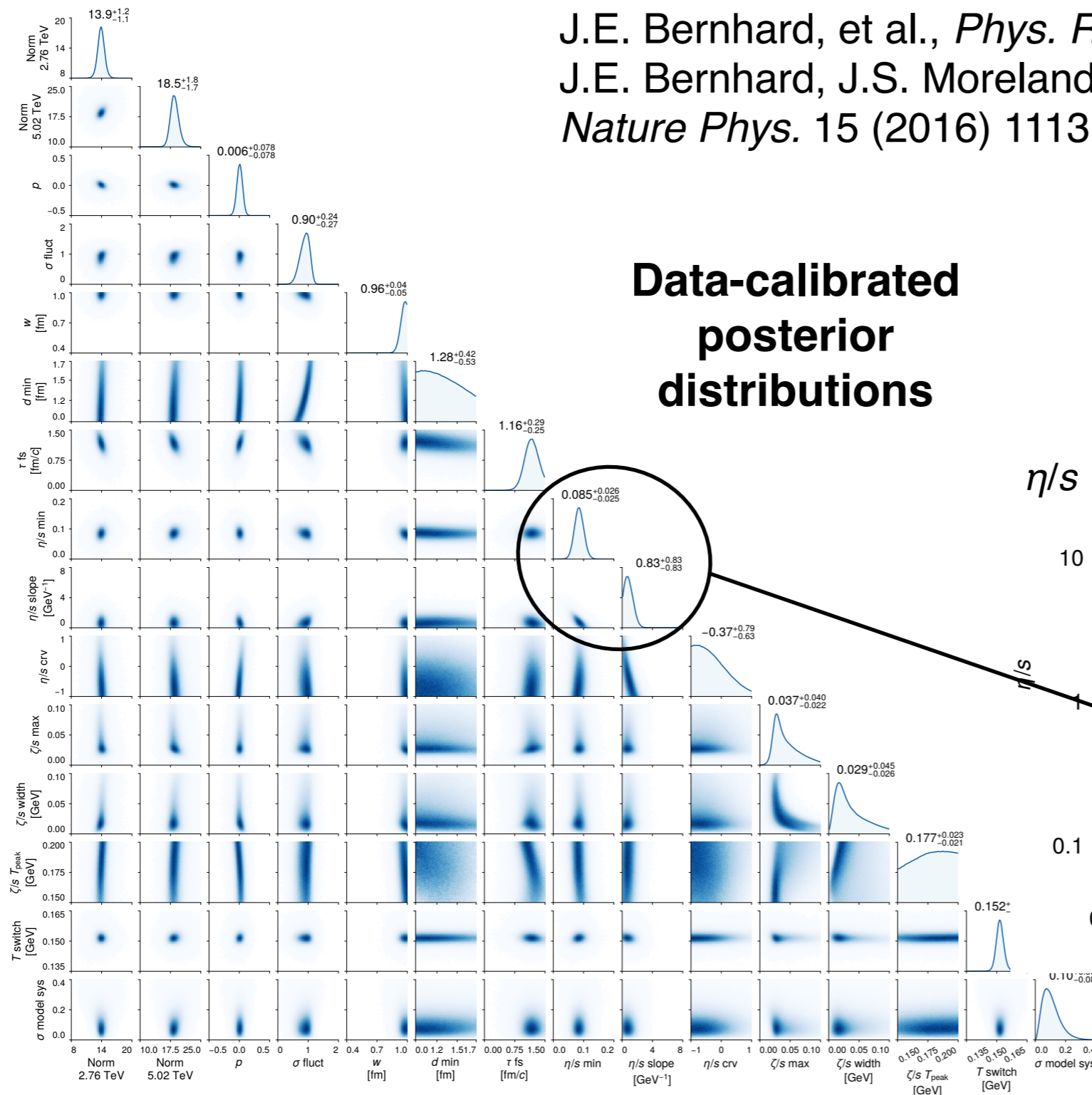
Model
initial conditions, model parameters



extracted QGP properties

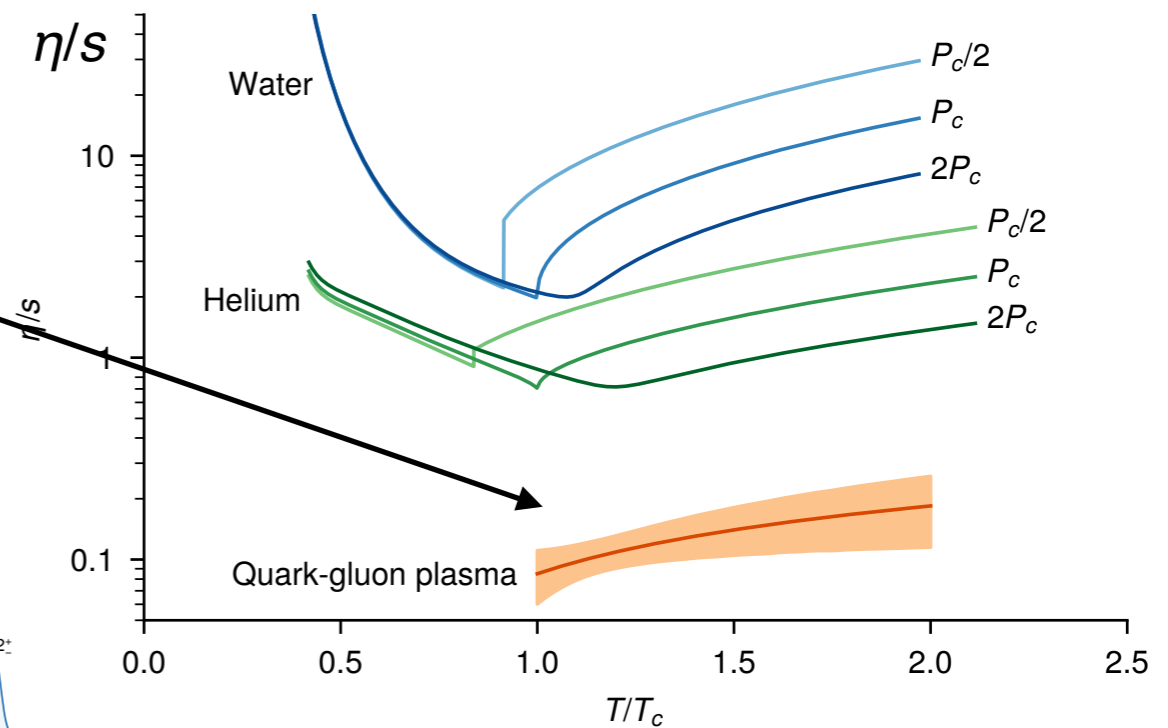
Bayesian Posterior Distributions

J.E. Bernhard, et al., *Phys. Rev C* 91 (2015) 054910
 J.E. Bernhard, J.S. Moreland, S.A. Bass,
Nature Phys. 15 (2016) 1113



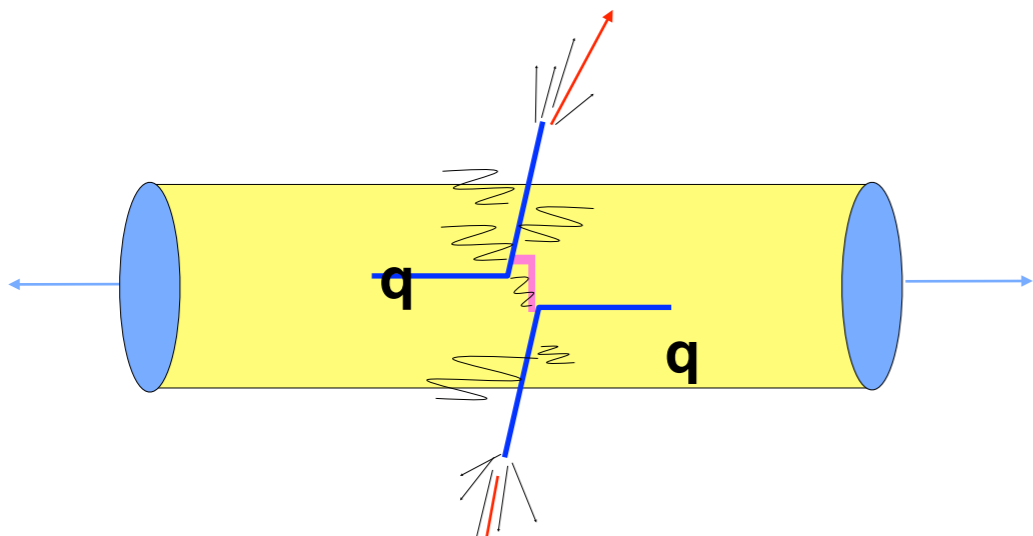
**Data-calibrated
posterior
distributions**

**Temperature-dependent viscosity
from the data-calibrated posterior:**



**Confirms “perfect fluid” nature of
the quark-gluon plasma**

Jet quenching



Parton energy loss parameter \hat{q} measures transverse color field correlations along the light cone = gluon density of the QGP:

$$\hat{q} = \frac{4\pi^2 \alpha_s C_2}{N_c^2 - 1} \int dy^- \langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0) \rangle$$

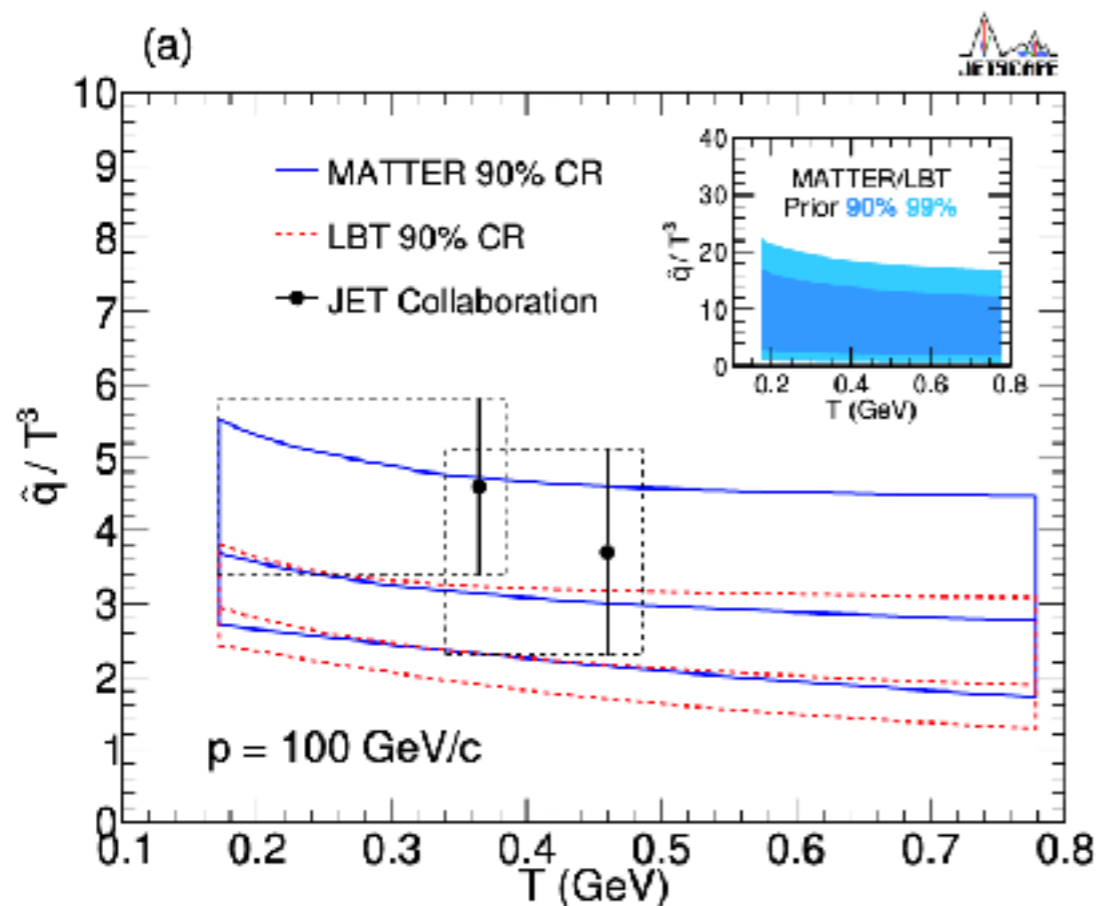
$$\frac{dE}{dx} = -C_2 \alpha_s \hat{q} L$$

Energy loss of leading parton by gluon radiation

First systematic determination from data by JET Collaboration: *PRC 90 (2014) 014909*

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

New combined analysis of RHIC and LHC data by JETSCAPE collaboration:
S. Cao et al., arXiv: 2102.11337

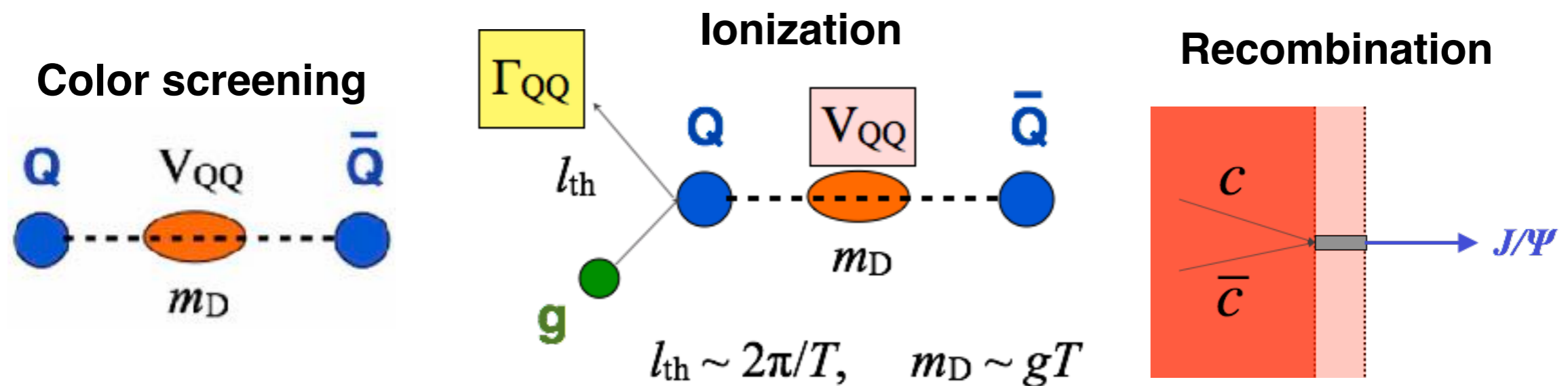


Color screening

Static color fields are screened in the QGP by the concerted action of thermal partons.

$$m_D = - \lim_{|x| \rightarrow 0} \frac{1}{|x|} \ln \langle U(0, x) E_i^a(x) U(x, 0) E_i^a(0) \rangle \sim gT$$

This leads to the dissolution (“melting”) of bound states of heavy quarks (quarkonia), when the screening length is shorter than the bond length [Matsui & Satz (1986)].



The dynamical description is complicated by the fact that quarkonia can also be dissolved by thermal ionization and regenerated by recombination at hadronization.

Quarkonium suppression

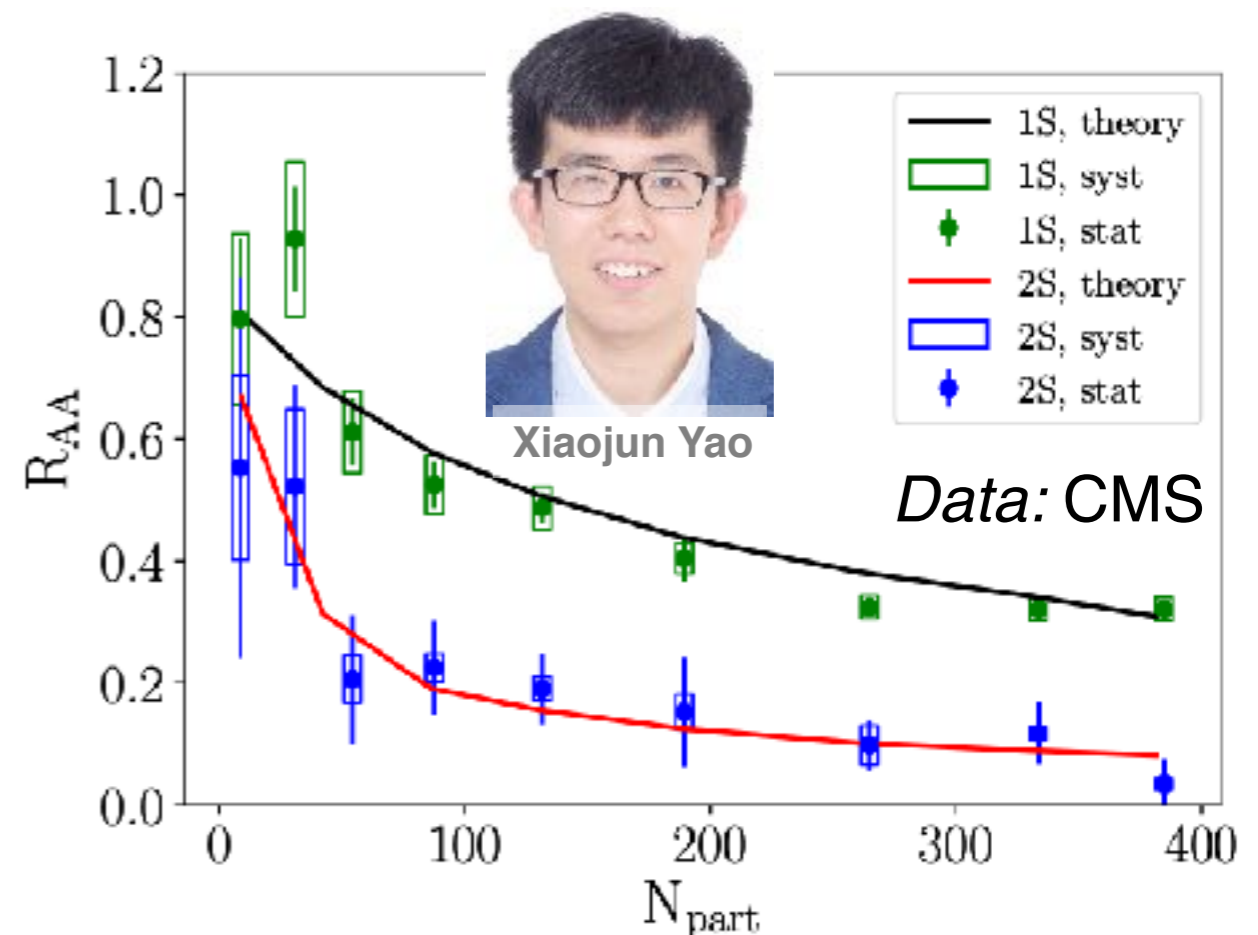
Quarkonium transport in the QGP has been formulated rigorously in the framework of non relativistic QCD with HTL EFT where the $Q\bar{Q}$ is treated as an “open” quantum system (X. Yao, T. Mehen, BM, *Phys. Rev. D* 95 (2019) 116002; Y. Akamatsu, arXiv: 2009.10059; N. Brambilla, *et al.*, arXiv:2012.01240; X. Yao, arXiv: 2102.01736)

Input is a small number of rigorously defined and calculable quantities.

X. Yao, W. Ke, Y. Xu, S.A. Bass, BM,
JHEP 21 (2020) 046

X. Yao, W. Ke, Y. Xu, S.A. Bass, T. Mehen,
Nucl. Phys. A 1005 (2021) 121854

Future high statistics data from RHIC (sPHENIX), LHC, and EIC (nuclear PDFs) will reduce still sizable uncertainties in the theory-data comparison.



Summary



Forensic Analysis

- Diagnostics of the QGP has come a long way from its origins in the 1980s/-90s to enter a phase of rigorous theory-based analysis.
- The systematic formulation of observables in terms of effective field theory and transport parameters connects data to well-defined properties of the QGP.
- Bayesian multi-parameter model-data comparisons allow extraction of values for these parameters with quantifiable uncertainties.
- Some of what we have learned:
 - The QGP contains unconfined, collectively flowing quarks.
 - We have multiple, consistent determinations of its gluon content.
 - Color screening and near-“perfect” fluidity have been established.
 - RHIC BES 2, sPHENIX, and LHC Run 3 will further improve the “textbook” results obtained over the past 5 years.

Present and former Duke QCD Group members



THANK YOU
for your attention!

Questions?