Higher twist fragmentation and mass generation

Andrea Signori

University of Pavia and INFN

Sardinian Workshop on Spin (SarWorS) 2021

September 6, 2021

Outline

Quark hadronization, propagation, mass generation

Inclusive jets

Semi-inclusive processes

Some references:

A selection of references related to the topics discussed in this talk:

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

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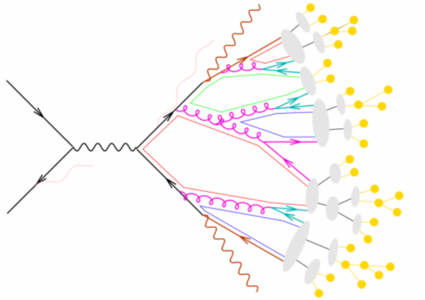
- Pion parton distribution and fragmentation functions beyond the leading twist in a confining Nambu–Jona-Lasinio model
  I. Cloet, A. Signori - in preparation

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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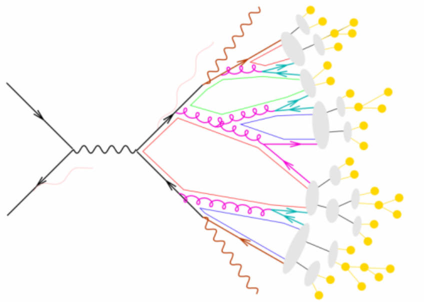

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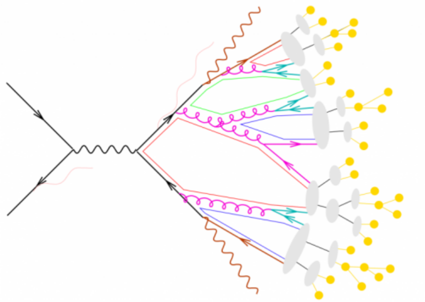

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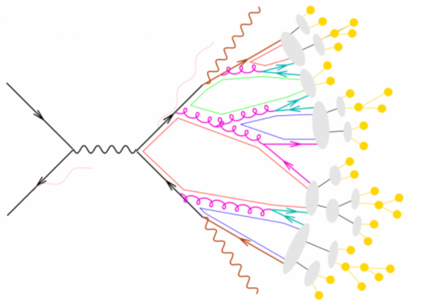

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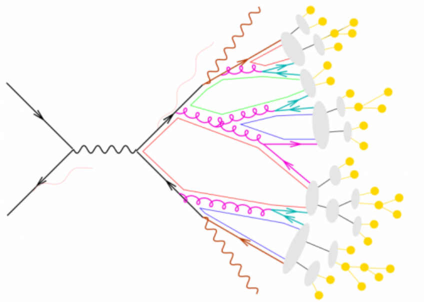

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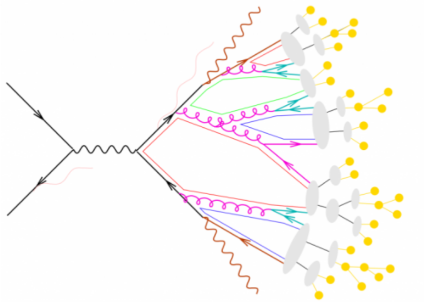

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"fully" inclusive jet → propagator

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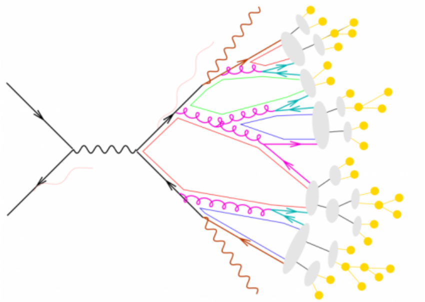

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The generation of mass

What generates the masses of partons and hadrons?

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

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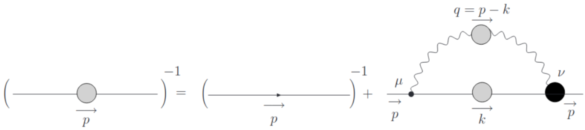
  e.g. in the NJL model of QCD: $M_q = m_q - 4G_\pi \langle \bar{q}q \rangle \gg m_q$



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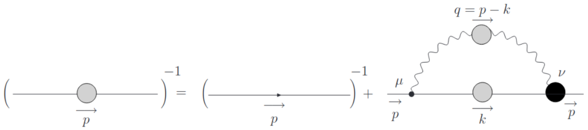

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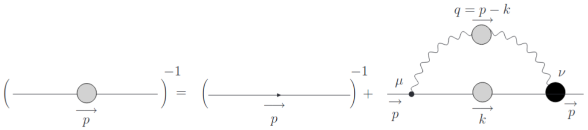
- Energy Momentum Tensor $\to$ hadron mass decomposition
- "mass sum rule" for fragmentation functions - new and observable!



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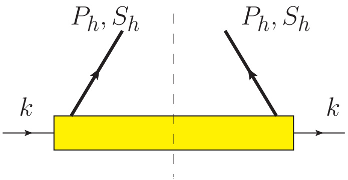
Quark 1h-FFs

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



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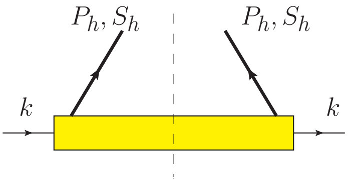

quark pol. (columns) / hadron pol. (rows)

	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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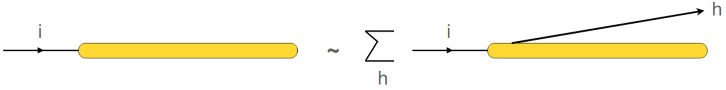
T	D_T, $D_T^\perp$	G_T, $G_T^\perp$	H_T, $H_T^\perp$, E_T, $E_T^\perp$

Black and magenta: survive transverse momentum integration
Red and magenta: T-odd
Blue: T-even, w/o collinear counterpart

Inclusive jets and 1h-FFs

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

"Fully" inclusive jet *correlator* (quark propagator)
$\equiv$ inclusive limit of 1h-fragmentation *correlator*



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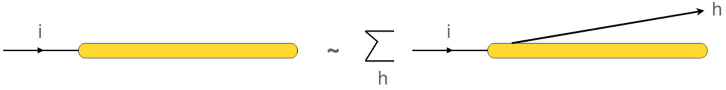

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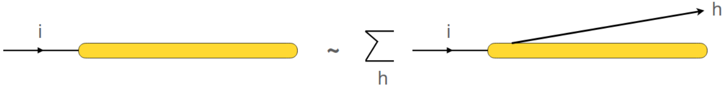

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Dirac projections:

momentum sum rules for FFs in terms of quark propagator

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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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:

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

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

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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*

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estimate of M_j in NJL model

evolution: large-N_c and LO in α_s

(A. Belitsky - hep-ph/9703432)

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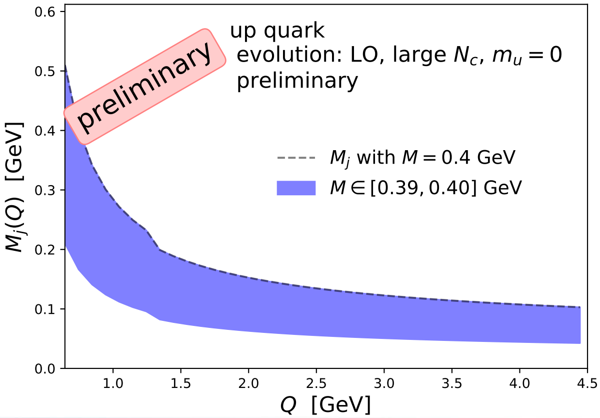

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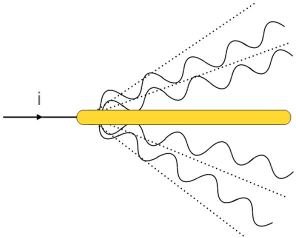

Inclusive jet function $J_i(s)$:
sensitive to the jet virtuality s

(within a defined cone)

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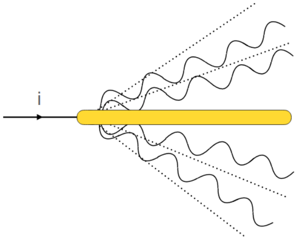

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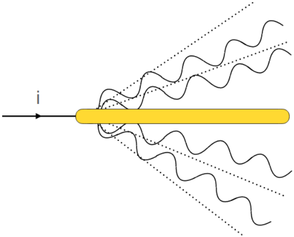

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"Composition" of the jet:

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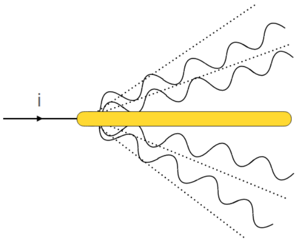
- non-perturbative radiation (low s, dashed lines)

Inclusive jets



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- non-perturbative quark propagation (yellow blob)

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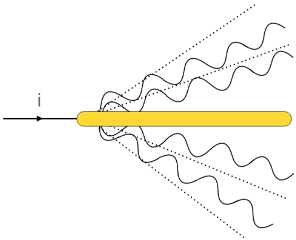

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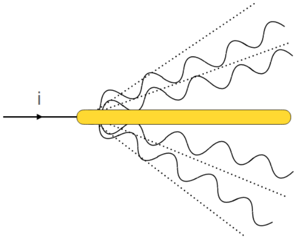
- non-perturbative quark propagation (yellow blob) $\leftarrow$ relevance?

Inclusive jets and FJFs

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



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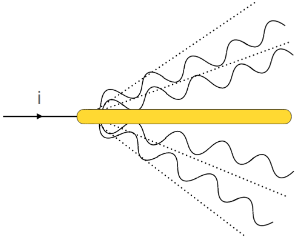

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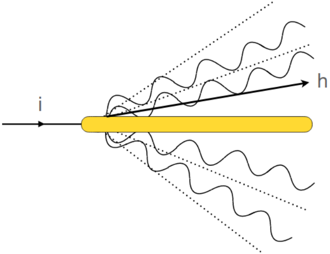

Fragmenting jet function (FJF) $\mathcal{G}^{i \to h}(s, z)$:
sensitive to jet virtuality s
and hadron momentum fraction z
(less inclusive)

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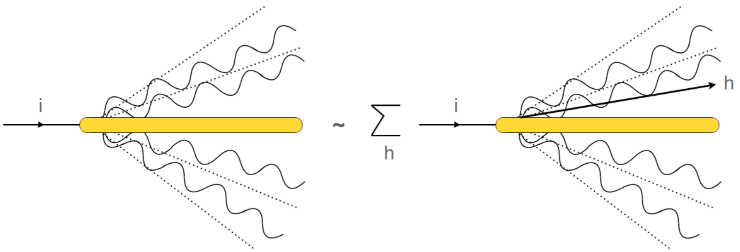
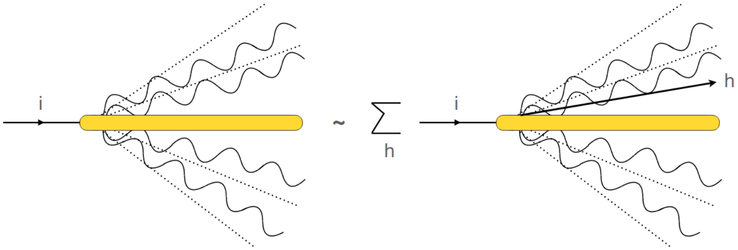


Inclusive jets and FJFs

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



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

Connection between the unpolarized (twist 2) jet function and FJFs :
jet as the "inclusive" limit of the in-jet fragmentation

FJFs and 1h-FFs

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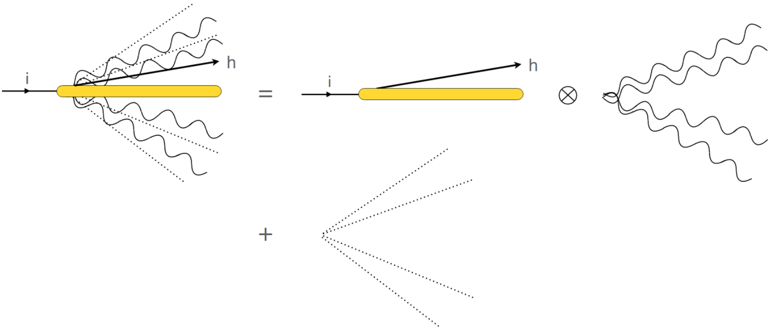

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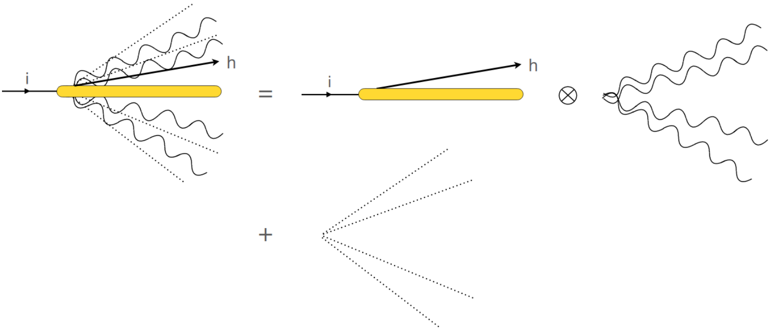

$$\mathcal{G}^{i\to h}(s,z) = \sum_j \mathcal{J}_{ij}(s,z) \otimes D_1^{j\to h}(z) + \mathcal{O}(\Lambda_{qcd}^2\, s^{-1})$$

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

Twist two jets

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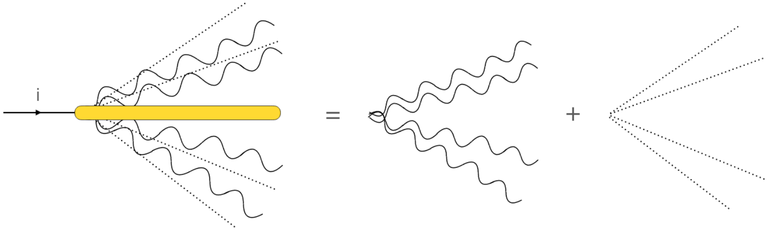

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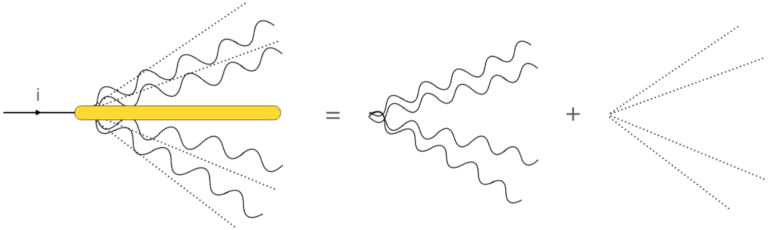

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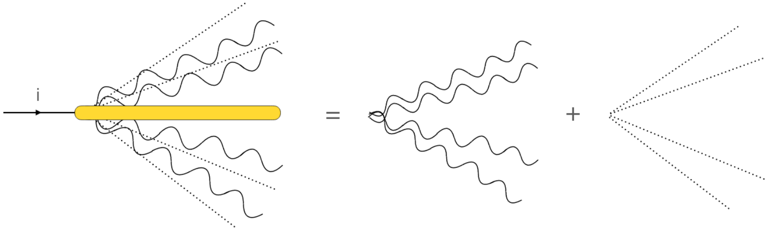

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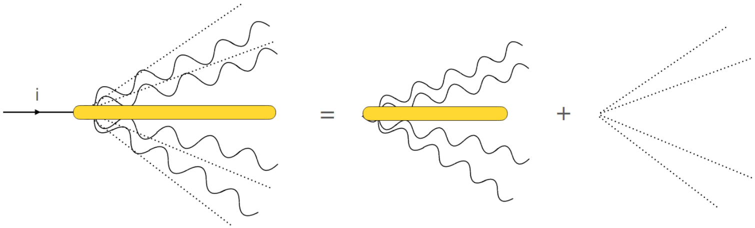
At twist 2 the jet function $J_i(s)$ "decouples" from the 1h-FF $D_1(z)$ and the non-perturbative structure gets simplified

Twist three jets



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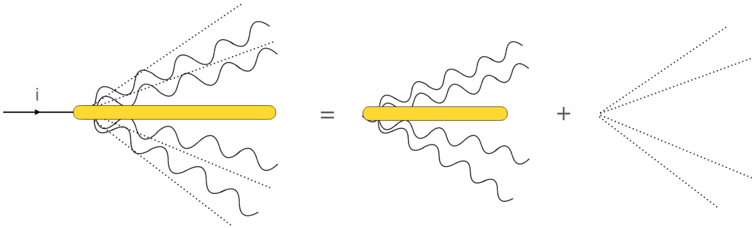

$$\tilde{J}_i(s) \sim M_j \otimes \tilde{J} + \mathcal{O}(\Lambda_{qcd}^2\, s^{-1}) \qquad \text{("mass sum rule" for } E)$$

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

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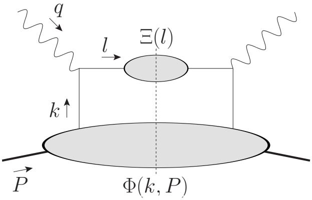

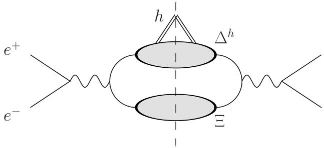

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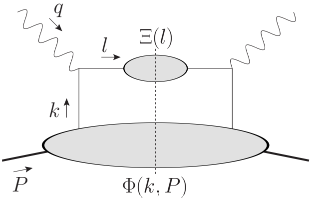

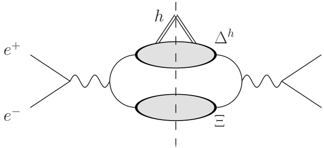

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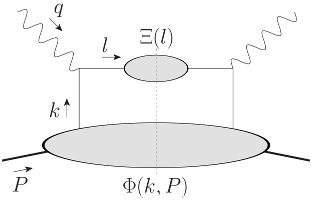

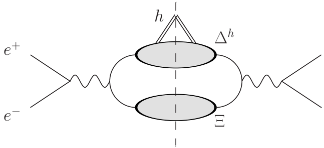

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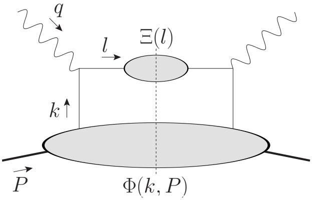
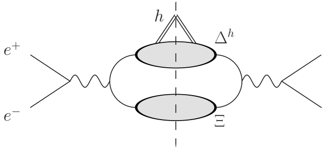
- calculable: quark E FFs $[M_j = \sum_h \int dz \, M_h \, E^h(z)]$ $\leftarrow$ this work!





Outline

Quark hadronization, propagation, mass generation

Inclusive jets

Semi-inclusive processes

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- We can study the phenomenology of the dynamical mass in (semi-) inclusive hard processes
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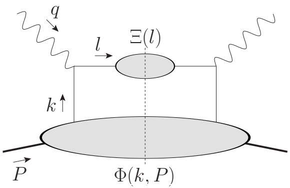

dynamical mass coupled to the transversity PDF

A. Accardi, A. Bacchetta - 1706.02000 - PLB

Semi-inclusive processes

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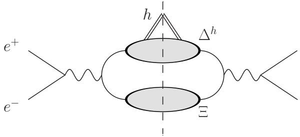

(Accardi, Signori et al. - in progress)

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

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

Conclusions

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

FF2021 @ INT

Organizers:

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- Andrea Signori, University of Pavia and INFN Pavia (IT), Jefferson Lab (VA, USA), andrea.signori@unipv.it

Diversity Coordinator:

- Ralf Seidl, RIKEN (Japan), Riken BNL Research Center (NY, USA), rseidl@riken.jp

Program Coordinator:

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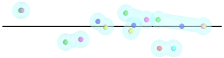
Application Form



https://sites.google.com/uw.edu/int/programs/21-80w

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

The NJL model of QCD

The Nambu–Jona-Lasinio (NJL) model of QCD is a chiral effective theory which is useful to help understand non-perturbative phenomena in low energy QCD. In particular:

- it encapsulates dynamical chiral symmetry breaking (gap equation)
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Proper-time regularization scheme: it can incorporate aspects of confinement

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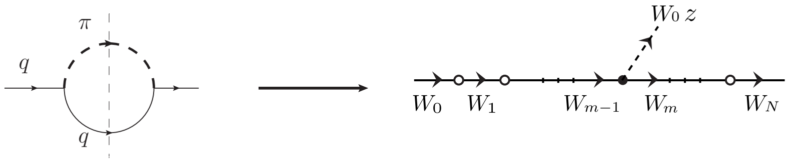
The NJL model has been used to describe:

- hadrons as bound states of quarks
- nuclear matter and nuclei in terms of quarks (medium modifications)
- phases of strongly interacting matter at high densities (e.g. neutron stars, etc.)

(Klevansky - Rev.Mod.Phys. 64 (1992) 649-708)

The NJL-jet model for FFs



- Within the NJL it is possible to calculate PDFs and FFs by calculating and regularizing the associated Feynman diagrams
- A more realistic model of FFs: take into account that the fragmentation process occurs as a *cascade*: the NJL-jet (Ito et al. - 0906.5362)

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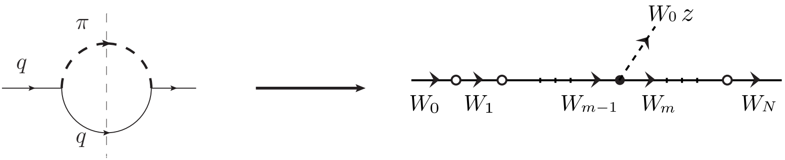

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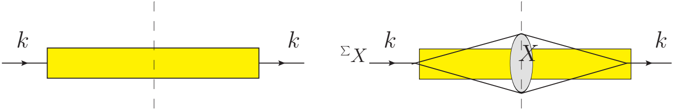
$$D_q^{\pi}(z) = \sum_{m=1}^{N} \int_0^1 d\eta_1 \cdots \int_0^1 d\eta_N \, 6^N \sum_{Q_N} d_q^{Q_1}(\eta_1) \cdots d_{Q_{m-1}}^{\pi}(z) \cdots d_{Q_{N-1}}^{Q_N}(\eta_N)$$

The physical FF D_q^{π} can be calculated from the *elementary* d_q^{π} solving two integral Volterra equations

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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  - only the discontinuity is considered → on-shellness
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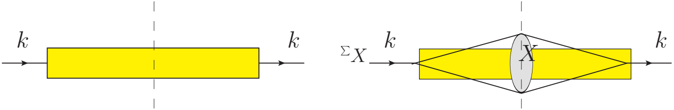

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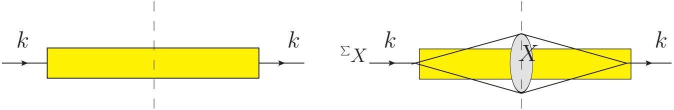

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- insights into dynamical generation of mass and momentum and chiral symmetry breaking

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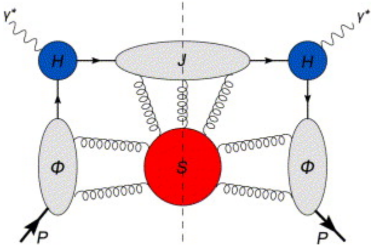
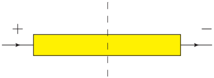


See Sterman NPB 281 ('87) 310, Chen et al. NPB 763 ('07) 183, Accardi et al. - 0805.1496, Collins et al. - 0708.2833 (and refs. therein)
(figure from Chen et al.)

- Ξ emerges in the factorization theorem for DIS at *large x*, where a new semi-hard scale appears
- Ξ captures the physics at $Q^2(1-x) \sim Q\Lambda_{QCD}$, which becomes increasingly non-perturbative at low energy and large x
- the end-point factorization should be extend to different processes (e.g. e^+e^-)
- here we study the properties of Ξ and Δ regardless of processes

The quark/jet mass

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

$\sim$ 

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

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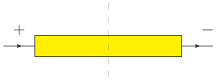
$\sim$ 

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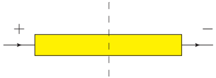

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This mass term:

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

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 :
  - (?) $pp^{\uparrow} \to h_1 h_2 j X \quad \xrightarrow[\text{sum rule}]{\text{mass}} \quad f_1(x_1) \otimes h_1(x_2) \otimes D_1(z) \otimes m_q^{corr}$
    (fixed-target configuration at LHC)
- (?) potentially also TMD factorization
- in order to make quantitative predictions and extractions the ("end-point") factorization of these processes has to be addressed