Scientific Opportunities in pA & dA Collisions

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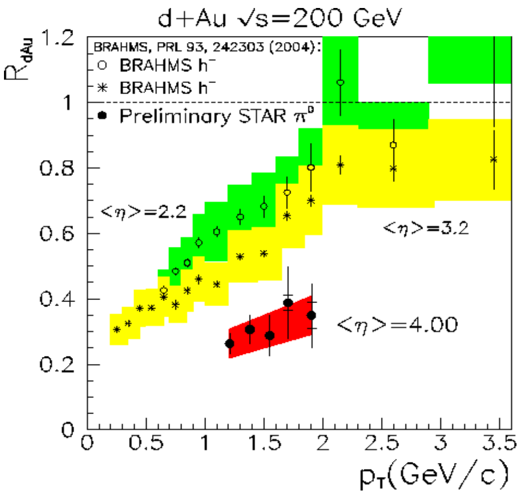
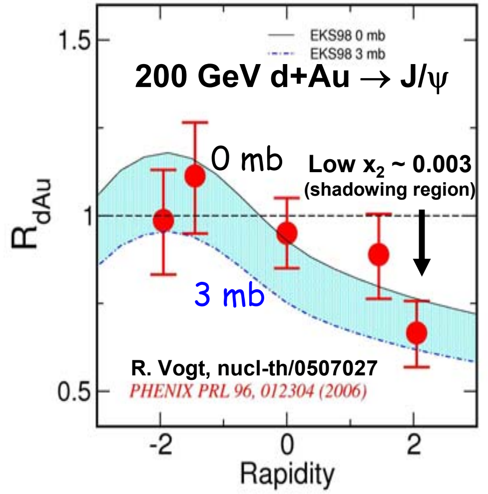
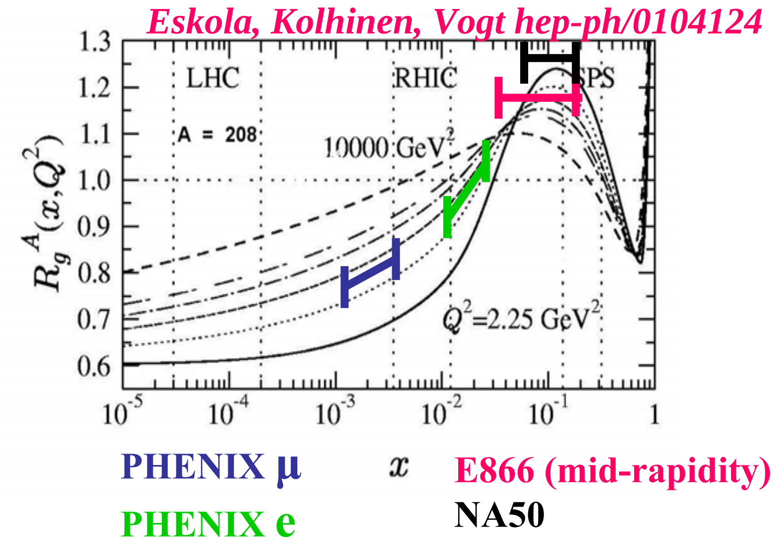
Rutgers NP Town Meeting – 12 January 2007

- gluon saturation & shadowing
  - small-x suppression
- cold nuclear matter (CNM) effects
  - on J/ψ & heavy quarks
  - parton energy loss
- baseline for AA collisions
- RHIC-II rates & reach
- contrasting with LHC





Cold Nuclear Matter (CNM) Effects
Gluon Shadowing and Saturation



Phenomenological fit to DIS & Drell-Yan data

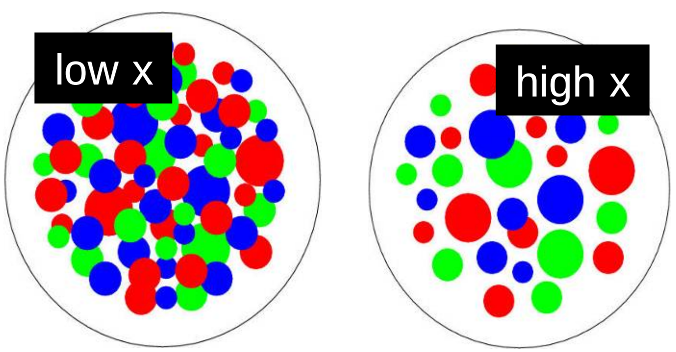
- e.g. "EKS", Nucl. Phys. A696, 729 (2001).

Leading twist gluon shadowing

- e.g. "FGS", Eur. Phys. J A5, 293 (1999)

Coherence approach and many others

Amount of gluon shadowing differs by up to a factor of three between diff models!

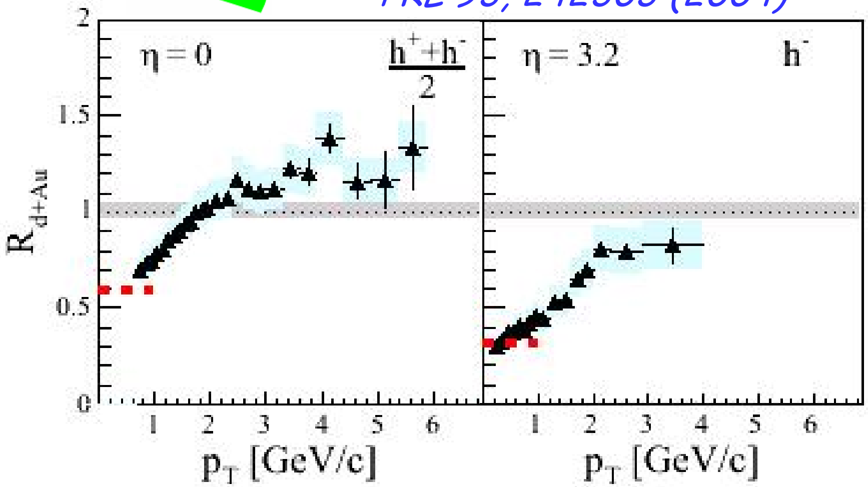


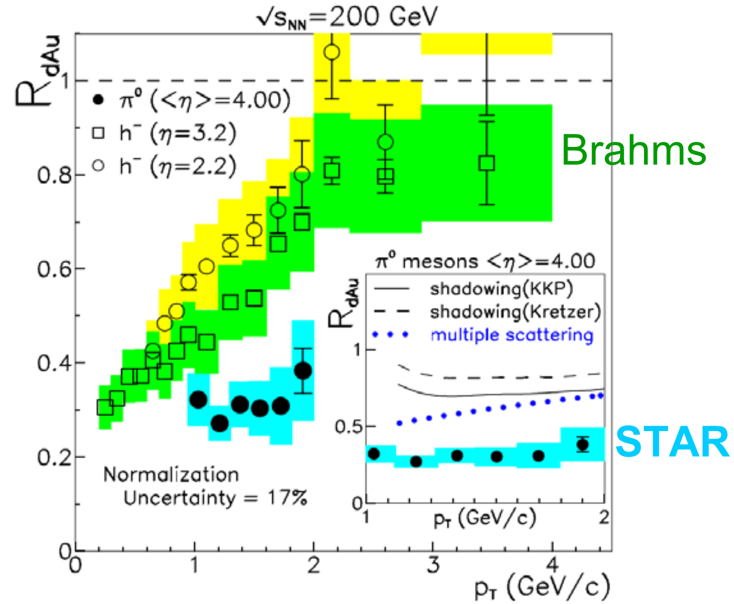
Saturation or Color Glass Condensate (CGC)

- At low-x there are so many gluons that $2 \rightarrow 1$ diagrams become important and deplete low-x region
- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon

Hadrons at forward rapidity (small-x)

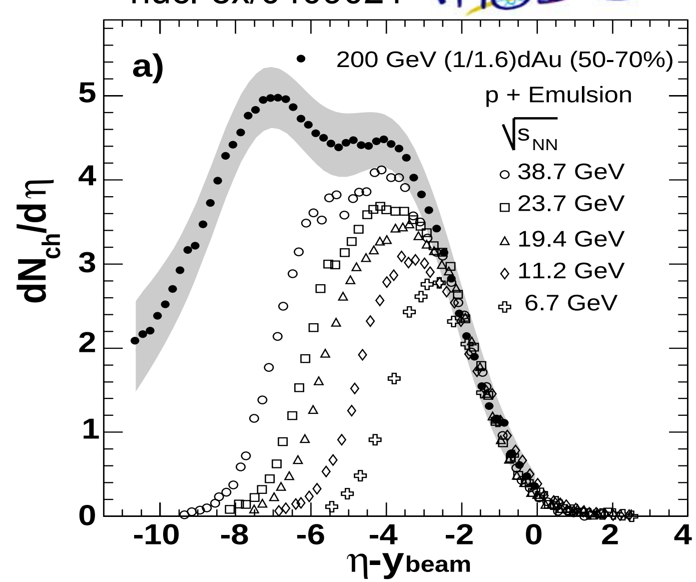
BRAHMS *PRL 93, 242303 (2004)*





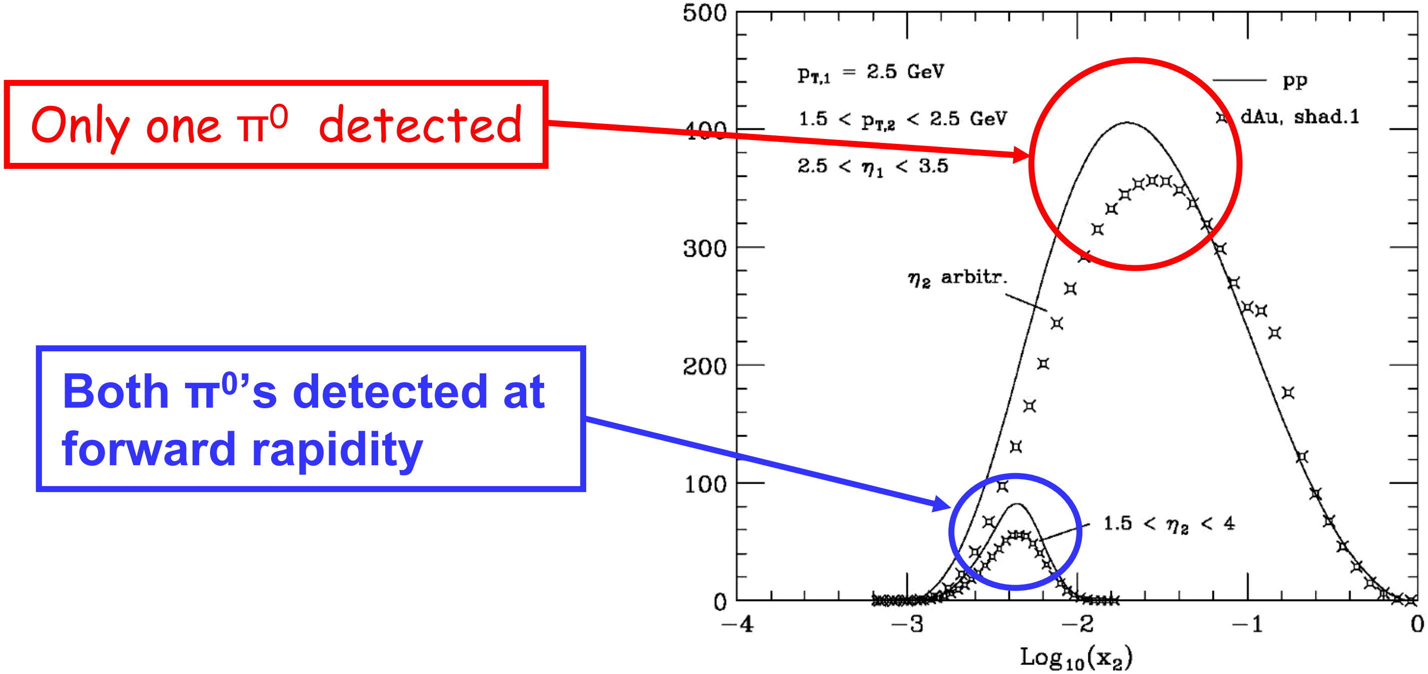
- Increasing suppression at forward rapidity w.r.t. binary scaling
- limiting fragmentation seen in comparison to lower energy measurements
- many physics issues to consider - shadowing, gluon saturation, initial-state parton energy loss, Sudakov suppression?

nucl-ex/0409021



But do forward π^0's really probe small x?

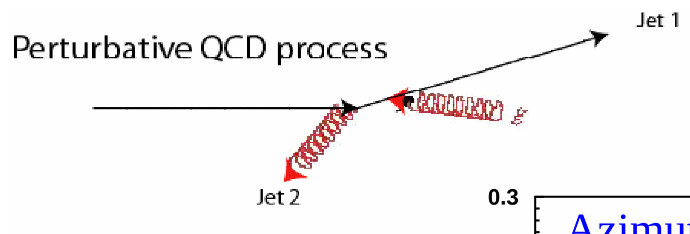
Guzey, Strikman, and Vogelsang, PL B603, 173 (2004)

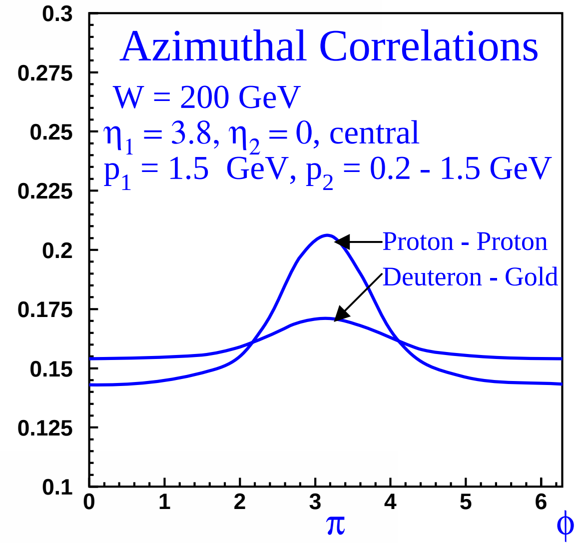


However, they also show that if one measures two forward hadrons (π^0's) then one CAN pin down x_2 to small values

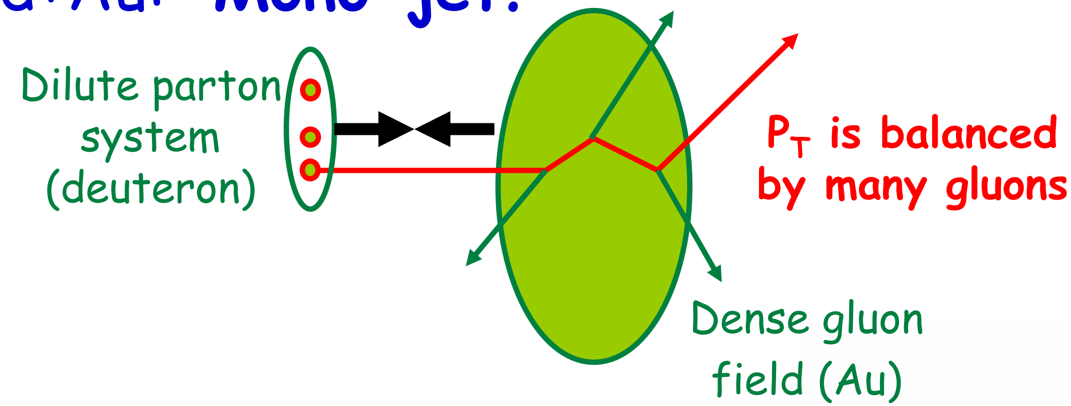
Mono-jets from the CGC picture

p+p: **Di-jet**

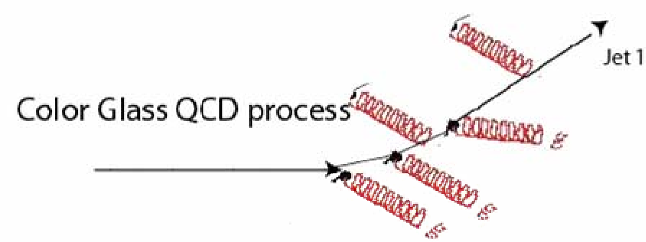




d+Au: **Mono-jet?**

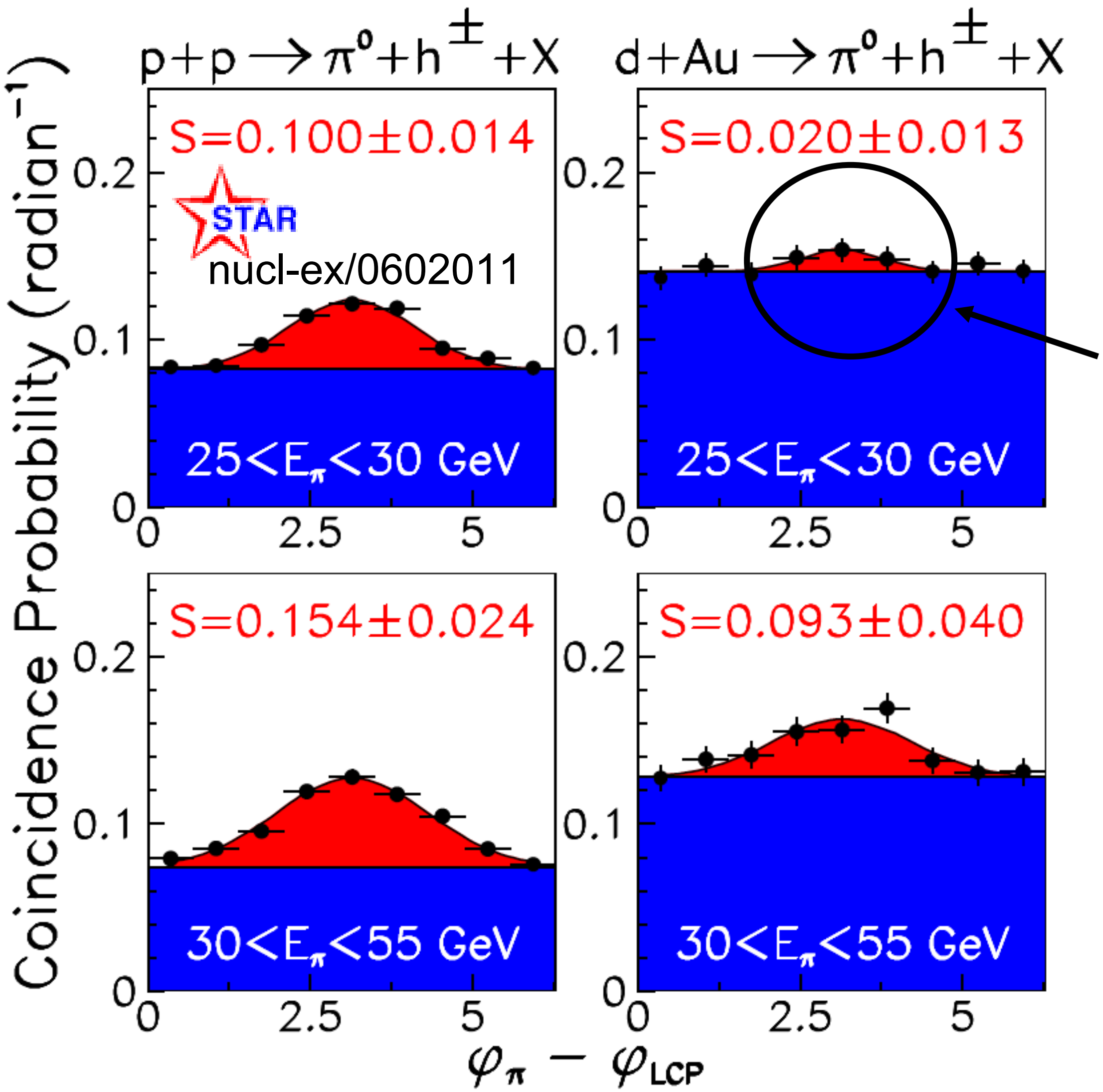


Kharzeev, Levin, McLerran give physics picture (NPA748, 627)



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

$\pi^0 + h^{\pm}$ Correlations in dAu Collisions



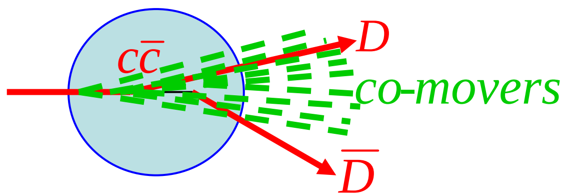
π^0 $\langle\eta\rangle$ = 4 and $h^{\pm}$ p_T>0.5 GeV/c

"S" is area of the coincident peak

The back-to-back correlation peak is smaller in dAu compared to pp, qualitatively 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?

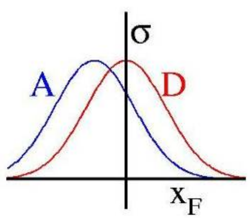
Cold Nuclear Matter Effects for J/ψ
Absorption & Energy Loss

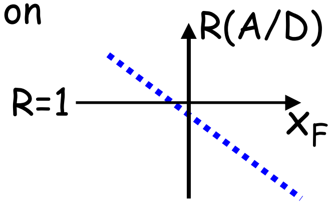
J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:



Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

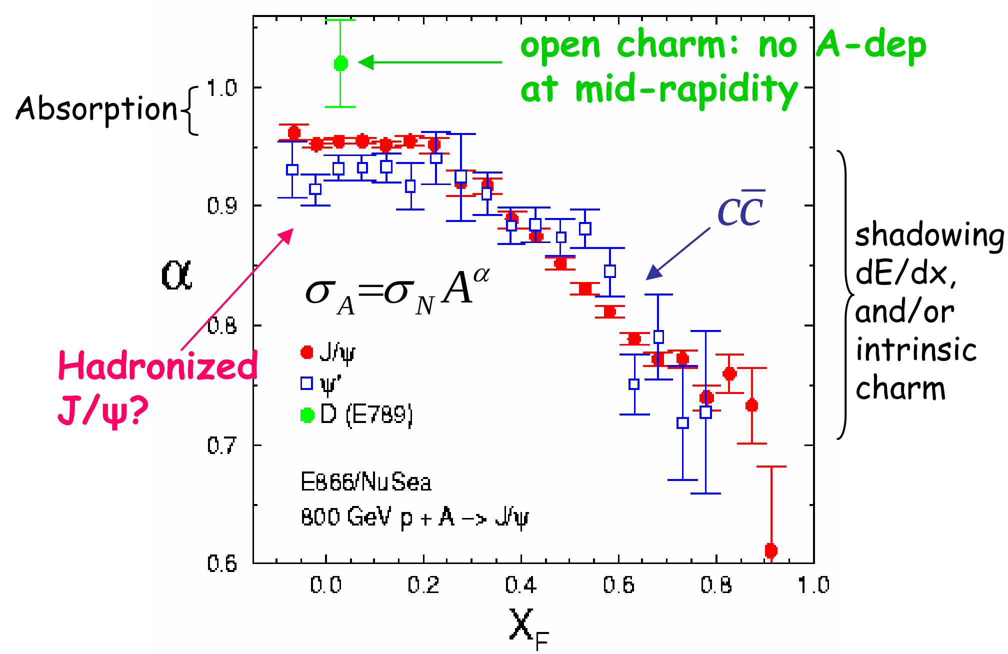
Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F



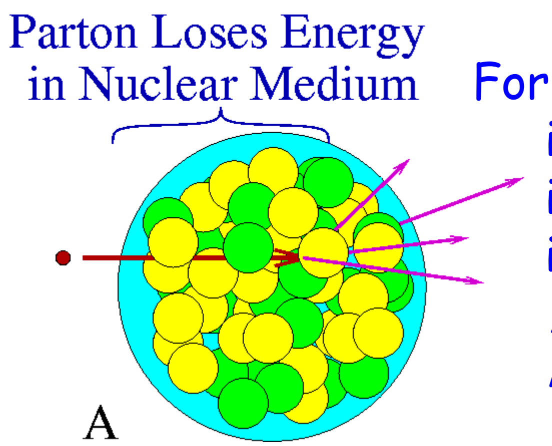


800 GeV p-A (FNAL)

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



FNAL E906 (120 GeV) or JPARC (50 GeV) quark energy loss in nuclei



For Drell-Yan only initial state interactions are important—*no final state strong interactions.*

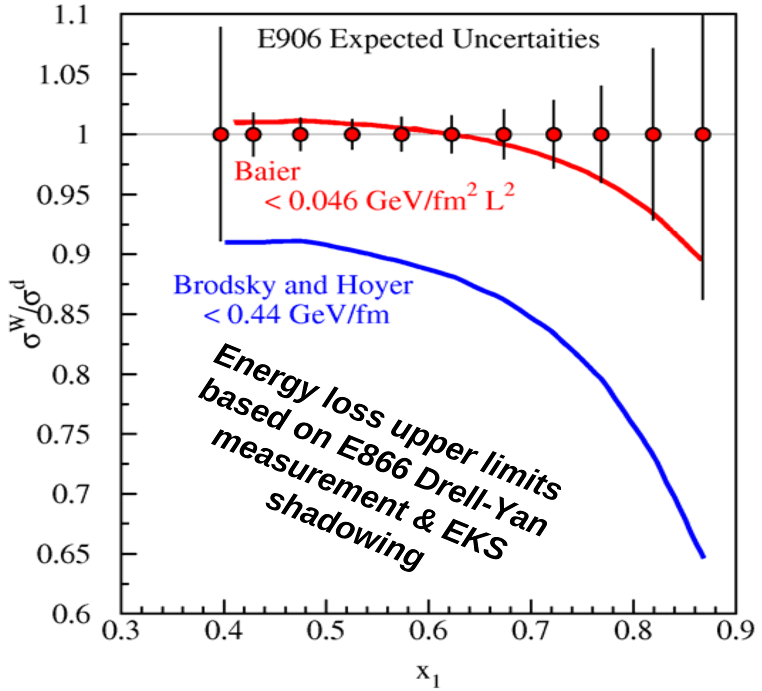
At 800 GeV, the nuclear dependence of Drell-Yan on nuclear targets could not unambiguously separate shadowing and dE/dx effects at low x

- *E866 data are consistent with no energy loss (using EKS shadowing)*
- *or with Kopeliovich shadowing, Johnson et al. find 2.2 GeV/fm from the same data*

- for 120 or 50 GeV p-A Drell-Yan x > 0.1 & only quark dE/dx remains (no shadowing)
- also stronger, dE/dx ~ 1/s

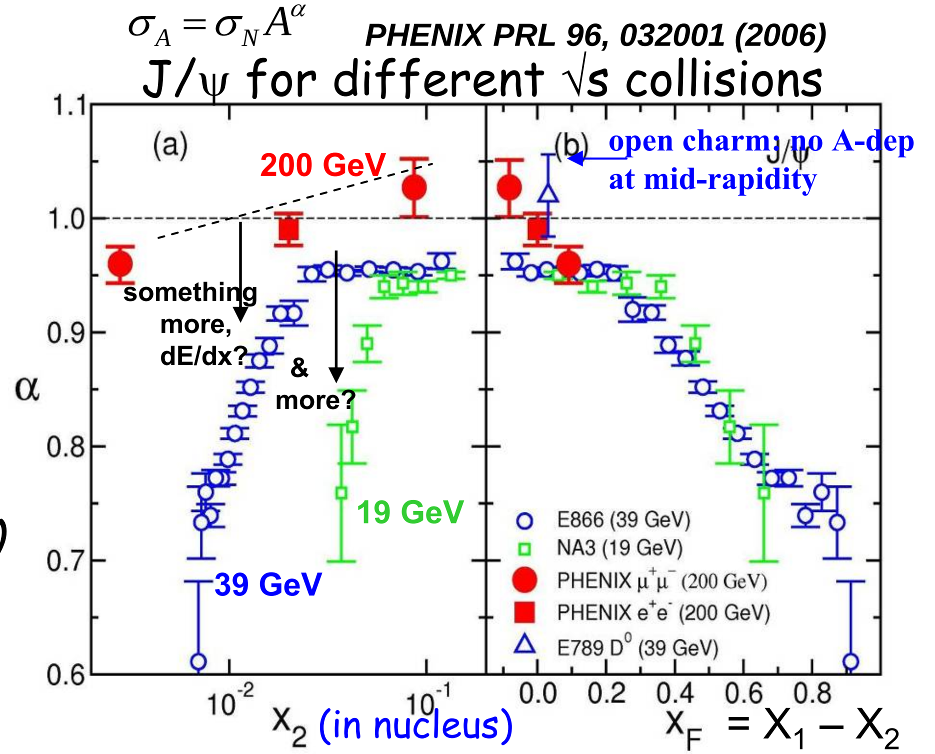
Important for understanding of RHIC data

E906 expected uncertainties
Shadowing region removed

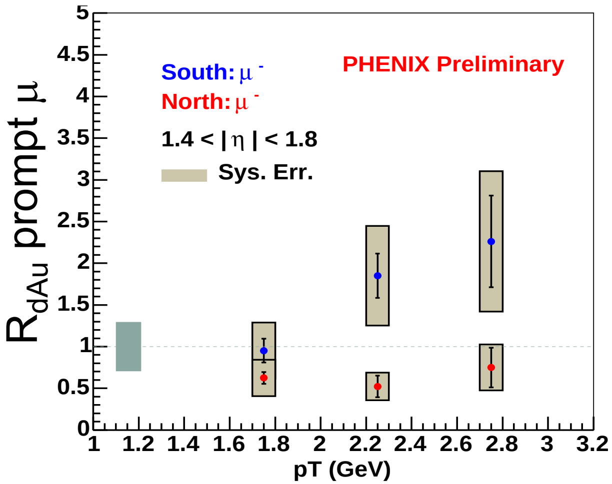


Heavy quarks at forward rapidity & small-x

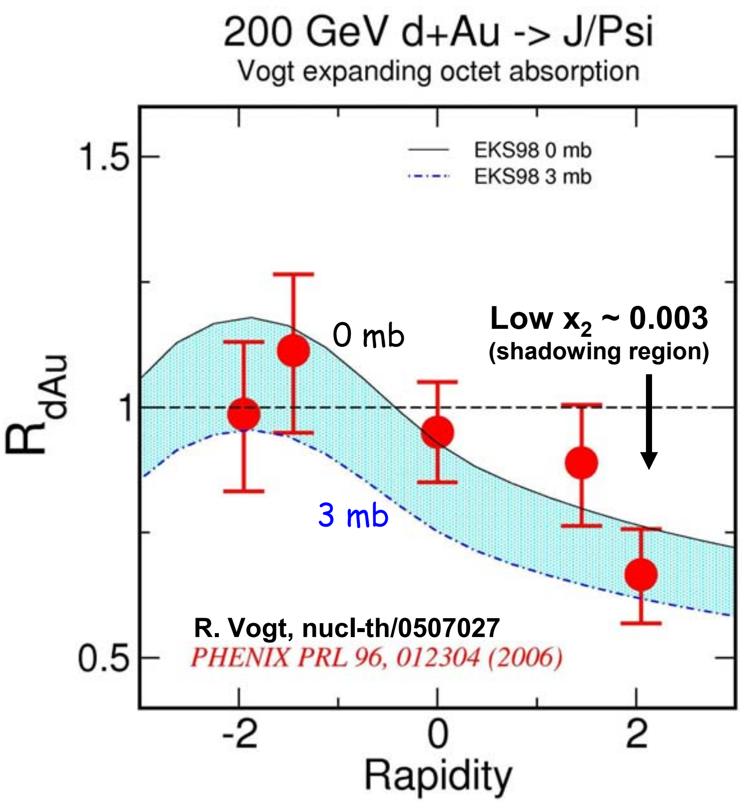
- J/ψ suppression does not scale like shadowing with x_2
- Apparent scaling with x_F is similar to limiting fragmentation in hadron production
- but other models involving Sudakov suppression (energy conservation) *Kopeliovich et al, hep-ph/0501260 (2005)*
- or (large) initial-state gluon energy loss could also explain this x_F scaling

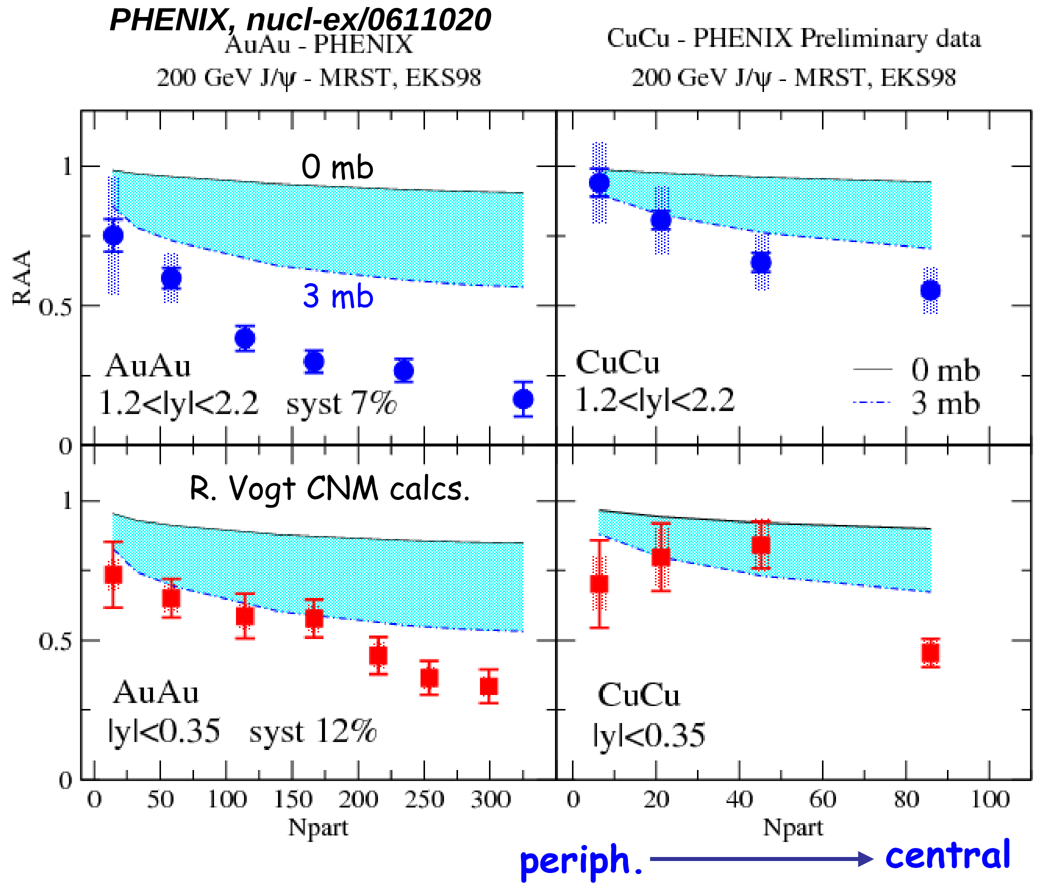


Prompt muons from open charm & beauty also suppressed at forward rapidity



J/ψ suppression in AA collisions & CNM baseline
(CNM = Cold Nuclear Matter)





Cold nuclear matter baseline poorly constrained by present d+Au J/ψ data so far – an example of the importance of d+Au for A+A studies

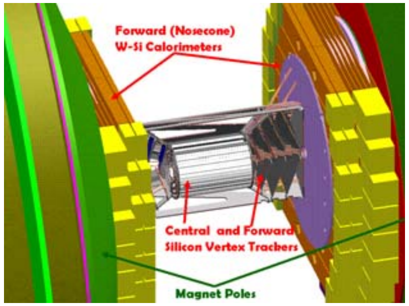
Detector Upgrades - enabling our physics goals

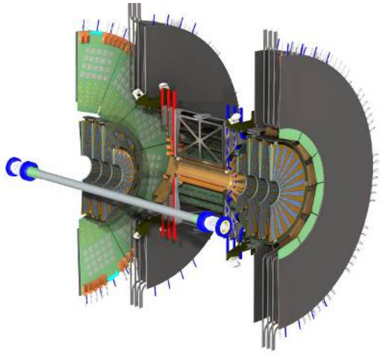
PHENIX Nosecone Calorimeter (NCC)
- forward γ & π^0
- $\chi_C \rightarrow J/\psi\ \gamma$

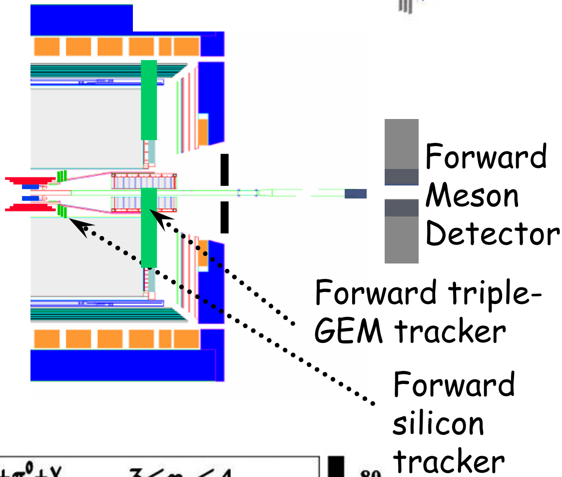
STAR Forward Meson Spectrometer
- forward π^0 (also PHENIX MPC's)

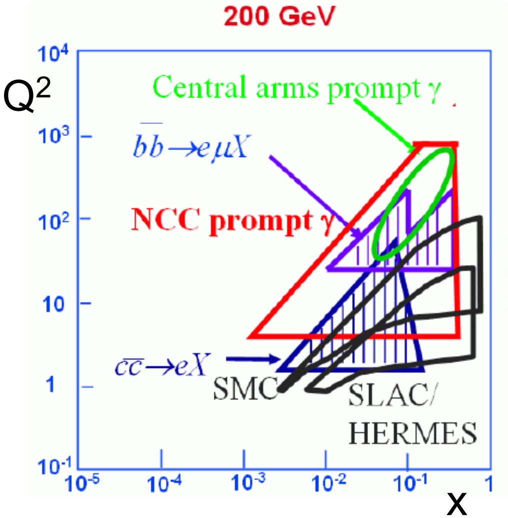
PHENIX Forward Vertex Detector
- $B \rightarrow J/\psi\ X$
- robust D & B with reduced bkgd.
- improved bkgd. & mass resolution for quarkonia & dimuons

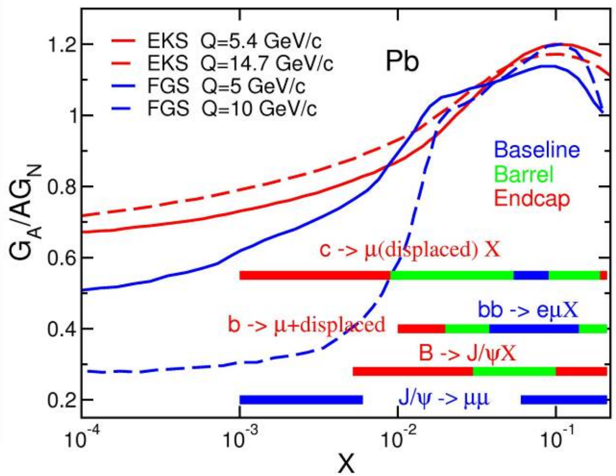
STAR Forward Tracker Upgrade
- charge sign for W's
- help other forward physics as well??

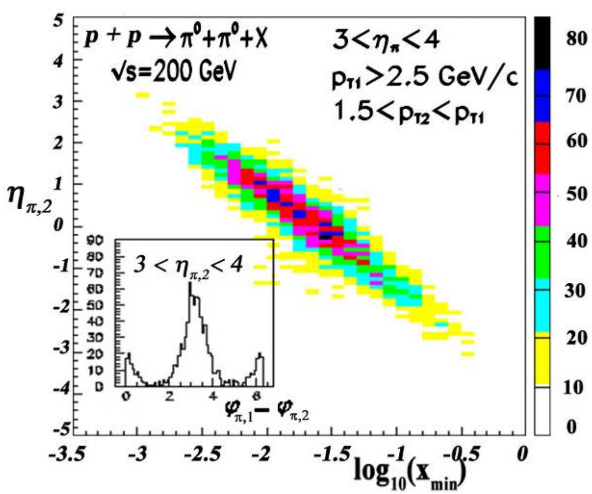








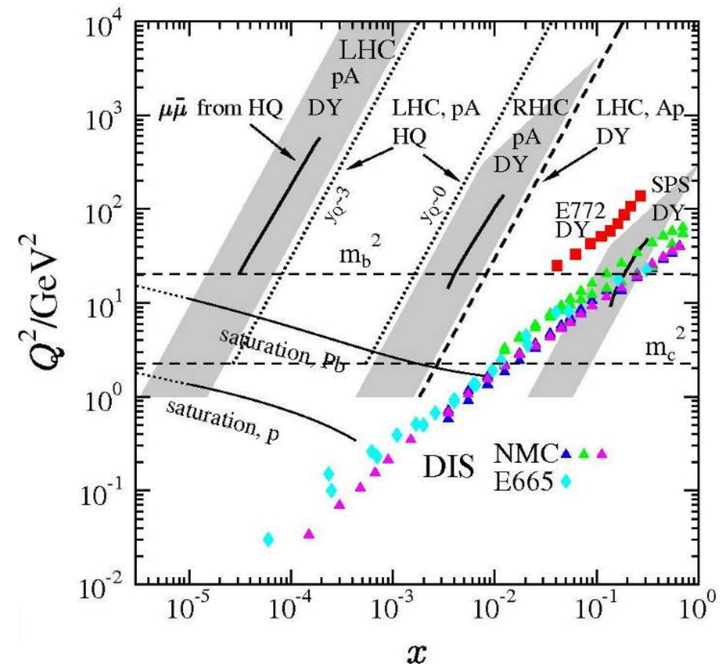




Contrasting small-x physics at RHIC-II and the LHC

At RHIC/RHIC-II measurements explore the onset of shadowing or saturation, while at the LHC most measurements will be deep into the saturation region

- exploring the onset at RHIC-II will be key to understanding saturation and complimentary to those at the LHC
- quarkonia annual rates similar at RHIC-II and LHC



From the LHC pA Workshop (May 2005):

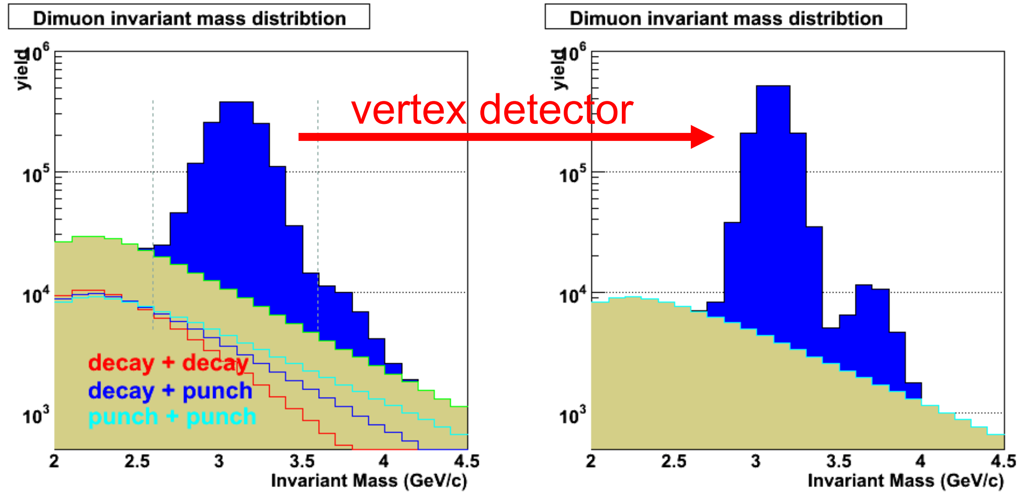
- p+A at the LHC is still officially an upgrade
- First year that LHC might run p+Pb: 2010
- Possible "target" luminosity: 10^{29} cm^{-2}s^{-1} (RHIC-II: 2x10^{30} cm^{-2}s^{-1} avg)
- N-N CM not at lab y=0 (Δy=-0.46 for 8.8 TeV p+A)
- Has to share 1-month/yr with HI running – difficult to build a systematic program

Goals for the Future

Accurate data from multiple probes to allow quantitative analysis & isolation of gluon saturation from other effects (parton energy loss, coherence effects causing shadowing, Sudakov suppression)

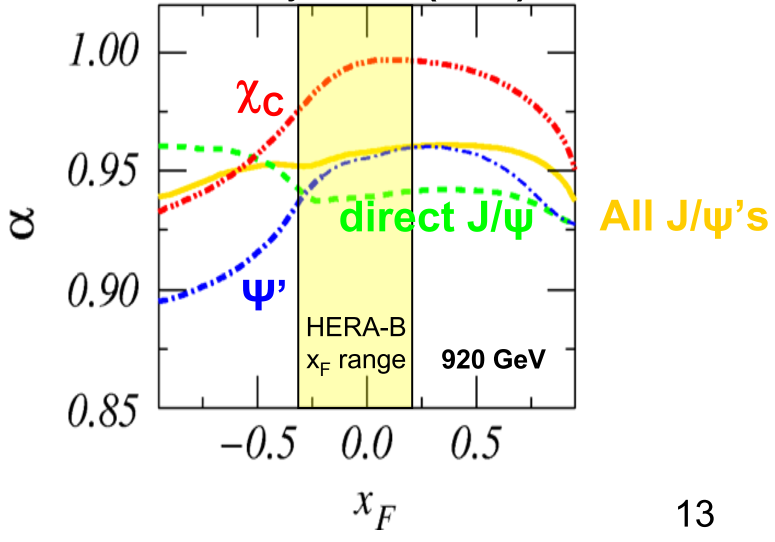
Quarkonia:

- higher luminosity (RHIC-II) to enable precision for rare probes (J/ψ, ψ', Υ)
- lower backgrounds via detached vertices (vertex detector upgrades)
- better onia mass resolution to isolate states (J/ψ from ψ'; Υ family)
- ψ' where there is no feed down - the physics is cleaner
- Υ where x probed is larger than J/ψ ($x \sim m_Q/\sqrt{s}$)
- and $\chi_C \to J/\psi\ \gamma$ (forward calorimeters)



R. Vogt, NRQCD calculations

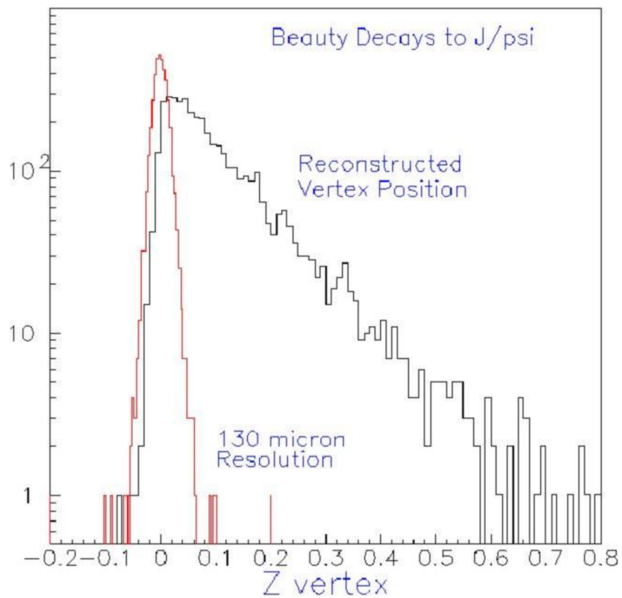
Nucl. Phys. A700 (2002) 539



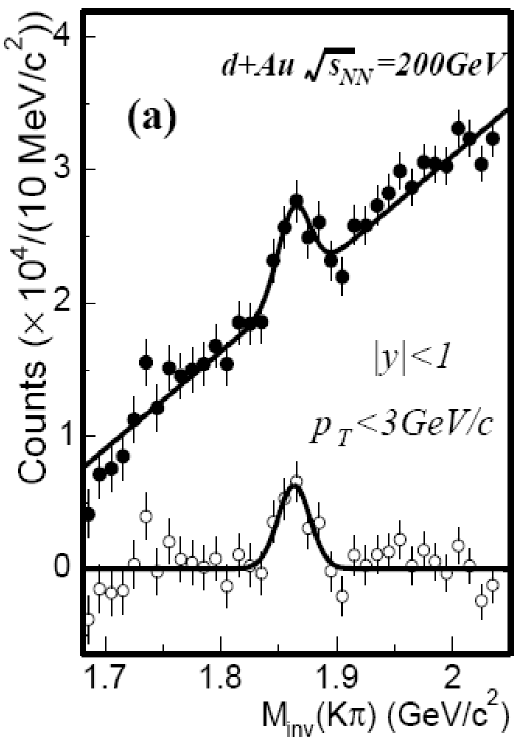
Goals for the Future continued

Open-heavy:

- explicit identification of open heavy semi-leptonic decays via detached vertices
  - lower backgrounds, smaller systematic uncertainties
- explicit isolation of beauty via $B \rightarrow J/\psi\ X$
- explicit $D \rightarrow K\ \pi$ (at central rapidity with STAR upgrades, but don't know about forward??)
- high precision comparison of open and hidden heavy to isolate physics



Separation of $B \rightarrow J/\psi\ X$ from prompt J/ψ via detached vertex



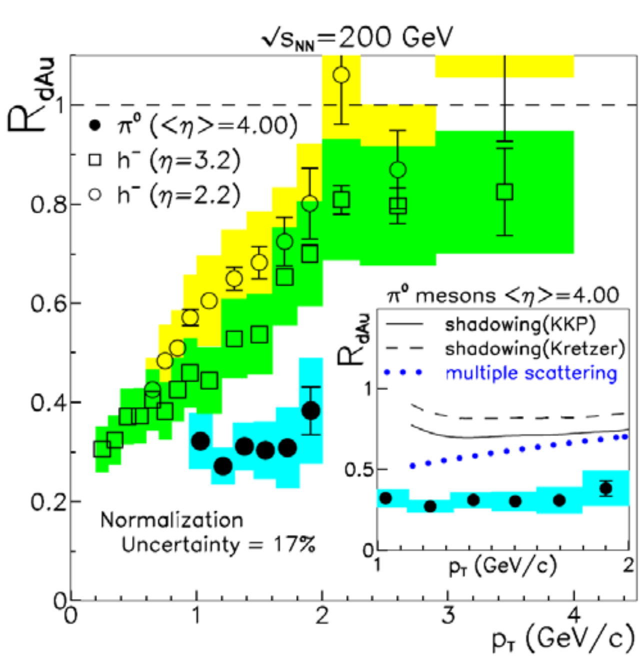
$D \rightarrow K\ \pi$ in dAu at central rapidity from STAR

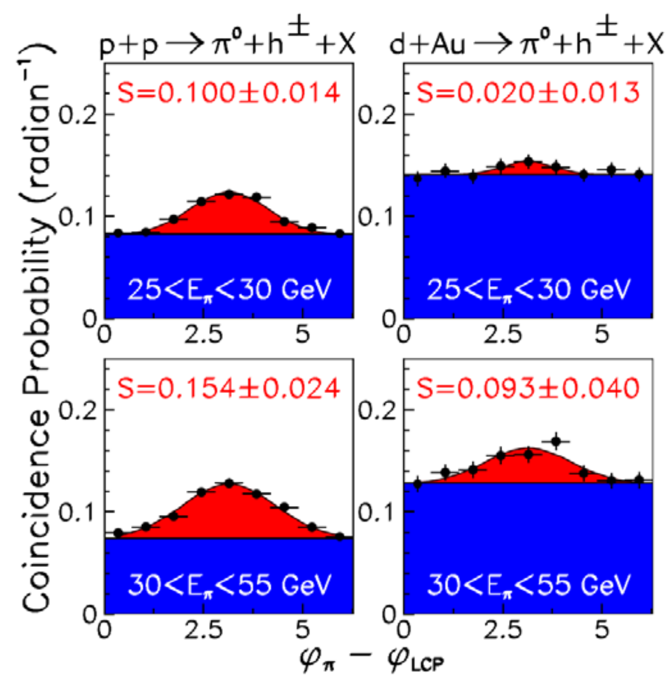
Goals for the Future continued

Lepton pairs (Drell-Yan) with reduced π,K decay & open charm backgrounds (vertex upgrades)

π^0 & γ at large rapidity to probe saturation at small x (forward calorimeters)

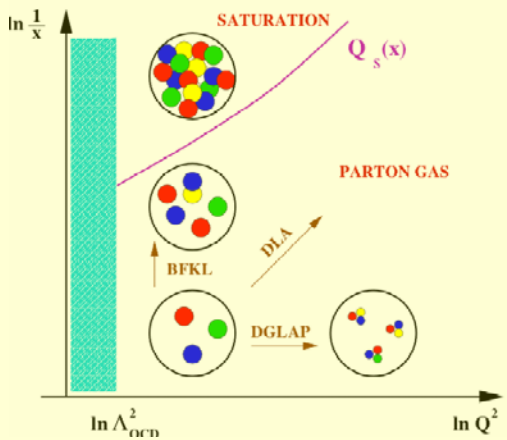
2-particle correlations and search for mono-jets (forward calorimeters)



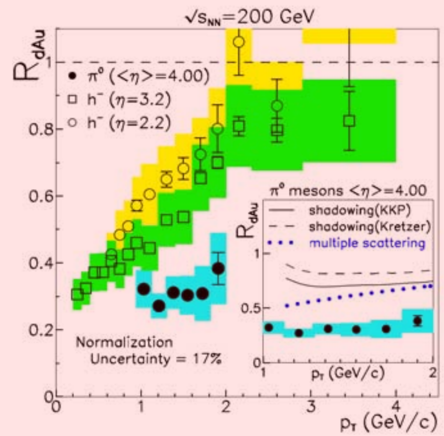


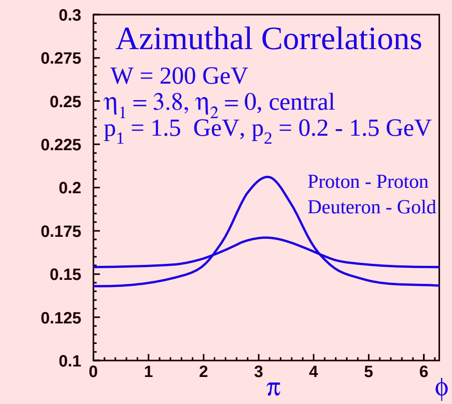
mono-jets??

Summary - p+A and d+A Opportunities

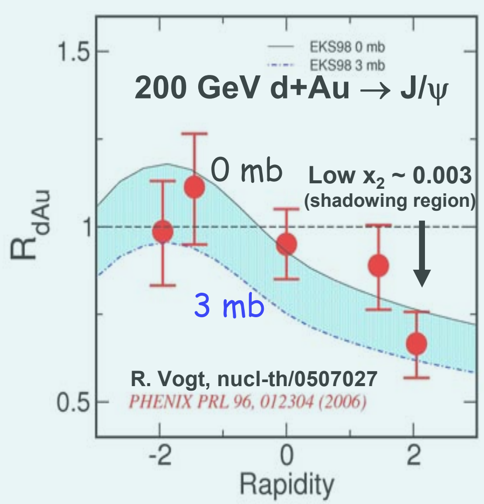


Is gluon saturation the source of forward-y (small-x) suppression?

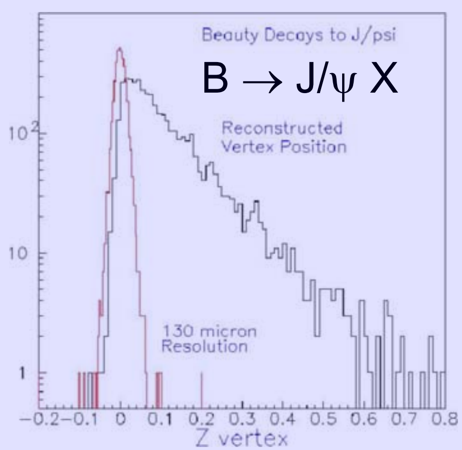




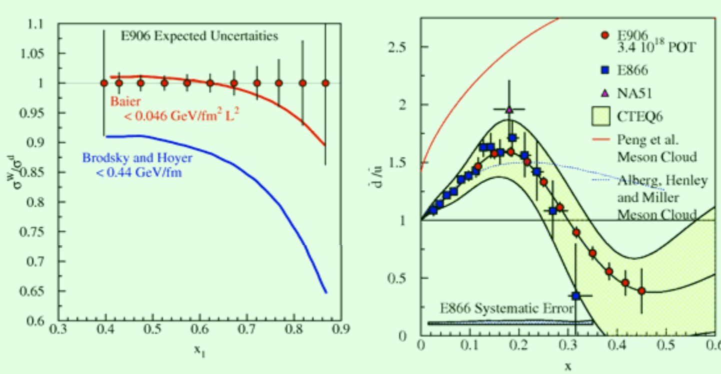
Forward hadron suppression.
Are there mono-jets?



Solving the J/ψ CNM puzzle



Contrasting open-heavy with J/ψ & light hadrons; separating B's from D's



CNM dE/dx?
Source of the nucleon sea?

Extra Slides

A few rates for RHIC-II

Substantial increase in rates of rare processes at RHIC-II
- J/ψ yields still smaller than the 1.5M at FNAL E866/NuSea but quite good for a collider!

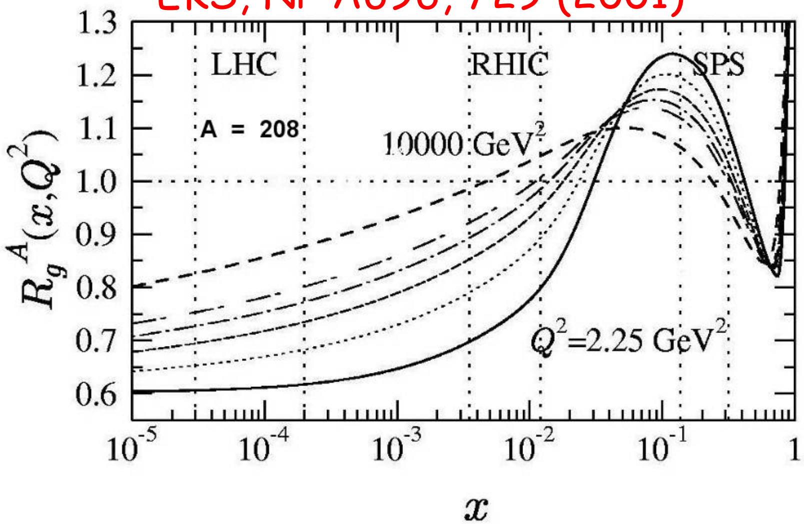
								p_T>10 GeV/c	
	J/ψ	ψ'	Υ	χ_C	$B \to J/\psi X$	D	B	π^0	direct γ
Run-3	~900								
RHIC-I	13k	230	40	1.4k	350	38M	440k	8.2k	1k
RHIC-II	200k	3.6k	650	22k	5.5k	600M	7M	130k	17k

- Est. yields in one PHENIX forward spectrometer in a 10-week d+Au run
- use RHIC-II at 62 nb^{-1}/week; RHIC-I at 3.9 nb-1/week luminosities
- compared to ~0.27 nb^{-1}/week in Run-3
- with the PHENIX Forward Vertex and Nose Cone Calorimeter upgrades

Rates for STAR FMS double π^0 coincidence ~100k in 10-week RHIC-II d+Au run

Cold Nuclear Matter Effects
Gluon Shadowing

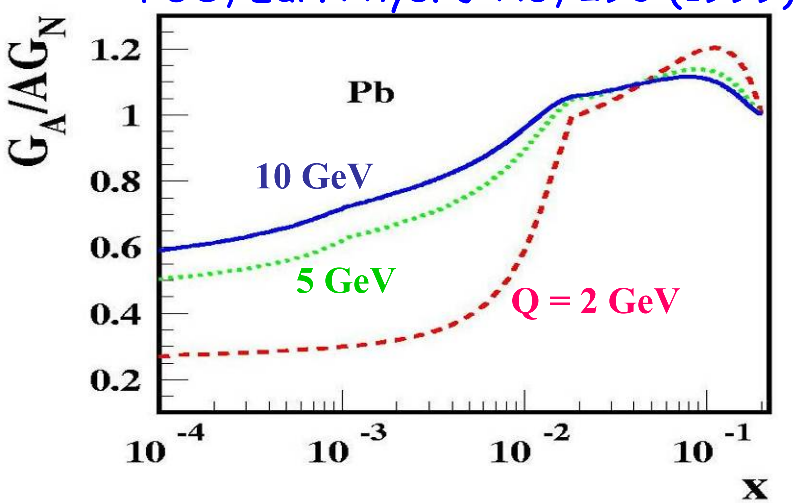
EKS, NP A696, 729 (2001)



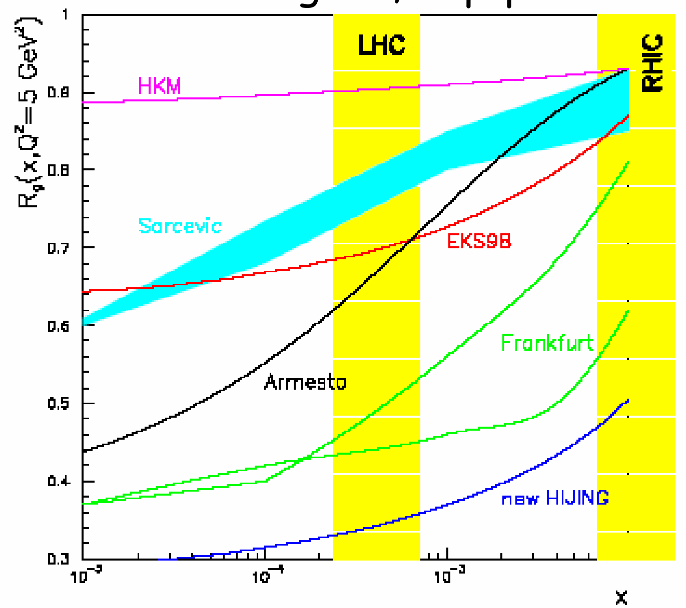
- Phenomenological fit to Deep-Inelastic Scattering & Drell-Yan data
- Leading twist gluon shadowing
- Coherence approach, and many others

Amount of gluon shadowing differs by up to a factor of three between diff models!

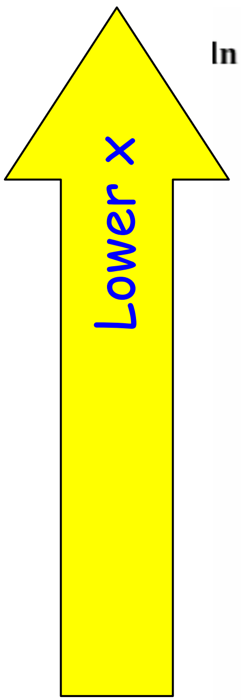
FGS, Eur. Phys. J A5, 293 (1999)

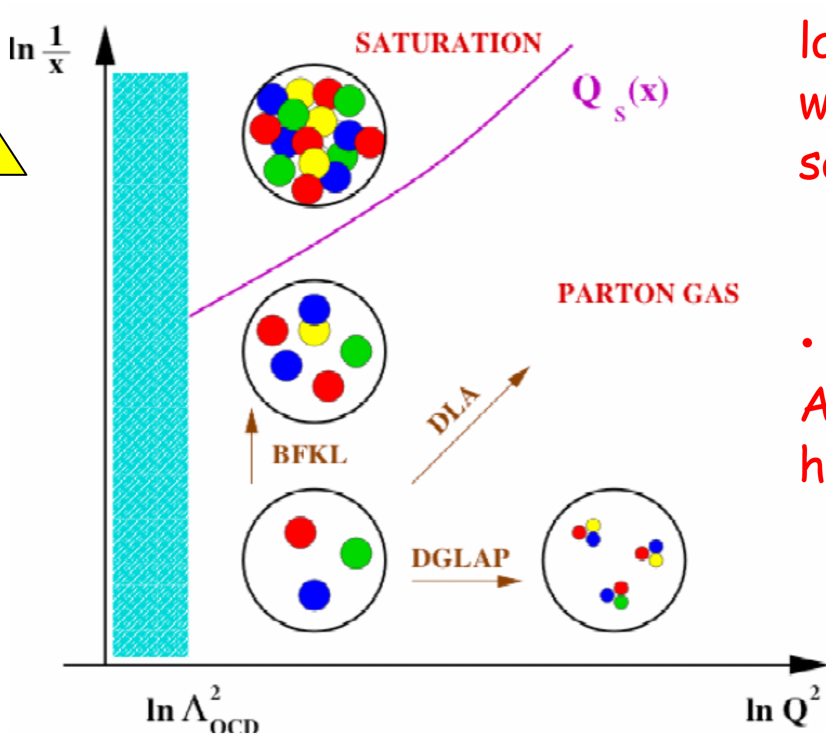


Armesto & Salgado, hep-ph/0308248



Cold Nuclear Matter Effects
Gluon Saturation & the Color Glass Condensate (CGC)

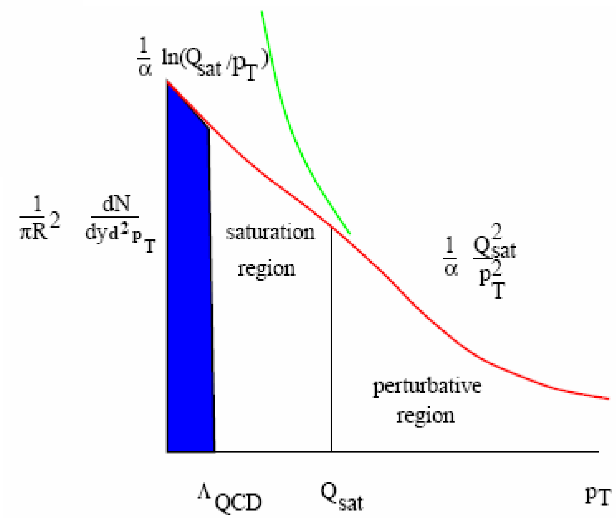




At low-x gluon density becomes very large & a non-linear evolution regime with 2 → 1 gluon processes sets in at saturation scale Q_s

- CGC is an effective theory for that regime

- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon
  - gives "shadowing"



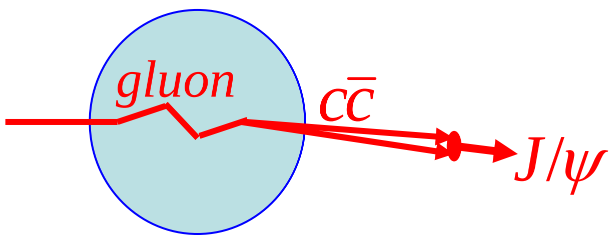
More saturation at Lower x

y~log(1/x)

Lower x → forward rapidity

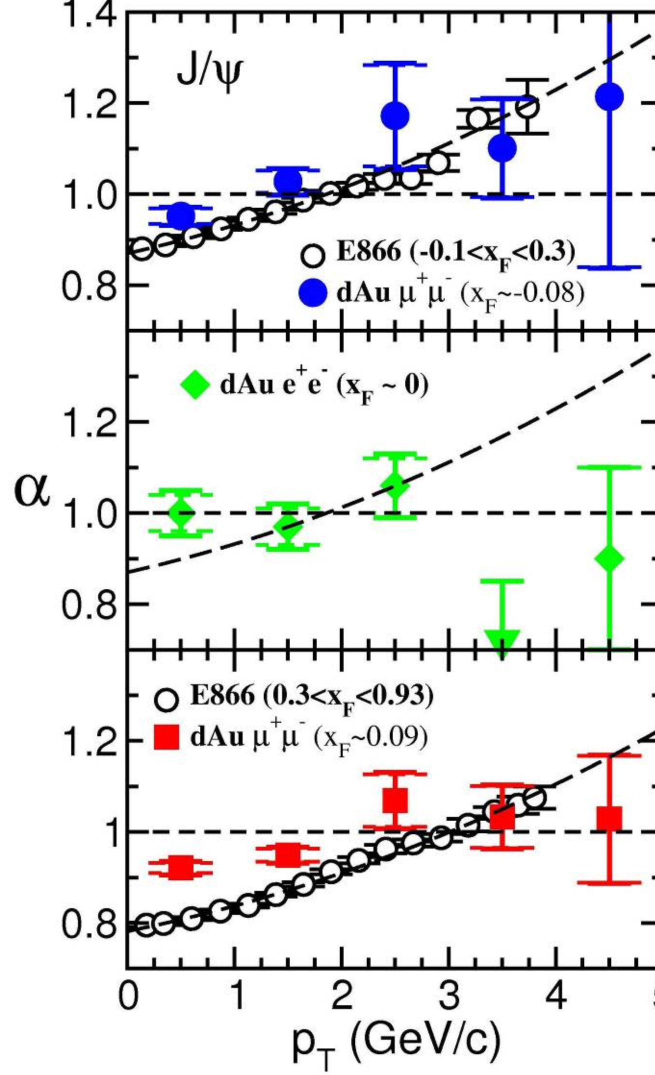
Cold Nuclear Matter for J/ψ Transverse Momentum Broadening

$$\sigma_A = \sigma_N A^{\alpha}$$



Initial-state gluon multiple scattering causes **p_T broadening** (or Cronin effect)

PRL 96, 012304 (2006)



High x_2 ~ 0.09

PHENIX 200 GeV results show p_T broadening comparable to that at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

Low x_2 ~ 0.003

Alternative picture for forward charm suppression in dAu

Vitev, Goldman, Johnson, Qiu – hep-ph/0605200

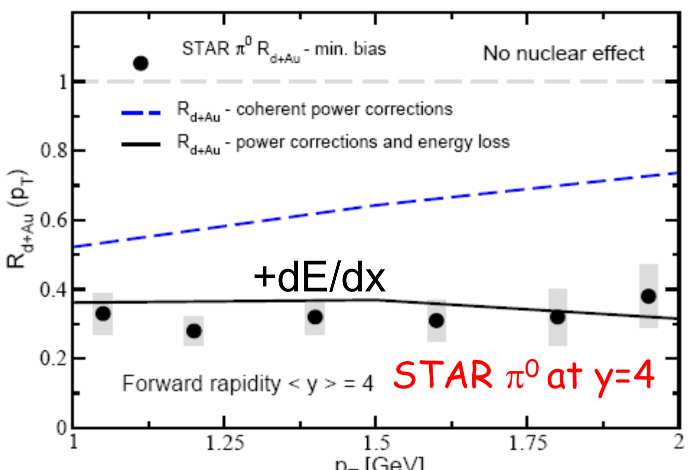
cg & cq dominate inclusive D production

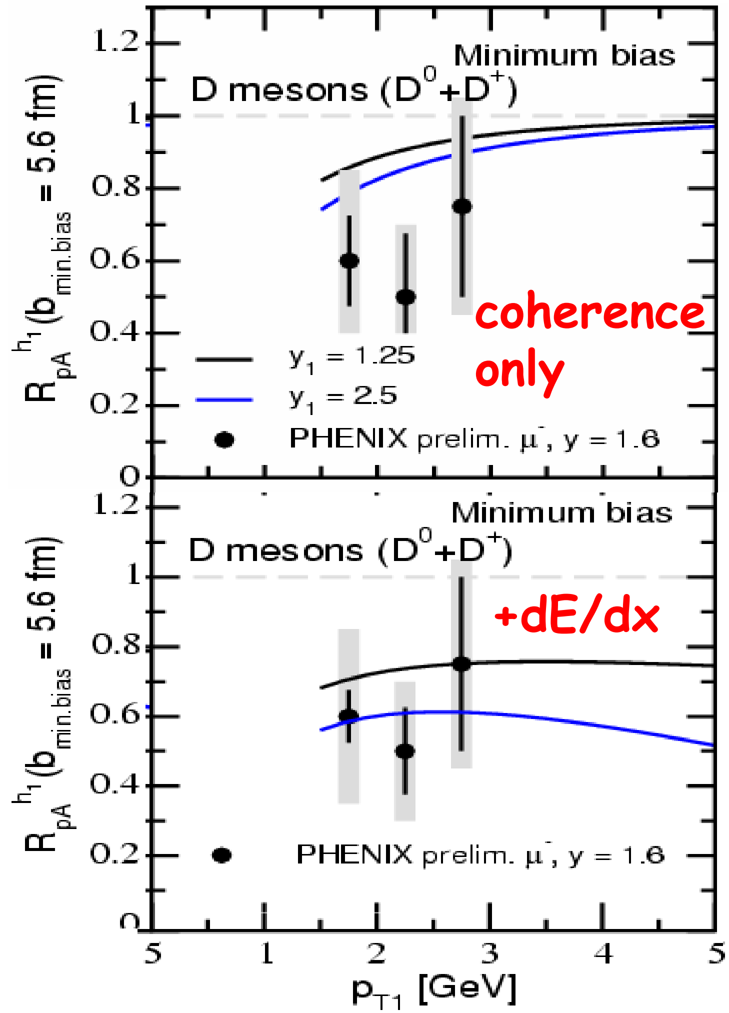
final-state coherence effects

- 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

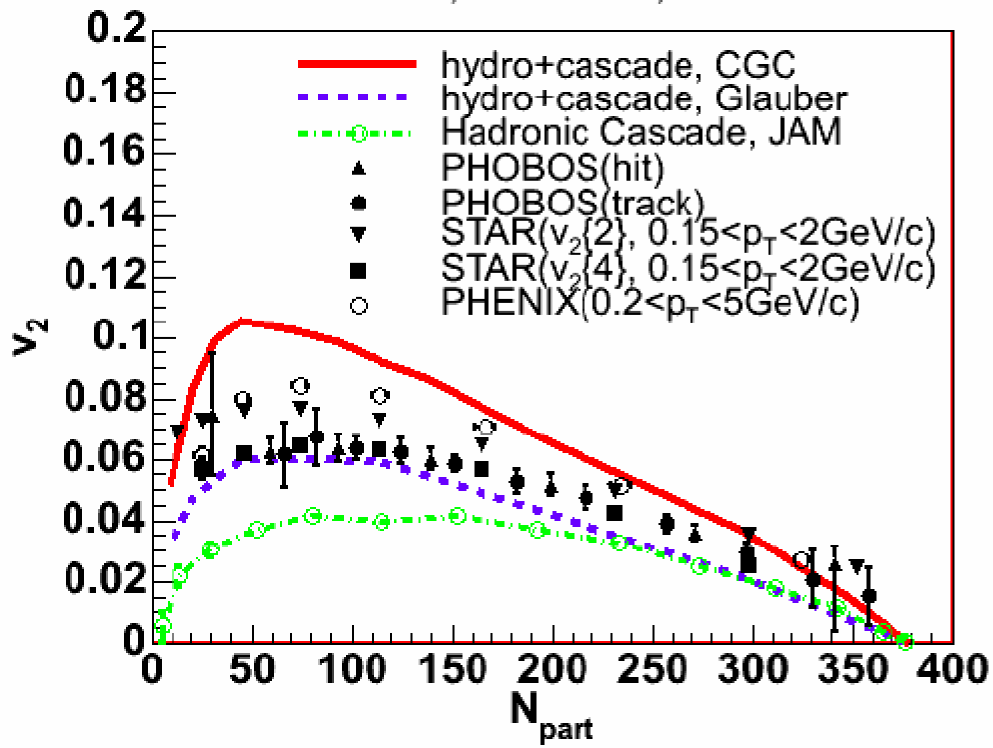
- large dE/dx - average parton loses 10% of its energy!

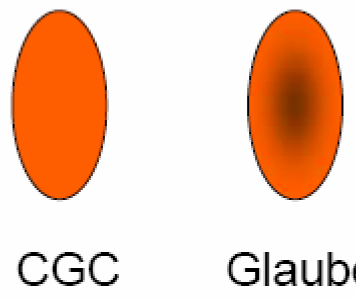




Another urgent d+Au question: v_2 and the hydro limit--Glauber vs Color Glass Condensate

Hirano et al, PLB 636, 299





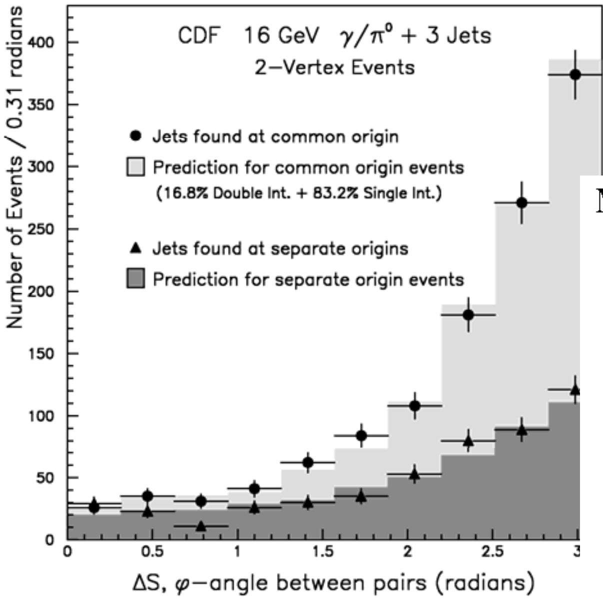
CGC: Treats the nucleus as a saturated gluon field

Effects initial eccentricity of the overlap zone

- Do we have Glauber matter distribution + perfect liquid, or Color Glass Condensate distribution + viscous matter?
- Understanding the initial state is **crucial to understand what we are seeing in the final state**

Double parton correlations

CDF, PRL 79, 584



PRL 88, 031801

Measuring Double-Parton Distributions in Nucleons at Proton-Nucleus Colliders

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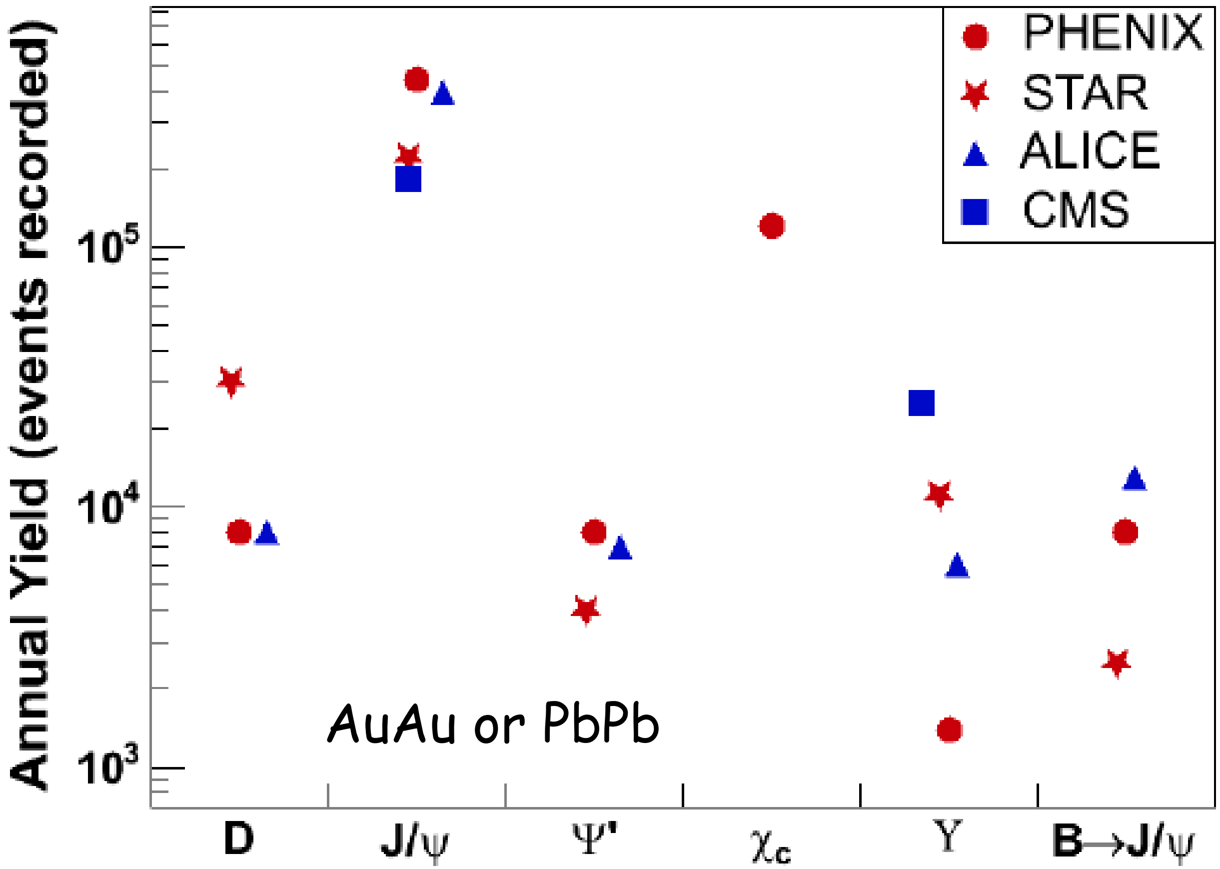
We predict a strong enhancement of multijet production in proton-nucleus collisions at collider energies, as compared to a naive expectation of a cross section $\propto A$. The study of the process would allow one to measure, for the first time, the double-parton distribution functions in a nucleon in a model-independent way and hence to study both the longitudinal and the transverse correlations of partons.

A-dependence of 4-jet yields in p+A collisions can be used to measure $x_1 - x_2$ momentum correlations within the proton.

- This would require pA, not dA collisions!

Annual yields at RHIC II & LHC are similar



RHIC-II:
- AuAu 12 weeks

LHC HI:
- PbPb 10^6 sec ($500\ \mu b^{-1}$)

from RHIC-II White Paper.

RHIC-II & LHC rate comparisons (RHIC: 12 weeks of AuAu; LHC: 1 month of PbPb). From RHIC-II White paper,

	RHIC-II				LHC Heavy Ions					
Signal	PHENIX	|η|	STAR	|η|	ALICE	|η|	CMS	|η|	ATLAS	|η|
$J/\psi \to ee$	55k	<0.35	220k	<1	9.5k	<0.9				
$J/\psi \to \mu\mu$	470k	1.2-2.4			740k	2.5-4	24k	<2.4	8-100k	<2.5
$\psi' \to ee$	990	<0.35	4k	<1	190	<0.9				
$\psi' \to \mu\mu$	8.5k	1.2-2.4			14k	2.5-4	440	<2.4	1.4k-1.8k	<2.5
$\chi_C \to ee\gamma$	3.6k	<0.35								
$\chi_C \to \mu\mu\gamma$	139k	1.2-2.4								
$\Upsilon \to ee$	200	<0.35	11.2k	<1	2.6k	<0.9				
$\Upsilon \to \mu\mu$	500	1.2-2.4			8.4k	2.5-4	26k	<2.4	15k	<2
$B \to J/\psi \to ee$	300	<0.35	2.5k	<1						
$B \to J/\psi \to \mu\mu$	3k	1.2-2.4								
$D \to K\pi$	?		30k	<1	8k	<0.9				

Proton Structure: By What Process Is the Sea Created?

- Meson Cloud in the nucleon

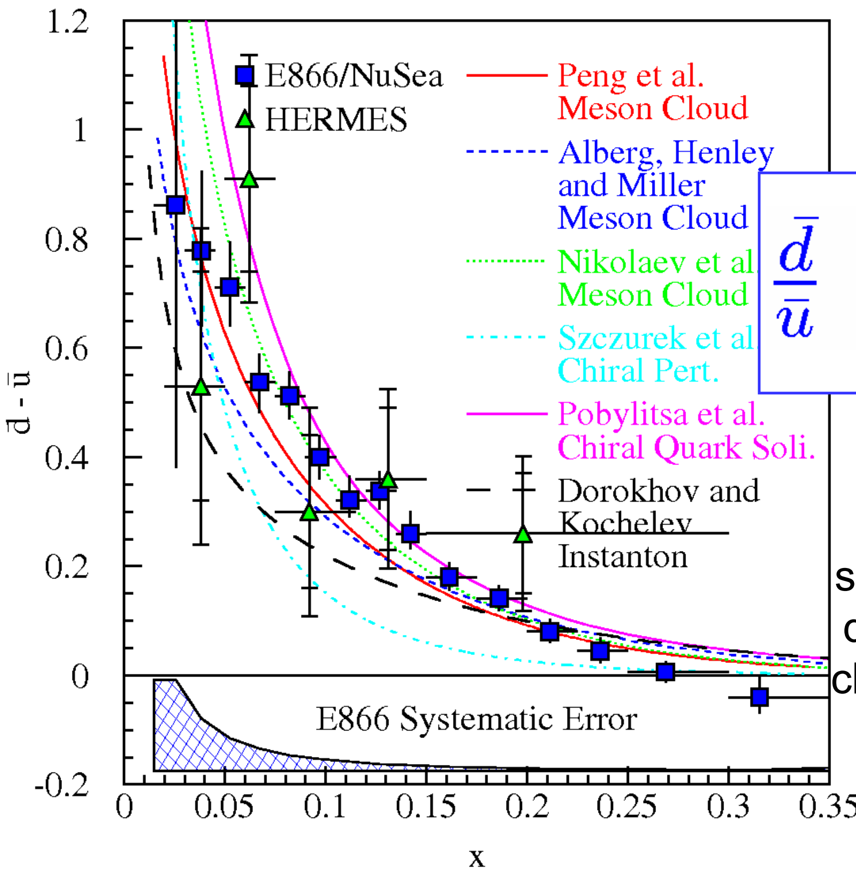
  Sullivan process in DIS

  $|p\rangle = |p_0\rangle + \alpha\,|N\pi\rangle + \beta|\Delta\pi\rangle + \ldots$

- Chiral Models

  Interaction between Goldstone Bosons and valence quarks

  $|u\rangle \rightarrow |d\pi^{+}\rangle$ and $|d\rangle \rightarrow |u\pi^{-}\rangle$



$$\frac{\bar{d}}{\bar{u}} = \frac{\bar{d}^{\pi} + \bar{q}}{\bar{u}^{\pi} + \bar{q}}$$

Perturbative sea apparently dilutes meson cloud effects at large-x