Relativistic Heavy Ion Collisions: Status and Future

Steve Vigdor

DNP Meeting, East Lansing

October 26, 2011

I. D. Kovar's role in establishing RHIC
II. Ongoing development of the facility
III. Framing RHIC and LHC heavy-ion science
IV. The Learning Curve: Early results & discoveries; recent developments; profound open questions
V. Completing the Narrative Arc: 2nd & 3rd acts in American (i.e., D. Kovar) lives and American labs

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

The Intertwined Histories of RHIC and Dennis

1983 LRP: ***recommend a relativistic heavy-ion collider "as the next new major construction item for nuclear science," just after HEPAP voted to discontinue construction of CBA in tunnel already dug at BNL.***

1989 LRP: ***"We strongly reaffirm the very high scientific importance of the Relativistic Heavy Ion Collider. … We urge a swift beginning…"***

1990: ***Kovar moves from ANL to DOE as Program Manager for Heavy Ion Nuclear Physics***

1996: ***Kovar named DOE Project Officer for RHIC construction – wears out S. Ozaki by insisting on full examination of entire ring circumference!***

1996 LRP: ***"RHIC remains our highest construction priority." Also endorsement of RHIC Spin program.***

1998: ***DK takes over as Director of DOE Div. of NP***

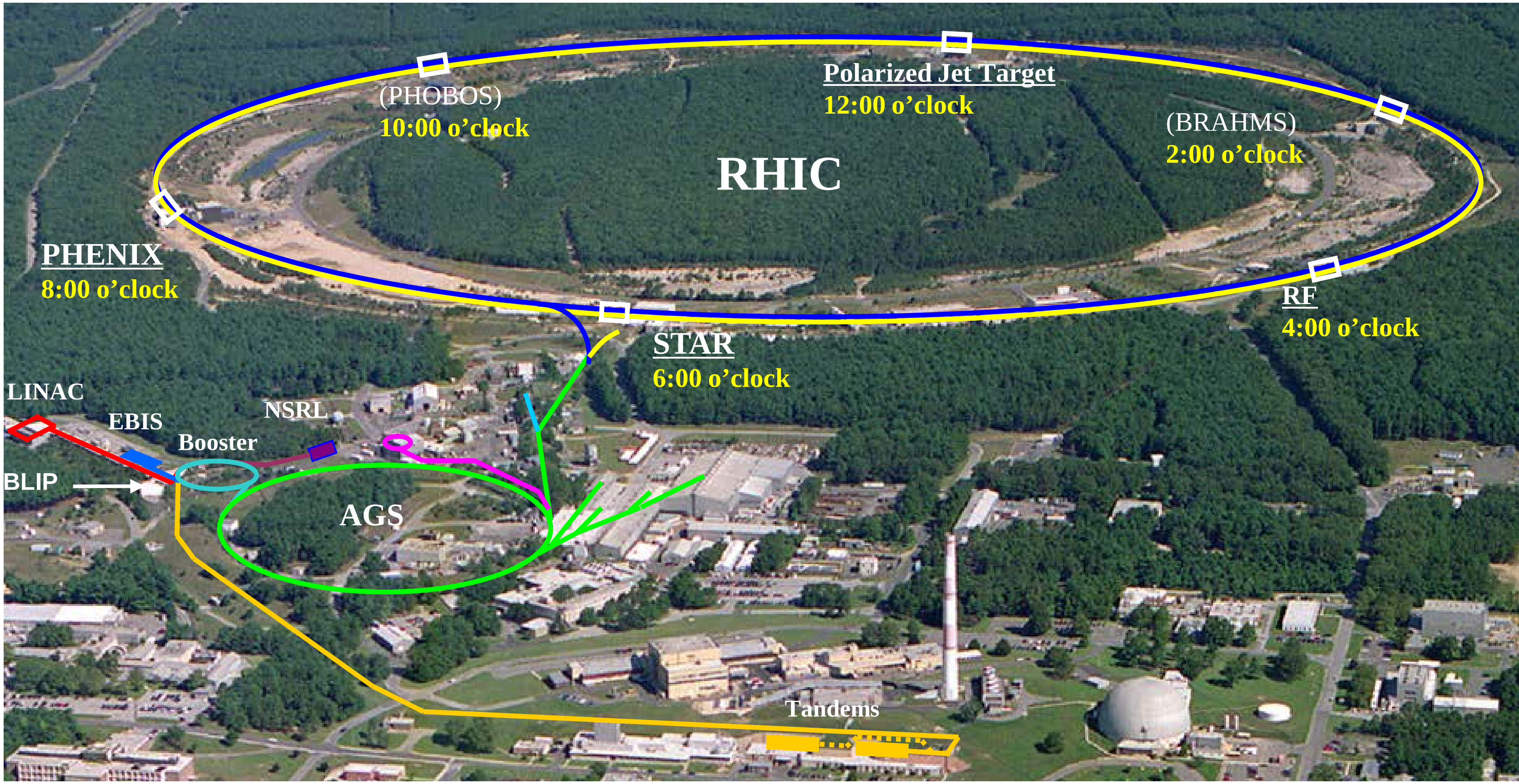
2000: ***RHIC operations start***

2003: ***DK named AD of Science for Nuclear Physics***

D. Kovar, S. Ozaki & friends, celebrating completion of RHIC magnet production, Sept. 17, 1998

Dennis not only midwifed RHIC, but also oversaw launch of modest US contributions to LHC heavy ion program

RHIC's First Decade: A Discovery Machine



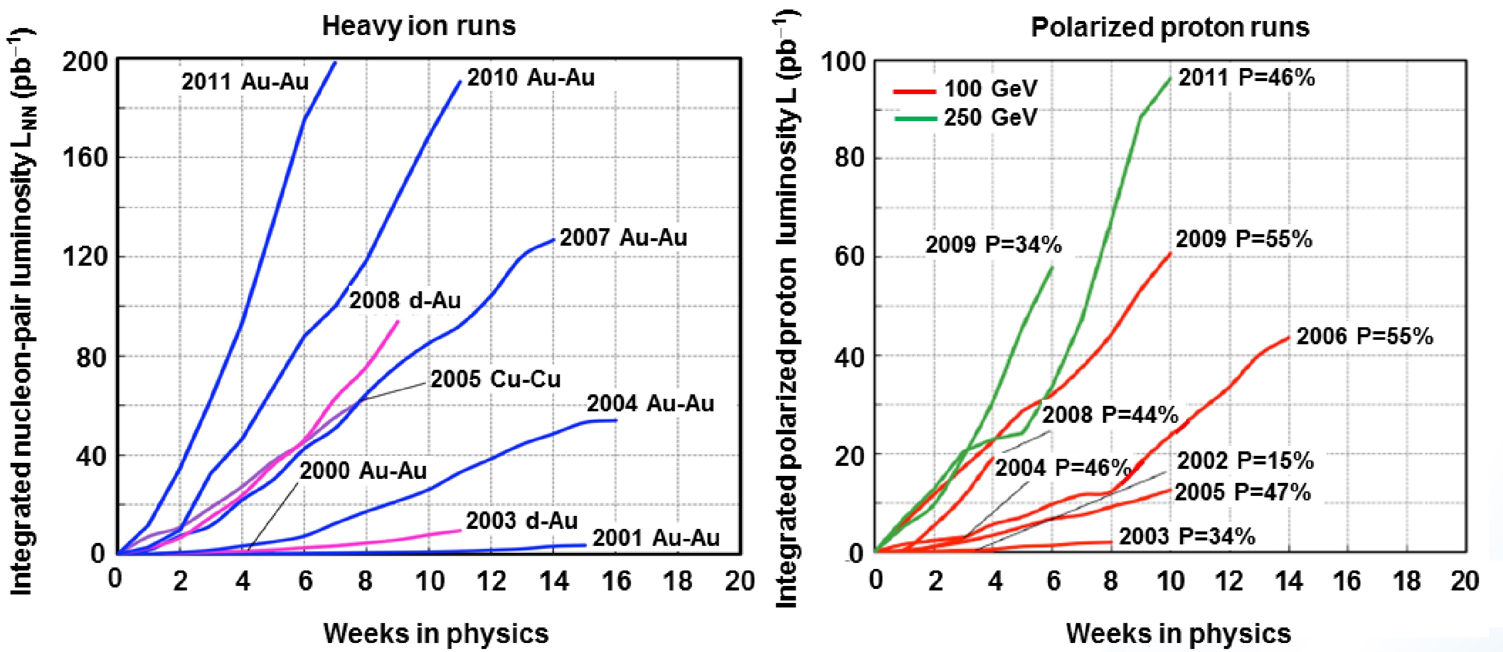
RHIC hallmarks:

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

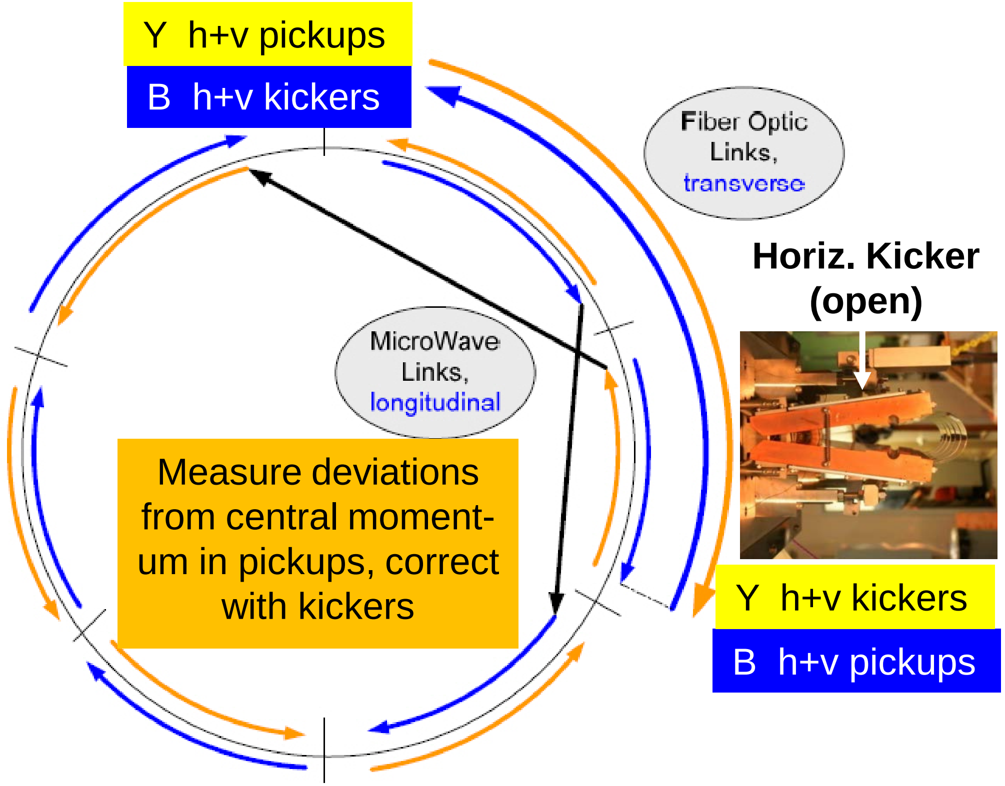
Versatile – wide range of beam energies and ion species ⇒ string of definitive discoveries in both hot and cold QCD matter

Incremental Upgrades ⇒ Steadily Improving Performance

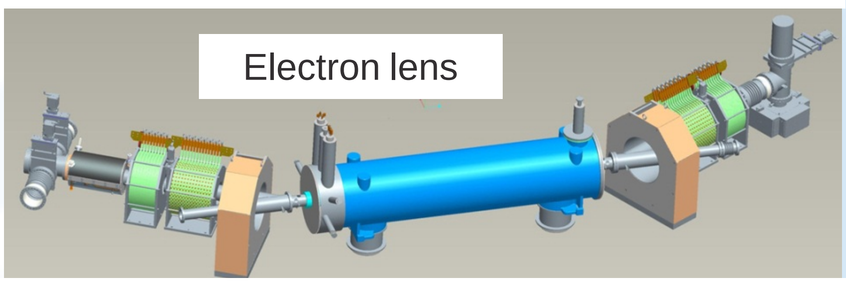


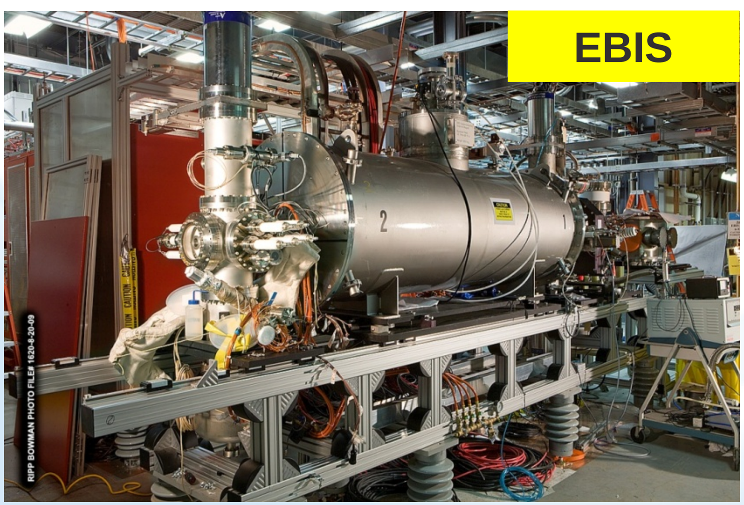
Collision partners	Beam energies (GeV/nucleon)	Peak pp-equivalent luminosities achieved to date, scaled to 100 GeV/n[b)]
Used to date		
Au+Au	3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 28, 31, 65, 100	195×10^{30} $cm^{-2}s^{-1}$
d+Au[a)]	100	100×10^{30} $cm^{-2}s^{-1}$
Cu+Cu	11, 31, 100	80×10^{30} $cm^{-2}s^{-1}$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

Recent and Ongoing 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***
- ***Much of the new system commissioned during 2010-11, rest anticipated for 2012-2014 runs (aided by ARRA funds).***
- ***Electron lenses (ARRA + AIP) to be installed for 2013 run to improve polarized pp luminosity by factor ~2***



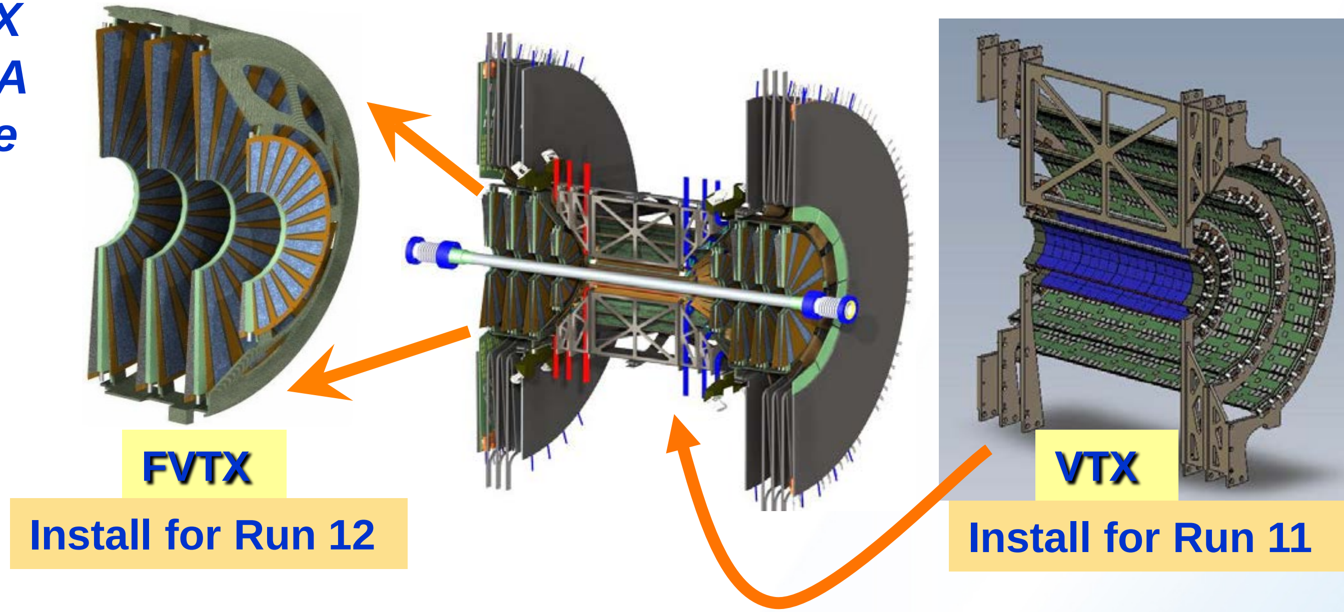


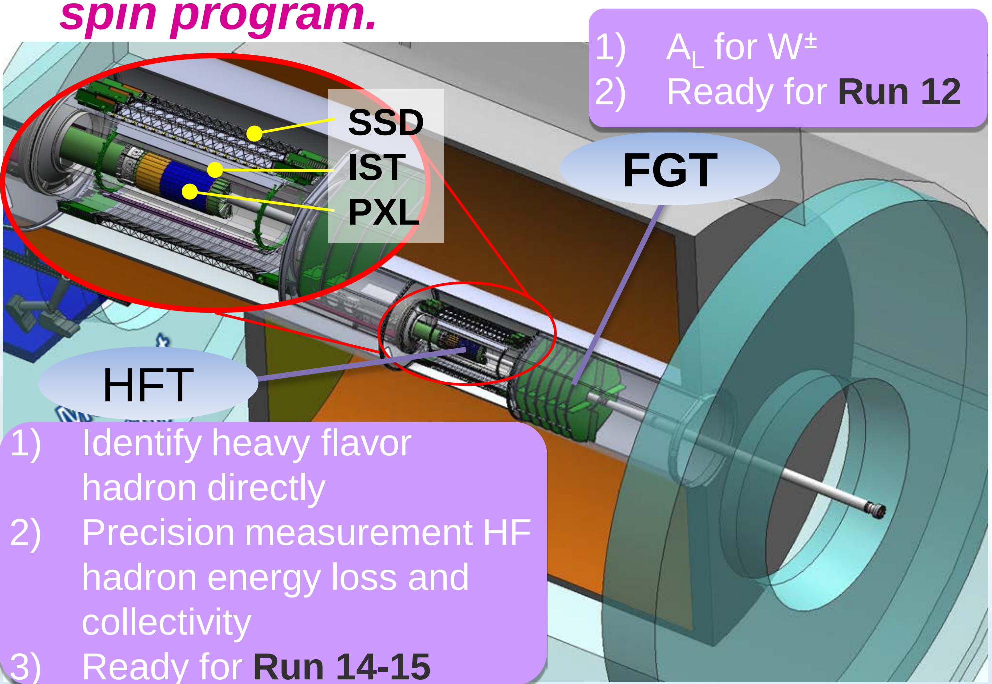
- ***New Electron Beam Ion Source (EBIS, ONP + NASA) expands range of ions available and enhances cost-effectiveness of operations***

A Suite of Ongoing Detector Upgrades

- ***PHENIX VTX & FVTX upgrades (MIE & ARRA funds) greatly improve vertex resolution, heavy flavor ID***

- ***μ trigger upgrade (NSF + Japanese funds) installed in FY10-11 enhances W prod'n triggering for spin program.***

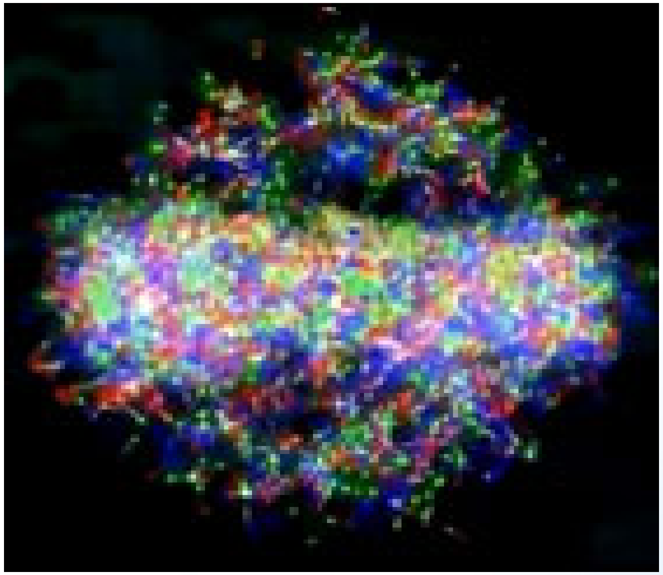




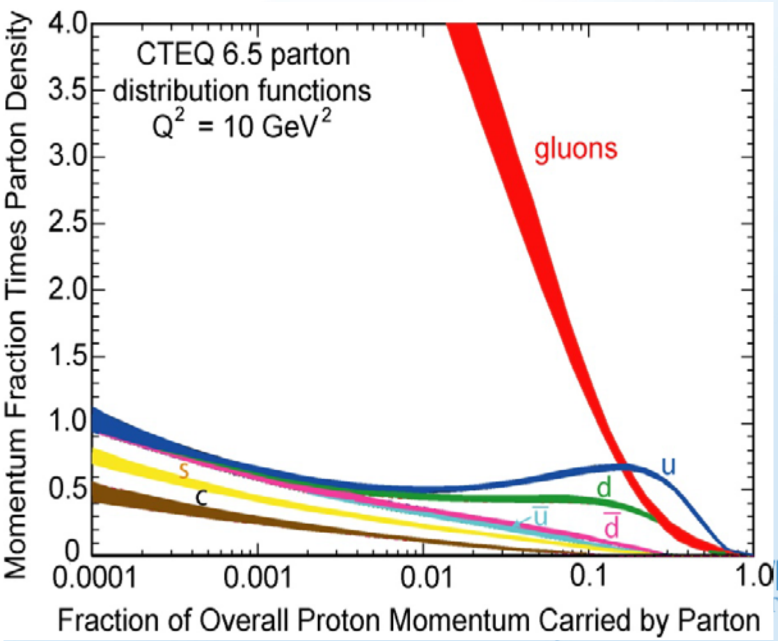
- ***STAR Heavy Flavor Tracker receives CD-1 in FY10; CD-2/3 review in July 2011. Will permit topological reconstruction of charmed hadrons.***

- ***STAR Forward GEM Tracker (RHIC capital equipment project) to be installed for Run 12, will enhance forward tracking, W charge sign discrimination.***

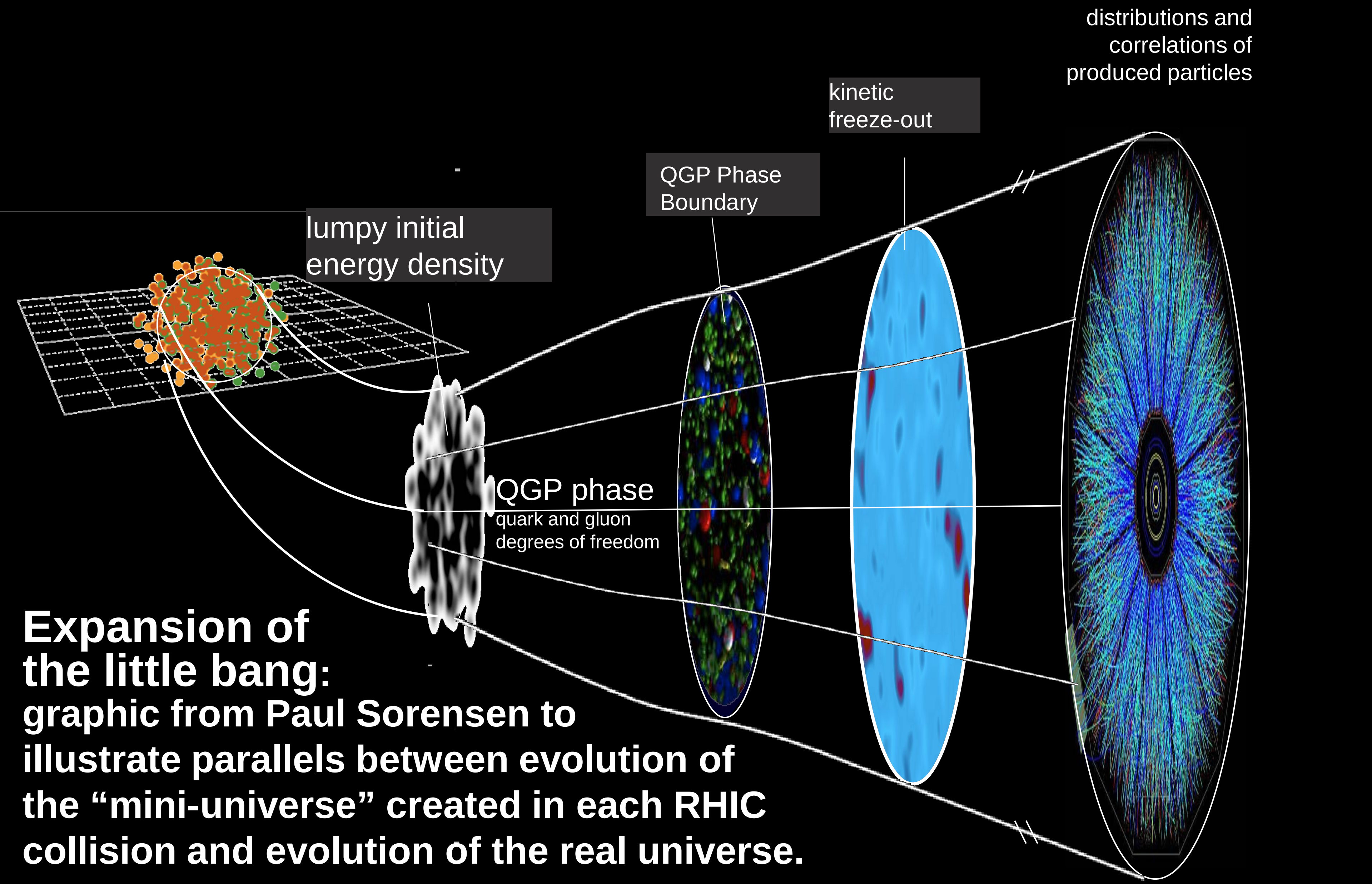
RHIC Science: Condensed Matter Physics with a Force of a Different Color



What are the unique *emergent pheno-mena* 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?

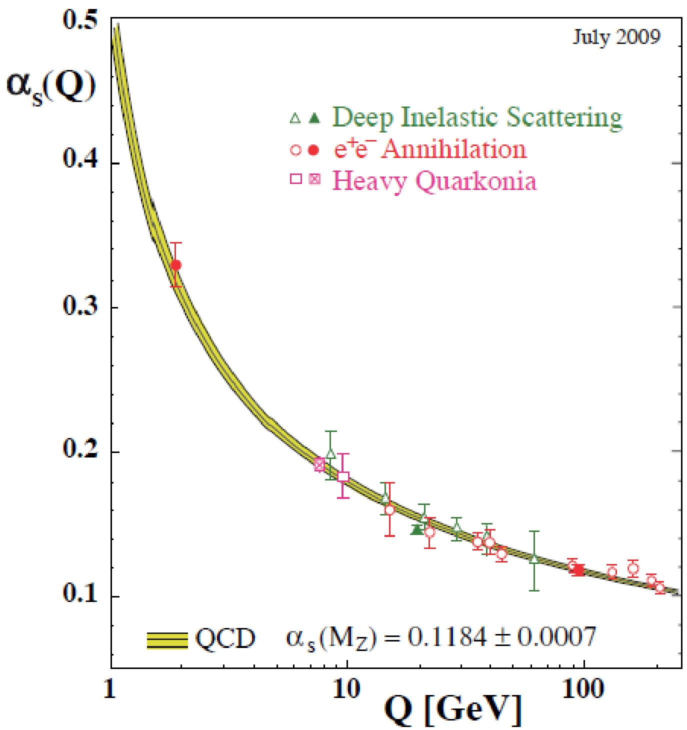


Examples of the Learning Curve:
Progress on 5 Illustrative Questions for QCD Matter

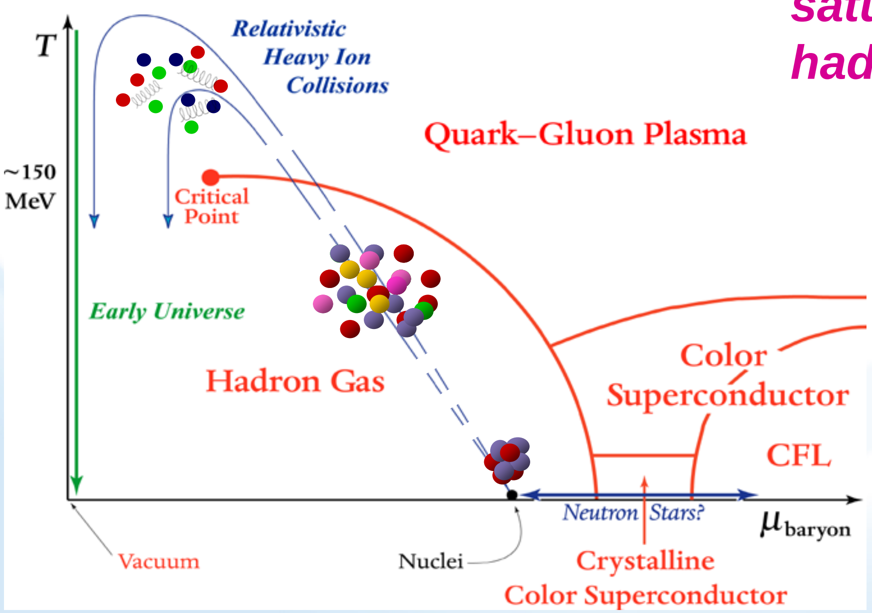


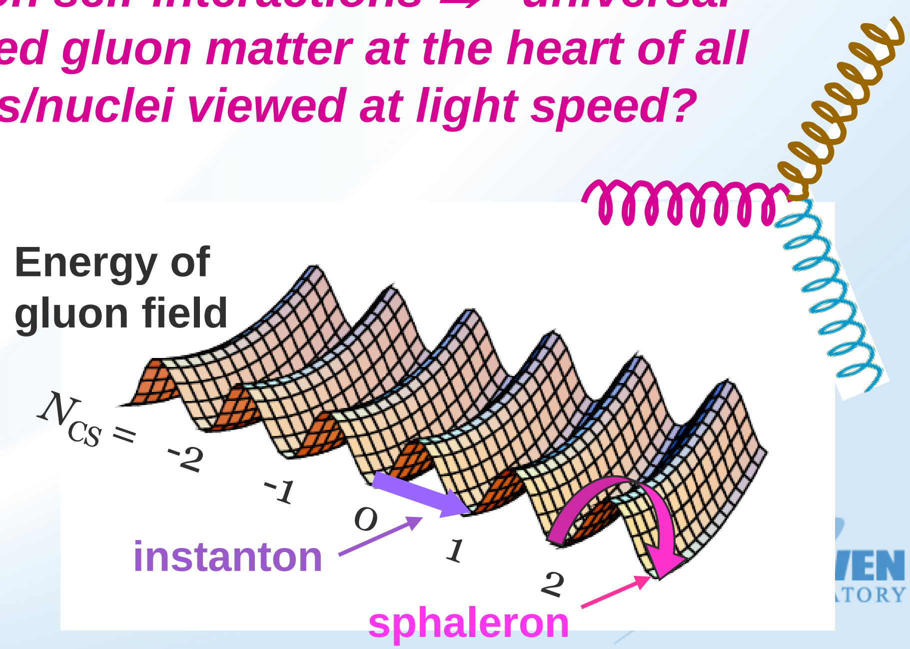
Expansion of the little bang:
graphic from Paul Sorensen to illustrate parallels between evolution of the "mini-universe" created in each RHIC collision and evolution of the real universe.

The Five Illustrative Questions



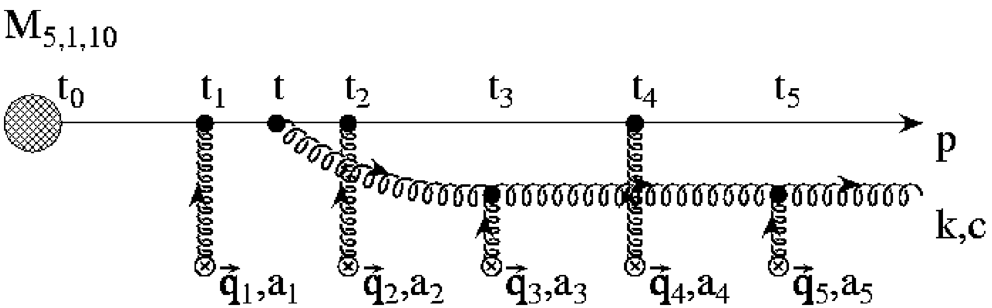
1) *How can we pump/probe the fleeting matter to measure its response?*
2) *Does asymptotic freedom ⇒ high-density (of color charge) ideal Quark-Gluon Plasma gas?*
3) *Does rich topological structure of QCD vacuum ⇒ local symmetry violation from high-temp. "sphaleron" fluctuations near QGP transition, analogous to EW transition sphalerons as possible site of baryon-antibaryon imbalance?*
4) *Is there a unique Critical Endpoint in the QCD phase diagram?*
5) *Do gluon self-interactions ⇒ "universal" saturated gluon matter at the heart of all hadrons/nuclei viewed at light speed?*



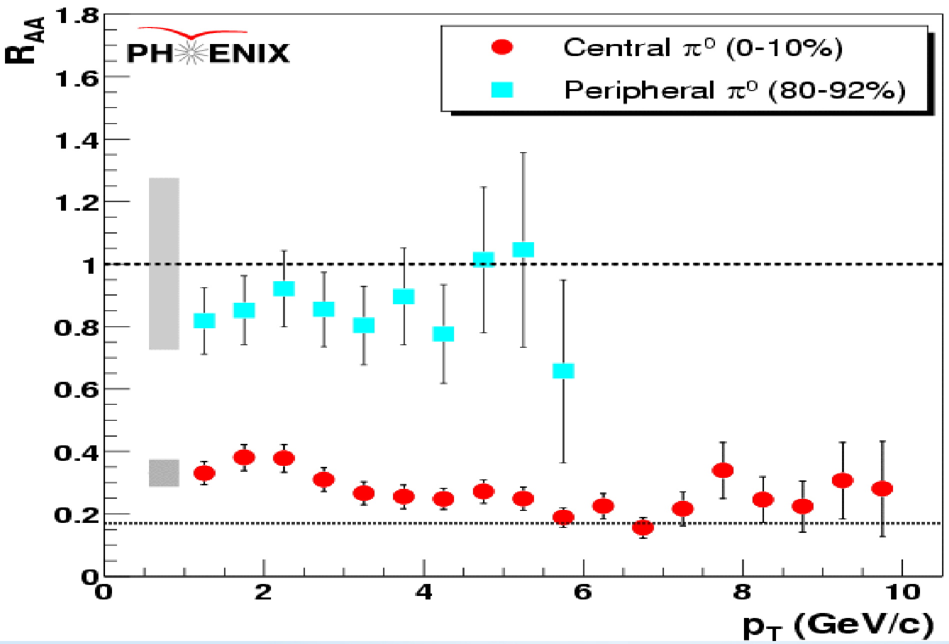


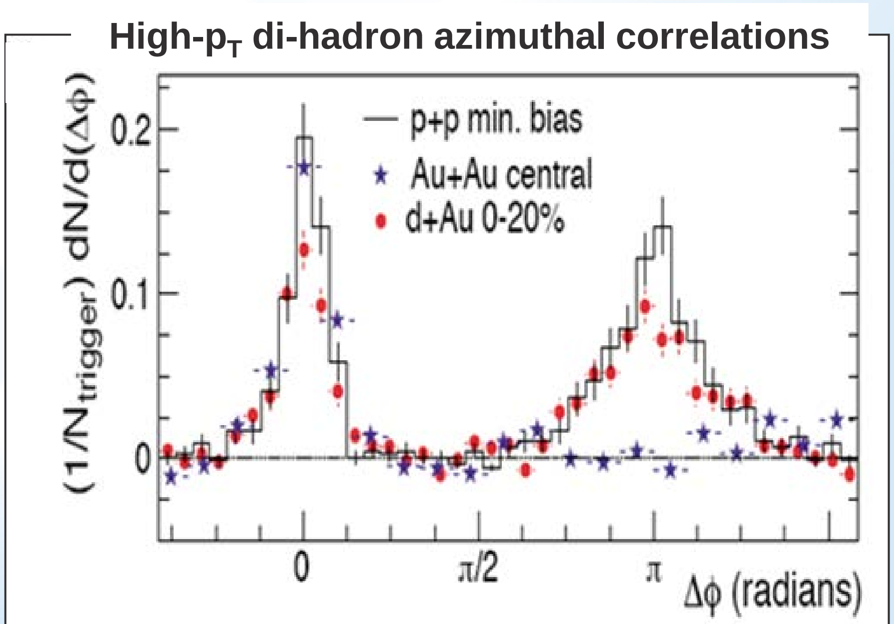
Q1: How to Pump/Probe the Fleeting Matter?

Bjorken (1983): energetic partons, generated in early hard scattering, should *radiate* gluons and energy before fragmenting, leading to *suppression of jets & emerging high-p_T hadrons,* sensitive to color charge density.

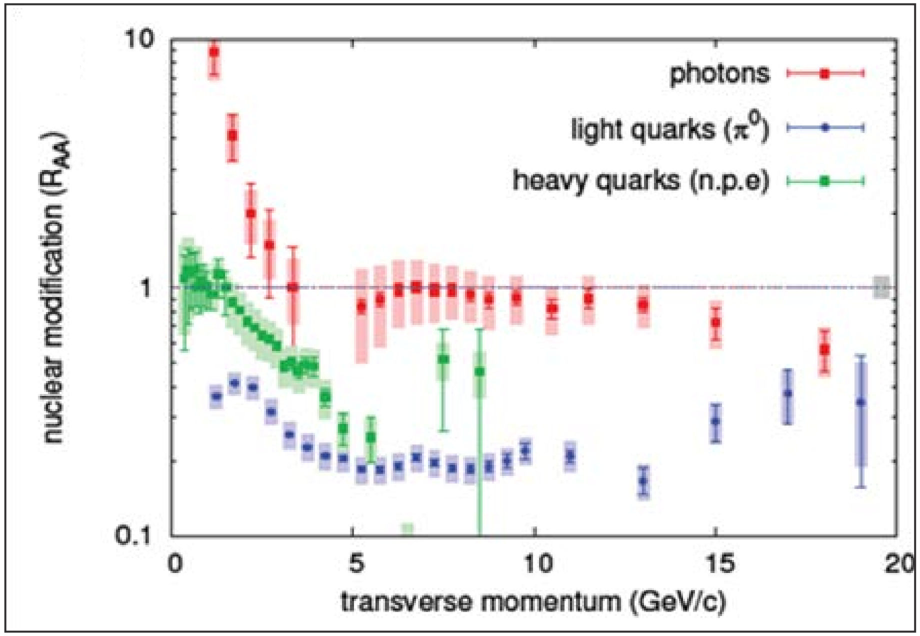


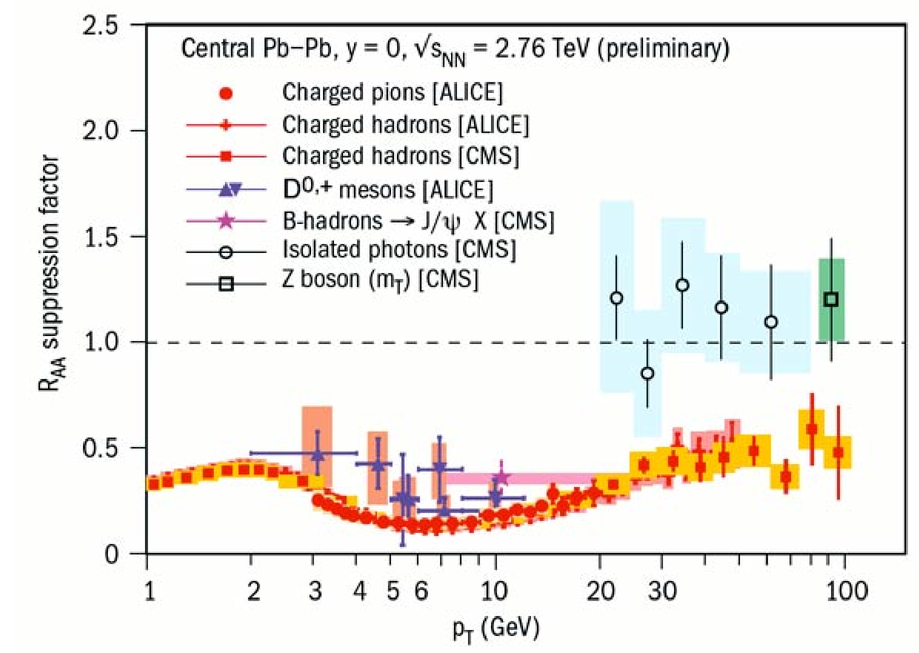
Early RHIC results indeed revealed a factor ~5 suppression of high-p_T hadron yield and quenching of the away-side jet peak in ~central Au+Au collisions.





Similar Hadron Suppression at RHIC & LHC



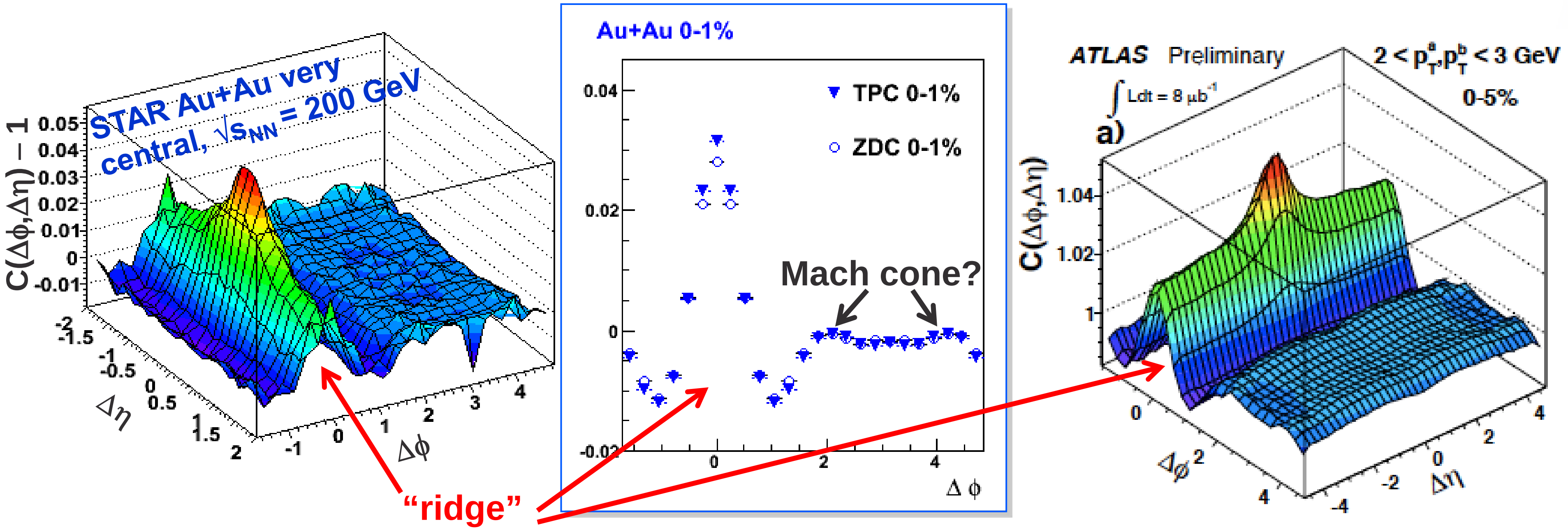


- *All light-quark hadrons experience similar suppression.*
- *Suppression @ LHC nearly the same, but extended to broader p_T range.*
- *Photons and Z's "shine right through" the matter without suppression.*
- *Heavy quarks seem to lose energy at almost the same rate as light quarks, in marked contrast to early predictions ⇒ collisional E loss also important!*

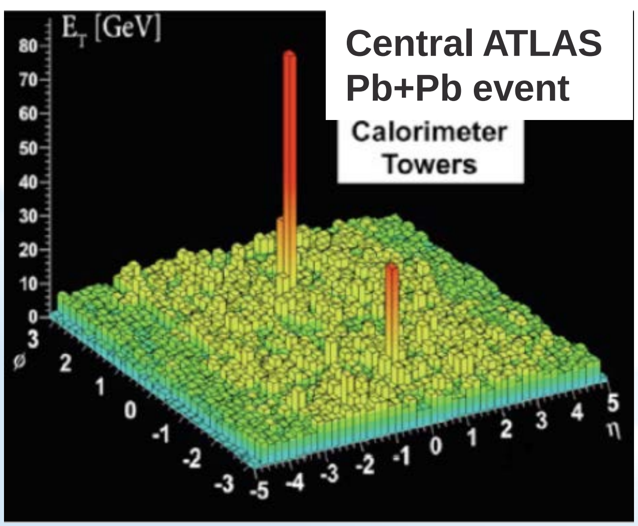
Important next steps:

- **Improve heavy flavor ID & statistics to separate c from b effects**
- **Constrain in-medium parton interaction models to explain heavy vs. light quark and lack of strong √s-dependence simultaneously**

How Does the Medium Respond to Energy Loss of Partons?

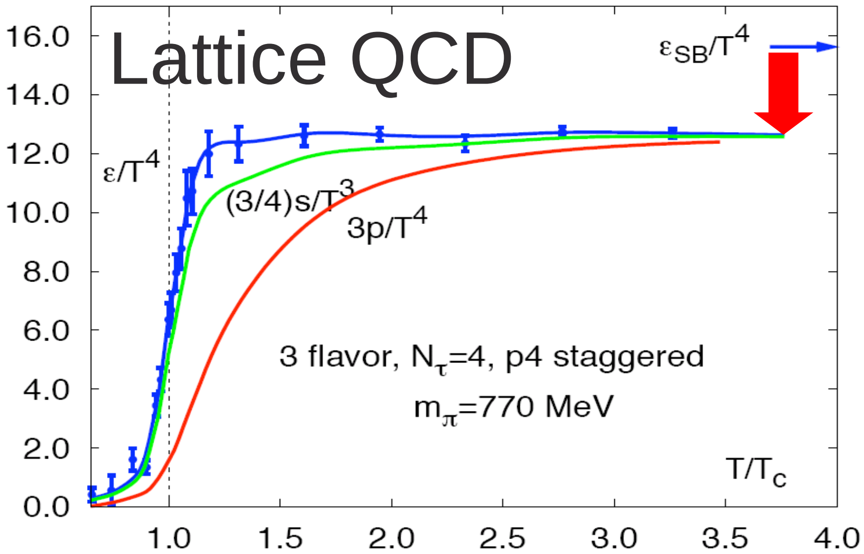


- *Moderate-p_T di-hadron correlations at RHIC & LHC ⇒ near-side "ridge" and away-side "Mach cone" structures as features of medium response?*

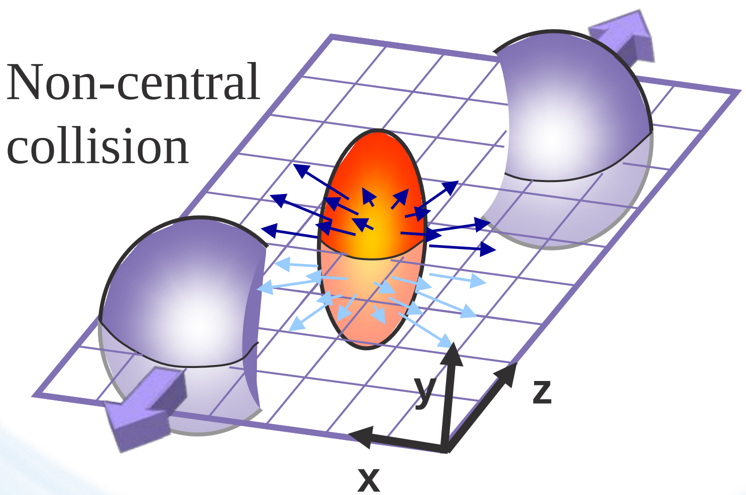


- *Lost jet energy spread among many softer hadrons, over broad angle ranges – ~indistiguishable from event bkgd @ LHC*

Q2: Ideal Gas Quark-Gluon Plasma?

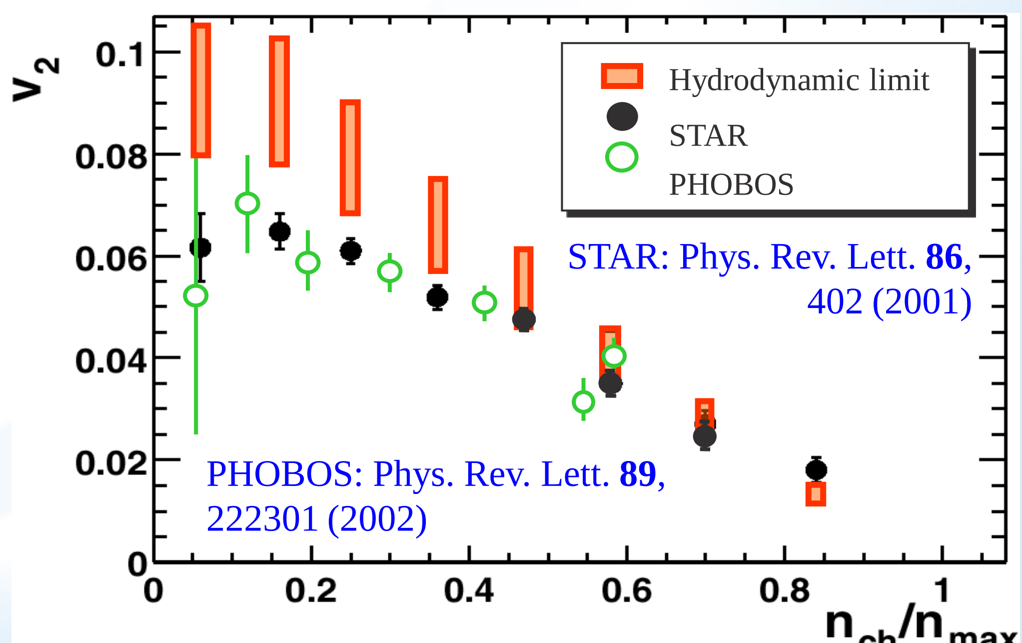


- ***LQCD results ≈ 80% of Stefan-Boltzmann limit led to expectations of ~ideal gas behavior before RHIC***
- ***But earliest RHIC results on elliptic flow in near-central Au+Au collisions already indicated expansion consistent with ideal (non-viscous) relativistic hydrodynamics***



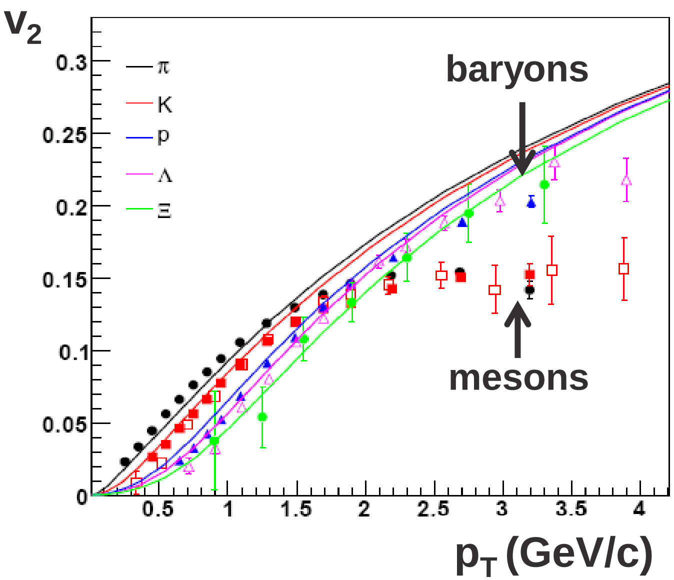
Initial spatial anisotropy ⇒ quadrupole pattern in emerging hadron p_T spectra:

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_R)] + \dots$$

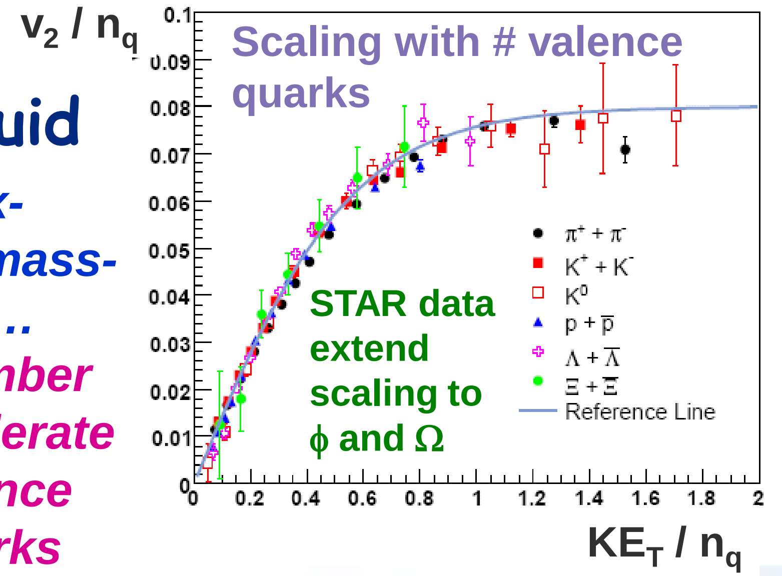


Compilation and Figure from M. Kaneta

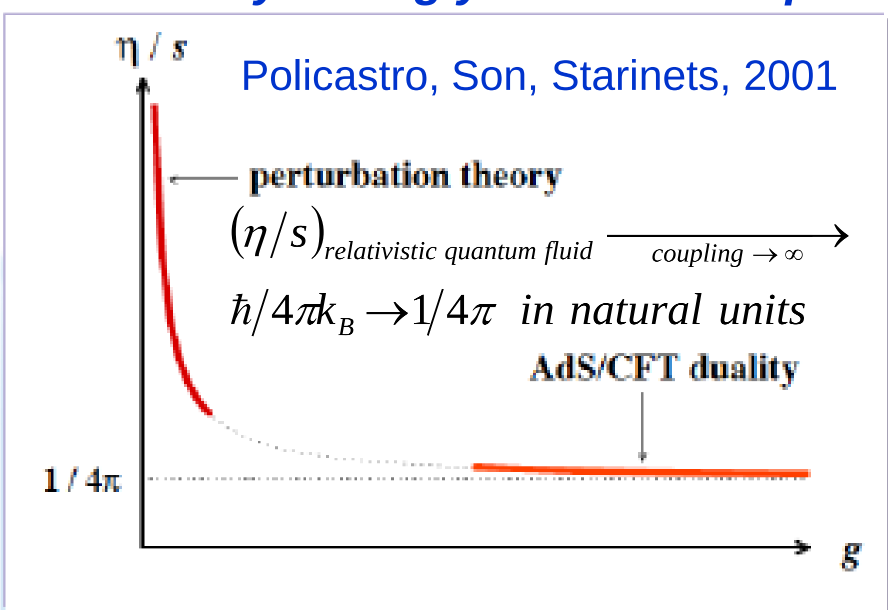
Narrowing in on the "Perfect" Liquid

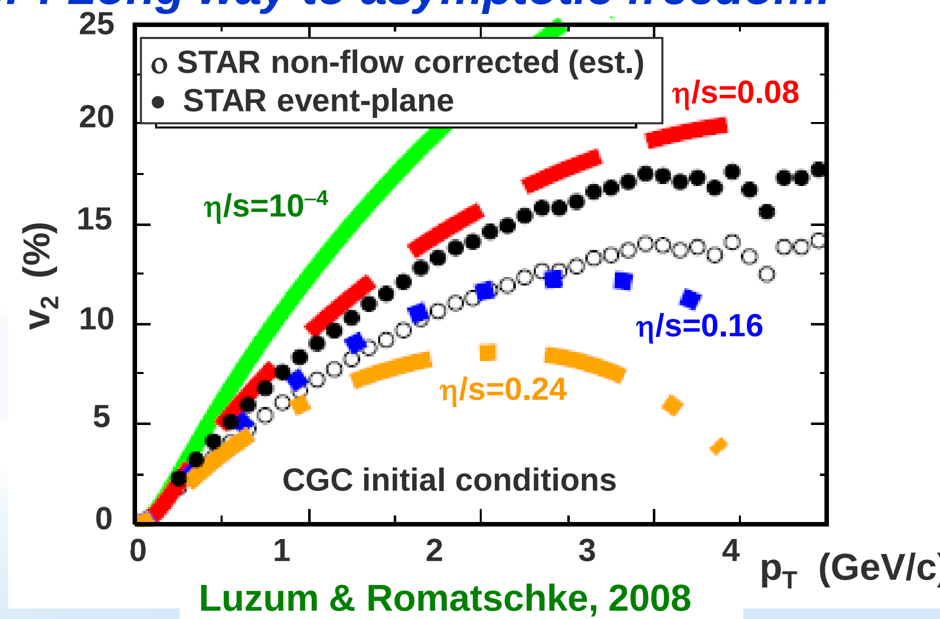


- *PID flow ⇒ expected hydro mass-dep. @ low p_T …*
- *But quark number scaling at moderate p_T ⇒ coalescence of flowing quarks*

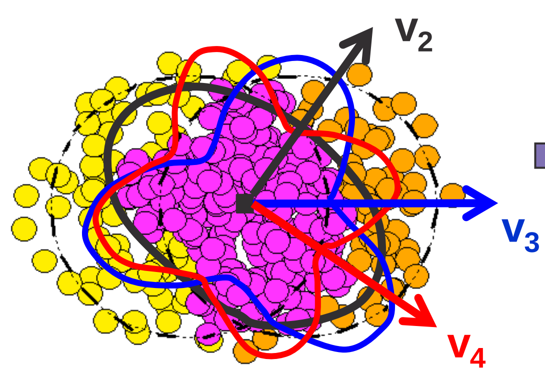


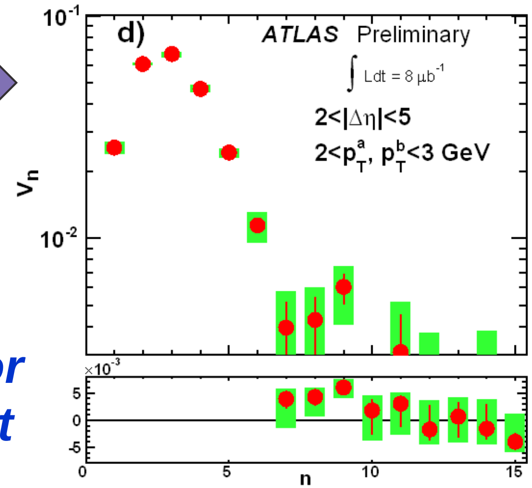
- *AdS/CFT duality ⇒ lower quantum limit on shear viscosity/entropy density*
- *Viscous hydro ⇒ η/s within ~ 1-3 x quantum limit, but significant uncertainties remain from model-dependence of initial geometry & fluctuations*
- *A very strongly correlated liquid QGP! Long way to asymptotic freedom!*

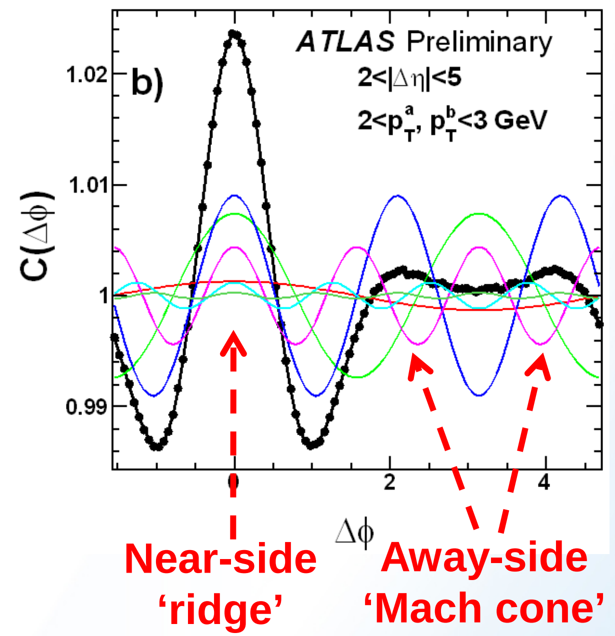




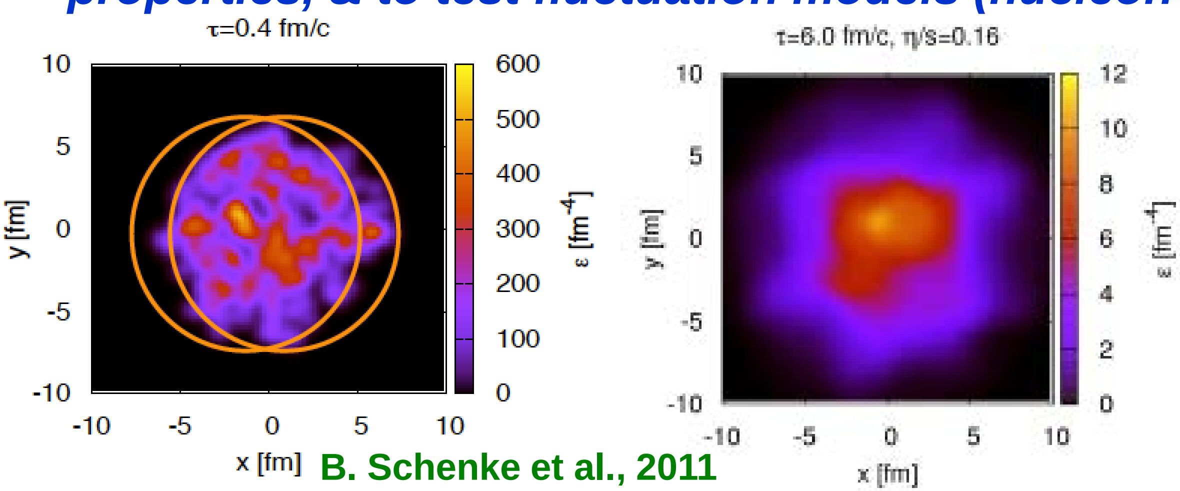
Beyond v_2 to Quantify Near-Perfection



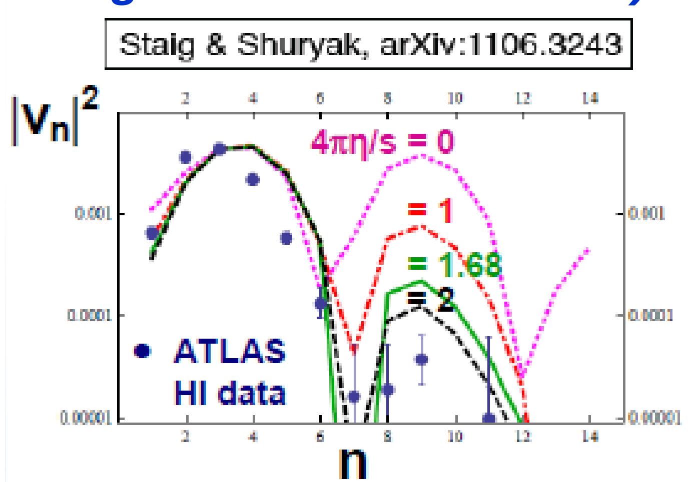




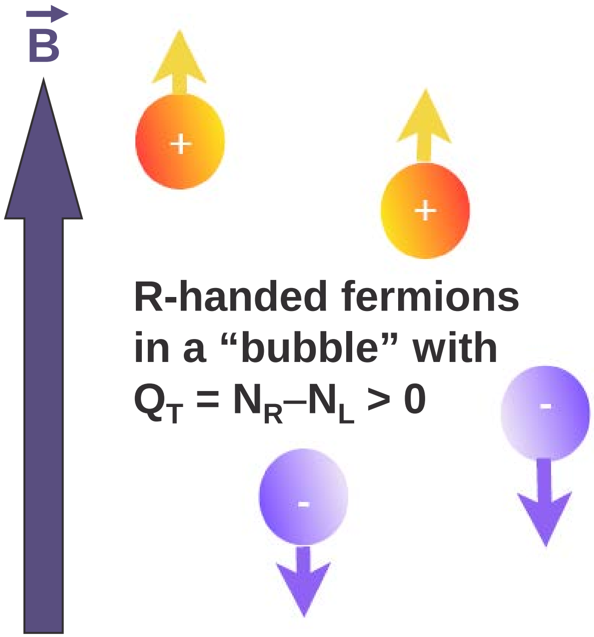
- ***Low $\eta/s \Rightarrow$ asymmetry or lumpiness in initial event density distribution can seed higher flow multipoles, including odd ones.***
- ***All RHIC & LHC exp'ts confirm that full flow power spectrum, esp. n = odd, accounts ~ fully for the "ridge" and "Mach cone"***
- ***Higher n more rapidly damped, as per new 3+1-D event-by-event viscous relativistic hydro $\Rightarrow$ path to quantify η/s precisely, plus other QGP transport properties, & to test fluctuation models (nucleon arrangements? Gluon field?)***



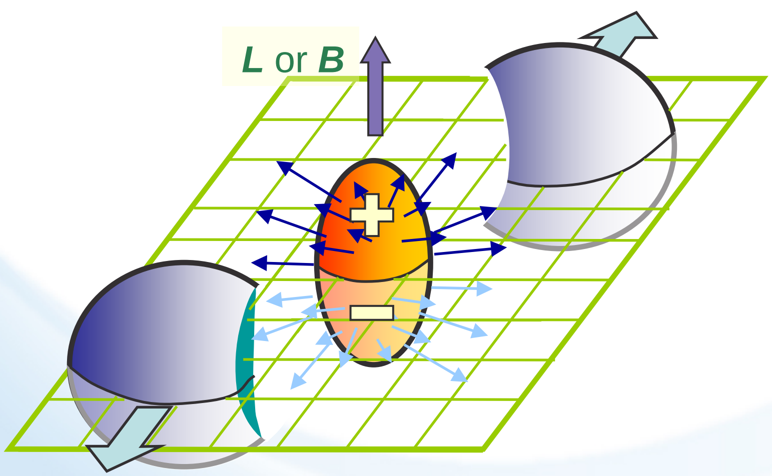
B. Schenke et al., 2011



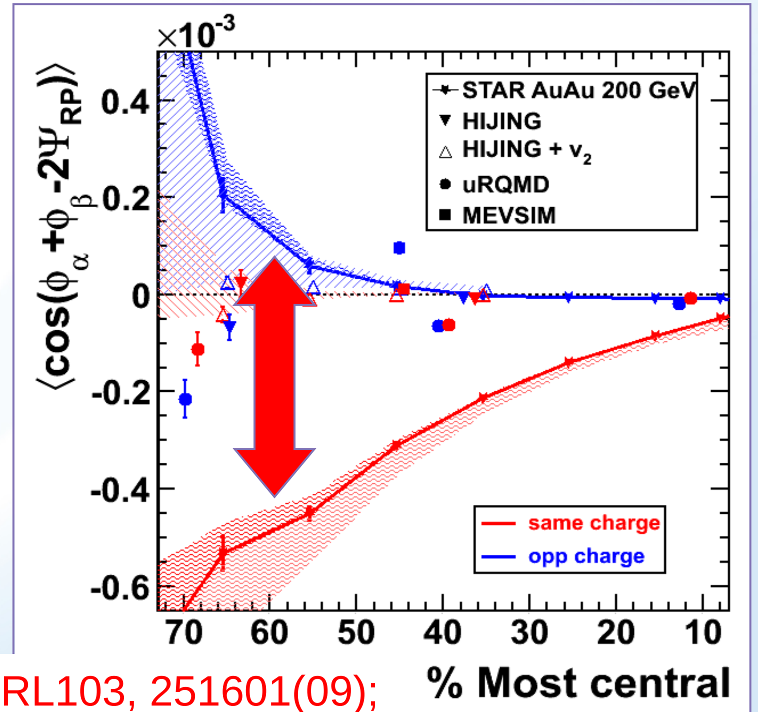
Q3: Excited QCD Vacuum Fluctuation Effects?



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

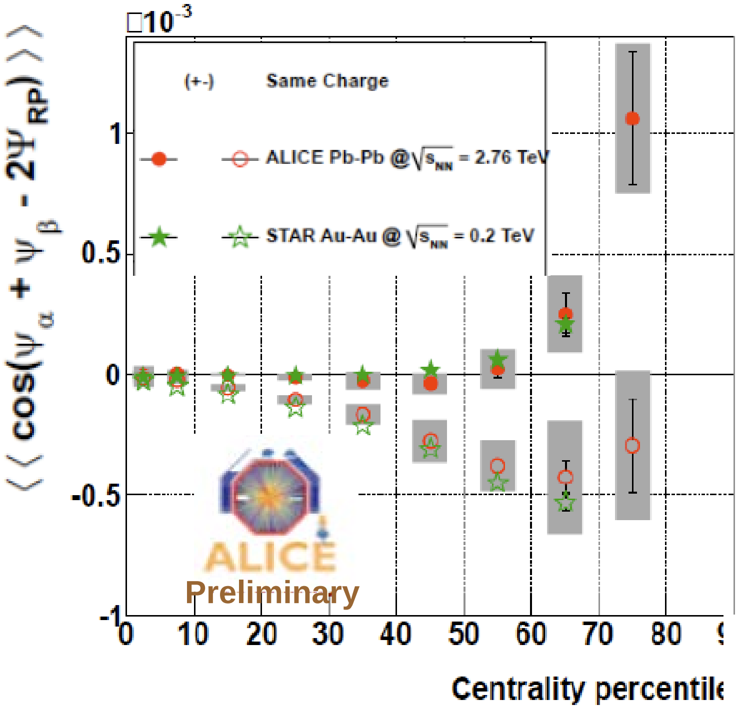


- *QCD sphalerons ⇔ leftward or rightward "twists" in gluon field ⇒ local chiral imbalance*
- *Coupling with very strong magnetic field (~10^{17} G) in ⇒ Chiral Magnetic Effect ⇒ event EDM (D. Kharzeev et al.)*
- *Charge separation can survive passage through chirally restored QGP*
- *EDM sign can differ from bubble to bubble, event to event ⇒ event asymmetry, but no global CPV*
- *STAR found P- and CP-even, but EDM-like, charged-particle correlations qual. consistent with predicted effect*

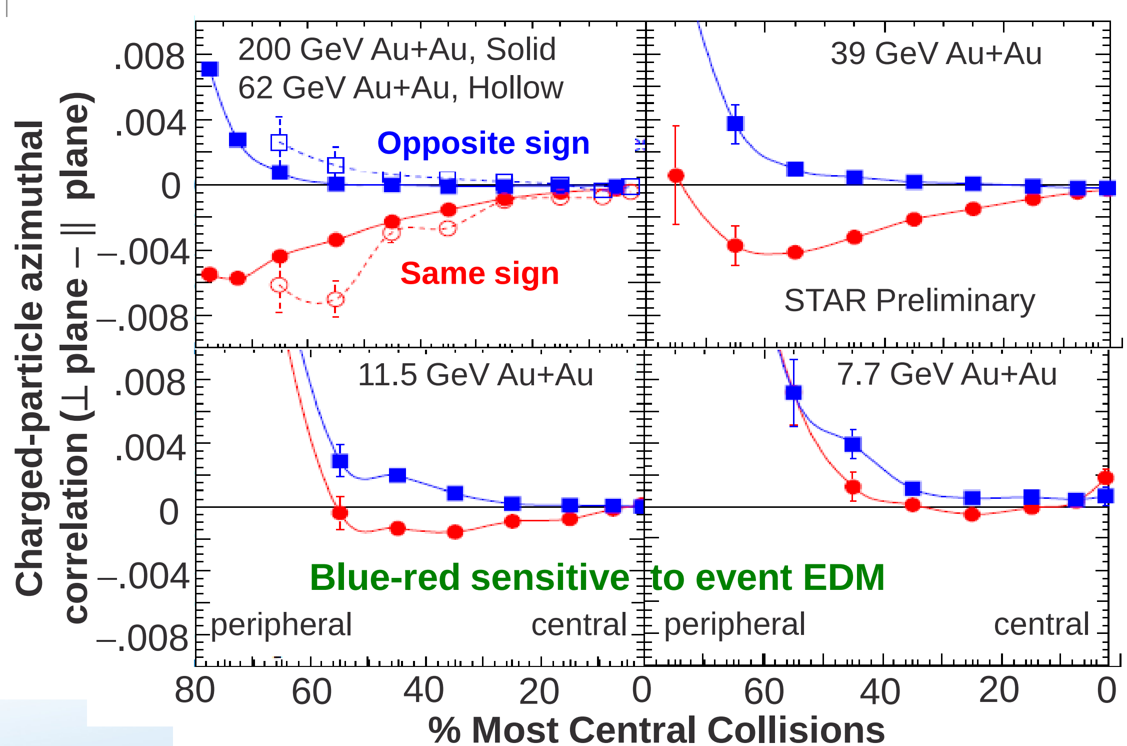


STAR; PRL103, 251601(09); 0909.1717 (PRC)

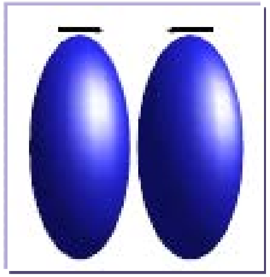
Does Effect Vanish When QGP Not Formed?

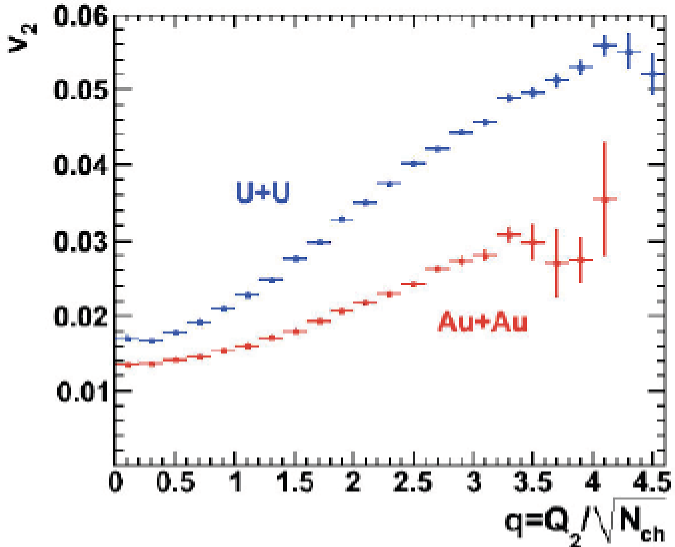


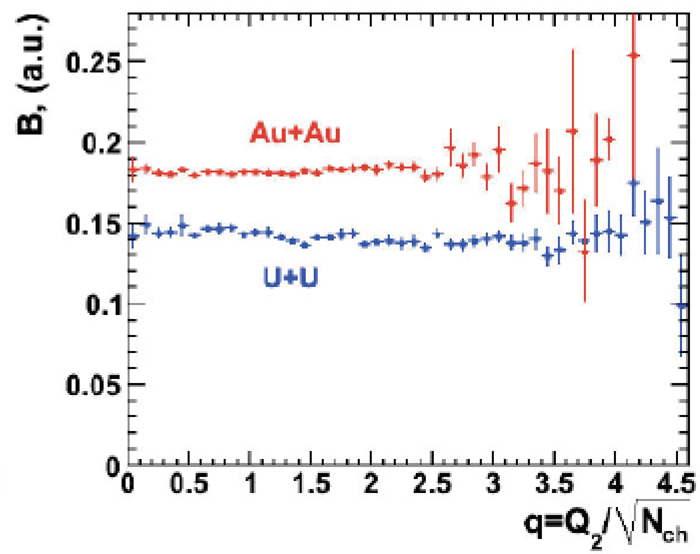
- ***ALICE preliminary results from LHC ⇒ ~ identical to STAR 200 GeV results, despite difference of factor =14 in $\sqrt{s_{NN}}$***
- ***But STAR measurements during 2010 RHIC beam energy scan show rapid vanishing of charge-dependent correl'n below ~39 GeV***
- ***Consistent with onset of chiral symmetry restor-ation & deconfinement within RHIC range***
- ***But need other signals to rule out mundane bkgd. associated with flow, rather than magn. field***



Future Steps for Quantum (Sphaleron) Snapshots

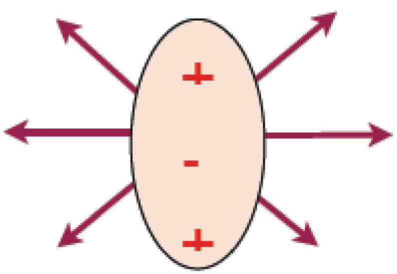






- ***Enhance bkgd. contributions via deformed U+U collisions, where ~central body-body configurations give rise to enhanced flow with reduced magnetic field***

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

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

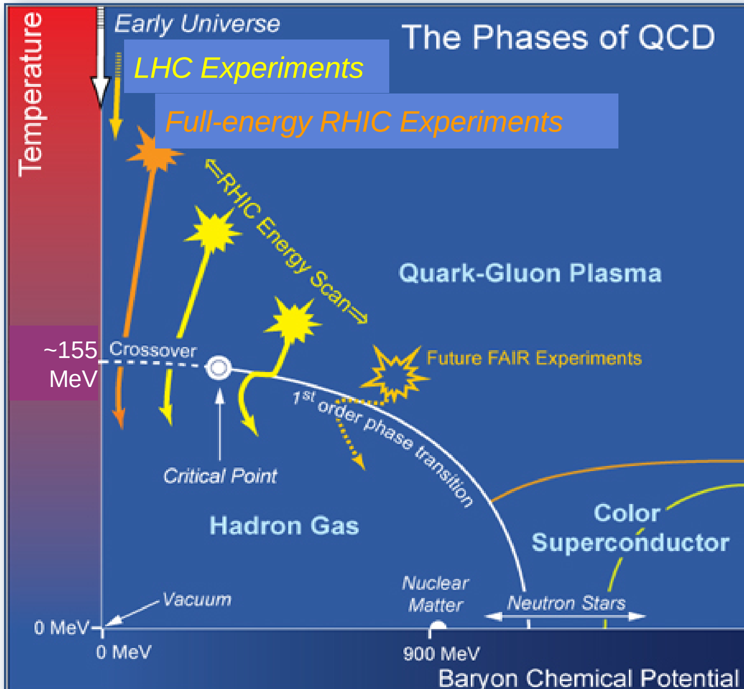
CME

Vorticity-induced "Chiral Vortical Effect"

$\Rightarrow$ ***A baryon current correlated with charge current when baryochemical potential $\neq 0$***

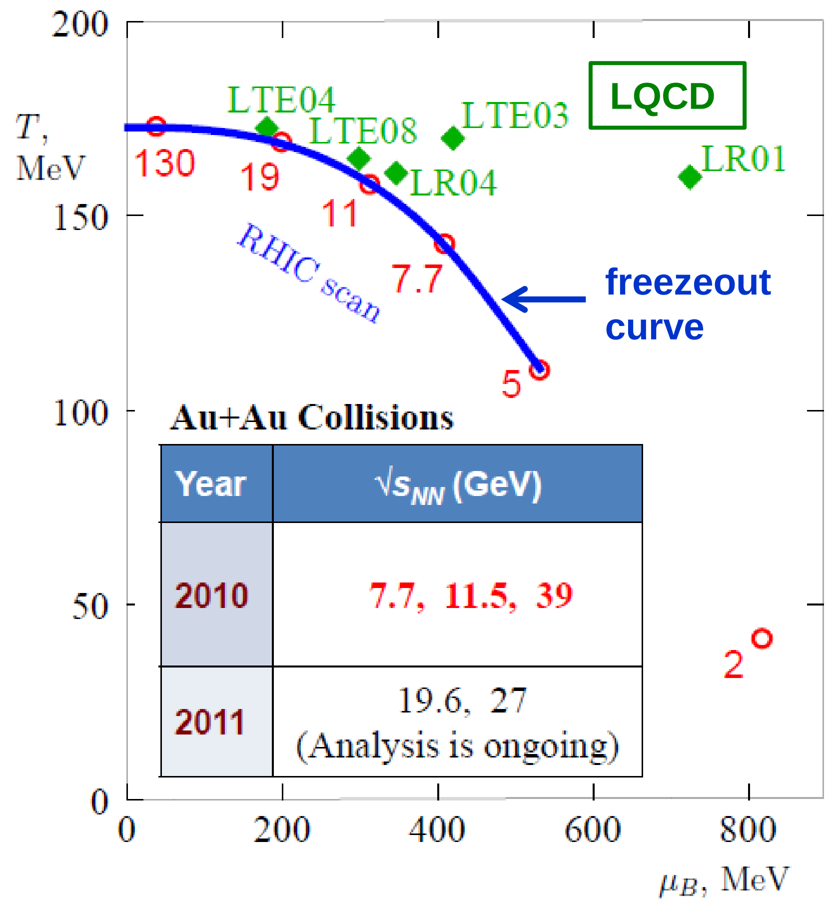
$\Rightarrow$ ***e.g., Λ's should be preferentially correlated with π^+ and $\overline{\Lambda}$'s with π^-, normal to reaction plane, @ $\sqrt{s_{NN}}$ = 39 GeV***

Q4: Critical Point (CP) in the 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***
- ***Critical point would be unique fixed point in QCD landscape***

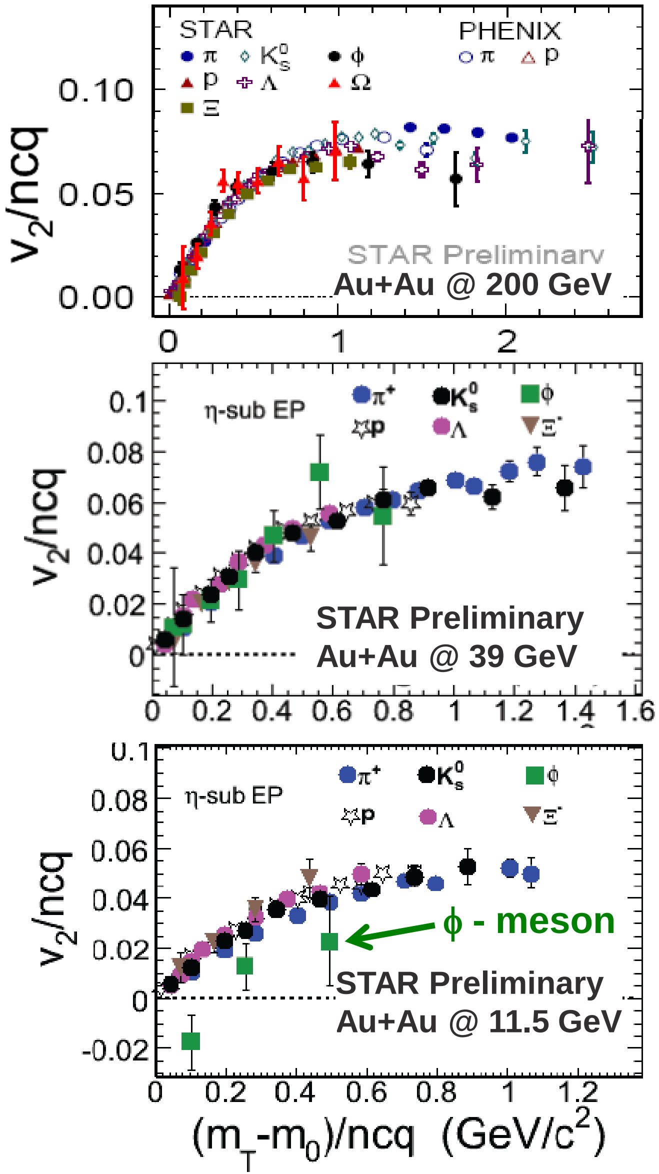


- ***At $\mu_B \neq 0$, normal MC sampling techniques invalid ⇒ LQCD CP estimates (green diamonds at right) all over map***
- ***Vary μ_B via RHIC $\sqrt{s}$ – if freezeout curve crosses near CP, should see enhanced non-Gaussian fluctuations***
- ***1st phase $\sqrt{s}$ scan 2010-11 exploits RHIC flexibility, ~const. det. acceptance***

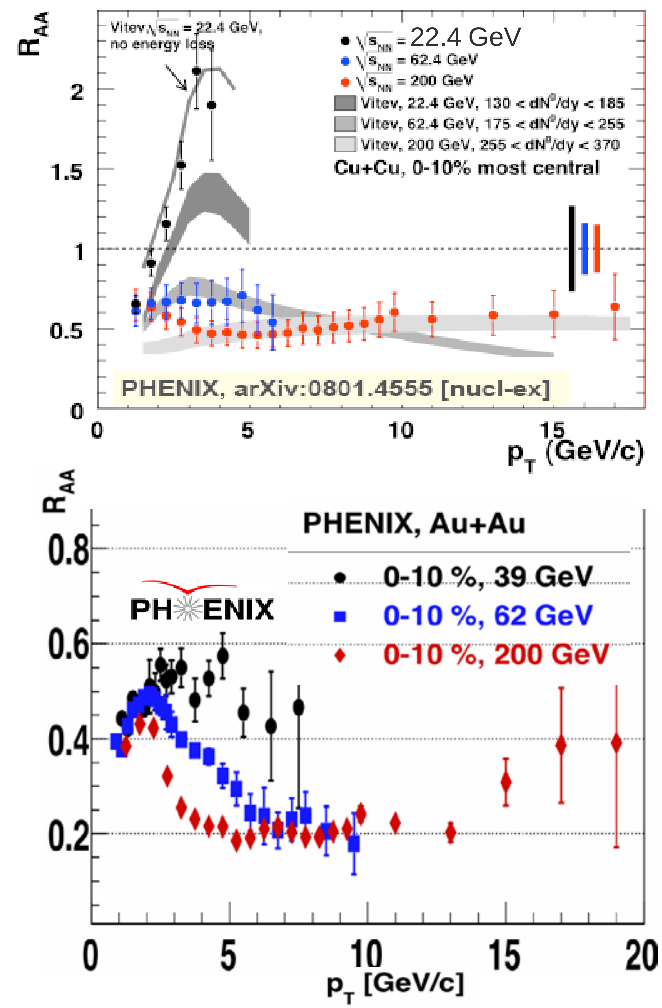
Onset of Deconfinement?

- ***Early results from beam energy scan reveal changes in behavior of several signals tied to QGP, in addition to EDM-like correlations***

Constituent-quark scaling of elliptic flow less apparent < 39 GeV



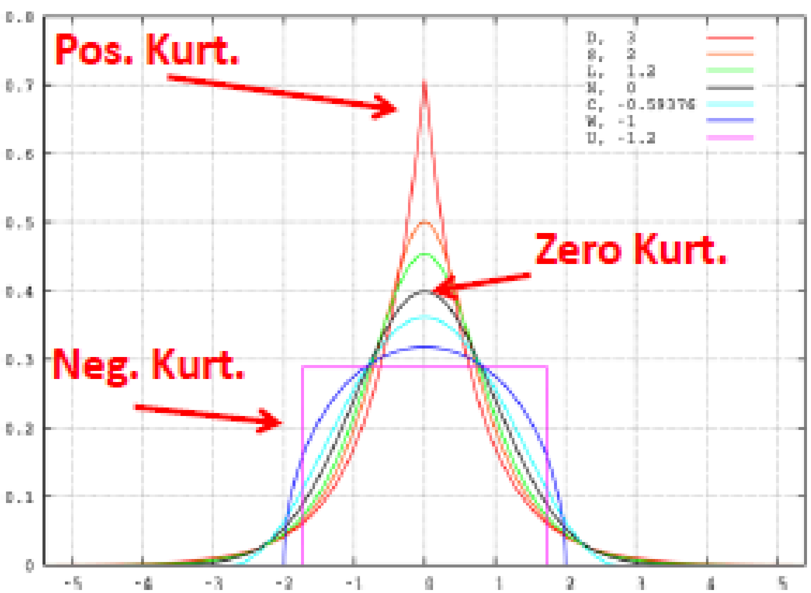
High-p_T hadron suppression
→ enhancement < 39 GeV

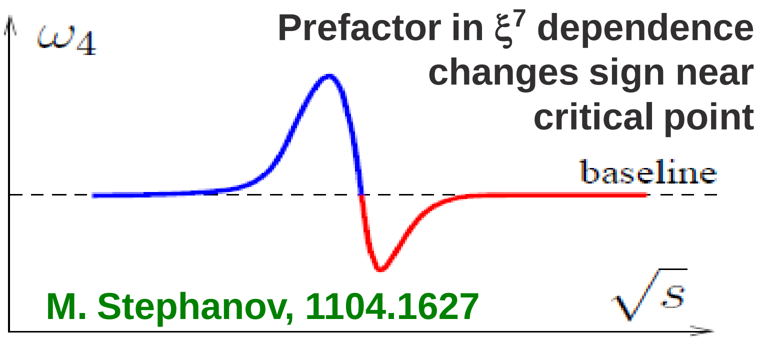


Searching for Critical Point Fluctuations

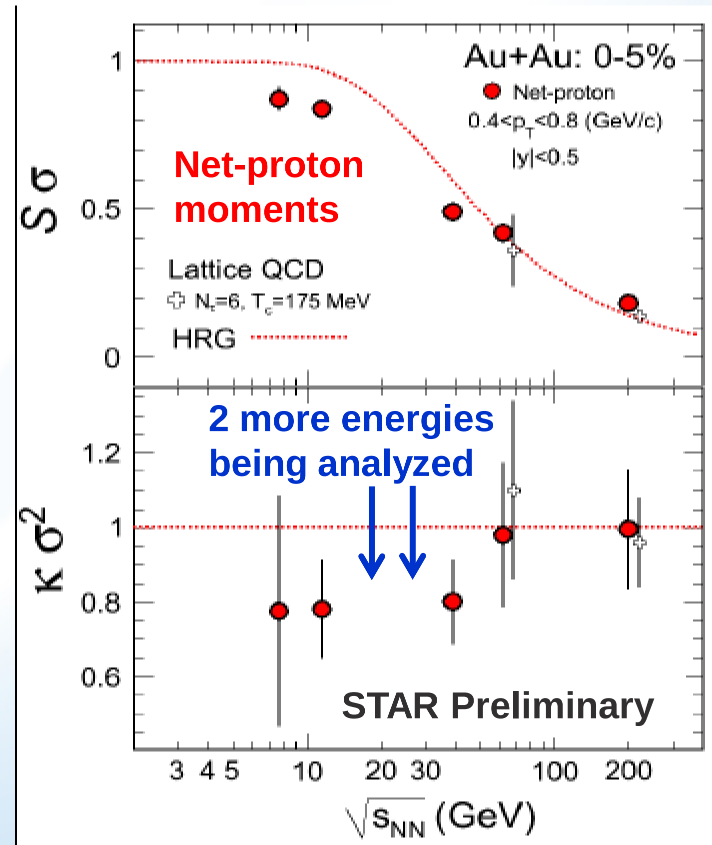
Skewness: $$s = \frac{<(N-<N>)^3>}{\sigma^3} \sim \xi^{4.5}$$

Kurtosis: $$\kappa = \frac{<(N-<N>)^4>}{\sigma^4} - 3 \sim \xi^7$$

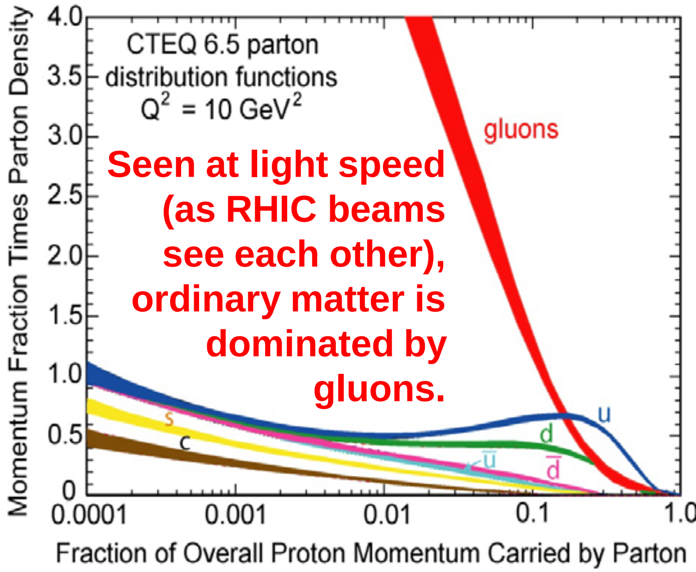




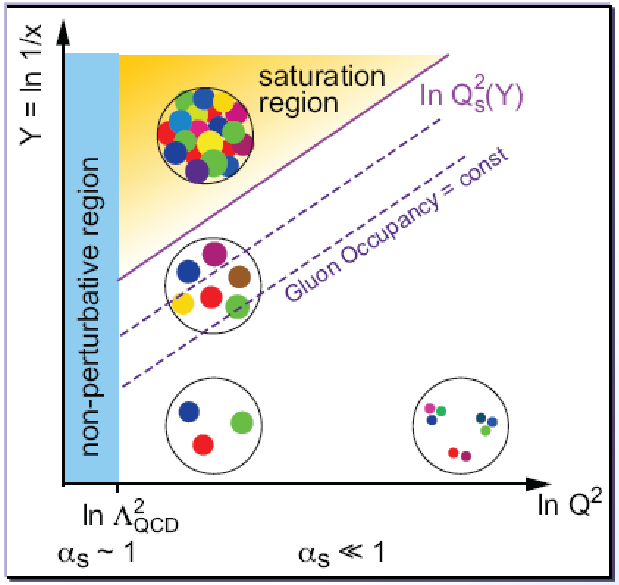
- *Expect non-Gaussian fluctuations in event-by-event distributions of conserved quantities: charge, baryon #*
- *Higher moments depend more strongly on correlation length ξ*
- *Early STAR results consistent with both Hadron Resonance Gas and LQCD at higher energies – stay tuned!*



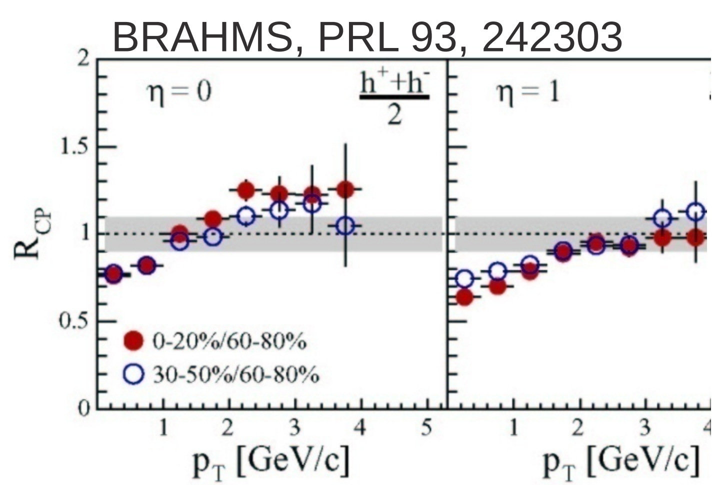
Q5: Gluon Saturation?

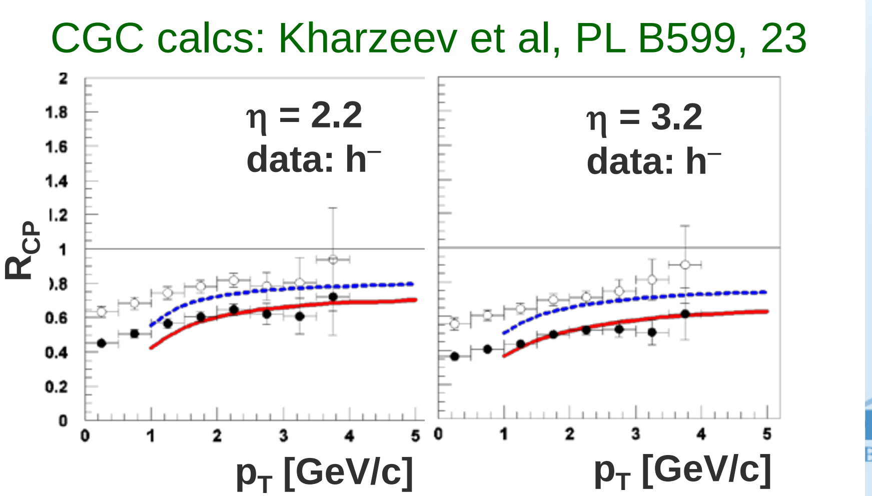


- ***Gluon densities must saturate @ low x & moderate Q^2 to avoid unitarity violation***
- ***Color Glass Condensate (CGC) regime has weak coupling but high gluon occupancy ⇒ intense, ~classical gluon field***



- ***Coherent effects in nuclei ⇒ precocious onset of saturation***
- ***Forward hadron production, sensitive to gluon density at low x, should be suppressed in collisions with cold nuclei vs. nucleons***
- ***Early BRAHMS d+Au results show suppression increasing with rapidity***

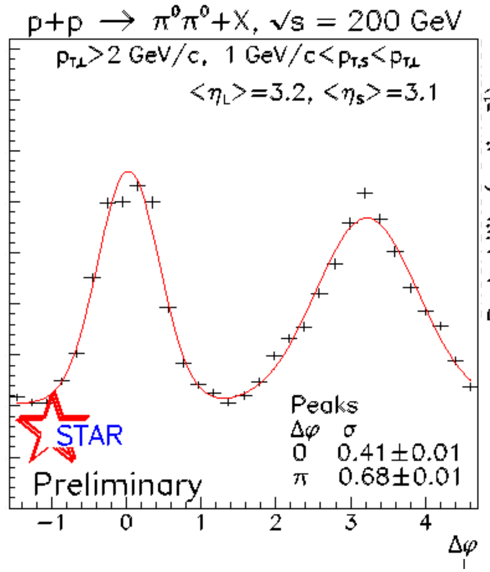




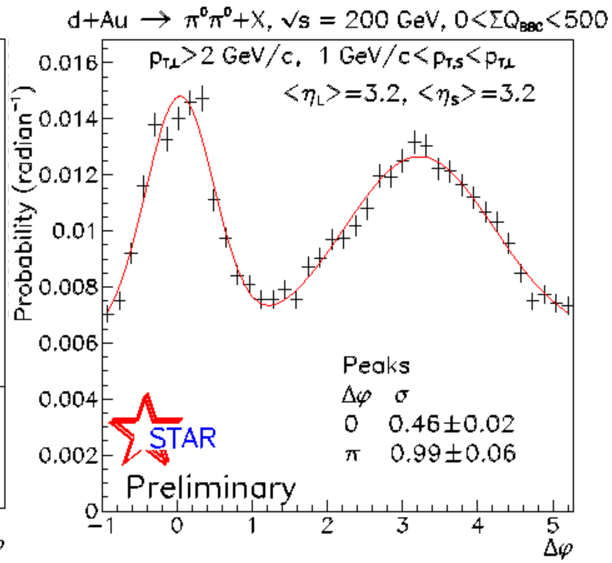
More Recent Evidence from RHIC

Uncorrelated Coincidence Probability (radian⁻¹)

pp data

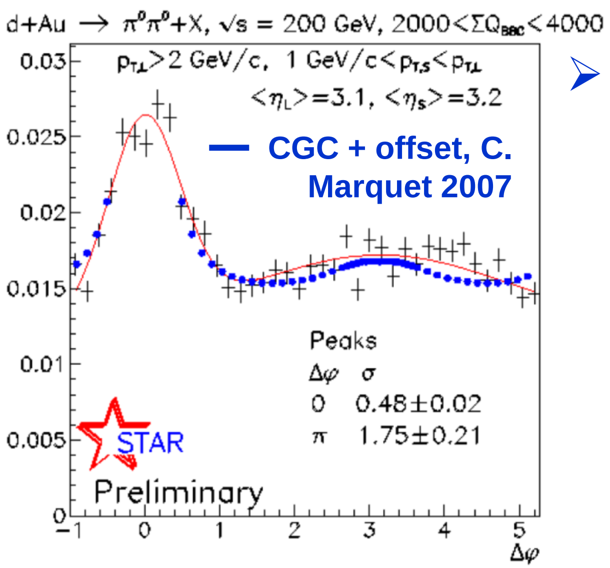


dAu peripheral

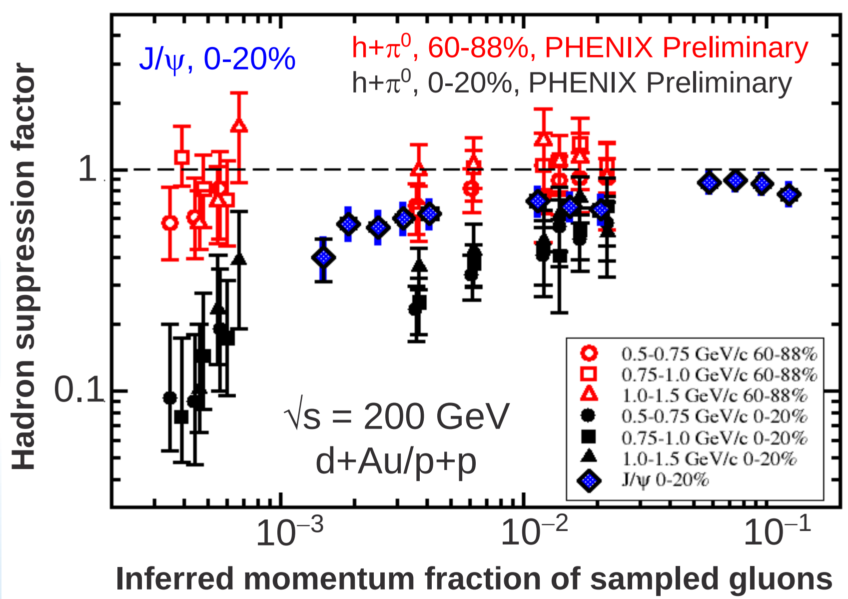


- ***Forward di-hadron coincidences probe very asymmetric parton collisions, involving low-x gluon from one beam***
- ***In CGC regime, expect 2→2 parton scattering to be replaced by scattering from a coherent gluon field ⇒ "monojets"***

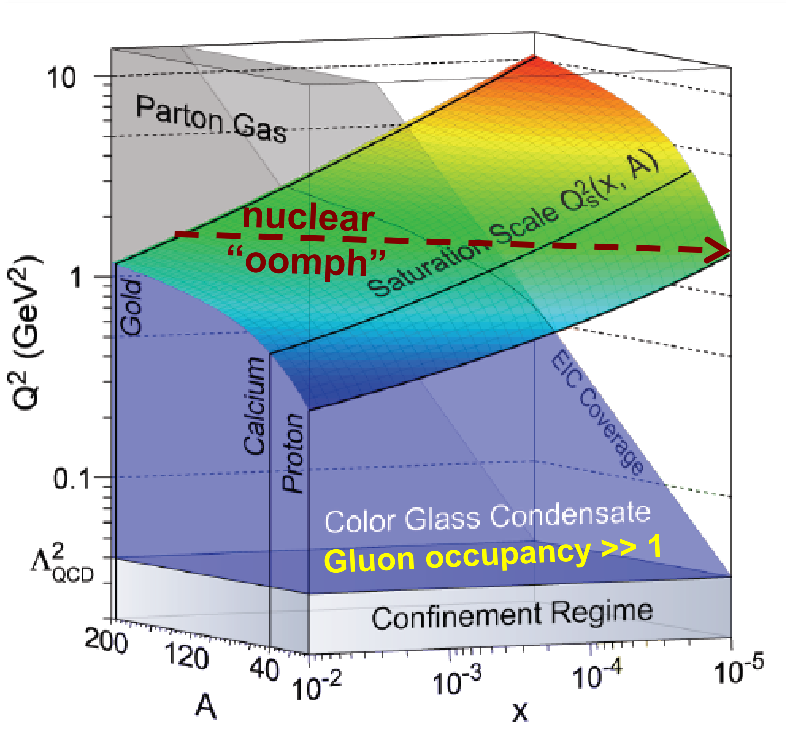
dAu central



- ***New STAR & PHENIX data confirm disappearance of away-side jet in central d+Au forward-forward di-hadron coinc.***



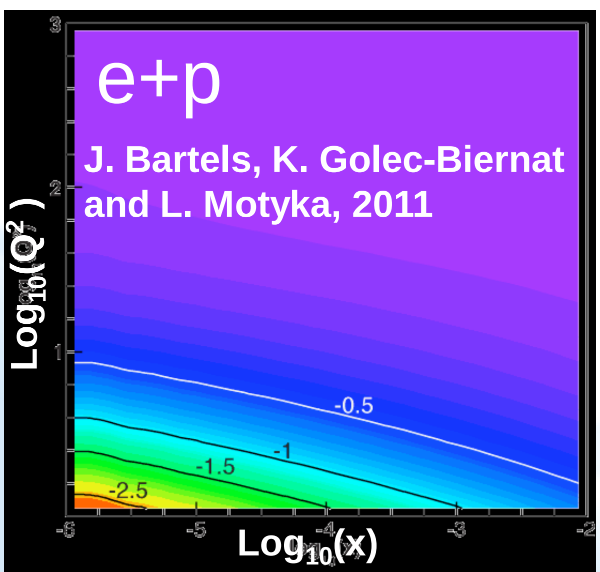
Best Probe of Soft Gluon Densities is e+A Collider

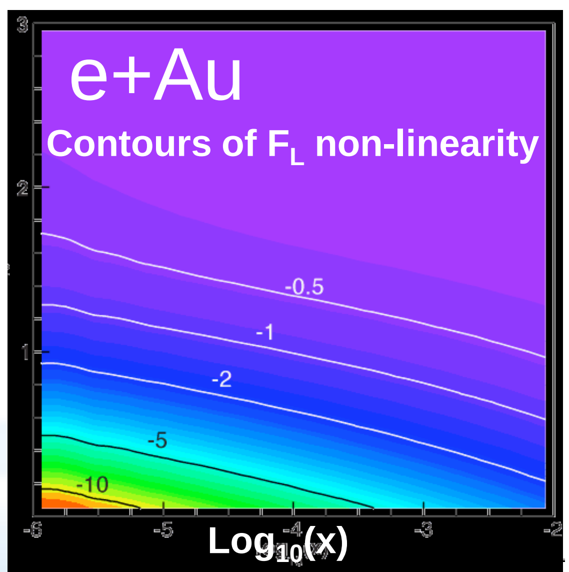


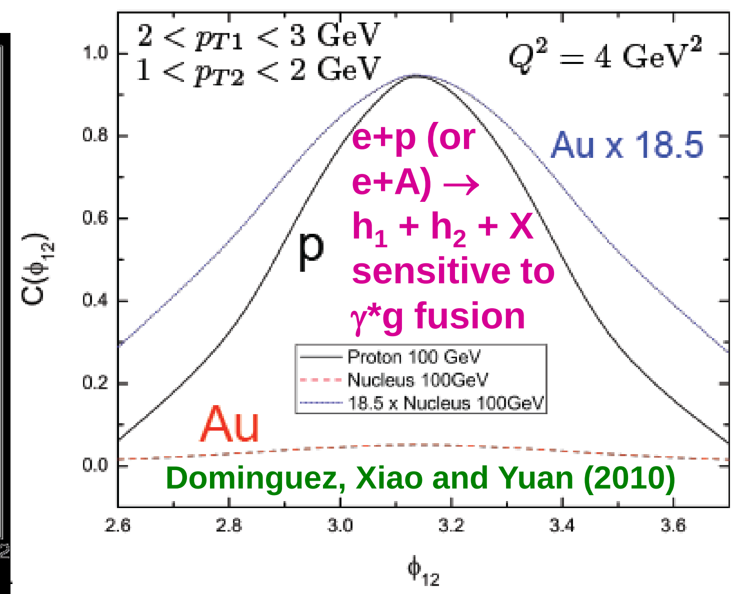
- *In low-x e+A DIS, when γ^* coherence length $L \sim (2m_N x)^{-1}$ > nuclear diam., probe interacts coherently with all nucleons along path.*
- *e+A can reach comparable gluon densities to e+p at factor ~ A lower Bjorken x*

$$(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

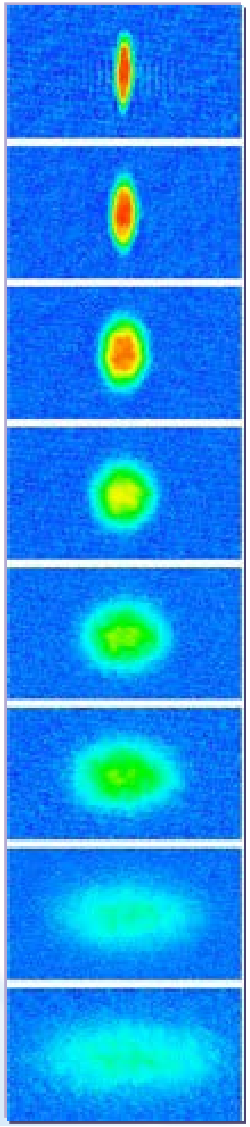
- *Can extract gluon densities via scaling violations in F_2 or by isolating longitudinal structure fcn. F_L from $\sqrt{s}$ scan: $F_L \sim \alpha_s G(x,Q^2)$*
- *e+A sensitivity indicated by early onset of F_L non-linearity, or di-hadron coinc. calcs.*







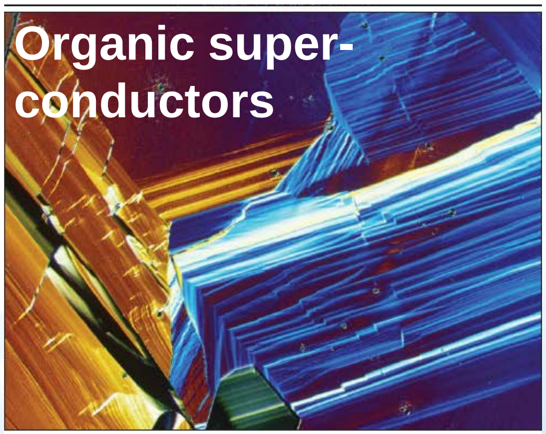
Unanticipated Intellectual Connections

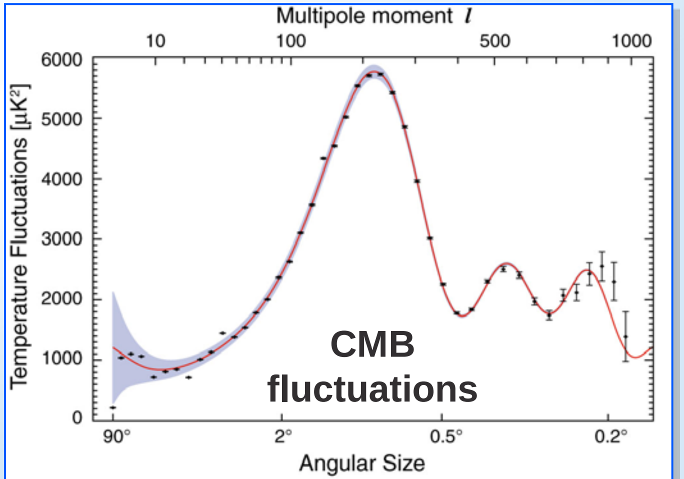


RHIC results have established ties to other forefront science:

- ❑ String Theory studies of black hole behavior led to prediction of quantum lower bound on η/s
- ❑ Ultra-cold atomic gases, at temperatures 21 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.

Trapped ultra-cold atom clouds





Completing the Narrative Arc: Kovar

F. Scott Fitzgerald: ***"There are no second acts in American lives"***

≠ "no second chances"!

Dramatically, 2nd acts provide the profound evolution of character and circumstance that bridges from establishment/exposition of situation in Act I to the resolution/dénouement in Act III

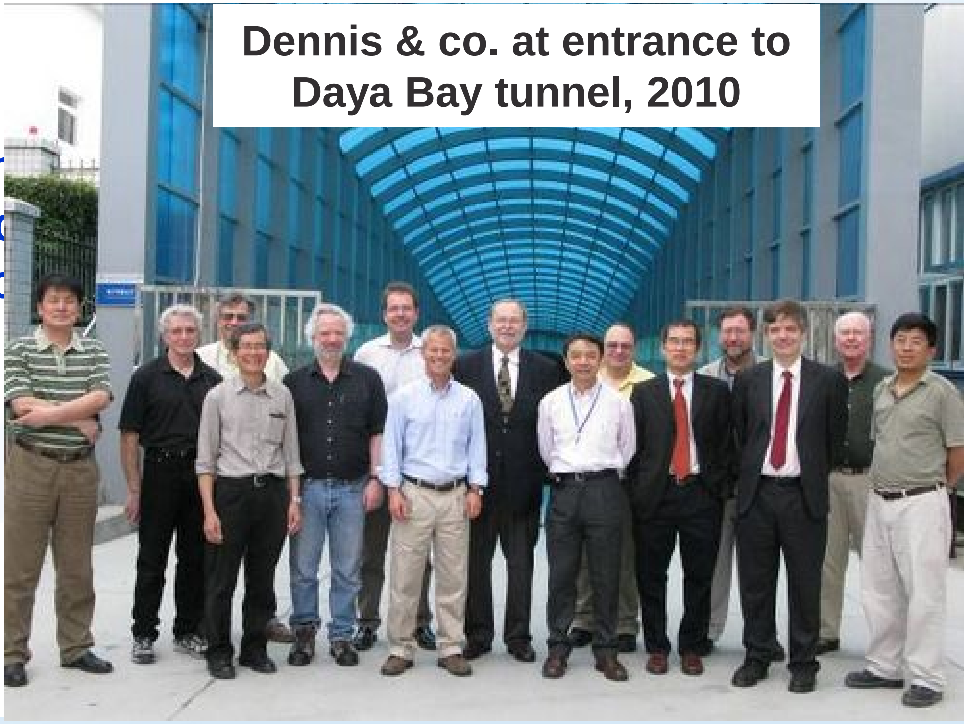
The time we celebrate here – Dennis' time in the Nuclear Physics Office – was his Act II.

Act I was Dennis' period (1973-1990) as an enthusiastic, careful, sharp experimenter in heavy-ion reaction physics at ANL ***(where I served as his post-doc 1974-6)***

Dennis' success in planning for N
community to deal effectively with
2005 Tribble subpanel -- and the c
which he was held within the Offic

2007-2010: DK serves as DOE AD of Science for High Energy Physics

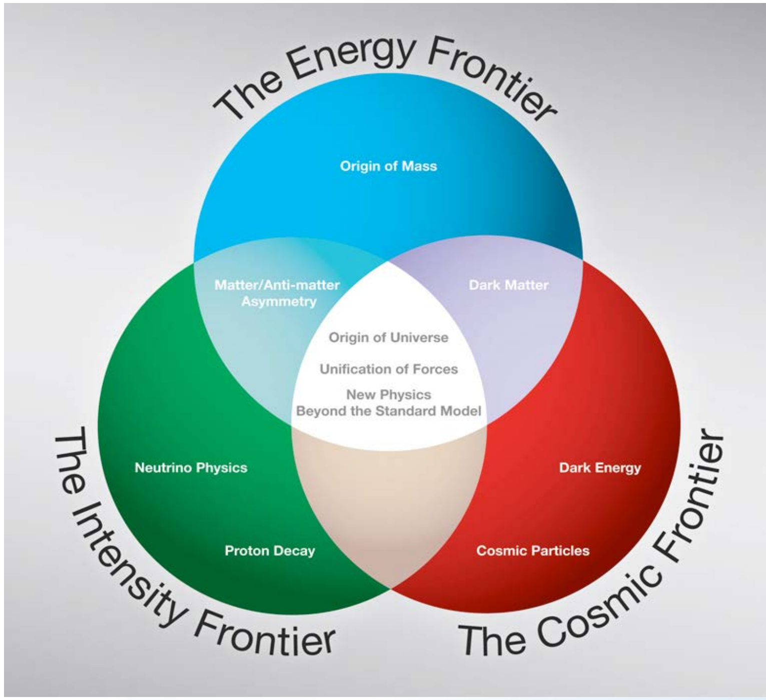
where, among many other things, Dennis learned that reactor ν exp'ts are High Energy Physics…


Dennis & co. at entrance to Daya Bay tunnel, 2010

Kovar Act III: "The Opportunity to Fail Again"

A tumultuous period in U.S. HEP:

- *FY08 budget challenges lead to cessation of HEP facility operations at SLAC, serious cuts in U.S. participation in ILC R&D*
- *The 2008 P5 process to reevaluate priorities & plans for U.S. HEP ⇒ adoption of an NP-like "three-frontier" approach*
- *Identification of FNAL Project X and Long Baseline Neutrino Exp't @ DUSEL as centerpieces of the Intensity Frontier*

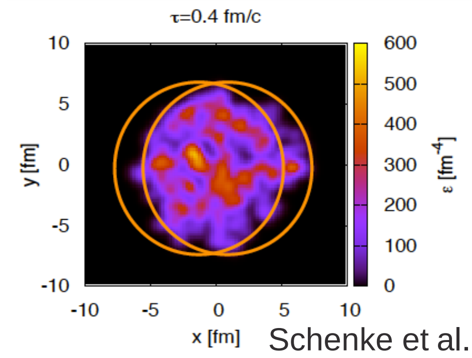


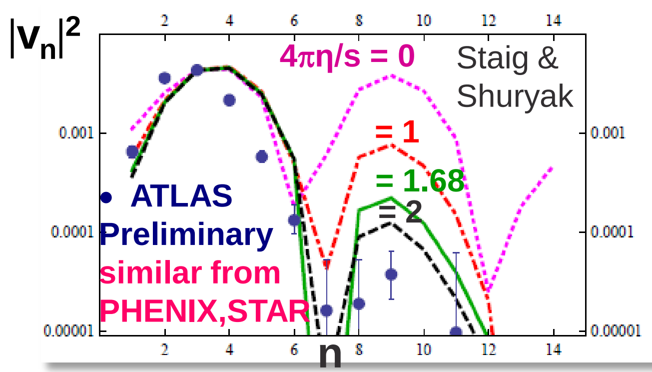

Kovar, Baltay, Oddone at June 2008 Workshop on Physics with a High Intensity Proton Source

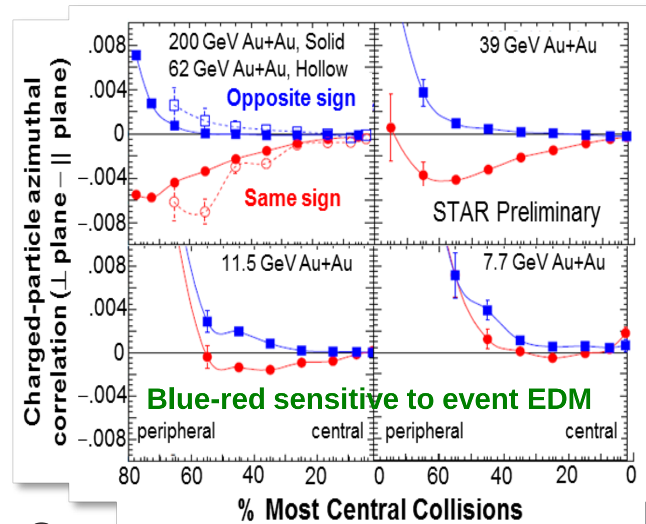
- *Start-up of LHC, with strong U.S. contributions*
- *Termination of Tevatron ops*
- *NSB withdrawal from DUSEL lab constr. & ops.*
- *Ongoing efforts to define Project X science need*

Dennis led OHEP, labs through it all with great dignity and widespread respect from all.

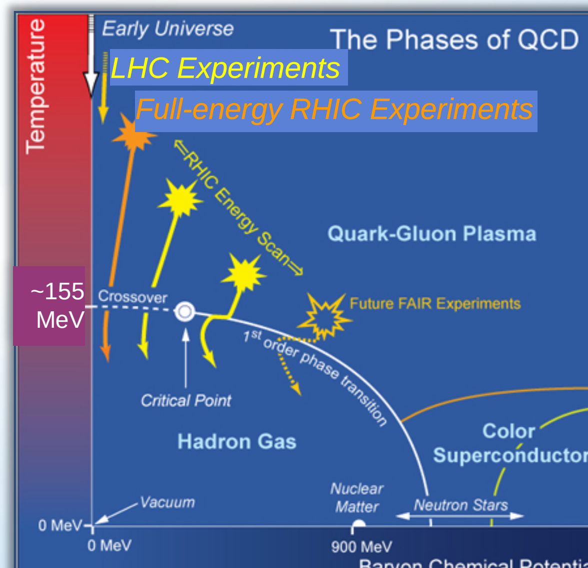
RHIC Act II: Quantification Fueled by Upgrades







- **How perfect is the near-perfect liquid?**
  Fourier power spectra for collective flow, above & below deconfinement transition (energy "sweet spot" @ RHIC)
- **How do fluctuations affect "mini-universe" evolution?**
  Initial density fluctuations: Odd vs. even flow for symmetric & asymmetric collisions; quantum fluctuations in gluon field?
  Excited QCD vacuum fluctuations: Further tests of event-by-event CP violation, including U+U collisions
- **Is there a critical endpoint in the QCD phase diagram?**
  Critical fluctuations in conserved quantity distrib'ns vs. √s
- **How do quarks and gluons lose energy in QGP?**
  Jet quenching vs. √s, parton flavor, system size, orientation
- **Where is the "missing" proton spin?**
  Di-jet, W and Drell-Yan prod'n in polarized pp



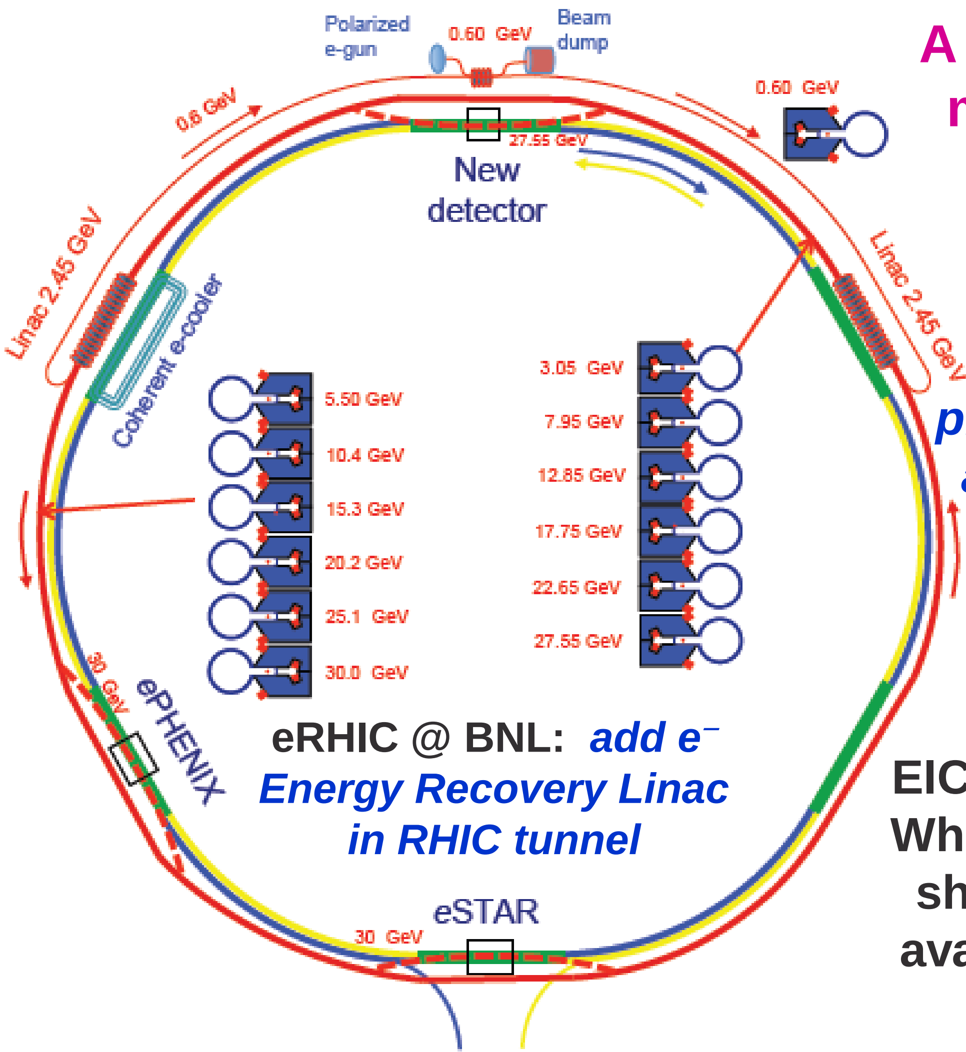
Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

All exploit RHIC's unique capabilities!

RHIC Remains Essential to Pursue Upcoming Science

- Spans the energy "sweet spot" where transition to QGP appears to set in, permitting study of early universe matter above and below transition
  - ***Can't be done at LHC, where injection energy is well above top RHIC E***
- Flexibility in colliding beam species + dedicated heavy-ion focus permits systematic unraveling of various sensitivities of QGP behavior
  - ***Magnet design and pp focus makes this very challenging at LHC***
- In combination with LHC, provides very large energy lever arm to constrain how quarks and gluons interact inside QGP
- RHIC detectors best suited for measurements related to QGP temperature determination
- RHIC is world's only polarized proton collider, yielding unique spin program
  - ***Polarized protons extraordinarily difficult technically at LHC energies, and would not yield sizable quark spin preferences***
- Provides cost-effective path to a future polarized Electron-Ion Collider identified in 2007 Nuclear Physics Long Range Plan as highest priority next-generation facility for study of quarks and gluons in matter
- Maintains critical collider R&D capabilities in U.S., where RHIC is now only operating collider

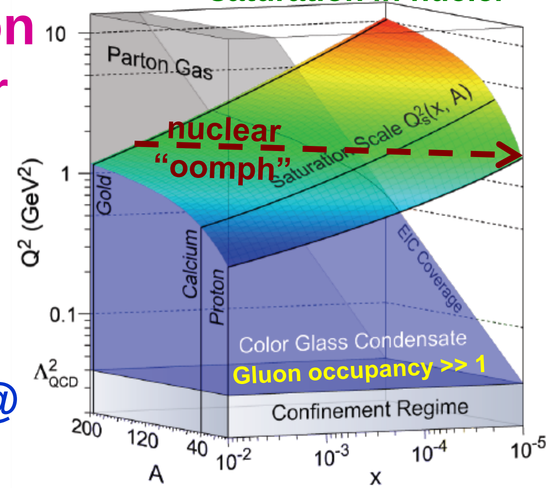
RHIC Act III: Reinvention as eRHIC

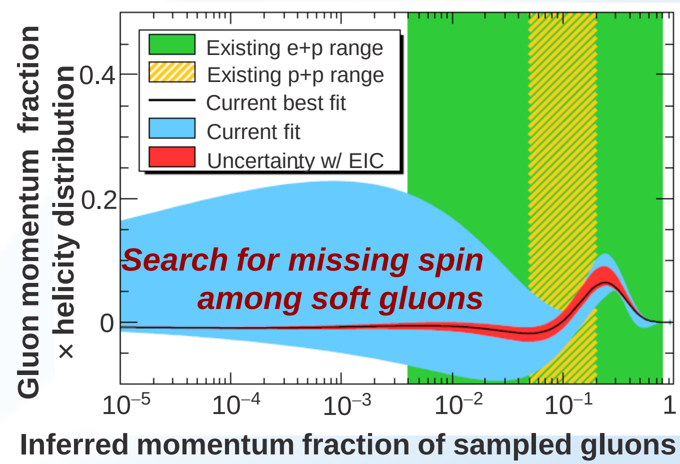


eRHIC @ BNL: ***add e⁻ Energy Recovery Linac in RHIC tunnel***

A high-resolution microscope for cold gluon-dominated matter:
2010 INT program report @ arXiv:1108.1713

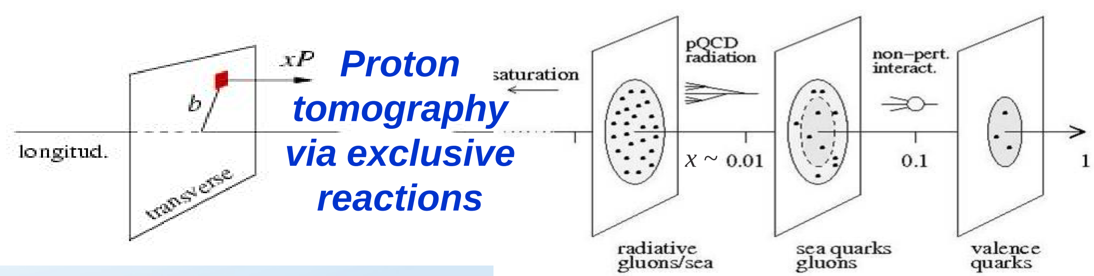
Probe onset of gluon saturation in nuclei





EIC Science White Paper should be available in 2012

Design allows easy staging of machine in energy. Technical & cost reviews in 2011-12.



Conclusions

Dennis viewed his role in ONP as that of stewarding our dreams to reality.

To accomplish this, he demanded that we:

1) *Articulate the science goals in a clear and compelling way*
2) *Face "brutal facts" regarding funding and prioritize accordingly*
3) *Deliver on the promises that drove our dreams*

In the case of RHIC, he did all this with great effectiveness and patience!

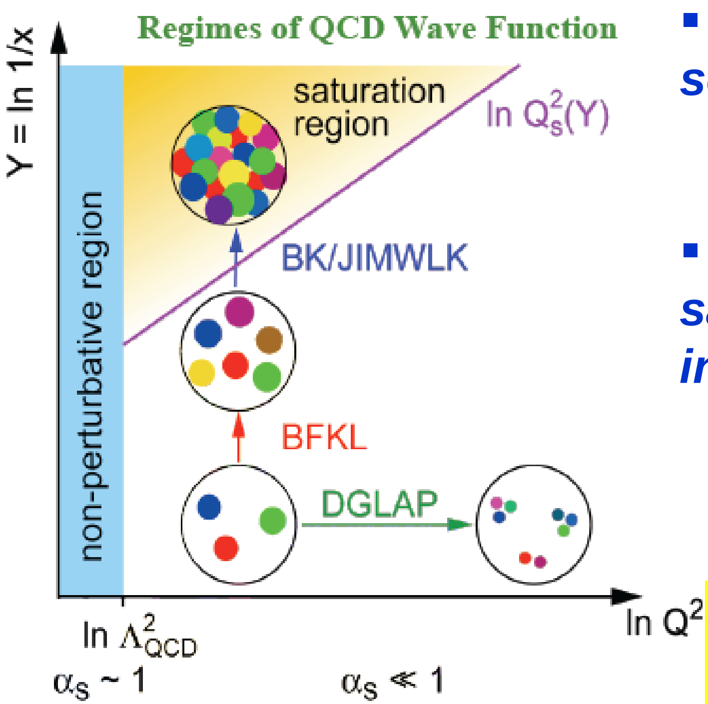
We continue to work hard on our end of the bargain:

1) *We have explored matter at extreme energy density and discovered QGP (as per LRP's in 1983-2002), but "it's not your father's QGP!"*
2) *We have developed the pathways to quantify QGP transport properties and search for a QCD Critical Point (as per 2007 LRP)*
3) *We're pursuing the next generation of dreams!*

Backup Slides

RHIC's Future Science Themes: Cold QCD Matter

- *Complete determination of gluon and sea-antiquark contributions to p spin*
  - *jet (hadron), di-jet (di-hadron) and W production asymmetries in RHIC p+p; but need e+p @ EIC to constrain low-x contributions*
- *Test QCD understanding of transverse spin asymmetries*
  - *compare p+p Drell-Yan @ RHIC to semi-inclusive e+p DIS @ HERMES, COMPASS, EIC*
- *Make pioneering measurements of nucleon's electroweak structure fcns.*
  - *charged-current DIS in e+N @ EIC*
- *Image transverse parton spin, momentum, spatial structure in nucleons*
  - *semi-inclusive DIS and deep exclusive e+N reactions @ EIC*

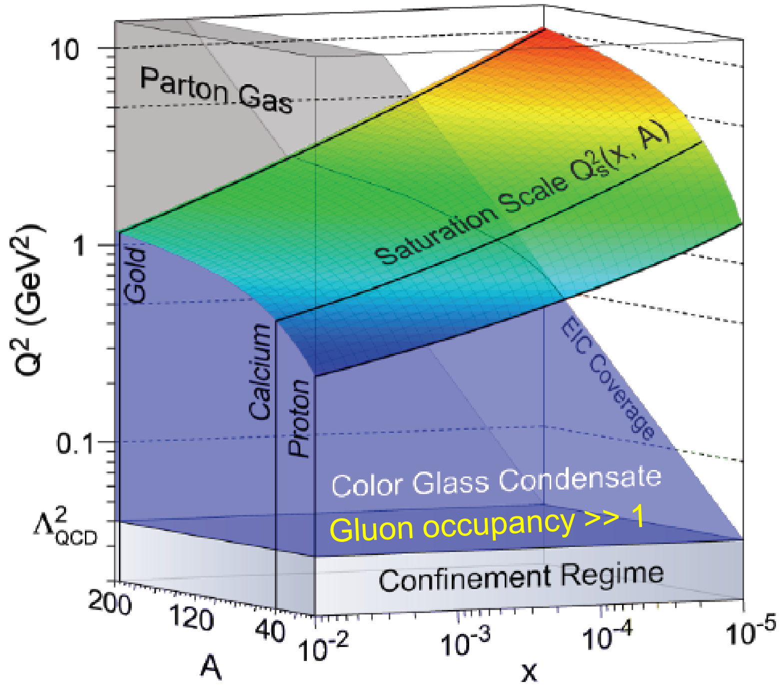


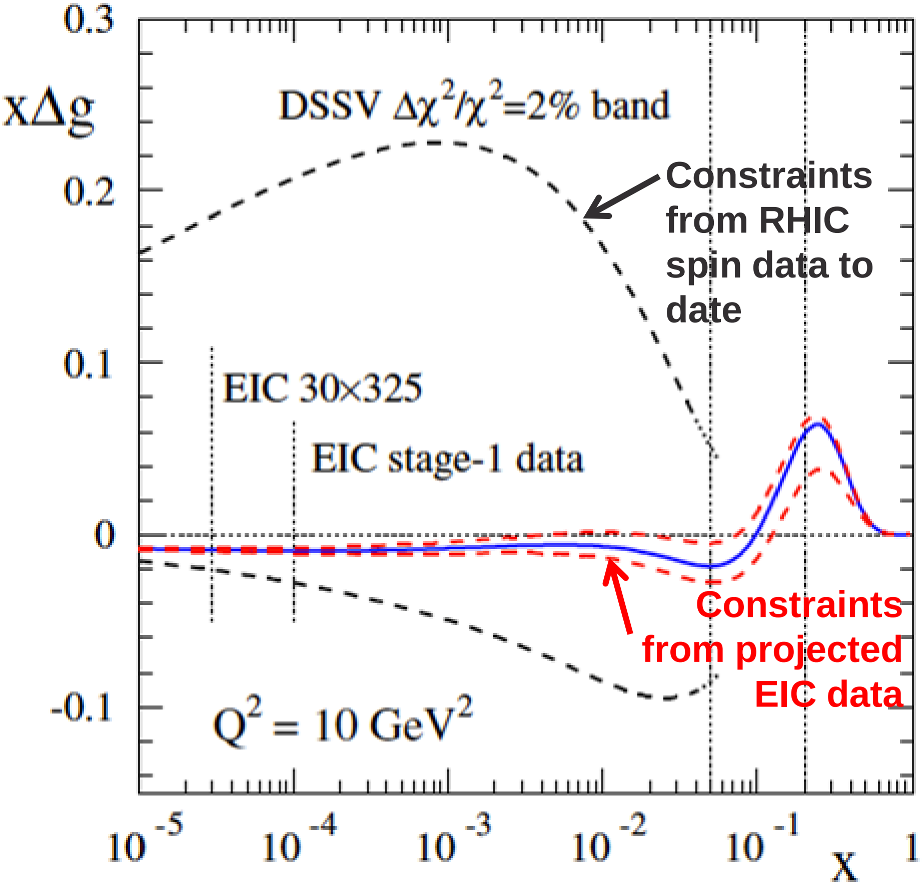
- *Map initial gluon distributions in cold nuclei, as seen by colliding beams at RHIC & LHC*
  - *start with d+A and p+A @ RHIC, LHC; but quantify with e+A DIS @ EIC*
- *Study transition from dilute partonic matter to saturated gluonic matter and test understanding in critical non-linear QCD regime*
  - *full-energy e+A program @ EIC, including novel gluonic form factors of nuclei via diffractive vector meson production*

An Electron-Ion Collider is needed to study gluon-dominated cold matter quantitatively.

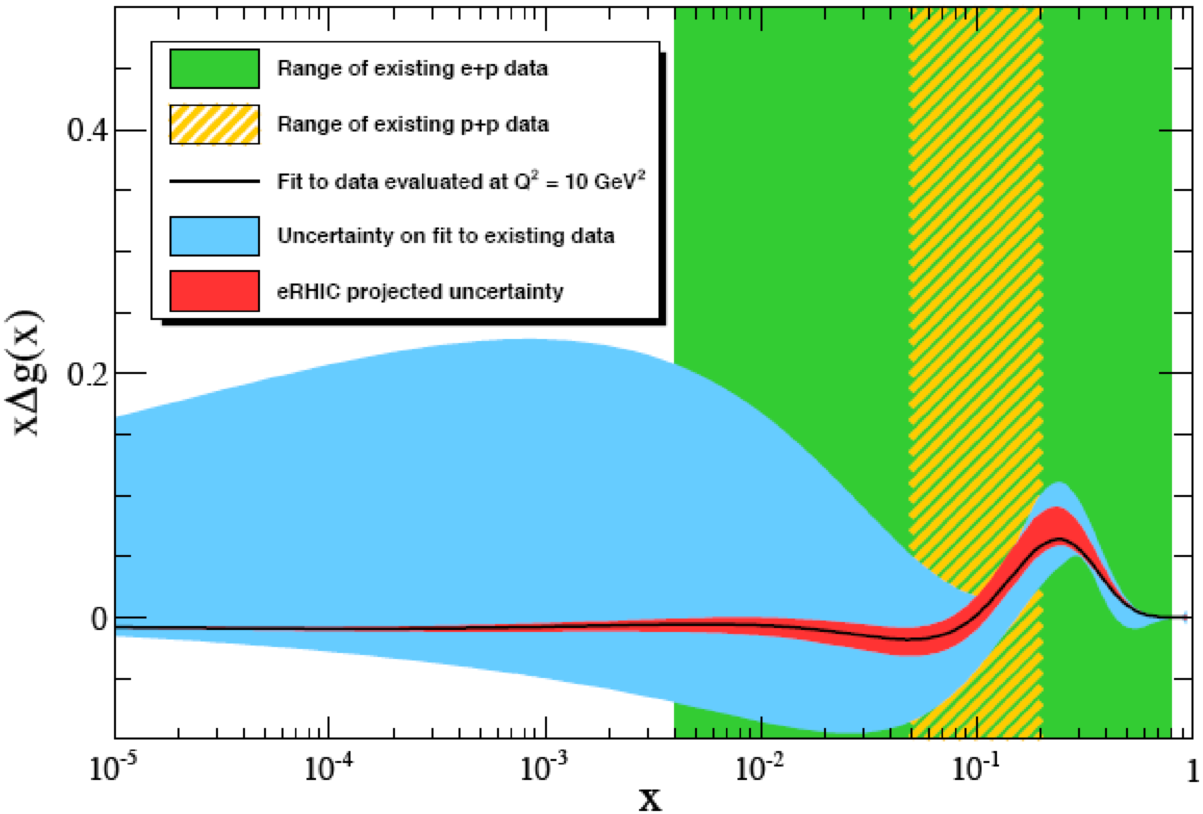
What Will EIC Have That HERA Didn't?

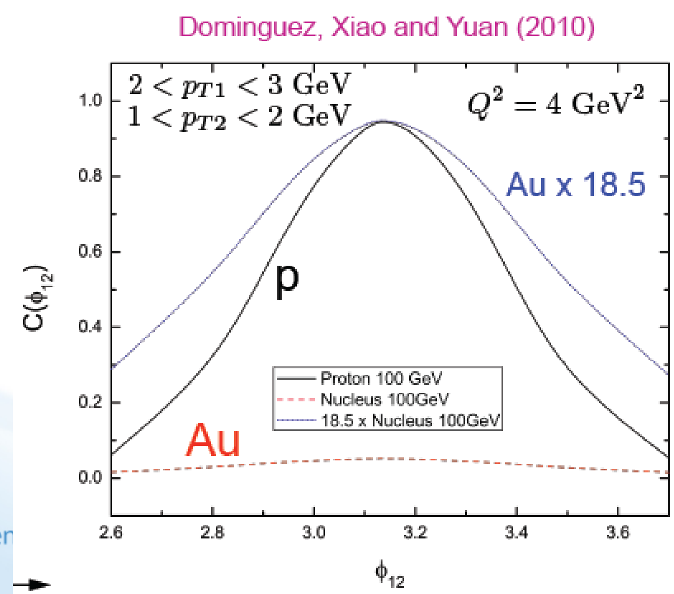
1) *Heavy-ion beams to take advantage of coherent contributions of many nucleons to gluon density, provide more cost-effective reach into gluon saturation regime when QCD coupling is still weak.*

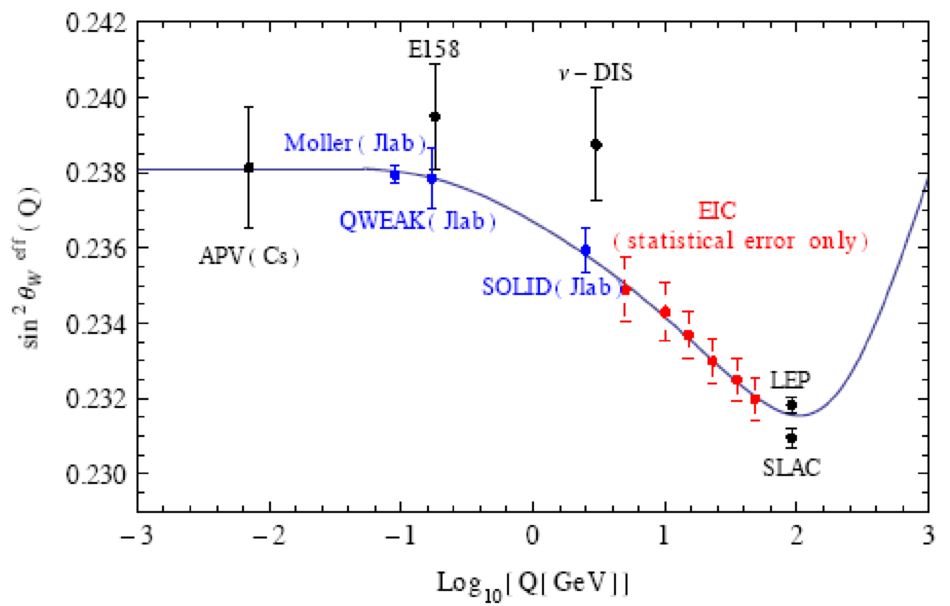




2) *Polarized proton and ^{3}He (for neutron), as well as electron, beams to pursue search for gluon contributions to nucleon spin down to very soft gluons, and map spin-momentum correlations of quarks and gluons inside nucleons.*

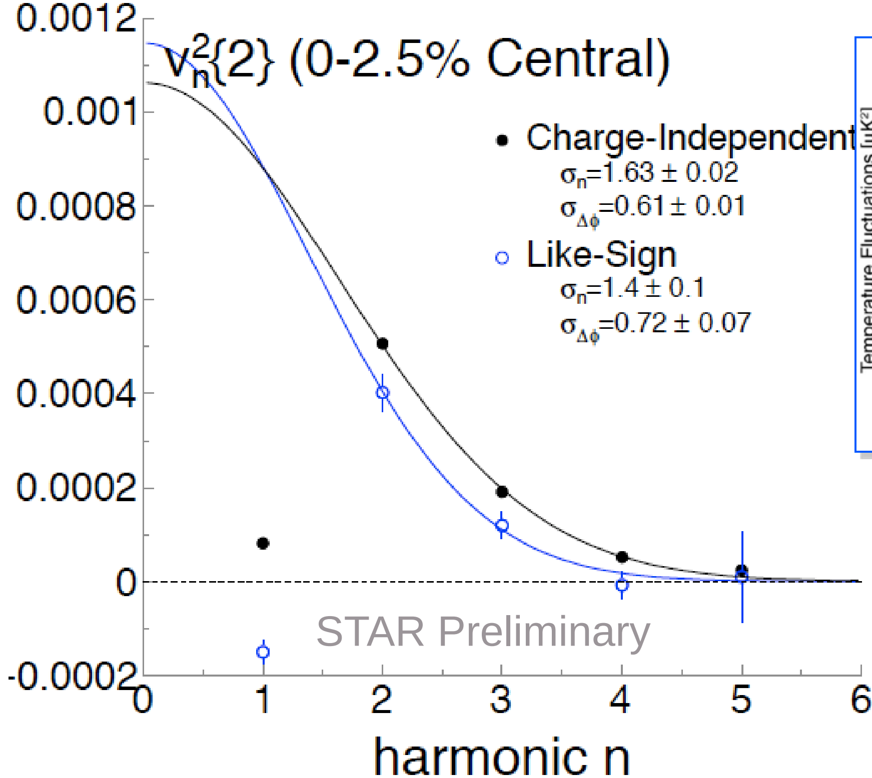

Range of existing e+p data
Range of existing p+p data
Fit to data evaluated at Q^2 = 10 GeV^2
Uncertainty on fit to existing data
eRHIC projected uncertainty
$x\Delta g(x)$
0.4
0.2
0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

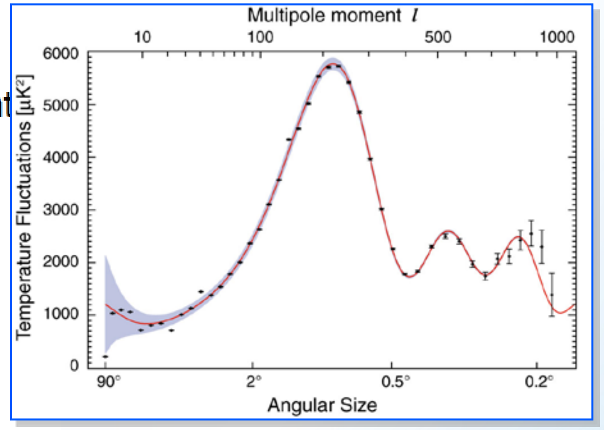

Dominguez, Xiao and Yuan (2010)
$2 < p_{T1} < 3$ GeV
$1 < p_{T2} < 2$ GeV
$Q^2 = 4$ GeV^2
Au x 18.5
p
Au
Proton 100 GeV
Nucleus 100GeV
18.5 x Nucleus 100GeV
$C(\phi_{12})$
ϕ_{12}


E158
ν – DIS
Moller (Jlab)
QWEAK (Jlab)
APV (Cs)
SOLID (Jlab)
EIC
(statistical error only)
LEP
SLAC
$\sin^2\theta_W^{eff}(Q)$
Log_{10}(Q[GeV])

$v_n^2\{2\}$ vs n for 0-2.5% Central

This is the Power Spectrum of Heavy-Ion Collisions





Power spectrum fit by a Gaussian except for n=1. The width can be related to length scales like mean-free-path and size of hot spots

P. Staig and E. Shuryak, arXiv:1008.3139 [nucl-th]
A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]
A. Adare [PHENIX], arXiv:1105:3928

Mean-free-path is related to the viscosity of the QGP and the early universe!

Viscosity in the little bang plays a much larger role than in the big bang.