Proton fragmentation in high-energy collisions

(<u>fragmentation</u> region, not suppressed by power of energy)

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Motivation / interests :

- structure of baryons (val. quarks, diquarks, junctions, ...)
- baryon number "flow" (stopping, $Q \sim B$) 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)

typical inelastic p+p produces leading baryon \rightarrow (leading particle effect)

If the proton passes through a **strong** field it should "decay" into a beam of leading mesons \rightarrow *multi-parton scattering* !

Aside: this is not "stopping", $t \rightarrow -p_T^2$ at high E, light-cone momentum is conserved !

Proton fragmentation in pp / pA : (Yu. Dokshitzer, hep-ph/0106348, 0306287)





"leading particle effect" in min-bias $pp \rightarrow p+X$ at low energy





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

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

"... 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 $Q^2 = 1 \text{ GeV}^2$ "

- Combining "parton fragmentation picture" with strong color field QCD $p \rightarrow$ "beam of mesons" for z >~ 0.1 (A.D., Gerland, Strikman: hep-ph/0211324)
- * factorization formula:

TBK) $z\frac{d\sigma^{pA\to hX}}{dzd^{2}k_{t}d^{2}b} = \frac{1}{(2\pi)^{2}}\int dx \,\frac{x}{z}f_{q/p}(x,Q_{s}^{2})D_{h/q}\left(\frac{z}{x},Q_{s}^{2}\right)C\left(\frac{xk_{t}}{z}\right)$

* predicts "pT-broadening" of leading particle spectra

* "limiting fragmentation"
$$\mathbf{x}_{\mathrm{F}}$$
 distribution

$$\frac{d\sigma^{B-\overline{B}}}{dz \, d^2 b} = \int_{z}^{1} \frac{dx}{x} \left[f_{q/p}(x, Q_s^2) - f_{\overline{q}/p}(x, Q_s^2) \right] \\
\left[D_{B/q}(\frac{z}{x}, Q_s^2) - D_{\overline{B}/q}(\frac{z}{x}, Q_s^2) \right] \frac{d\sigma^{qA}}{d^2 b} \\$$
however, QCD scaling violations w/ variation of Qs²:
Mellin moments at unitarity
$$Q^2 \frac{\partial}{\partial Q^2} \langle z^N \rangle = 2\gamma (N+1, \alpha_s) \langle z^N \rangle$$

Mellin moments at unitarity



dipole scattering amplitude

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

$$\langle \operatorname{tr} V(\vec{x}) V^{\dagger}(\vec{y}) \rangle$$
$$V(\vec{x}) = \mathcal{P} e^{-ig \int dx^{+} A^{a-}(x^{+},\vec{x}) t_{\mathcal{R}}^{a}}$$

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



non-linear QCD evolution + "hybrid factorization" at NLO : comparison to LHCb data

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

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

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suppression at semi-hard pT ->
    Mark Strikman's "pT broadening"
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^f suppression of RpA and baryon xF-distribution in forward region are related phenomena



 p_T [GeV

• pPb, 4.0 < y < 4.3

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 ~ 75% ! (recall Dokshitzer's idea)

but diquark \rightarrow 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)



⇒leading mesons

- * Regge trajectory with intercept $\alpha_J(0) = \frac{1}{2}$ * Note: no "stopping" of valence charges
- * Note: no "stopping" of valence charges...
- * soft Reggeon exchange, not related to hard pT-broadening in forward region
- * does not link shift of bayon number in x_F to limiting fragmentation

"Beam remnants" in Pythia, new model w/ multiparticle interactions: (Sjöstrand & Skands, hep-ph/0402078)

Parton in beam remnant
Parton going to hard interaction
Composite object







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

also, recent paper by SUNY-SB group about DIS, 2312.15039

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

- proton structure (at moderate x)
- unitarity ("strong field / high gluon density") limit of QCD
 -> hard scale Qs, suppression of RpA, "limiting" fragmentation, shift of baryon charge would be related
- probes multi-parton scattering