Towards "universal" PDF and FF fits in the EIC era

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Hampton U. and Jefferson Lab

EIC Users Group Meeting

Trieste, July 21st, 2017

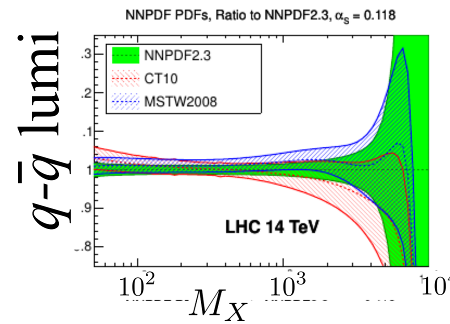
CTEQ-Jefferson Lab Collaboration

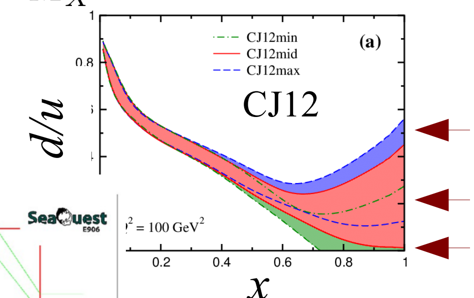
Jefferson Lab Angular Momentum Collaboration

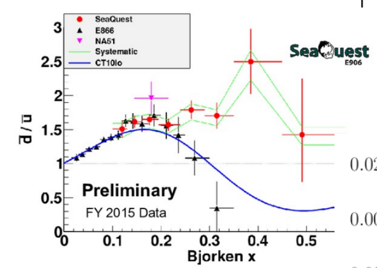
Why PDFs ?

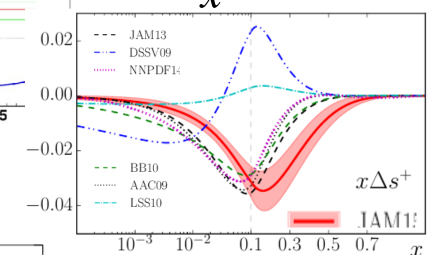
Accardi – PoS (DIS2015) 001
Jimenez-Delgado, Melnitchouk, Owens, JPG 40 (2013) 093102
Forte and Watt – Ann.Rev.Nucl.Part.Sci. 63 (2013) 291

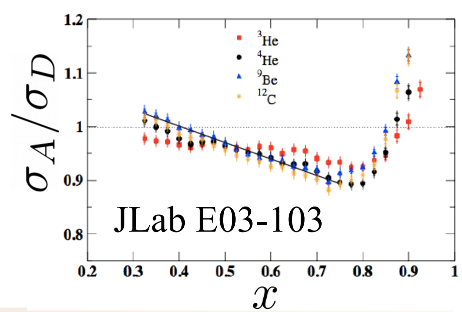
- **High-energy** *(large to small x)*
  - Beyond the Standard Model searches
  - Precision (Higgs) physics
  - Gluonic "matter" at small *x*
- **Hadron structure** *(large to medium x)*
  - Effects of confinement on valence quarks
  - q – qbar asymmetries; isospin asymmetry
  - Strangeness, intrinsic charm
  - Spin structure:
    - Longitudinal (spin puzzle)
    - Transverse
- **Nuclear physics**
  - Bound nucleons, EMC effect, SRC
  - p+A and A+A collisions at RHIC / LHC
  - Color propagation in nuclear matter











Many distributions, “single” fits

→ *Zurita [129]*

nucl PDF

PDF → *Nocera [129]*

pol PDF

Frag Fns → *Nocera[129]*

(nucl pol PDF)

nucl FF

But physics is not isolated

→ *Zurita [129]*

nucl PDF

IS & FS nuclear matter effects (w/ deuteron, heavier nuclei)

Accardi, PoS DIS2015 001

PDF

→ *Nocera [129]*

Helicity separation

Flavor separation (w/ SIDIS, pp→hX)

pol PDF

Flavor separation (w/ SIDIS, pp→hX)

Frag Fns

→ *Nocera [129]*

(nucl pol PDF)

nucl FF

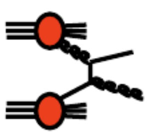
35+ years of unpolarized global PDF fits

	JLab & BONUS	HERMES	HERA I+II	Tevatron new W,Z	LHC	ν+A di-μ	Large-x treatment: Nucl.	HT TMC	Flex *d*	low-W DIS
CJ15 *	✓	✓	✓	✓	*in prog.*	✗	✓✓	✓	✓	✓
CT14			DIS 2016	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.0					✓	✓		TMC only		
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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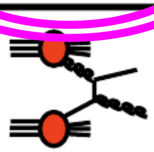
	✔ included in fit (no $W^{\pm}$ yet)	✔ (jets, $W^{\pm}$) via reweighting	(soon)

Needs FFs !!

Important insights also from "less global" studies:

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

5+ years: new fitting methods

- More computing power, efficient implementations
  - **New fitting, analysis methods**

- In traditonal fits:
  - Detailed χ^2 scans, refined statistical analysis

- Monte Carlo fitting methods:
  - **NNPDF**: bootstrap + neural network fit *→ Nocera's talk*
  - **JAM**: bootstrap + Iterative Monte Carlo (IMC) approach *→ Sato, Ethier et al (since 2015)*

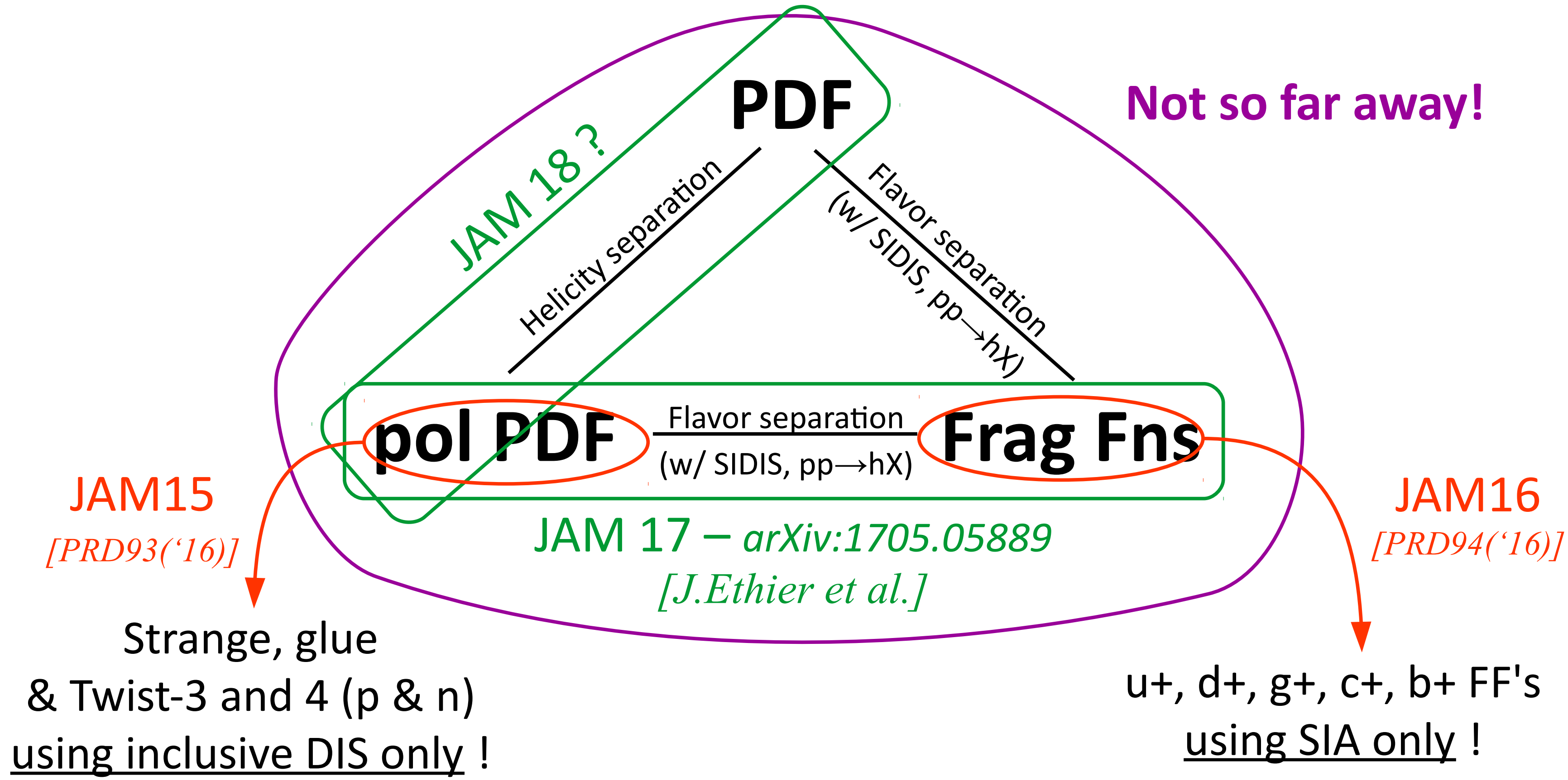
  Large number of parameters, trustable uncertainty estimates

- 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

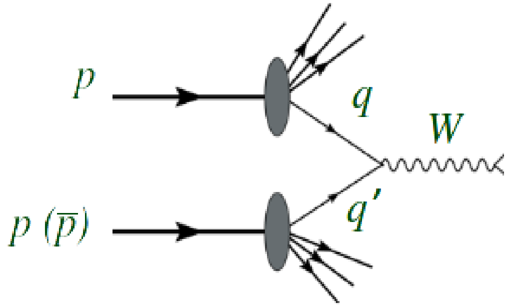


Two examples

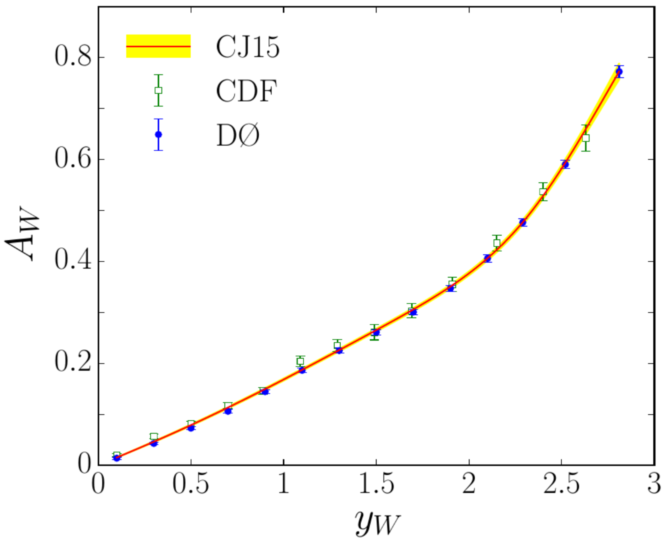
Example 1: Tevatron as NUCL facility (!)

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

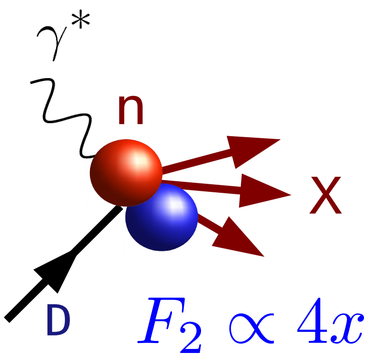
- ***Reconstructed W*** $\longrightarrow$ constrain ***d*-quark** at largest x on proton targets



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



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

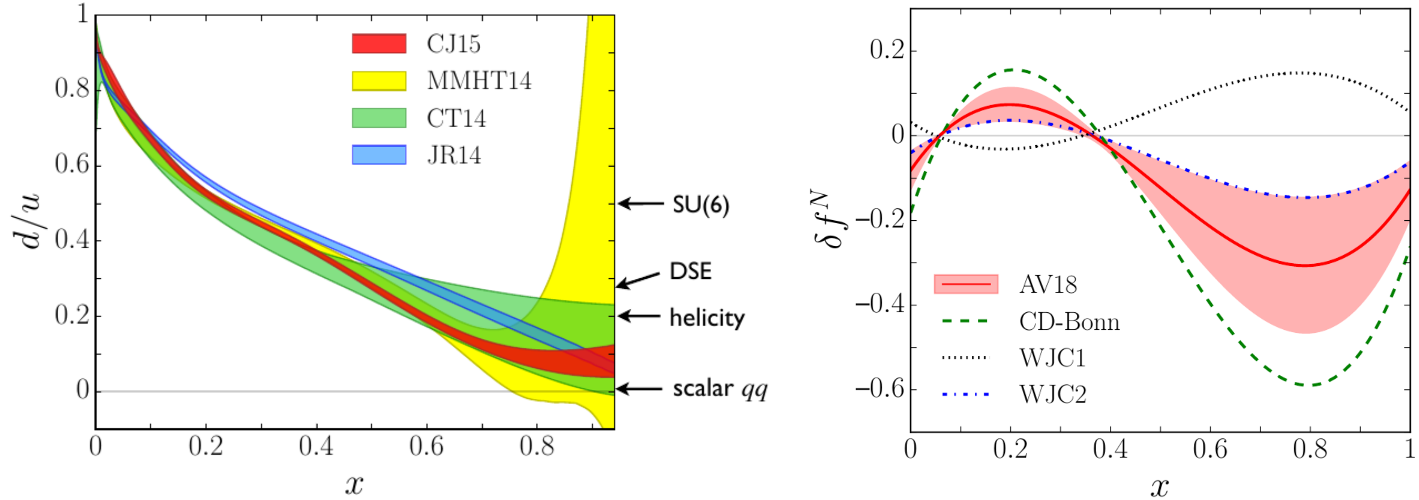


$$F_2 \propto 4xu(x) + xd(x)$$

Example 1: Tevatron as NUCL facility (!)

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

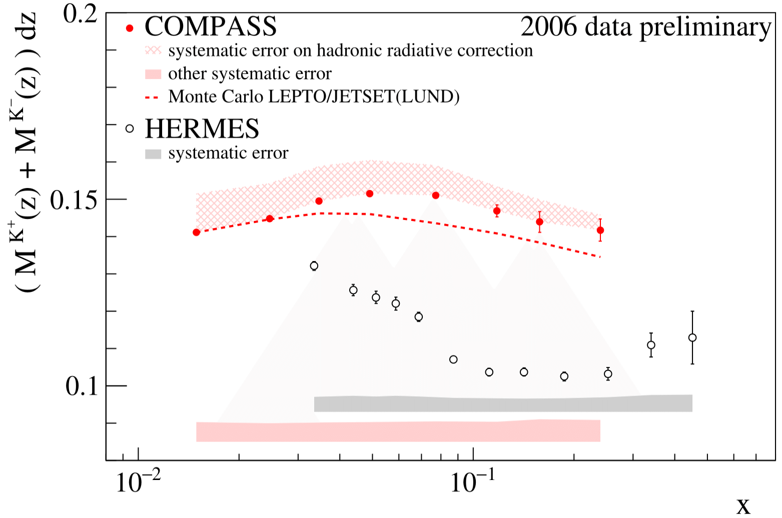
- **Combined fit: d/u and binding effects**
  - → confinement at large x (using flexible large-x d-quark)
  - → bound nucleon corrections in deuteron PDFs



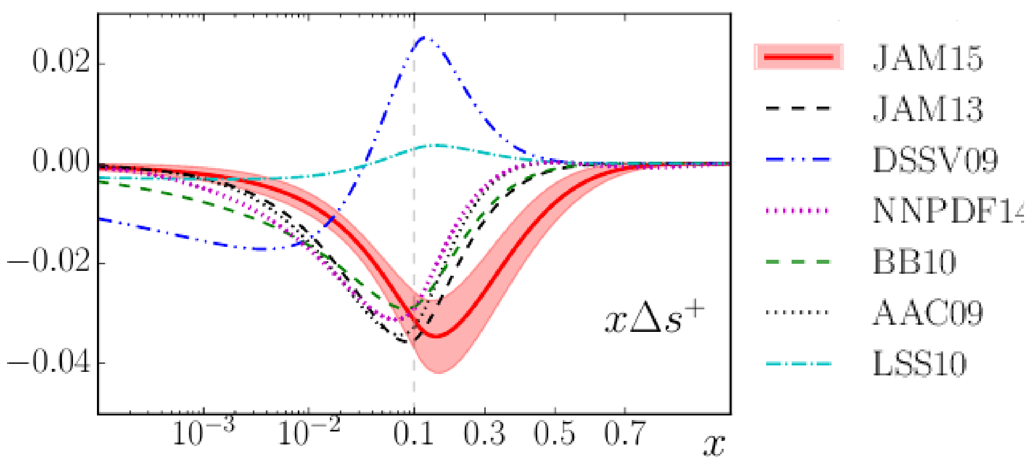
- **Opens novel possibilities**: test nuclear theory ideas against <u>other</u> data:
  - – Test "EMC effect" models (of course)
  - – On the lattice: "nucleon response to external color field"
  - – ...

Example 2: strange strange quarks

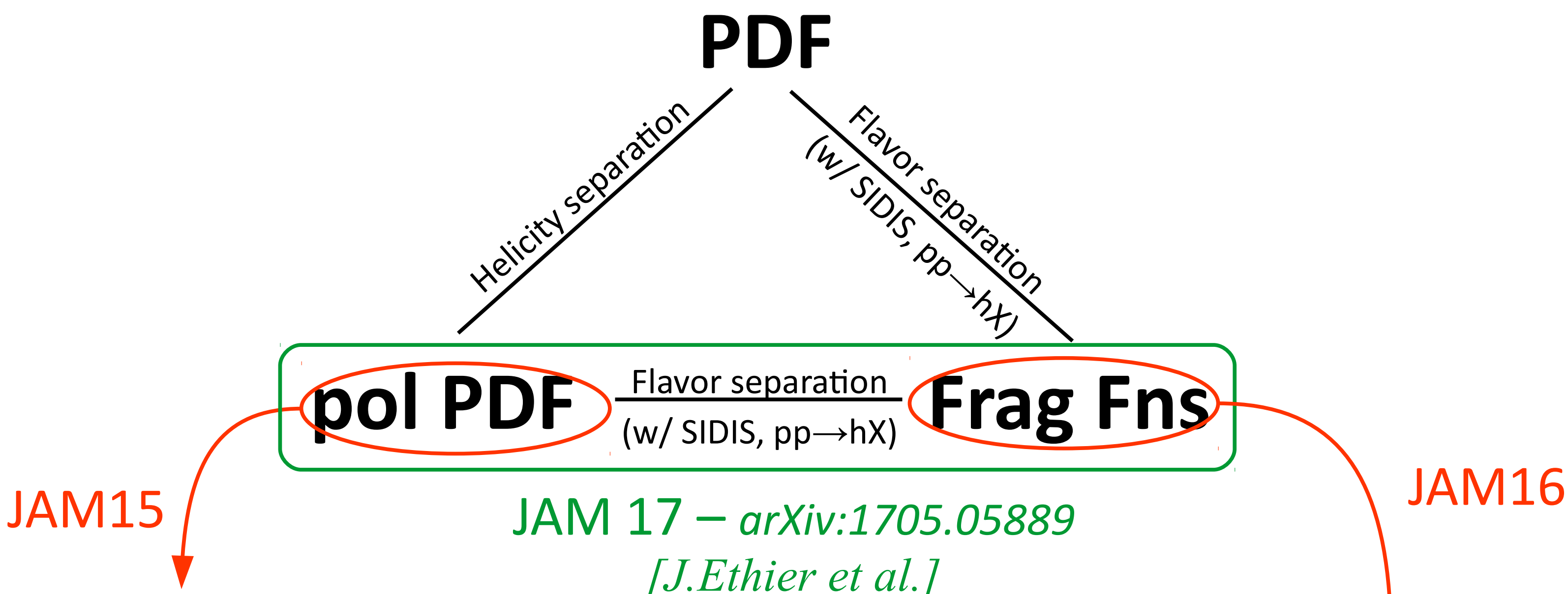
- **s : large or small?**
  - Possibly, large Hadron Mass effects
    Guerrero, Accardi, in preparation
  - Extraction of s(x) strongly affected by **kaon FF systematic uncertainty**



- **Δs : positive or negative?**
  - Depends on **kaon FF used in SIDIS calculations!**
  - What about the unpol s ?



Need combined fits!



Strange, glue
& Twist-3 and 4 (p & n)
<u>using inclusive DIS only</u> !

[N.Sato, et al.,, PRD93('16)]

u+, d+, g+, c+, b+ FF's
<u>using SIA only</u> !

[N.Sato, et al.,, PRD94('16)]

Need 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. Melnitchouk[2]

[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

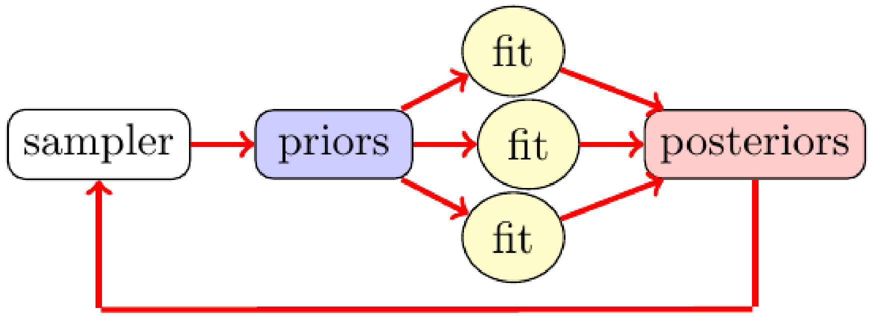
First combined PDF and FF fit!

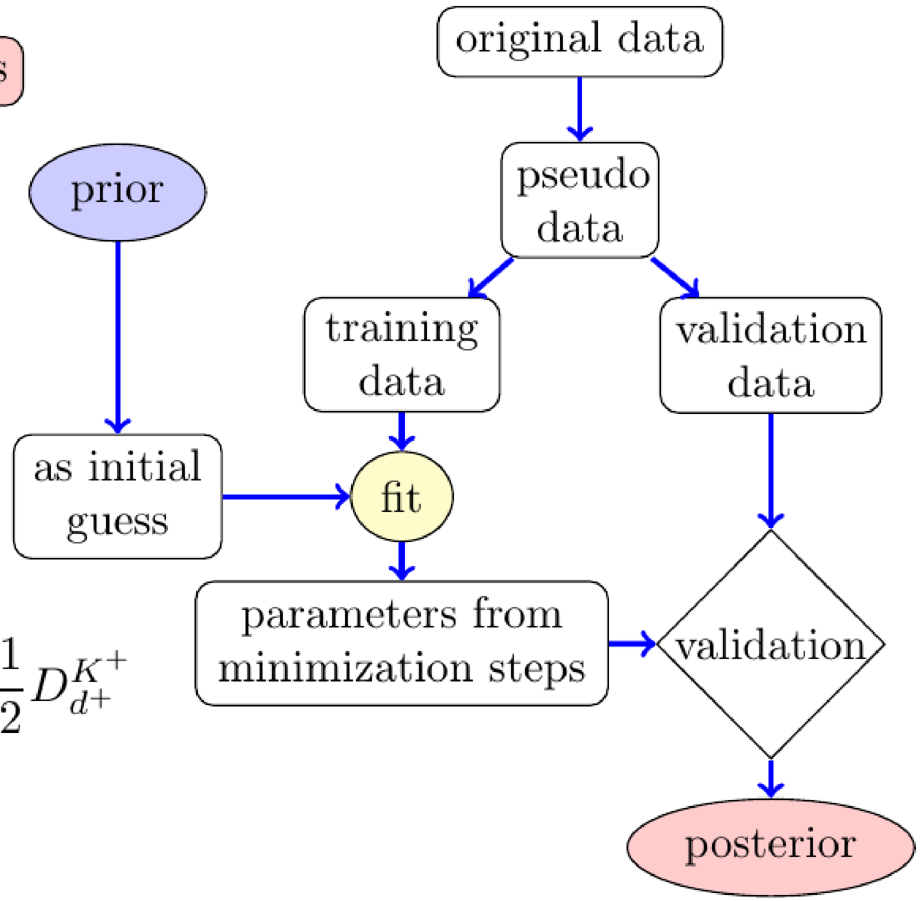
- **Data set**

process	target	N_{dat}	χ^2
DIS	$p, d, {}^3$He	854	854.8
SIA $(\pi^\pm, K^\pm)$		850	997.1
SIDIS $(\pi^\pm)$			
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:**
  - Q2 > … W2 > … Z > … (avoid HT, hadron mass effects)

Iterative Monte Carlo (IMC) analysis





- Use "template functions"

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

Pions:

$$D_{\bar{u}}^{\pi^+} = D_d^{\pi^+} = \mathrm{T}(z; \boldsymbol{a})$$

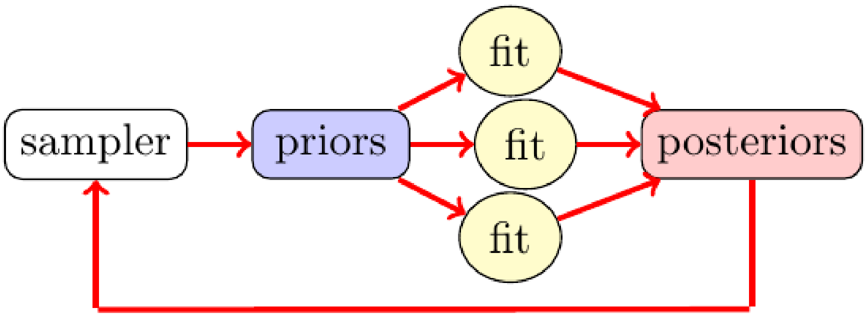
$$D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = \frac{1}{2} D_{s+}^{\pi^+}$$

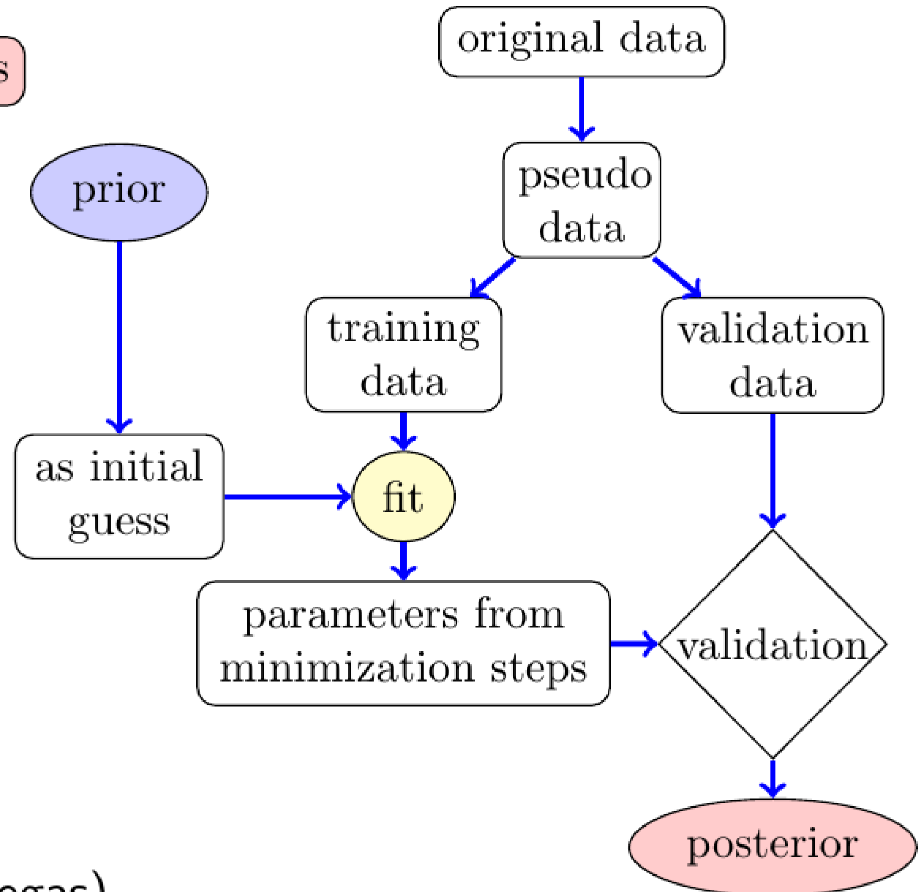
Kaons:

$$D_{\bar{u}}^{K^+} = D_d^{K^+} = \frac{1}{2} D_{d+}^{K^+}$$

$$D_s^{K^+} = \mathrm{T}(z; \boldsymbol{a})$$

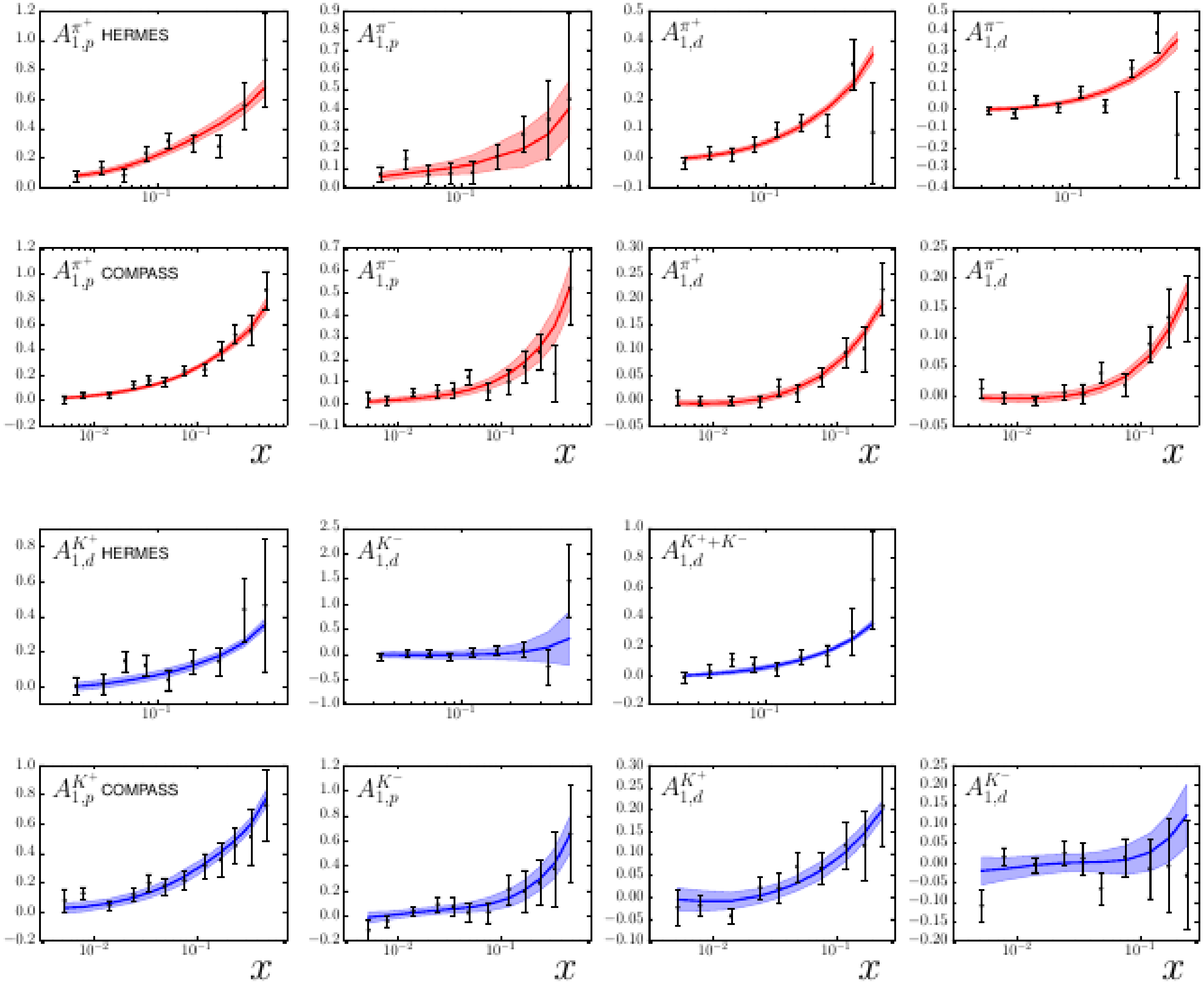
Iterative Monte Carlo (IMC) analysis in a nutshell





- Use "template functions"
  $T(x) = {\color{red}N} x^{\color{red}a} (1-x)^{\color{red}b} (1 + {\color{red}c}\sqrt{x} + {\color{red}d}x)$
- Keep all the parameters free.
  No assumptions on the exponents
- Avoid over-fitting by Cross-Validation
- **Iterative procedure**
  → Adaptive MC integration (like in Vegas)
- Robust estimation of uncertainties

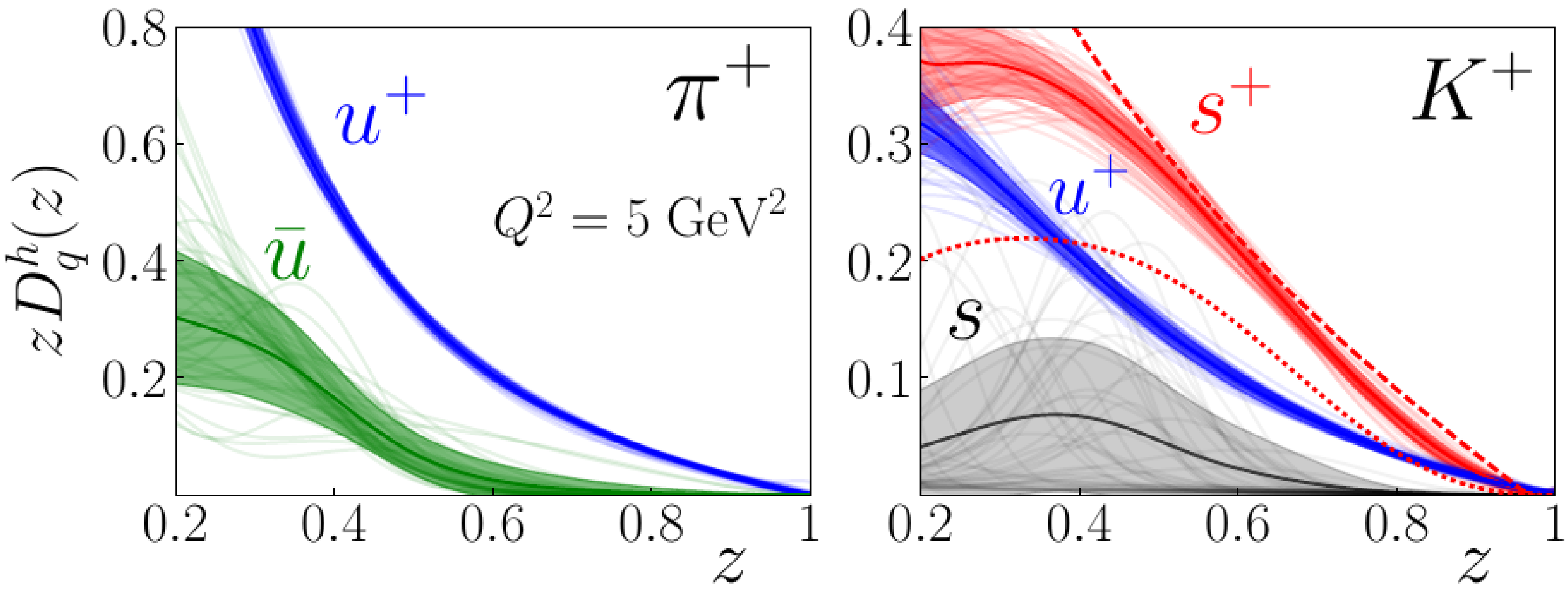
Data vs. Theory - SIDIS



π

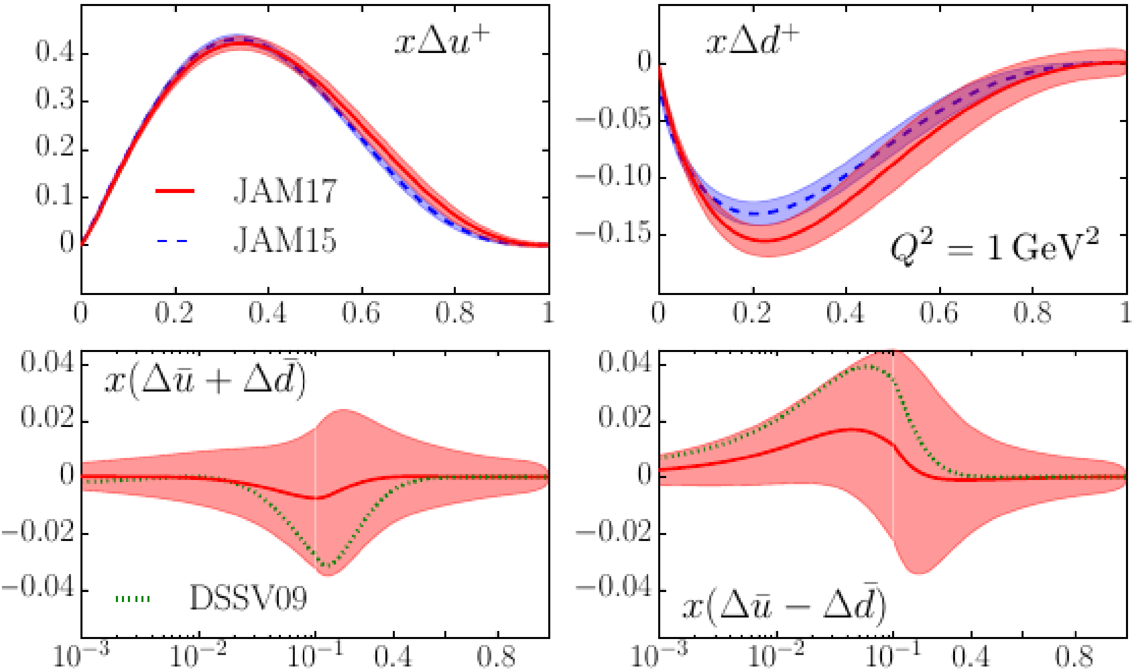
K

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 ū to π distribution smaller than s to K
  → Due to lower precision kaon production data

Polarized PDFs

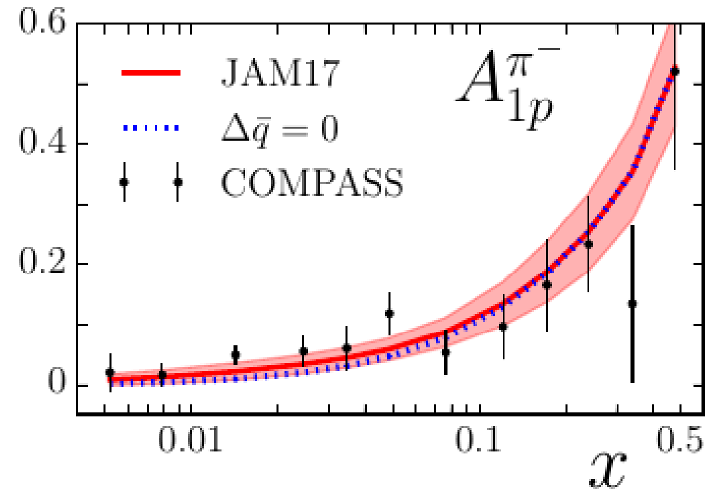


- Δu+ consistent with previous analysis
- Δd+ slightly larger in magnitude

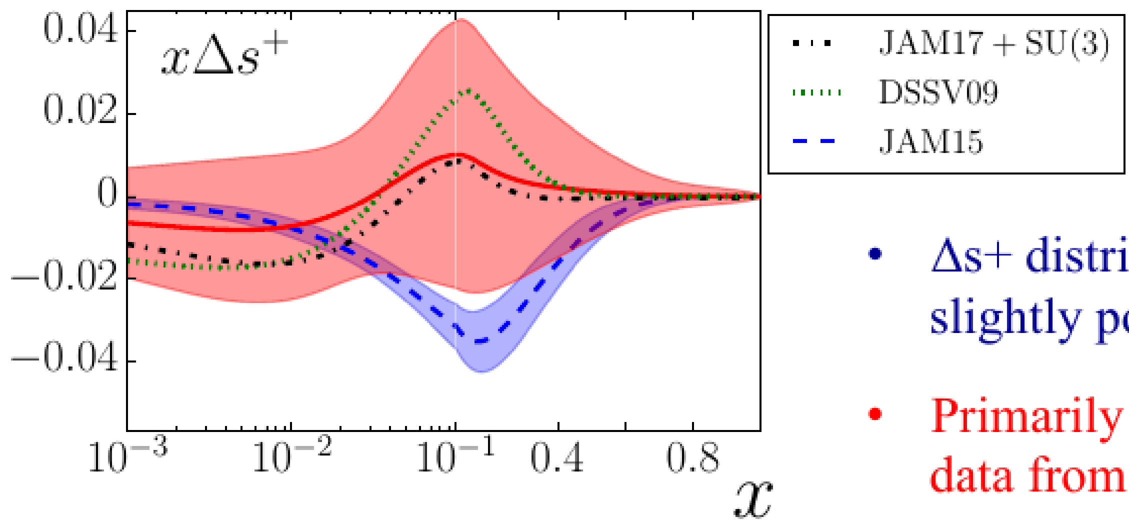
  → Anti-correlation with Δs+, which is less negative than JAM15 at $x \sim 0.2$

- 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

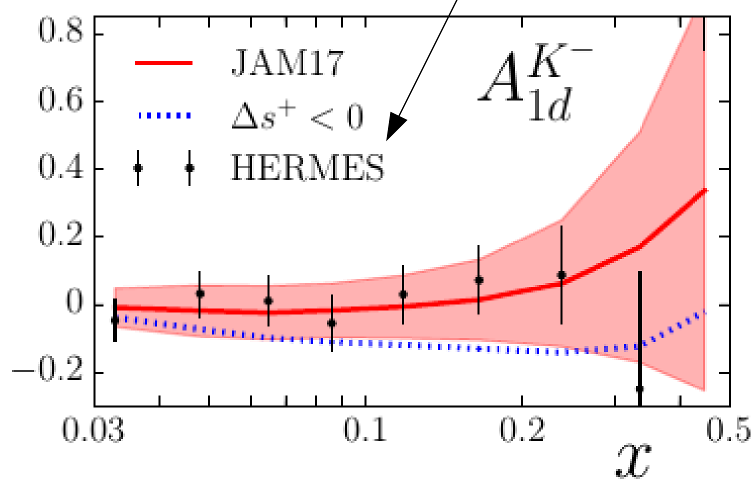


Strange polarization



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

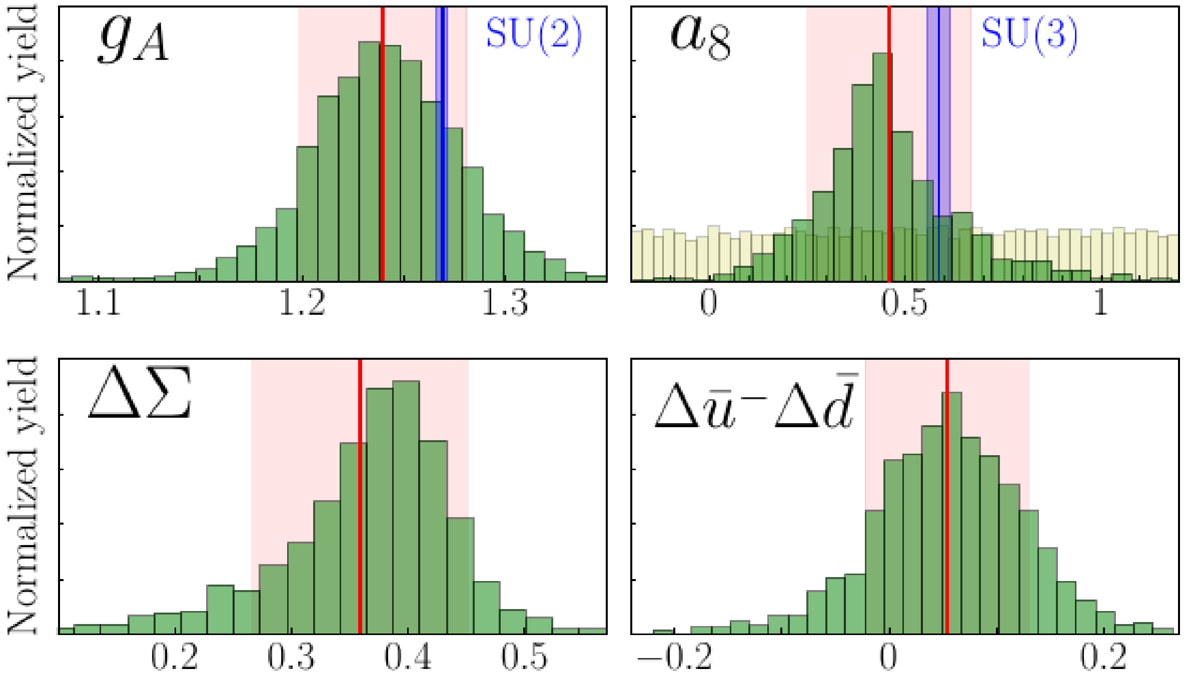
But, possibly large hadron mass effects



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 ~6-10, producing a peak at x~0.1

Moments



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

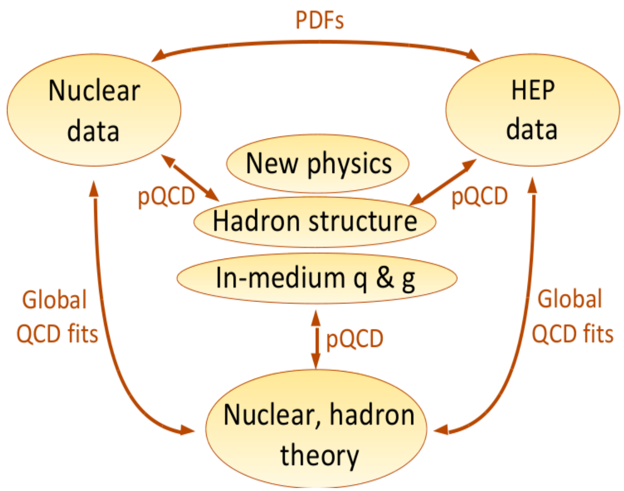
$a_8 = 0.46 \pm 0.21$ ~20% SU(3) breaking ± ~20%; large uncertainty

- Need better determination of $\Delta s+$ moment to reduce a_8 uncertainty!

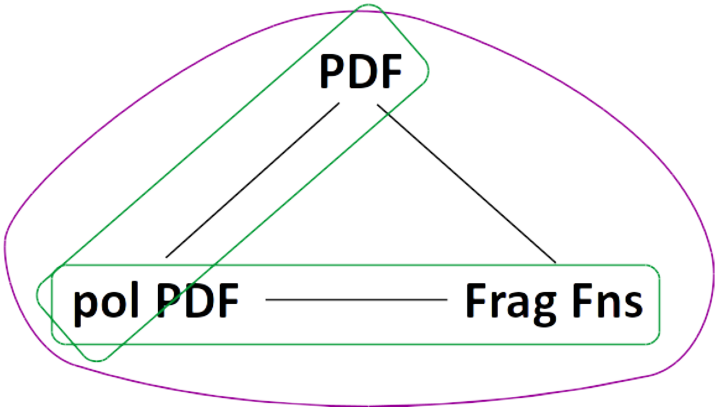
$$\Delta s^+ = -0.03 \pm 0.09$$

Final thoughts

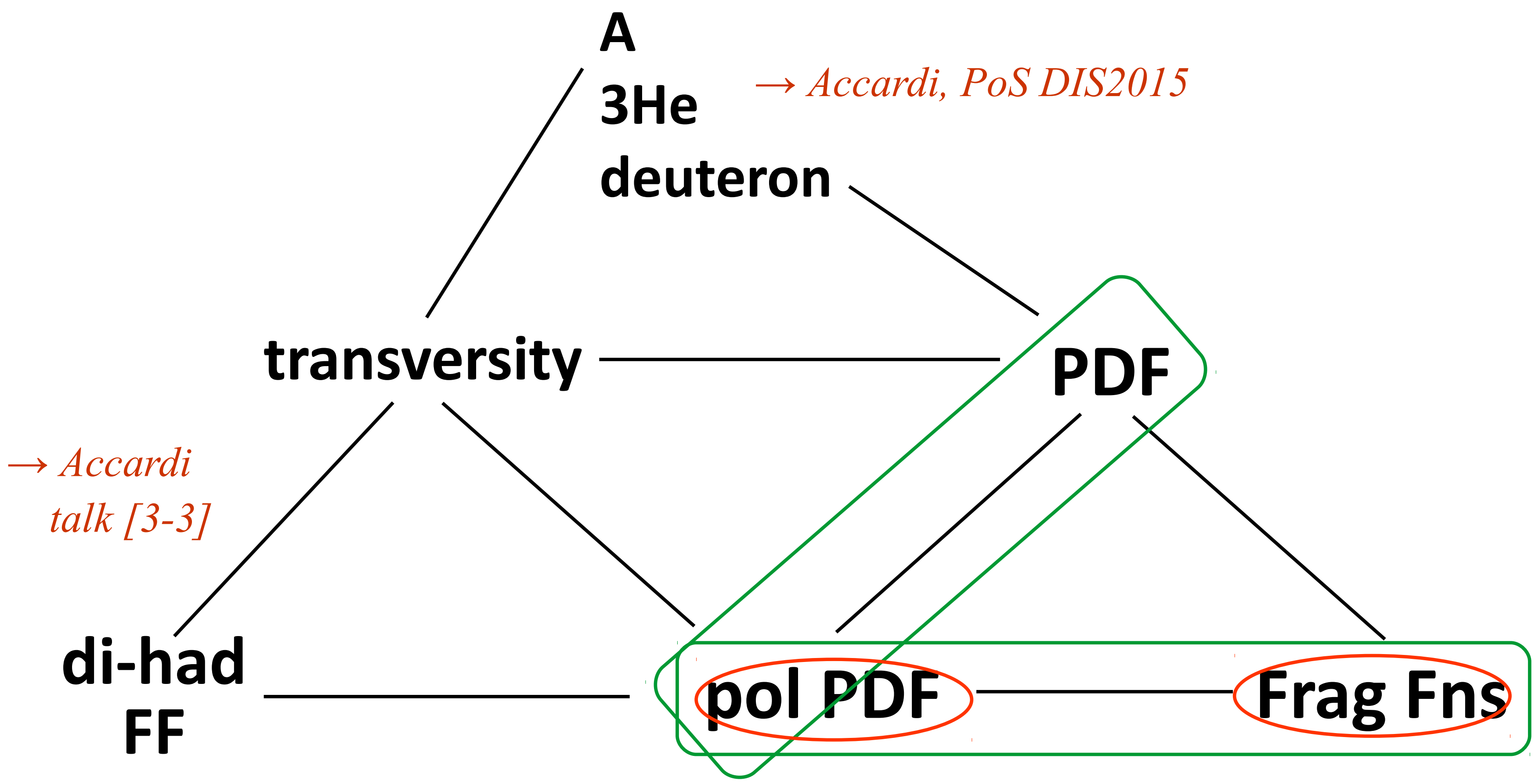
Final thoughts



- **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



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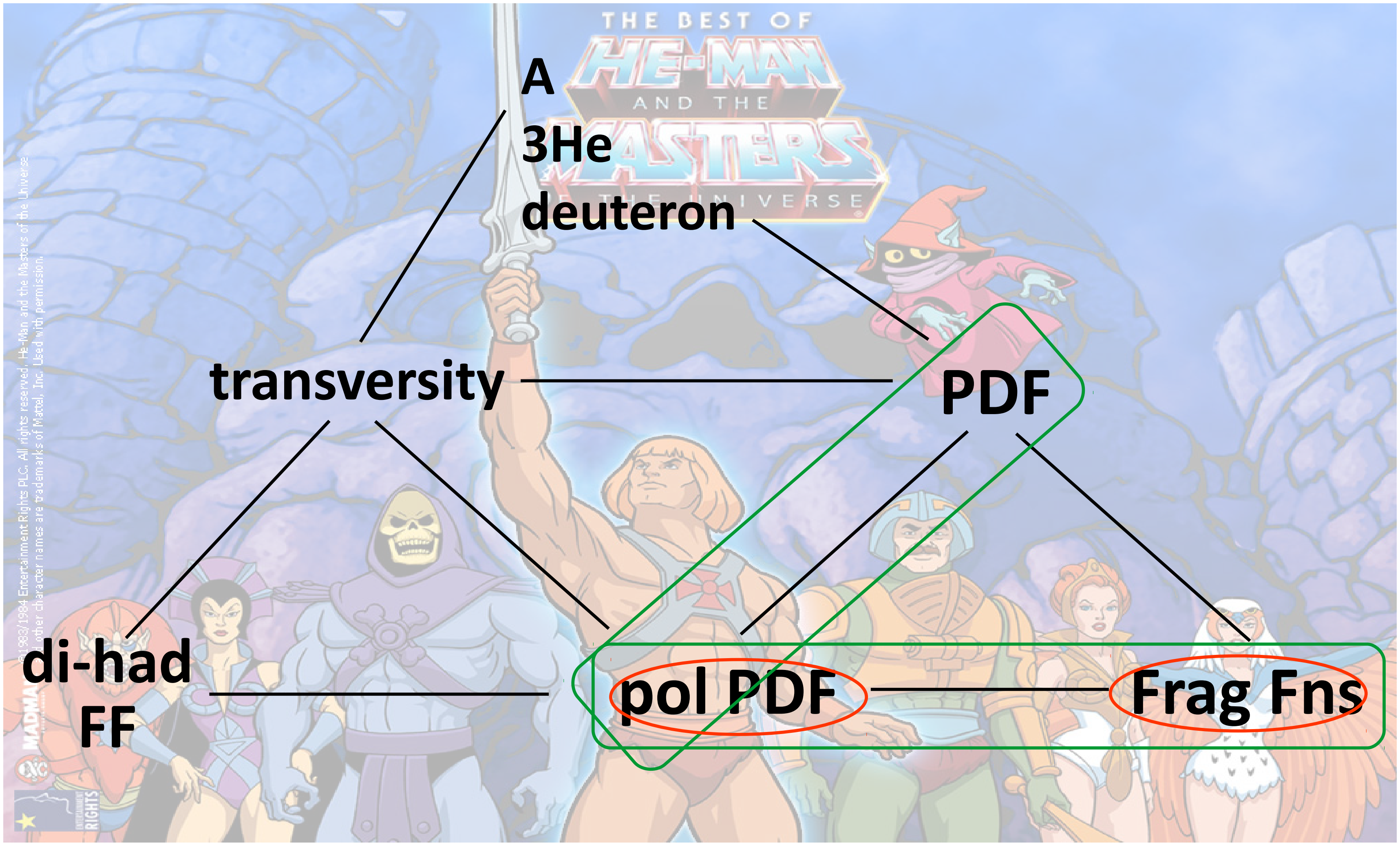

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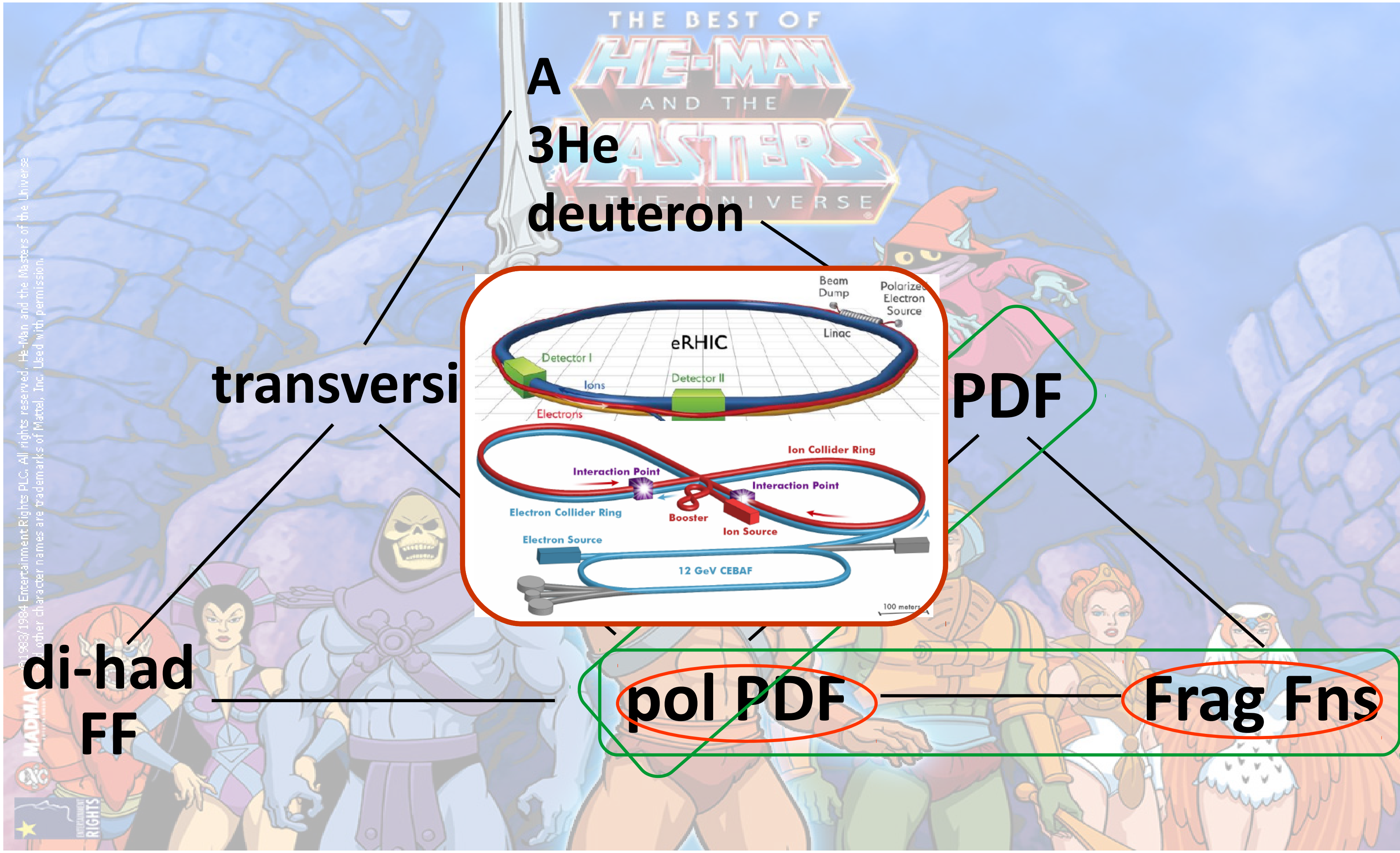
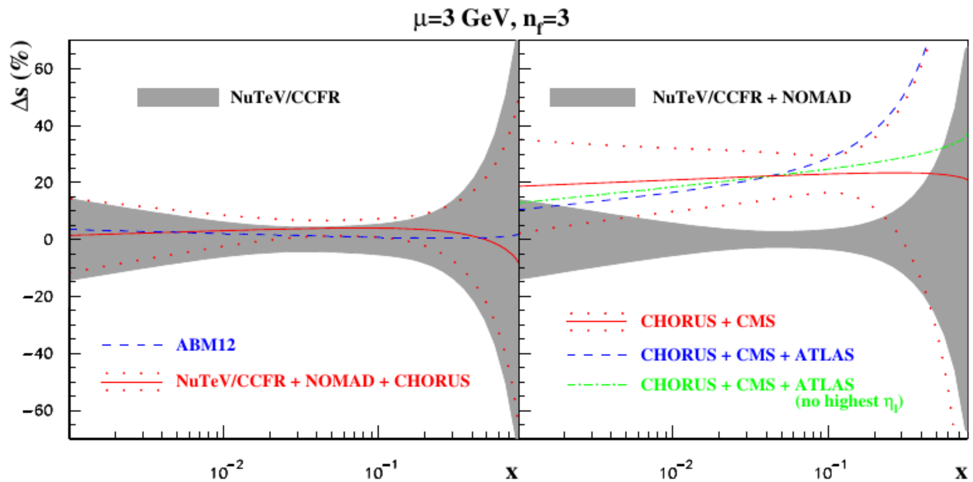


Backup

Strange strange quarks

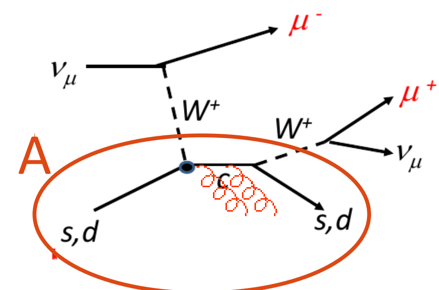
- ν+*A* → dimuons *vs.* *p+p* → *W+c* at LHC — *Alekhin et al., arXiv:1404.6469*



$$g\, s_p \rightarrow W\, c$$

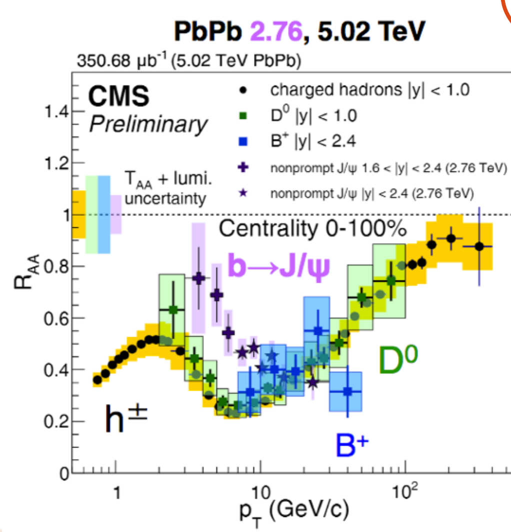
$$\nu\, s_A \rightarrow \mu^-\, \mu^+\, \nu_\mu\, s$$

FSI ?



- **Heavy quark puzzle at RHIC / LHC:**
  - Color propagation in QCD matter not under theoretical control!

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



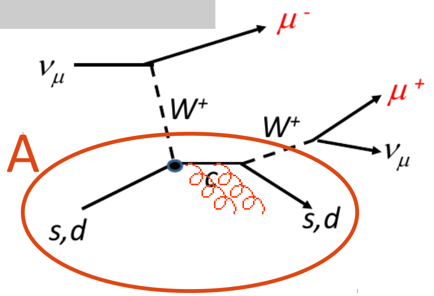
Yen-Jie , Quark Matter 2017

Strange strange quarks

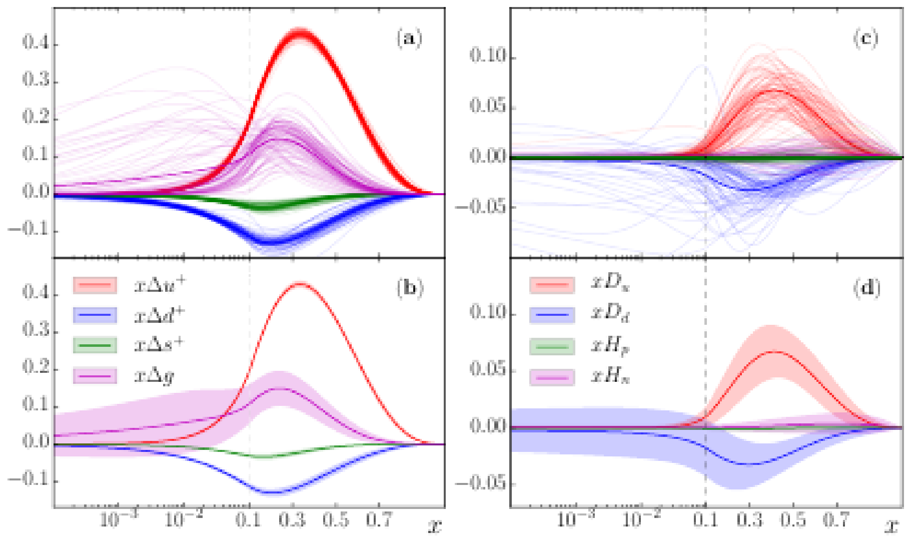
- What next?
  - **Use data on proton targets to fix s** → *CJ17, in progress*

	Observable	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

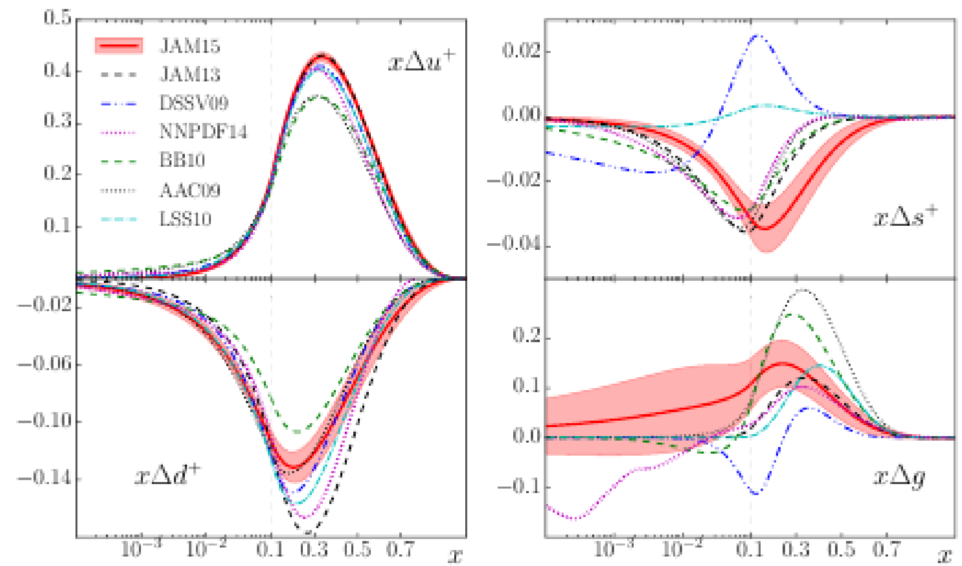
  - **Use dimuons on nuclear targets to study charm quark propagation in nuclear matter**



The JAM15 polarized PDFs

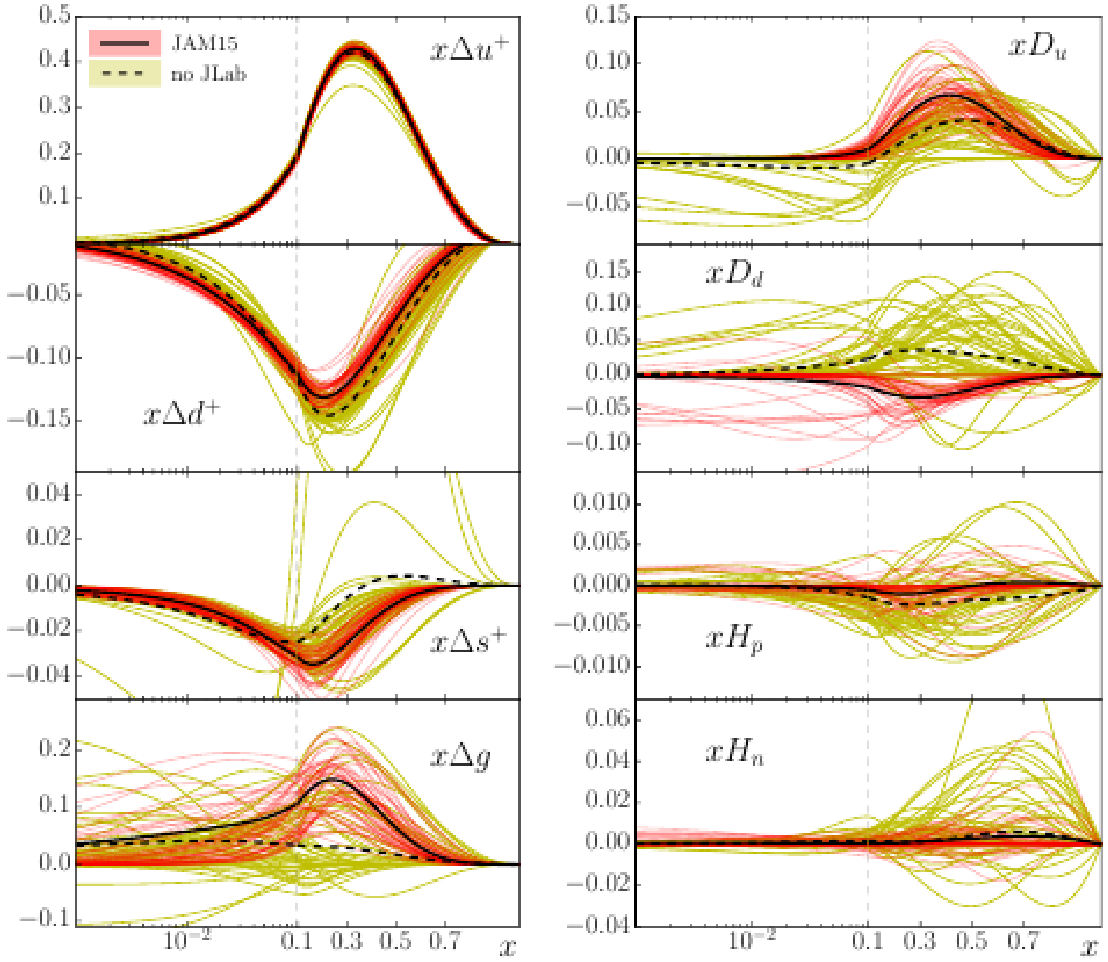


moment	truncated	full
Δu^+	0.82 ± 0.01	0.83 ± 0.01
Δd^+	-0.42 ± 0.01	-0.44 ± 0.01
Δs^+	-0.10 ± 0.01	-0.10 ± 0.01
$\Delta\Sigma$	0.31 ± 0.03	0.28 ± 0.04
ΔG	0.5 ± 0.4	1 ± 15
d_2^p	0.005 ± 0.002	0.005 ± 0.002
d_2^n	-0.001 ± 0.001	-0.001 ± 0.001
h_p	-0.000 ± 0.001	0.000 ± 0.001
h_n	0.001 ± 0.002	0.001 ± 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 → $0.1 < x < 0.7$
- Constraints on small x from large x → weak baryon decay constraints
- Large uncertainties in Δs^+, Δg removed by JLab data
- Non vanishing T3 quark distributions
- T4 distributions consistent with zero

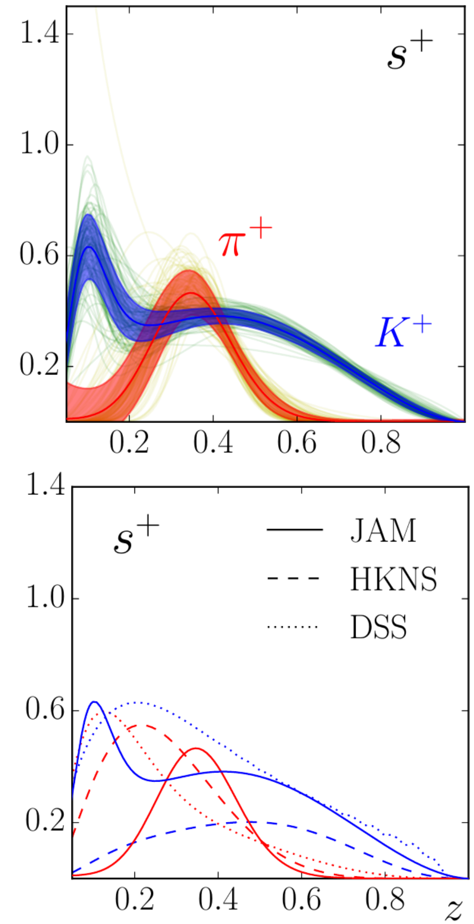
The JAM FF 2016 fit

- Kaon FF too uncertain, correlated to strange PDF in SIDIS
  - Cannot take kaon FF off the shelf
  - Need in-house extraction

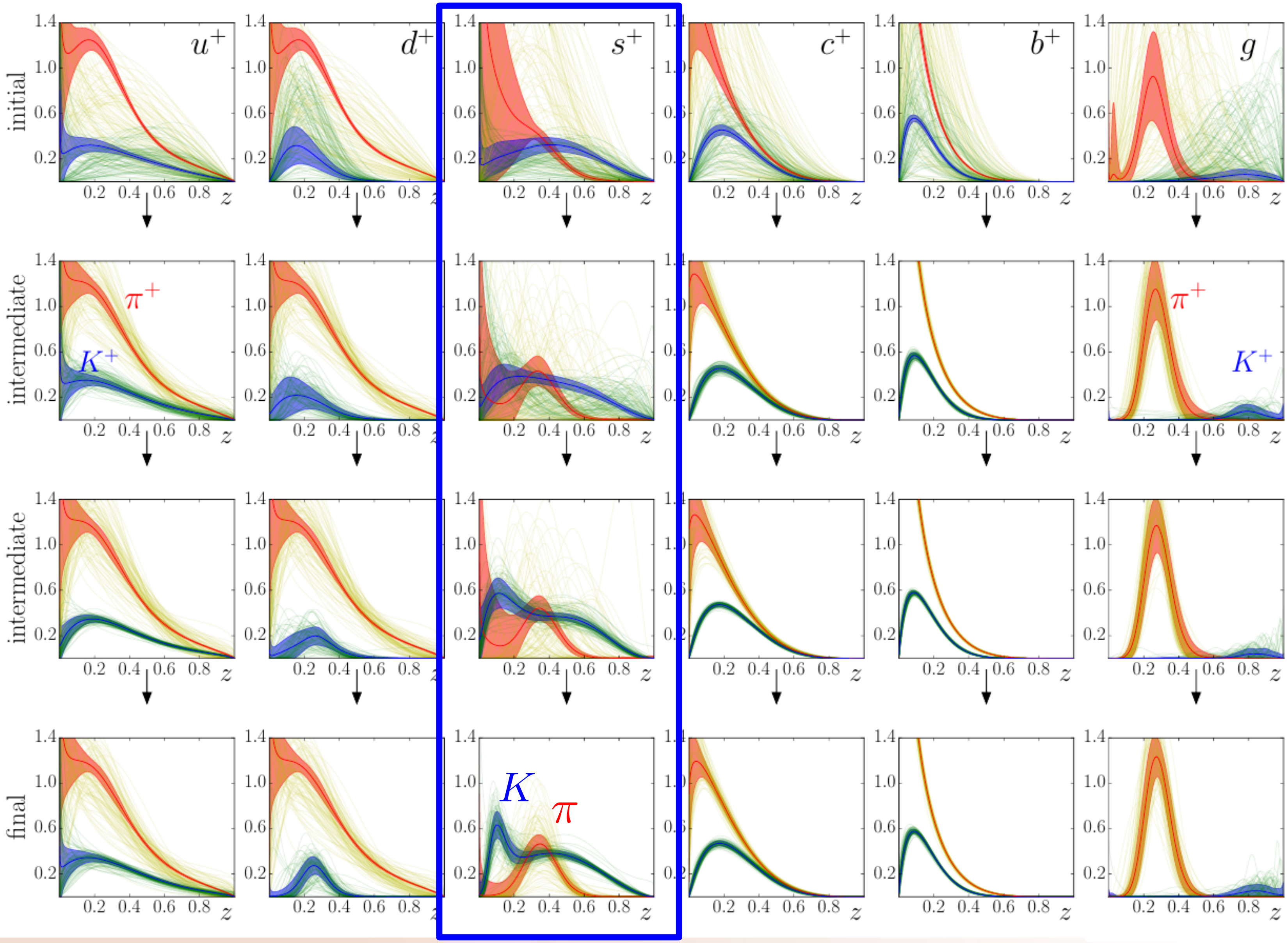
- **Iterative MC approach**
  - Only SIA data used : npts=245, χ2 = 305.2

- **Strange-to-kaon FF:**
  - Between HKNS and DSS
  - Will it give a negative Δs ??

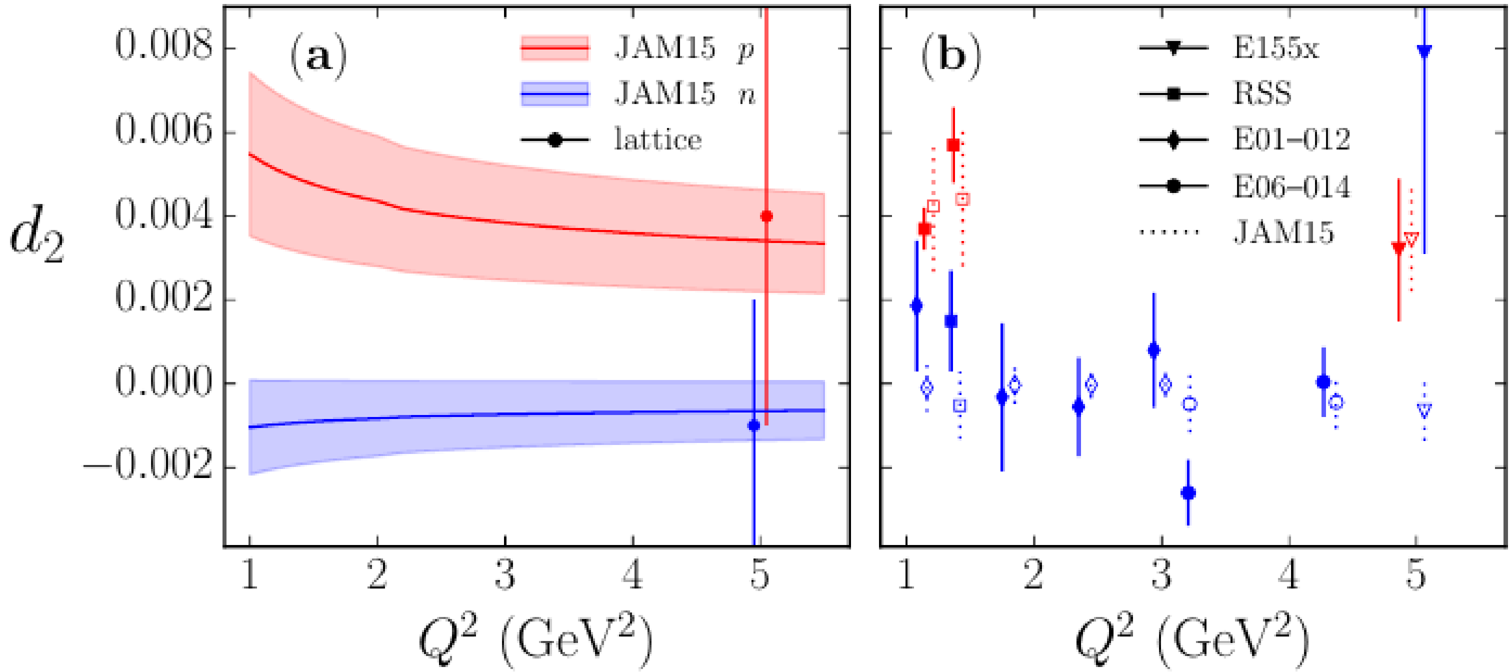
  - **Combined pol SIDIS + FF analysis underway!**



IMC method in action



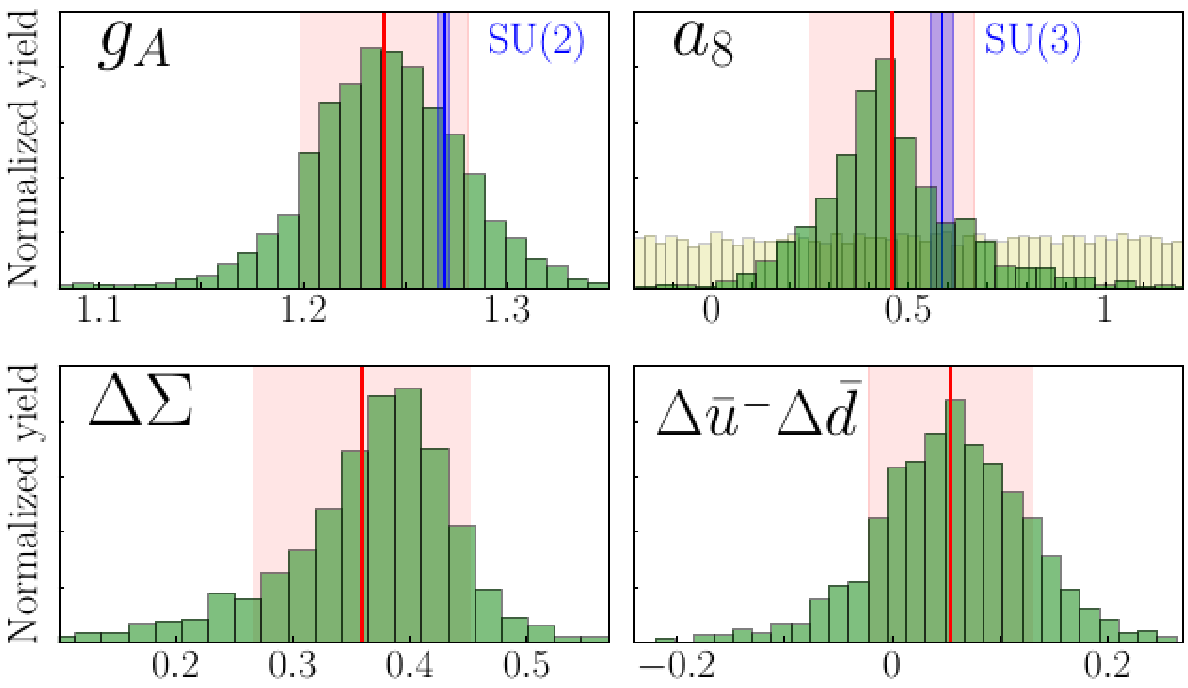
Higher twist and color polarizability



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

Lattice calcs from Goeckele et al. 2005 – time to revist?
(needs about 10 x precision, see next)

JAM 17 - Moments



$$\Delta\Sigma = 0.36 \pm 0.09$$

Slightly larger central value than previous analyses, but consistent within uncertainty

Preference for slightly positive sea asymmetry; not very well constrained by SIDIS

$$\Delta\bar{u} - \Delta\bar{d} = 0.05 \pm 0.08$$