Once and Future RHIC Science: Profound Issues, Addressed and Open

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RHIC/AGS Users Meeting

May 28, 2008

What is past is prologue
--W. Shakespeare

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
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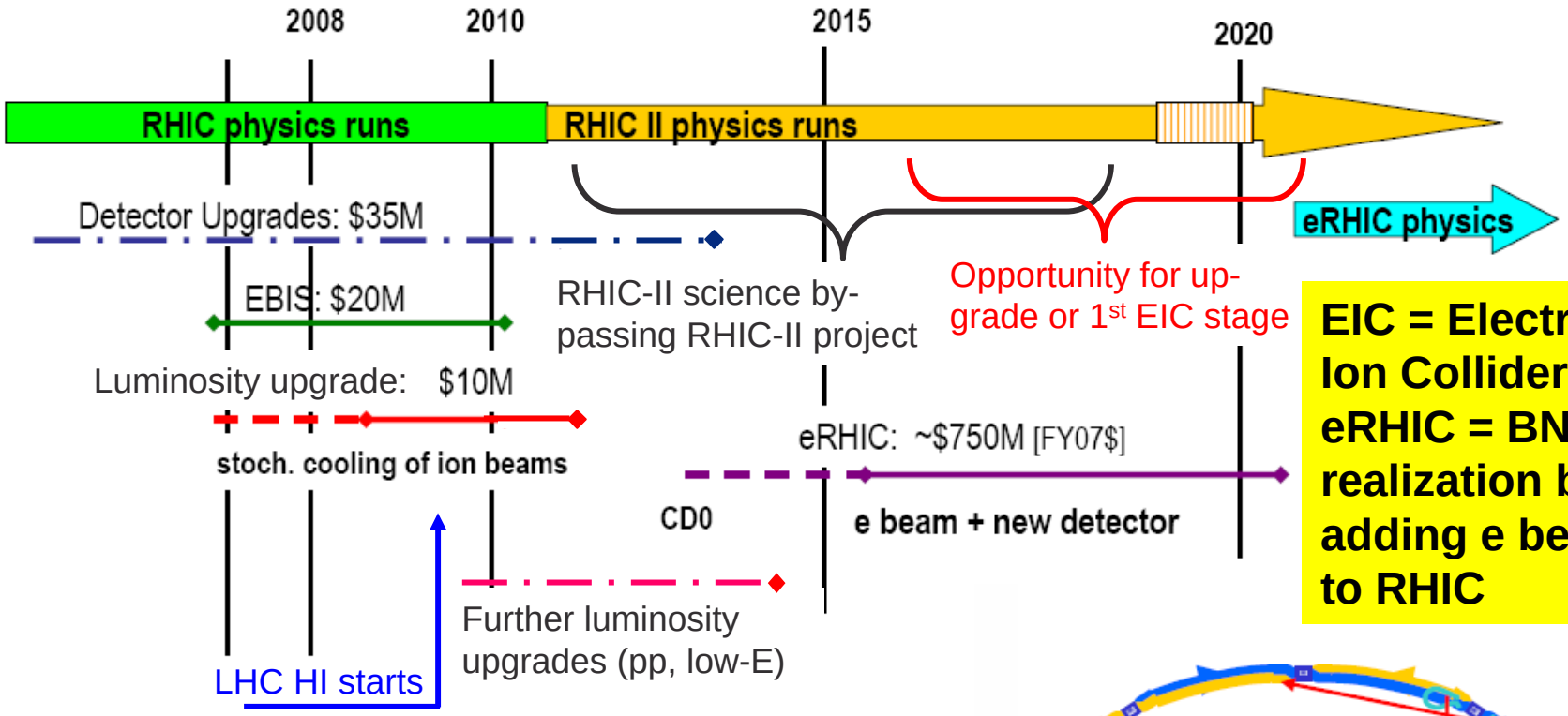
A Long Term (Evolving) Strategic View for RHIC

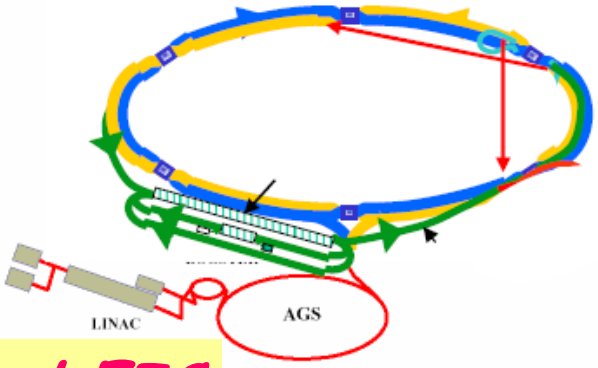


EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC

Legend:

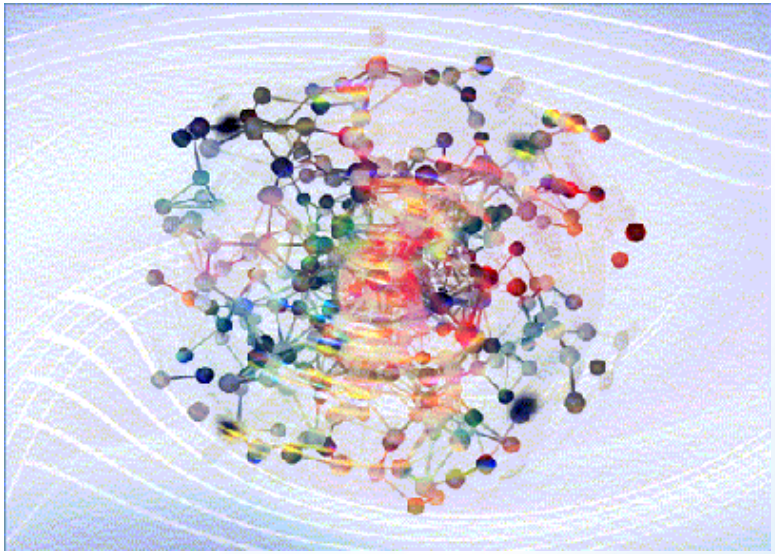
- *R&D*
- *Construction*
- *Multiple small projects*

CD0: DOE Critical Decision, mission need



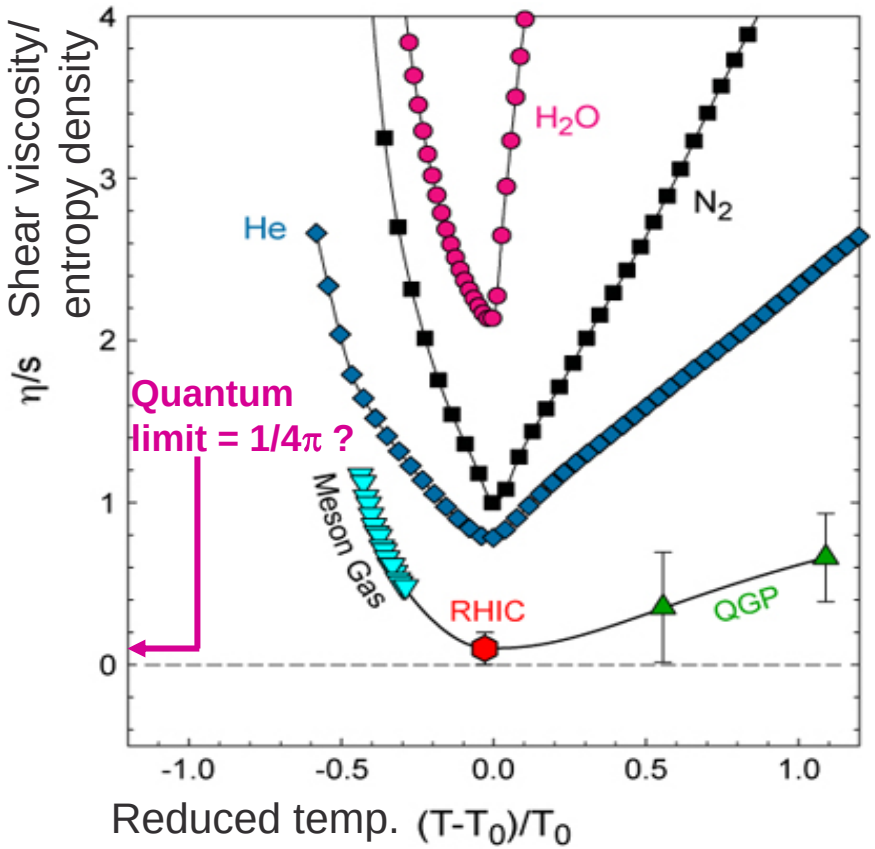
RHIC, RHIC-II, LHC-HI and EIC science share a common theme…

RHIC Science: Condensed Matter Physics with a Force of a Different Color



What are the unique quantum many-body manifestations of a *non-Abelian* gauge theory and self-interacting force carriers? Are there lessons for other fundamental theories, that are more difficult to subject to laboratory investigation? How do we pump/probe fleeting partonic matter in 10^{-23} s?

Studying New Matter…



The matter produced in near-central ion-ion collisions at RHIC flows as a more nearly perfect (very low shear viscosity) liquid than any previously known.

∴ RHIC probes matter in the very strong coupling limit of QCD: LQCD ⇒ quantitative theory for static properties; AdS/CFT ⇒ qualitative insight + gravity connection.

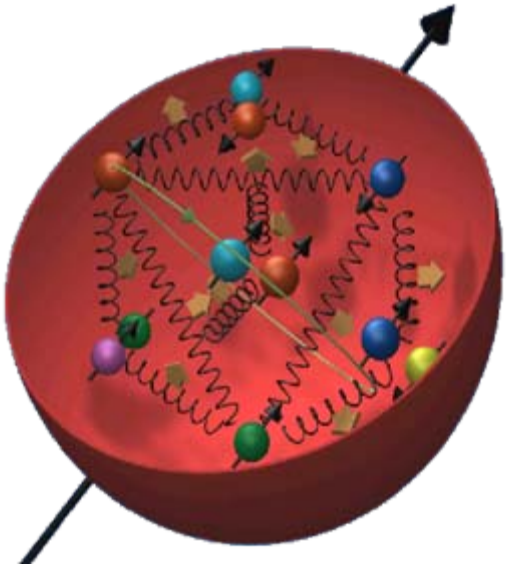
Questions for the (near) future: how close is shear viscosity/entropy density ratio to conjectured quantum lower limit? What happens to bulk viscosity? How does viscosity evolve with temperature? How do its other quantitative properties inform theoretical approaches to QCD matter?

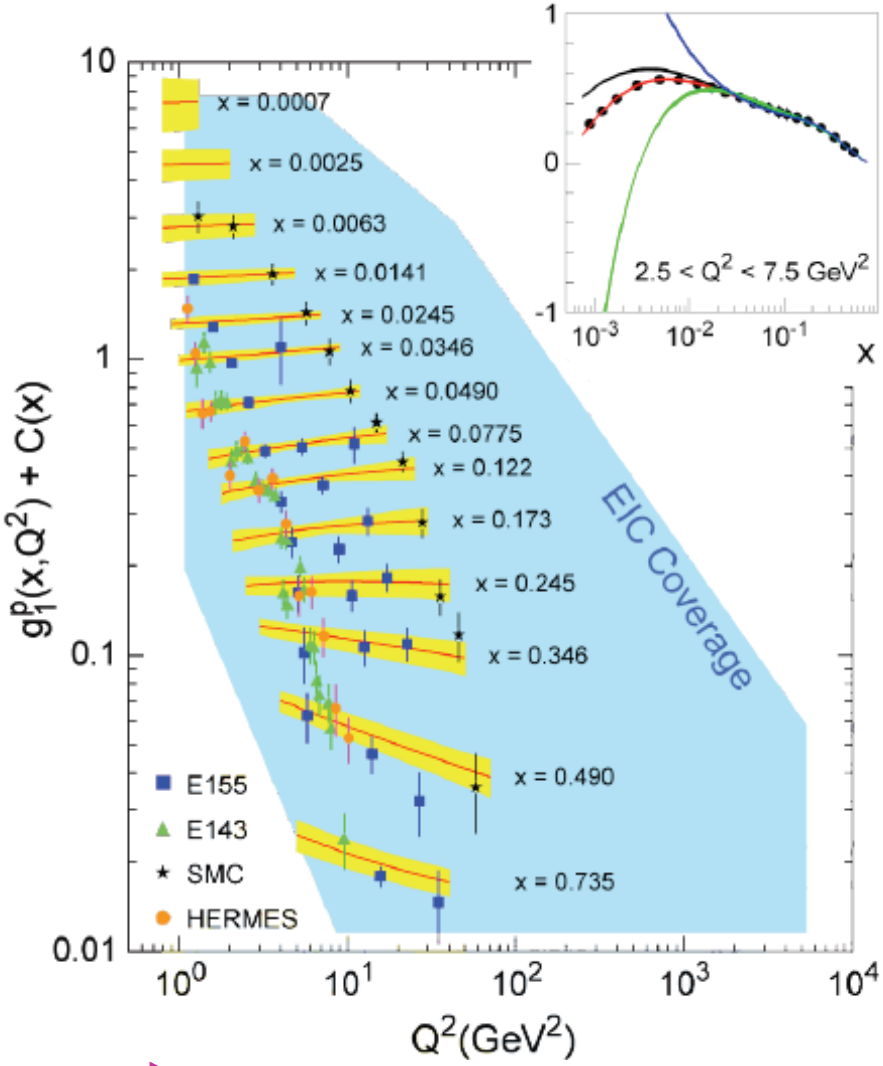
Needs RHIC-II luminosities & upgrades

Old Matter…

$\vec{p}$-$\vec{p}$ at RHIC addresses:

1) What does the share of $\vec{p}$ spin carried by gluons and sea quarks/ antiquarks reveal about effective degrees of freedom?

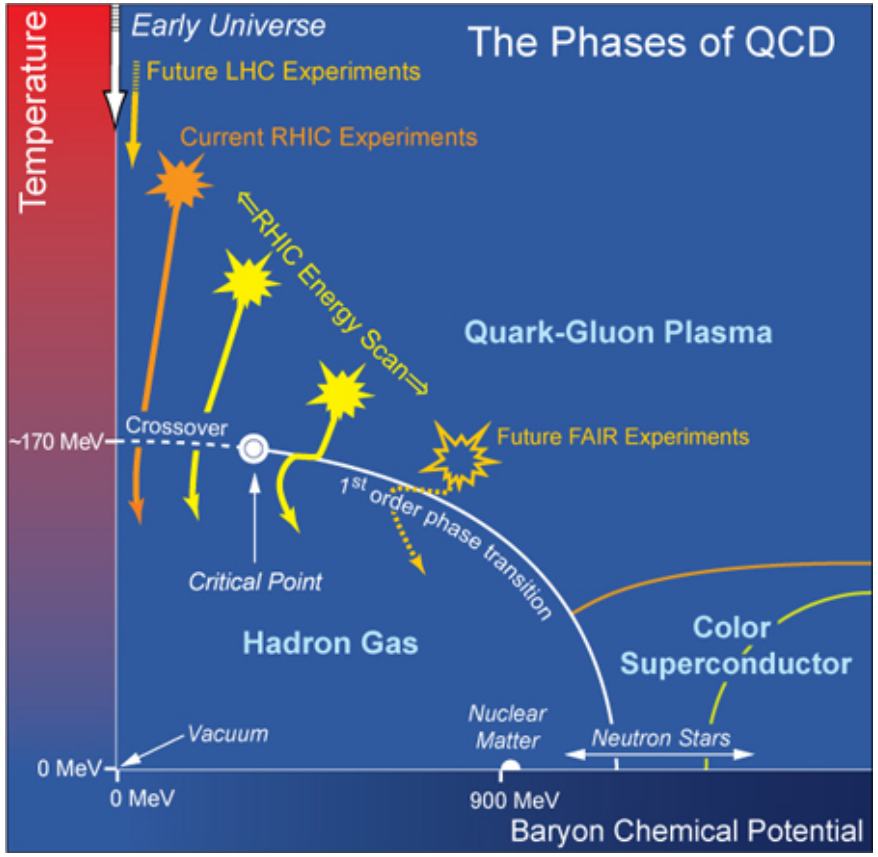




2) How is parton orbital motion inside $\vec{p}$ manifested in transverse spin asymmetries?

$\vec{e}$-$\vec{N}$ at EIC would exploit scaling violations & exclusive reactions to extend study to completely gluon-dominated region at low momentum fraction.

Hot Matter…



Is there a high-temperature critical point in the phase diagram of QCD matter?

Can we develop robust correlated experimental signatures to reveal its location in an energy scan at RHIC? (Learn from traditional CM physicists!)

Can the measurements help to guide development of approximate solutions of lattice QCD for net quark density $\neq 0$?

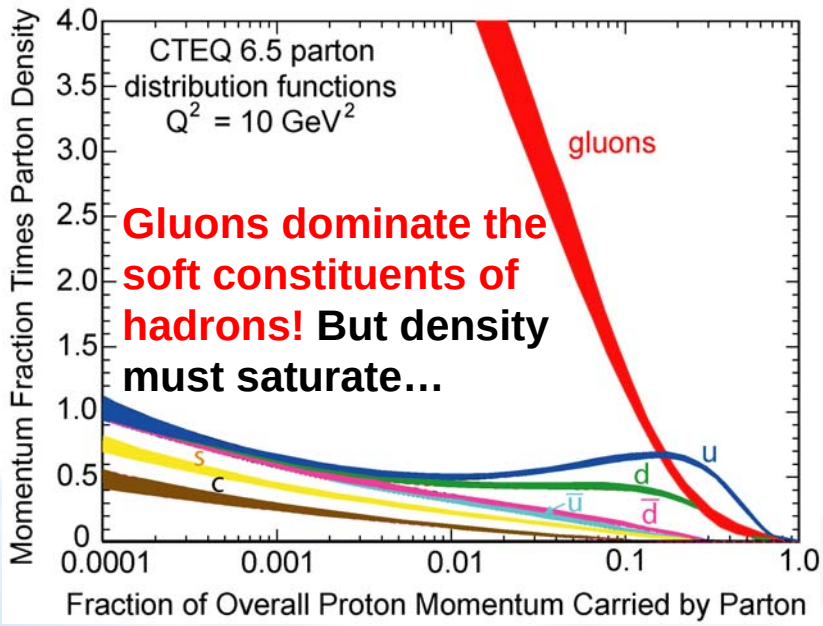
The flexibility and focus of RHIC are essential to carry out these systematic studies and exploit their discovery potential. Energy scan to begin in earnest ~2011.

Cold Matter

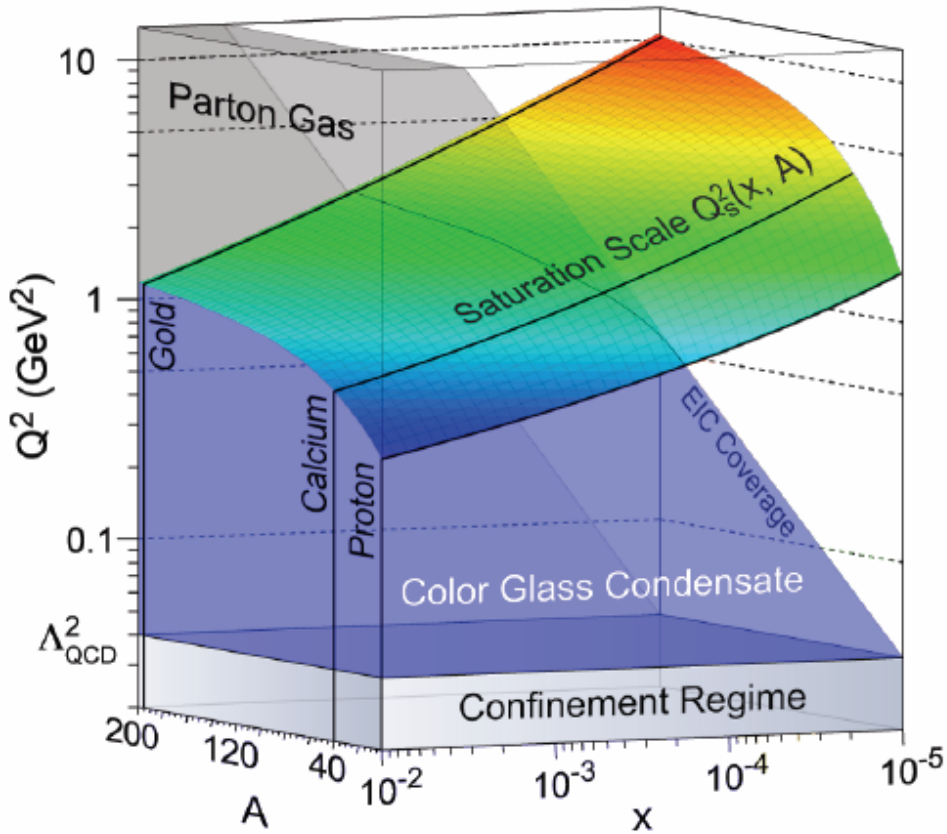
Search for supersymmetry @ LHC, ILC (?): ***seeking to unify matter and forces***

Electron-Ion Collider: ***reveal that Nature blurs the distinction***

Deep inelastic scattering @ HERA ⇒



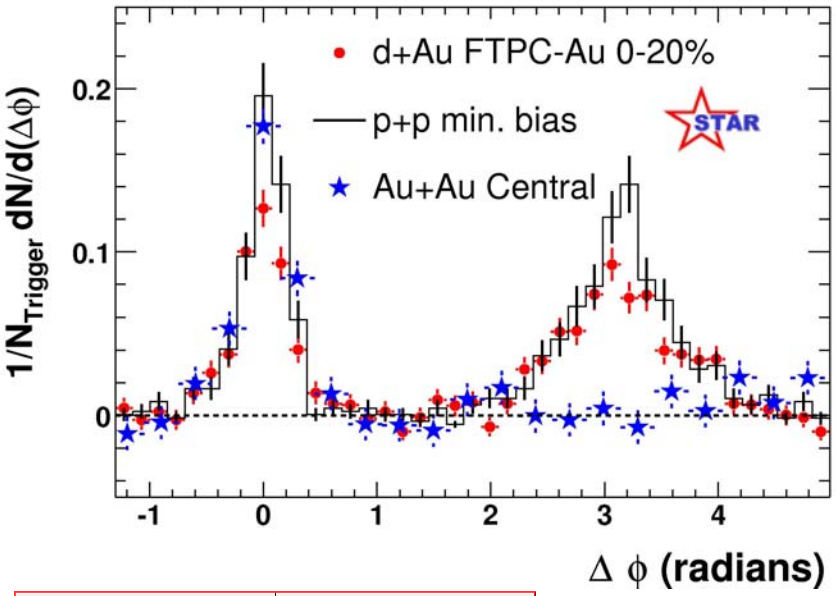
Gluons dominate the soft constituents of hadrons! But density must saturate…



EIC probes *weak* coupling regime of very high gluon density, where gauge boson occupancy >> 1. *All ordinary matter has at its heart an intense, semi-classical force field* -- can we demonstrate its universal behavior?

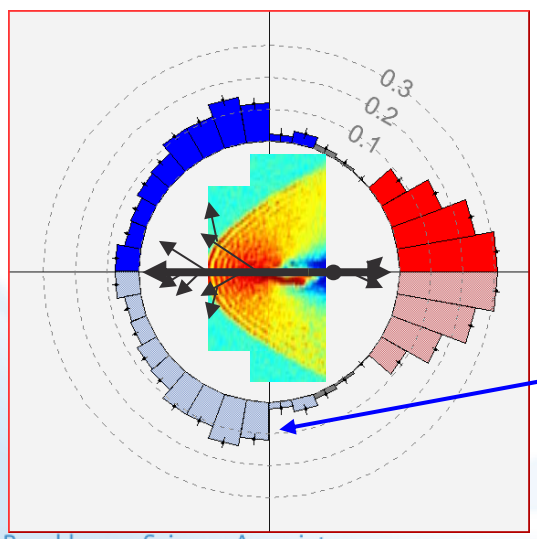
Meeting Fundamental Experimental Challenges…

How do we pump/probe partonic matter in 10^{-23} s?

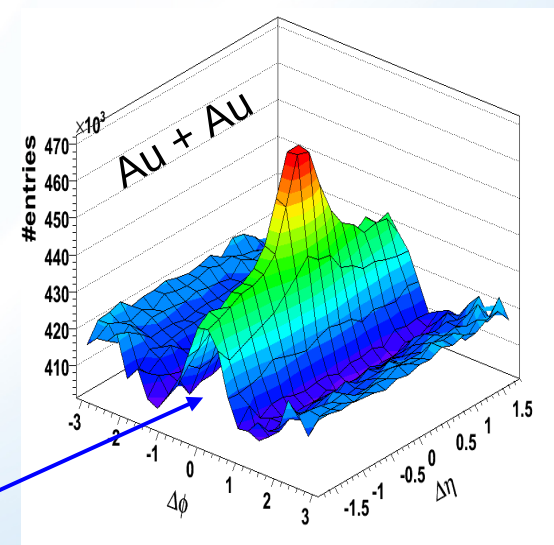


E.g., jets from hard-scattered partons ⇒

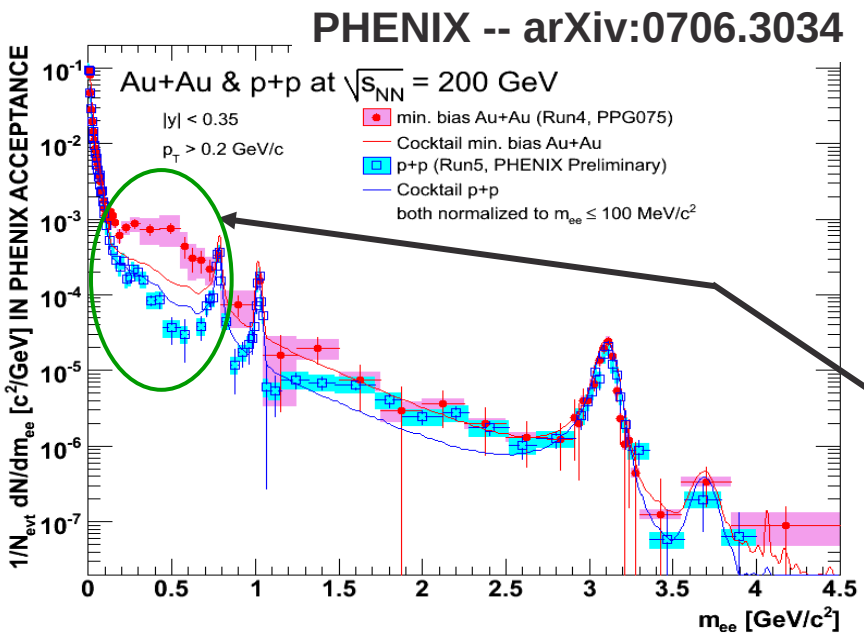
The medium modifies the jets -- e.g., disappearance of some hard fragments on away-side. We learn about QCD interactions and color charge density in the medium.



We measure the medium's collective response to the jet stimulus -- e.g., softer fragments emitted along Mach-like cone on away side (speed of sound?) + "dragged" longitudinally on near side.



Can We Develop Robust Experimental Signatures for Transformation of the Vacuum ?

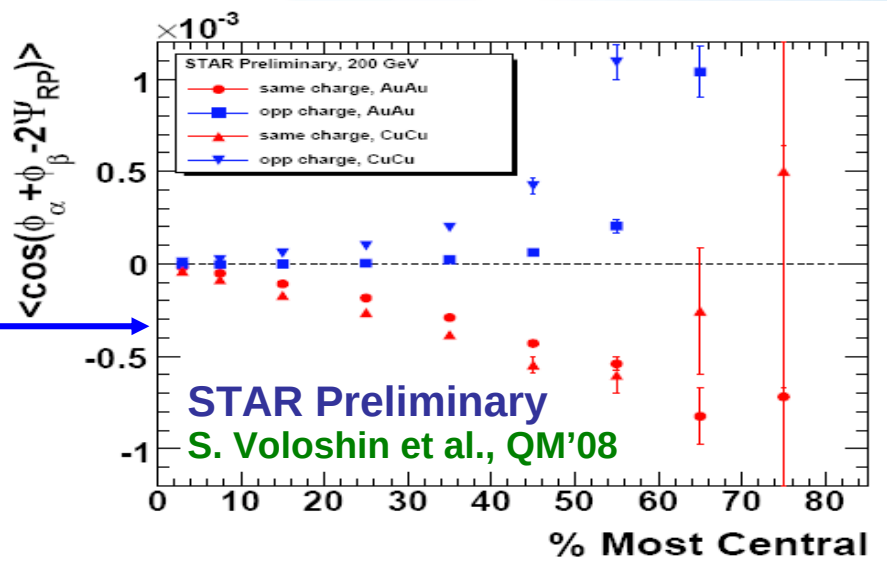


The nature of the QCD vacuum itself can be altered at high temp.

Restoration of chiral symmetry -- spontaneously broken at low temp. -- is predicted.

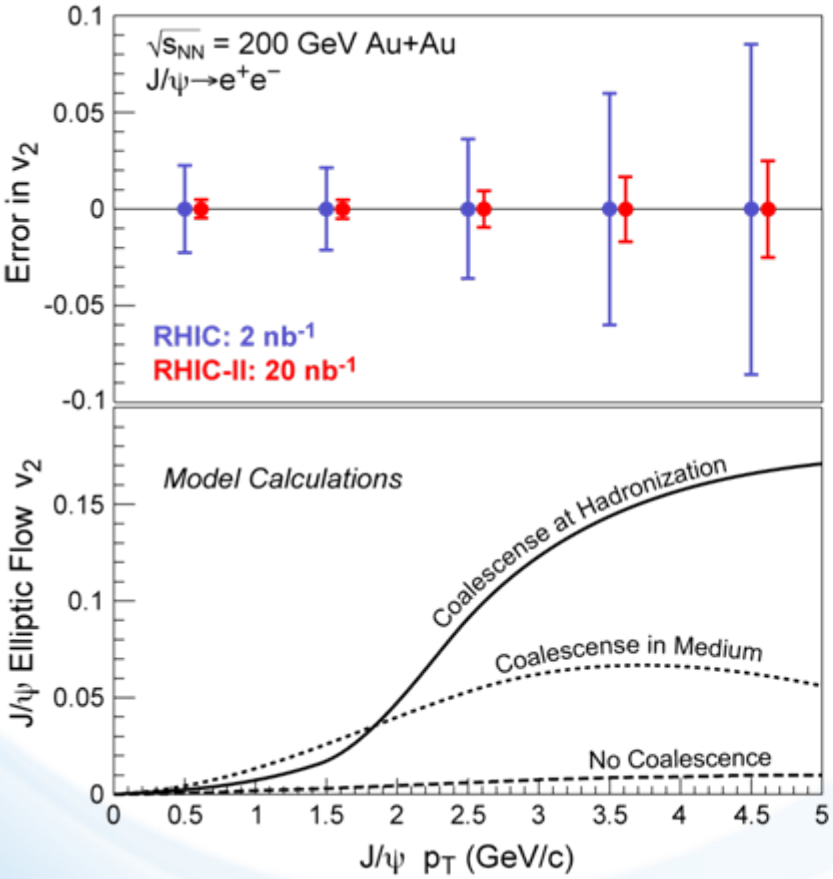
Does low-mass dilepton surplus seen by PHENIX (and at SPS) signal chiral restoration via modified ρ - response?

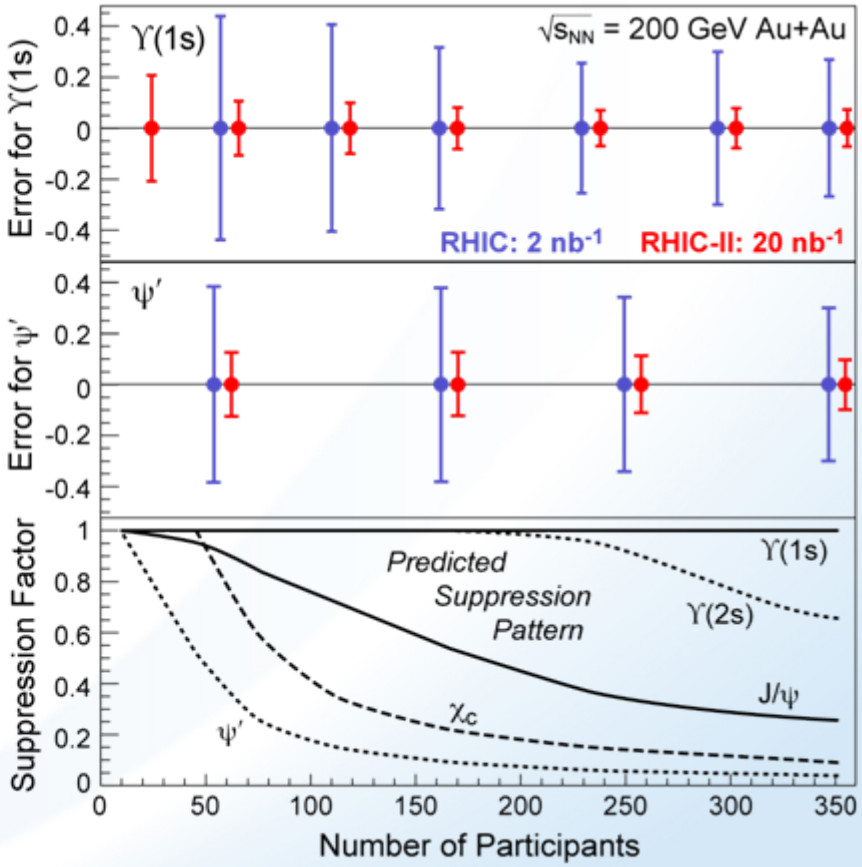
CP-symmetry, conserved at low temp., may be spontaneously broken at high-temp. Are there correlated CP-even signals (e.g., EDM-like charge correlations $\perp$ reaction plane) for CP violation that changes sign from event to event?



Can We Probe the Quark-Quark Interaction in the Medium?

Enhanced luminosity + detector upgrades enable rare probe studies of yield and flow of quarkonia ($q\bar{q}$ systems), sensitive to color screening and parton equilibration/coalescence in the quark-gluon plasma





Extending QCD Theory

RHIC results are stimulating, testing, exploiting important extensions of QCD theoretical approaches to previously intractable regimes:

1) ***Approximating solution to Lattice QCD at non-zero net quark density ($\mu_B \neq 0$)***

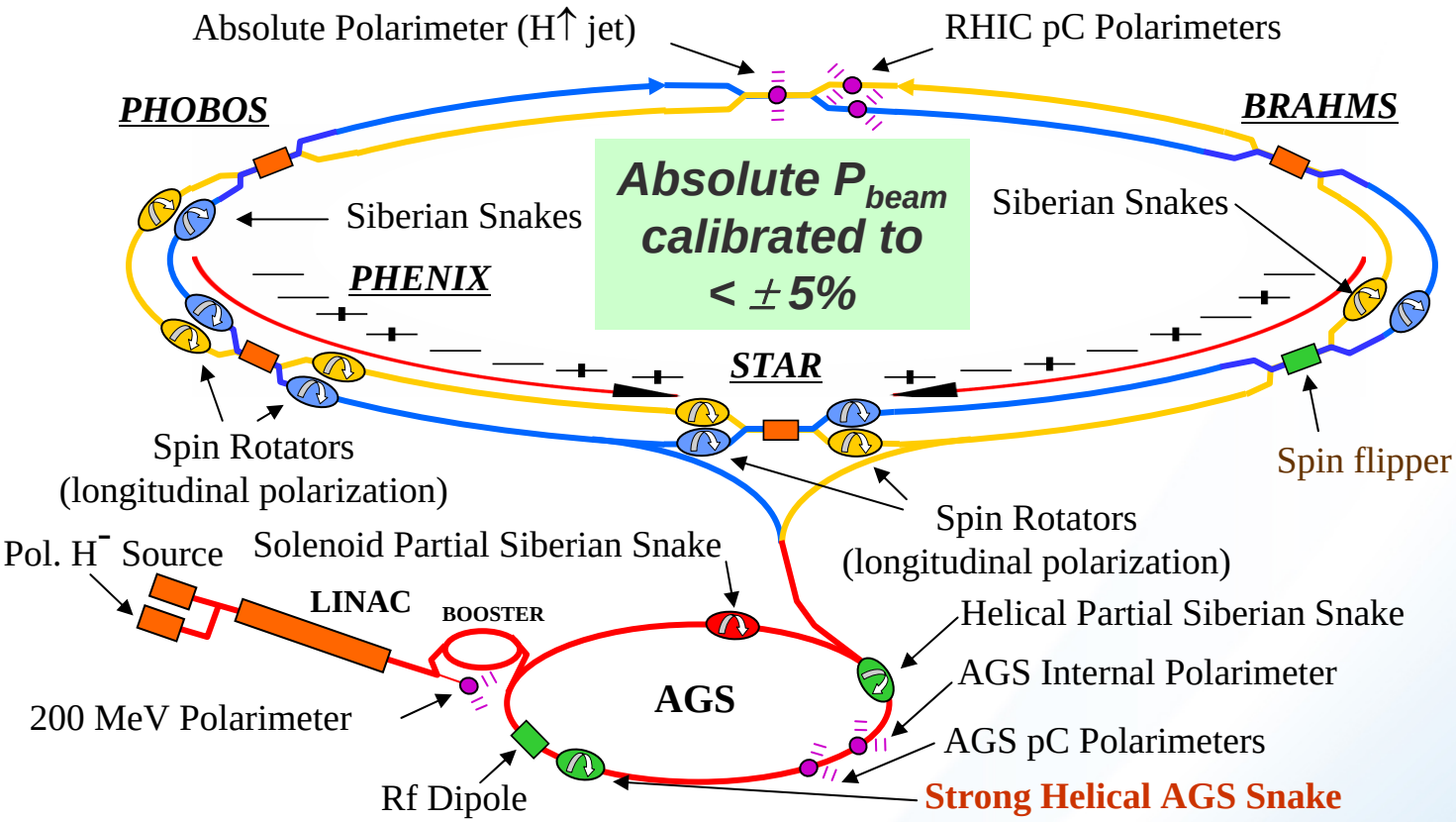
2) ***AdS/CFT to describe the very strong coupling limit ("channeling Maldacena")***

3) ***Color Glass Condensate approach to an effective theory for the highly non-linear regime of high gluon density, but weak coupling ("seeing the forest through the trees")***

4) ***Moving toward a unified perturbative treatment of transverse spin phenomena, incorporating transverse-momentum-dependent parton distributions***

BNL theory groups have played leading roles in (1), (3) and (4).

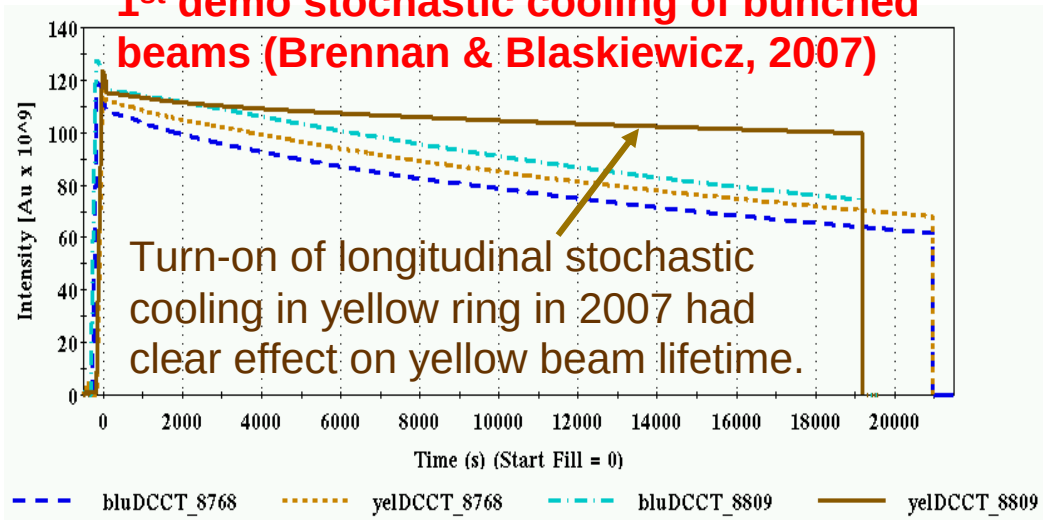
Advancing Accelerator Physics…



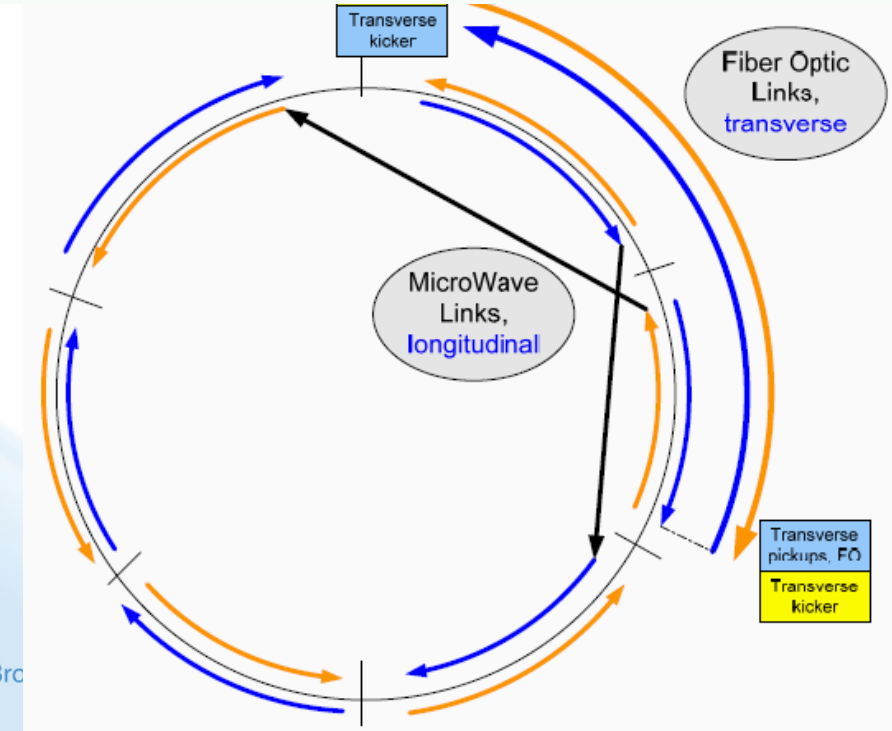
Accelerating polarized beams to 250 GeV and providing useful collider luminosities ⇒ a huge advance, fueling RHIC spin program.

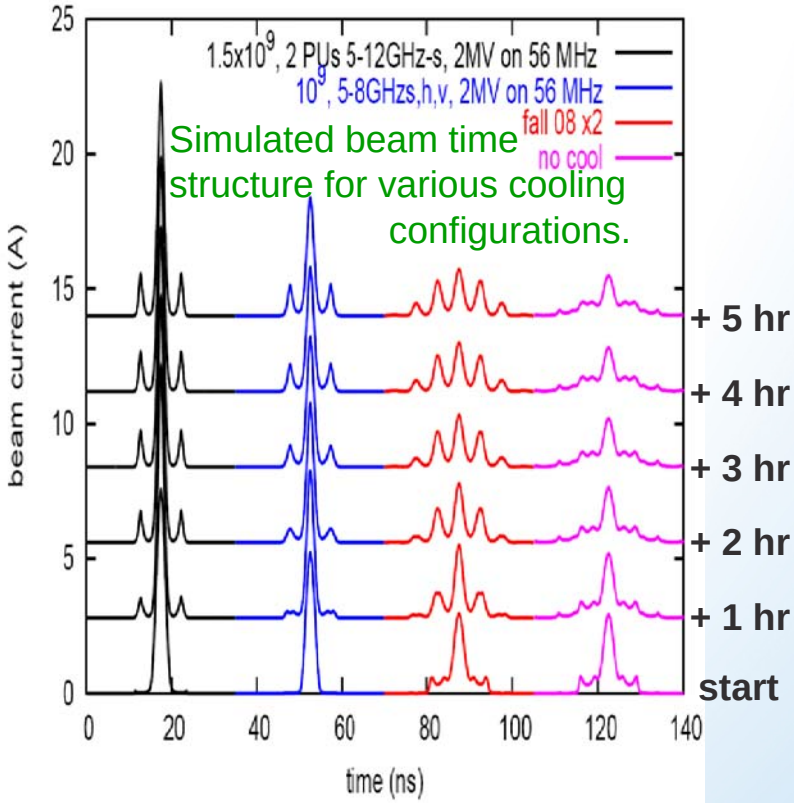
Allowing RHIC-II Science Without the RHIC-II Project

1st demo stochastic cooling of bunched beams (Brennan & Blaskiewicz, 2007)



Turn-on of longitudinal stochastic cooling in yellow ring in 2007 had clear effect on yellow beam lifetime.

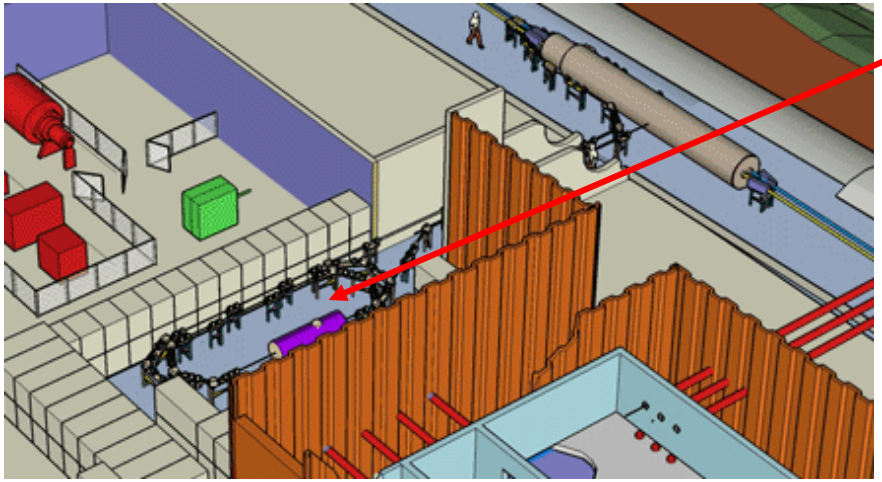




Simulated beam time structure for various cooling configurations.

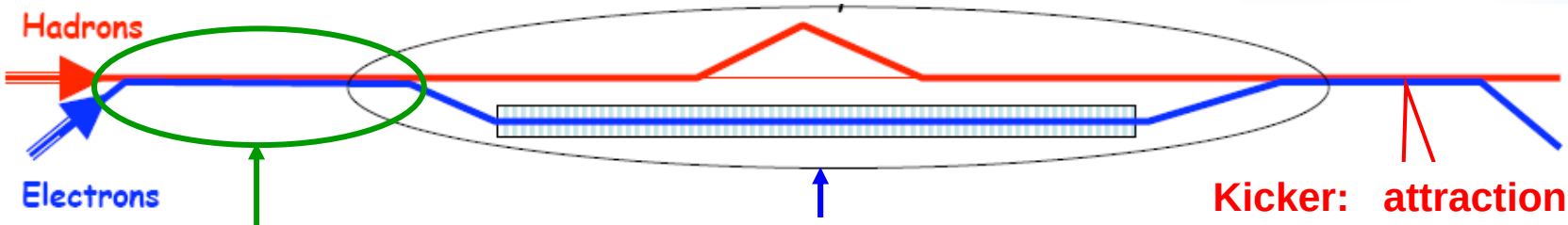
Particle tracking simulations (above) reproduce 2007 observations, predict behavior for full stoch. cooling system anticipated by 2011-12 (at left): gain factor ~6-8 in integrated luminosity within useful vertex cut (including 56 MHz SRF upgrade) !

Turning RHIC Into a Hotbed of Beam Cooling



Developing Energy Recovery Linac (ERL) technology for medium-E electron beams, in anticipation of e-cooling needs.

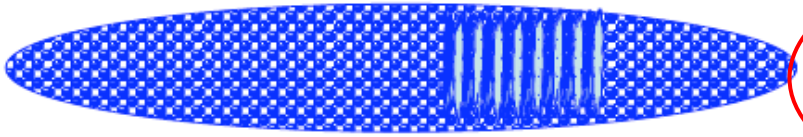
Applying the advanced technology to test innovative concepts for even more efficient cooling techniques…

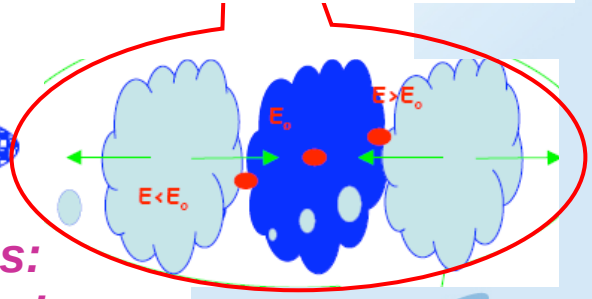


Modulator: hadron beam structure introduces density modulation in e-beam

Wiggler: FEL amplification (x $10^{2\text{-}3}$) of e-beam modulations, while chicane adds dispersion to h beam

Kicker: attraction to e-beam density peak reduces ion-beam E spread.





Coherent Electron Cooling of high-energy hadron beams: high-gain FEL based on high-brightness ERL (V. Litvinenko & Y. Derbenev) ⇒ potential to boost LHC and EIC luminosities.

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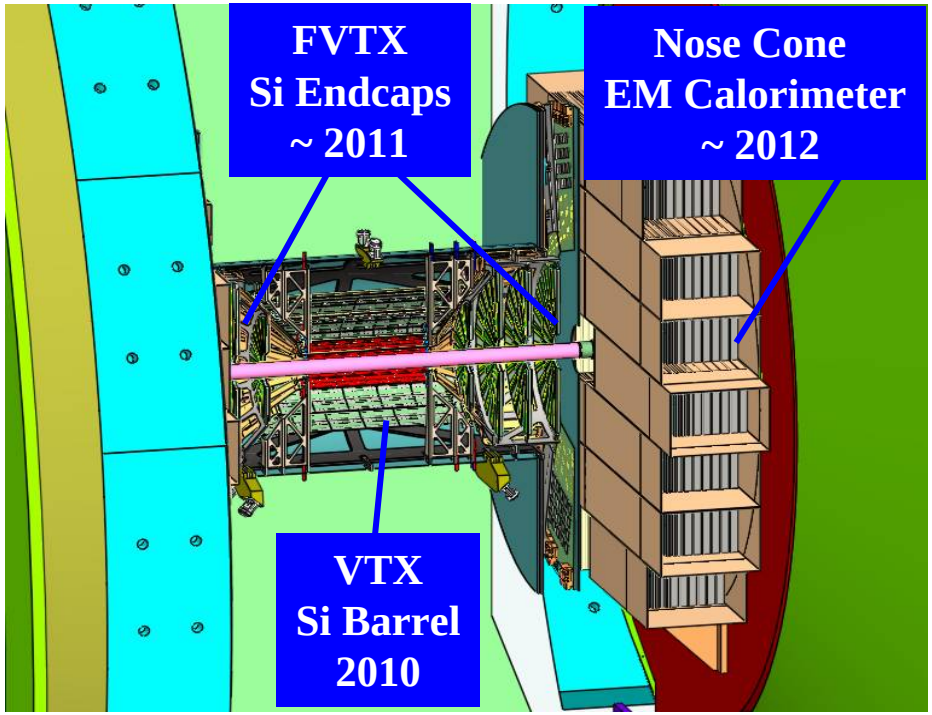
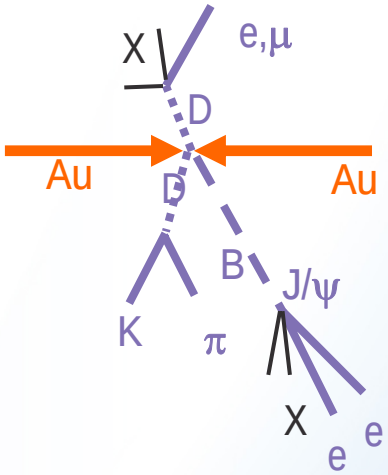
Pushing the State of the Art on Detector Technology

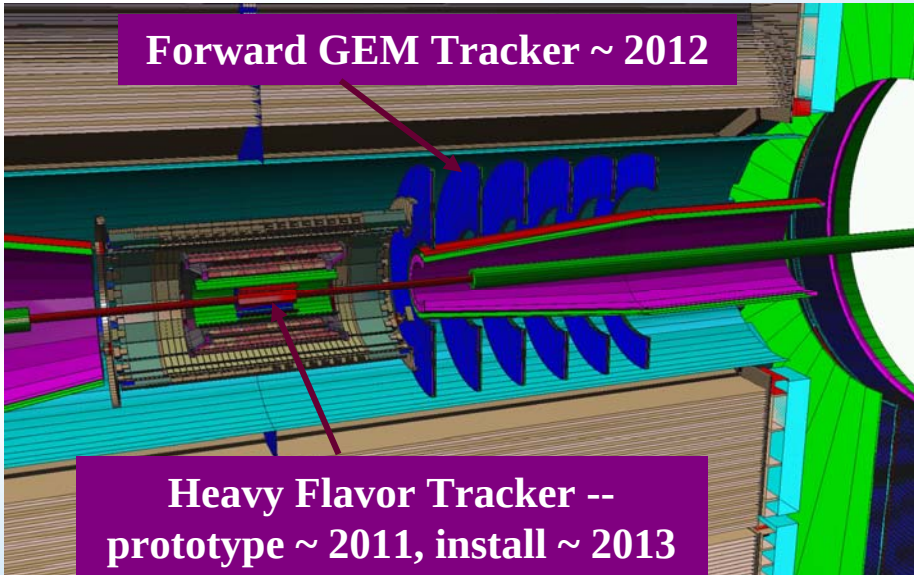


- ***PHENIX, STAR vertex upgrades provide resolution to reconstruct slightly displaced vertices associated with heavy flavor hadron decays ⇒ study heavy-quark flow & equilibration in "perfect liquid".***

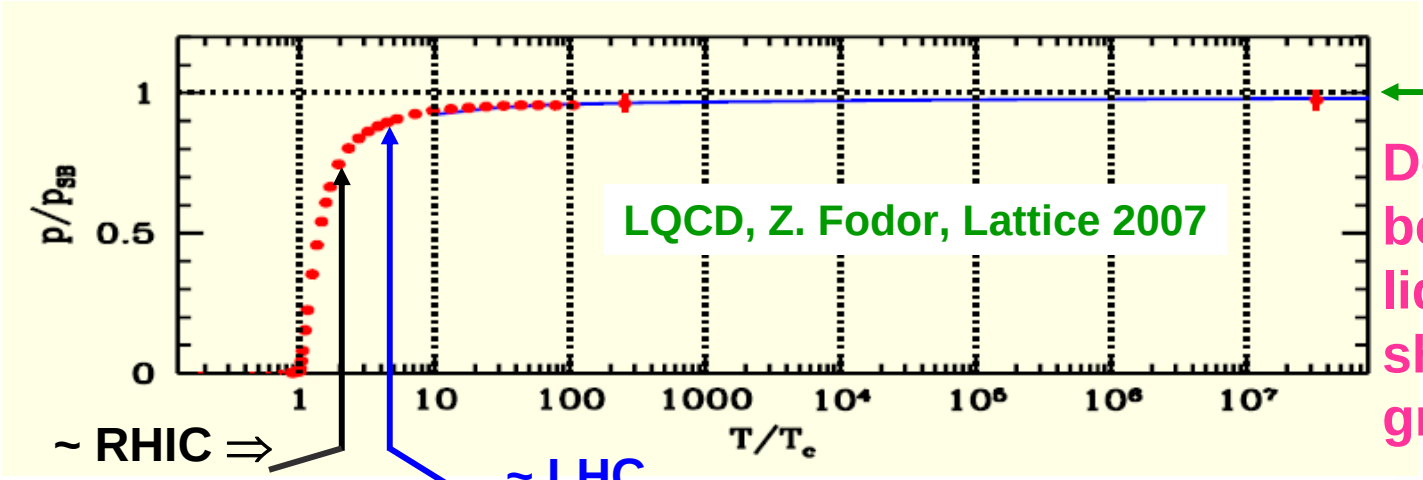


- ***Improved forward calorimetry enhances γ - jet acceptance to study light quark E loss and gluon contribution to proton spin***

- ***Improved forward tracking (STAR) enhances W sign determination to study antiquark polarization in proton.***



Where Do Heavy-Ion Collisions at LHC Fit In?

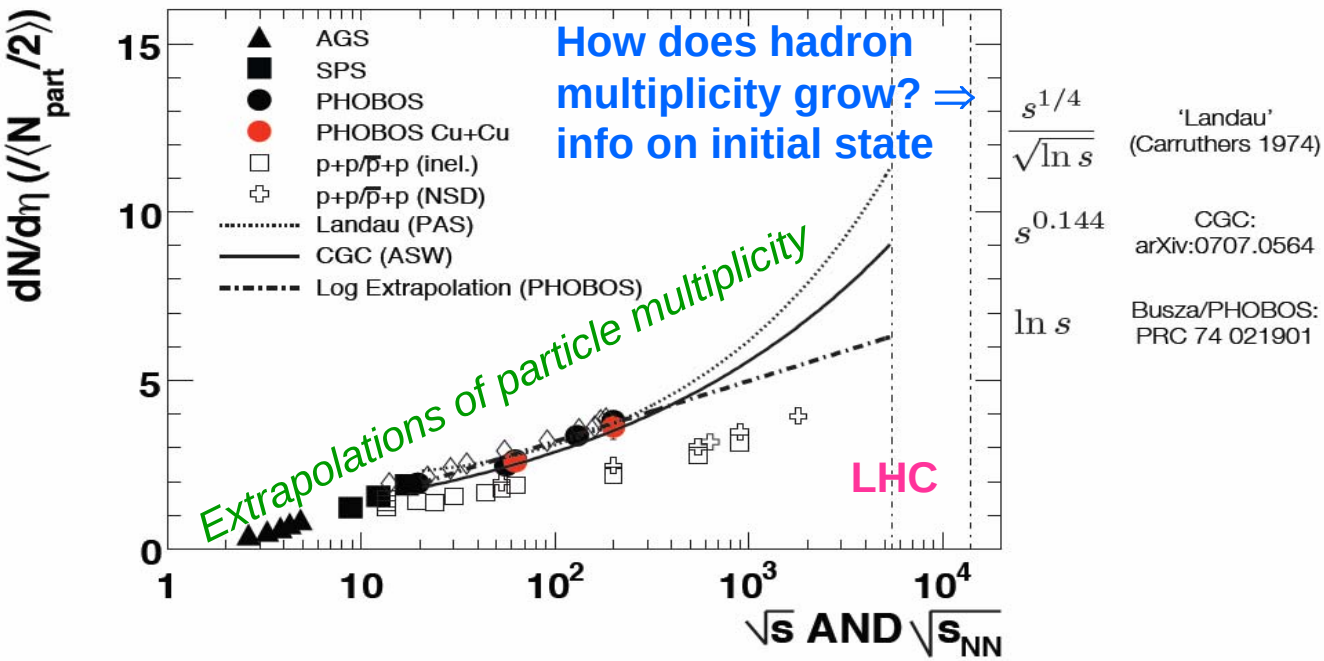


Ideal gas

Does matter still behave as an ideal liquid, or does shear viscosity grow from RHIC?

~ RHIC ⇒ "perfect liquid"

~ LHC Pb+Pb



Some pump/probe tools get sharper at LHC -- *e.g., full jet reconstruction/ resolution* -- but effects of interest *(parton E loss)* may be small or vanishing perturbations: *LHC is exploratory.*

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Making It All Happen, in 3 Acts…

I. **Push time scale for RHIC-II science program earlier than Long Range Plan (~2017 start)**

-- with stochastic cooling, luminosity upgrade by 2012; detector upgrades ongoing, all completed by ~2014

II. **Formulate upgrade plan for ~2016-2021 period**

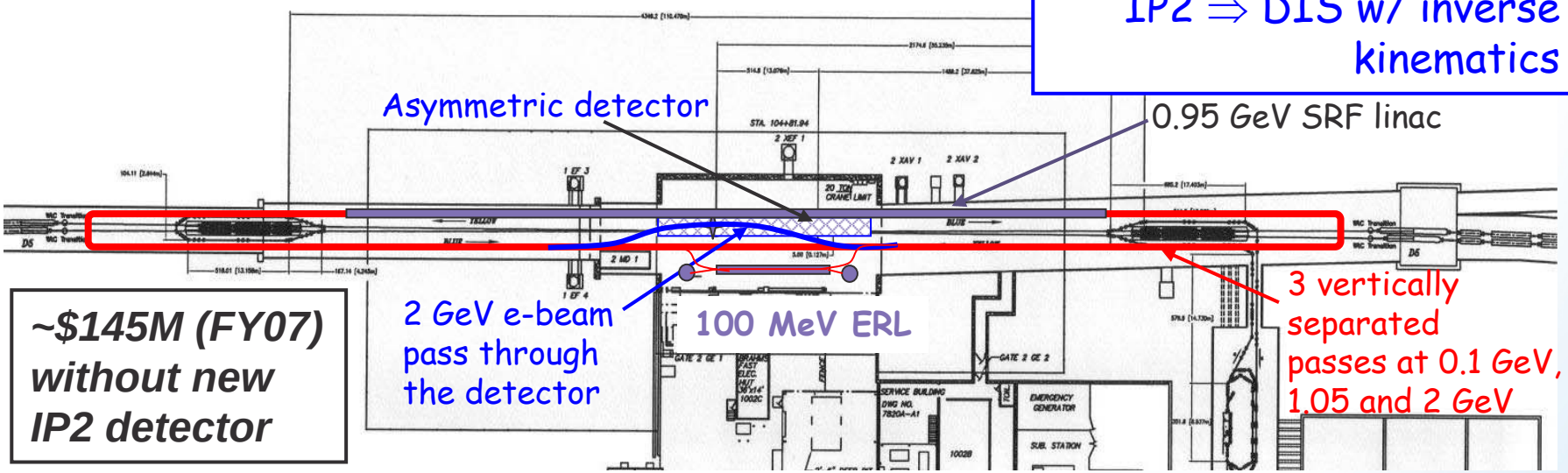
-- possibilities on following slides: 1st stage EIC; highly enhanced pp luminosities; AGS precision experiments

III. **Make EIC science case and technical feasibility more compelling by next LRP (~2012-13?), for implementation in early 2020's**

-- deepen (more transformational, less incremental) and broaden (add electroweak symmetry tests) science case; grow e-A experimental community; continue aggressive R&D program; consider staging strategies; work with JLab to move toward optimized design.

Intermediate-Term Possibilities: 1st (Medium Energy) Stage of EIC?

MEIC with 2 GeV ERL @ IP2 ⇒ DIS w/ inverse kinematics

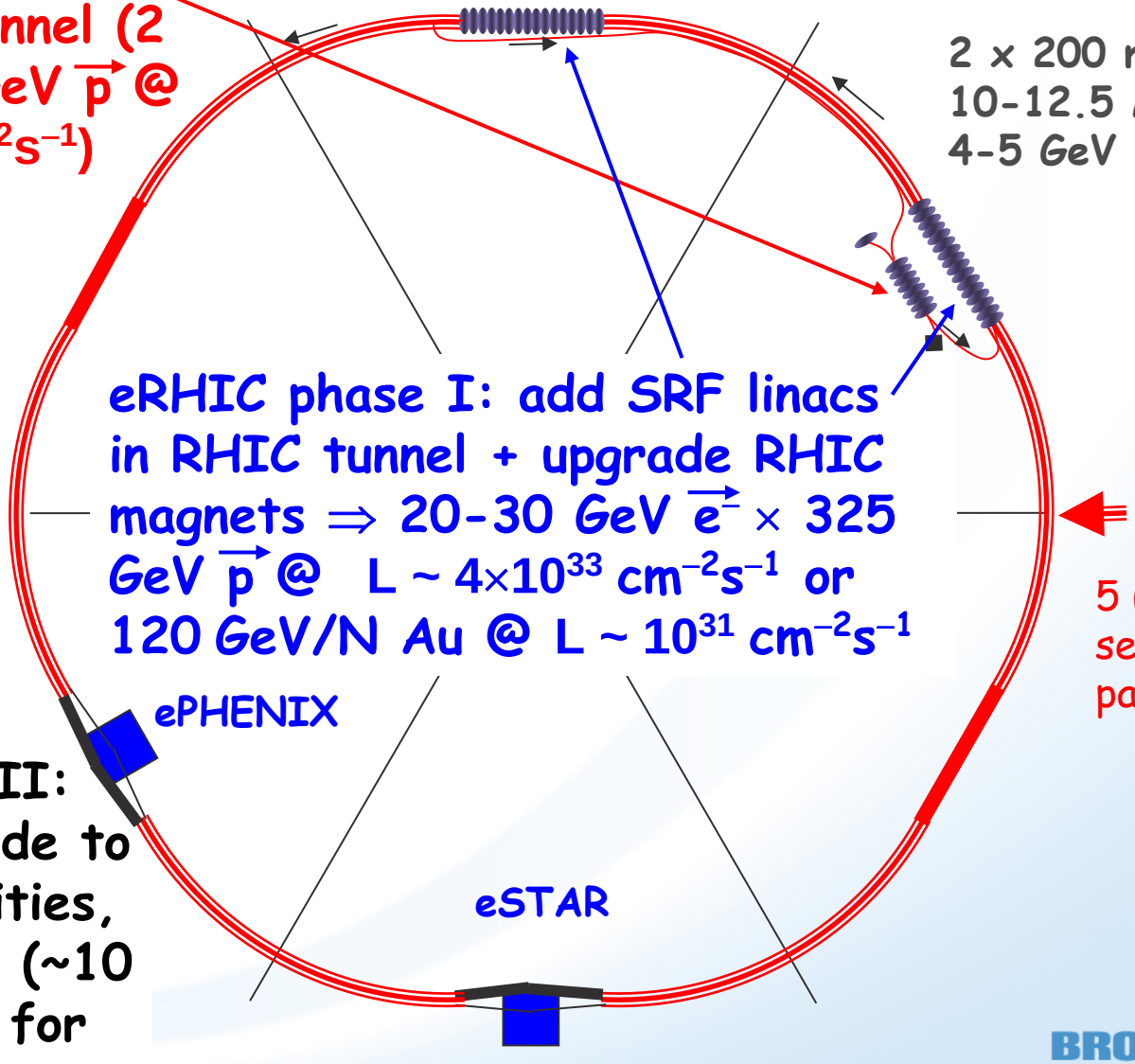


~$145M (FY07) without new IP2 detector

- ***Would enable 2 GeV $\vec{e}^-$ on 100 GeV/N heavy ions and 250 GeV $\vec{p}$***
- ***First look at saturation surface for nuclei, emphasizing diffraction tests of high gluon occupancy***
- ***e-p program emphasizing detection of target fragments to probe spin-dependent correlations in proton internal wave function***
- ***Need $\mathcal{L} \sim 10^{33}$ cm^{-2}s^{-1} to be competitive? Develop science case.***
- ***Most equipment would be reused later in full EIC***

Possible EIC Staging (as per V. Litvinenko)

MEIC - RHIC + ERL inside RHIC tunnel (2 GeV $\vec{e}^-$ × 250 GeV $\vec{p}$ @ L ~ 10^{32} $cm^{-2}s^{-1}$)



2 x 200 m SRF linac
10-12.5 MeV/m
4-5 GeV per pass

5 (6) vertically separated passes

eRHIC phase II: Luminosity upgrade to ~10^{35} (crab cavities, etc.) at reduced (~10 GeV e) energy for exclusive reactions

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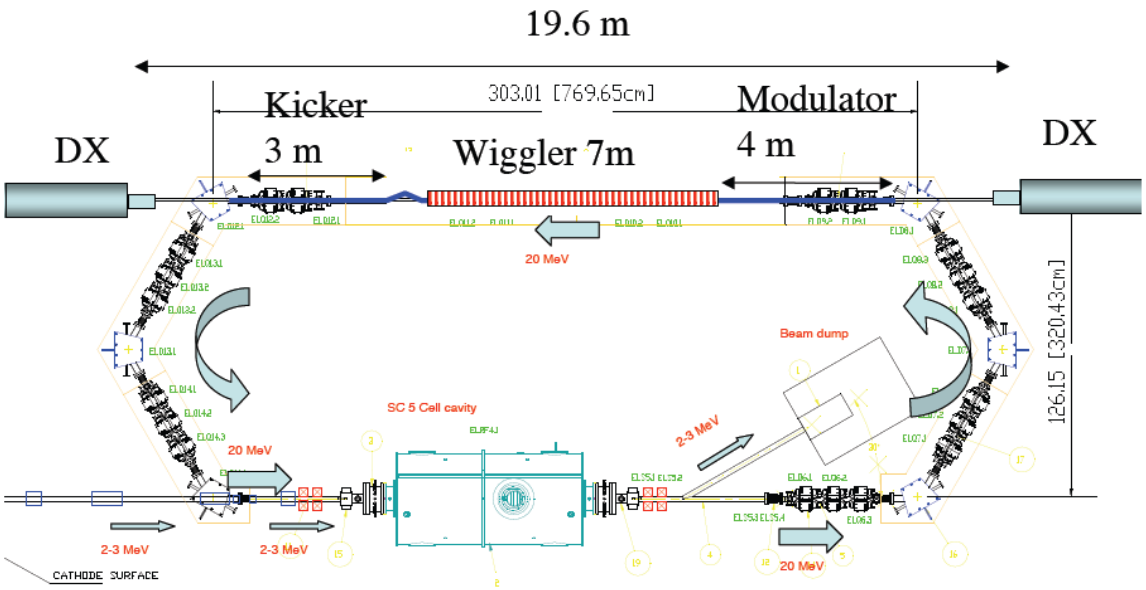
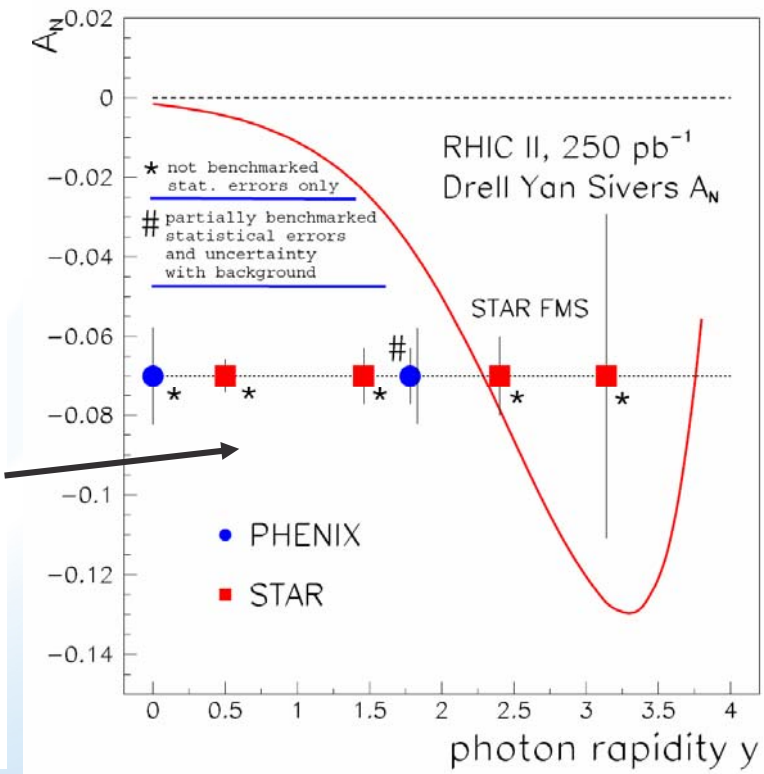
Intermediate-Term Possibilities: CeC-Fueled Order-of-Magnitude Upgrade in $\vec{p}+\vec{p}$ Luminosity?

IR-2 layout for Coherent Electron Cooling proof-of-principle experiment



Planning proof of principle demo of coherent e-cooling in RHIC, using ~20 MeV e from ERL already being developed + 40 GeV/N Au beams.

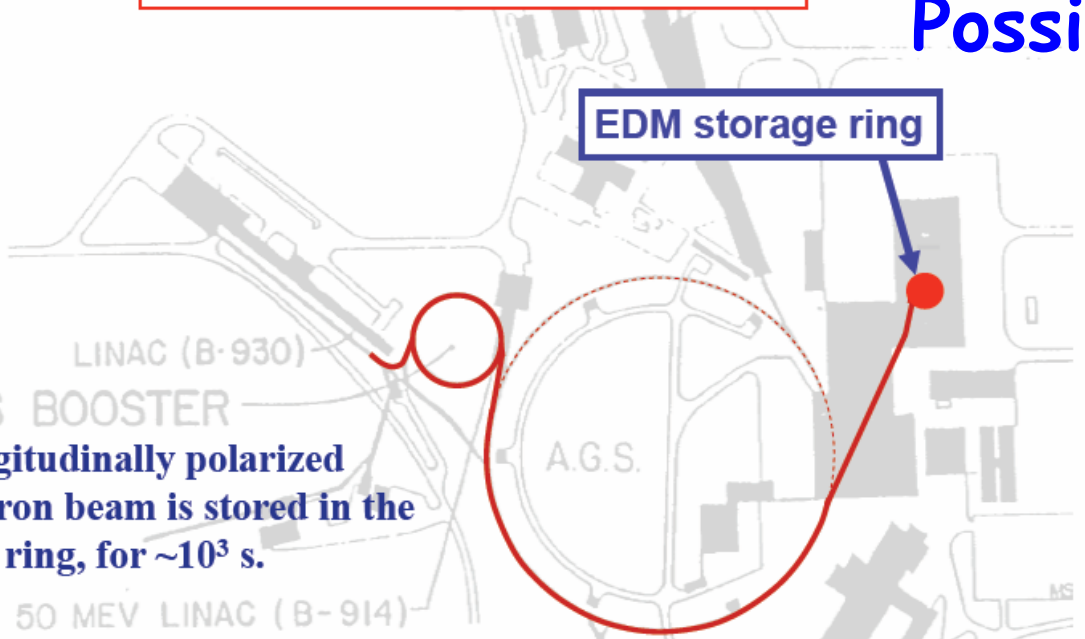
If successful, consider CeC for $\vec{p}$ beams at RHIC → EIC.



- ***Cooling time for p @ RHIC ~ 0.1-0.3 hours***
- ***Enhanced $\mathcal{L}$ facilitates contemplated measurements, e.g.:*** ***Drell-Yan test of QCD for transverse spin asym.; parity violation in hard jet prod'n; W-charm coincidences to probe strangeness contribution to proton spin.***
- ***Can detectors handle higher rates, pileup?***

Alternative Futures? Possible NP Symmetry Exp'ts @ AGS

deuteron EDM search at BNL



A longitudinally polarized deuteron beam is stored in the EDM ring, for ~10^3 s.

The strong effective E*-field~V×B will precess the deuteron spin out of plane if it possesses a non-zero EDM

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	<1.6×10^{-26}	~10^{-28}	10^{-28}
199Hg atom	<2×10^{-28}	~2×10^{-29}	10^{-25}-10^{-26}
^{129}Xe atom	<6×10^{-27}	~10^{-30}-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		~10^{-29}	3×10^{-29}-5×10^{-31}

dEDM exp't proposed to PAC in May 2008, with sensitivity goal of 10^{-29} e·cm

Spokesperson: Yannis Semertzidis (BNL)

23 collaborating institutions

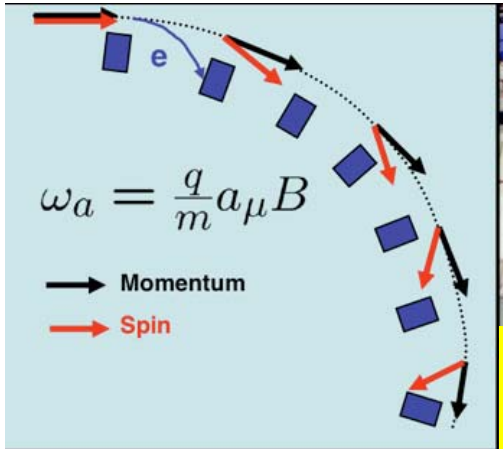
If nEDM is discovered at 10^{-28} e·cm level?

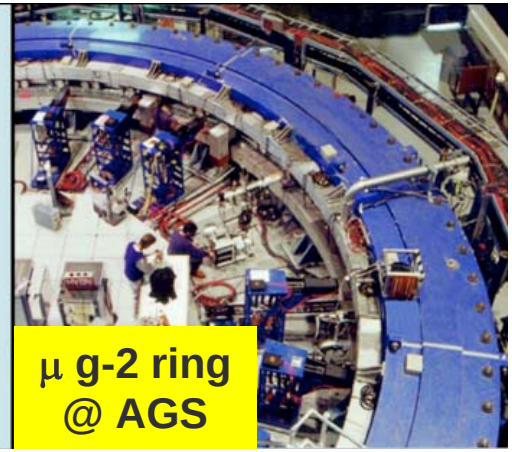
- If $\bar{\theta}$ is the source of the EDM, then $d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 1/3 \Rightarrow d_D \approx 3\times10^{-29}\,\mathrm{e\cdot cm}$

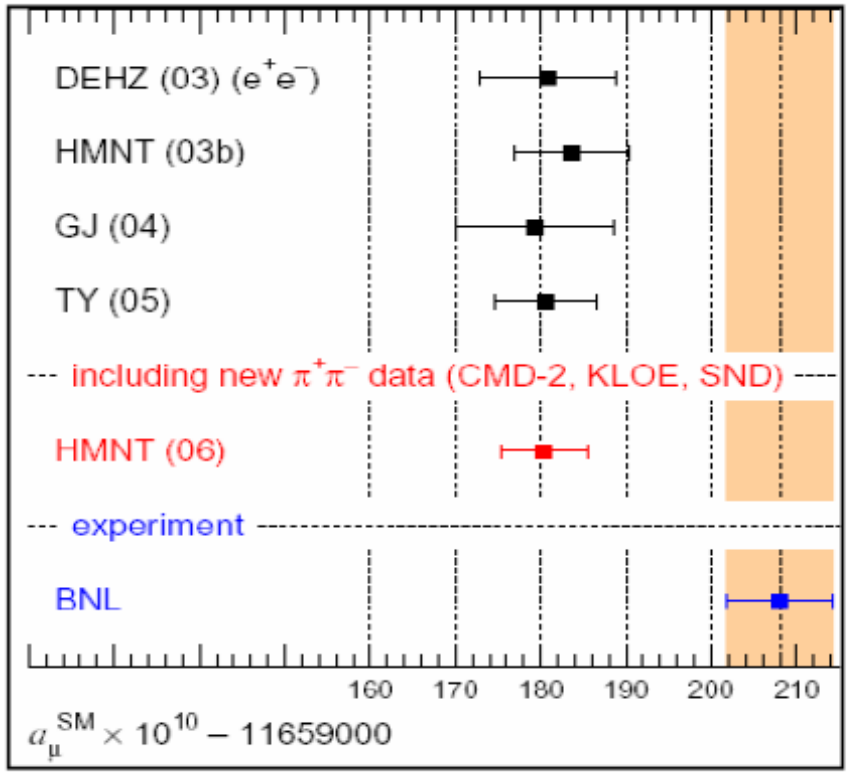
- If SUSY is the source of the EDM (isovector part of T-odd N-forces), then $d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 20 \Rightarrow d_D \approx 2\times10^{-27}\,\mathrm{e\cdot cm}$

The deuteron EDM is complementary to neutron and in fact has better sensitivity.

Precision Options: Muon g-2







Physics Beyond the Standard Model: Supersymmetry

SUSY working group report: Les Houches 2007 (Feb 08 archive)

"The strongest hint for a TeV-scale modification of the Standard Model originates from the anomalous magnetic moment of the muon."

$\Delta a_\mu(\text{expt-thy}) = (29.5 \pm 8.8) \times 10^{-10}$ (3.4 σ)

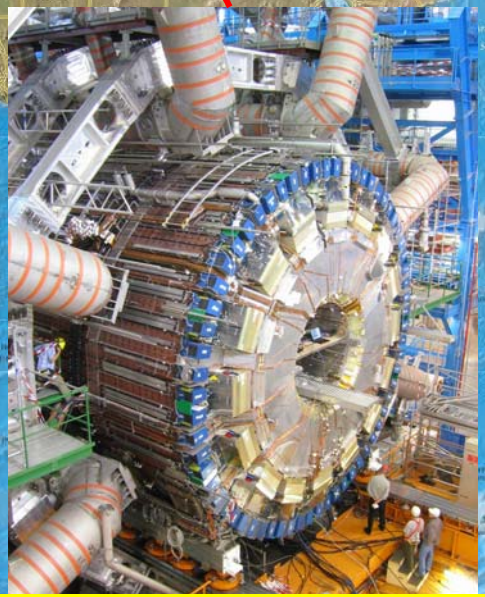
Based on de Rafael's theory summary (2007), using inputs from Davier (2006) and HMNT (2006). Rep.Prog.Phys. **70**, 795 (2007).

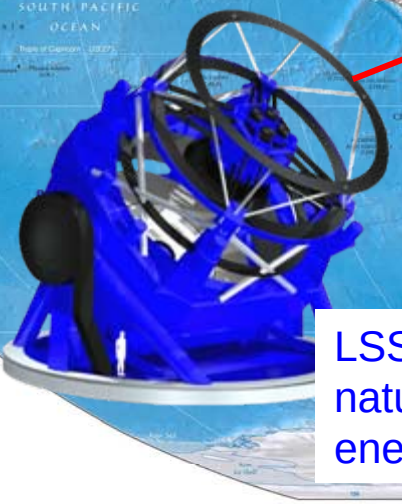
- ***Proposed new exp't to 0.1 ppm ⇒ 6σ sensitivity would need ~$55M (0.25 ppm "fast" version ~$30M)***
- ***Ring and expertise exist at BNL (AGS ops costs shared with NP?); FNAL version offers some technical advantages in muon accumulation; J-PARC?***
- ***BNL wants to see the physics done: will support regardless of location***

Maintaining a Complementary Forefront Program in Physics of the Universe, Around the Planet

Long baseline ν probes CPV, matter-antimatter asymmetry

μ Collider R&D ⇒ next generation energy frontier option





LSST to constrain nature of dark energy

ATLAS @ LHC searches for supersymmetric partners as possible dark matter candidates

Daya Bay reactor ν exp't ⇒ best sensitivity to θ_{13} mixing angle

Take-Away Messages…

1. RHIC has pioneered a new subfield, providing laboratory study of condensed strongly interacting matter. Important results, surprises and theory advances have resulted!
2. The same confluence of innovative accelerator physicists, artful experimenters and creative theorists provides the foundation for a robust future. Keep up the great work!
3. Upgraded luminosity and detectors will facilitate use of rare probes and multi-particle coincidences to quantify properties of the "perfect liquid" in the RHIC-II science era.
4. Heavy-ion collisions at LHC and at RHIC during the coming decade will be complementary and mutually stimulating.
5. A fleshed-out science and facility plan for upgrades during the 2nd half of the next decade is needed soon.
6. A very strong user community and a transformational science program will be needed to secure funding for an Electron-Ion Collider as the next generation QCD facility.