

Inclusive jets and dynamical mass effects

Alberto Accardi

Hampton University and Jefferson Lab

DIS 2021: The XXVIII International Workshop
on Deep-Inelastic Scattering and Related Subjects

April 13, 2021

Some references:

A [selection of references](#) related to the topics discussed in this talk:

- ▶ On the connection between quark propagation and hadronization

A. Accardi, A. Signori - 2005.11310 - EPJC

- ▶ Quark fragmentation as a probe of dynamical mass generation

A. Accardi, A. Signori - 1903.04458 - PLB

- ▶ Accessing the nucleon transverse structure in deep-inelastic scattering

A. Accardi, A. Bacchetta - 1706.02000 - PLB

- ▶ Collinear factorization for deep inelastic scattering structure functions at large Bjorken x_B

A. Accardi, J.W. Qiu - 0805.1496 - PRD

Outline

Introduction

Inclusive jets

Hadronization and mass generation

Semi-inclusive processes

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Hadron physics

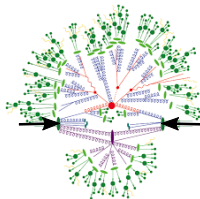
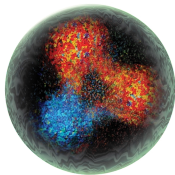
Hadron physics \leftrightarrow (non-)perturbative QCD

The two faces of confinement:

- ▶ **hadron structure (tomography):** hadron \rightarrow quark/gluon transition
- ▶ **hadronization:** hadron \leftarrow quark/gluon transition

Motivations:

- ▶ **conceptual:** understand QCD, in particular confinement, dynamical breaking of chiral symmetry
- ▶ **practical:** reactions involving hadrons in the initial and/or final state

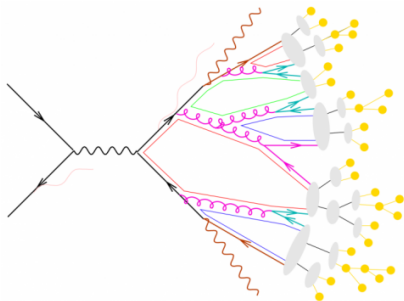


Fragmentation and jet functions

Hadronization: dynamical generation of hadronic properties from quarks/gluons
→ fundamental topic

It follows QCD hard scattering and populates the final states with hadrons

Maps of hadronization: fragmentation functions (FFs) and Jet Functions (JF):

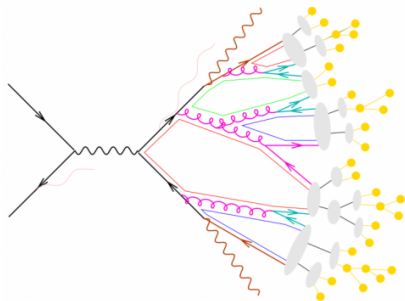


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Maps of hadronization: fragmentation functions (FFs) and Jet Functions (JF):



Momentum and energy distributions:

$D_1^{a \rightarrow h}(z)$: collinear FF

$D_1^{a \rightarrow h}(z, P_T^2)$: TMD FF

$J_a(s)$: inclusive jet function

$\mathcal{G}^{a \rightarrow h}(s, z)$: fragmenting jet function

...

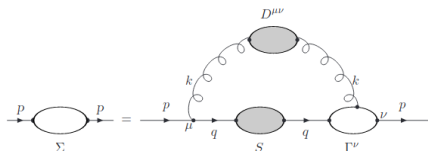
The generation of mass in QCD

What generates the masses of partons and hadrons?

- ▶ Higgs mechanism, only quark masses: $m_q \sim \text{MeV} \ll M_{p/n} \sim 1 \text{ GeV}$
- ▶ the rest comes from the **dynamics of QCD** \rightarrow **dynamical mass**

The dynamical generation of mass in QCD can be addressed in different ways:

- ▶ gap equation
e.g. in the NJL model of QCD: $M_q = m_q - 4G_\pi \langle \bar{q}q \rangle \gg m_q$
- ▶ Energy Momentum Tensor \rightarrow hadron mass decomposition
- ▶ “mass sum rule” for **fragmentation functions** - **new and observable!**



Outline

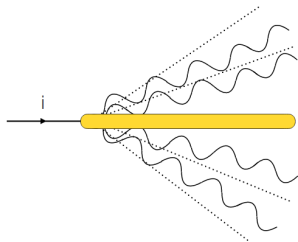
Introduction

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Hadronization and mass generation

Semi-inclusive processes

Inclusive jets



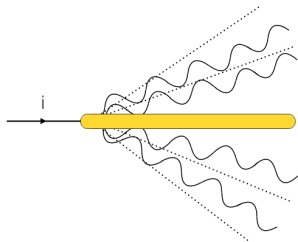
Inclusive jet function $J_i(s)$:
sensitive to the jet virtuality s

“Composition” of the jet:

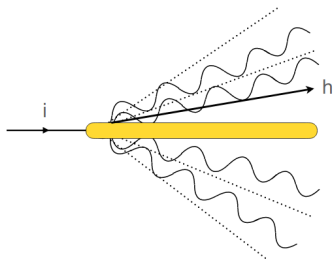
- ▶ perturbative radiation (large s , wiggles)
- ▶ non-perturbative radiation (low s , dashed lines)
- ▶ non-perturbative quark propagation (yellow blob) ← today's focus

Inclusive jets and FJFs

Procura, Stewart 0911.4980 - PRD
Jain, Procura, Waalewijn 1101.4953 - JHEP



Inclusive jet function $J_i(s)$:
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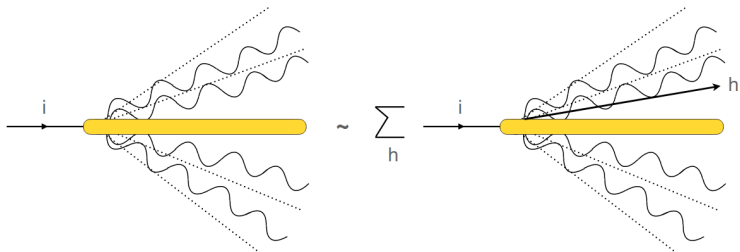


Fragmenting jet function (FJF) $\mathcal{G}^{i \rightarrow h}(s, z)$:
sensitive to jet virtuality s
and hadron momentum fraction z
(less inclusive)

Inclusive jets and FJFs

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Sum rule!



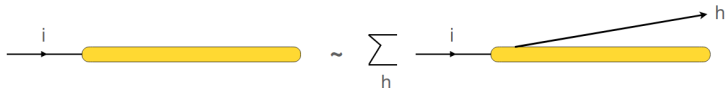
$$J_i(s) = \frac{1}{2(2\pi)^3} \sum_h \int dz z \mathcal{G}^{i \rightarrow h}(s, z)$$

Connection between the unpolarized jet function and FJFs :
jet as the “inclusive” limit of the in-jet fragmentation

Inclusive jets and 1h-FFs

Accardi, Signori 1903.04458 - PLB
Accardi, Signori 2005.11310 - EPJC

In a similar way, one can interpret the gauge-invariant quark propagator (aka *inclusive jet correlator*) as the *inclusive limit* of the *1h-fragmentation correlator*:

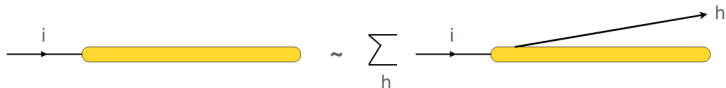


$$k^\mu \Xi^i(k) = \sum_{h, S_h} \int \frac{d^4 P_h}{(2\pi)^3} \delta(P_h^2 - M_h^2) P_h^\mu \Delta^{i \rightarrow h}(k, P_h, S_h)$$

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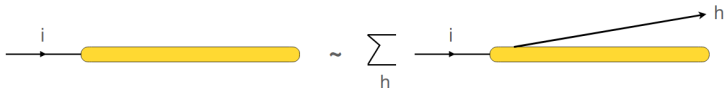
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Unpolarized Dirac projection: momentum sum rule for $D_1(z)$
corresponds to sum rule between $J_i(s)$ and $\mathcal{G}^{i \rightarrow h}(s, z)$
at the **leading order** and **integrated** over the jet virtuality s .

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Novelty: consider **all the Dirac projections up to twist 3**
and connect **1h-FFs** to the **non-perturbative properties** of the **quark propagator**.

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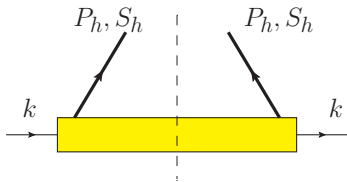
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Semi-inclusive processes

Quark 1h-FFs

$$\Delta_{ij}(k, P_h, S_h) = \int \frac{d^4\xi}{(2\pi)^4} e^{ikx} \frac{\text{Tr}_c}{N_c} \langle \Omega | \hat{T} W_1(\infty, \xi) \psi_i(\xi) a^\dagger a \bar{\psi}_j(0) W_2(0, \infty) | \Omega \rangle$$



		quark pol.		
		U	L	T
hadron pol.	U	D_1		H_1^\perp
	L		G_{1L}	H_{1L}^\perp
	T	D_{1T}^\perp	G_{1T}	H_1, H_{1T}^\perp

8 (TMD) fragmentation functions at leading twist

Quark higher twist 1h-FFs

Twist 3 transverse momentum dependent FFs $\mathcal{D}_{\dots}^{a \rightarrow h}(z, P_{h\perp}^2)$
for a quark hadronizing into a spin 1/2 hadron

		quark pol.		
		U	L	T
hadron pol.	U	D^\perp	G^\perp	E, H
	L	D_L^\perp	G_L^\perp	H_L, E_L
	T	D_T, D_T^\perp	G_T, G_T^\perp	$H_T, H_T^\perp, E_T, E_T^\perp$

Black and magenta: survive transverse momentum integration

Red and magenta: T-odd

Blue: T-even, w/o collinear counterpart

Quark propagator

Källén-Lehman representation in terms of **spectral functions** $\rho_{1,3}$:

$$\Xi(k) \rightarrow S_F(k) = \int \frac{d\mu^2}{(2\pi)^4} \{ \not{k} \rho_3(\mu^2) + \sqrt{\mu^2} \rho_1(\mu^2) \mathbb{I} \} \frac{\theta(\mu^2)}{k^2 - \mu^2 + i\epsilon}$$

Quark propagator

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Projecting the operator sum rule between Ξ^i and $\Delta^{i \rightarrow h}$ one obtains:

twist 2 (γ^-):

$$\sum_h \int_0^1 dz z D_1^h(z) = \int_0^{+\infty} d\mu^2 \rho_3(\mu^2) \equiv 1 \quad (\text{QFT!})$$

twist 3 (\mathbb{I}):

$$\sum_h \int_0^1 dz M_h E^h(z) = \int_0^{+\infty} d\mu^2 \sqrt{\mu^2} \rho_1(\mu^2) \equiv M_j$$

The **non-perturbative** structure of the **jet** is **trivial** at **twist 2**, **but not at twist 3!**

Hadronization and mass generation

“Mass sum rule” for twist 3 E fragmentation function:

$$\sum_h \int dz M_h E^h(z) = M_j$$

quark/jet dynamical mass M_j as the average of produced hadron masses weighted by chiral-odd E FF

Hadronization and mass generation

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QCD equations of motions: $E^h = \tilde{E}^h + \frac{m_q}{M_h} z D_1^h$

Wandzura-Wilczek (WW) approximation: $\tilde{E}^h = 0 \implies M_j = m_q$

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Full QCD: $M_j = m_q + m_q^{corr}$ (current and dynamical components), where

$$\sum_h \int dz M_h \tilde{E}^h(z) = M_j - m_q = m_q^{corr}$$

\tilde{E} and m_q^{corr} probe quark-gluon-quark $\sim \langle 0 | \bar{\psi} A \psi | 0 \rangle$ dynamical correlations

Hadronization and mass generation

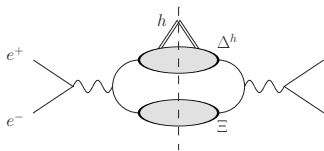
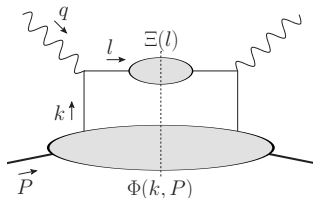
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quark/jet dynamical mass M_j as the average of produced hadron masses weighted by chiral-odd E FF

Quark/jet mass M_j and its dynamical component m_q^{corr} :

- ▶ related to the “mass function” from the QCD gap equation
- ▶ gauge invariant and **observable**
- ▶ **contribute to physical observables** at twist 3 in the chiral-odd sector



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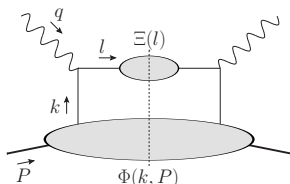
(Semi)-inclusive processes

- ▶ We can study the phenomenology of the dynamical mass in (semi-) inclusive hard processes
- ▶ interesting but challenging: **chiral-odd** sector at least at **twist-3**

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- ▶ **Inclusive DIS** in collinear factorization :

$$\ell N^\dagger \rightarrow \ell j X: h_1(x) \otimes m_q^{corr}$$



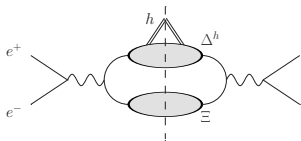
dynamical mass coupled to the transversity PDF

A. Accardi, A. Bacchetta - 1706.02000 - PLB

(Semi)-inclusive processes

- ▶ We can study the phenomenology of the dynamical mass in (semi-) inclusive hard processes
- ▶ interesting but challenging: **chiral-odd** sector at least at **twist-3**
- ▶ **Semi-Inclusive Annihilation** in collinear factorization :

$$e^+e^- \rightarrow h^\uparrow j X: H_1(z) \otimes m_q^{corr}$$



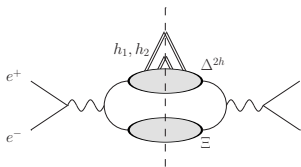
(Accardi, Signori et al. - in progress)

$$\frac{d\sigma^L(e^+e^- \rightarrow h^\uparrow X)}{d\Omega dz} = \frac{3\alpha^2}{Q^2} \lambda_e \sum_a e_a^2 \left\{ \frac{C(y)}{2} \lambda_h G_{1L}(z) \right. \\ \left. + D(y) |\mathbf{S}_T| \cos(\phi_S) \frac{2M_h}{Q} \left(\frac{G_T(z)}{z} + \frac{m_q^{corr}}{M_h} H_1(z) \right) \right\}$$

(Semi)-inclusive processes

- ▶ We can study the phenomenology of the dynamical mass in (semi-) inclusive hard processes
- ▶ interesting but challenging: **chiral-odd** sector at least at **twist-3**
- ▶ **Semi-Inclusive Annihilation** in collinear factorization :

$$e^+e^- \rightarrow \{h_1 h_2\} X: H_1^{\triangleleft} \otimes m_q^{corr}$$



Also requires lepton polarization

Accardi, Signori et al. - work in progress

Conclusions

- ▶ Hadronization \longrightarrow a **fundamental** aspect of QCD
- ▶ The **non-perturbative structure of inclusive jets** can be related to the properties of the quark propagator, in particular to the normalization of the **spectral functions**

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- ▶ At **twist three** the non-perturbative structure emerges as a **mass term** with a current and a **dynamical** component (explicit and dynamical CSB)
- ▶ This mass is **gauge-invariant** (see EPJC article) ...
- ▶ ...and the dynamical component **can be accessed** at twist three in scattering experiments and via momentum sum rules for twist three FFs

Conclusions

- ▶ Hadronization \longrightarrow a **fundamental** aspect of QCD
- ▶ The **non-perturbative structure of inclusive jets** can be related to the properties of the quark propagator, in particular to the normalization of the **spectral functions**
- ▶ At **twist three** the non-perturbative structure emerges as a **mass term** with a current and a **dynamical** component (explicit and dynamical CSB)
- ▶ This mass is **gauge-invariant** (see EPJC article) ...
- ▶ ...and the dynamical component **can be accessed** at twist three in scattering experiments and via momentum sum rules for twist three FFs
- ▶ The connection to IJFs at LO is tantalizing and under exploration

Backup

Useful references/1:

A selection of useful references related to inclusive jets and dynamical mass effects:

- ▶ Fully unintegrated parton correlation functions and factorization in lowest order hard scattering
J.C. Collins, T.C. Rogers, A.M. Stasto - 0708.2833
- ▶ Collinear factorization for deep inelastic scattering structure functions at large Bjorken x_B
A. Accardi, J.W. Qiu - 0805.1496
- ▶ Quark fragmentation as a probe of dynamical mass generation
A. Accardi, A. Signori - 1903.04458
- ▶ On the connection between quark propagation and hadronization
A. Accardi, A. Signori - 2005.11310
- ▶ Accessing the nucleon transverse structure in deep-inelastic scattering
A. Accardi, A. Bacchetta - 1706.02000

Useful references/2:

A selection of useful references dealing with fragmentation functions, inclusive jets in pQCD, e^+e^- annihilation:

- ▶ Parton fragmentation functions (review)

A. Metz, A. Vossen - 1607.02521

- ▶ Quark fragmentation within an identified jet

M. Procura, I. Stewart - 0911.4980

- ▶ Parton fragmentation within an identified jet at NNLL

A. Jain, M. Procura, W. Waalewijn - 1101.4953

- ▶ Asymmetries in polarized hadron production in e^+e^- annihilation up to order $1/Q$

D. Boer, R. Jakob, P.J. Mulders - hep-ph/9702281

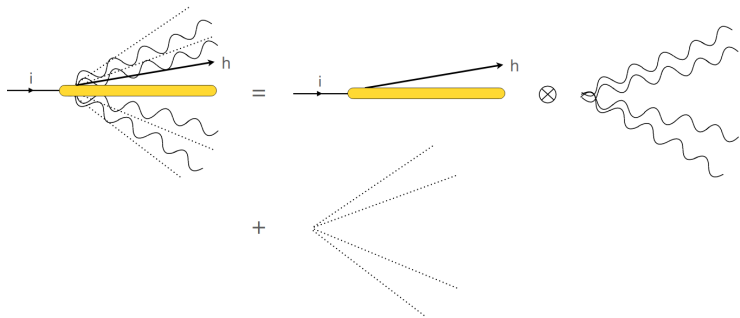
- ▶ Angular dependences in inclusive two-hadron production at Belle

D. Boer - 0804.2408

FJFs and 1h-FFs

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Jain, Procura, Waalewijn 1101.4953 - JHEP

Separating radiation and non-perturbative fragmentation:

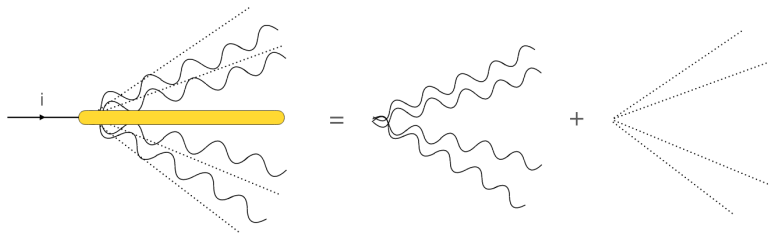


$$\mathcal{G}^{i \rightarrow h}(s, z) = \sum_j \mathcal{J}_{ij}(s, z) \otimes D_1^{j \rightarrow h}(z) + \mathcal{O}(\Lambda_{qcd}^2 s^{-1})$$

Large- s expansion of the unpolarized FJF \mathcal{G}
on the single-hadron collinear FF D_1

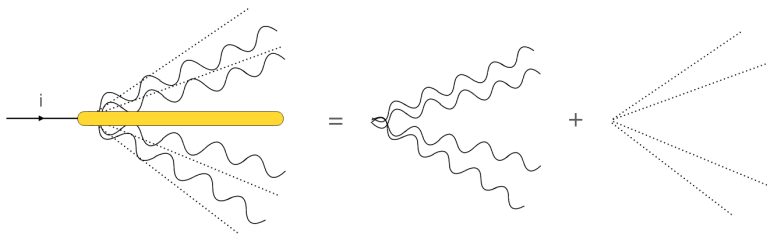
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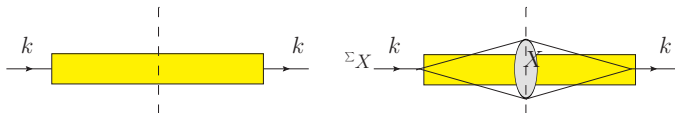


$$J_i(s) = \frac{1}{(2\pi)^3} \sum_j \int_0^1 du u \mathcal{J}_{ij}(s, u) + \mathcal{O}(\Lambda_{qcd}^2 s^{-1})$$

At **twist 2** the jet function $J_i(s)$ “**decouples**” from the 1h-FF $D_1(z)$ and the **non-perturbative structure** gets **simplified**

The cut quark propagator

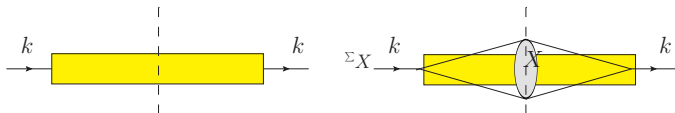
$$\Xi_{ij}(k; v) = \text{Disc} \int \frac{d^4\xi}{(2\pi)^4} e^{ikx} \frac{\text{Tr}_c}{N_c} \langle \Omega | \hat{T} W_1(\infty, \xi; v) \psi_i(\xi) \bar{\psi}_j(0) W_2(0, \infty; v) | \Omega \rangle$$



- ▶ **Partonic picture:** gauge invariant dressed quark correlator
 - ▶ only the discontinuity is considered \rightarrow on-shellness
 - ▶ the color is neutralized

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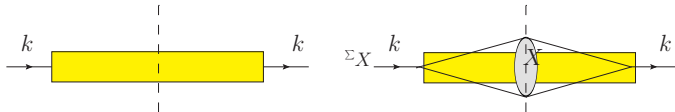
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- ▶ **Hadronic picture:** “fully inclusive jet” correlator
 - ▶ X : the complete set of hadronization products crossing the cut
 - ▶ no hadrons are measured
 - ▶ the scale is defined by the end-point kinematics

The cut quark propagator

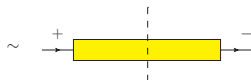
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 - ▶ X : the complete set of hadronization products crossing the cut
 - ▶ no hadrons are measured
 - ▶ the scale is defined by the end-point kinematics
- ▶ insights into **dynamical generation** of mass and momentum and **chiral symmetry** breaking

The quark/jet mass

$$M_j(k^-) \sim \int dk^+ \text{Tr}_D [\Xi \mathbb{I}]$$

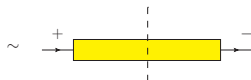


Mass associated with the scalar term (**chiral-odd**) of the cut quark propagator:

- ▶ inclusive “**jet mass**” or color-screened dressed **quark mass**

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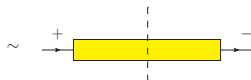
- ▶ inclusive “**jet mass**” or color-screened dressed **quark mass**

In the light-cone gauge we can relate it to the chiral-odd spectral function for the quark propagator:

$$M_j = \int_0^{+\infty} d\mu^2 \sqrt{\mu^2} \rho_1^{l_{cg}}(\mu^2)$$

The quark/jet mass

$$M_j(k^-) \sim \int dk^+ \text{Tr}_D [\Xi \mathbb{I}]$$



Mass associated with the scalar term (chiral-odd) of the cut quark propagator:

- ▶ inclusive “jet mass” or color-screened dressed quark mass

In the light-cone gauge we can relate it to the chiral-odd spectral function for the quark propagator:

$$M_j = \int_0^{+\infty} d\mu^2 \sqrt{\mu^2} \rho_1^{l_{cg}}(\mu^2)$$

This mass term:

- ▶ gauge-invariant
- ▶ renormalization scale dependent
- ▶ calculable via the spectral functions of the cut quark propagator
- ▶ accessible via momentum sum rules for twist-3 FFs

Semi-inclusive processes

- ▶ We can study the phenomenology of the dynamical mass in (semi-) inclusive hard processes
- ▶ interesting but challenging: **chiral-odd** sector at least at **twist-3**
- ▶ working in collinear factorization :
 - ▶ (?) $pp^\uparrow \rightarrow h_1 h_2 j X \xrightarrow[\text{sum rule}]{\text{mass}} f_1(x_1) \otimes h_1(x_2) \otimes D_1(z) \otimes m_q^{\text{corr}}$
(fixed-target configuration at LHC)
- ▶ (?) potentially also TMD factorization
- ▶ in order to make quantitative predictions and extractions the factorization of these processes has to be addressed