1st ECFA-CERN LHeC Workshop
Divonne-les-Bains, September 2nd 2008

From ep to AB collisions

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See the talks by G. Altarelli, S. J. Brodsky, J. Bartels, P. Newman, D. d'Enterria, F. Arleo,...

Contents:

1. Introduction.

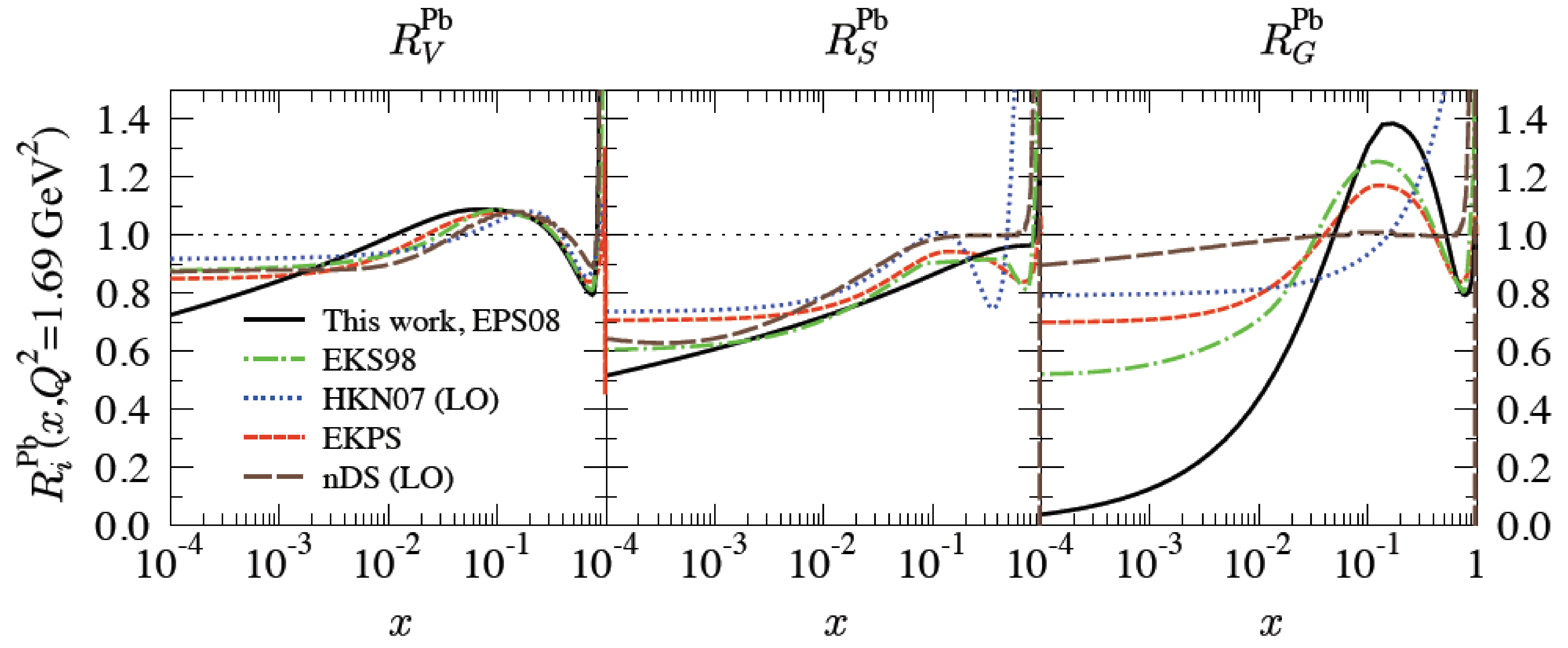
2. Phenomenology:
    2.1. ep.
    2.2 eA.
    2.3. pA at RHIC.
    2.4. AA at RHIC.
    2.5. LHC.

3. Summary.

1. Introduction (I):

- **From ep to particle production in AB**: nucleon and nuclear pdf’s plus factorization (collinear for large scales-DGLAP, ~~k_T? for intermediate scales-BFKL/BK?~~). $E_{cm} \gg (\sim)Q \gg \Lambda_{QCD}$

- Uncertainties in standard DGLAP npdf’s are huge at small x and small Q^2 for gluons: few/no data available.



I. Introduction (I):

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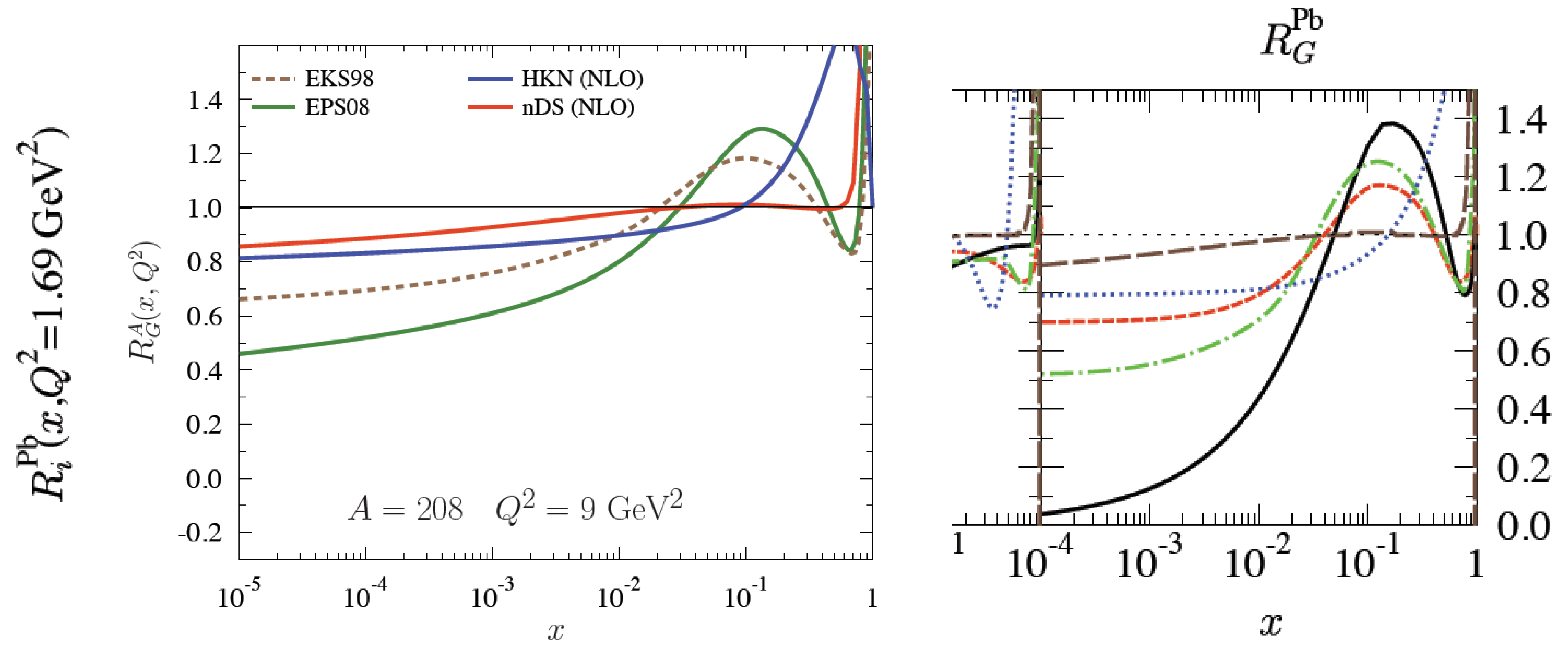
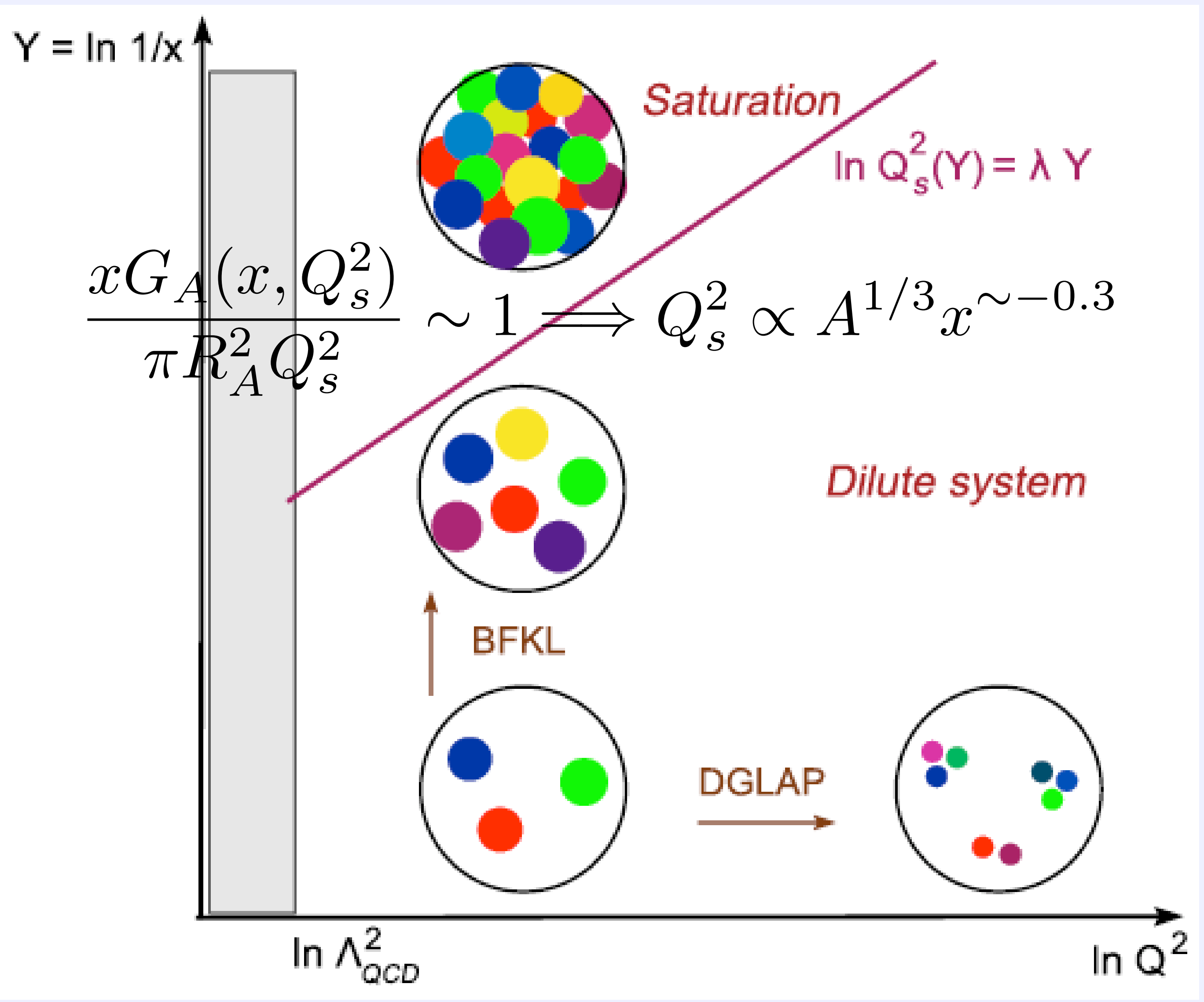


I. Introduction (II):

- **Saturation physics**: framework to discuss ep and eA, and bulk production in pA and AB.
- At small enough x, the CGC offers a description of the hadron WFs. The x-evolution equation is Balitsky-Kovchegov (LO, NLO).

$$x \leq \frac{1}{2m_N R_A} \sim 0.1 A^{-1/3}$$

- **Our aims: understanding** Unitarity in a QFT; The behavior of QCD at large energies; The initial conditions in HIC.



$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

- (No) k_T-like factorization in pA (AB) (Gelis, Venugopalan,...) with BK (?): use geometric scaling to discuss the way from ep to AB.

2. Phenomenology:

2.1. ep.

2.2 eA.

2.3. pA at RHIC.

2.4. AA at RHIC.

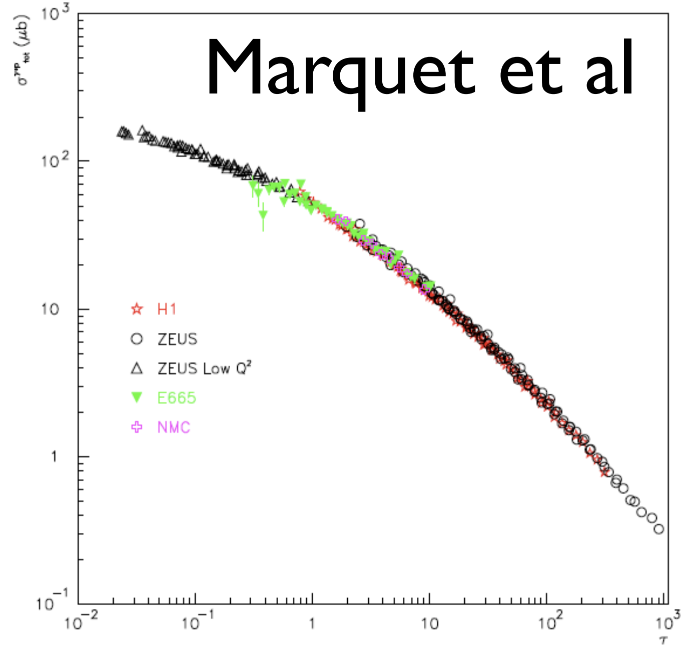
2.5. LHC (arXiv:0711.0974, now in JPG).

See the talk by J. L. Albacete at Hard Probes 2008.

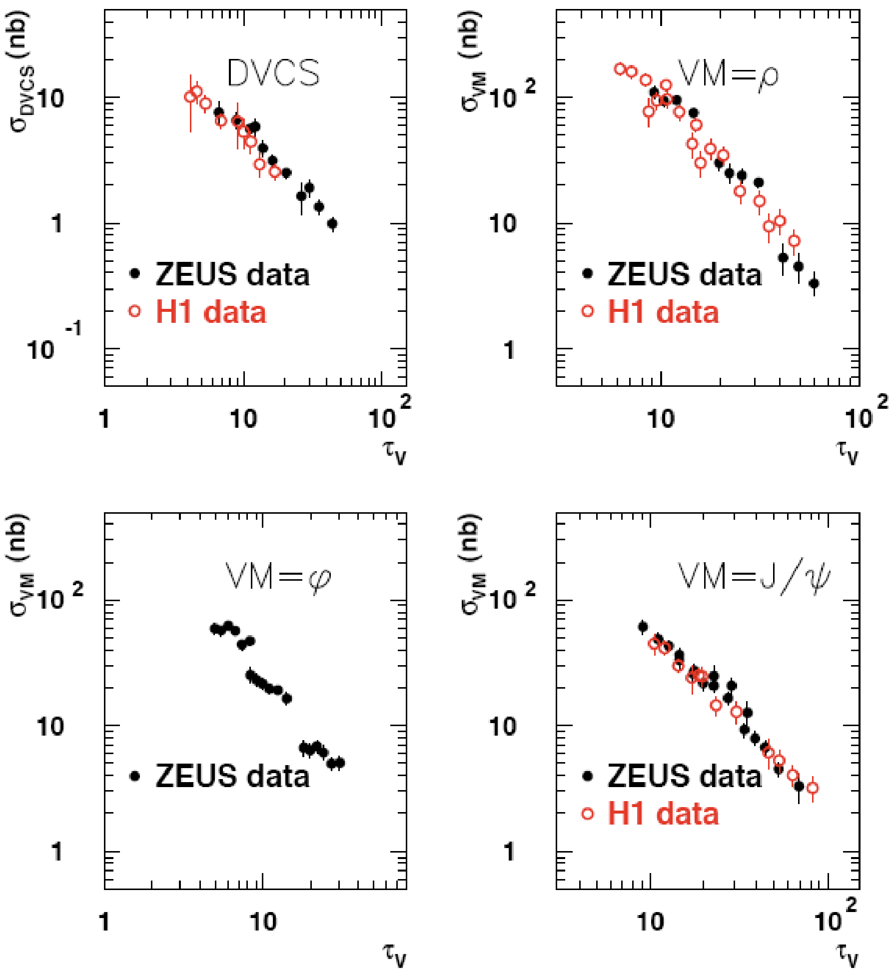
2.1. ep:

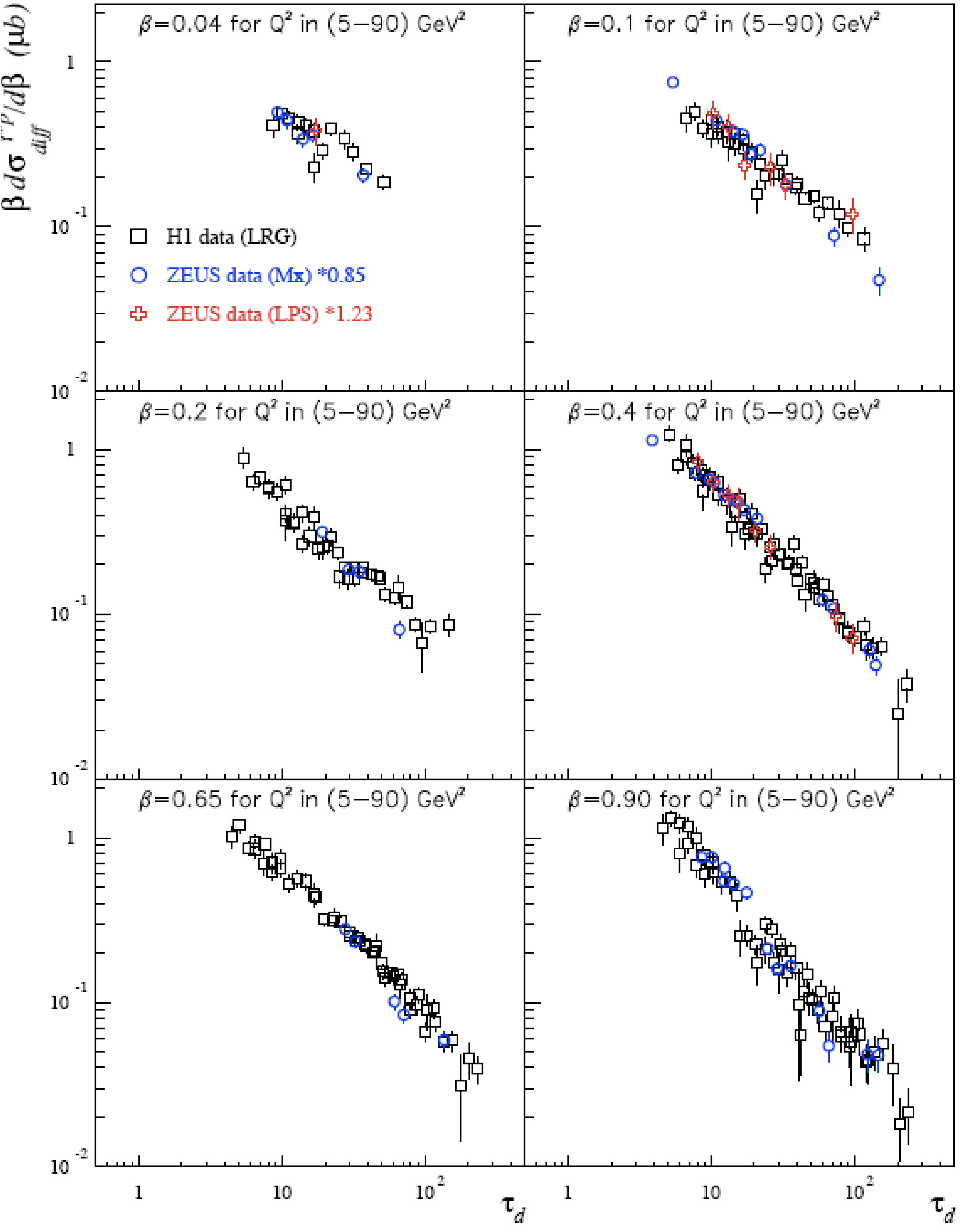
- The key feature of data is **geometric scaling** (Golec-Biernat et al).

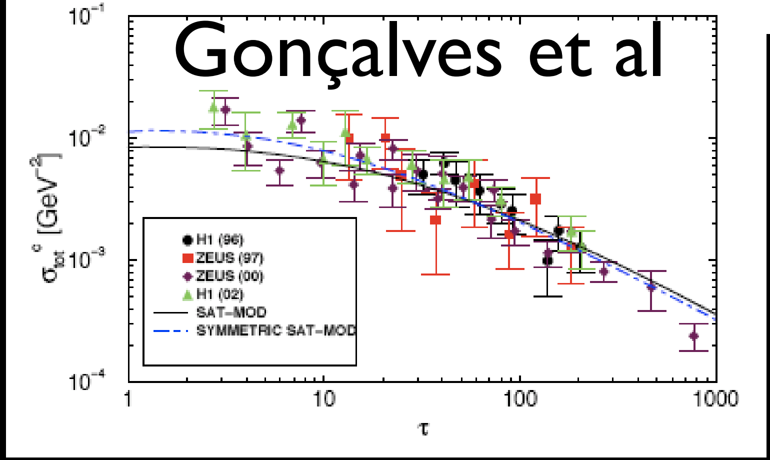
$$\tau = \frac{Q^2}{Q_s^2(x)}, \quad \tau_D = \frac{Q^2}{Q_s^2(x_P)} \ \text{at fixed}\ \beta, \quad \tau_V = \frac{Q^2 + M_V^2}{Q_s^2(x_P)}$$



Marquet et al







Gonçalves et al

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

$$\lambda_{(GBW)} \sim 0.25 \div 0.3$$

2.2. eA:

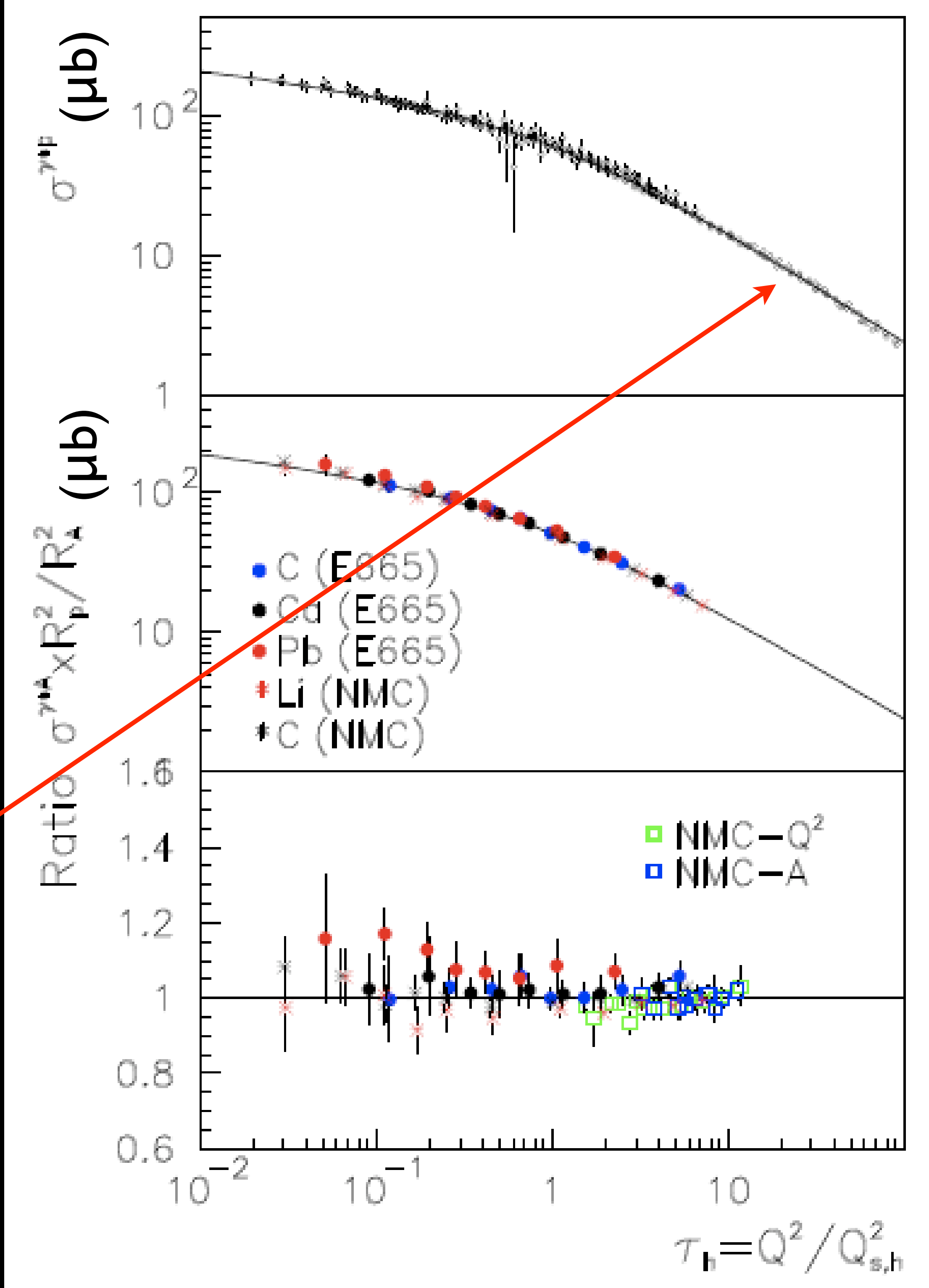
➪ Geometric scaling also found in eA (Rummukainen et al, NA et al).

$$\frac{\sigma^{\gamma^* A}(\tau_A)}{\pi R_A^2} = \frac{\sigma^{\gamma^* p}(\tau_A)}{\pi R_p^2}$$

$$\frac{Q^2_{\mathrm{s,A}}}{Q^2_{\mathrm{s,p}}} = \left(\frac{A\pi R_p^2}{\pi R_A^2}\right)^{\frac{1}{\delta}} \Rightarrow \frac{\tau_A}{\tau_p} = \left(\frac{\pi R_A^2}{A\pi R_p^2}\right)^{\frac{1}{\delta}}$$

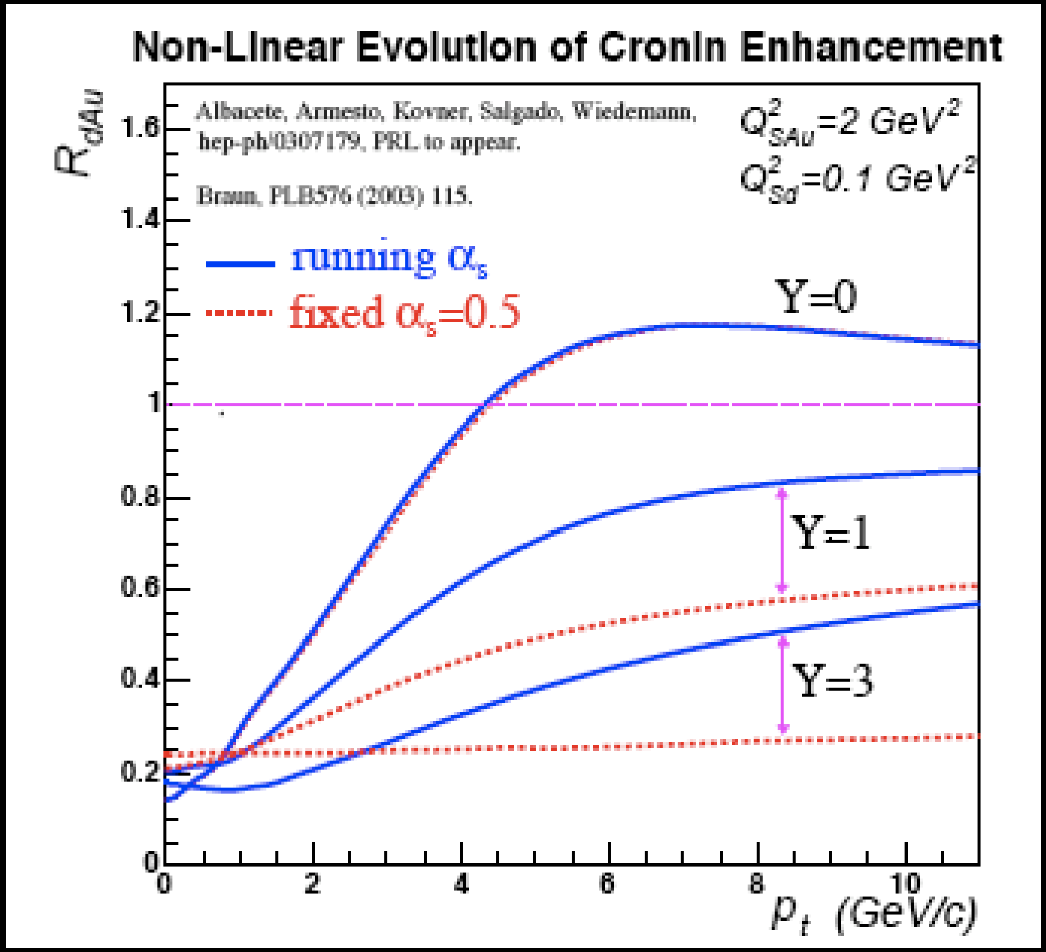
$\delta = 0.79 \pm 0.02$ $(x < 0.02)$.

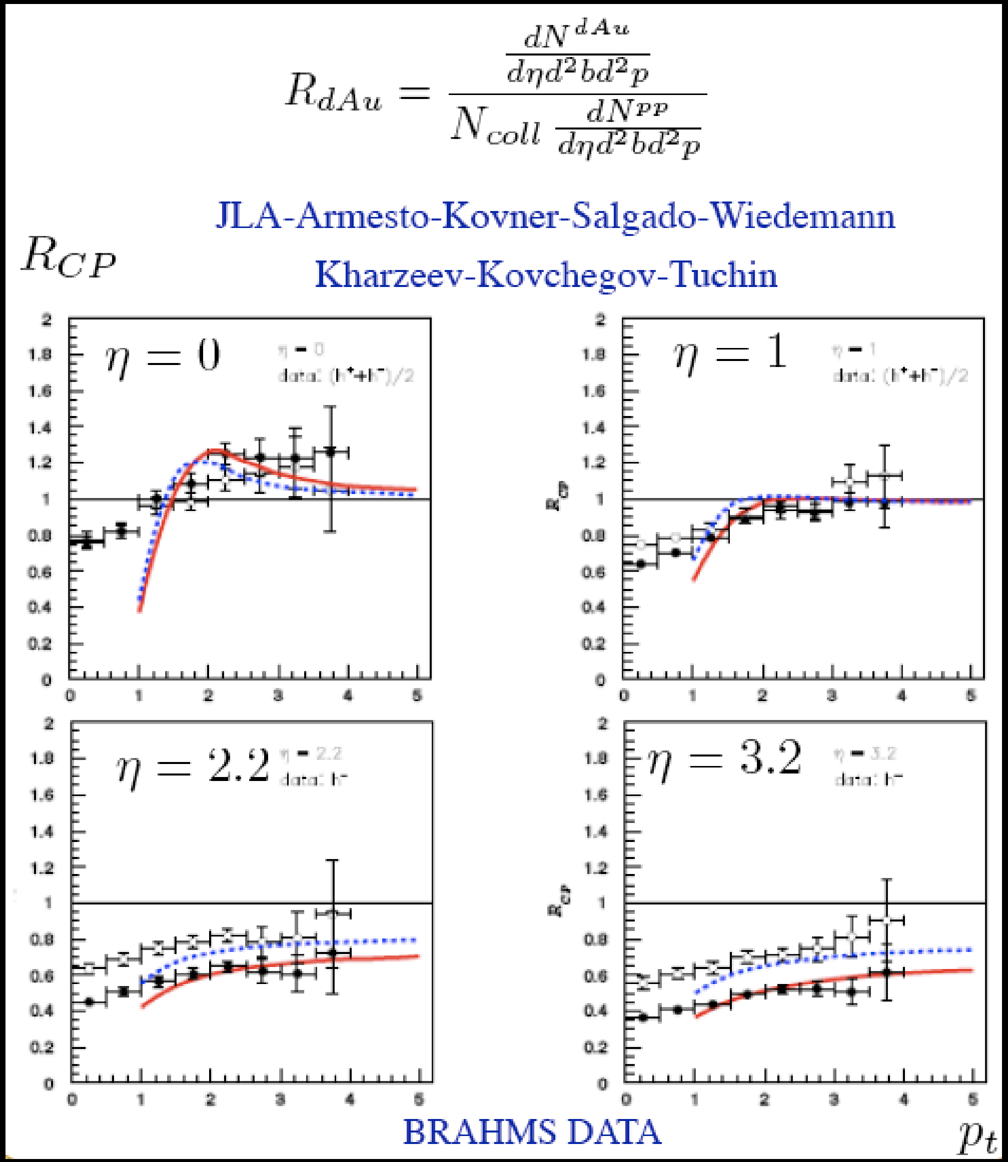
BK/data	λ	δ	γ
Data	0.25-0.3	≤1	0.75
fc	$4.88\alpha_s$	i.c.	0.63
rc	OK	small evol.	?



2.3. pA at RHIC (I):

- ➪ Control experiment for initial state effects in AA: Cronin effect in dAu at midrapidity ruled out initial state effects as the explanation for the suppression observed in AA.
- ➪ Suppression at forward rapidities was predicted by small-x evolution (BK).



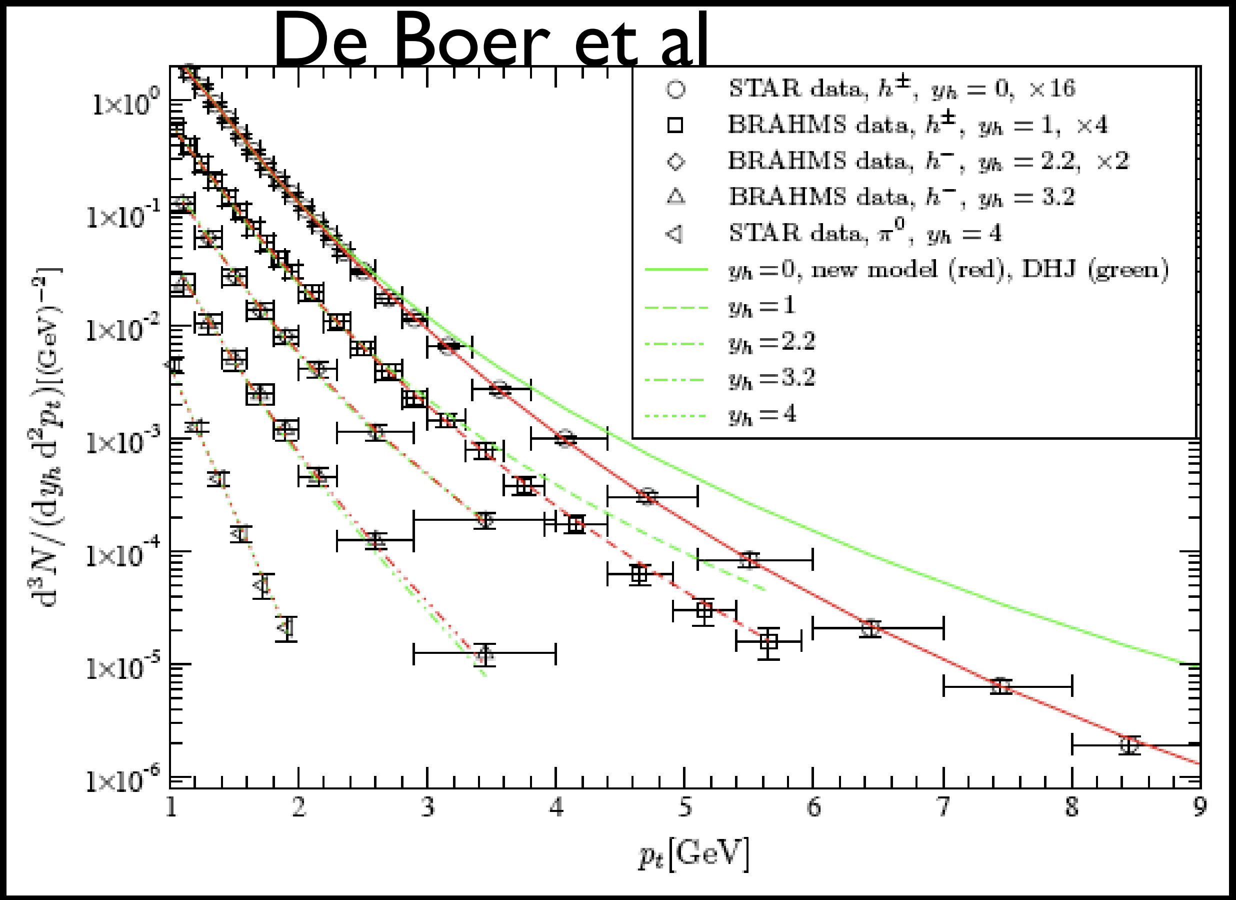


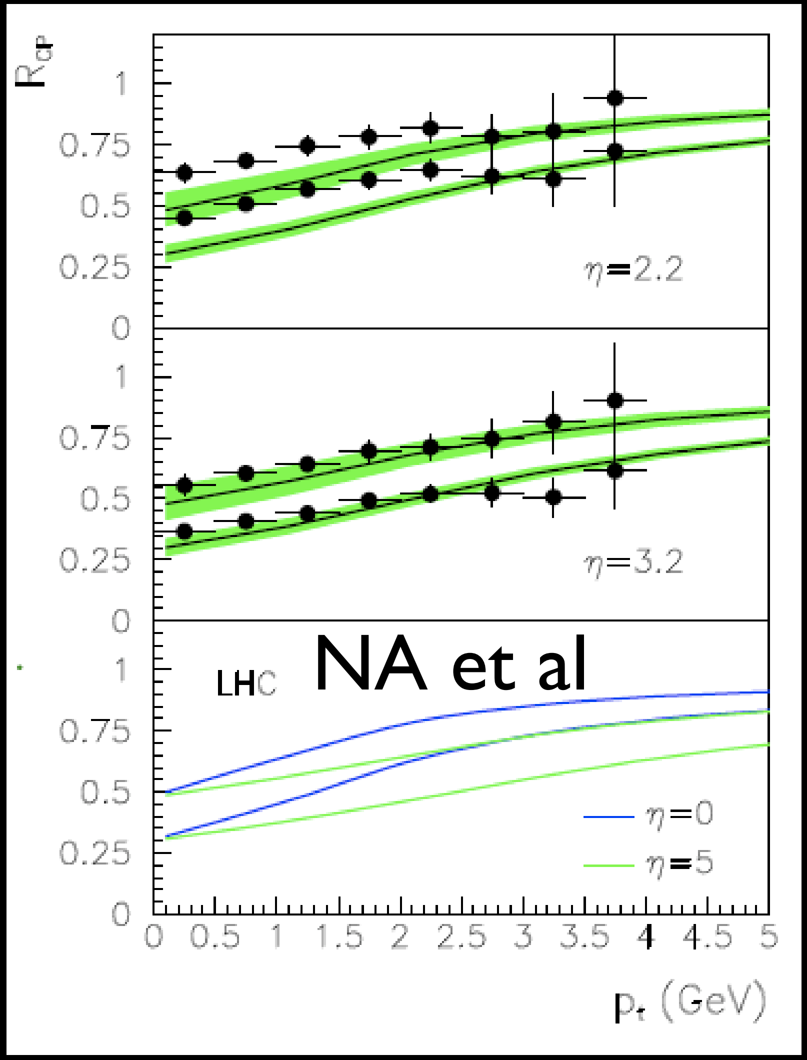
$$R_{dAu} \to_{y\to\infty} A^{-(1-\gamma/\delta)/3}(fc)$$

Kharzeev et al, Baier et al.

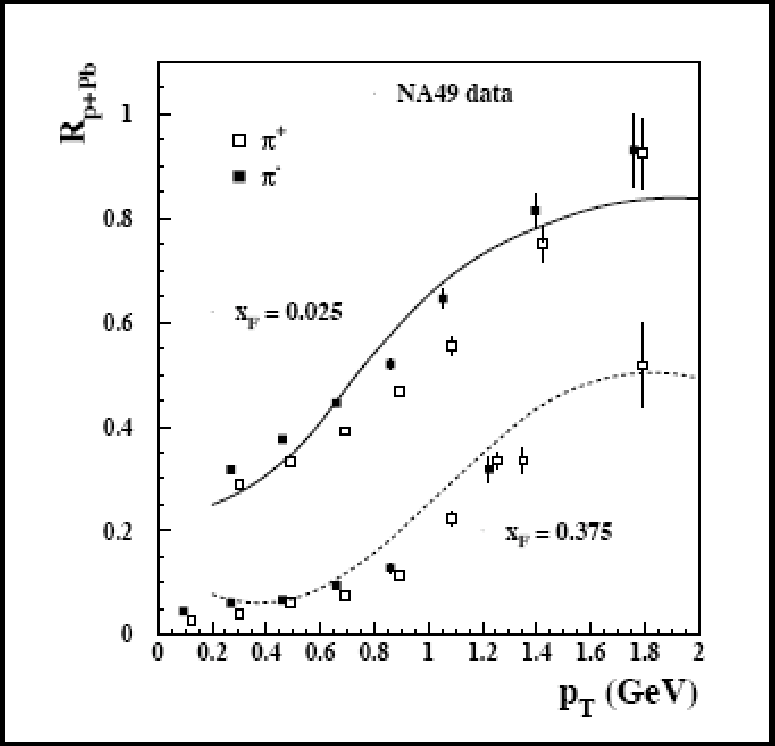
2.3. pA at RHIC (II):

➪ This suppression is compatible with ugd+factorization: ugd’s in agreement with ep + $A^{1/3}$ prescription for Q_s^2. It is also compatible with the ratio of geometric ep/eA scaling functions.

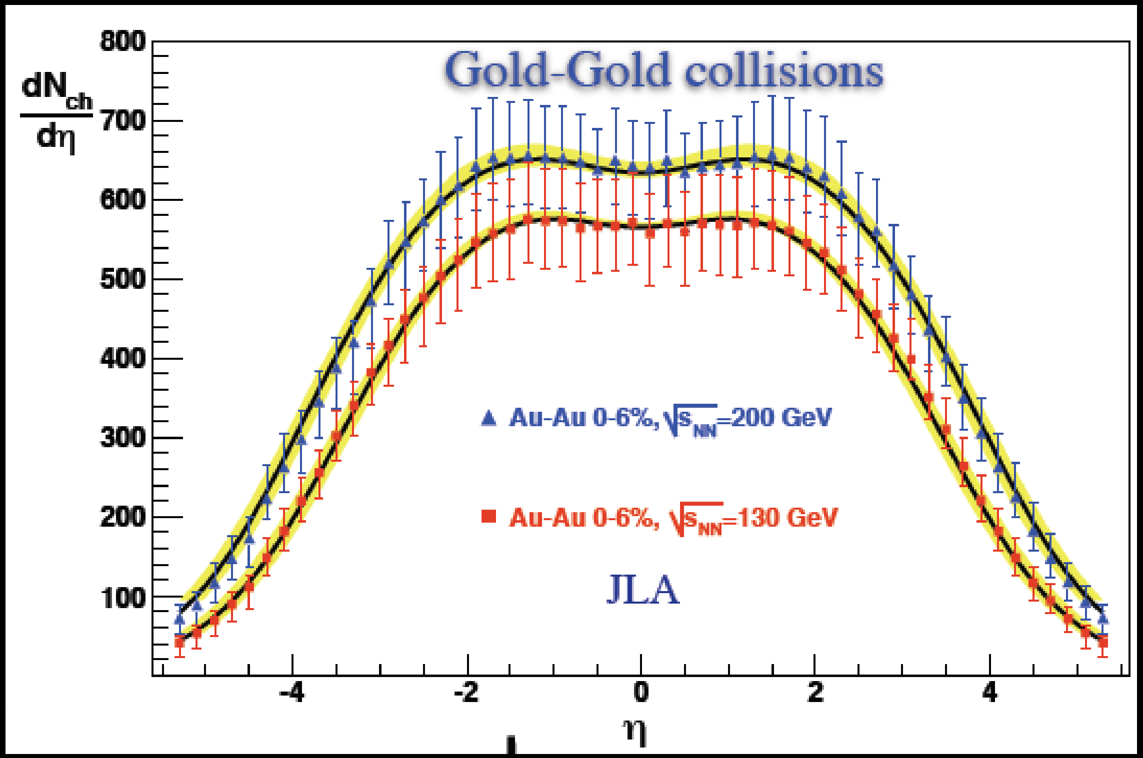

De Boer et al


LHC NA et al

➪ Warning: $<x_A> > 0.02$ (Guzey et al), and such suppression also happens at SPS/FNAL energies (Nemchik et al, Kopeliovich et al, Capella et al): finite energy corrections, eloss?



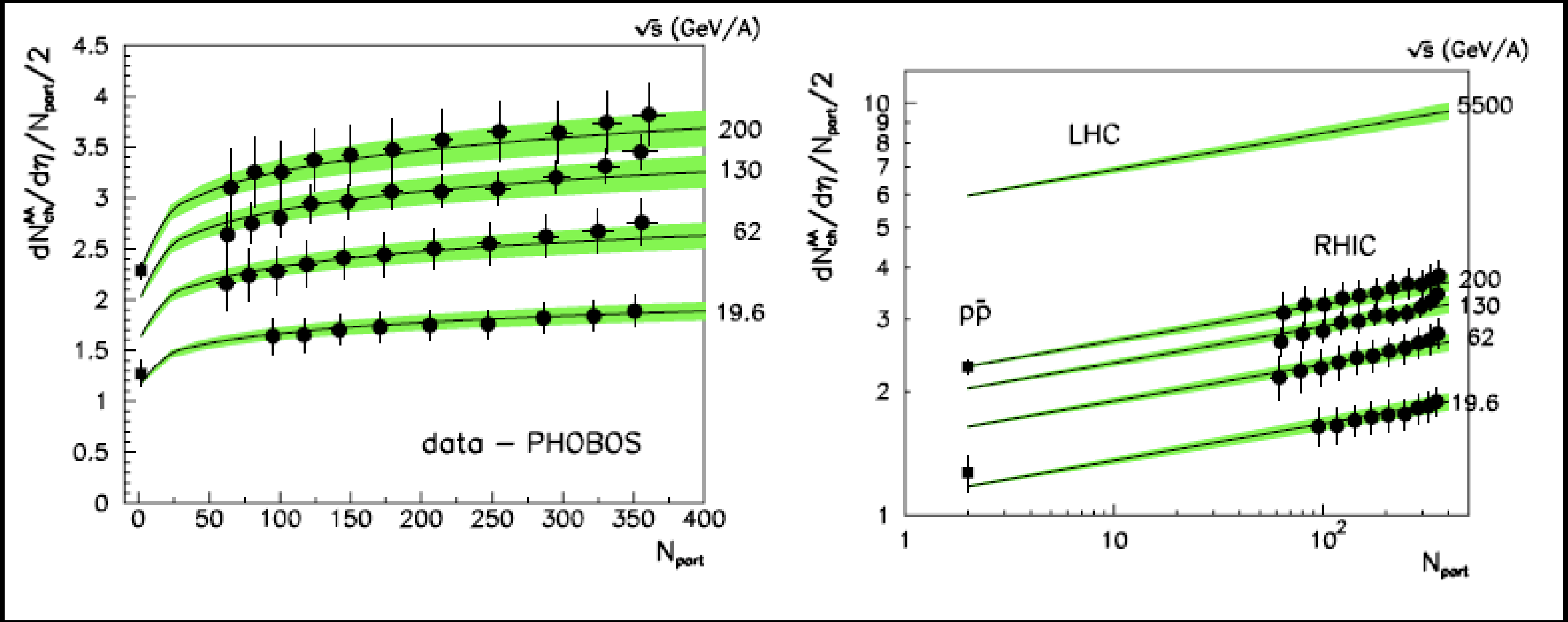
2.4. AA at RHIC (I):



- Assuming factorization, multiplicities (evolution with centrality and pseudorapidity) can be computed.

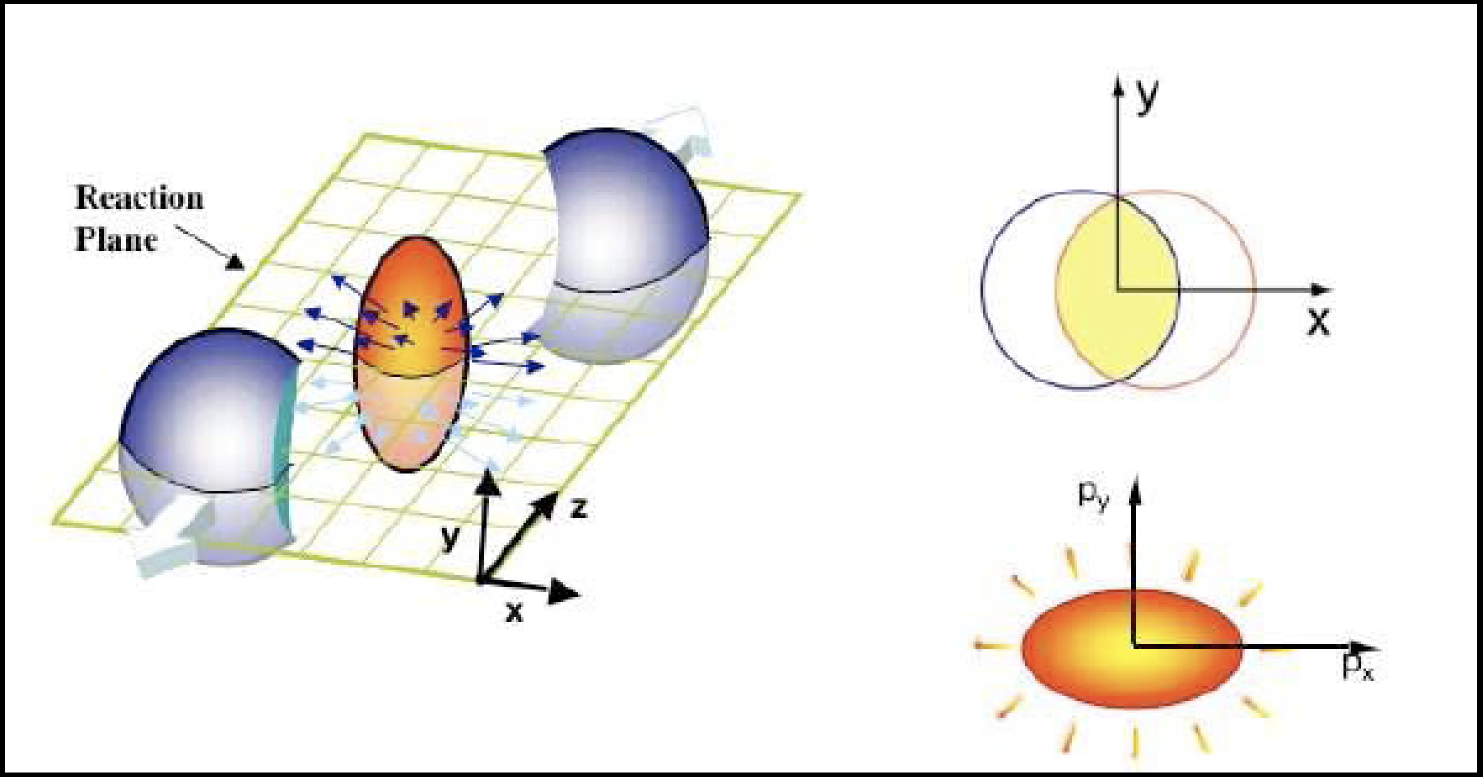
$$\frac{1}{N_{part}}\frac{dN^{g}_{AA}}{d\eta}\Big|_{\eta=0} \approx \begin{cases} \sqrt{s}^{\lambda}\ln\left(\sqrt{s}^{\lambda}N_{part}\right) & \text{Kharzeev-Levin Nardi} \\ \sqrt{s}^{\lambda}N_{part}^{\frac{1-\delta}{3\delta}} & \text{Armesto-Salgado Wiedemann} \end{cases}$$

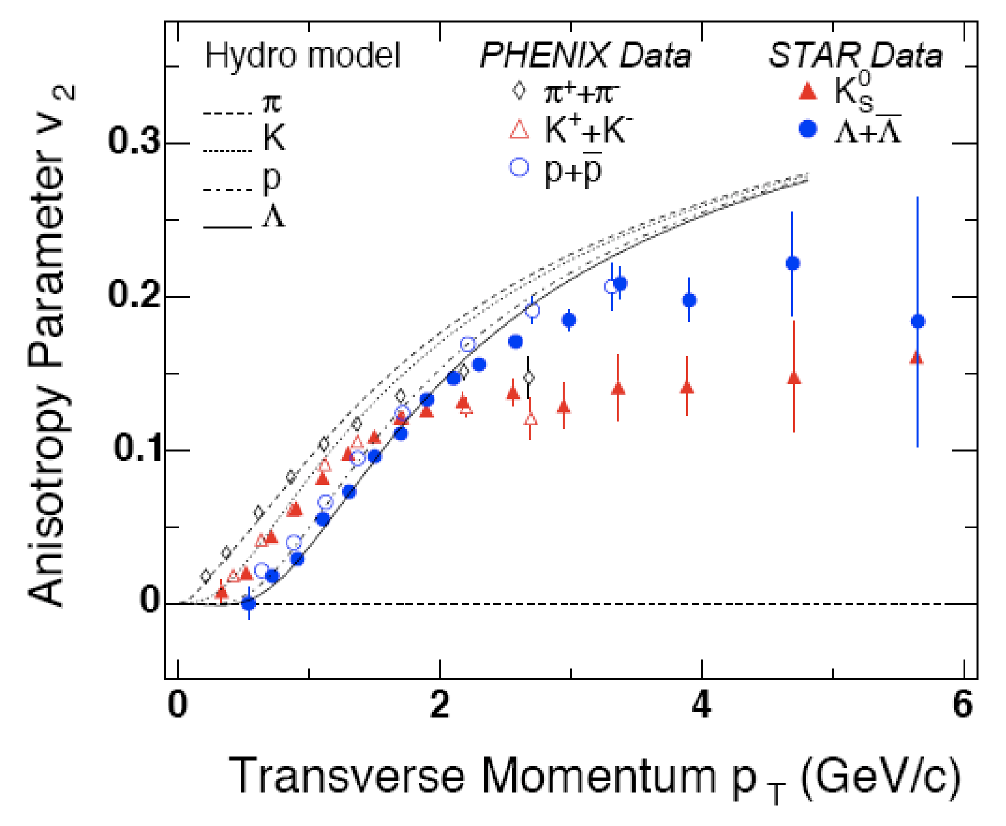
- Now it has been done with the available NLO-BK machinery (Albacete).

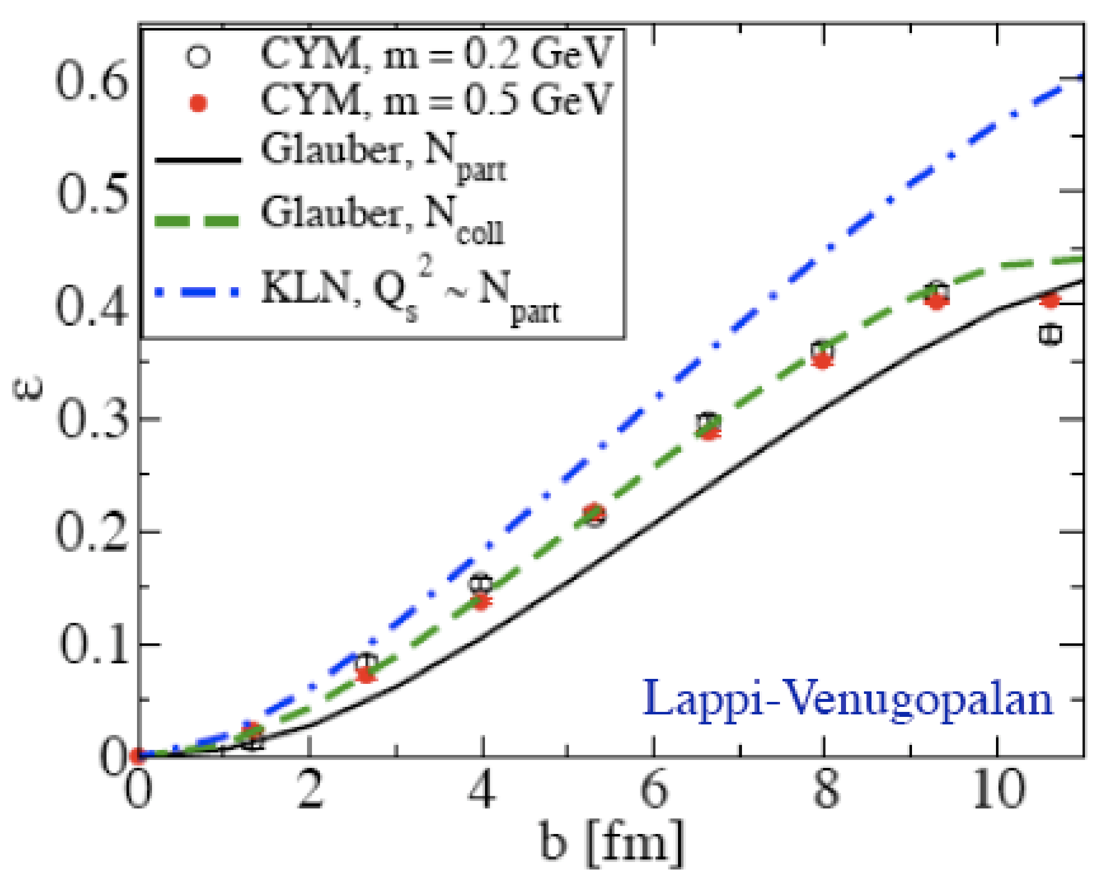


- Geometric scaling is enough: factorization of geometry and energy dependences.

2.4. AA at RHIC (II):



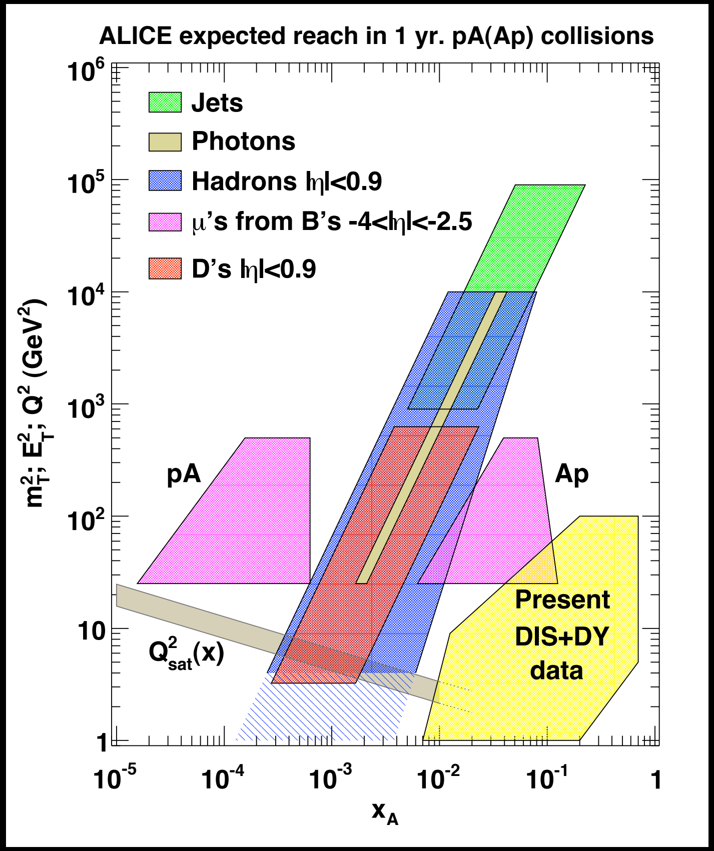


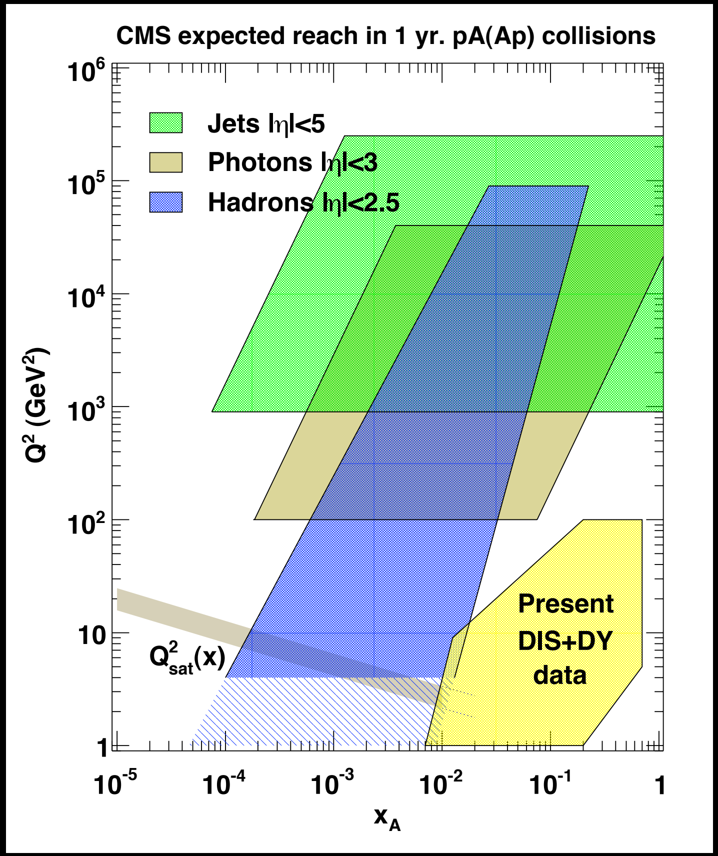


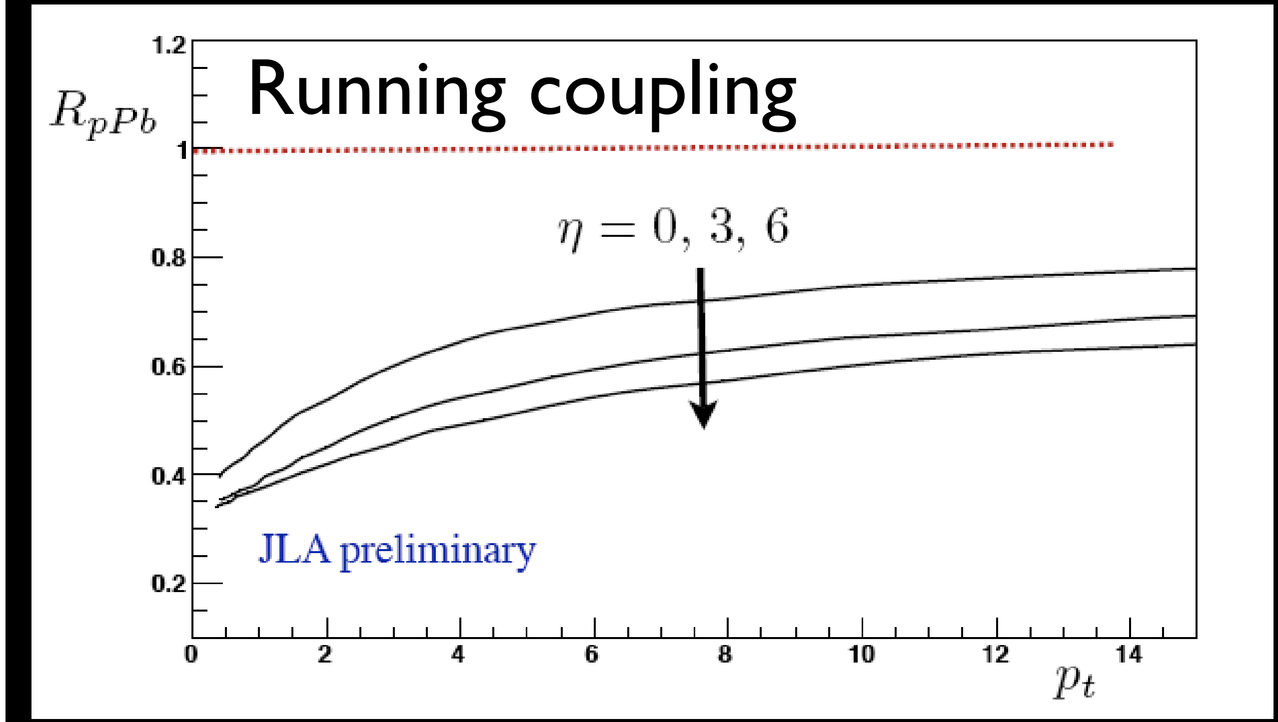
➪ Initial conditions for hydrodynamical evolution are a key ingredient in those calculations. CGC gives larger eccentricity: room for viscosity or larger equilibration times.

➪ This initial conditions are not only needed in hydro: transport codes.

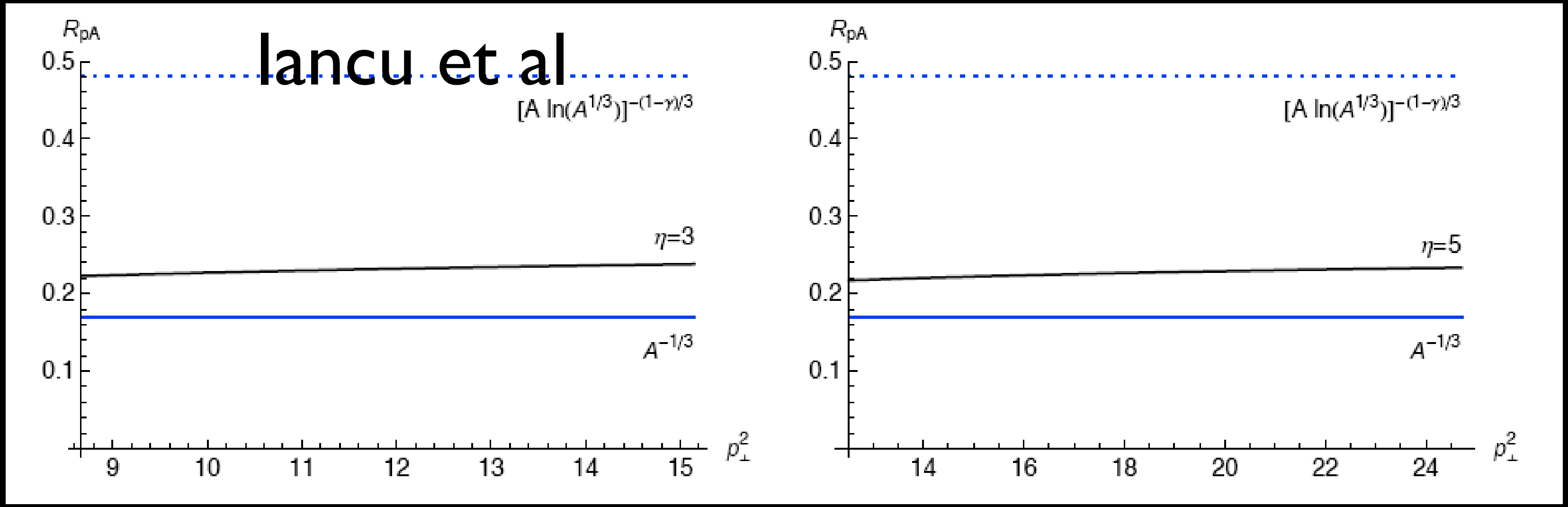
2.5. LHC (I):

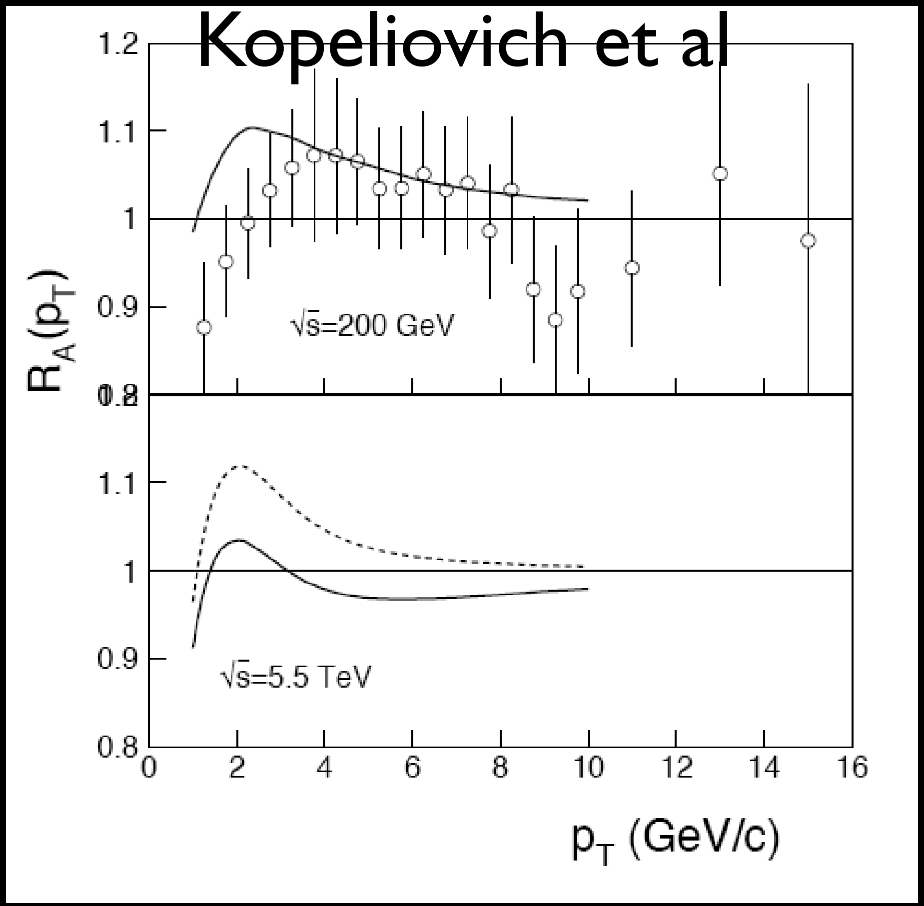




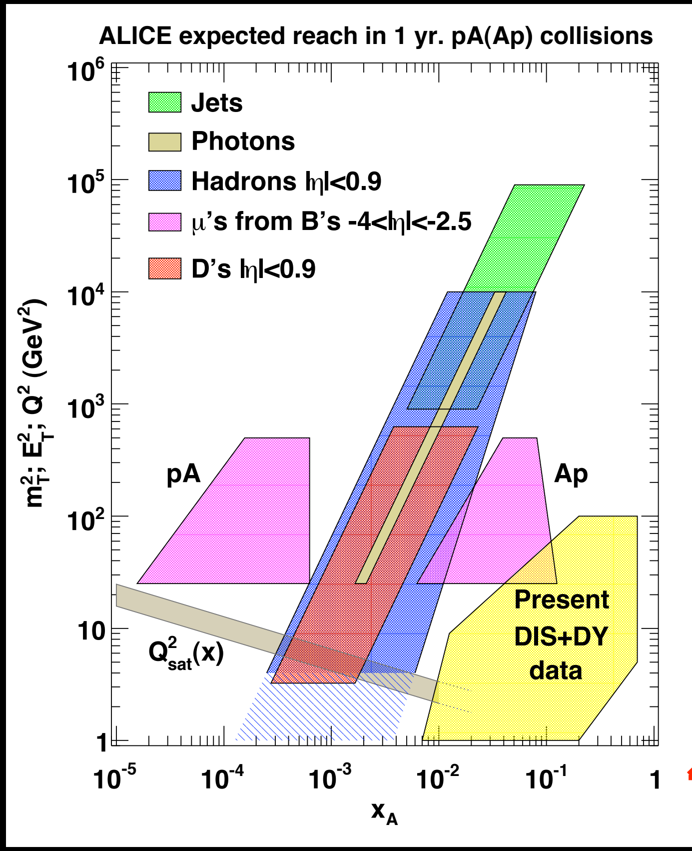

Running coupling

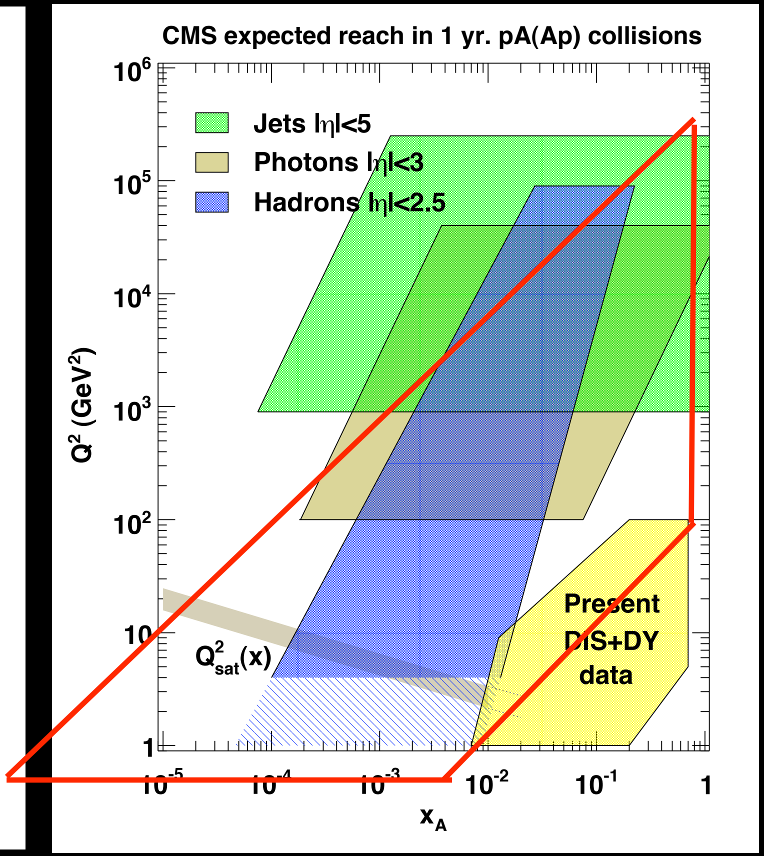
➪ pA (and UPC) at the LHC offer a huge kinematic coverage: testing ground.

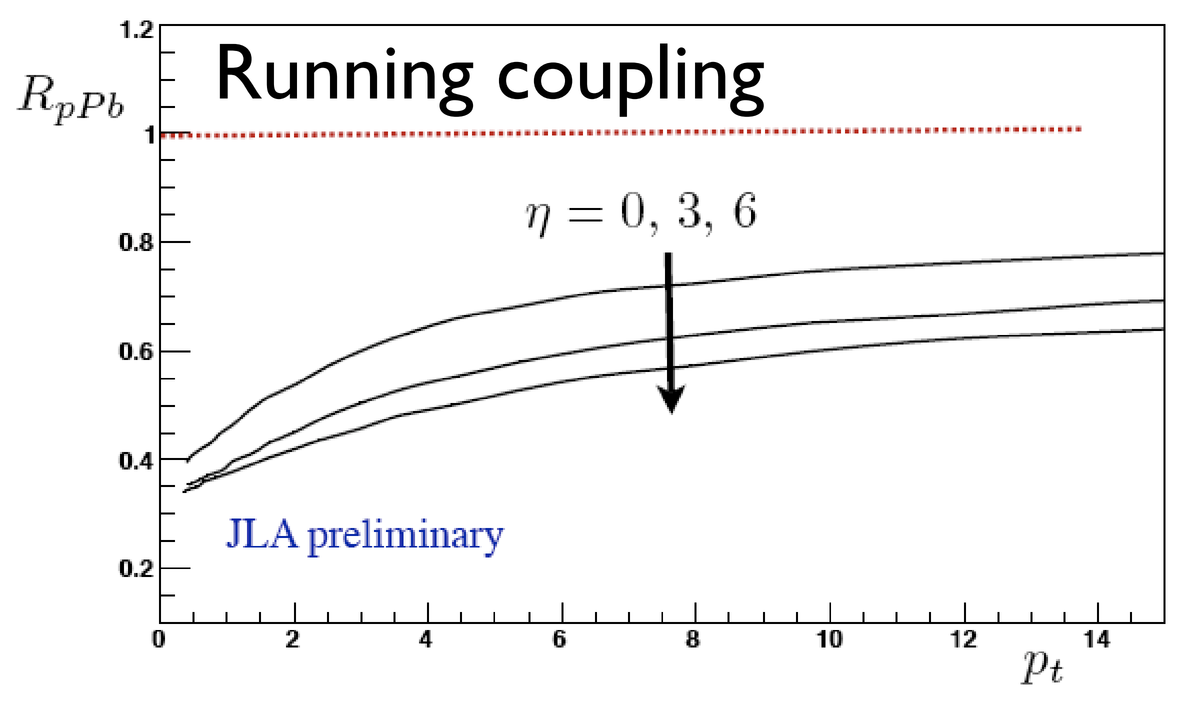

Iancu et al


Kopeliovich et al

2.5. LHC (I):







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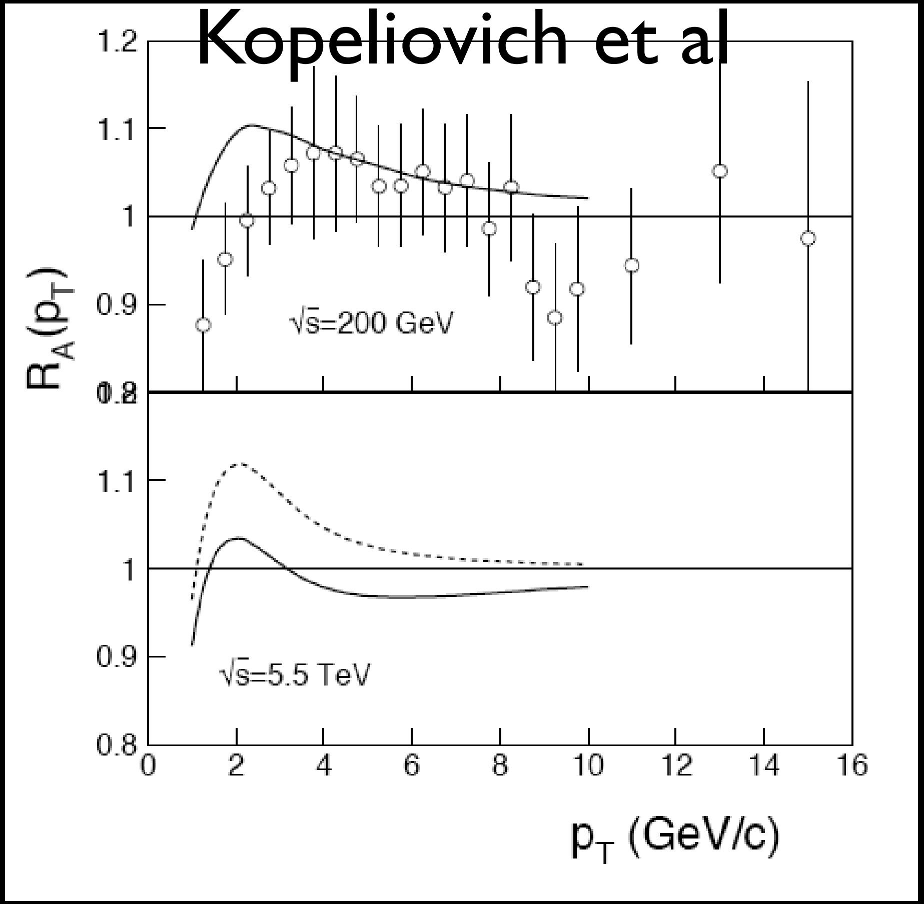
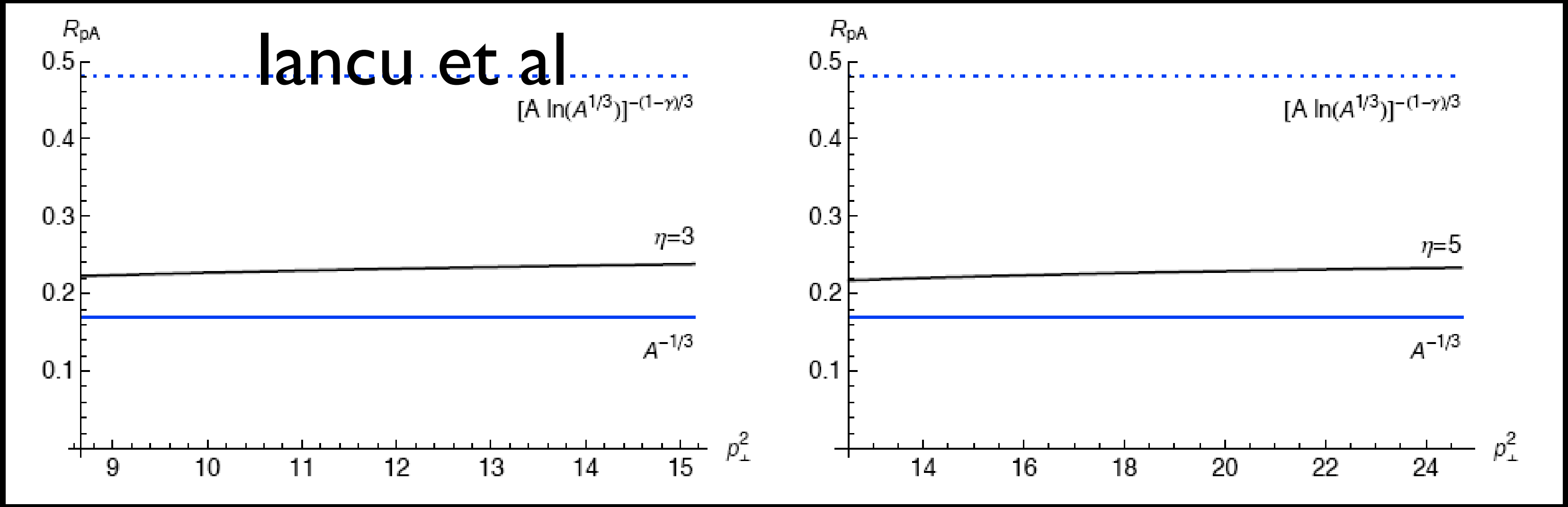
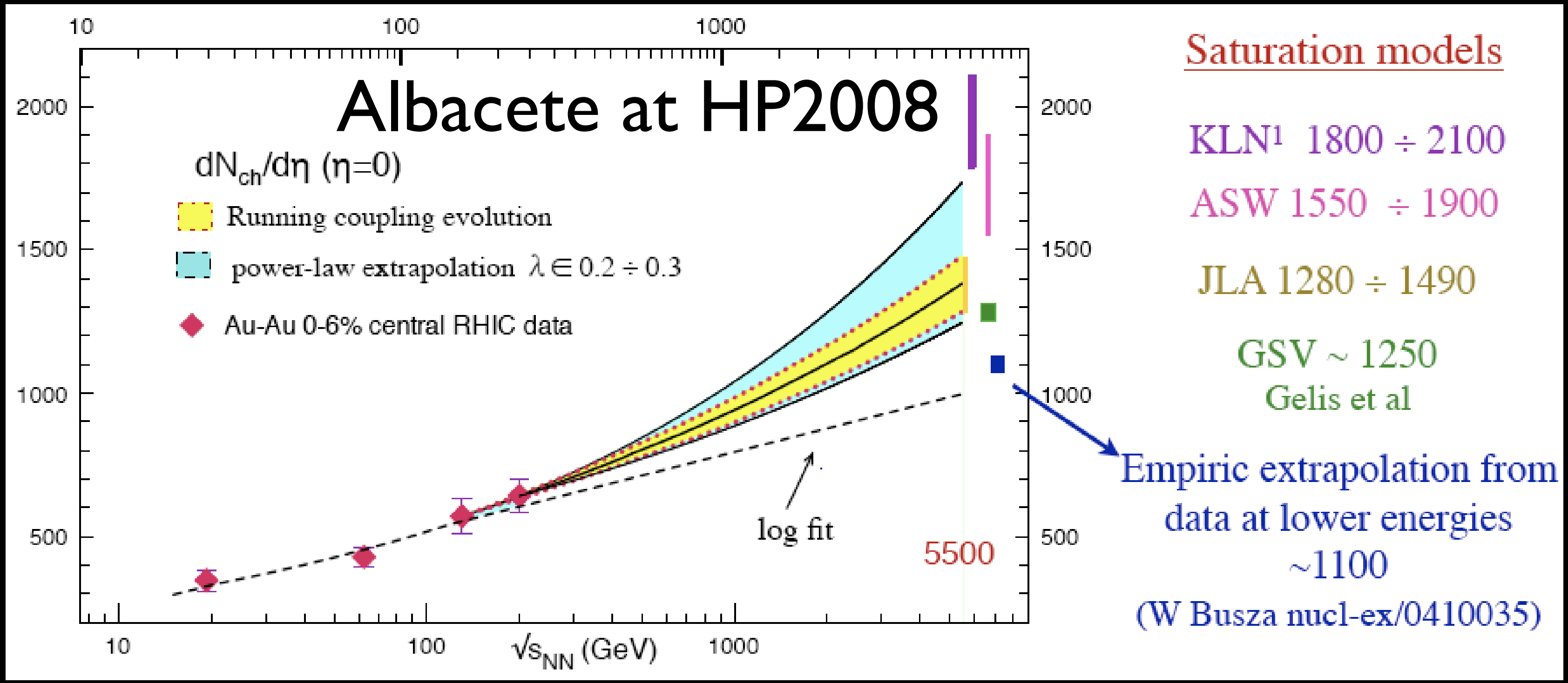
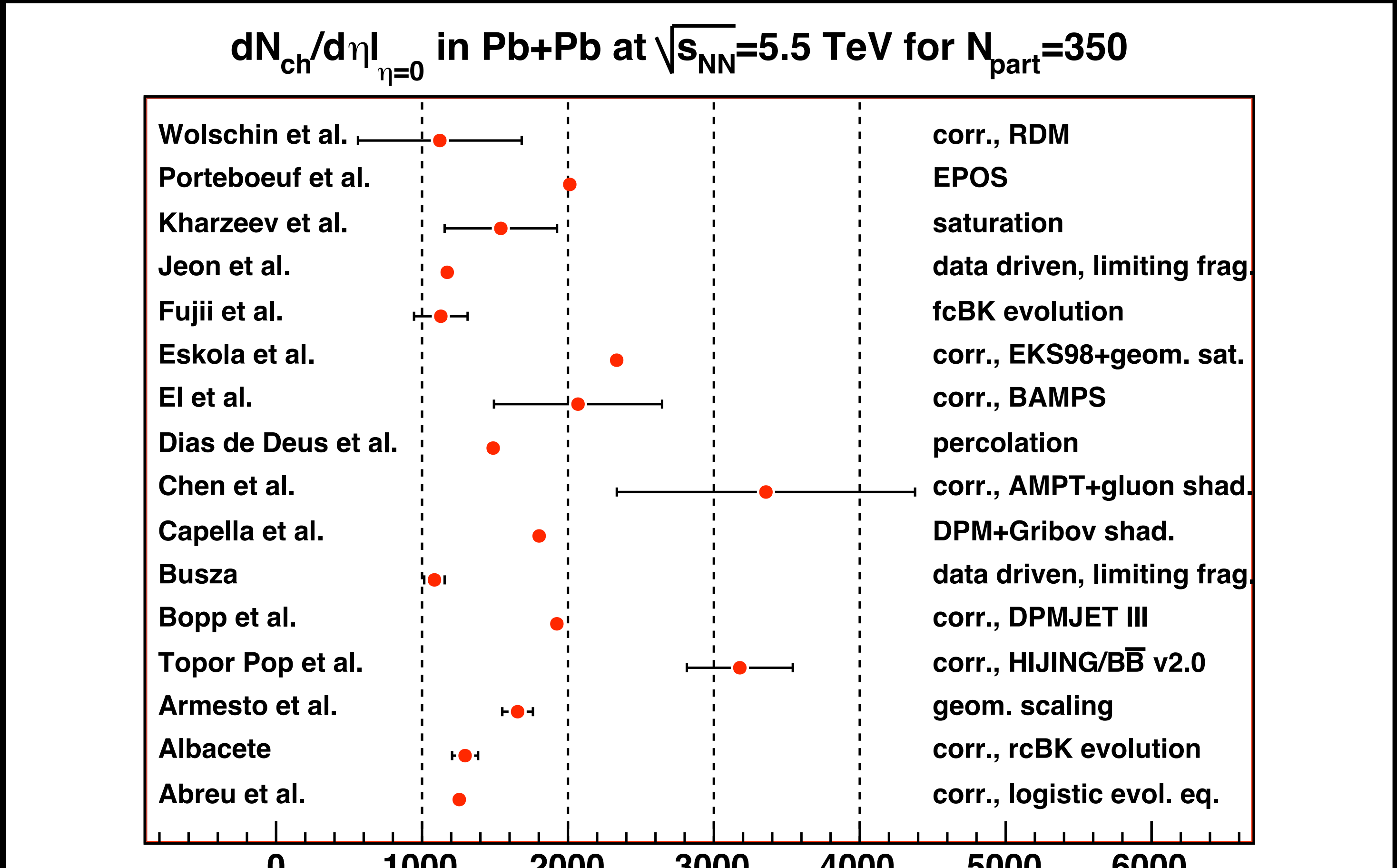




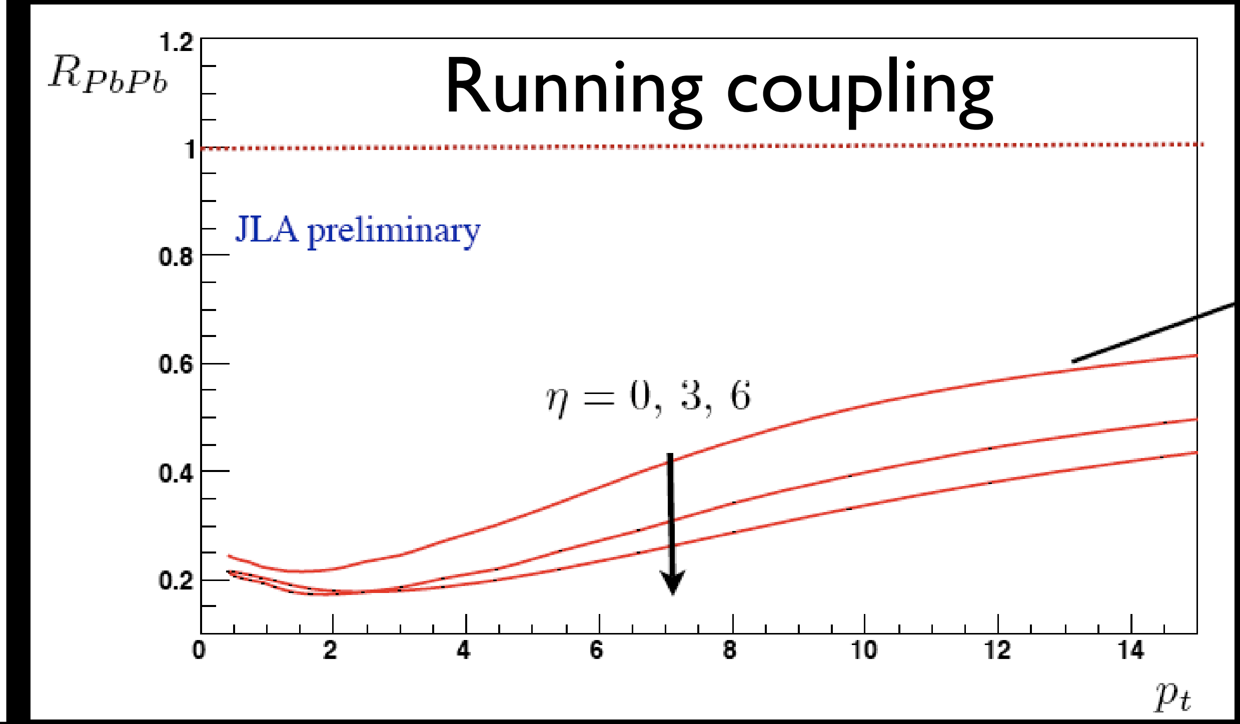
2.5. LHC (II):



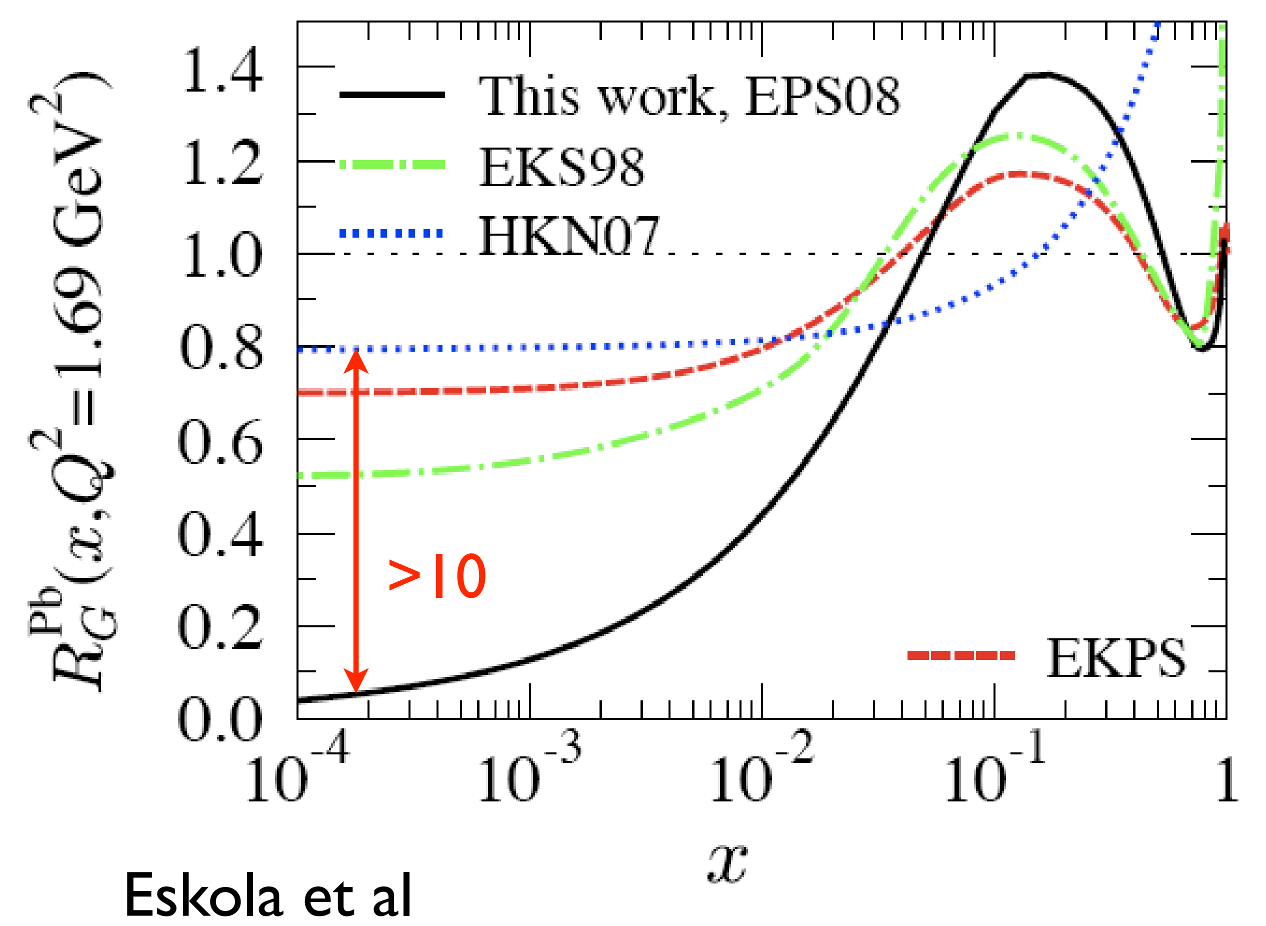
- ➪ A 1st day observable: charged multiplicity at midrapidity, will have discriminating power on models.
- ➪ $dN_{ch}/d\eta|_{\eta=0}>2000$ will be a challenge for saturation physics.



NA at QM08



3. Summary:



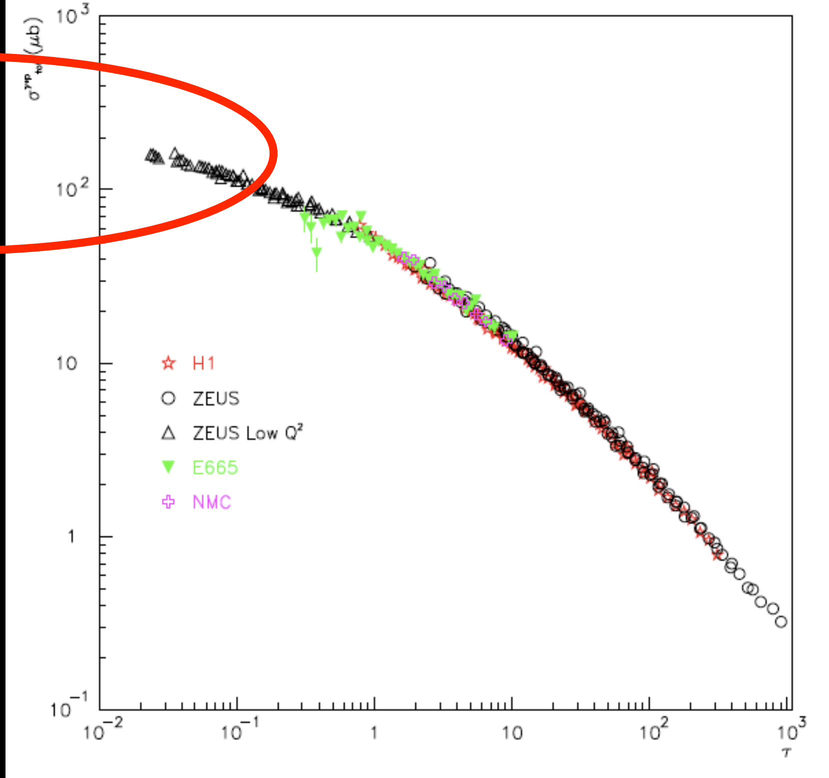
Eskola et al

- **Saturation physics**: nice theoretical framework to discuss HIC starting from ep and eA. Still, many things missing.

- **Geometric scaling is the most striking phenomenon. Saturation models are not the only ones showing it.**

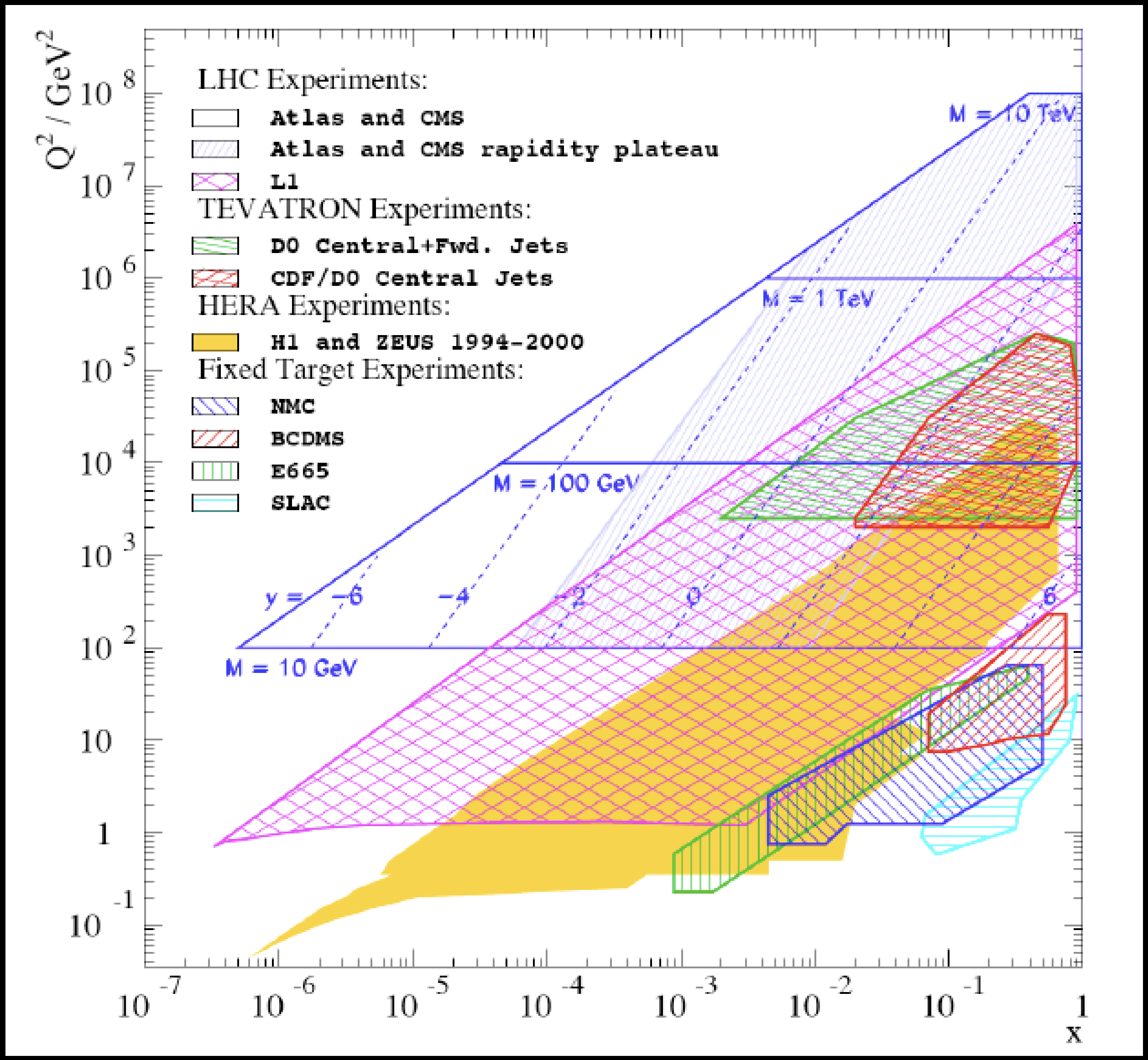
- Uncertainties in standard DGLAP npdf's are huge at small x and Q^2 for g.

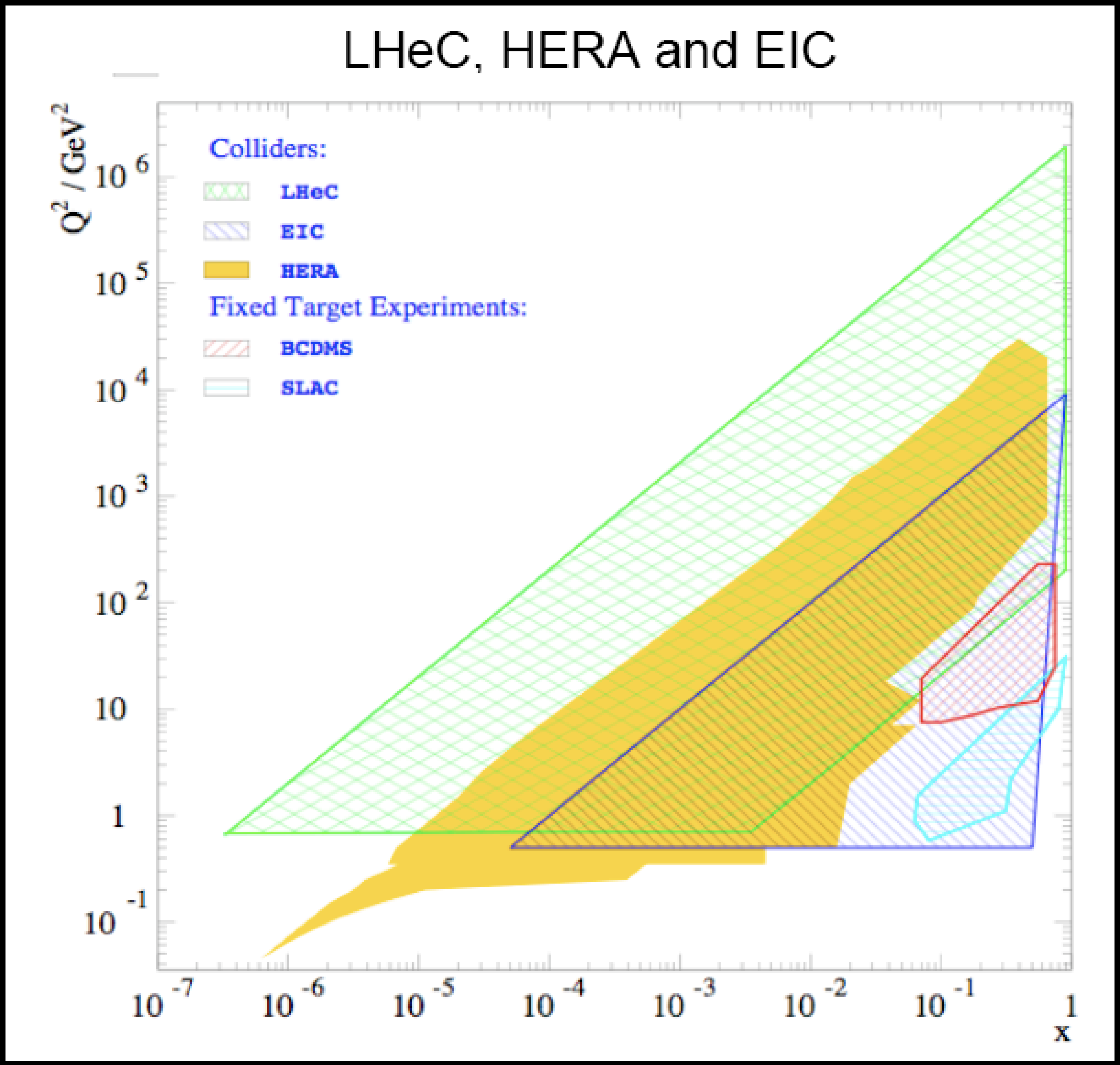
?



- **We need pA data at the LHC, and ep and eA data at smaller x.**

4. Prospects:

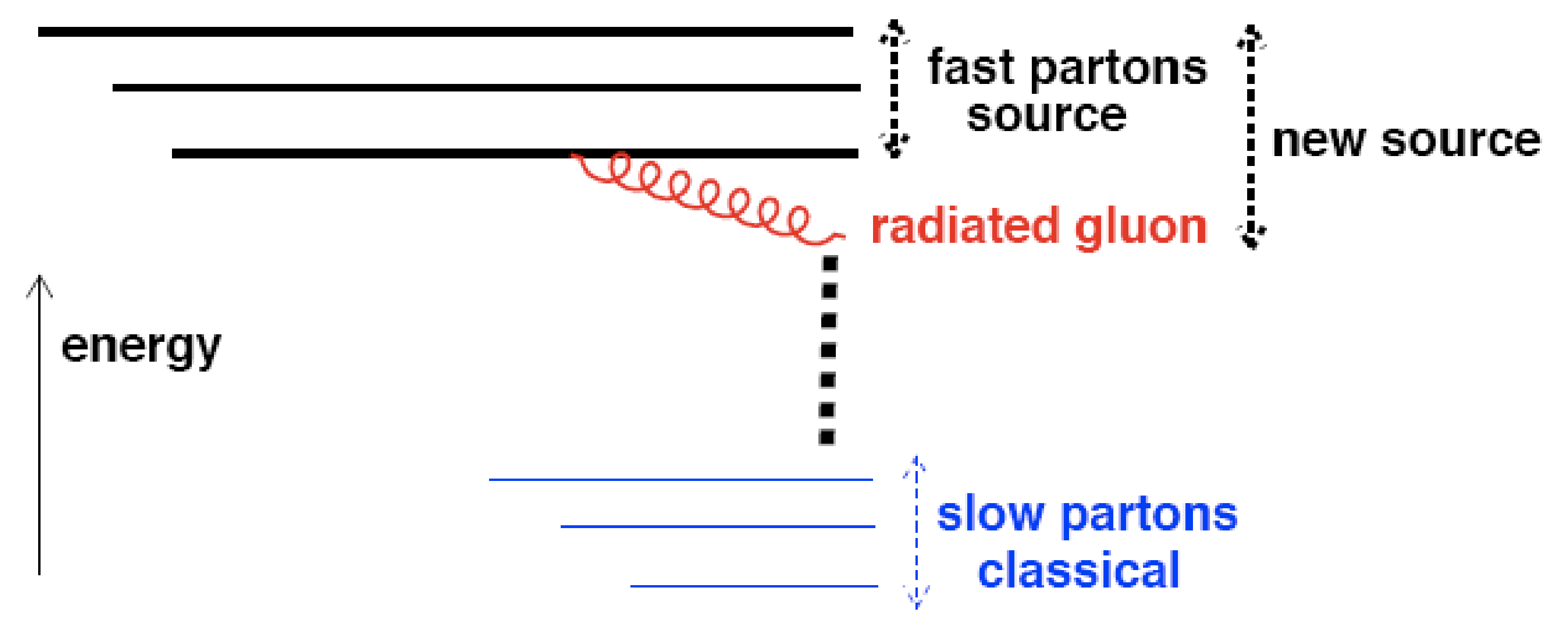




1st ECFA-CERN LHeC workshop:
Divonne-Les-Bains, September 1st-3rd 2008.
Everybody is invited!!!

I. Introduction (II):

➪ At **small enough x** for the projectile to interact coherently with the whole hadron, the CGC offers a description of the hadron wave function. $x \le \frac{1}{2m_N R_A} \sim 0.1 A^{-1/3}$



➪ The RG equation for the slow/fast separation (JIMWLK) was derived for scattering of a dilute projectile on a dense target.

➪ Its mean-field version (the Balitsky-Kovchegov equation) is the tool for phenomenology.

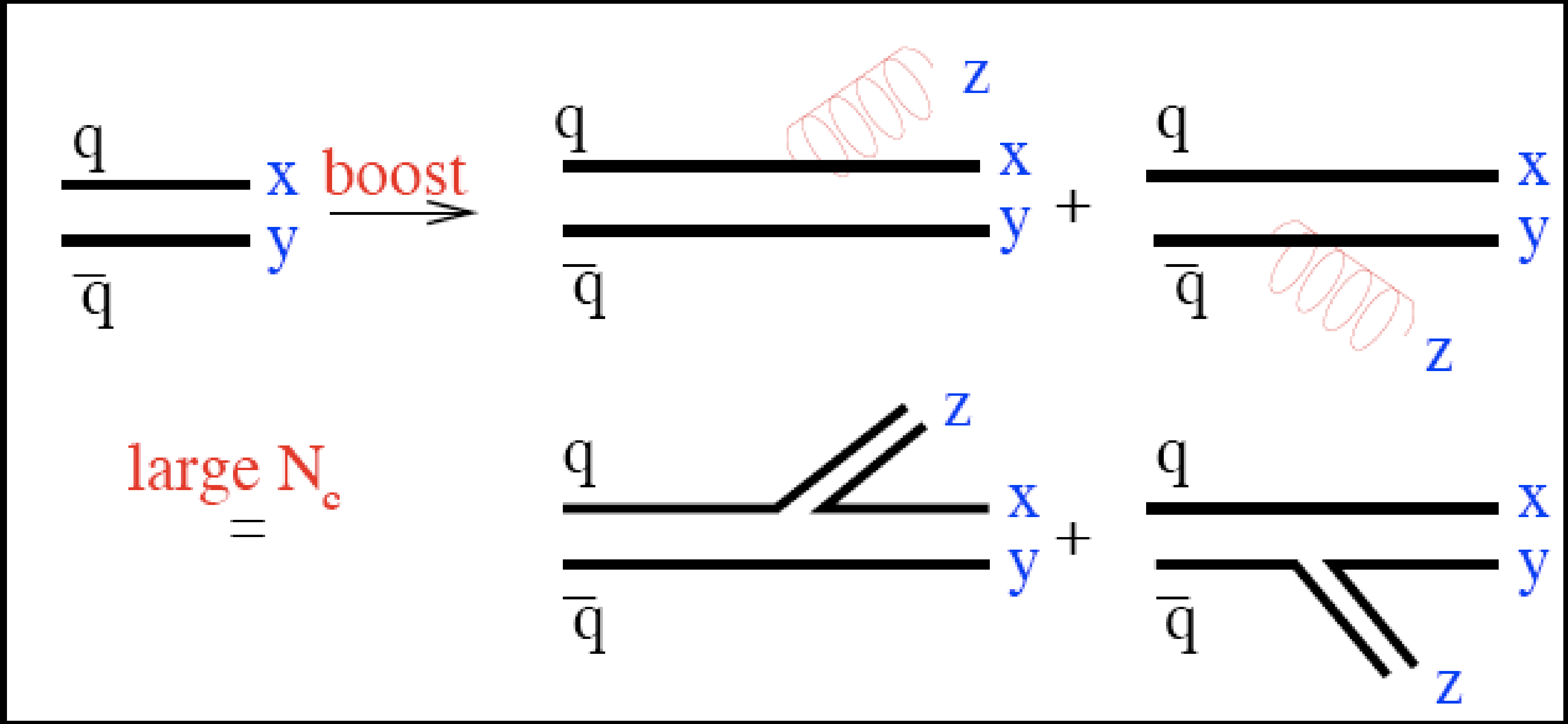
2. Theory:

2.1. Small-x evolution: BK-JIMWLK:

* The Balitsky-Kovchegov equation.
* Properties at fixed coupling.
* Running coupling.
* Impact parameter.
* Beyond JIMWLK (see the talk by D. Triantafyllopoulos at Hard Probes 2008).

2.2. Factorization.

2.1. The BK equation:



➪ Neglecting the difference between $\langle W^\dagger W W^\dagger W \rangle_{tar}$ and $\langle W^\dagger W \rangle_{tar} \langle W^\dagger W \rangle_{tar}$: **BK equation**.

$$\frac{\partial N(r,Y)}{\partial Y} = \int \frac{d^2 z}{2\pi} K(\vec{r},\vec{r}_1,\vec{r}_2) \left[N(r_1,Y) + N(r_2,Y) - N(r,Y) - N(r_1,Y)N(r_2,Y) \right]$$

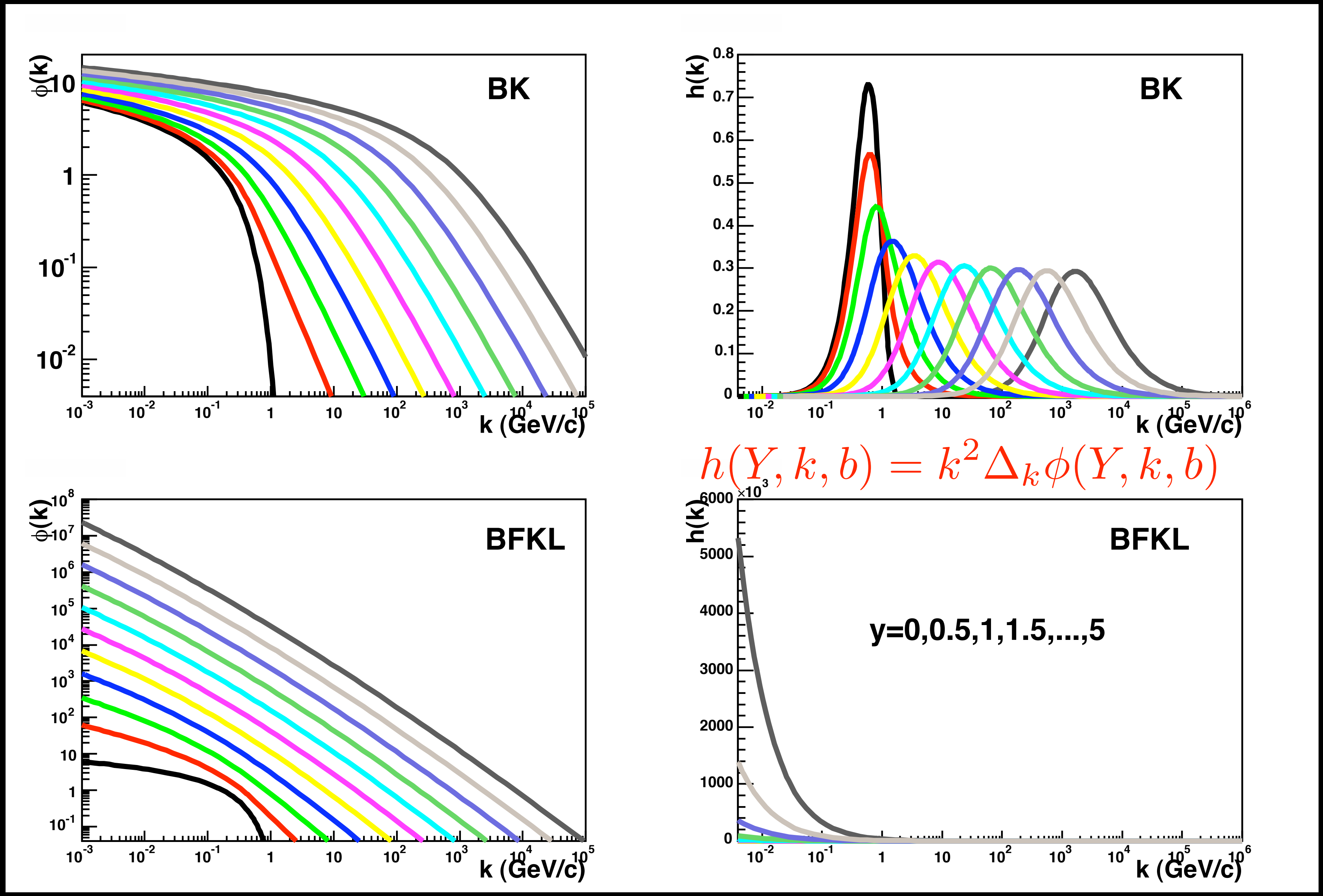
$$K(\vec{r},\vec{r}_1,\vec{r}_2) = \bar{\alpha}_s \frac{r^2}{r_1^2 r_2^2} \quad , \quad \bar{\alpha}_s = \frac{\alpha_s N_c}{\pi}$$

$$\phi(Y,k,b) = \int \frac{d^2 r}{2\pi r^2} e^{i\vec{k}\cdot\vec{r}} N(Y,r,b)$$

➪ Neglecting the dependence on impact parameter:

$$\frac{\partial \phi(y,k)}{\partial y} = H_{BFKL} \otimes \phi(y,k) - \phi^2(y,k), \quad y = \bar{\alpha}_s Y$$

2.1. Properties at fc:



$$h(Y,k,b) = k^2 \Delta_k \phi(Y,k,b)$$

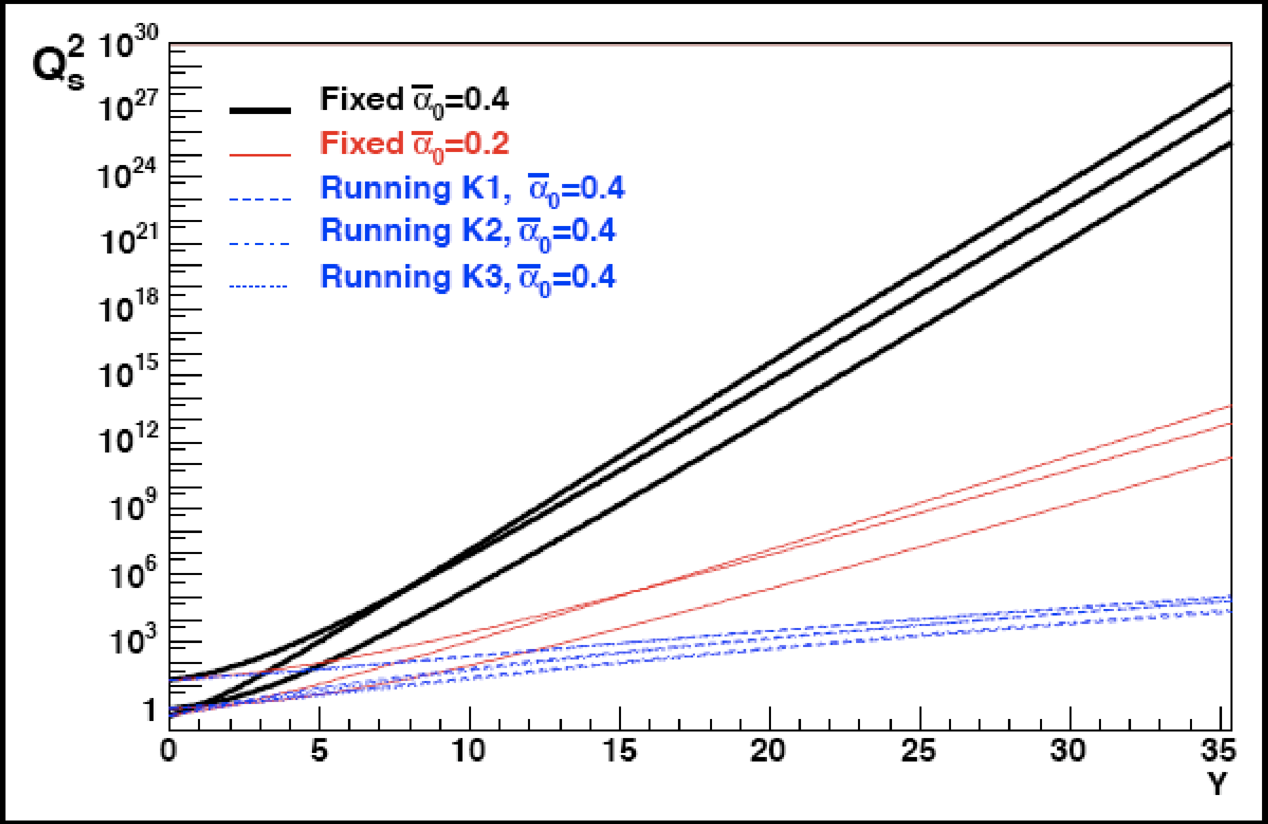
➪ IR safety.

➪ Solutions tend to a universal form independent of the initial condition (NA et al; Lublinksky; Golec-Biernat et al; Munier et al; Iancu et al; Mueller et al): **scaling.**

$$\phi(Y,k,b) = \phi\left(\frac{k}{Q_s(Y,b)}\right) \quad Q_s^2(Y) = \exp(\lambda Y), \quad \lambda \simeq 4.88\bar{\alpha}_s$$

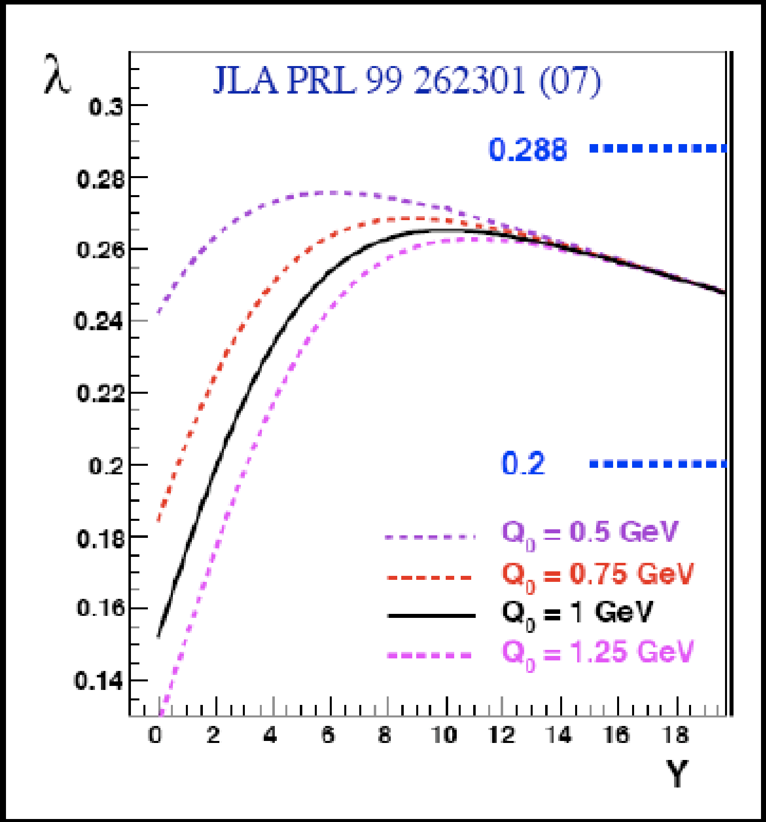
➪ Shape goes from logarithmic in the $k<Q_s$ region to power-like $(1/k^2)^{Y\sim 0.63}$ in the scaling window $Q_s<k<Q_s^2/k_0$ to $1/k^2$ at large k.

2.1. Running coupling:

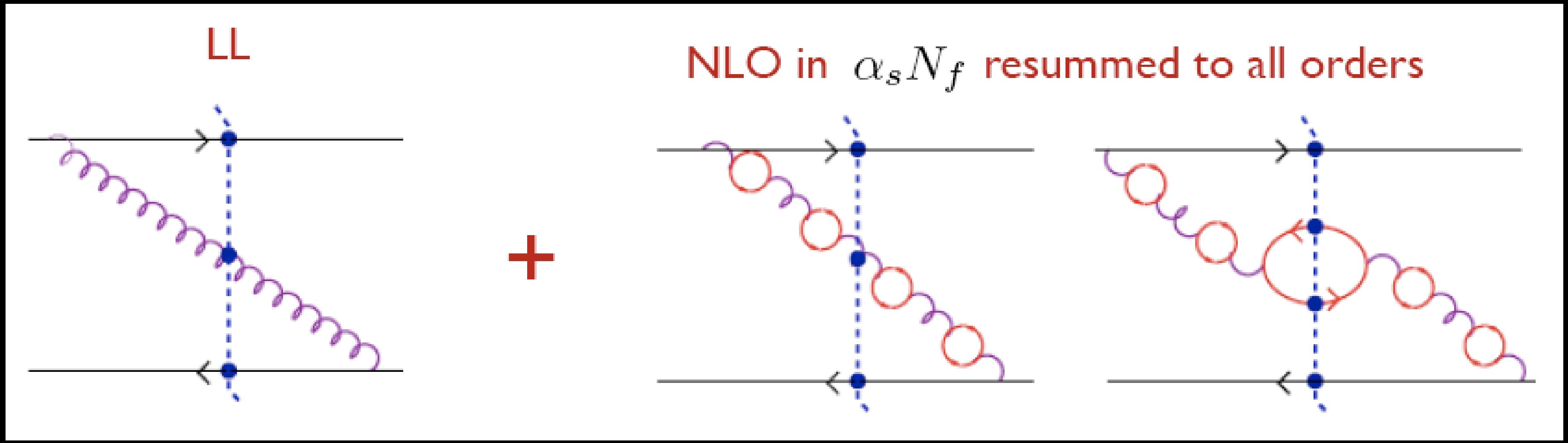


➪ Heuristic implementations (Braun, Albacete et al, Mueller et al, Triantafyllopoulos) showed: slowing-down of the evolution, scaling, vanishing A-dependence of Q_s, different shape from fc in the scaling window?!

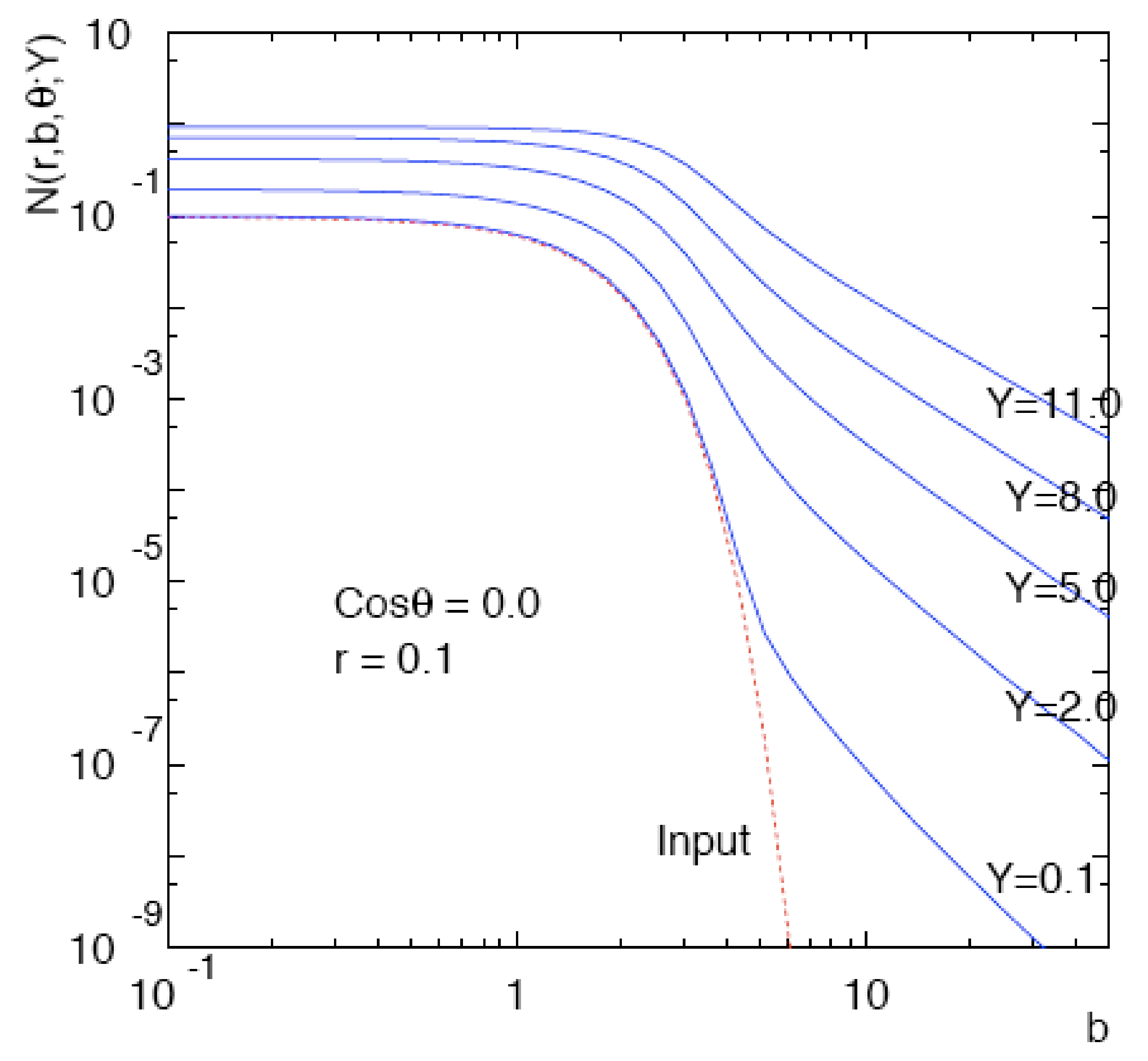
$$Q_s^2(Y) \propto \exp\sqrt{dY + X}$$



➪ Part of the NLO correction computed (quark loops used à la BLM): Balitsky, Kovchegov-Weigert-Albacete, Rummukainen et al. IR problems?



2.1. Impact parameter:



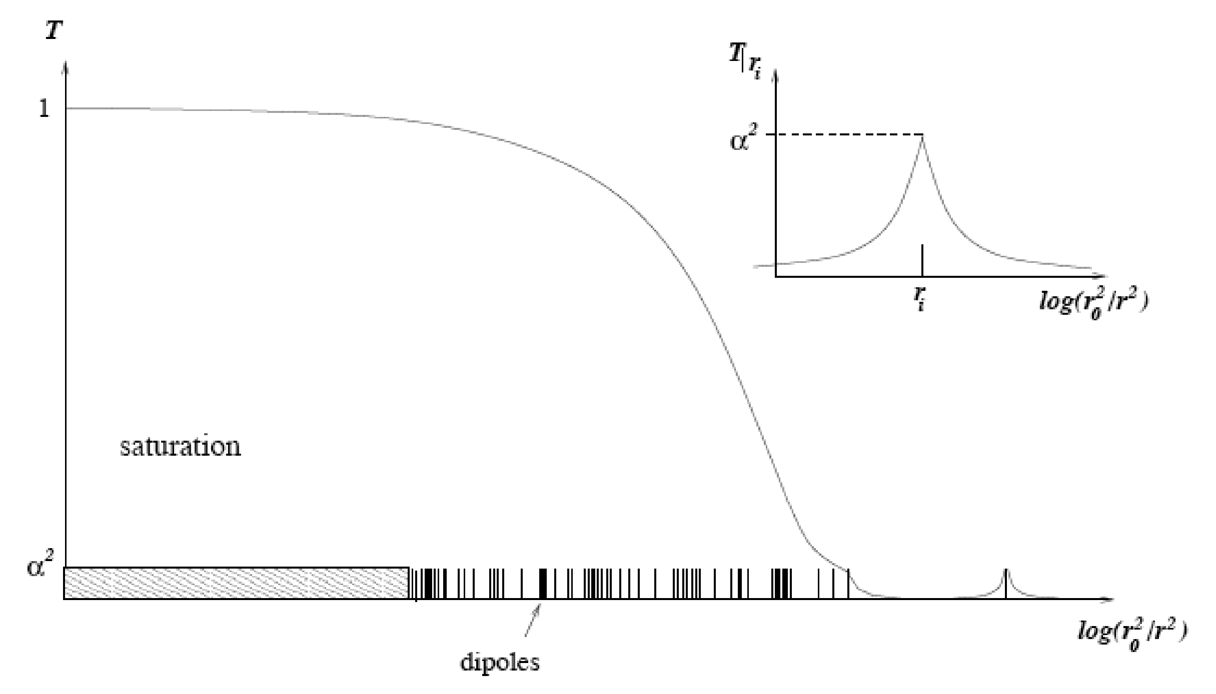
- Dependence on impact parameter usually neglected: large homogeneous nucleus.

- This dependence is crucial for total cross sections, and for the transition from the dense to the dilute regime at the nuclear edge: behavior of Q_s with b required e.g. to use CGC to provide i.c. for hydro.

- BK generates a Coulomb tail ($1/b^4$) independent of the starting i.c. in b: violation of the Froissart bound (but massless gluons): Kovner et al, Ferreiro et al, McLerran et al, Golec-Biernat et al. Kernel must be made short-range.

2.1. Beyond JIMWLK:

- Going beyond the mean field approximation in JIMWLK for the 4 W case gives effects < 15 % (Rummukainen et al).



- JIMWLK fails in dense-dense and dilute-dilute: corrections, generically referred to as Pomeron loops or fluctuations (from ’04 on: Iancu et al, Mueller et al, Kovner et al, Levin et al).

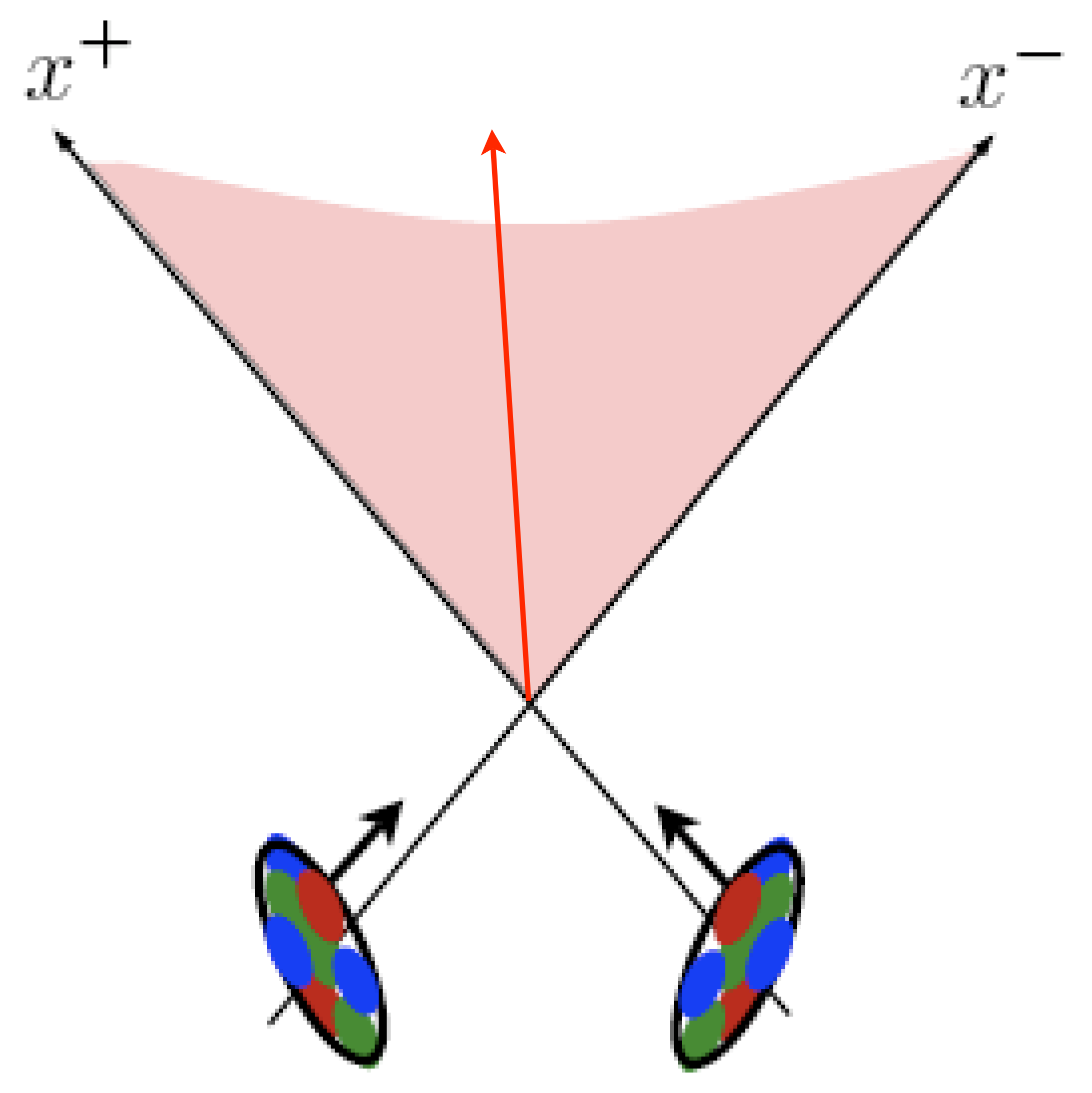
- Only general properties known, no full theory, no numerical computation with the existing pieces. Information from statistical mechanics analogies: reaction-diffusion processes, diffusive scaling

$$A(\rho,Y)=\frac{1}{\sigma\sqrt{2\pi}}\int d\rho_s\, T(\rho)|_Y\, \exp\left(-\frac{(\rho_s-\langle\rho_s\rangle)^2}{2\sigma^2}\right)$$

$$\sigma\propto\sqrt{\bar{\alpha}Y},$$

- Competition of these new LL pieces and NLO corrections (Iancu et al, Bondarenko et al, NA et al, Peschanski).

2.2. Factorization (I):



- Gluon production on nuclear targets at τ=0 is usually computed through a generalization of k_t-factorization: convolution of ugd's (tentatively evolved with BK) with an off-shell matrix element computed in pQCD.

$$\frac{dN^g_{AB}}{d\eta} \sim \int \frac{d^2p}{p^2} \int d^2k \, \varphi_A(x_1, k) \, \varphi_B(x_2, |p-k|)$$

- Alternatively, you can try and solve classical gluodynamics (Krasnitz et al, Lappi).

- After production, gluons are projected onto hadrons using LHPD or standard fragmentation functions (evolving with DGLAP in the vacuum, with the eventual effects of a dense created medium as modifications of these ff's).

2.2. Factorization (II):

➪ Proofs or disproofs of these statements in AA are missing. Several groups attempt to prove factorization formulas for gluon or quark production:

* In momentum space, the Pomeron language (Braun, Bartels et al).

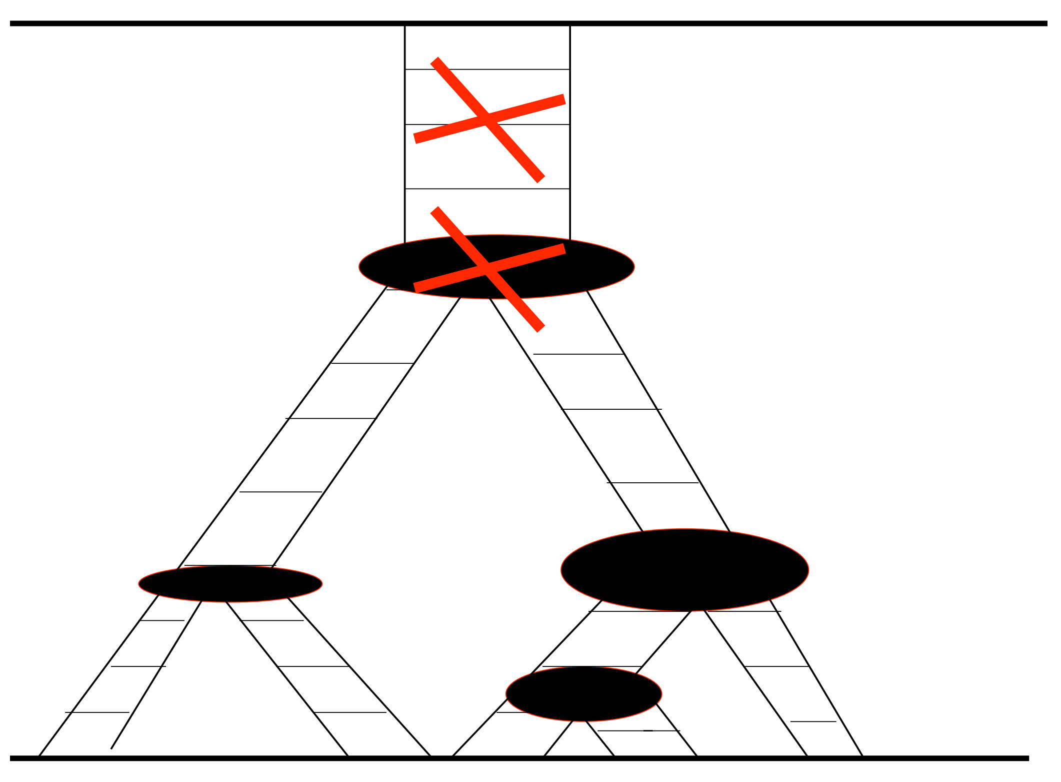
* In the dipole model (Kovchegov et al).

* In classical gluodynamics: expansion in projectile and target densities (Gelis et al, Balitsky et al, McLerran et al, Marquet, Fukushima et al).

* Hadron wave function (Nikolaev et al, Kovner et al).

➪ In dilute-dense: k_t-factorization OK for single gluon, not for quark or for 2 gluons. Several pieces evolving BK-like.

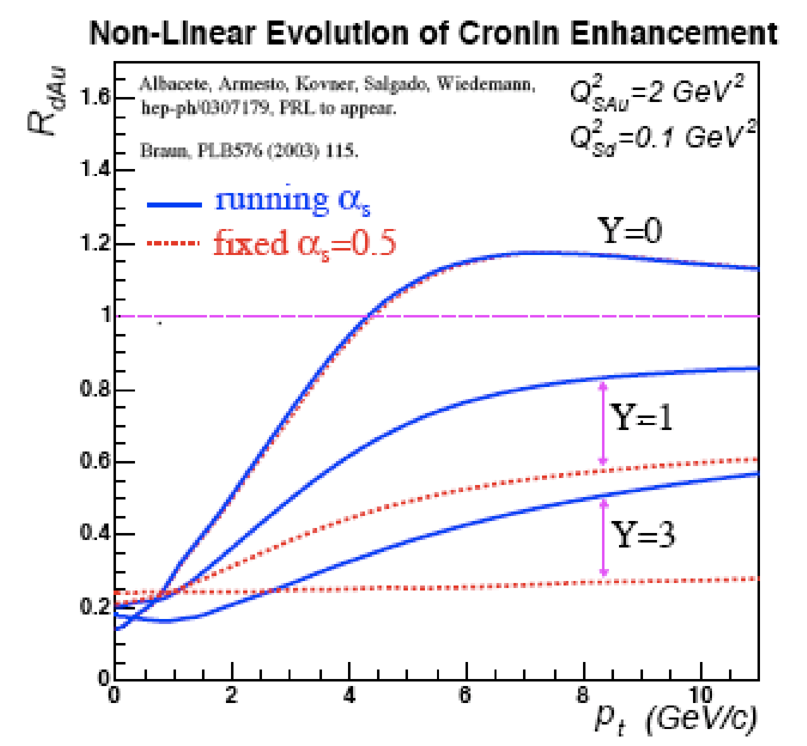
➪ In dense-dense, usual k_t-factorization not valid (quantitative inaccuracy?); factorization becomes more involved.

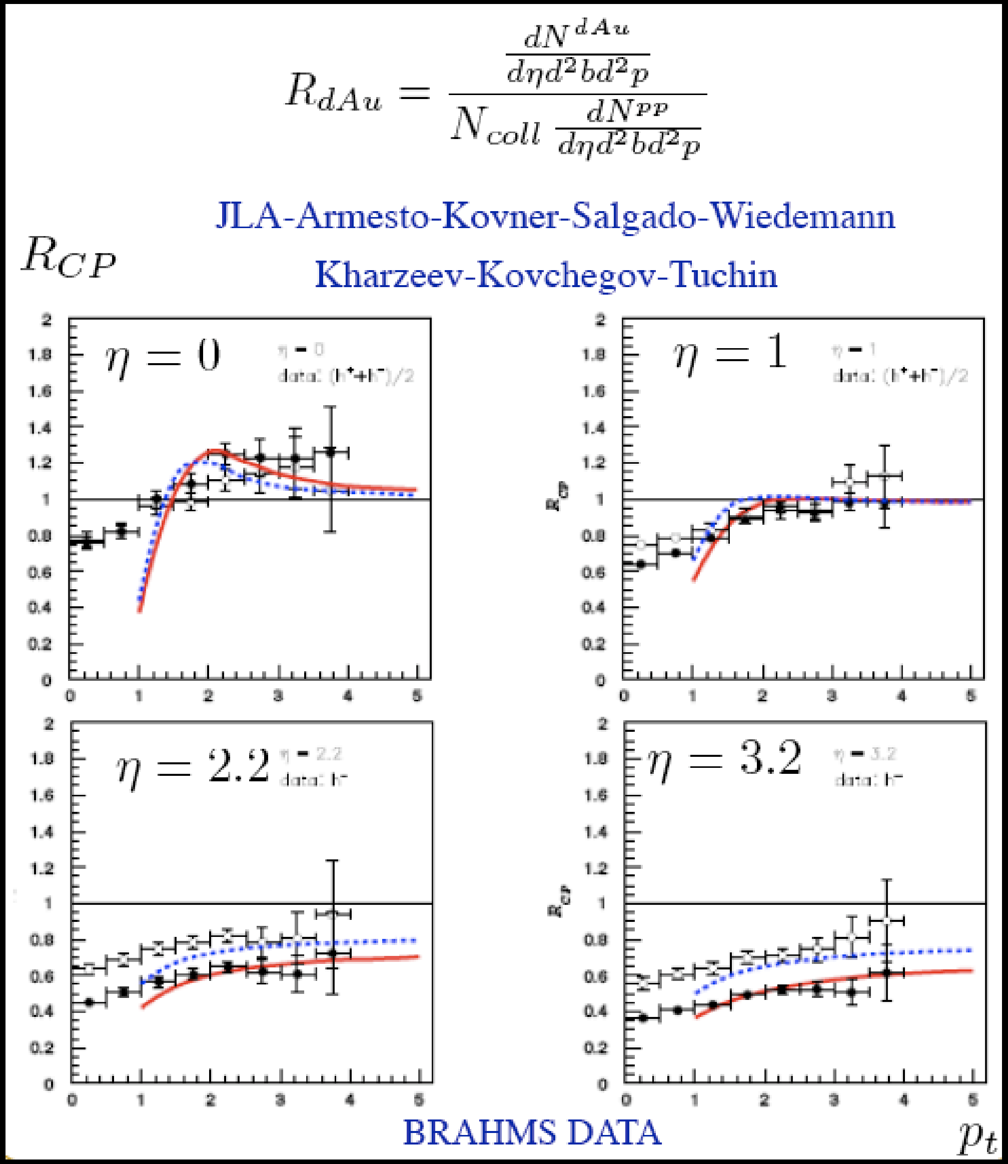


From eA to AA at RHIC and the LHC: 2. Theory.

2.3. pA at RHIC (I):

- Control experiment for initial state effects in AA: Cronin effect in dAu at midrapidity ruled out initial state effects as the explanation for the suppression observed in AA.
- Suppression at forward rapidities was predicted by small-x evolution (BK).





$$R_{dAu} \rightarrow_{y\rightarrow\infty} A^{-(1-\gamma/\delta)/3}(fc)$$

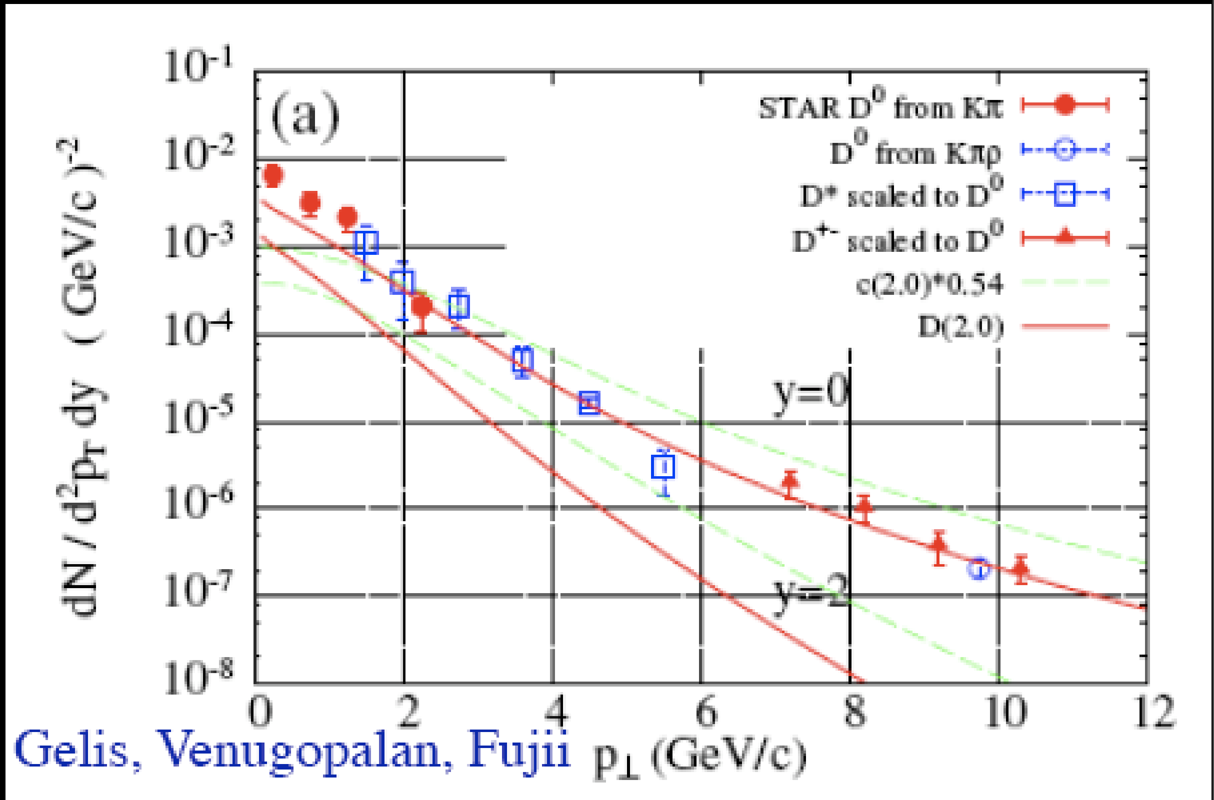
$$A^{-1/3}(rc, fluctuations)$$

Kharzeev et al, Baier et al,
Iancu et al, Kozlov et al.

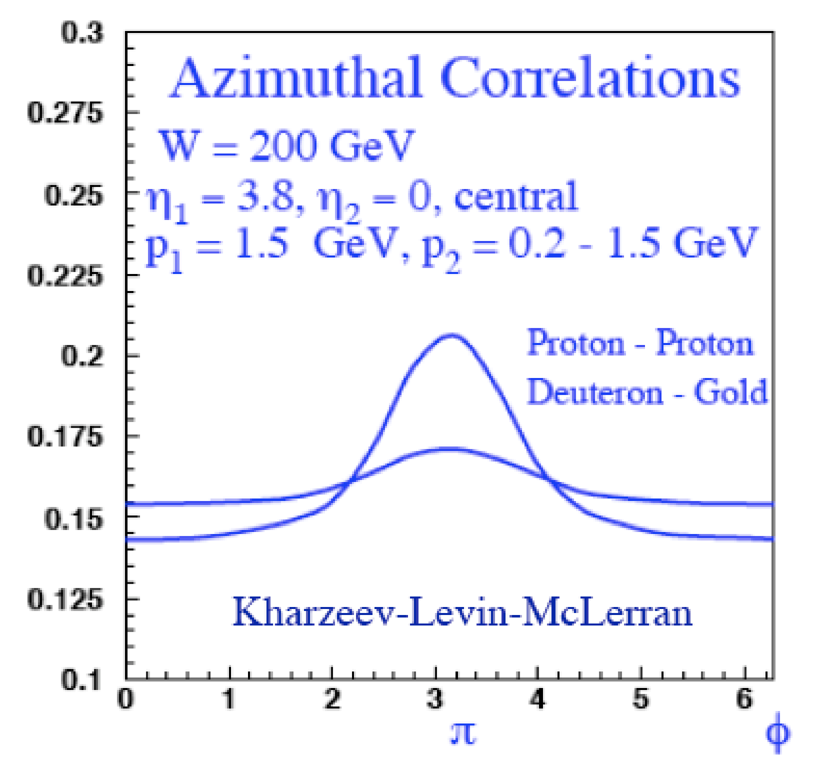
3.3. pA at RHIC (III):

➪ Azimuthal correlations may also indicate small-x dynamics: tale of the two-particle inclusive distributions (Baier et al, Kovchegov et al, Marquet).

$$\frac{d\sigma}{dy_1\, dy_2\, d^2p_1\, d^2p_2\, d\Delta\phi}$$



Gelis, Venugopalan, Fujii



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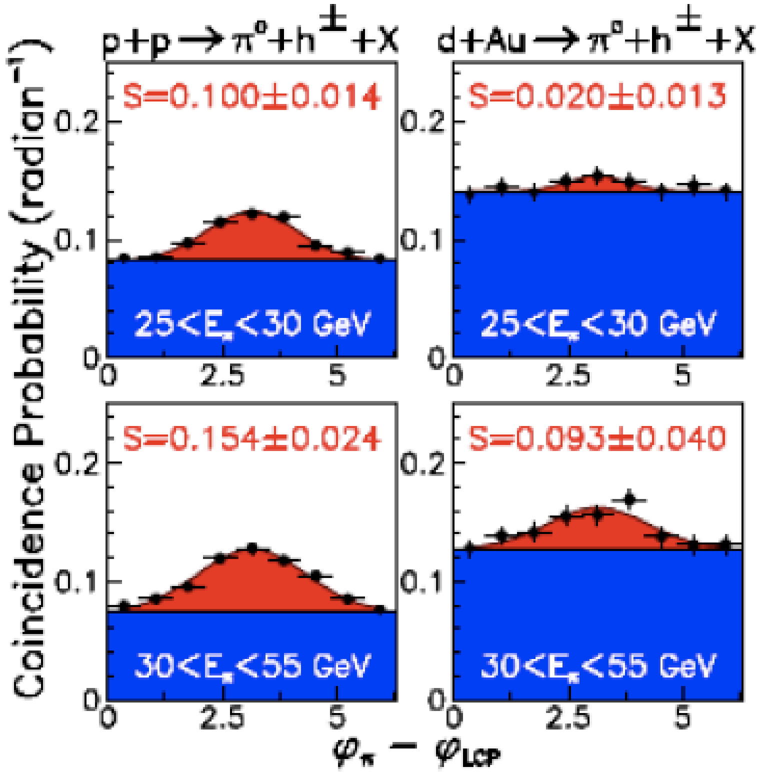


➪ Charm production described (also Kharzeev et al, Tuchin).

3.4. AA at RHIC (III):

- CGC may offer initial conditions for QGP formation: transverse fields transform into longitudinal (Glasma) (Lappi et al, Romatschke et al).

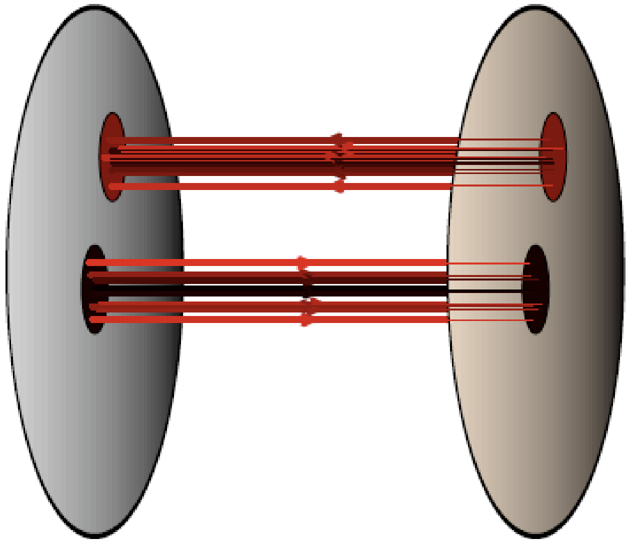
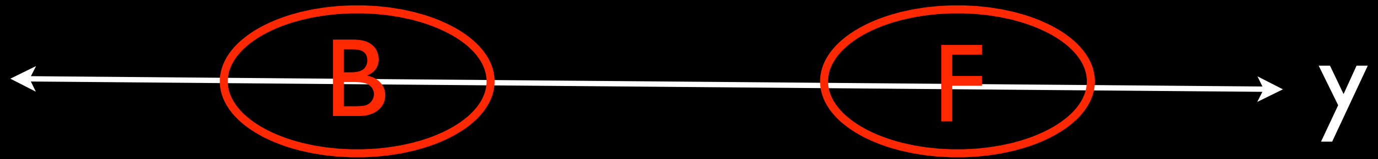


Figure 4: Glasma flux tubes. The transverse size of the flux tubes is of order $1/Q_s$.

- QCD basis for good old string models.



$$\langle n_B \rangle_F = a + b n_F\,, \quad b \equiv D^2_{FB}/D^2_{FF}\,,$$

$$b = \frac{1}{1 + c\alpha_s^2}\,.$$

- Correlations in rapidity are a place to look for such origin of particle production (Capella et al, NA et al, Dumitru et al, Fukushima et al).

4. Summary:

➪ **Saturation physics** offers a nice theoretical framework to discuss bulk characteristics of HIC starting from ep and eA.

➪ **Theory**: we miss

* Initial conditions: apart from MV, we have very little.
* NLO corrections completed and understood.
* Fluctuations/Pomeron loops: are they important?
* Factorization/particle production.

➪ **Phenomenology**: we miss

* Geometric scaling: is it too nice to be true?
* Treatment of non-perturbative effects and b-dependence.

➪ **We miss data at smaller x: pA and AA at the LHC, and above all, eA.**