Transversity in inclusive DIS

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Transversity 2017

Laboratori Nazionali di Frascati,
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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
  - Cross section & g_2 revisited
- **Twist-3 TMD sum rules**
  - New results, old ones revisited
- **Measuring the jet correlator**
- **Concluding thoughts**

Inclusive DIS with jet correlators

Accardi, Bacchetta, PLB 773 (2017) 632

TMDs in spin ½ targets

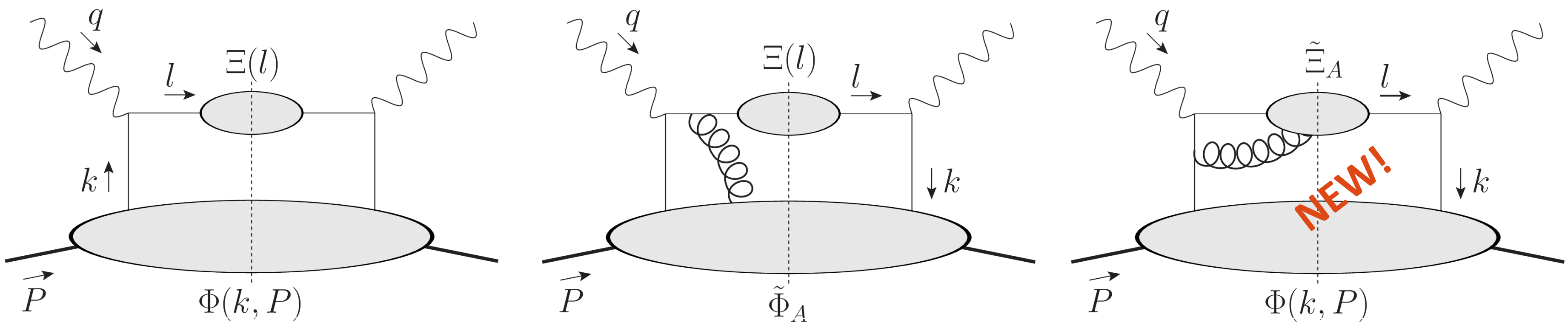
QUARKS	PARTON SPIN: γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^\alpha\gamma_5$
TARGET SPIN: U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

→ *P. Mulders, QCDev2017*

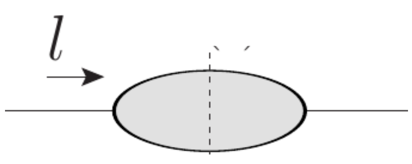
- Integrated (collinear) correlator: only circled ones survive
- Christ-Lee theorem (1970): ***h*** $_{\boldsymbol{1}}$ **not observable in inclusive DIS**
- Not quite true:
  - Vacuum fluctuations can flip the spin of the struck quark
  - **Large contribution ~*h*$_1$ pops up in the $g_2 - g_2^{WW}$ structure function**

Inclusive DIS with jet correlators

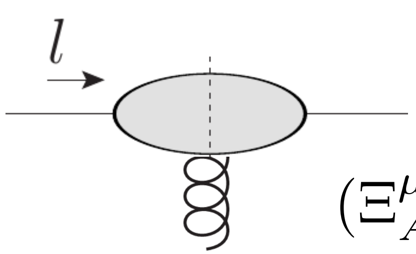
AA, Bacchetta, PLB 773 ('17) 632



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

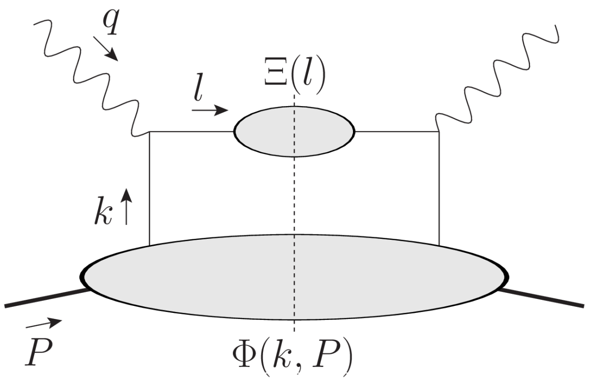


$$\Xi_{ij}(l, n_+) = F.T. \langle 0 | \mathcal{U}^{n_+}_{(+\infty,\eta)} \, \psi_i(\eta) \bar{\psi}_j(0) \, \mathcal{U}^{n_+}_{(0,+\infty)} \, |0\rangle$$



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

Factorization



- At order $1/Q$, neglect k^- compared to q^-
  - The cross section 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 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

- Positivity constraints imply

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

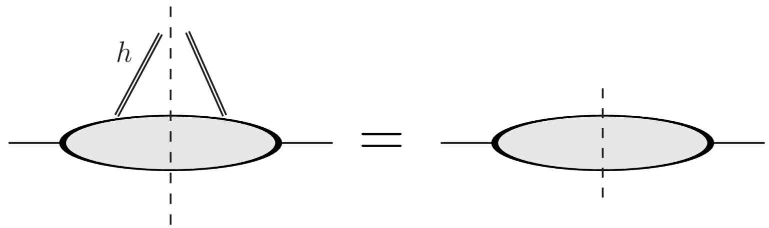
Much larger than m_q !

Jet and TMD sum rules

- Utilize the following jet correlator sum rule:

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

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



- At TMD level, this implies:

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

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

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

Novel TMD sum rules

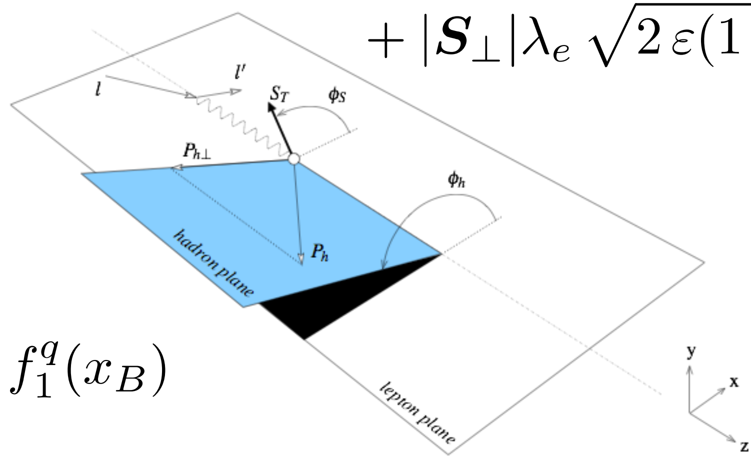
$M_q^{\text{pert}} = m_q \Rightarrow$ Old ones

(see later for more...)

Finally, the DIS cross section

- Inclusive DIS

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



- Integrating the SIDIS 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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$$\frac{d\sigma}{\ldots} \propto \Big\{ F_T + \varepsilon F_L + S_{\parallel}\lambda_e\sqrt{1-\varepsilon^2}\; F_{L\ldots}$$

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^{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, can show that

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

Color force distribution

Transversity in inclusive DIS!

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

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

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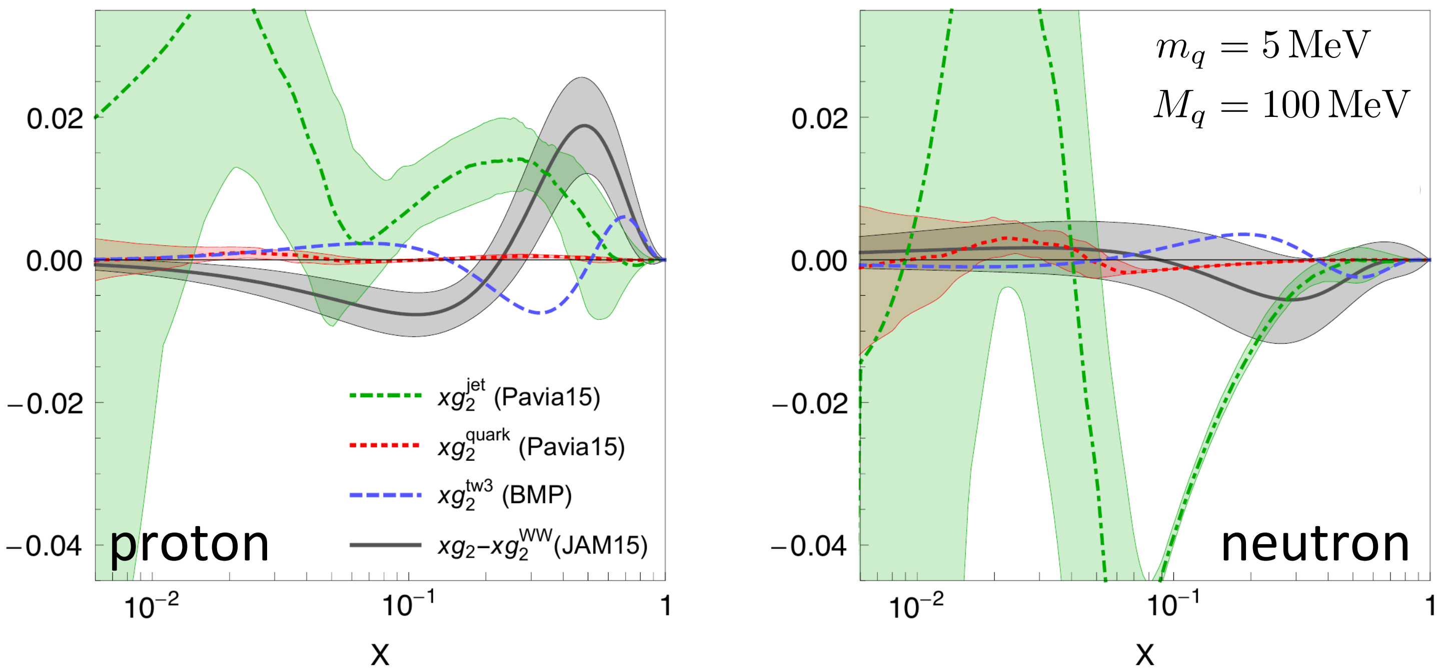

Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

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

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!

$\longrightarrow$ Is BC breaking finite?

Perturbatively, yes (h~x) but...

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$\rightarrow$ Small-*x* asymptotics:

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

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

But h_1 is also non-singlet, expect

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

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

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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 …?

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Efremov-Teryaev-Leader

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

$\rightarrow$ $\boxed{\text{Novel way to measure the tensor charge!}}$

Novel non-perturbative sum rules

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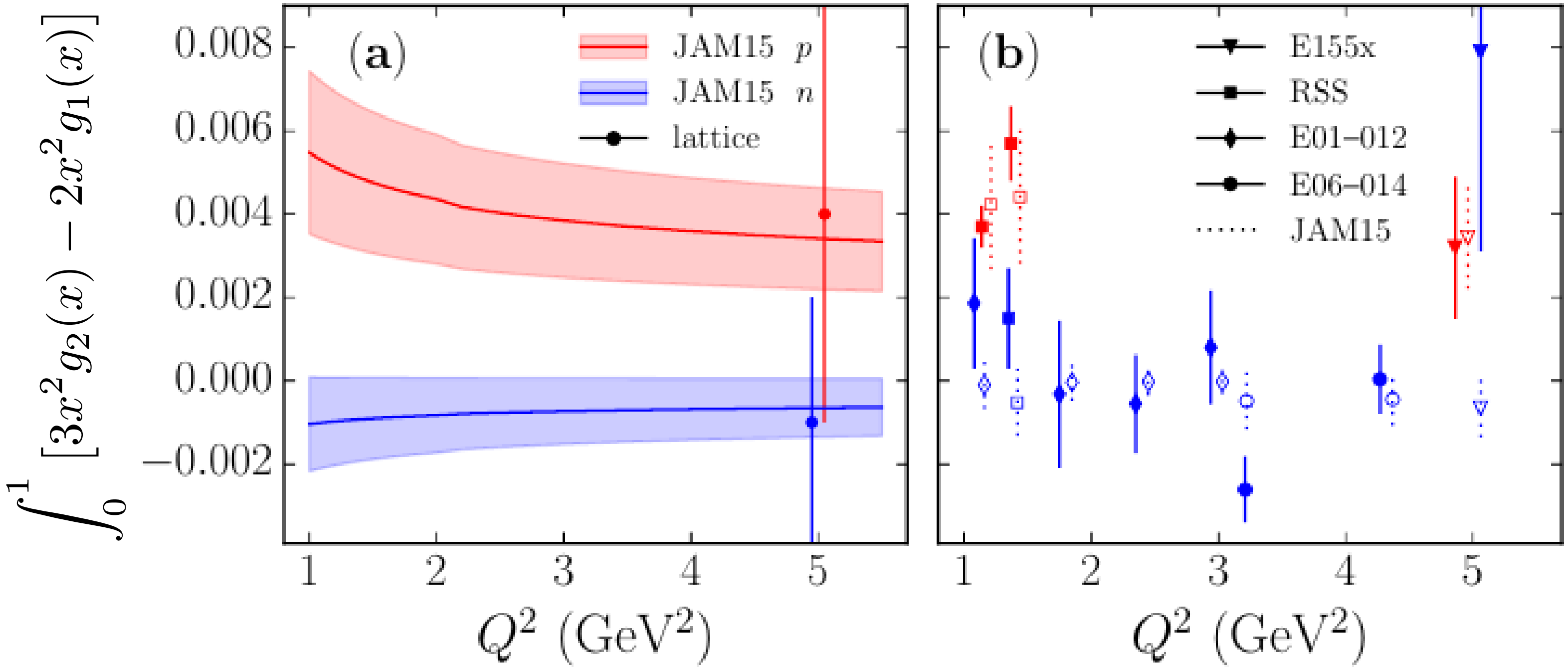
Color polarizability $$\int_0^1 \left[3x^2 g_2(x) - 2x^2 g_1(x)\right]$$

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

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

Higher twist and color polarizability

N.Sato et al., PRD93 (2015) 074005



Lattice calcs from Goeckele et al. 2005 – time to revist?

Higher twist and color polarizability

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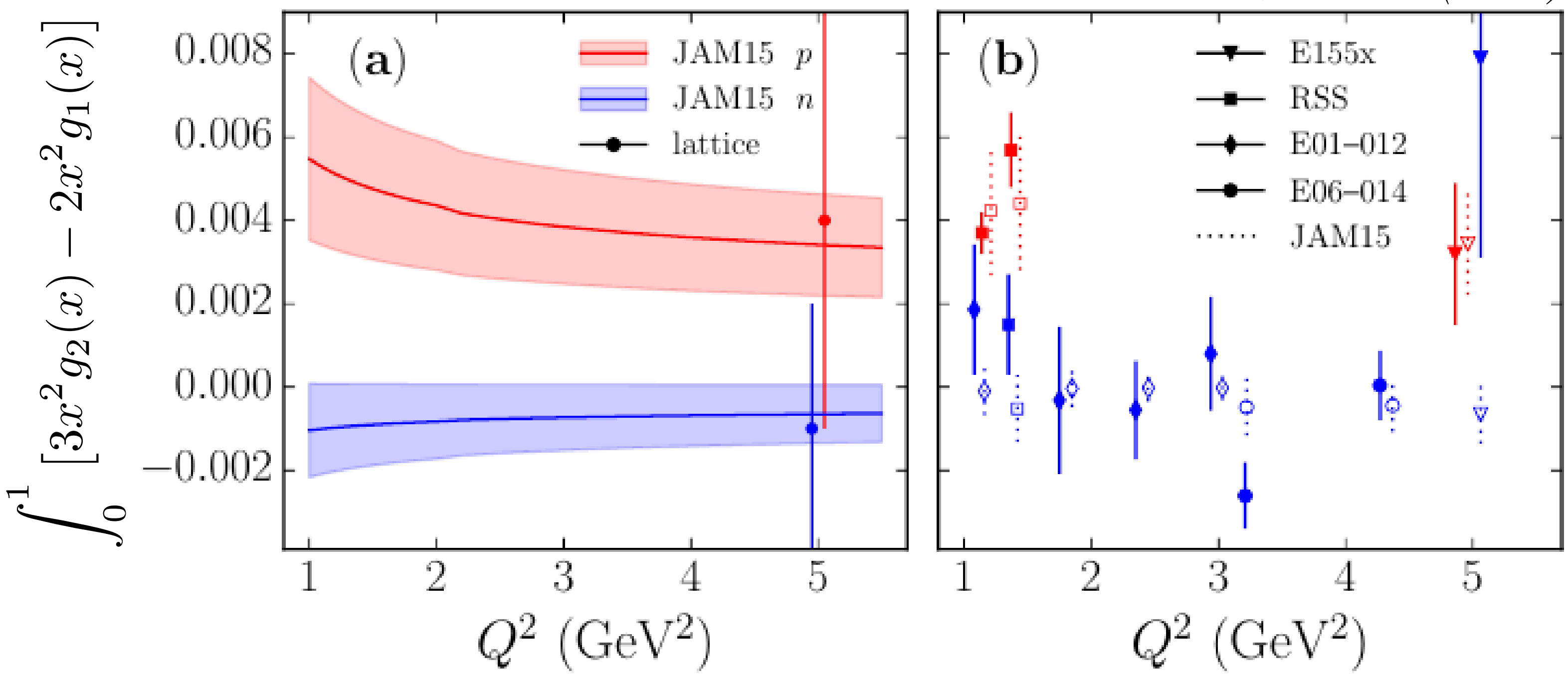


Lattice calcs from Goeckele et al. 2005 – time to revist?

Can one also calculate Mjet on the lattice?

New TMD sum rules

Accardi, Signori, in preparation

Quark-quark TMD sum rules

- General jet correlator sum rule:

AA, Bachetta '17
Meissner, Metz, Pitonyak '10

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

- At TMD level, take suitable traces and find:

	Longitudinal	**Transverse**
Twist-2	*Collins-Soper* $\sum_h \int dz\, z\, D_{1h}(z) = 1$	*Schaefer-Teryaev* $\sum_h \int dz\, z\, H_{1h}^{\perp(1)}(z) = 0$
Twist-3	$\sum_h \int dz\, E_h(z, p_{hT}) = \frac{M_q}{\Lambda}$ **NEW!**	$\sum_h \int dz\, G_h^{\perp(1)}(z) = 0$ **NEW!**
	$\sum_h \int dz\, H_h(z) = 0$ **NEW!**	$\sum_h \int dz\, D_h^{\perp(1)}(z) =$ IN PROGRESS

Quark-gluon-quark TMD sum rules

- Combine q-q sume rules using Equation of Motion relations:

$$\sum_h \int dz\, \widetilde{E}_h(z) = \frac{M_q - m_q}{\Lambda} \qquad \Longrightarrow \qquad \text{Transversity in DIS!}$$

NEW!

$$\sum_h \int dz\, \widetilde{H}_h(z) = 0 \qquad \Longrightarrow \qquad \int dz\, z\, F_{UT}^{\sin\phi_S}(x,z) = 0$$

NEW!

Diehl-Sapeta

NEW: proven at correlator level

$$\sum_h \int dz\, \widetilde{D}^{\perp}(z) =$$

Measuring the jet correlator

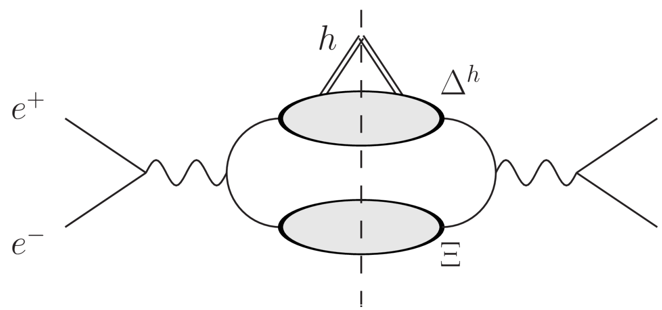
In collaboration with
A.Bacchetta, M.Radici, A.Signori

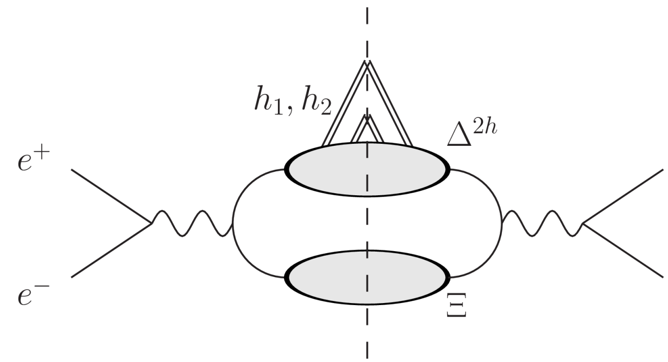
Measuring the jet correlator

Related to confinement, mass generation [C.Roberts]

Accardi, Bacchetta, Radici, in prep.

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





  - 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	super KEKB	ILC	JLab/BNL
E beam [GeV]	1.9	4 (e^{-}) 7 (e^{-})	250	?
√s [GeV]	3 – 5	10	500	?
polarization	?	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), …

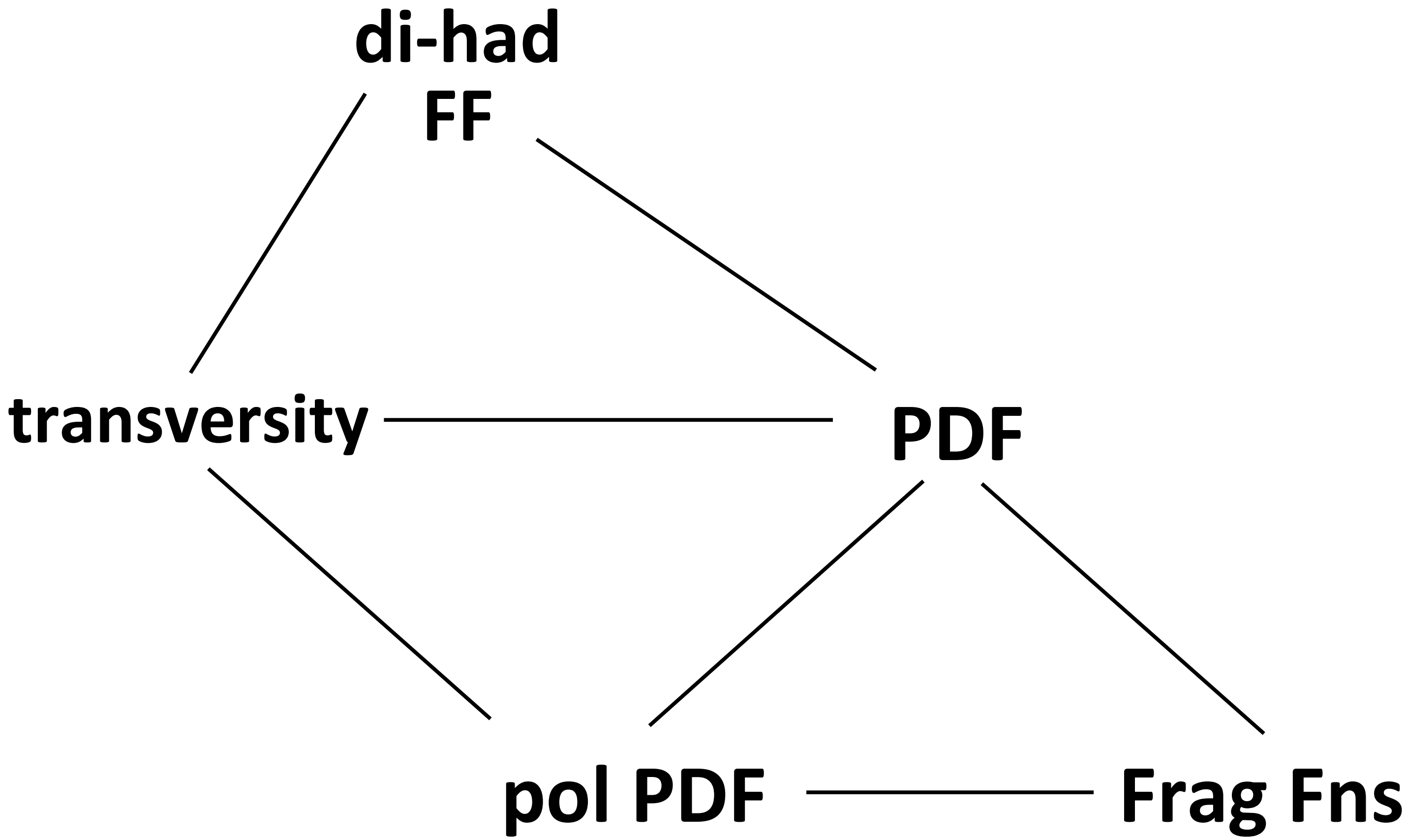
Ideas?

Final thoughts

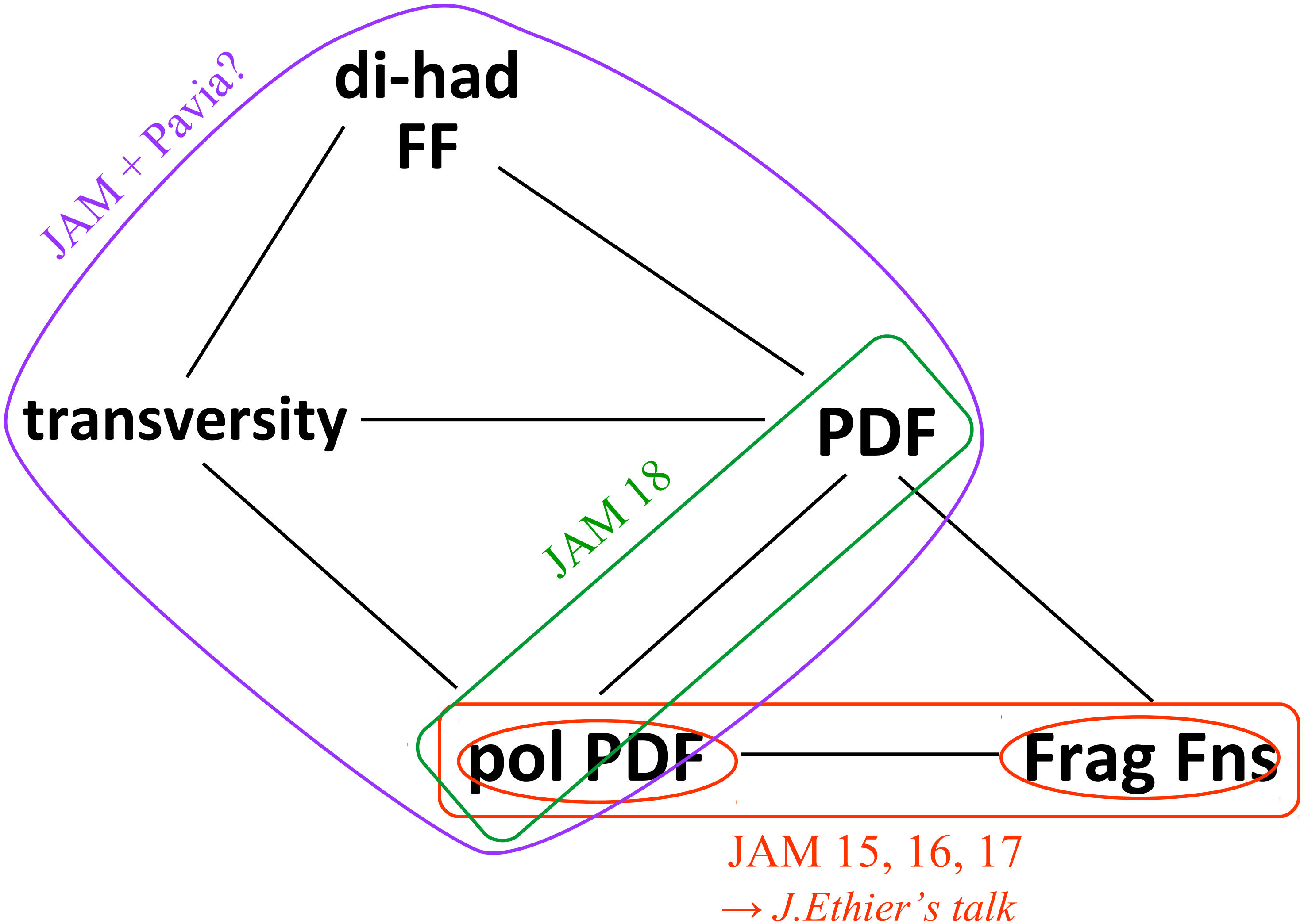
Final thoughts

- **Jet correlators open up new theory and phenomenology**
  - Transversity contributes to inclusive g_2
  - Extended BC and ETL sum rules
    - New handle on proton tensor charge
  - Open question: spin transport to small *x* !
  - New twist-3 TMD sum rules
- **How to measure jet correlators?**
  - Polarized e+e- collider
  - Observables in p+p ??
- **How to calculate jet correlators?**
  - In lattice QCD?
  - Any relation to chiral condensate?
  - What can we learn from OPE?

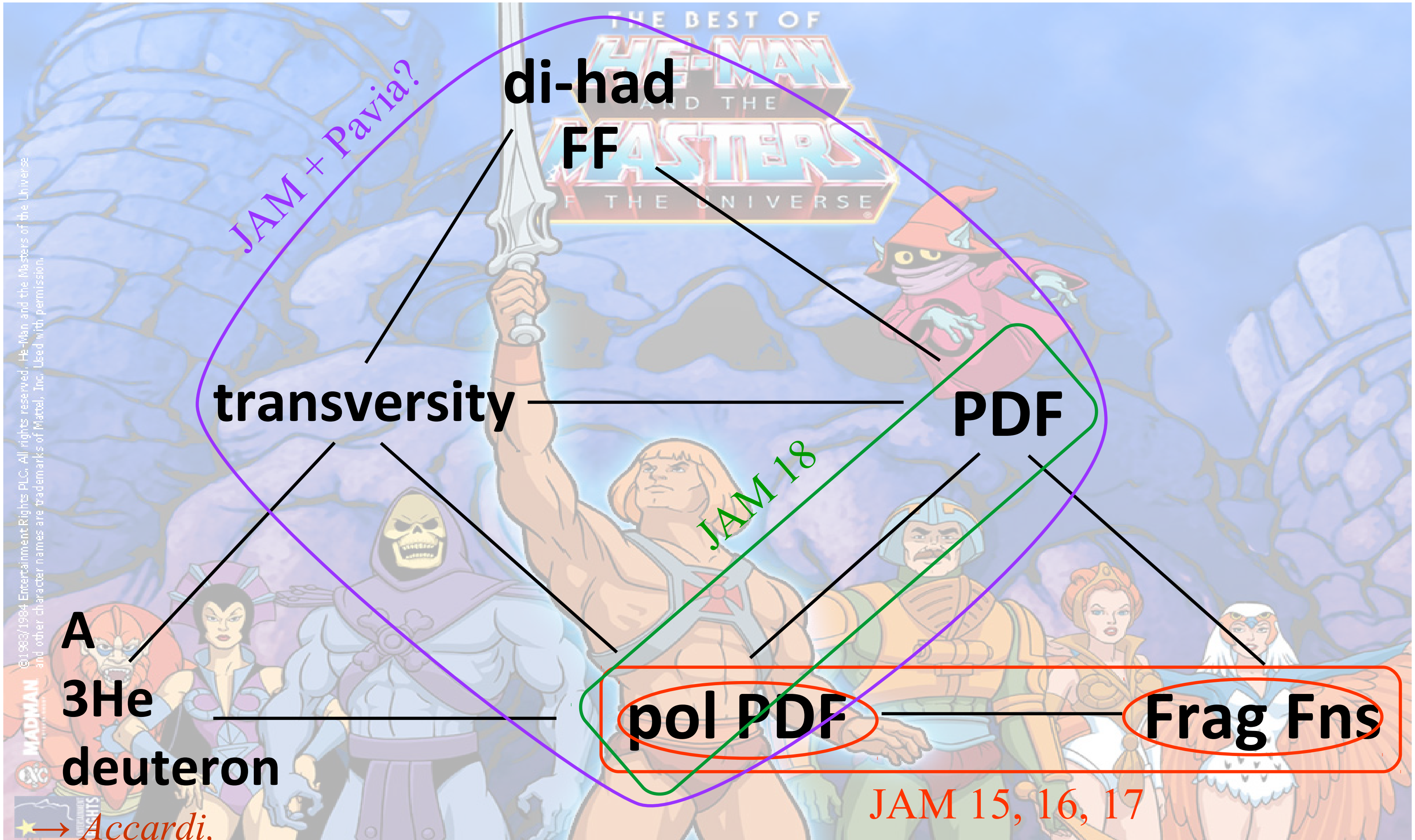
Towards “universal” fits



Towards "universal" fits



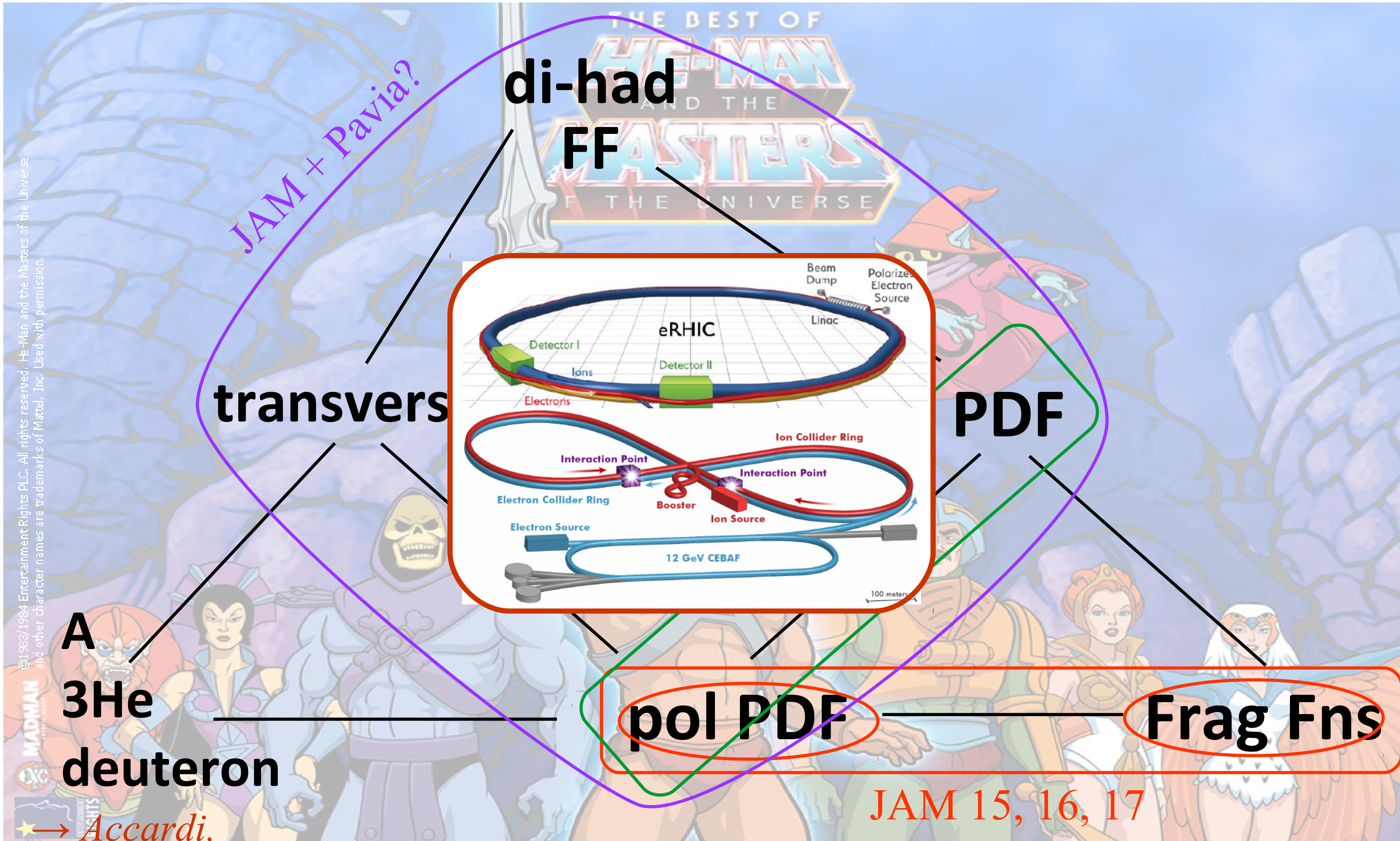
Masters of the Universe



→ Accardi, PoS DIS2015

→ J.Ethier's talk

Masters of the Universe



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Thank you!