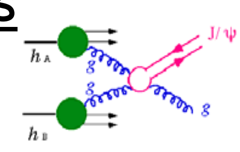
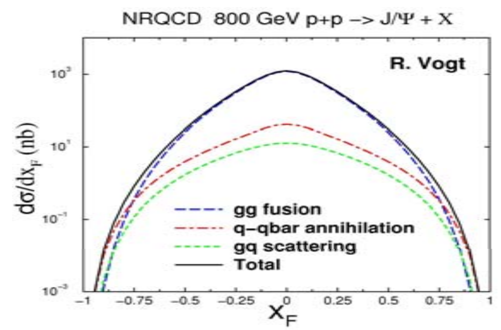
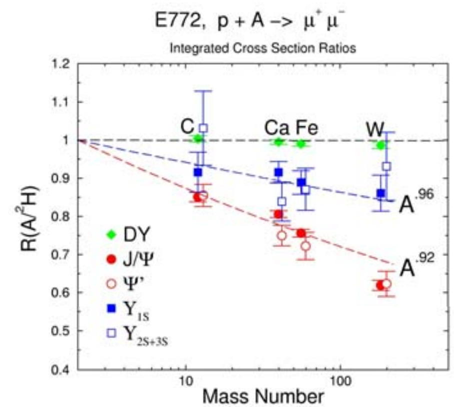
Nuclear Physics with p-p, p-A and A-A Collisions in P-25 at RHIC & FNAL



- **Production issues & spin:**
  - Parton distribution functions
  - Production mechanisms for heavy quarks, angular distributions, total cross sections
  - Spin – the spin crises & dbar/ubar via W's
- **Cold nuclear matter effects:**
  - Modification of structure functions, e.g. shadowing
  - Incident parton energy loss, multiple scattering (Cronin effect)
  - Absorption of heavy-quark resonances and contributions from feed-down
  - closed & open-charm comparisons
  - Critical baseline for A-A studies
- **Hot dense matter in nucleus-nucleus collsions**
  - sQGP – deconfined partonic matter
  - Color screening for heavy-q bound states
  - Energy loss of partons leaving the dense region
  - Modification of jet momenta and their fragmentation or cone distributions and back-to-back correlations
  - Variation wrt reaction plane





RHIC Spin Physics

How does the proton get its spin?

- On average, quarks account for only ~20% of the proton's spin ("spin crises")
- how much do the gluons contribute?
- is there significant orbital angular momentum?

Are the sea antiquarks polarized?

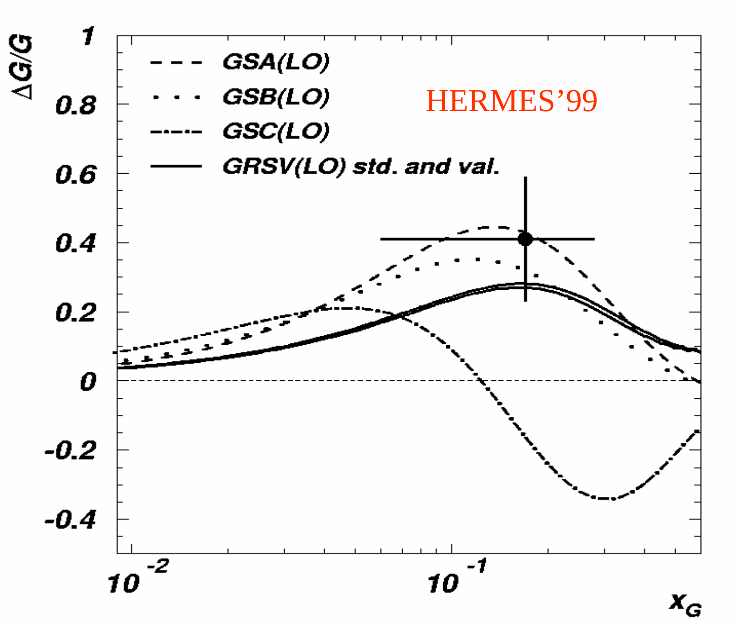
- parity-violating spin asymmetries in $W^{\pm}$ production are sensitive to quark and antiquark polarization.

How does the transverse spin structure (transversity) compare to the longitudinal spin structure?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_{G+q}$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.31 \pm 0.04$$

$$\Delta s = -0.10 \pm 0.02$$



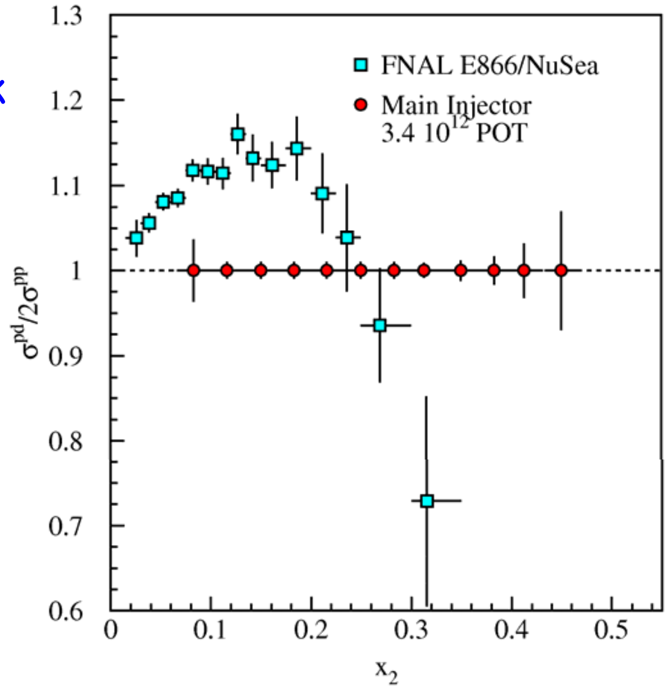
LANL experimental approach:

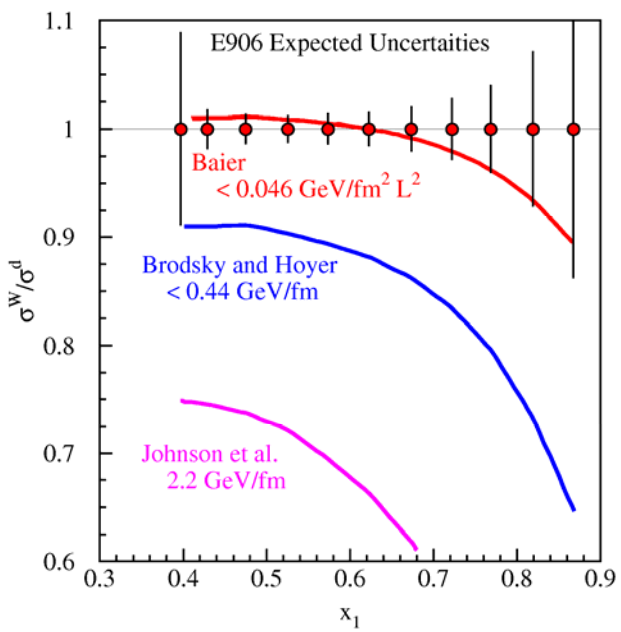
heavy quarks – sensitivity to gluons

FNAL E906 – flavor asymmetry of the nucleon to larger x & quark energy loss in nuclei

dbar/ubar > 1 for $x_2 < 0.25$

- probably due to meson cloud of proton, i.e. quark counting (p → n + π+ → n + dbar-u)
- does gluon splitting dominate at larger x_2 and give dbar=ubar?
- 120 GeV Drell-Yan D/H measurement needed to push to larger x_2!
- polarized p-p collisions at RHIC can explore spin structure of dbar/ubar with W's – see Ming's talk





At 800 GeV, the nuclear dependence of Drell-Yan on nuclear targets could not unambiguously separate shadowing and dE/dx effects at low x

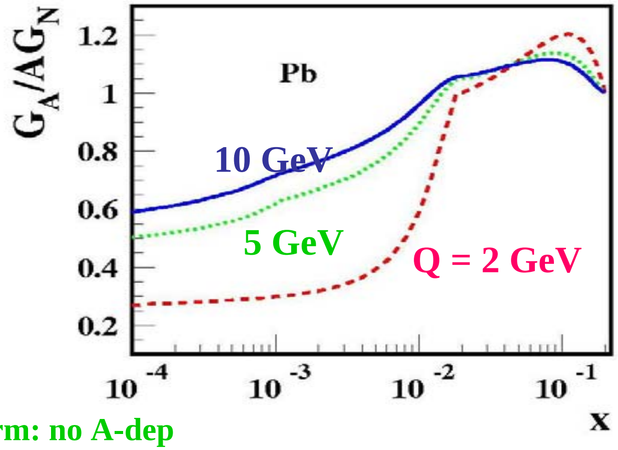
- **for 120 GeV p-A Drell-Yan only quark dE/dx remains and can be isolated**

Nuclear modification of parton level structure & dynamics

Modification of parton momentum distributions of nucleons embedded in nuclei

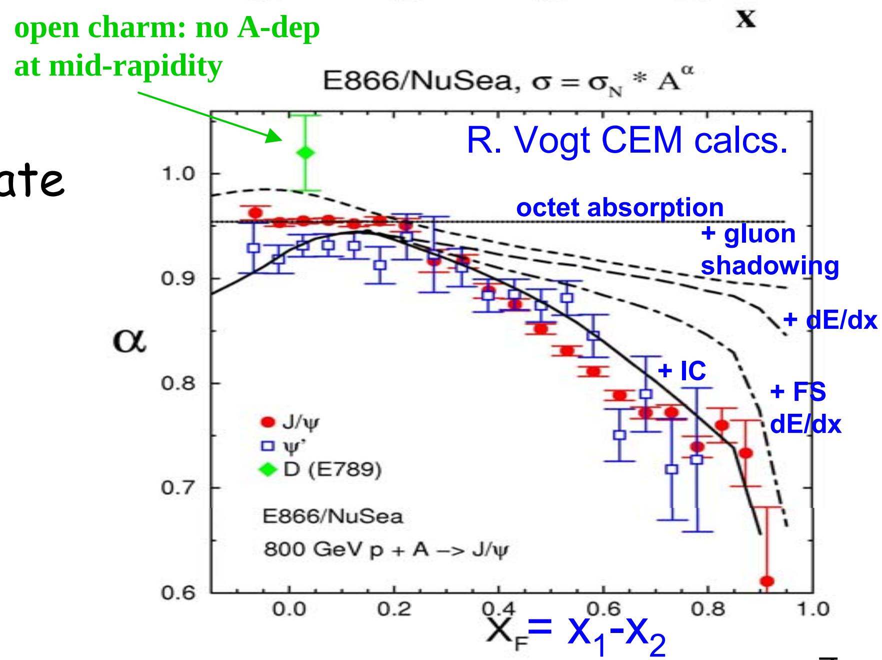
- shadowing – depletion of low-momentum partons (gluons)
- coherence & dynamical shadowing
- gluon saturation – e.g. color glass condensate, a specific/fundamental model of gluon saturation which gives shadowing in nuclei

Gluon shadowing
Gerland, Frankfurt, Strikman, Stocker & Greiner (hep-ph/9812322)



Nuclear effects on parton "dynamics"

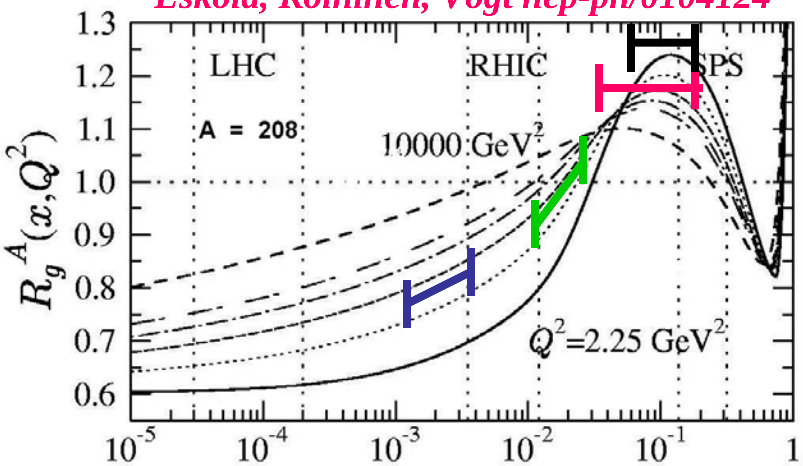
- energy loss of partons as they propagate through nuclei
- and (associated?) multiple scattering effects (Cronin effect)
- absorption of J/ψ on nucleons or co-movers; compared to no-absorption for open charm production



Gluon Shadowing

- **Shadowing** of gluons → depletion of the small x gluons
- Very low momentum fraction partons have large size & number density, overlap with neighbors, and fuse; thus enhancing the population at higher momenta at the expense of lower momenta
- Or alternate but equivalent picture: coherent scattering resulting in destructive interference for coherence lengths longer than the typical intra-nucleon distance

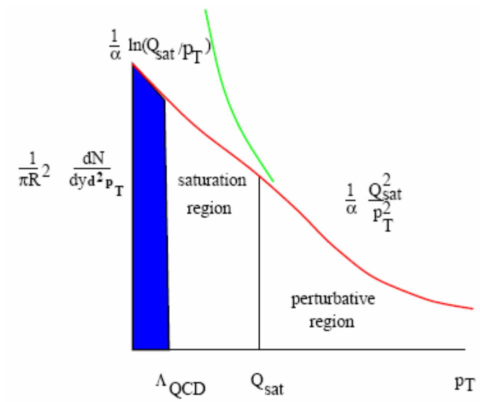
Eskola, Kolhinen, Vogt hep-ph/0104124



PHENIX μ
PHENIX e
E866 (mid-rapidity)
NA50

<u>Color glass Condesate (CGC):</u>

- Gluons saturate and the distribution stops growing.
- Recently, a new way to look at this phenomena (McLerran, Venugopalan et al.)

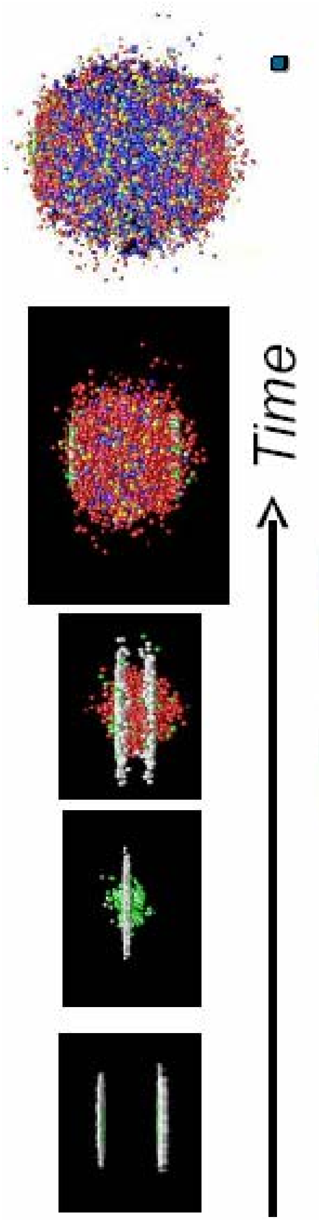


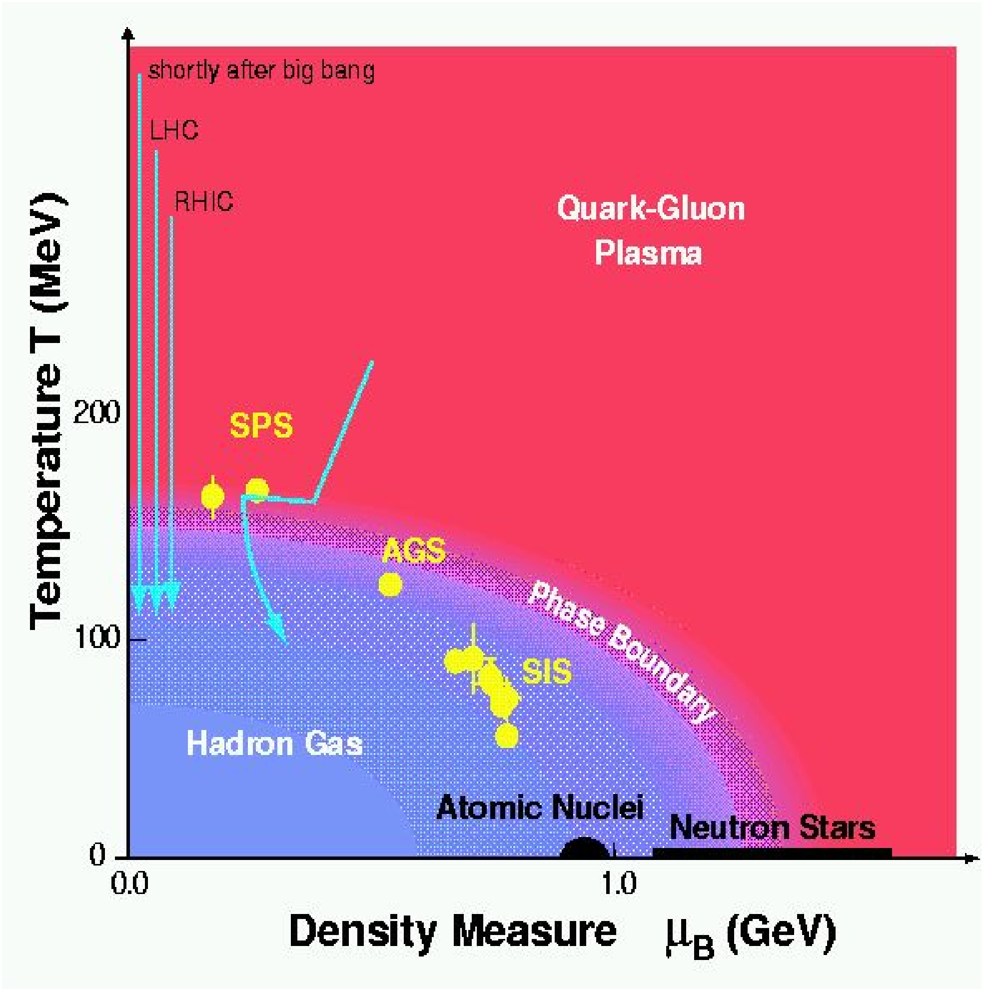
Nuclear Amplification:

- Need to reach $x_p \sim 10^{-4}$ → $x_{Au} \geq 10^{-2}$

What is a Quark Gluon Plasma?

***Phases of Matter*: Quarks and gluons become deconfined as the temperature and/or density is increased through and beyond a phase boundary**



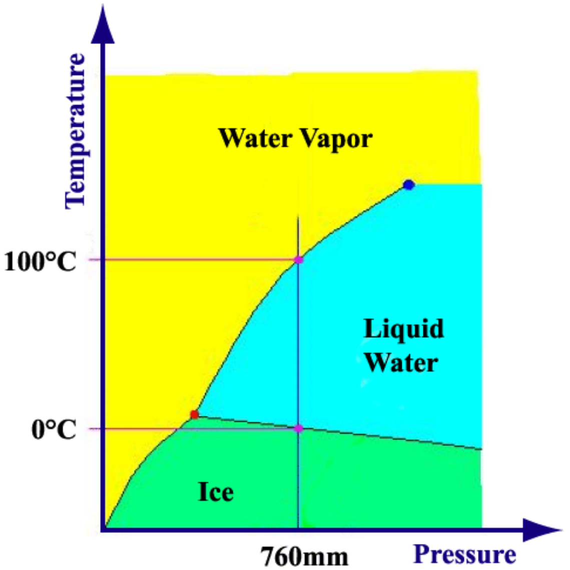


***Phases of Water*:**

…Water Vapor

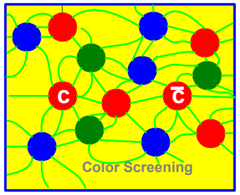
…Liquid Water

Ice …

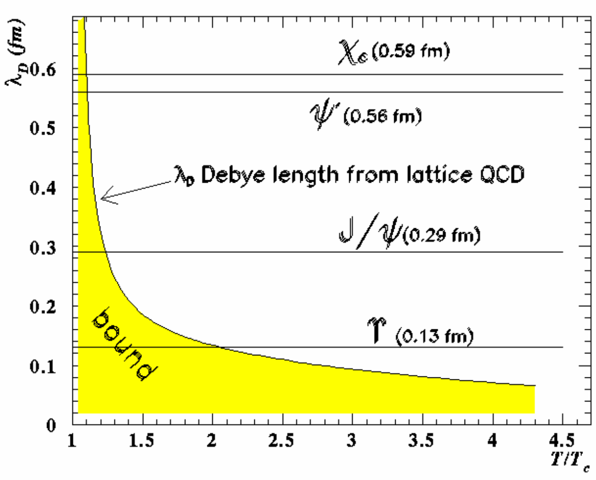


AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

- Debye screening predicted to destroy J/ψ's in a QGP



- Different states "melt" at different temperatures due to different binding energies.
- but recent charm recombination models might instead cause an enhancement?



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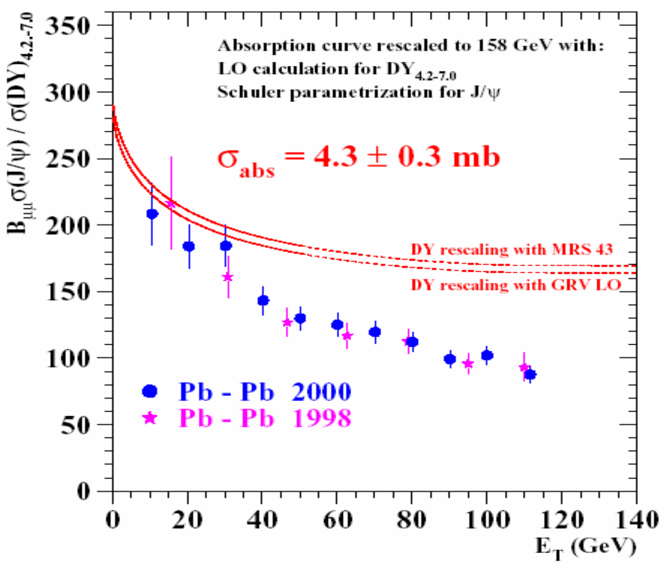
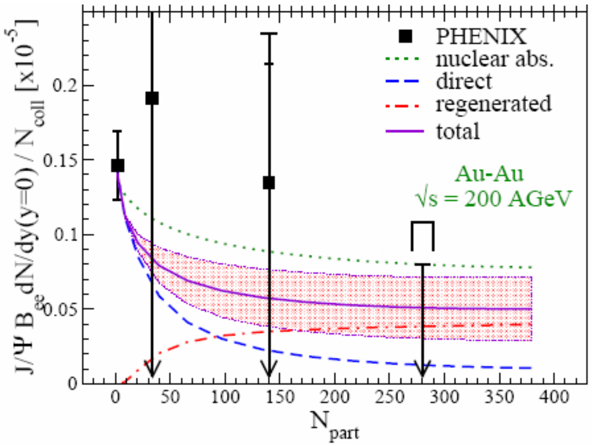
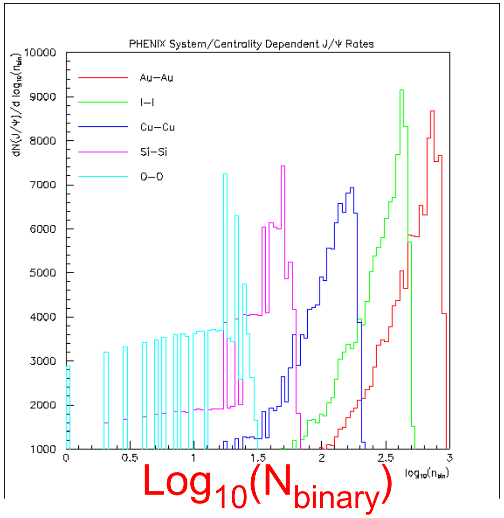


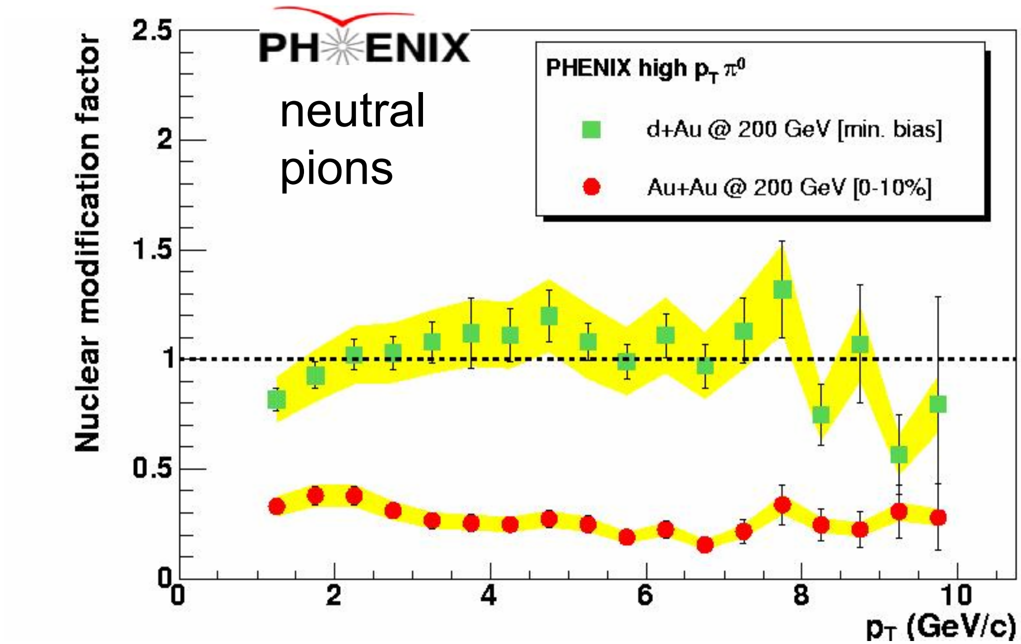
Grandchamp, Rapp, Brown hep-ph/0403204

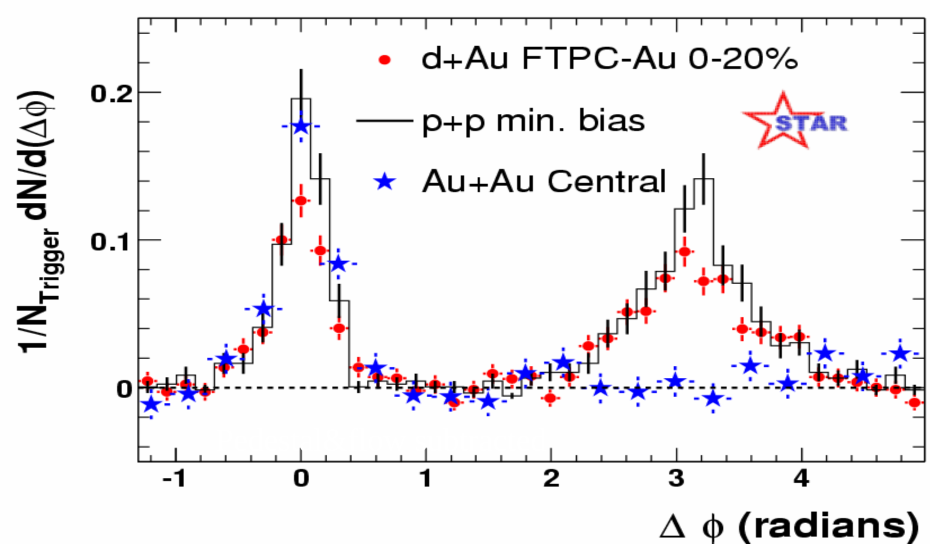


Lighter species collisions to explore range of energy densities



Jet Quenching

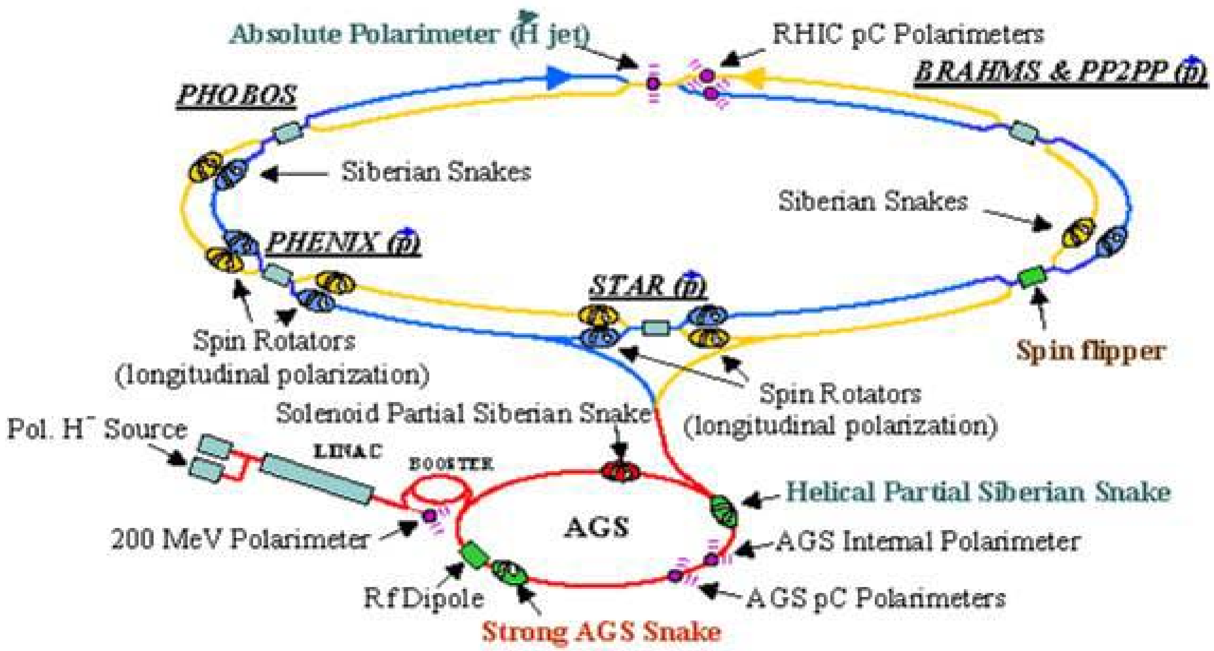




- d+Au @ RHIC shows "Cronin" p_T broadening as seen in lower $\sqrt{s}$ p+A
- Suppression in central Au+Au due to final-state effects -> 15x normal nuclear density

- back-to-back di-hadron correlations are very similar in p+p and d+Au
- but strongly suppressed in central Au+Au collisions at 200 GeV

RHIC pp accelerator complex



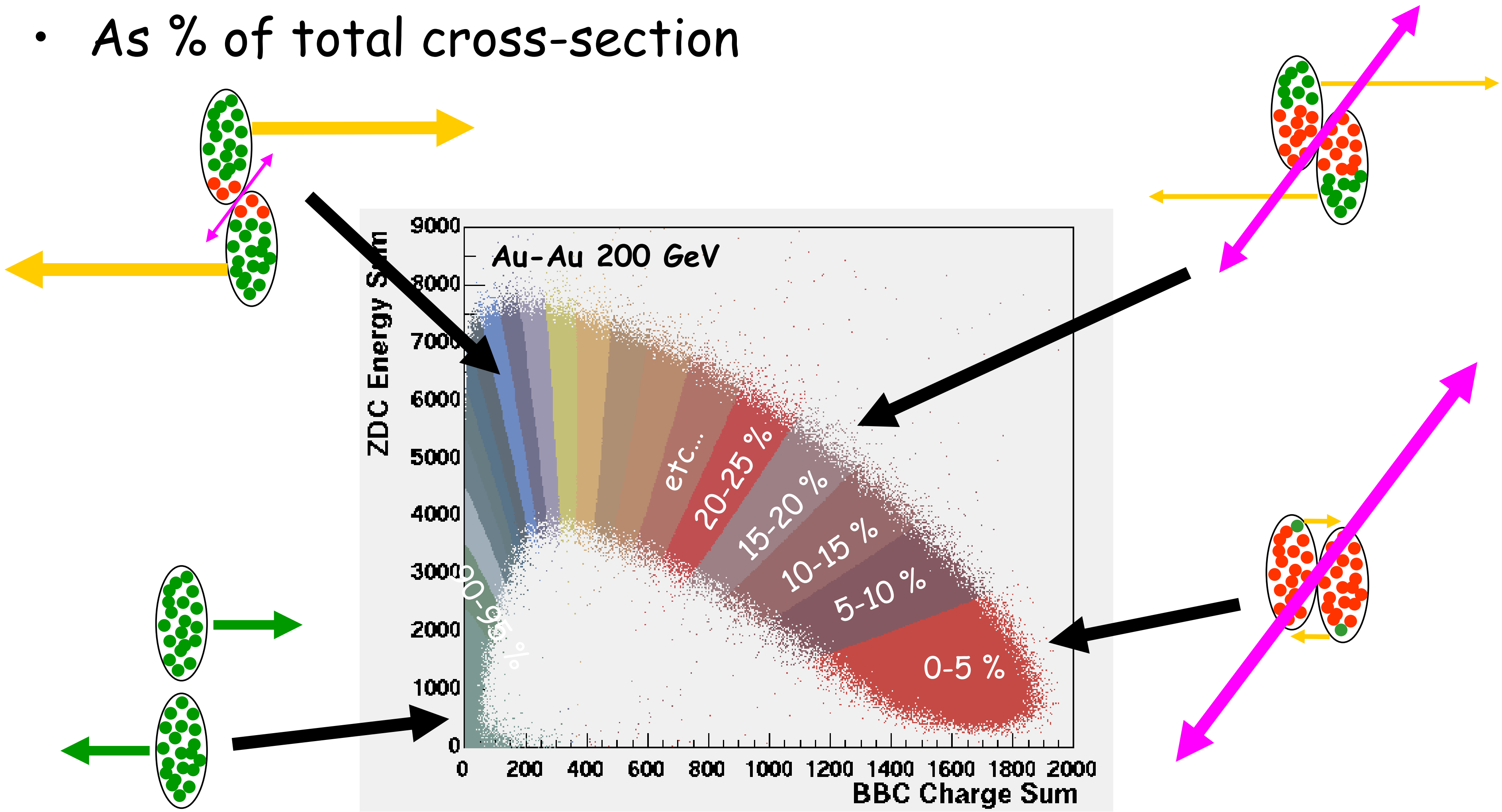
- Installed and commissioned during run 4
- Planned to be commissioned during run 5
- Planned to be installed and commissioned in run 5

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory collides all types of ions (Au+Au, d+Au, and Cu+Cu planned for run 5) at CM energies $20 \leq \sqrt{s_{NN}} \leq 200$ GeV and spin polarized (transverse or longitudinal) protons at CM energies up to $\sqrt{s}=500$ GeV

⇒ probe QCD states of matter and spin structure of proton

Collision centrality: Au-Au

- E_{ZDC} (spectators) / BBC (secondary particles) correlation
  - "zero degree calorimeter" + "beam-beam counter"
- As % of total cross-section

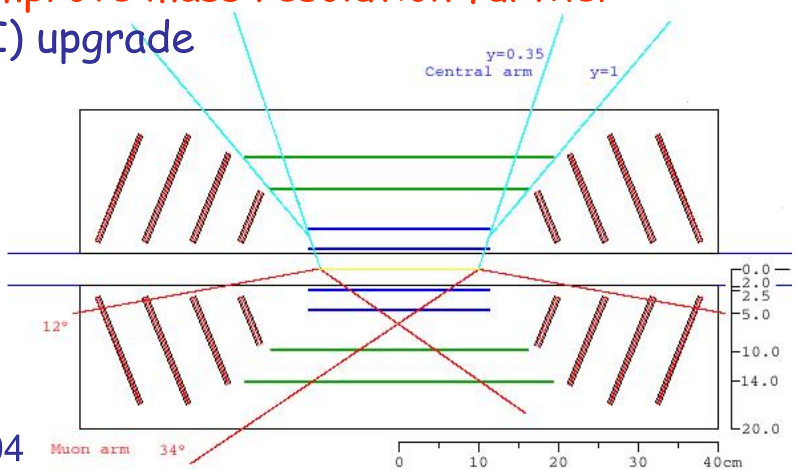


Some comments about the future at RHIC/PHENIX

- Present p-p in "Run5" is supposed to bring ~4.1 pb^{-1}
  - would give ~13k J/ψ, 400 ψ', 6 Υ (in 2 muon arms) & ~5k $J/\psi \rightarrow e^+e^-$
  - compared to ~0.2 pb^{-1} in Run3 with ~450 $J/\psi \rightarrow \mu^+\mu^-$
  - and ~0.2 pb^{-1} in Run4 with ~850 $J/\psi \rightarrow \mu^+\mu^-$ (?)
- A new higher luminosity d-Au run (by 2009?) needed
  - projected to give ~39 nb^{-1}
  - which would give ~50k $J/\psi \rightarrow \mu^+\mu^-$ & ~12k $J/\psi \rightarrow$ e+e-
  - compared to ~1.5 nb^{-1} in "Run3" which gave ~1.7k $J/\psi \rightarrow \mu^+\mu^-$ (~400 $J/\psi \rightarrow$ e+e-)
- Muon arm performance also is improved:
  - better efficiency with reduced beam backgrounds, by as much as a factor of two (see Run4 vrs Run3 pp above)
  - better mass resolution σ ~ 200 MeV $\rightarrow$ 150 MeV or better
- Silicon vertex upgrade to PHENIX will improve mass resolution further
- Υ is tough without a luminosity (RHIC-II) upgrade

Vector meson	Lepton pair	1.5 nb^{-1} Au-Au	30 nb^{-1} Au-Au RHIC-II
ψ'	ee	100	2k
	μμ	1.4k	28k
Υ	ee	8	155
	μμ	35	700

From Axel Drees CAARI 2004



Other Physics Goals for the Future

- Some future LANL physics focuses:
    - anomolous suppression or enhancement of J/Psi's in central Au-Au collisions?
    - angular distibutions for J/ψ to try to determine production mechanism
    - J/ψ and other signals vrs reaction plane, e.g. to better isolate final-state effects
    - ψ' as a cleaner physics window into shadowing and other nuclear effects (the ψ', unlike the J/ψ, has no feeddown from higher mass resonances)
    - open beauty from single muons at higher p_T
    - Υ production and its nuclear dependence
    - more exclusive studies of heavy-quark production using a silicon vertex upgrade
- Most of these require higher luminosity running for AA or dAu along with similar pp runs for comparison.
    - planning and physics justification for RHIC-II

Backup

Current PHENIX Run Request

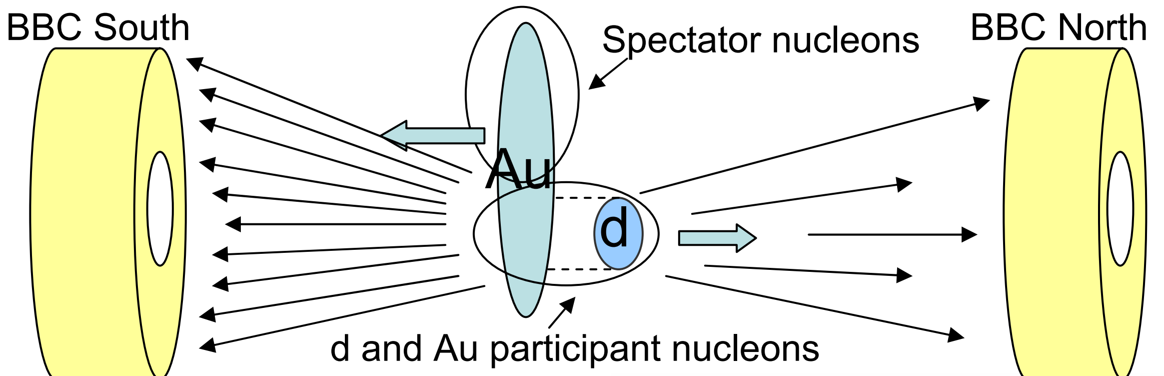
- An extensive program of luminosity and polarization development for p+p, with the goal of the earliest practicable measurement of DG
- Light-ion running, to investigate dependence on system size
- A reduced energy run, again with emphasis on obtaining highest possible integrated luminosity
- High integrated luminosities achieved via minimal variations in species and energies, as per CAD guidance

Table 2: The PHENIX Beam Use Proposal for 31 cryo weeks in Run-5, and 27 cryo weeks in latter years.

RUN	SPECIES	$\sqrt{s_{NN}}$ (GeV)	PHYSICS WEEKS	$\int \mathcal{L}dt$ (delivered)	p+p Equivalent
5	Cu+Cu	200	10	7.0 nb^{-1}	27.6 pb^{-1}
	p+p	200	11	13.1 pb^{-1}	13.1 pb^{-1}
6	Au+Au	62.4	9	111 μb^{-1}	4.3 pb^{-1}
	p+p	200	8	15.0 pb^{-1}	15.0 pb^{-1}
7	p+p	200	20	122 pb^{-1}	122 pb^{-1}
8	Au+Au	200	20	4140 μb^{-1}	161 pb^{-1}
9	p+p	500	20	359 pb^{-1}	359 pb^{-1}
10	d+Au	200	20	91.6 nb^{-1}	36 pb^{-1}

Centrality in d-Au

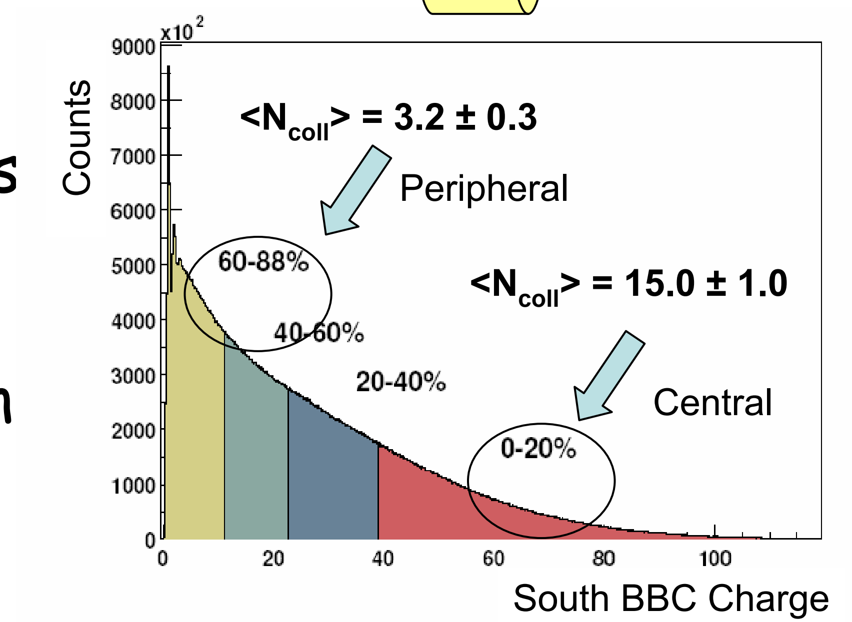
Au breaks up in our south beam counter



- Define 4 centrality classes
- Relate centrality to $\langle N_{coll} \rangle$

through Glauber computation

- $\langle N_{coll}^{MB} \rangle = 8.4 \pm 0.7$

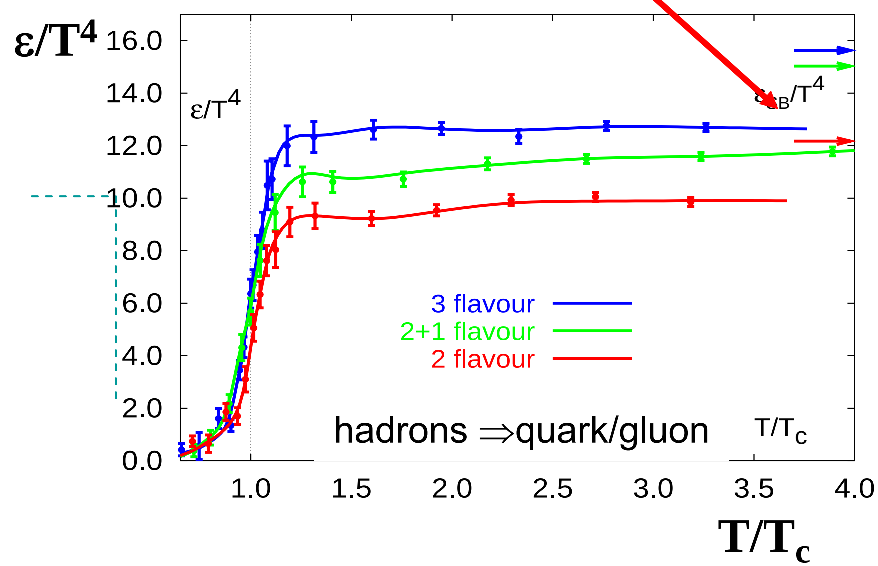


Quark Gluon Plasma

Lattice QCD predicts a phase transition to a Quark Gluon Plasma at high temperature where the number of degrees of freedom is significantly increased.

$$\varepsilon = g\frac{\pi^2}{30}T^4$$

Non-Interacting Gas Limit



Phase Transition:

T = 170 MeV ~ 10^{12} ^{0}F

ε = 0.8 GeV/fm^3

Assumes thermal system.

Expect a "weakly" interacting gas of quarks and gluons where the long range confining potential is screened.

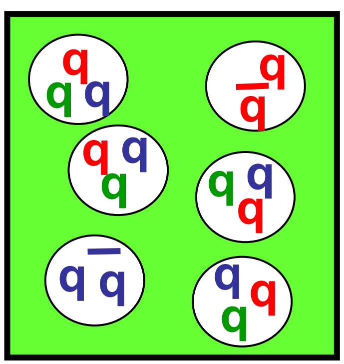
Deconfinement

QCD in Vacuum

- linear increase with distance from color charge
- strong attractive force
- **confinement of quarks** to hadrons baryons (qqq) and mesons (qq)

QCD in dense and hot matter

- screening of color charges
- potential vanishes for large distance scales
- restoration of approximate chiral symmetry
- **deconfinement of quarks and gluons !**



Lattice QCD calculation