Forward particle production in the CGC approach

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I - Leading baryons in pp and AA

II – Average p_T in pp and AA

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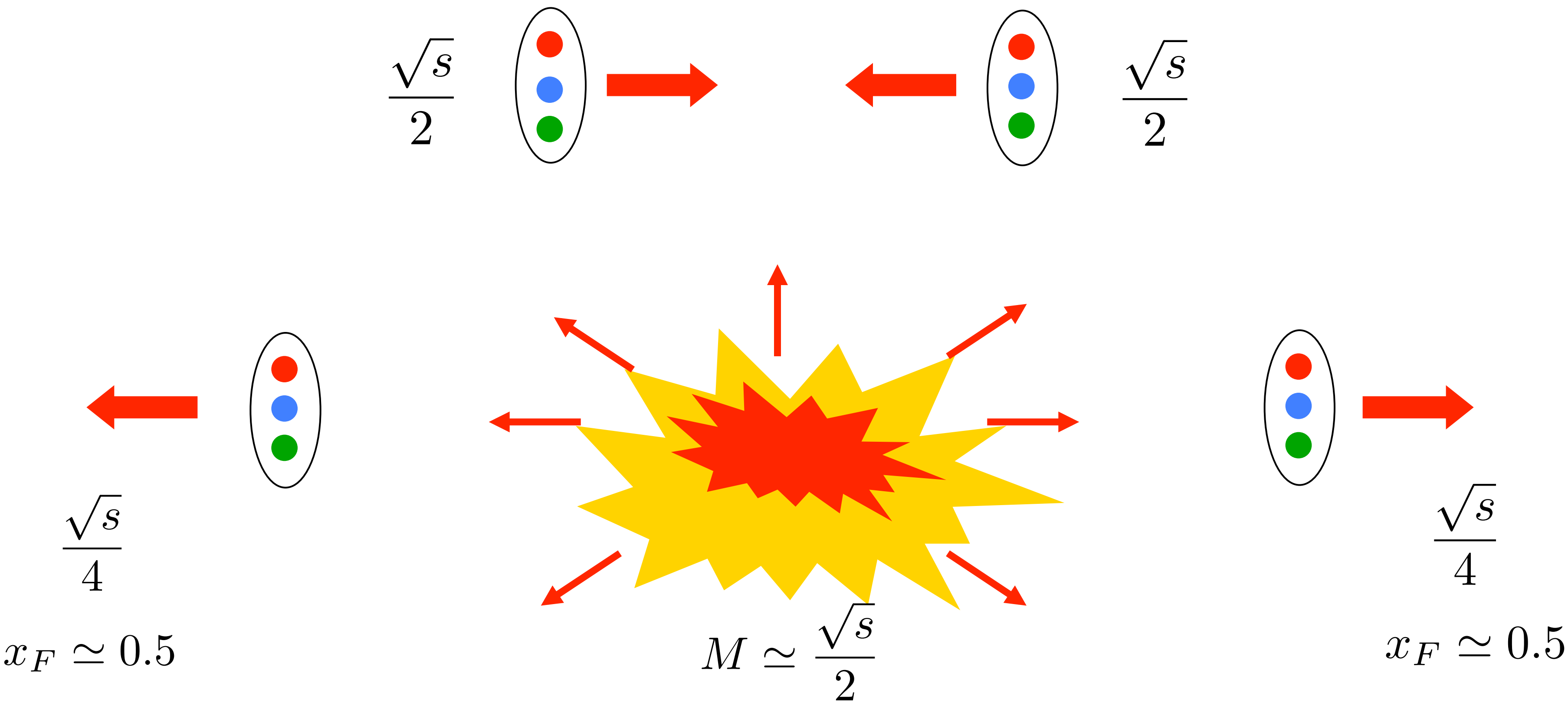
I

Leading Baryons in pp and AA

Leading protons in pp

$\sqrt{s} = 10 - 60$ GeV



Feynman x

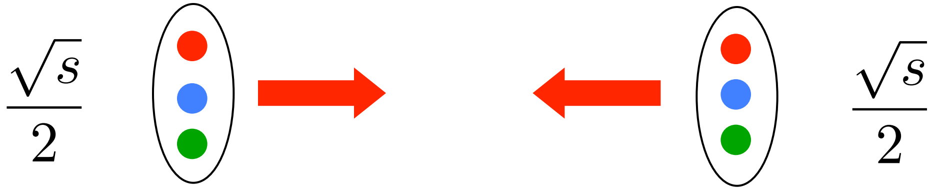
$$x_F = x_L = \frac{p_{\text{baryon}}}{p_{\text{beam}}}$$

inelasticity

$$K = \frac{M}{\sqrt{s}} \simeq 0.5$$

stopping

$$x_F < 1$$



How does it happen microscopically ?

Is there a simple QCD understanding ?

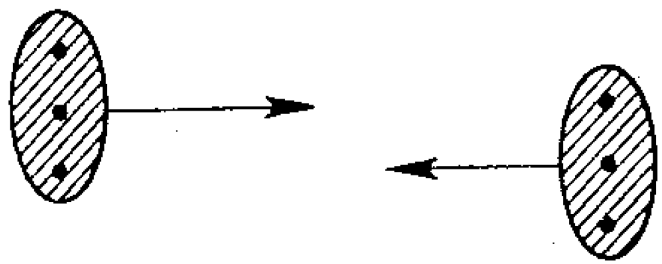
What happens at higher energies ?

“Gluon stripping” and valence quark recombination

Pokorski, Van Hove, NPB 86 (1975) 243 Carruthers, Duong-Van, PRD 28 (1983) 130

Gluons carry half of the momentum of the proton

Gluon interactions are stronger $\sigma_{gg} > \sigma_{qg} > \sigma_{qq}$



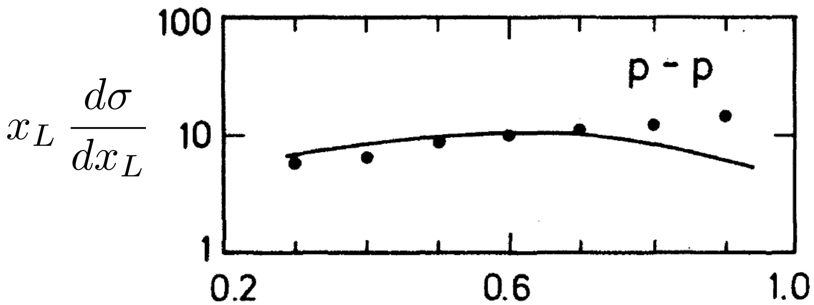
(a)

$$M \simeq \frac{\sqrt{s}}{2}$$

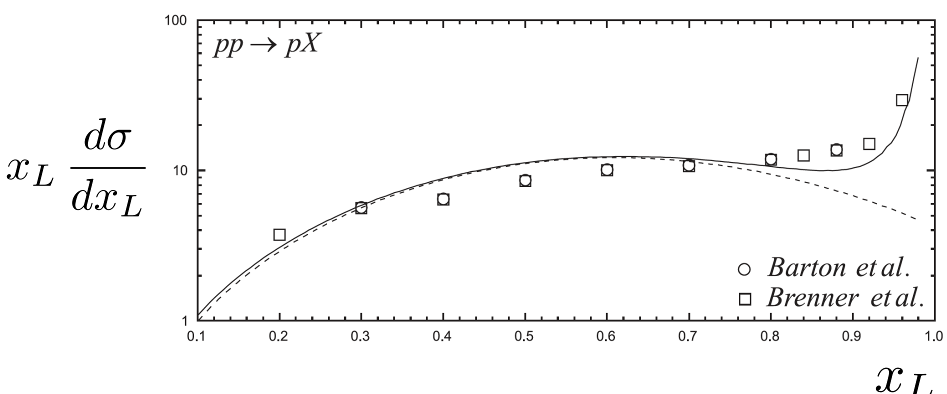
"Gluon stripping" and

valence quark recombination

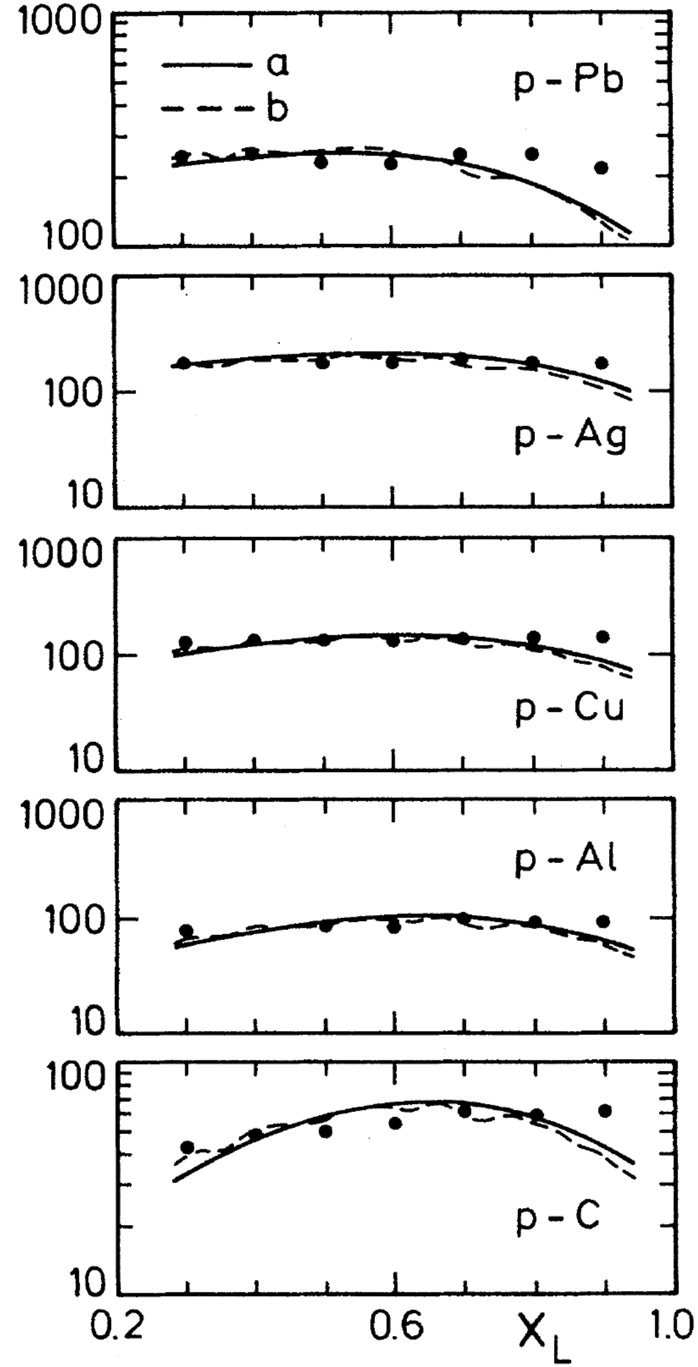
Duraes, FSN, Wilk, hep-ph/0412293



Barton et al., PRD (1983) x_L

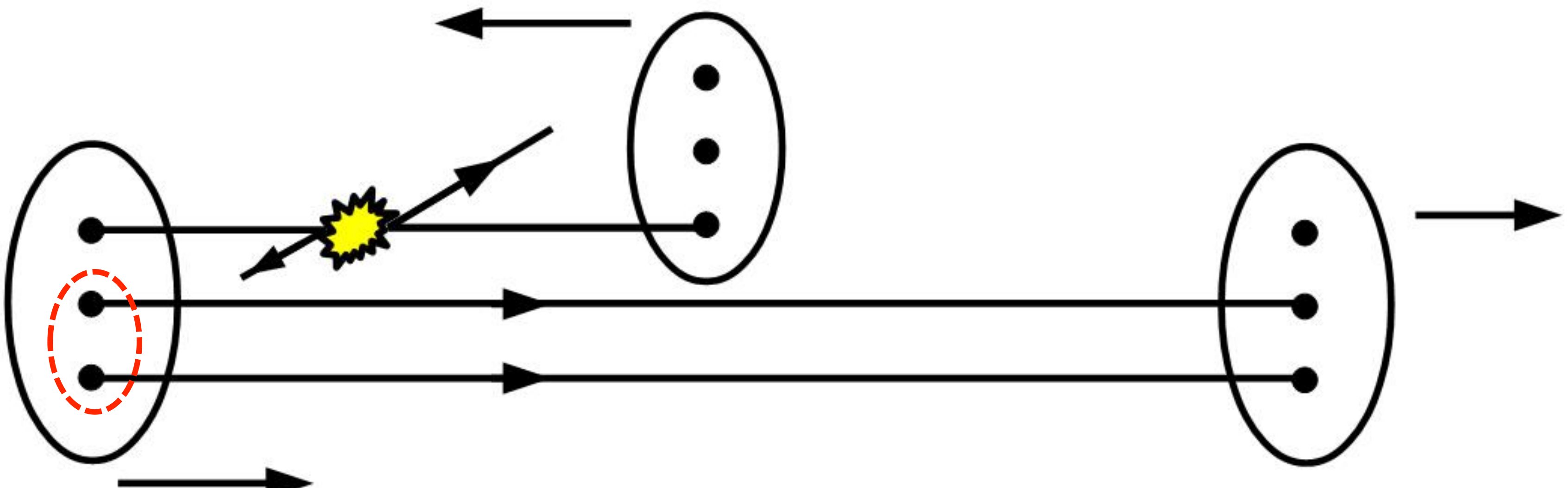


Brenner et al., PRD (1982)



Valence diquark fragmentation

Strikman et al., hep-ph/9604299



$x_F \simeq 0.33$

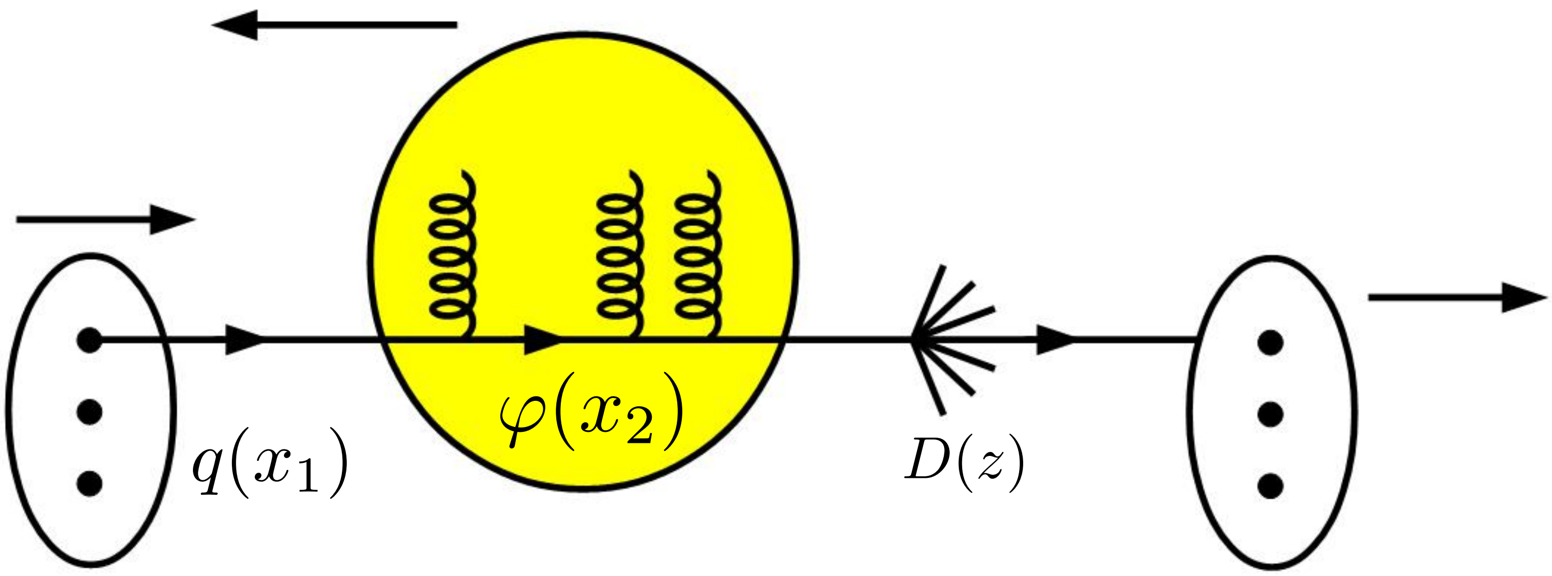
$< x_{gluons} > \simeq \frac{1}{2}$ $< x_{quark} > \simeq \frac{1}{3}\frac{1}{2}$ $< x_{di} > \simeq \frac{2}{6}$

Valence quark independent fragmentation: color glass condensate

Dumitru, Jalilian-Marian, hep-ph/0111357

Dumitru, Gerland, Strikman, hep-ph/0211342

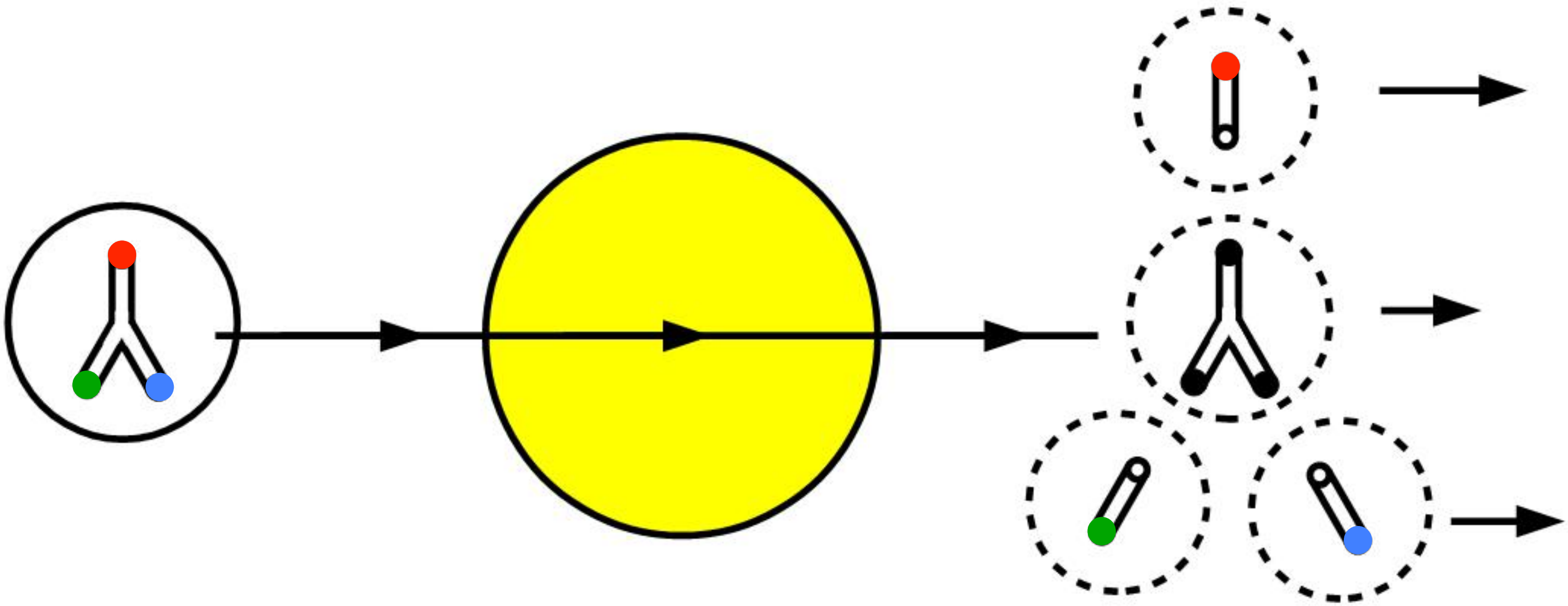
Albacete, Kovchegov, hep-ph/0605053

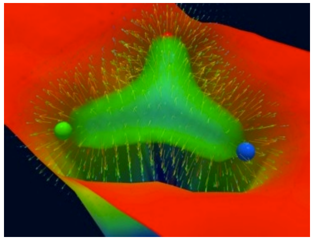


$$< x_{quark} > \simeq \frac{1}{6} \qquad D(z) \simeq \frac{1}{z} \qquad z = \frac{E_{baryon}}{E_{quark}} \simeq \frac{x_L}{x_1}$$

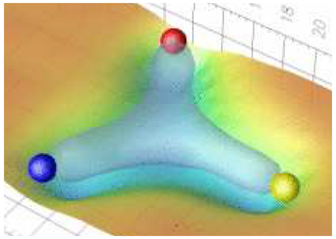
Baryon junction excitation

Kharzeev, PLB (1996)



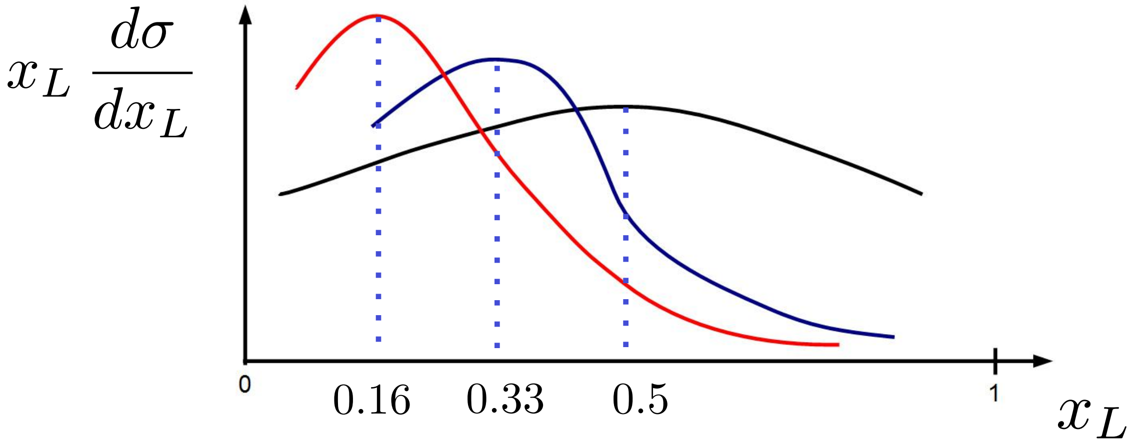


Suganuma et. al
hep-lat/0006005
hep-lat/0204011



Leinweber et al.
hep-lat/0606016]

Quark fragmentation ⬅ Diquark fragmentation ⬅ Recombination

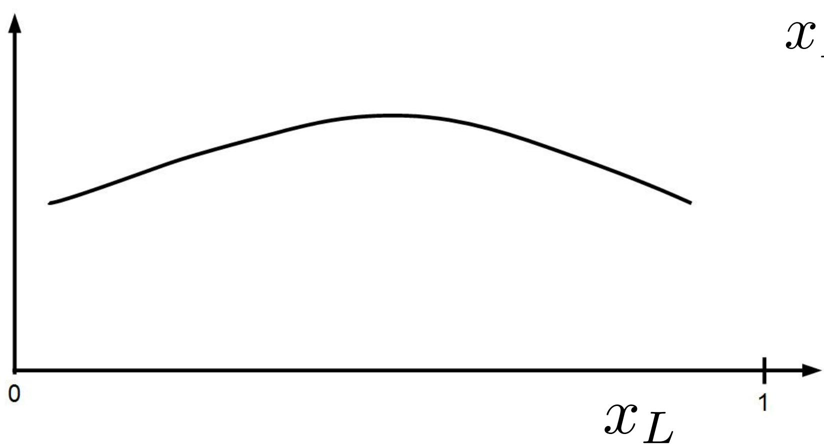


Higher energies

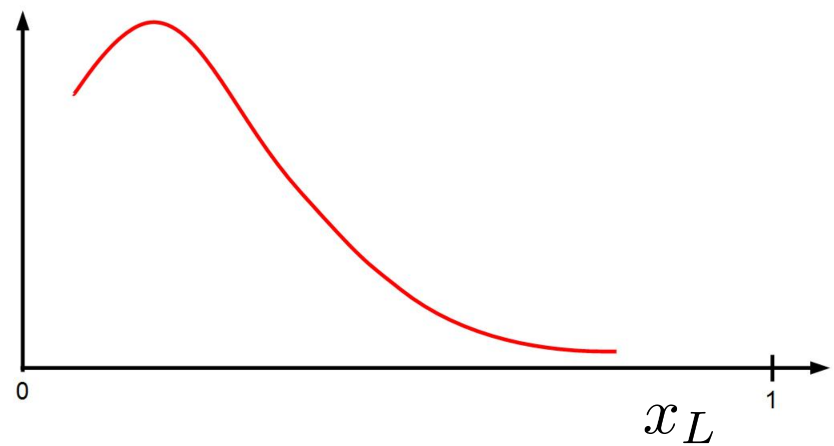
- more gluons
- low x gluons in the target
- $< p_T >$ grows
- Transverse "kick" destroys projectile coherence
- no recombination !

CGC:
onset at Qsat !

Recombination → Independent fragmentation



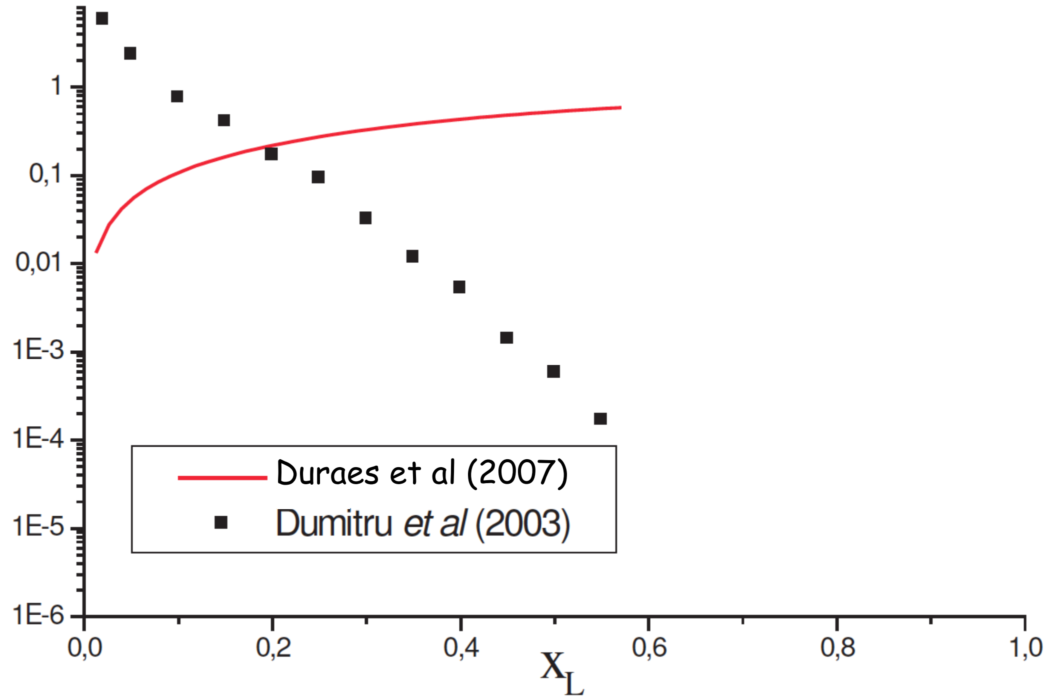
$$x_L \frac{d\sigma}{dx_L}$$



Softening of the LP spectrum in cosmic rays

Dumitru, Gerland, Strikman, hep-ph/0211342

$$x_L \frac{d\sigma}{dx_L}$$

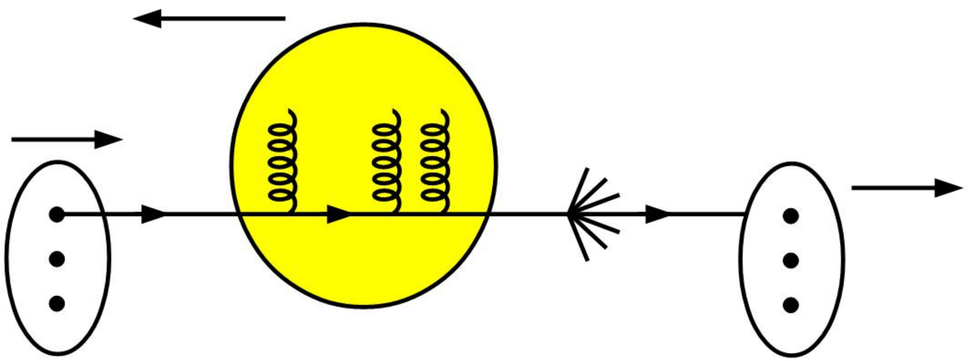


Large x_L : clear separation between recombination and independent fragmentation

Start with pp, increase the energy and use the LHCf

Leading baryons in AA

CGC approach



Valence quarks "go through"

Valence quarks are in the net baryon distribution: $B - \bar{B}$

Not always forward production: "large y" → medium to small x_F

$$x_F = \frac{p_T}{\sqrt{s}}\, e^y \qquad \left\{ \begin{array}{l} y = 4 \\ p_T = 4\,\mathrm{GeV} \\ \sqrt{s} = 5000\,\mathrm{GeV} \end{array} \right. \longrightarrow \quad x_F \simeq 0.04$$

Mehtar-Tani, Wolschin, arXiv:1102.3134, arXiv:1001.3617, arXiv:0907. 5444

Duraes, Goncalves, Giannini, FSN, arXiv:1401.7888

$$\frac{dN}{d^2p_T dy} = \frac{1}{(2\pi)^2} \int_{x_F}^{1} \frac{dz}{z^2} D(z) \frac{1}{q_T^2} \, x_1 q_v(x_1) \, \varphi\,(x_2, q_T)$$

Dumitru, Jalilian-Marian, hep-ph/0204028

Valence quark distribution

$$x\, q_v^A(x, Q^2) \;=\; N_{\rm part} x\, q_v^{proton}(x, Q^2)$$

Martin, Stirling, Thorne Phys.Lett. B636 (2006)

"Net baryon" fragmentation function

$$D(z) \equiv D_{\Delta B/q}(z) = D_{B/q}(z) - D_{\bar{B}/q}(z)$$

Albino, Kniehl, Kramer, arXiv:0803.2768

Unintegrated gluon distribution

$$\varphi(x_2, q_T) = 2\pi q_T^2 \int r_T dr_T \mathcal{N}(x_2, r_T) J_0(r_T q_T)$$

Dipole scattering amplitude $\mathcal{N}(x_2, r_T)$

$$q_T = \sqrt{p_T^2 + m^2}/z$$

$$x_1 = q_T\, e^y/\sqrt{s}$$

$$x_2 = q_T\, e^{-y}/\sqrt{s}$$

$$x_F = \sqrt{p_T^2 + m^2}\, e^y/\sqrt{s}$$

$$p_{T_{max}} = \sqrt{s}\, e^{-y}$$

Dipole scattering amplitude

$$\mathcal{N}(x, r_T) = 1 - \exp\left[-\frac{1}{4}(r_T^2 Q_s^2)^{\gamma(x,r_T^2)}\right]$$

Golec-Biernat – Wüsthoff (GBW): $\gamma = 1$

$$\varphi(x_2, q_T) = 4\pi \frac{q_T^2}{Q_s^2(x_2)} \exp\left(-\frac{q_T^2}{Q_s^2(x_2)}\right)$$

$$Q_s^2 = Q_0^2\, A^{1/3} \left(\frac{x_0}{x}\right)^\lambda$$

Boer - Utermann – Wessels (BUW): $\gamma(x, r_T) = \gamma_s + (1-\gamma_s)\frac{(\omega^a - 1)}{(\omega^a - 1) + b}$

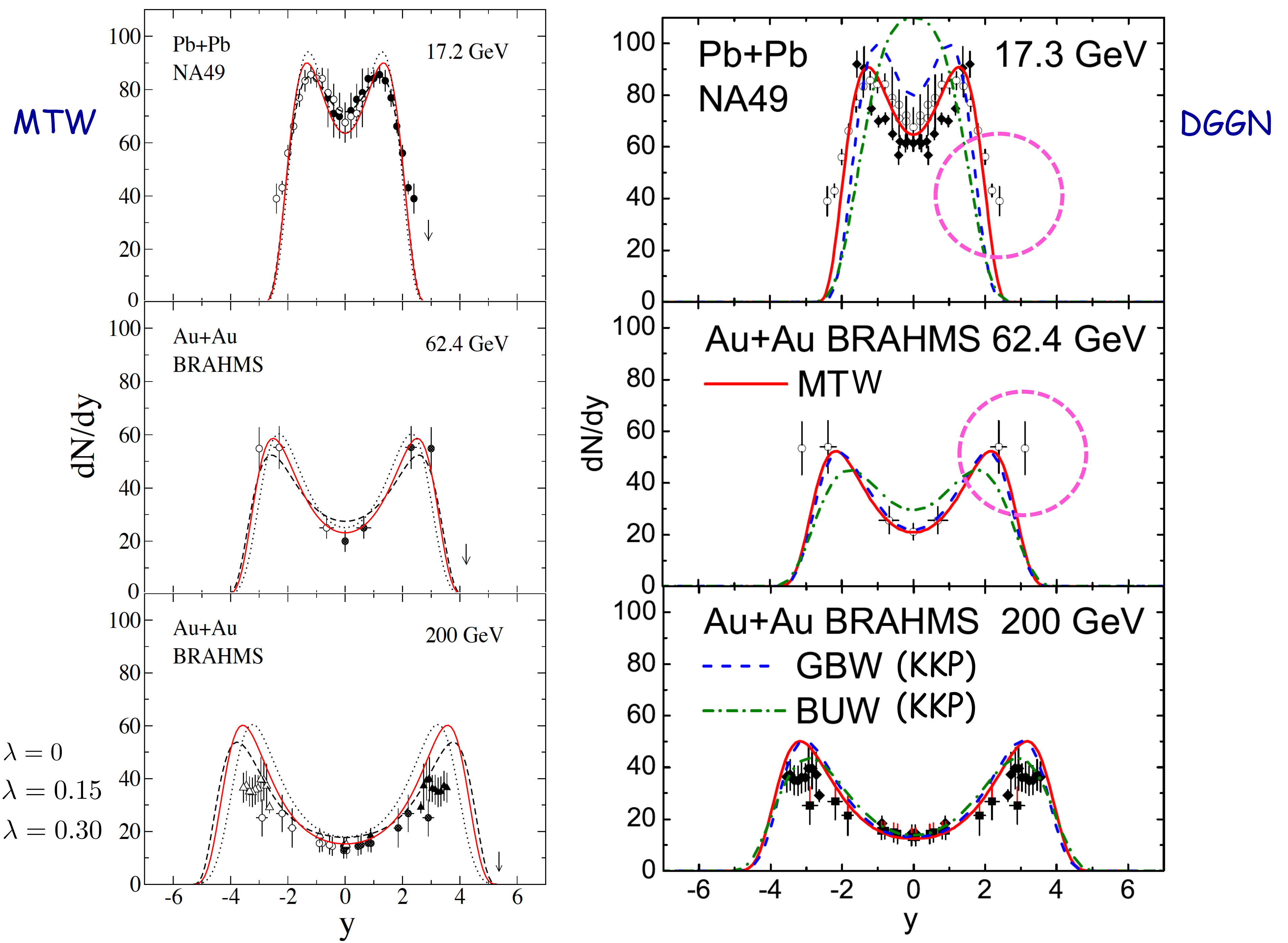
arXiv:0711.4312

$$\omega \equiv 1/(r_T Q_s(x))$$

scaling variable

$$\varphi(x_2, q_T) \propto \frac{1}{q_T^4}$$

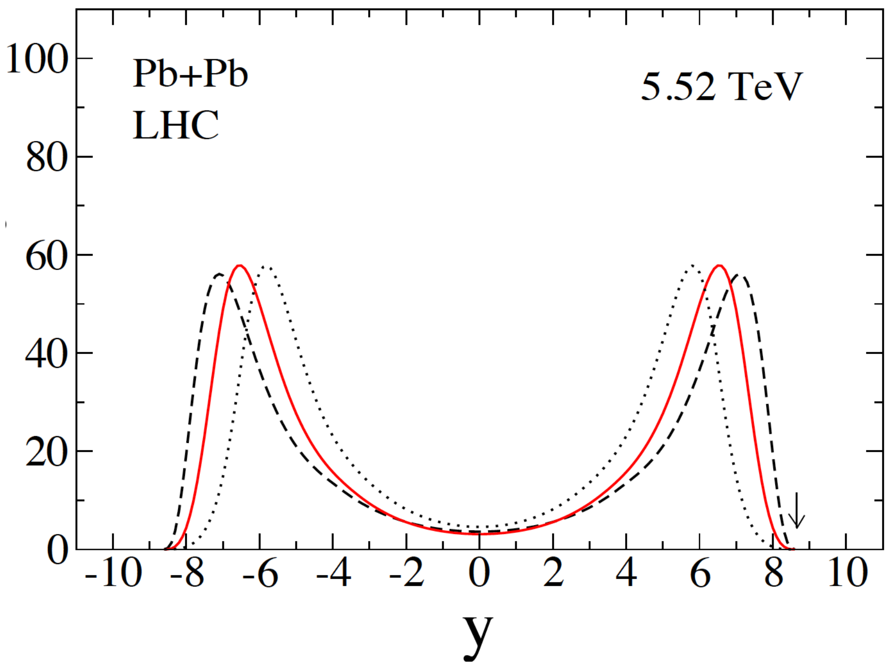
Correct linear limit !

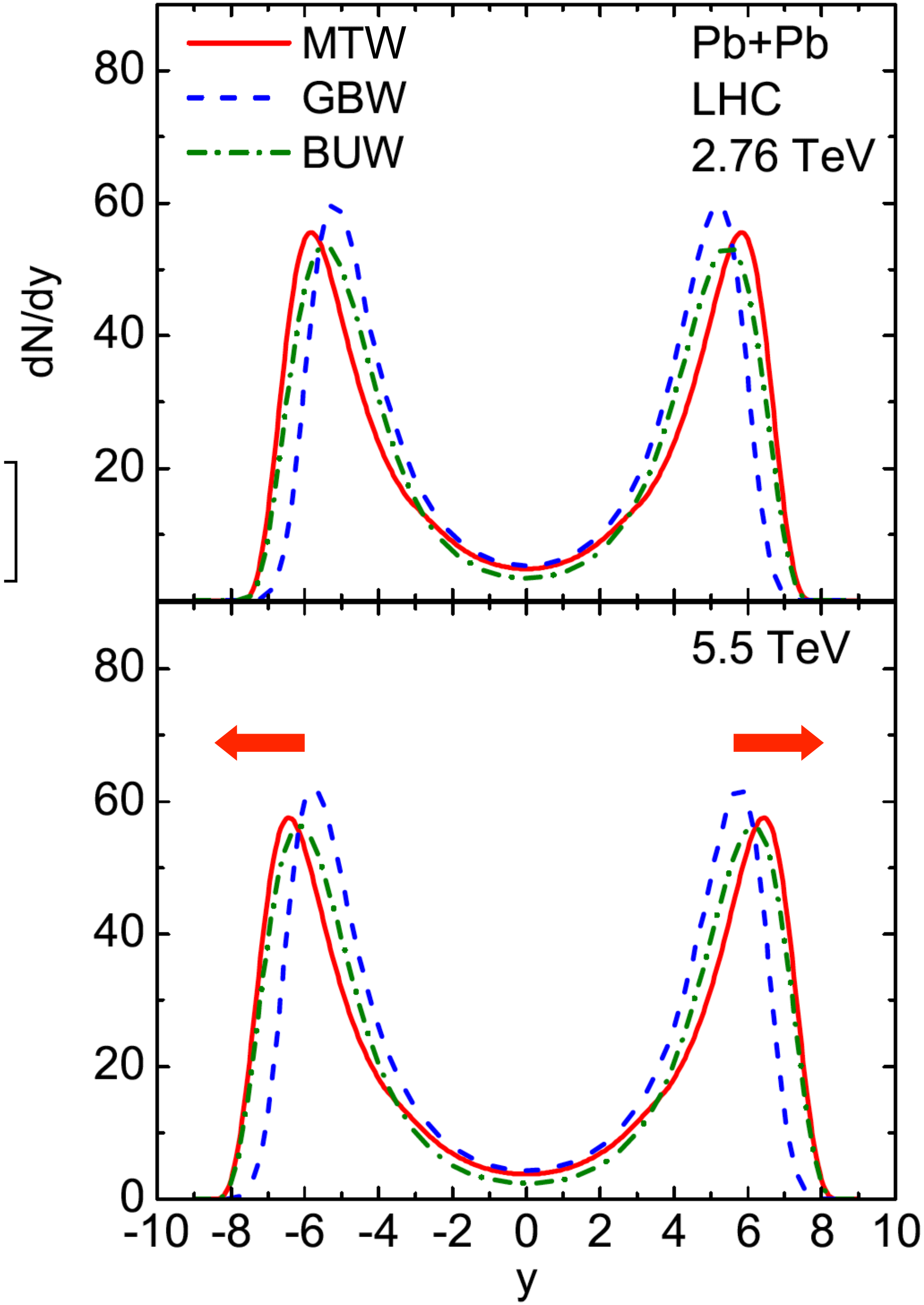


MTW
DGGN
Pb+Pb
NA49
17.2 GeV
Au+Au
BRAHMS
62.4 GeV
200 GeV
dN/dy
y
λ = 0
λ = 0.15
λ = 0.30
17.3 GeV
Au+Au BRAHMS 62.4 GeV
MTW
Au+Au BRAHMS 200 GeV
GBW (KKP)
BUW (KKP)

Predictions

$$y_{peak} = \frac{1}{1+\lambda}\left[ln\left(\frac{\sqrt{s}}{m_p}\right) - ln\, A^{1/6}\right]$$

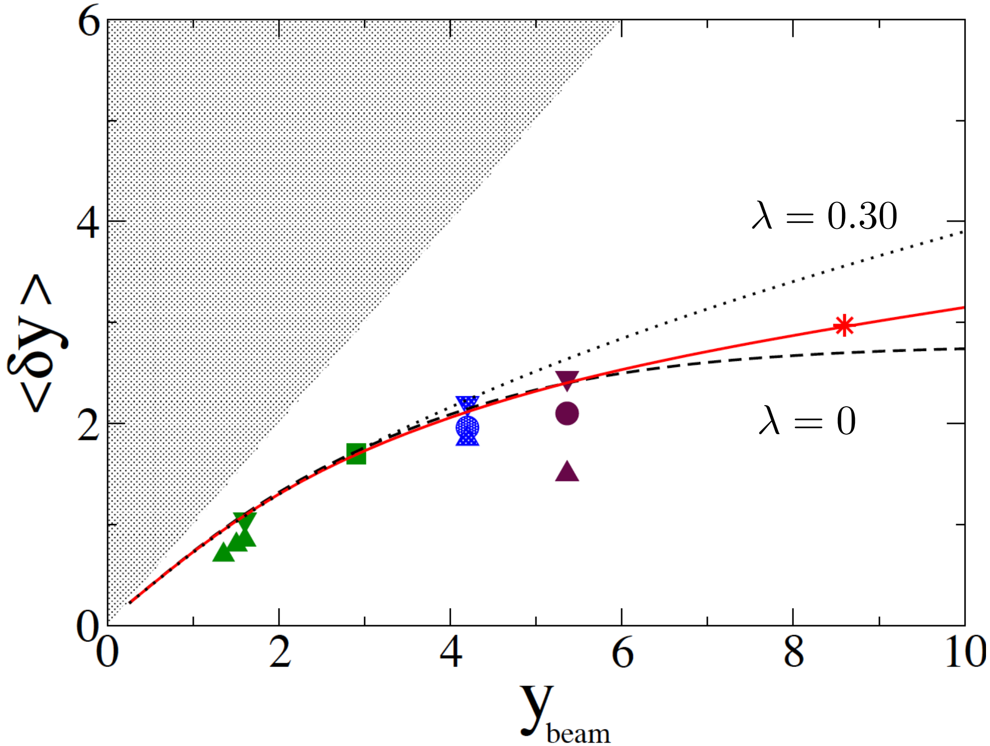




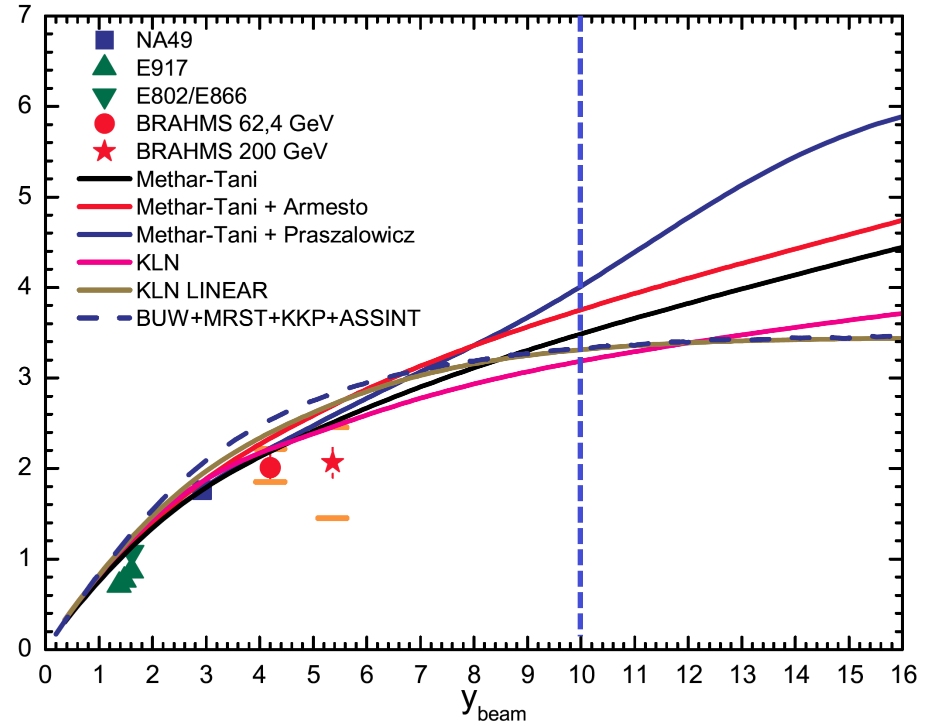
Mean Rapidity Loss

$$< \delta y >= y_{beam} - \frac{\int_0^{y_{beam}} dy\, y\, \frac{dN}{dy}}{\int_0^{y_{beam}} dy\, \frac{dN}{dy}}$$

MTW

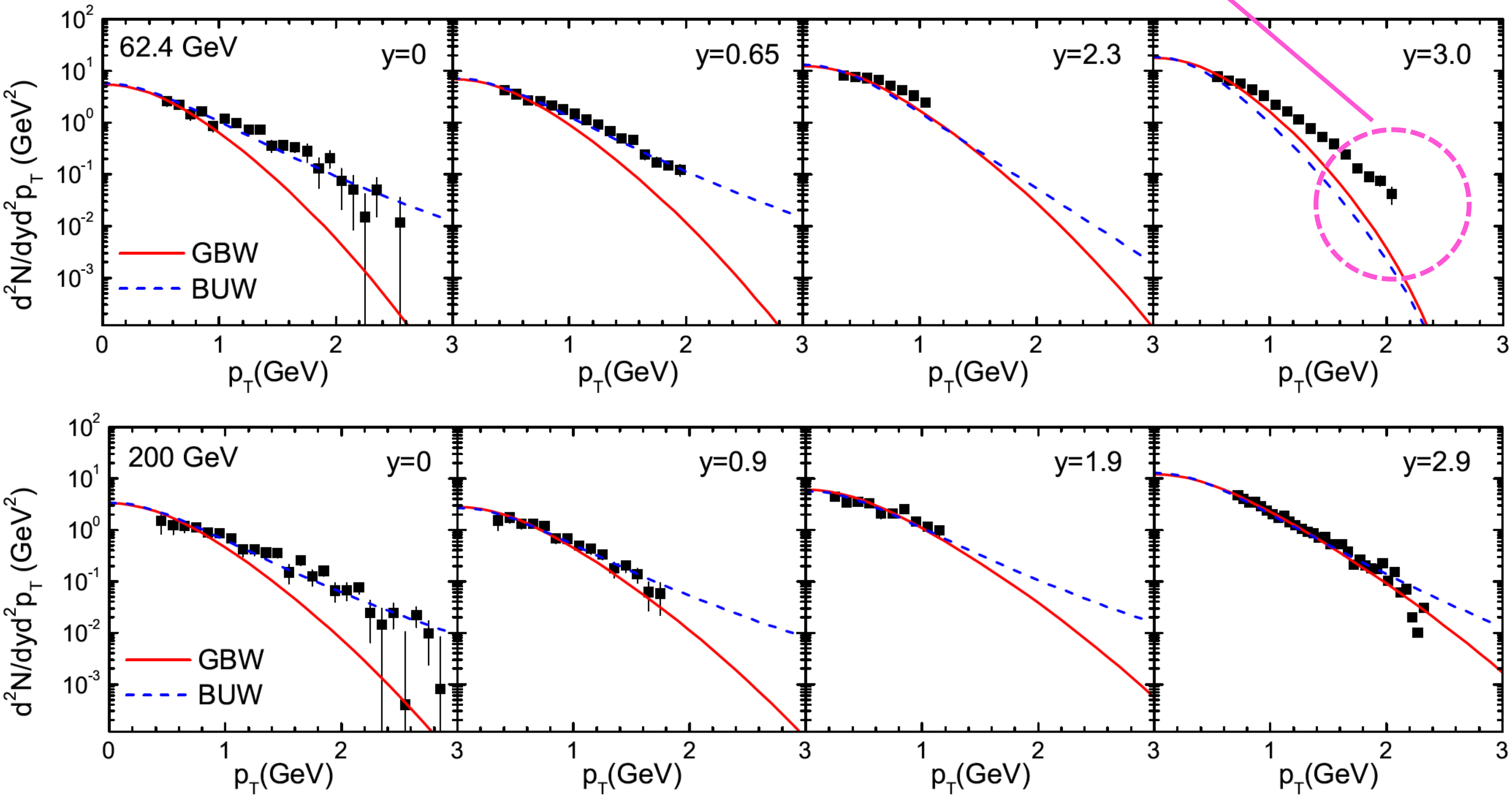


DGGN



large x_F :
failure of independent
fragmentation ?

$x_F \simeq 0.6$



$x_F \simeq 0.2$

BUW works! $exp(-q_T^2) \rightarrow 1/q_T^4$ $x_F = \frac{p_T}{\sqrt{s}} e^y$

Summary I

Observable:

Net baryons: they carry the valence quarks

Valence quarks probe the low gluons in the target (test for saturation)

Physics:

Transition from recombination to independent fragmentation

Onset of the CGC regime

Results:

CGC approach works (!)

Onset of independent fragmentation (?)

Future:

Forward baryon production (cosmic rays, LHCf, ?)

II

Average p_T versus rapidity in p A Collisions

p-Pb : CGC or hydrodynamics ?

"Ridge effect": long range correlations in rapidity and azimuthal angle

CGC: Dusling, Venugopalan, arXiv:1302.7018, arXiv:1211.3701, arXiv:1201.2658

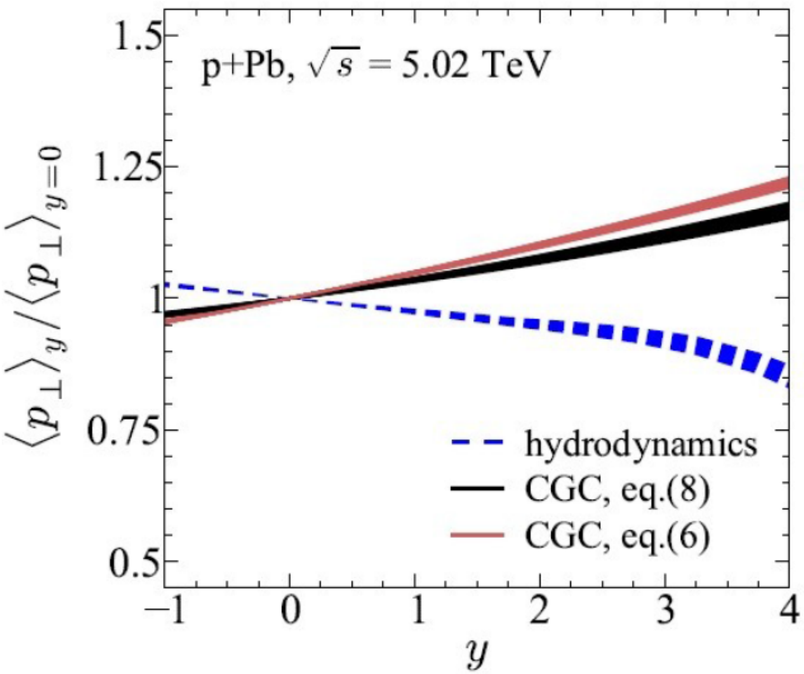
Hydro:
- Alver, Roland, Phys. Rev.C81, 054905 (2010).
- Bozek, Eur. Phys. J.C71, 1530 (2011); Phys. Rev.C88, 014903 (2013)
- Bozek, Broniowski,Torrieri, Phys. Rev. Lett.111, 172303 (2013).
- Shuryak, Zahed, Phys. Rev. C88, 044915 (2013).
- Werner, Bleicher, Guiot, Karpenko, Pierog, Phys. Rev. Lett.112, 232301 (2014).

Azimuthal asymmetries and elliptic and triangular flow

CGC:
- Dumitru, Giannini, Nucl. Phys. A933, 212 (2014)
- Dumitru, McLerran and Skokov, arXiv:1410.4844
- Lappi, Phys. Lett. B744, 315 (2015)
- Schenke, Schlichting, R. Venugopalan, Phys. Lett. B747, 76 (2015)
- Dumitru, Giannini, Skokov, arXiv:1503
- Lappi, Schenke, Schlichting, Venugopalan, arXiv:1509.03499

Hydro:
- Bozek, Eur. Phys. J. C71, 1530 (2011); Phys. Rev. C85, 014911 (2012).
- Bozek, Broniowski, Phys. Lett. B718, 1557 (2013); Phys. Rev. C88, 014903 (2013).
- Bozek, Broniowski. Torrieri, Phys. Rev. Lett.111, 172303 (2013).
- Bzdak, Schenke, Tribedy, Venugopalan, Phys. Rev. C87,064906 (2013).
- Shuryak, Zahed, Phys. Rev. C88, 044915 (2013).
- Werner, Bleicher, Guiot, Karpenko, Pierog, Phys. Rev. Lett.112, 232301 (2014).
- Schenke, Venugopalan, arXiv:1405.3605

How to disentangle CGC from hydrodynamics ?



P. Bozek, A. Bzdak and V. Skokov, Phys. Lett. B728, 662 (2014).

Striking difference between CGC and hydro!

(Very) Naively, in the CGC,

$$\langle p_T \rangle \sim Q_s \sim Q_0 N_{part}^{Pb} e^{\lambda y/2}$$

but for hydro it decreases due to less particles being produced in the forward region

However, they made use of:

- The kt factorization (good for mid rapidity; questionable for forward region)
- Analytical approx. of the unintegrated gluon distrib. not describing the exp. data
- No phase space restrictions at large rapidities (the CGC curves grow forever as y → infinity)

$$\frac{dN_h}{d^2 p_T \, d\eta}$$

Color Glass Condensate: the Hybrid Formalism

Dumitru, Hayashigaki and Jalilian-Marian, NPA 765, 464 (2006); NPA 770, 57 (2006)

The min. bias invariant yield for single-inclusive hadron production

$$\frac{dN_h}{dy d^2 p_T} = \frac{K(y)}{(2\pi)^2} \int_{x_F}^{1} dx_1 \, \frac{x_1}{x_F} \Big[f_{q/p}(x_1,\mu^2) \, \tilde{N}_F\left(\frac{x_1}{x_F} p_T, x_2\right) D_{h/q}\left(\frac{x_F}{x_1}, \mu^2\right) + f_{g/p}(x_1,\mu^2) \, \tilde{N}_A\left(\frac{x_1}{x_F} p_T, x_2\right) D_{h/g}\left(\frac{x_F}{x_1}, \mu^2\right) \Big]$$

$x_F = \frac{m_T}{\sqrt{s}} e^y$ Feynman-x;

$q_T = \frac{x_1}{x_F} p_T$ parton momentum;

$x_2 = x_1 e^{-2y}$ momentum fraction of the target partons

$z = x_F / x_1$ momentum fraction of the produced hadron

$x_1 f(x_1, \mu^2)$ projectile Parton Dist. Function → CTEQ5L

$D_{\mathrm{h/parton}}(z, \mu^2)$ Frag. Function → KKP

$$\tilde{N}_{A,F}(x, p_T) = \int d^2 r \, e^{i \vec{p}_T \cdot \vec{r}} \left[1 - \mathcal{N}_{\mathcal{A},\mathcal{F}}(x, r)\right]$$

Unintegrated Gluon Distribution → encodes the nonlinear effects at small-x

A = Adjoint rep. → quark dipole ; F = Fundamental rep. → gluon dipole

Dipole models

anomalous dimension

$$\mathcal{N}(x, r_T) = 1 - \exp\left[-\frac{1}{4}(r_T^2 Q_s^2)^{\gamma(x, r_T^2)}\right]$$

$$Q_s^2 = A^{1/3}\left(\frac{x_0}{x}\right)^\lambda$$

$$x_0 = 3 \times 10^{-4}$$

$$\lambda = 0.288$$

Dumitru, Hayashigaki and Jalilian-Marian, NPA 765, 464 (2006); NPA 770, 57 (2006)

$$\gamma(x, r_T)_{DHJ} = \gamma_s + (1 - \gamma_s)\frac{|\log(1/r_T^2 Q_s^2)|}{\lambda y + d\sqrt{y} + |\log(1/r_T^2 Q_s^2)|}$$

violates geometric scaling!

$d = 1.2$, $\gamma_s = 0.628$ → fit of the pt-spectra from forward d+Au collisions at RHIC

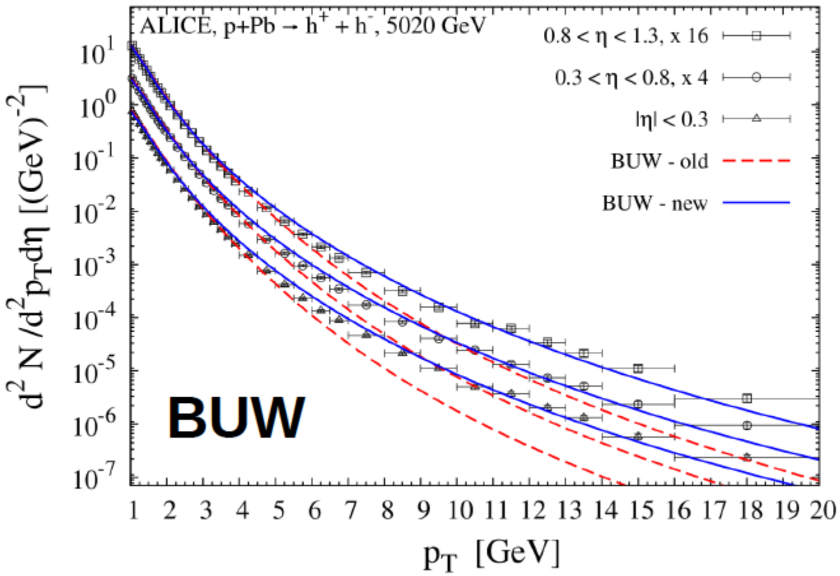
Boer, Utermann and Wessels, Phys. Rev. D77, 054014 (2008)

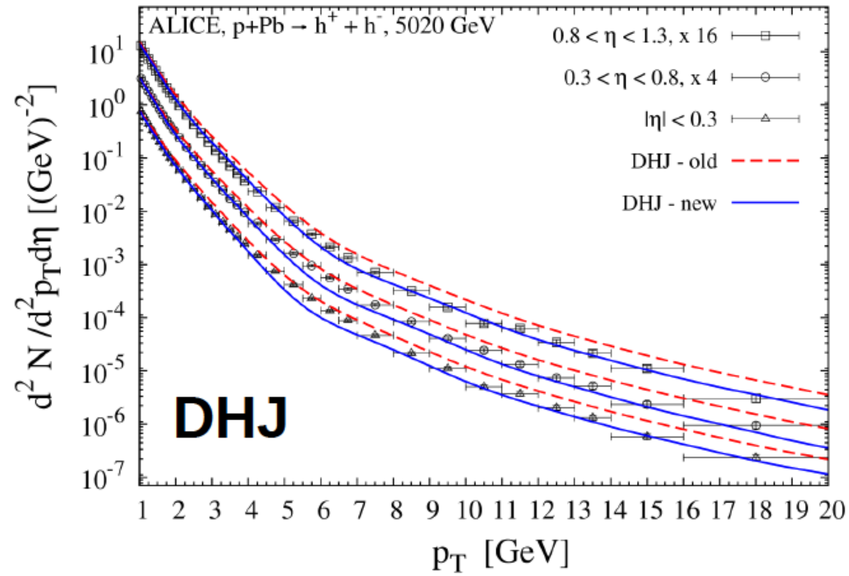
$$\gamma(\omega = q_T/Q_s)_{BUW} = \gamma_s + (1 - \gamma_s)\frac{(\omega^a - 1)}{(\omega^a - 1) + b}$$

satisfies geometric scaling!

$a = 2.82$, $b = 168$, $\gamma_s = 0.628$ → fit the same data; also works for p+p and it is consistent with the HERA data for the total $\sigma^{\gamma * p}$ x-section (x < 0.01)

p+Pb→ch. Particles @ LHC (5.02 TeV)





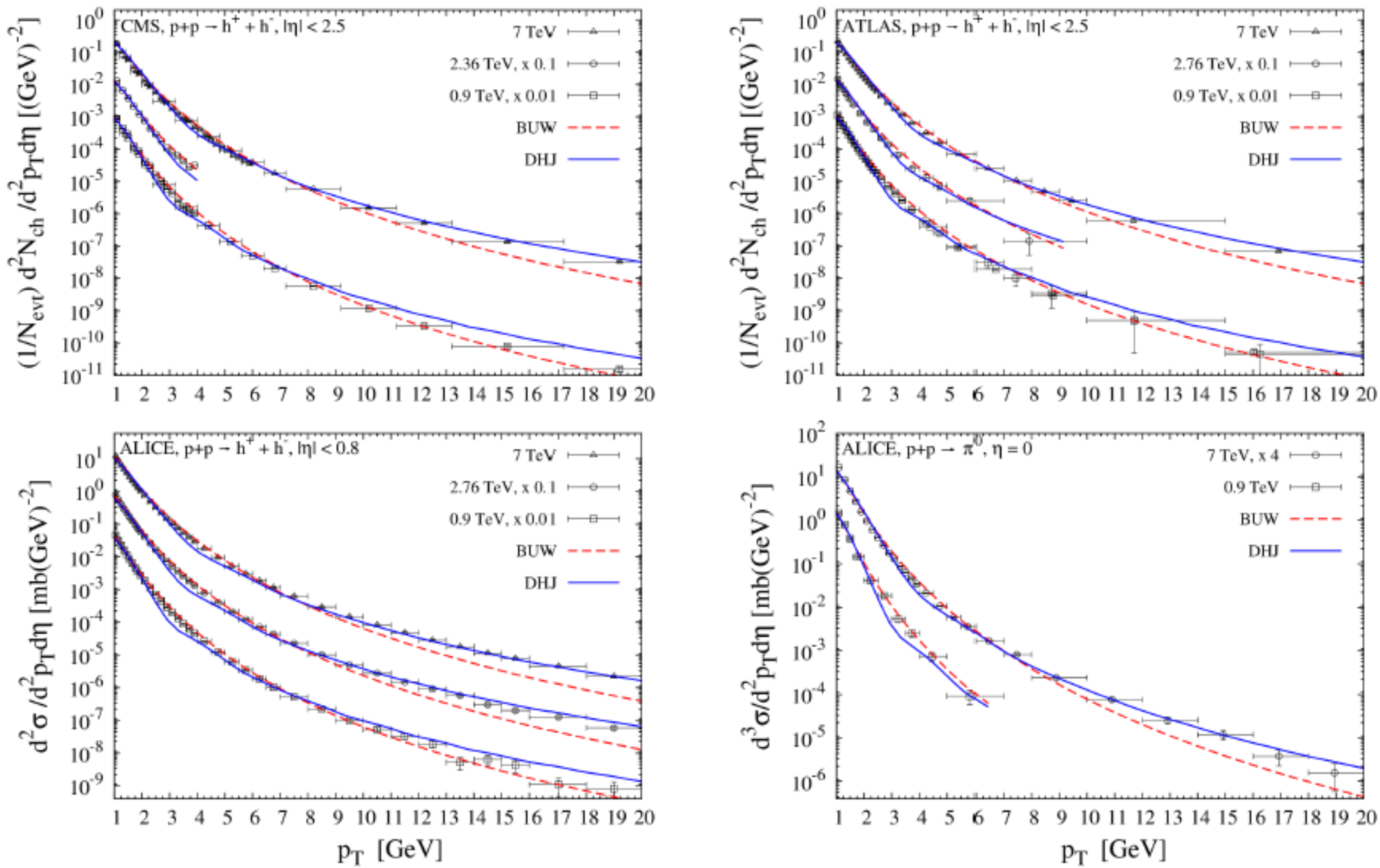
- - - - old parameters, fitting the RHIC data

——— new parameters, fitting the LHC data

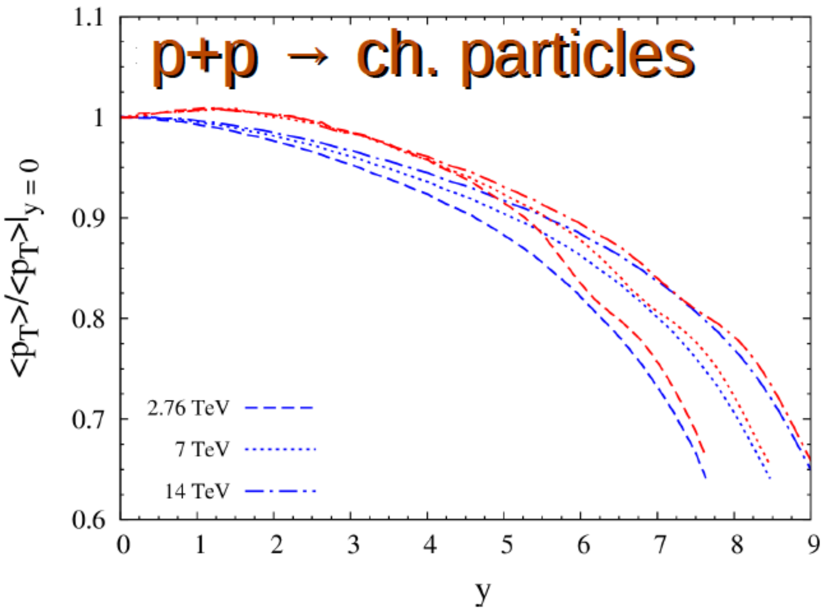
BUW: $a = 2.0$, $b = 125$, $\gamma_s = 0.74$

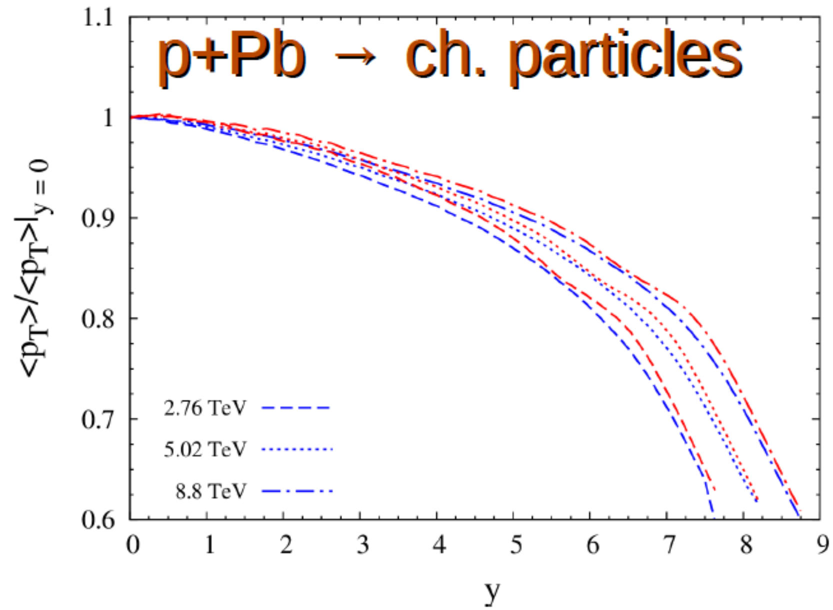
DHJ: $d = 1.0$, $\gamma_s = 0.7$

p+p → ch. particles and neutral pions @ LHC (0.9 – 7 TeV)



$$R = \frac{\langle p_T(\sqrt{s}, y)\rangle}{\langle p_T(\sqrt{s}, y=0)\rangle}$$





Similar behavior for both models, with **DHJ** being slightly larger than **BUW**

The ratio **increases** with the energy as the phase space opens up...
… but it **decreases** with the rapidity of the produced particles

a behavior **similar** to that obtained using a **hydrodynamical approach**

Summary II

- updated previous phenomenological models for the forward scattering amplitude through the p+Pb @ LHC data

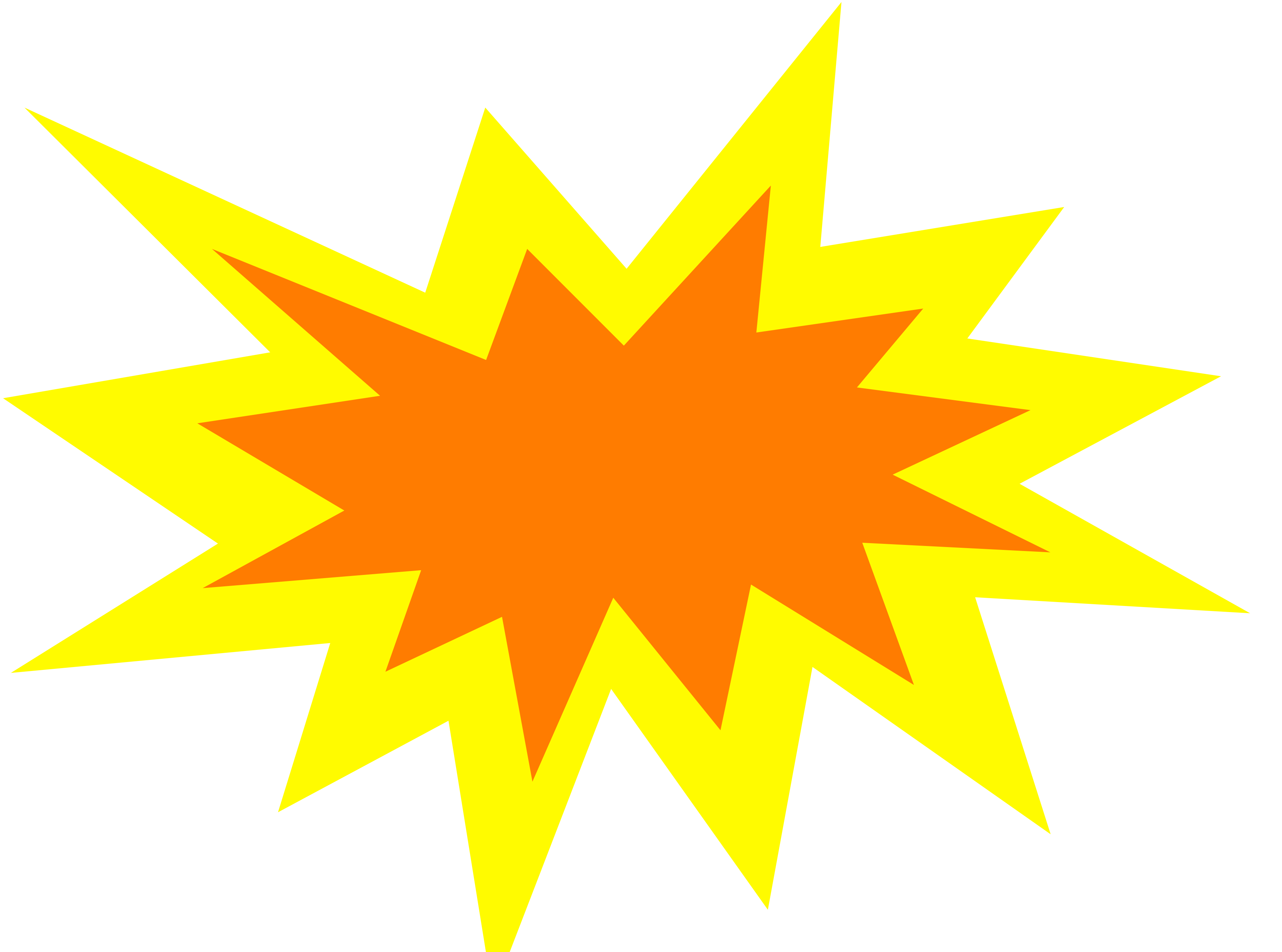
- showed they are able to describe the pt-spectra of charged particles and neutral pions from: i) p+p collisions @ LHC up to 20 GeV; ii) d+Au and p+p @ RHIC in the forward region

- calculated $\langle p_T(\sqrt{s}, y)\rangle$ in p+p and p+Pb collisions and estimated the energy and rapidity dependencies of

$$R = \frac{\langle p_T(\sqrt{s}, y)\rangle}{\langle p_T(\sqrt{s}, 0)\rangle}$$

- showed that R(s,y) increases with energy for fixed rapidity and decreases with rapidity for fixed energy having a behaviour similar to that predicted by hydrodynamical approaches

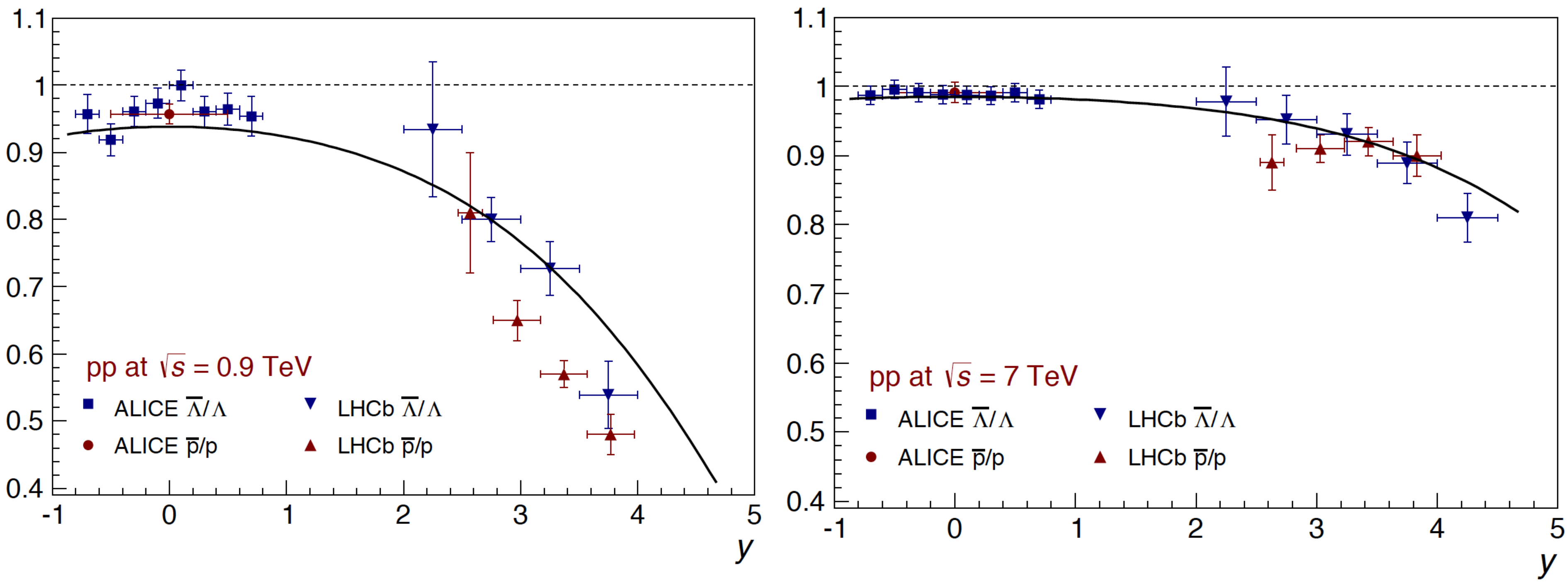
- Finally, this behaviour is almost independent of the model used for $\mathcal{N}(x, r_T)$ in p+p and p+Pb collisions



Central region: $N_{\text{protons}} \simeq N_{\text{antiprotons}}$

$$N_p - N_{\bar{p}} = \text{"Net protons"} \simeq 0$$

Protons from sea quarks and gluons

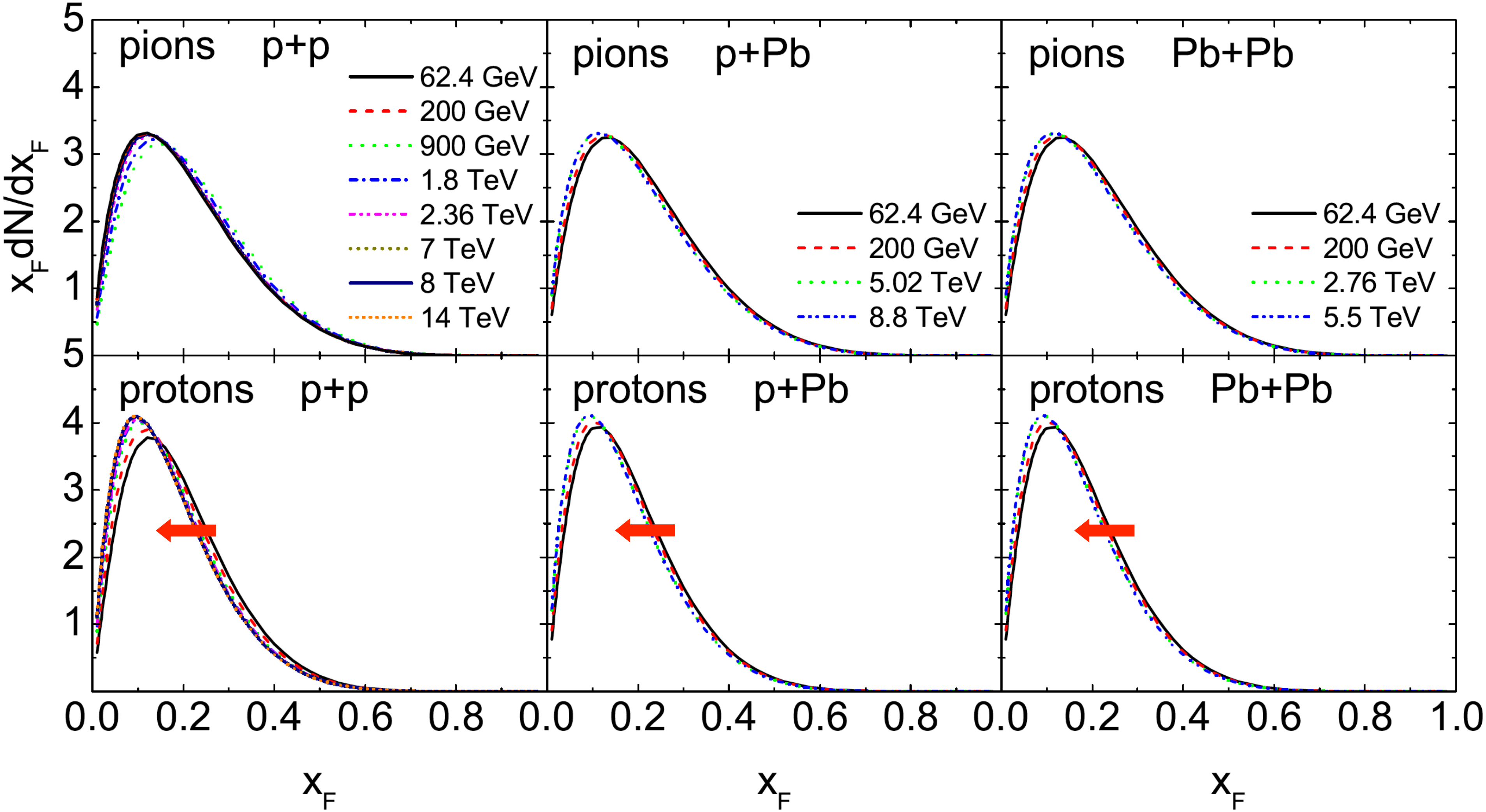


ALICE, arXiv:1305.1562

Forward region: $N_{\text{protons}} > N_{\text{antiprotons}}$

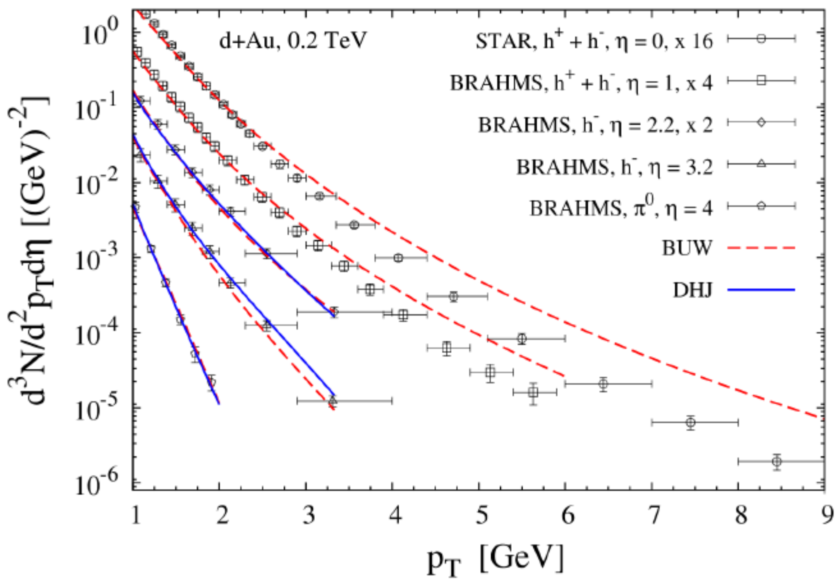
$$N_p - N_{\bar{p}} = \text{"Net protons"} > 0$$

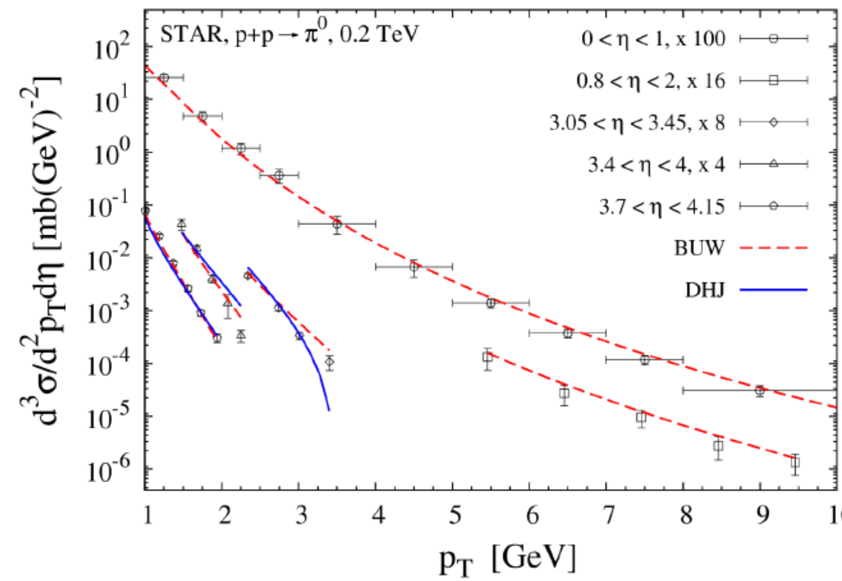
Protons from valence quarks



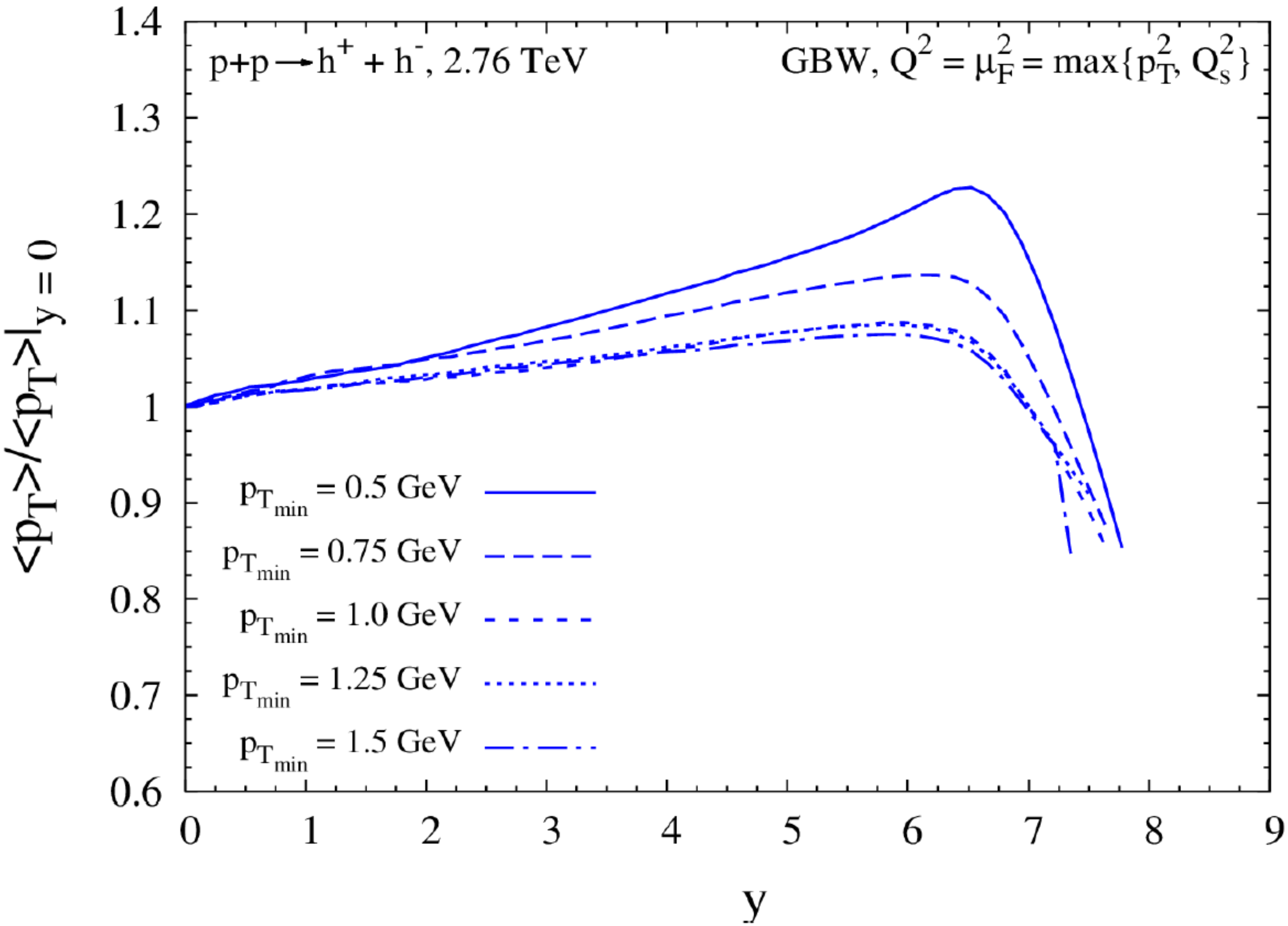
Feynman scaling ?

d+Au and p+p @ RHIC (0.2 TeV)



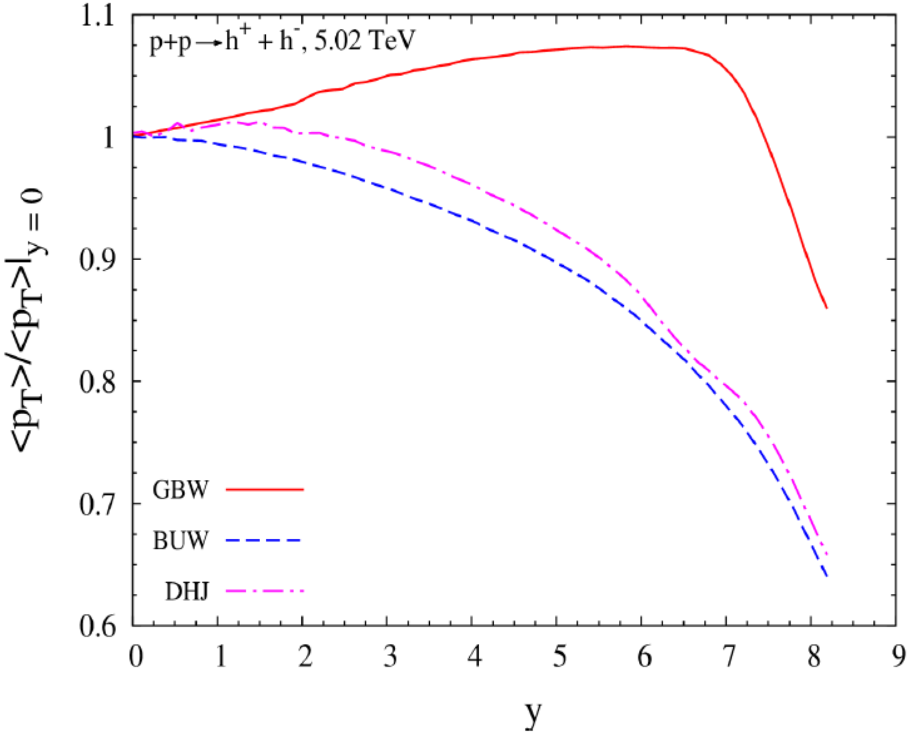


$\langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$:with GBW model

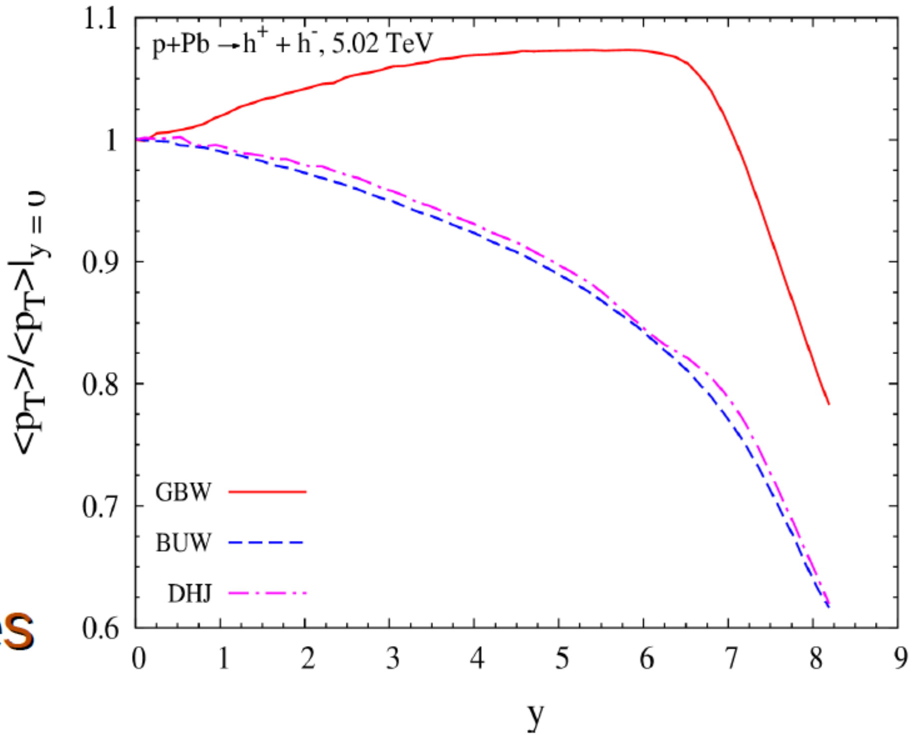


The GBW model – $\gamma(x, r_T^2) = 1$ – * does not * describe the pt-spectra data!

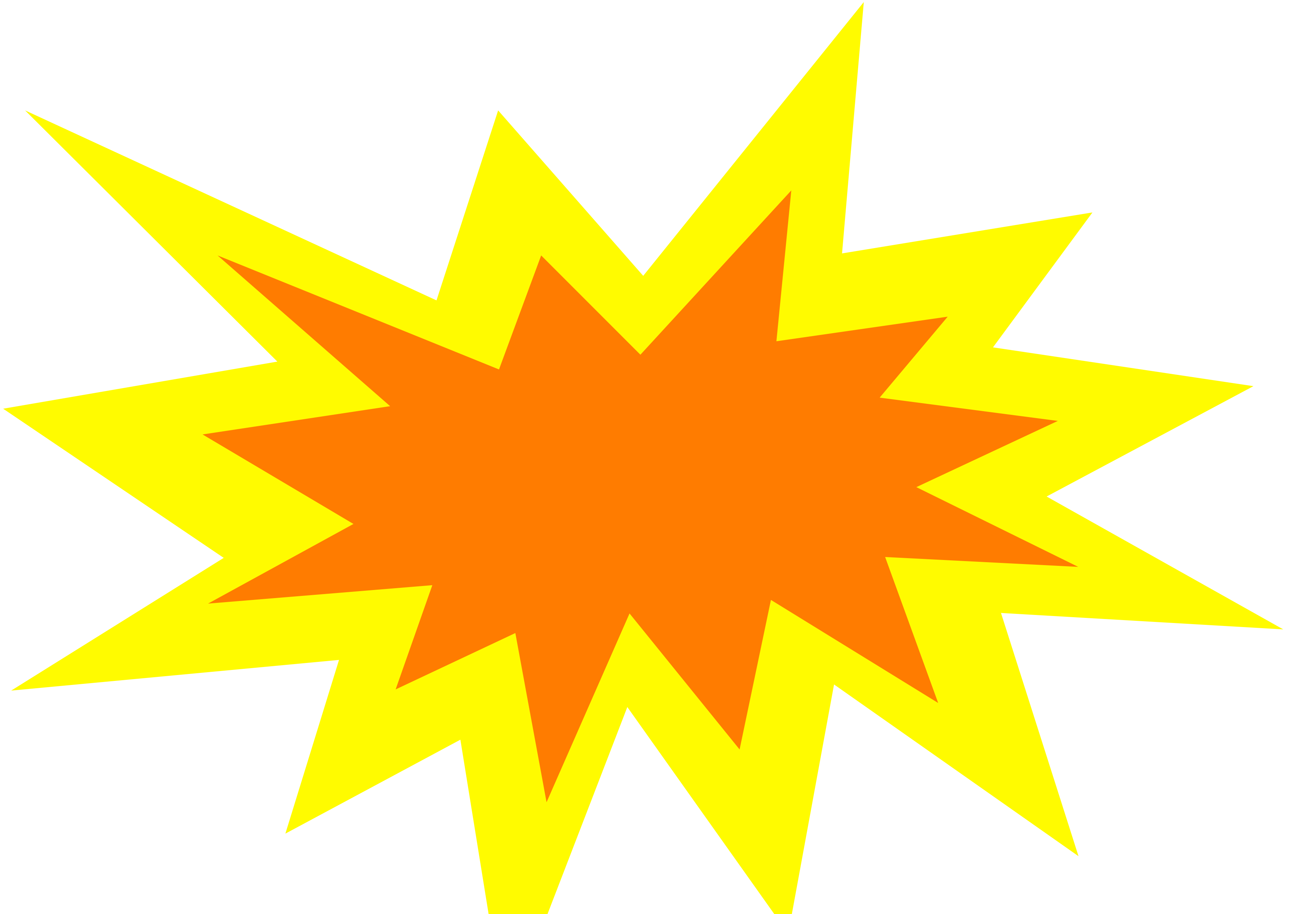
$\langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$: with GBW model



p+p → ch. particles



p+Pb → ch. particles



Nucleus-Nucleus Collisions

Valence quarks "go through"

Valence quarks are in the net baryon distribution: $B - \bar{B}$

Not really forward production: "large y" → medium to small x_F

$$x_F = \frac{p_T}{\sqrt{s}}\, e^y \qquad \left\{ \begin{array}{l} y = 4 \\ p_T = 4\,\mathrm{GeV} \\ \sqrt{s} = 5000\,\mathrm{GeV} \end{array} \right. \longrightarrow \qquad x_F \simeq 0.04$$

CGC: hard valence quarks with no-recoil

$$\frac{dN}{d^2p_T dy} = \frac{1}{(2\pi)^2} \int_{x_\mathrm{F}}^1 \frac{dz}{z^2} D(z) \frac{1}{q_T^2}\; x_1 q_v(x_1)\; \varphi\left(x_2, q_T\right) \qquad \text{DJ}$$

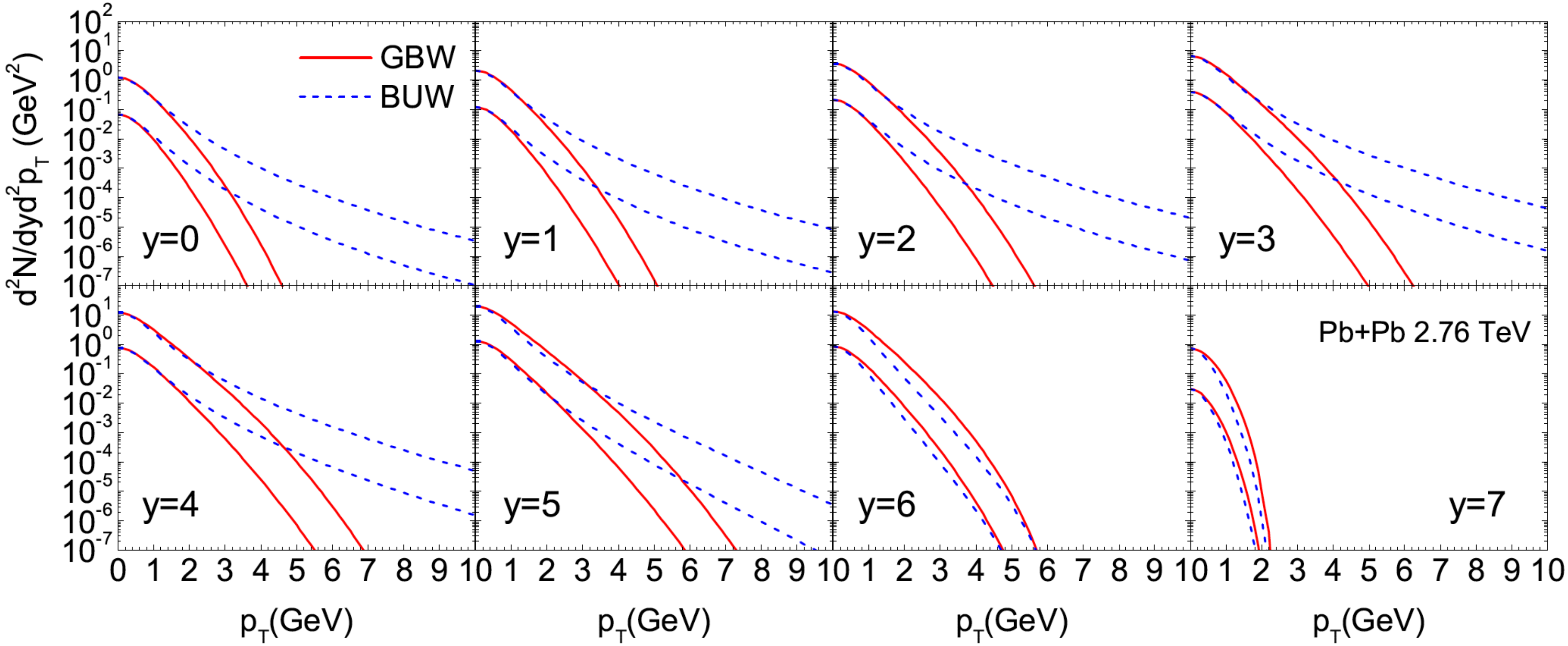
Dumitru, Jalilian-Marian, hep-ph/0204028

When does the transition Recombination to Independent Fragmentation occur ?

Start with pp, increase the energy and use the LHCf

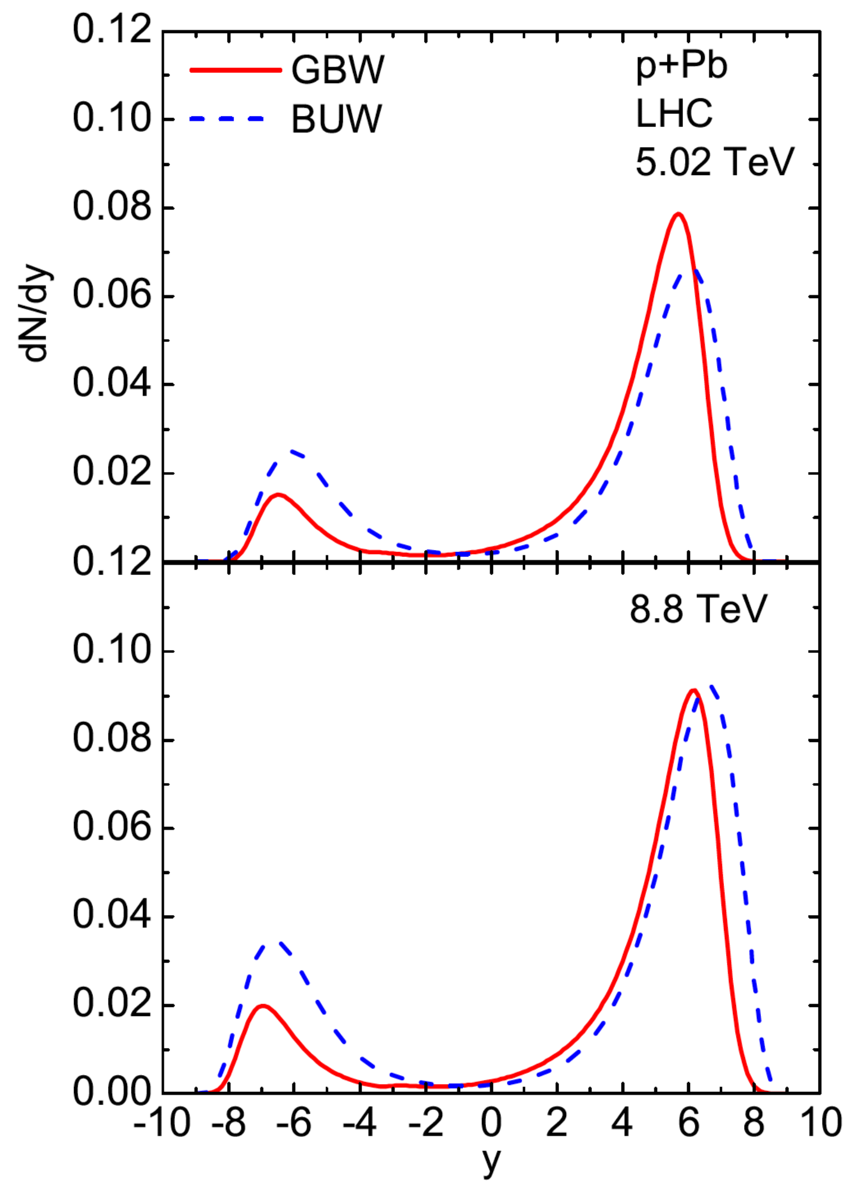
Another way to follow the valence quarks:

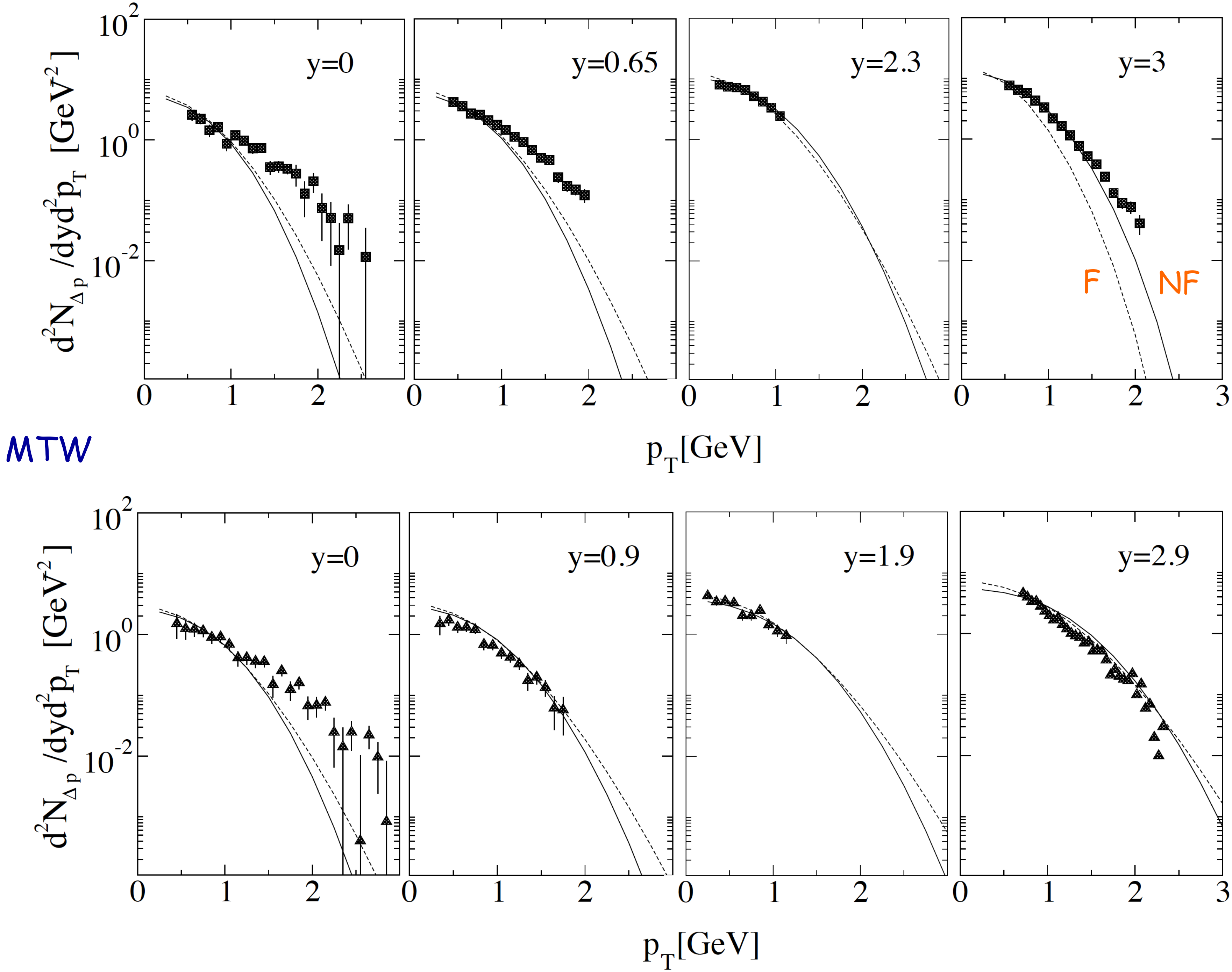
Look for net-baryons in AA plus indep. frag.



d²N/dyd²p_T (GeV²)
GBW
BUW
y=0
y=1
y=2
y=3
y=4
y=5
y=6
y=7
Pb+Pb 2.76 TeV
p_T(GeV)
p_T(GeV)
p_T(GeV)
p_T(GeV)

Proton-Nucleus

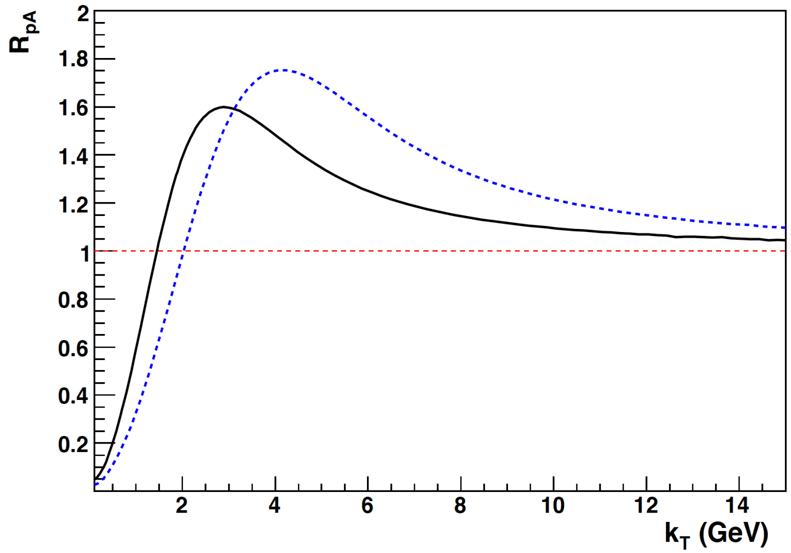


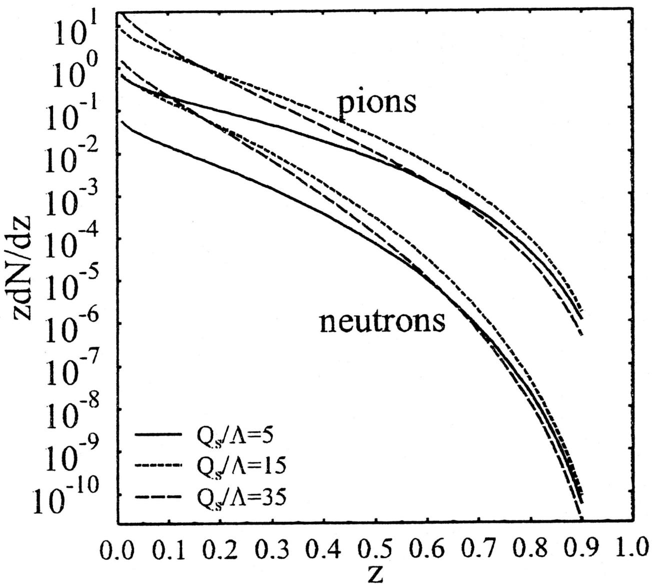


y=0
y=0.65
y=2.3
y=3
F
NF
$d^2N_{\Delta p}/dyd^2p_T$ [GeV^{-2}]
p_T[GeV]
MTW
y=0
y=0.9
y=1.9
y=2.9
$d^2N_{\Delta p}/dyd^2p_T$ [GeV^{-2}]
p_T[GeV]

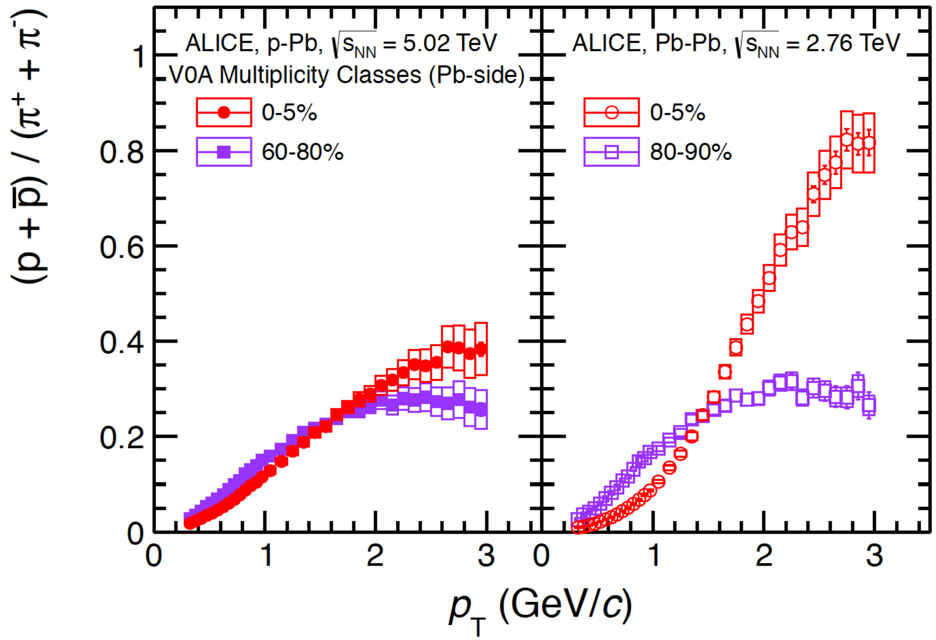
Albacete, Kovchegov,
hep-ph/0605053

Y=0
“soft” valence quarks

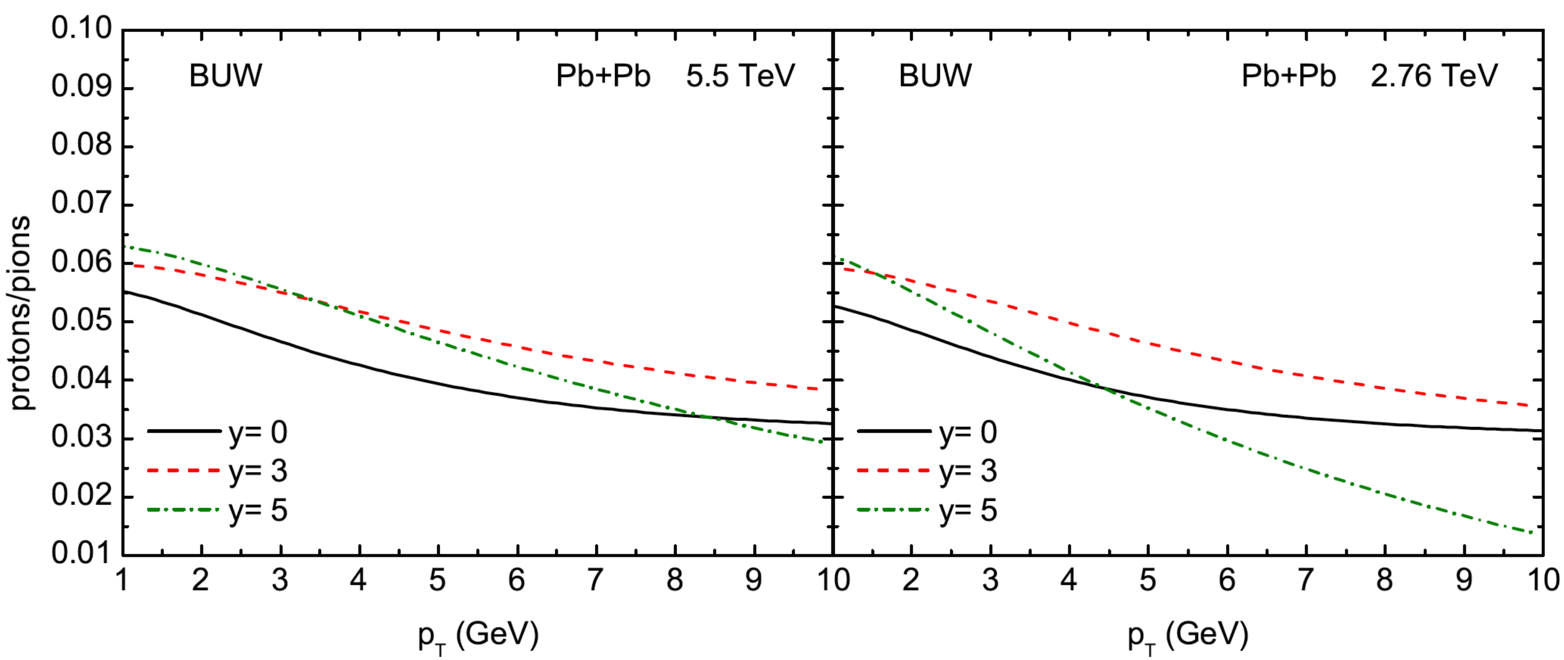




p/π ratio



Net-protons: no enhancement !



Baryon stopping

I) Mehtar-Tani, Wolschin (MTW)

GBW dipole amplitude

AKN fragmentation functions

$$D_{p-\bar{p}}(z) = N z^a (1-z)^b$$

Albino, Kniehl, Kramer, arXiv:0803.2768

Put constraints on φ

Determine λ

$$Q_s^2 = Q_0^2 A^{1/3} \left(\frac{x_0}{x}\right)^\lambda$$

II) Duraes, Goncalves, Giannini, FSN (DGGN)

BUW dipole amplitude

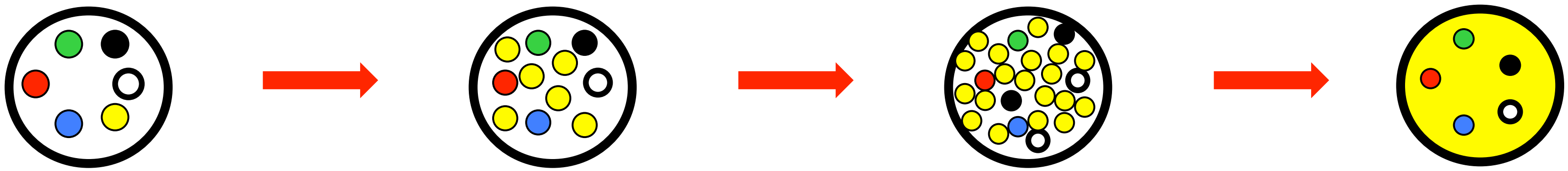
KKP fragmentation functions

$$y_{beam} = ln\,(\frac{\sqrt{s}}{m_p})$$

$$y_{peak} = \frac{1}{1+\lambda}\left(y_{beam} - ln\,A^{1/6}\right)$$

Higher energies

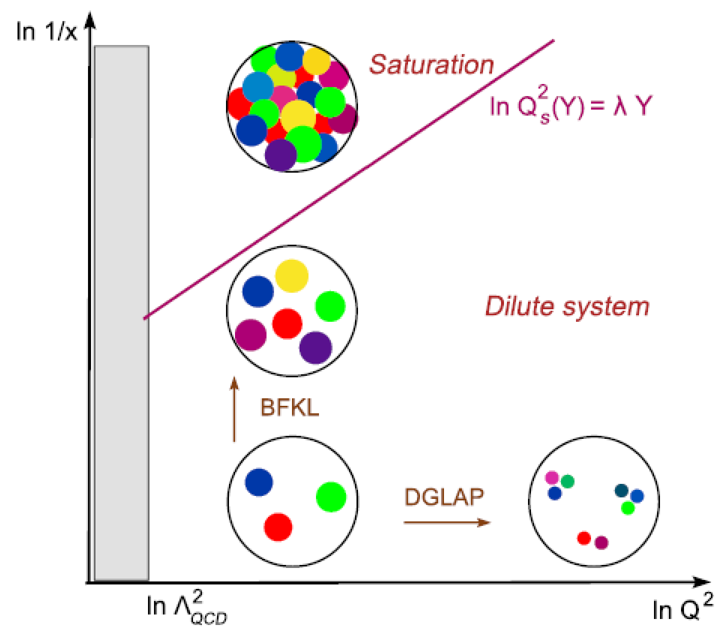
Number of quarks, antiquarks and gluons ("partons") grows !



Parton distribution (= "number of partons"): $f(x, Q^2)$

x = momentum fraction of the proton

Q^2 = 4-momentum squared of the probe ("resolution")

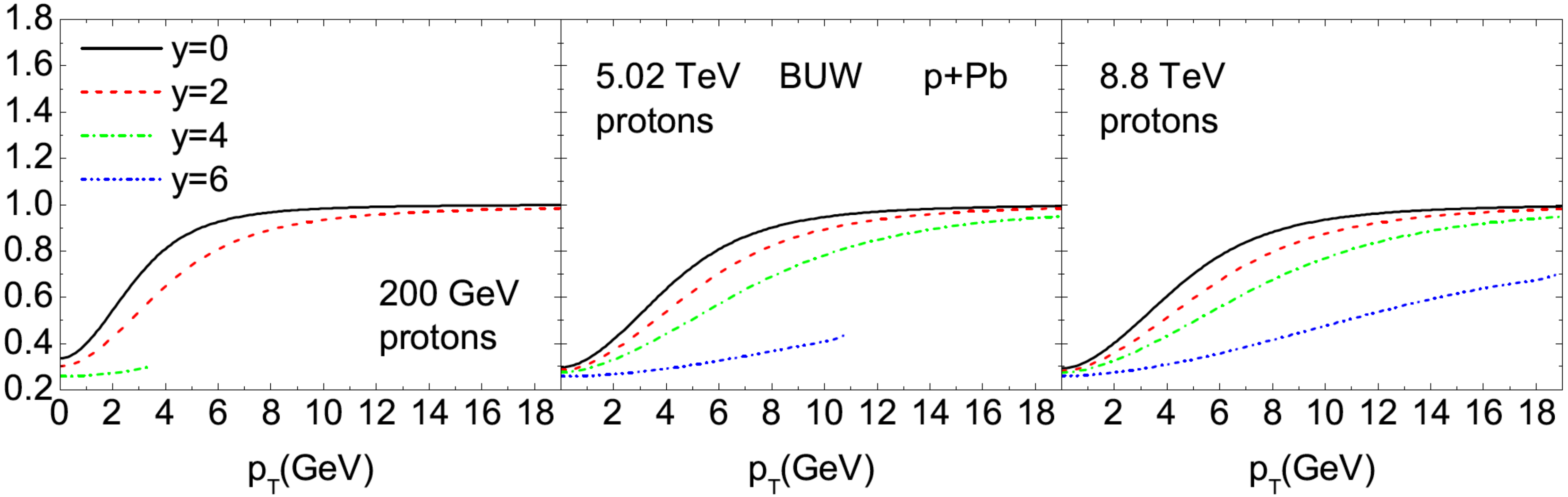


$f(x, Q^2)$ grows with energy (~1/x)

More and harder partons → saturation !

Color Glass Condensate (CGC)

Proton-Nucleus: Nuclear Modification Ratio

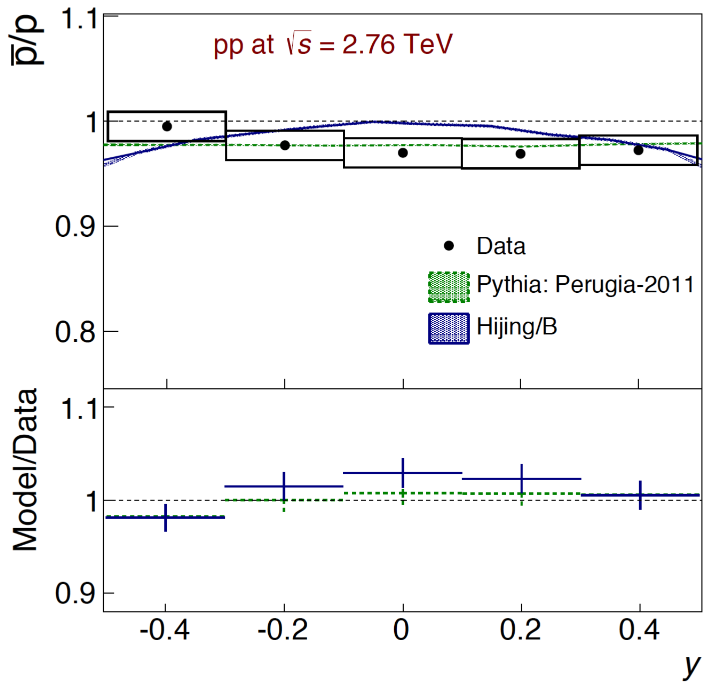


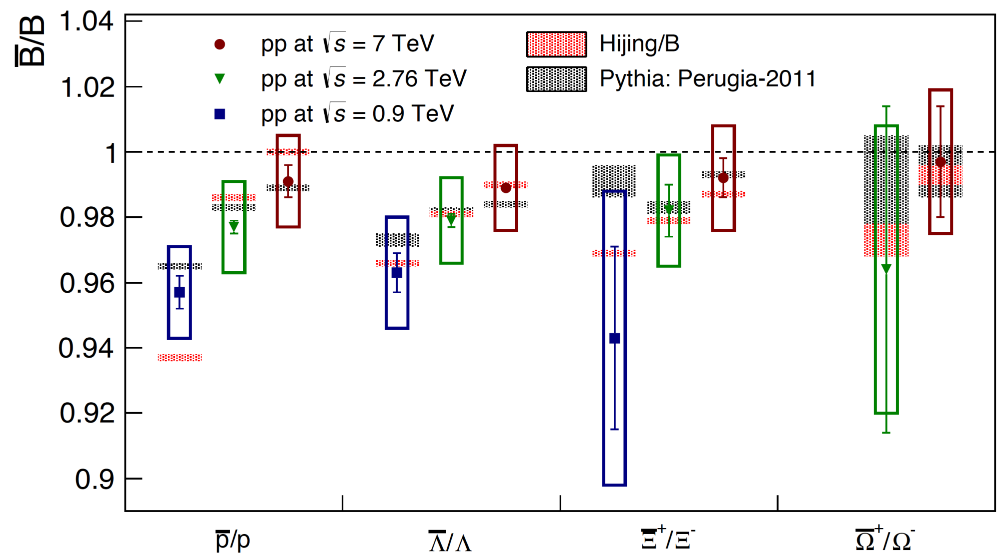
$$R_{pA} = \frac{\frac{d^2 N_{pA}}{dy d^2 p_T}}{A \frac{d^2 N_{pp}}{dy d^2 p_T}}$$

Baryon production in high energy collisions:

Central region: from sea quarks and gluons

$$N_{\rm protons} \simeq N_{\rm antiprotons}$$





ALICE, arXiv:1305.1562

Forward region: from valence quarks (“leading baryons”)

$$N_{\rm protons} >> N_{\rm antiprotons}$$

Valence quark recombination ("coalescence")

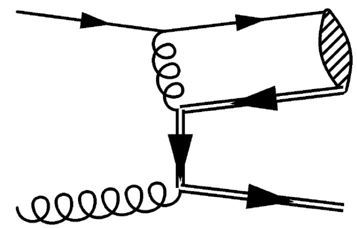
Model for quark coalescence

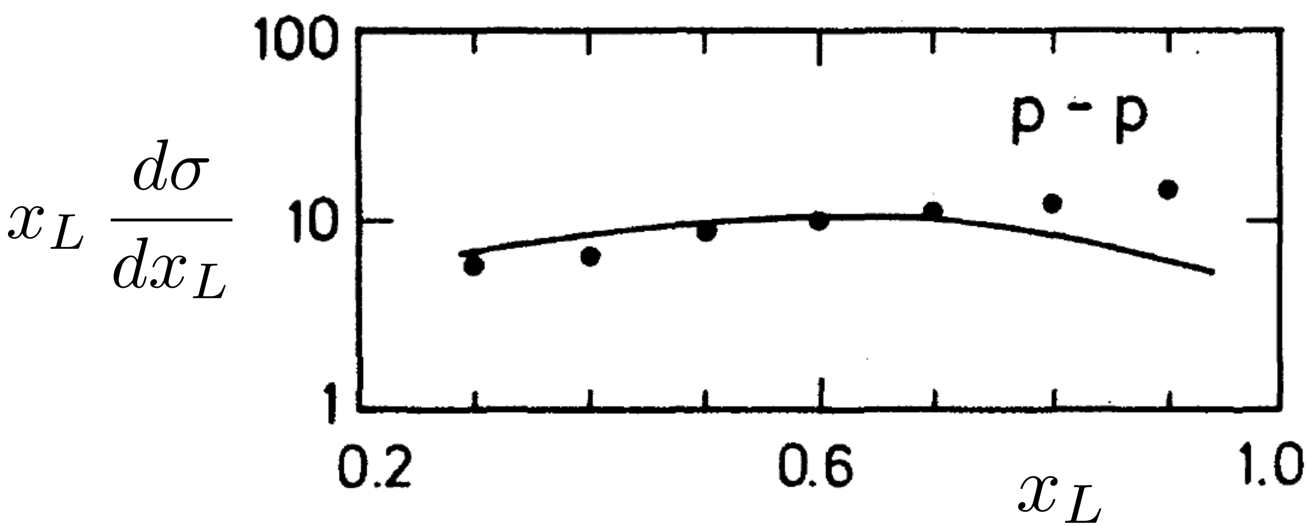
Hwa, Yang, Zhong, nucl-th/0401001

Rapp, Shuryak, hep-ph/0301245

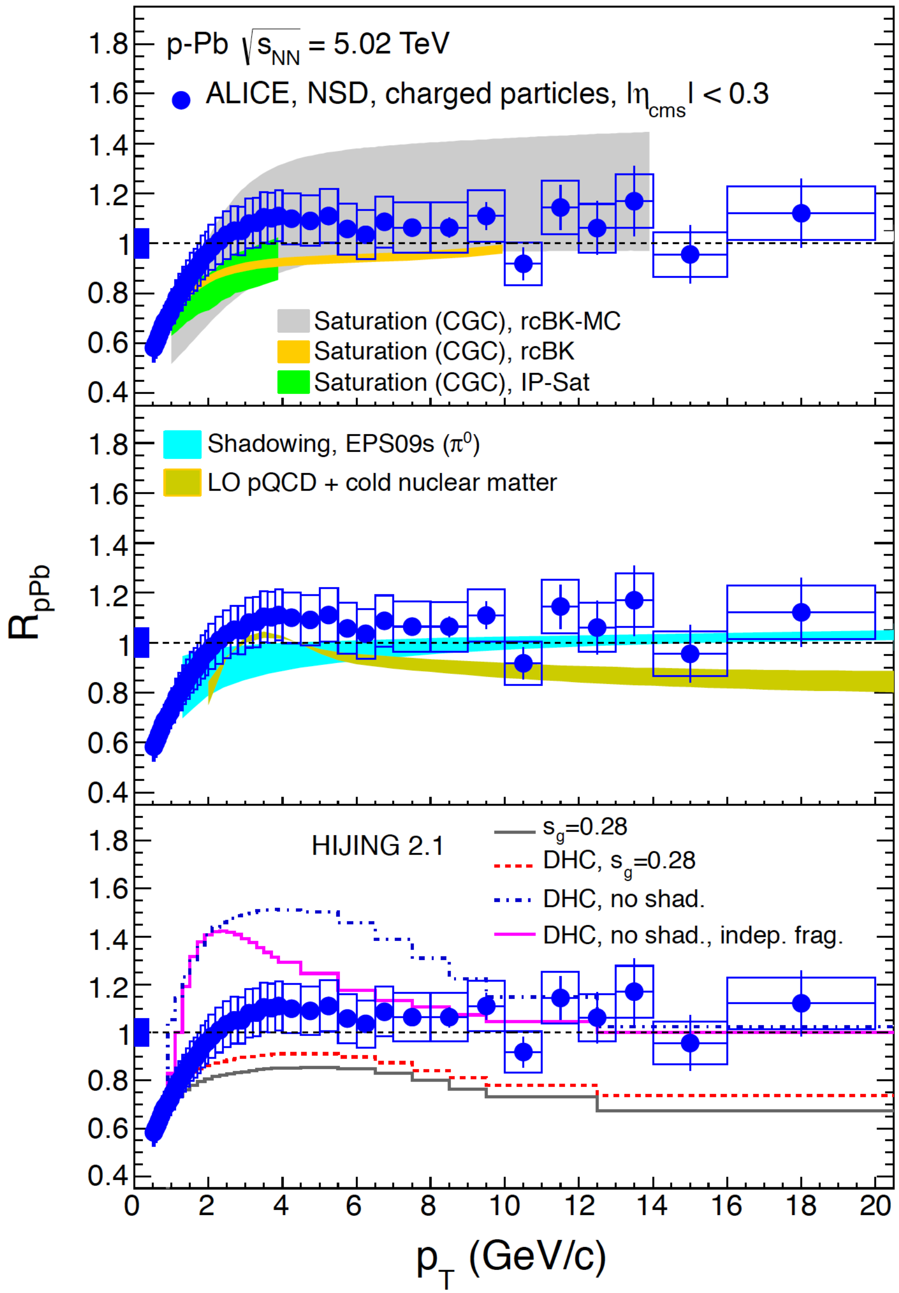
Effective theory for heavy quark recombination

Braaten, Jia, Mehen, hep-ph/0108201





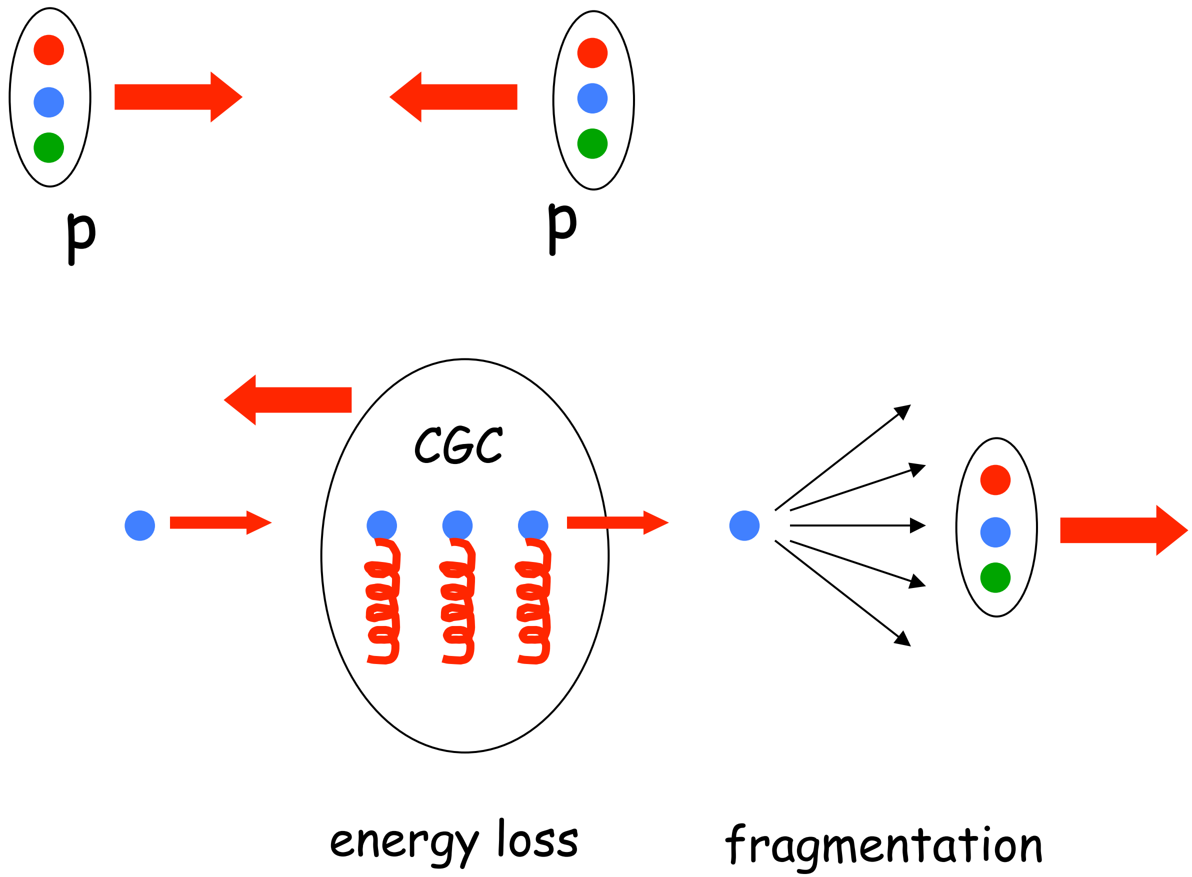
Duraes, FSN, Wilk,
hep-ph/9809309
hep-ph/0412293



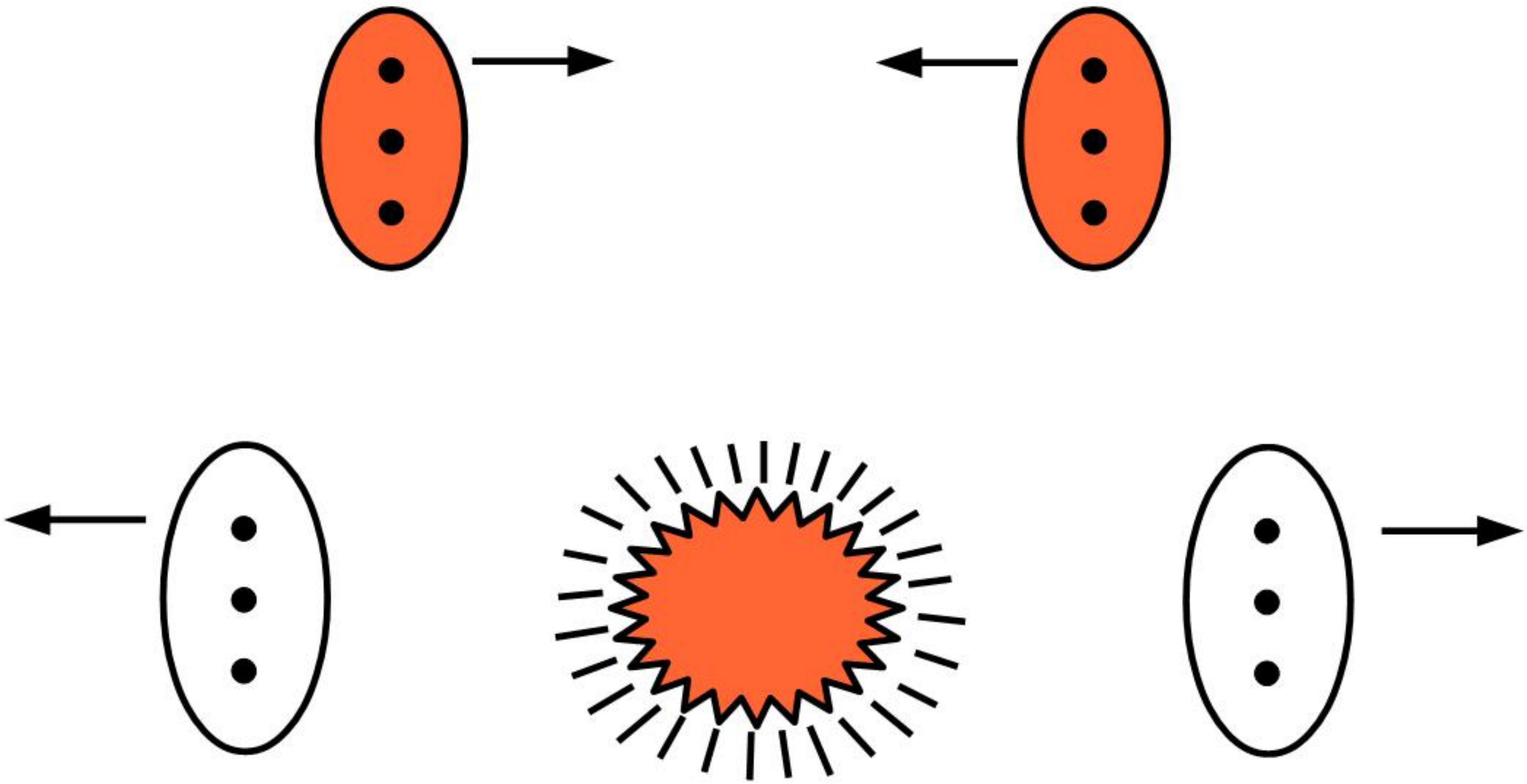
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
ALICE, NSD, charged particles, $|\eta_{cms}| < 0.3$
Saturation (CGC), rcBK-MC
Saturation (CGC), rcBK
Saturation (CGC), IP-Sat
Shadowing, EPS09s (π^0)
LO pQCD + cold nuclear matter
HIJING 2.1
s_g=0.28
DHC, s_g=0.28
DHC, no shad.
DHC, no shad., indep. frag.
R_{pPb}
p_T (GeV/c)

Test of CGC at large rapidity with heavy nuclei : Q_s is large !

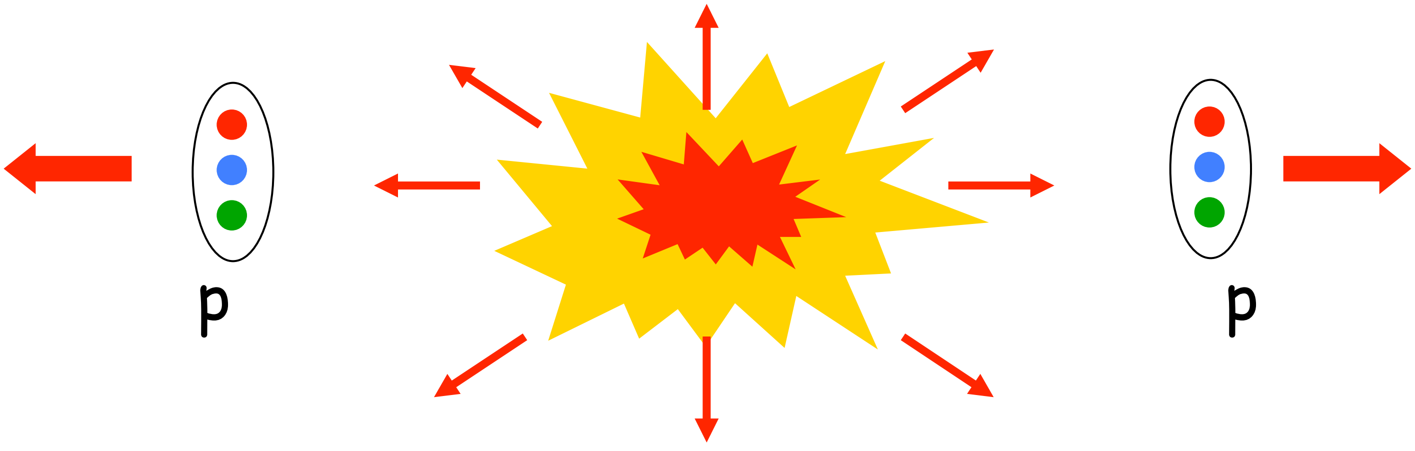
Energy loss of one valence quark + independent fragmentation



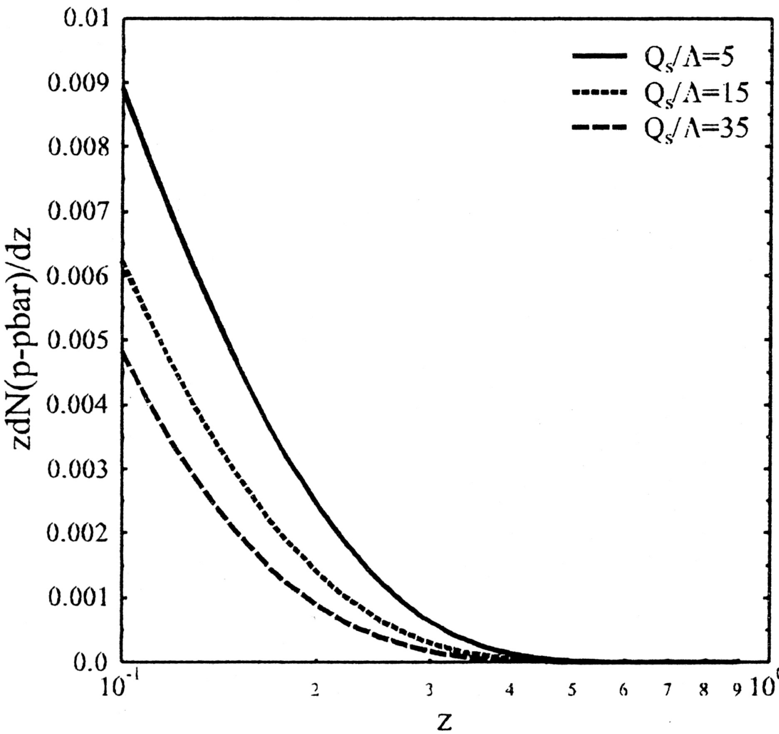
$$D(z) \approx \frac{1}{z}$$



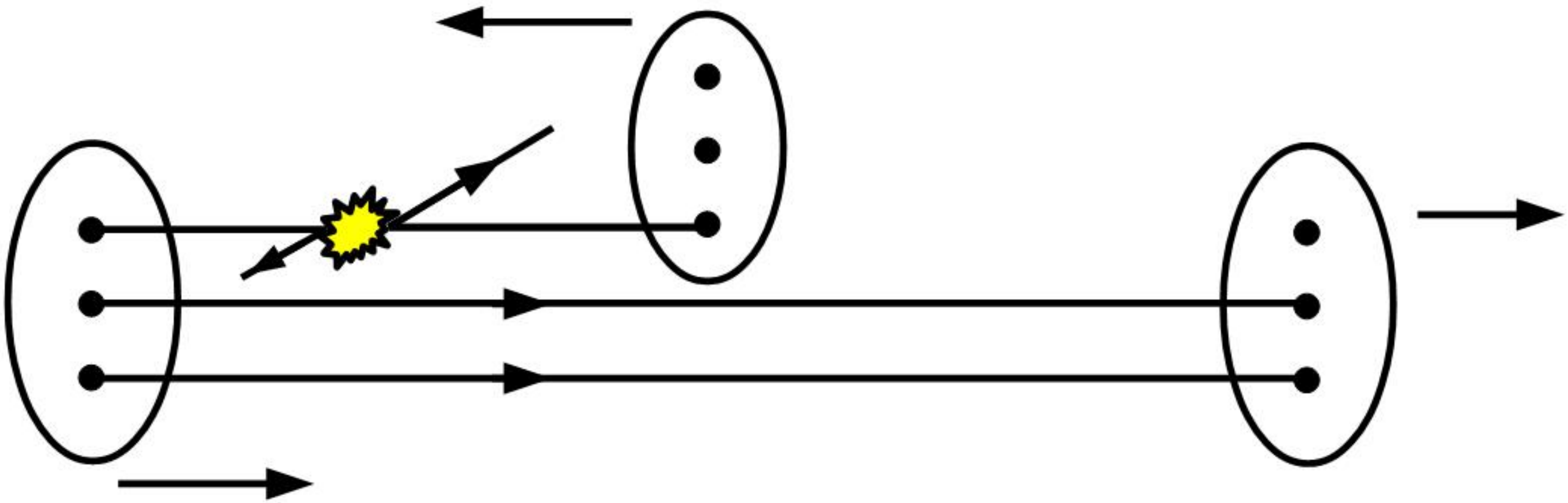
Valence quark recombination



No strong baryon stopping: baryon "transparency"



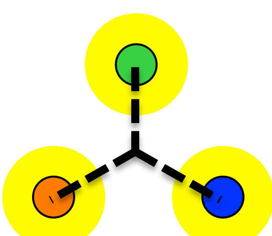
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0
zdN(p-pbar)/dz
$Q_s/\Lambda=5$
$Q_s/\Lambda=15$
$Q_s/\Lambda=35$
10^{-1}
2
3
4
5
6
7
8
9
10^{0}
z



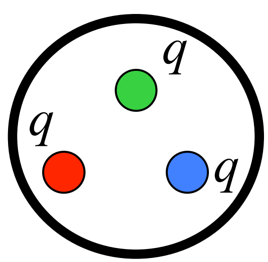
Pictures of the nucleon

E. Shuryak, hep-ph/9603354

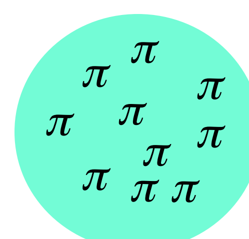
Non-relativistic quark model



MIT bag model



Skyrmion



Chiral bag