

Towards “universal” QCD fits

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ICAS Institute on the Spinf of the Proton

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Overview

- ❑ **Intro: global and universal fits**
- ❑ **Two examples**
 - Deuteron corrections from proton data
 - Strange, strange quarks
- ❑ **JAM: 2015-2017**
 - Pol. PDFs, FFs, and both combined
- ❑ **Transversity in inclusive DIS (!!)**
 - Interplay with g2
 - Need for (new) e+e- colliders
- ❑ **Final thoughts**
- ❑ **EXTRAS:** Hadron Mass Corrections (ask me);
More on strange (in appendix)

Many distributions, single “global” fits

Jimenez-Delgado, Melnitchouk, Owens, JPG 40 (2013)
Forte and Watt – Ann.Rev.Nucl.Part.Sci. 63 (2013) 291
Metz, Vossen, Prog.Part.Nucl.Phys. 91 (2016) 136-202

nucl PDF

PDF

pol PDF

→ *Nocera, Sassot,
Vogelsang*

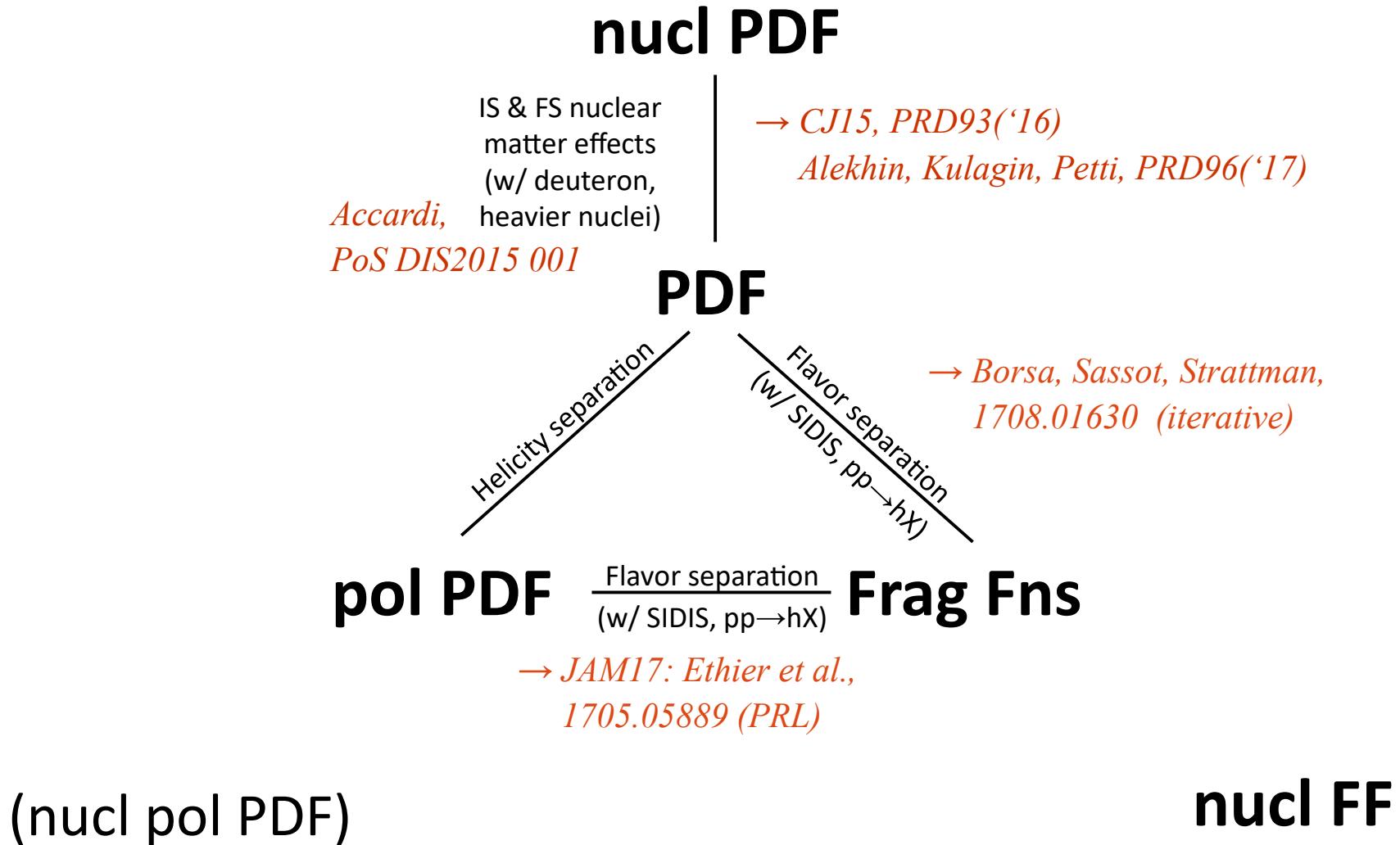
(nucl pol PDF)

Frag Fns

→ *Nocera, Sassot*

nucl FF

But physics is not isolated: need “universal” fits



35+ years of unpolarized global PDF fits

	JLab & BONUS	HERMES	HERA I+II	Tevatron new W,Z	LHC	v+A di- μ	Large-x treatment			
	Nucl.	HT TMC	Flex d	low-W DIS						
CJ15 *	✓	✓	✓	✓	<i>in prog.</i>	✗	✓	✓	✓	✓
CT14			DIS 2016	✓ ✘	✓	✓			✓	
MMHT14			✗	✓ ✘	✓	✓	✓			
NNPDF3.1			✓		✓	✓		✓		
JR14	✓				✓	✓	✓	✓		
ABM15 **				✓ ✘	✓	✓	✓	✓		✓
HERAPDF2.0			✓	✗						

* NLO only ** No jet data ✘ see 1503.05221 ✘ see 1508.06621 ✘ no reconstructed W

20+ years of polarized global PDF fits

→ Vogelsang,
PDFLattice 2017

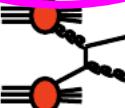
	DSSV	NNPDF	JAM
method	“standard” input type Mellin space uncertainties via Lagrange multipliers	Neural network technique x space	“standard” input type Mellin space iterative Monte-Carlo technique
	✓	✓	✓ (Jlab, higher twist, TMC, nucl. corr.)
	✓	✗	(soon)
	✓ included in fit (no W^\pm yet)	✓ (jets, W^\pm) via reweighting	(soon)

Important insights also from “less global” studies:

Leader, Stamenov, Sidorov; Blümlein, Böttcher;
Hirai, Kumano; Bourrely, Buccella, Soffer;
COMPASS (Andrieux et al.);
Arbabifar et al.

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	DSSV	NNPDF	JAM
method	“standard” input type Mellin space uncertainties via Lagrange multipliers	Neural network technique x space	“standard” input type Mellin space iterative Monte-Carlo technique
FFs	  	Needs FFs !!	 (Jlab, higher twist, TMC, nucl. corr.)
included in fit (no W^\pm yet)		 ($jets, W^\pm$) via reweighting	 (soon)

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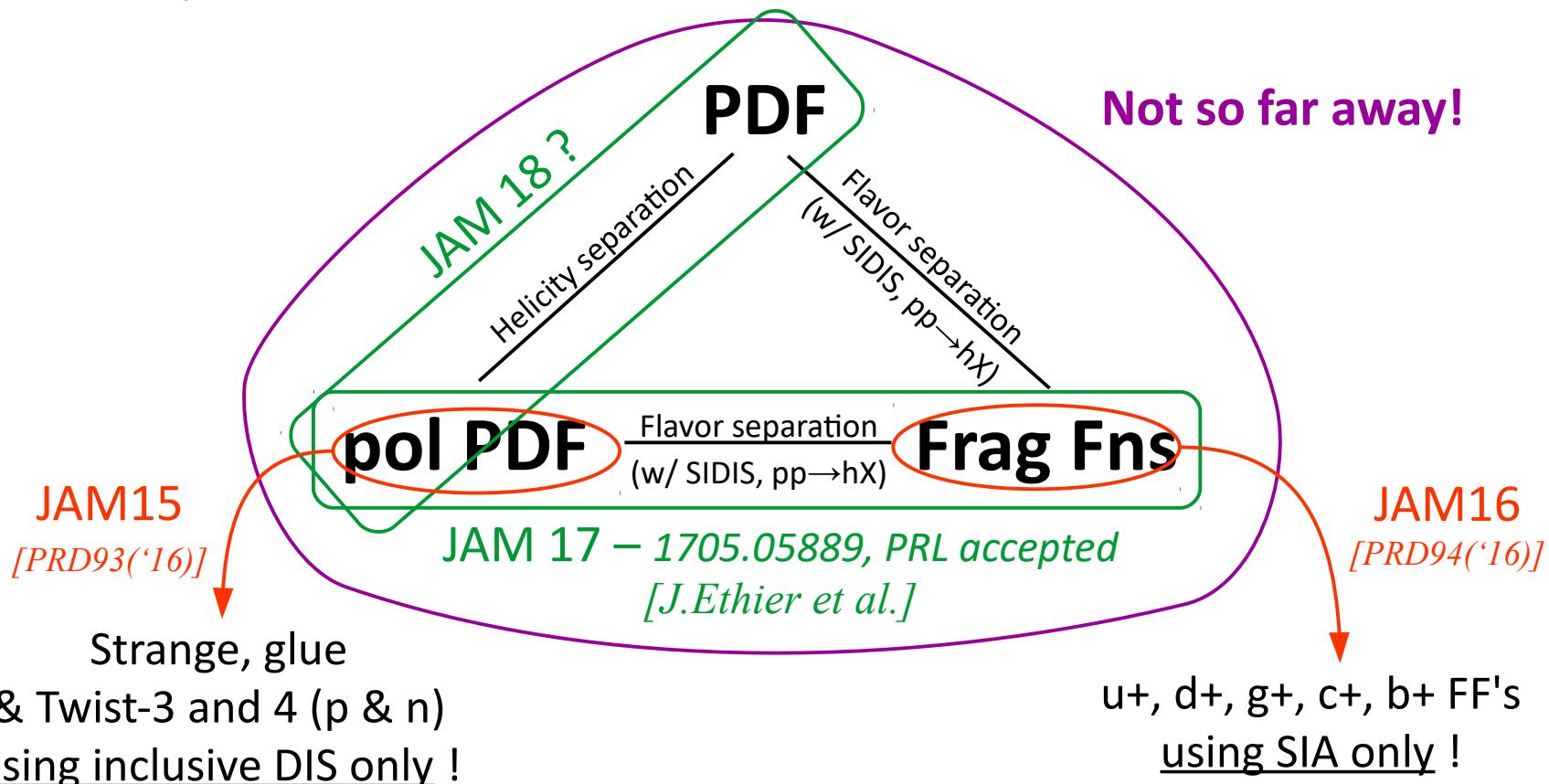
5+ years: new fitting methods

- More computing power, efficient implementations
 - New fitting, analysis methods
- In traditional fits:
 - Detailed χ^2 scans, refined statistical analysis
- Monte Carlo fitting methods:
 - **NNPDF**: bootstrap + neural network fit → *Nocera*
 - **JAM**: bootstrap + Iterative Monte Carlo (IMC) approach
 - *Sato, Ethier et al (since 2015)*
- Self organizing maps → *Liuti et al.*

JAM - Iterative Monte Carlo approach

N.Sato et al [JAM], PRD93 (2016) 074005 and PRD94 (2016) 114004

- Provides control over large number of parameters
- Maximizes extraction of physics information from data
- Statistically robust uncertainties

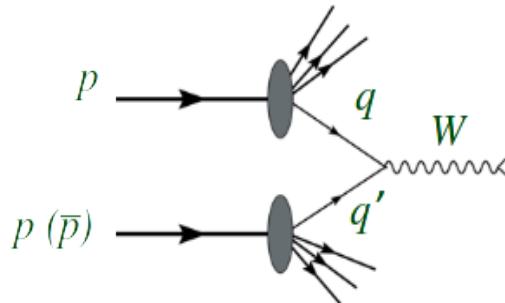


Two examples

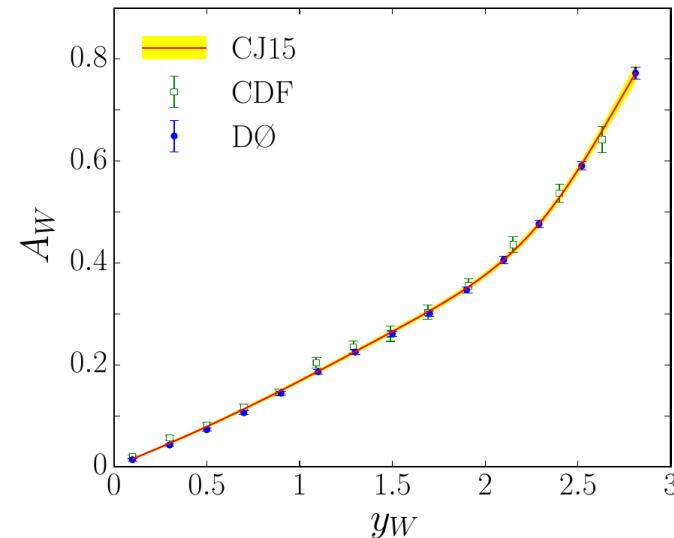
Example 1: Tevatron as NUCL facility (!)

Accardi, Brady, Melnitchouk, Owens, Sato, PRD93 (2016) 114017

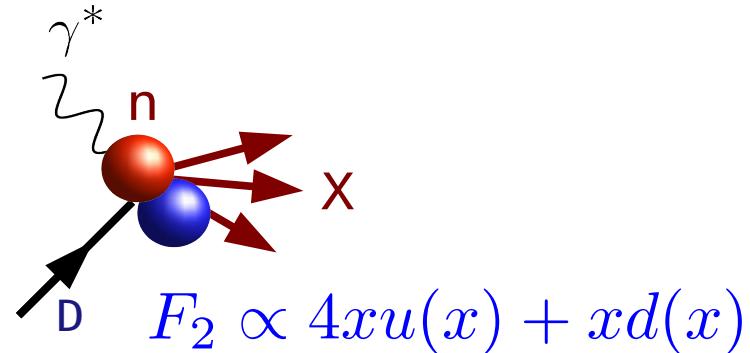
- **Reconstructed W** → constrain **d -quark** at largest x on proton targets



$$A_W(y) \xrightarrow{y \rightarrow y_{max}} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$



- Compare to abundant deuteron **DIS data**:
 - constrain **deuteron corrections**
 - **precise u, d flavor separation**

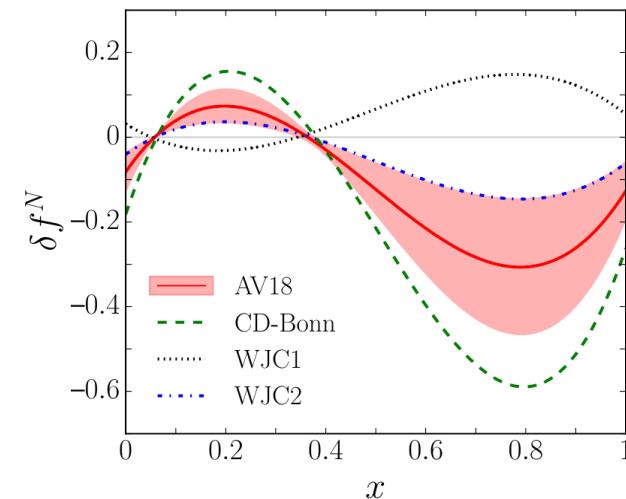
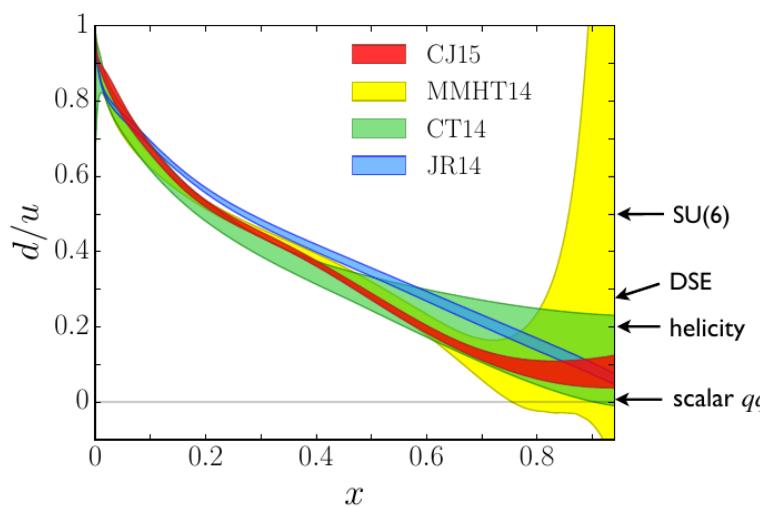


Example 1: Tevatron as NUCL facility (!)

Accardi, Brady, Melnitchouk, Owens, Sato, PRD93 (2016) 114017

□ Universal fit: d/u and binding effects

- confinement at large x (using flexible large- x d-quark)
- bound nucleon corrections in deuteron PDFs

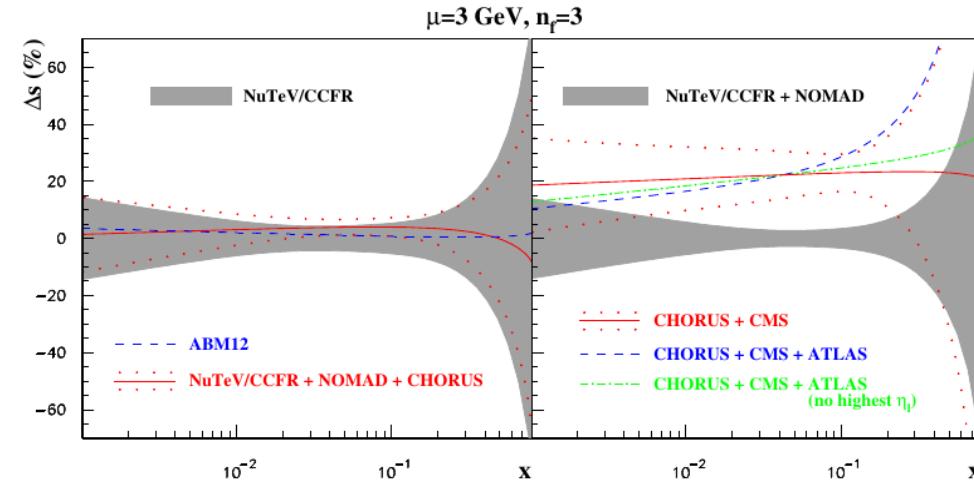


□ Opens novel possibilities: test nuclear theory ideas against other data:

- Test “EMC effect” models (of course)
- On the lattice: “nucleon response to external color field”
- ...

Example 2: strange strange quarks

□ $\nu+A \rightarrow \text{dimuons}$ vs. $p+p \rightarrow W+c$ at LHC

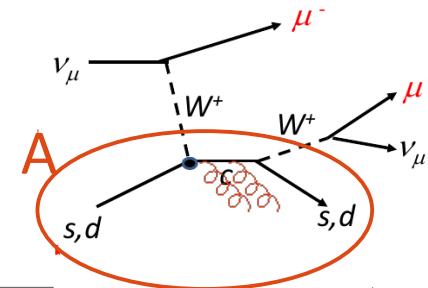


Alekhin et al., arXiv:1404.6469

$$g s_p \rightarrow W c$$

$$\nu s_A \rightarrow \mu^- \mu^+ \nu_\mu s$$

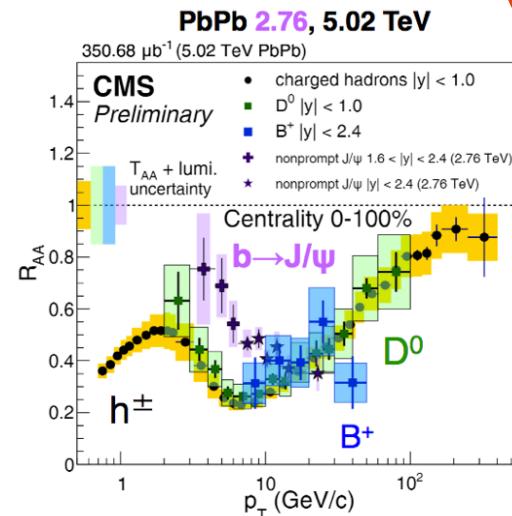
FSI
?



□ Heavy quark puzzle at RHIC / LHC:

- Color propagation in QCD matter not under theoretical control!

$$R_{AA}^h = \frac{(dN^h/d^2p_T)_{AA}}{N_{col} \times (dN^h/d^2p_T)_{pp}}$$

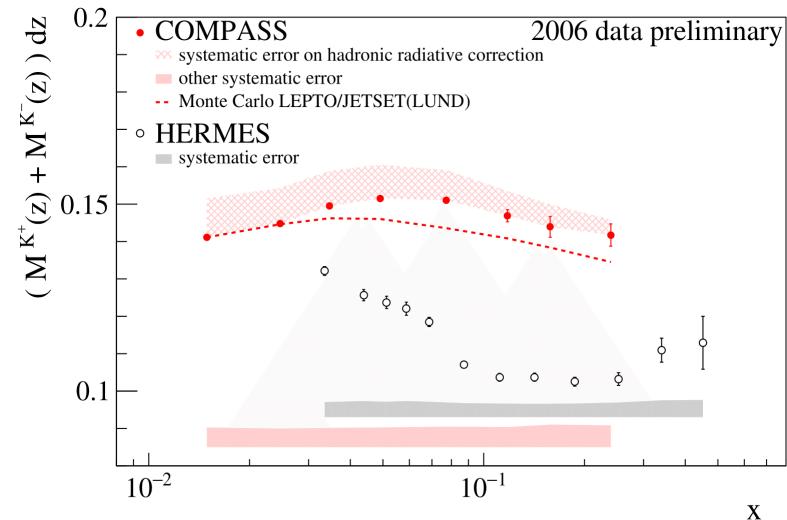


Yen-Jie,
Quark Matter 2017

Example 2: strange strange quarks

□ **s : large or small?**

- Possibly, large Hadron Mass effects
Guerrero, Accardi, in preparation
- Extraction of $s(x)$ strongly affected by **kaon systematic uncertainty**



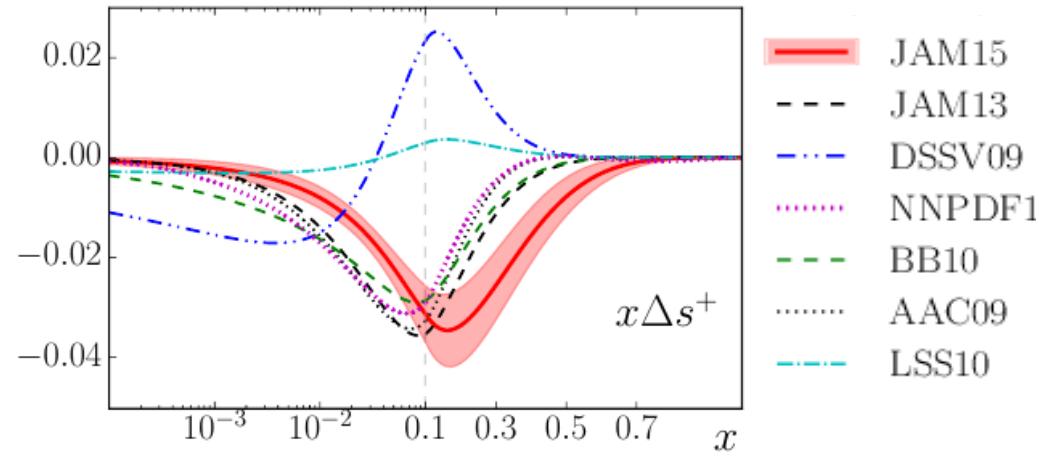
□ **Δs : positive or negative?**

- Depends on **kaon FF used in SIDIS calculations!**

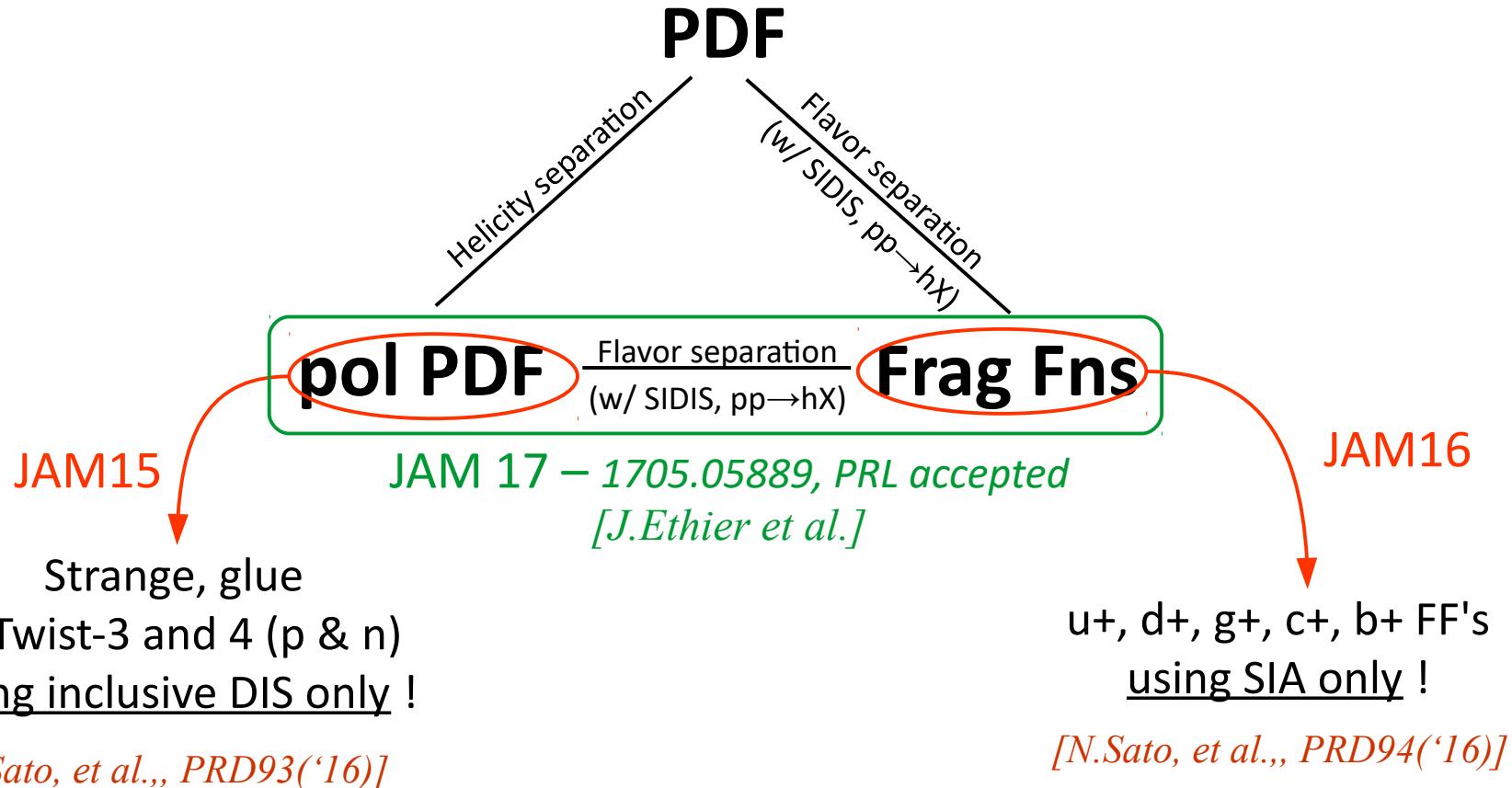
LSS, PRD 84&91

$$A_1^h(x, z, Q^2) = \frac{g_1^h(x, z, Q^2)}{F_1(x, z, Q^2)}$$

- What about the unpol s ?

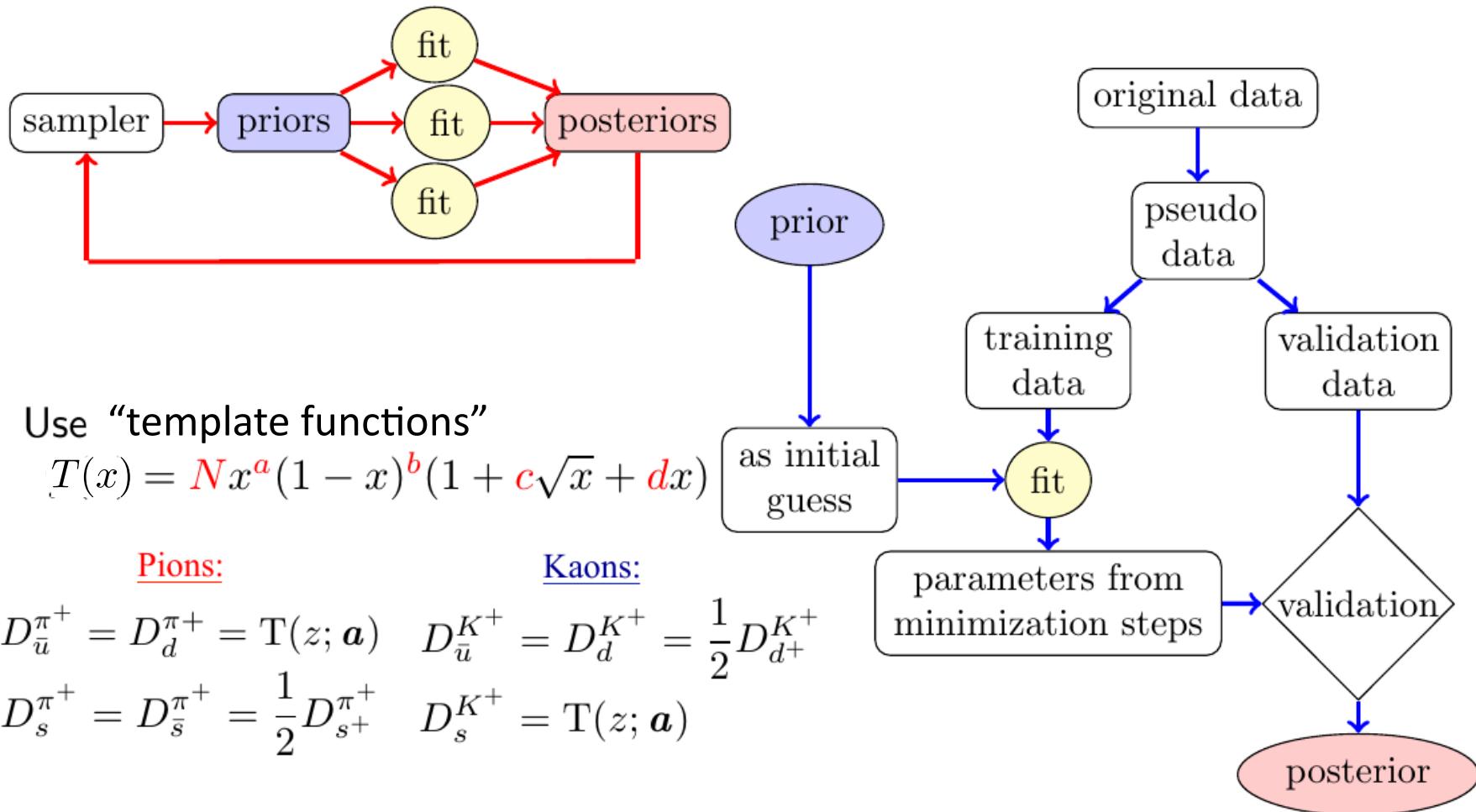


Need combined fits!



JAM: 2015-2017
and rolling...

Iterative Monte Carlo (IMC) analysis



■ Use “template functions”

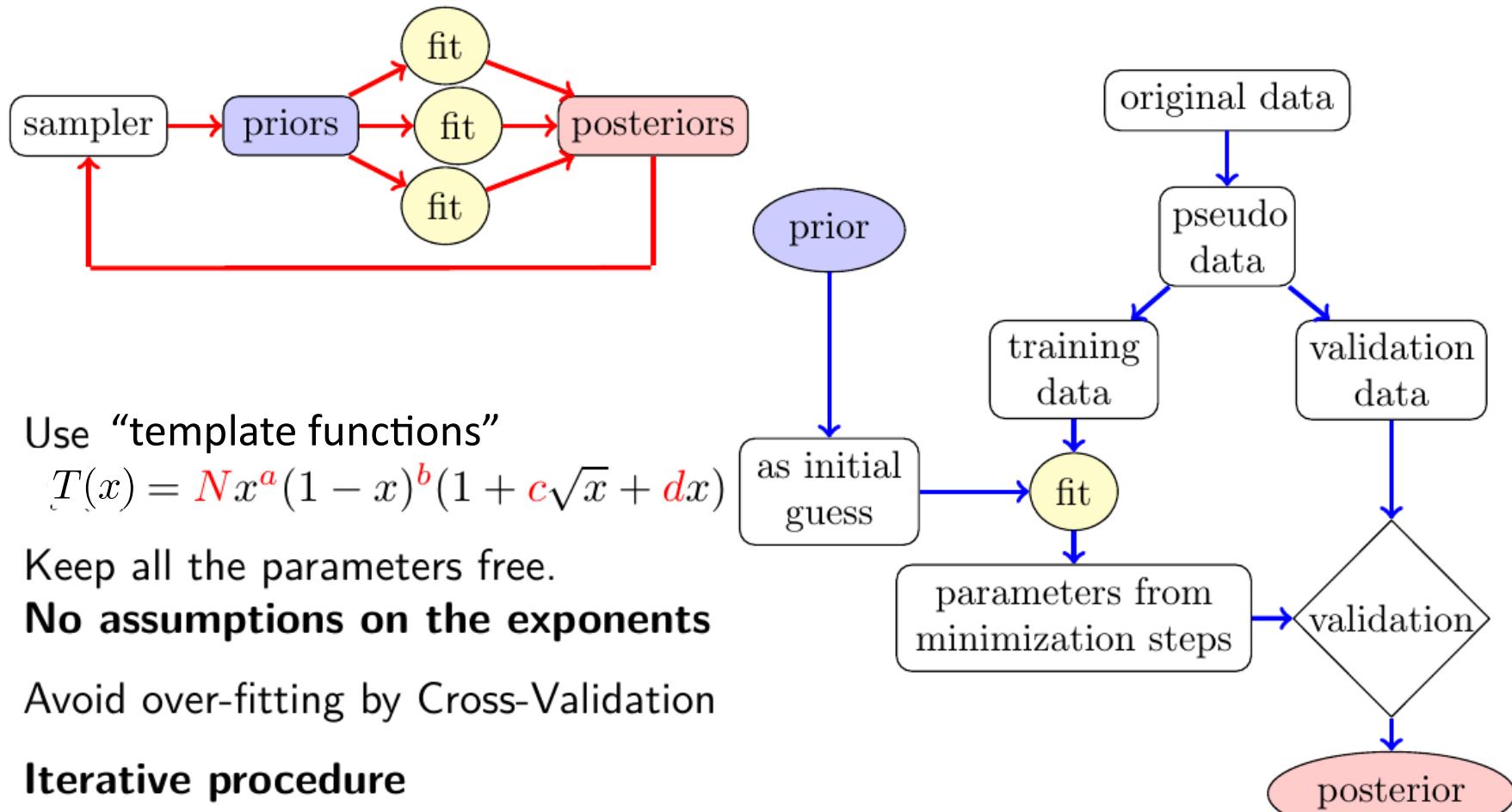
$$T(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$$

Pions:

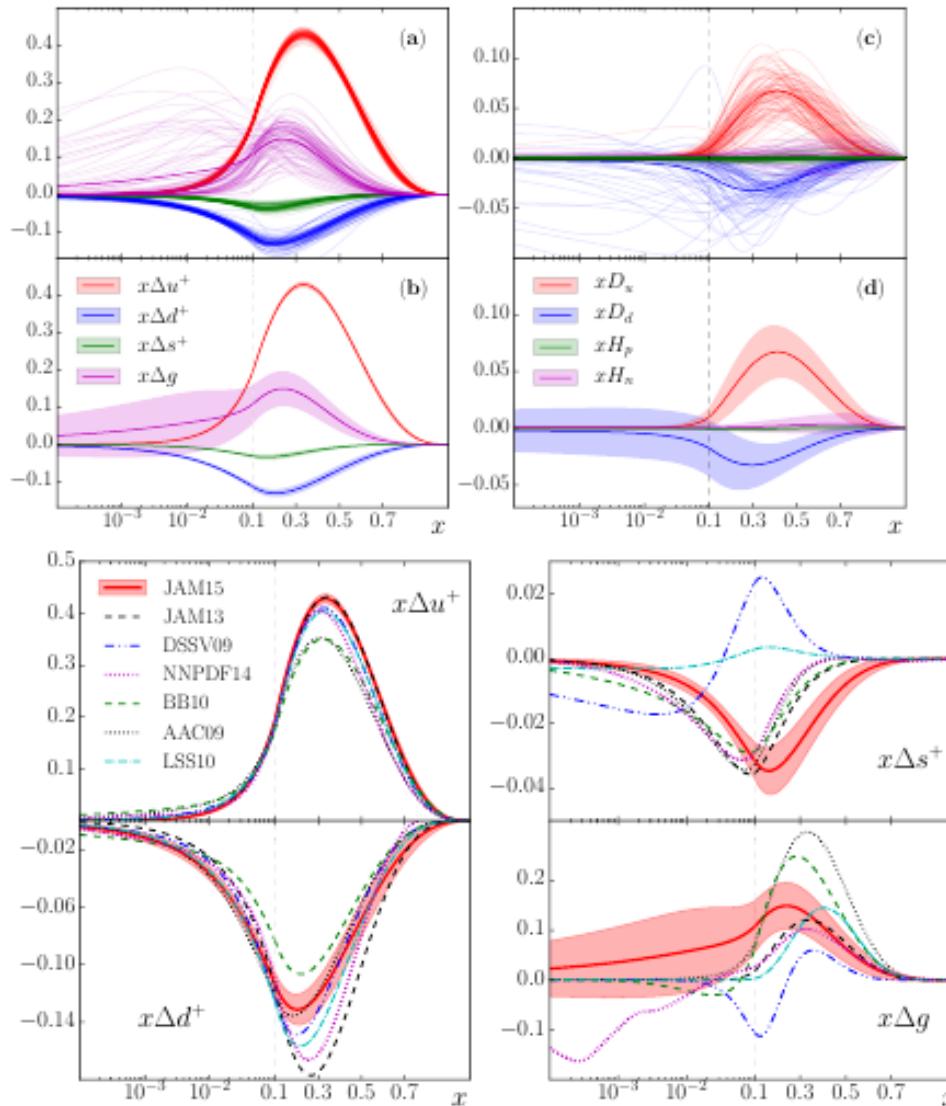
$$\begin{aligned} D_{\bar{u}}^{\pi^+} &= D_d^{\pi^+} = T(z; \mathbf{a}) & D_{\bar{u}}^{K^+} &= D_d^{K^+} = \frac{1}{2} D_{d^+}^{K^+} \\ D_s^{\pi^+} &= D_{\bar{s}}^{\pi^+} = \frac{1}{2} D_{s^+}^{\pi^+} & D_s^{K^+} &= T(z; \mathbf{a}) \end{aligned}$$

Kaons:

Iterative Monte Carlo (IMC) analysis in a nutshell



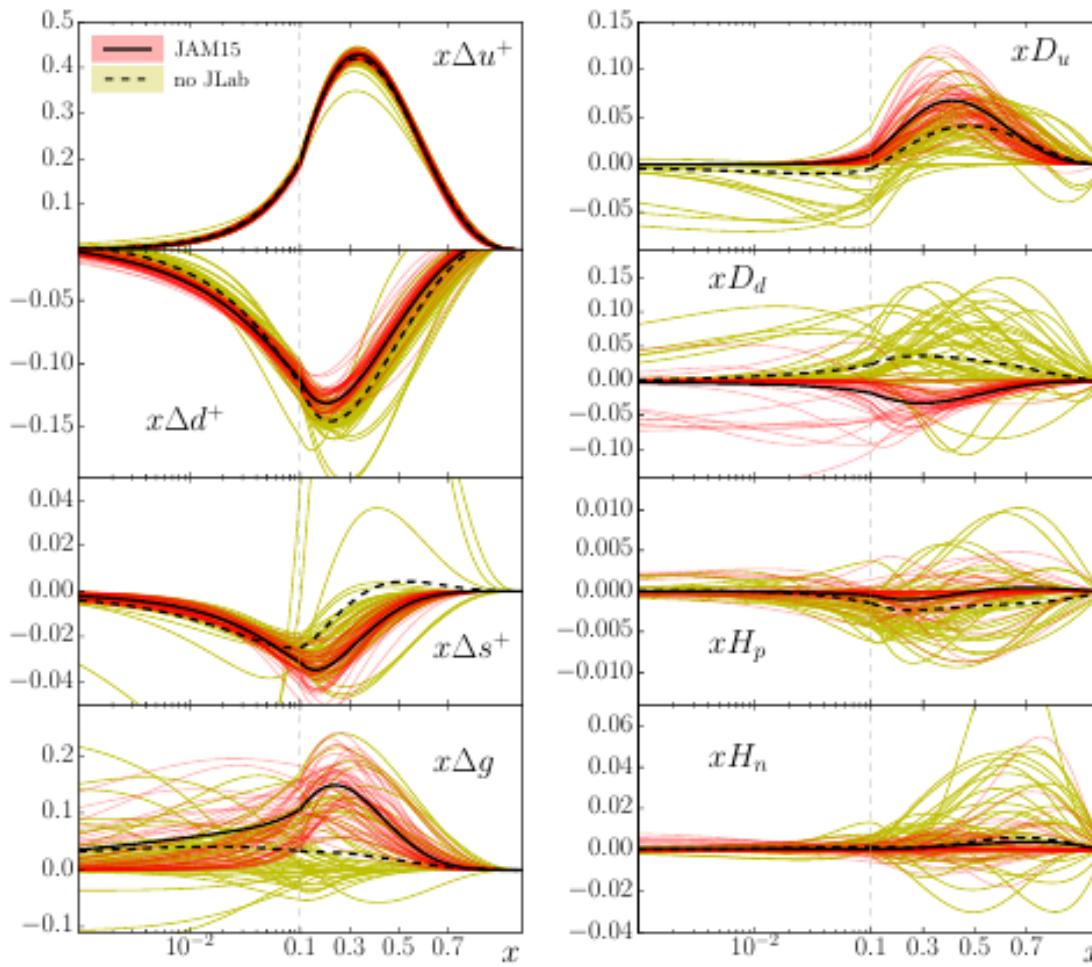
The JAM15 polarized PDFs



moment	truncated	full
Δu^+	0.82 ± 0.01	0.83 ± 0.01
Δd^+	-0.42 ± 0.01	-0.44 ± 0.01
Δs^+	-0.10 ± 0.01	-0.10 ± 0.01
$\Delta \Sigma$	0.31 ± 0.03	0.28 ± 0.04
ΔG	0.5 ± 0.4	1 ± 15
d_2^p	0.005 ± 0.002	0.005 ± 0.002
d_2^n	-0.001 ± 0.001	-0.001 ± 0.001
h_p	-0.000 ± 0.001	0.000 ± 0.001
h_n	0.001 ± 0.002	0.001 ± 0.003

- Significant constraints on Δs^+ and Δg
- Non zero T3 quark distributions
- T4 contribution to g_1 consistent with zero
- **Negative Δs^+**
- JAM15 Δg compatible with recent DSSV fits.

Impact of JLab data



- JLab data $\rightarrow 0.1 < x < 0.7$
- Constraints on small x from large $x \rightarrow$ weak baryon decay constraints
- Large uncertainties in Δs^+ , Δg removed by JLab data
- Non vanishing T3 quark distributions
- T4 distributions consistent with zero

The JAM16 FF fit

❑ Kaon FF too uncertain, correlated to strange PDF in SIDIS

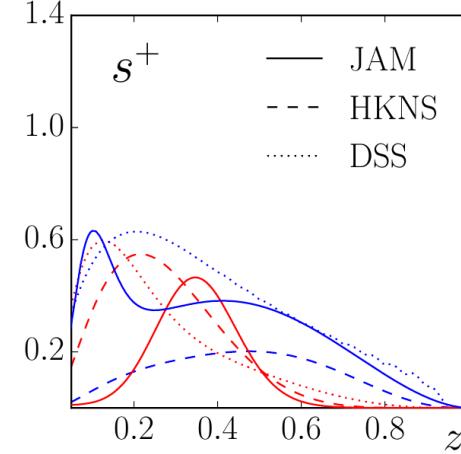
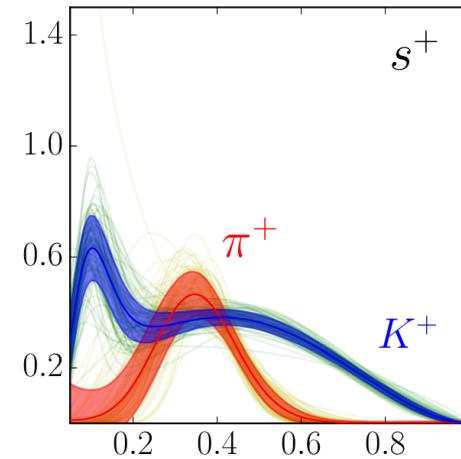
- Cannot take kaon FF off the shelf
- Need in-house extraction

❑ Iterative MC approach

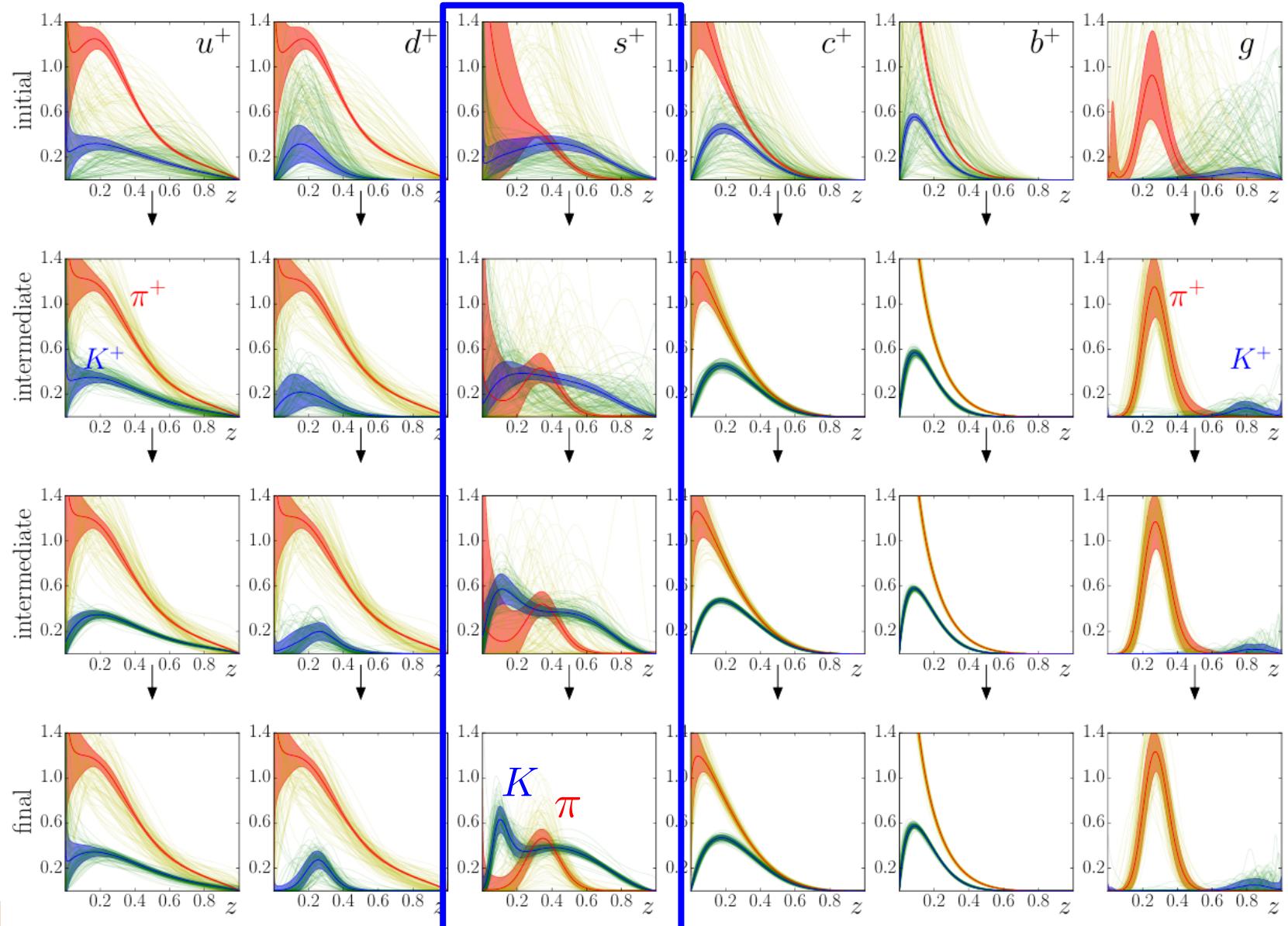
- Only SIA data used :
 $npts=245, \chi^2 = 305.2$

❑ Strange-to-kaon FF:

- Between HKNS and DSS
- Will it give a negative Δs ??



IMC method in action



Combined fits!

First simultaneous extraction of spin-dependent parton distributions and fragmentation functions from a global QCD analysis

J. J. Ethier,^{1,2} N. Sato,³ and W. Melnitchouk²

¹*College of William and Mary, Williamsburg, Virginia 23187, USA*

²*Jefferson Lab, Newport News, Virginia 23606, USA*

³*University of Connecticut, Storrs, Connecticut 06269, USA*

Jefferson Lab Angular Momentum (JAM) Collaboration

(Dated: May 18, 2017)

We perform the first global QCD analysis of polarized inclusive and semi-inclusive deep-inelastic scattering and single-inclusive e^+e^- annihilation data, fitting simultaneously the parton distribution and fragmentation functions using the iterative Monte Carlo method. Without imposing SU(3) symmetry relations, we find the strange polarization to be very small, consistent with zero for both inclusive and semi-inclusive data, which provides a resolution to the strange quark polarization puzzle. The combined analysis also allows the direct extraction from data of the isovector and octet axial charges, and is consistent with a small SU(2) flavor asymmetry of the polarized sea.

Most slides by **J.Ethier** – mistakes, misinterpretations are all on me

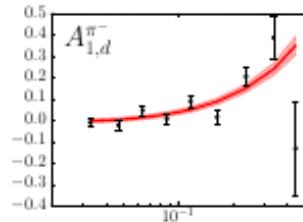
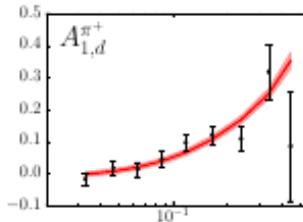
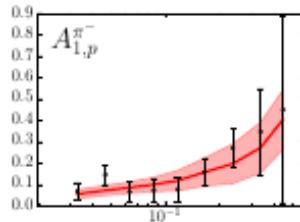
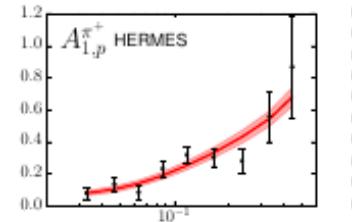
First combined PDF and FF fit!

<input type="checkbox"/> Data set	process	target	N_{dat}	χ^2
	DIS	$p, d, {}^3\text{He}$	854	854.8
	SIA (π^\pm, K^\pm)		850	997.1
	SIDIS (π^\pm)			
	HERMES [15]	d	18	28.1
	HERMES [15]	p	18	14.2
	COMPASS [16]	d	20	8.0
	COMPASS [17]	p	24	18.2
	SIDIS (K^\pm)			
	HERMES [15]	d	27	18.3
	COMPASS [16]	d	20	18.7
	COMPASS [17]	p	24	12.3
	Total:		1855	1969.7

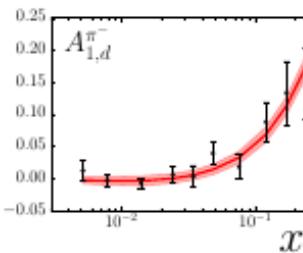
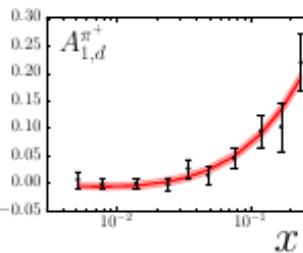
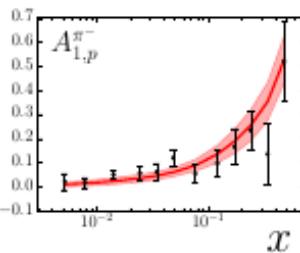
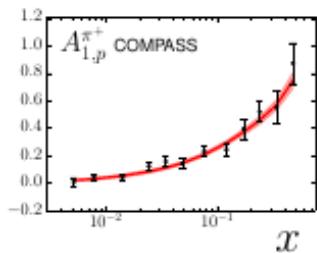
Cuts:

- $Q^2 > 1 \text{ GeV}^2 ; W^2 > 10 \text{ GeV}^2 ; z > 0.2$
(avoid HT, hadron mass effects for now)

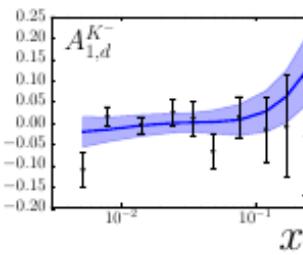
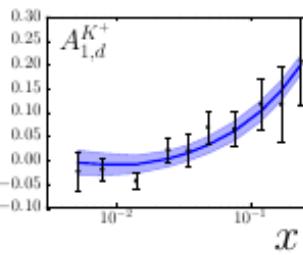
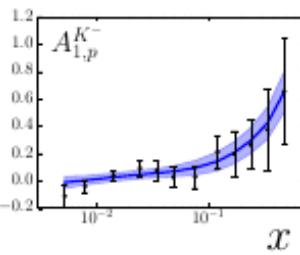
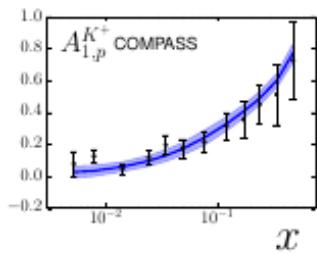
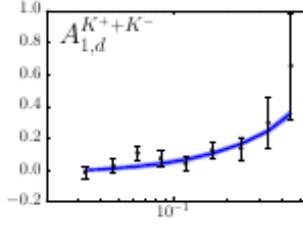
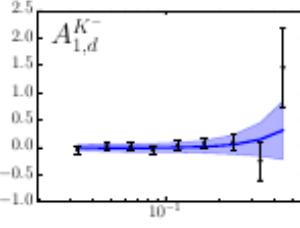
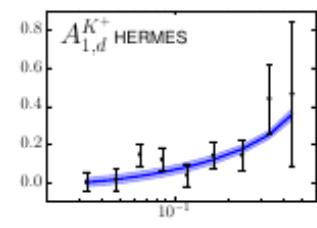
Data vs. Theory - SIDIS



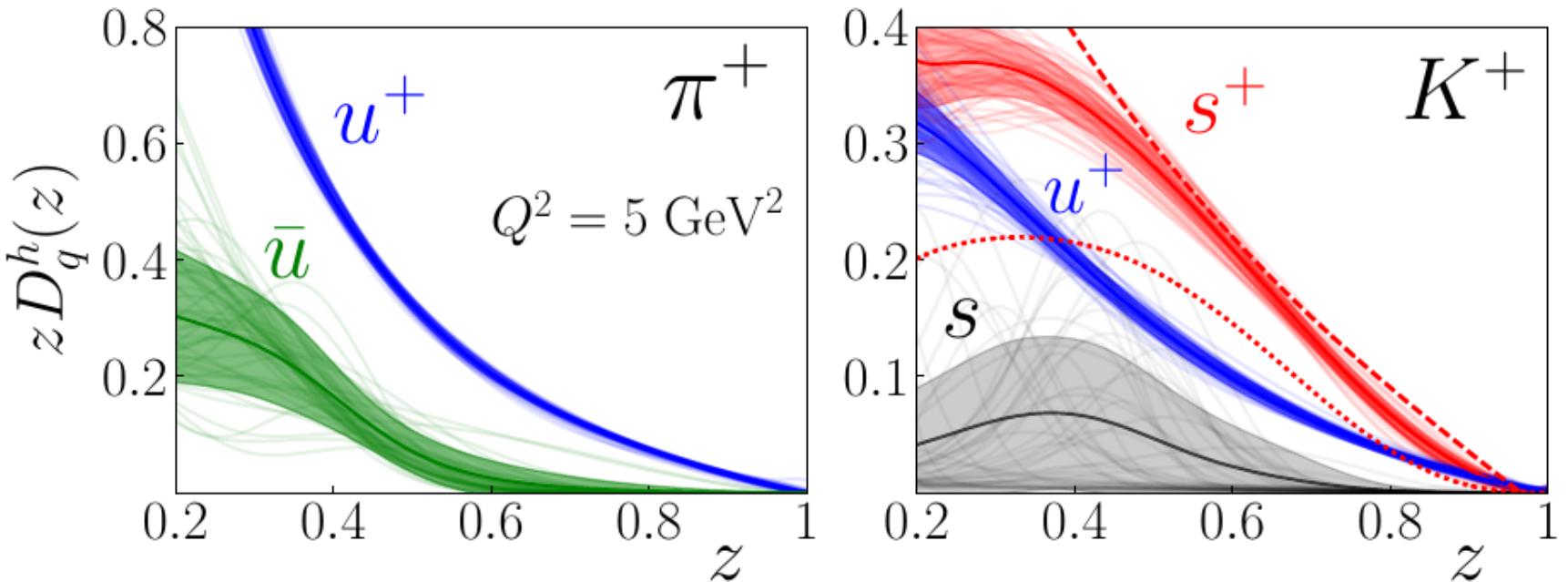
π



K



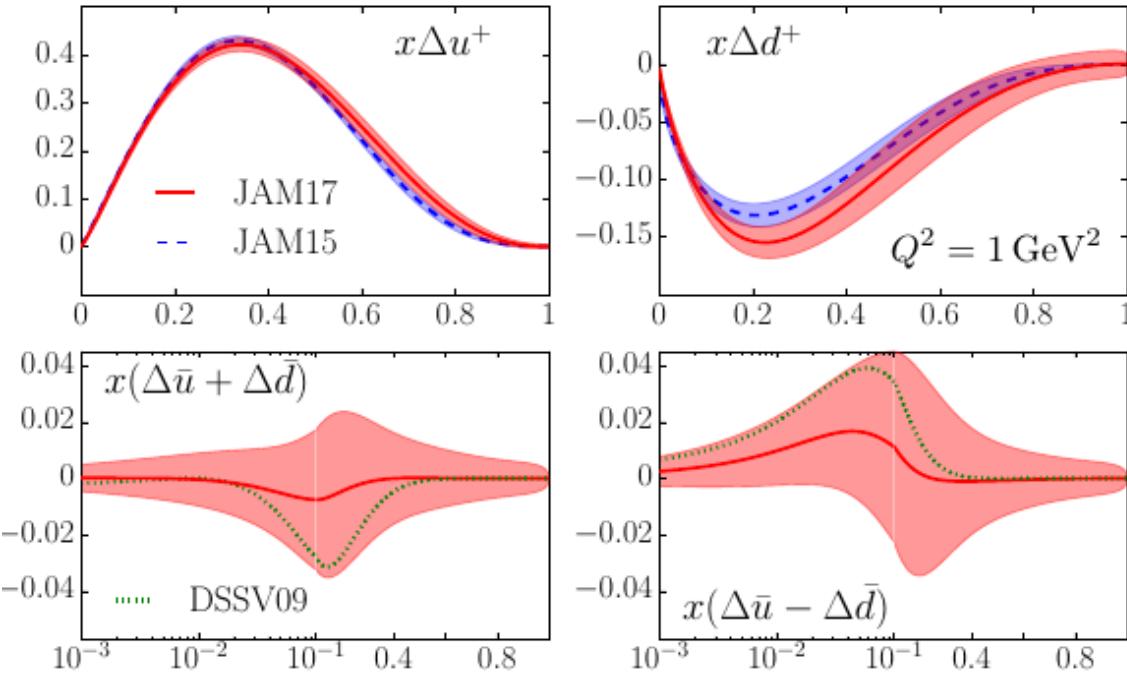
Fragmentation Functions



- Little change in ‘plus’ distributions from JAM16
→ s^+ to K^+ FF marginally smaller at low- z compared to JAM16
- Agreement with DSS’s strange FF (dashed red line)
- Uncertainty for unfavored \bar{u} to π distribution smaller than s to K
→ Due to lower precision kaon production data

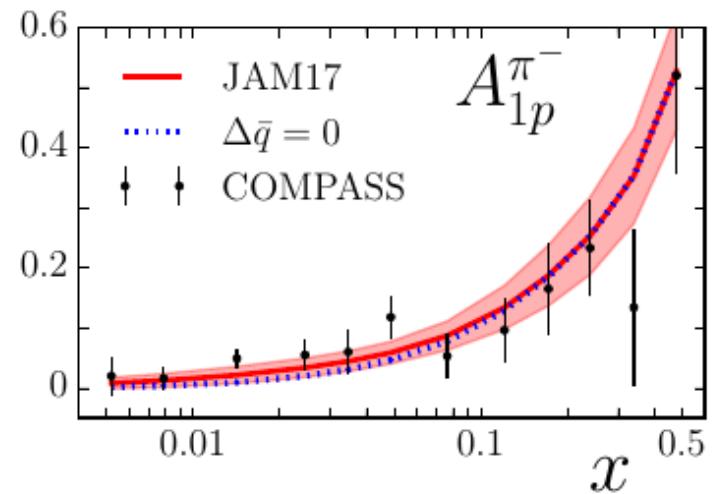


Polarized PDFs

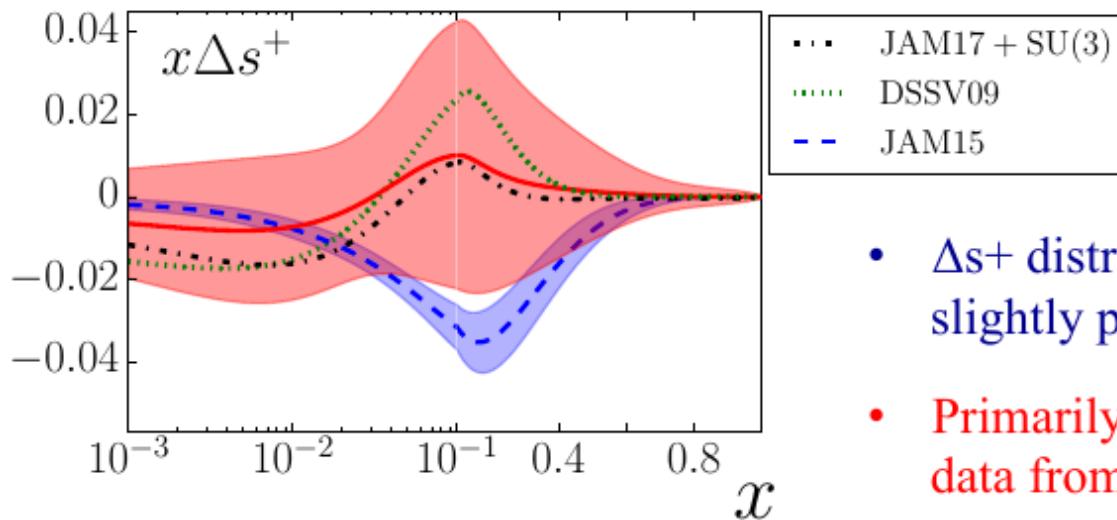


- Isoscalar sea distribution consistent with zero
- Isovector sea slightly prefers positive shape at low x
 - Non-zero asymmetry given by small contributions from SIDIS asymmetries

- Δu^+ consistent with previous analysis
- Δd^+ slightly larger in magnitude
 - Anti-correlation with Δs^+ , which is less negative than JAM15 at $x \sim 0.2$



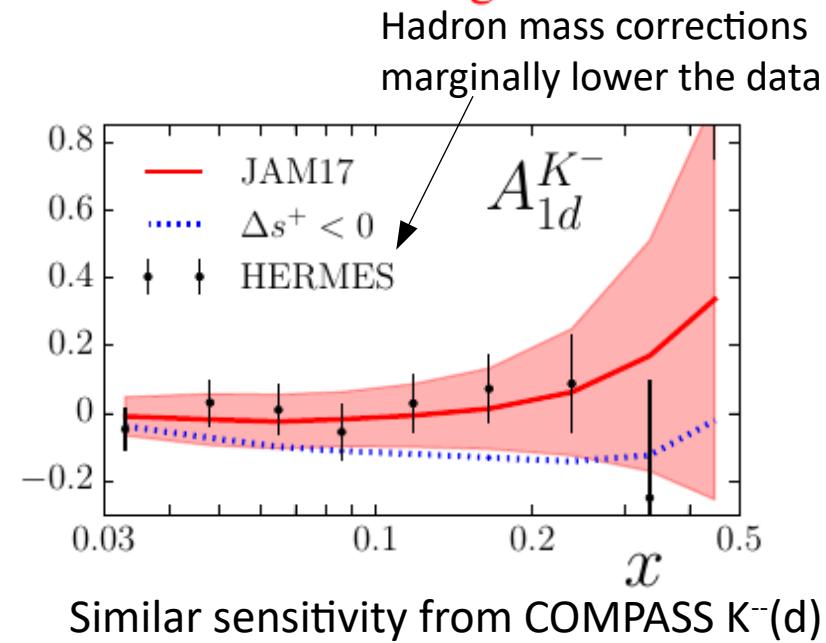
Strange polarization



- Δs^+ distribution consistent with zero, slightly positive in intermediate x range
- Primarily influenced by HERMES K-data from deuterium target

Why does DIS+SU(3) give large negative Δs^+ ?

- Low x DIS deuterium data from COMPASS prefers small negative Δs^+
- Needs to be more negative in intermediate region to satisfy SU(3) constraint
- b parameter for Δs^+ typically fixed to values $\sim 6-10$, producing a peak at $x \sim 0.1$



Strange polarization

❑ What drives the strange negative in DIS-only analyses?

- Mostly the octet axial charge constrain $a_8 = \Delta u^+ + \Delta d^+ - 2\Delta s^+$
 - 5 COMPASS bins at lowest x favor slightly negative asymmetry
 - Remove, DIS-only fit happy with DSSV shapes
 - Include, get the negative dip
- Secondly, assumptions on $b \sim 6-10$ exponent in

$$\Delta s \propto x^a (1-x)^b (1+c\sqrt{x})$$

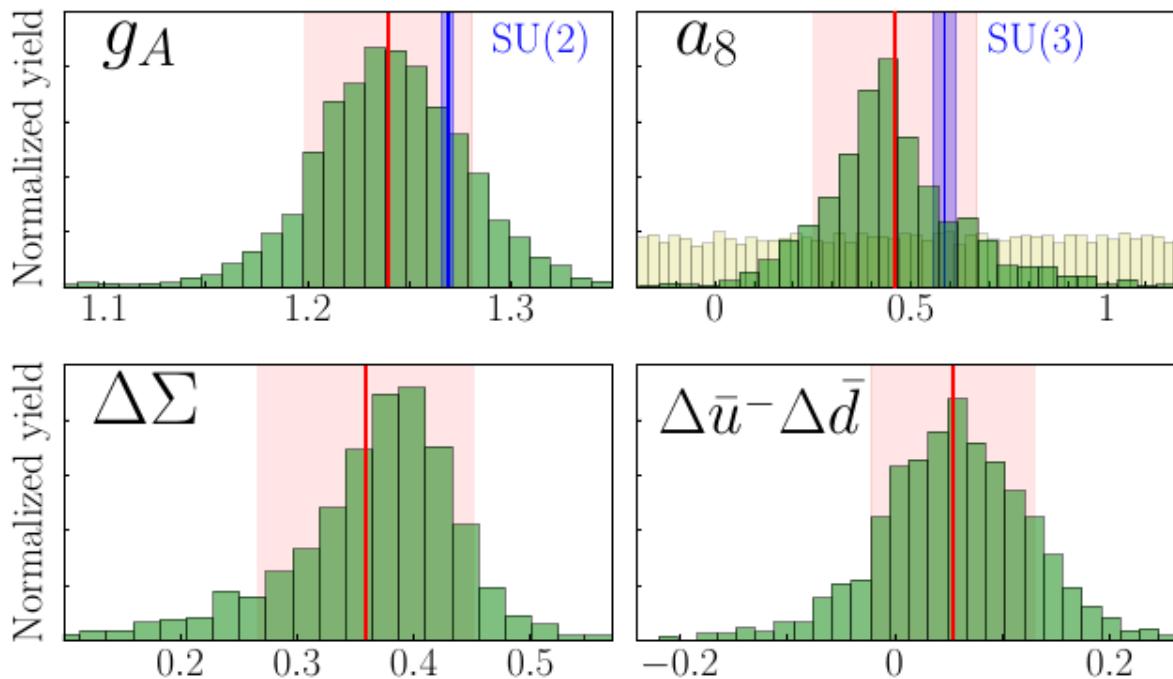
❑ Cross check: DIS-only fit

- without a_8 constrain
- With $\Delta s=0$ at input scale

}

Same chi² as

Moments



$g_A = 1.24 \pm 0.04$ Confirmation of SU(2) symmetry to $\sim 2\%$

$a_8 = 0.46 \pm 0.21$ $\sim 20\%$ SU(3) breaking $\pm \sim 20\%$; large uncertainty

- Need better determination of Δs^+ moment to reduce a_8 uncertainty!

$$\Delta s^+ = -0.03 \pm 0.09$$

Transversity in inclusive DIS!

*In collaboration with A.Bacchetta
Physics Letters B 773 (2017) 632*

TMDs in spin $\frac{1}{2}$ 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}	$h_1^\perp h_{1T}^\perp$

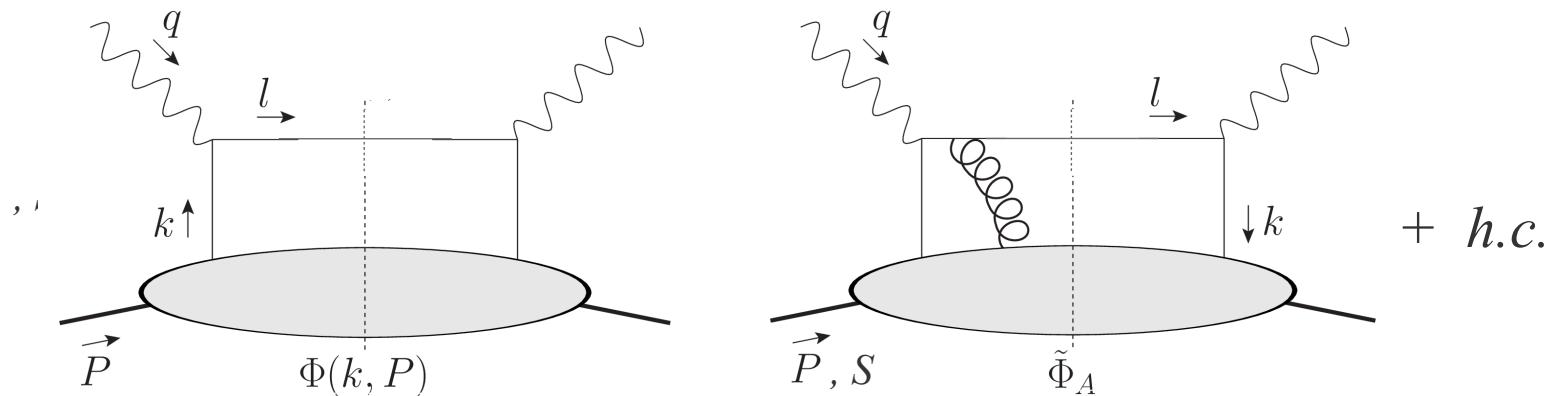
→ P. Mulders, QCDev2017

- Integrated (collinear) correlator: 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 $\sim h_1$ pops up in the $g_2 - g_2^{WW}$ structure function

g_2 structure function - standard analysis

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

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



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

↑ Wandzura-Wilczek term
↑ “pure twist-3” (qqq 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 $\sim \delta(x)$ → *Jaffe, Ji '91*
→ *Burkardt, Koike, '02*

... or large spin-flip contributions → *Burkhardt, Cottingham '70*

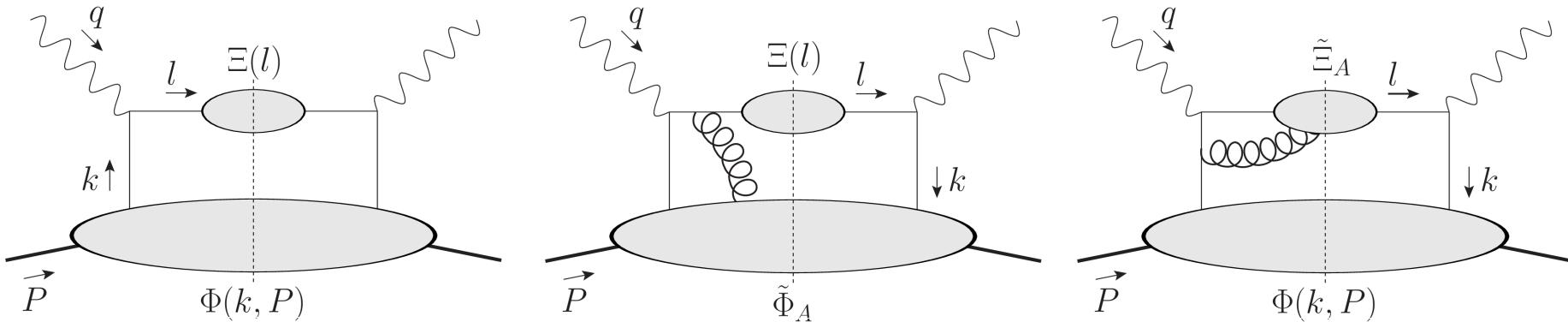
□ “pure twist-3” effects, e.g.,

Color force experienced by struck quark → *M.Burkardt*

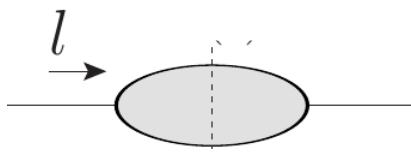
$$\begin{aligned} d_2 &\equiv \int_0^1 dx x^2 [g_2(x) - g_2^{WW}(x)] \\ &= 3g_2[2] + 2g_1[1] \sim \langle P | \bar{\psi} \gamma^+ F^{+\alpha} \psi | P \rangle \end{aligned}$$

Inclusive DIS with jet correlators

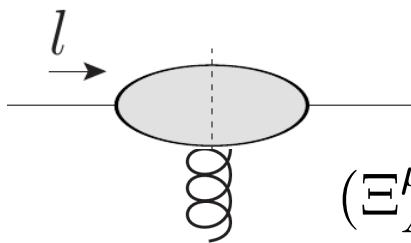
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Jet correlators



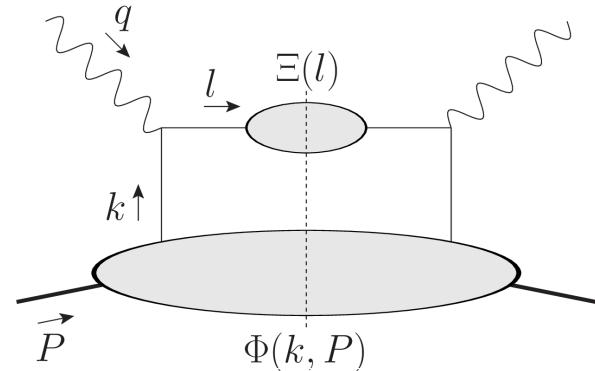
$$\Xi_{ij}(l, n_+) = F.T. \langle 0 | \mathcal{U}_{(+\infty, \eta)}^{n_+} \psi_i(\eta) \bar{\psi}_j(0) \mathcal{U}_{(0, +\infty)}^{n_+} | 0 \rangle$$



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

Factorization

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



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

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

$$\xi_1 = \int d\mu^2 \frac{\mu}{\Lambda} J_1(\mu^2) \equiv \boxed{\frac{M_q}{\Lambda}} \quad \begin{array}{l} \text{Spin-flip average "jet" mass} \\ \rightarrow \text{can couple to transversity!} \end{array}$$

$$\xi_2 = \int d\mu^2 J_2(\mu^2) = 1 \quad \begin{array}{l} \text{Exactly} \end{array}$$

- Positivity constraints imply

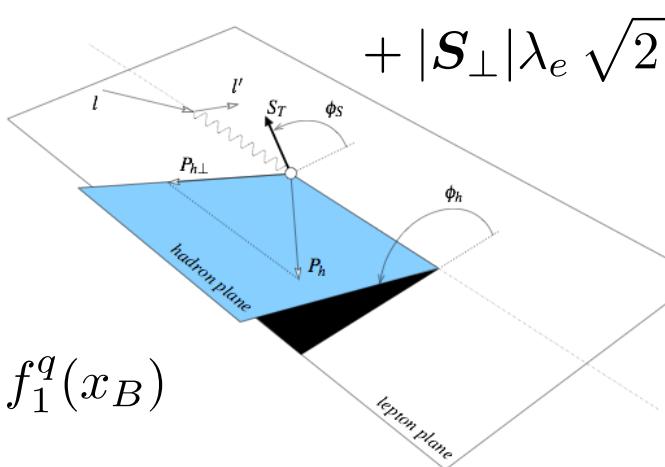
$$0 < M_q < \int d\mu^2 \mu J_2(\mu^2) \implies \boxed{M_q = O(100 \text{ MeV})}$$

Much larger than m_q !

Finally, the DIS cross section

- ❑ Inclusive DIS

$$\frac{d\sigma}{dx_B dy d\phi_S} \propto \left\{ F_T + \varepsilon F_L + S_{||} \lambda_e \sqrt{1 - \varepsilon^2} F_{LL} + |S_{\perp}| \lambda_e \sqrt{2\varepsilon(1 - \varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right\}$$



- ❑ Structure functions:

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

$$F_L = 0$$

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

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

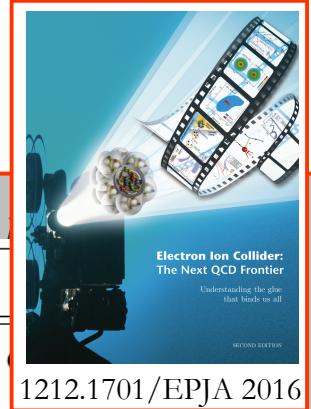
Transversity in inclusive DIS!

Finally, the DIS cross section

Inclusive DIS

$$\frac{d\sigma}{dQ^2} \propto \left\{ F_T + \varepsilon F_L + S_{\parallel} \lambda_e \sqrt{1 - \varepsilon^2} F_L \right\}$$

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



1212.1701/EPJA 2016

Table 2.2: Science Matrix for TMD: 3D structure in transverse momentum space: (upper) 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

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- Using EOM, Lorentz Invariance Relations, can show that

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

Color force distribution Transversity in inclusive DIS!

- Consequences:

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

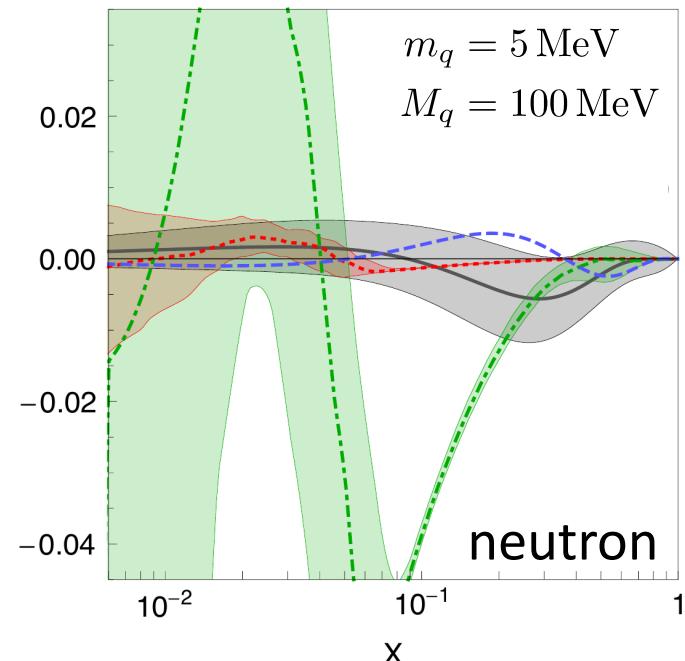
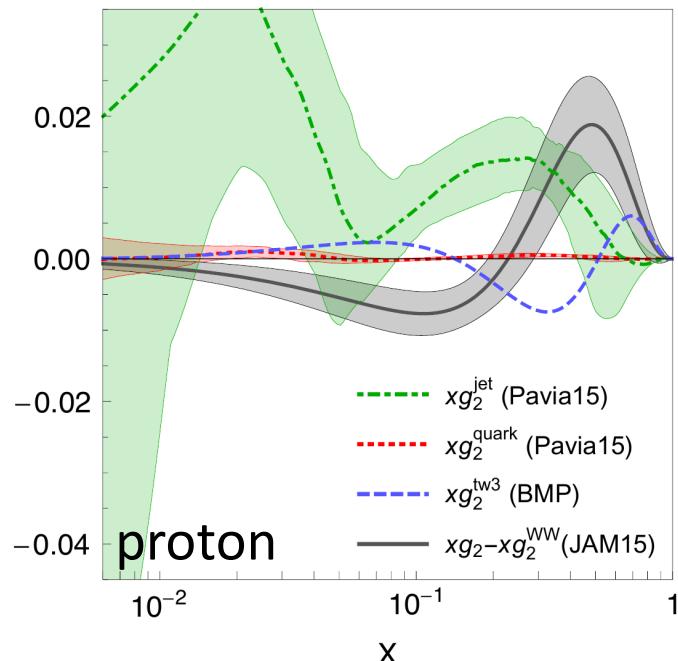
$$f^*(x) = -f(x) + \int_x^1 \frac{dy}{y} f(y)$$

g2 structure function revisited

AA, Bacchetta, PLB 773 ('17) 632

- Using EOM, Lorentz Invariance Relations, can show that

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



Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

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

Burkardt-Cottingham

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

- unlikely to still be zero!
- Is BC broken by finite amount?
Perturbatively, yes ($h \sim x$) but...

→ Small-x asymptotics:

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

→ Kovchegov, Pitonyak, Sievert
PRD(2017)93

But h_1 is also non-singlet, expect

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

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

Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

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PRD(2017)93

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But h_1 is also non-singlet, expect

How does spin propagate to small x ?

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

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



Novel non-perturbative sum rules

AA, Bacchetta, PLB 773 ('17) 632

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

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

Efremov-Teryaev-Leader

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

→ 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

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

Efremov-Teryaev-Leader

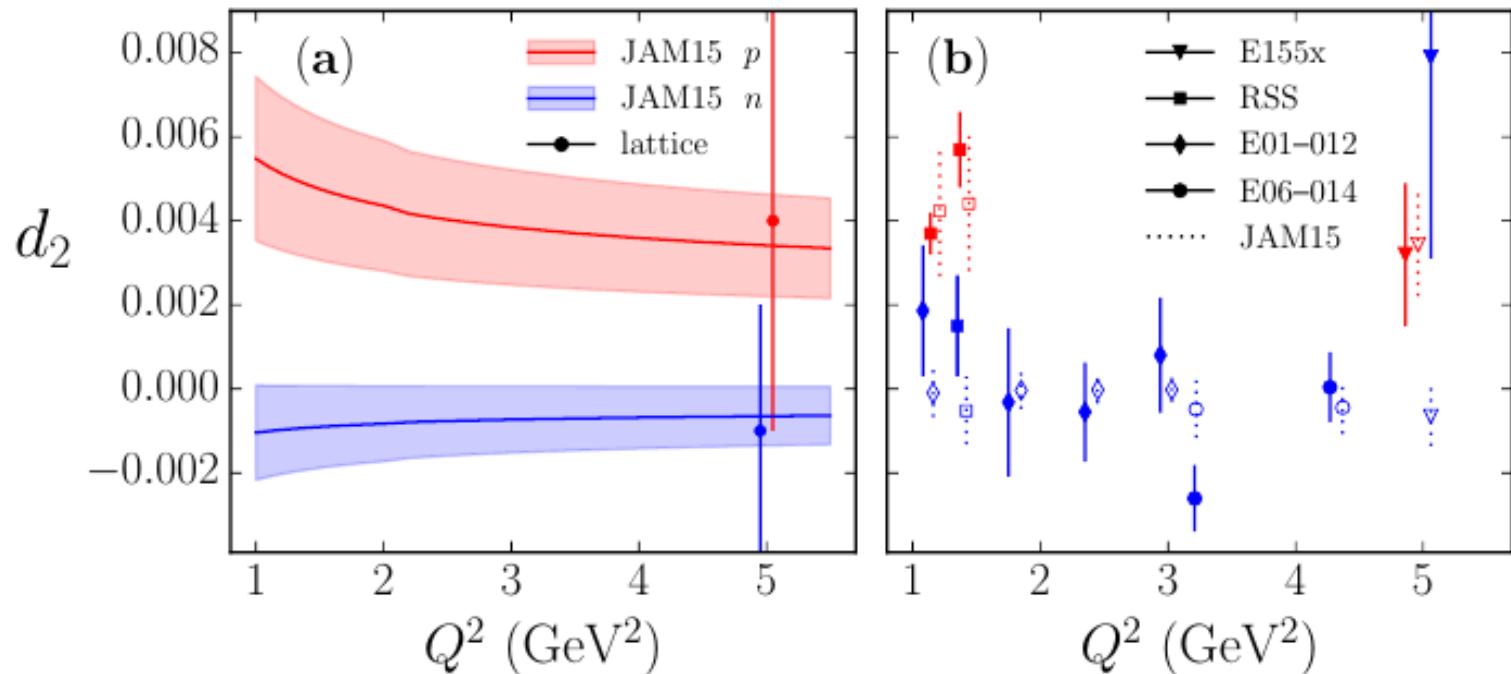
$$\int_0^1 x g_2^{q-\bar{q}}(x) = 2 M^{“jet”} \underbrace{\int_0^1 dx h_1^{q-\bar{q}}(x)}_{\text{Tensor charge } \delta_T}$$

Color polarizability

$$\int_0^1 [3x^2 g_2(x) - 2x^2 g_1(x)] = d_2 + 3 M^{“jet”} \int_0^1 x h_1(x) + O(m_q)$$

↑
“pure twist-3”

Higher twist and color polarizability



- $d_2(Q^2) \equiv \int_0^1 dx x^2 [2g_1^{\text{T3}}(x, Q^2) + 3g_2^{\text{T3}}(x, Q^2)]$
- d_2 is related to “color polarizability” or the “transverse color force” acting on quarks.

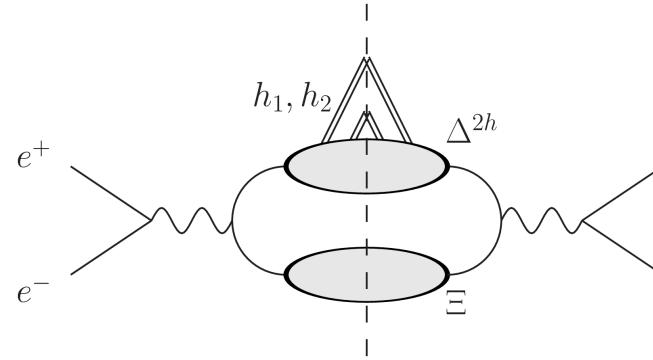
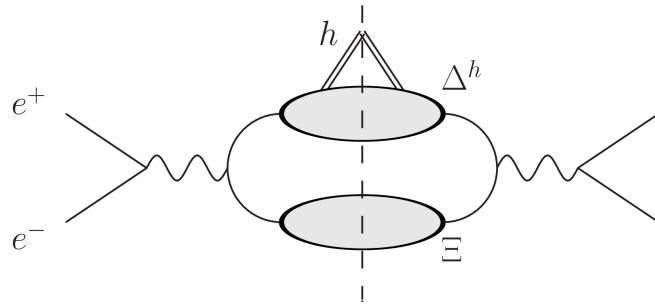
Lattice calcs from Goeckele et al. 2005 – time to revisit?

Measuring the jet correlator

Accardi, Bacchetta Radici, in prep.

Related to confinement, mass generation [C.Roberts]

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



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

$$\frac{d\sigma^L(e^+e^- \rightarrow \text{jet } h X)}{d\Omega dz}$$

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

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



Where can we measure jet correlators?

- Can we get a (polarized) e+ e- collider at JLab / BNL?
 - At JLab12 ? JLEIC ? eRHIC?
- Are existing facilities enough?

	BEPC	super KEKB	ILC	JLab/BNL
E beam [GeV]	1.9	4 (e ⁻) 7 (e ⁻)	250	?
\sqrt{s} [GeV]	3 – 5	10	500	?
polarization	?	maybe	80% e ⁻ 60% e ⁺	YES!

- What else is interesting to study?
 - Factorization tests for FFs (low s, unpol), ... Ideas?

Final thoughts

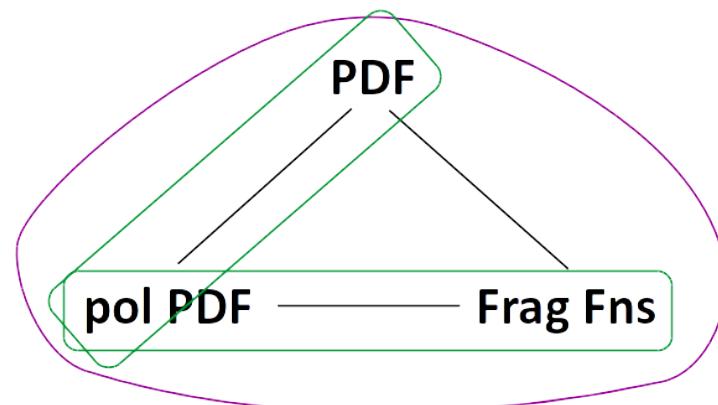
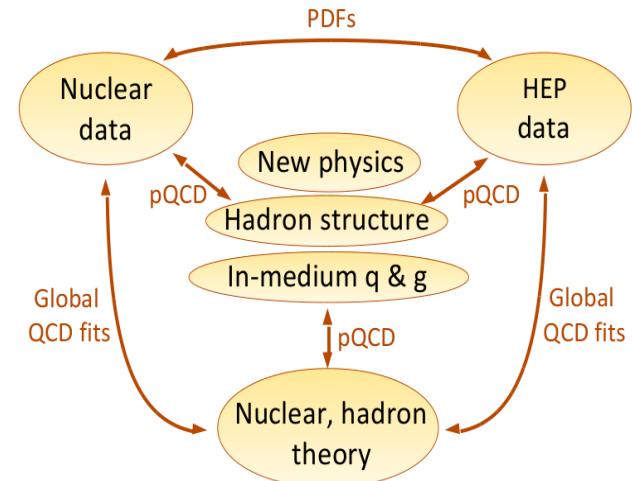
Final thoughts

❑ Entering a new PDF precision era:

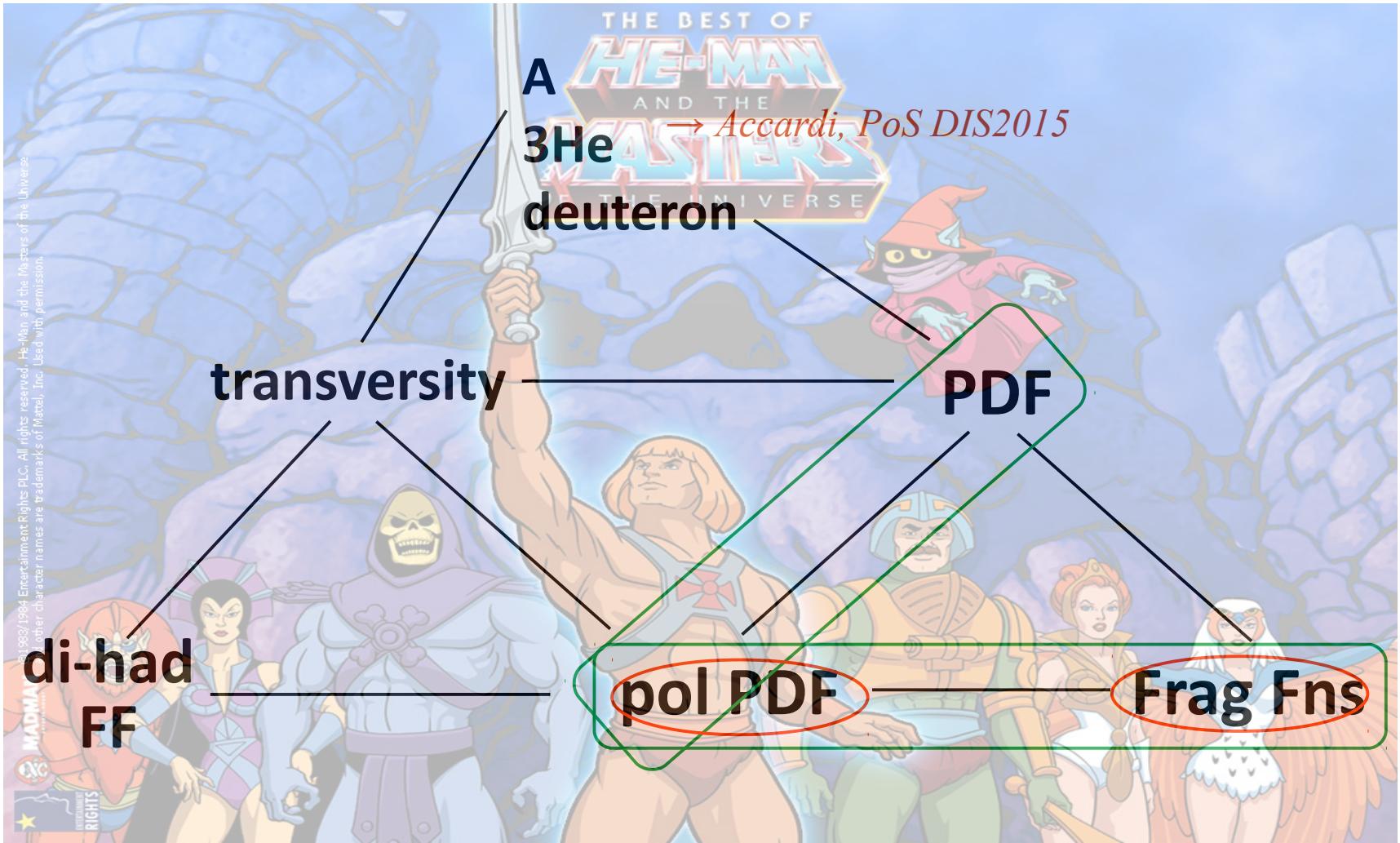
- New combined fitting approaches
 - Hadronic, nuclear physics output
 - Improved PDF accuracy and precision
- Entering the **Jlab12 & EIC** era
 - With the complicity of RHIC, LHC / Compass, E906, ...

❑ What else?

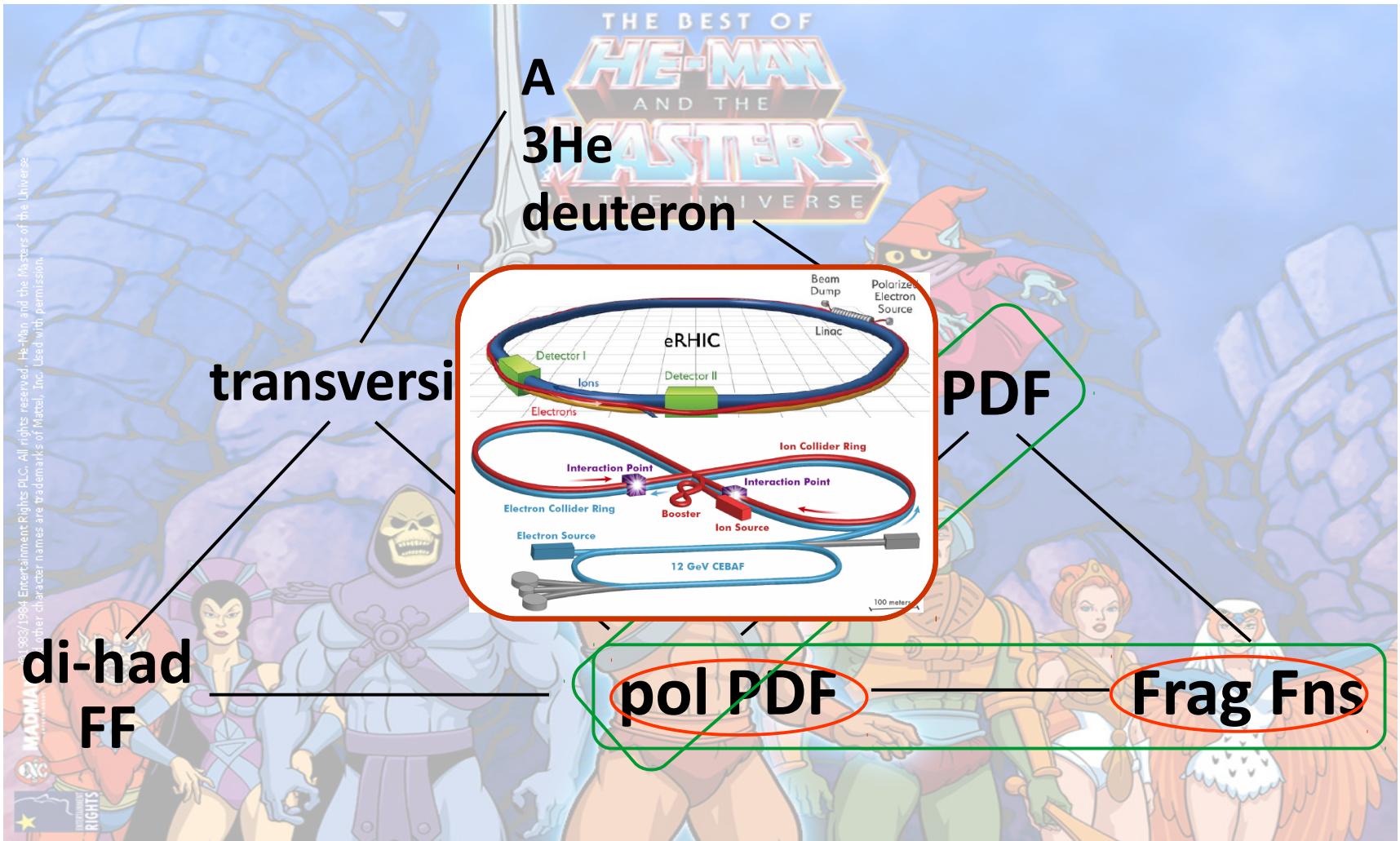
- towards “universal” collinear PDF+pPDF+FF fits+...



Masters of the Universe



Masters of the Universe



Extra

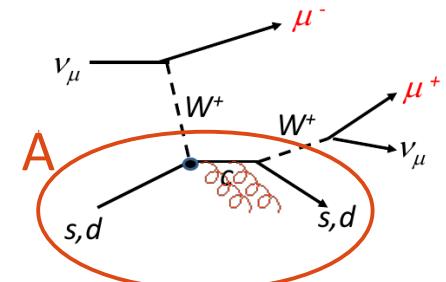
More on strange quarks

Strange strange quarks

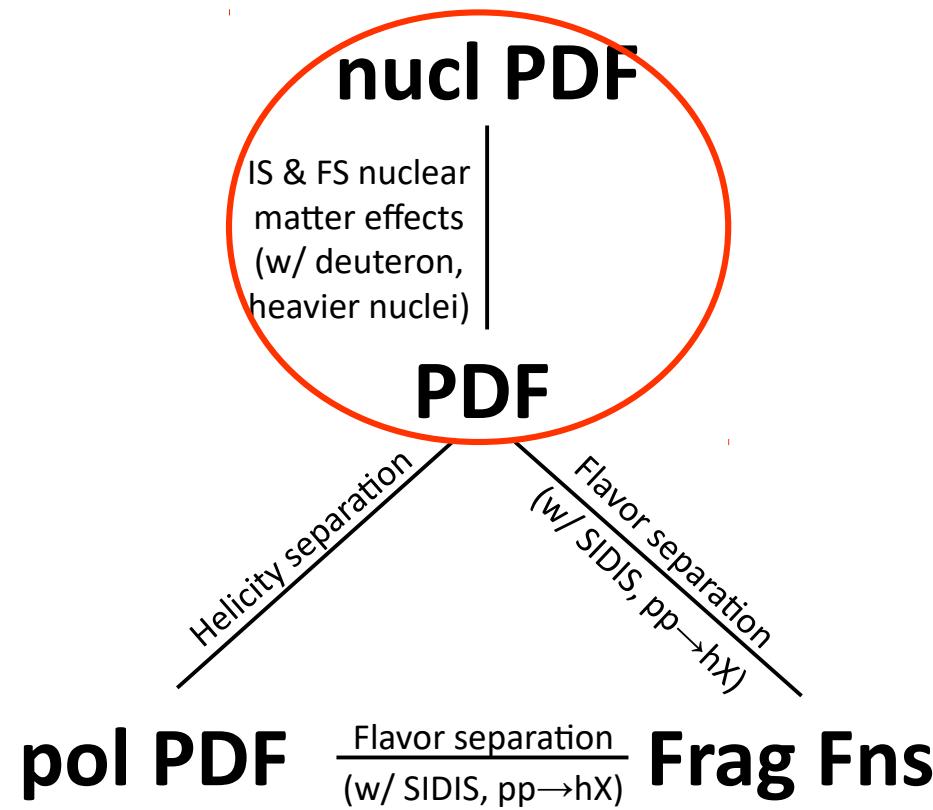
- How to make progress in s-quark determination?
 - Use data on proton targets to fix s → CJ17, *in progress*

	Obs.	x	Q^2 [GeV 2]
LHC	W, Z, W+c	$10^{-4} - 10^{-1}$	> 6400
JLab 12 [M.Dalton]	PVDIS	0.1 – 0.4	1 – 4
EIC [Y.Zhao, Aschenauer]	PVDIS, CC	$10^{-3} - 0.5$	1 – 5000

- Use dimuons on nuclear targets to study charm quark propagation in nuclear matter



Yet another combined fit needed!



(nucl pol PDF)

nucl FF

Another possibility

Measure charged current cross sections with a muon tag to select charm final states

$$e^+ s \rightarrow \bar{\nu} c \quad \text{followed by} \quad c \rightarrow s \mu^+ \nu_\mu$$

and

$$e^- \bar{s} \rightarrow \nu \bar{c} \quad \text{followed by} \quad \bar{c} \rightarrow \bar{s} \mu^- \bar{\nu}_\mu$$

- Note that the sign of the muon is the same as the sign of initial state lepton
- Potentially capable of separating s from \bar{s}

J.Owens, JPos 2017



Another possibility

□ How?

- Inclusive muon production
 - like $p+p \rightarrow K+X$, but here $e+p \rightarrow \mu+X$
- $\pi \rightarrow \mu$ decay background
 - Remove by subtracting $e^+ \rightarrow \mu^+$ and $e^- \rightarrow \mu^-$ cross sections?
- Cross section is likely tiny, but JLab luminosity is rather high
- Completely crazy or somewhat sort of feasible?