Overview of RHIC Status & Plans

Steve Vigdor

NSAC Implementation Subcommittee Hearings

Sept. 7, 2012

Upcoming Speakers & Topics:

I. S. Vigdor (BNL ALD) – Facility status and plans; science accomplishments and goals; timeline for next decade; path to eRHIC

II. U. Wiedemann (CERN) -- Theory drivers & view from LHC

III. P. Sorensen (2008 George E. Valley Prize) – RHIC physics with soft probes

IV. Y. Akiba (2011 Nishina Memorial Prize) – RHIC physics with hard probes

V. S. Vigdor – Take-away messages & answers to questions

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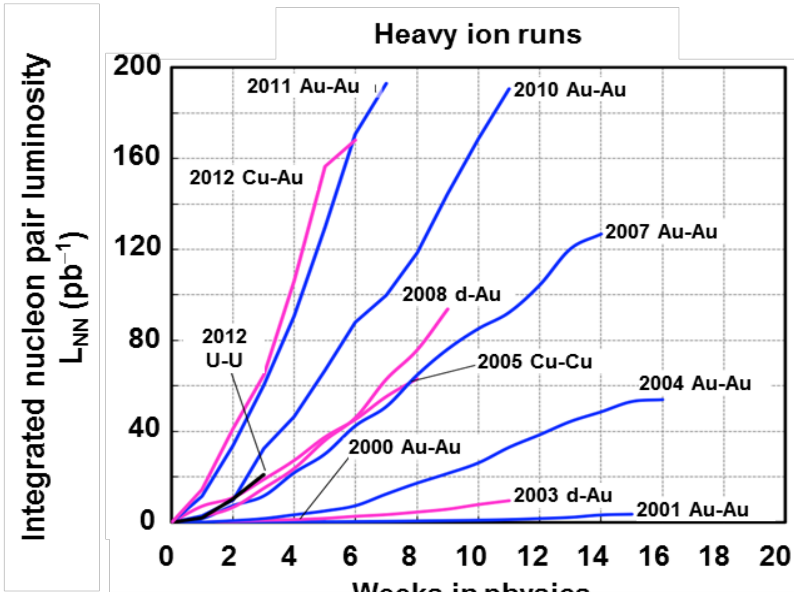
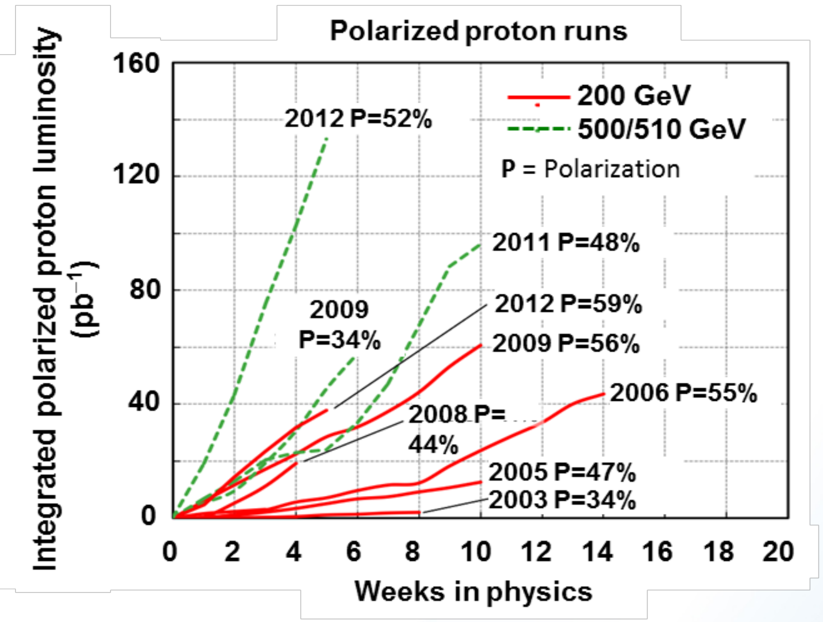
Incremental Upgrades ⇒ Dramatic Improvements in Collider Performance & Versatility

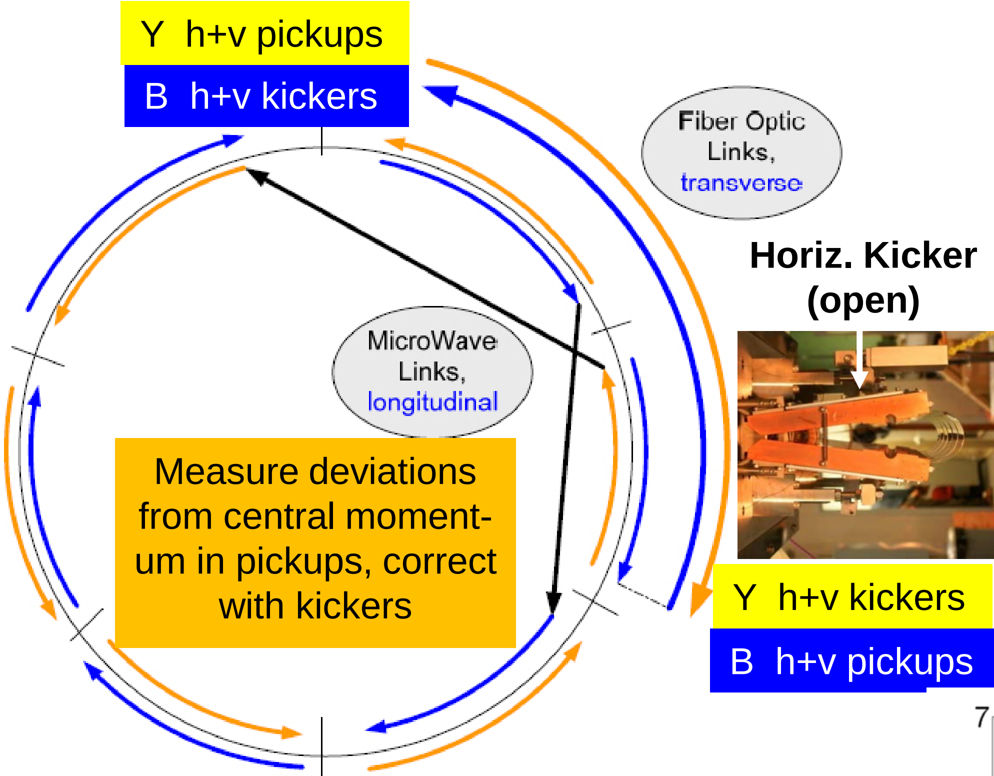




Collision partners	Beam energies (GeV/nucleon)	Peak pp-equivalent luminosities achieved to date, scaled to 100 GeV/n[b)]
Used to date		
Au+Au	3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 31, 65, 100	195×10^{30} $cm^{-2}s^{-1}$
d+Au[a)]	100	100×10^{30} $cm^{-2}s^{-1}$
Cu+Cu	11, 31, 100	80×10^{30} $cm^{-2}s^{-1}$
p↑+p↑ (polarized)	11, 31, 100, 205, 250, 255	165×10^{30} $cm^{-2}s^{-1}$ at 255 GeV
Cu+Au[a)]	100	230×10^{30} $cm^{-2}s^{-1}$
U+U	96	60×10^{30} $cm^{-2}s^{-1}$
Considered for future		
Au+Au	2.5, 7.5	
p+Au	100	
p↑+ ^{3}He↑ [a)]	166	

2 new colliding beam species in 2012

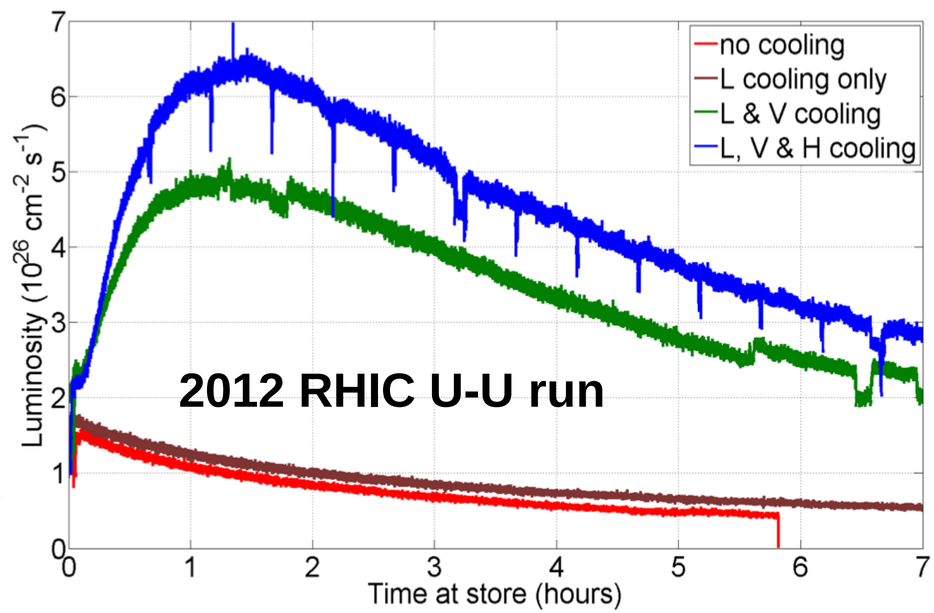
RHIC-II Era is Here, Done Very Cost-Effectively !



- ***RHIC breakthrough in bunched-beam stochastic cooling*** ⇒ ***now ~x18 over original design HI luminosity, 5 years earlier, at ~1/7 the cost in 2007 NP LRP***

- ***New Electron Beam Ion Source used in 2012 for new species, e.g., U beams***

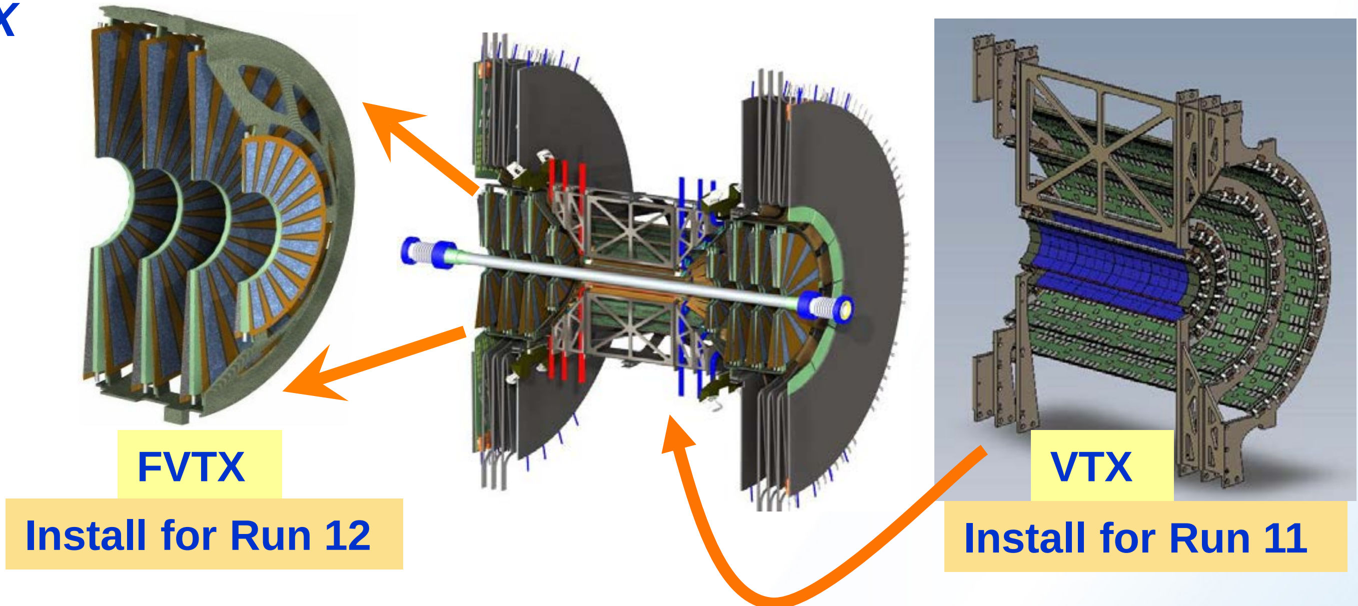
- ***Install electron lenses for 2013 run to*** ⇒ ***~×2 polarized pp luminosity***

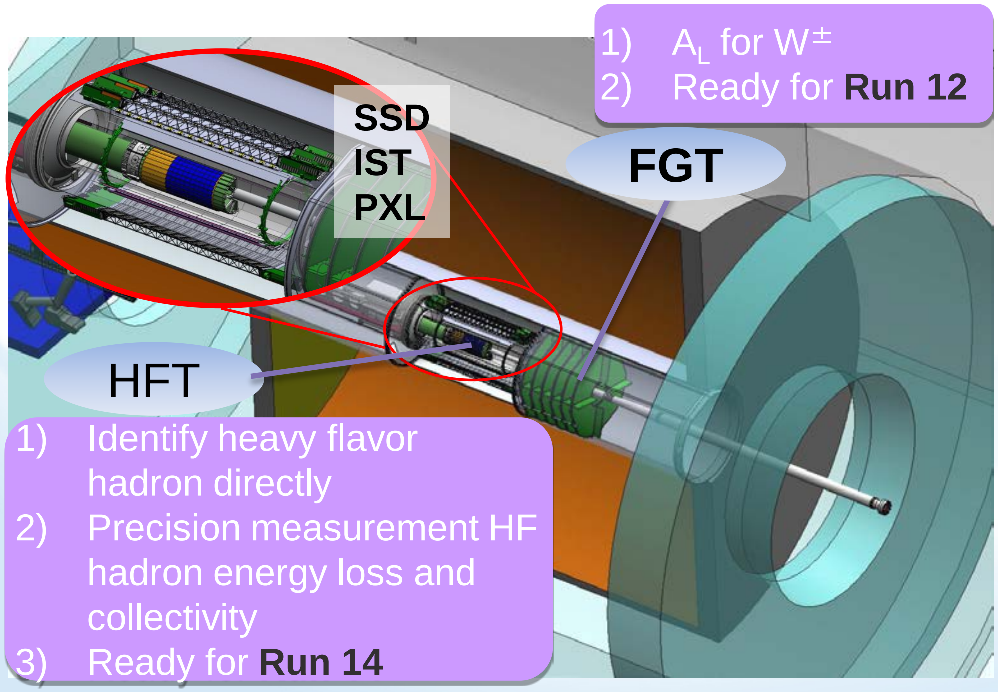


A Suite of Ongoing Detector Upgrades

- ***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 approval in 2011. Will permit topological recon-struction of charmed hadrons.*

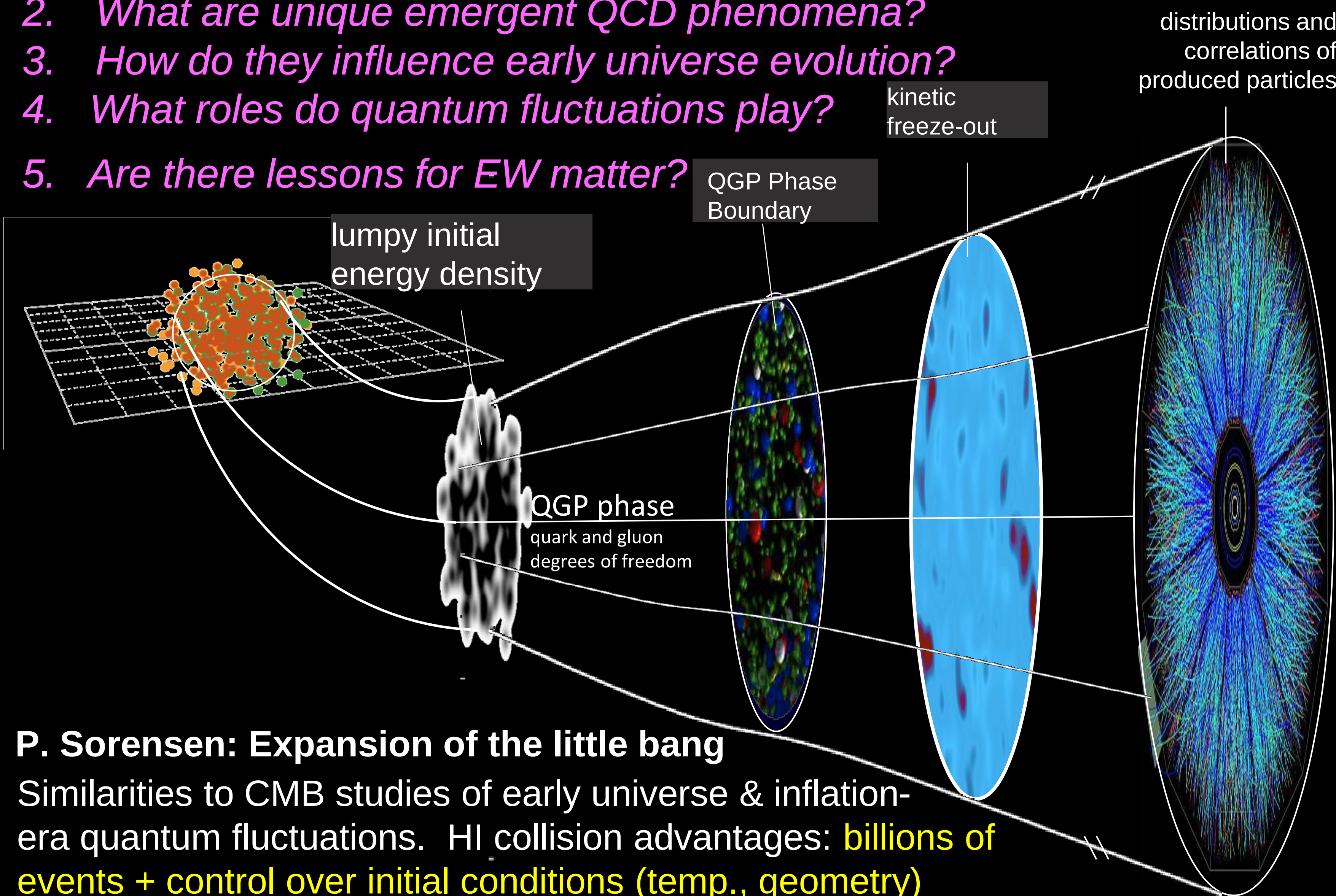
- ***STAR Forward GEM Tracker** to be installed for Runs 12 and 13, will enhance forward tracking, W charge sign discrimination.*

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

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?*



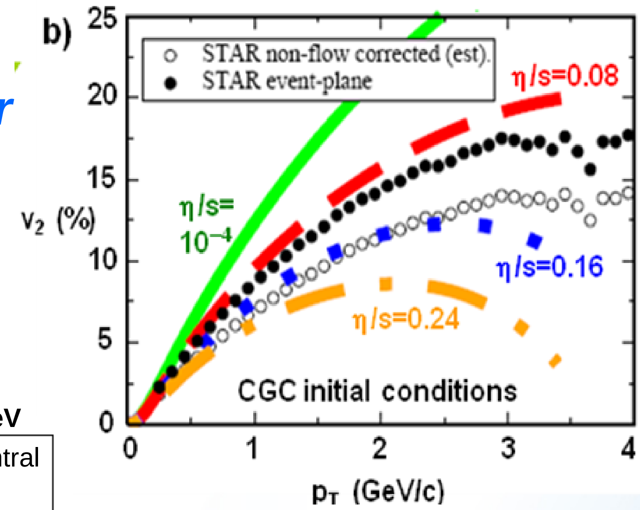
P. Sorensen: Expansion of the little bang

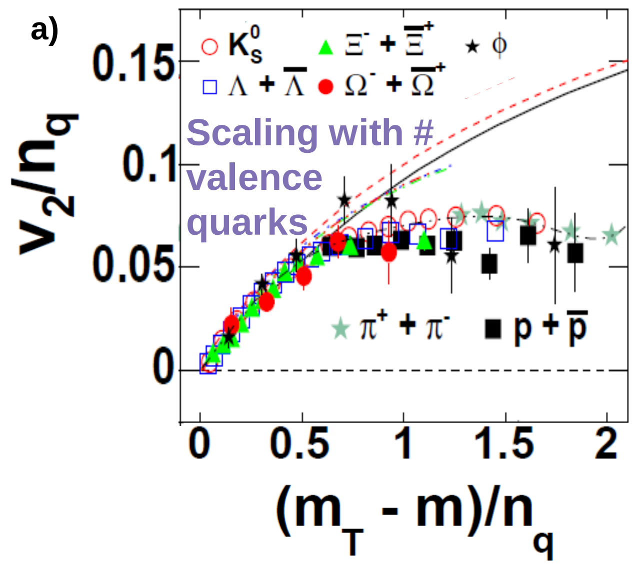
Similarities to CMB studies of early universe & inflation-era quantum fluctuations. HI collision advantages: billions of events + control over initial conditions (temp., geometry)

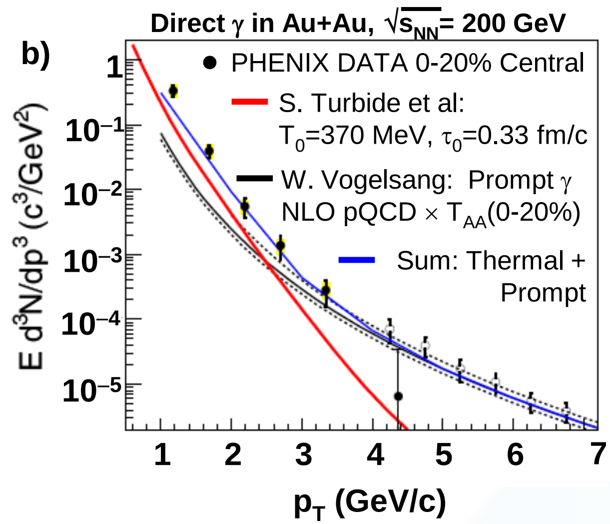
RHIC Past: Hot QCD Discoveries

- ❑ *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*





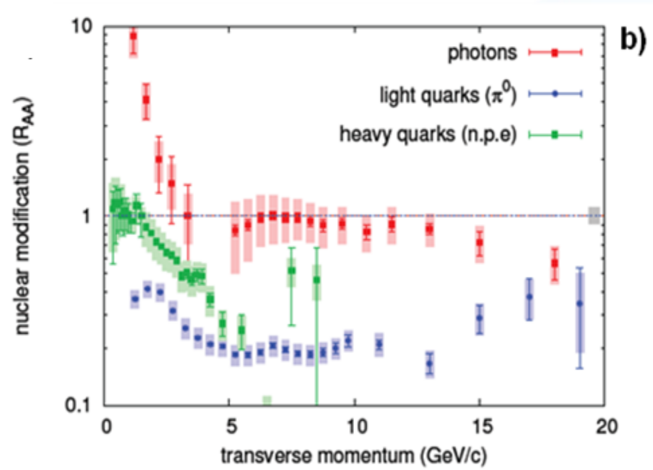


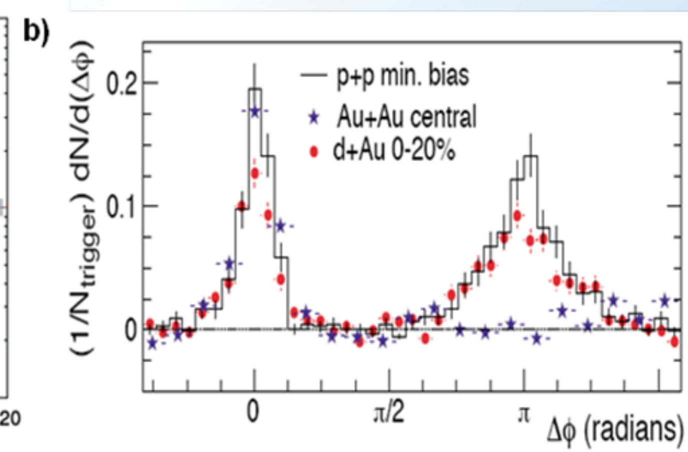
- ❑ *Collective flow established at quark level via n_q scaling*

- ❑ *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*

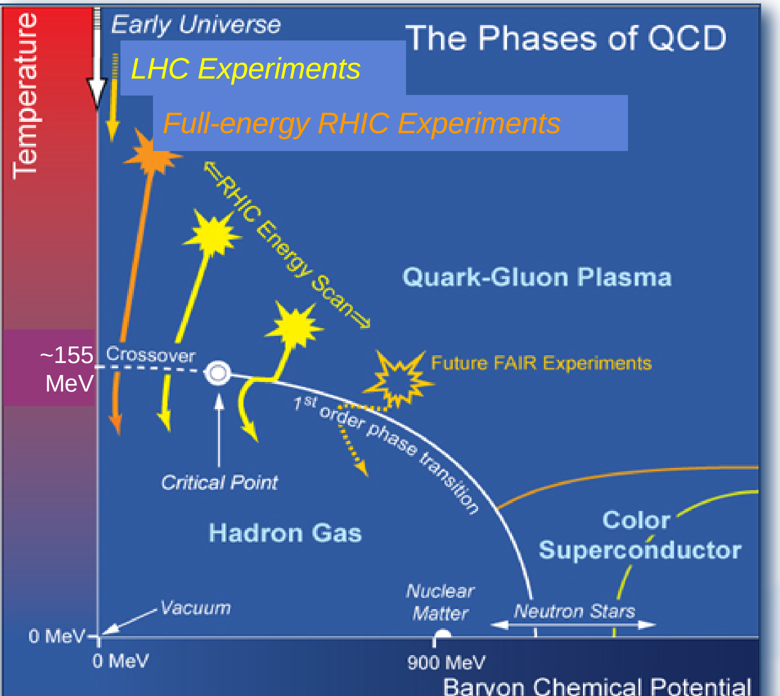




Broad Science Goals for the Next Decade

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.

Exploit new discovery potential in searches for a QCD critical point and for the nature and influence of quantum fluctuations in initial densities and the excited QCD vacuum (sphalerons).



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

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

RHIC and LHC are complementary. Both are needed to explore the temperature-dependence of QGP properties (span factor ~1000 in √s). RHIC has unique reach to search for the QGP onset, unique ion species versatility and unique polarized proton capability, until EIC is realized. And QCD matter is RHIC's primary focus.

10 Basic Questions Going Into the RHIC Era

		Basic questions going into the RHIC era	RHIC/LHC answers to date
	1)	Is RHIC's kinematic reach sufficient to create matter in the anticipated Quark-Gluon Plasma (QGP) phase?	Yes
	2)	Is the QGP weakly coupled, with approximately ideal gas (i.e., asymptotic freedom) behavior?	No
	3)	Can we experimentally demonstrate the transition from hadronic to quark-gluon degrees of freedom in reaching QGP?	Hints[a)]
	4)	Do partons lose energy rapidly in traversing QGP?	Yes
	5)	Does color screening in the QGP suppress the formation of quarkonium (i.e., bound states of same flavor quark-antiquark systems)?	Strong Hints[a)]
	6)	Can we find evidence of high-temperature excited QCD vacuum fluctuations, analogous to the electroweak sphalerons postulated as the source of the universe's baryon asymmetry?	Hints[a)]
	7)	Is there a locus of first-order phase transitions and a Critical Point in the QCD phase diagram?	Hints[a)]
p/d + A	8)	Do we see evidence of gluon density saturation in cold nuclear matter at low Bjorken x?	Strong Hints[a)]
$\vec{p}+\vec{p}$	9)	Do gluon spin preferences account for a significant part of the "missing" proton spin?	Yes
	10)	Is there a significant flavor-dependence in sea quark polarizations within a polarized proton?	Insufficient data to date

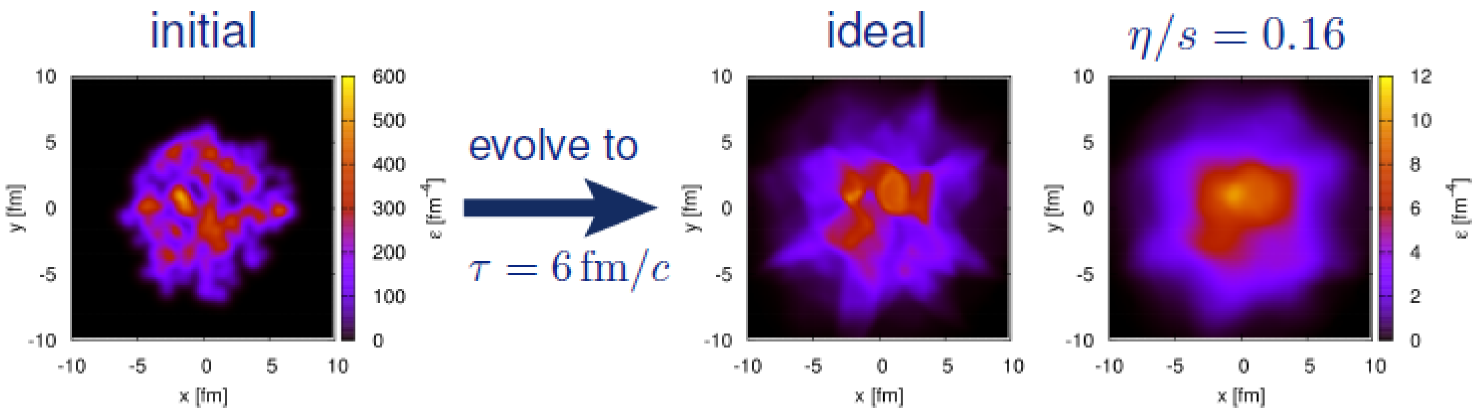
It is the responsibility of RHIC and LHC to design measurements to address the more quantitative 2^{nd}-generation questions emerging from the definitive answers above, and to resolve the hints surrounding the others.

Questions For the Next Decade

Question	Facilities Needed to Answer	Comments	Related Table 1 Question #'s
1) How perfect is "near-perfect" liquid?	RHIC & LHC (& ⇒ BOTH REQ'D)	Flow power spectra, next 5 years	1 + 2
2) Nature of initial density fluctuations?	RHIC, LHC & EIC	Benefits from asymmetric ion collisions at RHIC	2 + 8
3) How does strong coupling emerge from asymptotic freedom?	RHIC & LHC	Following 5 years @ RHIC; jets need sPHENIX upgrade	2 + 4
4) Evidence for onset of deconfinement and/or critical point?	RHIC; follow-up @ FAIR, NICA	Phase 2 E scan in following 5 years, needs low-E electron cooling	3 + 7
5) Sequential melting of quarkonia?	RHIC & LHC	LHC mass resolution a plus; RHIC det. upgrades help; $\sqrt{s}$-dependence important	5
6) Are sphaleron hints in RHIC data real?	Mostly RHIC	Exploits U+U and $\mu_B \neq 0$ reach at RHIC	6
7) Saturated gluon densities?	RHIC, LHC & EIC	Want to see onset at RHIC; need EIC to quantify	8
8) Where is missing proton spin?	RHIC & EIC	EIC will have dramatic impact	9 + 10

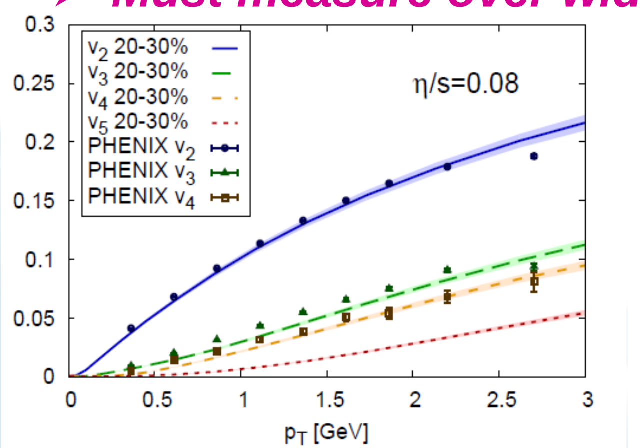
Addressing these questions requires an ~10-year program of A+A (various ion species), p+p and p/d + A runs at various RHIC energies.

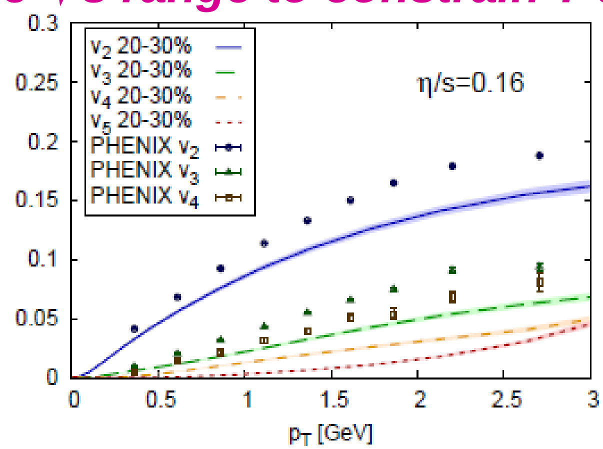
Providing Answers: Degree of Perfection

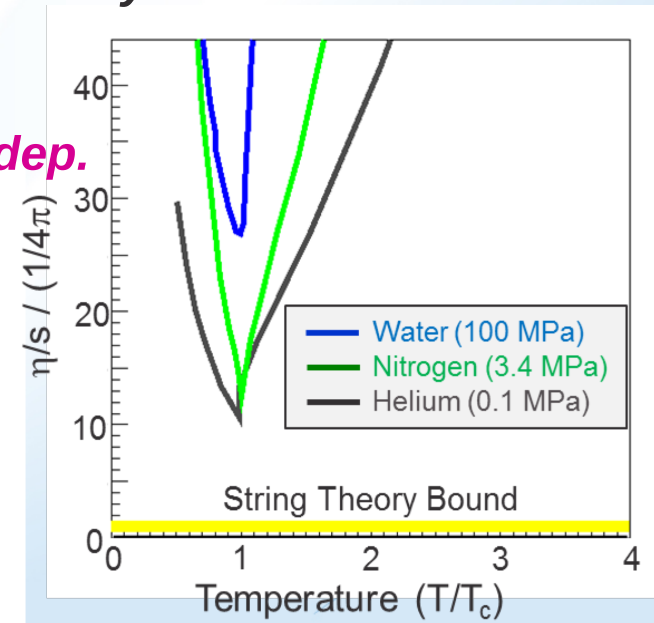


More in P. Sorensen talk

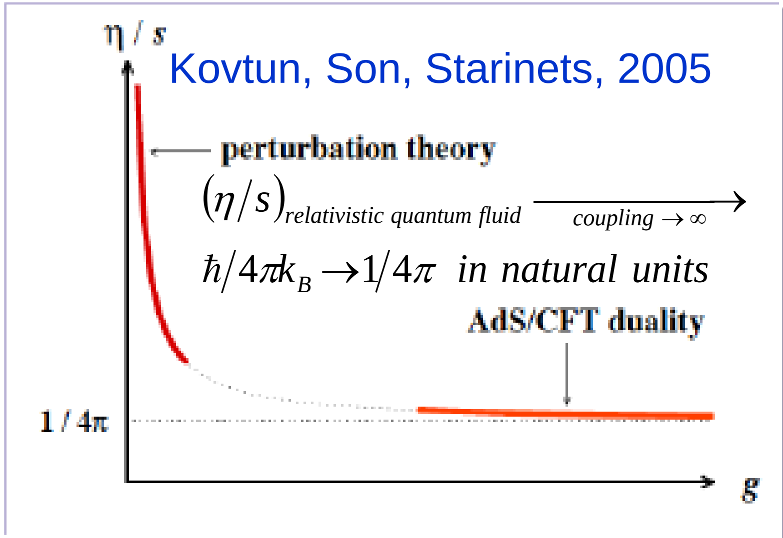
- ***Increasing sophistication in 3+1-D viscous hydrodynamics and measurement of Fourier power spectra for collective flow ⇒ clear path to quantify***
- ***Present comparisons ⇒ η/s within factor 2-3 of string theory bound***
- ***Detailed future measurement /theory program outlined in RHIC White Paper to ⇒ improved $[\eta/s]_{min}$ (~±10% goal) + nature of density fluctuations***
- ***η/s minimum at transition temp.? Deviation from AdS/CFT bound and implications?***
- ***Must measure over wide √s range to constrain T-dep.***



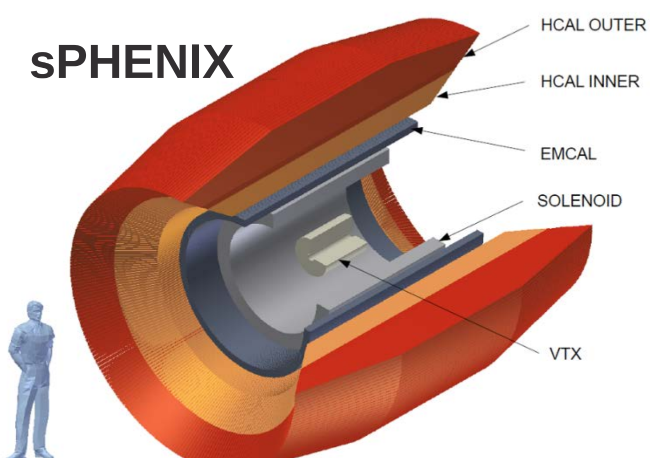


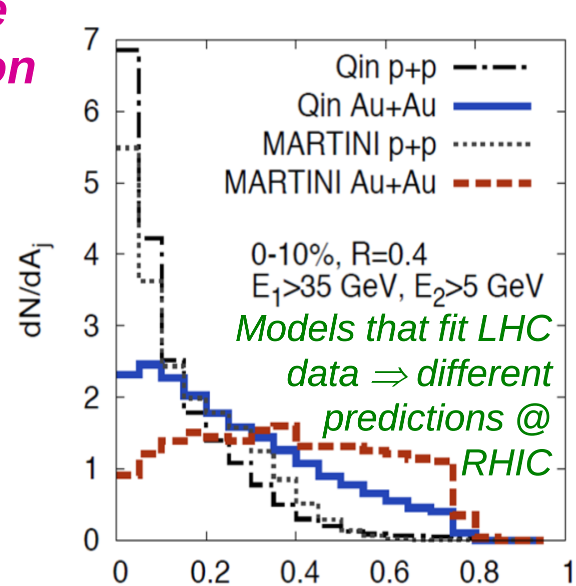


Providing Answers: Emergence of Strong Coupling

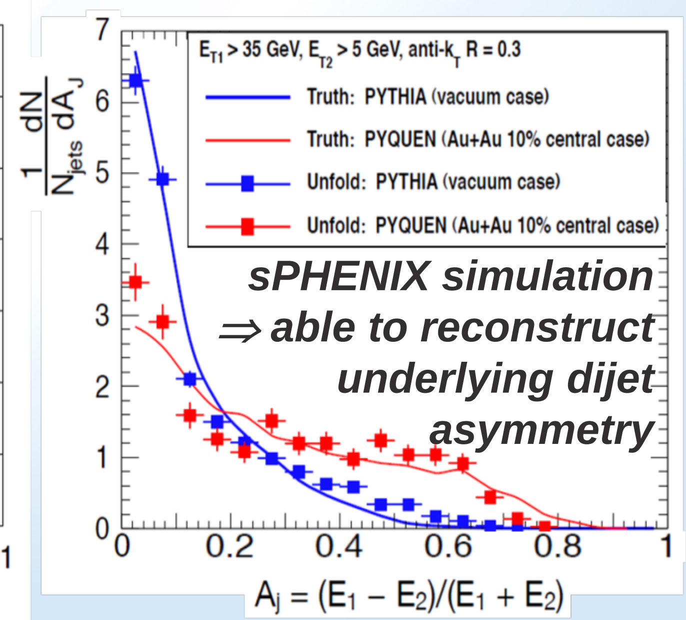


- *Low viscosity, rapid thermalization, strong jet quenching all ⇒ strong coupling (or at least strong correlations)*
- *Parton energy loss characterized by transport coefficient $\hat{q}$, also temperature-dep.*
- *Majumder, Muller & Wang ⇒* $\hat{q} = 1.25T^3/(\eta/s)$ *in weak coupling limit, so independent determination of $\hat{q}(T)$, $\eta/s(T)$ ⇒ eff. coupling*
- *Need measurements of jet, di-jet, γ-jet quenching, plus jet shapes, fragmentation, flow, all at multiple $\sqrt{s}$, to constrain $\hat{q}(T)$ and path-length-dep. of parton E loss*
- *Need sPHENIX upgrade for full jet reconstruction*



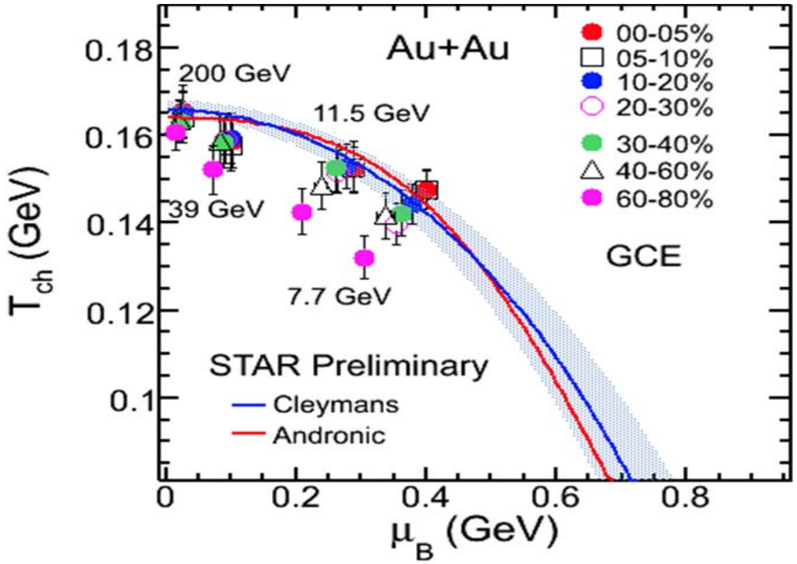


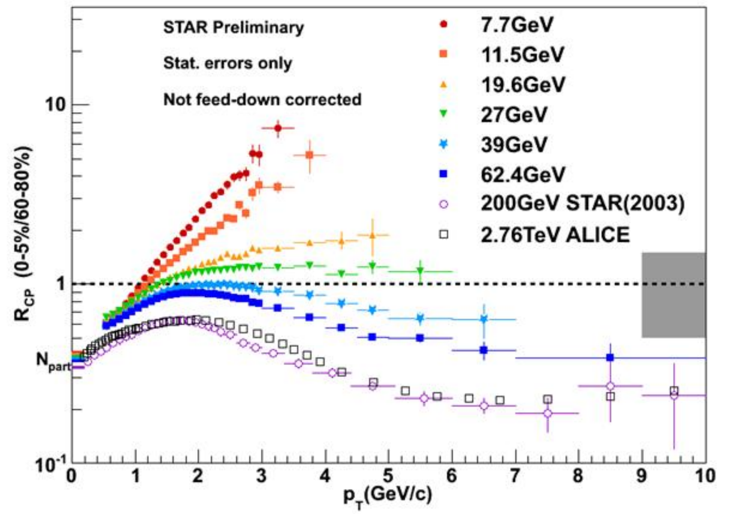
Di-jet energy asym. $A_j = (E_1 - E_2)/(E_1 + E_2)$



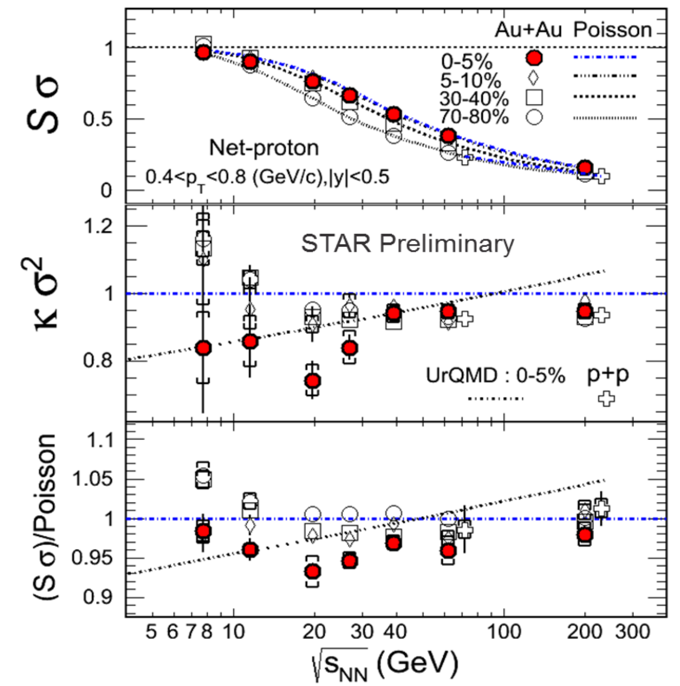
More in Y. Akiba talk

Providing Answers: Onset of Deconfinement





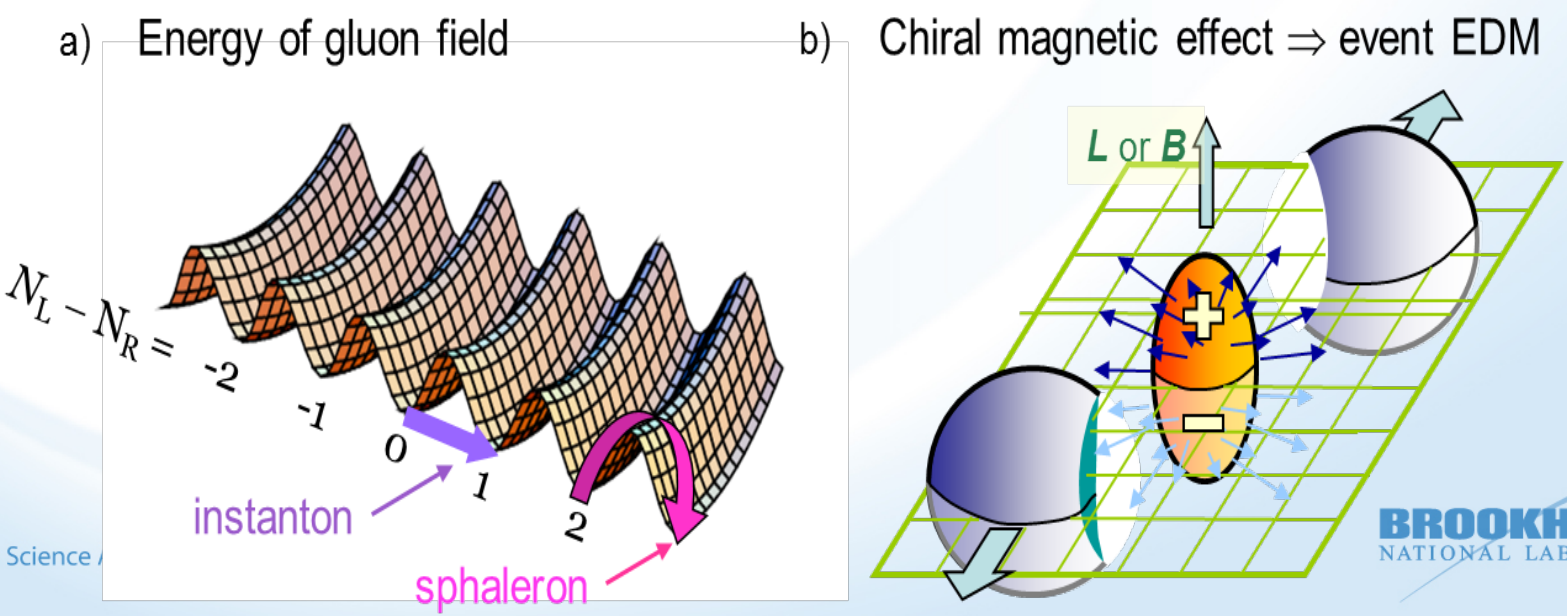
a)



- *Phase 1 beam energy scan ⇒ march outward in phase diagram ⇒ rapid changes below ~27 GeV: hadron suppression → enhancement; strangeness yield drops; n_q scaling breaks down; etc.*
- *Also see non-statistical fluctuations ~20 GeV ⇒ approaching critical point?*
- *Need low-energy e-cooling to improve stat. @ √s < 20 GeV for fluctuations in conserved quantities, particle ID flow, sphaleron-sensitive correlations (next slide), …*

Providing Answers: Sphaleron Effects?

- *Hot (e.g., early universe) matter subject to non-Abelian interactions can exhibit unique and important emergent phenomena associated with transitions among degenerate vacuum states.*
- *Such “sphalerons” at the EW phase transition are speculated to be the origin of the baryon-antibaryon imbalance in the infant universe.*
- *RHIC offers unique opportunity to search for effects of analogous QCD sphalerons, which can $\Rightarrow$ spatially localized regions with chiral imbalance.*
- *Add ultra-strong magnetic field in non-central collisions $\Rightarrow$ observable consequences: e.g., an event-by-event fluctuating electric dipole moment (locally violating P, CP) and electric quadrupole moments in matter that begins with a net non-zero electric charge.*



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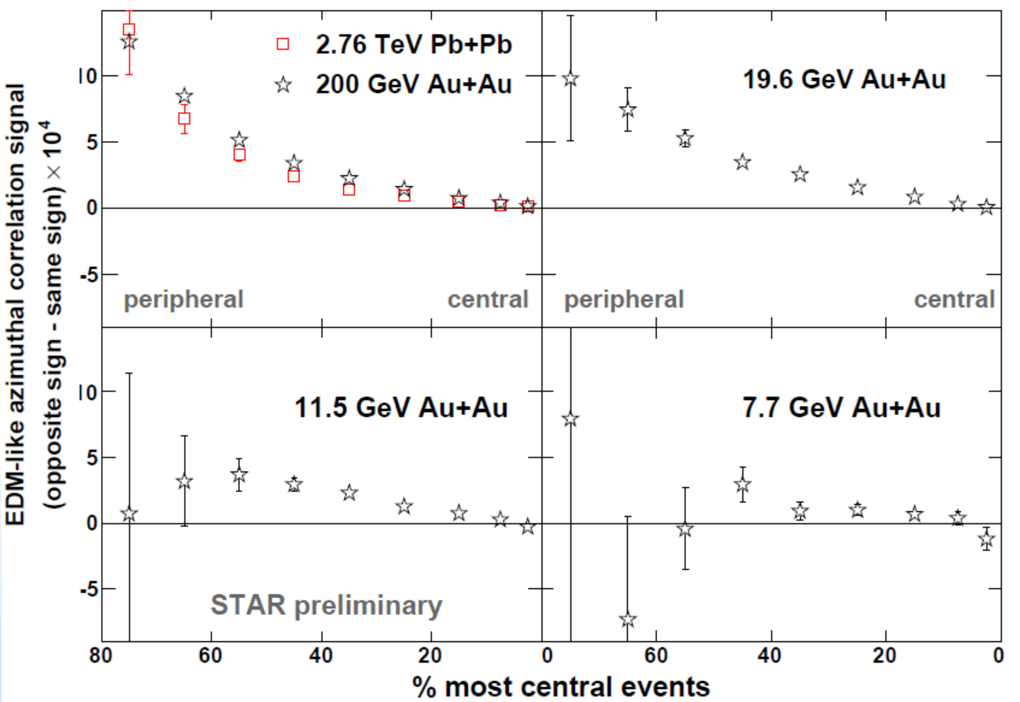
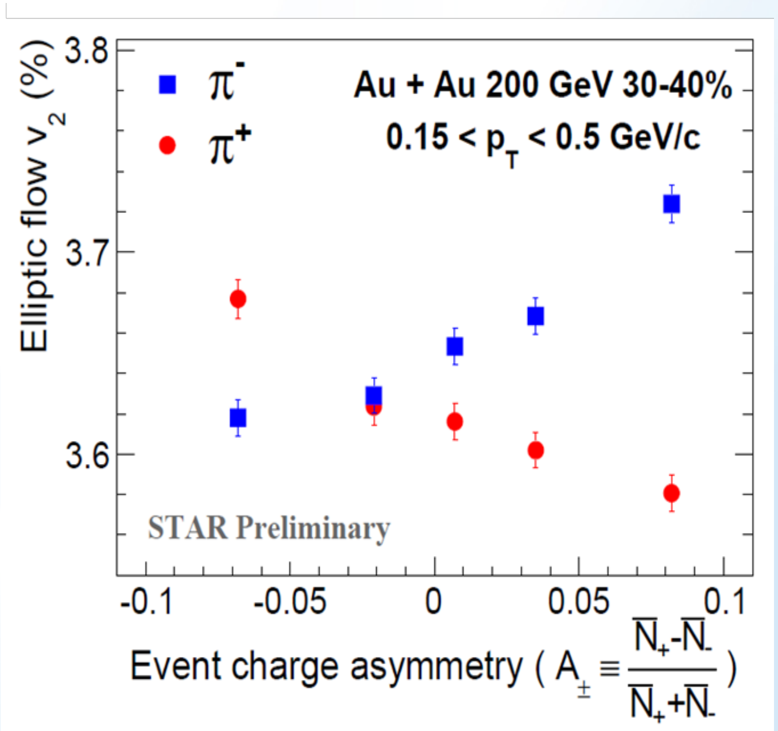
Providing Answers: Sphaleron Effects? (cont.)

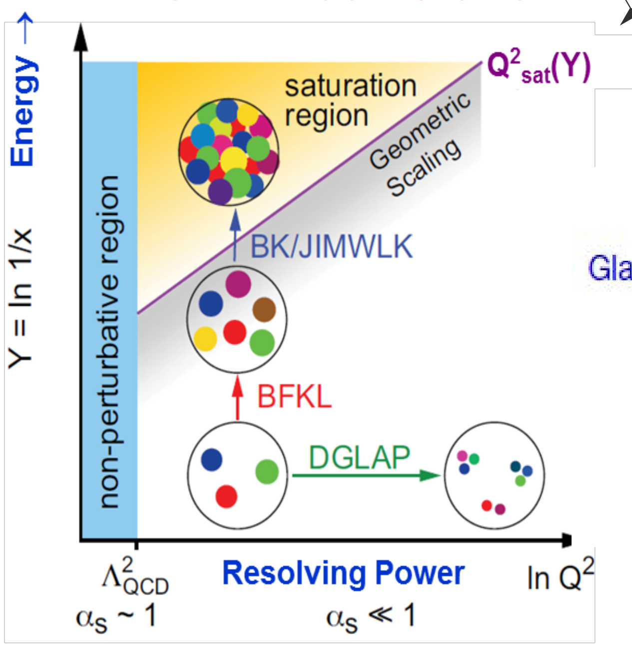
- *Intriguing RHIC data searching for EDM-like correlations and flow differences between pions of different charge when net charge$\neq$0.*
- *Pursue with improved statistics for U+U, highly central and lower-E collisions where signficant flow can cause backgrounds not associated with the magnetic field and sphalerons.*
- *Also search for other related predicted effects of chiral imbalance and QCD triangle anomaly, e.g., a baryon current correlated with EDM current in matter with net baryon density $\neq$0 (requires lower RHIC energies, ~40 GeV).*



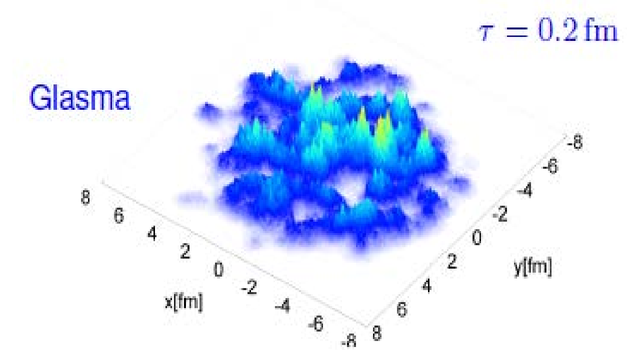


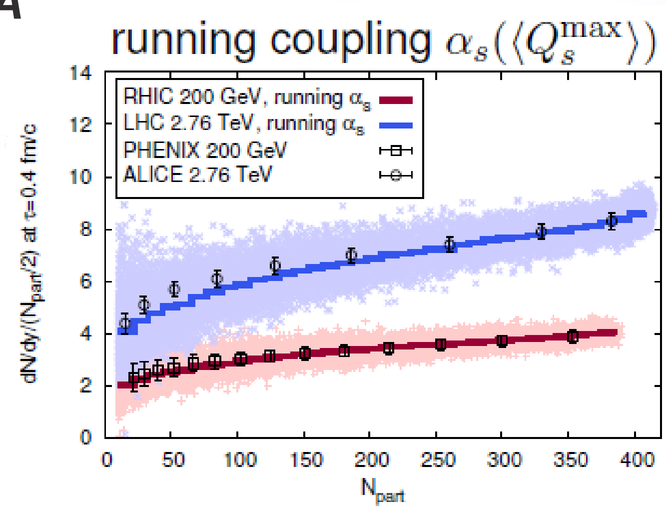
Providing Answers: Gluon Saturation

- *Studying QCD matter in the weak coupling, high density, highly non-linear regime (Color Glass Condensate – CGC) ⇒ entrance channel for RHIC and LHC A+A collisions*

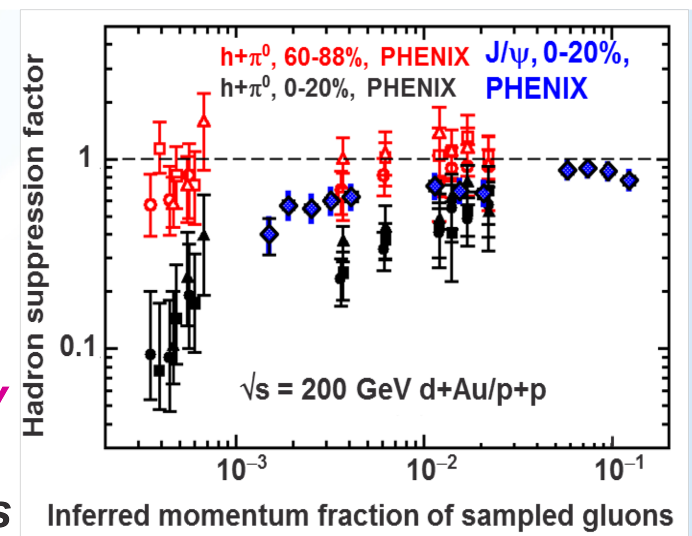


- *CGC + glasma ⇒ remarkably successful 3+1-D hydro account for A+A multiplicities and flow*

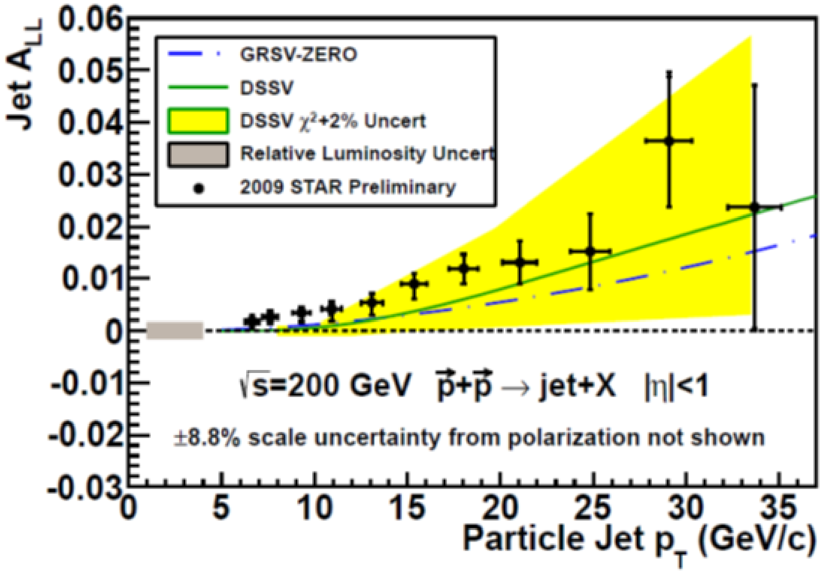




- *Also consistent with observed suppression of forward hadron and di-hadron production in d+Au collisions at RHIC*
- *Next steps: forward $\vec{p}$+A – γ production probes gluon densities at low x; transverse spin asyms. for h prod'n in $\vec{p}$+A/$\vec{p}$+p probes sat'n scale directly*
- *Need forward det. upgrades and realizable path to EIC – program unifies all RHIC program aspects*

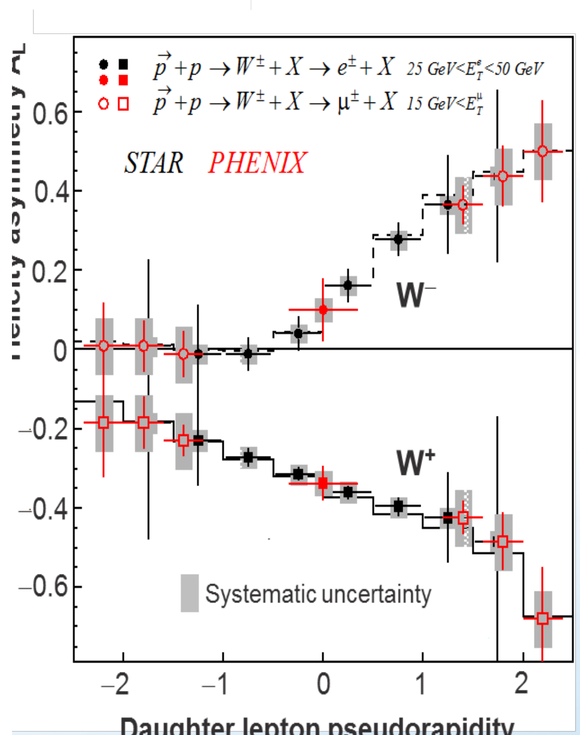


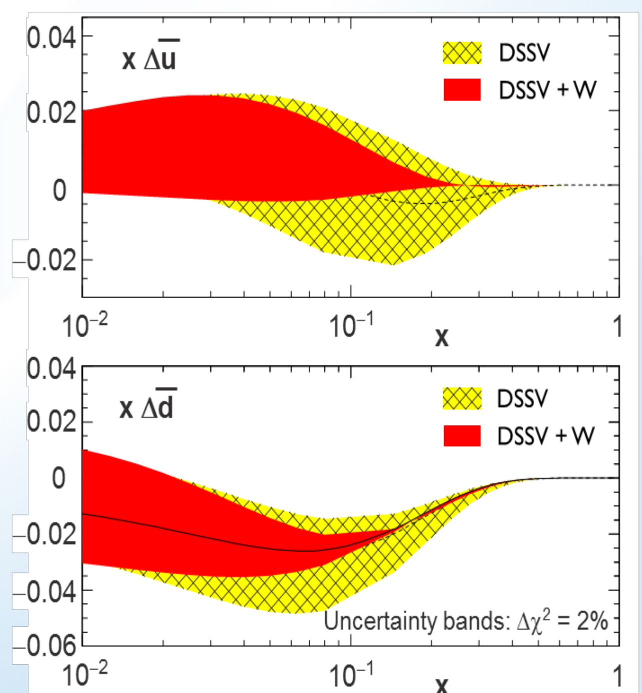
Providing Answers: Missing Proton Spin



- *Latest RHIC $\vec{p}+\vec{p}$ spin results ⇒ gluon helicity preferences over $0.05 < x_g < 0.2$ contribute ~ 20% to overall proton spin*
- *Gluons contribute comparably to quarks!*
- *Further measurements @ $\sqrt{s}$ = 500 GeV and for di-jets will extend x-range downward and provide info on x-dependence*
- *Access to abundant softer gluons and sensitivity to orbital contrib'ns needs EIC*

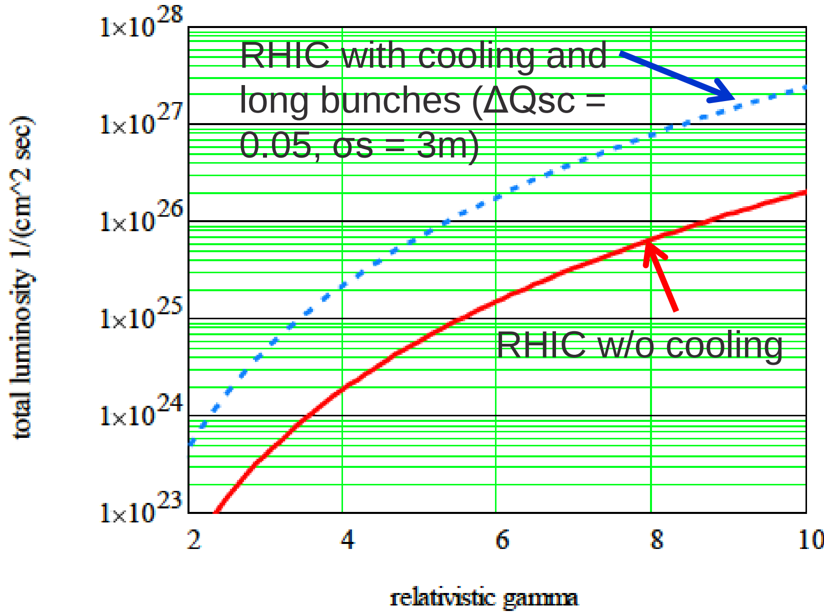
- *500 GeV $\vec{p}+\vec{p}$ luminosity and polarization now sufficient for vigorous pursuit of $W^{\pm}$ production asymmetries ⇒ constraints on $\bar{u}$ vs. $\bar{d}$ sea-quark polarization*
- *Forward upgrades will facilitate transverse spin asyms. for Drell-Yan di-leptons ⇒ test QCD color ISI vs. FSI in SIDIS*





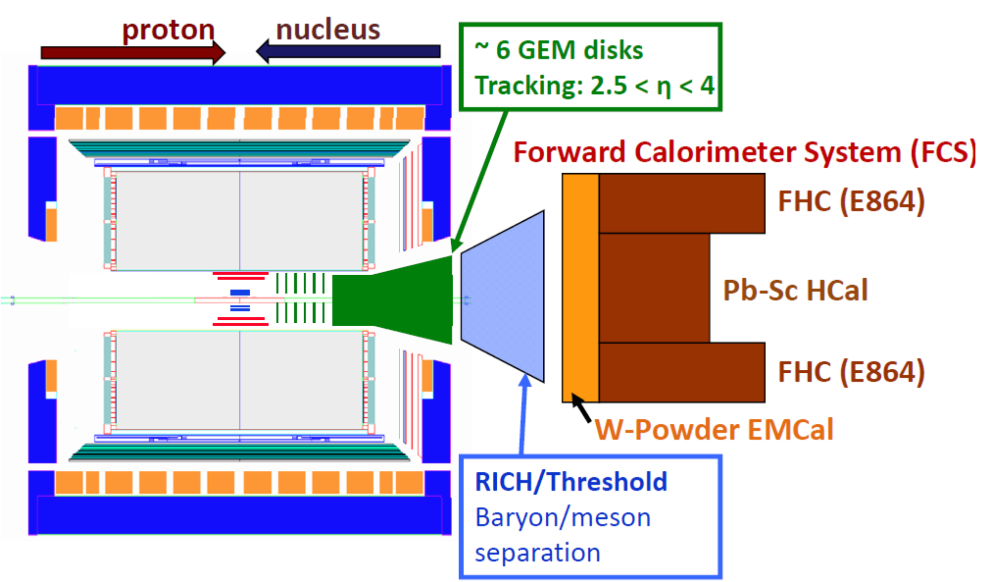
Contemplated Future Upgrades

Will likely use high brightness SRF electron gun for bunched beam electron cooling; up to ~10x L; ready after 2017 [Fermilab Pelletron (cooled 8 GeV pbar for Tevatron use) is alternative option]



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

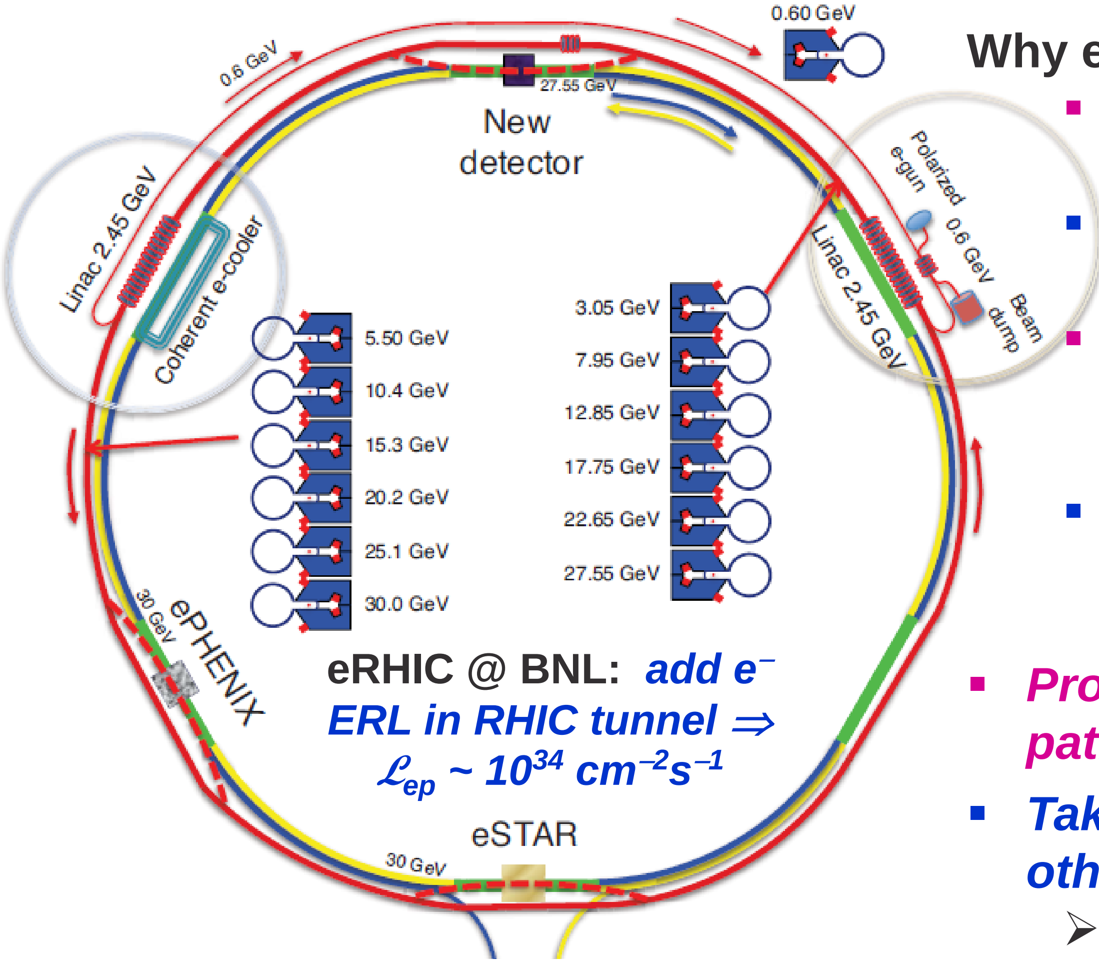
- *Low-E electron cooling for further pursuit of onset of deconfinement/CP*
- *sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC*
- *STAR forward upgrade for p+A and transverse spin (e.g., DY) physics*
- *PHENIX MPC-EX, STAR TPC pad rows*



Timeline for RHIC's Next Decade

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 500 GeV $\vec{p}+\vec{p}$ • 15 GeV Au+Au	• Sea antiquark and gluon polarization • QCD critical point search	• Electron lenses • upgraded pol'd source • STAR HFT
2014	• 200 GeV Au+Au and baseline data via 200 GeV p+p (needed for new det. subsystems)	• Heavy flavor flow, energy loss, thermalization, etc. • quarkonium studies	• 56 MHz SRF • full HFT • STAR Muon Telescope Detector • PHENIX Muon Piston Calorimeter Extension (MPC-EX)
2015-2017	• High stat. Au+Au at 200 and ~40 GeV • U+U/Cu+Au at 1-2 energies • 200 GeV p+A • 500 GeV $\vec{p}+\vec{p}$	• Extract $\eta/s(T_{min})$ + constrain initial quantum fluctuations • further heavy flavor studies • sphaleron tests @ $\mu_B \neq 0$ • gluon densities & saturation • finish p+p W prod'n	• Coherent Electron Cooling (CeC) test • Low-energy electron cooling • STAR inner TPC pad row upgrade
2018-2021	• 5-20 GeV Au+Au (E scan phase 2) • long 200 GeV + 1-2 lower $\sqrt{s}$ Au+Au w/ upgraded dets. • baseline data @ 200 GeV and lower $\sqrt{s}$ • 500 GeV $\vec{p}+\vec{p}$ • 200 GeV $\vec{p}+A$	• x10 sens. increase to QCD critical point and deconfinement onset • jet, di-jet, γ-jet quenching probes of E-loss mechanism • color screening for different $q\bar{q}$ states • transverse spin asyms. Drell-Yan & gluon saturation	• sPHENIX • forward physics upgrades

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



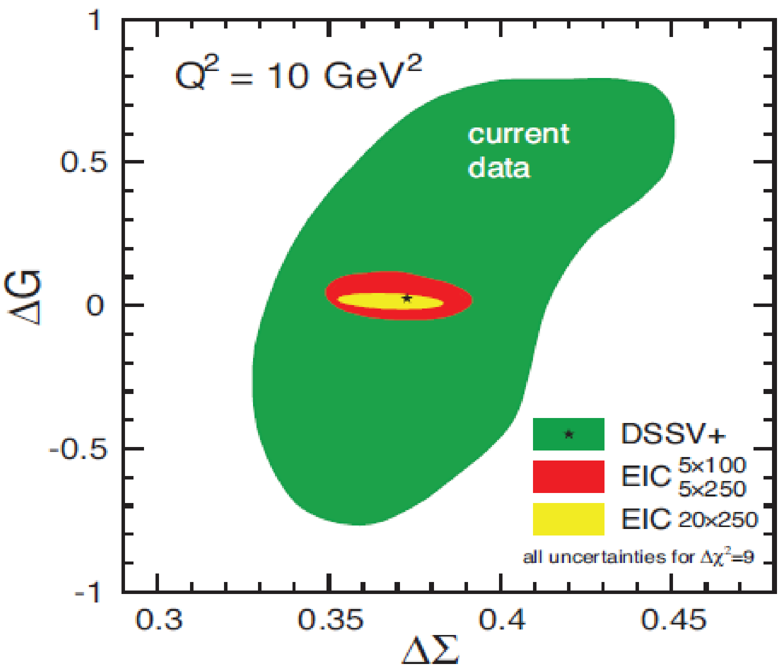
eRHIC @ BNL: *add e⁻ ERL in RHIC tunnel ⇒ $\mathcal{L}_{ep} \sim 10^{34}\ cm^{-2}s^{-1}$*

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:

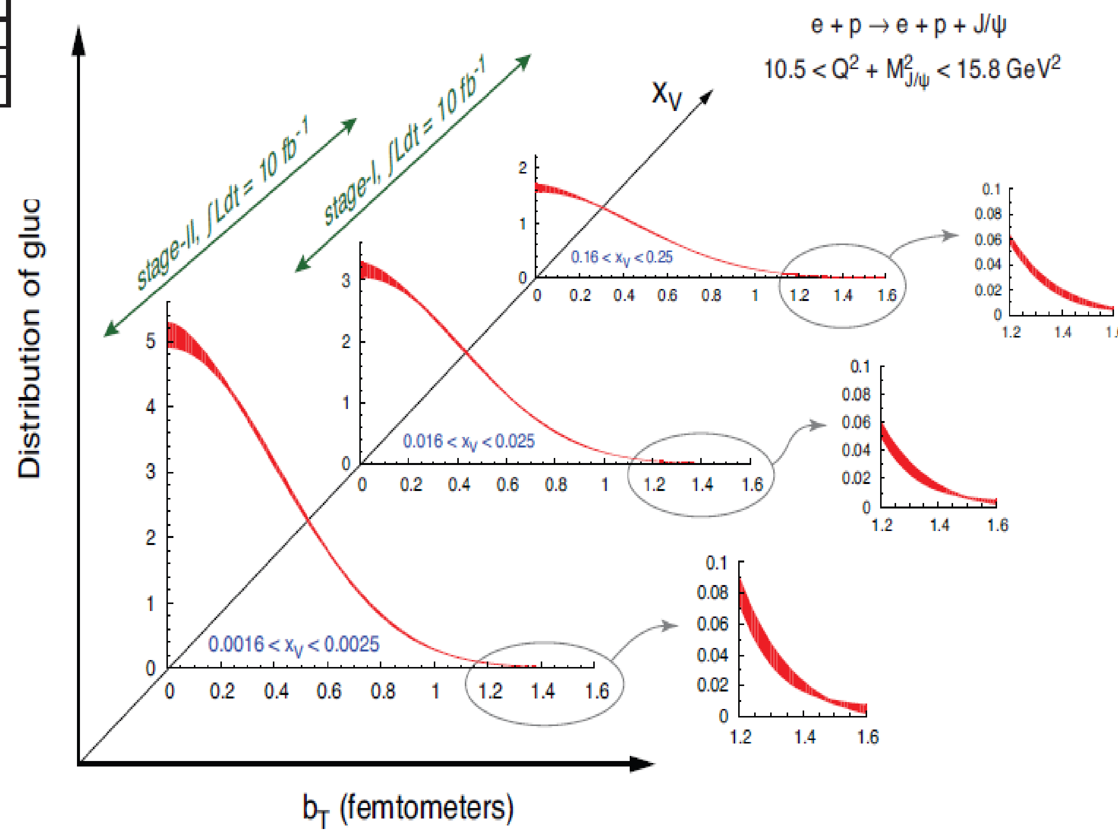
- *Reuses RHIC tunnel & detector halls ⇒ minimal civil construct'n*
- *Reuses significant fractions of STAR & PHENIX detectors*
- *Exploits existing HI beams for precocious access to very high gluon density regime*
- *Polarized p beam and HI beam capabilities already exist – saves ~$2B RHIC replacement cost*
- *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*

How eRHIC Complements RHIC: Spin & Imaging

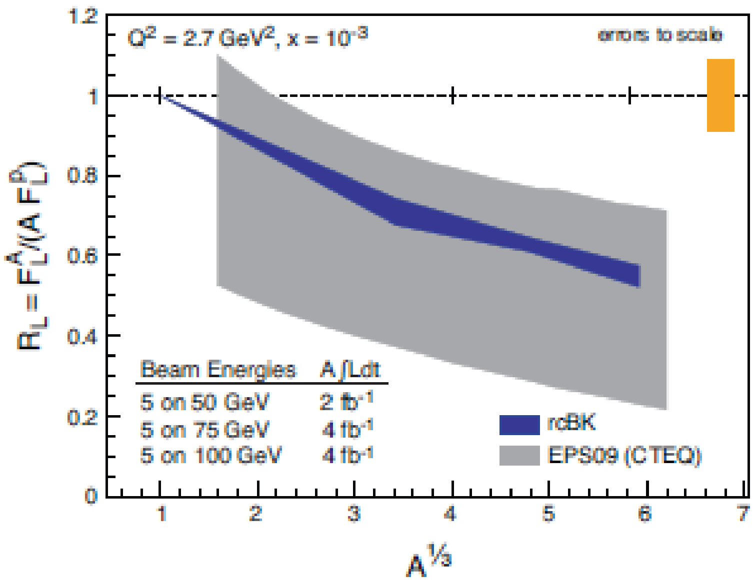


- *e+p DIS @ $\sqrt{s}$ > 50 GeV ⇒ access to softer gluons, much tighter constraints on total gluon and quark contributions to p spin*
- *Charged-current DIS ⇒ new electroweak structure functions that further constrain flavor-dependence of sea quark polariz'ns*

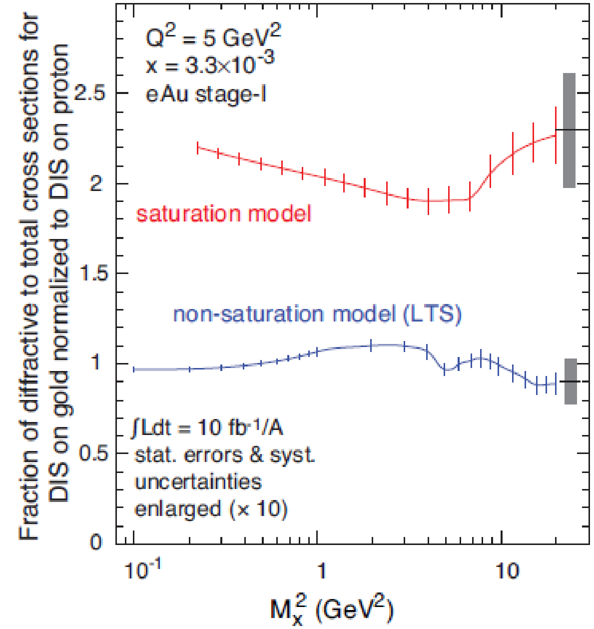
- *Semi-inclusive DIS and deep exclusive reactions take us from 1D (vs. x_{Bj}) to 3D (add transverse space or momentum dim'ns) imaging of nucleon*
- *E.g., exclusive J/ψ prod'n ⇒ unprecedented info on transverse spatial distrib'n of gluons as fcn. of x*



How eRHIC Complements RHIC: Initial State

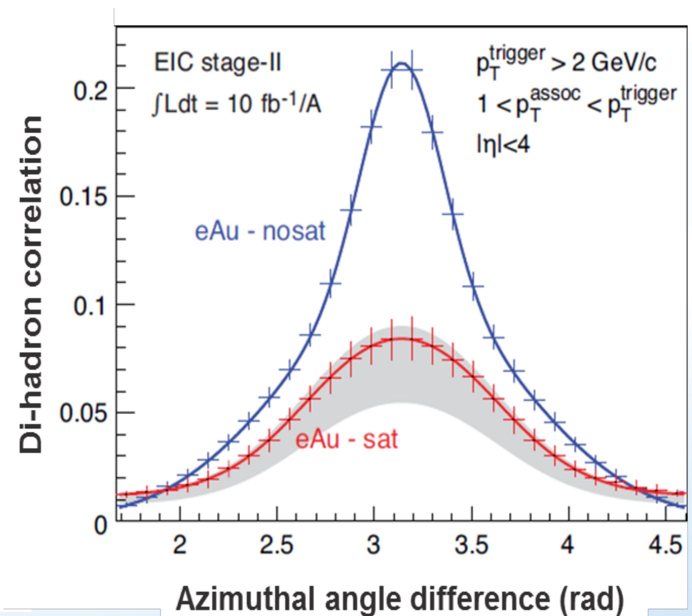


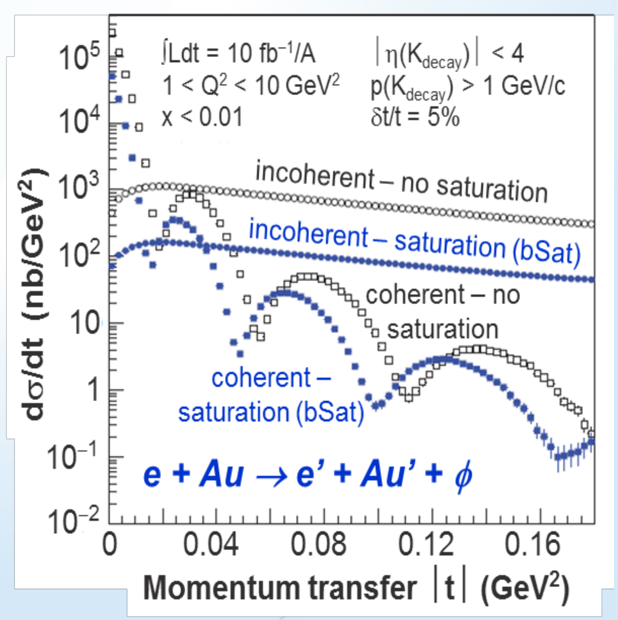
- *Coherent contrib'ns from many nucleons in heavy nucleus ⇒ precocious access to saturation regime*
- *e+A DIS measures low-x gluon density far more precisely than they are known*



- ***Inclusive diffractive cross sections greatly enhanced by saturation***

- *Exclusive diffractive prod'n of vector mesons of size > $1/Q_{sat}$ ⇒ "gluonic form factor" of nuclei*
- *Di-jet and di-hadron coinc. yields suppressed in e+A*

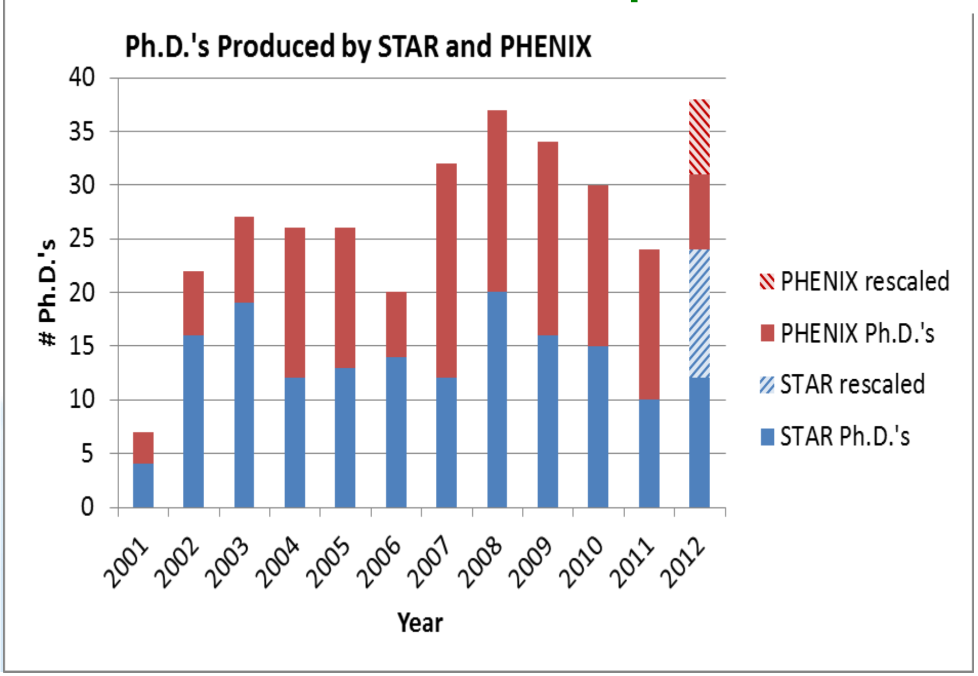


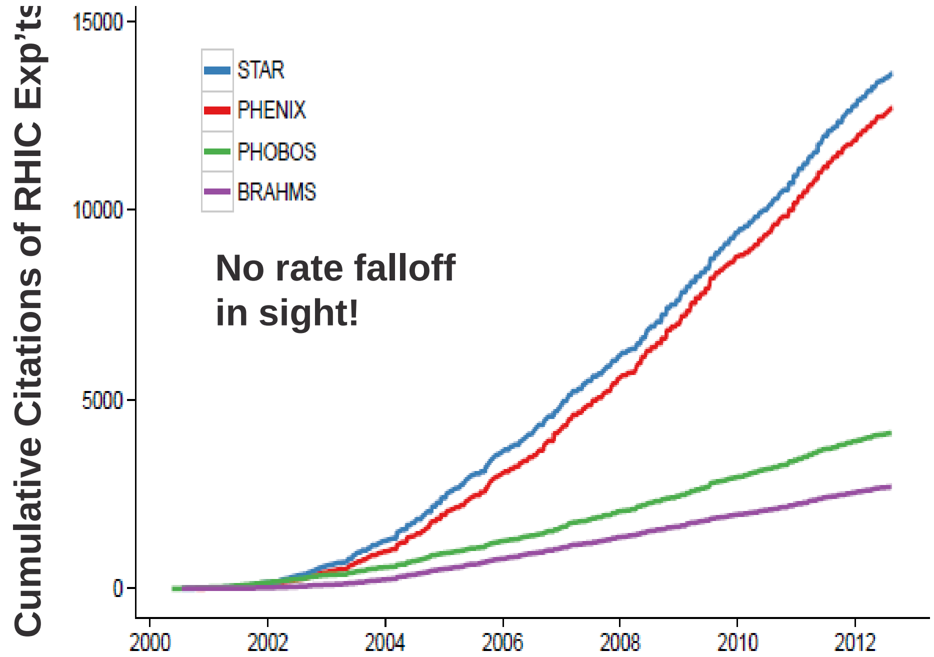


RHIC's Most Important Products: Productivity, Impact, Education

Collaboration	Total # Refereed Papers	Total # Citations for Refereed Papers	# PRL's	# Citations for 2005 White Paper	Position of 2005 White Paper Among Most Cited NP Papers 2001-12	# Papers with >250 Citations
PHENIX	126	13,292	57	1358	5	12
STAR	160	14,434	54	1382	4	15
PHOBOS[a)]	39	4057	15	1049	7	1
BRAHMS[b)]	22	2649	10	1040	8	3
Total =	**347**	**34,432**	**136**	**4829**		**31**

Also, >40% of all-time top-cited Nuclear Theory arXiv papers are RHIC-related!





Plus >150 tenured faculty positions worldwide + 5 cover story articles +…

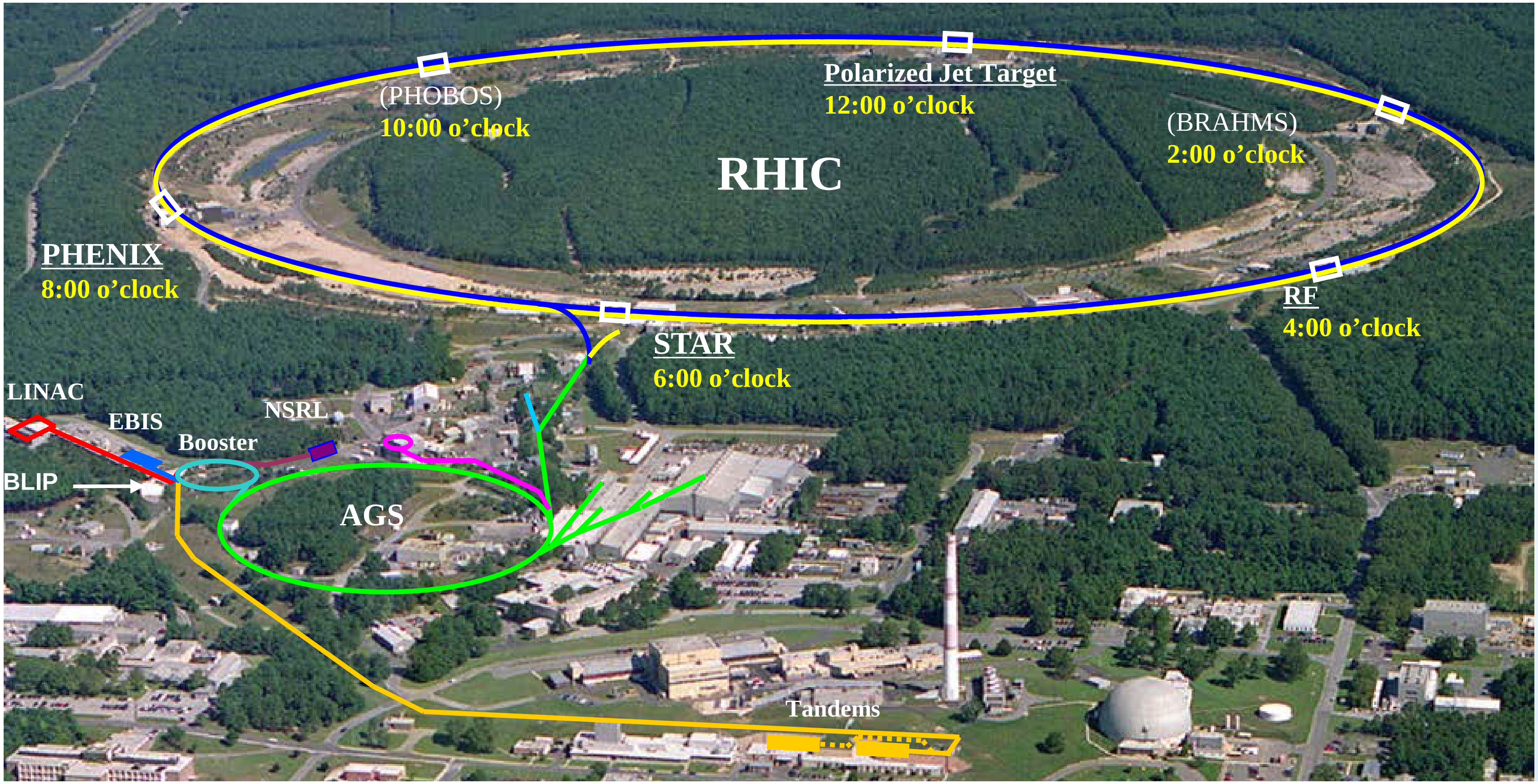
Summary

1) RHIC's first 12 years have been marked by:
   - Important discoveries in QCD matter
   - High productivity
   - High scientific impact $\Rightarrow$ increased visibility for U.S. NP
   - Great technical versatility and breakthroughs
   - Cost-effective upgrades to facility performance & versatility

2) RHIC's next decade is required to:
   - Quantify transport properties of the Quark-Gluon Plasma
   - Pursue discovery potential unveiled by results to date
   - Combine with LHC heavy ion program to span suitably wide initial temperature range to accomplish the above
   - Reap science payoff from just completed and ongoing RHIC facility upgrades
   - Pursue the unique accelerator science and spin physics opportunities that come with only operating U.S. collider and only worldwide polarized collider
   - Provide a cost-realizable path to an Electron Ion Collider

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, >30K citations, >300 Ph. D.'s in 1st 12 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