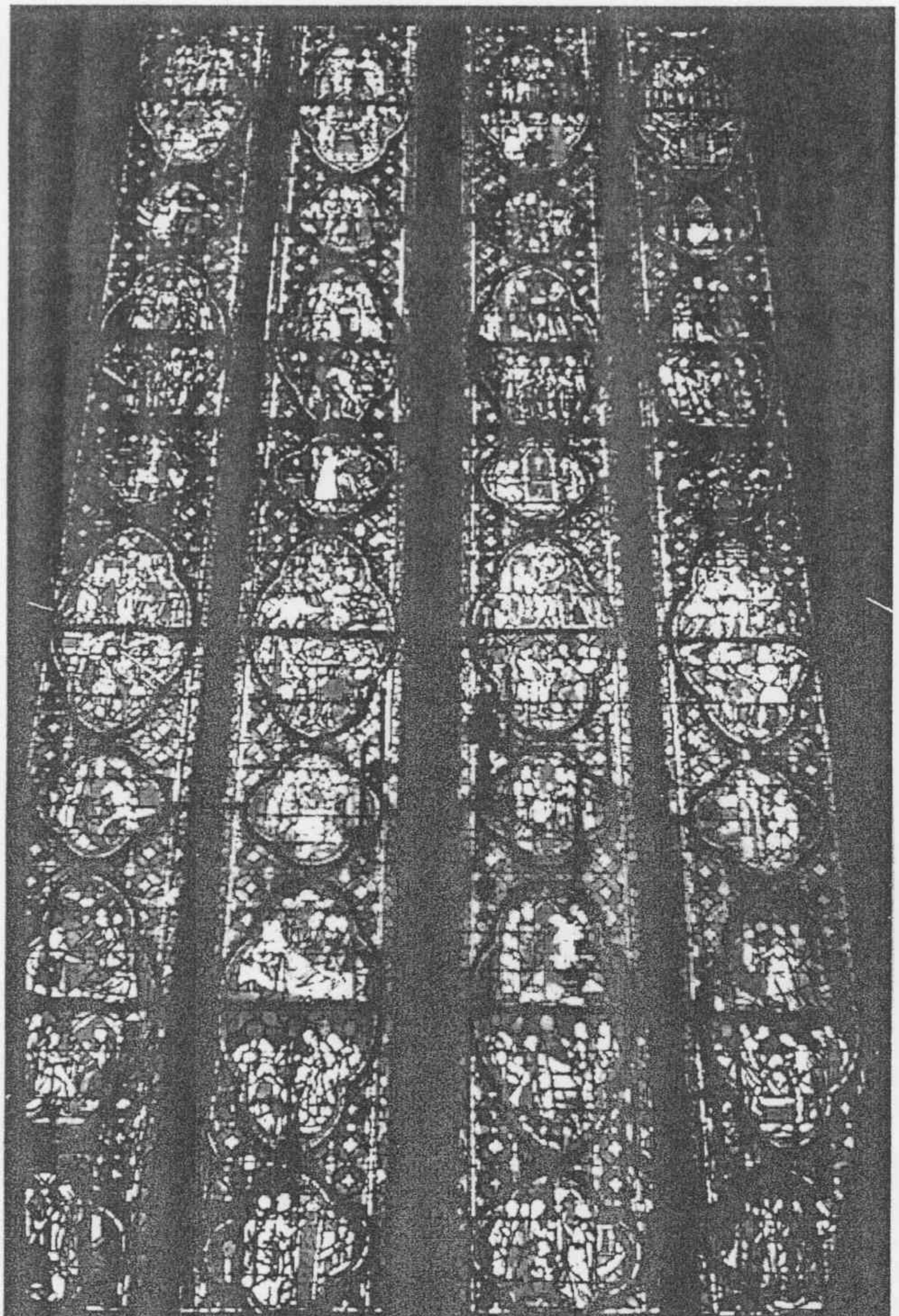
DURHAM
DEC. 5th - 7th, 200

IS QCD AT HIGH ENERGIES A COLOR GLASS CONDENSATE?

Raju Venugopalan.
BNL & RIKEN-BNL.



ST. CHAPPELLE, PARIS, FRANCE.

Outline of Talk:

* Introduction:

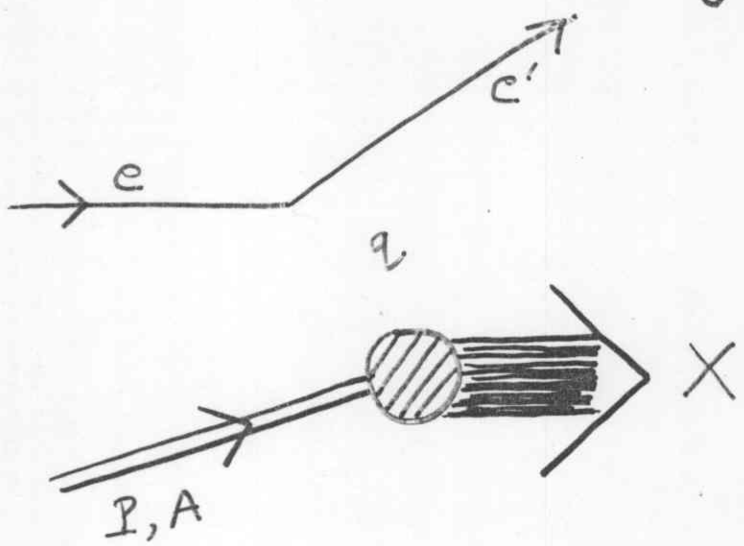
* Effective field theory for high energy QCD.
  – the Color Glass Condensate.

* A non-linear Wilsonian Renormalization Group for small x.

* Melting the Color Glass Condensate in Heavy Ion Collisions – from CGC to QGP?

* Summary.

The DIS Paradigm...



$$Q^2 = -q^2 > 0$$

$$x_{Bj} = \frac{Q^2}{2p \cdot q} \simeq x_F$$

$$\boxed{x_{Bj} \simeq \frac{Q^2}{s}}$$

The Bjorken Limit:

$$Q^2 \to \infty$$
$$s \to \infty$$
$$x_{Bj} \equiv \text{fixed}.$$

pQCD is enormously successful.

$\mapsto$ running of α_s – asymptotic freedom.

$\mapsto$ the OPE & RG – compute large variety of hard processes.

However... tails of distributions...

$$\frac{d\sigma}{dx_{Bj}\, dQ^2} \propto \underline{\underline{\frac{1}{Q^4}}} F_2$$

$$\left(Q^2 \gg \Lambda^2_{QCD}\right)$$

QCD does not yet explain the vast bulk of cross-sections: soft and semi-hard processes.

Phenomenology inspired by Regge theory
- hard to understand in QCD framework.

The small x_{Bj} limit:

$$x_{Bj} \to 0$$
$$s \to \infty$$
$$Q^2 \equiv \text{fixed} \gg \Lambda^2_{QCD}.$$

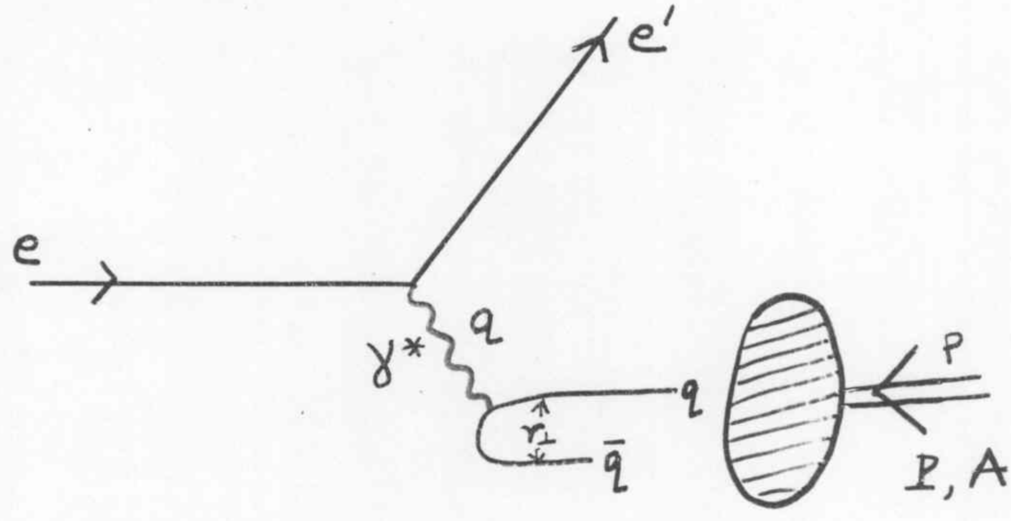
$\mapsto$ regime of high parton densities...

novel "condensed matter" regime of the theory?

Small x Parton Distributions In DIS

$Q^2 = -q^2 > 0$

$x_{Bj} = \dfrac{Q^2}{2p \cdot q} \simeq x_F$



$$\boxed{x_{Bj} \simeq \frac{Q^2}{s}}$$

$$\sigma_{\gamma^* p} = |\Psi|^2_{\gamma^* \to q\bar{q}} \otimes \hat{\sigma}_{q\bar{q}\cdot P/A}(x, r_\perp)$$

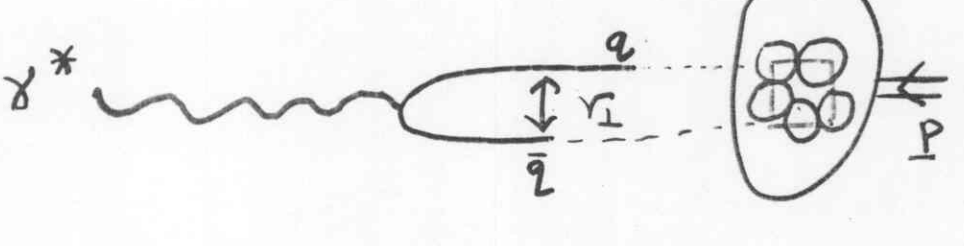
$\mapsto$ Parton Distributions Grow Rapidly At Small x_{Bj} (HERA)

$\mapsto$ QCD Linear Evolution Eqns.

"DGLAP" & "BFKL" Predict Rapid Rise For $x \ll 1$.

Gribov, Levin, Ryskin,
Mueller, Qiu. 7

PARTONS IN TRANSVERSE PLANE OVERLAP
WHEN DENSITY IS LARGE
- THEY SATURATE (i.e., grow very slowly.)



$$\boxed{r_\perp \sim \frac{1}{Q} << 1\ \text{fm}}$$

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

Golec-Biernat,
Wusthoff.

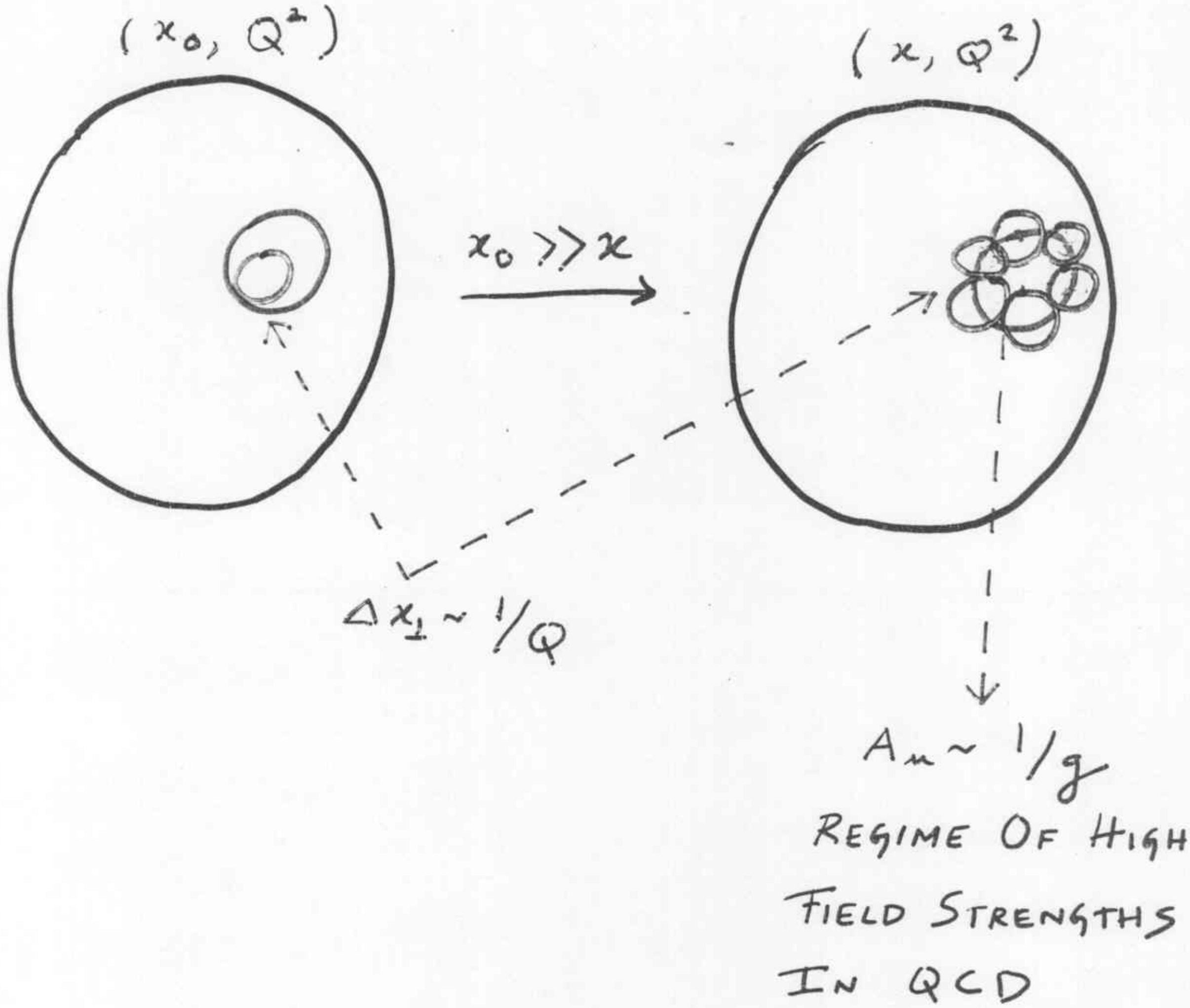
$\mapsto$ SATURATION $\simeq \ln\left(\frac{Q_s^2}{Q^2}\right)$ for $Q_s^2 r_\perp^2 >> 1$

DIS SCALING $\simeq Q_s^2/Q^2$ for $Q_s^2 r_\perp^2 << 1$

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

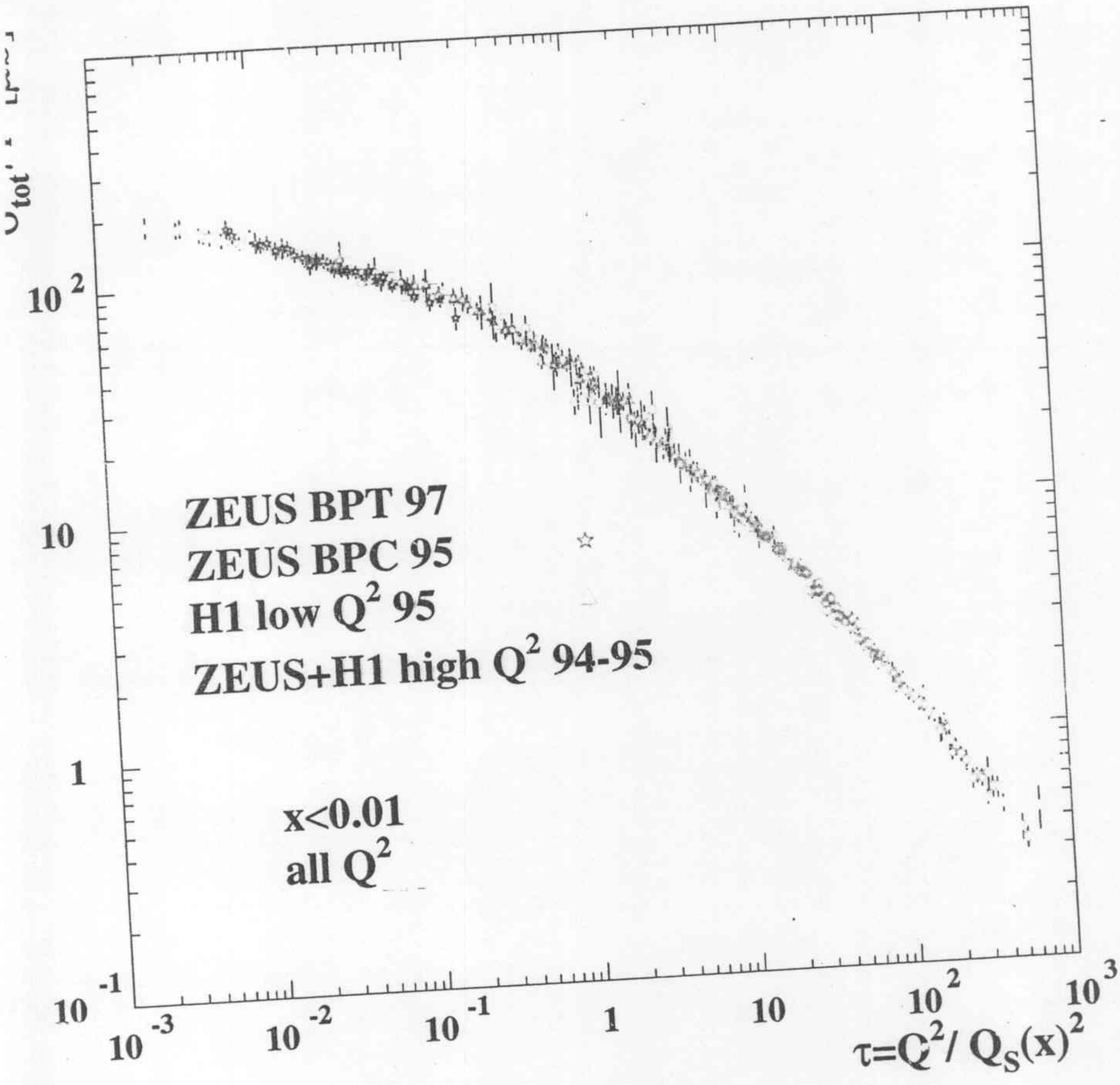
$Q_0 = 1$ GeV ; from fits: $\lambda = 0.29$; $x_0 = 3 * 10^{-4}$
$\sigma_0 = 23$ mb.

FORM OF $\hat{\sigma}$ PREDICTED IN pQCD BASED MODELS Nikolaev-Zakharov, Mueller, ...



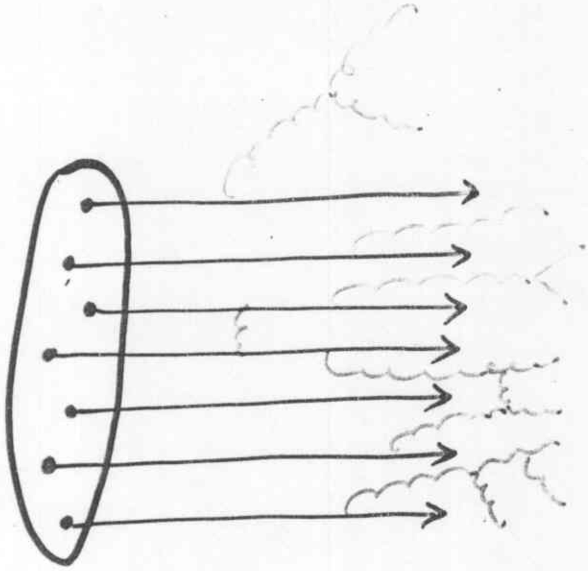
- PARTON DISTRIBUTIONS <u>SATURATE</u> — THEY GROW VERY SLOWLY — FORMING A <u>COLORED</u> <u>GLASS</u> <u>CONDENSATE</u>

Golec-Biernat, Kwiecinski, Stasto.



- HERA DIFFRACTIVE DIS DATA EXPLAINED — NO ADDITIONAL PARAMETERS.

Golec-Biernat + Wusthoff



$$\Big| \underbrace{qqq\cdots q}_{3A}\ \underbrace{ggg\cdots g\, q\bar{q}\cdots q\bar{q}}_{\text{"wee partons"}} \Big\rangle$$

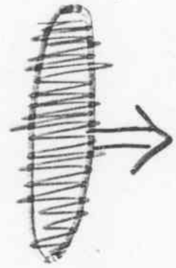
Each wee parton carries a small fraction of nuclear momentum.

$\longrightarrow$ Physics of multi-particle production at high energies is small x physics.

McLerran + R.V.

Construct Effective Theory...

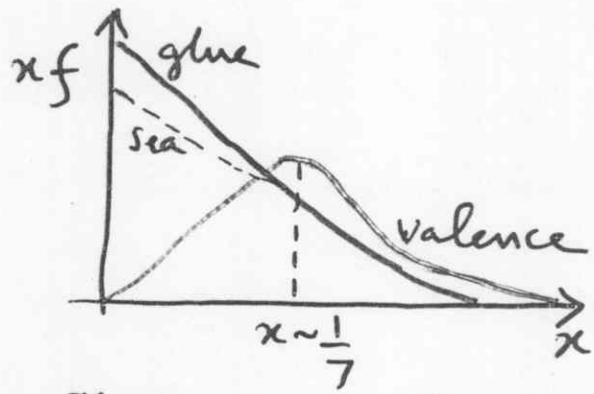
) **IMF:**



$$\frac{P^+}{m} \gg 1$$

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

) **Born-Oppenheimer:**

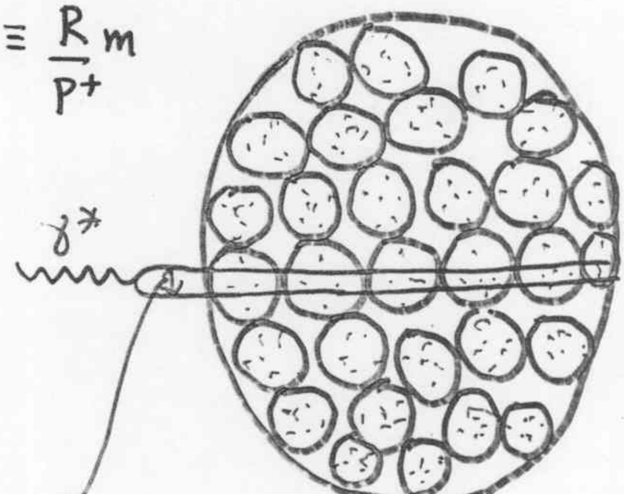


$$\tau_{wee} \sim \frac{1}{k^-} = \frac{2k^+}{k_\perp^2} \equiv \frac{2xP^+}{k_\perp^2} \ll \tau_{valence} \equiv \frac{2P^+}{k_\perp^2}$$

) **Random Sources:**

$$\lambda_{wee} \sim \frac{1}{k^+} \equiv \frac{1}{xP^+} \gg \lambda_{val} \equiv \frac{R}{P^+} m$$

$$\Rightarrow \quad x \ll A^{-1/3}$$



$$\langle \rho^a \rangle = 0$$

$$\langle \rho^a \rho^b \rangle = \mu^2 \delta^{ab}$$

$$x_\perp \ll \frac{1}{\Lambda_{QCD}}$$

Effective Action :

$$Z[j_{ext}] = \int \mathcal{D}\rho \; W[\rho] \int \mathcal{D}A^{\mu} \, \delta(A^{+})$$

$$* \; e^{i S[A,\rho] - i \int j_{ext} \cdot A}$$

$$S[A,\rho] \to \int F_{\mu\nu}^{2} + \rho \cdot A^{-}$$

For a large nucleus $W[\rho] \to \exp\left[-\int \frac{\mathrm{Tr}(\rho^2)}{\mu^2}\right]$

Color charge squared per unit area: $\mu^2 \propto A^{1/3} \, \mathrm{fm}^{-2}$.

If $\mu^2 \gg \Lambda^2_{QCD}$, $\boxed{\alpha_s \equiv \alpha_s(\mu^2) \ll 1}$

$\Downarrow$

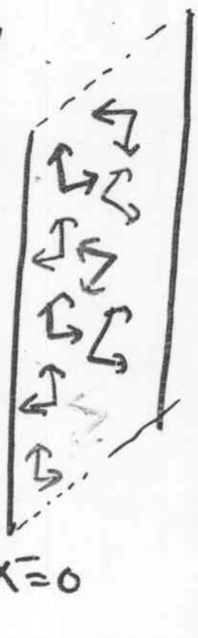
Weak coupling applicable.

- **Classical Theory**

$A^{+} = 0$

$A^{-} = 0$

$A_{\perp} = 0$



$x^{-} = 0$

$A^{+} = 0$

$A_{\perp} = \frac{1}{ig} U \nabla_{\perp} U^{+}$

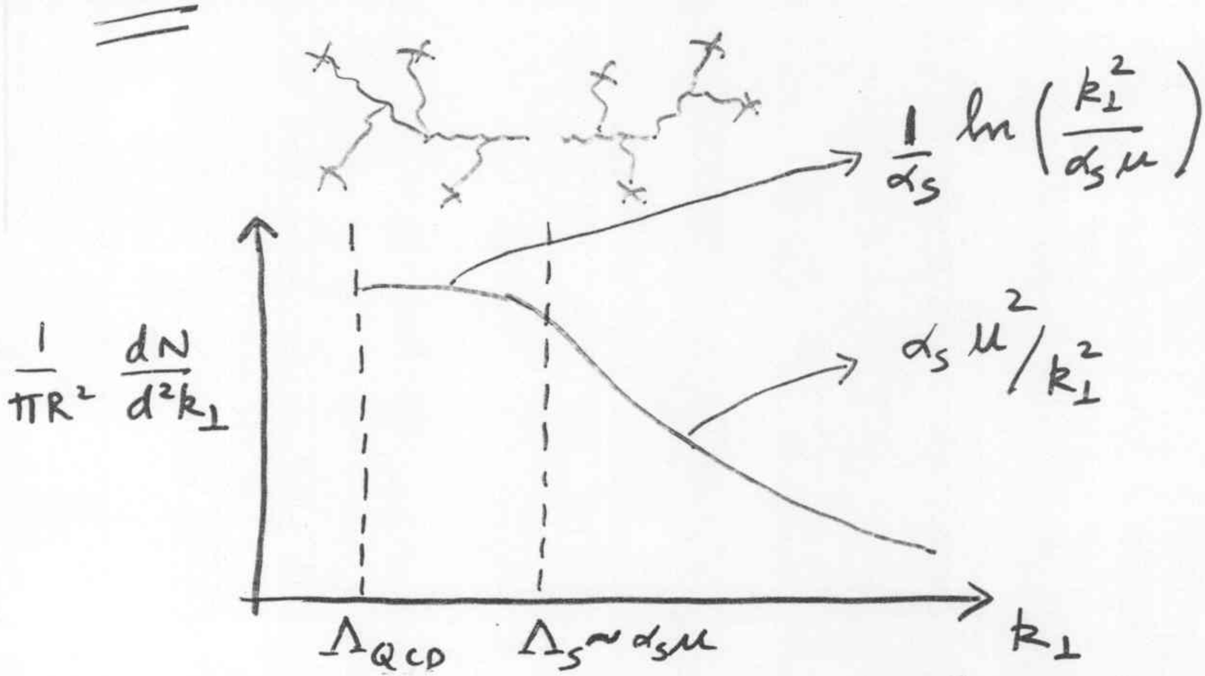
$A^{-} = 0$

non-Abelian Weizsäcker-Williams.

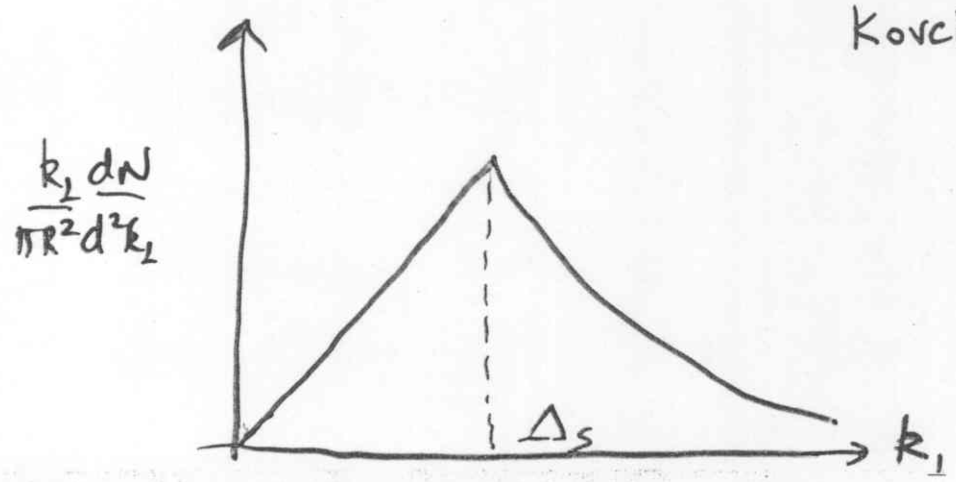
Classical Correlation Functions In 2-D Effective Theory.

$$\left\langle A^{i,a}(0)\, A^{i,a}(x_\perp) \right\rangle = \int \mathcal{D}\rho \, \exp\left(-\int d^2x_\perp \frac{\mathrm{Tr}(\rho^2)}{\mu^2} \right) * A^\rho_{cl}(0)\, A^\rho_{cl}(x_\perp)$$

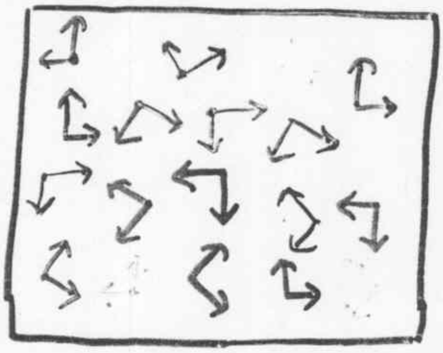
$$= \frac{N_c^2-1}{\pi \alpha_s N_c} \left(1 - \exp\left[-\frac{g^4 \mu^2 N_c\, x_\perp^2 \ln(x_\perp^2 \Lambda^2)}{16\pi} \right] \right) \frac{1}{x_\perp^2}$$



Jalilian-Marian, Kovner, McLerran, Weigert; Kovchegov.



COLORED GLASS CONDENSATE



Why Colored Glass Condensate?

Colored : QCD

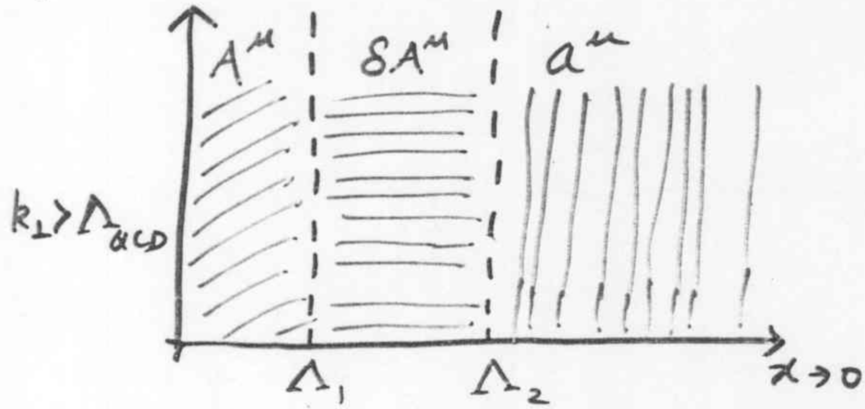
Glass : Strong analogy of the system to spin glasses in condensed matter physics. Parisi-Sourlas.

Condensate : Large occupation # of gluons in system $\propto \frac{1}{\alpha_s}$ - peaked about saturation momentum scale Λ_s.

RENORMALIZATION GROUP AT SMALL x_{Bj}.

Jalilian-Marian
Kovner
Leonidov
McLerran
Weigert

A Wilson RG:



$$\alpha_s \ln\left(\frac{\Lambda_1}{\Lambda_2}\right) \ll 1$$

$\mapsto$ Construct theory at scale Λ_1

$\mapsto$ Integrate out small fluctuations: $\Lambda_1 > k^+ > \Lambda_2$

$$\rho \longrightarrow \rho + \underbrace{\delta\rho}_{}(\delta A^\mu)$$

$\hookrightarrow$ induced charge

$\mapsto$ Recover theory at scale Λ_2 but

$$W[\rho] \to W[\rho']$$

Weight function obeys non-linear RG

JKLW equation:

$$\frac{\partial W[\rho]}{\partial \tau} = \alpha_S \left\{ \frac{1}{2} \frac{\delta^2}{\delta\rho_\tau(x)\,\delta\rho_\tau(y)} \left[W_\tau \chi_{xy} \right] - \frac{\delta}{\delta\rho_\tau(x)} \left[W_\tau \sigma_x \right] \right\}$$

$$\tau = \ln\left(\frac{1}{x}\right)$$

$$\alpha_S \ln\left(\frac{1}{x}\right) \sigma_a(x_\perp) = \int dx^- \langle \delta\rho_a(x) \rangle$$

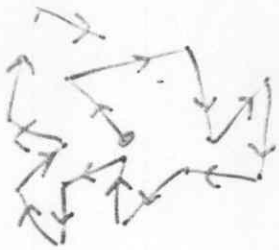
$$\alpha_S \ln\left(\frac{1}{x}\right) \chi_{ab}(x_\perp, y_\perp) = \int dx^- \int dy^- \langle \delta\rho_a(x^-, \vec{x}) \, \delta\rho_b(x^-, \vec{y}) \rangle$$

For low parton densities,

$$\boxed{\text{JKLW Eqn.} \longrightarrow \text{BFKL Eqn.}}$$

Iancu
Leonidov
McLerran.

JKLW is a diffusion eqn. in functional space.

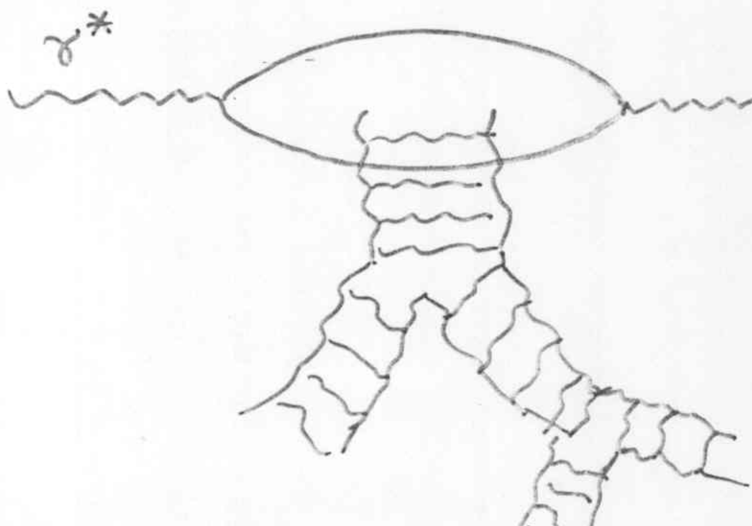


$$\frac{\partial W}{\partial \tau} = \frac{\alpha_s}{2} \int d^2x \int d^2y \, \frac{\delta}{\delta \alpha_x^a} \left(\eta_{xy}^{ab} \frac{\delta W}{\delta \alpha_y^b} \right)$$

$$= - H W$$

JIMWLK.

It is exactly equivalent to the Balitsky - Kovchegov Eqn. for the evolution of the scattering cross-section of a color-dipole on a hadron/nucleus



"FAN DIAGRAMS"

Mueller;
Bartels, Wusthoff

Numerical solution to the Balitsky-Kovchegov Equation:

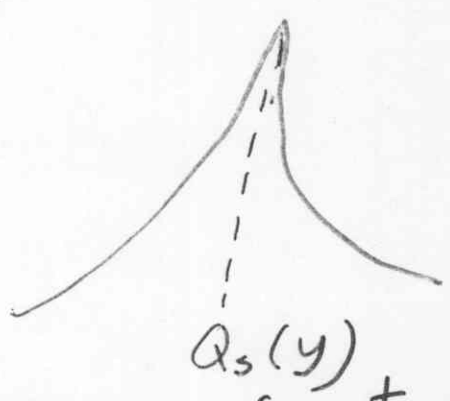
Levin, Tuchin;
Lublinsky;
Armesto, Braun;
Golec-Biernat,
Motyka, Stasto.

$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \int d^2r\, dz \left\{ |\psi_T|^2 + |\psi_L|^2 \right\} \hat{\sigma}(x, r)$$

$$\hat{\sigma}(x, r) \to 2 \int d^2\vec{b}\, N(r, \vec{b}, Y)$$

$\mapsto$ non-linear evolution leads to unitarization of BFKL Pomeron.

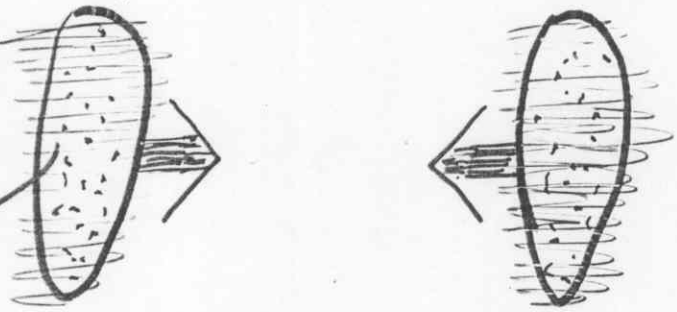
$\mapsto$ N-L evolution also suppresses diffusion of momenta into the infra-red (characteristic of BFKL)



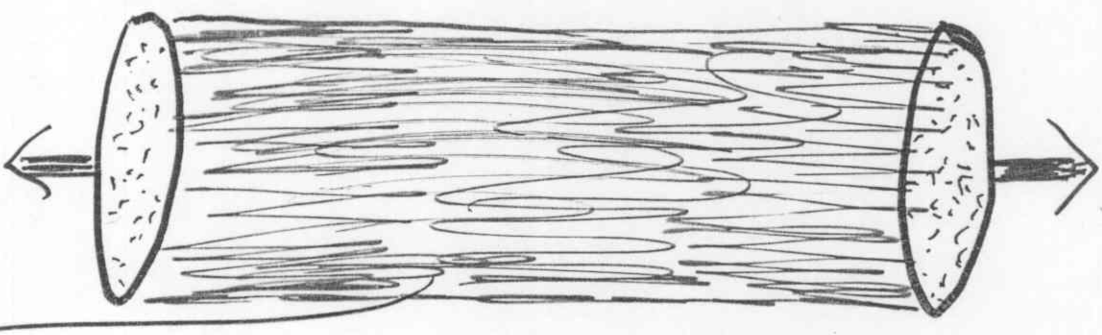
$Q_s(Y)$

Natural emergence of saturation scale.

Probing The CGC In HI-Collisions



Bulk scale $\underline{\underline{\Lambda_s}}$ controls the distribution of partons in incoming nuclei.



Λ_s also controls the initial multiplicity and transverse energy of produced glue.

$\Lambda_s \simeq 2\ \mathrm{GeV}$ for RHIC

$\simeq 4\ \mathrm{GeV}$ for LHC.

The CGC and RHIC data.

* Centrality dependence of RHIC data

  - $\frac{1}{0.5 N_{part}} \frac{dN}{d\eta}$ vs N_{part} — Kharzeev, Nardi

* Energy and rapidity dependence. — Kharzeev, Levin.

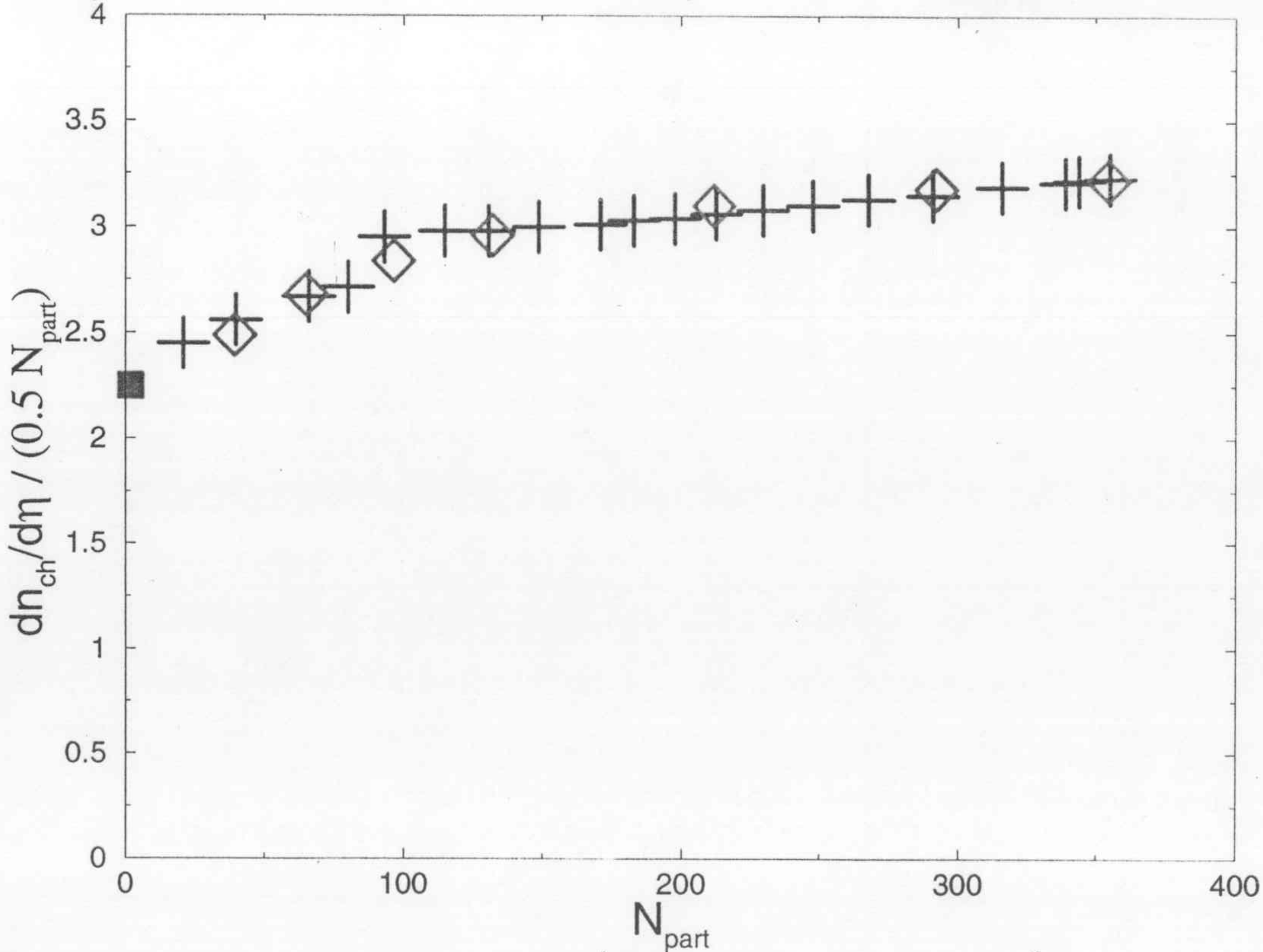
* Generalized m_t scaling. — Schaffner-Bielich, Kharzeev, McLerran, Venugopalan.

* $$V_2 \left(= \frac{\int d\phi \, \cos(2\phi) \int dp_\perp \, p_\perp \frac{dN}{p_\perp dp_\perp d\varphi d\eta}}{\int d\phi \int dp_\perp \, p_\perp \frac{dN}{p_\perp dp_\perp d\varphi d\eta}} \right)$$

  "Elliptic Flow" — Nara, Krasnitz, Venugopalan.

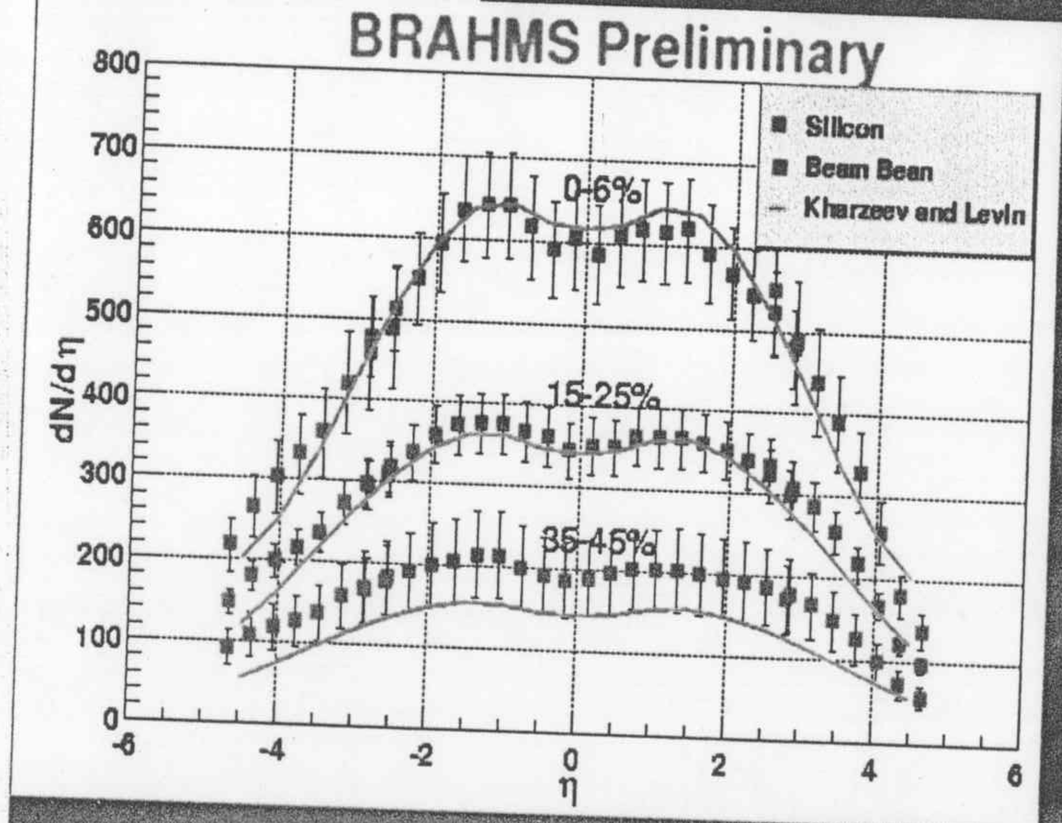
N_{part}

$$\Diamond \quad \frac{dN}{d^2b\,d\eta} = c_N \frac{N_c^2-1}{N_c} \frac{1}{\alpha_s} Q_s^2 \Rightarrow \frac{2}{N_{part}} \frac{dN^{ch}}{d\eta} \simeq 0.82 \ln\left(\frac{Q_s^2(b)}{\Lambda^2_{QCD}}\right) ; \quad c_N = 1.23 \pm 0.2$$



GLAUBER AGREES WITH CLASSICAL SATURATION

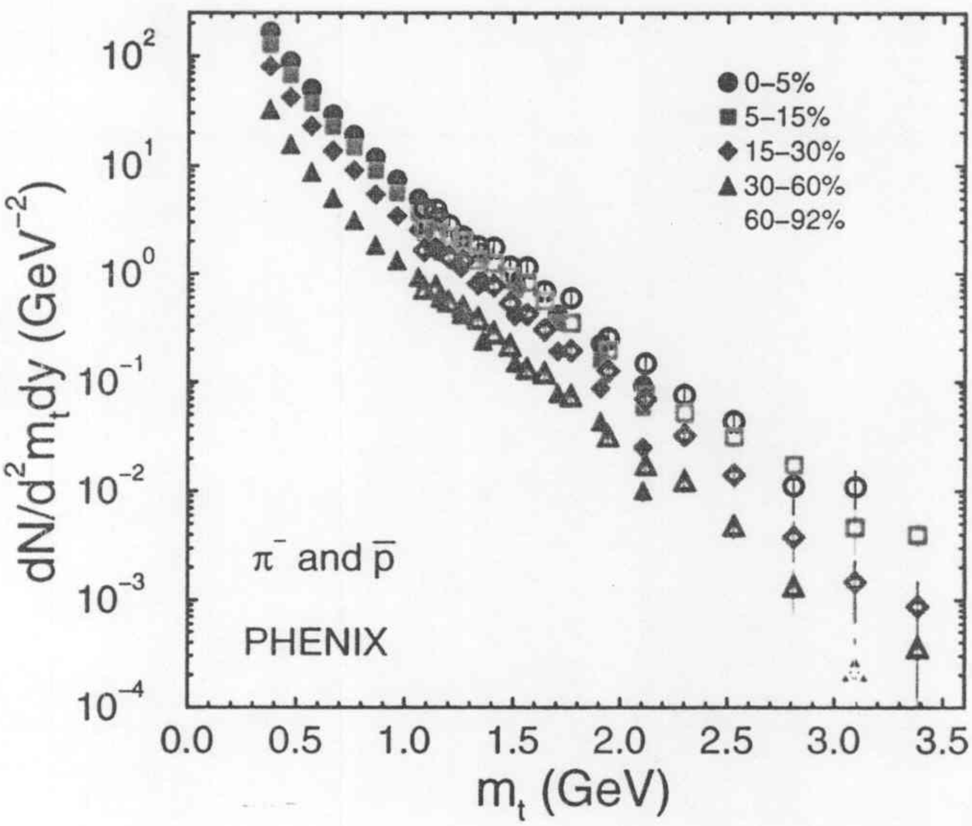
BRAHMS 200AGEV



Scaling with centrality

generalized m_t scaling for all centralities?

check for π^- and $\bar{p}$:

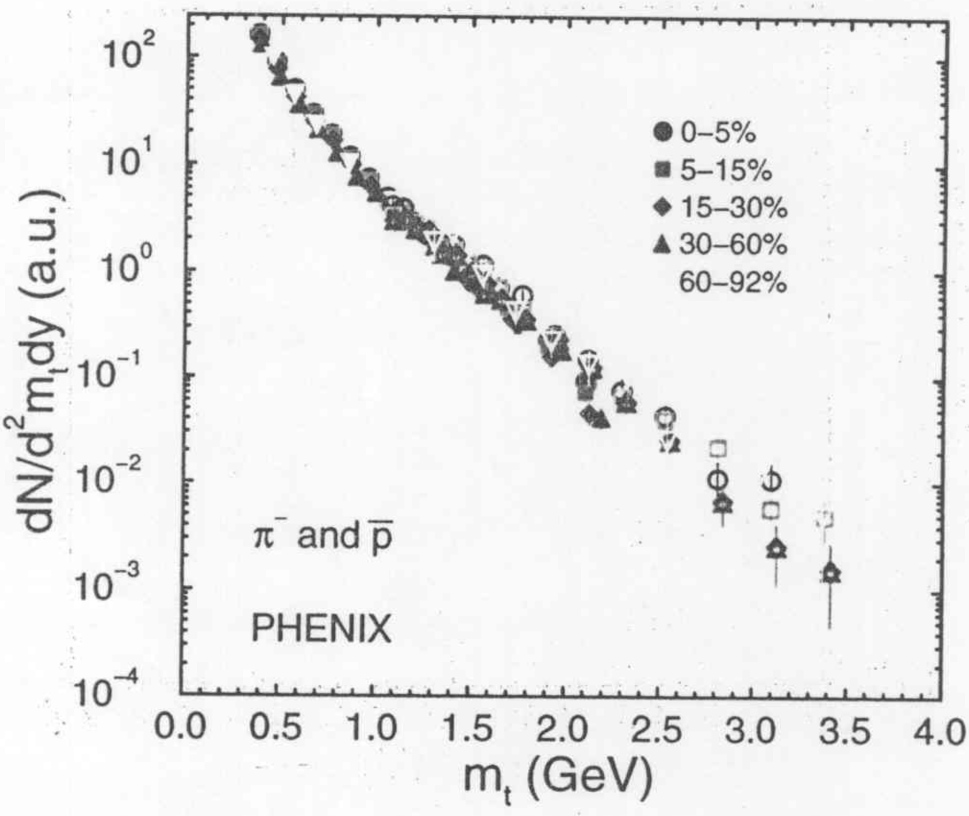


$\Longrightarrow$ π^- and $\bar{p}$ data form a continuous curve for each centrality bin

Rescaled m_t distributions

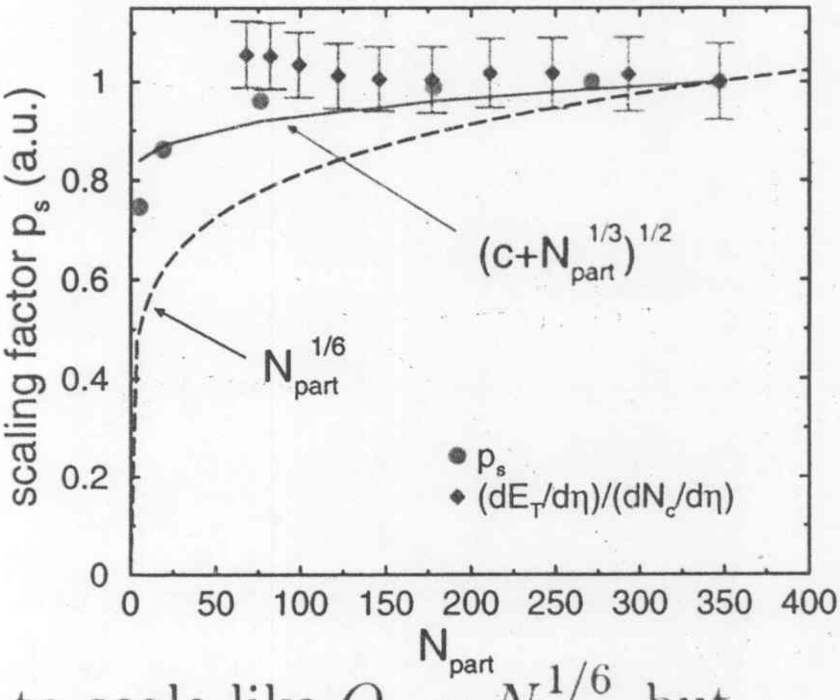
rescale different centrality bins as

$$\frac{1}{\sigma}\frac{dN_h}{dyd^2m_t} \rightarrow \frac{1}{\lambda}\frac{1}{\sigma}\frac{dN_h}{dyd^2m_t} \quad \text{and} \quad m_t \rightarrow \frac{m_t}{\lambda'}$$



$\Longrightarrow$ one universal function f describing all centrality bins!

Scaling of the transverse momentum parameters p_s normalized to most central bin:



expect to scale like $Q_s \sim N_{\text{part}}^{1/6}$ but

$$p_s^2/p_{s,c}^2 = c + c' \cdot N_{\text{part}}^{1/3} = 0.61 + 0.39(N_{\text{part}}/347)^{1/3}$$

compatible with transverse energy per charged particle

(PHENIX coll., PRL 87, 0523201 (2001))

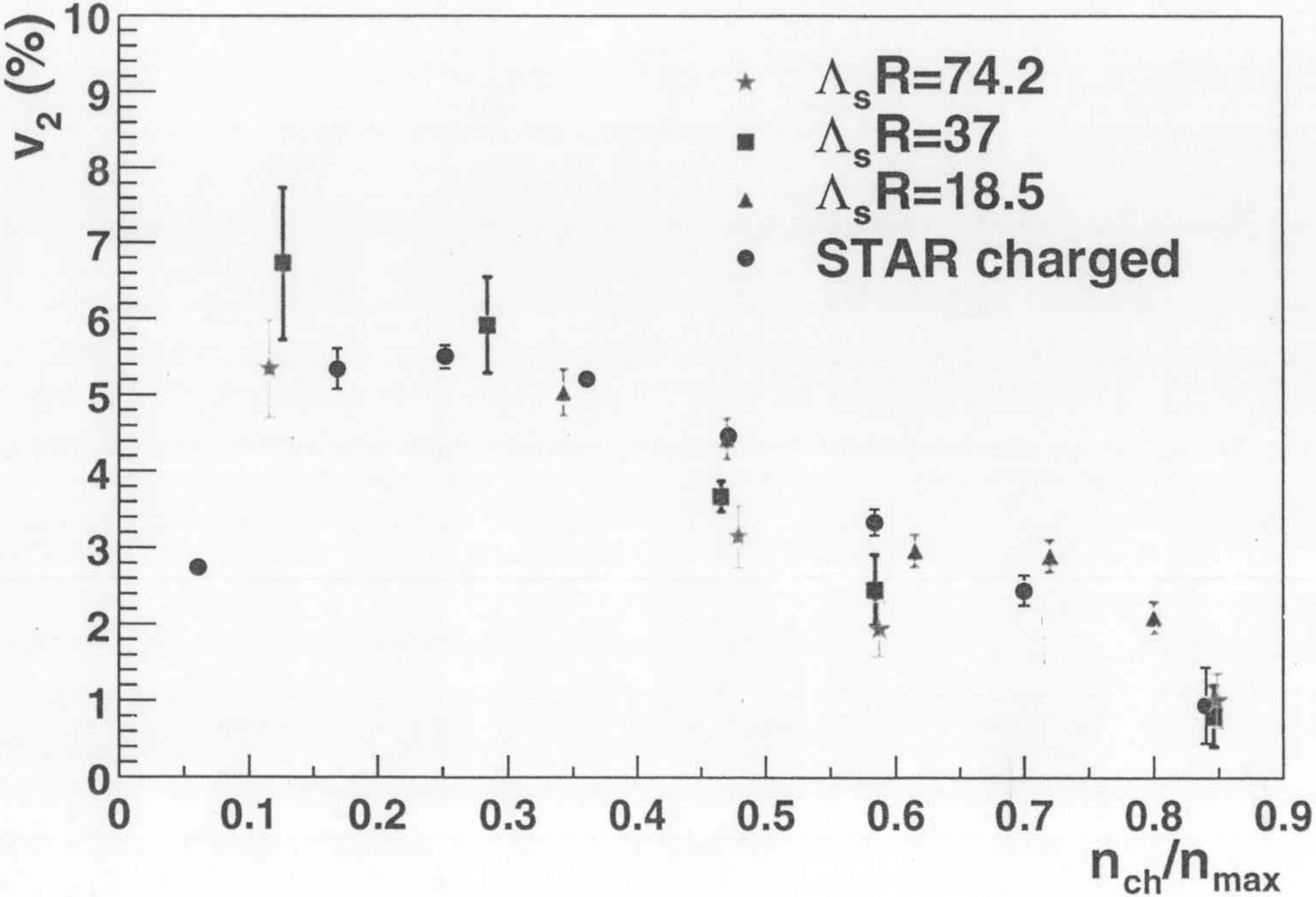
constant c stands for the finite transverse momenta for pp

collisions ($\langle p_t \rangle \sim p_s$),

compatible with $\langle p_t \rangle$ reported by UA1 and STAR

(392/508 = .77)

Centrality dependence of v_2



Open Questions:

* **Is small x physics universal?**

Short lived, long wavelength modes
- insensitive to fragmentation region dynamics.

* **Are nuclei simpler?**

High parton densities more easily attained in nuclei.

* **A quantitative theory of the QGP?**

Initial conditions (read: small x) tell all.

* **What about confinement?**

Ancient conundrum rears its ugly head...