The Status of Saturation, CGC and Glasma

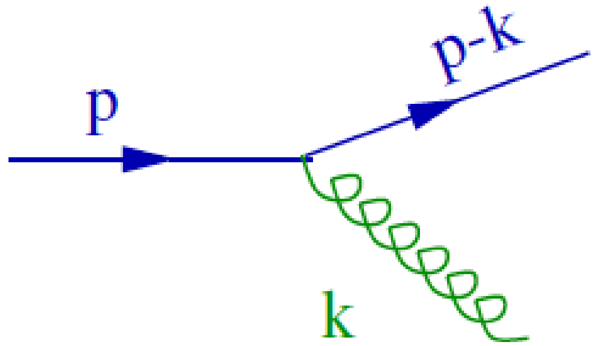
« What have we learned from RHIC? »

BNL, May 12, 2010

Summary - Orsay 8/06/10

J.-P. Blaizot, IPhT, CEA Saclay and CNRS

Radiation and multiplication of partons



$$\mathrm{d}\mathcal{P} \simeq \alpha_s \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \frac{\mathrm{d}x}{x}$$

One can calculate the change of the wave-function (its **'evolution'**), **not** the wave-function itself **-> Evolution equations** (with respect to directions of enhanced emission):

$$\frac{\mathrm{d}k_\perp^2}{k_\perp^2} \longrightarrow \mathrm{d}\ln Q^2$$

DGLAP

$$\frac{\mathrm{d}x}{x} \longrightarrow \mathrm{d}\ln\frac{1}{x}$$

BFKL

Growth of structure functions is tamed by non-linear evolution

[Gribov, Levin, Ryskin,83']

For instance,

$$\frac{\partial^2 \, xG(x,Q^2)}{\partial \ln(1/x)\,\partial \ln Q^2} = \frac{3\alpha_s}{\pi}\, xG(x,Q^2) - \frac{3\alpha_s^2}{\pi^2 R^2}\,\frac{[xG(x,Q^2)]}{Q^2}$$

[Gribov, Levin, Ryskin,83'- Mueller, Qiu, 86']

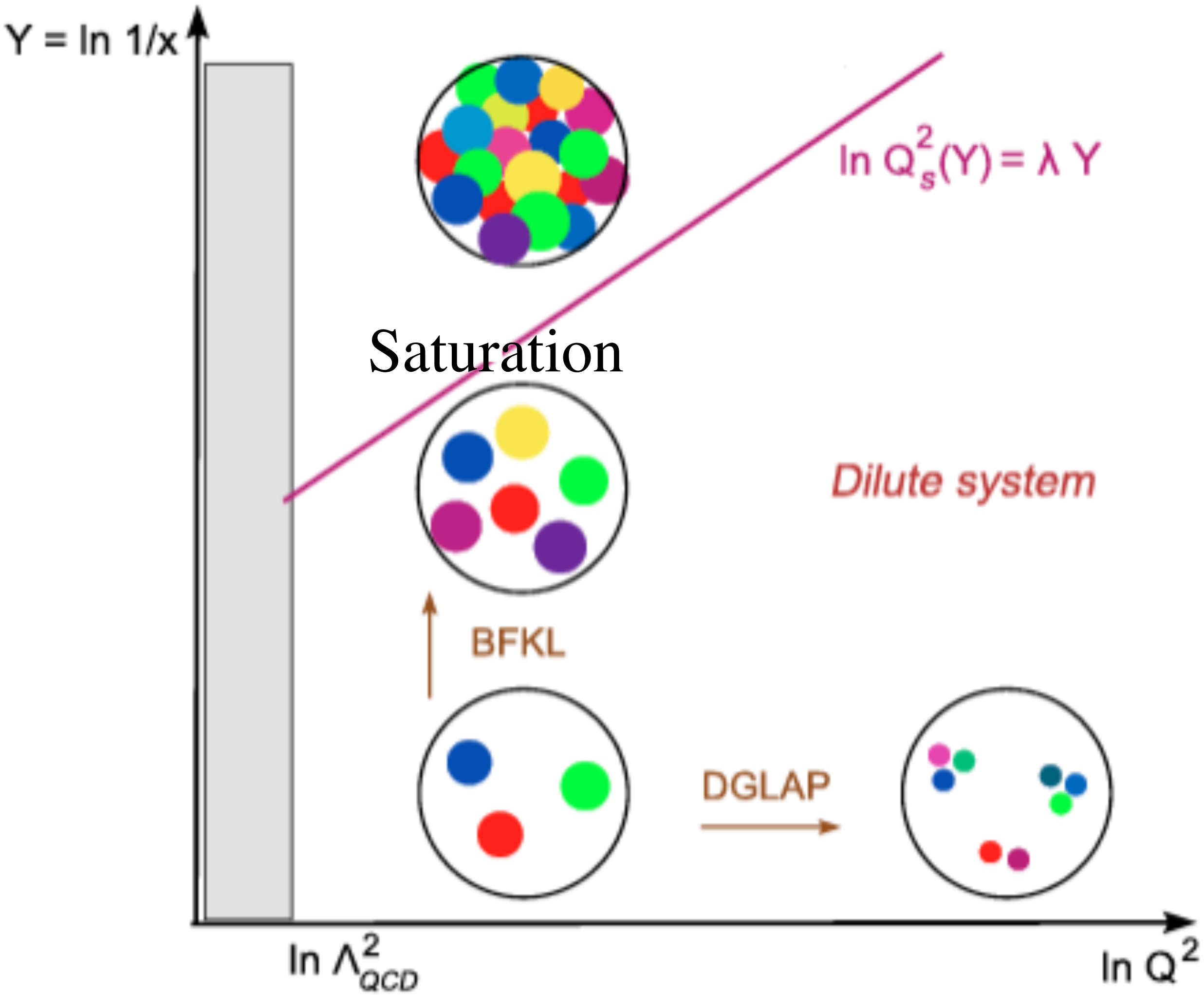
Emergence of a scale: the **saturation momentum**

$$Q_s^2 = \frac{\alpha_s}{\pi R^2}\, xG(x,Q_s^2)$$

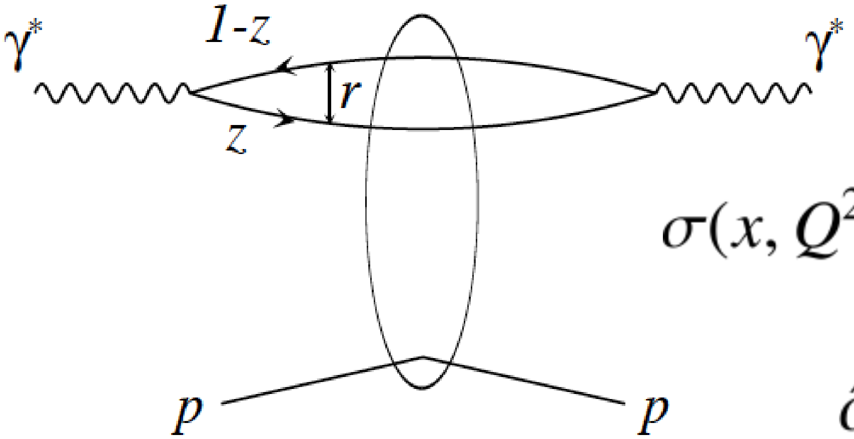
More elaborate equations have been derived (BK, JIMWLK, ..)

(More on these soon !)

The qualitative picture



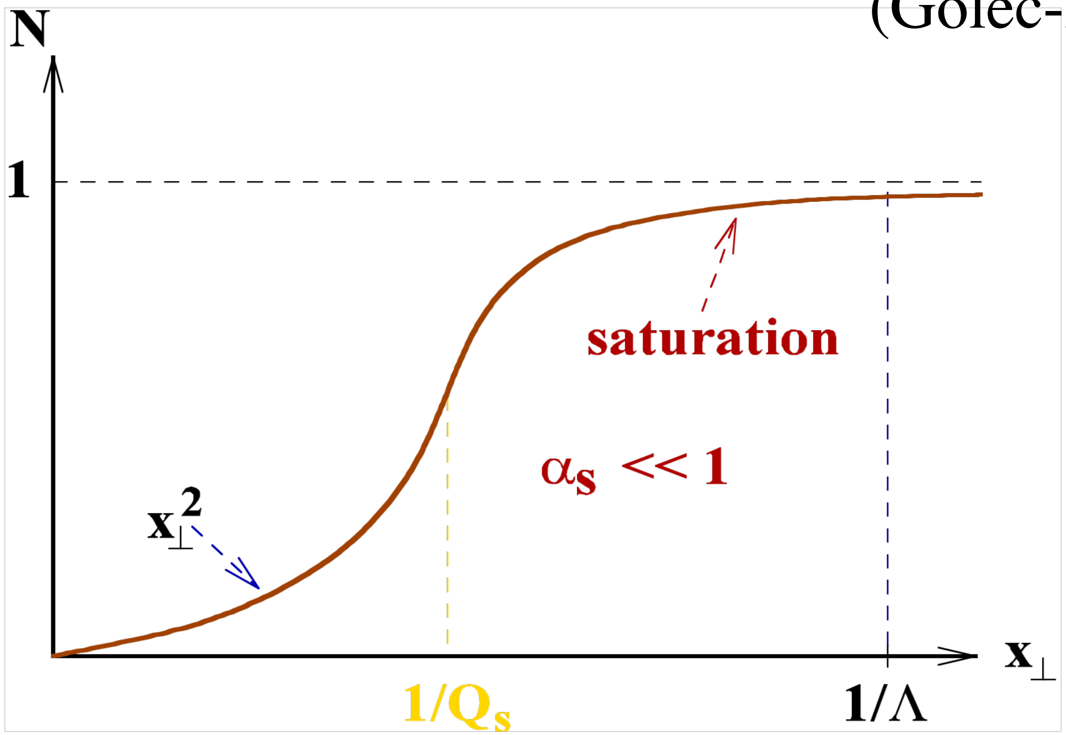
Seeing saturation in DIS



$$\sigma(x, Q^2) = \int d^2\mathbf{r} \int dz\, |\psi(z, \mathbf{r})|^2\, \hat{\sigma}(x, r^2)$$

$$\hat{\sigma}(x, r^2) = \sigma_0 \left(1 - \mathrm{e}^{-r^2 Q_s^2/4}\right)$$

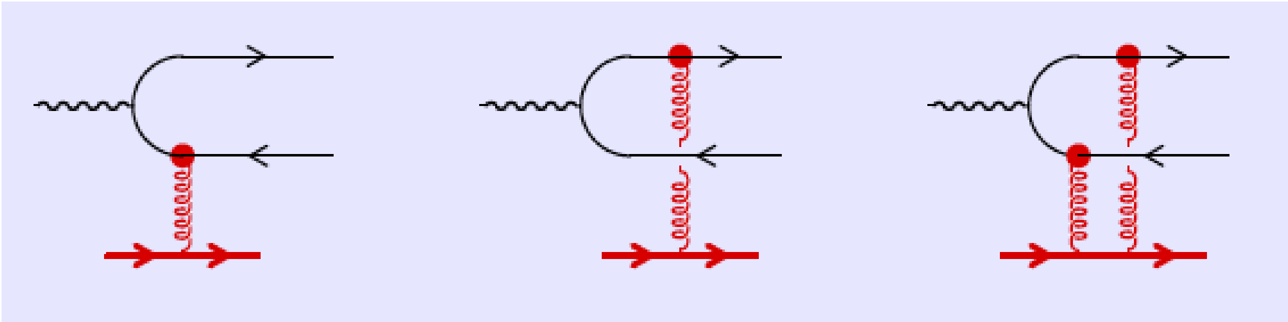
(Golec-Biernat, Wüsthoff, 98')



(from Kovchegov)

CGC and Glasma

Focus on small x (or rapidity) evolution



$$\sigma_{dipole} = \frac{2}{N_c} \int d^2 x_\perp \mathrm{Tr} \left\langle 1 - U\left(x_\perp + \frac{r_\perp}{2}\right) U^\dagger \left(x_\perp - \frac{r_\perp}{2}\right)\right\rangle_Y$$

$$U(x_\perp) = P \exp\left\{ig \int dx^- A^+(x^-, x_\perp)\right\}$$

$$\langle \cdots \rangle_Y = \int \mathcal{D}A \, |\Phi_Y[A]|^2 \, \langle A| \cdots |A\rangle$$

During interaction process, the field A of the target is frozen (separation of scales - adiabatic approximation)

‘Classical CGC’

McLerran Venugopalan Model

$$\left[D_\mu, F^{\mu\nu}\right] = J^\nu \qquad \text{(frozen source)}$$

$$J^\mu = \delta^{\mu +}\rho(x_\perp, x^-)$$

Gaussian average over color source

$$\langle \rho^a(x_\perp, x^-)\rho^b(y_\perp, y^-)\rangle = g^2\mu\, \delta^{ab}\delta(x_\perp - y_\perp)\delta(x^- - y^-)$$

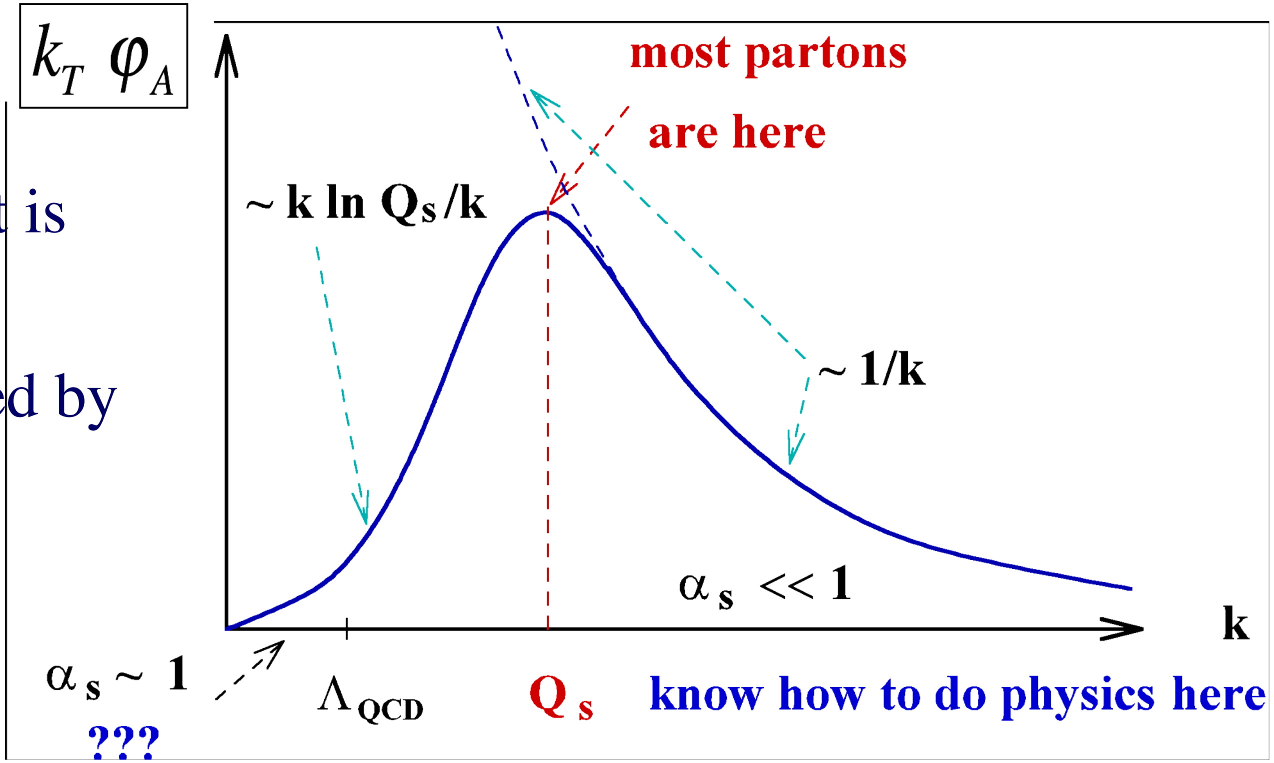
Capture some features of saturation $\qquad Q_s^2 \sim g^2\mu$

But no evolution. Often used as ‘initial condition’.

Classical Gluon Distribution

(Kovchegov)

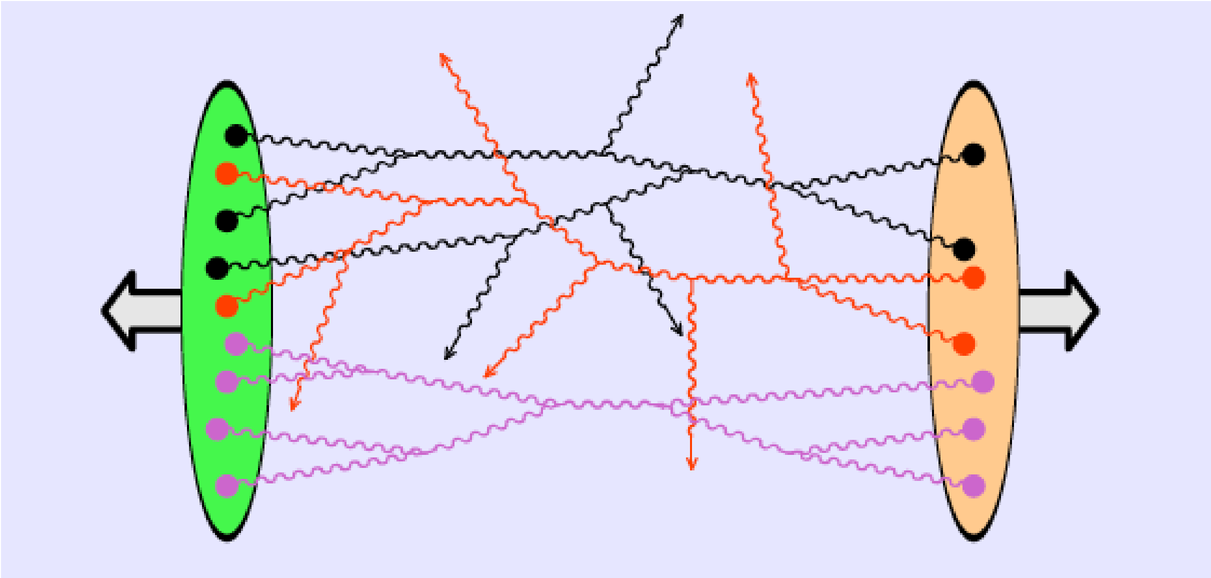
A good object to plot is the classical gluon distribution multiplied by the phase space k_T:



⇨ Most gluons in the nuclear wave function have transverse momentum of the order of $k_T \sim Q_S$ and $Q_S^2 \sim A^{1/3}$

⇨ We have a small coupling description of the whole wave function in the classical approximation.

From the wave function to the initial stage of nucleus-nucleus collisions : the Glasma



(Gelis)

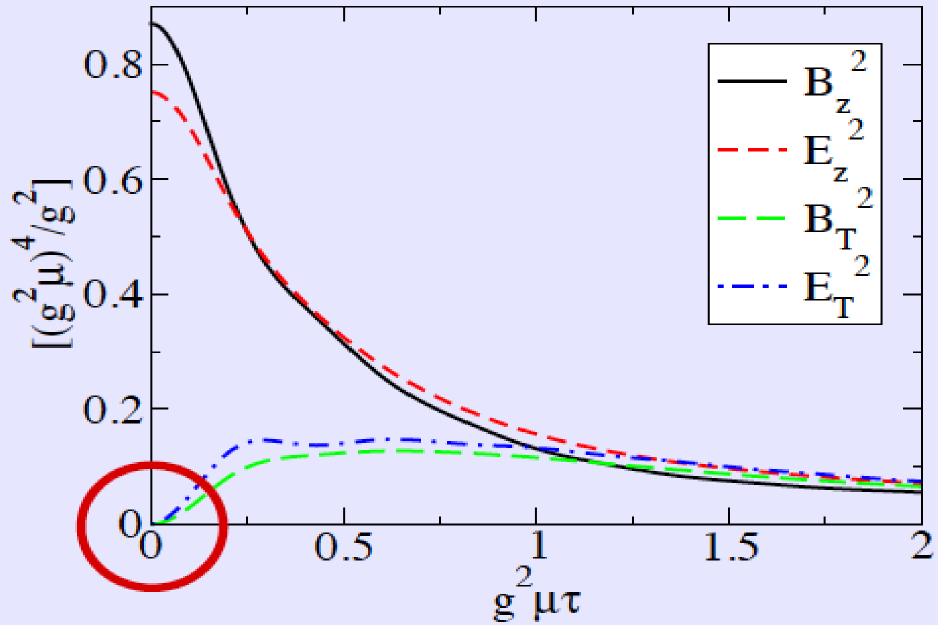
Energy-Momentum tensor at Leading Log accuracy

$$\langle T^{\mu\nu}(\tau, \eta, \vec{\boldsymbol{x}}_\perp) \rangle_{\text{LLog}} = \int [D\rho_1 \, D\rho_2] \; W_1[\rho_1] \; W_2[\rho_2] \; \underbrace{T^{\mu\nu}_{\text{LO}}(\tau, \vec{\boldsymbol{x}}_\perp)}_{\text{for fixed } \rho_{1,2}}$$

Initial classical fields, Glasma

Lappi, McLerran (2006)

- Immediately after the collision, the chromo-$\vec{E}$ and $\vec{B}$ fields are purely longitudinal and boost invariant :



- Glasma = intermediate stage between the CGC and the quark-gluon plasma

Phenomenology

CGC calculations and ‘CGC inspired’ models confronted to data

$$Q_s^2 = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda} \qquad Q_0^2 \propto A^{1//3} \qquad Q_s^2(b) = Q_s^2(0)\sqrt{1 - b^2/R^2}$$

$$\alpha_s = \alpha_s(Q_s)$$

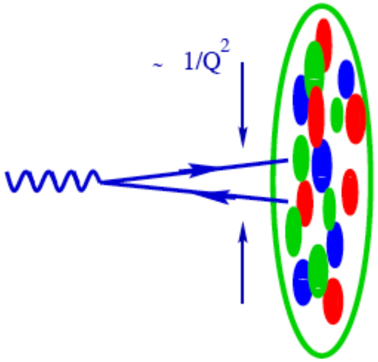
$$\frac{dN}{dy d^2 p_T} \sim \frac{1}{p_T^2} \int \frac{d^2 k_T}{(2\pi)^2} \phi_A(x_1, k_T) \phi_B(x_2, p_T - k_T)$$

DEEP INELASTIC SCATTERING

(Diffraction)

Geometrical scaling

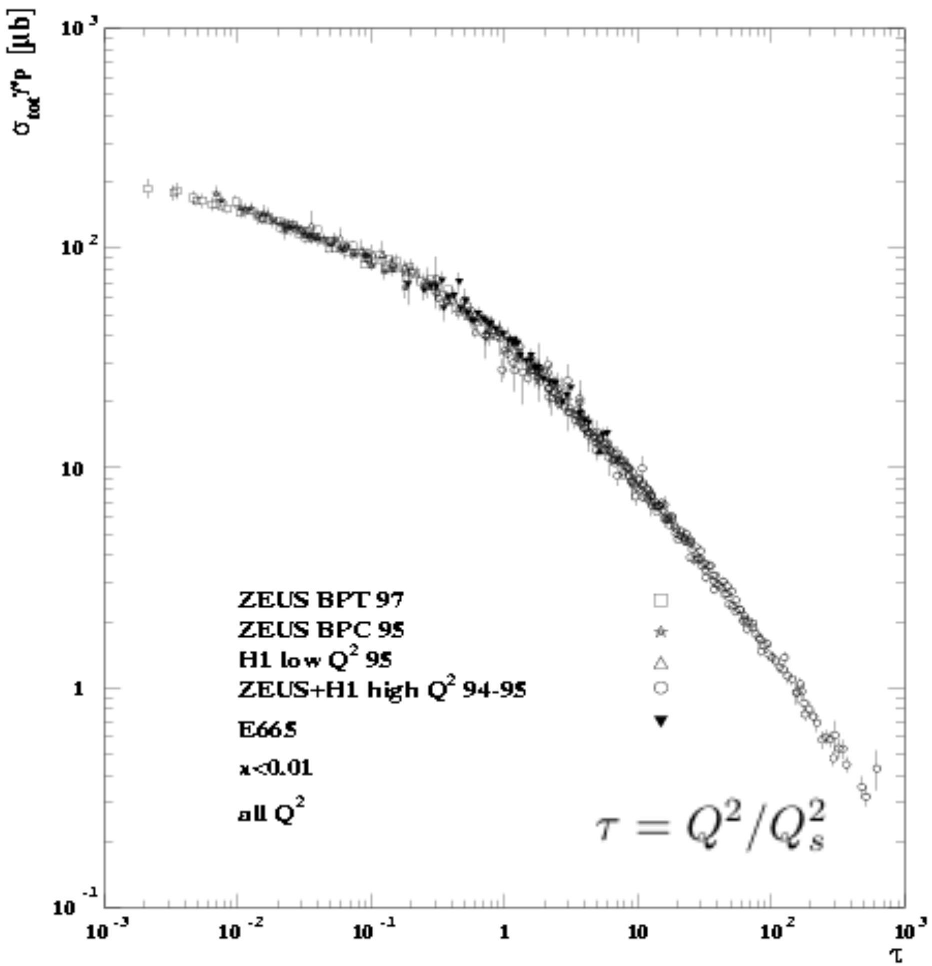
$$\sigma_{\gamma^* A}(x,Q^2) = \int dz \int d^2\boldsymbol{r}\; \underbrace{\left|\psi(z,\boldsymbol{r};Q^2)\right|^2}_{QED}\; \underbrace{2\int d^2\boldsymbol{b}\;(1 - S_\tau(\boldsymbol{x},\boldsymbol{y}))}_{\sigma_{dipole}}$$



$$\sigma_{dip} = \sigma_0\left[1 - \exp(-r_\perp^2 Q_s(x)^2)\right]$$

$$Q_s^2(x) \equiv Q_0^2\left(\frac{x_0}{x}\right)^\lambda$$

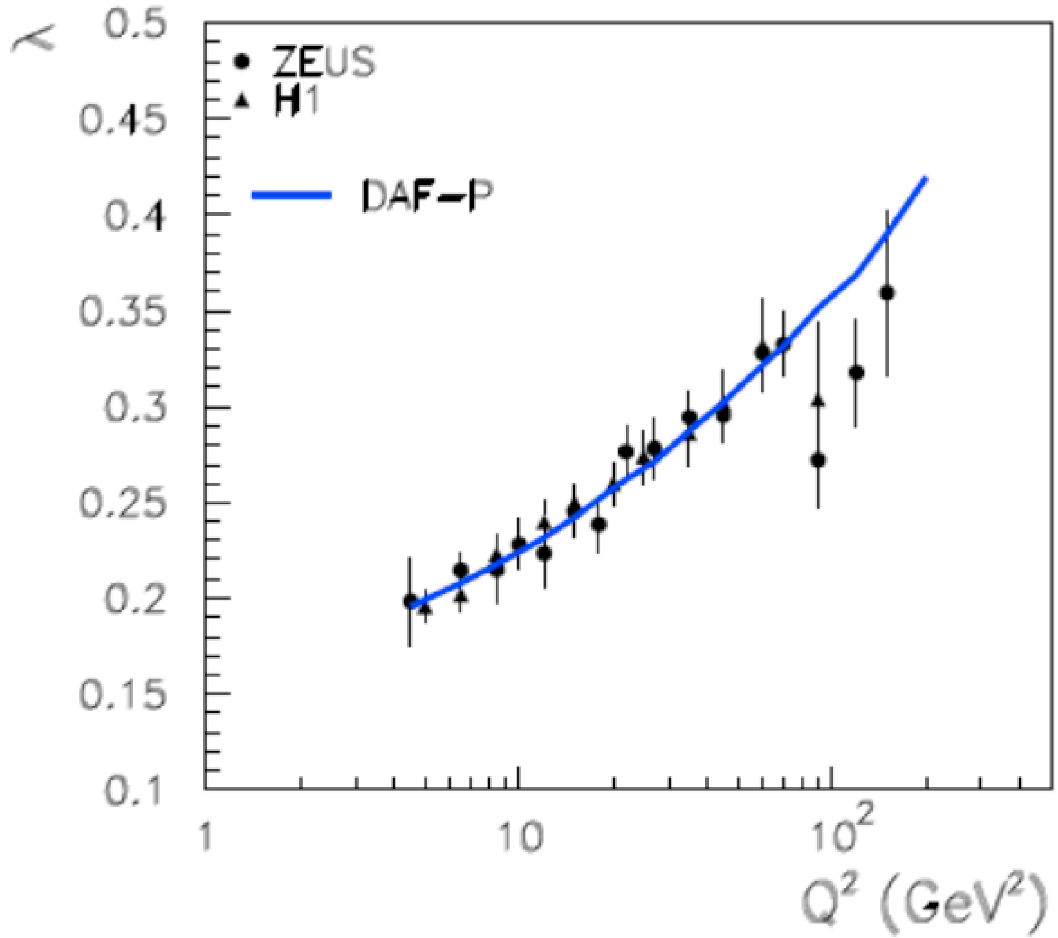
(Golec-Biernat,Kwiecinski,Stasto)



(H. Kowalski)

The rate of rise λ

$F_2 \sim (1/x)^{\lambda}$



The first successful pure BFKL desciption of the λ plot.

For many years it was claimed that BFKL analysis was not applicable to HERA data because of the observed substantial variation of λ with Q^2

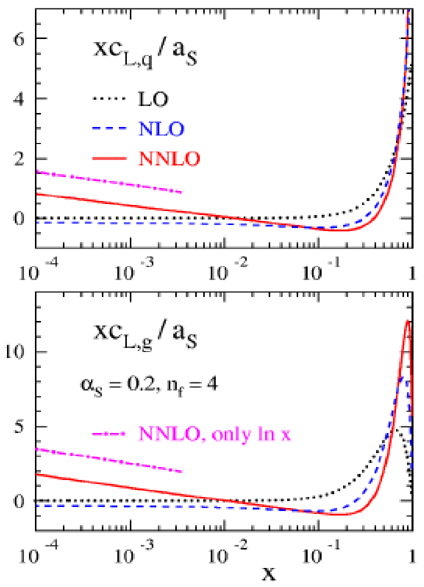
SMALL x PHYSICS FROM THE PERTURBATIVE END

THE NNLO CORRECTIONS

THEORY

THE COEFFICIENT FUNCTION C_L

(Moch, Vermaseren, Vogt 2005)

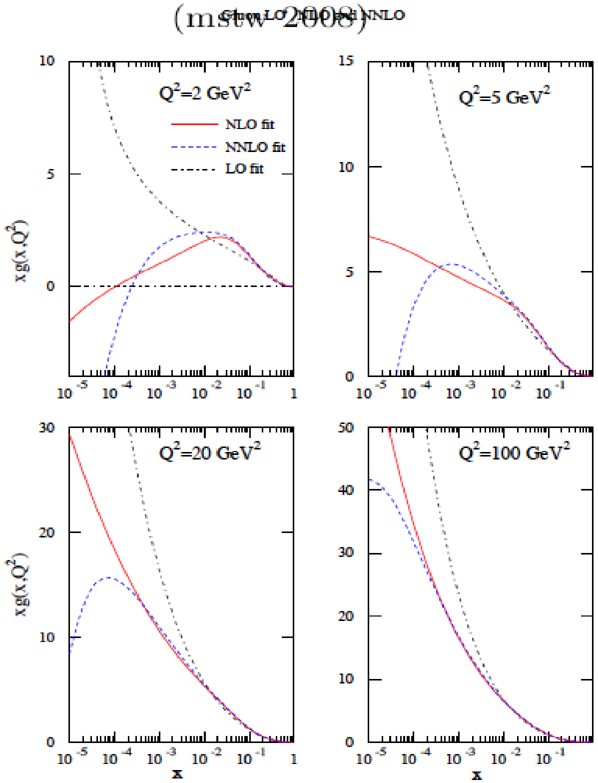


- PERTURBATIOMN THEORY UNSTABLE
- LEADING LOG APPROX POOR

PHENOMENOLOGY

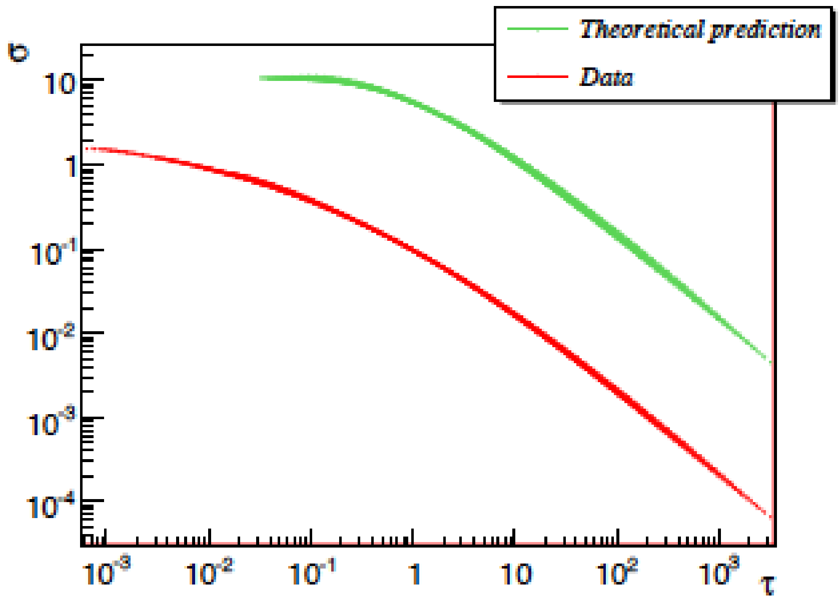
THE BEST–FIT GLUON

(mstw 2008)



(S. Forte)

Geometric scaling from DGLAP

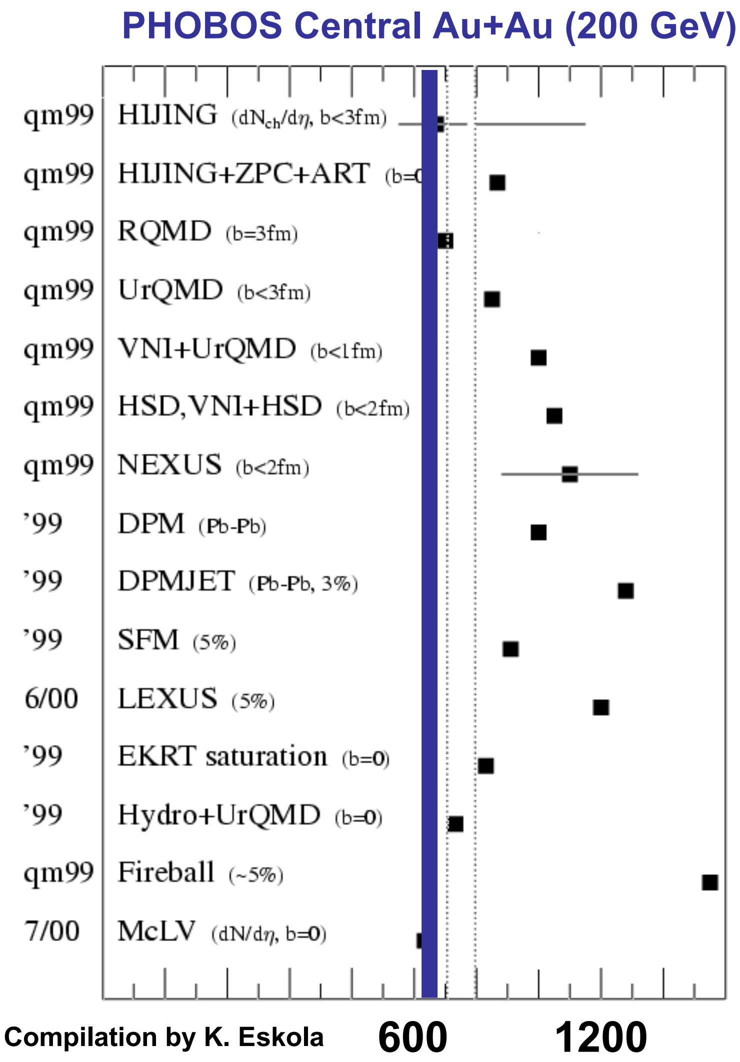


From F. Caola, in arXiv 0901.2504

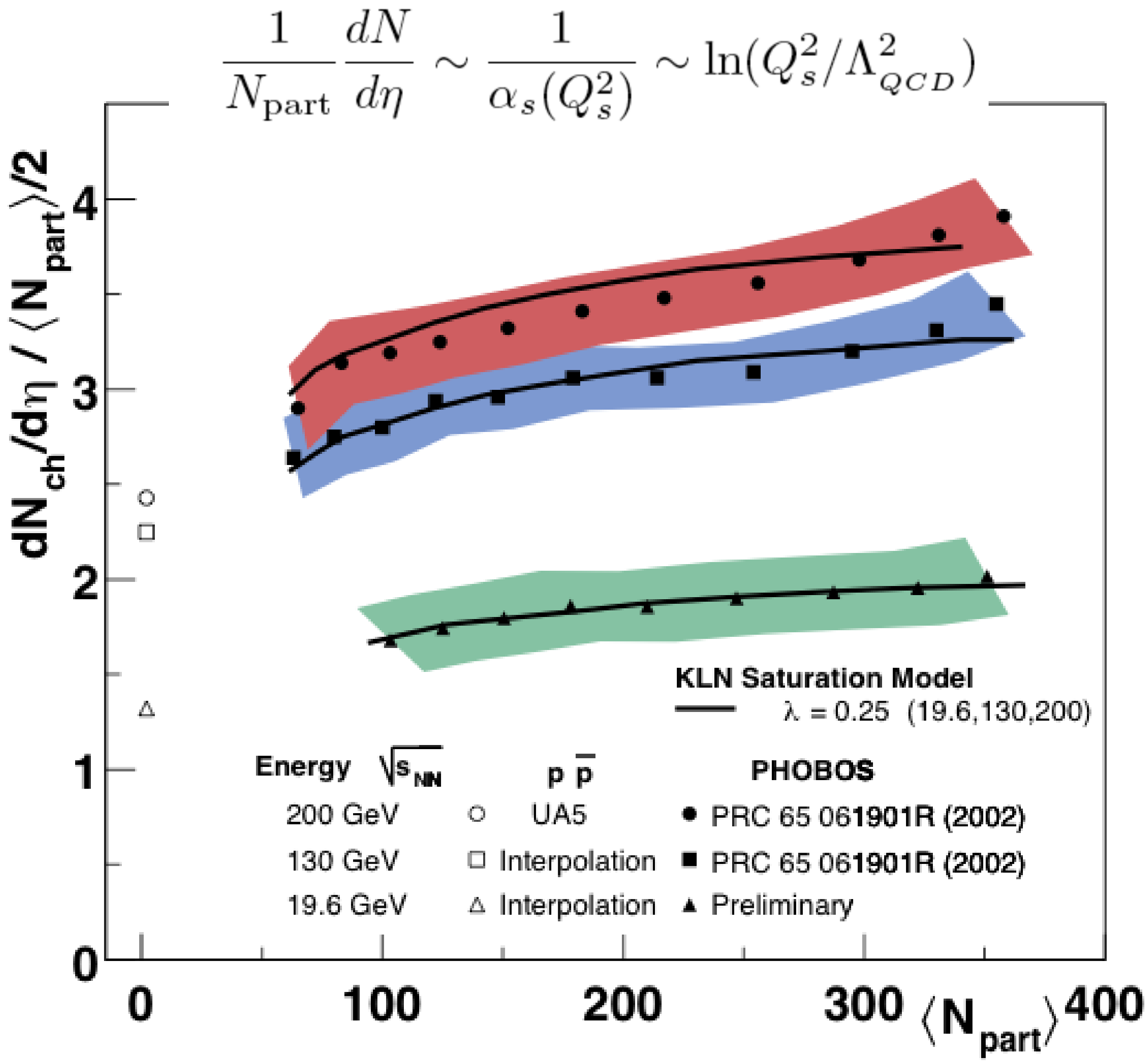
Nucleus-nucleus collisions
Proton-nucleus collision

Particle multiplicities

Total multiplicities



Compilation by K. Eskola



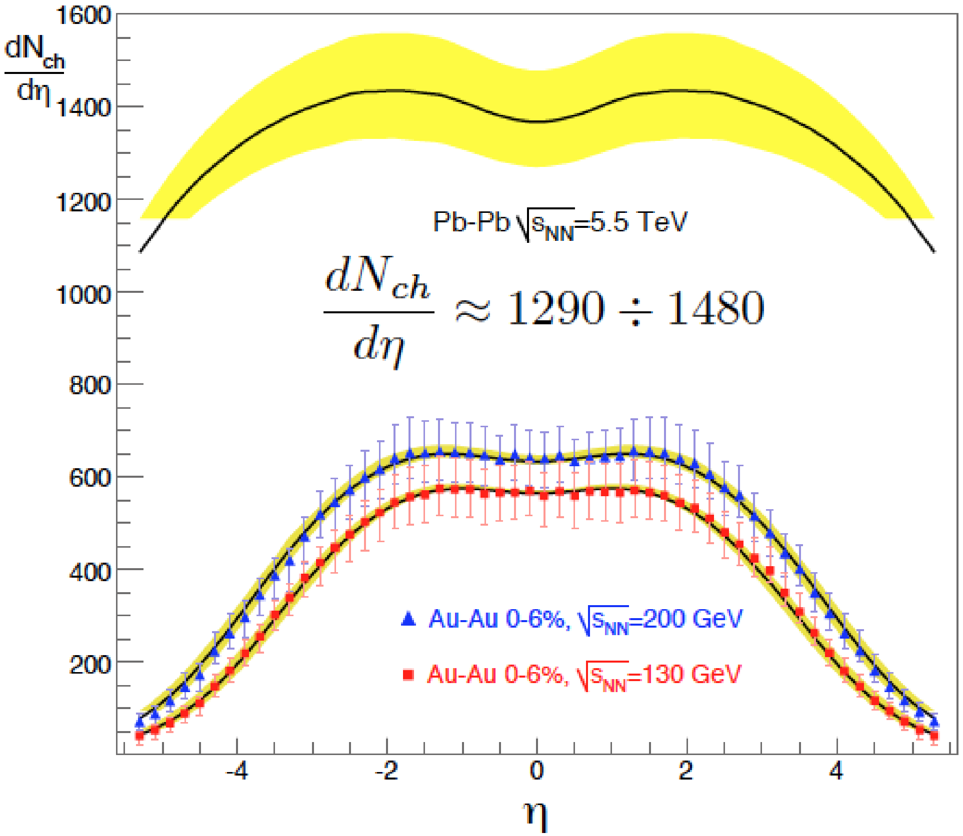
$$\frac{1}{N_{\rm part}}\frac{dN}{d\eta} \sim \frac{1}{\alpha_s(Q_s^2)} \sim \ln(Q_s^2/\Lambda_{QCD}^2)$$
$dN_{ch}/d\eta$ / $\langle N_{part}\rangle/2$
$\langle N_{part}\rangle$
0
1
2
3
4
0
100
200
300
400
KLN Saturation Model
λ = 0.25 (19.6,130,200)
Energy $\sqrt{s_{NN}}$
p $\bar{p}$
PHOBOS
200 GeV
UA5
PRC 65 061901R (2002)
130 GeV
Interpolation
PRC 65 061901R (2002)
19.6 GeV
Interpolation
Preliminary

(Albacete)

Fit parameters consistent with NLO-CGC analyses of other observables:

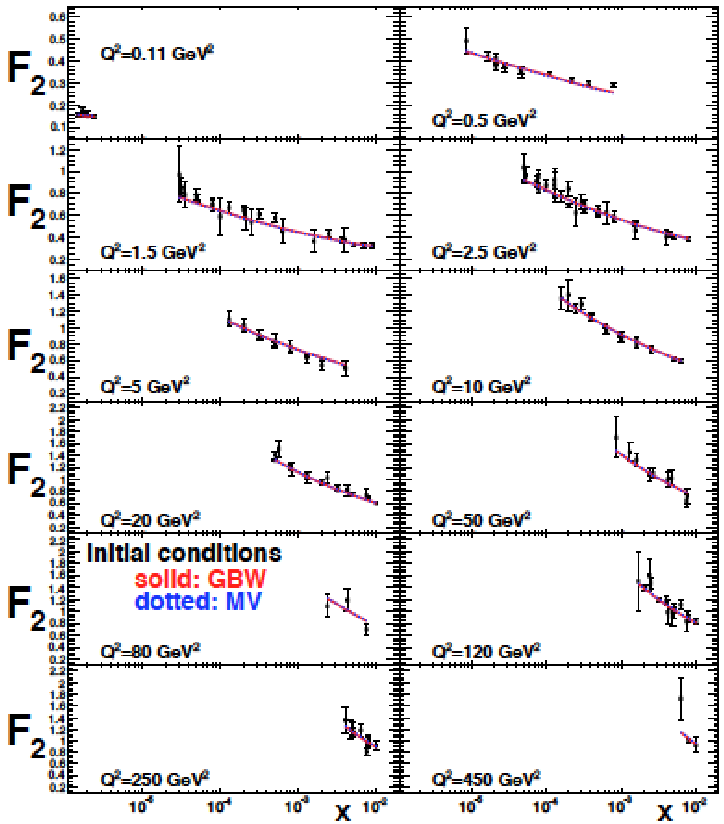
Multiplicities in RHIC Au+Au

JLA



F_2, F_L and F_D in e+p HERA collisions

JLA-Armesto-Milhano-Salgado
Goncalves et al.



$$\frac{Q^2_{0A}}{Q^2_{0proton}} \sim 2 \div 2.5 = cA^{1/3}$$ compatible with e+A data. K. Dusling et al

Two-particle correlations in forward d+Au at RHIC (Cyrille Marquet's talk)

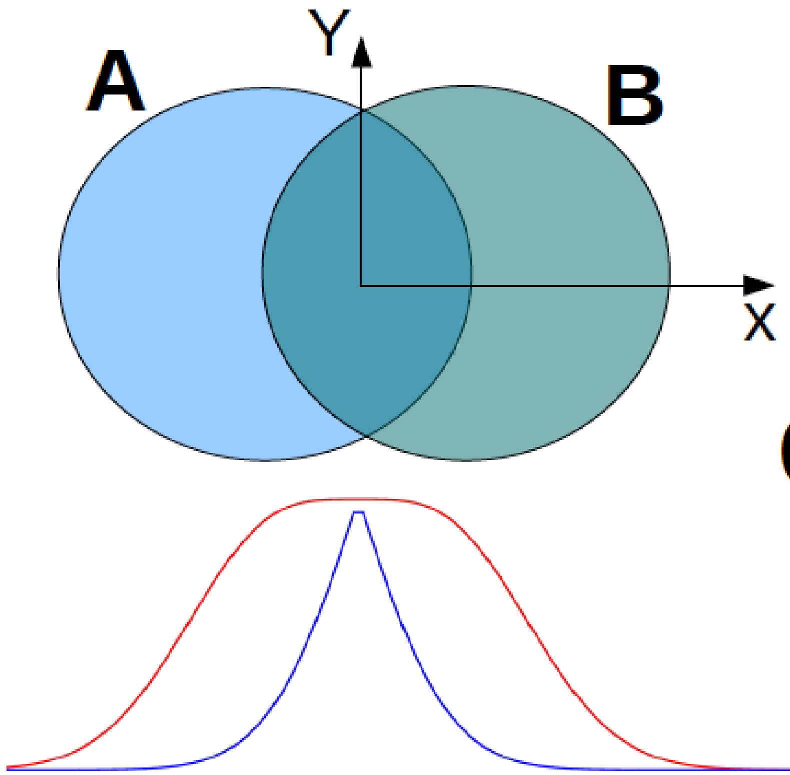
Transverse density:

(Dumitru)

nucl-th/0605012

$$\frac{dN_g}{d^2 r_\perp dy} = \frac{4\pi N_c}{N_c^2-1}\int\frac{d^2 p_t}{p_t^2}\int d^2 k_t\,\alpha_s\,\phi(x_1,k_t^2)\,\phi(x_2,(p_t-k_t)^2)$$

$$\sim \underline{\underline{Q^2_{s\ min}}}\,\log\frac{Q^2_{s\ max}}{Q^2_{s\ min}}$$



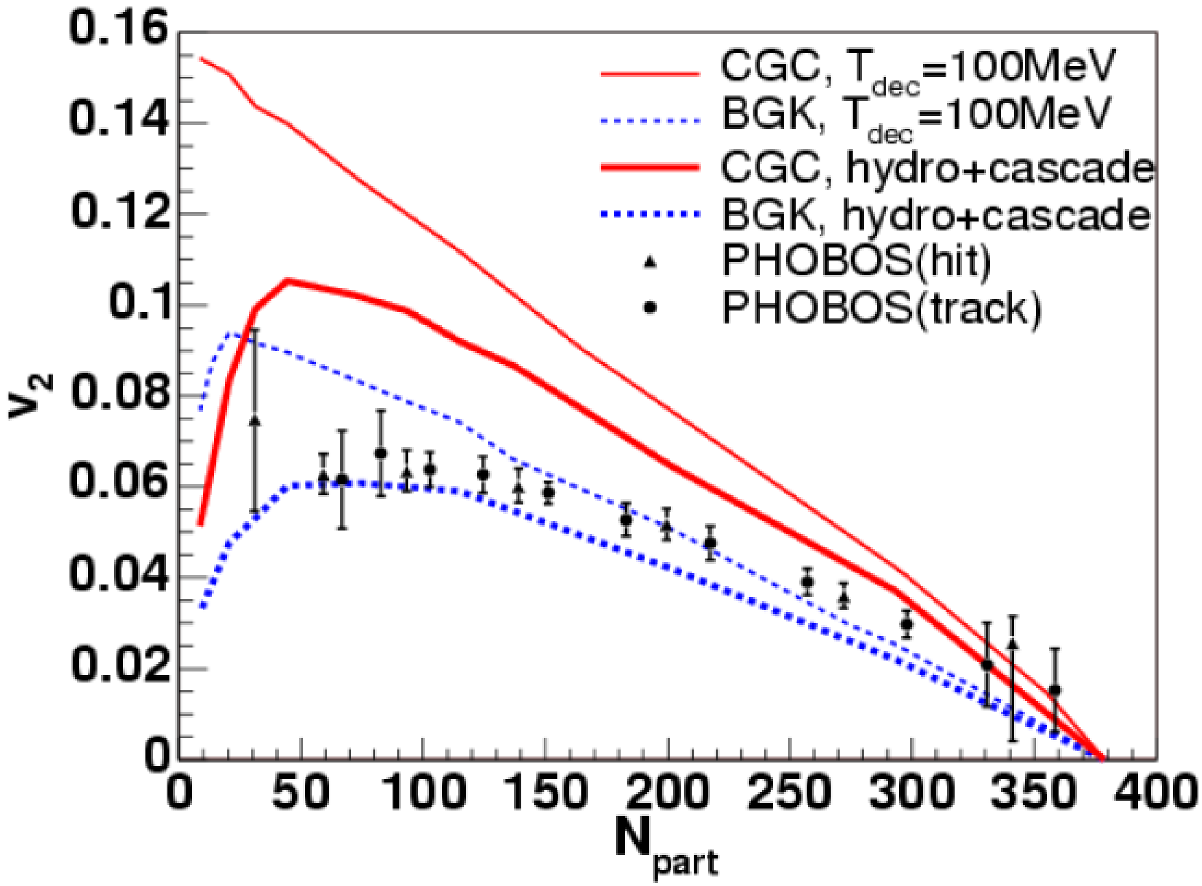
$$\text{CGC: } \frac{dN}{dy\,d^2 r} \sim \min\left(\rho^A_{\text{part}},\rho^B_{\text{part}}\right)$$

$$\text{Glauber: } \frac{dN}{dy\,d^2 r} \sim \frac{\rho^A_{\text{part}}+\rho^B_{\text{part}}}{2}$$

$$\rightarrow \boxed{\epsilon_{CGC} > \epsilon_{Glauber}}$$

(Dumitru)

ideal Hydro with CGC vs. Glauber initial conditions

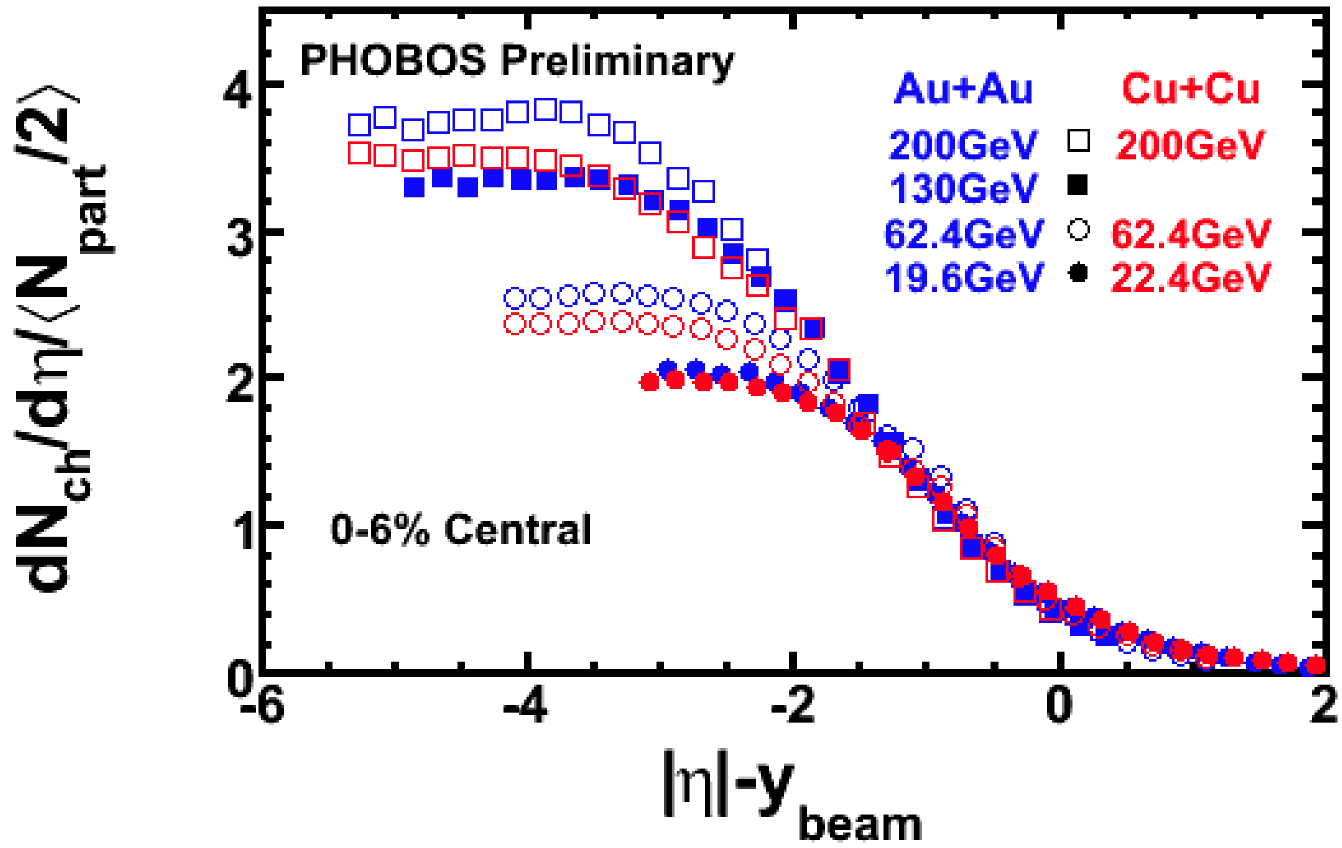


T. Hirano at al., Phys. Lett. B636 (2006) 299

Limiting fragmentation

(Busza)

« Extended longitudinal scaling »



(Stasto)

k_T *factorization and gluon saturation*

k_t factorization for gluon production at high energy $s \gg p_T$:

$$\frac{dN}{dyd^2p_T} = \frac{\alpha_s S_{AB}}{2\pi^4 C_F S_A S_B} \frac{1}{p_T^2} \int \frac{d^2k_T}{(2\pi)^2} \phi_A(x_1,k_T)\, \phi_B(x_2,|p_T - k_T|)$$

- $S_{A,B}$ total transverse area for nuclei, S_{AB} transverse area for an overlap region.
- p_T transverse momentum of the produced gluon.
- $x_1 = \frac{p_T}{m} e^{y-Y_{\text{beam}}}, x_2 = \frac{p_T}{m} e^{-y-Y_{\text{beam}}}$; longitudinal momentum fractions of the gluons probed in target and projectile.
- Functions $\phi(x,k_T)$ are *unintegrated* gluon distributions:

$$xg(x,Q^2) \sim \int^{Q^2} d^2k_T\, \phi(x,k_T)$$

- Experimentally measure hadrons, need to include the fragmentation from gluons (quarks) to pions.

Kharzeev, Levin, Nardi; Kovchegov, Tuchin; Czech, Szczurek ...

Scaling in limiting fragmentation

(Stasto)

$$\boxed{\frac{dN}{dY} \simeq \mathcal{N} x_1 f(x_1) = \mathcal{F}(Y - Y_{beam}), x_1 \gg x_2}$$

scaling with $Y - Y_{beam}$ (recall $x_1 \sim \exp(Y - Y_{beam})$).

For comparison with data:

- Need to model $\phi_A(x_1, k_T)$ at large x_1.
- Since $x_1 f(x_1)$ should obey x_1 scaling

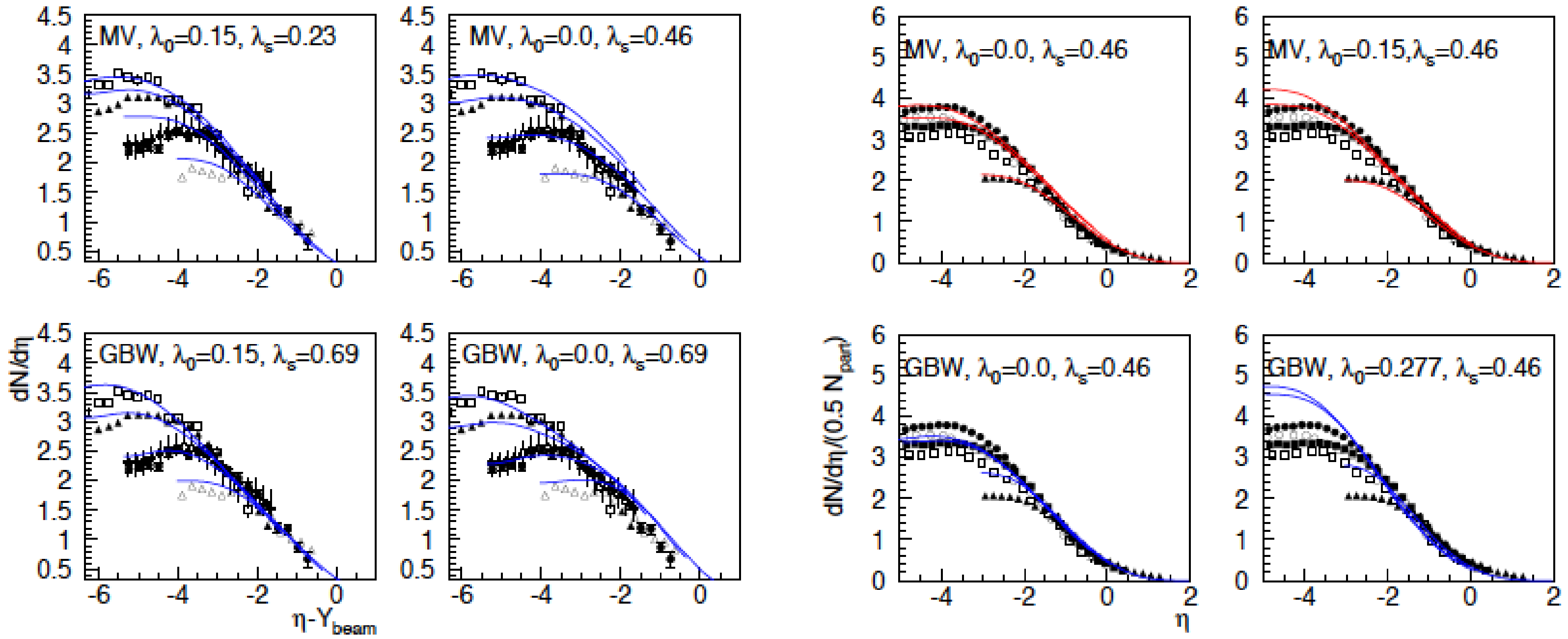
$$\boxed{x_1 f(x_1) = x_1 f(x_1, Q_s^2) = \int^{Q_s^2} dk^2 \phi_A(x_1, k)}$$

  the distribution ϕ_A must be peaked at very low k_T and sharply fall for large k_T.
- $\phi_A(x_1, k_T)$ at large x_1 is the largest source of uncertainty when comparing with the data.

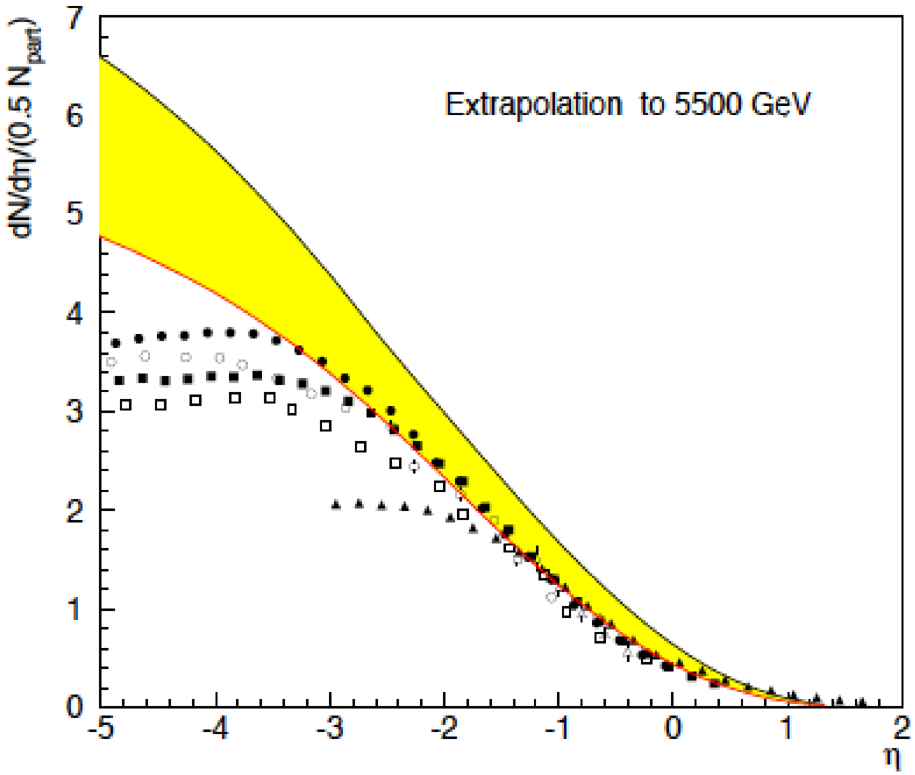
Proton-antiproton and AuAu(central) collisions

Gelis, Venugopalan, A.S.

proton-proton: Gold-Gold central:



- Small violations of limiting fragmentation scaling due to the fact that in some models we do not have approximately scaling of $x_1 f(x_1)$.
- Additional uncertaintes due to $y \leftrightarrow \eta$ change and fragmentation functions.



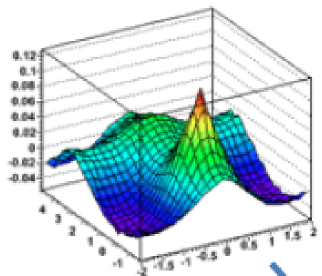
Extrapolation to 5500 GeV
dN/dη/(0.5 N_part)
η
0
1
2
3
4
5
6
7
-5
-4
-3
-2
-1
0
1
2

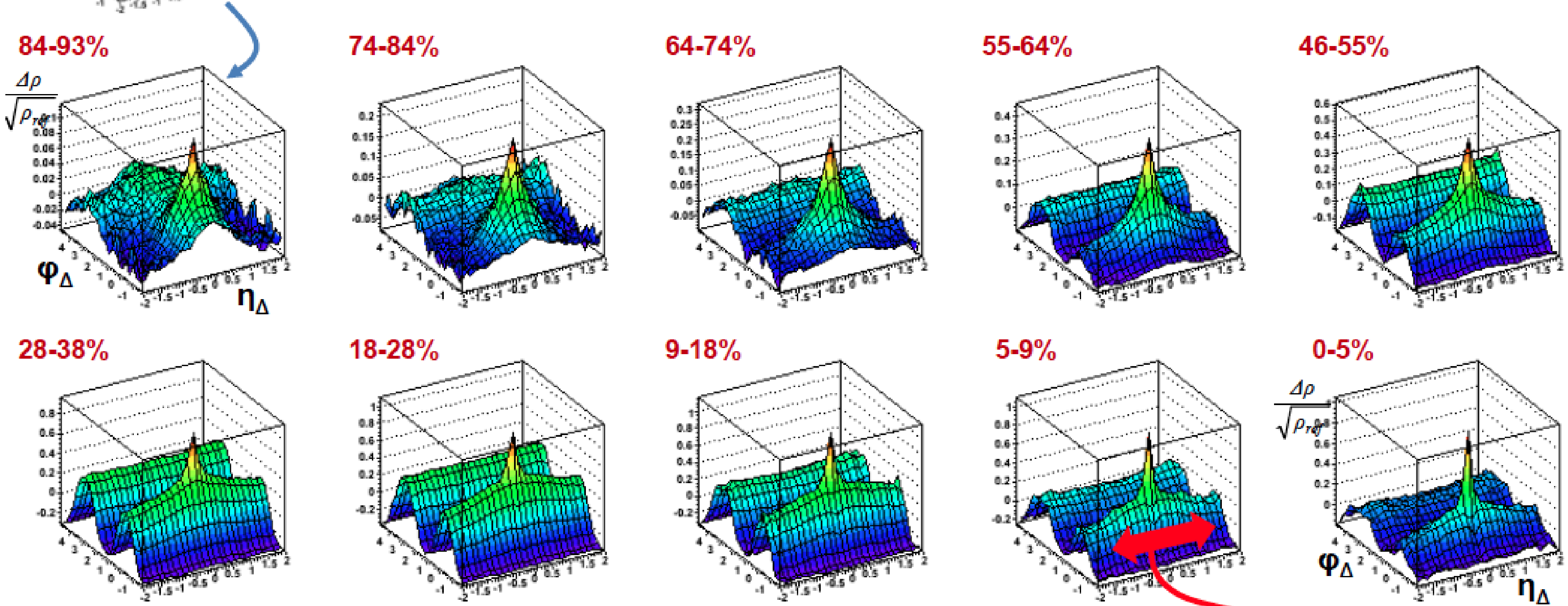
The Glasma and rapidity correlations

200 GeV Au-Au data

(Ray)

Analyzed 1.2M minbias 200 GeV Au+Au events;
included all tracks with $p_t > 0.15$ GeV/c, $|\eta| < 1$, full φ





STAR Preliminary

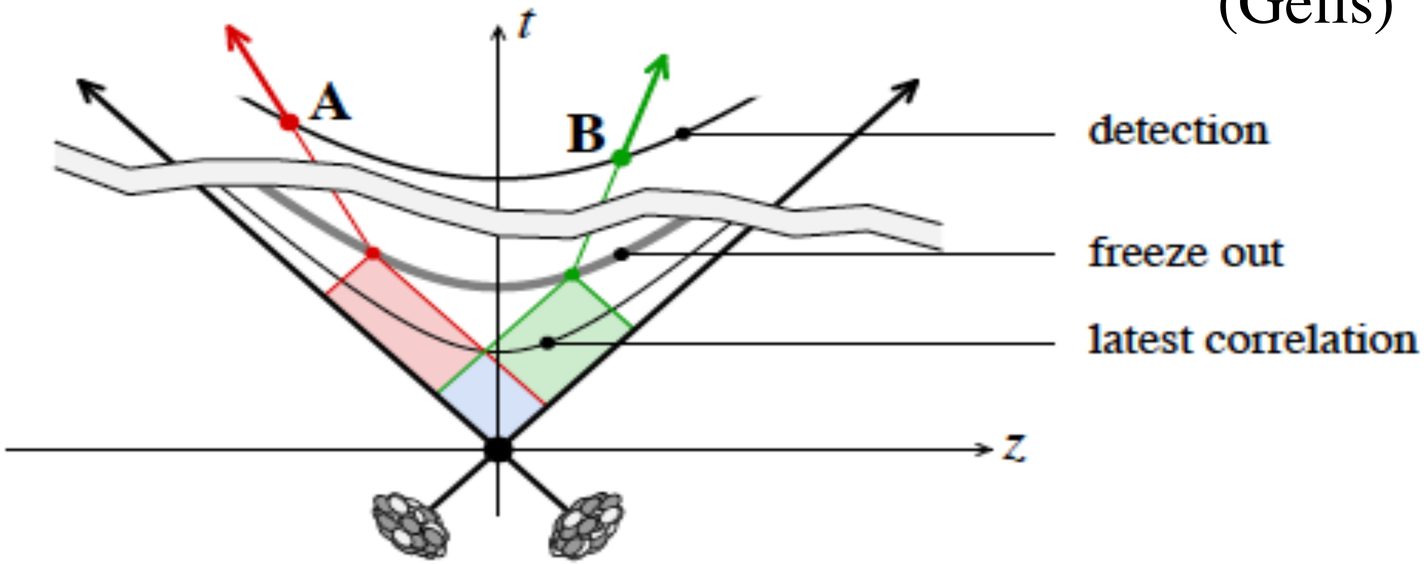
We observe the evolution of several correlation structures including the same-side low p_t ridge

Similar analysis was done for minbias Au-Au at 62 GeV and Cu-Cu at 62 and 200 GeV

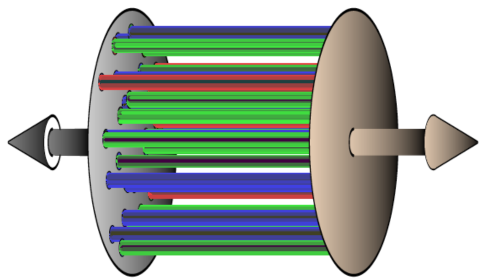
From M. Daugherity's Ph.D Thesis (2008)

Rapidity correlations are established at early times

(Gelis)



The glasma has such correlations
(but other models also - Pajares/Milhano)



(Gavin)

Glasma + Blast Wave ⇒ Ridge Height

pair correlation function -- Cooper Frye freeze out

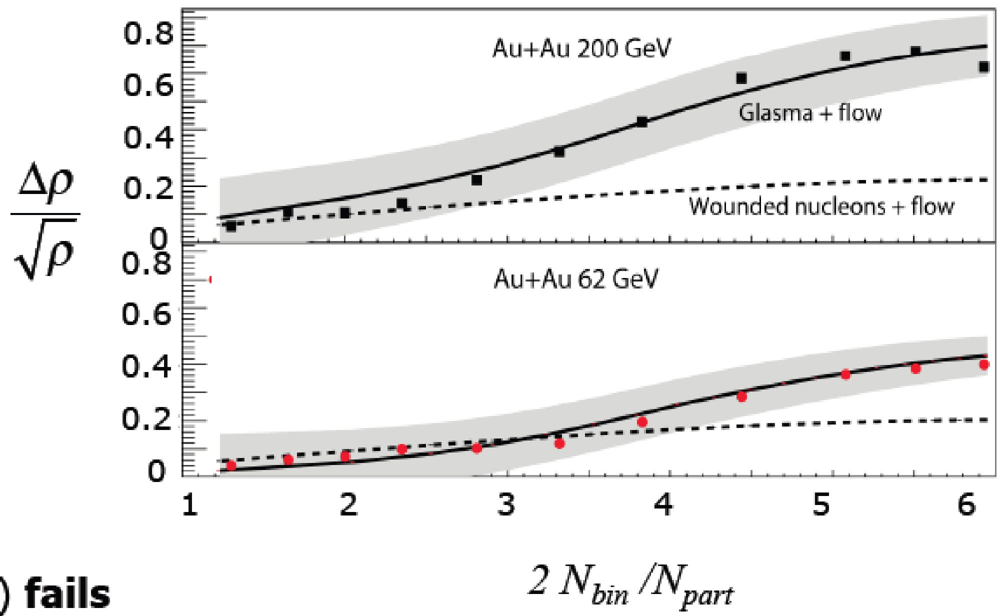
$$\Delta\rho \equiv \text{pairs} - (\text{singles})^2 \quad \propto \iint_{\text{freezeout surface}} f(p_1,x_1)\, f(p_2,x_2)\, c(x_1,x_2)$$

- blast wave $\rightarrow f(p,x)$
- scale factor to fit 200 GeV only
- Glasma energy dependence

$$\mathcal{R}\, dN/dy \propto \alpha_s^{-1}(Q_s)$$

STAR Data, J.Phys. G35 (2008) 104090

SG, McLerran, Moschelli et al. PRC 79 (2009) 051902



Glasma Q_s dependence: 200 GeV Au+Au ⇒ 62 GeV, Cu+Cu

wounded nucleon model (dashed) **fails**

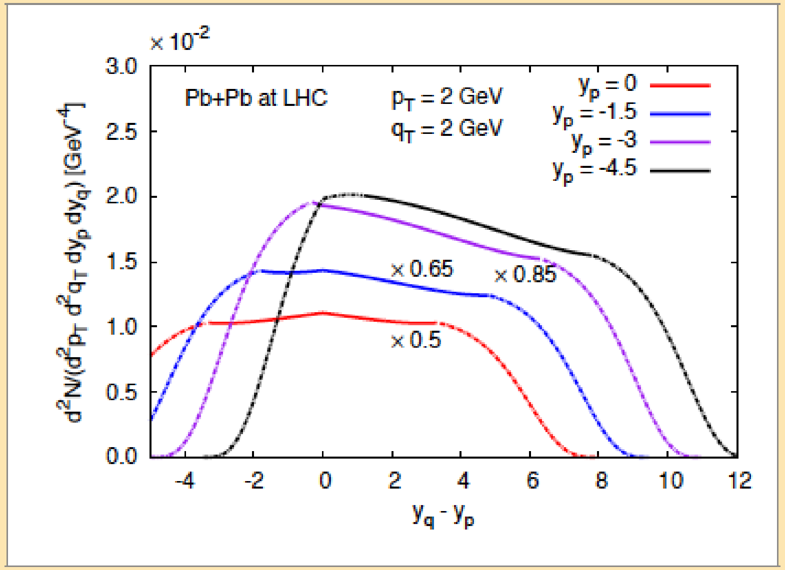
First calculation of rapidity dependence

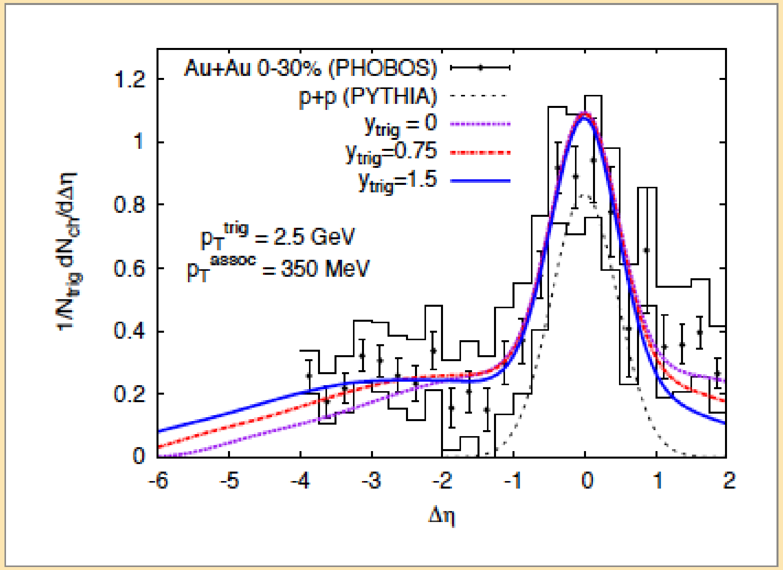
(Lappi)

k_T-factorized approximation Dusling, Gelis, T.L., Venugopalan, -09

$$C(\mathbf{p},\mathbf{q}) \sim \int_{\mathbf{k}_T} \Big\{ \overbrace{\Phi^2_{A_1}(y_p,\mathbf{k}_T)\Phi_{A_2}(y_p,\mathbf{p}_T-\mathbf{k}_T)}^{3 \text{ at } y_p} \overbrace{\Phi_{A_2}(y_q,\mathbf{q}_T+\mathbf{k}_T)}^{1 \text{ at } y_q}$$

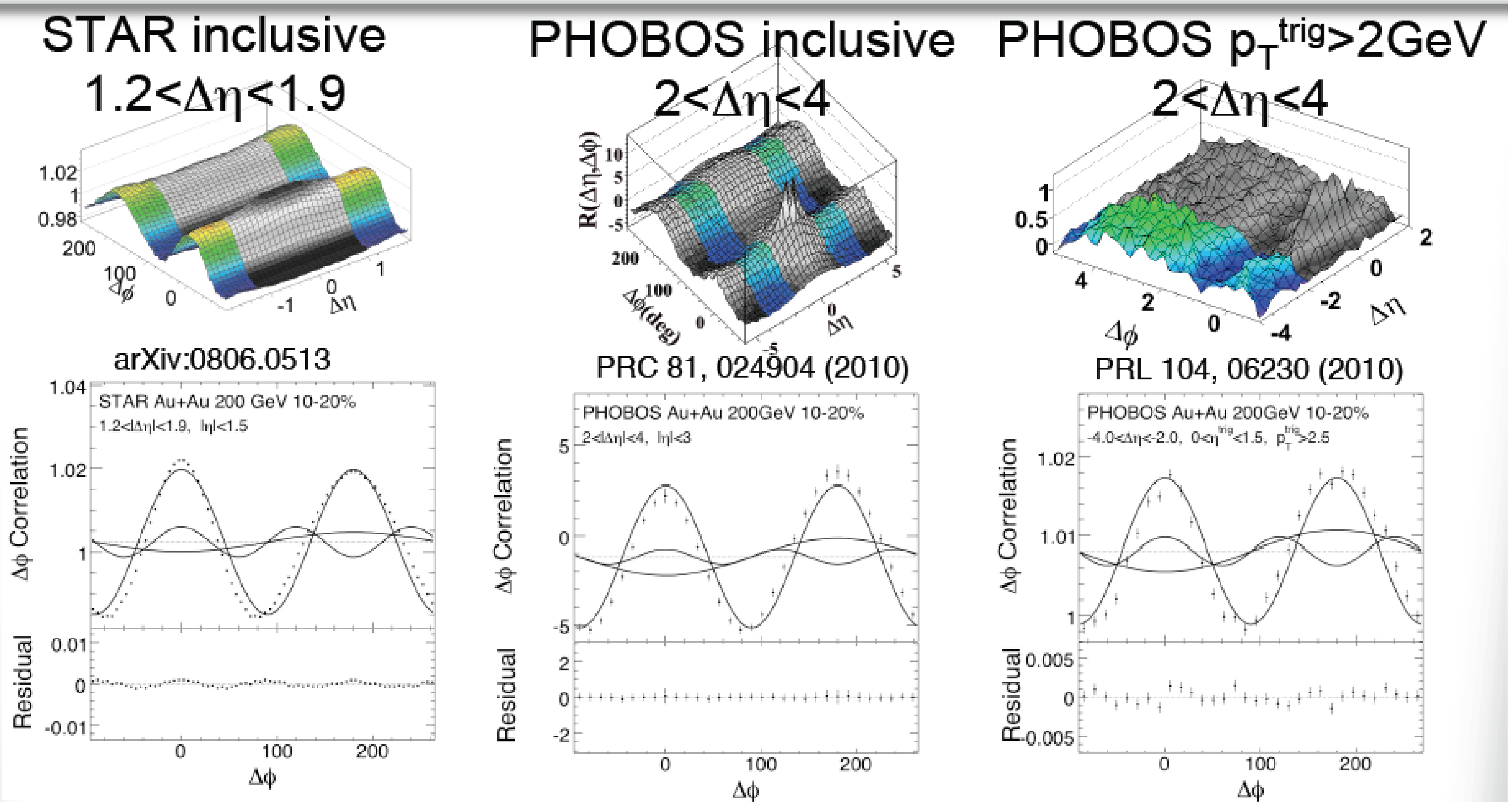
$$+ (\mathbf{k}_T \leftrightarrow -\mathbf{k}_T) + (A_1 \leftrightarrow A_2) \Big\}$$





(Alver)

Correlations at large $\Delta\eta$

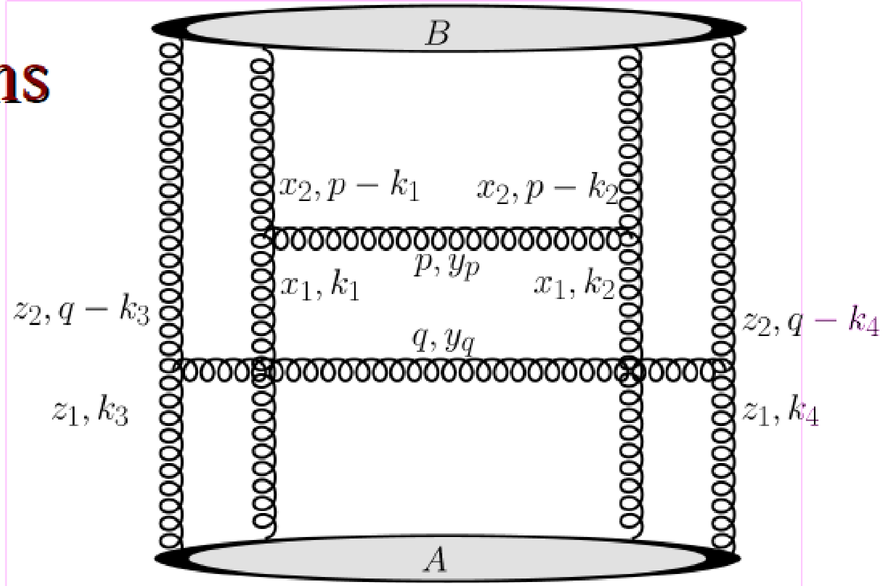


Long range correlations are well described by 3 Fourier Components.

BA, G.Roland, arXiv:1003.0194 (PRC in press)

(Dumitru)

genuine B-JIMWLK terms from THIS diagram:



B-JIMWLK four-point function (in Gaussian approximation), incl. "Nc corrections":

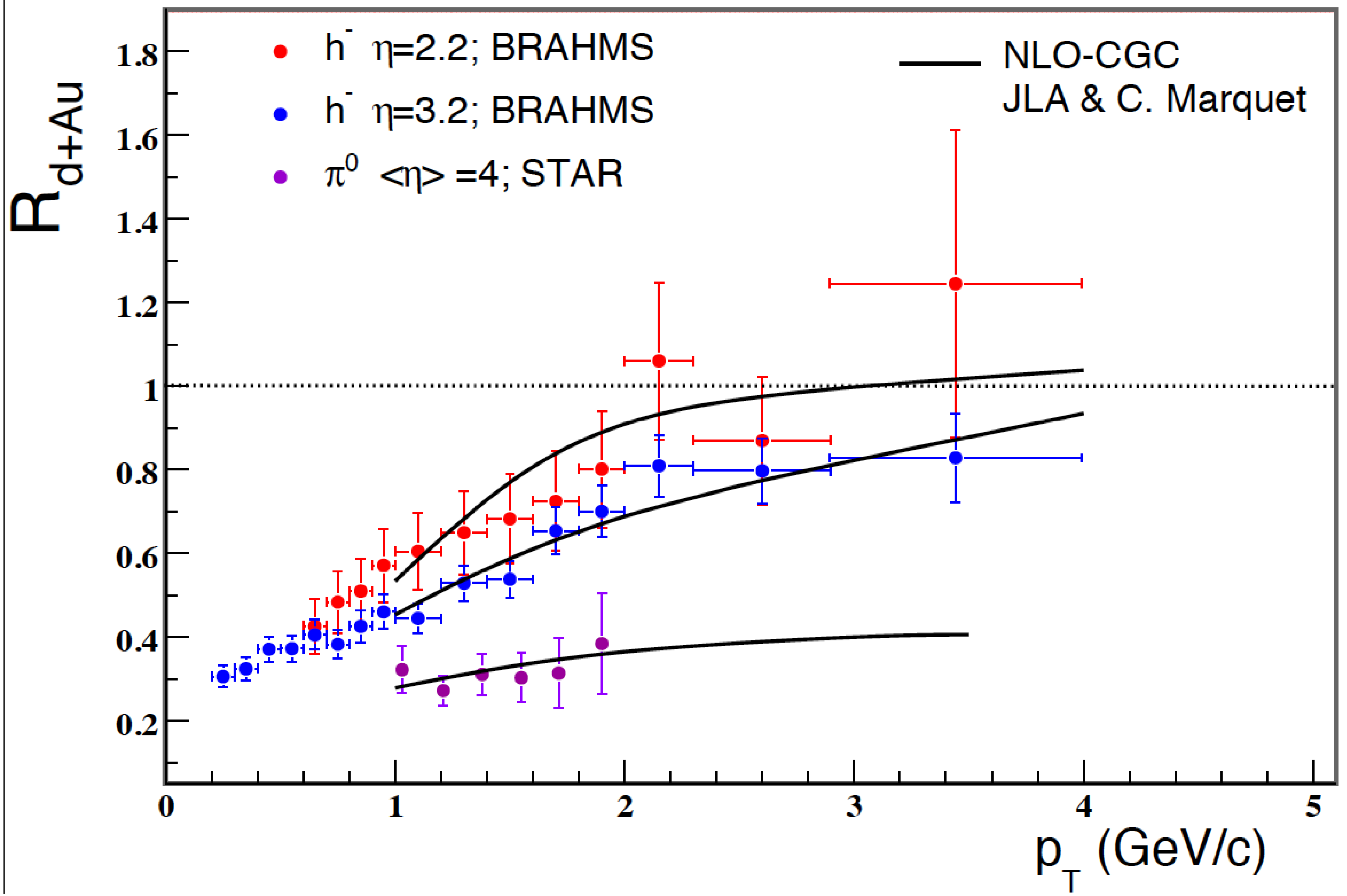
$$\left\langle \rho^a \rho^b \rho^c \rho^d \right\rangle \;=\; \delta^{ab}\delta^{cd}\left\langle \rho^2 \right\rangle^2 + \frac{1}{N_c} f^{abe} f^{cde} \mathcal{F}(k_i) \left\langle \rho^2 \right\rangle^2 + \cdots$$

A.D., J. Jalilian-Marian, arXiv:1001.4820

★ **ridge in pp @ LHC ?!**

Forward rapidity

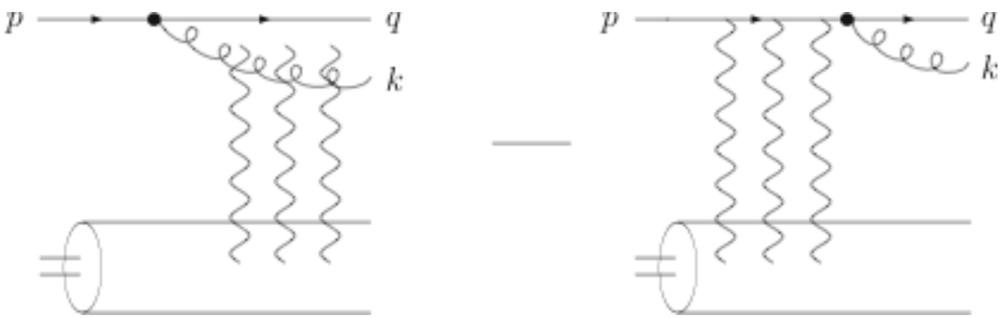
(Albacete)



R_{d+Au}
h^- η=2.2; BRAHMS
h^- η=3.2; BRAHMS
π^0 <η> =4; STAR
NLO-CGC
JLA & C. Marquet
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
p_T (GeV/c)

(Marquet)

Forward di-jet production



b: quark in the amplitude
x: gluon in the amplitude
b': quark in the conj. amplitude
x': gluon in the conj. amplitude

Fourier transform $k_\perp$ and $q_\perp$ into transverse coordinates

collinear factorization of quark density in deuteron

$$\frac{d\sigma^{dAu\to qgX}}{d^2k_\perp dy_k d^2q_\perp dy_q} = \alpha_S C_F N_c\, x_d q(x_d,\mu^2) \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2b}{(2\pi)^2}\frac{d^2b'}{(2\pi)^2}\, e^{ik_\perp.(\mathbf{x}'-\mathbf{x})} e^{iq_\perp.(\mathbf{b}'-\mathbf{b})}$$

$$\left|\Phi^{q\to qg}(z,\mathbf{x}-\mathbf{b},\mathbf{x}'-\mathbf{b}')\right|^2 \underbrace{\Big\{S^{(4)}_{qg\bar{q}\bar{g}}[\mathbf{b},\mathbf{x},\mathbf{b}',\mathbf{x}';x_A] - S^{(3)}_{qg\bar{q}}[\mathbf{b},\mathbf{x},\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A] - S^{(3)}_{\bar{q}gq}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{x}',\mathbf{b}';x_A] + S^{(2)}_{q\bar{q}}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]\Big\}}_{\text{interaction with hadron 2 / CGC}}$$

pQCD $q \to qg$ wavefunction

$$z = \frac{|k_\perp|e^{y_k}}{|k_\perp|e^{y_k}+|q_\perp|e^{y_q}}$$

interaction with hadron 2 / CGC

n-point functions that resums the powers of $g_S A$ and the powers of $\alpha_S \ln(1/x_A)$

computed with JIMWLK evolution at NLO (in the large-Nc limit), and MV initial conditions

no parameters

(Marquet)

Monojets in central d+Au

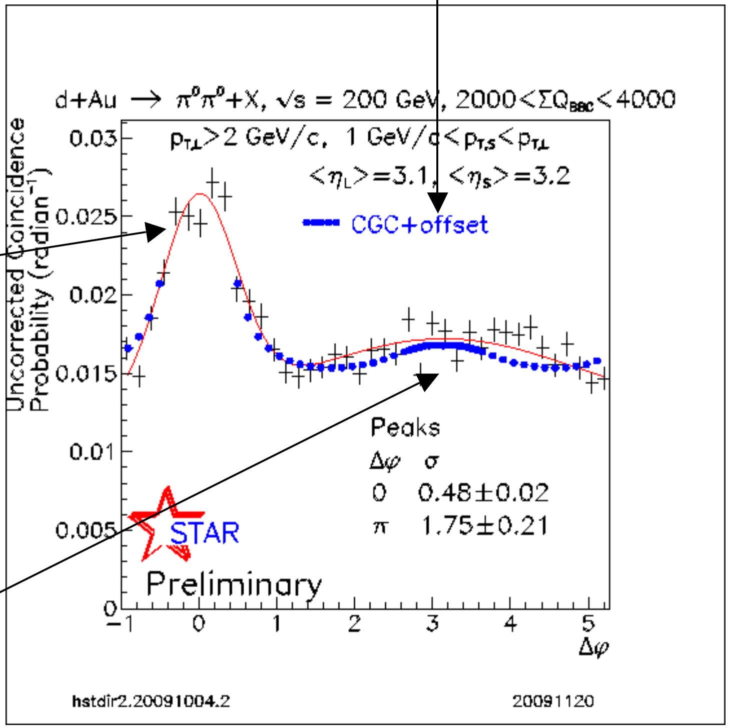
- in central collisions where Q_S is the biggest

there is a very good agreement of the saturation predictions with STAR data

Albacete and C.M., to appear

an offset is needed to account for the background

to calculate the near-side peak, one needs di-pion fragmentation functions



- the focus is on the away-side peak

where non-linearities have the biggest effect

suppressed away-side peak

standard (DGLAP-like) QCD calculations cannot reproduce this

(Strikman)

Independent of details - the observed effect is a strong evidence for breaking pQCD approximation in the kinematics sensitive to strong gluon field in nuclei

New forward forward pion data qualitatively consistent with increase of the suppression for this kinematics in 2 $\to$2 scenario as the second jet is also in BDR. Stronger post selection effect - enhanced effective energy losses.

Relevant effects:

- ☛ second jet is mostly from gluons which have larger effective energy losses
- ☛ x_2 is in the region where gluon shadowing is a factor of 2 - a factor of two smaller relative contribution of forward- forward vs forward inclusive
- ☛ forward- forward events correspond to larger x_1 than forward triggers (next slide) - further enhancement of suppression due to fractional energy losses.

J/Psi

(Kopeliovich)

Nuclear effects

3 Initial state saturation of gluons

Due to saturation gluons experience broadening $\Delta p_T^2 = 2C(s)\,T_A(b)$ with the coefficient $C(s)$ known from DIS data.

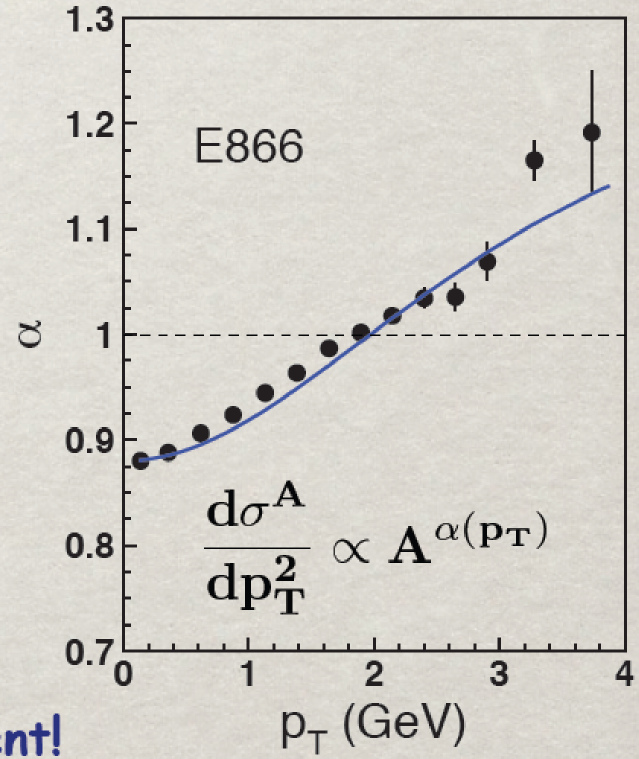
The p_T distribution of J/Ψ has the form:

$$\frac{d\sigma}{dp_T^2} \propto \left(1 + \frac{p_T^2}{6\langle p_T^2\rangle}\right)^{-6}$$

Broadening results in $\langle p_T^2\rangle \Rightarrow \langle p_T^2\rangle + \Delta p_T^2$

$$R_T(p_T) = \frac{\left.\frac{d\sigma}{dp_T^2}\right|_{\langle p_T^2\rangle + \Delta p_T^2}}{\left.\frac{d\sigma}{dp_T^2}\right|_{\langle p_T^2\rangle}}$$

★ This can be tested with the E866 data for J/Ψ production in pA at 800 GeV:



Works amazingly well with no adjustment!

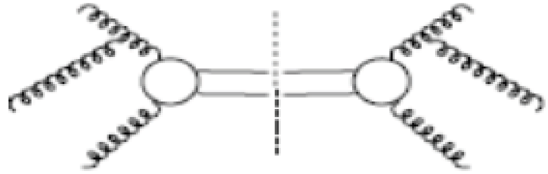
NIVERSIDAD TECNICA

(Qiu)

Broadening of heavy quarkonia

Kang, Qiu, PRD77(2008)

❑ Initial-state only:



$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi} = C_A\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\,\lambda^2\,A^{1/3}\right)$$

$$\Delta\langle q_T^2\rangle_{\rm DY} \approx C_F\left(\frac{8\pi^2\alpha_s}{N_c^2-1}\,\lambda^2\,A^{1/3}\right)$$

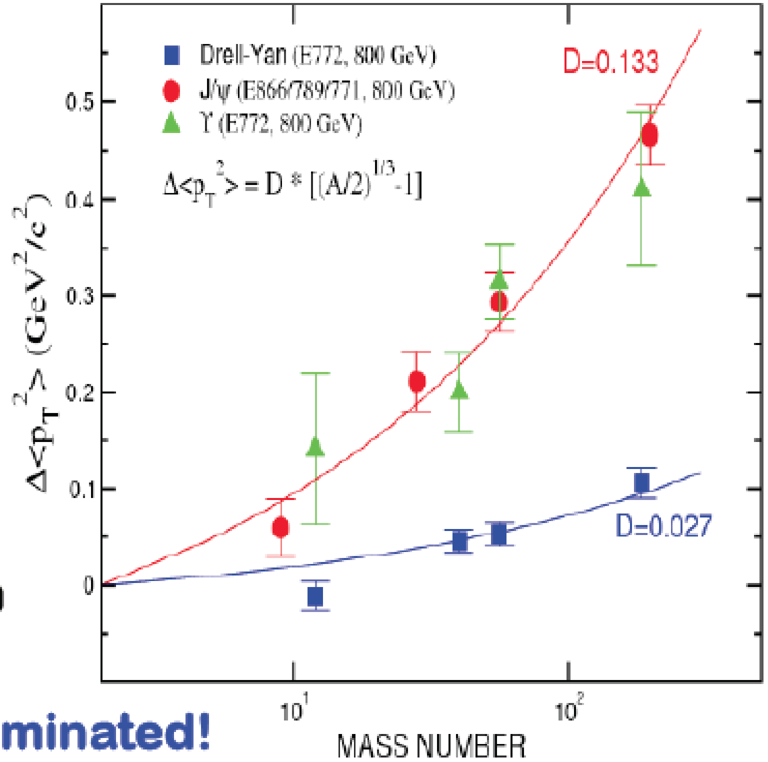
❑ Experimental data from d+A:

Clear $A^{1/3}$ dependence

But, wrong normalization!

$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi}\,/\,\Delta\langle q_T^2\rangle_{\rm DY}\Big|_{\rm thy} = C_A/C_F = 2.25$$

$$\Delta\langle q_T^2\rangle^{(I)}_{J/\psi}\,/\,\Delta\langle q_T^2\rangle_{\rm DY}\Big|_{\rm exp} = 0.133/0.027 \approx 4.9$$



J.C.Peng, hep-ph/9912371

Johnson,et al, 2007

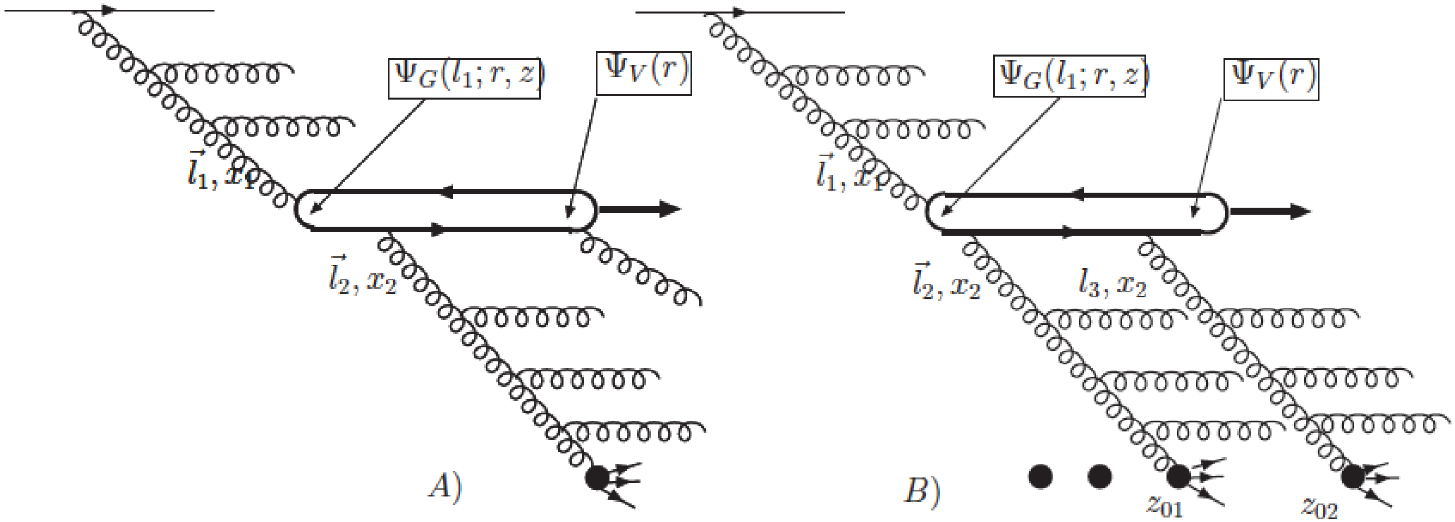
Final-state effect – octet channel dominated!

Only depend on observed quarkonia

(Tuchin)

Production of J/ψ: pp vs pA

Kharzeev, KT,2005
Kharzeev, Levin, Nardi, KT,2009



hadron – hadron collisions

hadron – nucleus collisions

$$\alpha_s^3 A^{1/3} = \alpha_s(\alpha_s^2 A^{1/3}) \sim \alpha_s$$

$$\alpha_s^4 A^{2/3} = (\alpha_s^2 A^{1/3})^2 \sim 1$$

This mechanism is dominant for central collisions

Summary