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The Target Fragmentation Region of SIDIS: A Few Remarks

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Final hadrons in SIDIS are found not only in the Current Fragmentation Region, but also among the remnants of the struck target, i.e. in the **Target Fragmentation Region** (TFR)

The QCD description of TFR is based on the concept of **Fracture Function** (Trentadue, Veneziano (1994))

Fracture functions describe the **structure** of a nucleon when it **fragments** into a hadron. They are the conditional probabilities to find a quark with a given momentum inside a nucleon, when this emits a hadron

The formalism of polarized and TMD fracture functions has been developed in Anselmino, VB, Kotzinian (2011-12)

In the $\gamma^* N$ cm frame: $z_h \sim \frac{P_h^+}{q^+}$

The magnitude of P^+ determines the fragmentation region ($q^+ \sim Q$):

Current fragmentation region (CFR): $P_h^+ \sim Q \to z_h$ finite

Target fragmentation region (TFR): $P_h^+ \sim 0 \to z_h \to 0$

In terms of Feynman's variable $x_F = 2P_{h\parallel}/W$:

CFR corresponds to $x_F > 0$, TFR corresponds to $x_F < 0$ (γ^* in the $+z$ direction)

Explicitly, z_h is given by (in the $\gamma^* N$ cm frame):

$$z_h = \frac{E_h}{E(1-x_B)} \frac{1-\cos\theta}{2} \qquad \text{TFR}: \theta \to 0$$

Convenient variables for TFR:

$$z = \frac{E_h}{E(1-x_B)} \simeq |x_F|$$

$$\zeta = P_h^+/P^+ \simeq (1-x_B)\zeta \simeq (1-x_B)|x_F|$$

Separation of CFR and TFR

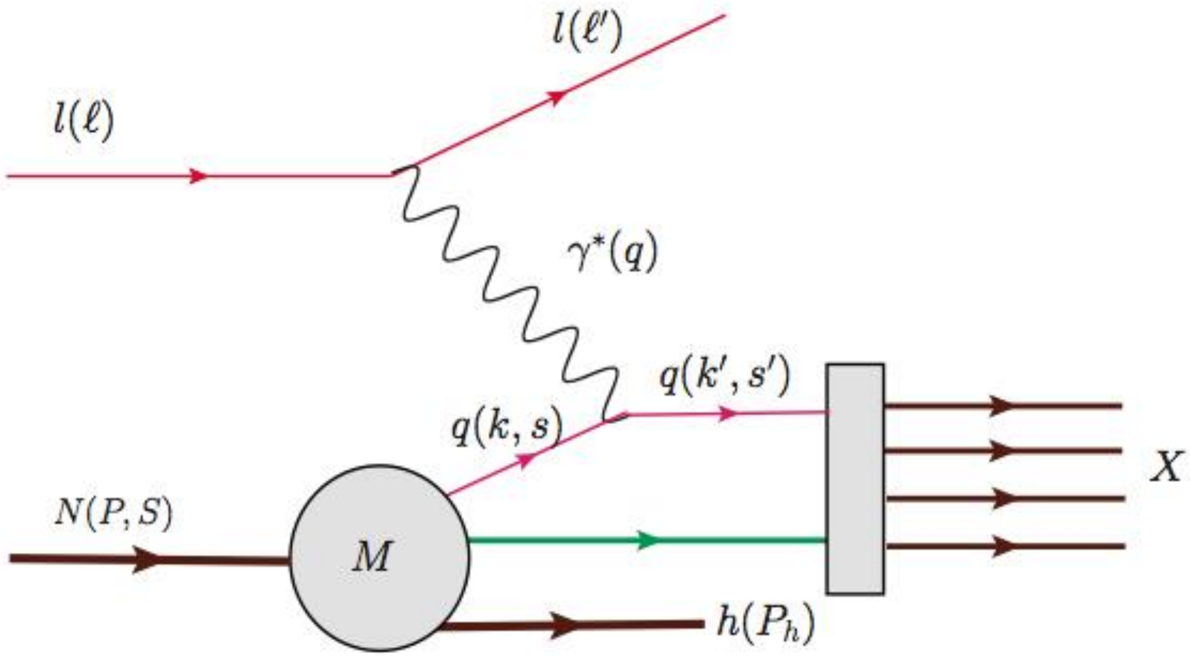
Rapidity separation between current and target fragments [Berger (1987)]:

$$\Delta y = \ln \frac{W^2}{M^2} = \ln \frac{Q^2(1 - x_B)}{x_B \, M^2}$$

If $\Delta y >$ few units (~ 4, but this number is somehow a guess), hadrons in the whole z_h range belong to CFR (this corresponds to $W > 7.4$ GeV)

For smaller W, a lower cut on z_h is needed in order to exclude hadrons produced in the TFR

JLab, HERMES, COMPASS require W larger than 2, 3, 5 GeV, respectively



Cross section : $$\frac{d\sigma^{\mathrm{TFR}}}{dx\,dy\,d\zeta} = \sum_a e_a^2\,(1-x)\,M_a(x,\zeta)\,\frac{d\hat{\sigma}}{dy}$$

Fracture Function

16 fracture functions (production of a spinless hadron)

Unpolarized fracture functions:

$$\mathcal{M}^{[\gamma^-]} = \hat{M} + \frac{\boldsymbol{P}_{h\perp} \times \boldsymbol{S}_\perp}{m_h}\, \hat{M}_T^h + \frac{\boldsymbol{k}_\perp \times \boldsymbol{S}_\perp}{m_N}\, \hat{M}_T^\perp + \frac{S_\parallel\, (\boldsymbol{k}_\perp \times \boldsymbol{P}_{h\perp})}{m_N\, m_h}\, \hat{M}_L^{\perp h}$$

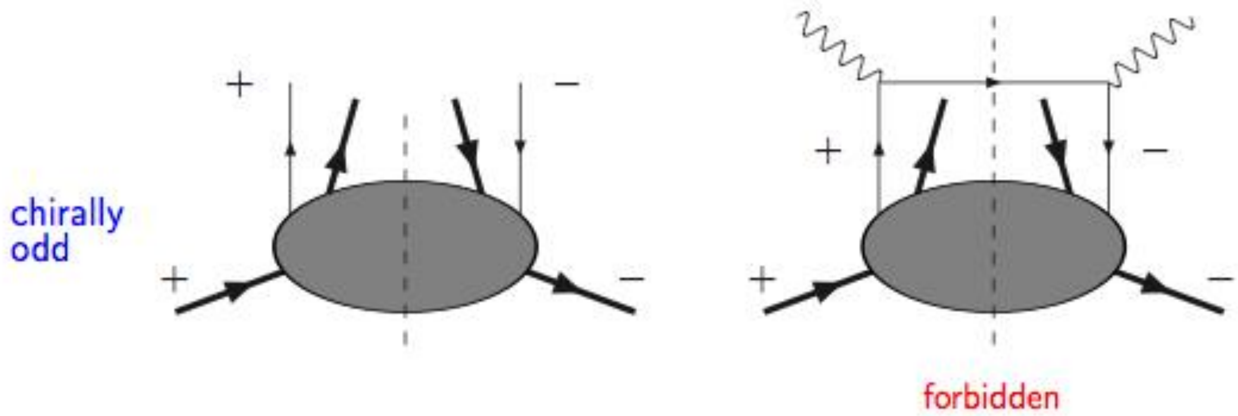
Longitudinally polarized fracture functions:

$$\mathcal{M}^{[\gamma^-\gamma_5]} = S_\parallel\, \Delta\hat{M}_L + \frac{\boldsymbol{P}_{h\perp} \cdot \boldsymbol{S}_\perp}{m_h}\, \Delta\hat{M}_T^h + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp}{m_N}\, \Delta\hat{M}_T^\perp + \frac{\boldsymbol{k}_\perp \times \boldsymbol{P}_{h\perp}}{m_N\, m_h}\, \Delta\hat{M}^{\perp h}$$

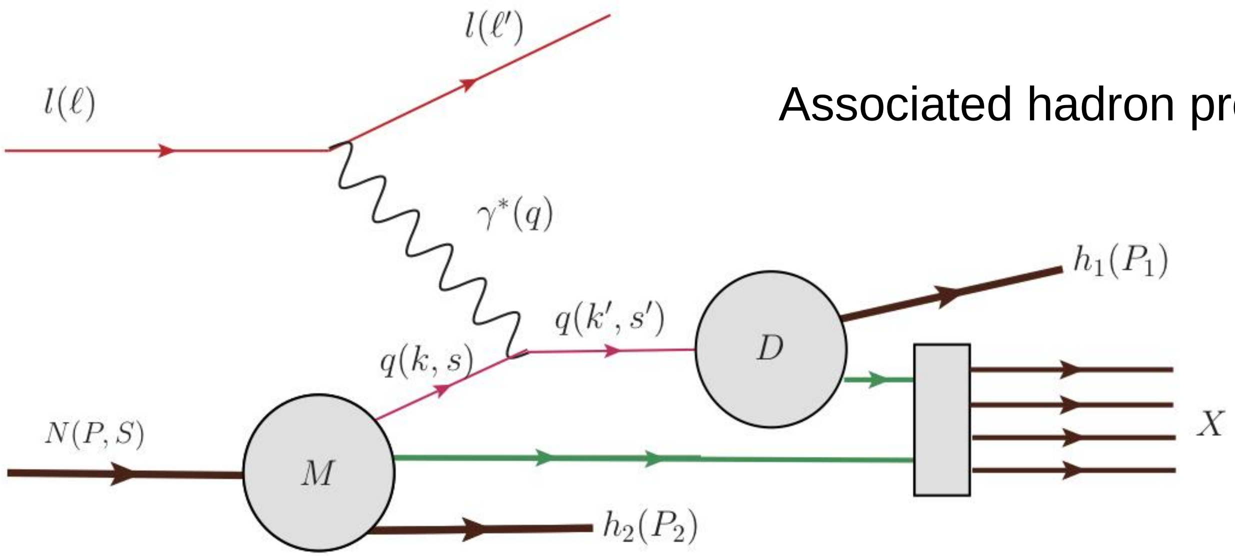
Transversely polarized fracture functions:

$$\begin{aligned}
\mathcal{M}^{[\mathrm{i}\,\sigma^{i-}\gamma_5]} \quad = \quad & S_\perp^i\, \Delta_T\hat{M}_T + \frac{S_\parallel\, P_{h\perp}^i}{m_h}\, \Delta_T\hat{M}_L^h + \frac{S_\parallel\, k_\perp^i}{m_N}\, \Delta_T\hat{M}_L^\perp \\
& + \frac{(\boldsymbol{P}_{h\perp} \cdot \boldsymbol{S}_\perp)\, P_{h\perp}^i}{m_h^2}\, \Delta_T\hat{M}_T^{hh} + \frac{(\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp)\, k_\perp^i}{m_N^2}\, \Delta_T\hat{M}_T^{\perp\perp} \\
& + \frac{(\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp)\, P_{h\perp}^i - (\boldsymbol{P}_{h\perp} \cdot \boldsymbol{S}_\perp)\, k_\perp^i}{m_N\, m_h}\, \Delta_T\hat{M}_T^{\perp h} \\
& + \frac{\epsilon_\perp^{ij}\, P_{h\perp j}}{m_h}\, \Delta_T\hat{M}^h + \frac{\epsilon_\perp^{ij}\, k_{\perp j}}{m_N}\, \Delta_T\hat{M}^\perp
\end{aligned}$$

Fracture functions of transversely polarized quarks are not probed in single-particle productiuon



Associated hadron production



Case I: spinless (or unpolarized) hadron production

Sivers-like

Unpolarized quarks

$$\mathcal{M}^{[\gamma^-]} = M(x,\zeta,\boldsymbol{P}_{h\perp}^2) + \frac{\boldsymbol{P}_{h\perp} \times \boldsymbol{S}_\perp}{m_h} M_T(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$\mathcal{M}^{[\gamma^-\gamma_5]} = S_\parallel \, \Delta M_L(x,\zeta,\boldsymbol{P}_{h\perp}^2) + \frac{\boldsymbol{P}_{h\perp} \cdot \boldsymbol{S}_\perp}{m_h} \Delta M_T(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

Longitudinally polarized quarks

g_{1T} like

Cross section for production of a spinless hadron in TFR

$$\frac{d\sigma^{\mathrm{TFR}}}{dx\,dy\,d\zeta\,d^2\boldsymbol{P}_{h\perp}\,d\phi_S} = \frac{2\alpha_{\mathrm{em}}^2}{Q^2 y}\left\{\left(1-y+\frac{y^2}{2}\right)\right.$$

$$\times\sum_a e_a^2\left[M(x,\zeta,\boldsymbol{P}_{h\perp}^2) - |\boldsymbol{S}_\perp|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,M_T(x,\zeta,\boldsymbol{P}_{h\perp}^2)\sin(\phi_h-\phi_S)\right]$$

$$+\lambda_l\,y\left(1-\frac{y}{2}\right)\sum_a e_a^2\left[S_\parallel\,\Delta M_L(x,\zeta,\boldsymbol{P}_{h\perp}^2)\right.$$

$$\left.\left.+\ |\boldsymbol{S}_\perp|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,\Delta M_T(x,\zeta,\boldsymbol{P}_{h\perp}^2)\cos(\phi_h-\phi_S)\right]\right\}$$

SIDIS cross section: at LT, 2 + 2 terms in TFR, 2 + 2 + 4 terms in CFR

$$\frac{d^6\sigma}{dx\,dy\,dz_h\,d\phi_h\,dP_{h\perp}^2\,d\phi_S} = \frac{\alpha_{em}^2}{xyQ^2}\Big\{(1-y+\frac{1}{2}y^2)\,F_{UU,T}$$

$$+(1-y)\,\cos 2\phi_h\,F_{UU}^{\cos 2\phi_h} + S_\parallel\,(1-y)\,\sin 2\phi_h\,F_{UL}^{\sin 2\phi_h} + S_\parallel\,\lambda_\ell\,y(1-\frac{1}{2}y)\,F_{LL}$$

$$+S_\perp\,\sin(\phi_h-\phi_S)\,(1-y+\frac{1}{2}y^2)\,F_{UT}^{\sin(\phi_h-\phi_S)} + S_\perp\,(1-y)\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+S_\perp\,(1-y)\,\sin(3\phi_h-\phi_s)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + S_\perp\,\lambda_\ell\,y(1-\frac{1}{2}y)\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big\}$$

Case II: polarized hadron production from an unpolarized target

Polarizing fracture function (Sivers 2009)

$$\mathcal{M}^{[\gamma^-]} = M(x, \zeta, \boldsymbol{P}_{h\perp}^2) + \frac{\boldsymbol{P}_{h\perp} \times \boldsymbol{S}_{h\perp}}{m_h} M^T(x, \zeta, \boldsymbol{P}_{h\perp}^2)$$

$$\mathcal{M}^{[\gamma^-\gamma_5]} = S_{h\|}\, \Delta M^L(x, \zeta, \boldsymbol{P}_{h\perp}^2) + \frac{\boldsymbol{P}_{h\perp} \cdot \boldsymbol{S}_{h\perp}}{m_h} \Delta M^T(x, \zeta, \boldsymbol{P}_{h\perp}^2)$$

Cross section for production of a polarized hadron in TFR from an unpolarized target

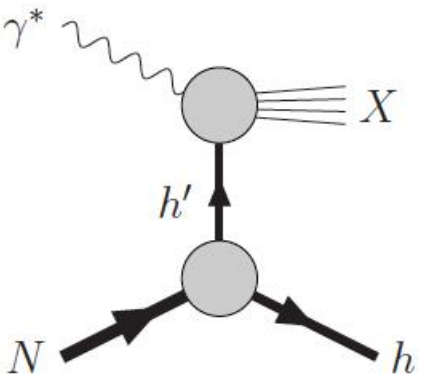
$$\frac{d\sigma^{\rm TFR}}{dx\,dy\,d\zeta\,d^2\boldsymbol{P}_{h\perp}\,d\phi_{S_h}} = \frac{2\alpha_{\rm em}^2}{Q^2 y}\left\{\left(1-y+\frac{y^2}{2}\right)\right.$$

$$\times \sum_a e_a^2 \left[M(x,\zeta,\boldsymbol{P}_{h\perp}^2) - |\boldsymbol{S}_{h\perp}|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,M^T(x,\zeta,\boldsymbol{P}_{h\perp}^2)\sin(\phi_h-\phi_{S_h})\right]$$

$$+\lambda_l\,y\left(1-\frac{y}{2}\right)\sum_a e_a^2\left[S_{h\parallel}\,\Delta M^L(x,\zeta,\boldsymbol{P}_{h\perp}^2)\right.$$

$$\left.\left. +\ |\boldsymbol{S}_{h\perp}|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,\Delta M^T(x,\zeta,\boldsymbol{P}_{h\perp}^2)\cos(\phi_h-\phi_{S_h})\right]\right\}$$

Meson-cloud model



The target nucleon fluctuates into a baryon-meson system

Structure function of hadron h'

↙

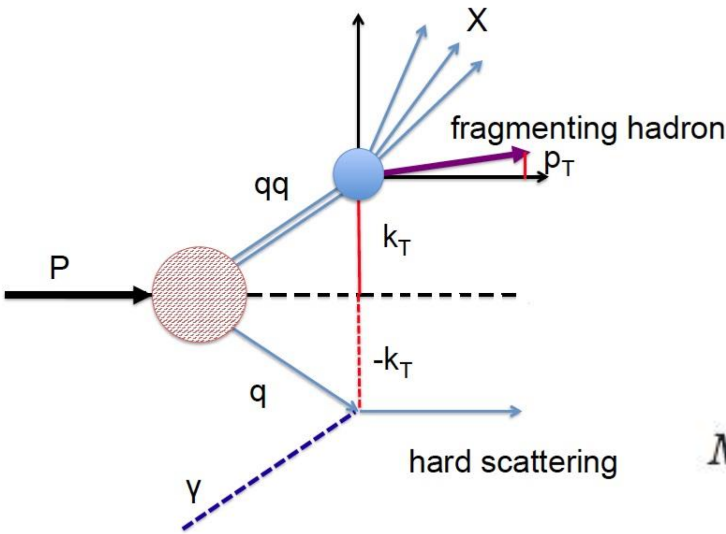
$$M_q^h(x,\zeta,P_{h\perp}^2) = \phi_{hh'}(\zeta,P_{h\perp}^2)\,F_q^{h'}\left(\frac{x}{1-\zeta}\right)$$

For instance, iπ^+ production in TFR involves the neutron structure function

Baryon production requires knowledge of meson structure functions

Spectator model for baryon production in TFR

(Goldstein, Liuti)



nucleon → quark – diquark

diquark → baryon - antiquark

$$M_q^h(x,\zeta,P_{h\perp}^2) = f_{qd}(x,\zeta,P_{h\perp}^2)\, D_d^h(x,\zeta,P_{h\perp}^2)$$

(Neglecting offshellness, the fracture function reduces to quark PDF × diquark fragmentation function)

(→ Ceccopieri)

Work in progress (Goldstein, Liuti, VB, Gonzalez)