Accessing the proton's tensor structure in inclusive DIS

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In collaboration with A.Bacchetta – arXiv:1706.02000

HAMPTON UNIVERSITY THE STANDARD OF EXCELLENCE

Jefferson Lab

Why jet correlators?

- **Quarks are not asymptotic states**
  - More mass than m_q produced in the current region!
    - "Jet mass corrections" *→ Accardi, Qiu, JHEP 2008*
    - Novel contributions to inclusive DIS structure functions *→ Accardi, Bacchetta, arXiv:1706.02000*
- **Collinear factorization with "jet correlators"**
  - Jet correlators, "jet mass" Mq, and new TMD sum rules
  - Transversity accessible in LT inclusive asymmetries:
    - New, large contribution to $g_2(x)$
    - Non-perturbative extension of BC sum rule
- **Some phenomenological consequences**
- **Outlook**

Collinear Factorization with Jet Correlators

TMDs in spin ½ targets

		PARTON SPIN	
QUARKS	γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^\alpha\gamma_5$
TARGET SPIN U	f_1		$h_1^\perp$
TARGET SPIN L		g_1	$h_{1L}^\perp$
TARGET SPIN T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

→ *P. Mulders, QCDev2017*

- Integrated (collinear) correlator: only circled ones survive
- Christ-Lee theorem (1970): ***h*** $_{\mathbf{1}}$ **not observable in inclusive DIS**
- Not quite true:
  - Vacuum fluctuations can flip the spin of the struck quark
  - **Large contribution ~*h*$_1$ pops up in the g$_2$ – g$_2^{WW}$ structure function**

Measuring g_2

- Need to measure **double L-T spin asymmetry in inclusive DIS**

$$\ell(l) + N(P) \longrightarrow \ell(l') + X$$

$$x_B = \frac{Q^2}{2P\cdot q} \qquad Q^2 = (l-l')^2$$

$$\gamma = 2Mx_B/Q$$

$$y = \frac{P\cdot q}{P\cdot l} \qquad \epsilon = \frac{1-y-\gamma^2y^2/4}{1-y+y^2/2+\gamma^2y^2/4}$$

(ignore hadrons for now, will come back later)

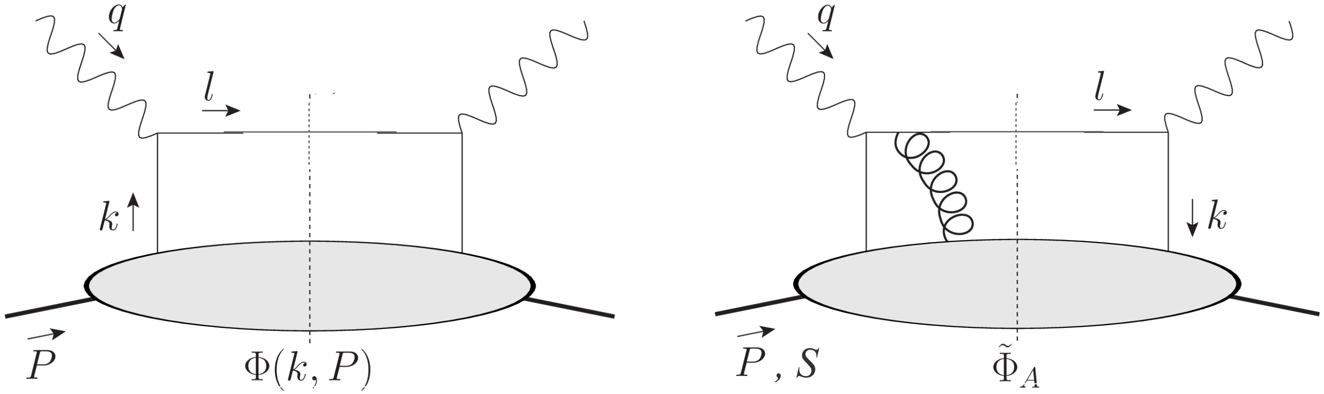
Long. pol. beam
Trans. pol. target

$$\frac{d\sigma_{LT}}{dx\,dy\,d\phi_S} \propto \lambda_e |S_\perp| \sqrt{2\epsilon(1-\epsilon)} \cos\phi_S \underbrace{F_{LT}^{\cos\phi_S}(x,Q^2)}_{-2x\gamma\left(g_1(x,Q^2)+g_2(x,Q^2)\right)}$$

g_2 structure function - standard analysis

AA, Bacchetta, Melnitchouk, Schlegel, 2009
Jaffe, Ji, 1991

$$W_{\mu\nu} = i_{\mu\nu\lambda\sigma}\frac{q^\lambda}{p\cdot q}\left[g_1 S^\sigma + g_2\left(S^\sigma - p^\sigma\frac{q\cdot S}{q\cdot p}\right)\right]$$



$+ \; h.c.$

$$g_2(x_B) - g_2^{WW}(x_B) = g_2^{tw3}(x_B) + \frac{m_q}{M}\left(\frac{h_1}{x}\right)^\star(x_B)$$

Wandzura-Wilczeck term

"pure twist-3" (qgq correlations)

quark mass term (negligible for light quarks)

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

g_2 moments - standard analysis

- **Burkhardt-Cottingham sum rule**

$$\int_0^1 dx\, g_2(x) = 0$$

Unless g_2^{tw3} pathological at large distances, or J=0 pole contributions ~ $\delta(x)$ $\rightarrow$ *Jaffe,Ji '91*

$\rightarrow$ *Burkardt, Koike, '02*

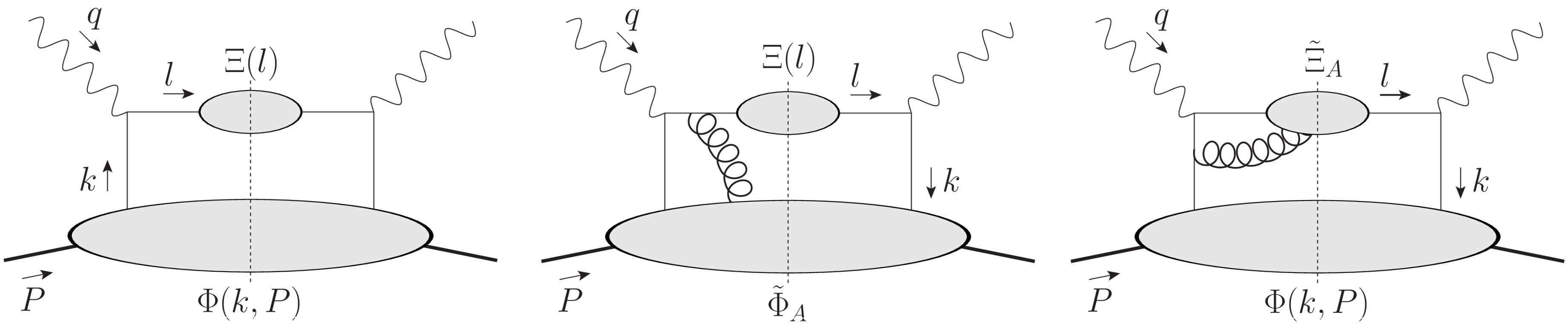
... or large spin-flip contributions $\rightarrow$ *Burkhardt, Cottingham '70*

- "pure twist-3" effects, e.g.,
Color force experienced by struck quark $\rightarrow$ *M.Burkardt*

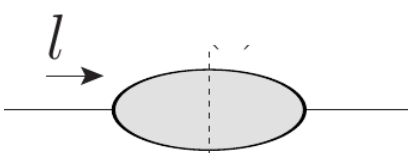
$$d_2 \equiv \int_0^1 dx\, x^2 [g_2(x) - g_2^{WW}(x)]$$
$$= 3g_2[2] + 2g_1[1] \sim \langle P|\bar{\psi}\gamma^+ F^{+\alpha}\psi|P\rangle$$

Inclusive DIS with jet correlators

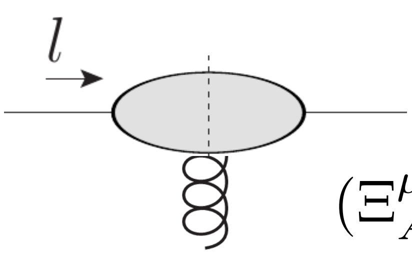
AA, Bacchetta, arXiv:1706.02000



Jet correlators

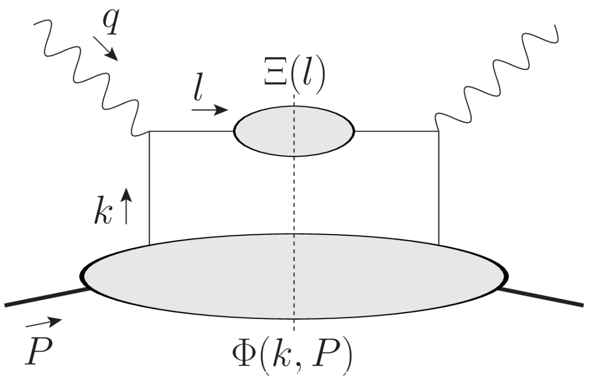


$$\Xi_{ij}(l,n_+) = F.T.\langle 0|\, \mathcal{U}^{n_+}_{(+\infty,\eta)}\, \psi_i(\eta)\bar\psi_j(0)\, \mathcal{U}^{n_+}_{(0,+\infty)}\, |0\rangle$$



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

Factorization



- At order $1/Q$, neglect k^- compared to q^-
  - The cross section depends only on the **integrated jet correlator**

$$\Xi(l^-, \boldsymbol{l}_T) \equiv \int \frac{dl^2}{2l^-}\,\Xi(l) = \frac{\Lambda}{2l^-}\,\xi_1 \mathbf{1} + \xi_2 \frac{\not{n}_-}{2} + \text{ h.t. terms}$$

- Coefficients can be interpreted in terms of quark spectral functions:

$$\xi_1 = \int d\mu^2 \frac{\mu}{\Lambda} J_1(\mu^2) \equiv \frac{\boxed{M_q}}{\Lambda}$$

Spin-flip average “jet” mass
→ **can couple to transversity!**

$$\xi_2 = \int d\mu^2 J_2(\mu^2) = 1$$

Exactly, due to CPT invariance

- Positivity constraints imply

$$0 < M_q < \int d\mu^2 \mu\, J_2(\mu^2) \quad \Longrightarrow \quad \boxed{M_q = O(100 \text{ MeV})}$$

Much larger than m_q !

Full twist-3 analysis

- Convenient and instructive to integrate the SIDIS tensor

$$W^{\mu\nu}(x_B) = \sum_h \int dz\, d^2p_{hT}\, z\, W_h^{\mu\nu}(z, p_{hT}, x_B)$$

- The piece of the SIDIS tensor with jet mass contributions is

[Bacchetta et al, JHEP 2007]

$$2\Lambda W^{\mu\nu} = i\frac{2\Lambda}{Q}\hat{t}^{[\mu}\epsilon_\perp^{\nu]\rho}S_{\perp\rho}$$
$$\times \sum_q e_q^2 \left[2x_B g_T^q(x_B) D_1^{q,h}(z, p_{hT}) + 2h_1^q(x_B)\tilde{E}^{q,h}(z, p_{hT})\right] + \ldots$$

Where e.o.m. relate the twist-3 TMD-FF $\tilde{E}$ to twist-2 TMD-FFs :

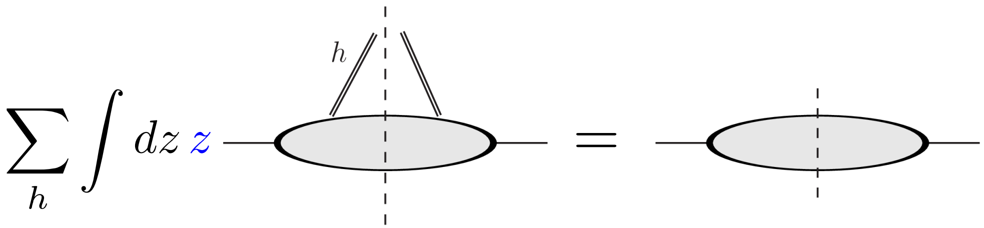
$$\tilde{E} = E - \frac{\boxed{m_q}}{\Lambda} z D_1$$

Current quark mass
~ few MeV

Jet and TMD sum rules

- Utilize the following jet correlator sum rule: → *AA, Bacchetta, arXiv:1706.02000*

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



- At TMD level, this implies:

$$\sum_h \int dz d^2 p_{hT} z D_1^h(z, p_{hT}) = \xi_2 = 1$$

$$\sum_h \int dz d^2 p_{hT} E^h(z, p_{hT}) = \xi_1 = \boxed{\frac{M_q}{\Lambda}}$$

$$\sum_h \int dz d^2 p_{hT} \tilde{E}^{q,h}(z, p_{hT}) = \boxed{\frac{M_q - m_q}{\Lambda}}$$

Novel TMD sum rules

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

Finally, the DIS cross section

- Inclusive DIS

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

- Structure functions:

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

$$F_L = 0$$

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

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

Transversity in inclusive DIS!

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Transversity in inclusive DIS!

Finally, the DIS cross section

- Inclusive DIS $\frac{d\sigma}{\ldots} \propto \Big\{ F_T + \varepsilon F_L + S_{\parallel}\lambda_e \sqrt{1-\varepsilon^2}\, F_{L\ldots}$

Deliverables	Observables	What we learn
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital ... 3D Imaging of quark's motion: valence + sea 3D Imaging of gluon's motion QCD dynamics in a unprecedented Q^2 (P_{hT}) range
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	$3^{\rm rd}$ basic quark PDF: valence + sea, tensor charge Novel spin-dependent hadronization effect QCD dynamics in a chiral-odd sector with a wide Q^2 (P_{hT}) coverage

Table 2.2: Science Matrix for TMD: 3D structure in transverse momentum space: (up... golden measurements; (lower) the silver measurements.

1212.1701/EPJA 2016

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

Transversity in inclusive DIS!

Some phenomenological consequences

g2 structure function revisited

- Using EOM, Lorentz Invariance Relations, can show that

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

Color force distribution

Transversity in inclusive DIS!

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

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

g2 structure function revisited

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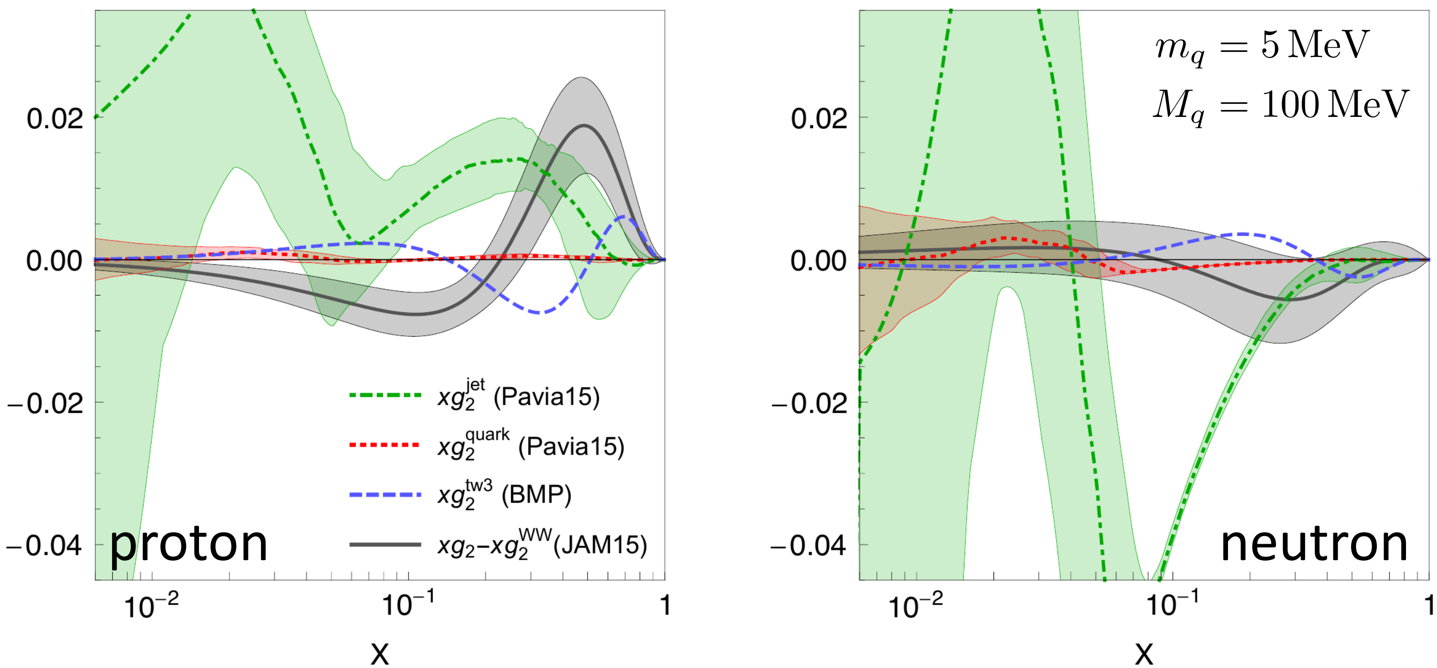
$$= \frac{1}{2}\sum_a e_a^2 \left(g_2^{q,\mathrm{tw3}}(x_B) + \overbrace{\frac{m_q}{M}\left(\frac{h_1^q}{x}\right)^{\star}(x_B)}^{\equiv\, g_2^{quark}} + \overbrace{\boxed{\frac{M_q - m_q}{M}\frac{h_1^q(x_B)}{x_B}}}^{\equiv\, g_2^{jet}} \right)$$



Novel non-perturbative sum rules

Accardi, Bacchetta – in preparation

- Taking moments of g2 with $M_u \approx M_d \equiv M_{jet}$

Burkardt-Cottingham

$$\int_0^1 g_2(x) = M_{\text{“jet”}} \int_0^1 dx \, \frac{h_1(x)}{x}$$

$\longrightarrow$ unlikely to still be zero!

$\longrightarrow$ <u>if</u> BC broken by finite amount, constrains:

$$h_1^q(x) \propto x^\epsilon \quad \epsilon > 0$$

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$\longrightarrow$ Small-*x* asymptotics:

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

$$g_1^{NS} \sim x^{\epsilon_g} \quad \epsilon_g = -\sqrt{\alpha_s N_c/\pi} \approx -0.6$$

But h_1 is also non-singlet, expect

$$h_1 \sim x^{\epsilon_h} \quad \epsilon_h = \epsilon_g < 0!!$$

– Is BC badly broken? 1/Nc corrections non negligible? Or …?

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$$g_1^{NS} \sim x^{\epsilon_g} \qquad \epsilon_g = -\sqrt{\alpha_s N_c/\pi} \approx -0.6$$

But h_1 is also non-singlet, expect

How does spin propagate to small x?

$$h_1 \sim x^{\epsilon_h} \qquad \epsilon_h = \epsilon_g < 0!!$$

– Is BC badly broken? 1/Nc corrections non negligible? Or … ?

Novel non-perturbative sum rules

Accardi, Bacchetta – in preparation

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Burkardt-Cottingham $$\int_0^1 g_2(x) = M_{\text{“jet”}} \int_0^1 dx\, \frac{h_1(x)}{x}$$

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

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

$\longrightarrow$ *Bacchetta's talk*

Novel non-perturbative sum rules

Accardi, Bacchetta – in preparation

- Taking moments of g2 with $M_u \approx M_d \equiv M_{jet}$

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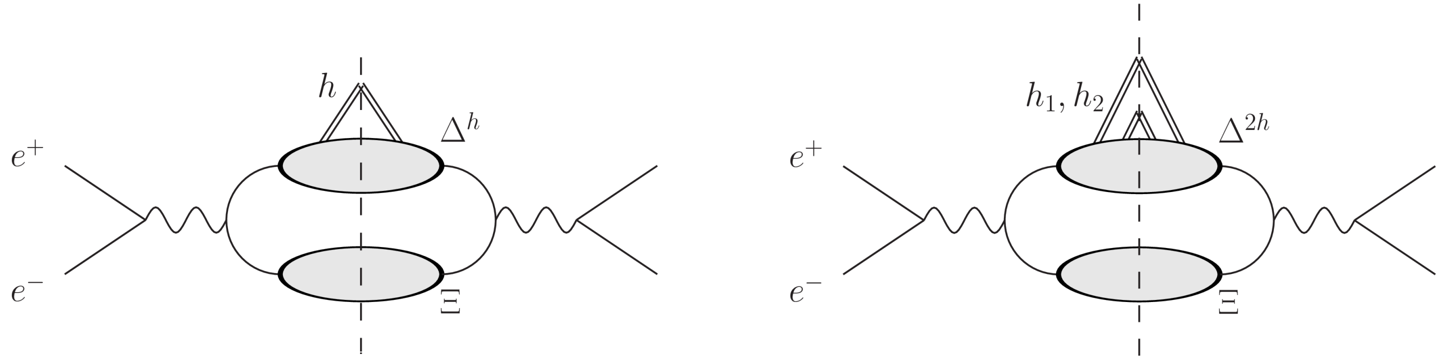
Color polarizability

$$\int_0^1 \left[3x^2 g_2(x) - 2x^2 g_1(x)\right] = \underbrace{d_2}_{\text{“pure twist-3”}} + 3\, M_{\text{“}jet\text{”}} \int_0^1 x h_1(x) + O(m_q)$$

Measuring the jet correlator

Related to confinement, mass generation → *Roberts' talk*

- **e- e+ collisions:** semi-inclusive Λ and di-hadron production



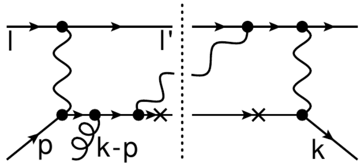
- **Universal fits:** → *AA parallel sessions*
  also Ethier, Sato, Melnitchouk, 1705.05889
  - Interplay of q, Δq, δq
  - Leave M_q as a free parameter

- **Lattice QCD:**
  - How to measure M_q (or the jet functions J_i themselves)?
  - Any relation to the quark condensate?

Outlook

Where are we going?

- **Jet correlators open a novel and rich phenomenology**
  - New terms in old observables (tensor charge in DIS!)
  - Signal enhancement in less studied channels
    - e.g. spin flip in single transverse target spin asymmetry
  - New observables



→ *Afanasiev et al., PRD77(2008)*
Schelegel, PRD87(2013)

- **Open theoretical questions**
  - Jet correlator effects in (interacting fields) OPE?
  - Small x behavior and BC sum rule

- **Need new data:**
  - Large x: JLab
  - Small x: EIC

  } g_2, h_1

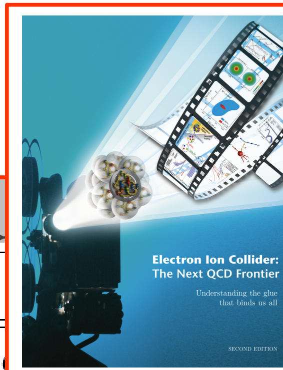
  - New asymmetries in e+e- $\longrightarrow$ hX

  } jet correlator M_q

Universal fits:
PDFs h_1, g_1 & g_2, f_1
FFs, di-h, ...

Where are we going?

- Jet correlators open a novel and rich phenomenology



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– Small x: EIC } g_2, h_1

– New asymmetries in e+e- ⟶ hX } jet correlator M_q

Universal fits:

PDFs h_1, g_1 & g_2, f_1

FFs, di-h, ...

Extra

Example: color polarizability

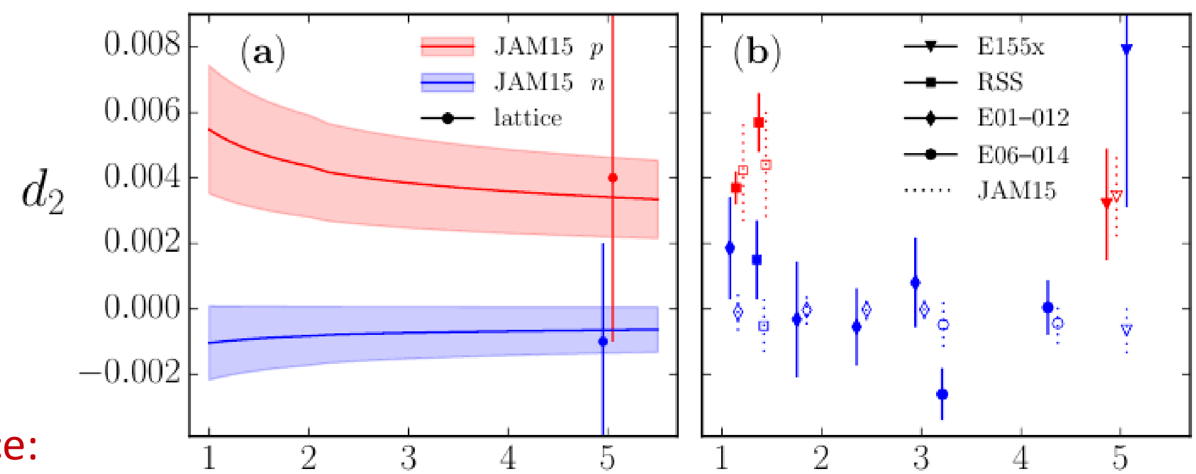
- Need to subtract jet term to obtain "pure twist-3" $d_2 \sim \langle \bar{q}\gamma^+ F^{+y} q \rangle$

$$d_2 = \int_0^1 dx\, [3x^2 g_2(x) - 2x^2 g_1(x)] - 3\, M_{\text{“}jet\text{”}} \underbrace{\int_0^1 dx\, x\, h_1(x)}$$

Data –> global fits (e.g. JAM15)
(in future also from lattice:
Chambers et al., arXiv:1703.01153)

?

Experiments
(what precision now, expected?)
Global fits (Pavia, Torino)
(Can use constraints from new sum rules)
Lattice ?



Lattice:
Goeckele et al., 2005 Q^2 (GeV^2) Q^2 (GeV^2)