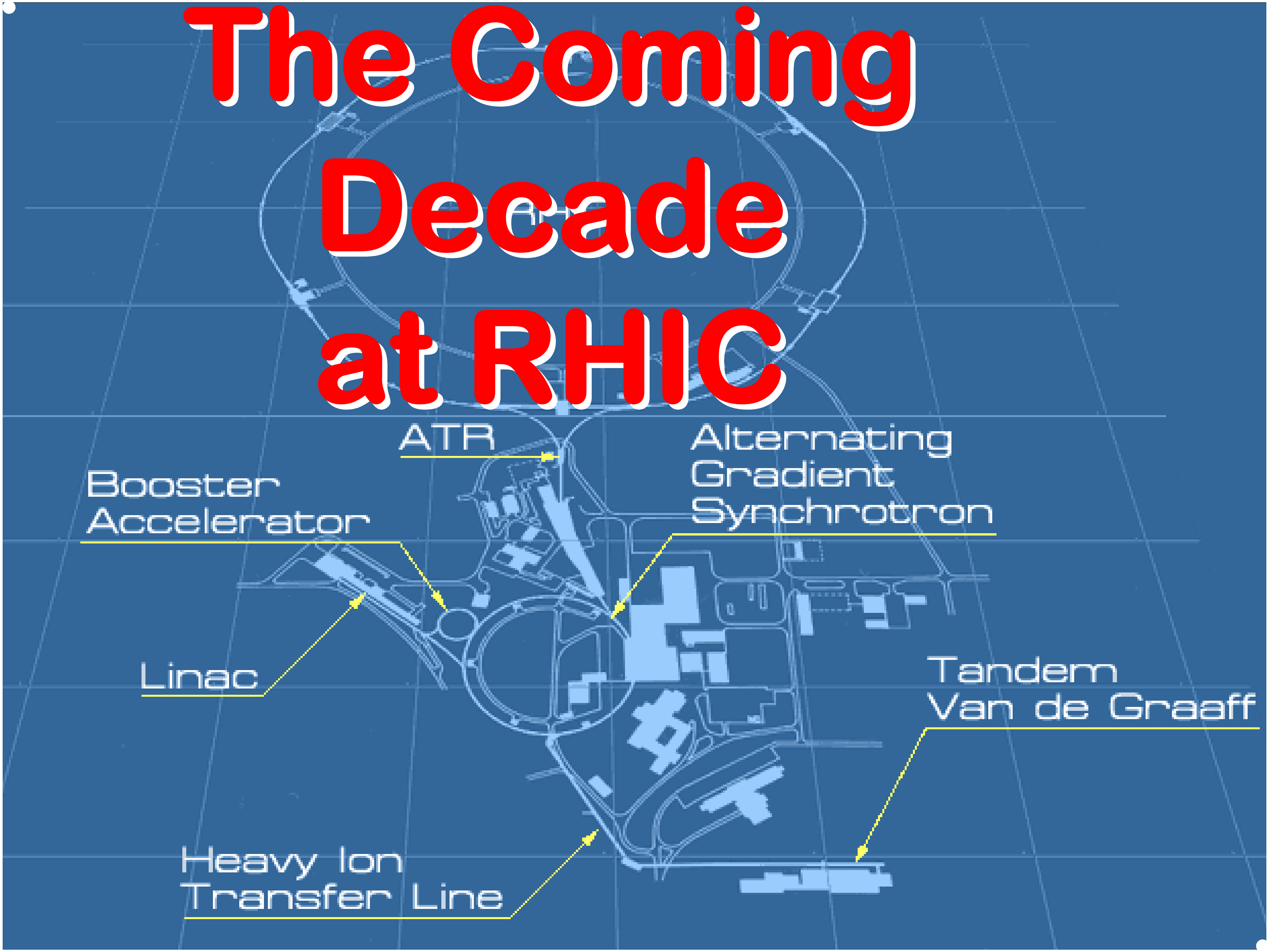
The Coming Decade at RHIC



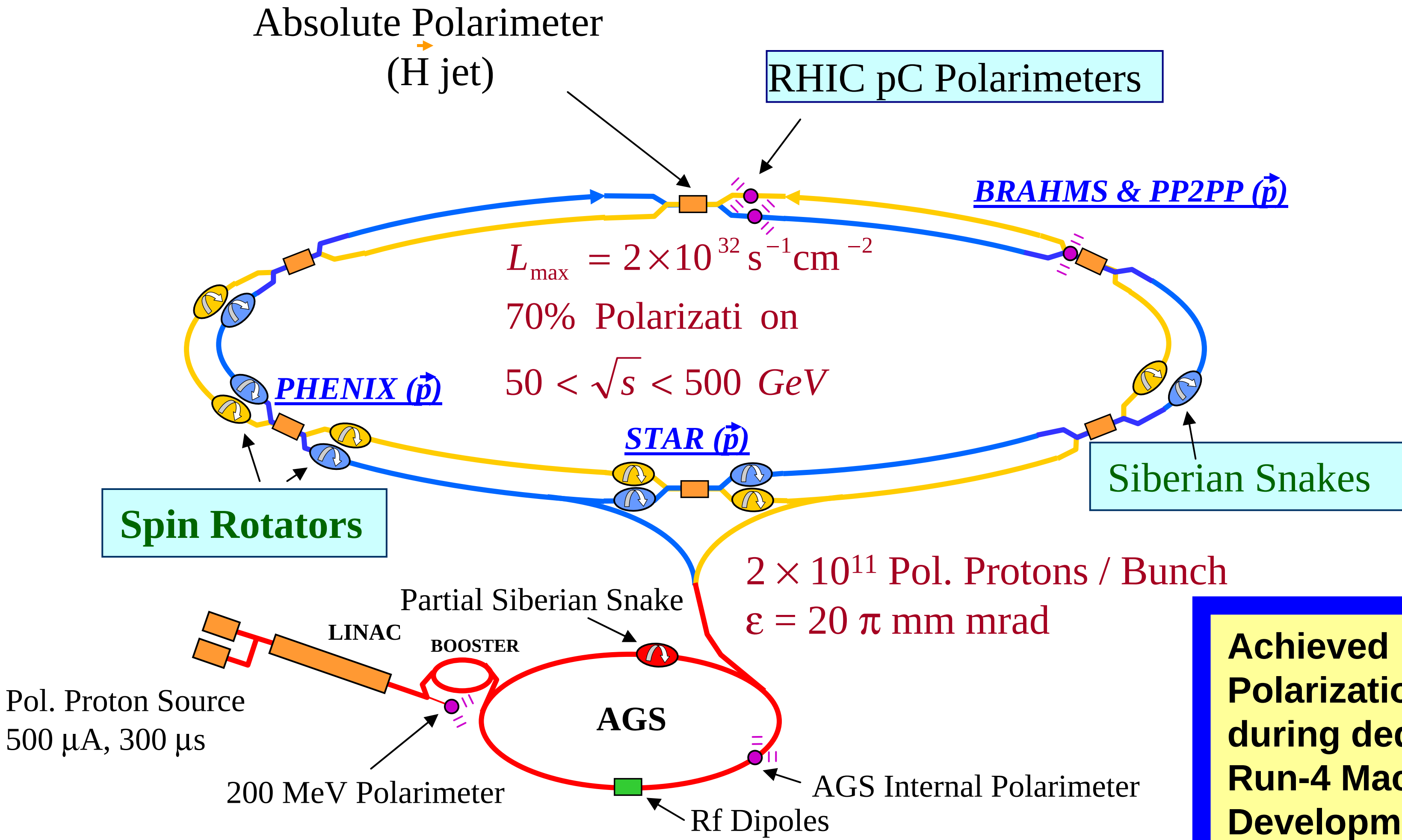
Summary

- 2000-2004: A period of unprecedented discovery in the initial operation of RHIC
- 2005-2009: RHIC as the premiere QCD facility in the world
- 2010-2015: RHIC II as the premiere QCD facility in the world
- 2015++ : eRHIC and RHIC II as the premiere QCD facility in the world

RHIC Achievements to Date

- **Machine :**
  - **Runs 1-4:**
    - Au+Au: operation at 4 energies (19, 62, 130, 200 GeV)
    - d+Au comparison run (200 GeV)
    - p+p baseline (200 GeV)
  - **Routine operation in excess of twice design luminosity !**
  - **First polarized hadron collider !**
- **Experimental Operations:**
  - **Routine collection, analysis of 100 Tb datasets**
  - **>50 publications in Physical Review Letters !**
  - **Excellent control of systematics and inter-experiment comparisons**
- **Experimental Results:**
  - **Record densities created ~100 times normal nuclear density**
  - **New phenomena clearly observed ("jet" quenching)**
  - **Strong suggestions of a new state of matter**

Spin in RHIC



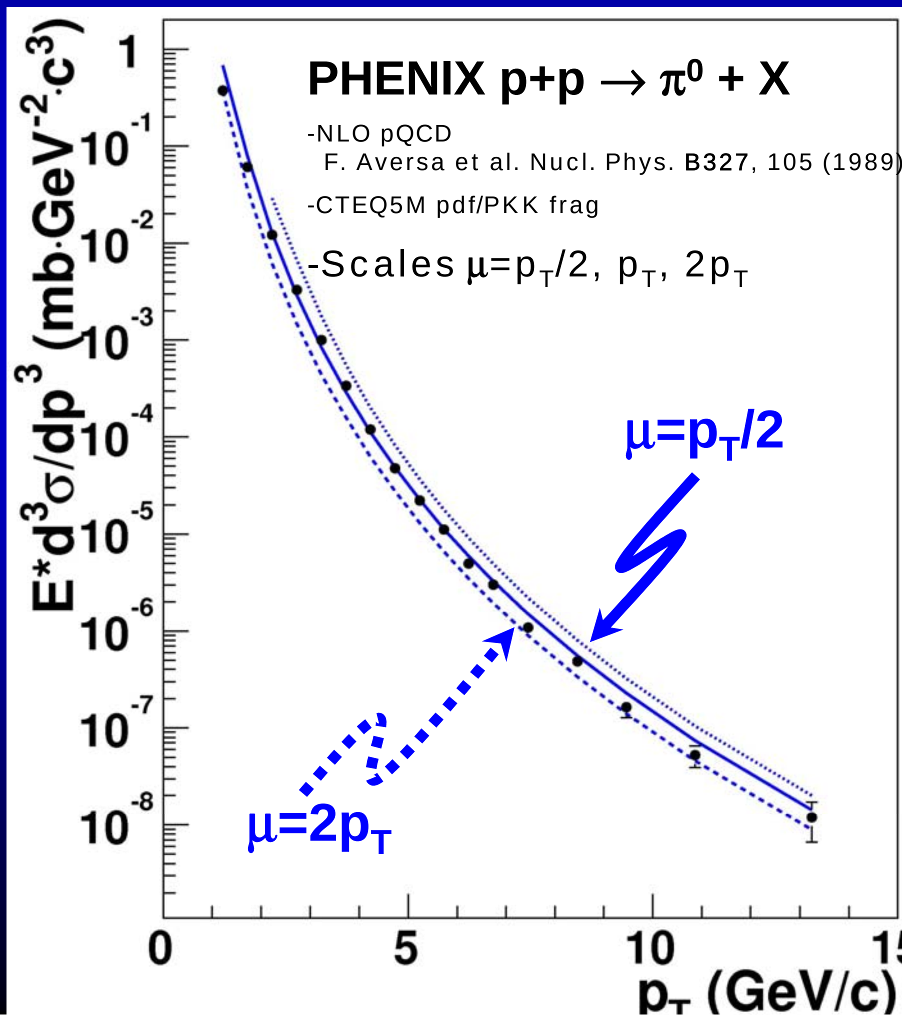
RHIC accelerates heavy ions to 100 GeV/A
and polarized protons to 250 GeV

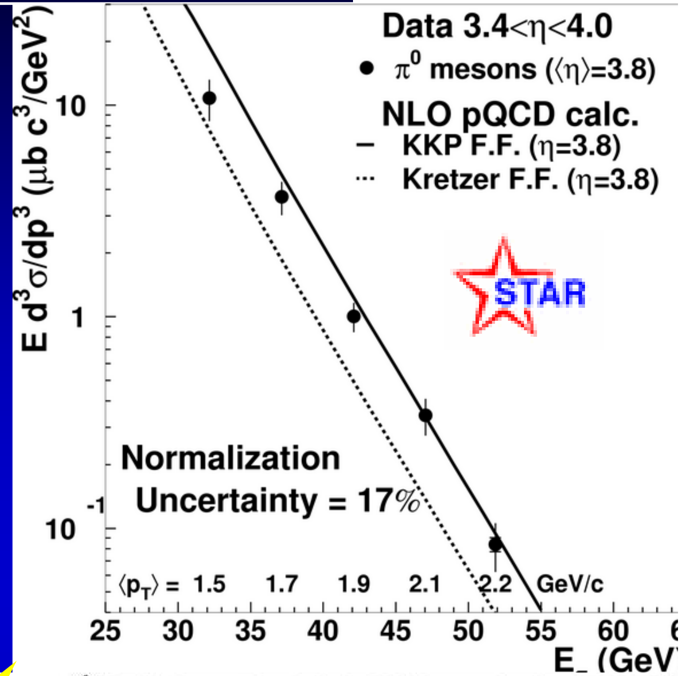
Achieved Polarization 40-45% during dedicated Run-4 Machine Development Period!

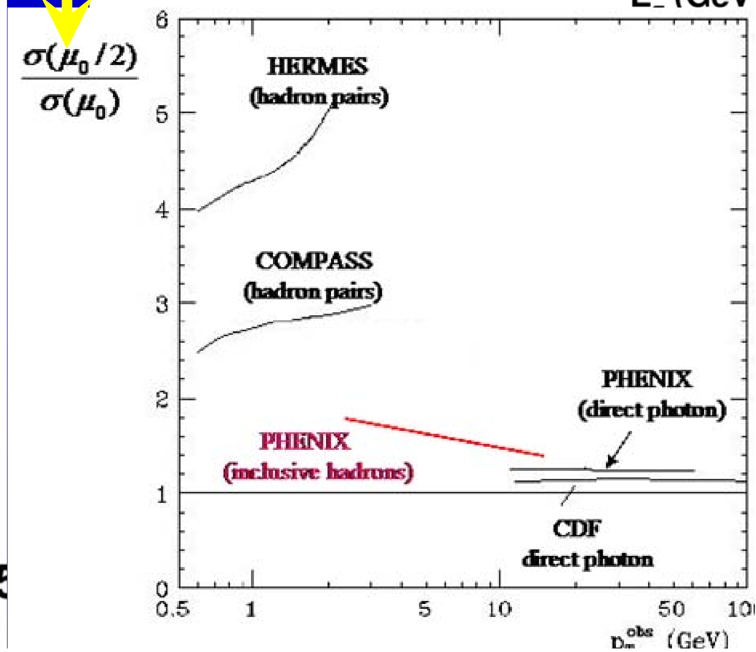
(details in M. Bai talk)

RHIC Energy Reduces Scale Dependence

- The high $\sqrt{s}$ of RHIC
  - makes contact with rigorous pQCD calculations
  - minimizes "scale dependence"
- A huge advantage in
  - Spin program
  - Providing calibrated probes in A+A







A Four-In-One

- YES!
- Run-3: *a cr* ... -Au collisions

HEPAP on RHIC

- In ***Quantum Universe: The Revolution in 21st Century Particle Physics:***
  - ☞ Currently, the most intensely studied cosmic phase transition is connected with quantum chromodynamics (QCD), the theory of the nuclear force. During the QCD phase transition, the baryonic matter in the present universe condensed from a plasma-like state of quarks and gluons. The Relativistic Heavy Ion Collider (RHIC) facility at BNL is currently creating collisions of heavy ions to study quark-gluon plasma; the laboratory plans upgrades to enhance these studies. The Lattice Computational Facilities will enable calculations furthering the understanding of the RHIC data and the conditions during this epoch in the evolution of the early universe.

NRC on RHIC

- In *Connecting Quarks with the Cosmos*:

  - ☞ what happens when matter is compressed to greater baryon density or heated to higher temperature? To address this question, a major facility, the Relativistic Heavy Ion Collider has been constructed at Brookhaven National Laboratory. .. A strong experimental program at RHIC will be carried out over the next few years to see what the states of matter are at extreme energy density.

NSAC on RHIC:

- In *Opportunities in Nuclear Science: A Long Range Plan for the Next Decade*

  - ☞ the completion of RHIC at Brookhaven has ushered in a new era. Studies are now possible of the most basic interactions predicted by QCD in bulk nuclear matter at temperatures and densities great enough to excite the expected phase transition to a quark-gluon plasma. As the RHIC program matures, experiments will provide a unique window into the hot QCD vacuum, with opportunities for fundamental advances in the understanding of quark confinement, chiral symmetry breaking, and, very possibly, new and unexpected phenomena in the realm of nuclear matter at the highest densities.

  - ☞ By colliding beams of ions from protons to gold, with center- of-mass energies from 20 to 200 GeV per nucleon pair, RHIC will create conditions favorable for melting the normal vacuum and creating states of matter unknown in the universe since the Big Bang. With these unique capabilities, RHIC addresses all of the fundamental questions posed on page 44. The U.S. thus now possesses the premier laboratory in which to study these questions.

What Are Those "Fundamental Questions"?

RHIC

- **Again from the Long Range Plan:**
  - In relativistic heavy-ion collisions, how do the created systems evolve? UI
    Does the matter approach thermal equilibrium? Y
    What are the initial temperatures achieved? UI - TBD
  - Can signatures of the deconfinement phase transition be located as the hot matter produced in relativistic heavy-ion collisions cools? UI - TBD
    What is the origin of confinement? TBD
  - What are the properties of the QCD vacuum and what are its connections to the masses of the hadrons? TBD
    What is the origin of chiral symmetry breaking? TBD
  - What are the properties of matter at the highest energy densities? UI
    Is the basic idea that this is best described using fundamental quarks and gluons correct? UI

- **In Addition:**
  - What is the role of Color Glass Condensate (CGC) in determining initial conditions? UI
  - What are the transport properties of the medium? UI - TBD

Y = Yes | UI = Under Investigation | TBD = To Be Determined

The Challenges For The Next Decade

RHIC

A. Move from *exploration of* new matter formed in A+A collisions to *characterization of* its properties

B. Accelerate progress in the developing spin program

C. Maximize running time to allow for
- Complete spectrum of A+A physics
- World-class spin measurements
- New domain in p+A physics

D. Upgrade detectors to
- Maximize items A, B and C
- While maintaining physics program by minimizing shutdowns

E. Upgrade RHIC to
- Maximize items A, B, C and D
- While maintaining physics program by minimizing shutdowns

A Tale of Two Plans

- **PHENIX Decadal Plan**

  "A superlative set of measurements to elucidate the states of both hot and cold nuclear matter, and to measure the spin structure of the proton has been identified. The components of this plan include"

  - Definitive measurements that will establish the nature of the matter created in nucleus+nucleus collisions, that will determine if the description of such matter as a quark-gluon plasma is appropriate, and that will quantify both the equilibrium and non-equilibrium features of the produced medium.
  - Precision measurements of the gluon structure of the proton, and of the spin structure of the gluon and sea-quark distributions of the proton via polarized proton+proton collisions.
  - Determination of the gluon distribution in cold nuclear matter using proton+nucleus collisions.

- **STAR Decadal Plan**

  "a vision of the compelling science STAR proposes to accomplish (a picture being developed). Three "Must do" STAR Physics Goals in the next 5+ years that drive the planned use of RHIC:"

  - Have we produced the quark-gluon plasma?
    - p_T dependence of suppression
    - Measurement of open charm and charmonium
    - Full flow systematics (mesons, baryons, multiply strange baryons, open charm)
    - Evolution versus energy/species
  - Gluon contribution to the nucleon spin
    - A_{LL} for mid-rapidity jet production
    - A_{LL} for direct photon + jet
  - Gluon density saturation in cold nuclei at very low Bjorken x
    - Inclusive leading hadrons/jets in d+Au collisions
    - Search for mono-jets in d+Au collisions

Common Themes

- Both collaborations take note of the three complementary programs (A+A, p+A, spin) made available by RHIC
- Both studies identify the tremendous incremental benefit for operations beyond the nominal 27 weeks per year
- Both proposals call for continuous development of the experiments via:
  - Expanded apertures
  - Improved triggering and DAQ
  - New capabilities (micro-vertexing, low-mass di-leptons)
- Both plans
  - Maintain the investment in these productive $100M+ investments
  - Capitalize on existing infra-structure
  - Identify a compelling set of physics measurements for the next ten years.

From Exploration to Characterization

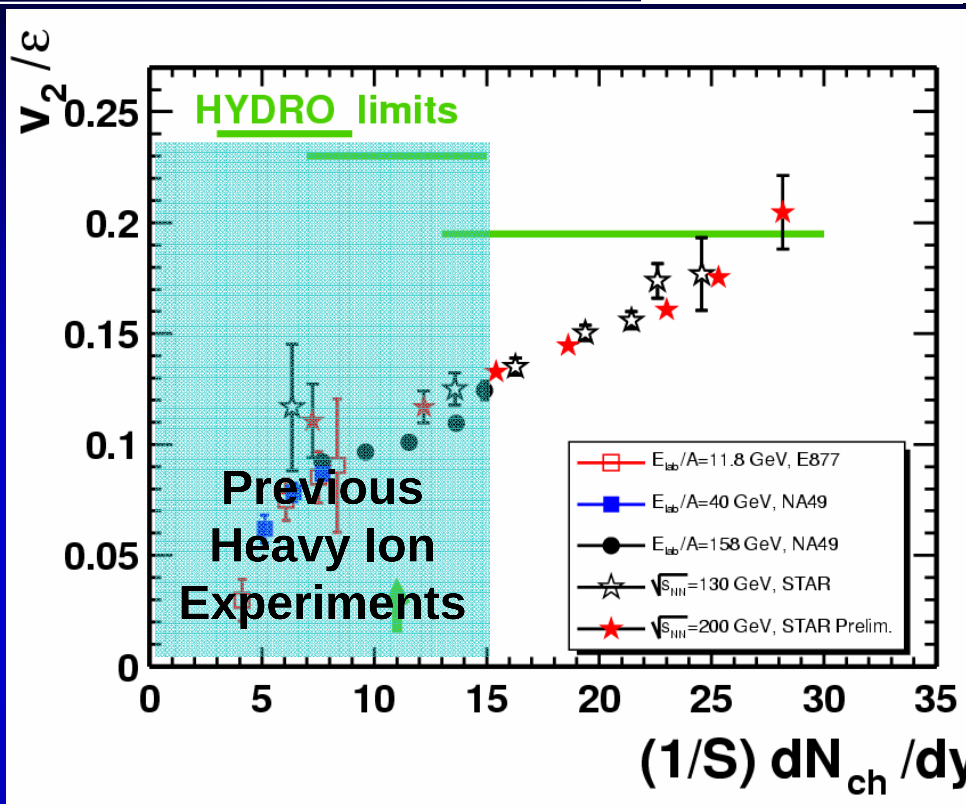
- We can state confidently that
  - RHIC has created matter at unprecedented densities
  - The yields of final state particles are in excellent agreement with thermal abundances
  - The matter has bulk velocity fields described by ideal hydrodynamics
  - The matter shows a jet extinction pattern never previously (clearly) observed
- We can not state confidently
  - What this matter "is":
  - Is it
    - Deconfined?
    - A quark-gluon plasma?
    - A strongly-coupled plasma?
- But we can state confidently
  - which additional measurements can be performed to characterize (and extend) the initial discoveries made at RHIC

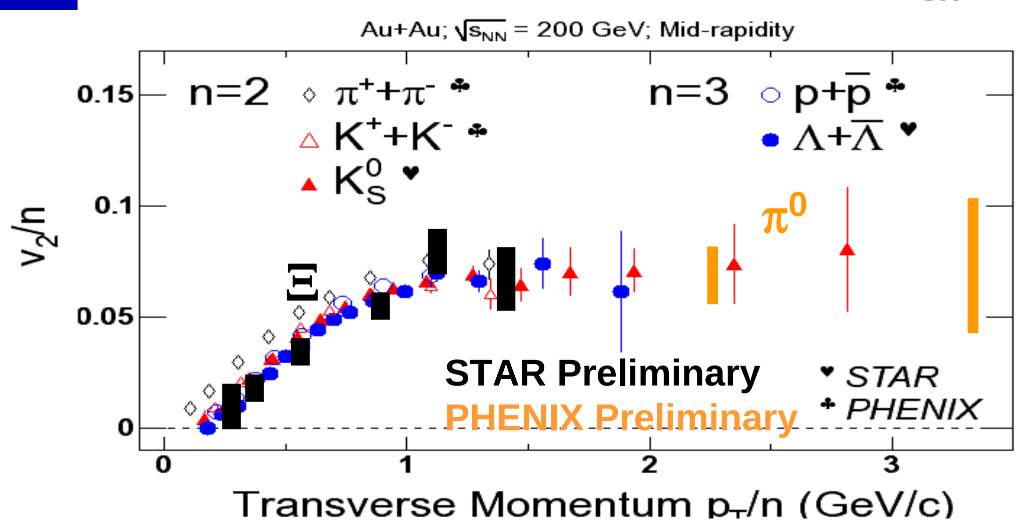
Characterization

- Three main thrusts have been identified:
  - A. Systematic study of dependence of all observables via
    - Species dependence (only Au+Au studied to date)
    - Energy dependence
    - Note: the successes to data argue strongly for companion measurements:
      - d+Au
      - p+p baseline
    - Massive unbiased event samples
  - B. Electromagnetic Probes
  - C. Heavy Flavor
- All three of these items rely on
  - Higher luminosity
  - Detector upgrades

Systematic Investigation

- (Elliptic flow as an example)
- Flow has played an essential role in the initial round of RHIC discoveries
- Open questions:
  - Is it at truly at the "hydro limit"?
    - Study in U+U (EBIS)
    - Higher √s?
  - How does it depend on system size?
    - Investigation begins in Run-5
  - At what p_T (if any) does it vanish?
  - Do the recombination systematics establish a deconfined phase?
  - Does heavy flavor participate in the collective flow?
    - Definitive results may required upgraded vertexing and higher $\mathcal{L}$.





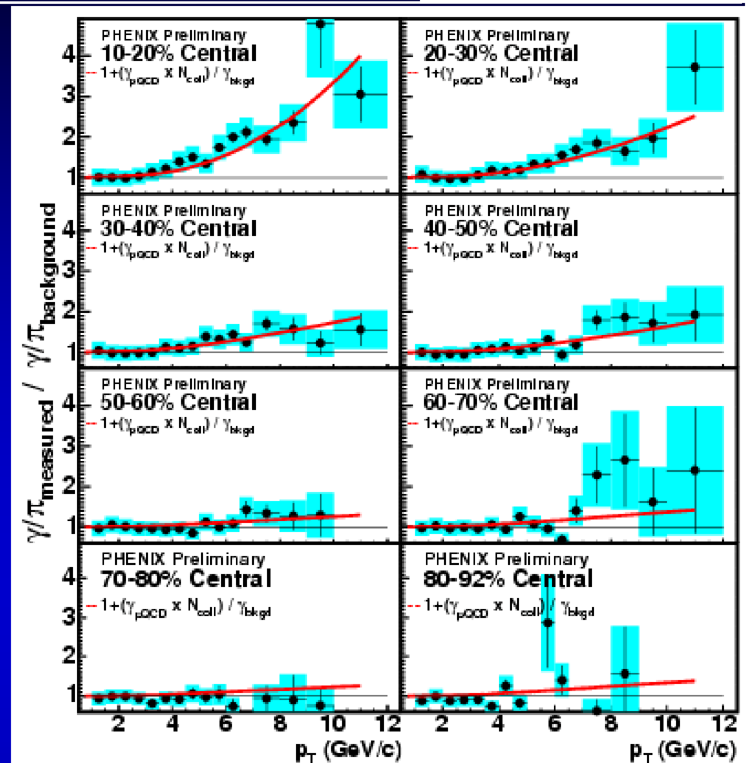
From RHIC I to RHIC II

- Design Luminosity for Au+Au:
  - $\mathcal{L}_D = 2 \times 10^{26}\ cm^2\ s^{-1}$
  - Integrated (delivered) luminosity per week ~ 0.06 nb^{-1}
  - Run-4 performance establishes 2 x $\mathcal{L}_D$ in hand (for Au+Au)
  - Suggests "ultimate" RHIC I Au+Au run delivers 2-4 nb^{-1}
- However
  A. Many crucial characterization measurements require well in excess of 10 nb^{-1}
  B. Full utilization of the facility requires that such samples *and* comparable
     - p+p baseline
     - d+Au control

     be acquired as rapidly as efficiently as possible
- Both "A" and "B" argue for RHIC II ≡ 40 x $\mathcal{L}_D$

EM Probes (Direct Photons)

- An essential probe in
  - A+A (thermal radiation, γ+jet)
  - p+A (shadowing)
  - p+p (baseline, ΔG)
- All 3 programs benefit from increases of 10-1000 in current data samples.



HIGH-ENERGY PHOTONS FROM PASSAGE OF JETS THROUGH QUARK GLUON PLASMA.

by R. J. Fries, B. Muller and D. K. Srivastava, Phys.Rev.Lett.90:132301, 2003

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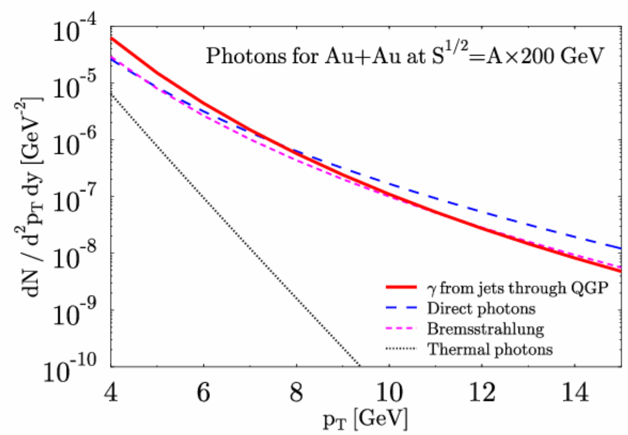
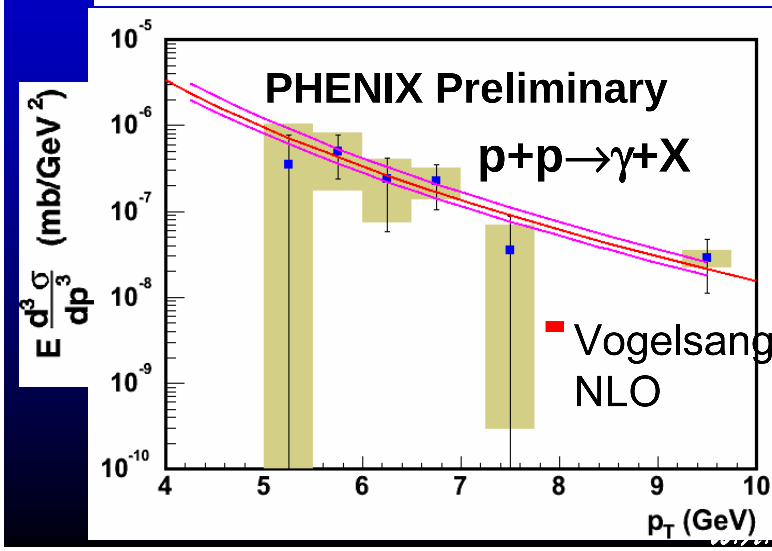


FIG. 1: Spectrum $dN/d^2p_\perp dy$ of photons at $y=0$ for central collision of gold nuclei at $\sqrt{S_{NN}} = 200$ GeV at RHIC. We show the photons from jets interacting with the medium (solid line), direct hard photons (long dashed), bremsstrahlung photons (short dashed) and thermal photons (dotted).



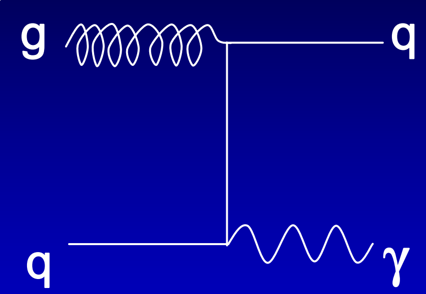
EM Probes (γ + jet)

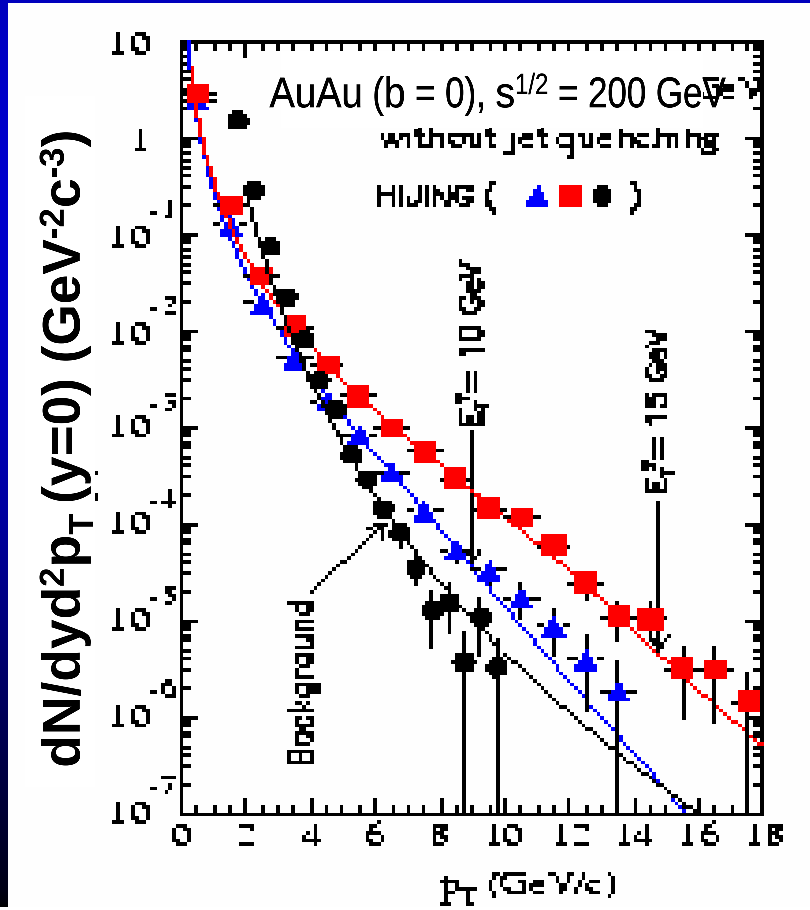
Q. How best to study suppression physics?

A. With a "tagged photon" beam

- **Good news:**
  RHIC supplies same via γ+jet
- **Challenging news:**
  - **One needs high energy γ's to perform "away side fragmentation physics"**
  - **Yields in STAR aperture (central Au+Au):**
    - **E_γ = 10 GeV: 6 nb / GeV**
    - **E_γ = 15 GeV: 0.6 nb / GeV**

➡ ***This measurement requires RHIC II luminosity***





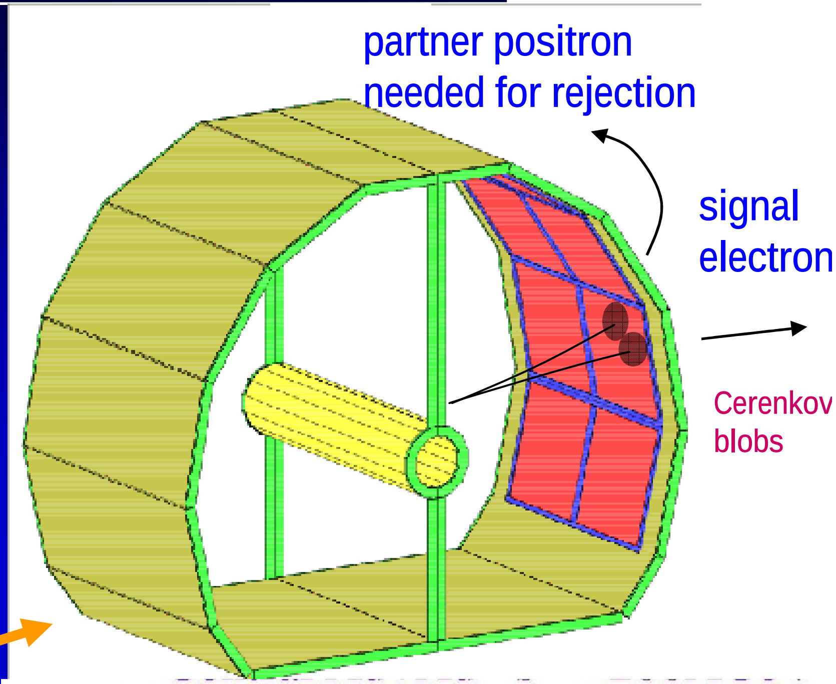
EM Probes (via e^+e^-)

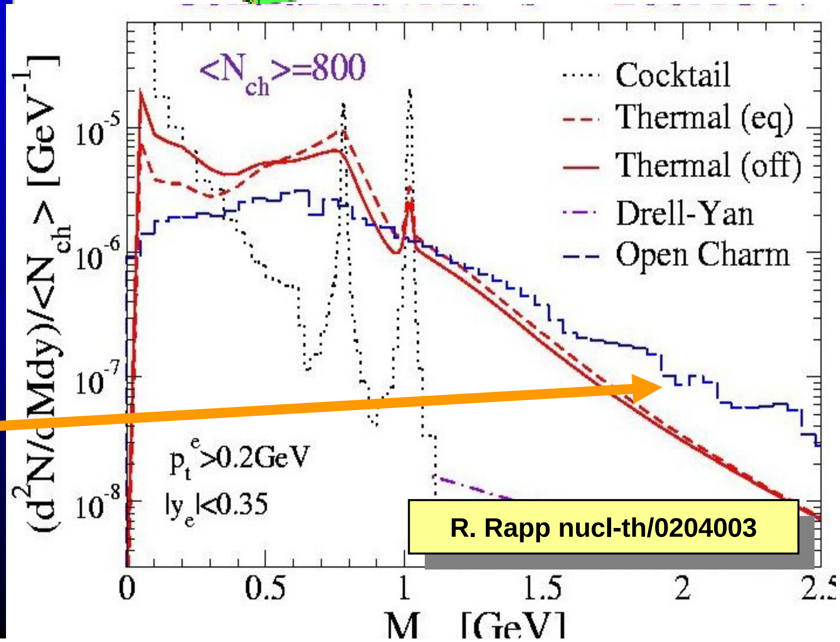
- **Sensitive to**
  - **Medium modifications of vector mesons**
    - **Chiral symmetry breaking**
    - **Persistence of bound states in sQGP ?**
  - **Thermal radiation**
- **Measurement is**
  - **Technology driven**
    - **Ongoing R&D to develop "Hadron Blind" technology**
  - **Technology and luminosity driven**
    - **Need microvertex detector**

      and

    - **L*dt**
      to quantify charm contribution

(Details in A. Drees talk)





Heavy Flavor

- All length scales in the QCD plasma are "degenerate":
  - i.e. they all are proportional to 1/T (times various powers of g)
- Fix this by introducing heavy flavor:
  - $M_c \sim 1.3$ GeV
  - $M_b \sim 5.0$ GeV

to introduce new scales
  - $1 / M_c \sim 0.15$ fm
  - $1 / M_b \sim 0.04$ fm
  - ⇨ Flavor tagged jets

Bohr radii (onium):
  - $J/\Psi \sim 0.29$ fm
  - $\Upsilon \sim 0.13$ fm
  - ⇨ "Onium" spectroscopy

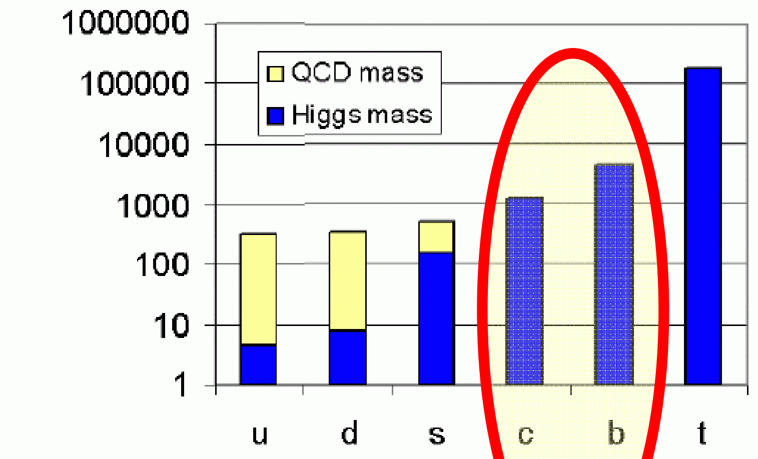
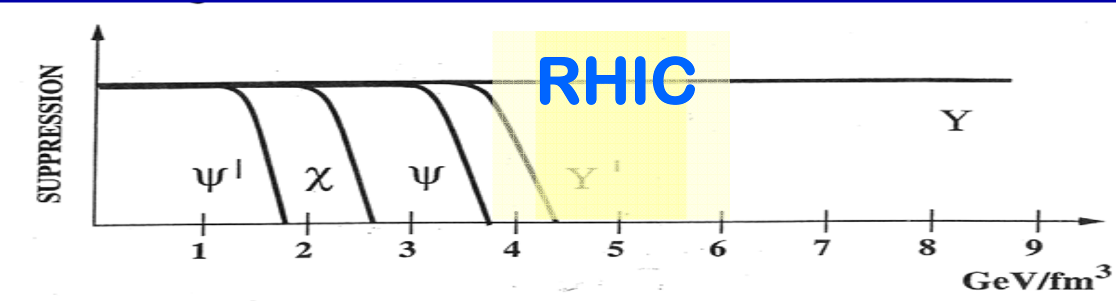


FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale.



Heavy Flavor in PHENIX

- **Definitive measurements requires integrated luminosities of 1-10 nb^{-1}**

➡ ***These measurements require RHIC II luminosities***

- **Of course will also need measurements with similar p_T or x_T reach in p+p, d+A, lighter systems.**

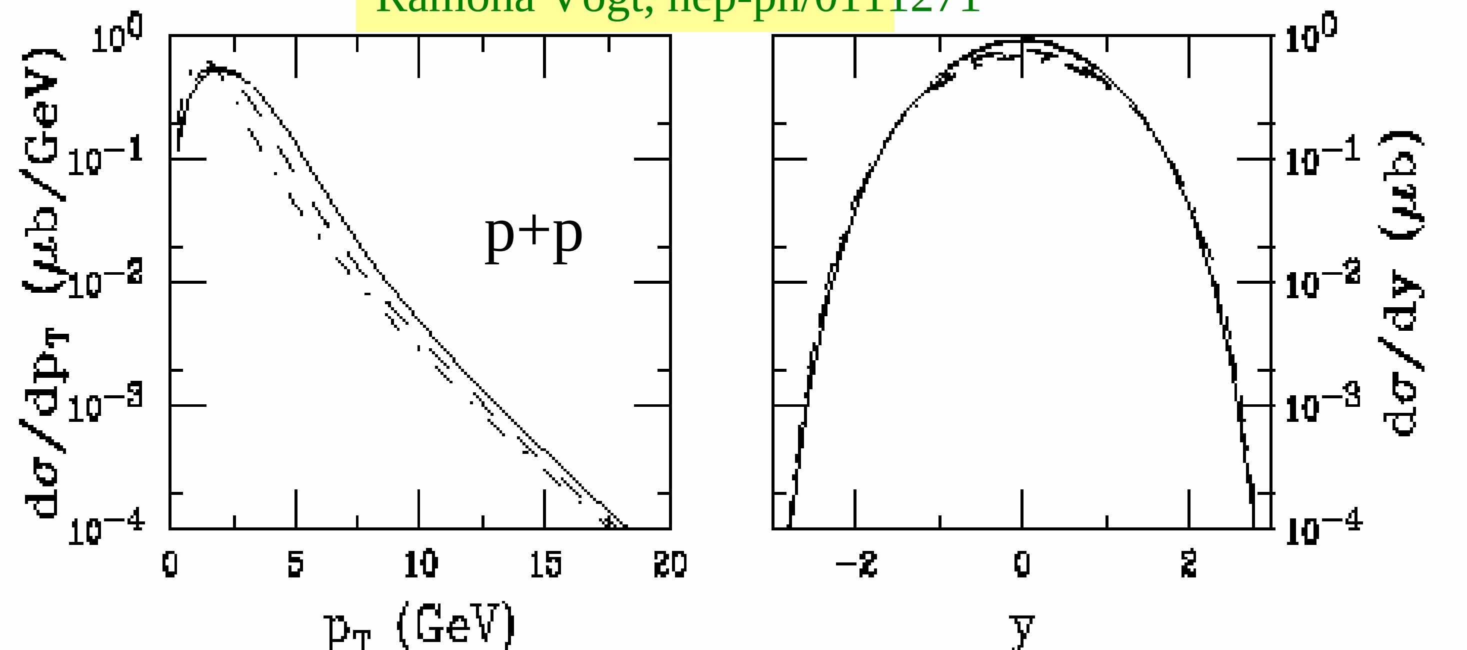
Υ(1S), Υ(2S), and Υ(3S) peaks

Topic	Signals	p_T (GeV/c)	Recorded $\mathcal{L}$ dt (μb^{-1})	Requires
open charm	$D \to \mu, e + X$	$0.5 - 2.5$	300	
(energy loss, $\sigma(c\bar{c})$, $flow$)	$D \to \mu, e + X$	$0.3 - 6$	1000	VTX
	$D \to K + \pi$	> 2	1000	VTX
open beauty	$B \to \mu, e + X$	$1 - 6$	1000	VTX
(energy loss, $\sigma(b\bar{b})$)	$B \to J/\psi \to e^+e^-, \mu^+\mu^- + X$	all	1000	VTX
Prompt charmonium	$J/\psi \to e^+e^-, \mu^+\mu^-$	all	300	
(suppression, coalescence)	$\psi' \to e^+e^-, \mu^+\mu^-$	all	1000	(VTX)
	$\chi_{cJ} \to \gamma\ J/\psi \to \gamma\ e^+e^-$	all	1000	
Charmonium background	$B \to J/\psi \to e^+e^-, \mu^+\mu^- + X$	all	1000	VTX
Bottomonium	$\Upsilon, \Upsilon', \Upsilon'' \to e^+e^-, \mu^+\mu^-$	all	3300	VTX
		~ Delivered $\mathcal{L}$ dt / 3		μ trigger

Heavy Flavor Tagged Jets in STAR

- **Complete measurements possible only with RHIC II + Detector upgrades**

Ramona Vogt, hep-ph/0111271



- **$p_T \sim 15$ GeV/c: σ (p+p) ~5 x 10^{-4} μb/Gev $\Rightarrow$ σ (Au+Au) ~20μb/Gev centrally produced**
- **But *5 years* of RHIC I Au+Au (10 nb^{-1}) needed $\Rightarrow$ 200K b-bar pairs**
- **See T. Hallman talk for details of extraction w. μVTX detector**

➡ ***These measurements require RHIC II luminosities***

RHIC Spin Program

- Based on pQCD hard scattering as definitive probe of non-perturbative QCD spin structure
- Fundamental questions addressed:
  - Does preferential spin orientation of gluons account for a major portion of the "nucleon spin puzzle"?
    - Either answer interesting! If not gluon spins, then $L_{orbital}$!
  - Do sea antiquarks have a substantial and flavor-dependent helicity preference in a polarized nucleon?
    - Illuminates the relative roles of gluon splitting vs. pseudoscalar meson clouds in generating the "sea".
  - How to unravel the contributions to transverse spin asymmetries (an area of intense recent theoretical development) from:

    a) quark transverse *spin* preferences in a transversely polarized proton (p↑)
    - "transversity" ⇔ quark property decoupled from gluons

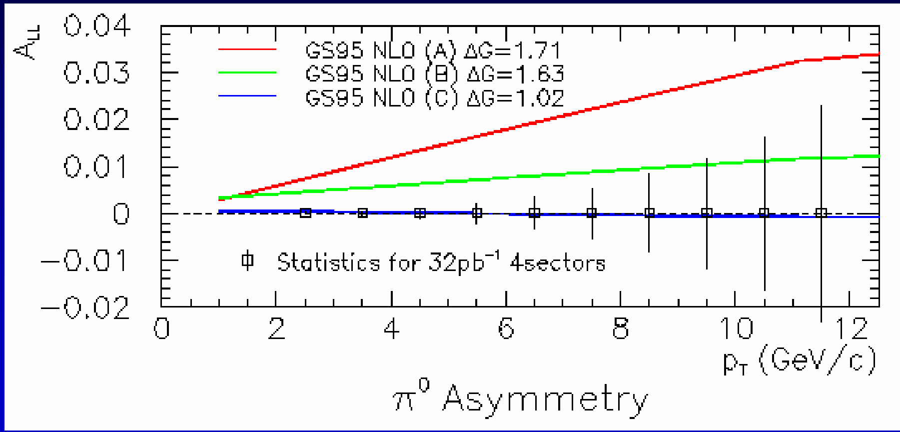
    b) quark transverse *motion* preferences in p↑
    - spin- k_T correlation related to quark orbital angular momentum

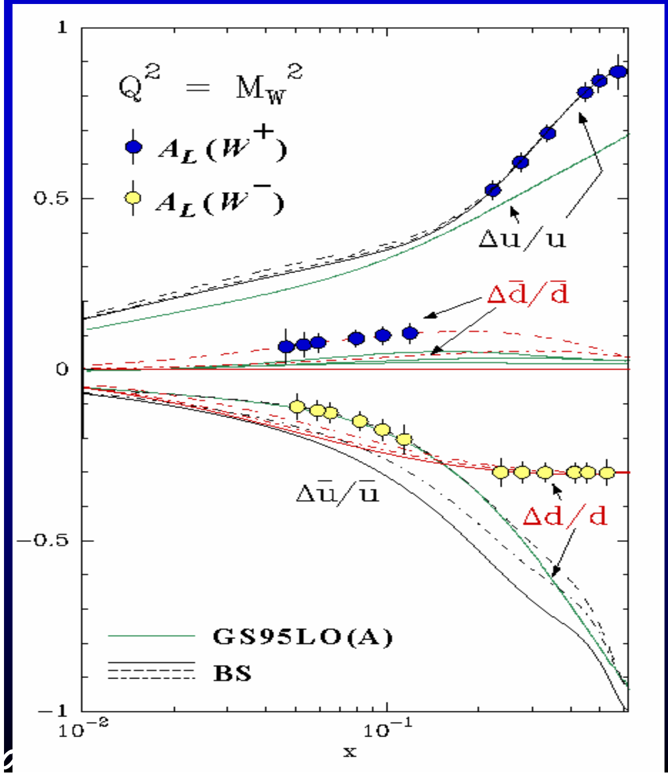
    c) explicit chiral symmetry breaking from m_q terms in L_{QCD}.

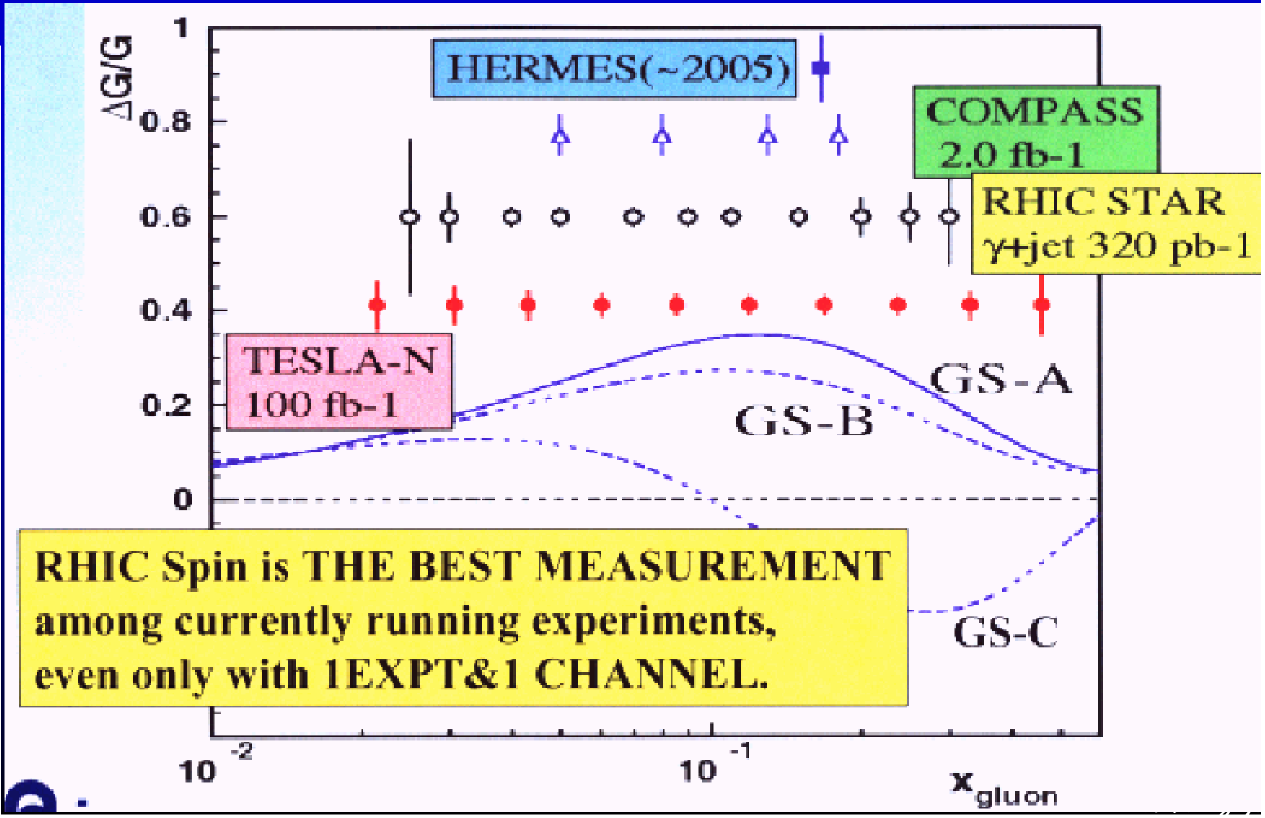
(Slide content courtesy of S. Vigdor)

RHIC Spin Potential

- Wide range of measurements in many channels to address
  - ΔG
  - Sea quark polarization
  - Transversity
- A world class program in polarized structure function physics

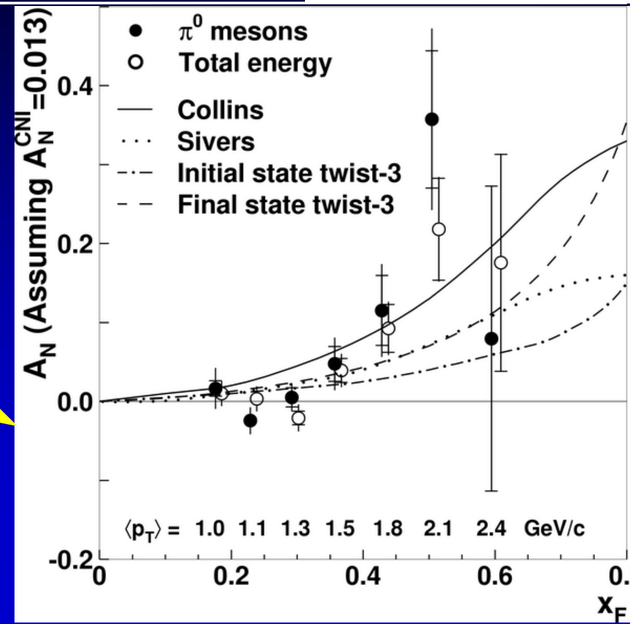


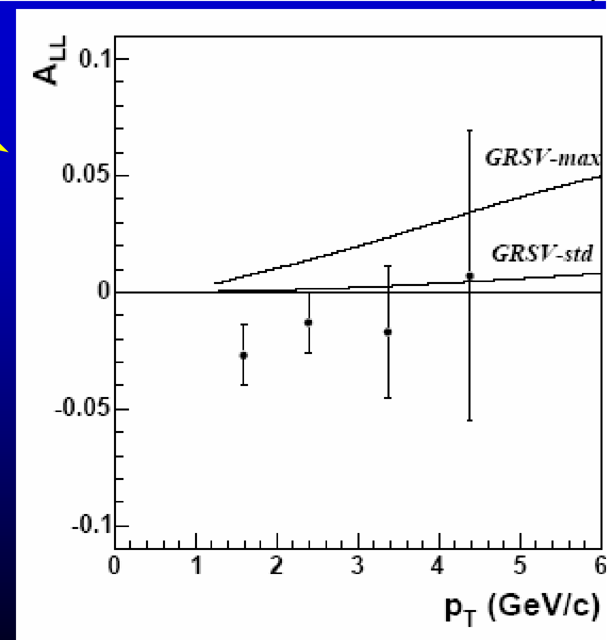




Current Spin Status

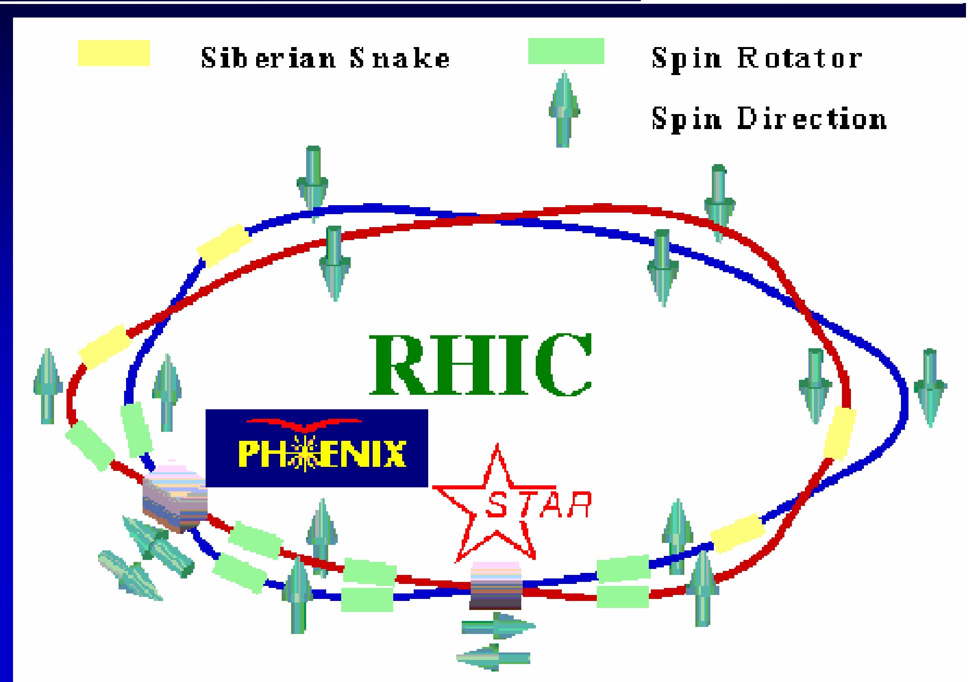
- To date:
  - Cross Sections and Transverse Single-Spin Asymmetries in Forward π^0 Production from Proton Collisions at $\sqrt{s}$ = 200 GeV, J. Adams *et al.* (STAR Collaboration) Phys.Rev.Lett. 92 (2004) 171801
    - 0.15 pb^{-1}, <P>=16%
  - Double Helicity Asymmetry in Inclusive Mid-Rapidity π^0 Production for Polarized p+p Collisions at $\sqrt{s}$=200 GeV, S. Adler *et al.* (PHENIX Collaboration), submitted to Phys. Rev. Lett.
    - 0.22 pb^{-1}, <P>=27%
- To do (partial list):
  - A_{LL} measurement in many channels at $\sqrt{s}$=200 GeV (Requires ~300 pb^{-1}, <P> ~ 70%)
  - A_L measurement via $W^{\pm}$ at $\sqrt{s}$=500 GeV (Requires ~800 pb^{-1}, <P> ~ 70%)
- Requires
  - (ongoing) beam development
  - Extensive running (to begin in Run-5)



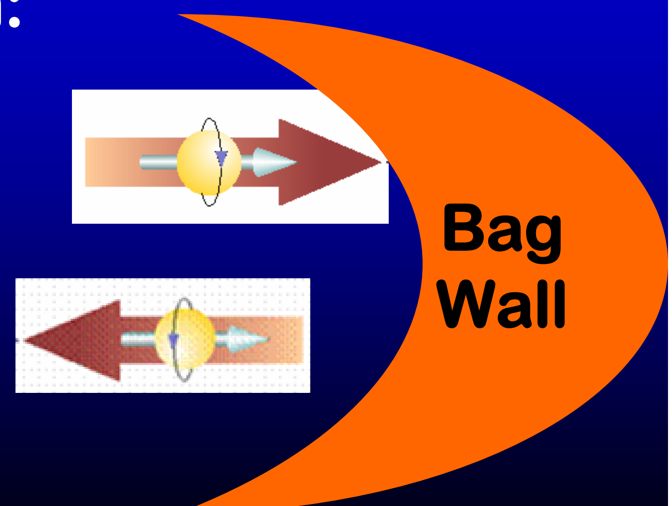


Connections (Spin)

- An obvious (in fact integral) programmatic connection
  - "Spin" sub-systems have proven benefit to A+A, p+A measurements
    - E.g., PHENIX Muons
    - E.g., STAR Endcap
  - Integrated presence in collaborations mutually beneficial



- An important intellectual connection:
  - Confinement
    ➔ mixing of helicity components
  - Transversity
    ➔ requires chiral symmetry breaking
  - "To understand the *inside* of the proton you must understand the *outside* of the proton." (R. Mawhinney)



Connections (p+A)

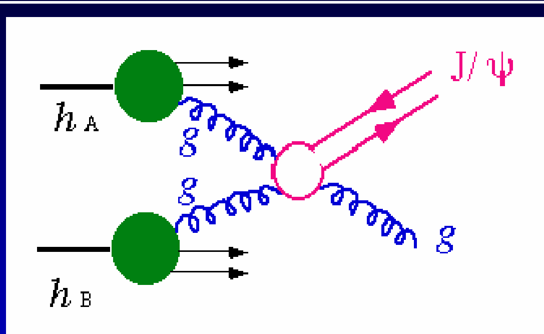
- Just as spin program at RHIC provides complementary information about
  - Structure functions
  - Chiral symmetry breaking effects

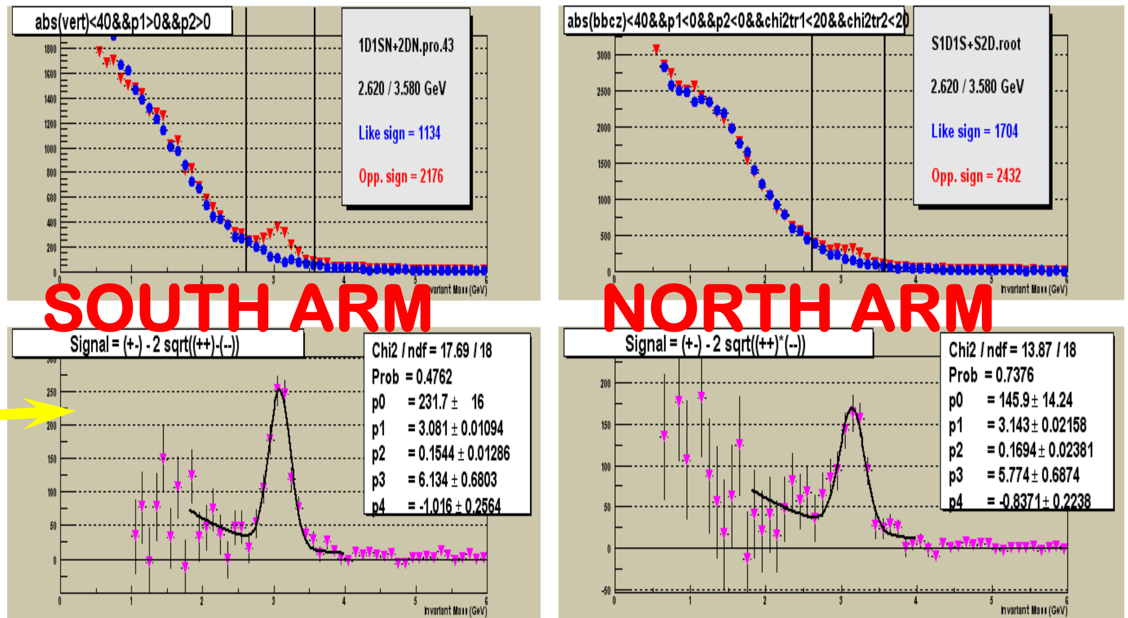
  in the nucleon wave-function…

- The p+A program probes
  - Modifications to the structure functions (shadowing)
  - Color Glass Condensate effects in the nuclear wave-function

  and (just as in spin program)
  - These investigations have a rich scientific basis of their own
  - Will present two "case studies"

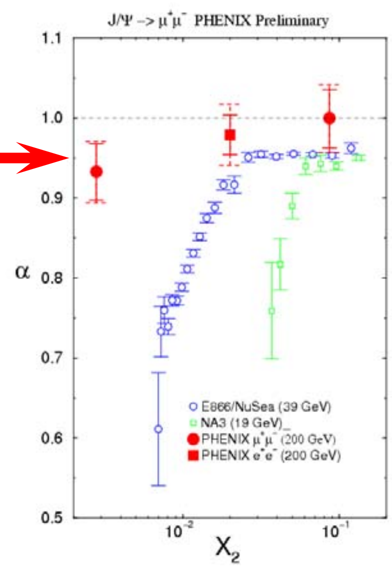
Run-3 J/Ψ's in d+Au

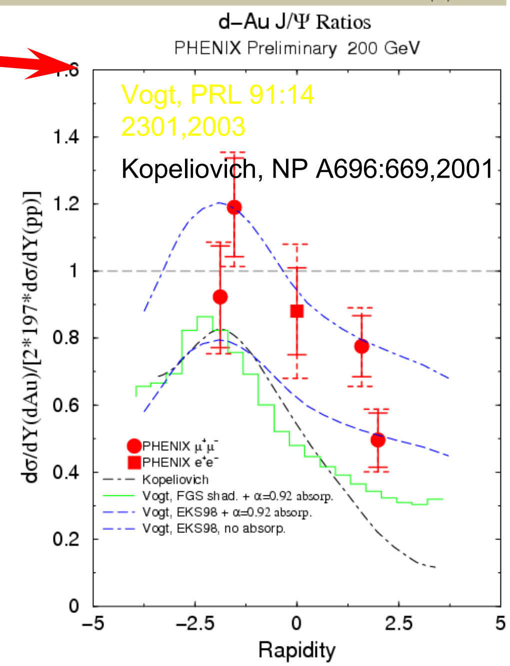




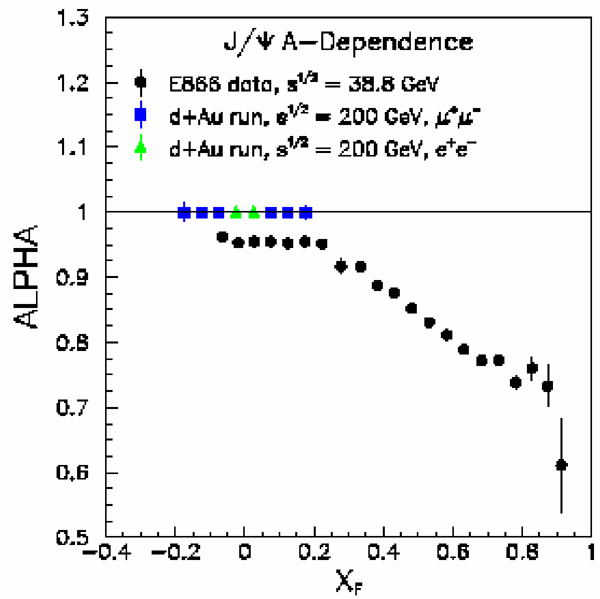
- 2.7 nb^{-1} d+Au
  - Provides clear J/Ψ signals
  - With modest discrimination power to test shadowing models
- A clear indication of the much greater x_2 range made available by RHIC
- A clear need for
  - 20 nb^{-1} : shadowing
  - 200 nb^{-1} : Ψ', Drell-Yan
  - >200 nb^{-1} : Υ's

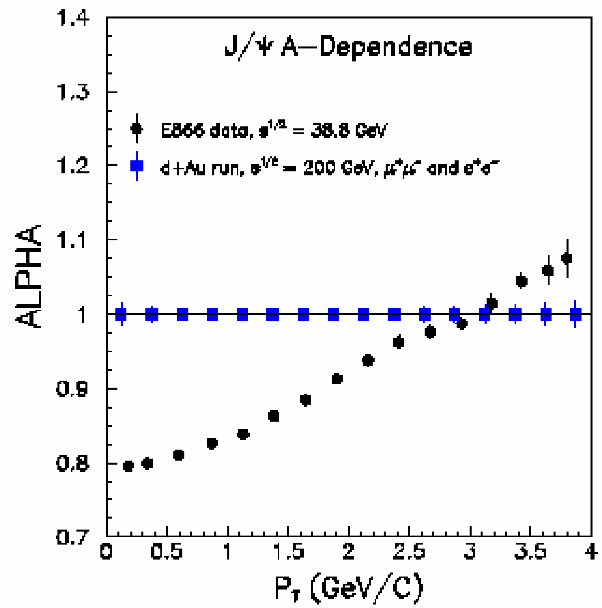
➡ ***Measurements beyond ~20 nb^{-1} require RHIC II luminosities***

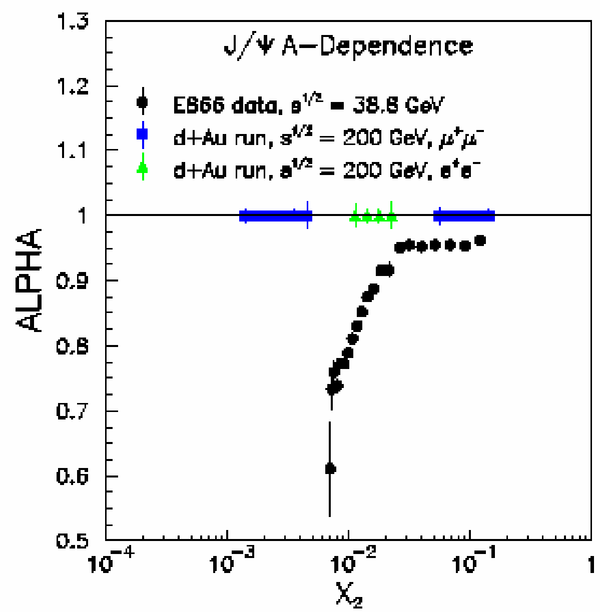




Extended Reach in d+Au







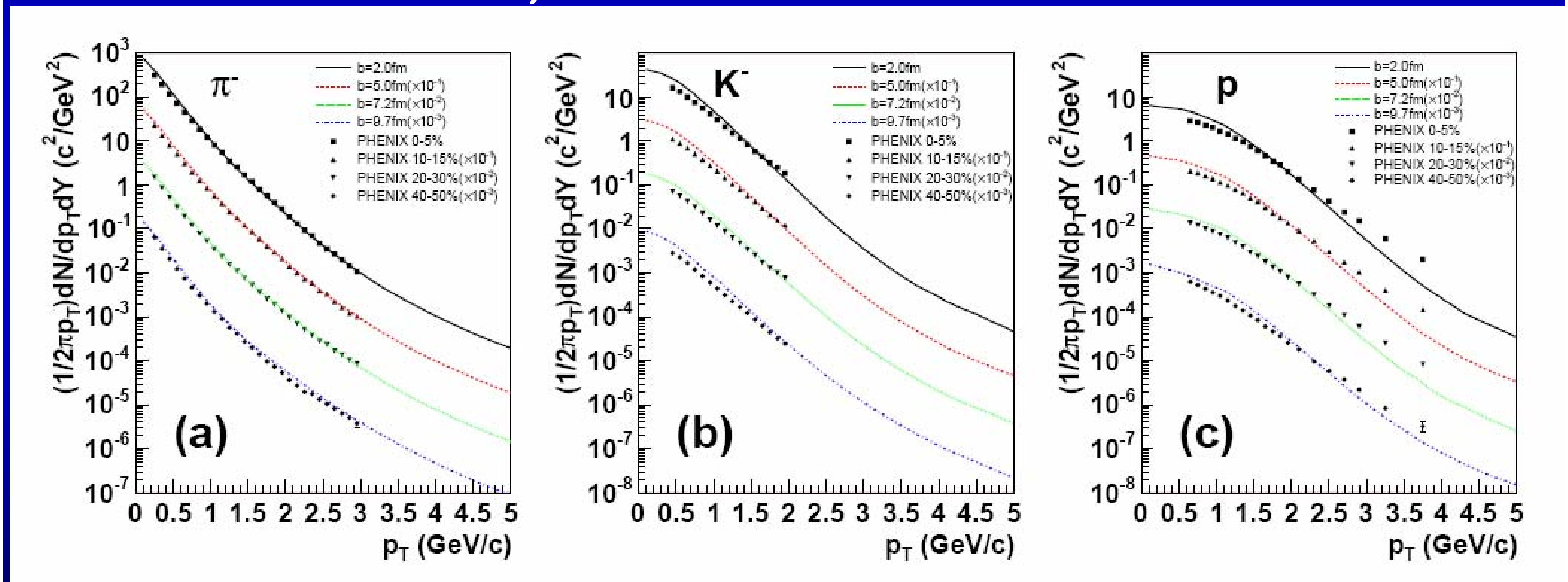
- What that first 20 nb^{-1} delivers
  - Extensive measurements
    - at higher $\sqrt{s}$
    - lower x_2
- Then the next 200 nb^{-1} …

Table 2.10: Estimated physics yields for d+Au collisions for several processes with various integrated luminosities. For the lower rate process such as the Υ this illustrates the much larger luminosities needed in order to reach this physics.

$\int \mathcal{L}dt$	Process	North Muons	South Muons	Electrons
20 nb^{-1}	J/Ψ	8.3k	6.4k	3.3k
200 nb^{-1}	Ψ'	1650	1280	660
200 nb^{-1}	Υ	47	40	56
200 nb^{-1}	Drell-Yan ($M > 4\ GeV$)	4.9k	3.8k	1k ($M > 3\ GeV$)
200 nb^{-1}	$D\bar{D}$ ($M > 1.6\ GeV$)	25k	20k	
200 nb^{-1}	$D \rightarrow \mu X$	2B	2B	
200 nb^{-1}	$B \rightarrow \mu X$	5M	5M	

CGC + Hydro + Jets

- A beautiful example of the convergence between
  - CGC as a description of the initial state
  - Hydrodynamics as a description of the bulk matter evolution
  - Jets as a probe of same
- T. Hirano and Y. Nara, nucl-th/0404039:



- *What measurements can we perform at RHIC to test the assumptions of CGC initial state?* (p+A measurements)

Hunting Color Glass at RHIC

- **Anticipated by theory community (below simple picture courtesy of R. Pisarski)**

Where to find the Color Glass: dA, by the *proton*

Fragmentation region: like looking in the rest frame.
Incident projectile gets Lorentz contracted:

proton fragmentation region

nuclear fragmentation region

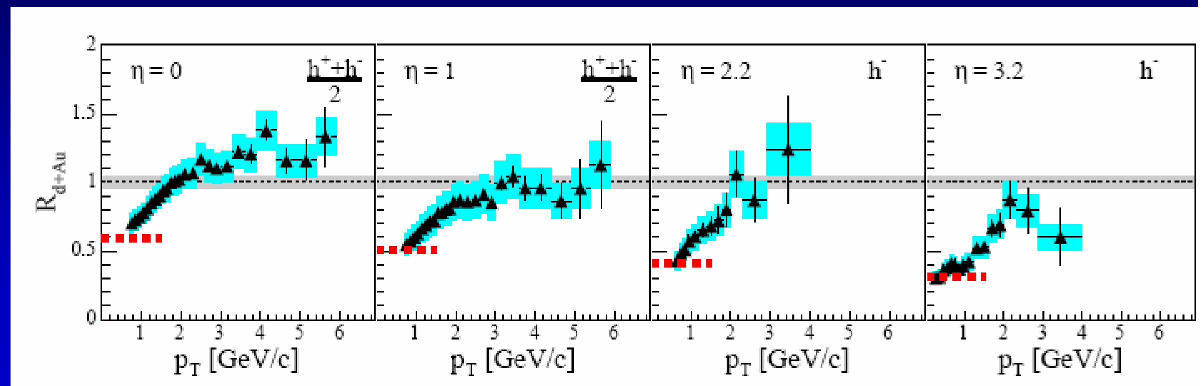
Nuclear frag. region: proton contracted. Study *final* state effects

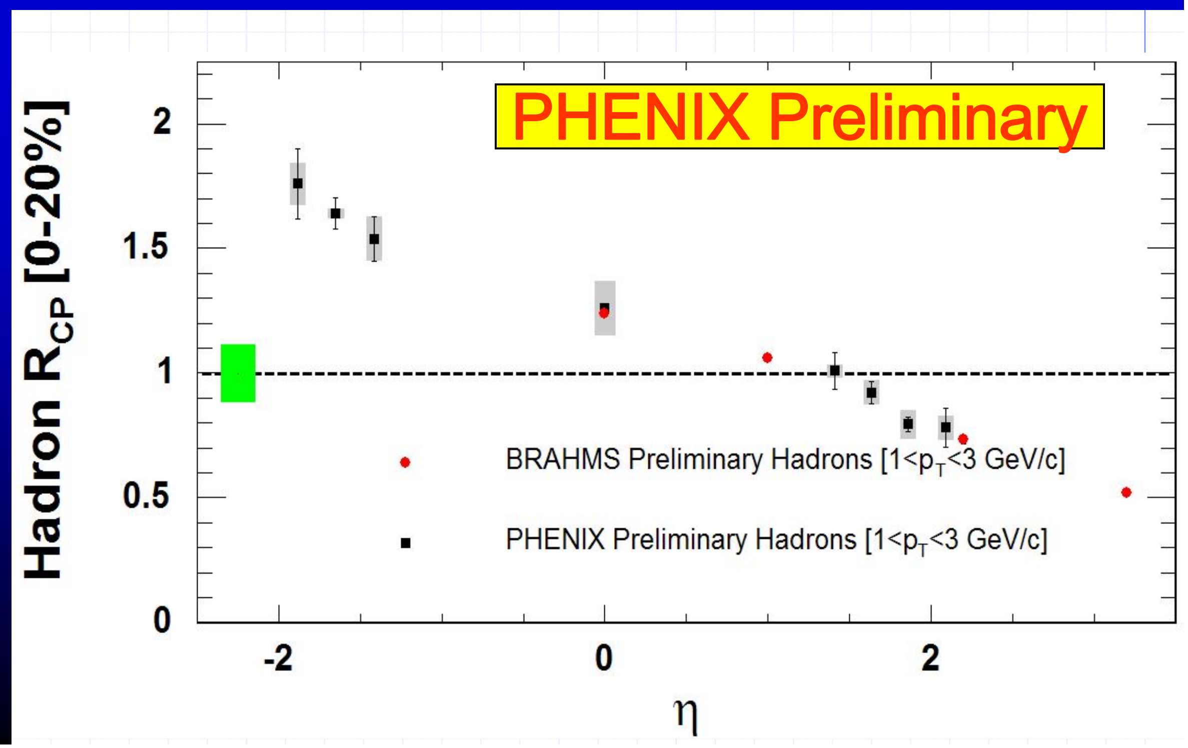
Proton frag. region: study *initial* state effects
(Dumitru & Jalilian-Marian, Gelis...)
Scatter valence quarks off classical (gluon) field=>π+/π- asymmetry

d+Au Viewed Through Colored Glass

- **BRAHMS publication (nucl-ex/0403005)**
  - Dependence on
    - Pseudorapidity
    - Centrality

    qualitatively consistent with CGC
- **PHENIX Preliminary Result**
  - Consistent with trend observed by BRAHMS
  - Extends these measurements to Au fragmentation regime
- **To do:**
  - Detailed studies:
    - Particle species
    - Nuclear mass
    - Transverse momentum
    - Di-jets (?!)





NSAC Performance Measures

- RHIC program of sufficient breadth that it encompasses two broad categories in the NSAC Performance Measures :
  - Physics of High Density and Hot Hadronic Matter:
    - ✓2005 Measure J/ψ production in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.
    - ✓2005 Measure flow and spectra of multiply-strange baryons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.
    - ✓2007 Measure high transverse momentum jet systematics vs. $\sqrt{s_{NN}}$ up to 200 GeV and vs. system size up to Au+Au.
    - 2009 Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC
    - ✓2010 Measure the energy and system size dependence of J/ψ production over the range of ions and energies available at RHIC.
    - ✓2010 Measure e^+e^- production in the mass range $500 \leq m_{e+e-} \leq 1000$ MeV/c^2 in $\sqrt{s_{NN}}$= 200 GeV collisions.
    - 2010 Complete realistic calculations of jet production in a high density medium for comparison with experiment.
    - ✓2012 Determine gluon densities at low *x* in cold nuclei via p+Au or d+Au collisions
  - Hadronic Physics
    - ✓2008 Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy $\sqrt{s}$ = 200 GeV.
    - ✓2013 Measure flavor-identified q and q contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
- Conclusion: ***All of the experimental measures listed above are achievable via the proposed program of detector and accelerator upgrades***

RHIC Operations

- As (already) a premiere facility, RHIC "suffers" from an embarrassment of riches:
  - World-class A+A program
  - World class polarized p+p program
  - World class p+A program
- There is a tremendous benefit to all 3 programs from the efficiencies provided by
  - *Significant* luminosity increases
  - *Longer* running periods
  - *Timely* exploitation of the tremendous physics opportunities

Summary

- **2000-2004: A period of unprecedented discovery in the initial operation of RHIC**

- **2005-2009: RHIC as the premiere QCD facility in the world**

- **2010-2015: RHIC II as the premiere QCD facility in the world**

- **2015++ : eRHIC and RHIC II as the premiere QCD facility in the world**

☞ ***2004 Status: We have only scratched the surface of the myriad physics opportunities accessible at RHIC***