

# Progress on RHIC Luminosity and Detector Upgrades

*Steve Vigdor  
NSAC Meeting  
February 26, 2010*

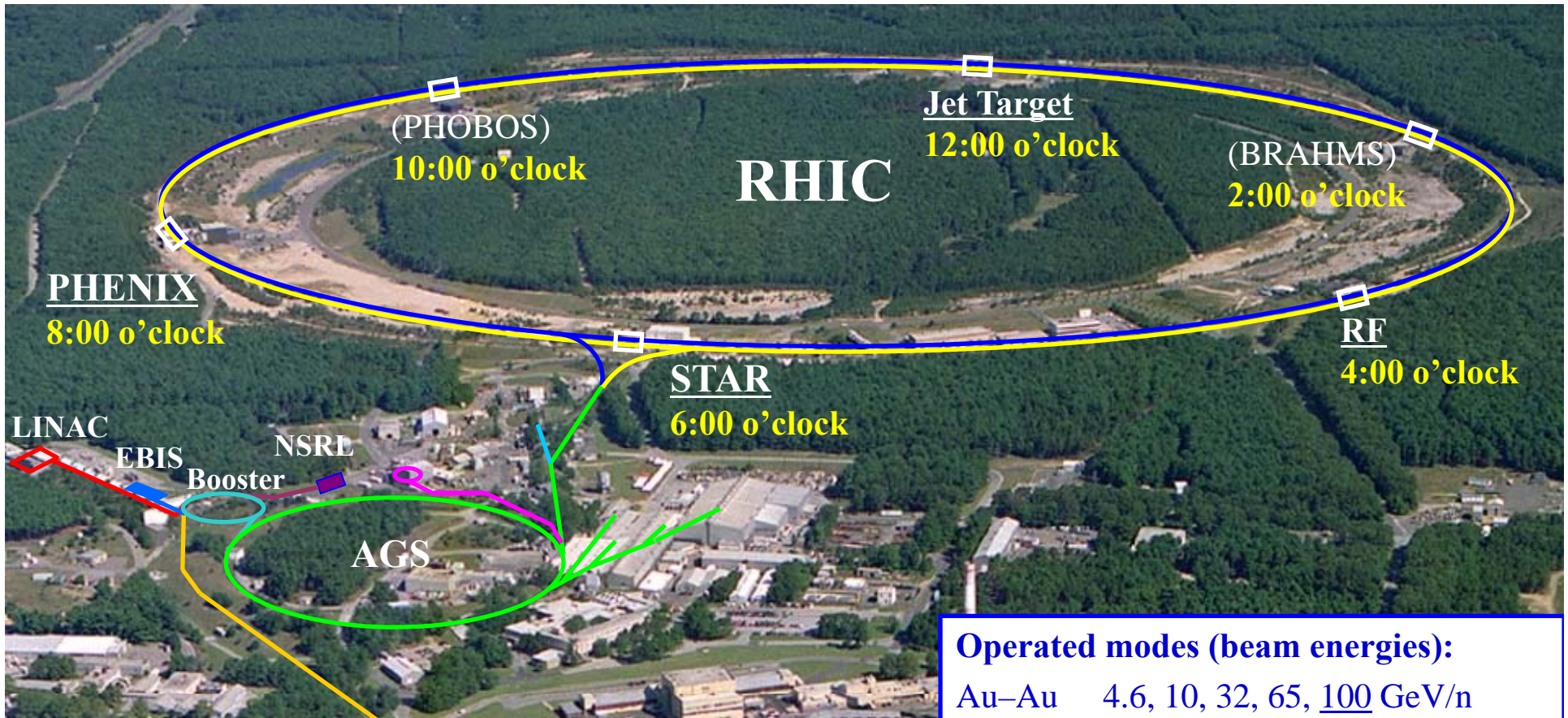
- I. Very Recent Results from RHIC**
- II. RHIC-II Science Goals**
- III. Status of Machine & Detector Upgrades**
- IV. Longer-Term Vision for RHIC**

**BROOKHAVEN**  
NATIONAL LABORATORY

*a passion for discovery*



# RHIC Provides Great Variety of Beam Species and Energies



**Achieved peak luminosities (100 GeV, nucl.-pair):**

Au–Au	$120 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
$p^\uparrow$ – $p^\uparrow$	$50 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$

**Other large hadron colliders (scaled to 100 GeV):**

Tevatron ( $p$ – $p$ bar)	$35 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
LHC ( $p$ – $p$ , design)	$140 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$



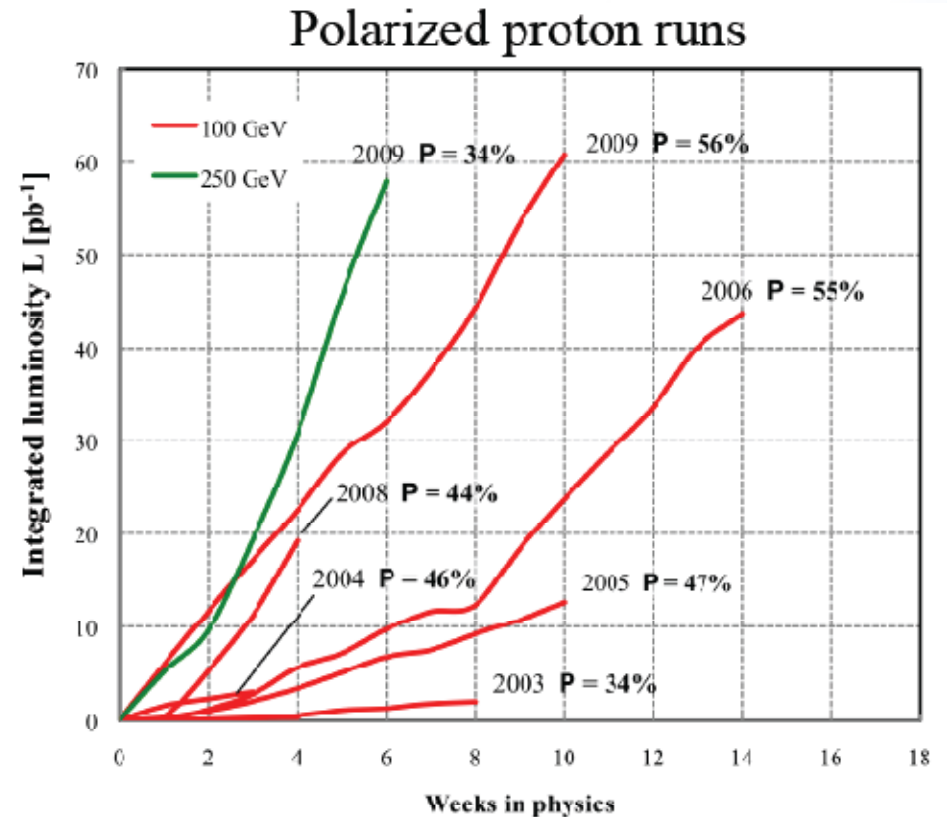
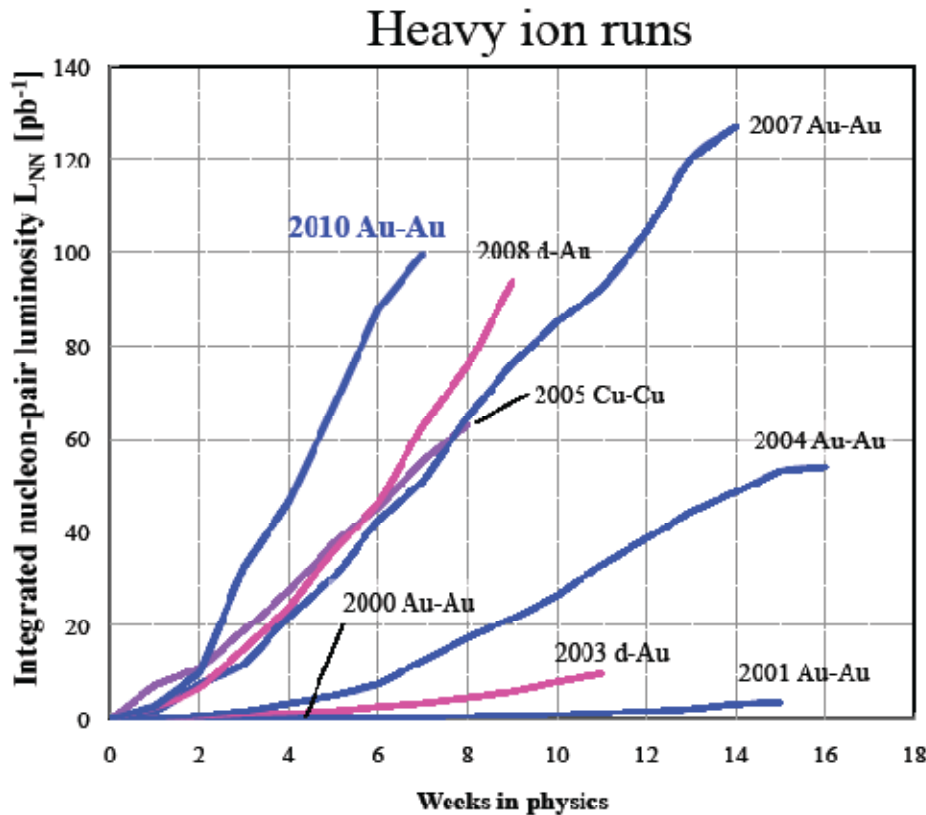
**Operated modes (beam energies):**

Au–Au	4.6, 10, 32, 65, <u>100</u> GeV/n
d–Au*	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
$p^\uparrow$ – $p^\uparrow$	11, 31, <u>100</u> , 250 GeV

**Planned or possible future modes:**

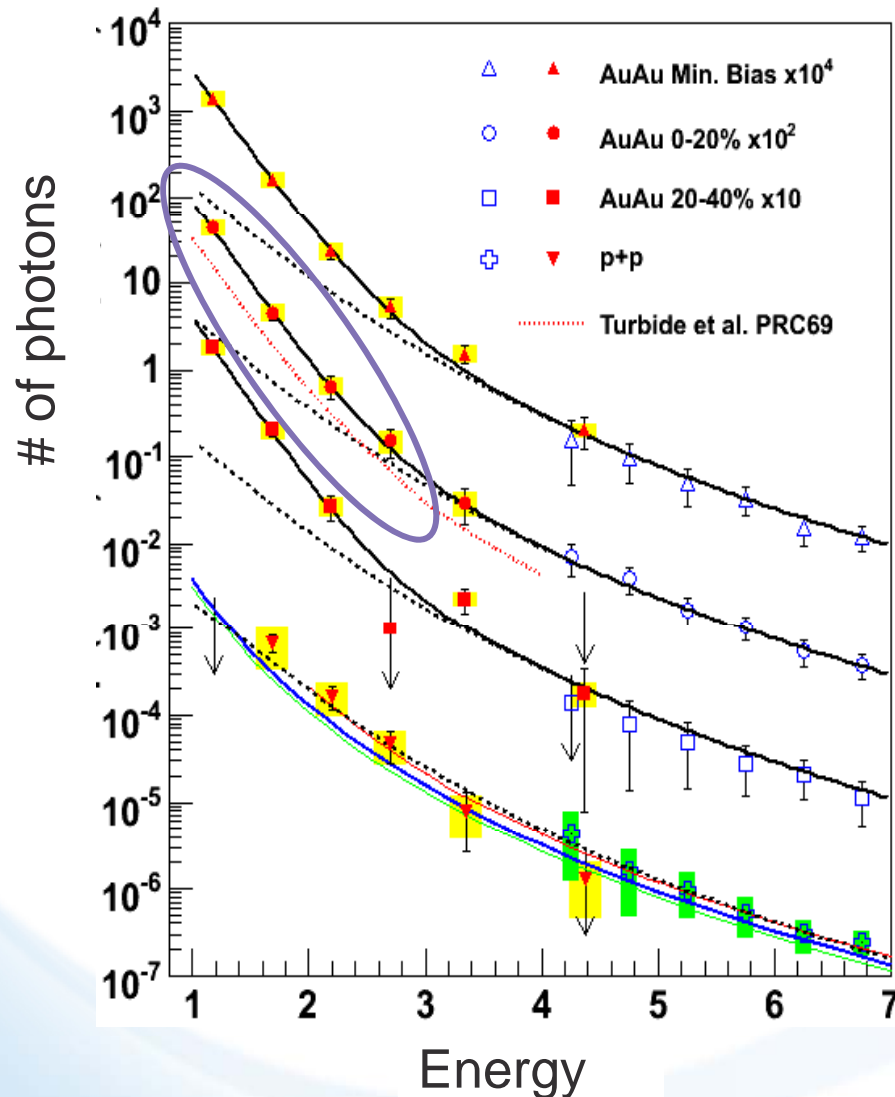
Au – Au	2.5 GeV/n (~ SPS cm energy)
$p^\uparrow$ – Au*	100 GeV/n (*asymmetric rigidity)

# Beam Performance Has Improved Substantially for All Species in Recent Years



*There have also been exciting new results emerging from the recent runs with different beam species...*

# 'Perfect Liquid' Hot Enough to be Quark Soup



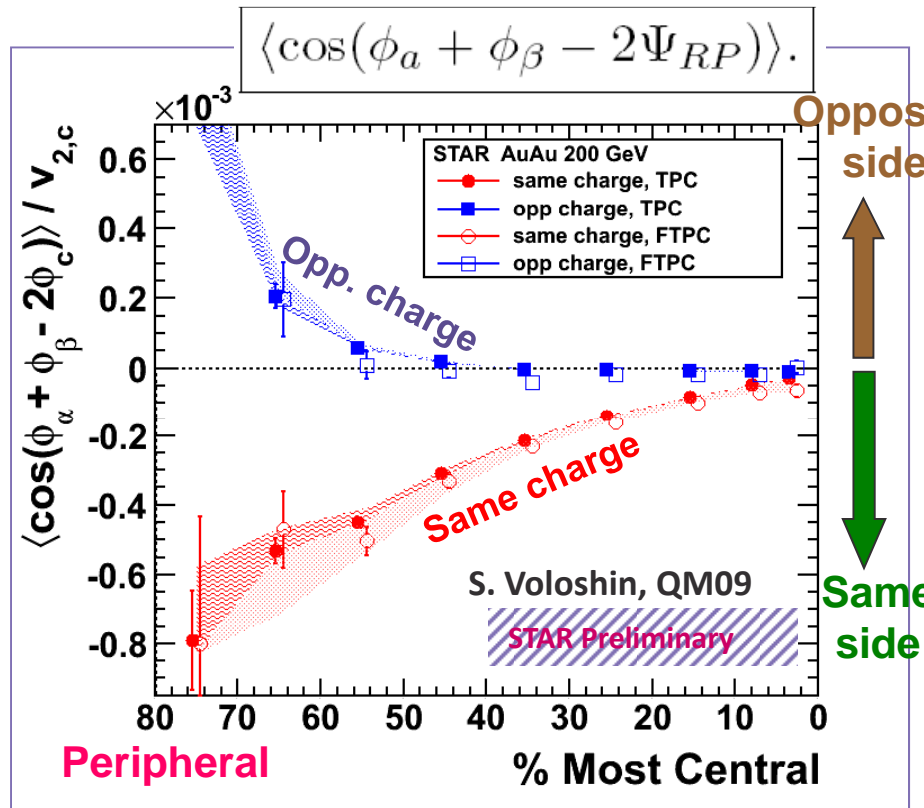
➤ PHENIX observes excess  $e^+e^-$  pairs at invariant mass  $< 300$  MeV and moderate  $p_T$  (1-5 GeV) in Au+Au vis-à-vis p+p

➤ Slope of excess  $\Rightarrow$  temp. averaged over time of virtual photon emission.

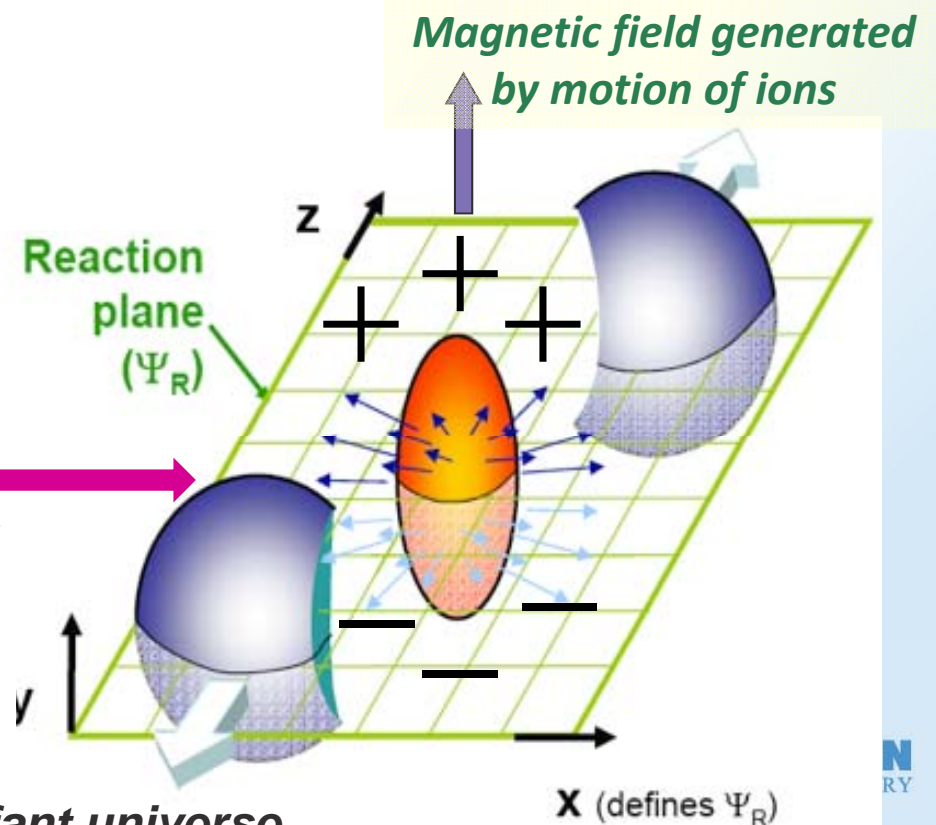
➤ Match to hydrodynamic calculations  $\Rightarrow$  initial temp.  $\sim 4 \times 10^{12}$  K  $\approx 2 \times$  LQCD transition temperature  $\approx 2 \times$  Hagedorn max. temp. for hadron gas

- hottest matter ever created in a laboratory
- $\sim 250,000$  times hotter than center of the Sun
- hot enough to melt protons and neutrons, as needed to create QGP
- consistent with other results indicating liberated quarks & gluons as 'perfect liquid's' constituents

# 'Bubbles' of Broken Symmetry in Quark Soup at RHIC?



➤ STAR observes event-by-event preference for like-sign (opposite-sign) charges to emerge in same (opposite) direction with respect to magnetic field produced by colliding nuclei



➤ Data suggest event-by-event EDM, predicted to arise from sphalerons near QGP phase transition  $\Rightarrow$  "bubbles" that locally violate parity (LPV) and CP

➤ Analogous to B-violating bubbles speculated at EW phase transition in infant universe

# Press Releases at APS Meeting 2/15/2010 Generate Worldwide Interest

**Newsweek**

Sharon Begley

Quark Soup

Physicists create conditions not seen since the big bang.

**nature**

Subatomic soup is hot stuff

Twisting vortices seen in fireballs could unravel matter-antimatter conundrum.

Eric Hand

**The New York Times**

In Brookhaven Collider, Scientists Briefly Break a Law of Nature

By [DENNIS OVERBYE](#)

**msnbc**

Hottest soup in the universe  
by Alan Boyle

**NEW YORK POST**

**Hot docs trigger 7T<sup>0</sup> blast**

WASHINGTON --The Department of Energy has created the hottest temperature ever, 7.2 trillion degrees Fahrenheit -- hot enough to break matter down into the kind of soup that existed microseconds after the universe's birth.

*In all, >500 articles, with global coverage, including several radio & TV interviews.*

*Plus nearly 80,000 views so far of video animation on YouTube*

# Noteworthy Results from RHIC Run 8

pp data

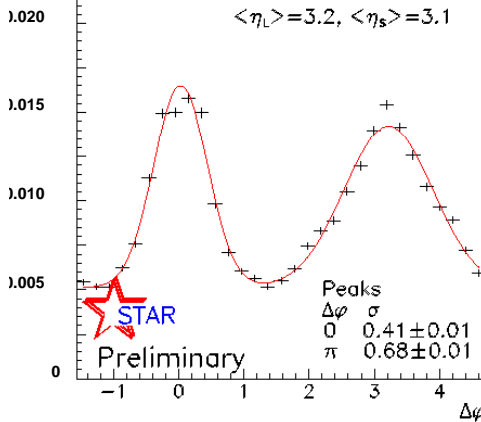
dAu peripheral

d+Au J/ψ production

Uncorrelated Coincidence Probability (radian<sup>-1</sup>)

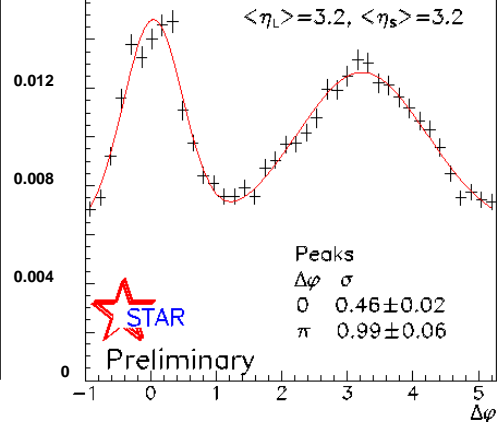
p+p → π<sup>0</sup>π<sup>0</sup>+X, √s = 200 GeV

p<sub>T,L</sub> > 2 GeV/c, 1 GeV/c < p<sub>T,S</sub> < p<sub>T,L</sub>  
 <η<sub>L</sub>> = 3.2, <η<sub>S</sub>> = 3.1



d+Au → π<sup>0</sup>π<sup>0</sup>+X, √s = 200 GeV, 0 < ΣQ<sub>bec</sub> < 500

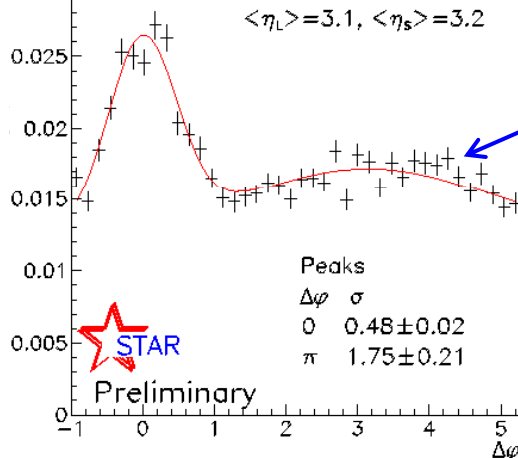
p<sub>T,L</sub> > 2 GeV/c, 1 GeV/c < p<sub>T,S</sub> < p<sub>T,L</sub>  
 <η<sub>L</sub>> = 3.2, <η<sub>S</sub>> = 3.2



dAu central

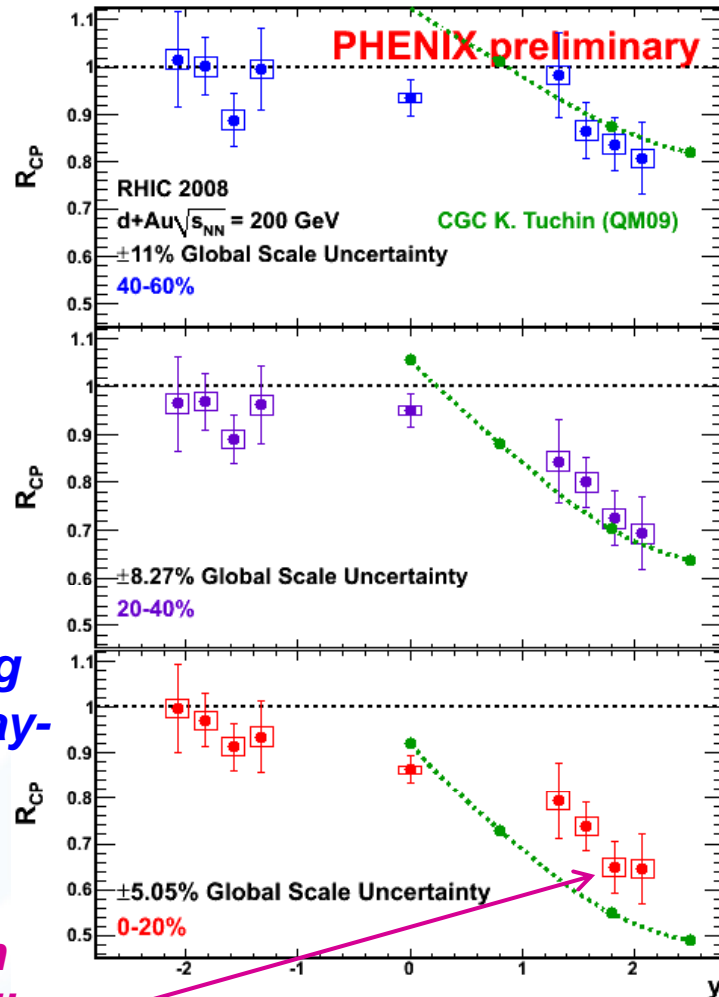
d+Au → π<sup>0</sup>π<sup>0</sup>+X, √s = 200 GeV, 2000 < ΣQ<sub>bec</sub> < 4000

p<sub>T,L</sub> > 2 GeV/c, 1 GeV/c < p<sub>T,S</sub> < p<sub>T,L</sub>  
 <η<sub>L</sub>> = 3.1, <η<sub>S</sub>> = 3.2



In central d+Au:

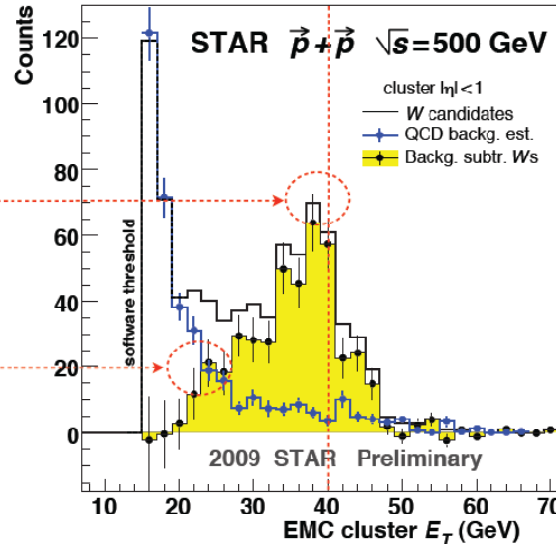
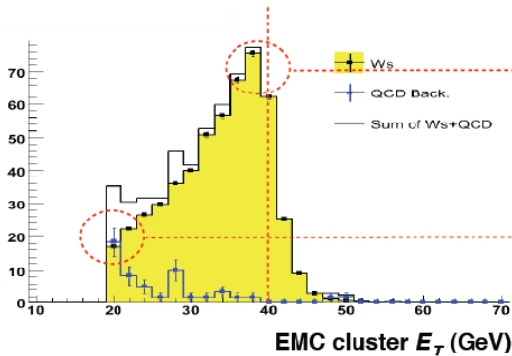
- STAR sees strong suppression of away-side forward π-π correlations
- PHENIX sees strong suppression of forward J/ψ prod'n



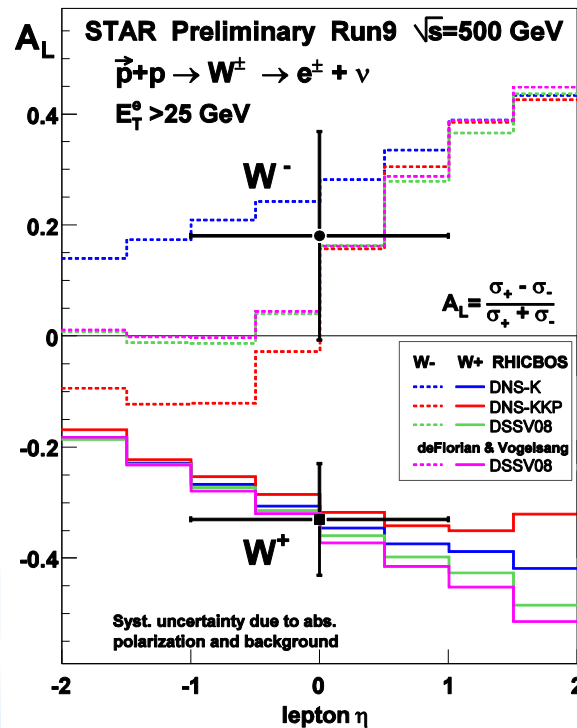
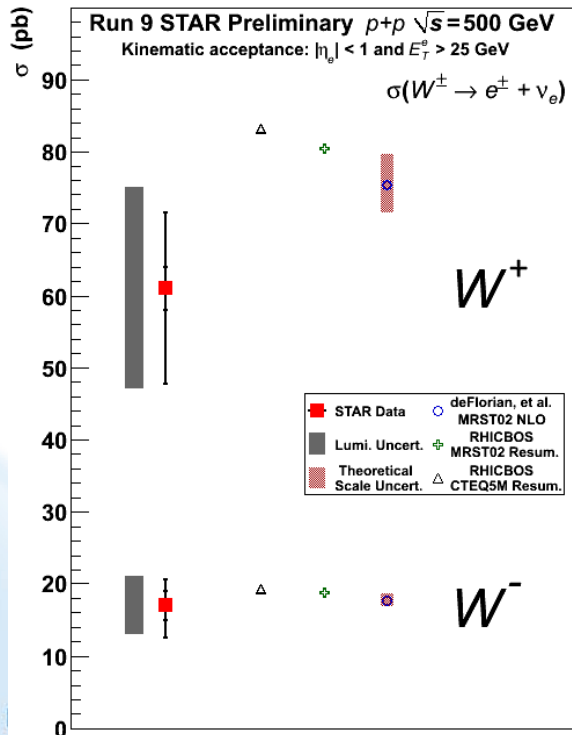
**Both effects are predicted signatures of the Color Glass Condensate!**

# Noteworthy Results from RHIC Run 9

W PYTHIA MC Simulation (10pb<sup>-1</sup>)



**Both STAR and PHENIX see clear W production signals above QCD background from 1st 500 GeV pp collisions.**

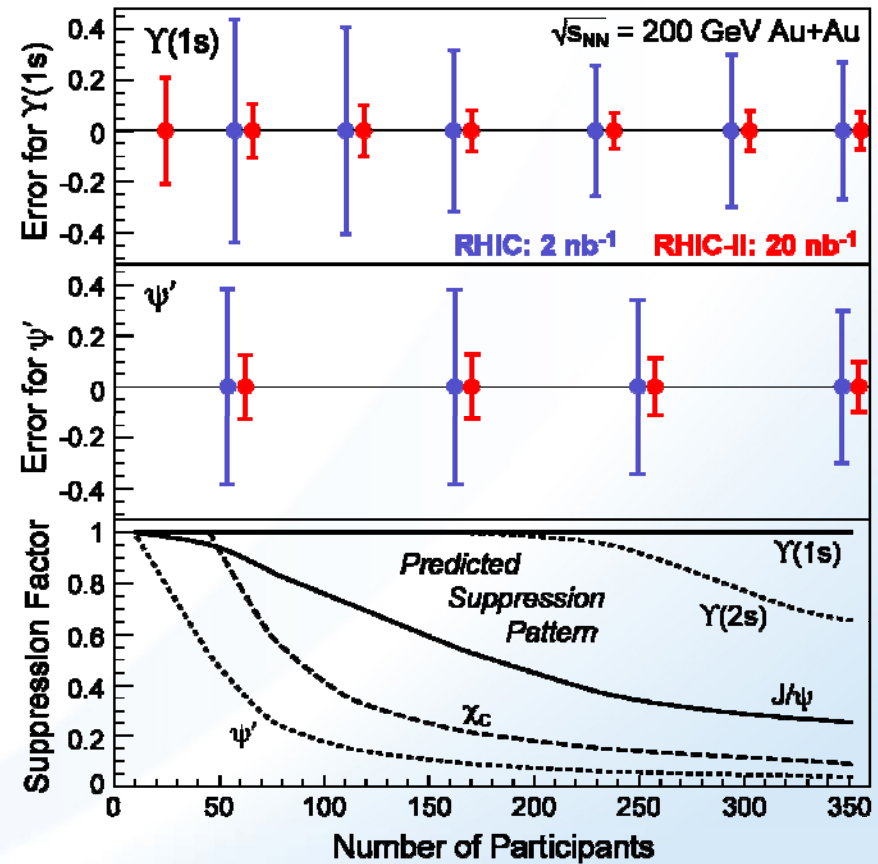
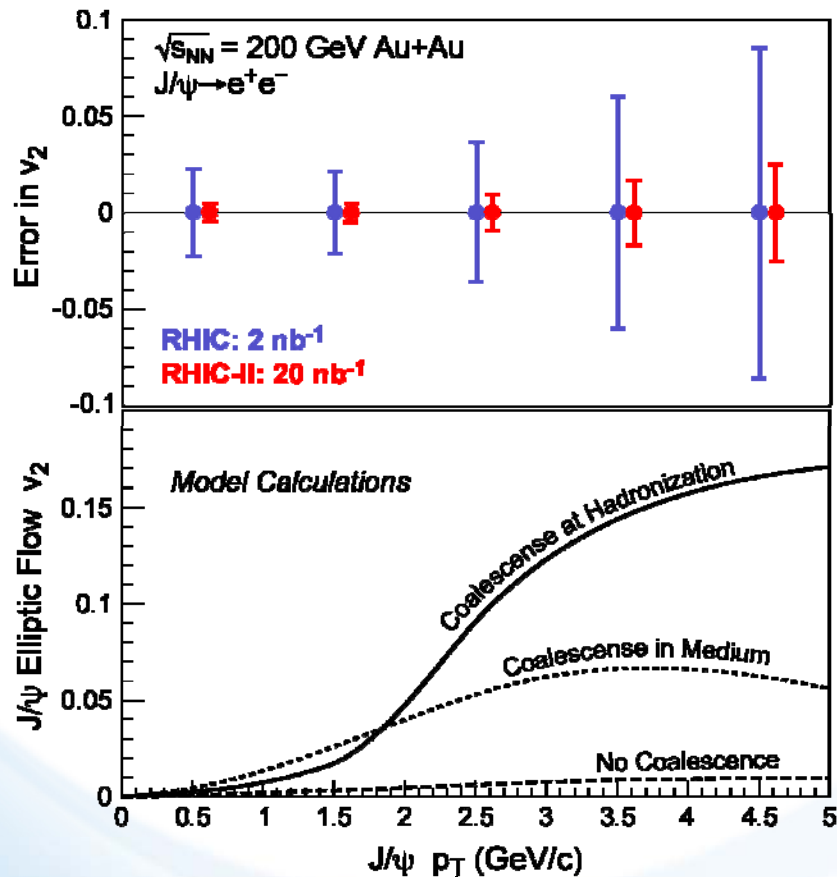


**Preliminary cross section and helicity asymmetry results consistent with theory, demonstrate RHIC's ability to isolate W production cleanly**



# RHIC-II Science: Quantifying Properties of the Perfect Liquid

I. 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

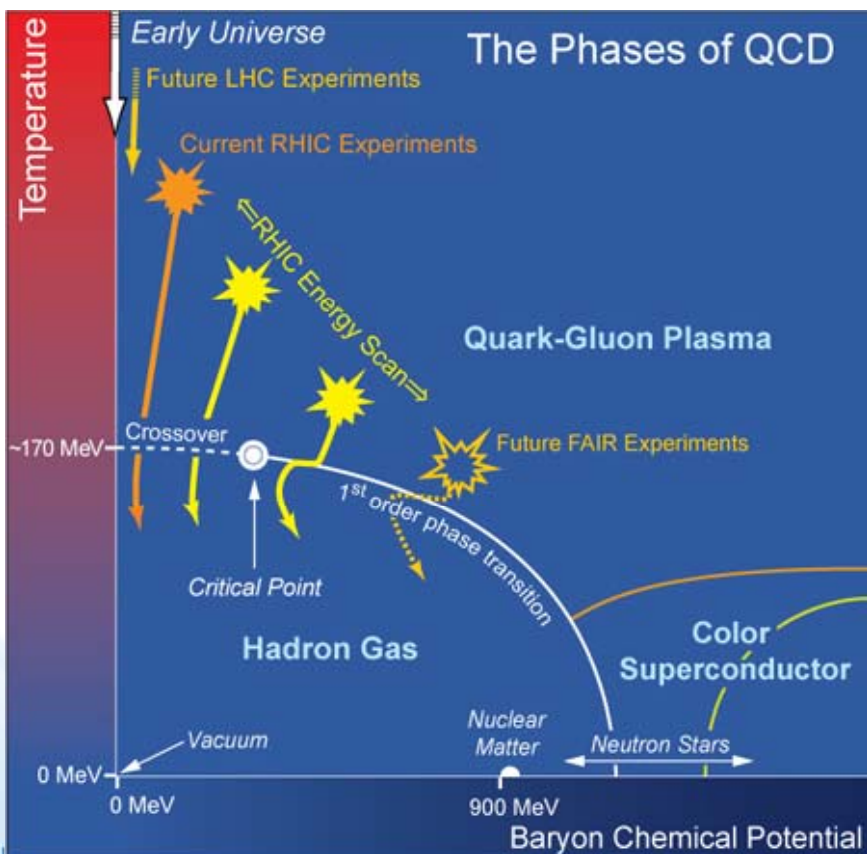


## *RHIC-II Science: Quantifying Properties of the Perfect Liquid*

II. Facilitate rare- and multi-particle correlation measurements:  $\gamma$  + jet to quantify energy loss transport coefficient; multi-hadron to study possible Mach cone, extract speed of sound.

III. Improve exp't-theory comparison of particle-identified (esp. heavy quark) flow, to quantify shear viscosity (how perfect?).

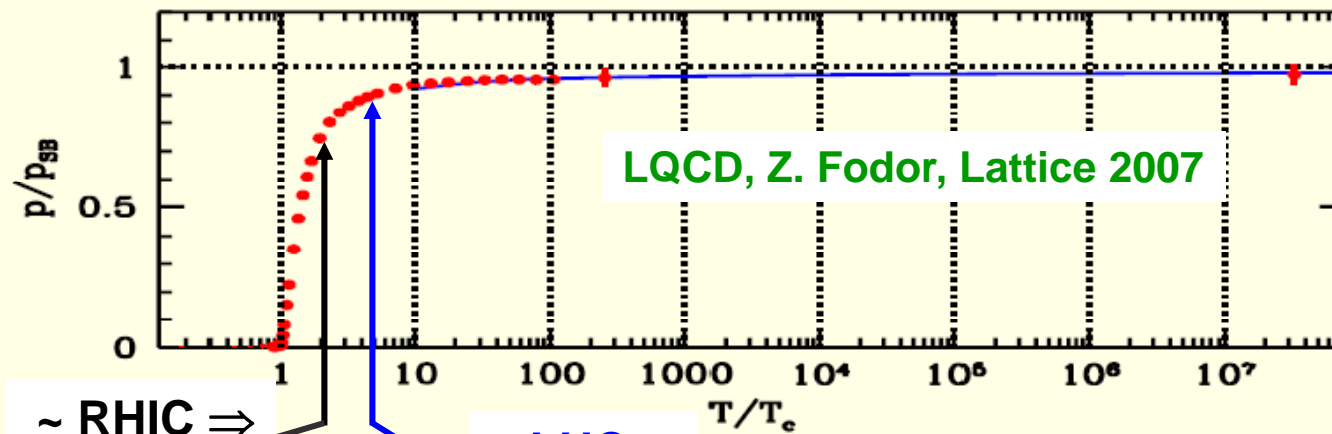
IV. Improve measurements at low collision E to search for QCD critical point and onset of deconfinement (e.g., disappearance of jet quenching or of evidence for local parity-violating bubbles)



## Complementarity of LHC HI and RHIC-II

*LHC and RHIC-II HI results should be complementary & mutually stimulating: similar matter produced? How do properties evolve with temperature? Thermalization consistent?*

*Quantitative interpretation of both requires coherent theory assault!*

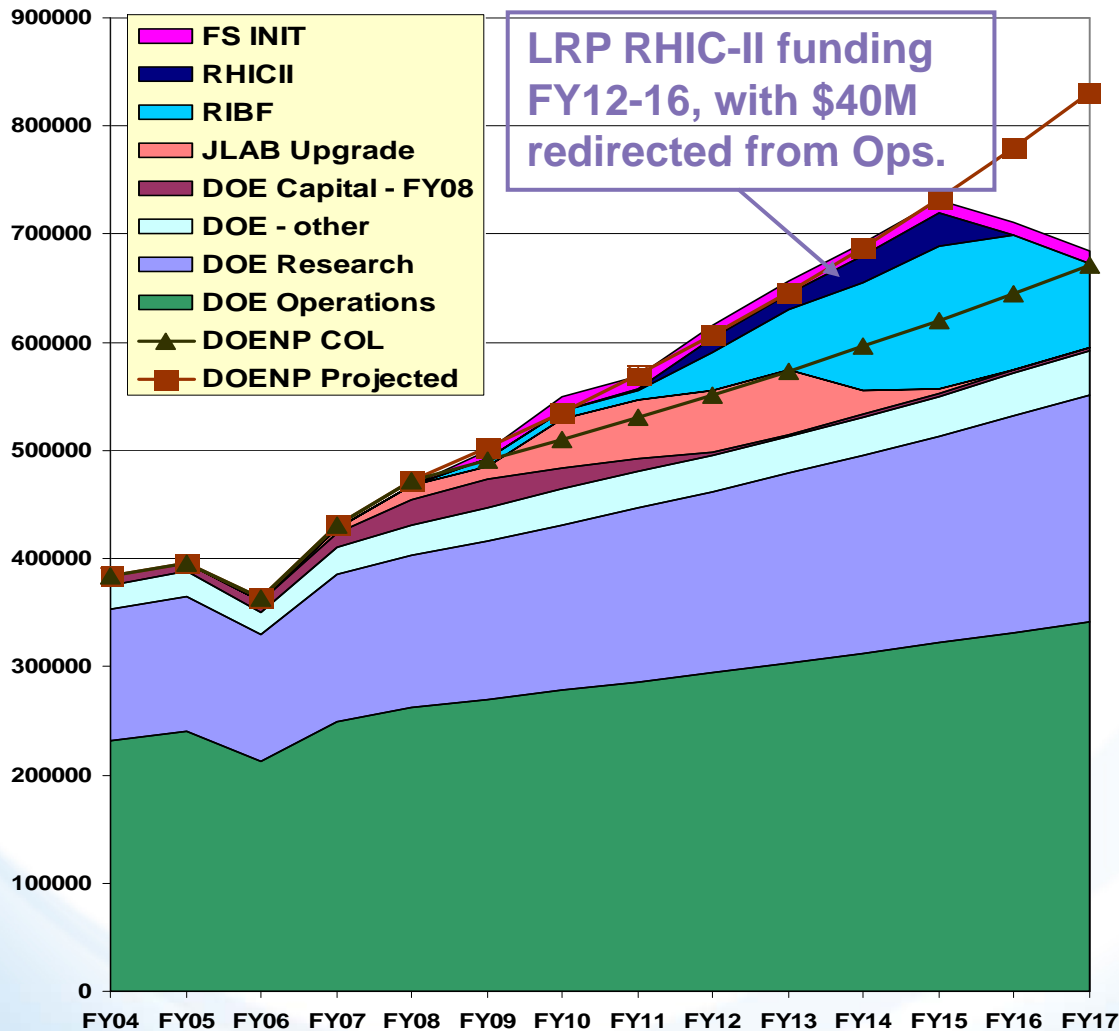


← Ideal gas  
Does matter still behave as an ideal liquid, or does shear viscosity grow from RHIC?

~ RHIC ⇒  
“perfect liquid”

~ LHC  
Pb+Pb

# Reminder of RHIC-II ca. 2007 (LRP)

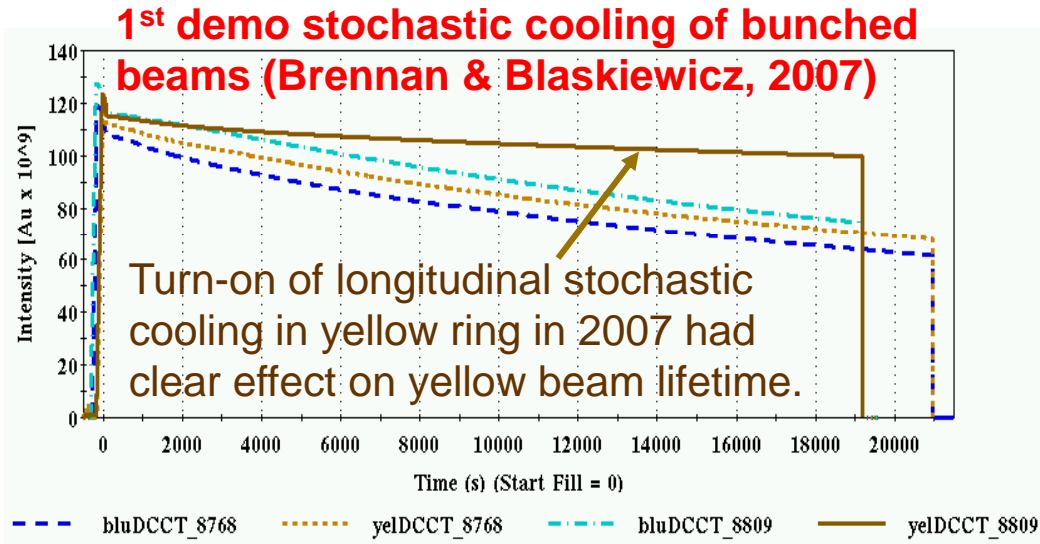


*At time of LRP, RHIC-II realization was envisioned via electron cooling, at cost of ~\$95M (in addition to ~\$35M of detector upgrades).*

*LRP timeline would have yielded upgraded luminosity by ~2017, hampering achievement of the science goals.*

*Technological advances at RHIC came to the rescue...*

# Allowing RHIC-II Science Without the RHIC-II Project

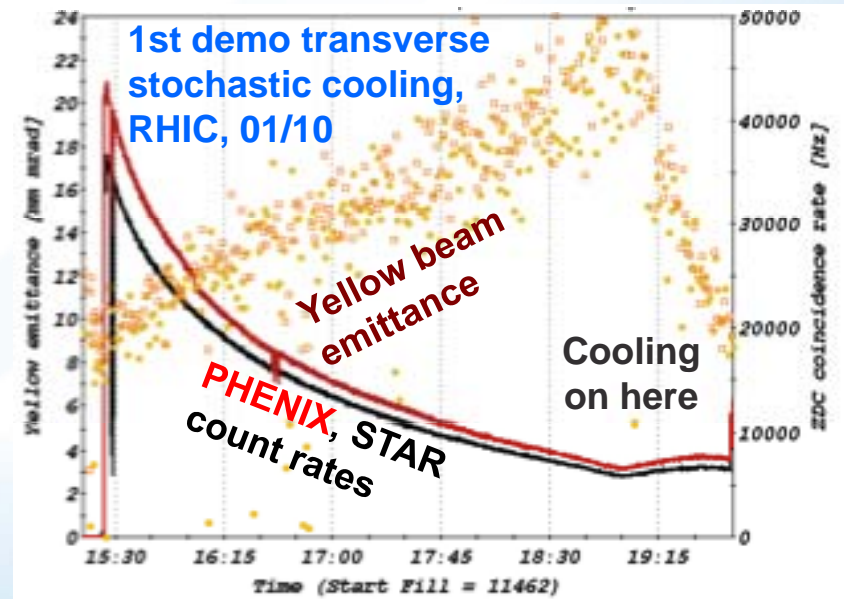


*R&D program improved state of the art in low-noise multi-GHz pickups and kickers to achieve stochastic cooling of a high-energy bunched beam for the 1<sup>st</sup> time ⇒ path to lumi. upgrade at order of magnitude less cost & ~5 years faster than e-cooling plan.*

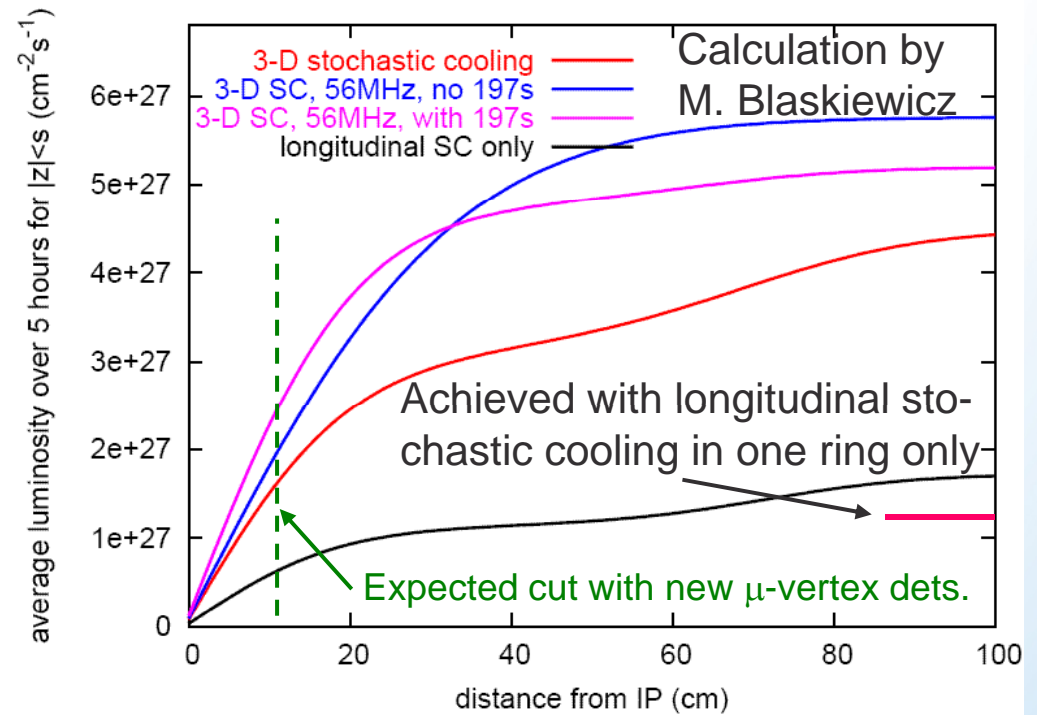
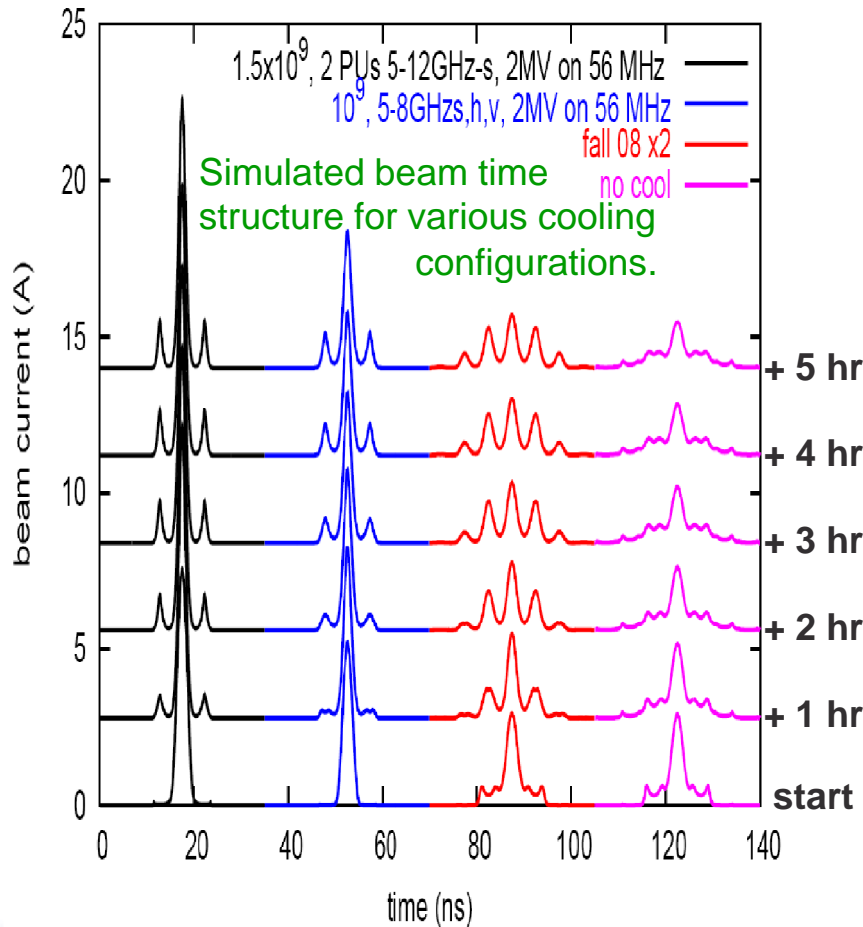
*Longitudinal stochastic cooling demonstrated in 2007 Au+Au run ⇒ ~15% improvement in ave. lumi.*

*Transverse stochastic cooling demonstrated in 2010 Au+Au run.*

*Stochastic cooling works to overcome intrabeam scattering, improve beam lifetime, emittance.*

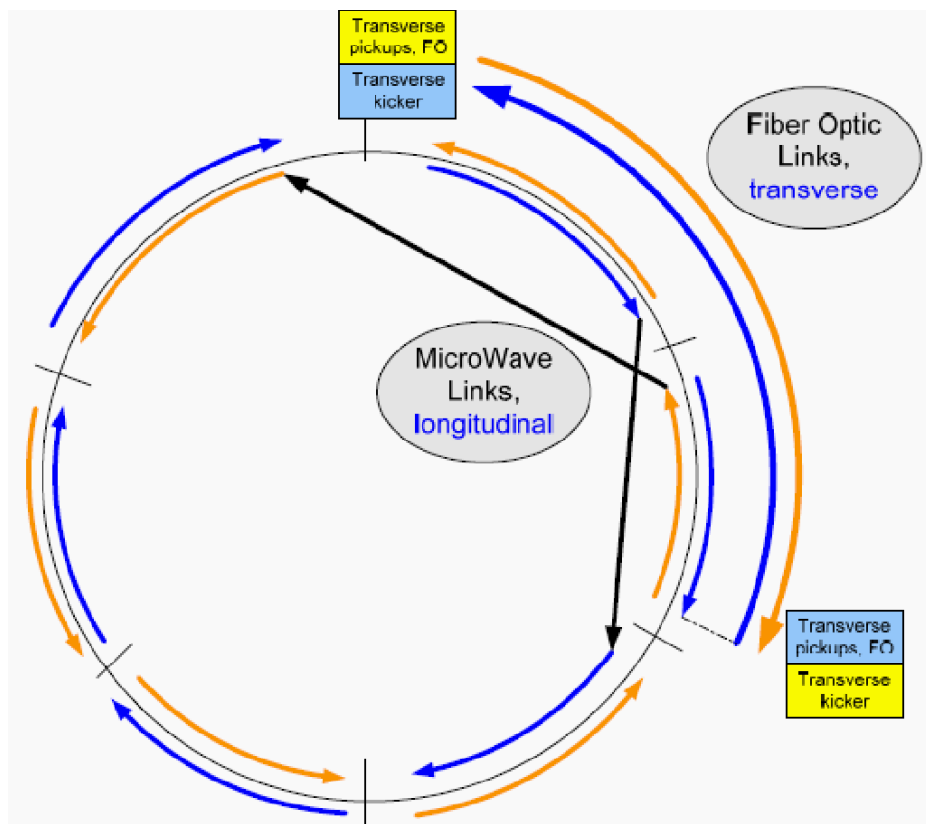


# Simulations $\Rightarrow$ ~Order of Magnitude Improvement in Useful Collision Luminosity for Full Energy Au+Au



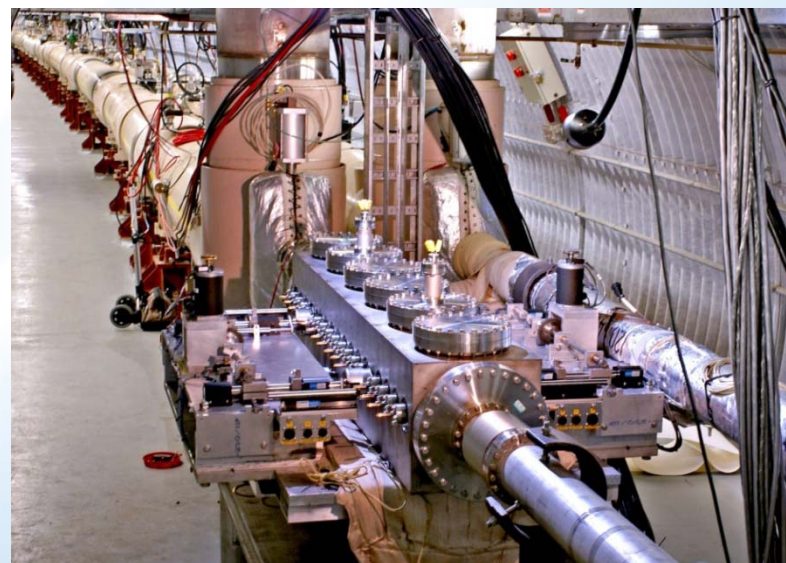
**Particle tracking simulations (above) reproduce 2007 observations, predict behavior for full stoch. cooling system anticipated by 2013: gain factor ~6-8 in integrated luminosity within useful vertex cut (including 56 MHz SRF upgrade) !**

# Stochastic Cooling Implementation and Status

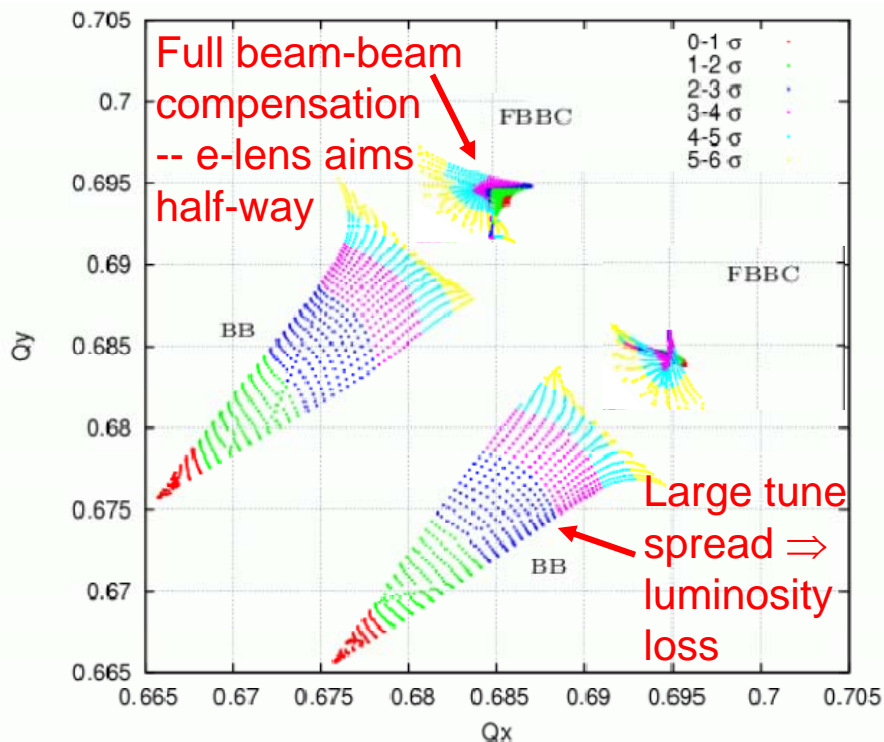


- **Longitudinal & vertical pickups and kickers installed in each ring for 2010 run**
- **Transverse cooling successfully demonstrated**
- **Vertical systems cool both transverse planes via betatron tune coupling**
- **Commissioning issues so far complicate simultaneous operation of all 4 systems**

- **Blue and yellow horizontal cooling under construction with ARRA funds for Run 12, will reduce transverse cooling time**
- **56 MHz SRF system anticipated for Run 13**  
⇒ **full anticipated luminosity gain**
- **Both beams must be cooled simultaneously for optimal lumi. improvement**



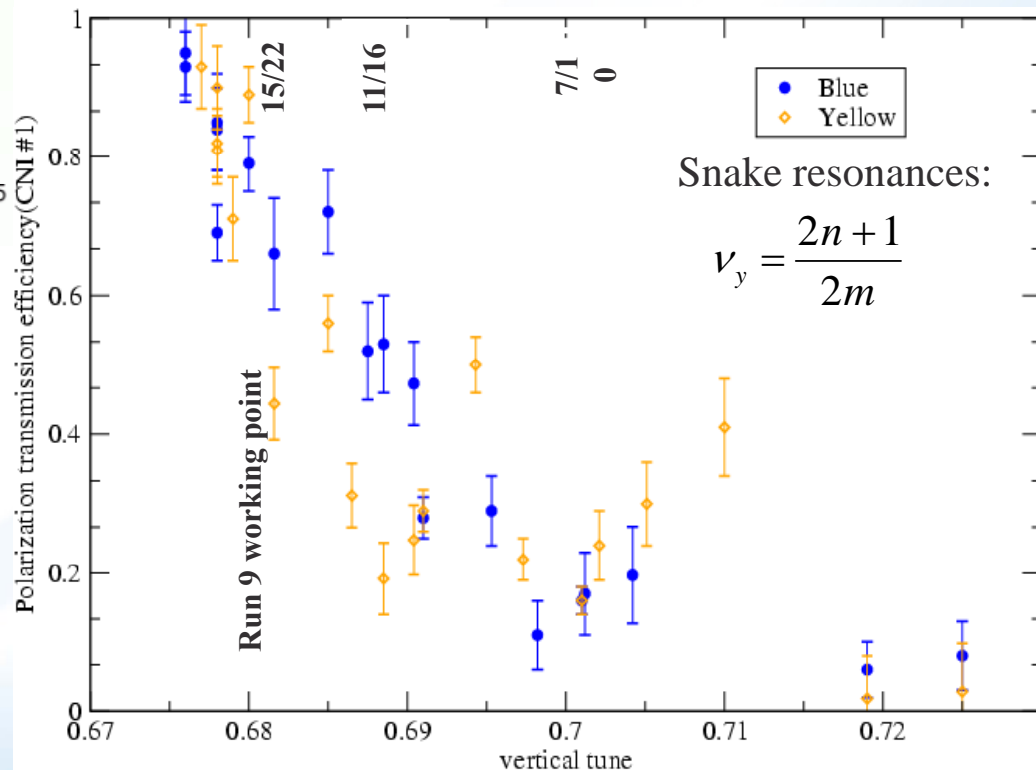
# Plans to Improve pp Luminosity & Polarization



- Run 9 pol'n at 250 GeV limited by Snake resonances
- Mitigate via improved power supply stability, permitting operation nearer 2/3 resonance
- Further improvements to source pol'n and AGS pol'n loss under way

Brc

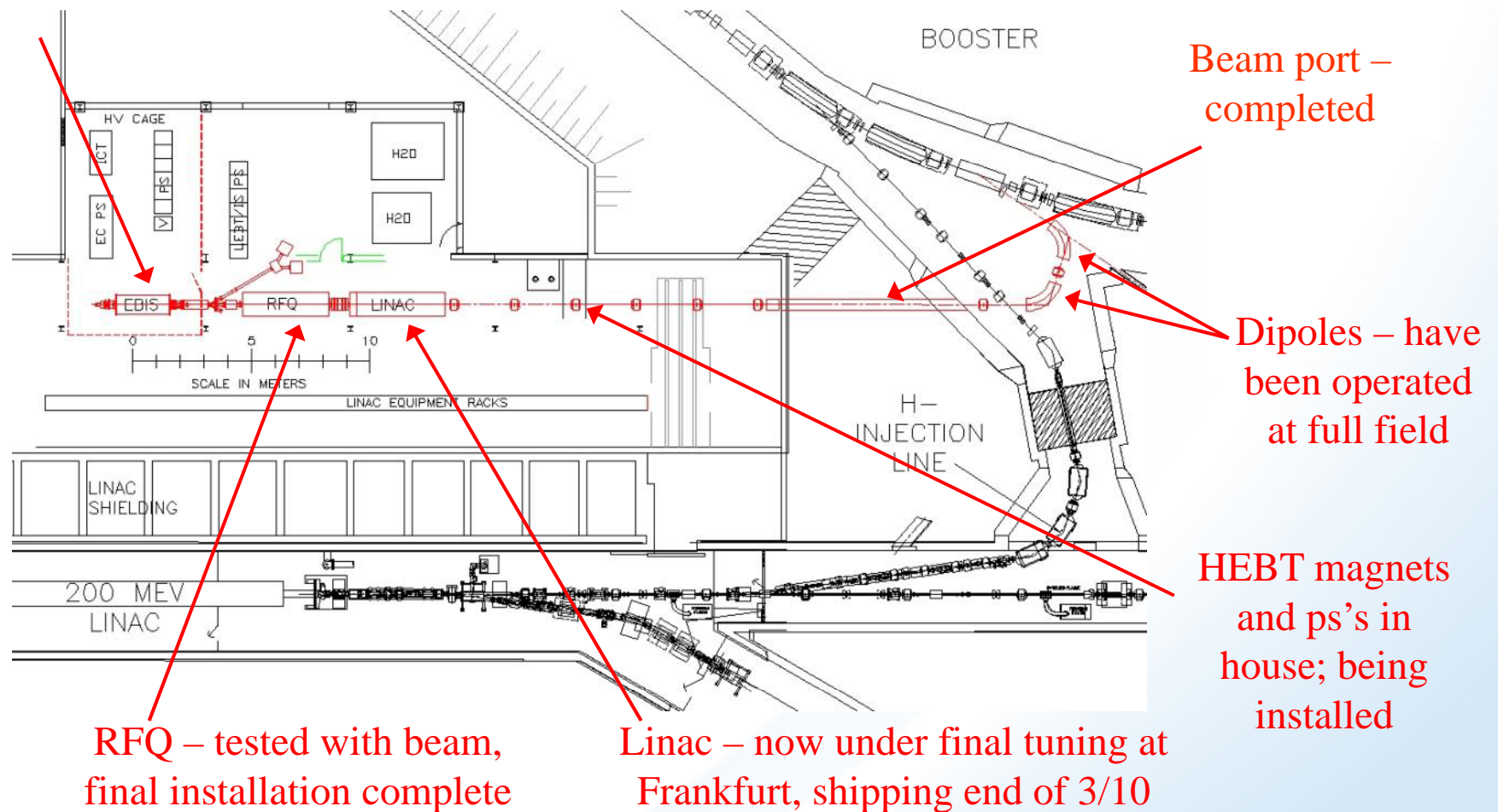
- pp lumi. limit from beam-beam tune spread encountered at 200 GeV in Run 9
- Expect larger dynamic aperture, less stringent limit at 500 GeV
- Constructing electron lenses with ARRA funds to compensate pp beam-beam effect via interaction with  $\sim 5$  keV  $e^-$  beam  $\Rightarrow$  factor  $\sim 2$  in  $L_{pp}$  after  $\sim 2013$





# Other Machine Upgrades: Electron Beam Ion Source

EBIS is operational

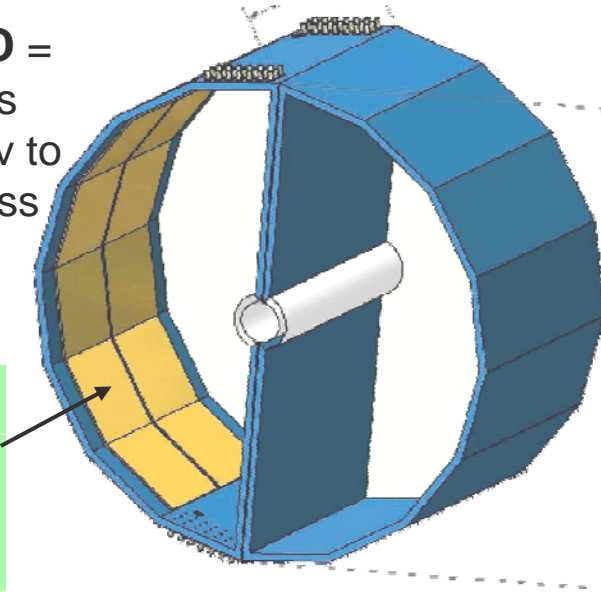


**New high-brightness high charge state pulsed ion source, ideal for RHIC, built via ONP + NASA (\$19M) funding, on schedule for Q4 FY10 completion. Will provide U+U collisions to increase energy density, distinguish effects of elliptic flow from ones due to ion-ion magnetic field (e.g., for LPV tests).**

# New Detector Subsystems Critical for Upcoming Science Work Well in Run 9

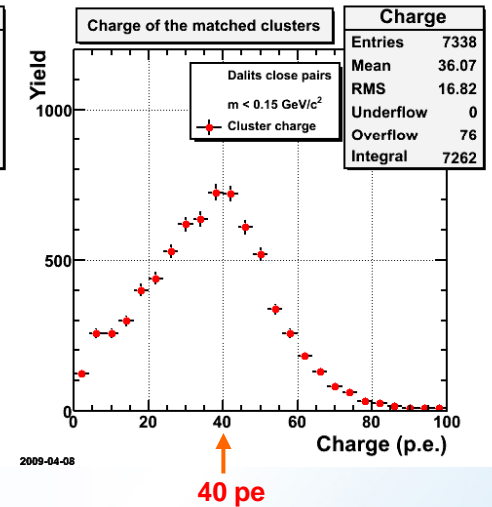
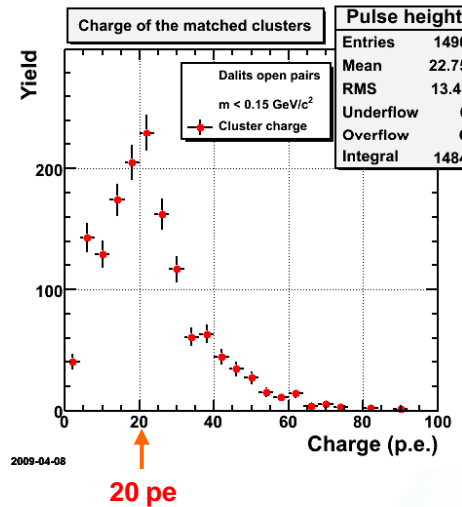
**PHENIX HBD** =  
windowless gas  
(CF<sub>4</sub>) Cerenkov to  
identify/suppress  
Dalitz pair  
backgrounds

CsI photo-  
cathode  
covering  
triple GEMs

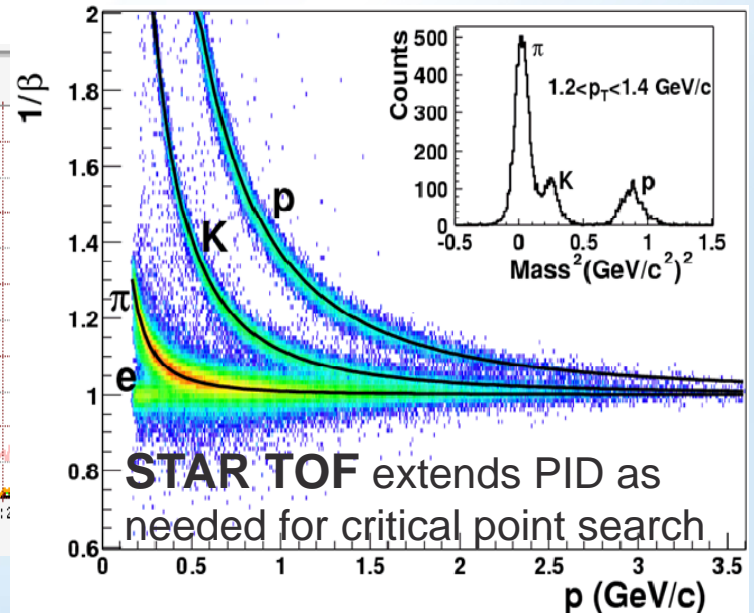
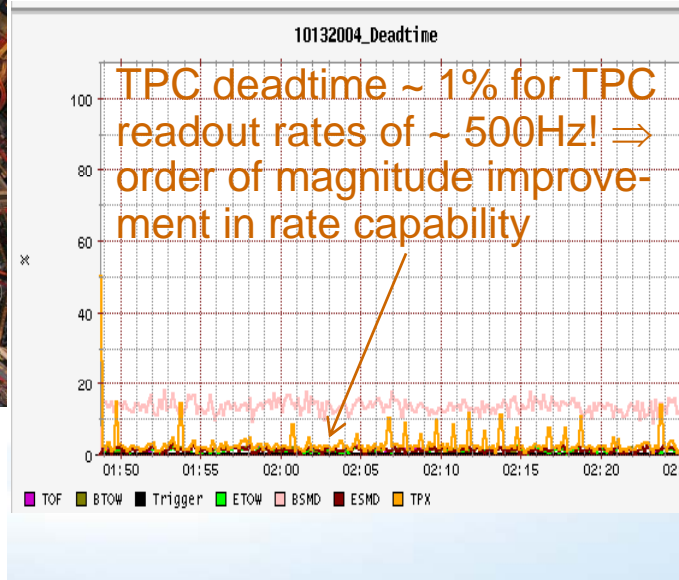


Single electrons

Double electrons

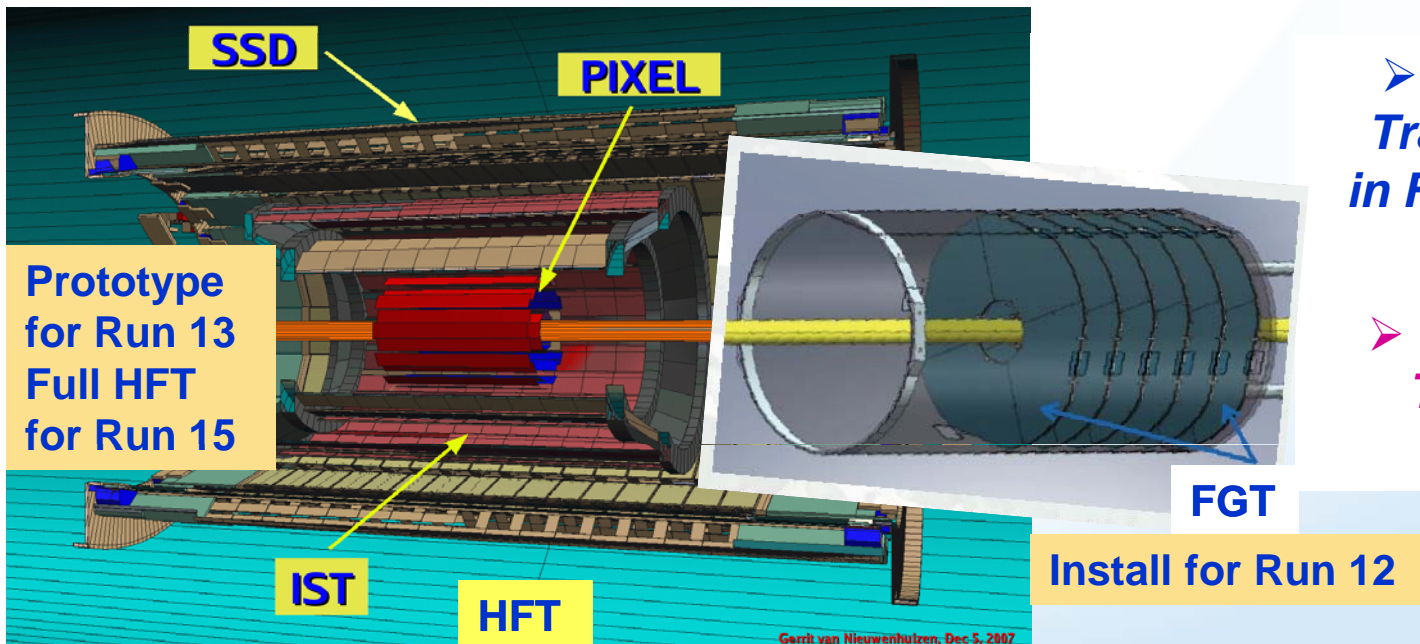
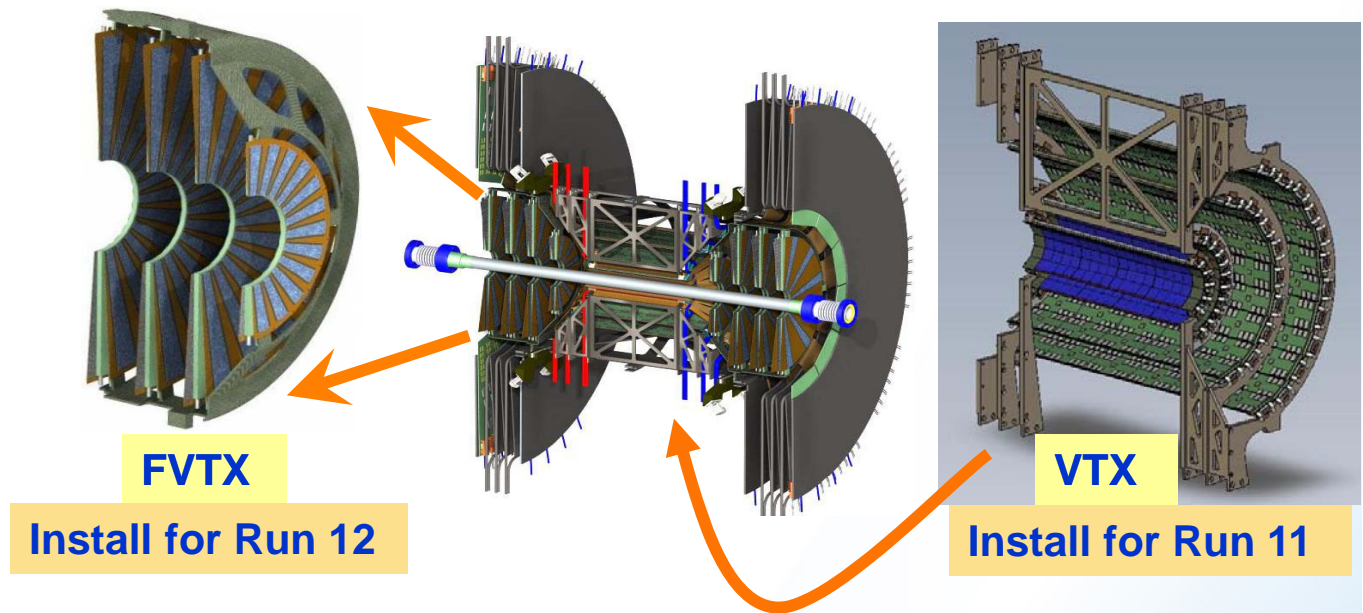


**STAR DAQ1000**  
replaces all TPC  
readout electronics



# Progress Toward RHIC-II Science: Detector Upgrades

- FY09 ARRA funds ensure timely completion of PHENIX VTX & FVTX upgrades
- Awaiting updated plan, sharpened physics focus, for PHENIX FOCAL
- Successful  $\mu$  trigger rescoping in FY09



- STAR Heavy Flavor Tracker receives CD-0 in FY09; CD-1 approval anticipated soon
- STAR Forward GEM Tracker launched as Cap. Equip. project

# RHIC 5-Year Run Plan from July 2009 S&T Review

*Assumes sufficient ops. funding for healthy 2-species run each year; aimed at meeting NP Performance Milestones on schedule; will be updated as we have definitive information about upgrade schedule and/or budget changes*

Year	Likely Beam Species	Science Goals	New Detector Sub-systems	New Machine Upgrades	Gain from Machine Upgrades	Comments
<b>FY10</b>	Au+Au at 200, 62.4 GeV + assorted lower E	Low-mass dilepton spectrum; early collision temp.; improved jet quenching studies (especially $e^-$ from heavy quarks); begin energy scan for critical pt.	STAR TOF completed; PHENIX HBD for heavy ions	Blue ring longitudinal + yellow and blue vertical stochastic cooling; yellow longitudinal cooling ( $\mu$ wave link) upgrade	Factor >2 increase in average store luminosity for full-energy Au+Au	Need 4-8 weeks early in run to (re)commission all 4 stoch. cooling systems, demonstrate gain in lumi. lifetime
<b>FY11</b>	Sub-injection Au+Au; 500 GeV p+p; short 200 GeV U+U	Continue critical pt. search; gluon polarization at low x + antiquark pol'n from W production; 1 <sup>st</sup> characterization of deformation effects in U+U centrality distrib'ns	PHENIX VTX; upgraded PHENIX trigger ( $t_0$ ) barrel	EBIS (tandem as backup); <b>9 MHz cavity</b> ;  AGS tune jump quads (comm'd in Run 10); <b>RHIC spin flipper</b>	U beam capability; <b>improved pp vertex distrib'n</b> ; improved pol'n from AGS; <b>reduced syst. errors</b>	9MHz requires upgrade to main PS + "bouncer" cavity for both rings + longitudinal damper or Landau cavity for each ring.

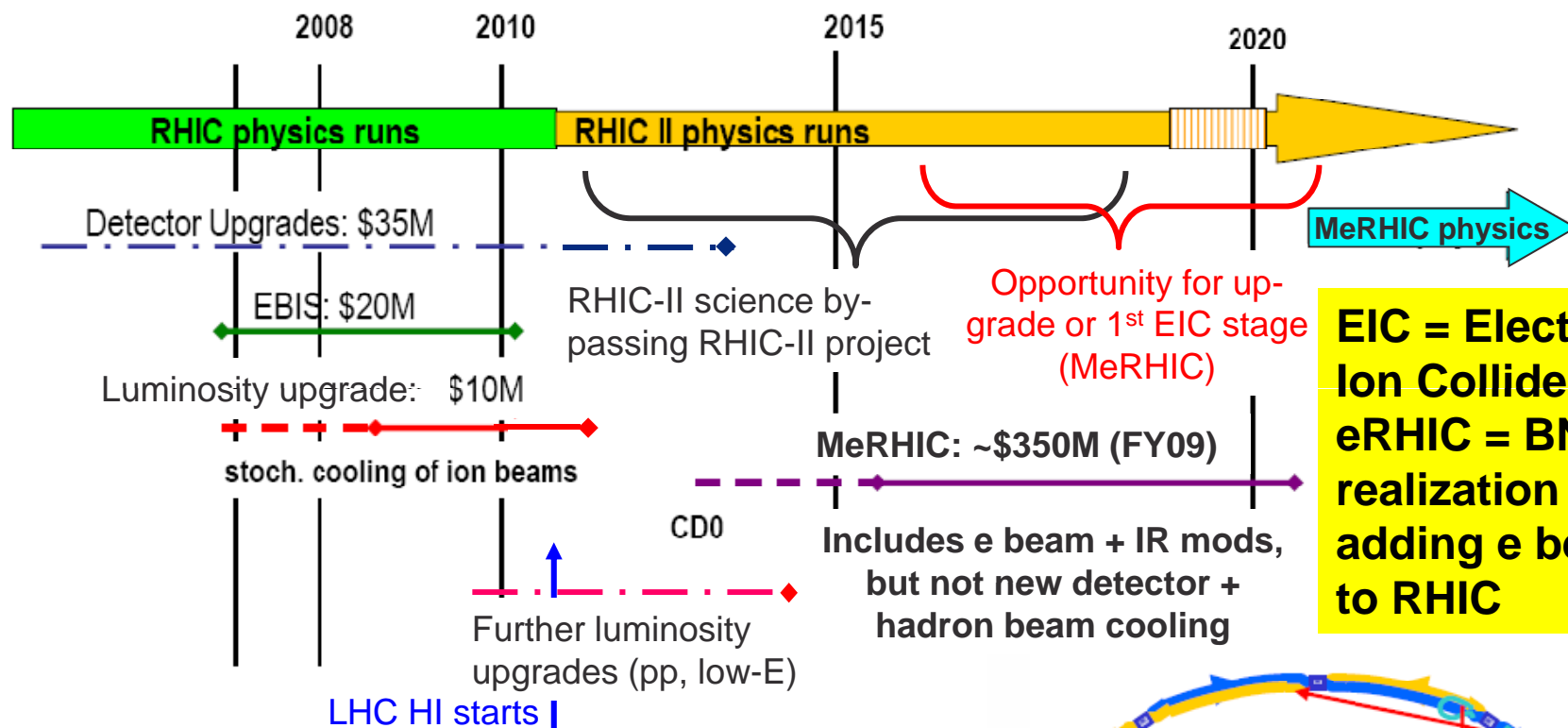
<b>Year</b>	<b>Likely Beam Species</b>	<b>Science Goals</b>	<b>New Detector Sub-systems</b>	<b>New Machine Upgrades</b>	<b>Gain from Machine Upgrades</b>	<b>Comments</b>
<b>FY12</b>	Au+Au at 200 GeV; 500 GeV p+p	RHIC-II heavy-ion goals: heavy flavor, $\gamma$ -jet, quarkonium, multi-particle correlations; anti-quark polarizations in proton	PHENIX FVTX and $\mu$ trigger; STAR FGT + HFT prototype;	Yellow + blue horiz. stoch. cooling (installed FY11); 56 MHz SRF; e-lenses; OPPIS solenoid + "proton cannon"; RHIC collimator upgrade	Full RHIC-II heavy-ion luminosity + improved vertex & store length; improved pp luminosity + polarization	Electron lens commissioning $\Rightarrow$ Run 12 gains possible; detailed collimator upgrade plans still to be developed
<b>FY13</b>	200 GeV p+p; further heavy-ion running to complement earlier runs	Continue RHIC-II heavy-ion goals; transverse spin asymmetry for $\gamma$ + jet (2015 spin milestone); pp reference data for new subsystems	PHENIX FOCAL?	Catchup for ambitious FY12 upgrades plan		N.B. "Proton cannon" increases pol. source current, to allow scraping to improve polarization
<b>FY14</b>	200 GeV Au+Au; low-E Au+Au dictated by Run 10+11 results	Continue pursuit of $\gamma$ + jet, energy scan and identified heavy flavor (DM10-12) milestones.	Full STAR HFT	RHIC low-E electron cooling; R&D ERL to RHIC for coherent e-cooling test	Factor of several increase in lowest-E Au+Au luminosity	Low-E cooling relies on Pelletron from FNAL in late 2011

# Decadal Plan Charges to PHENIX and STAR

I am therefore asking you to generate a document for each Collaboration, to be delivered to me by August 1, 2010, that provides the following information:

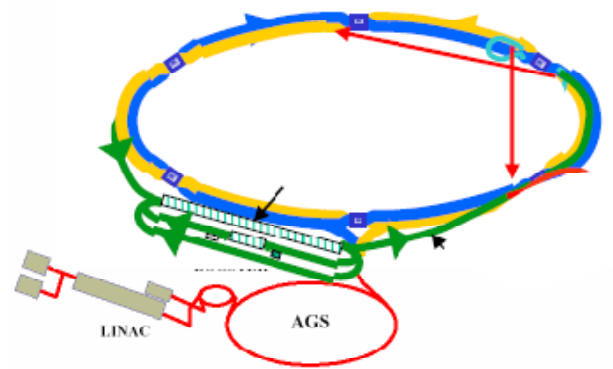
- 1) **A brief summary of the detector upgrades already (or soon to be) in progress**, the timelines for completing them, the new science capabilities each adds in combination with upgraded RHIC luminosity...
- 2) The **compelling science goals** you foresee for RHIC A+A, p+p, and d+A collisions **that can only be carried out with additional upgrades (or replacements) of detector subsystems or machine capabilities** (e.g., further luminosity or diamond size improvements). ...
- 3) **Prioritized, or at least time-ordered, lists of the major (above \$2M total project cost) and more modest (below \$2M total project cost) new detector upgrades your Collaboration foresees**, together with R&D milestones that may have to be passed to demonstrate their technical feasibility. ...
- 4) Any plans or interest your Collaboration has in **adapting your detector or detector subsystems (or detector R&D) to study electron-nucleon and electron-ion collisions with an eventual eRHIC upgrade**. This is relevant only near the end of the decade addressed here, but will be important for planning purposes. ...
- 5) **The envisioned evolution of your Collaboration through the decade:** institutions that may leave, others that might join, any plans to keep your Collaboration healthy and vibrant as RHIC becomes a “mature” facility.

# A Long Term (Evolving) Strategic View for RHIC



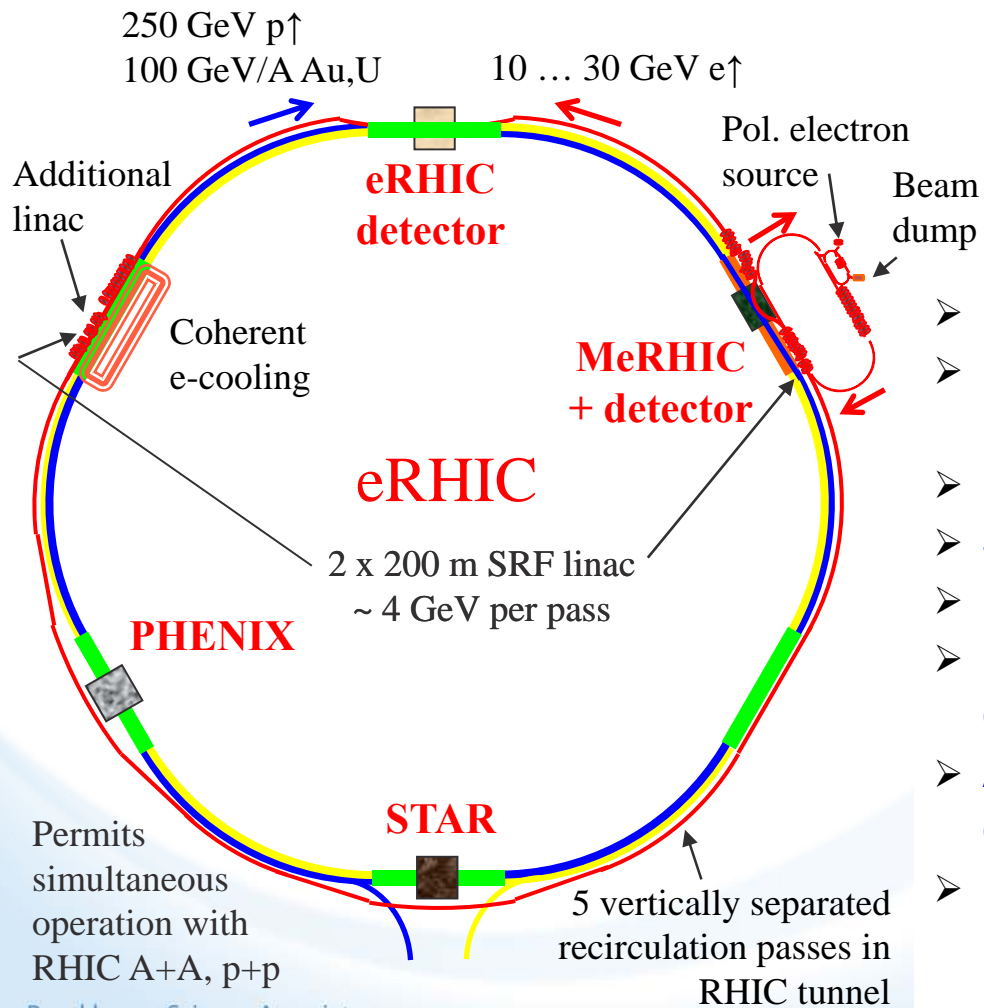
**EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC**

**Legend:**  
 - - - - - R&D  
 ◀ —▶ Construction  
 - · - · - Multiple small projects  
 CD0: DOE Critical Decision, mission need



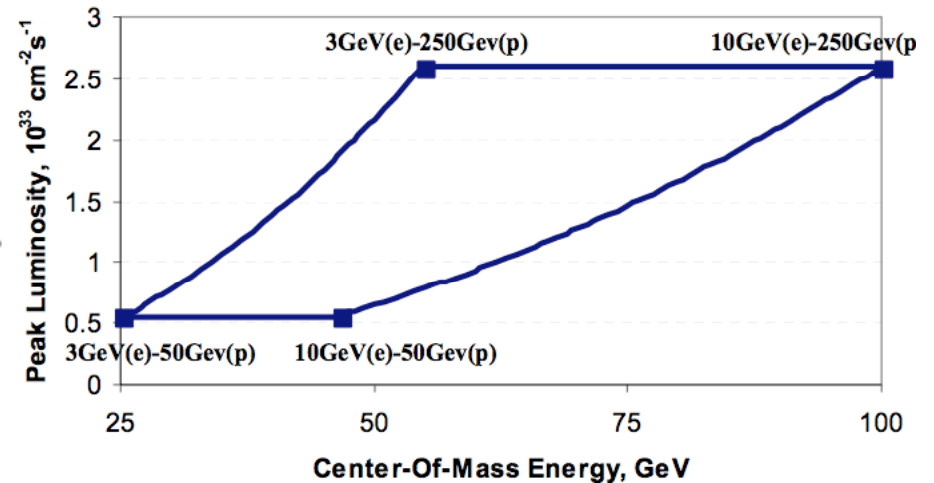
➤ **Start with MeRHIC: 4 GeV electron ERL to  $\Rightarrow$  collisions at one IP with already existing RHIC ion beams**

➤ **Later add e linac sections in RHIC tunnel to increase energy & # IP's**



Brookhaven Science Associates

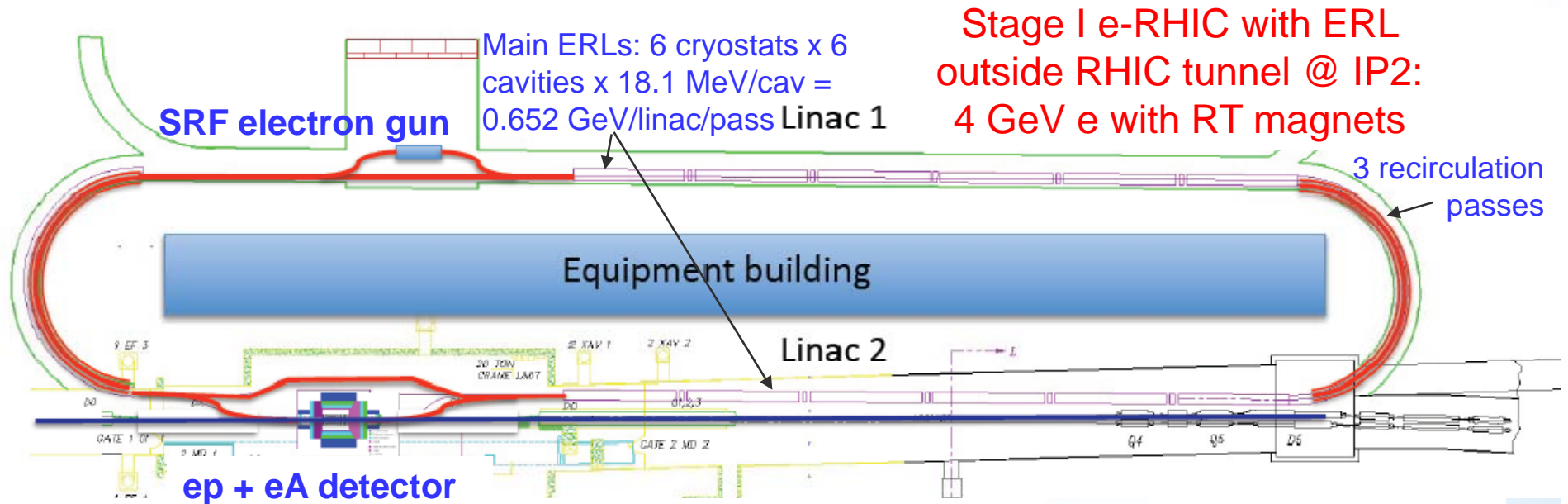
## eRHIC @ BNL



- Full use of MeRHIC
- 10 GeV electron design energy. Possible upgrade to 20 – 30 GeV.
- Peak luminosity:  $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- 5 recirculation passes in the RHIC tunnel
- Multiple electron-hadron IP's possible
- Full polarization transparency at all energies for the electron beam
- Ability to take full advantage of transverse cooling of the hadron beams
- Possible options to include polarized  $e^+$  at lower luminosity: compact storage ring or ILC-type polarized positron source



# Considerable FY09-10 Progress on Design of Possible 1<sup>st</sup> (Medium Energy, MeRHIC) Stage



Stage I e-RHIC with ERL  
outside RHIC tunnel @ IP2:  
4 GeV e with RT magnets

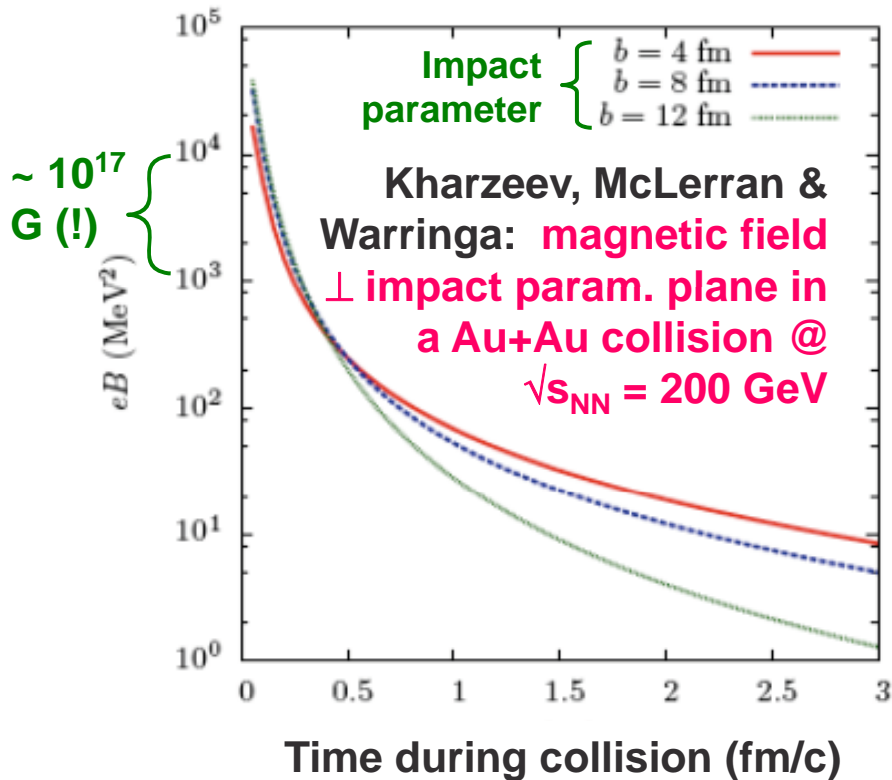
- **Would enable 4 GeV  $\vec{e}^-$  on 100 GeV/N heavy ions and 250 GeV  $\vec{p}$ , with most equipment to be reused later in full EIC**
- **1<sup>st</sup> look at saturation surface for nuclei in e+A DIS: confirm nuclear “oomph” factor & measure gluon densities relevant to RHIC initial state; e+A diffraction tests of high gluon occupancy**
- **$\vec{e}^- \vec{p}$  program extending  $\vec{DIS}$ , adding: transverse-spin SIDIS over broad  $Q^2$ -range  $\Rightarrow$  TMD evolution; detection of boosted target fragments to probe spin-dependent correlations in nucleon.**
- **Developing science case, detector design, cost estimate.**

# Summary

- 1) *RHIC on track for order of magnitude improvement in full-energy HI collisions by 2013; attaining intermediate improvements along the way*
- 2) *Independent approaches being pursued to improve pp collision luminosity and beam polarization, on similar time scale*
- 3) *Many detector upgrades proposed in ~2003 decadal plans for STAR and PHENIX now in place or under way. New decadal charge issued for 2010*
- 4) *Further RHIC detector & machine upgrades need to be integrated with plans for an Electron Ion Collider – part of the new decadal plan charge*
- 5) *2<sup>nd</sup> generation measurements at RHIC are yielding significant new physics results & surprises. Together with improved collider and detector performance, this promises continuing RHIC vitality through next decade.*

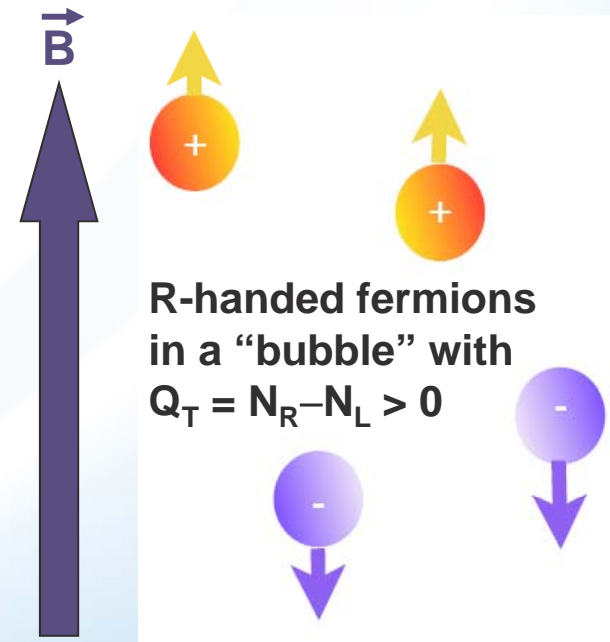
# Backup Slides

# The Chiral Magnetic Effect (D. Kharzeev et al.)



- The strong magnetic field in a non-central HI collision orients spins for + and - quarks oppositely.
- In a “bubble” with non-zero topological charge ( $\Rightarrow$  chiral imbalance), this leads to a net electric current and P- and CP-violating EDM.
- Charge separation can become “macroscopic” in deconfined matter.

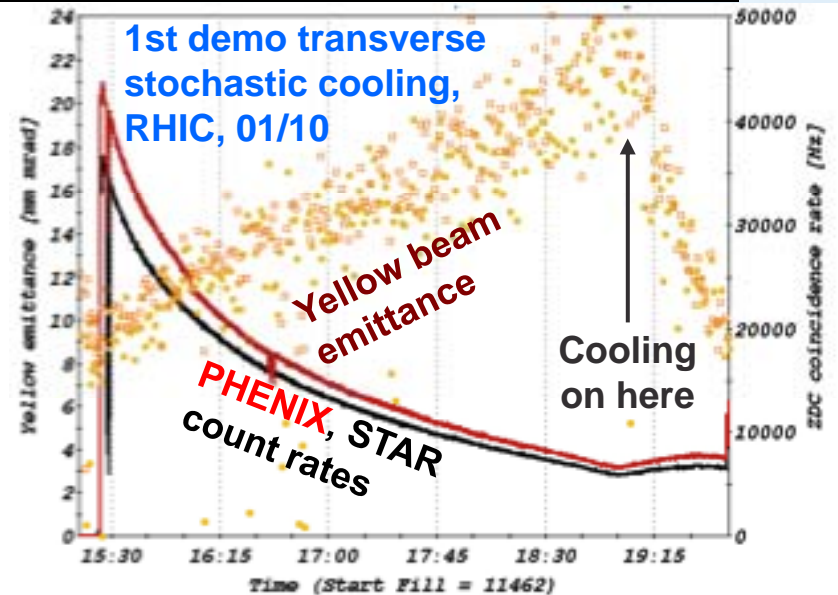
The sign of the EDM can differ from bubble to bubble, and event to event  $\Rightarrow$  **no global CPV!** But can look for particle correlations indicative of **local parity and CP violation.**



# FY10 RHIC Run Plan

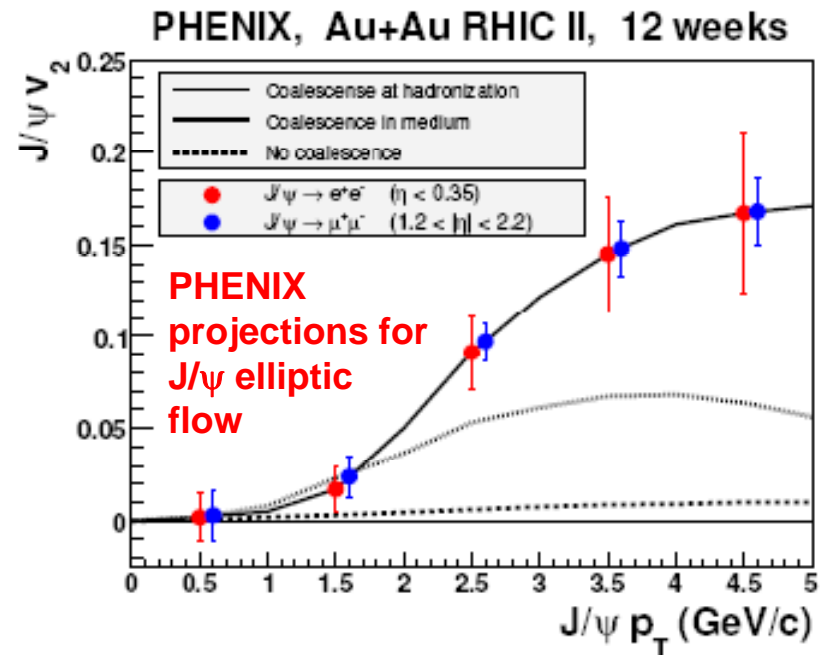
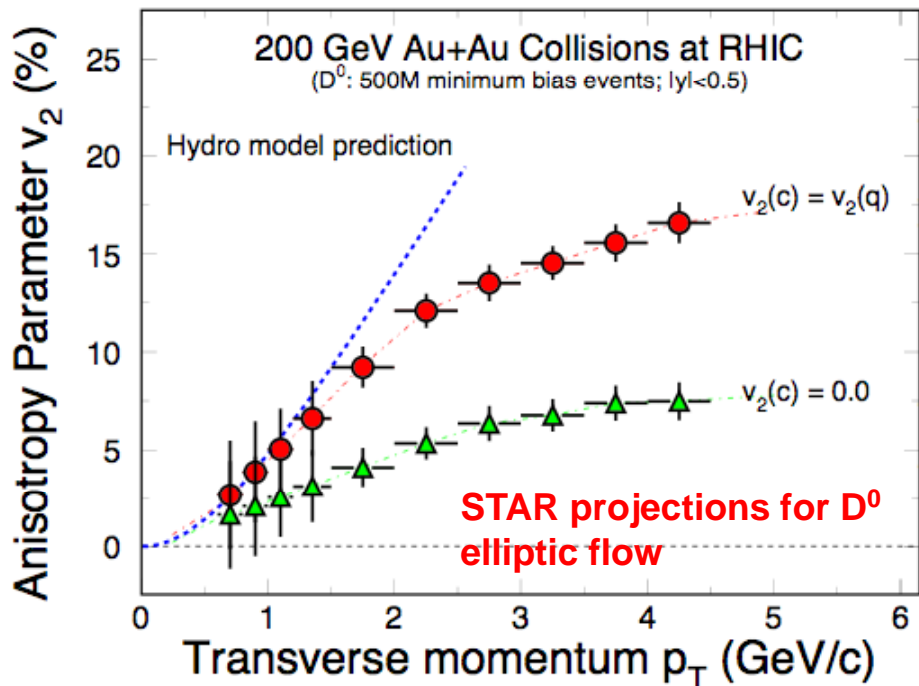
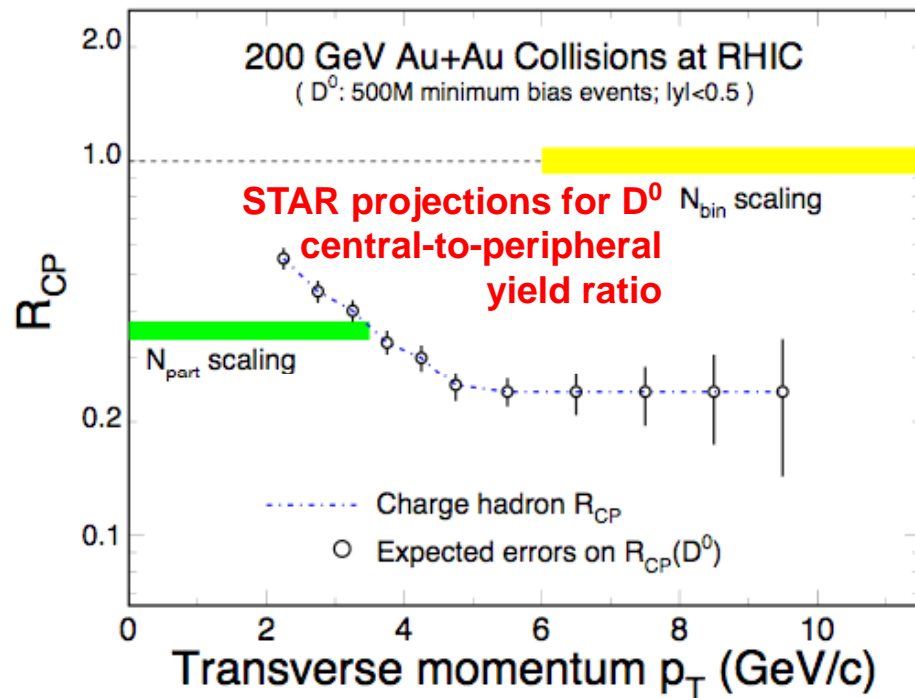
$\sqrt{s_{NN}}$ (GeV)	Physics production or beam studies weeks	
	25-cryoweeek run	27-cryoweeek run
200	10	10
62.4	4	4
39	1.5	1.5
27	0	0
18	0	0
11.5 @ STAR	0	2
7.7	4	4
Beam studies @ 5 GeV and @ $v \approx 0.67$	0.5	0.5

- *Improve high-E Au+Au statistics, esp. for  $e^+e^-$  studies with PHENIX Hadron Blind Det.*
- *Launch low-energy scan searching for evidence of QCD critical endpoint*
- *Commission 4 planes stochastic cooling*
- *Carry out beam tests relevant to improve polarized pp performance in FY11*



# Detector & Luminosity Upgrades $\Rightarrow$ New Physics Milestones

*Measure hadron suppression and flow for identified heavy-quark mesons, possibly baryons ( $\Lambda_c$ )*

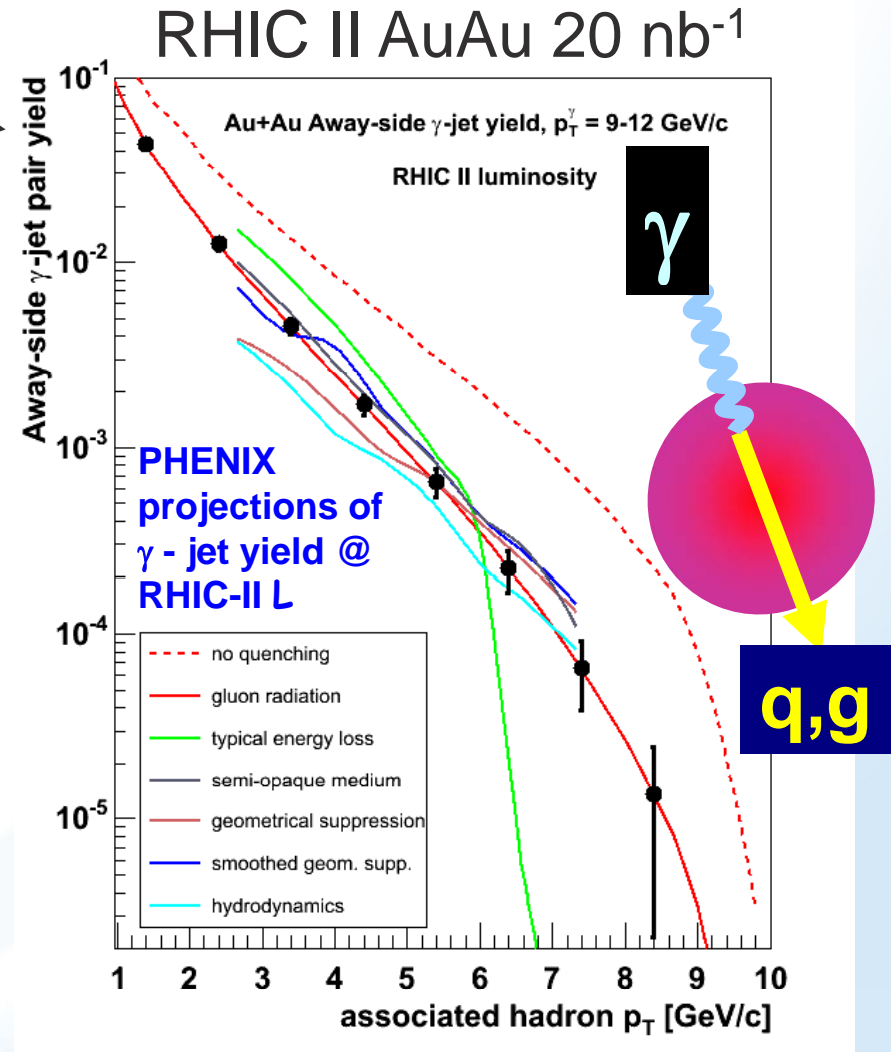
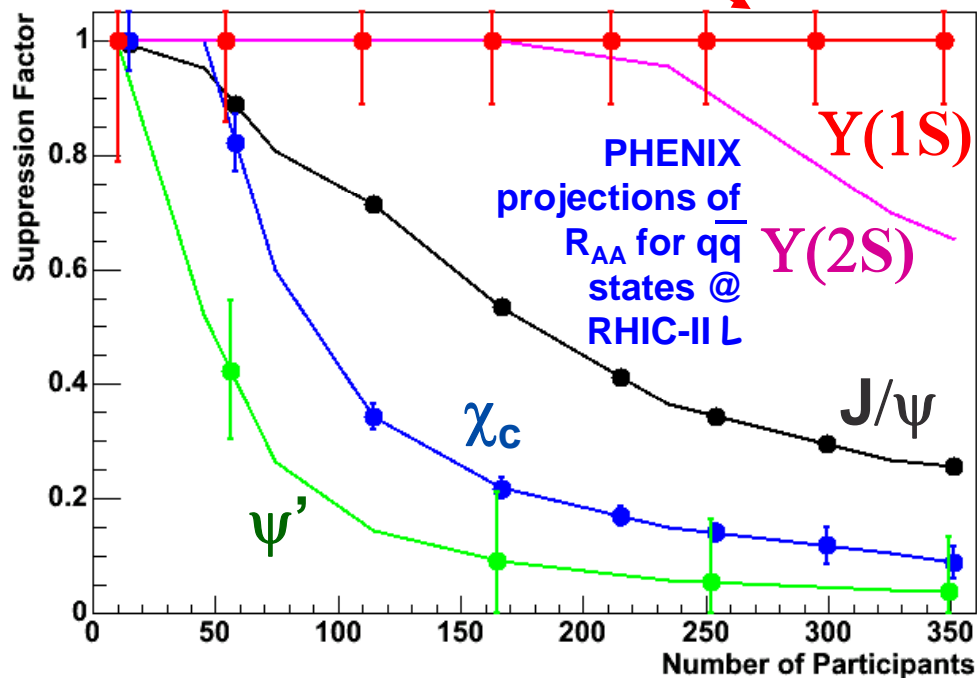


*Addresses new 2016 NP milestone (DM12) covering “identified hadrons with heavy-flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma”*

# Detector & Luminosity Upgrades $\Rightarrow$ New Physics Milestones

➤ Calibration of light-quark energy loss via  $\gamma$ -tagging (DM10, 2014)

➤ Definitive map of quarkonium melting, to search for effects of deconfinement and probe the (heavy) quark-quark interaction in the medium



## Scientific Impact - High & still growing!

Since 2001:

78 publications (47 PRL)

> 7580 citations

Renowned papers!

White paper -

725 citations

Jet quenching discovery

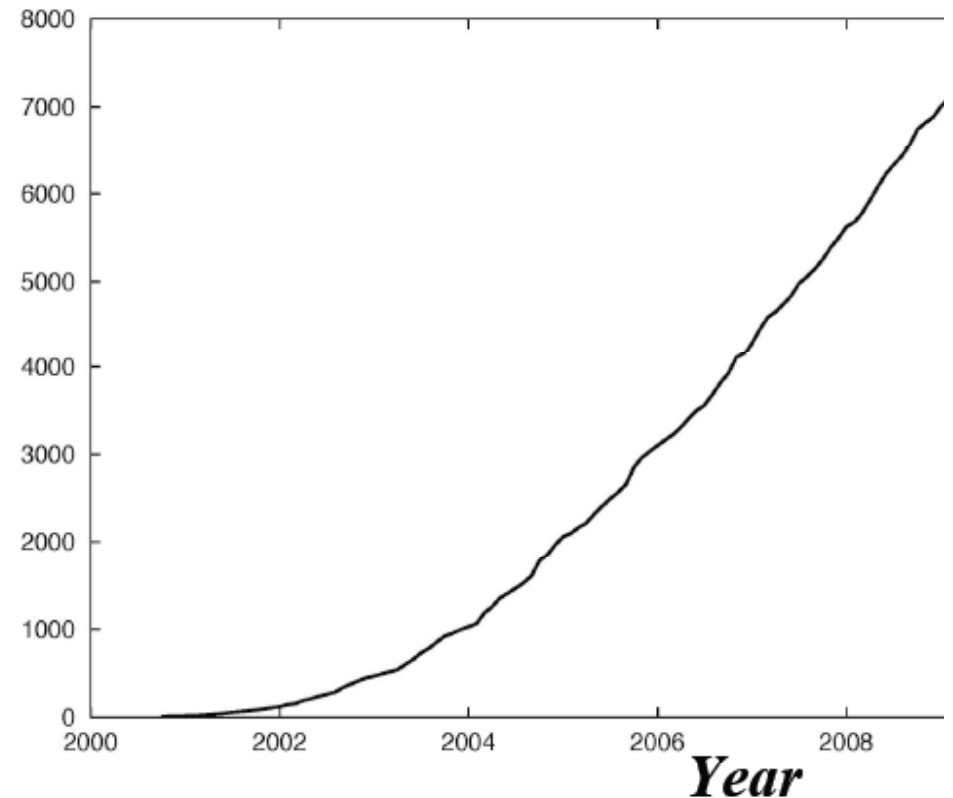
513 citations

+ 4 other physics papers with > 250 citations

+ 18 more papers with  $\geq 100$  citations

+ 27 additional 50+ Topcite papers

Citations (cumulative)

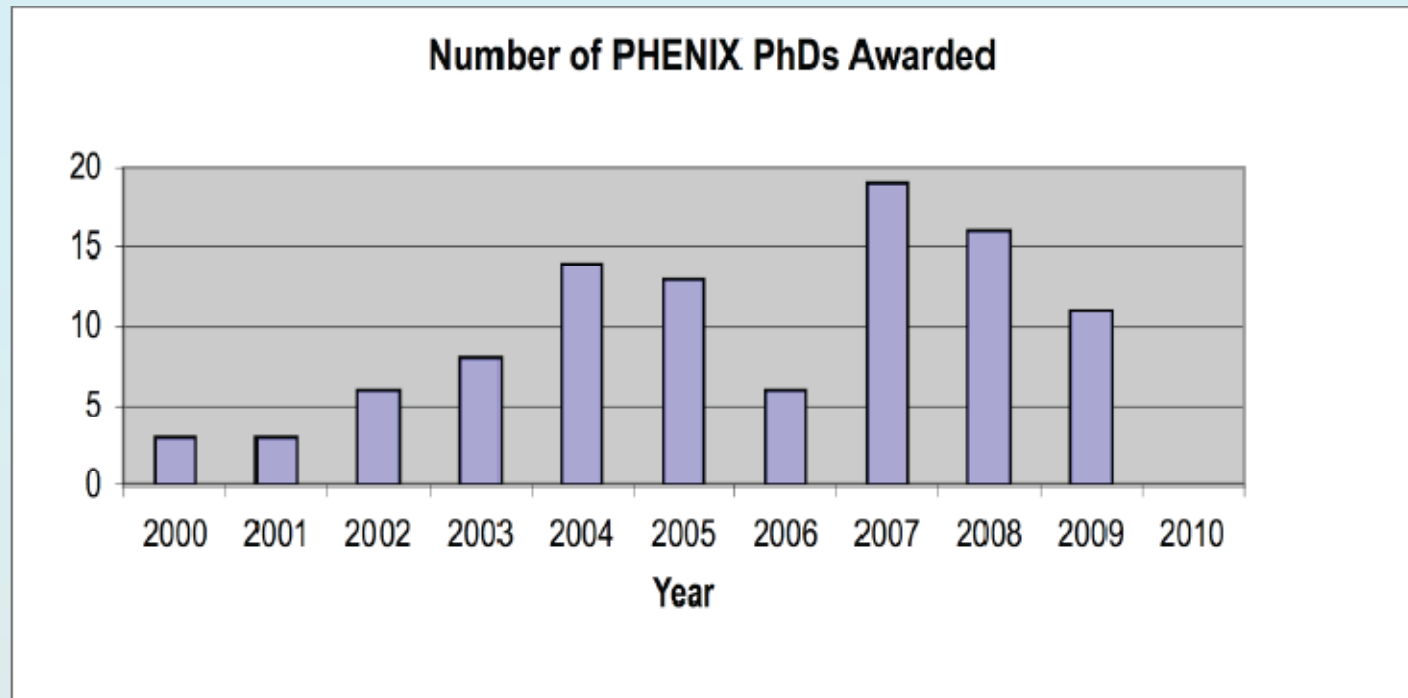


*hadron correlations: PRC78, 014901, 2008 (primary author J.Ji)*  
*most cited Nuclear Experiment paper of 2008, 2nd of all Nuclear*

#72 in all physics in 2008 (SPIRES)



## 89 Ph.D. degrees earned on PHENIX



**15 Masters/Diploma theses**

**+ 79 *Ph.D. students working***



# Publications

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Total # of refereed publications: 94 !

- *Phys. Rev. Lett.* 44, *Phys. Rev.* 38, *Phys. Lett. B.* 8, *J. Phys. G:* 3, ***Nucl. Phys. A:* 1**

Total # of citations: 8185 !

Number of Renowned (500+): 1

Number of Famous (250-499): 6

Number of Very Well Known (100-249): 18

Number of Well Known (50-99): 22

Total # of publications since last review: 12

- *Phys. Rev. Lett.* 5, *Phys. Rev.* 7 and 9 manuscripts are in referee process.

Total # of Quark Matter 2009 talks: 22+3

115 Ph.D degrees  
21 other degrees

(Since last review: 12)

**STAR continues to do an excellent  
job of educating  
the next generation of physicists!**

# Electron Beam Ion Source (EBIS)

- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions, uranium (RHIC) and polarized He<sup>3</sup> (eRHIC)
- Prototype achieved  $1.7 \times 10^9$  Au<sup>33+</sup> in 20  $\mu$ s pulse with 8 A electron beam (60% neutralization)
- RHIC EBIS source completed and operating (first ions were extracted in December)
- Construction schedule: FY2006 – 10 (CD4: 4Q FY2010)
- Funding profile:

	FY2005	FY2006	FY2007	FY2008	FY2009	Total
DOE NP	0.7	2.1	5.1	4.2	2.7	14.8
NASA	0.5	3.0	1.0			4.5
Total	1.2	5.1	6.1	4.2	2.7	19.3

