Inclusive jets and dynamical mass effects

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University of Pavia and Jefferson Lab

9^{th} workshop of the APS topical Group on Hadronic Physics (GHP)

April 15, 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

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- 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

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

Hadron physics

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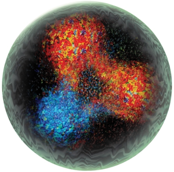
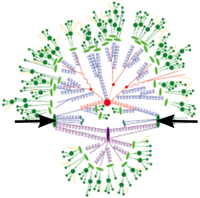
Motivations:

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



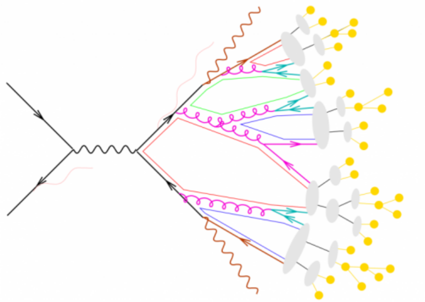


Fragmentation functions

Hadronization: dynamical generation of hadronic properties from quarks/gluons $\rightarrow$ fundamental topic

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

Maps of hadronization in momentum space: fragmentation functions (FFs)



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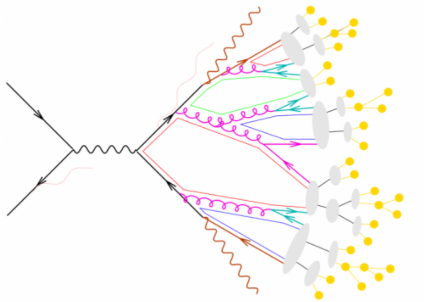

Momentum distributions:

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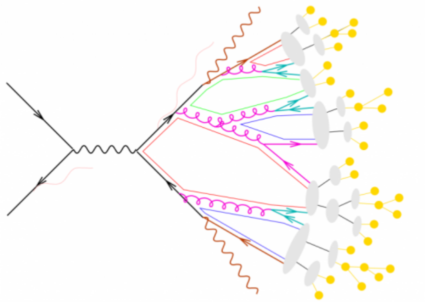

Momentum distributions:

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

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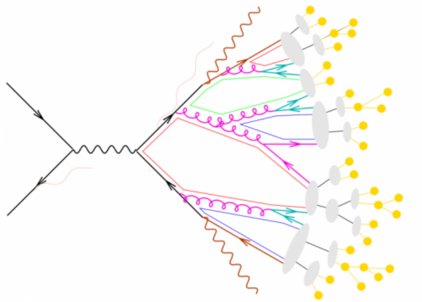

Momentum distributions:

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

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

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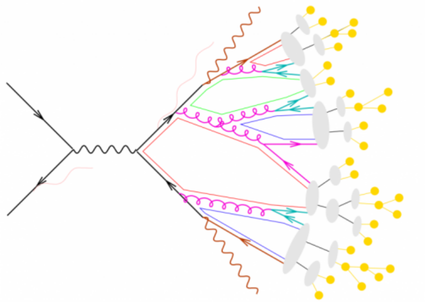

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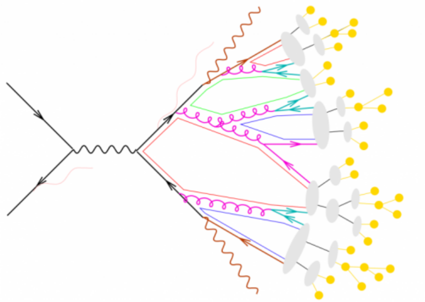

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$\mathcal{G}^{a\rightarrow h}(s, z)$: fragmenting jet function

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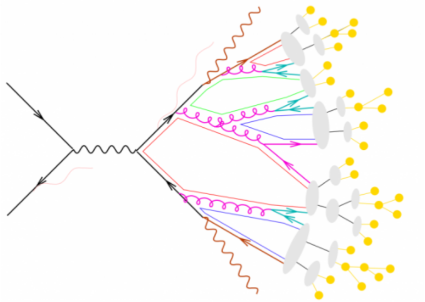

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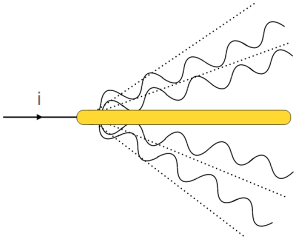
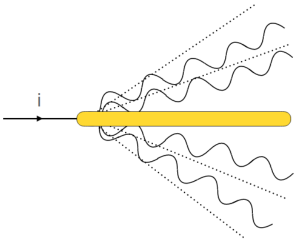
Inclusive jets



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

Inclusive jets



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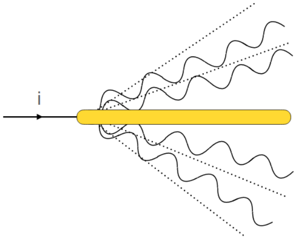
"Composition" of the jet:

- perturbative radiation (large s, wiggles)

Inclusive jets



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"Composition" of the jet:

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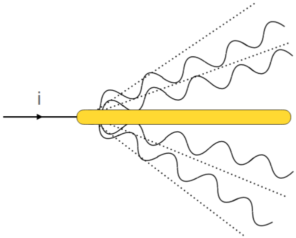
Inclusive jets



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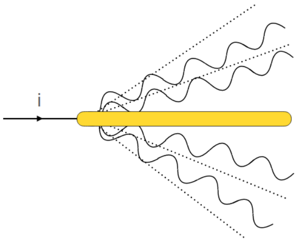
- non-perturbative radiation (low s, dashed lines)
- non-perturbative quark propagation (yellow blob)

Inclusive jets



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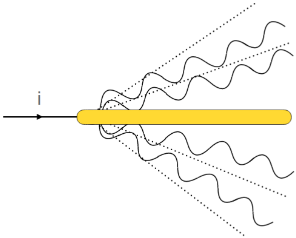
"Composition" of the jet:

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

Inclusive jets and FJFs

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



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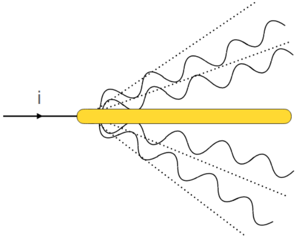

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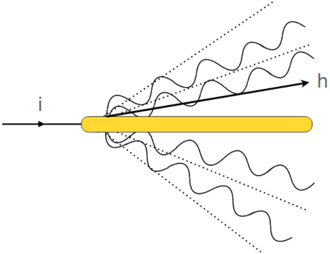

Fragmenting jet function (FJF) $\mathcal{G}^{i\to h}(s,z)$:
sensitive to jet virtuality s
and hadron momentum fraction z
(less inclusive)

Inclusive jets and FJFs

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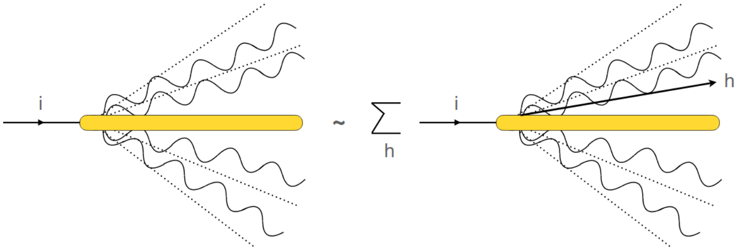

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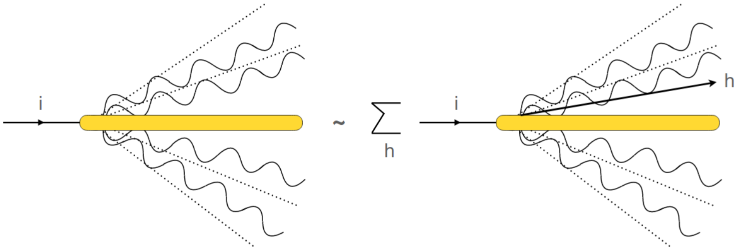


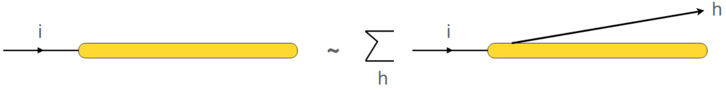
$$J_i(s) = \frac{1}{2(2\pi)^3} \sum_h \int dz\, z\, \mathcal{G}^{i\to h}(s,z)$$

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

Inclusive jet *correlator* (quark propagator) $\longleftrightarrow$ 1h-fragmentation *correlator*



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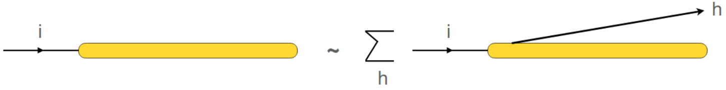

$$k^\mu \, \Xi^i(k) = \sum_{h,S_h} \int \frac{d^4 P_h}{(2\pi)^3} \, \delta(P_h^2 - M_h^2) \, P_h^\mu \, \Delta^{i \to h}(k, P_h, S_h)$$

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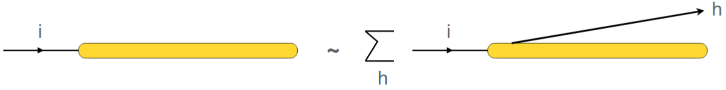

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Dirac projections: momentum sum rule for FFs

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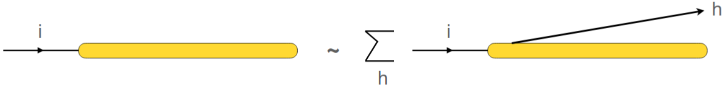

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Dirac projections: momentum sum rule for FFs

unpolarized case: $\sum_{h,S} \int dz \, z \, D_1^h(z) = 1$

$\equiv$ sum rule between $J_i(s)$ and $\mathcal{G}^{i\to h}(s,z)$ at leading order, integrated over s

Quark propagator

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

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

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twist 2 (γ^-):

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

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

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

Quark/jet mass

"Mass sum rule" for twist 3 E fragmentation function:

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

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

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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* $\sim \langle 0|\overline{\psi} A \psi|0\rangle$ *dynamical correlations*

FJFs and 1h-FFs

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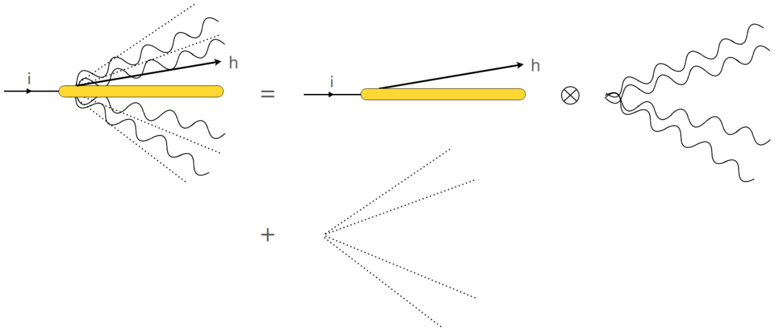

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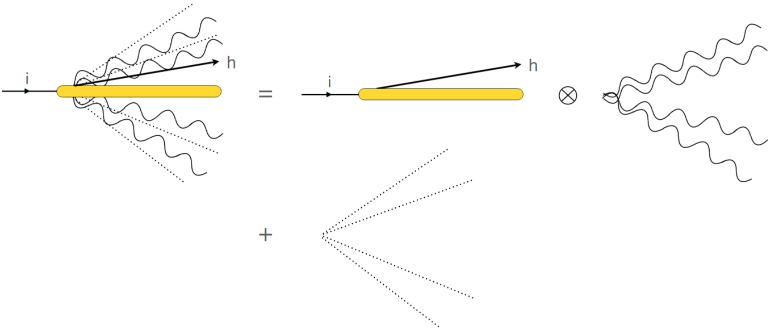

$$\mathcal{G}^{i\to h}(s,z) = \sum_j \mathcal{J}_{ij}(s,z) \otimes D_1^{j\to h}(z) + \mathcal{O}(\Lambda_{qcd}^2\, s^{-1})$$

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

Twist two jets

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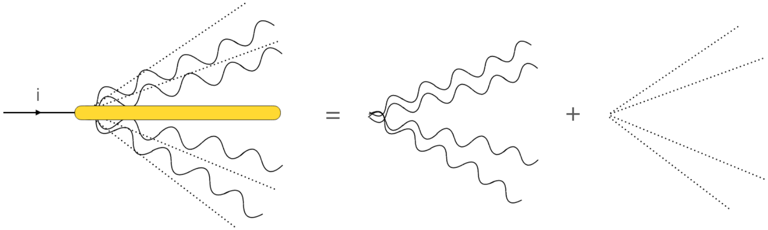

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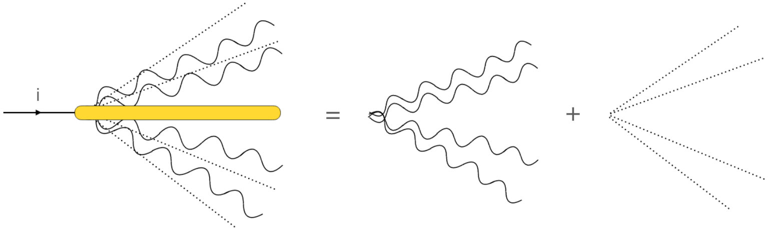

$$J_i(s) = \frac{1}{2(2\pi)^3} \sum_h \int dz\, z\, \mathcal{G}^{i\to h}(s,z) \qquad \text{(sum rule for } D_1\text{)}$$

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

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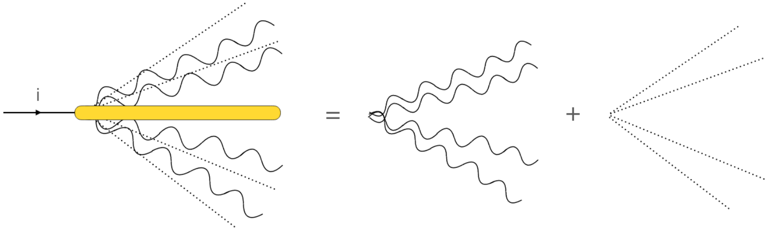

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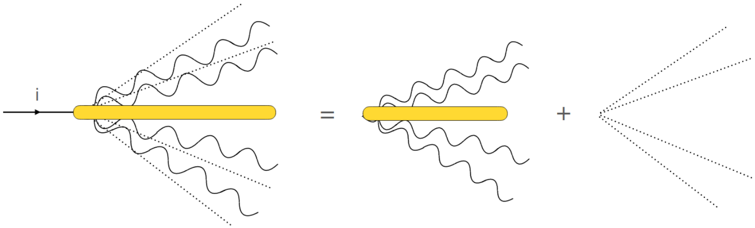
At twist 2 the jet function $J_i(s)$ "decouples" from the 1h-FF $D_1(z)$
and the non-perturbative structure gets simplified

Twist three jets



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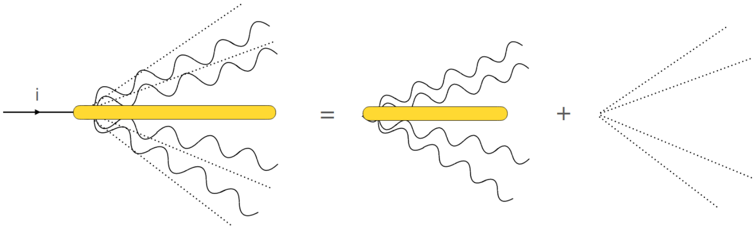

$$\tilde{J}_i(s) \sim M_j \otimes \tilde{J} + \mathcal{O}(\Lambda_{qcd}^2\, s^{-1}) \qquad \text{(sum rule for } E\text{)}$$

More complex non-perturbative structure:
normalization of the associated quark spectral function (ρ_1 in this case)

Just a speculation?

Just a speculation? **NO**

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

The quark/jet mass can have a sizeable impact on physical observables:

Just a speculation? **NO**

Accardi, Signori 1903.04458 - PLB
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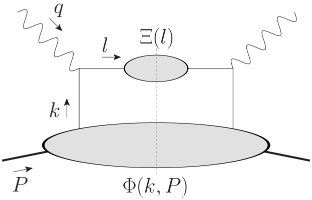

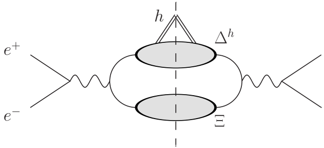

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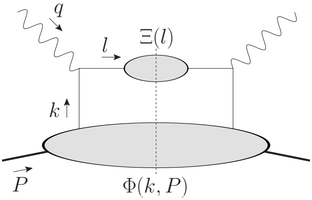

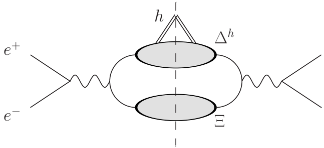

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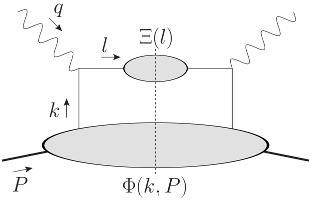

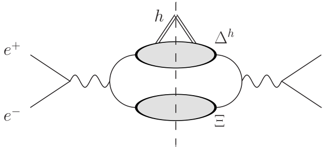

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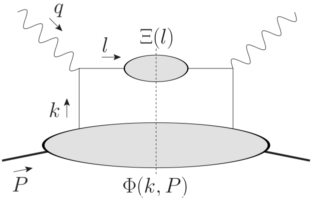

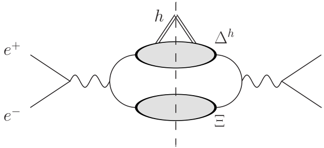

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- this mass is gauge-invariant, and the dynamical component can be measured at twist three in scattering experiments

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

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What generates the masses of partons and hadrons?

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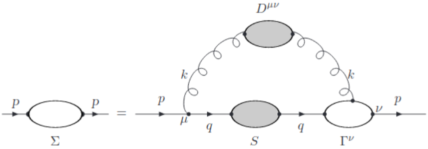

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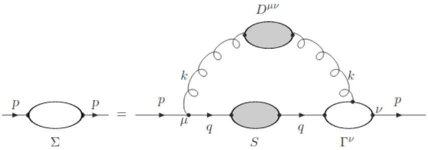

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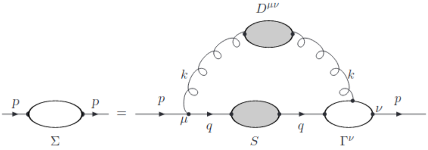
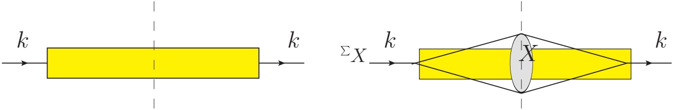
- "mass sum rule" for fragmentation functions - new and observable!



The cut quark propagator

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



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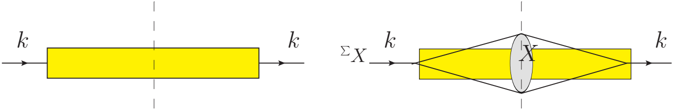

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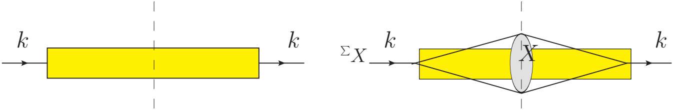

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- insights into dynamical generation of mass and momentum and chiral symmetry breaking

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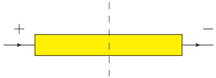
$\sim$ 

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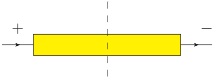
$\sim$ 

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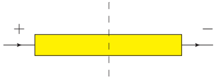

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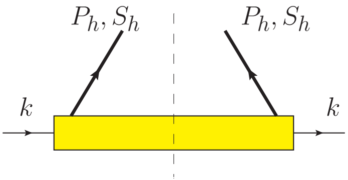
This mass term:

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

Quark 1h-FFs

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



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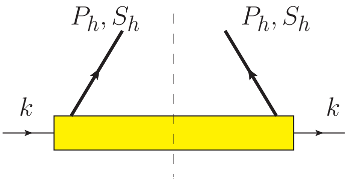

quark pol. (columns); hadron pol. (rows)

	U	L	T
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 $\mathcal{D}_{\dots}^{a\to h}(z, P_{h\perp}^2)$
for a quark hadronizing into a spin $1/2$ hadron

quark pol.

hadron pol.	U	L	T
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, $E_T^\perp$

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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

Semi-inclusive processes

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- interesting but challenging: chiral-odd sector at least at twist-3
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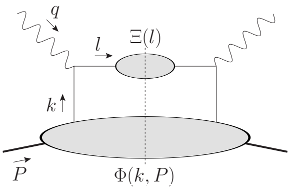

dynamical mass coupled to the transversity PDF

A. Accardi, A. Bacchetta - 1706.02000 - PLB

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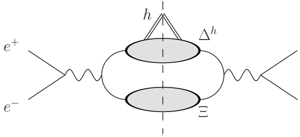

(Accardi, Signori et al. - in progress)

$$\frac{d\sigma^L(e^+e^- \to h^\uparrow X)}{d\Omega dz} = \frac{3\alpha^2}{Q^2}\,\lambda_e \sum_a e_a^2 \left\{ \frac{C(y)}{2}\lambda_h G_{1L}(z) \right.$$

$$\left. + D(y)\, |\boldsymbol{S}_T|\, \cos(\phi_S) \frac{2M_h}{Q} \left(\frac{G_T(z)}{z} + \frac{m_q^{corr}}{M_h} H_1(z) \right) \right\}$$

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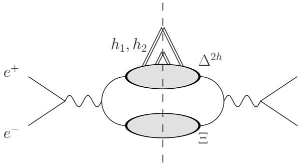

Also requires lepton polarization

Accardi, Signori et al. - work in progress

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  - (?) $pp^{\uparrow} \to h_1 h_2 j X \quad \xrightarrow[\text{sum rule}]{\text{mass}} \quad f_1(x_1) \otimes h_1(x_2) \otimes D_1(z) \otimes m_q^{corr}$
    (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