Color Glass Condensate at NLO: Phenomenology at HERA, RHIC and the LHC

Javier L. Albacete

IPhT CEA/Saclay

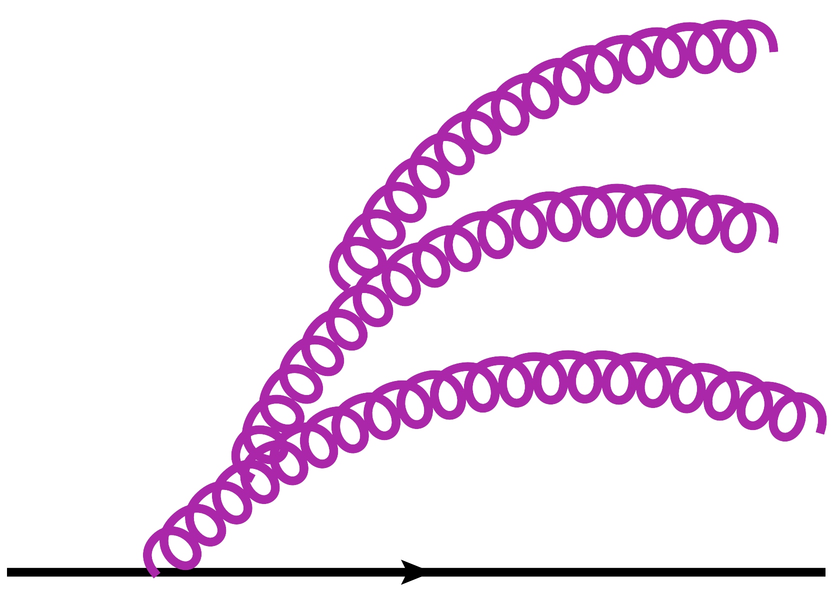
Antwerp, Belgium 21-25 2010

XL ISMD

Outline

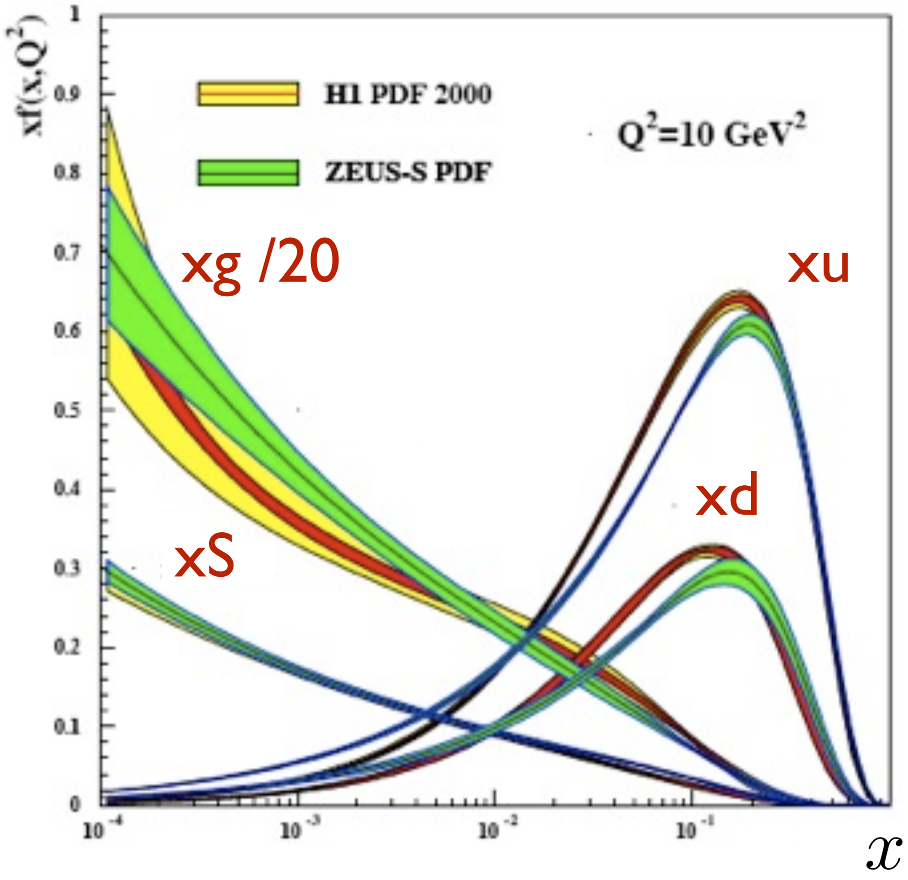
- ⇒ Motivation & Pocket Introduction to the CGC
- ⇒ Balitsky-Kovchegov equation including running coupling corrections
- ⇒ Structure functions in e+p collisions at HERA
- ⇒ Single inclusive hadron production in the CGC
- ⇒ Di-hadron correlations in d+Au collisions
- ⇒ Multiplicities in A+A collisions

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



Probability of n-soft gluon emission

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

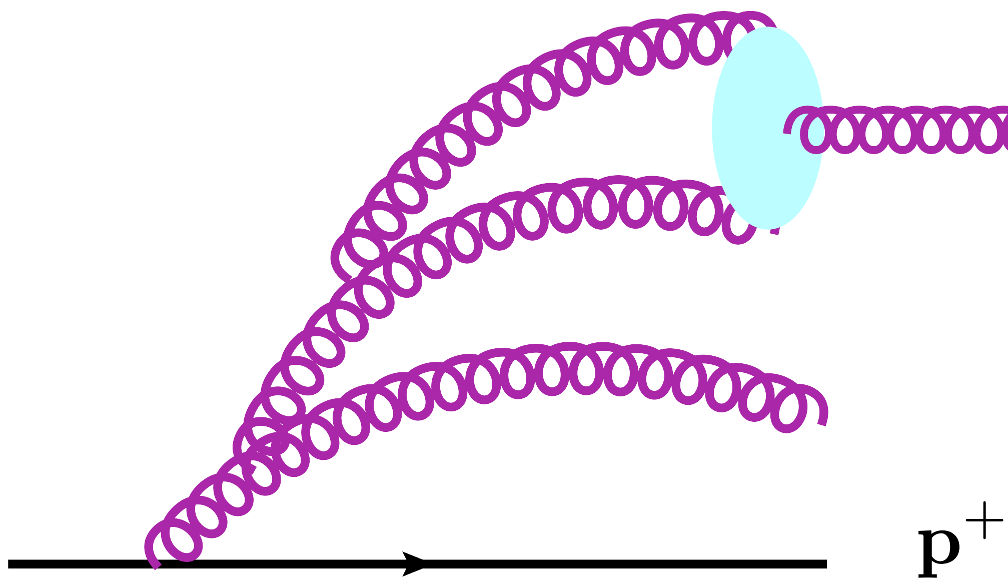


proton ugd from HERA

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

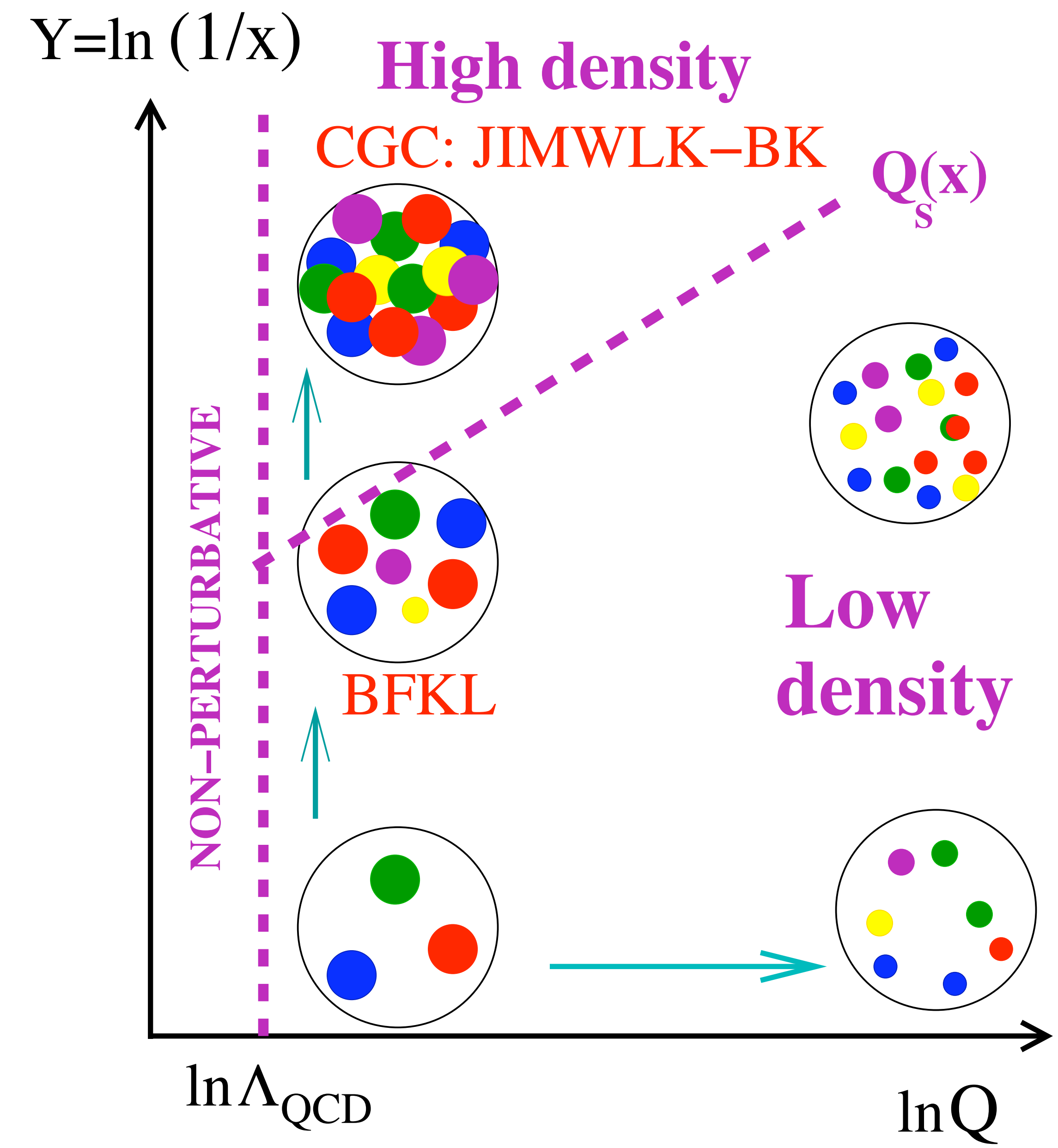


"BK-JIMWLK"

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

↓

Non-linear *recombination* corrections are demanded by UNITARITY



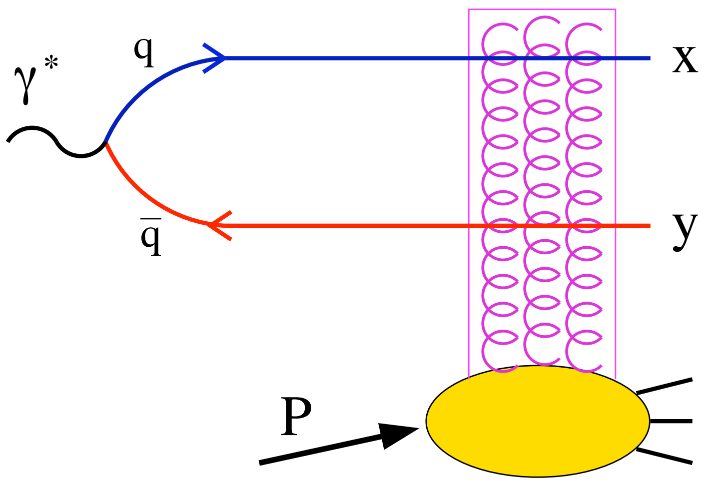
Saturation scale: transverse momentum scale which marks the onset of non-linear corrections

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

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

DIS in the dipole model

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:

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

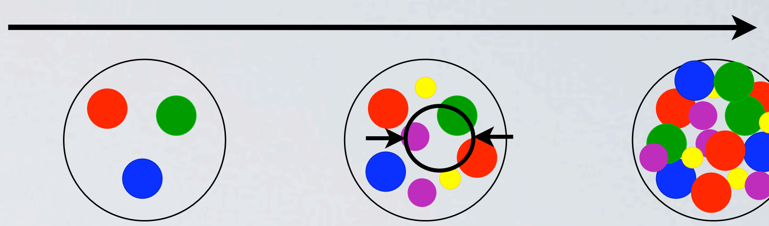
$$\sigma^{\gamma^* h}_{T,L}(x,Q^2)=\sum_{flavours}\int d^2r\int_0^1 dz\left|\Psi^{f,\gamma^*\to q\bar{q}}_{T,L}(z,r,Q^2)\right|^2\sigma^{dip}(r,x)$$

↓ QED piece ↓ Strong interactions are here

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

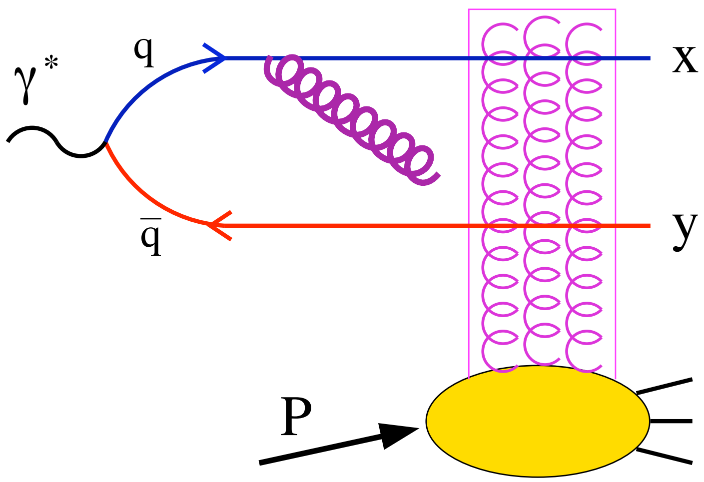
CGC evolution: The BK equation

Balitsky 96, Kovchegov 99



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

(large-Nc limit of full JIMWLK evolution)



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

unintegrated gluon distribution:

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

Increase the collision energy and resum small-x gluon radiation

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

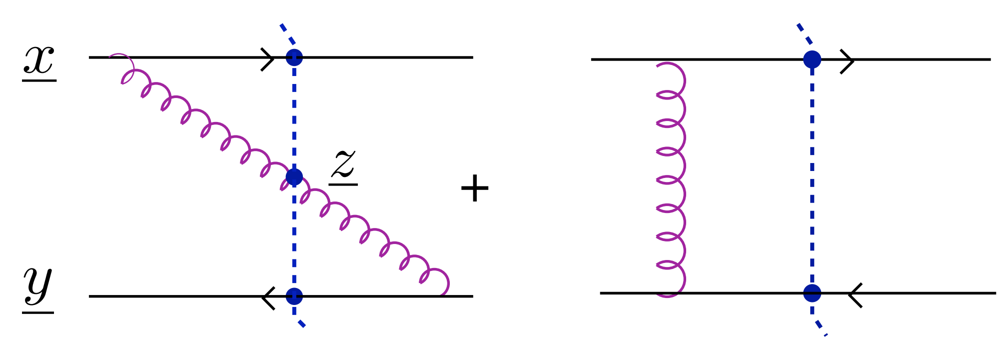
perturbative kernel

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

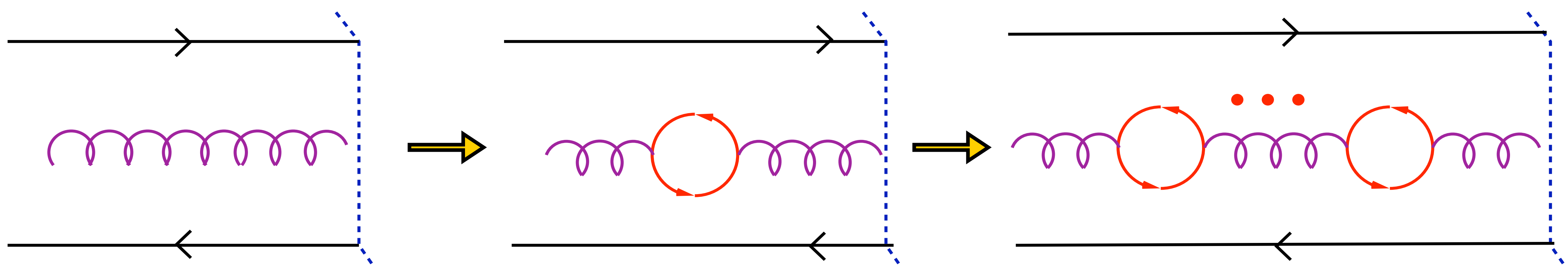
✓ NLO corrections to BK-JIMWLK equations have been calculated recently (Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al). Phenomenological tool: The BK equation including only running coupling corrections in Balitsky's scheme grasps most of the NLO corrections (JLA-Kovchegov)

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

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

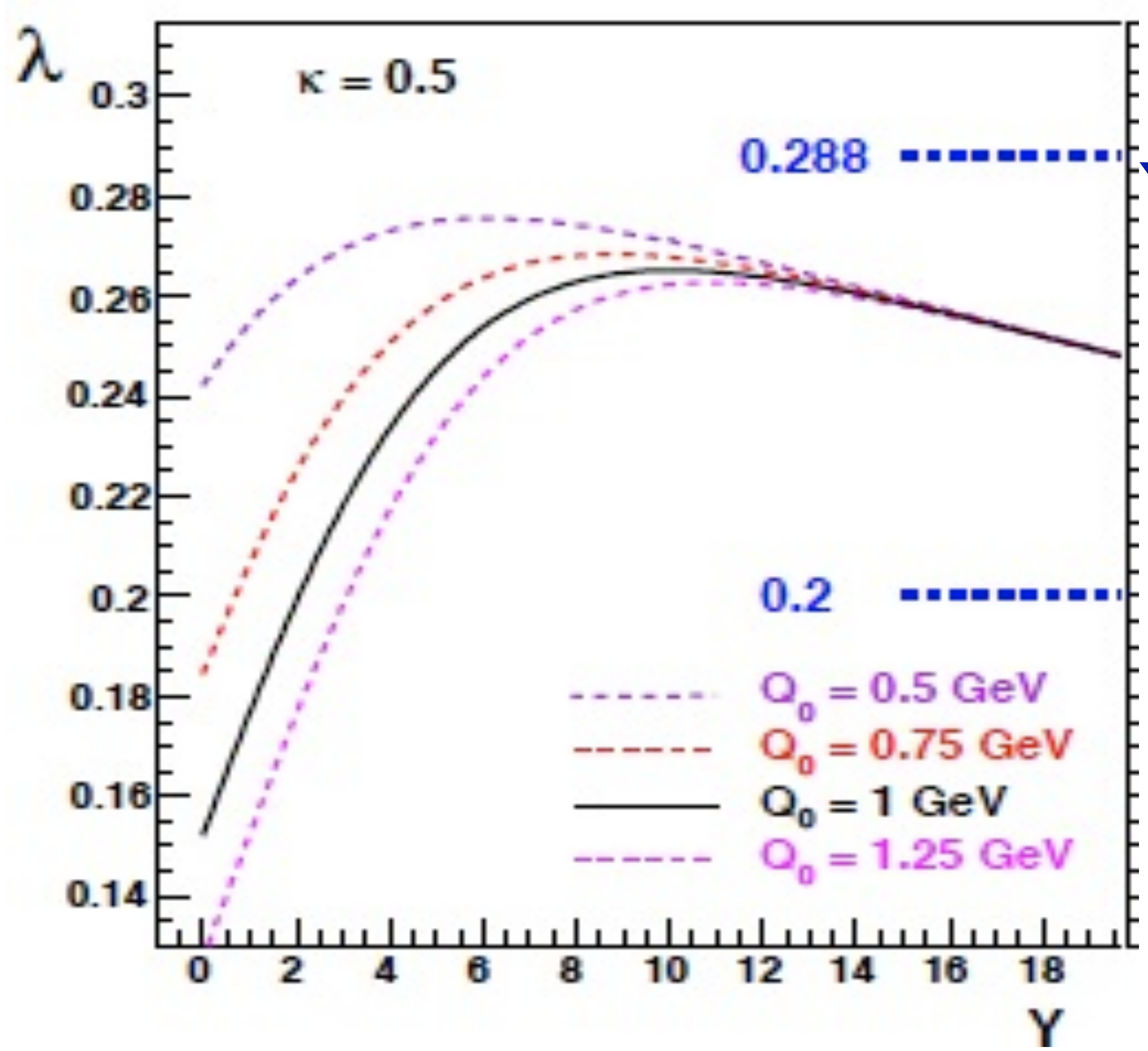


Gluon contribution: $N_f \to -6\pi\beta_2$

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

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

Fitting structure functions

• JLA, N. Armesto, J.G. Milhano, C. Salgado
Phys.Rev.D80:034031,2009;

⇒ Normalization $\int d^2b \to \sigma_0$

⇒ Initial Conditions

GBW: $$\mathcal{N}^{GBW}(r, x_0 = 10^{-2}) = 1 - \exp\left[-\left(\frac{r^2\,Q_{s0}^2}{4}\right)^{\gamma}\right]$$

MV: $$\mathcal{N}^{MV}(r, x_0 = 10^{-2}) = 1 - \exp\left[-\left(\frac{r^2\,Q_{s0}^2}{4}\right)^{\gamma}\ln\left(\frac{1}{r\,\Lambda_{QCD}}\right)\right]$$

⇒ IR regularization and FT

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

3 (4) free parameters:

⇒ Experimental data: ZEUS, H1 (HERA), NMC (CERN-SPS) and E665 (Fermilab) coll.

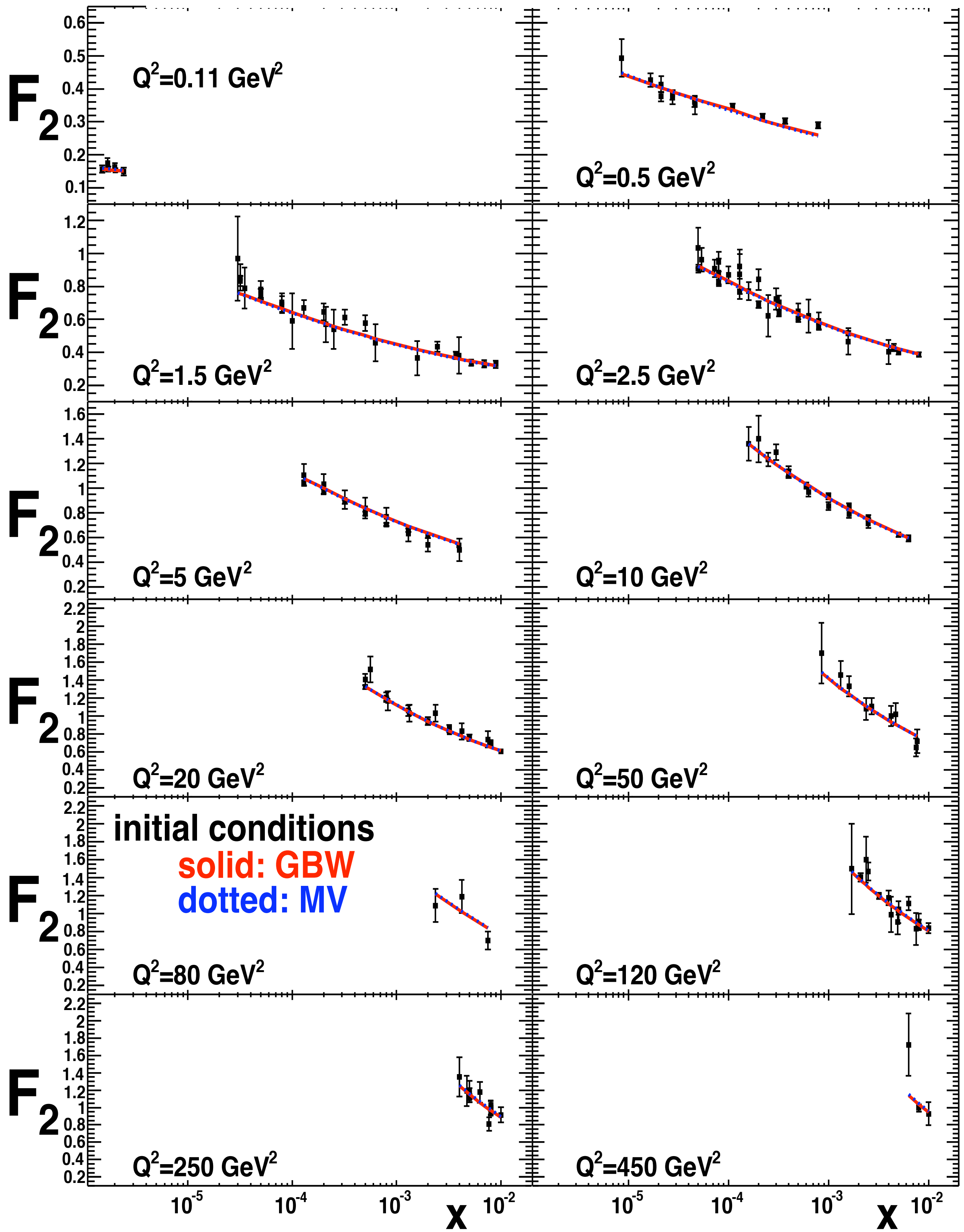
$x \le 10^{-2}$

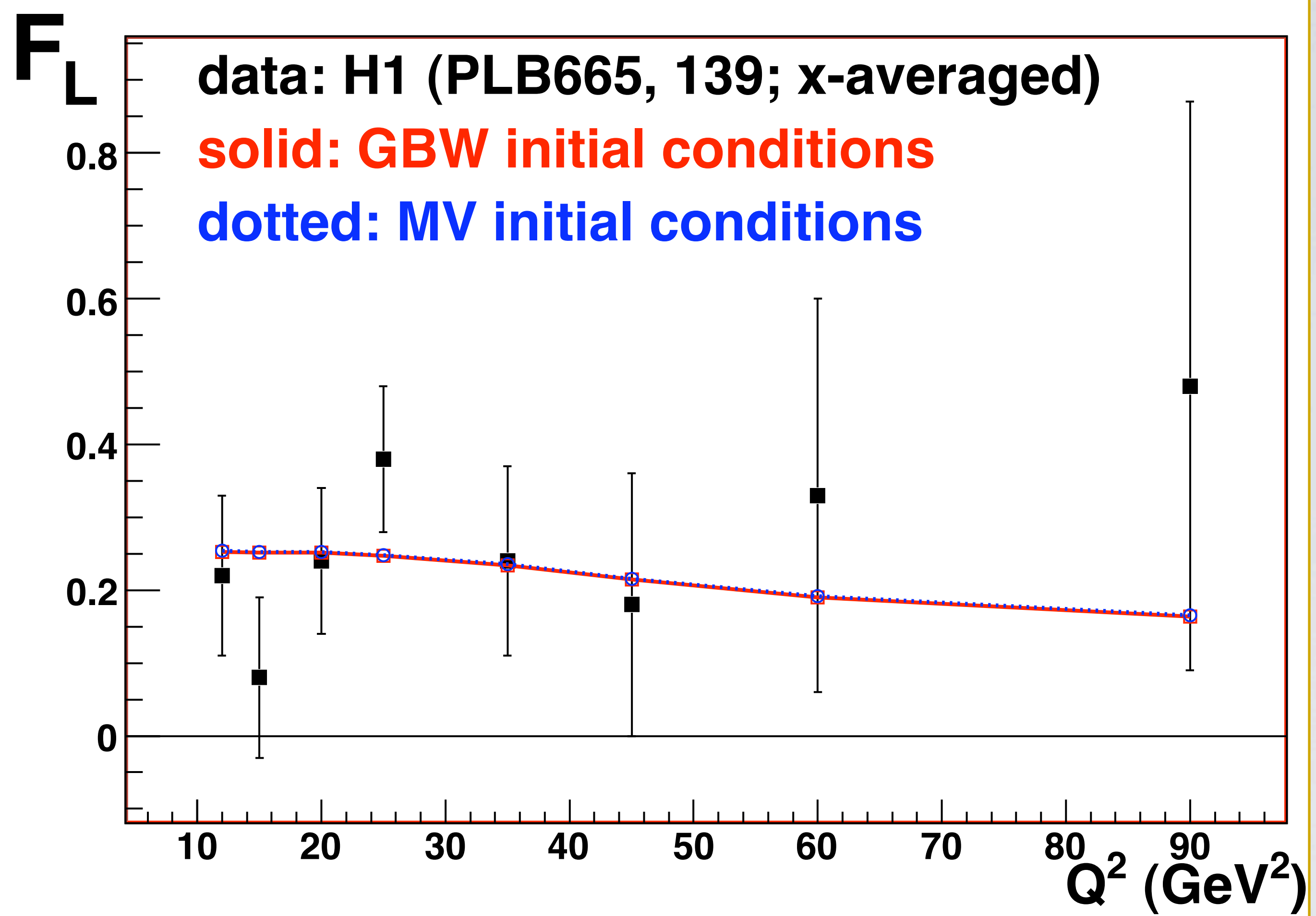
$0.045 < Q^2 < 800\,\mathrm{GeV}^2$ 847 data points

$0.045 < Q^2 < 50\,\mathrm{GeV}^2$ 703 data points

Fits are stable when large Q^2 data are not included in the fit

Initial condition	σ_0 (mb)	Q_{s0}^2 (GeV^2)	C^2	γ	χ^2/d.o.f.
GBW	31.59	0.24	5.3	1 (fixed)	916.3/844=1.086
MV	32.77	0.15	6.5	1.13	906.0/843=1.075





AAMS 1.0

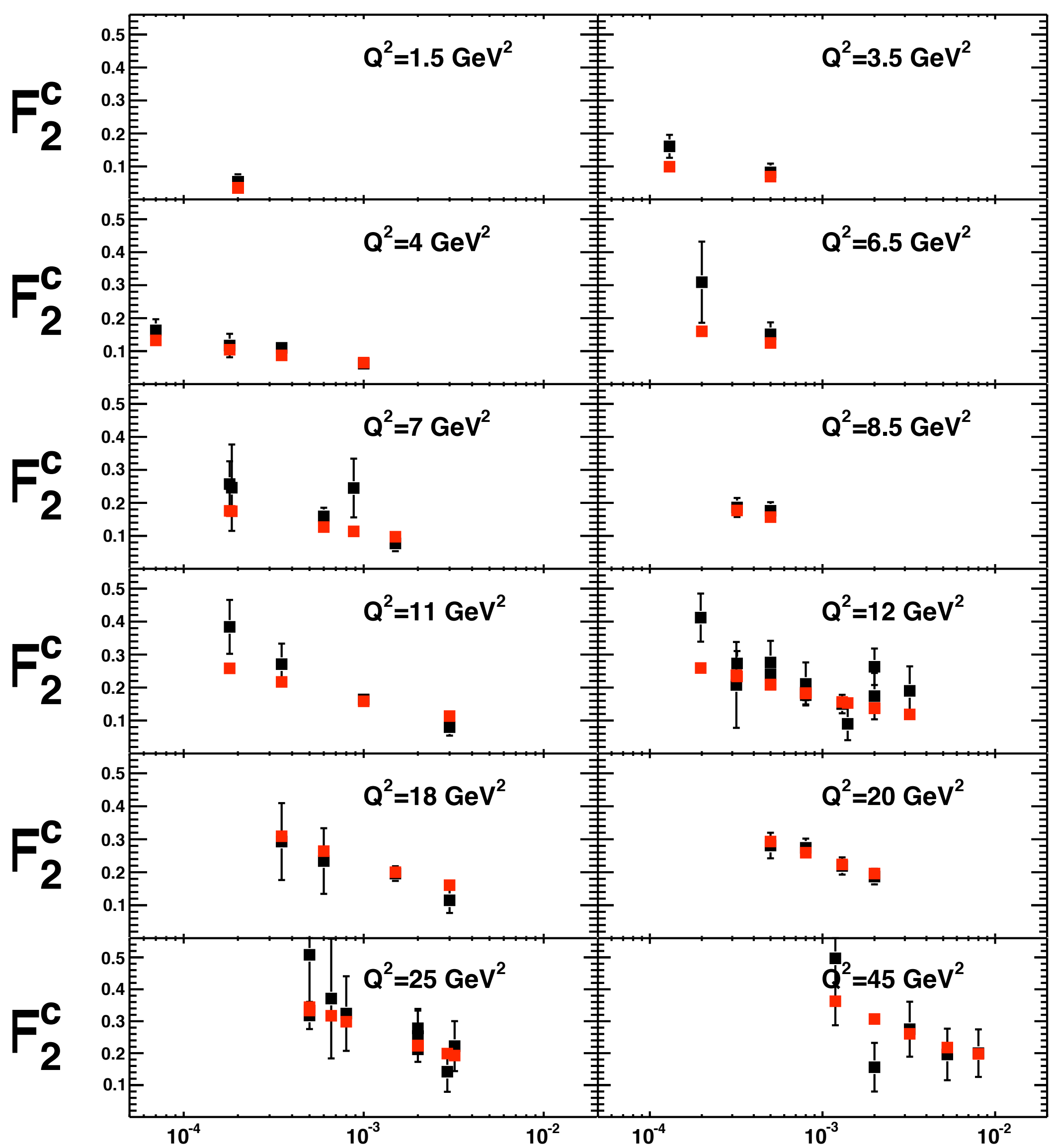
Preliminary results AAMQs 1.0 — AAMS+P. Quiroga in preparation

✓ 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

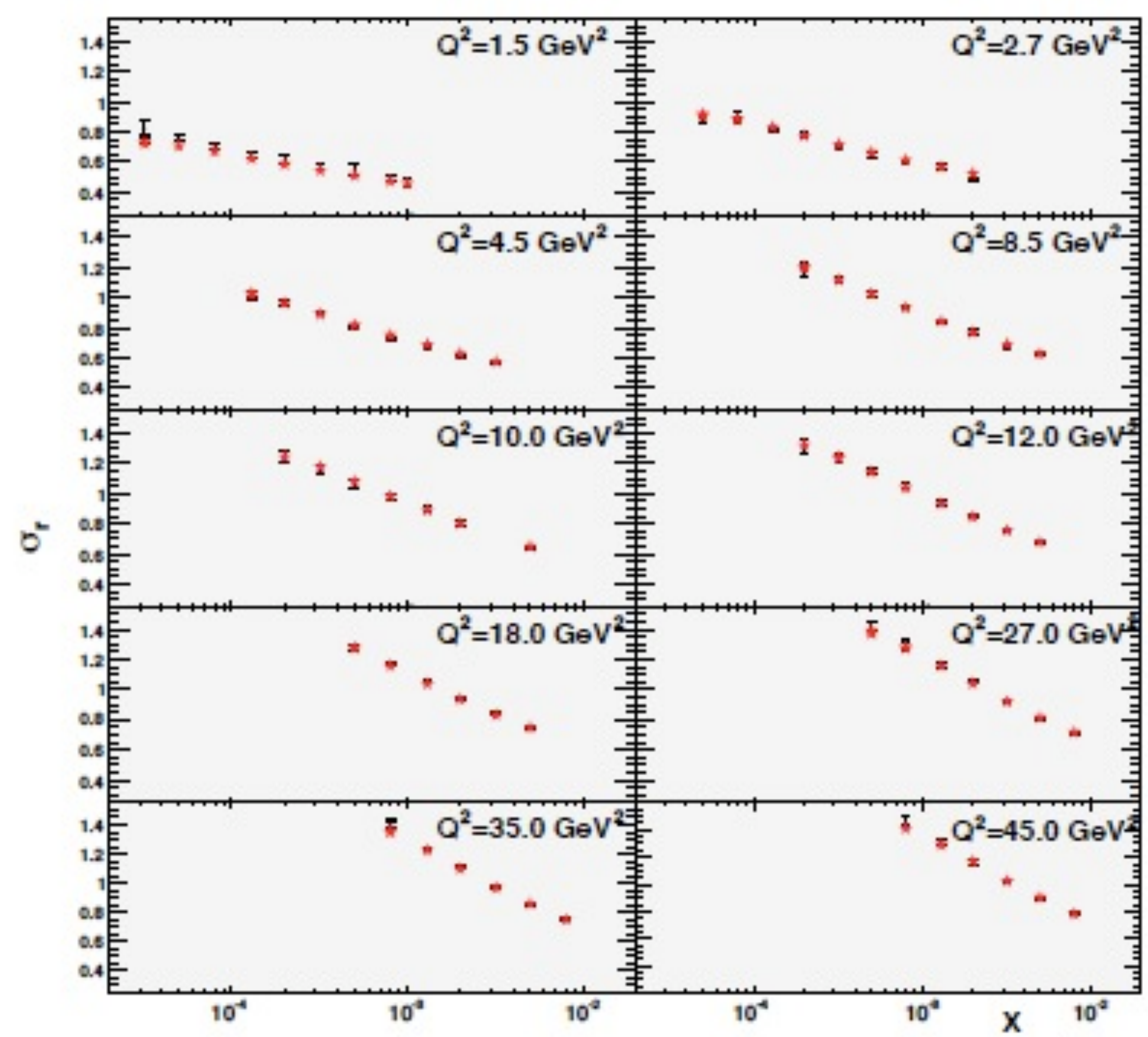
$$\chi^2/d.o.f \approx 1 \div 1.5$$

✓ Inclusion of charm and beauty

$$\sigma_0^{light} > \sigma_0^{charm}$$



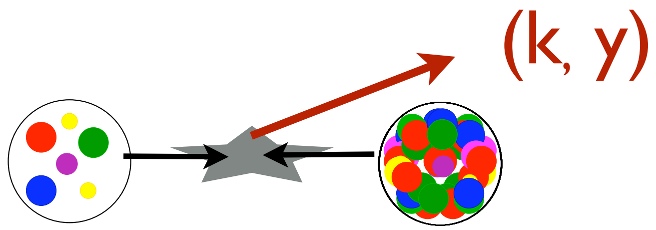
✓ Fits to new HERA data on reduced cross sections



d+Au and p+p collisions at RHIC

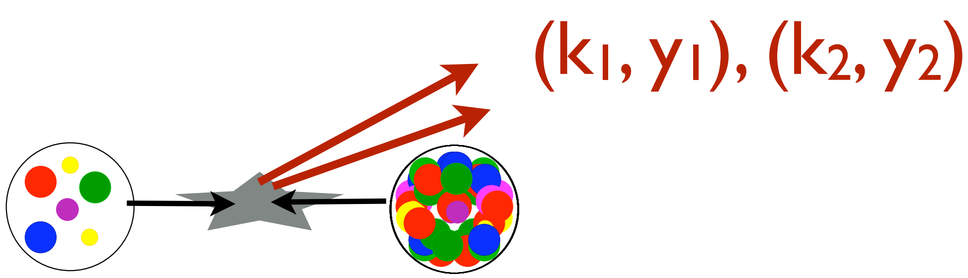
RHIC Kinematics:

- 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!



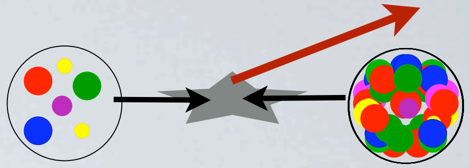
$$x_p = \frac{|k_1| e^{y_1} + |k_2| e^{y_2}}{\sqrt{s}}$$

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

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)

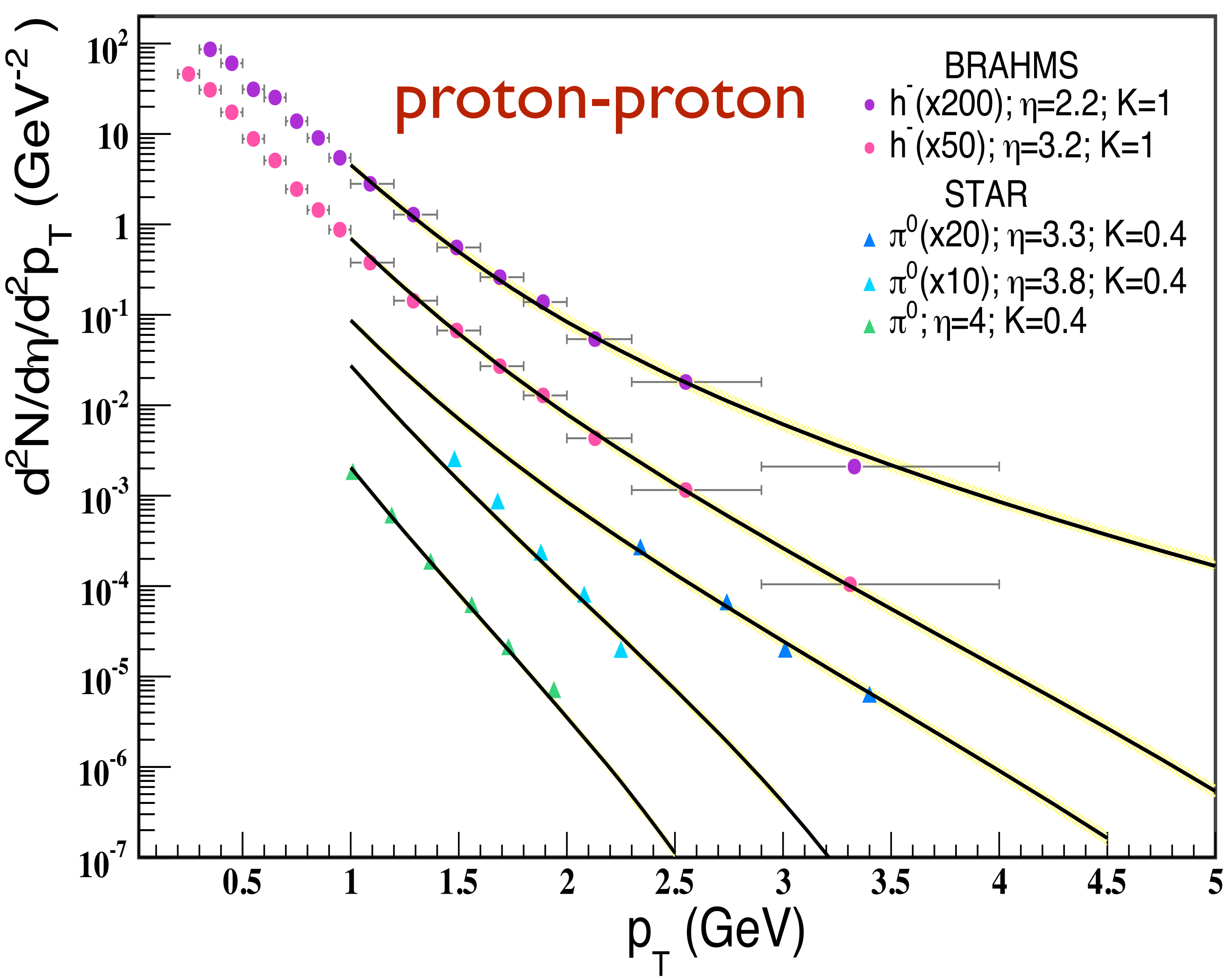
We use CTEQ6 pdf's and de Florian-Sassot ff's

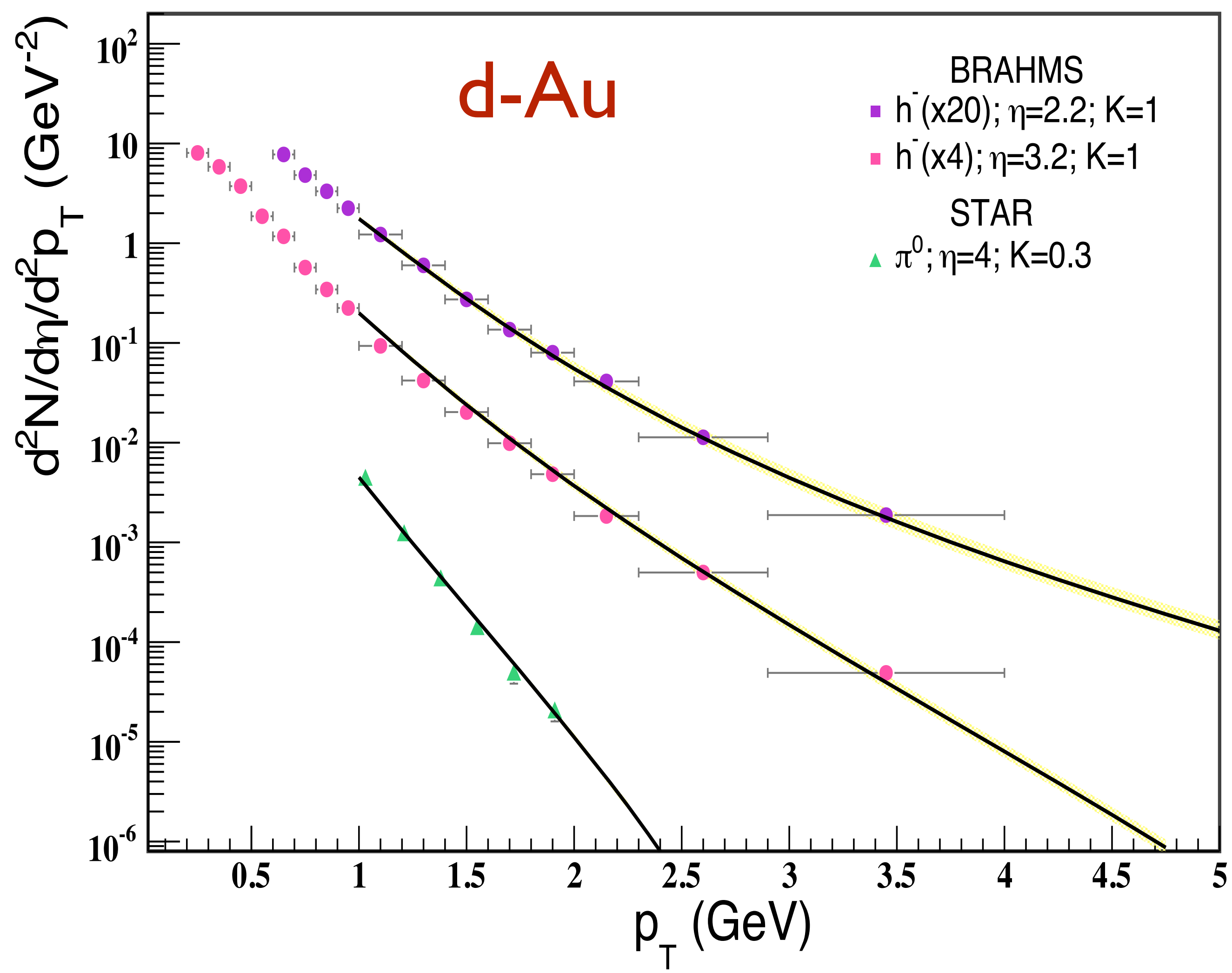
Alternative approaches: Modelization of quantum corrections

(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) ??





$$0.005 \leq x_0 \leq 0.01$$

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

$$0.01 \leq x_0 \leq 0.025$$

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

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

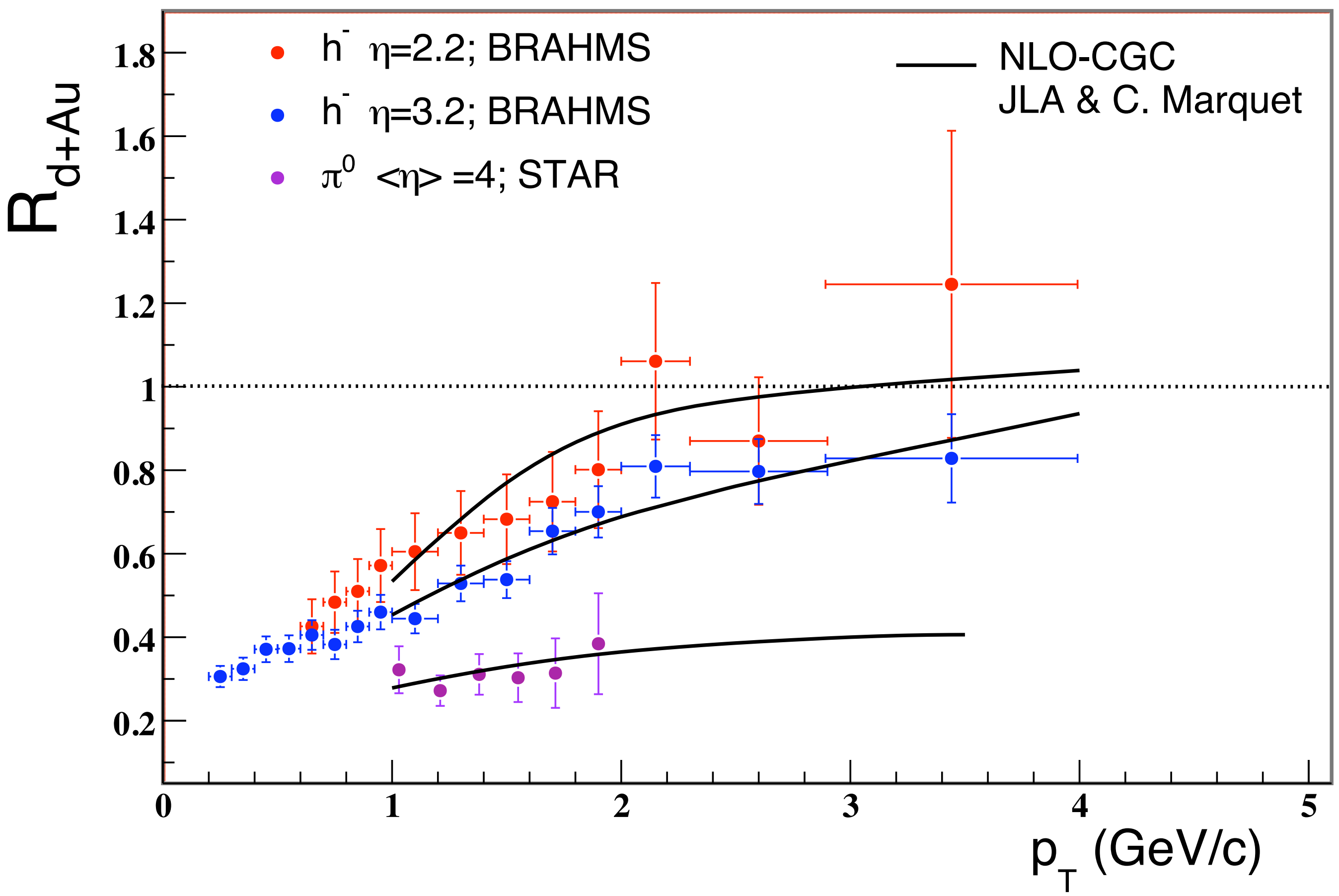
$$0.005 \leq x_0 \leq 0.01$$

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

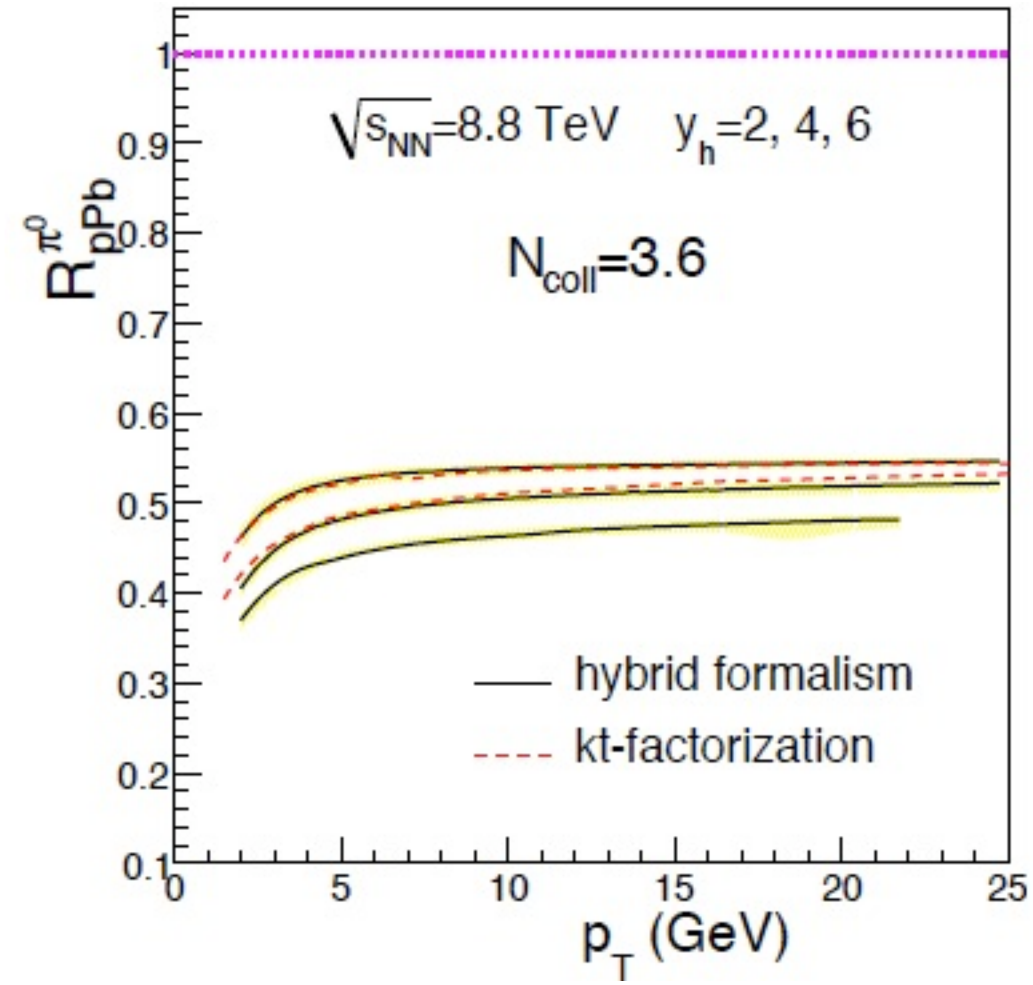
$$Q_{s0,\,gluon}^2 = 1.125\,\mathrm{GeV}^2$$

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

RHIC d+Au



LHC p+Pb

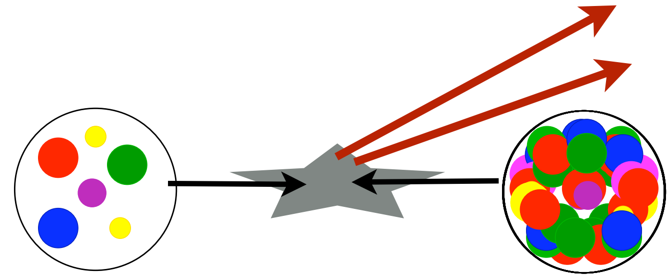


- We predict a similar suppression in p+Pb collisions at the LHC already at central rapidities

⇒ Double Inclusive forward hadron production in the CGC

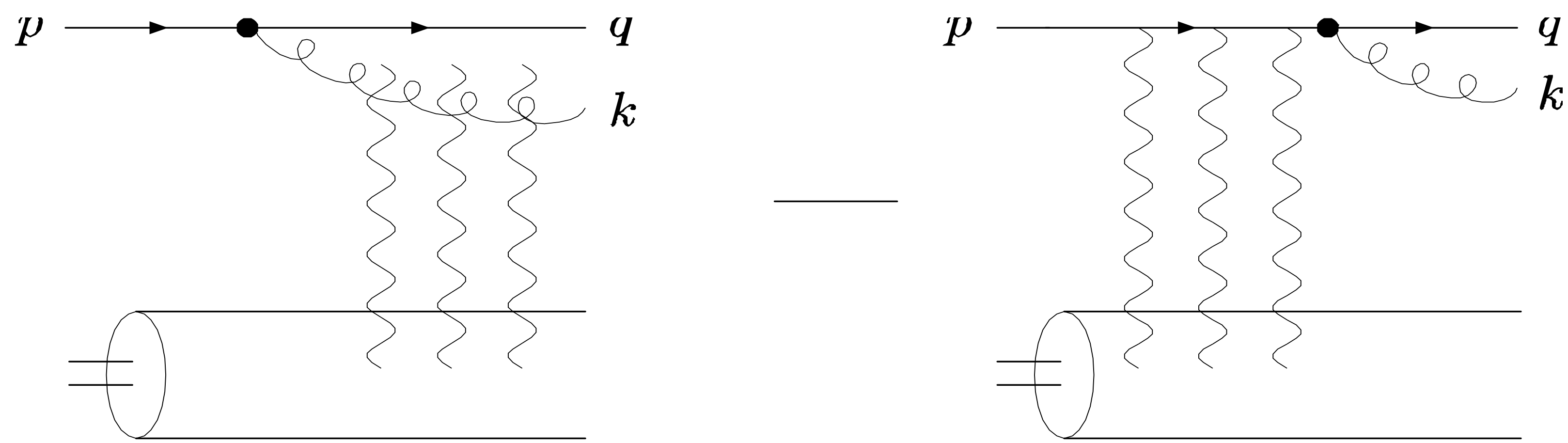
$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

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



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

Cyrille Marquet 07:



hard quark initiating scattering

Fourier transfrom coordinate space to momentum

q-> qg splitting (pQCD)

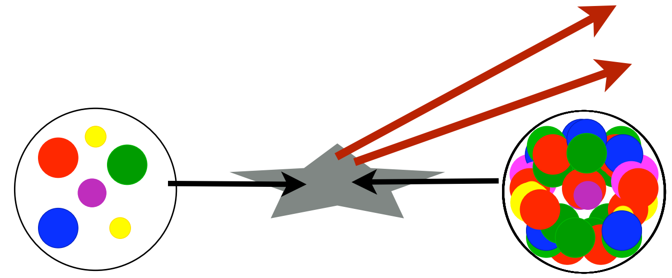
Scattering of the 2-parton system with the CGC target

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

⇒ Double Inclusive forward hadron production in the CGC

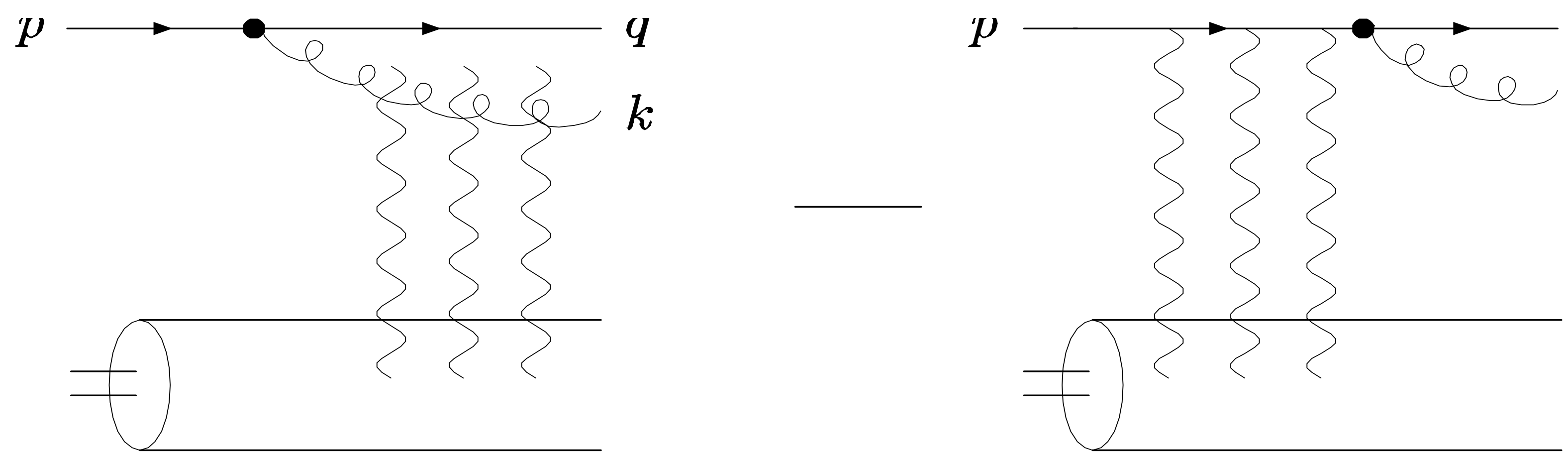
$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

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



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

Cyrille Marquet 07:



hard quark initiating scattering

Fourier transfrom coordinate space to momentum

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

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

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

q-> qg splitting (pQCD)

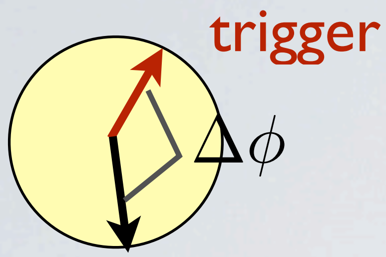
Scattering of the 2-parton system with the CGC target

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

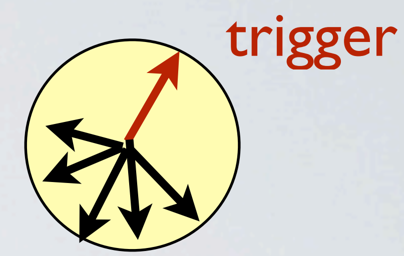
Involves more than 3 and 4 point functions. Calculated in the large Nc limit

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

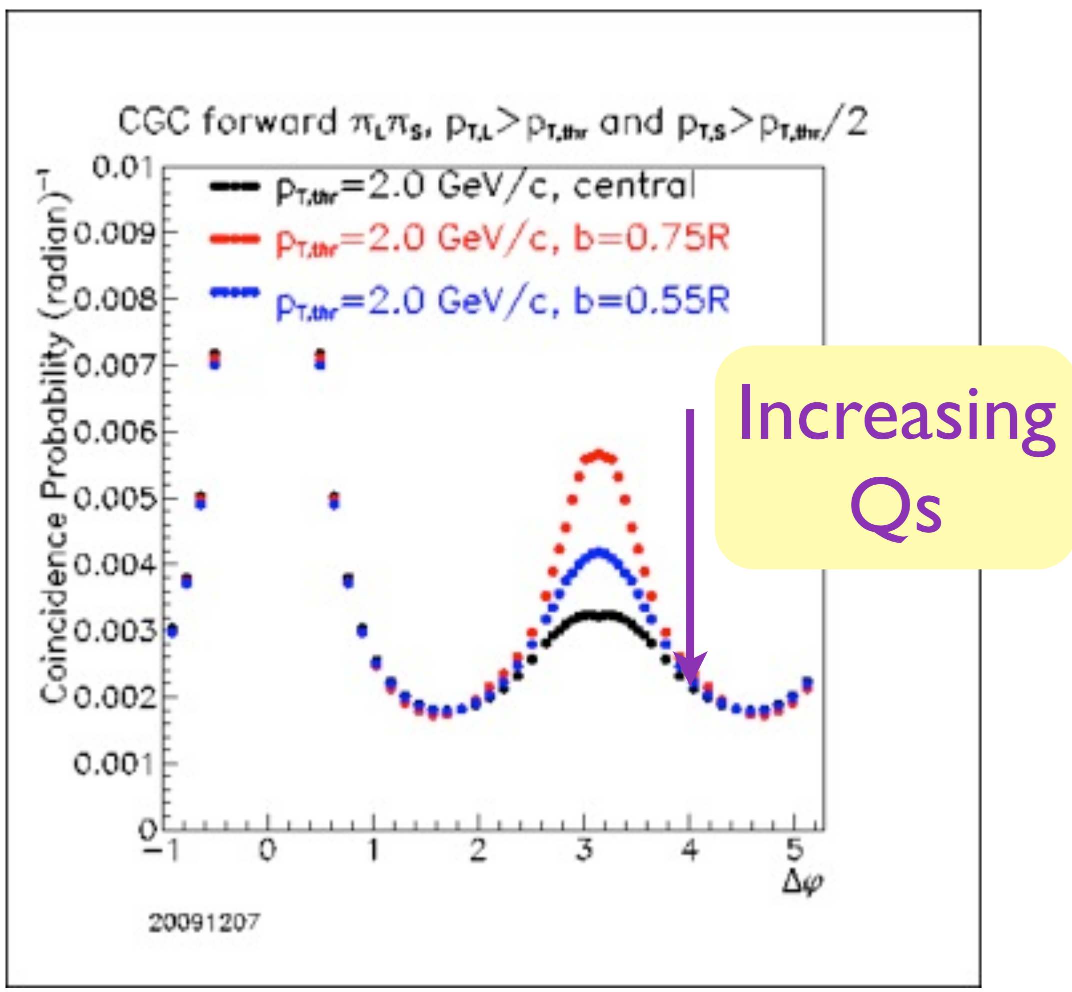
➡ "Coincidence probability" measured by STAR Coll. at forward rapidities:



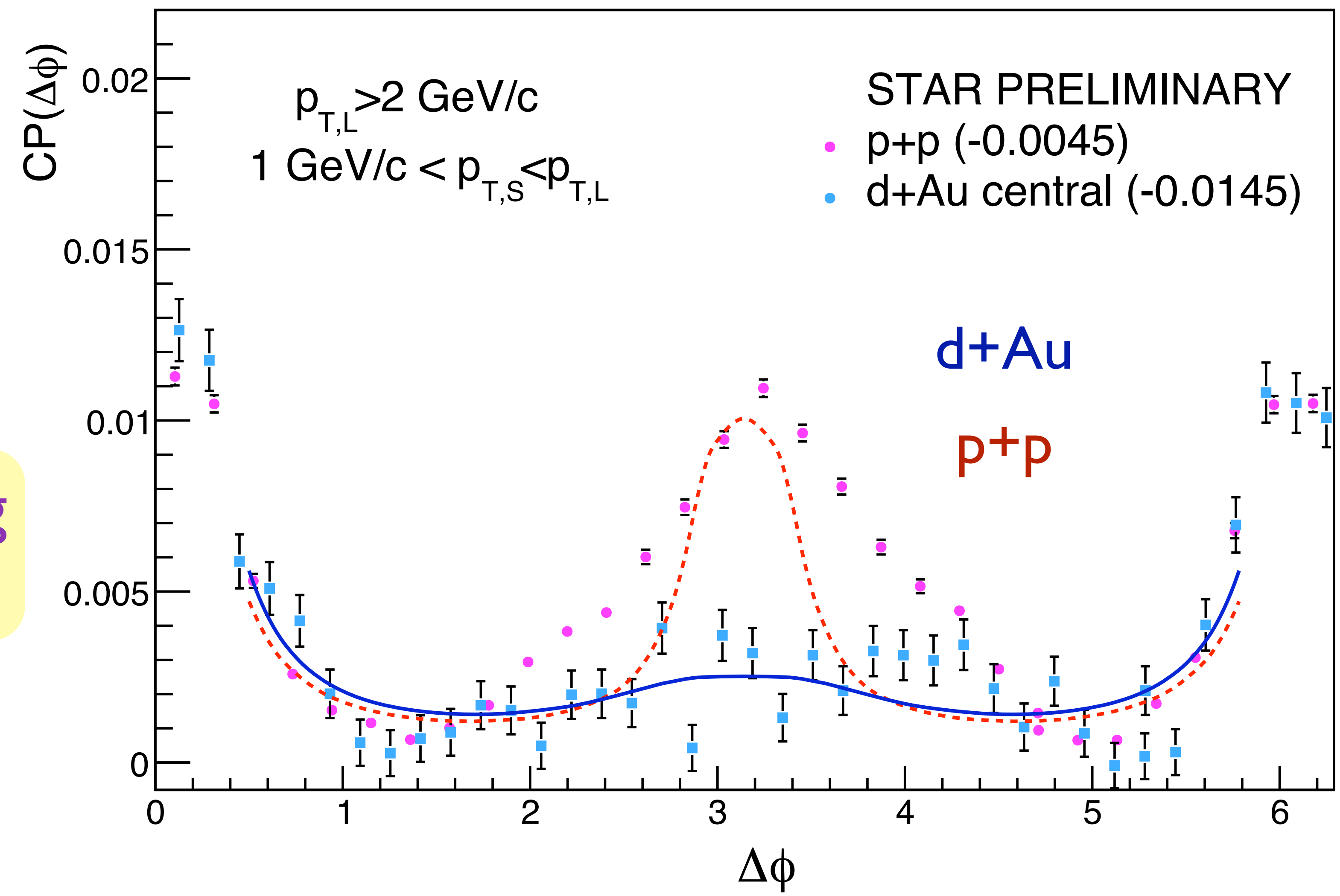
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$



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

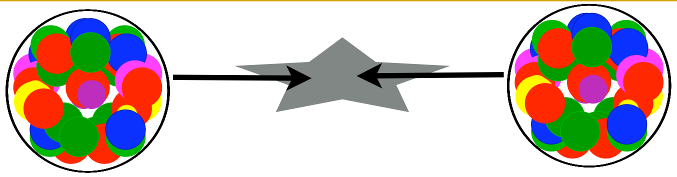


[JLA C. Marquet 10]



Parameter free!!: All info about nucleus w.f. from single inclusive analysis

⇒ Multiparticle production in A+A coll.



RHIC multiplicities smaller than expected.

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

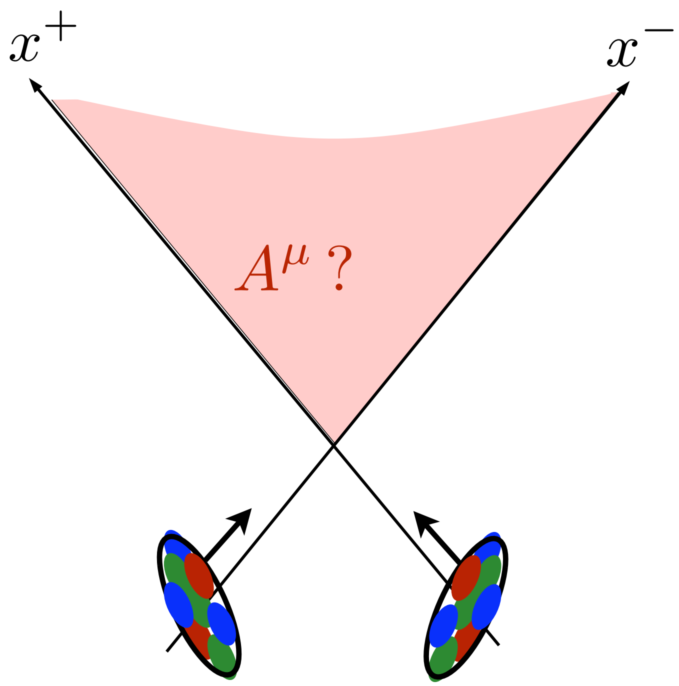
produces particles ~ # scattering centers

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 kt-factorization approaches yield a good description of energy, rapidity and geometry dependence of RHIC data

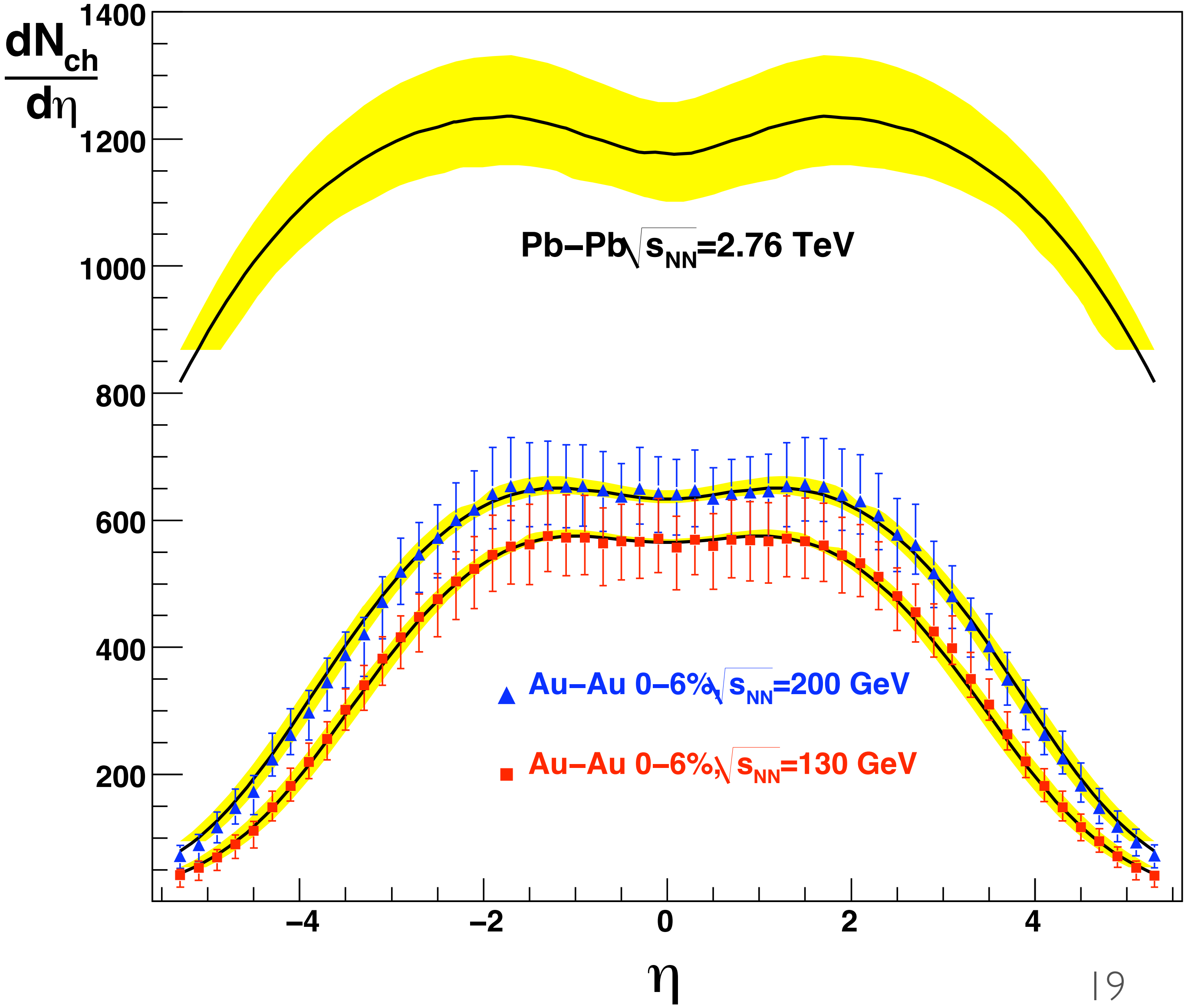
Local parton-hadron duality

$\varphi(x,k) \Rightarrow$ Solutions of BK with running coupling $\times (1-x)^4$

JLA 07

$m_h \approx 0.25\,\mathrm{GeV}, \quad 0.75 \leq Q_0 \leq 1.25\,\mathrm{GeV}, \quad 0.05 \leq x_0 \leq 0.1$

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



kt-factorization approaches yield a good description of energy, rapidity and geometry dependence of RHIC data

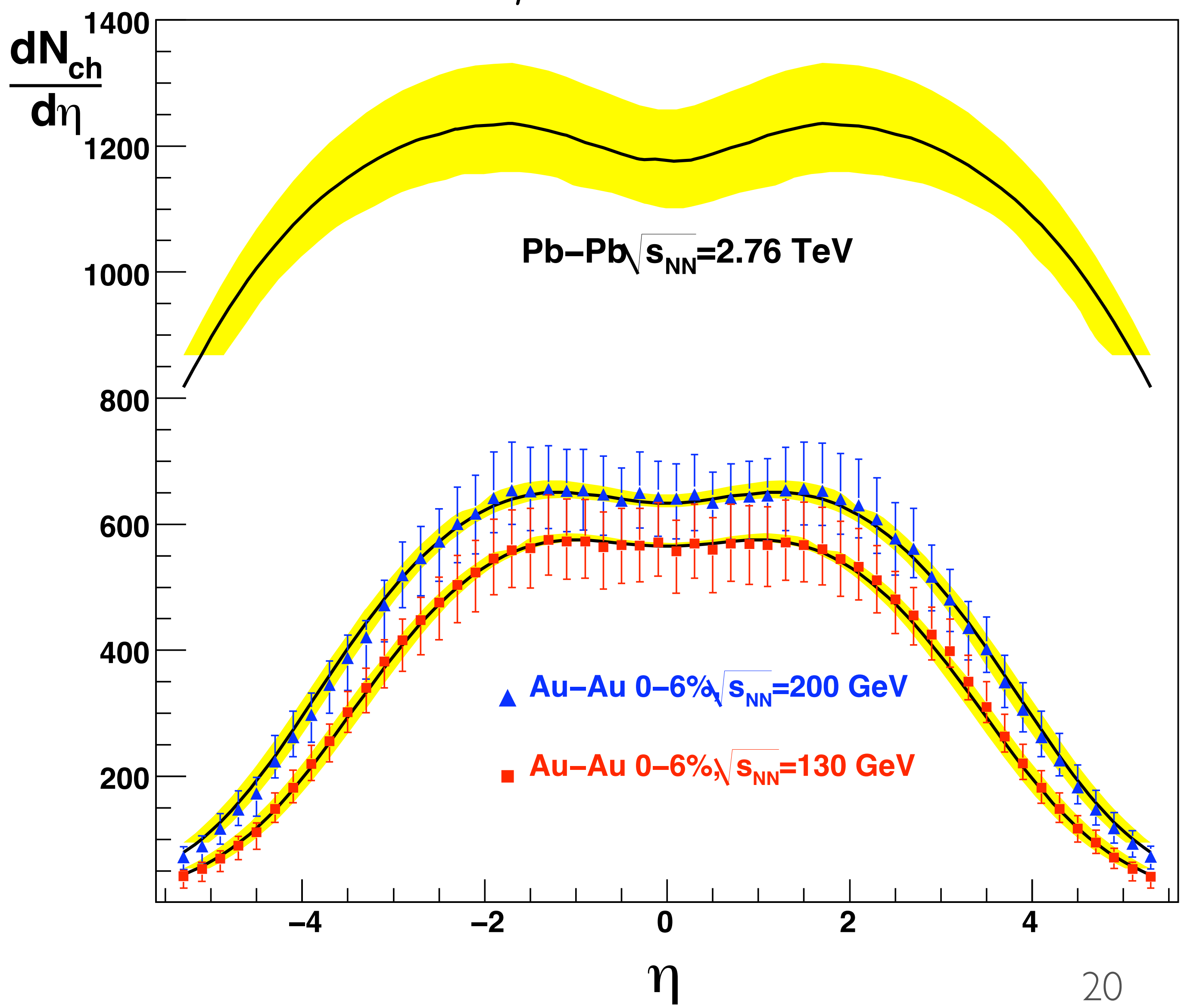
Local parton-hadron duality

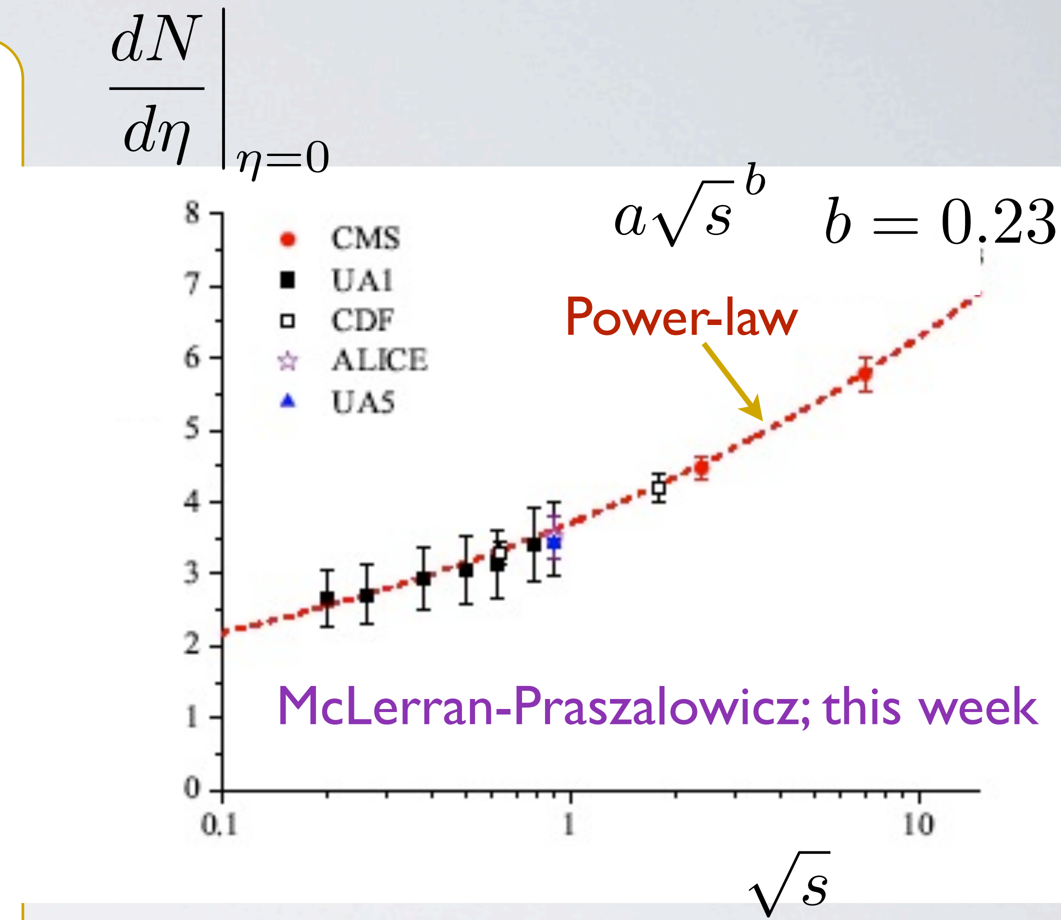
$\varphi(x,k) \Rightarrow$ Solutions of BK with running coupling $\times (1-x)$

JLA 07

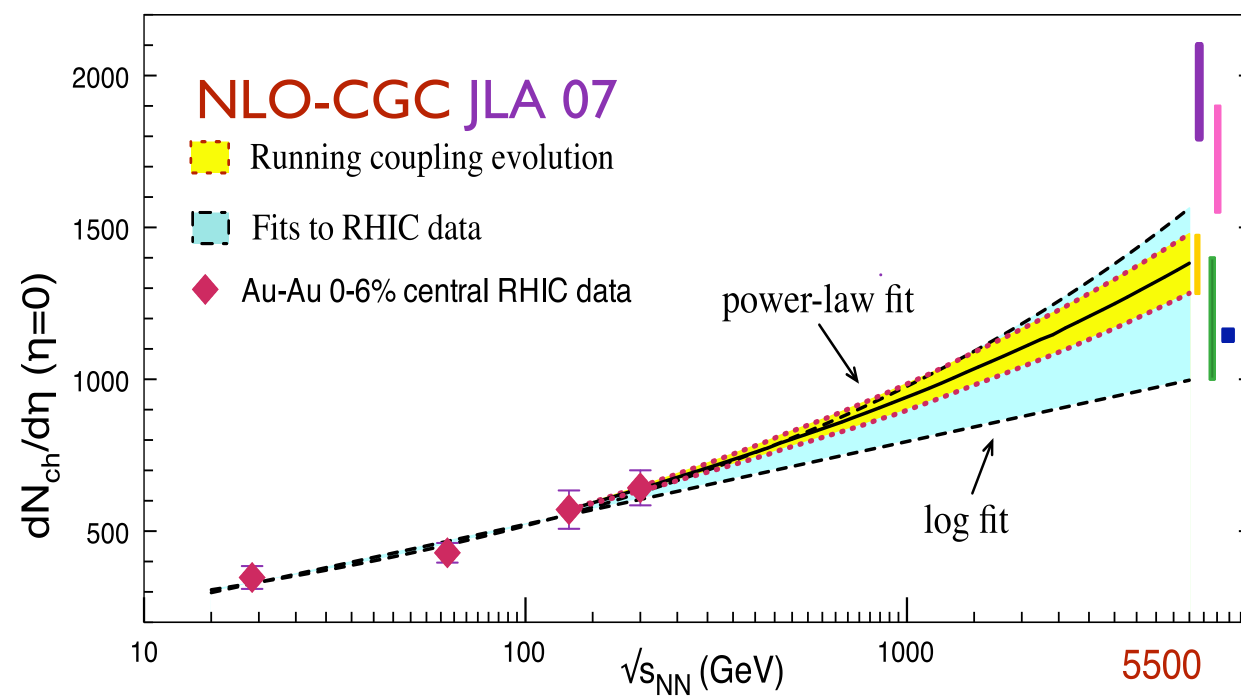
$$m_h \approx 0.25\,\mathrm{GeV}, \quad 0.75 \leq Q_0 \leq 1.25\,\mathrm{GeV}, \quad 0.05 \leq x_0 \leq 0.1$$

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





CGC prediction features the same power-law dependence as p+p LHC data



Conclusions

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

⇒ Good description of latest e+p data, including heavy flavour

⇒ Good description of forward particle production @ RHIC

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

Thanks!!!

Back up slides