Where Are We Now?

Where Do We Need to Go?

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Brookhaven National Laboratory

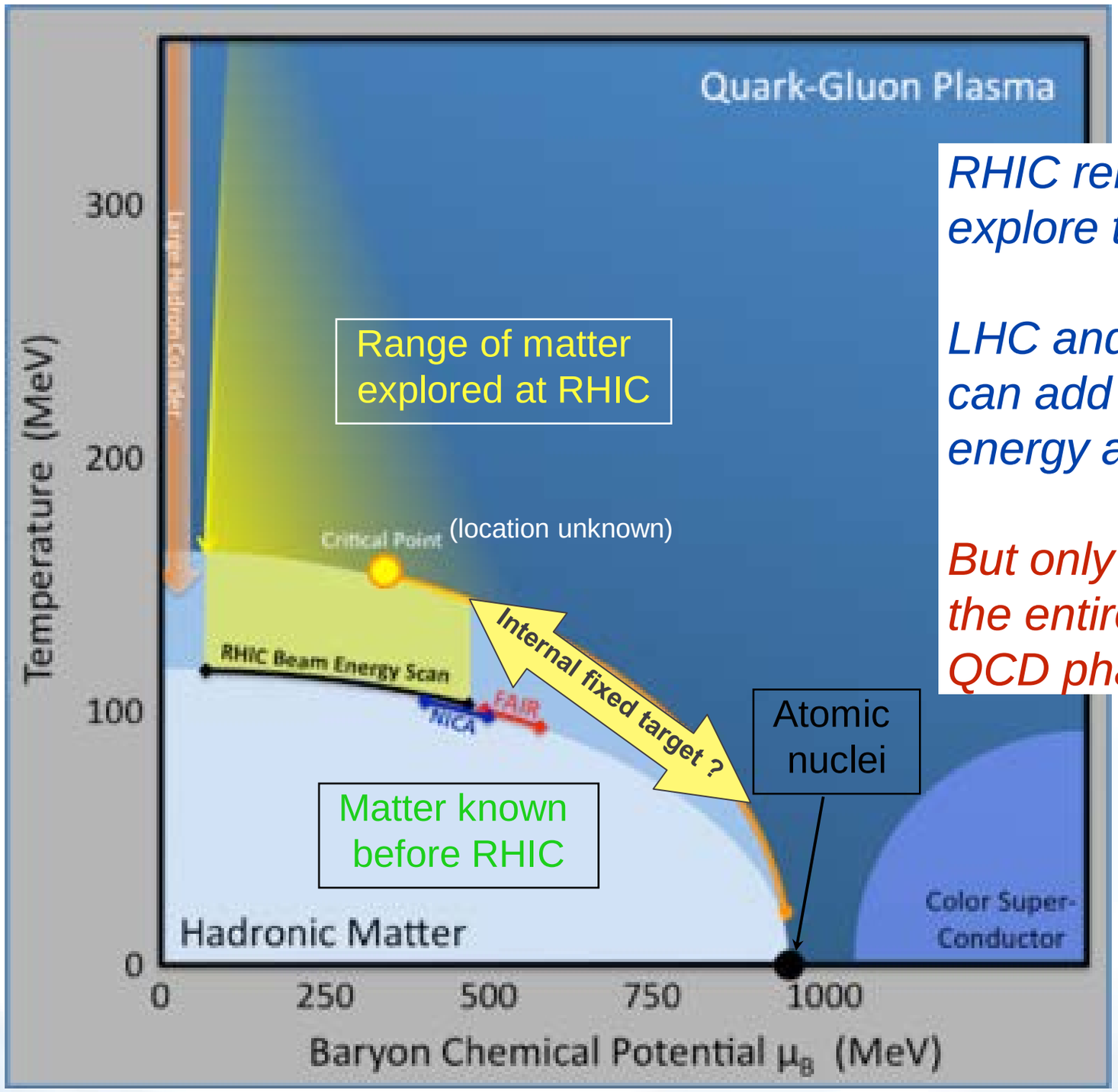
RHIC/AGS Users Meeting
17-20 June 2014

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

The Landscape



RHIC remains the premier facility to explore the phases of QCD matter.

LHC and, in the future, FAIR & NICA can add exciting capabilities at high energy and high baryon density.

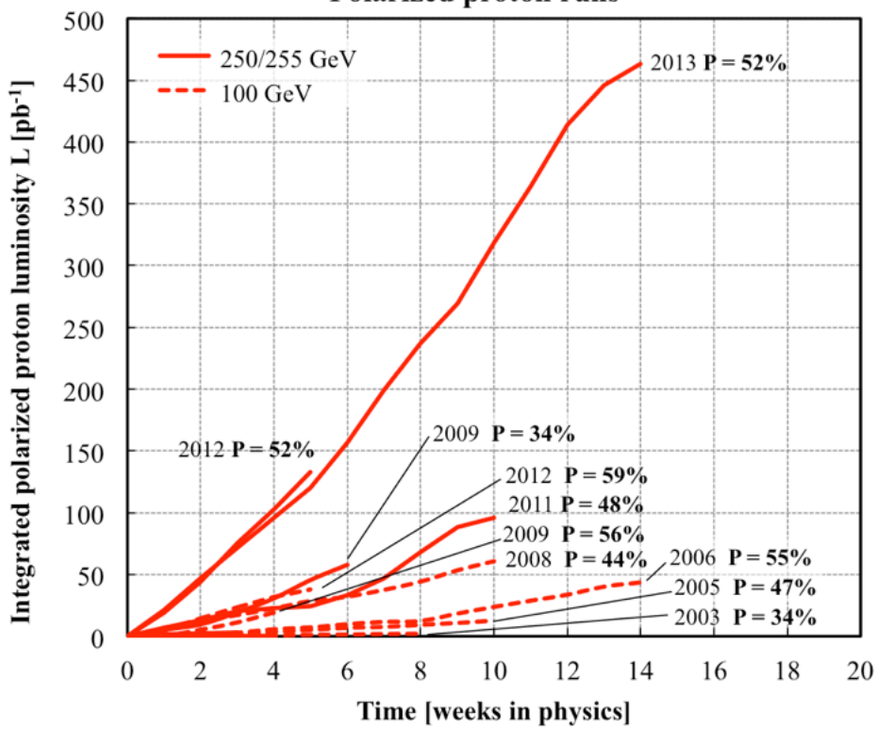
But only RHIC can cover essentially the entire accessible region along the QCD phase boundary.

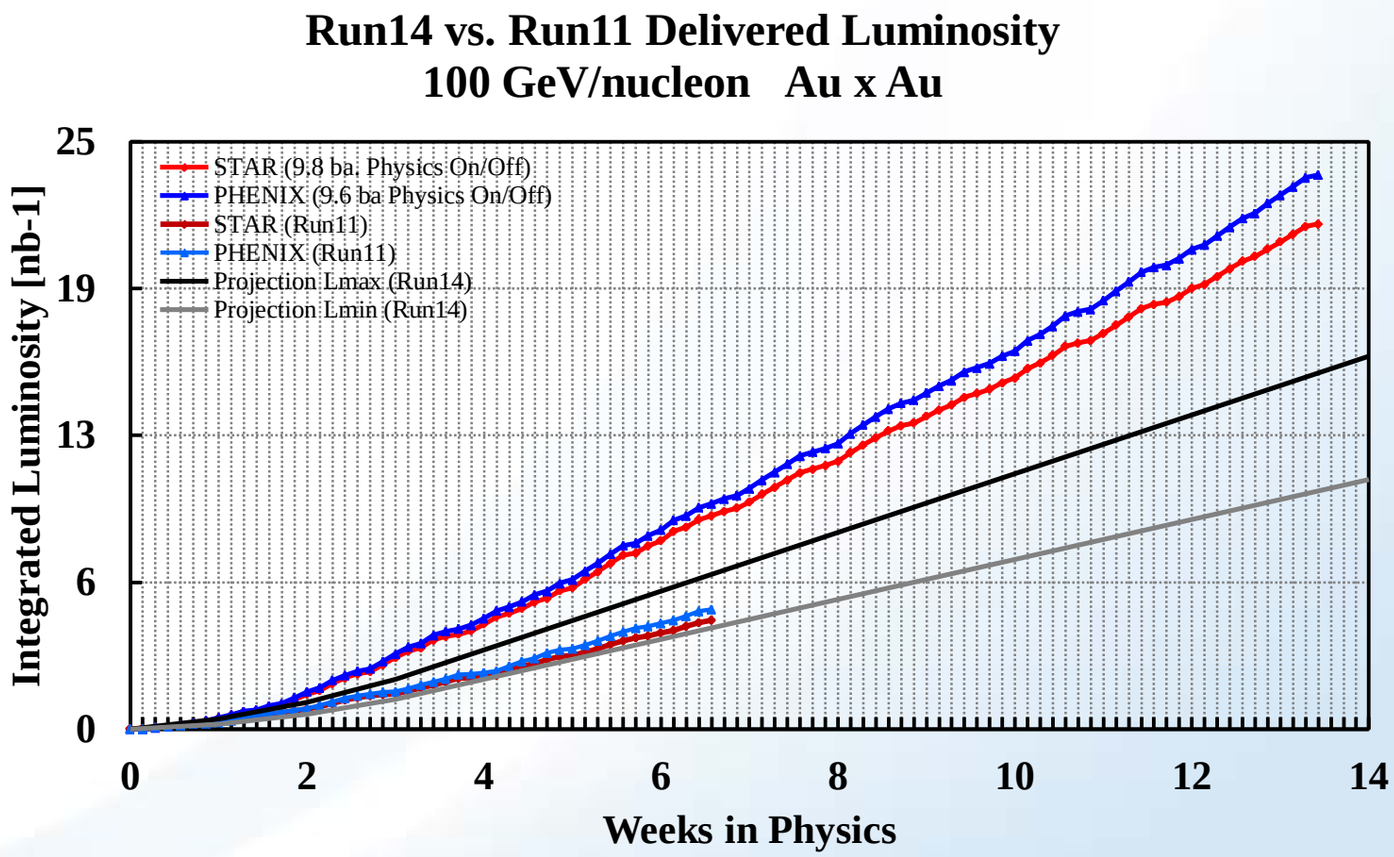
RHIC is in its prime!

The RHIC-II upgrades are complete:

- 3-D stochastic cooling
- EBIS ion source
- 56 MHz cavity and e-lenses

➥ Unprecedented luminosity



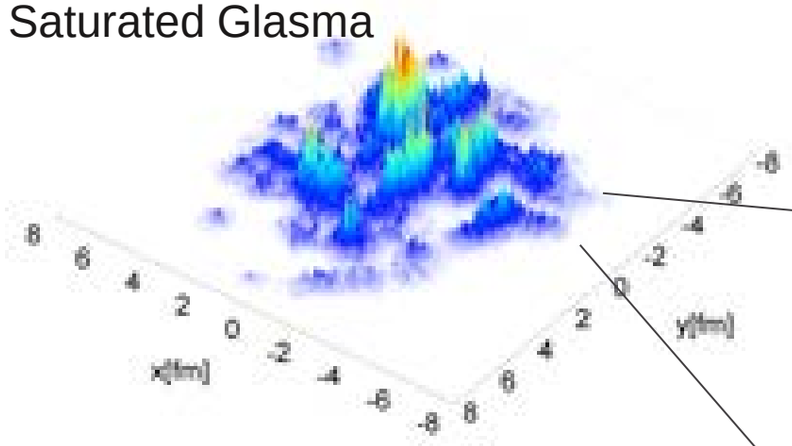


Main Discoveries

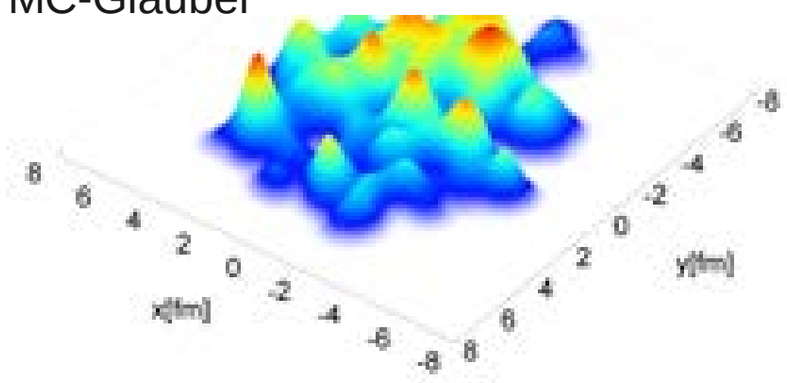
- Hot nuclear matter produced in collisions at RHIC/LHC is a **liquid** quark-gluon plasma. The plasma is made up of individually flowing quarks, not quarks bound into baryons and mesons.
- The QGP is a strongly coupled nearly "**perfect**" liquid (η/s near the quantum limit); RHIC's QGP is (on average) *closer to perfection* than the QGP produced at LHC.
- Energetic quarks and gluons moving through the QGP rapidly lose energy, causing jets to be strongly **quenched**.
- Light quarks (*u,d,s*) are completely **thermalized** in the QGP; these valence quarks recombine during hadronization.
- Heavy quark bound states (J/ψ, Υ') "**melt**" in the QGP due to color screening and ionization. RHIC and LHC data together indicate that charm quarks can recombine when the QGP hadronizes, adding to the evidence for quark deconfinement.

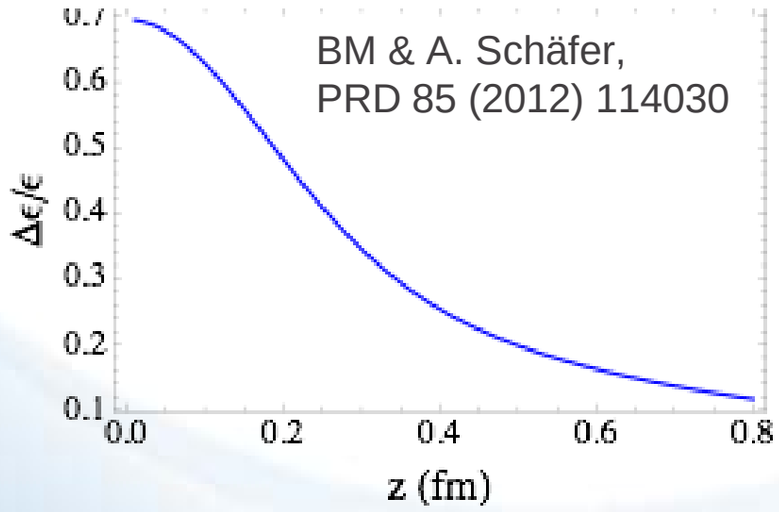
RHIC vs. LHC

Saturated Glasma

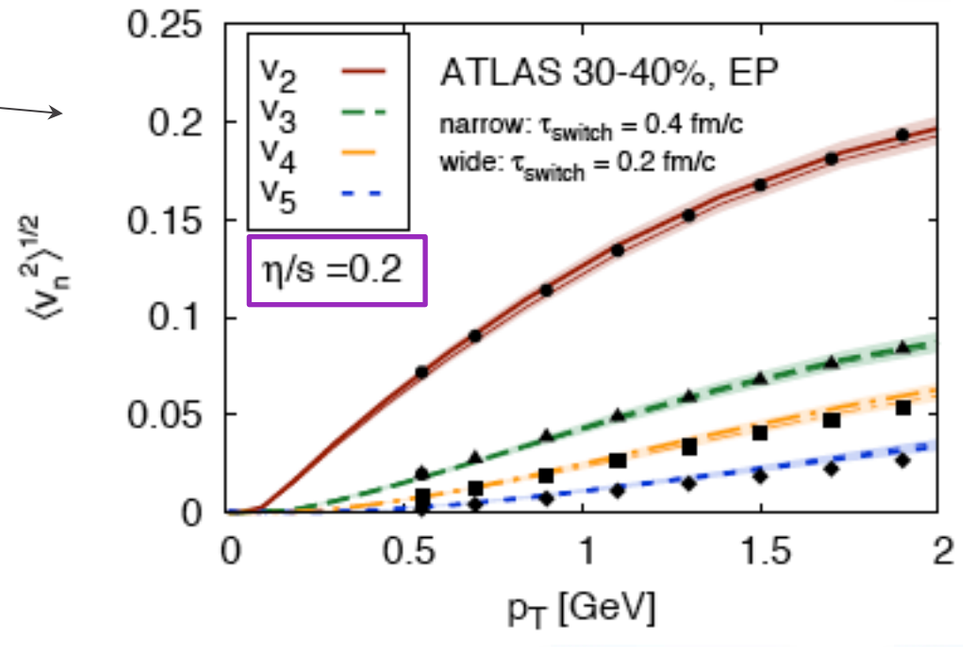


MC-Glauber

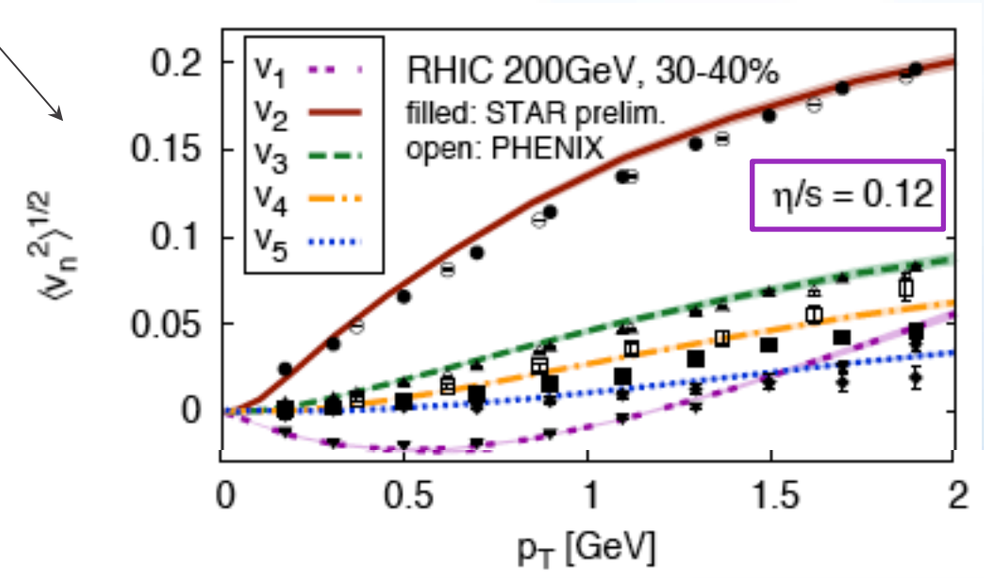




Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330



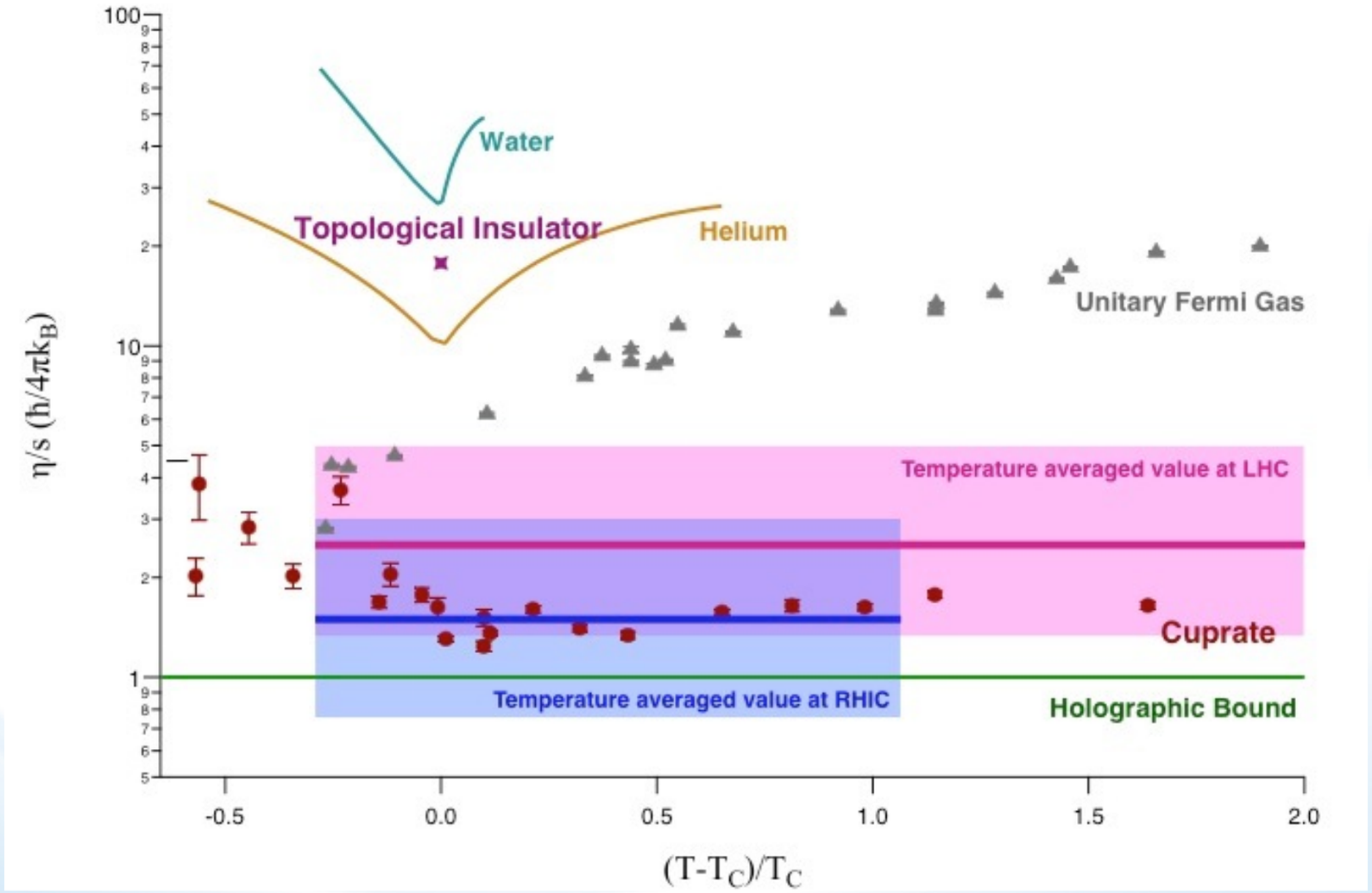
LHC

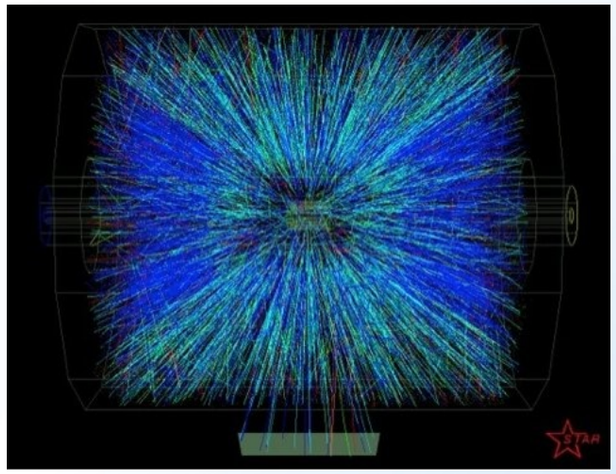


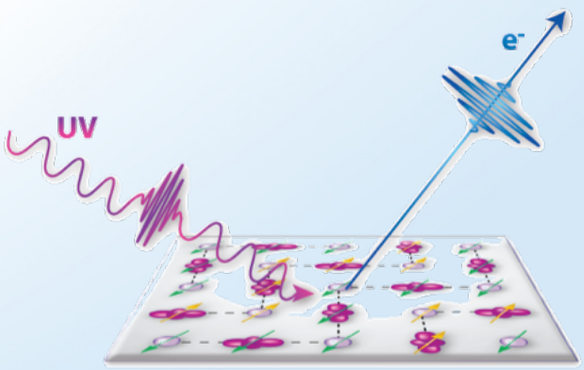
RHIC

Nearly Perfect Fluids discovered at BNL

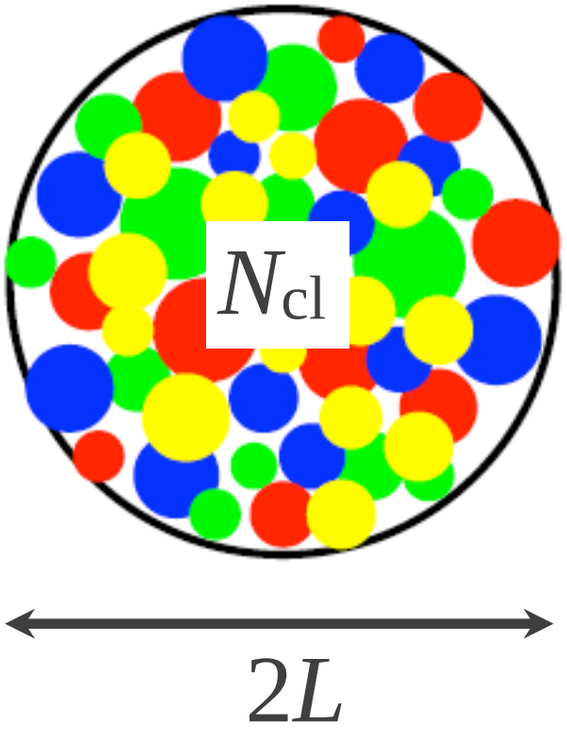
- Perfect fluids have the smallest ratio of shear viscosity to entropy density, η/s
- Quark-Gluon Plasmas (QGP) and unitary atomic Fermi gases are nearly perfect fluids near their critical temperatures (T_c)
- BNL scientists have observed that a high T_c cuprate superconductor is a nearly perfect fluid around, and above, its superconducting transition temperature







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:

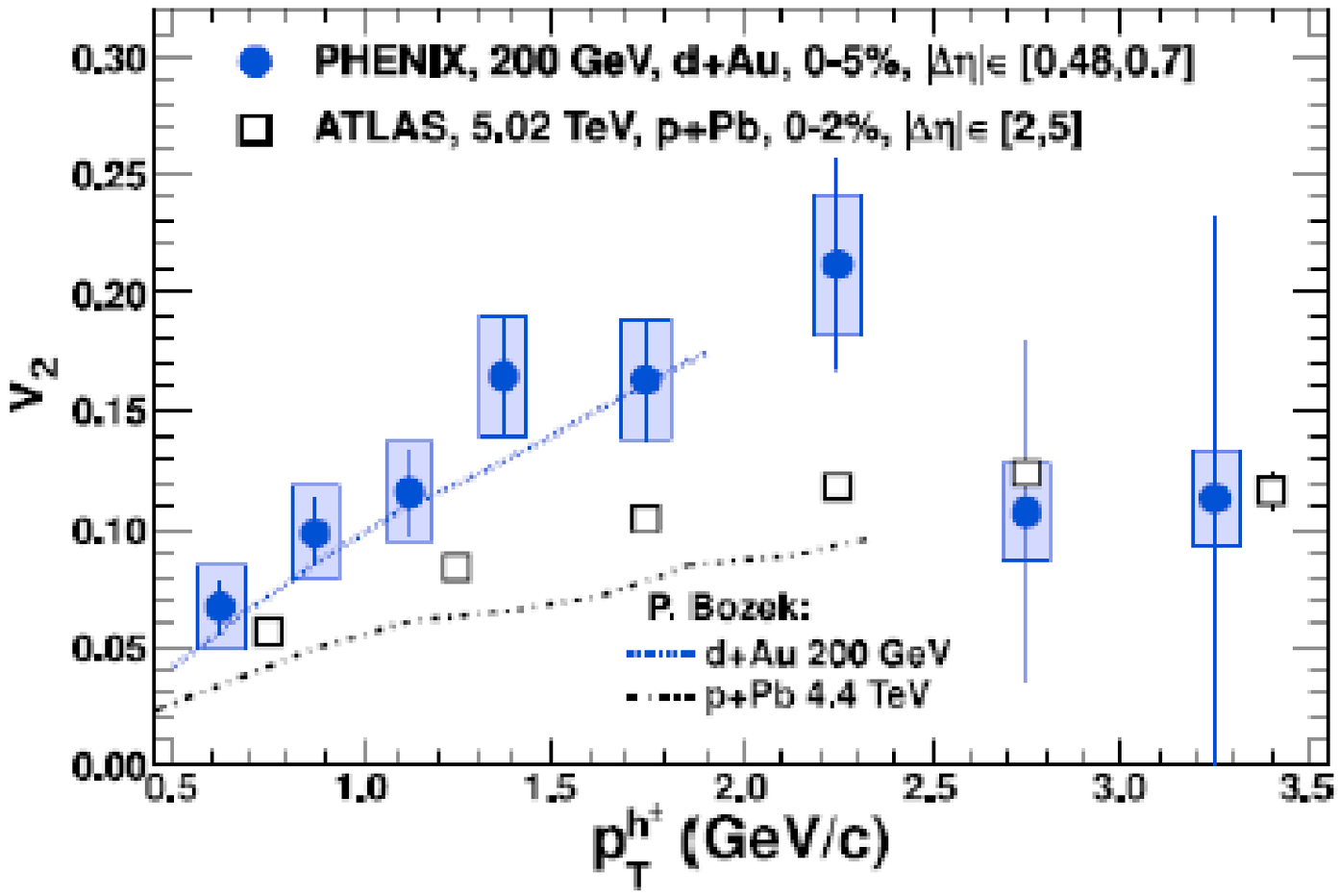
$$\mathrm{Re} = \frac{\ell_{mfp}}{L} \propto \frac{1}{Q_s L} \propto \frac{1}{\sqrt{dN/dy}}$$

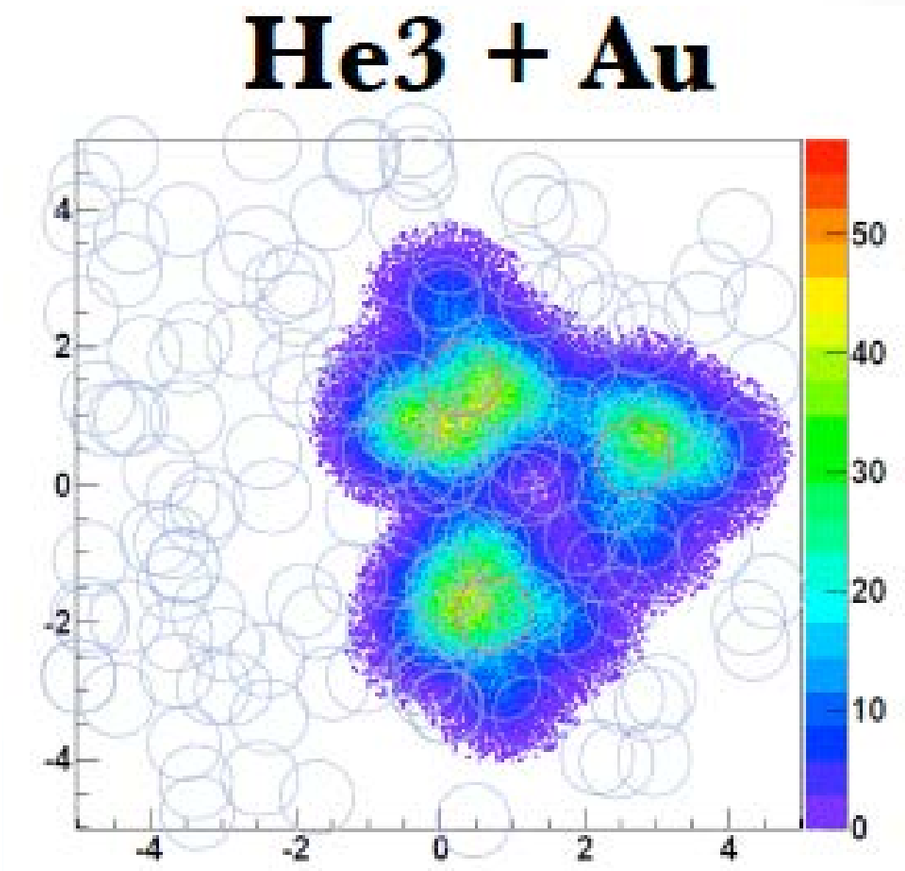
This does not mean that hydrodynamics applies for a given *dN/dy*, but it suggests that the transport is independent of size.

Eccentricity engineering

Deuteron has a much larger average ε_2
RHIC has done it!

^{3}He will generate a large ε_3
RHIC is running ^{3}He right now!





PHENIX: nucl-ex/1303.1794 [PRL 111 (2013) Highlight]

Completing the science mission of RHIC

Main Questions

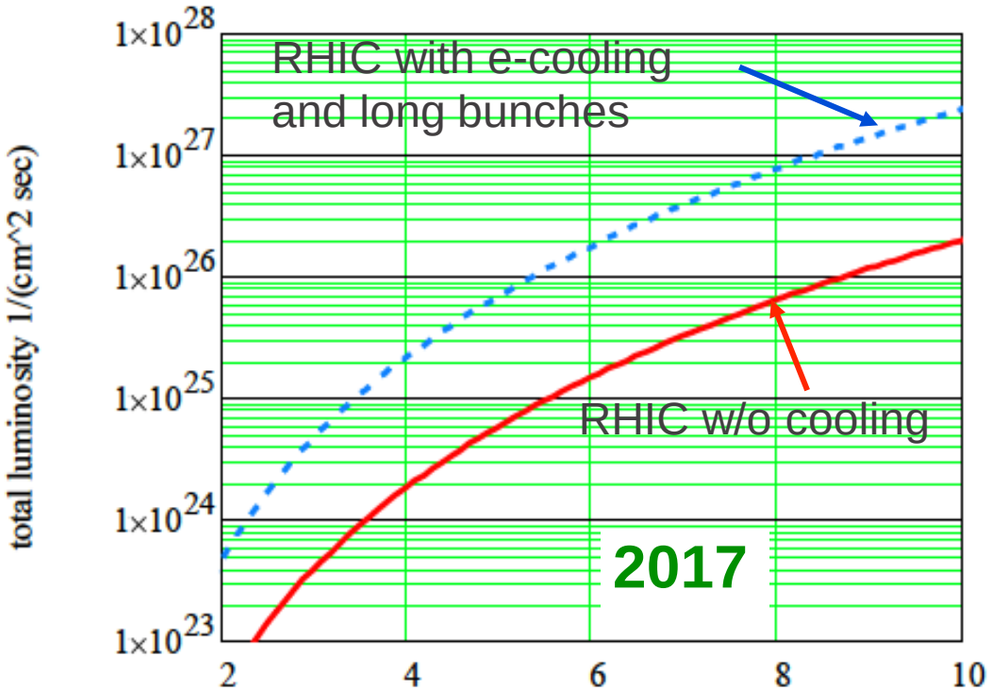
- What do we need to know about the initial state? Is it a weakly coupled color glass condensate? How does it thermalize?
- What do the data tell us about the initial conditions for the hydro-dynamic expansion? Can we determine it unambiguously?
- What is the smallest collision system that behaves collectively?
- What does the QCD phase diagram look like? Does it contain a critical point in the HG-QGP transition region? Does the HG-QGP transition become a first-order phase transition for large μ_B?
- What can jets and heavy flavors tell us about the structure of the strongly coupled QGP?
- What do the quarkonium (and other) data tell us about quark deconfinement and hadronization?
- Can we find unambiguous proof for chiral symmetry restoration?

Planned RHIC Upgrades

Machine upgrade:

Bunched beam electron cooling for low-E beams

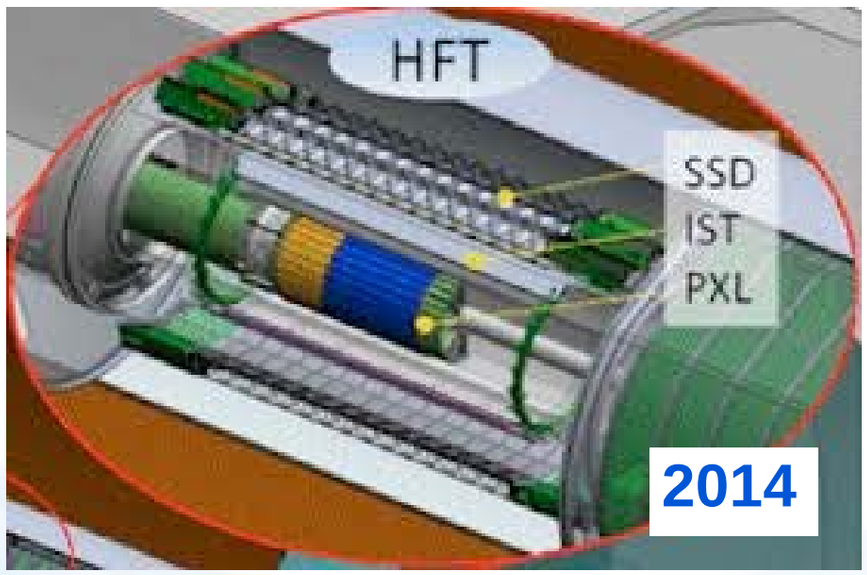
~10x luminosity



Detector upgrades:

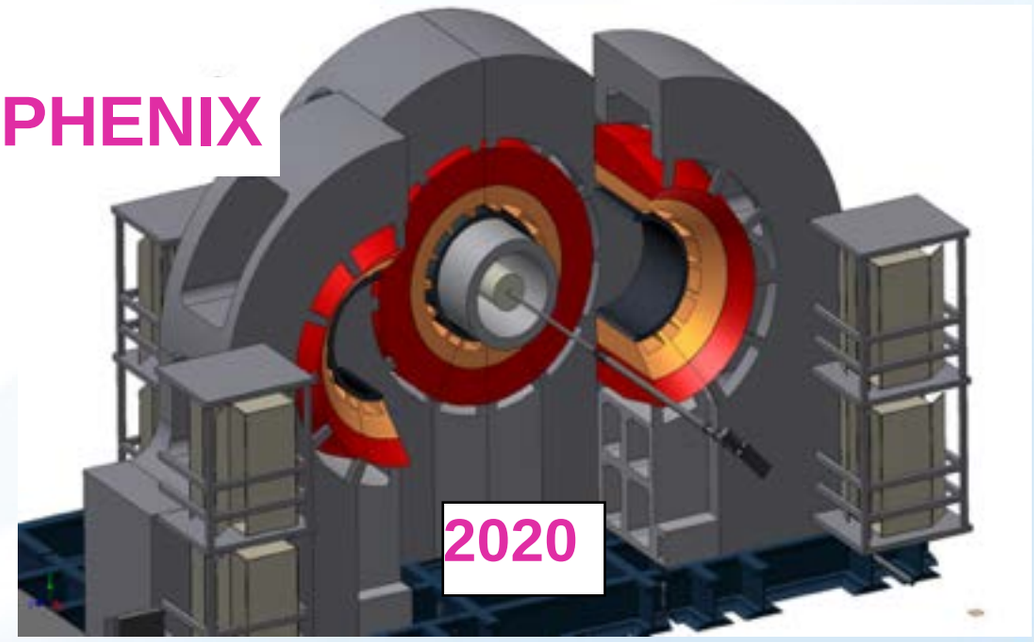
- **STAR HFT**
- **PHENIX MPC-EX**
- **STAR TPC pad rows**

- **sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC**



STAR Heavy Flavor Tracker

sPHENIX



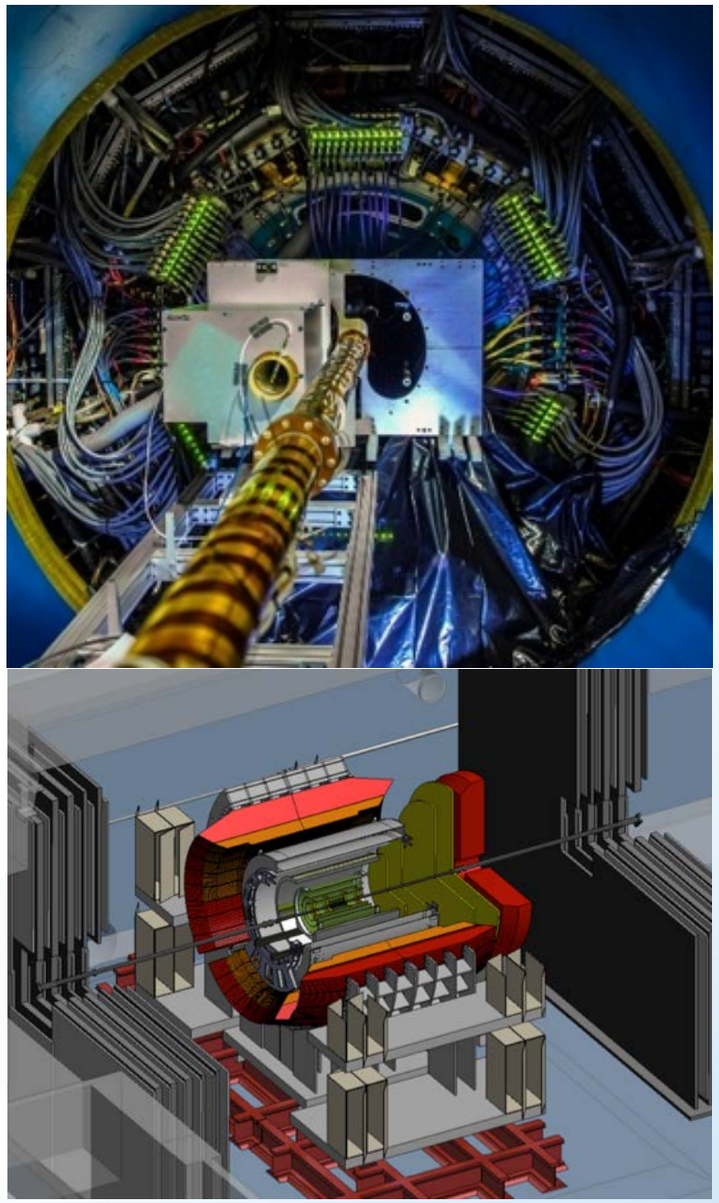
Completing the RHIC Mission

Status:

- RHIC-II configuration is now complete
  - Vertex detectors in STAR (HFT) and PHENIX
- RHIC Run 14 – Integrated Au+Au luminosity exceeds all previous Au+Au runs combined

Plan: Complete the RHIC Mission in 3 campaigns:

- **2014/15/16:** Heavy flavor probes of the QGP
  - Install low energy e-cooling in 2017
- **2018/19:** High precision scan of the QCD phase diagram
  - Install superPHENIX upgrade in 2020
- **2021/22:** Precision measurements of jet quenching and quarkonium suppression
  - RHIC shutdown and transition to eRHIC in 2023/2024



RHIC remains a unique discovery facility:
~3,000 citations/year, ~30 PhD's per year

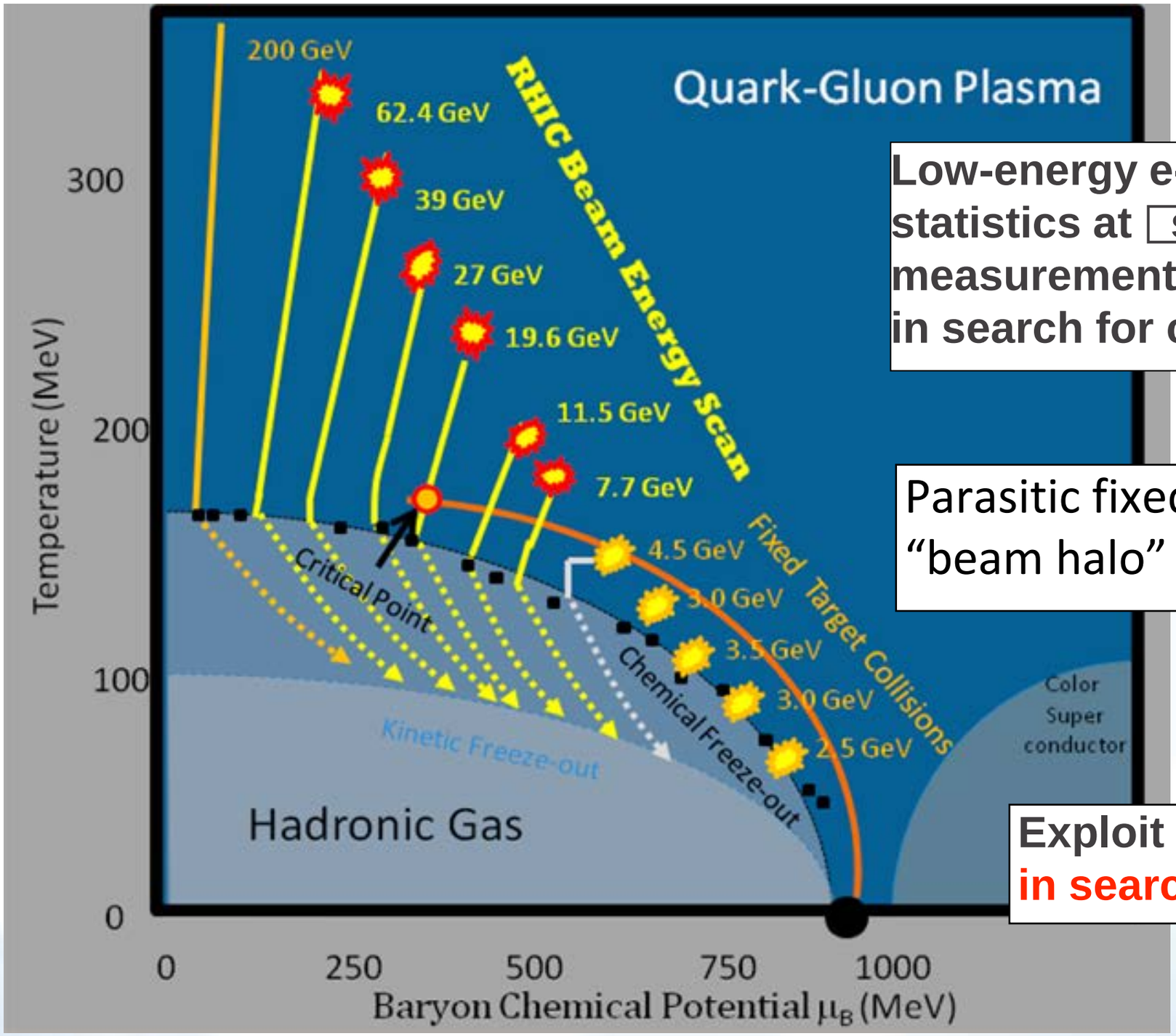
Proposed run schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	Pol. p+p at 200 GeV p+Au, p+Si at 200 GeV High statistics Au+Au Pol. p+p at 510 GeV? Au+Au at 62 GeV?	Extract η/s(T) + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX Coherent e-cooling test
2017	No Run		Low energy e-cooling upgrade
2018-19	5-20 GeV Au+Au (BES-2)	Search for QCD critical point and onset of deconfinement	STAR ITPC upgrade Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	200 GeV Au+Au with upgraded detectors Pol. p+p, p+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX
2023-24	No Runs		Transition to eRHIC

Goals for 2014-16 RHIC runs

- Precision determination of heavy quark interactions with the QGP; radiative vs. collisional energy loss.
- Heavy quark spectrum at hadronization to predict Q-Qbar recombination.
- Size dependence of collective effects for small systems.
- First study of polarized p+Au, p+Si interactions: A novel probe of parton saturation?
- Longitudinal and transverse spin effects in polarized p+p collisions (Sivers function, ΔG).
- Definitive measurement of gluon polarization over an extended x-range?
- Sign change of A_N between polarized DIS and DY ?
- Beam energy dependence of heavy quark dynamics?

Beam energy scan II



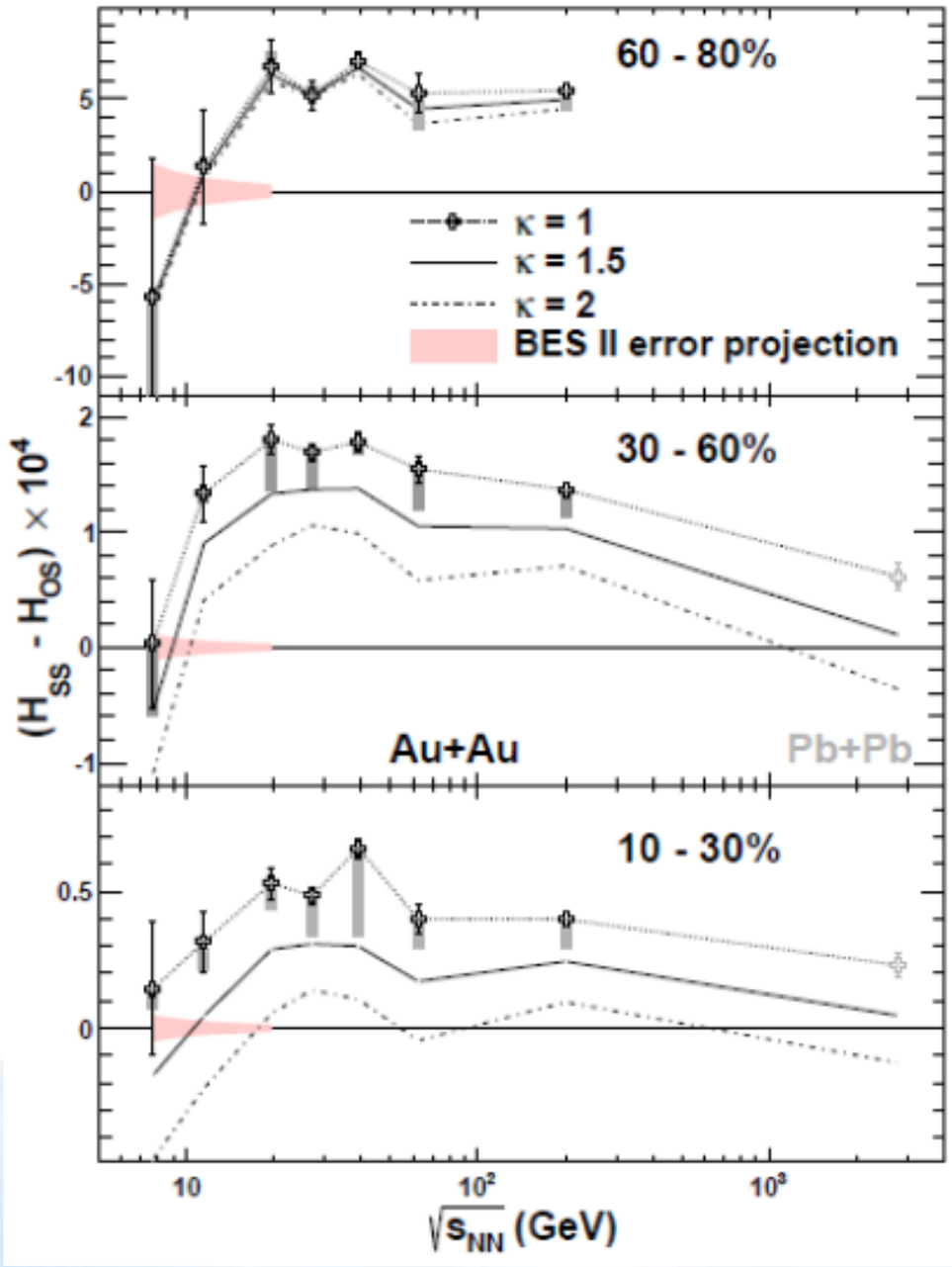
Low-energy e-cooling will improve statistics at $\sqrt{s_{NN}}$ < 20 GeV for detailed measurements of sensitive quantities in search for critical point

Parasitic fixed target mode by utilizing "beam halo" inside STAR detector ?

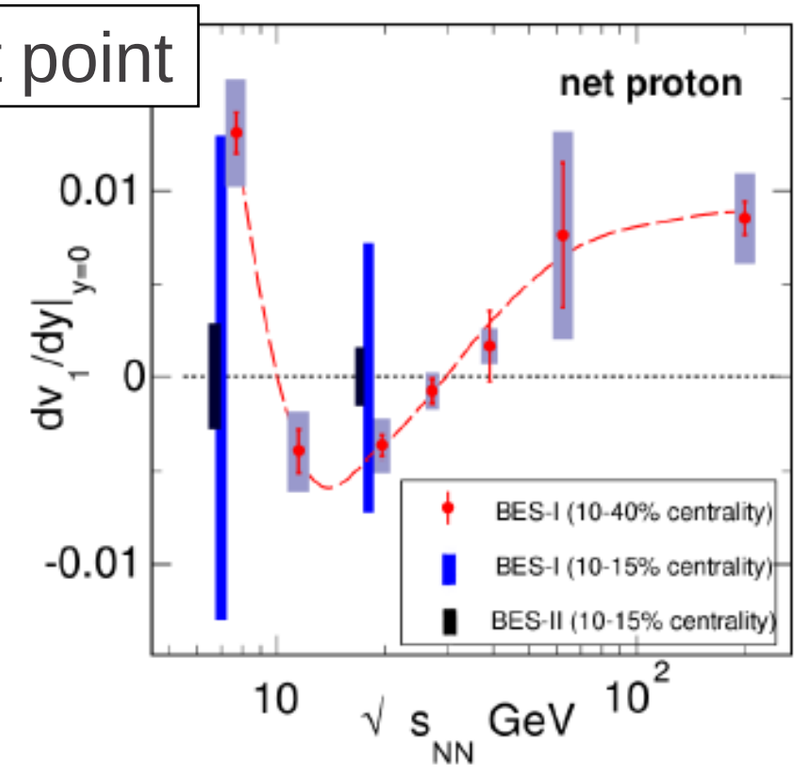
Exploit new discovery potential in search for a QCD critical point

BES-II highlights

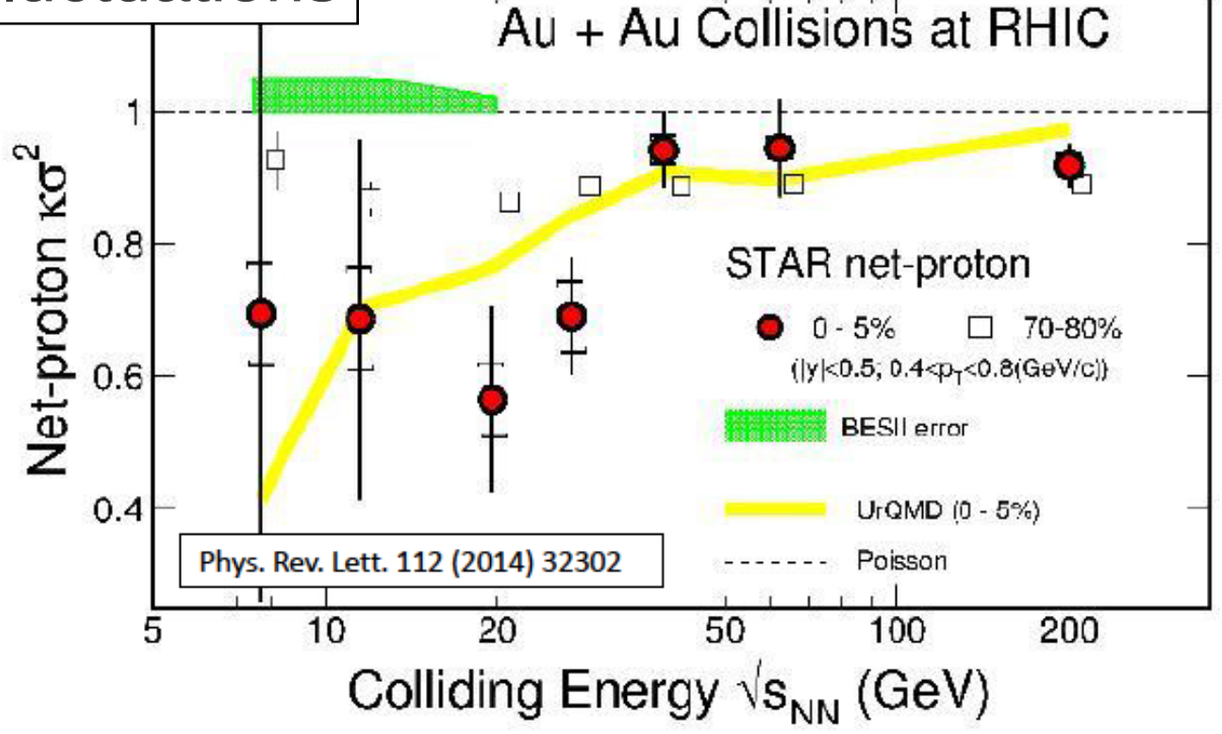
Chiral magnetic phenomena



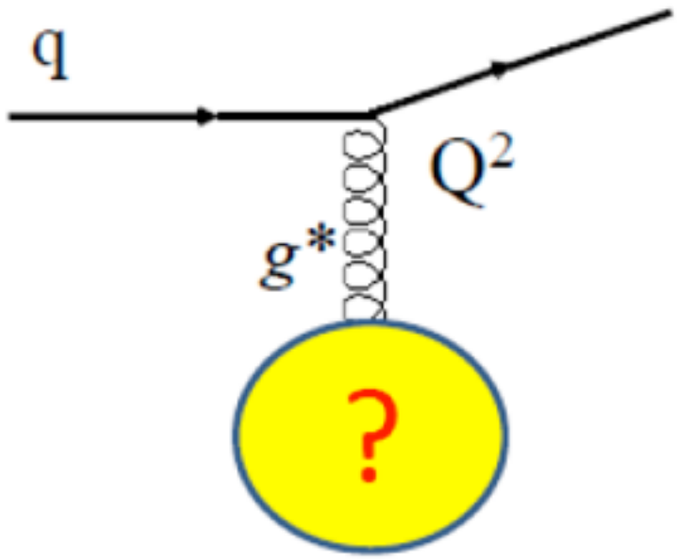
Softest point



Critical fluctuations



Probing the structure of the sQGP



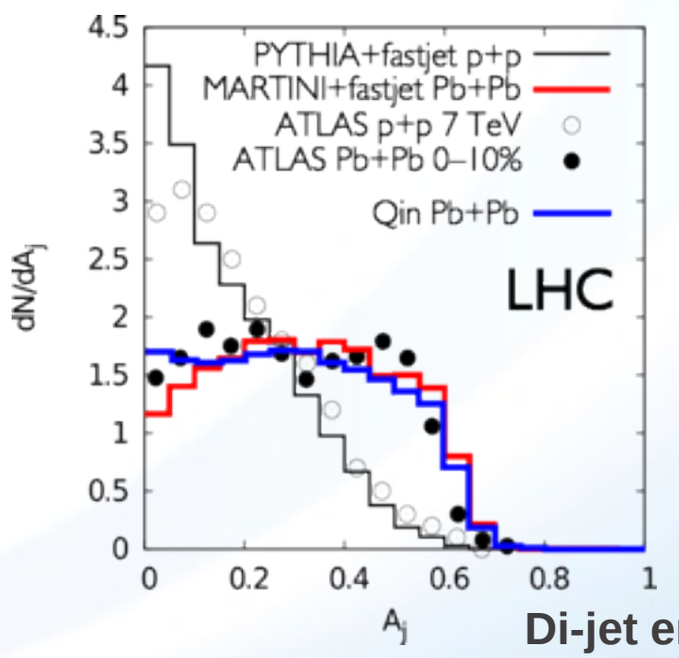
Low viscosity, rapid thermalization, and strong jet quenching are consequences of strong coupling

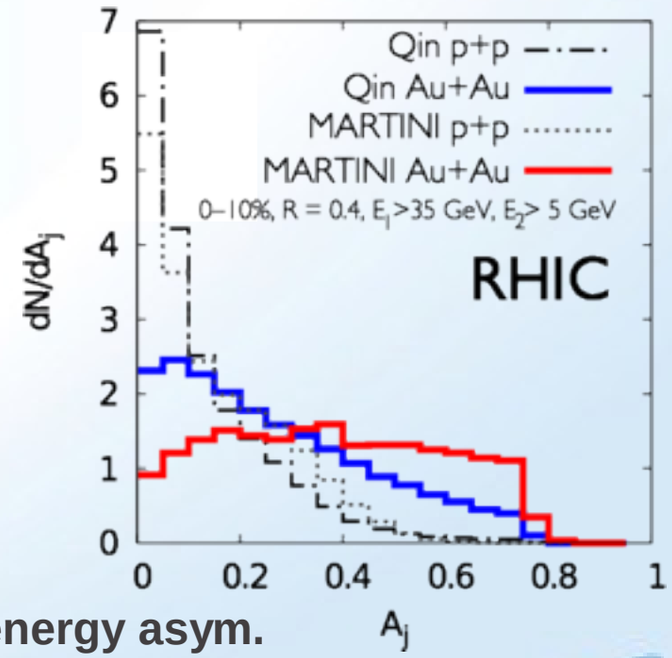
Determination of qhat(T), | /s(T) permits analysis of coupling strength

Requires measurements of jet, di-jet, ©-jet quenching, jet structure at multiple □$

sPHENIX upgrade will enable full jet reconstruction at RHIC

BaBar solenoid in its transfer frame

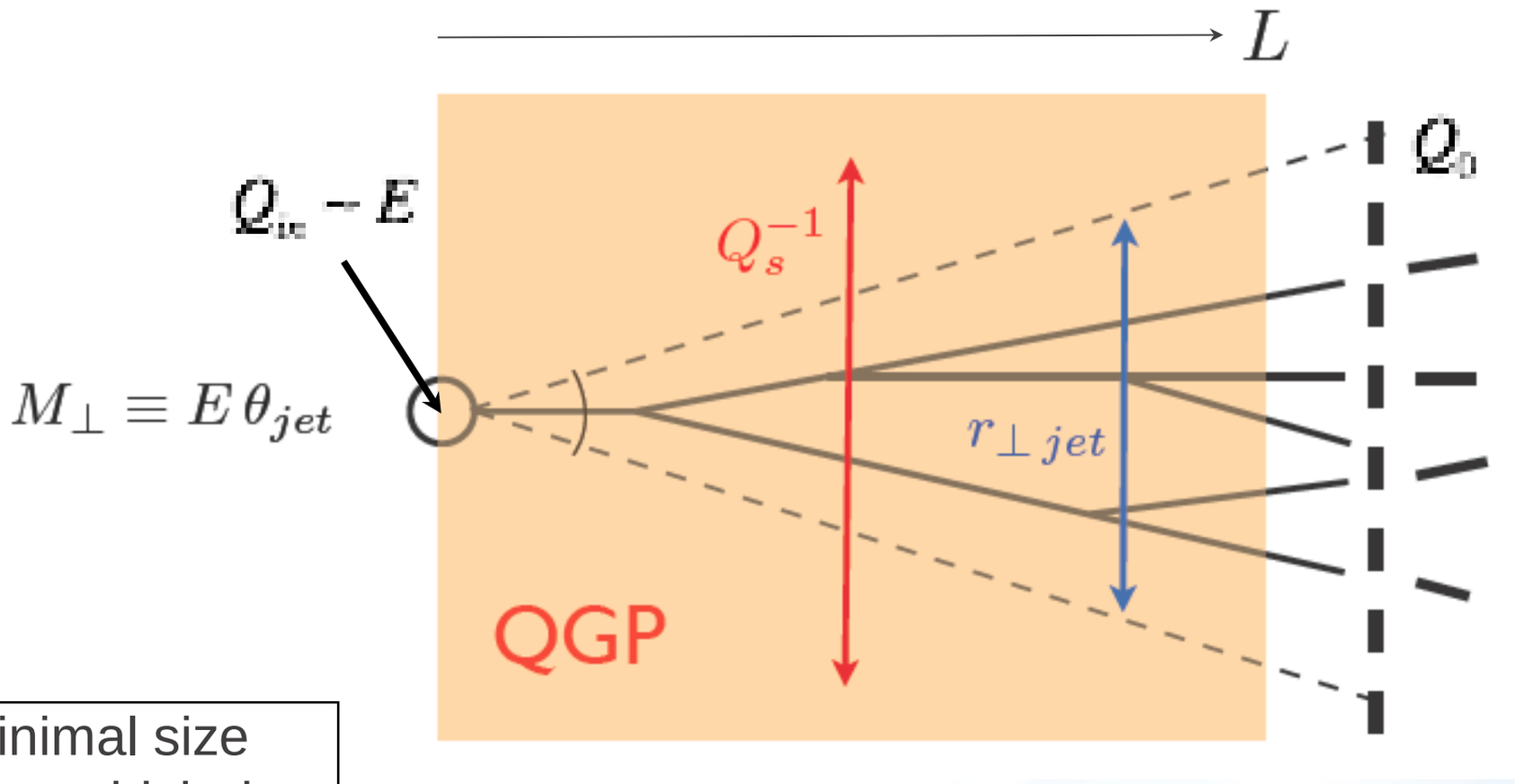




Di-jet energy asym.

RHIC +LHC data can discriminate between models

Why jets are a good medium probe



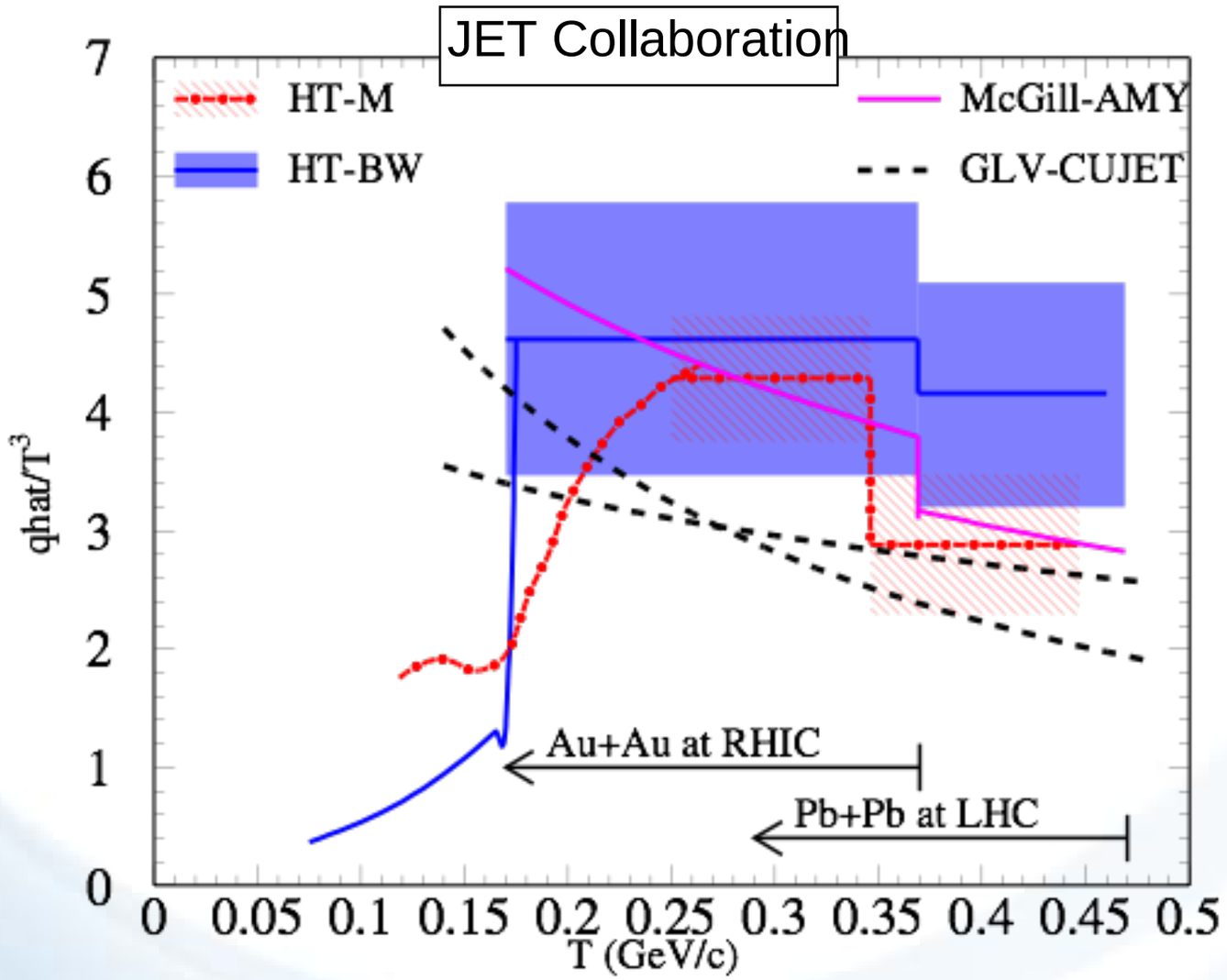
Q_s^{-1} = minimal size of probe to which the medium look opaque

Momentum scale of medium $Q_s = \sqrt{qL} = m_D\sqrt{N_{scatt}}$

Transverse size of jet $r_{\perp jet} = \theta_{jet} L$

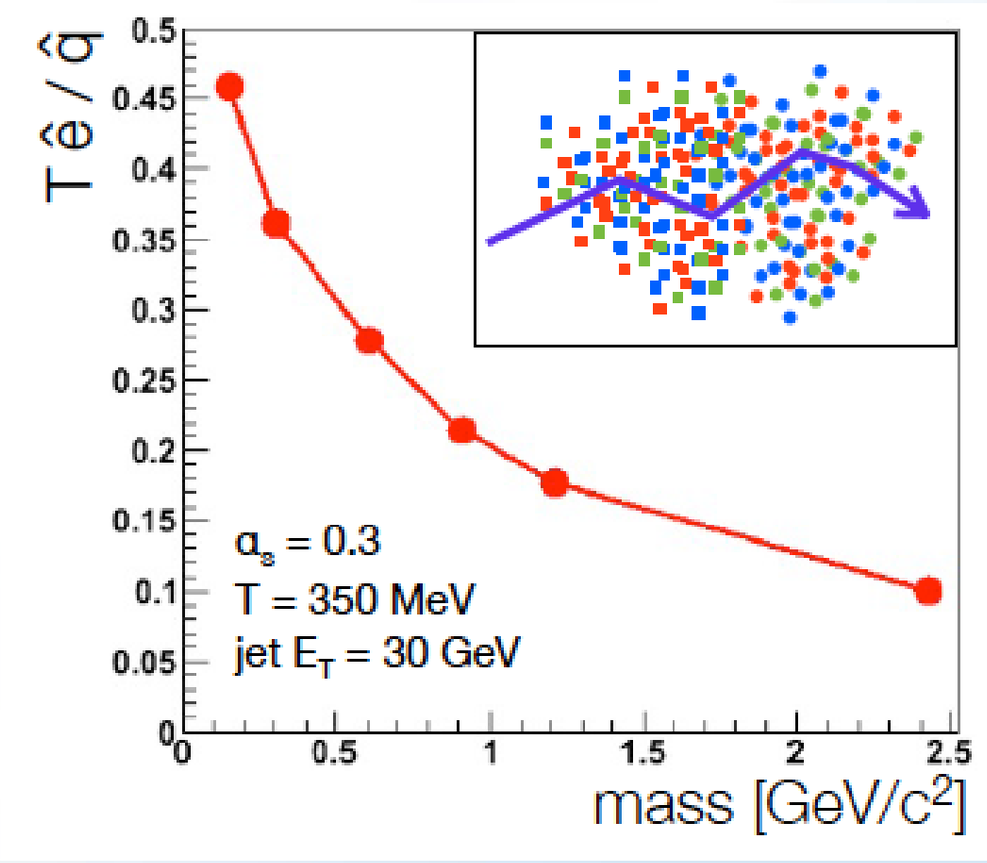
Extracting medium properties

Collaborative theoretical efforts now make the extraction of qhat and ehat from data possible.



C. Coleman-Smith (1209.3328):

The ratio of ehat/qhat is sensitive to the mass of QGP constituents.

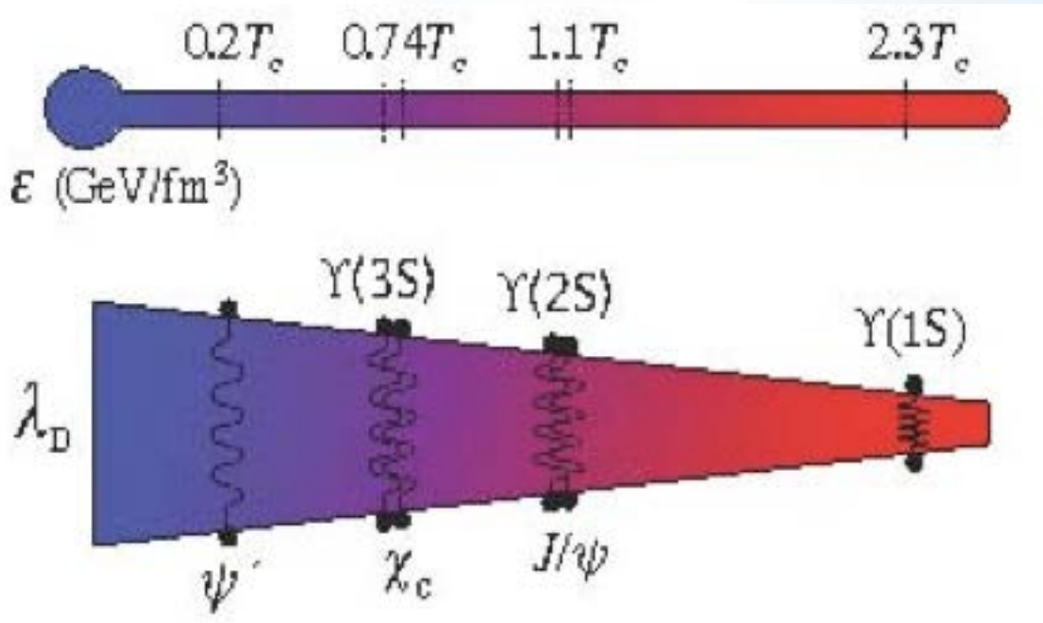


The *Plasma* in QGP

- **Plasma: An globally neutral state of matter with mobile charges**
- **Interactions among charges of many particles spread charge over a characteristic (Debye) length ➡ (chromo-) electric screening**
- **Strongly coupled plasmas: Only few particles in Debye sphere ➡ Nearest neighbor correlations ⇿ liquid-like properties**
- ***Test* QGP *screening with heavy quark bound states***

Do they survive? Which ones?

- **Ideal system: Upsilon states**
- **sPHENIX can resolve Y states**
- **Do residual correlations enhance recombination?**



Beyond RHIC

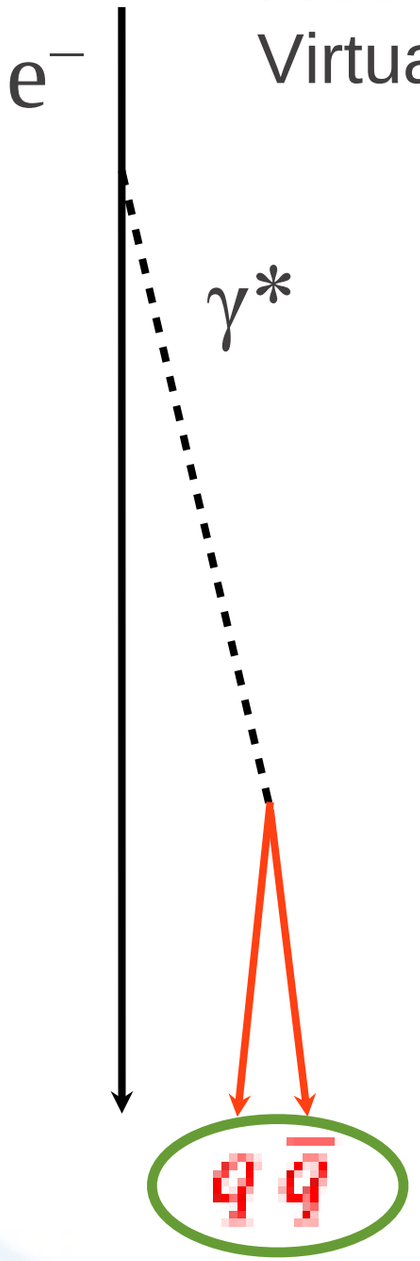
EIC: A color dipole microscope

Free color charges (e.g. quarks) do not exist, but **color dipoles** do!
Virtual photons are an excellent source of color dipoles.

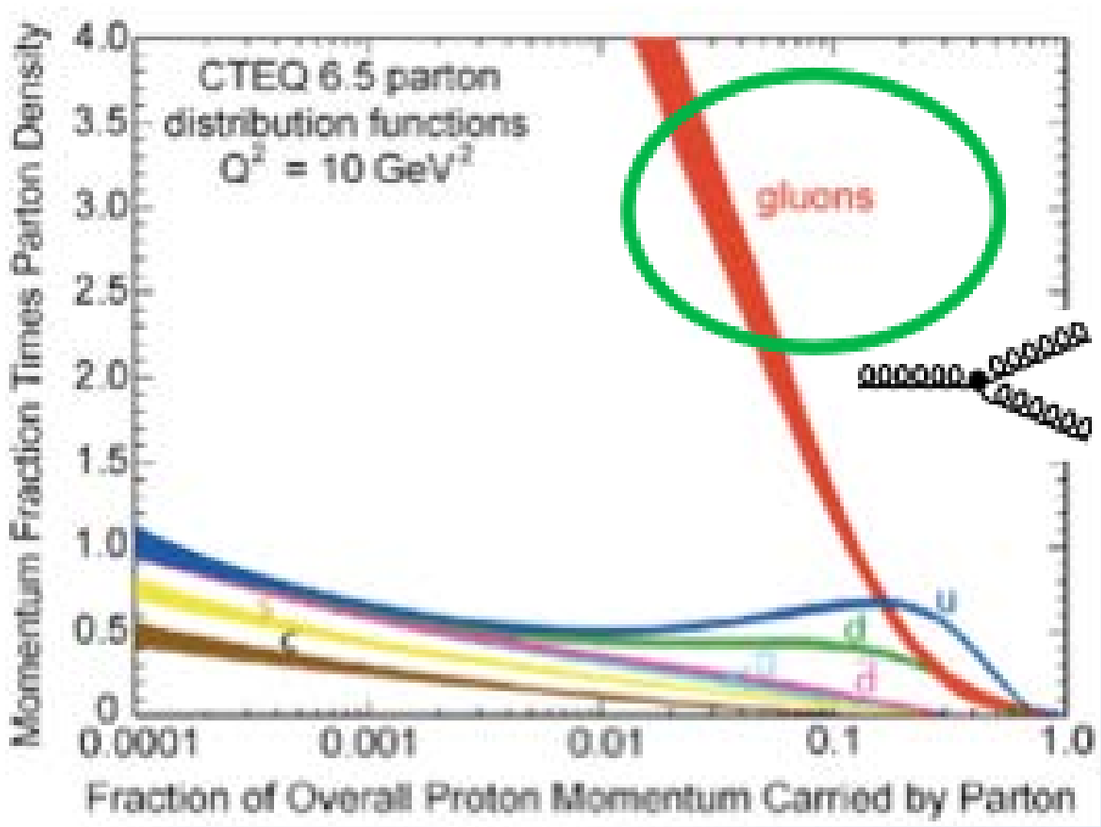
Two resolution scales:

- momentum k (longitudinal)
- virtuality Q (transverse)

⇒ More powerful than an optical microscope!



Color dipoles "see" gluons

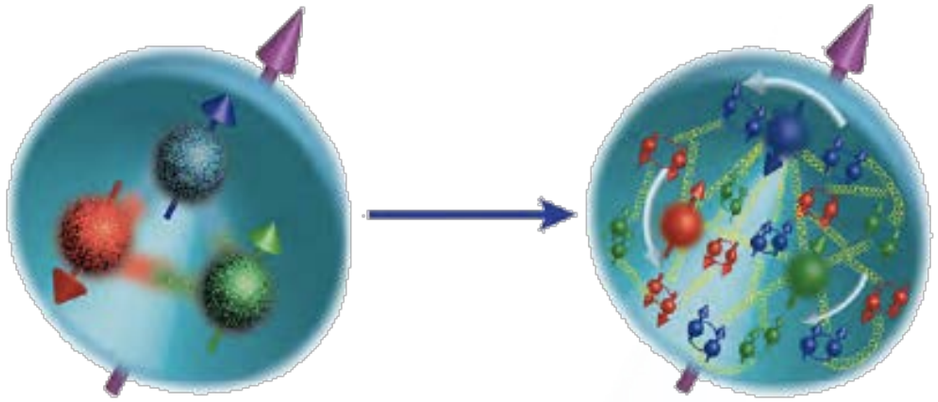


HERA was the 1st generation color dipole microscope, with limited intensity and no polarization.

EIC will be a 2nd generation color dipole microscope, **>100-fold intensity** and **polarization**!

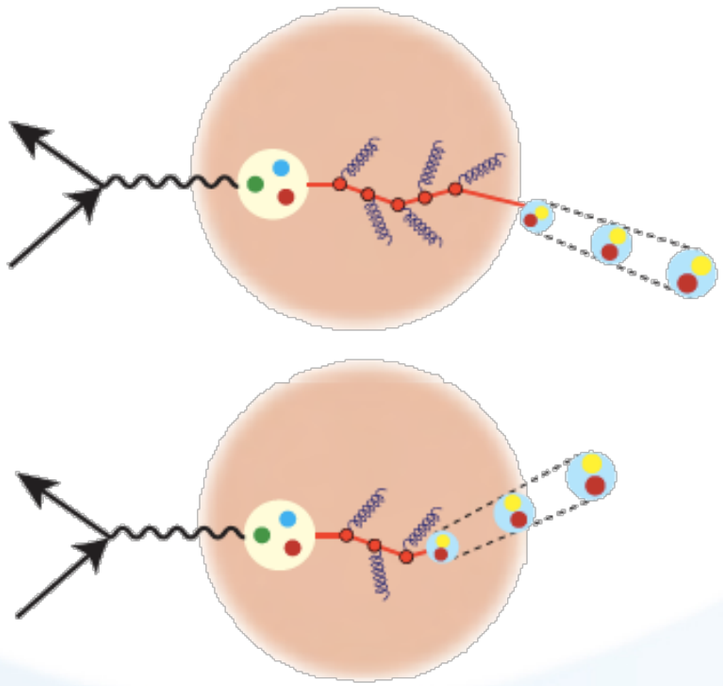
The EIC: A QCD Laboratory

Gluon structure of the proton:
How is the proton's mass generated and what carries its spin?

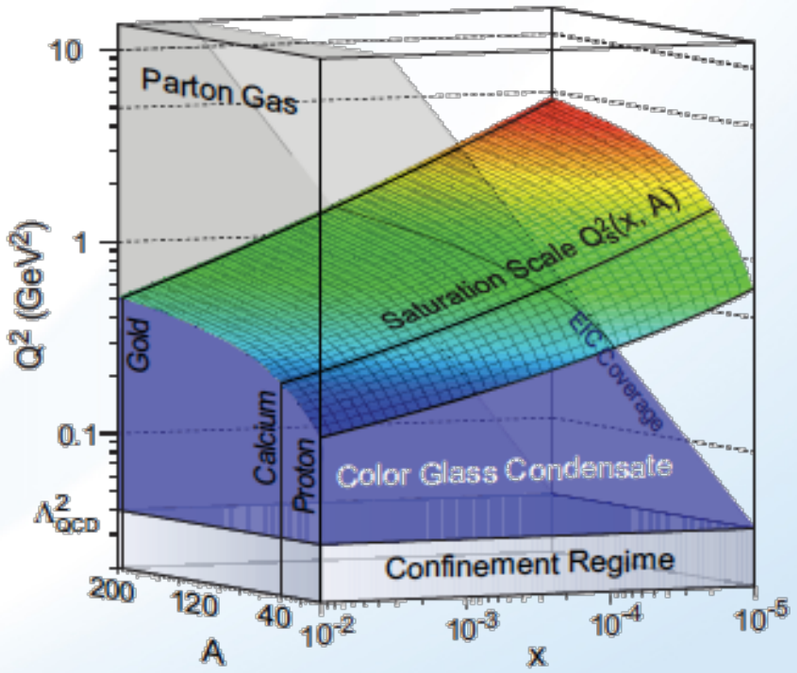


Today's proton Proton @ EIC

How do confined hadrons emerge from isolated quarks?



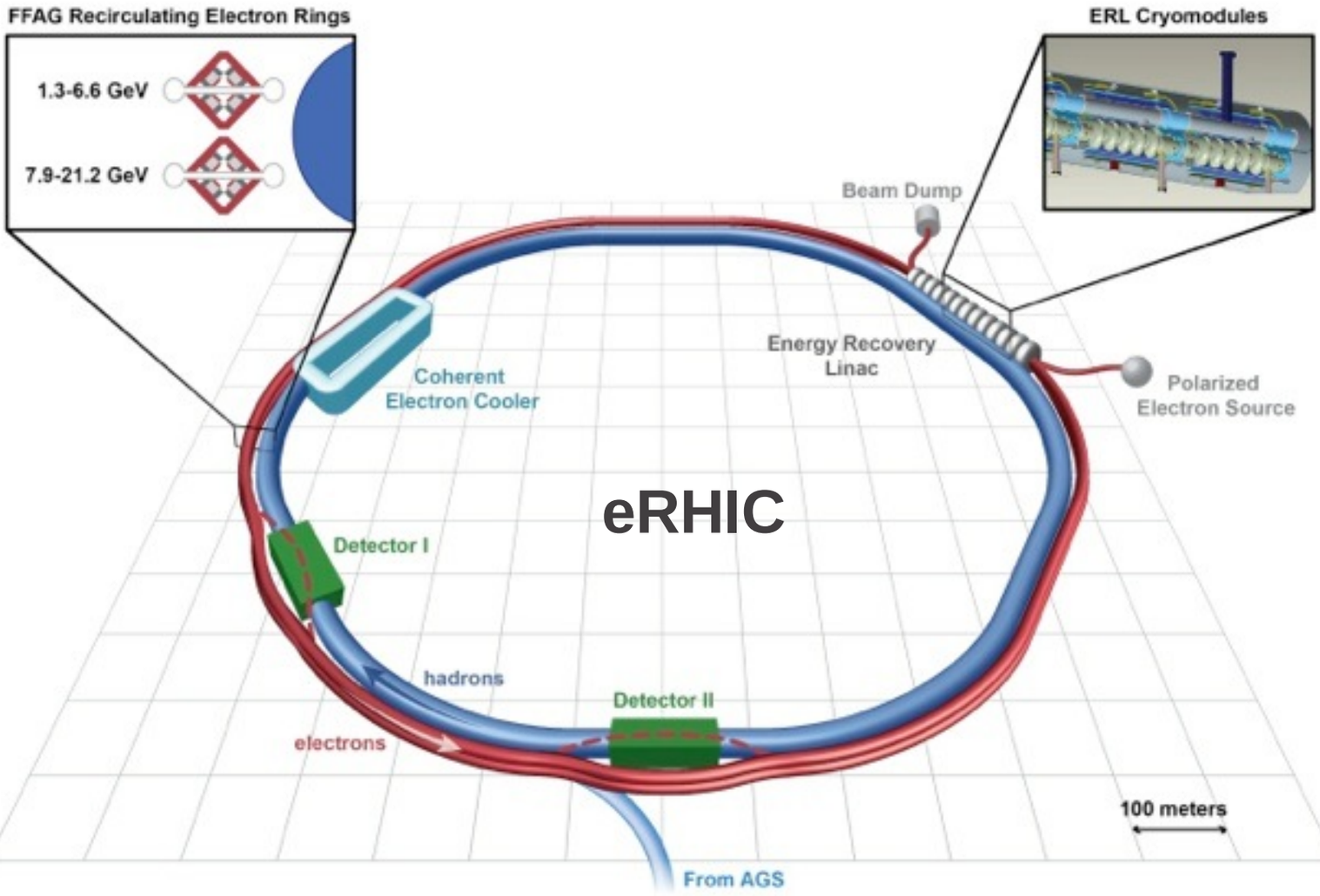
High density phase of cold gluon matter



BNL's EIC Concept

eRHIC ERL + FFAG ring design @ $10^{33}/cm^2s$

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



ePHENIX and eSTAR Letters of Intent

When completed, eRHIC will be the most advanced and energy efficient accelerator in the world

LRP Issues

- Convince the nuclear physics community of the need to complete the scientific mission of RHIC:
  - Emphasize unique features of RHIC (versatility, pol. p)
  - BES-II needs significant theoretical work using state of the art dynamical modeling including fluctuations
  - Opportunity for TEC-BES (*à la* TEC-HQM)
  - Much remains to be done after JET Collaboration ends; how to preserve infrastructure and momentum?
  - What remains to be done in the polarized p program?
  - How compelling at forward upgrades of STAR/sPHENIX?

- Further develop the science case for EIC:
  - Maintain JLab-BNL alliance on EIC physics and R&D
  - Sharpen science case
  - Continue to look for unidentified opportunities
  - More at EIC Users meeting next week at SBU

Out-of-the-Box

- Structure of the RHIC community after 2016:

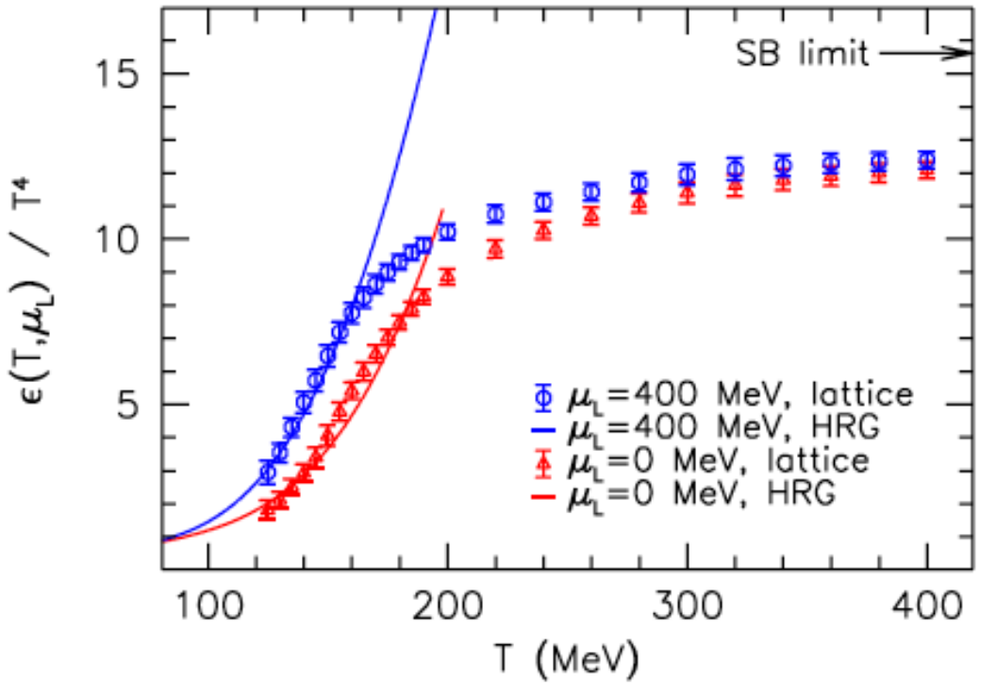
  - Cross-collaboration participation
    - PHENIX members joining STAR for the BES-II
    - STAR members contributing to construction of sPHENIX

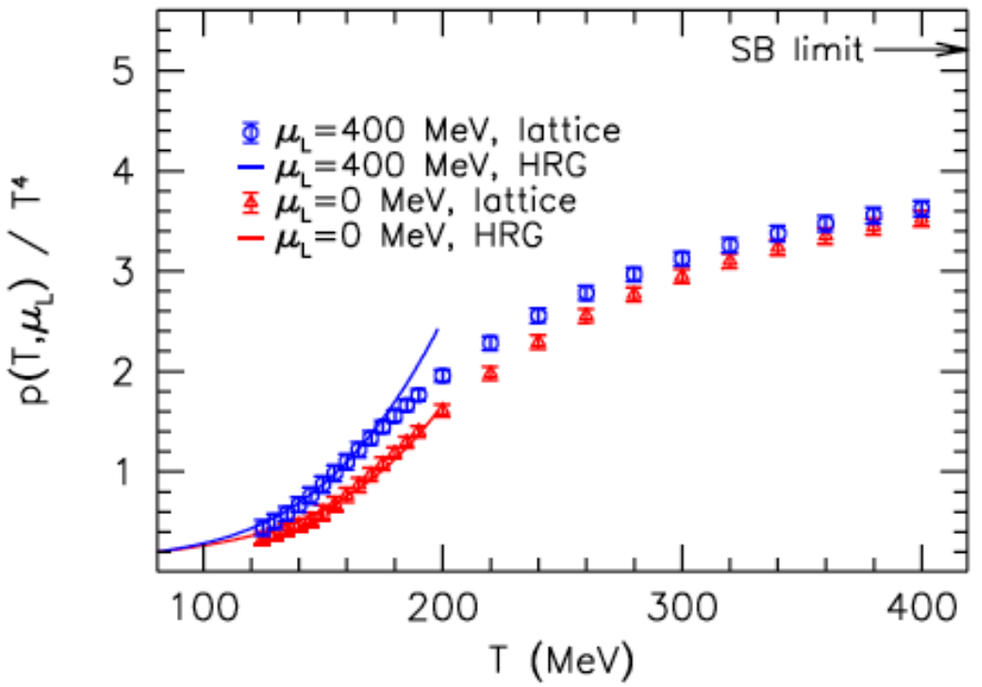
  - Enduring experiment-theory collaborations
    - Bulk transport and observables for BES-II
    - Jet modification in QGP
    - Heavy quark transport and quarkonium phenomenology

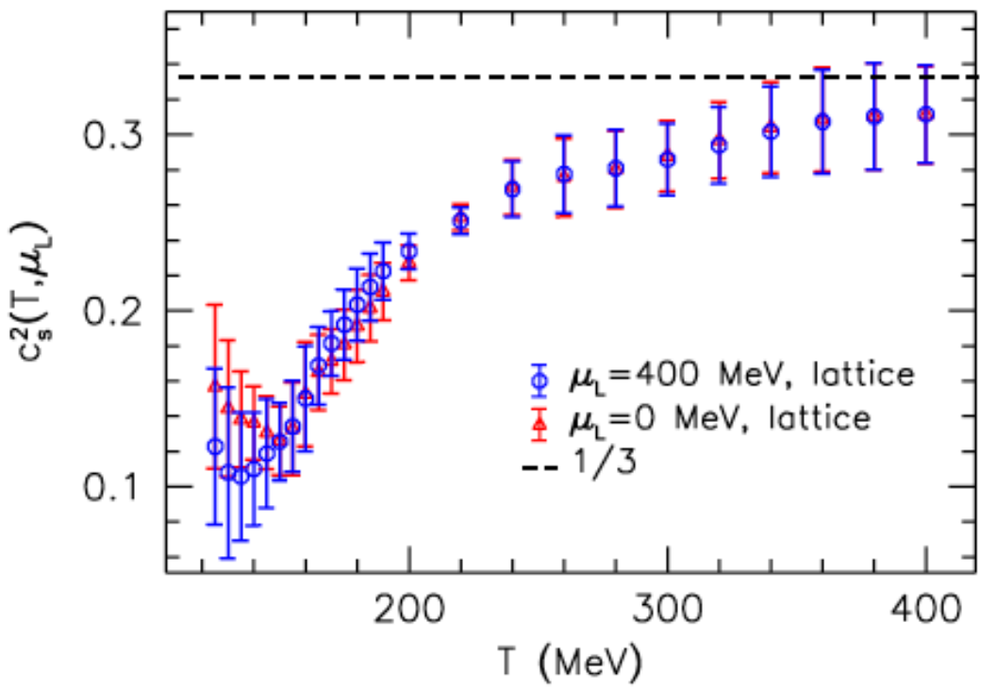
  - How can the existing RHIC users community and a nascent EIC users community coexist and benefit from each other?
    - If eRHIC is built, how will STAR and (s)PHENIX transit into eSTAR and ePHENIX?

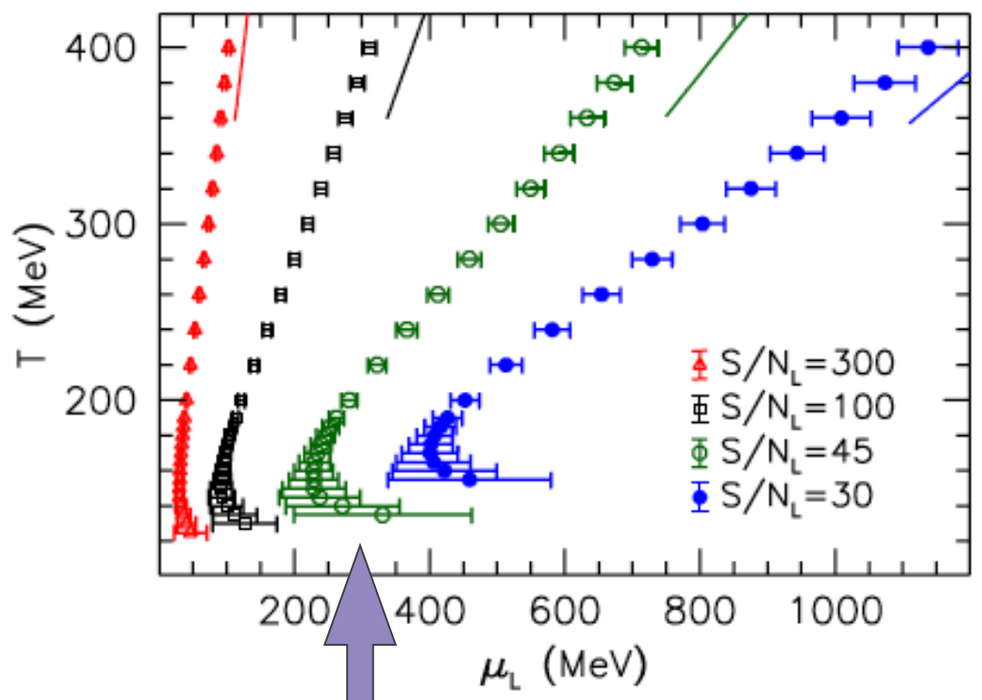
QCD EOS at $\mu_B \neq 0$

Borszanyi et al., arXiv:1204:6710









Approximate trajectories in QCD phase diagram