High energy QCD: when CGC meets experiment

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Excited QCD
Les Houches, February 20-25 2011

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

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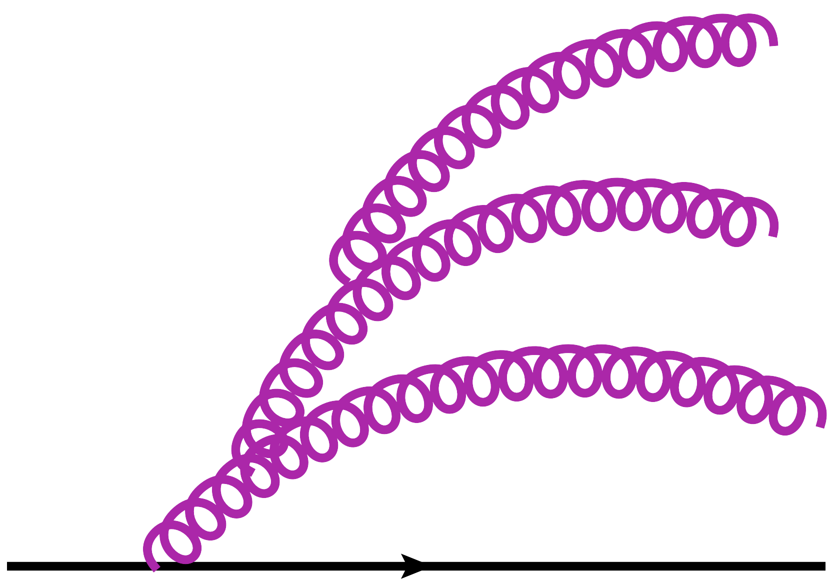
OUTLINE

- Brief Intro [cf Larry's Talk]
- Running coupling corrections to the BK equation.
- Fits e+p data **(in coll with N. Armesto, JG Milhano, P. Quiroga and C. Salgado)**
- RHIC: Single and double inclusive yields at forward rapidities **(in coll with C. Marquet)**
- rcBK Monte Carlo: Pb+Pb multiplicities at the LHC **(in coll with A. Dumitru)**

See also T. Ullrich's talk tomorrow

At high energies, or small Bjorken-x, hadron's gluon densities are large



$$\mathbf{k_n^+ = x_n\, p^+}$$

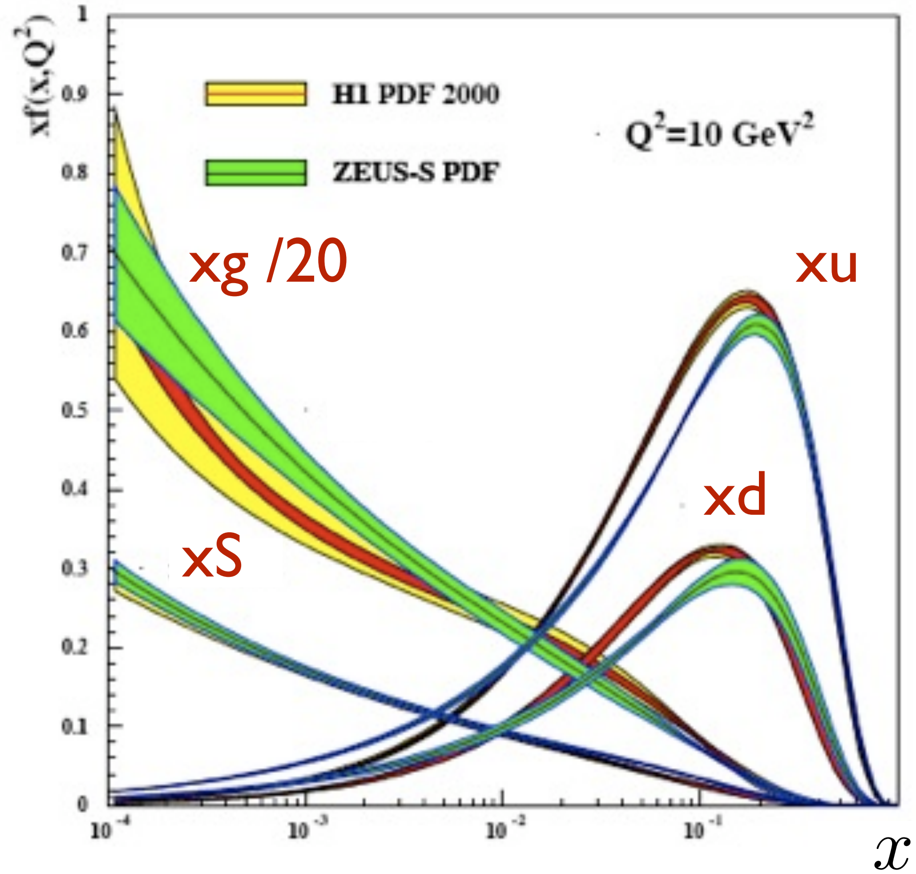
$$\mathbf{k_2^+ = x_2\, p^+}$$

$$\mathbf{k_1^+ = x_1\, p^+}$$

$$\mathbf{p^+}$$

Probability of n-soft gluon emission

$$\mathbf{P} \sim (\alpha_\mathbf{s} \ln \mathbf{1}/\mathbf{x})^\mathbf{n}$$

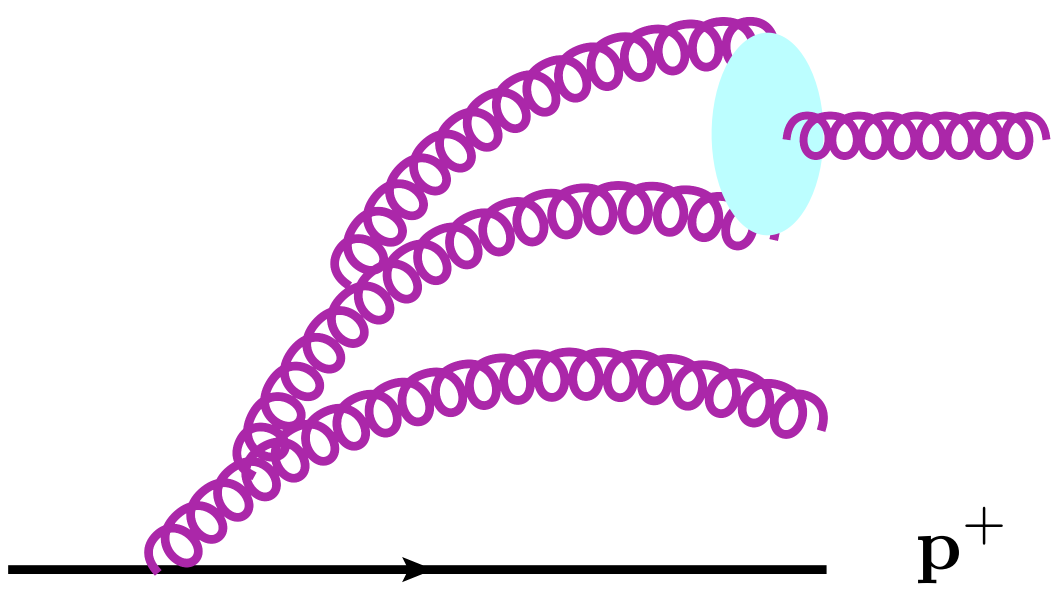


proton ugd from HERA

Multiple small-x gluon emissions are resummed by the BFKL equation

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})$$

Non-linear QCD evolution: At small-x gluon both radiative and recombination processes

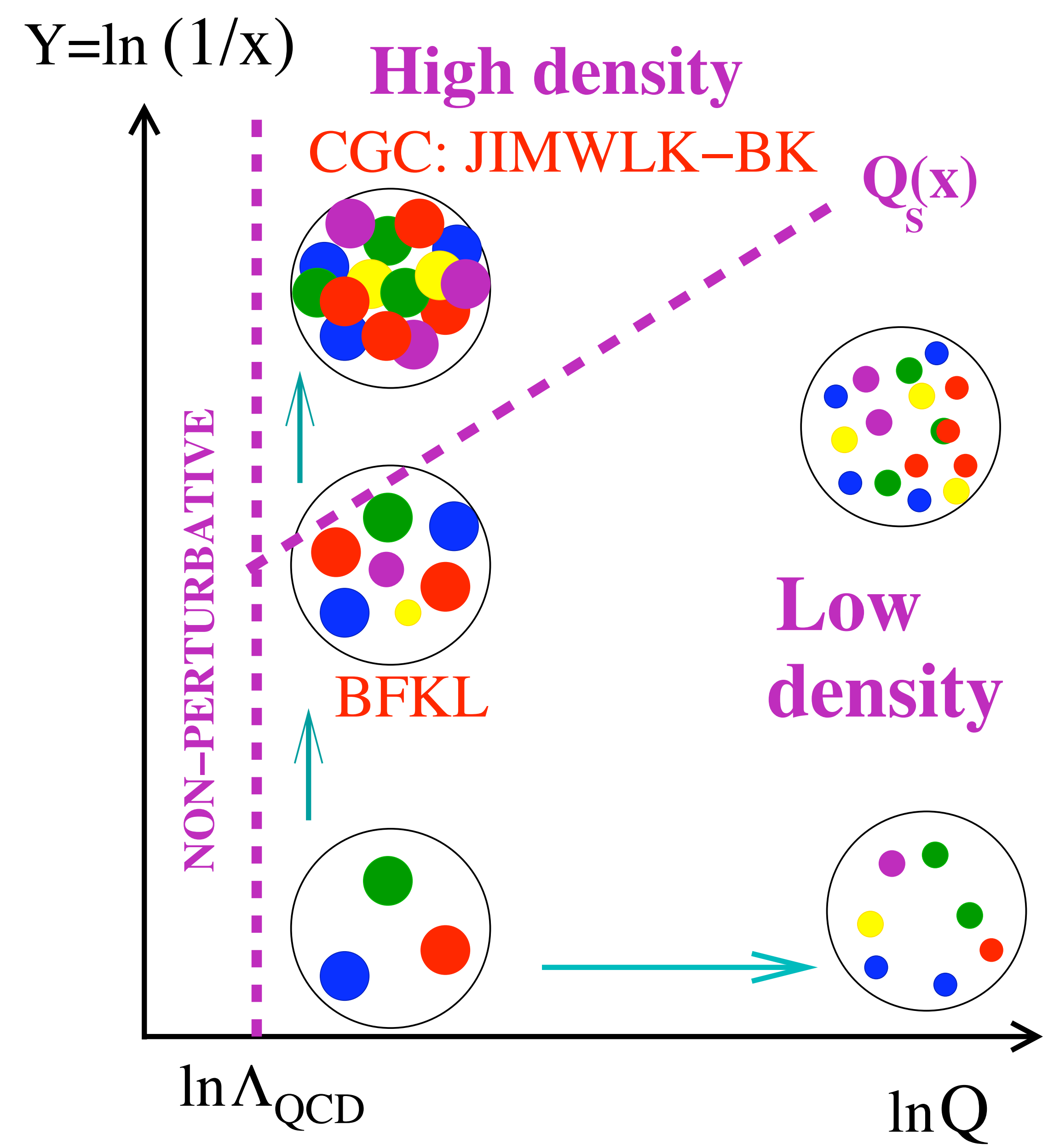


"BK-JIMWLK"

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2$$

↓

Non-linear *recombination* corrections
are demanded by UNITARITY



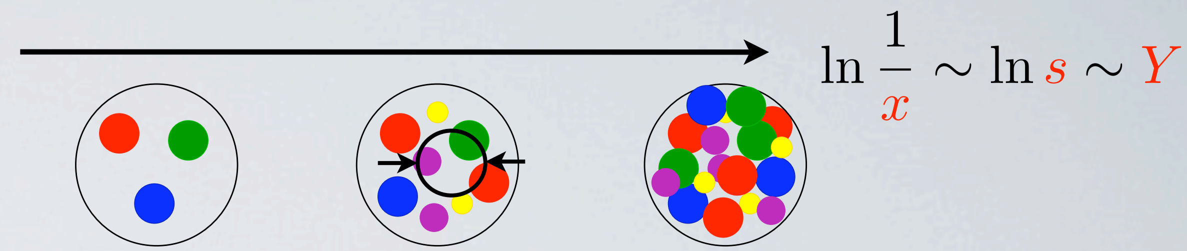
Saturation scale: transverse momentum scale which marks the onset of non-linear corrections

$$\mathcal{K} \otimes \phi(x, Q_s) \approx \phi(x, Q_s)^2$$

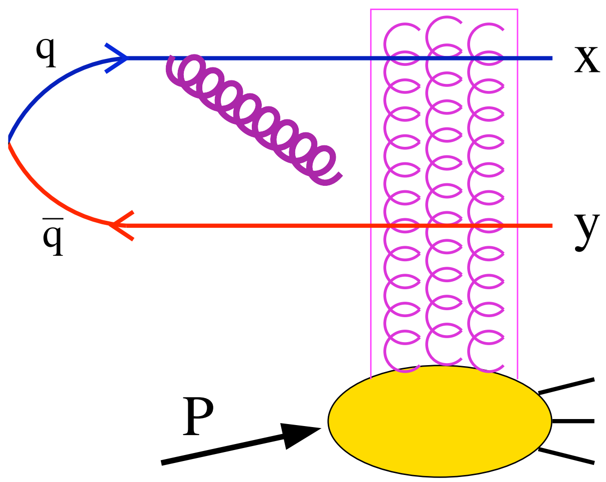
Nuclear enhancement: $Q^2_{sA} \approx A^{1/3} Q^2_{sp}$

CGC evolution: The BK equation

Balitsky 96, Kovchegov 99



(large-Nc limit of full JIMWLK evolution)



$$S(\underline{x}, \underline{y}; Y) = \frac{1}{N_c} \langle \mathrm{tr}\{U_{\underline{x}} U_{\underline{y}}^{\dagger}\} \rangle_Y = 1 - \mathcal{N}(\underline{x}, \underline{y}; Y)$$

unintegrated WW gluon distribution:

$$\varphi(x, k_t) = \int \frac{d^2 r}{2\pi\, r^2}\, e^{i\mathbf{k}\cdot\mathbf{r}} \mathcal{N}(r, x)$$

Increase the collision energy and resum small-x gluon radiation

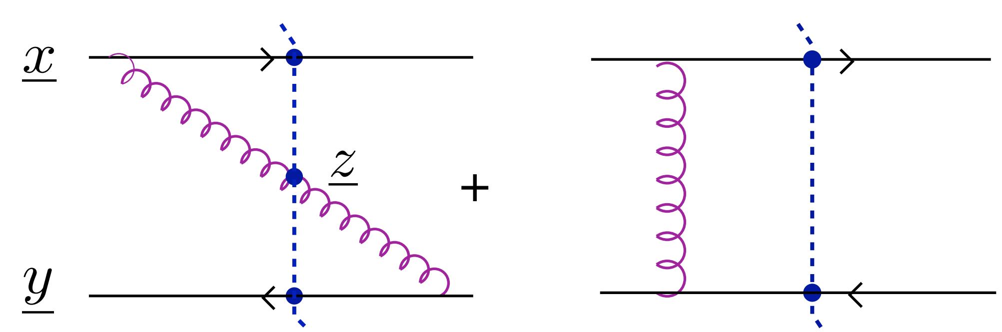
$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2 r_1\, K(r, r_1, r_2)\, [\mathcal{N}(r_1, x) + \mathcal{N}(r_2, x) - \mathcal{N}(r, x) - \mathcal{N}(r_1, x)\mathcal{N}(r_2, x)]$$

perturbative kernel

non-linear term

⇒ The kernel: probability of small-x gluon emission at leading-logarithmic accuracy in $\alpha_s \ln(1/x)$:

$$K(\underline{x}, \underline{y}, \underline{z}) = \frac{\alpha_s N_c}{2\pi^2} \frac{(\underline{x} - \underline{y})^2}{(\underline{x} - \underline{z})^2 (\underline{z} - \underline{y})^2} =$$



+ all possible permutations

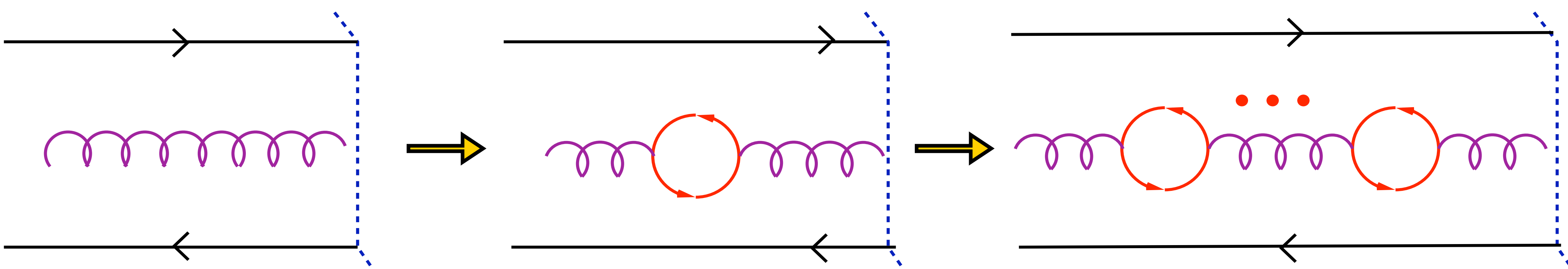
✓ NLO corrections to BK-JIMWLK equations have been calculated recently (Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al). Phenomenological tool: The BK equation including only running coupling corrections in Balitsky's scheme grasps most of the NLO corrections (JLA-Kovchegov)

BK eqn: $$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2r_1\, K(r,r_1,r_2)\left[\mathcal{N}(r_1,x)+\mathcal{N}(r_2,x)-\mathcal{N}(r,x)-\mathcal{N}(r_1,x)\mathcal{N}(r_2,x)\right]$$

Running coupling kernel: $$K^{\rm run}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\,r_2^2}+\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)}-1\right)+\frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)}-1\right)\right]$$

LO: $\alpha_s \ln(1/x)$
small-x gluon emission

"NLO": $\alpha_s N_f$
Quark loops resummed to all orders

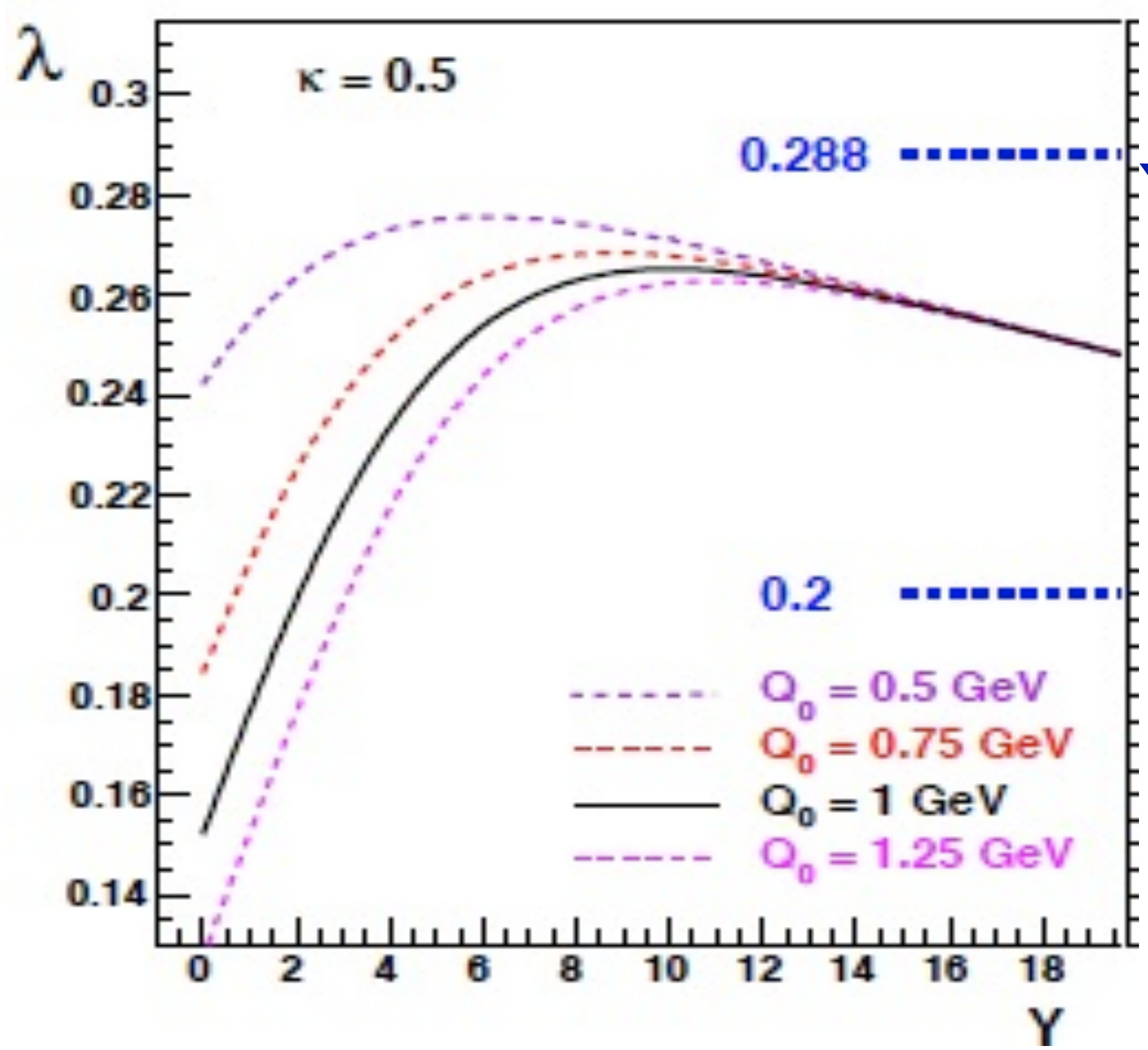


Gluon contribution: $N_f \to -6\pi\beta_2$

Running coupling corrections are large, rendering evolution compatible with experimental data.

$$\lambda(Y) = \frac{d \ln Q_s(Y)}{dY}$$

$$\lambda^{LO} \approx 4.8\,\alpha_s$$



values compatible with DIS and HIC data

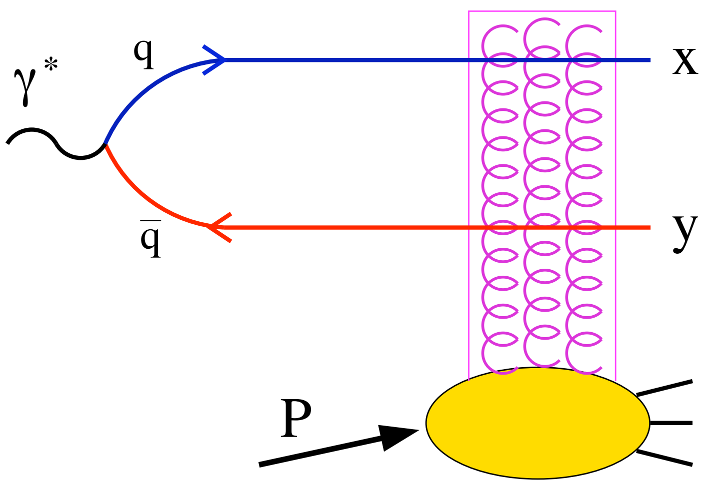
Free parameters in the (x,kt)-dependence of unintegrated gluon distributions corresponds to freedom in the choice of initial conditions:

MV + "anomalous dimension"

$$\mathcal{N}(r, x = x_0) = 1 - \exp\left[-\frac{\left(r^2\, Q_{s0}^2\right)^{\gamma}}{4} \ln\left(\frac{1}{r\,\Lambda} + e\right)\right]$$

AAMQS Fits to e+p data:

JLA, N. Armesto, J.G. Milhano, P Quiroga and C. Salgado



$$\sigma_{T,L}^{\gamma^* h}(x, Q^2) = \sum_{flavours} \int d^2 r \int_0^1 dz \left| \Psi_{T,L}^{f,\gamma^* \to q\bar{q}}(z, r, Q^2) \right|^2 \sigma^{dip}(r, x)$$

QED piece

Strong interactions are here

⇒ dipole cross section: $\sigma^{dip}(r, x) = 2 \int d^2 b \mathcal{N}(b, r, x) \approx \sigma_0 \mathcal{N}(b, r, x)$

⇒ Experimental data: ZEUS & H1 (HERA) combined data on reduced cross sections + older NMC (CERN-SPS) and E665 (Fermilab) coll. at $x < x_0 = 10^{-2}$ and $Q^2 < 50$ GeV^2

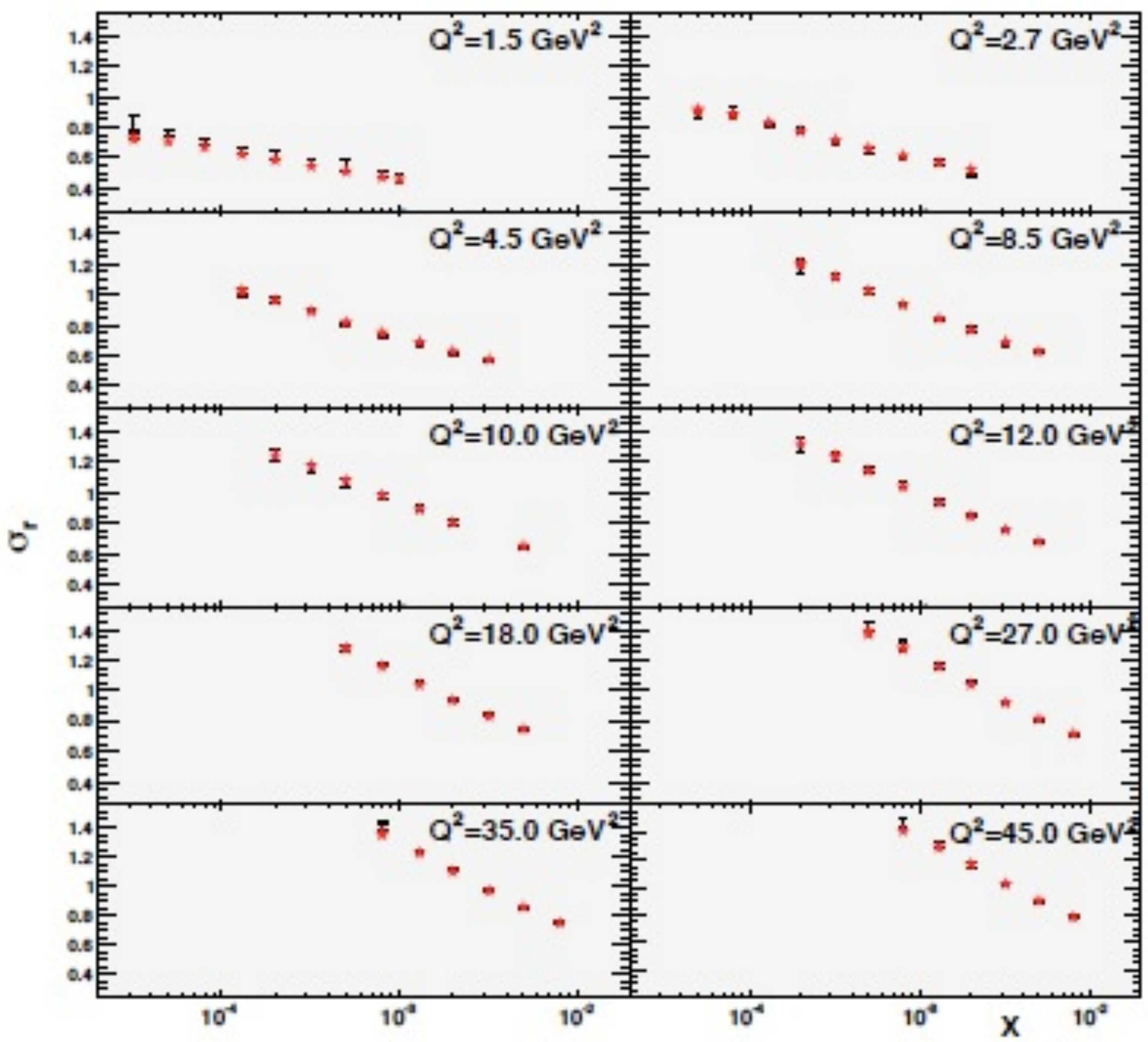
⇒ Regularization of the coupling:

$$\alpha_s(r^2) = \frac{12\,\pi}{(11\, N_c - 2\, N_f)\ln\left(\frac{4\, C^2}{r^2\, \Lambda_{QCD}}\right)} \quad \text{for } r < r_{fr}, \text{ with } \alpha_s(r_{fr}^2) \equiv \alpha_{fr} = 0.7$$

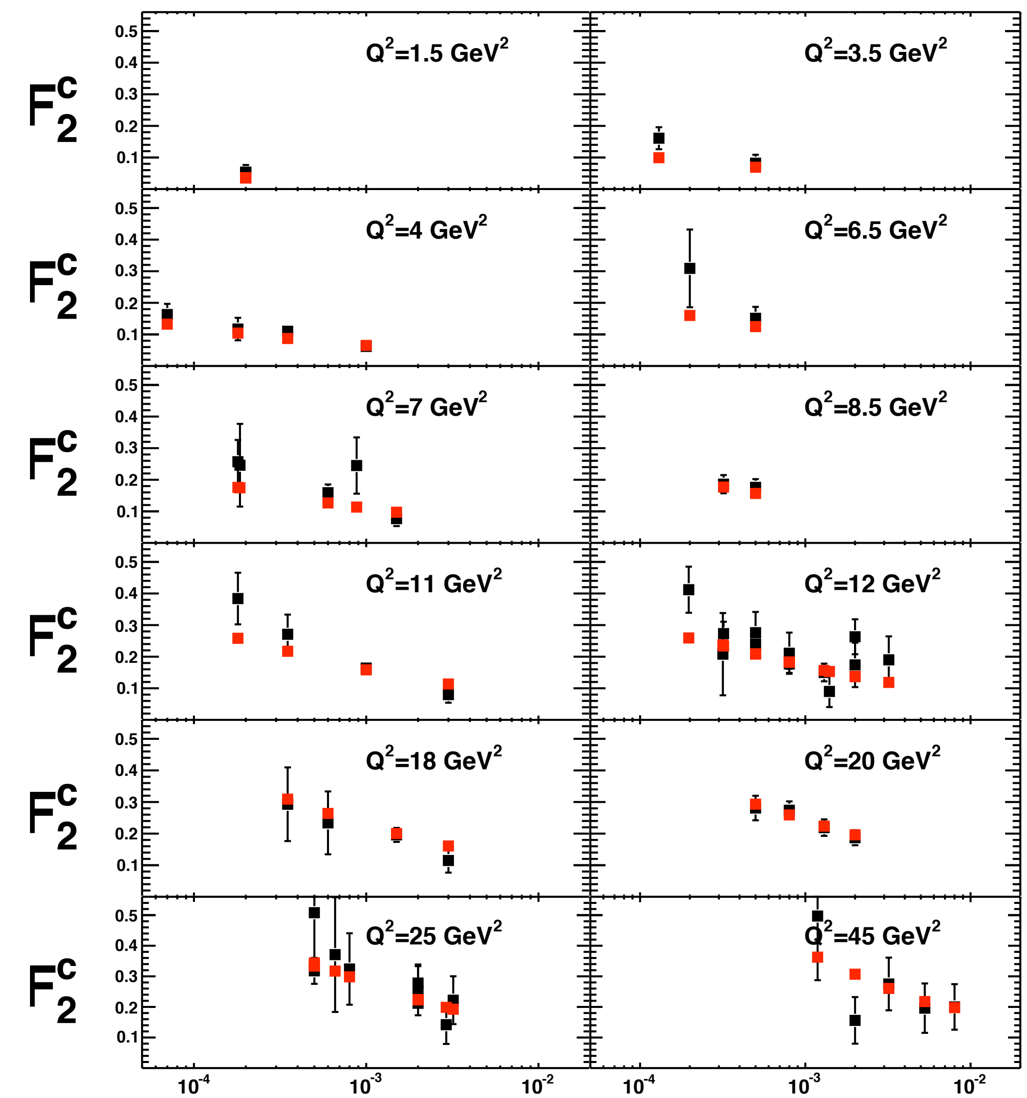
⇒ Charm contribution: Including charm in the sum over flavors we are account for charm contribution (~10% of total e+p cross section) and also describe available data on F_{2c} (extra parameters).

Variable flavour number scheme for the running of the coupling

Reduced cross section



Charm structure function

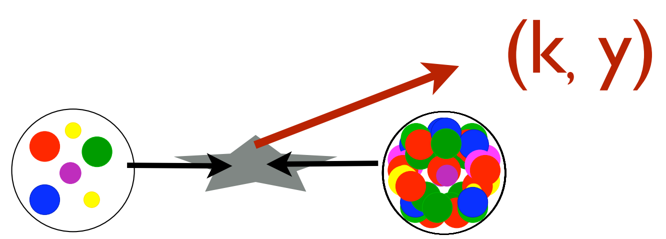


	fit	$\frac{\chi^2}{d.o.f}$	Q^2_{s0}	σ_0	γ	Q^2_{s0c}	σ_{0c}	γ_c	C	m_l^2
	MV									
e	$\alpha_{fr}=0.7$	1.395	0.1673	36.032	1.355	0.1650	18.740	1.099	3.813	fixed
f	$\alpha_{fr}=0.7$	1.244	0.1687	35.449	1.369	0.1417	19.066	1.035	4.079	1.445E-2
g	$\alpha_{fr}=1$	1.325	0.1481	40.216	1.362	0.1378	13.577	0.914	4.850	fixed
h	$\alpha_{fr}=1$	1.298	0.156	37.003	1.319	0.147	19.774	1.074	4.355	1.692E-2

d+Au and p+p collisions at RHIC

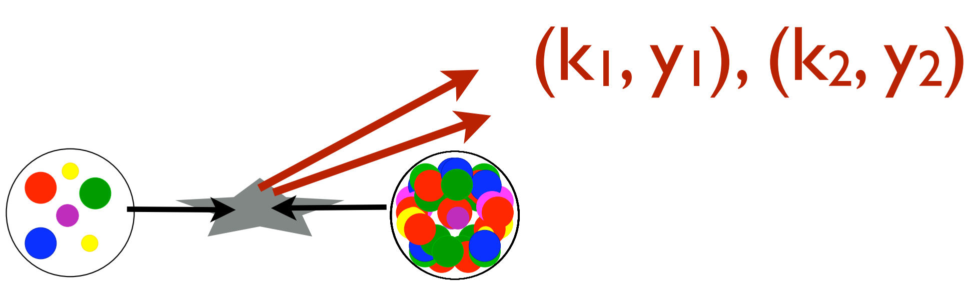
RHIC Kinematics:

- single particle production: Small-x ~ forward production



$$x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$$

- double inclusive production: Small-x ~ two particles in the forward region!



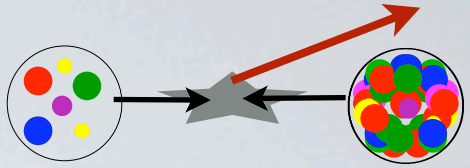
$$x_p = \frac{|k_1| e^{y_1} + |k_2| e^{y_2}}{\sqrt{s}}$$

$$x_A = \frac{|k_1|\, e^{-y_1} + |k_2|\, e^{-y_2}}{\sqrt{s}}$$

At RHIC energies, forward measurements needed to isolate small-x (<0.01) effects

⇒ Forward hadron production in the CGC

(Dumitru, Jalilian-Marian)



large-x parton from proj. (pdf)

small-x glue from target (CGC)

$$\frac{dN_h}{dy_h\, d^2p_t} = \frac{K}{(2\pi)^2} \sum_q \int_{x_F}^1 \frac{dz}{z^2} \left[x_1 f_{q\,/\,p}(x_1, p_t^2)\, \tilde{N}_F\left(x_2, \frac{p_t}{z}\right) D_{h\,/\,q}(z, p_t^2) \right.$$
$$\left. + \, x_1 f_{g\,/\,p}(x_1, p_t^2)\, \tilde{N}_A\left(x_2, \frac{p_t}{z}\right) D_{h\,/\,g}(z, p_t^2) \right]$$

→ fragmentation

Unintegrated gluon from running coupling BK

$$\tilde{N}_{F(A)}(x, k) = \int d^2\mathbf{r}\, e^{-i\mathbf{k}\cdot\mathbf{r}} \left[1 - \mathcal{N}_{F(A)}(r, Y = \ln(x_0/x))\right]$$

MV Initial conditions:

$$\mathcal{N}(r, x = x_0) = 1 - \exp\left[-\frac{r^2\, Q_0^2}{4} \ln\left(\frac{1}{r\,\Lambda} + e\right)\right]$$

JLA & C. Marquet 10

Two free parameters: (x_0, Q_0)

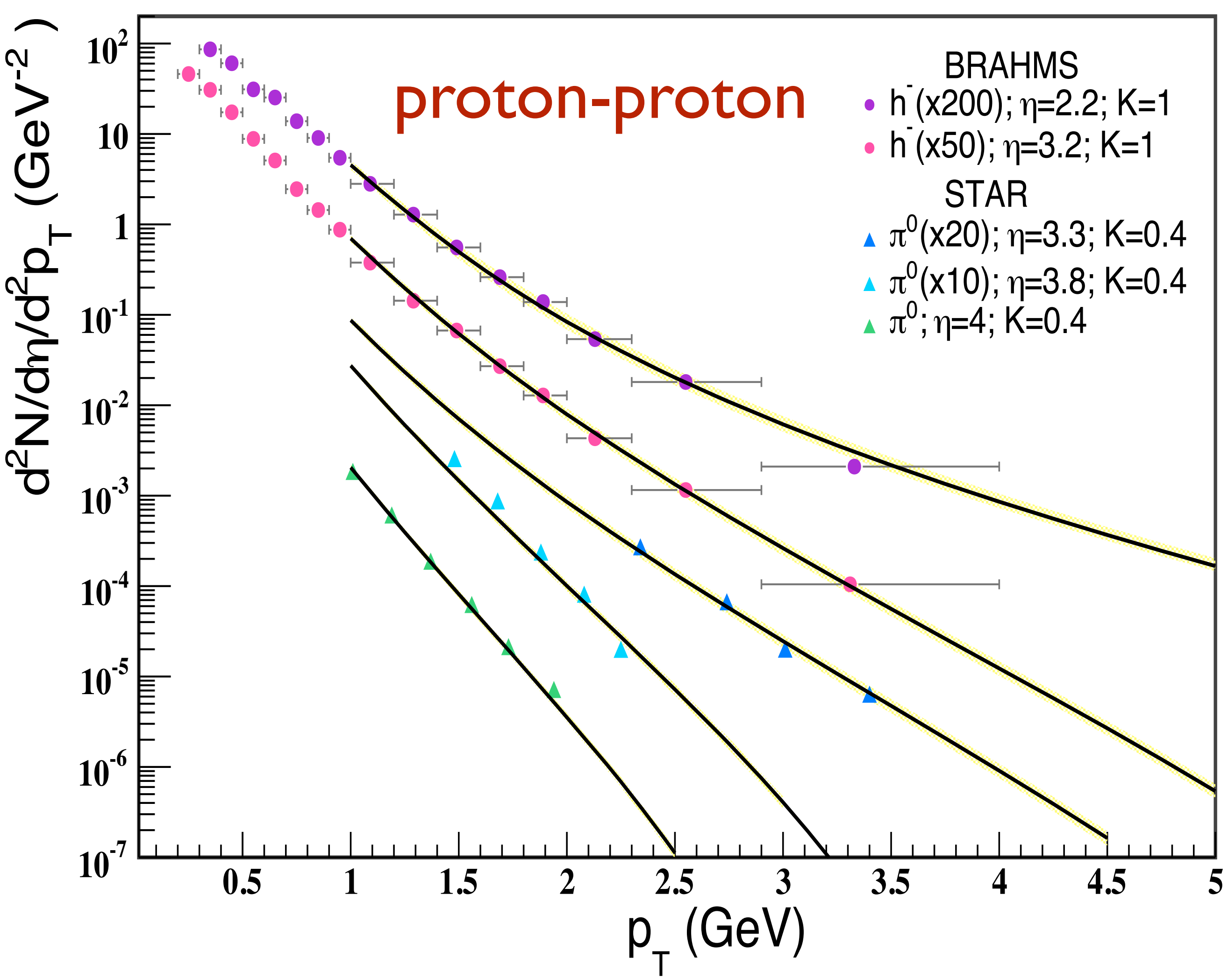
We use CTEQ6 pdf's and de Florian-Sassot ff's

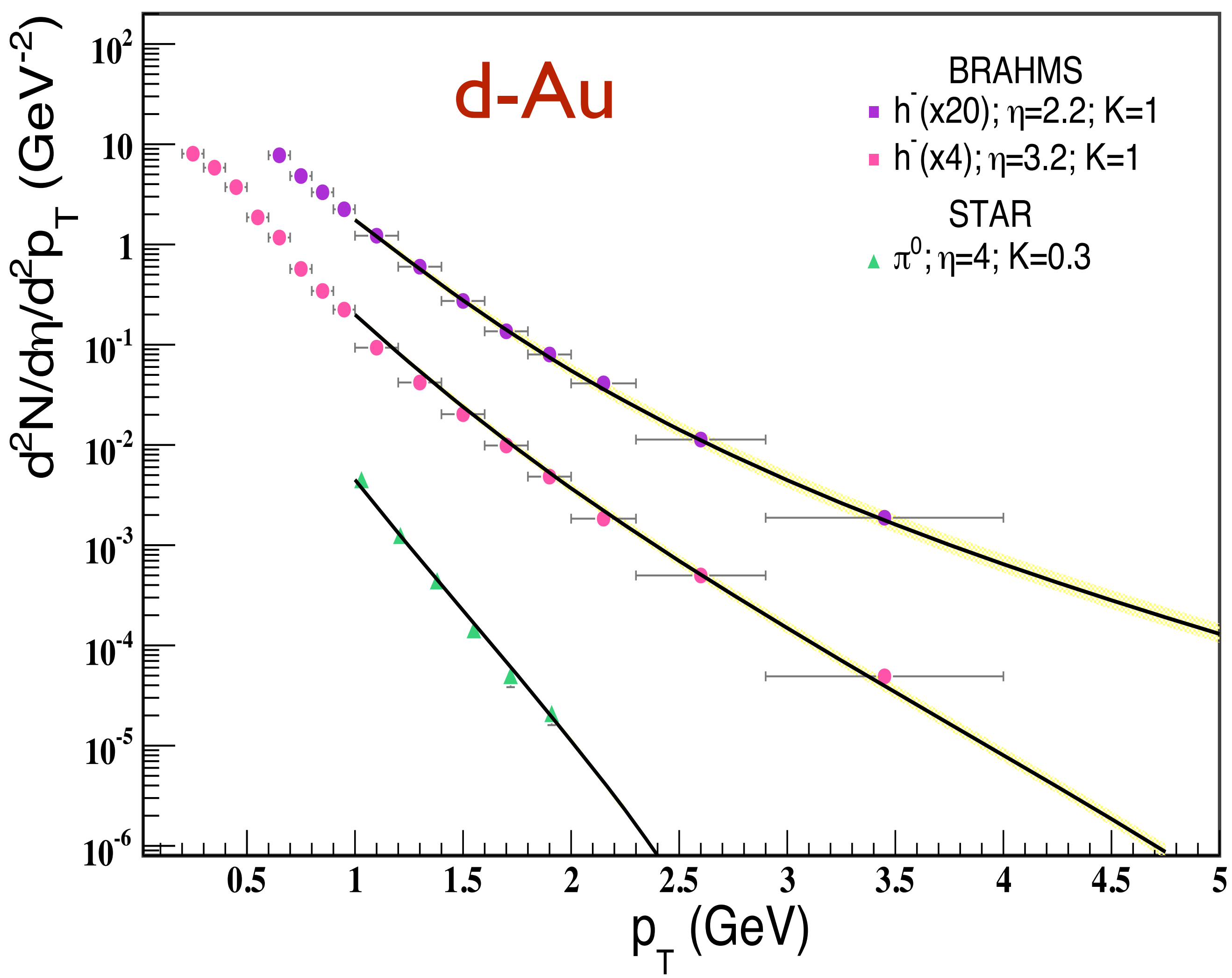
Alternative approaches: Modelization of quantum corrections

(Dumitru-JalilianMarian-Hayashigaki; De Boer-Utermann-Wessels; Goncalves et al; Kharzeev-Kovchegov-Tuchin)

Comparison to RHIC forward data [JLA, C. Marquet '10]

- Very good description of forward yields in proton+proton and d+Au collisions
- K=1 for h$^-$. K=0.4 (0.3) for neutral pions in p+p (d+Au) ??
- Energy loss related to high-xF effects not taken into account





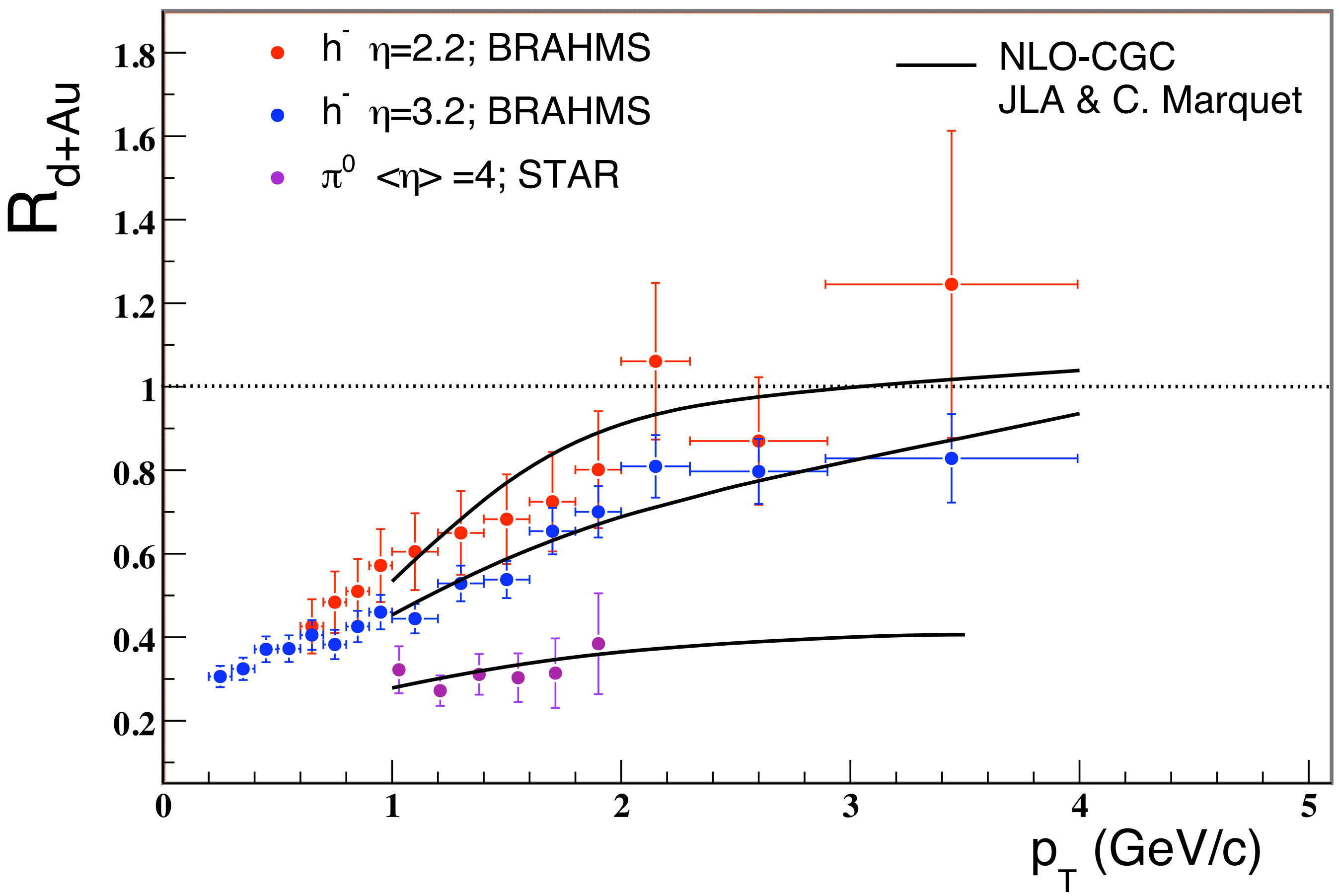
$$0.005 \leq x_0 \leq 0.01$$
$$Q^2_{s0} = 0.2\,\mathrm{GeV}^2$$

$$0.01 \leq x_0 \leq 0.025$$
$$Q^2_{s0} = 0.4\,\mathrm{GeV}^2$$
$$Q^2_{s0\,gluon} = 0.9\,\mathrm{GeV}^2$$

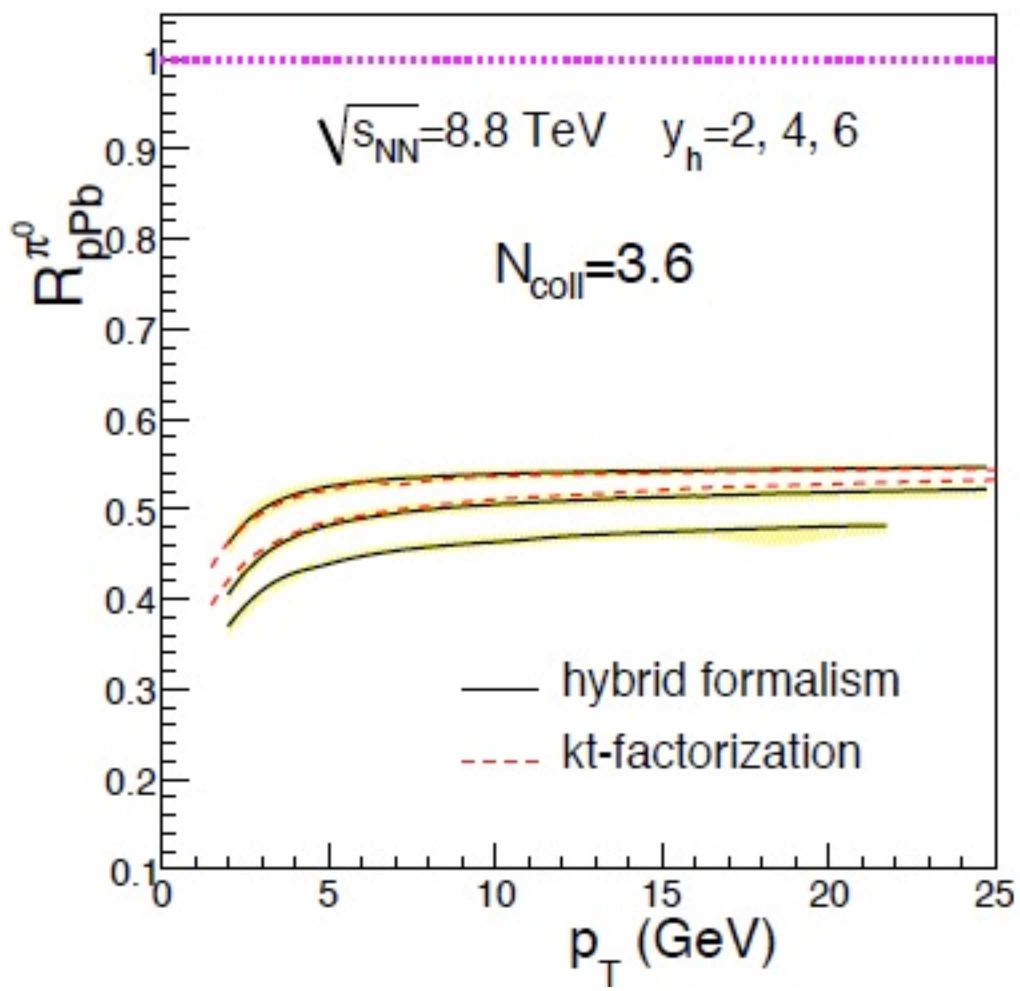
$$0.005 \leq x_0 \leq 0.01$$
$$Q^2_{s0} = 0.5\,\mathrm{GeV}^2$$
$$Q^2_{s0,\,gluon} = 1.125\,\mathrm{GeV}^2$$

- ...by simply taking the ratio of d+Au and p+p spectra we get a good description of the nuclear modification factor (not a trivial statement!!)

RHIC d+Au



LHC p+Pb

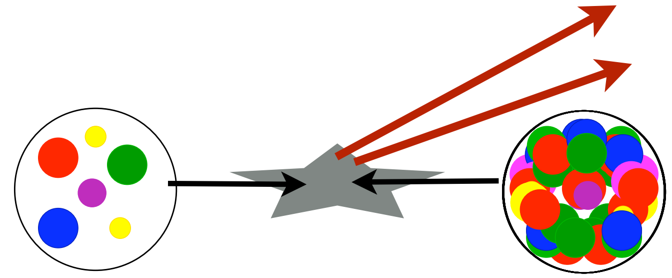


- We predict a similar suppression in p+Pb collisions at the LHC already at central rapidities

⇒ Double Inclusive forward hadron production in the CGC

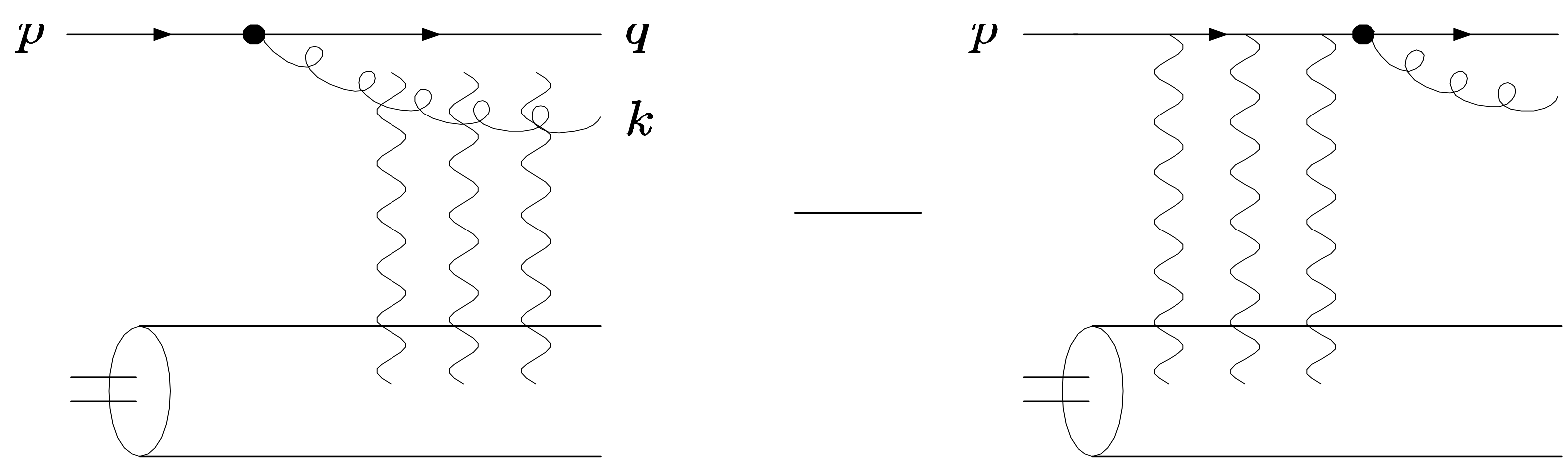
$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

$$x_A = \frac{|k_1|\,e^{-y_1} + |k_2|\,e^{-y_2}}{\sqrt{s}}$$



$(k_1, y_1), (k_2, y_2)$

Cyrille Marquet 07:



hard quark initiating scattering

Fourier transfrom coordinate space to momentum

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

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

$$-S^{(3)}_{\bar{q}gq}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{x}',\mathbf{b}';x_A] + S^{(2)}_{q\bar{q}}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]\Big\}$$

q-> qg splitting (pQCD)

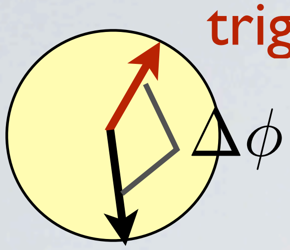
Scattering of the 2-parton system with the CGC target

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

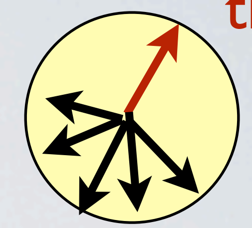
Involves more than 3 and 4 point functions. Calculated in the large Nc limit

⇒ "Monojets" in d+Au collisions at RHIC at forward rapidity

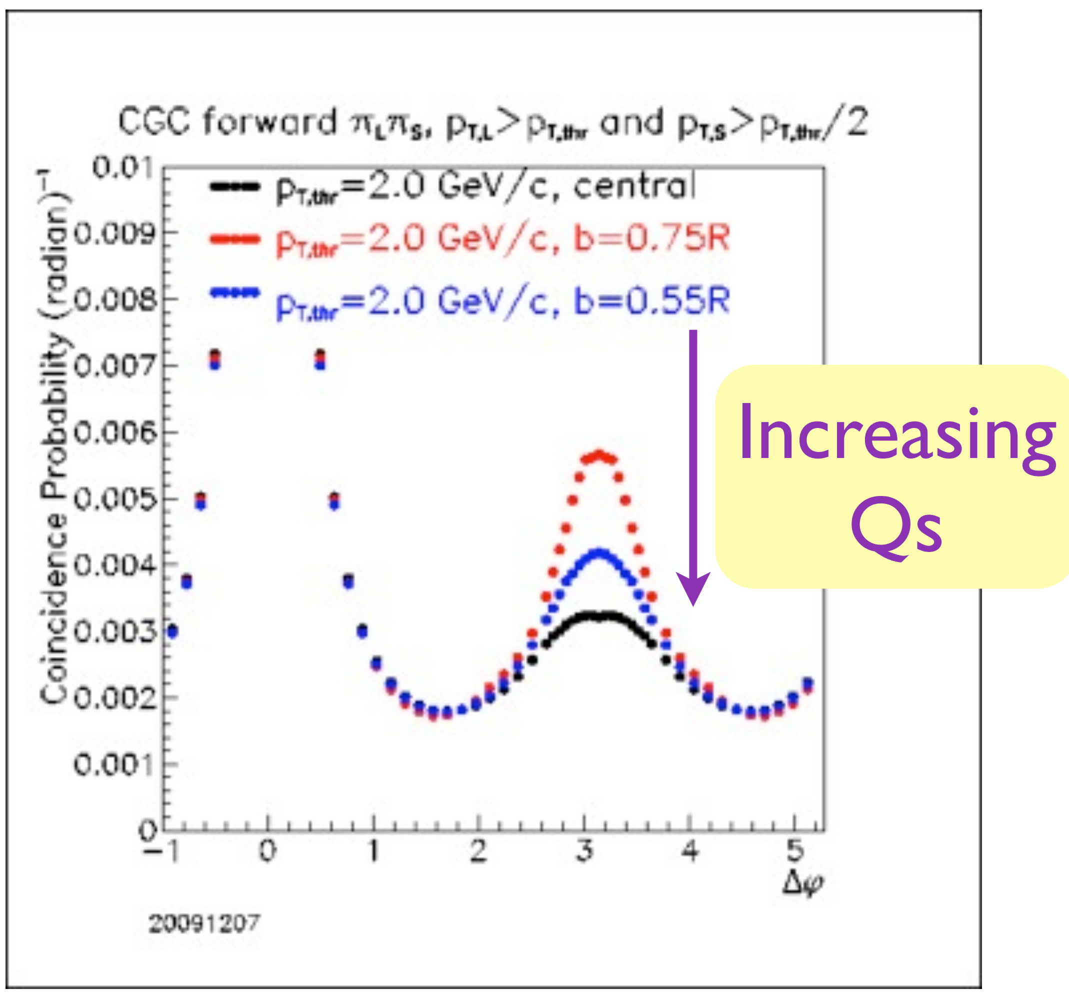
➡ "Coincidence probability" measured by STAR Coll. at forward rapidities:



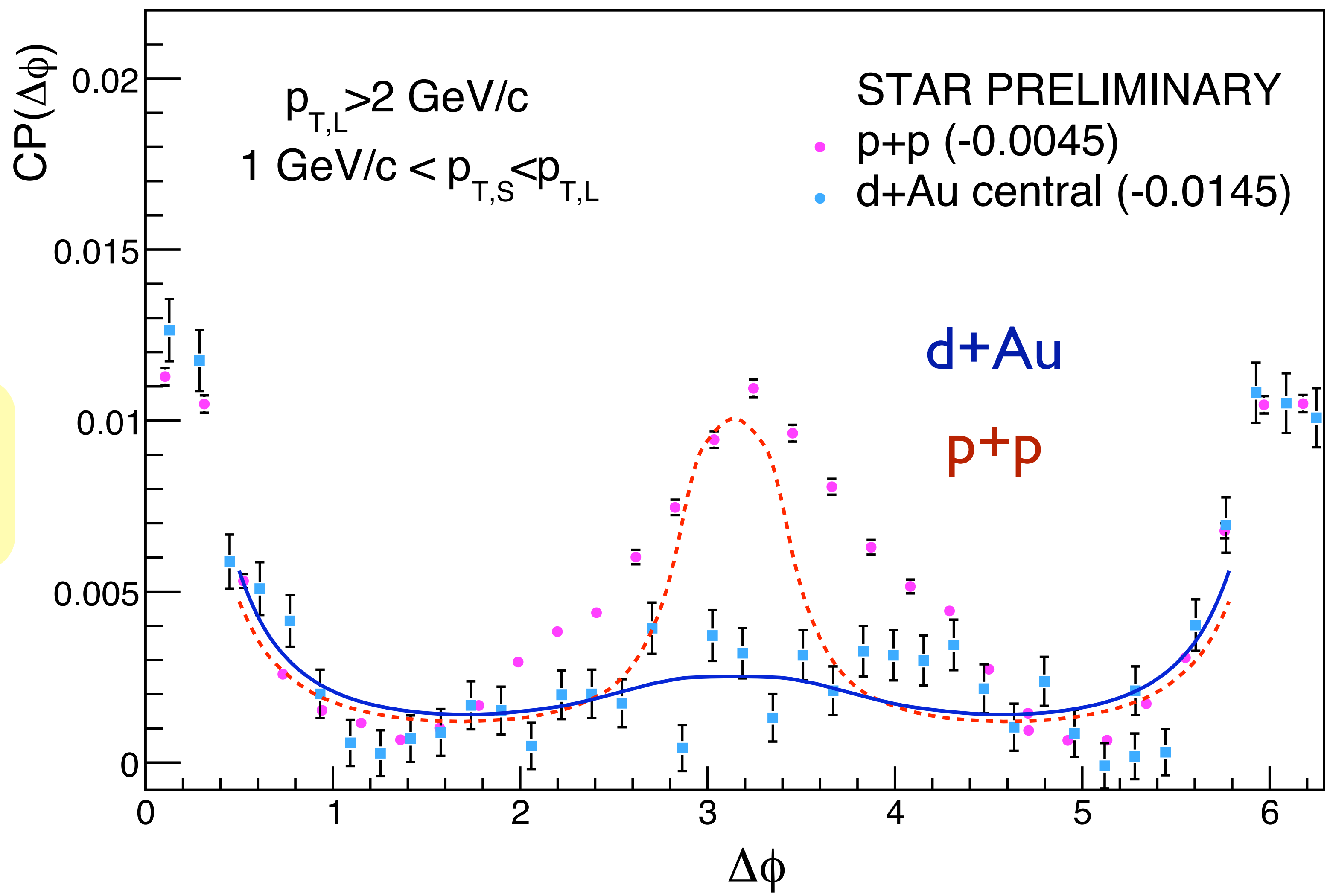
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$



➡ Dependence on the saturation scale of the target (centrality)



[JLA C. Marquet 10]

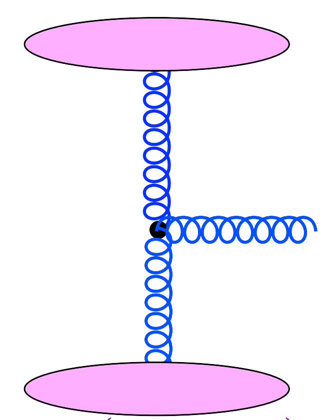


➡ Effect of enhanced pedestal due to double parton interactions not taken into account

Multiplicities at RHIC and the LHC

- Most of particles produced in the collision originate from small-x gluons in the saturation domain
- Other sources (genuinely soft processes, contribution from valence quarks etc) neglected
- Initial gluon production is calculated via kt-factorization and then mapped to final hadron spectra assuming local parton-hadron duality

"KLN model"



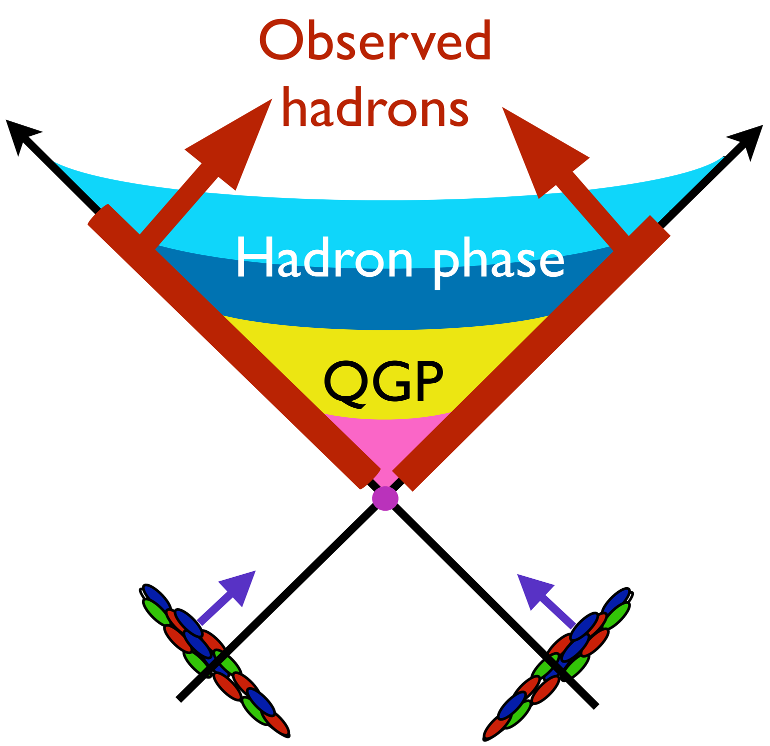
$$\frac{d\sigma^{A+B\to g}}{dy\, d^2p_t\, d^2R} = \kappa \frac{2}{C_F}\frac{1}{p_t^2}\int^{p_t}\frac{d^2k_t}{4}\int d^2b\, \alpha_s(Q)\, \varphi(\frac{|p_t+k_t|}{2}, x_1; b)\, \varphi(\frac{|p_t-k_t|}{2}, x_2; R-b)$$

$$x_{1(2)} = (p_t/\sqrt{s_{NN}})\exp(\pm y)$$

unintegrated gluon distributions

- Scaling toy model: N_part scaling:

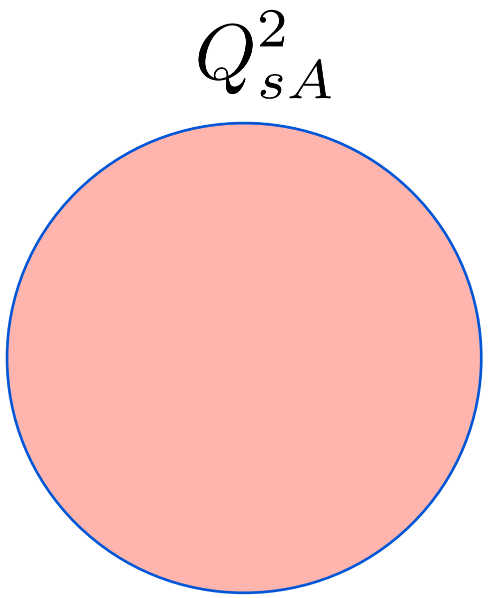
$$\left.\frac{dN_{AA}}{d\eta}\right|_{\eta=0} \propto Q_{sA}^2(\sqrt{s}, b) \sim \sqrt{s}^{\lambda}\, N_{part}$$



Nuclear geometry in rcBK approaches

JLA 2007

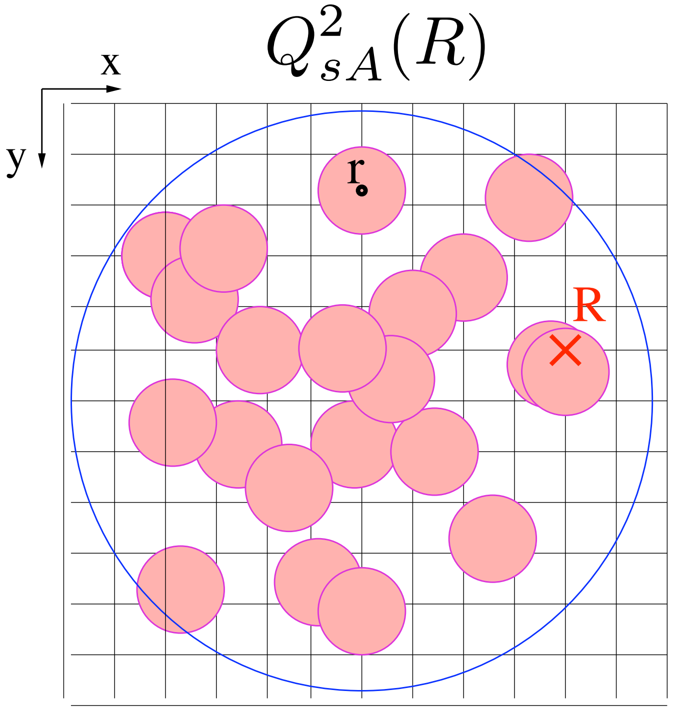
Homogeneous "disk" nucleus characterized by a single initial saturation scale, $Q_s^2 \sim 1\ \mathrm{GeV}^2$, adjusted to reproduce RHIC most central data



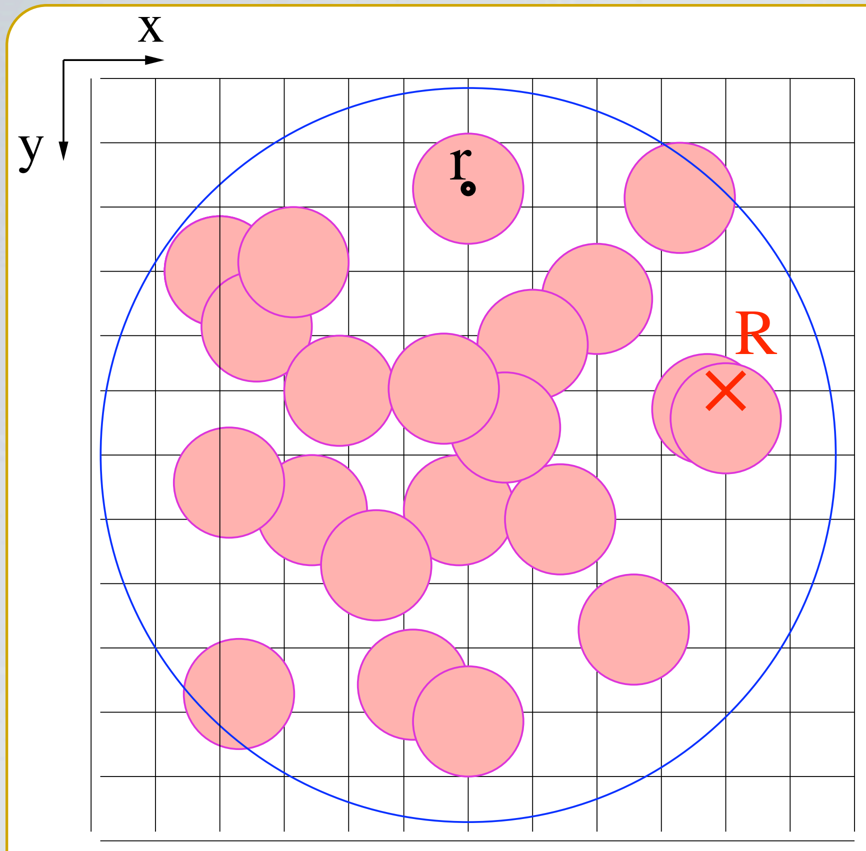
This approach underestimates data

JLA & Dumitru 2010

Monte Carlo treatment of nuclear geometry



rcBK Monte Carlo (JLA & Dumitru 2010)



1. Generate configurations for the positions of nucleons in the transverse plane (r_i, i=1...A). Wood-Saxons thickness function $T_A(R)$

2. Count the number of nucleons at every point in the transverse grid, R.

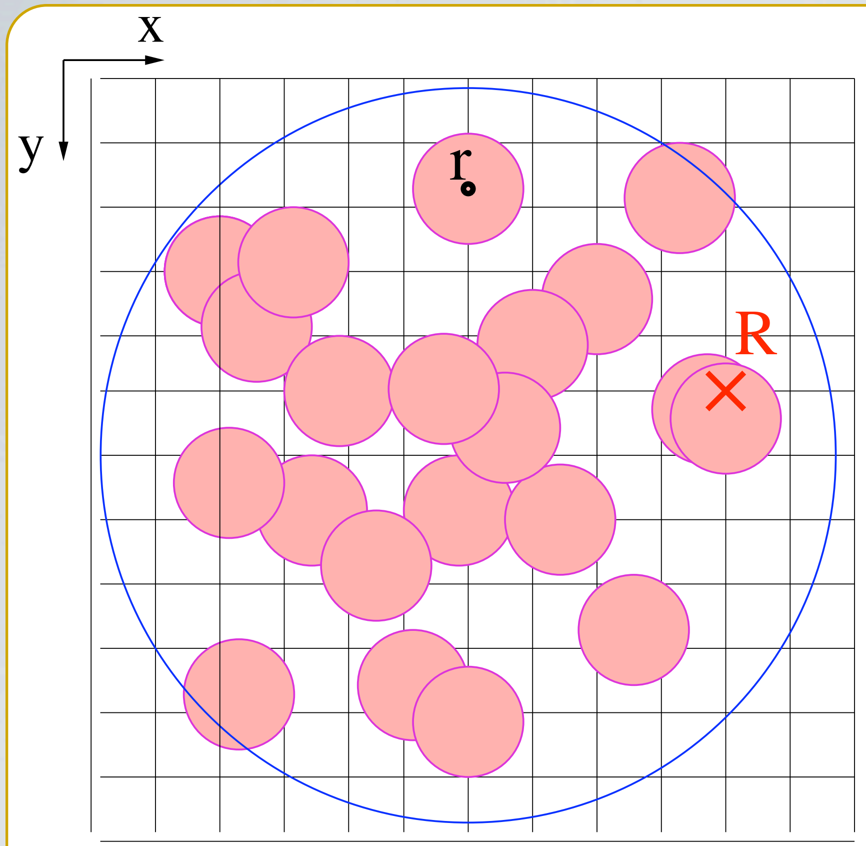
$$N(\mathbf{R}) = \sum_{i=1}^{A} \Theta\left(\sqrt{\frac{\sigma_0}{\pi}} - |\mathbf{R} - \mathbf{r_i}|\right) \qquad \sigma_0 \simeq 42 \text{ mb}$$

3. Assign a local initial ($x=x_0=0.01$) saturation scale at every point in the transverse grid, R:

$$Q_{s0}^2(\mathbf{R}) = N(\mathbf{R})\, Q_{s0,\,\text{nucl}}^2 \qquad Q_{s0,\,\text{nucl}}^2 = 0.2 \text{ GeV}^2;$$

$$\varphi(x_0 = 0.01, k_t, R) \xrightarrow{\text{rcBK equation}} \varphi(x, k_t, R)$$

rcBK Monte Carlo



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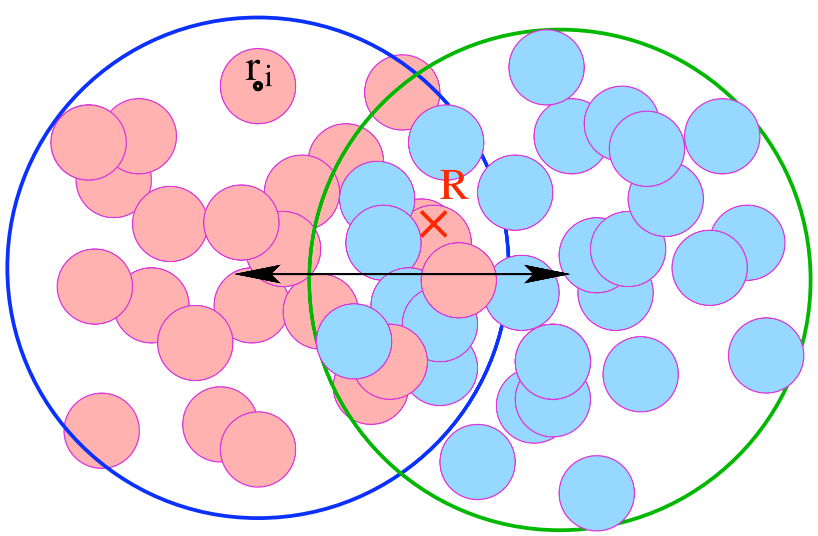
$$\varphi(x_0 = 0.01, k_t, R) \xrightarrow{\text{rcBK equation}} \varphi(x, k_t, R)$$

4. Gluon production is calculated at each transverse point according to kt-factorization

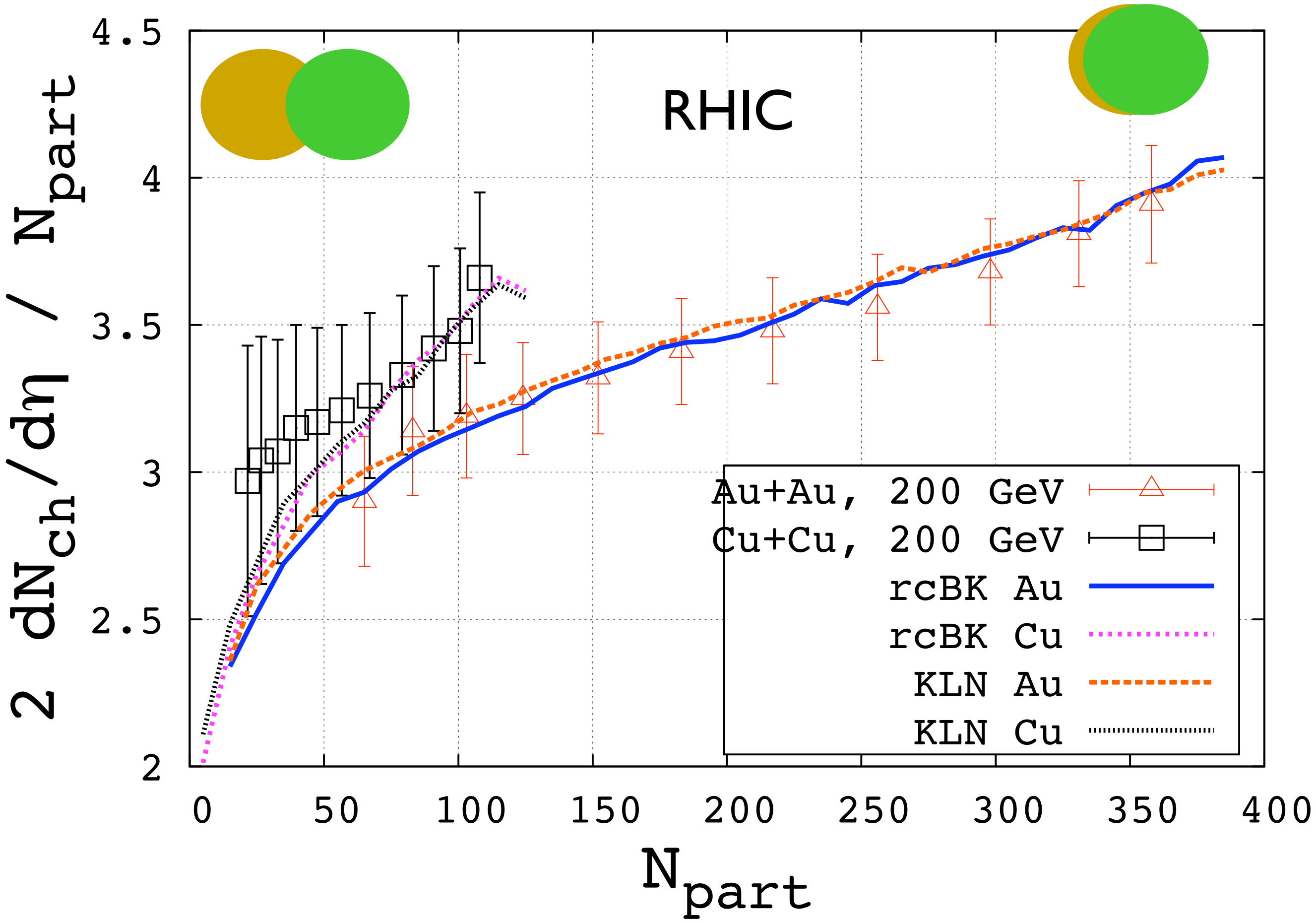


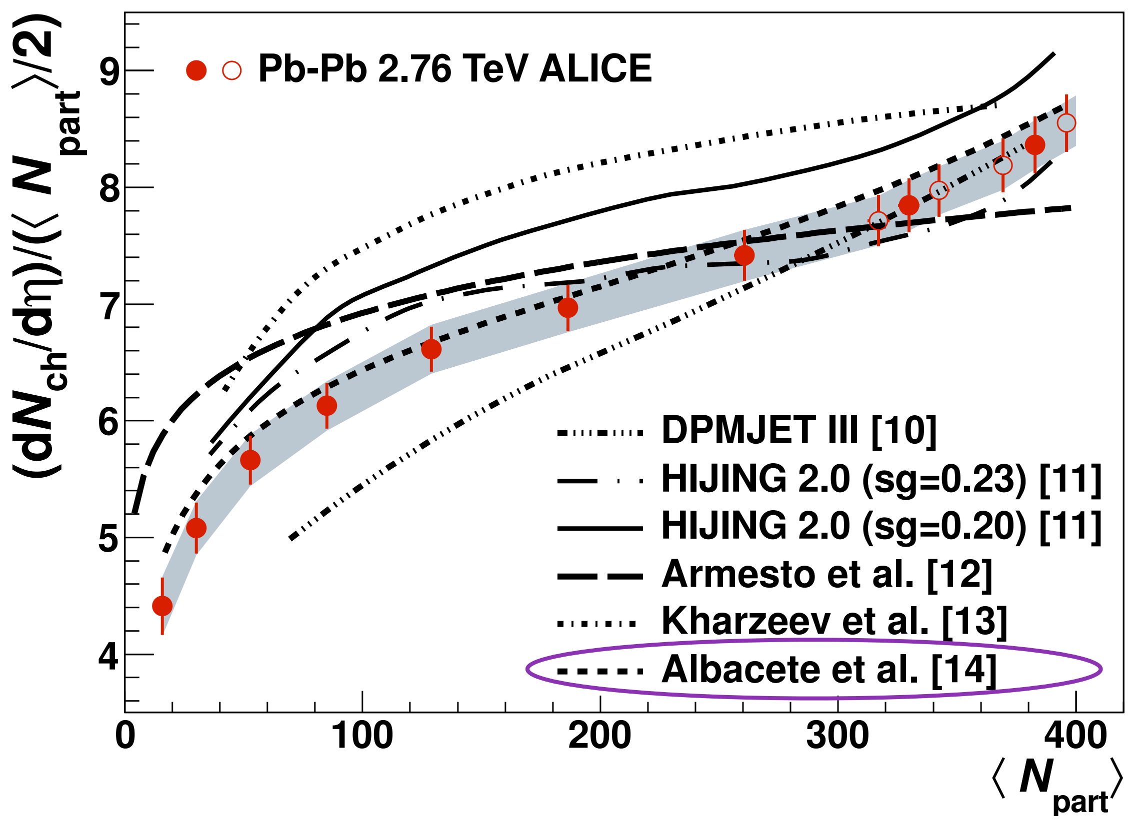
$$\frac{d\sigma^{A+B\to g}}{dy\, d^2p_t\, d^2R} = \kappa \frac{2}{C_F} \frac{1}{p_t^2} \int^{p_t} \frac{d^2k_t}{4} \int d^2b\, \alpha_s(Q)\, \varphi\left(\frac{|p_t + k_t|}{2}, x_1; b\right) \varphi\left(\frac{|p_t - k_t|}{2}, x_2; R - b\right)$$

$$\frac{dN_{\text{ch}}}{d\eta} = \frac{\cosh\eta}{\sqrt{\cosh^2\eta + m^2/P^2}} \frac{dN_{\text{ch}}}{dy} \qquad m = 350 \text{ MeV and } P = 400 \text{ MeV}$$

rcBK Monte Carlo

MV initial conditions: Good description of Npart dependence of RHIC Au+Au and Cu+Cu and LHC Pb+Pb multiplicities:



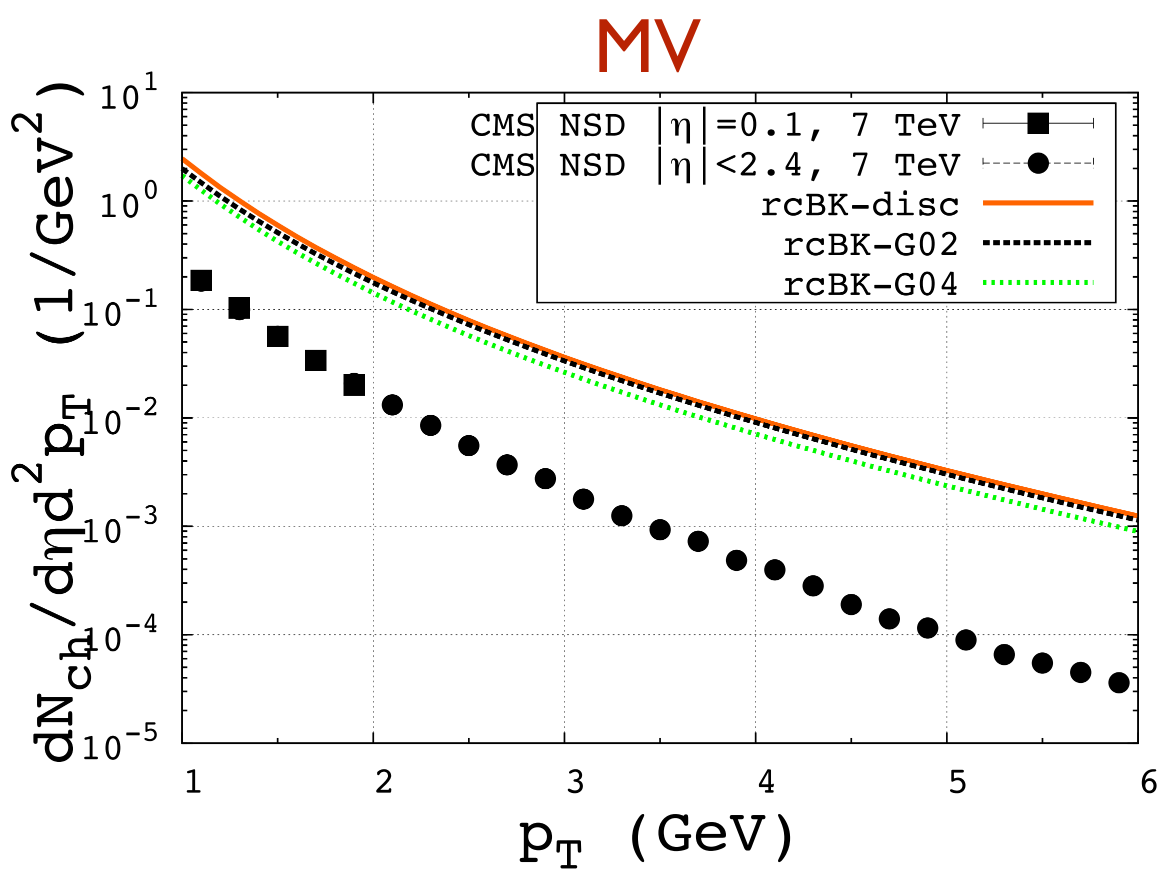


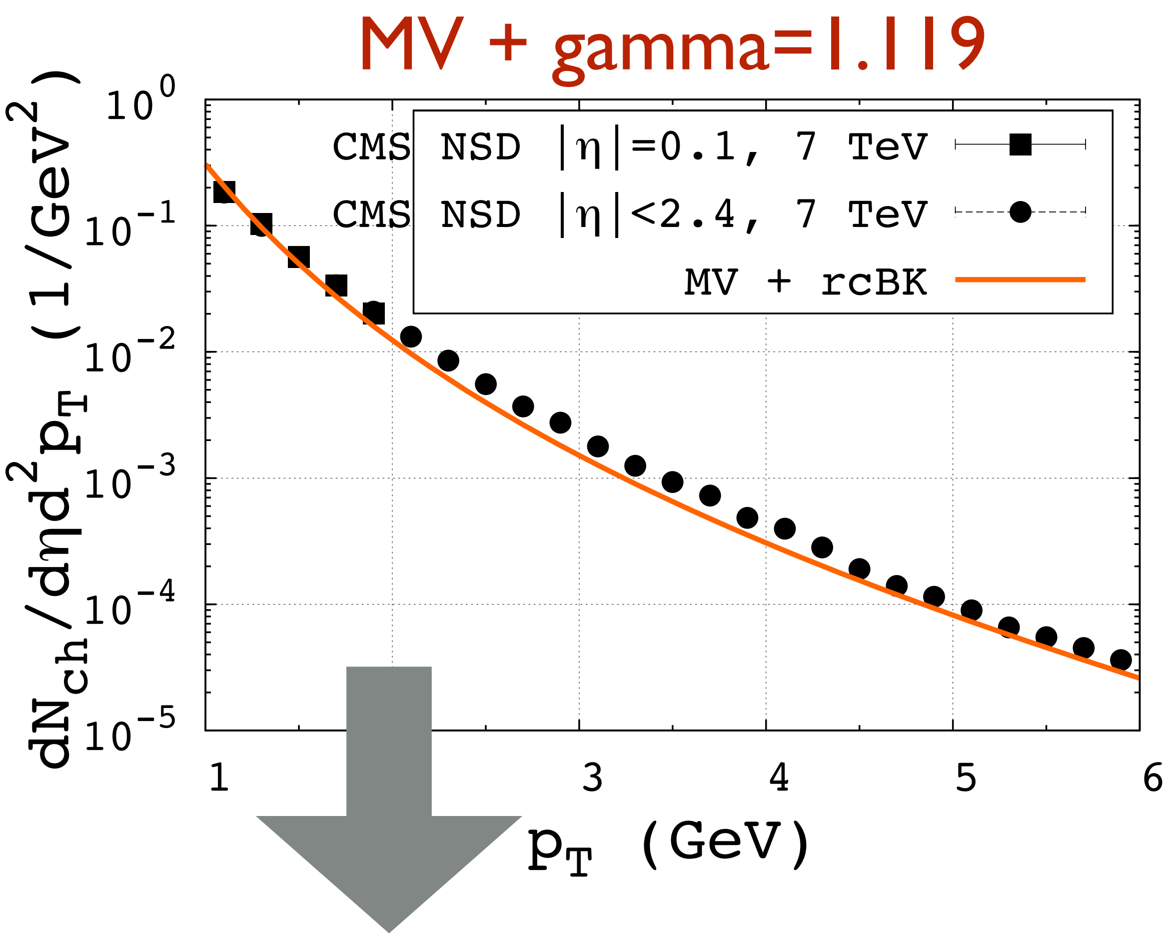
- Systematics: Changing the model parameters (average hadron mass, pt-cutoff ...) yield an equally good description of RHIC and LHC data by just adjusting the normalization (i.e the gluon to hadron ratio)

$$\kappa \approx 4.5 \div 7$$

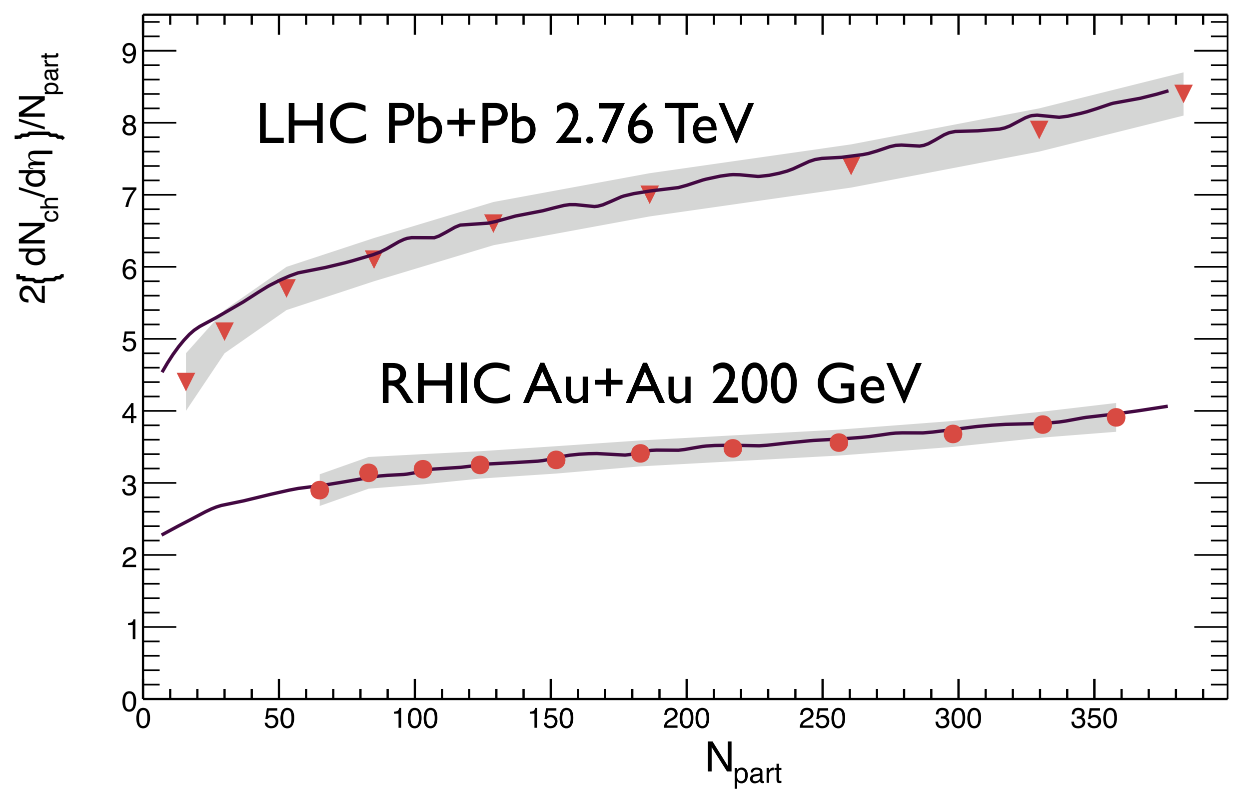
Constraining the initial conditions: p+p yields at the LHC

Steeper initial conditions than the MV model are needed to get a good description of p+p yields





Steeper initial conditions also provide a good description of RHIC and LHC multiplicity data:



Conclusions

- Running coupling corrections bring the CGC to a new period of quantitative and predictive phenomenology

- The CGC at its present degree of accuracy consistently describes data in the small-x region for a variety of colliding systems (e+p, p+p d+Au)

- However:
  - Alternative physics scenarios have been proposed for those different observables
  - HERA and RHIC data probe a relatively small range of energy evolution.
  - LHC data should offer much more constraints to model
  - A first successful test: description of multiplicities

- Still, many things remain to be done to refine the CGC as a precise phenomenological tool...

Thanks!!!

Back up slides