# Highlight of d+Au and p+p results from RHIC


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- Cold Nuclear Matter Effects
- Gluon Polarization

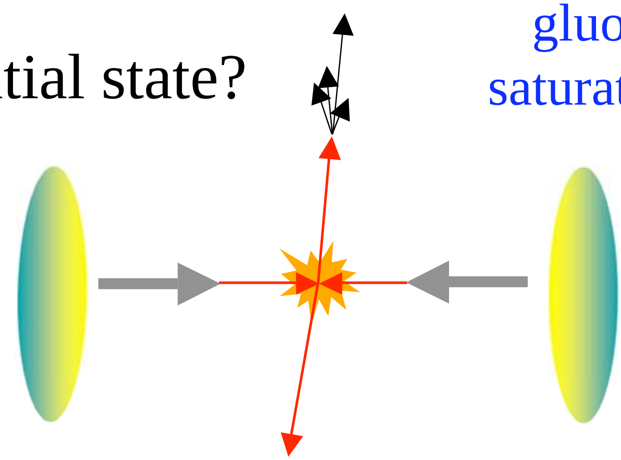
# Outline

- Physics with d+Au
  - Reference for A+A QGP Physics
  - Cold Nuclear Matter Effects
- Physics with polarized p+p
  - Spin Crisis and Gluon Polarization

# Particle Production in d+Au and Au+Au Collisions
## - Initial vs Final state effects

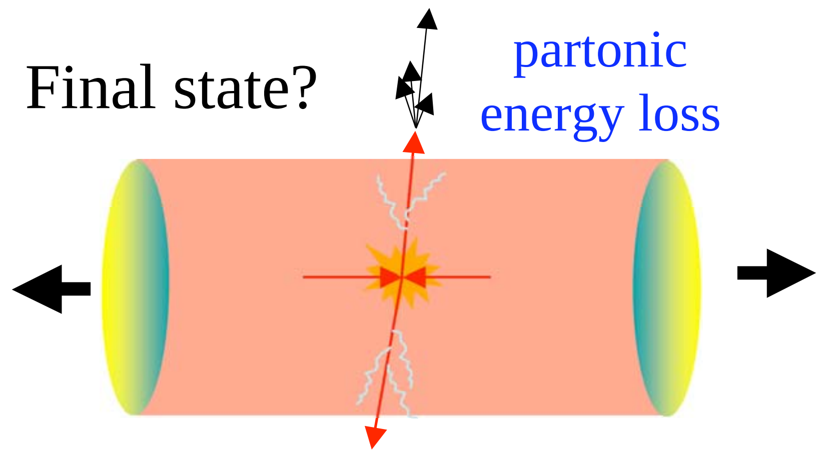
Initial state?

gluon saturation

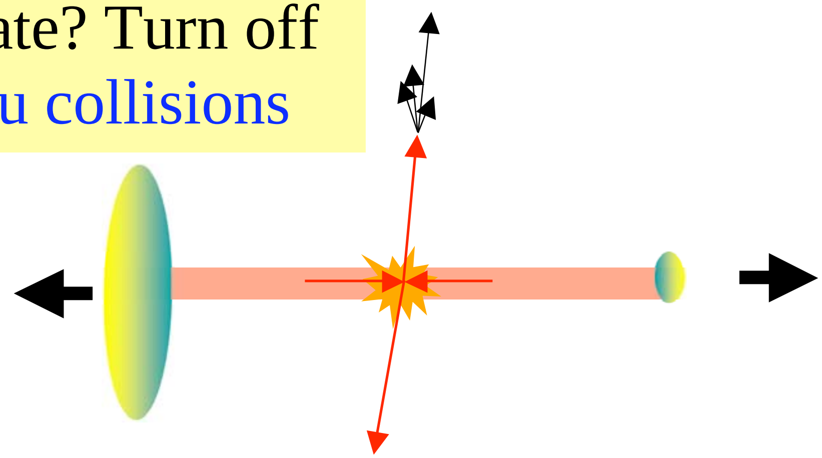


Final state?

partonic energy loss



How to discriminate? Turn off final state ⇒ d+Au collisions



# d+Au: QGP Physics and Beyond

Ref: PHENIX

Phys. Rev. Lett. 91, 072303 (2003).

- Striking difference of d+Au and Au+Au results in light hadron production in central rapidity y=0

  Strong evidence of formation of dense medium in AuAu collisions

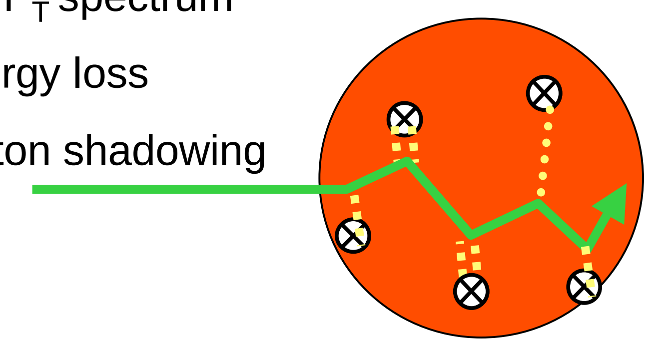
- How about cold nuclear medium effects on particle production?
  - explore other kinematics regions

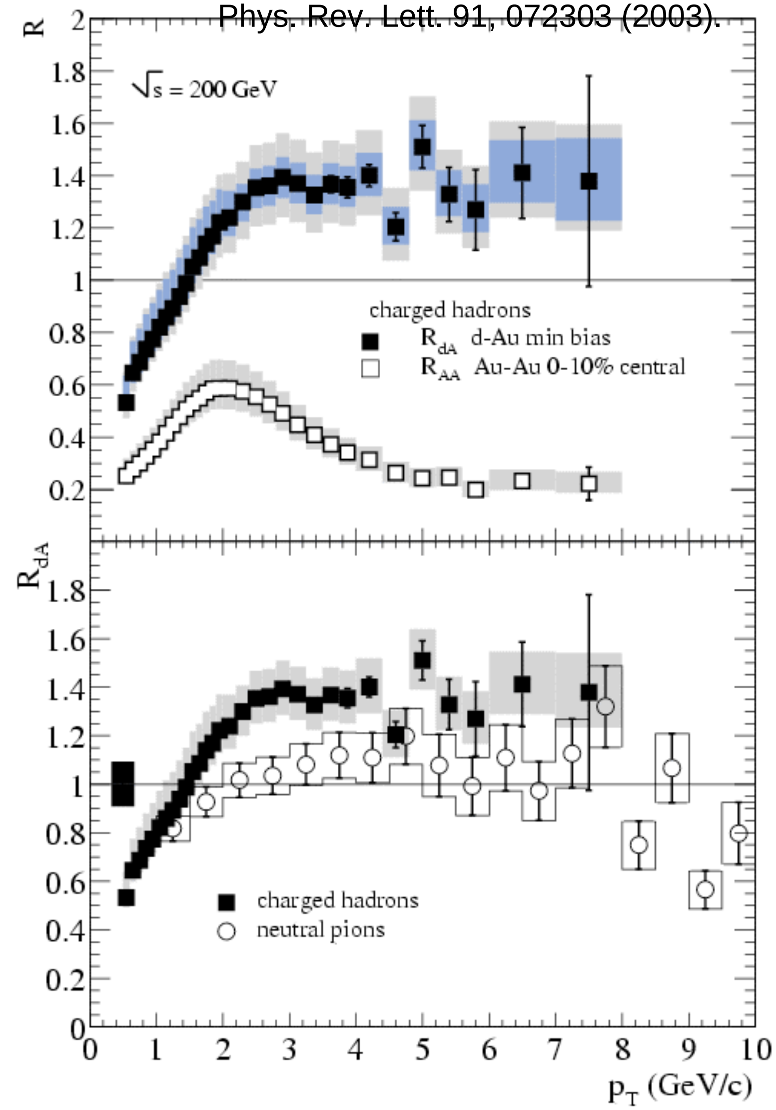
Cold Nuclear Effect:

•Multiple collisions broaden high $P_T$ spectrum

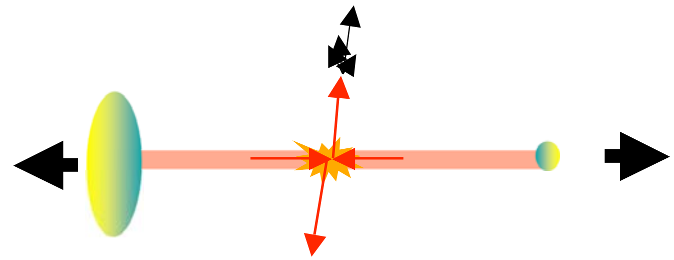
•Energy loss

•Parton shadowing



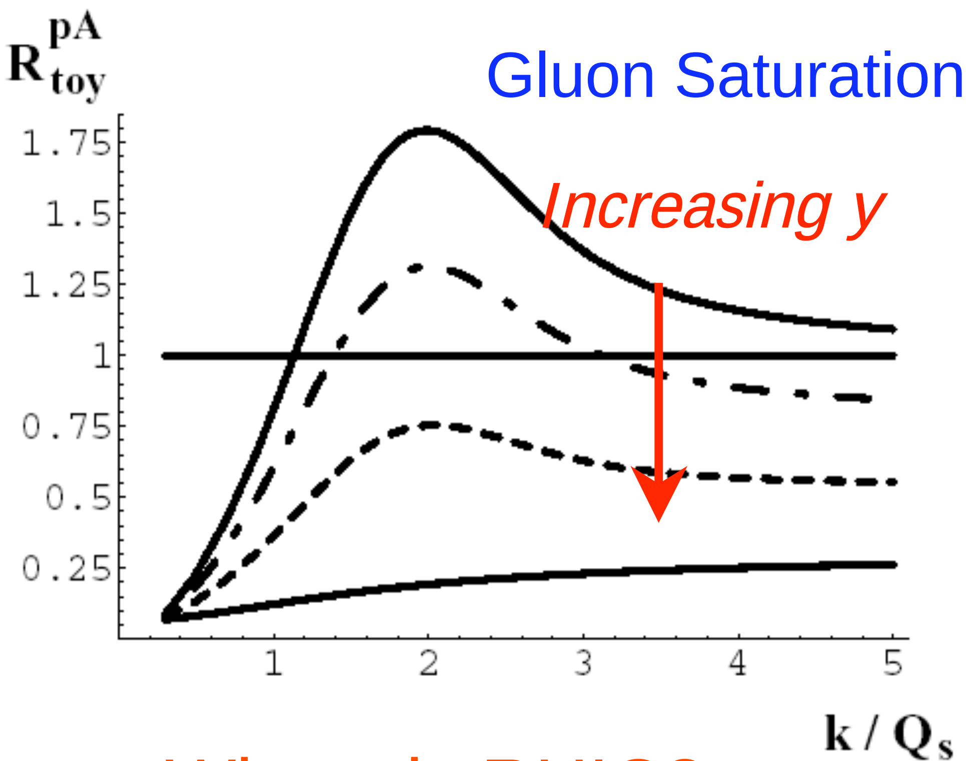


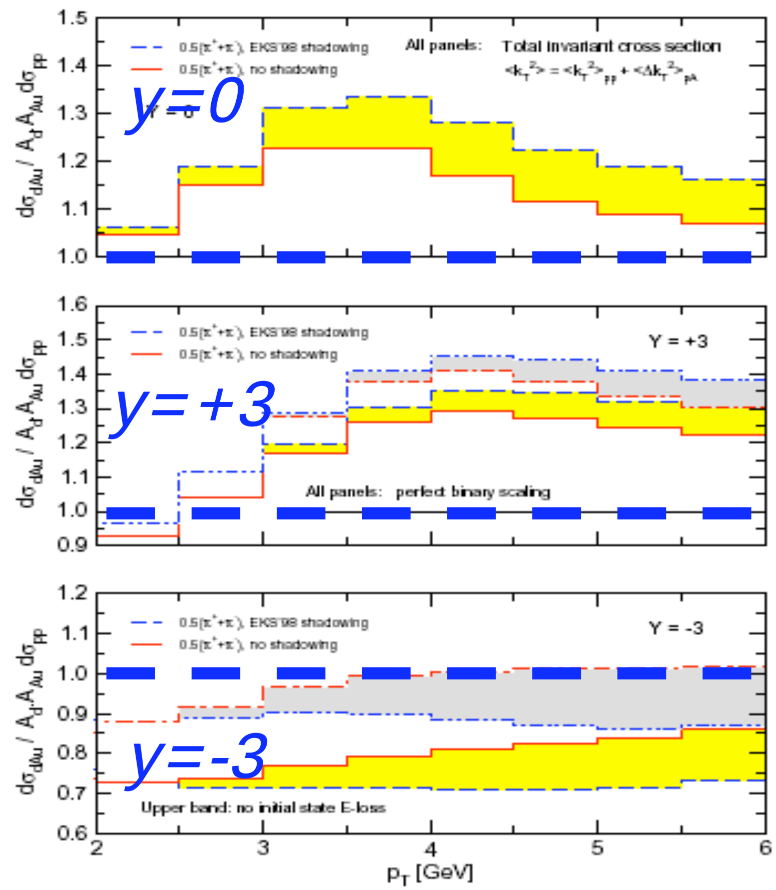
# Model Predictions



I. Vitev nucl-th/0302002

D. Kharzeev hep-ph/0307037



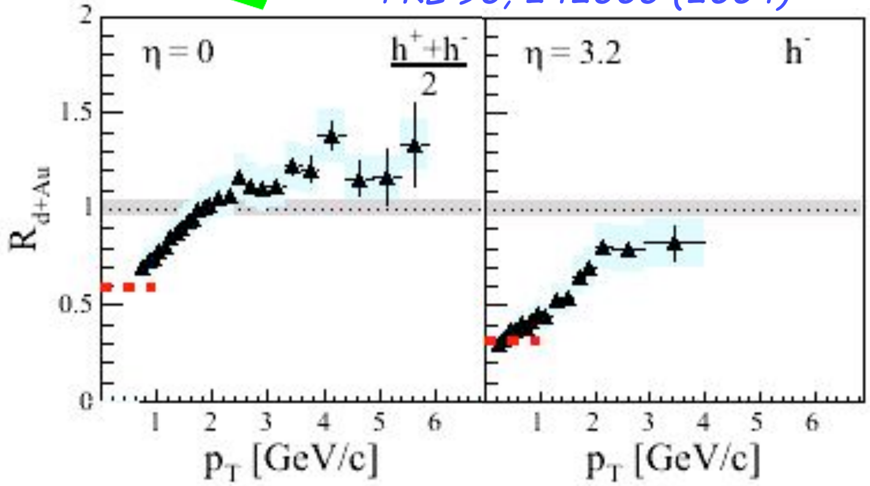



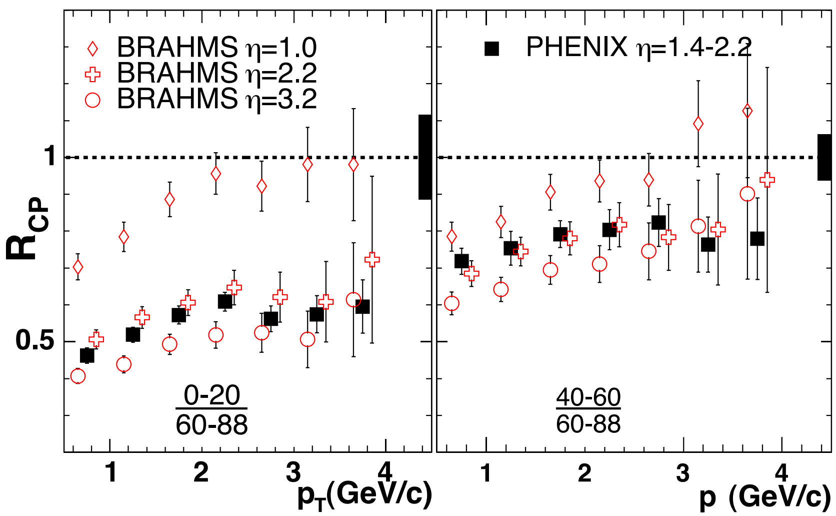

Where is RHIC?

Parton Gas Model

# Forward Hadrons

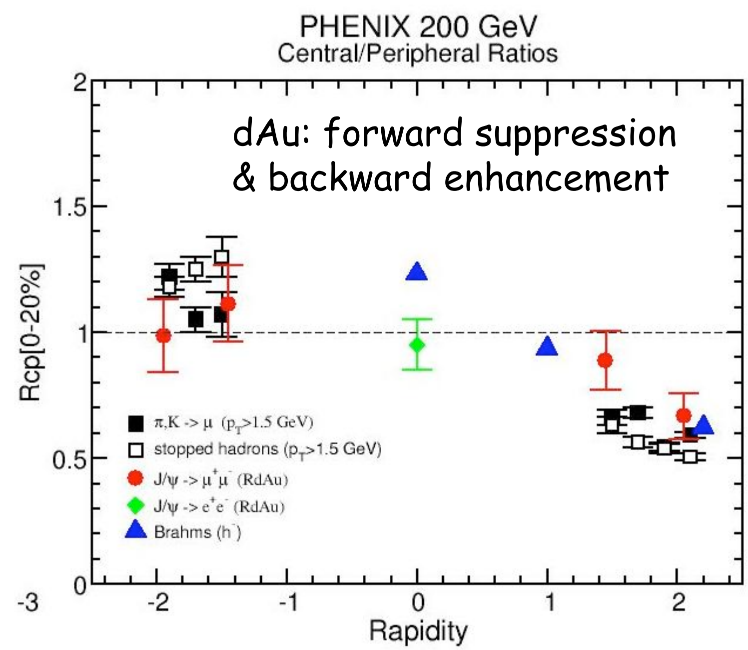
BRAHMS *PRL 93, 242303 (2004)*



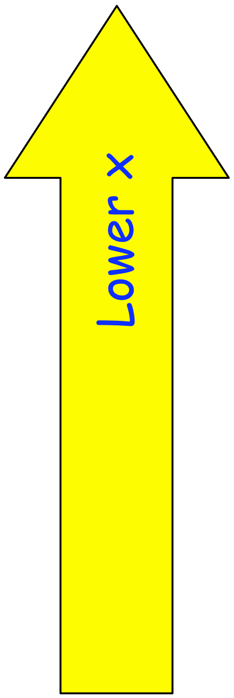



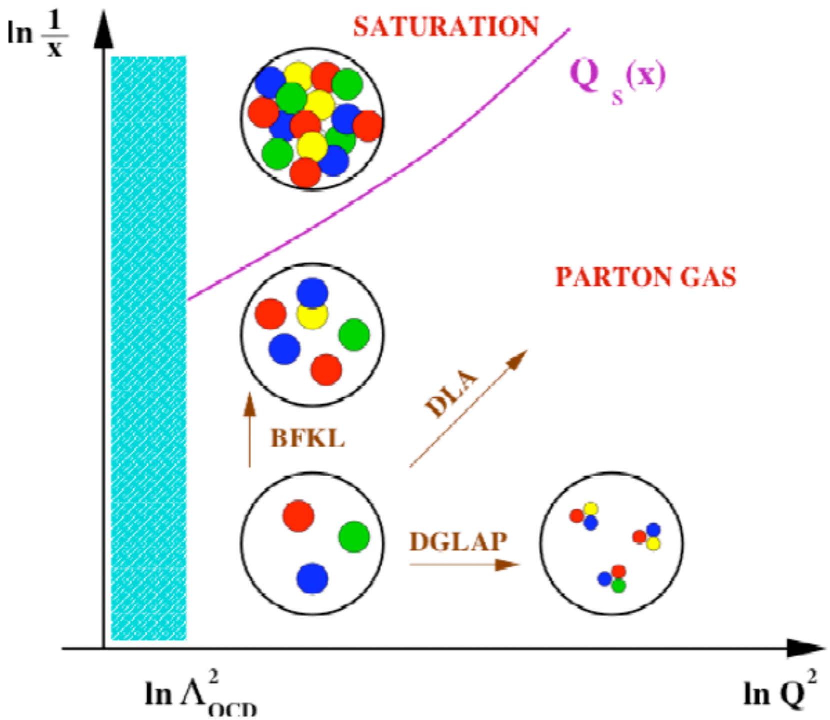

Charged particles are suppressed in the forward direction in d+Au collisions !

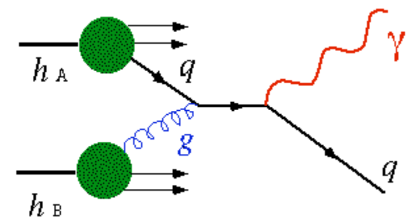
PRL 94, 082302 (2005)
& nucl-ex/0507032



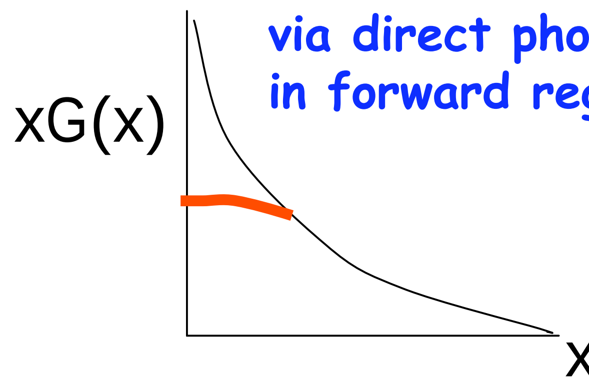
# Color Glass Condensate?




measure gluon saturation via direct photons in forward region




More saturation at Lower x

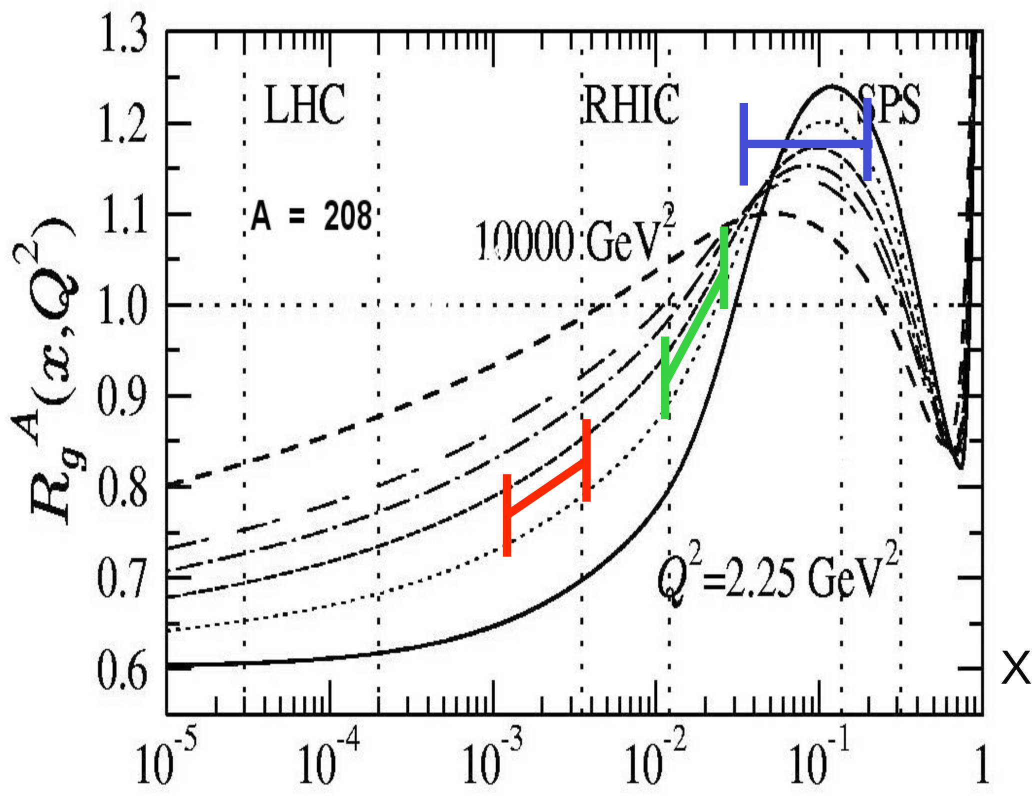
y~log(1/x)

Lower x → forward rapidity

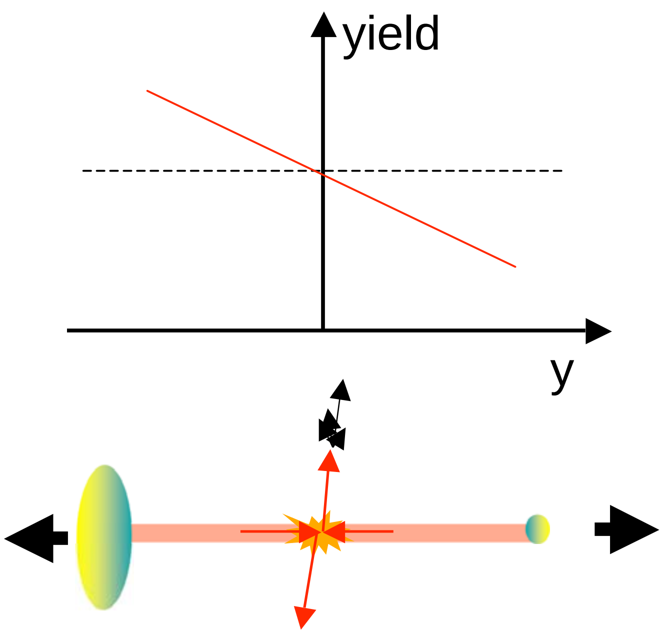
The Color Glass Condensate: The Initial Condition for Heavy Ion Collisions?

# Gluon Shadowing in Heavy Nucleus

From Eskola, Kolhinen, Vogt
Nucl. Phys. A696 (2001) 729-746.




**Universal**

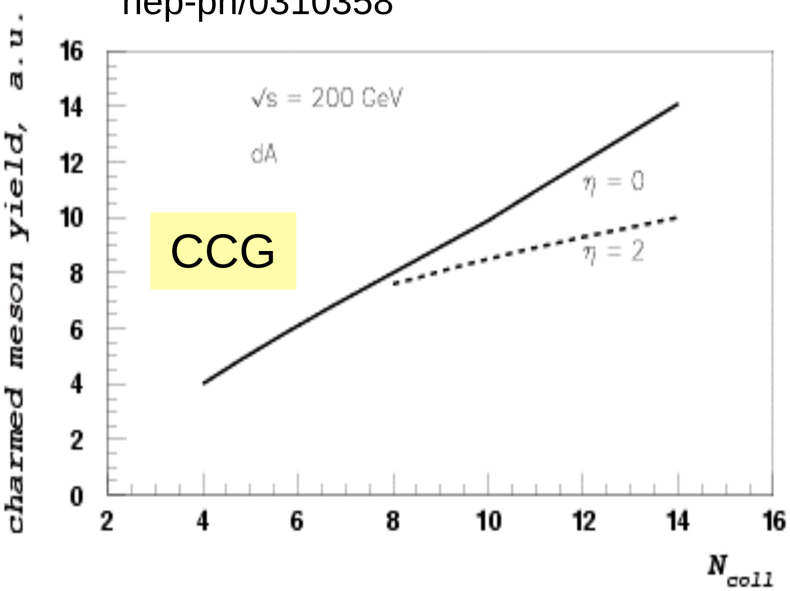



$$d\sigma^{p+p\rightarrow Q\overline{Q}} \propto \underline{F(x_1)\otimes F(x_2)}\otimes d\hat{\sigma}^{x_1+x_2\rightarrow Q\overline{Q}}\otimes D(z)$$

# Shadowing: Color Glass or Dynamic Multiple Scattering Power Correction?

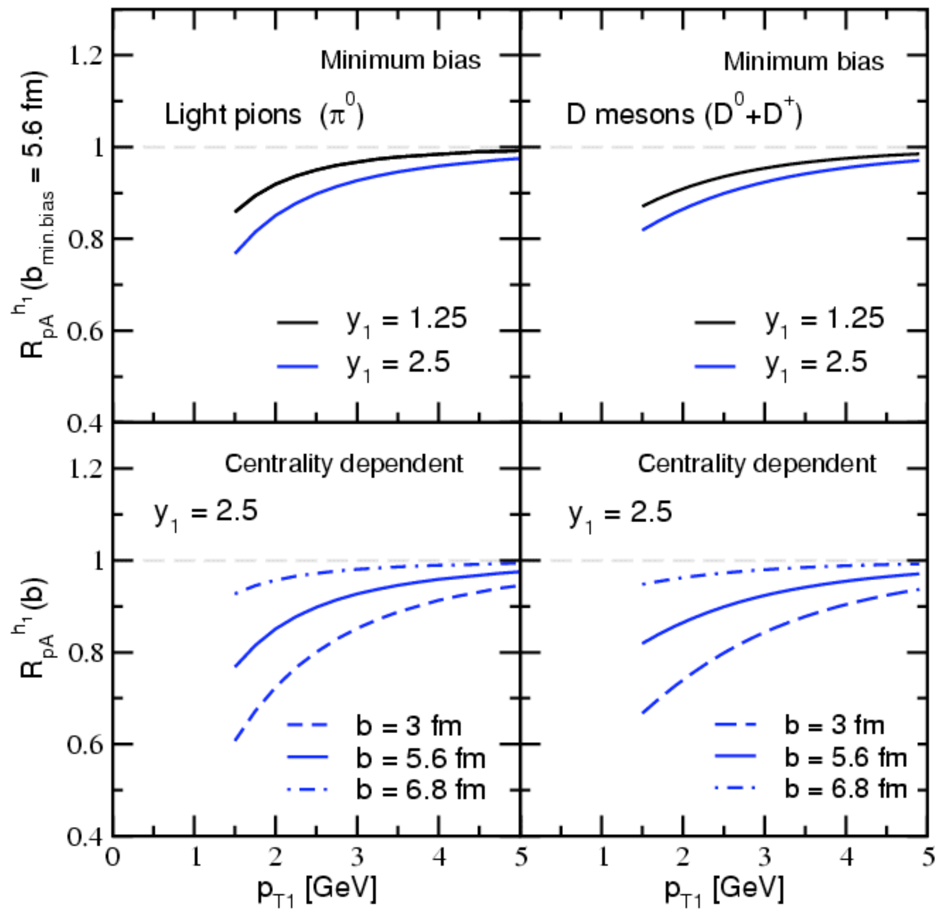
- A challenge!
  - Explore (x, Q) space
    - pT (Q^2) evolution
  - Collision energy scan
  - Different probes: light vs heavy!

D. Kharzeev & K. Tuchin
hep-ph/0310358



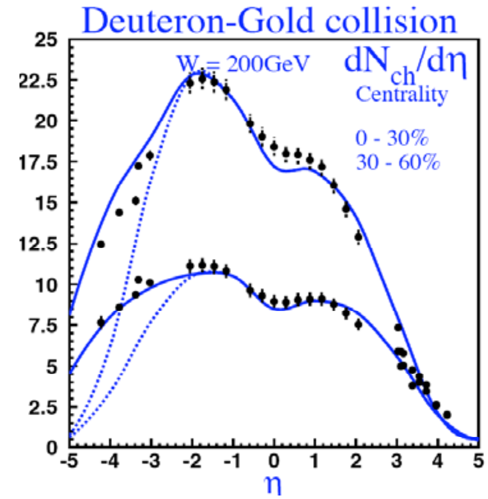

Power correction only

J. Qiu & I. Vitev



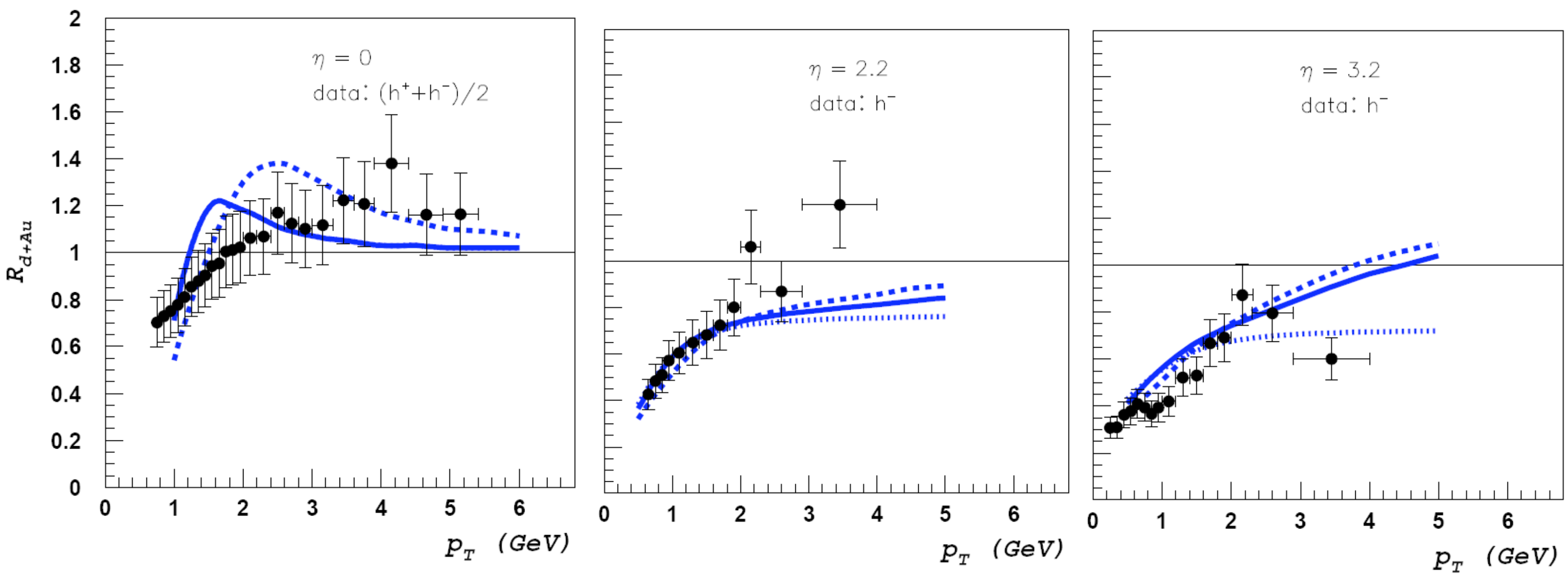
# Color Glass Condensate model

Reproduces charged particle multiplicity asymmetry in dAu




Kharzeev, Kovchegov, Tuchin, hep-ph/0405045

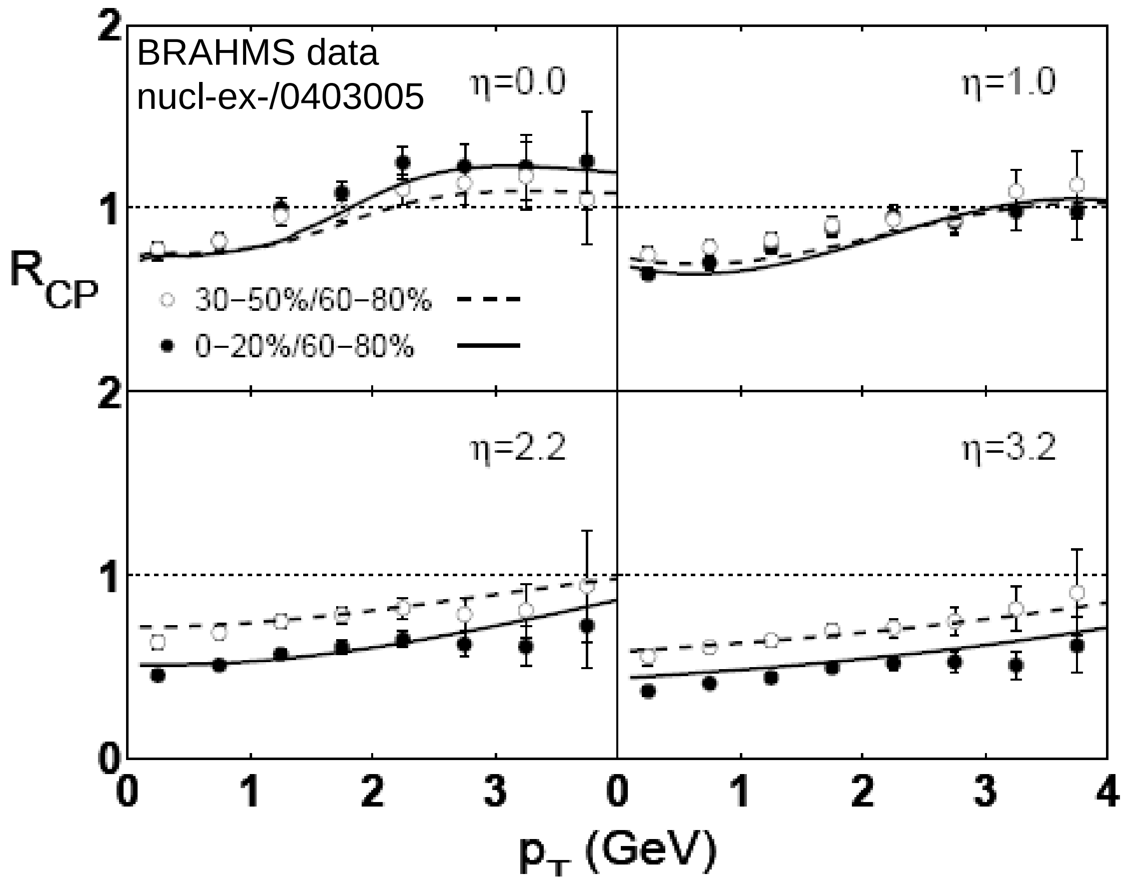
and Brahms hadron forward suppression pattern



# Parton Recombination & forward suppression

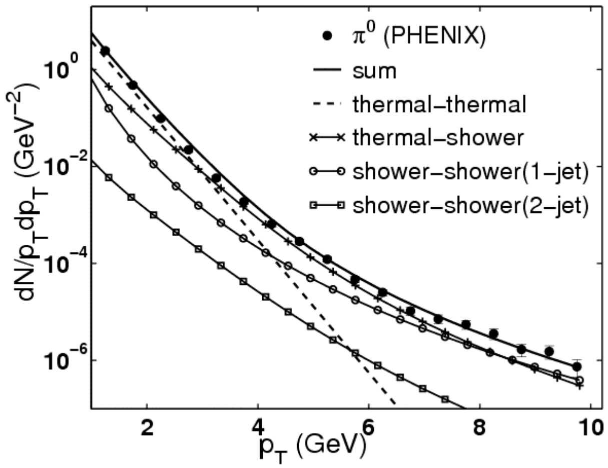
Hwa, Yang, Fries, PRC 71, 024902 (2005)

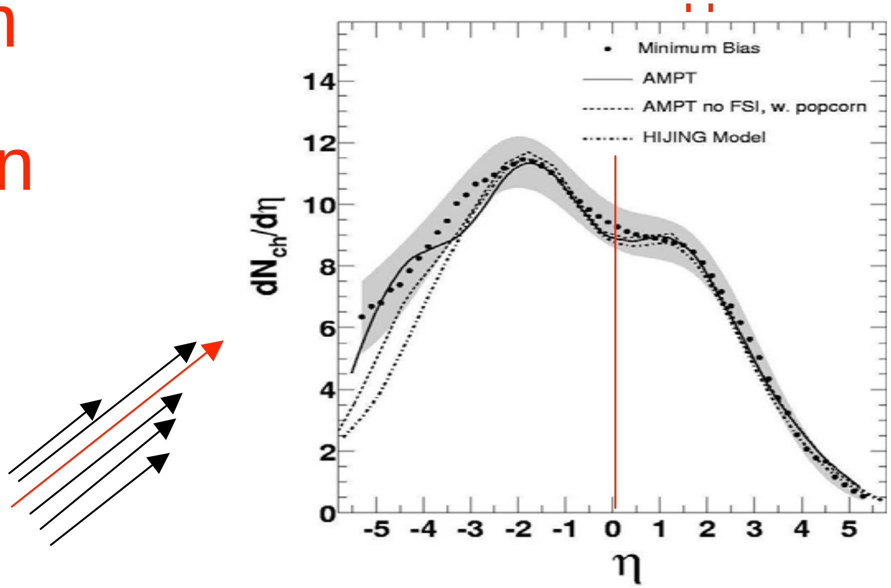
Suppression at forward rapidity due to fewer soft (thermal) partons on deuteron side that are available for recombination processes with semi-hard (shower) partons



# Recombination

- "Explains" light hadron yields in forward and backward rapidities
  - Input: low pT forward /backward hadron distributions
- Measurement of charm yields could provide additional constrains on these models

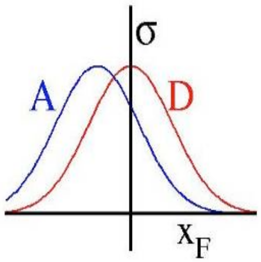


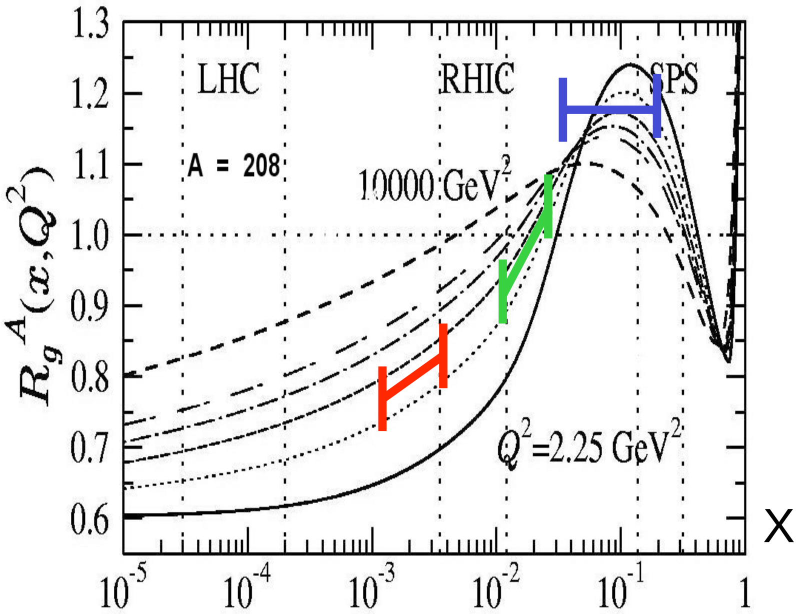



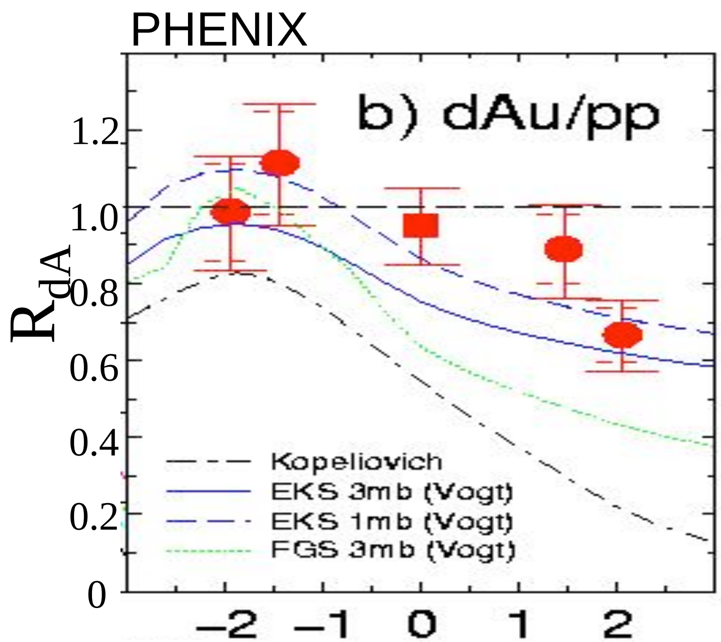
# Heavy Quarks: J/Psi

- **_NO_ Recombination!**
- Gluon shadowing/saturation
- Initial state parton energy loss
- Final state absorption -> need to check with open charm

**Energy loss** of incident gluon shifts effective $x_F$ and produces nuclear suppression which increases with $x_F$



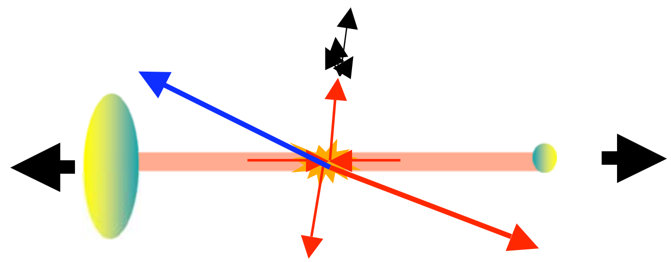



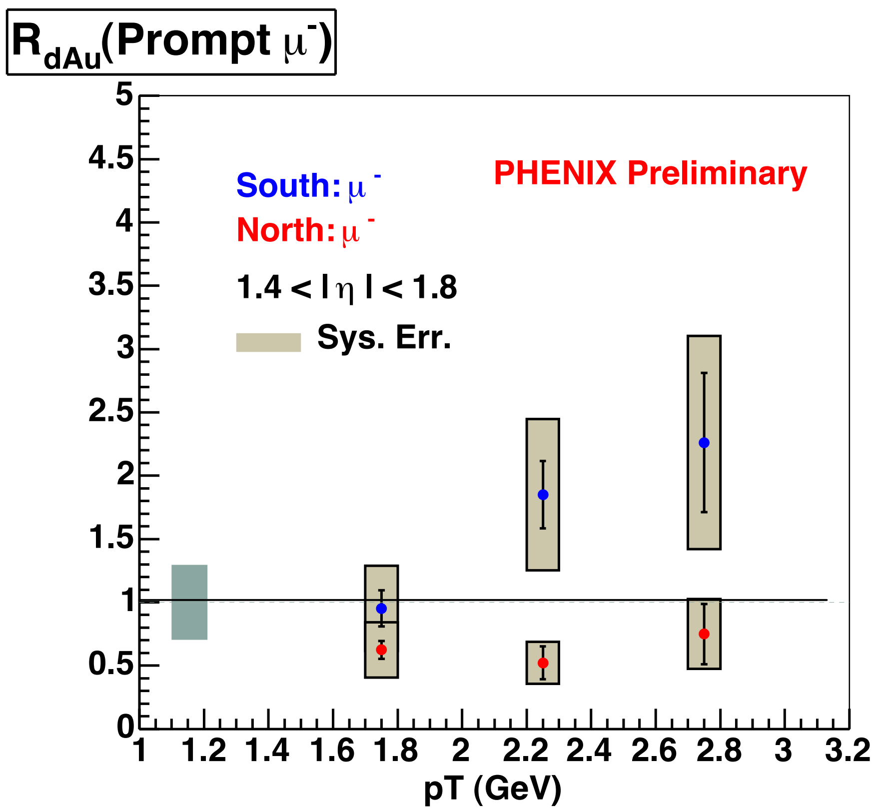



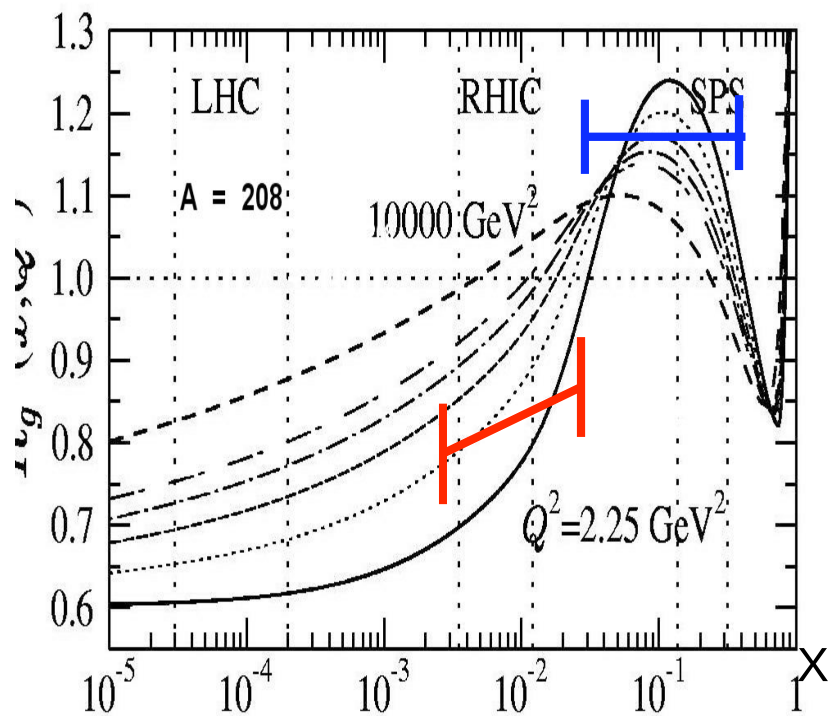
# Heavy Quarks: Open Charm

$$R_{dAu} \propto \frac{G_{Au}(x,Q^2)}{G_p(x,Q^2)}$$

or: Initial parton energy loss

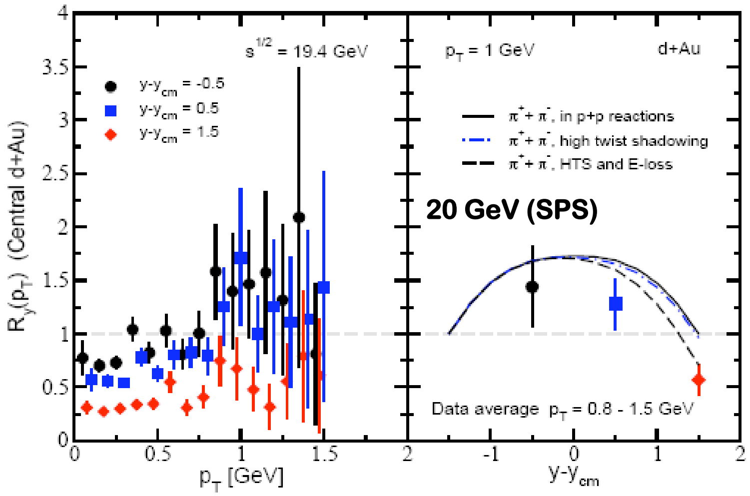




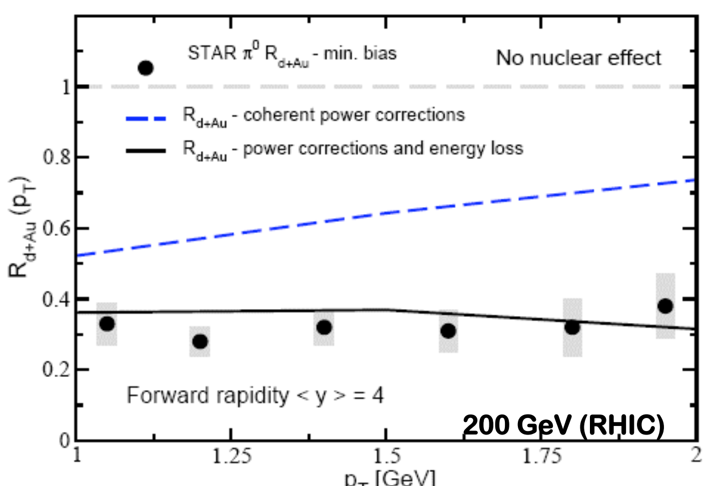



# Cold Nuclear Matter Energy Loss

## b) Initial state inelastic scattering




**T.Alber et al., E.Phys.J.C 2 (1998)**




**S.S.Adler et al., nucl-ex/0603017**

**I.V., T.Goldman, M.B.Johnson, J.W.Qiu, hep-ph/0605200**

**B.Kopeliovich, et al., Phys.Rev.C72 (2005)**

- **Shadowing parameterizations: (not)**

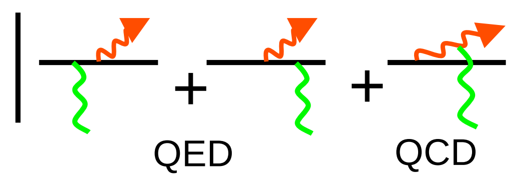
$$S_{LT} = S_{LT}(x, Q^2)$$

- **Dynamical calculations of high twist shadowing: (not)**

$$S_{HT} = S_{HT}(q(g); \hat{t}(z_1, (z_2)))$$

- **Energy loss: in combination with HTS (yes)**

### Initial state E-loss




$$\left| \ldots + \ldots + \ldots \right|^2 \sim |B|^2$$

**J.Gunion and G.Bertsch, Phys.Rev.D25 (1982)**

$$\frac{dN_g^{(BG)}}{dy d^2k_\perp} \propto \frac{\alpha_s}{\pi^2} \frac{q_\perp^{\,2}}{k_\perp^2 (k_\perp - q_\perp)^2} \qquad \phi(x, Q^2) \to \phi\left(\frac{x}{1-\varepsilon}, Q^2\right)$$

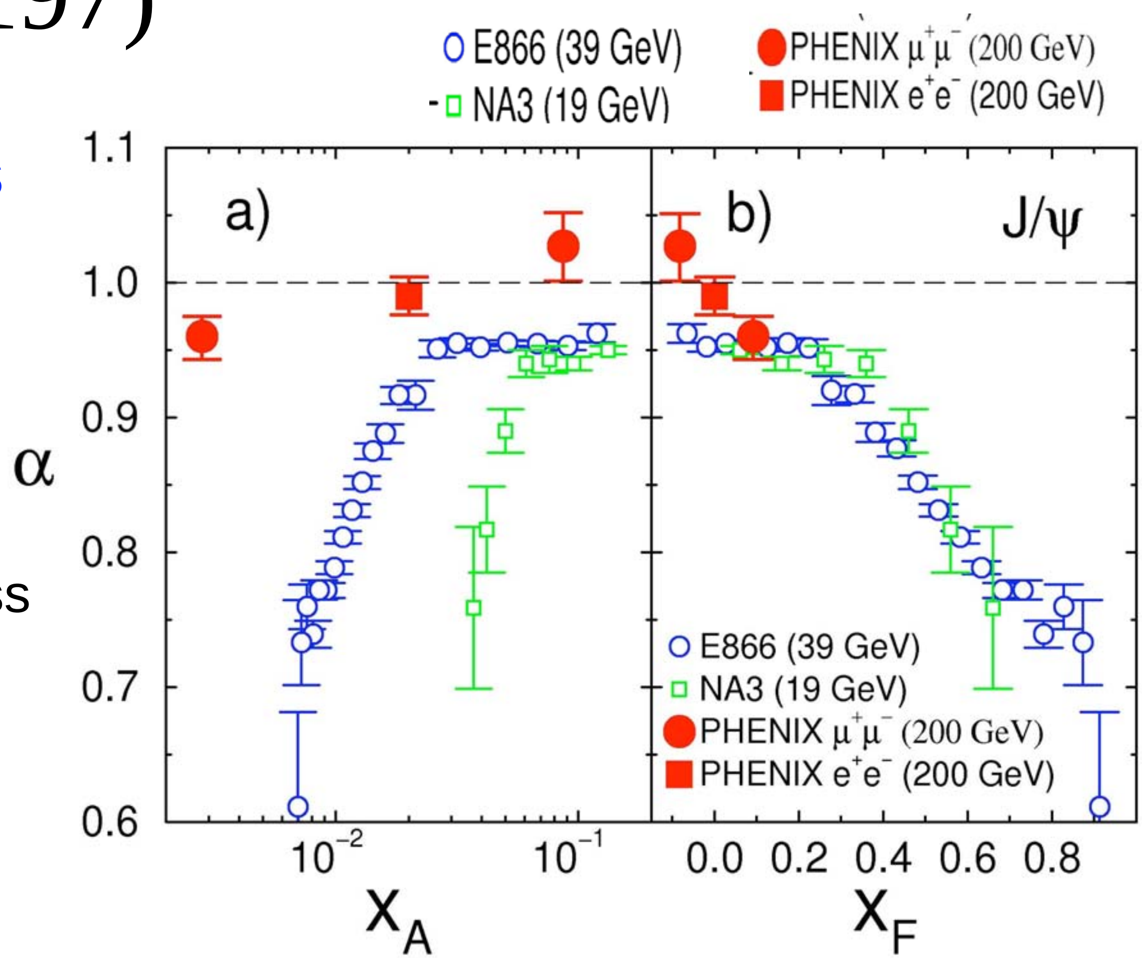
$$\varepsilon = \Delta E / E = kA^{1/3}, \quad k_{\text{min bias}} = 0.0175$$

**To investigate:** $k = k(\mu, \lambda_{jet}, E, m)$

# Shadowing or Energy Loss ?

$$\sigma_{dA} = \sigma_{pp}(2\times 197)^{\alpha}$$

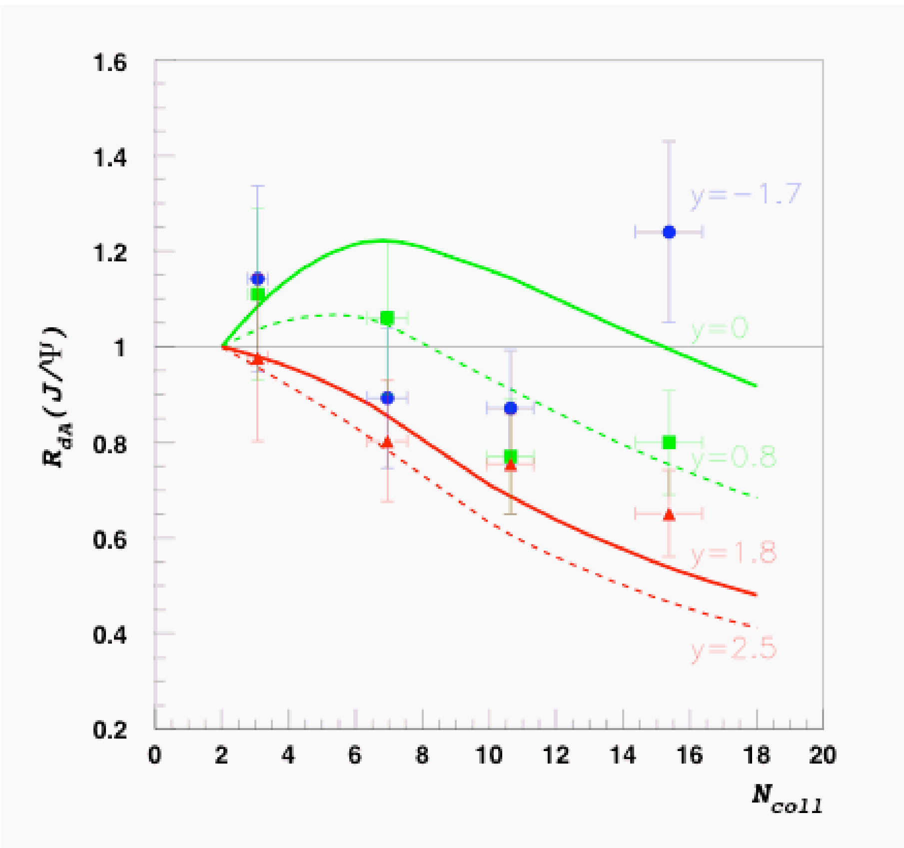
- Shadowing alone is not enough
- Initial state energy loss?
  - Incoming gluons loss a fraction of energy before the hard collisions
  - $X_1(\sim X_F)$ scaling

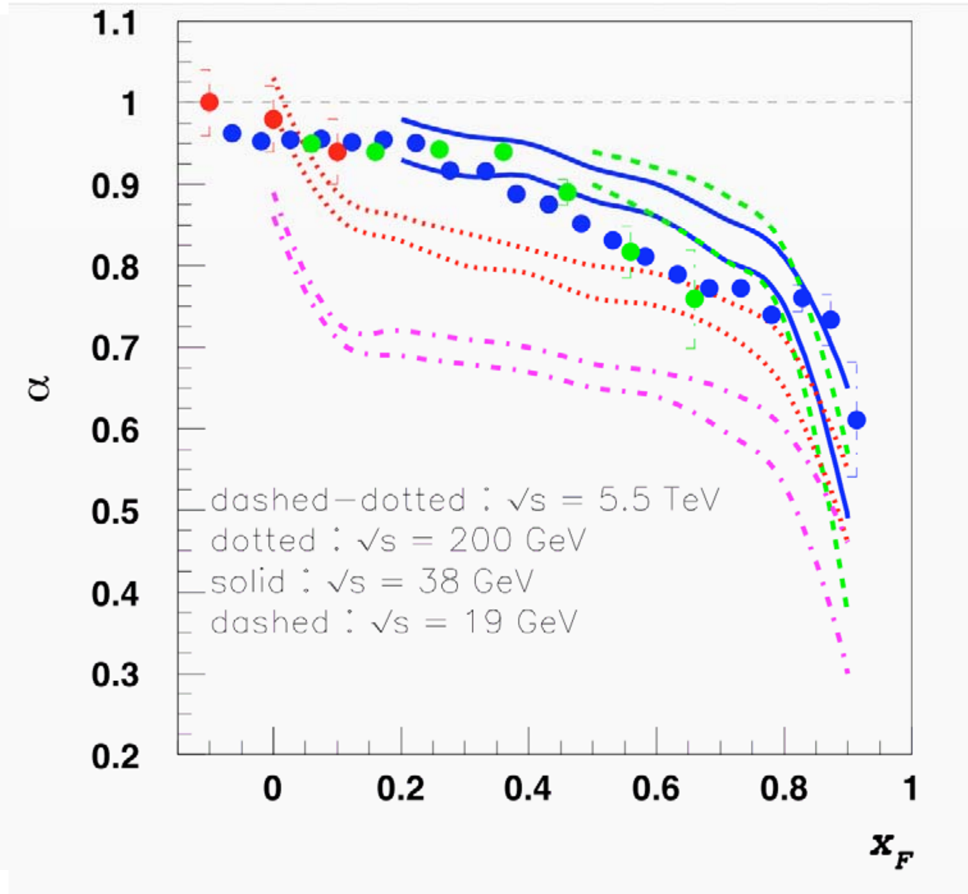


# Signature of CGC ?

## J/Psi in dAu @RHIC

Kharzeev & Tuchin hep-ph/0510358

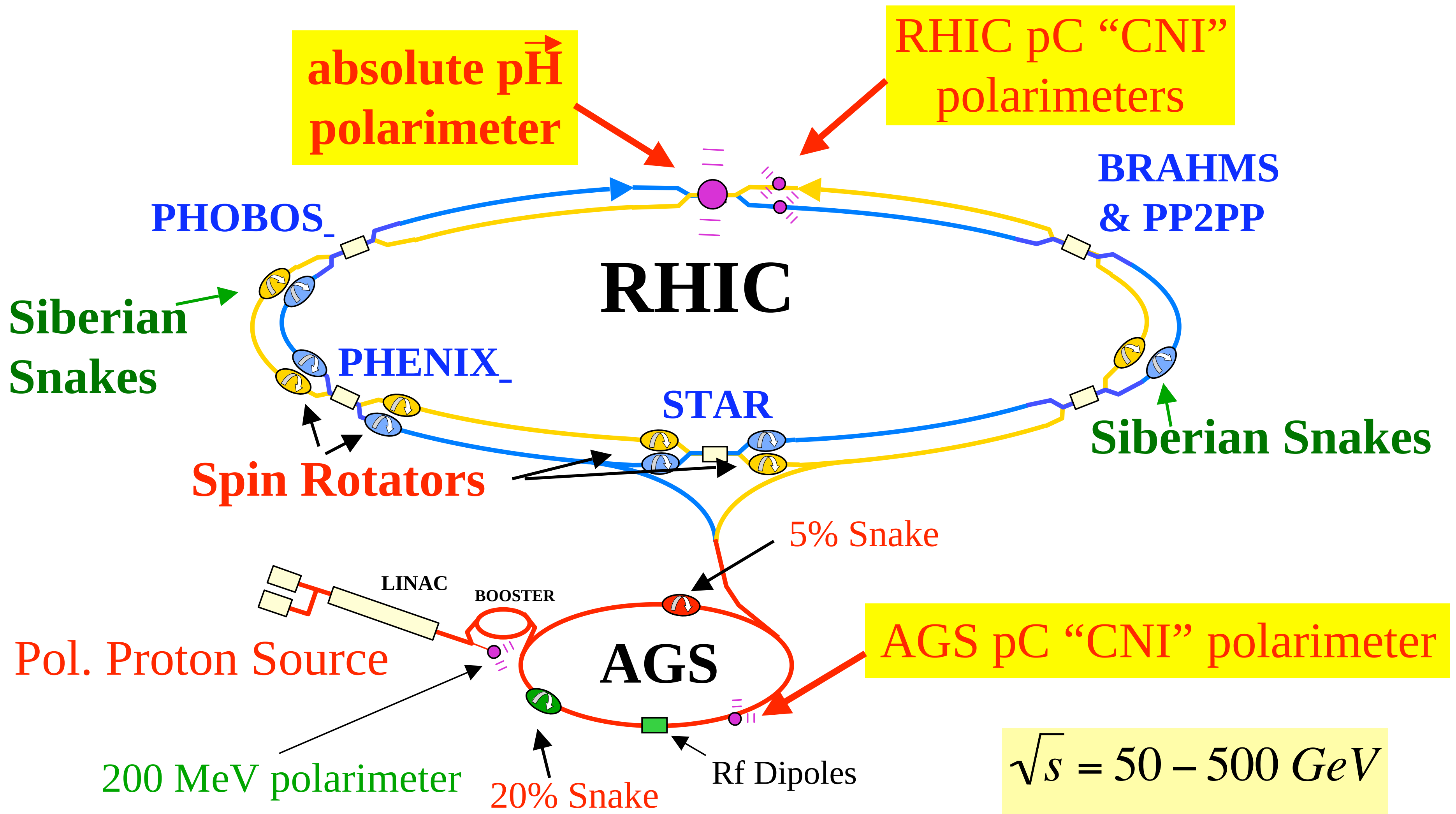


# Summary: d+Au

- Physics at Forward and Backward Rapidity:
  - Light hadrons
  - open charm, J/psi
- Observed: heavy ~ ligh hadrons
  - suppression in the forward
  - enhancement in the backward
- Causes for such effects are not very clear
  - Shadowing: CGC, Power correction
  - Initial state energy loss
  - Need more theoretical work and better data
- Future:
  - Lower energy dAu collisions: stay away from shadowing regions
  - Explore { x, Q, sqrt(s) } space -> (y, pT, sqrt(s)) experimentally
    - Parton energy loss vs shadowing
    - pT evolution – shadowing vs power correction
    - Shadowing vs recombination
  - Explore QCD dynamics in more details in coming years!

# RHIC *pp* Accelerator Complex




$$\sqrt{s} = 50 - 500\ GeV$$

$$Pol. = 70\%$$

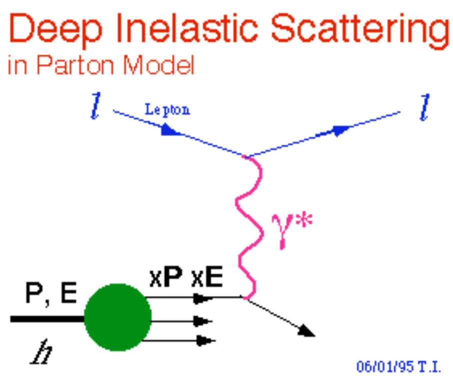
# RHIC-Spin Physics

## New Frontier of Nucleon Structure Research

- Proton Spin - **a major puzzle from polarized DIS experiments**
  - Proton Spin Decomposition

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

$$\mathit{Experimentally} \Longrightarrow \boxed{\Delta\Sigma = 0.31 \pm 0.04}$$



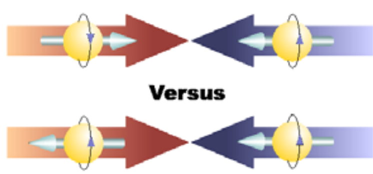

- Origin of Proton Spin:
  - ***gluon**, **sea quarks**, orbital angular momentum ?*
  - **DIS can't directly probe gluons and anti-quarks @LO**

- a new tool : RHIC-SPIN
  - **a polarized proton collider**
  - **quark-gluon, quark-quark and gluon-gluon interactions**
  - **directly explore gluon and sea quark distributions**

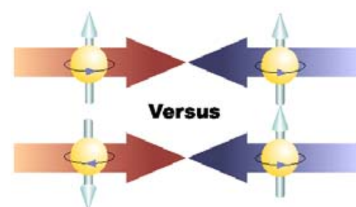
# Experimental Observables

- Asymmetries
  - PHENIX and STAR: all
  - BRAHMS: transverse beams only

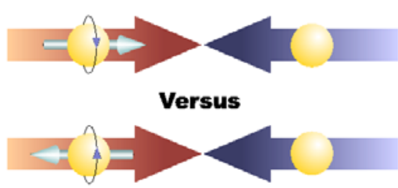
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



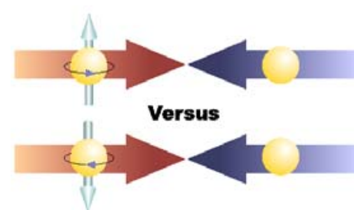

$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$




$$A_{L} = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$




$$A_{T} = \frac{\sigma(\uparrow)-\sigma(\downarrow)}{\sigma(\uparrow)+\sigma(\downarrow)}$$

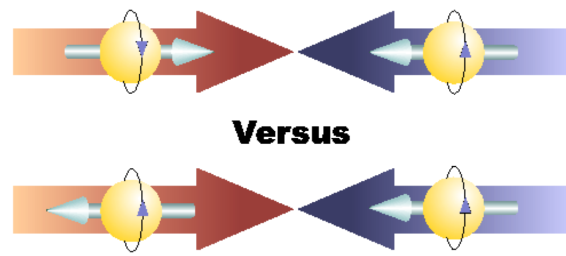


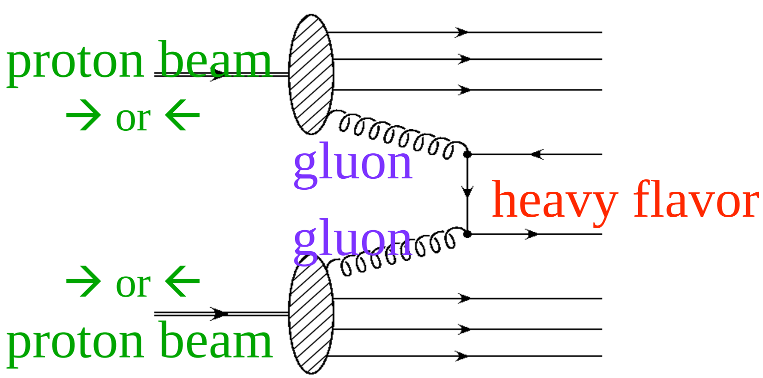
# ΔG @RHIC-SPIN

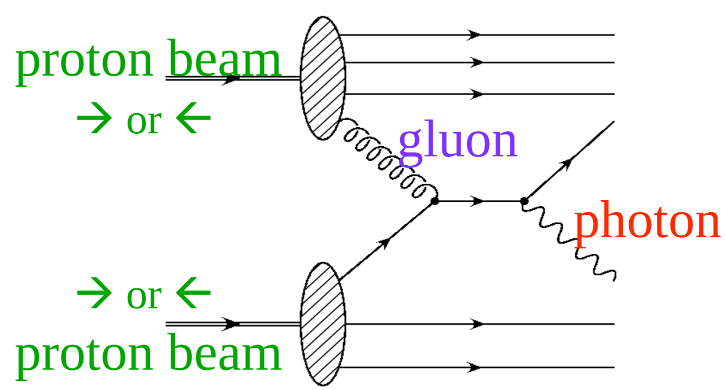
- Polarized hadron collisions
  - double longitudinal spin asymmetry

$$\boxed{A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} - \sigma^{+-}} \propto \Delta f_A^a(x_a, Q^2) \otimes \Delta f_B^b(x_b, Q^2) \otimes \frac{d\Delta\sigma_{ab}^{cd}}{dt}}$$

  - leading-order gluon interactions
    - heavy-flavor production
    - direct-photon production
    - Other channels (light hadrons etc.)



# Heavy Quark Production @RHIC

- Sensitive to gluon polarization: $\Delta G(x)$
- Gluon Fusion dominates at LO

PYTHIA estimate:

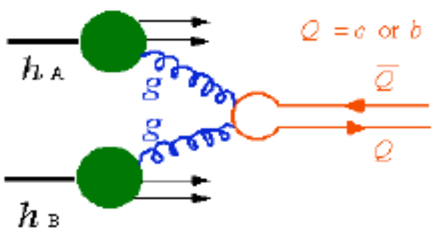
$$\sigma(gg \to Q\overline{Q}) : \sigma(q\overline{q} \to Q\overline{Q})$$

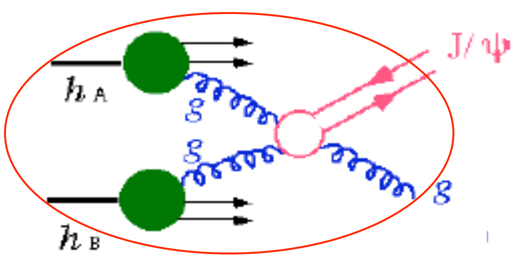
| GeV | Charm | Beauty |
|---|---|---|
| 200 | 95:5 | 85:15 |
| 500 | 97:3 | 92:8 |

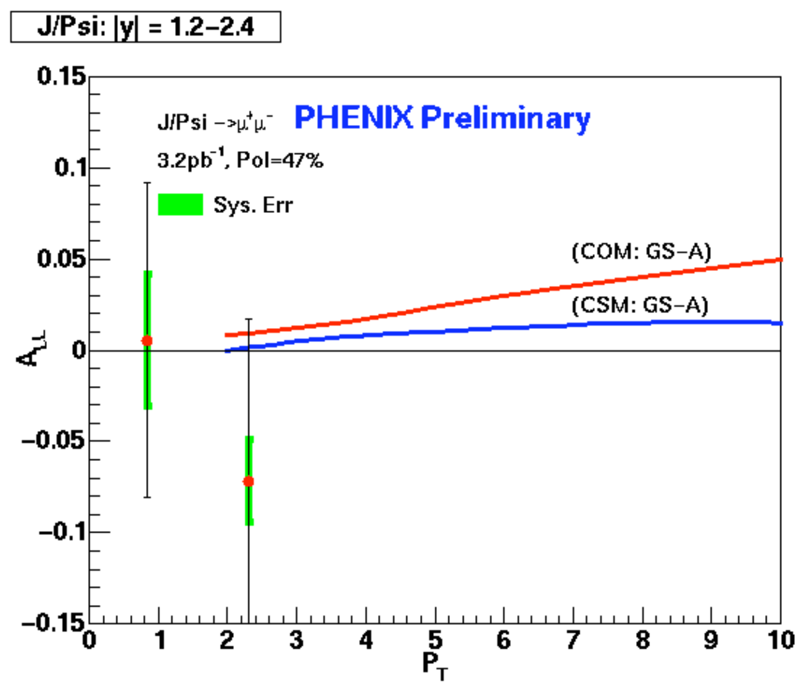
## Double spin asymmetry:

$$A_{LL} \approx \frac{\Delta G(x_1)}{G(x_1)} \frac{\Delta G(x_2)}{G(x_2)} a_{LL}^{gg \to Q\overline{Q}}$$

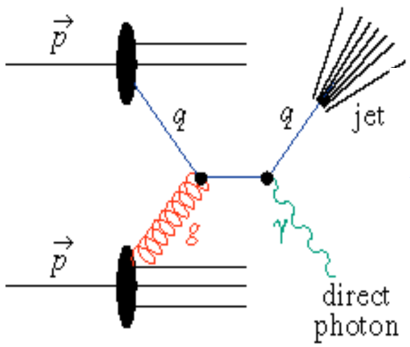
Gluon Fusion



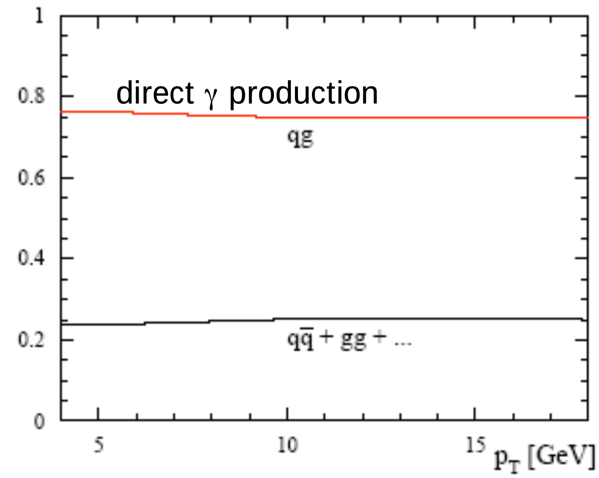



# Prompt Photon Production




Quark-Gluon Compton scattering dominates (~75%) direct $\gamma$ production




The cross section asymmetry $A_{LL}$ for $\vec{p} + \vec{p} \rightarrow \gamma + \text{jet} + X$ (at Leading Order):

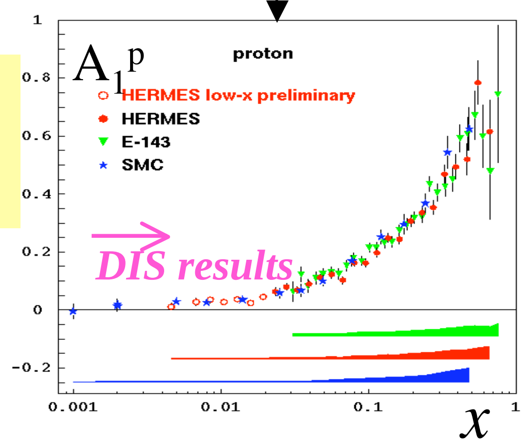
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \approx \boxed{\frac{\Delta g(x_g)}{g\,(x_g)}} \times \underbrace{\frac{\sum e_i^2 \Delta q_i(x_q)}{\sum e_i^2 q_i(x_q)}}_{=A_1^p} \times \underbrace{\hat{a}_{LL}(gq \rightarrow q\gamma)}$$

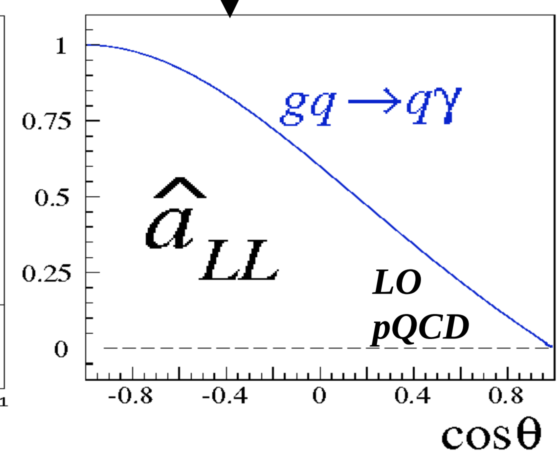
Direct measurement of gluon polarization

known from pol. DIS

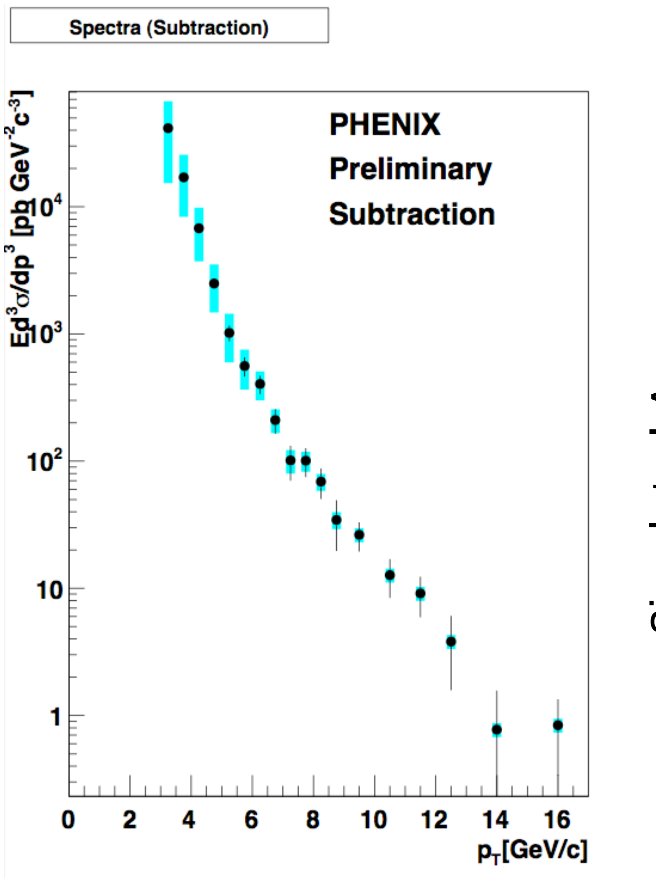
calculable in pQCD, scale ~ $p_T^2$ of $\gamma$

A golden channel:
parton kinematics reconstructed from photon and jet measurements:

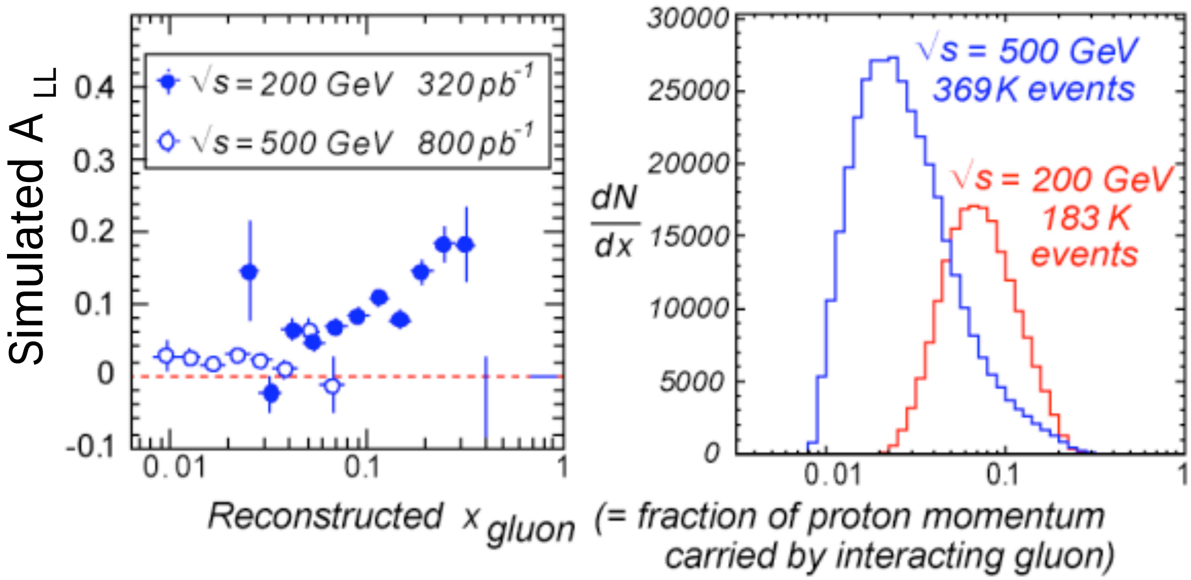


# Direct Photon @ RHIC

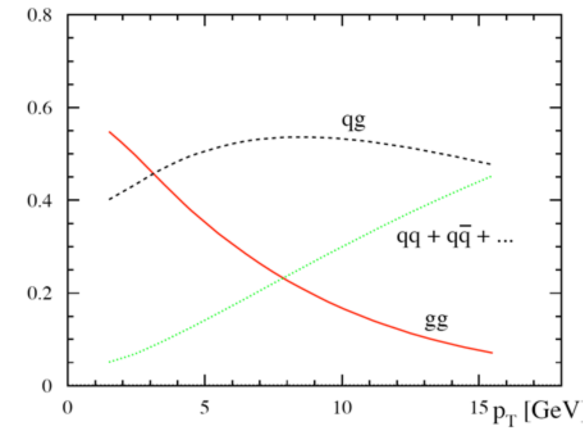



STAR projection

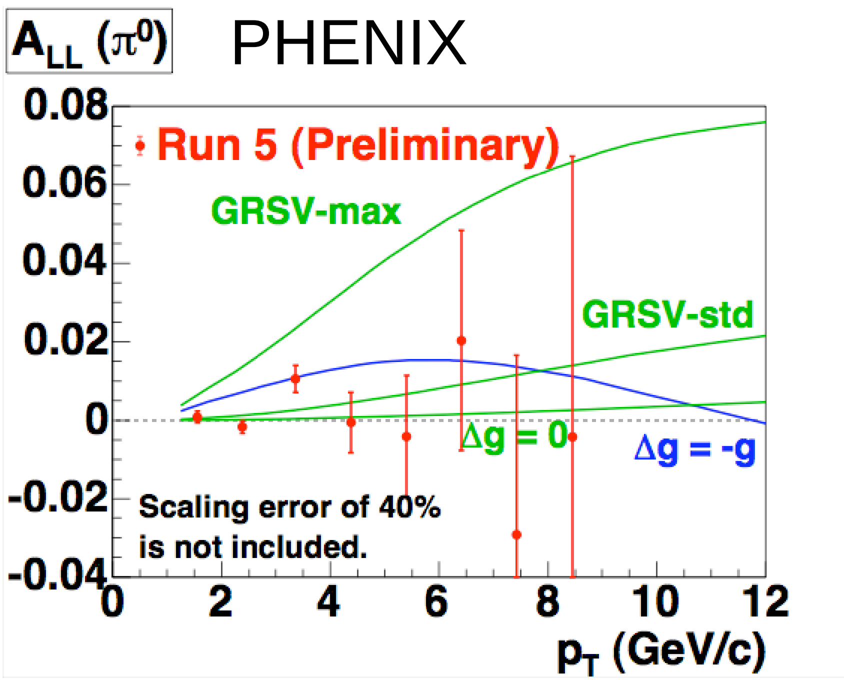


# $A_{LL}$ in Inclusive Particle Production

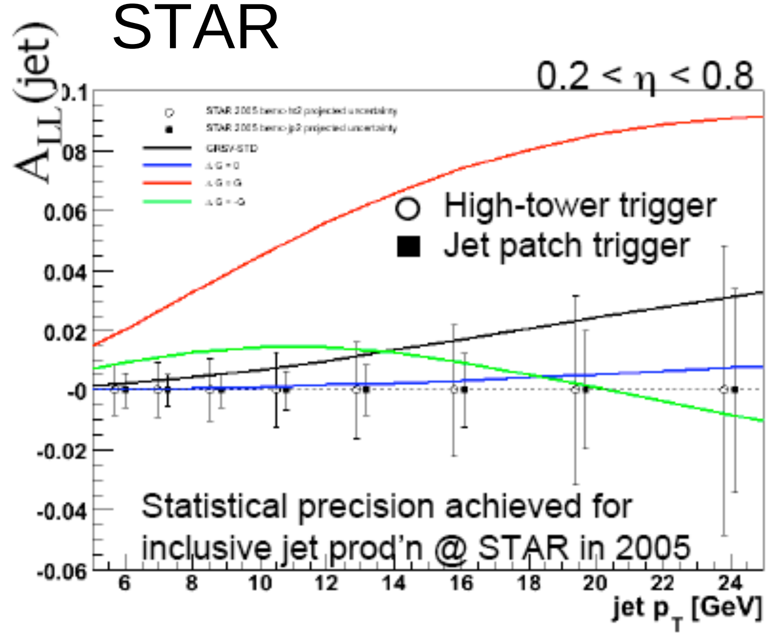
$$\boxed{A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} - \sigma^{+-}} \propto \Delta f_A^a(x_a, Q^2) \otimes \Delta f_B^b(x_b, Q^2) \otimes \frac{d\Delta\sigma_{ab}^{cd}}{dt}}$$




PHENIX




STAR



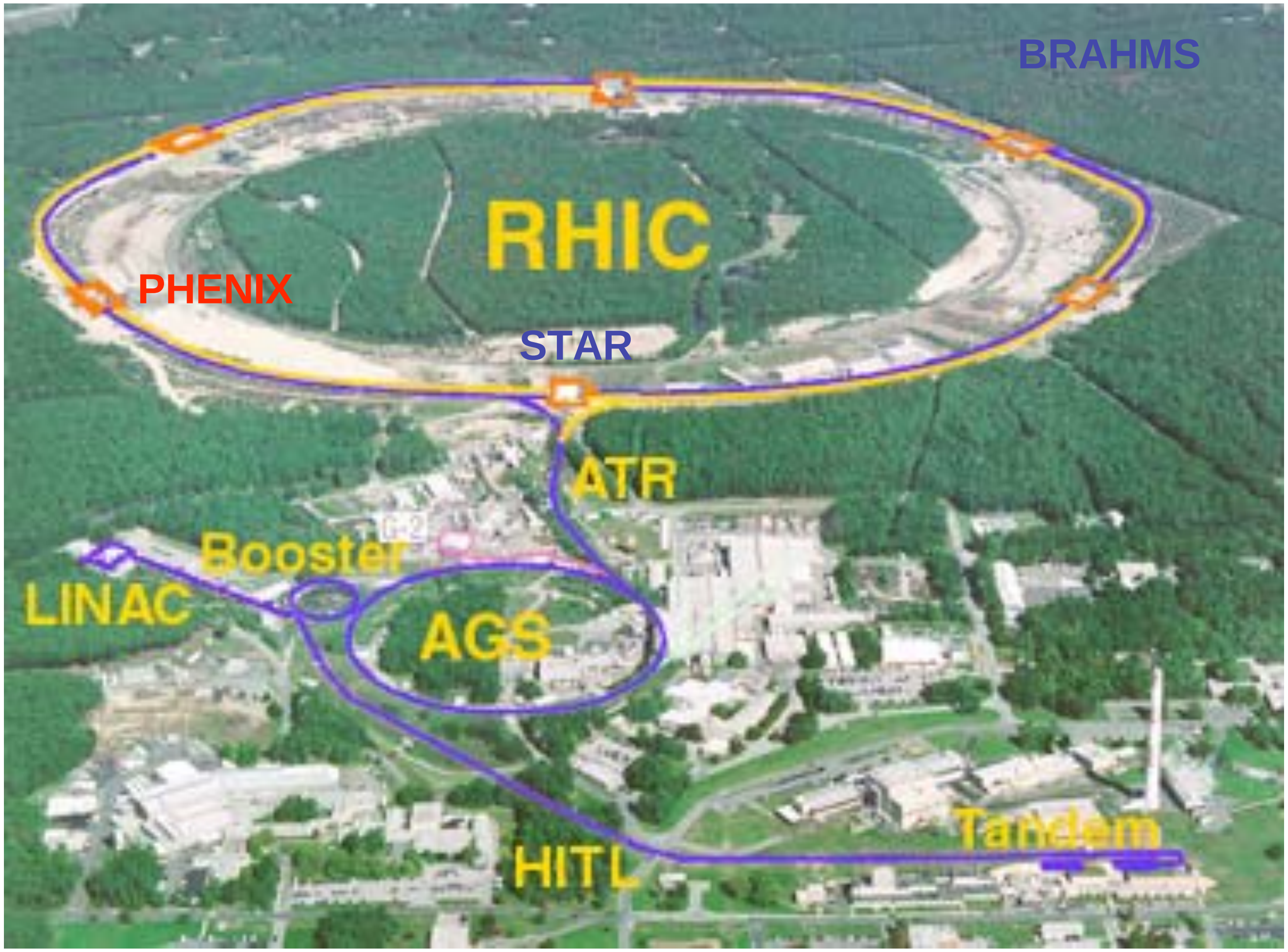
# Summary and Outlook

- Very rich physics program with polarized beams at RHIC
  - Spin Puzzle
    - Polarized gluon distribution
    - Flavor-identified polarized quark distributions
  - Excellent QCD test ground with polarized partons

- Latest news from RHIC-Spin:
  - Light hadrons: $\pi$, K, $\eta$, $\Lambda$, ...
  - Heavy quarks: J/Psi, open charm …
  - Explore orbital angular momentum: di-jet correlation etc.

- Where does the nucleon get its spin?
  - Still don't know … but RHIC-SPIN will help us to find the answer
  - and we will learn a lot more about the nature of strong interactions


# The Relativistic Heavy Ion Collider at Brookhaven National Laboratory




**R-HI**

New state of matter

QGP

De-confinement

…

**polarized proton**

Nucleon Spin Structure

Spin Fragmentation

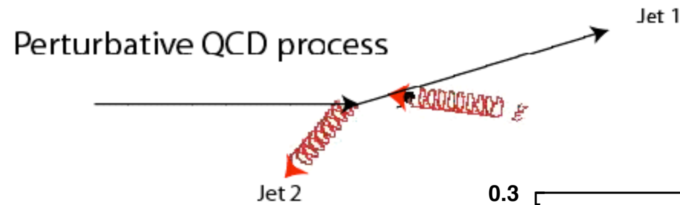
pQCD

…

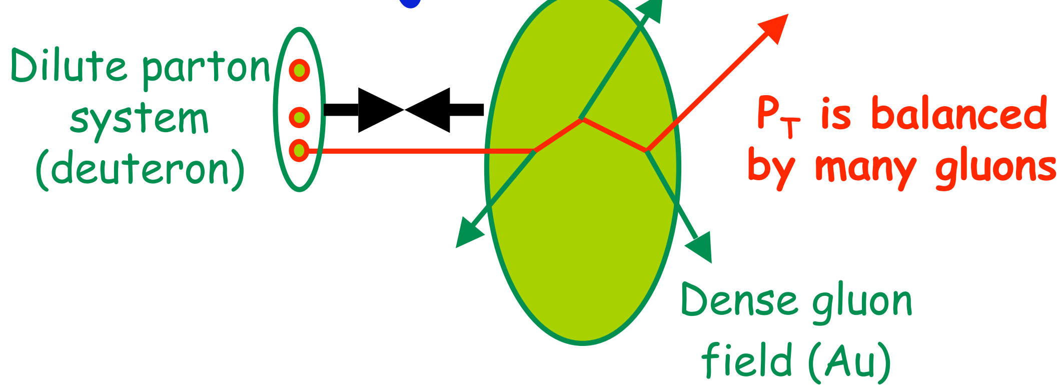
RHIC is a QCD lab

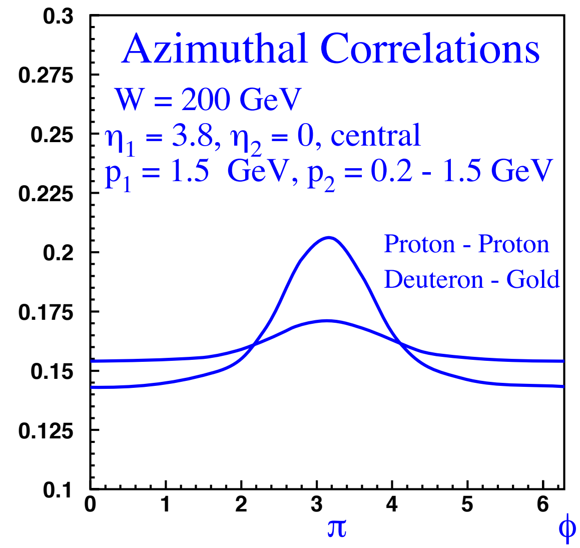
# Mono-jets from the CGC picture

**p+p: Di-jet**

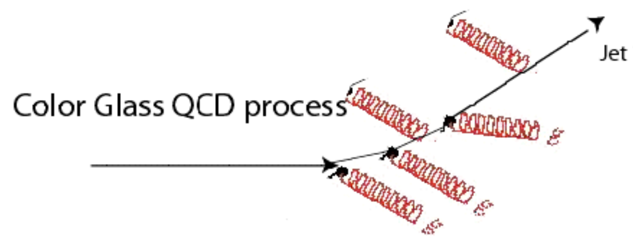



**d+Au: Mono-jet?**



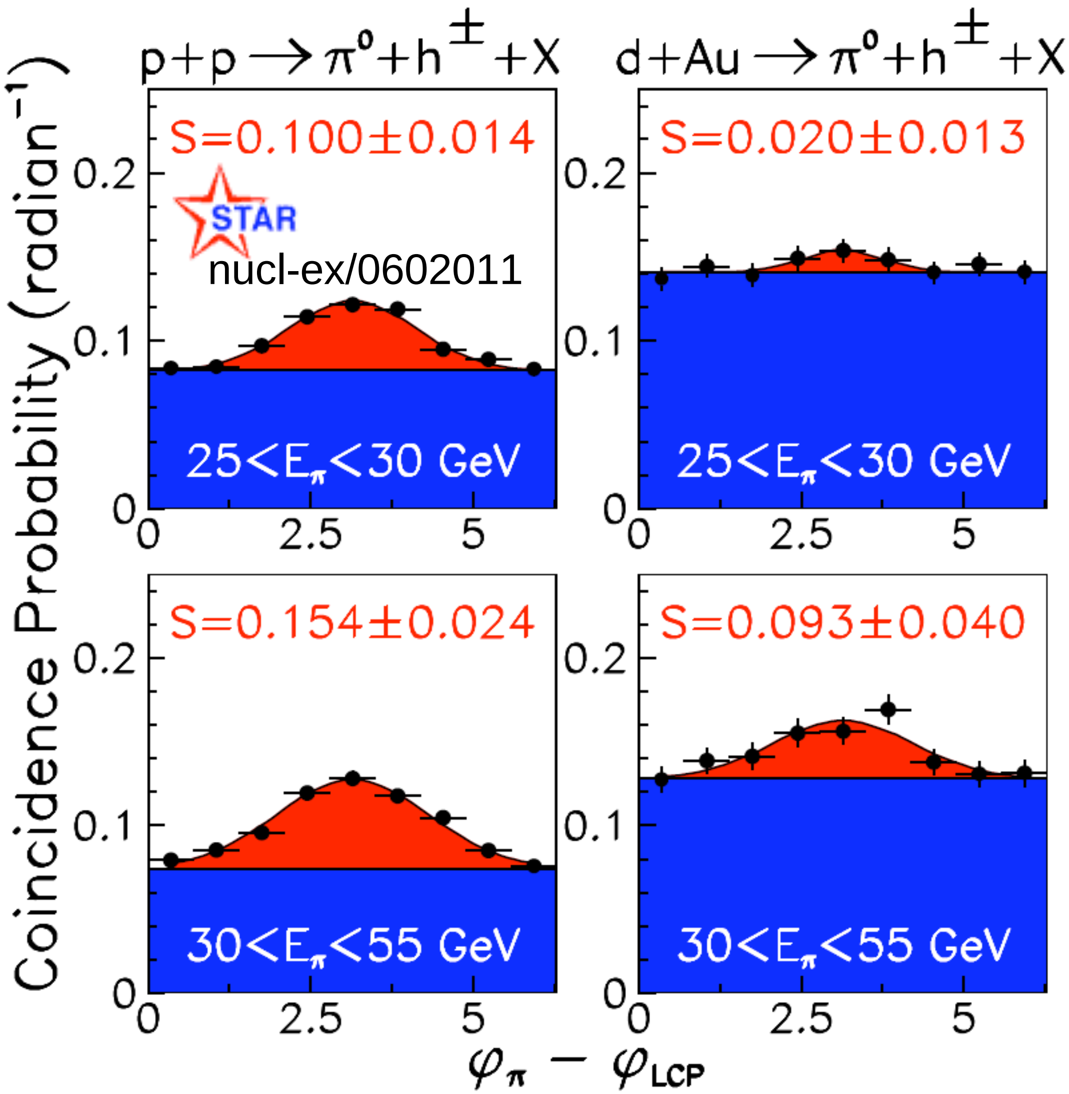




Kharzeev, Levin, McLerran give physics picture (NPA748, 627)




Color glass condensate predicts that the back-to-back correlation from p+p should be suppressed

# p0 + h± Correlations in dAu Collisions

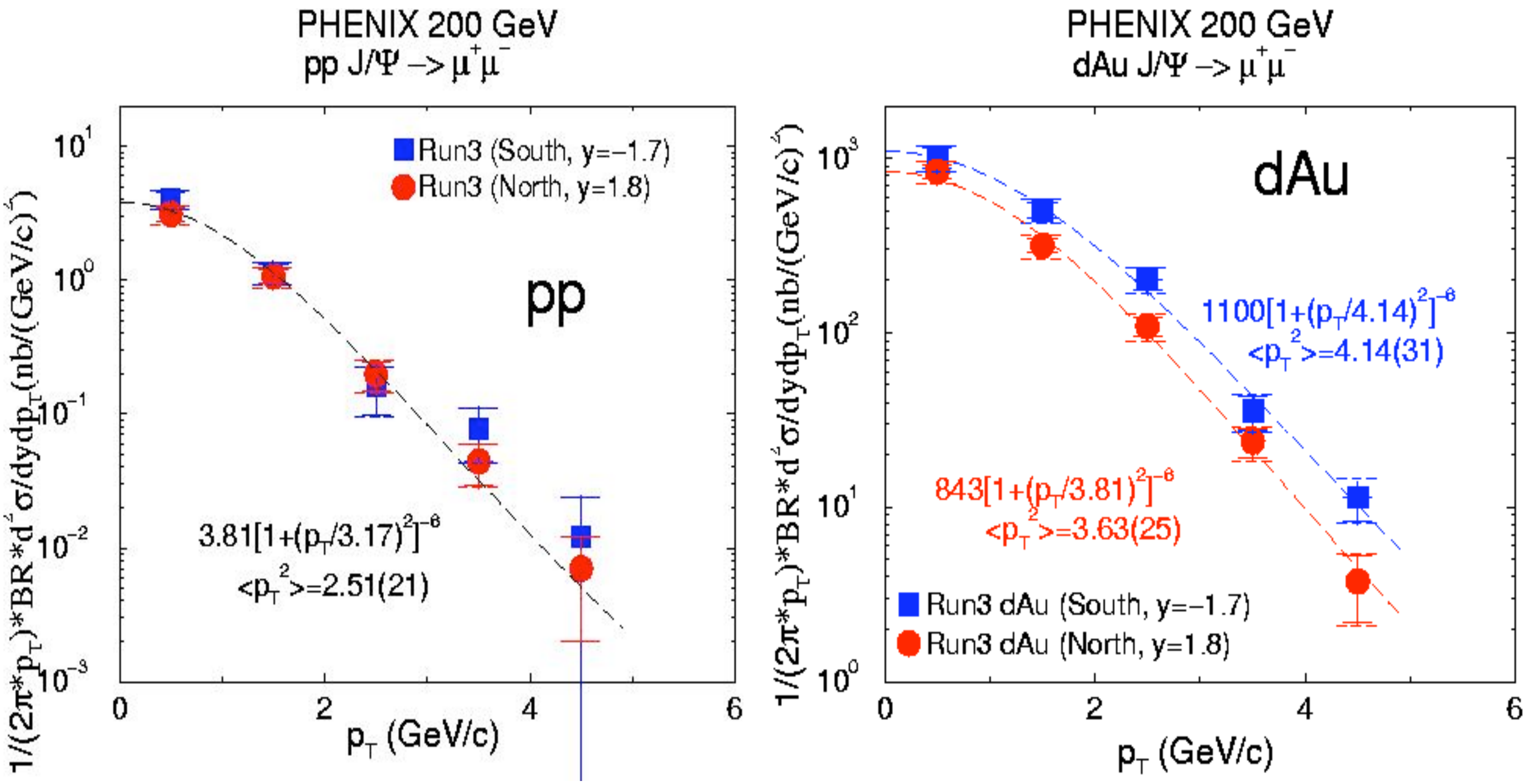



<η> = 4 and h± $p_T$>0.5 GeV/c

"S" is area of the coincident peak

The back-to-back correlation peak is smaller in dAu compared to pp, qualitativiely consistent with the mono-jet picture from the CGC or coherent scattering (Vitev, Qiu) models. But is the reduction really significant given the large background?

# $p_T$ broadening: Cronin Effect




Broadening of J/ψ $p_T$ distribution suggests initial scattering (maybe also energy loss) is important

# Charm production in dAu

## Vitev et al. – hep-ph/0605200

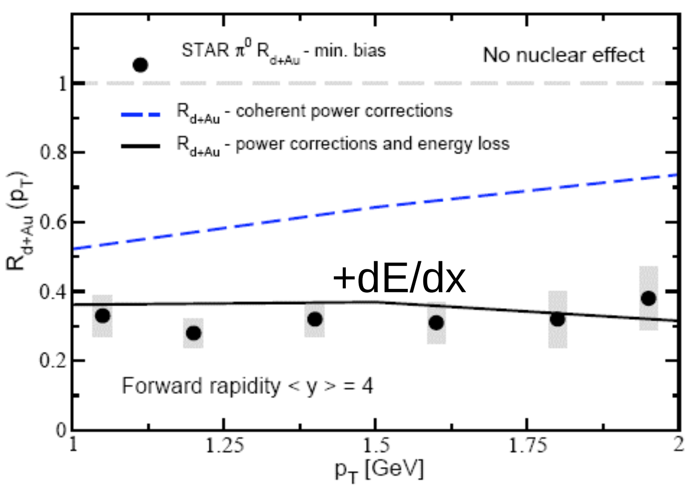
cg & cq dominate inclusive D production

final-state coherence effects

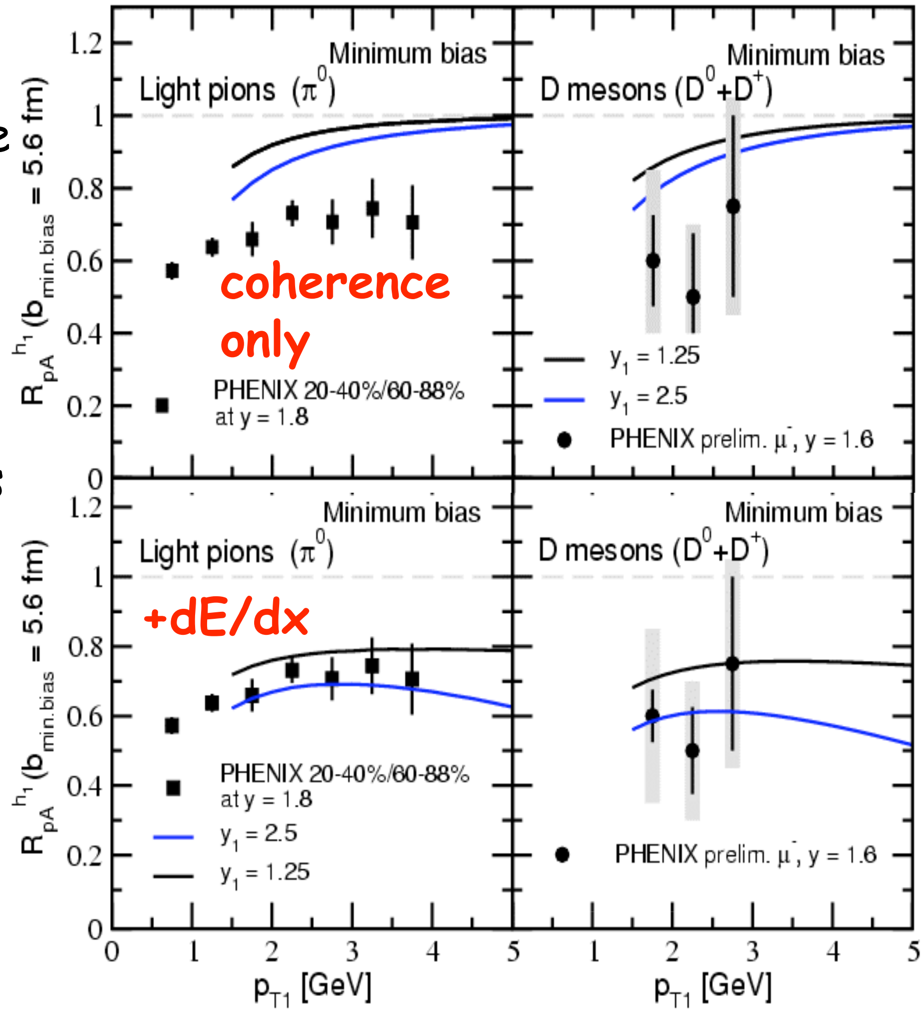
- simultaneous interaction with more than one nucleon ($x_N < 1/2r_0m_N$)
- equivalent to shift in effective x

initial-state inelastic radiative energy loss necessary to reproduce data

- large dE/dx - average parton loses 10% of its energy!



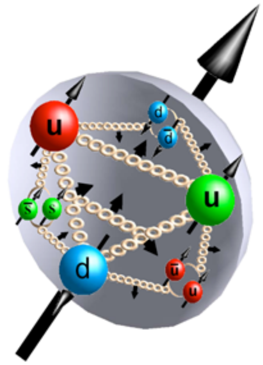

STAR
$\pi^0$ at y=4



# Polarized p+p Physics

- Proton Spin Puzzle:

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




$$\Delta\Sigma \approx 0.3 \quad vs \quad \Delta\Sigma^{QCD} \approx 0.6$$

- Asymptotic limit: $Q^2 \rightarrow \infty$

Ji:

$$J_q(Q^2) = \frac{1}{2}\Delta\Sigma + \Delta L_q \rightarrow \frac{1}{2}\frac{3n_f}{16+3n_f}$$
$$J_G(Q^2) = \Delta G + \Delta L_G \rightarrow \frac{1}{2}\frac{16}{16+3n_f}$$

- PCAC

$$\Delta\tilde{\Sigma}^{\exp} = \Delta\Sigma - N_f \frac{\alpha_s}{2\pi}\Delta G$$
$$\Delta\Sigma = 0.6 \rightarrow \Delta G \sim 3$$

Gluons may play a significant role !

# Gluon Polarization Measurements: (SI)DIS

- Semi-inclusive DIS
  - HERMES @ DESY
    - high-$p_T$ hadron pairs
  - SMC @ CERN
    - high-$p_T$ hadron pairs
  - COMPASS @ CERN
    - high-$p_T$ hadron pairs
    - open charm