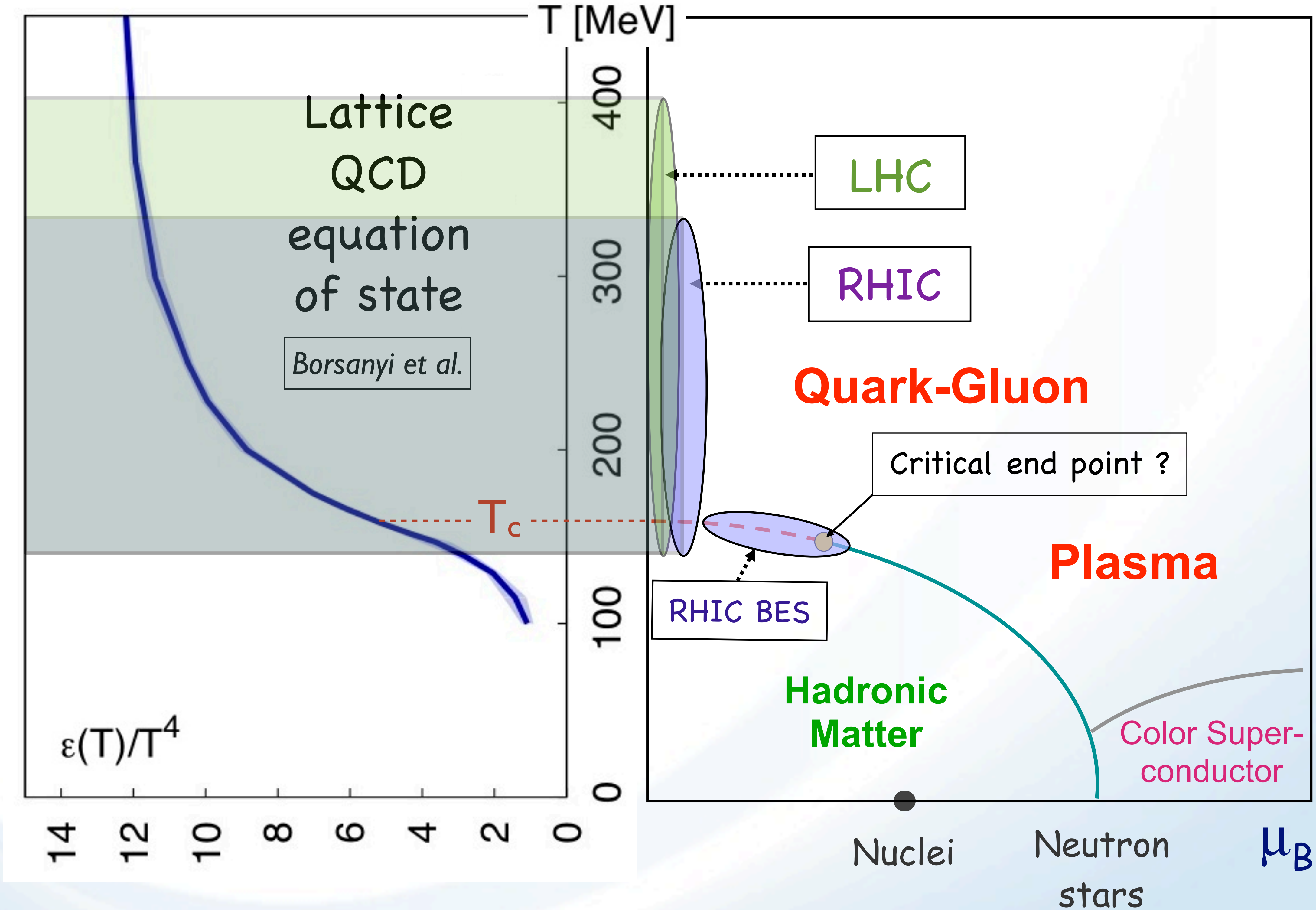
Relativistic Heavy Ion Collider

Physics Outlook

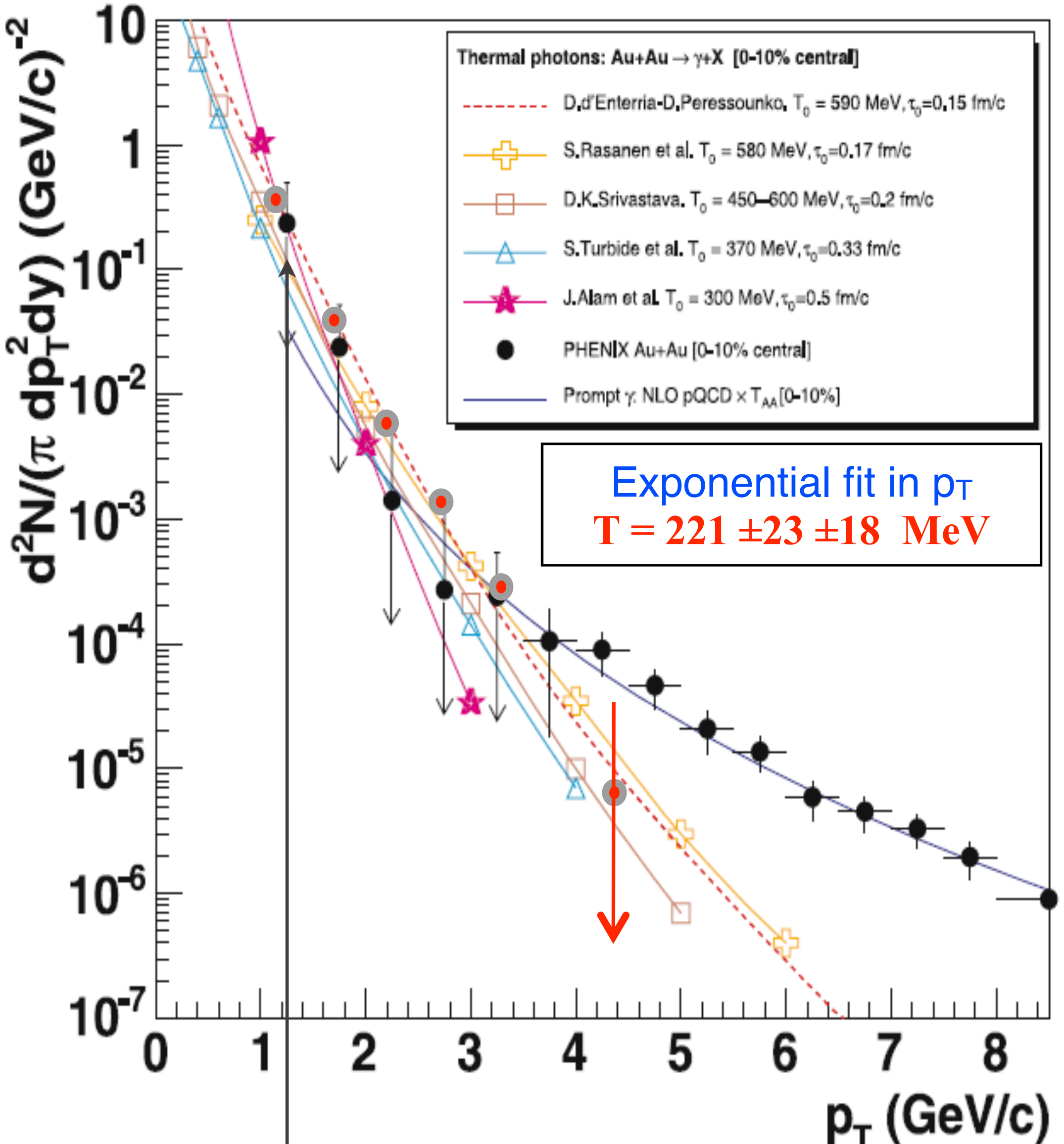
Berndt Mueller
ALD for Nuclear and Particle Physics
Brookhaven National Laboratory

RHIC Retreat
25-26 July 2013

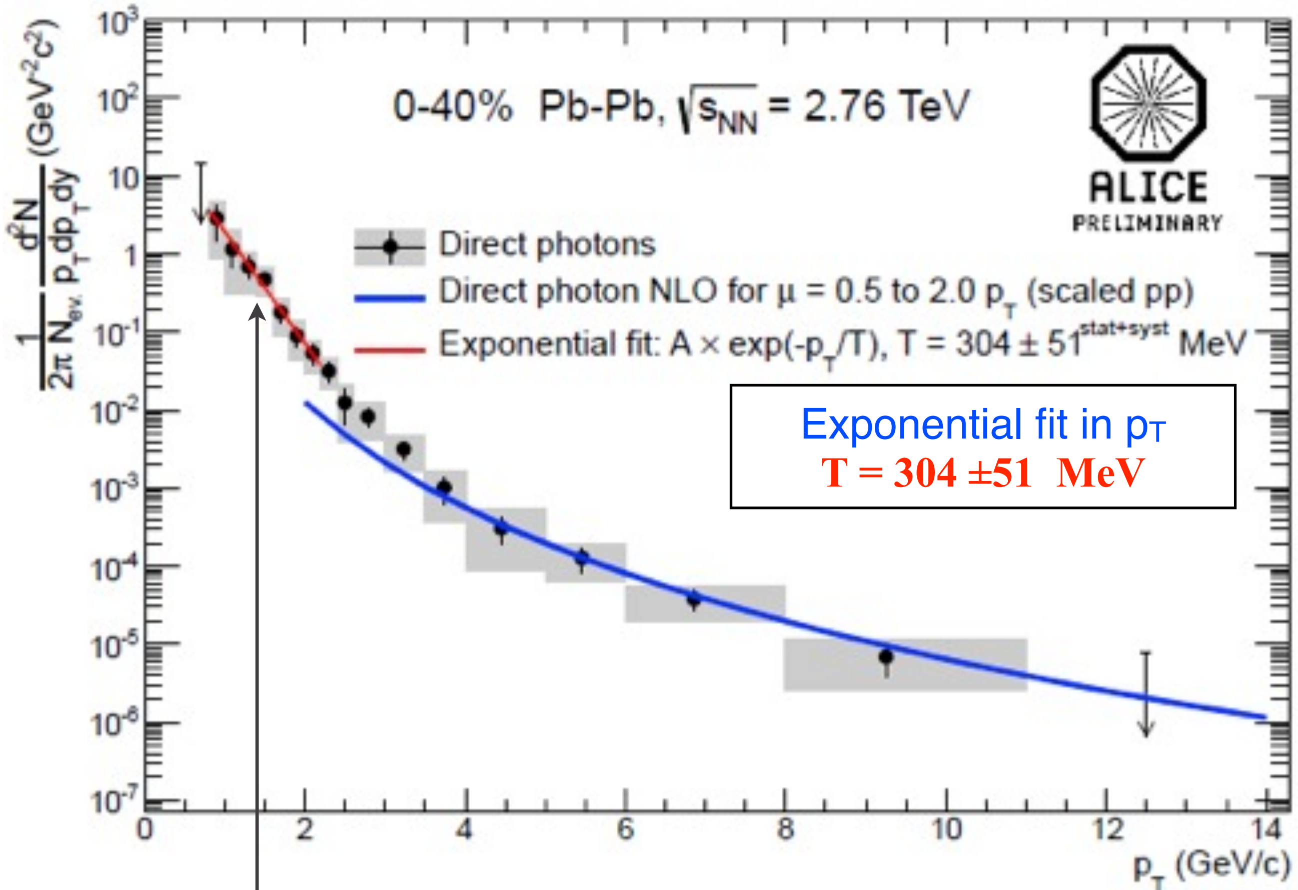
QCD Phase Diagram



The Hottest Places on the Planet



Corresponds to initial temperature:
$T_{init} \geq 300$ MeV



New **record temperature** measured at LHC:

$T_{LHC} = 1.37\ T_{RHIC}$

$T_{init} \geq$ 4 trillion degrees

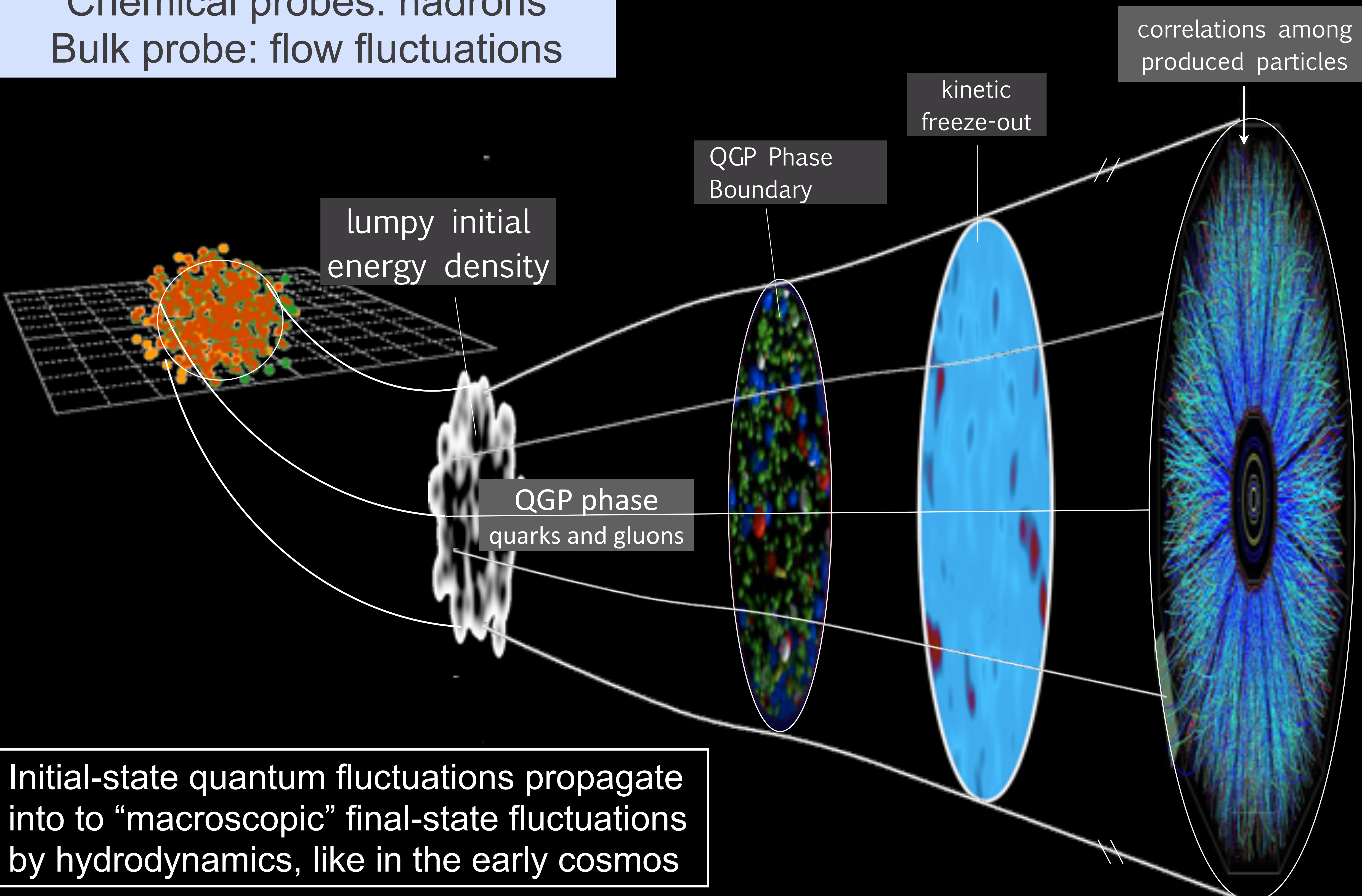
$T_{init} \geq$ 5.5 trillion degrees

RHIC's Main Discoveries

- Hot nuclear matter produced in collisions at RHIC is a quark-gluon plasma.
- The QGP is a strongly coupled "perfect" liquid (η/s near the quantum limit); RHIC's QGP is more "perfect" than that produced at LHC.
- The fluid is made up of individually flowing quarks, not quarks bound into baryons and mesons.
- Quarks moving through the QGP lose energy rapidly, causing jets to be strongly "quenched".
- Heavy quark bound states (J/ψ, Υ) "melt" in the QGP due to color screening and ionization. RHIC and LHC data together indicate that heavy quarks can recombine when the QGP hadronizes.
- Approx. 20% of the proton spin may be carried by gluons.

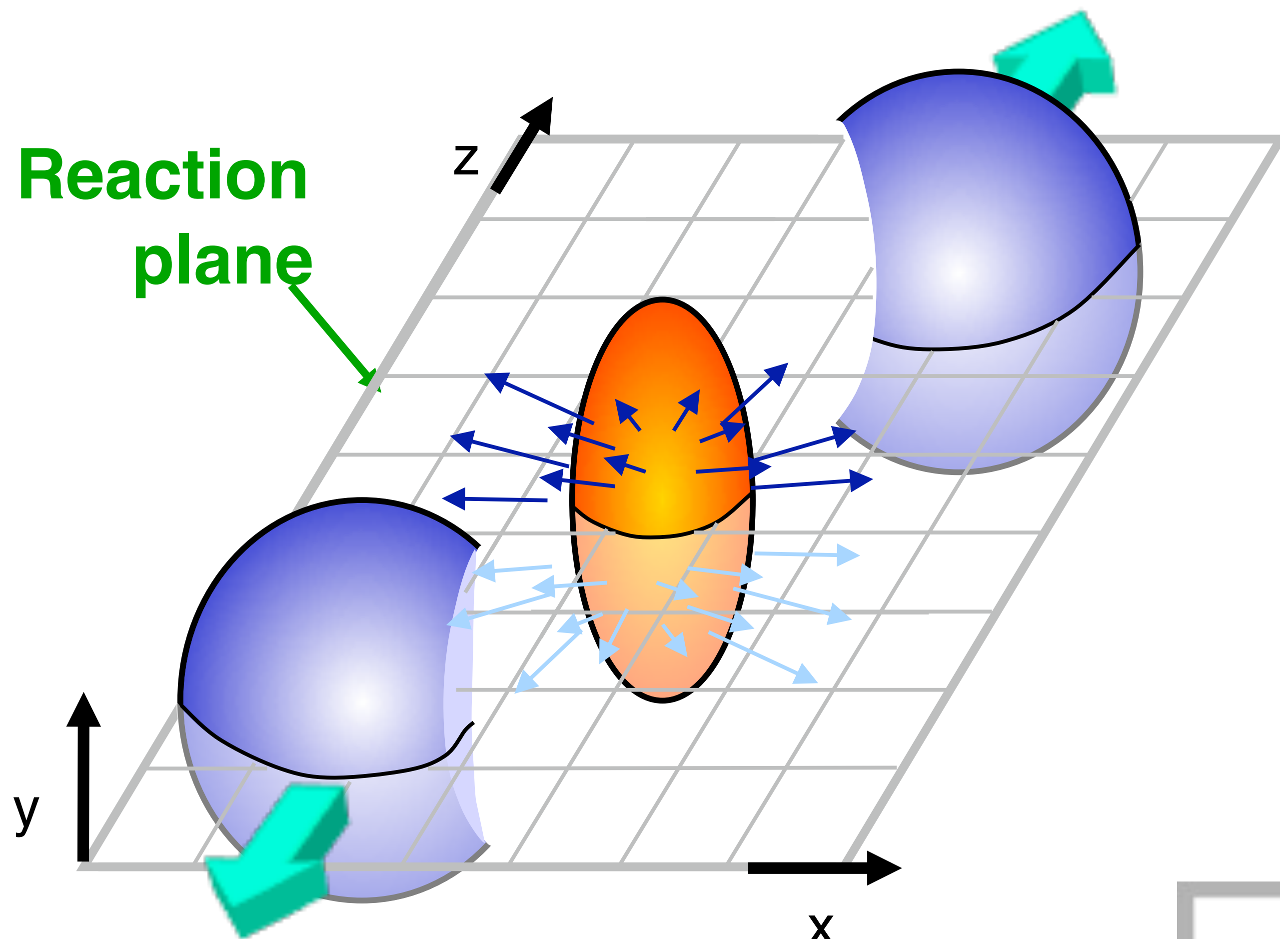
Probing Hot QCD Matter

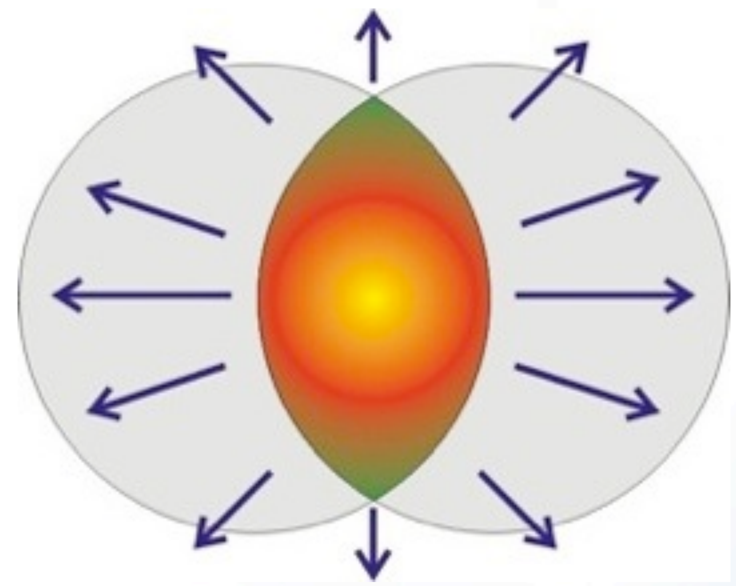
"Little Bang"
Penetrating probes: photons, jets
Chemical probes: hadrons
Bulk probe: flow fluctuations



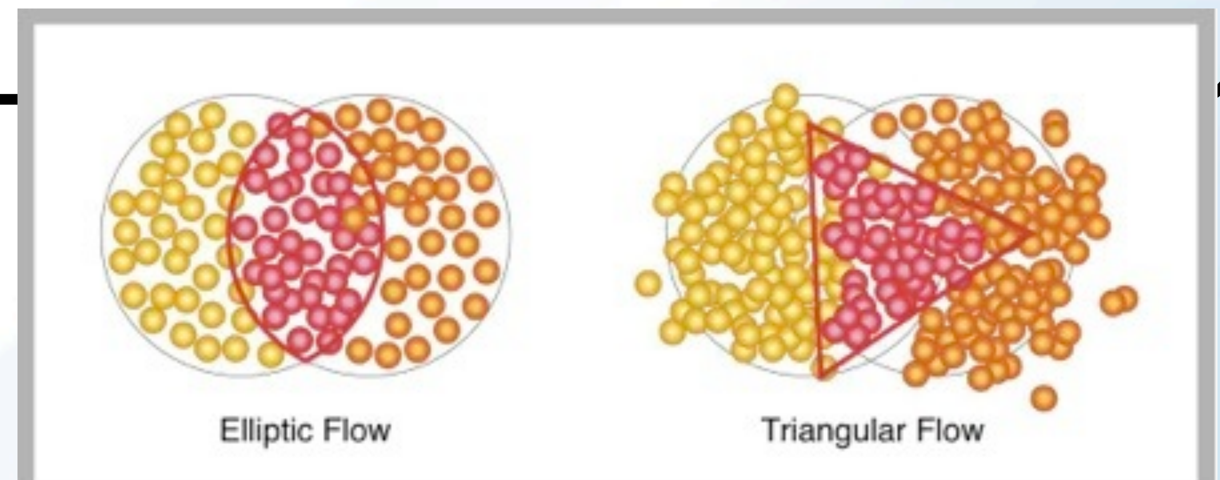
Initial-state quantum fluctuations propagate into to "macroscopic" final-state fluctuations by hydrodynamics, like in the early cosmos

Anisotropic flow





Only matter in the overlap area gets compressed and heated

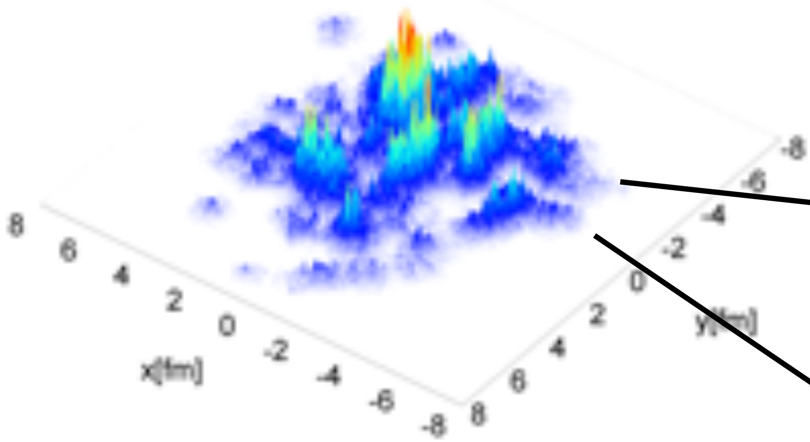


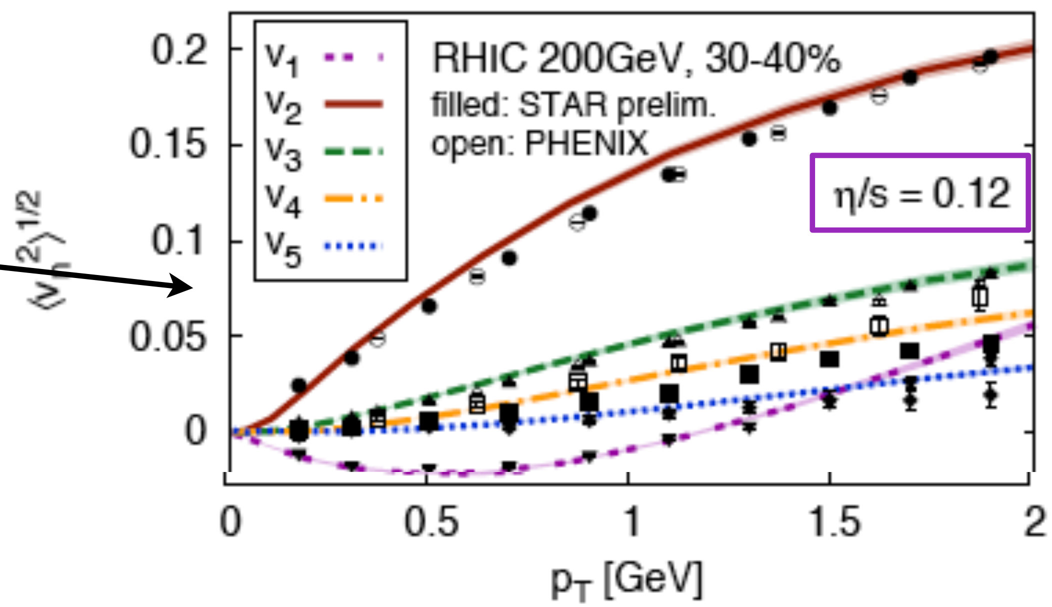
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2 \sum_n v_n(p_T, \eta) \cos n\left(\phi - \psi_n(p_T, \eta)\right) \right)$$

Measure of “fluidity”: (η/s)

QCD Matter at RHIC is most "perfect"

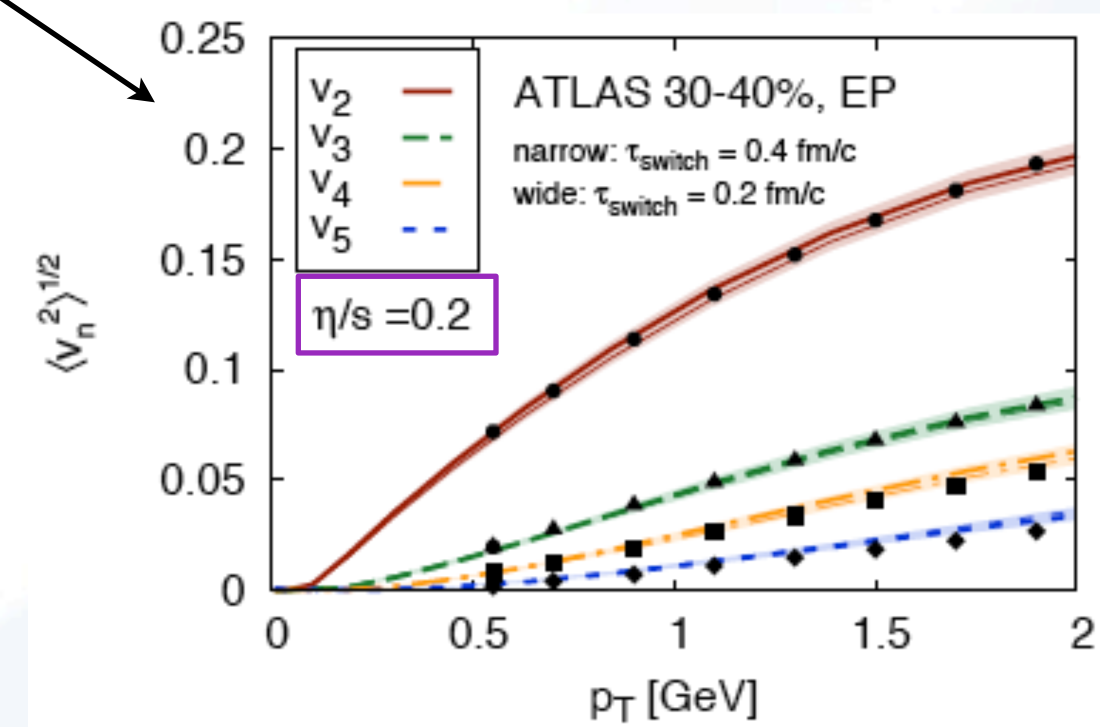
Initial density distribution





RHIC

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



LHC

A study of the opacity of the matter to energetic quarks (jets) confirms this conclusion:

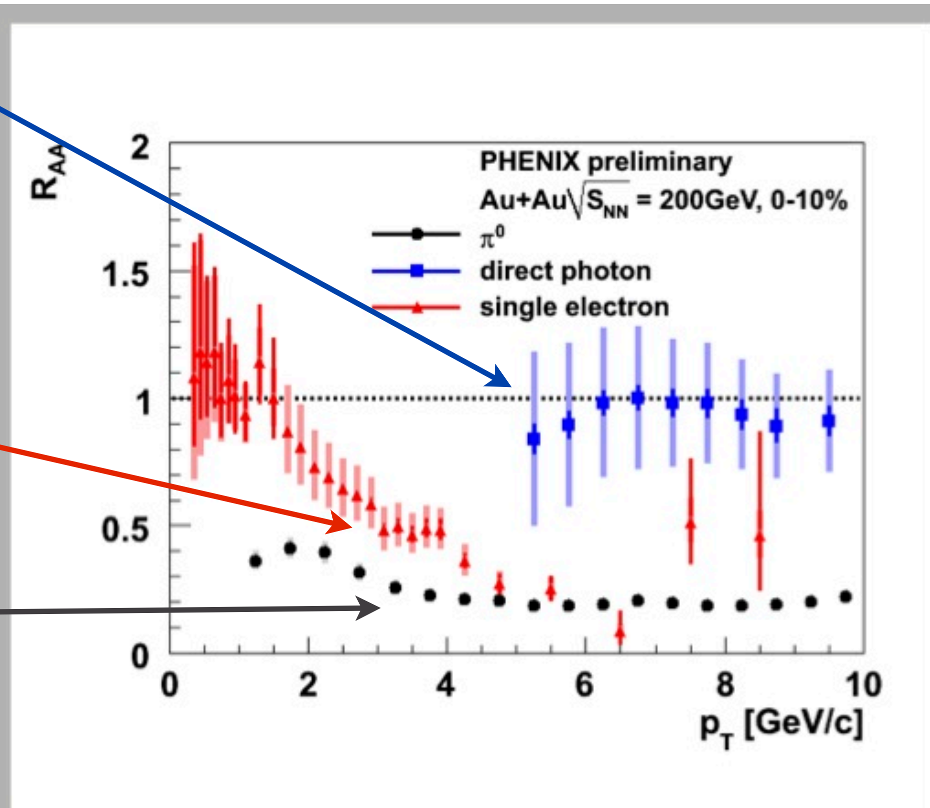
QCD matter at RHIC is less transparent by the same factor 0.6.

Jet quenching = parton energy loss

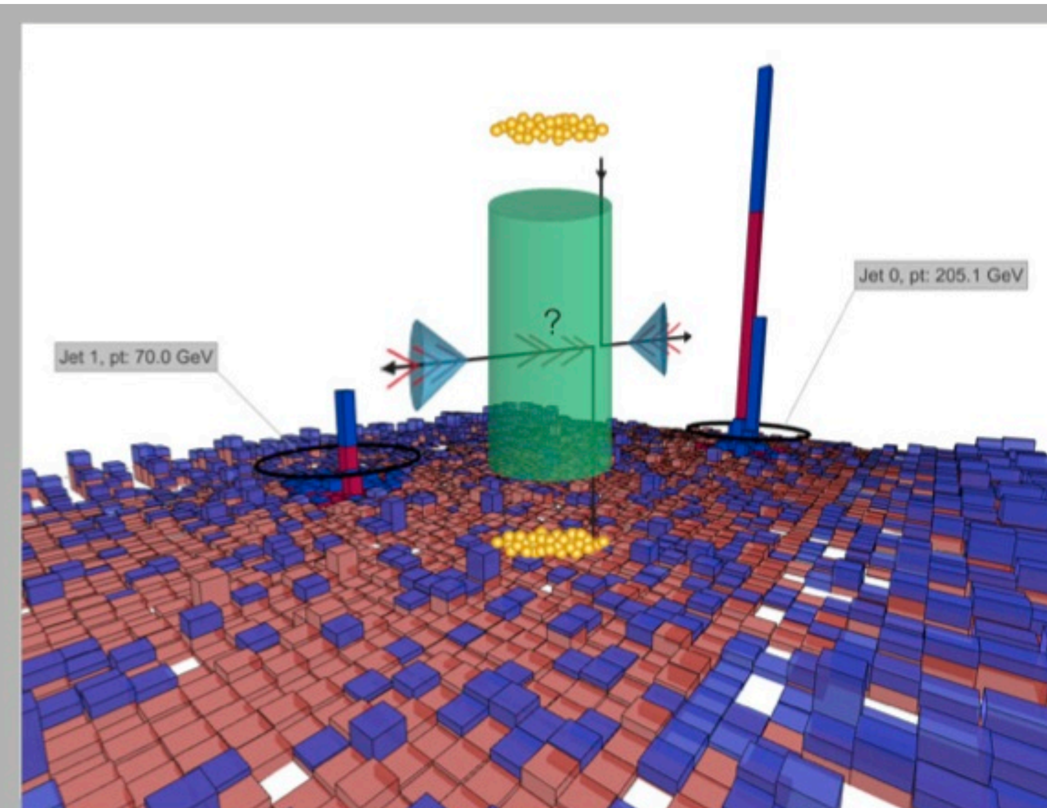
Photons don’t lose energy

Heavy quarks

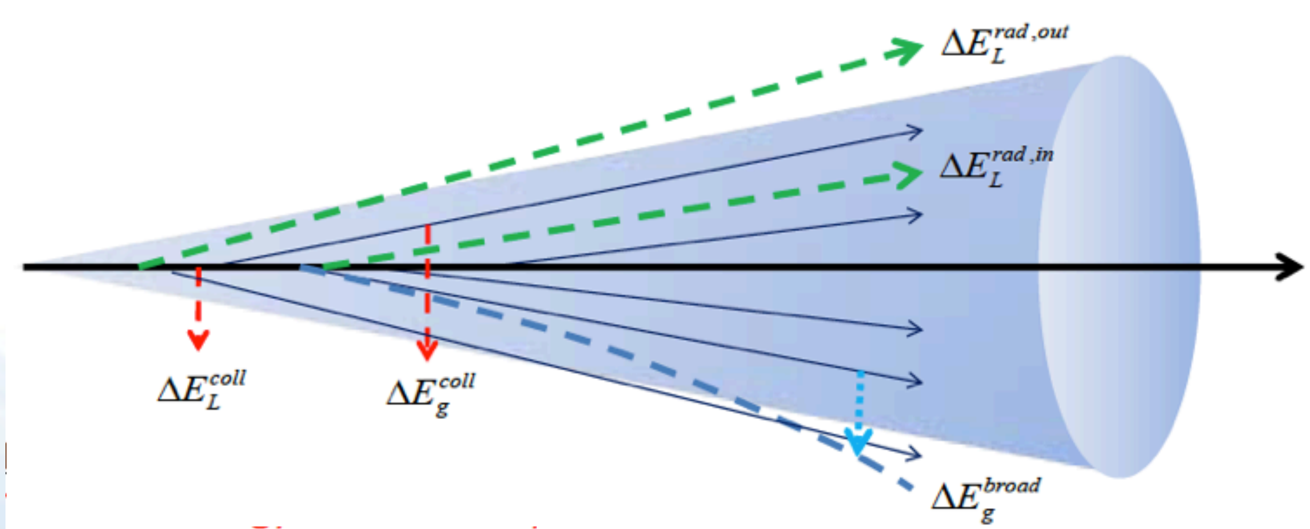
Light quarks



Jet quenching @ RHIC

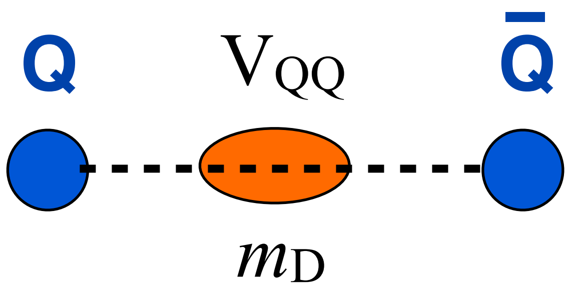


Jet quenching @ LHC

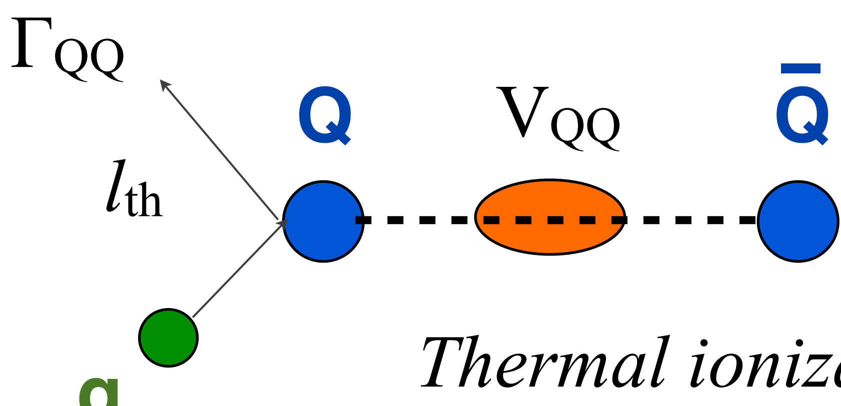


Energy is lost by the leading parton in interactions with the hot matter, scattered out of the jet cone and absorbed

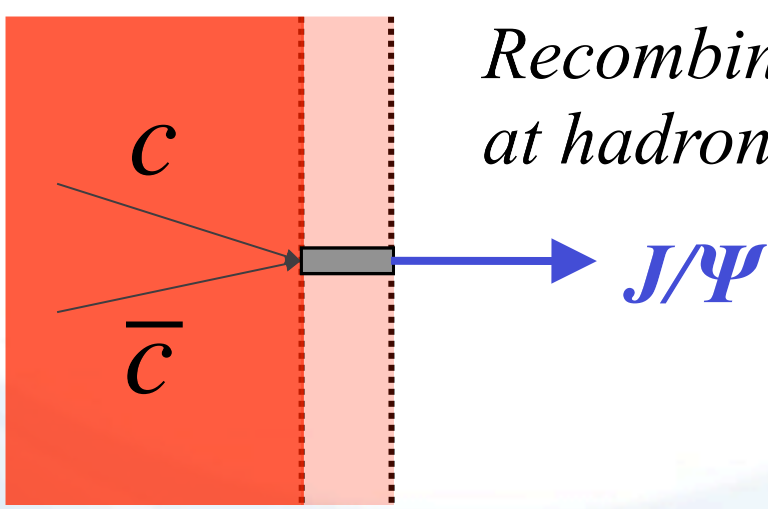
J/ψ suppression



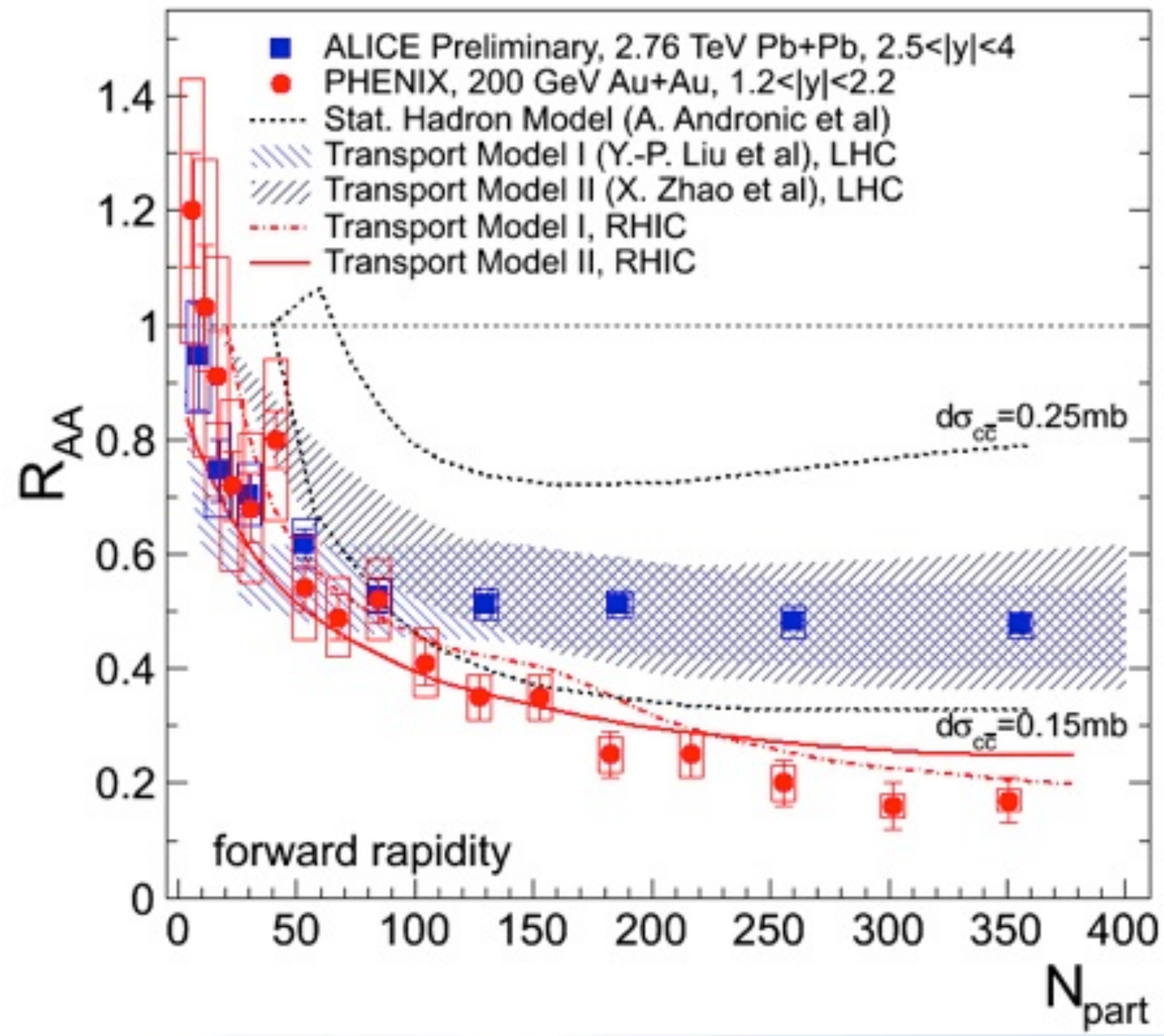
Color screening causes "melting"



Thermal ionization destroys QQ states



Recombination at hadronization



Less J/ψ suppression at LHC than at RHIC, at mid-rapidity and mid-forward rapidities:
c-cbar recombination explains data.

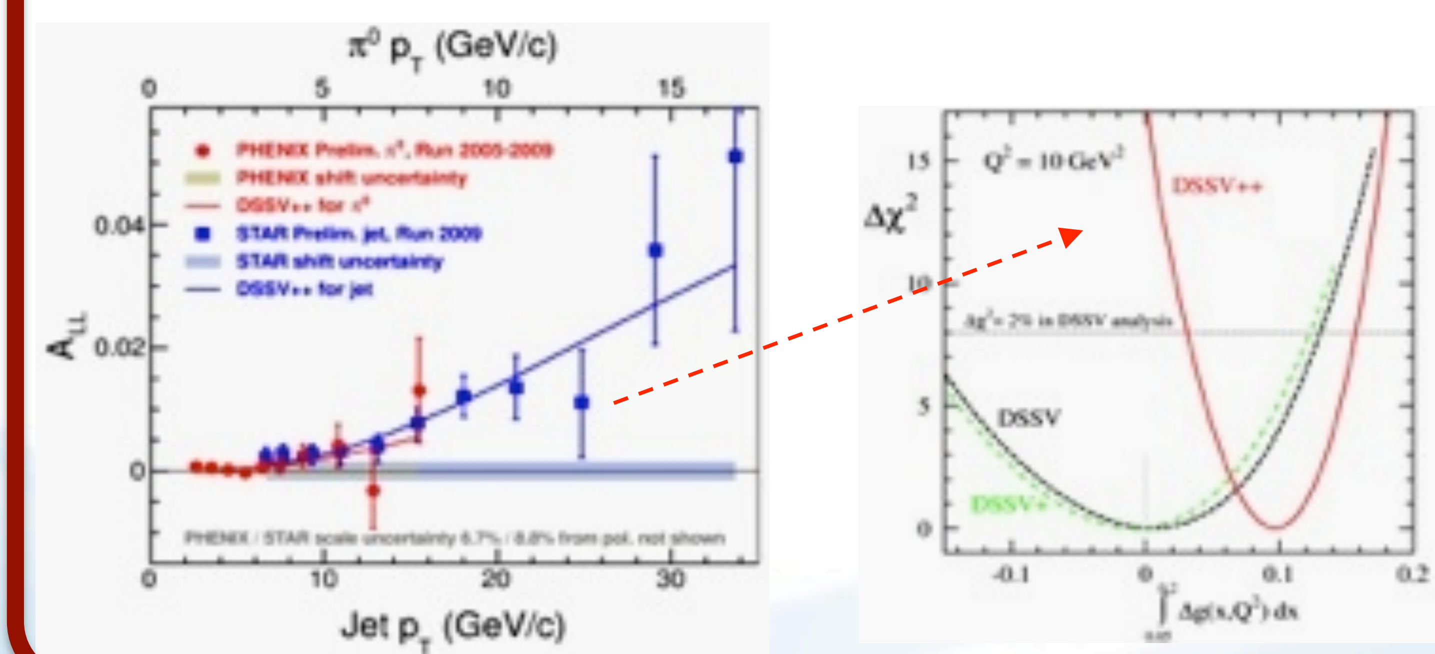
The “Missing” Proton Spin

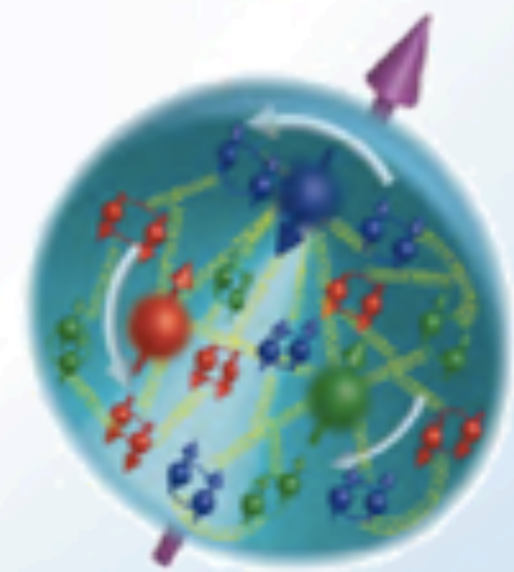
Spin of atoms resides in electrons and nuclei, not in the electric field. Is this different for protons?

First indications from Run-12 are that 20% of proton spin resides in the gluon field. Run-13 will yield precision results on gluon and quark sea contributions.

Precursor of the physics that can be done with much higher precision at an electron-ion collider (eRHIC) which will measure not just the total contribution of gluons to the spin, but provide complete images of the gluon distribution

$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2)\, dx = 0.10^{+0.06}_{-0.07}$$



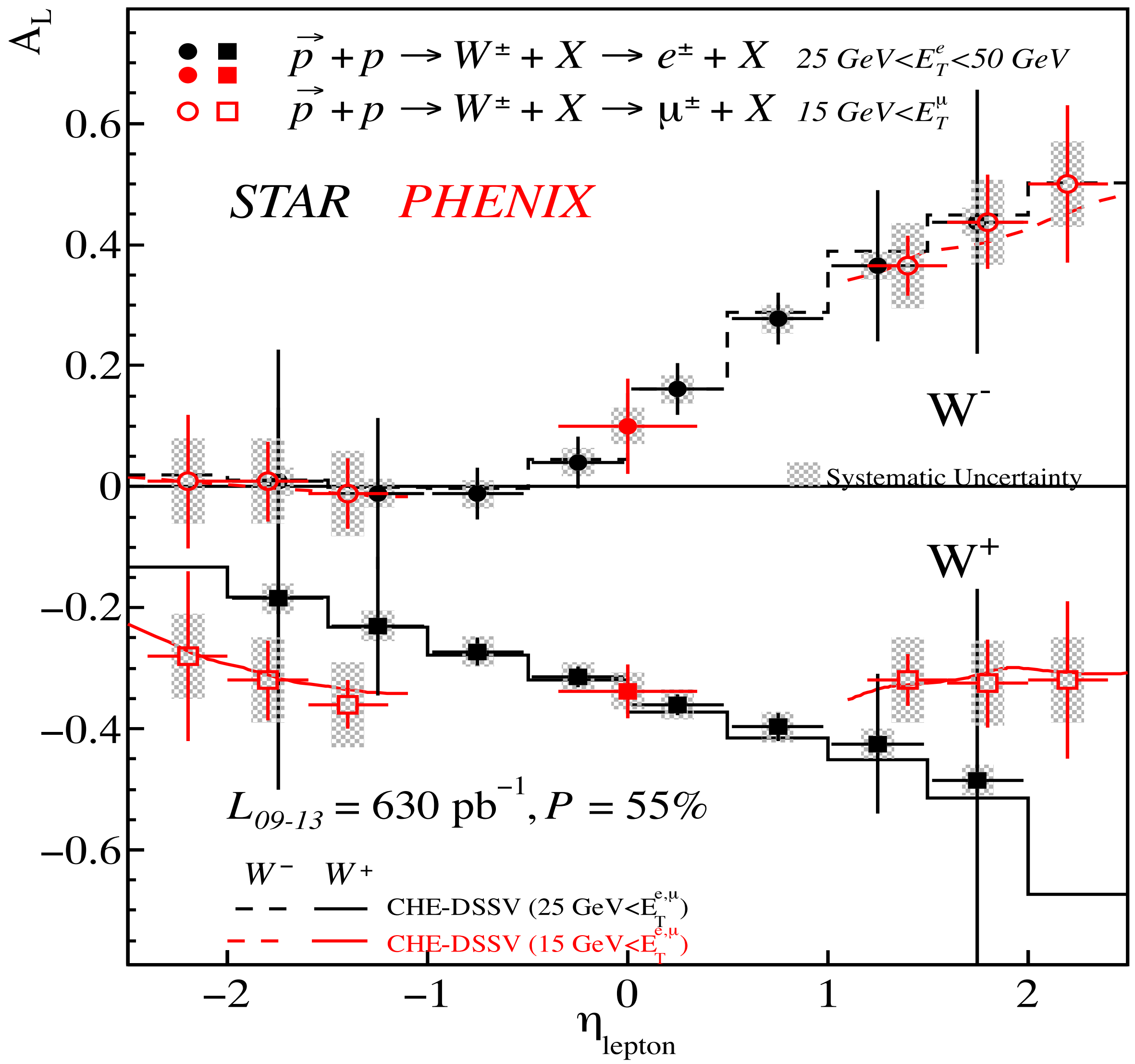


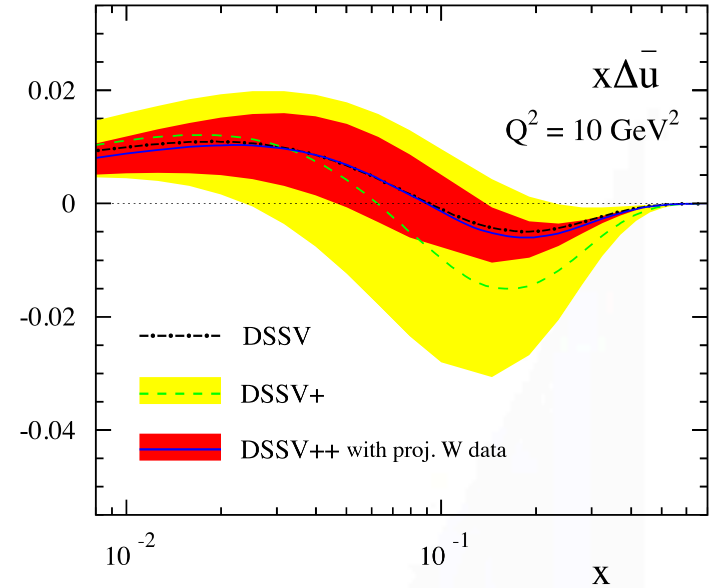
Open Physics Questions

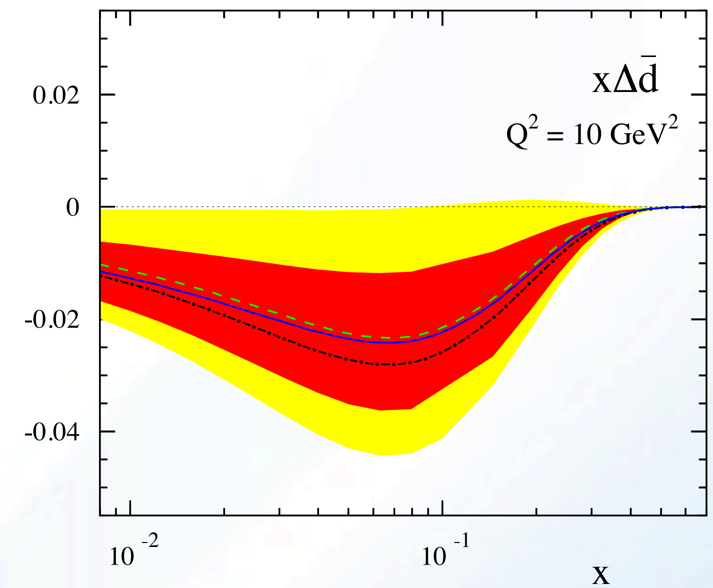
Questions	Facilities	Comments
1) How perfect is "near-perfect" liquid?	RHIC & LHC	Flow power spectra, next 3 years
2) Nature of initial density fluctuations?	RHIC, LHC & EIC	Benefits from asymmetric ion collisions at RHIC
3) How does strong coupling emerge from asymptotic freedom?	RHIC & LHC	After 2019 at RHIC; jets need sPHENIX upgrade
4) Evidence for onset of deconfinement and/or critical point?	RHIC; later FAIR, NICA	Phase 2 energy scan after 2017, needs electron cooling
5) Sequential melting of quarkonia?	RHIC & LHC	RHIC vertex detector upgrades; beam energy dependence important
6) Are sphaleron hints in RHIC data real?	Mostly RHIC	Exploits unique system and energy versatility of RHIC
7) Do gluon densities saturate?	RHIC, LHC & EIC	Want to see onset at RHIC; need EIC to quantify
8) Where is missing proton spin?	RHIC & EIC	RHIC shows that gluons contribute substantially

Addressing these questions requires a multi-year program of A+A, p+p and p/d + A runs at various energies.

Providing Answers: Missing Proton Spin







500 GeV p+p luminosity and polarization now sufficient for vigorous pursuit of W± prod. asymmetries constrainting sea-quark polarization

Forward upgrades will permit transverse spin asymmetries for DY dileptons to test initial-state vs. final-state effects

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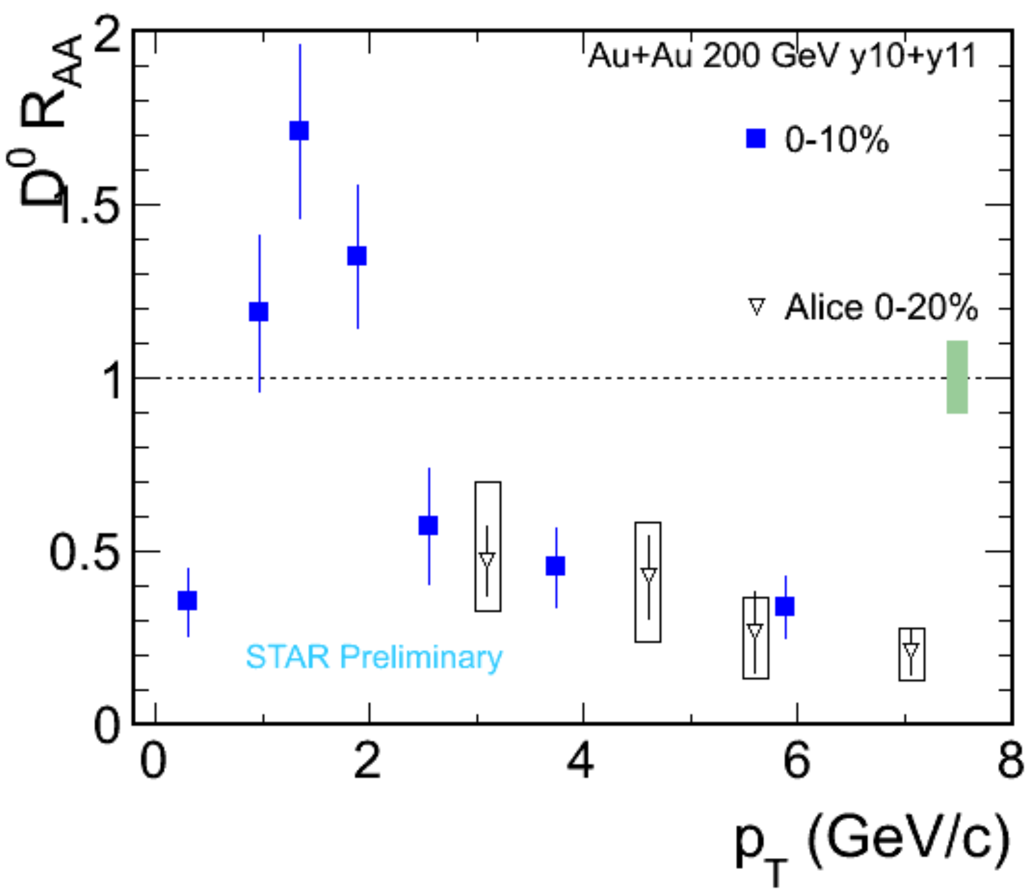
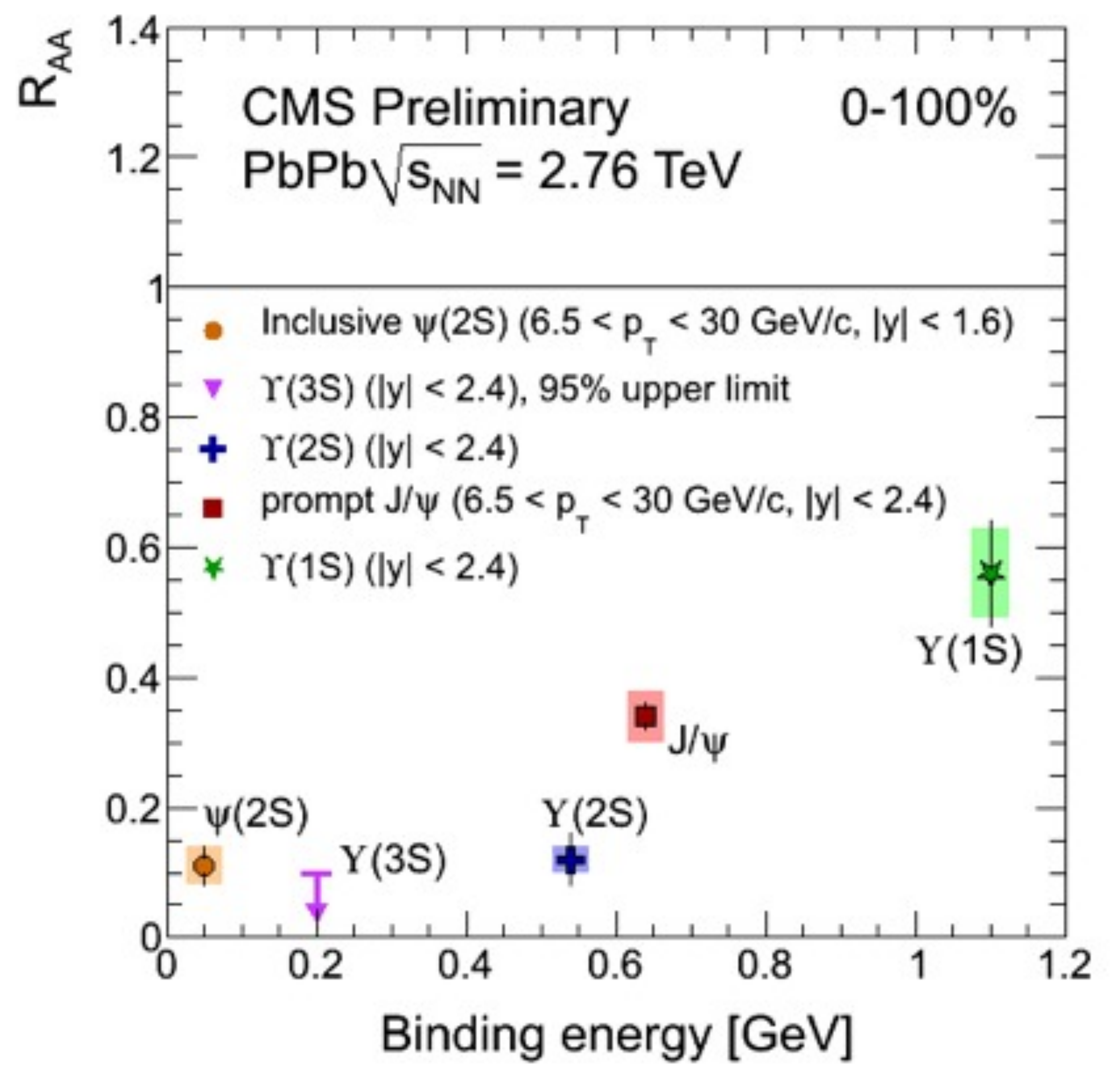
Providing answers: Color response of QGP

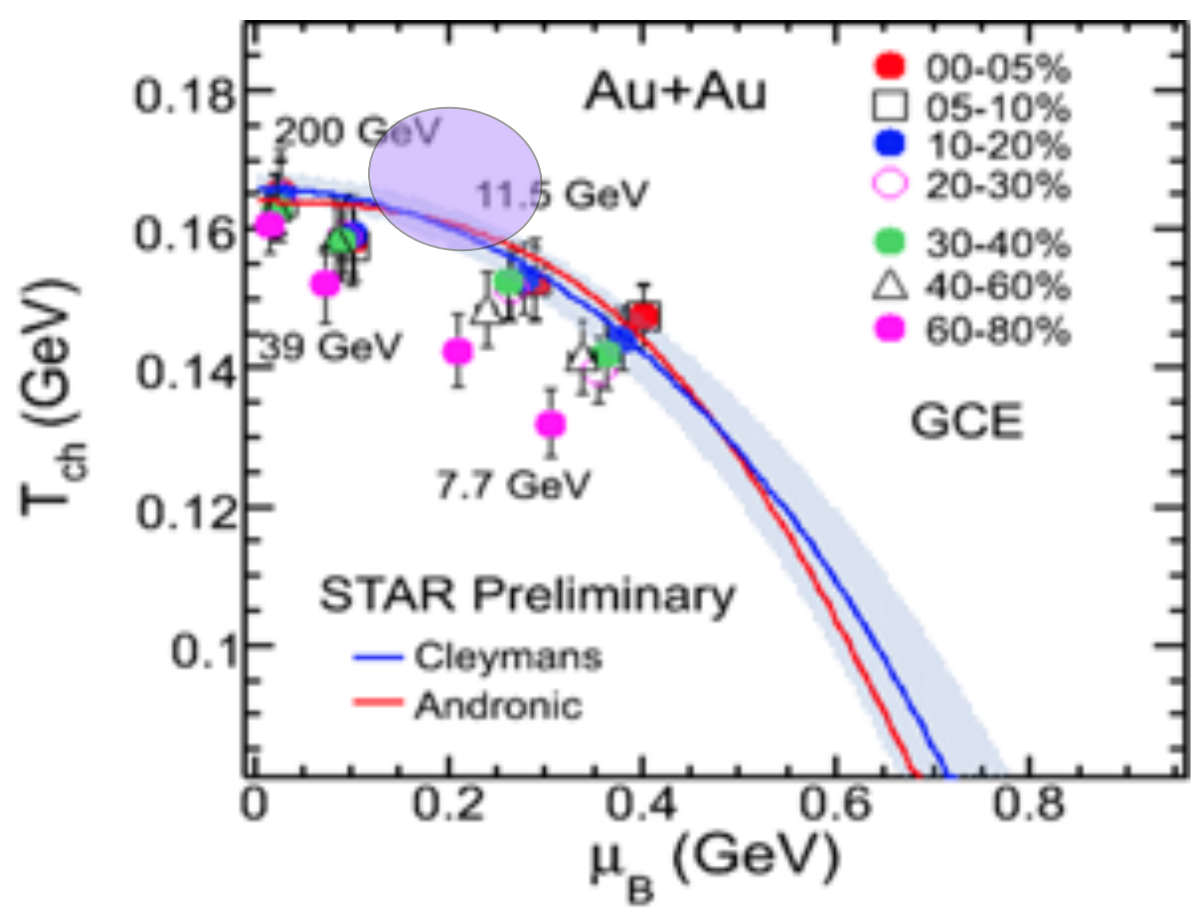


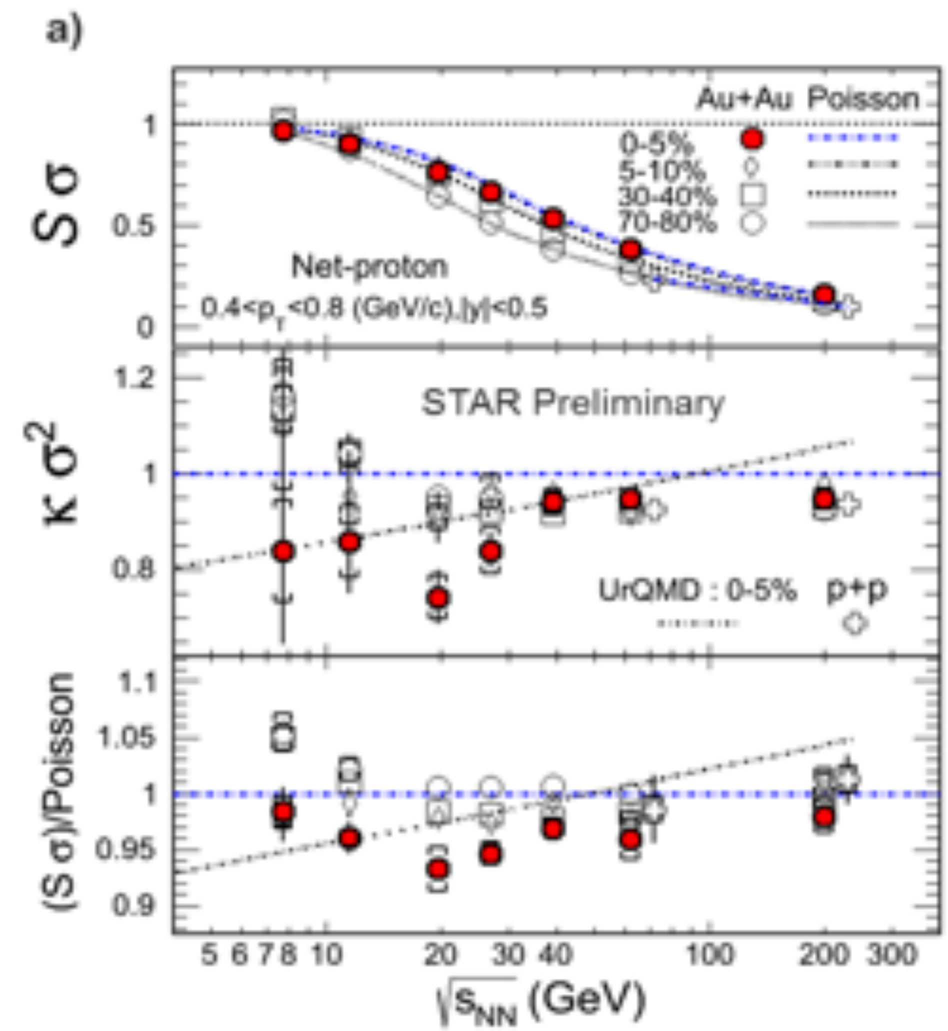
Suppression of mesons carrying open heavy flavor = energy loss of heavy quarks (*c, b*) explores mechanism of energy loss via color response of the medium.



Full range of quarkonium states needed at RHIC energy range for comparison.

Providing Answers: Onset of Deconfinement

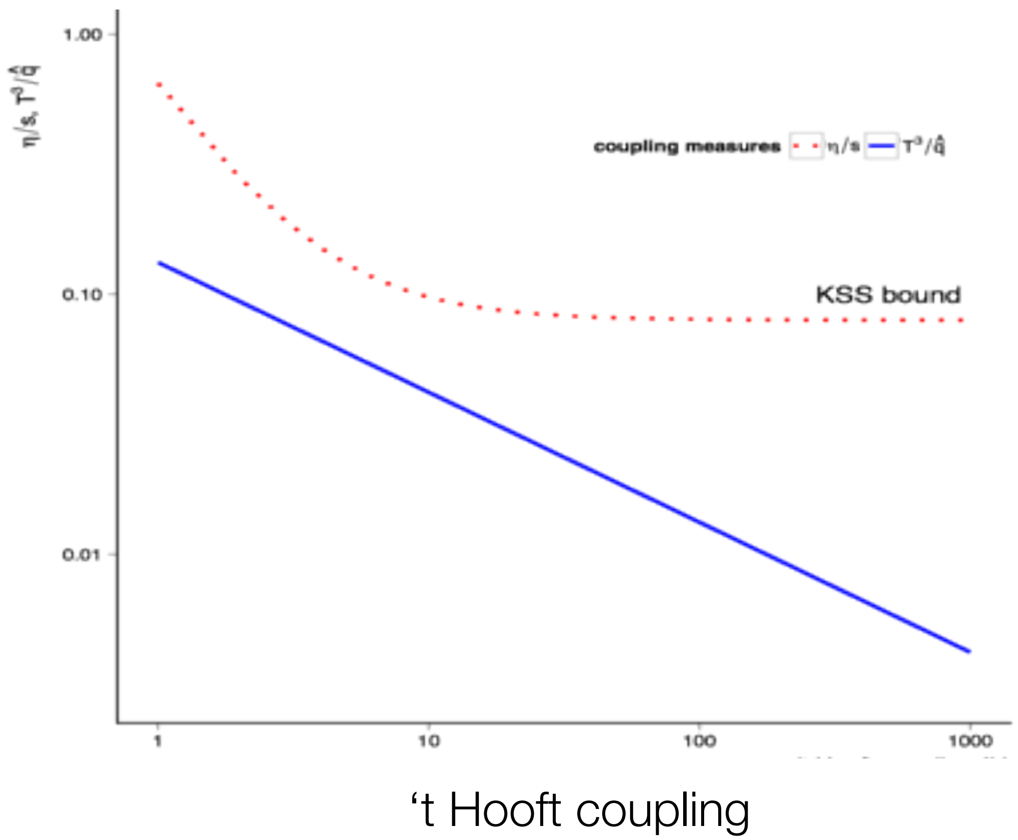




Phase 1 BES: Rapid changes below ~27 GeV:
single hadron suppression → enhancement; n_q scaling breaks down;
non-statistical net-proton fluctuations

Low-energy e-cooling will improve statistics at √s < 20 GeV for detailed measurements of sensitive quantities in search for critical point

Providing Answers: Emergence of Strong Coupling



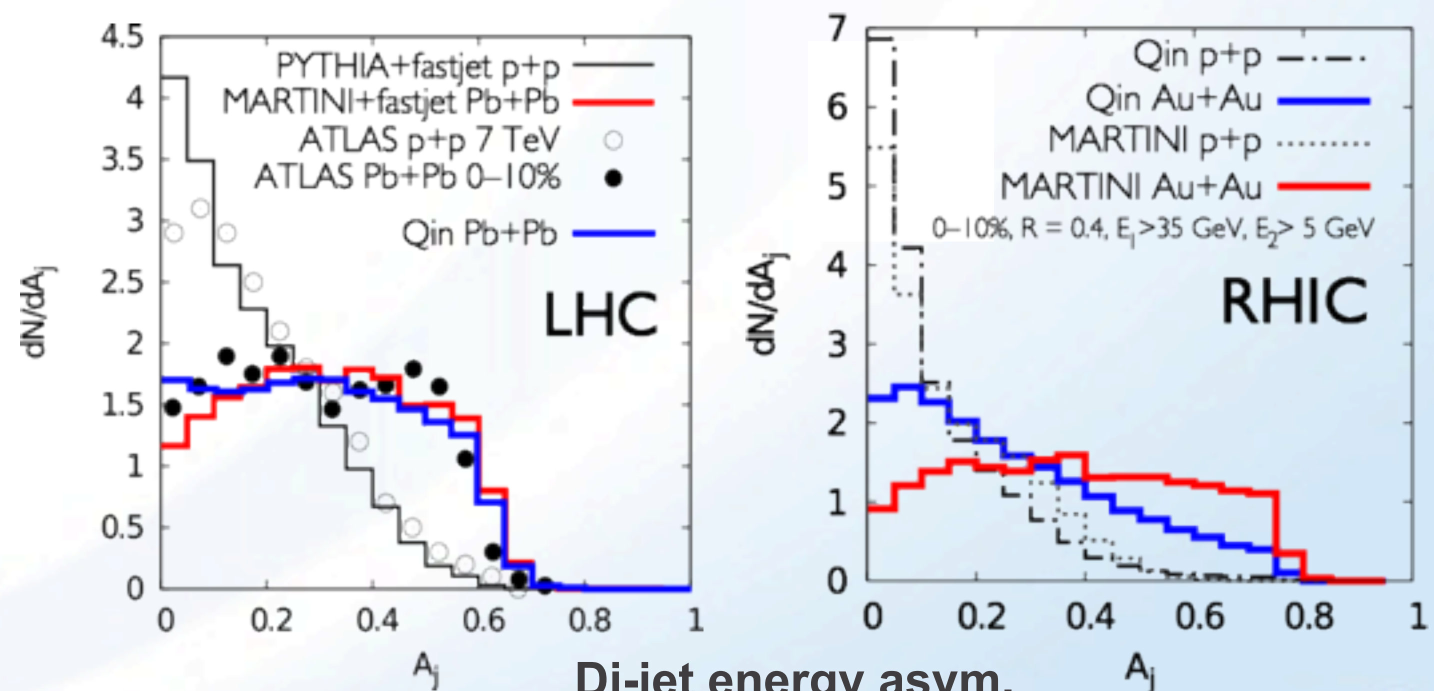
Low viscosity, rapid thermalization, and strong jet quenching are consequences of strong coupling

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

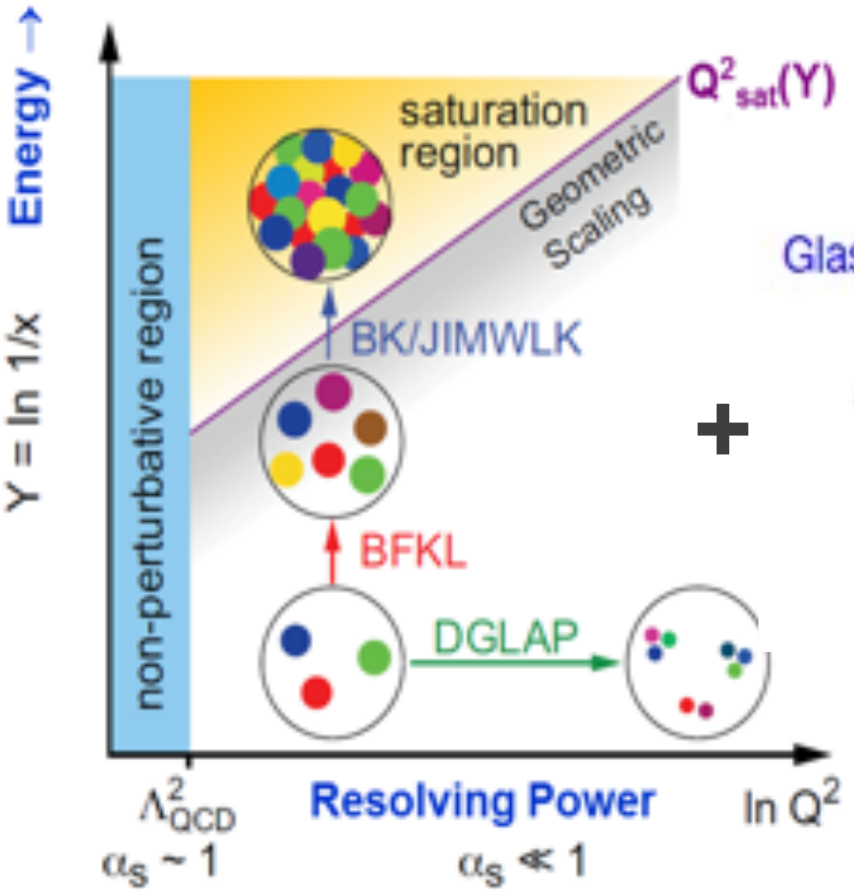
BaBar solenoid in its transfer frame



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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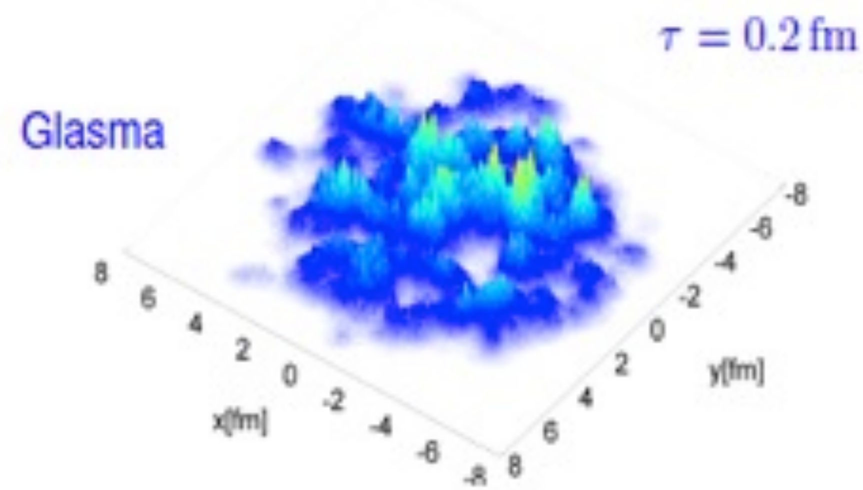

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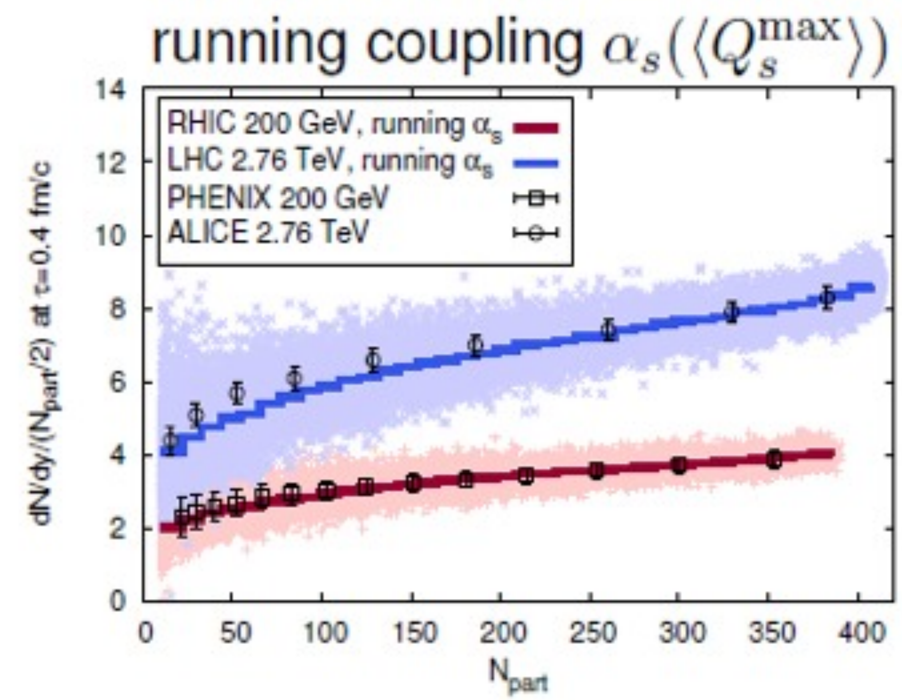
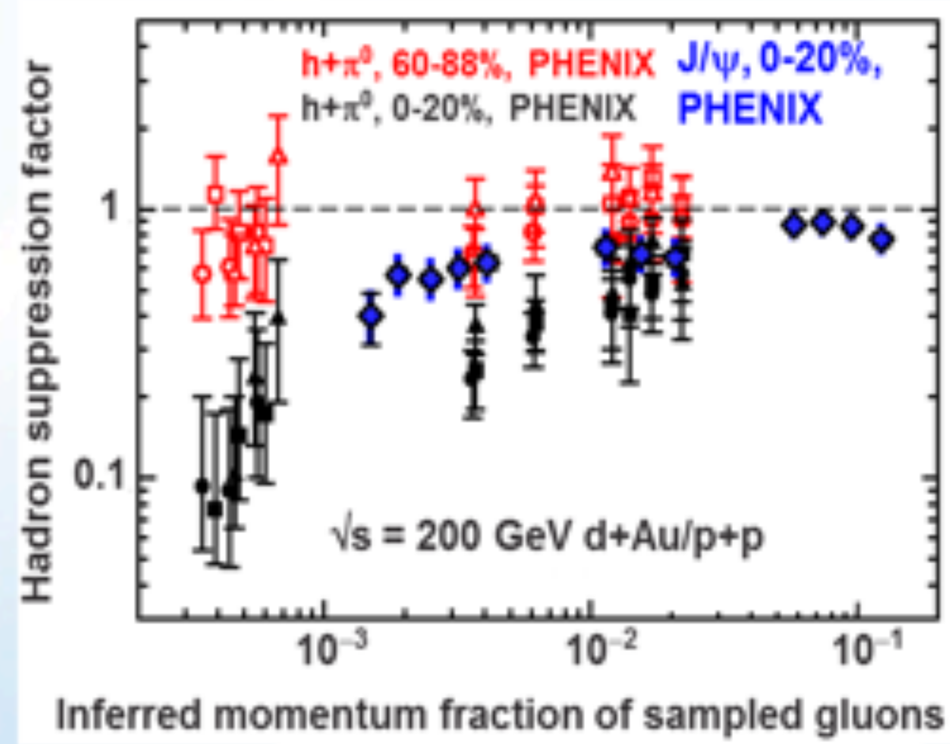


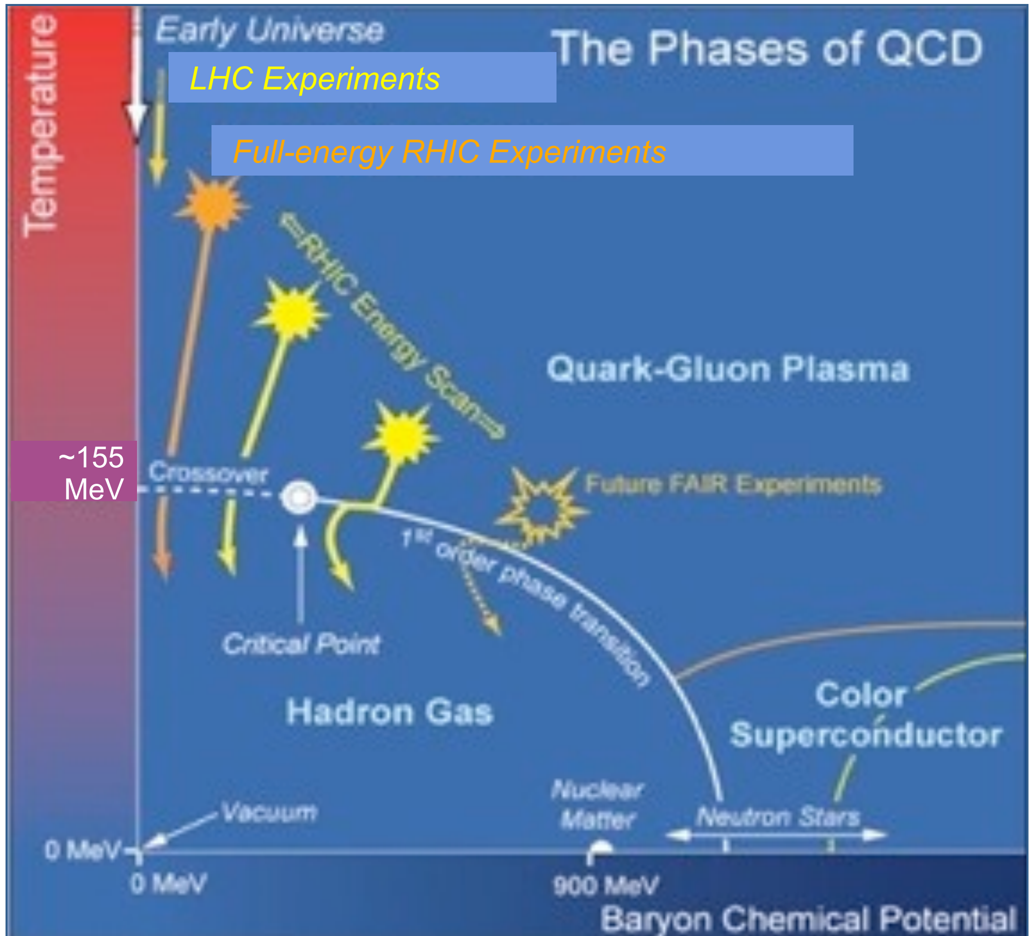
Consistent with observed suppression of forward hadron and di-hadron production in d+Au at RHIC

Next steps: forward p+A – γ production probes gluon densities at low x; transverse spin asymmetries for hadron prod. in p+A/p+p probes saturation scale Needs forward detector upgrades and later EIC.



Science Goals for the Next Decade

Quantify properties of the QGP and features of the QCD phase diagram as functions of temperature and net quark density from the onset of deconfinement toward even earlier universe conditions.



Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

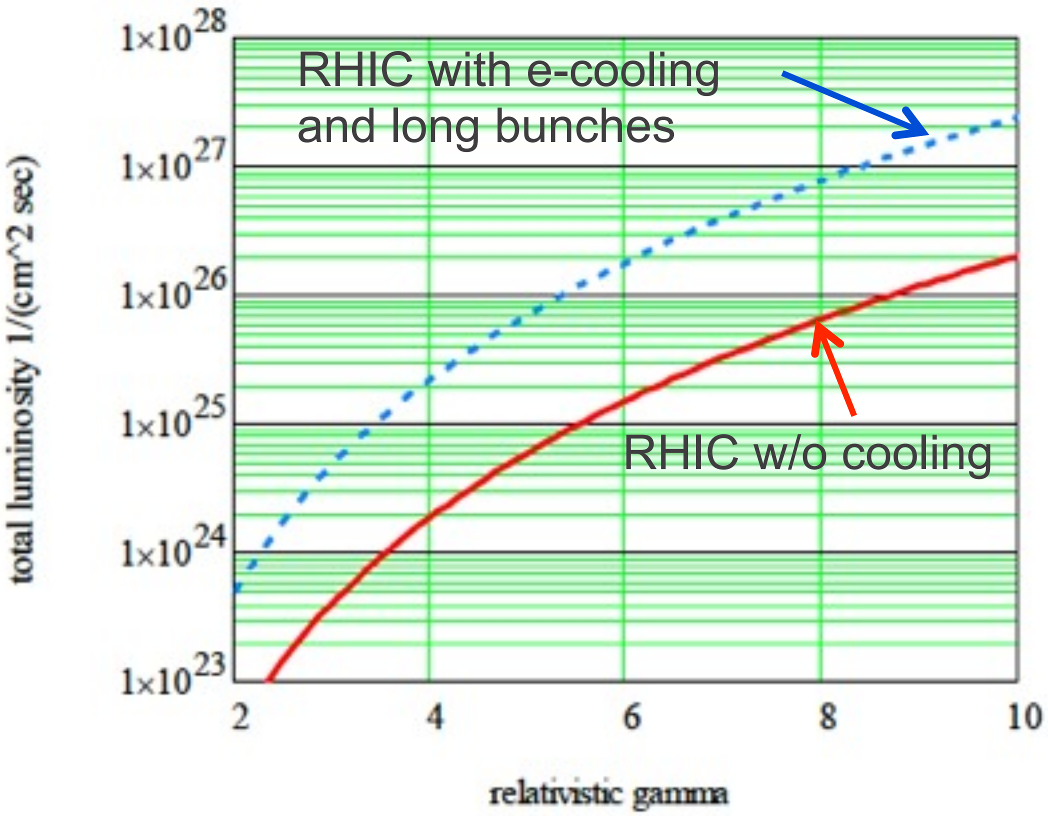
Exploit new discovery potential in searches for a QCD critical point and for the nature and influence of quantum fluctuations in initial densities and gluon vacuum excitations.

Continue explorations of the role of soft gluons in cold nuclear matter (gluon saturation, gluon and sea quark contributions to the proton spin).

Future Upgrades

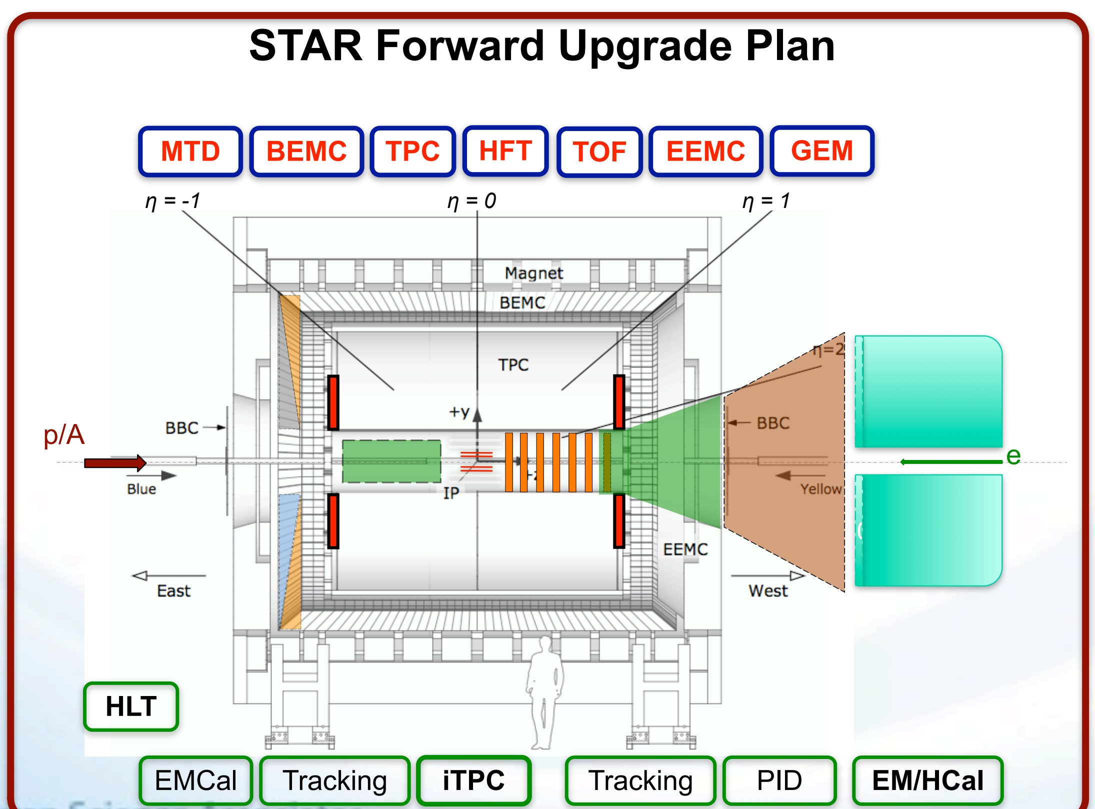
Bunched beam electron cooling; ~10x luminosity; ready after 2017

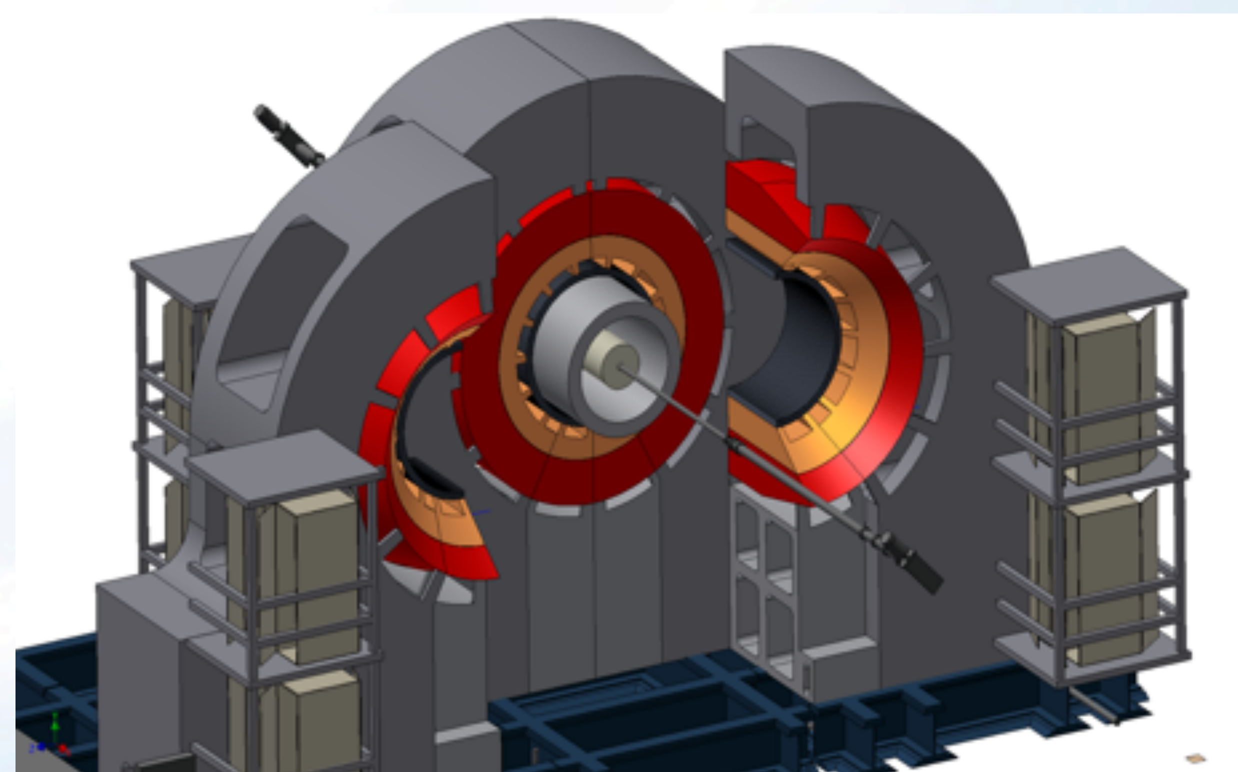
Other machine options: polarized ^{3}He; coherent e-cooling for p+p



Detector upgrades:

- **sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC**
- **STAR forward upgrade for p+A and transverse spin physics**
- **PHENIX MPC-EX,**
- **STAR TPC pad rows**





Run Schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 500 GeV pol p+p	• Sea quark and gluon polarization	• upgraded pol'd source • STAR HFT test
2014	• 200 GeV Au+Au • 15 GeV Au+Au • Fixed Au target test	• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies • QCD critical point search	• Electron lenses • 56 MHz SRF • full STAR HFT • STAR MTD
2015-2016	• p+p at 200 GeV • p+Au, d+Au, ^{3}He+Au at 200 GeV • High statistics Au+Au	• Extract η/s(T) + constrain initial quantum fluctuations • More heavy flavor studies • Sphaleron tests	• PHENIX MPC-EX • Coherent electron cooling test
2017	• No Run		• Electron cooling upgrade
2018-2019	• 5-20 GeV Au+Au (BES-2)	• Search for QCD critical point and deconfinement onset	• STAR ITPC upgrade
2020	• No Run		
2021-2022	• Long 200 GeV Au+Au w/ upgraded detectors • p+p/d+Au at 200 GeV	• Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism • Color screening for different QQ states	• sPHENIX
2023-24	• No Runs		• Transition to eRHIC

Beyond RHIC: e-RHIC

Add an electron accelerator to the existing RHIC accelerator complex:

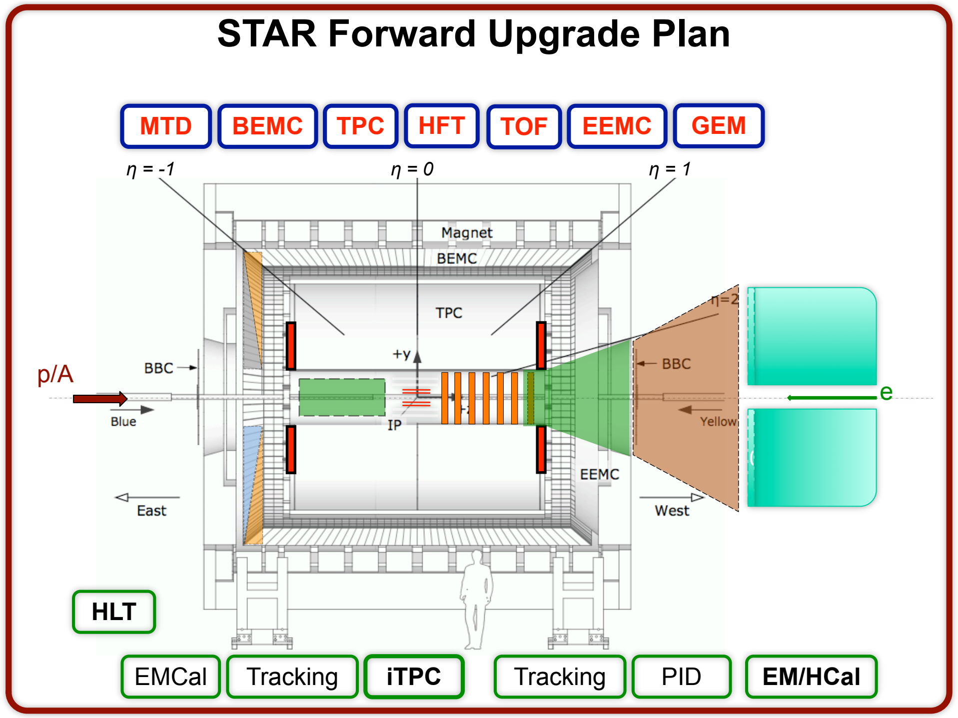
5-10 GeV e-beam accelerated with an Energy Recovery Linac (ERL) inside the existing RHIC tunnel and collides with RHIC beams (250 GeV polarized protons or 100 GeV/n heavy ions)

ERL provides fresh electron bunches for each collision resulting in high luminosity (10^{33} cm^{-2} s^{-1}) and high electron polarization over wide kinematic range

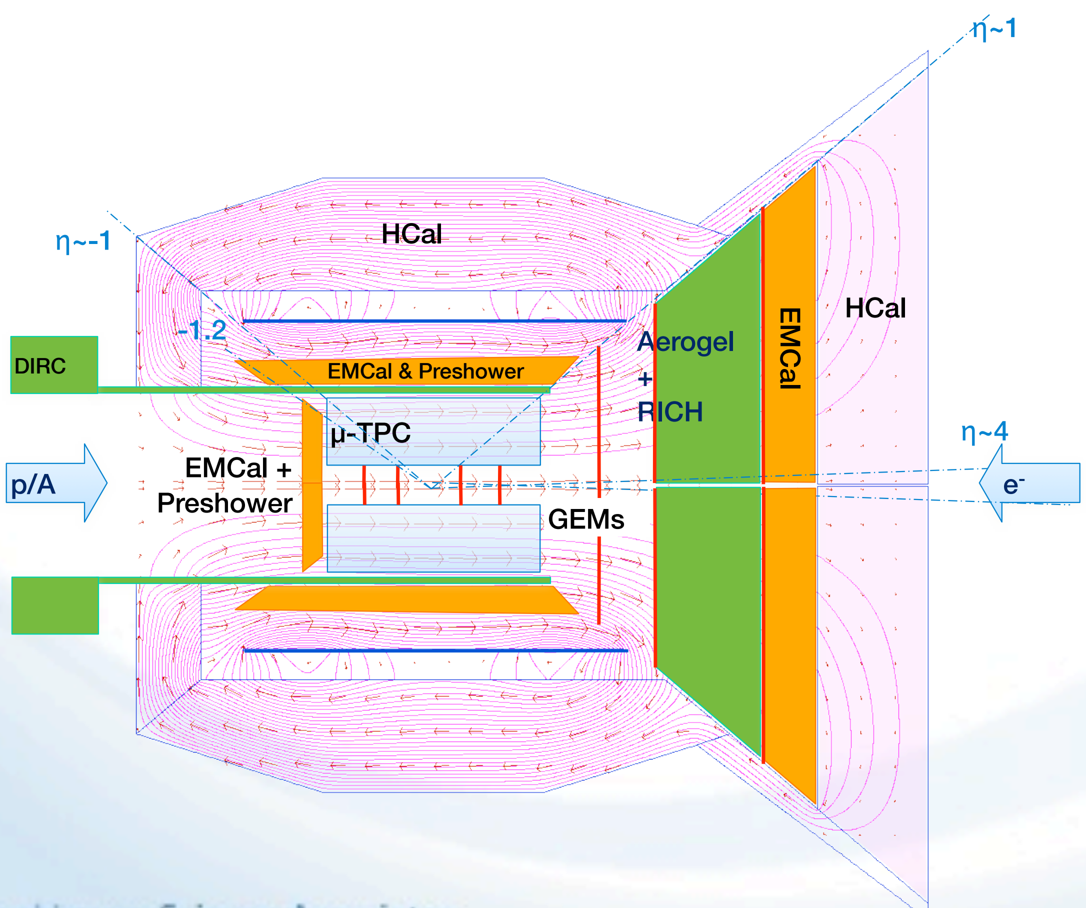
Preliminary cost estimate for 5 GeV e-beam with ~ 10^{33} cm^{-2} s^{-1} luminosity: $550M (FY12$) excluding detector. We hope that value engineering will allow us to reach 10 GeV electron energy for similar cost.

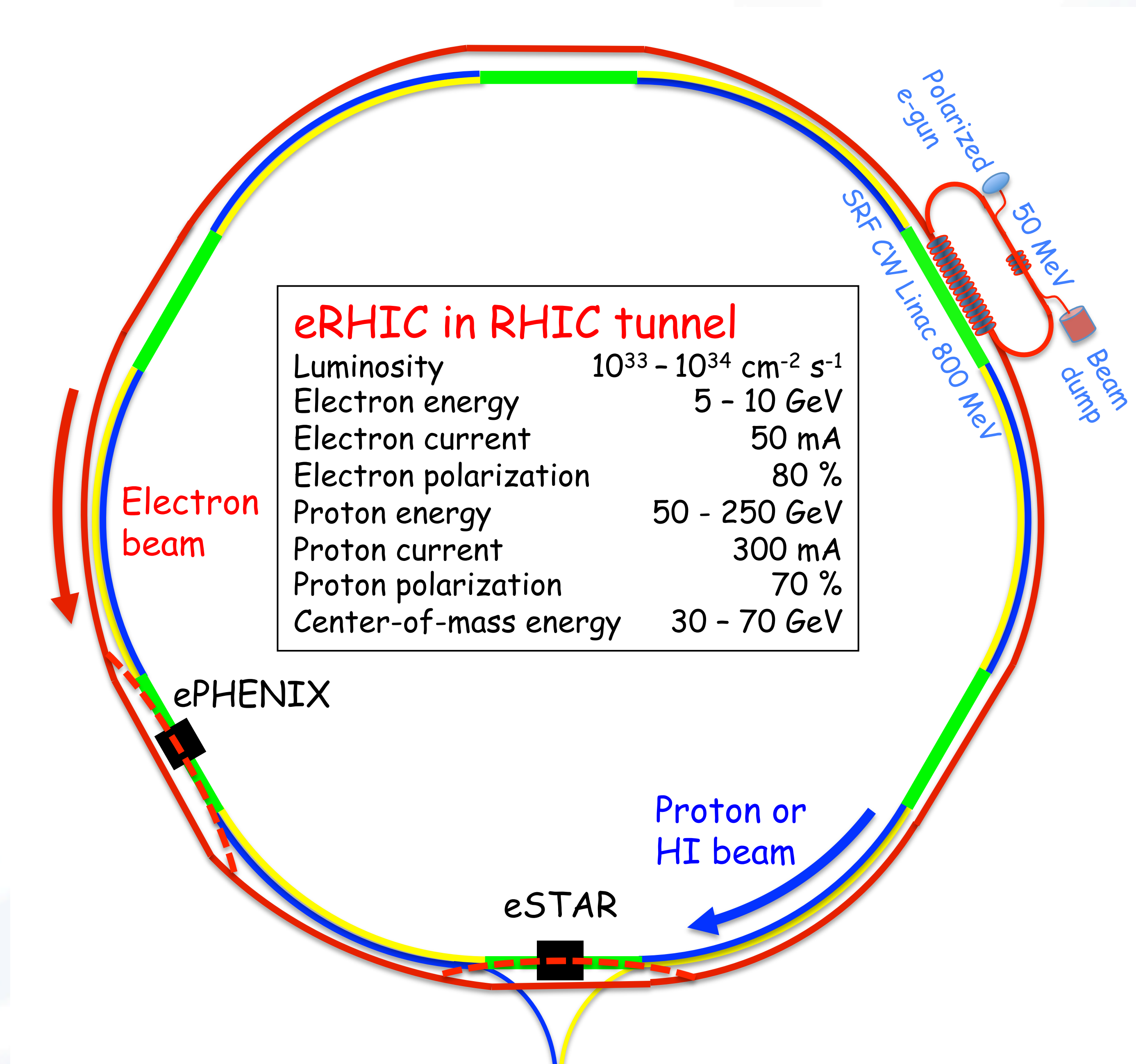
R&D is under way to support future upgrades to even higher luminosity (10^{34} cm^{-2} s^{-1}) and higher electron beam energy (30 GeV)

From RHIC to e-RHIC



RHIC Detector collaborations are developing LoI's for transition to eRHIC; studies for new detector designs proceed in parallel.





eRHIC in RHIC tunnel

Luminosity	10^{33} – 10^{34} cm^{-2} s^{-1}
Electron energy	5 - 10 GeV
Electron current	50 mA
Electron polarization	80 %
Proton energy	50 - 250 GeV
Proton current	300 mA
Proton polarization	70 %
Center-of-mass energy	30 – 70 GeV

Summary

- $2B facility uniquely capable of exploring QCD matter across the entire phase diagram
- RHIC is operated efficiently and effectively in pursuit of its scientific mission
- RHIC has an enviable record of successful upgrades
- RHIC sits at the sweet spot: most liquid & opaque QGP
- The discovery potential of RHIC is undiminished
- 2014 - 2021: Era of definitive (precision) measurements
- Measurements with HFT and SVT/FSVT in 2014-16
- Electron Cooling in 2017/18 with Beam Energy Scan-2 in 2018/19
- High statistics jet measurements with sPHENIX in 2021/22
- RHIC's path toward eRHIC (~2024) is now being delineated providing for a cost-effective realization of an EIC that has been rated by NSAC as "absolutely central" to the future U.S. nuclear science program