Initial state effects in the Color Glass Condensate

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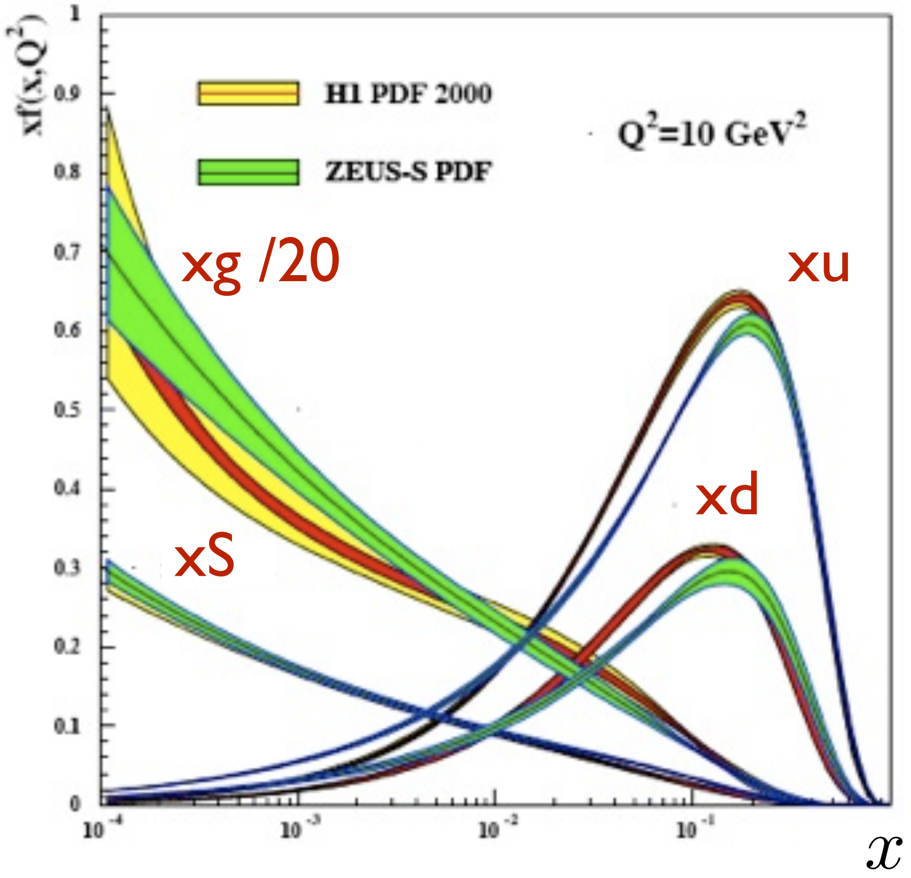
Outline

- ⇒ Motivation & Pocket Introduction to the CGC
- ⇒ Balitsky-Kovchegov equation including running coupling corrections
- ⇒ Single inclusive hadron production in the CGC
- ⇒ Multiplicities and di-hadron correlations in d+Au collisions
- ⇒ Heavy Quark production.

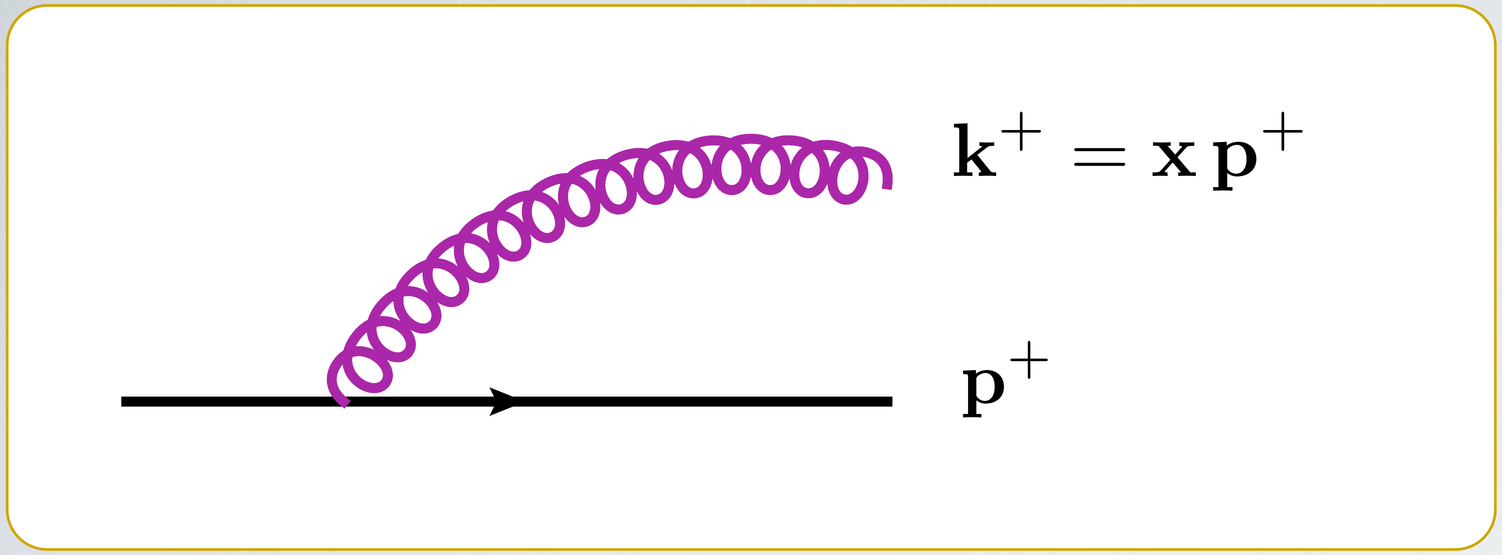
⇒ What do we know about the gluon distributions of hadrons at small values of Bjorken-x??

⇒ Empirical answer: They grow very strongly with decreasing x



proton pdf's measured in HERA

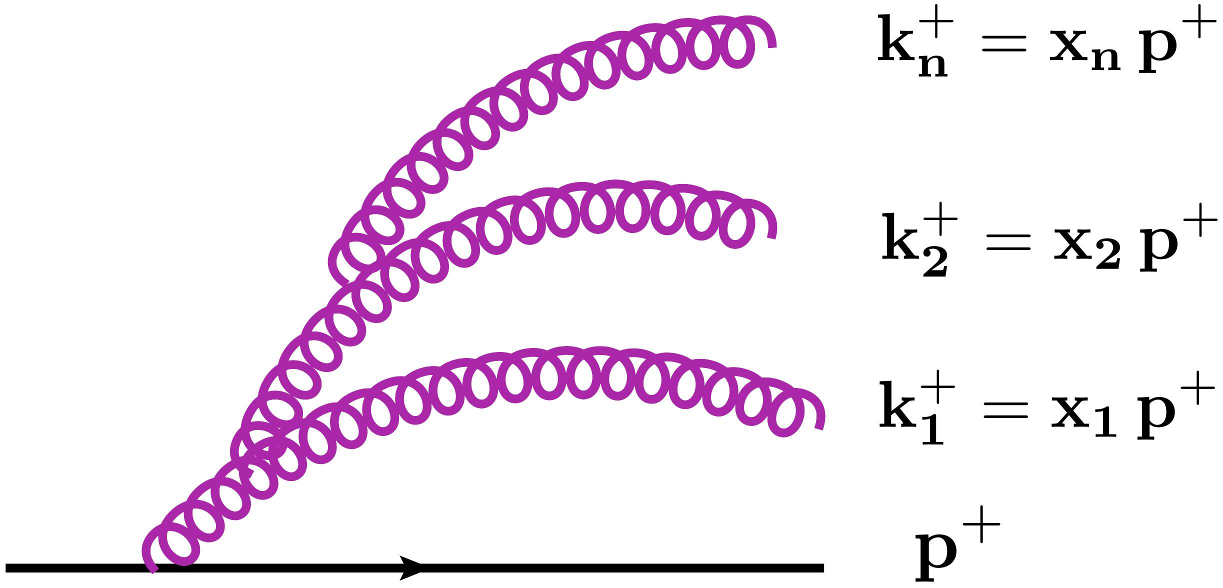
The wave function of an energetic valence parton gets dressed by quantum fluctuations



Probability of one soft gluon emission

$$\mathbf{dP} \propto \alpha_{\mathbf{s}} \frac{\mathbf{dx}}{\mathbf{x}}$$

Evolution equation: All orders resummation of soft gluon emissions



“BFKL”

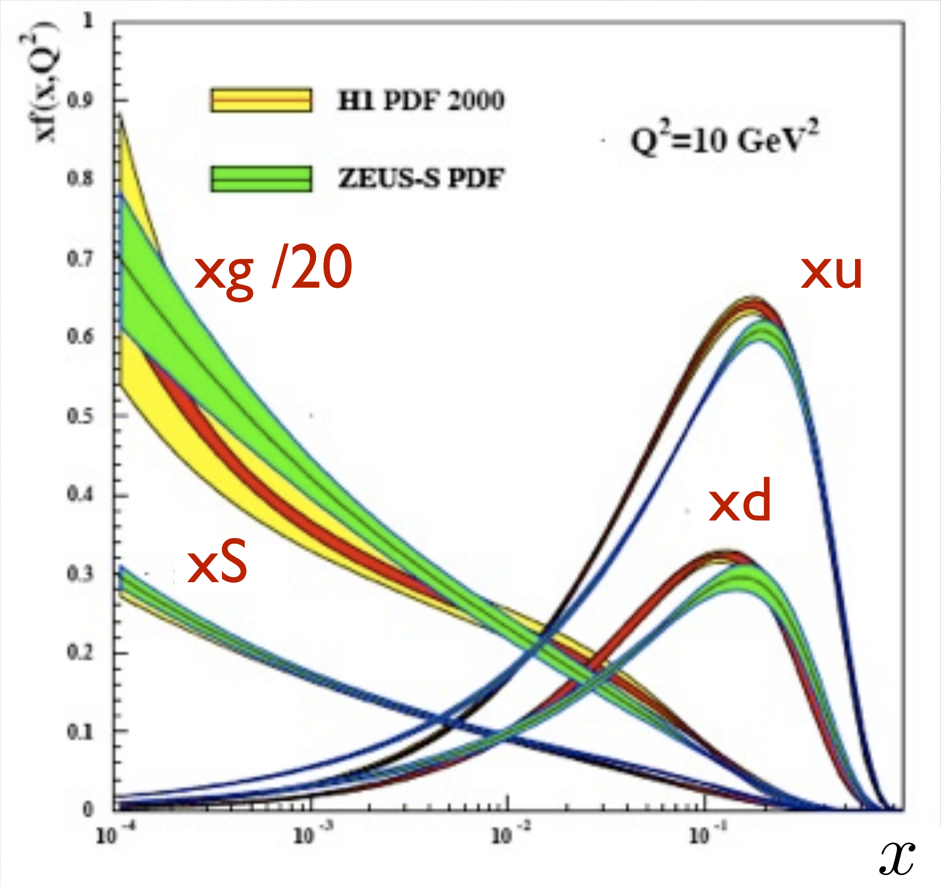
$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})$$

↓

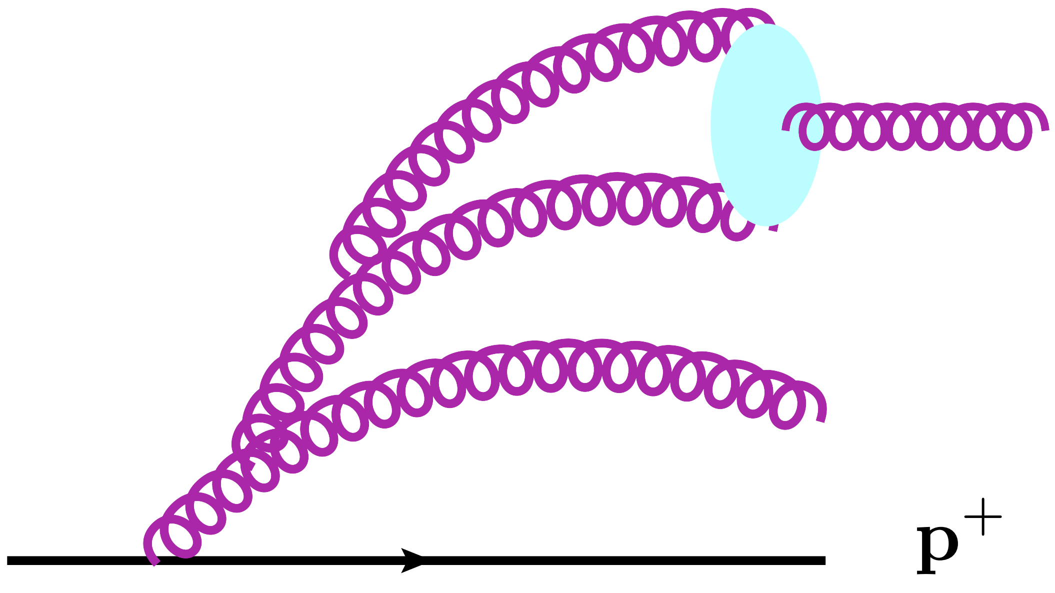
strong growth of gluon densities at small-x

Probability of n-soft gluon emission

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



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



"BK-JIMWLK"

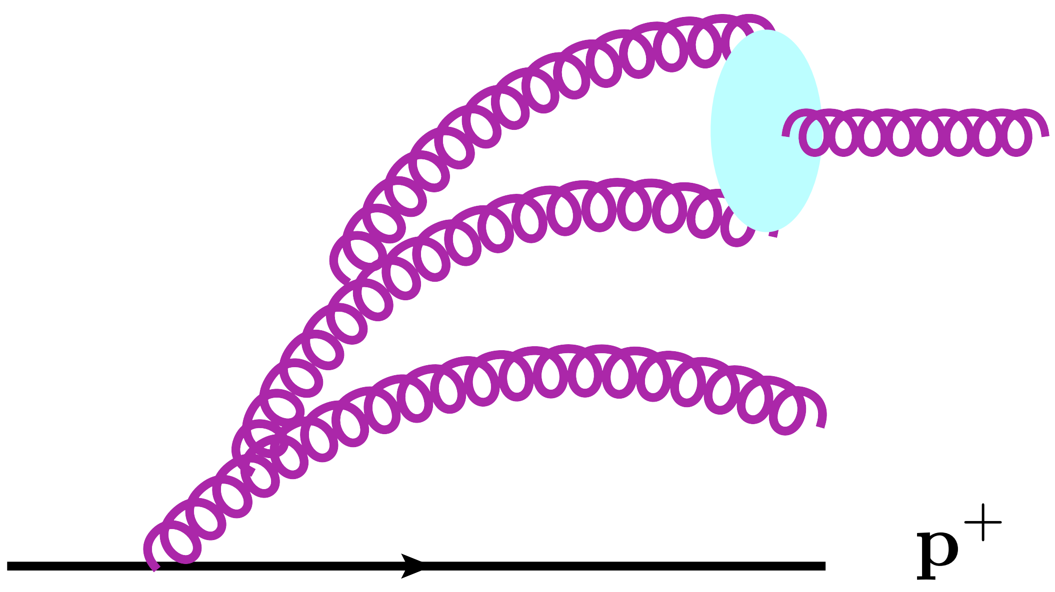
$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^{\mathbf{2}}$$

↓

Non-linear *recombination* corrections

are demanded by UNITARITY

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

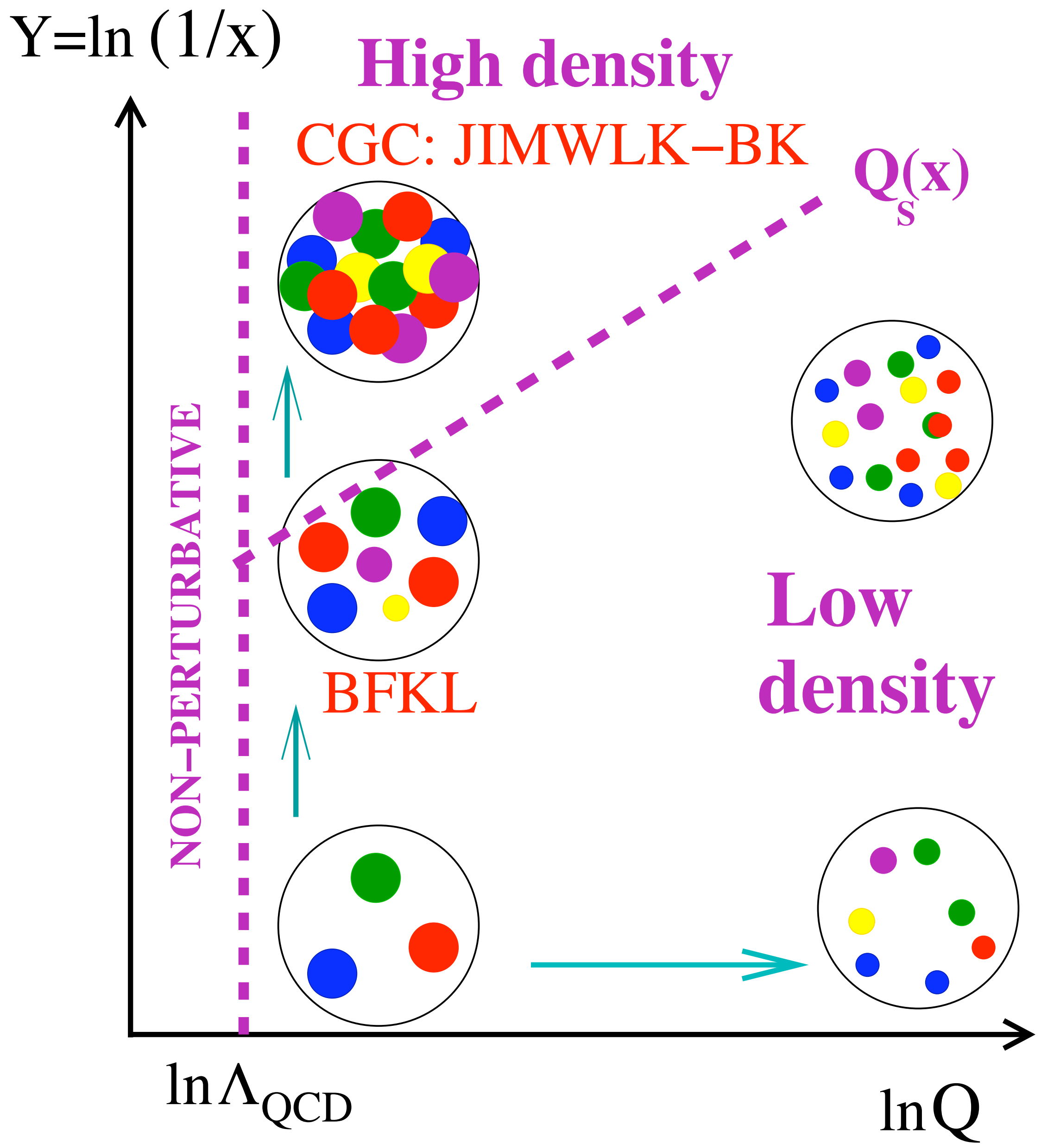


“BK-JIMWLK”

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

↓

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

The description of particle production also gets modified by saturation effects

Shadowing versus Saturation at small-x:

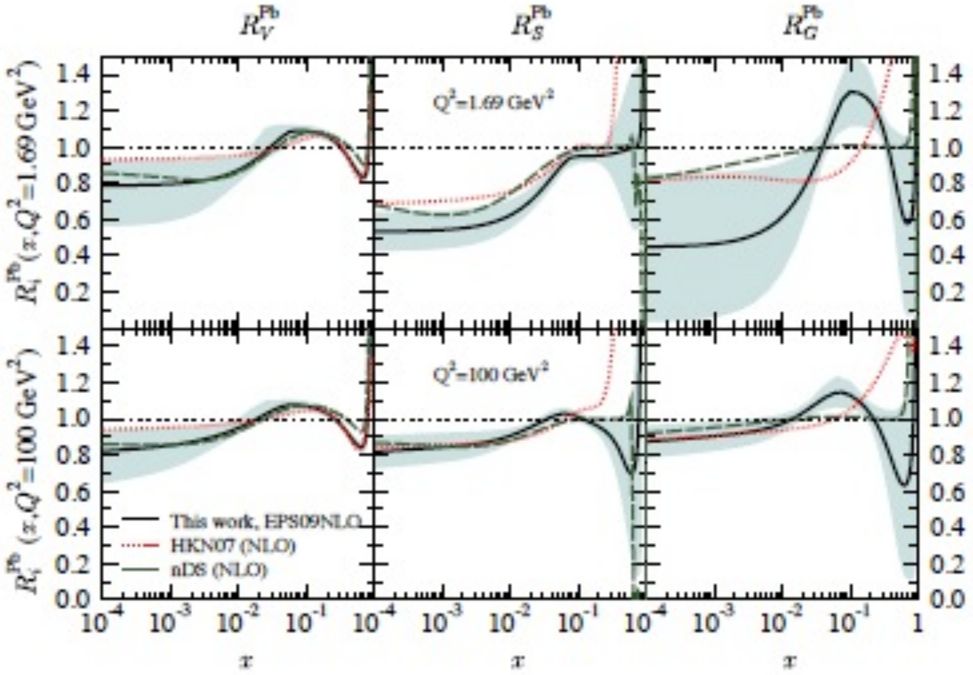
Shadowing parametrizations and nPDF's: Assume the validity of collinear factorization ("partons have no transverse momentum and are independent of each other"):

$$\frac{d\sigma^{AB\to hX}}{dyd^2k_t} \propto f_{a/A}(x_1,k_t^2)\, f_{b/B}(x_2,k_t^2) \otimes \frac{d\sigma^{ab\to cd}}{dyd^2k_t} \otimes D_{h/c}(z)$$

$$f_i^A(x,Q^2) = A\, R_i^A(x,Q^2)\, f_i^N(x,Q^2)$$

at small-x: $R_i^A(x,Q^2) < 1$

EPS 09 parametrization:



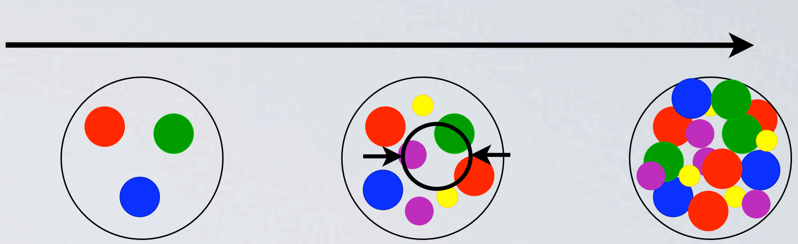
CGC (Saturation): Dynamical theory to describe small-x phenomena and coherence. Use of unintegrated gluon distribution and kt-factorization (or more complicated schemes)

$$xG(x,Q^2) \approx \int^{Q^2} d^2k_t\, \varphi(x,k_t)$$

Two different approaches to describe the same phenomena...

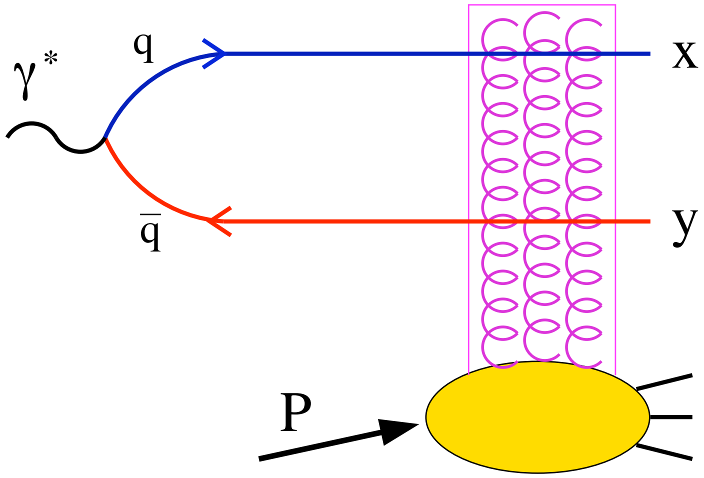
CGC evolution: The BK equation

Balitsky 96, Kovchegov 99



$\ln\frac{1}{x}\sim\ln s\sim Y$

Probe your hadron with a photon (color dipole). Eikonal scattering



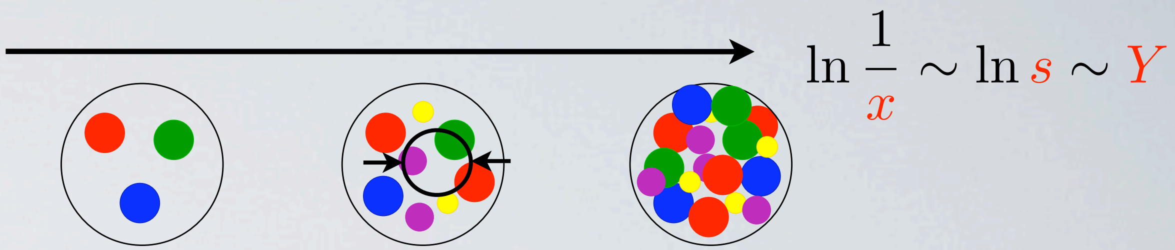
$$S(\underline{x},\underline{y};Y)=\frac{1}{N_c}\langle\mathrm{tr}\{U_{\underline{x}}\,U^{\dagger}_{\underline{y}}\}\rangle_Y\ =1-\mathcal{N}(\underline{x},\underline{y};Y)$$

unintegrated gluon distribution (2-point function):

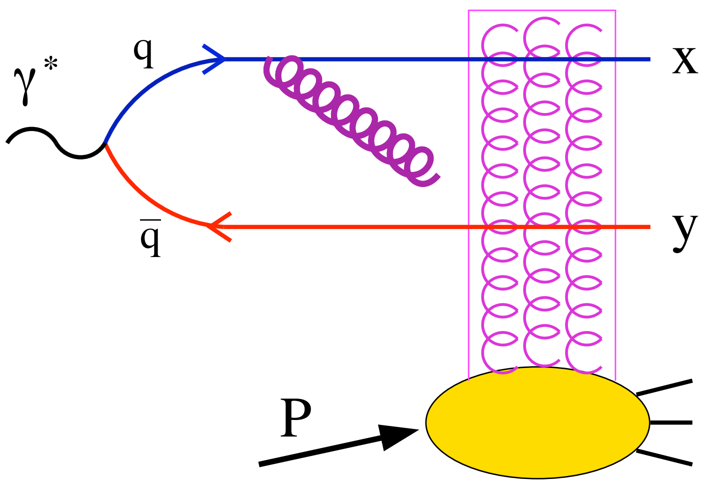
$$\varphi(x,k_t)=\int\frac{d^2r}{2\pi\,r^2}\,e^{i\mathbf{k}\cdot\mathbf{r}}\mathcal{N}(r,x)$$

CGC evolution: The BK equation

Balitsky 96, Kovchegov 99



Probe your hadron with a photon (color dipole). Eikonal scattering



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

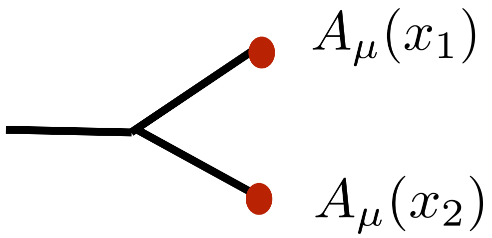
unintegrated gluon distribution (2-point function):

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

Increase the collision energy and resum small-x gluon radiation: Evolution of the 2-point function

$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2r_1\, \underset{\substack{\uparrow\\ \text{perturbative kernel}}}{K(r,r_1,r_2)}\, [\mathcal{N}(r_1,x) + \mathcal{N}(r_2,x) - \mathcal{N}(r,x) - \underset{\substack{\uparrow\\ \text{non-linear term}}}{\mathcal{N}(r_1,x)\mathcal{N}(r_2,x)}]$$

Projectile dipole-splitting →



← target gluon-recombination

✓ 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:

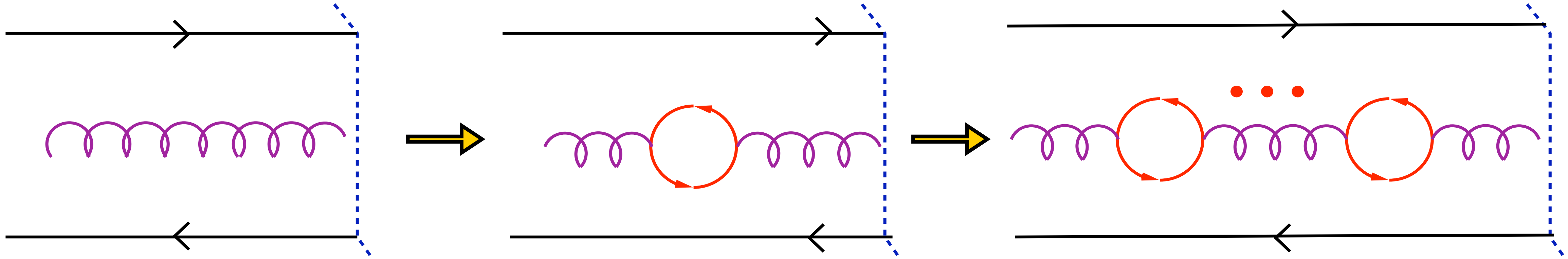
$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2r_1\, K(r,r_1,r_2)\left[\mathcal{N}(r_1,x)+\mathcal{N}(r_2,x)-\mathcal{N}(r,x)-\mathcal{N}(r_1,x)\mathcal{N}(r_2,x)\right]$$

Running coupling kernel:

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

LO: **α_s ln(1/x)**
small-x gluon emission

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



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

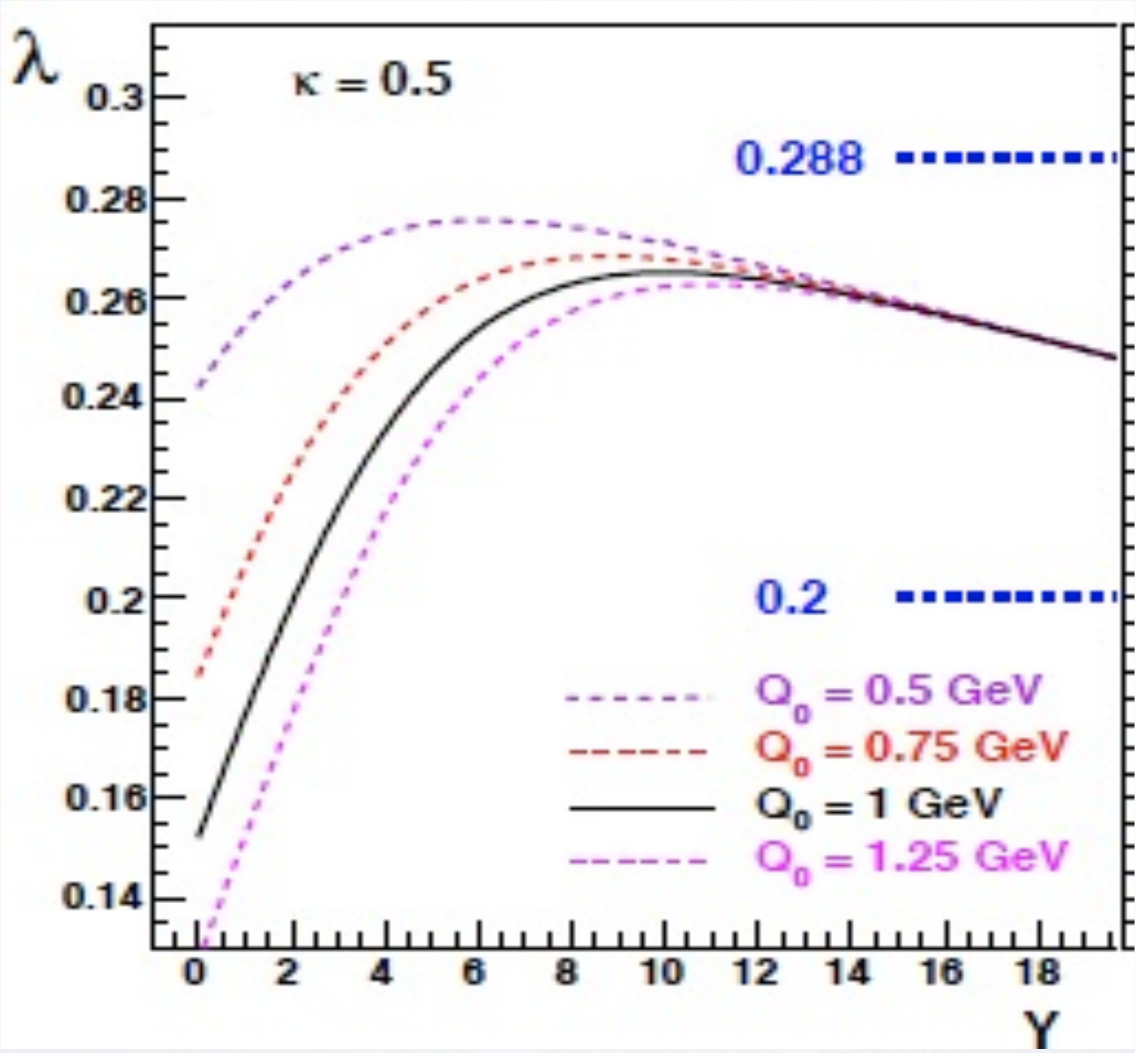
BK evolution at NLO

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

✓ NLO corrections are large, rendering evolution compatible with experimental data.

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

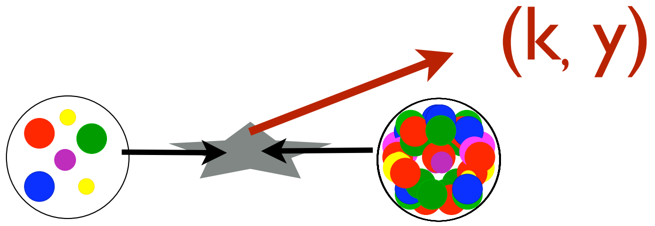
$$\lambda^{LO} \approx 4.8\, \alpha_s$$



values compatible with DIS and HIC data

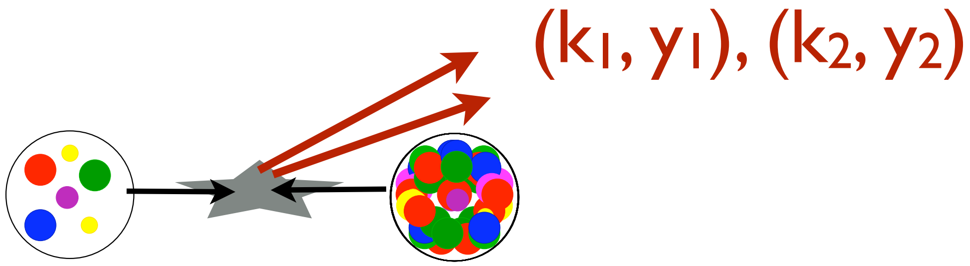
RHIC Kinematics:

- 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!



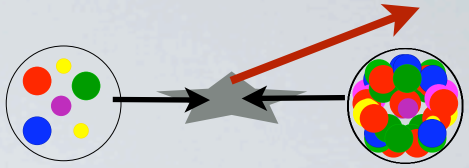
$$x_p = \frac{|k_1| e^{y_1} + |k_2| e^{y_2}}{\sqrt{s}}$$

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

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)

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

$$+\, x_1 f_{g\,/\,p}(x_1,p_t^2)\,\tilde{N}_A\left(x_2,\frac{p_t}{z}\right) D_{h\,/\,g}(z,p_t^2)\Big]$$

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)

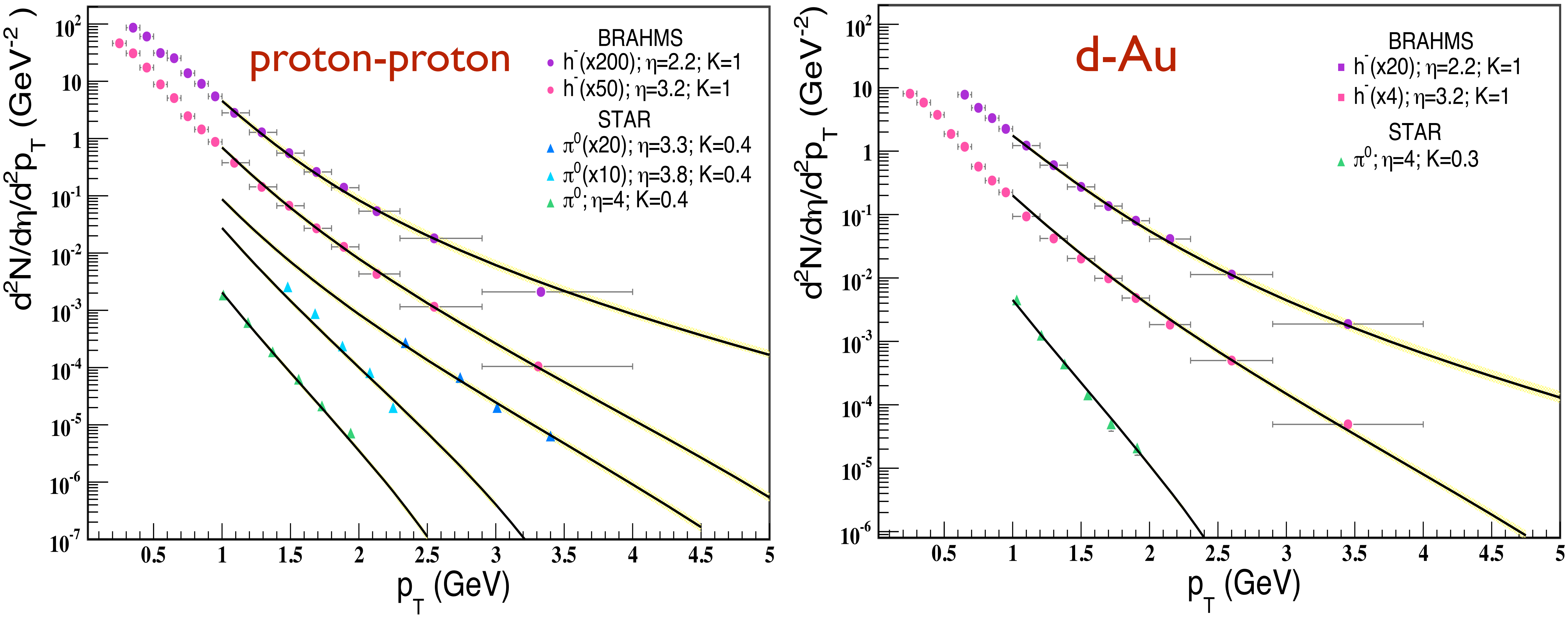
We use CTEQ6 pdf's and de Florian-Sassot ff's

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) ??



$$0.005 \leq x_0 \leq 0.01$$

$$Q_{s0}^2 = 0.2\,\mathrm{GeV}^2$$

$$0.01 \leq x_0 \leq 0.025$$

$$Q_{s0}^2 = 0.4\,\mathrm{GeV}^2$$

$$Q_{s0\,gluon}^2 = 0.9\,\mathrm{GeV}^2$$

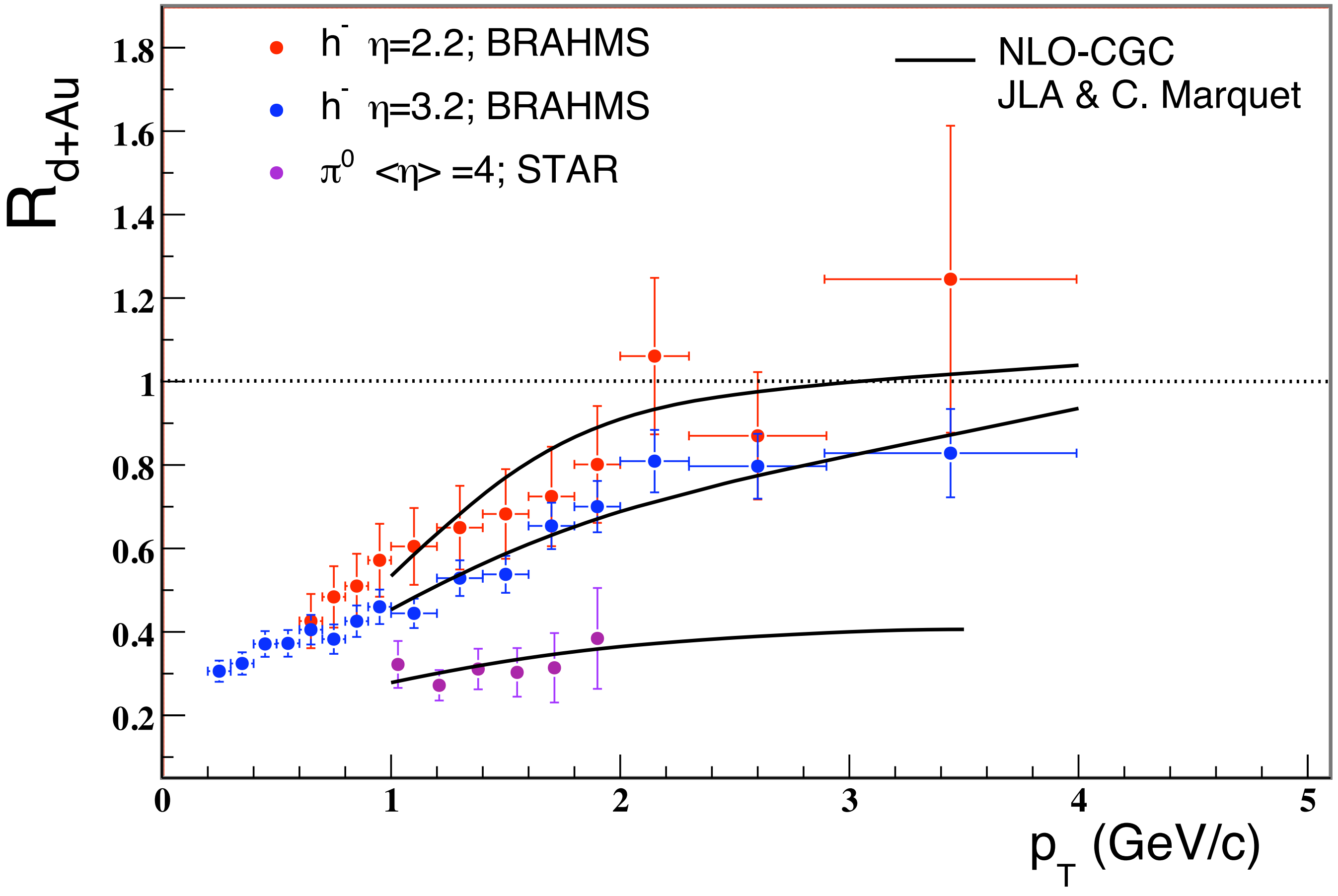
$$0.005 \leq x_0 \leq 0.01$$

$$Q_{s0}^2 = 0.5\,\mathrm{GeV}^2$$

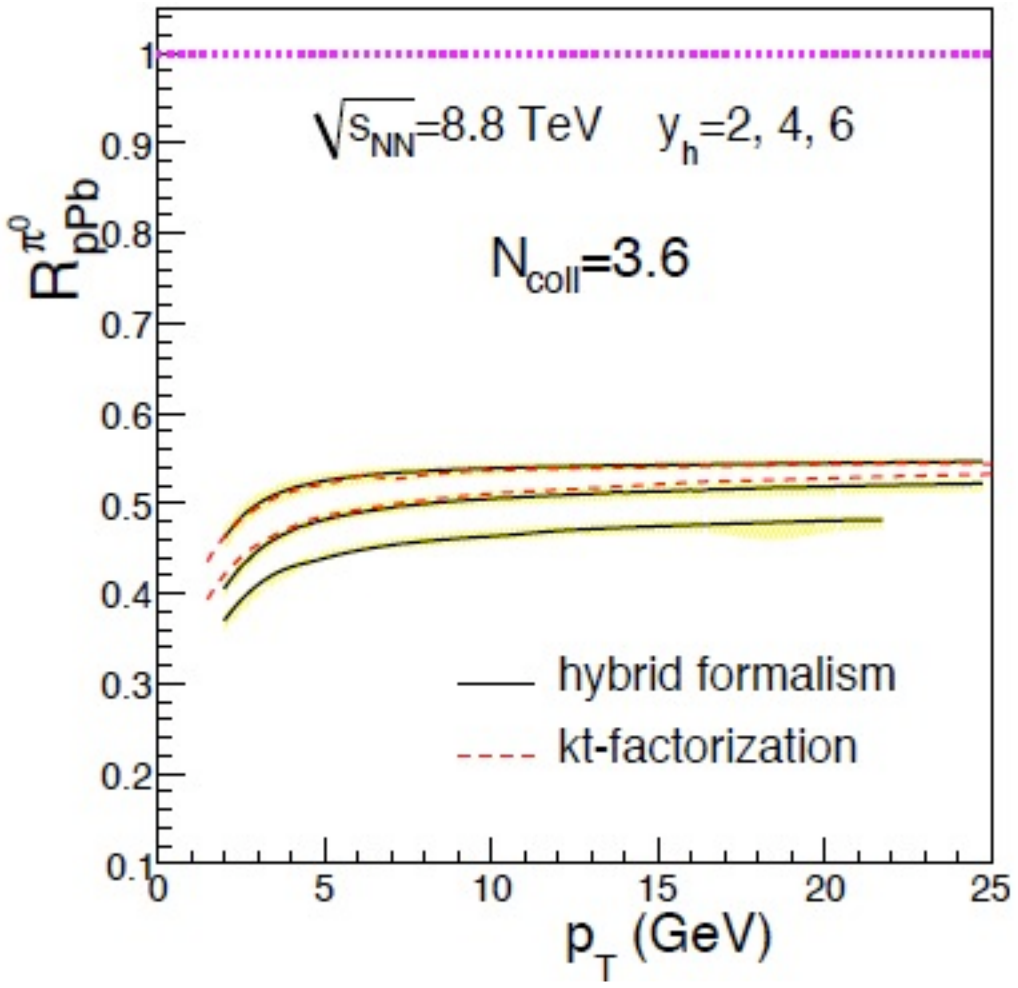
$$Q_{s0,\,gluon}^2 = 1.125\,\mathrm{GeV}^2$$

- ...by simply taking the ratio of d+Au and p+p spectra we get a good description of the forward suppression of hadron yields measured at RHIC

RHIC d+Au



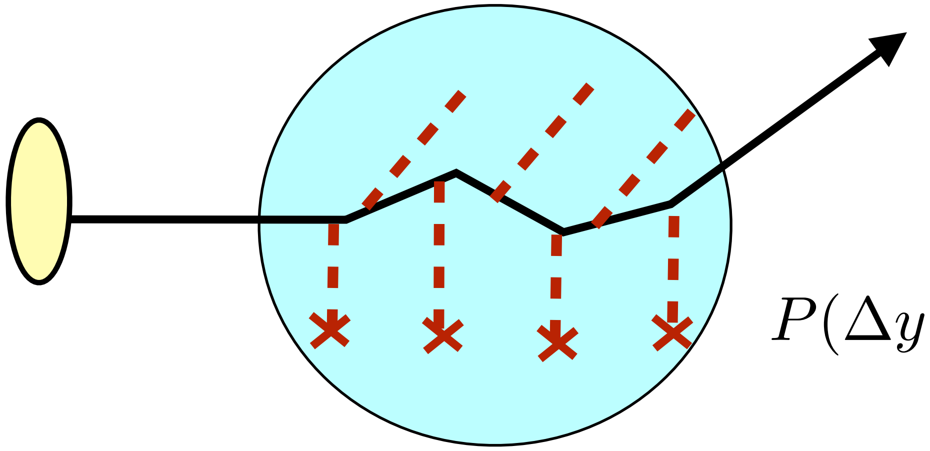
LHC p+Pb



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

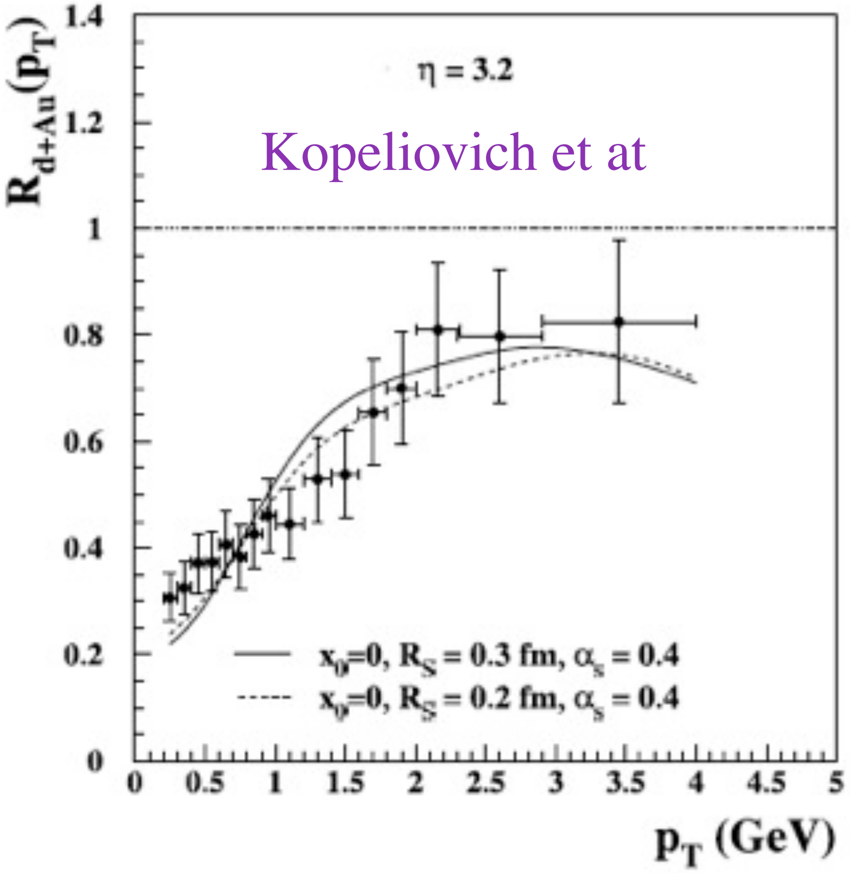
Alternative descriptions of data

- Energy conservation corrections (large-x effects). Interaction with the target induces gluon bremstahlung and energy loss, which is stronger in nuclei than in proton.



$$P(\Delta y) \approx e^{-n_G(\Delta y)} \approx (1 - x_F)^{\#}$$

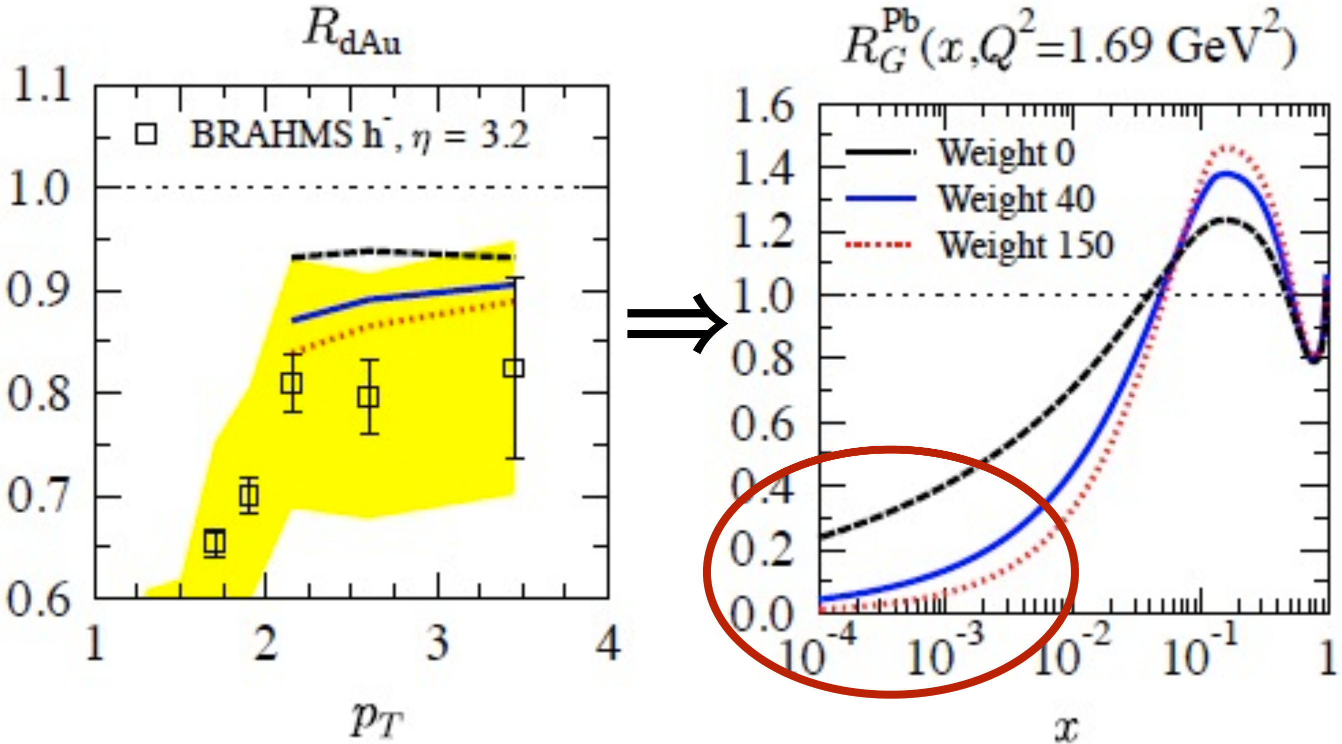
Francois Arleo's talk



Kopeliovich et at

- nPDF's description of forward suppression is possible, but involves a huge nuclear shadowing at small-x (EKS08)

- Forward RHIC data not included in most recent NLO parametrizations (EPS09)



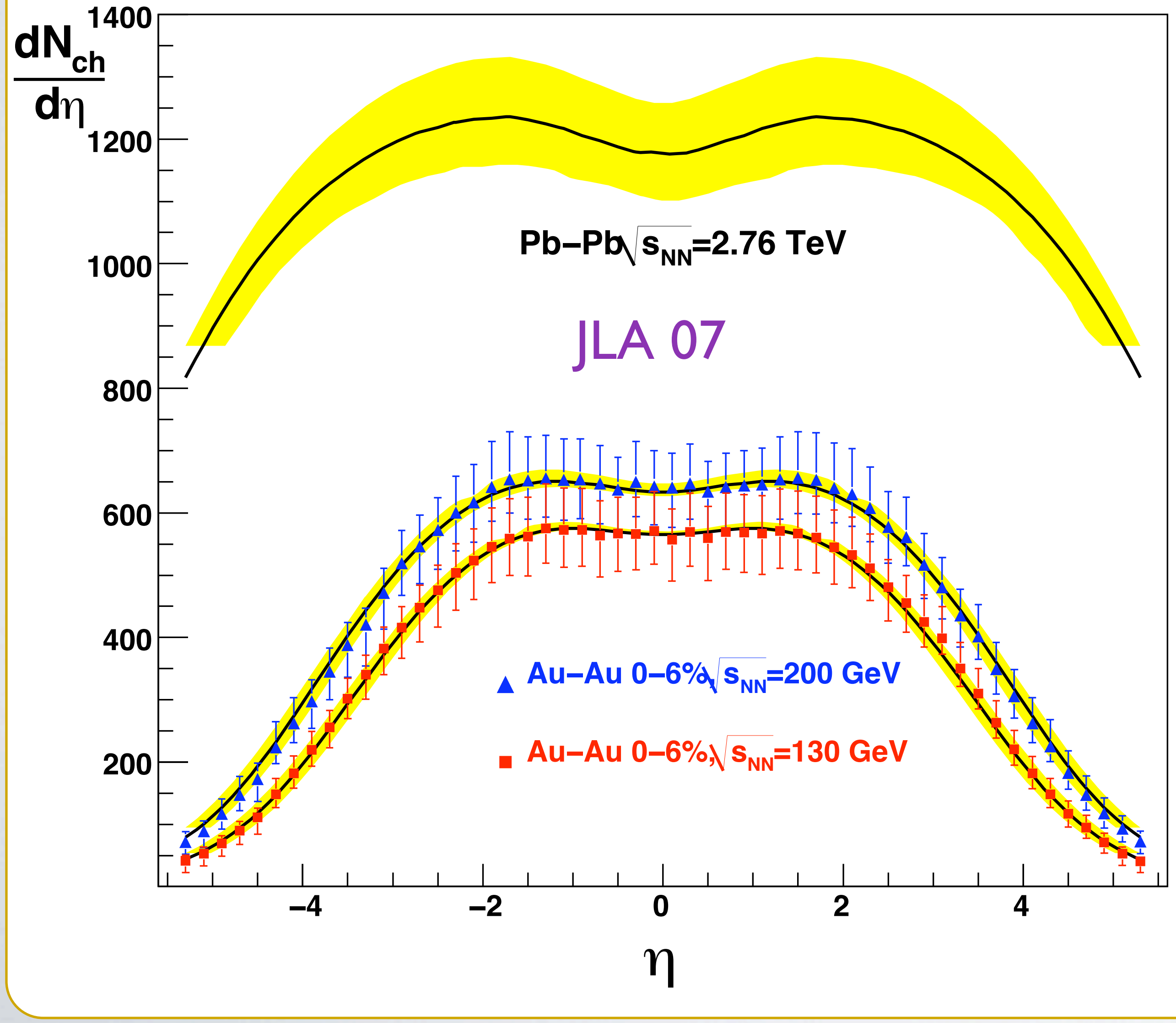
Eskola-Paukkunen-Salgado

⇒ More rcBK CGC phenomenology at RHIC

Total multiplicities:

The CGC naturally explains the lower than predicted observed at RHIC, together with its energy and rapidity dependence

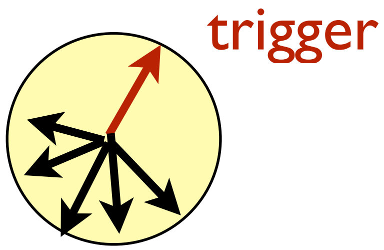
$$\frac{dN_{ch}^{Pb-Pb}(\sqrt{s}=2.75\,\text{TeV},\,\eta=0)}{d\eta} \approx 1100 \div 1250$$



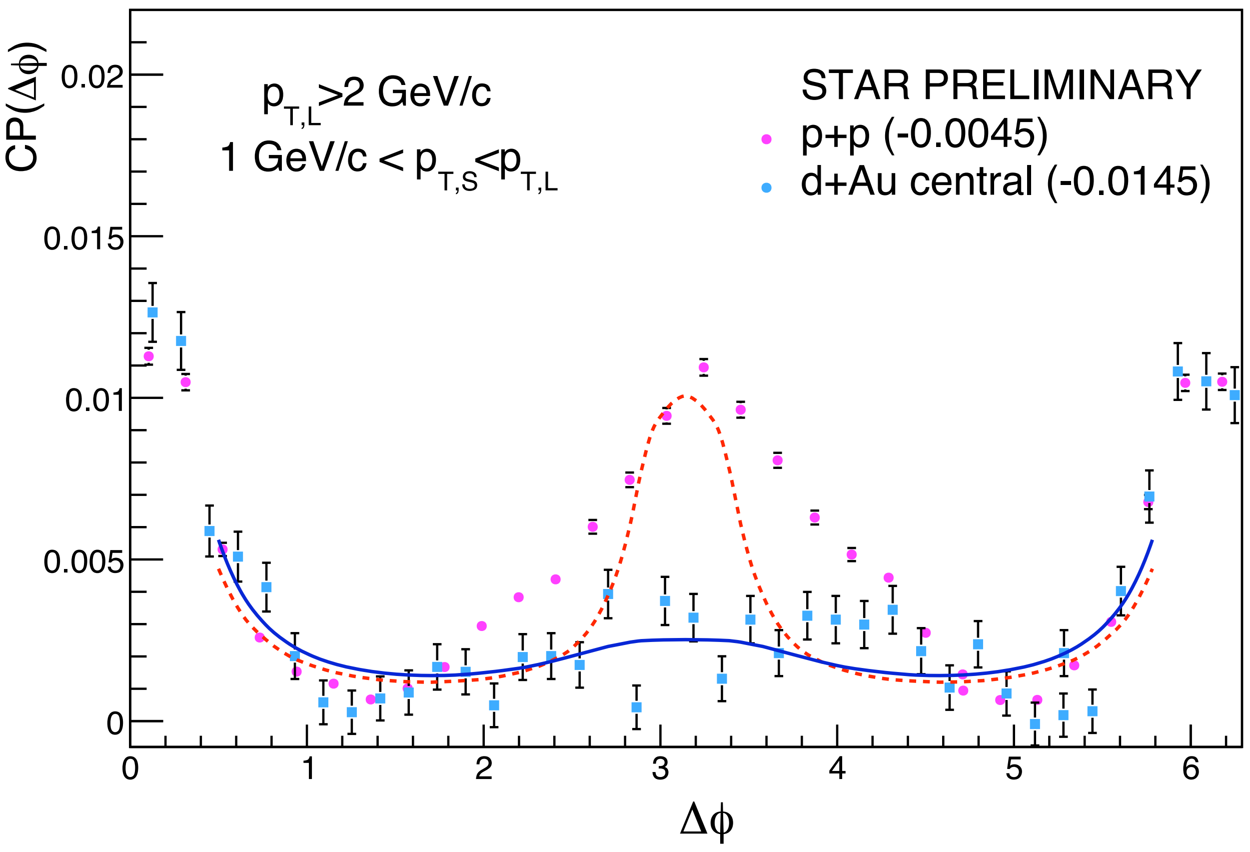
Forward di-hadron correlations in d+Au:

Disappearance of back-to-back correlations qualitatively predicted and quantitatively well described in the CGC

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

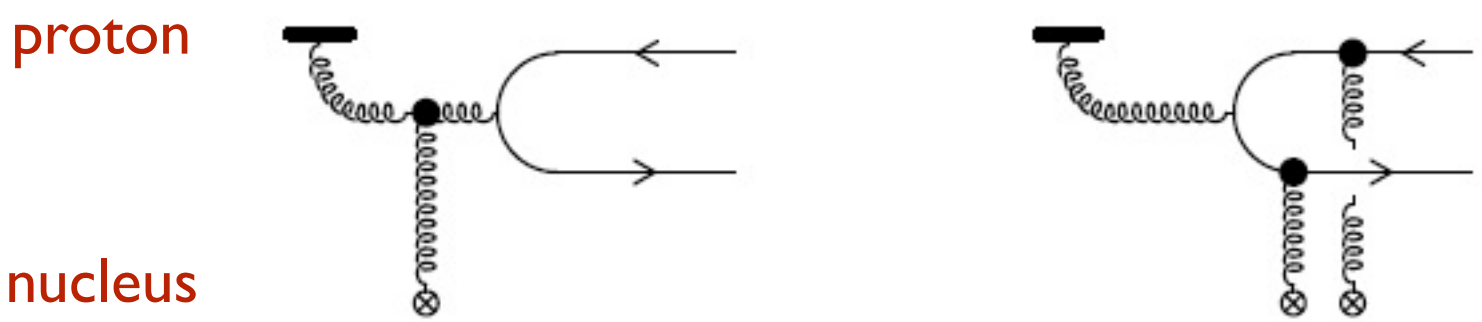


JLA and C. Marquet '10



⇒ Heavy Quark production in the CGC Blaizot-Gelis-Venugopalan-Fuji; Kovchegov-Tuchin

Full calculation, including multiple rescatterings and quantum evolution in p-A collisions available:
It violates kt-factorization:



proton ugd

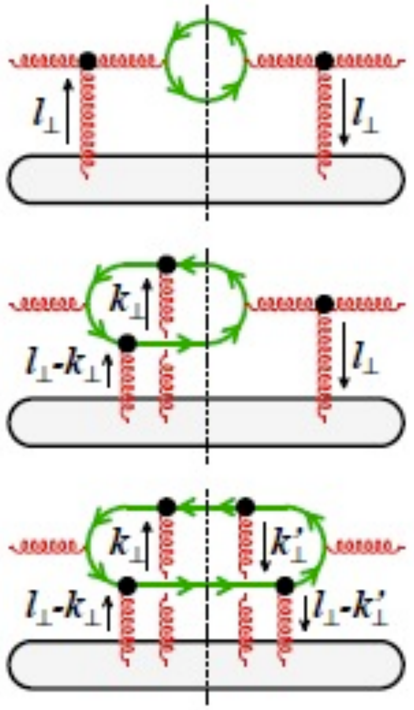
$$\frac{d\sigma}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q} = \frac{\alpha_s^2 N}{8\pi^4(N^2-1)} \int_{\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp}} \frac{\delta(\boldsymbol{p}_\perp+\boldsymbol{q}_\perp-\boldsymbol{k}_{1\perp}-\boldsymbol{k}_{2\perp})}{\boldsymbol{k}_{1\perp}^2\boldsymbol{k}_{2\perp}^2} \boxed{\varphi_p(\boldsymbol{k}_{1\perp})}$$

$$\times\Bigg\{ \int_{\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{q\bar{q}}(\not{p}-m)\gamma^0 T'^{\dagger}_{q\bar{q}}\gamma^0\Big]\phi_A^{q\bar{q},q\bar{q}}(\boldsymbol{k}_{2\perp};\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp)$$

$$+\int_{\boldsymbol{k}_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{q\bar{q}}(\not{p}-m)\gamma^0 T^{\dagger}_{g}\gamma^0 + h.c.\Big]\phi_A^{q\bar{q},g}(\boldsymbol{k}_{2\perp};\boldsymbol{k}_\perp)$$

$$+\mathrm{tr_d}\Big[(\not{q}+m)T_{g}(\not{p}-m)\gamma^0 T^{\dagger}_{g}\gamma^0\Big]\phi_A^{g,g}(\boldsymbol{k}_{2\perp})\Bigg\}. \qquad (6)$$

correlators of nucleus gluon fields



2-point

3-point

4-point

⇒ Heavy Quark production in the CGC

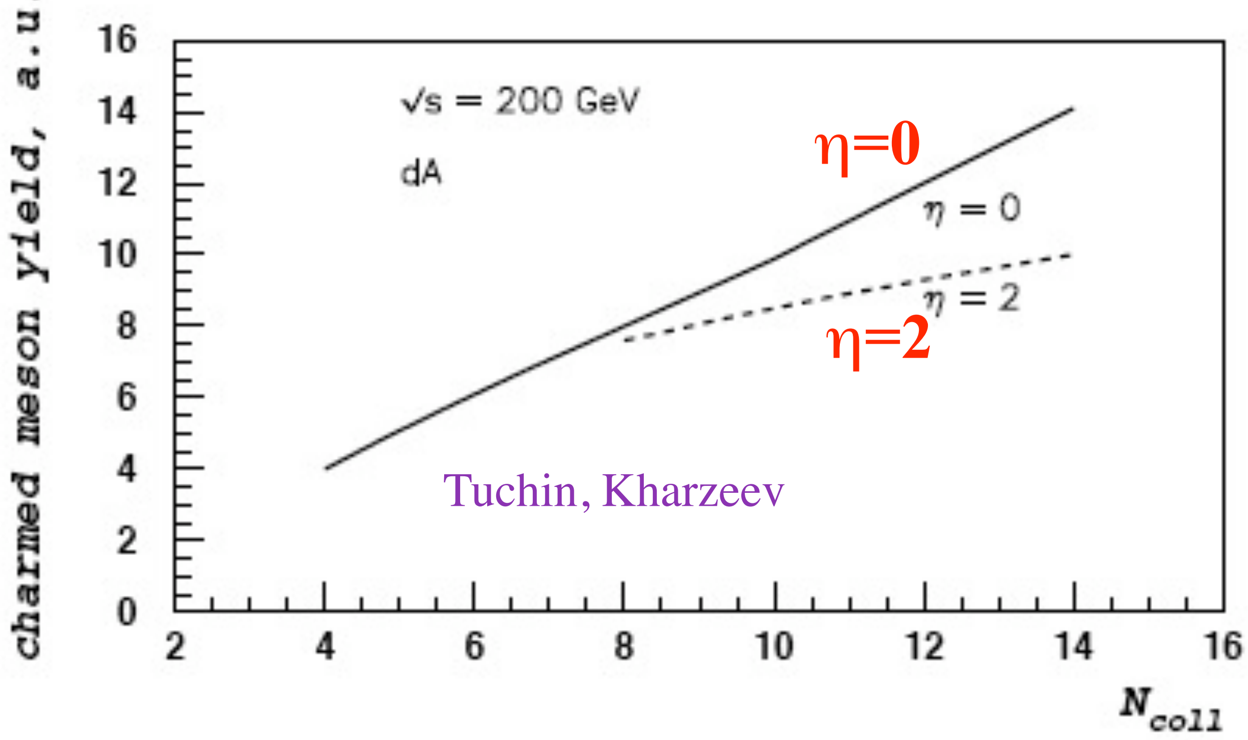
Two-scales problem:

if $Q_s(x) \ll m_Q$ the heavy quark is "heavy" $\longrightarrow \frac{dN}{dy} \sim N_{coll}$

if $Q\ \ (x) \geq m$ the heavy quark is "light" $\longrightarrow \frac{dN}{dy} \sim N_{part}$

Remember that the saturation scale grows with rapidity: $Q_s^2 \sim e^{0.28\eta}\, GeV^2$

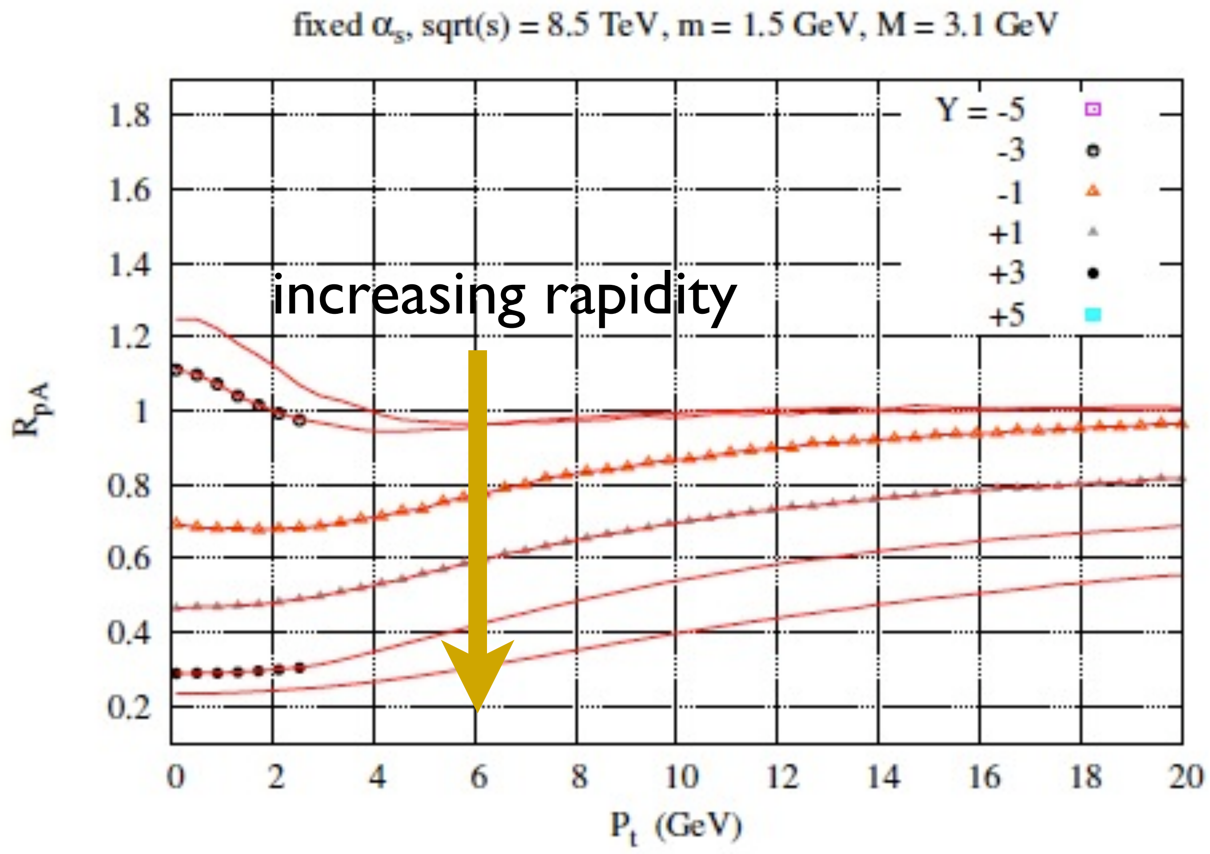
change of open charm yield with rapidity



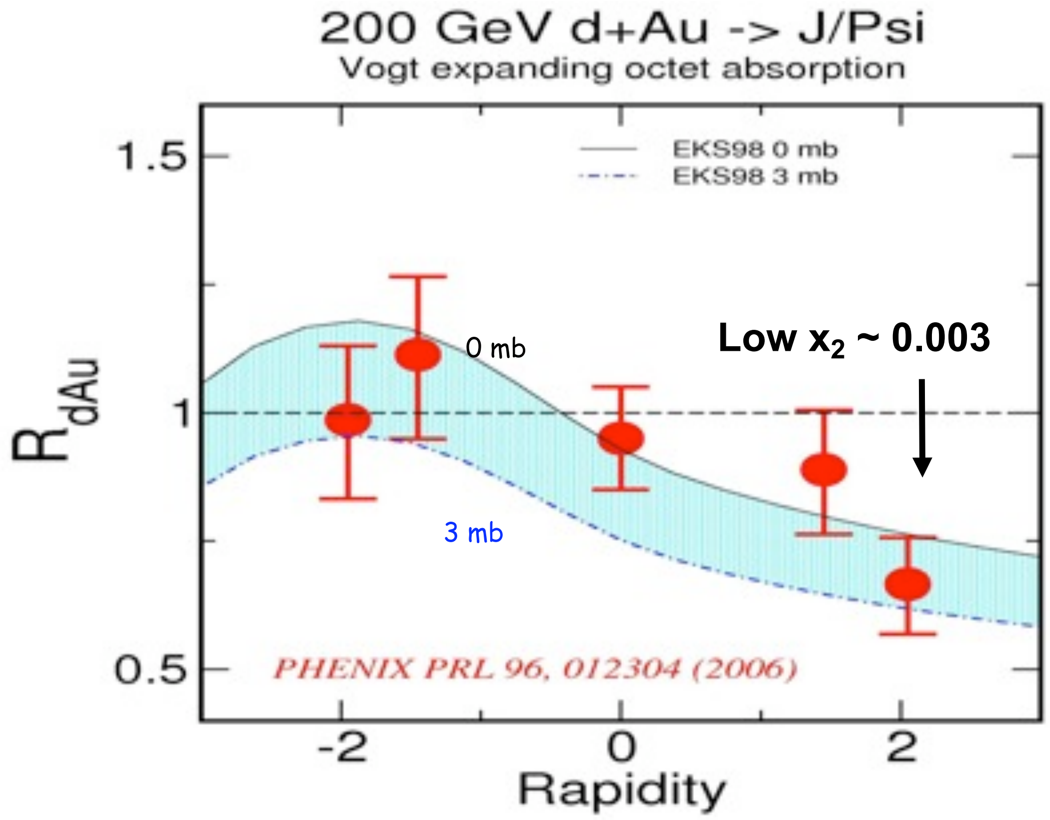
⇒ Heavy Quark production in the CGC

-CGC effects induce a moderate enhancement of QQ production at mid-rapidity at RHIC (only semi-classical rescatterings)

- The onset of quantum corrections induces a relative suppression at forward rapidities at RHIC (mid-rapidity at the LHC). Such is precisely the trend exhibited by RHIC data d+Au and Au+Au coll.



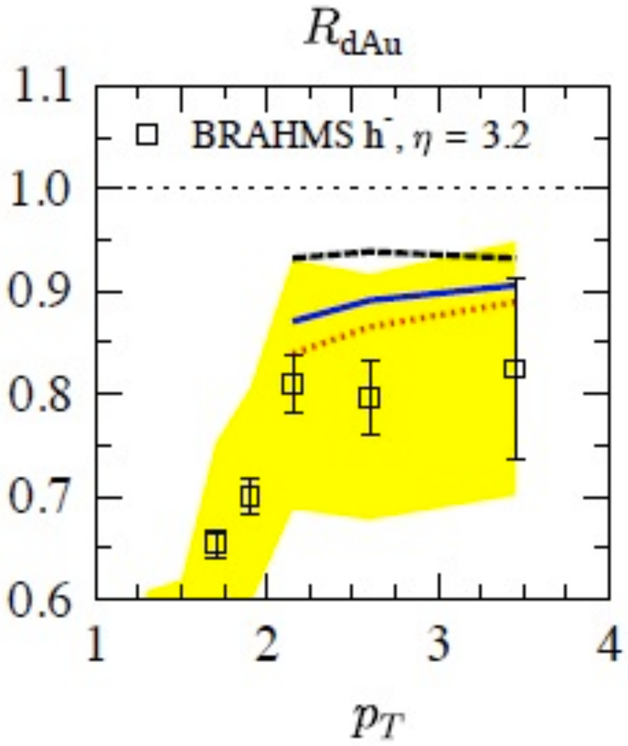
Gelis-Fuji-Venugopalan



It is plausible that part of the "anomalous" forward suppression observed at RHIC is due to CGC effects

- Shadowing parametrizations that describe well forward light hadron production in d+Au at RHIC require a less strong growth of “absorption” cross section with increasing rapidity

EPS08



σ_{abs} (y)

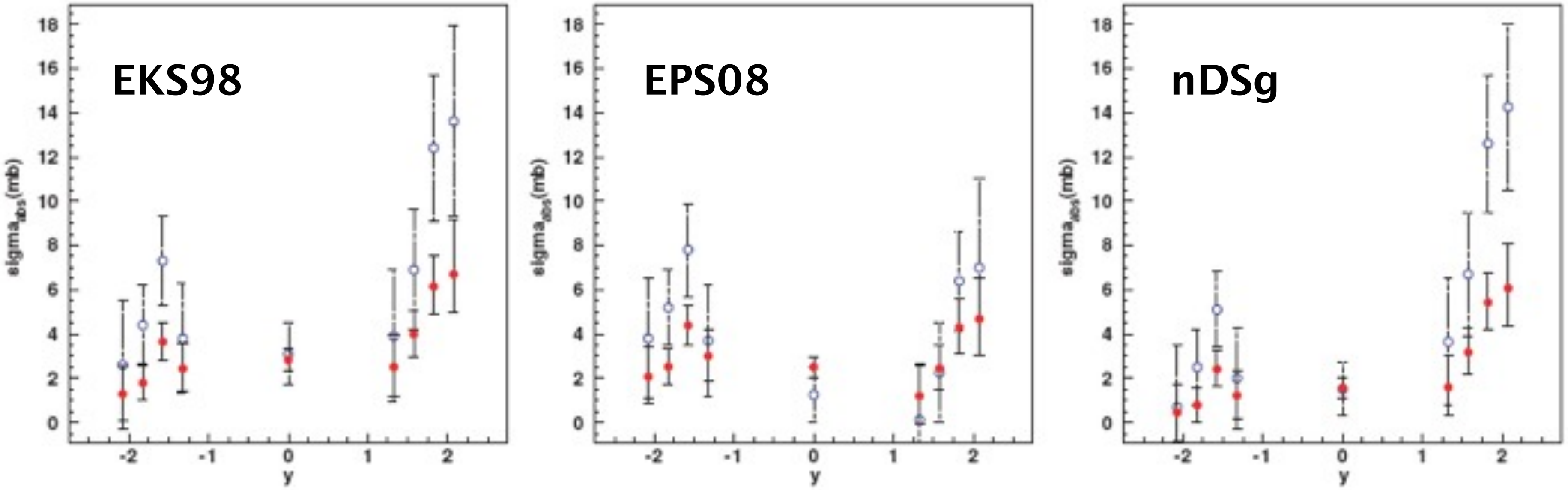


Fig by Elena Ferreiro

...one may be overestimating the anomalous absorption just due to putting too many initial gluons....

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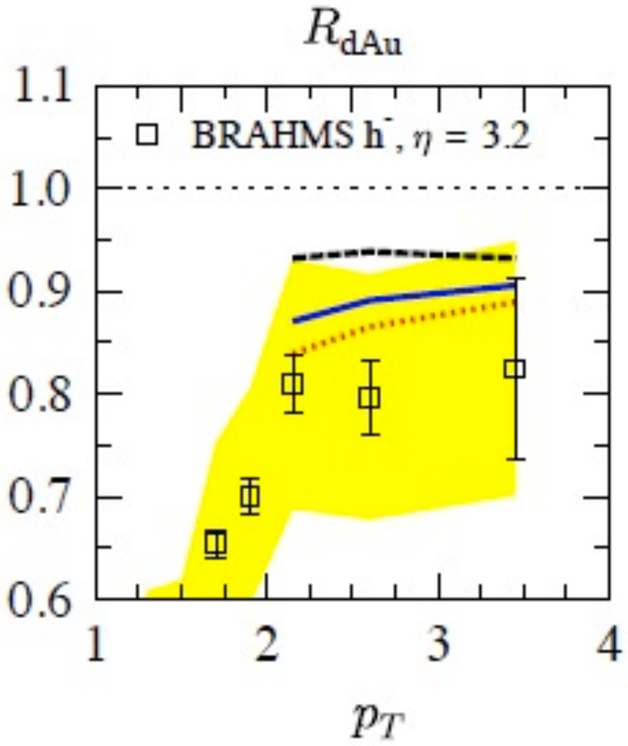
EPS08



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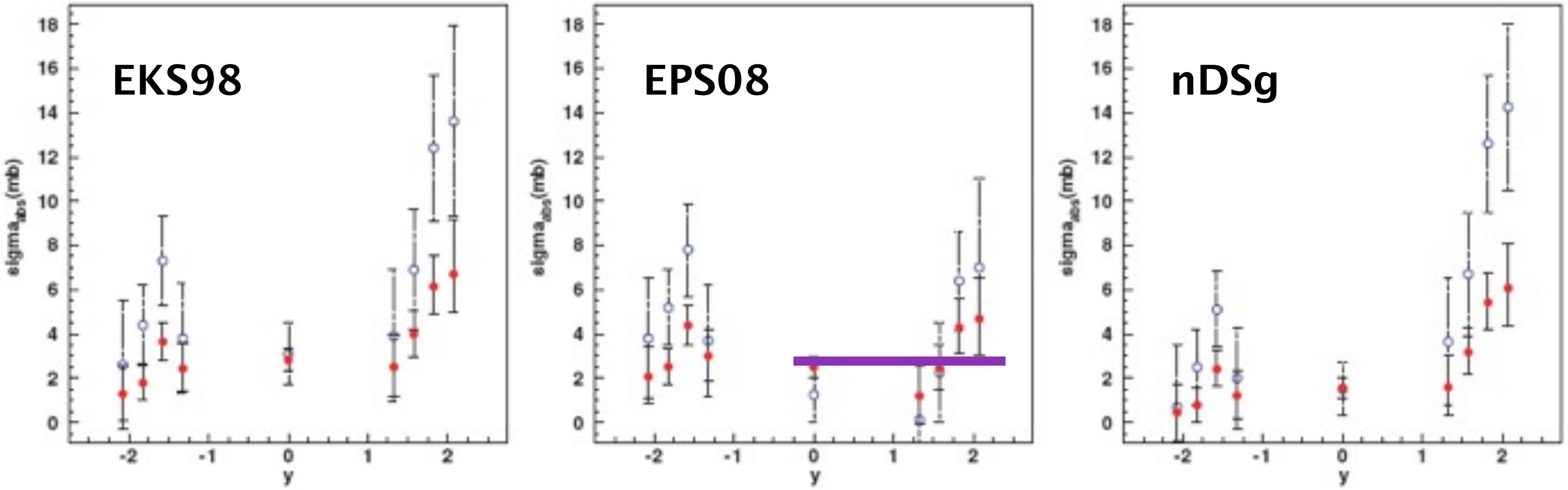


Fig by Elena Ferreiro

...one may be overestimating the anomalous absorption just due to putting too many initial gluons....

Conclusions

⇒ NLO corrections bring the CGC to a new period of quantitative and predictive phenomenology

⇒ Good description of forward particle production @ RHIC (multiplicities, single and double production). Also e+p data.

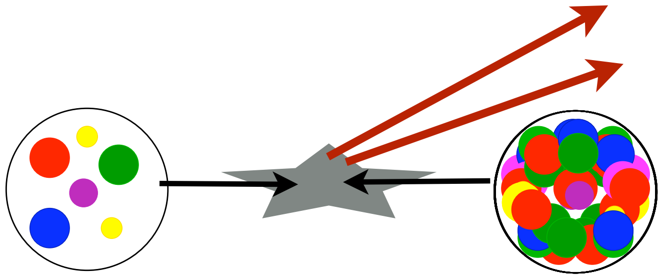
⇒ A systematic phenomenological study of CGC including NLO effects in heavy quark production at RHIC and the LHC is still missing

Back up slides

⇒ Double Inclusive forward hadron production in the CGC

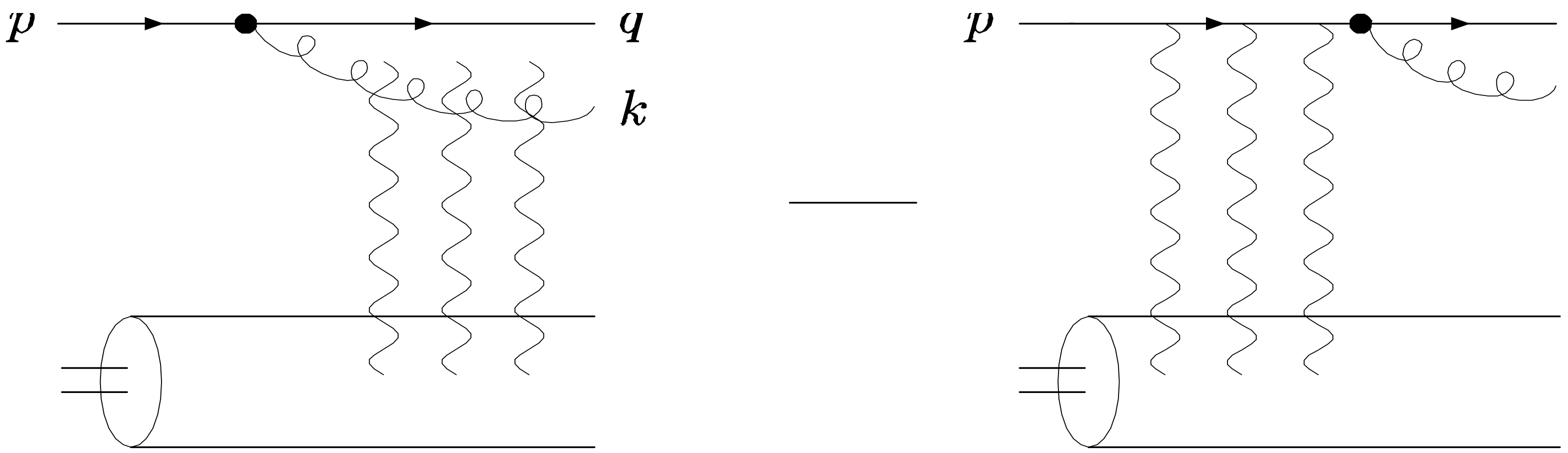
$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

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



(k₁, y₁), (k₂, y₂)

Cyrille Marquet 07:



hard quark initiating scattering

Fourier transfrom coordinate space to momentum

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

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

q-> qg splitting (pQCD)

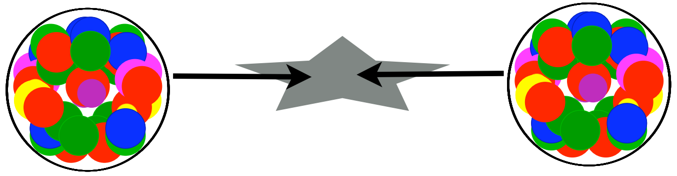
$$\underbrace{-S^{(3)}_{\bar{q}gq}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{x}',\mathbf{b}';x_A] + S^{(2)}_{q\bar{q}}[\mathbf{b}+z(\mathbf{x}-\mathbf{b}),\mathbf{b}'+z(\mathbf{x}'-\mathbf{b}');x_A]\Big\}}$$

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

⇒ Multiparticle production in A+A coll.



RHIC multiplicities smaller than expected.

Most of particles produces in RHIC Au+Au collisions are small-x gluons

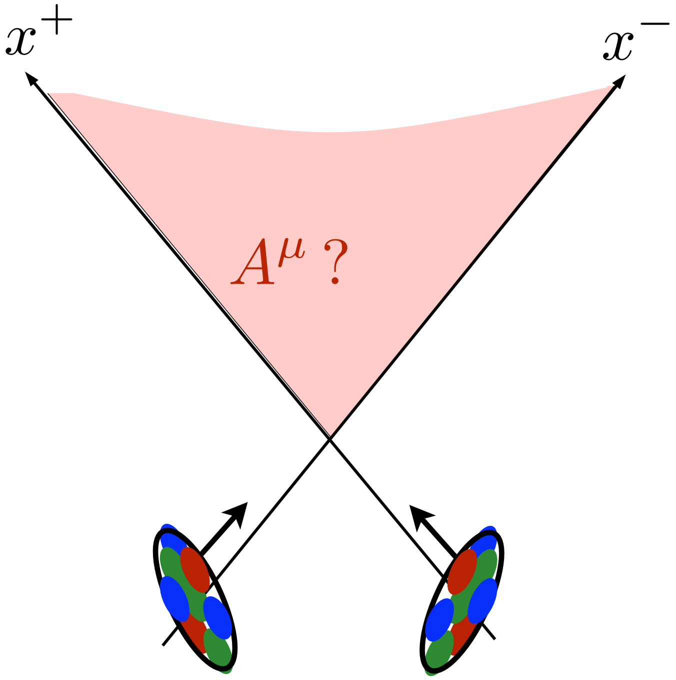
produces particles ~ # scattering centers

Two alternative approaches to describe multiparticle production within the CGC:

⇒ k_t-factorization (Valid in p+A coll.Violated in A+A collisions). Starting point to the Kharzeev-Levin-Nardi model

$$\frac{dN^g_{AB}}{d\eta} = \frac{4\pi N_c}{N_c^2-1}\int\frac{d^2p}{p^2}\int d^2k\,\alpha_s(Q^2)\,\varphi_A(x_1,k)\,\varphi_B(x_2,|p-k|)$$

⇒ Classical Yang-Mills (CYM) Kovner, McLerran, Weigert.



$$D_\mu\,F^{\mu\nu} \;=\; J^\nu \qquad \text{with} \quad J^\pm \sim \rho_{A(B)}[Q_s(x)]\,\delta(x^\pm)$$

More rigorous, but requires numerical implementation

Preliminary results AAMQs 1.0

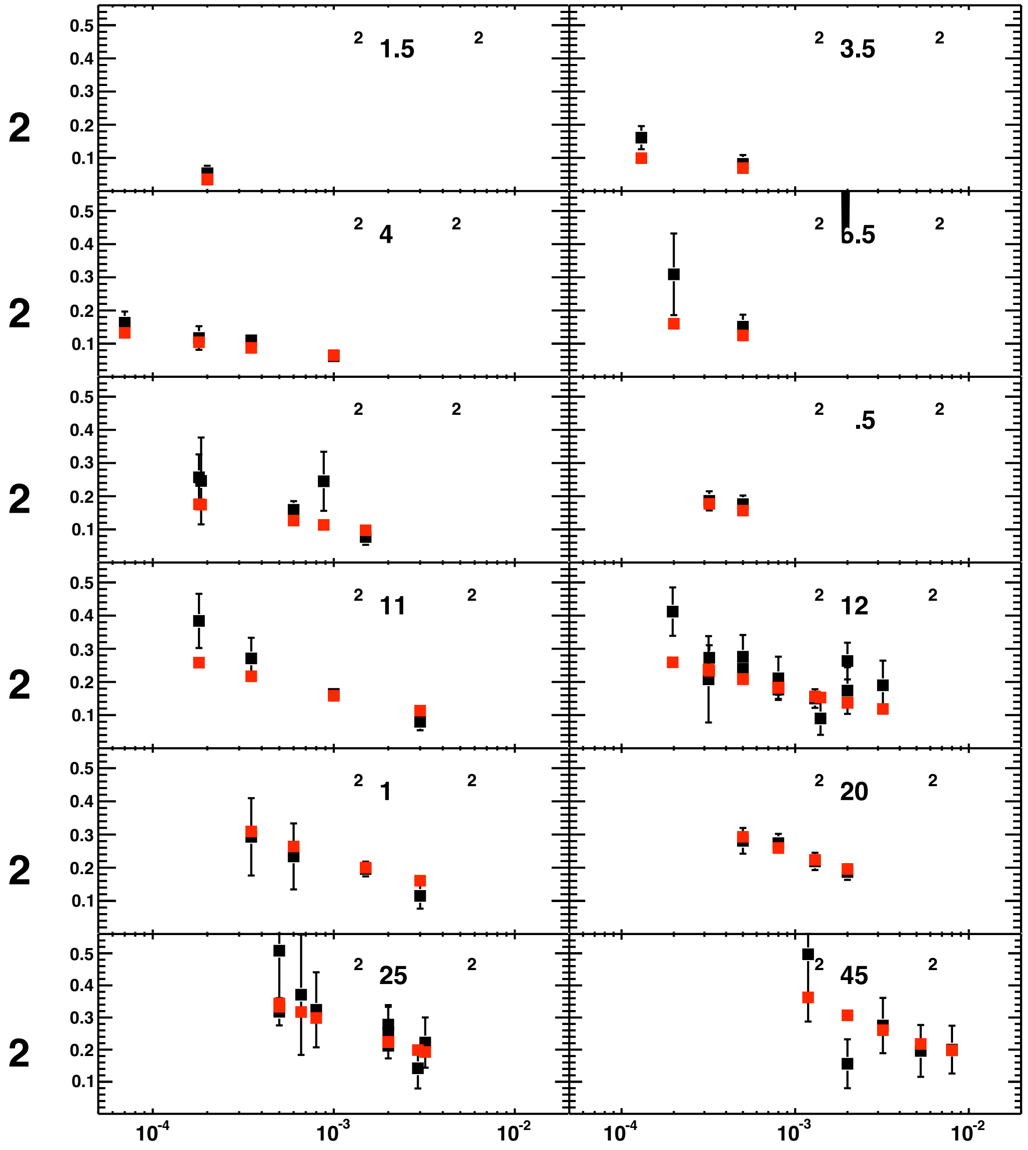
AAMS+P. Quiroga in preparation

✓ Good fits to data on reduced cross sections from combined analysis by H1 and ZEUS coll (much smaller error bars!). Fit parameters stable wrt to AAMS 1.0 analysis

$$^{2} \approx 1 \div 1\ 5$$

✓ Inclusion of charm and beauty

$$\sigma_0 > \sigma_0$$



✓ Fits to new HERA data on reduced cross sections