Forward Physics and Gluon Saturation in the RHIC-II Era

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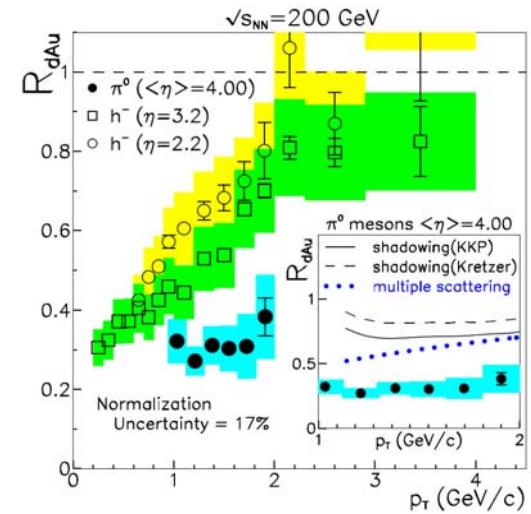
Future Prospects in QCD at High Energy, 17-22 July 2006, BNL

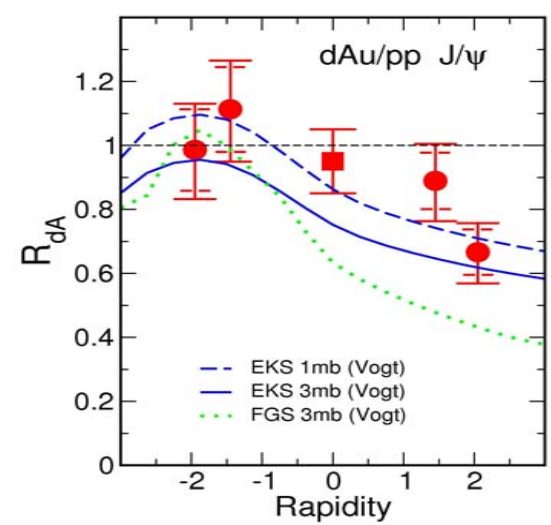
Physics at large rapidity & small-x: cold nuclear matter (CNM) effects & gluon saturation

- quarkonia
- forward hadrons
- correlations & mono-jets
- open heavy quarks
- UPC's

Future

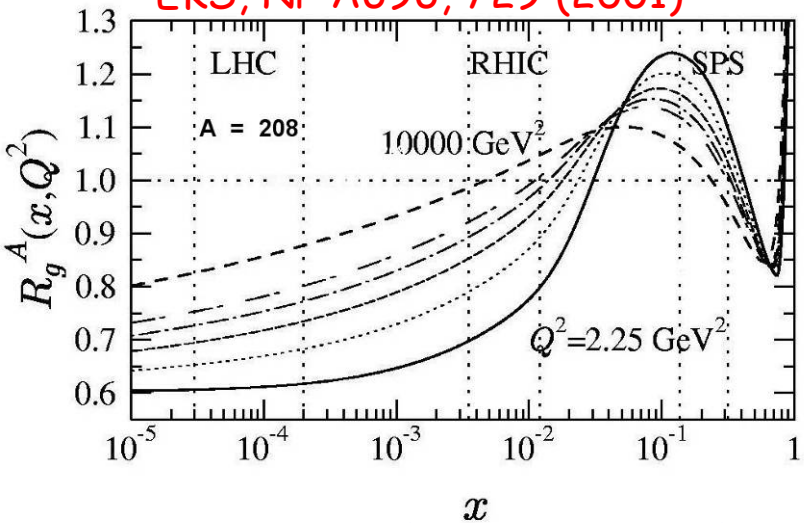
- physics goals
- upgrades & rates





Cold Nuclear Matter Effects
Gluon Shadowing

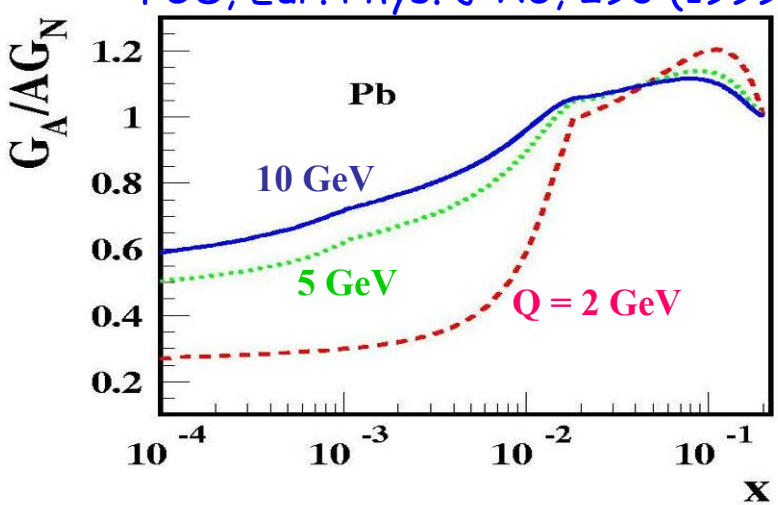
EKS, NP A696, 729 (2001)



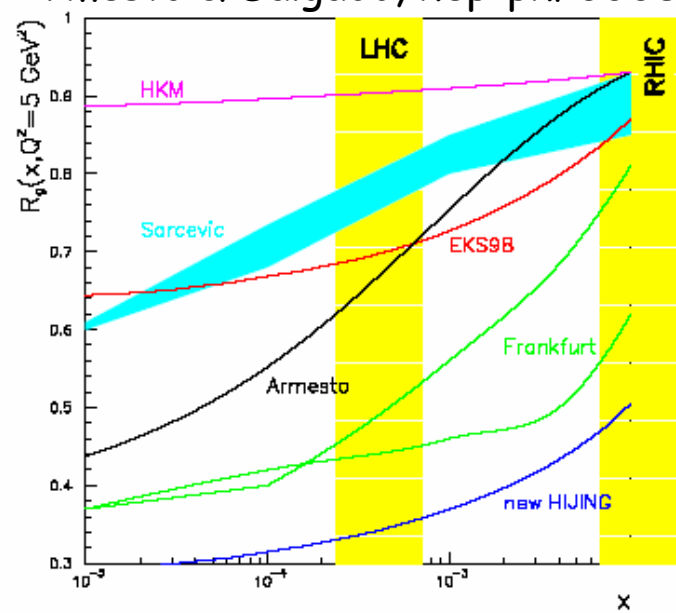
- Phenomenological fit to Deep-Inelastic Scattering & Drell-Yan data
- Leading twist gluon shadowing
- Coherence approach, and many others

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

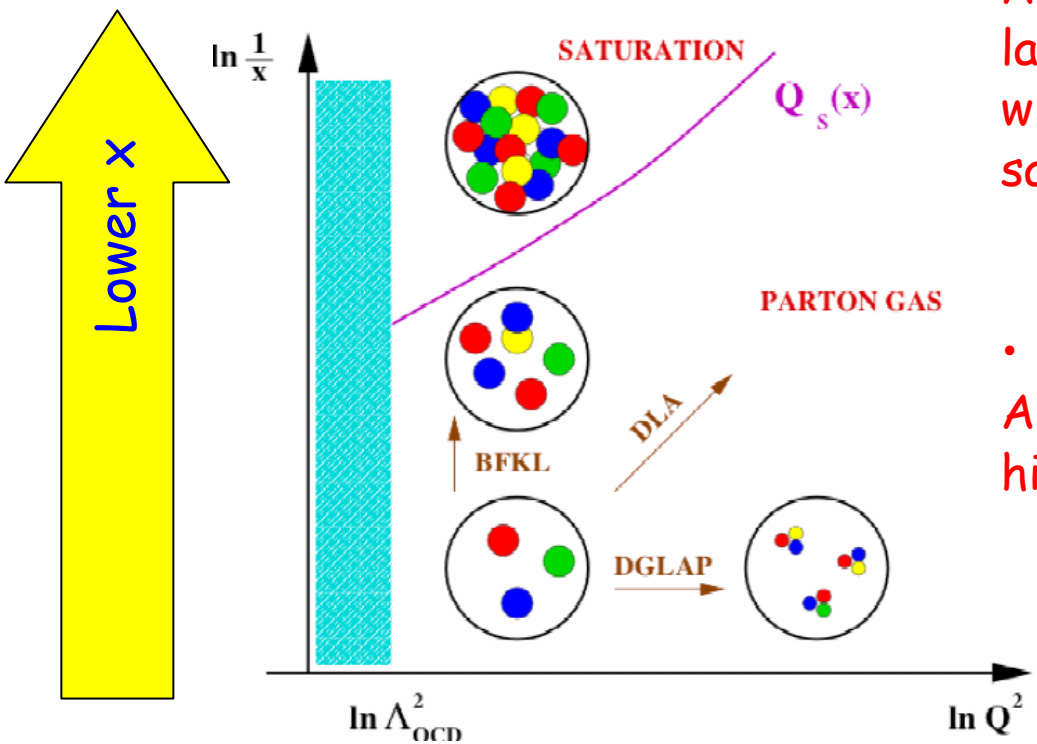
FGS, Eur. Phys. J A5, 293 (1999)



Armesto & Salgado, hep-ph/0308248



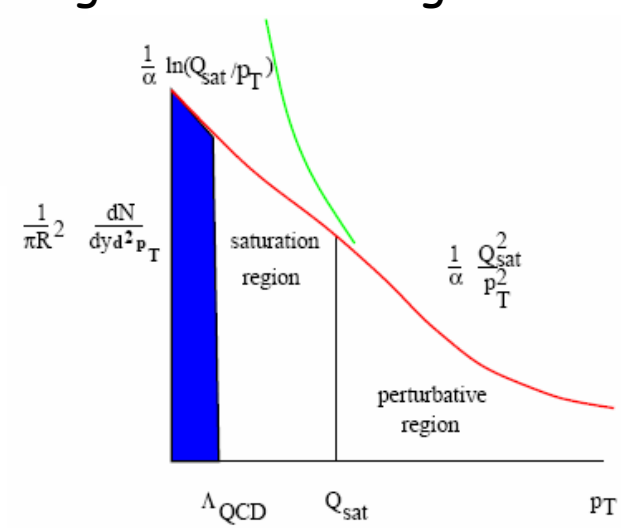
Cold Nuclear Matter Effects
Gluon Saturation & the Color Glass Condensate (CGC)



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"



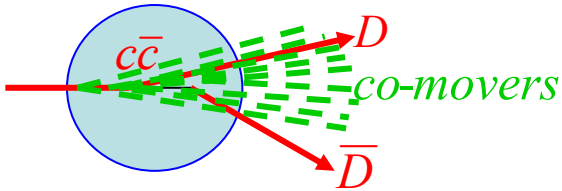
More saturation at Lower x

y~log(1/x)

Lower x → forward rapidity

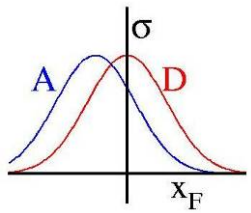
Cold Nuclear Matter Effects
The J/ψ - a Puzzle

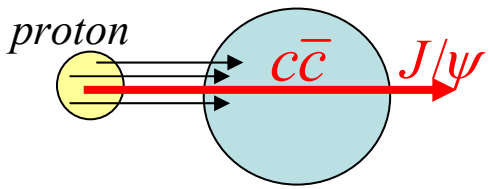
J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:



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

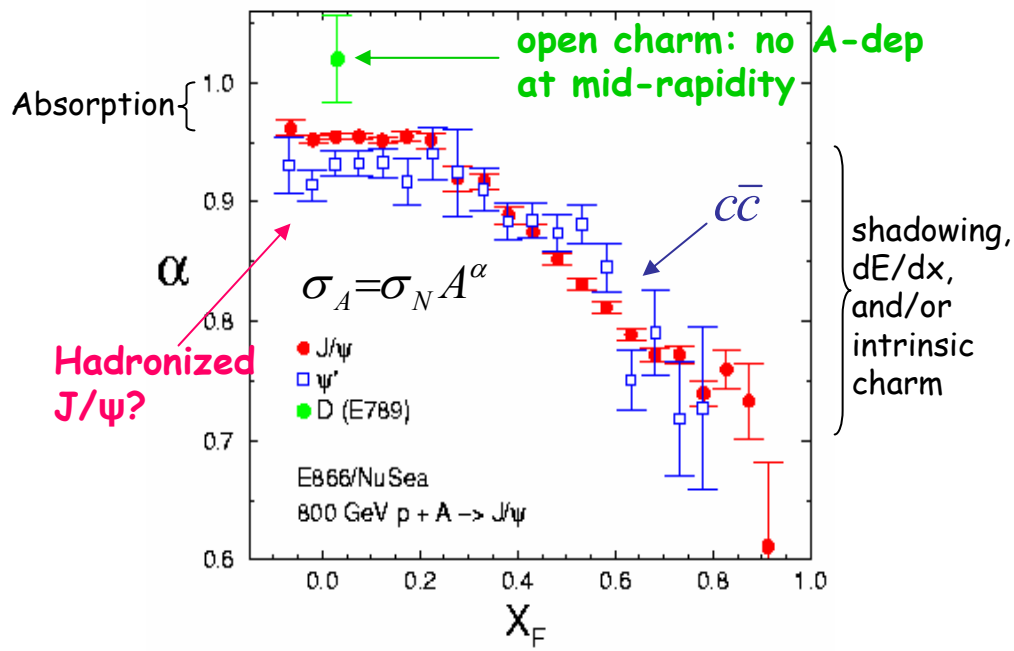




Intrinsic charm components of incident proton produce J/ψ at large x_F. $A^{2/3}$ dependence from surface stripping of proton's light quarks (Brodsky)

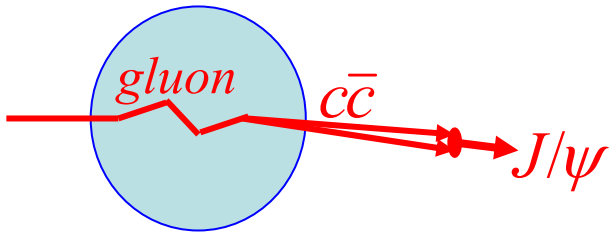
800 GeV p-A (FNAL)

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



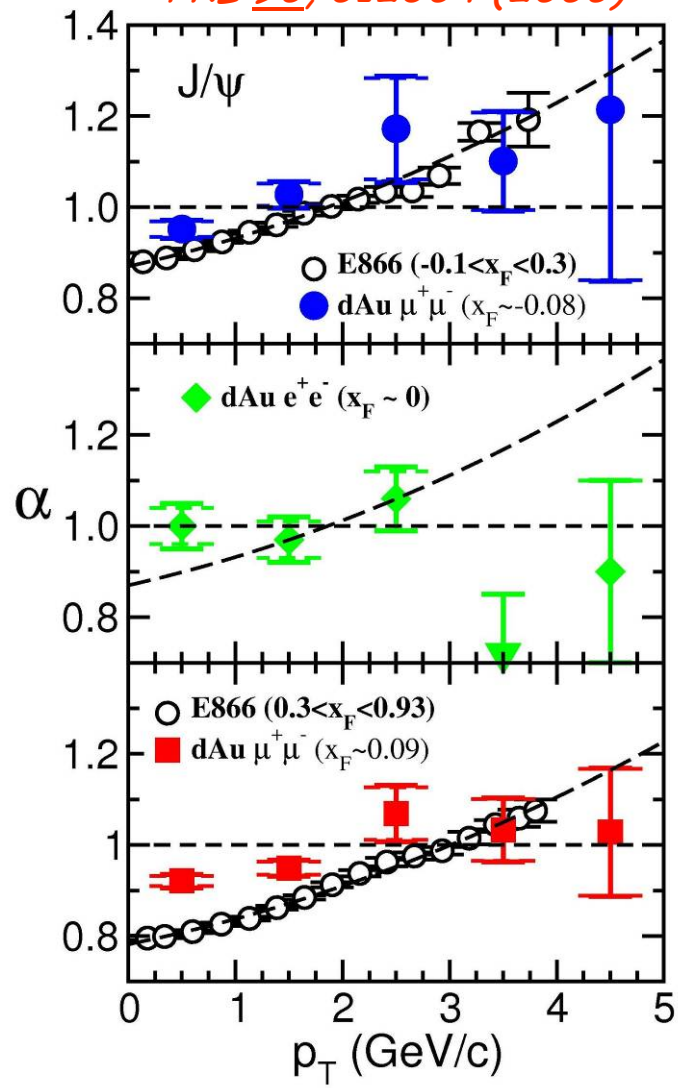
Transverse Momentum Broadening for J/ψ's

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



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

PRL 96, 012304 (2006)

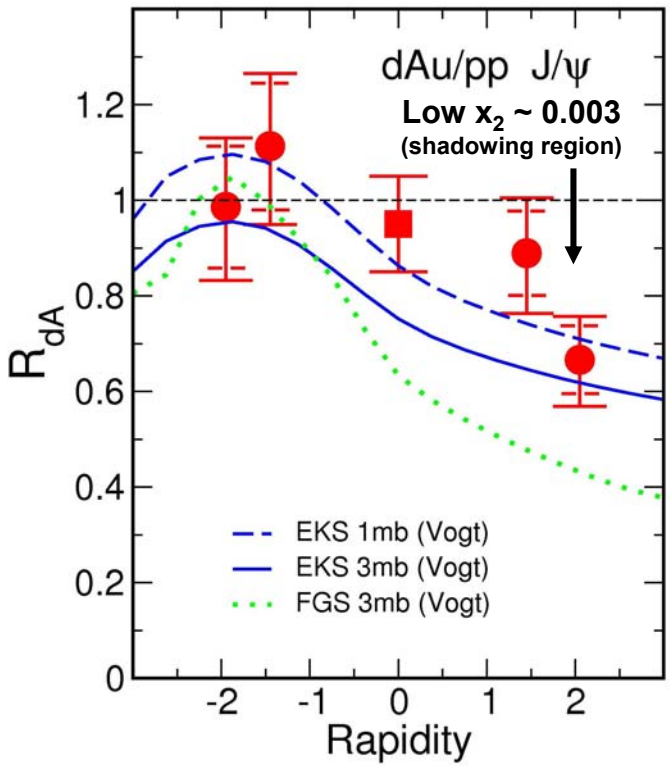


High x_2 ~ 0.09

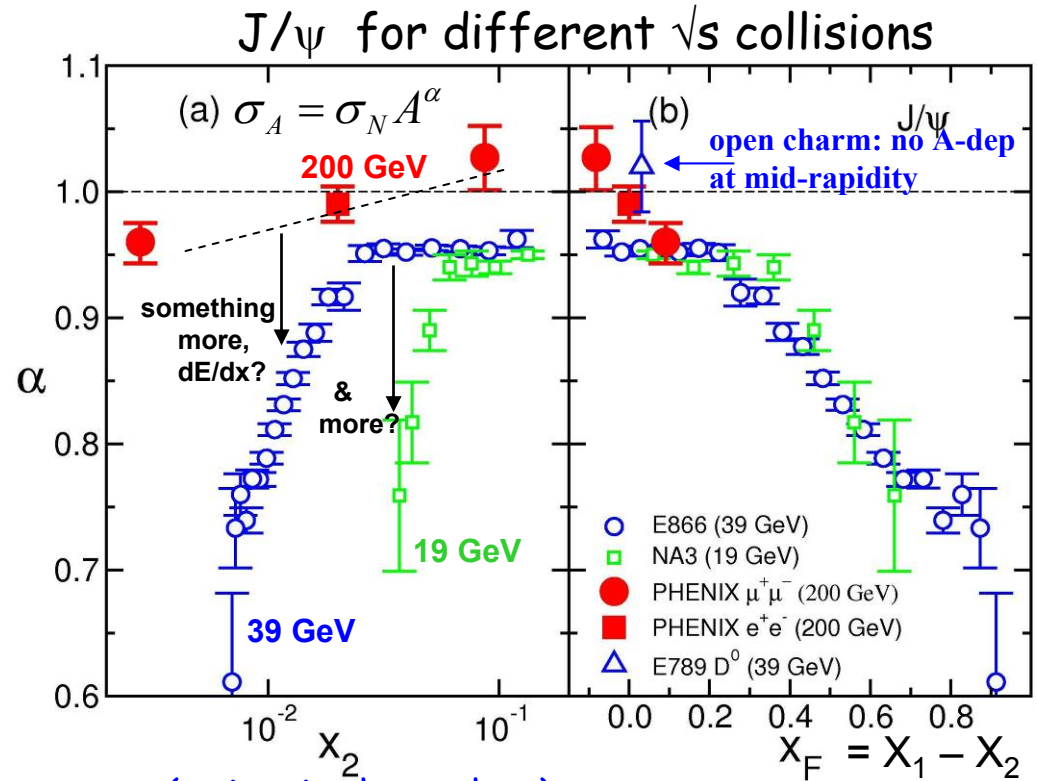
PHENIX 200 GeV results show p_T broadening comparable to that at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

Low x_2 ~ 0.003

PHENIX J/ψ Nuclear Dependence for 200 GeV pp and dAu collisions – PRL 96, 012304 (2006)



Klein,Vogt, PRL 91:142301,2003



(x_2 is x in the nucleus)

Data favors weak shadowing & absorption

- With limited statistics difficult to disentangle nuclear effects
- Will need another dAu run! (more pp data also)

Not universal vs x_2 as expected for shadowing, but does scale with x_F, why?

- initial-state gluon energy loss?
- Sudakov suppression (next slide)?

Sudakov suppression

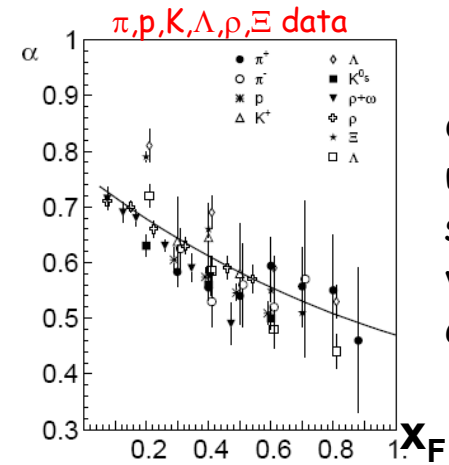
Kopeliovich hep-ph/0501260

Universal suppression at large x_F seen in data for various reactions:

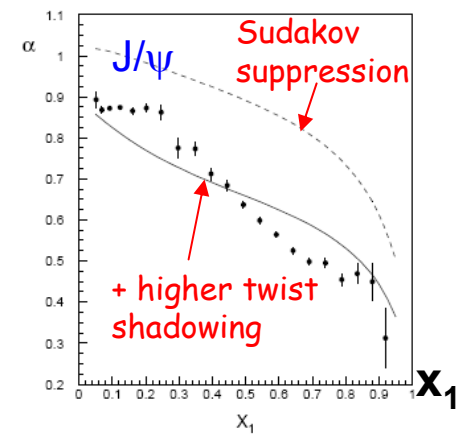
- forward light hadrons, Drell-Yan, heavy flavor
- often attributed to shadowing since x_2 is small

But this common suppression mechanism can also be viewed as:

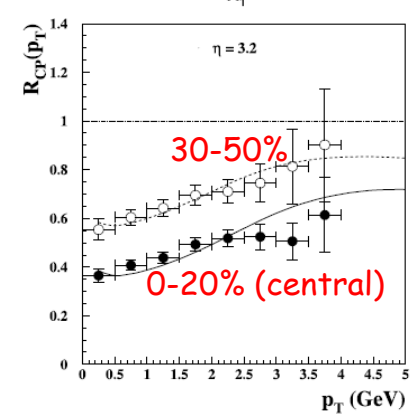
- Sudakov suppression – no particles produced as $x_F \rightarrow 1$ due to energy conservation; more multiple interactions make the effect larger in nuclei
- or Reduced survival prob. for large rapidity gap processes in nuclei as $x_F \rightarrow 1$



describes universal suppression vs x_F for low energy data



Close to 800 GeV J/ψ suppression vs x_1 ($x_1 \approx x_F$)



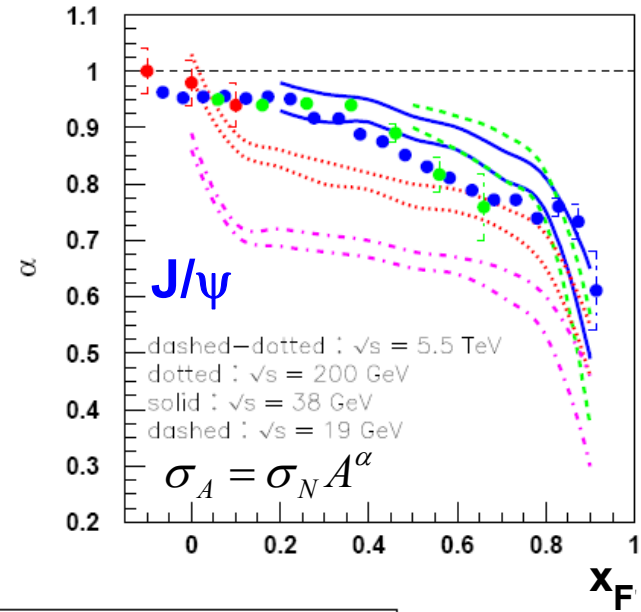
and Brahms forward rapidity (η=3.2) hadrons

J/ψ in Color Glass Condensate (CGC) model
Kharzeev, Tuchin, hep-ph/0510358

- Coherent production of heavy quarks at high energy, when $\tau_{Prod} > R_A$

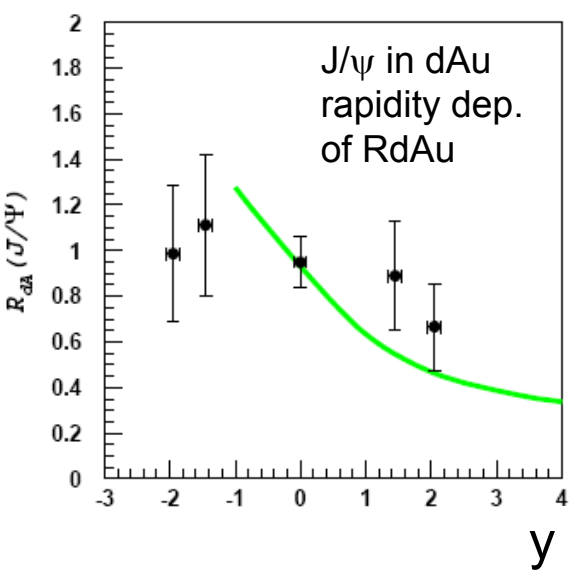
$$\tau_{Prod} \approx 15e^{y}\ fm \text{ (at RHIC)}$$

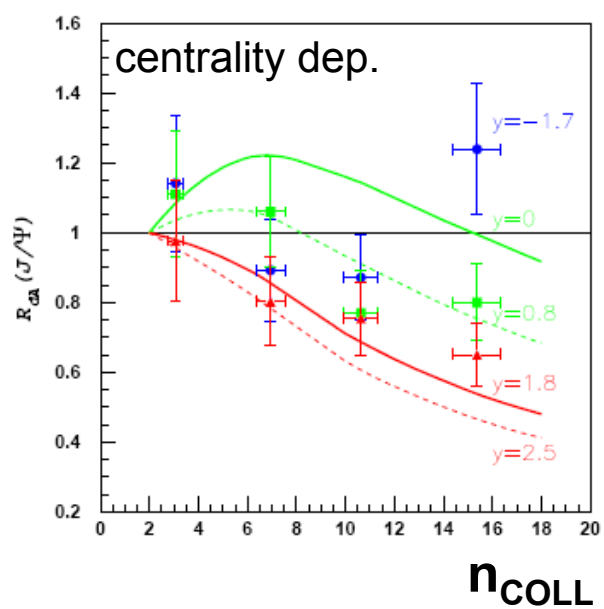
- Suppressed by saturated gluon wavefunction at forward y



x_F scaling at forward rapidity

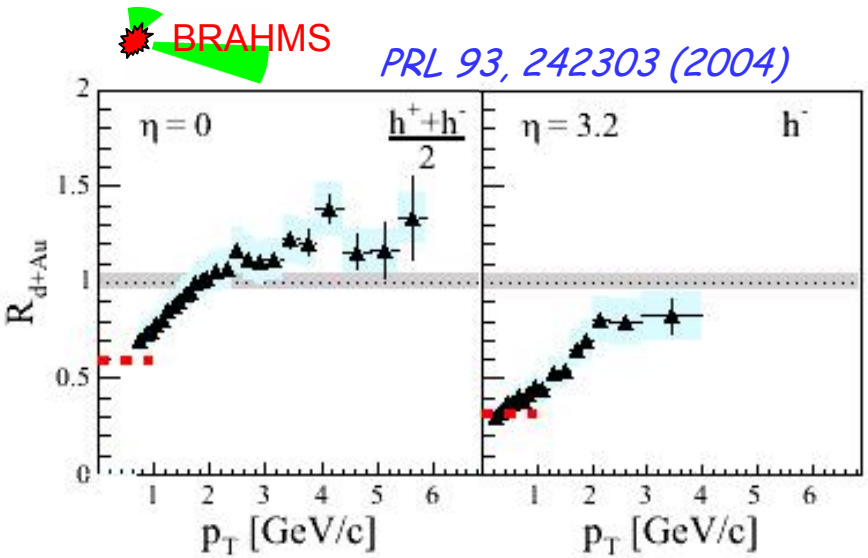
* NA3
* E866/NuSea
* PHENIX



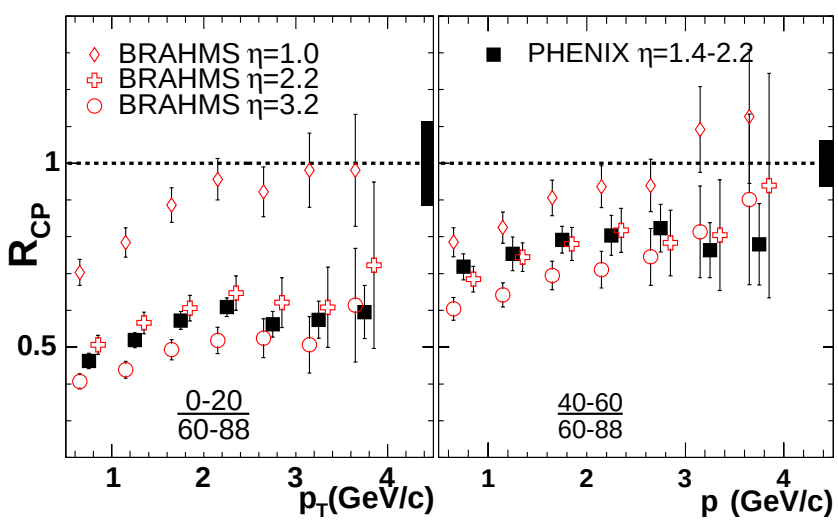


- Suppression at forward rapidity - increases with centrality;
- Enhancement for backward rapidity

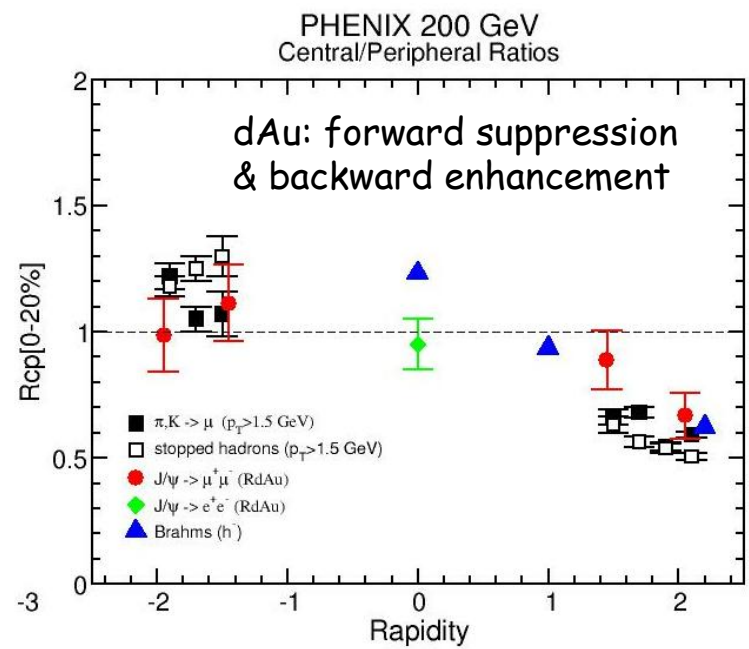
Forward hadrons



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

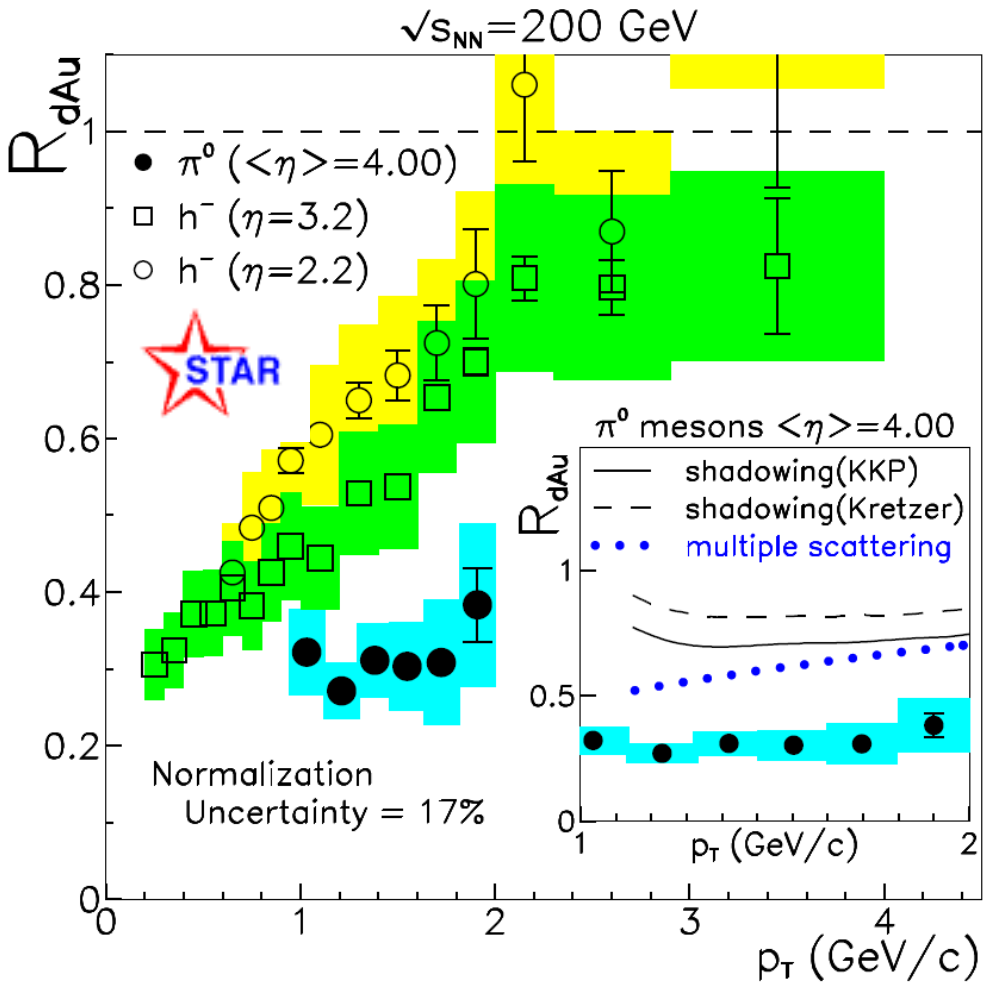


PRL 94, 082302 (2005)
& nucl-ex/0507032



η Dependence of R_{dAu}

Very forward π^0's



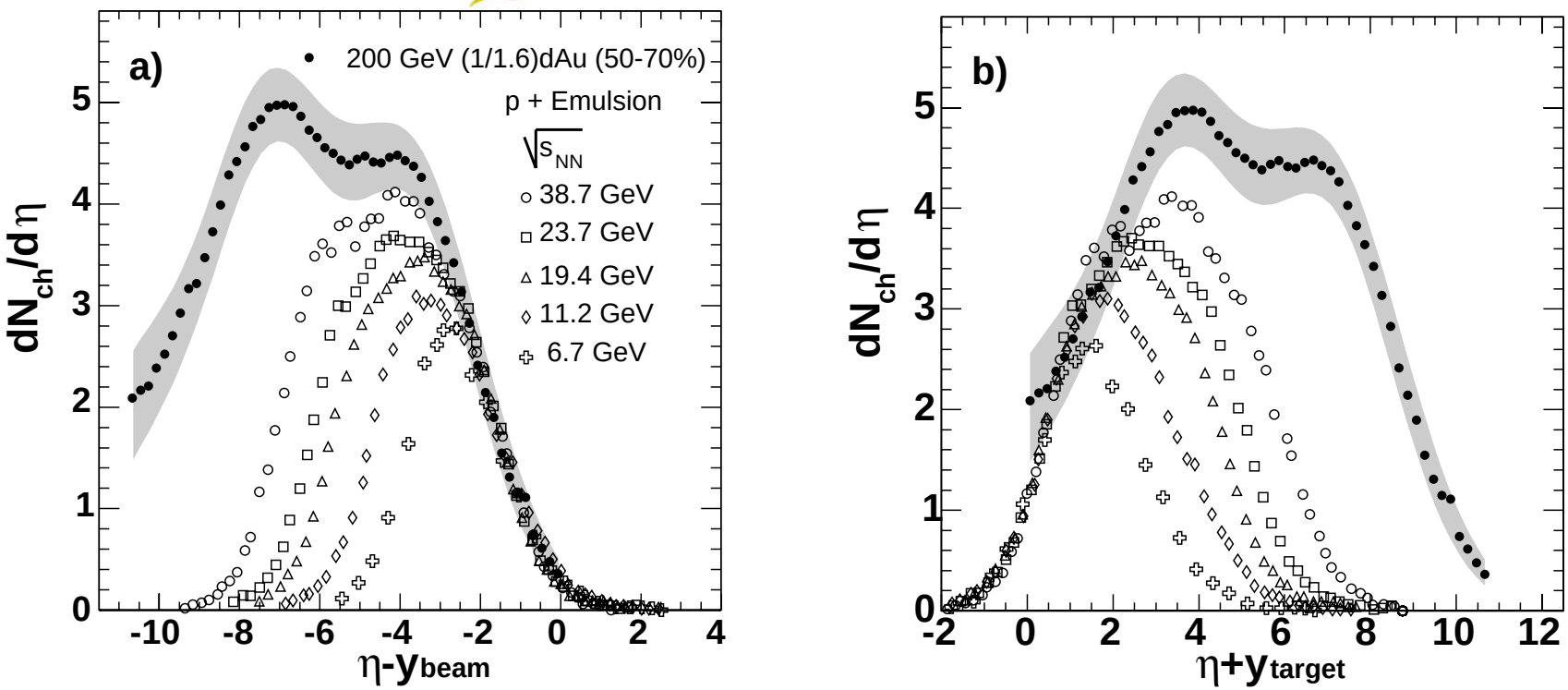
$$R_{\mathrm{dAu}} \approx \frac{1}{2\times 197}\frac{\sigma_{dAu}}{\sigma_{pp}}$$

(Brahms h^- data)

Observe **significant rapidity dependence**, similar to BRAHMS measurements and expectations from saturation framework.

Comparing d+Au dN/dη to p+emulsion

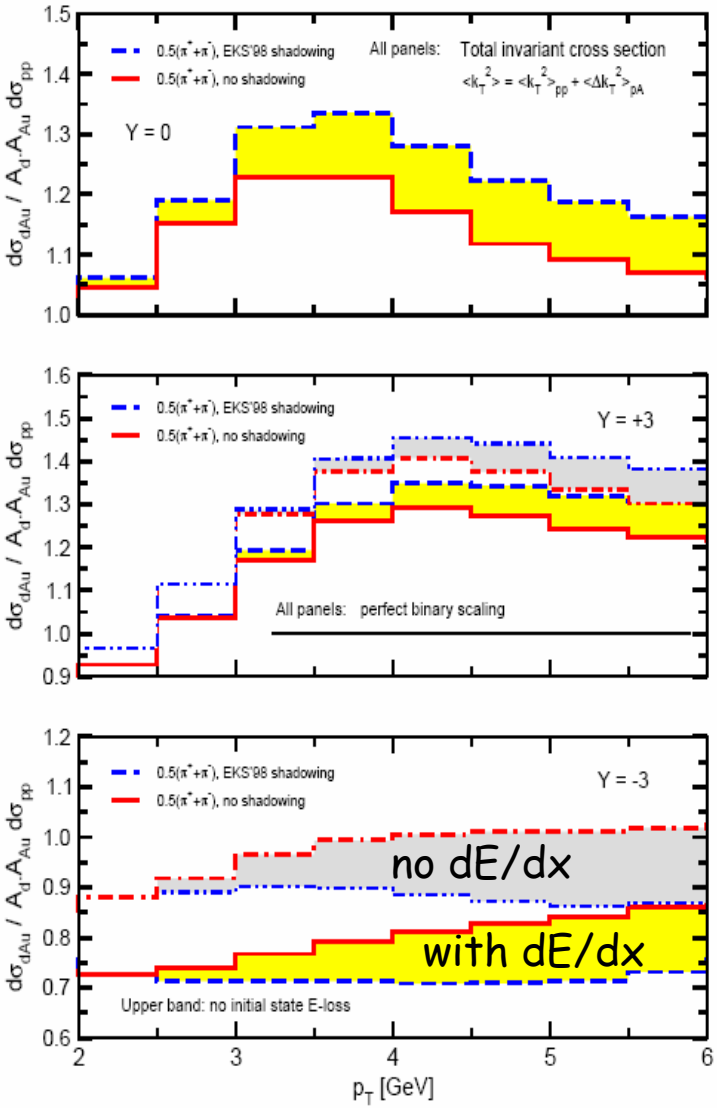
nucl-ex/0409021



Limiting Fragmentation Phenomena – a universal suppression pattern across diff. observed particles and collision energies

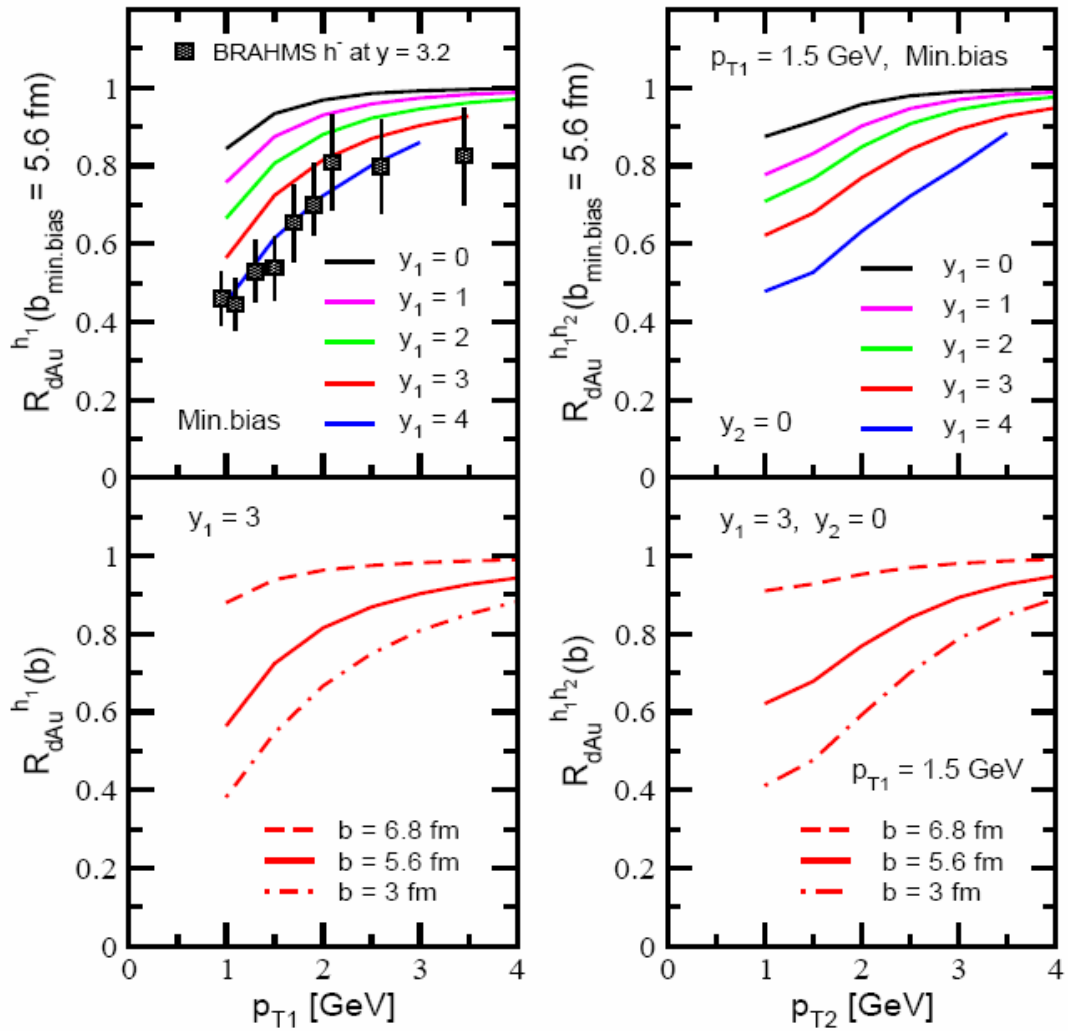
Vitev, nucl-th/0302002

elastic multiple scattering &
initial-state collisional energy loss



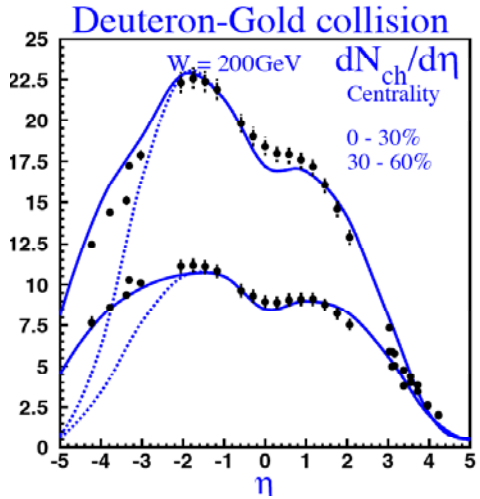
Vitev - forward hadron suppression
hep-ph/0405068

nuclear enhanced power corrections in
coherent multiple scattering



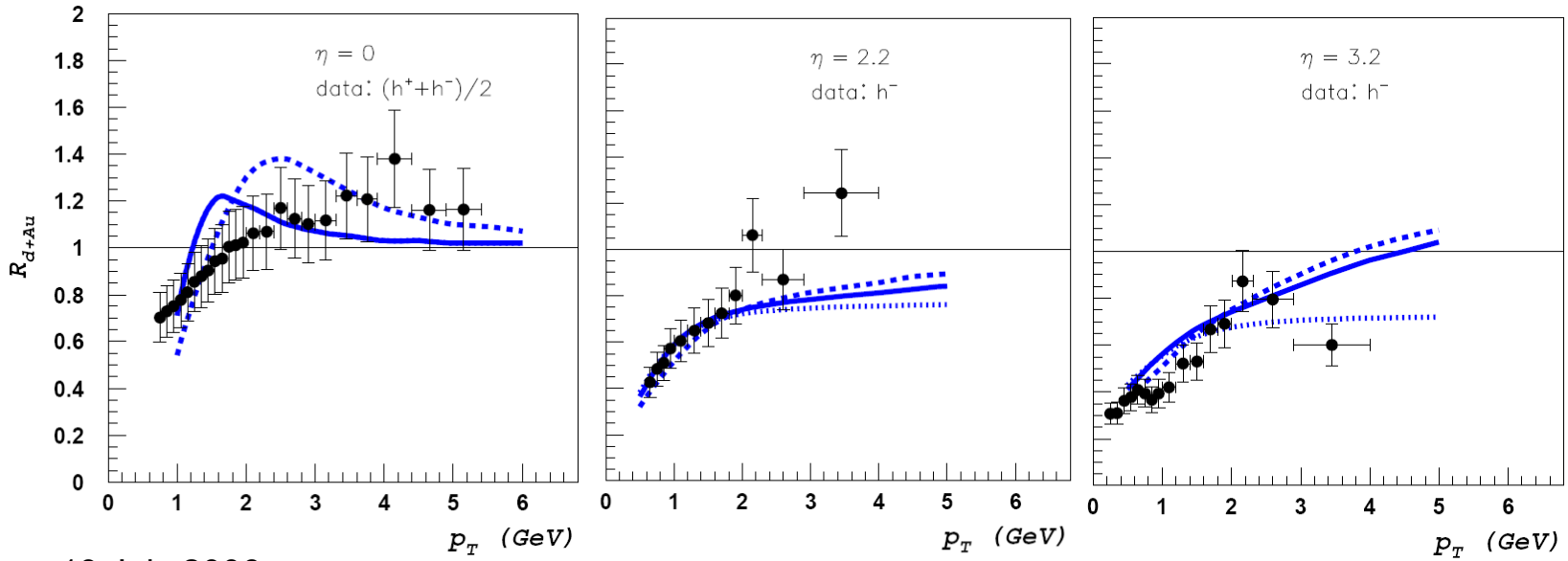
Color Glass Condensate (CGC) model

Reproduces charged particle multiplicity asymmetry in dAu



Kharzeev, Kovchegov, Tuchin, hep-ph/0405045

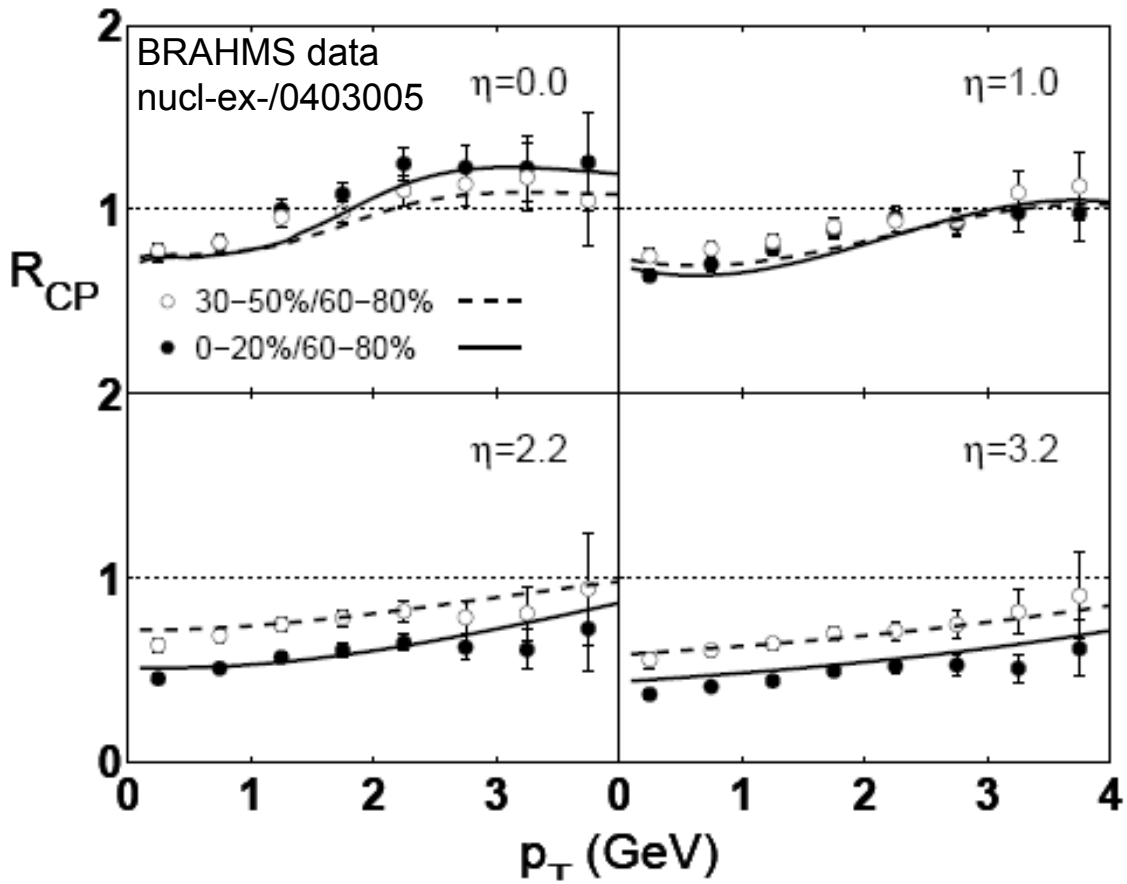
and Brahms hadron forward suppression pattern



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

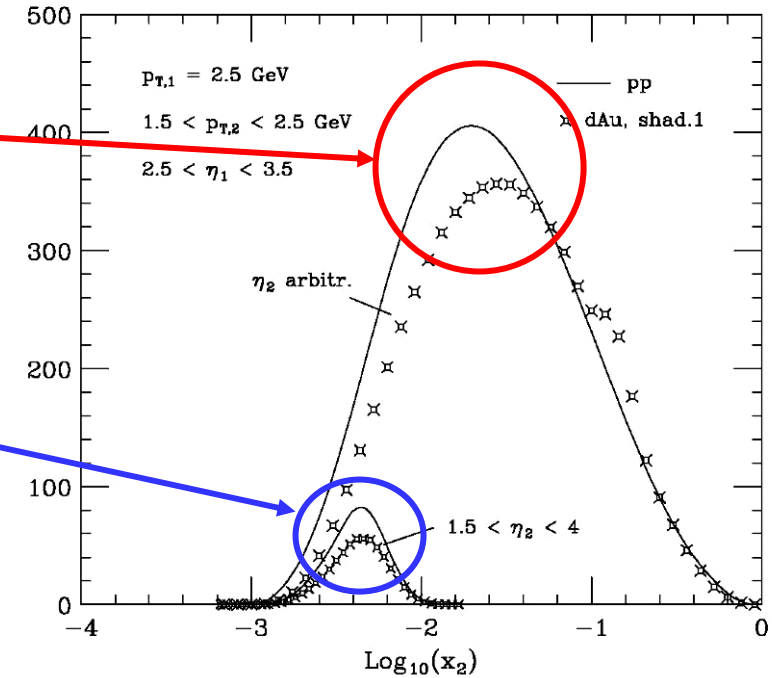


Guzey, Strikman, and Vogelsang - PL B603, 173 (2004)

But forward hadron production does not probe such small momentum fraction: $\langle x_g \rangle \sim 0.02$ in NLO pQCD calculations so leading twist shadowing & CGC saturation regions may not be probed

Only one π^0 detected

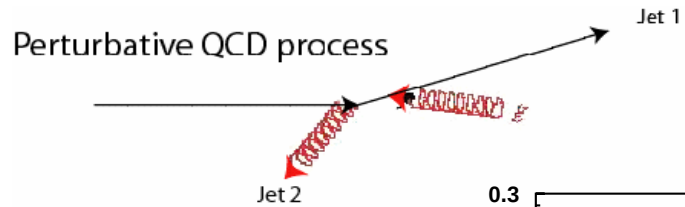
Both π^0's detected at forward rapidity



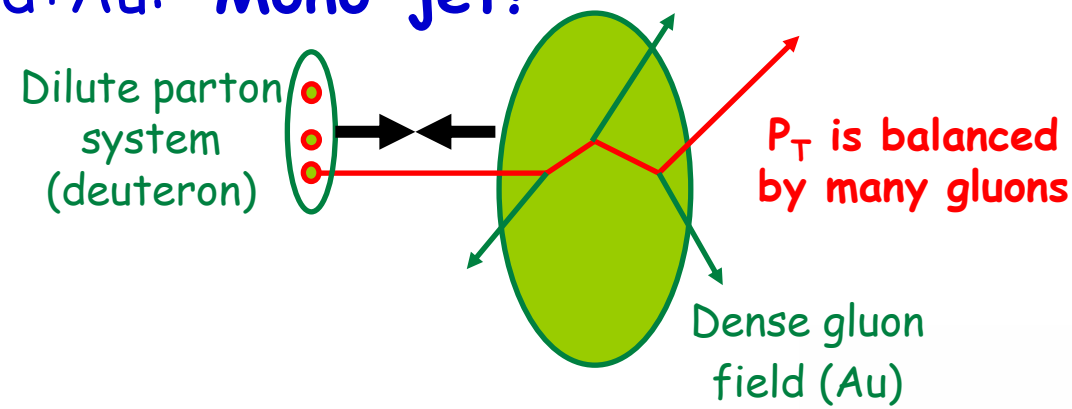
However, as shown by Guzey et al., if one measures two forward hadrons (π^0's) then one CAN pin x_2 down to small values

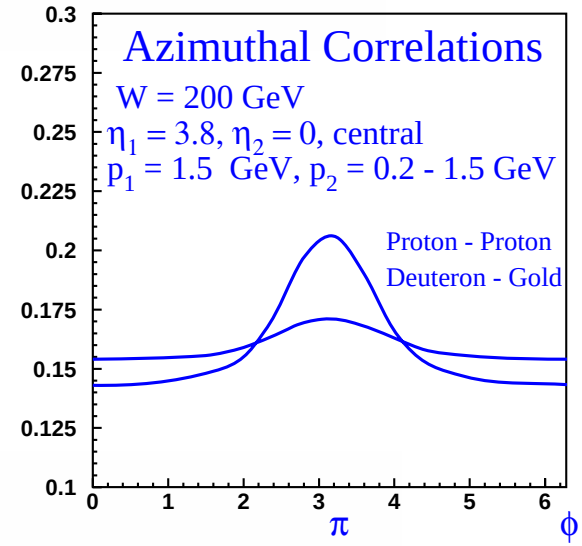
Mono-jets from the CGC picture

p+p: **Di-jet**

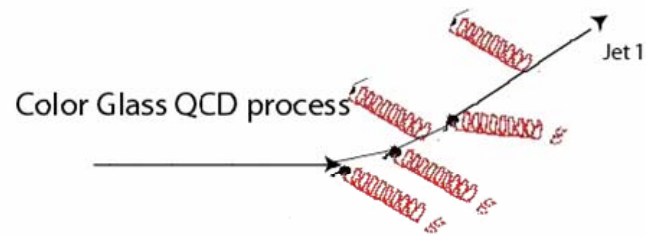


d+Au: **Mono-jet?**



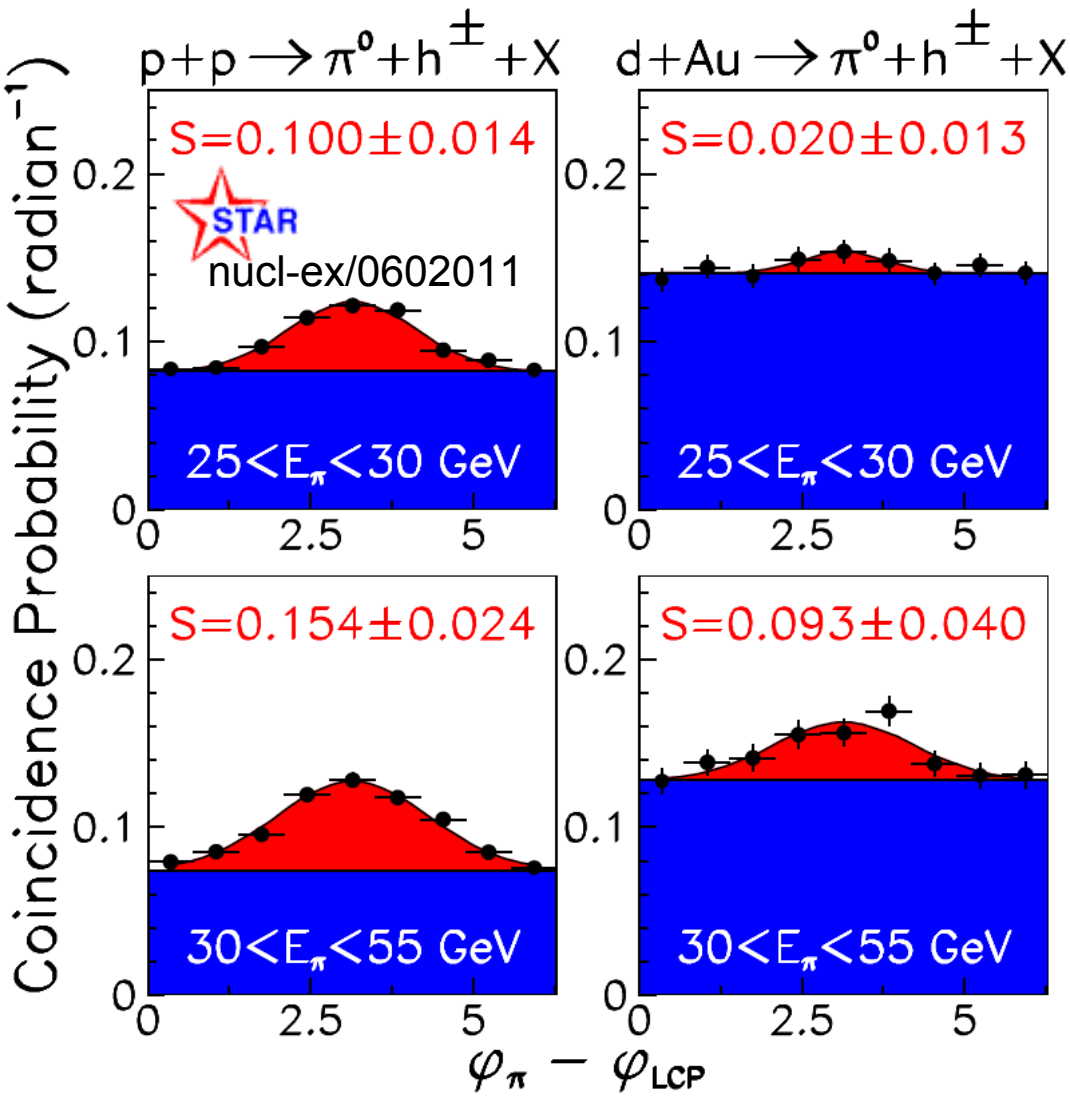


Kharzeev, Levin, McLerran give physics picture (NPA748, 627)



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

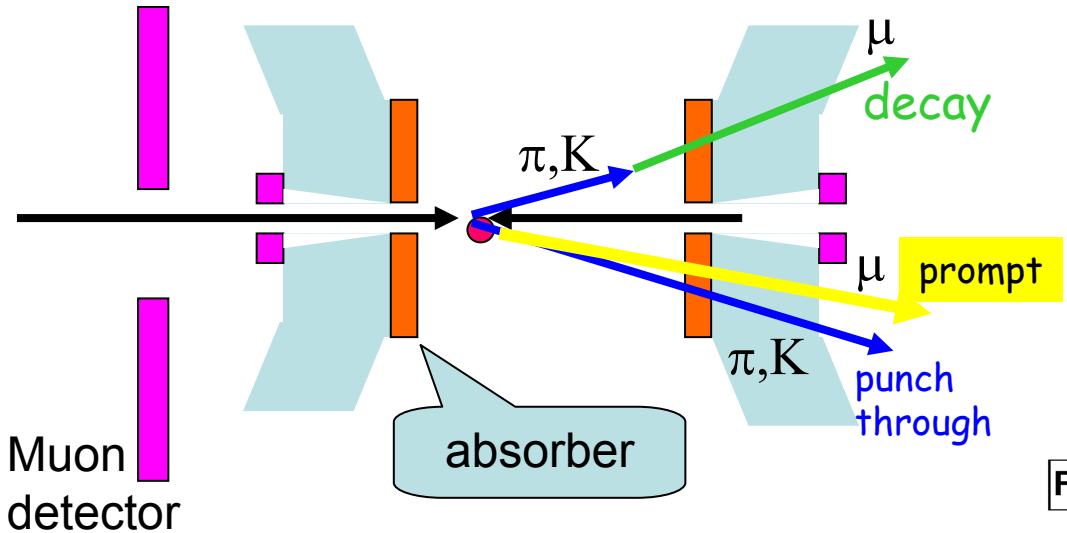
$\pi^0 + h^\pm$ Correlations in dAu Collisions

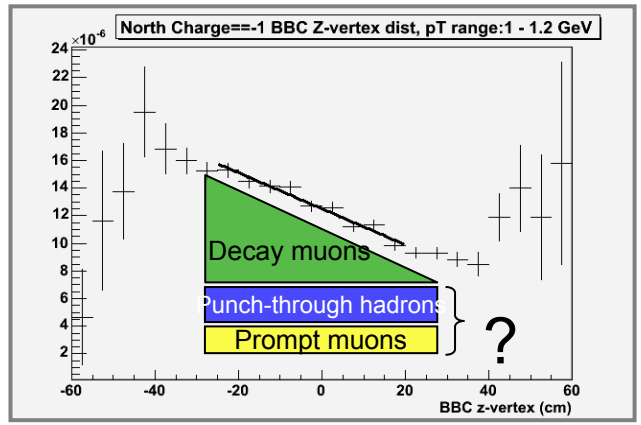


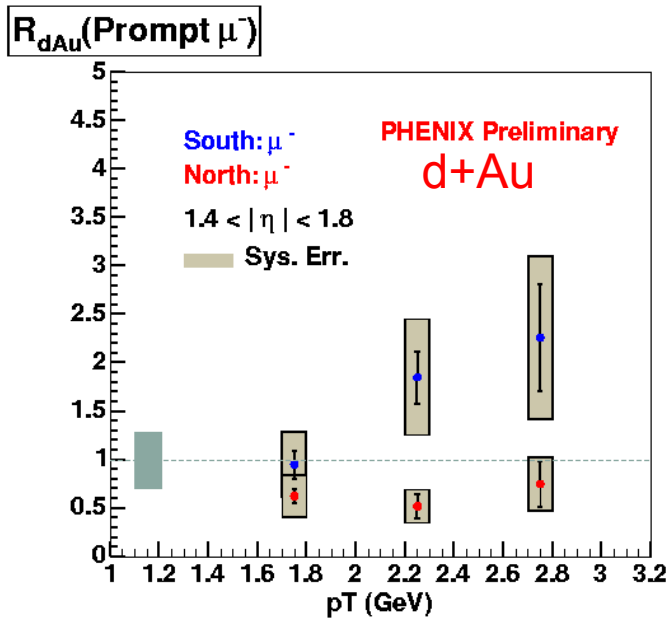
$\langle\eta\rangle$ = 4 and $h^\pm$ p_T>0.5 GeV/c
"S" is area of the coincident peak

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

CNM effects on single muons –charm and beauty







PHENIX prompt muon (charm & beauty) measurements from statistical subtraction methods show suppression at positive rapdity (small-x) and enhancement at negative rapidity (Au direction)

Charm production in dAu

Vitev et al. – hep-ph/0605200

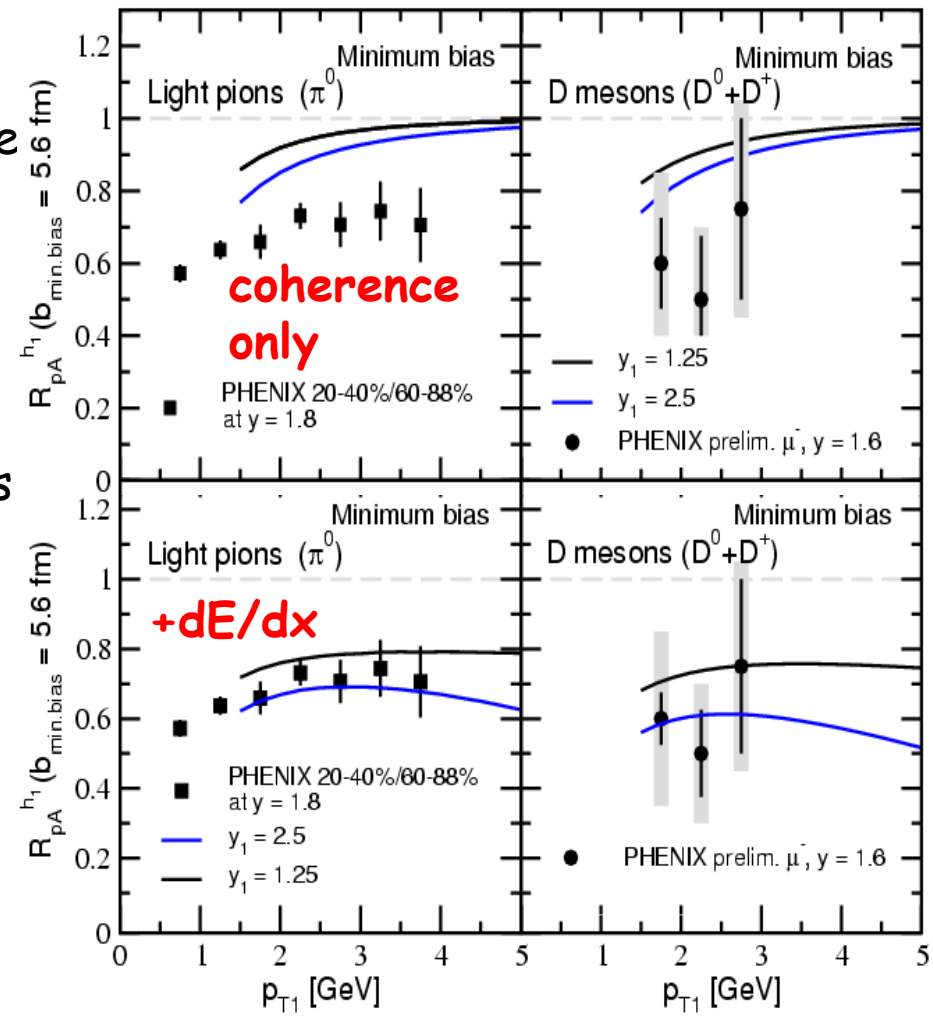
cg & cq dominate inclusive D production

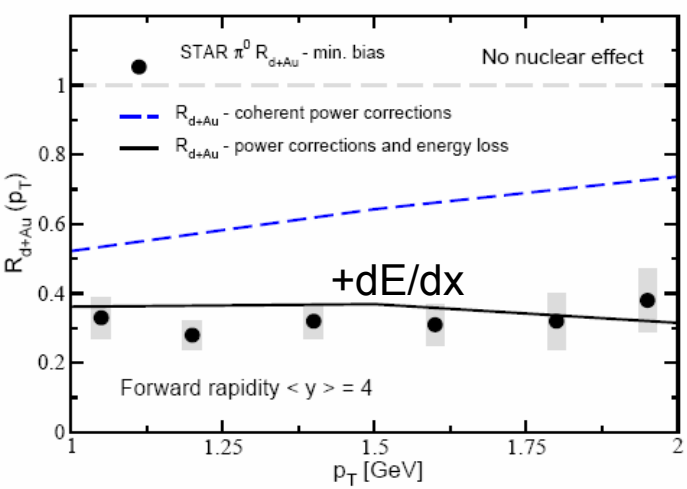
final-state coherence effects

- 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!



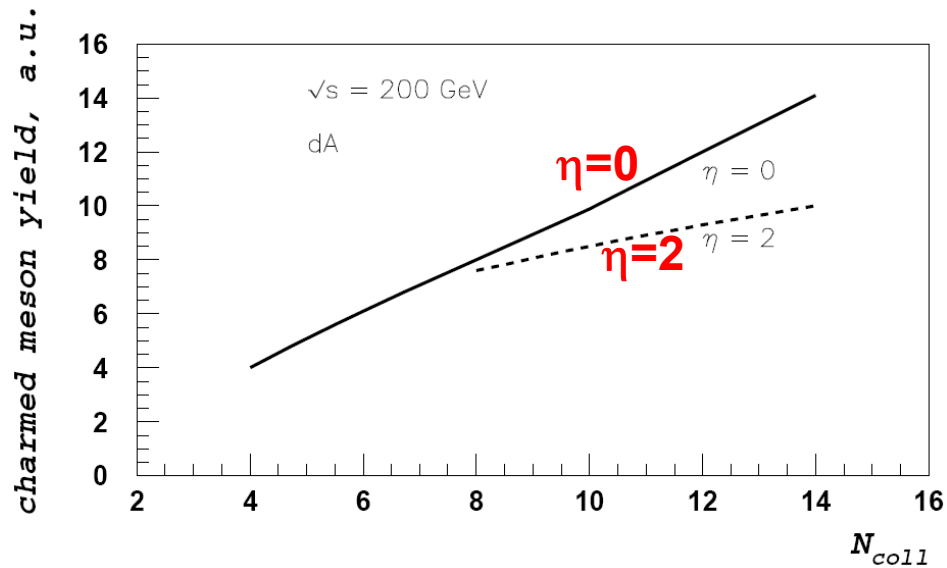


STAR π^0 at y=4

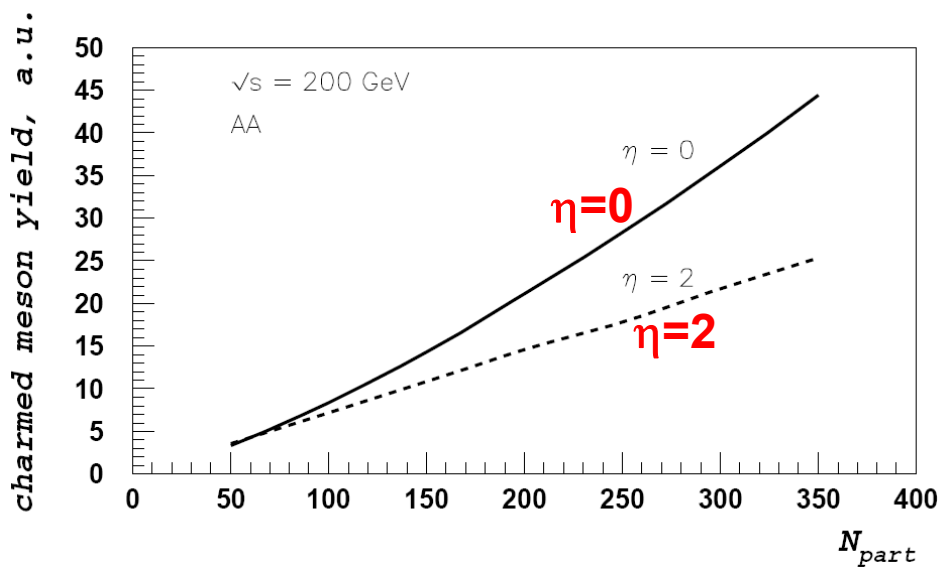
Open charm production in the CGC model

hep-ph/0402298

Suppression below binary scaling at forward rapidity (small-x) in dAu



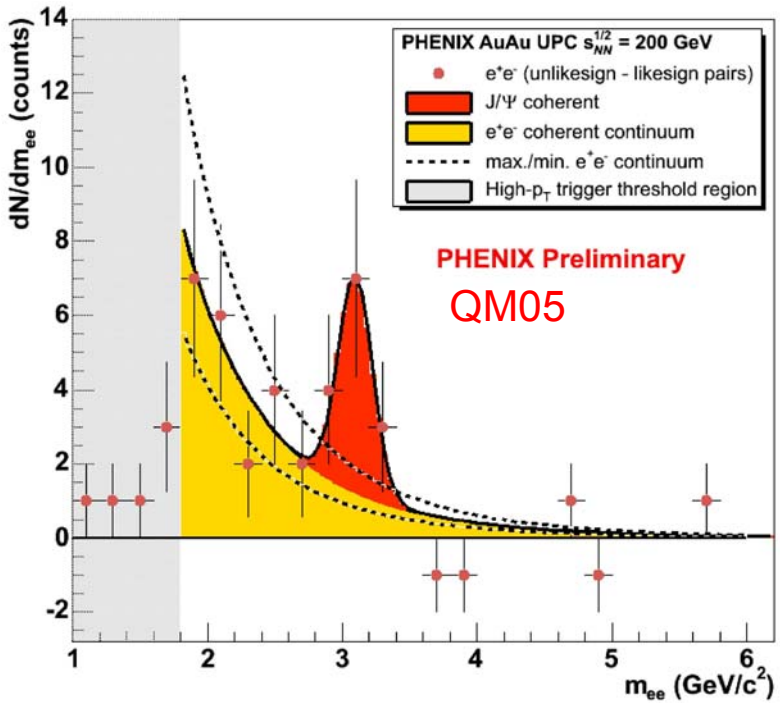
Further suppression at forward rapidity in AuAu



Ultra-peripheral Collisions (UPC's)

Can Ultra-peripheral reactions (UPC's) at forward rapidity probe small-x gluon shadowing or saturation?

- e.g. J/ψ production probes gluon distributions of nuclei (private comm. Mark Strikman)

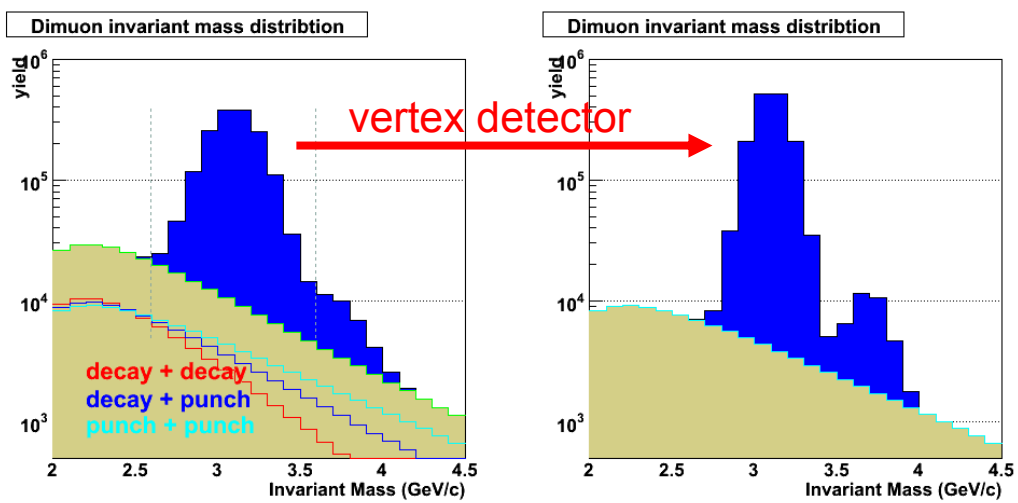


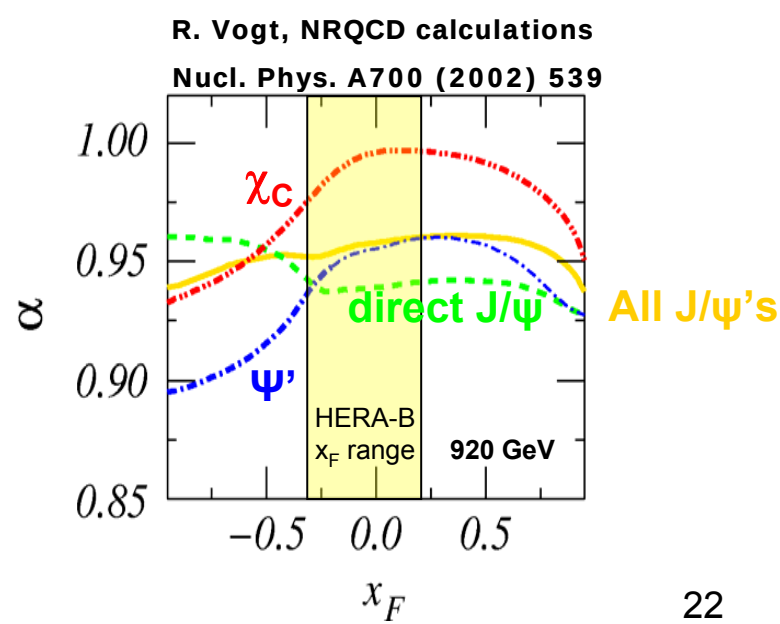
Goals for the Future

Accurate data from multiple probes to allow quantitative analysis & isolation of gluon saturation from other effects (energy loss, coherence, recombination, 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 ($x \sim m_Q/\sqrt{s}$)
- add $\chi_c \rightarrow J/\psi\ \gamma$ (forward calorimeters)

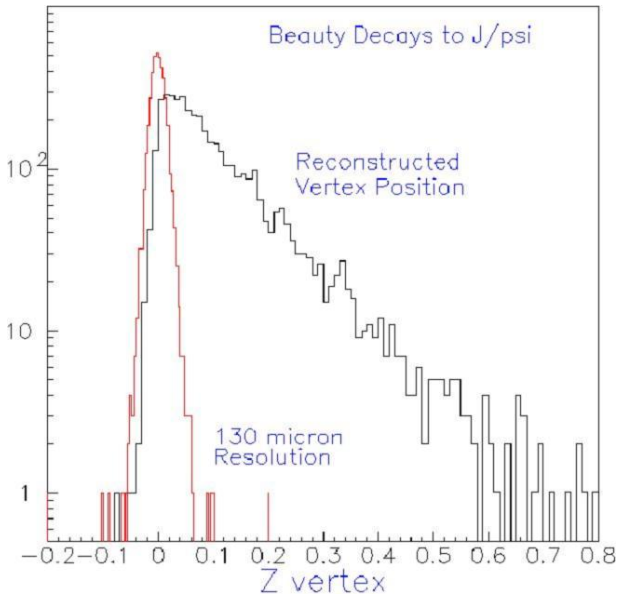




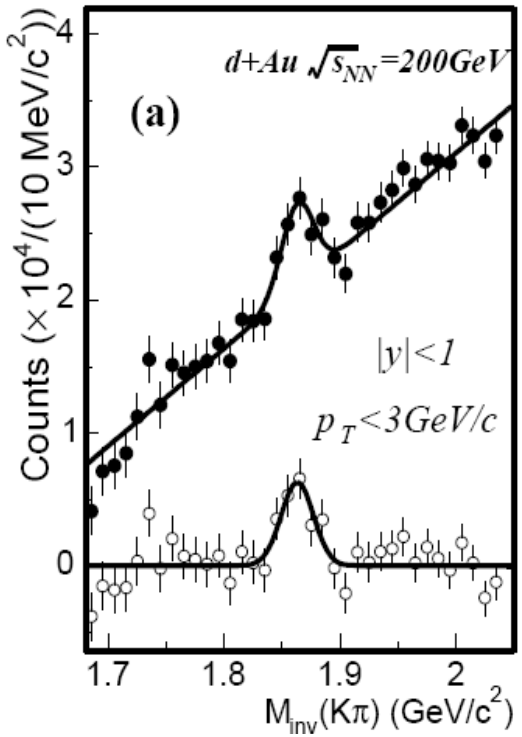
Goals for the Future continued

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



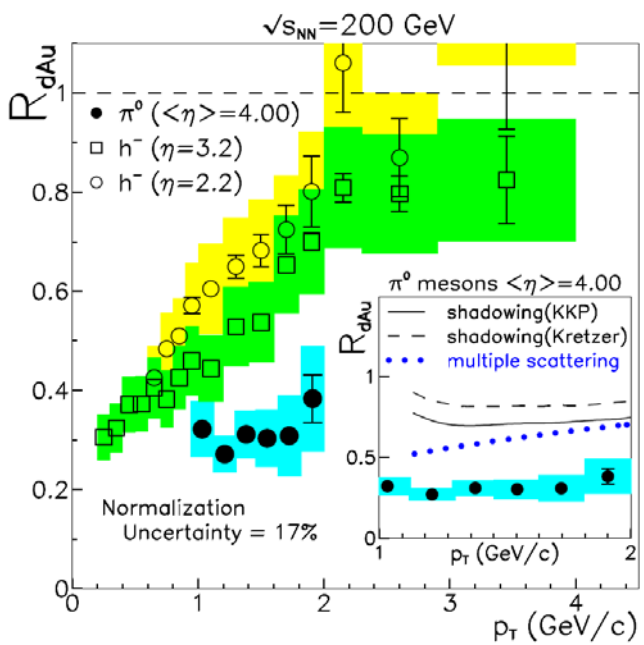
$D \rightarrow K\ \pi$ in dAu at central rapidity from STAR

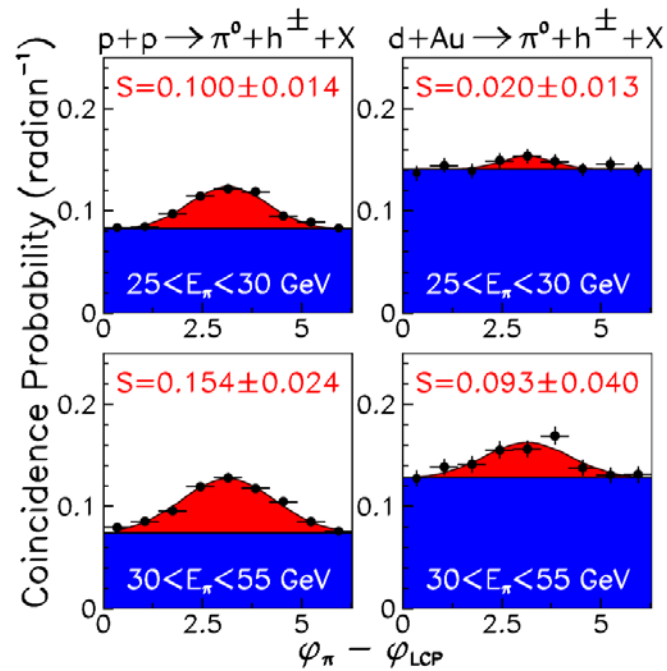
Goals for the Future continued

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)

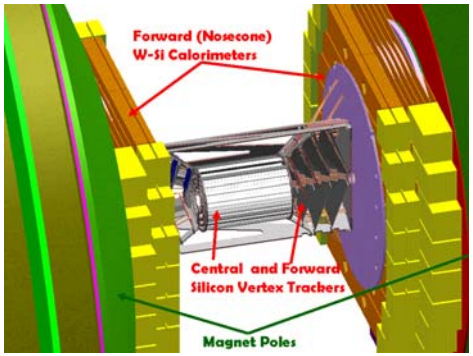
2-particle correlations and search for mono-jets (forward calorimeters)





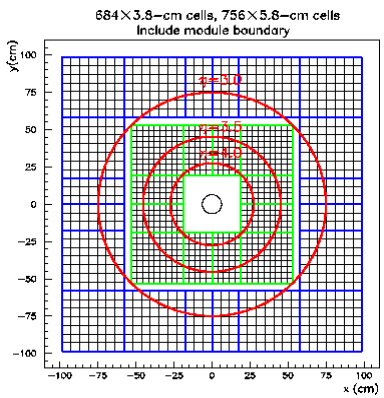
mono-jets??

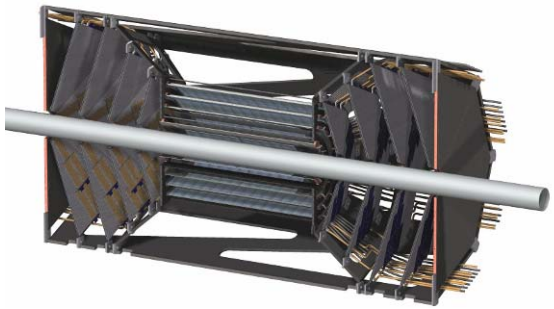
Detector Upgrades - enabling our physics goals



PHENIX Nosecone Calorimeter
- forward γ & π^0
- $\chi_c \rightarrow J/\psi\ \gamma$

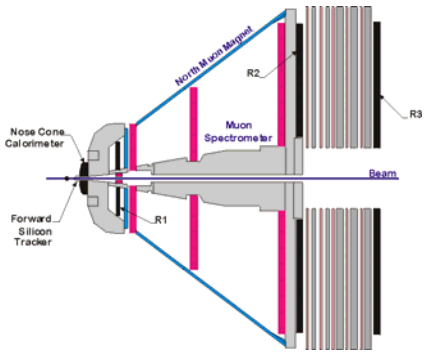
STAR Forward Meson Spectrometer
- forward π^0



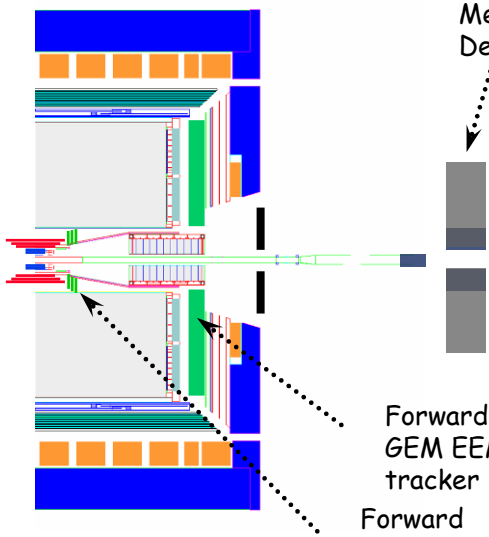


PHENIX Forward Vertex Detector
- $B \rightarrow J/\psi\ X$
- robust D & B with reduced bkgd.
- improved bkgd. & mass resolution for quarkonia & dimuons

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



PHENIX μ-Trigger
- high luminosity W trigger
- reduction of miss-identified high-p_T tracks



Forward Meson Detector

Forward triple-GEM EEMC tracker

Forward silicon tracker

A few of rates for RHIC-II

Rates per week for various processes in d+Au collisions at RHIC-II
for 62 nb^{-1}/week luminosity (compared to 4.5 nb^{-1} achieved so far)
As estimated for the PHENIX Forward Vertex and Nose Cone Calorimeter upgrades

	J/ψ	ψ'	Υ	χ_C	$B \rightarrow J/\psi X$	D	B	π^0 p_T>10 GeV/c	direct γ p_T>10 GeV/c
# per week	20k	360	65	2.2k	550	60M	0.7M	13k	1.7k

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
- studies at RHIC will be complimentary to those at the LHC

From the LHC pA Workshop (May 2005):
(**http://wwwth.cern.ch/pAatLHC/pAworkshop2.html**)

- 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: 2×10^{30} $cm^{-2}s^{-1}$ avg)
- N-N CM not at lab y=0 (Δy=-0.46 for 8.8 TeV p+A)
- "Company line": no need for p+p reference. Will come from interpolation between Tevatron and 14 TeV
- Has to share 1-month/yr with HI running – difficult to build a systematic program

Summary

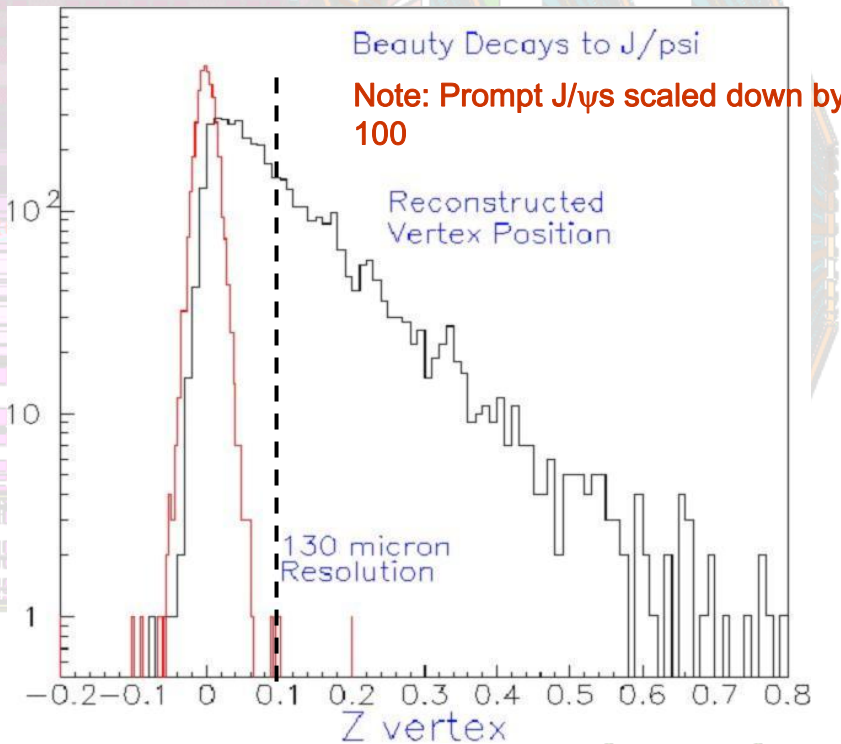
- Production of quarkonia, heavy-quarks and hadrons are all suppressed at forward rapidity in dAu collisions
- Competing physics pictures for this suppression are difficult to resolve
  - shadowing, gluon saturation, coherent multiple scattering, initial-state energy loss, Sudakov suppression, parton recombination
  - the lack of x_2 scaling for J/ψ production seems to rule out gluon shadowing as a dominant effect there
  - PQCD calculations suggest that x values may not actually be small for forward hadron production unless two forward hadrons are detected together
  - mono-jets are predicted by several pictures but experimental evidence is weak so far
  - we need theoretical clarification on how to experimentally distinguish the various pictures
- RHIC-II luminosity and detector upgrades will enable many new physics measurements
  - studies of cold nuclear matter effects at RHIC will remain complementary to those at the LHC, - given that RHIC covers the transition into the gluon saturation region, while the LHC lies deep in that region

Extra Slides

First Explicit Beauty Measurement Requires FVTX

Observable	Counts per RHIC-I p+p week	Counts per RHIC-I Au+Au week	Counts per RHIC-II p+p week	Counts per RHIC-II Au+Au week
Luminosity	9.9 pb^{-1}	0.33 nb^{-1}	33 pb^{-1}	2.5 nb^{-1}
$B \rightarrow J/\psi\ X \rightarrow \mu\ \mu$	~200	~220	~650	~1.7k

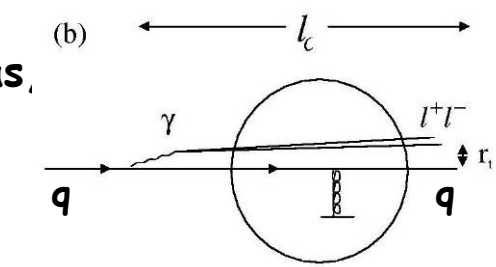
- Physics Motivation:
  - Open beauty measurement needed to separate charm and beauty components in single lepton measurements
- Only explicit measurement of open beauty
- Relatively free of background because prompt J/ψ AND displaced B-decay vertex J/ψ can be reconstructed
- Additionally, c and b may be separated by different lifetimes of D, B



Coherence Effects & Shadowing

Johnson, Kopeliovich et al., PRL 86, 4483 (2001)

In target rest frame Drell-Yan can be described as,



$$q \rightarrow q\gamma^* \text{ and } \gamma^* \rightarrow l\bar{l}$$

And the coherence length of this fluctuation is,

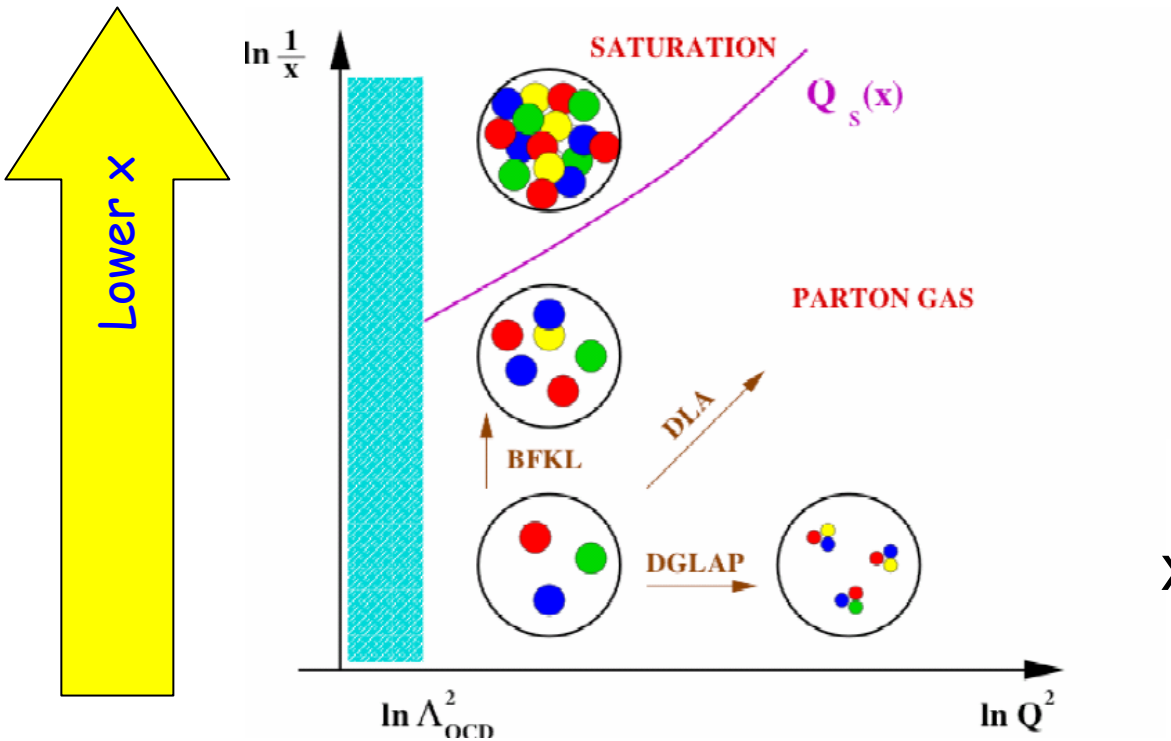
$$l_c = \frac{1}{q_L} = \frac{2E_q}{M^2_{q\gamma^*} - m_q^2}$$

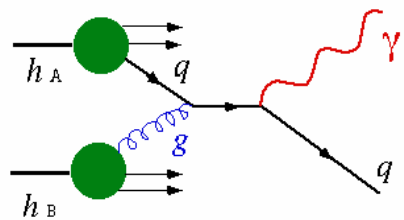
For $l_c << R_A$, i.e. short compared to nuclear size, the fluctuation appears for a very short time and therefore interacts with individual nucleons (no shadowing)

While for $l_c >> R_A$, the interaction is with the whole nucleus coherently and this can result in some nucleons being effectively hidden or shadowed and a nuclear dependence of $A^{2/3}$ (2D surface area)

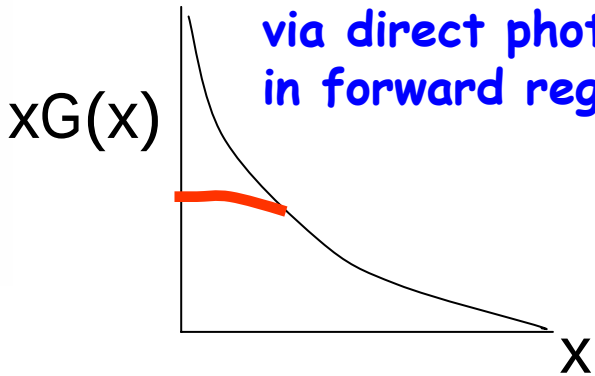
And for values in between, varying amounts of shadowing

QCD: Proton Nucleus Physics and the Colored Glass Condensate





measure gluon saturation via direct photons in forward region



More saturation at Lower x

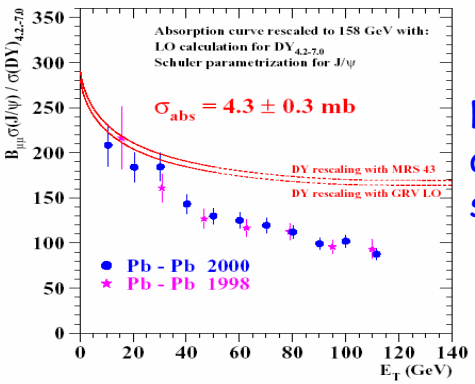
y~log(1/x)

Lower x → forward rapidity

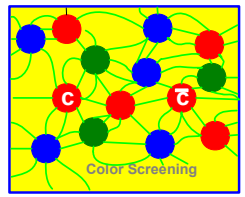
The Colored Glass Condensate: The Initial Condition for Heavy Ion Collisions?

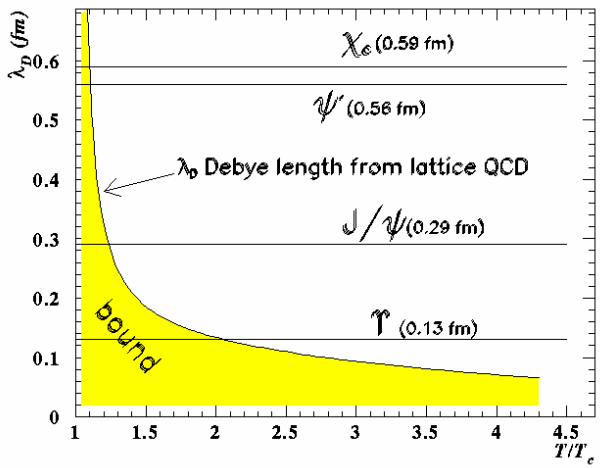
AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

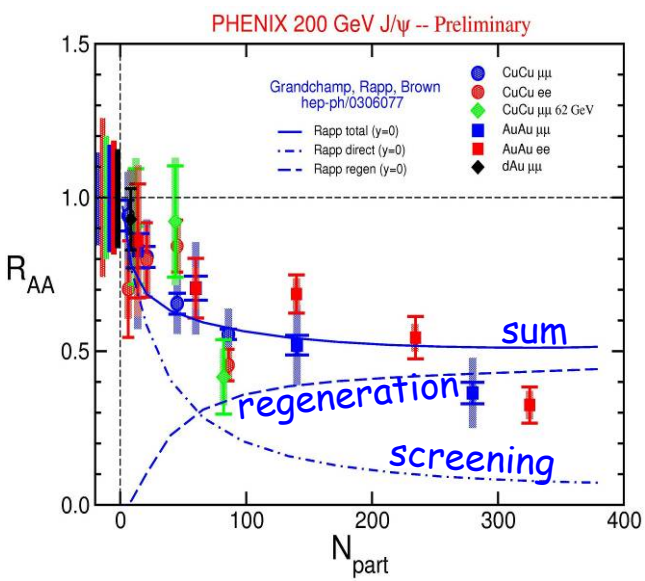
Debye screening predicted to destroy J/ψ's in a QGP with different states "melting" at different temperatures due to different binding energies.



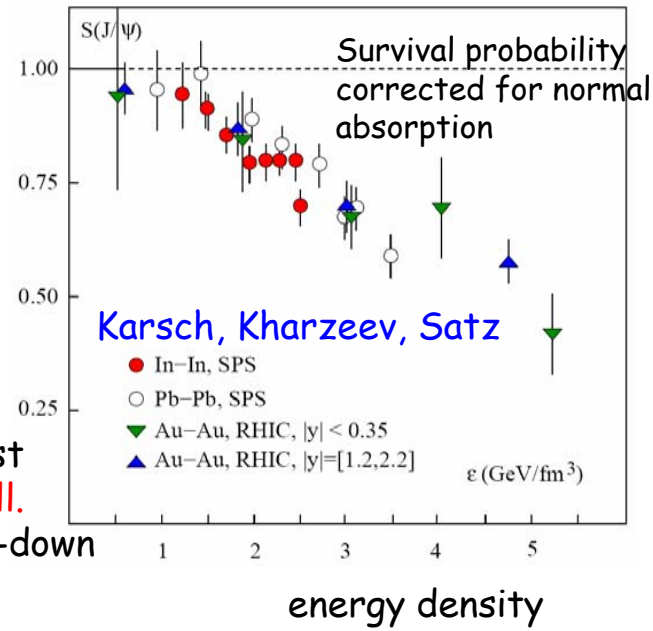
NA50 anomalous suppression







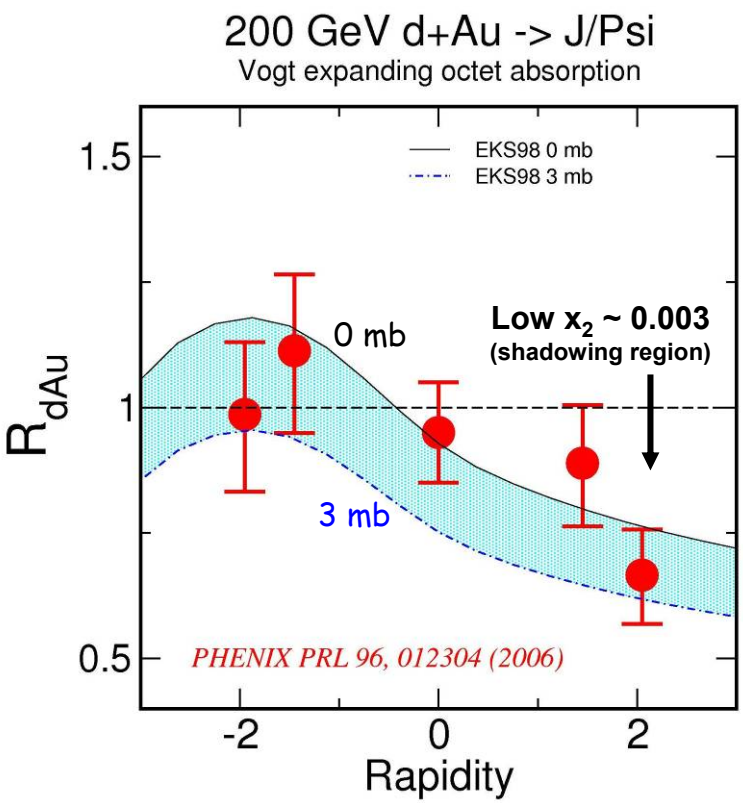
but recent regeneration models might give enhancement that compensates for screening?
Grandchamp, Rapp, Brown

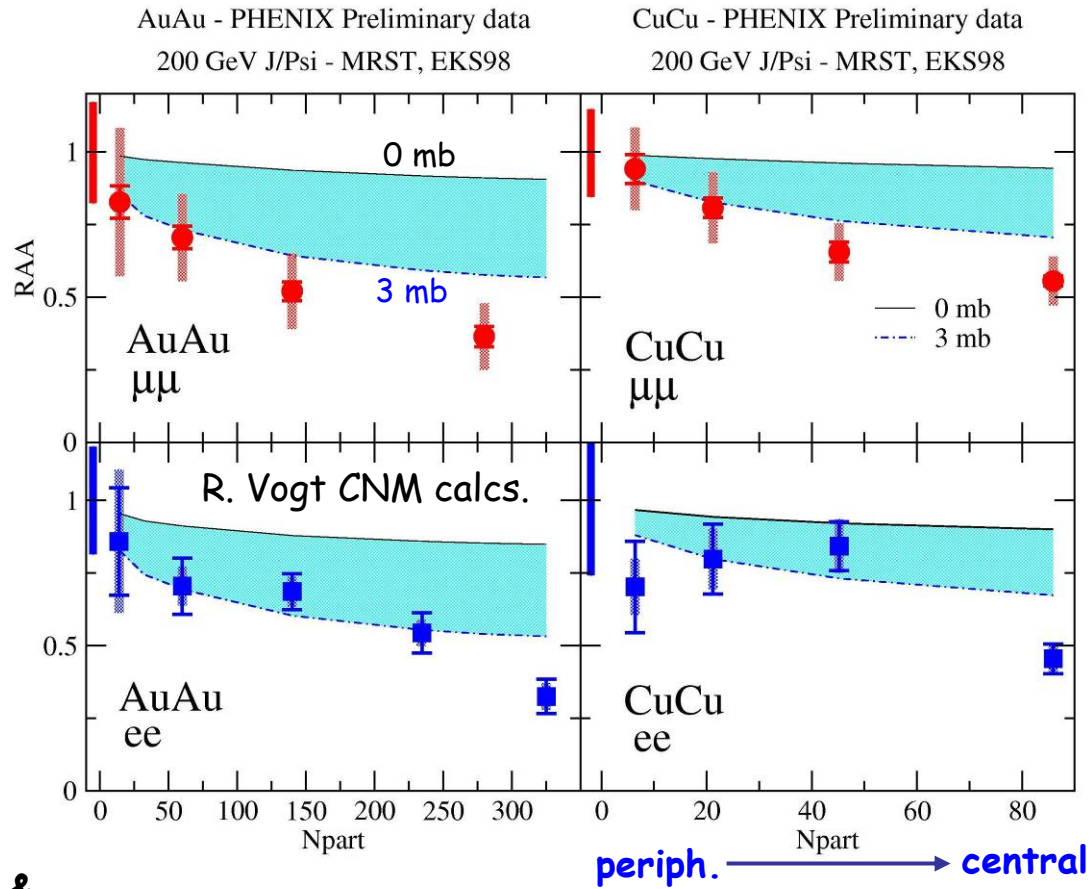


on the other hand, recent lattice calculations suggest J/ψ not screened after all.
Suppression only via feed-down from screened χ_c & ψ'

J/ψ suppression in AA collisions & CNM baseline

(CNM = Cold Nuclear Matter)

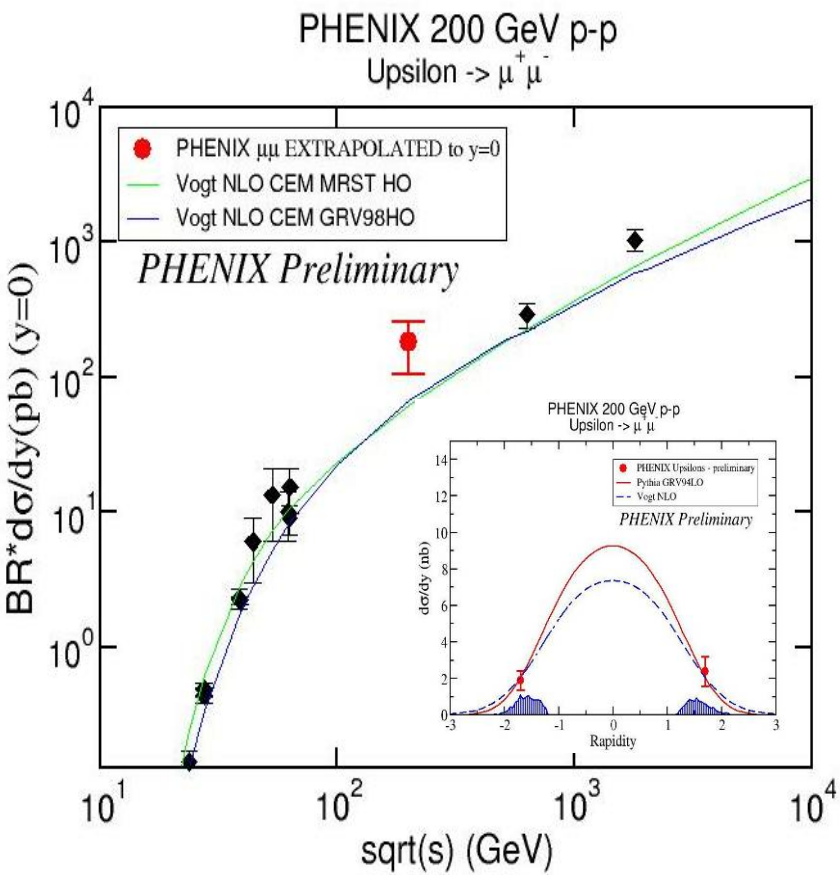




- **CNM calculations with shadowing & absorption**
- **present dAu data probably only constrains absorption to: σ_{ABS} ~ 0-3 mb**

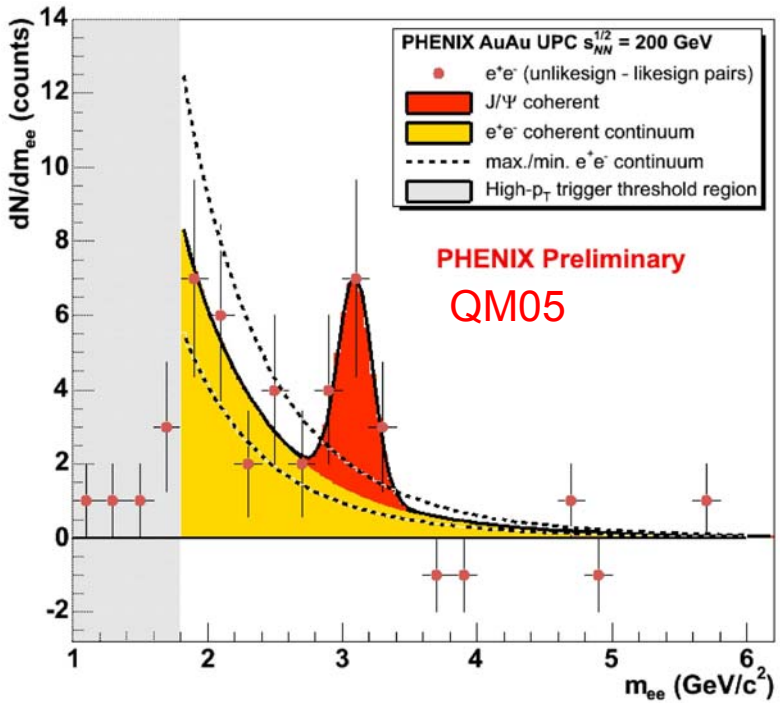
- **AA suppression is somewhat stronger than CNM calculations predict**
- **but really need more precise dAu constraint!**

Much More to Come!



1st Upsilons at RHIC from ~3pb^{-1} collected during the 2005 run.

Ultra-peripheral Collisions (UPC's)



UPC's : well calibrated EM probe of small-x gluon saturation