Proton fragmentation in proton - nucleus collisions at collider energies

CFNS online workshop on “Target fragmentation and diffraction physics with novel processes: Ultraperipheral, electron-ion, and hadron collisions”
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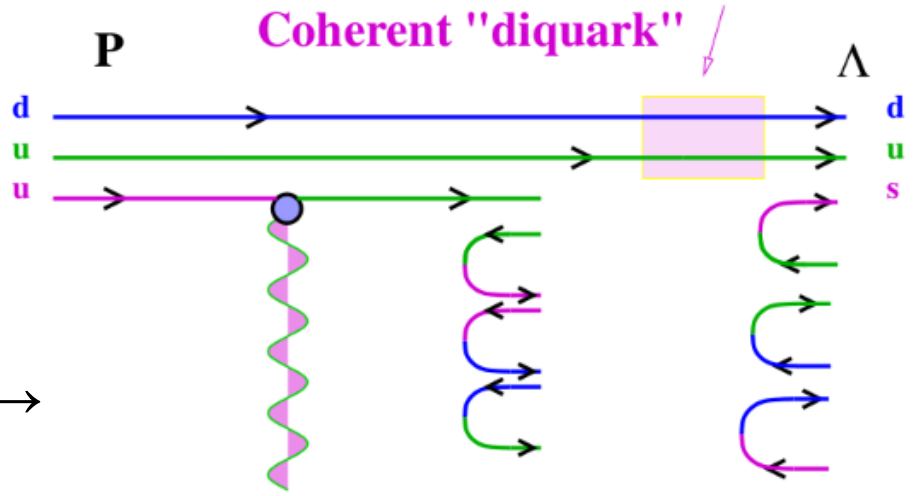
Motivation / interests :

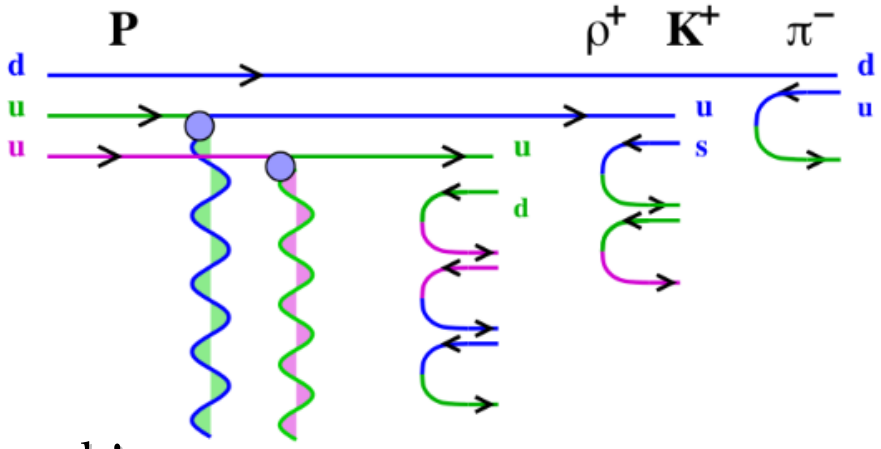
- structure of baryons (val. quarks, diquarks, junctions, …)
- baryon number “flow” (stopping) down in x_F, y
- physics of high gluon density (in the target)
- cosmic ray induced atmospheric air showers
  (muon puzzle: arXiv:2105.06148, 2202.03095)

Proton fragmentation in pp / pA :

(Yu. Dokshitzer, hep-ph/0106348, 0306287)



typical inelastic p+p produces leading baryon →
(leading particle effect)

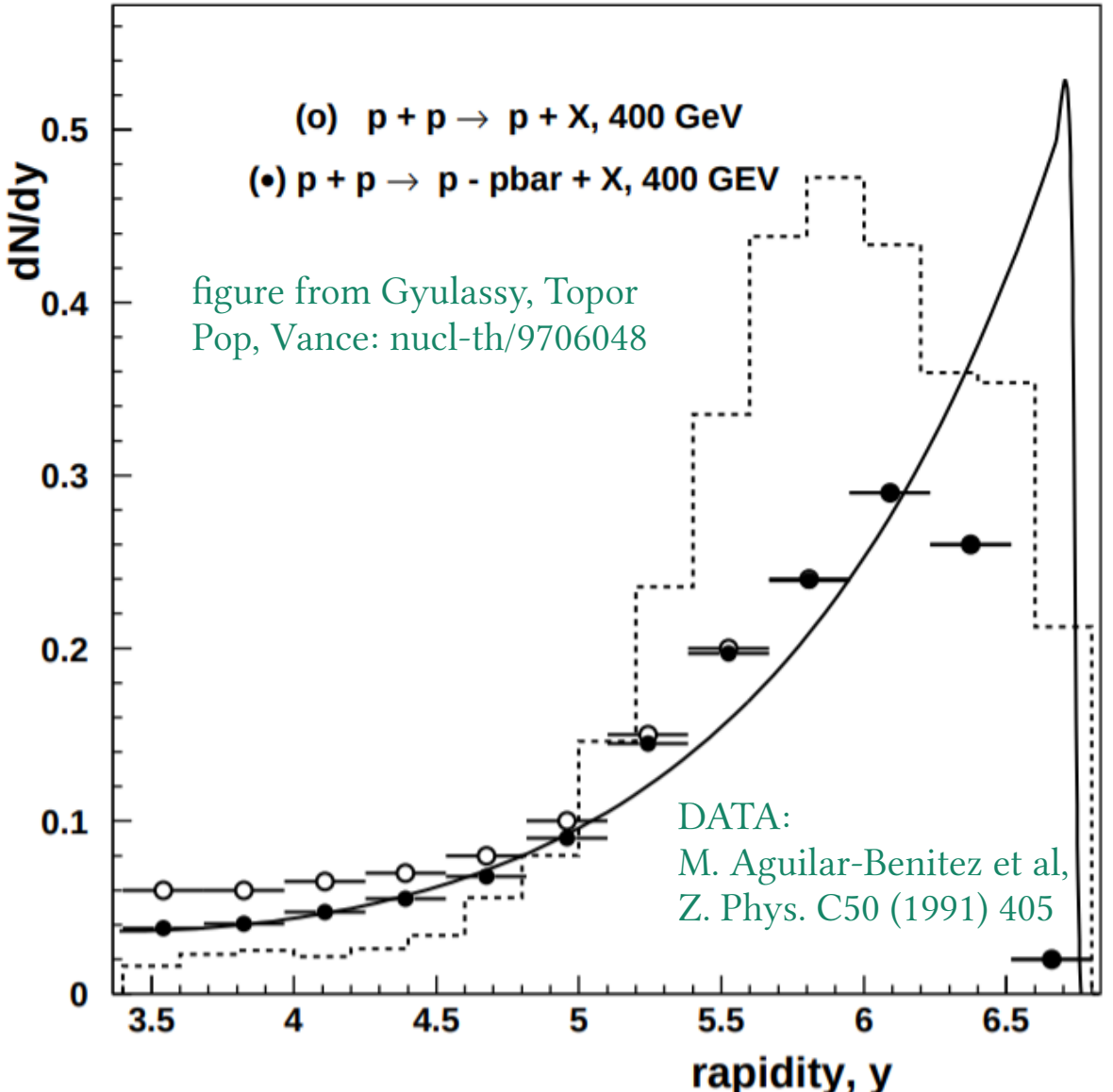


If the proton passes through a **strong** field it should "decay" into a beam of leading mesons →

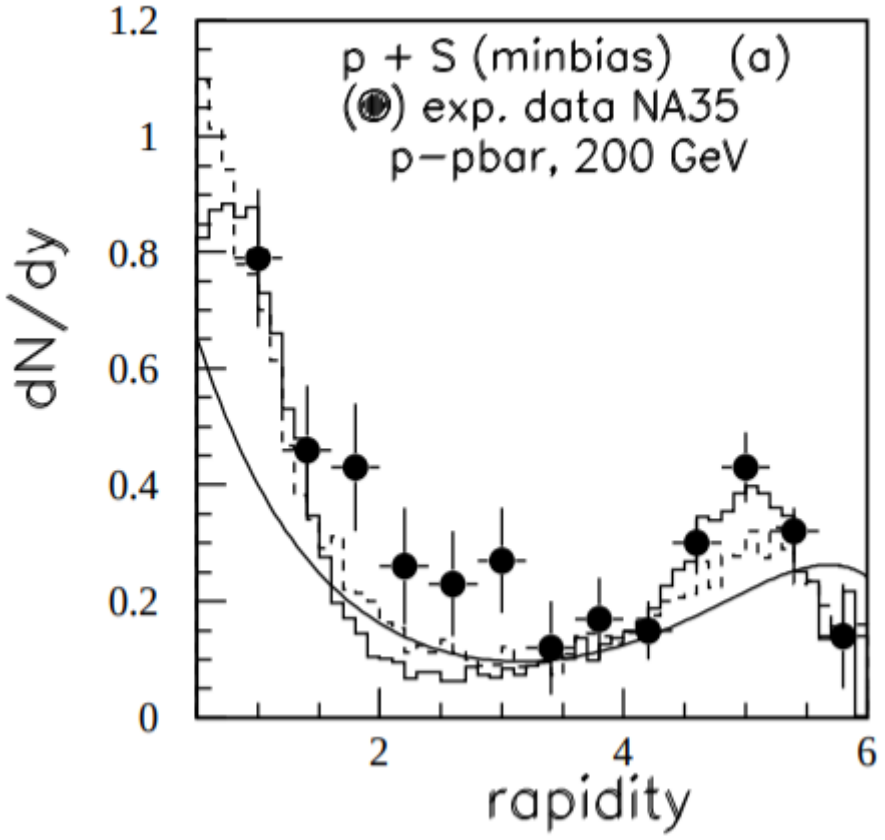
This is not "stopping": $t \longrightarrow -p_T^2$ at high E,

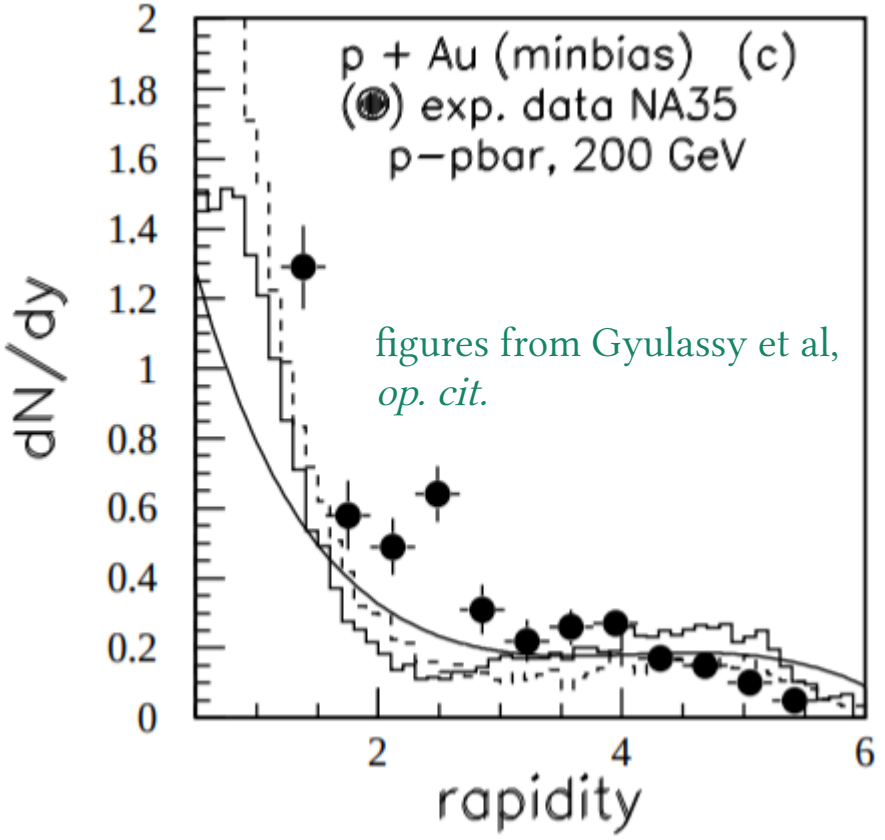
light-cone momentum is conserved !

"leading particle effect" in min-bias pp ⟶ p+X at low energy



min-bias pA ⟶ p+X at low energy





figures from Gyulassy et al, *op. cit.*

Partonic picture, independent fragmentation of leading (large-x) projectile partons :

(Berera, Strikman, Toothacker, Walker, Whitmore: hep-ph/9604299)

"In this limit, when the leading partons [...] fragment independently, it is possible to calculate the leading parton production cross section integrated over the transverse momentum pT"

$$z\frac{dN_A^{h/h_p}(z)}{dz} = \sum_{a=q,\bar{q},g} \int_z^1 dx \frac{z}{x} D^{h/a}(\frac{z}{x}, Q^2) f_{a/h_p}(x, Q^2),$$

"leading correction due to diffractive events "

"We set the virtuality at $Q^2 = 1$ GeV^2 "

Combining "parton fragmentation picture" with strong color field QCD

(A.D., Gerland, Strikman: hep-ph/0211324)

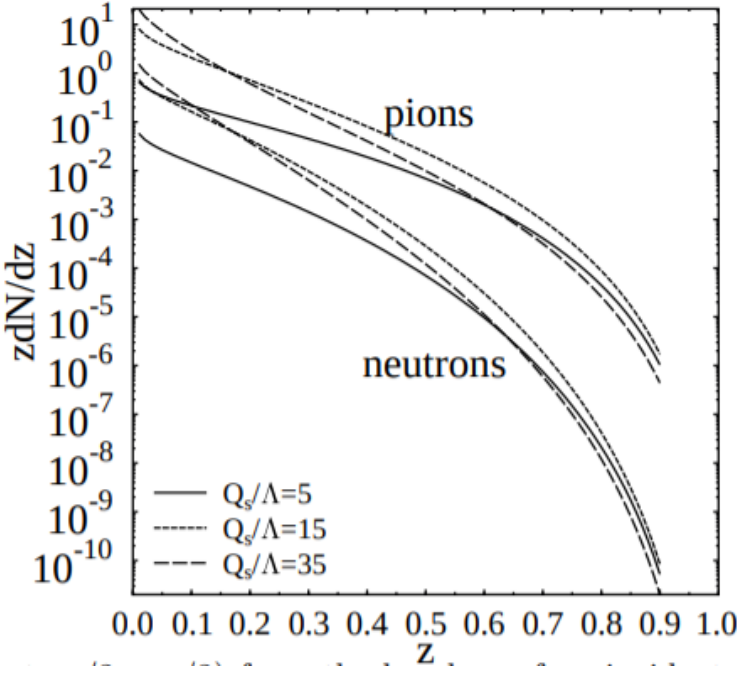
dipole scattering amplitude

$$z\frac{d\sigma^{pA\to hX}}{dzd^2k_td^2b} = \frac{1}{(2\pi)^2}\int_z^1 dx\,\frac{x}{z}f_{q/p}(x,Q_s^2)D_{h/q}\left(\frac{z}{x},Q_s^2\right)C\left(\frac{xk_t}{z}\right)$$

* predicts pT-broadening of leading particle spectra

* "limiting fragmentation" x_F distribution

* p ⟶ "beam of mesons" for z >~ 0.1



Dipole scattering amplitude resums *coherent* multiple (eikonal) interactions of projectile charge with field of target (Glauber/Mueller) :

$$\left\langle \mathrm{tr}\; V(\vec{x})\, V^\dagger(\vec{y}) \right\rangle$$

$$V(\vec{x}) \quad = \quad \mathcal{P}\, e^{-ig \int dx^+ \, A^{a\,-}(x^+,\vec{x})\, t^a_{\mathcal{R}}}$$

"Evolution" of this object with rapidity / x satisfies Balitsky / Kovchegov eqn
solutions with running coupling accuracy nowadays standard;
full NLO under construction

non-linear QCD evolution, charged particle production at NLO (!),
comparison to LHCb data

incorporates the growth of the scale of non-linearities ("saturation momentum")

- ~ $A^{1/3}$ (McLerran & Venugopalan)
- ~ $1/x^{\lambda}$ (Mueller, Balitsky, Kovchegov)

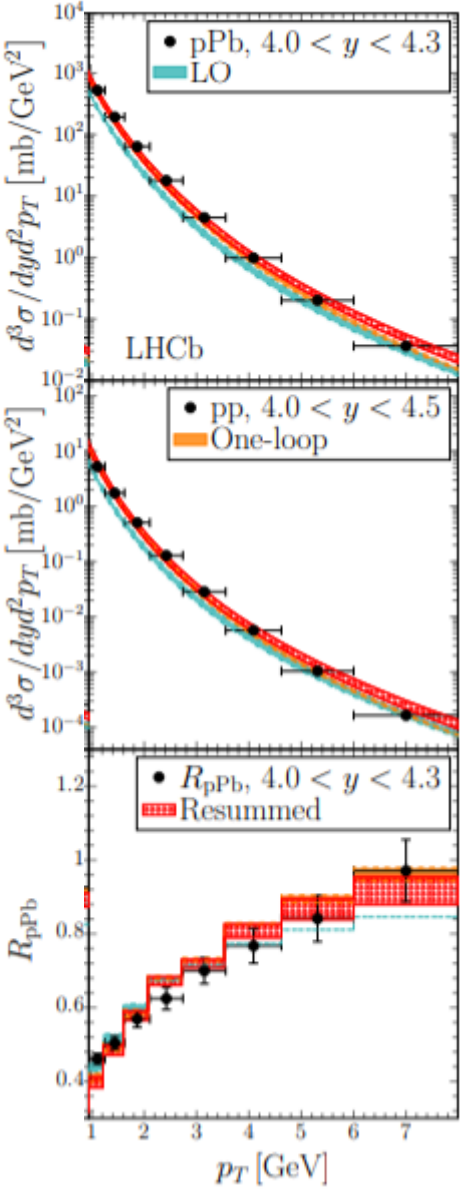


figure from Shi, Wang, Wei, Xiao: arXiv:2112.06975

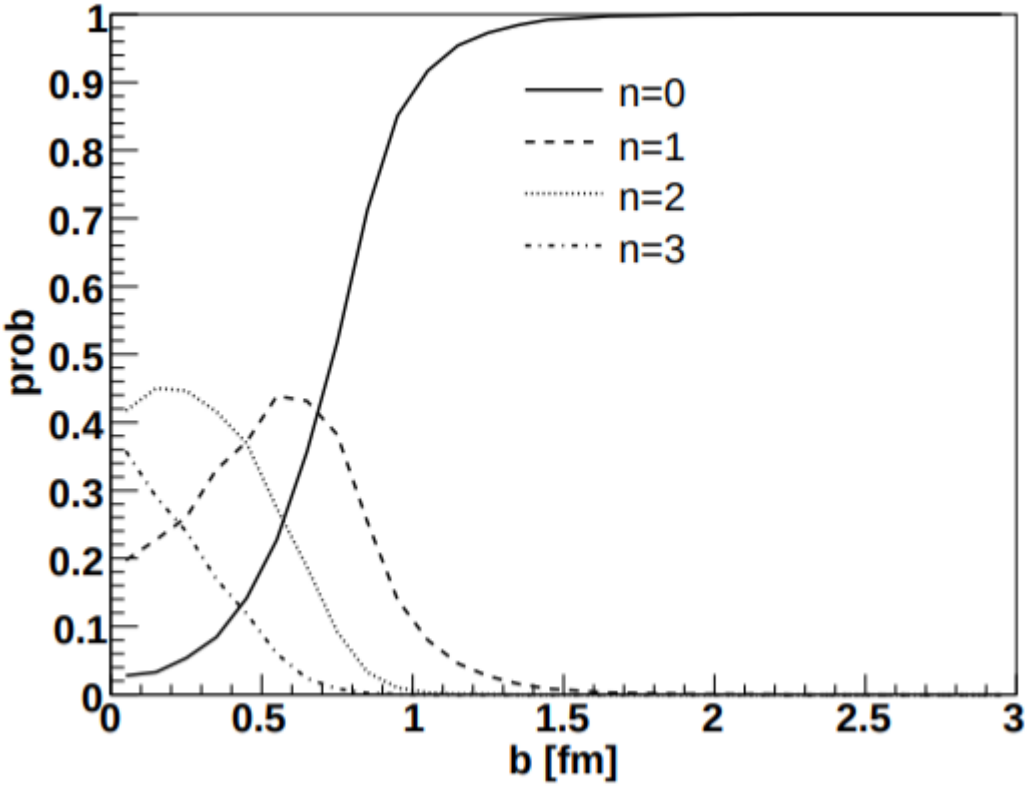
“Central” pp collisions at LHC energies

(Drescher, Strikman: hep-ph/0211324, PRL 100, 2008)

* they discuss centrality triggers for pp collisions

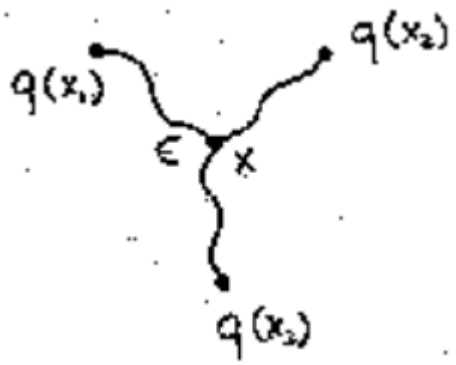
* at b~0 the prob. for scattering of n>=2 valence quarks ~ 80% ! (recall Dokshitzer’s idea)

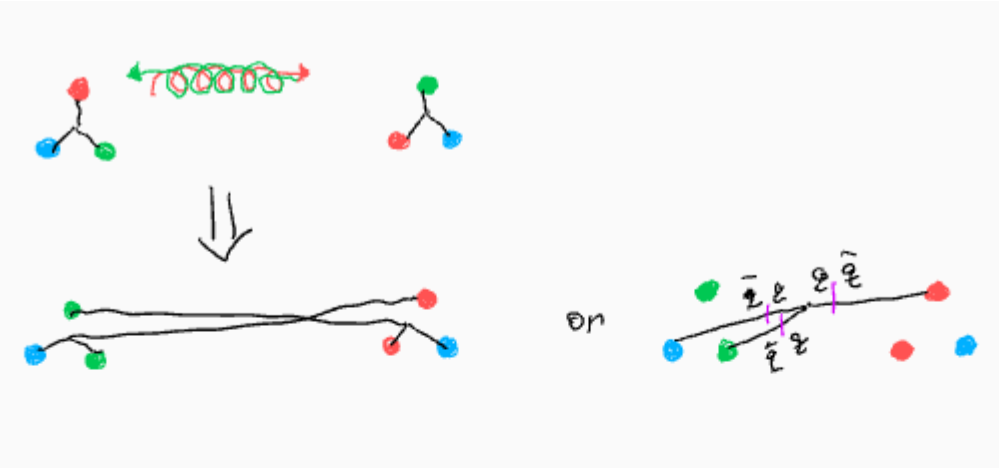
but diquark ⟶ baryon still not insignificant



Alternative to “parton fragmentation picture” : Baryon junction

(Kharzeev: nucl-th/9602027; Vance, Gyulassy, Wang: nucl-th/9806008; Kopeliovich, Povh: hep-ph/9810530)





* Regge trajectory with intercept $\alpha_J(0) = 1/2$

* soft Reggeon exchange, no reason for pT-broadening in forward region

* does not link shift of bayon number in x_F to limiting fragmentation

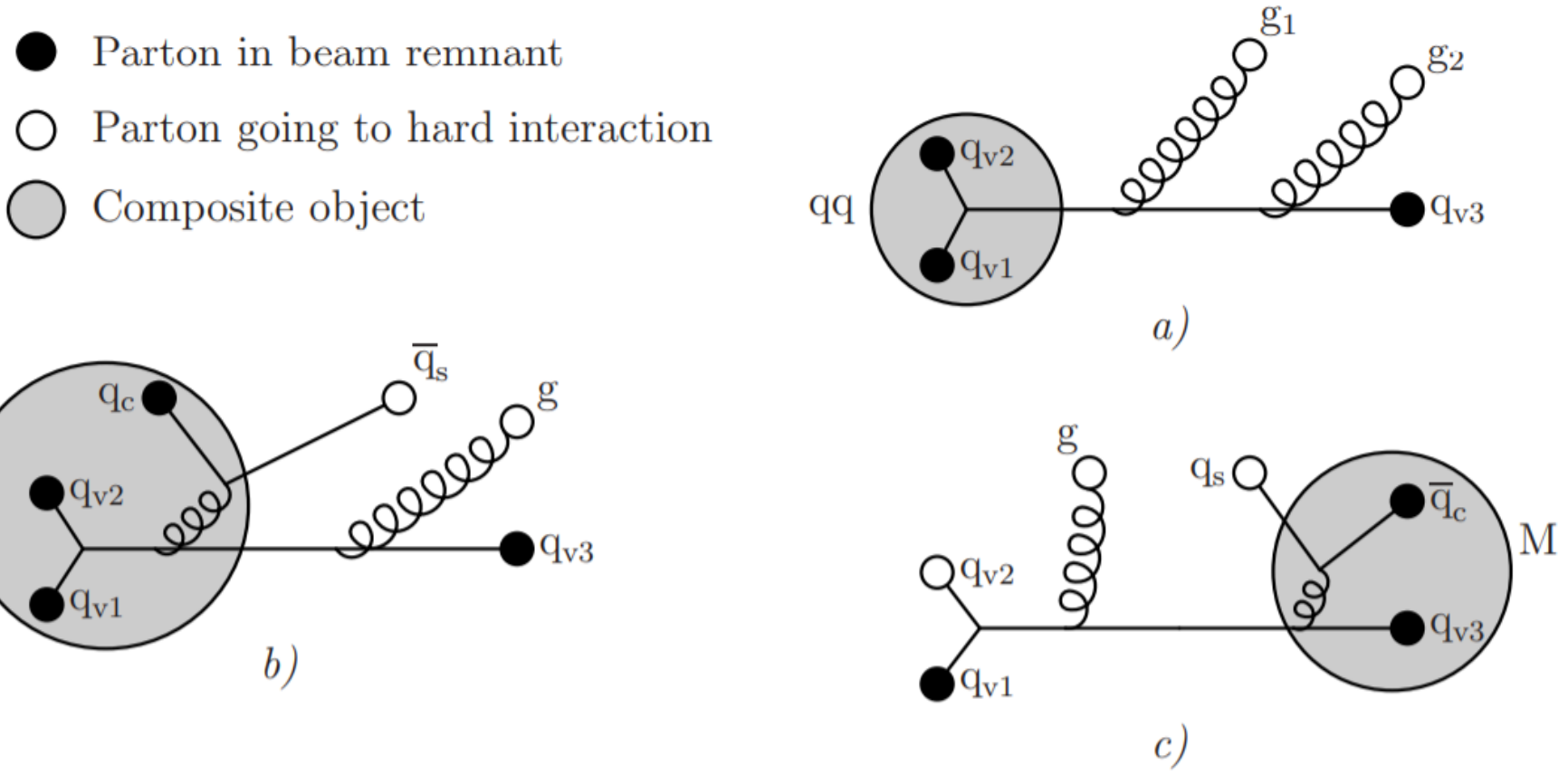
Regge trajectories of mesons vs. baryons ?

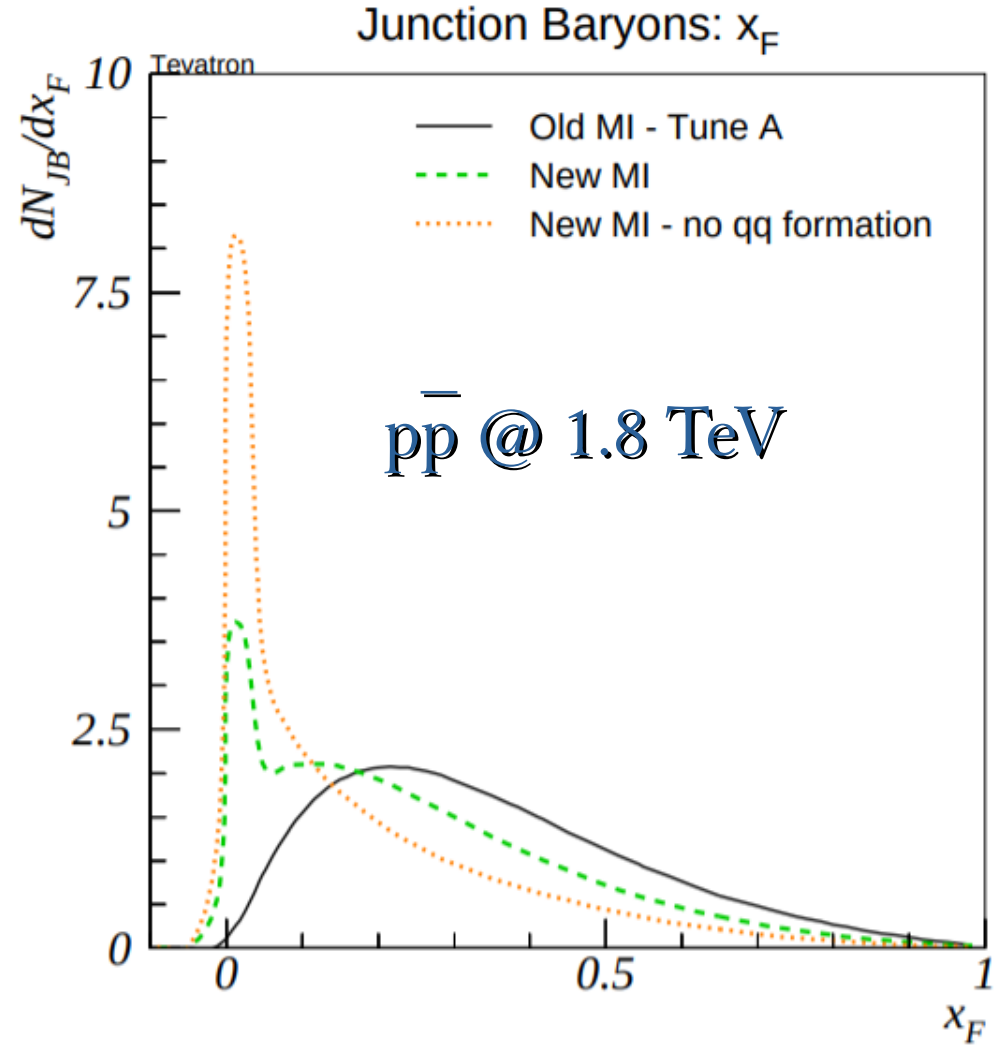
“For baryons we take either a sum of two-body potentials with half strength or a string of minimum length connecting the quarks, and find in both cases that the favoured configuration is a quark-diquark system and that the baryon and meson trajectories have the same slope.”

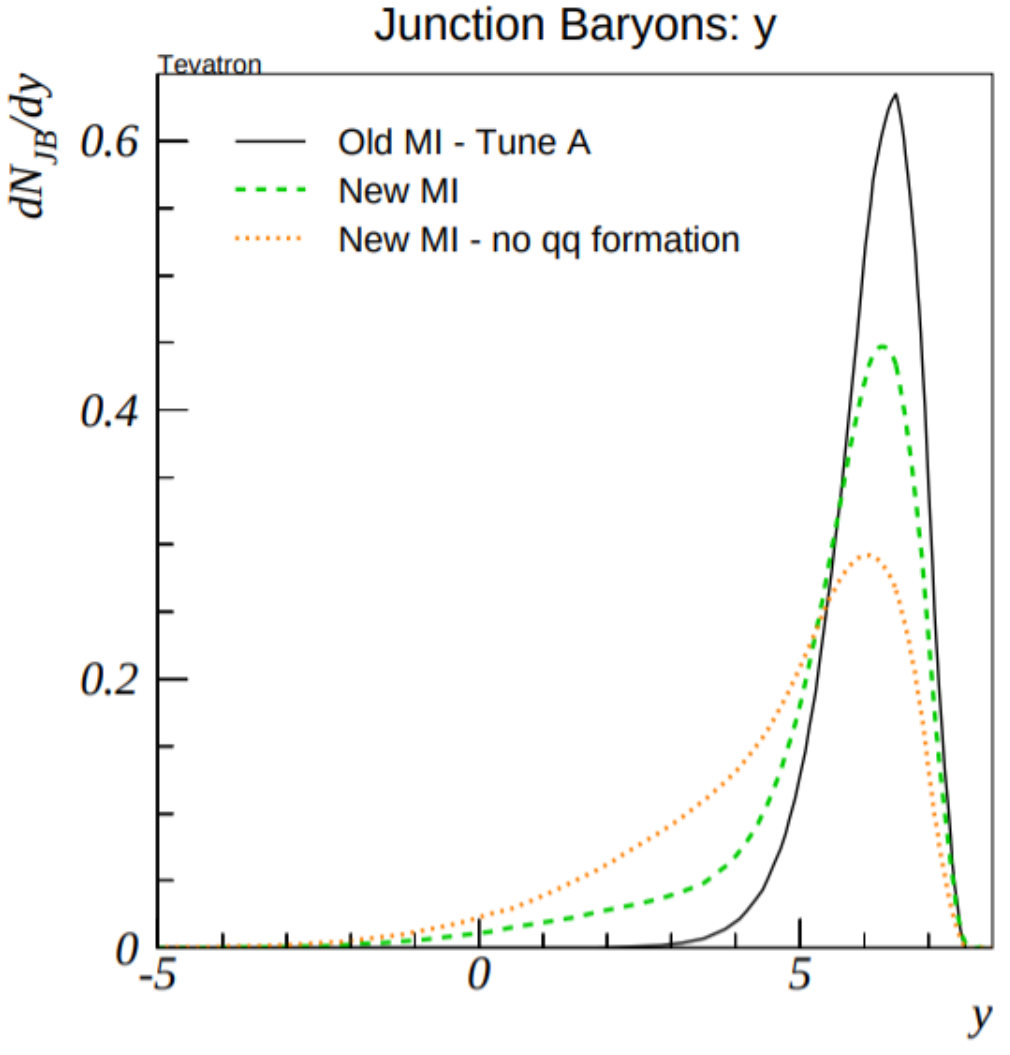
A. Martin, “REGGE TRAJECTORIES IN THE QUARK MODEL”, 21st Rencontres de Moriond, 1986
https://inspirehep.net/literature/220636

“Beam remnants” in Pythia, new model w/ multiparticle interactions:

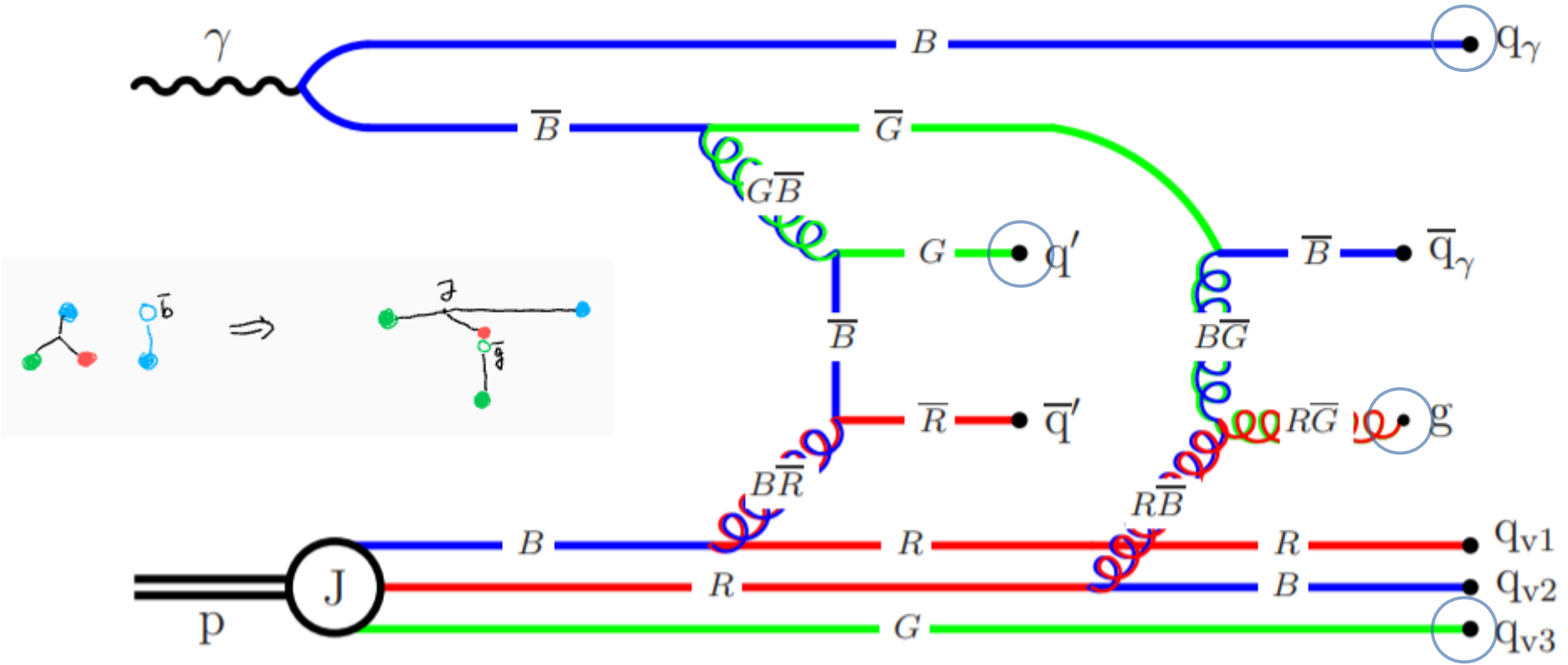
(Sjöstrand & Skands, hep-ph/0402078)




Junction Baryons: x_F
Tevatron
dN_{JB}/dx_F
10
7.5
5
2.5
0
0
0.5
1
x_F
Old MI - Tune A
New MI
New MI - no qq formation
$\bar{p}p$ @ 1.8 TeV

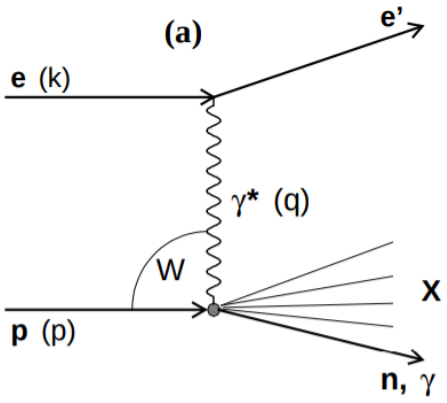

Junction Baryons: y
Tevatron
dN_{JB}/dy
0.6
0.4
0.2
0
-5
0
5
y
Old MI - Tune A
New MI
New MI - no qq formation

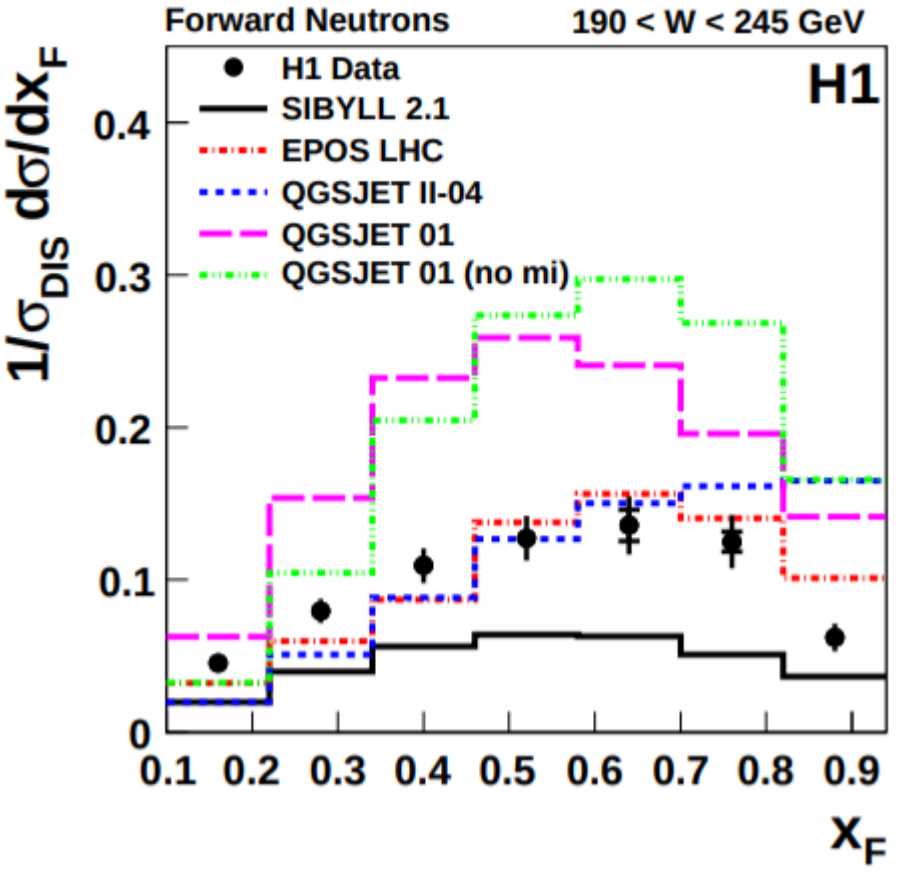
γ-p w/ double parton interaction in Pythia :



* The three circled quarks are at the endpoints of the strings that join in a junction (gluon viewed as a "kink" on the string)

Forward neutrons in DIS (H1 collab.: 1404.0201)





NC DIS Selection	
$6 < Q^2 < 100$ GeV^2	
$0.05 < y < 0.6$	
$70 < W < 245$ GeV	
Forward photons	**Forward neutrons**
$\eta > 7.9$	$\eta > 7.9$
$0.1 < x_F < 0.7$	$0.1 < x_F < 0.94$
$0 < p_T^* < 0.4$ GeV	$0 < p_T^* < 0.6$ GeV
W ranges for cross sections $\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dx_F}$	
$70 < W < 130$ GeV	
$130 < W < 190$ GeV	
$190 < W < 245$ GeV	

Recap : proton fragmentation in p-p, p-A, γ-p, γ-A

- proton structure
- unitarity (“high gluon density”) limit of QCD
- flavor composition of large-xF particles (s vs. q)

- diffractive vs. inelastic
- xF distribution of mesons, baryons
- pT broadening
- π-K, p-Λ separation