The Outlook for RHIC Physics

Steve Vigdor

RHIC Users' Meeting, June 15, 2012

I. Science Drivers for the Coming Decade

II. RHIC/LHC Complementarity

III. Facility Upgrades: Completed/Ongoing/ Contemplated

IV. Path to eRHIC

V. Funding Challenges

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science
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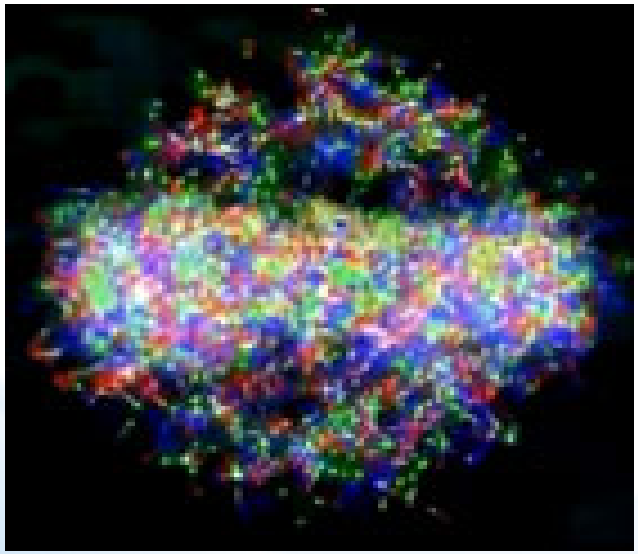
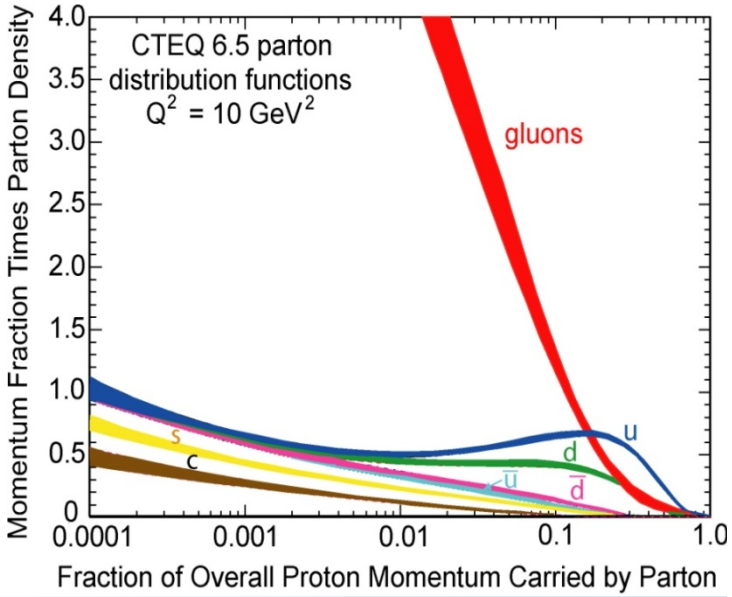
RHIC Has Pioneered Condensed Matter Physics with a Force of a Different Color

What are the unique *emergent phenomena* in quantum many-body systems governed by QCD? Especially under early-universe conditions? Are there lessons for other non-Abelian (e.g., EW) theories harder to subject to lab investigation? How do we pump/probe fleeting ultrahot quark-gluon matter that lives only ~ few x 10^{-23} s? Or take snapshots of quantum fluctuations on similar time scales?





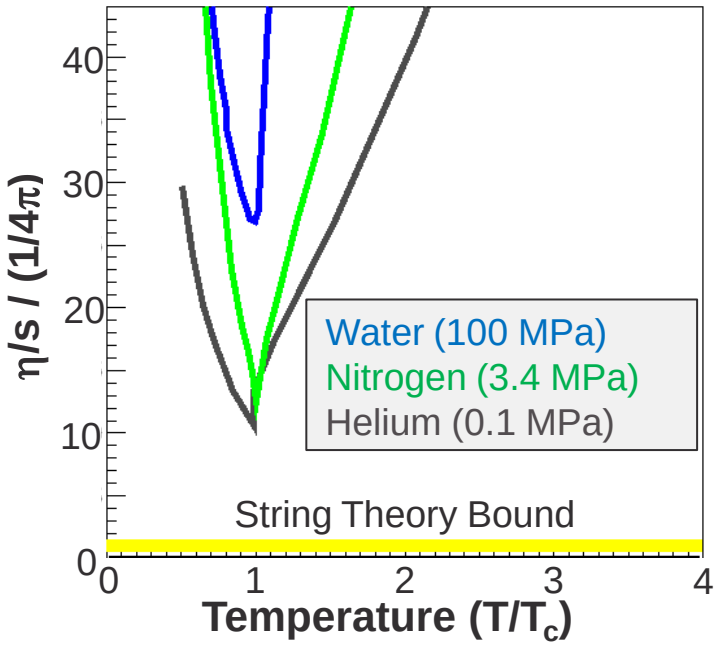
LHC extends the temperature and kinematic ranges for these studies. It complements, but does not supplant, RHIC. This is NOT Energy Frontier science!

10 Basic Questions Going Into the RHIC Era

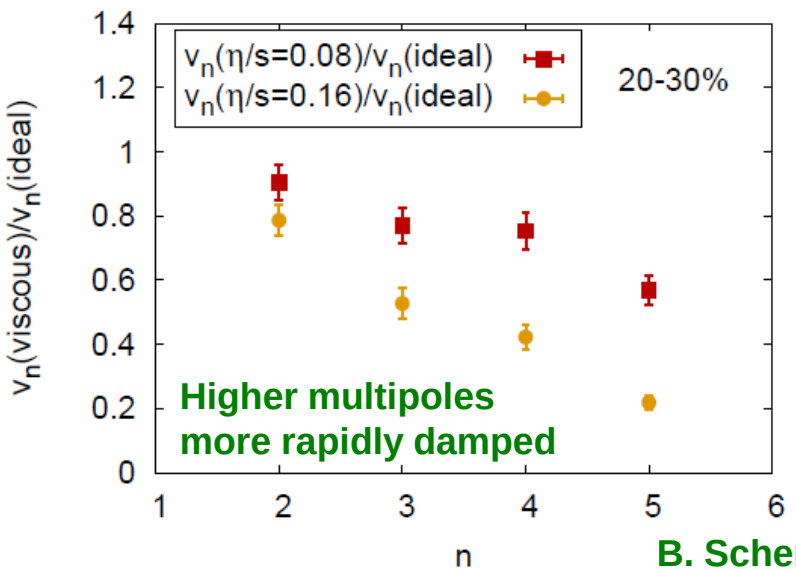
	RHIC answers to date:
1) Do we reach the QGP phase?	1) Yes
2) Is it weakly coupled, with ~ideal gas behavior?	2) No
3) Can we demonstrate the transition from hadronic degrees of freedom?	3) Maybe
4) Do partons lose energy rapidly in traversing QGP?	4) Yes
5) Does QGP color screening suppress quarkonium formation?	5) Maybe
6) Can we find evidence of high-temp. excited QCD vacuum fluctuations (sphalerons), analogous to EW sphalerons as source of universe's baryon asymmetry?	6) Maybe
7) Is there a locus of 1st-order phase transitions and a Critical Point in the QCD phase diagram?	7) Maybe
8) Do we see evidence of gluon density saturation in cold nuclear matter at very low Bjorken x?	8) Maybe
9) Do gluon spin preferences account for a significant part of the missing proton spin?	9) Maybe
10) Is there a significant flavor-dependence in sea quark polarizations?	10) Too little data to date

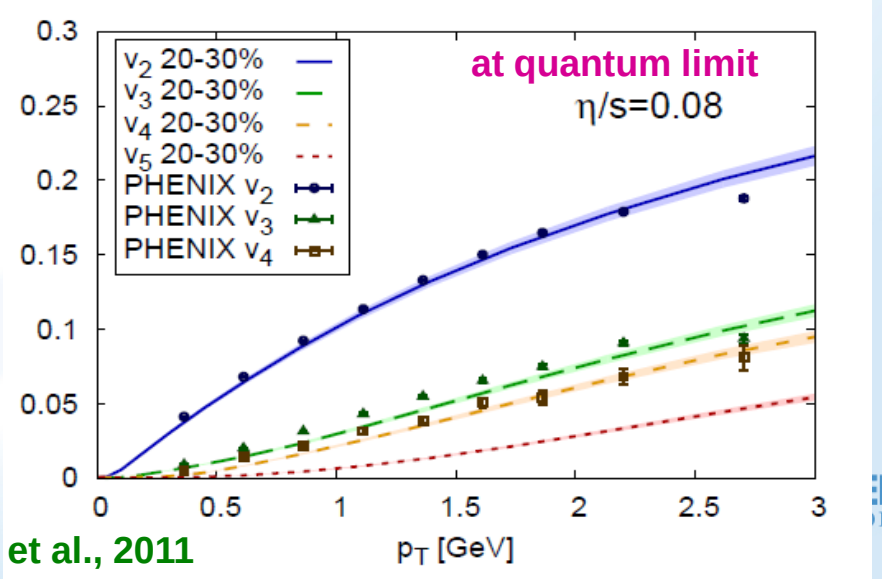
It is the responsibility of RHIC and LHC to design measurements to address the more quantitative 2nd-generation questions emerging from the definitive answers above, and to resolve the hints surrounding the others.

Question 1 for the Coming Decade: How perfect is the "near-perfect" liquid QGP, as a function of its temperature?



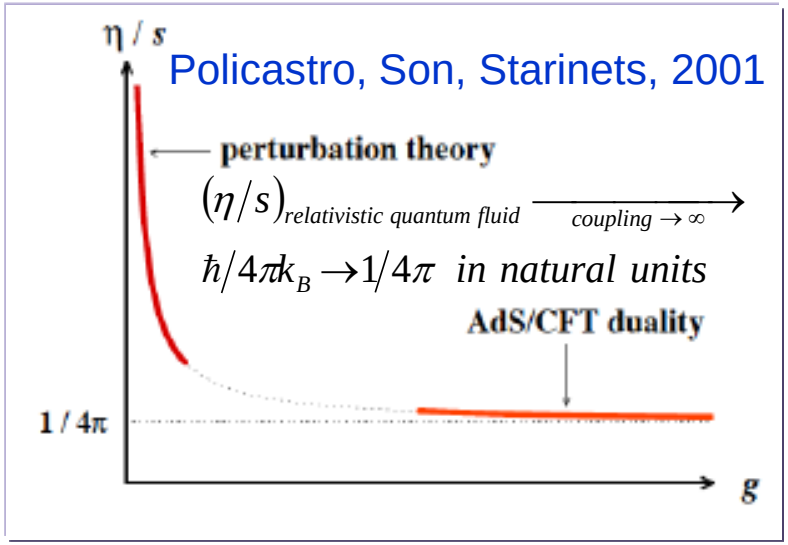
- *A number of common liquids exhibit η/s minima near phase transition. Does QGP?*
- *Path to quantify η/s relies on flow power spectrum measurements and viscous event-by-event hydro advances.*
- *Requires measurements at RHIC & LHC. Each averages over temperature evolution, but combination ⇒ factor ~2-3 range in T_0.*
- *Also study how heavy (c,b) quarks participate in flow.*



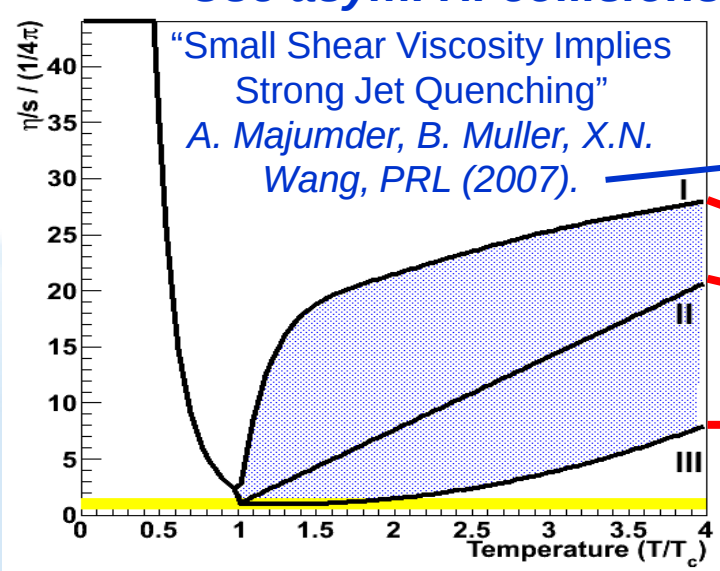


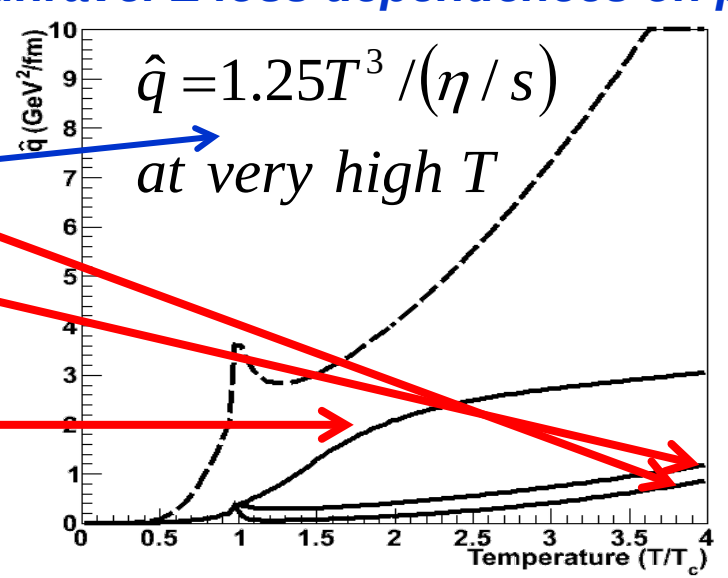
B. Schenke et al., 2011

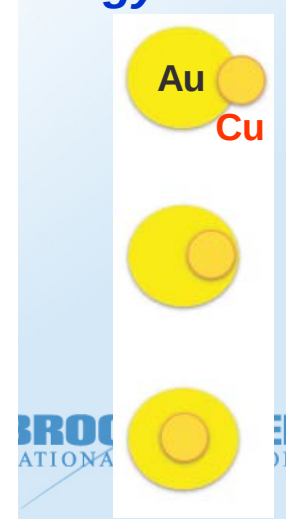
2) How Does Strongly Coupled Liquid Emerge from Asymptotically Free Theory?



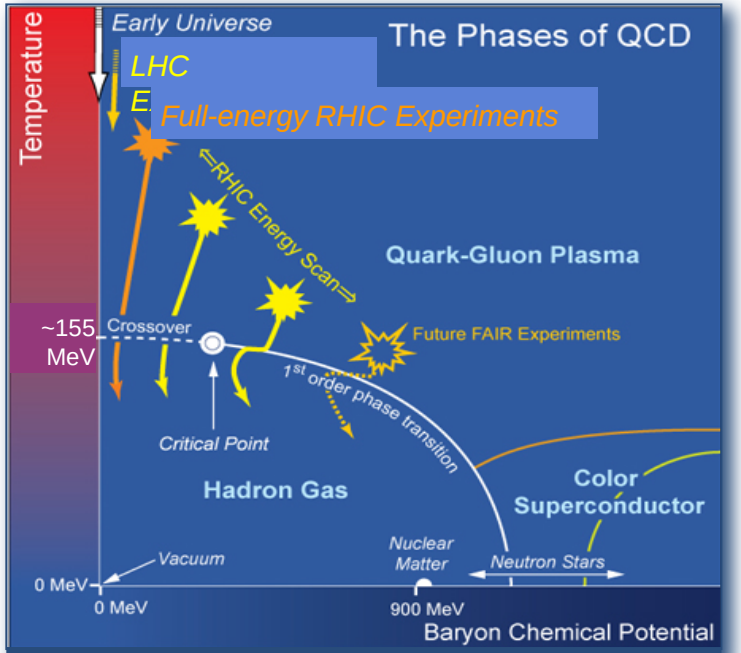
- ***Low shear viscosity, strong jet quenching, rapid thermalization all suggest effective strong coupling.***
- ***Is QGP shear viscosity correlated with energy loss transport coeff. $\hat{q}$, as anticipated at very high T?***
- ***Use jet quenching measurements at RHIC & LHC to constrain T-dependence.***
- ***Use range of jet energies and heavy vs. light quarks to probe parton interactions with medium at different scales.***
- ***Use asym. HI collisions to unravel E loss dependences on path length and energy density***





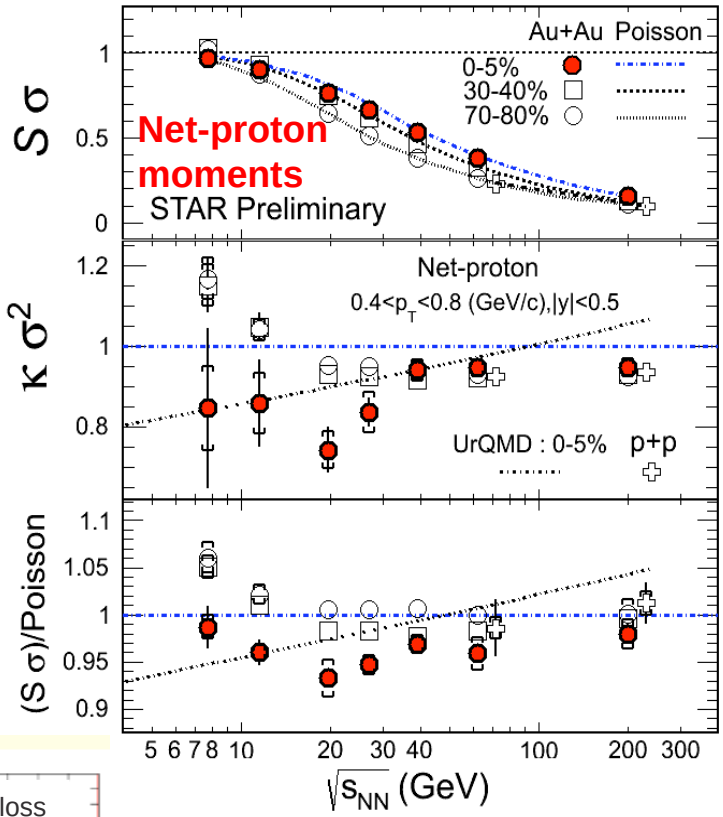


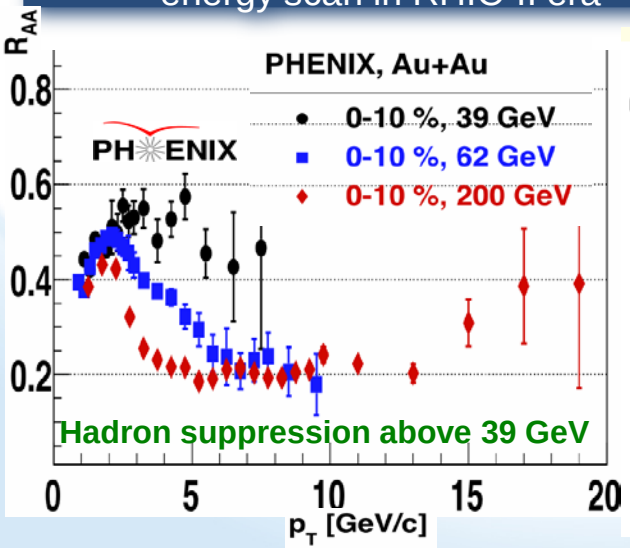
3) Do We Observe Evidence for Onset of Deconfinement and/or QCD Critical Point?

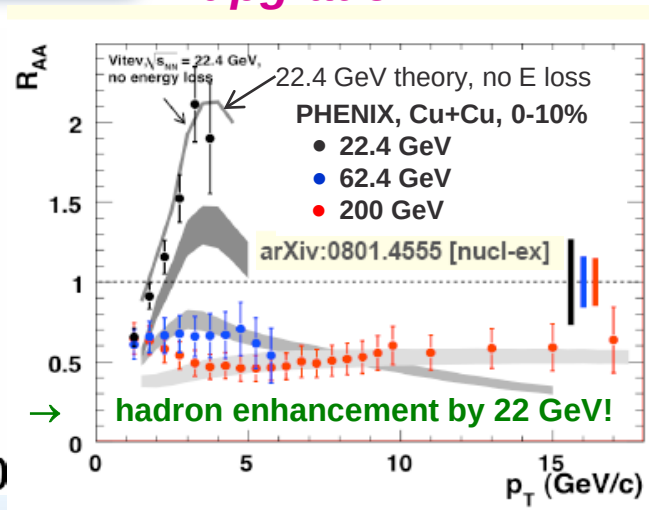


Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

- ***Hints of non-smooth √s – dependence in non-Gaussian fluctuations @ $\sqrt{s_{NN}}$ ~ 20 GeV must be pursued @ RHIC.***
- ***Lower √s measurements likely require low-E cooling upgrade.***

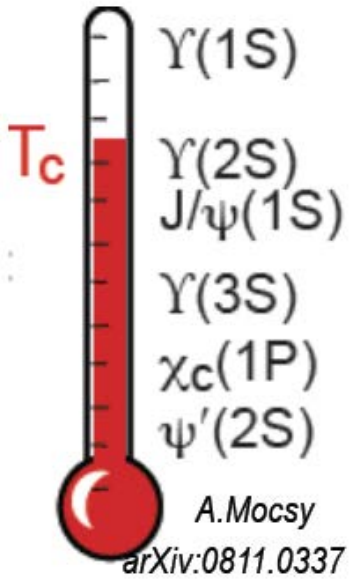


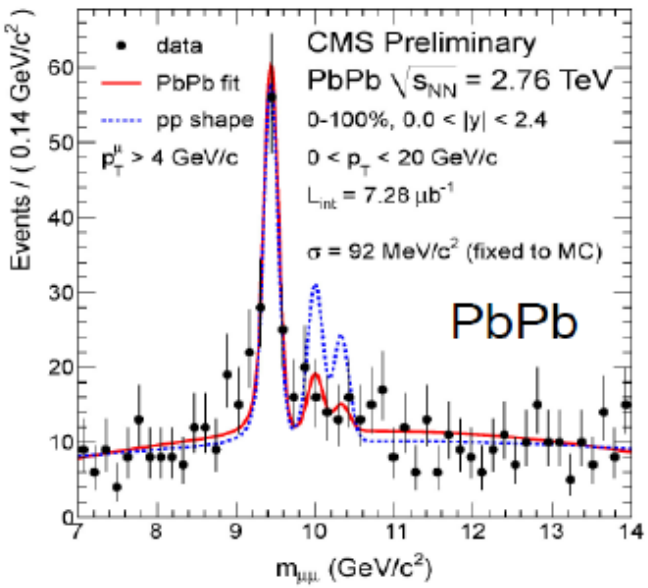


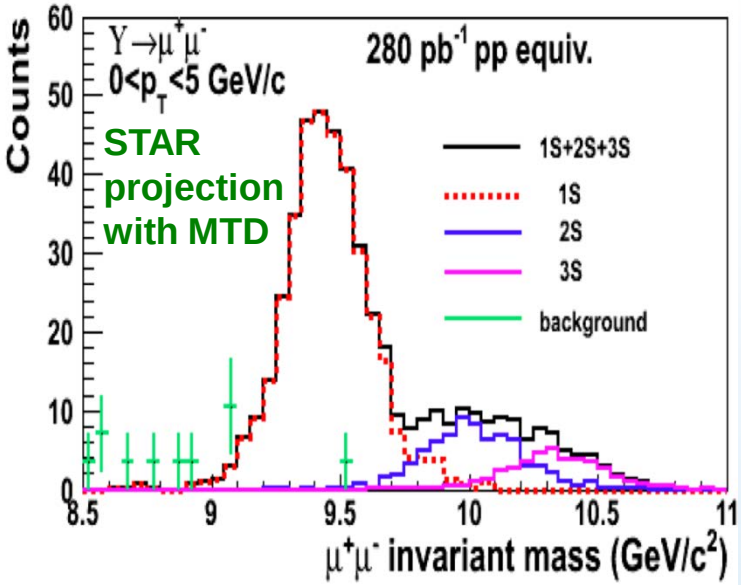


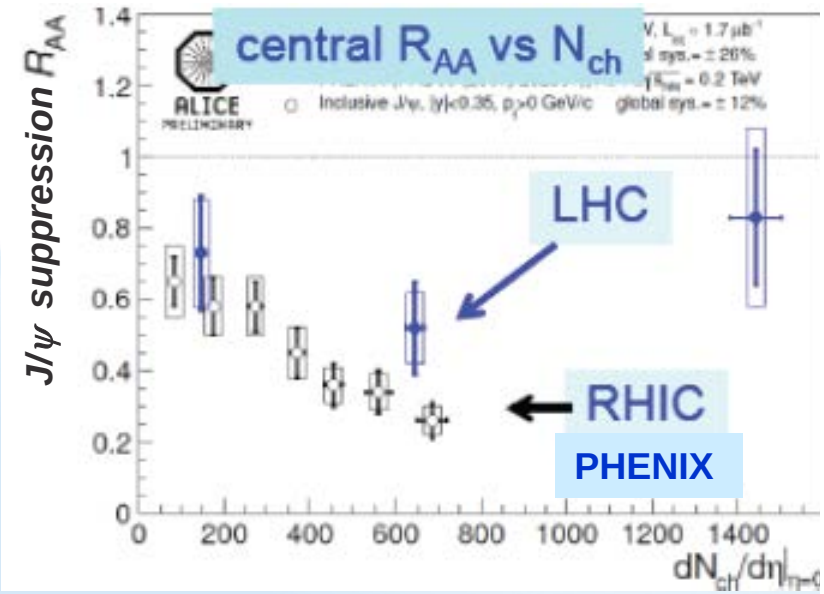
- ***Whether or not CP is found, also pursue rapid behavior changes in several QGP "signatures" @ √s <~ 20 GeV, hinting at deconfinement onset.***

4) Do We Observe Sequential Melting of Different Quarkonia?





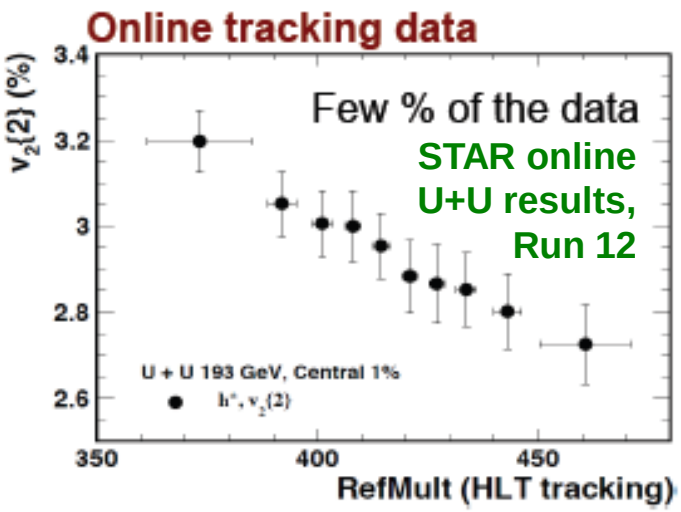


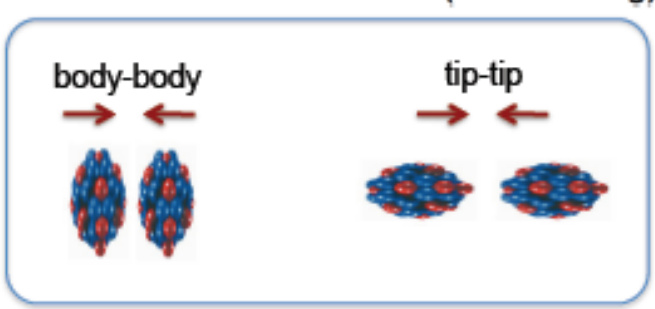


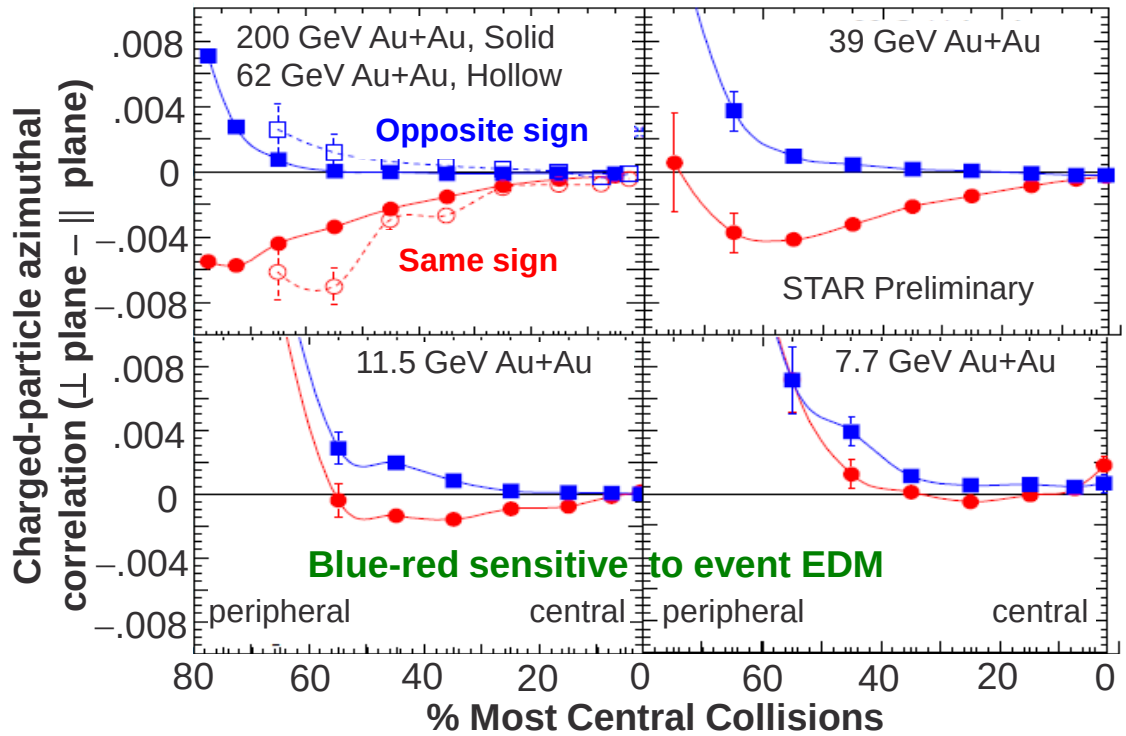
- *Different $q\bar{q}$ binding ⇒ different survival probabilities in QGP as fcn. of temp.*
- *CMS results clearly show suppression of ϒ(2s+3s) compared to ϒ(1s) in Pb+Pb.*
- *What will be seen at RHIC's lower T? Need resolution to separate upsilon states.*
- *J/ψ saga ⇒ important to measure vs. √s and rapidity, to unravel different dependences for color screening, initial-state shadowing and final-state regeneration.*

5) Are Sphaleron Hints Seen To Date Real?

- *Charge-dep. azimuthal correl'n does vanish at low $\sqrt{s}$, as might be expected if QGP no longer formed*
- *What happens in body-body U+U config., where large v_2 with small magnetic field enhances bkgrd/signal?*







- *Search @ RHIC for related effects from QCD triangle anomaly in hydrodynamic system, e.g., predicted by Kharzeev and Son:*

arXiv:1010.0038; PRL

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

CME — Vorticity-induced "Chiral Vortical Effect"

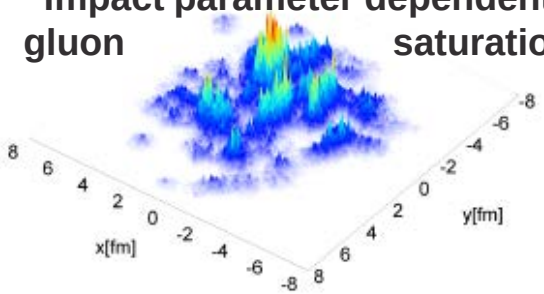
⇒ *Baryon current/charge current correl'n @ $\mu_B \neq 0$*

- *Λ's should preferentially emerge with π^+, $\bar{\Lambda}$'s with π^-, ⊥ reaction plane, @ $\sqrt{s_{NN}}$~ 20-40 GeV*

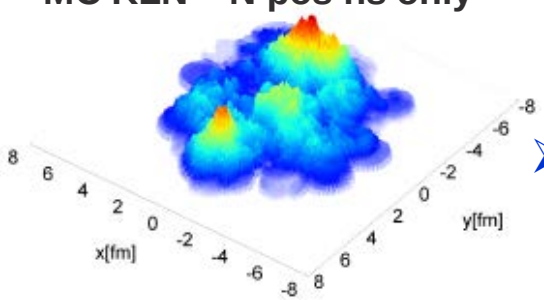
6) What is Nature of Initial Density Fluctuations?

- ***Initial density fluctuations influence RHIC collision evolution, just as inflation-era quantum fluctuations seed universe's large-scale structure.***
- ***Is it just initial nucleon positions, or also color charge (i.e., gluon field) distributions, that fluctuate? The two yield different characteristic length scales and rapidity dependence.***

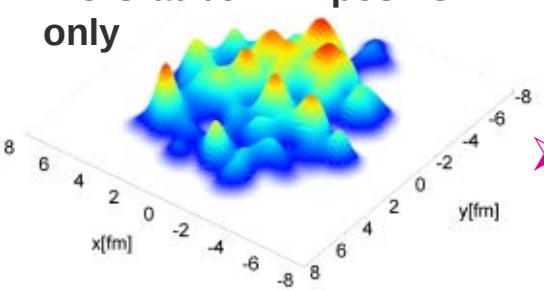
Impact parameter dependent gluon saturation



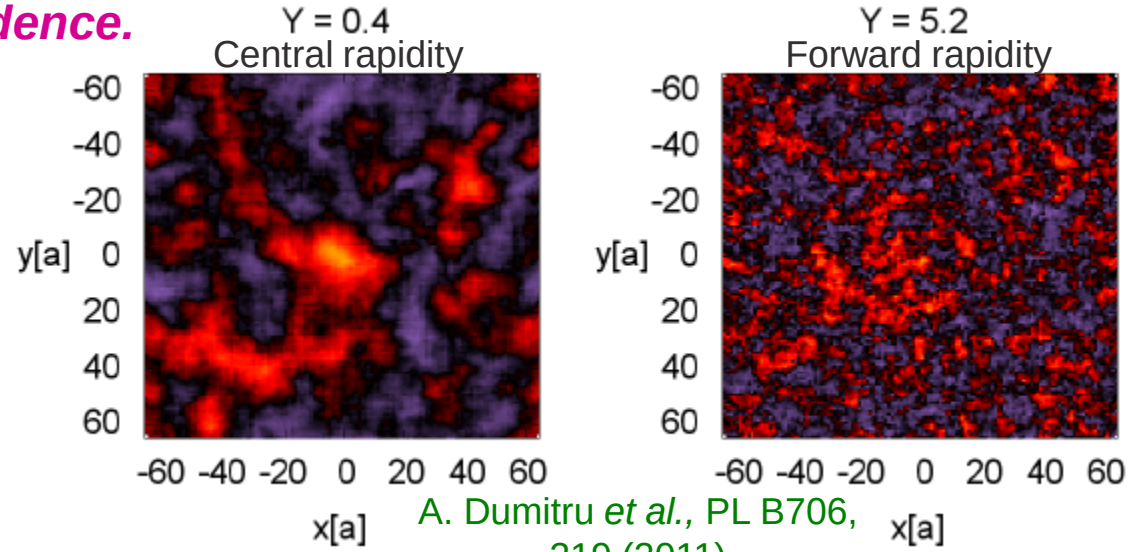
MC KLN – N pos'ns only



MC Glauber – N pos'ns only

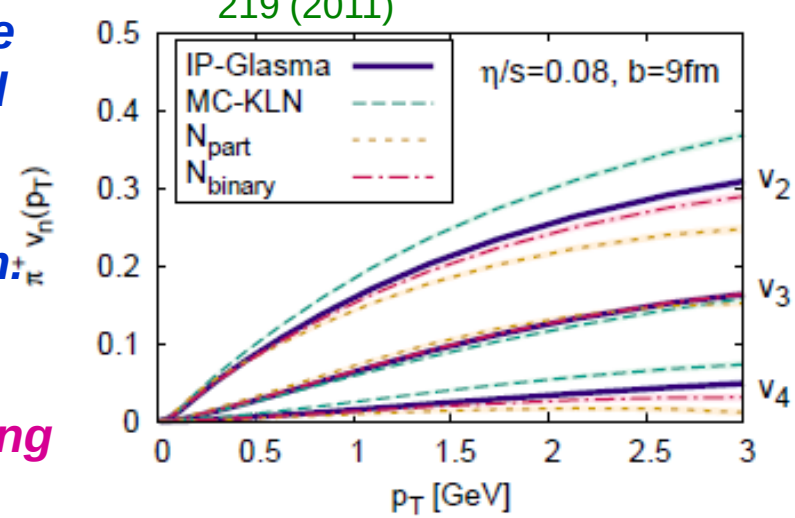


B. Schenke *et al.*, arXiv:1202.6646

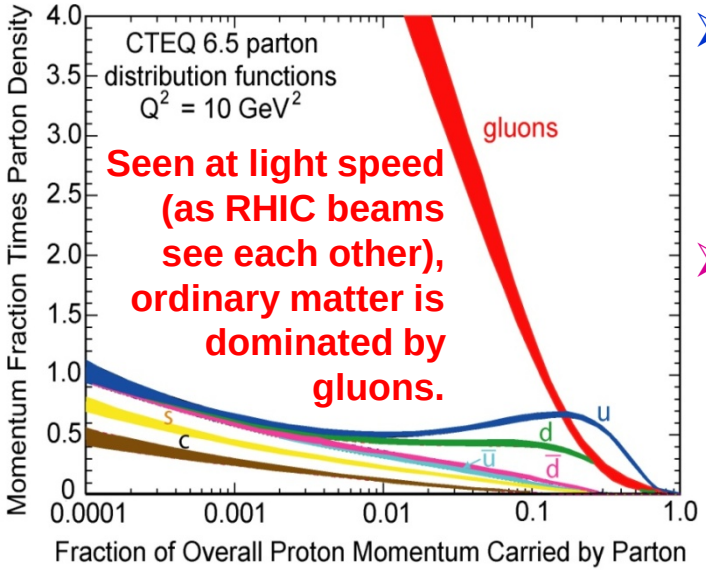


A. Dumitru *et al.*, PL B706, 219 (2011)

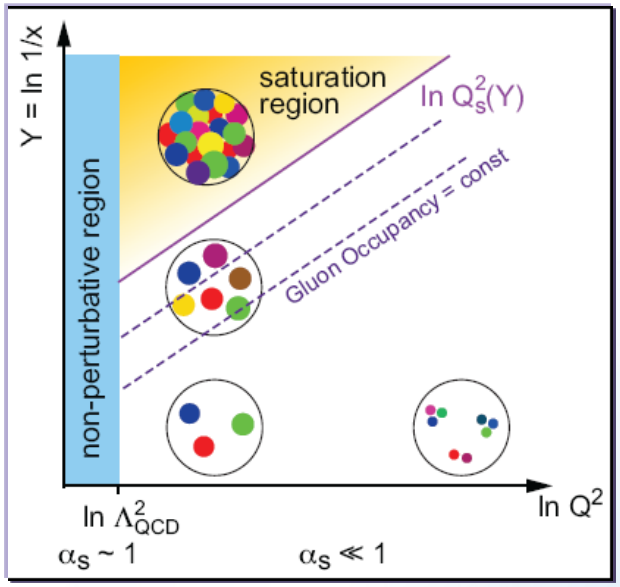
- ***Fluctuations can be constrained by odd vs. even flow harmonics, as fcn. of rapidity, & for asym. vs. symm. beams***
- ***Must be done together with pinning down η/s***



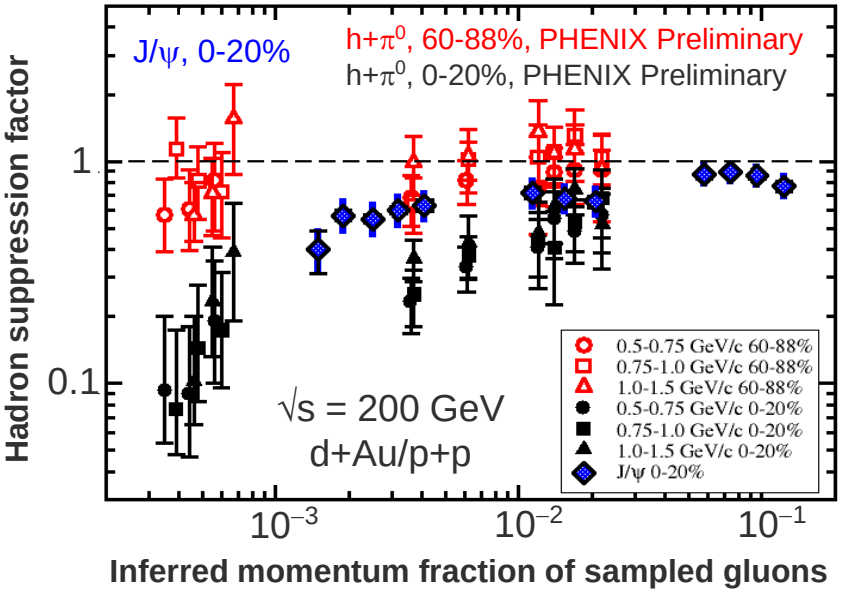
7) Do We Reach Saturated Gluon Density in RHIC d/p+A ?



- ***Gluon densities must saturate @ low x & moderate Q^2 to avoid unitarity violation***
- ***Color Glass Condensate (CGC) regime has weak coupling but high gluon occupancy ⇒ intense, ~classical gluon field***



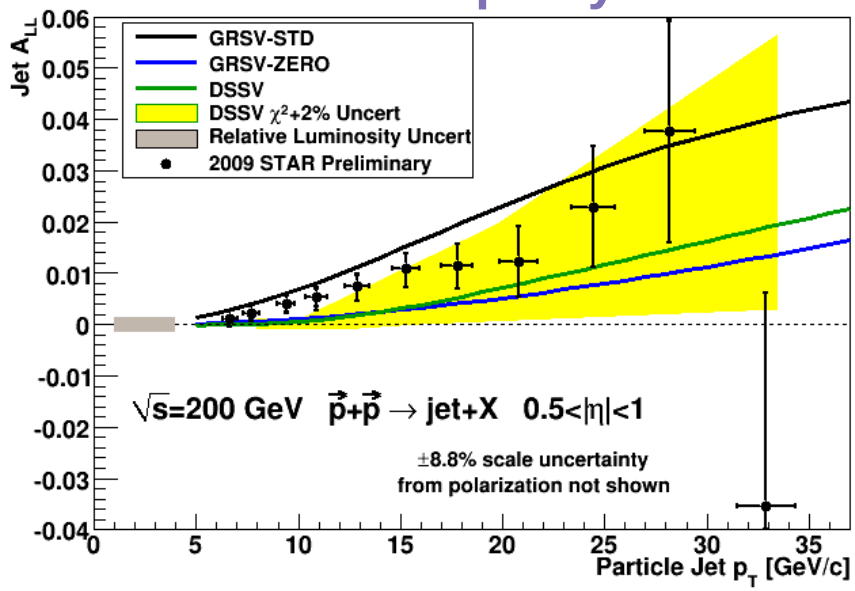
- ***Coherent effects in nuclei ⇒ precocious onset of saturation***



- ***Fwd hadron prod'n, sensitive to low-x gluon density, is suppressed in d+Au (e.g., BRAHMS) collisions @ RHIC.***
- ***Forward di-hadron coincidences probe very asymmetric parton collisions, involving low-x gluon from one beam.***
- ***PHENIX (left) & STAR recent d+Au results for forward di-hadrons consistent with "monojet" prod'n from coherent gluon field.***
- ***Use direct γ in RHIC p/d+A, and later EIC e+A DIS to quantify low-x gluon density.***

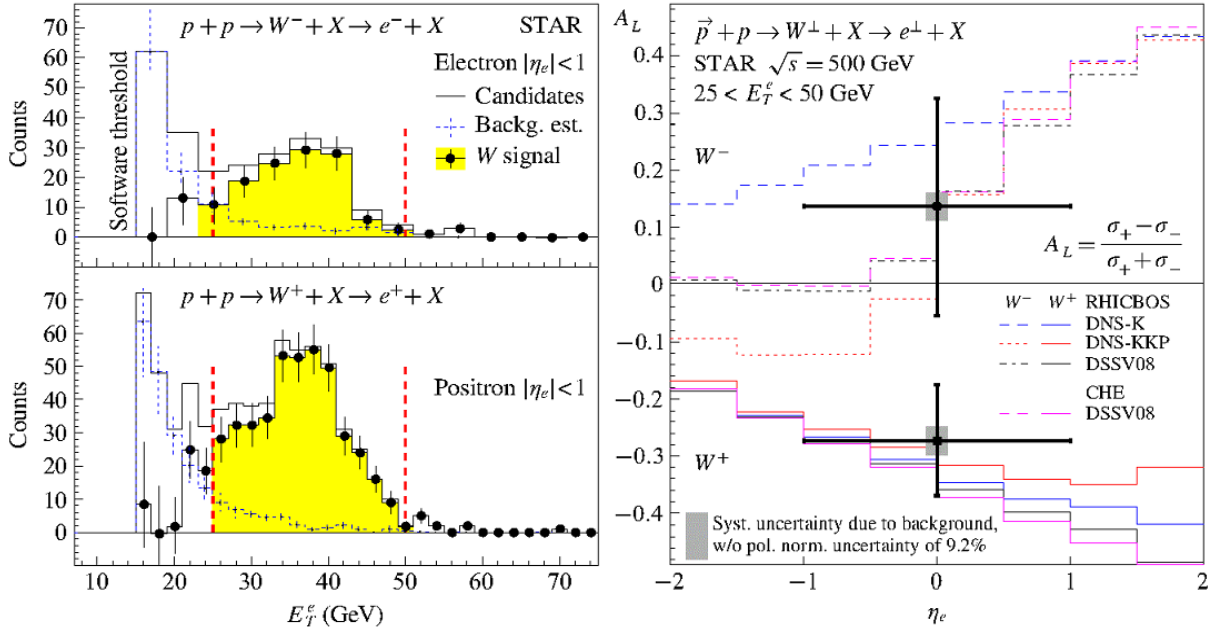
8) Where is the Missing Proton Spin?

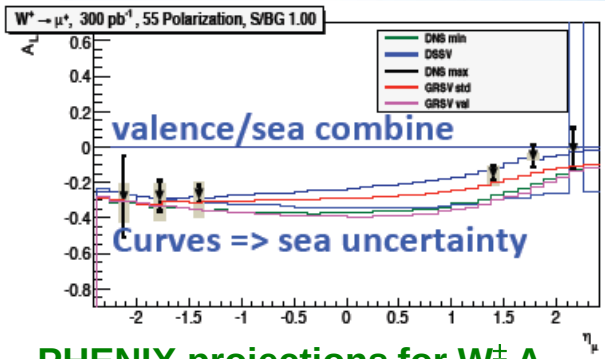
Forward rapidity



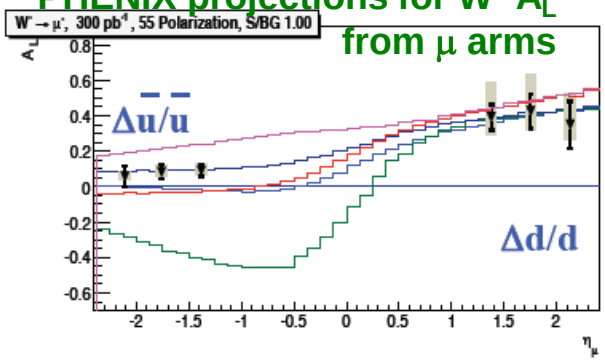
- $\overrightarrow{DIS} \Rightarrow$ only ~30% of spin from q spins
- Latest RHIC $\vec{p}+\vec{p}$ results for two-spin helicity asymmetries in inclusive jet prod'n $\Rightarrow$ small positive gluon spin contribution over sampled x-range.
- Extend to lower x via 500 GeV and di-jet data @ RHIC; later to much lower x via $\vec{e}+\vec{p}$ DIS @ EIC.
- Use $W^{\pm}$ prod'n to cleanly probe $\Delta\bar{u}(x)$ vs. $\Delta\bar{d}(x)$, sensitive to p χral structure

1st STAR and PHENIX W asyms. publ. in PRL106 (2011)





PHENIX projections for $W^{\pm}$ A_L from μ arms



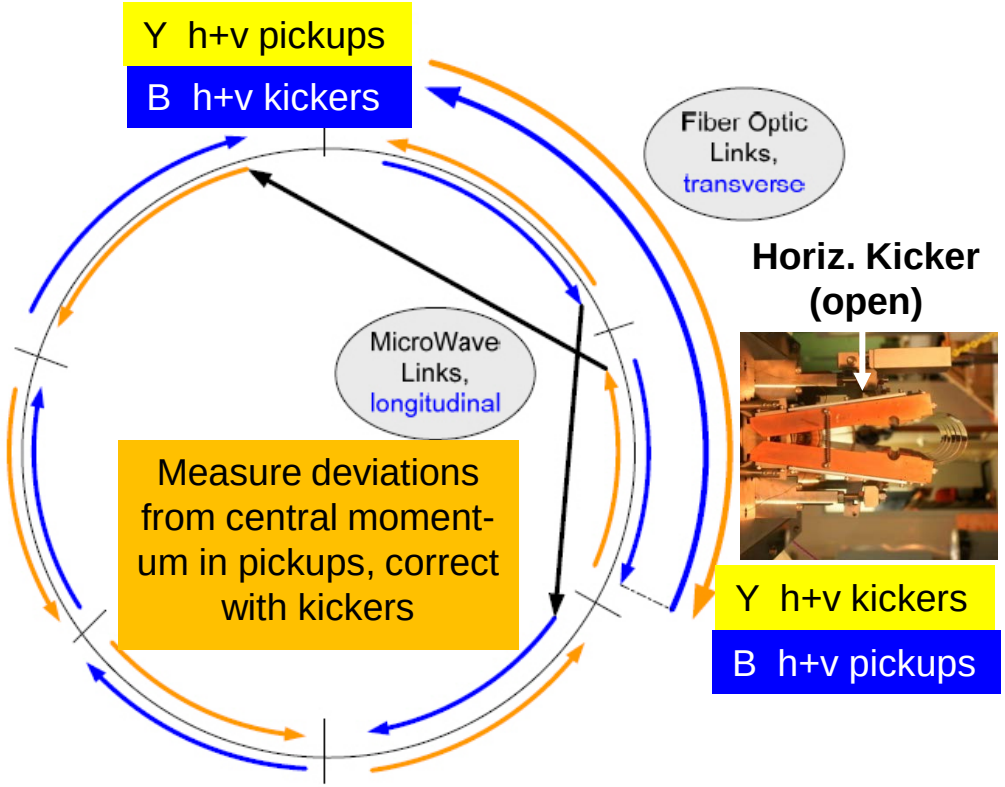
Which Facilities Are Needed To Address Above Questions?

Question	Facilities	Comments
How perfect is “near-perfect” liquid?	RHIC & LHC	Next 5 years
How does strong coupling emerge from asymptotic freedom?	RHIC & LHC	Following 5 years @ RHIC; needs sPHENIX upgrade
Evidence for onset of deconfinement and/or critical point?	RHIC alone	Following 5 years, needs low-E cooling
Sequential melting of quarkonia?	RHIC & LHC	LHC mass resolution a plus; $\sqrt{s}$-dependence important
Are sphaleron hints real?	Mostly RHIC	Exploits U+U and $\mu_B \neq 0$ reach
Nature of initial density fluctuations?	RHIC & LHC	Benefits from asymmetric ion collisions at RHIC
Saturated gluon densities?	RHIC, LHC & EIC	Want to see onset at RHIC; need EIC to quantify
Where is missing proton spin?	RHIC & EIC	EIC will have dramatic impact

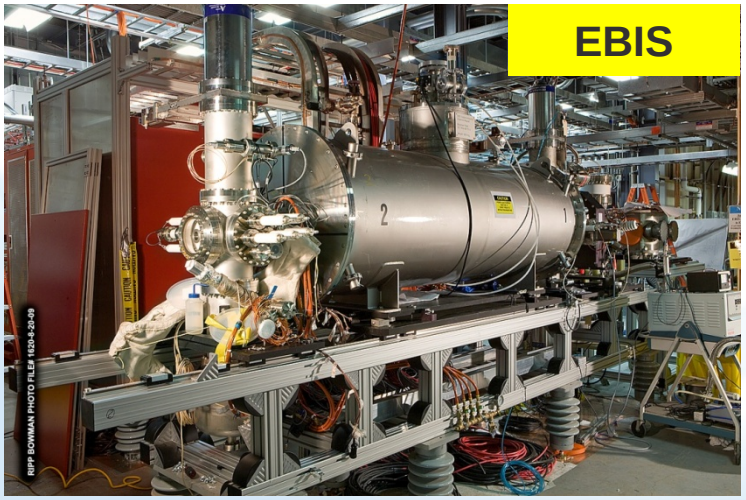
RHIC and LHC are complementary. Both are needed to explore temperature-dependence of QGP properties. RHIC has unique reach to QGP onset, unique ion species versatility and unique polarized capability, until EIC is realized.

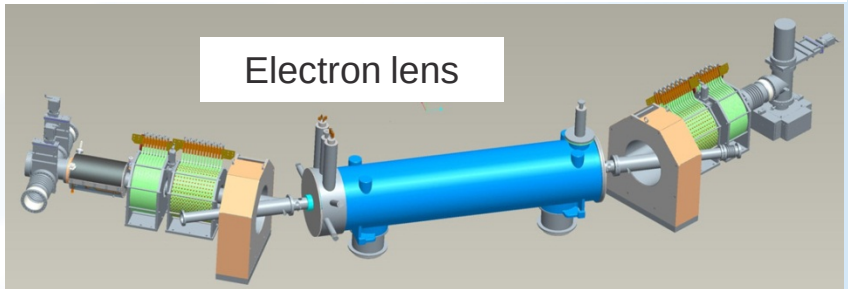
Addressing these questions requires an ~10-year program of A+A (various ion species), p+p and p/d + A runs at various RHIC energies.

RHIC-II Era is Here, Done Very Cost-Effectively !



- ***RHIC breakthrough in bunched-beam stochastic cooling facilitates ~x10 improvement in heavy-ion collision rates, 4 years earlier and at ~1/7 the cost envisioned in 2007 NP Long Range Plan, saving ~$80M***
- ***All (6 planes of pickups & kickers) of the new system commissioned during 2010-12, new SRF cavity anticipated for 2014 run.***
- ***Electron lenses to be installed for 2013 run to improve polarized pp luminosity by factor ~2***



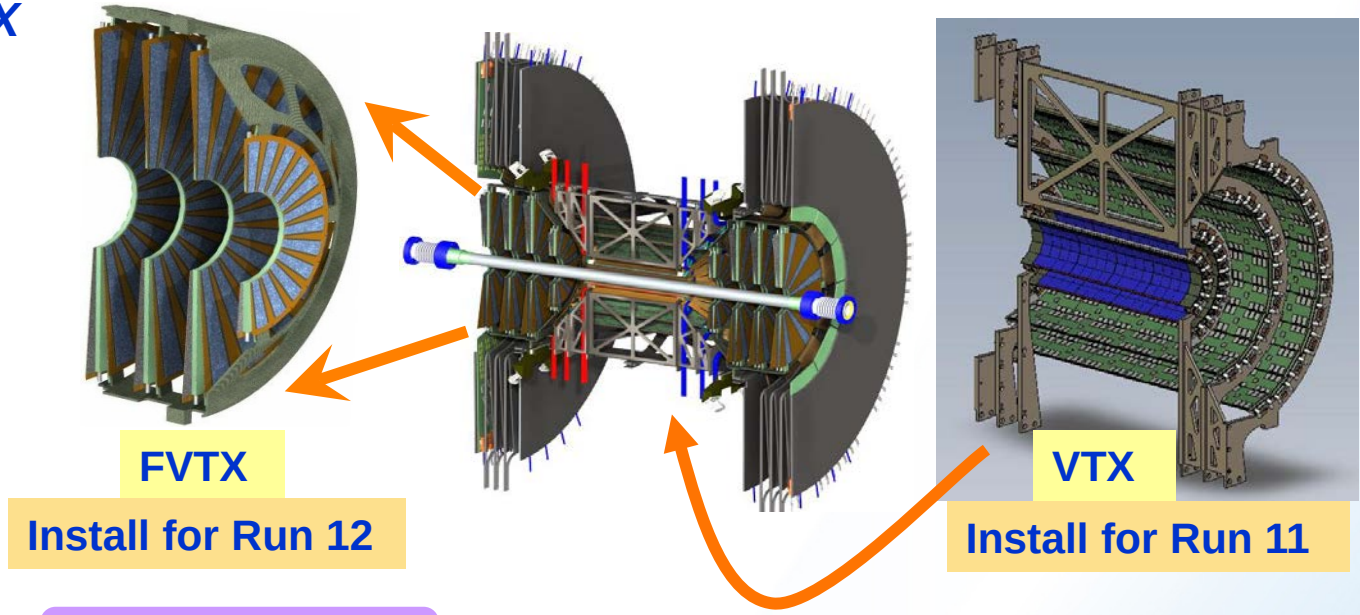


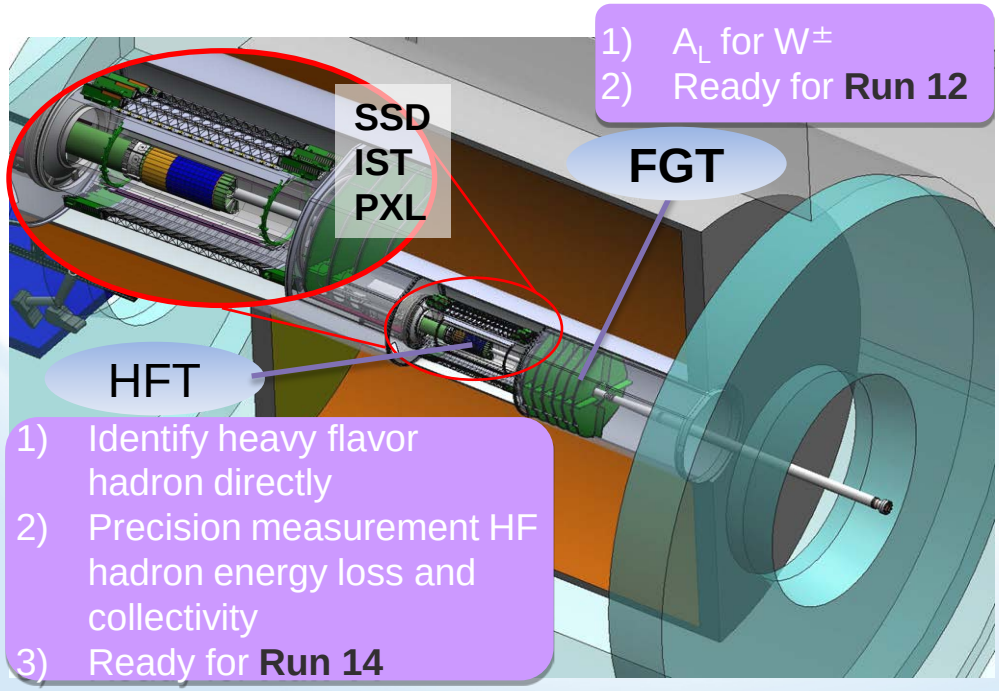
- ***New Electron Beam Ion Source (EBIS, 2012) expands range of ions available (e.g., U) and enhances cost-effectiveness of operations***

A Suite of Ongoing Detector Upgrades

- ***PHENIX VTX & FVTX upgrades greatly improve vertex resolution, heavy flavor ID***

- ***μ trigger upgrade installed in FY10-11 enhances W prod'n triggering for spin program.***



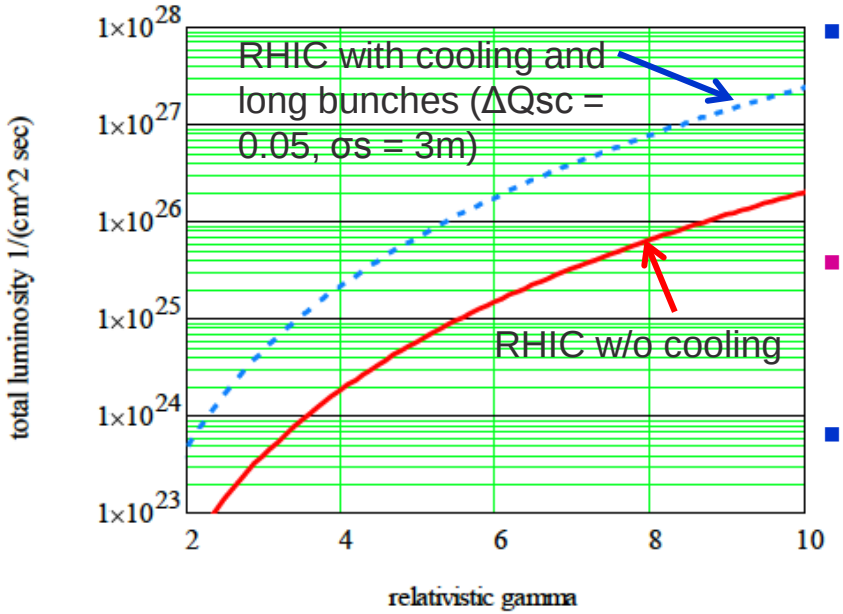


- ***STAR Heavy Flavor Tracker receives CD-2/3 review in 2011. Will permit topological recon-struction of charmed hadrons.***

- ***STAR Forward GEM Tracker to be installed for Runs 12 and 13, will enhance forward tracking, W charge sign discrimination.***

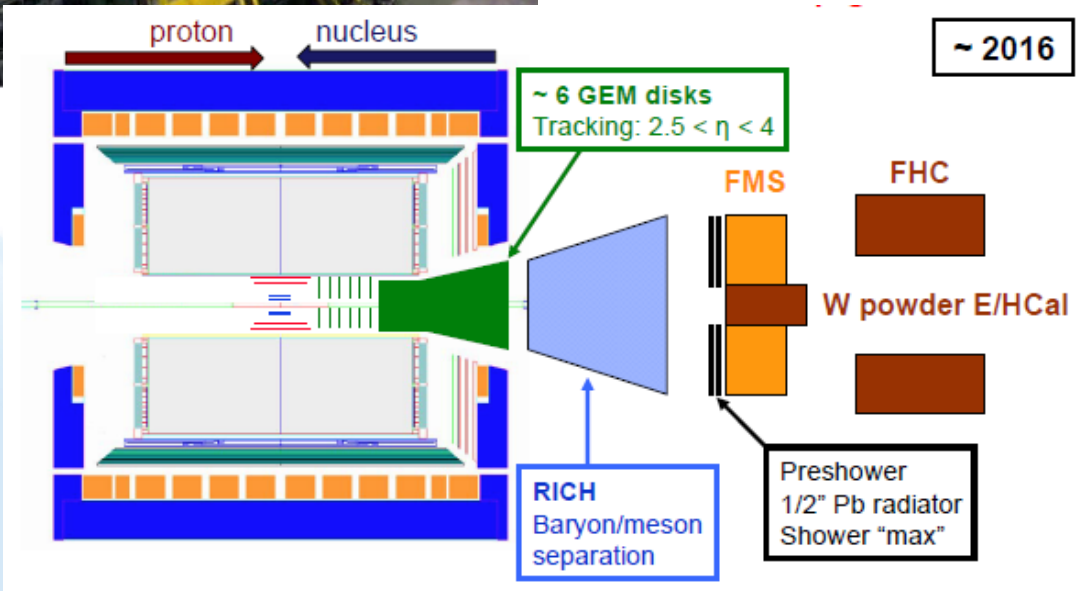
- ***STAR Muon Telescope Detector (Run 14) to improve quarkonium***

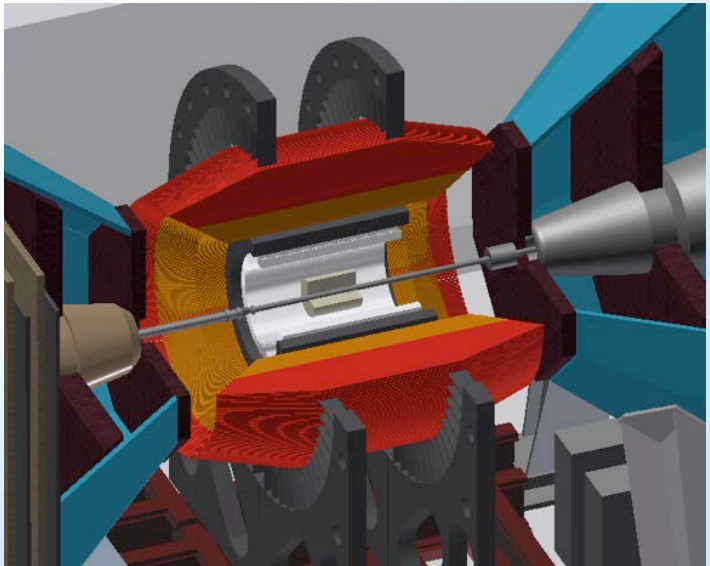
Contemplated Future Upgrades



- *Low-E electron cooling for further pursuit of onset of deconfinement/CP*
- *sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC*
- *STAR forward up-grade for p+A and transverse spin (e.g., DY) physics*
- *PHENIX MPC-EX, STAR TPC pad rows*

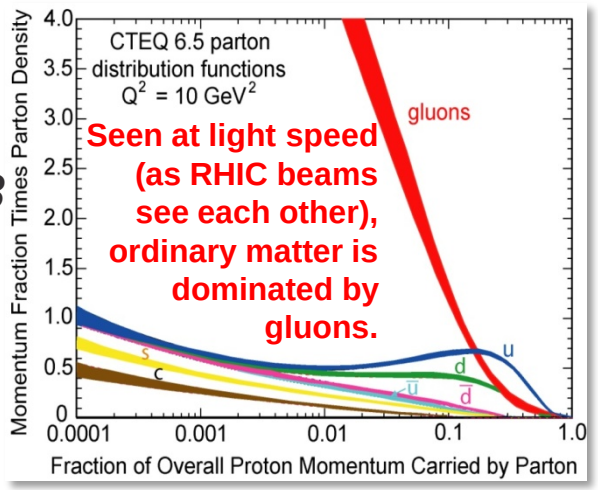
Other machine possibilities: pol'd ^{3}He; coherent e-cooling for $\mathcal{L}_{pp}$

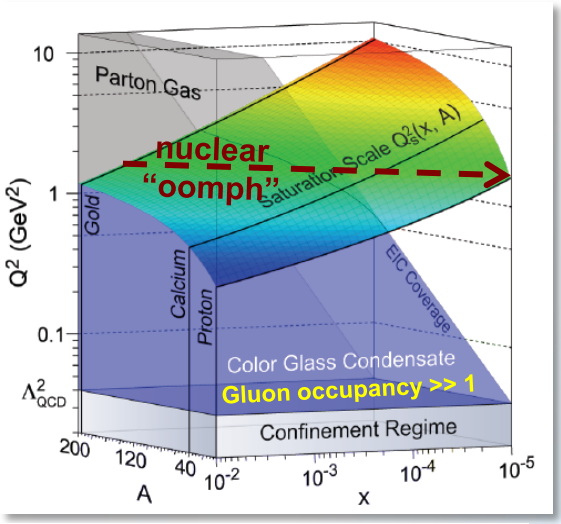




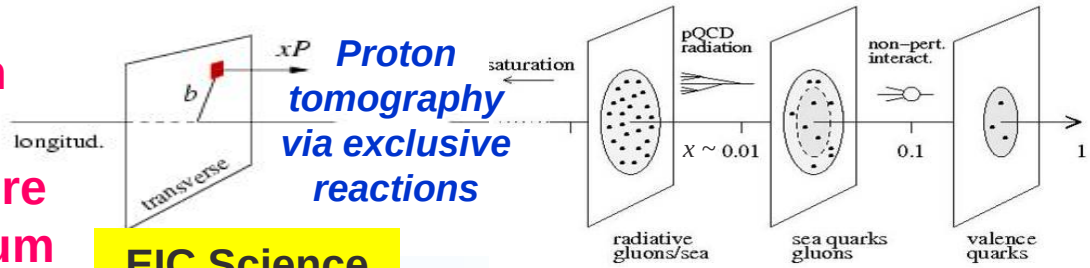
Electron-Ion Collider (EIC) Extends RHIC and JLab Science

EIC = high-resolution femtoscope for cold gluon-dominated matter: ***2010 INT program report arXiv:1108.1713***

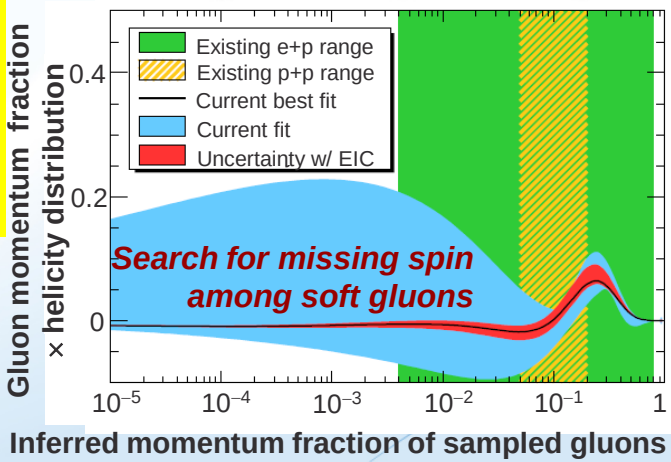




- **Probe the momentum-dependence of onset of gluon saturation in nuclei (initial state @ RHIC & LHC)**
- **Map the gluon densities and multidimensional spatial & spin distributions of partons in the gluon-dominated regime; explore parton orbital angular momentum**
- **Test effective theory approaches to highly non-linear, high-density & strong-field limit of QCD**

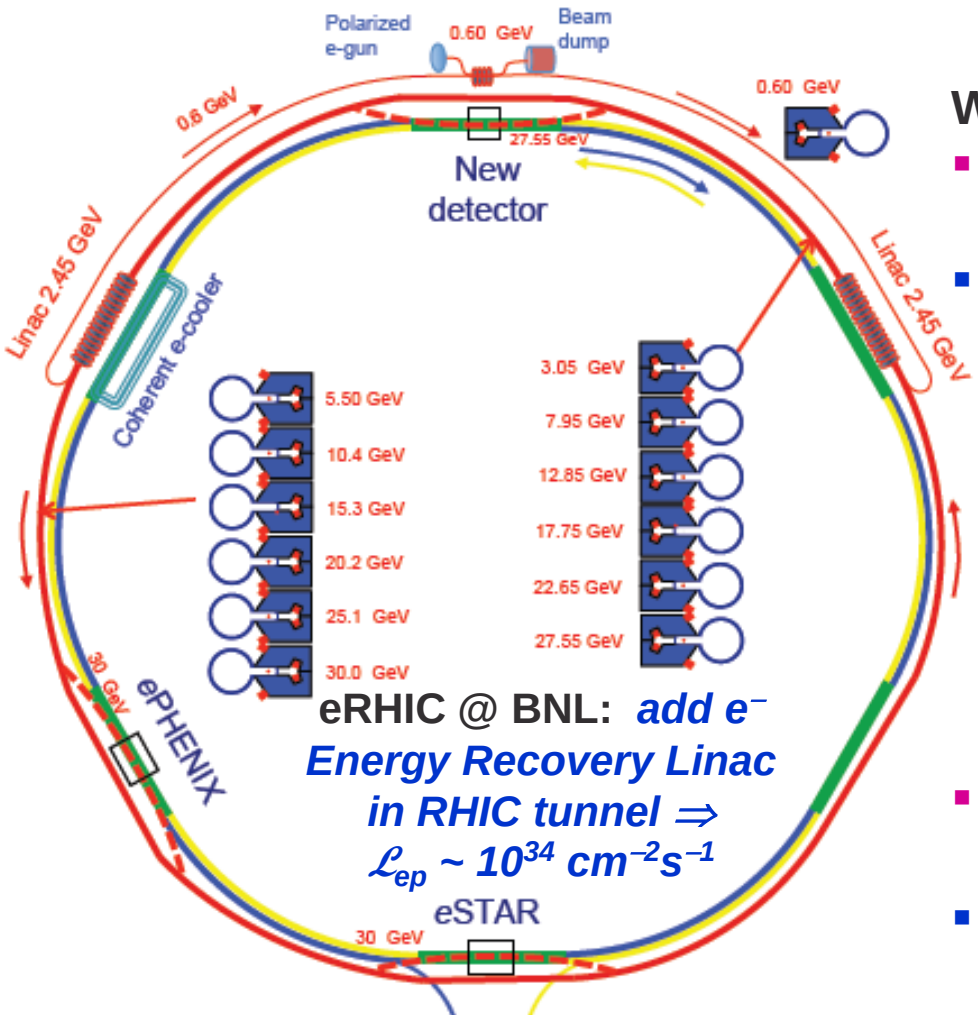


EIC Science White Paper will be available in 2012



Machine requirements: high √s (~100 GeV); high luminosity (~10^{34} cm^{-2}s^{-1}); polarized electron and nucleon beams; heavy-ion beams (to A~200); large variable energy range for F_L.

RHIC's 3rd Decade: Reinvention as eRHIC ⇒ Path Forward for Cold QCD Matter



Design allows easy staging (start w/ 5-10 GeV, upgrade to ~20 GeV e⁻). Underwent successful technical design review in 2011. Bottom-up cost eval. + value engineering in progress.

Why eRHIC is a cost-effective approach:

- ***Reuses RHIC tunnel & detector halls ⇒ minimal civil construction***
- ***Reuses significant fractions of existing STAR & PHENIX detectors***
  - ***Exploits existing HI beams for precocious access to very high gluon density regime***
  - ***Polarized p beam and HI beam capabilities already exist – less costly to add e⁻ than hadron accelerator***
- ***Provides straightforward upgrade path by adding SRF linac cavities***
- ***Takes advantage of RHIC needs and other accelerator R&D @ BNL:***
  - ***E.g., coherent electron cooling can also enhance RHIC pp lumi.***
  - ***E.g., FFAG developments for muon collider considered for significant cost reductions***

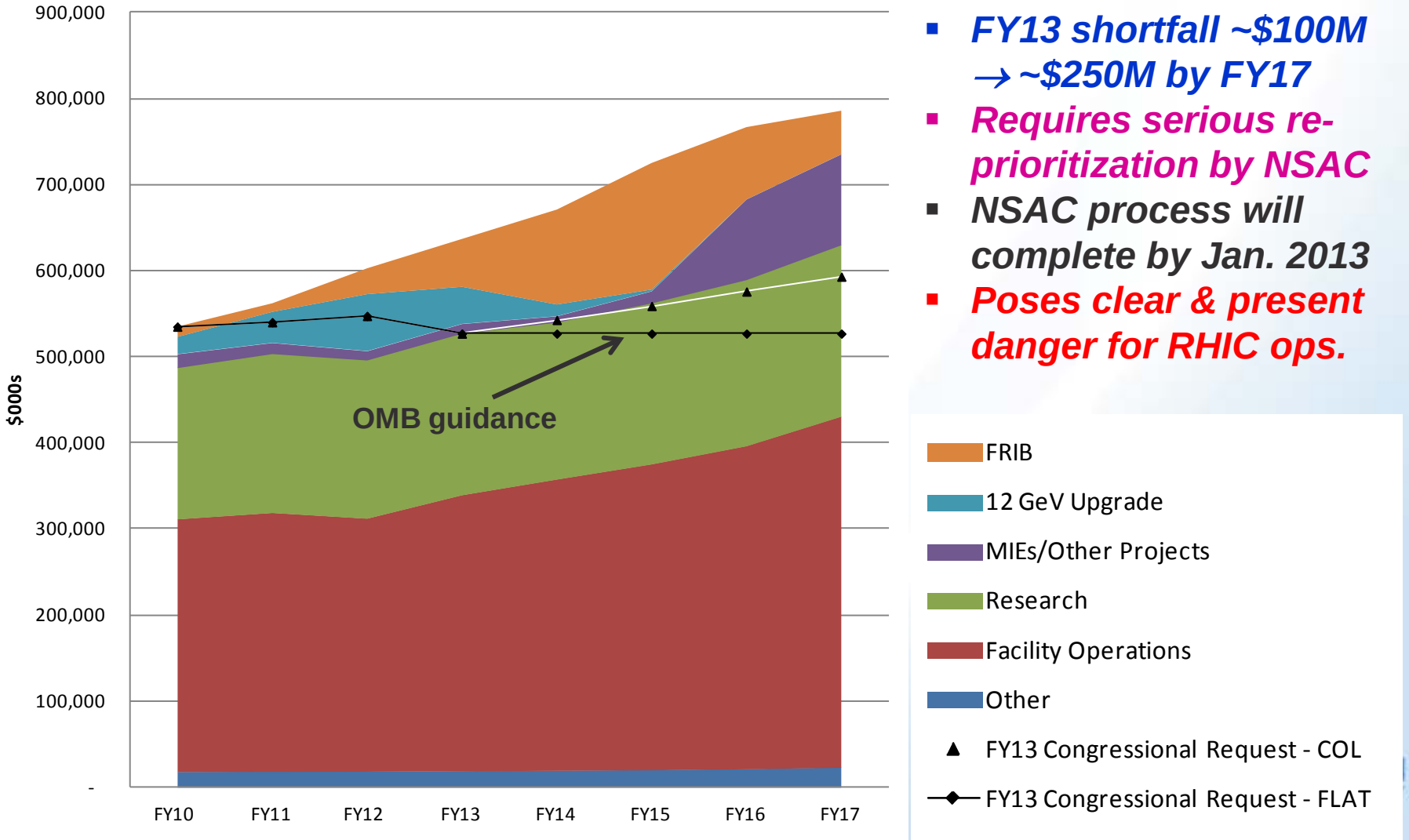
RHIC Future is Scientifically & Technically Robust, But Funding-Challenged

	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013P
RHIC Ops. $M	135.5	137.0	149.8	158.7	159.4	157.6	156.6
# cryowks.	20	19	22	28	26	~23	~15
Comments	Budget arrived late, other-wise could have supporte d more weeks	Unexpec-ted Omnibus bill causes early run termina-tion	Budget could have suppor-ted 25 weeks, but long CR led to very late start	Robust run, should maintain carry-over for early start on Run 11 even with CR	Long run possible due to carryover from FY10 + salary freeze. Finished end of June 2011	Extended via Xmas $3M add + lower power costs w/ new NYPA contract. Will end June 27.	Mandated 2-year salary freeze ends. @ BNL $ guidance for power, get to 15 wks. only by post-poning AIP

1) ***"RHIC Ops"= (collider + det.) [Ops. + R&D + CE] + AIP***
2) ***Flat budgets ⇒ lose ~$5M, or 12 cryoweeks/year, to inflation w/o mitigation***
3) ***If we get Congressional additions ($3-5M) in FY13, extend Run 13 to 20 wks***
4) ***Will focus mostly on 500 GeV pp for Run 13, 200 GeV Au+Au for Run 14***

The Out-Year Crisis for NP Funding

- This chart reflects the estimated funding needed to implement the majority of elements of the NSAC 2007 Long Range Plan (LRP) – not including EIC.
- The FY 2013 Congressional Request is reflected as two lines, one assuming 3% cost-of-living into the outyears and the other assuming flat funding into the outyears.



- ***FY13 shortfall ~$100M → ~$250M by FY17***
- ***Requires serious re-prioritization by NSAC***
- ***NSAC process will complete by Jan. 2013***
- ***Poses clear & present danger for RHIC ops.***

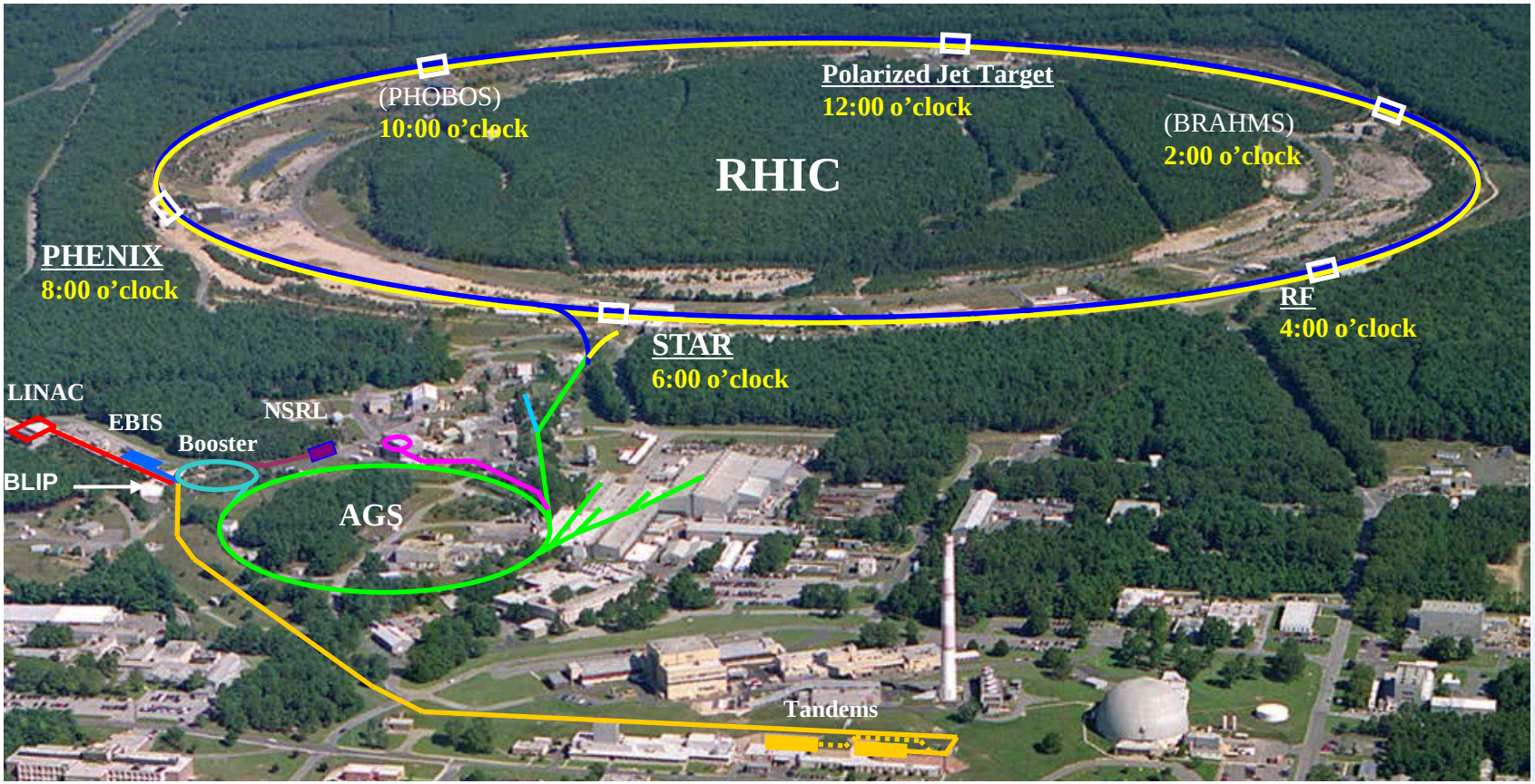
Upcoming Events & Summary

1) There is a clear decade-long measurement program, exploiting RHIC's versatility and new capabilities, to address critical questions for hot and cold QCD matter that have been raised, or not yet resolved, in RHIC's 1st decade.
2) Upgrade plans for the latter half of the coming decade are crystallizing now.
3) RHIC and LHC HI are complementary facilities, both needed to resolve many of the outstanding open questions. Long-term health is probably strongly correlated for the two.
4) RHIC provides quite possibly the only viable, cost-effective path to a next-generation Electron Ion Collider.
5) A series of upcoming events will be crucial in determining the future of the RHI program on both sides of Atlantic:

June 29: LHC HI Town Meeting (to inform Europe's HEP strategy)
July-August: White Paper(s) on RHIC and overall RHI next-decade goals
July-August: Community feedback on EIC Science White Paper
Aug. 12-18: Quark Matter 2012, with likely discussions (Town Meeting?) of strategy as well as new results in field
Sept. 7-9: Initial Tribble-II Panel hearings/presentations
Oct. 24-27: DNP meeting with Town Meetings for input to Tribble-II
December: Likely report of preliminary Tribble recommendations to NSAC

Backup Slides

RHIC's First Decade: A Discovery Machine



RHIC hallmarks:

Pioneering – 1st facility to clearly see transition to quark-gluon matter; world's only polarized collider

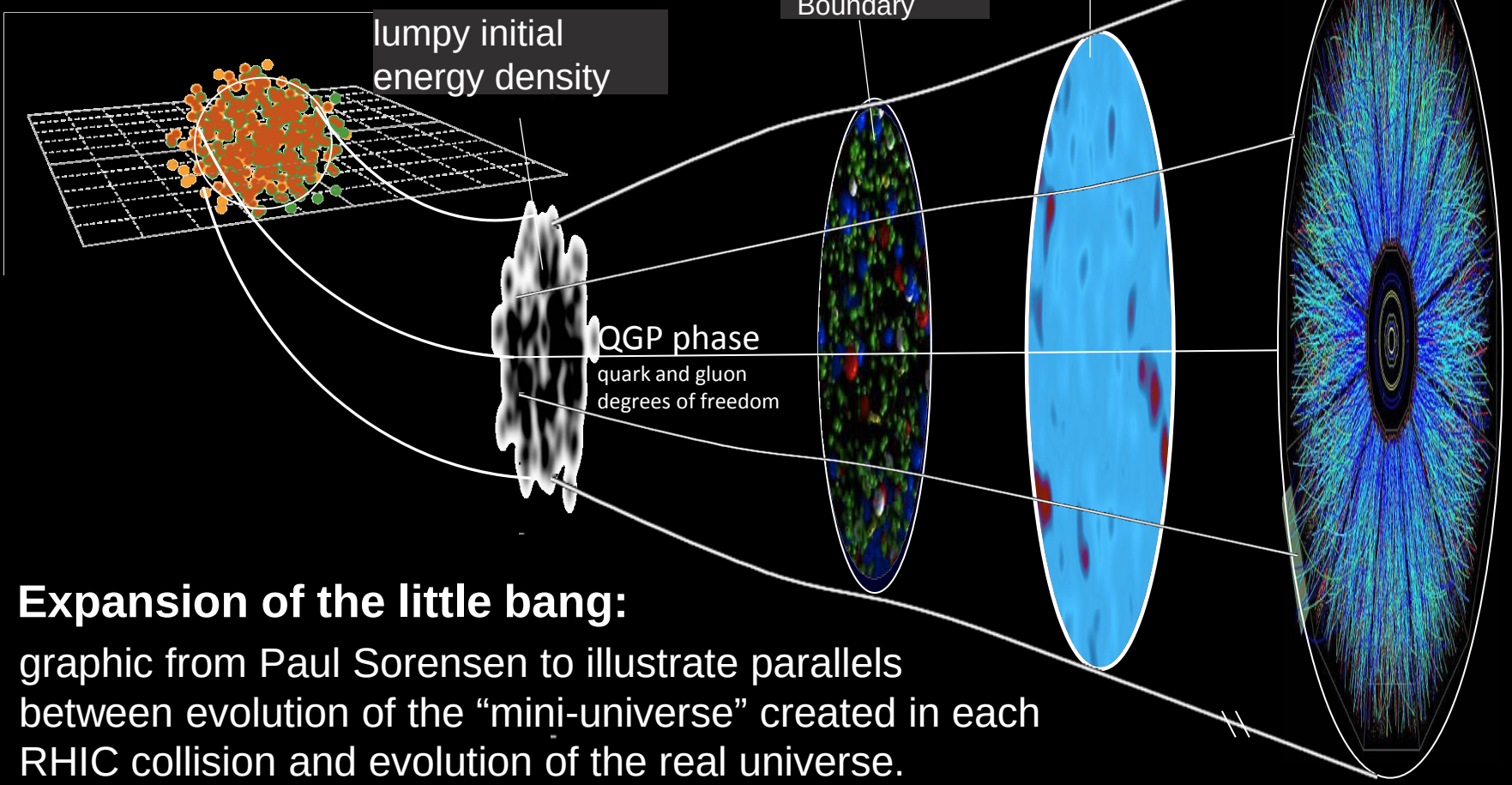
Productive -> 300 refereed papers, > 20K citations, > 200 Ph.D.'s in 1st 10 years, many more in pipeline, no rate falloff in sight

Versatile - wide range of beam energies and ion species ⇒ string of definitive discoveries in both hot and cold QCD matter

RHIC Has Pioneered Lab Study of Condensed QCD Matter

Challenges:

1. *How to pump/probe matter that lives ~10^{-23} seconds?*
2. *What are unique emergent QCD phenomena?*
3. *How do they influence early universe evolution?*
4. *What roles do quantum fluctuations play?*
5. *Are there lessons for EW matter?*



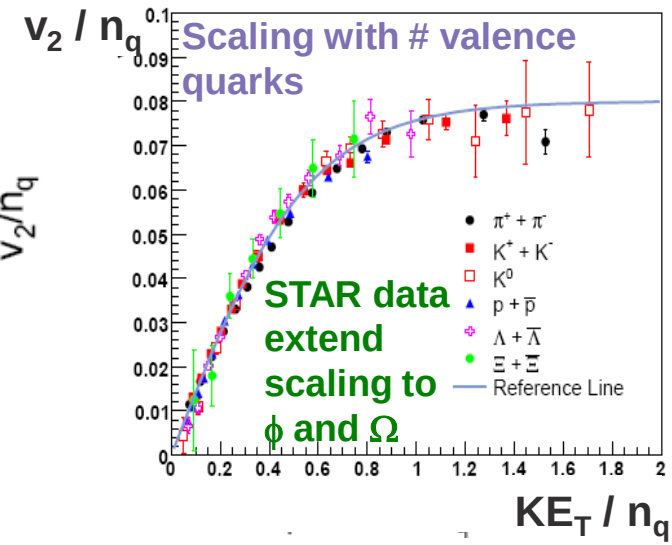
Expansion of the little bang:

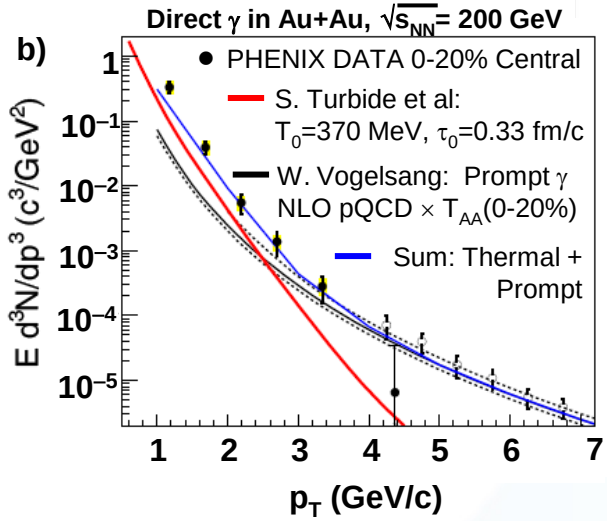
graphic from Paul Sorensen to illustrate parallels between evolution of the "mini-universe" created in each RHIC collision and evolution of the real universe.

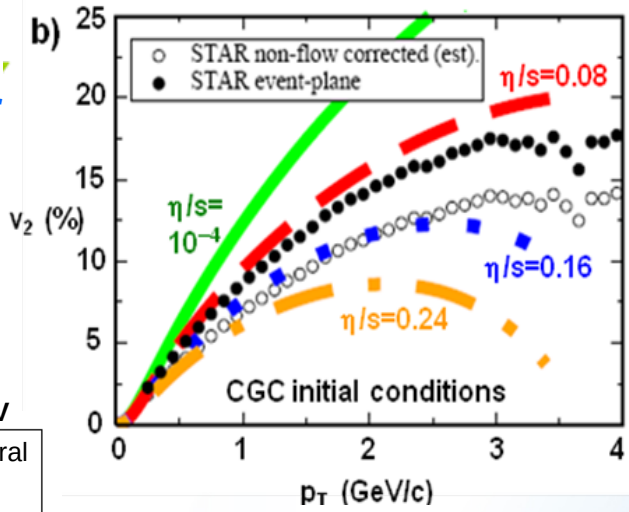
RHIC Past: Hot QCD Discoveries

- ***Near-perfect liquid nature of early universe matter – revealed via elliptic flow v_2 – markedly different from anticipated ideal gas***

- ***Shear viscosity near lower quantum limit predicted via String Theory work on black holes***





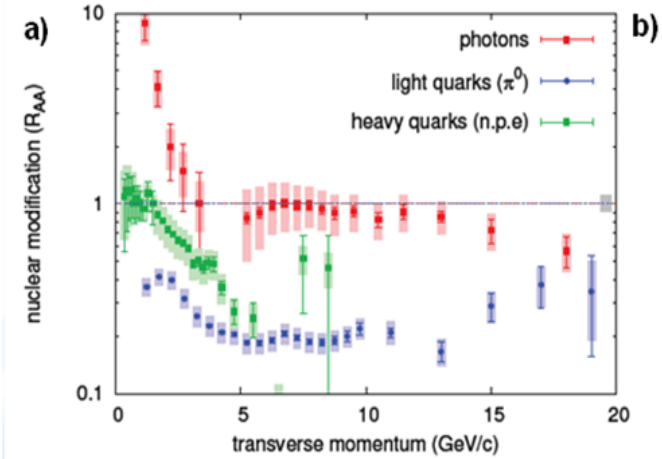


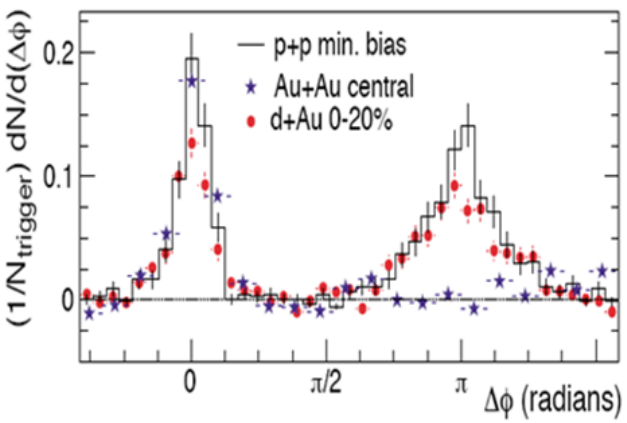
- ***Collective flow established at quark level via n_q scaling***

- ***Matter first equilibrates ~4×10^{12} K, well above max. allowed temp. for hadron gas***

- ***QGP is ~opaque to quarks and gluons, but transparent to photons***

Bottom Line: ***RHIC collisions produce deconfined QGP that behaves as inviscid fluid***





Examples of Recent S&T Breakthroughs

1) ***Measurement of higher flow multipoles + advances in hydrodynamics state-of-the-art $\Rightarrow$ path to quantify η/s, other transport properties, and role of quantum fluctuations***

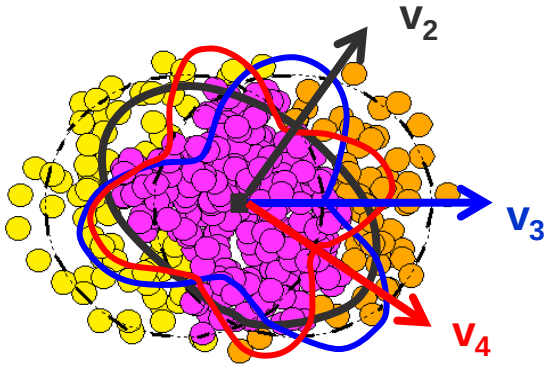
2) ***Charged-particle correlations hint at excited QCD vacuum fluctuations akin to EW sphalerons believed responsible for early-universe baryon-antibaryon imbalance***

3) ***RHIC beam energy scan hints at onset of deconfinement and possible QCD critical point***

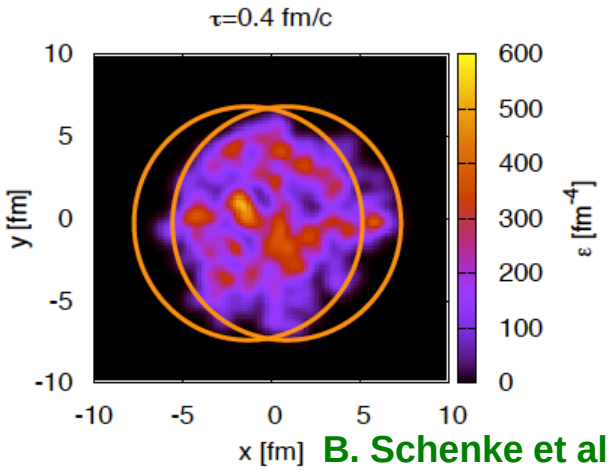
4) ***Stochastic cooling and EBIS upgrades have RHIC poised to pursue follow-up investigations to above and other 2nd-decade science questions***

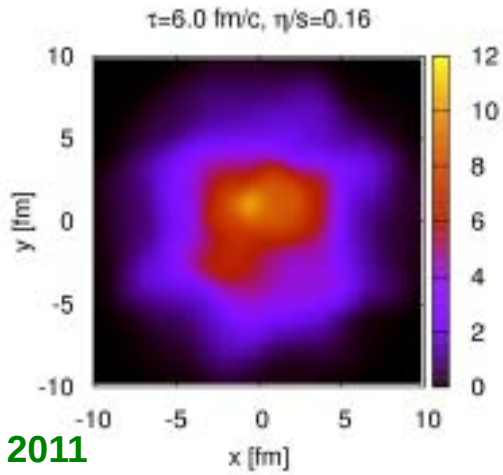
These are described, along with next steps in each case, in more detail on following slides…

Beyond v_2 to Quantify Near-Perfection

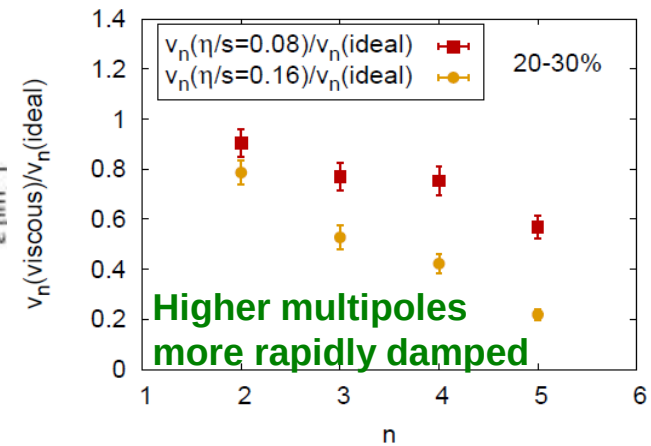


- *Small shear viscosity of QGP permits lumpiness & asymmetry in initial density to seed higher than quadrupole patterns in emerging particle momenta*
- *Recent v_n measurements and 3+1-D event-by-event viscous hydro calcs. ⇒ path to quantifying η/s*

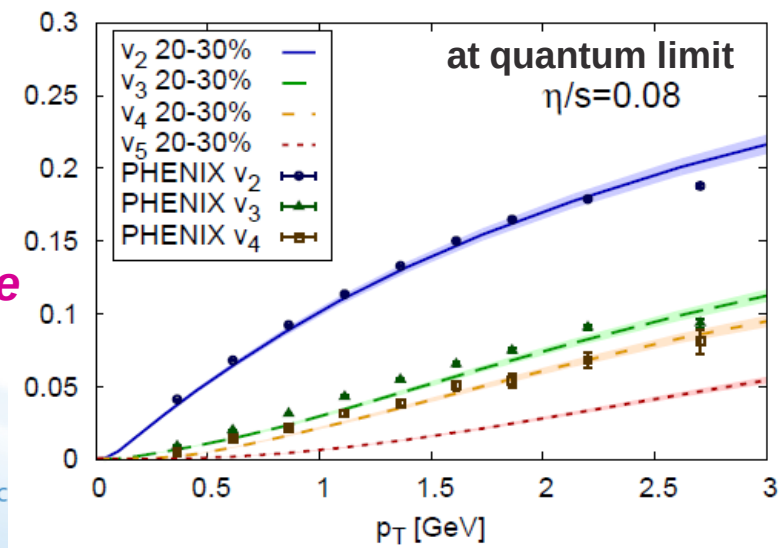


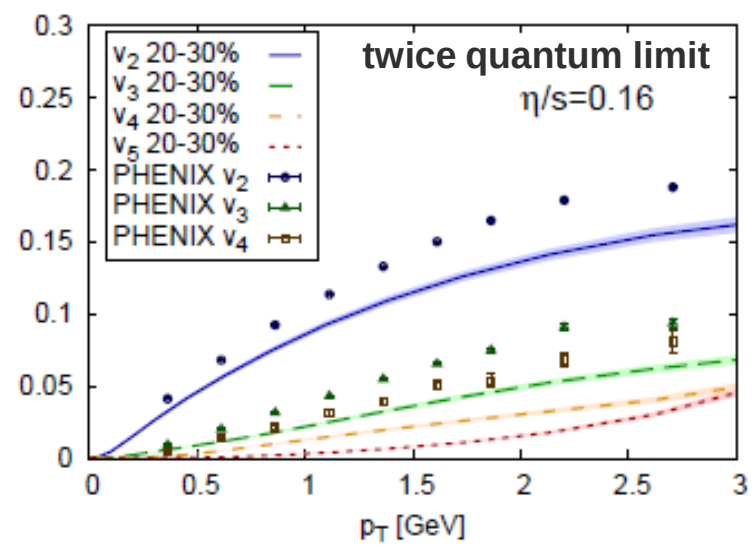


B. Schenke et al., 2011



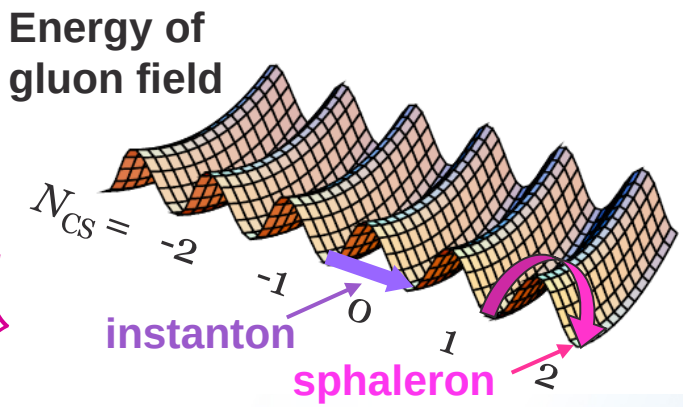
Comparison to new PHENIX data for $v_{2,3,4}$ ⇒ η/s very close to lower quantum bound !

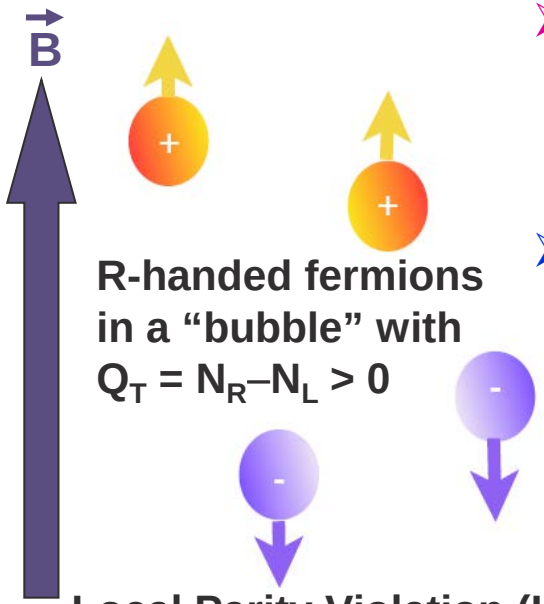




Do We See Excited QCD Vacuum Fluctuation Effects?

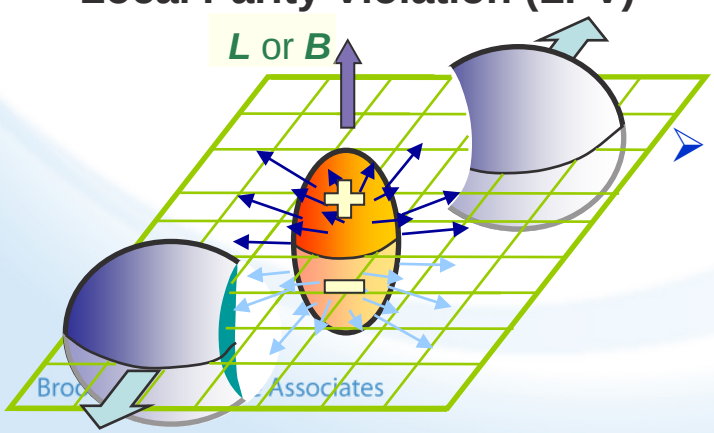
- *QCD sphalerons ⇔ leftward or rightward "twists" in gluon field ⇒ local chiral imbalance (analogous to EW sphalerons as possible source of baryon-antibaryon imbalance in universe)*





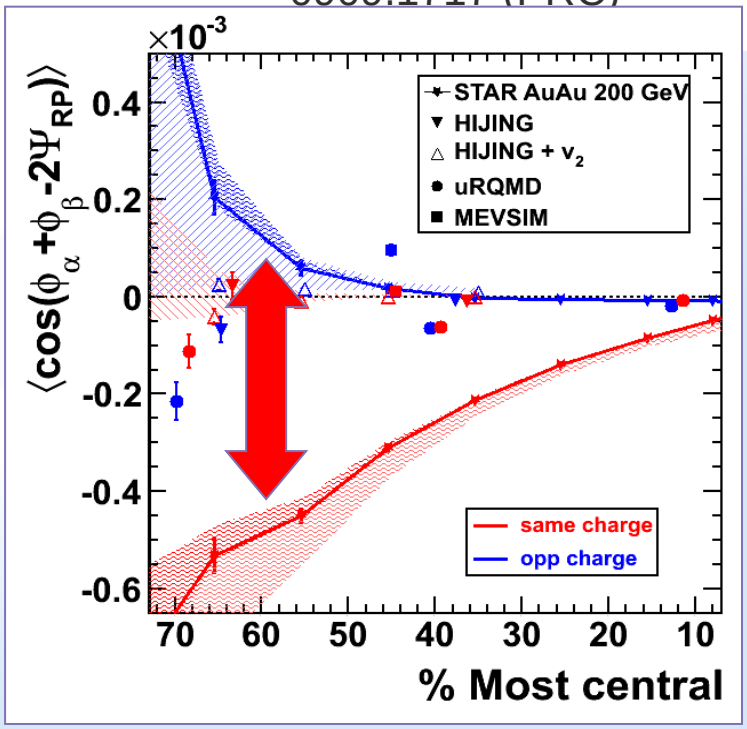
R-handed fermions in a "bubble" with $Q_T = N_R - N_L > 0$

Local Parity Violation (LPV)



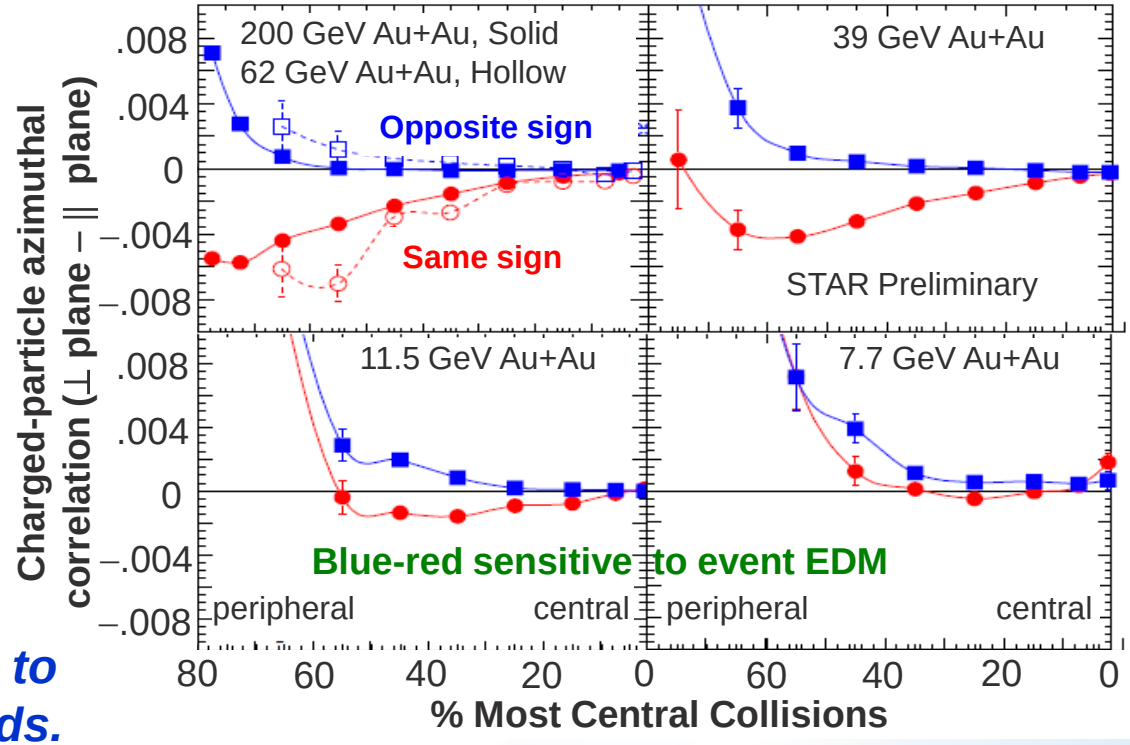
- *Coupling with very strong magnetic field (~10^{17} G) ⇒ Chiral Magnetic Effect ⇒ event EDM (D. Kharzeev et al.)*
- *Charge separation can survive passage through chirally restored QGP*
  - *EDM sign can differ from bubble to bubble, event to event ⇒ event asymmetry, but no global CPV*
  - *STAR finds P-, CP-even, but EDM-like, charged-particle correl'ns ~predicted effect*

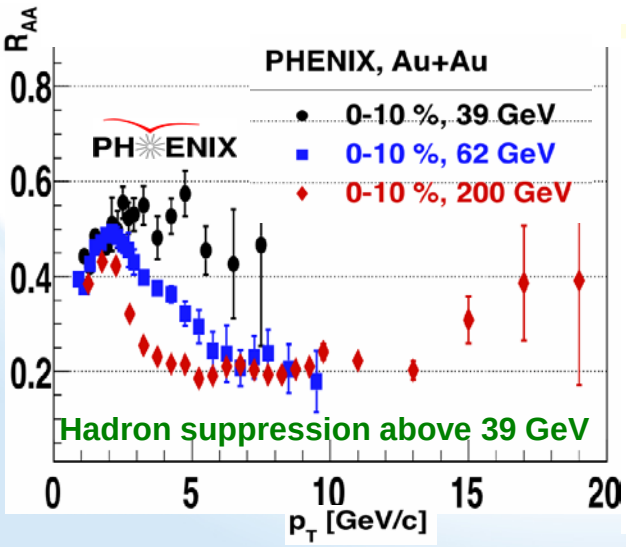
STAR; PRL103, 251601(09); 0909.1717 (PRC)

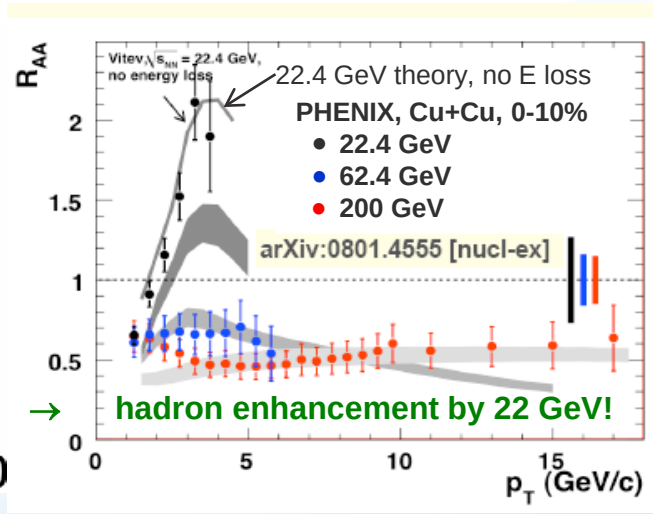


RHIC Beam Energy Scan: Onset of Deconfinement?

- *ALICE/LHC LPV results ~ identical to STAR 200 GeV, despite ×14 in $\sqrt{s_{NN}}$*
- *But STAR measurements during 2010 RHIC beam energy scan show rapid vanishing of charge-dependent correl'n < 39 GeV*
- *Consistent with onset of chiral symm. restoration & deconfinement within RHIC range, but need other signals to rule out flow-related LPV bkgds.*

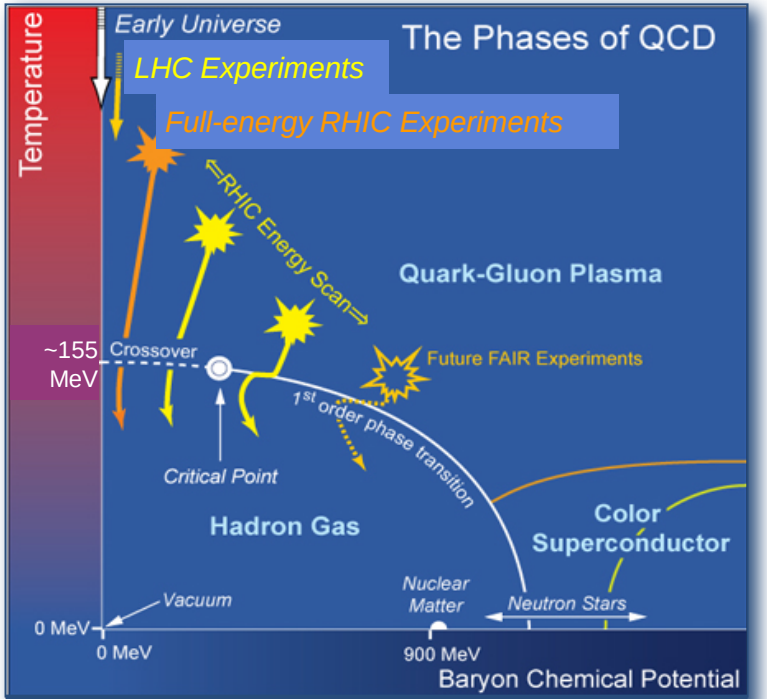






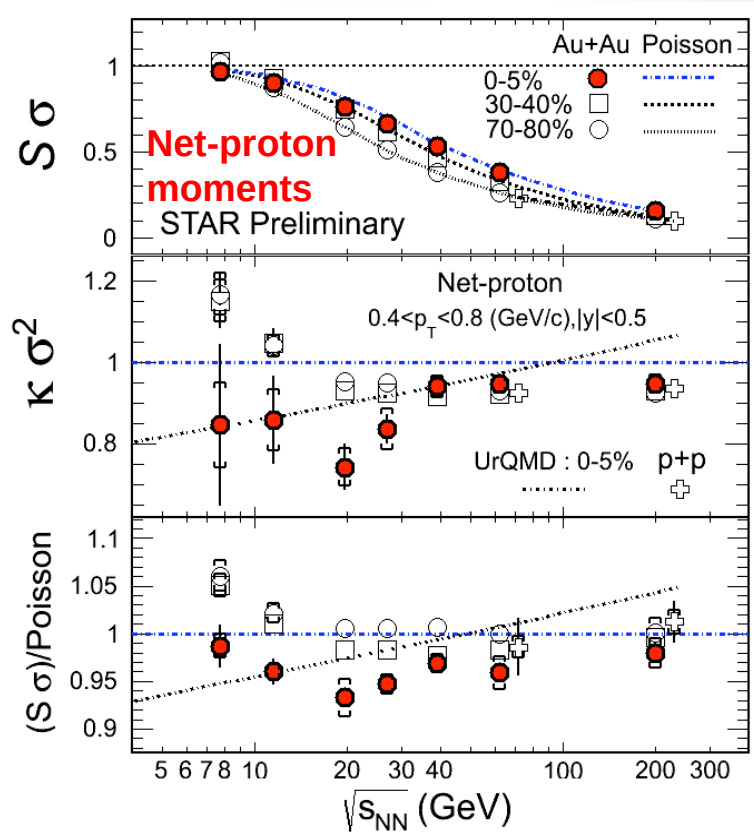
- *Other signals also suggest QGP onset @ RHIC, e.g., disappearance of high-p_T hadron suppression from parton E loss, deviations from n_q scaling of elliptic flow*
- *"Sweet spot" @ RHIC?*

Energy Scan: Critical Point (CP) in the QCD Phase Diagram?



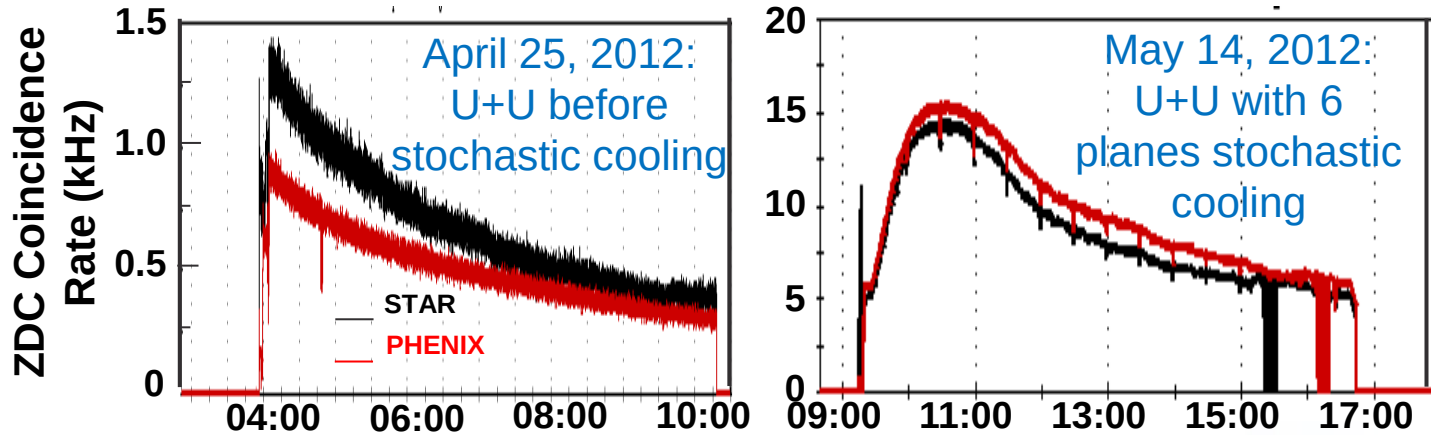
Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

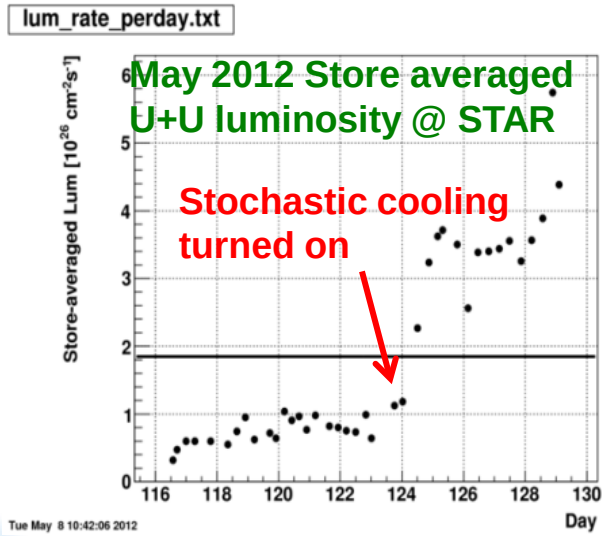
- ***At near zero net baryon density probed at top RHIC energy and LHC, LQCD ⇒ smooth crossover transition***
- ***At higher μ_B, theoretical arguments suggest 1st-order phase transition, but LQCD MC sampling invalid***
- ***Critical point would be unique fixed point in QCD landscape***

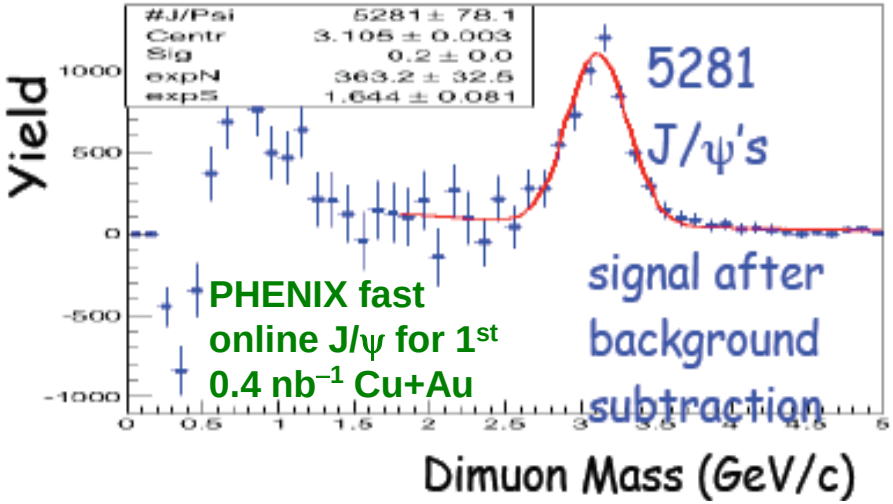


- ***Expect non-Gaussian fluctuations in event-by-event distributions of conserved quantities: charge, baryon #***
- ***Higher moments depend more strongly on correlation length ξ***
- ***Early STAR results for 3rd & 4th moments show tantalizing hints of deviations from Poisson expectations near 20 GeV – will need phase 2 $\sqrt{s}$ scan to delineate clearly.***

Just Completed Facility Upgrades Enable "Next Steps"



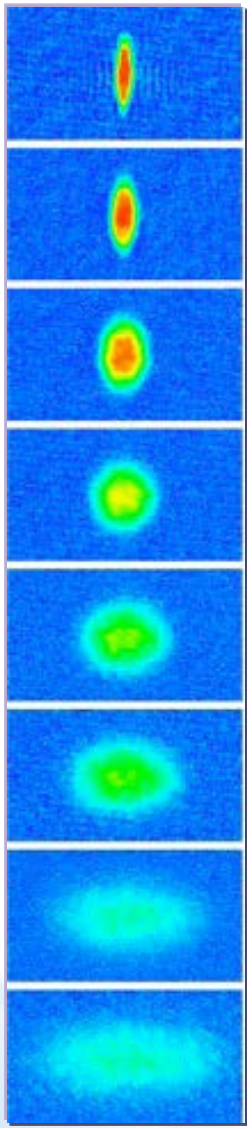




Yield sufficient to study vs. collision geom.

- ***Stochastic cooling dramatically increases rates for rare events***
- ***EBIS provides U beams to exploit deformation for initial geom. selection***
- ***EBIS simplifies asymmetric (e.g., Cu+Au) HI collisions for extra geom. control, e.g., to unravel dependences on energy density & path length***

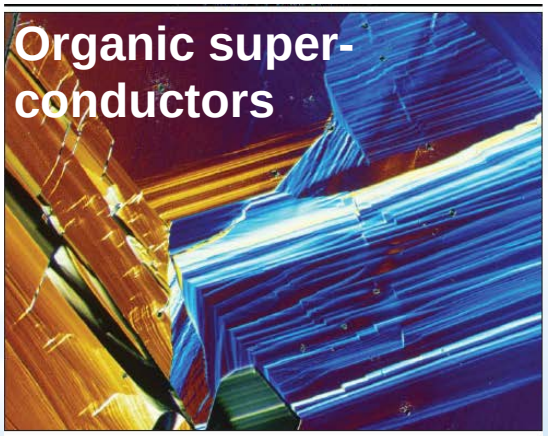
Unanticipated Intellectual Connections

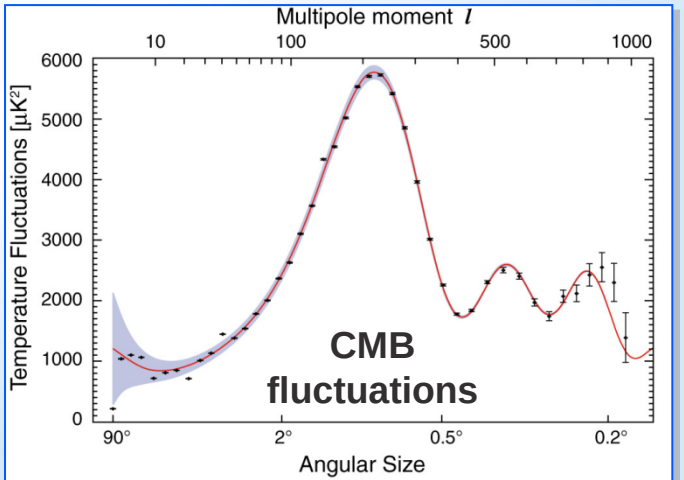


Trapped ultra-cold atom clouds

RHIC results have established ties to other forefront science:

- **String Theory studies of black hole behavior led to prediction of quantum lower bound on η/s**
- **Ultra-cold atomic gases, at temperatures 19 orders of magnitude below QGP, can also be "nearly perfect liquids"**
- **Similar liquid behavior seen and studied in a number of strongly correlated condensed matter systems**
- **Symmetry-violating bubbles in QGP analogous to speculated cosmological origin of matter-antimatter imbalance in universe**
- **Power spectrum of flow analogous to power spectrum of cosmic microwave background, used to constrain baryon acoustic oscillations & dark energy.**



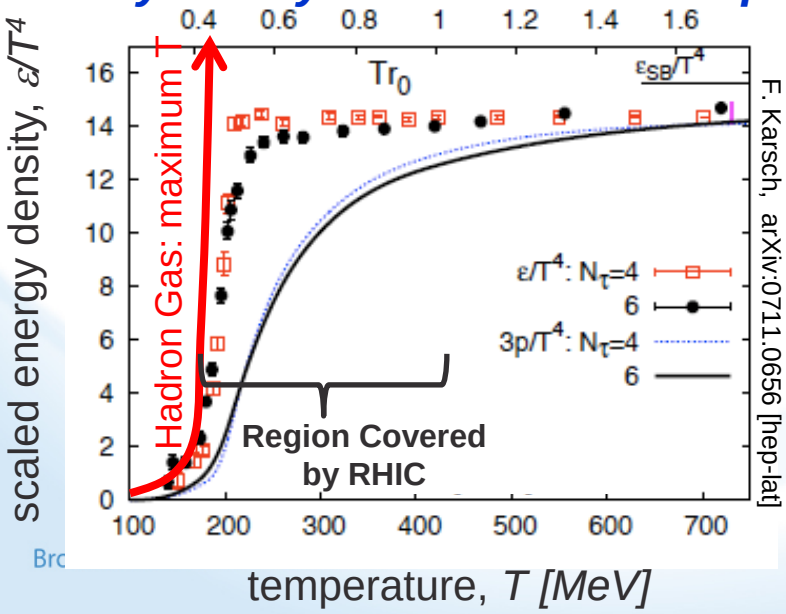


2nd Decade: Exploit √s "Sweet Spot" + RHIC's Versatility and Upgrades for Quantification & Further Discoveries

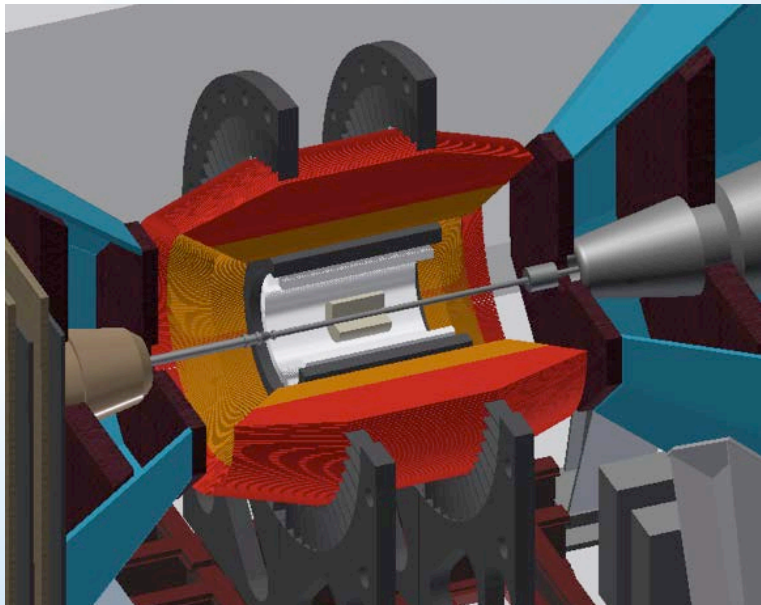
- How perfect is the near-perfect fluid, as fcn. of temp.?
- How do fluctuations (both initial density & excited QCD vacuum) affect evolution of "mini-universe"?
- Is there a critical endpoint in the QCD phase diagram?
- How do quarks and gluons lose energy in the QGP, as fcn. of quark flavor (including c,b) and temperature?
- Where is the "missing" p spin? Are transverse spin asyms. understood?

- ***Degrees of freedom and behavior of QCD matter change rapidly at QGP transition, but approach asymptopia very slowly above critical temperature.***

- ***Understanding parton E loss requires comparing jet quenching characteristics @ LHC vs. RHIC ⇒ need sPHENIX upgrade***



Program requires ~5 years before + ~5 years after next round of significant detector & collider upgrades



Are RHIC Operations Too Expensive?

- *A collider is needed to access the physics of early-universe matter, and colliders are costly to operate. RHIC ops are lean among colliders.*
- *54% of RHIC's $157M FY12 operating budget goes to staff salaries, fringe and overhead, supporting 436 direct FTE's (includes support of experiment operations, but excludes FTE's on indirect support)*
- *External reviews have judged the operating costs and staffing levels appropriate. E.g., the 2010 DOE review of RHIC Operations concluded: "The overall RHIC operations staff level is appropriate to support a facility of [its] size and complexity … The staff associated with ESSHQ … is a very modest effort for the scale of the RHIC facility and represents an efficient approach to meeting these essential requirements."*
- *Incremental cost per cryoweek in FY12 ≈$400K. This includes costs of ~$50/MW.h for power usage of 25 MW during machine operations.*
- *RHIC power usage is modest for a machine of this type. The Tevatron (70 MW) and LHC (120 MW) use(d) much more power. CEBAF currently uses 17 MW, but that will increase with upgrade to 12 GeV.*
- *BNL has taken a number of steps – including renegotiation of NYPA power contract – over the past decade to reduce RHIC costs & staffing.*

Bottom Line: NSAC must decide if it wants the visibility, impact, productivity and path to a future that RHIC brings to U.S. Nuclear Physics. If so, the costs cannot be reduced substantially below present levels.

Seller Beware: We estimate RHIC D&D costs to be ~$1B.

What Would be Lost if RHIC Were Terminated?

- Opportunity to map QCD matter properties across QGP transition and discover the possible Critical Point.
- Unique polarized pp access to nucleon spin structure.
- U.S. leadership in a vibrant NP subfield it pioneered.
- A major fraction of the productivity for U.S. NP over the better part of a decade – is this survivable?
- The last operating U.S. collider, hence a critical attractor for talented accelerator scientists and cutting-edge R&D.
- Quite possibly the only cost-realizable path to a future EIC.
- Home research base for >1000 domestic + foreign users.
- Strong foreign (esp. RIKEN) investment in U.S. facility.
- ~750 (direct + indirect) FTE's @ BNL.
- Many associated efforts will suffer collateral damage:
  - Lattice QCD thermodynamics leadership
  - Medical radioisotope production @ BNL
  - NASA Space Radiation studies @ BNL
  - Application offshoots in accelerator physics, esp. in next-generation hadron radiotherapy machine design
- Probably a sizable chunk of DOE ONP funding will be siphoned off to other agencies or program offices.