Nuclear physics at small x and (s)PHENIX

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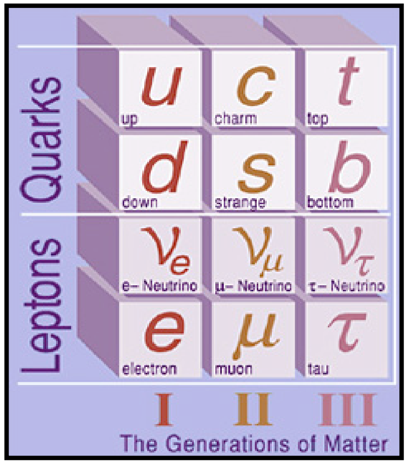
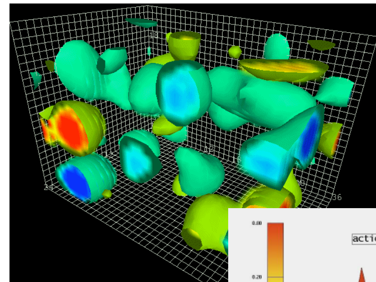
From particles to fields in QCD

Particles

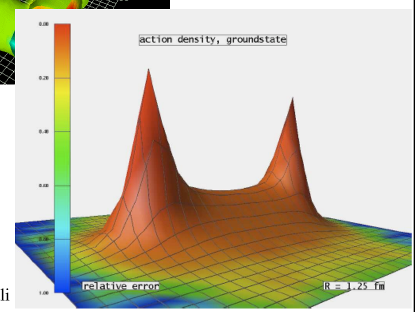


Fields

(Geometry)



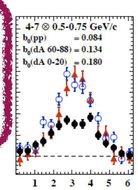
D. Leinweber



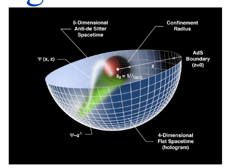
G. Bali

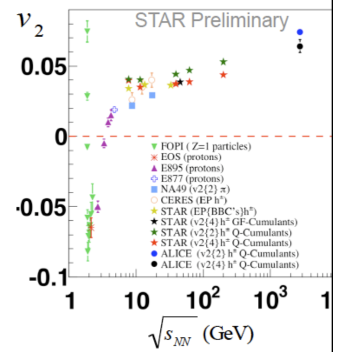
From particles to fields: collective phenomena as the essence of QCD

- From partons to strong color fields: nuclear wave functions at small x

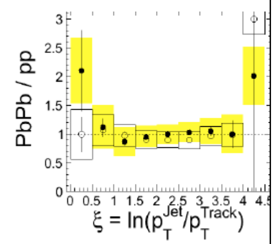


- Hydrodynamics and collective behavior: transport properties; phase diagram & fluctuations; anomalies and chiral magnetic effect



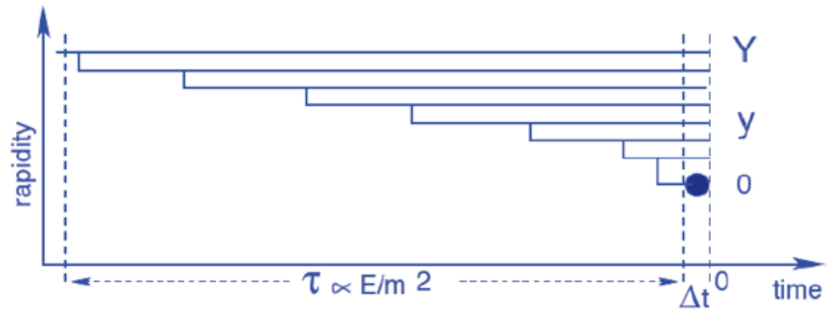


- Jets: the flow of energy and momentum in QCD



- The probes: heavy quarks, dileptons, ..

The space-time picture of high-energy interactions in QCD



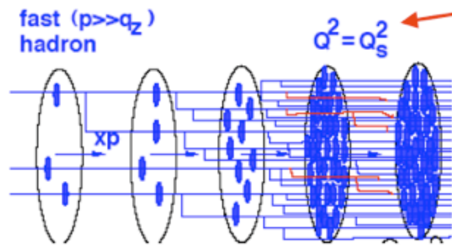
1. Fast (large y) partons live for a long time;
2. Parton splitting probability is $\sim \alpha_s y$ - not small!

From partons to fields at small x

Bjorken x : the fraction of hadron's momentum carried by a parton; high energies s open access to small $x = Q^2/s$

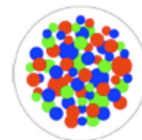
the boundary of non-linear regime: partons of size $1/Q > 1/Q_s$ overlap

Large x



Color Glass Condensate

small x



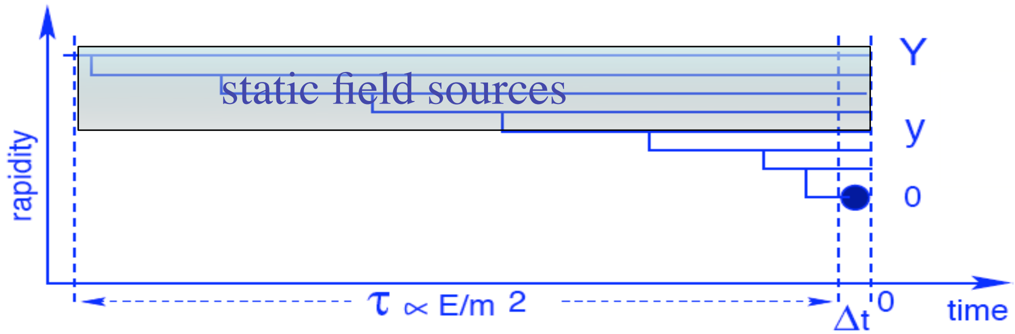
Because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$, the number of gluons at small x grows; the transverse area is limited

→ transverse density becomes large

L.Gribov, E.Levin, M.Ryskin; A.Mueller, J.Qiu

The origin of classical background field

Coherent field with occupation number $\sim \frac{1}{\alpha_s(Q_s)}$
suppression of hard processes at small x;
depletion of back-to-back (quantum) correlations



Gluons with large rapidity and large occupation number
act as a background field for the production of slower gluons

L.McLerran, R.Venugopalan **Color Glass Condensate**

QCD at small x: the parameters

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

Parameters of QCD lagrangian:
quark masses m_f and Λ_Q

New parameter at small x:
saturation momentum Q_s

is related to $\hat{q}$ by $Q_s^2 \quad q\ L$

Renormalization group and the effective action

RG constraints the form of the effective action:

$$\mathcal{L}_{\rm eff} = -\frac{1}{4\bar{g}^2(t)}\, G^2, \quad t \equiv \ln\left(\frac{G^2}{\Lambda^4}\right)$$

the coupling is defined through

$$t = \int_g^{\bar{g}(t)} \frac{dg}{\beta(g)}.$$

At large t (strong color field),

$$\frac{1}{\bar{g}^2(t)} \sim t + \dots \quad \text{and} \quad \mathcal{L}_{\rm eff} \sim G^2\ \ln\left(\frac{G^2}{\Lambda^4}\right)$$ 10

$$\frac{1}{N_{part}}\frac{dN}{d\eta} \sim \frac{1}{\alpha_s(Q_s^2)}$$ KLN

QCD evolution at small x: nuclear modification of hard processes

New parameter at small x:
saturation momentum

Therefore, instead of $\ln(Q/\Lambda \quad)$,

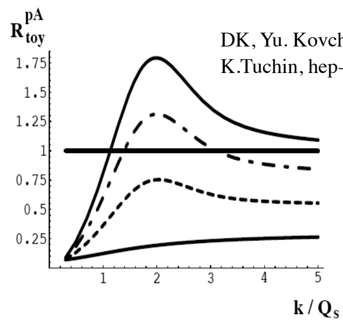
we get $\ln(Q/Q_s)$

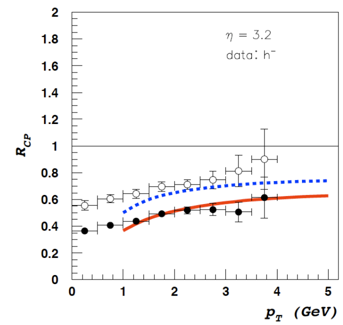
Resummation of these logs yields "anomalous dimensions" - and results in nuclear suppression of hard processes at small x

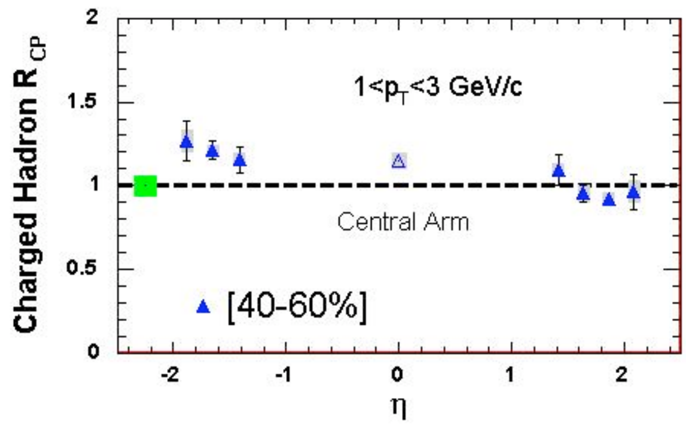
DK, E. Levin, L. McLerran, hep-ph/0210332

Nuclear suppression of hard processes at small x: an intuitive explanation

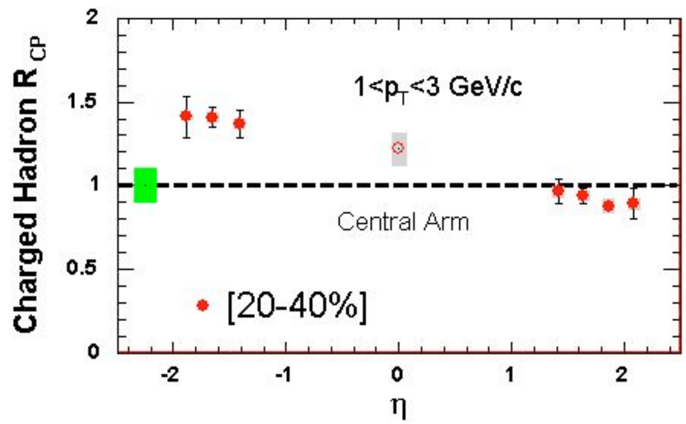
Saturation slows down the growth of gluon densities at small x; this effect is stronger in the nuclear wave function than in the proton wave function - thus R_{pA} decreases



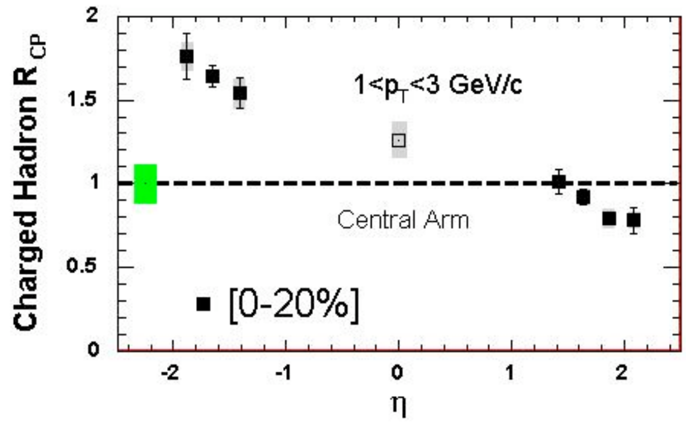



Charged Hadron R CP
1<p_T<3 GeV/c
Central Arm
[40-60%]
η
0
0.5
1
1.5
2
-2
-1
0
1
2

PHENIX data


Charged Hadron R_{CP}
2
1.5
1
0.5
0
1<p_T<3 GeV/c
Central Arm
[20-40%]
-2
-1
0
1
2
η

PHENIX data



PHENIX data

Recent theoretical studies:
A.Dumitru, J. Jalilian-Marian,
C.Marquet, K.Tuchin, ...

Baryons vs mesons at small x

At forward rapidities at RHIC, the nuclear modification of baryon production is linked to the mechanism of baryon number transport (diquarks? gluon junctions? Skyrmions?)

Measurement: production cross sections of PID hadrons: baryons (protons, hyperons), and mesons; compare mid- and forward-(+backward?) rapidities

Quarks vs gluons at small x

Quarks and gluons interact differently because of different color charge

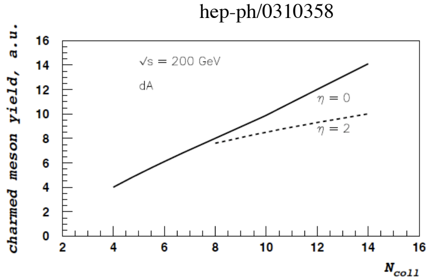
Measurement: production cross sections of photons and dileptons at forward rapidities

Flavor dependence of small x suppression

At forward rapidities at RHIC, the saturation momentum exceeds the charm quark mass (always the case at LHC!) so charm becomes "light" at small x - a sensitive probe of saturation

DK, K.Tuchin, hep-ph/0310358

Measurement: identified charm production cross section, compare mid- and forward- (+backward?) rapidities



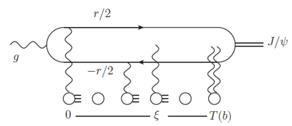
Charmonium suppression at small x

In the entire kinematical range of RHIC, the saturation momentum exceeds the inverse radius of charmonium, $(\alpha_s M_c)^{-1}$
so charmonium production is a sensitive probe of saturation

Measurement: different charmonia production (chi, psi', ...bottomonium?) compare mid- and forward- (+backward?) rapidities

Gluon saturation effects on the color singlet J/ψ production in high energy dA and AA collisions

F. Dominguez,[1] D.E. Kharzeev,[2,3] E.M. Levin,[4,5] A.H. Mueller,[1] and K. Tuchin[6]



arXiv:11091250 (Sep 6, 2011)

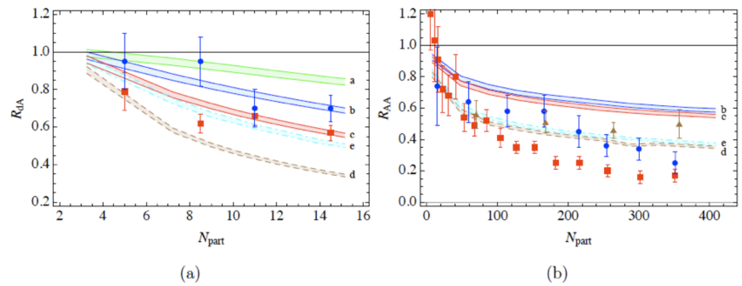
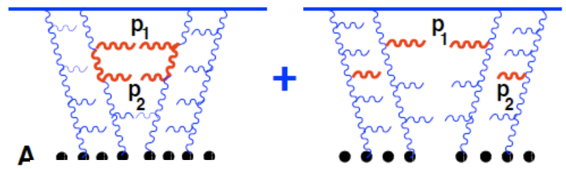


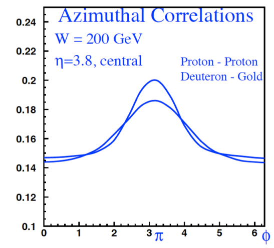
FIG. 3: Nuclear modification factor vs $N_{\rm part}$ in (a) dAu and (b) AA collisions using the DHJ model [13]. Band 'a' (green) represents rapidity $y = -1.7$ at $\sqrt{s} = 200$ GeV, 'b' (blue): $y = 0$, $\sqrt{s} = 200$ GeV, 'c' (red): $y = 1.7$, $\sqrt{s} = 200$ GeV, 'd' (brown): $y = 3.25$, $\sqrt{s} = 2.76$ TeV, 'e' (cyan): $y = 0$, $\sqrt{s} = 5.5$ TeV. $m = 1.5$ GeV, $C = 1$. Experimental data [16–19] is represented by (blue) circles in 'b', by (red) squares in 'c' and by (brown) triangles in 'd'. (Color online).

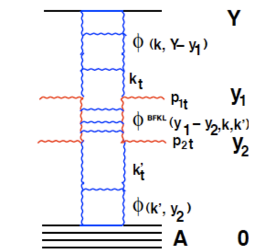
no factorization!

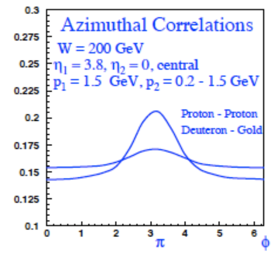
AA is **NOT** reproduced, neither at RHIC nor at LHC

Disappearance of di-jet correlations at small x and at large rapidity separations

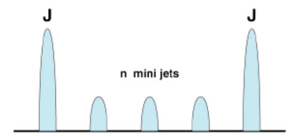






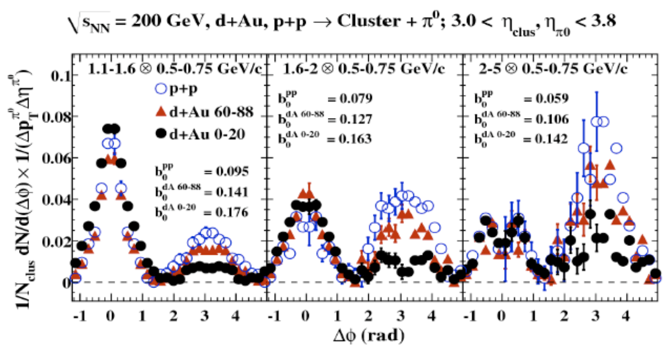


DK, E.Levin, L.McLerran
hep-ph/0403271

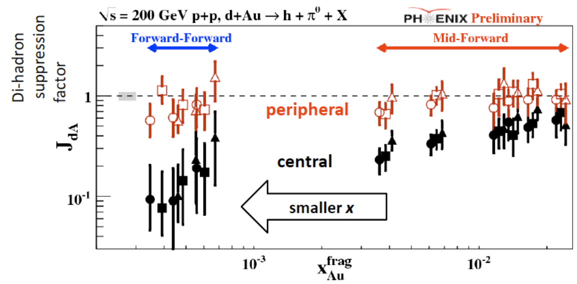


Measurement: di-jet(leading hadron) correlations with large rapidity separation (forward-backward)

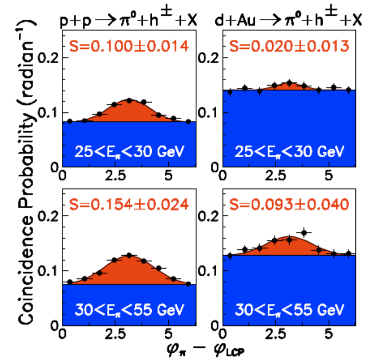
Di-hadron correlations at small x



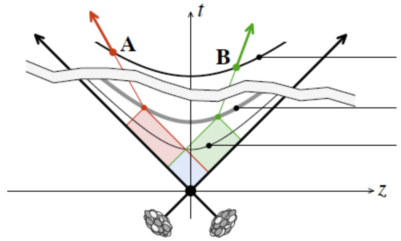
PHENIX Coll,
QM 2011
arXiv:1105.5112



STAR Coll,
arXiv:0602011 (PRL)



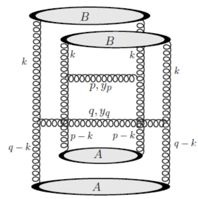
Probes of coherent gluon fields at small x: long-range correlations in rapidity

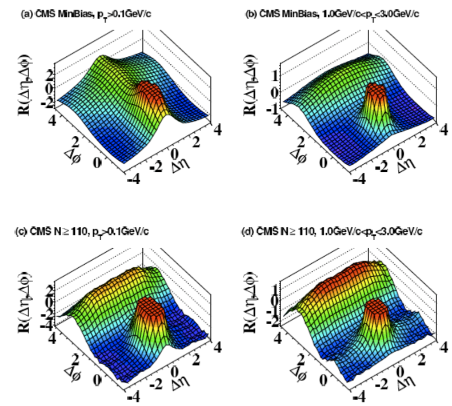


causality:

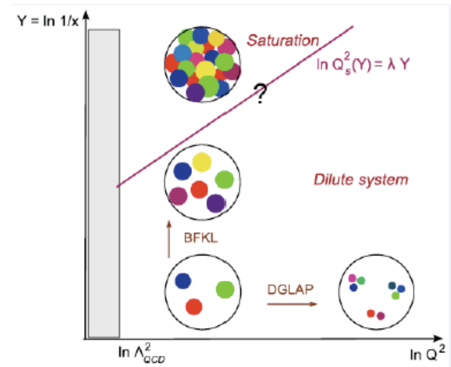
$$\tau_{\text{init.}} = \tau_{\text{f.o.}} \exp\left(-\frac{1}{2}\Delta y\right)$$

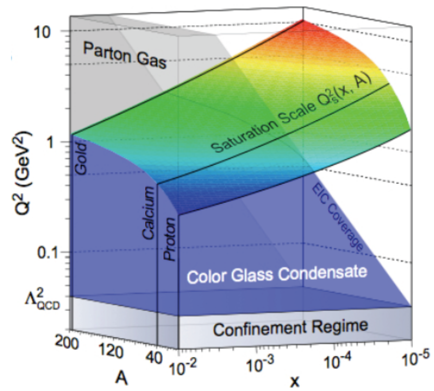
A.Dumitru, K. Dusling, F. Gelis,
J. Jalilian-Marian, T. Lappi, R. Venugopalan,
arXiv: 1009.5295





The path to eRHIC





Some speculative ideas:

- Polarized protons on nuclei?
(spin asymmetries are due to quark interactions with gluon fields; study the dependence on the gluon field strength)

- Double-(single-)diffractive production of hadrons (light and charmonia) at mid-(forward-)rapidity in polarized pp collisions (was never done before?) - spin contents at small x; glueballs; sphalerons; mechanism of charmonium production; ....