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

Javier L. Albacete
IPhT-CEA-Saclay

ICHEP, July 22-29, 2010
Paris

OUTLINE

- ✓ The Color Glass Condensate (pocket introduction)
- ✓ NLO CGC phenomenology at HERA. Structure functions
- ✓ NLO CGC phenomenology at RHIC
  - ➡ Single inclusive forward hadron production
- ✓ Summary

References:

- JLA and Y. Kovchegov, Phys.Rev.D75:125021,2007.
- JLA Phys.Rev.Lett.99:262301,2007
- JLA, N. Armesto, J.G. Milhano, P. Quiroga and C. Salgado Phys.Rev.D80:034031,2009; in preparation 2010
- JLA, C. Marquet Phys.Lett.B687:174-179,2010

2

The Color Glass Condensate (CGC)

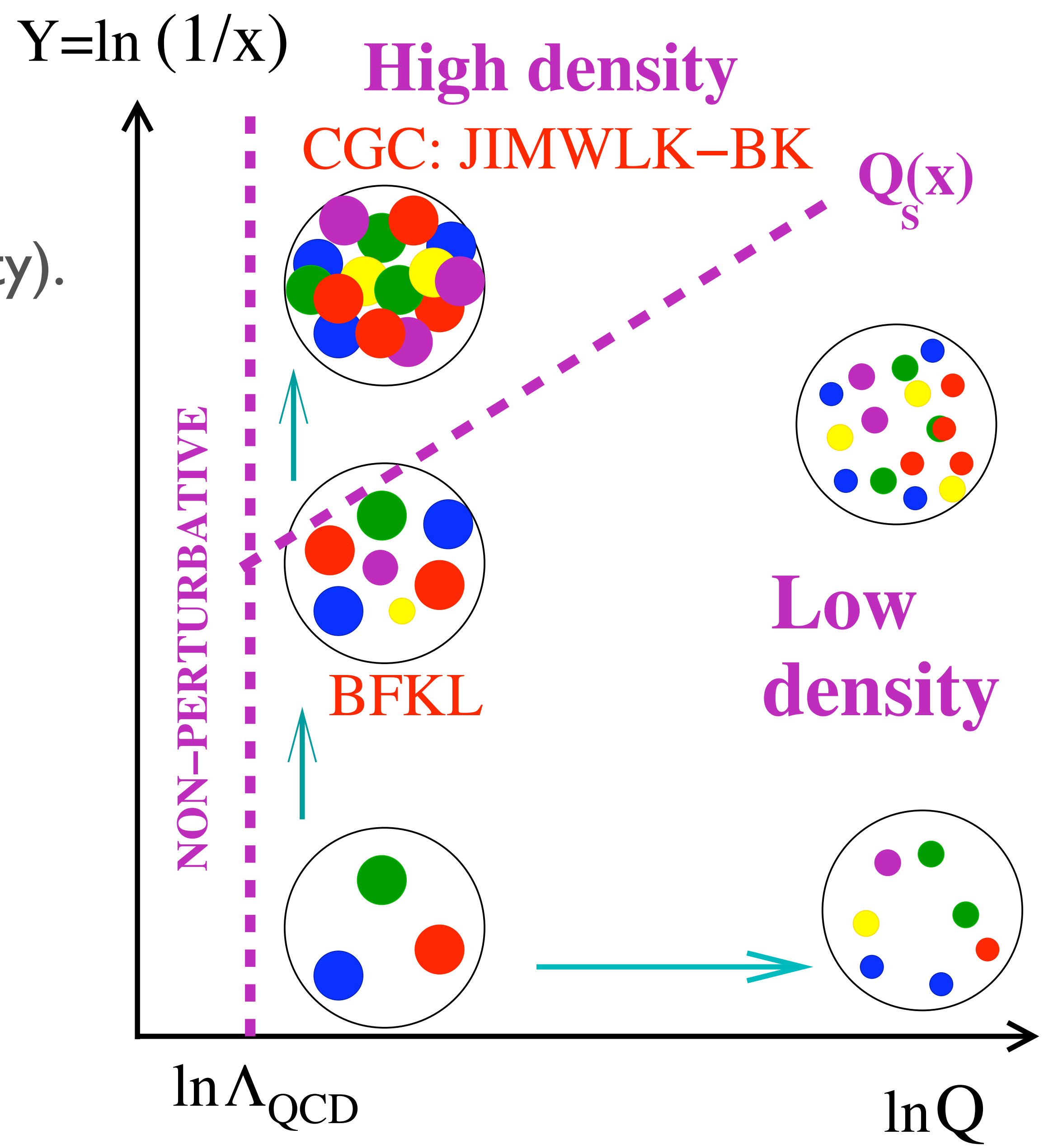
✓At fixed virtuality and small-x the gluon density within a hadron becomes large and non-linear "recombination" effects become important (Unitarity).

CGC

- ✓ Semiclassical methods to compute g.d.f.
- ✓ Description of particle production in "dense" partonic environment
- ✓ Non-linear small-x BK-JIMWLK renormalization group equations for hadron's wavefunction

$$\frac{\partial \varphi(x)}{\partial \ln(x_0/x)} \approx \tilde{K} \otimes \varphi - \varphi^2$$

radiation recombination



Saturation scale

CGC at NLO

✓ LO BK-JIMWLK resums terms ~ αs ln(1/x) terms + non-linearities. Impossible to reconcile with experimental data

✓ NLO corrections to BK-JIMWLK equations have been calculated recently. They have a rather complicated structure (Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al).

✓ Phenomenological tool: The BK equation (large-Nc limit) including only running coupling corrections in Balitsky's scheme grasps most of the effect of 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:

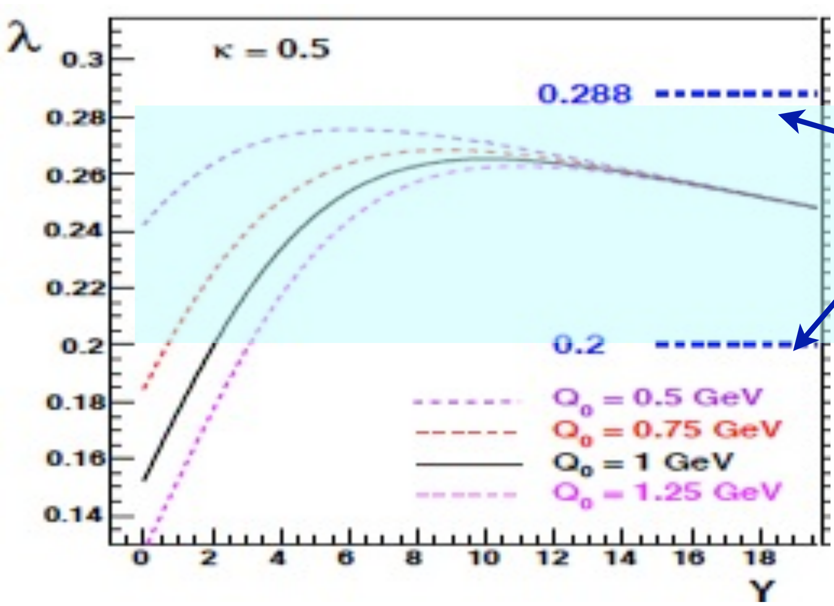
$$K^{\rm run}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\,r_2^2}+\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)}-1\right)+\frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)}-1\right)\right]$$

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:

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

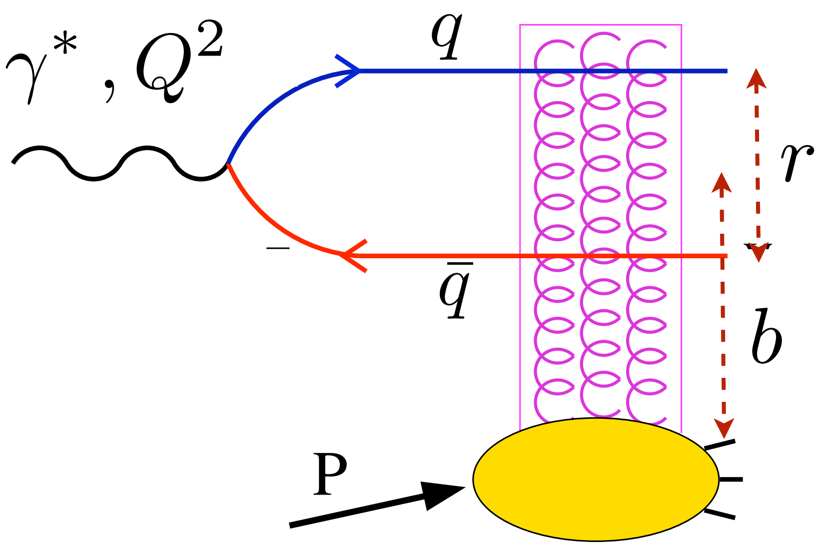


values compatible with DIS and HIC data

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

HERA phenomenology. Dipole model of DIS

⇒ Dipole models including saturation describe a large amount of HERA data (inclusive and longitudinal structure functions, diffraction, DVCS, VM, geometric scaling..).



Calculable in QED

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

$$\sigma^{dip}(x, r) = 2 \int d^2 b \mathcal{N}(x, b, r) \rightarrow$$

Dipole cross section. Strong interactions and x-dependence are here

Small-x dynamics of the dipole amplitude can be calculated by solving the rcBK evolution equation

Fitting structure functions

⇒ 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.

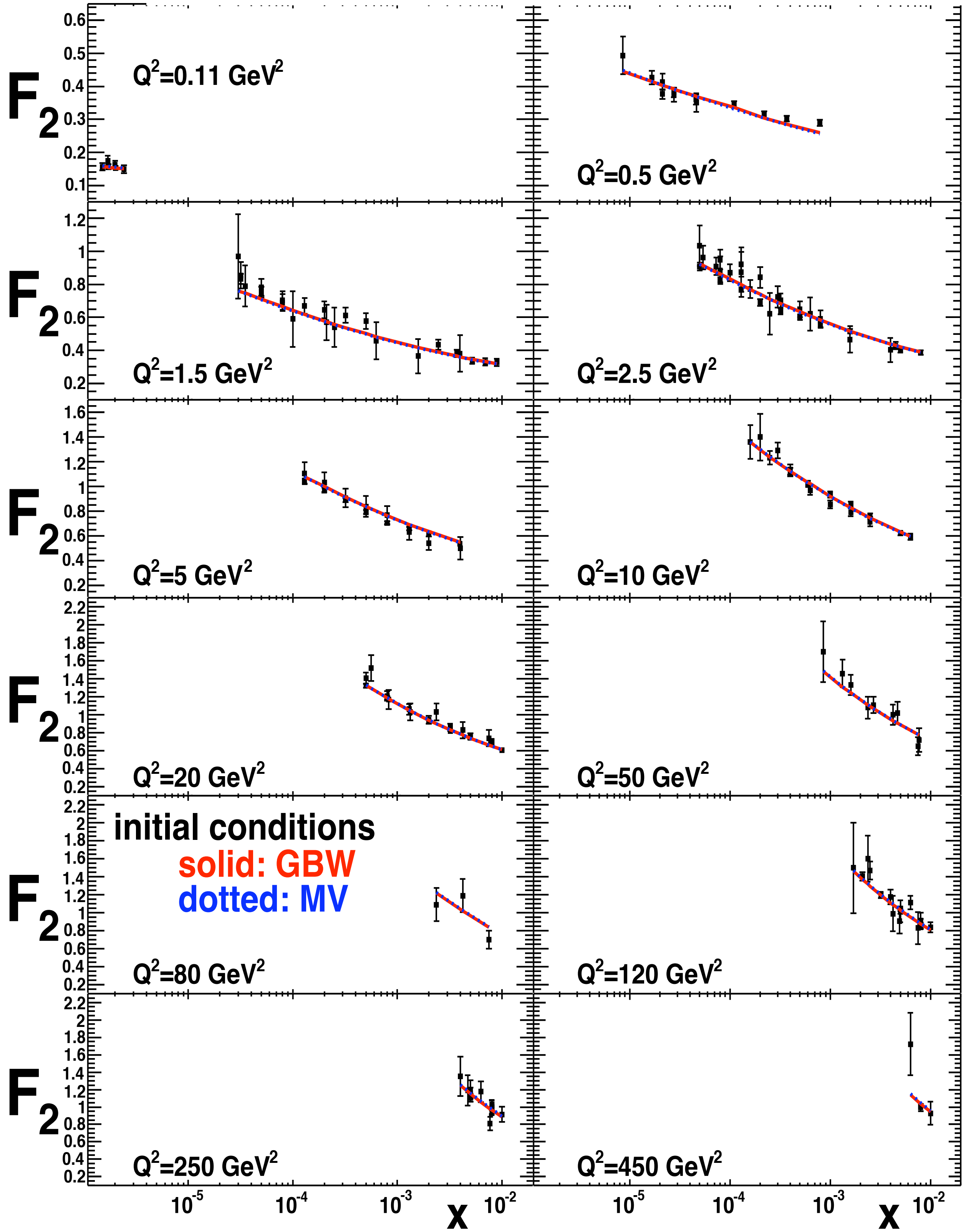
$x \leq 10^{-2}$

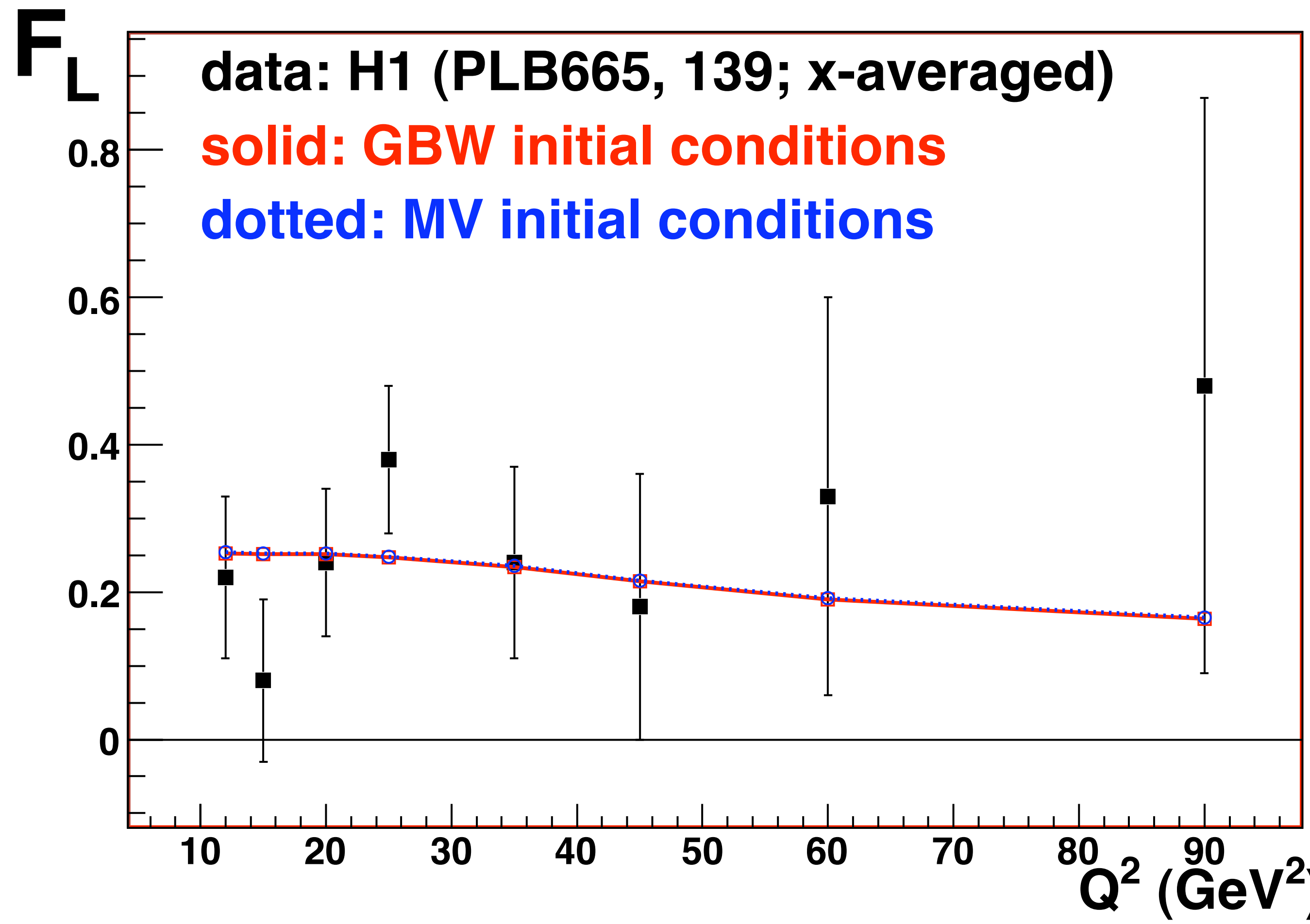
$0.045 < Q^2 < 800\,\text{GeV}^2$ — 847 data points

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

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

Initial condition	σ_0 (mb)	Q^2_{s0} (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

- JLA, N. Armesto, J.G. Milhano, P. Quiroga and C. Salgado Phys.Rev.D80:034031,2009;

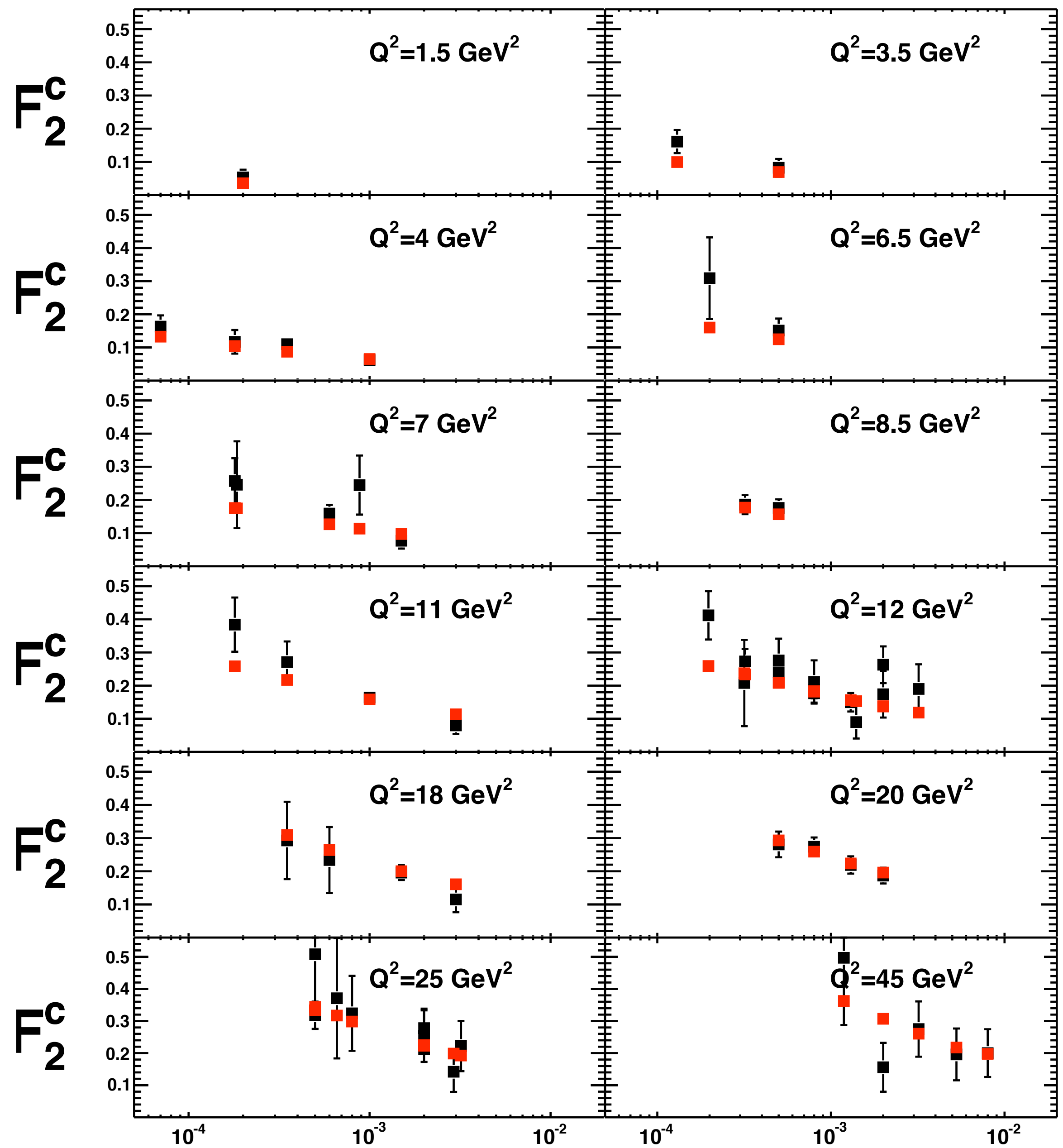
Preliminary results AAMQs 1.0

AAMS+P. Quiroga in preparation

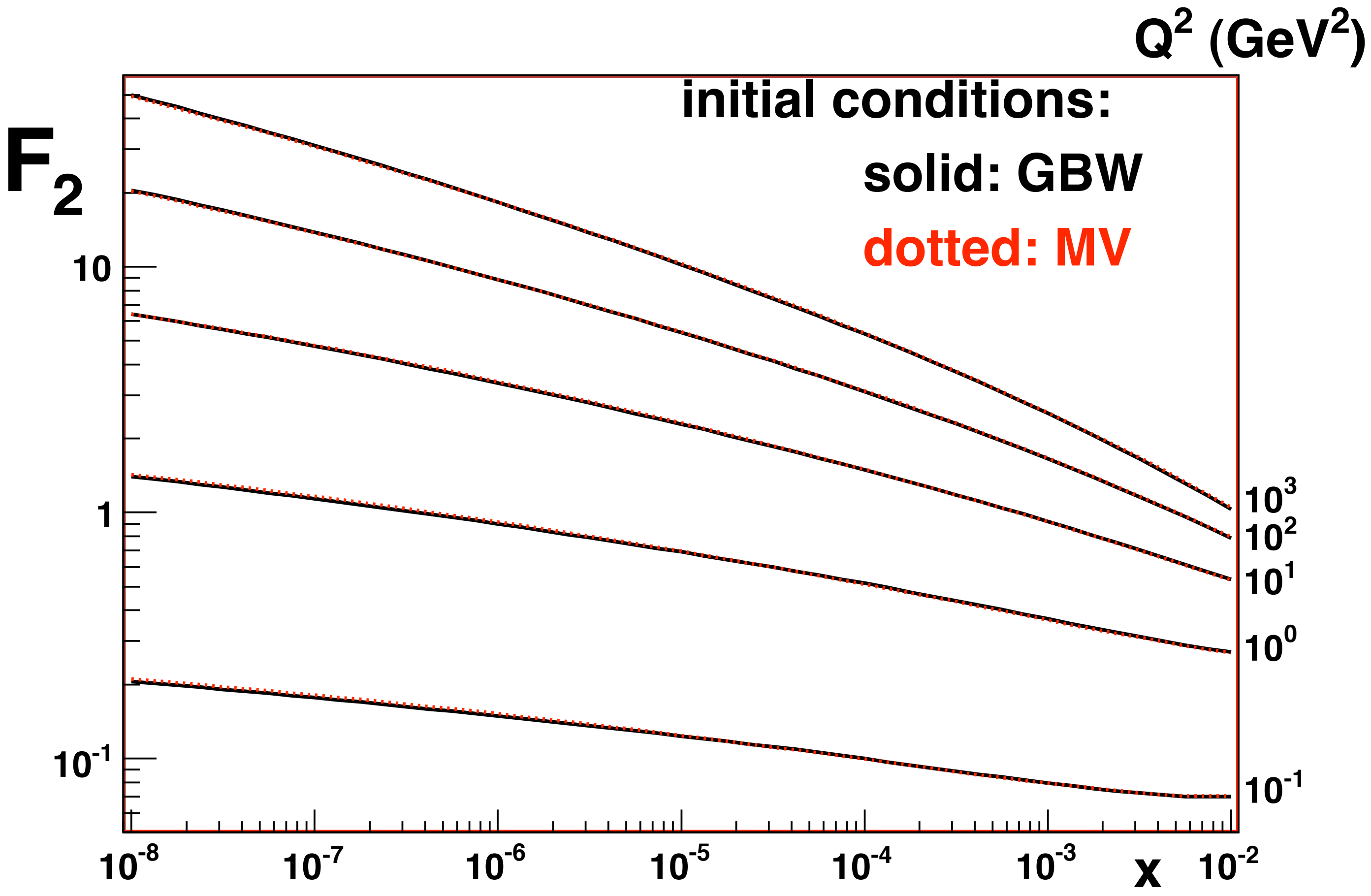
✓ Good fits to data on reduced cross sections from combined analysis by H1 and ZEUS coll (much smaller error bars!). Fit parameters stable wrt to AAMS 1.0 analysis

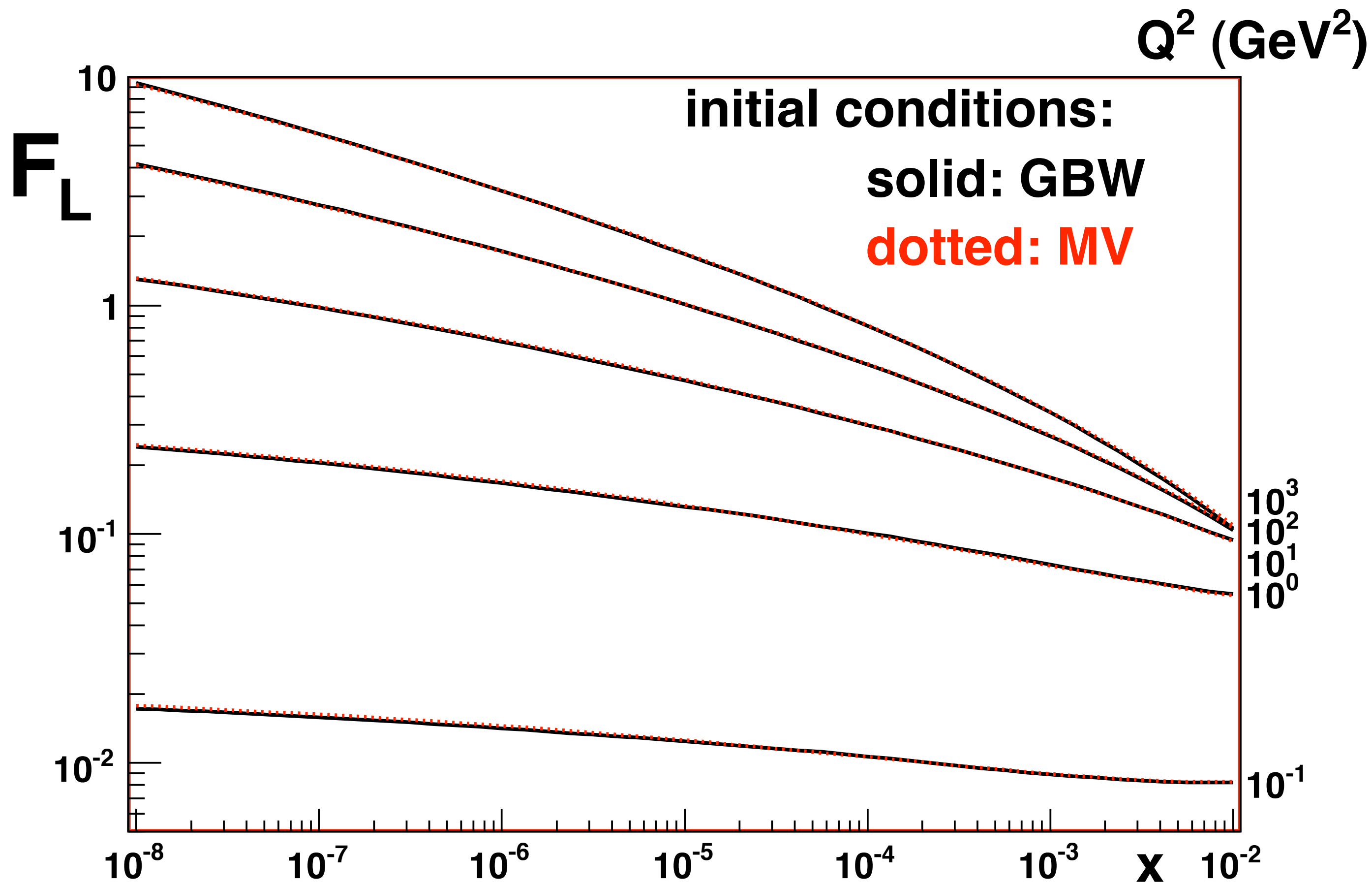
$$\chi^2/d.o.f \approx 1 \div 1.5$$

✓ Inclusion of heavy quark (charm and beauty) contribution. $\sigma_0^{light} > \sigma_0^{charm}$



⇒ Predictions for future colliders EIC, LHeC:





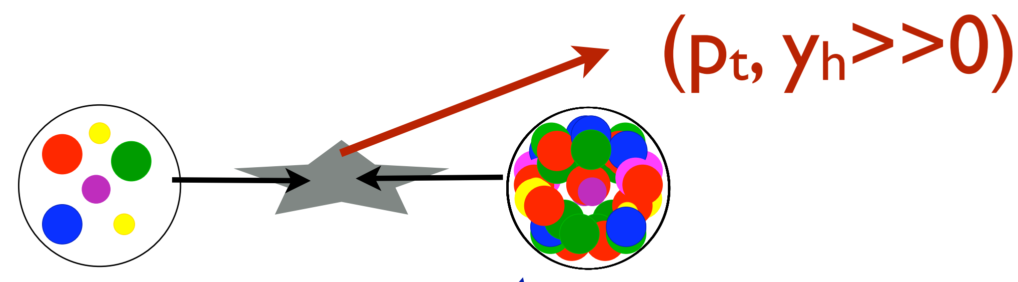
- Extrapolation to lower-x completely driven by non-linear pQCD dynamics
- Almost insensitive to i.c. Good!!!
- Saturation effects are stronger for F_L than for F_2
- F_L is a very sensitive probe of the gluon d.f. Different calculations yield pretty different predictions in the low-x low-Q2 region

Inclusive particle production @ RHIC and the LHC

c.f. C. Marquet's talk on double inclusive production

⇒ Single Inclusive forward hadron production

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



large-x parton from proj. (pdf)

small-x glue from target (CGC)

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

fragmentation

(Dumitru, Jalilian-Marian)

unintegrated gluon distribution

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

In order to ensure $x_1 \geq x_0$, $x_2 \leq x_0$ with $x_0 \approx 0.01 \longrightarrow y_h \geq 2$

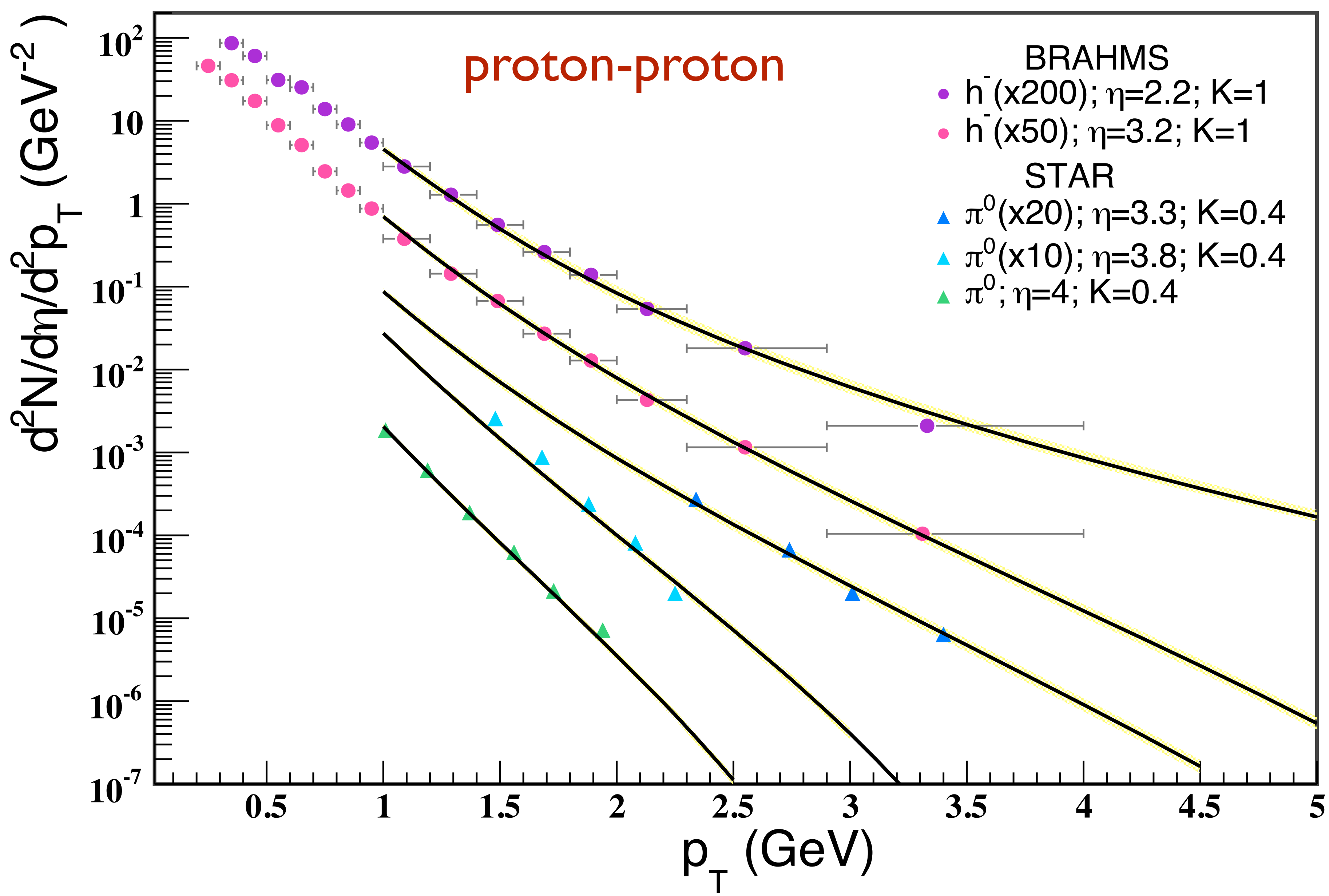
We allow for a rapidity dependent K-factors to account for the normalization

We use CTEQ6 pdf's and de Florian-Sassot ff's. We only consider MV initial conditions

RHIC data at $s^{1/2}$ = 200 GeV; $y_h \geq 2$

- Very good description of forward yields in proton+proton collisions.
- parameters compatible with analysis of HERA data for structure functions in e+p scattering
- K=1 for h^-. K=0.4 for neutral pions (?)

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

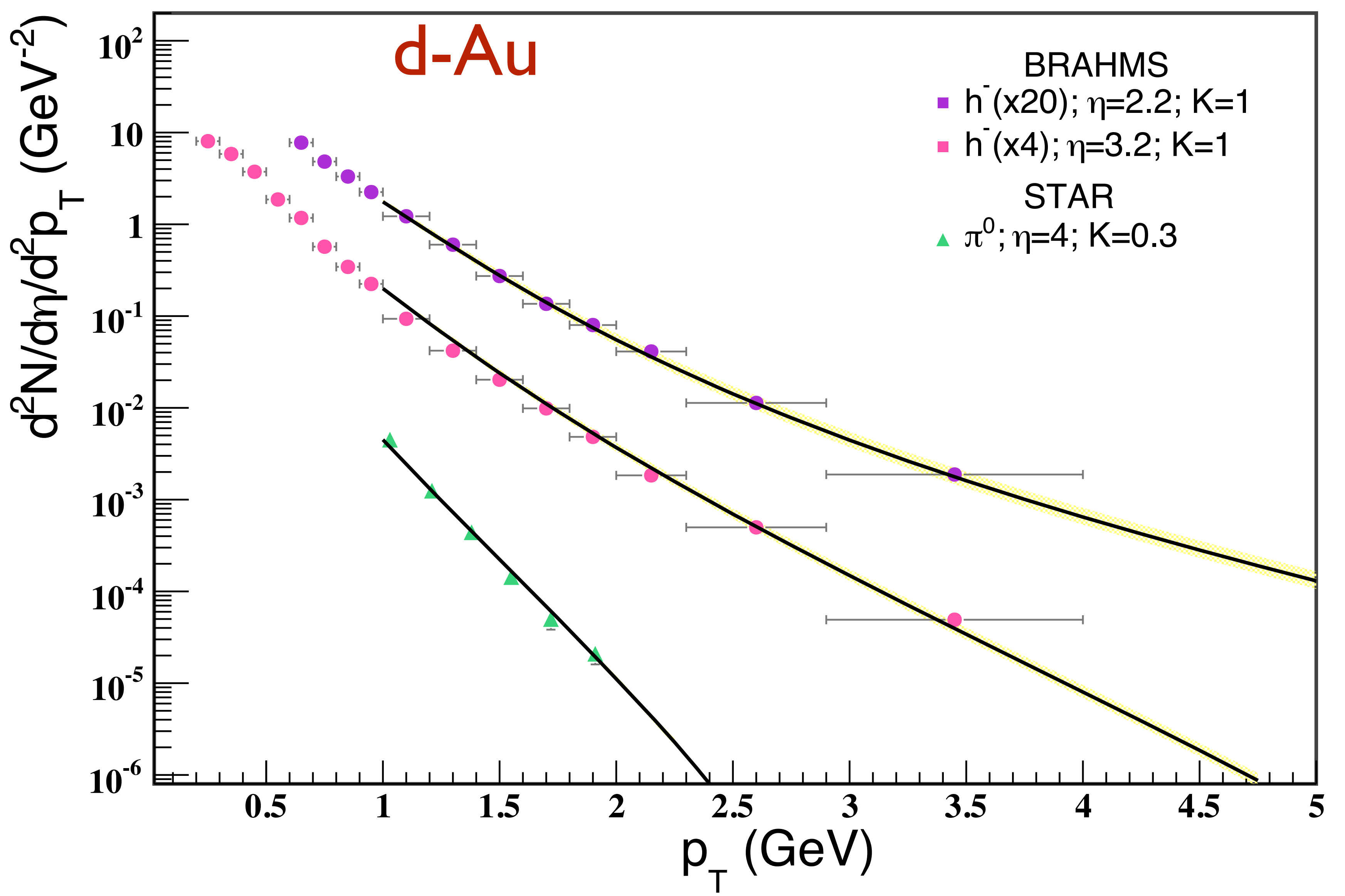


RHIC data at $s^{1/2}$ = 200 GeV; $y_h \geq 2$

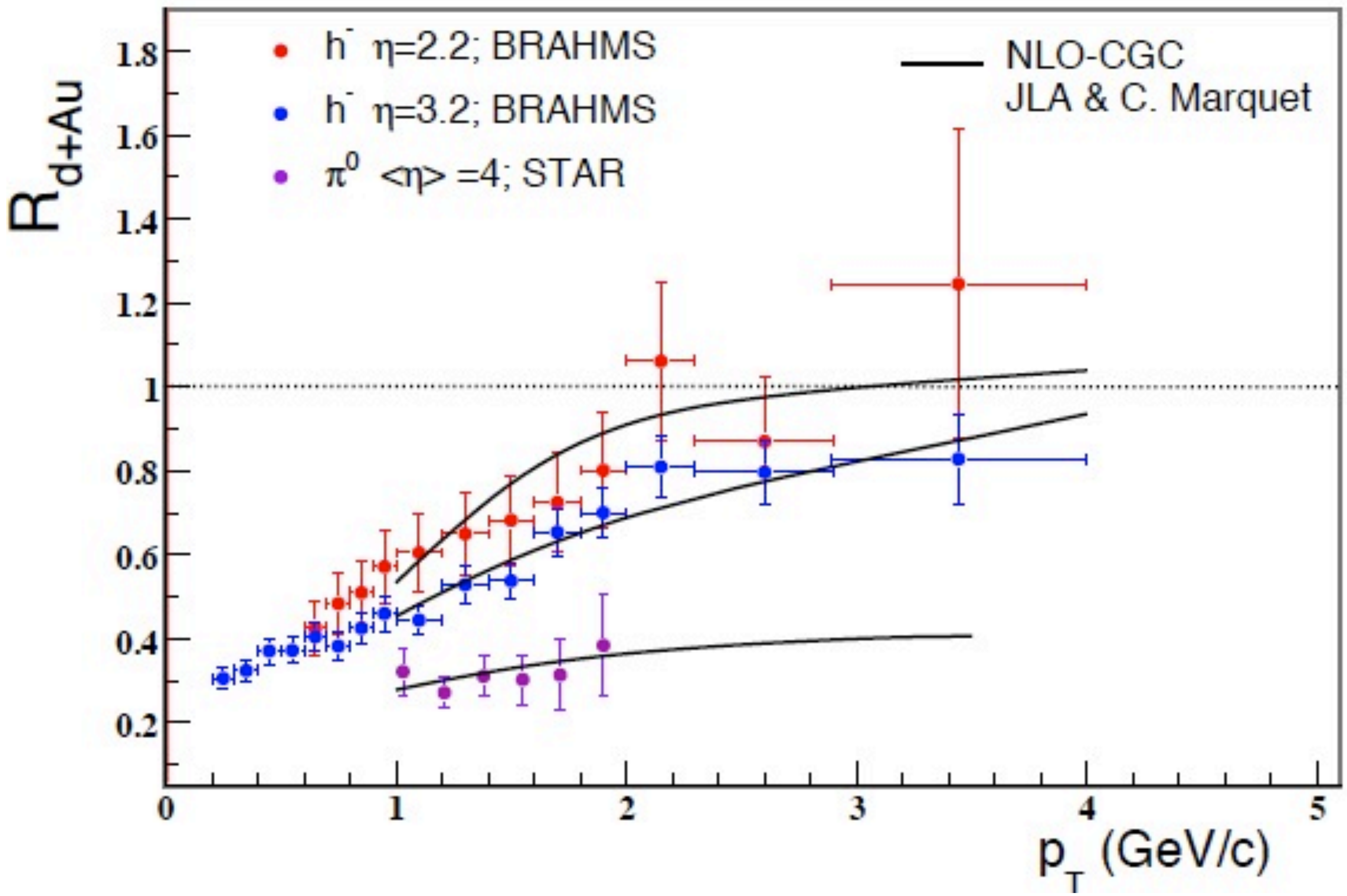
- Very good description of forward yields in d+Au collisions
- parameters compatible analysis of nuclear DIS data ax x=0.0125 Dusling et al. NPA836:159-182,10.
- K=1 for h^-. K=0.3 for neutral pions (?)

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

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

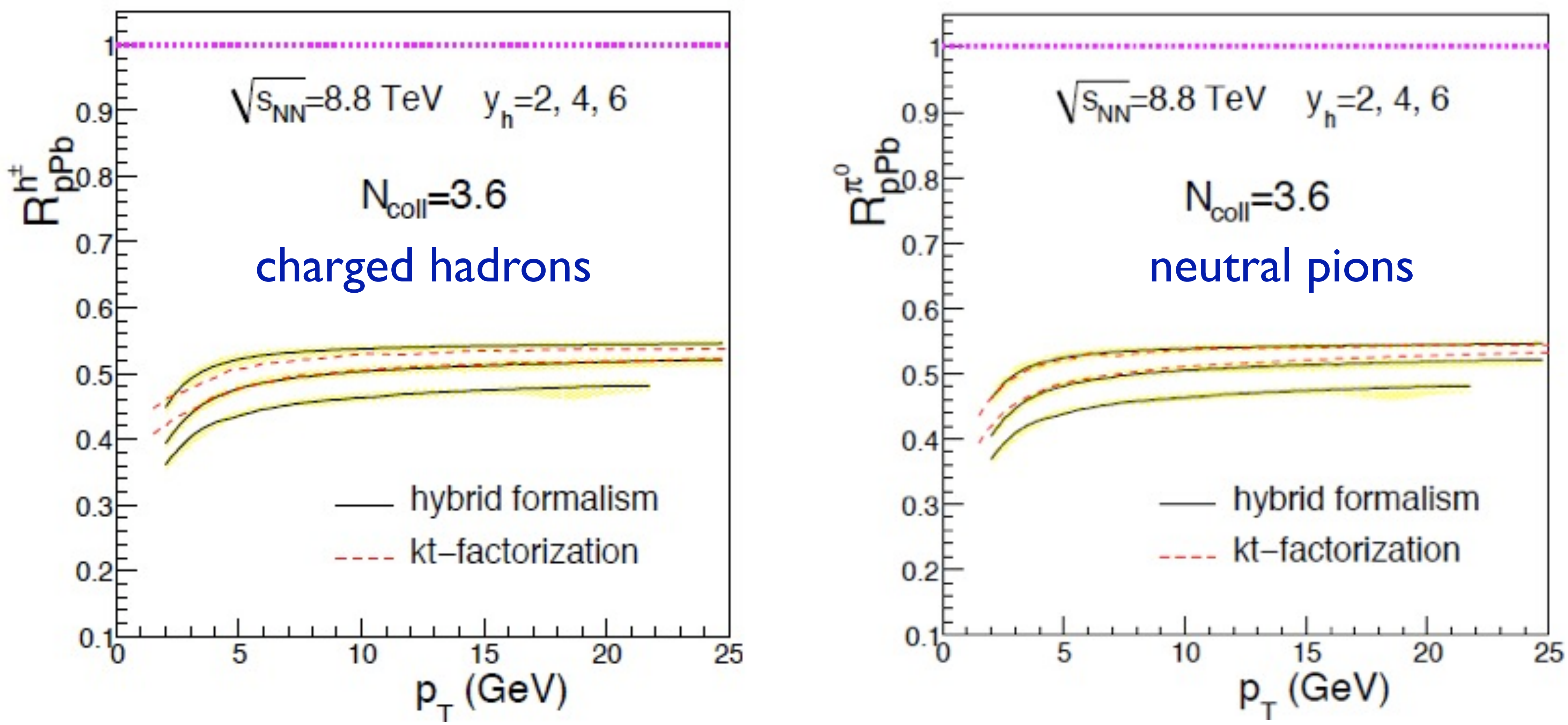


- ...by simply taking the ratio of d+Au and p+p spectra we get a good description of observed suppression of the nuclear modification factor at forward rapidities.



Predictions for the LHC. Nuclear modification factor in p+Pb collisions

$$R_{pPb} = \frac{1}{N_{\text{coll}}} \frac{dN_h^{pPb}}{dy_h\, d^2p_t} \Big/ \frac{dN_h^{pp}}{dy_h\, d^2p_t}$$



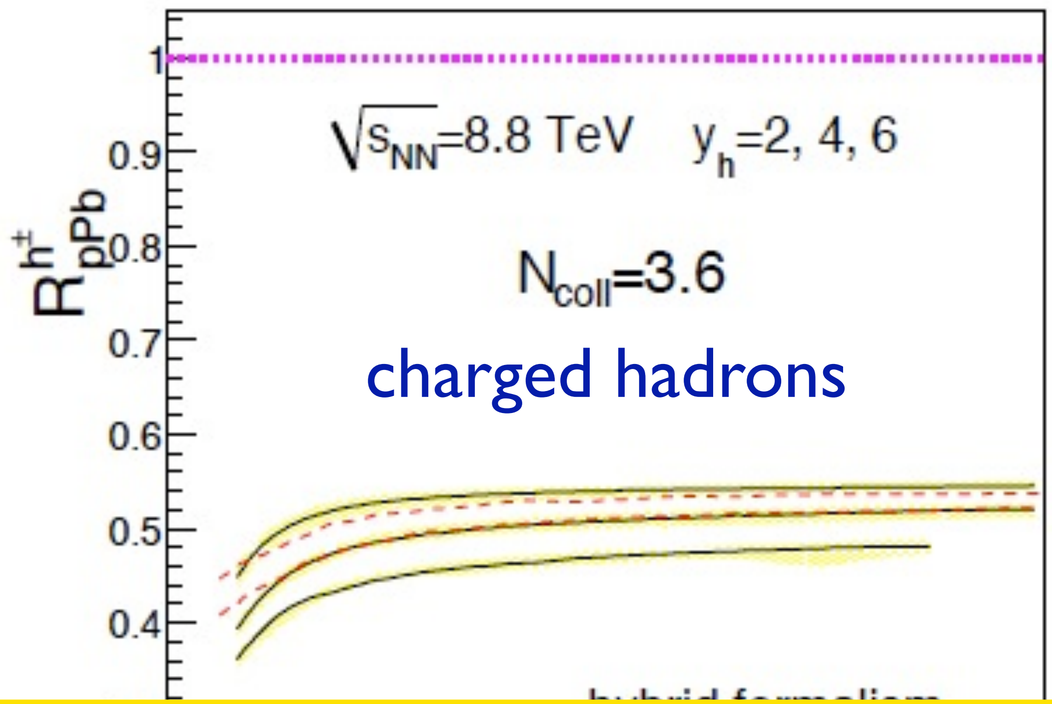
A similar suppression is expected at y=0

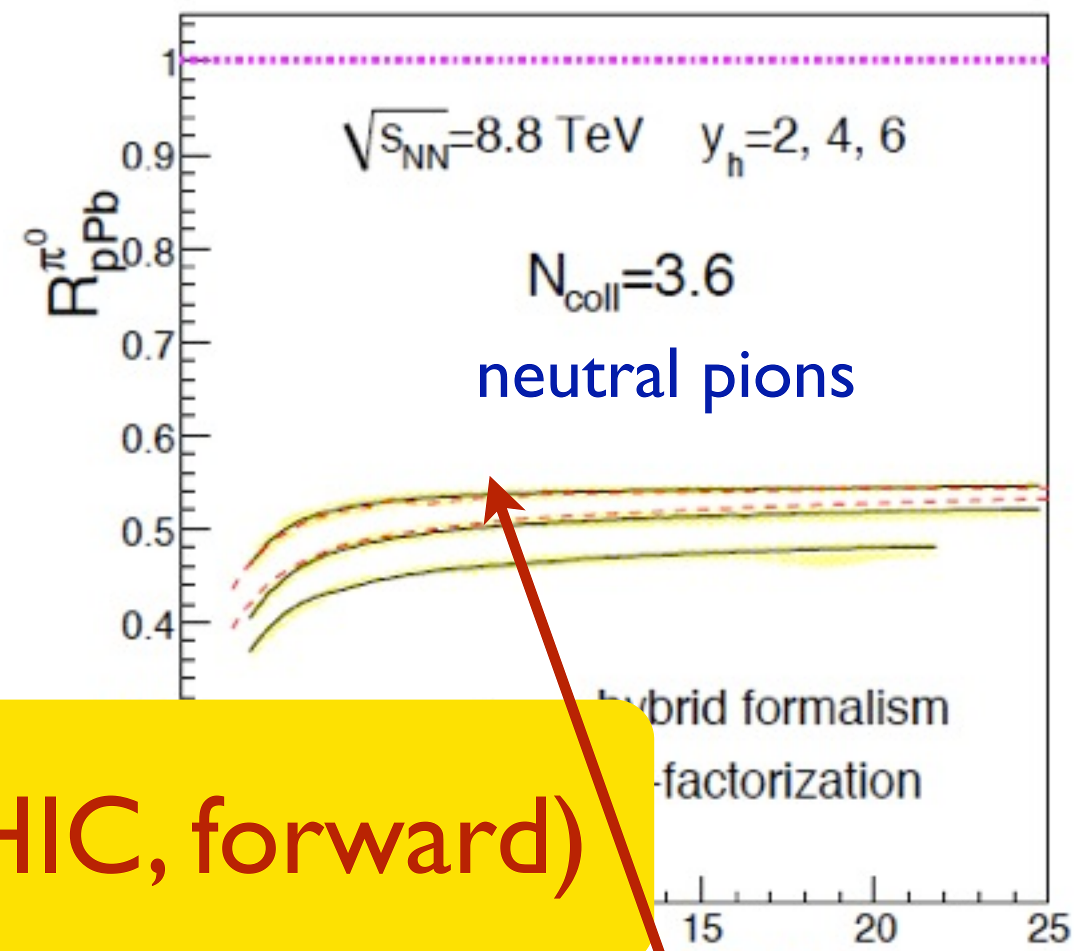
Again, the extrapolation to LHC energies is parameter free

Note: Similar to experiments, we take input from Galuber model to normalize the ratios

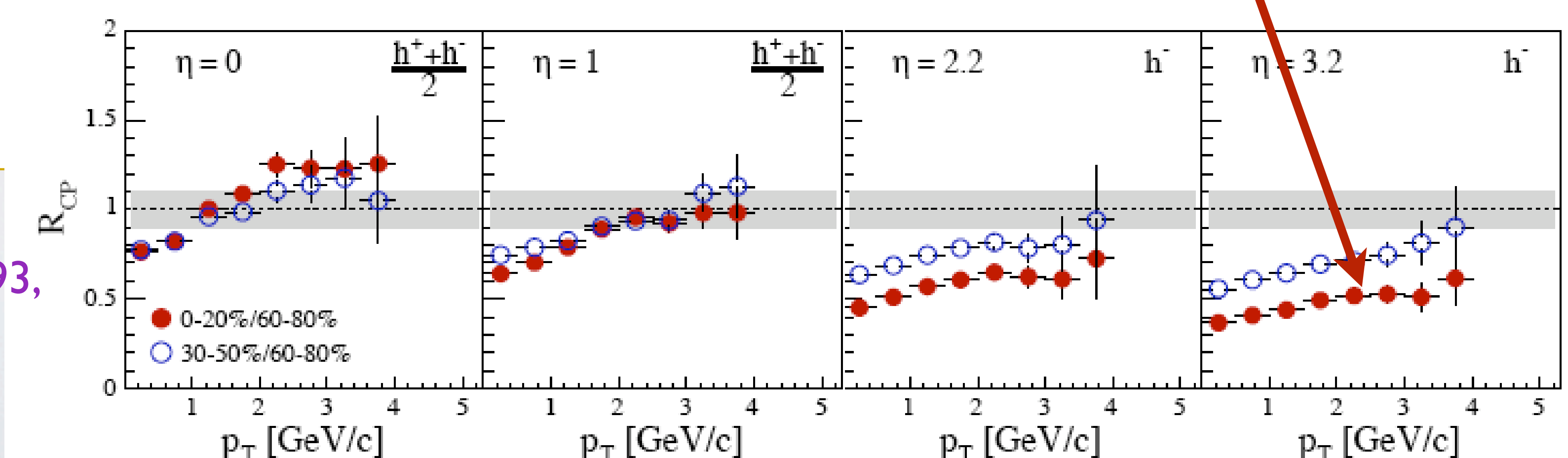
Predictions for the LHC. Nuclear modification factor in p+Pb collisions

$$R_{pPb} = \frac{1}{N_{\rm coll}} \frac{dN_h^{pPb}}{dy_h\, d^2p_t} \Big/ \frac{dN_h^{pp}}{dy_h\, d^2p_t}$$





R_{pPb}(LHC,central)~R_{dAu}(RHIC, forward)

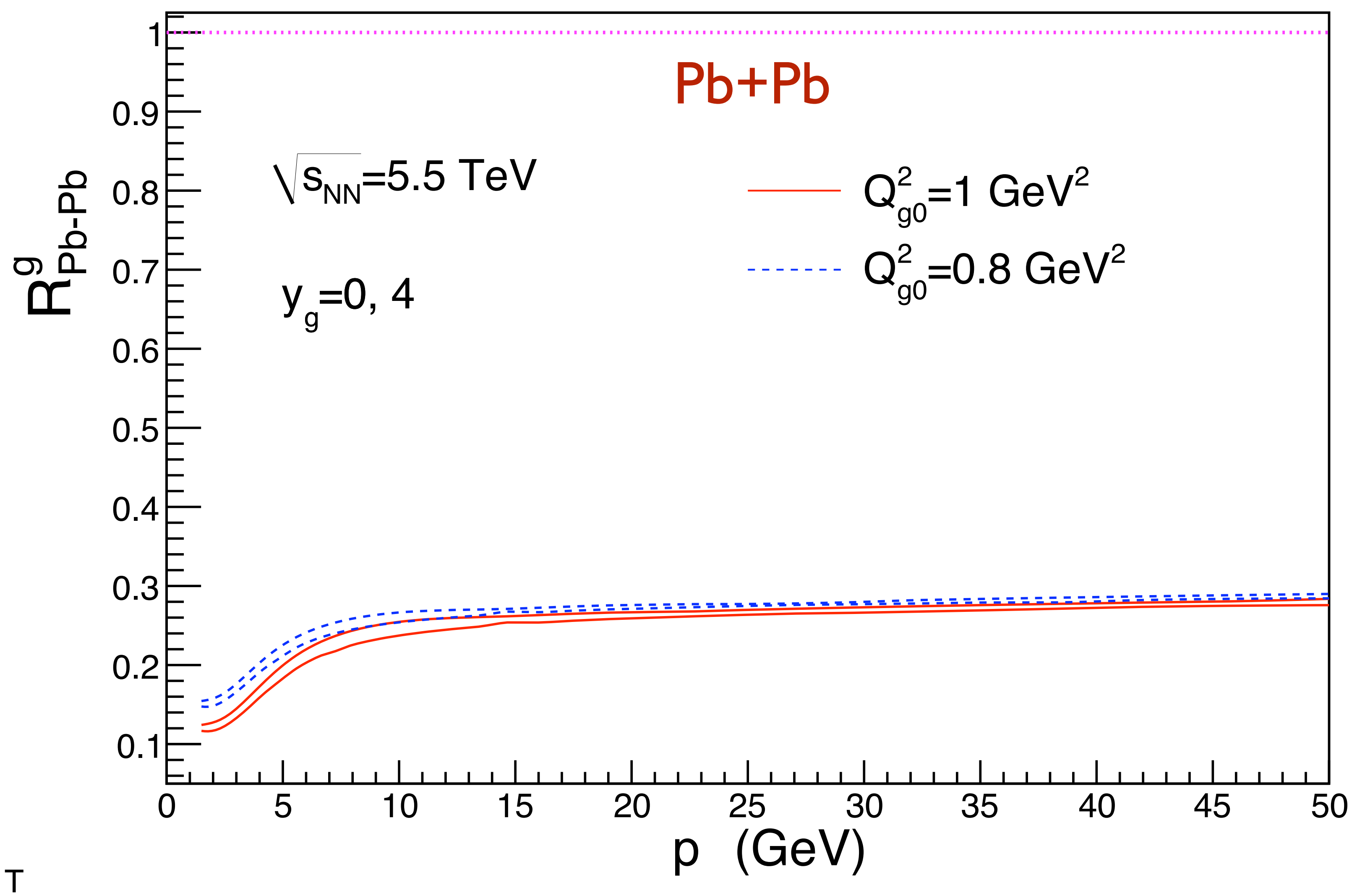


BRAHMS, PRL93, 242303

Predictions for the LHC. Gluon modification factor in Pb+Pb collisions

- The suppression in p+A collisions is rooted in the shadowing of the nucleus wavefunction
- The same mechanism should yield an even larger suppression in A+A collisions
- We estimate the suppression of initial gluon production in Pb+Pb coll. using kt-factorization:

$$R^g_{PbPb} = \frac{1}{N_{coll}} \frac{dN^g_{PbPb}}{dyd^2p_t} \Big/ \frac{dN^g_{pp}}{dyd^2p_t}$$



Large suppression of gluon production in PbPB collisions purely from initial state effects.

SUMMARY

✓ The calculation of NLO corrections brings the CGC to a new period of precision phenomenology

✓ NLO CGC provides a good description of DIS data on structure functions and reduced cross sections (preliminary), also of heavy quark contribution, at $x<0.01$ and all Q^2.

✓ The same wavefunctions determined from DIS analysis provide a good description of forward particle production at RHIC both in p+p and d+Au collisions. See Cyrille's talk on di-hadron correlations later on.

✓ These analyses, together with the use of the rcBK evolution equation, build up an effective phenomenological tool to safely extrapolate to higher energies/ smaller-x

Parametrizations of the dipole amplitude available at

http://www-fp.usc.es/phenom/software.html

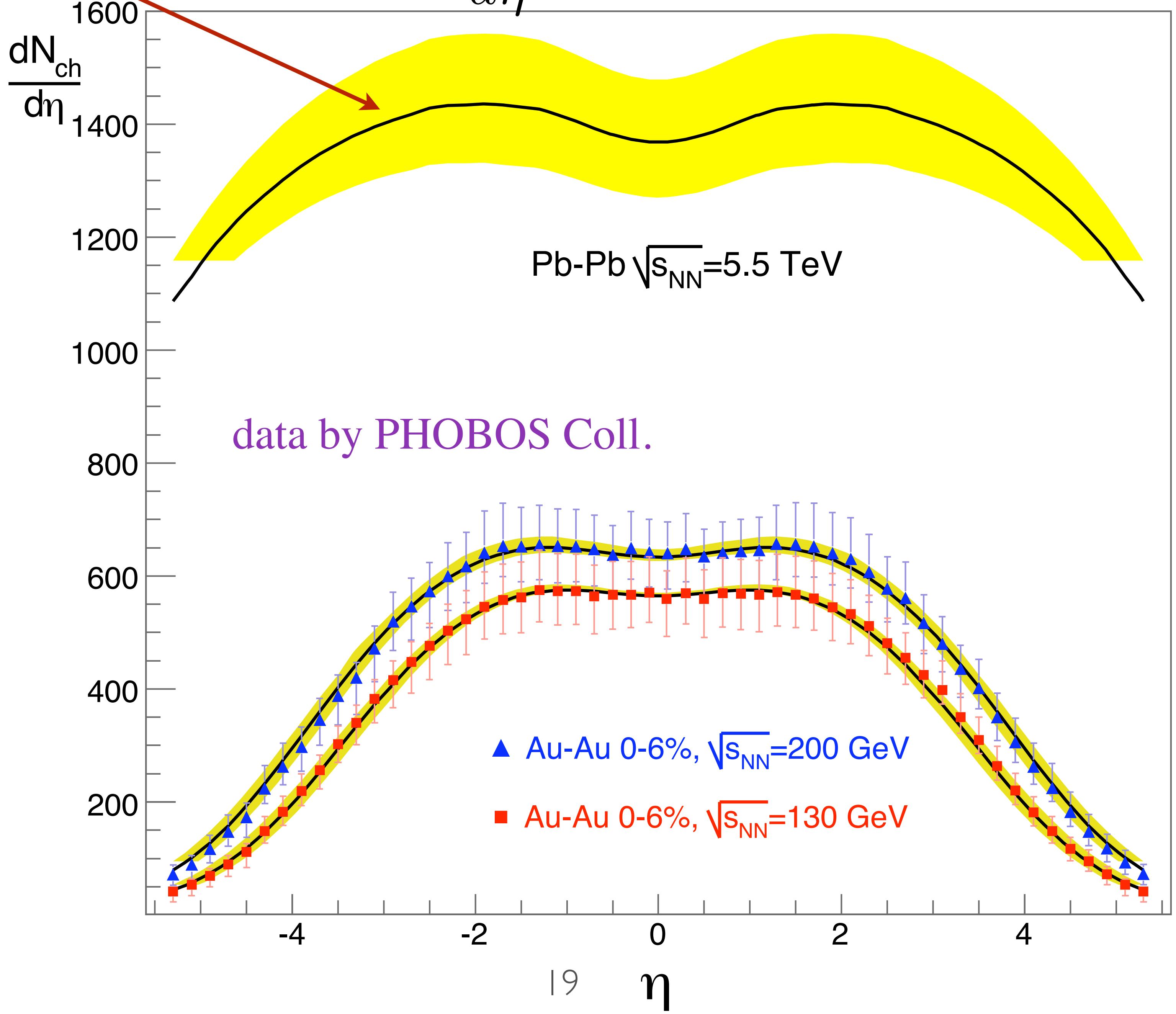
⇒ Hadron multiplicities in A+A collisions

Very good description of RHIC Au+Au data for most central collisions (JLA 07)

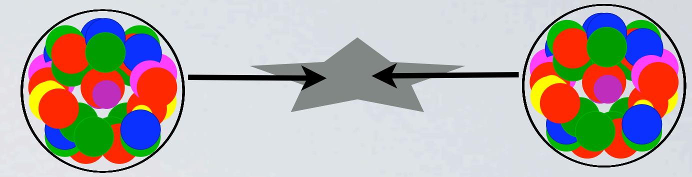
$$m_h \approx 0.25\,\text{GeV}, \quad 0.75 \le Q_0 \le 1.25\,\text{GeV}, \quad 0.05 \le x_0 \le 0.1$$

Prediction for Pb+Pb at the LHC:

$$\frac{dN_{ch}^{Pb-Pb}(\sqrt{s} = 5.5\,\text{TeV}, \eta = 0)}{d\eta} \approx 1290 \div 1480$$



⇒ Hadron multiplicities in A+A collisions



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

produces particles ~ # scattering centers

Kt-factorization in high energy scattering for inclusive gluon production:

$$\frac{dN^{AB\to gX}}{dy\, d^2p_t} = \frac{S_A\, C_F}{\pi}\, \frac{\alpha_s}{p_t^2} \int d^2q\, \varphi_A(x_A, q)\, \varphi_B(x_B, p_t - q)$$

Kharzeev-Levin-Nardi

$$\frac{dN^{AB}}{d\eta} = C \int d^2p_t\, J(\eta,\, p_t,\, m_h)\, \frac{dN^{AB\to gX}}{dy d^2p_t}$$

$$x_{A(B)} = \frac{m_t}{\sqrt{s}} e^{\pm y}$$

$C \sim (\#\ \text{hadrons})/\text{gluon}$

parton-hadron duality

$m_h \sim$ average hadron mass

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

Unintegrated gluon distribution ⇔ Dipole scattering amplitude

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

20