Spectral analysis of the gauge invariant quark propagator

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Based on: arXiv 2307.10152
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Jefferson Lab
Exploring the Nature of Matter

Outline

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

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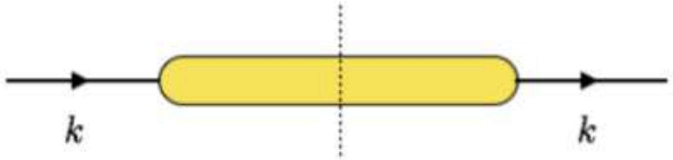
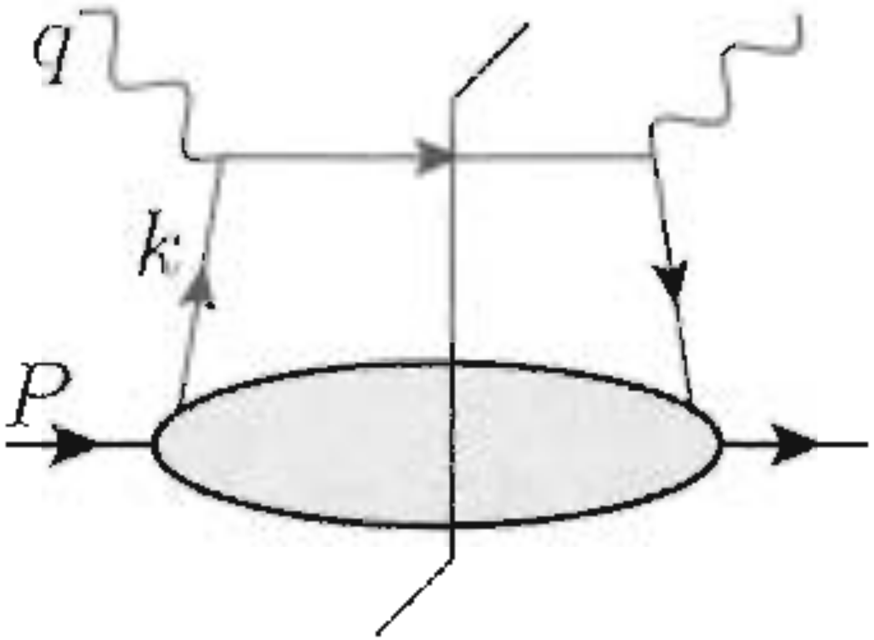
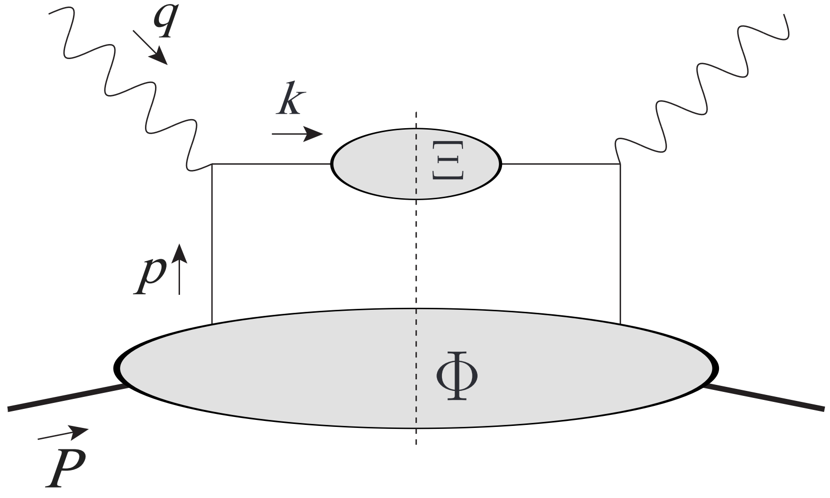
Nonperturbative: Gauge invariant quark propagator/jet correlator



- These QCD features are intimately related to *hadronization*
- How color neutral and massive hadron emerge out of colored and massless quarks and gluons?


q
k
P



q
k
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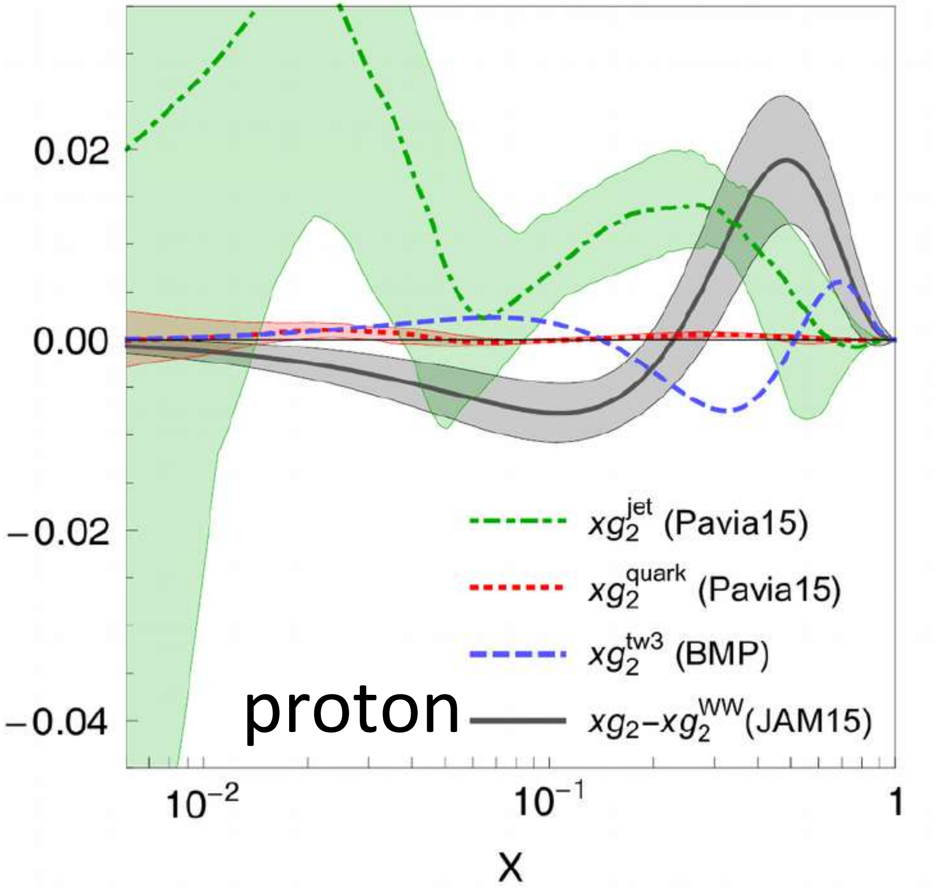
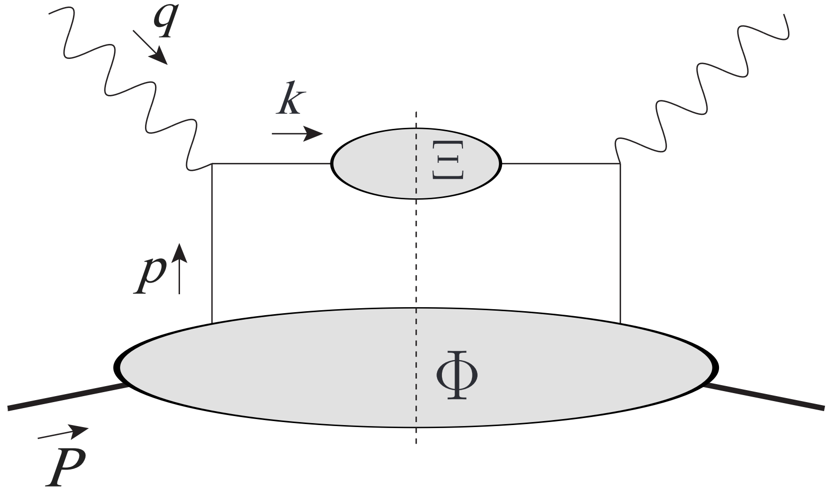
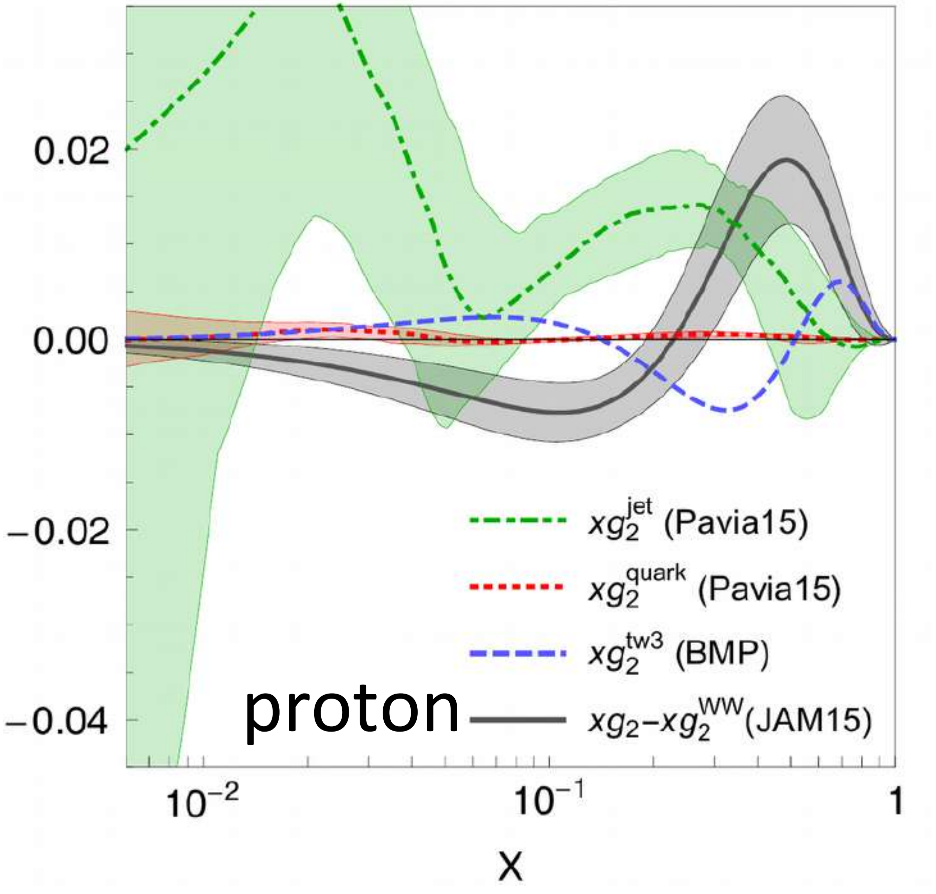
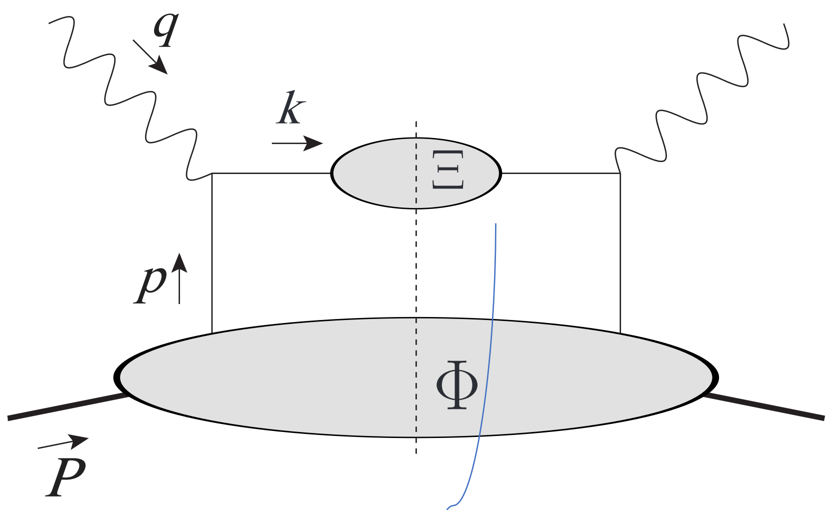




$$g_2(x_B) - g_2^{WW}(x_B) = \frac{1}{2}\sum_a e_a^2 \left(g_2^{tw-3}(x_B) + \overbrace{\frac{m_q}{M}\left(\frac{h_1^q}{x}\right)^{\star}}^{g_2^{quark}}(x_B) + \frac{M_q - m_q}{M}\,\frac{h_1^q(x_B)}{x_B} \right)$$

AA, Bacchetta (2017)





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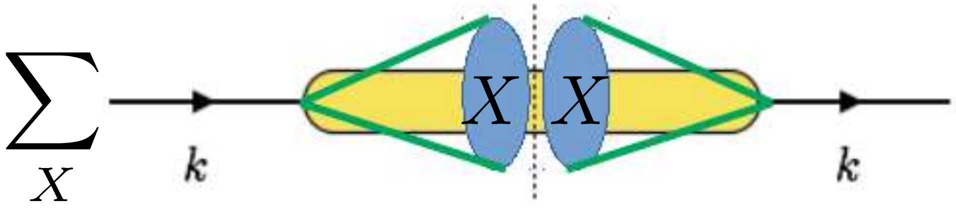
- Hadronization of a quark into an unobserved jet of particles (fully inclusive)



q → X amplitude

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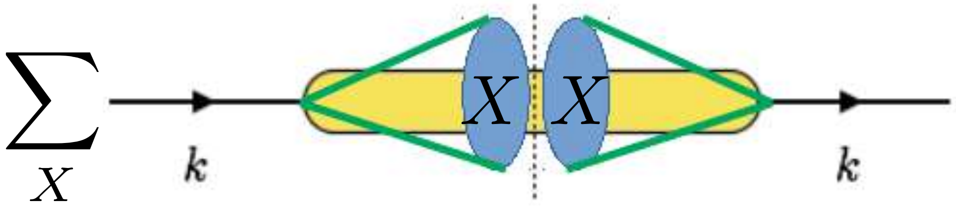
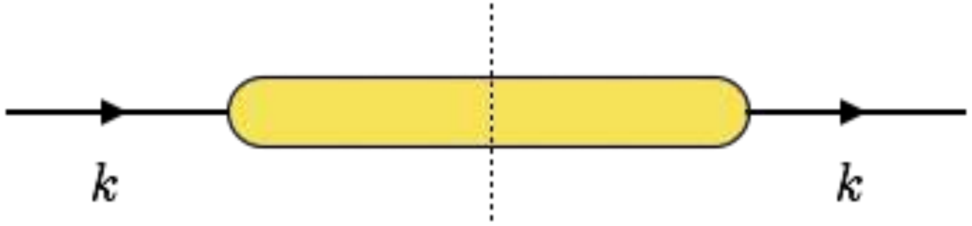


$$\Xi_{ij}(k;n_+) = \mathrm{Disc}\int \frac{d^4\xi}{(2\pi)^4} e^{\mathrm{i}k\cdot\xi} \frac{\mathrm{Tr}_c}{N_c} \langle\Omega|\psi_i(\xi)\overline{\psi}_j(0) W(0,\xi;n_+)|\Omega\rangle$$

- ❑ 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

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

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

Gauge invariant quark propagator

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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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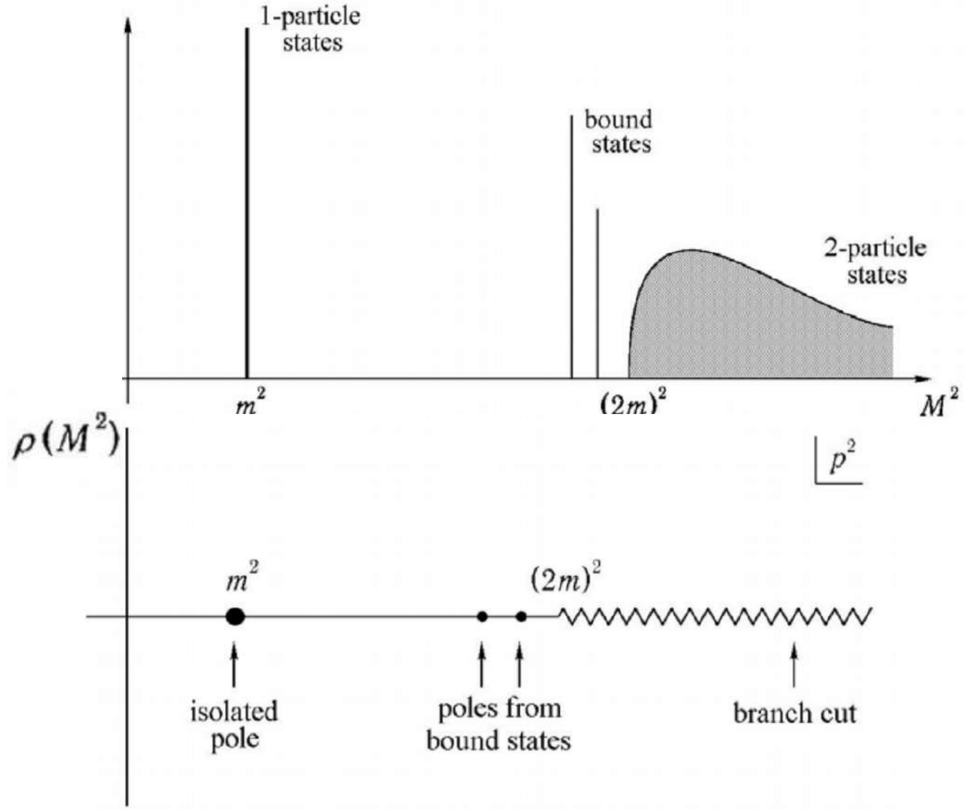
(lightlike axial gauges)

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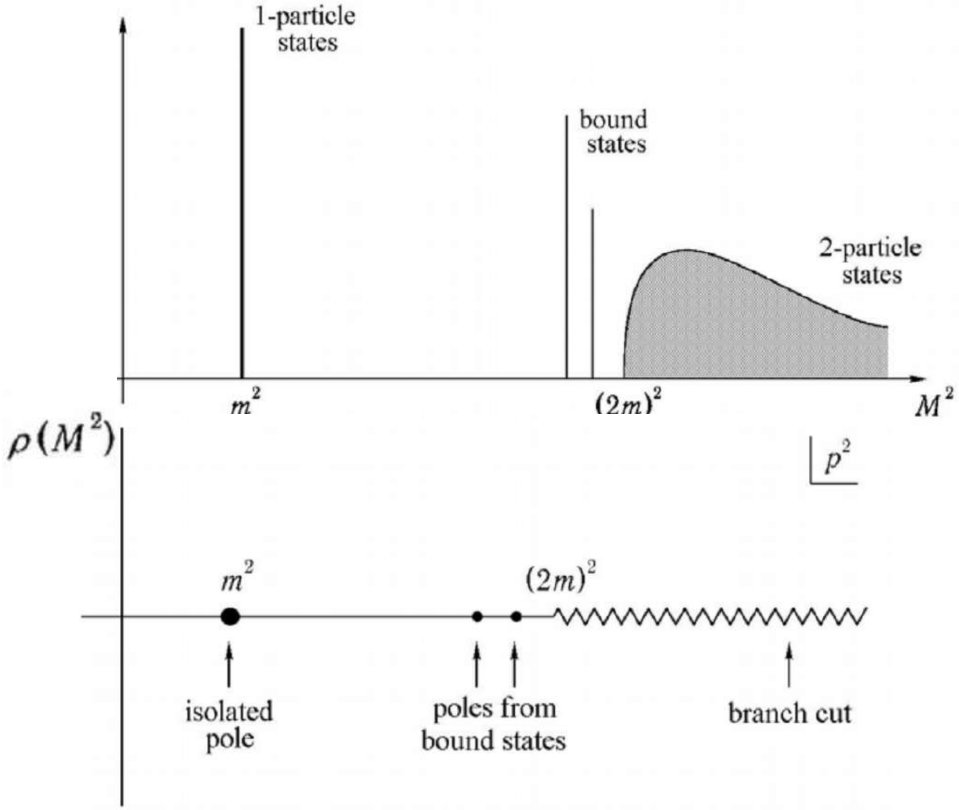

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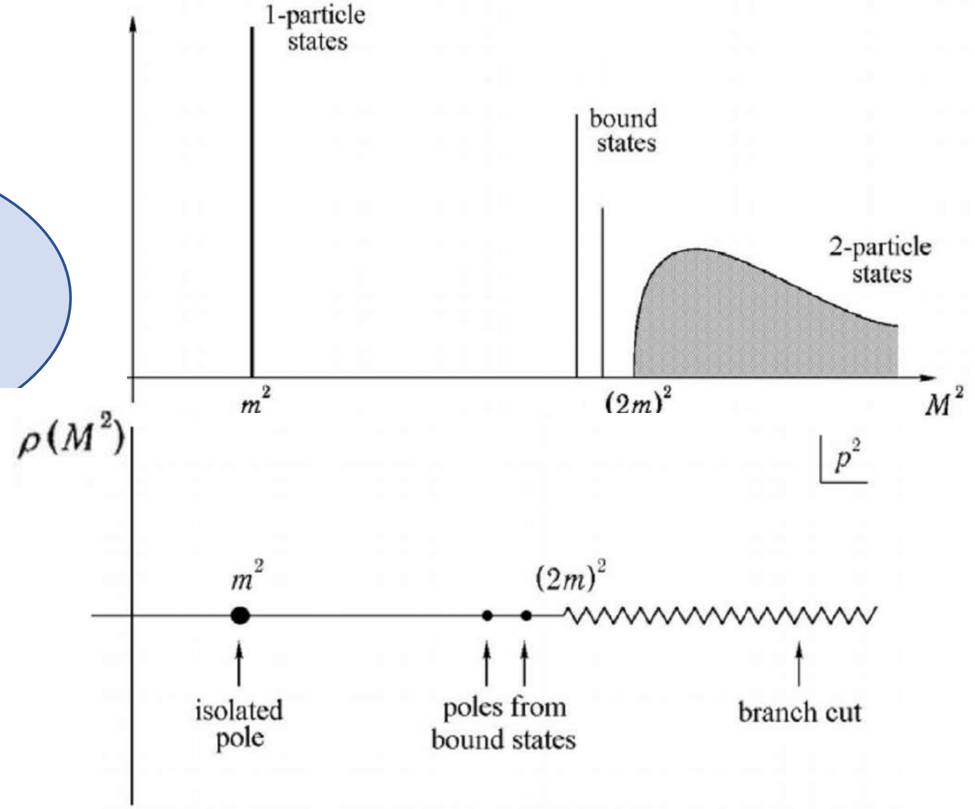

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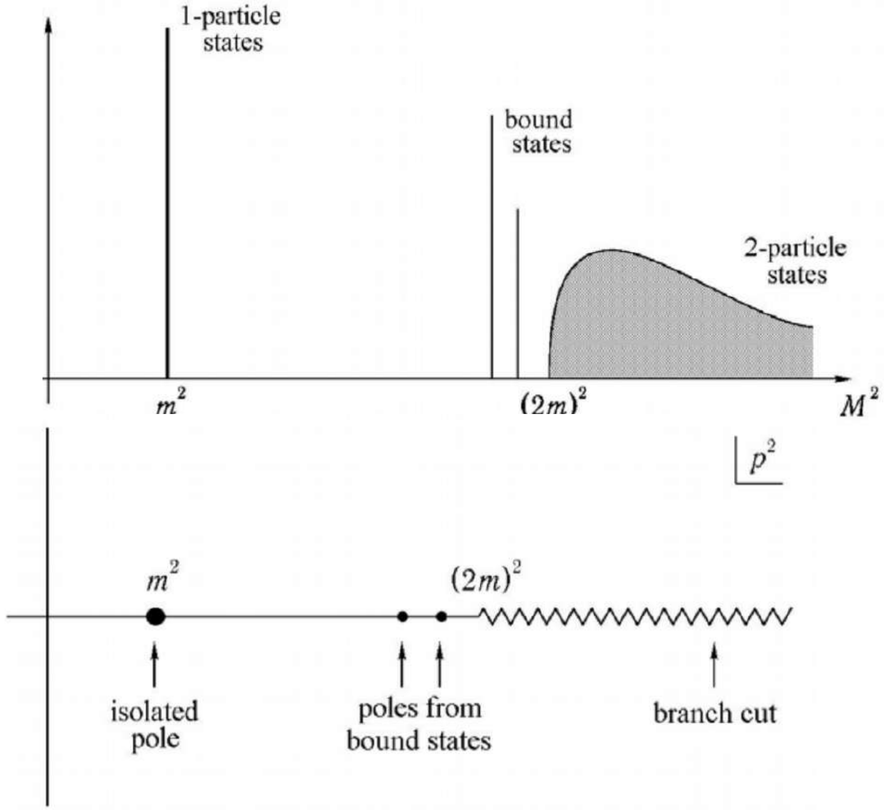


$$\mathrm{Disc}\frac{\mathrm{Tr_c}}{N_c}\langle\Omega|i\tilde{S}(p)|\Omega\rangle = \frac{1}{(2\pi)^3}\rho(p^2)\theta(p^2)\theta(p^-)$$

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

Integrated g.i. quark propagator

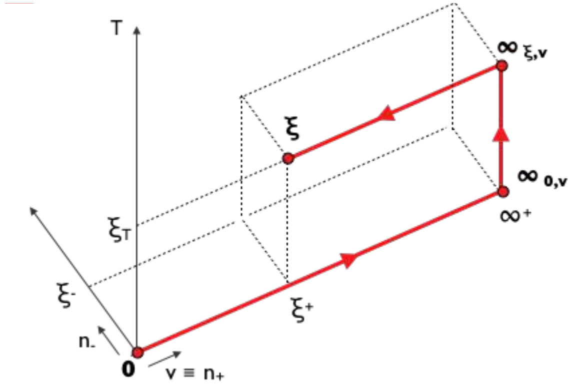
- Boost quark at large light-cone momentum:

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

$$\boxed{w = n^+}$$

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 $1/k^-$

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

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

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

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

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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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$$\boxed{\not{k} + m = k^- \gamma^+ + \not{k}_\perp + m\mathbb{I} + \frac{m^2 + \boldsymbol{k}_\perp^2}{2k^-}\gamma^-}$$

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Integrated g.i. quark propagator

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

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- In *any gauge*:

$$(k\quad) = J^{[\quad]} = \frac{\theta(k\quad)}{2(2\pi)^3}\int_0^\infty dp^2\, \boxed{\rho_3(p^2)}$$

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$$\zeta(k \quad) = \frac{k}{\Lambda} J^{[\,]} = \frac{\theta(k \quad)}{2\Lambda(2\pi)^3} \int dp^2 \, \boxed{\sqrt{p^2}\,\rho_1(p^2)}$$

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$$\omega(k\ \ , \boldsymbol{k_T}) = \left(\frac{k}{\Lambda}\right)^2 J^{[\ \ ]} = \frac{\theta(k\ \ )}{(2\Lambda)^2(2\pi)^3} \boxed{\mu_j^2 + \tau_j^2 + \boldsymbol{k_T^2})}$$

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Sum rules

- In *__any gauge__*:

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

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

$$0 = \int_0^\infty dp^2 \, p^2 \, \rho_0(p^2)$$

- Can be used to verify actual calculations of the quark propagator!

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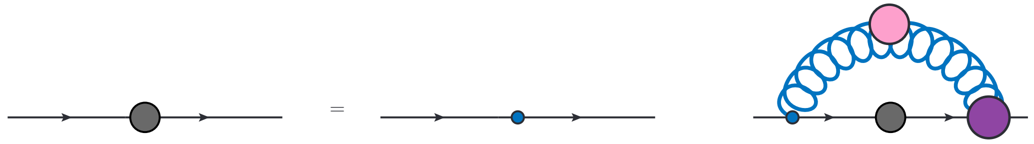

(e.g, DSE calculations)

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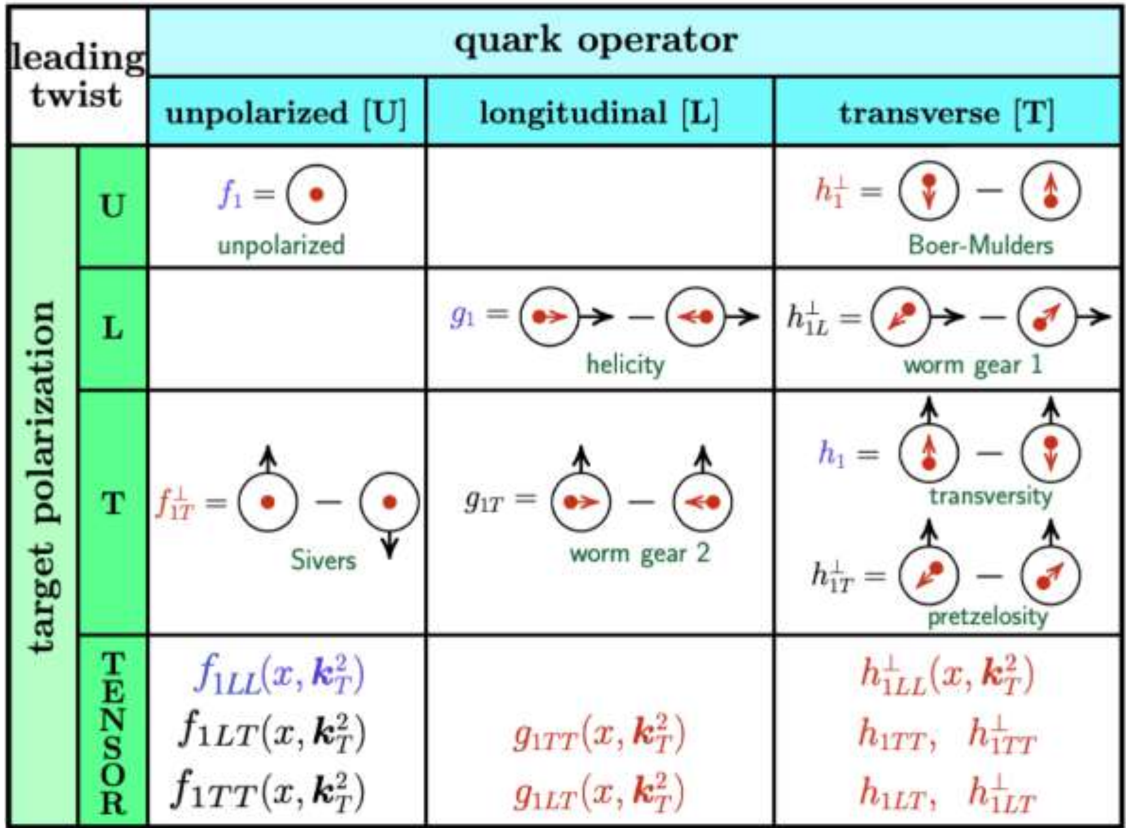
Gauge invariant generalization of the gauge dependent dressed quark mass



leading twist		quark operator		
		unpolarized [U]	longitudinal [L]	transverse [T]
target polarization	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***:

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

Final state interactions ”vanish”

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Final state interactions "vanish"

- But in other gauges

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

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

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

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- But in other gauges

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

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

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

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

Summary

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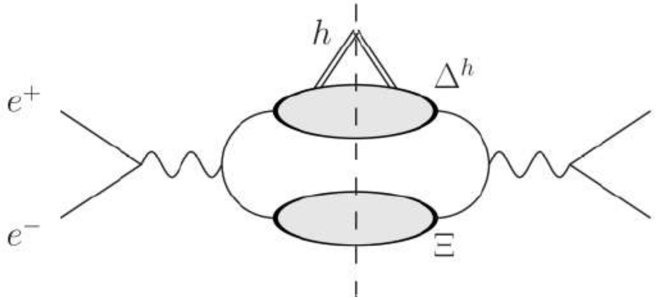

Summary

- M_j color screened gauge invariant mass
  - Non-vanishing even in the chiral limit
  - Provides a direct way to probe dynamical chiral symmetry breaking
  - It’s calculable, but moreover.. It can be measured!

(In progress)