Accessing the proton's transversity in inclusive DIS

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Hampton U. and Jefferson Lab

COMPASS analysis meeting

CERN, Jul 20th, 2018

Based on: Accardi, Signori, work in progress & DIS2018 proc.
Accardi, Bacchetta, PLB 773 (2017) 632

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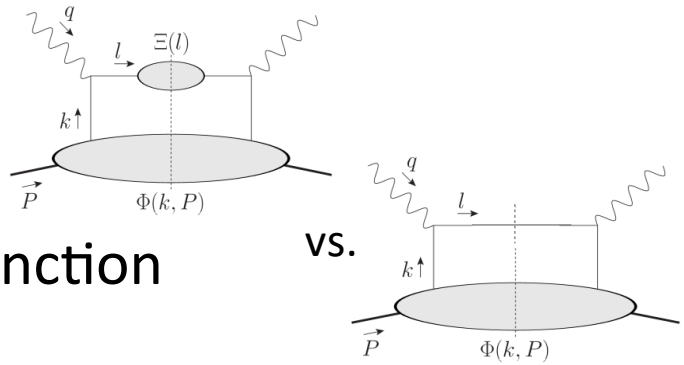
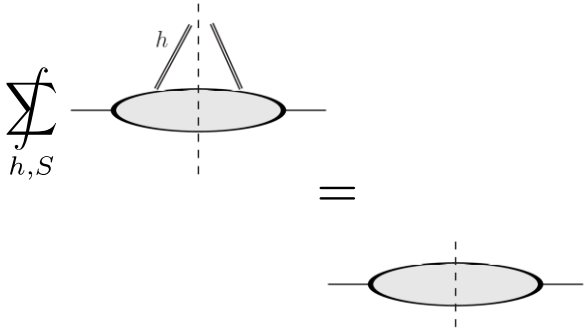
Overview

- **DIS with a jet correlator**
  - Quarks are not asymptotic states
  - Jet correlator and quark spectral function



- **Novel TMD sum rules**
  - 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**

DIS with a jet correlators

Accardi, Bacchetta, PLB 773 (2017) 632

TMDs in spin ½ targets

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

- Integrated (collinear) correlators: only circled ones survive
- Christ-Lee theorem (1970): ***h*** $_1$ **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 $_2$ structure function**

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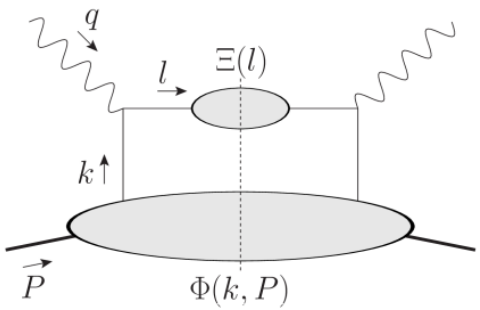
Inclusive DIS with a jet correlator

- **Color confinement: quarks are not asymptotic states!**
  - Minimally the quark needs to hadronize into a "jet" of hadrons
  - Use a handbag diagram with a jet correlator on top

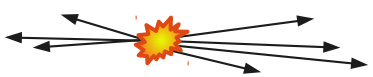


- **Diagram with jet correlator justified at large x_B:**

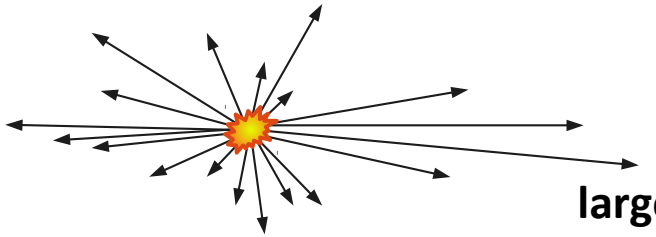
  As invariant mass M_x becomes smaller and smaller,

$$M_X = Q^2 \left(\frac{1 - x_B}{x_B} \right) + M_p^2$$

  - sum over final states incomplete: unitarity cannot be applied to "remove" hadronization effects in inclusive processes
  - event more and more jet like (Breit frame pic below)



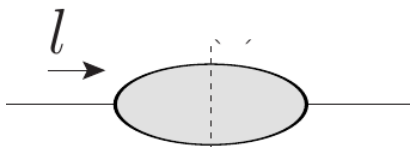
Small Mx
cannot produce much pT



large Mx
less and less restriction

The quark-quark "jet" correlator

- **"jet" correlator** == quark correlator on the QCD vaccum



Wilson lines in lightcone n^+ direction

$$\Xi_{ij}(l, n_+) = \int \frac{d^4\eta}{(2\pi)^4}\, e^{il\cdot\eta}\, \langle 0|\, \mathcal{W}^{n_+}_{(+\infty,\eta)}\, \underbrace{\psi_i(\eta)\bar{\psi}_j(0)}_{\text{Quark fields}}\, \mathcal{W}^{n_+}_{(0,+\infty)}\, |0\rangle$$

- **Dirac expansion**
  - Analogous to FF TMD correlator, but less vectors to play with:

Power counting scale

$$\Xi(l, n_+) = \Lambda A_1(l^2)\mathbf{1} + A_3(l^2)\not{l} + \frac{\Lambda^2}{k\cdot n_+} B_1(l^2)\not{n}_+$$

twist-3 twist-2 twist-4 (neglect in this talk)

Connection to quark spectral functions

- **Spectral representation of the quark propagator**

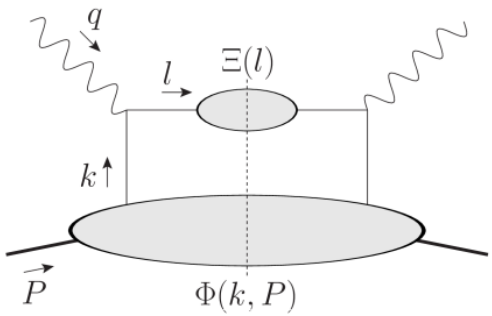
$$\Xi(l) = \int d\sigma^2 \left[J_1(\sigma^2)\, \mathbb{I} + J_2(\sigma^2) \not{l} \right] \delta(l^2 - \sigma^2)$$

  - σ interpreted as mass of the particles inside the jet
  - "jet functions" J_1, J_2 are mass distributions (viz. chiral odd and even)

- CPT invariance and positivity constraints imply

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

Connection to quark spectral functions



- 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 $J_{1,2}$:

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

"Current jet" mass

→ **can couple to transversity!**

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

Exactly

- Positivity constraints imply

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

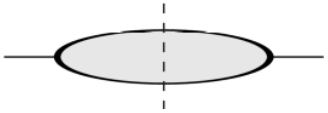
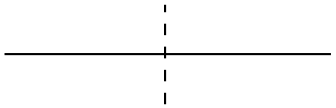
Much larger than m_q !

Connection to quark spectral functions

- **Summary**:
  - the integrated jet correlator needed in the analysis of the inclusive DIS cross section up to twist-3 reads

$$\boxed{\Xi(l) = 1\!\!\!/ + M_q\,\mathbb{I} \;+\; \text{twist-4 terms}}$$

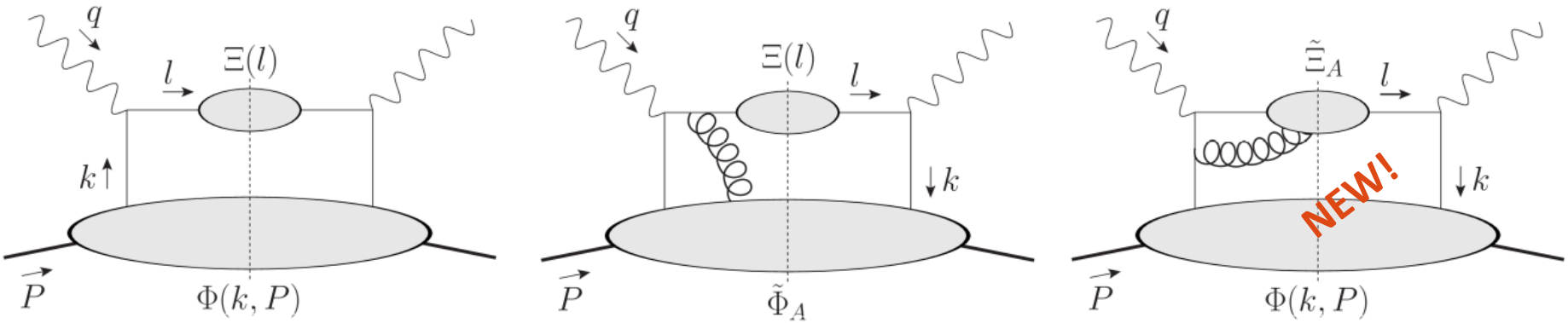
$$M_q \equiv \int d\mu^2\,\mu\,J_1(\mu^2) \sim O(100\text{MeV}) \qquad \gg \qquad m_q = O(1\text{MeV})$$

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

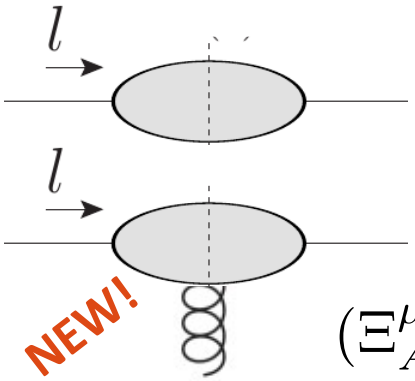
  - using the perturbative vacuum in the jet correlator definion, we are back to the usual business: $M_q^{\text{pert}} = m_q$
  - The larger M_q is due to the quark's interaction with the nonperturbative QCD vacuum

DIS at twist-3 with jet correlators

- **For g2 analysis, need to also consider "twist-3" diagrams**
  - These arealso needed for gauge invariance with non-zero jet mass



Jet correlators: → non-asymptotic quark states



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

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

DIS at twist-3 with jet correlators

- Rather than calculating these directly in inclusive DIS:
  - **Integrate and sum over flavors the SIDIS cross section**

Diehl et al., JHEP 0702 (2007) 093

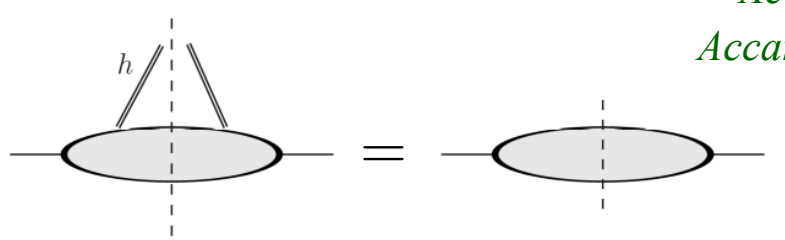
$$\frac{d\sigma}{dx_B\, dy\, d\phi_S} = \sum_{h,S_h} \int (dp_h) \frac{d\sigma^{h,S_h}}{dx_B\, dy\, d\phi_S\, (dp_h)}$$

Lorentz invariant integration measure

  - **Make use of TMD-FF sum rules involving the jet correlator** (and equation of motion relations to realte twist-3 and twist-2)

Accardi, Bacchetta '17
Accardi, Signori, in prep.

$$\sum_{h,S_h} \int d^2 p_{hT} dz$$



New TMD-FF sum rules

Accardi, Signori, in preparation
& DIS 2018 proceedings (to appear soon)

Accardi, Bacchetta, PLB 773 (2017) 632

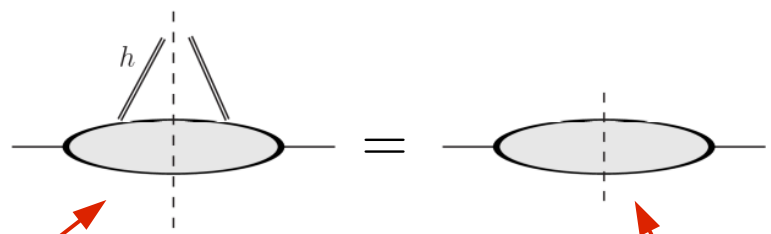
Semi-inclusive vs. jet correlators - 1

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

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

Graphically:

$$\sum_{h,S_h} \int d^2 p_{hT} dz$$



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

"Jet" $q \to X$ 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)*

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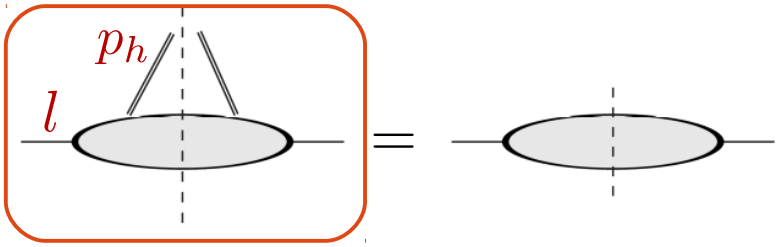
Graphically:

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



SIDIS $q \to h{+}X$ correlator:

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

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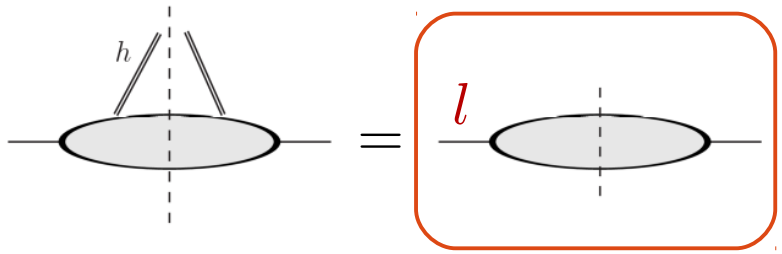

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"Jet" $q \to X$ correlator

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Quark-quark TMD sum rules

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

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

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- For TMDs, take suitable traces:

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

(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

$$\sum_{h,S_h} \int dz\, \widetilde{E}_h(z) = \frac{M_q - m_q}{\Lambda}$$ NEW!

$$\sum_{h,S_h} \int dz\, \widetilde{H}_h(z) = 0$$ NEW!

Transverse

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

$$\sum_{h,S_h} \int dz\, \widetilde{G}^{\perp(1)}(z) = 0$$ NEW!

$M_q^{\rm pert} = m_q \Rightarrow$ Old sum rule

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

Quark-gluon-quark TMD sum rules

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

Longitudinal

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

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

Diehl-Sapeta

NEW: proven at correlator level

Transverse

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

$$\sum_{h,S_h} \int dz\, \widetilde{G}^{\perp(1)}(z) = 0$$ NEW!

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Transversity in inclusive DIS

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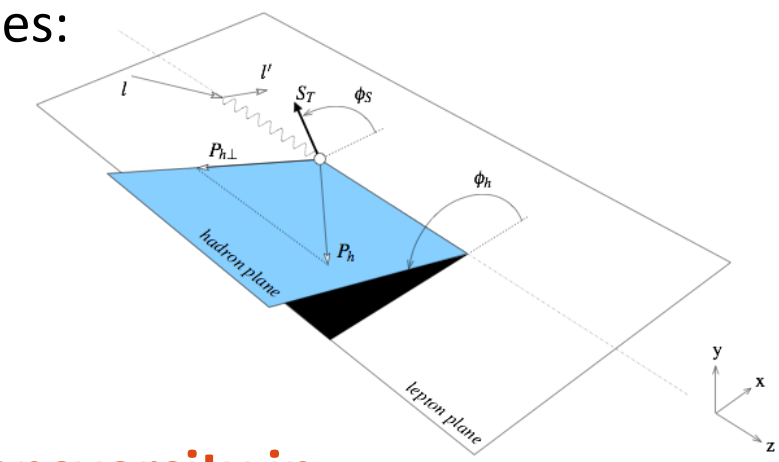
DIS cross section

- 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 *Ph*, use TMD sum rules:



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

$$F_L = 0$$

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

Proven for first time at correlator level

$$F_{UT}^{\sin\phi_S} = 0$$

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

Transversity in inclusive DIS!

g2 structure function revisited

AA, Bacchetta, PLB 773 ('17) 632

- Using EOM, Lorentz Invariance Relations:

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

Color force distribution

Transversity in inclusive DIS!

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

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

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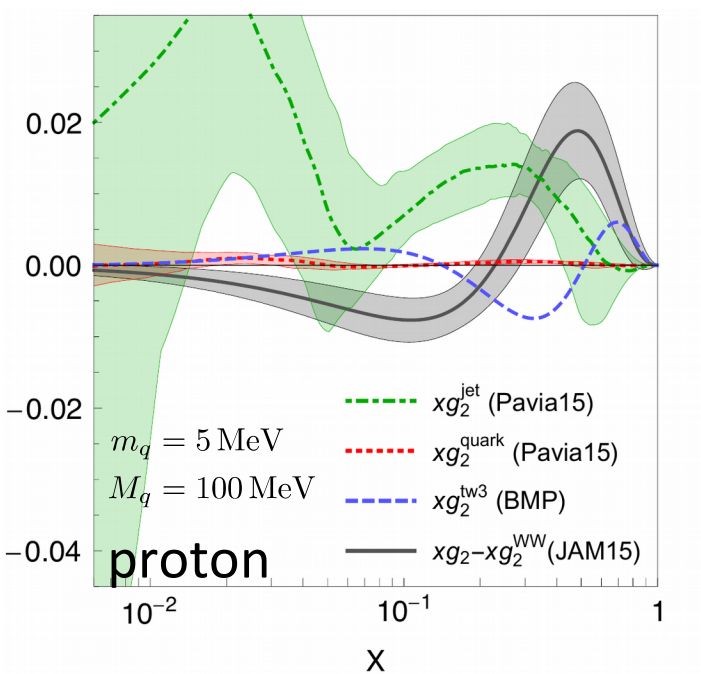

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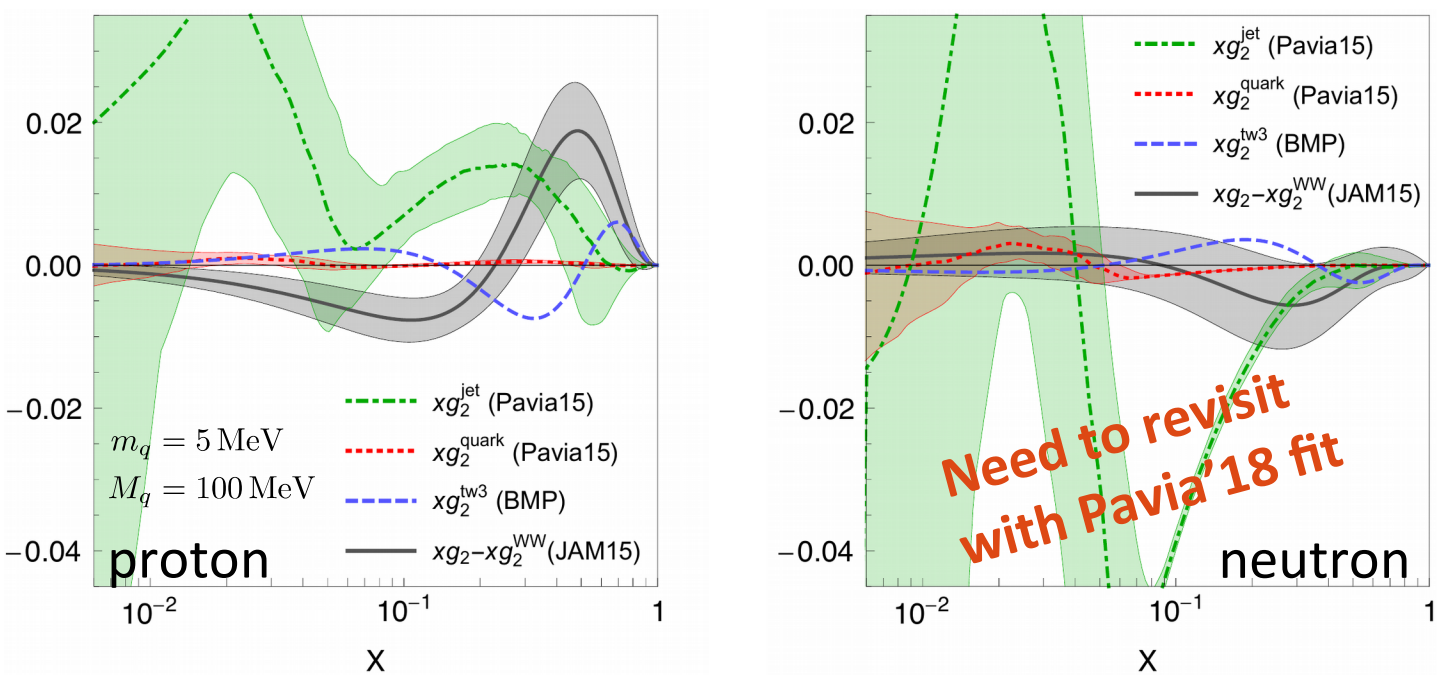

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AA, Bacchetta, PLB 773 ('17) 632

- Using EOM, Lorentz Invariance Relations:

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

- **Region of validity:** $W_\infty^2 \gg Q^2(1/x_B - 1) \gg M_{\mathrm{jet}}^2$

Minimum invariant mass to apply completeness, recover standard handbag diagram

Needed to integrate jet spectral functions over all σ, avoid "jet mass corrections"

AA, Qiu, 2008

  - Phenomenologically, can switch off jet mass with form factor $\mathcal{F}$

$$M_q - m_q \longrightarrow (M_q - m_q)\mathcal{F}(W^2)$$

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 $$\int_0^1 g_2(x) = M_{\rm jet} \int_0^1 dx \, \frac{h_1(x)}{x} \mathcal{F}(Q^2(1/x_B - 1))$$

$\longrightarrow$ 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>:

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

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

But h_1 is also non-singlet, expect

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

– **BC breaking term likely finite thanks to $\mathcal{F}$**

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

$$\int_0^1 g_2(x) = \underbrace{M_{\text{“jet”}} \int_0^1 dx \, \frac{h_1(x)}{x} \mathcal{F}}_{\Delta_{BC}}$$

Efremov-Teryaev-Leader

$$\int_0^1 x g_2^{q-\bar{q}}(x) = 2\, M_{\text{“jet”}} \underbrace{\int_0^1 dx \, h_1^{q-\bar{q}}(x) \mathcal{F}}_{\Delta_{ETL}}$$

$$\boxed{\Delta_{ETL} < 2 M_{jet} \delta_T} = 2 M_{jet} \int dx h_1(x)$$

Tensor charge !

→ Novel limit on tensor charge!

Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

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

Burkhardt-Cottingham

$$\int_0^1 g_2(x) = \underbrace{M_{\text{“jet”}} \int_0^1 dx\, \frac{h_1(x)}{x} \mathcal{F}}_{\Delta_{BC}}$$

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$$\int_0^1 x g_2^{q-\bar{q}}(x) = 2\, M_{\text{“jet”}} \underbrace{\int_0^1 dx\, h_1^{q-\bar{q}}(x) \mathcal{F}}_{\Delta_{ETL}}$$

Color polarizability

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

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

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

Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

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

How large is W_∞ ?

How fast does the coupling to h_1 switch off?

i.e., $\mathcal{F} = \mathcal{F}(Q^2(1/x_B - 1)) = ?$

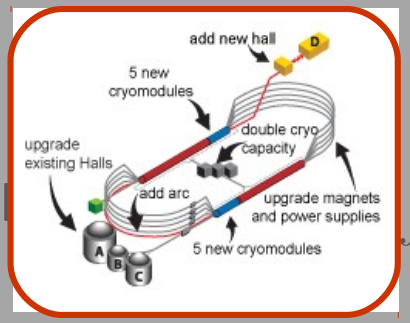
Burkhardt-Cottingham

$$\int_0^1 g_2(x)\, dx = M_{\text{"jet"}} \underbrace{\int_0^1 dx\, \frac{h_1(x)}{x}\, \mathcal{F}}_{\text{"background"}}$$

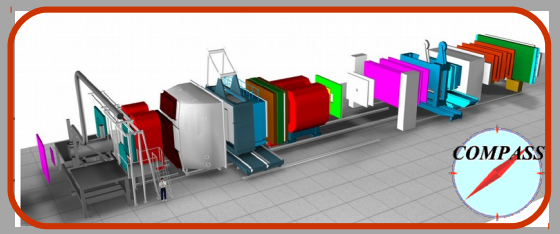
Efremov-Teryaev-Leader

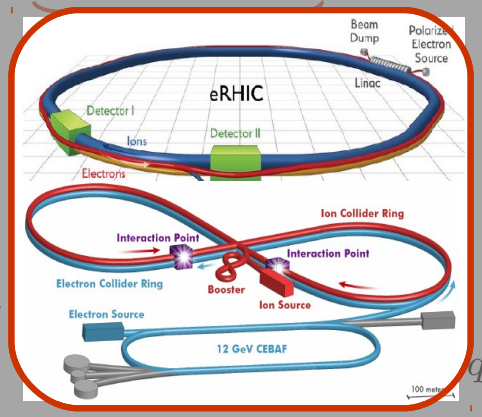
$$\int_0^1 x g_2^{q-\bar{q}}(x)\, dx = 2\, M_{\text{"jet"}} \int_0^1 dx\, h_1^{q-\bar{q}}(x)\, \mathcal{F}$$

Color



$$\int_0^1$$





$$= d_2 + 3\, M_{\text{"jet"}} \int_0^1 \qquad q)$$

Color force – Burkardt $\sim \langle P|\bar{\psi}\gamma^+ F^{+\alpha}\psi|P\rangle$

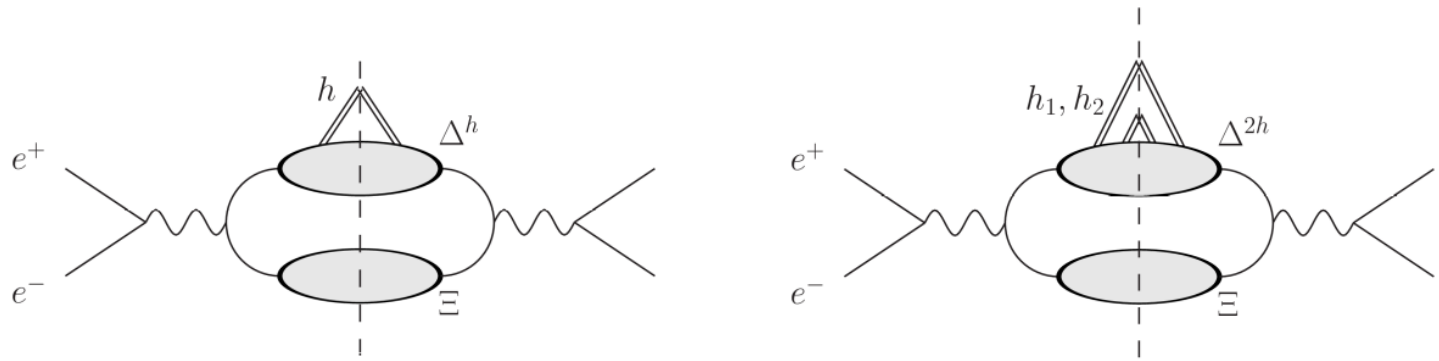
"pure twist-3"

"background"

Measuring the jet correlator

Accardi, Bacchetta, Signori, Radici, in prep.

- Jet mass **M_{jet} can be also accessed in polarized $e^+ + e^-$:**



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

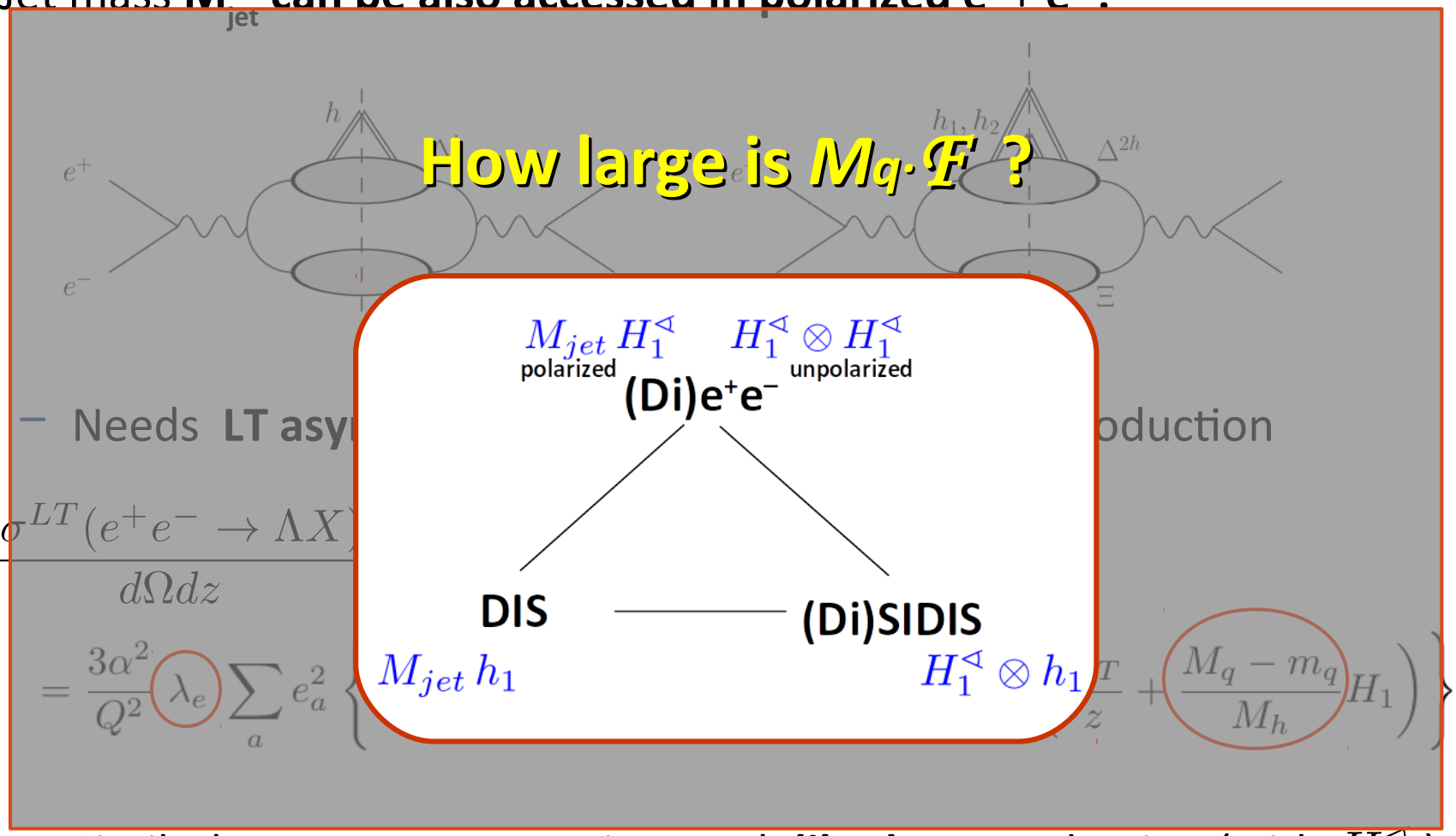
$$\frac{d\sigma^{LT}(e^+e^- \to \Lambda X)}{d\Omega dz} = \frac{3\alpha^2}{Q^2}\lambda_e \sum_a e_a^2 \left\{ \frac{C(y)}{2}\lambda_h G_1 + D(y)|\boldsymbol{S}_T| \cos(\phi_S)\frac{2M_h}{Q}\left(\frac{G_T}{z} + \frac{M_q - m_q}{M_h}H_1\right)\right\}$$

  - Similarly a **LU asymmetry** in unpol **dihadron** production (with $H_1^{\sphericalangle}$)

Measuring the jet correlator

Accardi, Bacchetta, Signori, Radici, in prep.

- Jet mass M_{jet} **can be also accessed in polarized $e^+ + e^-$:**

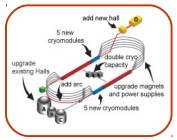


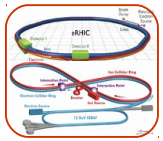
- Similarly a **LU asymmetry** in unpol **dihadron** production (with $H_1^{\sphericalangle}$)

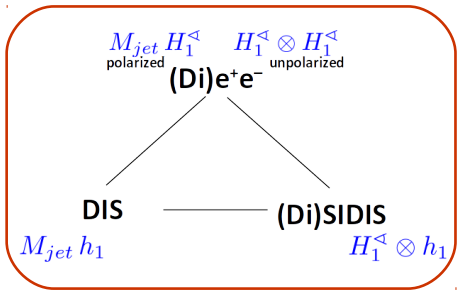
Conclusions and perspective

Conclusions and perspective

- **New FF sum rules**
  - FF: quark-quark & q-gluon-q (complete up to twist 3)
- **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 questions:
  - **how do jet correlator effects switch off?**
    - g1, g2, h1, across energy range
  - **how to measure jet correlators?**
    - Need a new "universal fit" of M_q, h_1, $H_1^{\sphericalangle}$







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

PHYSICAL REVIEW LETTERS **120,** 192001 (2018)

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

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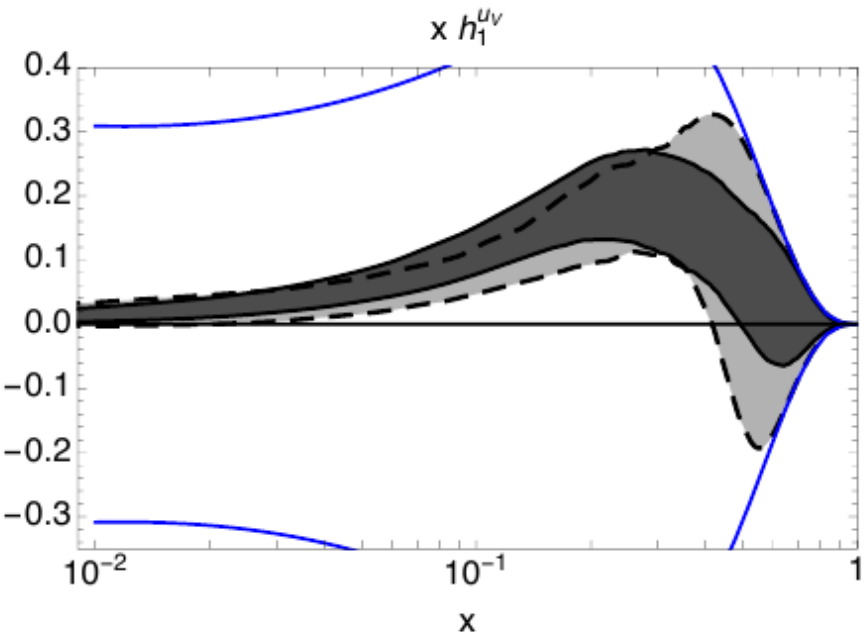

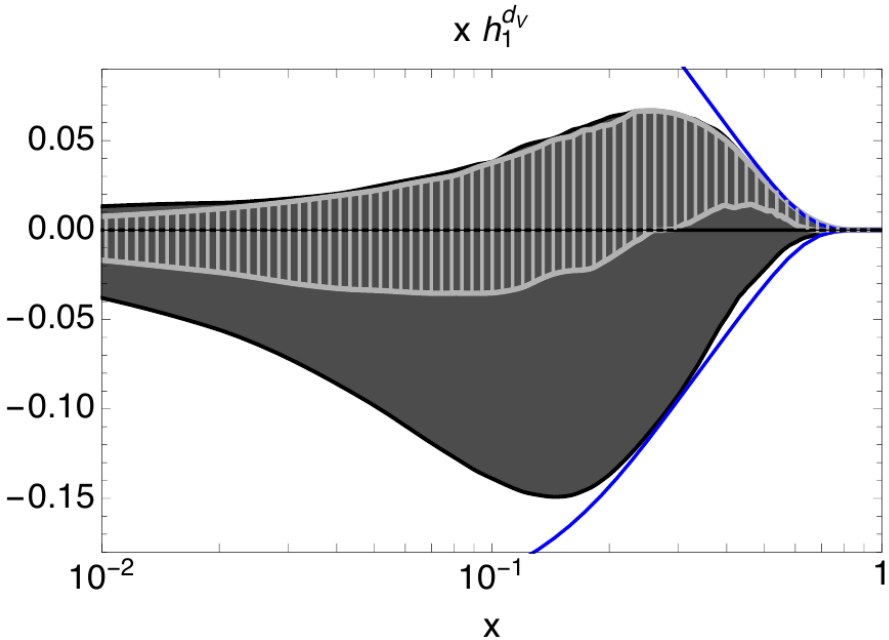

Older Pavia 15 transversity fit (used in g2 plots)

Improved extraction of valence transversity distributions from inclusive dihadron production

doi:10.1007/JHEP05(2015)123

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