The Case for Continuing RHIC Operations

Steve Vigdor

RHIC PAC Meeting, June 7, 2012

Tribble Panel Hearings Sept. 7-9, 2012 – likely RHIC presentations (time allotted not yet clear):

1) *Sam Aronson on RHIC's place in BNL plans*
2) *SV on Overview of Case for RHIC*
3) *? on Summary of Next Decade Program with Soft Probes*
4) *? on Summary of Next Decade Program with Hard Probes*
5) *? on eRHIC Science and Path to Get There*

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science U.S. DEPARTMENT OF ENERGY

Appreciate feedback on basic elements of case; presentation details still very preliminary

Drafting a White Paper to Make the Case Concisely

Paper organization (goal ~15 pages):

I. The case in a nutshell – 1 page
II. Hot QCD Matter: RHIC's Intellectual Challenges and Greatest Hits To Date – 1.5 pages
III. Recent Breakthroughs and RHIC's Versatility Inform the Path Forward – ~6 pages
IV. Unanticipated Intellectual Connections – 1 page
V. RHIC Program for the Coming Decade – ~2-3 pages
VI. Cold QCD Matter and the Path to EIC in RHIC's Third Decade – ~3-4 pages

Appendix A: History of RHIC Beam Performance

Appendix B: Graphs of Publications, Citations, Ph.D.'s

Appendix C: RHIC and RHIC-Inspired Publications and Coverage in Broad Science Journals

When ready (later this month), the draft will be vetted within the RHIC user and support community and by BNL management

The Four Most Important Reasons for Continuing RHIC

1) RHIC has pioneered a vibrant new subfield – condensed QCD matter physics – and has led the rapid climb up a steep learning curve marked by continuing S&T breakthroughs. **By terminating RHIC, the U.S. would unilaterally cede leadership in this high-impact field.**

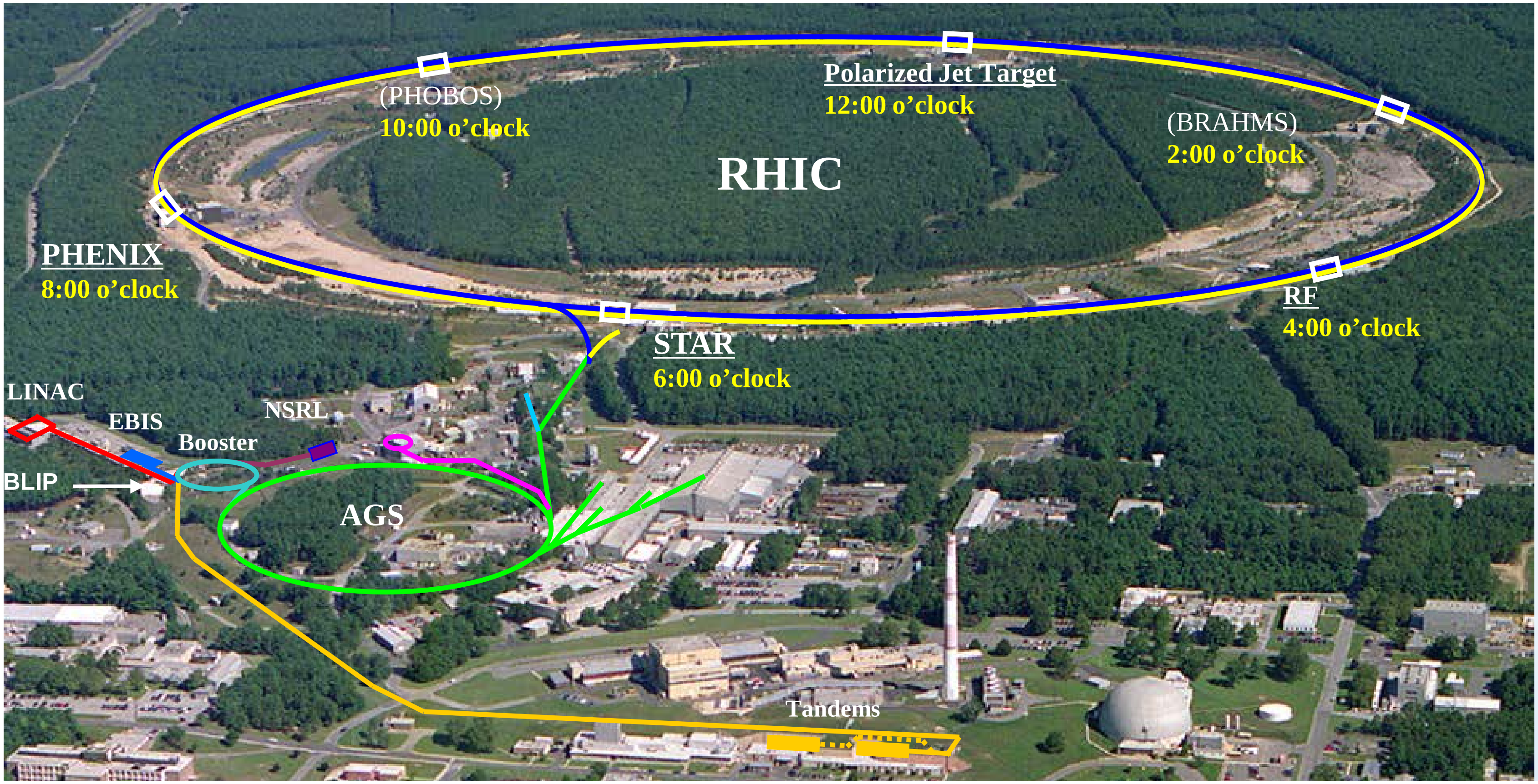
2) Discoveries and techniques at RHIC have established deep intellectual connections to other physics forefronts. **These give RHIC much broader scientific impact than other Nuclear Physics research avenues.**

3) Critical directions for future research in this subfield involve probing hot QCD matter from below to above the transition to Quark Gluon Plasma. **This transition appears to occur within the RHIC energy range, at energies not accessible at LHC. This is NOT energy frontier science!**

4) RHIC has nearly completed major performance upgrades that facilitate the next decade's science. It also provides the most cost-effective base to realize the next QCD frontier with EIC. **Short-term crisis management for U.S. NP must preserve a viable path to a vibrant long-term future.**

Terminating RHIC ops. would lead with certainty to a devastating loss of U.S. scientific leadership, and in all likelihood simultaneously to a significant loss of funding for the U.S. NP program.

RHIC's First Decade: A Discovery Machine



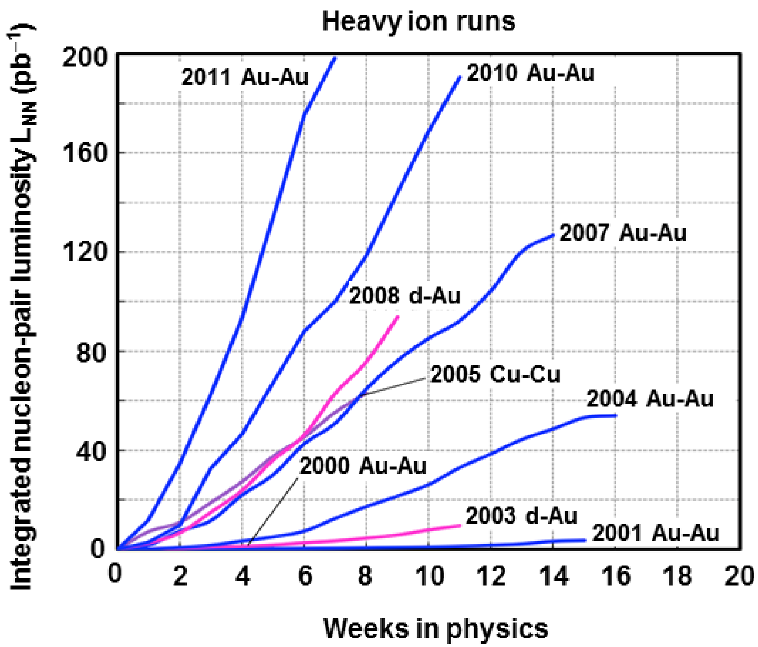
RHIC hallmarks:

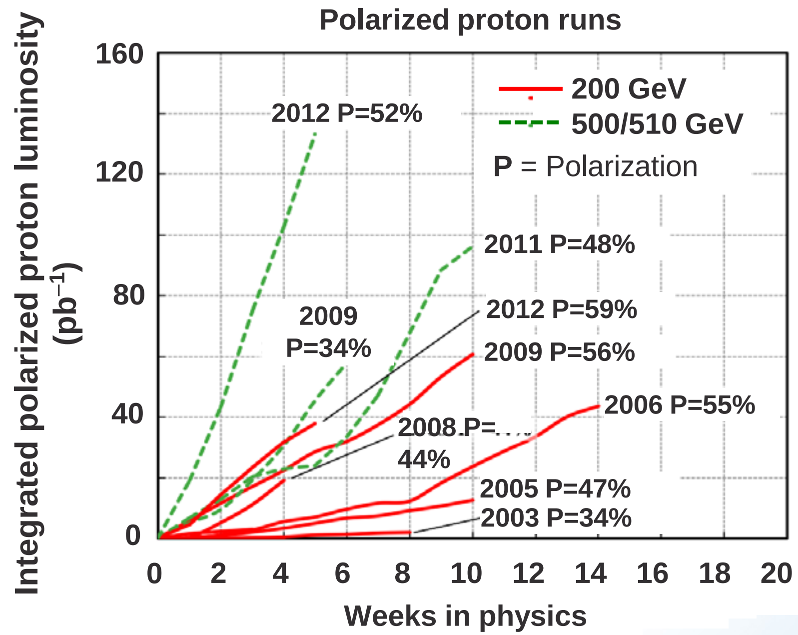
Pioneering *– 1st facility to clearly see transition to quark-gluon matter; world's only polarized collider*

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*

Incremental Upgrades ⇒ Steadily Improving Performance

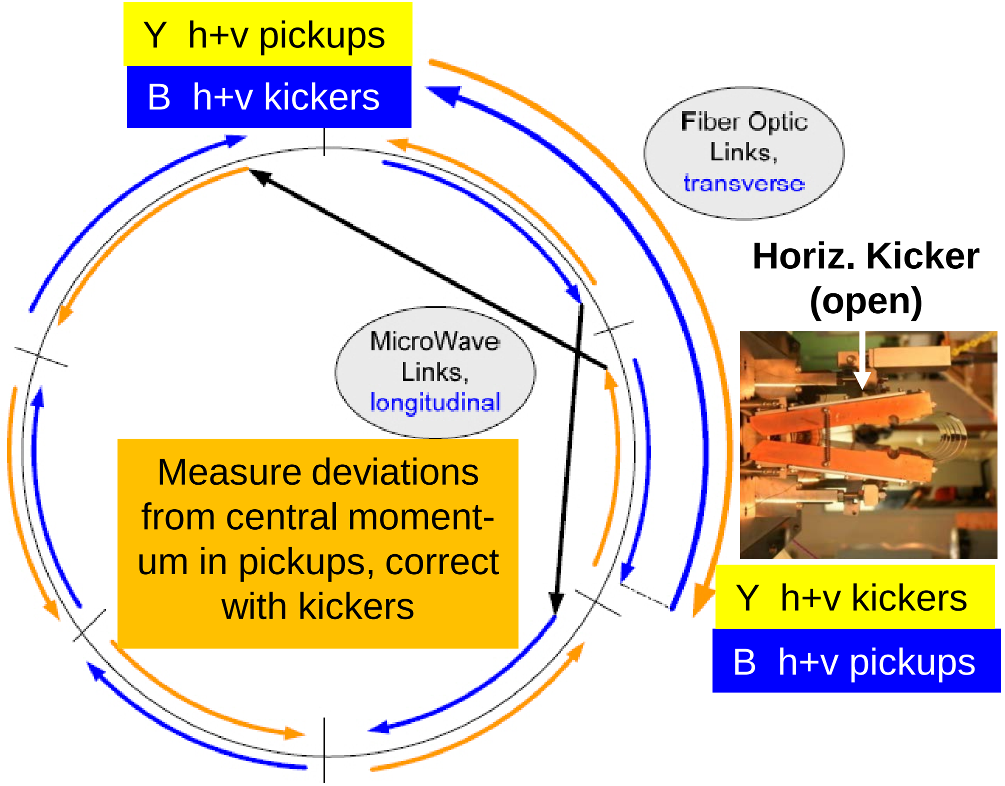




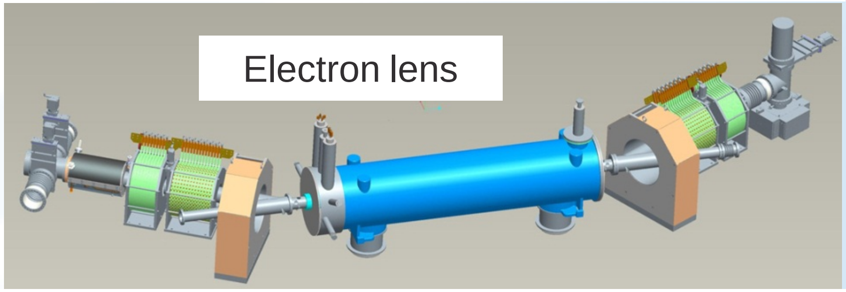
Collision partners	Beam energies (GeV/nucleon)	Peak pp-equivalent luminosities achieved to date, scaled to 100 GeV/n[b)]
Used to date		
Au+Au	3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 28, 31, 65, 100	195×10^{30} cm^{-2}s^{-1}
d+Au[a)]	100	100×10^{30} cm^{-2}s^{-1}
Cu+Cu	11, 31, 100	80×10^{30} cm^{-2}s^{-1}
p↑+p↑ (polarized)	11, 31, 100, 205, 250, 255	150×10^{30} cm^{-2}s^{-1} at 250 GeV
Considered for future		
Au+Au	2.5, 7.5	
Cu+Au[a)]	100	Running in May 2012
U+U	96	Running in April-May 2012

2 new colliding beam species in 2012

Recent and Ongoing Cost-Effective Machine Upgrades



- 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

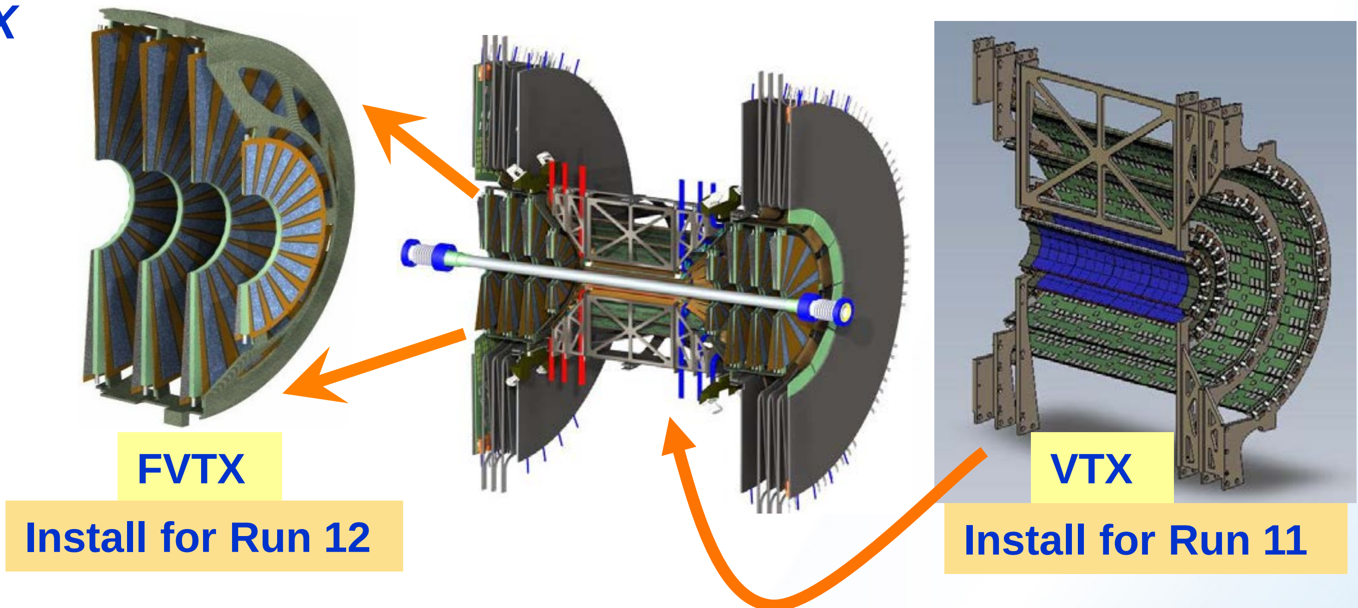


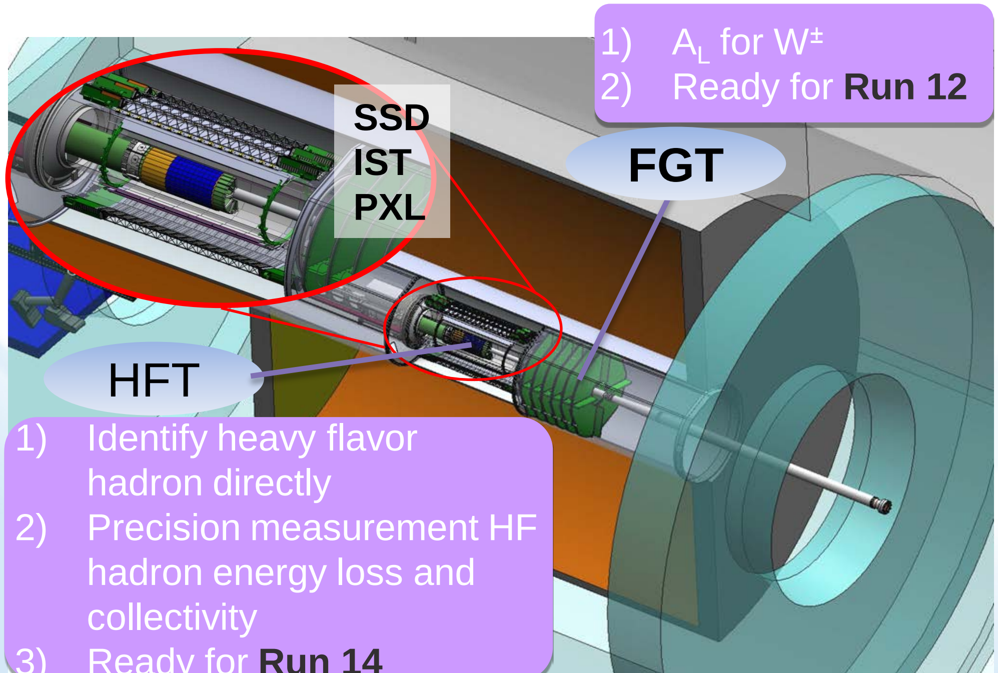
- New Electron Beam Ion Source (EBIS, 2012) expands range of ions available (e.g., U) and enhances cost-effectiveness of operations

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.***

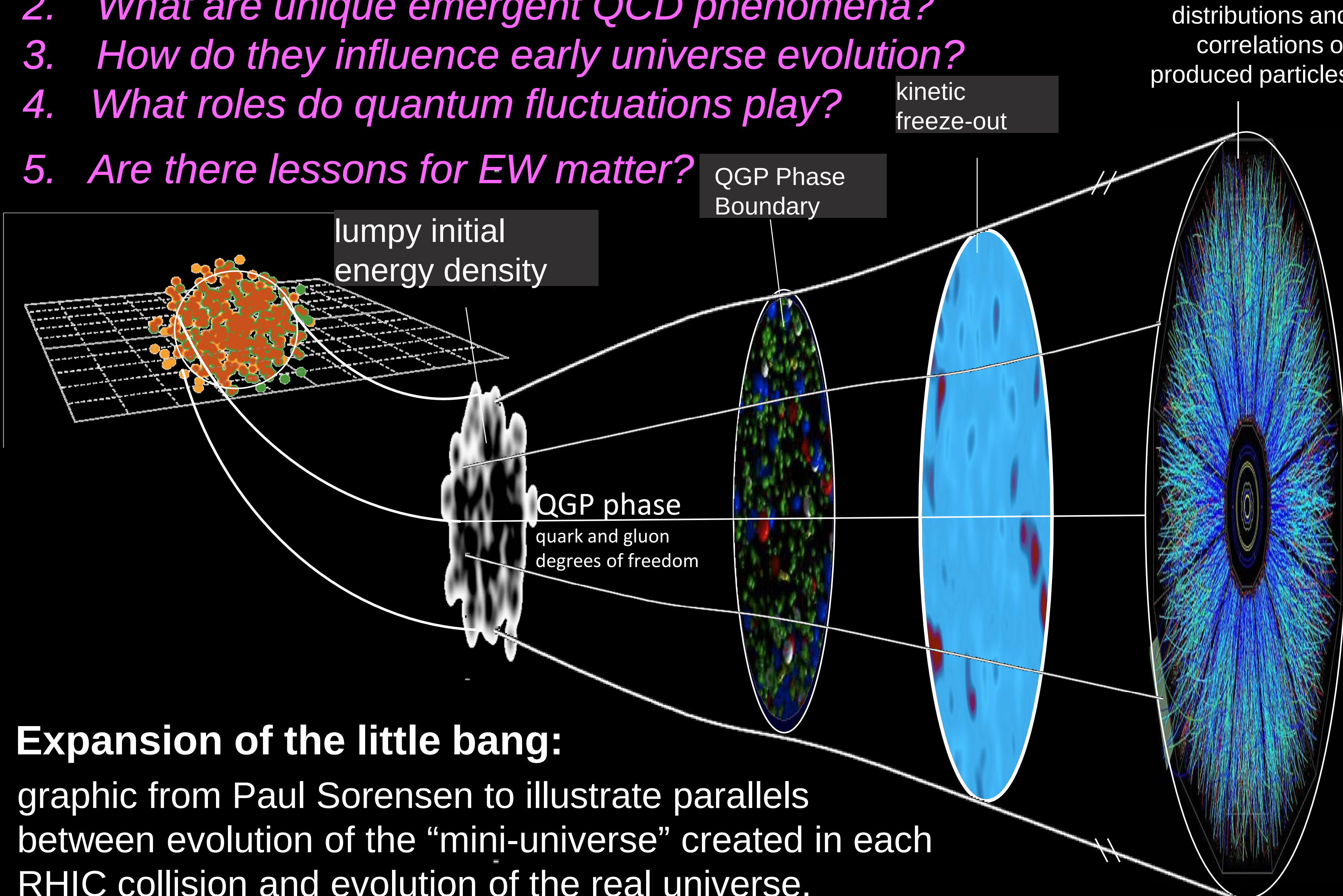
- ***STAR Forward GEM Tracker to be installed for Runs 12 and 13, will enhance forward tracking, W charge sign discrimination.***

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

RHIC Has Pioneered Lab Study of Condensed QCD Matter

Challenges:

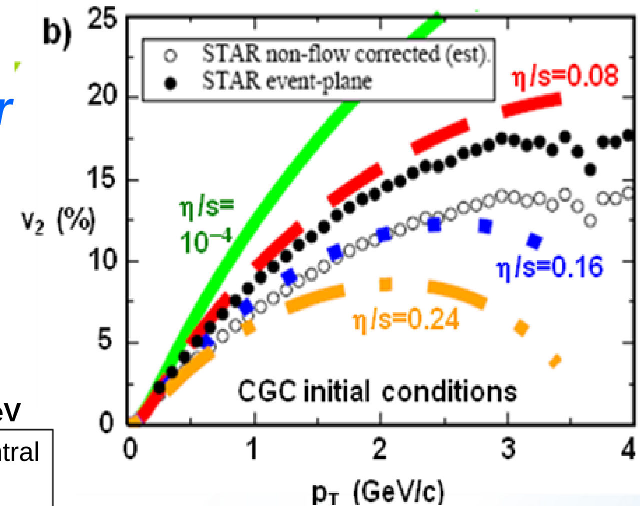
1. *How to pump/probe matter that lives ~10^{-23} seconds?*
2. *What are unique emergent QCD phenomena?*
3. *How do they influence early universe evolution?*
4. *What roles do quantum fluctuations play?*
5. *Are there lessons for EW matter?*



Expansion of the little bang:

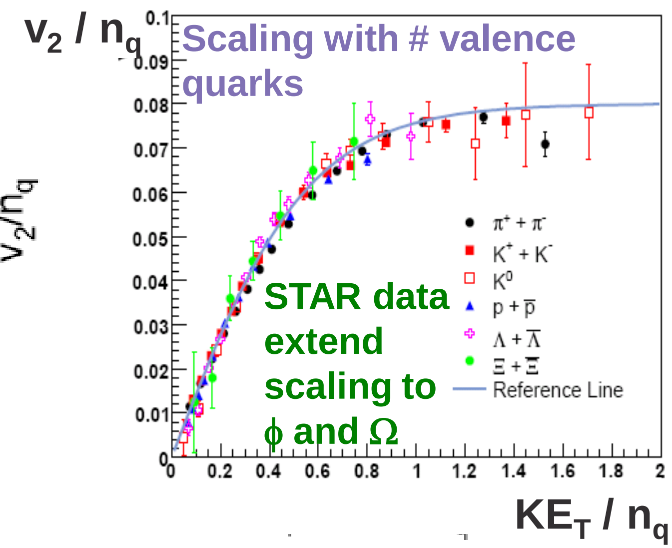
graphic from Paul Sorensen to illustrate parallels between evolution of the “mini-universe” created in each RHIC collision and evolution of the real universe.

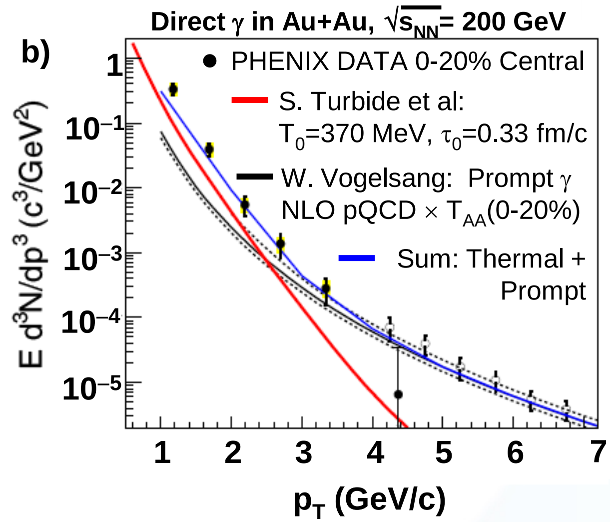
RHIC Past: Hot QCD Discoveries



- ❑ ***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***

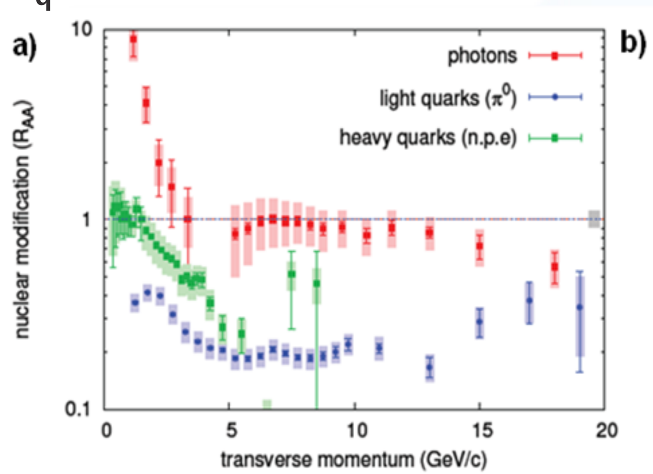


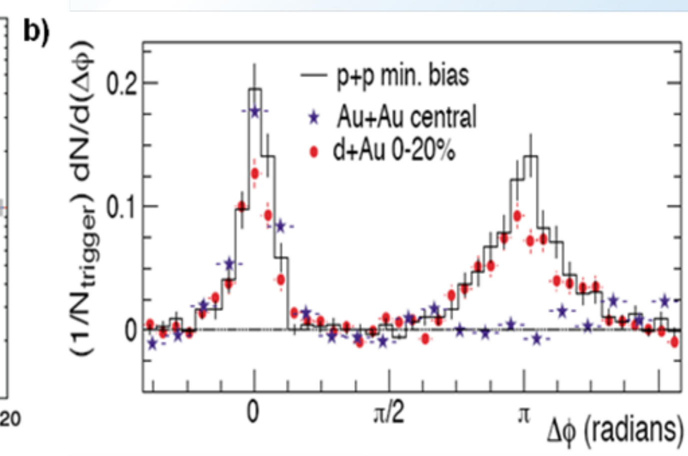


- ❑ ***Collective flow established at quark level via n_q scaling***

- ❑ ***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

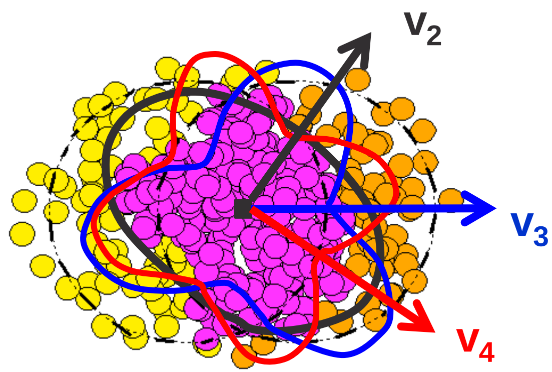
1) *Measurement of higher flow multipoles + advances in hydrodynamics state-of-the-art $\Rightarrow$ path to quantify η/s, other transport properties, and role of quantum fluctuations*

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*

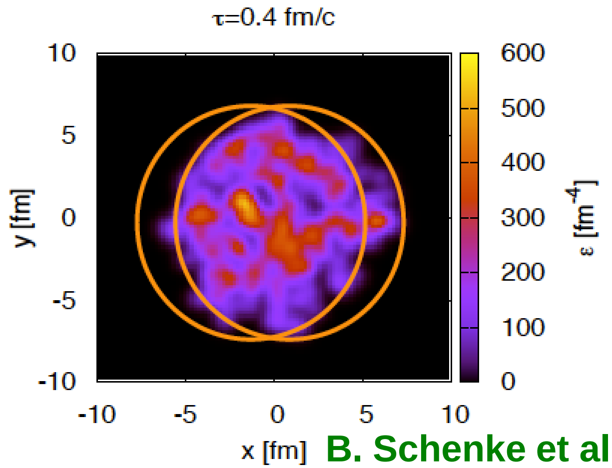
4) *Stochastic cooling and EBIS upgrades have RHIC poised to pursue follow-up investigations to above and other 2nd-decade science questions*

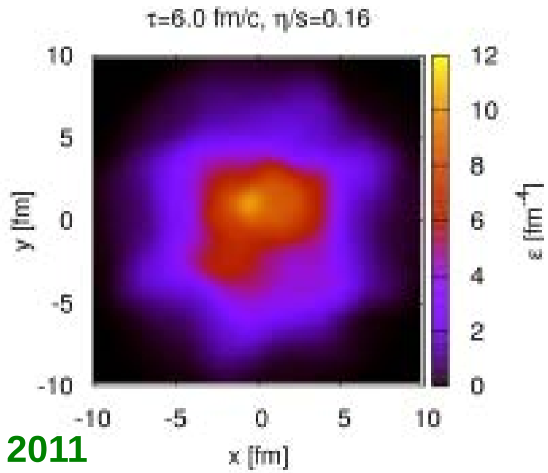
These are described, along with next steps in each case, in more detail on following slides…



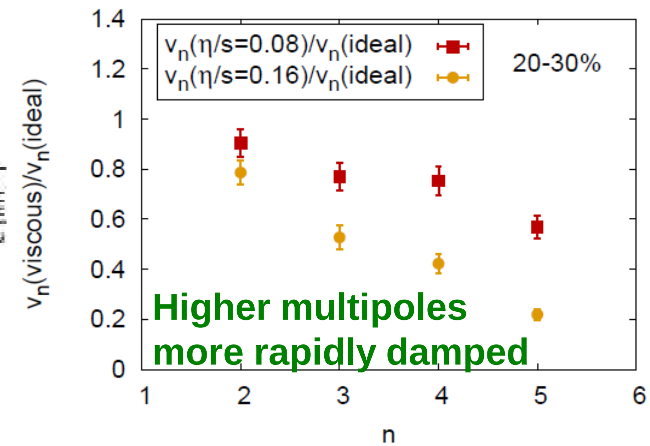
Beyond v_2 to Quantify Near-Perfection

- *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. $\Rightarrow$ path to quantifying η/s*

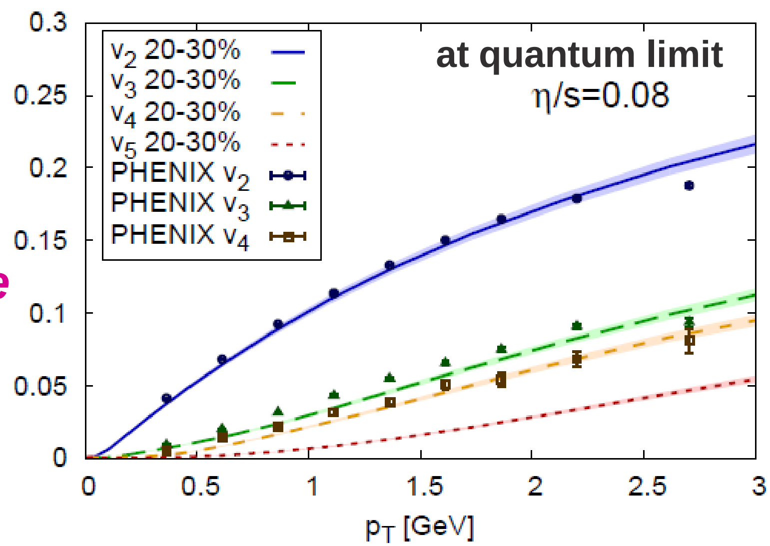


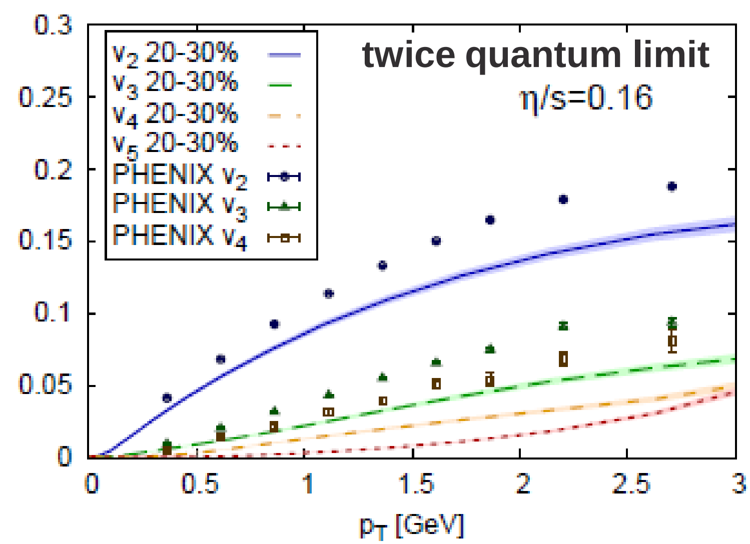


B. Schenke et al., 2011



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



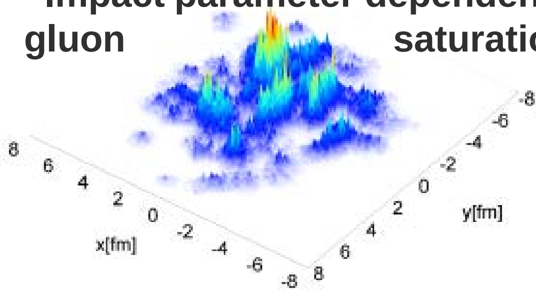


Next Steps: Constraining Initial Fluctuations

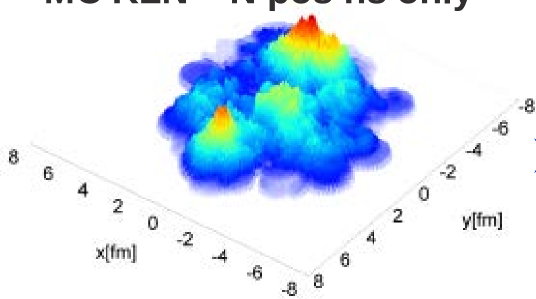
- ***Initial density fluctuations influence RHIC collision evolution, just as inflation-era quantum fluctuations seed universe's large-scale structure.***
- ***Is it just initial nucleon positions, or also color charge (i.e., gluon field) distributions, that fluctuate? The two yield different characteristic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

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

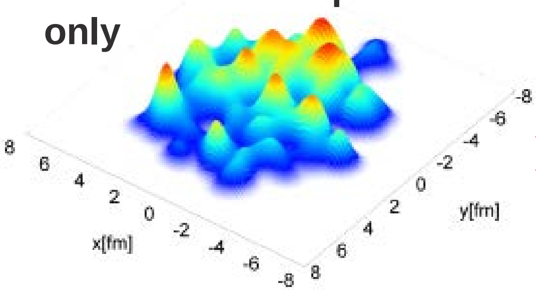
Impact parameter dependent gluon saturation

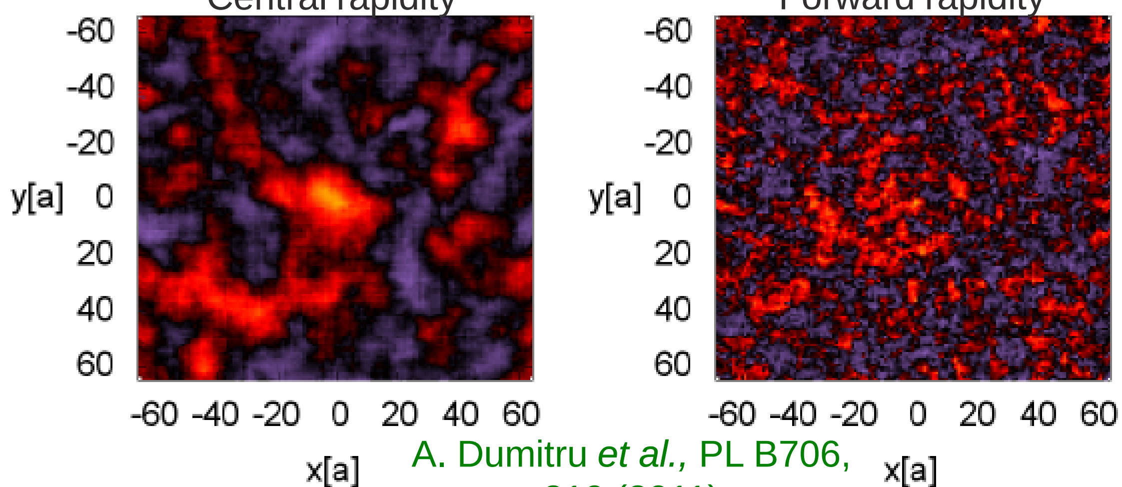


MC KLN – N pos'ns only



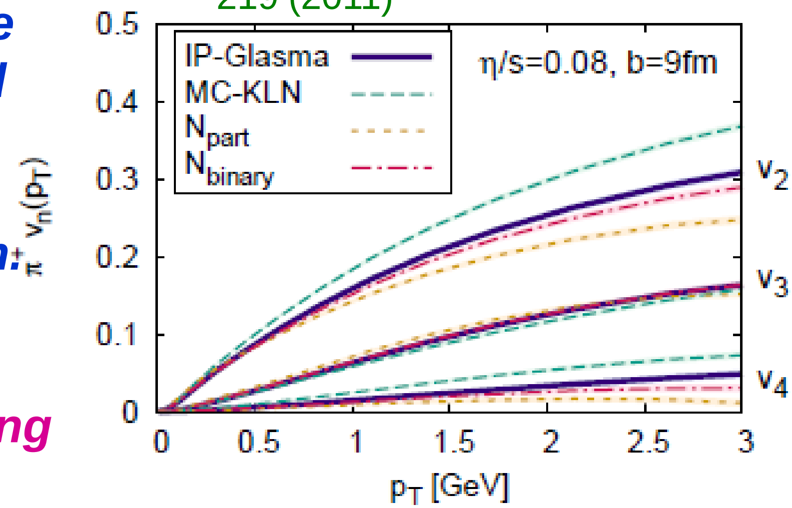
MC Glauber – N pos'ns only



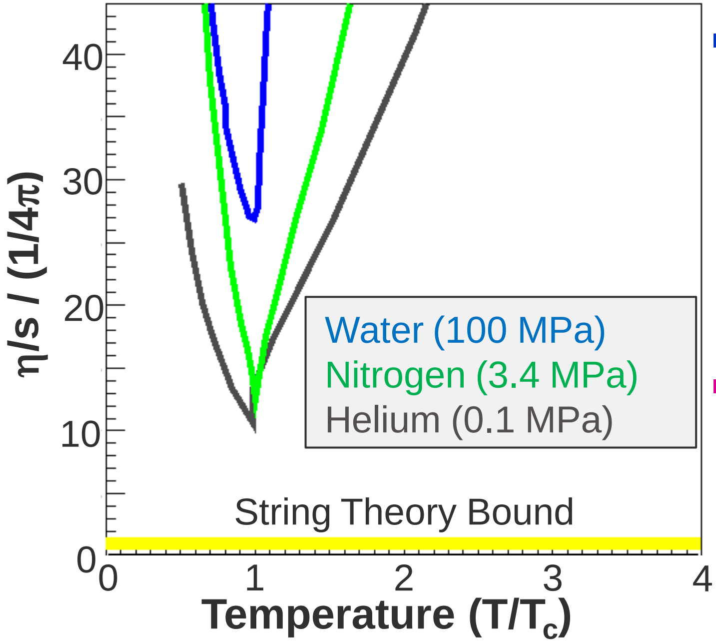


A. Dumitru *et al.*, PL B706, 219 (2011)

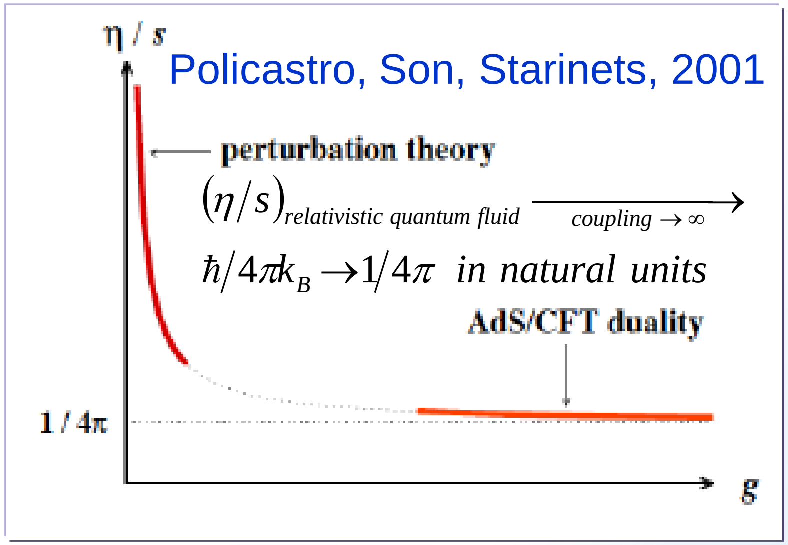
- ***Fluctuations can be constrained by odd vs. even flow harmonics, as fcn. of rapidity, & for asym. vs. symm. beams***
- ***Must be done together with pinning down η/s***



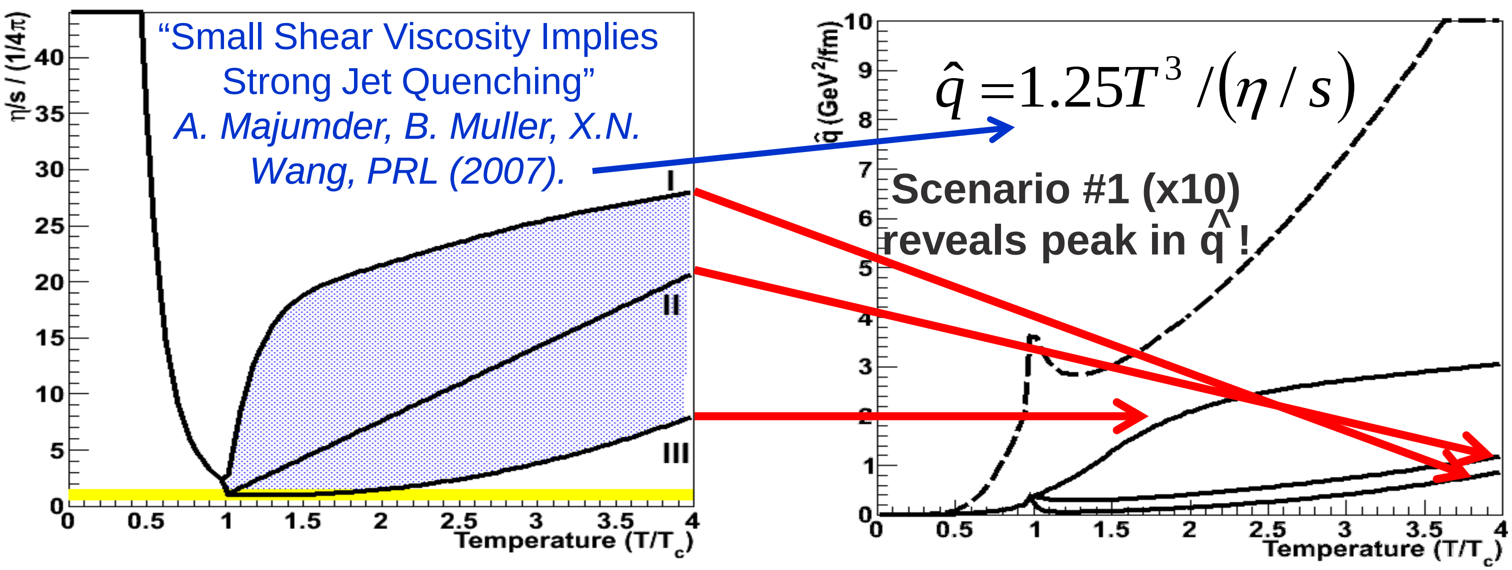
Next Steps: QCD Transport Properties vs. Temp.



- *Many common fluids exhibit η/s minima at or near phase transitions – does QGP?*
- *How does strongly coupled liquid emerge from asymptotically free theory?*



- *Is QGP shear viscosity correlated with parton energy loss?*

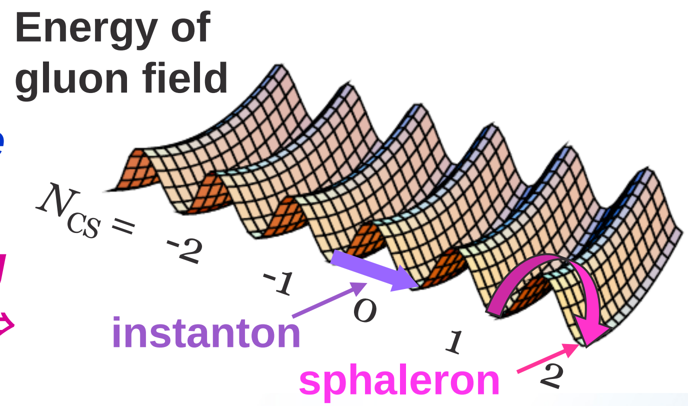


Measure vs. √s:

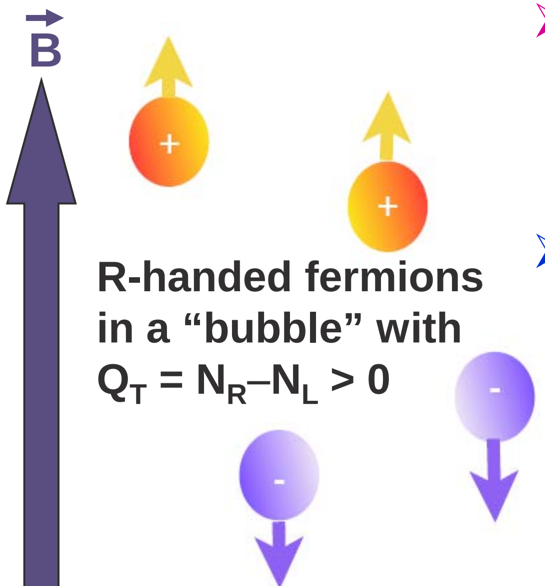
- *Flow power spectrum for η/s*
- *Di-jet asym. for q-hat (parton p_T^2 loss/length)*
- *Requires RHIC + det. upgrades*

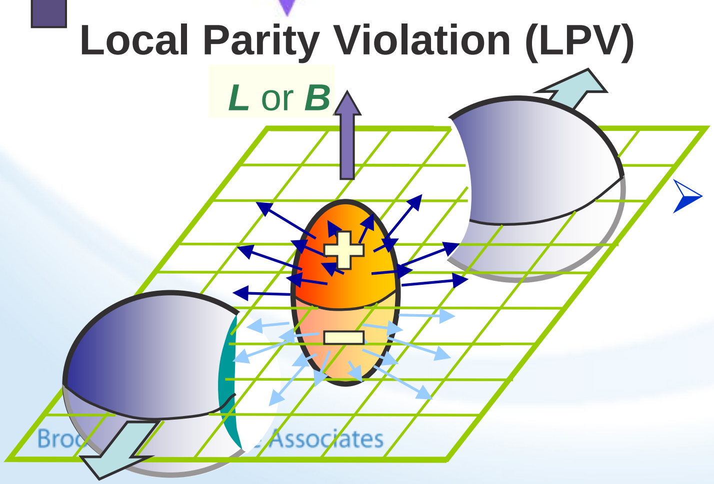
Do We See Excited QCD Vacuum Fluctuation Effects?

- ***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)***

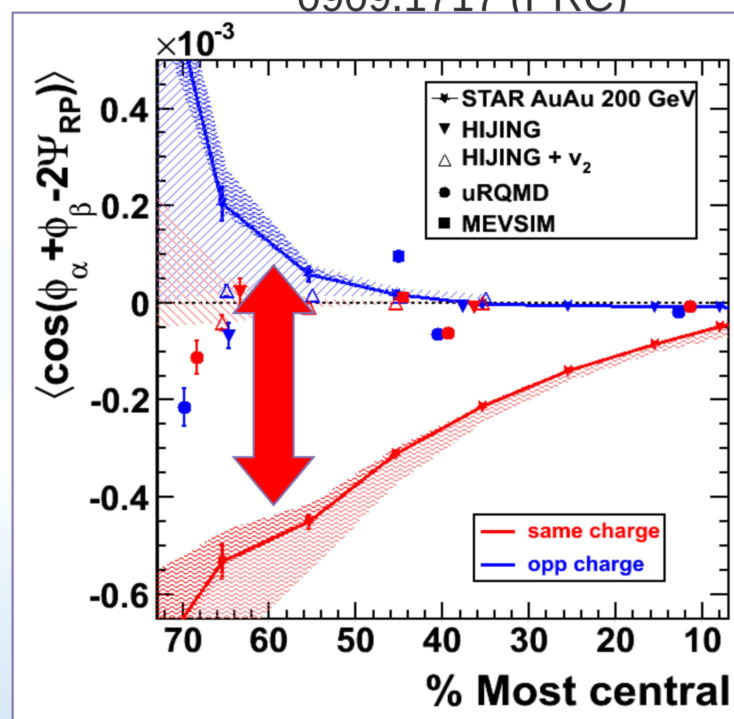


- ***Coupling with very strong magnetic field (~10^{17} G) ⇒ Chiral Magnetic Effect ⇒ event EDM (D. Kharzeev et al.)***
- ***Charge separation can survive passage through chirally restored QGP***
  - ***EDM sign can differ from bubble to bubble, event to event ⇒ event asymmetry, but no global CPV***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



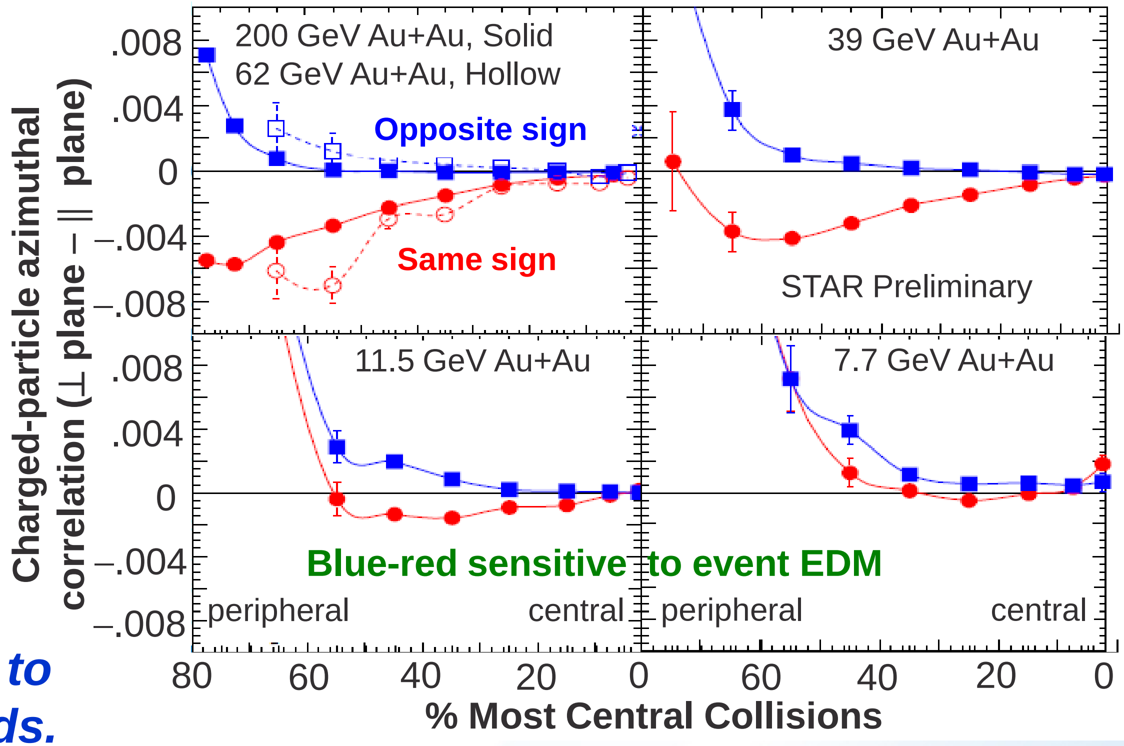


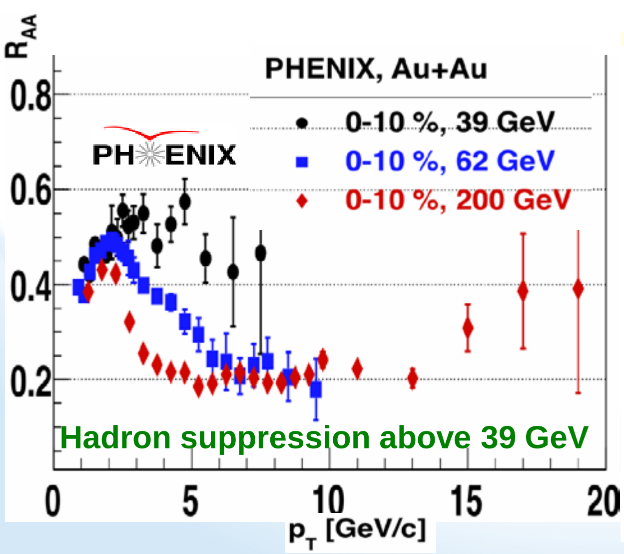
STAR; PRL103, 251601(09); 0909.1717 (PRC)



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.***





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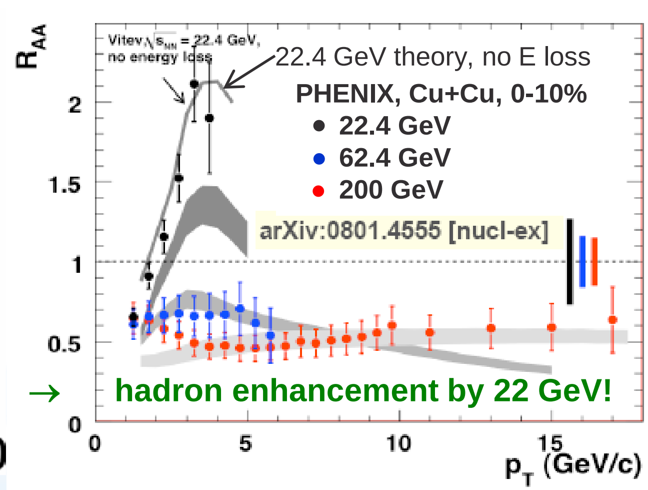
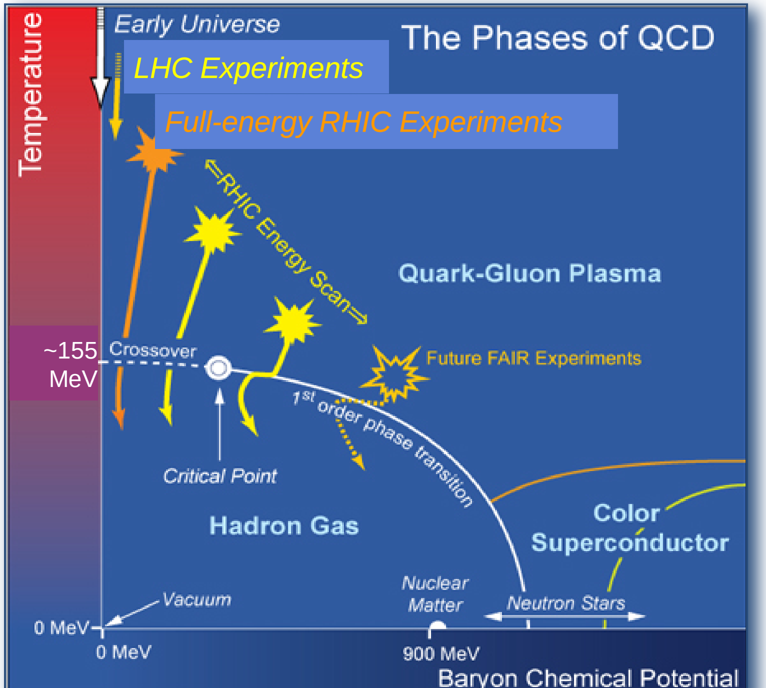


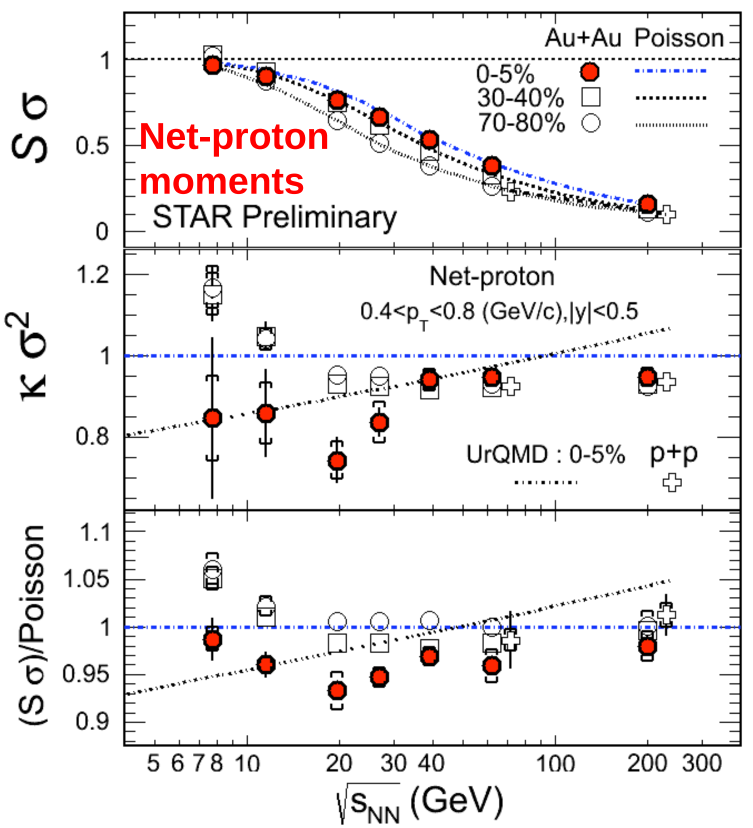
- ***Other signals also suggest QGP onset @ RHIC, e.g., disappear-ance of high-p_T hadron suppression from parton E loss, deviations from n_q scaling of elliptic flow***
- ***"Sweet spot" @ RHIC?***

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



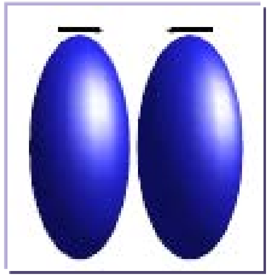
Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

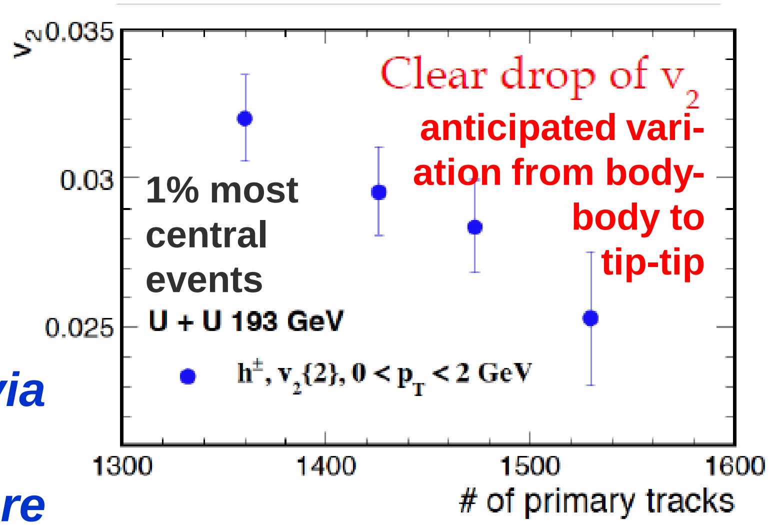
- *At near zero net baryon density probed at top RHIC energy and LHC, LQCD ⇒ smooth crossover transition*
- *At higher μ_B, theoretical arguments suggest 1st-order phase transition, but LQCD MC sampling invalid*
- *Critical point would be unique fixed point in QCD landscape*

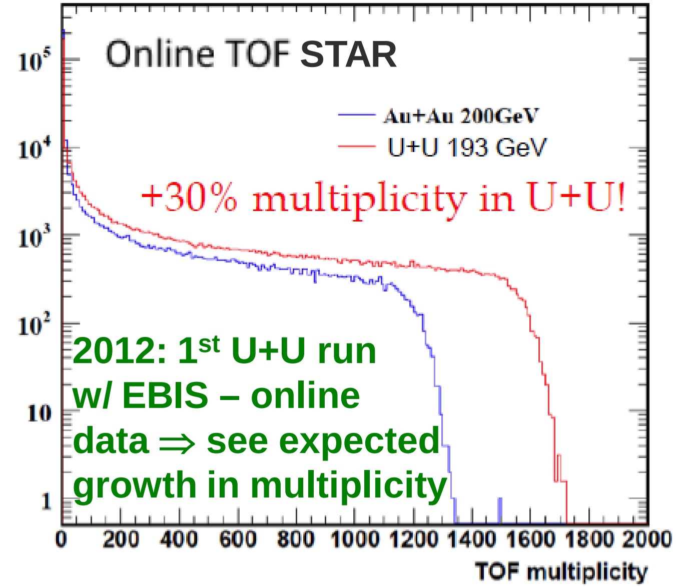


- *Expect non-Gaussian fluctuations in event-by-event distributions of conserved quantities: charge, baryon #*
- *Higher moments depend more strongly on correlation length ξ*
- *Early STAR results for 3rd & 4th moments show tantalizing hints of deviations from Poisson expectations near 20 GeV – will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

Next Steps for Quantum (Sphaleron) Snapshots

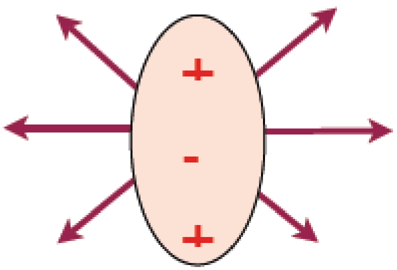






- ***Enhance bkgd. contributions via deformed U+U collisions, where ~central body-body configurations give rise to enhanced flow with reduced magnetic field***

Y.Burnier, DK, J. Liao, H.-U.Yee,
arXiv:1103.1307 - PRL



Anomaly-induced quadrupole moment **at finite baryon density**

- ***Search for related effects from QCD triangle anomaly in hydrodynamic system, predicted by Kharzeev et al.***

DK, D.T.Son
arXiv:1010.0038; PRL

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

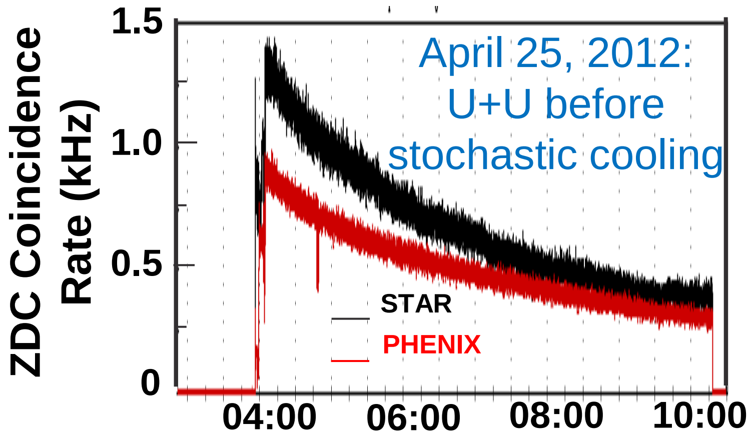
CME

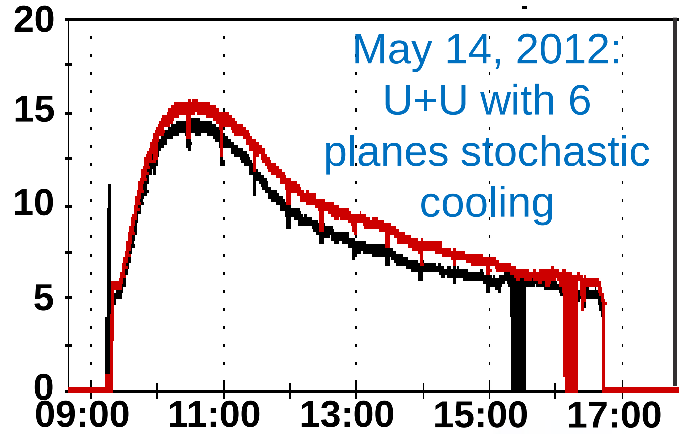
Vorticity-induced
"Chiral Vortical Effect"

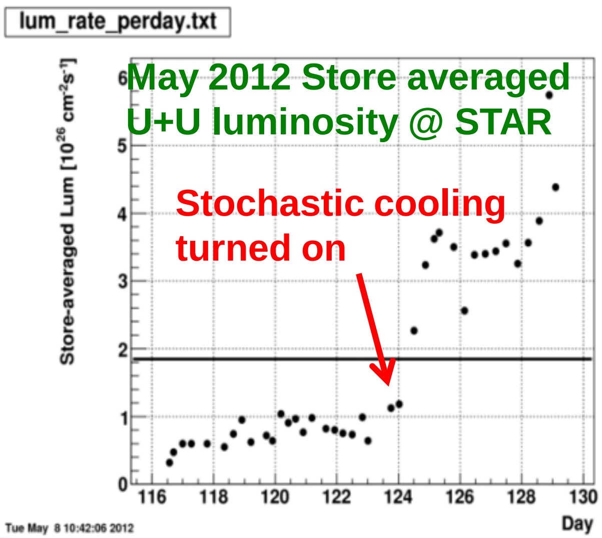
⇒ ***A baryon current correlated with charge current when baryochemical potential ≠ 0***

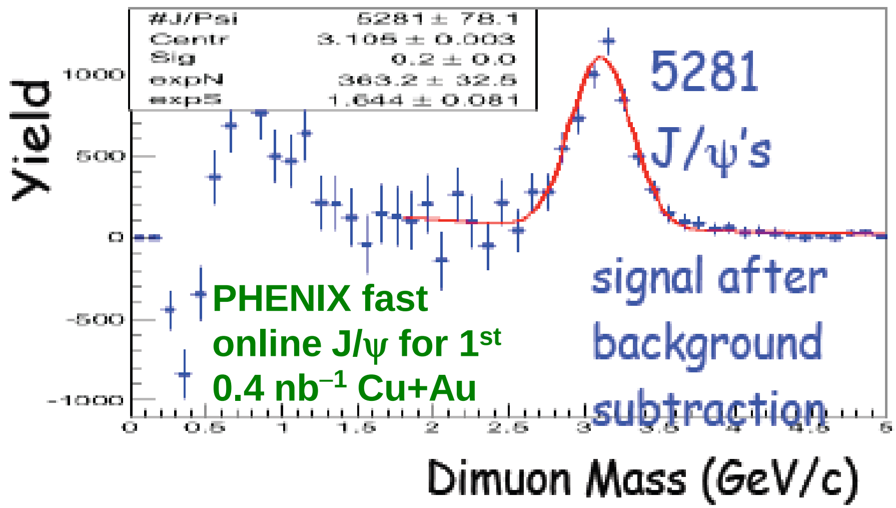
⇒ ***e.g., Λ's should be preferentially correlated with π^+ and $\bar{\Lambda}$'s with π^-, normal to reaction plane, @ $\sqrt{s_{NN}}$ = 39 GeV***

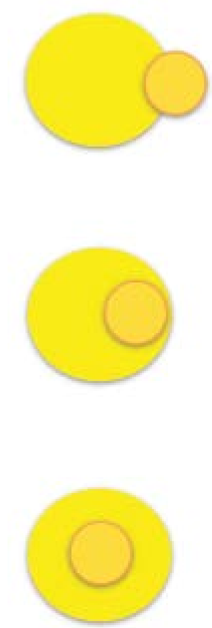
Just Completed Facility Upgrades Enable "Next Steps"







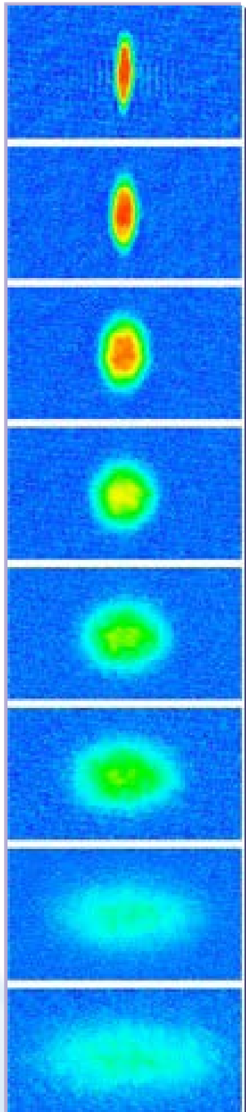




Yield sufficient to study vs. collision geom.

- ***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***

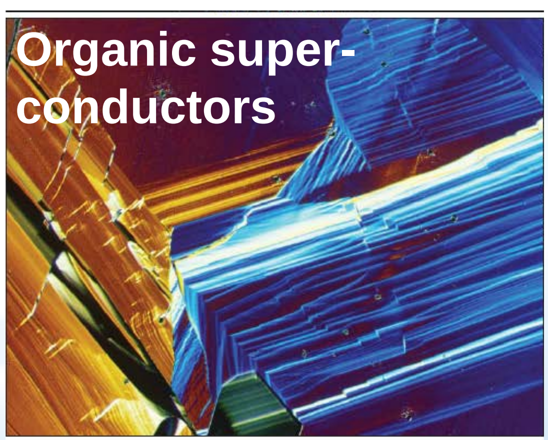
Unanticipated Intellectual Connections

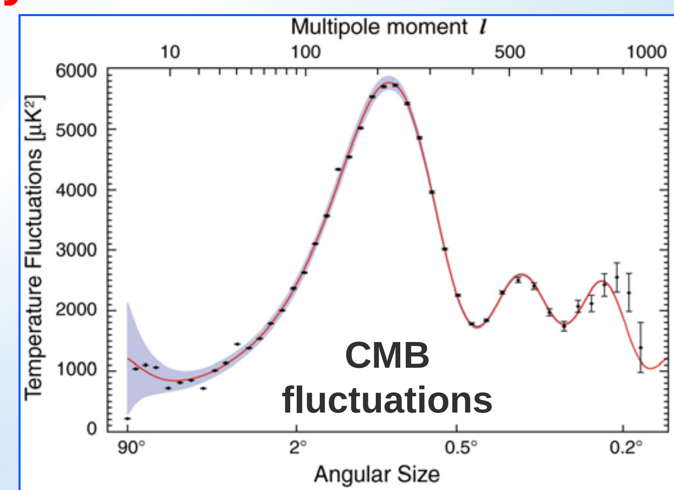


Trapped ultra-cold atom clouds

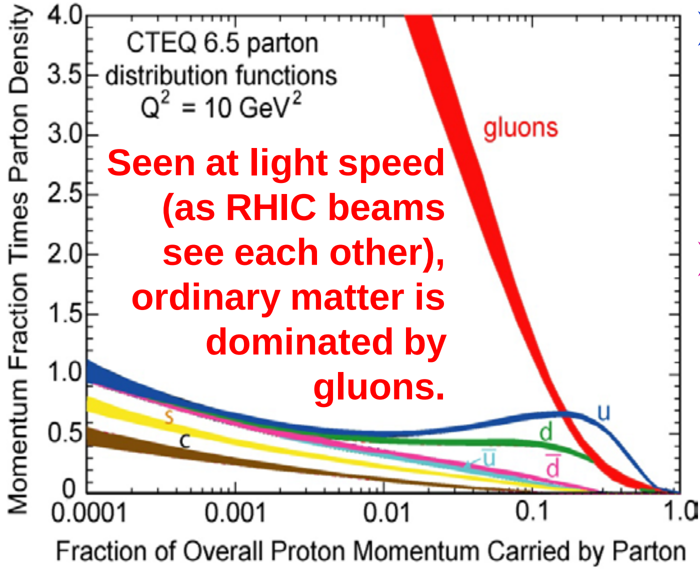
RHIC results have established ties to other forefront science:

- 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.

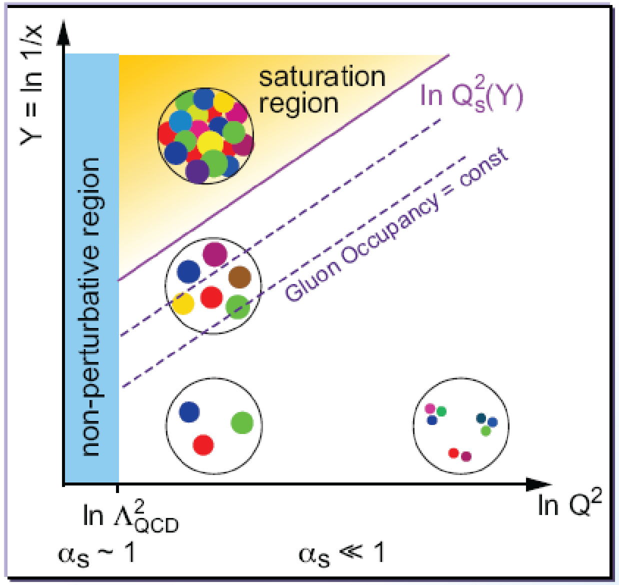




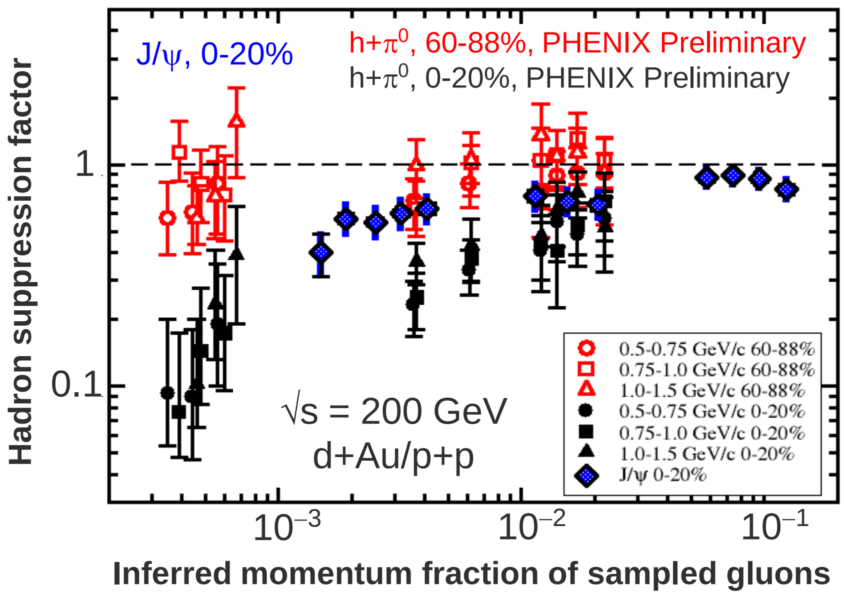
Cold QCD Matter: Do Gluon Densities Saturate?



- *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*

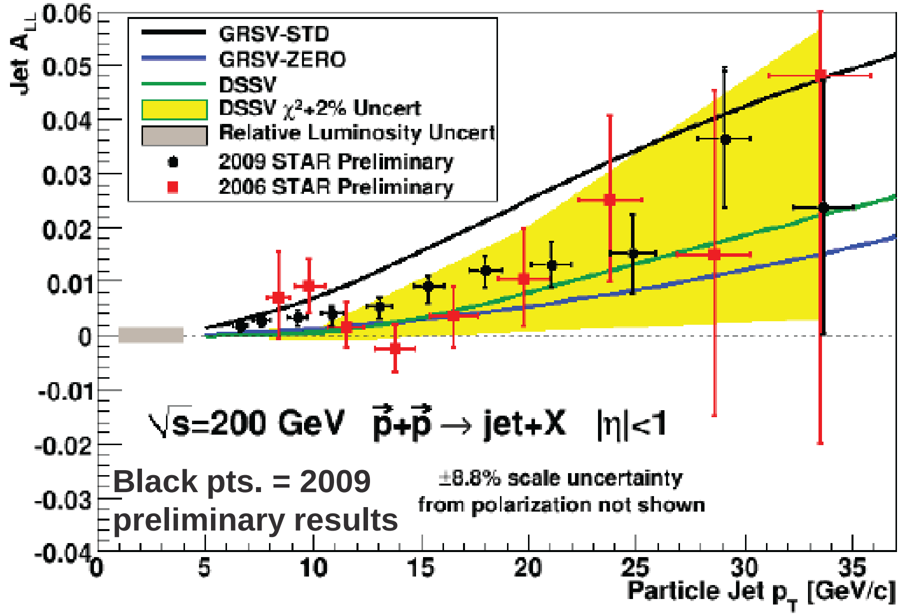


- *Coherent effects in nuclei ⇒ precocious onset of saturation*



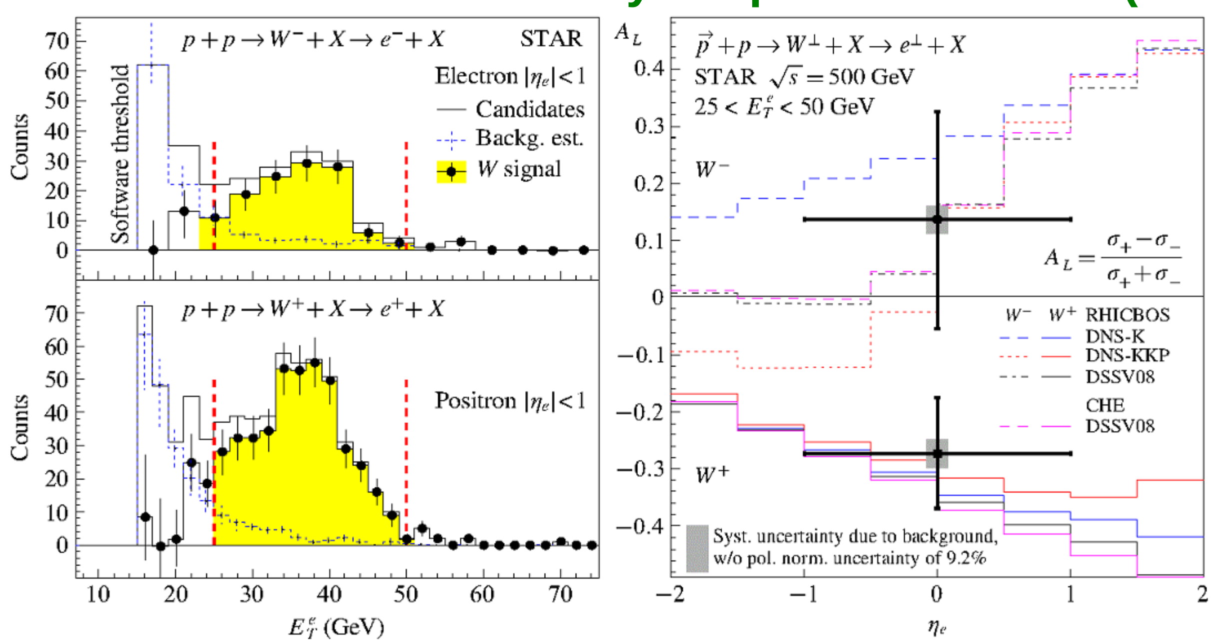
- *Forward hadron production, sensitive to gluon density at low x, is suppressed in d+Au collisions @ RHIC, as seen in early BRAHMS results*
- *Forward di-hadron coincidences probe very asymmetric parton collisions, involving low-x gluon from one beam*
- *In CGC regime, expect 2→2 parton scattering to be replaced by scattering from a coherent gluon field ⇒ "mono-jets," consistent w/ new PHENIX (left) & STAR results*

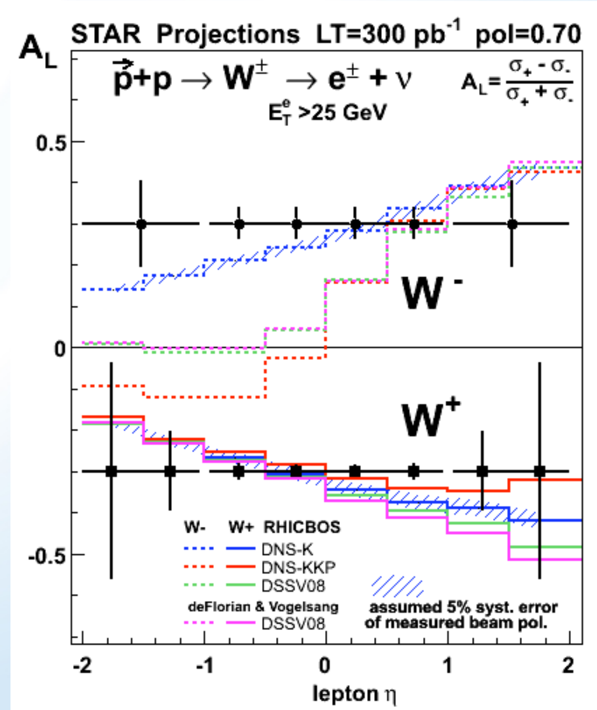
Cold QCD Matter: Where is the Missing Proton Spin?



- $\overrightarrow{DIS} \Rightarrow$ *only ~30% of spin from q spins*
- *RHIC spin program exploits pQCD interaction dominance in hard $\vec{p}+\vec{p}$ collisions, with strong sensitivity to gluon helicity preference $\Delta G(x)$*
- *Best results so far from inclusive jet prod'n $\Rightarrow$ ΔG small > 0, but extrapolation to x < 0.05 highly uncertain*
- *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)

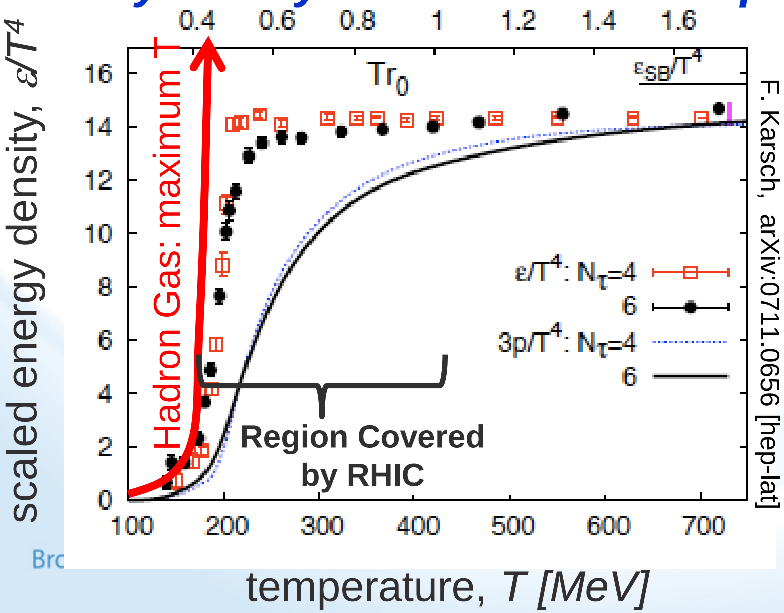




2^{nd} Decade: Exploit $\sqrt{s}$ "Sweet Spot" + RHIC's Versatility and Upgrades for Quantification & Further Discoveries

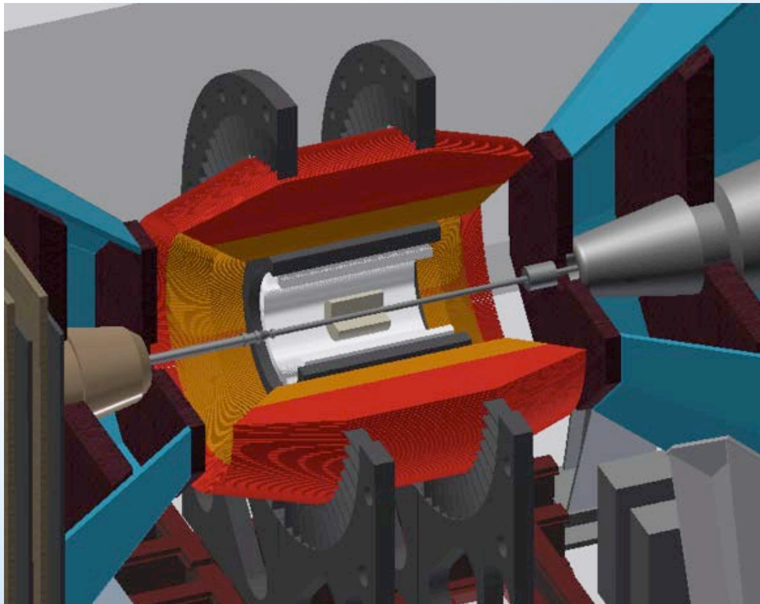
- How perfect is the near-perfect fluid, as fcn. of temp.?
- How do fluctuations (both initial density & excited QCD vacuum) affect evolution of "mini-universe"?
- Is there a critical endpoint in the QCD phase diagram?
- How do quarks and gluons lose energy in the QGP, as fcn. of quark flavor (including 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.***



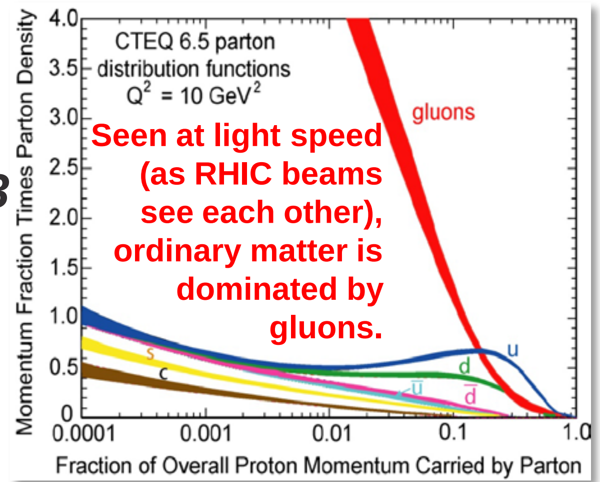
Program requires ~5 years before + ~5 years after next round of significant detector & collider upgrades

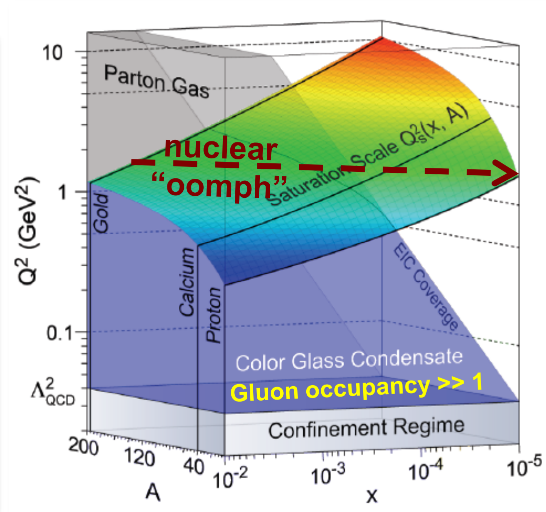
- ***Understanding parton E loss requires comparing jet quench-ing characteristics @ LHC vs. RHIC ⇒ need sPHENIX upgrade***



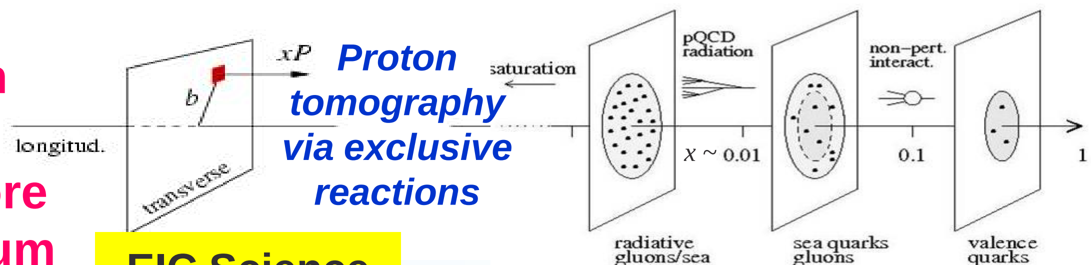
Electron-Ion Collider (EIC) Extends RHIC and JLab Science

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

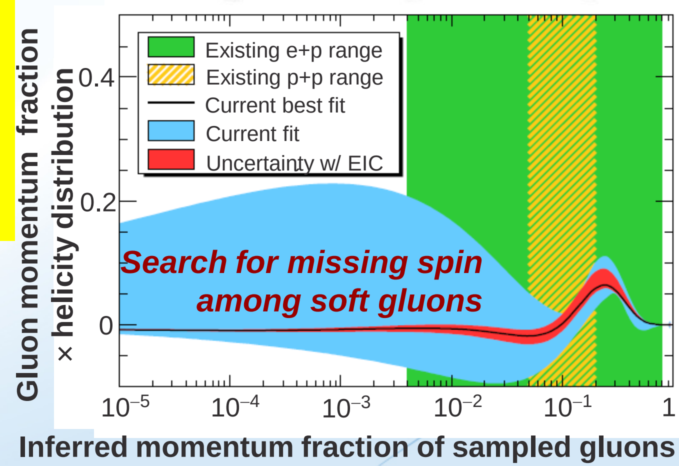




- **Probe the momentum-dependence of onset of gluon saturation in nuclei (initial state @ RHIC & LHC)**
- **Map the gluon densities and multidimensional spatial & spin distributions of partons in the gluon-dominated regime; explore parton orbital angular momentum**
- **Test effective theory approaches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

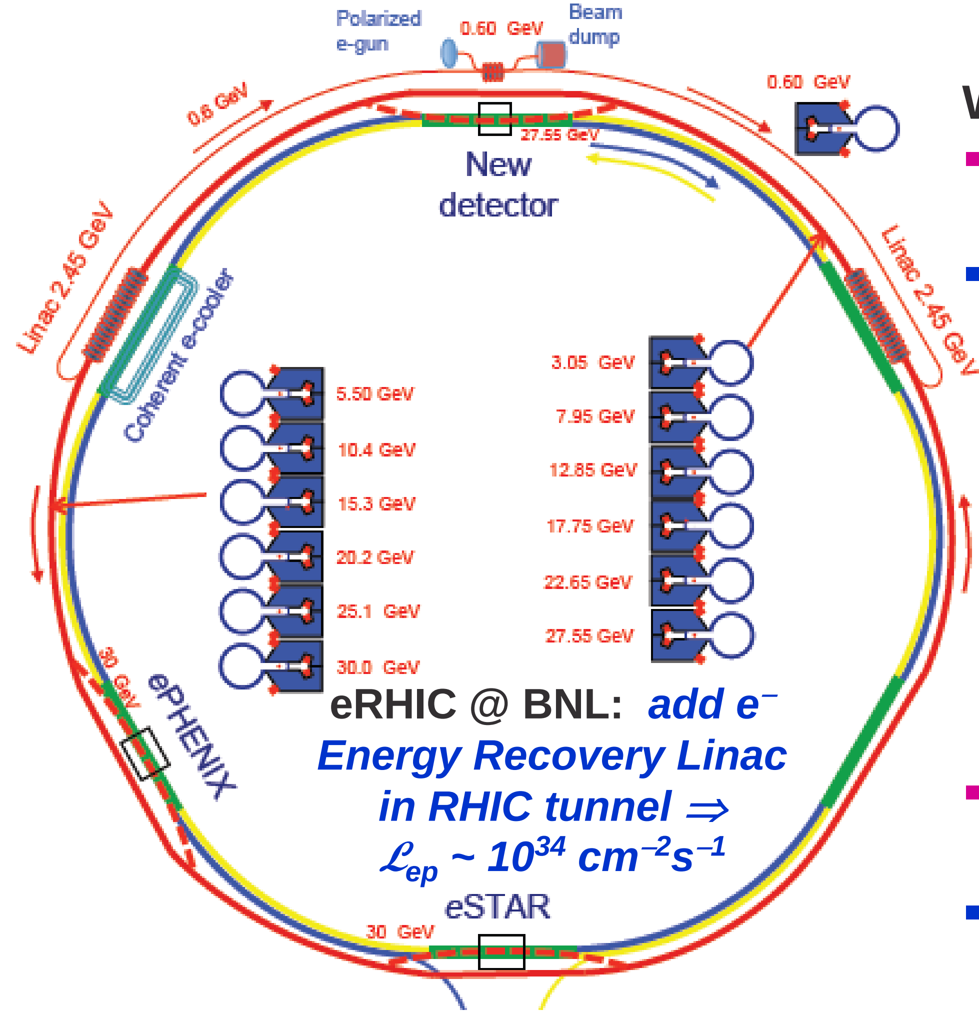


EIC Science White Paper should be available in 2012



Machine requirements: high $\sqrt{s}$ (~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



eRHIC @ BNL: ***add e⁻ Energy Recovery Linac 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 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***

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.

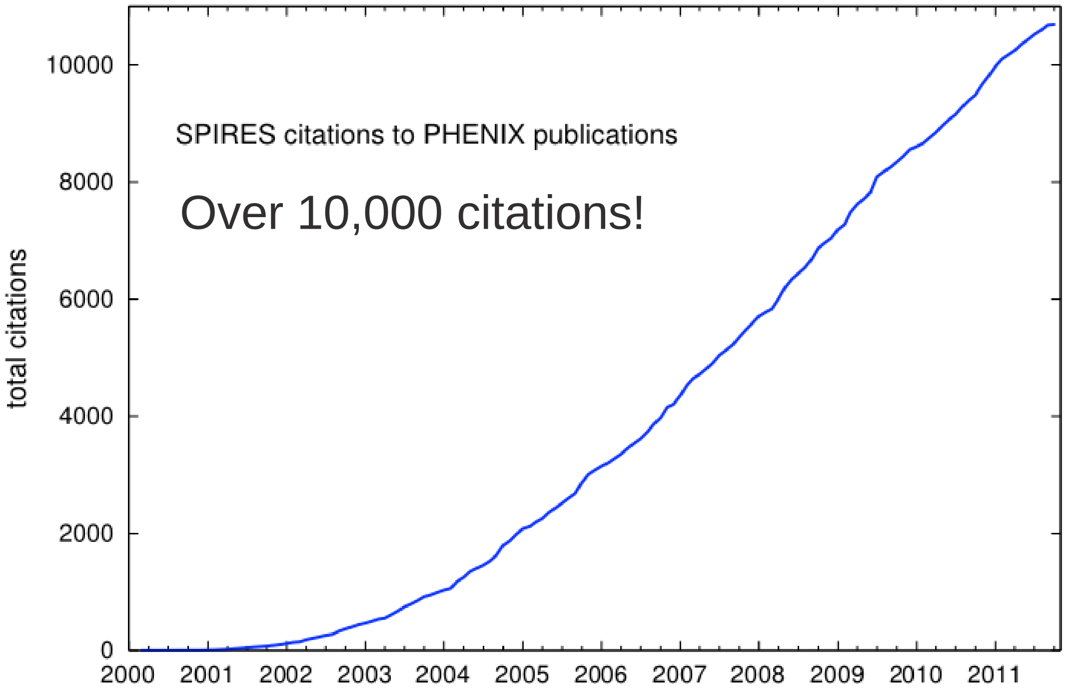
Seller Beware: We estimate RHIC D&D costs to be ~$1B.

What Would be Lost if RHIC Were Terminated?

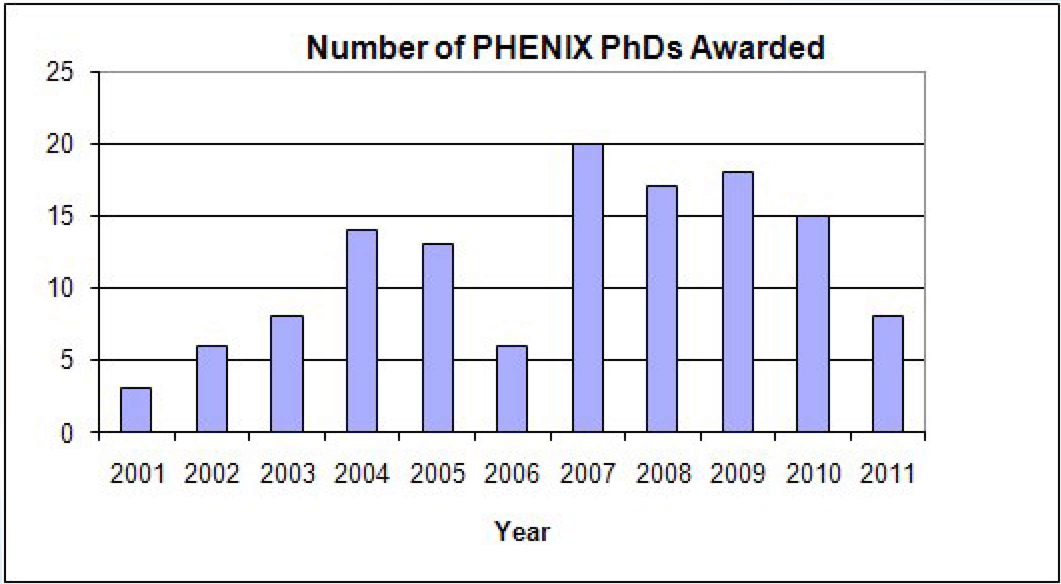
- Opportunity to map QCD matter properties across QGP transition and discover the possible Critical Point.
- Unique polarized pp access to nucleon spin structure.
- U.S. leadership in a vibrant NP subfield it pioneered.
- A major fraction of the productivity for U.S. NP over the better part of a decade – 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.

Backup Slides

PHENIX has published 108 papers!



Need similar plots from STAR.



7 Most cited papers of PHENIX

	committee	citation count	Japanese members of paper writing
1.	NPA757(2005) 184	1186	Akiba*/Esumi (2/10)
2.	PRL88 (2002) 022301	611	
3.	PRC69 (2004) 034909	473	Chujo*/Kiyomichi/Miake (3/4)
4.	PRL91 (2003) 072301	462	
5.	PRL91 (2003) 182301	438	Esumi*/Masui/Miake/Sakai (4/5)
6.	PRL91 (2003) 072303	348	
7.	PRL98 (2007) 172301	325	Akiba/Kajihara/Sakai (3/5)

Will include such a list for RHIC experiments overall.

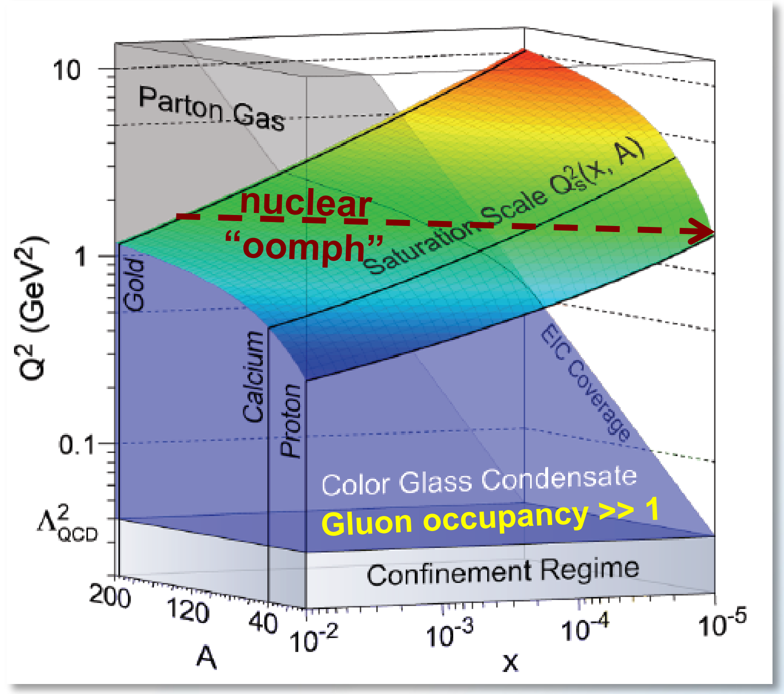
* Chairman of the paper writing committee

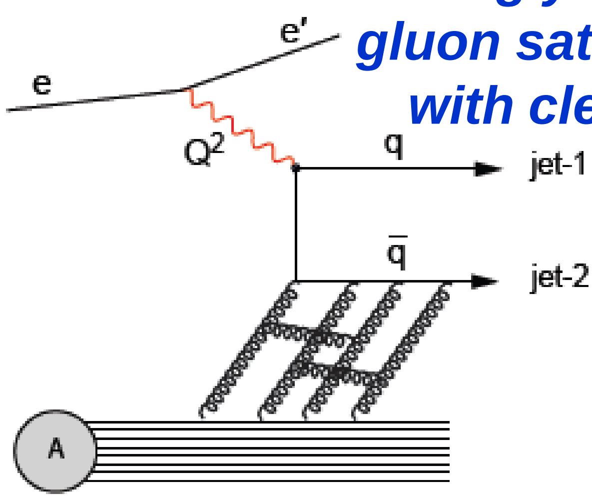
RHIC-Related Articles in General Science Journals

What Will EIC Have That HERA Didn't?

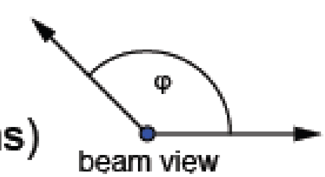
1) ***Heavy-ion beams to take advantage of coherent contributions of many nucleons to gluon density, provide more cost-effective reach into gluon saturation regime when QCD coupling is still weak.***

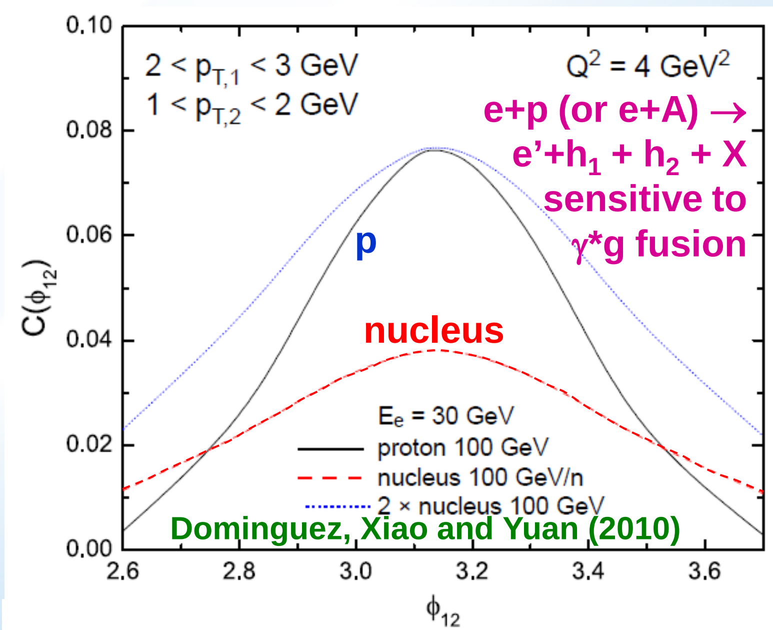
E.g., dijet or dihadron correlations, normally dominated by γ^*g fusion, should be strongly suppressed by gluon saturation in e+A, with cleaner interpret-ability than in d+A or p+A





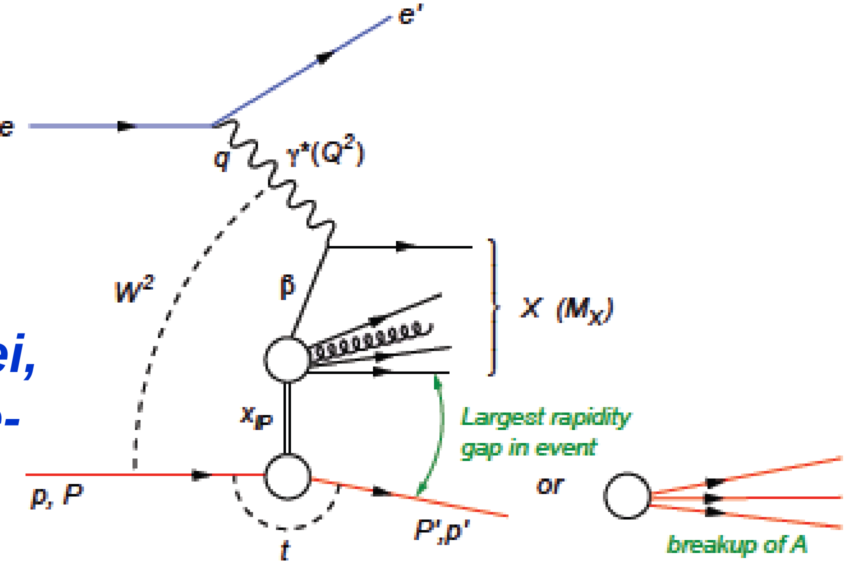
Either Jets or use leading hadrons from jets (dihadrons)

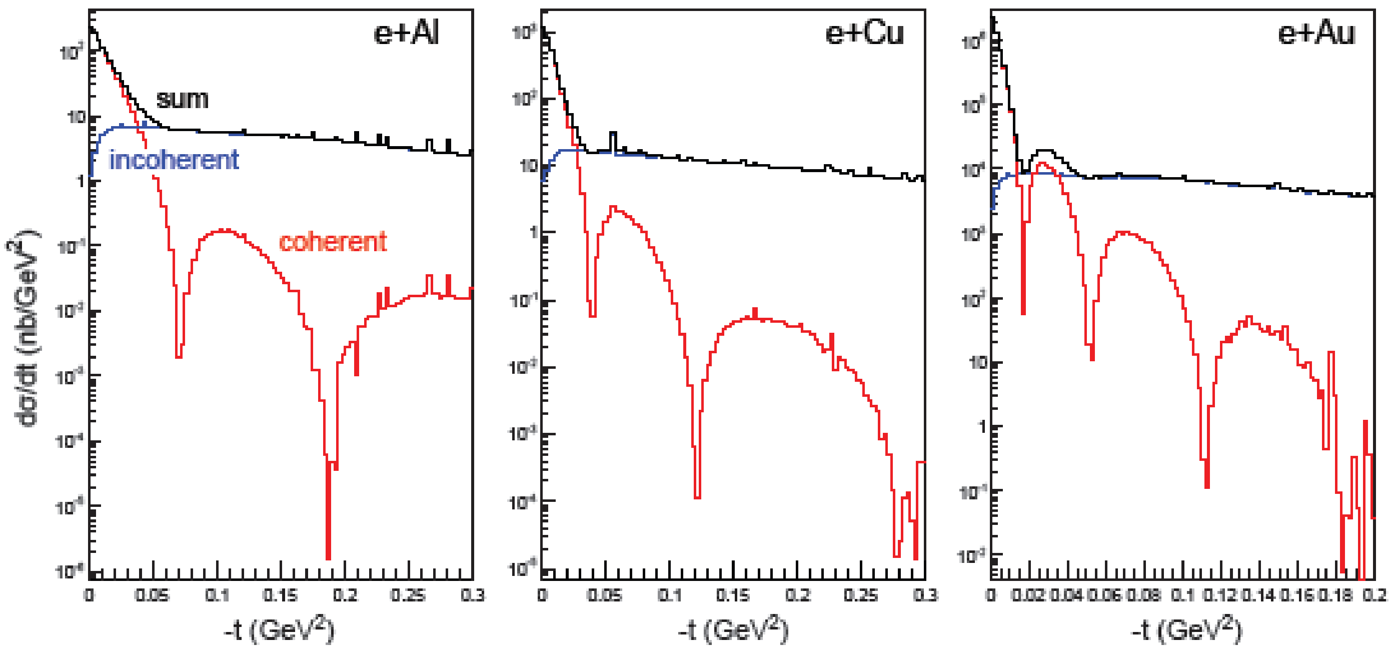




e+A Diffractive Processes Also Very Sensitive to Gluon Densities

- *Diffraction should give an even larger fraction of total X-section than @ HERA: → 25-40% in e+A !*
- *Coherent diffractive VM production probes "gluonic form factor" in nuclei, if far forward fragment veto adequately suppresses incoherent bkgd.*
- *How does spatial distrib'n of gluons evolve as gluon density saturates?*





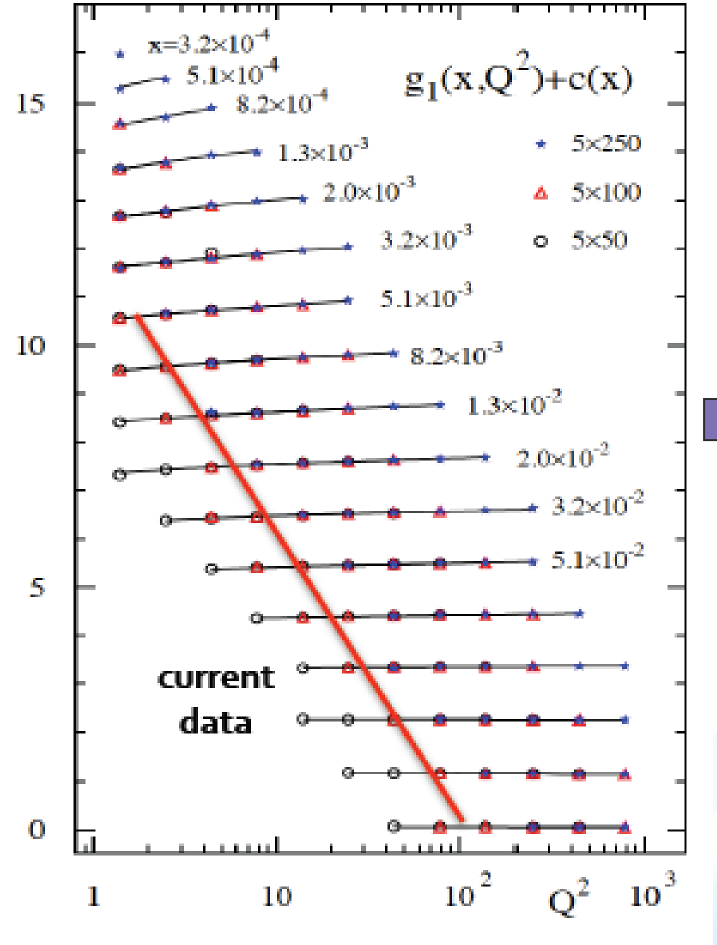
$e + A \rightarrow e' + J/\psi + A'$

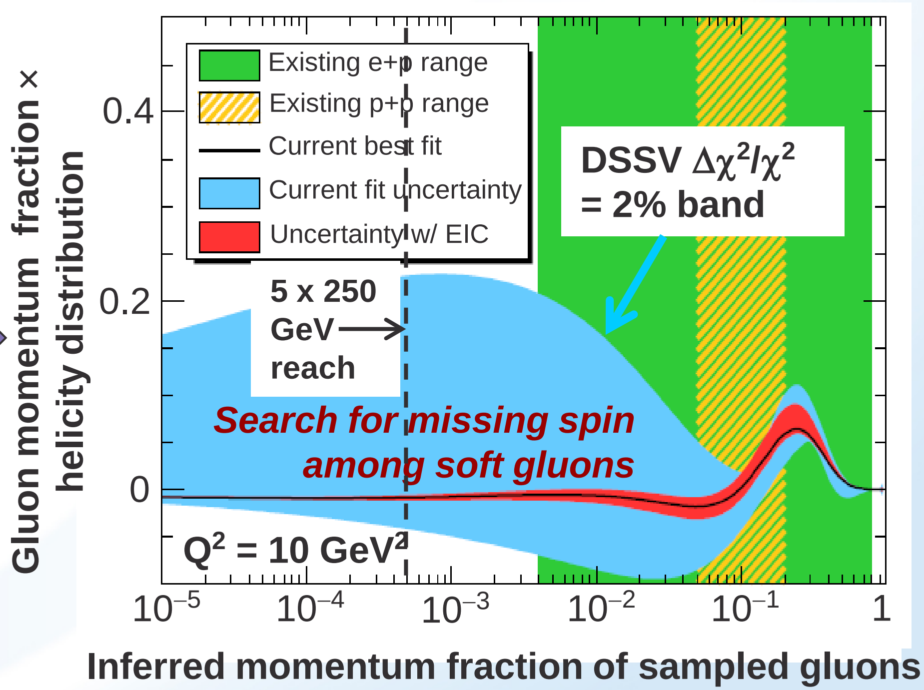
dσ/dt is Fourier Transform of $\rho_{glue}(b)$

"Gluonic Form Factor"

What Will EIC Have That HERA Didn't?

2) *Polarized proton and ^{3}He (for neutron), as well as electron, beams to pursue search for gluon contributions to nucleon spin down to very soft gluons, and map spin-momentum correlations of quarks and gluons inside nucleons.*





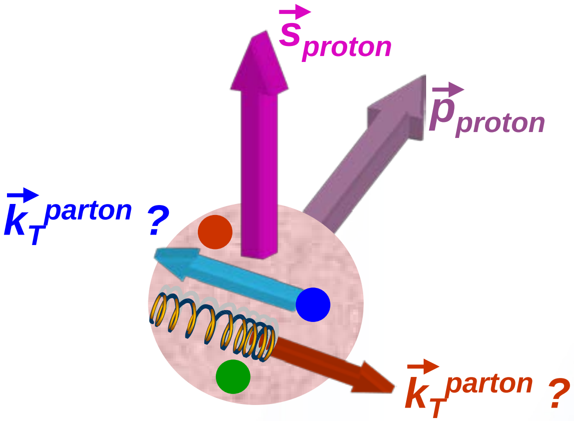
BROOKHAVEN NATIONAL LABORATORY

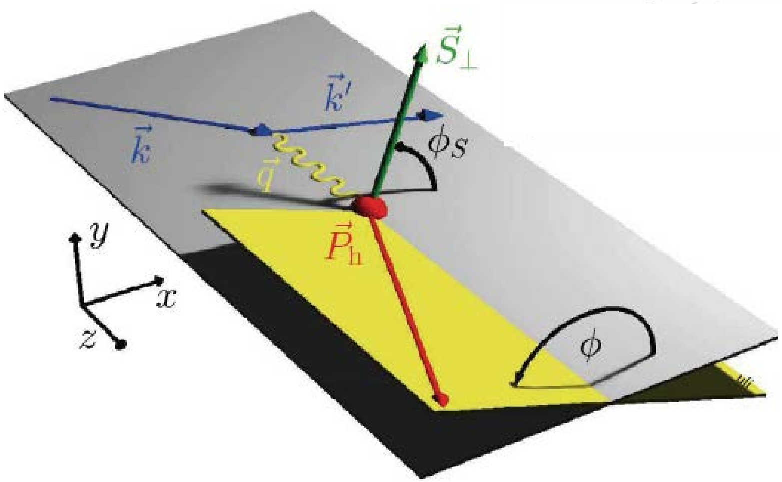
Spin-Momentum Correlations of Partons in Nucleons

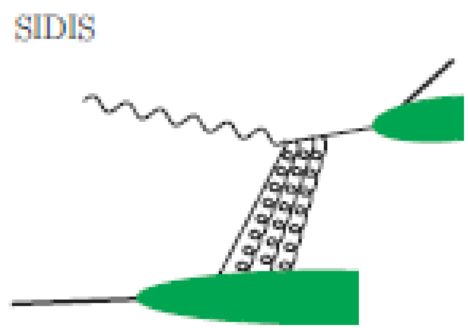
For example, the Sivers effect:

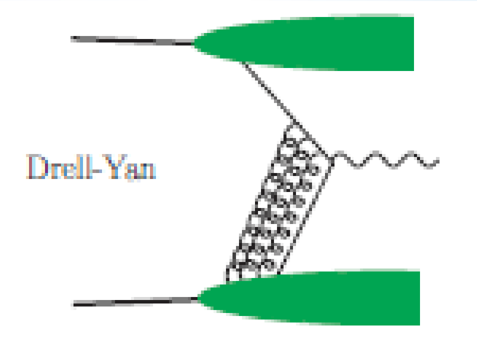
$$\left\langle \vec{s}_{proton} \cdot \left(\vec{p}_{proton} \times \vec{k}_T^{\,parton} \right) \right\rangle_{observed\ \ process} \neq 0$$

Sensitive to parton orbital components in proton wave function, but also needs initial- and/or final-state interactions to evade TRV.









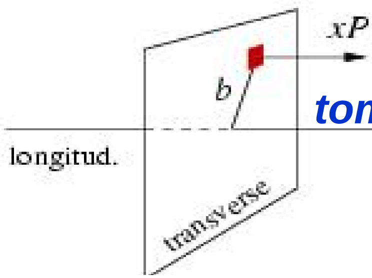
- partons are not isolated but embedded in environment of gluons
- Sivers distribution = indicator for this effect; color structure of FSI vs. ISI ⇒ changes sign between SIDIS and DY (RHIC measurements)
- Sivers distribution essentially unknown for sea quarks and gluons

What Will EIC Have That HERA Didn't?

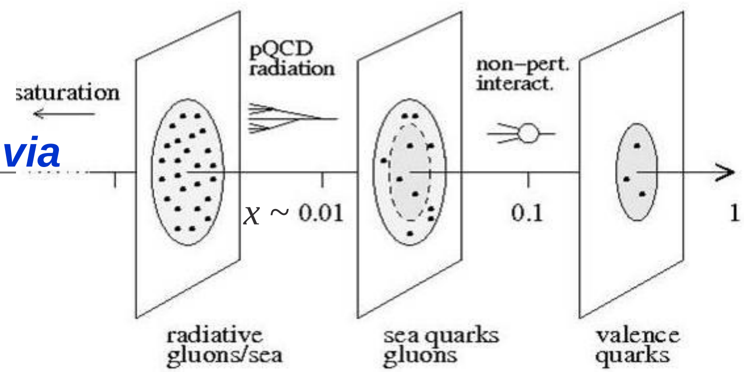
3) *2—3 orders of magnitude higher collision luminosity to facilitate exclusive reaction studies yielding 2+1- dim'l maps of internal nucleon wave function, and symmetry violation studies of fundamental electroweak interaction properties.*

Deep exclusive measurements in ep/eA with an EIC:

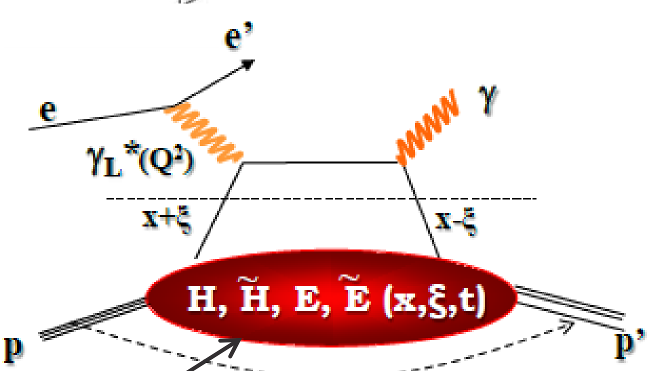
diffractive:	transverse gluon imaging	J/ψ, ϕ, ρ^o, γ (DVCS)
non-diffractive:	quark spin/flavor structure	π, K, ρ^+, …



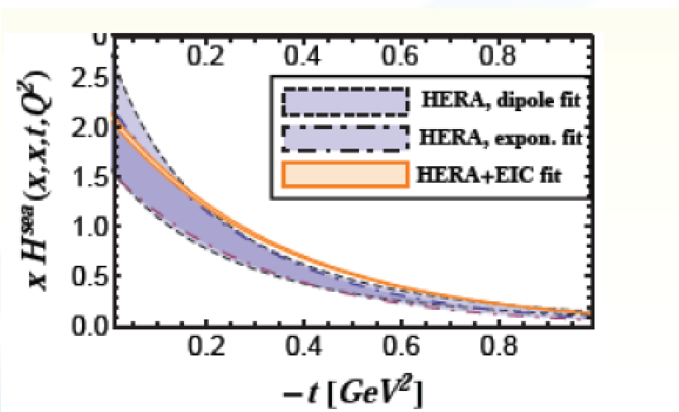
Proton tomography via exclusive reactions

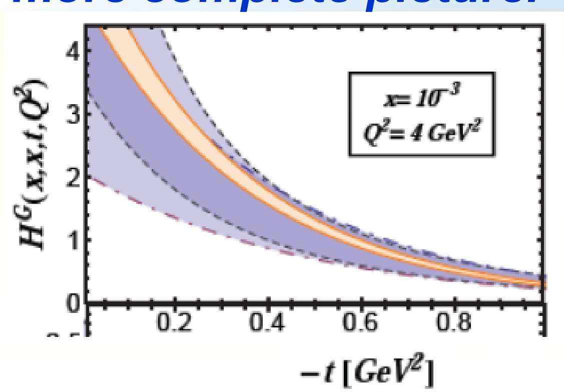


EIC 20 x 250 GeV DVCS x-sect. data (1 month run) ⇒ much improved constraints on GPD H. Spin & meson prod'n + multi-dim'l binning ⇒ more complete picture.

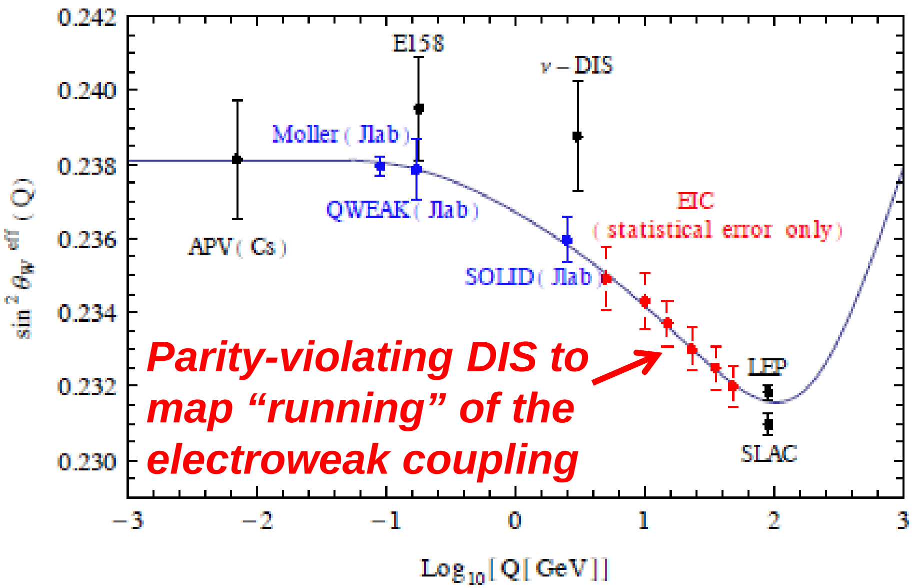


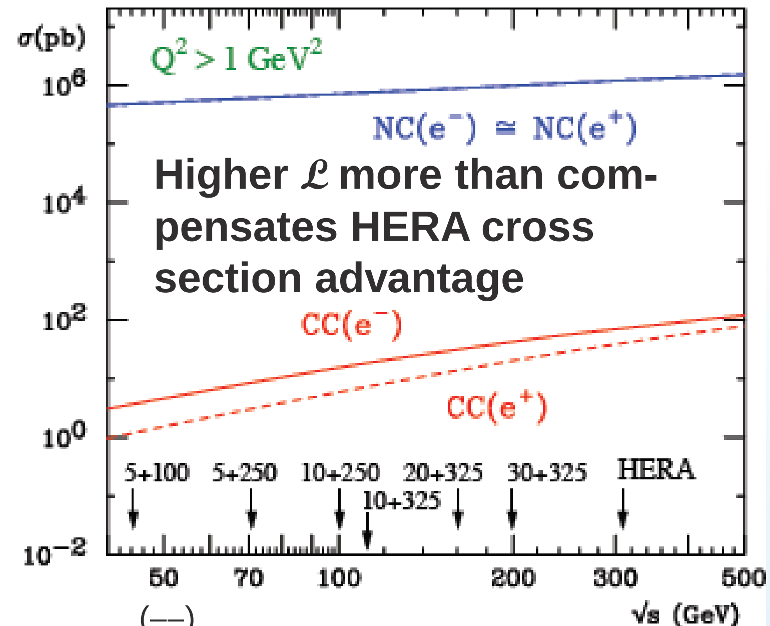
GPD's contain t form factor & parton distrib'n info combined

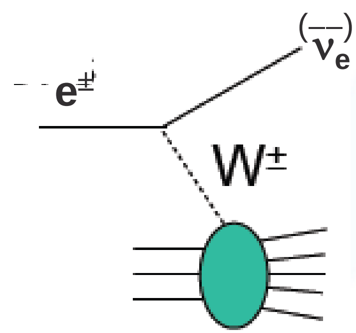




High Luminosity + Polariz'n Facilitate ElectroWeak Studies







Parity-violating electron helicity asymmetries in DIS probe running of weak coupling @ high Q^2, but below Z-pole.

Parity-violating N helicity asymmetries for CC DIS probe PDF combos distinct from γ-exch. Reconstruct x, Q^2 from final-state hadrons.

- Work in progress
  - evaluation of background
  - systematic errors
  - precision of polarization measurements?

CC:

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$
$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$
$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

What Will EIC Have That HERA Didn't?

4) Wide variability in both electron and hadron energy, permitting separation of longitudinal from transverse structure functions for eN, eA:

$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \qquad y = Q^2/xS \qquad Y_+ = 1 + (1-y)^2$$

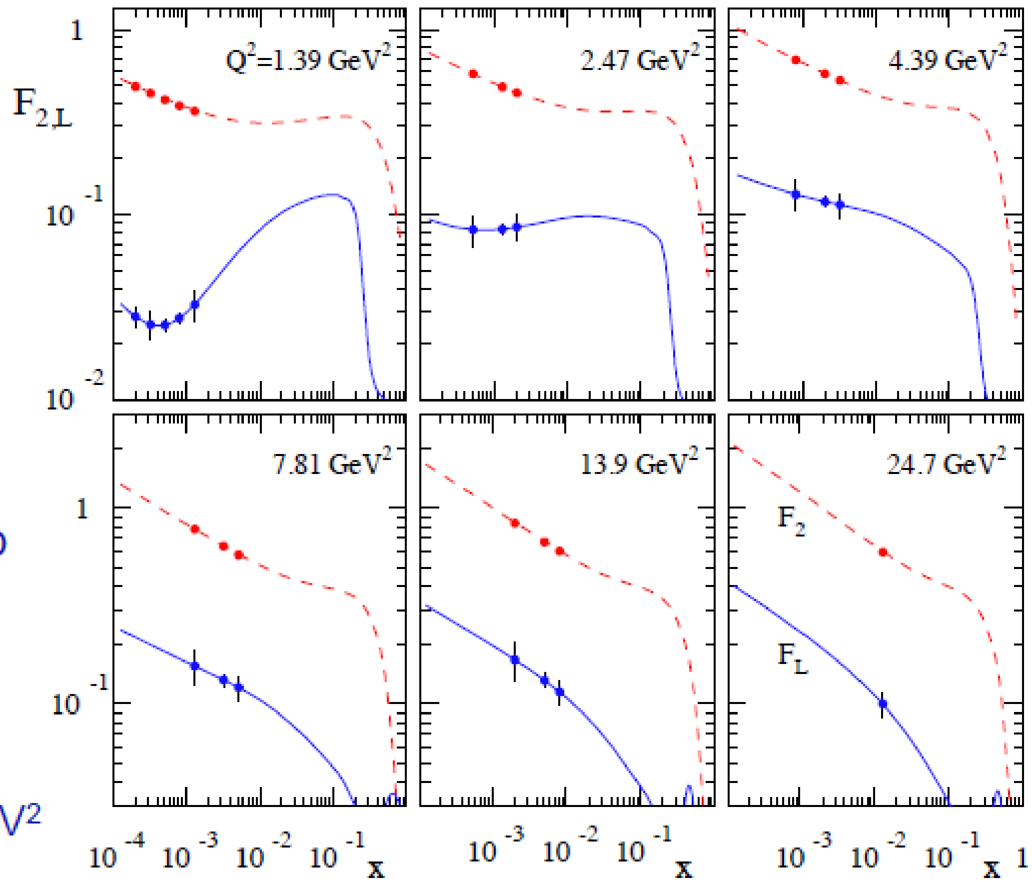
F_L gives direct information on gluon density, determined from slope of y^2/Y_+ for different S at fixed x,Q^2

$F_{2,L}$ extracted from pseudo-data generated for 1 month running at 3 eRHIC energies

- 5+100 GeV
- 5+250 GeV
- 5+325 GeV

Data points added to theoretical expectations from ABKM09 PDF set to visualize stat. errors

- valid for $Q^2 > 2.5\ GeV^2$



Range of data would be expanded with higher e energies as well.

Impacts of radiative corr'ns (esp. e+A) and σ syst. errors at different √s need to be considered carefully.