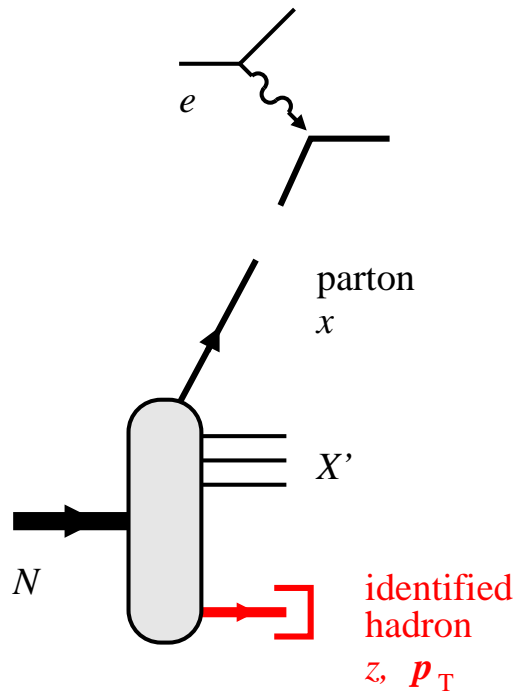


# Target fragmentation in DIS: Kinematics, factorization, structures

C. Weiss (JLab), Target fragmentation physics with EIC, CFNS Stony Brook, 29-Sep-2020



- Hadron production in high-energy scattering

Soft vs. hard interactions

Target fragmentation region?

- Variables

Rapidity  $\eta$ , Feynman  $x_F$ , light-cone fraction  $z$

- Target fragmentation in QCD

Factorization, conditional PDFs, evolution

Domain of applicability?

- Structures and dynamics

Hadronization dynamics

Spin/flavor effects, transverse momentum

Parton correlations  $\leftrightarrow$  chiral vacuum

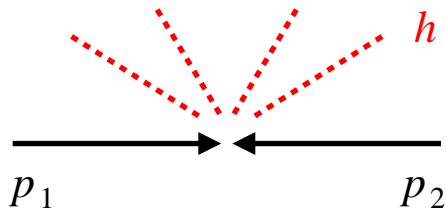
## This presentation:

Review concepts

Pose problem

Ask questions  $\leftarrow$

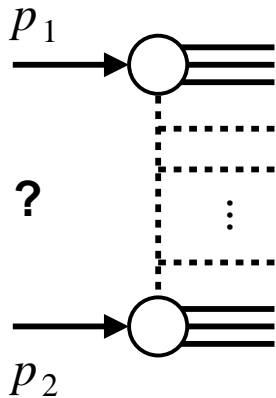
# Hadron production: Soft interactions



- High-energy scattering  $s \gg M_h^2$

Includes hadron-hadron,  $\gamma$ -hadron,  $\gamma^*$ -hadron

Hadron production  $\langle N_h \rangle \propto \log s$



- Tasks and questions

Explain pattern of hadron production!

Separate “structure of colliding objects” from “interactions”? Relativity, strong interactions...

- Soft interactions: Hadron-hadron scattering

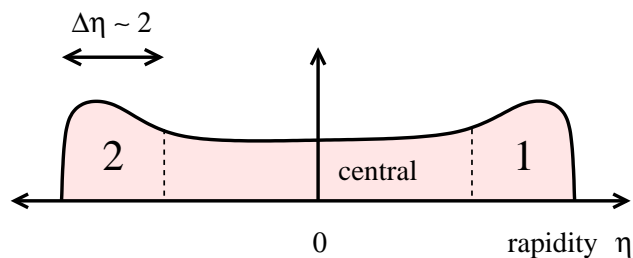
Interactions quasi-local in rapidity

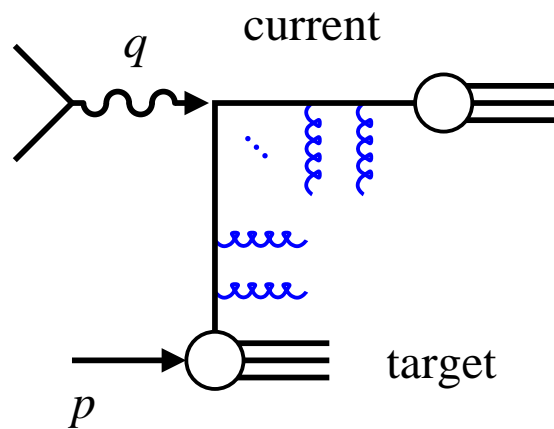
Symmetric situation

Natural separation: Hadron 2 – Central – Hadron 1

Hadron regions:  $\Delta\eta \sim 1-2$ , carry quantum numbers

Universality of hadron and central regions





- Hard interactions: DIS

QCD radiation associated with hard process

How does it materialize?

How does it influence hadron  $p_T$ ?

How does it change with  $Q^2$ ,  $W$ ?

Hadron structure described in partonic DoF

Connection with inclusive cross sections?

Universality?

Factorization theorems

- Target fragmentation region

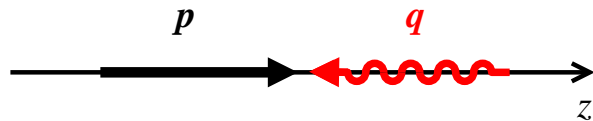
Is there a region of hadron production that can naturally be associated with “target structure”?

Non-symmetric situation current-target

Identified in context of factorization theorem → later

Quantitative criteria? Domain of applicability?

# Variables: Collinear frames



- Collinear frames

$$\mathbf{p} \parallel \mathbf{q}, \text{ along } z \text{ axis}$$

Class of frames related by longitudinal boosts

$$q^+ = -xp^+ \quad [\text{up to } O(M^2/Q^2)]$$

- Light-cone vector components

$$v^\pm = v^0 \pm v^z, \quad \mathbf{v}_T$$

Simple boosts  $v^\pm \rightarrow e^{\pm\bar{\eta}}v^\pm$ , boost rapidity  $\bar{\eta}$

- Special cases

Target rest frame

$$p^+ = M$$

Center-of-mass frame  $\gamma^*$ -target  $|\mathbf{p}| = |\mathbf{q}|$

$$p^+ = Q/\sqrt{x(1-x)}$$

Breit frame  $q^0 = 0$

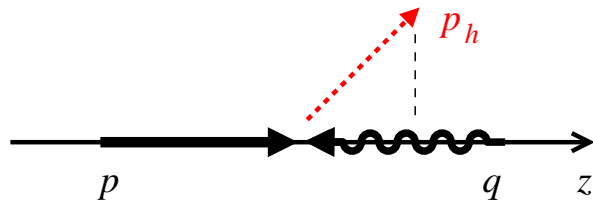
$$p^+ = Q/x$$

Cover all cases of interest for DIS final states. Transition simply by changing  $p^+$

[Event-by-event frames; momenta in detector depend on scattered electron kinematics]

# Variables: Hadron rapidity

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- Hadron rapidity

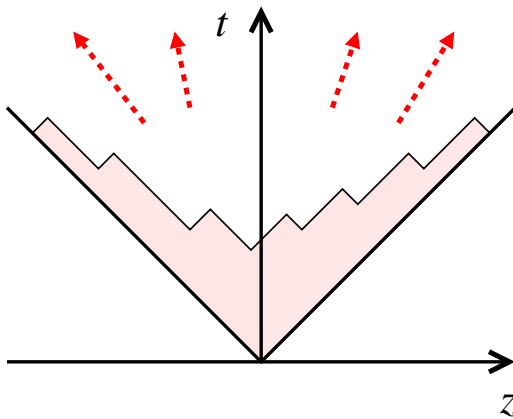
$$\eta_h = \frac{1}{2} \log \frac{p_h^+}{p_h^-} = \frac{1}{2} \log \frac{E_h + p^z}{E_h - p^z}$$

Boost-covariant  $\eta_h \rightarrow \eta_h + \bar{\eta}$

- Rapidity in soft interactions

Soft string fragmentation produces hadrons with constant average density in rapidity

Simple energy evolution: Self-similar

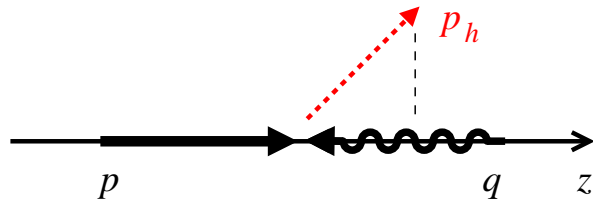


- Rapidity in DIS

Used in TMD factorization in current fragmentation region

Collins 11 → Talk Rogers/Prokudin

How to define target fragmentation region?  
 $\Delta\eta = \text{const}$ ? How large? Growing  $\propto \log W$ ?



- Feynman variable  $x_F$

$$x_F = \frac{p_h^z}{p_h^z(\text{max})} \quad \text{in CM frame } |\mathbf{p}| = |\mathbf{q}|$$

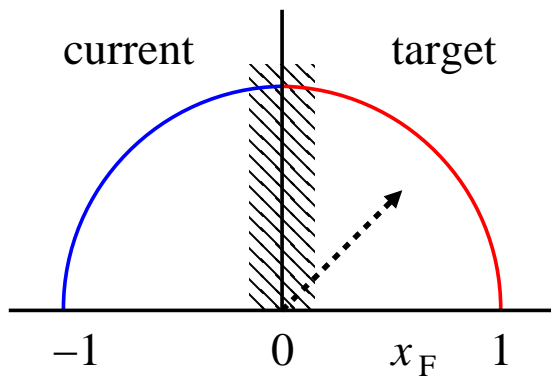
$$-1 \leq x_F \leq 1$$

[Here  $\mathbf{p}$  in positive,  $\mathbf{q}$  in negative direction]

- $x_F$  in soft interactions

Feynman scaling hypothesis:

$$dN_h = \mathcal{F}(x_F, p_{Th}) d^2 p_{Th} dp_h^z / \epsilon_h$$



- $x_F$  in DIS

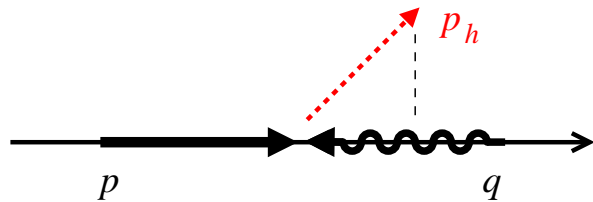
Suggests separation based on  $x_F < 0, > 0$

Not natural for non-symmetric  $\gamma^*$ -target situation

Target fragmentation region  $x_F \sim 1$ . Lower limit?

# Variables: Hadron light-cone momentum

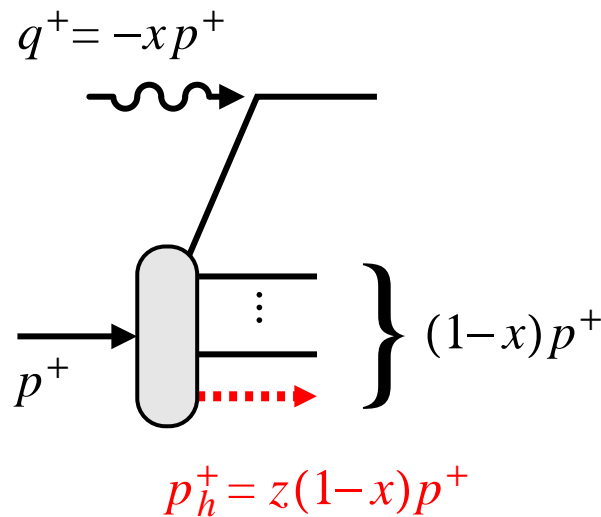
- Light-cone momentum of produced hadron



$$z = \frac{p_h^+}{(1-x)p^+} = \frac{\text{hadron}}{\text{remnant}}$$

Virtual photon removes  $-xp^+$  from target, remnant system carries  $(1-x)p^+$

$z \approx x_F$  simple relation (if not  $z, x_F \ll 1$ )



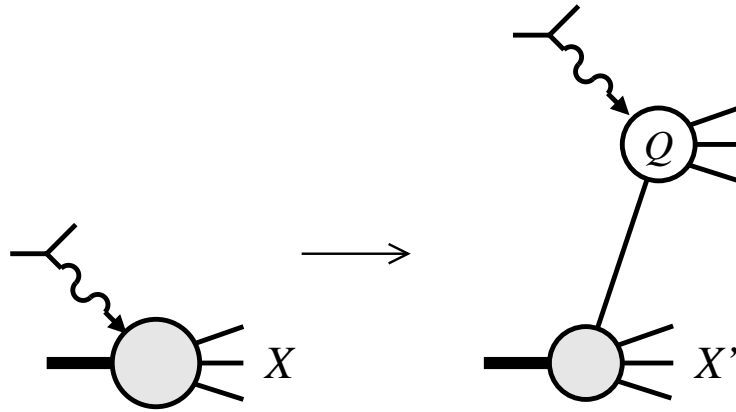
- Light-cone momentum variable in DIS

Natural variable in parton picture

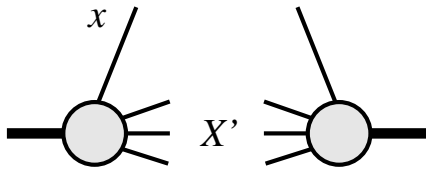
Target fragmentation region  $z = O(1)$

Practical lower limit?

[Note: The variable  $z$  used here is **not the same** as the SIDIS energy fraction  $z = E_h/\nu$ ]



$$\sigma = f(x) \times \sigma_{\text{hard}}(x, Q^2)$$



$$f(x) = \sum_{X'} \int d^2 k_T \langle P | a^\dagger | X' \rangle \langle X' | a | P \rangle_{k^+ = xP^+}$$

[Naive expression: renormalization, gauge invariance...]

- Factorization

DIS limit  $W^2 \sim Q^2 \gg \mu_{\text{had}}^2$

Separate scales  $Q^2 \gg \mu_{\text{had}}^2$

$\sigma_{\text{hard}}$  calculable in pQCD

QCD radiation with  $\mu_{\text{had}}^2 \lesssim p_T^2 \lesssim Q^2$

- Parton distribution PDF

Light-cone momentum density in target, probabilistic interpretation

QCD radiation:  $\log Q^2$  dependence, DGLAP evolution

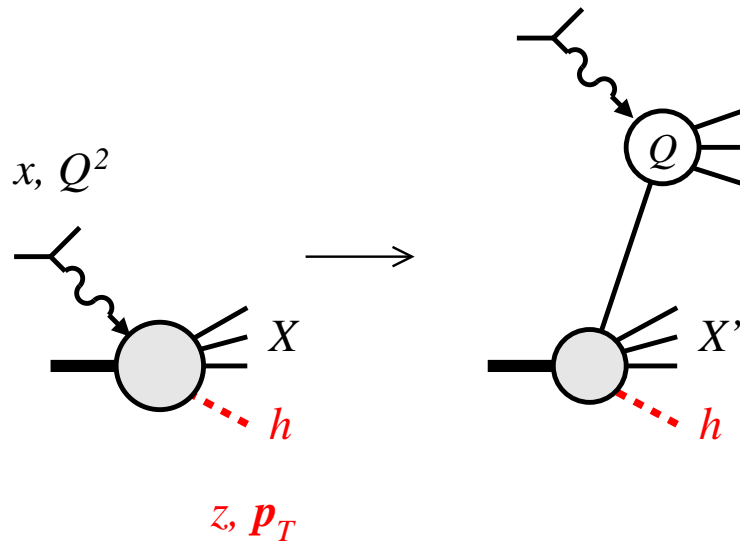
- Universality

PDF independent of hard process

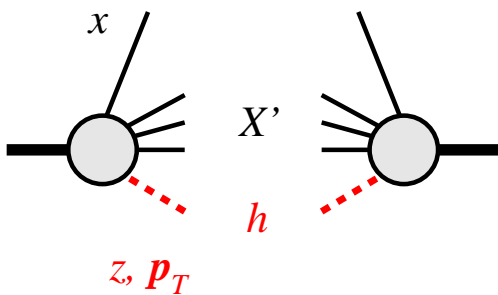
Same in  $\nu N \rightarrow X$ ,  
 $NN \rightarrow X + \text{jets, dileptons}$



# Factorization: Target fragmentation



$$\sigma = f_h(x; \beta, p_T) \times \sigma_{\text{hard}}(x, Q^2)$$



$$f_h(x; \beta, p_T) = \sum_{X'} \int d^2 k_T \langle P | a^\dagger | h X' \rangle \langle h X' | a | P \rangle_{k^+ = x P^+}$$

- Factorization

Trentadue, Veneziano 94; Collins 98

$\sigma_{\text{hard}}$  same as in inclusive

$Q^2$  scaling for fixed  $z, p_T \ll Q$   
Can be tested experimentally

- Conditional parton distribution cPDF

Alt. Fracture function

Probability to find hadron with  $z, p_T$  after removing parton with  $x$

DGLAP evolution, same as PDF:  
Increasing active parton resolution does not change its interactions with remnant

Independent of hard process - universal

Expresses target structure and hadronization dynamics

# Factorization: Region of applicability

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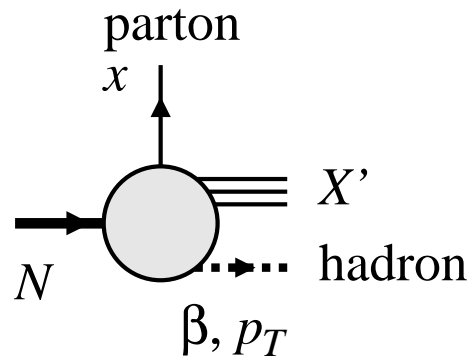
**Q:** In what kinematic domain of  $z$  (or  $x_F$ , rapidity, ...) can the factorized approximation to conditional DIS factorization be applied?

Theoretical arguments based on space-time evolution, e.g. Breit frame?

Experimental data from HERA, EMC, COMPASS, JLab12? → Talk Avakian

→ “Practical definition” of target fragmentation region!

Question for discussion!



- cPDF is object in itself

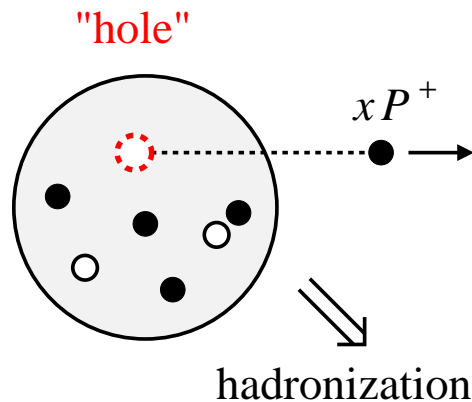
Defined by factorization theorem, universal

Can be extracted from data

→ Talk Ceccopieri

- Use to explore structure and dynamics

Hadronization of nucleon with "hole"  
in partonic wave function

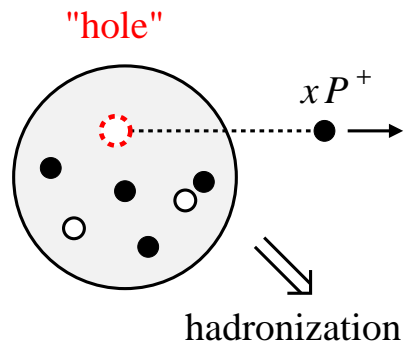


Dynamics of hadronization:  
Chiral vacuum structure, color connections, . . . ?

Charge/spin/flavor dependence?

Parton correlations?

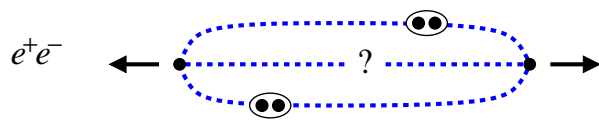
[Mesonic degrees of freedom?]



- What dynamics governs nucleon fragmentation?

Color forces: Range, mechanism?

Chiral symmetry breaking:  $q\bar{q}$  pair condensate, effective spin-flavor interactions?

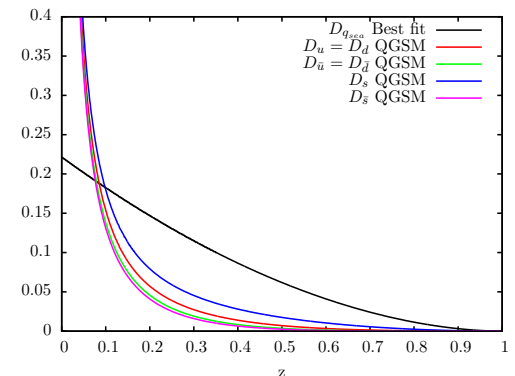
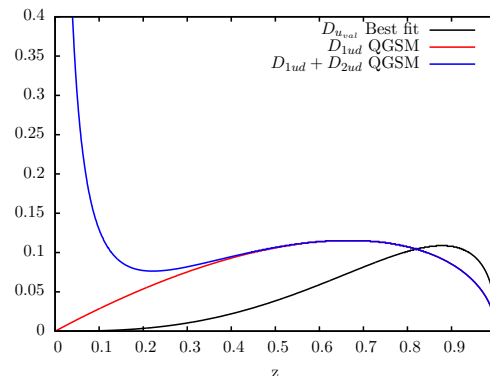
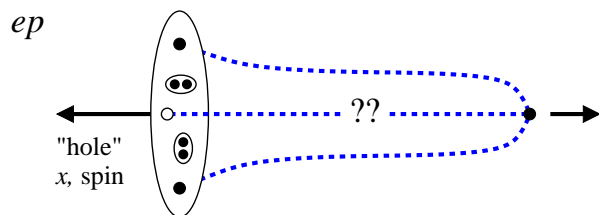


- String fragmentation model

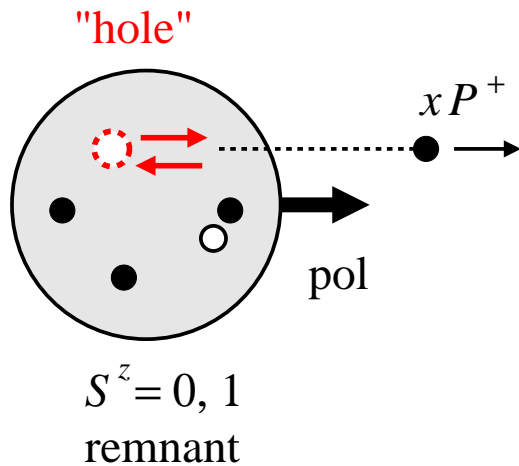
Andersson et al 80's. Basic template for color neutralization

$e^+e^-$   $q\bar{q}$  string

$e^+N$   $q(qq)$  string



$\Lambda$  production cPDFs from neutrino and DIS data [Ceccopieri, Mancusi 12]. Strong discrepancy with string-based model [Kaidalov Piskounova]



- Polarized DIS leaves remnant system with definite spin

Study spin dependence of hadronization at fixed  $x$  and  $z$

- Observables sensitive to remnant spin

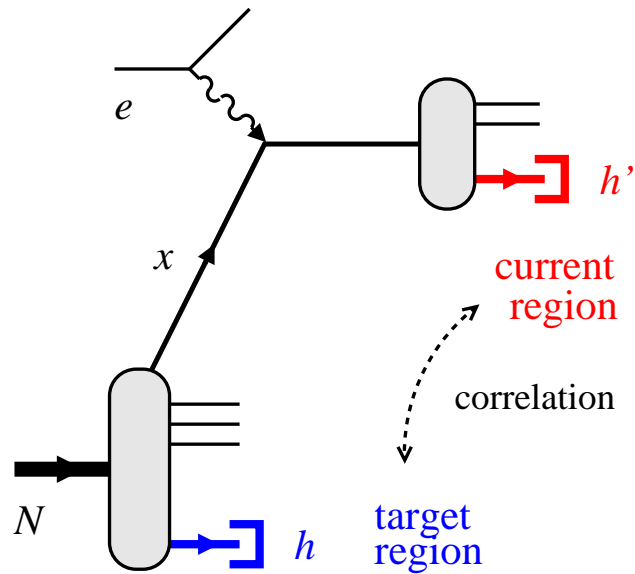
$\Delta-N$  production ratio [Strikman 13](#)

Polarized  $\Lambda$  production

- Azimuthal asymmetries in target fragmentation with beam/target spin  
[Anselmino, Barone, Kotzinian 11](#)

$$\frac{d^5\sigma}{dx dQ^2 dz_h dp_{hT} d\phi_h} = [\dots] + \sum_n [\dots] \cos n\phi_h + \sum_m [\dots] \sin m\phi_h$$

$T$ -even and  $T$ -odd structures, cf. SIDIS in current fragmentation region

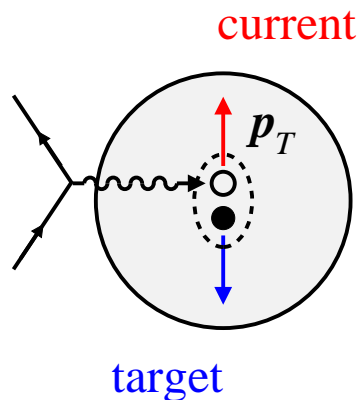


- Control charge/ flavor of removed quark through current fragmentation hadrons

Singlet–nonsinglet separation with  $\pi^+ \pm \pi^-$

Antiquarks with current antiprotons (?)

Strangeness with  $K^+, K^-$



- Beyond collinear:  $p_T$  dependent correlations

Sea quarks in correlated pairs of size  $\rho_{\text{chiral}} \ll 1 \text{ fm}$

Back-to-back correlations between current and target hadrons

Schweitzer, Strikman, Weiss 11 → Talk Schweitzer

Dynamical origin of intrinsic  $p_T$ ?

## Target fragmentation region in DIS:

Fragmentation regions in DIS not naturally symmetric as in soft interactions

Target fragmentation region identified in several variables: rapidity,  $x_F$ , light-cone fraction

Target fragmentation region defined parametrically in factorization theorem

What are the numerical boundaries? Need dynamical arguments. . .

## Conditional PDFs:

Defined through factorization theorem, universal = process-independent

Leading-twist objects, DGLAP evolution = same as PDFs

Contain rich information about nucleon structure and hadronization dynamics

Need realistic model-building to guide studies. . .