Small-x physics and pA control measurements

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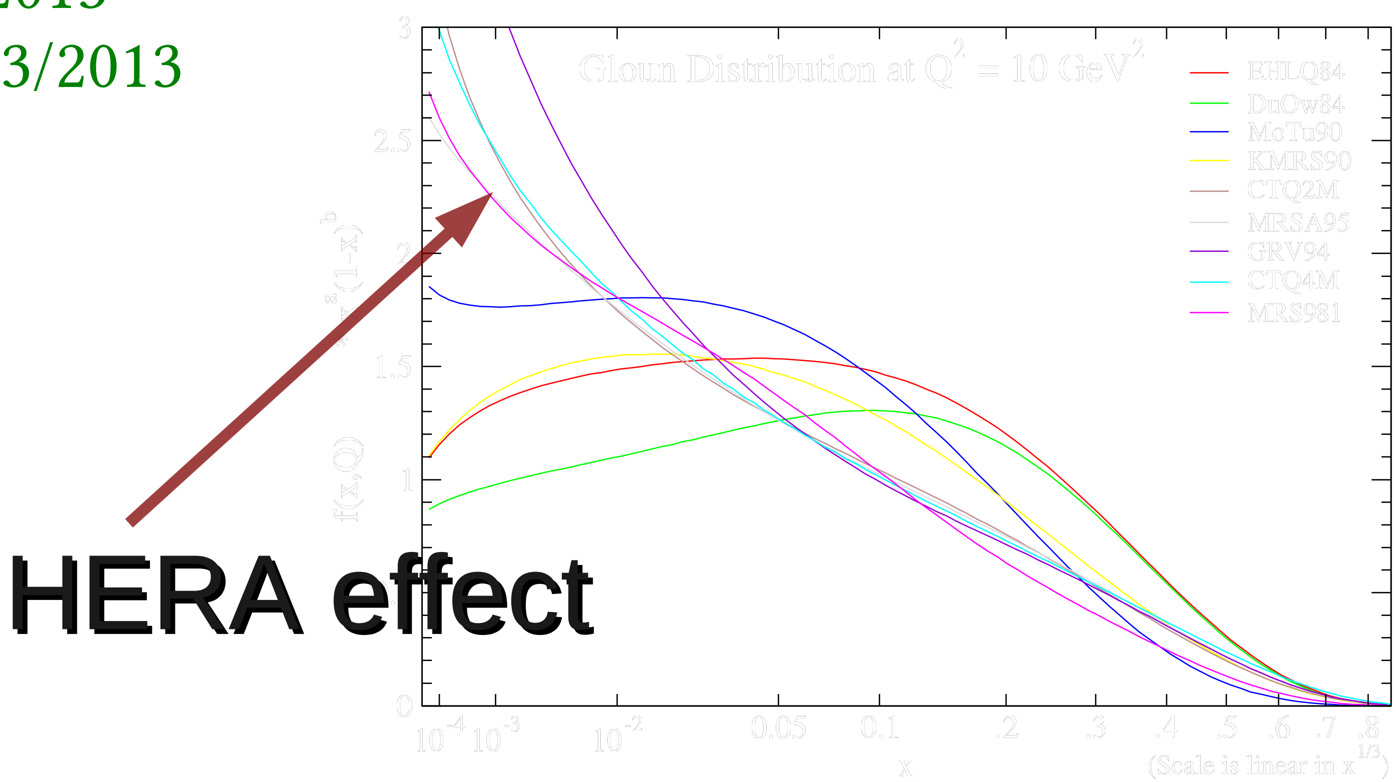


rcBK evolution:

basic “degrees of freedom”: dipole scattering amplitude in fund. rep. **(2-point fct)**

$$\mathcal{N}_F(r,Y;b,A) \equiv \frac{1}{N_c} \mathrm{tr}\, \langle 1 - V^\dagger(y) V(z) \rangle_Y$$

$$\mathbf{r} = \mathbf{y} - \mathbf{z}$$

BK equation (incl. non-linear terms → saturation of scattering amplitude!)

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

$$\mathbf{r} = \mathbf{r}_1 - \mathbf{r_2}$$

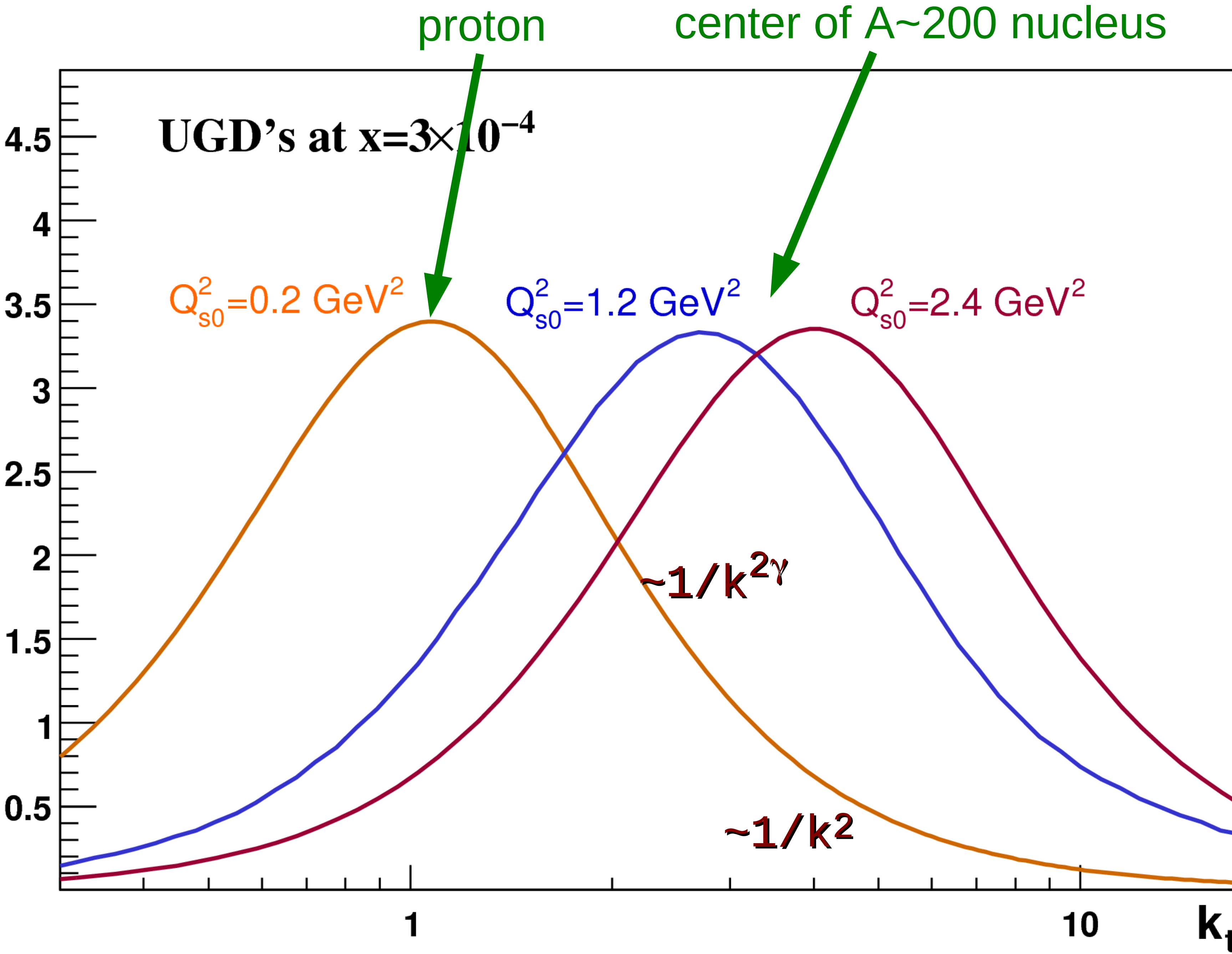
running-coupling kernel (Balitsky prescription)

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

$$\alpha_s(r^2) = \frac{4\pi}{\beta \log\left(4 \frac{C^2}{r^2 \Lambda^2} + \mu\right)}$$

dipole scattering amplitude in adj. rep. $\mathcal{N}_A = 2\,\mathcal{N}_F - \mathcal{N}_F^2$

uGD at $x = 3x10^{-4}$ (e.g. pt=2GeV, y=0, √s=7TeV)



what is the initial condition for rcBK evolution ?

- don't really know, small-x doesn't tell
- needs to be set at “sufficiently” small x_0 so that rcBK can take it from there; in practice, x_0=0.01 ?
- for large A, MV model may provide a decent ini. cond. :

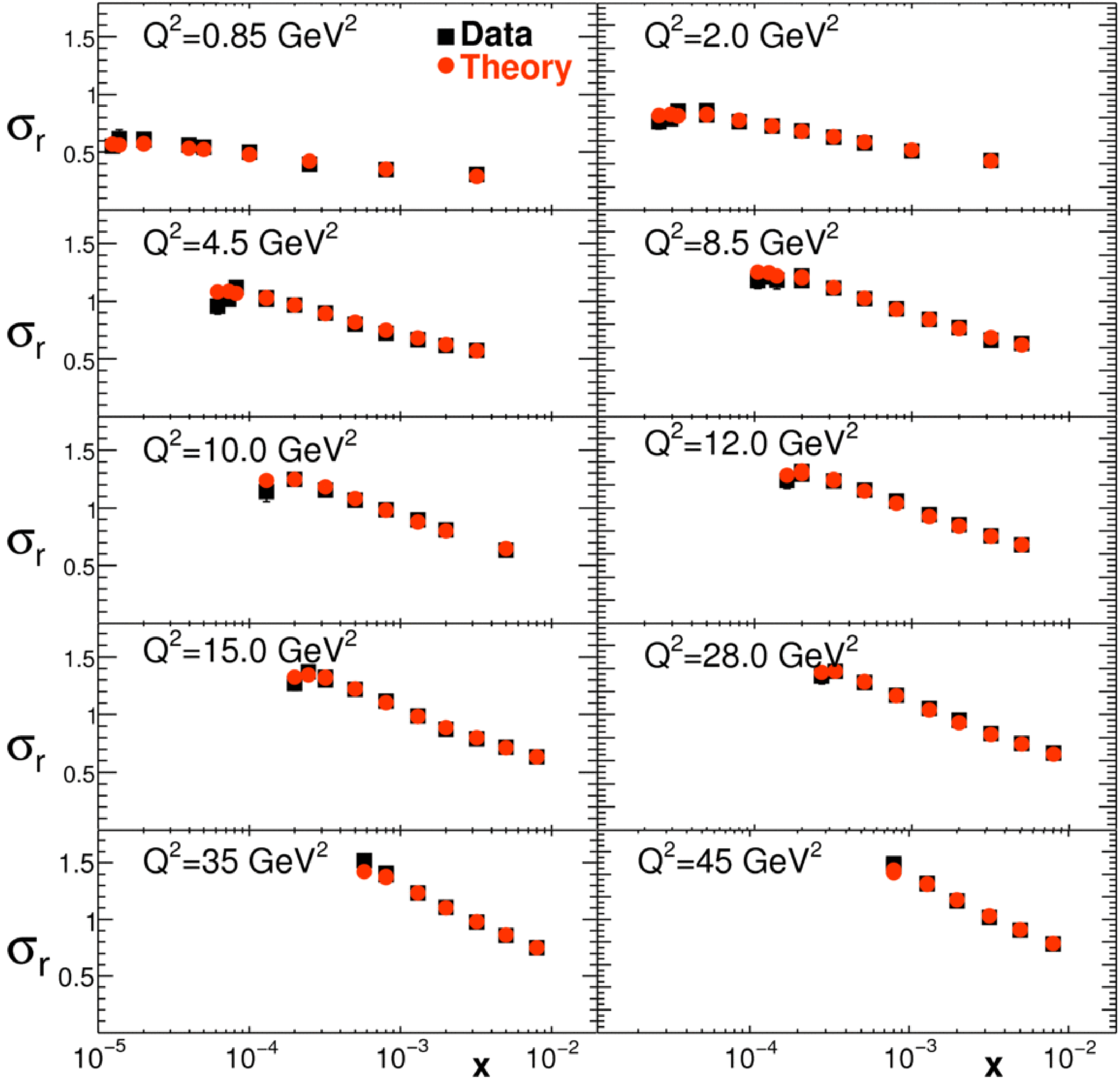
$$\mathcal{N}_F(r, Y=0; b) = 1 - \exp\left[-\frac{r^2\, Q_{s0}^2(b)}{4}\, \ln\left(\frac{1}{\Lambda\, r} + e\right)\right]$$

- alternative I.C. (AAMQS 2011), also denoted by MV$^{\gamma}$ or Set 2 (γ>1 !):

$$\mathcal{N}_F(r, Y=0; b) = 1 - \exp\left[-\frac{\left[r^2\, Q_{s0}^2(b)\right]^{\gamma}}{4}\, \ln\left(\frac{1}{\Lambda\, r} + e\right)\right]$$

$\gamma^* p$ Fit with only light quarks

AAMQS:
EPJ C71 (2011)



J. Albacete et al (“AAMQS”): arXiv:1012.4408

	fit	$\frac{\chi^2}{d.o.f}$	Q^2_{s0}	σ_0	γ	C	m_l^2
	GBW						
a	$\alpha_{fr} = 0.7$	1.226	0.241	32.357	0.971	2.46	fixed
a’	$\alpha_{fr} = 0.7\ (\Lambda_{m_\tau})$	1.235	0.240	32.569	0.959	2.507	fixed
b	$\alpha_{fr} = 0.7$	1.264	0.2633	30.325	0.968	2.246	1.74E-2
c	$\alpha_{fr} = 1$	1.279	0.254	31.906	0.981	2.378	fixed
c’	$\alpha_{fr} = 1\ (\Lambda_{m_\tau})$	1.244	0.2329	33.608	0.9612	2.451	fixed
d	$\alpha_{fr} = 1$	1.248	0.239	33.761	0.980	2.656	2.212E-2
	MV						
e	$\alpha_{fr} = 0.7$	1.171	0.165	32.895	1.135	2.52	fixed
f	$\alpha_{fr} = 0.7$	1.161	0.164	32.324	1.123	2.48	1.823E-2
g	$\alpha_{fr} = 1$	1.140	0.1557	33.696	1.113	2.56	fixed
h	$\alpha_{fr} = 1$	1.117	0.1597	33.105	1.118	2.47	1.845E-2
h’	$\alpha_{fr} = 1\ (\Lambda_{m_\tau})$	1.104	0.168	30.265	1.119	1.715	1.463E-2

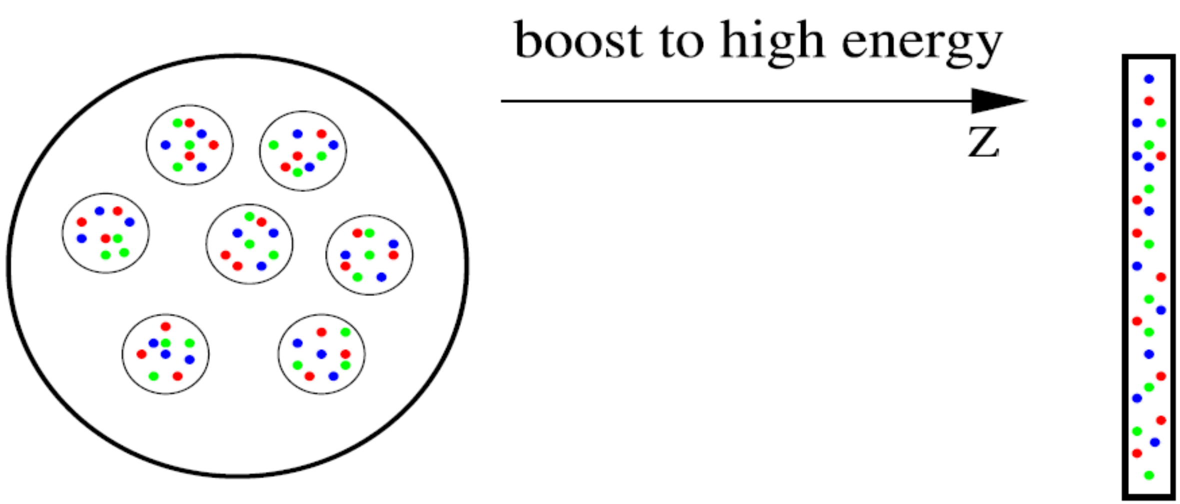
Table 1: Parameters from fits with only light quarks to data with $x \leq 10^{-2}$ and for all available values of $Q^2 \leq 50$ GeV^2 for different initial conditions, fixed values of the coupling in the infrared $\alpha_{fr} = 0.7$ and 1 and light quark masses either taken fixed $m_l = 0.14$ GeV or left as a free parameter. Fits a’, c’ and h’ correspond to taking the τ mass as reference scale for the running of the coupling. Units: Q^2_{s0} and m_l^2 are in GeV^2 and σ_0 in mb.

- in what follows, this I.C. is used even for a nucleon, with

MV: $Q^2_{s0,N} = 0.2\ \mathrm{GeV}^2$ $\qquad$ MV^{γ}: $Q^2_{s0,N} = 0.168\ \mathrm{GeV}^2$

- for nucleus, at transv. position b:

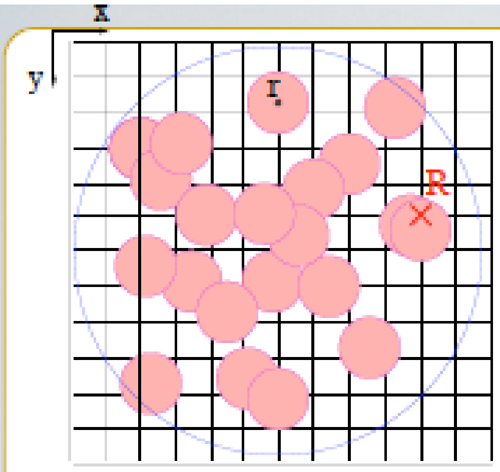
$$Q^2_{s0}(b) = (\#\ \text{nucleons at b})\ \ \mathrm{X}\ \ Q^2_{s0,N}$$



side view

McLerran &
Venugopalan

fluctuations of valence partons in ⊥ plane



1. Initial conditions for the evolution (x=0.01)

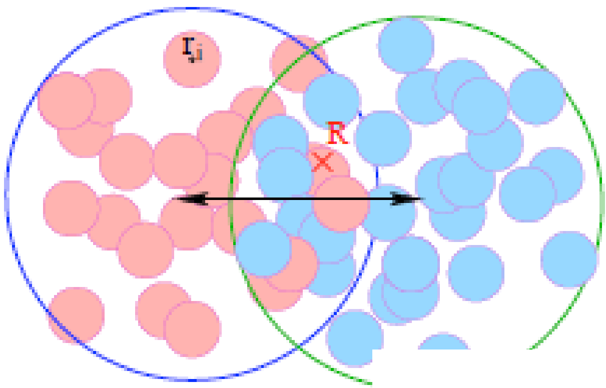
$$N(\mathbf{R}) = \sum_{i=1}^{A} \Theta\left(\sqrt{\frac{\sigma_0}{\pi}} - |\mathbf{R} - \mathbf{r_i}|\right) \longrightarrow Q^2_{s0}(\mathbf{R}) = N(\mathbf{R})\, Q^2_{s0,\,\mathrm{nucl}}$$

$$\varphi(x_0 = 0.01, k_t, R)$$

2. Solve local running coupling BK evolution at each transverse point

rcBK equation or KLN model

$$\varphi(x, k_t, R)$$



3 Calculate gluon production at each transverse point according to kt-factorization

INPUT: $\varphi(\mathbf{x} = \mathbf{0.01}, \mathbf{k_t})$ FOR A SINGLE NUCLEON:

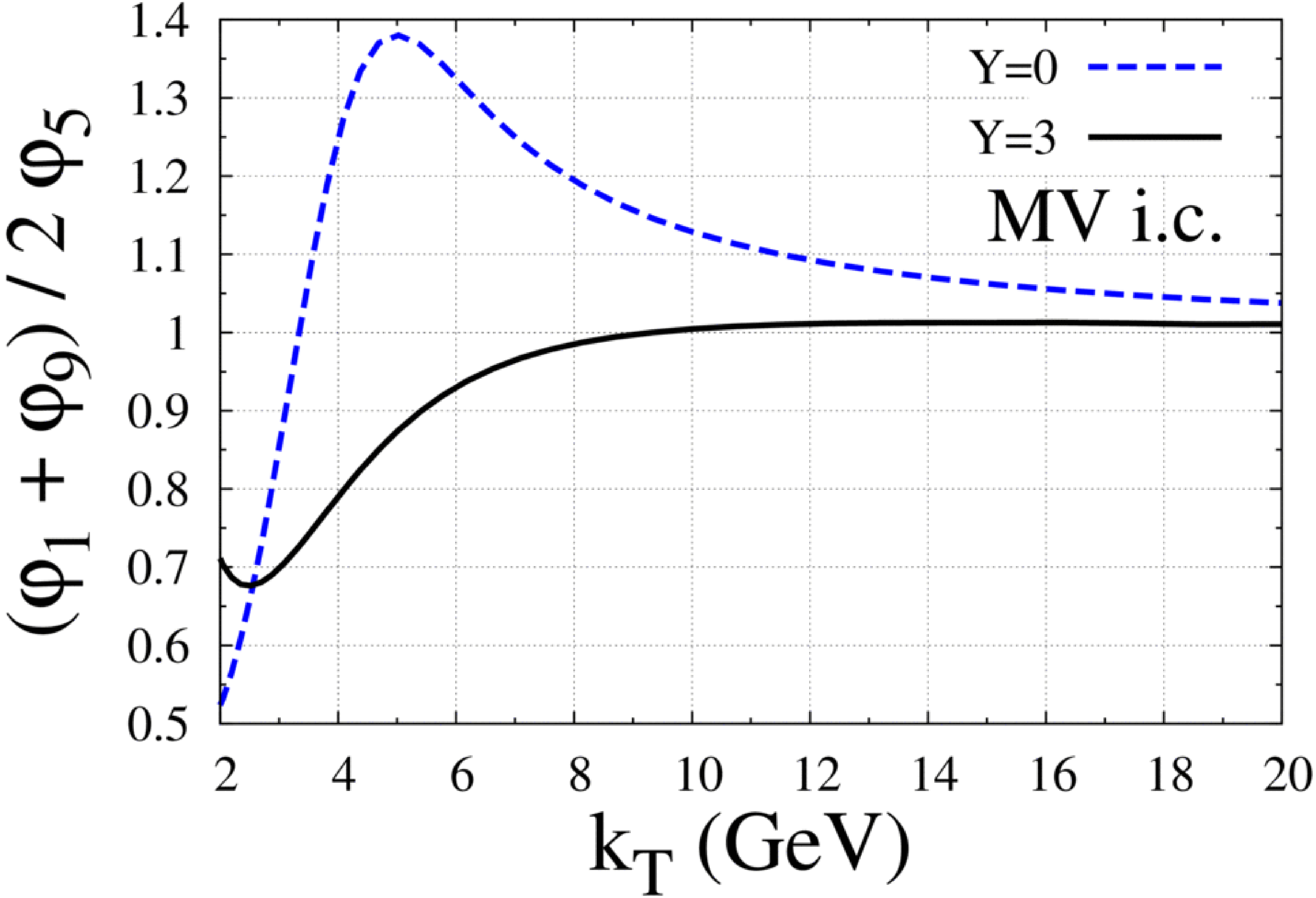
$$N_{\mathrm{part,A}}(\vec{b}) = \sum_{i=1\cdots A} \Theta\left(P(\vec{b} - \vec{r}_i) - \nu_i\right) \; .$$

$$P(b) = 1 - \exp[-\sigma_g T_{pp}(b)], \qquad T_{pp}(b) = \int d^2s\, T_p(s)\, T_p(s-b)$$

$$T_p(r) = \frac{1}{2\pi B} \exp[-r^2/(2B)] \qquad \sigma_{NN}(\sqrt{s}) = \int d^2b\, (1 - \exp[-\sigma_g T_{pp}(b)])$$

thickness fluctuations:

(average of 1 / 9 nucleon target compared to 5-nucl. target)



$k_\perp$-factorization, multiplicity in A+B --> g+X

unintegrated gluon distribution:

$$\varphi(k,Y;b,A) = \frac{C_F\,k^2}{\alpha_s(k)} \int \frac{d^2\mathbf{r}}{(2\pi)^3}\, e^{-i\mathbf{k}\cdot\mathbf{r}} \mathcal{N}_A(r,Y;b,A)$$

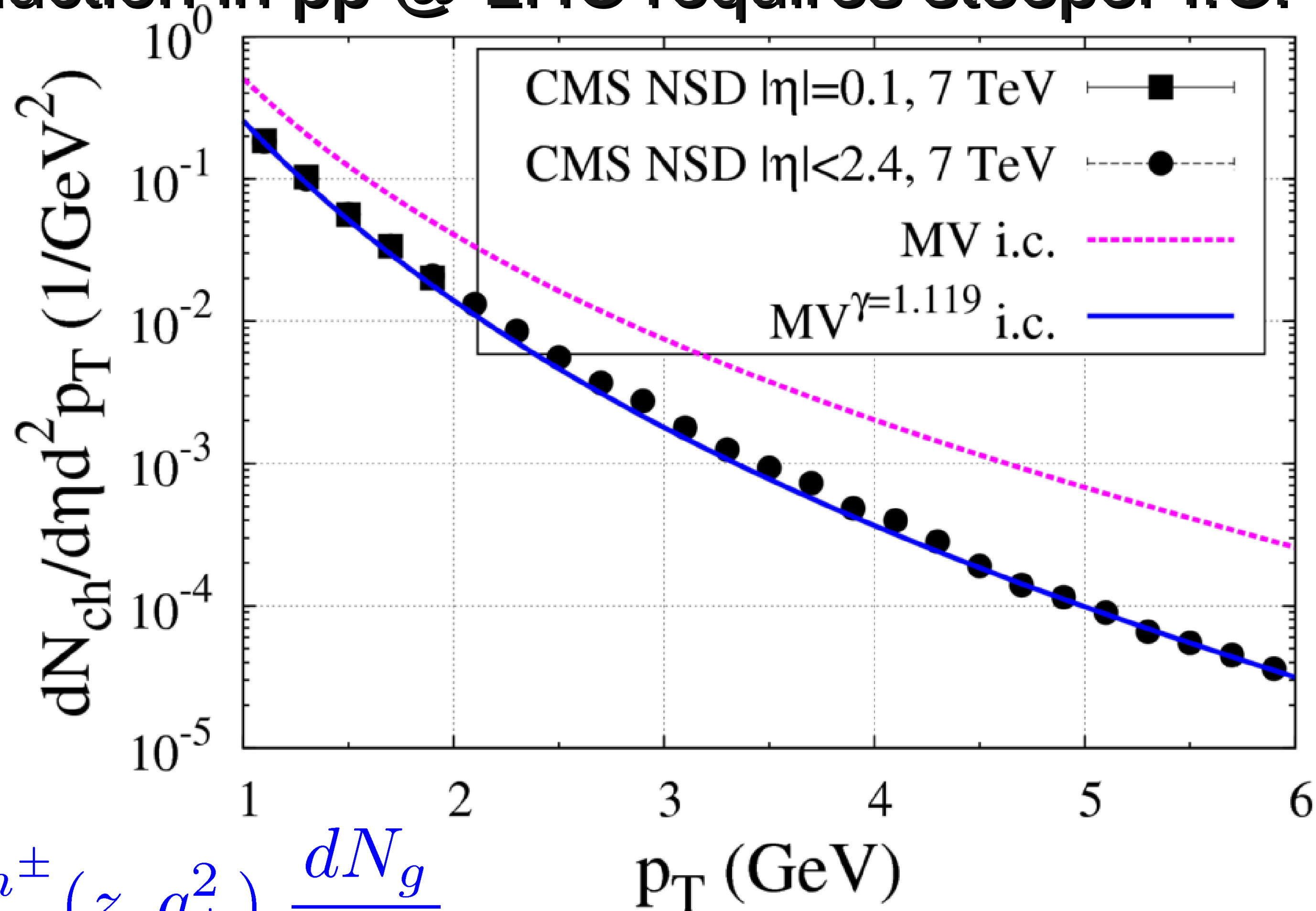
multiplicity:

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

Notes:

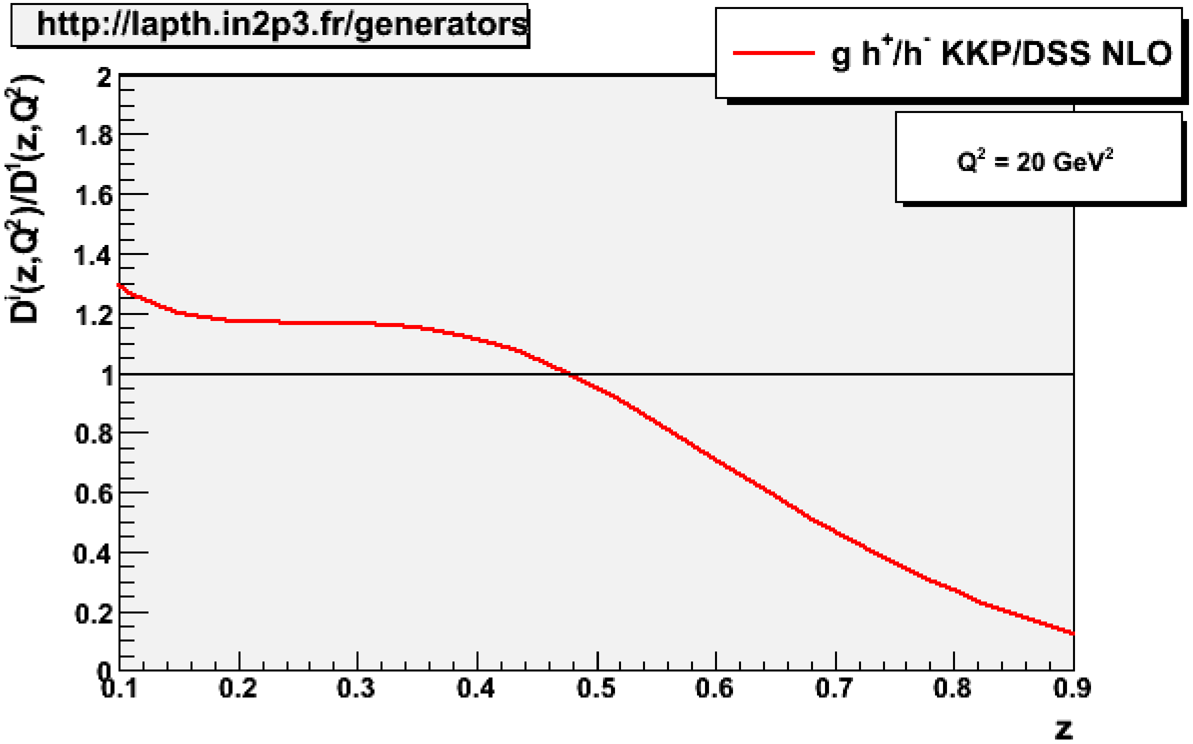
- finite as $p_t \to 0$ if UGD does not blow up
- $x_{1,2} = (p_t/\sqrt{s})\,\exp(\pm y)$; $Y_{1,2} = \log(x_0/x_{1,2})$
  where $x_0=0.01$ is assumed onset of rcBK evol.
- K = 1.5 – 2, appears reasonable

high-pt hadron production in pp @ LHC requires steeper I.C.

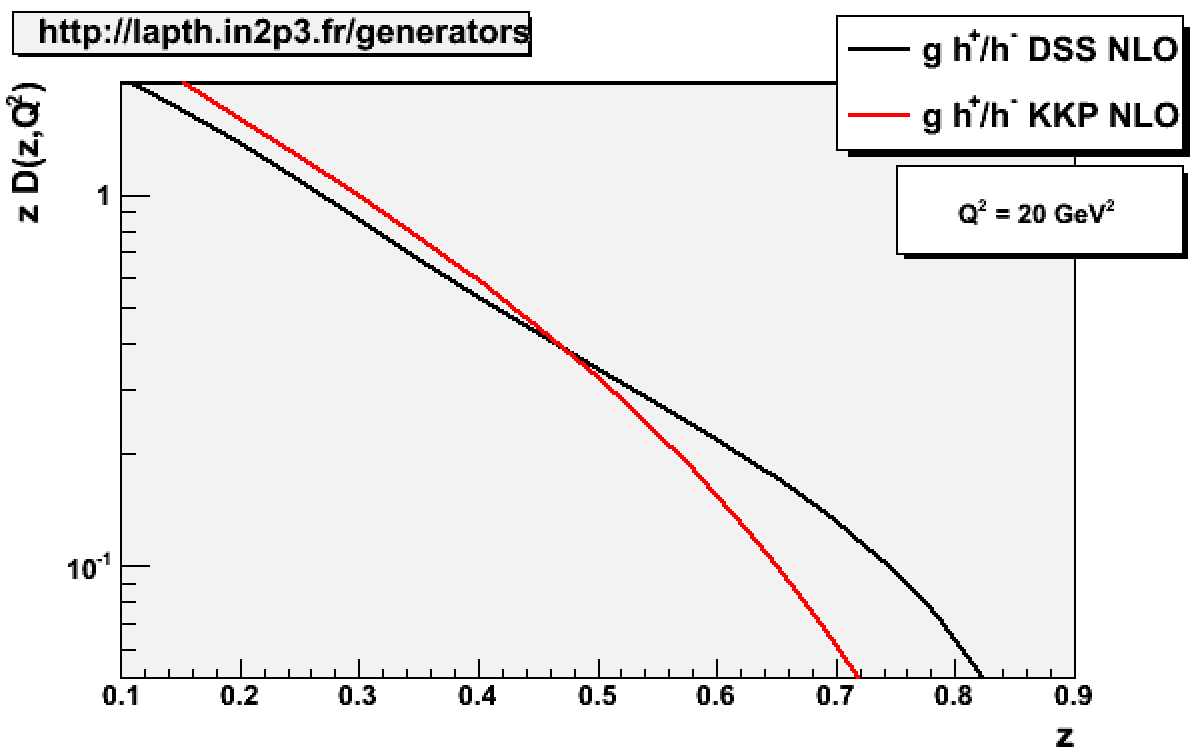


$$\frac{dN_{h^\pm}}{d^2p_\perp} = \int \frac{dz}{z^2} D_g^{h^\pm}(z, q_\perp^2) \, \frac{dN_g}{d^2q_\perp}$$

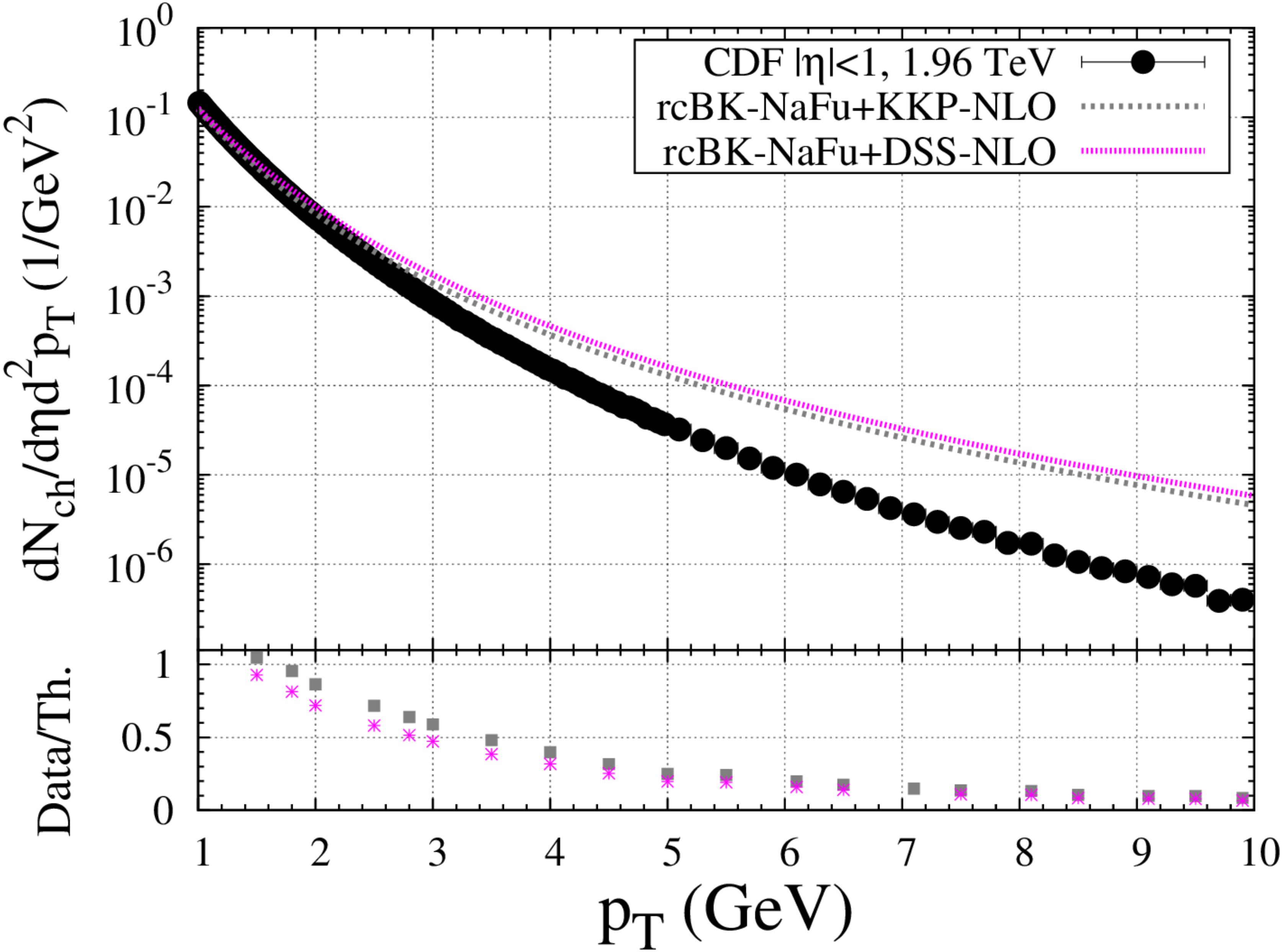
- no g ⟶ h multiplication factor κ here!
  (normalization set by Fragm. Func.)
- rcBK in dilute regime
- LHC constrains initial condition



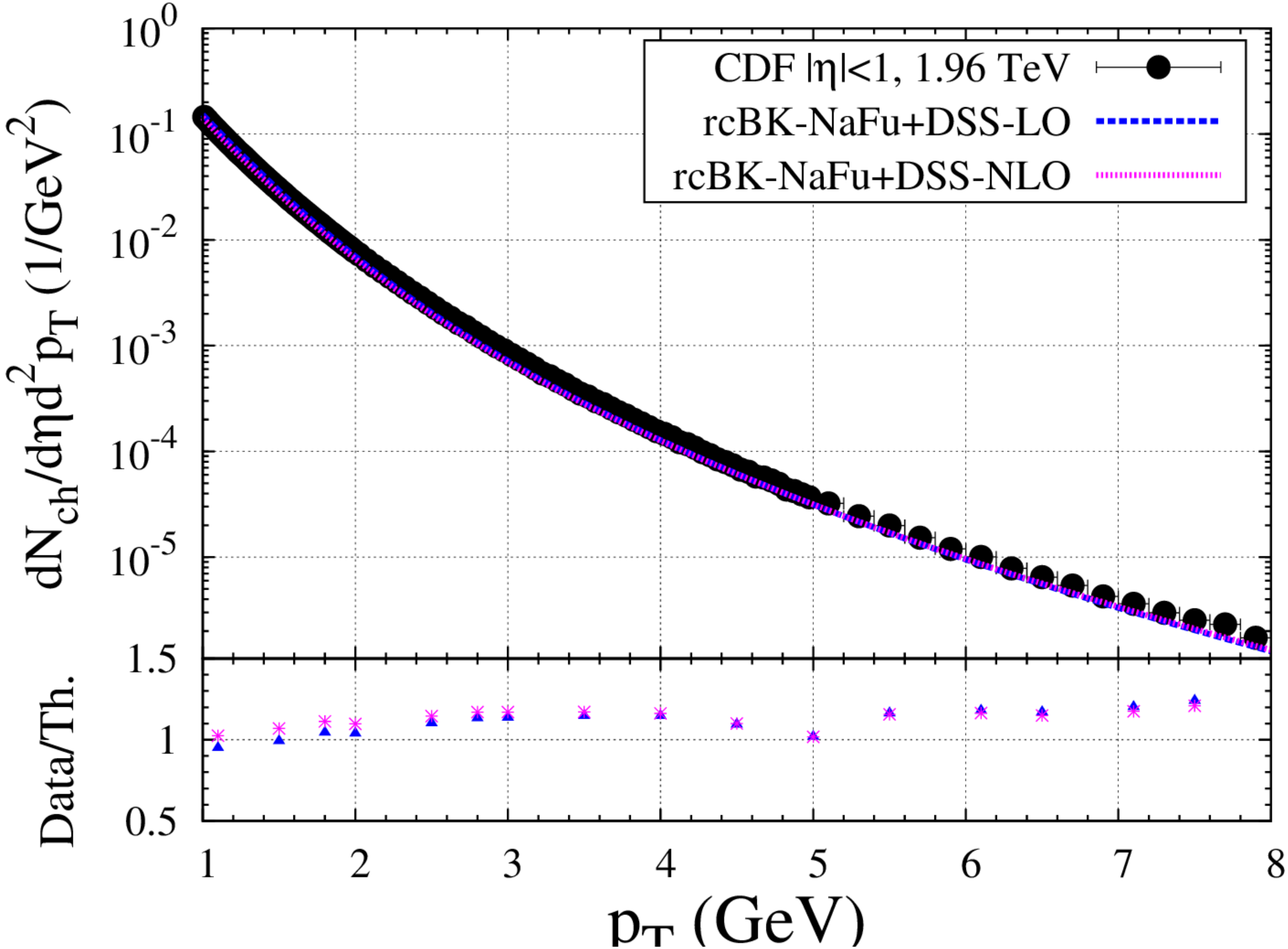
http://lapth.in2p3.fr/generators
g h+/h- KKP/DSS NLO
Q2 = 20 GeV2
Di(z,Q2)/D1(z,Q2)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
z

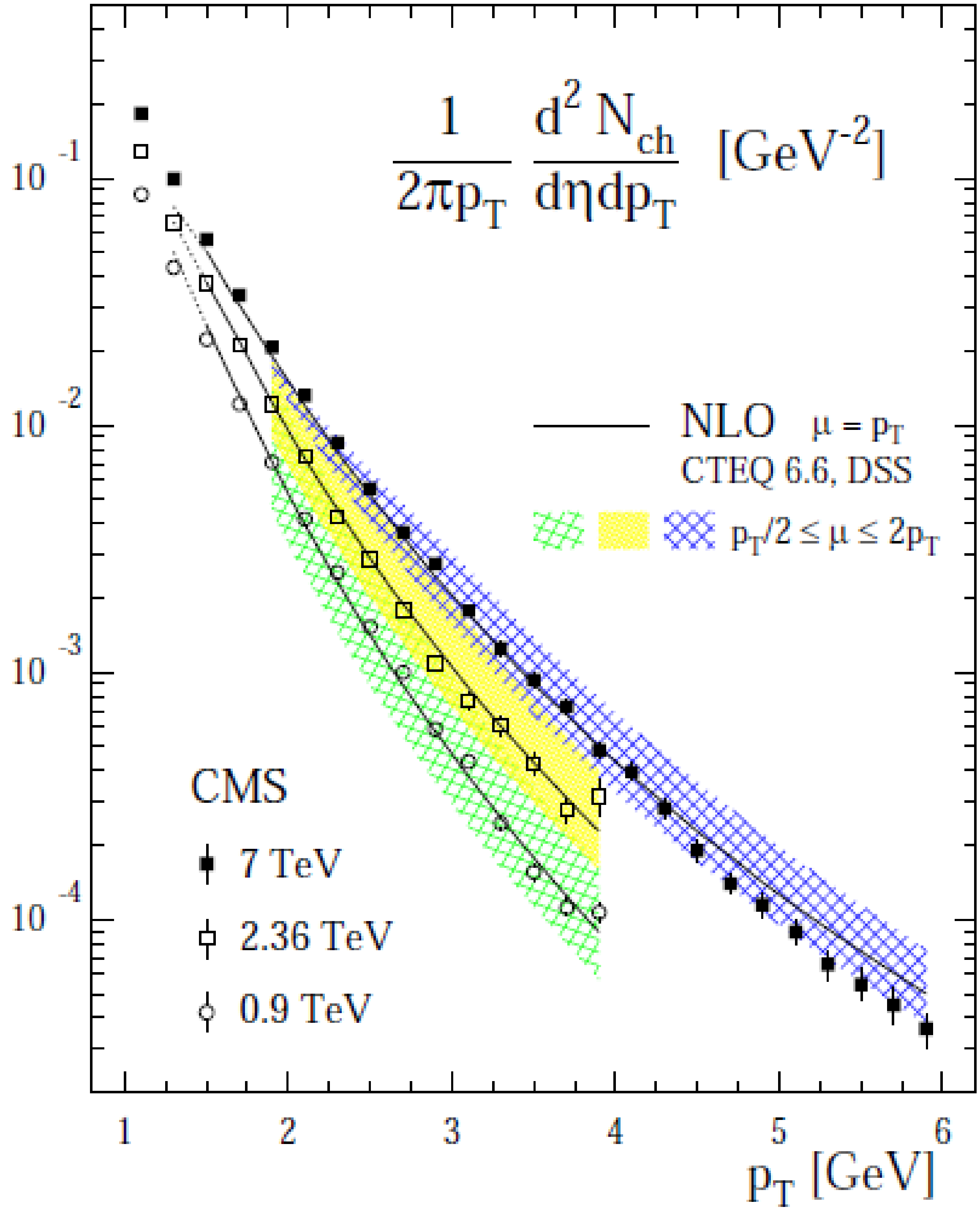


http://lapth.in2p3.fr/generators
g h+/h- DSS NLO
g h+/h- KKP NLO
Q2 = 20 GeV2
z D(z,Q2)
1
10-1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
z


CDF |η|<1, 1.96 TeV
rcBK-NaFu+KKP-NLO
rcBK-NaFu+DSS-NLO
$dN_{ch}/d\eta d^2p_T$ (1/GeV^2)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Data/Th.
1
0.5
0
1
2
3
4
5
6
7
8
9
10
p_T (GeV)

pt distributions in pp → ch at TEVATRON / LHC energies





Collinear pQCD fact.

Sassot, Zurita, Stratmann
PRD 82 (2010)

$$\mathcal{N}_F(r, Y=0; b) = 1 - \exp\left[-\frac{\left[r^2\, Q_{s0}^2(b)\right]^\gamma}{4}\, \ln\left(\frac{1}{\Lambda\, r} + e\right)\right]$$

for nuclei:

- do we use same γ as for a proton ?
- do we assume $Q_{s0}^2 \sim T_A$ or $Q_{s0}^2 \sim T_A^{1/\gamma}$

→ **w/o a better idea of where the AAMQS parameter comes from, we need to factor this into uncertainties...**

$A^{1/3}$ dependence of initial conditions for BK/JIMWLK beyond MV action

$$
\begin{aligned}
S \;=\; \int d^2x_\perp \Big\{ & \frac{1}{2\mu^2}\rho^a\rho^a - \frac{1}{\kappa_3} d^{abc}\rho^a\rho^b\rho^c + \\
& \Big[\frac{1}{\kappa_4}\left(\delta^{ab}\delta^{cd} + \delta^{ac}\delta^{bd} + \delta^{ad}\delta^{bc}\right) + \\
& \frac{1}{\kappa_4'}\left(d^{abe}d^{cde} + d^{ace}d^{bde} + d^{ade}d^{bce}\right)\Big]\rho^a\rho^b\rho^c\rho^d \Big\}
\end{aligned}
$$

+ soft YM fields + coupling of soft $\leftrightarrow$ hard

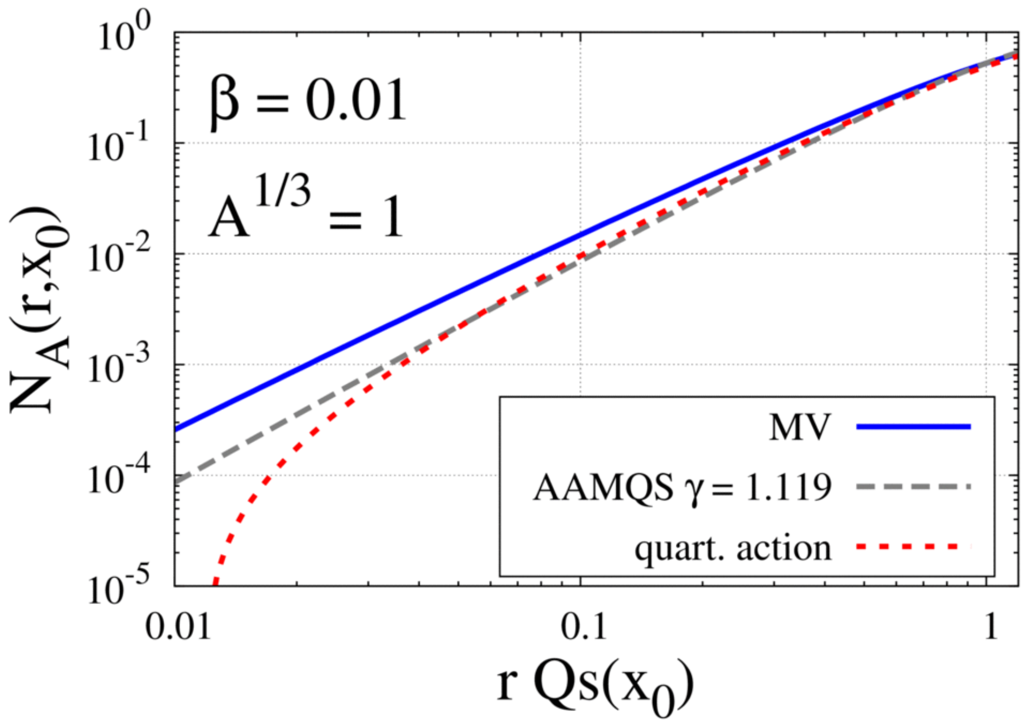
- $\mu^2 \sim g^2 A^{1/3}$; $\kappa_3 \sim g^3 A^{2/3}$; $\kappa_4 \sim g^4 A$

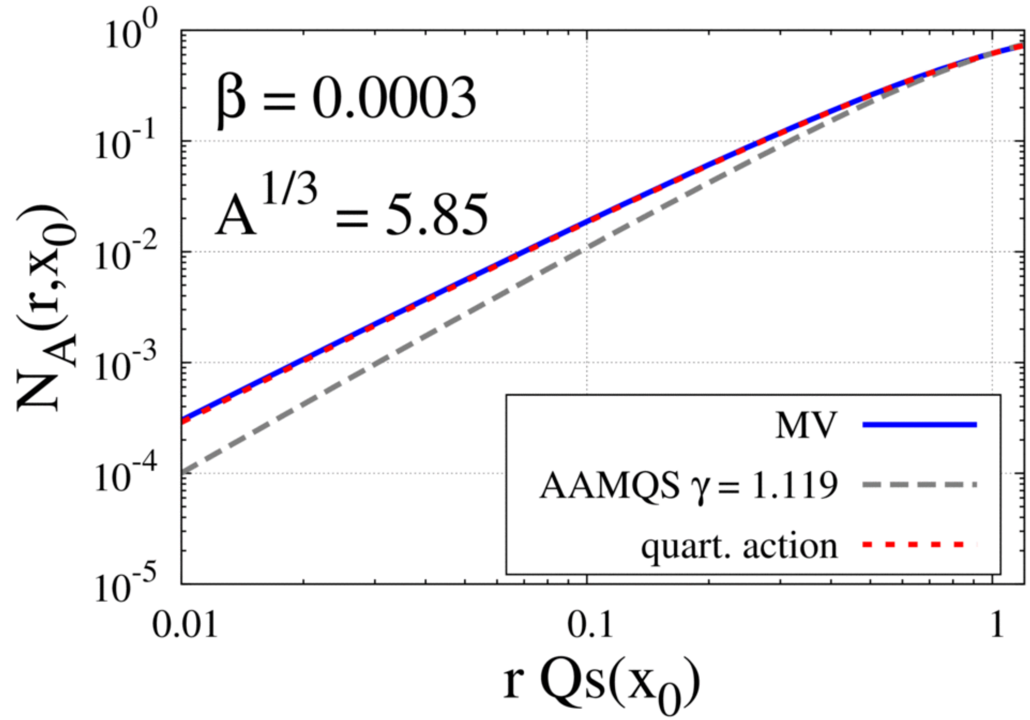
Elena Petreska et al: PRD 2011

E. Petreska + A.D., NPA 2012

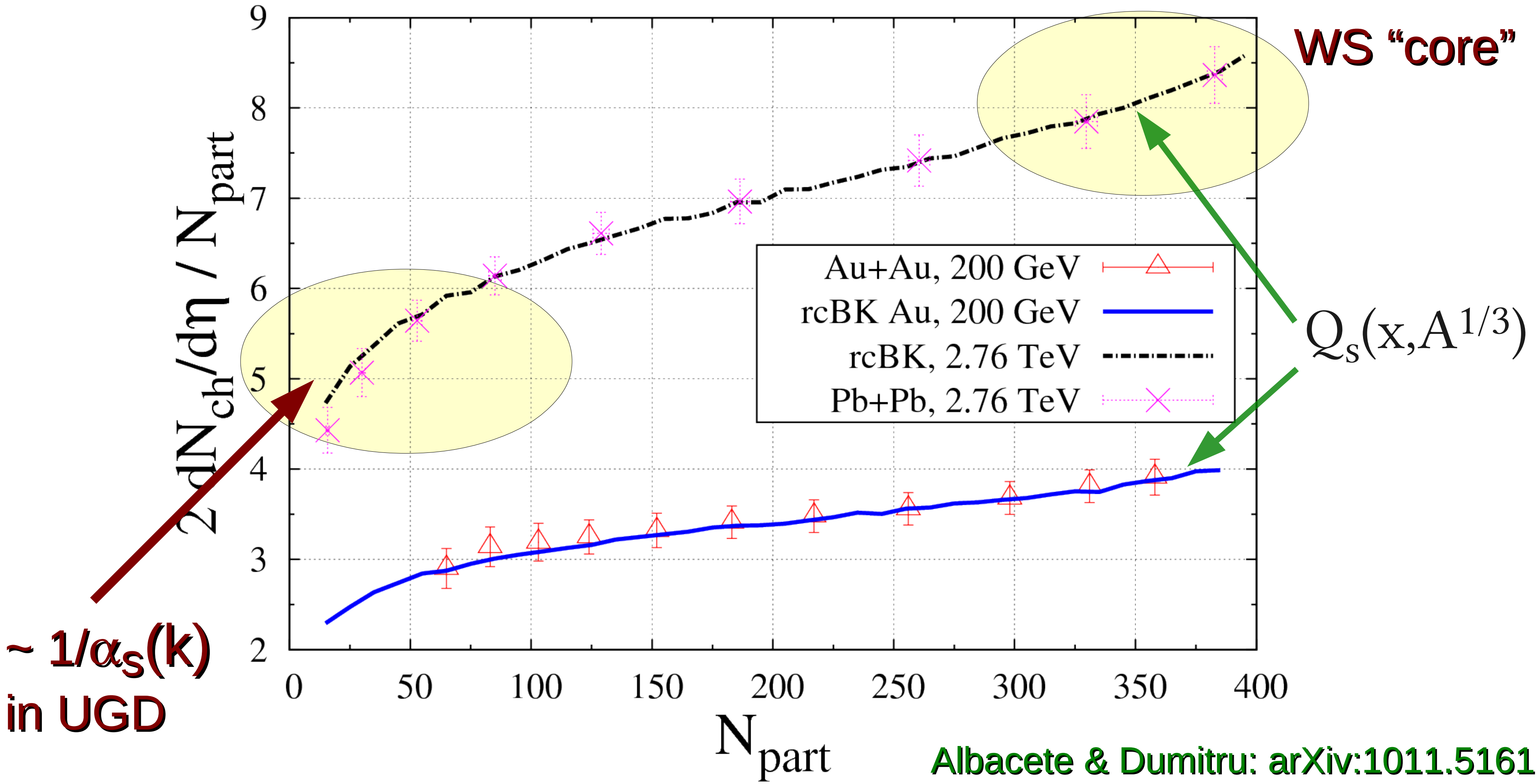
$$1 - \mathcal{N}(r, x_0) = \frac{1}{4} r^2 Q_{s0}^2 \log \frac{1}{r\Lambda} - \frac{1}{6\pi^3} \frac{g^8}{\kappa_4} \left(\int dx^- \mu^4(x^-) \right)^2 r^2 \log^3 \frac{1}{r\Lambda}$$

(in log (1/rΛ) » 1 limit)





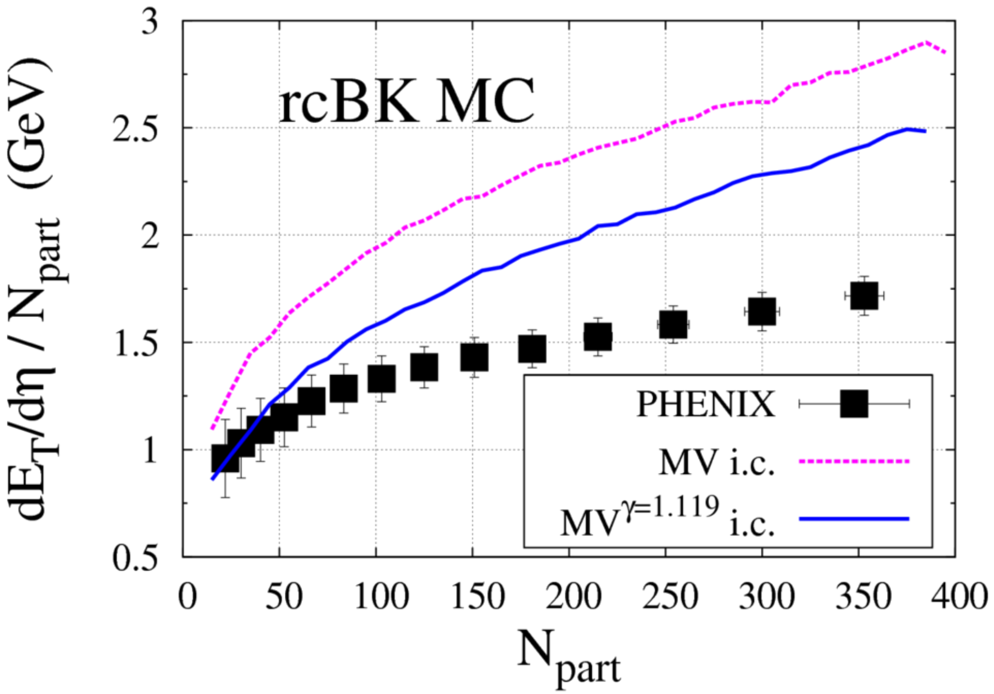
Let's start with AA : centrality and energy dependence of multiplicities; (confirms KLN idea)

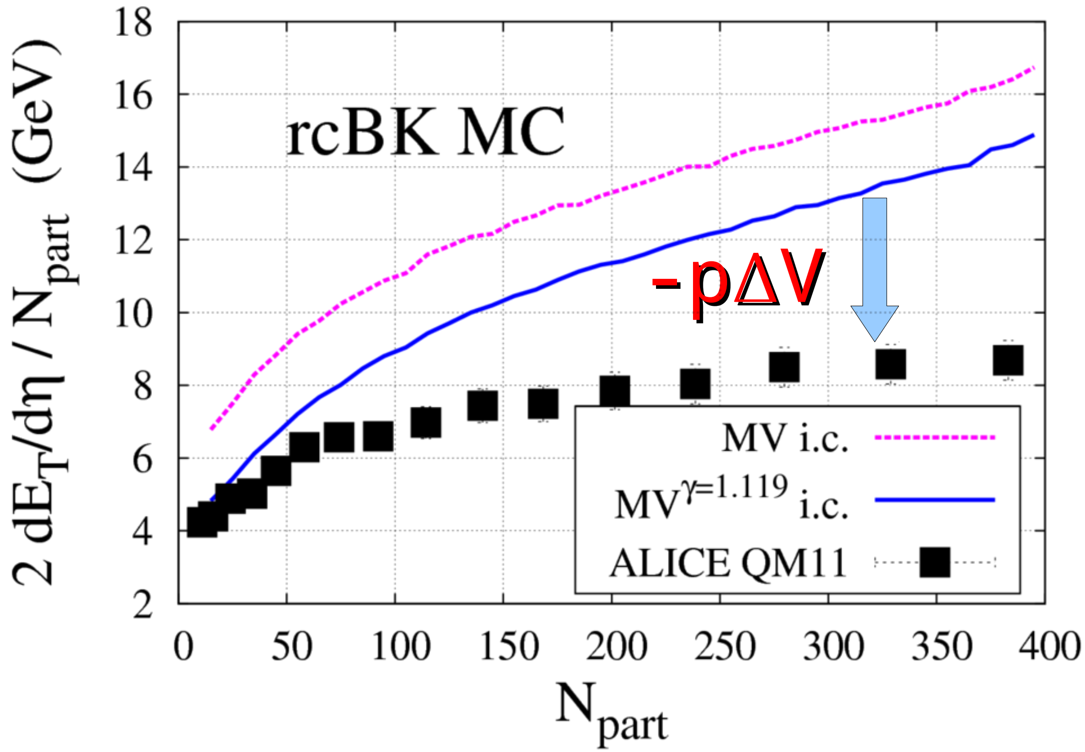


Albacete & Dumitru: arXiv:1011.5161

- assumes $N_{hadr} = \kappa \cdot N_{glue}$ with $\kappa \cong 5$

Back to AA : centrality and energy dependence of E⊥

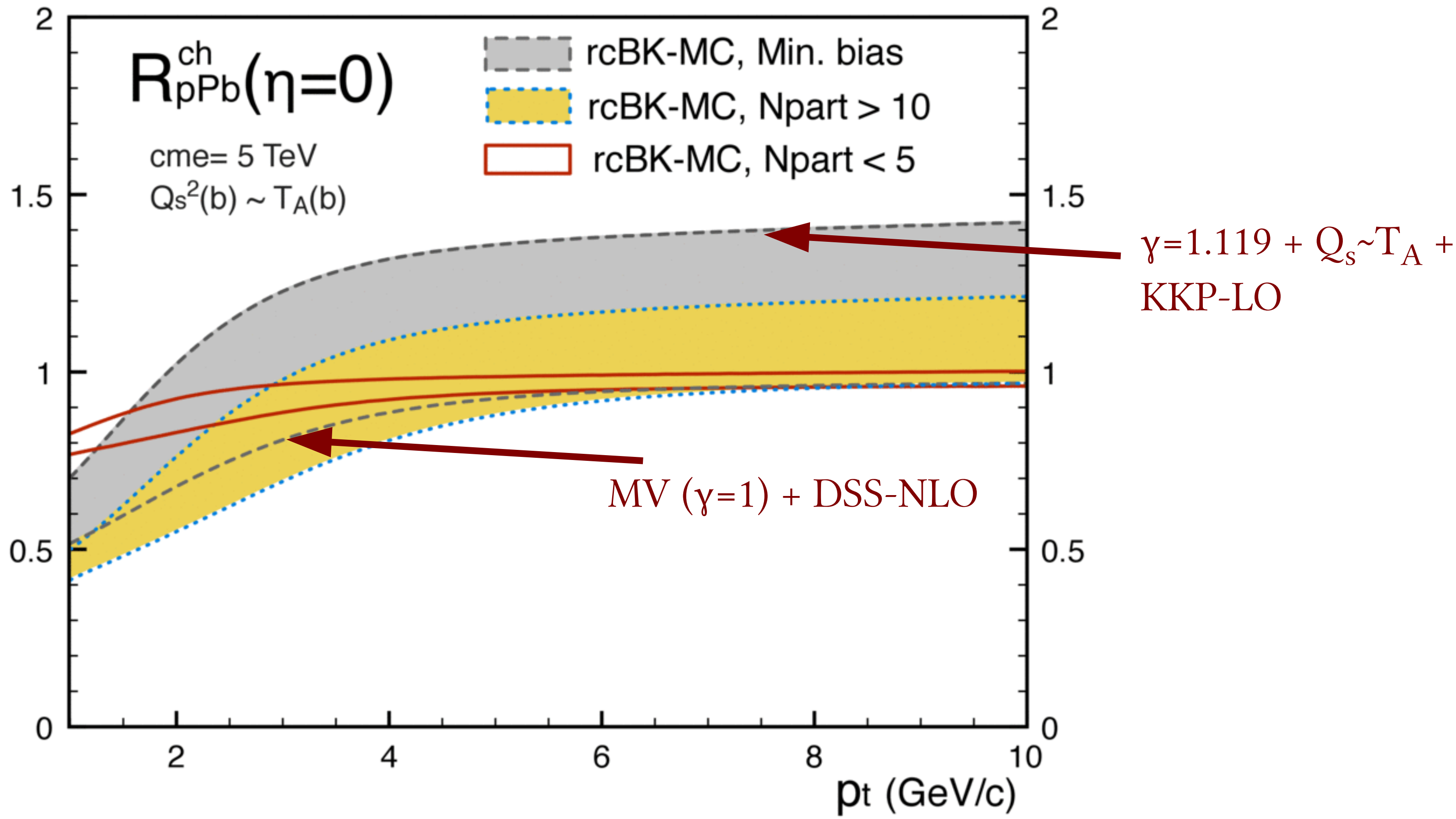




- (again, no g ⟶ h multiplication factor κ here)
- 1d ideal hydro: $E_\perp^f / E_\perp^i \approx T_f / T_i \approx 1/2$
- interesting: $(dE_\perp/d\eta) / (A\sqrt{s}) \approx 0.5\%$ at LHC_{2760}, centrl Pb+Pb !

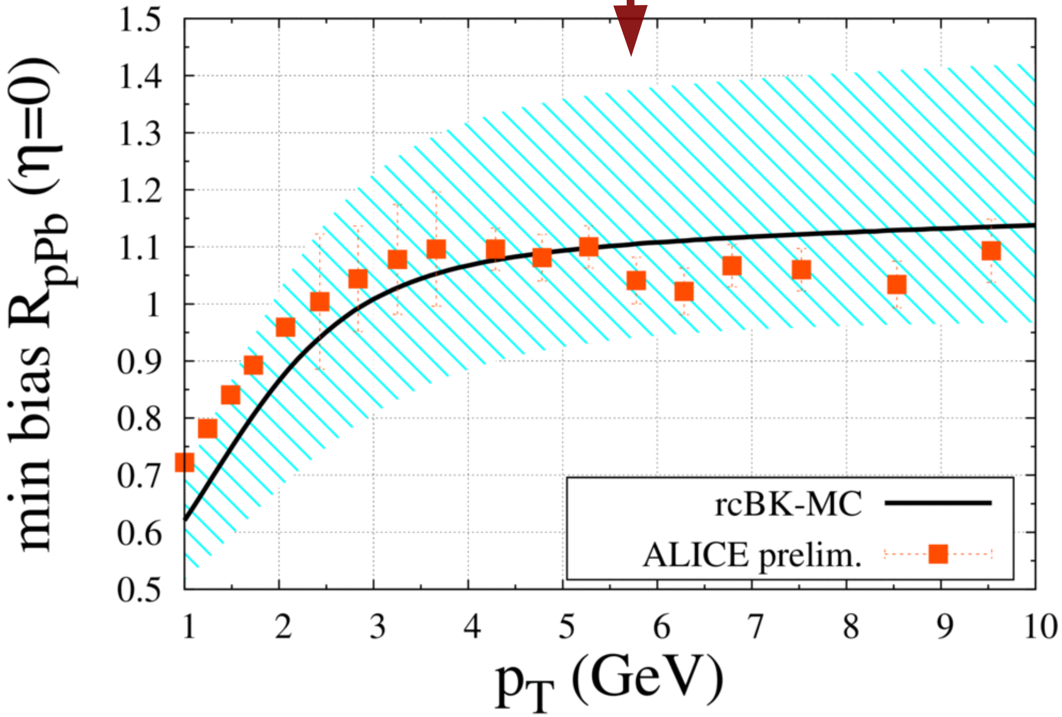
R_{pA} for p+Pb at 5 TeV :

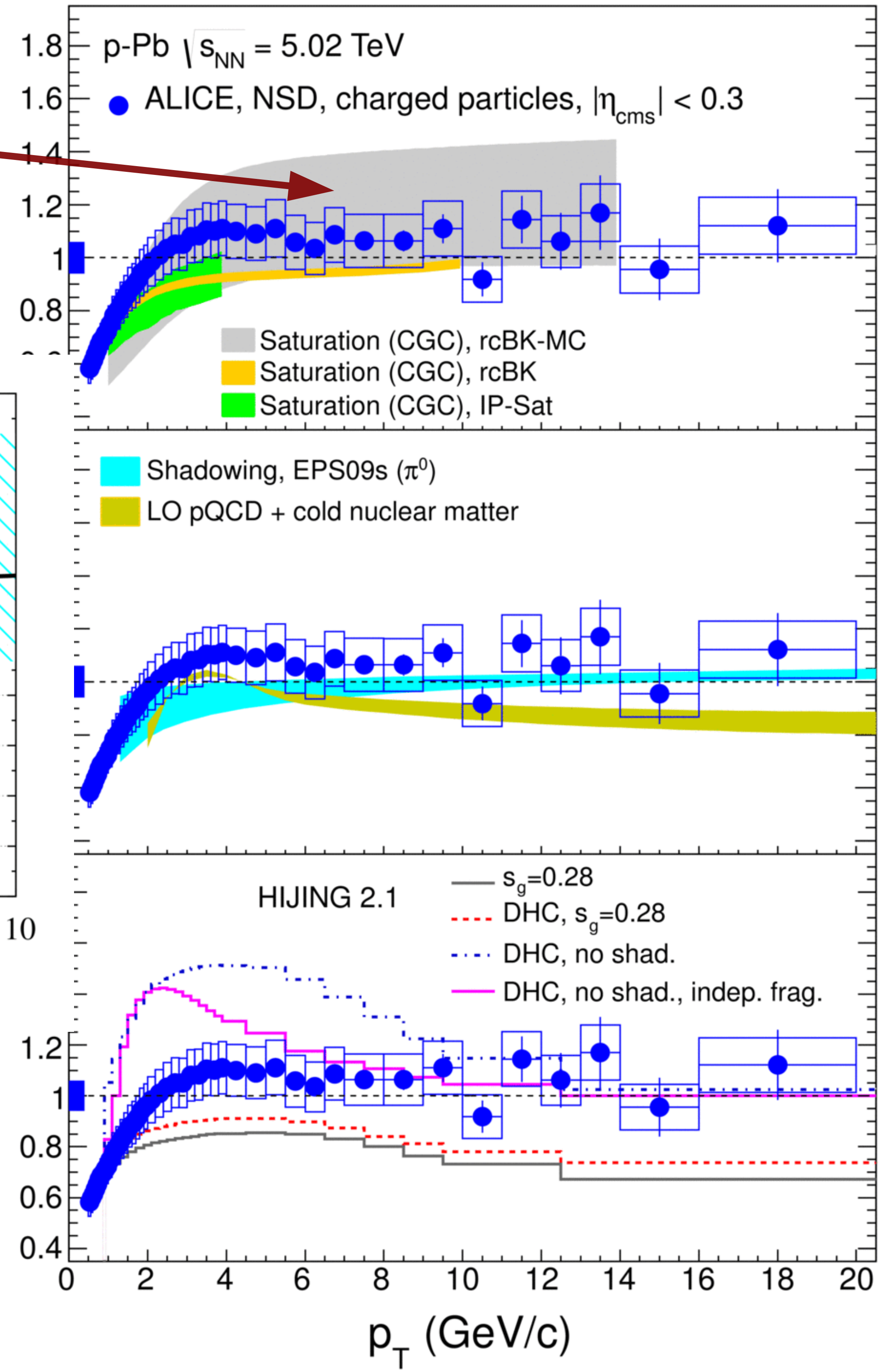
$$R_{pA}(p_T) = \frac{dN_{\rm ch}^{pA}/d^2p_Td\eta}{N_{\rm coll}\; dN_{\rm ch}^{pp}/d^2p_Td\eta}$$



- $R_{pA} < 1$ at $p_{T(\rm hadron)} \sim$ 1-2 GeV
- R_{pA} decreases (slightly) with rapidity
- generically R_{pA}(central) < R_{pA}(mb)
- Cronin peak washed out by evolution

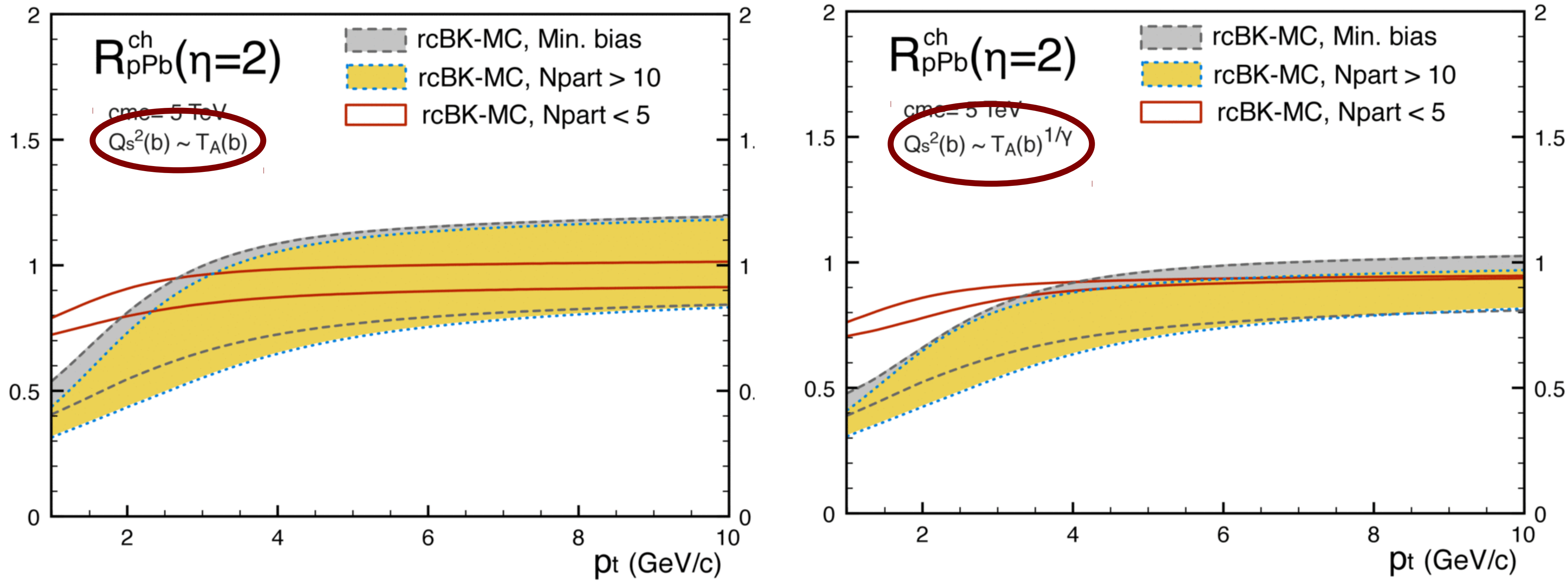
R_{p+Pb} at 5 TeV





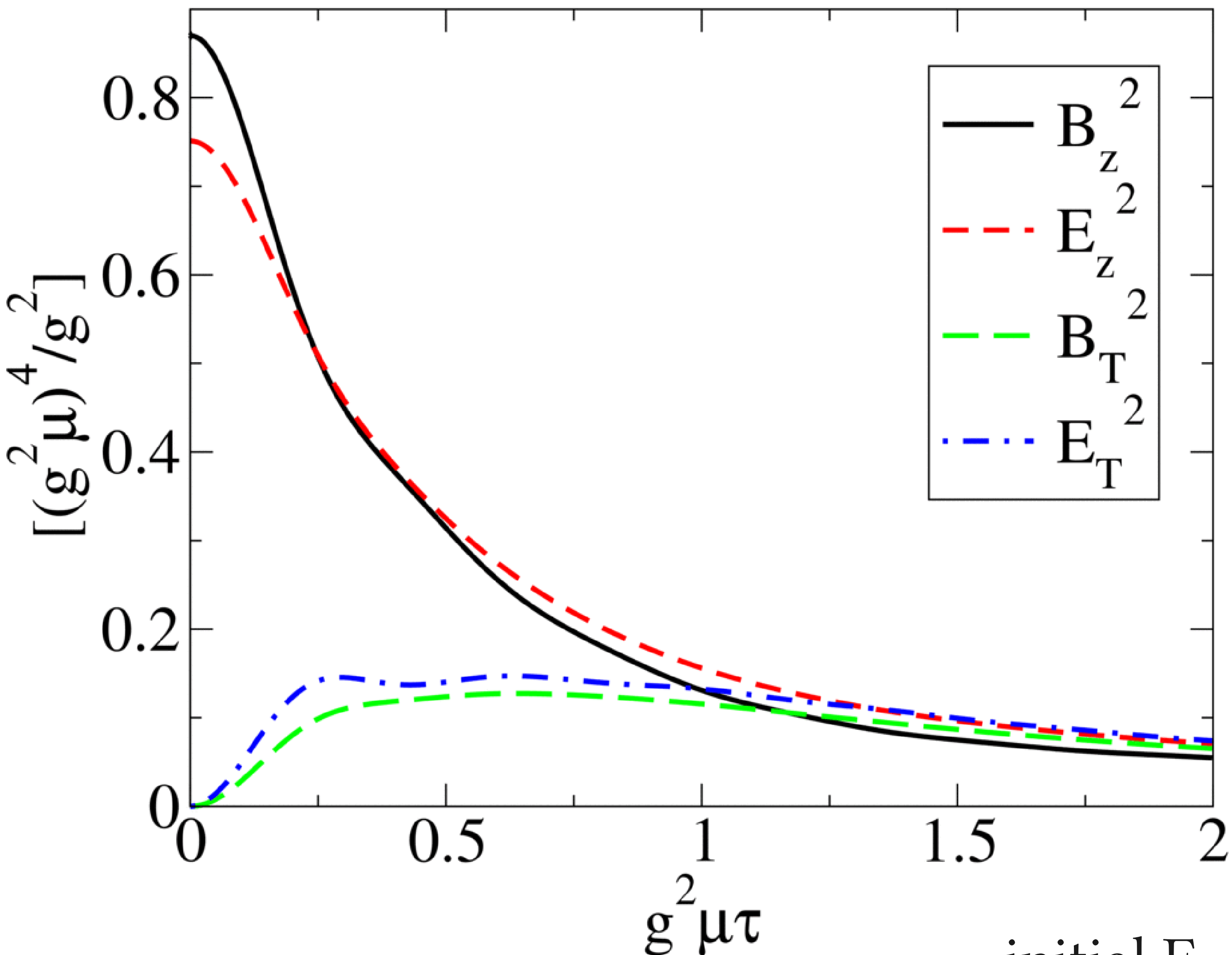
- clearly, no “initial state quenching” above ~ 3 GeV

forward rapidity :



- more suppression due to small-x evolution
- R_{pA} goes down by some 0.1 – 0.2

More detailed view of the “medium” in AA ?



initial E_z, B_z fields

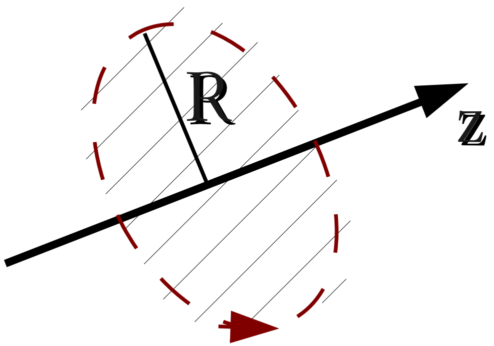
(Fries, Kapusta, Li;
Lappi, McLerran 2006)

Analyze classical field configurations at midrapidity: η=0, 2D

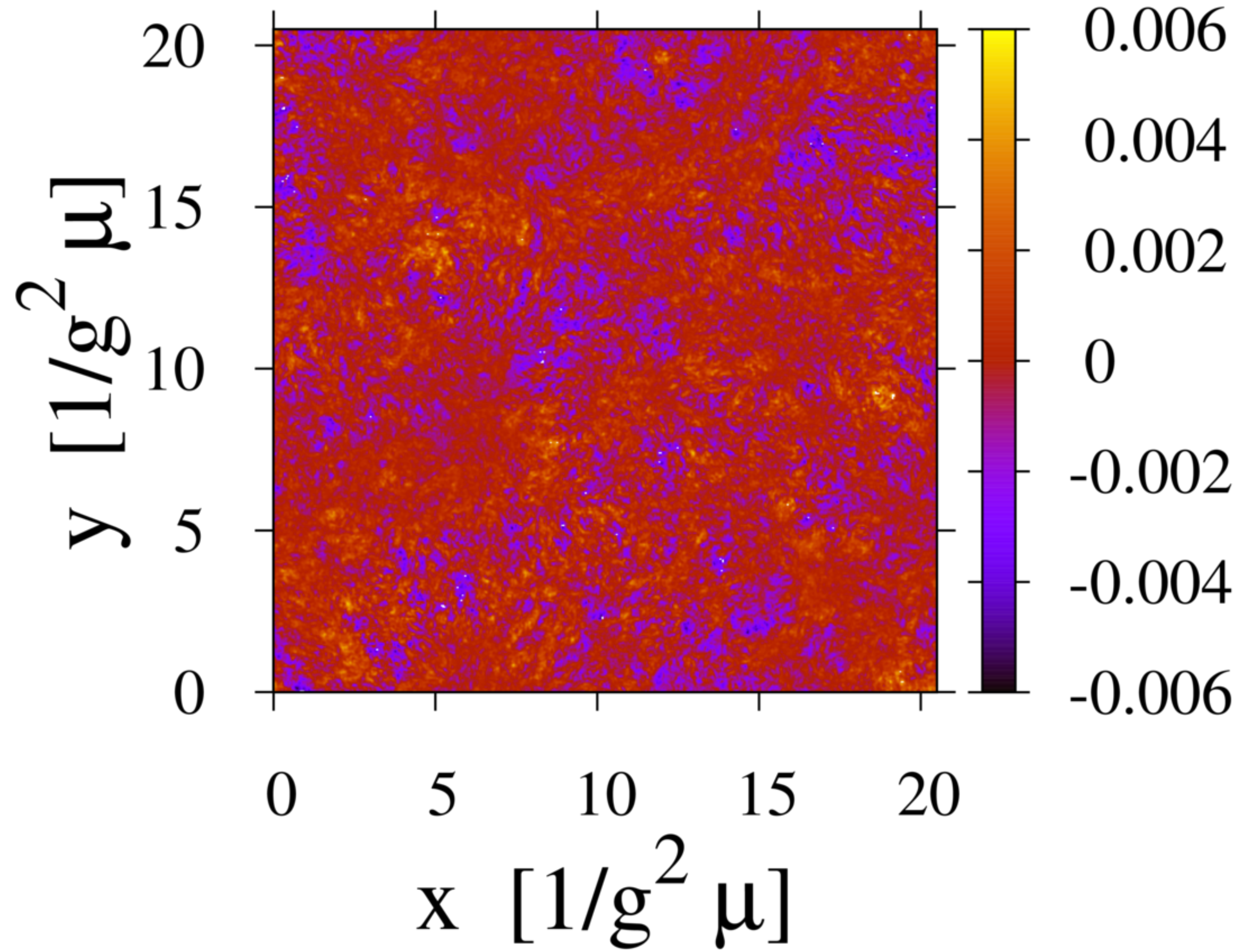
what is structure of B_z field ?

magnetic flux loop in x-y plane:

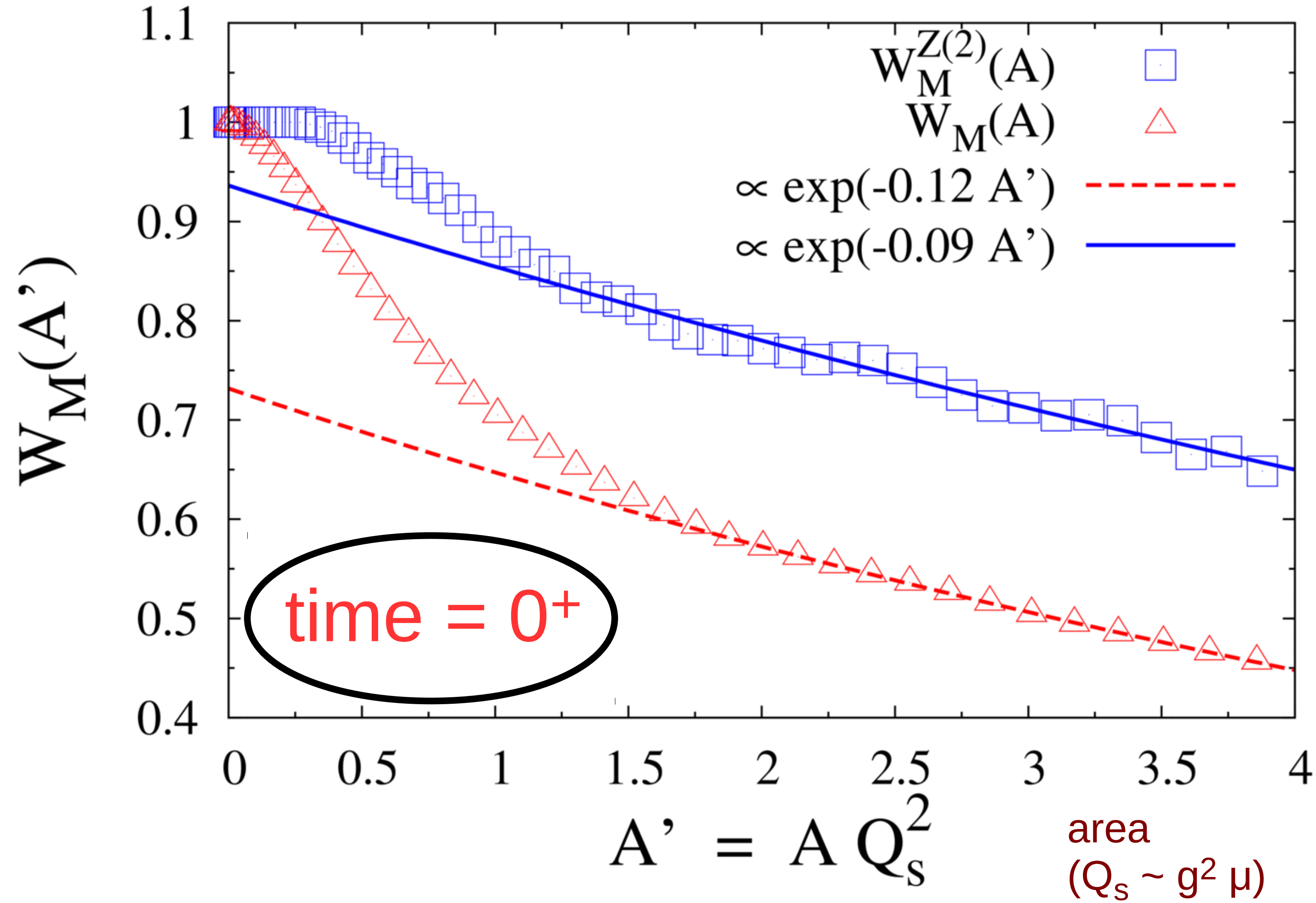
$$
\begin{aligned}
M(R) &= \mathcal{P}\exp\left(ig\oint dx^i A^i\right) \\
W_M(R) &= \frac{1}{N_c}\langle \mathrm{tr}\ M(R)\rangle \\
W_M^{Z(2)}(R) &= \langle \mathrm{sgn}\ \mathrm{tr}\ M(R)\rangle
\end{aligned}
$$



Magnetic field domains ($B_z{}^3$ at τ=0)



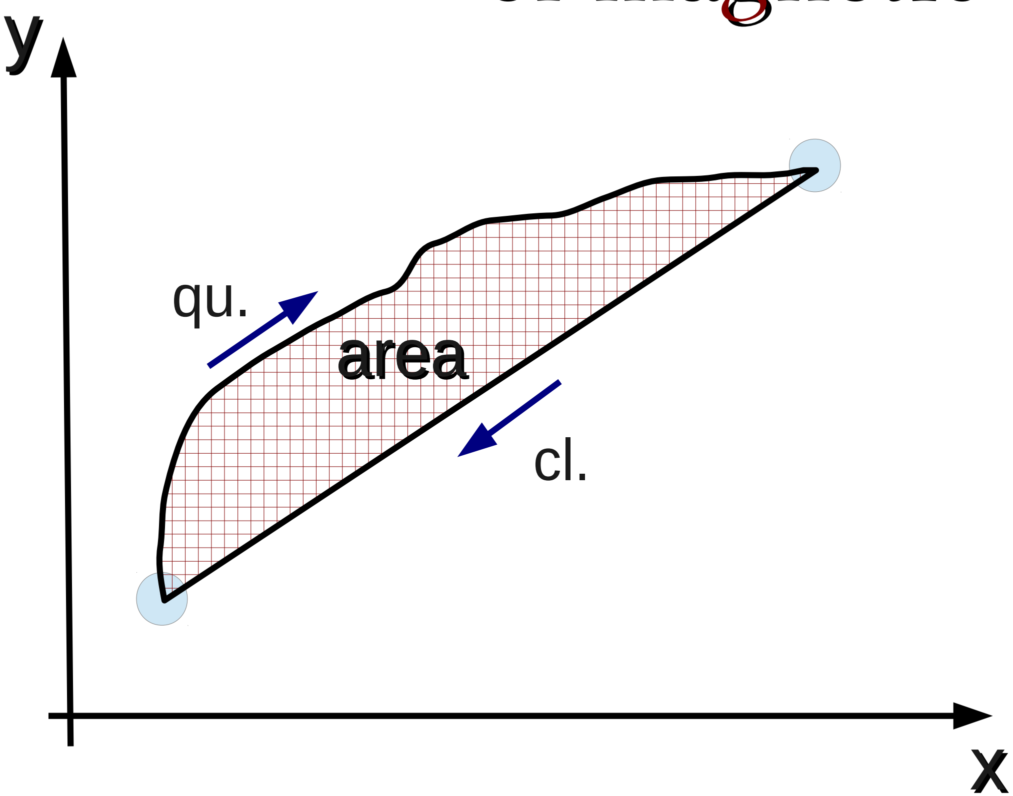
SU(2) solution :



- area law for loops with area $A \geq 1.5 - 2$
- $\sigma_M \sim 0.12\ Q_s^2$; thermal SU(N): $\sigma_M \sim g_{3D}^2 \sim (g^2T)^2$
- small loops $\notin$ Z(2) but roughly ok for large ones!
- structure of B_z ~ uncorrelated vortices ?!
- $R_{vtx} \sim 1/Q_s$ from onset of area law

A.D., Y. Nara, E. Petreska: arXiv:1302.2064

Propagation of hard particles in background of magnetic Z(N) vortices



classical trajectory ?

- only if paths within one de Broglie length ($1/p_T$) have *same Aharonov-Bohm phase*
- destructive interference leads to Anderson localization

$$\int_0^\infty ds \int \mathcal{D}x^\mu \left\langle \exp i \int_0^s d\tau \left(m\dot{x}^2 + gA_\mu \dot{x}^\mu\right) \right\rangle \sim$$

$$\int_0^\infty ds \int \mathcal{D}x^\mu \exp \left(i \int_0^s d\tau \, m\dot{x}^2 \right) \exp(-\sigma_M A) = \frac{i}{p^2 + i\sigma_M \frac{m}{p_T}}$$

Summary

- p+Pb @ LHC control shows no “initial state jet quench”;
  (wasn't expected by more recent/realistic CGC predictions)
  suppression *was predicted and seen* at semi-hard pt ~ a few GeV
- forward rapidity data from LHC very important
- the “medium” appears much more interesting than featureless homogenous soup: density fluctuations, long. fields, vortices, ...