Baryon stopping in high energy collisions

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XXXI Winter Workshop on Nuclear Dynamics

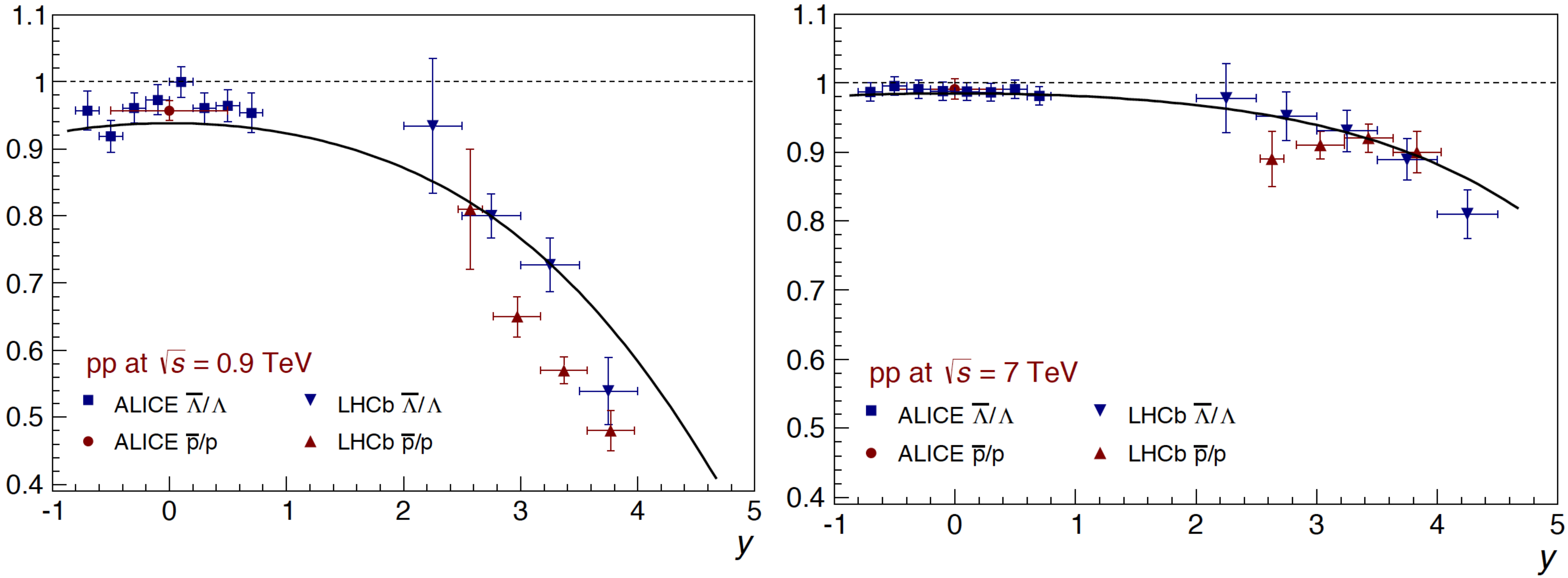
Leading Baryons
and
Stopping in p p Collisions

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

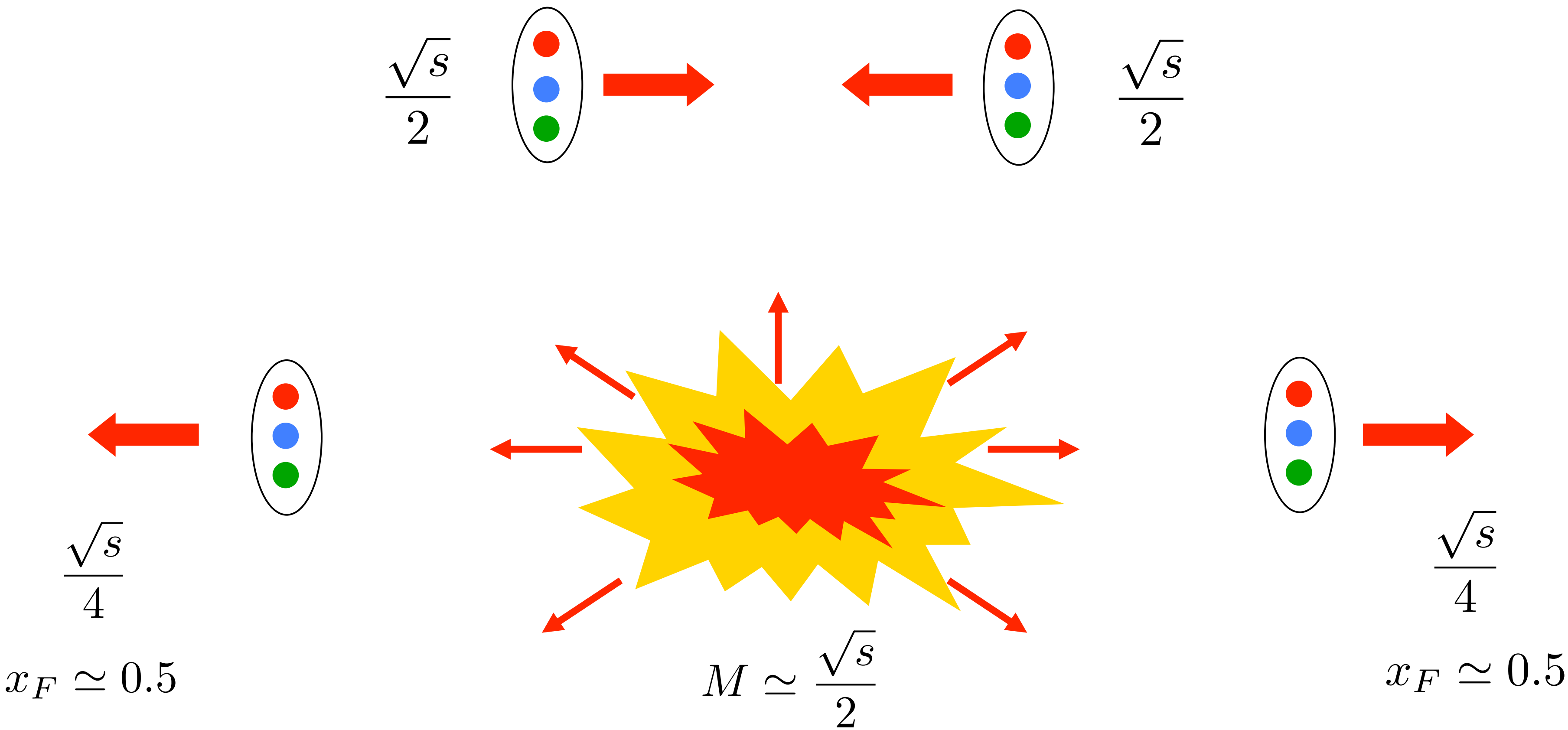
Forward region:

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

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

Protons from valence quarks

Leading proton production $\sqrt{s} = 10 - 60$ 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 ?

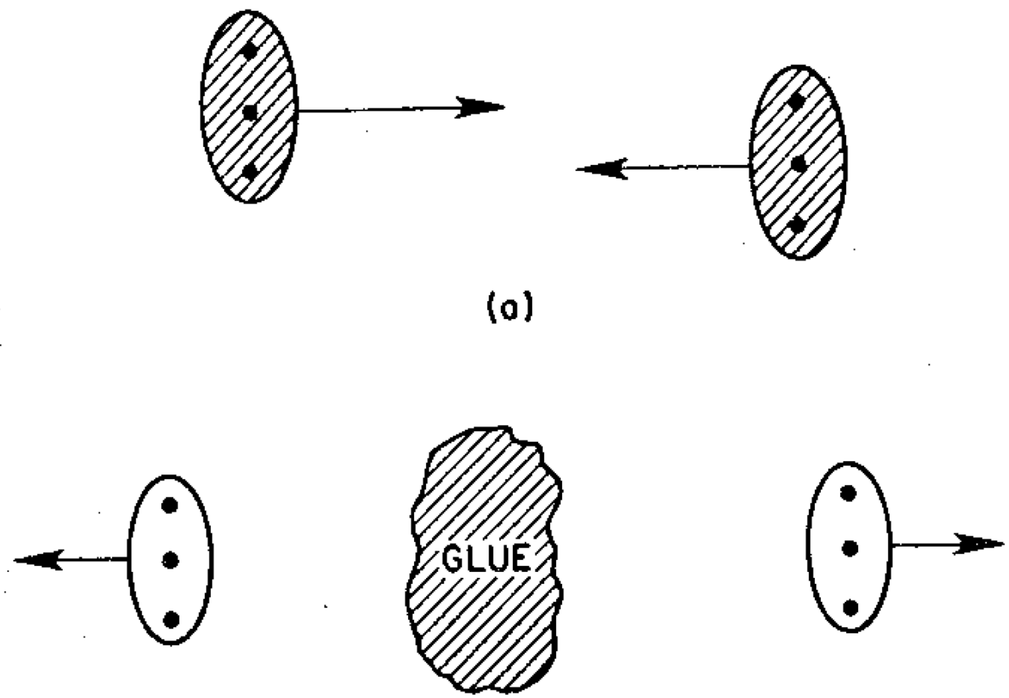
Some qualitative ideas…

“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

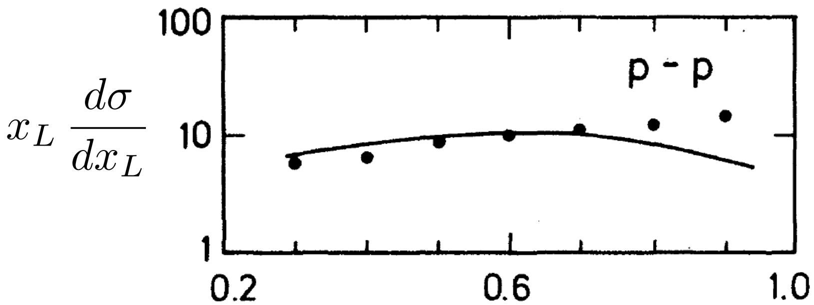
Gluon interactions are stronger $\sigma_{gg} > \sigma_{qg} > \sigma_{qq}$



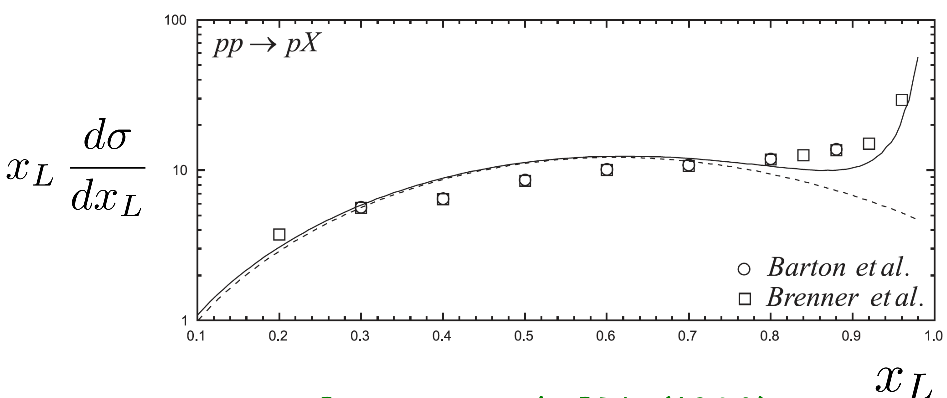
$$M \simeq \frac{\sqrt{s}}{2}$$

“Gluon stripping” and valence quark recombination

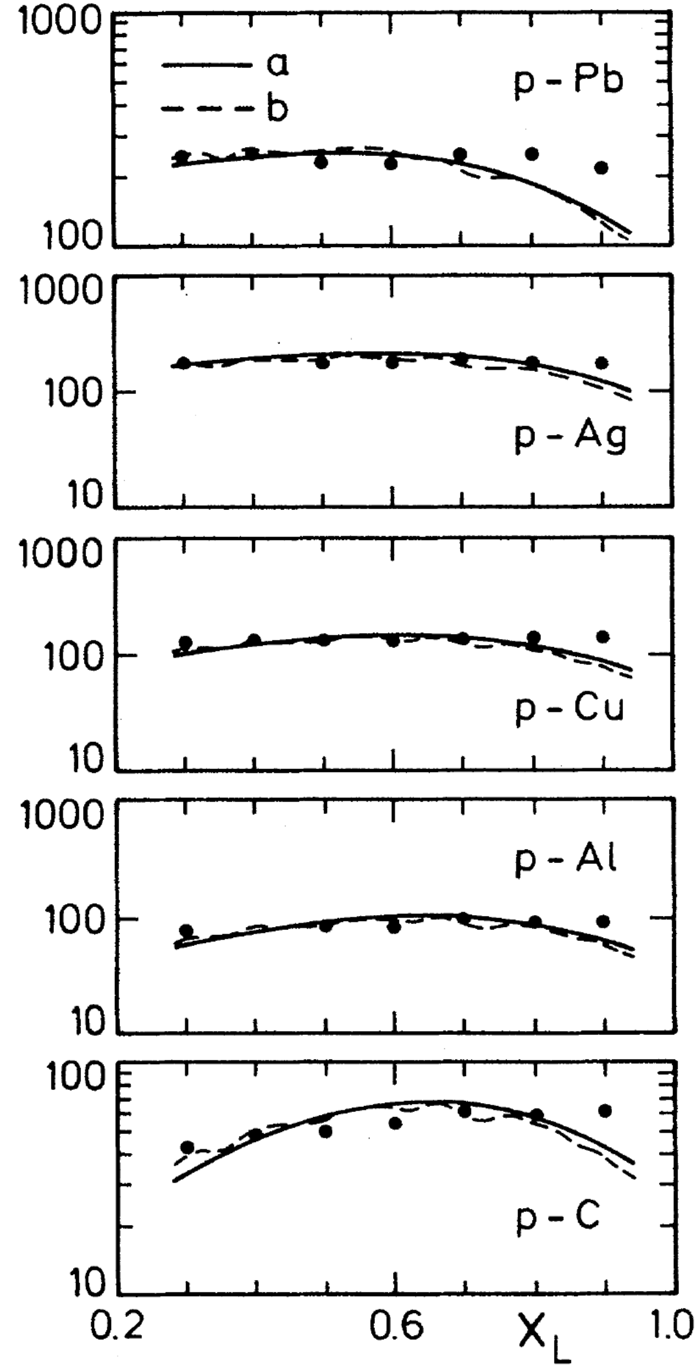
Duraes, FSN, Wilk, hep-ph/0412293



Barton et al., PRD (1983)

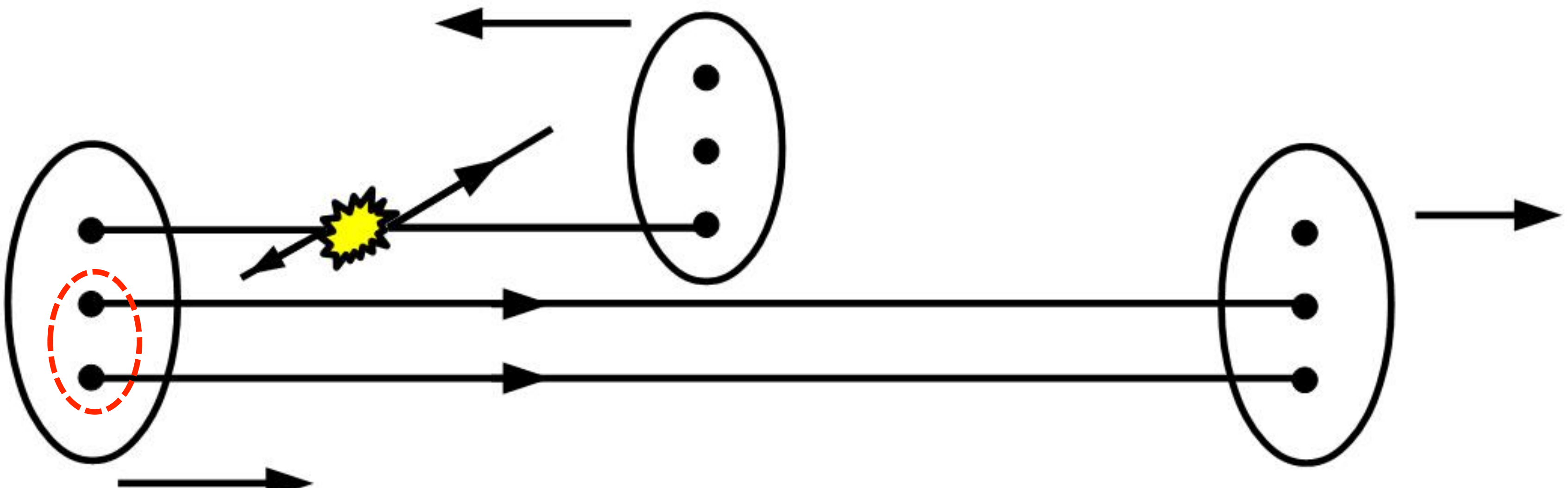


Brenner et al., PRD (1982)



Valence diquark fragmentation

Strikman et al., hep-ph/9604299



$x_F \simeq 0.33$

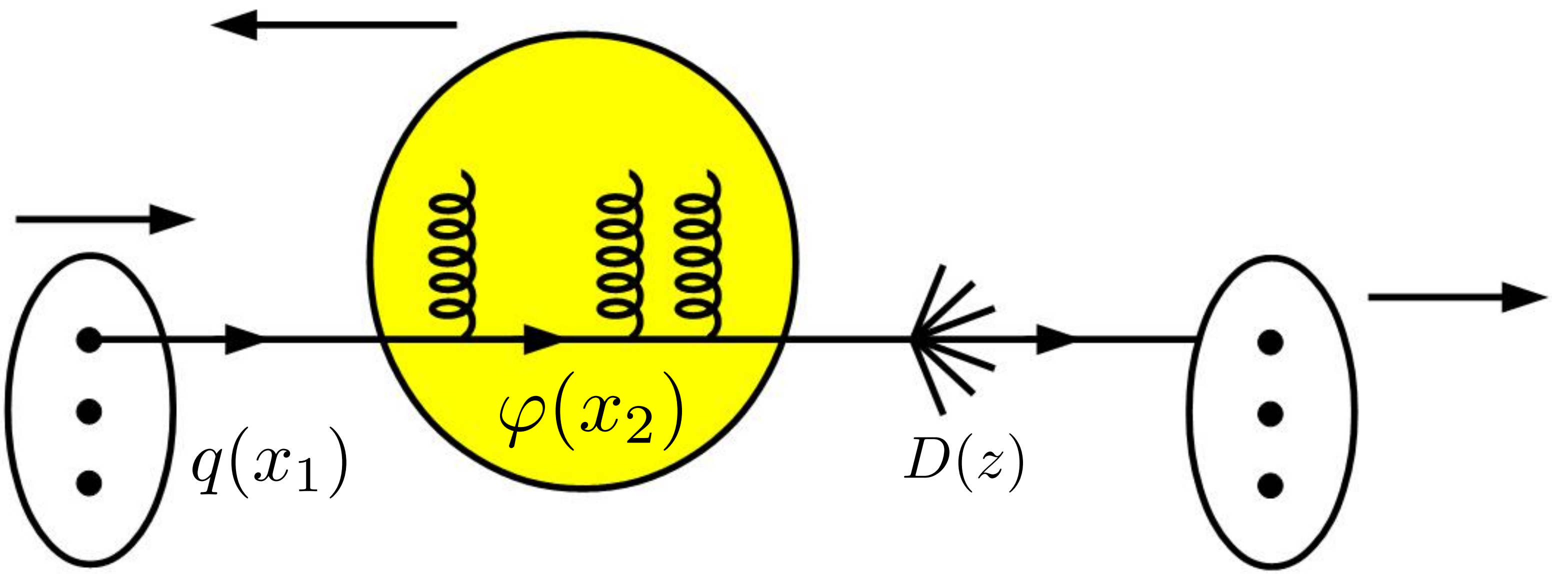
$< x_{gluons} > \simeq \frac{1}{2}$ $< x_{quark} > \simeq \frac{1}{3}\frac{1}{2}$ $< x_{di} > \simeq \frac{2}{6}$

Valence quark independent fragmentation: color glass condensate

Dumitru, Jalilian-Marian, hep-ph/0111357

Dumitru, Gerland, Strikman, hep-ph/0211342

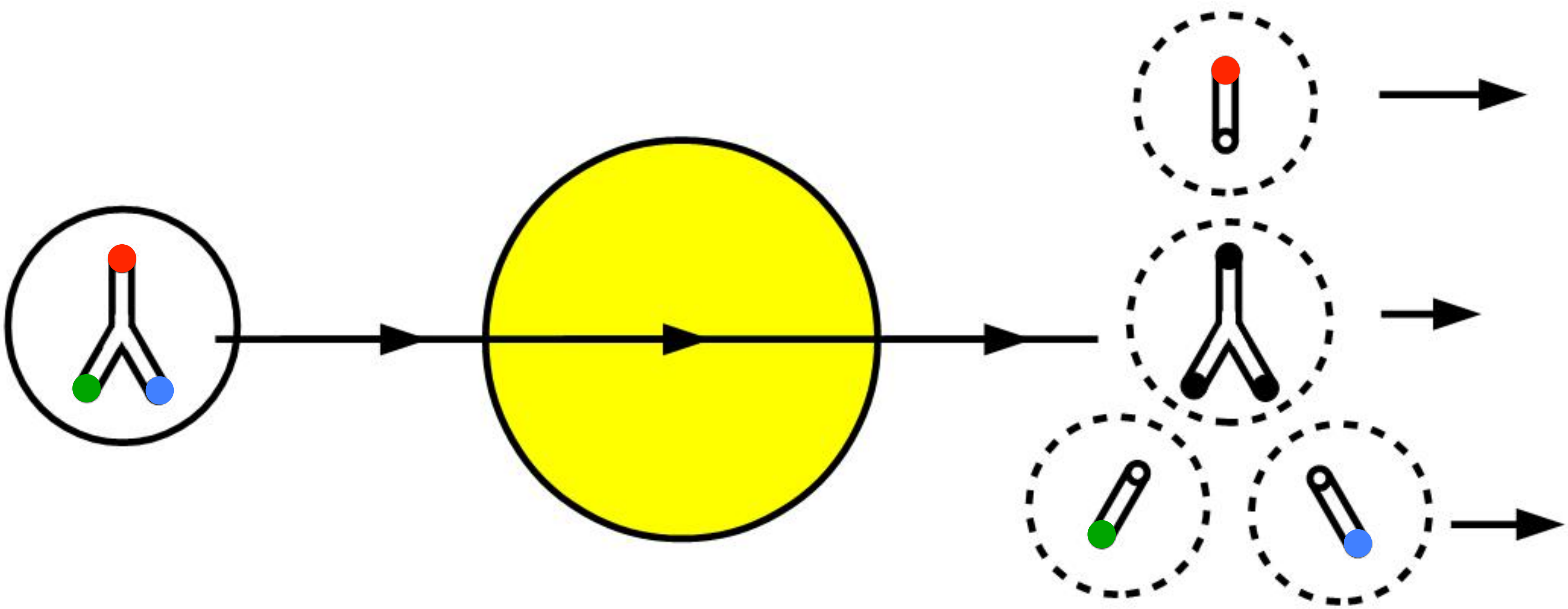
Albacete, Kovchegov, hep-ph/0605053

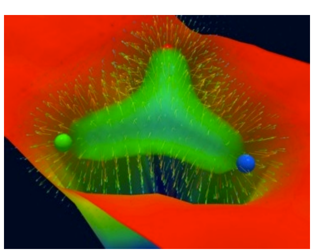


$$< x_{quark} > \simeq \frac{1}{6} \qquad D(z) \simeq \frac{1}{z} \qquad z = \frac{E_{baryon}}{E_{quark}} \simeq \frac{x_L}{x_1}$$

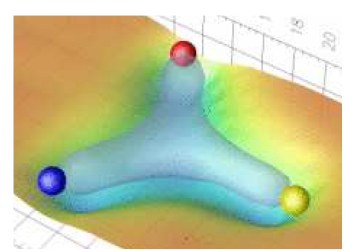
Baryon junction excitation

Kharzeev, PLB (1996)

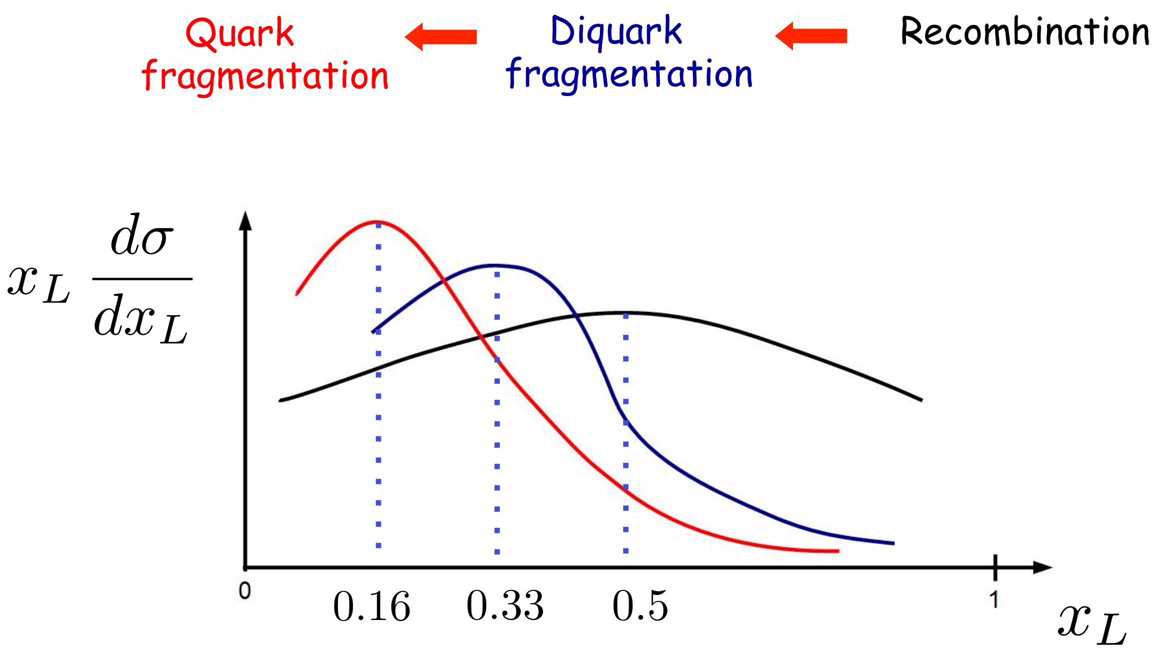




Suganuma et. al
hep-lat/0006005
hep-lat/0204011



Leinweber et al.
hep-lat/0606016]



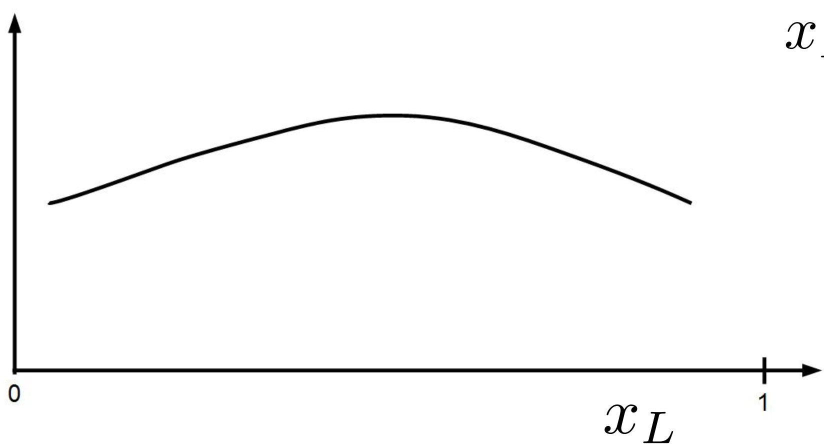
All this may happen at the same time…

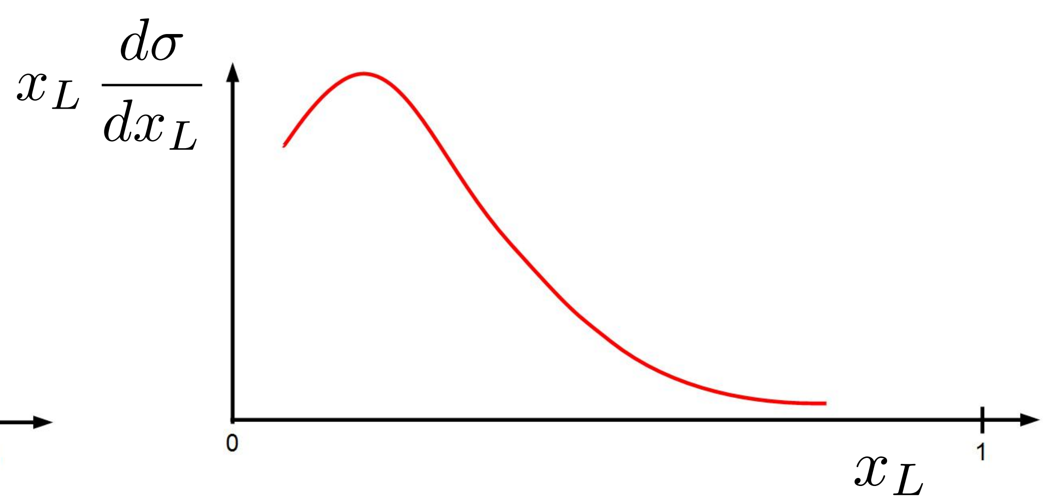
Higher energies

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

CGC:
onset at Qsat !

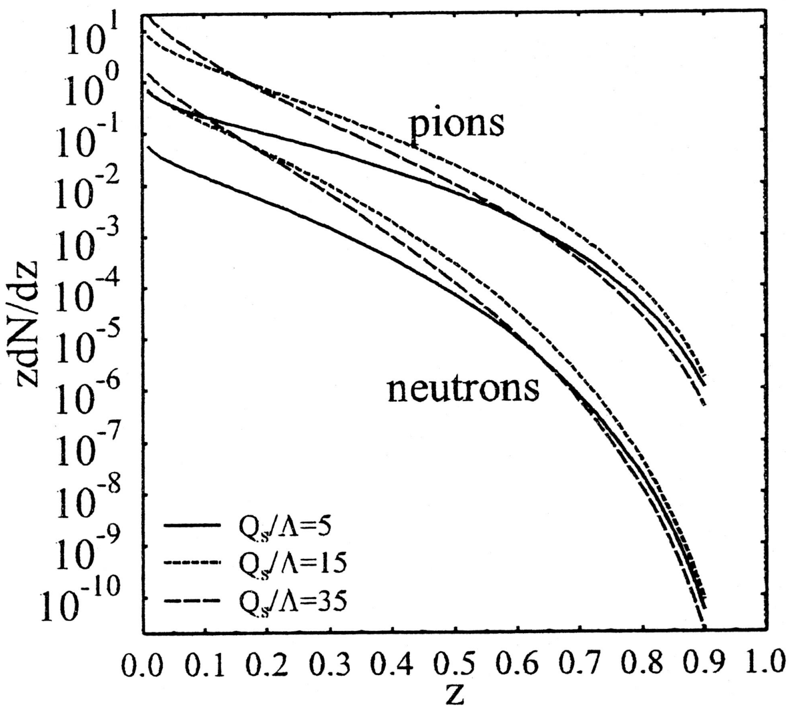
Recombination → Independent fragmentation

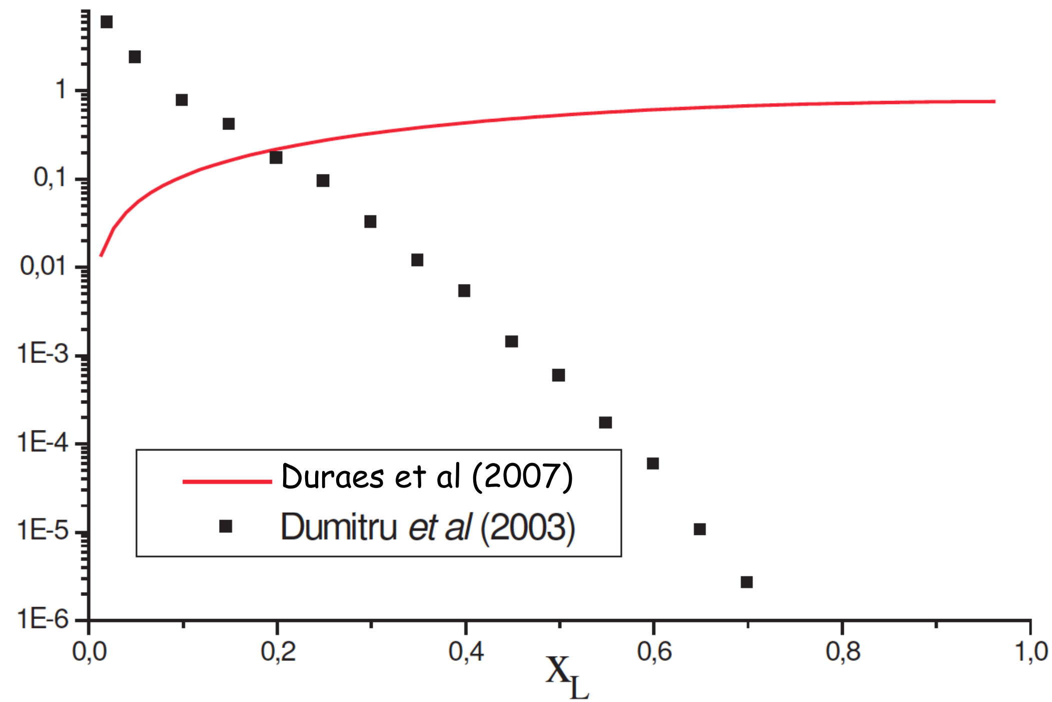




Softening of the LP spectrum in cosmic rays

Dumitru, Gerland, Strikman, hep-ph/0211342





Large x_L : clear separation between recombination and independent fragmentation

When does the transition Rec -> Ind. Frag. occur?

Start with pp, increase the energy and use the LHCf

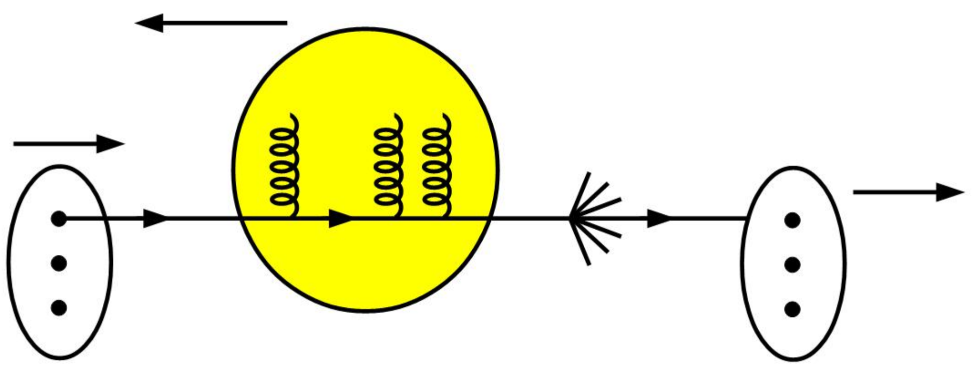
(with good particle identification)

Another way to follow the valence quarks:

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

Baryon Stopping in Nuclear Collisions

CGC approach



Mehtar-Tani, Wolschin, arXiv:1102.3134, arXiv:1001.3617, arXiv:0907. 5444, arXiv:0811.1721

Duraes, Goncalves, Giannini, FSN, arXiv:1401.7888

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: k_T factorization : (hard valence quarks with no-recoil)

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

DJ

Dumitru, Jalilian-Marian, hep-ph/0204028

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

Valence quark distribution

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

(MRST01-LO)

"Net baryon" fragmentation function

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

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 !

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

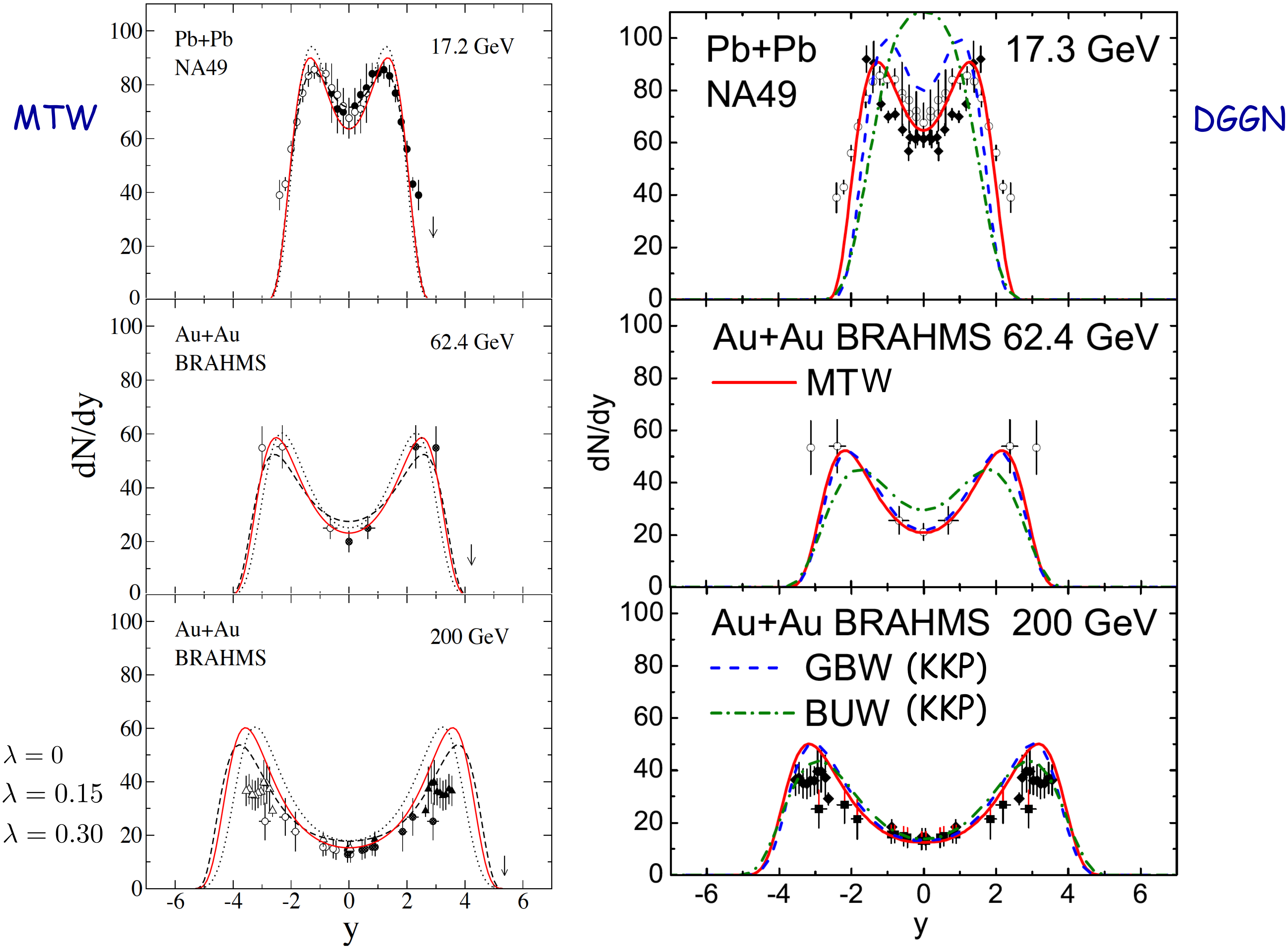
$$Q_s^2 = Q_0^2 A^{1/3} \left(\frac{x_0}{x}\right)^{\lambda}$$

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

BUW dipole amplitude

KKP fragmentation functions

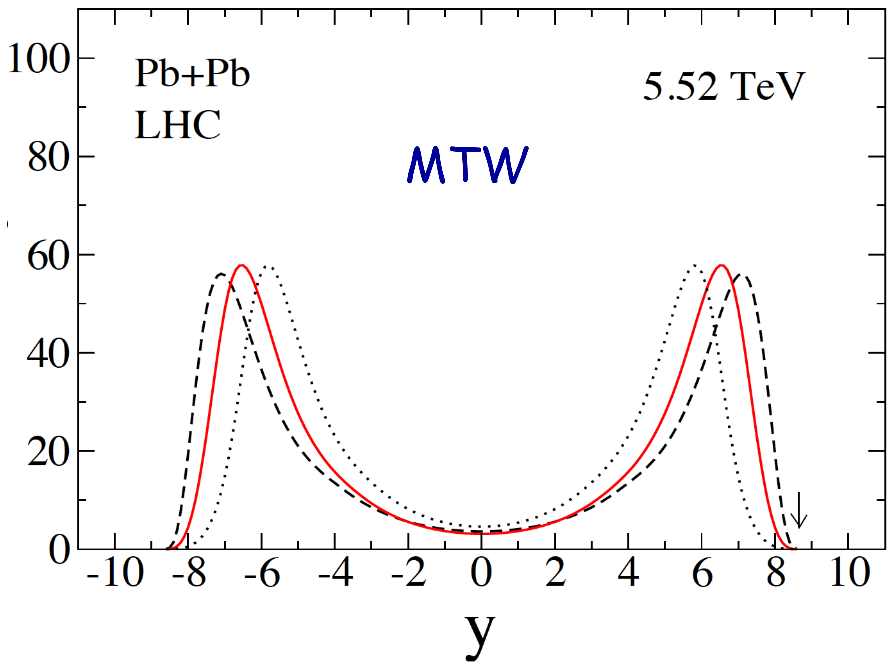
Rapidity Distributions

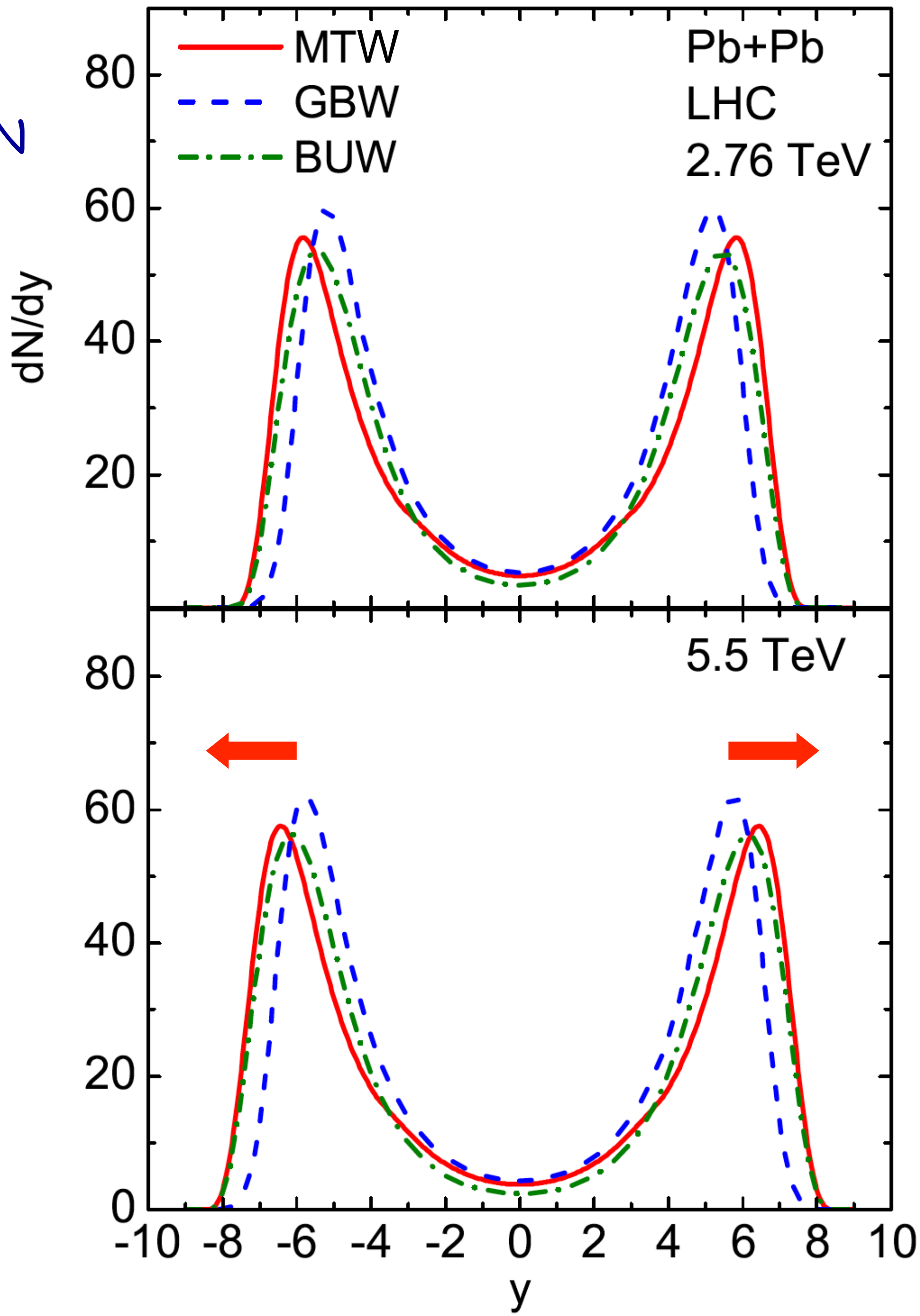


MTW
DGGN
Pb+Pb
NA49
17.2 GeV
17.3 GeV
Au+Au
BRAHMS
62.4 GeV
200 GeV
Au+Au BRAHMS 62.4 GeV
MTW
Au+Au BRAHMS 200 GeV
GBW (KKP)
BUW (KKP)
dN/dy
y
$\lambda = 0$
$\lambda = 0.15$
$\lambda = 0.30$

Predictions DGGN

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

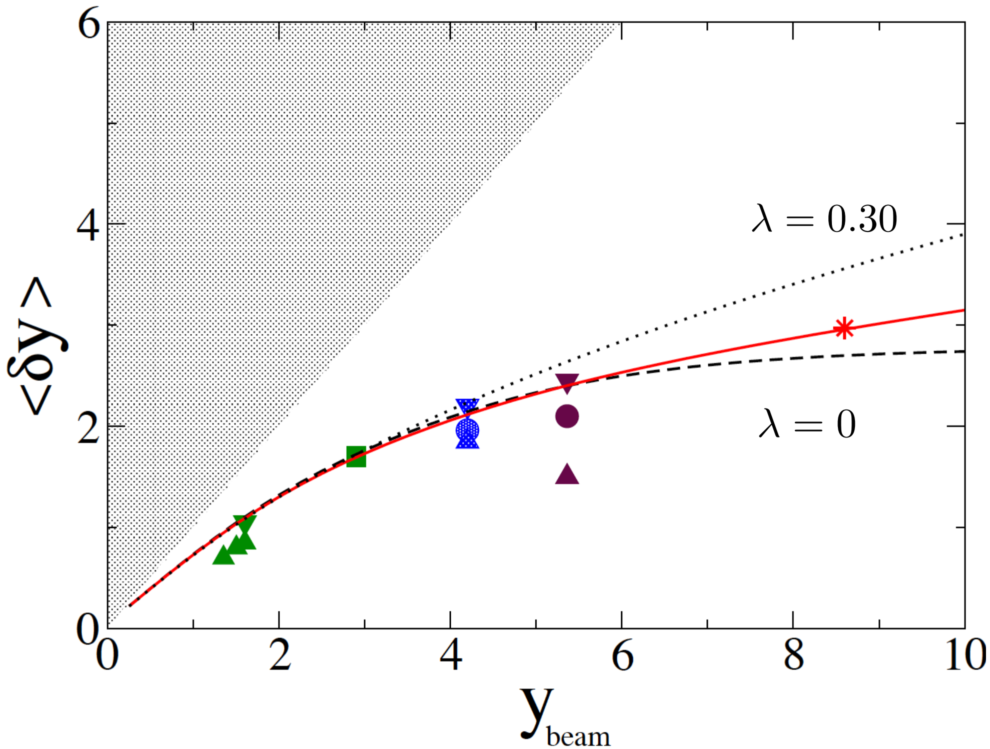




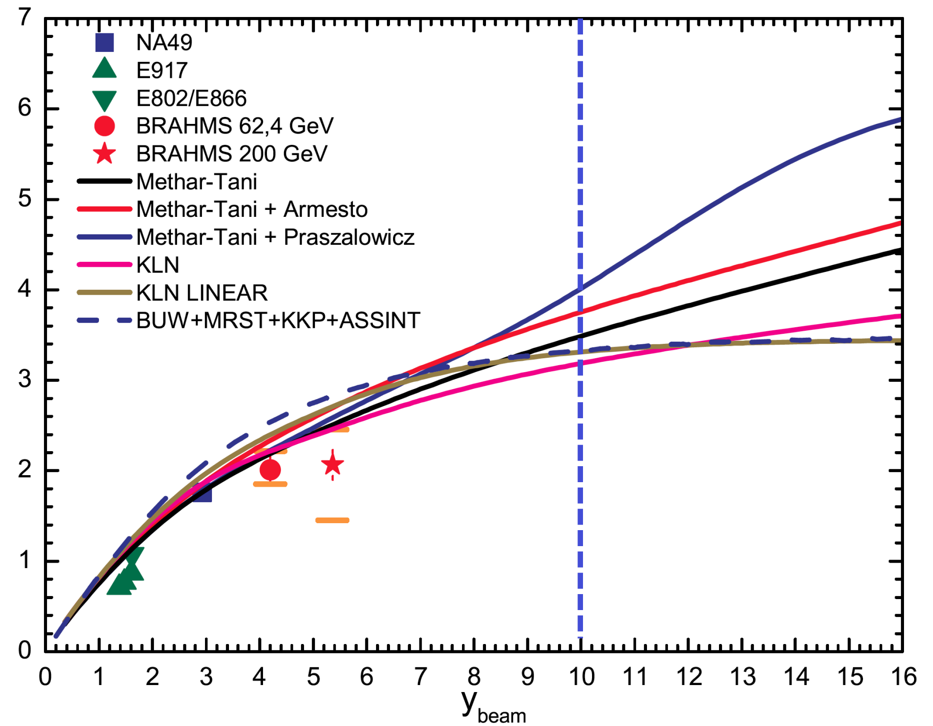
Mean Rapidity Loss

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

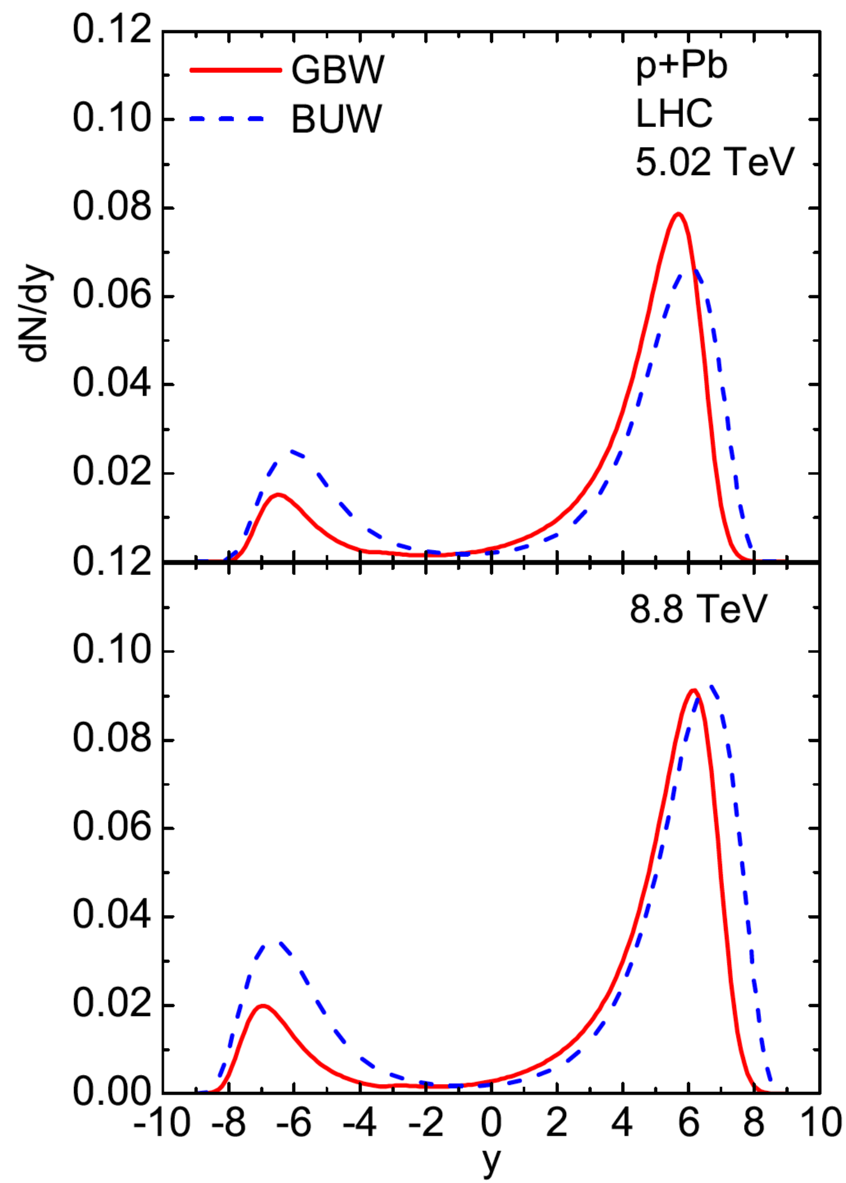
MTW

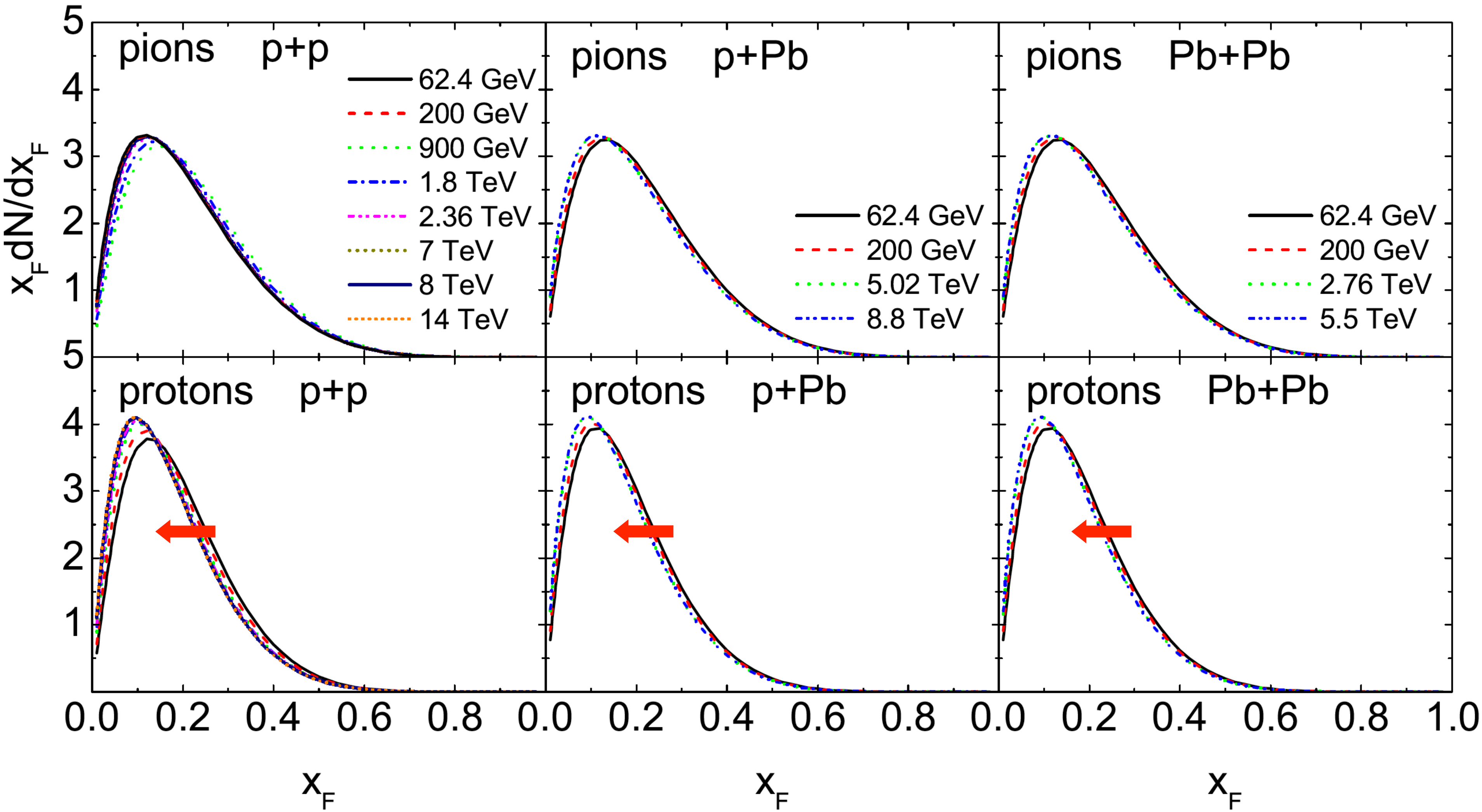


DGGN



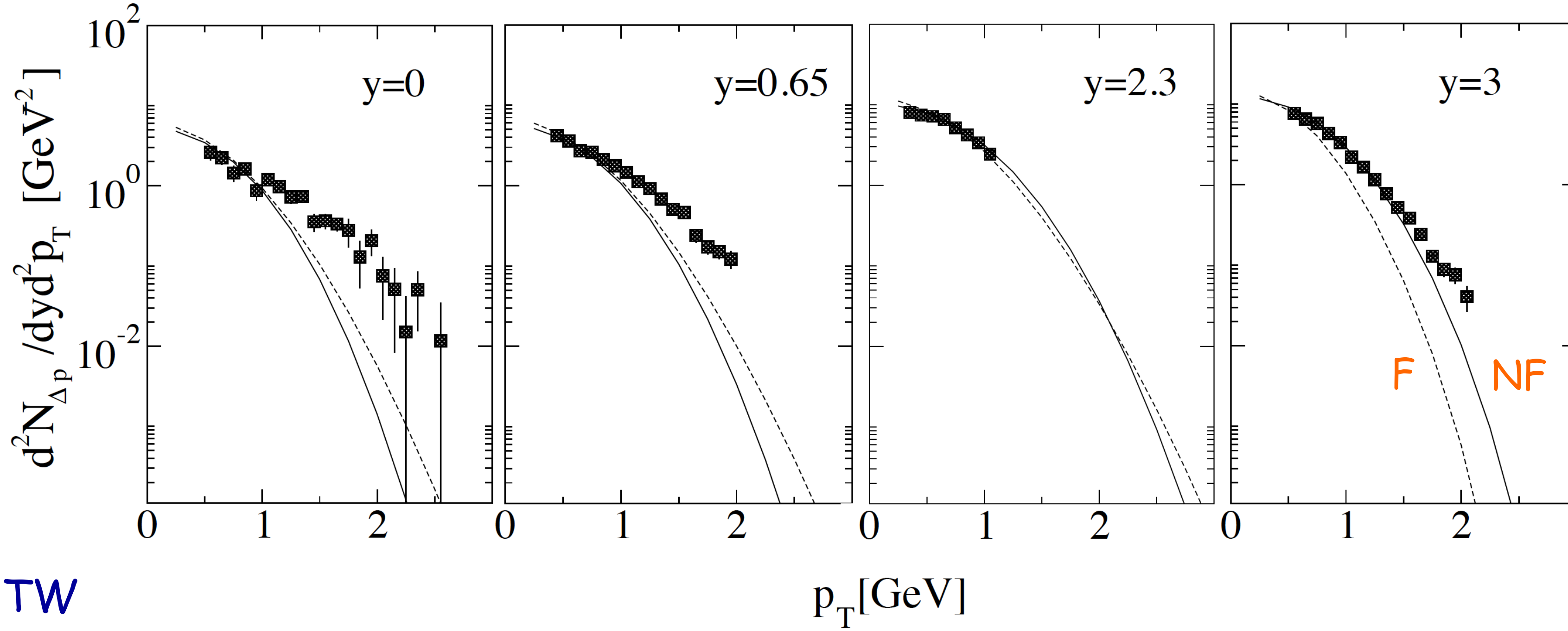
Proton-Nucleus





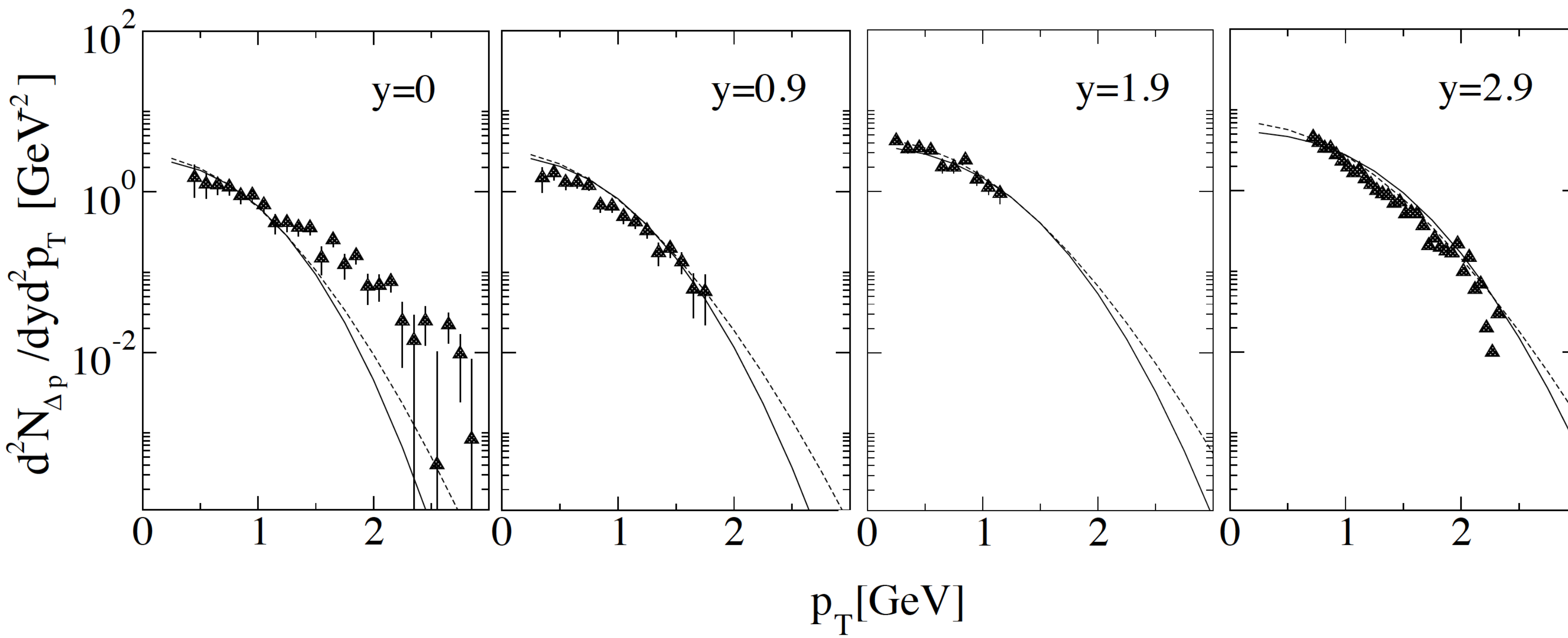
Feynman scaling ?

Transverse Momentum Distributions



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

MTW

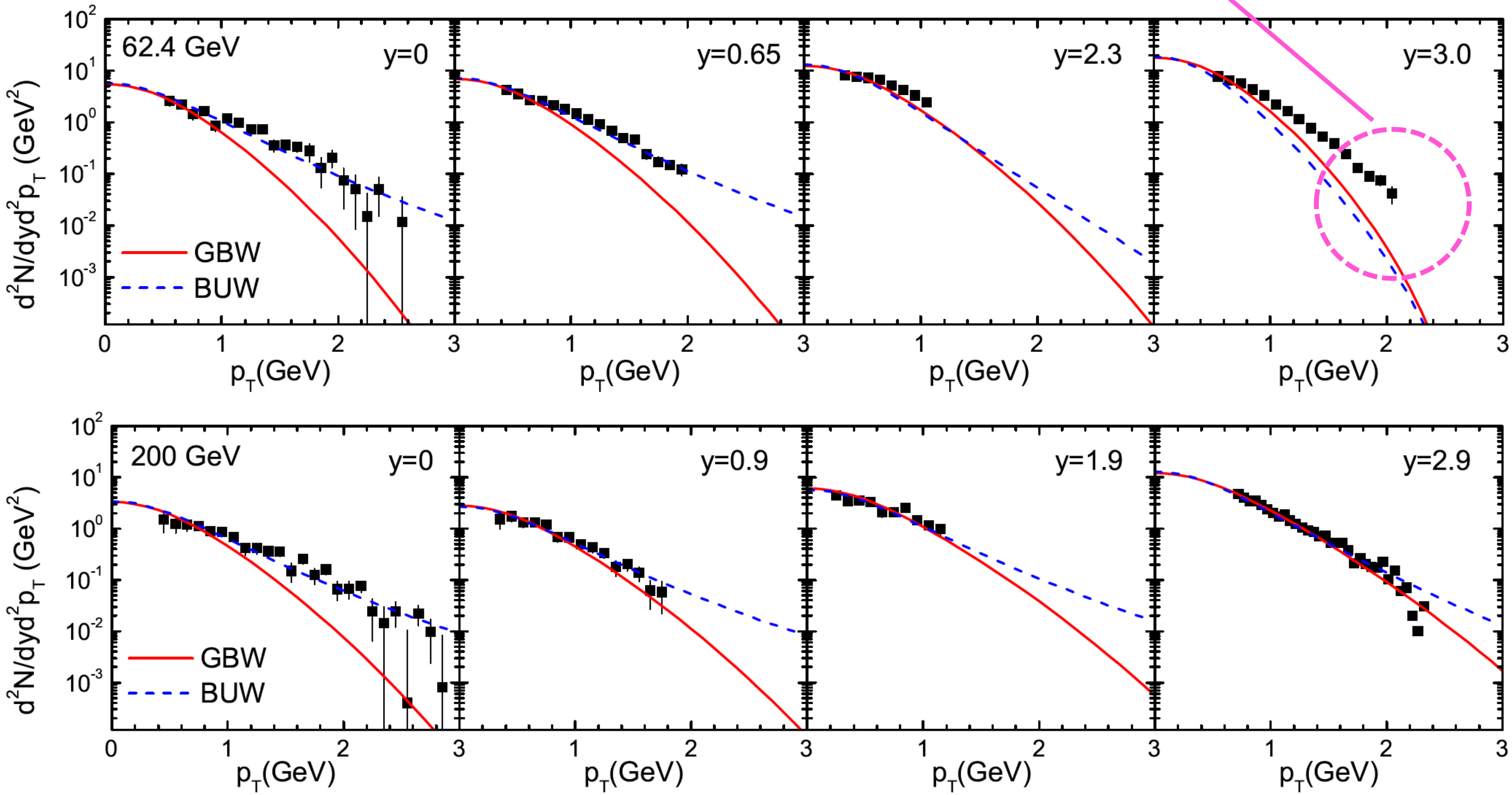


$d^2N_{\Delta p}/dyd^2p_T$ [GeV^{-2}]
y=0
y=0.9
y=1.9
y=2.9
p_T[GeV]

DGGN

large x_F :
failure of independent
fragmentation ?

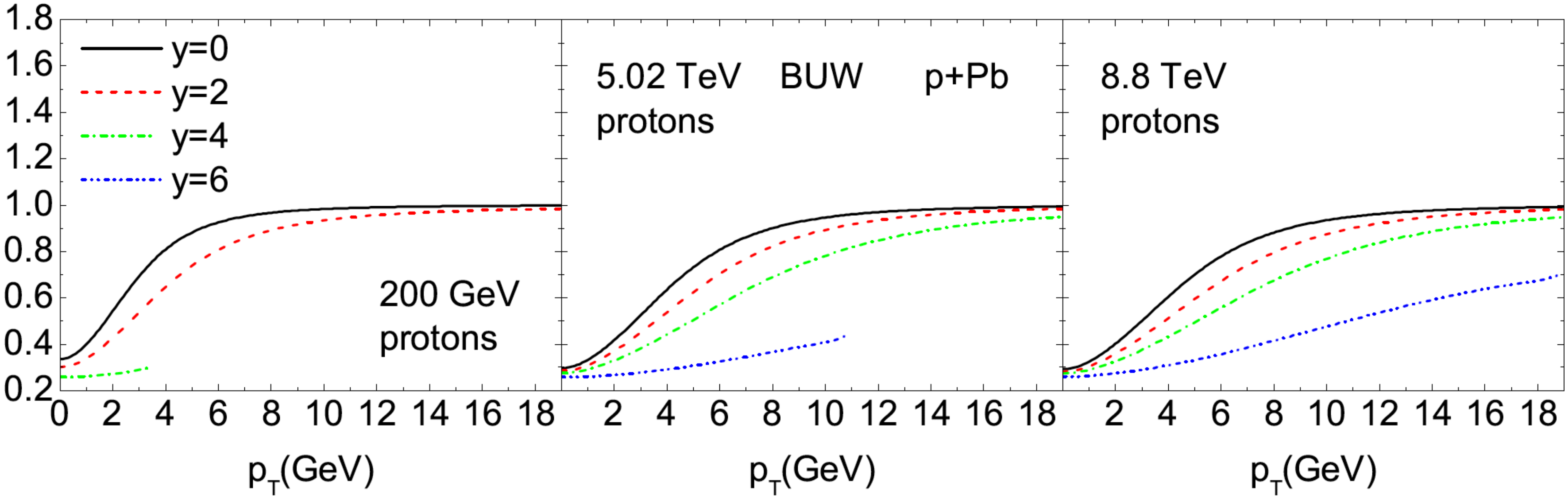
$x_F \simeq 0.6$



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

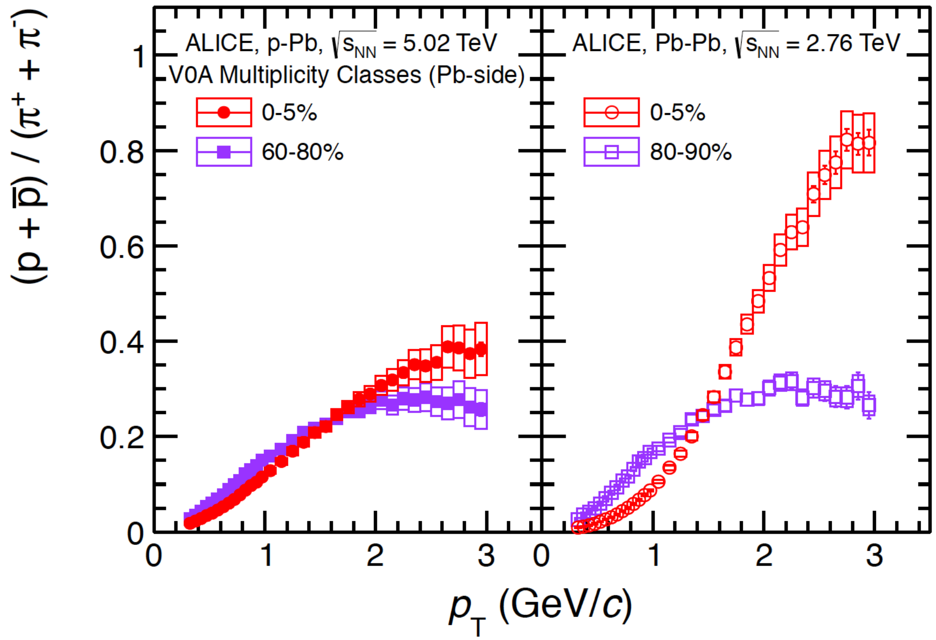
$x_F \simeq 0.2$

Proton-Nucleus: Nuclear Modification Ratio

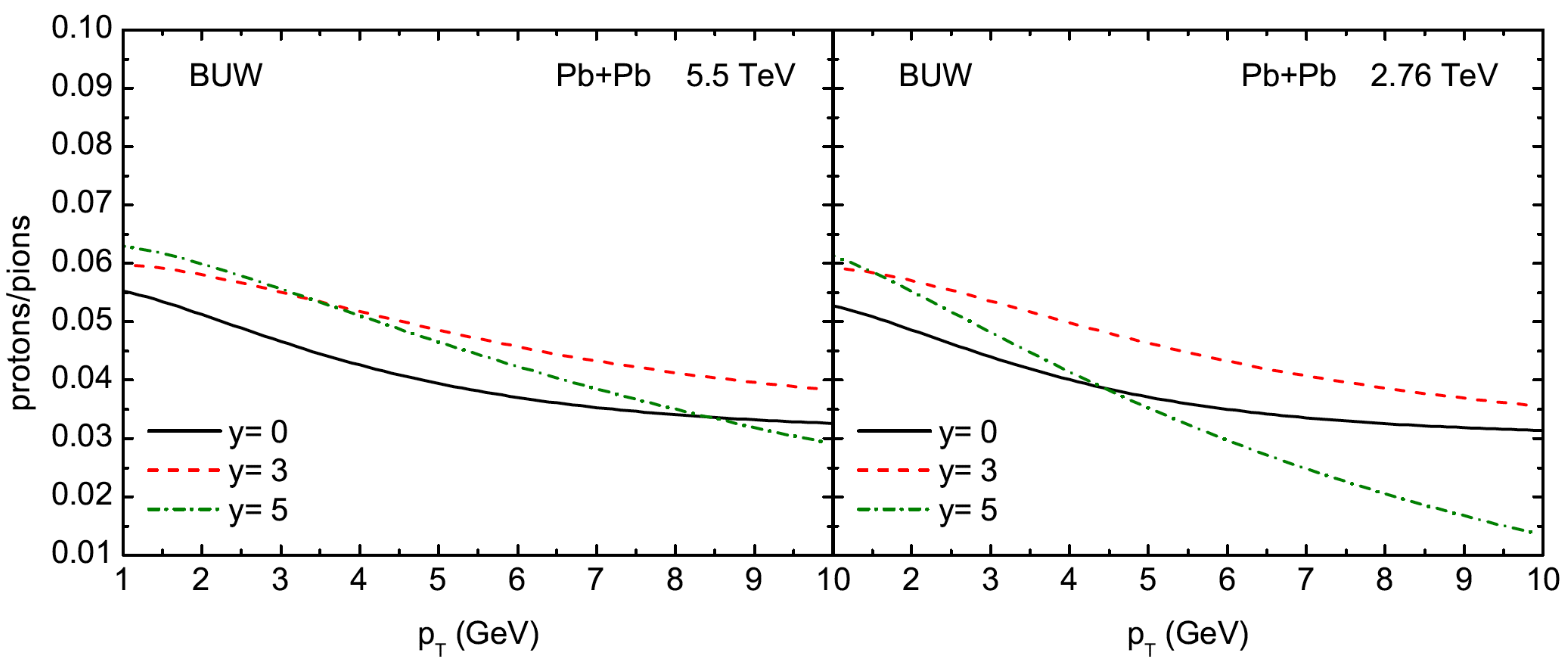


$$R_{pA} = \frac{\frac{d^2N_{pA}}{dyd^2p_T}}{A\frac{d^2N_{pp}}{dyd^2p_T}}$$

p/π ratio



Net-protons:
no enhancement !



Summary

Net baryons are interesting: they carry the valence quarks

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

CGC approach works (!) but should be improved

Transition from recombination to independent fragmentation

Forward baryon production (cosmic rays and LHCf)

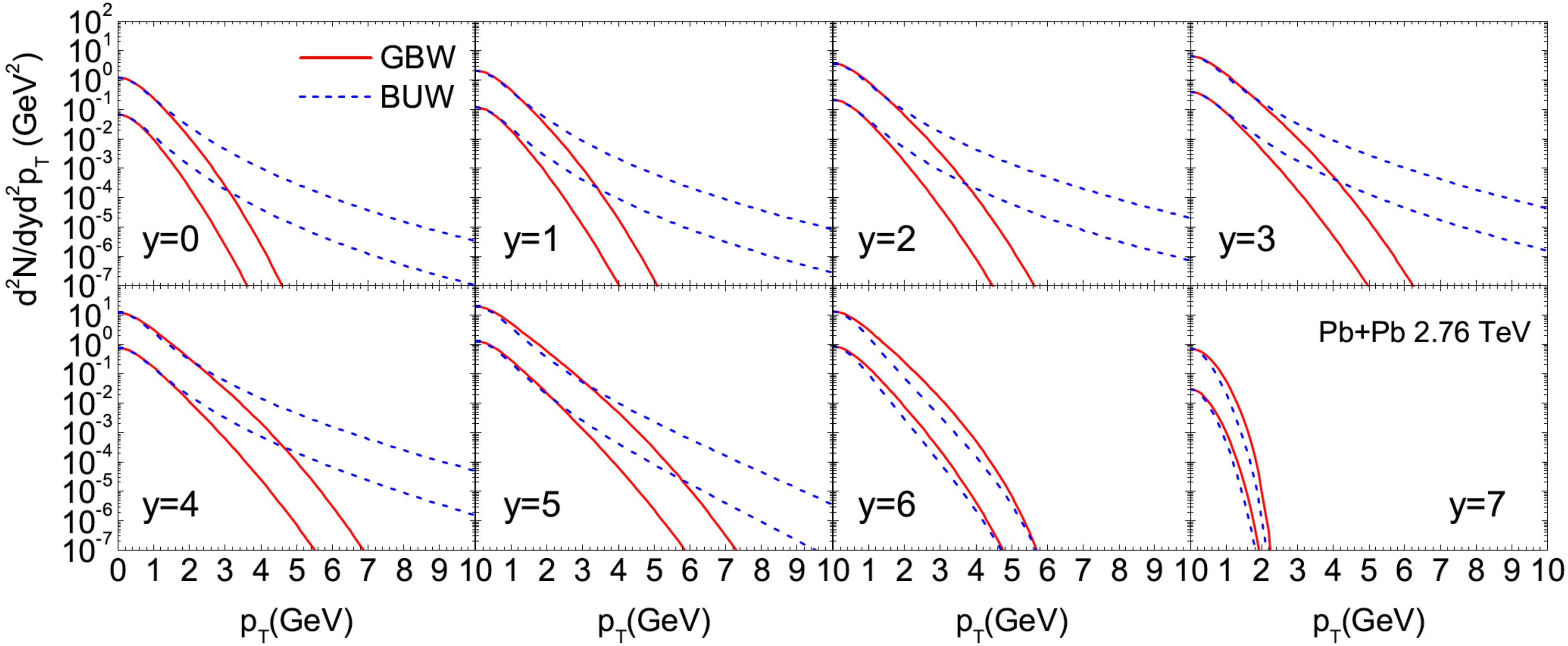
DJ formula: is there energy conservation ?

Energy loss ?

Why CGC only at high energies ?

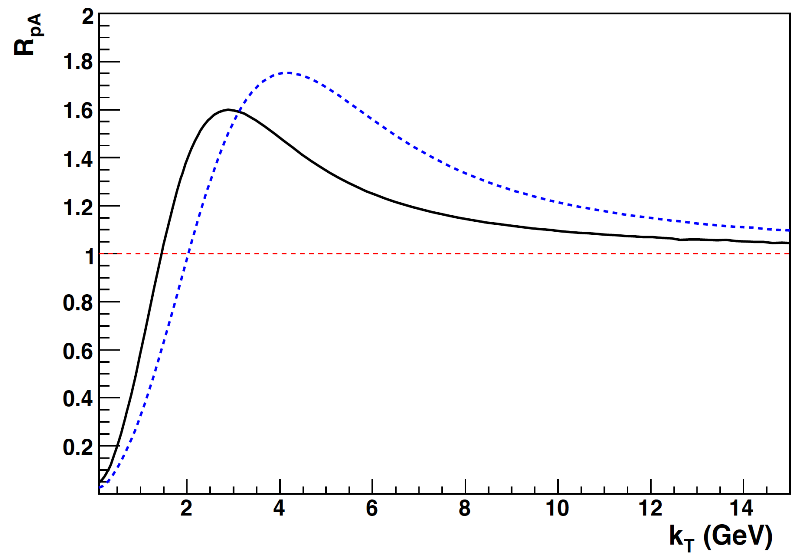
Normalization of dn/dy

Novidade BUW (melhor porque ?)


GBW
BUW
y=0
y=1
y=2
y=3
y=4
y=5
y=6
y=7
Pb+Pb 2.76 TeV
d^2N/dyd^2p_T (GeV^2)
p_T(GeV)

Albacete, Kovchegov,
hep-ph/0605053

Y=0
"soft" valence quarks



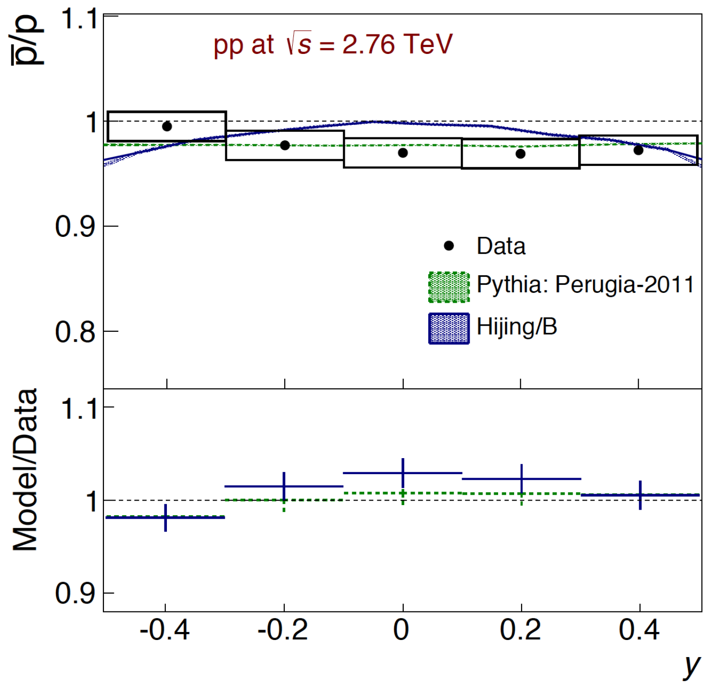
Other models for pp: strings ?

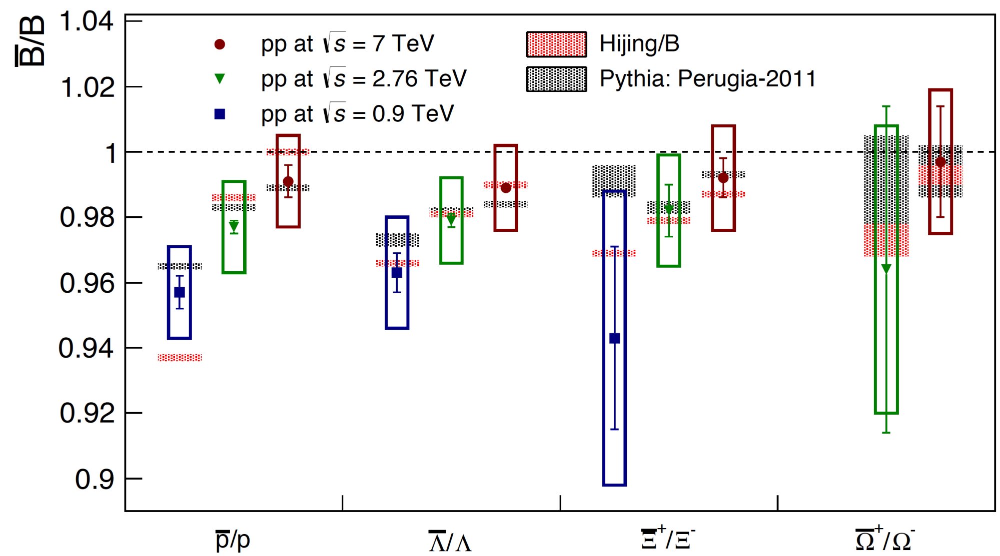
Energy loss of the valence quark ?

Baryon production in high energy collisions:

Central region: from sea quarks and gluons

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





ALICE, arXiv:1305.1562

Forward region: from valence quarks ("leading baryons")

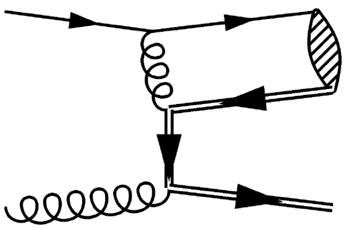
$$N_{\text{protons}} >> N_{\text{antiprotons}}$$

Valence quark recombination ("coalescence")

Model for quark coalescence

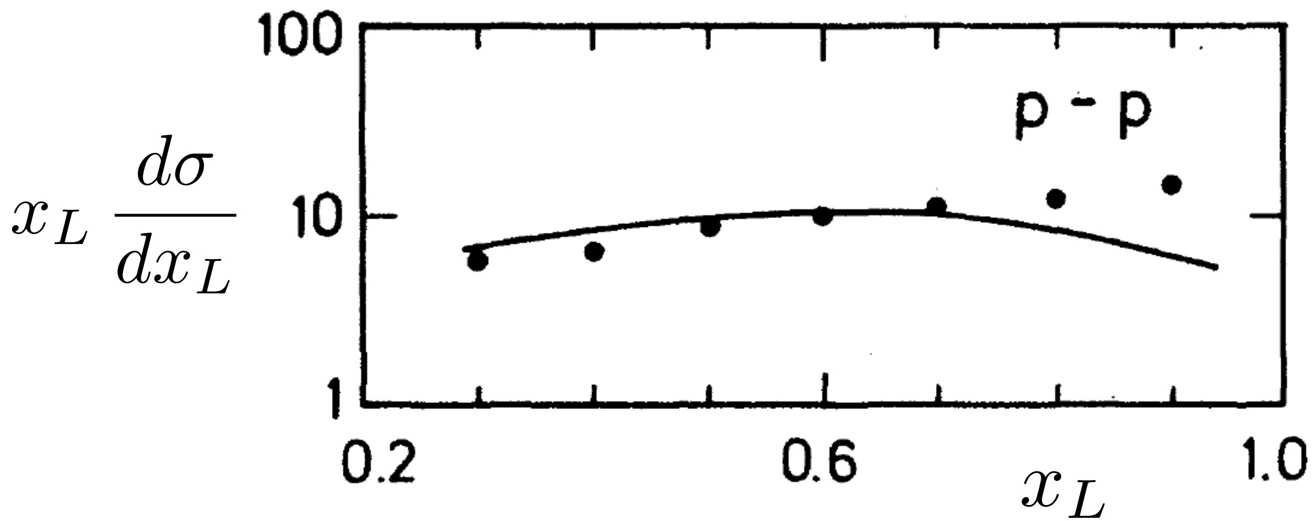
Hwa, Yang, Zhong, nucl-th/0401001

Rapp, Shuryak, hep-ph/0301245

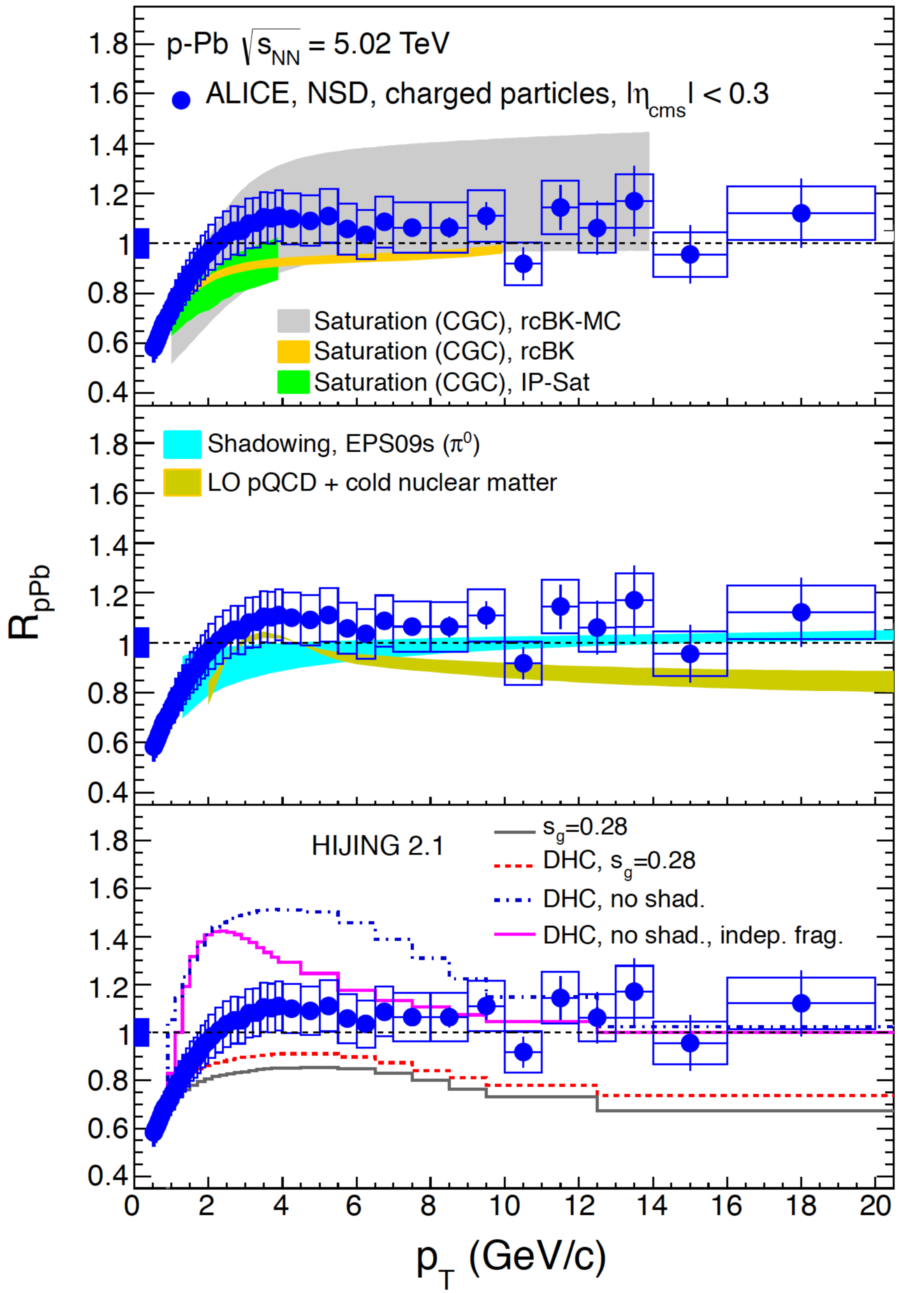


Effective theory for heavy quark recombination

Braaten, Jia, Mehen, hep-ph/0108201



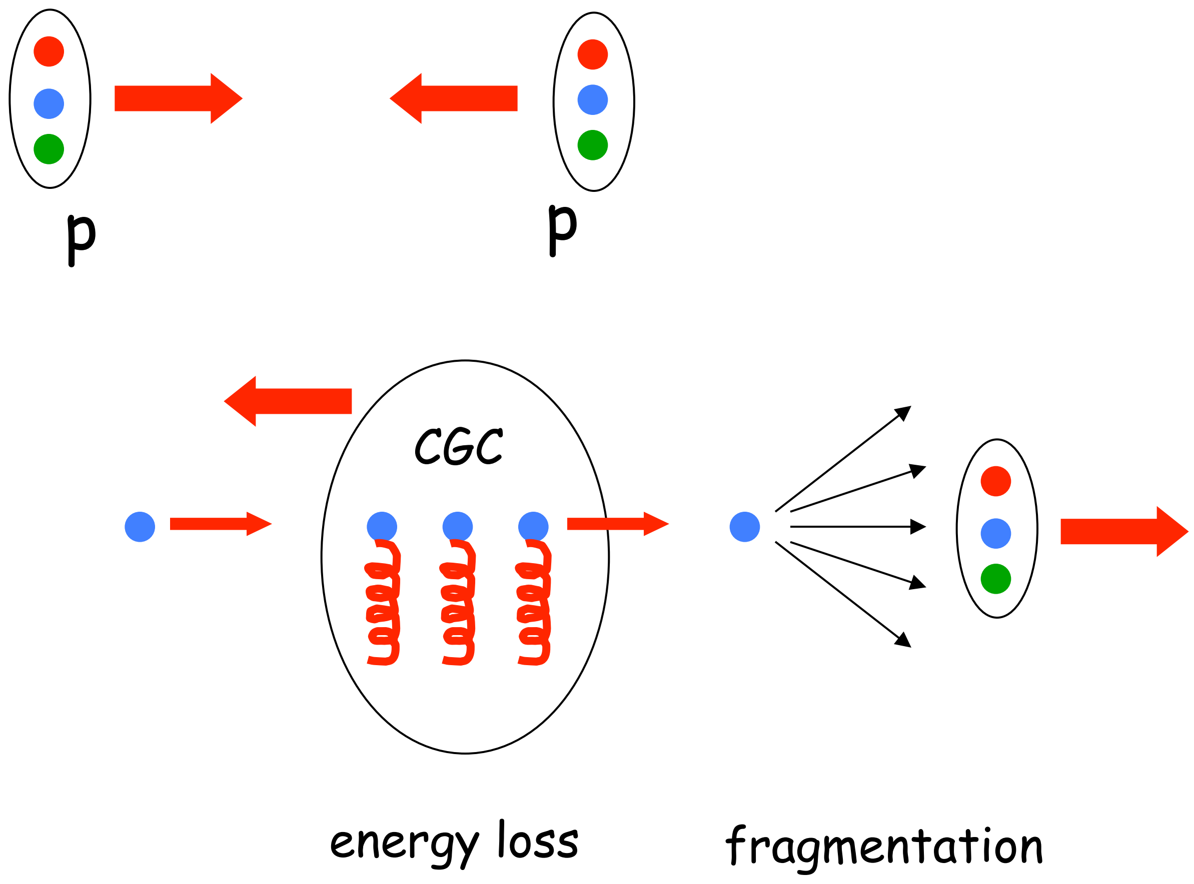
Duraes, FSN, Wilk, hep-ph/9809309 hep-ph/0412293



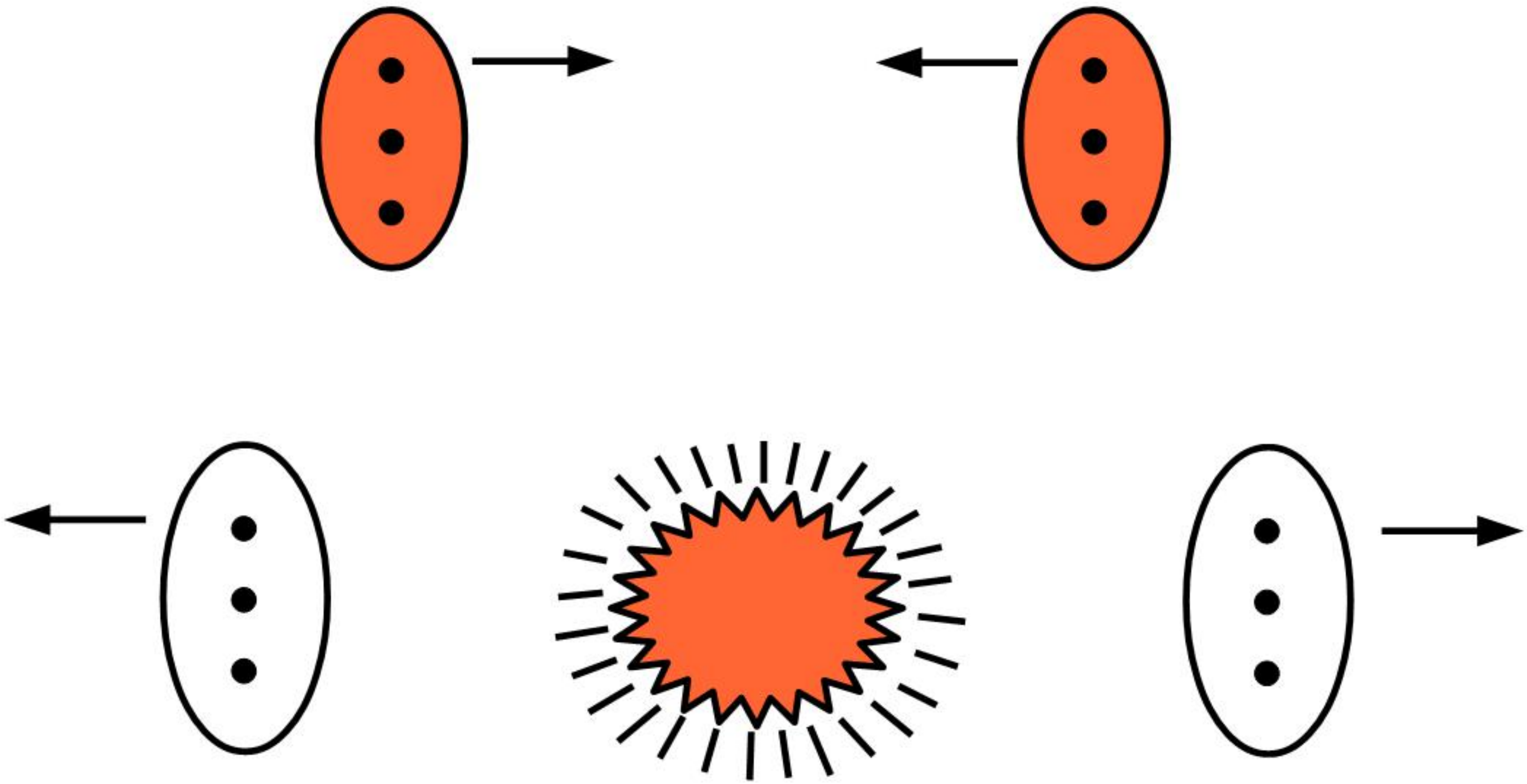
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
ALICE, NSD, charged particles, $|\eta_{cms}| < 0.3$
Saturation (CGC), rcBK-MC
Saturation (CGC), rcBK
Saturation (CGC), IP-Sat
Shadowing, EPS09s (π^0)
LO pQCD + cold nuclear matter
HIJING 2.1
s_g=0.28
DHC, s_g=0.28
DHC, no shad.
DHC, no shad., indep. frag.
R_{pPb}
p_T (GeV/c)

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

Energy loss of one valence quark + independent fragmentation

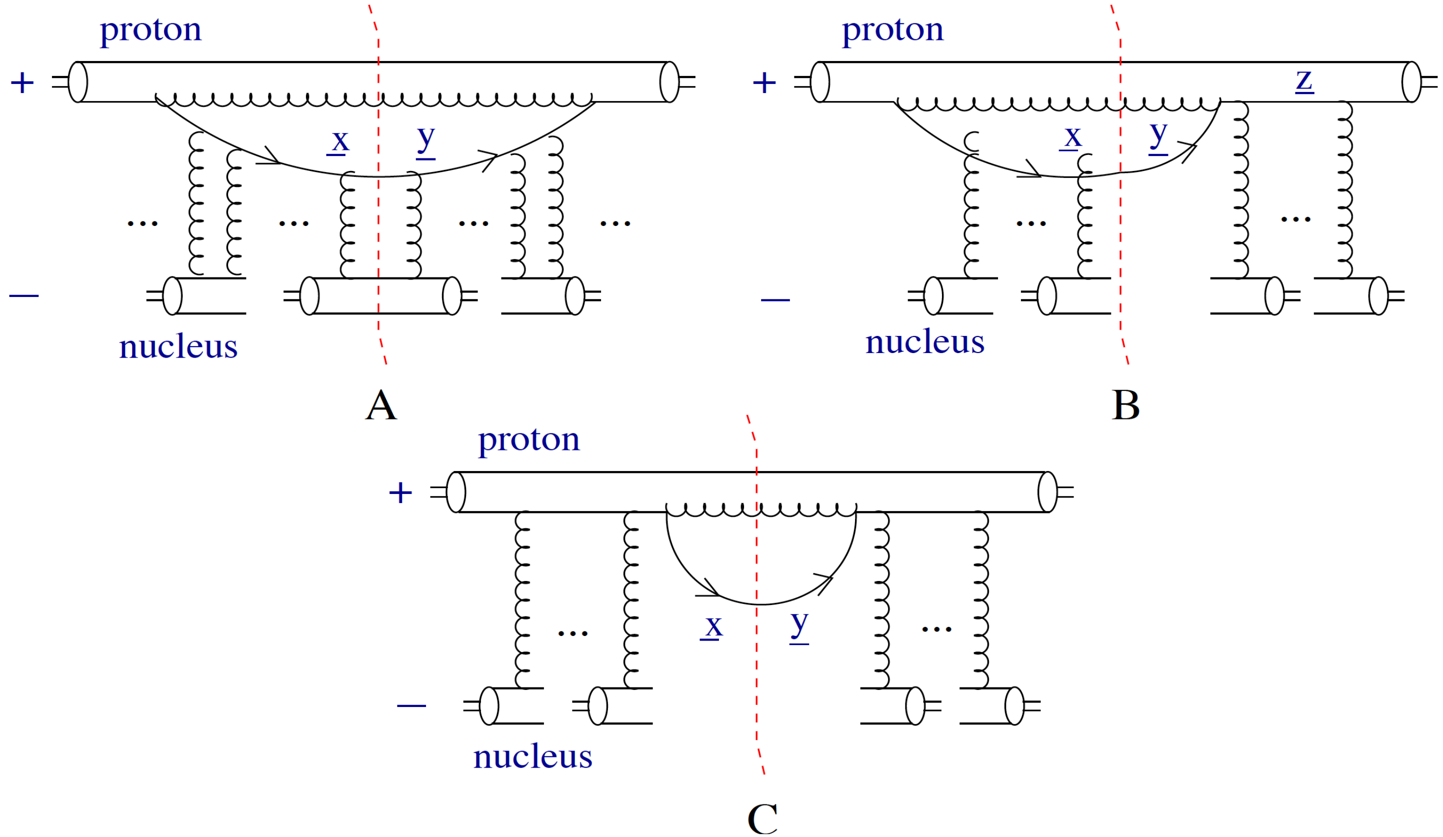


$$D(z) \approx \frac{1}{z}$$

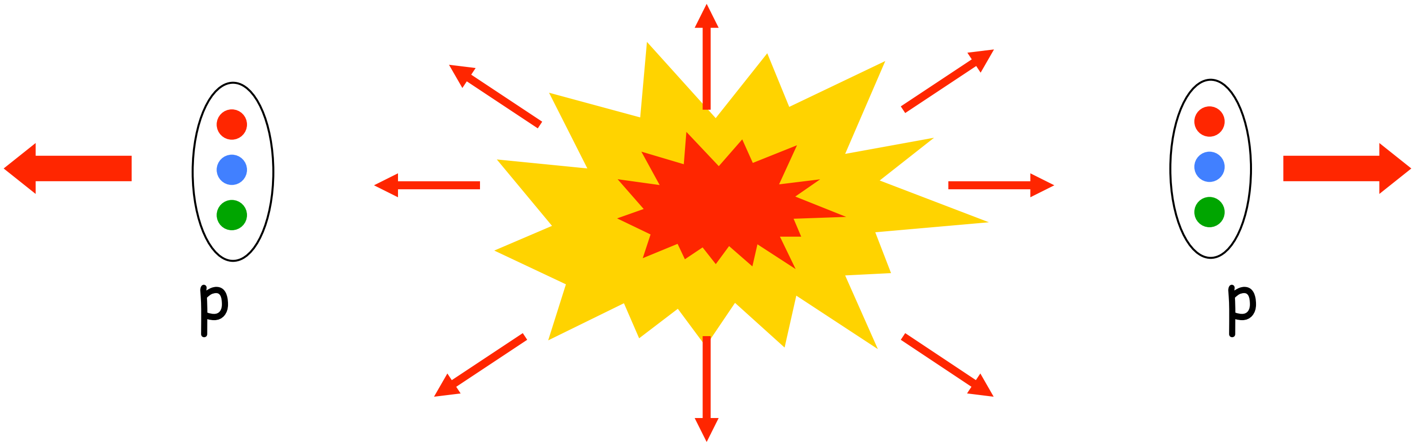


Color glass condensate

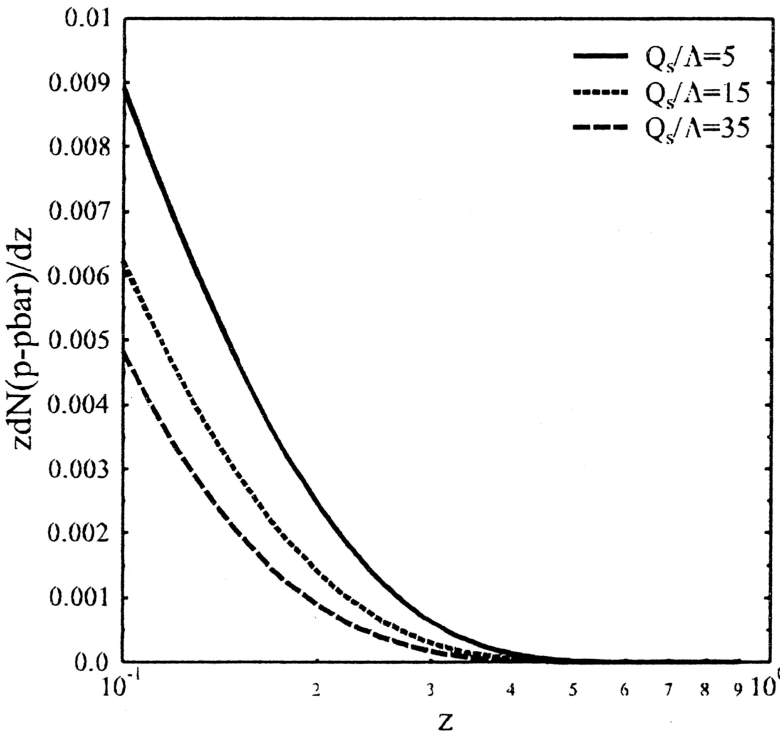
Albacete, Kovchegov, hep-ph/0605053



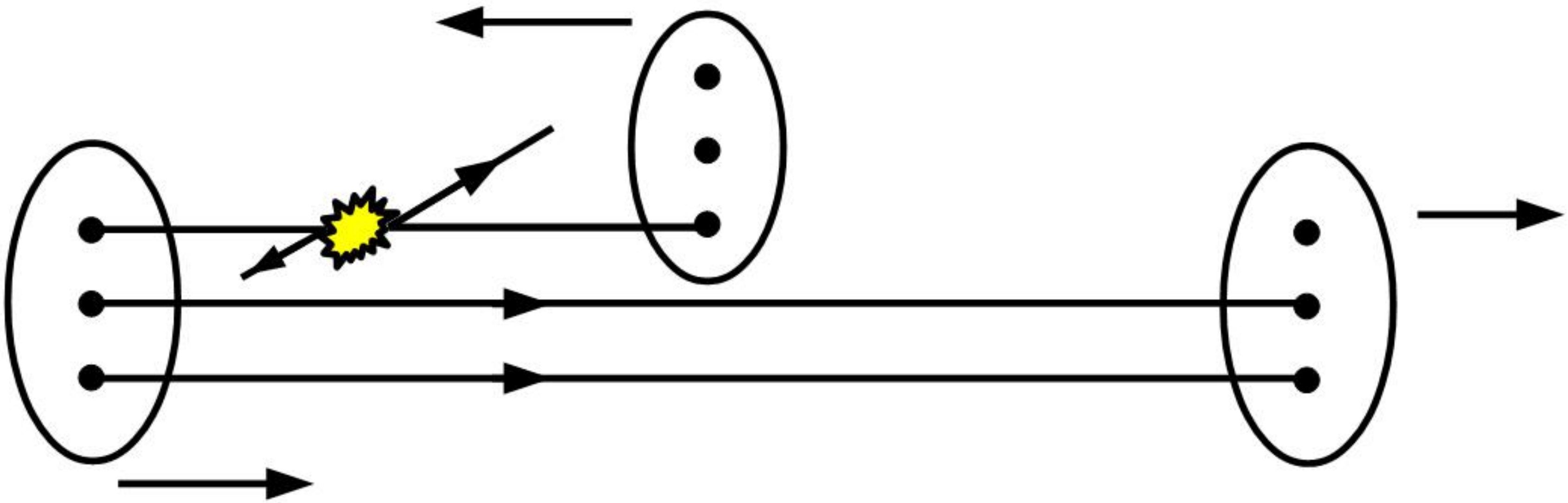
Valence quark recombination



No strong baryon stopping: baryon “transparency”



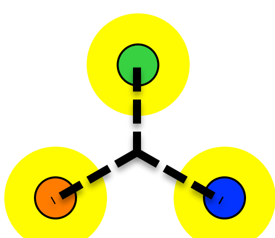
$Q_s/\Lambda=5$
$Q_s/\Lambda=15$
$Q_s/\Lambda=35$
zdN(p-pbar)/dz
z
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0
10^{-1}
2
3
4
5
6
7
8
9
10^{0}



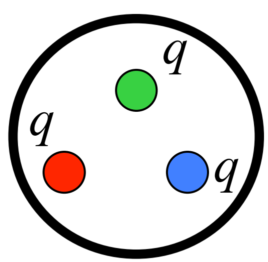
Pictures of the nucleon

E. Shuryak, hep-ph/9603354

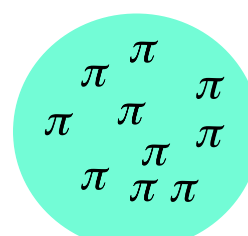
Non-relativistic quark model



MIT bag model



Skyrmion



Chiral bag