The Unbearable Burden of Being Light:

Exploring the emergence of ordinary matter from quarks and gluons

Berndt Mueller

Wigner Institute, Budapest

November 13, 2018

70 YEARS OF DISCOVERY

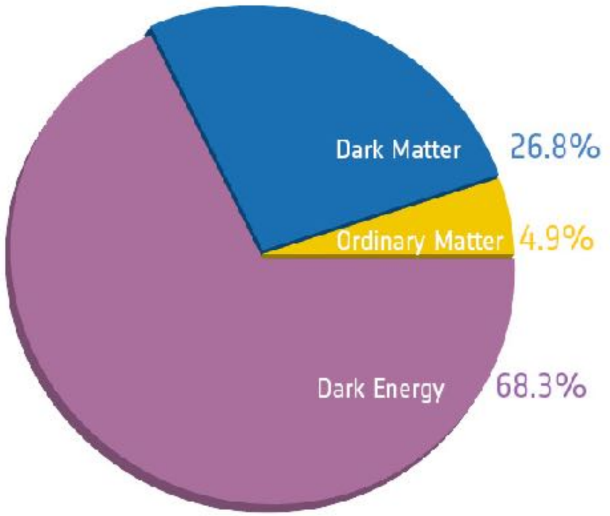
A CENTURY OF SERVICE

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Mass Balance of the Universe

Planck satellite CMB data

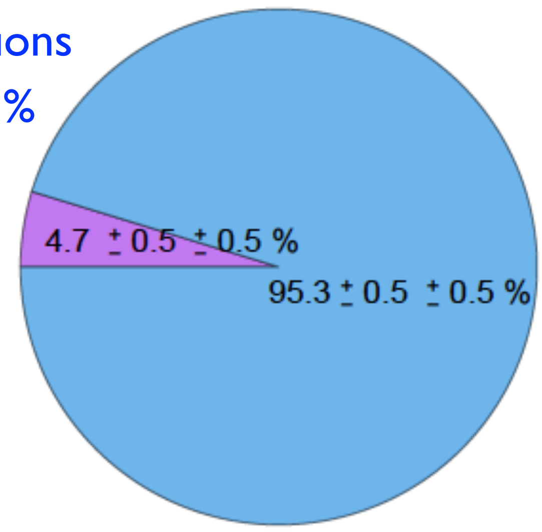


Approximately 5% of the mass in the present universe is made up of ordinary matter, i.e. atoms and molecules. The overwhelming fraction (>99.9%) of that mass is due to protons and neutrons in the form of nuclei.

But where do nucleons derive their mass from?

Mass contribution from gluons (direct and indirect) = 95.3%

Explicit contribution from u/d quark masses = 4.7%



The BIG Question: How do gluons, which are themselves massless, create more than 95% of the mass of nucleons and, thus of ordinary matter?

The Question of Mass

- Classical physics:
  - "Mass" = Energy/c^2 of a body when viewed at rest
  - The mass M of a body is a fixed number
- Quantum physics:
  - "Mass" = Energy/c^2 of a particle when viewed at rest
  - The mass of a particle depends on the resolution Δx at which it is measured: $M = M(Q)$.
  - $Q = \hbar/\Delta x$ is the momentum scale associated with Δx.
  - Whether the M increases or decreases with momentum scale Q depends on whether quantum fluctuations add or subtract from the particle's mass.
    - QED (electron): $M(Q)$ *increases* with growing Q.
    - QCD (quarks): $M(Q)$ *decreases* with growing Q.

Quark masses

For quarks (more generally for spin-1/2 particles) mass plays a dual role. It describes the energy for the particle at rest, but it also breaks a special symmetry called "*chiral symmetry*". In the absence of mass, left-handed (left spinning) and right-handed (right spinning) quarks behave like separate species of particles; mass mixes these two types of quarks. Expressed in the QCD Lagrangian as:

$$\mathcal{L}_q = i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R + m\left(\bar{q}_L q_R + \bar{q}_R q_L\right)$$

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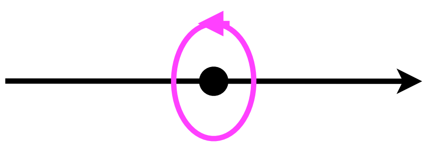
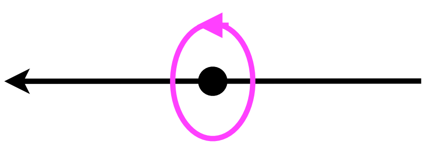
Intuitive physical picture: When quarks have mass, you always can out-run a moving quark, and thus change the orientation of its spin with respect to its direction of motion. This implies that ***chirality cannot be conserved when quarks have mass***.



observer at rest



fast moving observer

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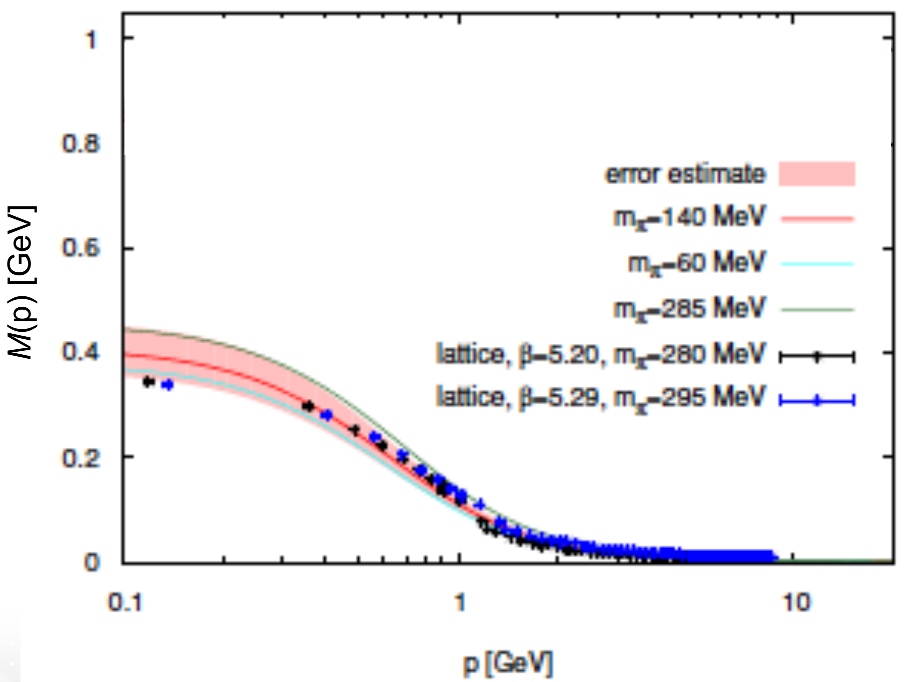
observer at rest *fast moving observer*

In the presence of a surrounding medium that breaks the Lorentz invariance of the vacuum, e.g. a thermal quark-gluon plasma, quarks can have mass without chiral symmetry breaking

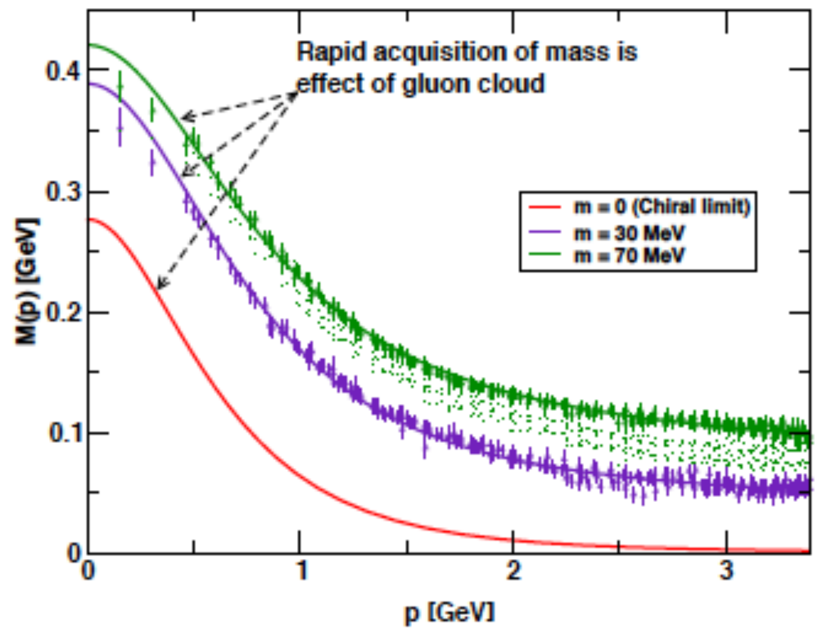
Dynamical quark mass *M*(*p*)

Lattice QCD and functional renormalization group or Schwinger-Dyson equation calculations confirm χSB: $M(p=0) \approx 400$ MeV.

Cyrol, Mitter, Pawlowski & Strodthoff, arXiv:1706.06326

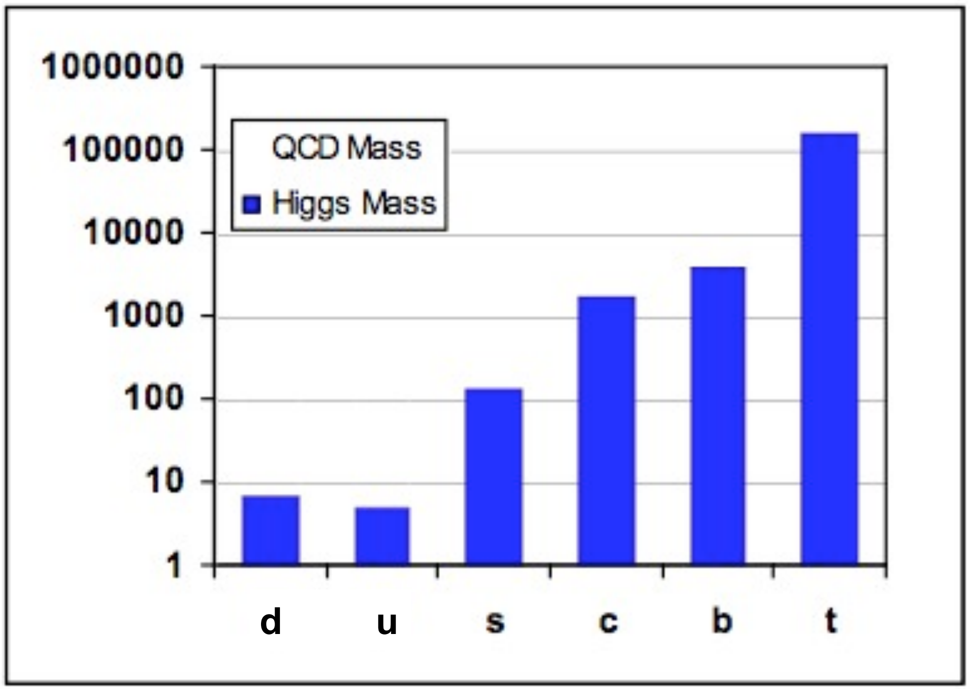


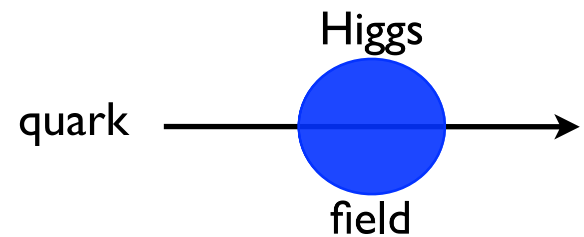
Chang, Roberts & Wilson, PoS QCD-TNT-II2011 (2011) 039



Quark masses

For quarks more than one interaction contributes: Higgs field and QCD (and QED!).





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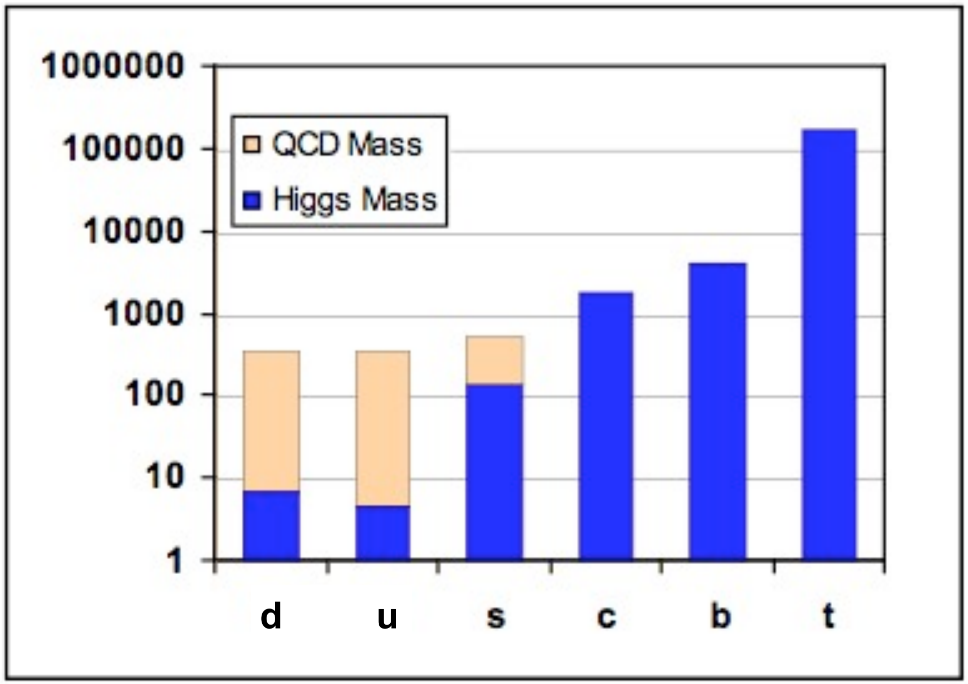

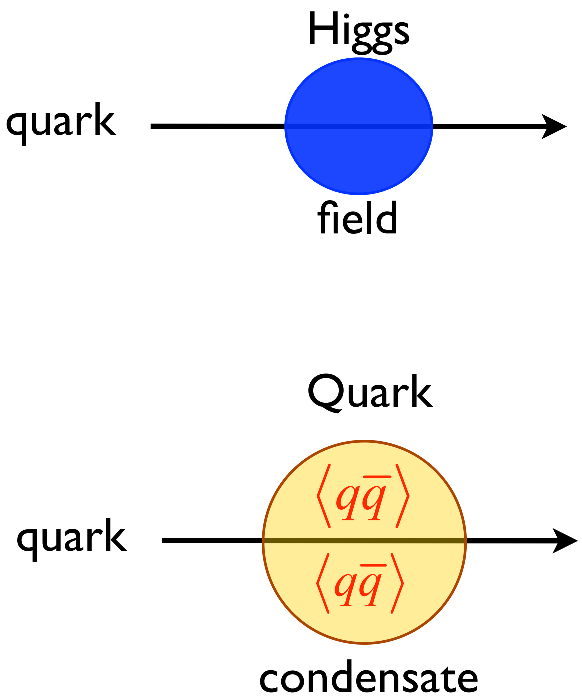

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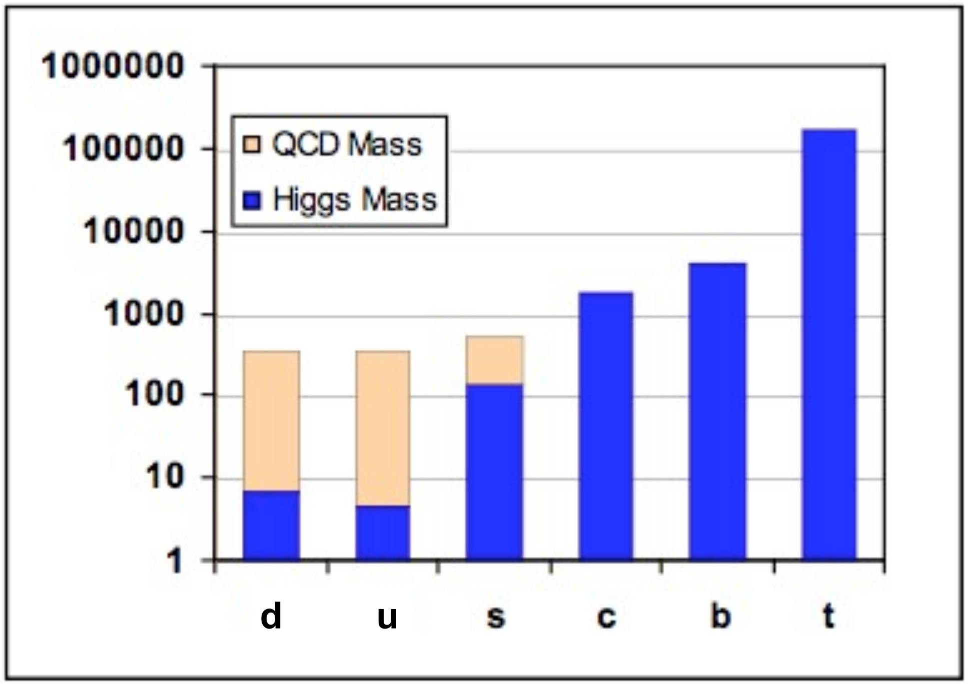
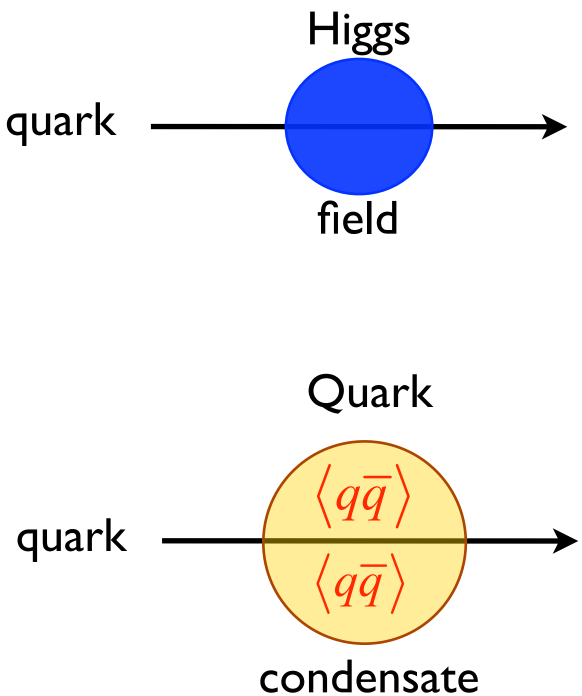
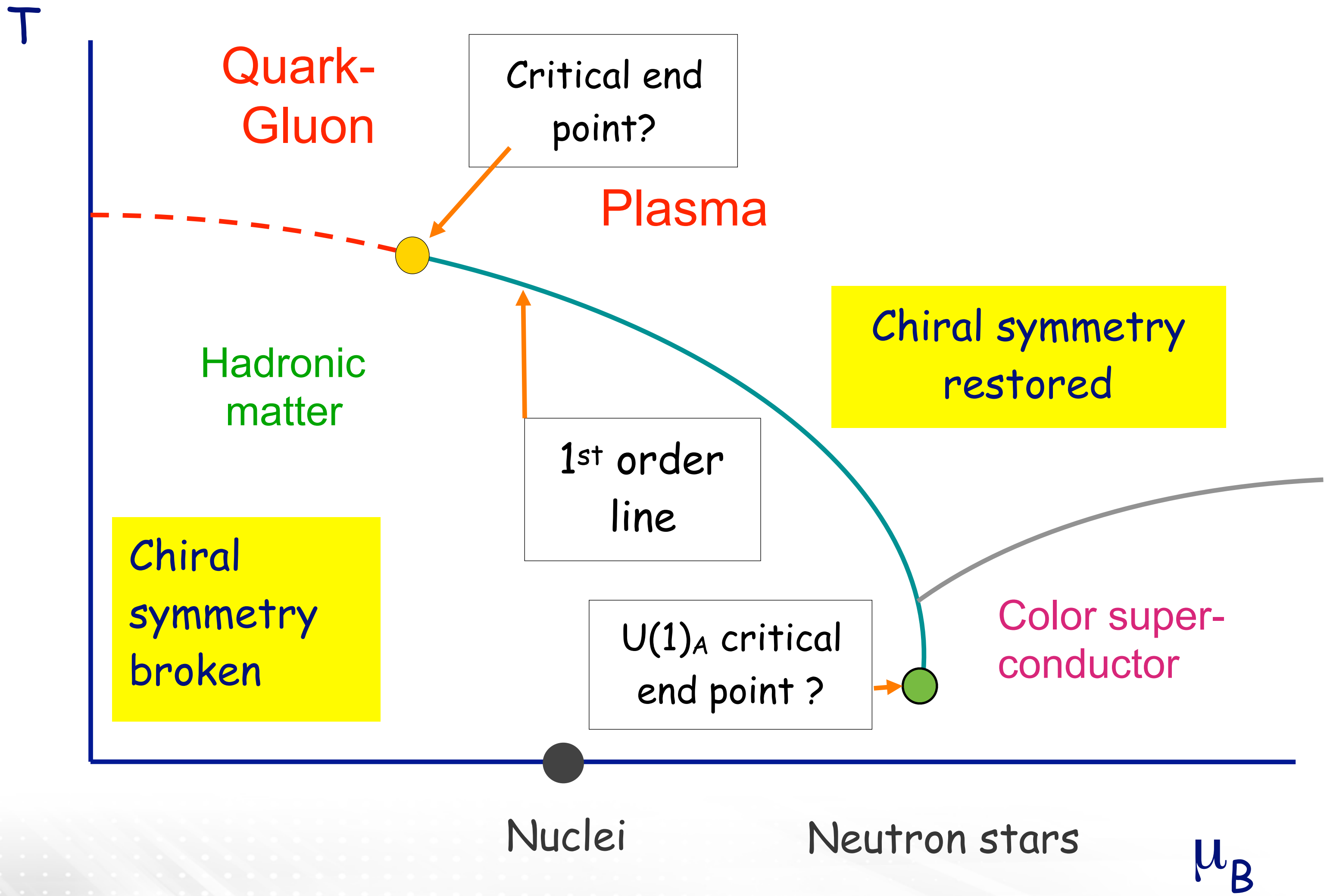


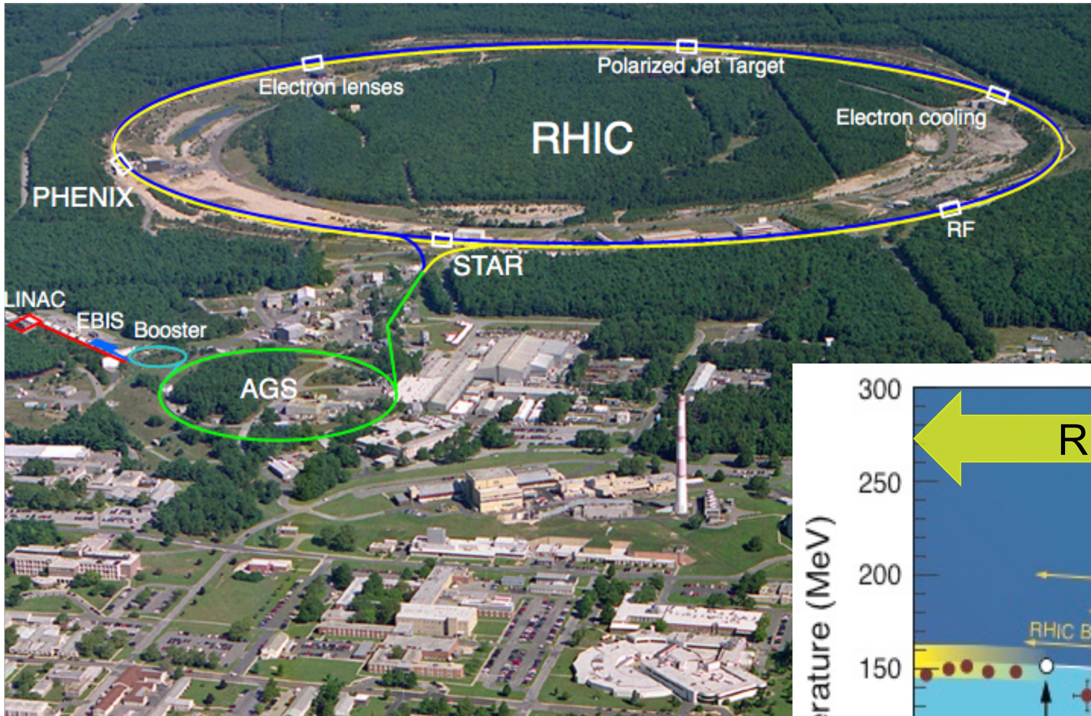


The strange quark is special:
Its Higgs mass is comparable to its QCD mass

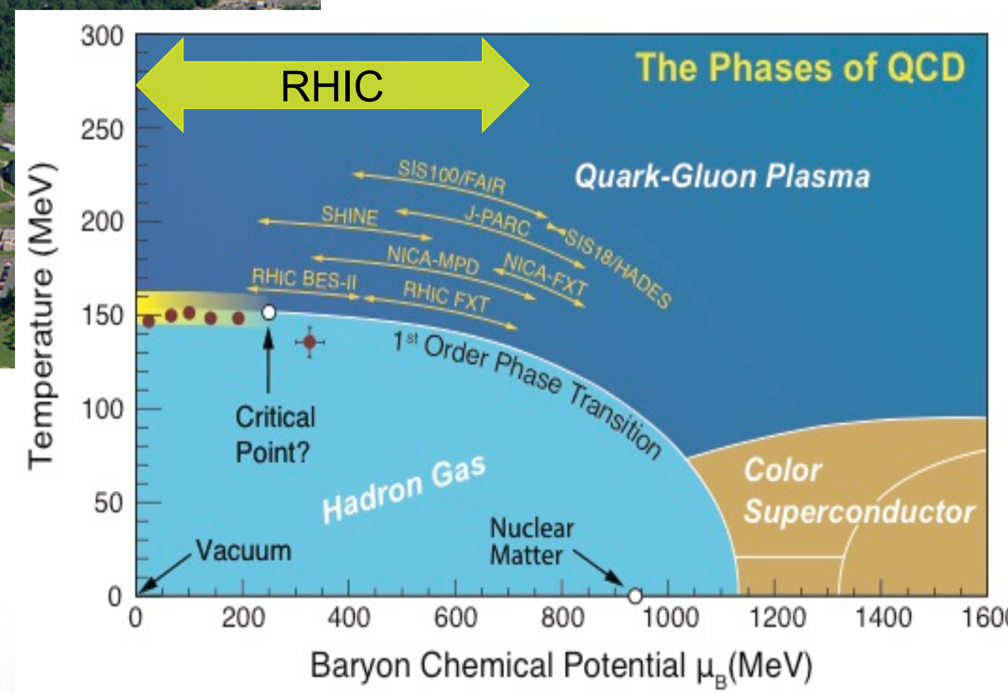
QCD phase diagram



Relativistic Heavy Ion Collider (RHIC)



Aerial view of RHIC at Brookhaven National Laboratory



RHIC is the world's most versatile facility for the exploration of the phases of QCD matter from high temperature to high baryon density.

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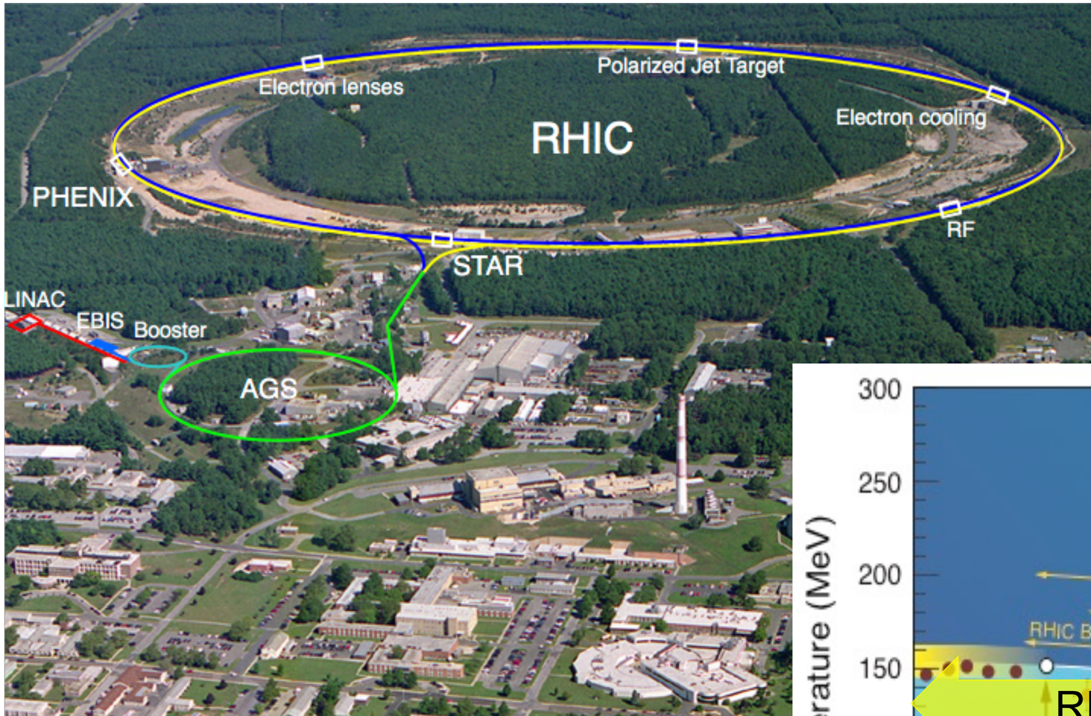

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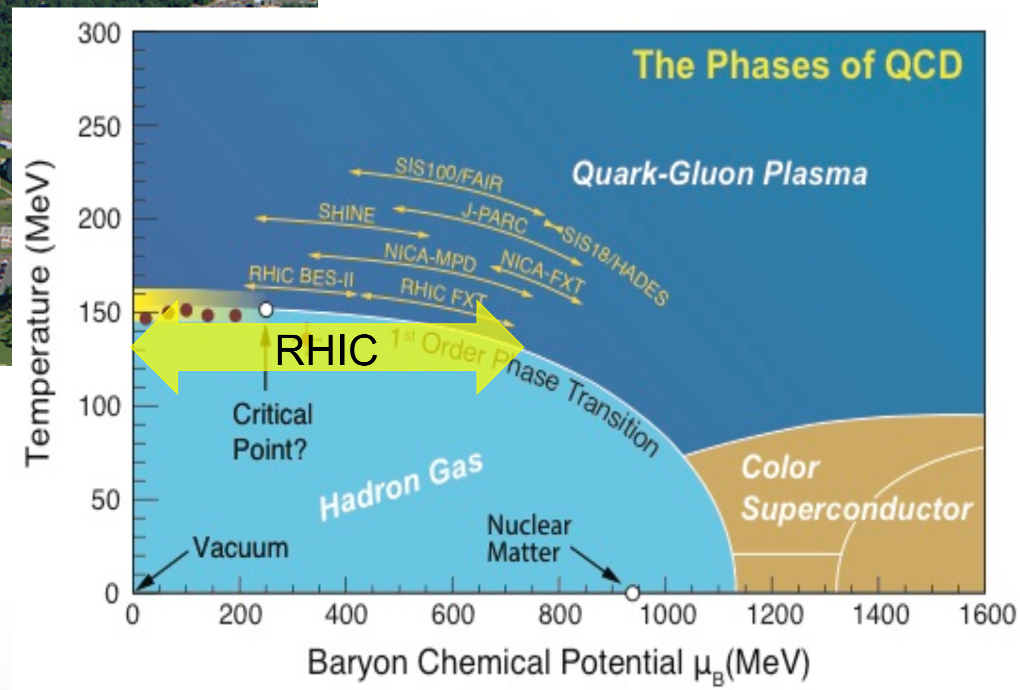

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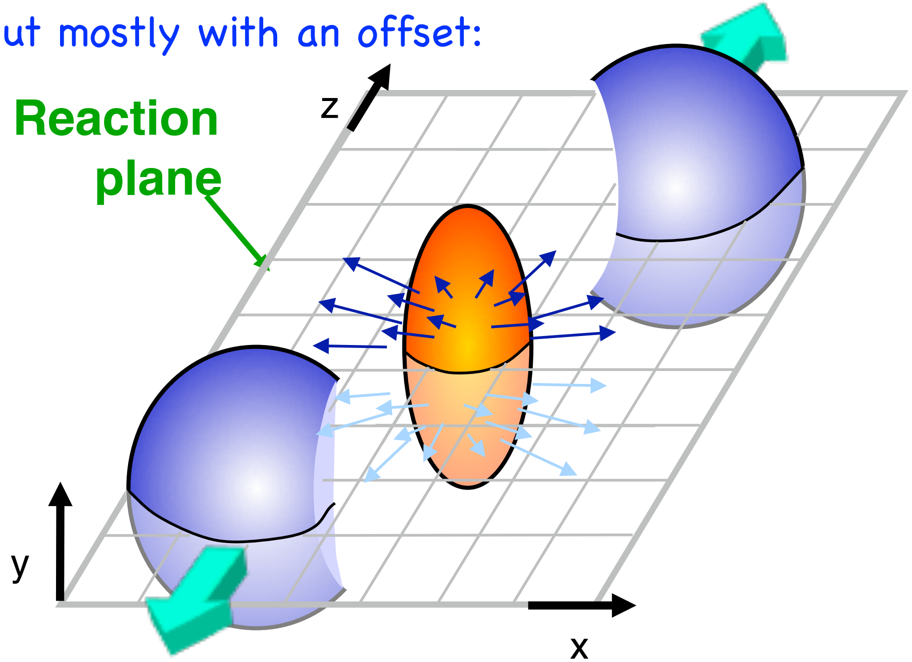
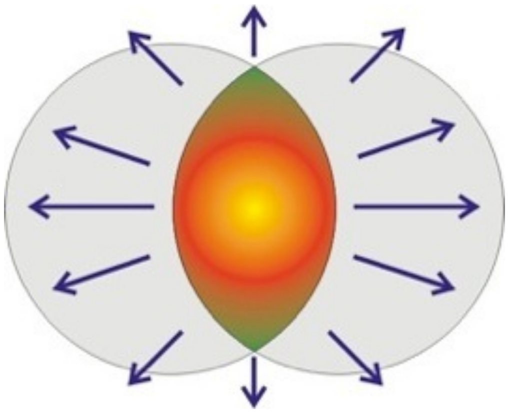
Quark-Gluon Plasma:
A near-perfect fluid

Elliptic flow

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





only matter in the overlap area gets compressed and heated

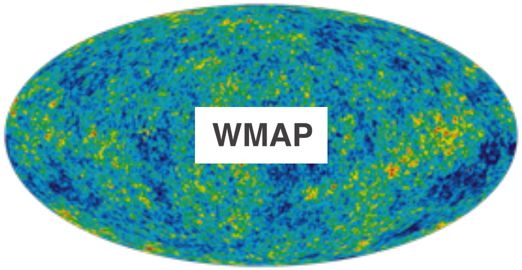
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n v_n(p_T, \eta) \cos n\left(\phi - \psi_n(p_T, \eta)\right) \right)$$

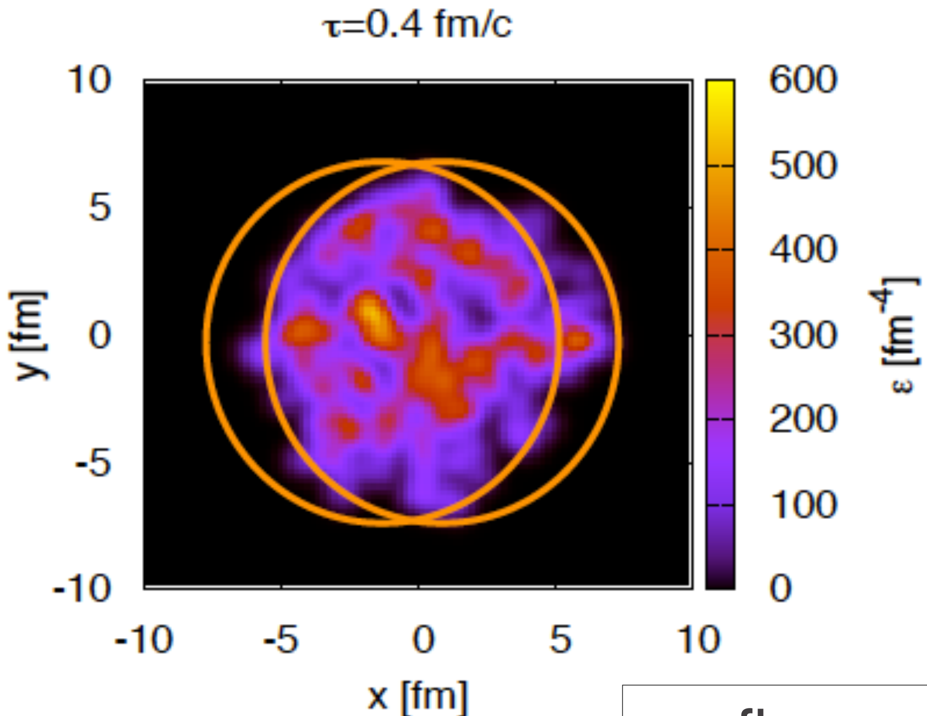
anisotropic flow coefficients

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



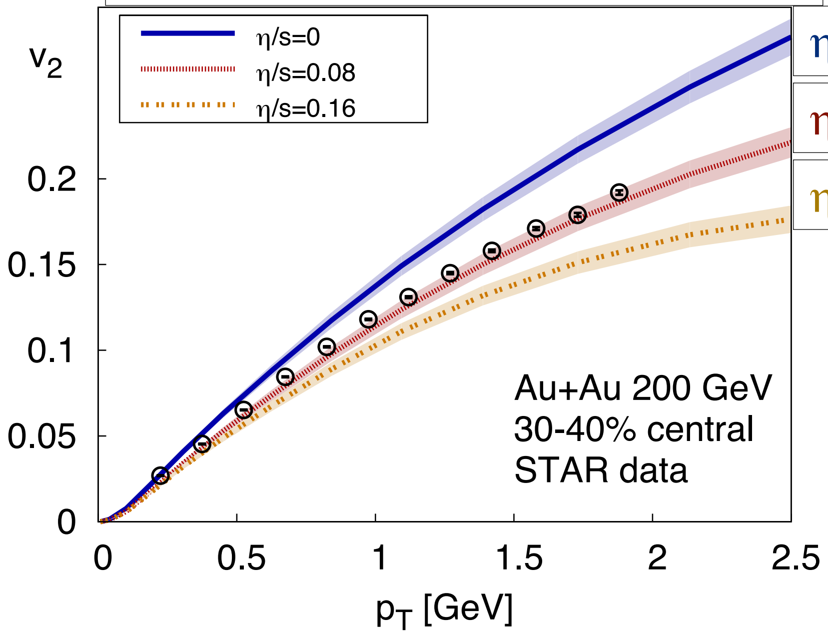


Idea: Energy density fluctuations in transverse plane from initial state quantum fluctuations. These thermalize to different temperatures locally and then propagate hydrodynamically to generate angular flow velocity fluctuations in the final state.

⇒ flows v_1, v_2, v_3, v_4,...

Elliptic flow "measures" η_{QGP}

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



$\eta/s = 0$

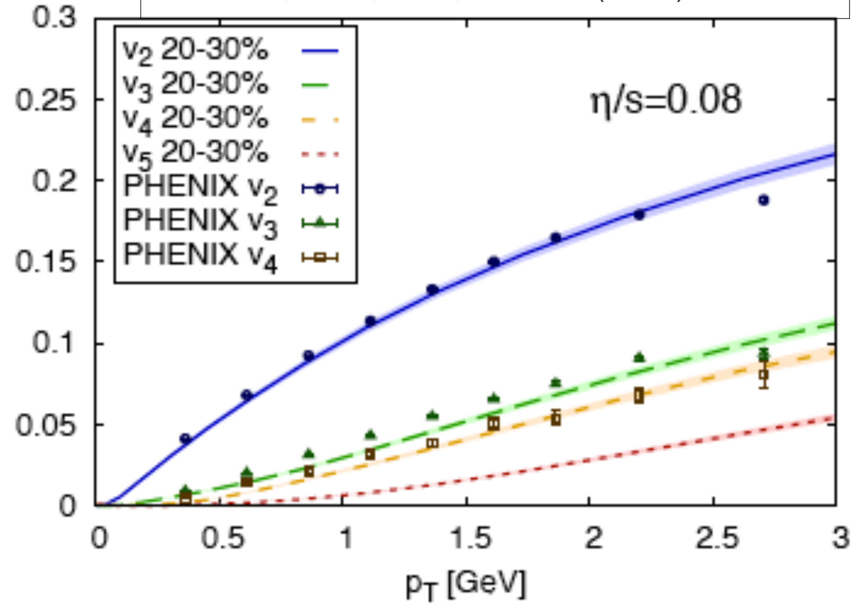
$\eta/s = 1/4\pi$

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

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

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

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



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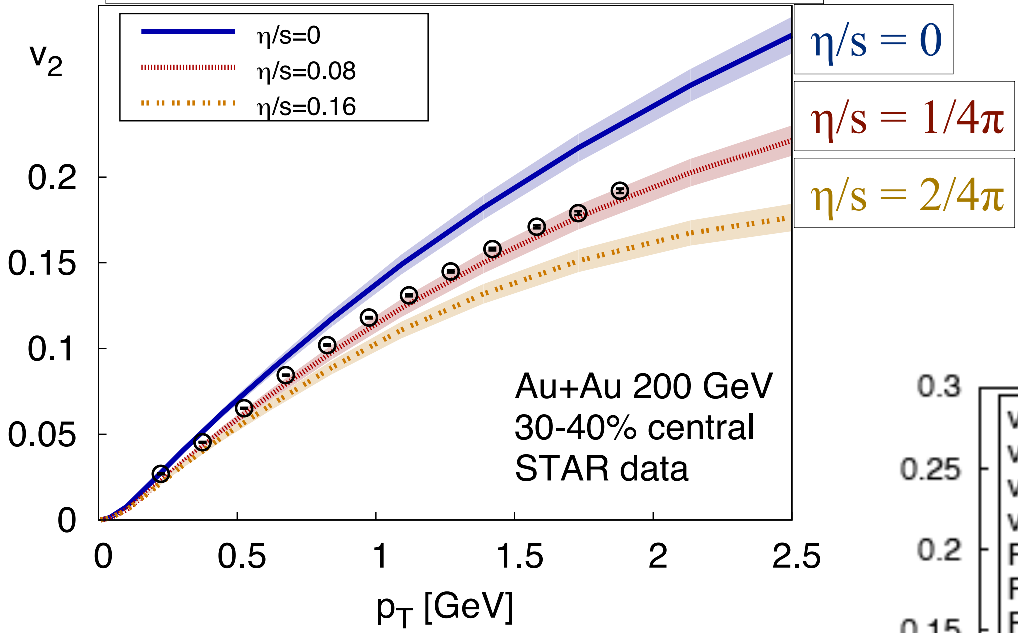

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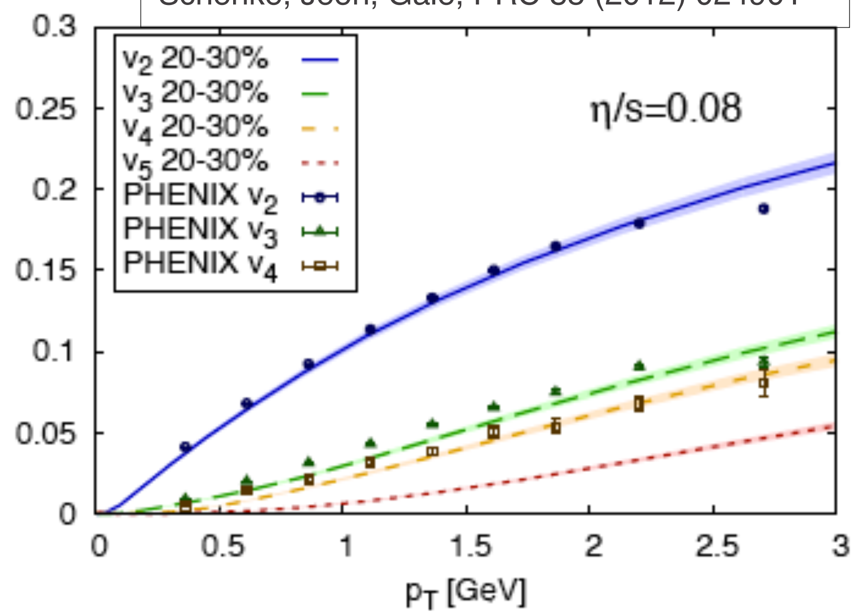
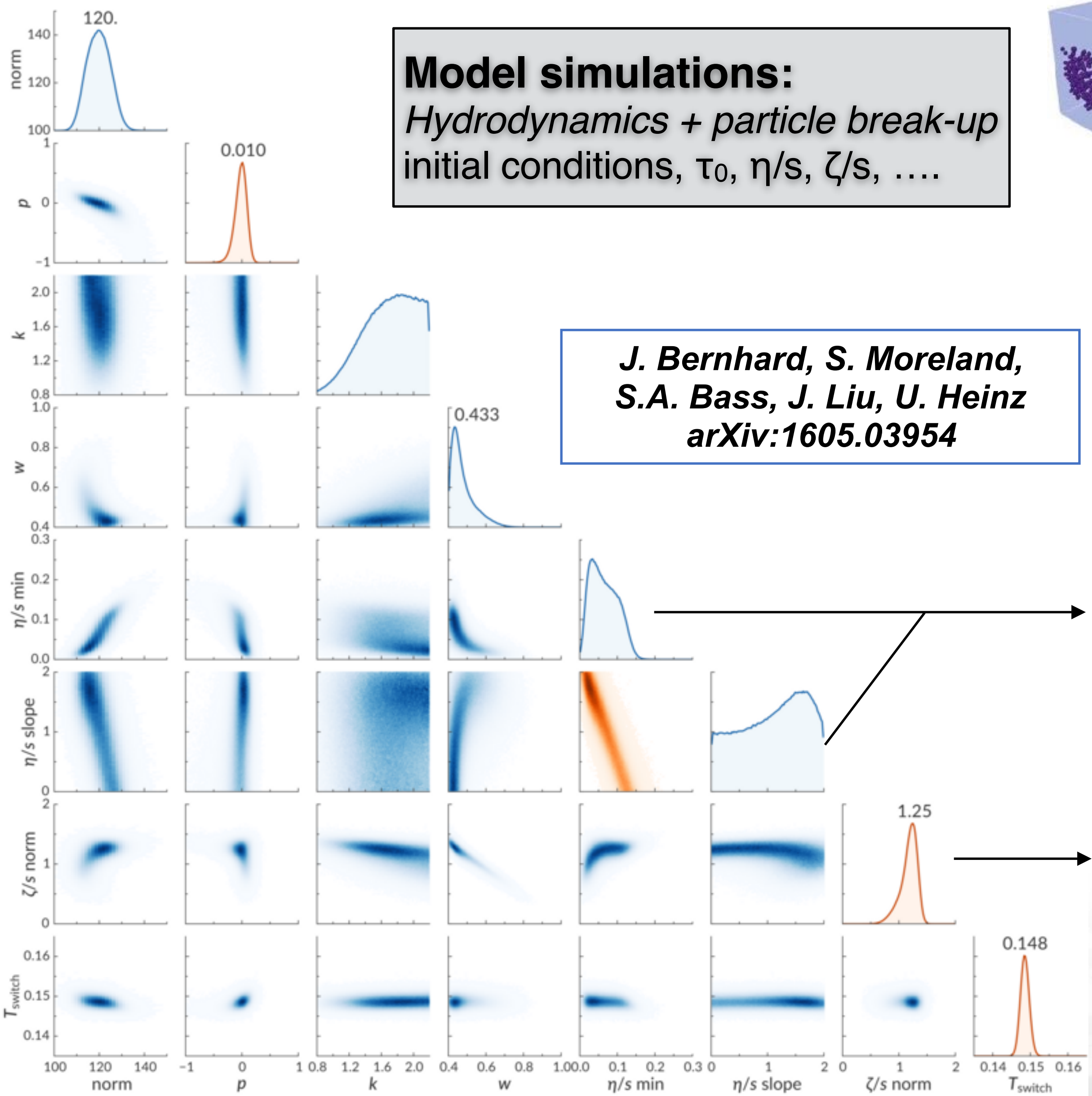
The "Perfect" Liquid

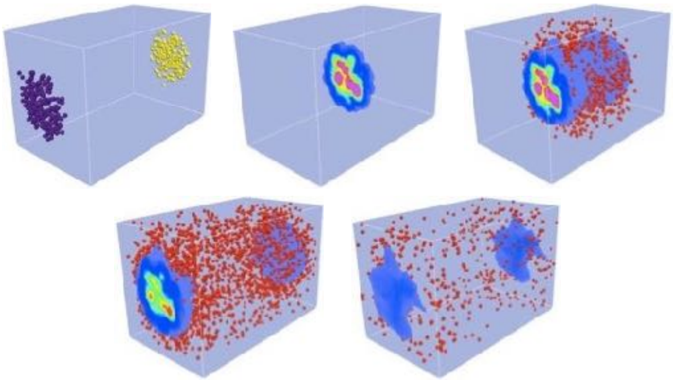
Schenke, Jeon, Gale, PRC 85 (2012) 024901



Bayesian multi-parameter analysis

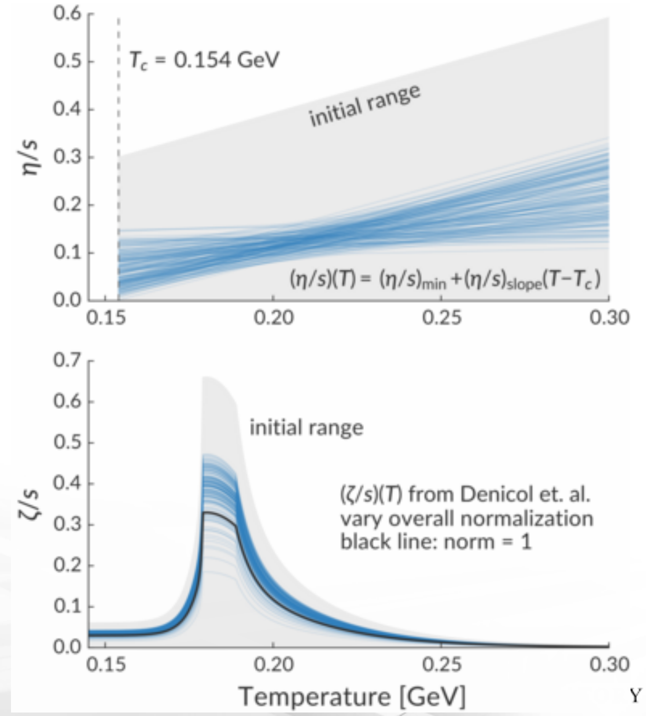


Model simulations:
Hydrodynamics + particle break-up
initial conditions, τ_0, η/s, ζ/s, ….



J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz arXiv:1605.03954

Temperature-dependent viscosities: Posterior distributions



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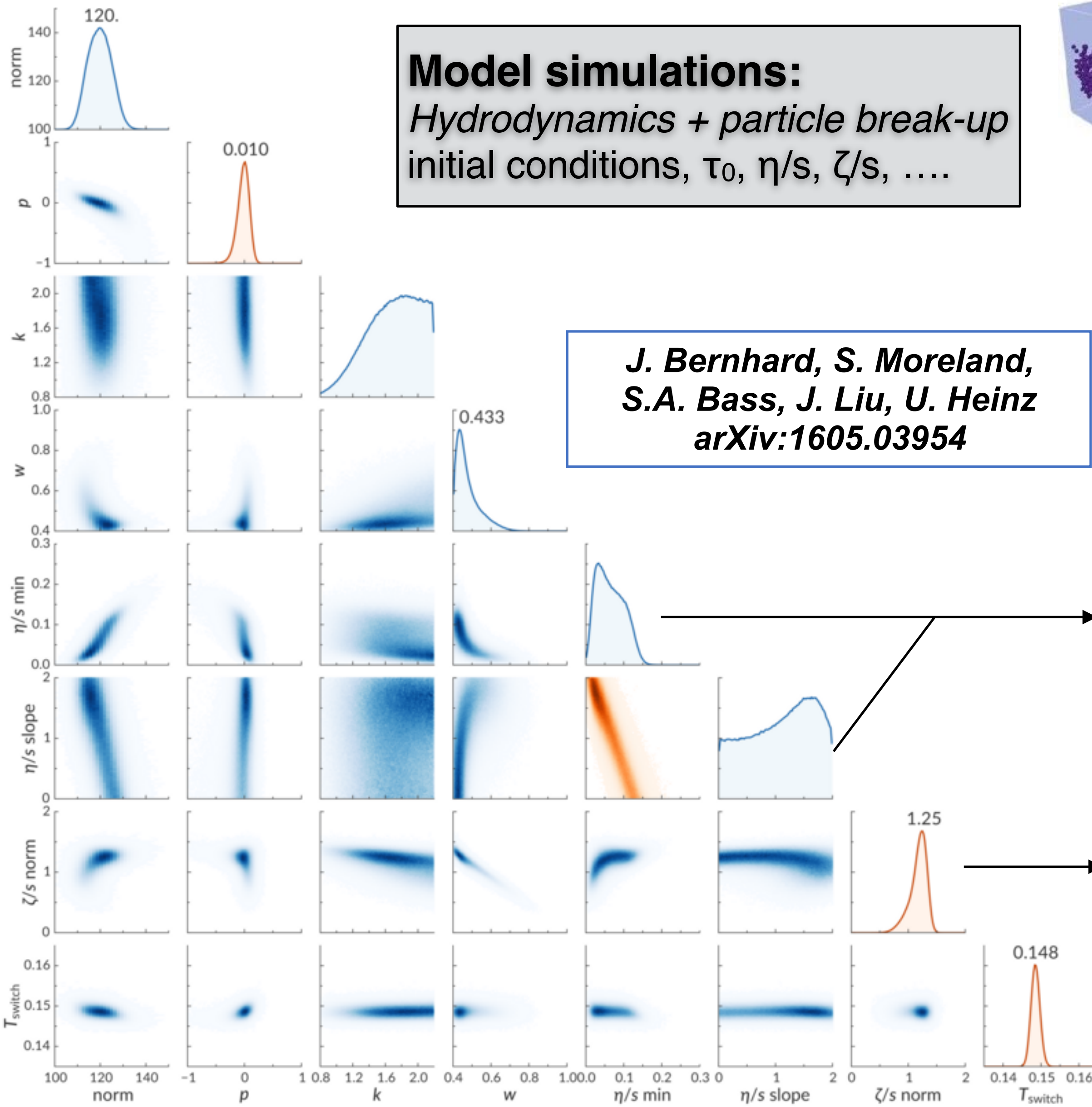

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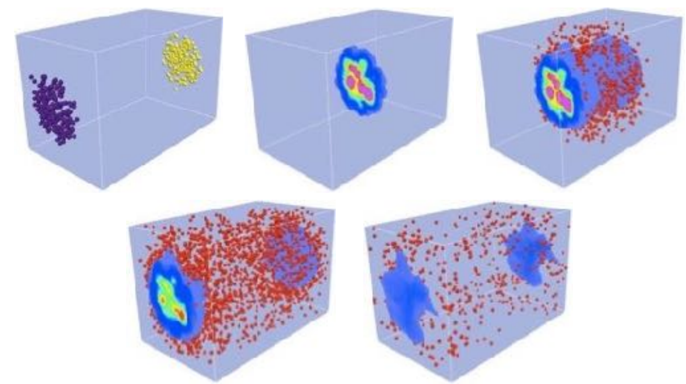

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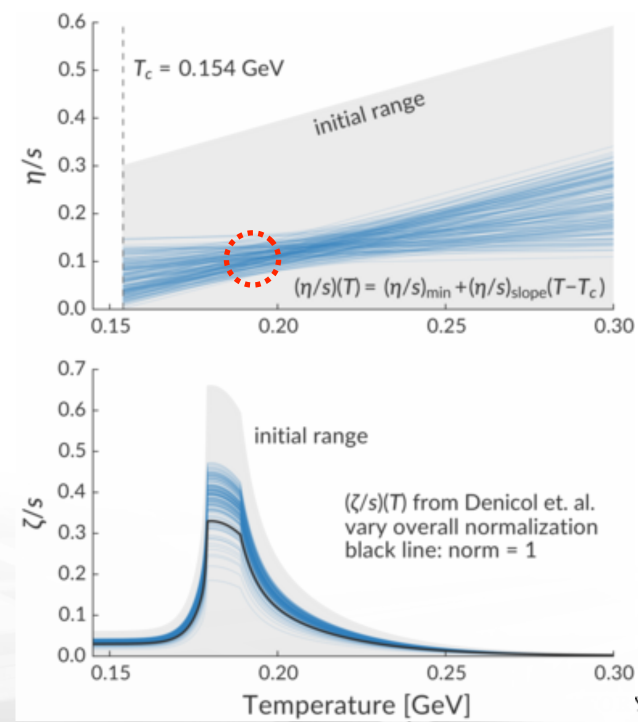
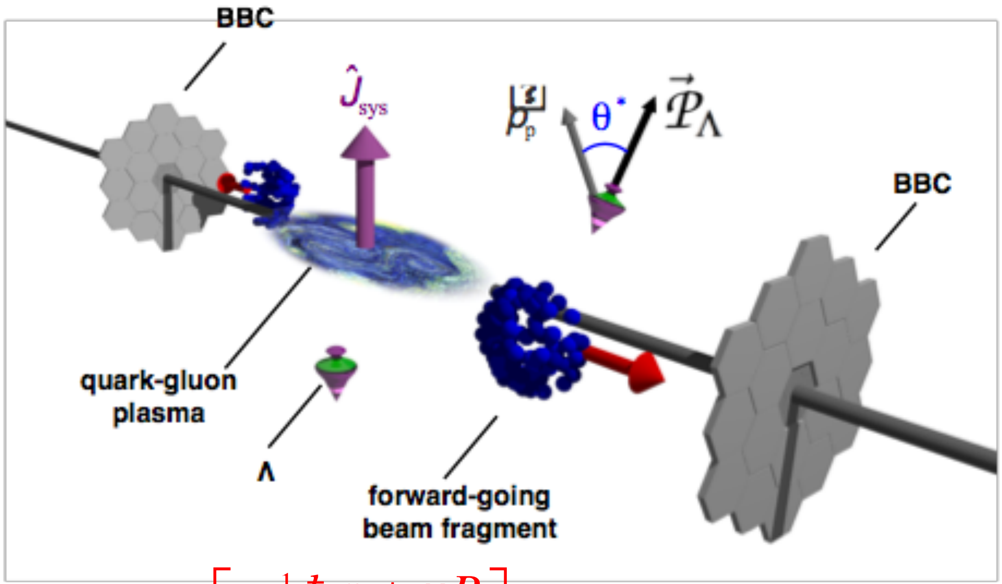
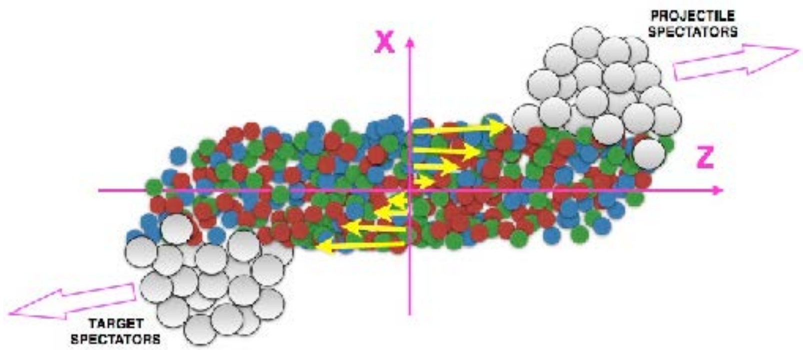


Most vortical fluid

QGP: The most vortical fluid

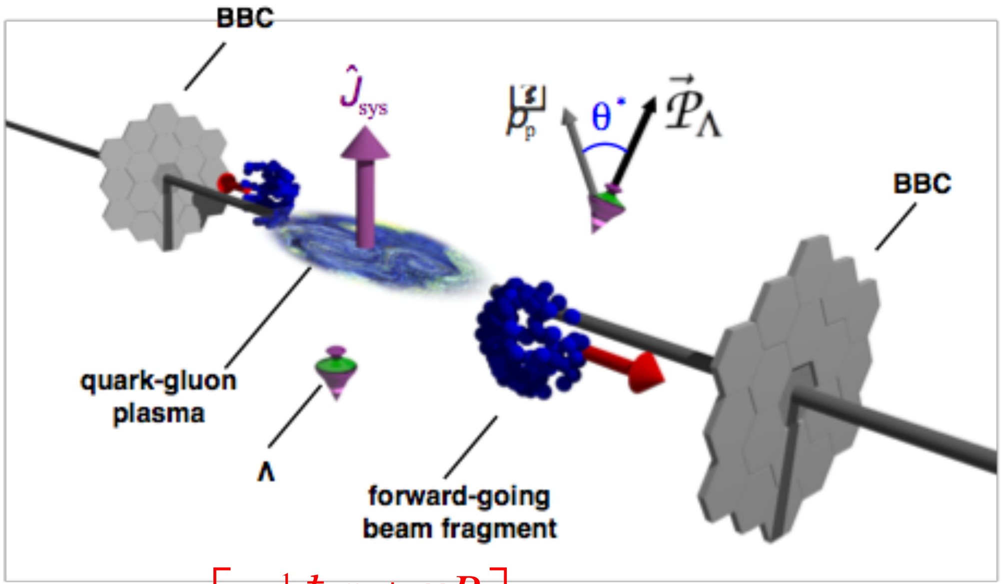


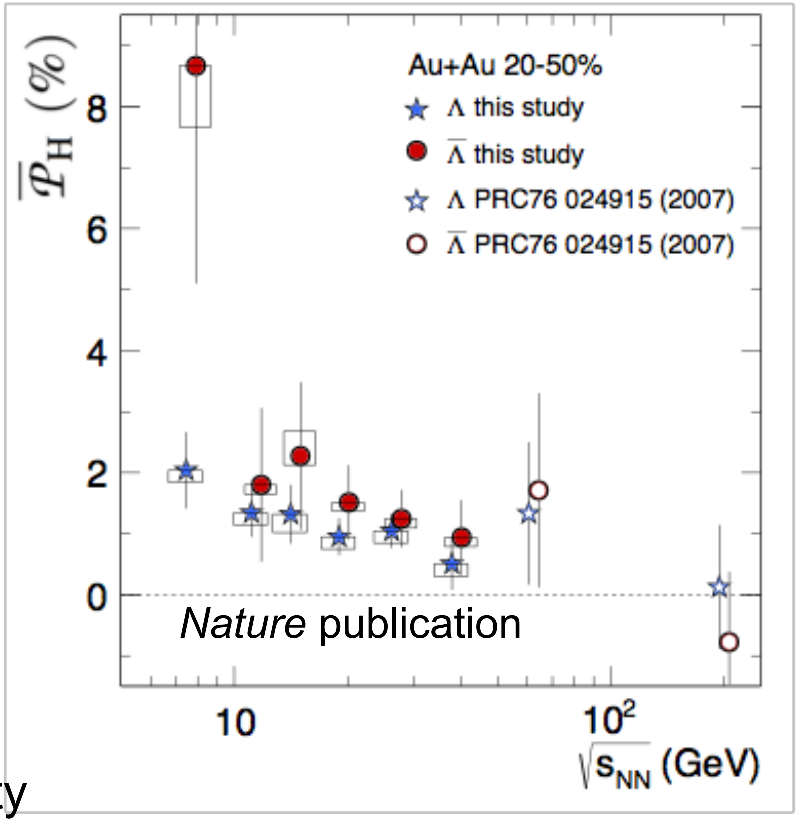


Global angular momentum generates QGP vorticity

$$P_{\pm} \sim \exp\left[\pm \frac{\frac{1}{2}\hbar\omega + \mu B}{T} \right] \qquad \left(\mu_\Lambda = -\mu_{\bar{\Lambda}}\right)$$

QGP: The most vortical fluid





$$P_\pm \sim \exp\left[\pm \frac{\frac{1}{2}\hbar\omega + \mu B}{T}\right] \qquad (\mu_\Lambda = -\mu_{\bar{\Lambda}})$$

Global Lambda Polarization is signal of vorticity

- Strongest signal at Beam Energy Scan (BES-II) energies

Signal is consistent with vorticity ω = (9 ± 1) x $10^{21}s^{-1}$, greater than previously observed in any system, including nuclei in high-spin states

Holds potential for measurement of late time magnetic field in BES-II

The Vorticity Puzzle

- The vorticity of an ideal fluid is conserved.
- A fluid with minimal shear viscosity, such as the QGP, can preserve its vorticity for a long time.
- But it is difficult to create vorticity in a fluid with minimal shear viscosity.

Thus it is easy to understand why the QGP maintains record vortical motion until its break-up into hadrons; but how does it acquire it vorticity.

Conclusion: The QGP must be “born” with the vorticity imprinted in its flow. How this happens is still not understood.

We have taken more data at the optimal energy in the 2018 RHIC run.

Quark-Gluon Plasma: Microscopic properties

QGP: Microscopic Properties

- Theory predicts the QGP to be a “perfect” fluid composed of unconfined gluons and quarks without chiral symmetry violating mass
- The near-perfect fluidity of the QGP has been experimentally confirmed by quantitative model-data comparison: $\eta/s < 0.2$
- How can the other properties be verified experimentally:
  - Quark deconfinement ?
  - Chiral symmetry restoration ($M_q = M_{Higgs}$) ?
- What are the limits (phase boundary) of ordinary nuclear matter, i.e. matter composed of baryons and mesons ?
- Can the existence of a critical point in the QCD phase diagram be confirmed experimentally?

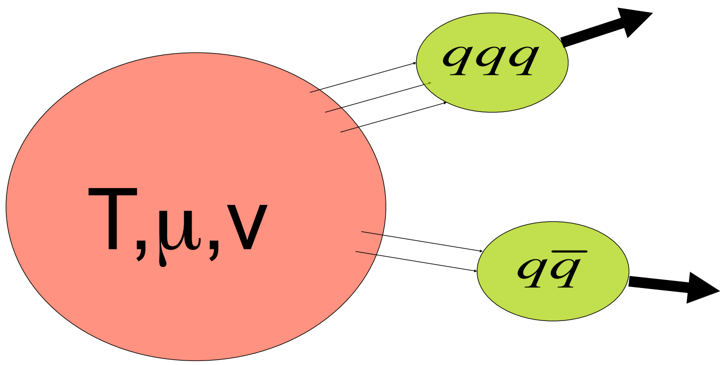
- *Existing evidence and plans for future tests at RHIC*

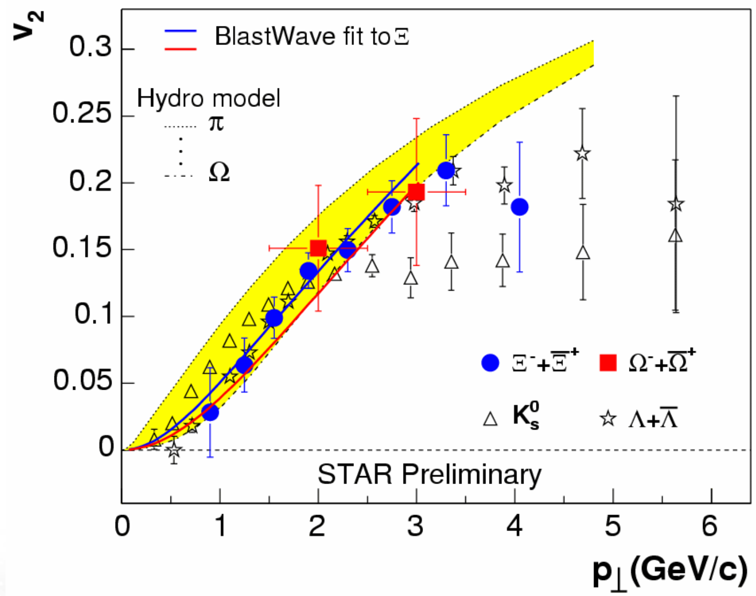
Are quarks deconfined in the QGP?

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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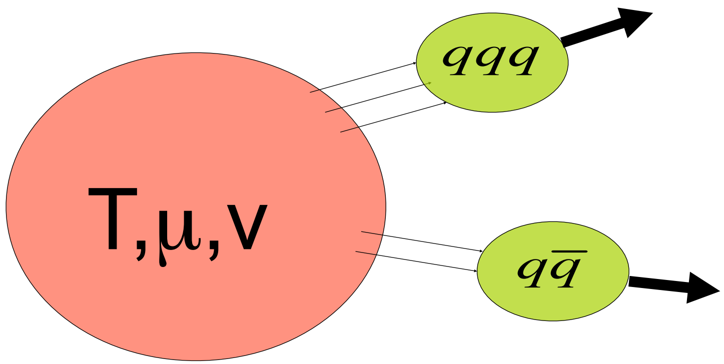
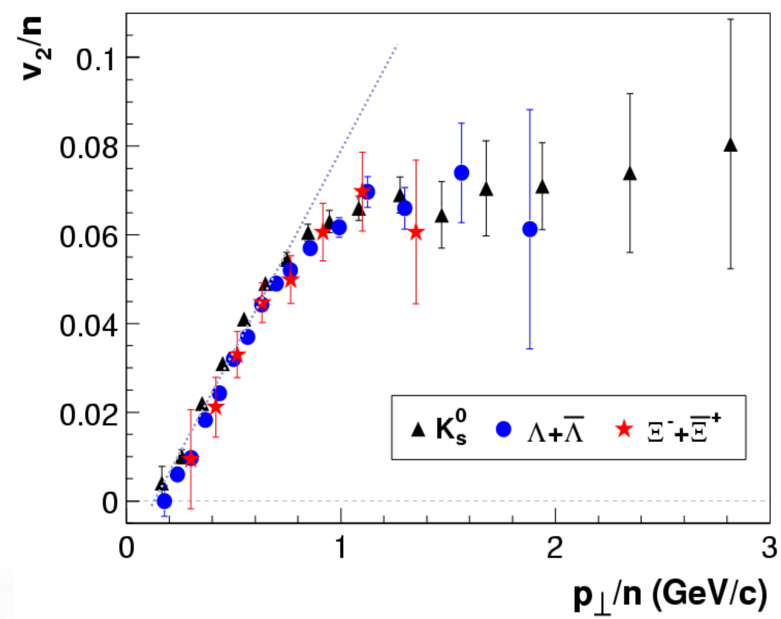
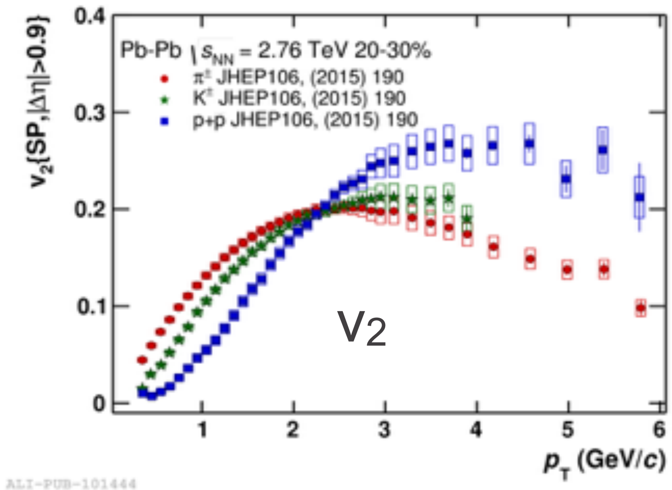
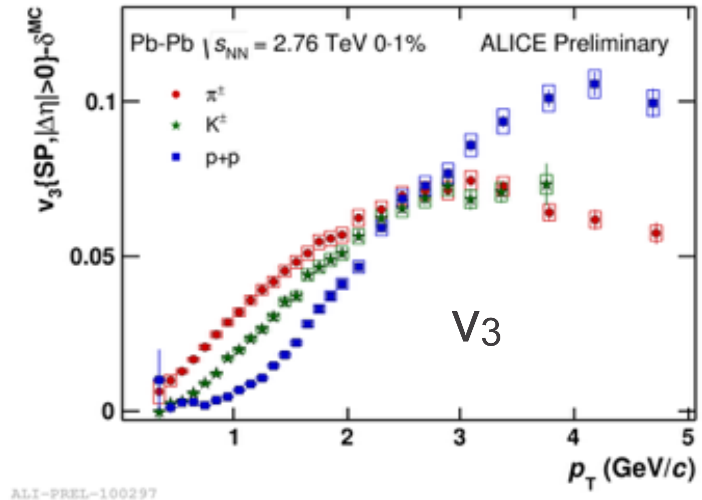




Emitting medium is composed of unconfined, flowing quarks.

N_Q scaling at LHC





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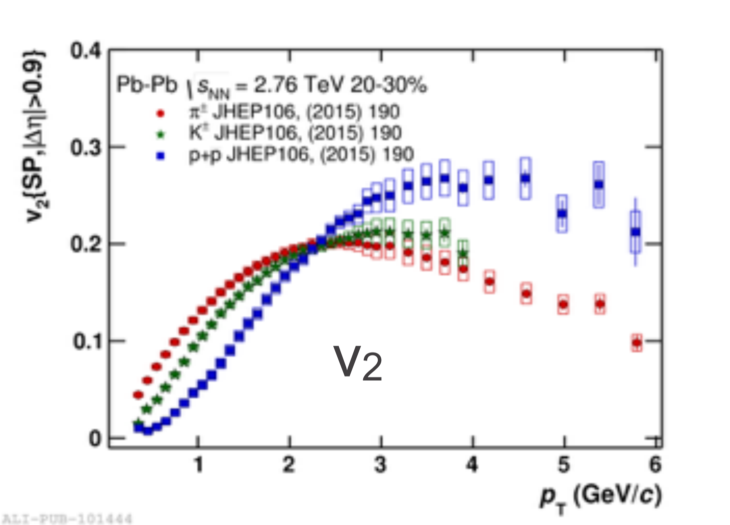

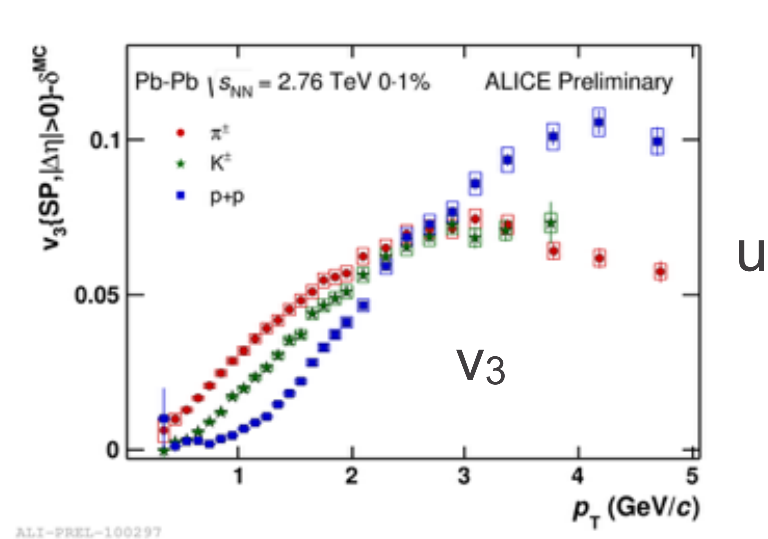

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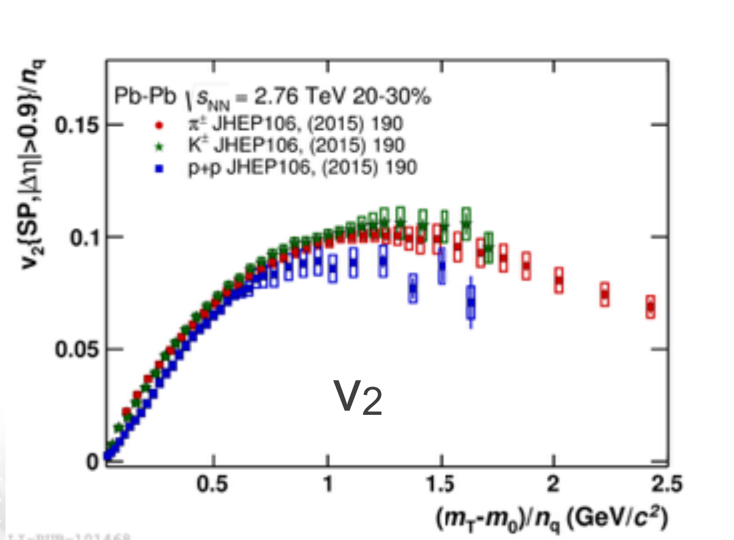

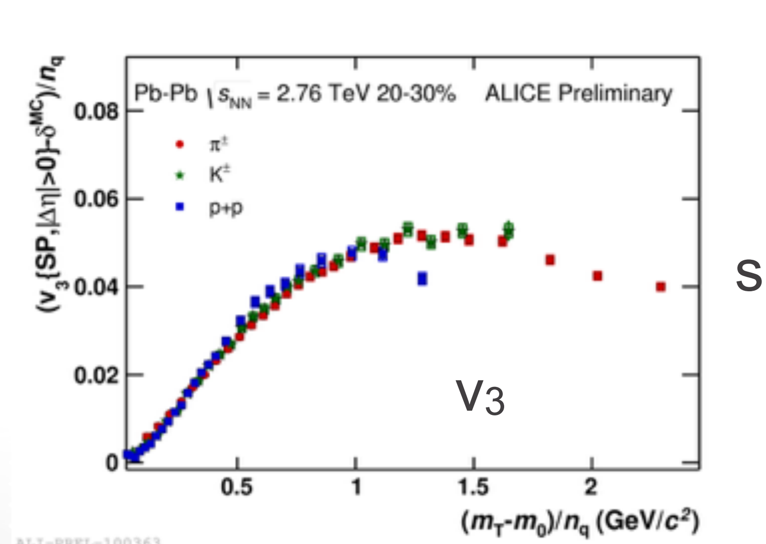

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Is chiral symmetry really restored in the QGP?

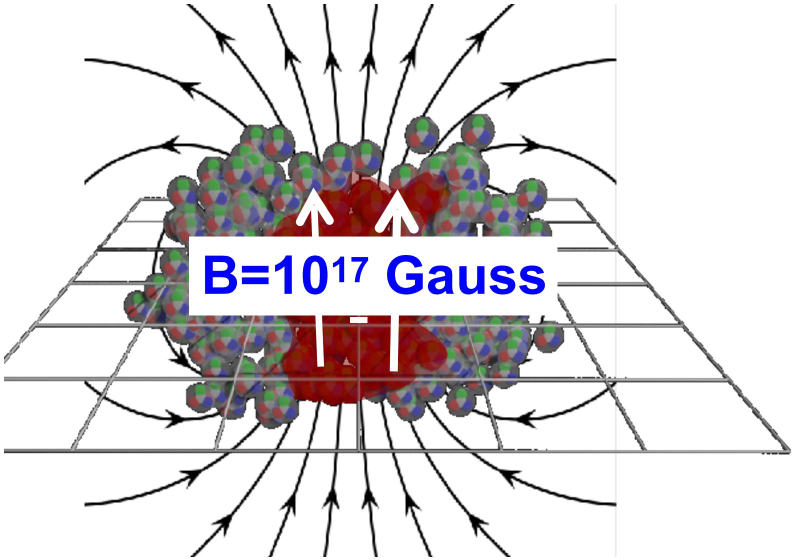
Chiral Symmetry & QCD Topology

Gauge field topology is a fundamental characteristic of QCD
Observation of topological field fluctuations requires
- (nearly) massless quarks = chiral symmetry
- superstrong magnetic fields

Heavy ion collisions provide both!

The chiral anomaly of QCD couples the gluon field topology to the number of left/right handed quarks and creates **local fluctuations in the number of left- and right-handed quarks**

An excess of right- or left-handed quarks will cause an electric current to flow along the magnetic field: **Chiral Magnetic Effect (CME)**



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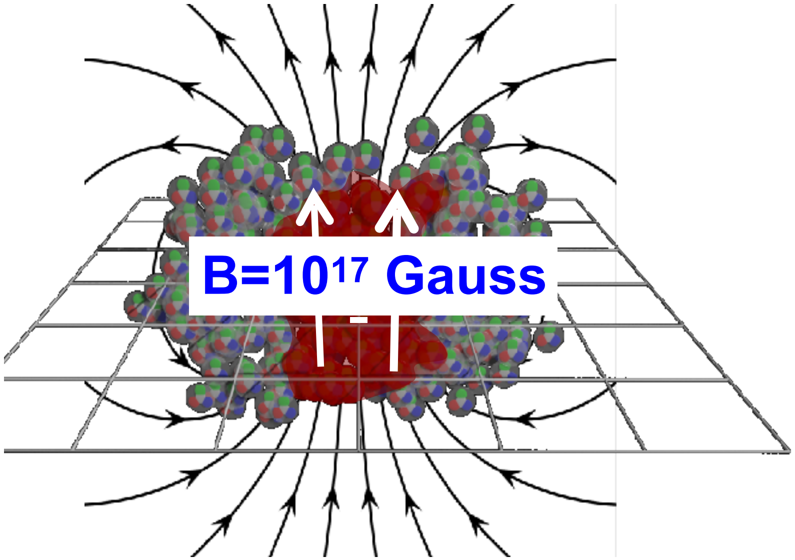
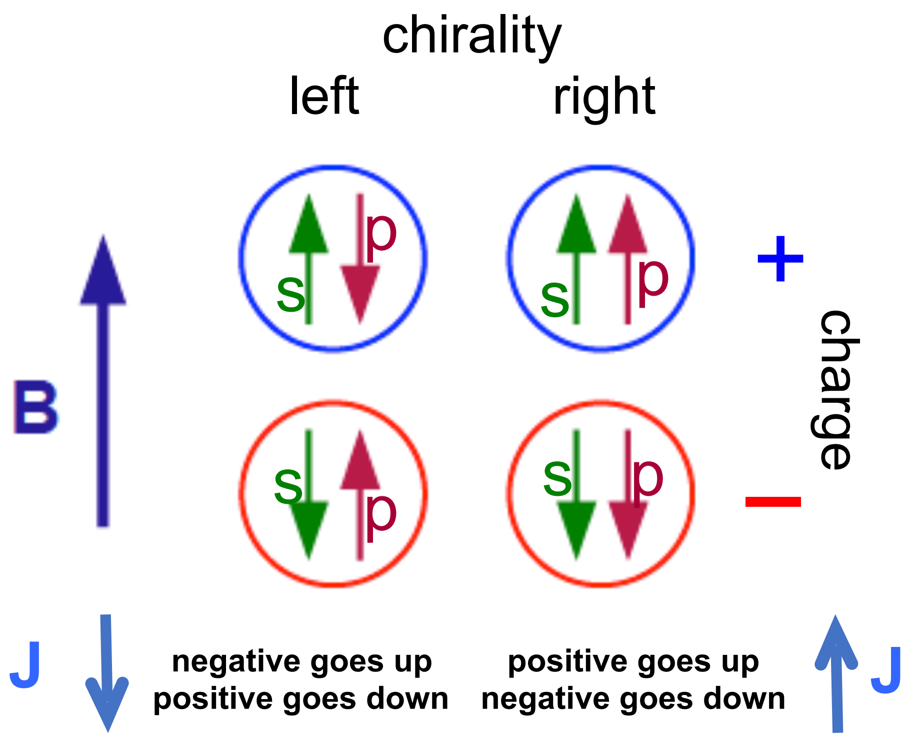


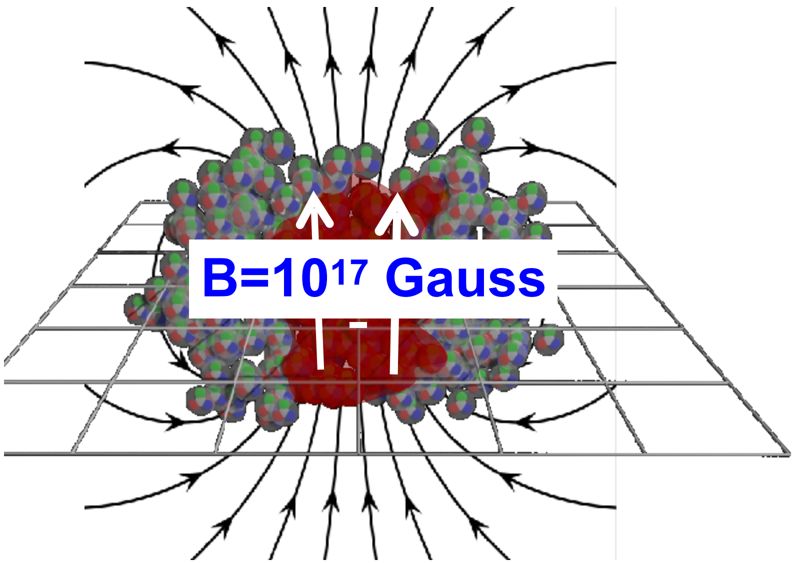
An excess of right- or left-handed quarks will cause an electric current to flow along the magnetic field: **Chiral Magnetic Effect (CME)**

When clearly established experimentally, the CME provides for an unambiguous signal of chiral symmetry restoration.

Chiral Magnetic Effect (CME)

The chiral anomaly of QCD creates local fluctuations in the number of left and right handed quarks





An excess of right- or left-handed quarks will cause an electric current to flow along the magnetic field

Anomalous Hydrodynamics

Erdmenger, Haack, Kaminski & Yarom, JHEP 0901 (2009) 055
Son & Surowka, PRL 103 (2009) 191601

$$\partial_\mu T^{\mu\nu} = eF^{\nu\lambda} j_\lambda, \qquad T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - p\eta^{\mu\nu},$$

$$\partial_\mu j^\mu = 0, \qquad j^\mu = nu^\mu + \kappa_B B^\mu,$$

$$\partial_\mu j_5^\mu = -CE_\mu B^\mu, \qquad j_5^\mu = n_5 u^\mu + \xi_B B^\mu,$$

Axial current j_5 has only fluctuating contributions - randomly distributed initially

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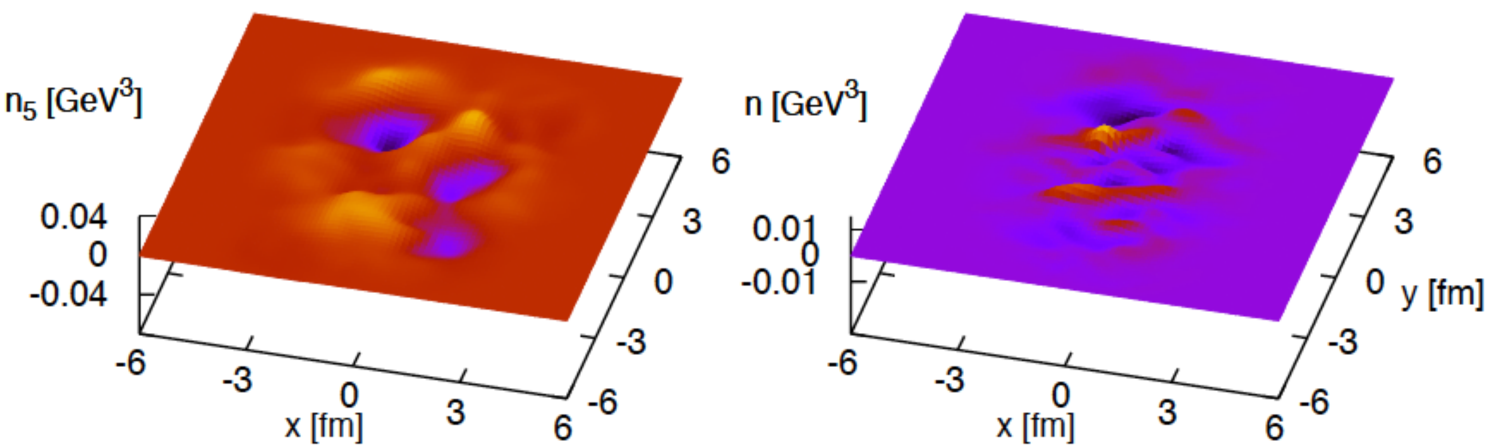
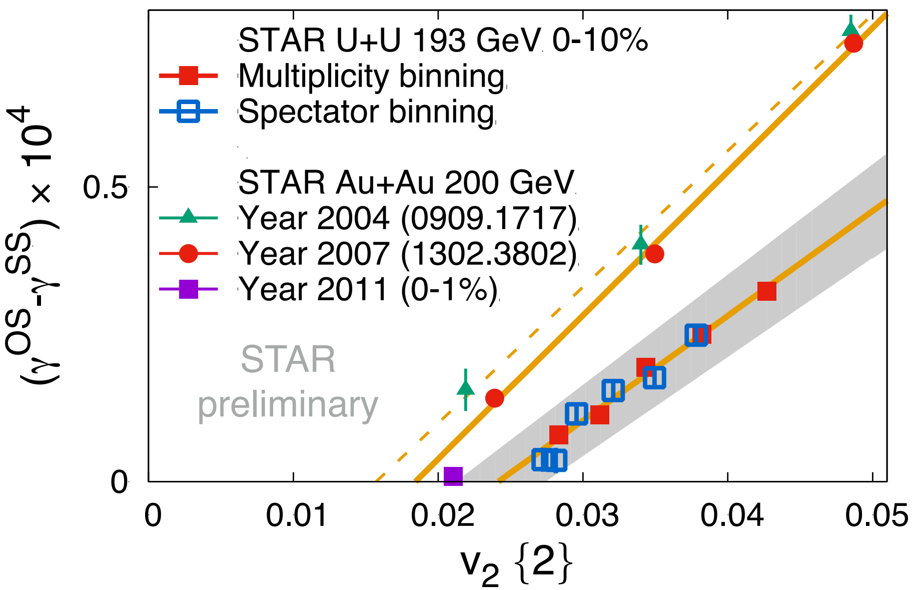


Hirono, Hirano & Kharzeev, arXiv:1412.0311

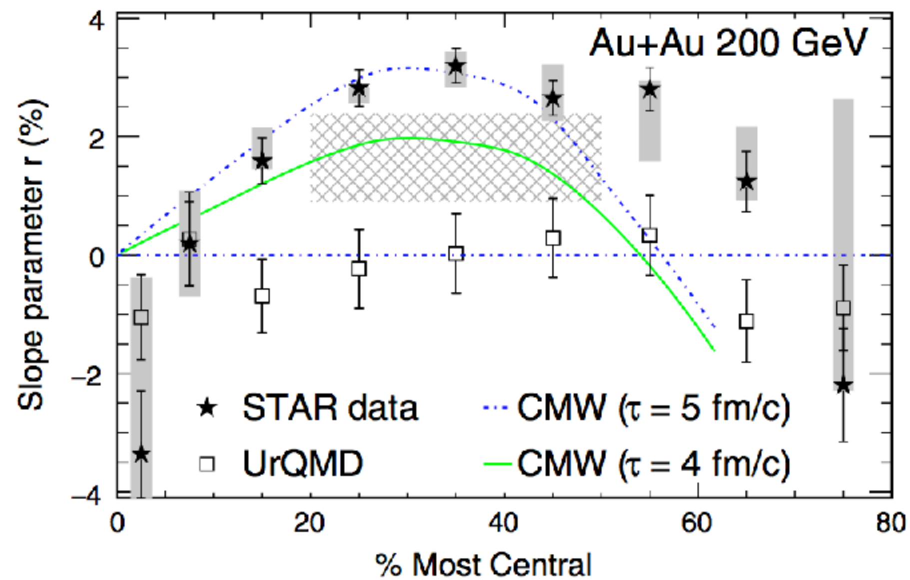
Phenomenology

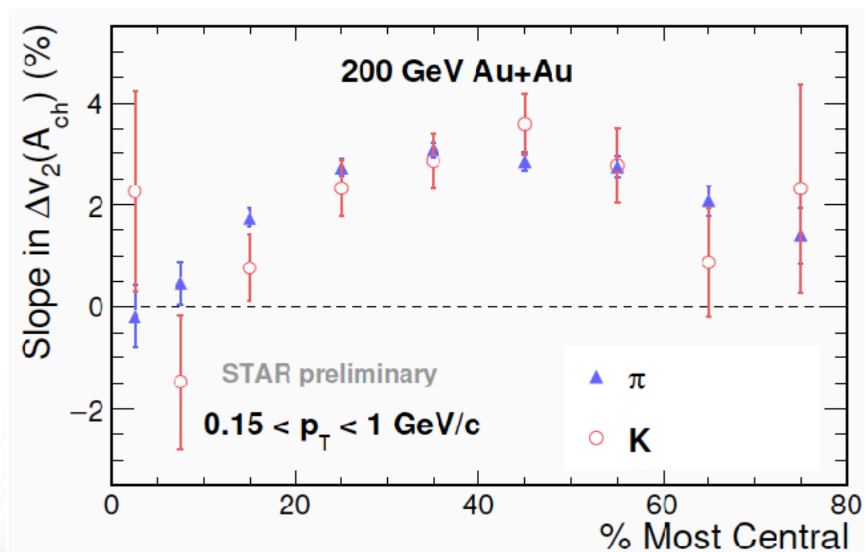
"Chiral Magnetic Wave"?

U+U and Au+Au central data:
Intercept at non-zero v_2



Measured kaon slope is positive; was predicted to be negative in one background model without CMW





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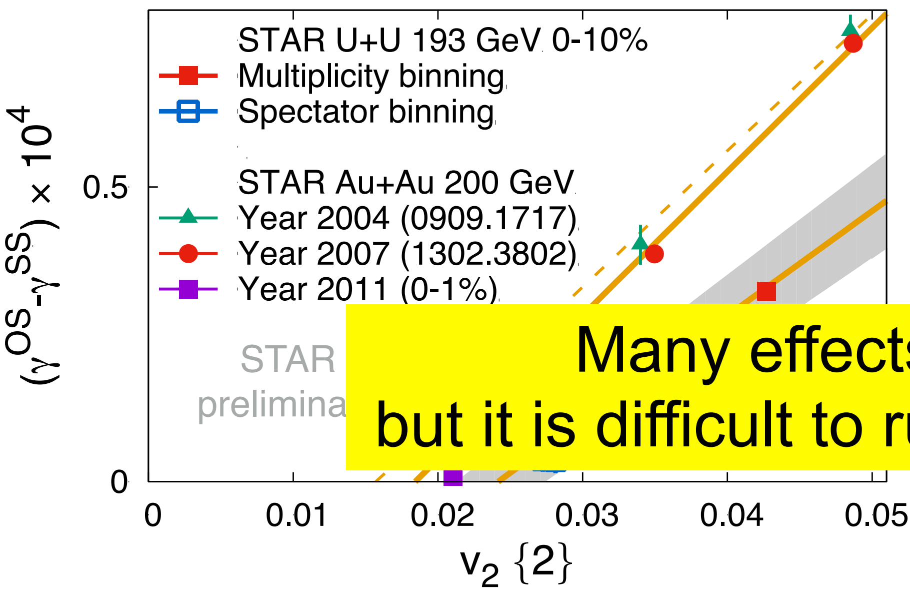
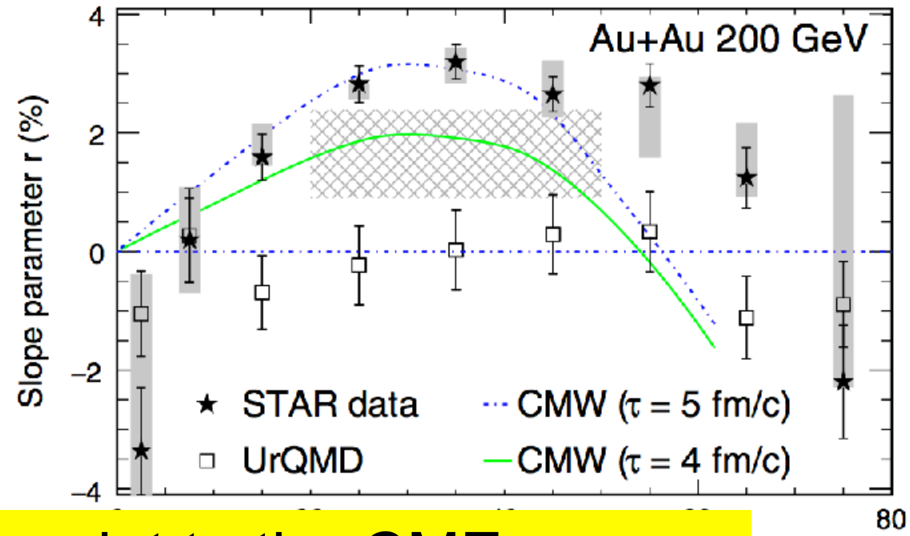
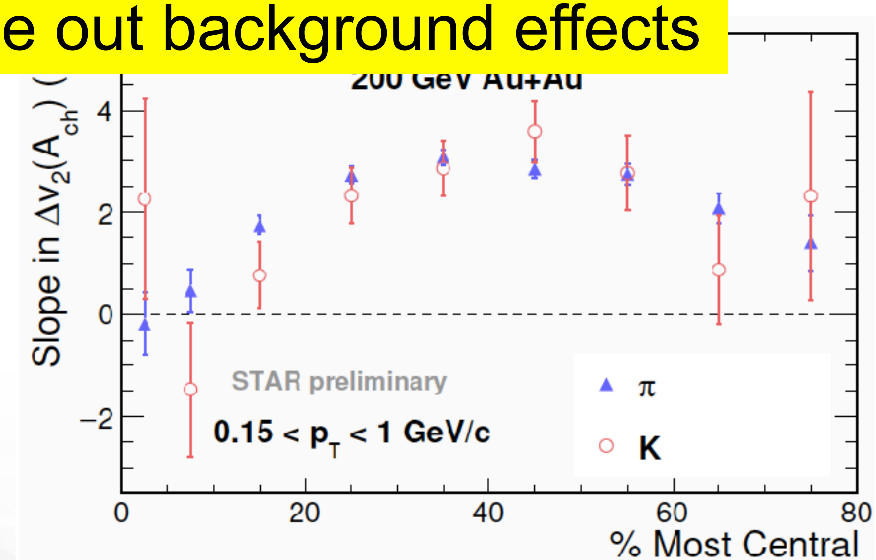


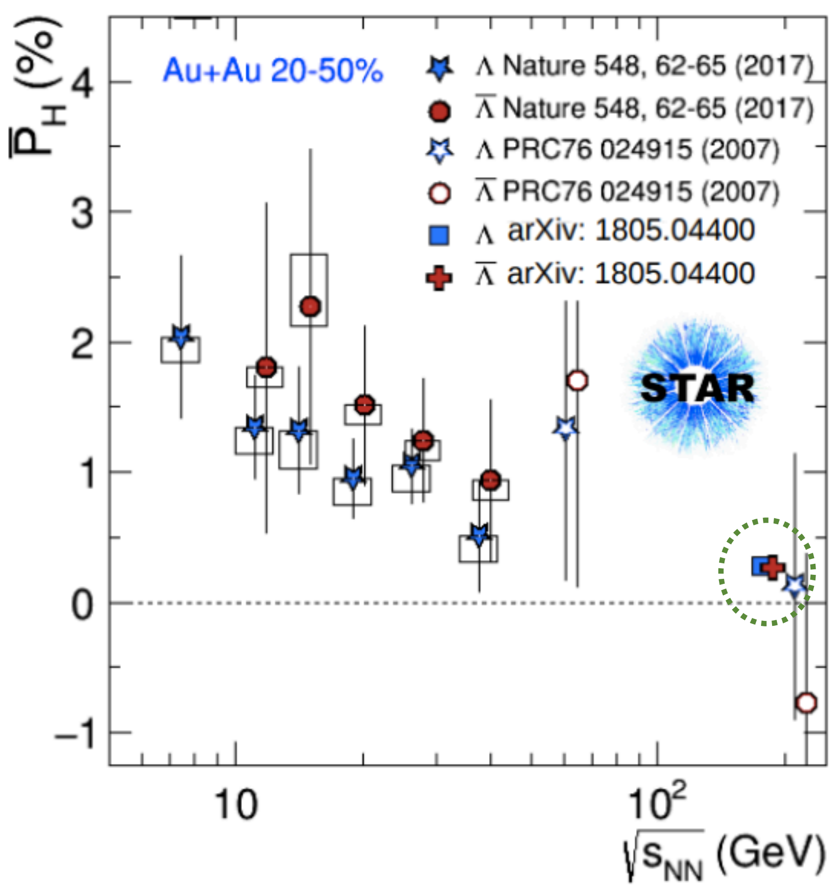


Many effects point to the CME,
but it is difficult to rule out background effects



Measured kaon slope is positive; was predicted to be negative in one background model without CMW

Late-time magnetic fields?



$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\text{stat}) \pm^{0.039}_{0.049}\ (\text{sys})$$

$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\text{stat}) \pm^{0.061}_{0.045}\ (\text{sys})$$

New, high statistics result put stringent limit on late-time magnetic field during hadronization:

$$\Delta\mathcal{P} = \frac{2\mu_\Lambda B}{T_s}$$

The new STAR data provide the bound

$$|B| = \frac{T_s\ |\Delta\mathcal{P}|}{2|\mu_\Lambda|} < 8.9 \times 10^{11}\ \mathrm{T}$$

or $$e|B| < 0.0027\ m_\pi^2$$

The quantity controlling the CME is:

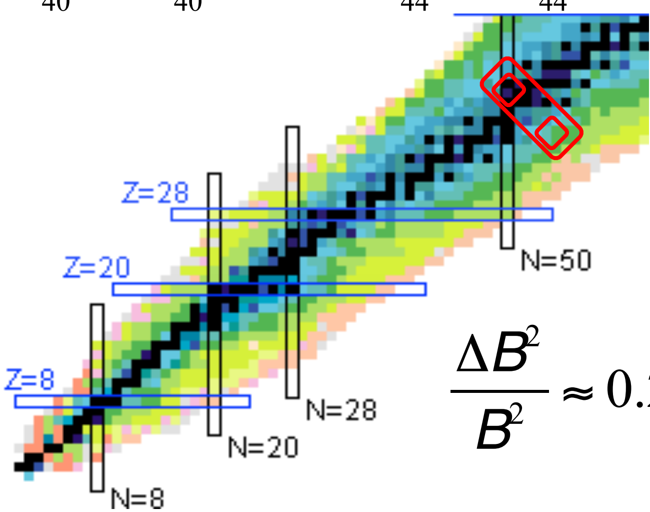
$$\int_0^{t_s} eB(t)\ dt < 50\ \mathrm{MeV}.$$

This is consistent with the observation that the CME can contribute at most 10-15% to the observed net charge fluctuation phenomena [*BM, A. Schaefer, Phys. Rev. D98 (2018) 071902*]

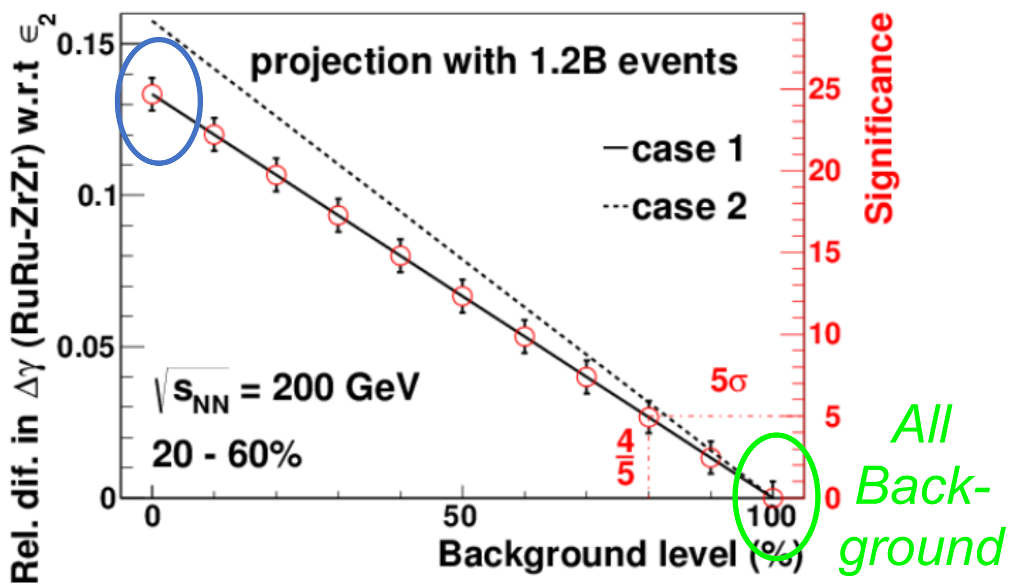
Isobar Comparison Run (2018)

Various signals of fluctuating charge separation with respect to the reaction plane have been observed, but these could be caused by background effects in correlation with elliptic flow.

$^{96}_{40}Zr + ^{96}_{40}Zr$ vs. $^{96}_{44}Ru + ^{96}_{44}Ru$



$$\frac{\Delta B^2}{B^2} \approx 0.2$$

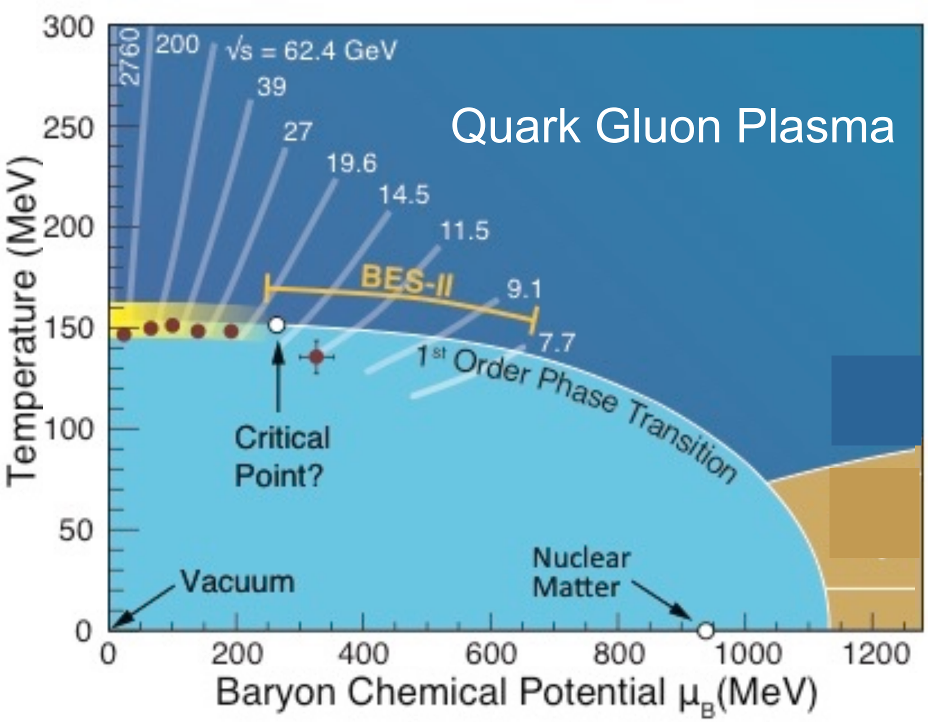


The isobar comparison run in 2018 can tell us to with +/- 4% precision what fraction of the observed charge separation is due to the CME.

What does the QCD phase diagram look like?

Mapping the Phases of QCD

A unique RHIC capability -- a unique opportunity for U.S. science



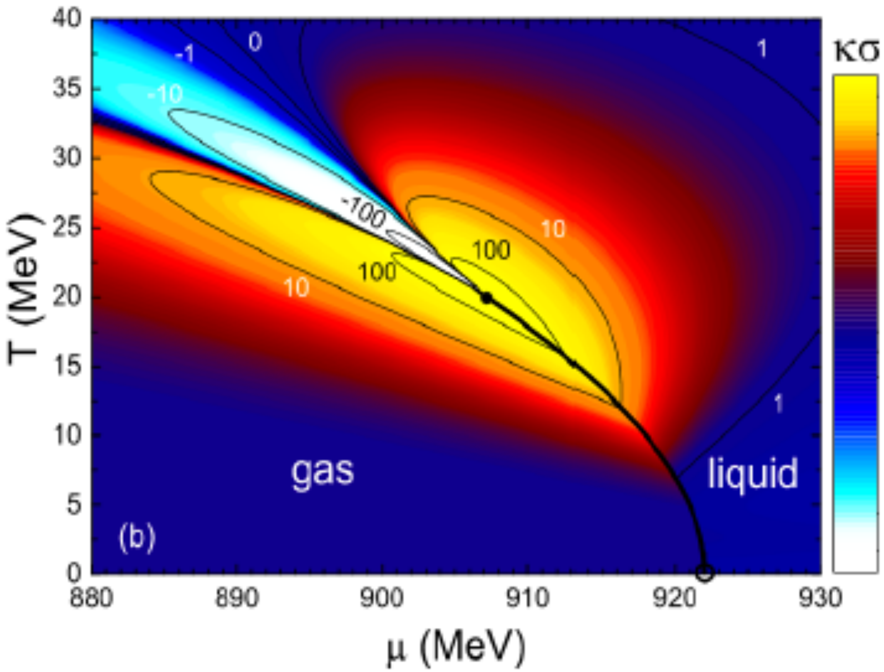
Critical Opalescence

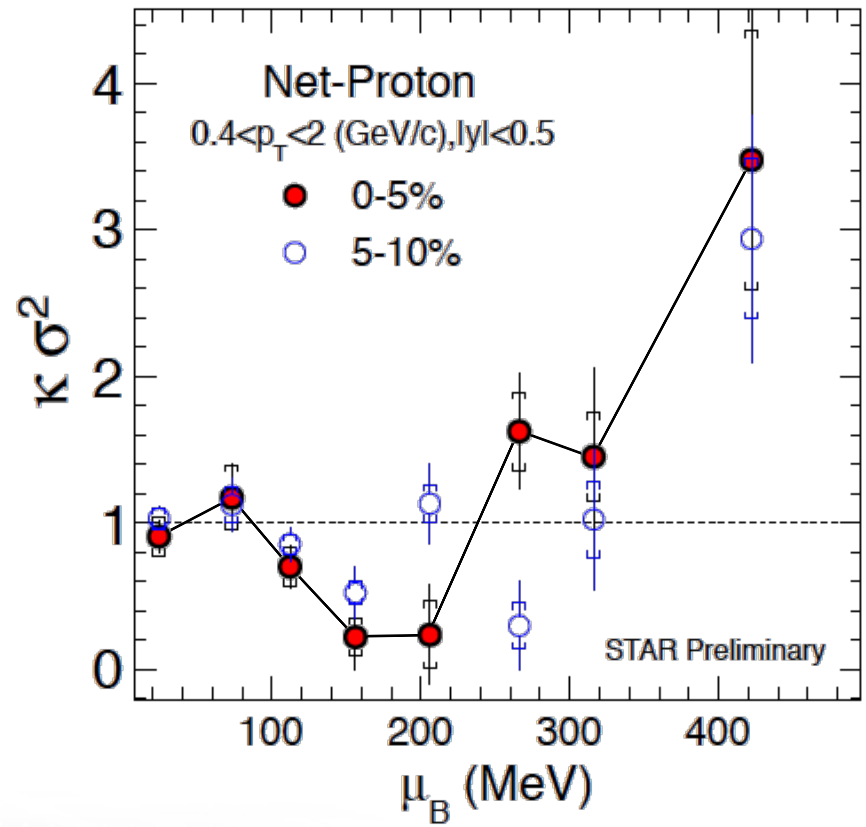
Breaking of chiral symmetry in QCD generates most of the visible mass of the universe. Is chiral symmetry restored in these collisions?

At low density, the phase transition between QGP and hadrons is smooth. Is there a 1st order transition and a critical point at higher density?

Critical behavior

The moments of the distributions of conserved charges are related to susceptibilities and are sensitive to critical fluctuations





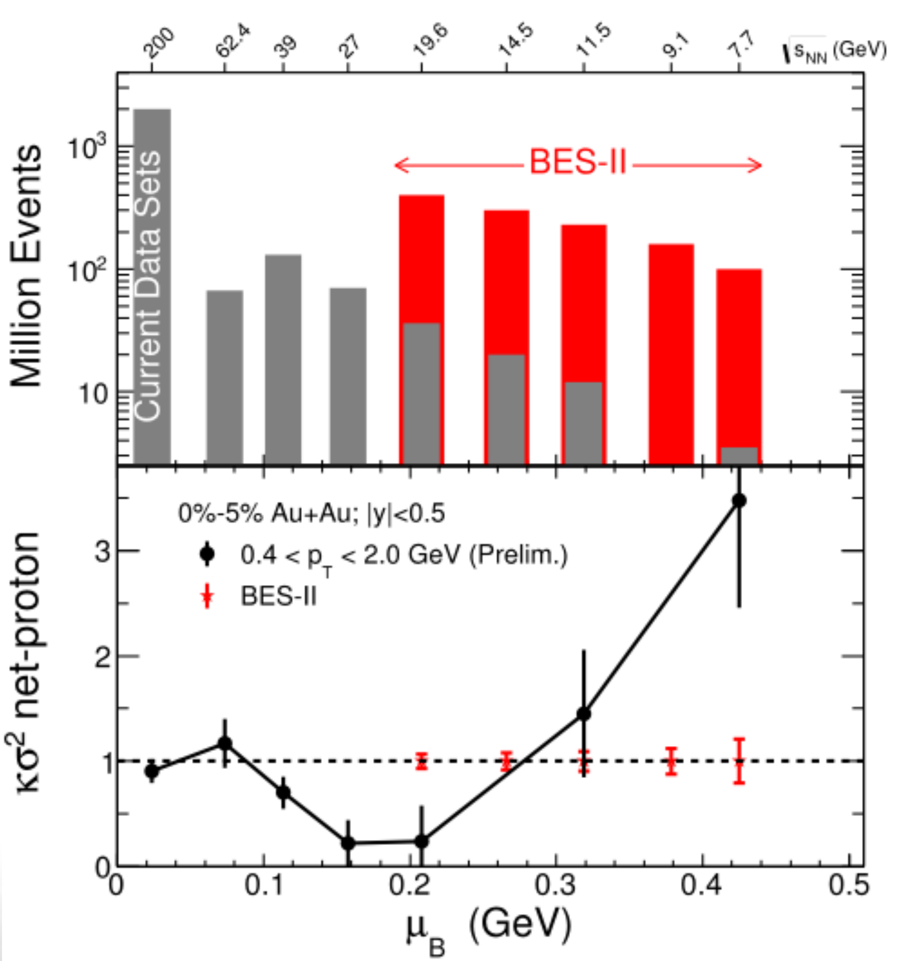
Higher moments like kurtosis × variance ($\kappa\sigma^2-1$) change sign near a critical point

Non-monotonic trend has been observed with limited statistical precision!

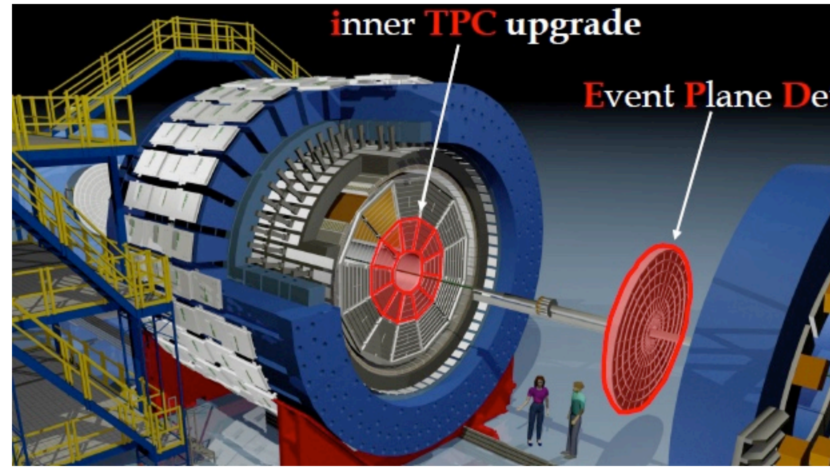
Upgrades for the BES-II

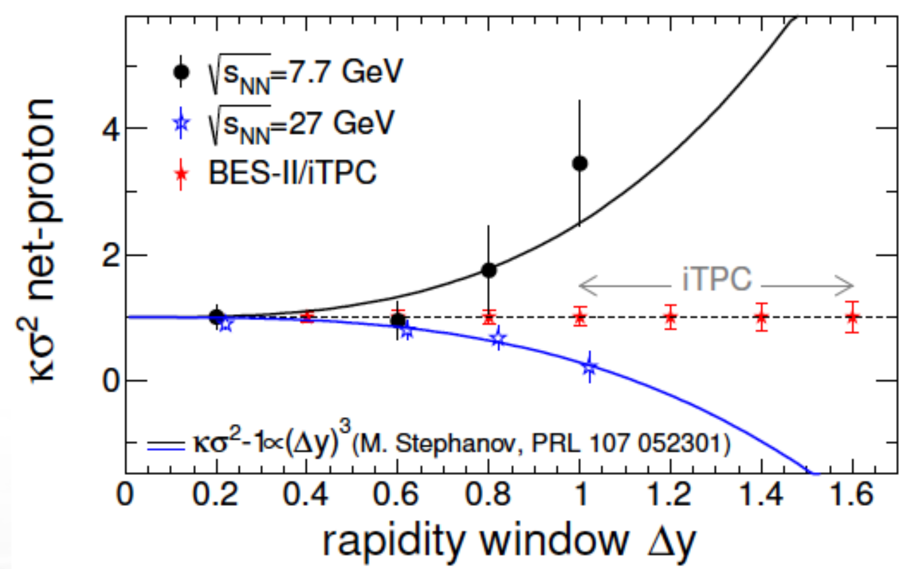
Higher statistics

Low energy RHIC electron cooling upgrade

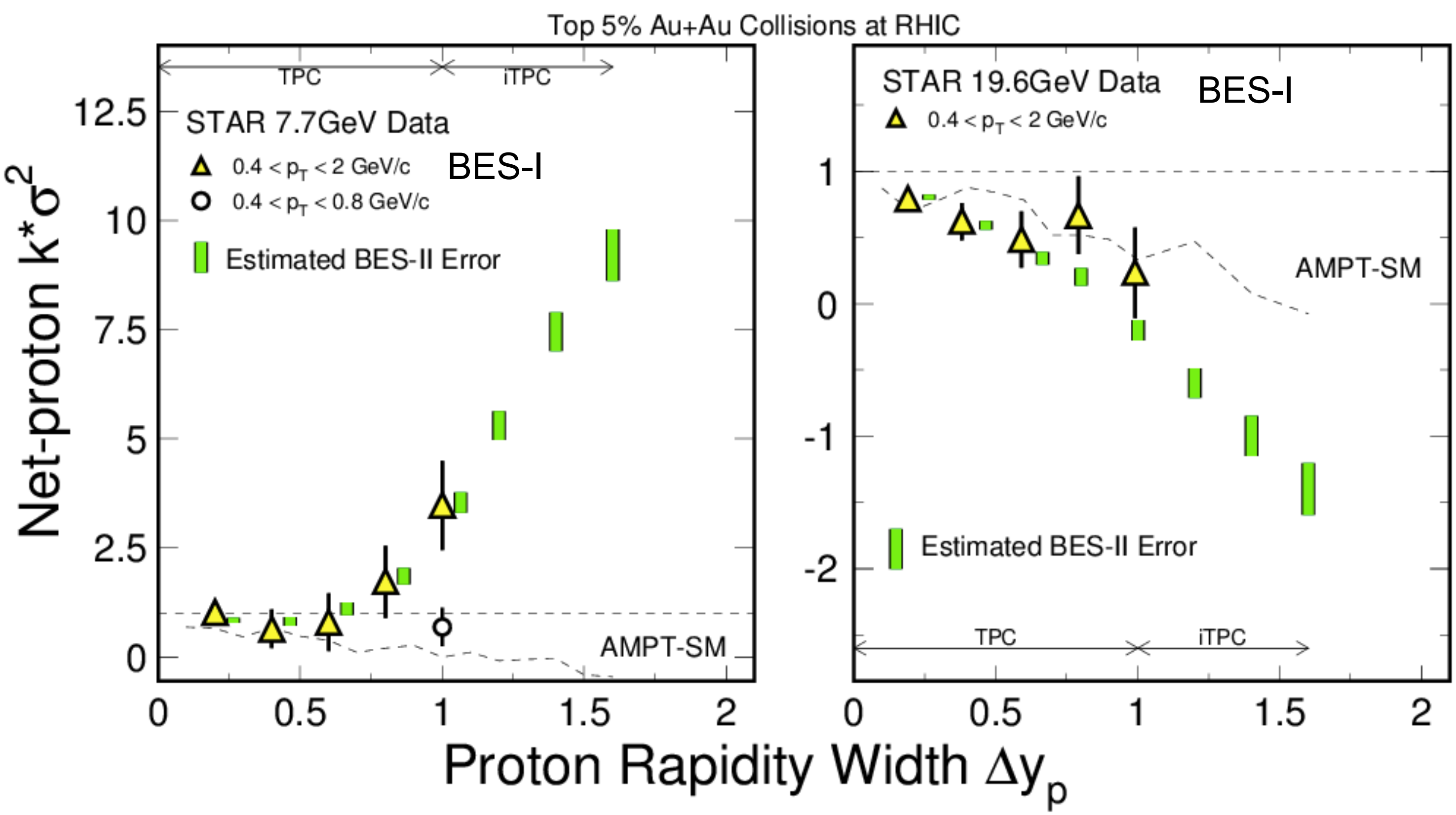


Larger acceptance





Increased statistics and acceptance



Kurtosis (fourth-order fluctuations) signal grows like $(\Delta y)^3$

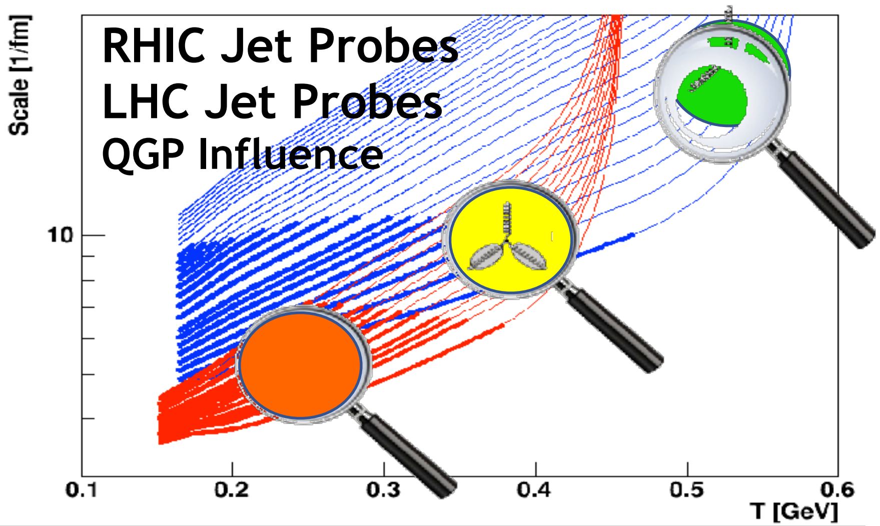
➔ **Detector coverage is critical for a definitive measurement**

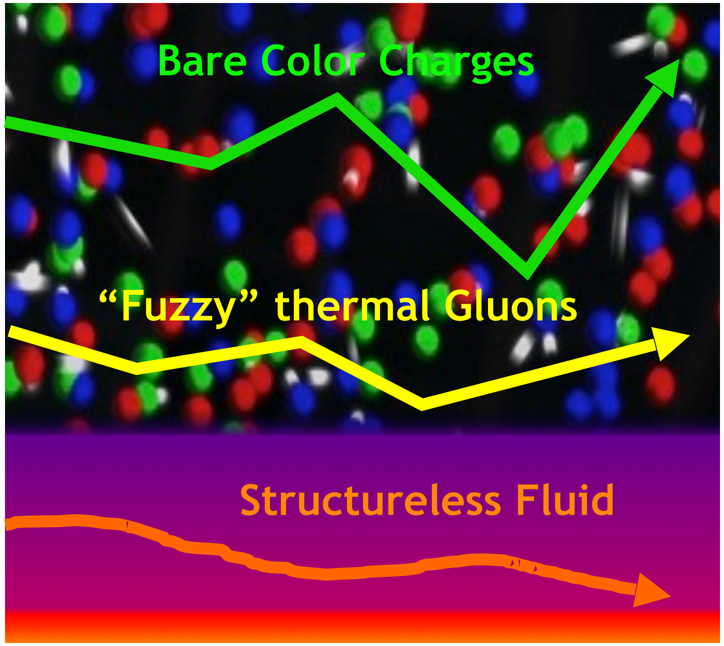
Increased luminosity reduces error bars

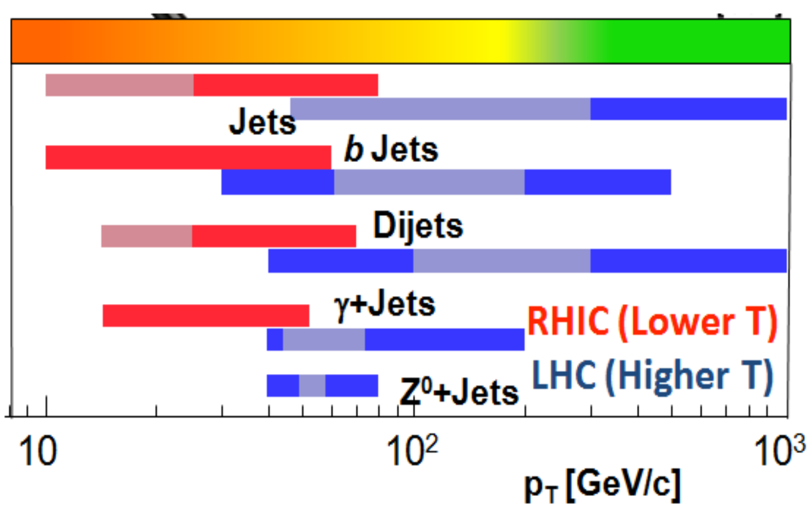
How do partons become a "Perfect" Liquid?

Jet Probes of QCD Structure

Parton virtuality evolves quickly and is sensitive to the medium at the scale it probes







Unique critical microscope resolution range at RHIC

Kinematic overlap between RHIC and LHC provides complementarity

Beyond the BES-II: sPHENIX

State-of-the-art jet (and Upsilon & open heavy flavor) detector

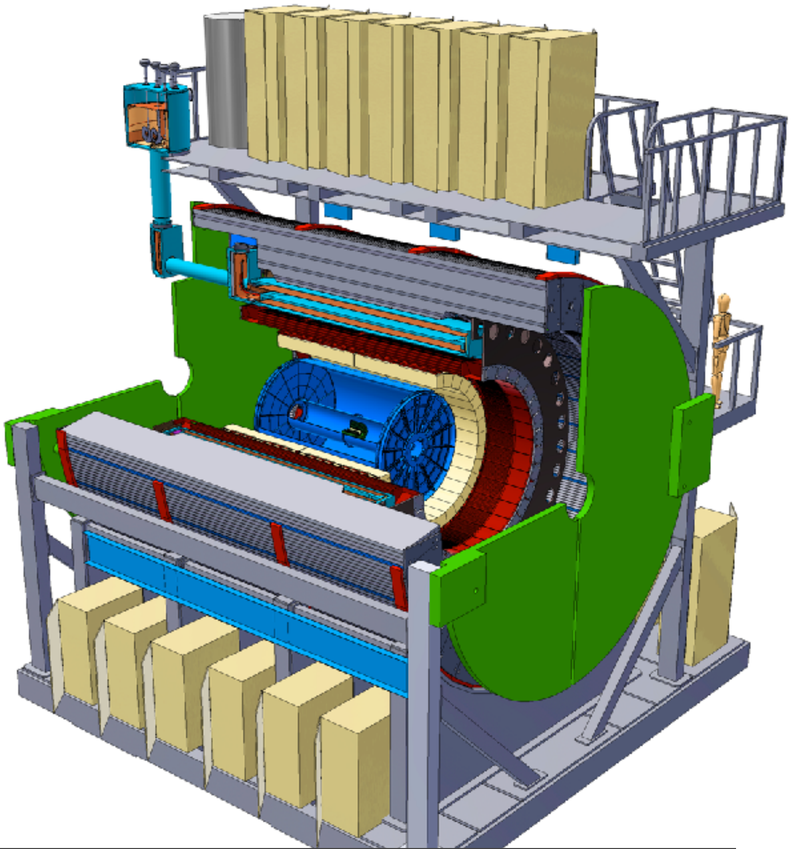
SC BaBar Solenoid 1.5 T

Coverage $|\eta| \leq 1.1$

Inner Si Tracking
Fast TPC w/GEM Read-out

Projective Electromagnetic Calorimeter

Hadronic Calorimeter

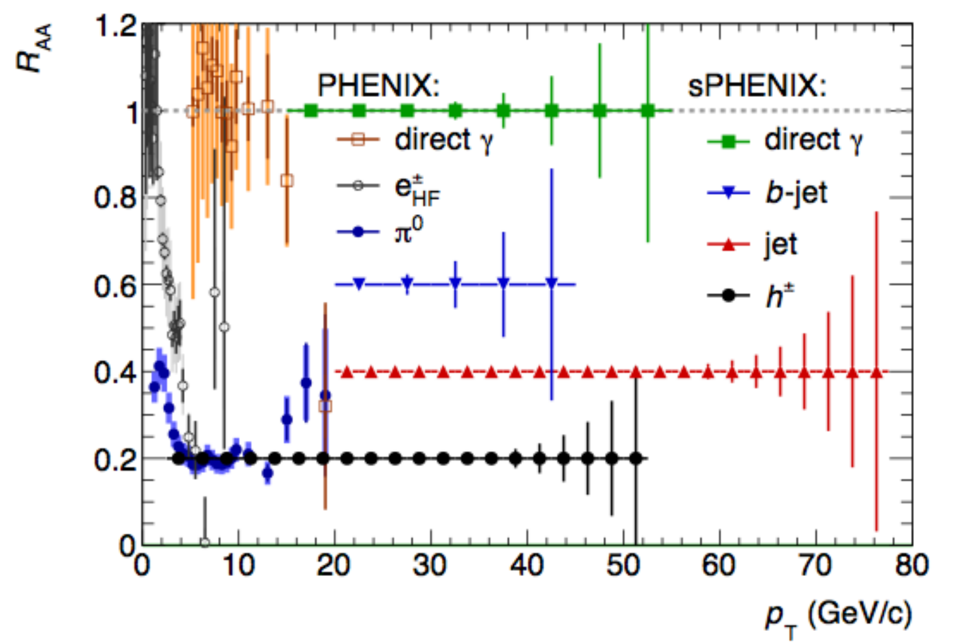


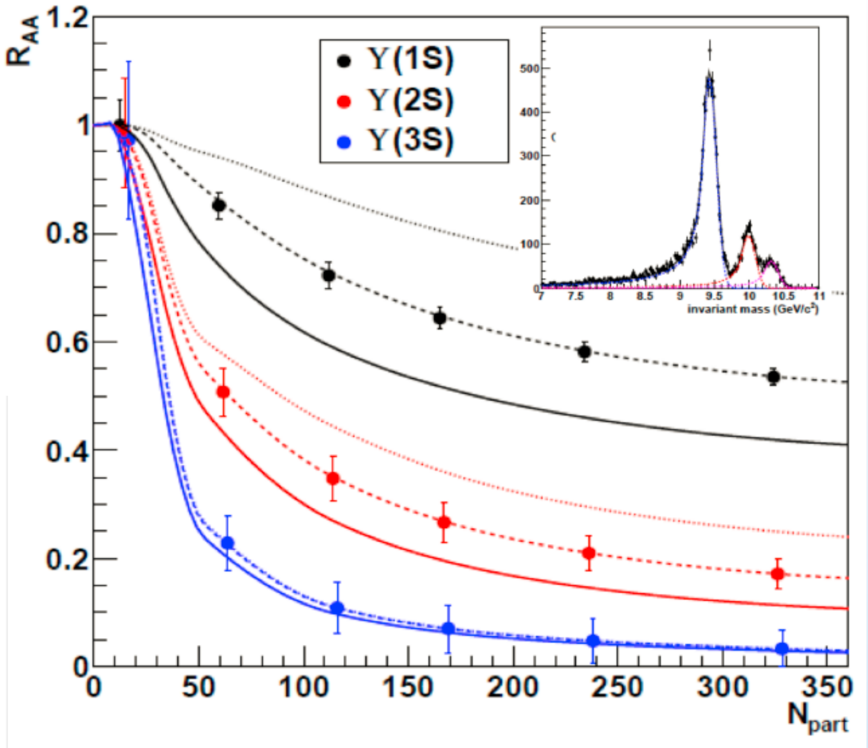
Capable of sampling 600 billion Au+Au interactions and recording 100 billion min bias events per year

Jets & Upsilon states

sPHENIX capabilities

Complete calorimetric jet spectroscopy





Completely resolved Upsilon spectroscopy

RHIC Summary

- Over the next few years, RHIC plans to mount a diverse and exciting program of investigations of the microscopic properties and limits of ordinary hadronic matter
- The isobar comparison run in 2018 will test several concepts:
  - Chiral symmetry restoration in the QGP
  - Topological gauge field fluctuations in QCD
  - The chiral magnetic effect (demonstrated experimentally for the first time in $ZrTe_5$ in 2016)
- The Beam Energy Scan II will perform high statistics measurements of the properties of hot/dense QCD matter over a wide range ($T \sim T_c$ and 250 MeV < μ_B < 700 MeV) and search for a critical point in the phase diagram

Beyond RHIC

EIC Planning

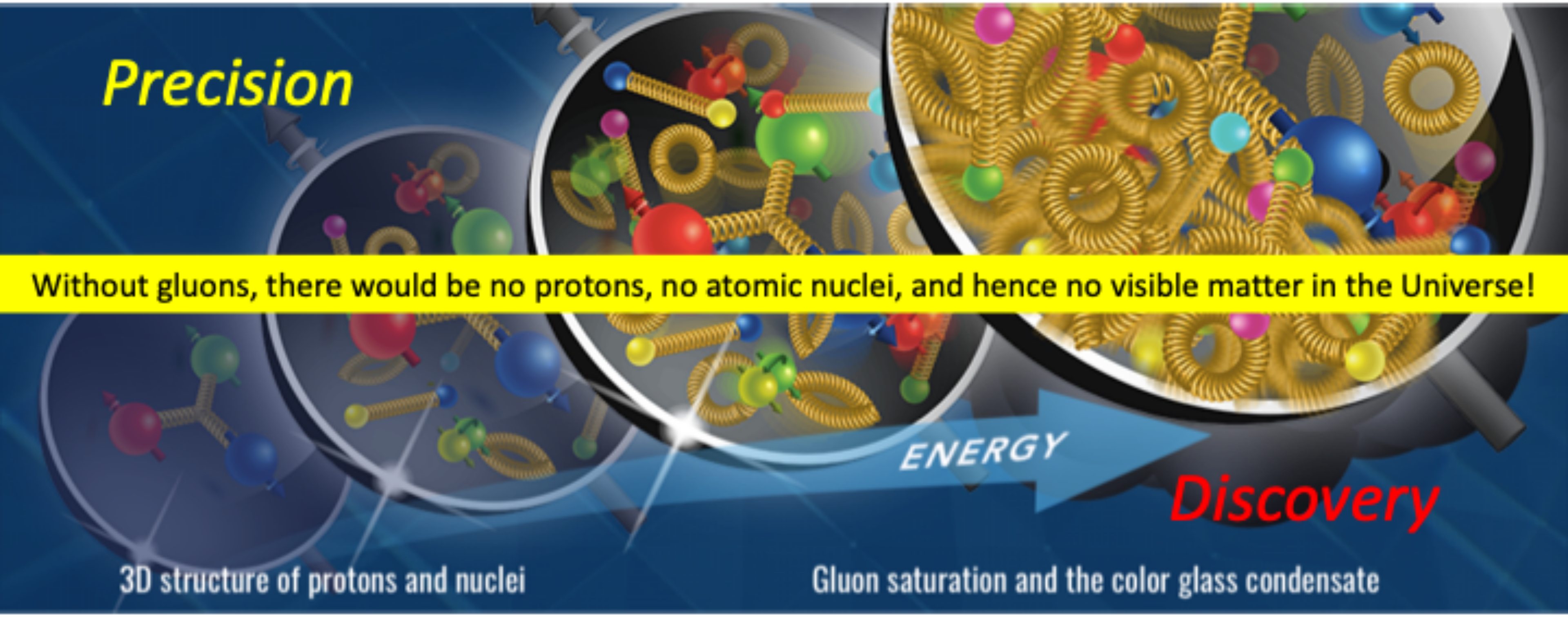
NSAC Long Range Plan (2015) - Recommendation III

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

National Academy of Sciences Study of the Science Case for a U.S. Based Electron-Ion Collider (Released July 24, 2018)

In summary, the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics.

EIC Science Pillars



The EIC will collide high-energy electrons with high-energy protons or heavier atomic nuclei to produce "freeze-frame" snapshots of their inner structure, creating precise first-ever tomographic images of the "ocean" of gluons within. These images will tell us how gluons and quarks bind each other to form the particles that lie at the core of all atoms.

New experiments and advances in theory suggest that protons, neutrons, and nuclei appear as dense "walls" of gluons when probed at high energy, creating what are conjectured the strongest fields in nature. Discovering and studying this new form of matter, the "color glass condensate," will give us additional insight into why matter in this sub-atomic realm is stable.

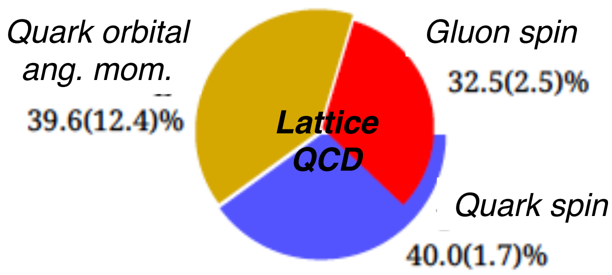
EIC Science Program was reaffirmed by NAS Study (July 2018)

Big Questions

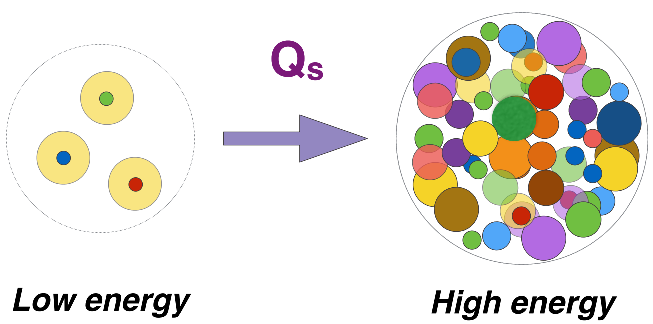
Proton spin:

Quark spin contributes only ~30% to the proton's spin
How do quark and gluon dynamics generate
the remainder of the proton's spin?

The EIC will definitively resolve this question.



Gluon saturation:



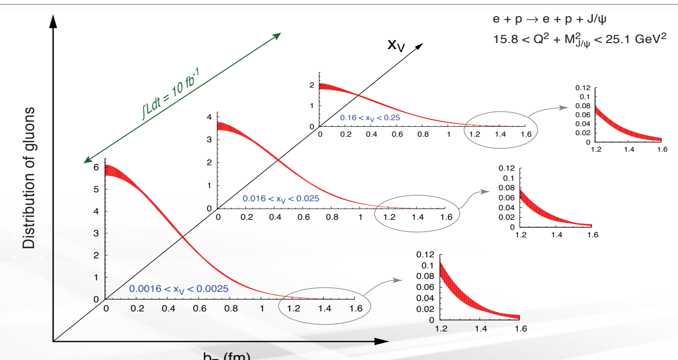
Gluons proliferate at high energy (small Bjorken-x)
How does the gluon density saturate to avoid violation
of fundamental principles like unitarity?

The EIC will explore this question using heavy nuclei.

Proton transverse structure:

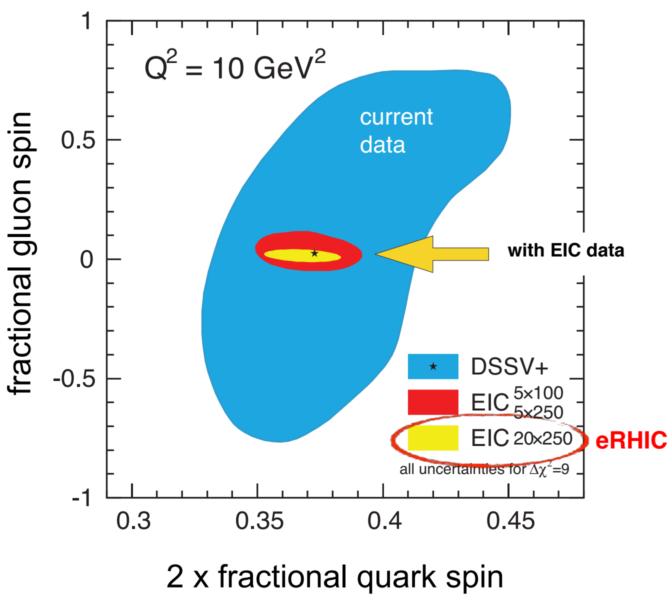
We know the 1-D (longitudinal) structure of a
moving proton very well
What does the proton look like in 3 dimensions?

The EIC will definitively answer this question.

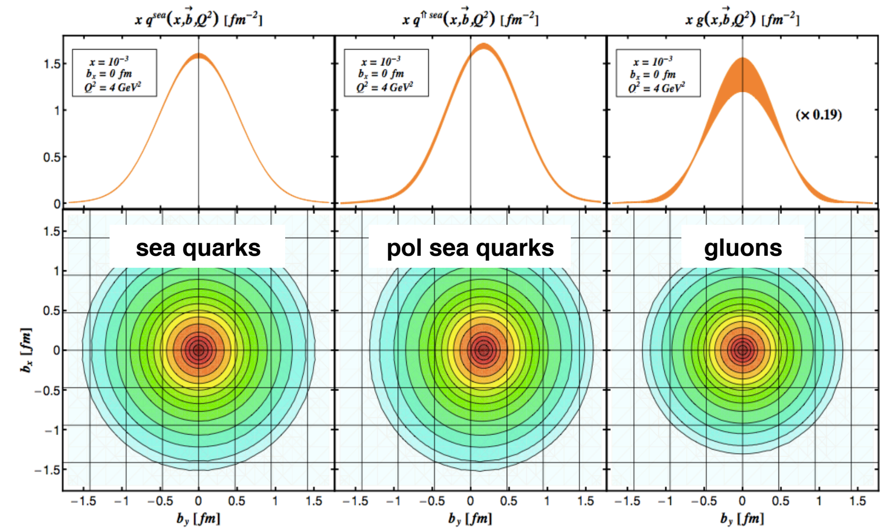


Key measurements

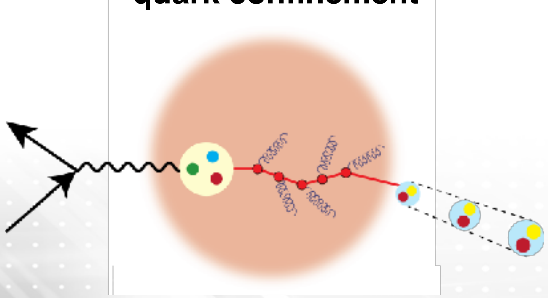
Proton spin decomposition

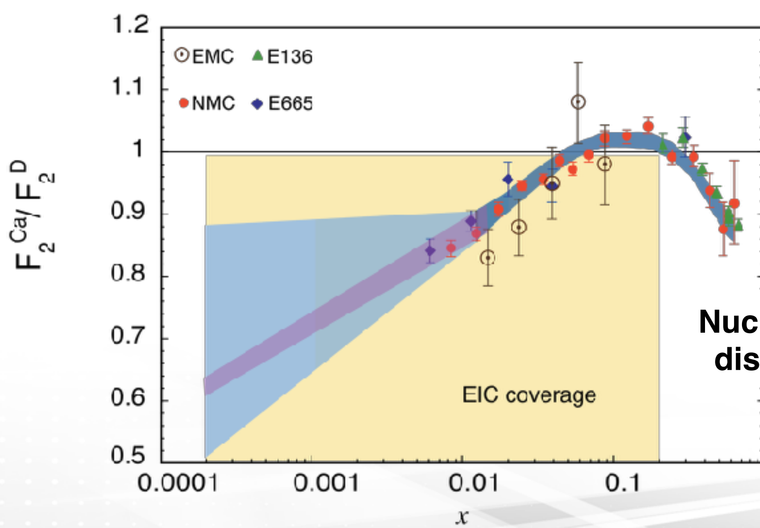


Imaging using GPDs and TMDs



Nuclei as a probes of quark confinement





Nuclear parton distributions

Origin of the proton mass

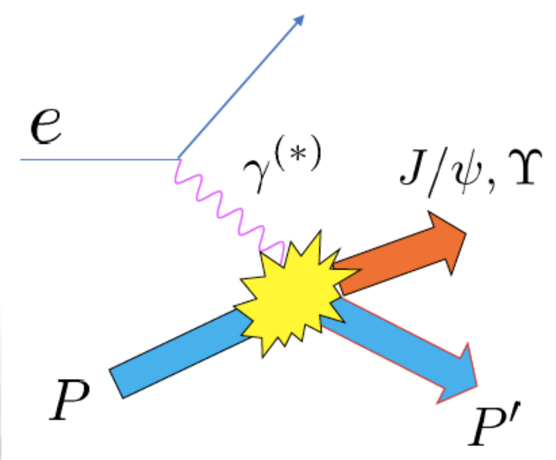
Proton mass is related to the trace of the energy-momentum tensor:

$$T^{\mu\nu} = -F^{\mu\lambda}F_{\nu\lambda} + \frac{1}{4}\eta^{\mu\nu}F^2 + i\bar{q}\gamma^{(\mu}D^{\nu)}q$$

$$\langle P|T^{\mu}_{\mu}|P\rangle = 2M^2$$

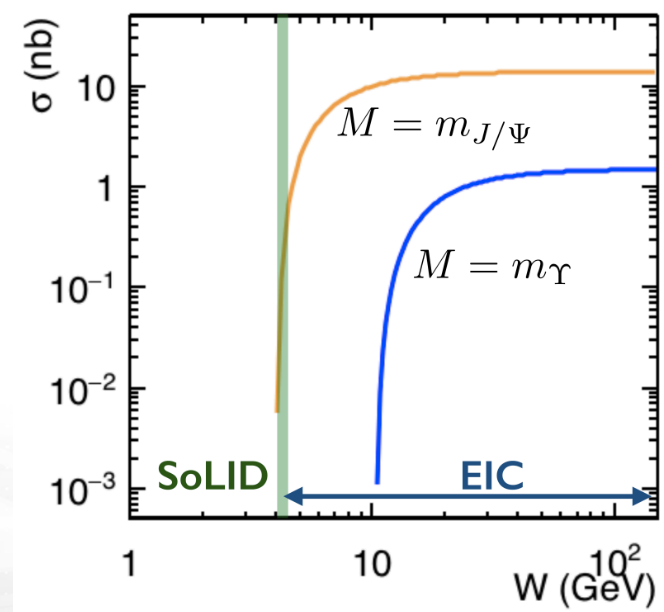
QCD trace anomaly relates this expression to the gauge field invariant:

$$T^{\mu}_{\mu} = \frac{\beta(g)}{2g}F^2 + m\left(1+\gamma_m(g)\right)\bar{q}q$$

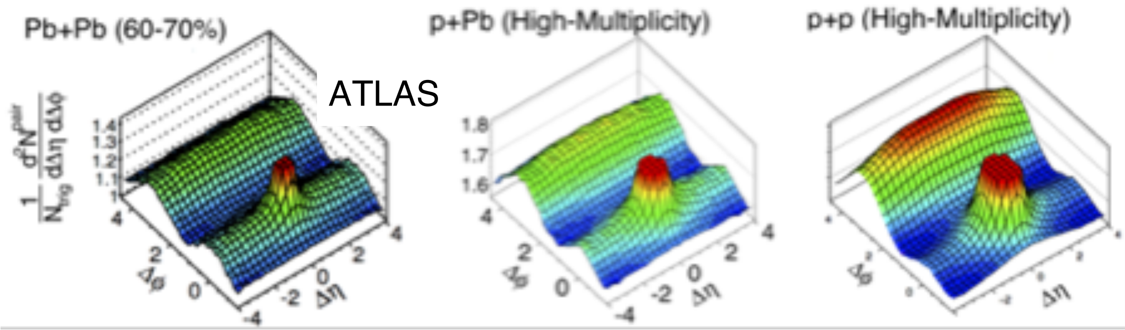


Anomaly term
can be related to
quarkonium production
near threshold

Kharzeev et al (1998)



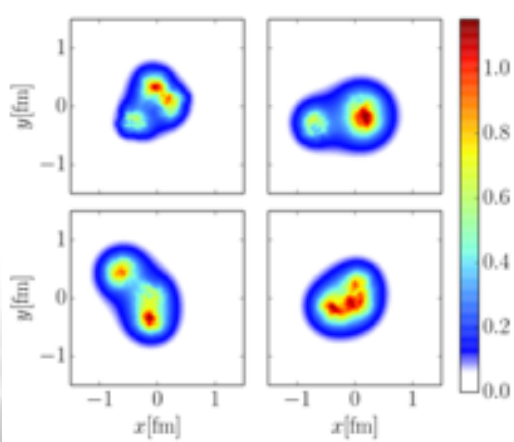
Proton structure in pp and pA collisions



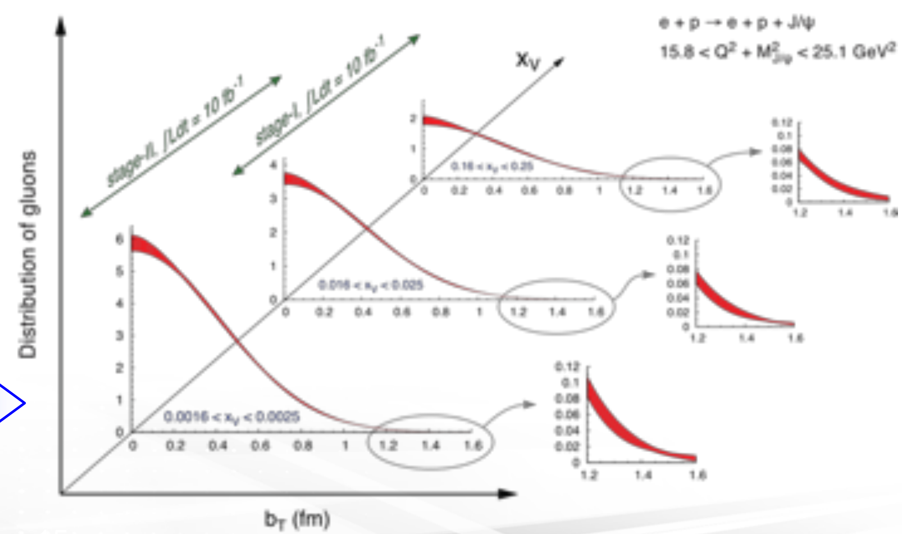
EIC will map out the spatial quark and gluon structure of the proton

Shape fluctuations of the proton at $x = 10^{-2} - 10^{-3}$ are essential to explaining the observed collective behavior of pA and pp

Proton density profiles at $x \sim 10^{-3}$



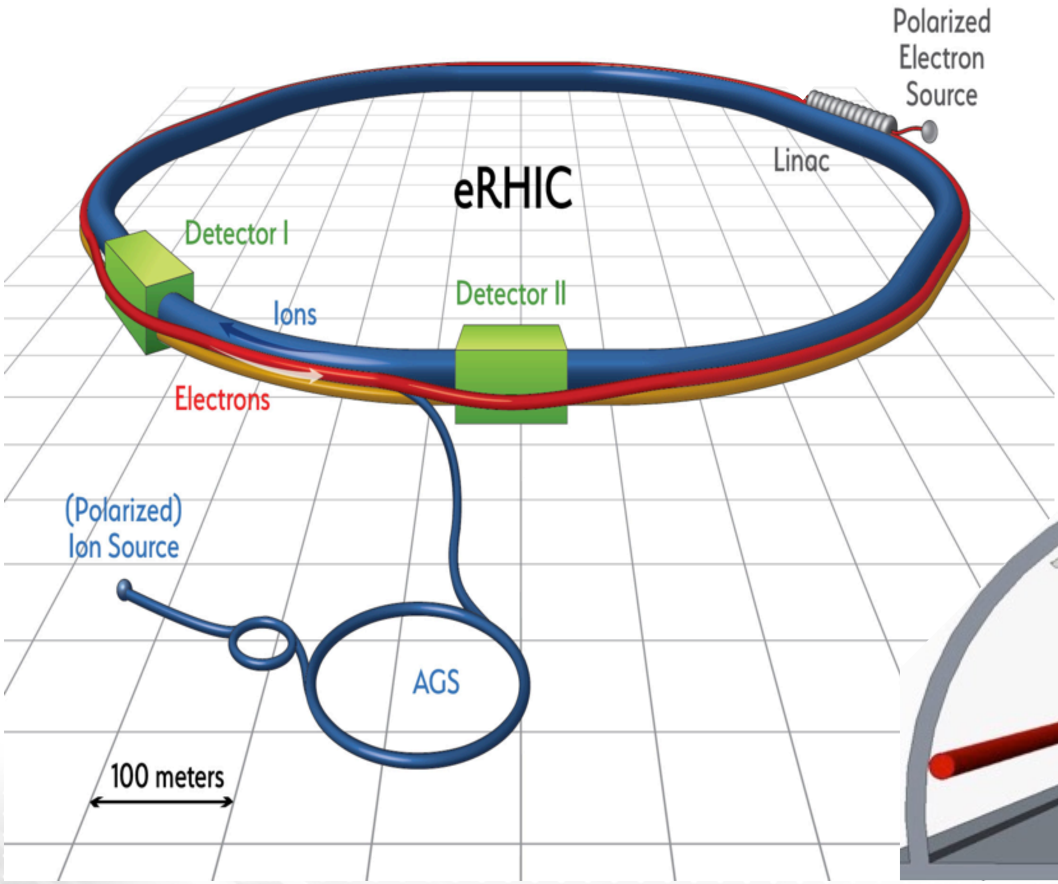
Coherent and incoherent J/Ψ production



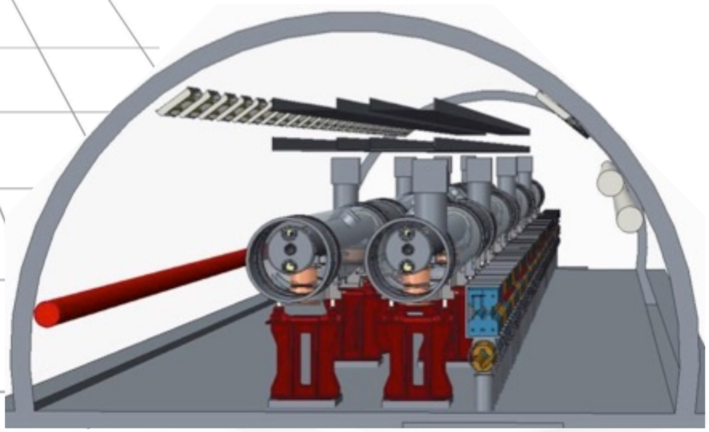
BNL EIC Design: eRHIC

eRHIC ring-ring based design @ peak $10^{34}/cm^2s$

18 GeV e^- + 255 GeV p or 100 GeV/u Au.



Day-1 Detector



Summary

- Over the next few years, RHIC plans to mount a diverse and exciting program of investigations of the microscopic properties and limits of ordinary hadronic matter.
- The Beam Energy Scan II will explore the limits of ordinary matter.
- sPHENIX will probe the structure of the QGP liquid at sub-fm scale.

- Longer term, a high-luminosity polarized Electron-Ion Collider will permit unprecedented detailed studies of the internal structure of nucleons and nuclei and explore how their properties (e.g. their QCD mass) arise from the properties of quarks and gluons.

- Exciting times lie ahead!

QUESTIONS?