Spectral analysis of the gauge invariant quark propagator

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2023, Sept 14th

Based on: arXiv 2307.10152

In collaboration with:
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Jefferson Lab
Exploring the Nature of Matter

Outline

- Introduction
- Gauge invariant quark propagator
- Quark propagator spectral representation
- Conclusions

- **Confinement:** Quarks and gluons are not asymptotic states of QCD: are confined inside hadrons

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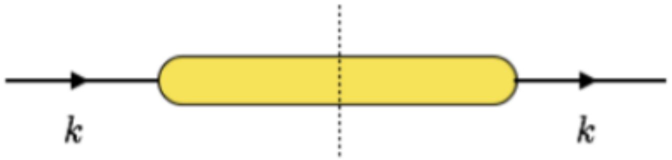
- **DCSB:** Mass generation

Nonperturbative: Gauge invariant quark propagator/jet correlator



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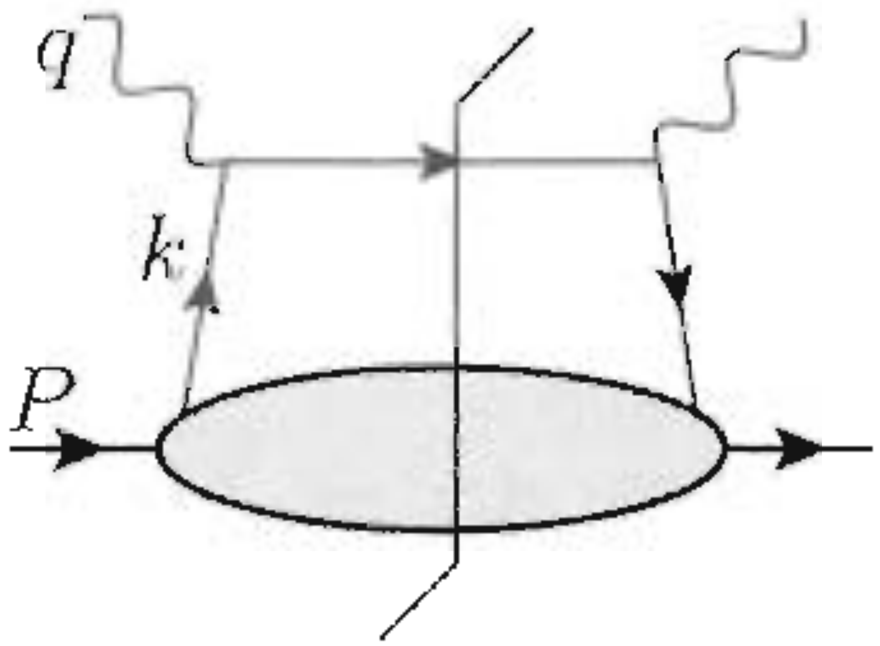
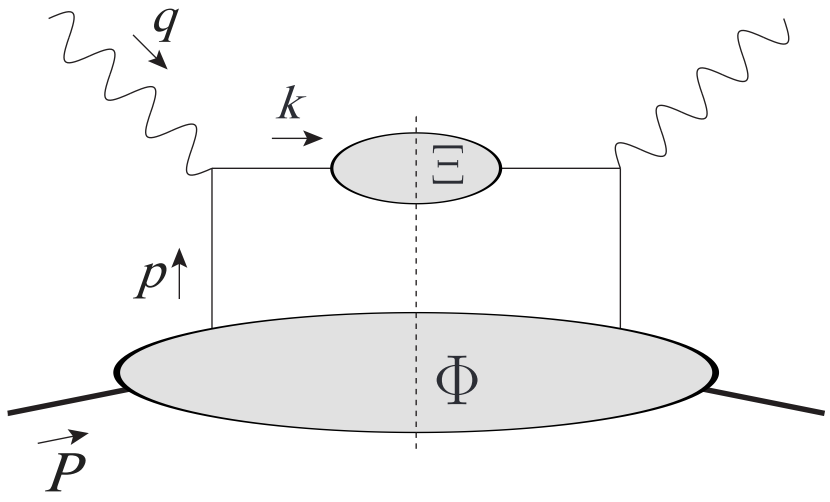
- How color neutral and massive hadron emerge out of colored and massless quarks and gluons?


q
k
P



q
k
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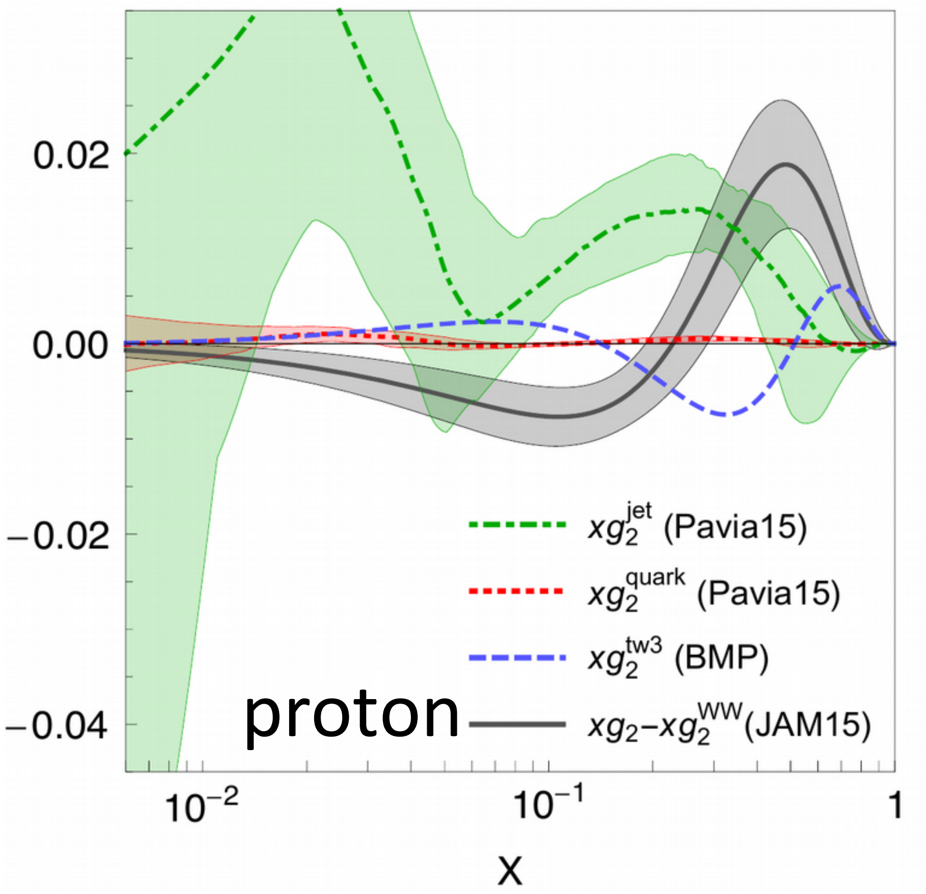
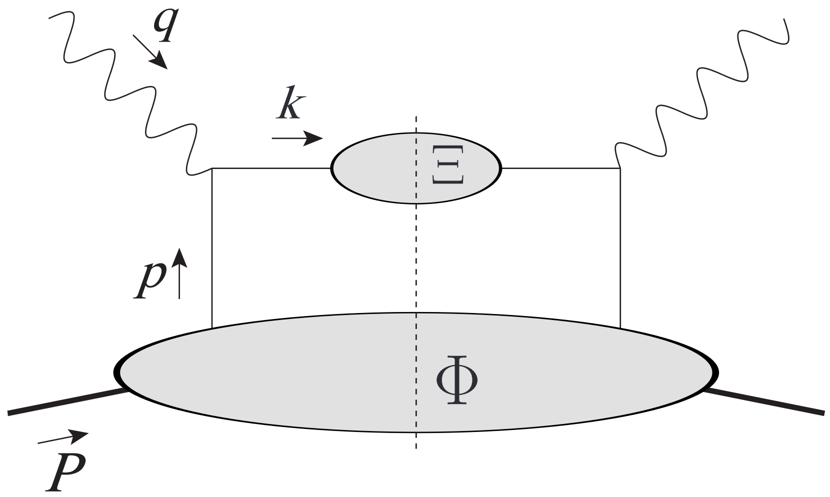
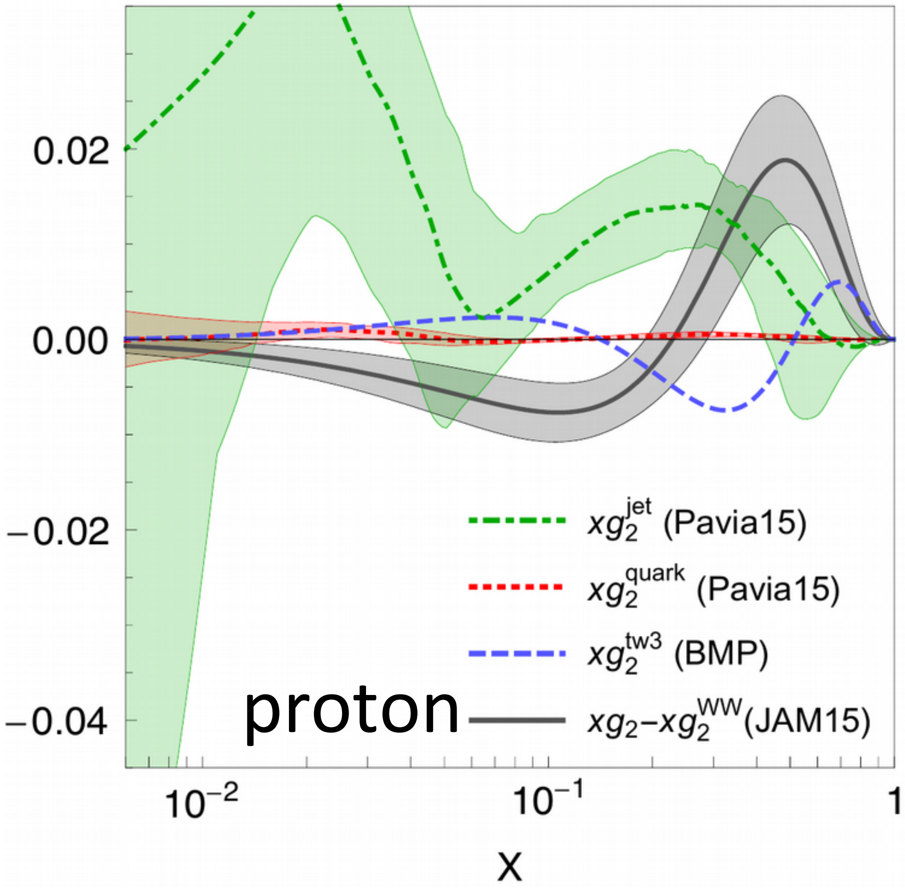


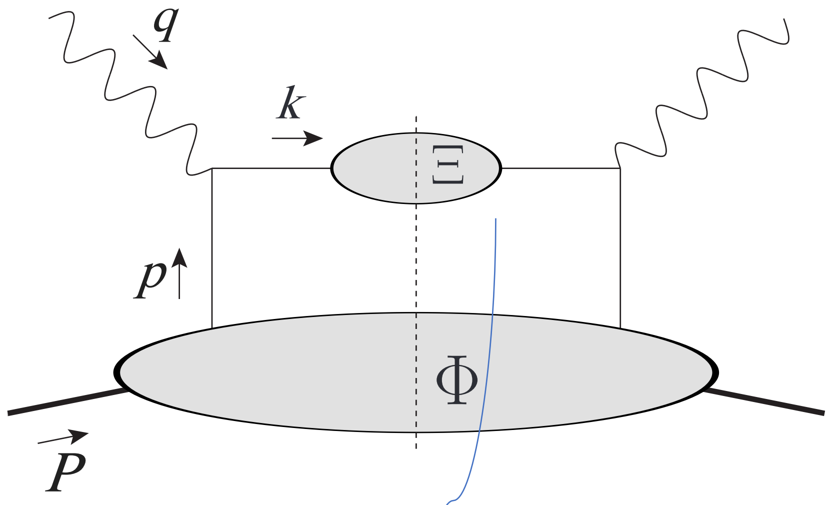


g_2^{quark}

$$g_2(x_B) - g_2^{WW}(x_B) = \frac{1}{2}\sum_a e_a^2 \left(g_2^{tw-3}(x_B) + \underbrace{\frac{m_q}{M}\left(\frac{h_1^q}{x}\right)^{\star}}_{g_2^{quark}}(x_B) + \frac{M_q - m_q}{M}\frac{h_1^q(x_B)}{x_B} \right)$$

AA, Bacchetta (2017)





g_2^{quark}

dynamically generated mass: nonvanishing even when m_q =0

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Gauge invariant quark propagator

$$\Xi_{ij}(k;w) = \mathrm{Disc} \int \frac{d^4\xi}{(2\pi)^4} e^{\mathrm{i}k\cdot\xi} \, \frac{\mathrm{Tr}_c}{N_c} \, \langle\Omega| \big[\, \mathcal{T}\, W_1(\infty,\xi;w)\psi_i(\xi)\big] \, \big[\, \overline{\mathcal{T}}\, \overline{\psi}_j(0) W_2(0,\infty;w)\big] |\Omega\rangle$$

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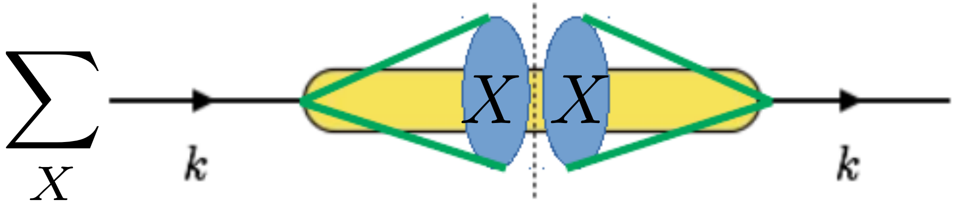
- ❑ Hadronization of a quark into an unobserved jet of particles (fully inclusive)



q → X amplitude

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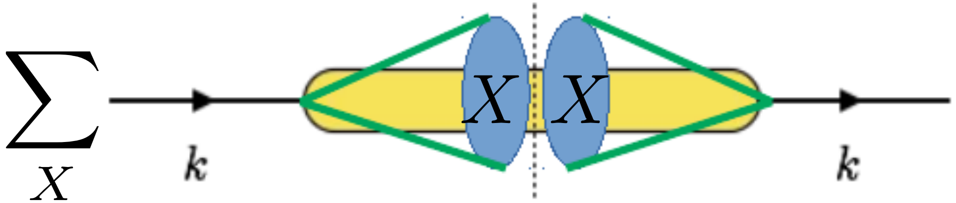

$$\Xi_{ij}(k;n_+) = \mathrm{Disc}\int \frac{d^4\xi}{(2\pi)^4} e^{ik\cdot\xi} \frac{\mathrm{Tr}_c}{N_c} \langle\Omega|\psi_i(\xi)\overline{\psi}_j(0) W(0,\xi;n_+)|\Omega\rangle$$

- Gauge invariant generalization of the fully dressed quark propagator

Gauge invariant quark propagator

- Can be given a convolution representation

$$\Xi_{ij}(k;w) = \text{Disc} \int d^4p \frac{\text{Tr}_c}{N_c} \langle \Omega | i\widetilde{S}_{ij}(p;v) \widetilde{W}(k-p;w,v) | \Omega \rangle$$

where

$$i\widetilde{S}_{ij}(p,v) = \int \frac{d^4\xi}{(2\pi)^4} \, e^{i\xi\cdot p} \, \mathcal{T} \, \psi_i(\xi) \overline{\psi}_j(0)$$

$$\widetilde{W}(k-p;\, w,v) = \int \frac{d^4\xi}{(2\pi)^4} \, e^{i\xi\cdot(k-p)} \, W(0,\xi;w,v)$$

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- Decomposition of the quark bilinear operator

(axial gauges)

$$i\widetilde{S}_{ij}(p,v) = \hat{s}_3(p^2, p\cdot v) \not{p}_{ij} + \sqrt{p^2}\, \hat{s}_1(p^2, p\cdot v)\, \mathbb{I}_{ij} + \hat{s}_0(p^2, p\cdot v) \not{v}_{ij}$$

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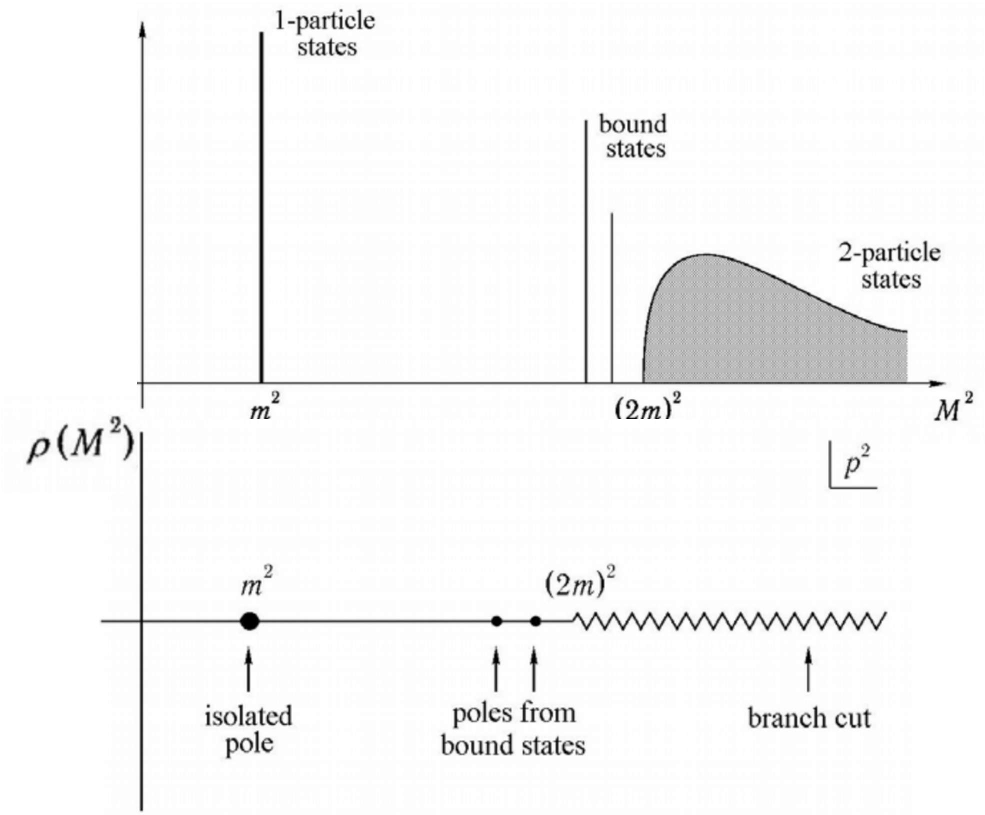
(lightlike axial gauges)

$\hat{s}_3(p^2)$ $\hat{s}_1(p^2)$ $\hat{s}_0(p^2)$: spectral operators

Spectral representation of the quark propagator in the lcg

$$\frac{\mathrm{Tr_c}}{N_c}\langle\Omega|i\tilde{S}(p)|\Omega\rangle = \frac{1}{(2\pi)^4}\int_{-\infty}^{\infty} d\sigma^2 \rho(\sigma^2)\frac{i}{p^2-\sigma^2+i\epsilon}\theta(\sigma^2)$$



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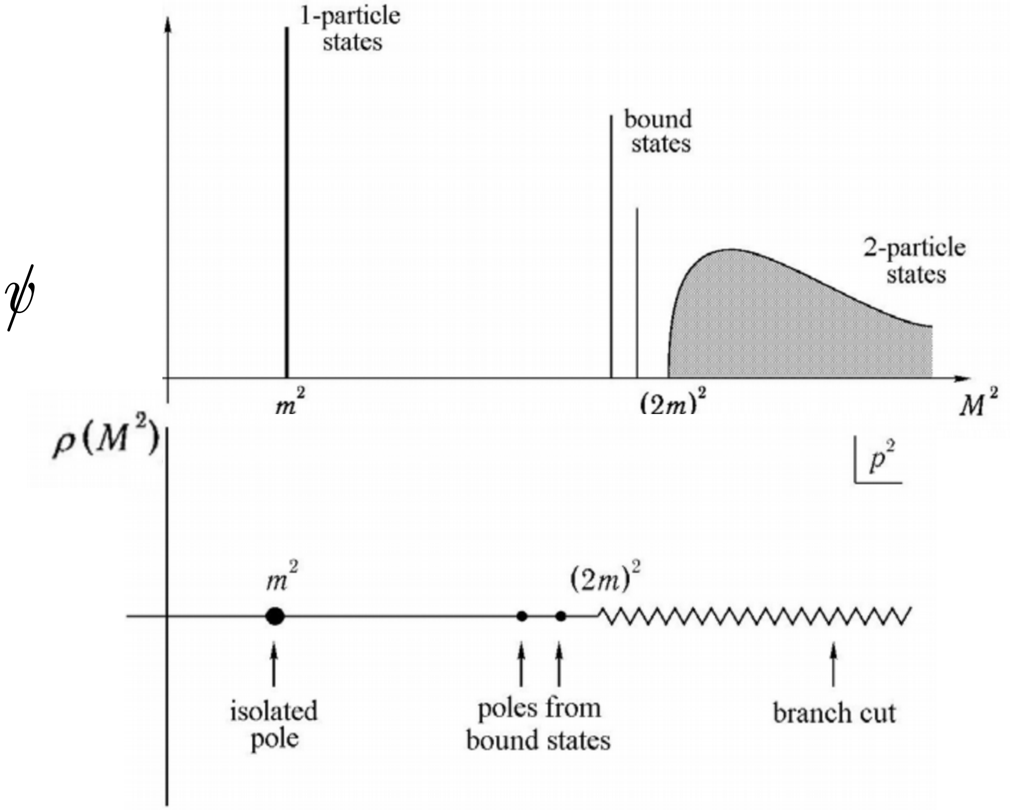

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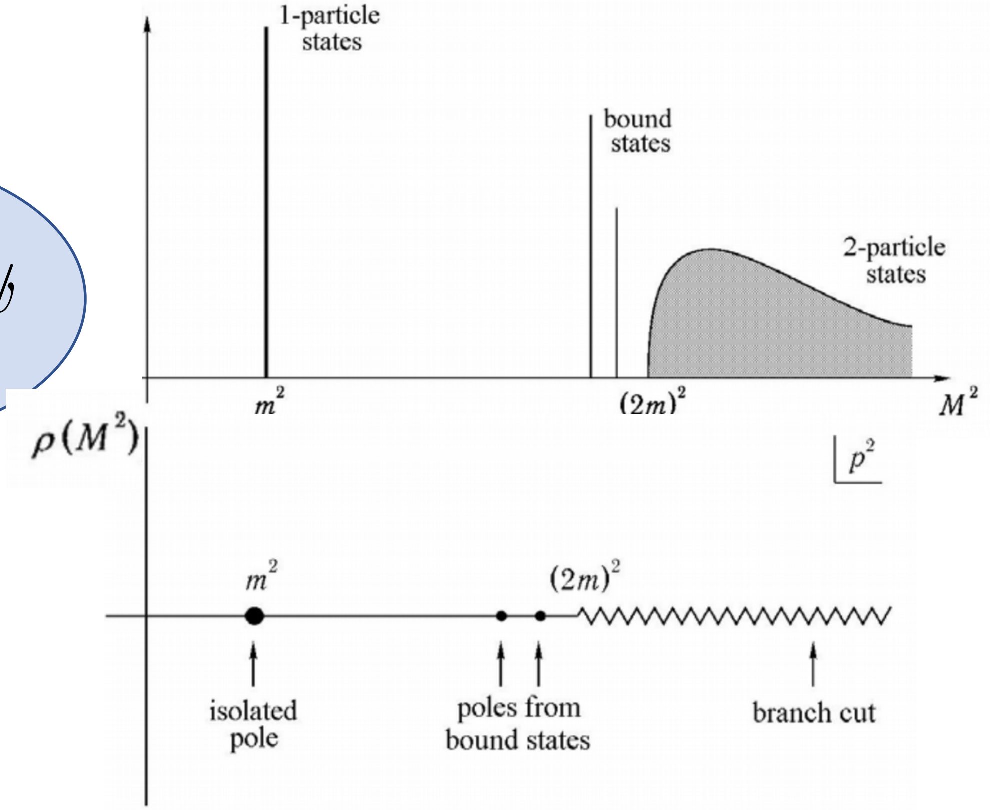

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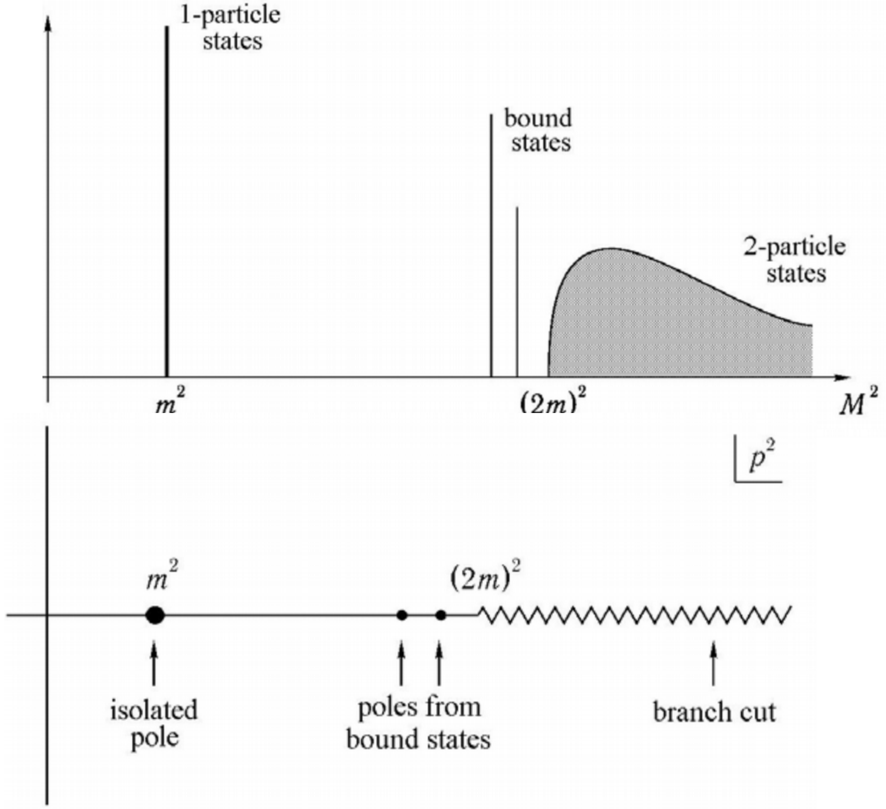
$$\mathrm{Disc}\frac{\mathrm{Tr}_c}{N_c}\langle\Omega|i\tilde{S}(p)|\Omega\rangle = \frac{1}{(2\pi)^3}\rho(p^2)\theta(p^2)\theta(p^-)$$

$$\mathrm{Disc}\frac{\mathrm{Tr}_c}{N_c}\langle\Omega|\hat{s}_{3,1,0}(p,v)|\Omega\rangle = \frac{1}{(2\pi)^3}\rho_{3,1,0}(p^2)\theta(p^2)\theta(p\ )$$



Integrated g.i. quark propagator

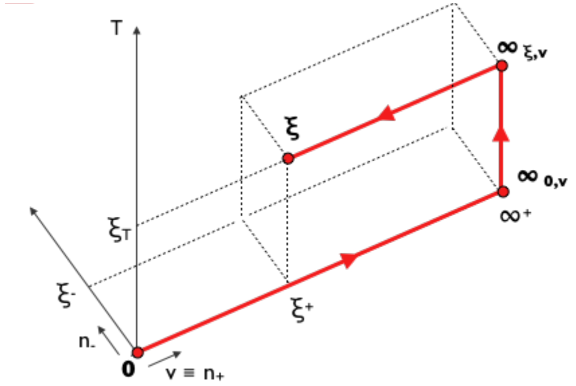
- Boost quark at large light-cone momentum:

$$k^- \gg |\mathbf{k}_\perp| \gg k^+$$

$w = n^+$

Integrate out the suppressed component of the quark momentum:

$$J_{ij}(k^-, \vec{k}_\perp; n_+) \equiv \frac{1}{2} \int dk^+ \Xi_{ij}(k; n_+)$$



- Generalizes the perturbative quark propagator that appears in inclusive and semi-inclusive DIS

$$W_{\rm TMD}(\xi^+, \boldsymbol{\xi}_\perp) = \mathcal{U}_{n_+}[0^-, 0^+, \mathbf{0}_\perp; 0^-, \infty^+, \mathbf{0}_\perp]\, \mathcal{U}_{\boldsymbol{n}_\perp}[0^-, \infty^+, \mathbf{0}_\perp; 0^-, \infty^+, \boldsymbol{\xi}_\perp]\, \mathcal{U}_{n_+}[0^-, \infty^+, \boldsymbol{\xi}_\perp; 0^-, \xi^+, \boldsymbol{\xi}_\perp]$$

$$W_{\rm coll}(\xi^+) = \mathcal{U}_{n_+}[0^-, 0^+, \mathbf{0}_\perp; 0^-, \xi^+, \mathbf{0}_\perp]$$

Integrated g.i. quark propagator

- Expand in Dirac structures, in powers of $1/k^-$

$$J(k^-, \boldsymbol{k}_\perp; n_+) = \frac{1}{2}\alpha(k^-)\gamma^+ + \frac{\Lambda}{k^-}\left[\zeta(k^-)\mathbb{I} + \alpha(k^-)\frac{\not{\boldsymbol{k}}_\perp}{\Lambda}\right] + \frac{\Lambda^2}{2(k^-)^2}\omega(k^-, \boldsymbol{k}_\perp^2)\gamma^-$$

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$$\alpha(k^-) = J^{[\gamma^-]}$$

$$\zeta(k^-) = \frac{k^-}{\Lambda} J^{[\mathbb{I}]}$$

$$\omega(k^-, \boldsymbol{k}_\perp^2) = \left(\frac{k^-}{\Lambda}\right)^2 J^{[\gamma^+]}$$

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$$J(k^-, \boldsymbol{k}_T; n_+) = \frac{\theta(k^-)}{4(2\pi)^3\, k^-}\left\{k^-\,\gamma^+ + \not{k}_T + M_j\mathbb{I} + \frac{K_j^2 + \boldsymbol{k}_T^2}{2k^-}\gamma^-\right\}$$

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Average mass of all the hadronization products produced during the fragmentation of a quark

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Sum rules

- In *any gauge*:

$$1 = \int_0^\infty dp^2 \rho_3(p^2)$$

$$M_j = \int_0^\infty dp^2 \, \sqrt{p^2} \, \rho_1(p^2)$$

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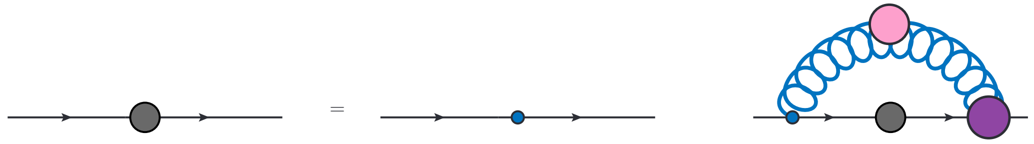

(e.g, DSE calculations)

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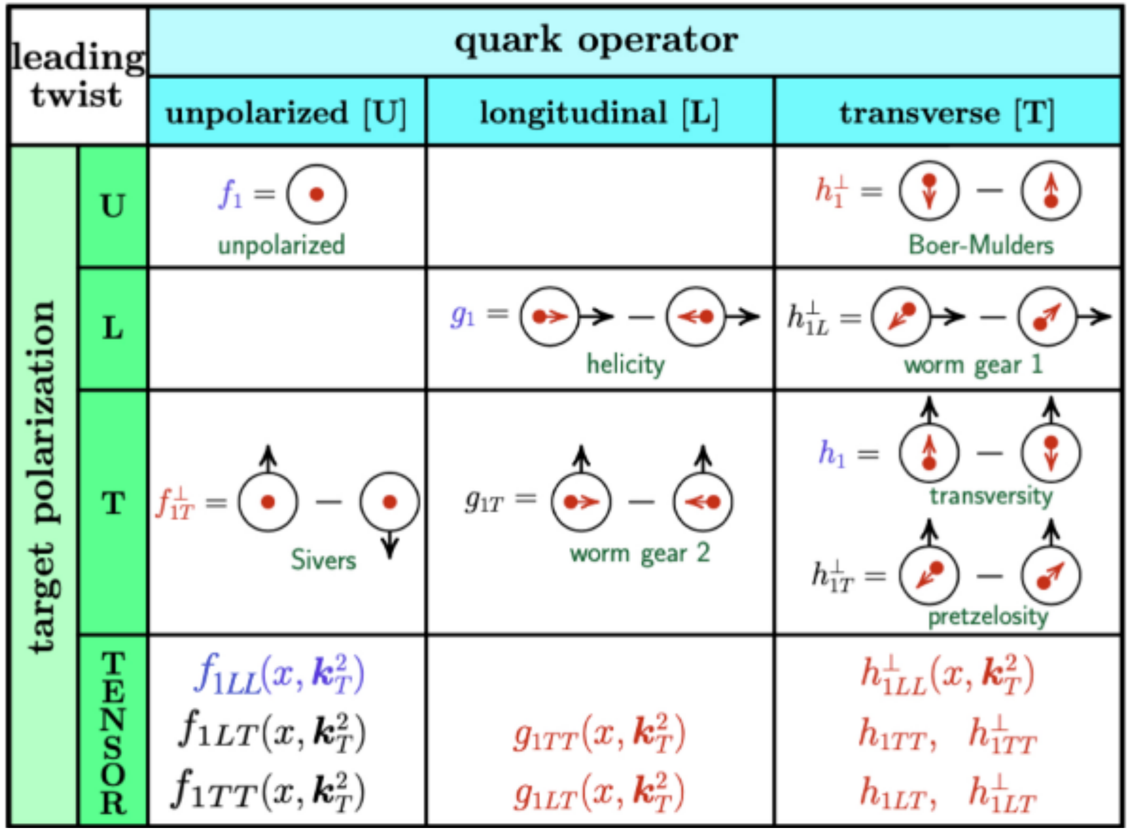
Gauge invariant generalization of the gauge dependent dressed quark mass



leading twist / target polarization	quark operator: unpolarized [U]	longitudinal [L]	transverse [T]
U	$f_1 =$ unpolarized		$h_1^\perp =$ − Boer-Mulders
L		$g_1 =$ − helicity	$h_{1L}^\perp =$ − worm gear 1
T	$f_{1T}^\perp =$ − Sivers	$g_{1T} =$ − worm gear 2	$h_1 =$ − transversity $h_{1T}^\perp =$ − pretzelosity
TENSOR	$f_{1LL}(x, \boldsymbol{k}_T^2)$ $f_{1LT}(x, \boldsymbol{k}_T^2)$ $f_{1TT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^\perp(x, \boldsymbol{k}_T^2)$ $h_{1TT}, \; h_{1TT}^\perp$ $h_{1LT}, \; h_{1LT}^\perp$

Experimentally accessible in double spin assymetry measurements!

(table from Satvir Kaur's talk yesterday)

❑ In *light-cone gauge*:

$$K_j^2 = \mu_j^2 + \tau_j^2 = \int_0^\infty dp^2 \; p^2 \; \rho_3^{\mathrm{lcg}}(p^2)$$

Final state interactions ”vanish”

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$$K_j^2 = \mu_j^2 + \tau_j^2$$

$$\tau_j^2 = (2\pi)^3 \int_0^\infty dp^2 \, \mathrm{Disc} \frac{\mathrm{Tr_c}}{\mathrm{N_c}} \langle \Omega | \hat{\sigma}_3(p^2) ig \, \boldsymbol{D}_\perp \left(\boldsymbol{A}^\perp(\boldsymbol{\xi}_\perp) + \mathcal{Z}^\perp(\boldsymbol{\xi}_\perp) \right)_{\boldsymbol{\xi}_\perp = 0} |\Omega\rangle$$

$$\mathcal{Z}^\perp(\boldsymbol{\xi}_\perp) = \int_0^{\infty^+} ds^+ \boldsymbol{D}_\perp \Big(U_{n_+}[0^-, 0^+, \boldsymbol{\xi}_\perp; 0^-, s^+, \boldsymbol{\xi}_\perp] G^{\perp -}(0^-, s^+, \boldsymbol{\xi}_\perp) U_{n^+}[0^-, s^+, \boldsymbol{\xi}_\perp; 0^-, \infty^+, \boldsymbol{\xi}_\perp] \Big) |\Omega\rangle$$

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$$K_j^2 = \mu_j^2 + \tau_j^2$$

$$\tau_j^2 = (2\pi)^3 \int_0^\infty dp^2\, \text{Disc} \frac{\text{Tr}_c}{\text{N}_c} \langle \Omega | \hat{\sigma}_3(p^2) ig\, \boldsymbol{D}_\perp \left(\boldsymbol{A}^\perp(\boldsymbol{\xi}_\perp) + \mathcal{Z}^\perp(\boldsymbol{\xi}_\perp) \right)_{\boldsymbol{\xi}_\perp = 0} |\Omega\rangle$$

$$\mathcal{Z}^\perp(\boldsymbol{\xi}_\perp) = \int_0^{\infty^+} ds^+ \boldsymbol{D}_\perp \Big(U_{n_+}[0^-, 0^+, \boldsymbol{\xi}_\perp; 0^-, s^+, \boldsymbol{\xi}_\perp] G^{\perp -}(0^-, s^+, \boldsymbol{\xi}_\perp) U_{n^+}[0^-, s^+, \boldsymbol{\xi}_\perp; 0^-, \infty^+, \boldsymbol{\xi}_\perp] \Big) |\Omega\rangle$$

Summary

- Completed the analysis of the gauge invariant quark propagator
- Full calculation of the twist-4 coefficient
- Formal demonstration of the gauge invariance of the twist-2, twist-3 and twist-4 coefficients of the g.i. quark propagator/jet correlator
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  - New sum rules for the quark spectral functions (needed: numerical checks)
- In particular:
  - Second moment of ρ_0 vanishes
  - First moment of the chiral odd quark spectral function gives a mass M_j that is a gauge invariant generalization of the gauge dependent quark mass

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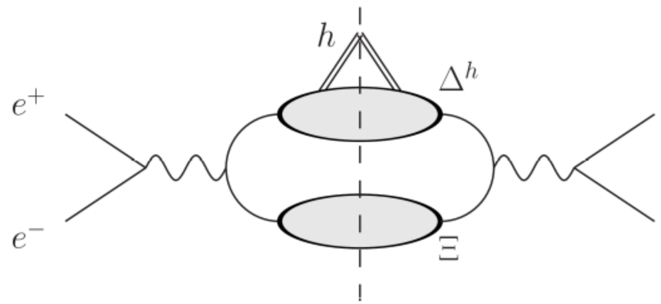

Summary

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  - It's calculable, but moreover.. It can be measured!

(In progress)