The Physics of QCD Matter

Challenges and Opportunities

Berndt Mueller
Brookhaven National Laboratory
& Duke University

New Frontiers in QCD 2013
Yukawa Institute, Kyoto
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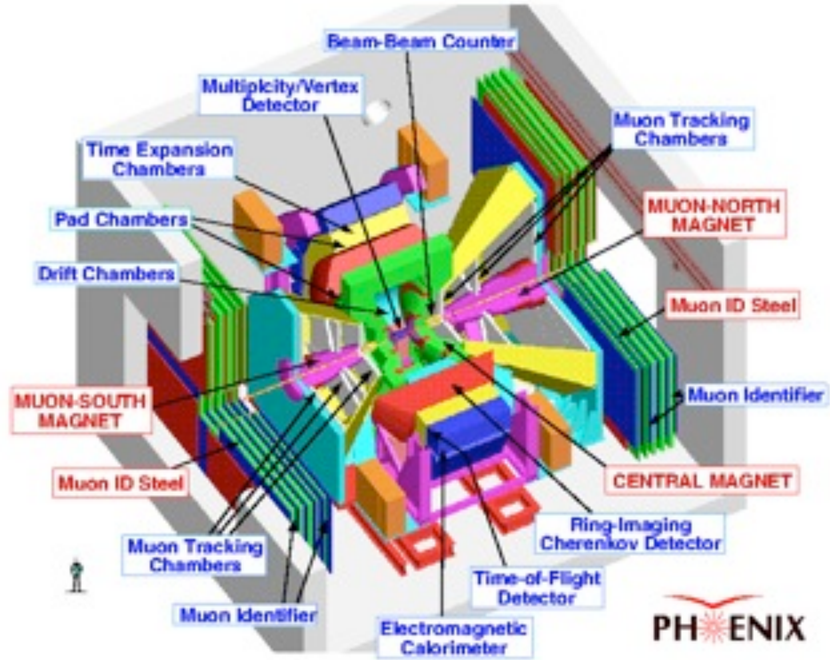
Where we are

The Accelerators

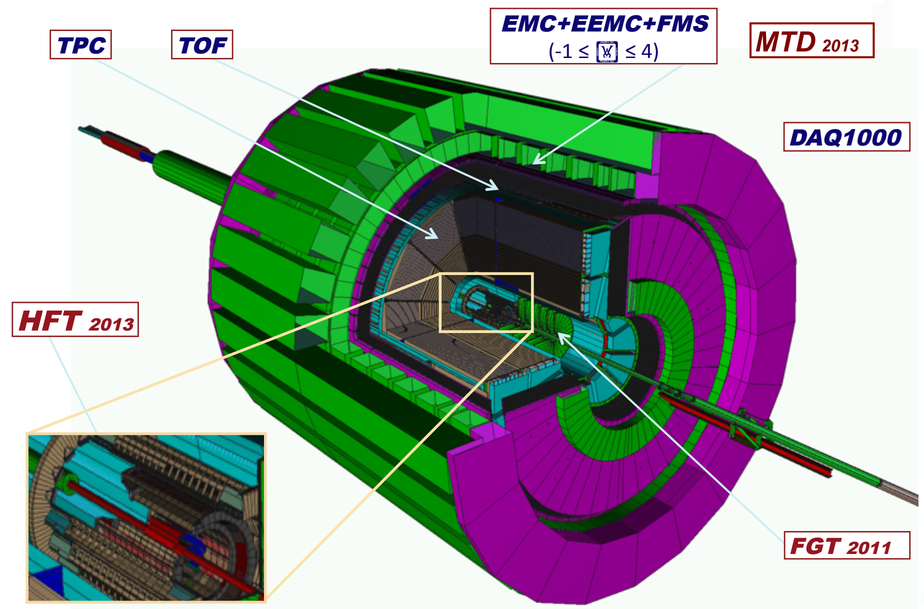
Large Hadron Collider
27 km circumference
Energy: E_{cm} = 2.76 TeV/NN

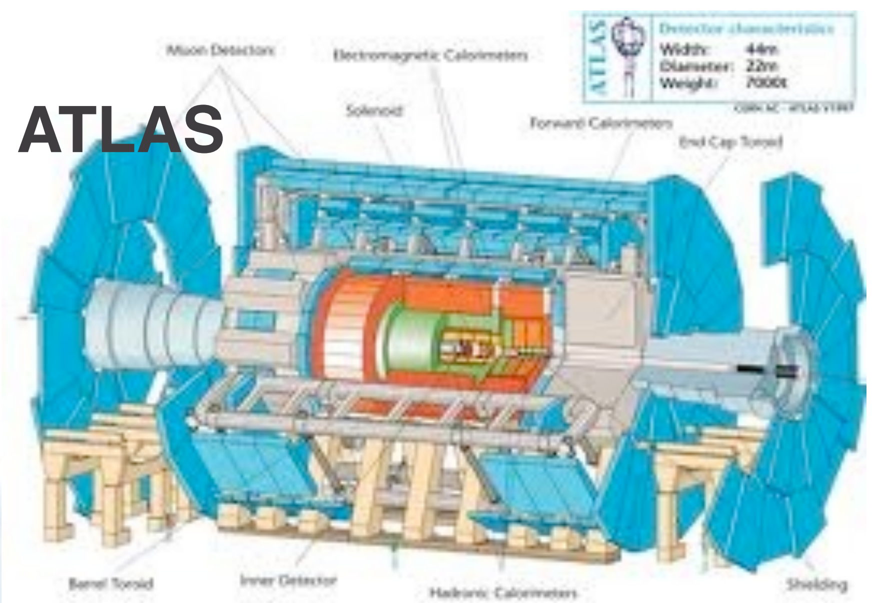
Relativistic Heavy Ion Collider
3.8 km circumference
Top energy: E_{cm} = 200 GeV/NN
RHIC also collides polarized p

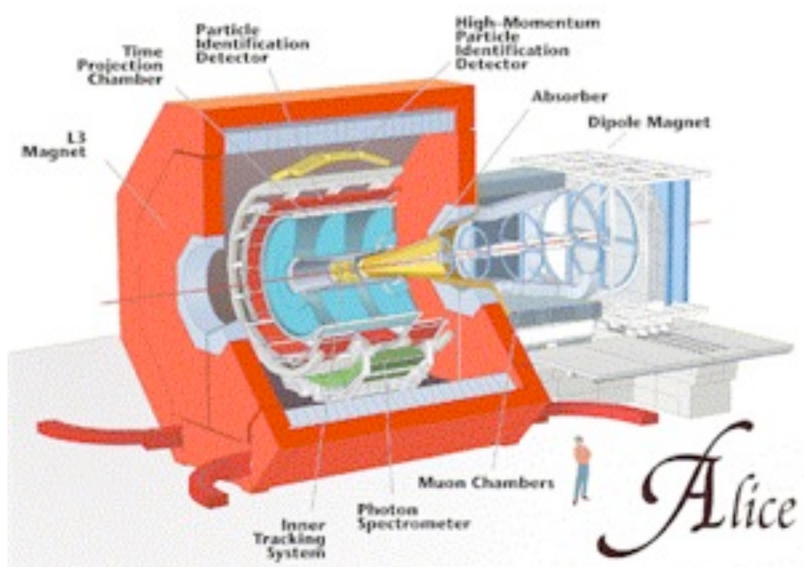
The Detectors



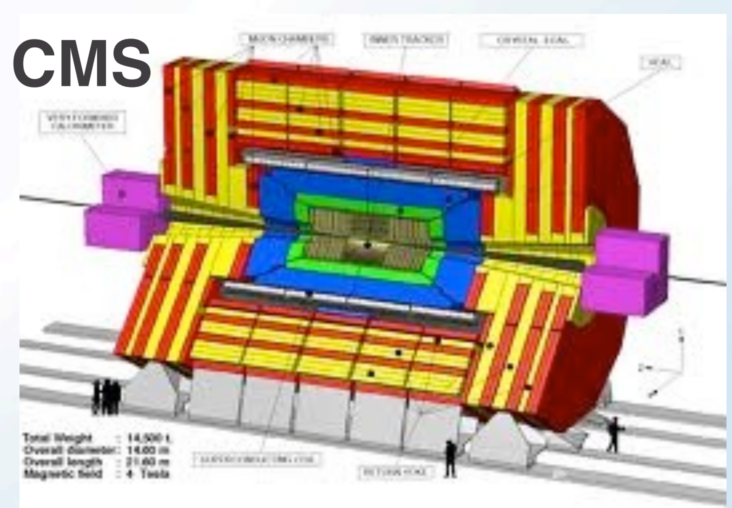
STAR Detector



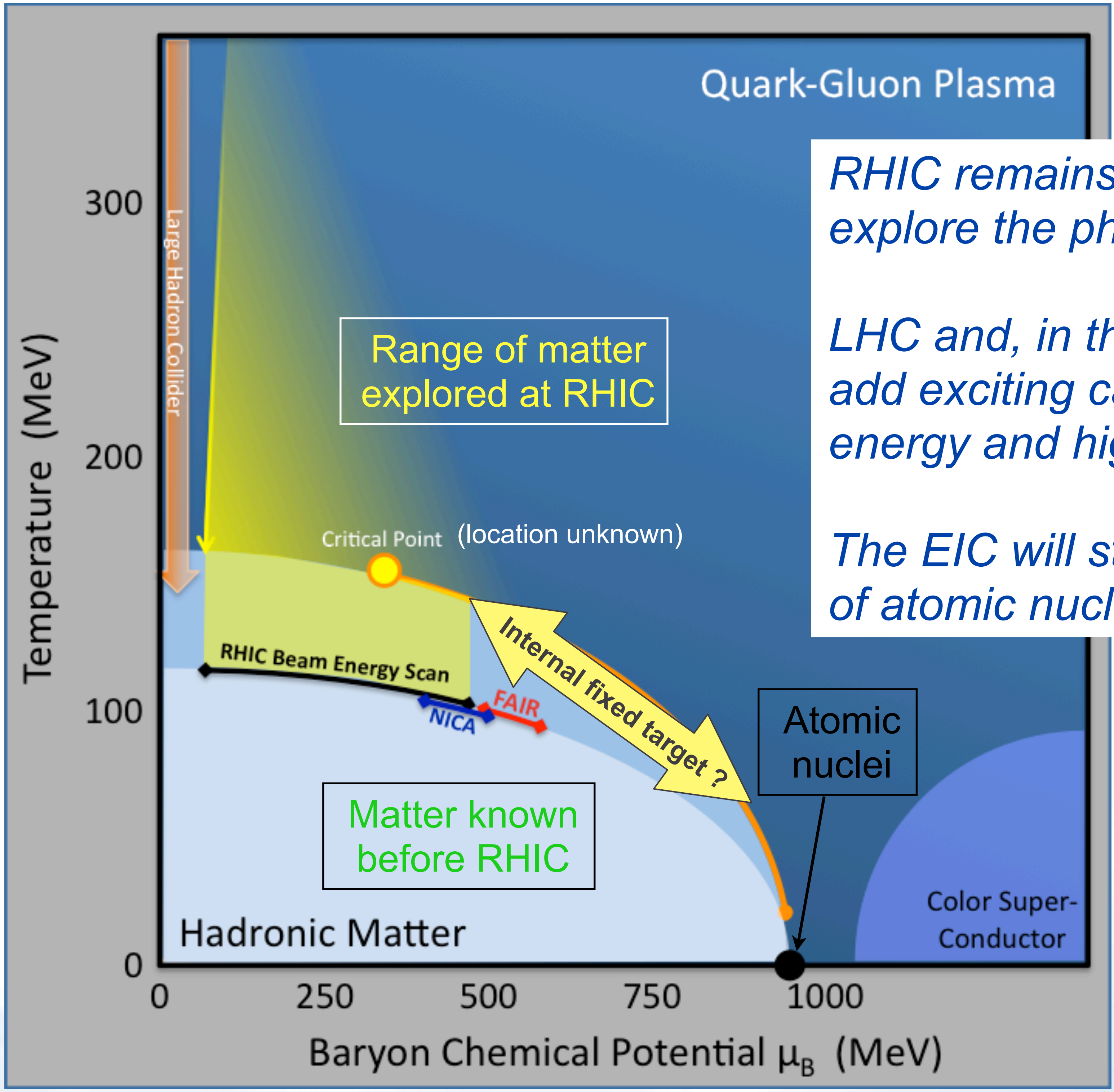




CMS



The Landscape



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

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

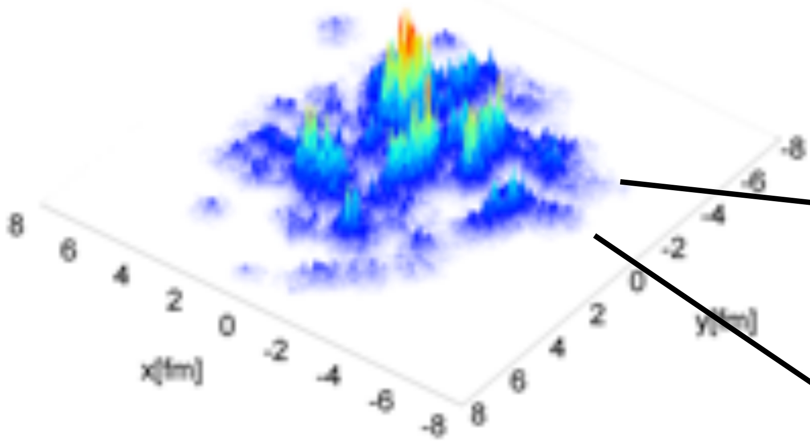
The EIC will study the parton structure of atomic nuclei in the field domain.

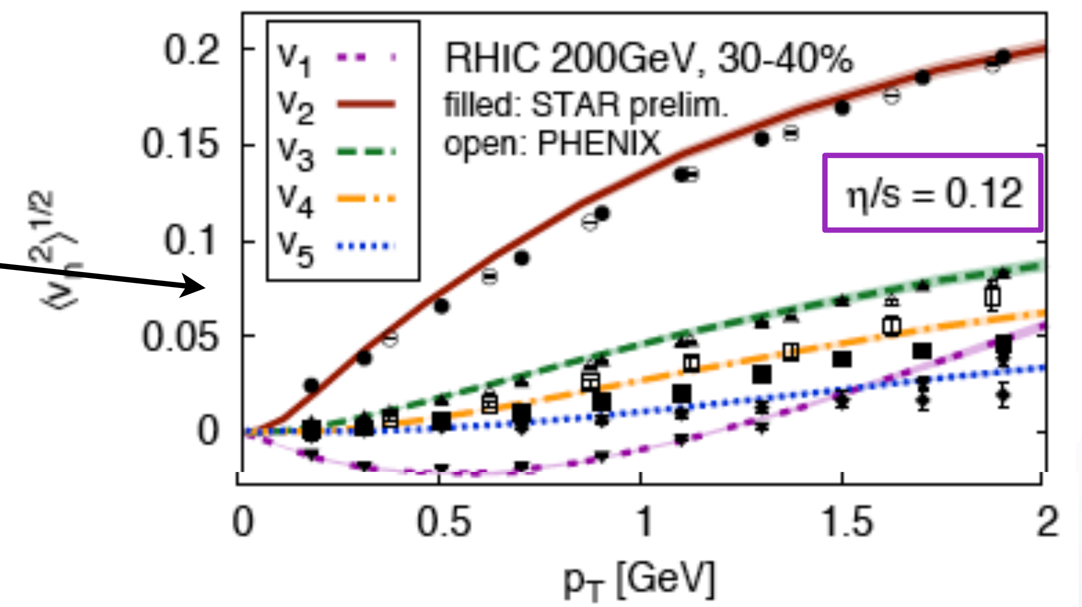
Main Discoveries

- 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.
- Approx. 20% of the proton spin is probably carried by **gluons**.

QCD Matter at RHIC is most "perfect"

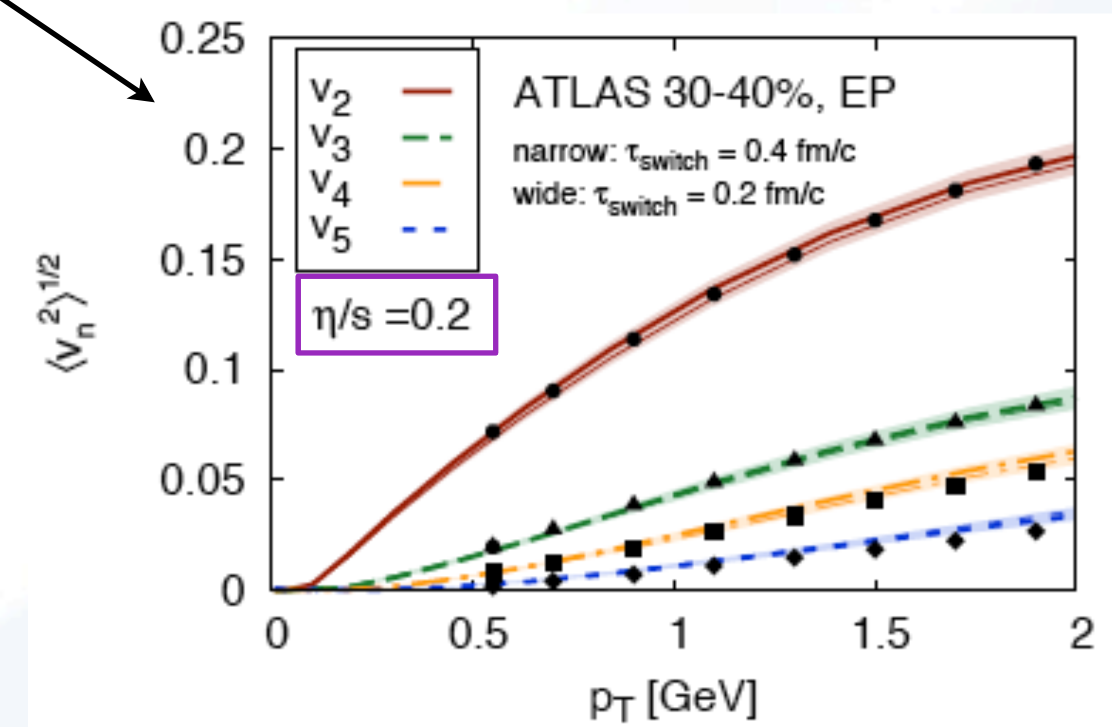
Initial density distribution





RHIC

Quantum limit: $\eta/s = 0.08$.



LHC

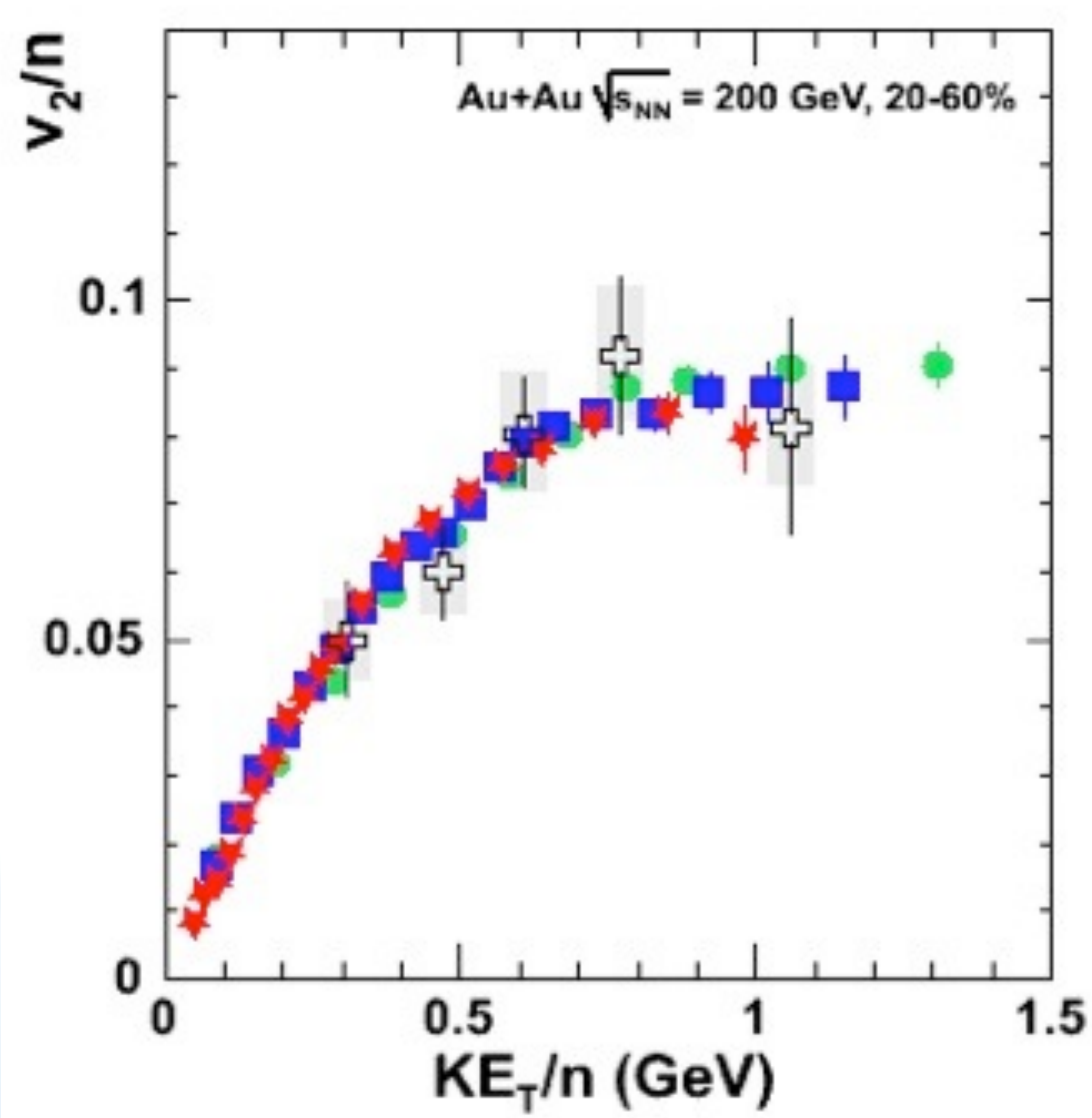
$(\eta/s)_{\mathrm{RHIC}} \approx 0.6\ (\eta/s)_{\mathrm{LHC}}$

This is an average statement. The temperature dependence of η/s may be much steeper.

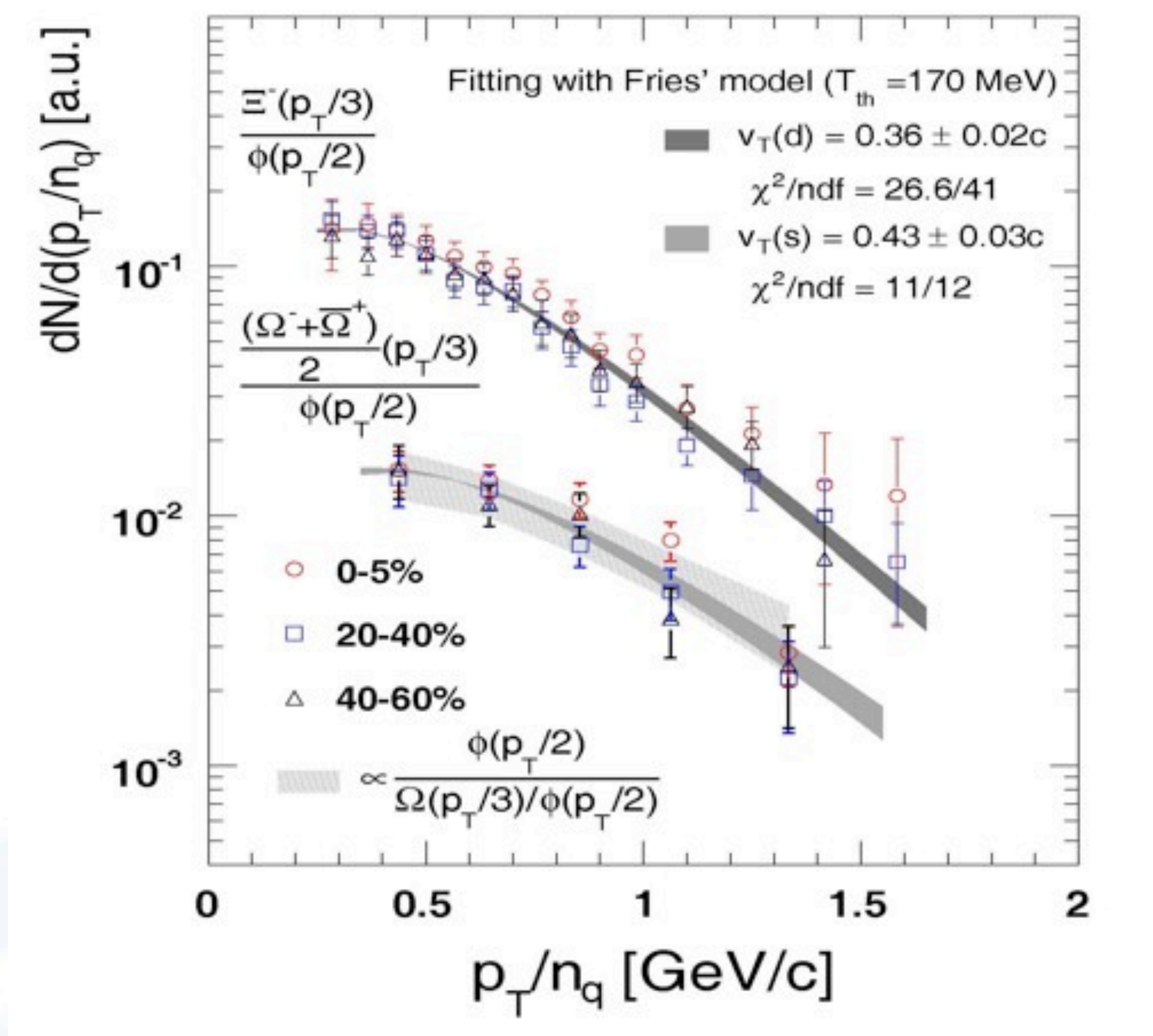
Quark number scaling

Emitting medium is composed of unconfined, flowing quarks.

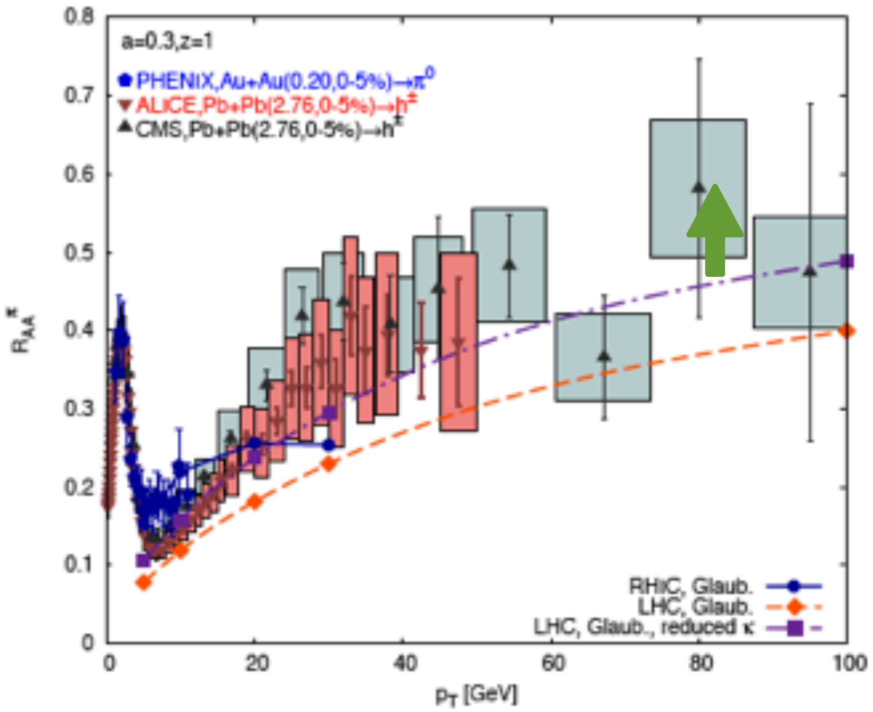
$$\frac{1}{2}v_2^M(p_t) = v_2^Q\left(\frac{p_t}{2}\right) \qquad \frac{1}{3}v_2^B(p_t) = v_2^Q\left(\frac{p_t}{3}\right)$$

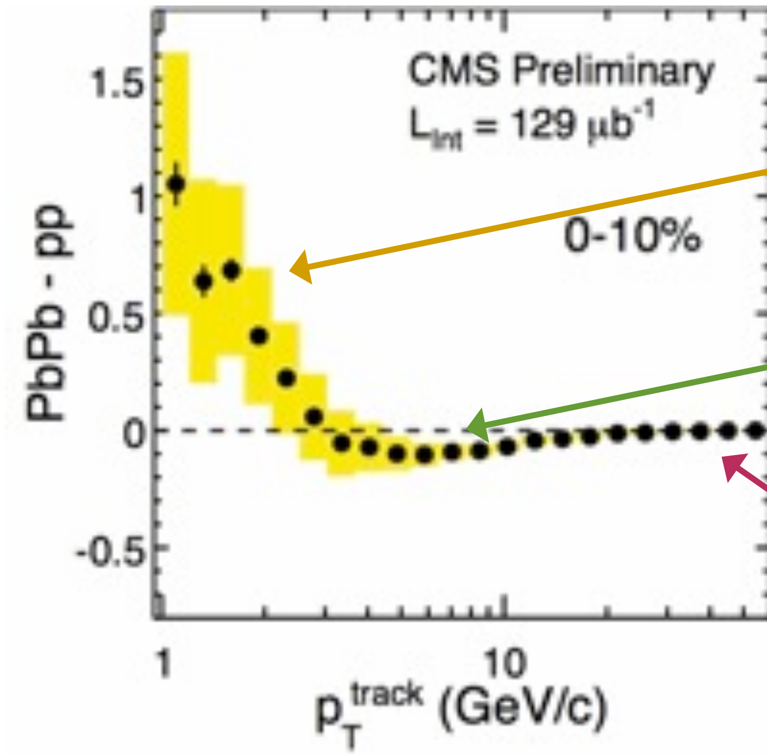


STAR/UCLA group



Jet quenching

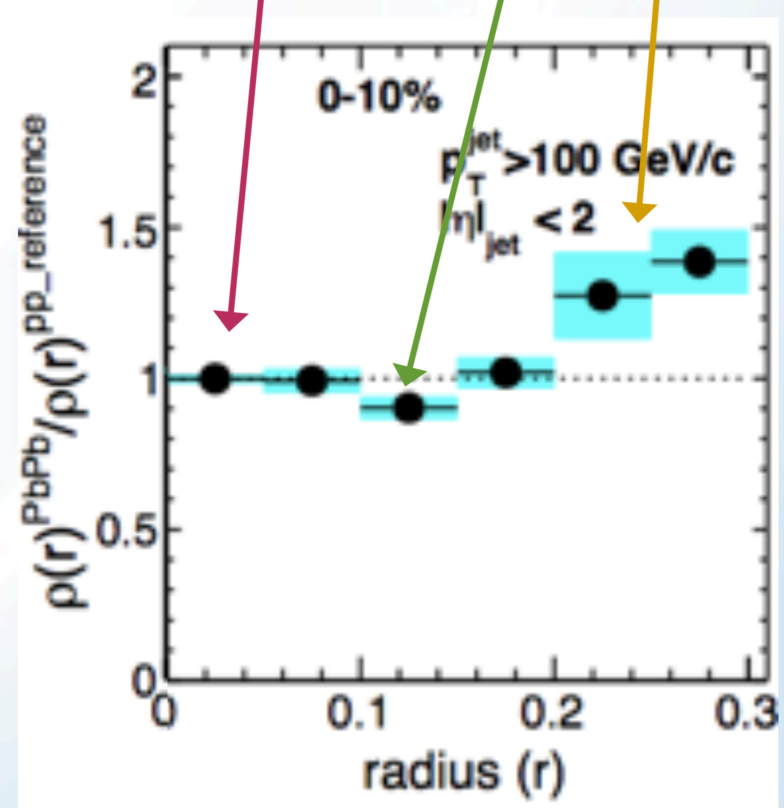


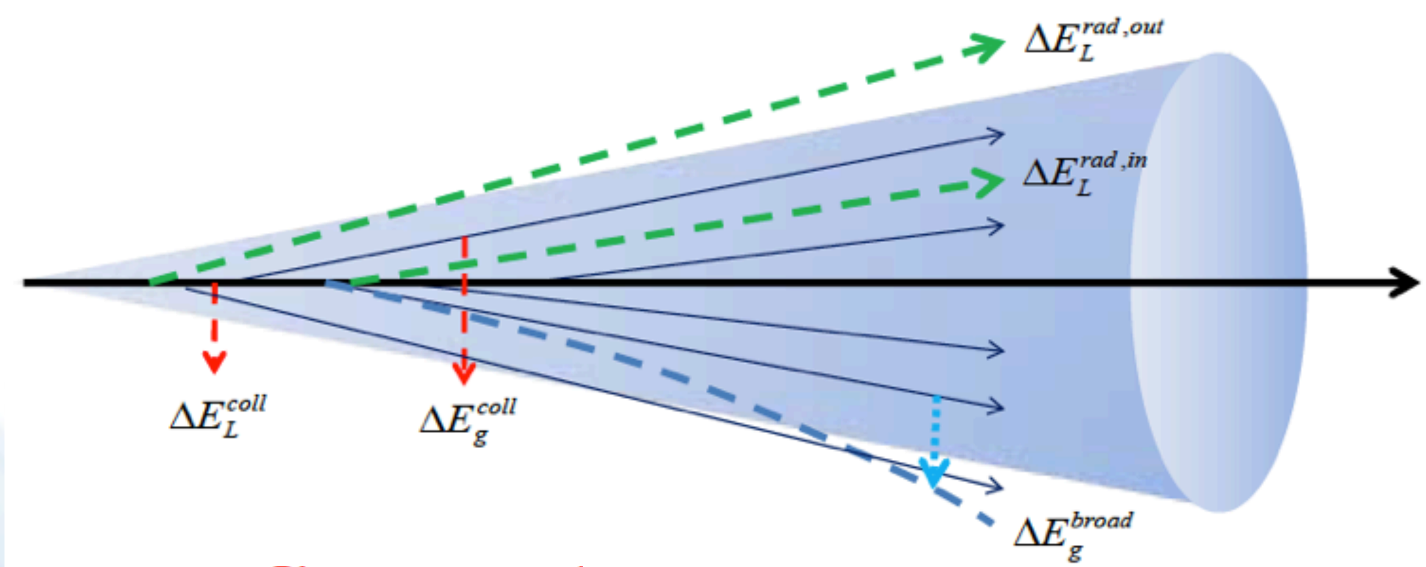


Excess at large r, low p_T

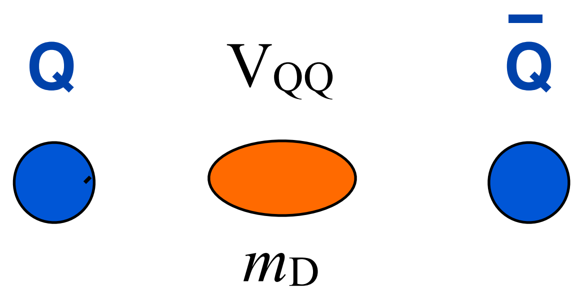
Depletion at intermediate r, p_T

No change at small r, high p_T

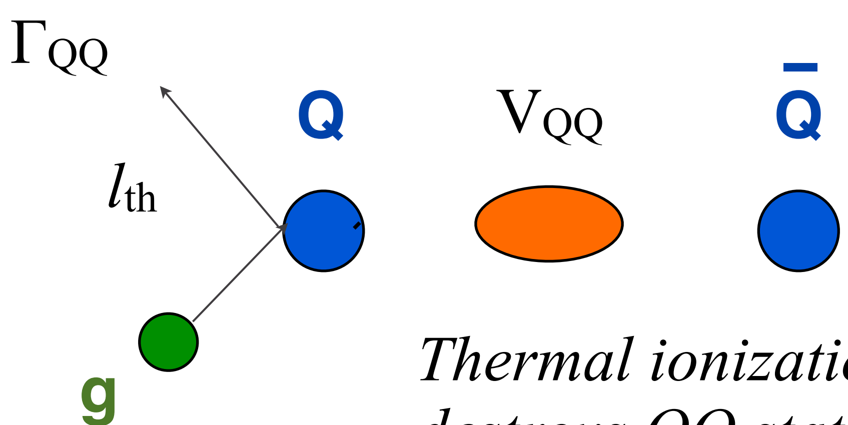




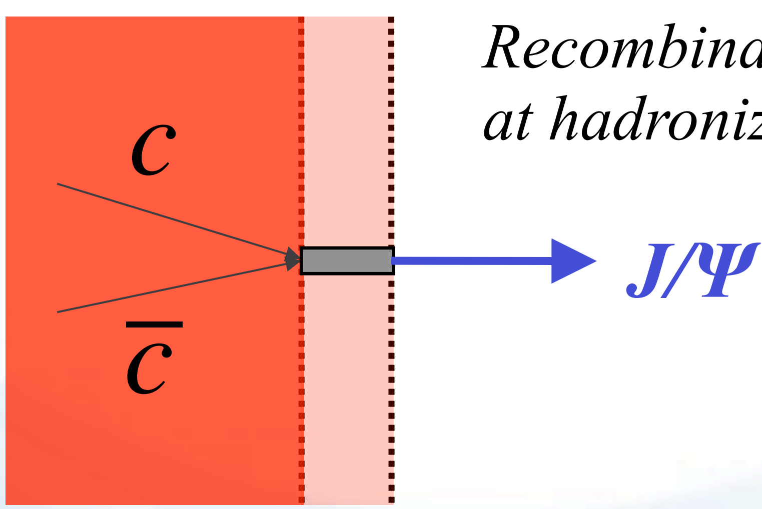
J/ψ suppression



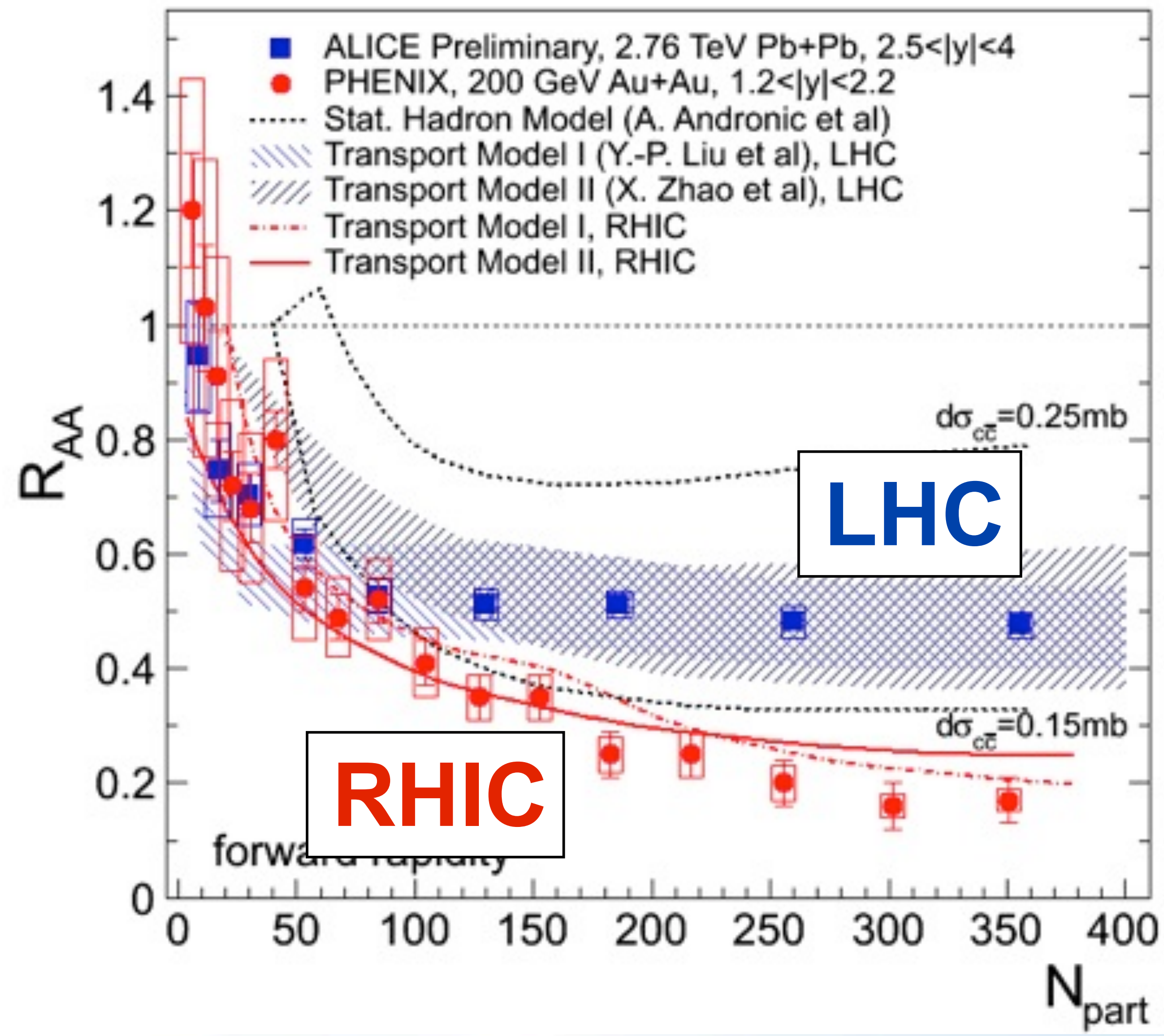
Color screening causes "melting"



Thermal ionization destroys QQ states



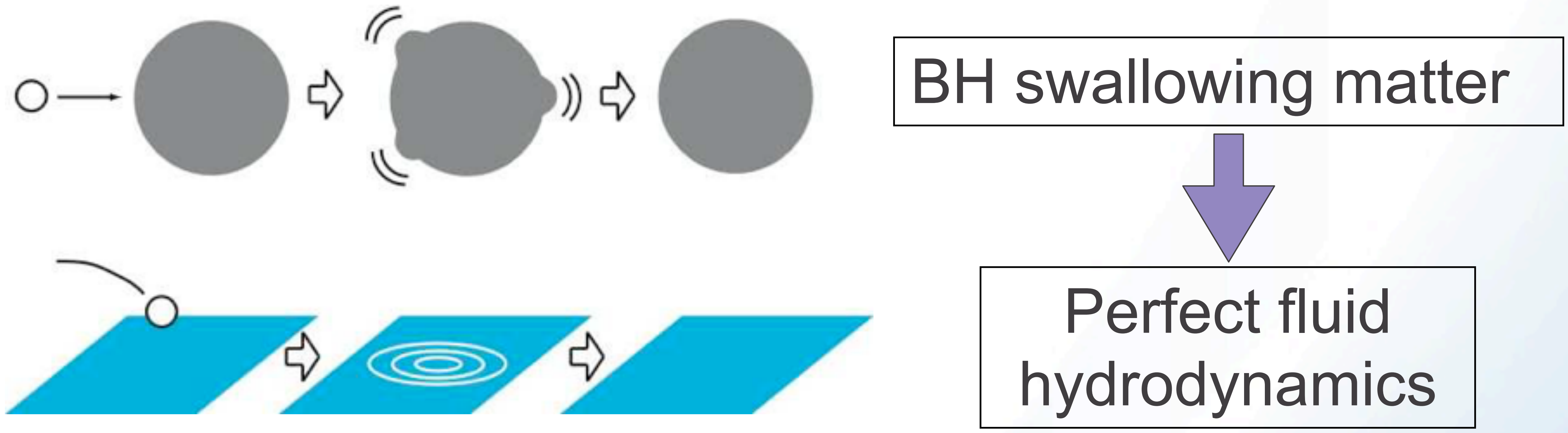
Recombination at hadronization



J/ψ suppression at RHIC is stronger than at LHC: Fewer c-quarks which can recombine!

The Black Hole connection

Dynamics of hot QCD matter can be mathematically mapped on black hole dynamics in 4+1 dimensions (AdS_5 space).

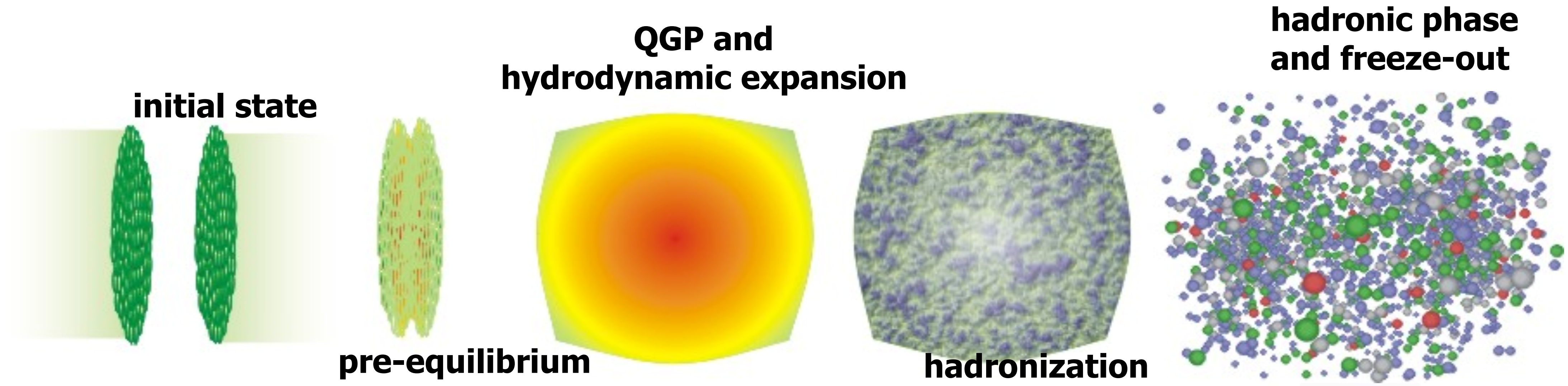


Formation of hot QCD matter at RHIC is similar to formation of a black hole, tied to information loss. This is probably true for any QFT, but the gravity dual of QCD is not known, and it is unclear whether g^2N_c is large enough to apply the classical limit of the dual theory.

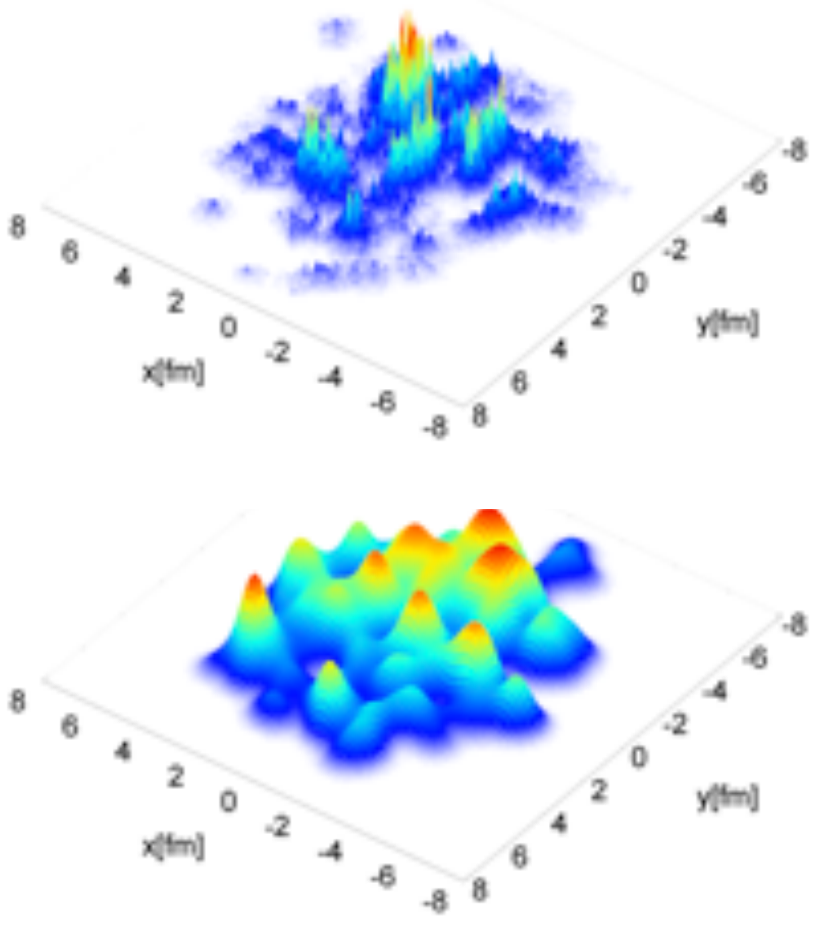
Open questions

There are many!

Bulk dynamics



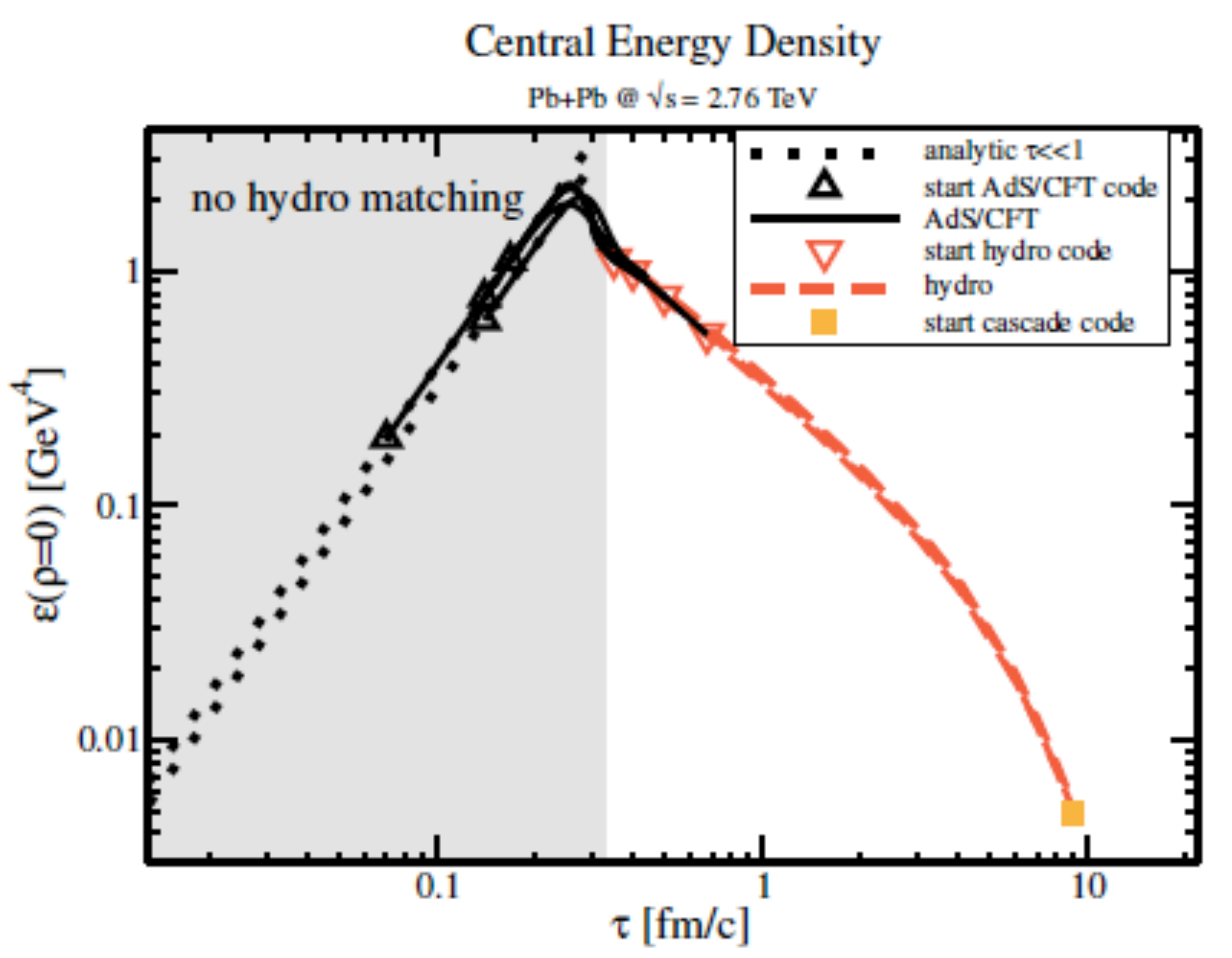
CGC | "Glasma" | Hydrodynamics | Hadronic gas

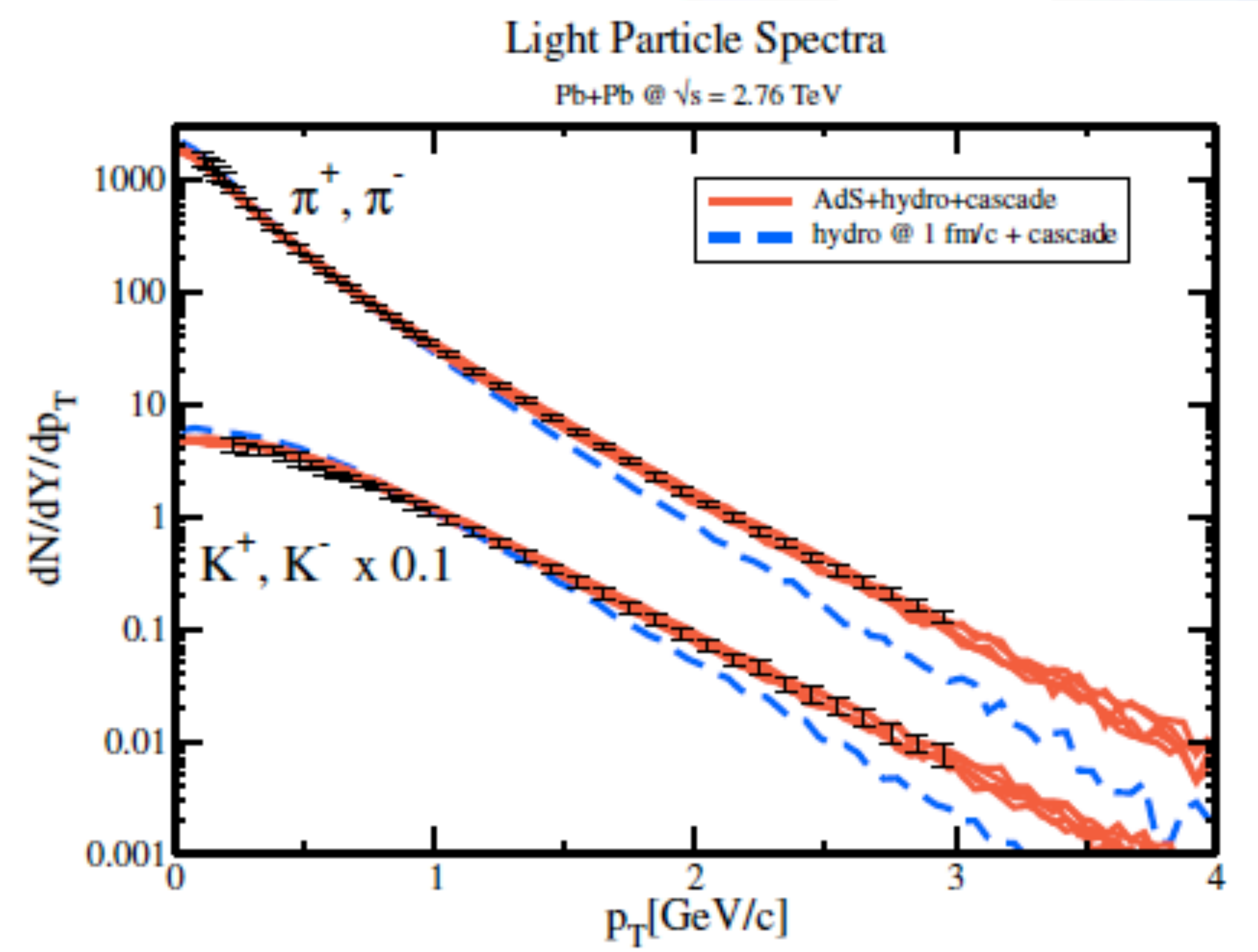


- Initial state and equilibration mechanism
  - Do they matter, if hydrodynamics works?
    - Can CGC be distinguished from AdS/CFT?
    - In CGC: How does the glasma equilibrate?
    - What are the most discriminating observables?
- Check on system dependence
  - Cu+Cu, Cu+Au, U+U, also p+Pb, d+Au !

AdS/CFT + Hydro works

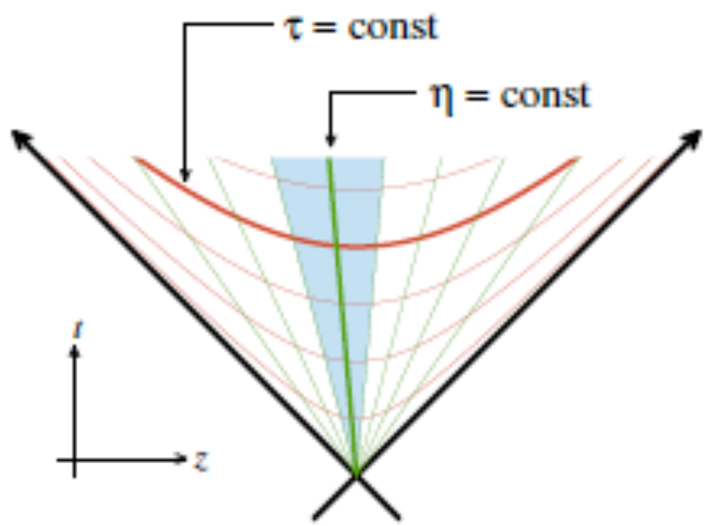
van der Schee, Romatschke, Pratt: Collision of two nuclear "shock waves"in AdS/CFT, followed by hydrodynamic evolution and hadronic cascade final scattering. Main results (at strong coupling):
Hydro works after 0.35 fm/c; Spectra fit LHC and RHIC data (w/o free param's).

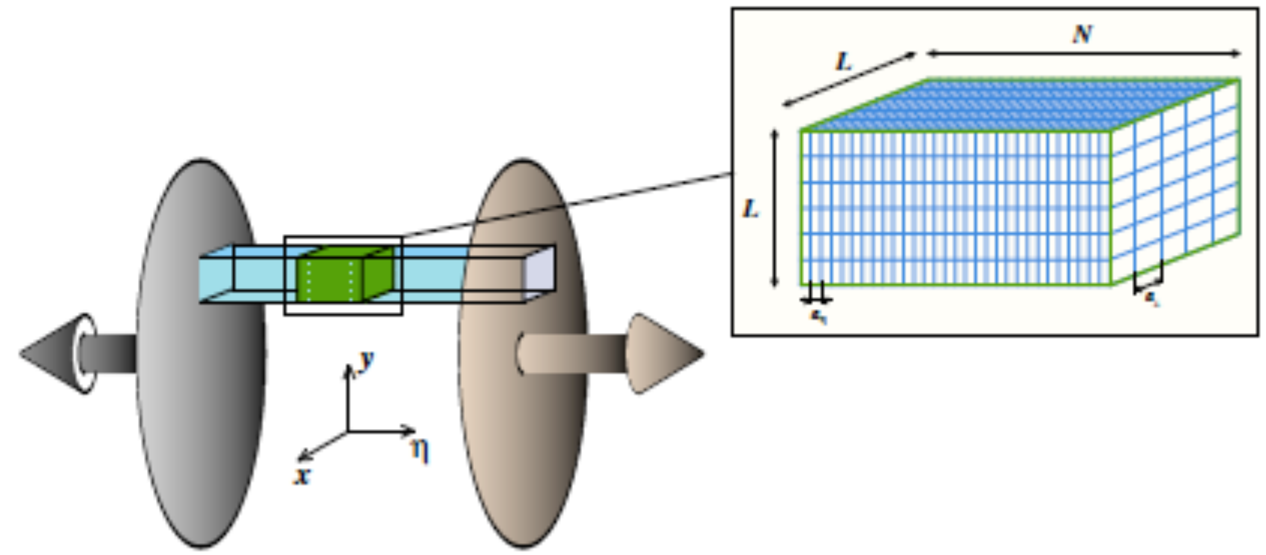


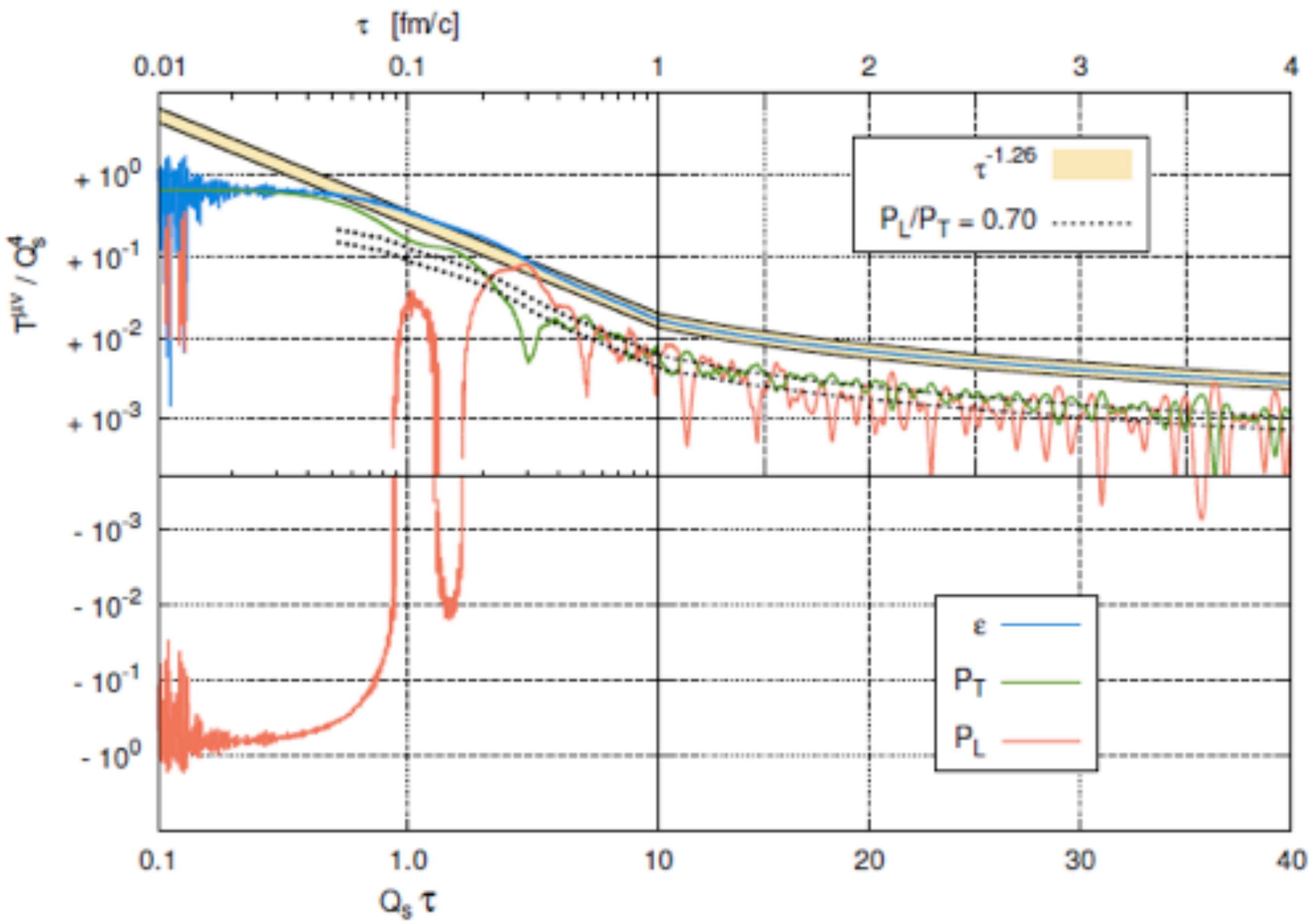


arXiv:1307.2539, accepted in PRL.

Glasma equilibration







T. Epelbaum & F. Gelis
arXiv: 1307.2214

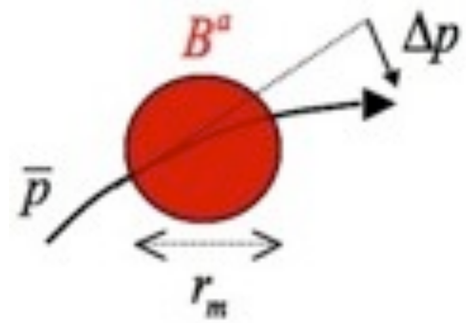
P_L/P_T = 0.70 after 0.4 fm/c !

Fit to: $\varepsilon(\tau) = \varepsilon_0\, \tau^{-4/3} - 2\, \eta_0\, \tau^{-2}$

Consistent with $\eta/\varepsilon^{4/3} \approx 0.25$
or $\eta/s \approx 0.12$ ($s \approx 2\, \varepsilon^{4/3}$).

Alternative mechanisms

Anomalous viscosity due to dynamically local field domains:

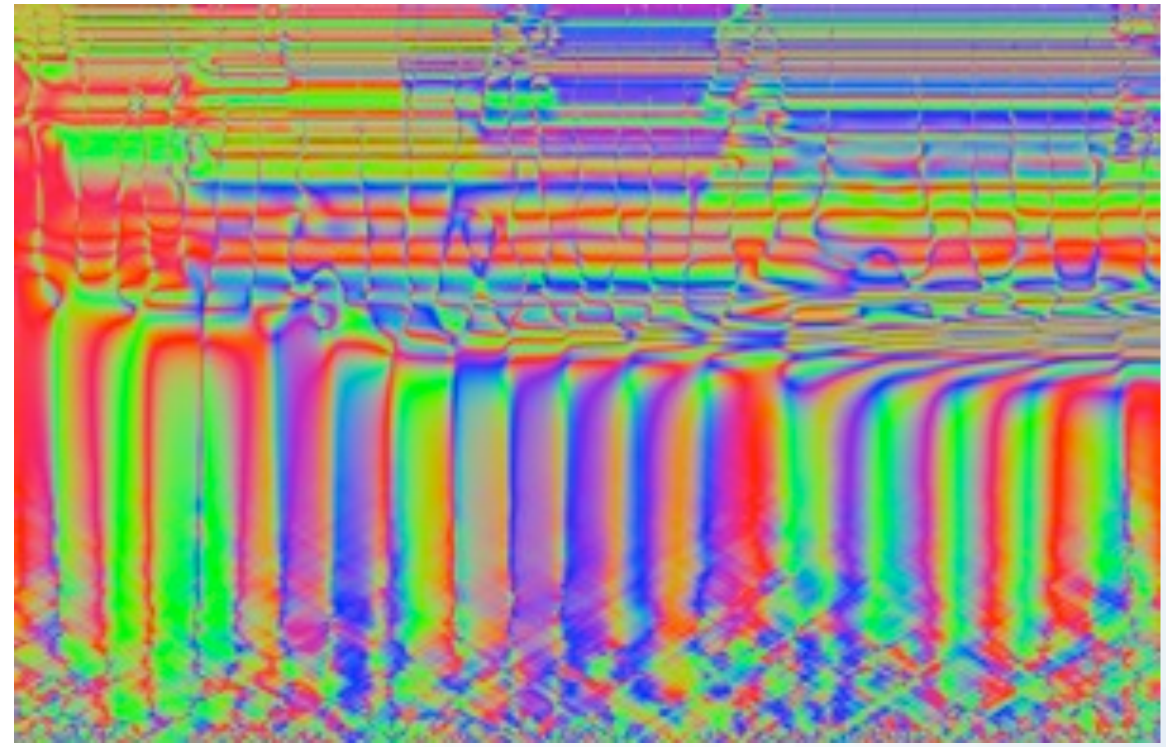


Momentum change per domain:

$$\Delta p \approx g Q^a B^a r_m$$

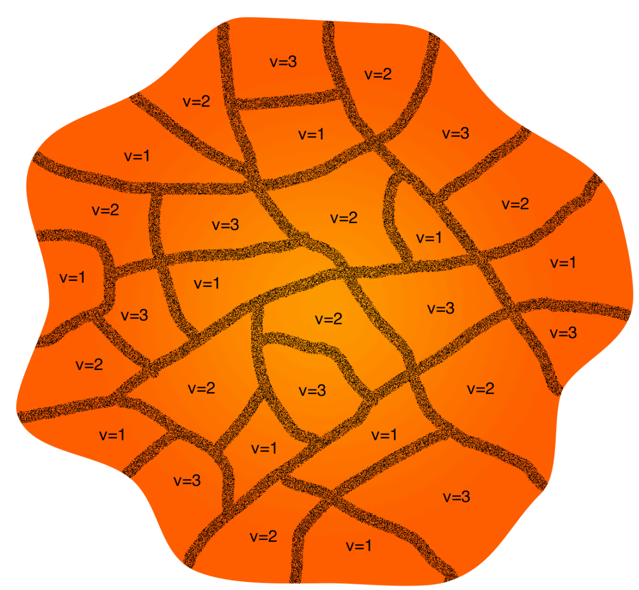
$$\frac{\eta_A}{s} \approx \frac{9T^3}{5g^2 N_c \langle B^2 \rangle r_m}$$

Asakawa, Bass & BM, PRL 96 (2006) 252301



Turbulent color fields

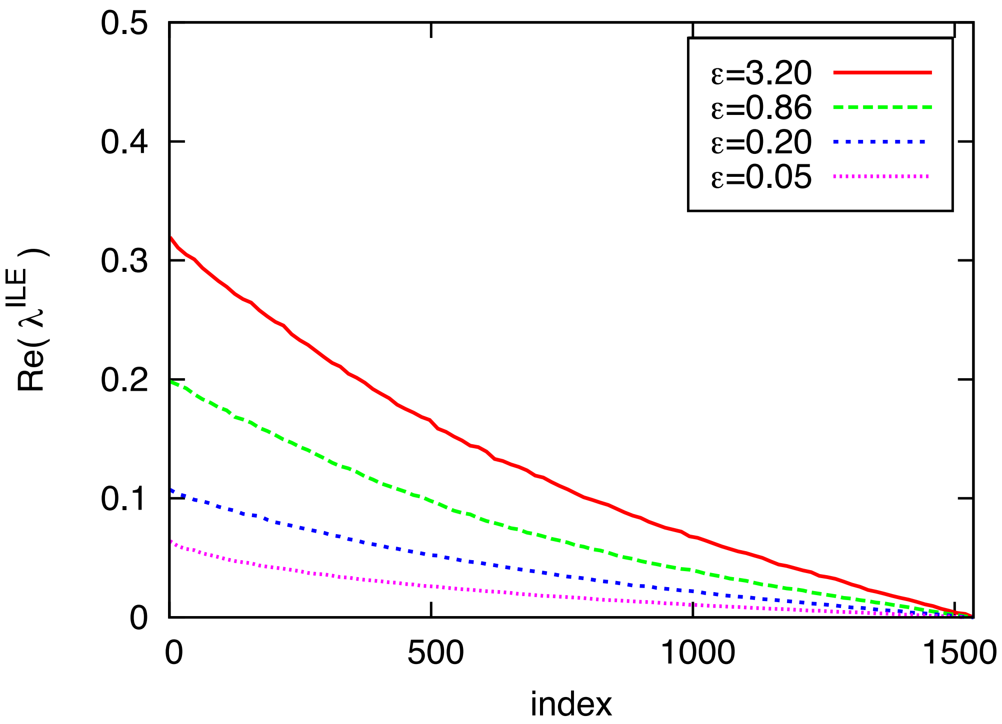
Center (Z_3) domains



Asakawa, Bass & BM,

PRL 110 (2006) 202301

Classical lattice gauge theory

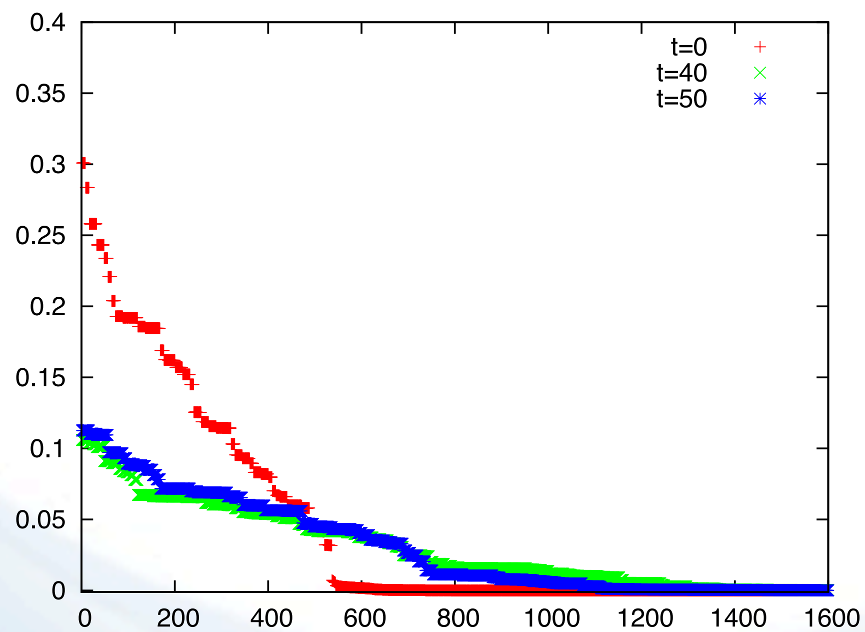


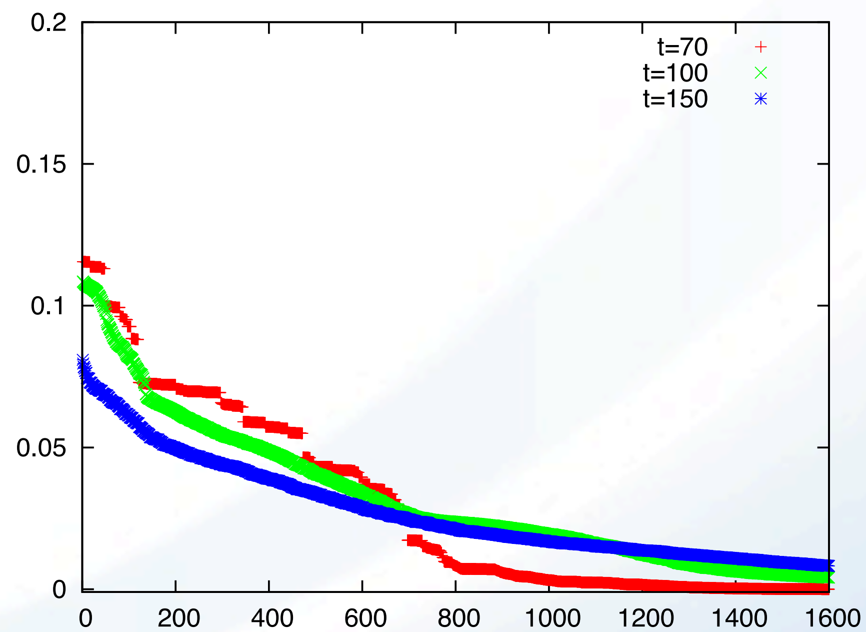
T. Kunihiro, BM, A. Ohnishi, A. Schäfer, T. Takahashi & A. Yamamoto, PRD 82 (2010) 114015

Lattice gauge fields exhibit extensive spectrum of positive (intermediate) Lyapunov exponents.

➥ Finite KS entropy density.

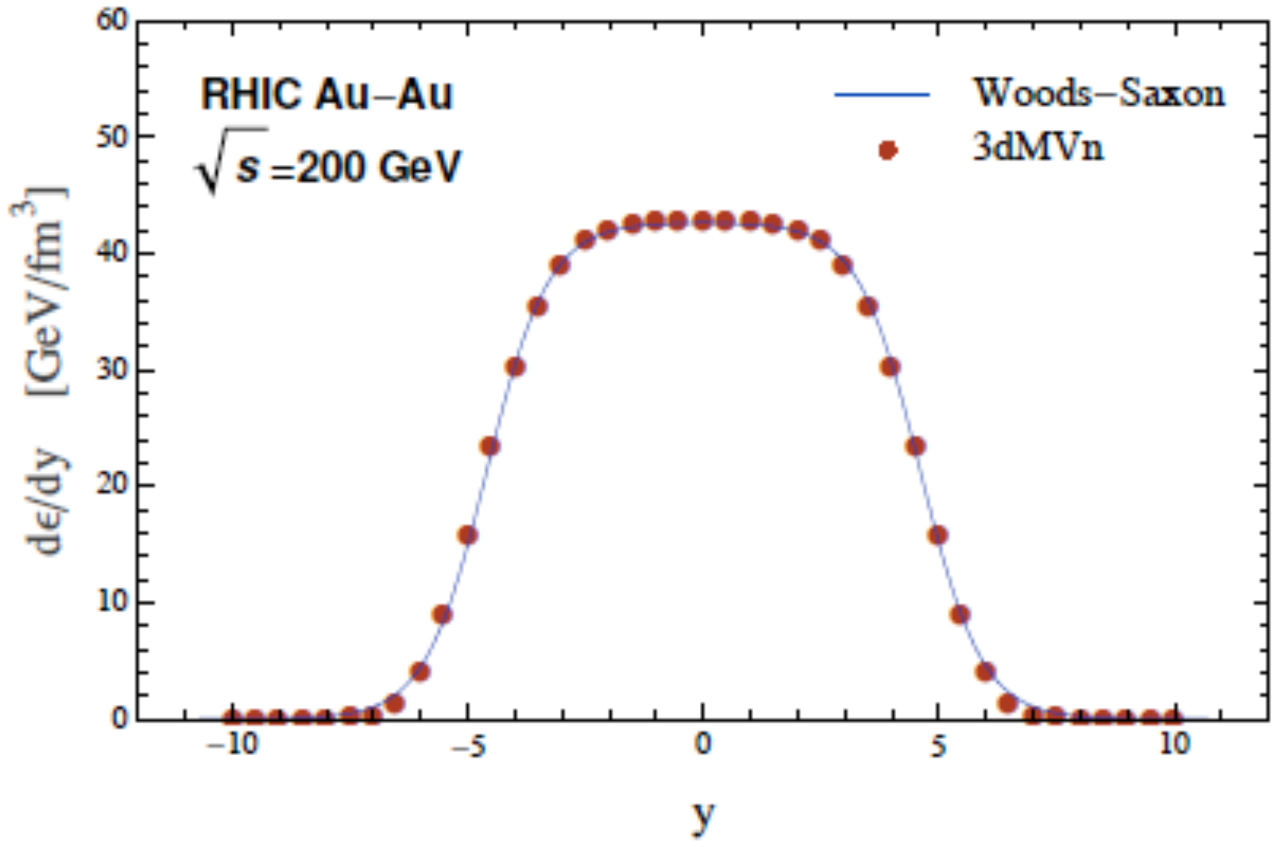
H. Iida, T. Kunihiro, BM, A. Ohnishi, A. Schäfer & T. Takahashi, PRD (2013) in print

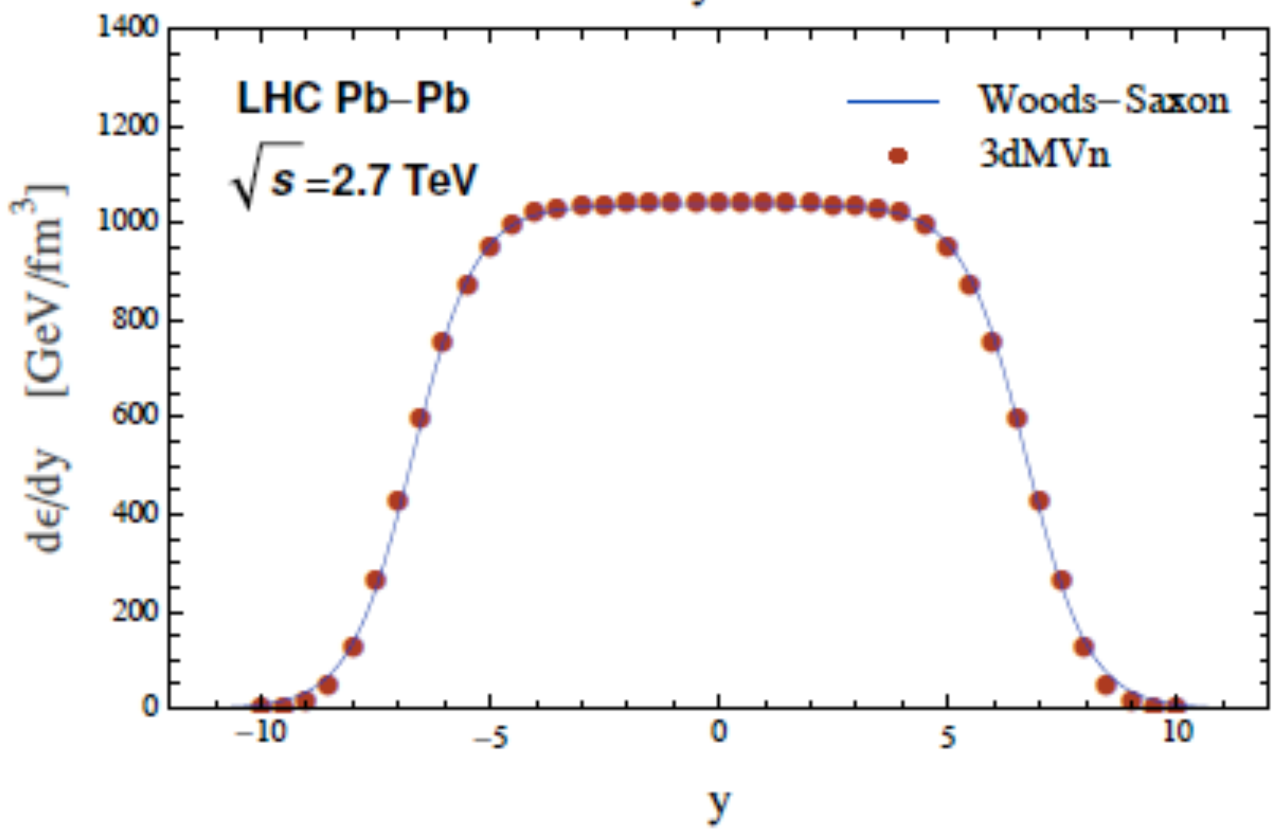




Lyapunov exponents initially depend on time and initial cond's, but later assume a universal spectrum dependent on energy density.

Towards 3-D CGC





Ozonder and Fries, 1311.3390

using 3-D CGC model developed by Lam and Mahlon. Color charge distribution in nuclear rest frame:

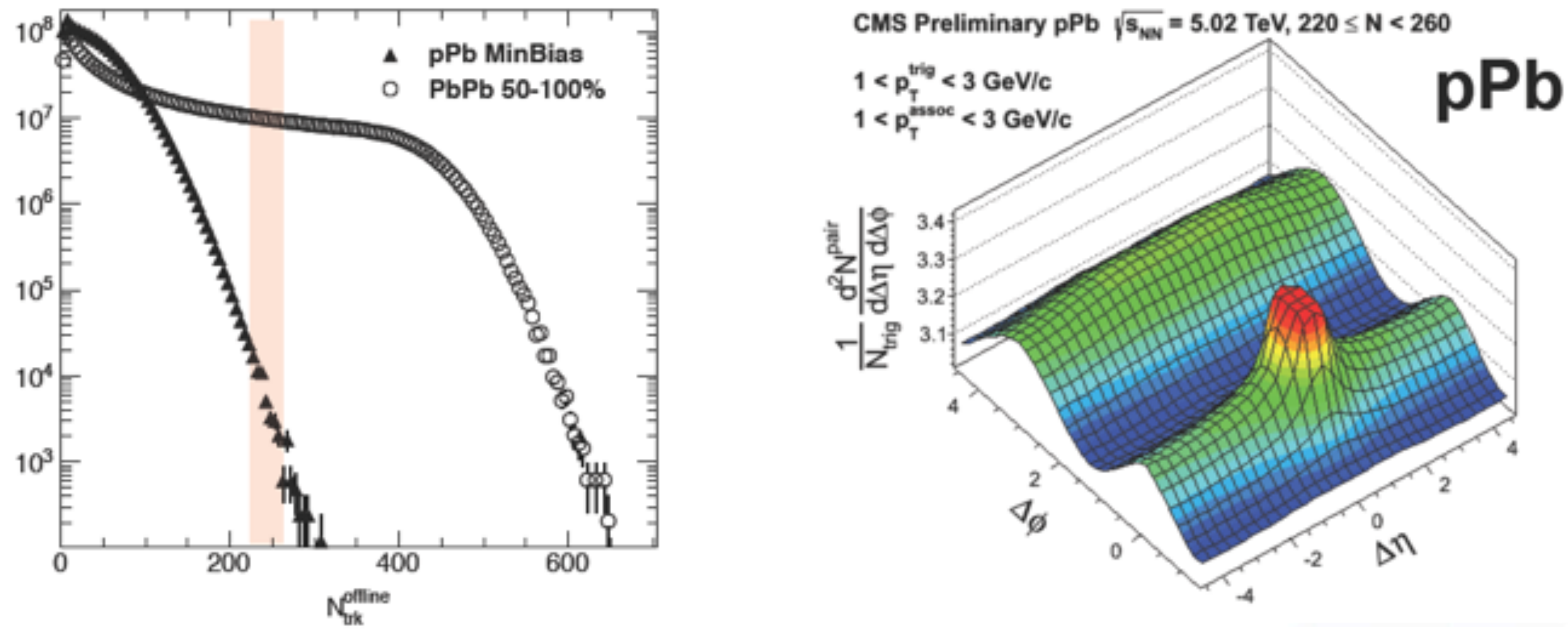
$$\langle \rho^a(0)\rho^b(\boldsymbol{x})\rangle = \delta^{ab}\kappa_A^3 \left[\delta^3(\boldsymbol{x}) - \frac{3\exp\left(-\frac{\sqrt{3}|\boldsymbol{x}|}{\lambda}\right)}{4\pi\lambda^2|\boldsymbol{x}|}\right]$$

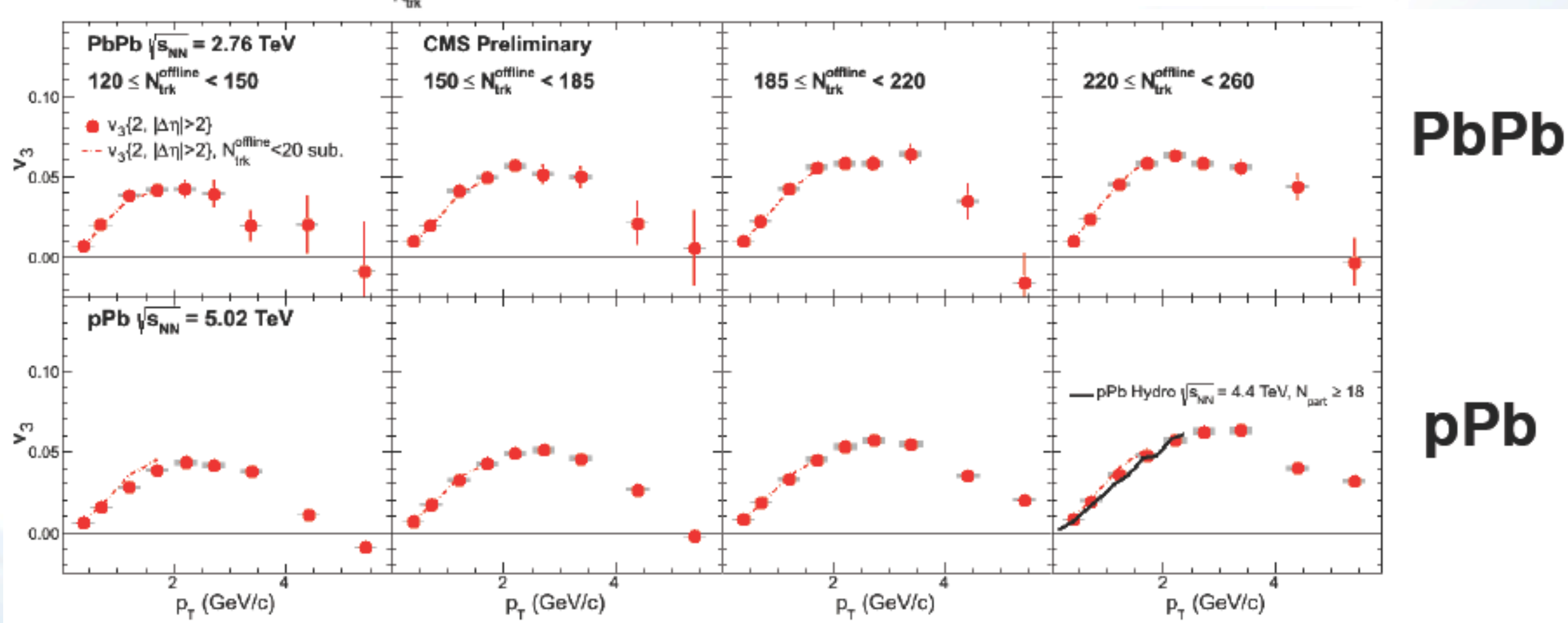
Missing x-evolution of color charge density, which leads to a stronger rapidity dependence.

BROOKHAVEN NATIONAL LABORATORY

Sunday, December 1, 13

QGP in p+Pb ?

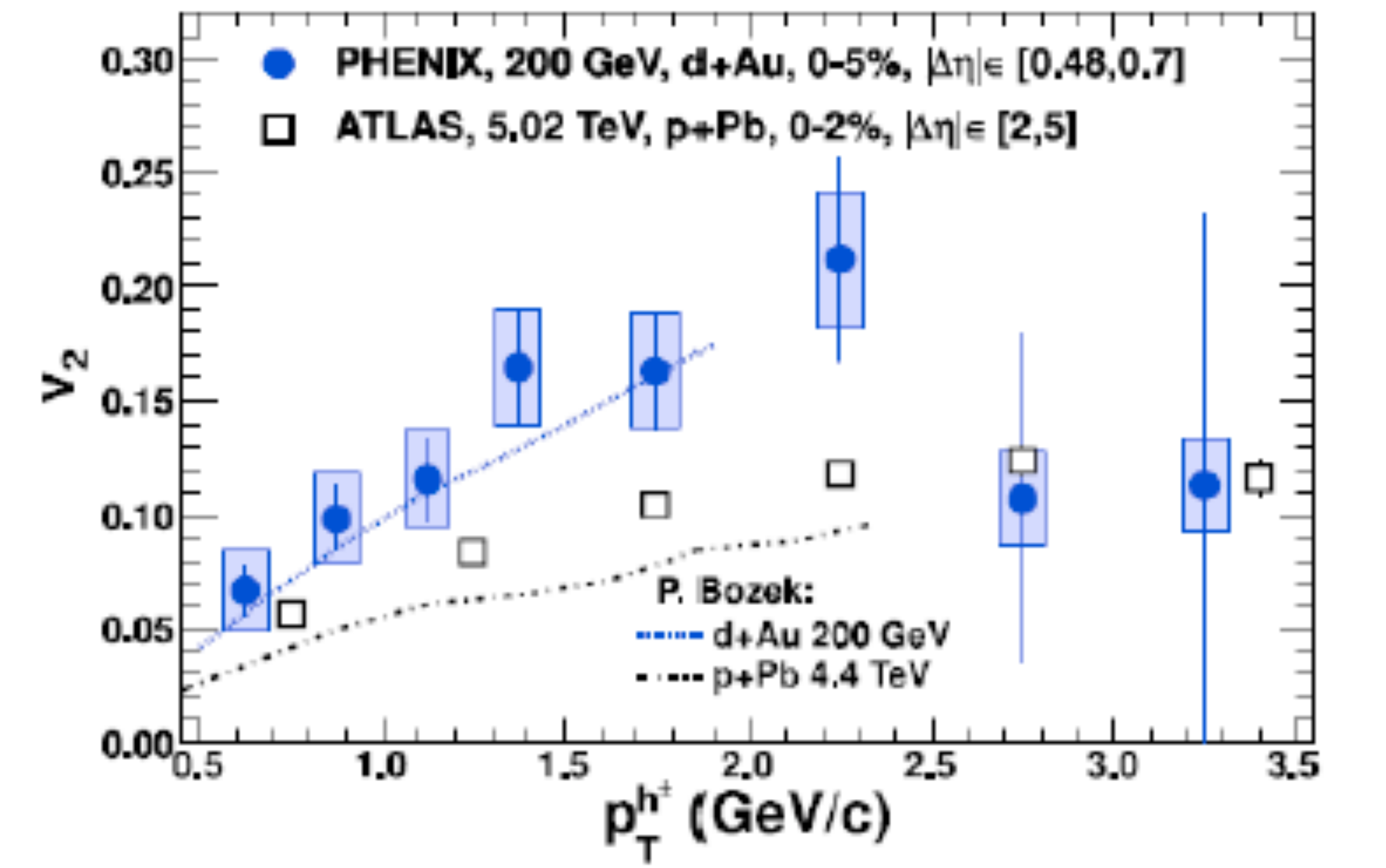

pPb MinBias
PbPb 50-100%
$N_{trk}^{offline}$
CMS Preliminary pPb $\sqrt{s_{NN}}$ = 5.02 TeV, 220 ≤ N < 260
1 < p_T^{trig} < 3 GeV/c
1 < p_T^{assoc} < 3 GeV/c
pPb
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
Δφ
Δη

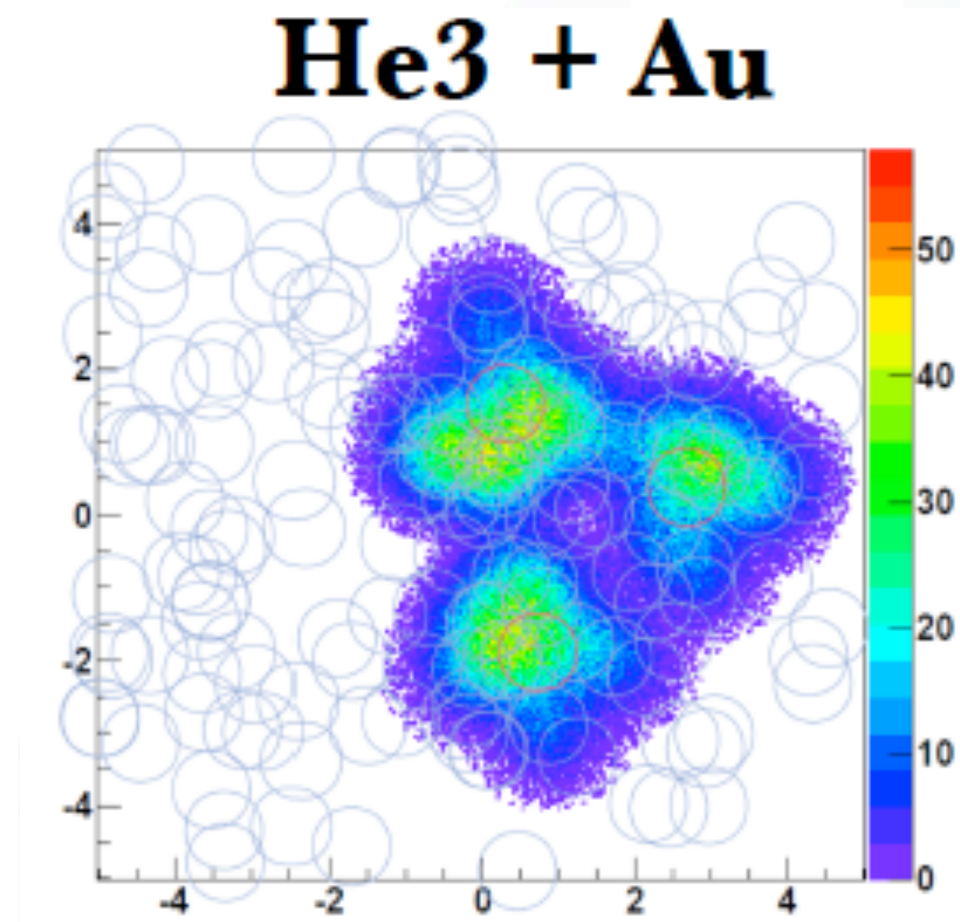

PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
120 ≤ $N_{trk}^{offline}$ < 150
$v_3\{2, |\Delta\eta|>2\}$
$v_3\{2, |\Delta\eta|>2\}$, $N_{trk}^{offline}$<20 sub.
CMS Preliminary
150 ≤ $N_{trk}^{offline}$ < 185
185 ≤ $N_{trk}^{offline}$ < 220
220 ≤ $N_{trk}^{offline}$ < 260
PbPb
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
pPb Hydro $\sqrt{s_{NN}}$ = 4.4 TeV, N_{part} ≥ 18
pPb
v_3
p_T (GeV/c)

Eccentricity engineering

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

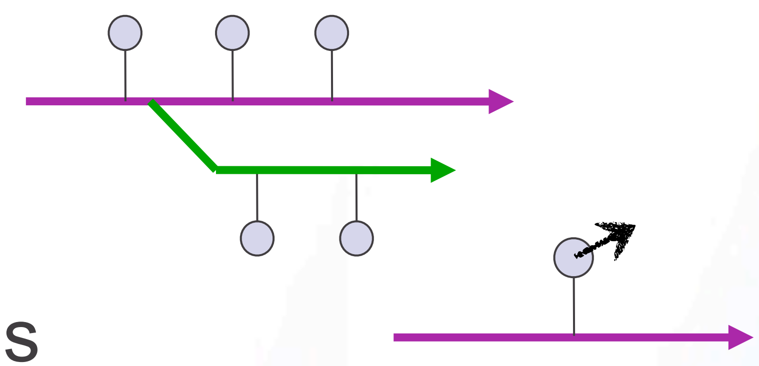
^{3}He will generate a large ε_3
RHIC can do it!





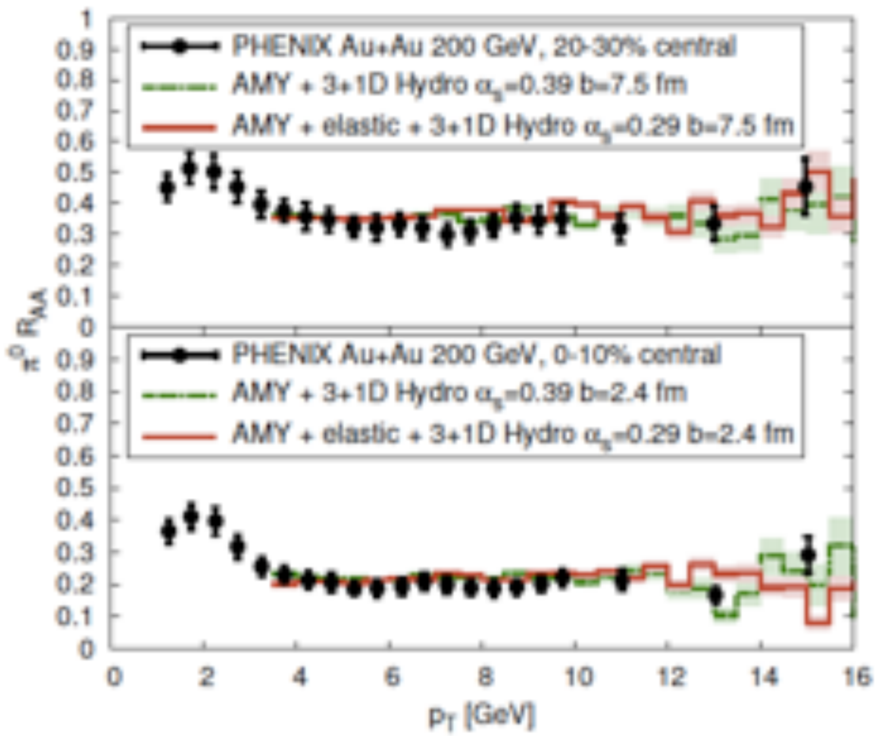
PHENIX: nucl-ex/1303.1794 [PRL 111 (2013) Highlight]

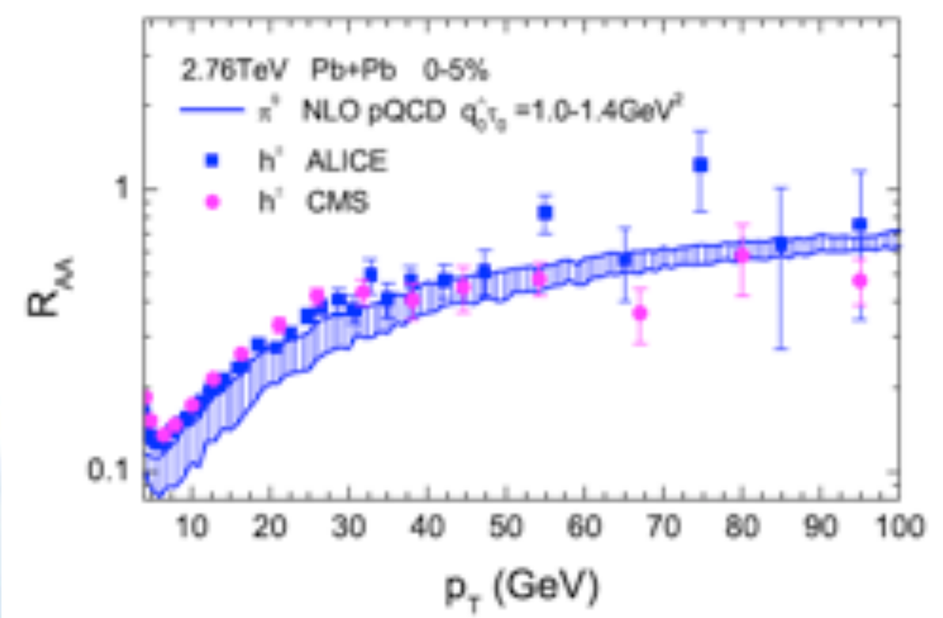
Jets quenching: Questions



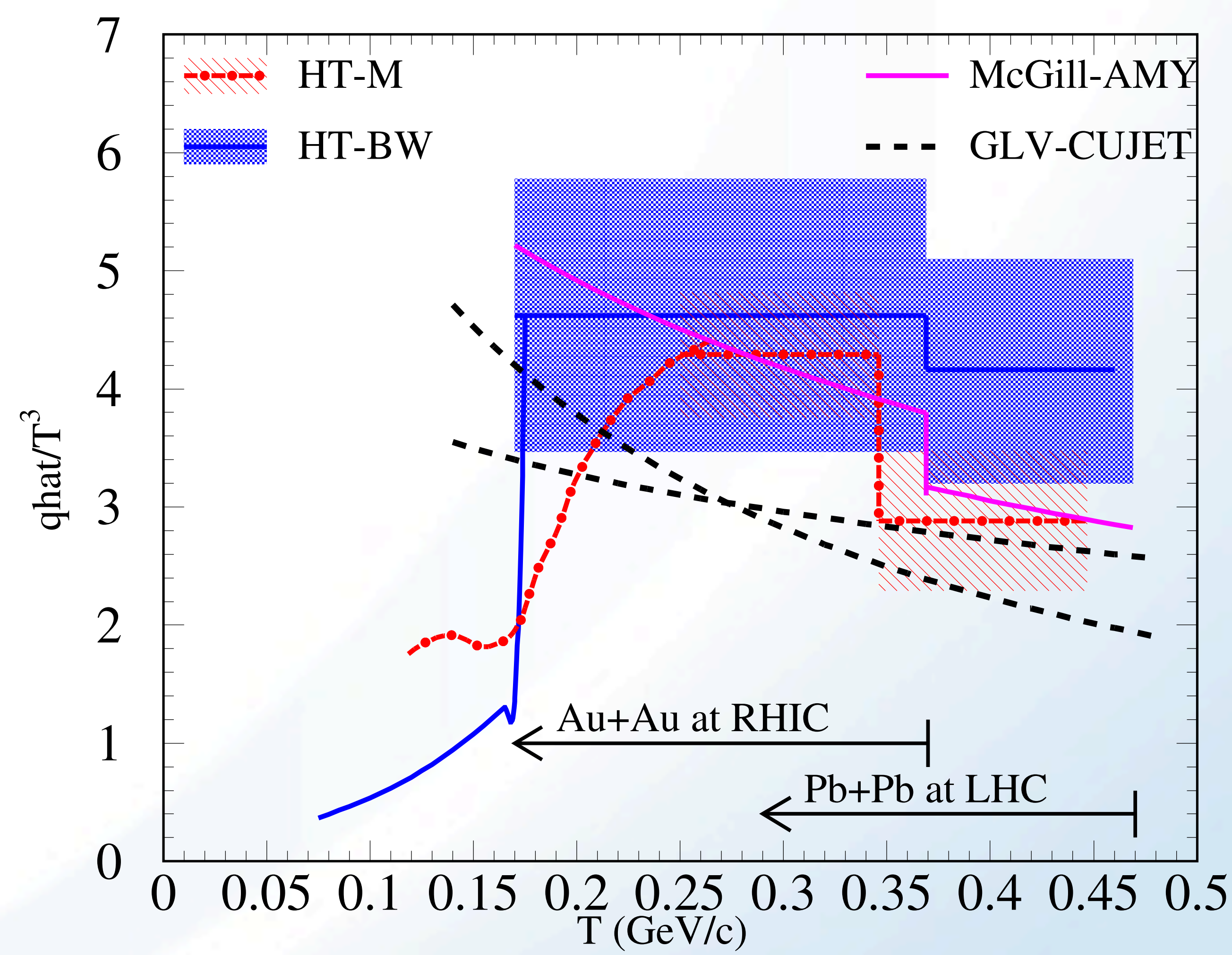
- What is the mechanism of energy loss ?
  - "radiative" = into non-thermal gluon modes
  - "collisional" = directly into thermal plasma modes
- How are radiative and collisional energy loss affected by the structure of the medium (are there quasiparticles or not)?
  - Quasiparticle with masses $m > \Gamma$?
  - AdS/CFT inspired models with weak-strong coupling transition?
- What happens to the lost energy and momentum ?
  - If EL is "radiative", how quickly does the radiation thermalize ⇔ What is the longitudinal momentum (z) distribution ?
  - What is the angular distribution of the jet energy (the jet shape) ⇔ How much of the energy is found in a cone of angular size R ?
- How do the answers depend on the parton flavor ?

Measuring q-hat





Collaborative theoretical efforts are making extraction of qhat and ehat from data possible.

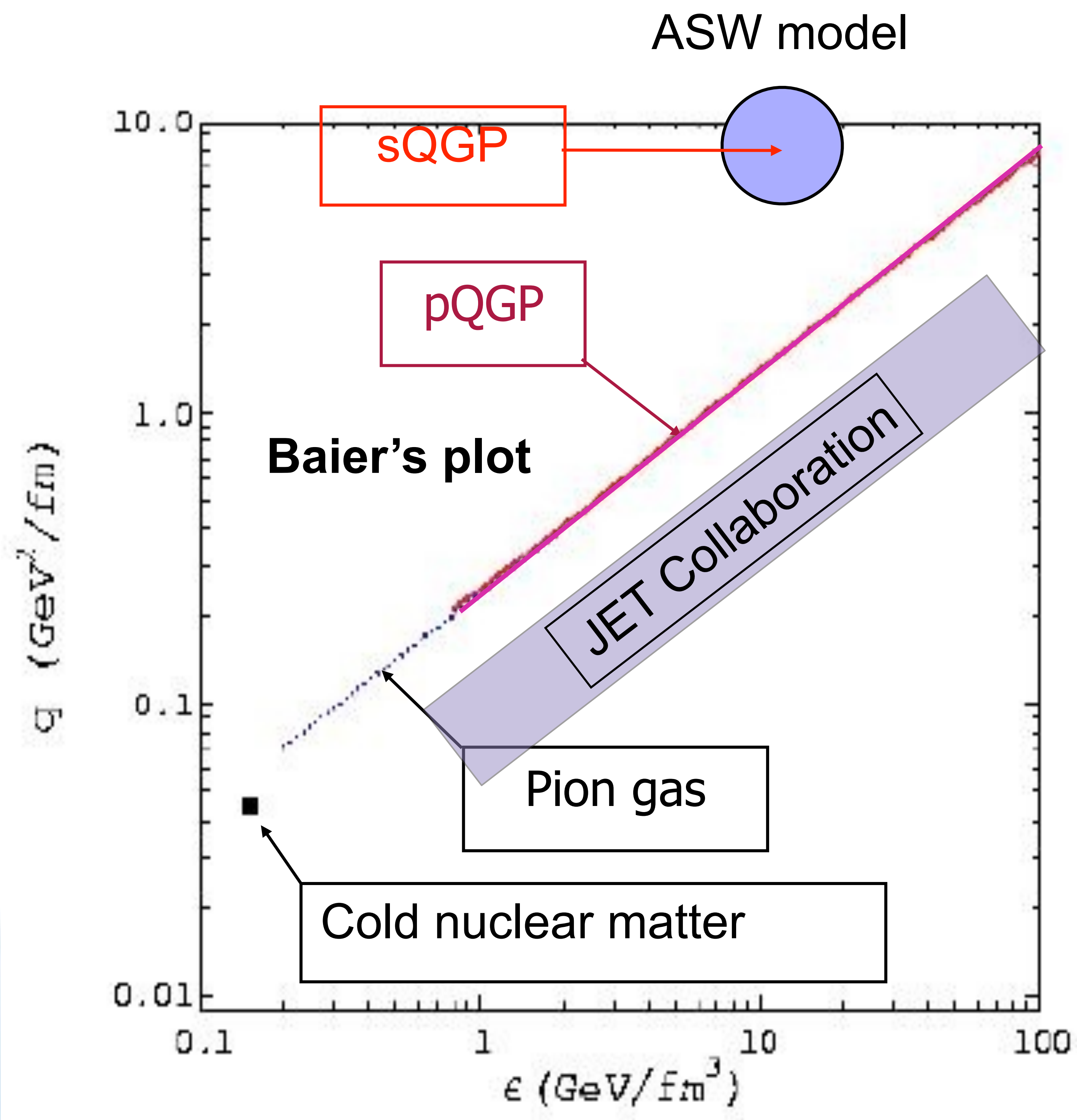


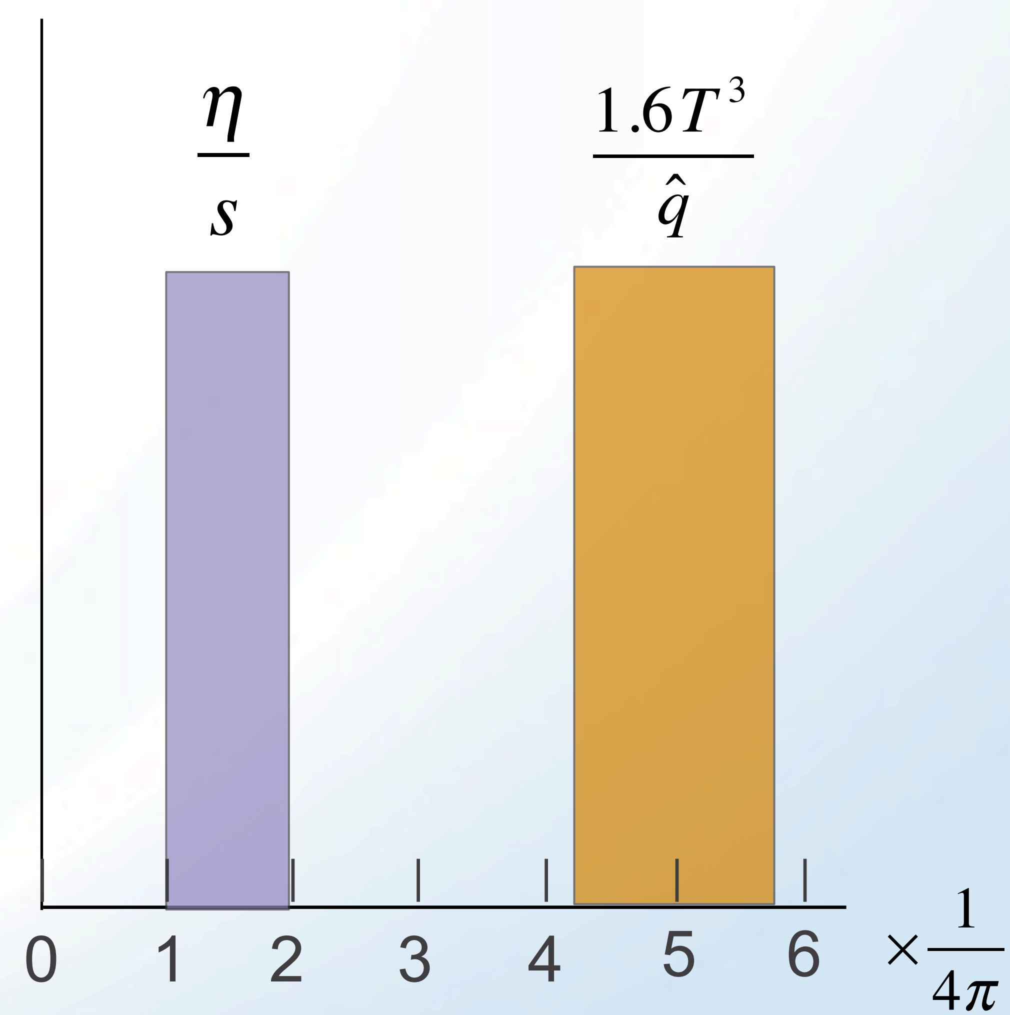
Jet quenching vs. η/s

Majumder, BM, Wang

$$\eta / s \approx \frac{0.065}{\alpha_s^2 \ln(q_{\max}^2 / m_D^2)}$$

$$T^3 / \hat{q} \approx \frac{0.04}{\alpha_s^2 \ln(q_{\max}^2 / m_D^2)}$$





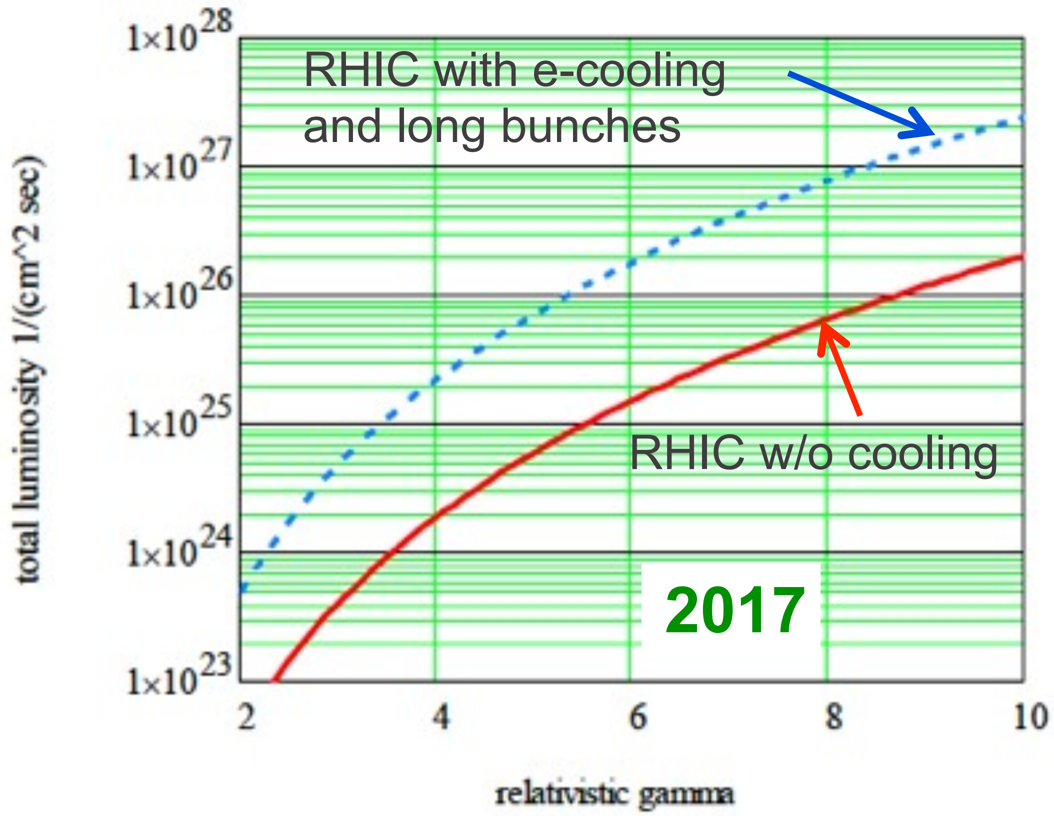
Finding answers: Experimental prospects

Planned Upgrades

Machine upgrade:

Bunched beam electron cooling for low-E beams

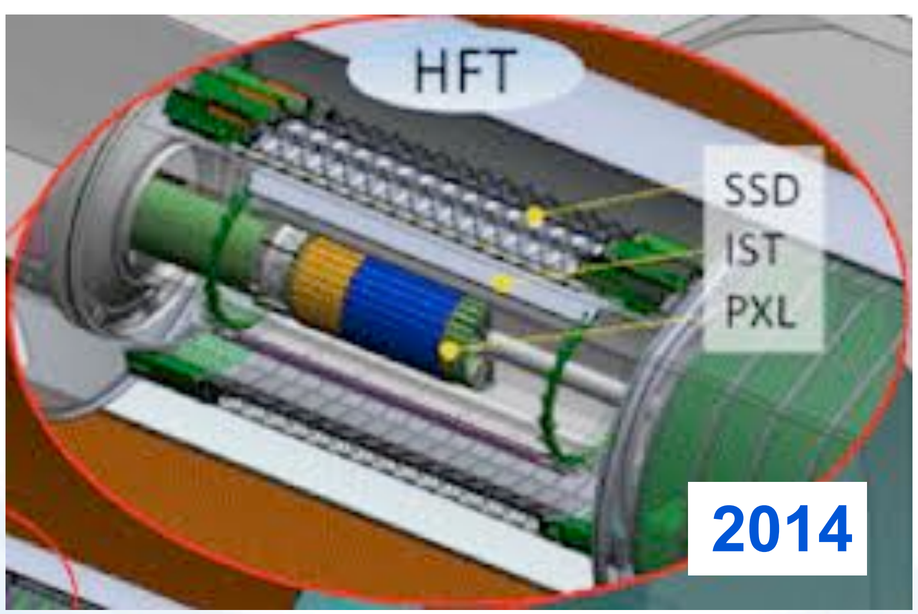
~10x luminosity



Detector upgrades:

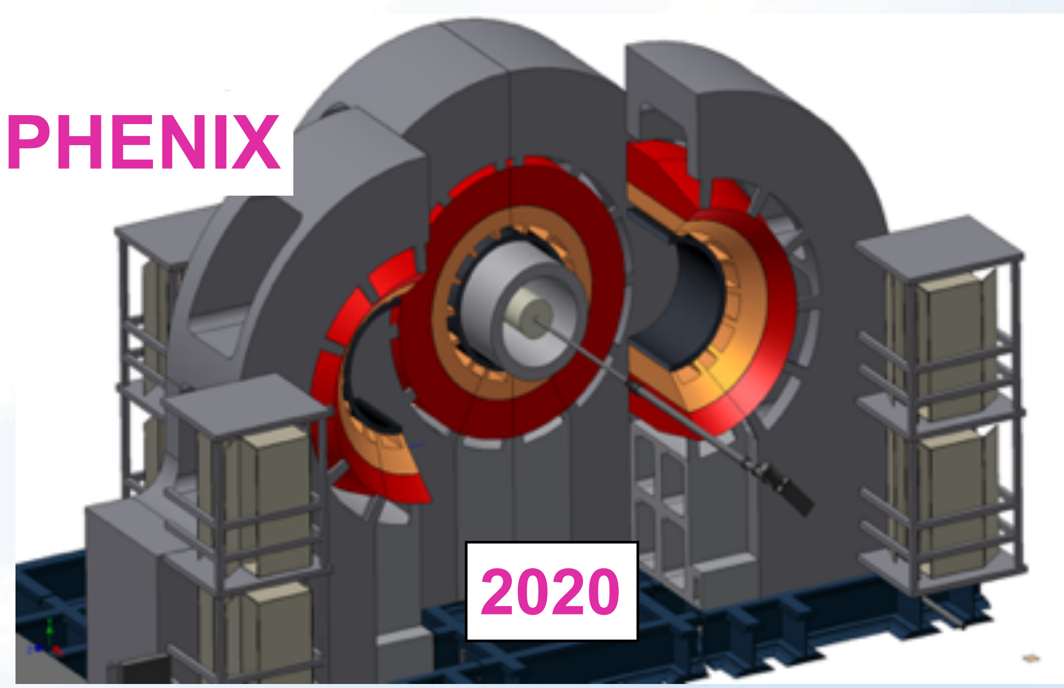
- **STAR HFT**
- **PHENIX MPC-EX**
- **STAR TPC pad rows**

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



STAR Heavy Flavor Tracker

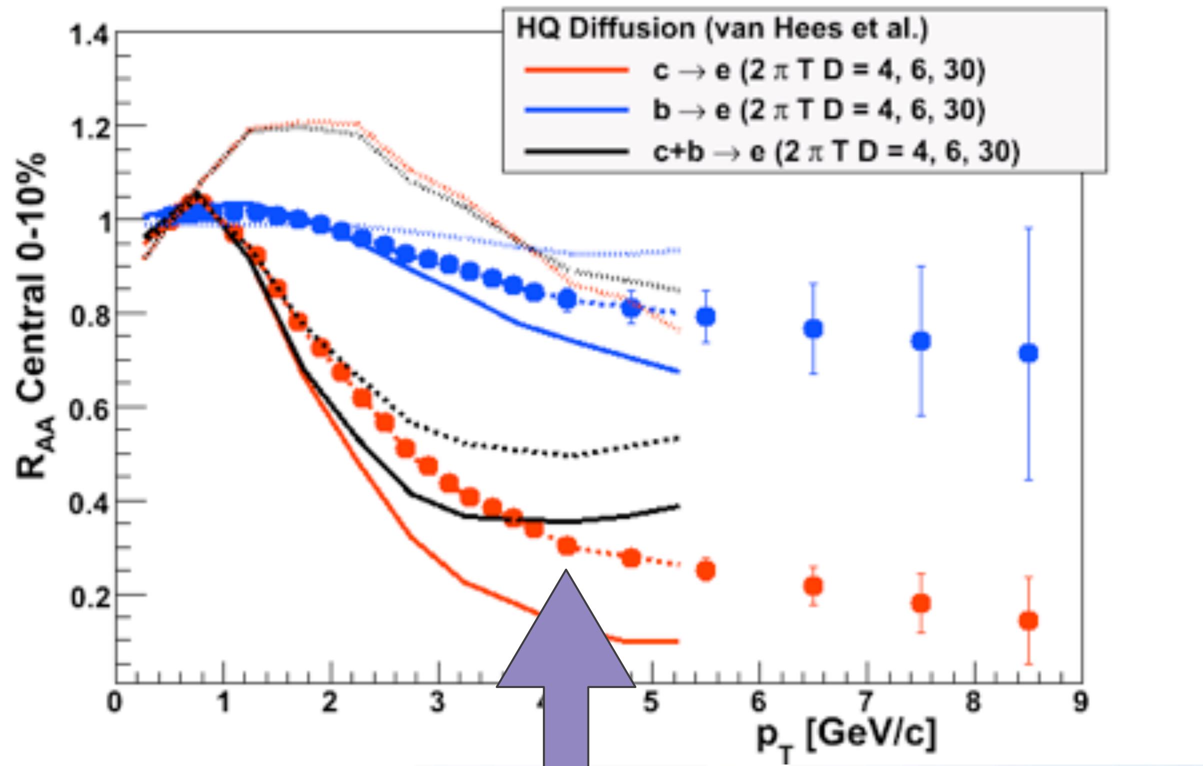
sPHENIX

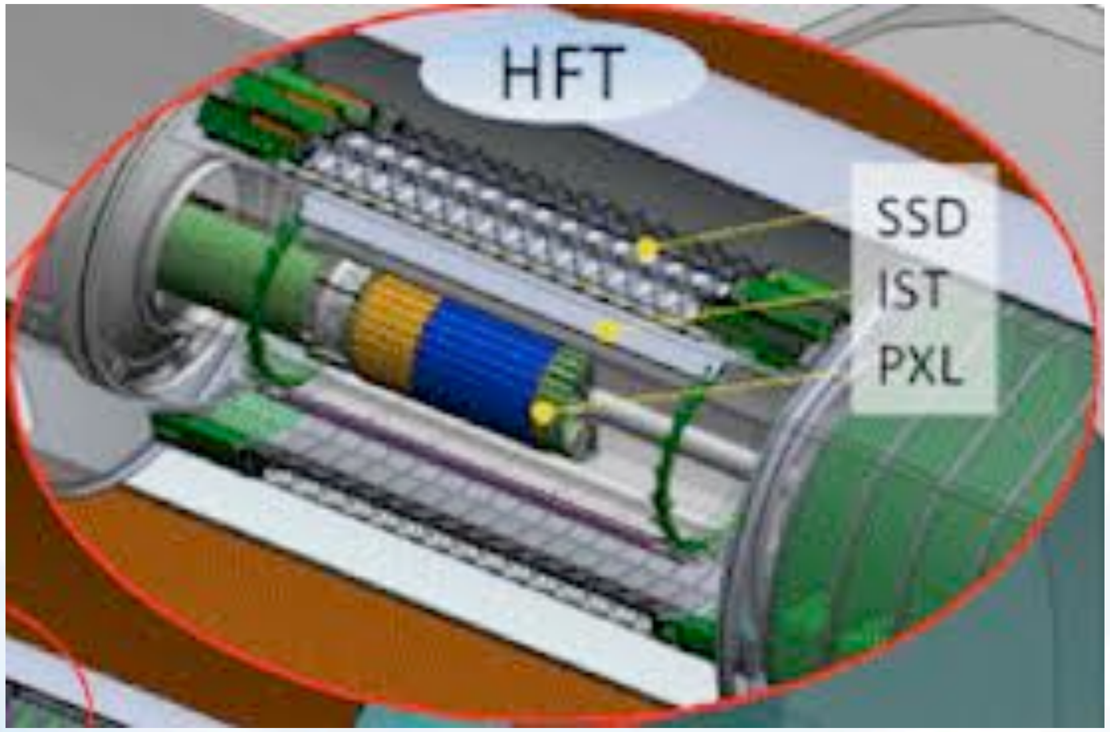


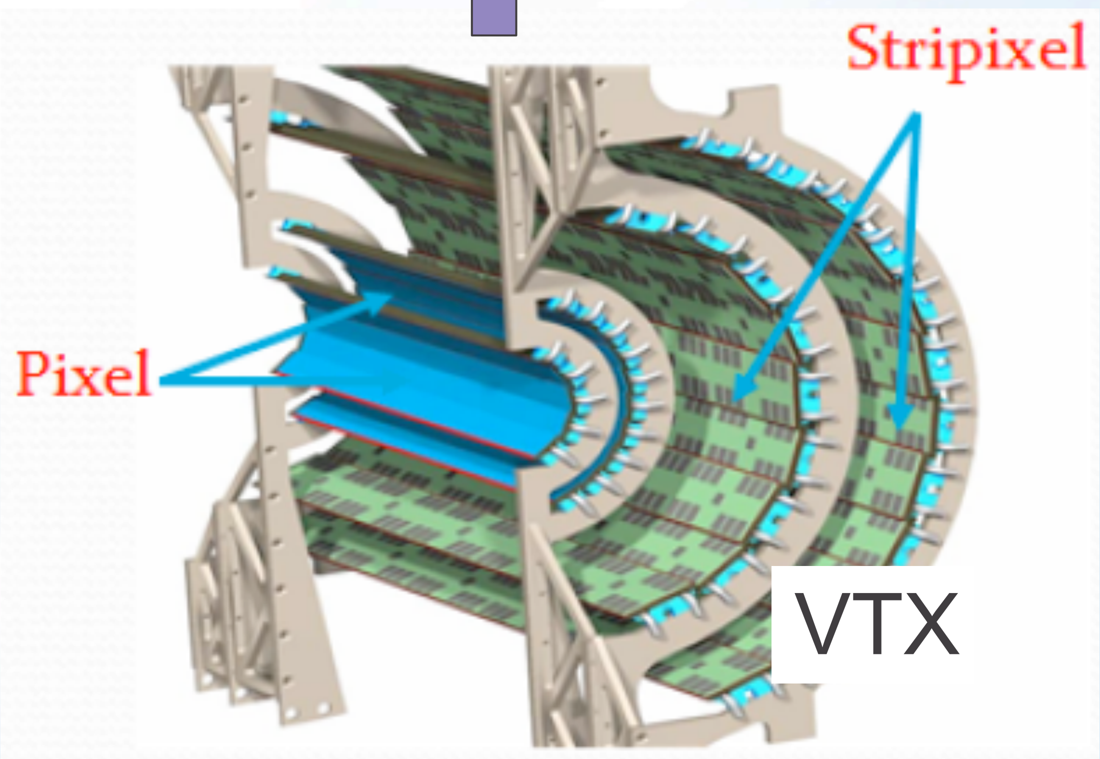
Probing the sQGP with heavy quarks

Suppression of mesons carrying open heavy flavor = energy loss of heavy quarks (*c, b*) explores mechanism of energy loss via medium color response; sensitive to medium structure.

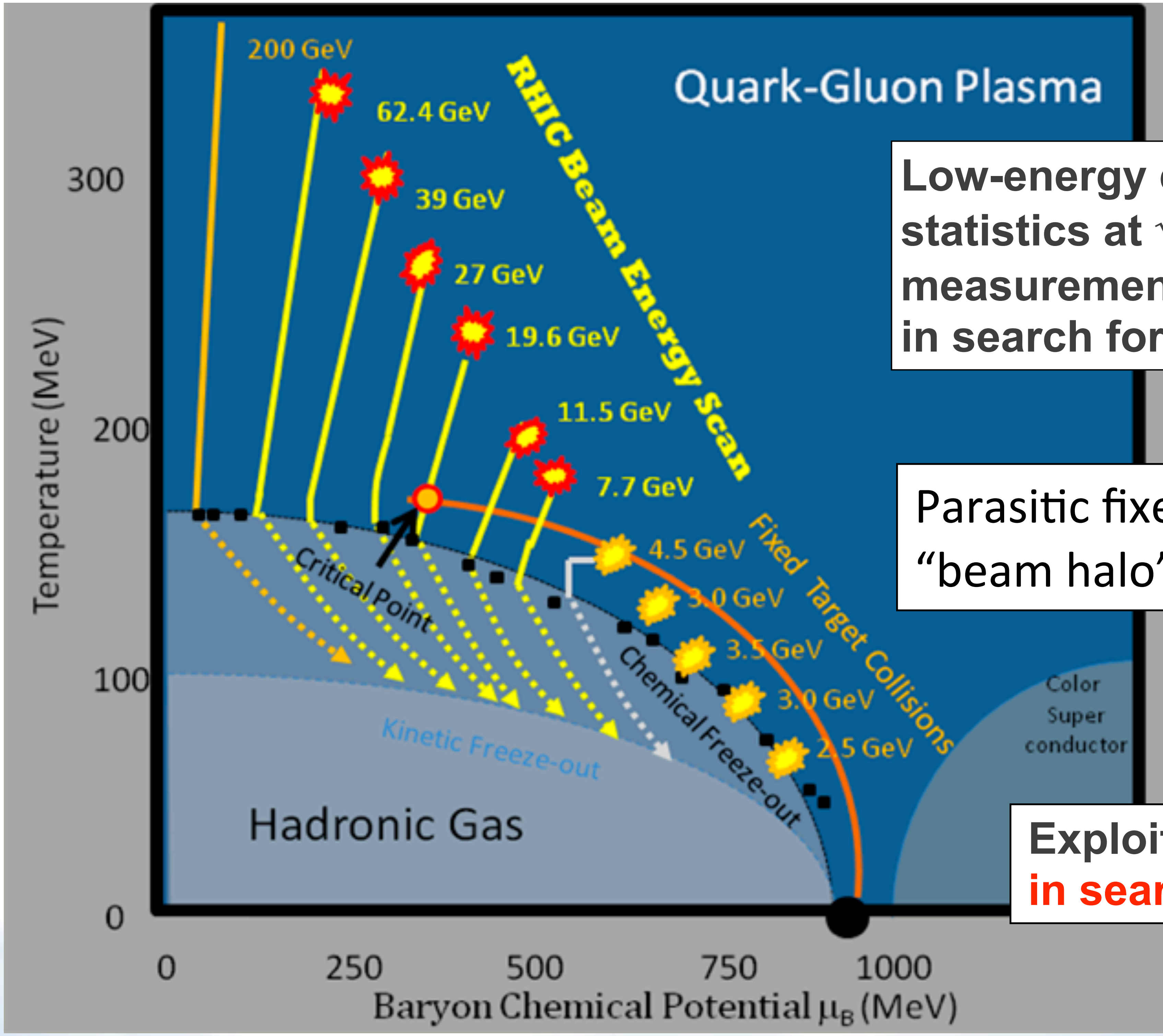
Spectrum of heavy quarks is important for understanding c-cbar recombination.







Beam energy scan II

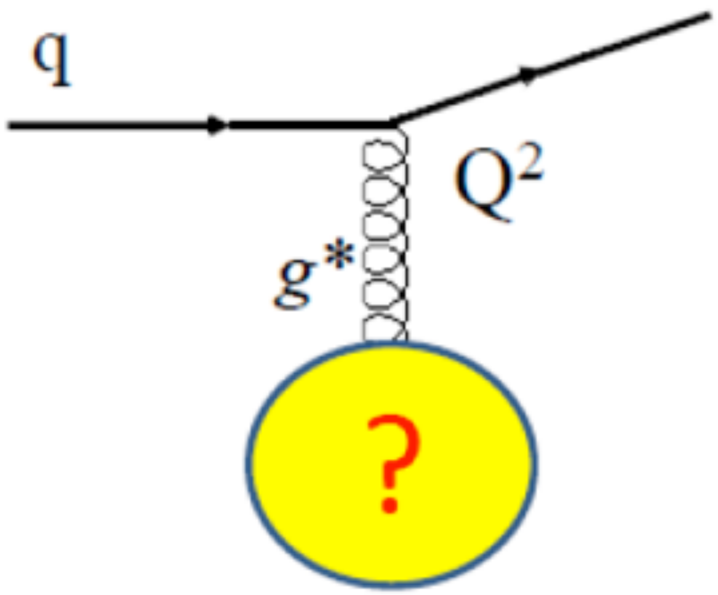


Low-energy e-cooling will improve statistics at $\sqrt{s}$ < 20 GeV for detailed measurements of sensitive quantities in search for critical point

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

Exploit new discovery potential in search for a QCD critical point

Providing Answers: Emergence of Strong Coupling



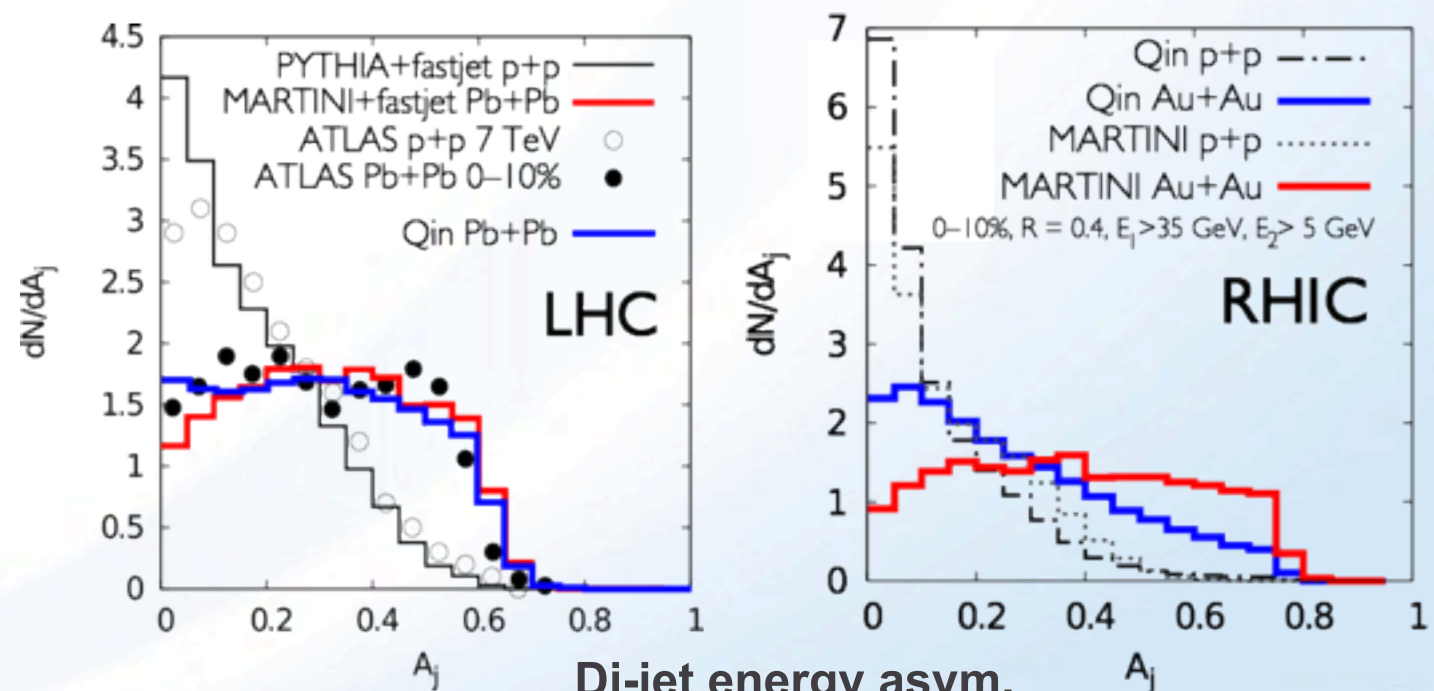
Low viscosity, rapid thermalization, and strong jet quenching are consequences of strong coupling

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

Requires measurements of jet, di-jet, γ-jet quenching, jet structure at multiple √s

sPHENIX upgrade will enable full jet reconstruction at RHIC

BaBar solenoid in its transfer frame

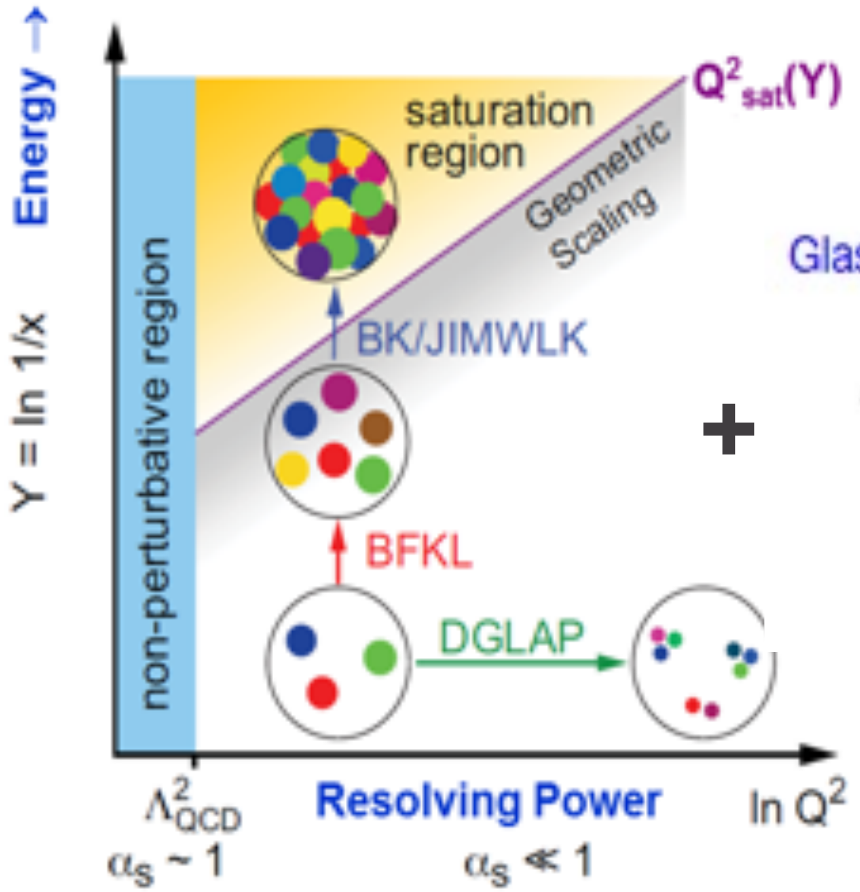


Di-jet energy asym.

RHIC +LHC data can discriminate between models

Providing Answers: Gluon Saturation

CGC + glasma thermalization provide for a remarkably successful 3+1-D hydro account for A+A multiplicities and event-by-event anisotropic flow.



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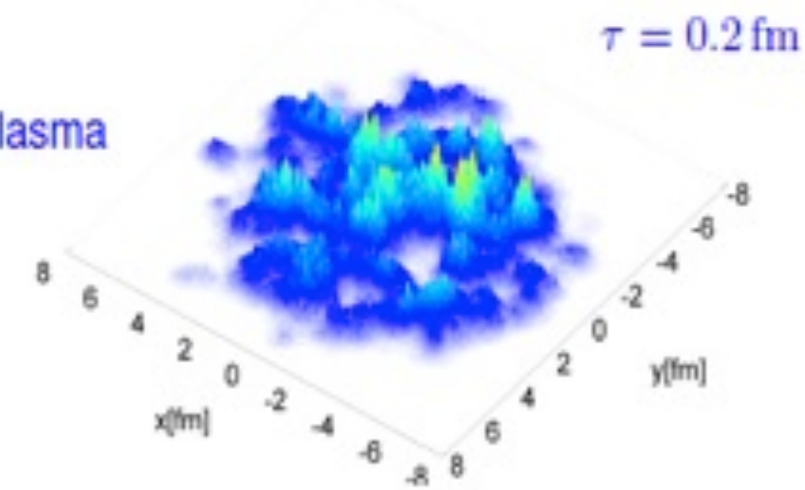

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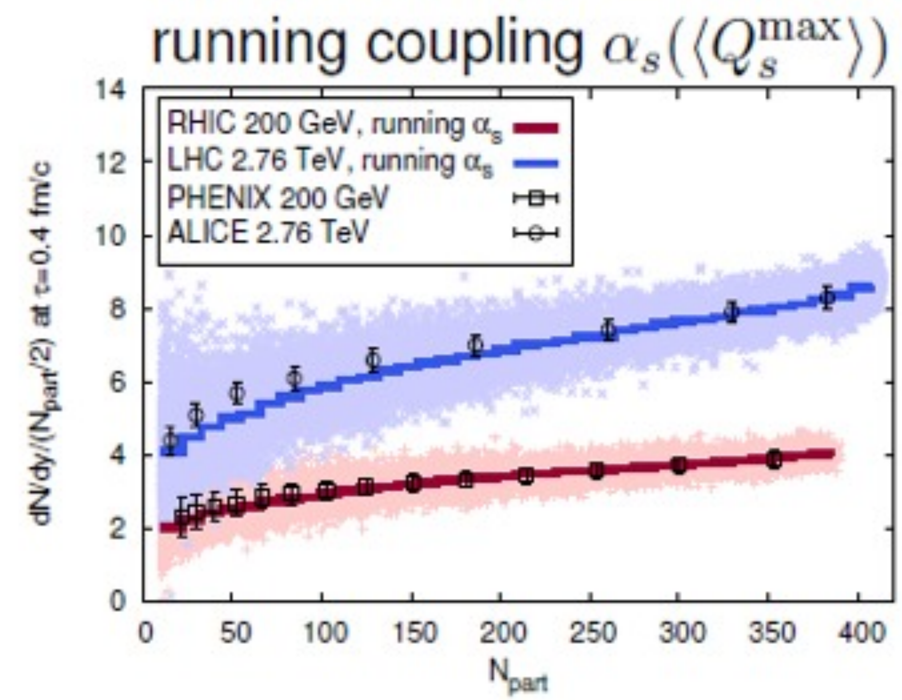
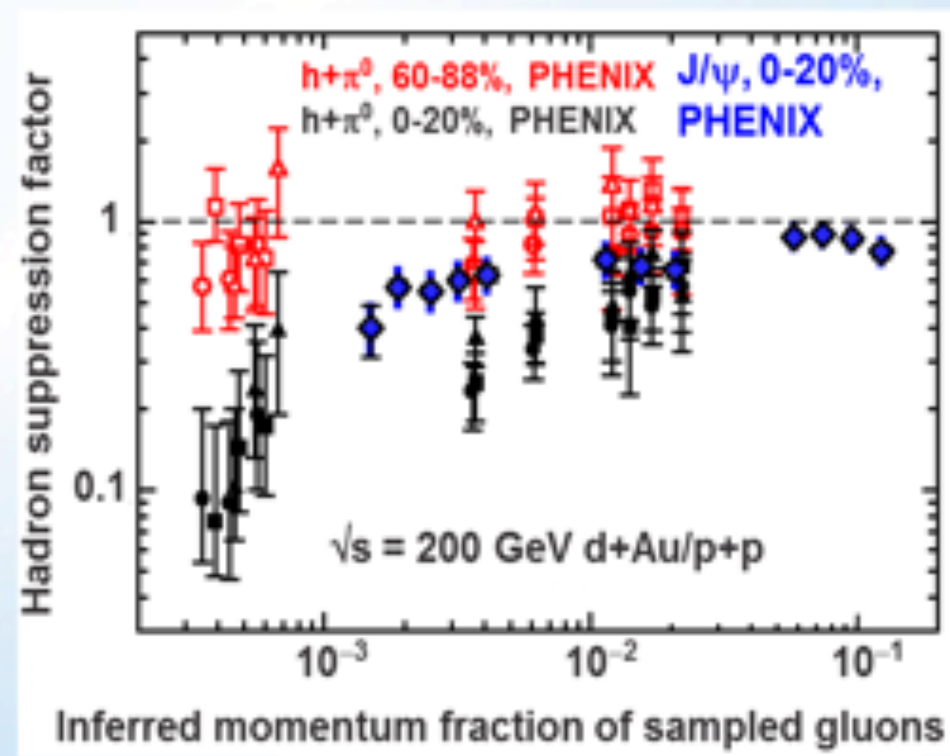


Consistent with observed suppression of forward hadron and di-hadron production in d+Au at RHIC.

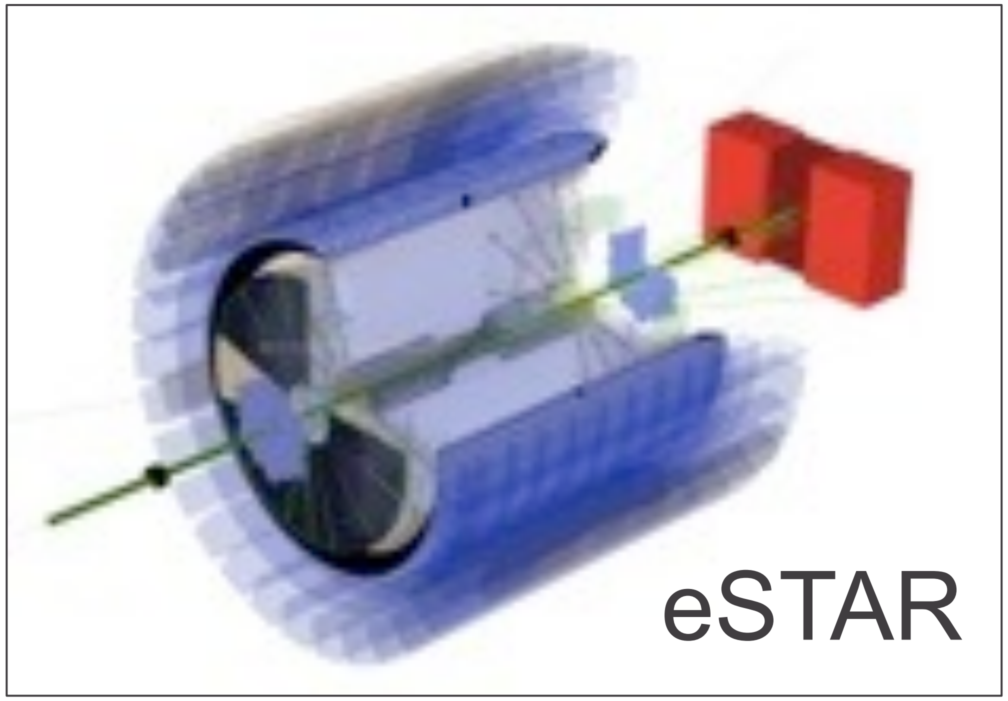
Forward γ production in p+A probes gluon densities at low x; transverse spin asymmetries in p+A probe the saturation scale. Forward detector upgrades and RHIC p+Au run in 2015 will make it possible.



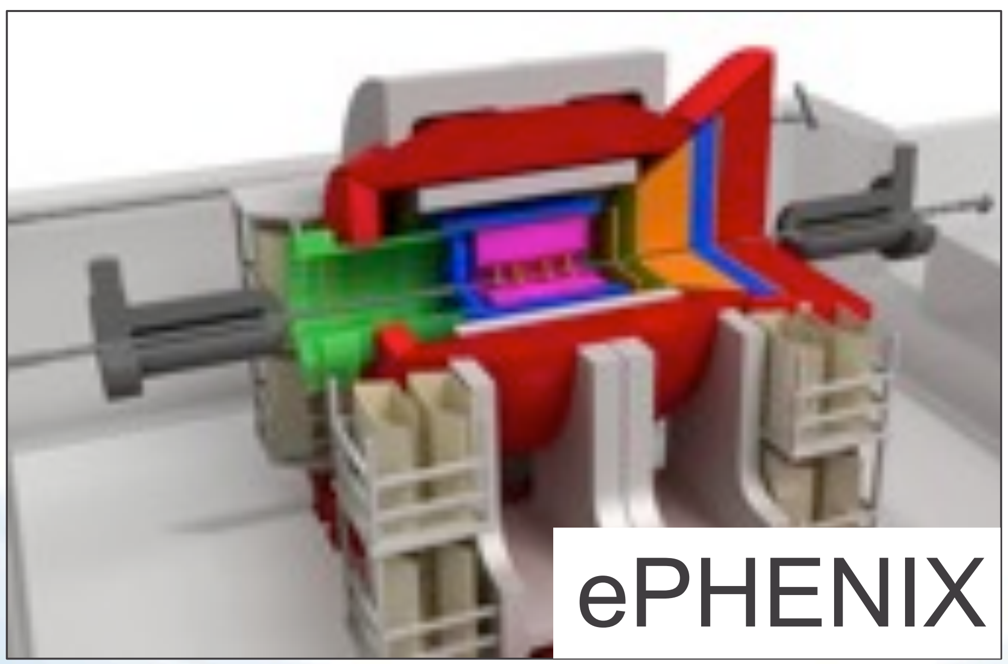
Run Schedule for RHIC

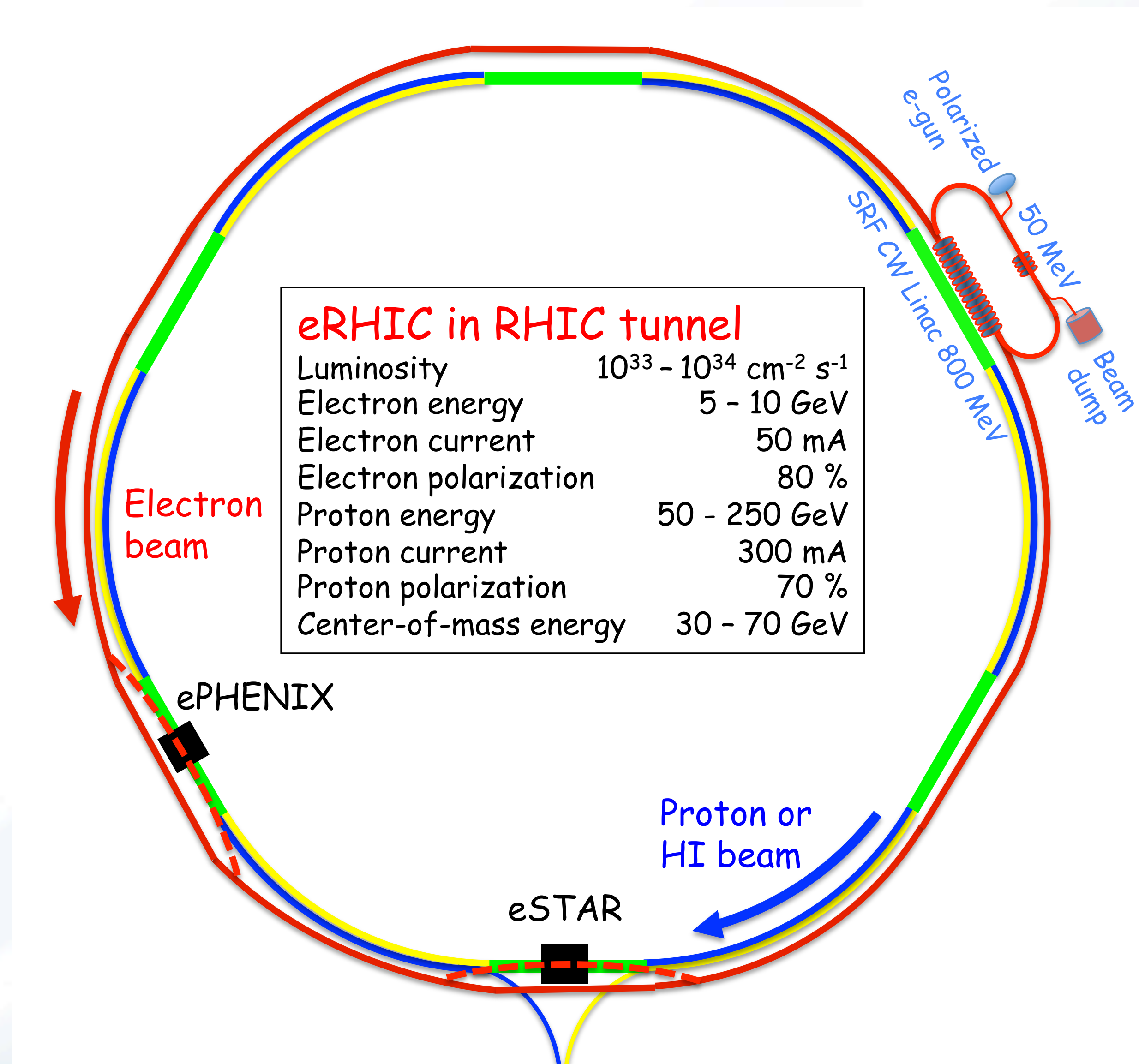
Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract $\eta/s(T)$ + 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	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+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

From RHIC to e-RHIC



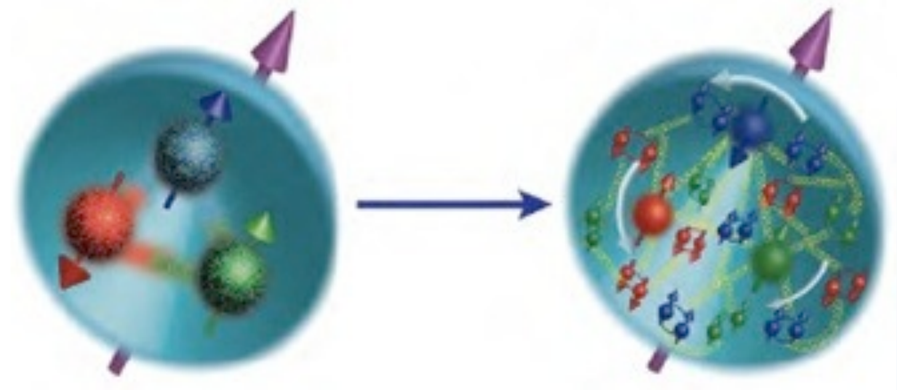
The 2013 NSAC *Subcommittee on Future Facilities* identified the physics program for an Electron-Ion Collider, as it was described in the 2013 EIC White Paper, as ***absolutely central*** to the U.S. nuclear science program in the next decade.



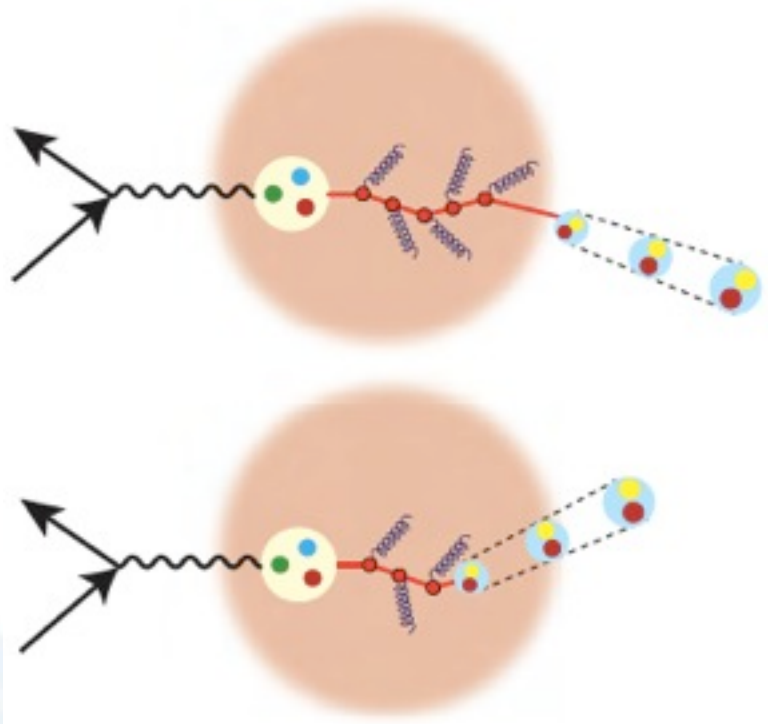


e-RHIC will be a QCD laboratory

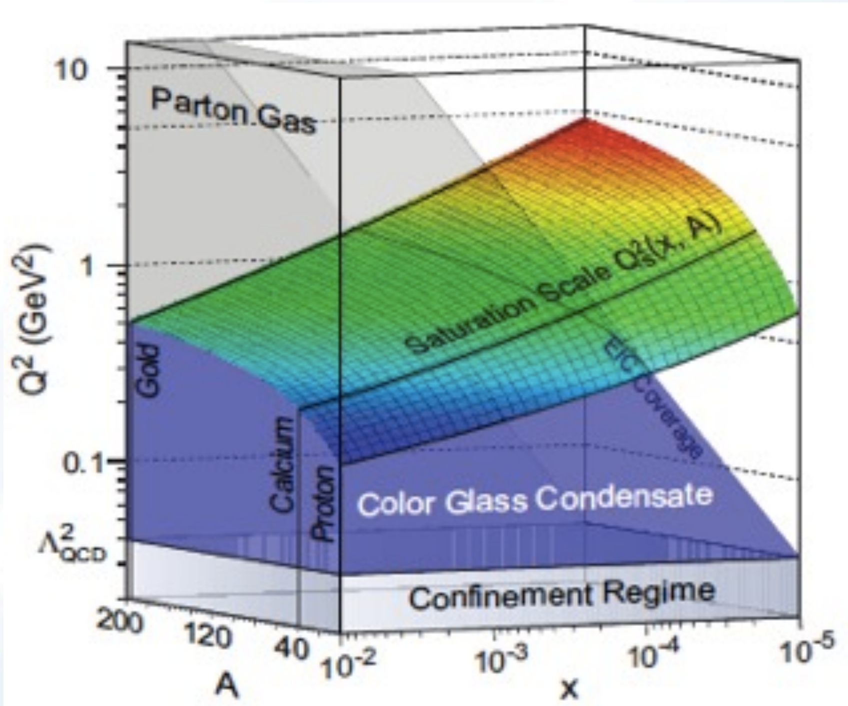
Gluon and sea quark structure of the proton, or what gives matter (most of) its mass ?



Use the nucleus as a fm-scale vertex detector to probe confinement



Is there a universal saturated gluon ocean (CGC) at low x ?



The far far future?

Sometimes it is there earlier than you think!

CERN is considering a future circular collider (FCC) with p+p CM energy of order 100 TeV (~ 7 times top LHC energy).

Kick-off meeting in mid-February 2014

Is it potentially interesting to study heavy ion collisions at such higher energy?

Can we make predictions of dn/dy, and phenomena, such as elliptic flow, higher Fourier components, jet quenching, depending on different temperature dependence models for η/s, q-hat, etc.?

Would a higher energy help to discriminate?

We certainly need some “low energy” runs at the LHC to bridge the gap to RHIC and explore T-dependence of QGP properties.

Maybe we can have some discussions at this meeting!?

Back to the Basics

- We want to understand how QCD works on the hadronic scale, in hadrons and in QGP.
- The "Plumpudding Model" did not work for the atom, but it surely fits our present understanding of the nucleon!
  - We have learned a lot about the "plums" (the valence quarks), but very little about the "pudding" (the color fields).
  - We want to know how the proton gets its mass and its spin.
- We know that the QGP behaves like an inviscid liquid, but we don't yet know how it gets there.
  - Is the QGP a weakly coupled state masquerading as a strongly coupled one by some nonperturbative mechanism?
- We want to determine some dynamical properties of the QGP that tell us about its structure:
  - Shear viscosity, diffusion constants, color screening length, chiral properties, phases at high baryon density

Instead of a summary

Let’s have lots
of (friendly) arguments
this week!