The dressed quark propagator and new TMD sum rules

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Hampton U. and Jefferson Lab

Light Cone 2018

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Based on: Accardi, Signori, work in progres

Accardi, Bacchetta, PLB 773 (2017) 632

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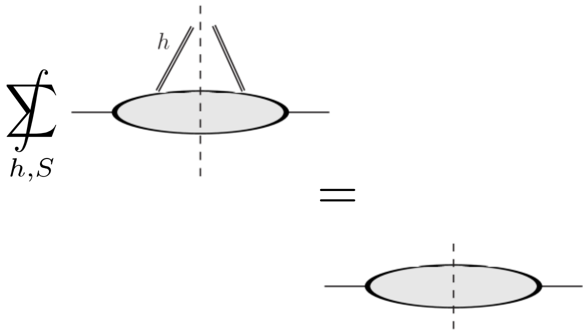
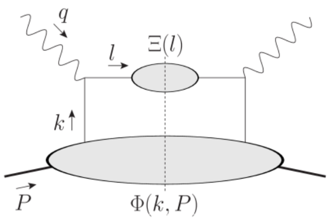
Jefferson Lab

Overview

- **Novel TMD sum rules**
  - Quarks are not asymptotic states
  - New sum rules, old ones revisited
  - Single, and di-hadron FFs
- **Inclusive DIS with jet correlators**
  - g2: new coupling to transversity
  - Burkhardt-Cottigham sum rule extended
  - Single-inclusive e^+-e^- annihilation
- **Final thoughts**





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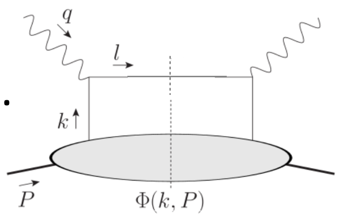


New momentum sum rules

Accardi, Signori, in preparation

Semi-inclusive vs. jet correlators - 1

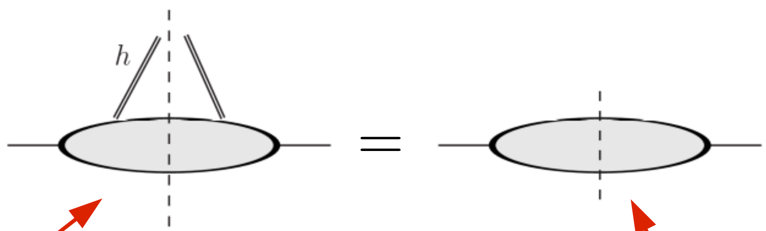
- Idea: generalize quark sum rule

AA, Bachetta '17
(Collins, Soper '82 ; Meissner, Metz, Pitonyak '10)

$$\sum_{h,S} \int d^2 p_{hT} \frac{dp_h^-}{2p_h^-} \, p_h^- \, \Delta^h(l, p_h) = l^- \, \Xi(l)$$

Graphically:

$$\frac{1}{2} \sum_{h,S} \int d^2 p_{hT} dz$$



SIDIS $q \rightarrow h{+}X$ correlator

"Jet" $q \rightarrow X$ correlator
(dressed & cut quark prop.)

- Dirac projections $\Longrightarrow$ TMD-level sum rules
- Use p_{hT}^{α} $\Longrightarrow$ further sum rules

Semi-inclusive vs. jet correlators - 2

- Idea: generalize quark sum rule *AA, Bachetta '17* *(Collins, Soper '82 ; Meissner, Metz, Pitonyak '10)*

$$\sum_{h,S} \int d^2 p_{hT} \frac{dp_h^-}{2p_h^-}\, p_h^- \, \Delta^h(l, p_h) = l^- \, \Xi(l)$$

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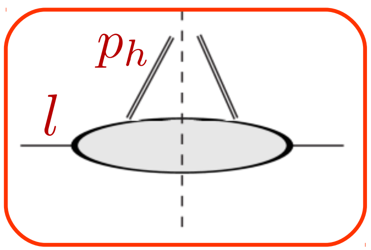

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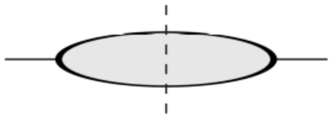

SIDIS $q \to h+X$ correlator:

$$\Delta_{ij}(l, p_h; n_+) = \sum_X F.T. \langle 0 | \mathcal{U}^{n_+}_{(+\infty,\eta)} \, \psi_i(\eta) | h, X\rangle \langle h, X | \bar{\psi}_j(0) \, \mathcal{U}^{n_+}_{(0,+\infty)} \, | 0 \rangle$$

Semi-inclusive vs. jet correlators - 2

- Idea: generalize quark sum rule

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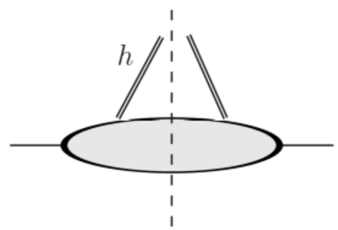
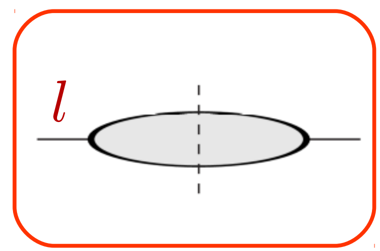
$$\frac{1}{2} \sum_{h,S} \int d^2 p_{hT} dz$$ 

$=$ 

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"Jet" $q \rightarrow X$ correlator

$$\Xi_{ij}(l, n_+) = F.T. \langle 0 | \, \mathcal{U}^{n_+}_{(+\infty,\eta)} \, \psi_i(\eta) \bar{\psi}_j(0) \, \mathcal{U}^{n_+}_{(0,+\infty)} \, | 0 \rangle$$

Connection to quark spectral function

- Dirac expansion:

$$\Xi(l, n_+) = \Lambda A_1(l^2) \; + A_2(l^2) \not{l} \; + O\Big(\frac{\Lambda^2}{l \cdot n^+}\Big)$$

- Quark spectral function:

$$\Xi(l) = \int d\mu^2 \big[\mu \, J_1(\mu^2) \, \mathbb{I} + J_2(\mu^2) \not{l} \, \big] \, \delta(l^2 - \sigma^2)$$

$$J_2(\sigma^2) \geq J_1(\sigma^2) \geq 0 \quad \text{and} \quad \int d\sigma^2 J_2(\sigma^2) = 1$$

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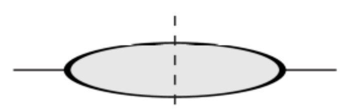
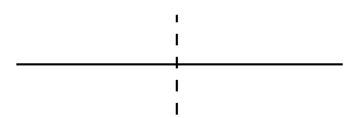
- Finally:

$$\boxed{\Xi(l) = 1\not{l} \; + M_q\,\mathbb{I} \; + \; \text{twist-4 terms}}$$

$$M_q \equiv \int d\mu^2\, \mu\, J_1(\mu^2) \sim O(100\text{MeV}) \qquad \gg \qquad m_q = O(1\text{MeV})$$

"jet mass" := $\mathrm{Tr}\big[$  $\big]$ $\qquad$ $\mathrm{Tr}\big[$  $\big]$

Quark-quark TMD sum rules

- General jet correlator sum rule: *AA, Signori '18*

$$\sum_h \int d^2 p_{hT} \frac{dp_h^-}{2p_h^-} p_h^\mu \, \Delta^h(l, p_h) = F.T. \langle 0 | \, \mathcal{U}^{n_+}_{(+\infty,\eta)} \, \psi_i(\eta) \, \hat{\boldsymbol{P}} \, \bar{\psi}_j(0) \, \mathcal{U}^{n_+}_{(0,+\infty)} \, |0\rangle$$

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$$\sum_h \int d^2 p_{hT} \frac{dp_h^-}{2p_h^-} p_h^\mu \Delta^h(l, p_h) = \begin{cases} l^\mu \, \Xi(l) & \mu = - \quad \text{longitudinal} \\ 0 & \mu = 1,2 \quad \text{transverse} \end{cases}$$

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- For TMDs, take suitable traces:

	Longitudinal	**Transverse**
Twist-2	*Collins-Soper* $\sum_{h,S_h} \int dz\, z\, D_{1h}(z) = 1$	*Schaefer-Teryaev* $\sum_{h,S_h} \int dz\, z\, H_{1h}^{\perp(1)}(z) = 0$

(see Collins, Soper '82 ; Meissner, Metz, Pitonyak '10)

$$f^{(1)}(z) \equiv \int d^2 P_{hT} \frac{P_{hT}^2}{2\Lambda^2} f(z, P_{hT})$$

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Twist-3	$\sum_{h,S_h} \int dz \, E_h(z, p_{hT}) = \frac{M_q}{\Lambda}$ **NEW!**	$\sum_{h,S_h} \int dz \, D_h^{\perp(1)}(z) = 0$ **NEW!**
	$\sum_{h,S_h} \int dz \, H_h(z) = 0$ **NEW!**	$\sum_{h,S_h} \int dz \, G_h^{\perp(1)}(z) = 0$ **NEW!**

$$f^{(1)}(z) \equiv \int d^2 P_{hT} \frac{P_{hT}^2}{2\Lambda^2} f(z, P_{hT})$$

Quark-gluon-quark TMD sum rules

- Using Equation of Motion relations in q-q sume rules:

Longitudinal

$$\left\{ \begin{array}{l} \displaystyle\sum_{h,S_h} \int dz\, \widetilde{E}_h(z) = \frac{M_q - m_q}{\Lambda} \quad \text{NEW!} \\ \displaystyle\sum_{h,S_h} \int dz\, \widetilde{H}_h(z) = 0 \quad \text{NEW!} \end{array} \right.$$

Transverse

$$\left\{ \begin{array}{l} \displaystyle\sum_{h,S_h} \int dz\, \widetilde{D}^{\perp(1)}(z) = \frac{\langle p_{hT}^2/z^2 \rangle}{2\Lambda^2} \,^* \quad \text{NEW!} \\ \displaystyle\sum_{h,S_h} \int dz\, \widetilde{G}^{\perp(1)}(z) = 0 \quad \text{NEW!} \end{array} \right.$$

* in the "parton frame", l_T=0
($= \langle l_T^2 \rangle$ in "hadron frame")

Quark-gluon-quark TMD sum rules

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NEW!

NEW!

Transverse

$$\begin{cases} \displaystyle\sum_{h,S_h} \int dz\, \widetilde{D}^{\perp(1)}(z) = \frac{\langle p_{hT}^2/z^2\rangle}{2\Lambda^2} \; {}^{*} \\ \displaystyle\sum_{h,S_h} \int dz\, \widetilde{G}^{\perp(1)}(z) = 0 \end{cases}$$

NEW!

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$\boxed{M_q^{\text{pert}} = m_q \Rightarrow \text{Old ones}}$

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Quark-gluon-quark TMD sum rules

- Using Equation of Motion relations in q-q sume rules:

Longitudinal

$$\sum_{h,S_h}\int dz\,\widetilde{E}_h(z) = \frac{M_q - m_q}{\Lambda} \quad \textbf{NEW!} \quad \Longrightarrow \quad \text{Transversity in DIS!}$$

Diehl-Sapeta

$$\sum_{h,S_h}\int dz\,\widetilde{H}_h(z) = 0 \quad \textbf{NEW!} \quad \Longrightarrow \quad \int dz\, z\, F_{UT}^{\sin\phi_S}(x,z) = 0$$

NEW: proven at correlator level

Transverse

$$\sum_{h,S_h}\int dz\,\widetilde{D}^{\perp(1)}(z) = \frac{\langle p_{hT}^2/z^2\rangle}{2\Lambda^2} \quad {}^{*} \quad \textbf{NEW!}$$

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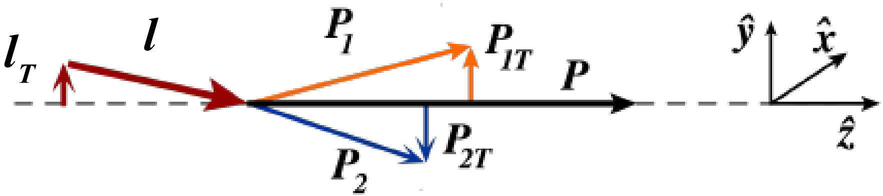
Di-hadron sum rules



→ *Matevosyan (Thu 9:45 am)*

- Two semi-inclusive hadrons
  - Di-hadron frame

$$P_{2h} = P_{h,1} + P_{h,2} \qquad z = P_{2h}^{-}/l^{-}$$

$$R = \frac{1}{2}(P_{h,1} - P_{h,2}) \qquad \zeta = P_{h,1}^{-}/P_{2h}^{-}$$

- Dihadron correlator:

$$\Delta^{2h}(l; P_{2h}, R) = F.T. \sum_X \langle 0|\psi(\xi)|P_{2h}, R, X\rangle\langle P_{2h}, R, X|\bar{\psi}(\xi)|0\rangle\rangle$$

- Two correlators → two sets of sum rules
  - **Total P_{2h}** : analogous to previous ones
  - **Relative R** : new!

Di-hadron sum rules

- **Relative momentum sum rules:**

$$\sum_{h_{1,2},S_{1,2}} \int dz\, d\zeta\, H_1^{\sphericalangle(0,1)}(z,\zeta) = 0$$

$$\sum_{h_{1,2},S_{1,2}} \int dz\, d\zeta\, D^{\sphericalangle(0,1)}(z,\zeta) = 0$$

$$\sum_{h_{1,2},S_{1,2}} \int dz\, d\zeta\, G^{\sphericalangle(0,1)}(z,\zeta) = 0$$

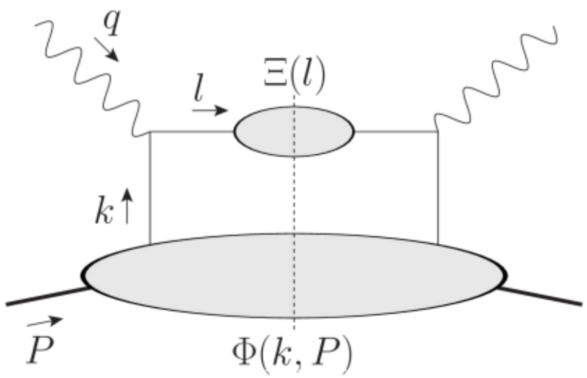
$$f^{(0,1)}(z) \equiv \int d^2R_{hT}\, R_T^2\, f(z, P_{hT}, R_T)$$

Inclusive DIS with jet correlators

Accardi, Bacchetta, PLB 773 (2017) 632

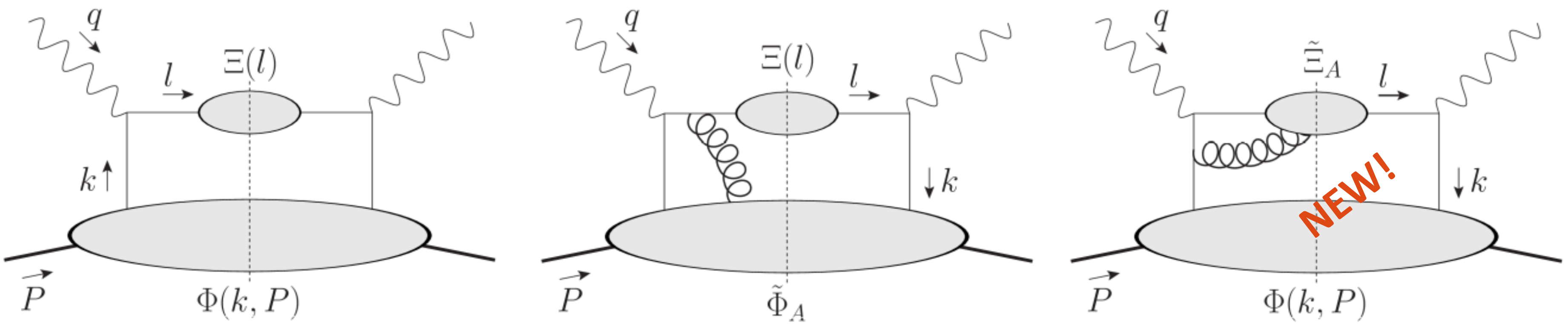
Inclusive DIS with jet correlators

AA, Bacchetta, PLB 773 ('17) 632



Inclusive DIS with jet correlators

AA, Bacchetta, PLB 773 (‘17) 632



Inclusive DIS with jet correlators

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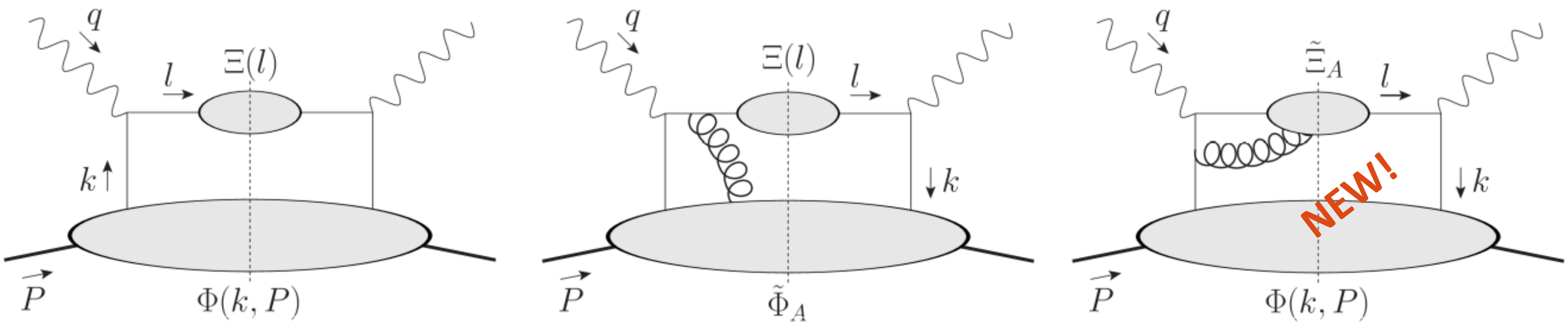
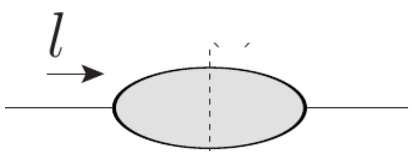


Jet correlators: $\rightarrow$ non-asymptotic quark states



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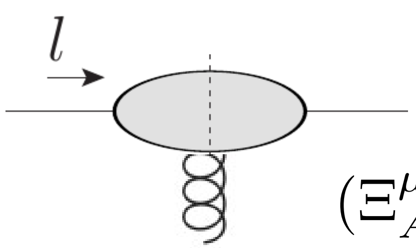
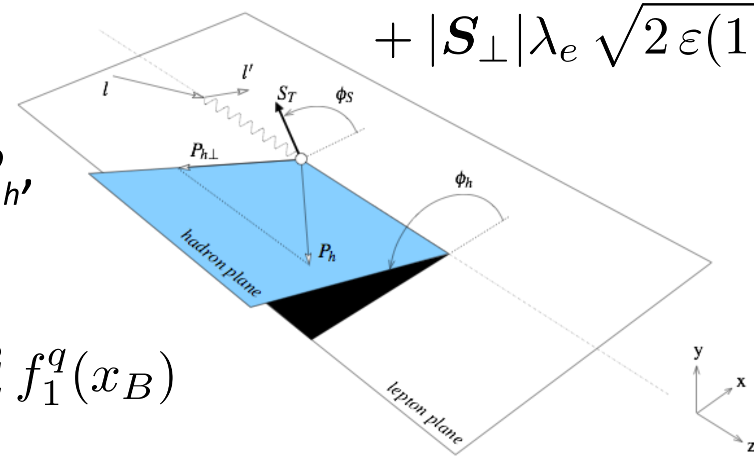


$$(\Xi^\mu_A)_{ij} = F.T.\,\langle 0|\,\mathcal{U}^{n_+}_{(+\infty,\eta)}\,gA^\mu(\eta)\;\psi_i(\eta)\;\bar{\psi}_j(0)\,\mathcal{U}^{n_+}_{(0,+\infty)}\,|0\rangle$$

DIS cross section

- Inclusive DIS

$$\frac{d\sigma}{dx_B\,dy\,d\phi_S} \propto \Big\{ F_T + \varepsilon F_L + S_\parallel \lambda_e \sqrt{1-\varepsilon^2}\; F_{LL} + |\boldsymbol{S}_\perp| \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\; \cos\phi_S\, F_{LT}^{\cos\phi_S} \Big\}$$



- Integrate SIDIS over P_h, use TMD sum rules:

$$F_T = x_B \sum_q e_q^2\, f_1^q(x_B)$$

$$F_L = 0$$

$$F_{LL} = x_B \sum_q e_q^2\, g_1^q(x_B)$$

Transversity in inclusive DIS!

$$F_{LT}^{\cos\phi_S} = -x_B \sum_q e_q^2 \frac{2M}{Q} \left(x_B g_T^q(x_B) + \boxed{\frac{M_q - m_q}{M} h_1^q(x_B)} \right)$$

g2 structure function revisited

AA, Bacchetta, PLB 773 ('17) 632

- Using EOM, Lorentz Invariance Relations:

$$g_2(x_B) - g_2^{WW}(x_B) = \frac{1}{2}\sum_a e_a^2 \Bigg(g_2^{q,\mathrm{tw3}}(x_B) + \overbrace{\frac{m_q}{M}\left(\frac{h_1^q}{x}\right)^{\star}}^{\equiv\, g_2^{quark}}(x_B) + \overbrace{\boxed{\frac{M_q - m_q}{M}\,\frac{h_1^q(x_B)}{x_B}}}^{\equiv\, g_2^{jet}} \Bigg)$$

Color force distribution

Transversity in inclusive DIS!

- Consequences:
  - h1 accessible in inclusive DIS! $\leftrightarrow$ Potentially large signal
  - new background to extraction of qGq effects

$$f^*(x) = -f(x) + \int_x^1 \frac{dy}{y} f(y)$$

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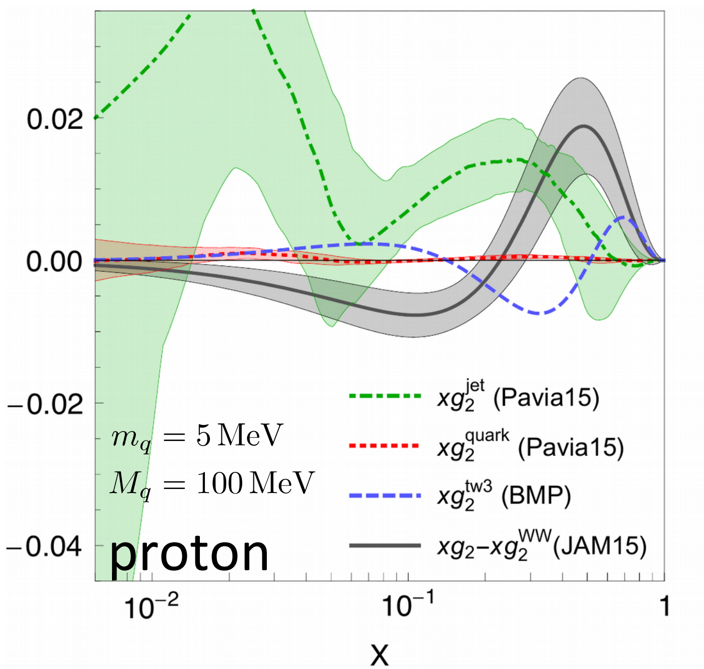

g2 structure function revisited

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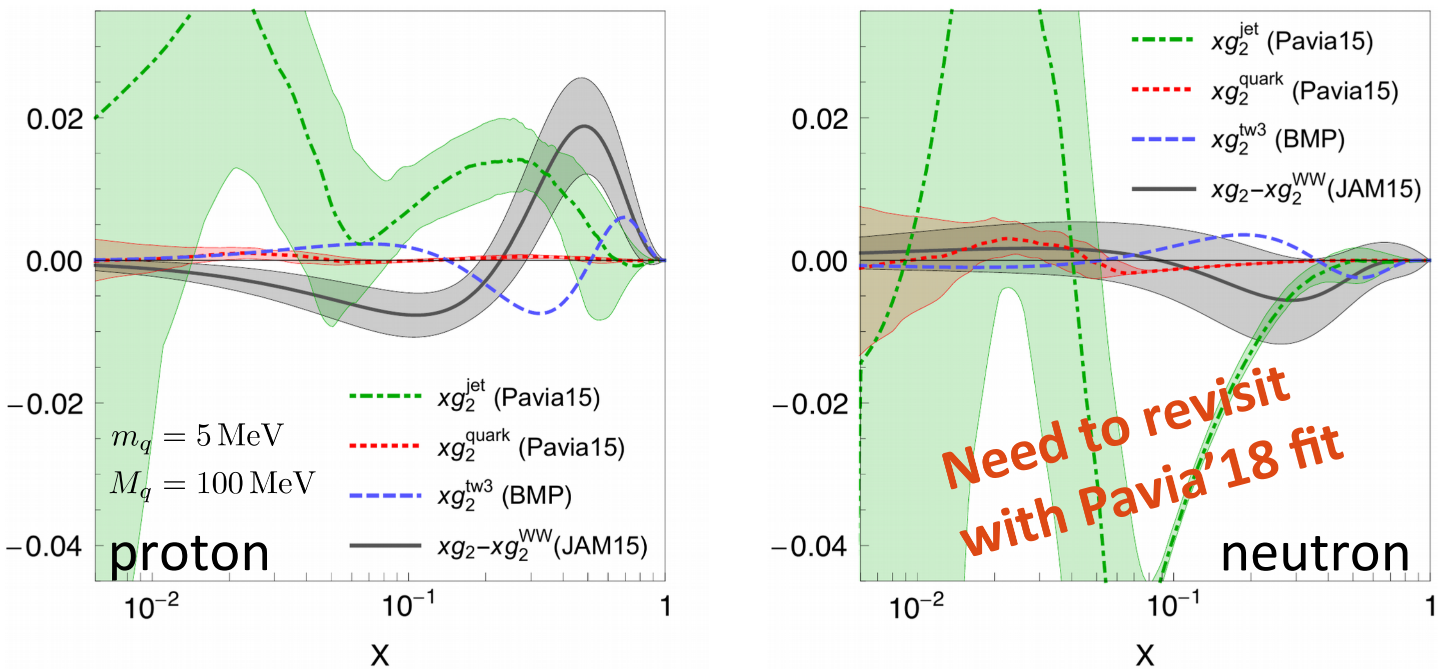

Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

- Taking moments of g_2 with $M_u \approx M_d \equiv M_{jet}$

Burkhardt-Cottingham $$\int_0^1 g_2(x) = M_{\text{``jet''}} \int_0^1 dx\, \frac{h_1(x)}{x}$$

$\longrightarrow$ Broken by quark vacuum fluctuations!

$\longrightarrow$ *see also caveat in original BC paper*

Perturbatively: $h_1 \sim x$

Small-x asymptotics:

$$g_1^{NS} \sim 1/x^{\epsilon_g} \quad \epsilon_g = \sqrt{\alpha_s N_c/\pi} \approx 0.56$$

$\rightarrow$ *Kovchegov, Pitonyak, Sievert PRD(2017)93*

But h_1 is also non-singlet, expect

$$h_1 \sim 1/x^{\epsilon_h} \quad \epsilon_h = \epsilon_g > 0 \quad !!$$

- Is BC badly broken? 1/Nc corrections non negligible? Or ...?

Novel non-perturbative sum rules

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Burkhardt-Cottingham

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→ Broken by quark vacuum fluctuations!

→ *see also caveat in original BC paper*

→ **How does spin propagate to small x?**

Perturbatively:

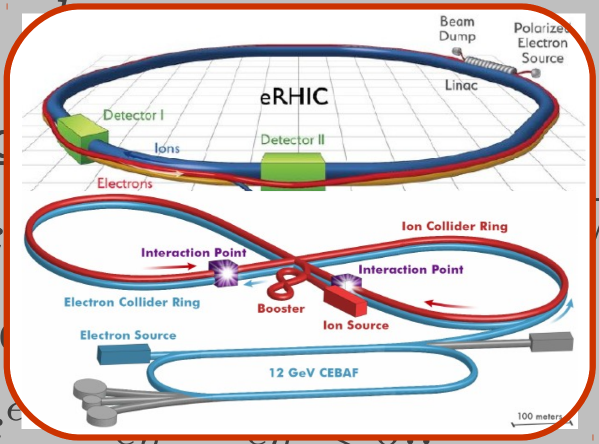
Small-x asympt

$g_1^{NS} \sim x$ … $\sqrt{2\pi} \approx -0.92$

→ *Kovchegov, Pitonyak, Sievert PRD(2017)93*

But h_1 is also n

$h_1 \sim x^{e}$



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Efremov-Teryaev-Leader

$$\int_0^1 x g_2^{q-\bar{q}}(x) = 2\, M_{“jet”} \underbrace{\int_0^1 dx\, h_1^{q-\bar{q}}(x)}_{\text{Tensor charge } \delta_T}$$

$\rightarrow$ Novel way to measure the tensor charge!

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Efremov-Teryaev-Leader

$$\int_0^1 x g_2^{q-\bar{q}}(x) = 2 \, M_{\text{“}jet\text{”}} \underbrace{\int_0^1 dx \, h_1^{q-\bar{q}}(x)}_{\text{Tensor charge } \delta_T}$$

Color polarizability

$$\int_0^1 \left[3x^2 g_2(x) - 2x^2 g_1(x) \right]$$

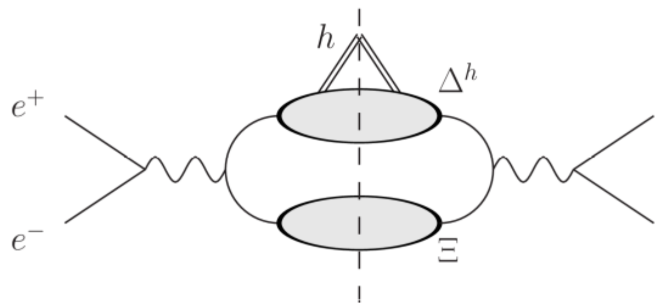
$$= d_2 + \underbrace{3 \, M_{\text{“}jet\text{”}} \int_0^1 dx \, x \, h_1(x)}_{\text{“background”}} + O(m_q)$$

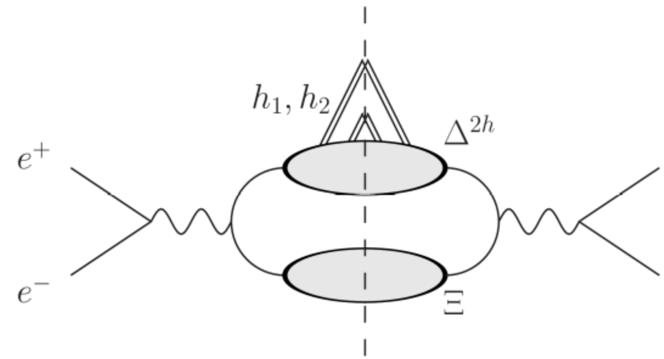
Color force – Burkardt “pure twist-3” $\sim \langle P | \bar{\psi} \gamma^+ F^{+\alpha} \psi | P \rangle$

Measuring the jet correlator

Accardi, Bacchetta, Signori, Radici, in prep.

- Jet mass $\mathbf{M_{jet}}$ **can be measured in polarized $e^+ + e^-$:**





  - Needs **LT asymmetry** in semi-inclusive **Lambda** production

$$\frac{d\sigma^{LT}(e^+e^- \to \Lambda X)}{d\Omega dz}$$

$$= \frac{3\alpha^2}{Q^2} \lambda_e \sum_a e_a^2 \left\{ \frac{C(y)}{2} \lambda_h G_1 + D(y) |\boldsymbol{S}_T| \cos(\phi_S) \frac{2M_h}{Q} \left(\frac{G_T}{z} + \frac{M_q - m_q}{M_h} H_1 \right) \right\}$$

  - Similarly a **LU asymmetry** in unpolarized **dihadron** production

Final thoughts

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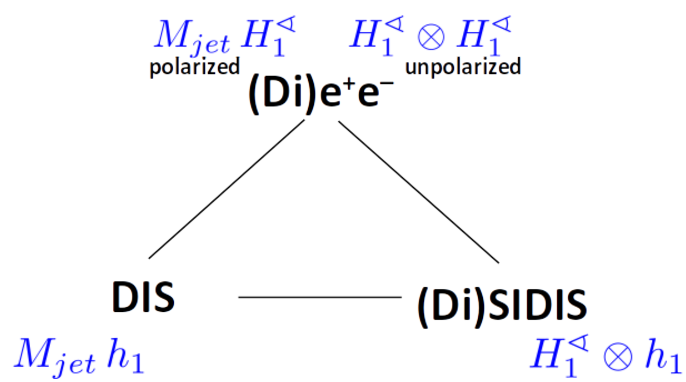
- **New FF sum rules**
  - FF: quark-quark & q-gluon-q (complete up to twist 3)
  - DiFF : quark-quark only (work in progrees)

- **New DIS theory and phenomenology**
  - Transversity contributes to <u>inclusive</u> g_2
  - Extended BC and ETL sum rules
    - New handle on proton tensor charge
  - Open question: spin transport to small *x* !

- **How to measure jet correlators?**
  - Need a new "universal fit" of M_{jet}, h_1, $H_1^{\sphericalangle}$

J.Ethier (Wed 8:55 am)



Thank you!

Need polarized e+e- colliders!

- Are **existing facilities** enough?

adapted from Paticle Data Book

	BEPC	HIEPA	super KEKB	ILC	JLab/eEIC ??
E beam [GeV]	1.9	symmetric	4 (e^{-}) 7 (e^{-})	250	?
√s [GeV]	3 – 5	2 – 7	10	500	?
polarization	? (beam self-polarization)	One beam	maybe	80% e^{-} 60% e^{+}	YES!

- Can we get a (polarized) **e+ e- collider at JLab / BNL?**
  - At JLab12 ? JLEIC ? eRHIC?
- What else is interesting to study?
  - Factorization tests for FFs (low s, unpol), …

Ideas?

Pavia 18 transversity fit

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First Extraction of Transversity from a Global Analysis of Electron-Proton and Proton-Proton Data

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