Transversity in inclusive DIS and novel sum rules

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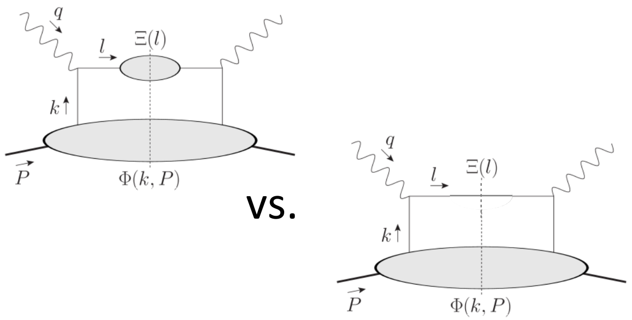
Based on: Accardi, Bacchetta, PLB 773 (2017) 632

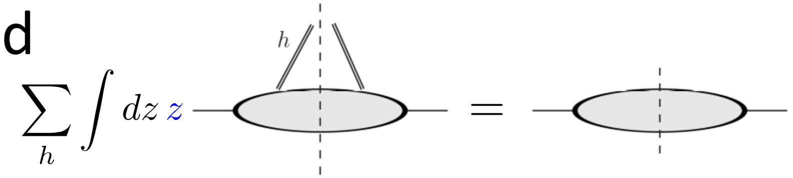
Accardi, Signori, work in progres

Overview

- **Inclusive DIS with jet correlators**
  - Quarks are not asymptotic states
  - g2: new coupling to transversity...
  - Burkhardt-Cottigham sum rule extended



- **Novel TMD sum rules**
  - New results, old ones revisited
  - Single, and di-hadron FFs



- **Final thoughts**

Inclusive DIS with jet correlators

Accardi, Bacchetta, PLB 773 (2017) 632

TMDs in spin ½ targets

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

PARTON SPIN

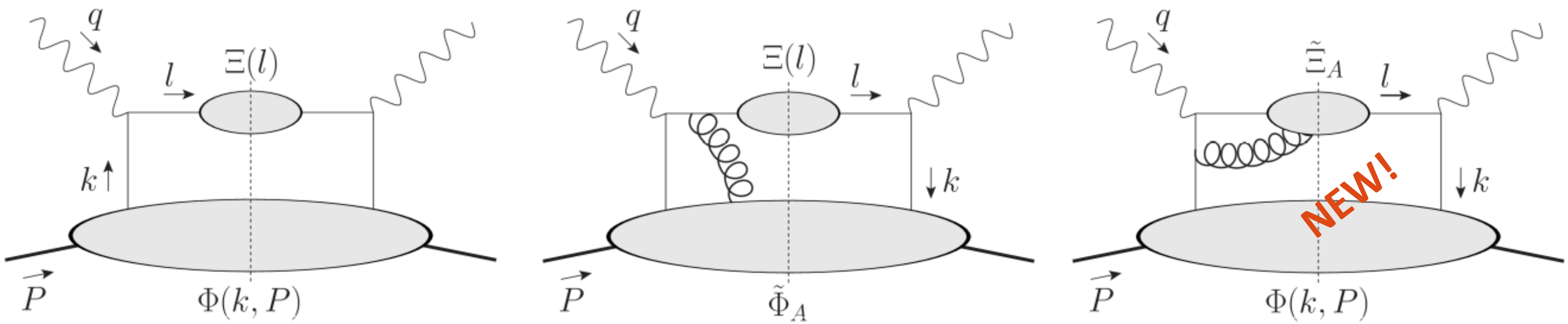
TARGET SPIN

→ *H.Gao - Monday*

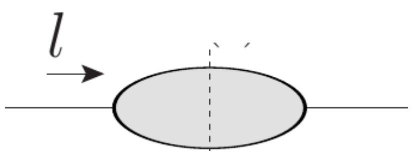
- Integrated (collinear) correlators: only circled ones survive
- Christ-Lee theorem (1970): ***h*** $_{\boldsymbol{1}}$ **not observable in inclusive DIS**
- Not quite true:
  - Vacuum fluctuations can flip the spin of the struck quark
  - **Large contribution ~h_1/x pops up in the $g_2 - g_2^{WW}$ structure fn**

Inclusive DIS with jet correlators

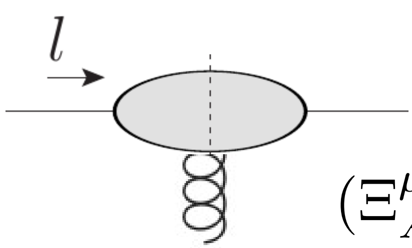
AA, Bacchetta, PLB 773 ('17) 632



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

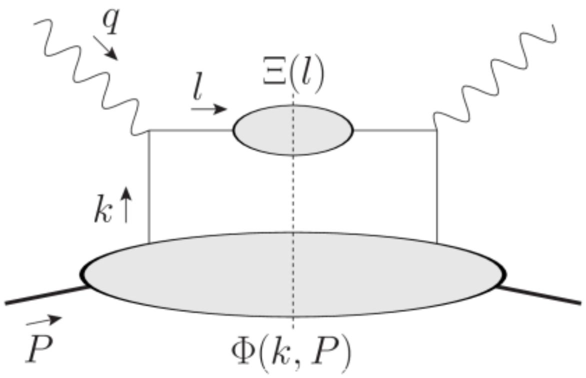


$$\Xi_{ij}(l,n_+) = F.T.\langle 0|\,\mathcal{U}^{n_+}_{(+\infty,\eta)}\,\psi_i(\eta)\bar{\psi}_j(0)\,\mathcal{U}^{n_+}_{(0,+\infty)}\,|0\rangle$$



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

Factorization



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

$$\Xi(l^-, l_T) \equiv \int \frac{dl^2}{2l^-}\,\Xi(l) = \frac{\Lambda}{2l^-}\,\xi_1 + \xi_2 \frac{\not{n}_-}{2} + \text{ twist-4 terms}$$

- Coefficients interpreted in terms of quark spectral functions $J_{1,2}$:

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

"Current jet" mass

→ **can couple to transversity!**

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

Exactly

- Positivity constraints imply

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

Much larger than m_q !

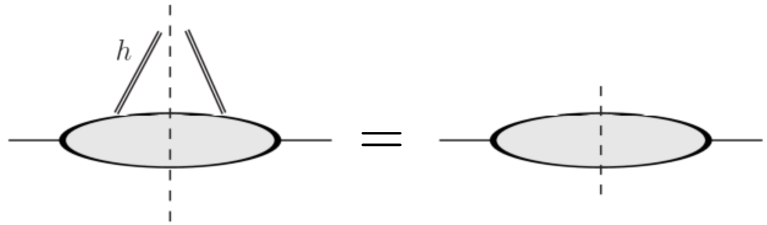
Jet and TMD sum rules

- Use the jet correlator sum rule:

AA, Bachetta '17
(see also Meissner, Metz, Pitonyak '10)

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

$$\sum_h \int dz\, z$$



- At TMD level, take Dirac projections:

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

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

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

Novel TMD sum rules

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

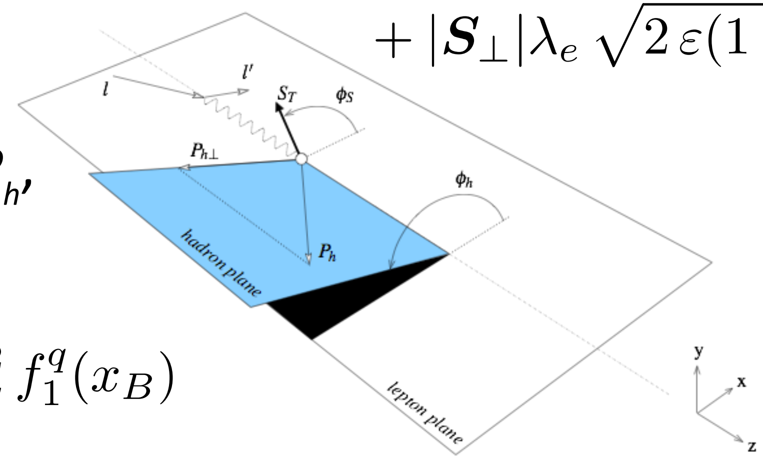
(see later for more...)

Finally, the DIS cross section

- Inclusive DIS

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

- Integrate SIDIS over P_h, use TMD sum rules:



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

$$F_L = 0$$

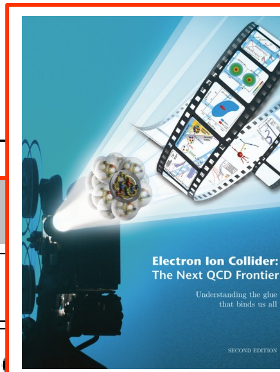
$$F_{LL} = x_B \sum_q e_q^2\, g_1^q(x_B)$$

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

Transversity in inclusive DIS!

Finally, the DIS cross section

- Inclusive DIS $\dfrac{d\sigma}{dx_B\,dy\,d\phi_S} \propto \Big\{ F_T + \varepsilon F_L + S_\parallel \lambda_e \sqrt{1 -$



1212.1701/EPJA 2016

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.

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

Transversity in inclusive DIS!

g2 structure function revisited

AA, Bacchetta, PLB 773 ('17) 632

- Using EOM, Lorentz Invariance Relations:

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

Color force distribution

Transversity in inclusive DIS!

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

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

g2 structure function revisited

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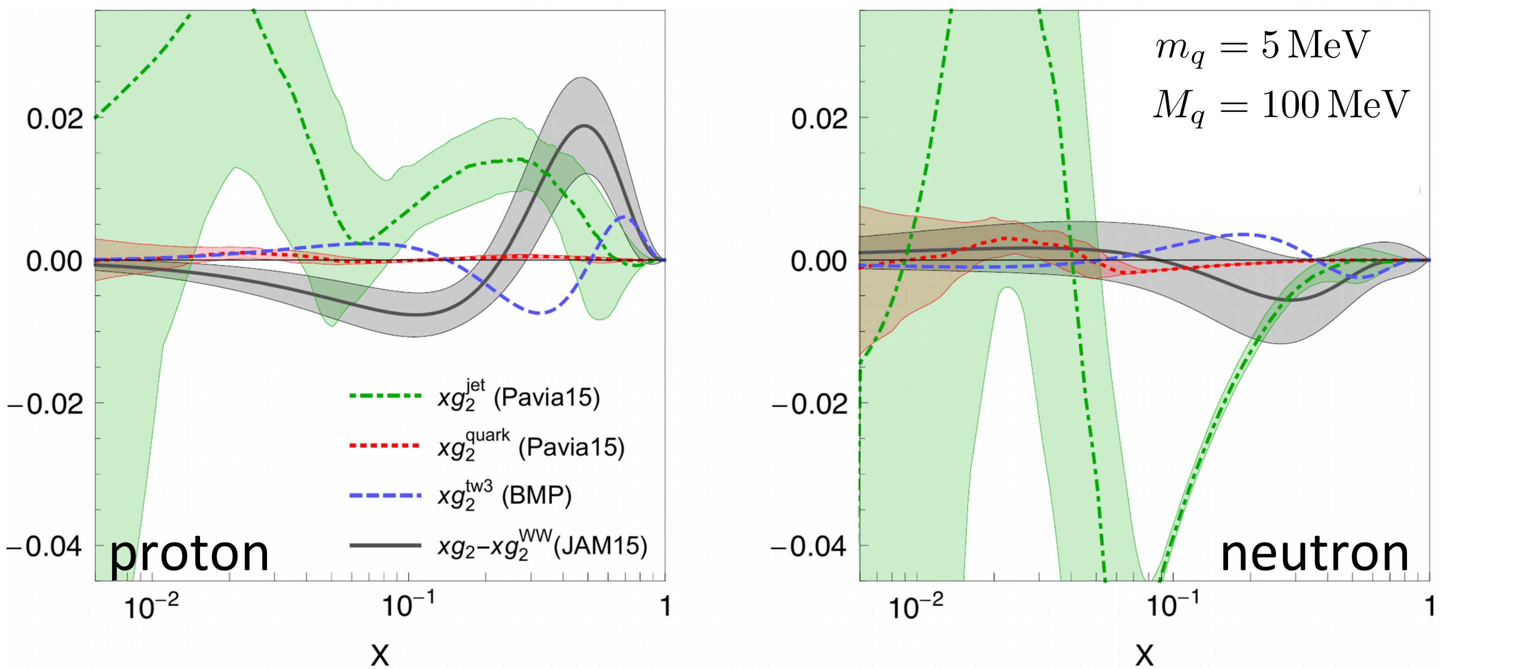

Novel non-perturbative sum rules

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

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

$\longrightarrow$ Broken by quark vacuum fluctuations!

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

<u>Perturbatively:</u> $h_1 \sim x$

<u>Small-x asymptotics</u>: $\longrightarrow$ *Sievert – WG6, Thu 11:20*

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

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

But h_1 is also non-singlet, expect

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

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

Novel non-perturbative sum rules

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→ Broken by quark vacuum fluctuations!

→ *see also caveat in original BC paper*

→ How does spin propagate to small x?

Perturbatively:

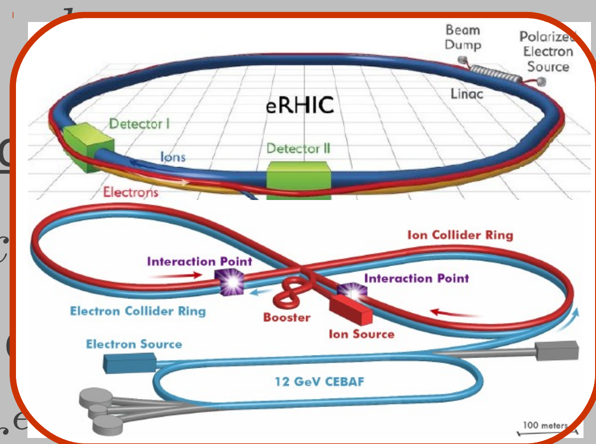
Small-x asympt…

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

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

But h_1 is also n…

$h_1 \sim x^{e}$ … ϵ_h … $\epsilon_g < 0.$…



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

Novel non-perturbative sum rules

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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

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

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

Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

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

Burkardt-Cottingham

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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" $\sim \langle P|\bar{\psi}\gamma^+ F^{+\alpha}\psi|P\rangle$

New momentum sum rules

Accardi, Signori, in preparation

Quark-quark TMD sum rules

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

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

- For TMDs, take suitable traces:

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

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

Quark-gluon-quark TMD sum rules

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

Longitudinal

$$\begin{cases} \displaystyle\sum_{h,S_h} \int dz\, \widetilde{E}_h(z) = \frac{M_q - m_q}{\Lambda} & \text{NEW!} \quad \Longrightarrow \quad \text{Transversity in DIS!} \\ \displaystyle\sum_{h,S_h} \int dz\, \widetilde{H}_h(z) = 0 & \text{NEW!} \quad \Longrightarrow \quad \displaystyle\int dz\, z\, F_{UT}^{\sin\phi_S}(x,z) = 0 \end{cases}$$

Diehl-Sapeta

NEW: proven at correlator level

Transverse

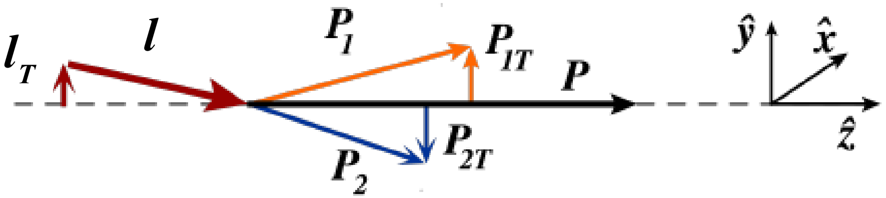
$$\begin{cases} \displaystyle\sum_{h,S_h} \int dz\, \widetilde{D}^{\perp(1)}(z) = \frac{\langle l_T^2 \rangle}{2\Lambda^2}\ {}^{*} & \text{NEW!} \\ \displaystyle\sum_{h,S_h} \int dz\, \widetilde{G}^{\perp(1)}(z) = 0 & \text{NEW!} \end{cases}$$

* in the "hadron frame", P_{hT}=0

($\langle p_{hT}/z \rangle$ in "parton frame")

Di-hadron sum rules

- Two semi-inclusive hadrons
  - Di-hadron frame



→ *M.Radici – WG6, Wed 10:10*

$$\vec{P}_H = \vec{P}_{h1} + \vec{P}_{h2} \qquad z = P_H^-/l^-$$

$$R = \frac{1}{2}(P_{h1} - P_{h2}) \qquad \zeta = p_1^-/l^-$$

- 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:

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

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

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

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

Final thoughts

Final thoughts

- **Jet correlators open up new 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 !

- **New momentum sum rules**
  - Quark-quark FF (complete up to twist 3) ; q-g-q (partial at twist 3)
  - DiFF : quark-quark only – work in progrees

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

A new "universal" fits

- **"Universal fits"**
  - Different PDF, FF "sectors" fitted simutaneously
  - *e.g.* polarized PDFs, and FFs → *N.Sato – WG1, Thu 10:20*

- **Chiral-odd collinear case:**

$M_{jet}\, H_1^{\sphericalangle}$ **polarized**

$H_1^{\sphericalangle} \otimes H_1^{\sphericalangle}$ **unpolarized**

(Di)e$^+$e$^-$

DIS

$M_{jet}\, h_1$

(Di)SIDIS

$H_1^{\sphericalangle} \otimes h_1$

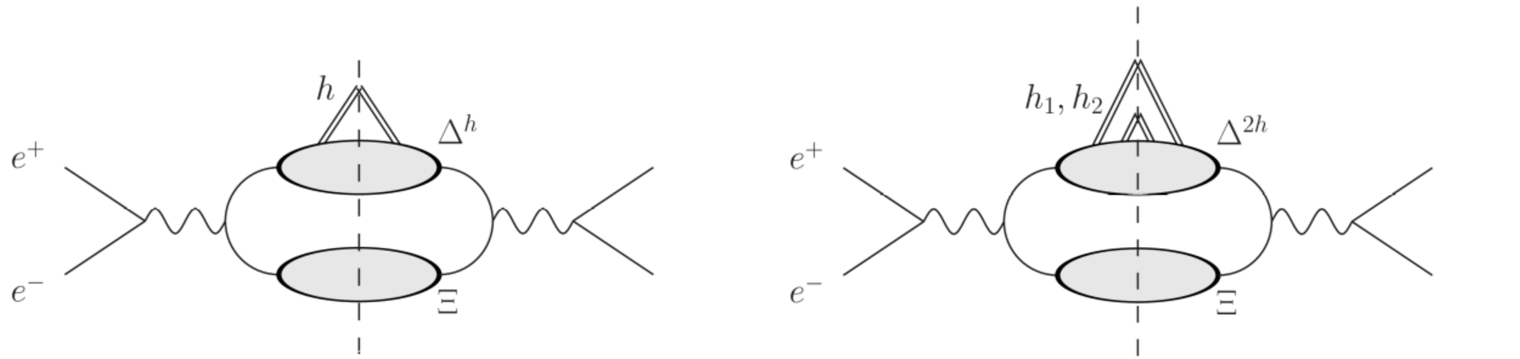
Thank you!

Measuring the jet correlator

Related to confinement, mass generation [C.Roberts]

Accardi, Bacchetta, Radici, in prep.

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



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

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

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

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	?
$\sqrt{s}$ [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?