Unpolarized and helicity distributions from global fits

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QCD-N'16

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CTEQ-Jefferson Lab Collaboration

Jefferson Lab Angular Momentum Collaboration

Overview

- **A PDF landscape**
- **Proton and neutron PDFs: the CJ15 fit**
  - Hadronic physics I : d/u ratio
  - Hadronic Physics II : dbar / ubar ratio
  - Nuclear Physics output: off-shell parton corrections
  - High-energy: BSM searches
- **Iterative Monte Carlo – the JAM approach**
  - "JAM15" helicity PDFs
  - A strange puzzle
  - "JAM-FF16" fragmentation functions

*REFERENCES***:**

* *Accardi,* ***PoS DIS2015 001*** *– "PDFs from protons to nuclei"*

* *Accardi et al,* ***PRDD93 (2016) 114017*** *– the CJ15 global fit*

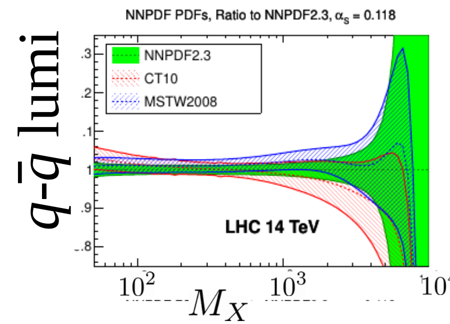
* *N.Sato at al,* ***PRD93 (2016) 074005*** *– the JAM15 fit*

A PDF landscape

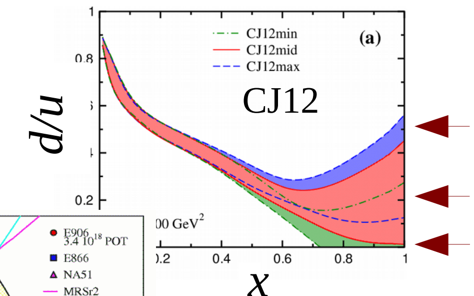
Why (n)(p)PDFs ?

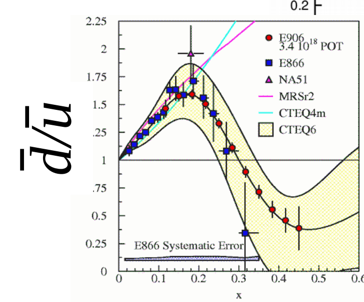
Accardi – Mod.Phys.Lett. A28 (2013) 35
Forte and Watt – Ann.Rev.Nucl.Part.Sci. 63 (2013) 291

- **High-energy** *(large to small x)* *→ J.Rojo's talk*
  - Beyond the Standard Model searches
  - NuTeV weak mixing angle
  - Precision (Higgs) physics
  - Small-*x* and gluonic "matter"

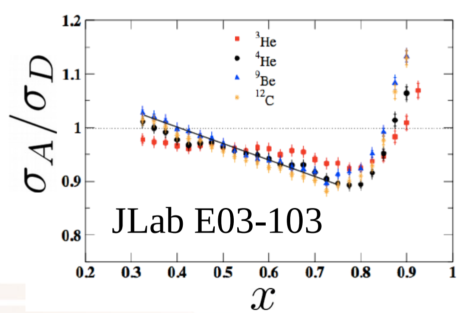


- **Hadron structure** *(large to medium x)* *→ THIS talk*
  - Effects of confinement on valence quarks
  - q – qbar asymmetries; isospin asymmetry
  - Strangeness, intrinsic charm
  - Spin, parton orbital motion, color dynamics

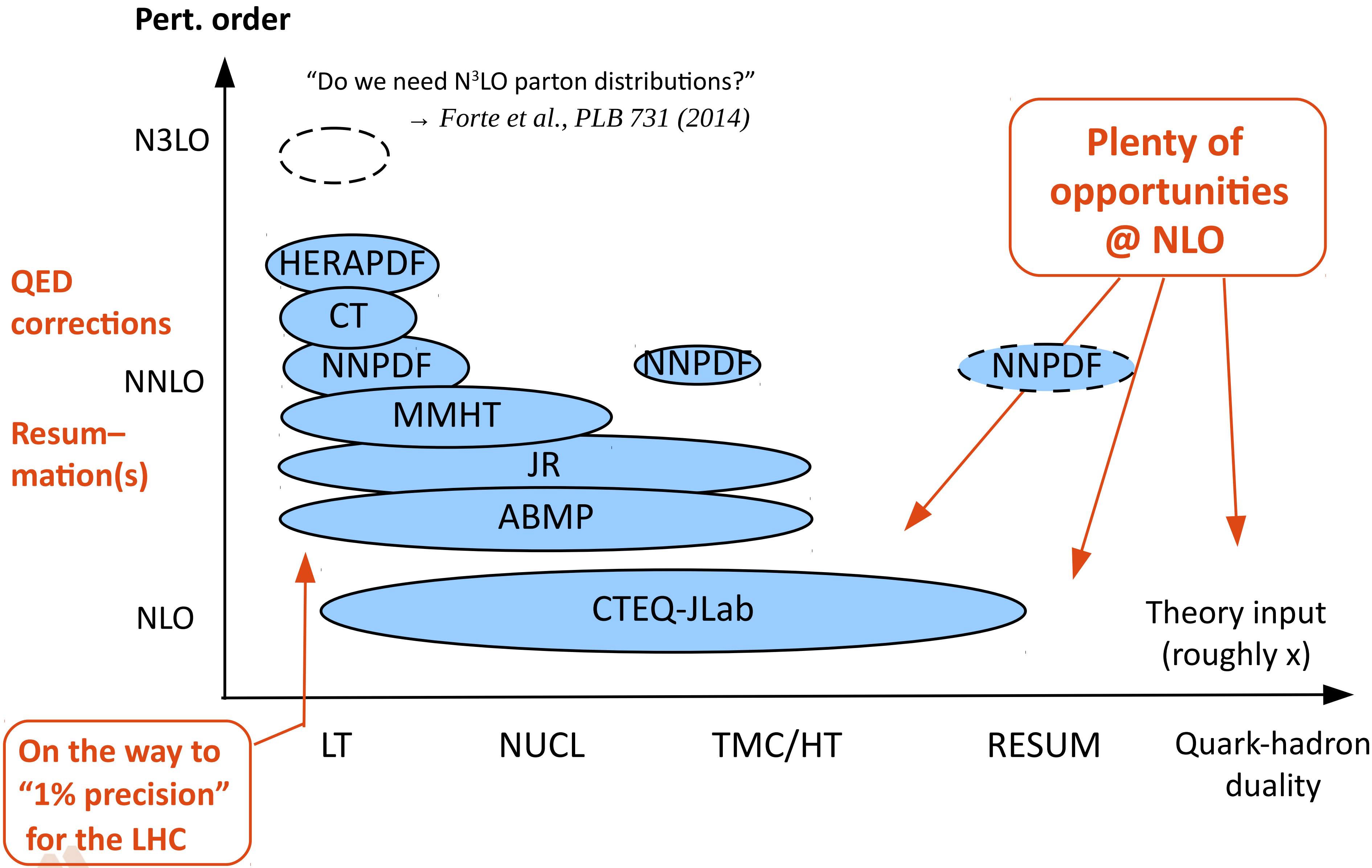




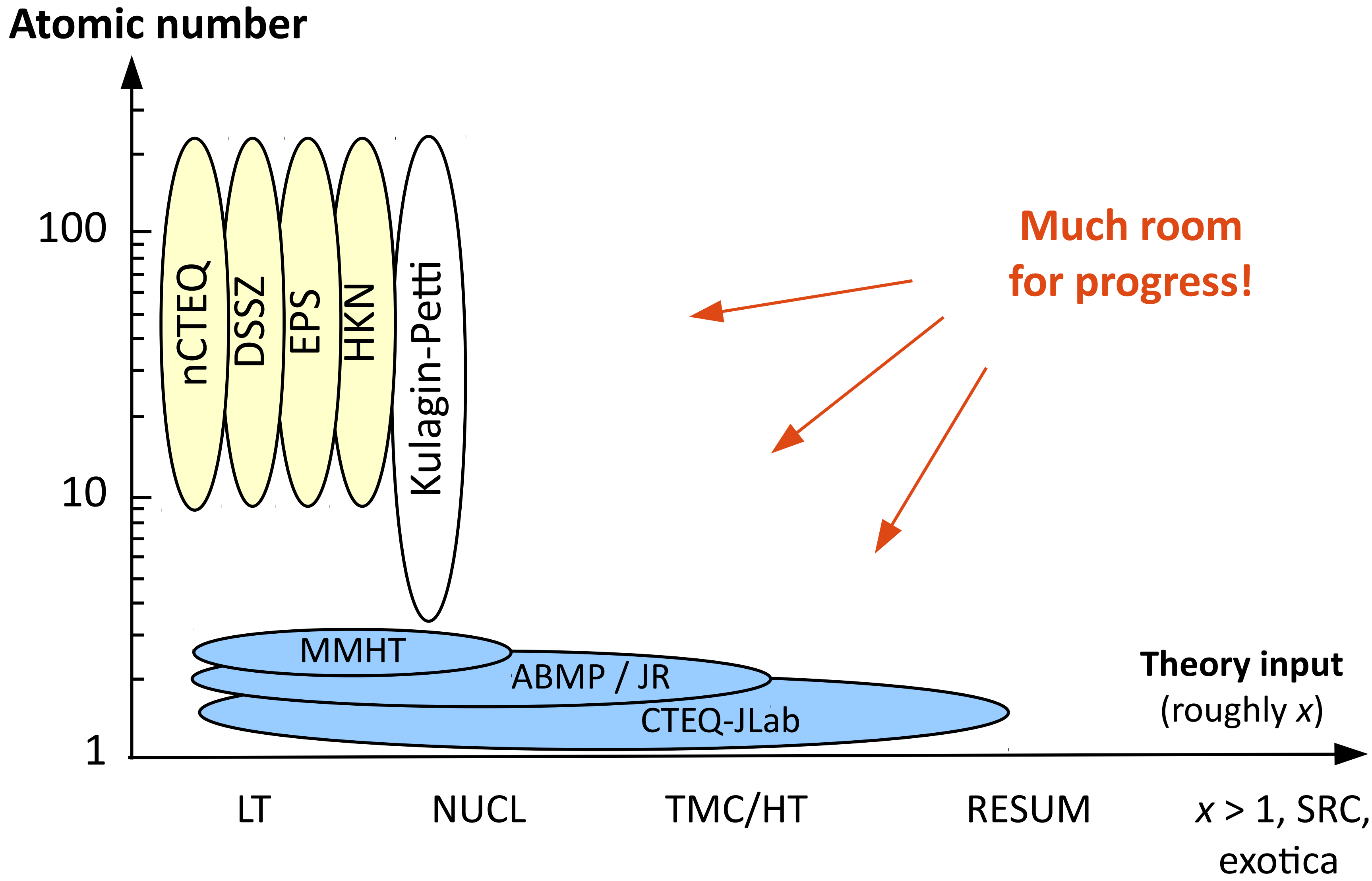
- **Nuclear Physics** *→ Mostly in backup*
  - Bound nucleons, EMC effect, SRC
  - p+A and A+A collisions at RHIC / LHC
  - Color propagation in nuclear matter



A PDF landscape

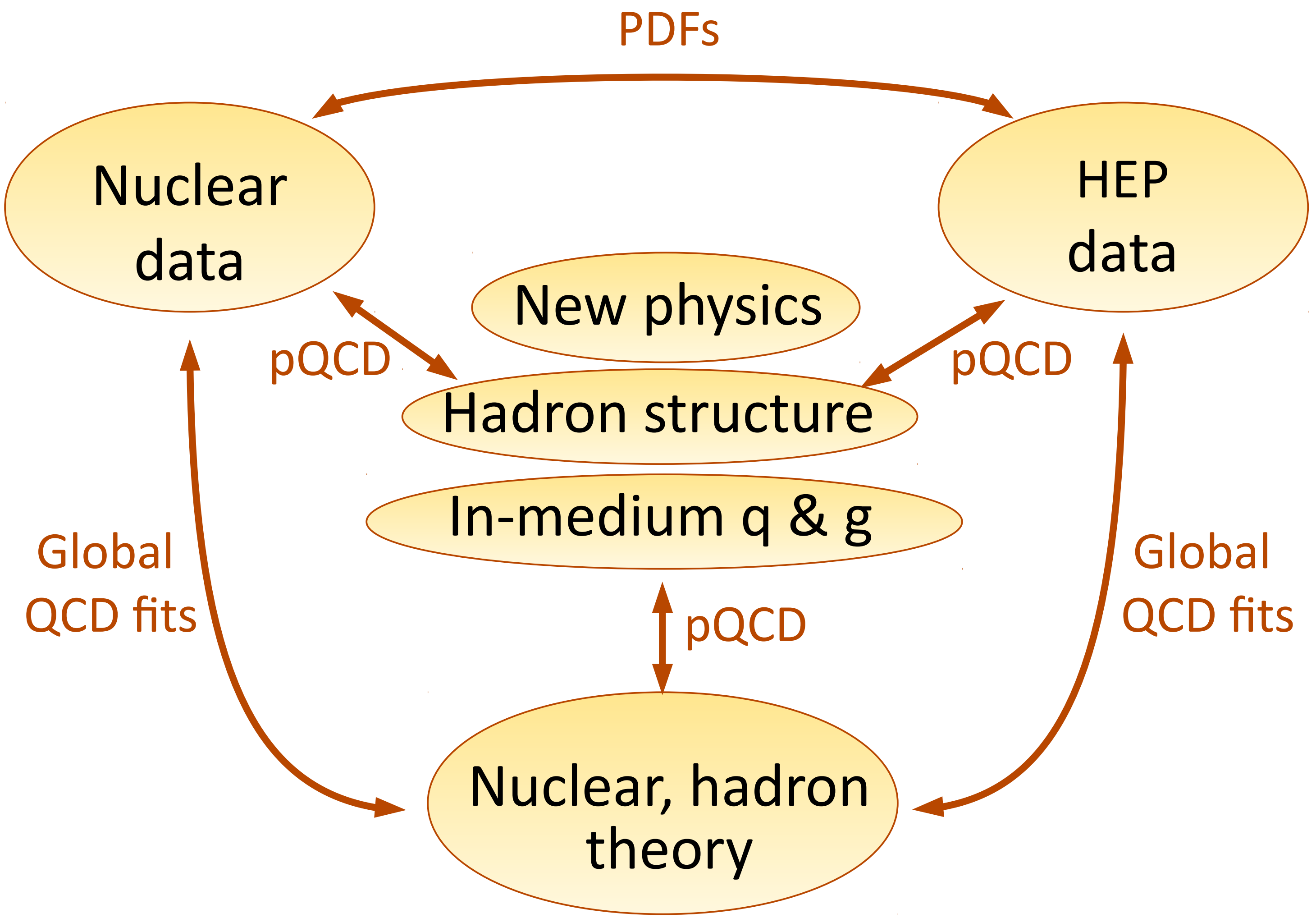


A nPDF landscape

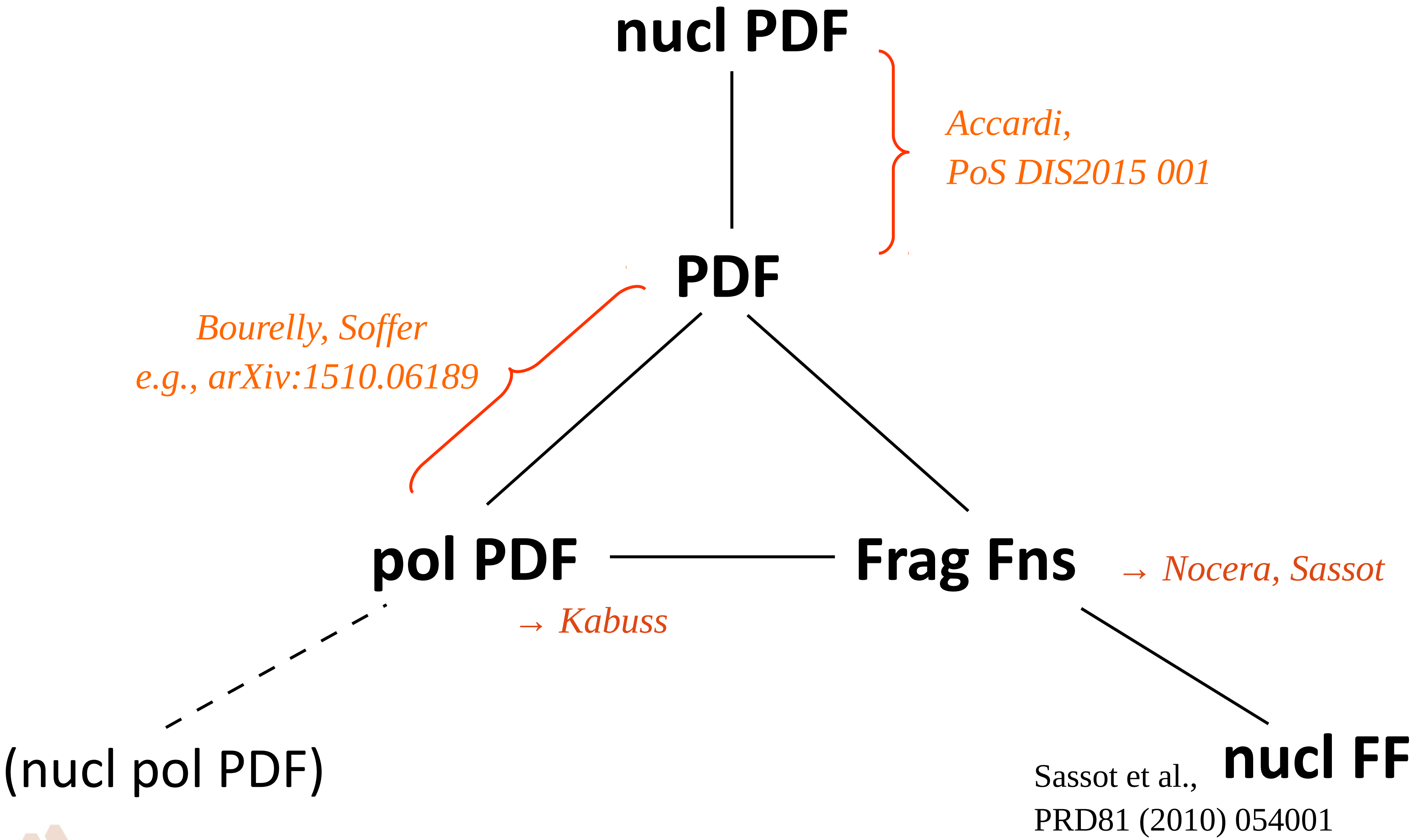


Needs the betrothal of HEP and NUCL

- **A global approach across subfields**



Other possible marriages



New fitting methods

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

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

- Monte carlo fitting methods:
  - **NNPDF**: bootstrap + neural network fit
  - **JAM**: bootstrap + Iterative Monte Carlo (IMC) approach

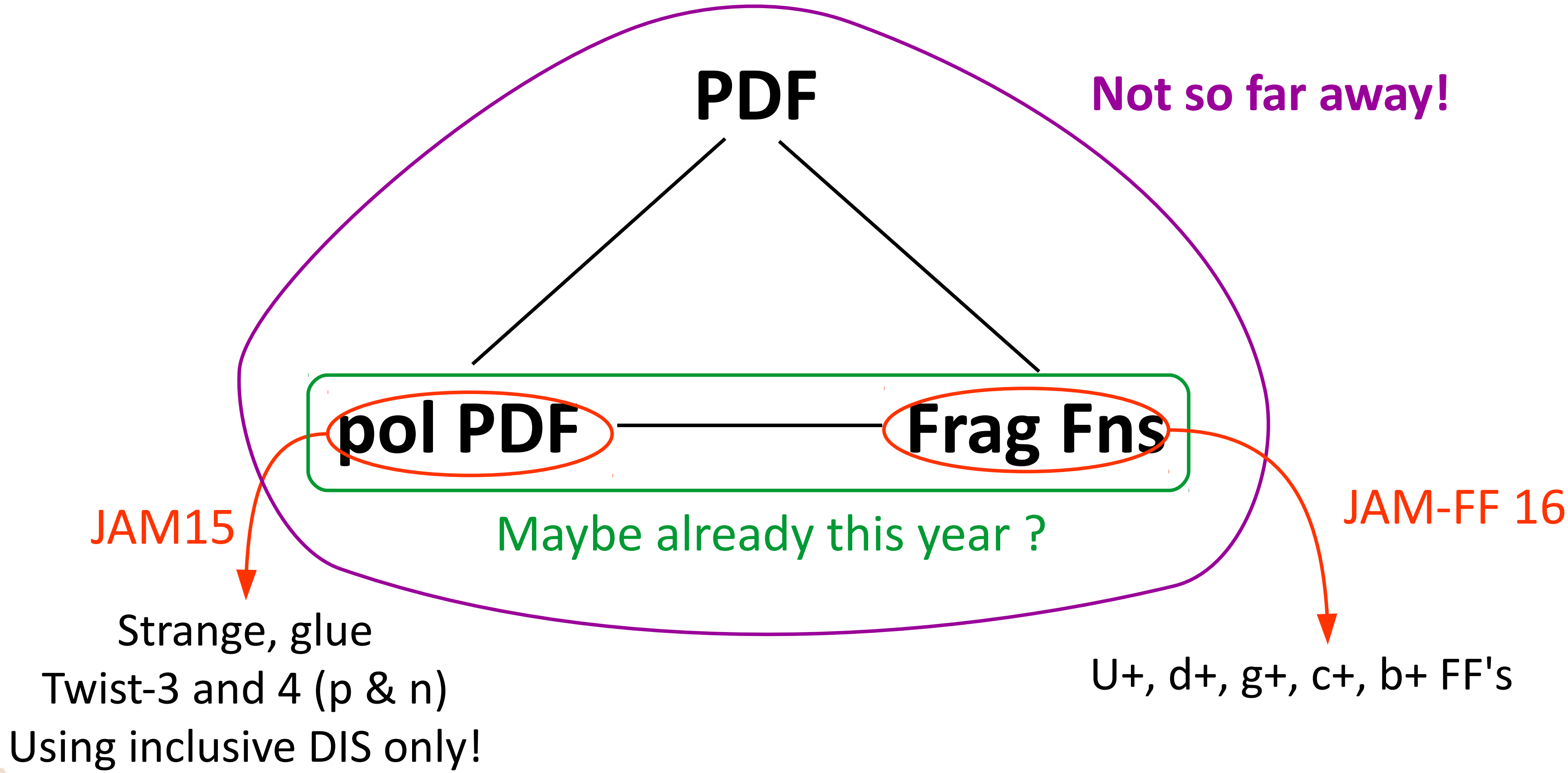
    → *Sato, Ethier, Kuhn, Melnitchouk, Accardi (2015)*

  Large number of parameters, trustable uncertainty estimates

- Self organizing maps → *Liuti et al.*

Iterative Monte Carlo approach

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



Proton and neutron PDFs
- the CJ15 global fit -

Accardi, Brady, Melnitchouk, Owens, Sato

PRD93 (2016) 114017

The CTEQ-JLab global fits

- **Collaborators:**
  - **Theory:** A.Accardi, W.Melnitchouk, J.Owens, N.Sato
  - **Experiment:** E.Christy, C.Keppel, P.Monaghan
- **All-*x* PDF global fits, focused on the "large" *x* region**
  - Maximize use of large-*x* data (esp. DIS)
  - Include all relevant large-*x* / small-Q^2 theory corrections
  - ***Quantitatively evaluate theoretical systematic errors***
  - ***Use PDFs as tools for nuclear and particle physics***
- **Latest public release: CJ15**
  - www.jlab.org/cj
  - Included in LHAPDF

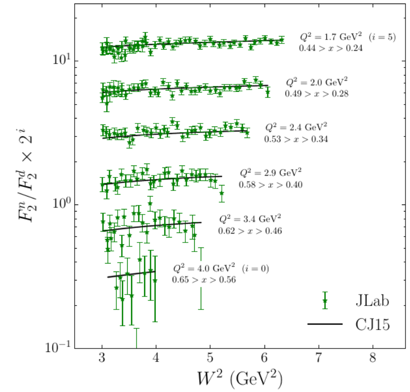
The CJ15 fit at a glance

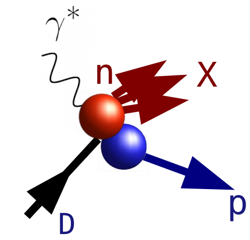
	JLab & BONUS	HERMES	HERA I+II	Tevatron new W,Z	LHC	ν+A di-μ	Large-x treatment: Nucl.	HT TMC	Flex *d*	low-W DIS
CJ15 *	✓	✓	✓	✓	*in prog.*	✗	✓✓	✓	✓	✓
CT14			DIS 2016	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.0					✓	✓		TMC only		
JR14	✓				✓	✓	✓	✓		
ABM15 **				✓ ¤¤	✓	✓	✓	✓		✓
HERAPDF2.0			✓	¤						

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

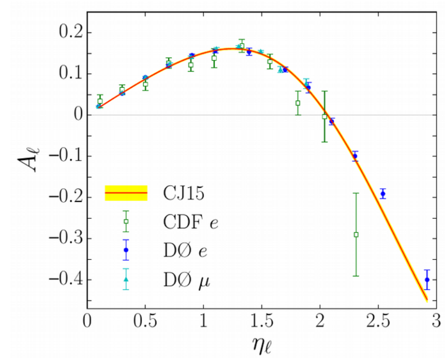
New in CJ15

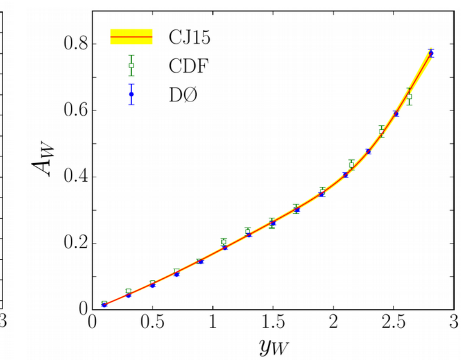
- s-ACOT scheme for heavy flavors

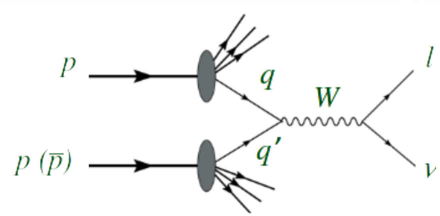


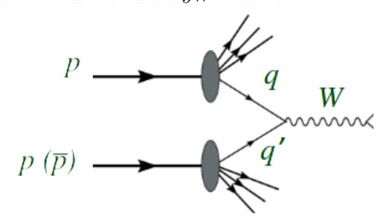


- **New data:**
  - BONUS spectator tagged DIS
  - HERA I+II combination
  - HERMES F2
  - High-statistics W-boson charge asymmetries from D0



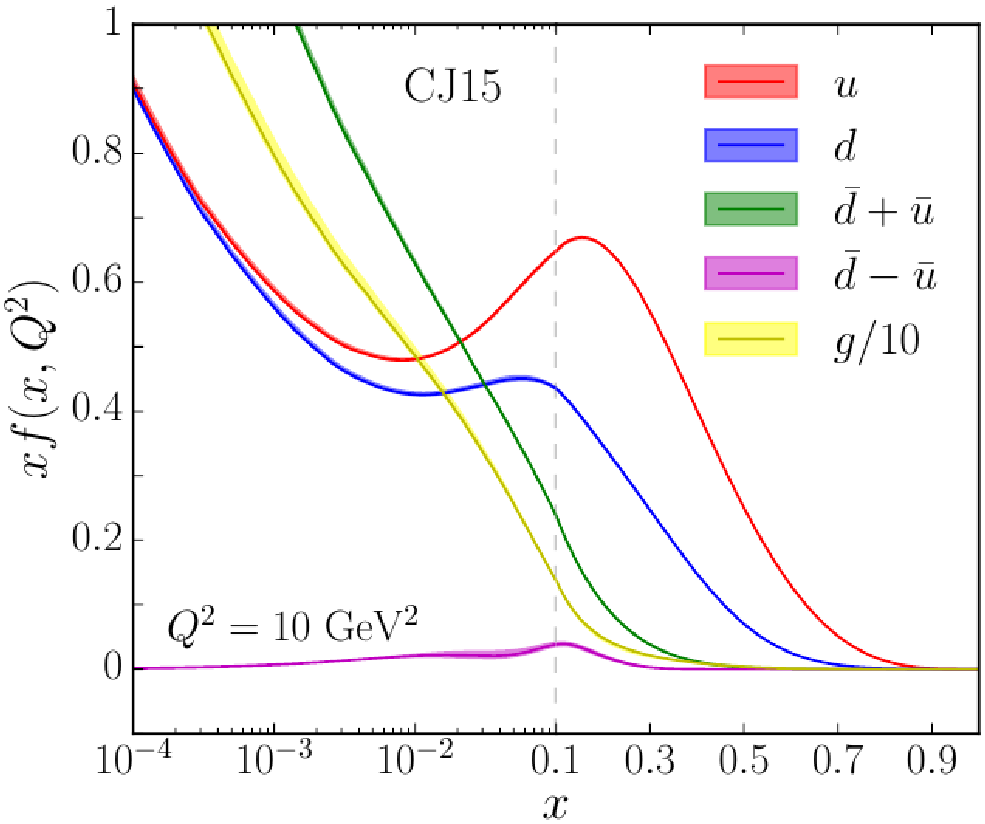






- **New off-shell nucleon treatment in deuteron targets (DIS and DY)**
  - Parametrized vs. modeled → absorbs wave function uncertainty
  - Comparison to extractions from deuteron and DIS on heavier targets

CJ15 – PDFs



- Hessian error analysis
  - Correlated errors where available
- Error bands displayed for

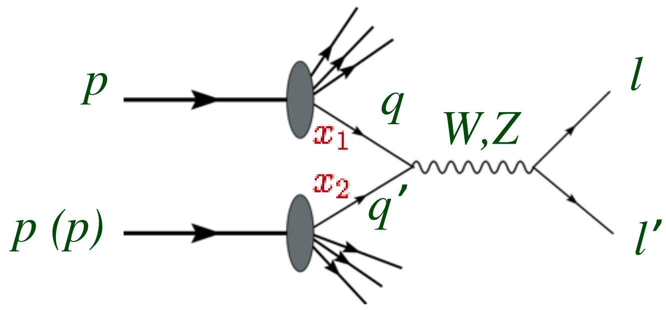
$$\Delta\chi^2 = 2.71$$

(90% confidence level in a perfect, Gaussian world)

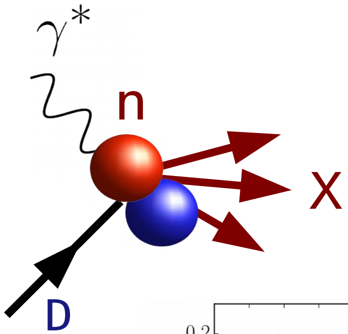
- NLO fit gives $\chi^2/\mathrm{datum} = 1.04$
- LO fit much worse – cannot accommodate Q^2 dependence of data

NUCL / HEP symbiosis

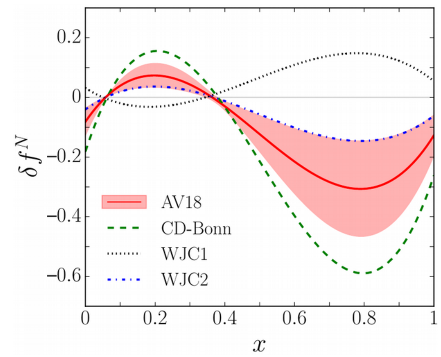
- *W* and *Z* → constrain *d*-quark at largest x on proton targets



$$A_W(y) \approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)}$$



- Compare to deuteron DIS
  - → constrain deuteron corrections
  - → **Off shell correction – first time in Deuteron!**



- Abundant DIS deuteron data
  - → precise *u*, *d* flavor separation

NUCL / HEP symbiosis

Observable	Experiment	# points	χ^2			
			LO	NLO	NLO (OCS)	NLO (no nucl)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440
	BCDMS (d) [81]	254	297	**292**	289	301
	SLAC (p) [82]	564	488	**434**	435	441
	SLAC (d) [82]	582	396	**376**	380	507
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13
	DØ (μ) [17]	10	37	**20**	19	29
	DØ (e) [18]	13	20	**29**	29	14
	CDF (W) [89]	13	16	**16**	16	14
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26
	DØ (Z) [91]	28	25	**16**	16	16
	⋮	⋮	⋮	⋮	⋮	⋮
χ^2/datum			1.33	**1.04**	1.04	1.09

NUCL / HEP symbiosis

Observable	Experiment	# points	χ^2 LO	χ^2 NLO	χ^2 NLO (OCS)	χ^2 NLO (no nucl)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440
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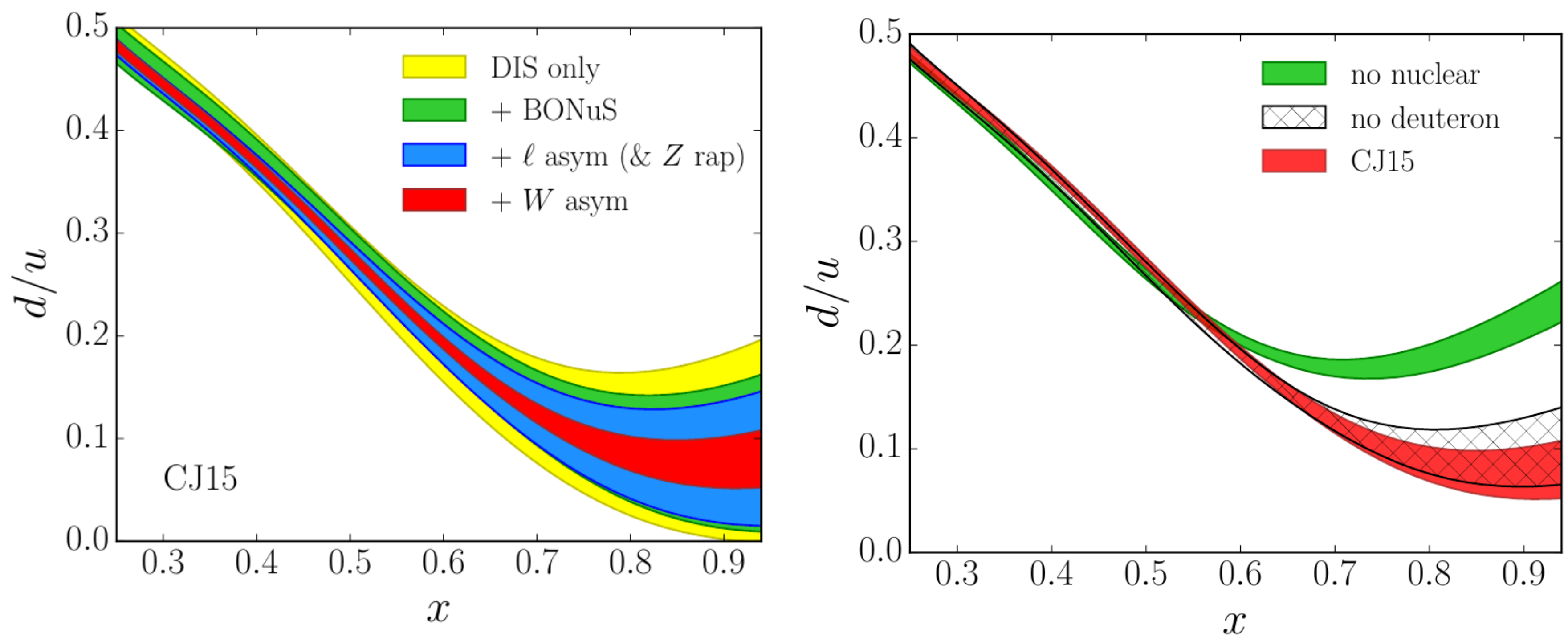
	CDF (W) [89]	13	16	**16**	16	14
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26

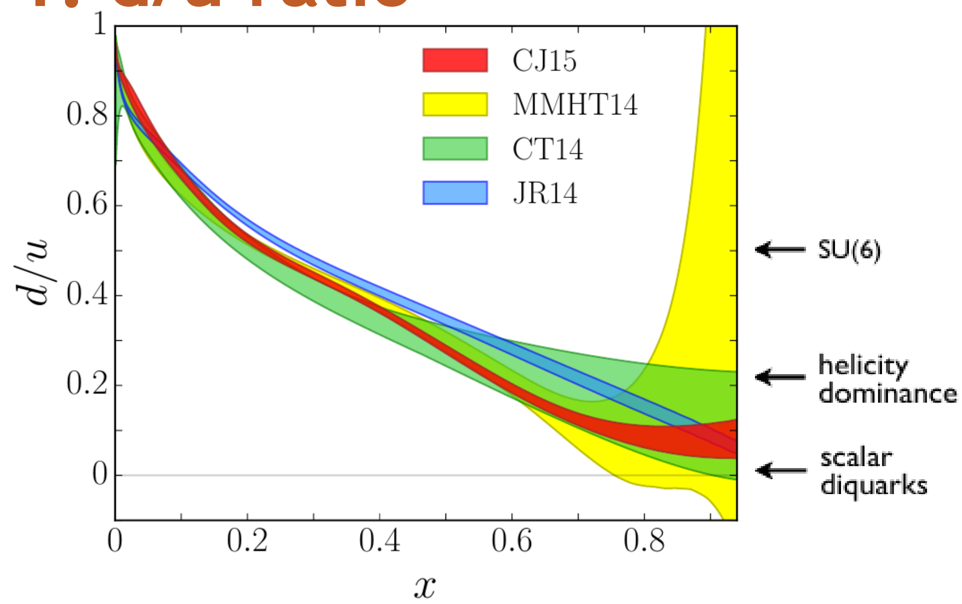
- Ignoring nuclear dynamics, SLAC(d) and D0(W) pull *d* quark in opposite directions
  - **D0 (W) data determine nuclear corrections !!**
  - other asymmetries inconclusive by themselves
  - **BONUS data validate DO(W) analysis**

Hadronic physics output 1: d/u ratio



- **d-quark determined by p+p → W+X**
- **Nuclear corrections dominant at large x**
  - SLAC(d)'s statistical power used to fit the off-shell function...
  - ... and to improve d/u flavor separation, esp. at x<0.3 (see backup)

Hadronic physics output 1: d/u ratio



→ d/u ratio at high x of interest for nonperturbative models of nucleon

→ **CJ15:**
more flexible parametrization

$$d \rightarrow d + b\,x^c\,u$$

allows finite, nonzero $x = 1$ limit

(standard PDF form gives 0 or ∞ unless $a_2^d = a_2^u$)

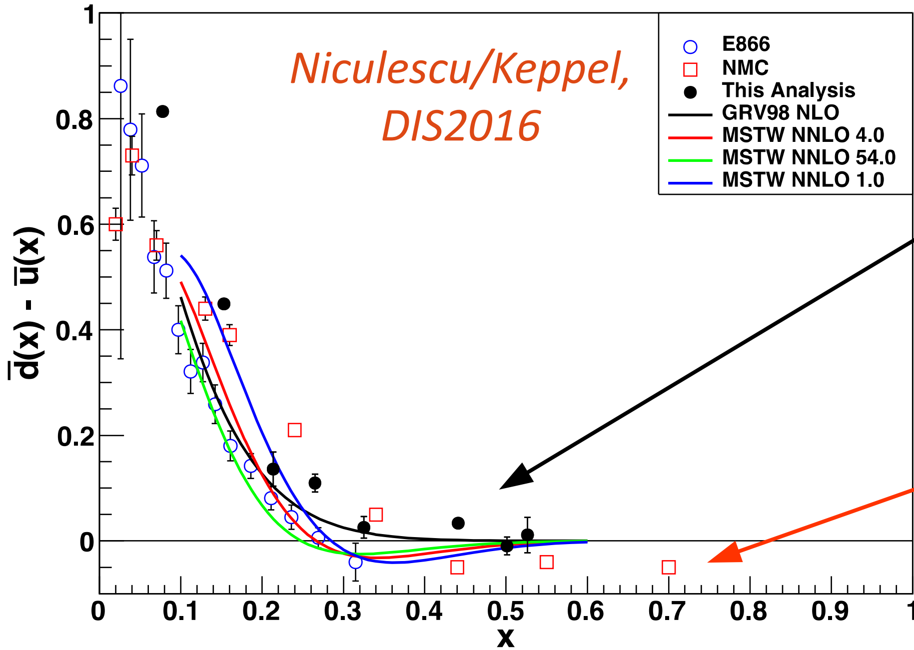
MMHT14: fitted deuteron corrections
standard *d* parametrization
→ **"UNDERCONSTRAINED"**

JR14 (and ABM12):
Similar deuteron corrections
standard *d* ; no lepton/W asym.
→ **"OVERCONSTRAINED"**

CT14: $\beta_u = \beta_d \implies d/u$ finite
No nuclear corrections

Hadronic physics output 2: dbar/ubar

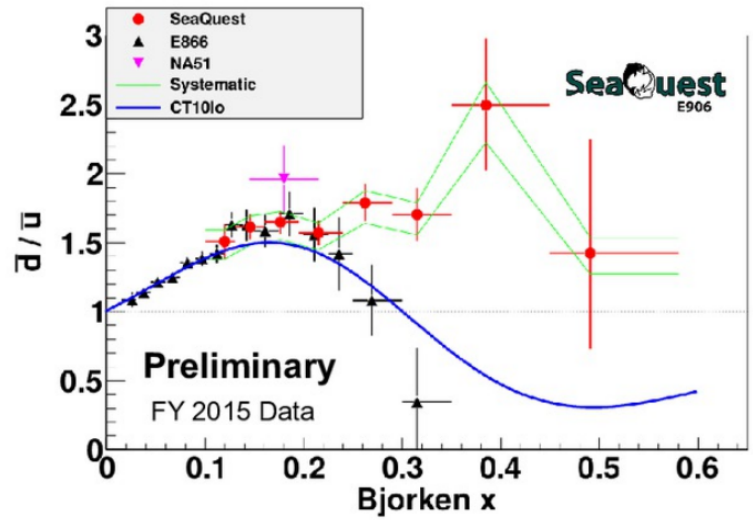
[AA, Keppel, Niculescu, DIS 2016]



This analysis: use CJ15 to "remove" nuclear corrections

NMC = Peng et al. analysis of NMC data as in publication (use MSTW08 for uv, dv)

- **No evidence fo sign change at large x !**
- **And SeaQuest agrees!**
  - presented for the first time a few days later



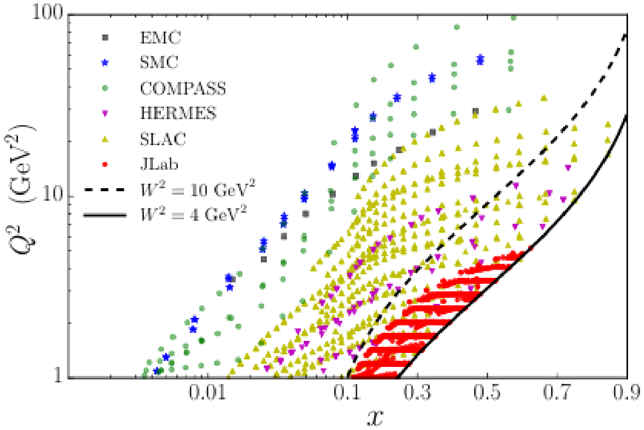
B.Kerns, DNP April 2016

Iterative Monte Carlo: the JAM approach

Sato, Ethier, Melnitchouk, Kuhn, Accardi

PRD 2016 [arXiv:1601.07782] & work in progress

Fitting strategy



Parametrization

- $xf(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$
- LT quark distributions $\rightarrow \Delta u^+, \Delta d^+, \Delta s^+, \Delta g$
- T3 quark distributions $\rightarrow D_u, D_d$
- T4 structure functions $\rightarrow H_p, H_n$

Chi-squared minimization $\rightarrow$ with correlated systematic uncertainties

$$\chi^2 = \sum_i \left(\frac{D_i - T_i(1-\sum_k r^k \beta_i^k / D_i)^{-1}}{\alpha_i} \right)^2 + \sum_k (r^k)^2$$

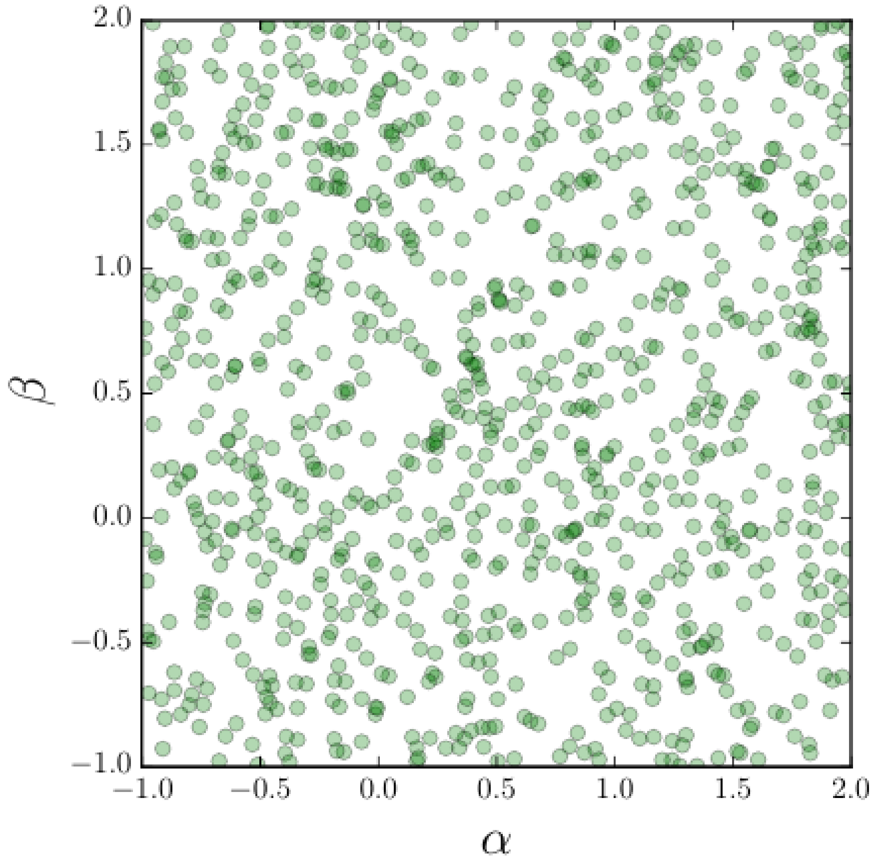
Issues

- Stability in the moments (e.g. $\Delta\Sigma^{(1)}$)
- Is the solution given by a single fit unique? $\rightarrow$ False minima
- Is over-fitting present in our fits?
- Which parameters should be fixed and at which value?
- Determination of uncertainty bands.

Solution $\rightarrow$ MC approach; iterate until convergence $\rightarrow$ **data driven uncertainties**

Iterative Monte Carlo (IMC) analysis

Toy example → fitting 2 model parameters α, β

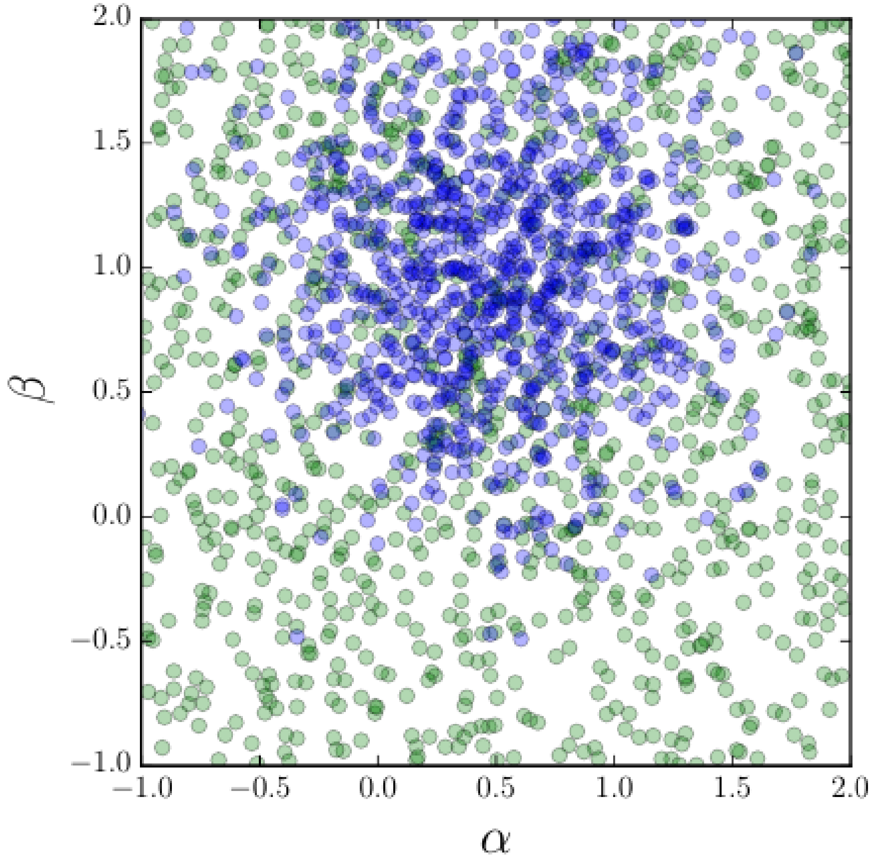


I. Flat sampling

Initial priors $\{(\alpha, \beta)\}$

Iterative Monte Carlo (IMC) analysis

Toy example → fitting 2 model parameters α, β



I. Flat sampling

Initial priors $\{(\alpha, \beta)\}$

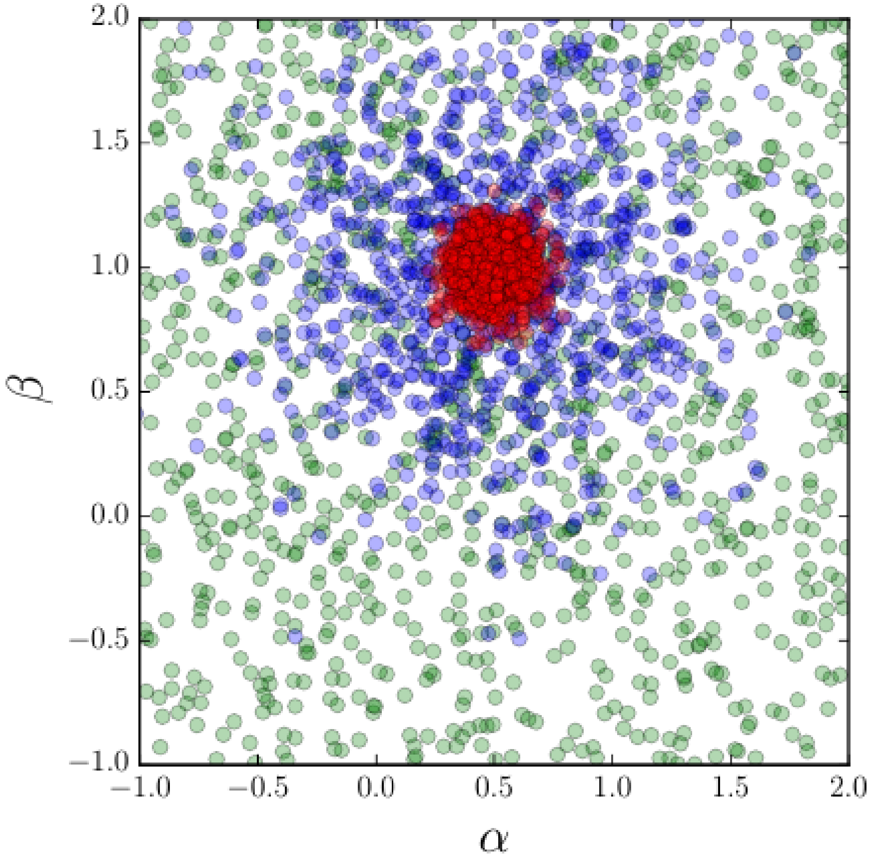
II. First iteration

priors $\{(\alpha, \beta)\}$

posteriors $\{(\alpha, \beta)\}$

Iterative Monte Carlo (IMC) analysis

Toy example → fitting 2 model parameters α, β



I. Flat sampling

Initial priors $\{(\alpha, \beta)\}$

II. First iteration

priors $\{(\alpha, \beta)\}$

posteriors $\{(\alpha, \beta)\}$

III. Second iteration

priors $\{(\alpha, \beta)\}$

posteriors $\{(\alpha, \beta)\}$

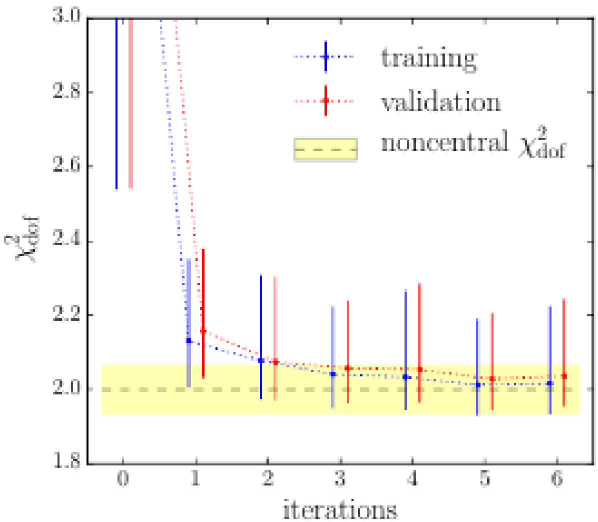
... until convergence

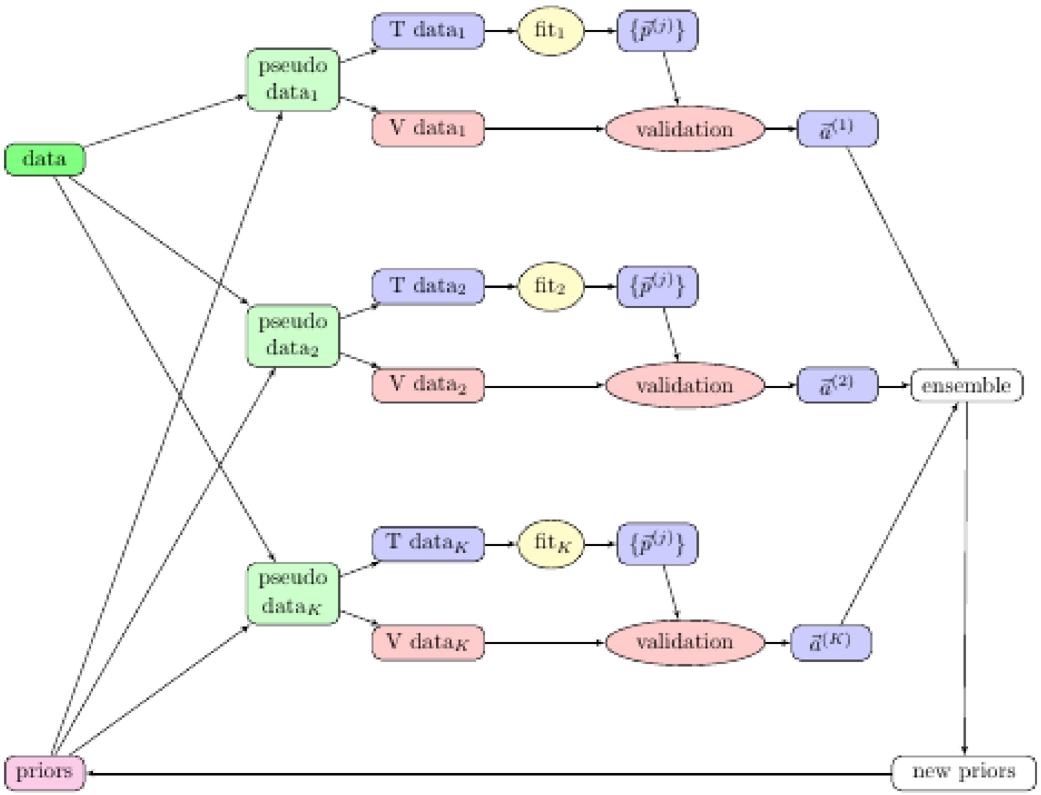
Iterative Monte Carlo (IMC) analysis

Each iteration

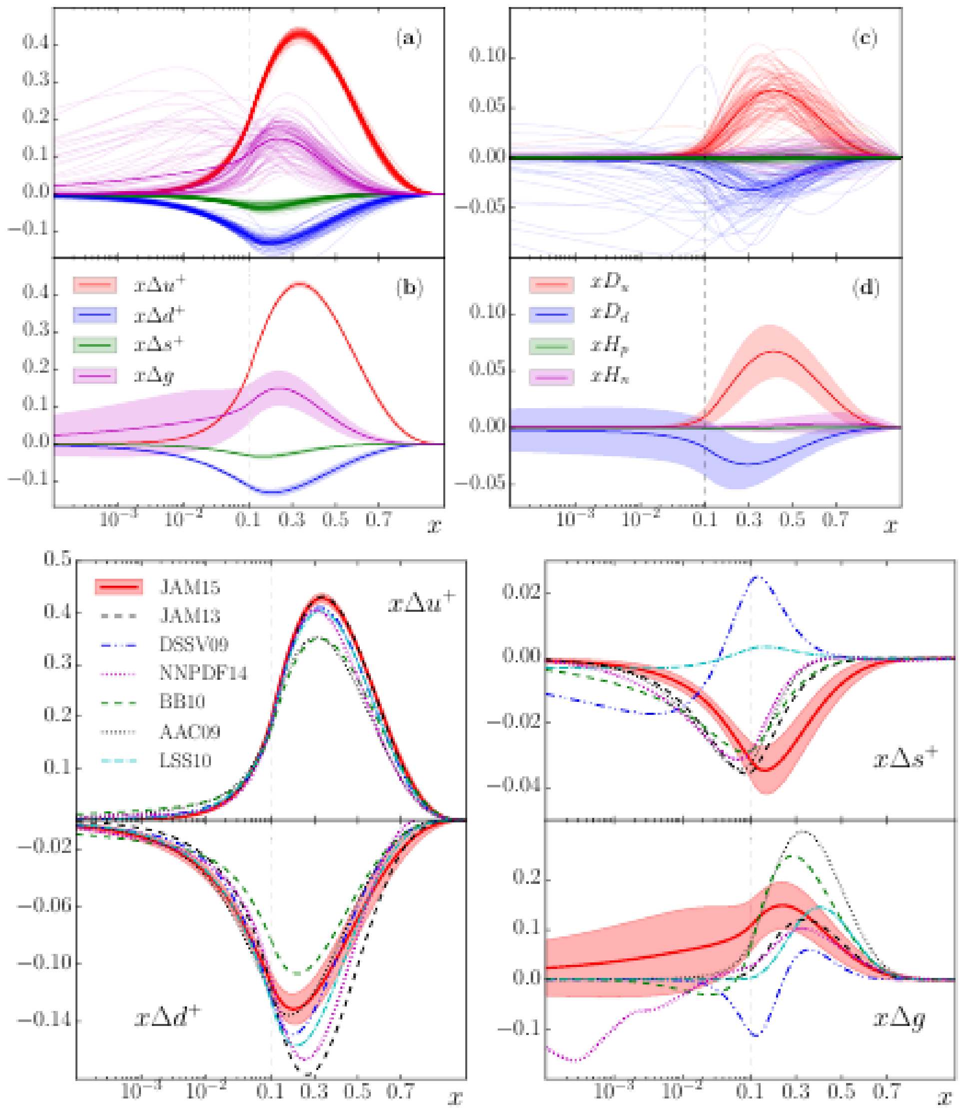
- Generate pseudo data sets via data resampling
- Random data partition → Training & Validation
- Fit the training set
- Validation

# of fits: 10000





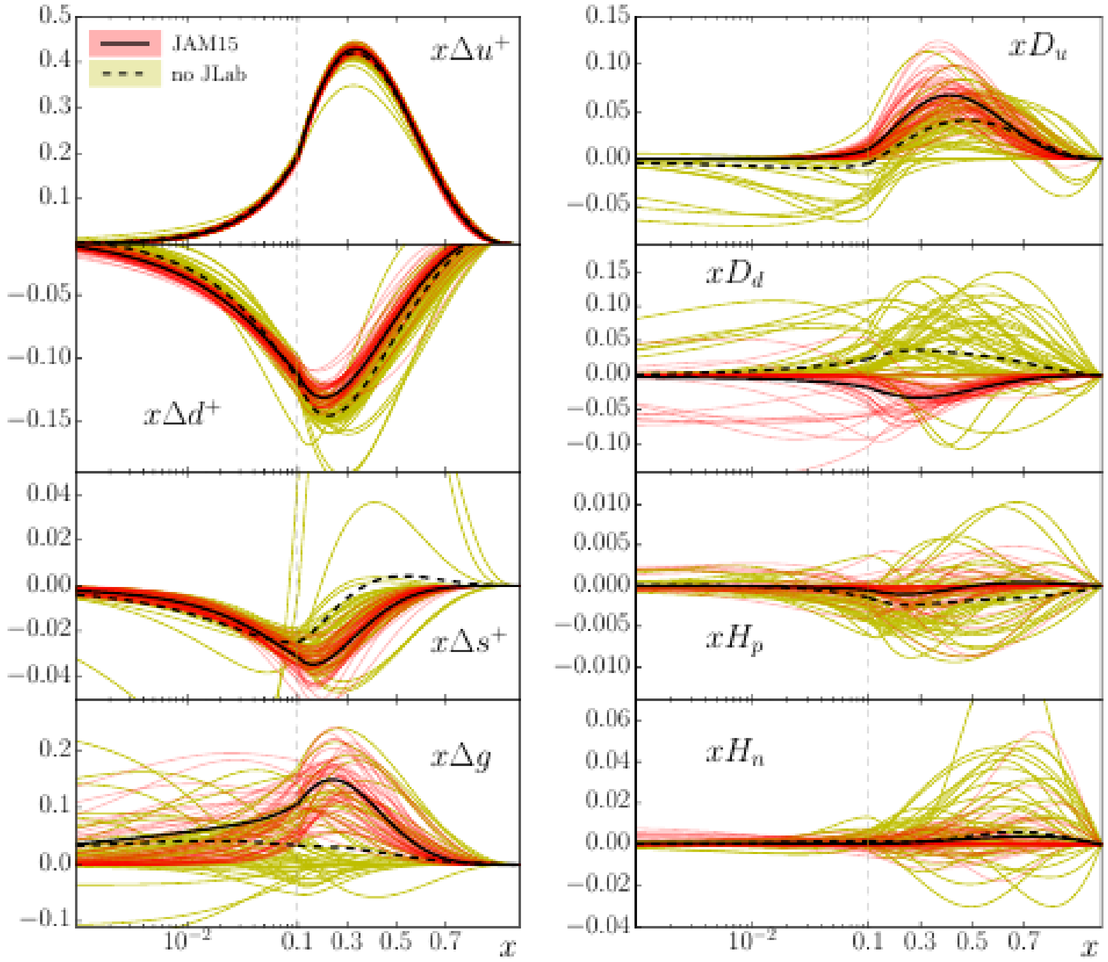
The JAM15 polarized PDFs



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.

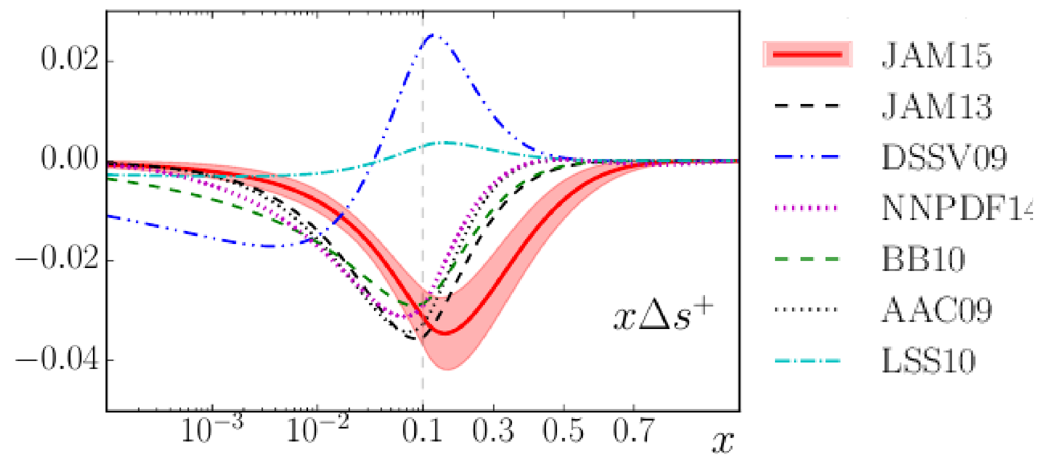
Impact of JLab data



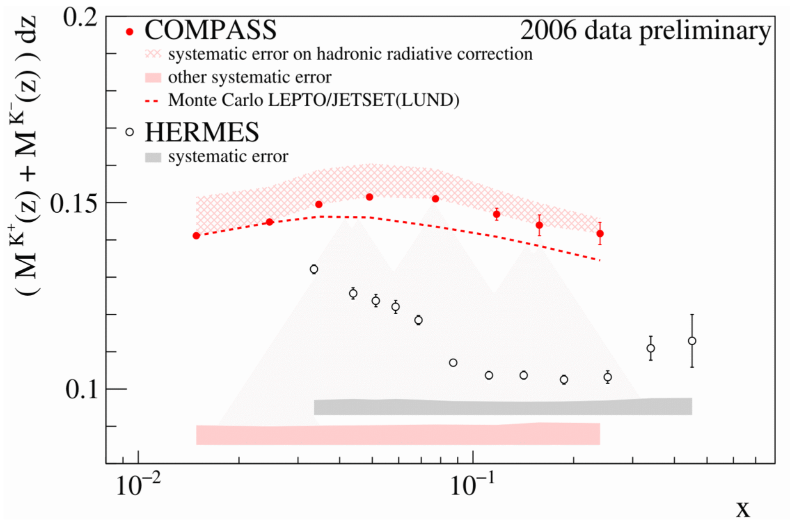
- JLab data $\rightarrow$ $0.1 < x < 0.7$
- Constraints on small x from large x $\rightarrow$ weak baryon decay constraints
- Large uncertainties in Δs^+, Δg removed by JLab data
- Non vanishing T3 quark distributions
- T4 distributions consistent with zero

A strange puzzle

- **Δs : positive or negative?**
  - Depends on kaon FF used in SIDIS calculations!



- **s : large or small?**
  - Difference in size reconciled by removing hadron mass corrections
    → see backup
  - Extraction of s(x) strongly affected on kaon FF <u>systematic</u> uncertainty



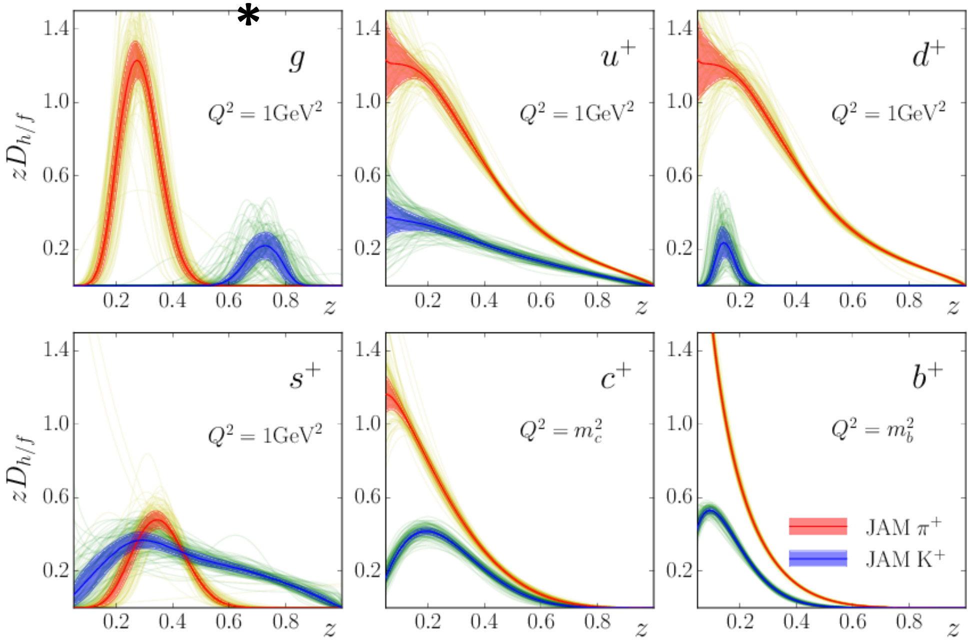
The JAM FF 2016 fit

- 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
  - Expect combined DIS/SIDIS analysis to give negative Δs (But wait and see!)

(nearly final) JAM-FF16 *

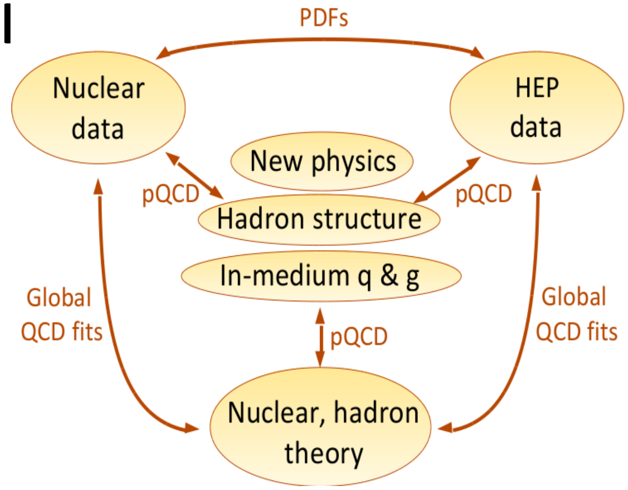


* not the official name, yet

Conclusions

- **Entering a new precision era in large-x PDFs**
  - Most groups are finally on board
    - Much to be learned from each other
  - New data (now and in the future), new fitting approaches
  - Conquering nuclear corrections – time for threshold resummation ?
  - Conquering the world: towards unified PDF+pPDF+FF fits
    - To the benefit of humankind (e.g., Δs)

- **High-energy and nuclear physics need to worl**
  - Progress in hadron / nuclear structure
  - Precision PDFs for BSM searches
  - Make the most of LHC and JLab 12
  - Prepare for the EIC



Appendix:
details on CJ15 fits

CJ15 - data set

$W^2 > 3.5\ \text{GeV}^2$

$\Longrightarrow \quad x \lesssim 0.85$

BONUS F_2^n / F_2^d

$x \lesssim 0.65$

HERA I+II

D0 A_ℓ : $x \lesssim 0.5$

D0 A_W : $x \lesssim 0.85$

Observable	Experiment	# points	χ^2 LO	χ^2 NLO	χ^2 NLO (OCS)	χ^2 NLO (no nucl)	χ^2 NLO (no nucl/D0)
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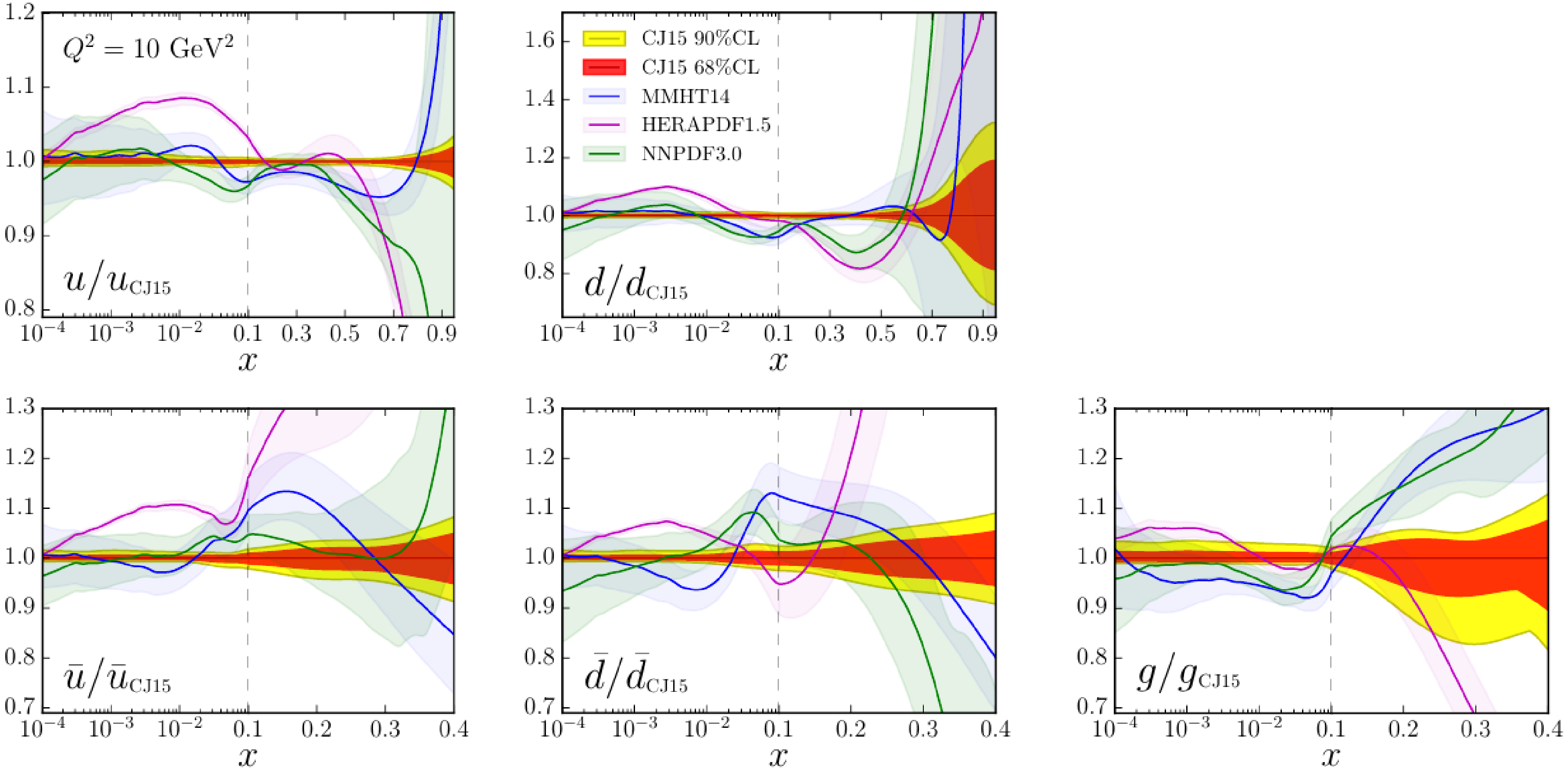
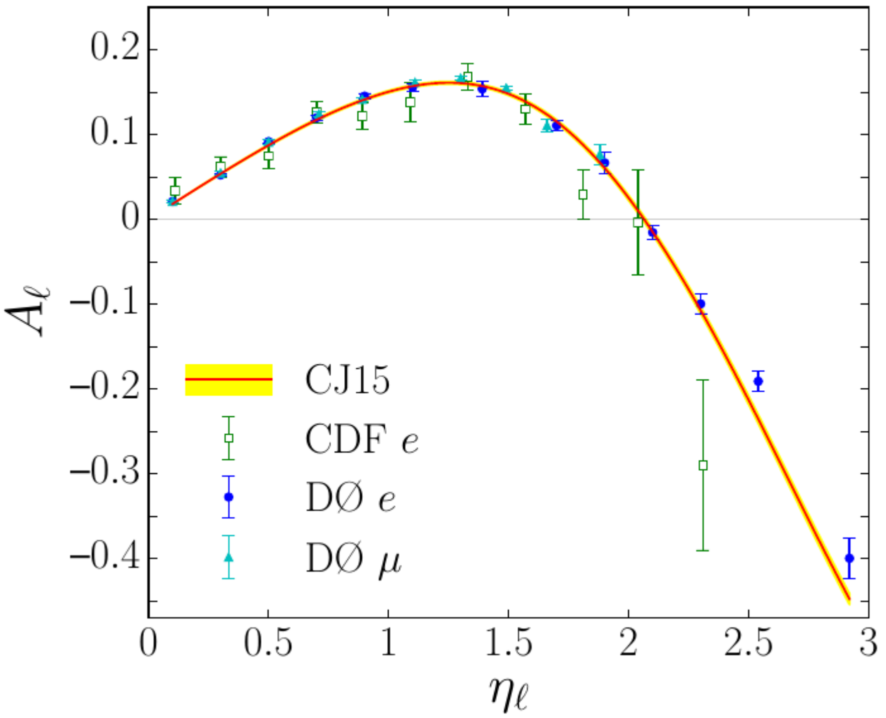
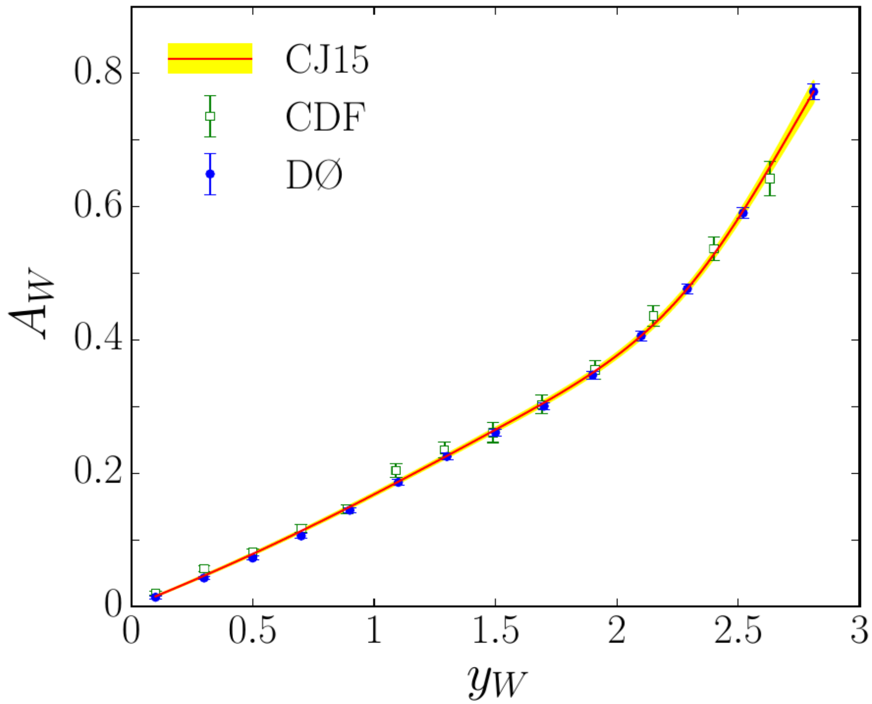
	SLAC (d) [82]	582	396	**376**	380	507	466
	NMC (p) [83]	275	431	**405**	404	405	403
	NMC (d/p) [84]	189	179	**172**	173	174	173
	HERMES (p) [86]	37	56	**42**	43	44	44
	HERMES (d) [86]	37	51	**37**	38	36	37
	Jefferson Lab (p) [87]	136	166	**166**	167	177	166
	Jefferson Lab (d) [87]	136	131	**123**	124	126	130
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219	219
DIS σ	HERA (NC e^-p) [85]	159	325	**241**	240	247	244
	HERA (NC e^+p 1) [85]	402	966	**580**	579	588	585
	HERA (NC e^+p 2) [85]	75	184	**94**	94	94	93
	HERA (NC e^+p 3) [85]	259	307	**249**	249	248	248
	HERA (NC e^+p 4) [85]	209	348	**228**	228	228	228
	HERA (CC e^-p) [85]	42	44	**48**	48	45	49
	HERA (CC e^+p) [85]	39	56	**50**	50	51	51
Drell-Yan	E866 (pp) [29]	121	148	**139**	139	145	143
	E866 (pd) [29]	129	207	**145**	143	158	157
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13	14
	DØ (μ) [17]	10	37	**20**	19	29	28
	DØ (e) [18]	13	20	**29**	29	14	14
	CDF (W) [89]	13	16	**16**	16	14	14
	DØ (W) [19]	14	39	**14**	15	82	—
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26	26
	DØ (Z) [91]	28	25	**16**	16	16	16
jet	CDF (run 2) [92]	72	33	**15**	15	23	25
	DØ (run 2) [93]	110	23	**21**	21	14	14
γ+jet	DØ 1 [94]	16	17	**7**	7	7	7
	DØ 2 [94]	16	34	**16**	16	17	17
	DØ 3 [94]	12	34	**25**	25	24	25
	DØ 4 [94]	12	76	**13**	13	13	13
total		4542	5894	**4700**	4702	4964	4817
total + norm			6022	**4708**	4710	4972	4826
χ^2/datum			1.33	**1.04**	1.04	1.09	1.07

CJ15 vs. others

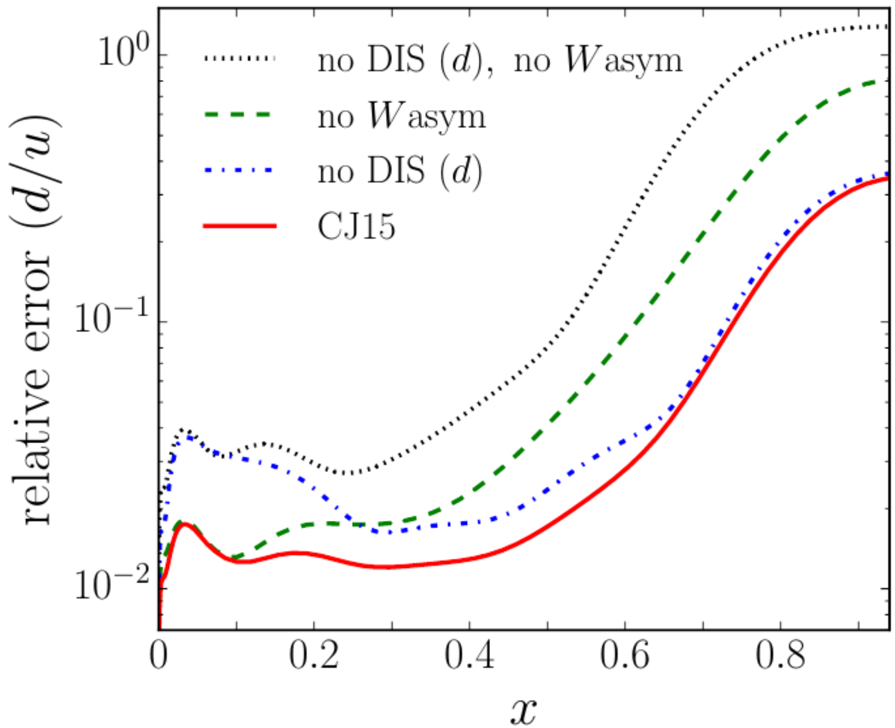


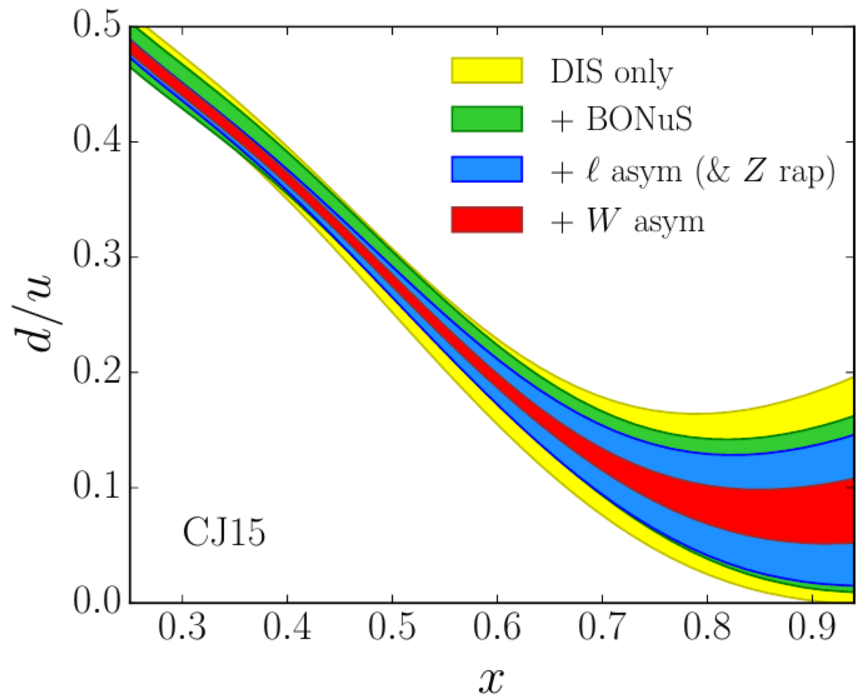
W-lepton and W asymmetry at Tevatron





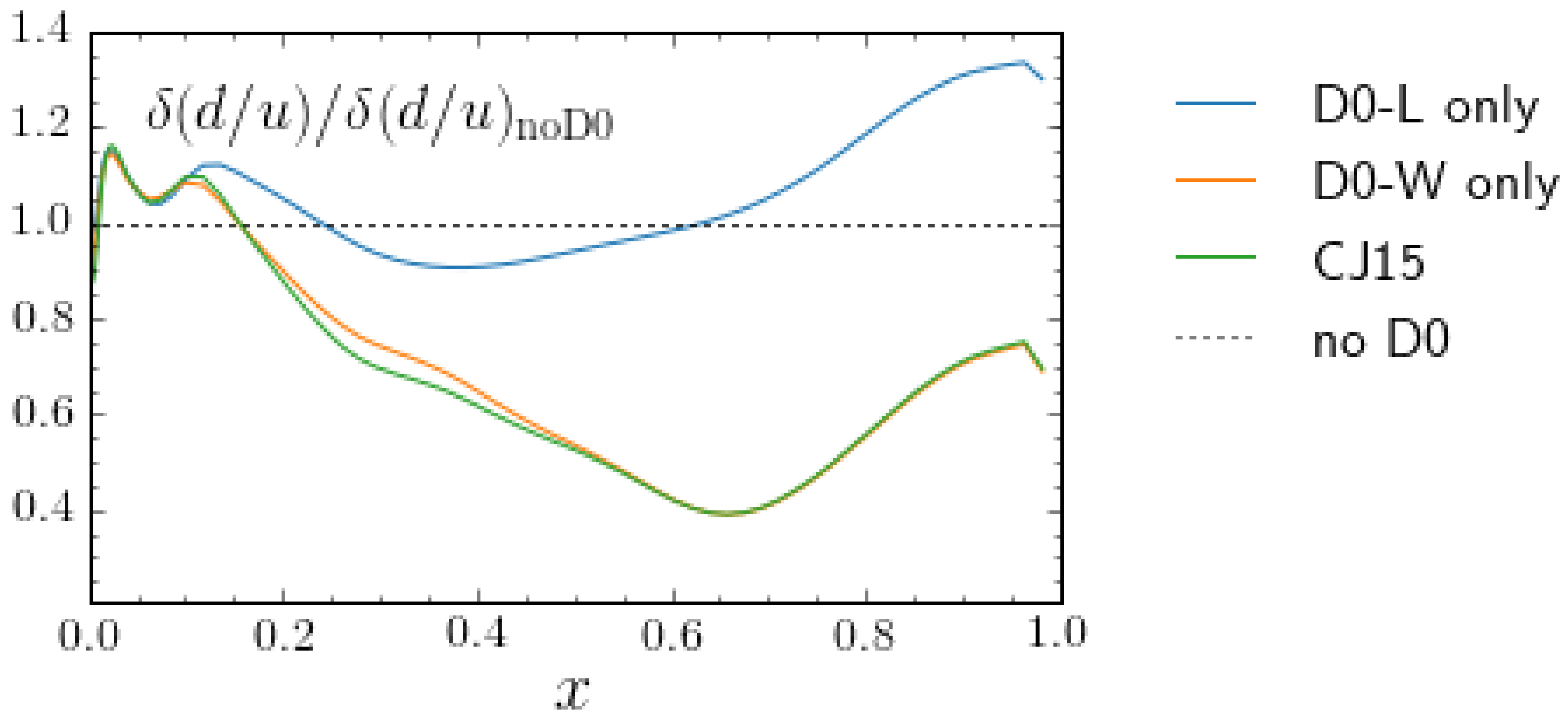
What fits what?





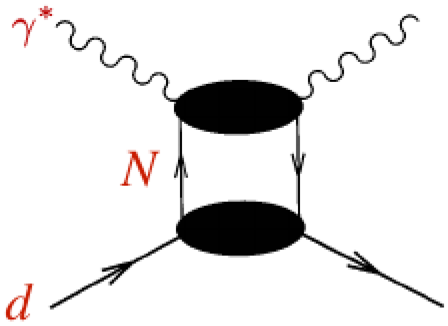
- **Large x > 0.3:**
  - D0's W-asymmetry determines the d-quark
  - SLAC(d)'s statistical power used to fit the off-shell function
- **Moderate x < 0.3:**
  - SLAC(d) enables precise d/u flavor separation

W-lepton and W asymmetry at Tevatron



Nuclear corrections

- At large x, DIS dominated by incoherent scattering from individual nucleons



$$q^d(x,Q^2) = \int \frac{dz}{z} dp^2\, f_{N/d}(z,p^2)\, \widetilde{q}^N(x/z,p^2,Q^2)$$

nucleon momentum distribution in d ("smearing function") ↗ ; ↖ PDF in bound (off-shell) nucleon

→ $z = \frac{p \cdot q}{p_d \cdot q} \approx 1 + \frac{p_0 + \gamma p_z}{M}$ $\left[p_0 = M + \varepsilon, \quad \varepsilon = \varepsilon_d - \frac{\vec{p}^2}{2M} \right]$

momentum fraction of d carried by N

→ at finite Q^2, smearing function depends on $\gamma = \sqrt{1 + 4M^2x^2/Q^2}$

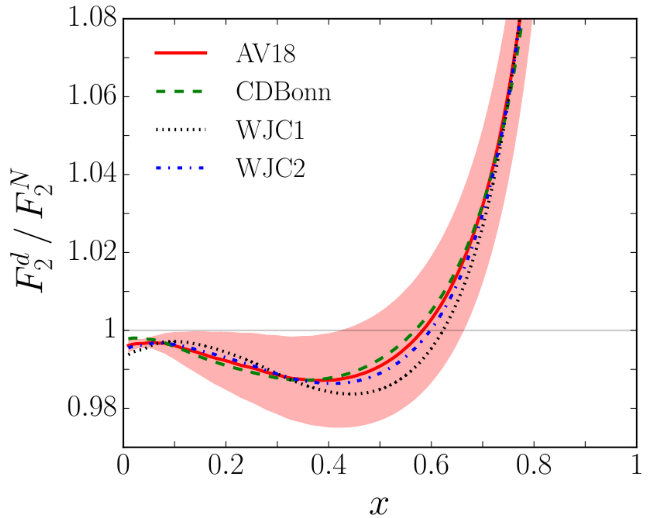
- Offshell expansion; parametrize first order coefficient, x_1 fixed with valence sum rule

$$\widetilde{q}^N(x,p^2) = q^N(x) \left[1 + \frac{(p^2 - M^2)}{M^2}\, \delta q^N(x) \right]$$

$$\delta q^N = C_N (x - x_0)(x - x_1)(1 + x - x_0) \qquad \int_0^1 dx\, \delta q^N(x) \left(q^N(x) - \bar{q}^N(x) \right) = 0$$

Nucleon off-shellness constrained by D0 data (!)

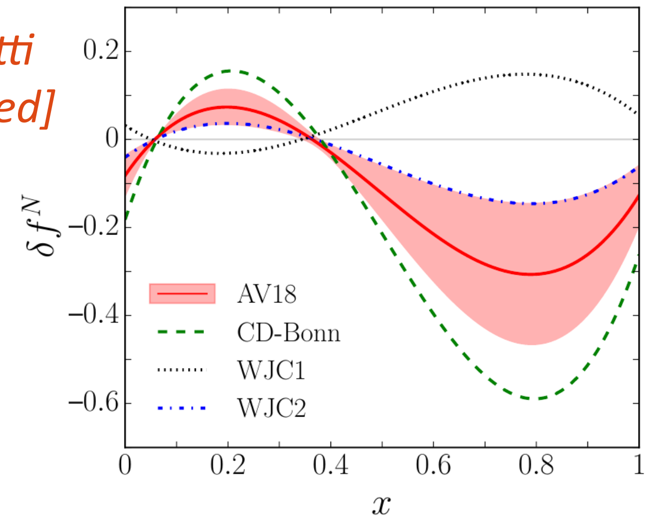
- The "wrong" nuclear corrections creates tension between DIS(D) and W asym
  - The fits then choses the "right" one
- **Deuteron to nucleon "EMC" ratio** D/(p+n)
  - Stable w.r.t. choice of nucleon w.fn. (WJC1 disfavored χ^2-wise)
  - No evidence for antishadowing



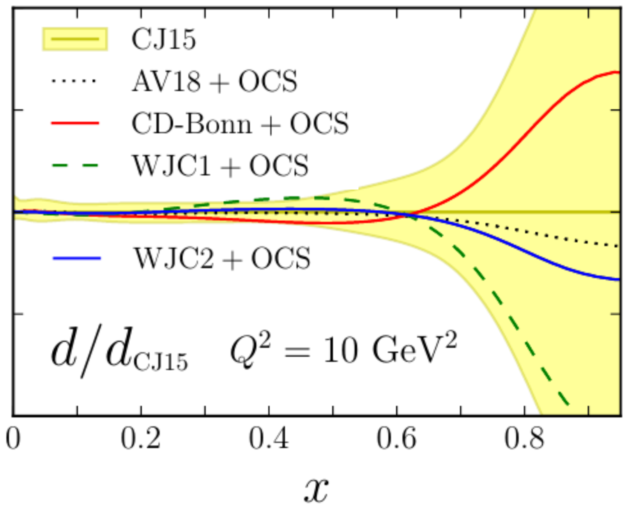
- **Off shell correction – first time in Deuteron!**
  - Good statistical precision!
  - Magnitude compensates for wave function's missing / excessive strength
  - Physical result or fitting away other physics?

→ *also: R. Petti [WG1 – Wed]*

$$\delta f^N = C(x - x_0)(x - x_1)(1 + x_0 - x)$$



Cross checks

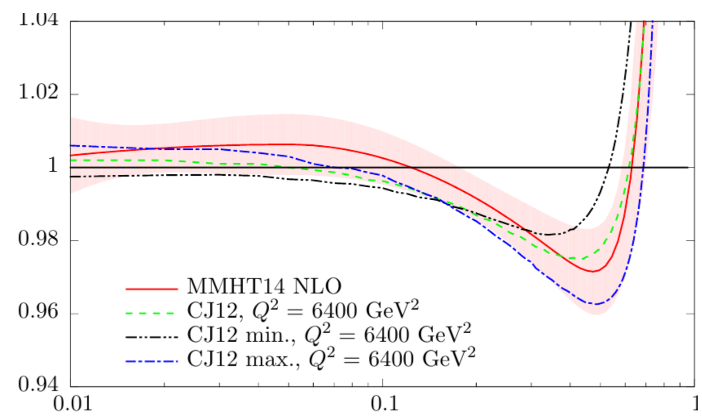


- Fit with with a 1-parameter model of the off-shell effects
  - Obtain comaptible *d* quarks

OCS = Off-shell Covariant Spectator model

- MMHT14 parametrize the whole nuclear effect
  - Obtain similar result
  - (but cannot explore the nuclear dynamics)

$$c(x) = F_2(D)/F_2(p+n)$$



MMHT14, EPJ C75 (2015) 204

Hadronic physics output 2: dbar/ubar

- Peng et al. suggest NMC F2 data indicate negative dbar/ubar

J.C. Peng *et al.*, PLB 736 (2014), 411-414

$$\bar{d}(x) - \bar{u}(x) = \frac{1}{2}[u_v(x) - d_v(x)] - \frac{3}{2x}[F_2^p(x) - F_2^n(x)]$$

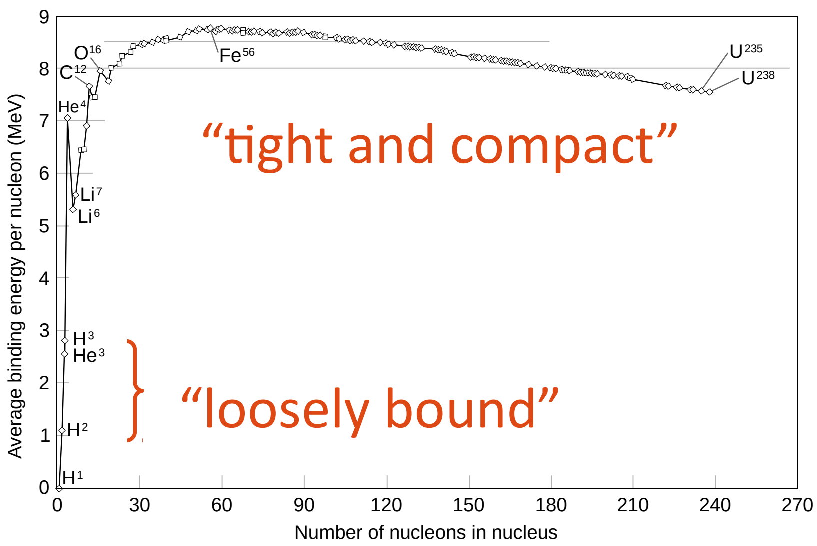
  - But extract F_2^n fwithout accounting for nuclear corrections
  - Note also:
    - Ambiguities in choice of valence or total up and down above
    - NLO effects not negligible when dbar/ubar ~ 0

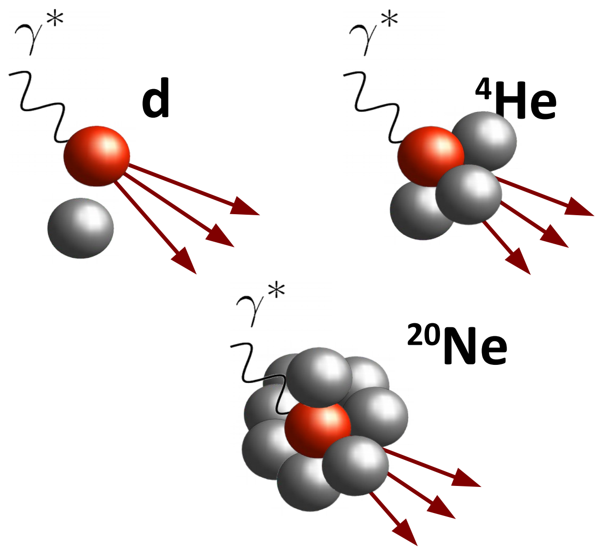
- Using CJ15 fit, can "remove" nuclear effects → *Niculescu & Keppel, DIS2016*

$$F_2^n \equiv F_2^d(\text{measured}) \times \frac{F_2^n}{F_2^d}(\text{CJ15})$$

Nuclear physics output

- **QUESTION:** Does the nuclear environment affect the off-shell behavior of a nucleon?
  - For example, partial deconfinment *[Close, Jaffe, Roberts (1985)]*

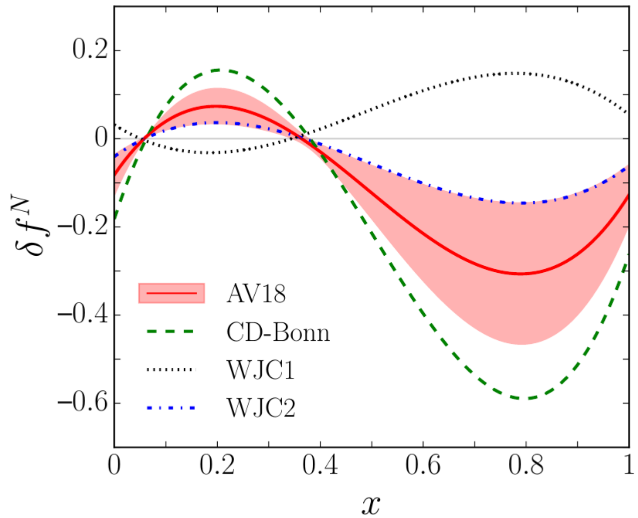




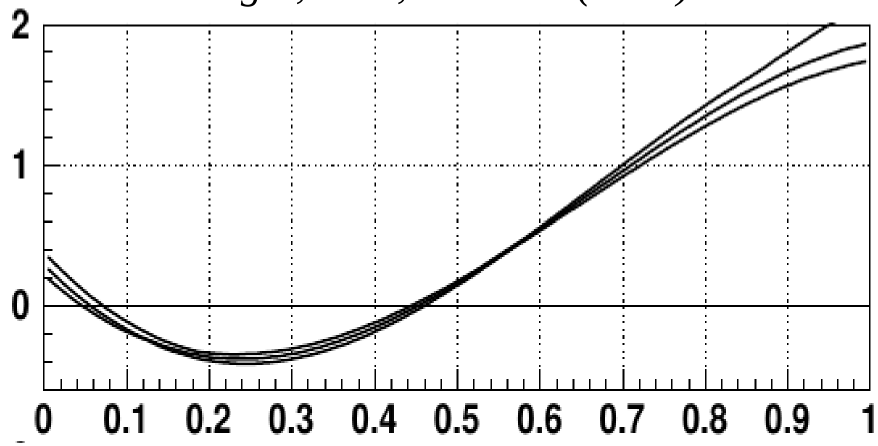
$$\delta q = \delta q(x; A) \; ??$$

Nuclear physics output

- **Compare to Kulagin-Petti fit to e+A collisions**
  - Same functional form (but different normalization)



Kulagin, Petti, NPA 765 (2006) 126-187



- Different shape and size

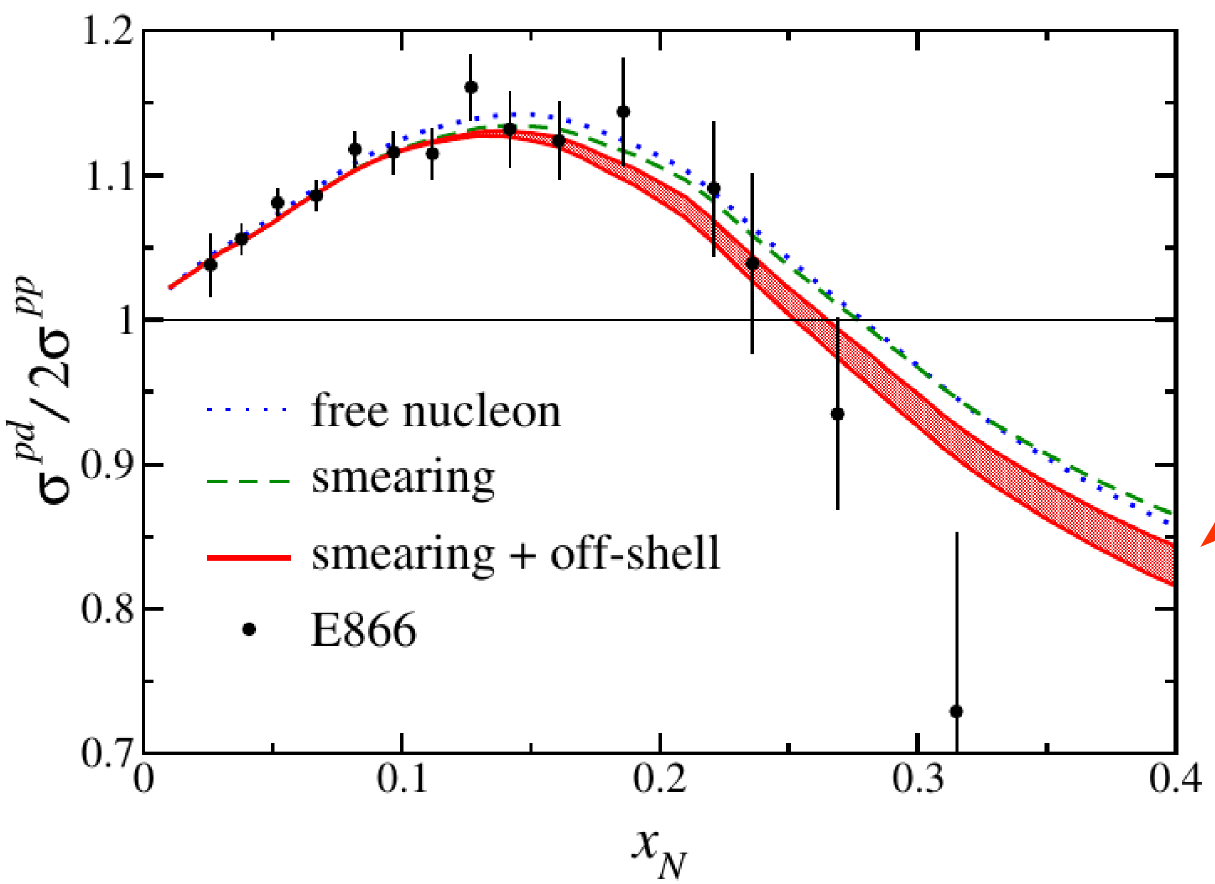
  → no nuclear universality ?? δf_N

  → too hard nuclear spectral function at large momentum ??

  → wrong parametrization? ——→ To be investigated

Nuclear corrections…

Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)

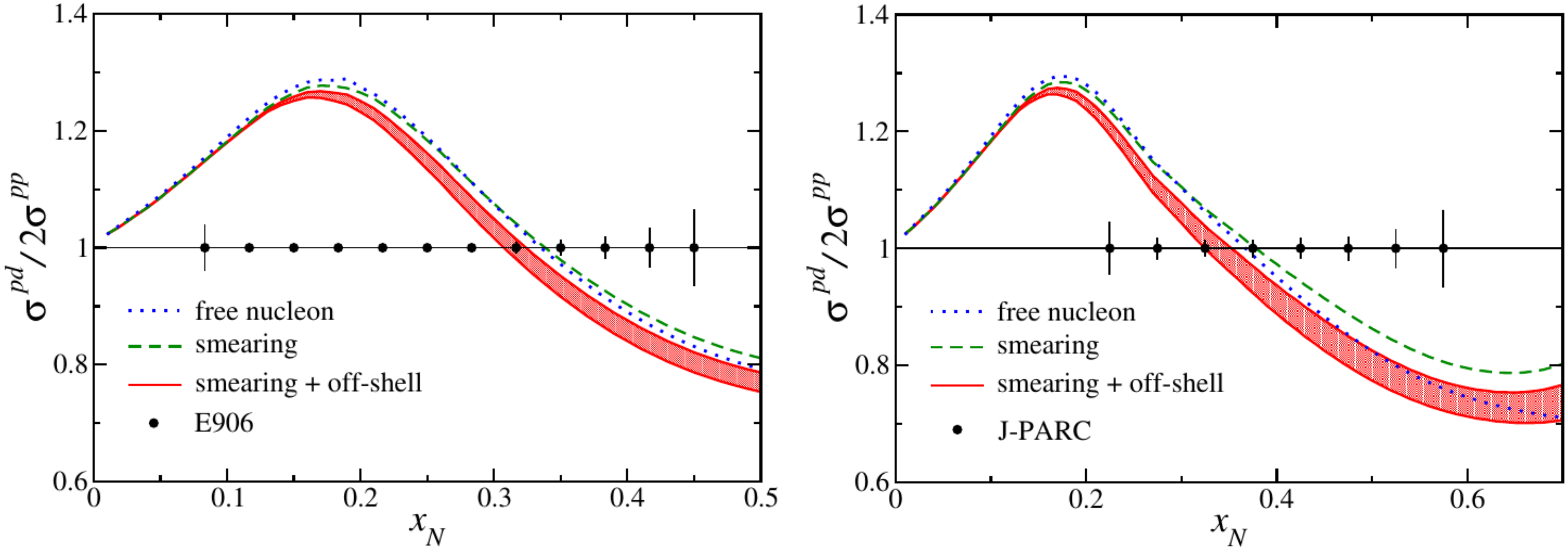


Red band: combined wave fn. & off-shell model uncertainty

- Off-shell corrections help make dbar-ubar stay positive

Future DY reaches into large-x

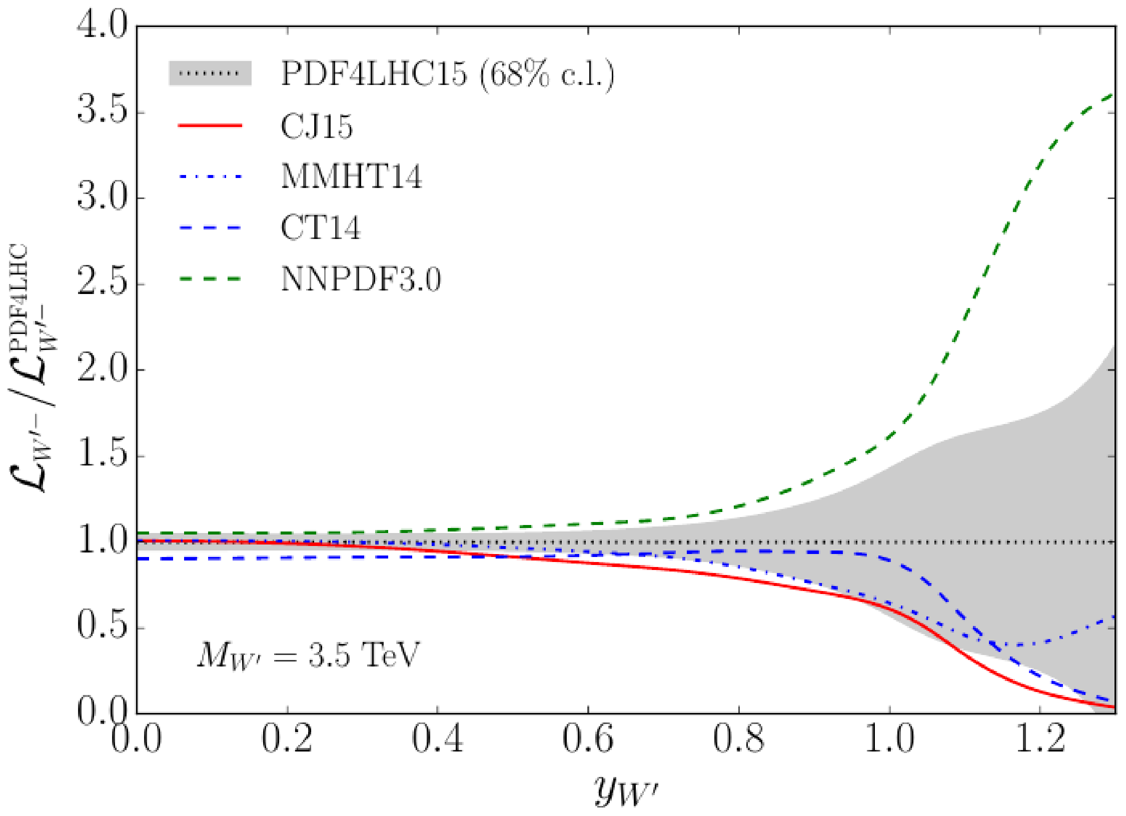
Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)



- **E906/Sea Quest:** off-shell effects even more important
- **J-PARC:** can cross-check nuclear smearing vs. DIS

BSM physics output

→ *see also: R.Placakyte [WG1 – Tue]*

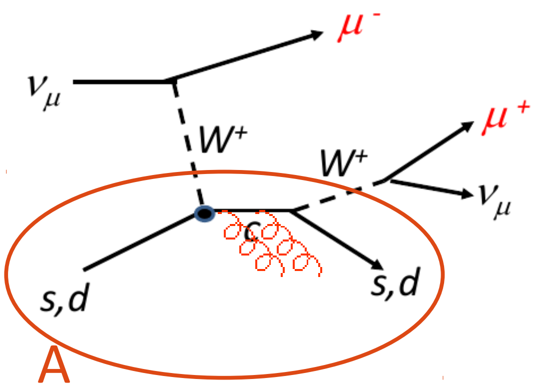


$$\mathcal{L}_{W'^-} = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \Big[\cos^2\theta_C \big(\bar{u}(x_2) d(x_1) + \bar{c}(x_2) s(x_1)\big) + \sin^2\theta_C \big(\bar{u}(x_2) s(x_1) + \bar{c}(x_2) d(x_1)\big) \Big] + (x_1 \leftrightarrow x_2)$$

Strangeness and strangeness asymmetry

$$s^{\pm}(x) = s(x) \pm \bar{s}(x) \qquad [s^{\pm}] = \int_0^1 dx\, x\, s^{\pm}(x)$$

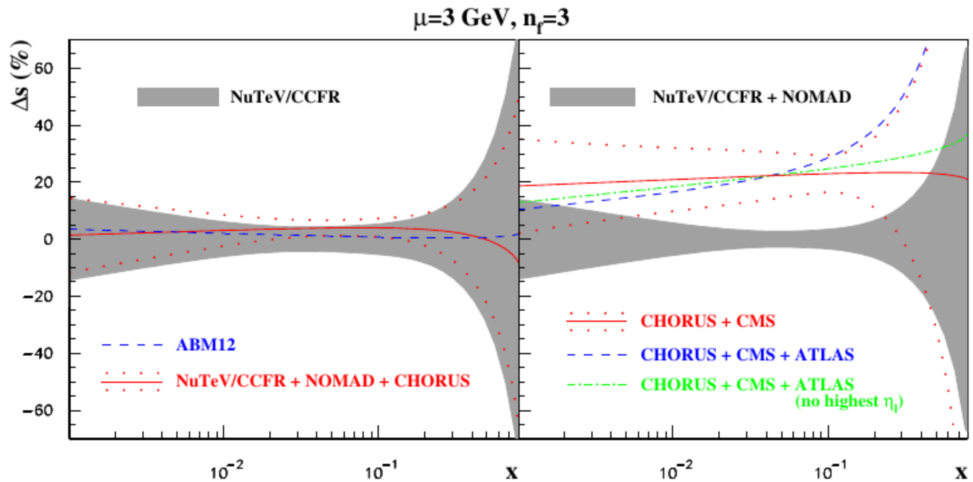
- In pre-LHC fits, mostly constrained by ν+A data
  - CCFR inclusive DIS
  - NuTeV muon pair production
  - NOMAD and CHORUS



- **Nuclear corrections again...**
  - **Initial state nuclear wave-function mods**
    - Partly under control using **nPDFs**
    - But: double counting!! → either use in nPDF or in PDF fits !
  - **Final state propagation of the charm quark / D meson**
    - Not under theoretical / phenomenological control (*cf.* heavy quark "puzzle" in A+A at RHIC, LHC)

Strange tensions

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



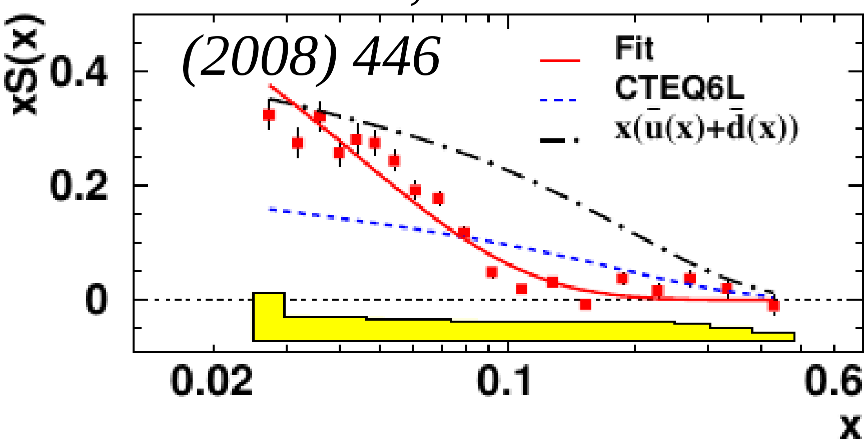
$g\, s_p \to W\, c$

FSI ?

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

- Kaons in *e*+*p* at HERMES
  - But.. fragmentation functions uncertainty

HERMES, PLB 666 (2008) 446

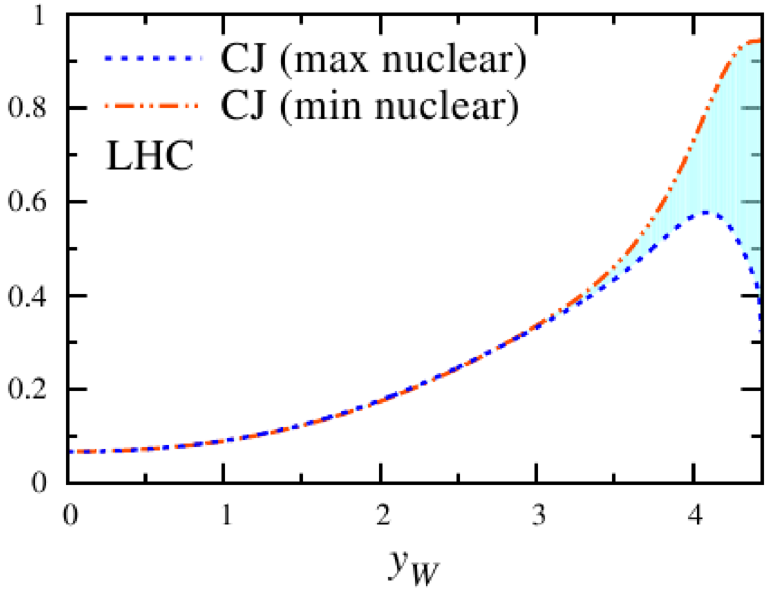


W charge asymmetry at LHC

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

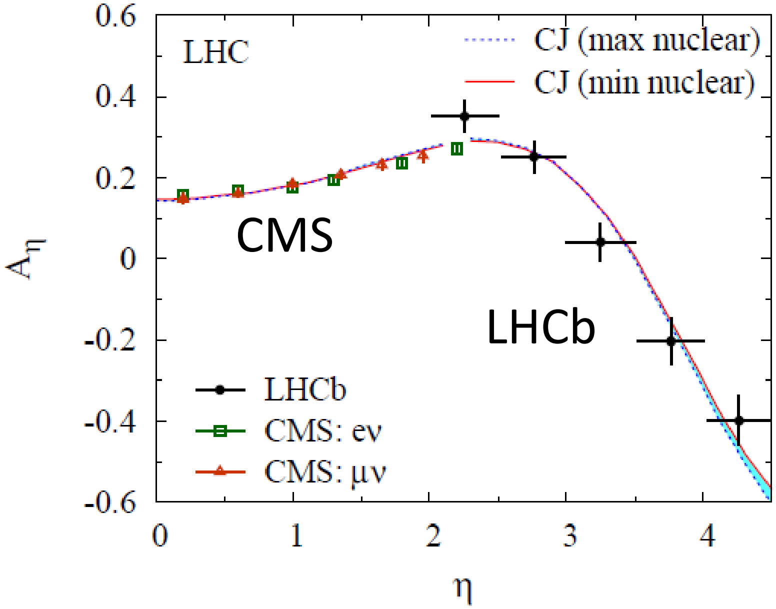
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

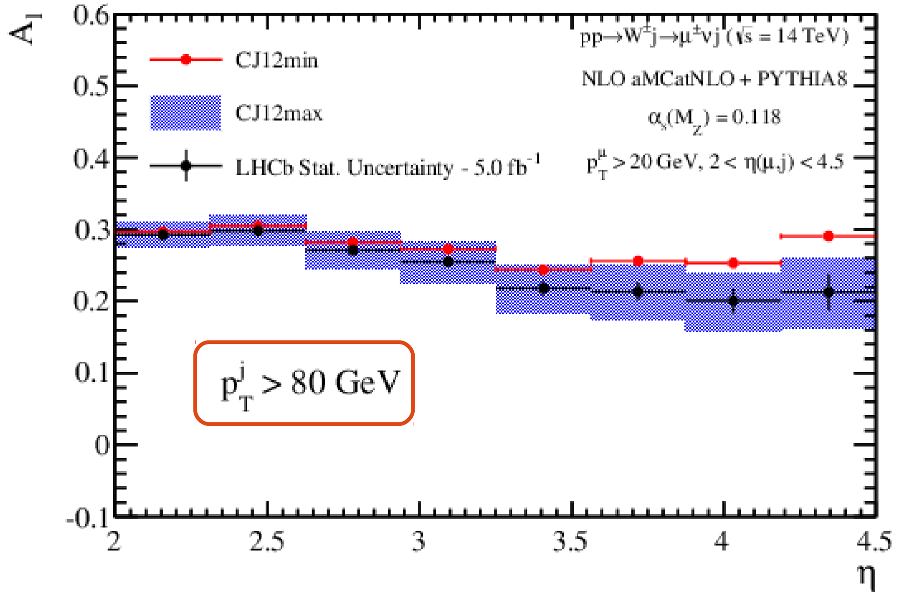
- smearing in *x*

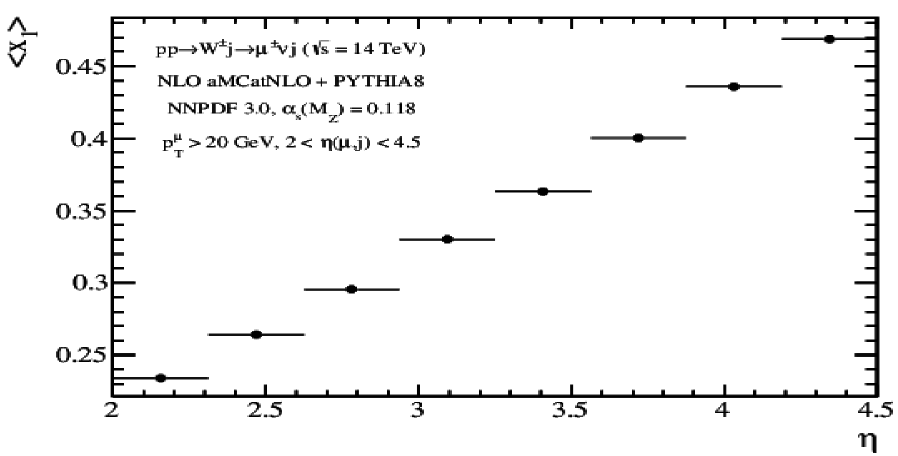


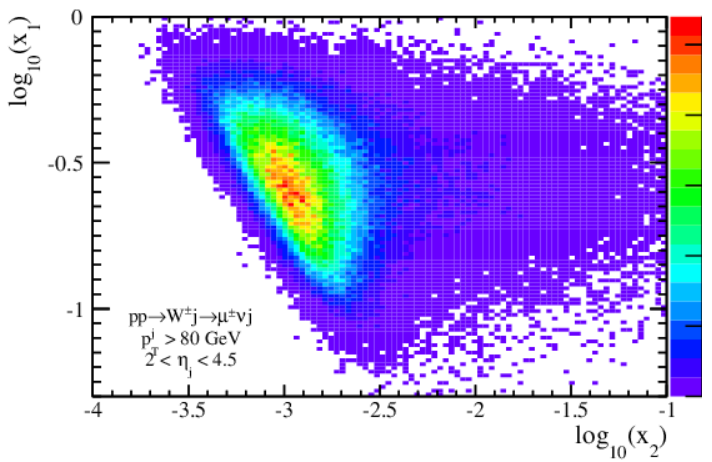
- **Would be nice to reconstruct *W* at**
  - **LHCb –** But I am told "too many holes"...
  - **RHIC –** how high in rapidity?
  - **AFTER@LHC ??**

W+*c* at LHCb

Farry and Gauld, PRD 93 (2016) 014008

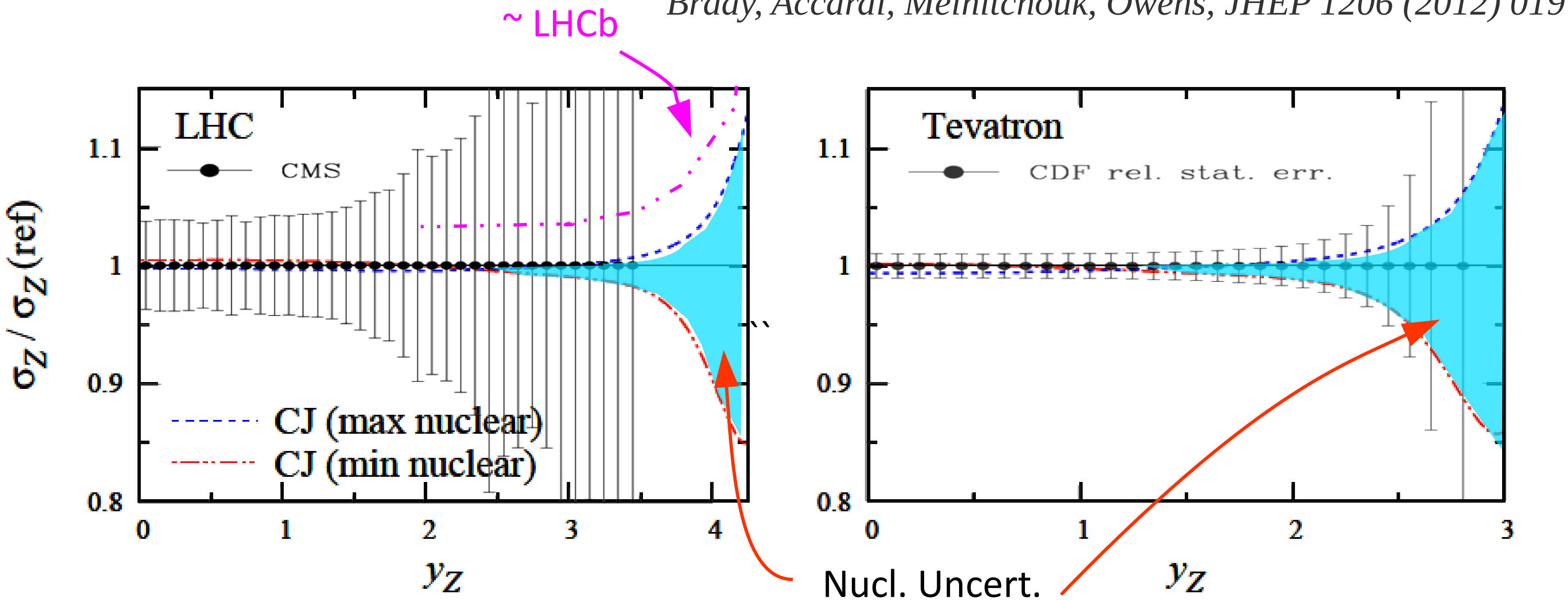






Z rapidity distribution

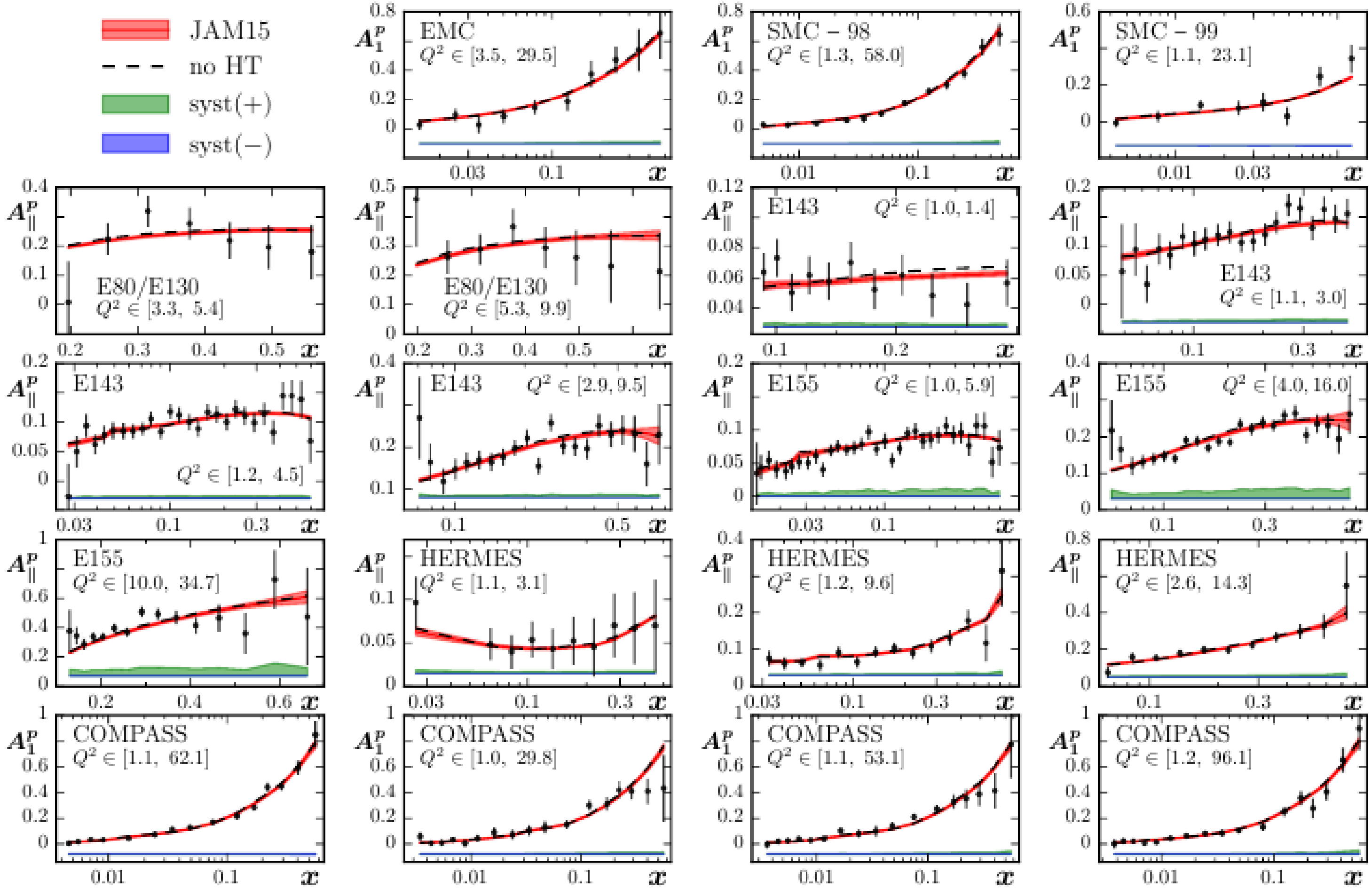
Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019



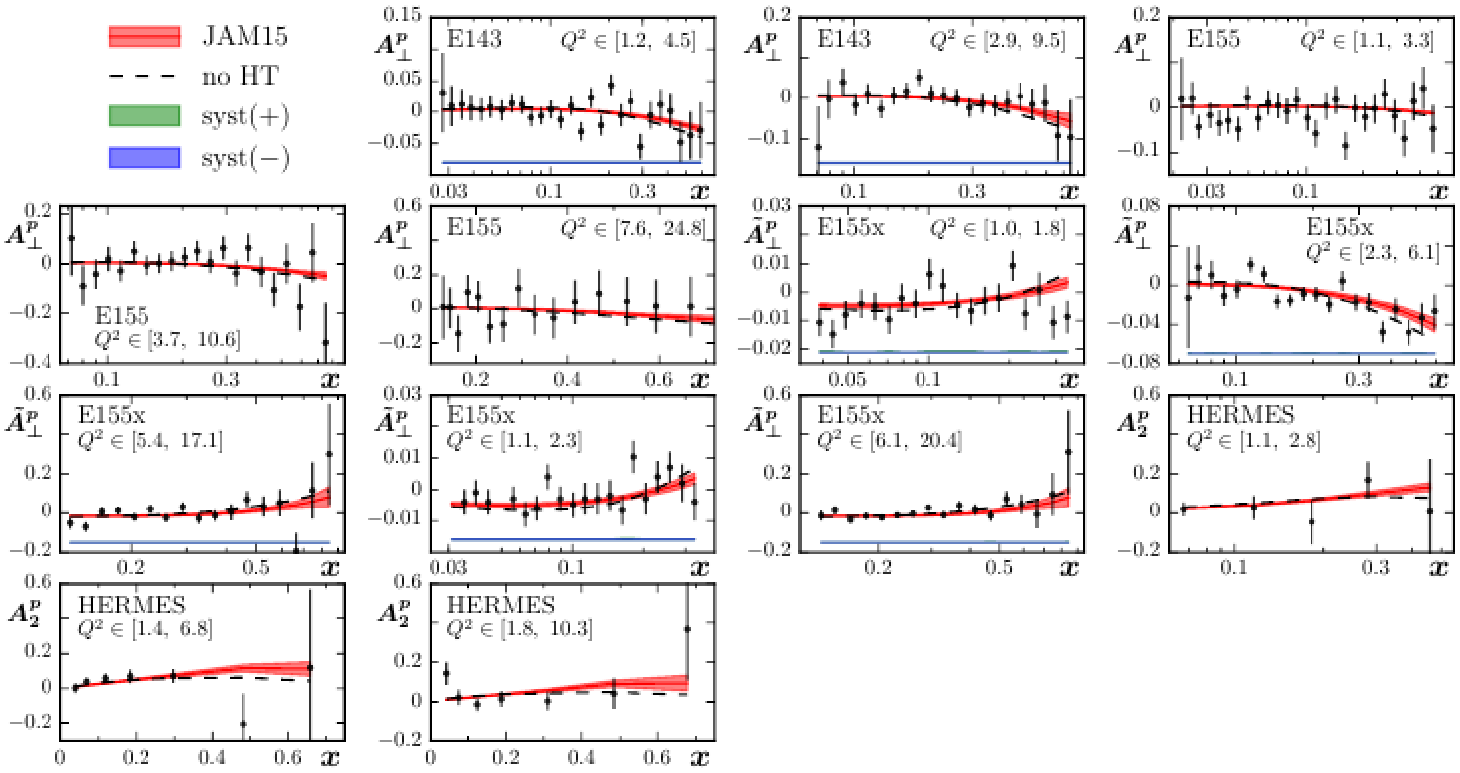
- Direct Z reconstruction is unambiguous in principle, but:
  - **Needs better than 5-10% precision at large rapidity**
  - Experimentally achievable?
    - At LHCb? RHIC? AFTER@LHC?
    - Was full data set used at Tevatron?

Appendix:
JAM15 polarized PDF

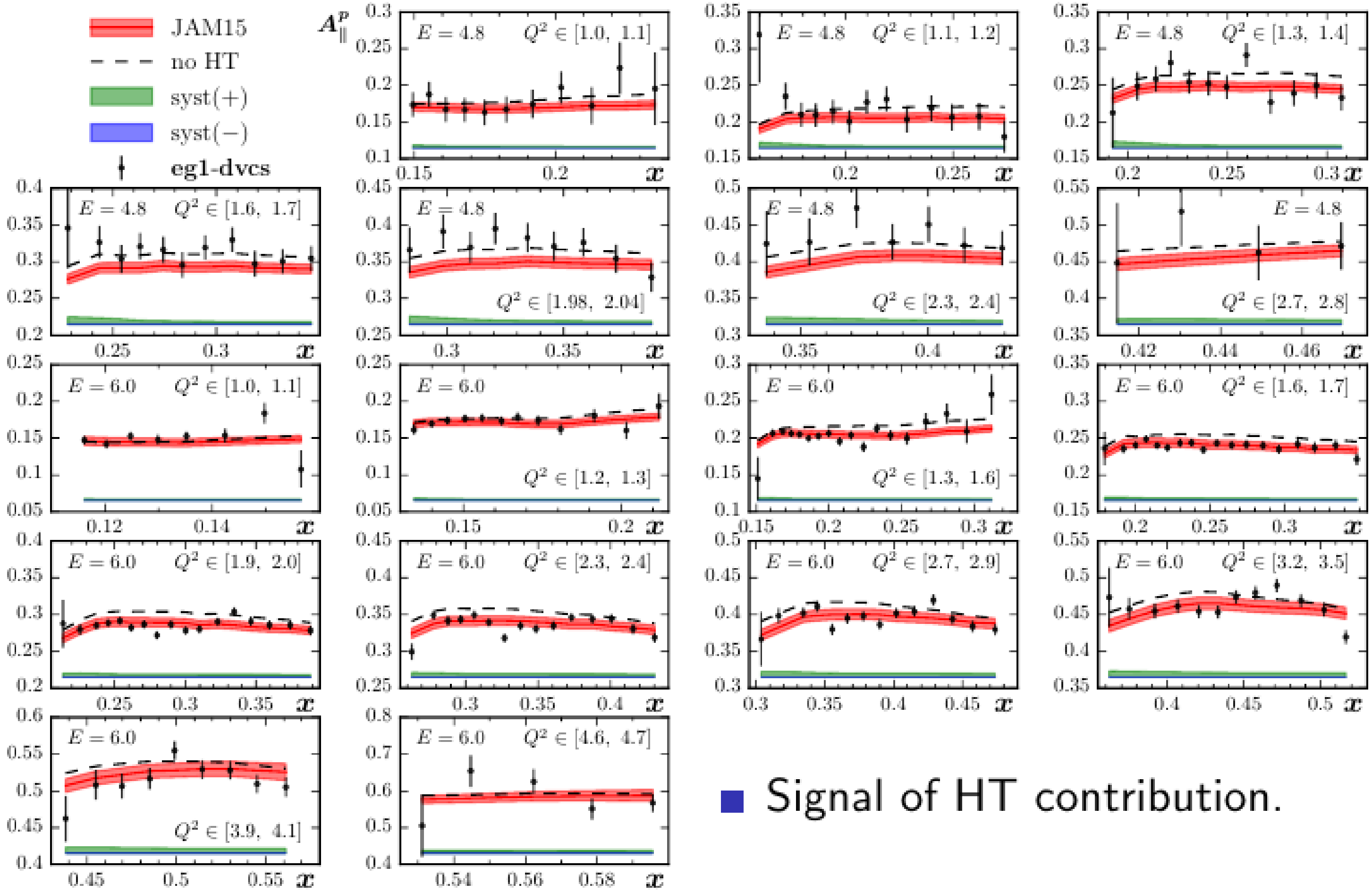
Data vs. theory: proton



Data vs. theory: proton

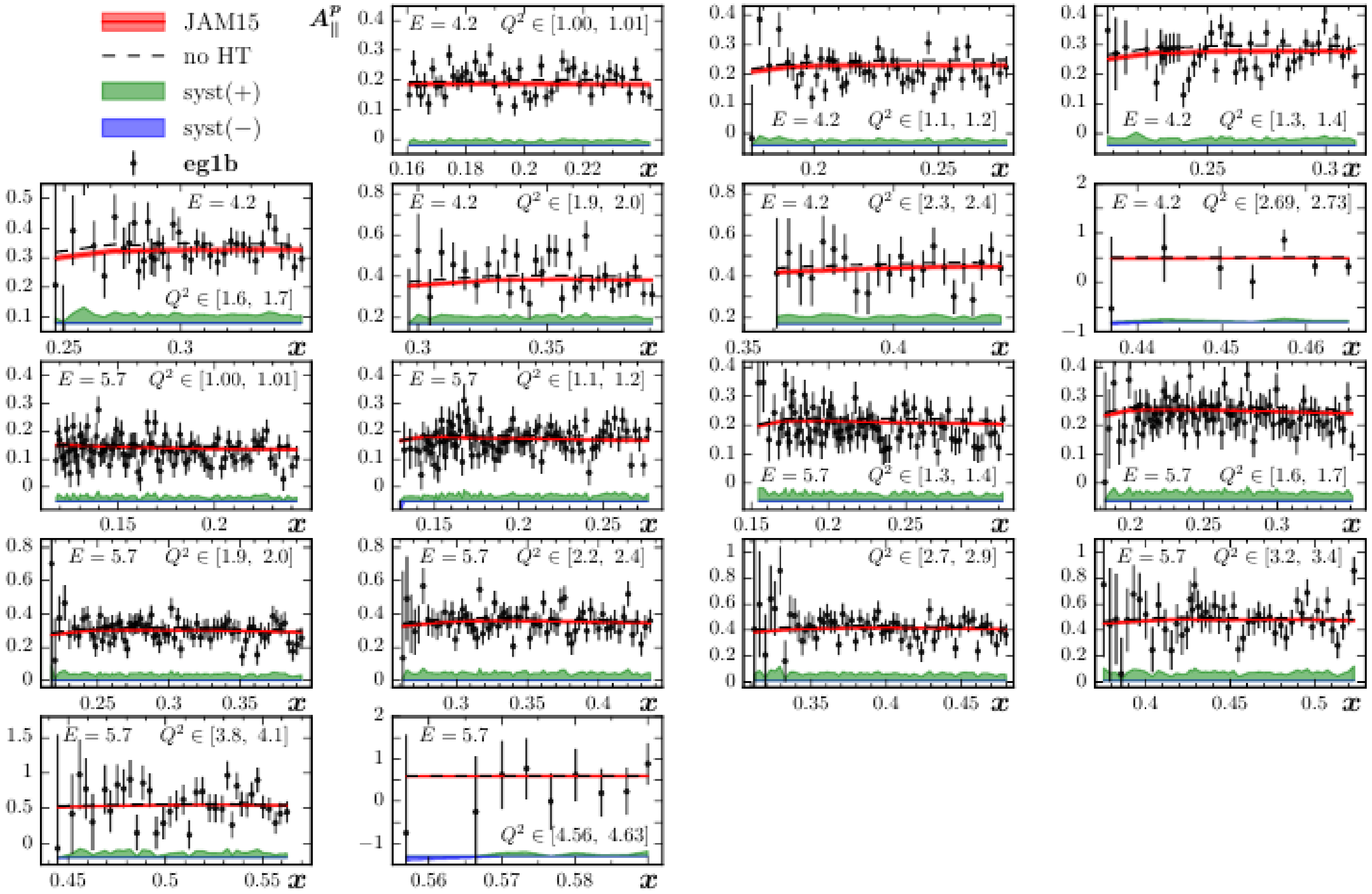


Data vs. theory: proton EG1b-DVCS

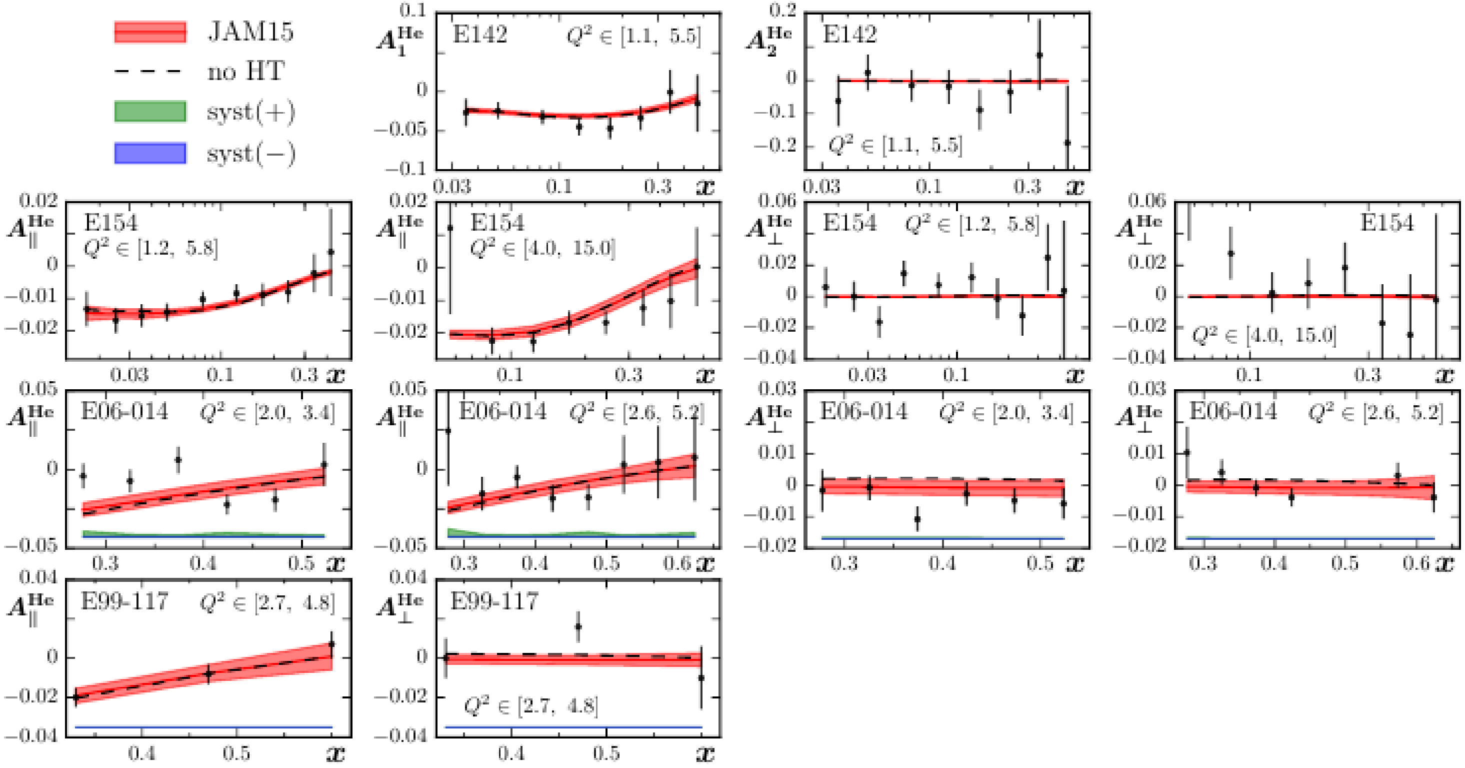


- Signal of HT contribution.

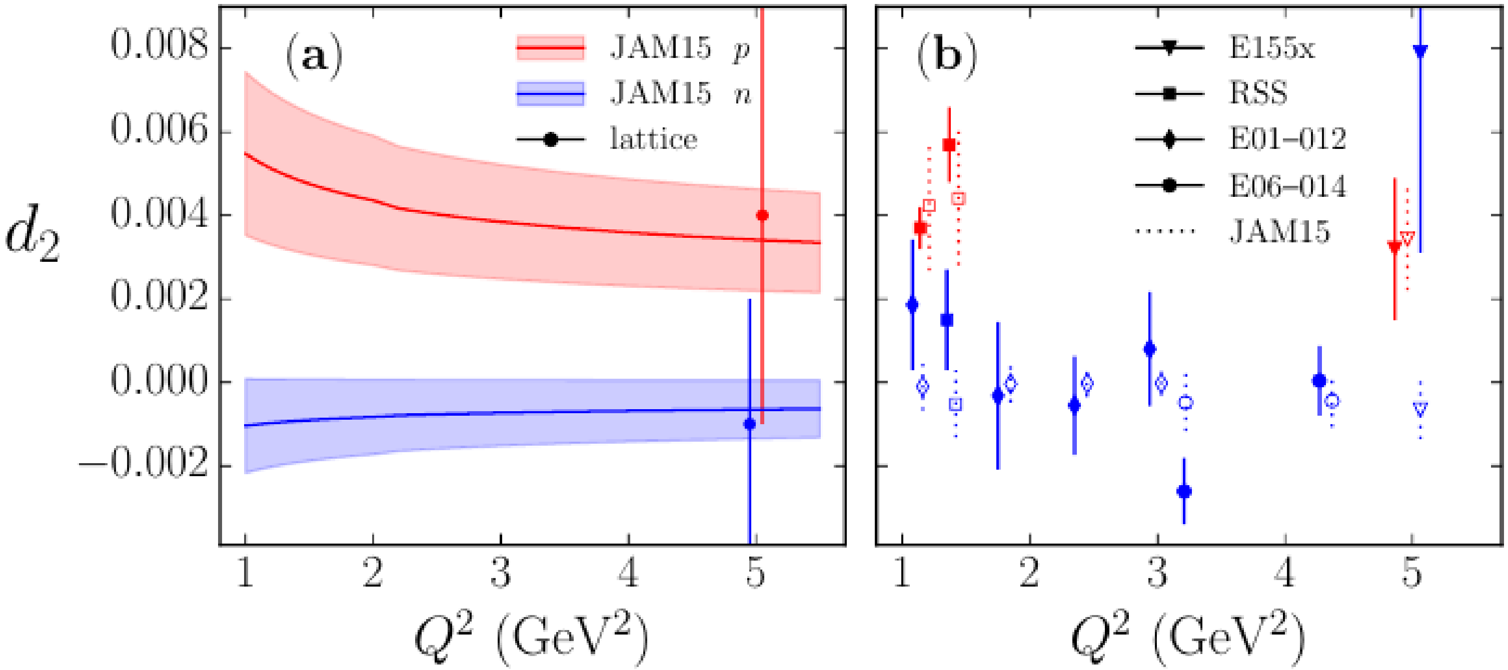
Data vs. theory: proton EG1b



Data vs. theory: 3He



d_2 matrix element

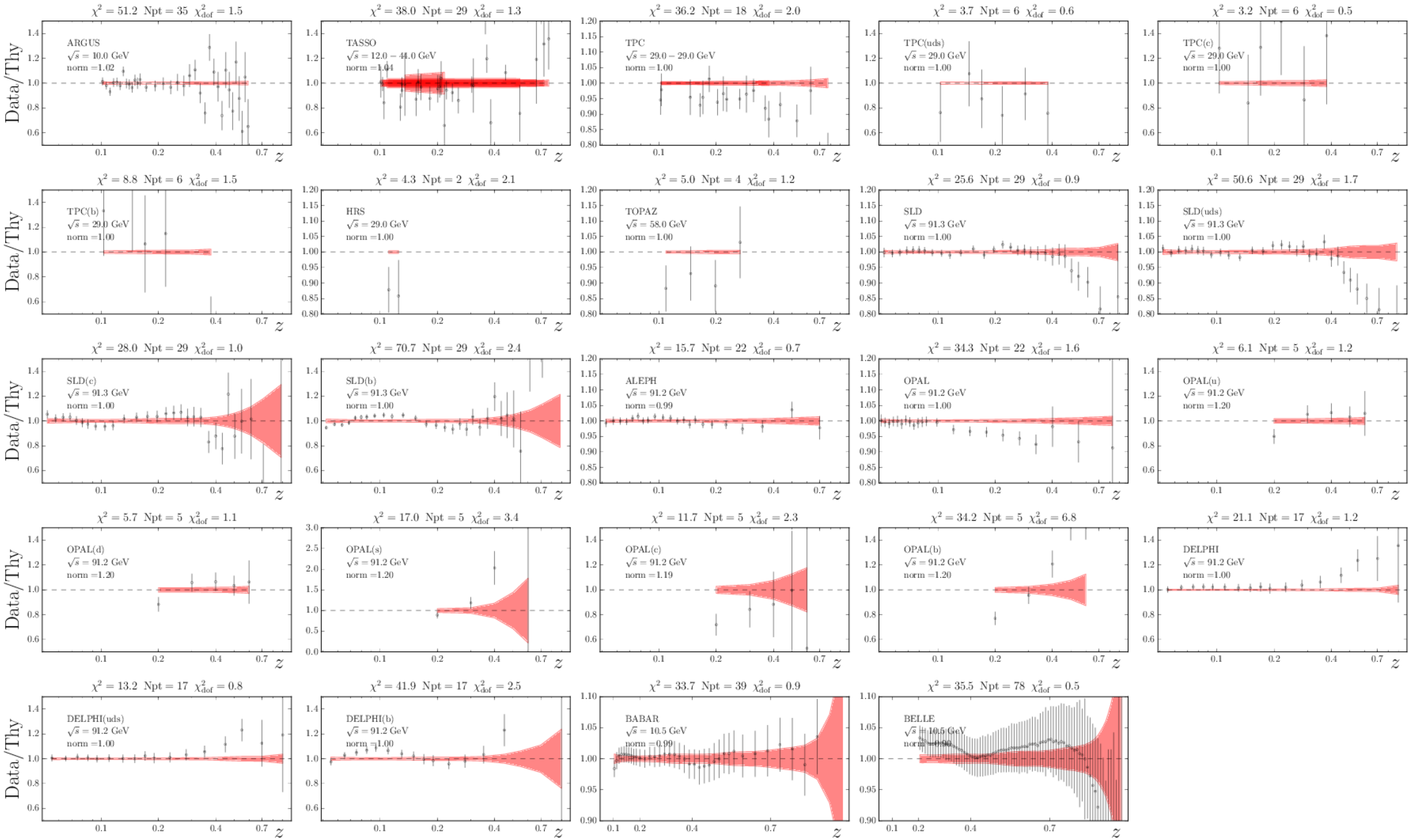


- $d_2(Q^2) \equiv \int_0^1 dx x^2 \left[2g_1^{\rm T3}(x,Q^2) + 3g_2^{\rm T3}(x,Q^2)\right]$
- d_2 is related to "color polarizability" or the "transverse color force" acting on quarks.
- Existing measurements of d_2 are in the resonance region (contains TMC T4 and beyond.)
- Agreement with data indicates quark-hadron duality

Appendix:
preliminary JAM FFs

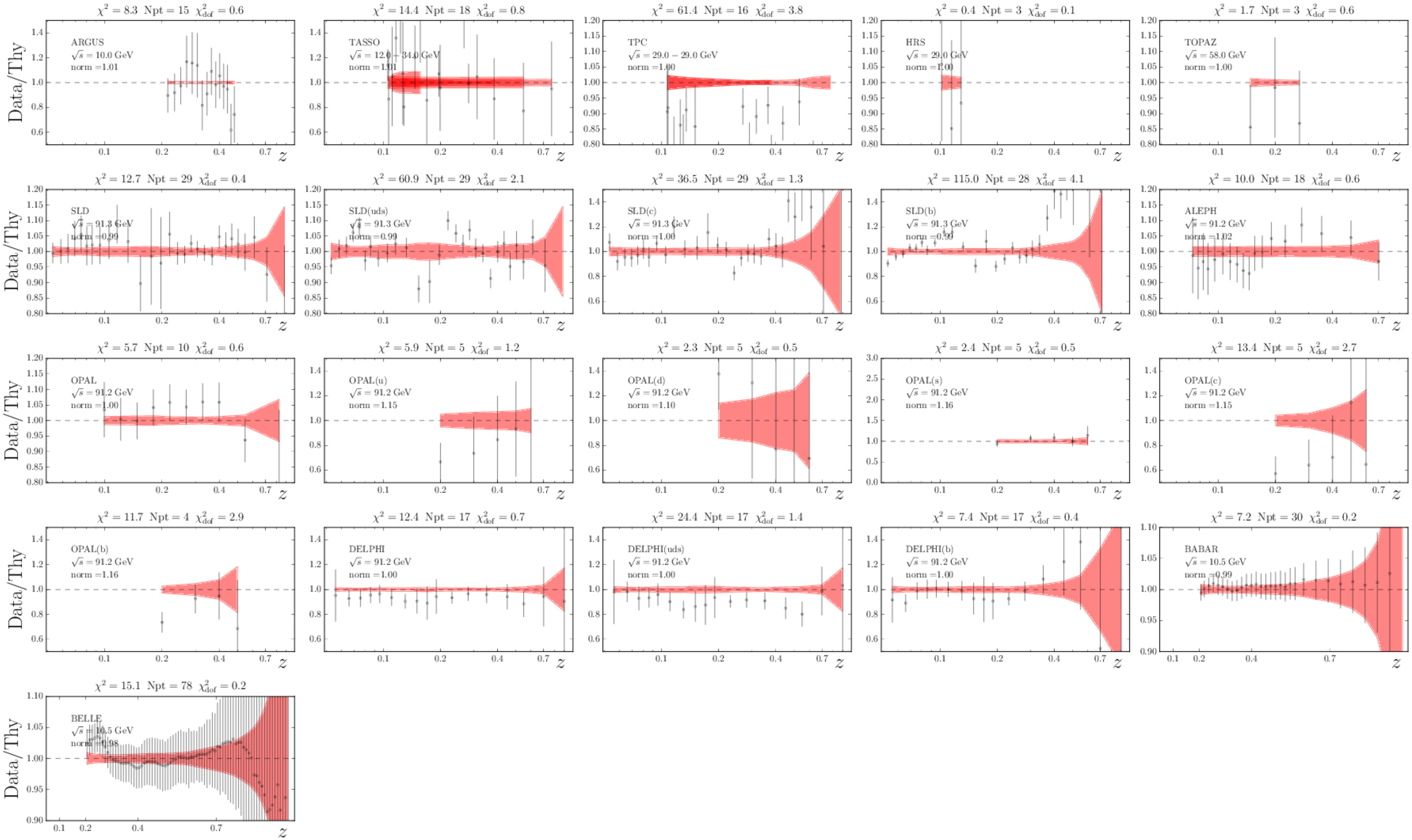
Pion fit vs. data

Sato, Ethier, Melnitchouk, Accardi – in progress



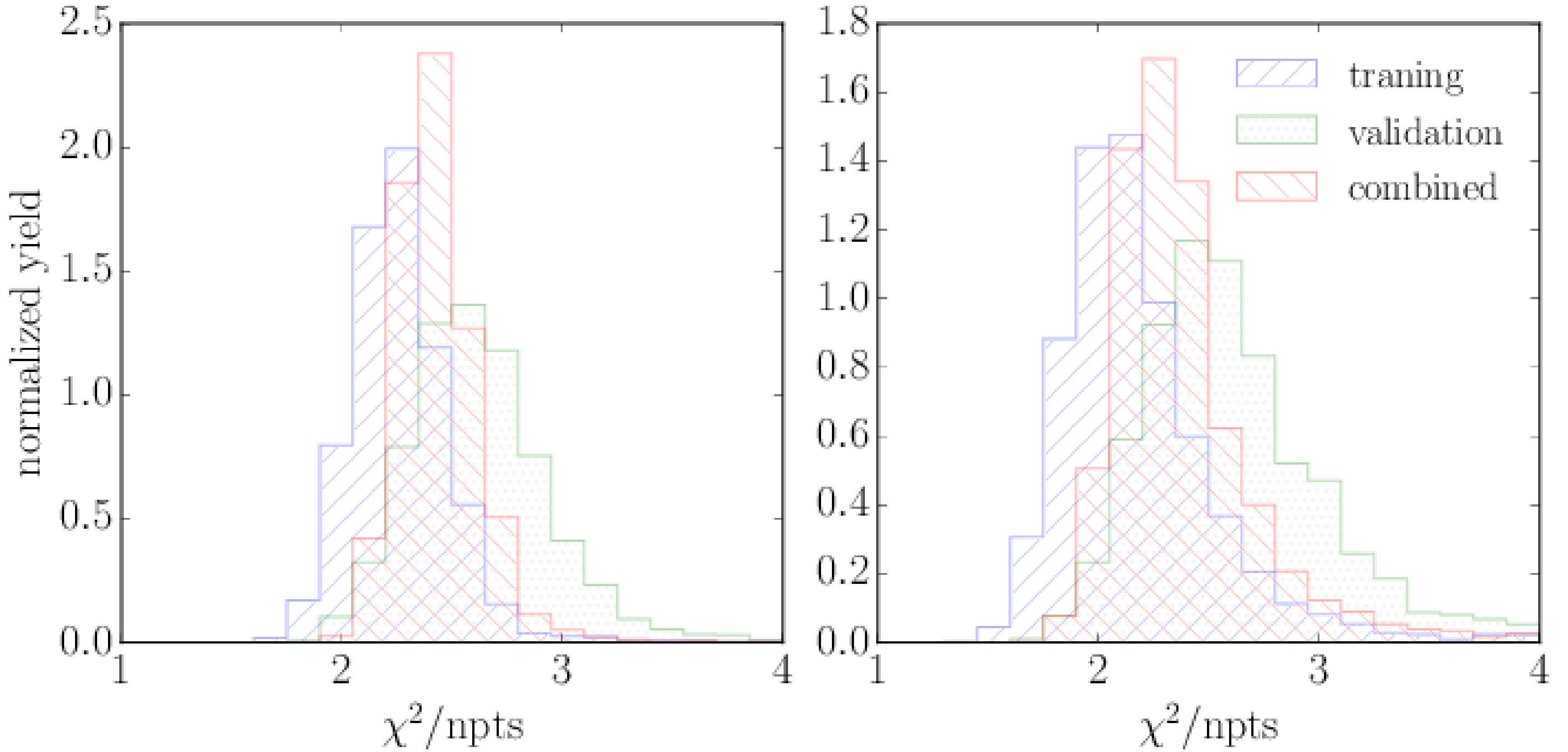
Kaon fit vs. data

Sato, Ethier, Melnitchouk, Accardi – in progress



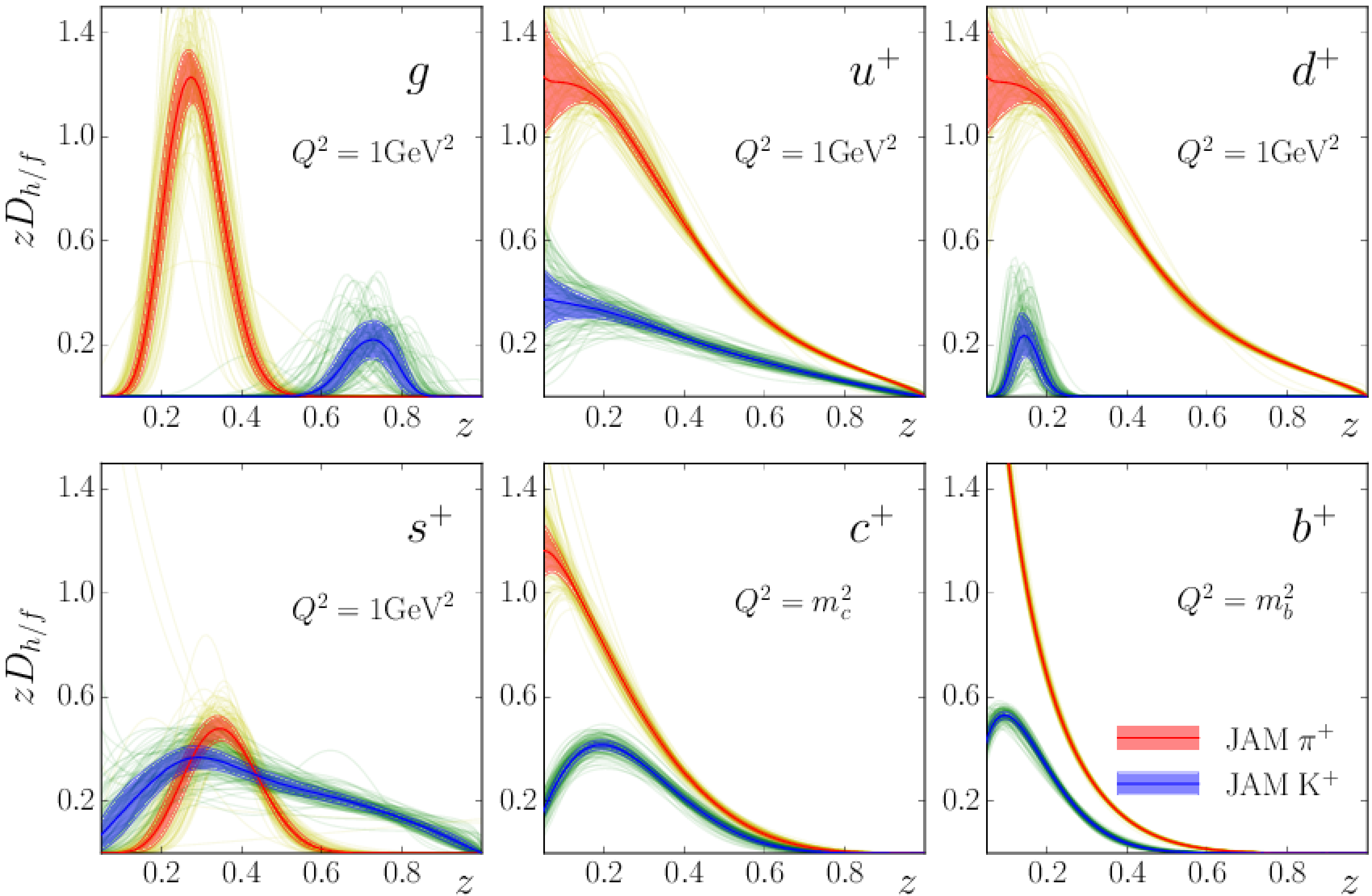
Chi^2 distribution (pions)

Sato, Ethier, Melnitchouk, Accardi – in progress



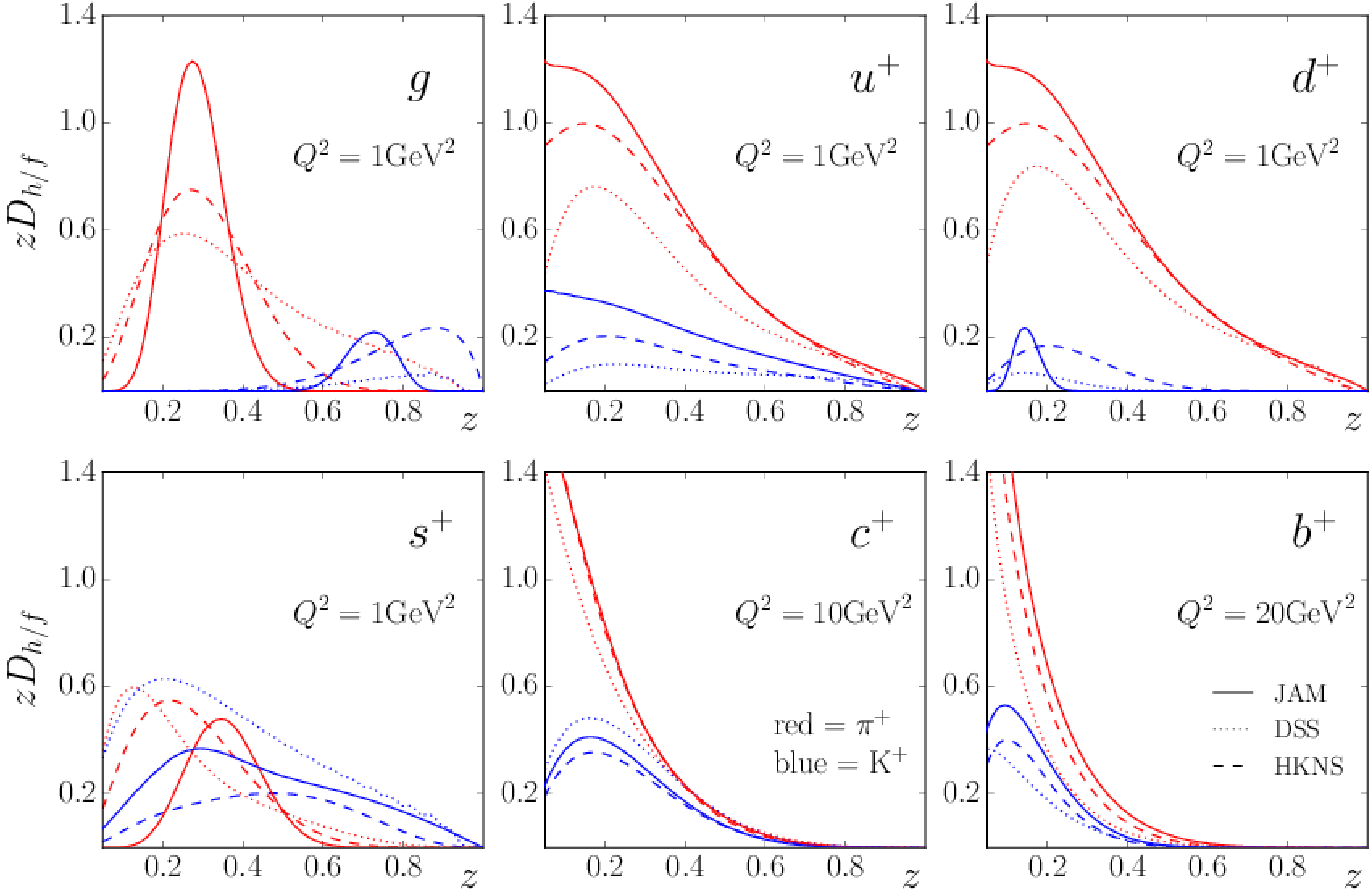
Pions vs. Kaons

Sato, Ethier, Melnitchouk, Accardi – in progress



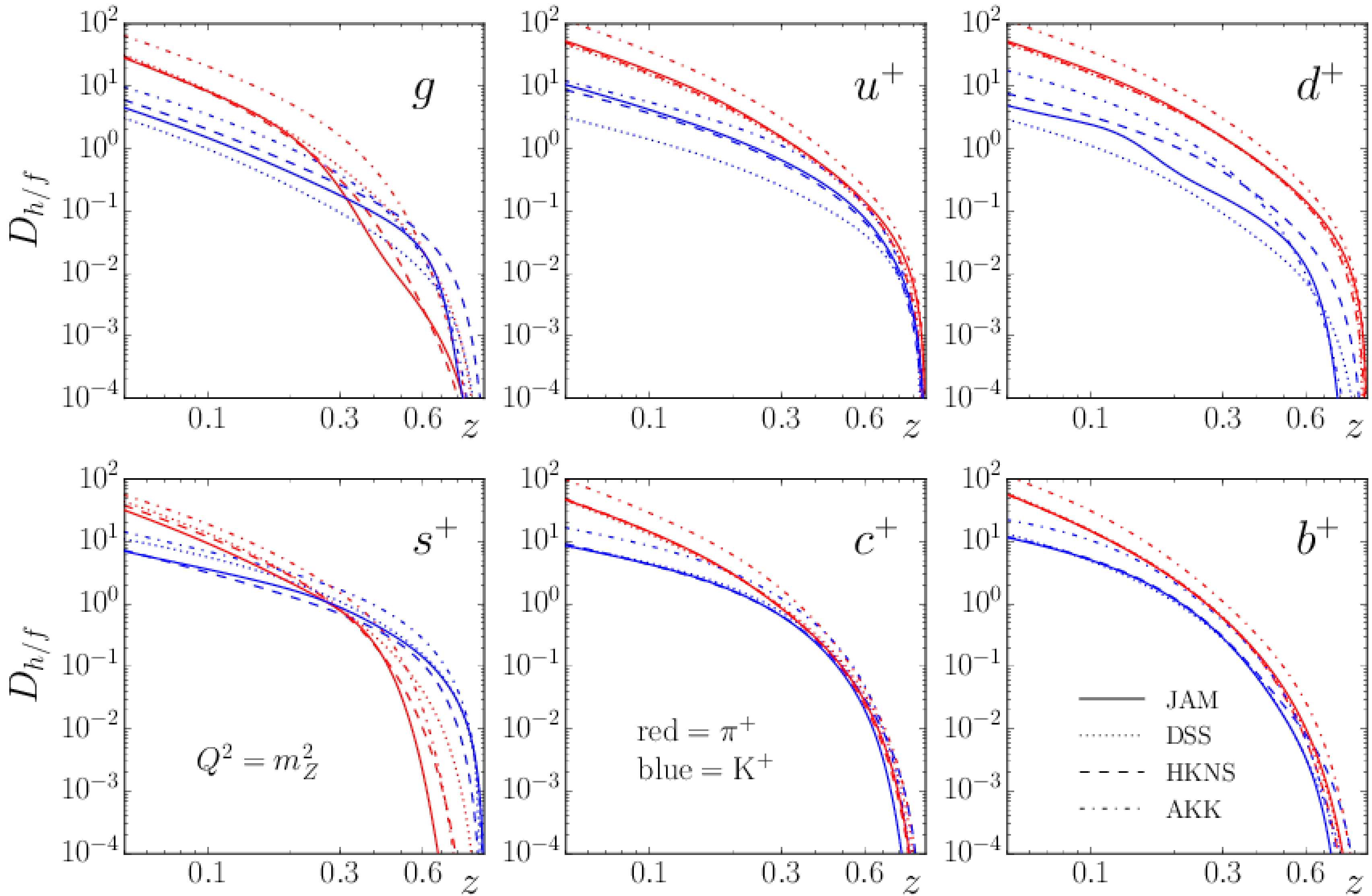
JAM-FF vs. others

Sato, Ethier, Melnitchouk, Accardi – in progress



JAM-FF vs. others

Sato, Ethier, Melnitchouk, Accardi – in progress

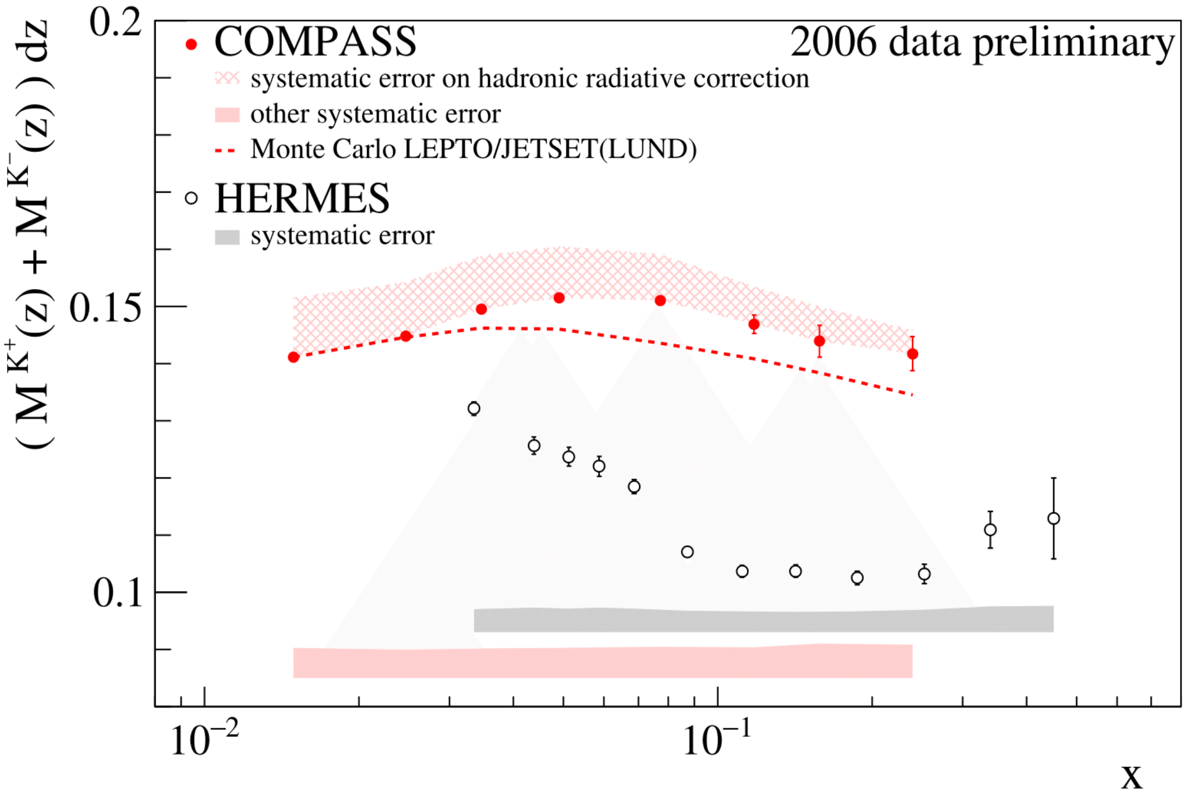


Appendix:
Hadron Mass Corrections,
HERMES vs. COMPASS

J.Guerrero, J.Ethier, AA, S.Casper, W.Melnitchouk, JHEP 1509 (2015) 169

J. Guerrero, A.Accardi, work in progress

In brief…



$$M^K_{\rm exp}(x_B, Q^2) = \frac{\int_{0.2}^{0.8\,(0.85)} \frac{dN^K}{dx_B\, dQ^2\, dz_h}}{\frac{dN^{DIS}}{dx_B\, dQ^2}}$$

Strange quark “tagging”

Hadron Mass corrections in brief

With a massive target nucleon, and massive hadron in final state:

- Respecting partonic 4-momentum conservation also requires a "massive" fragmenting parton with $\widetilde{k}'^2 \geq m_h^2/\zeta_h$.
- x_B and z_h mixed in the new scaling variables ξ_h and ζ_h

Parton model:

(ignoring mass effects)

$$M^{K(0)}(x_B, Q^2) = \frac{\sum_q e_q^2\, q(x_B, Q^2) \int dz_h\, D_q^h(z_h, Q^2)}{\sum_q e_q^2\, q(x_B, Q^2)}$$

With HMCs:

$$M^K(x_B, Q^2) = \frac{\int dz_h \sum_q e_q^2\, q(\xi_h, Q^2)\, D_q^h(\zeta_h, Q^2)}{\sum_q e_q^2\, q(\xi, Q^2)}$$

$$\xi_h = \frac{2x_B}{1+\sqrt{1+4x_B^2 M^2/Q^2}}\left(1+\frac{m_h^2}{\zeta_h Q^2}\right)$$

$$\zeta_h = \frac{z_h}{2}\frac{\xi}{x_B}\left(1+\sqrt{1-\frac{4x_B^2 M^2 m_{h\perp}^2}{z_h^2\, Q^4}}\right)$$

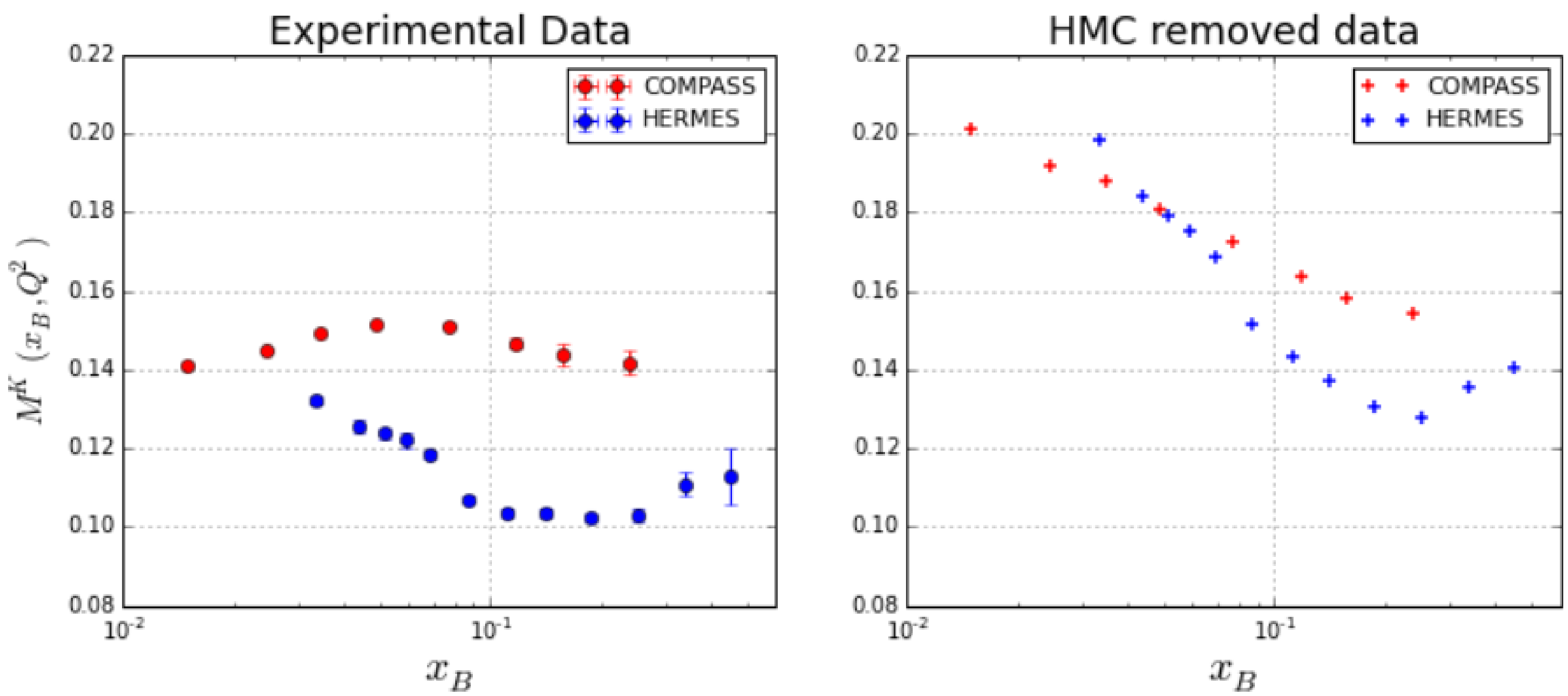
$$Q(x) \equiv u(x) + \overline{u}(x) + d(x) + \overline{d}(x)$$

$$S(x) \equiv s(x) + \overline{s}(x)$$

$$\mathcal{D}_Q^K(z) \equiv 4D_u^K(z) + D_d^K(z)$$

$$\mathcal{D}_s^K(z) \equiv 2D_s^K(z)$$

COMPASS vs. HERMES



"Remove" HMCs

$$M_{\rm exp}^{K(0)} \equiv M_{\rm exp}^{K} \frac{M^{K(0)}}{M^{K}}\Big|_{\rm theory}$$

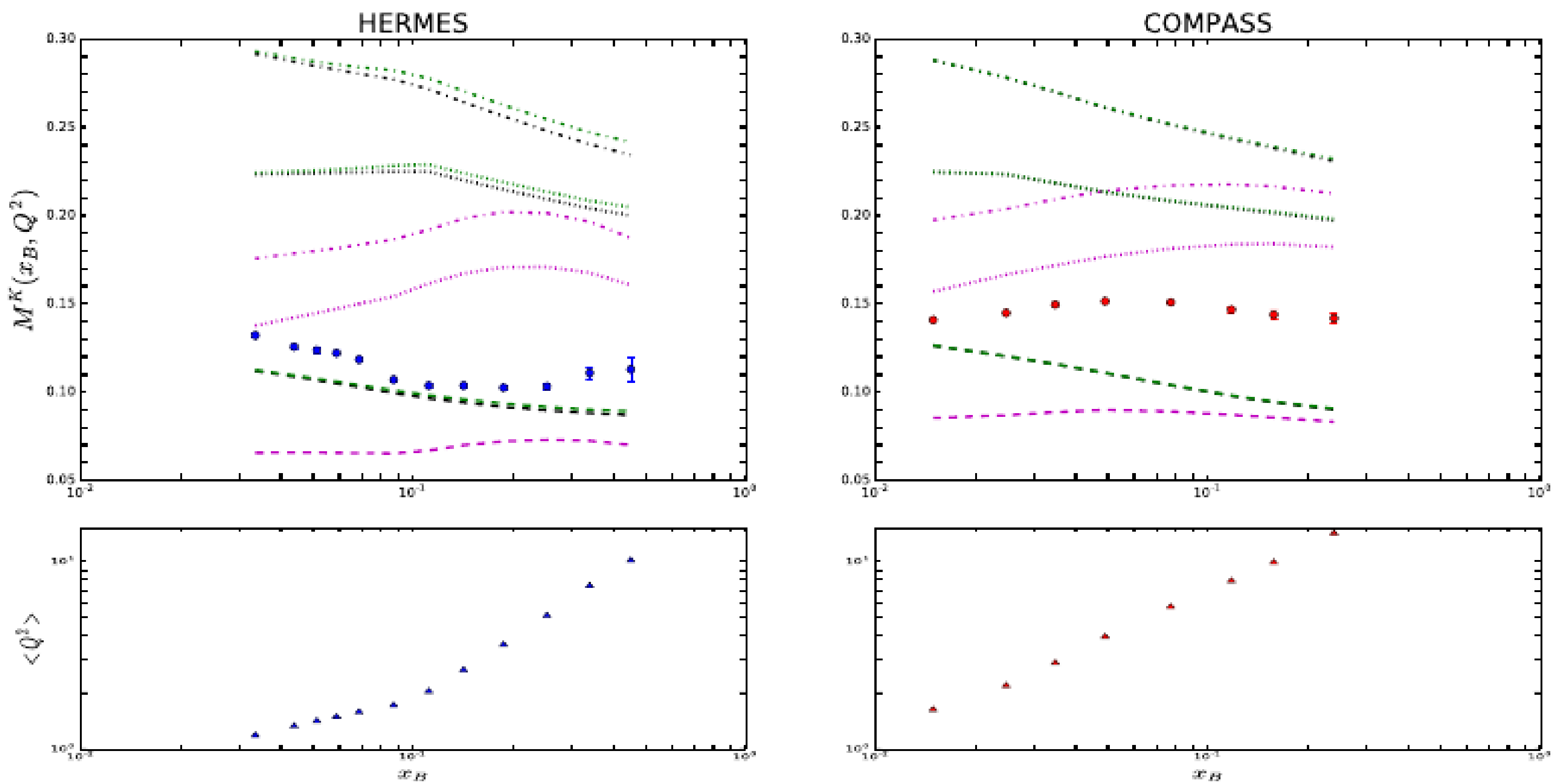
With massless hadrons

With HMC

→ **data become directly comparable to parton model**

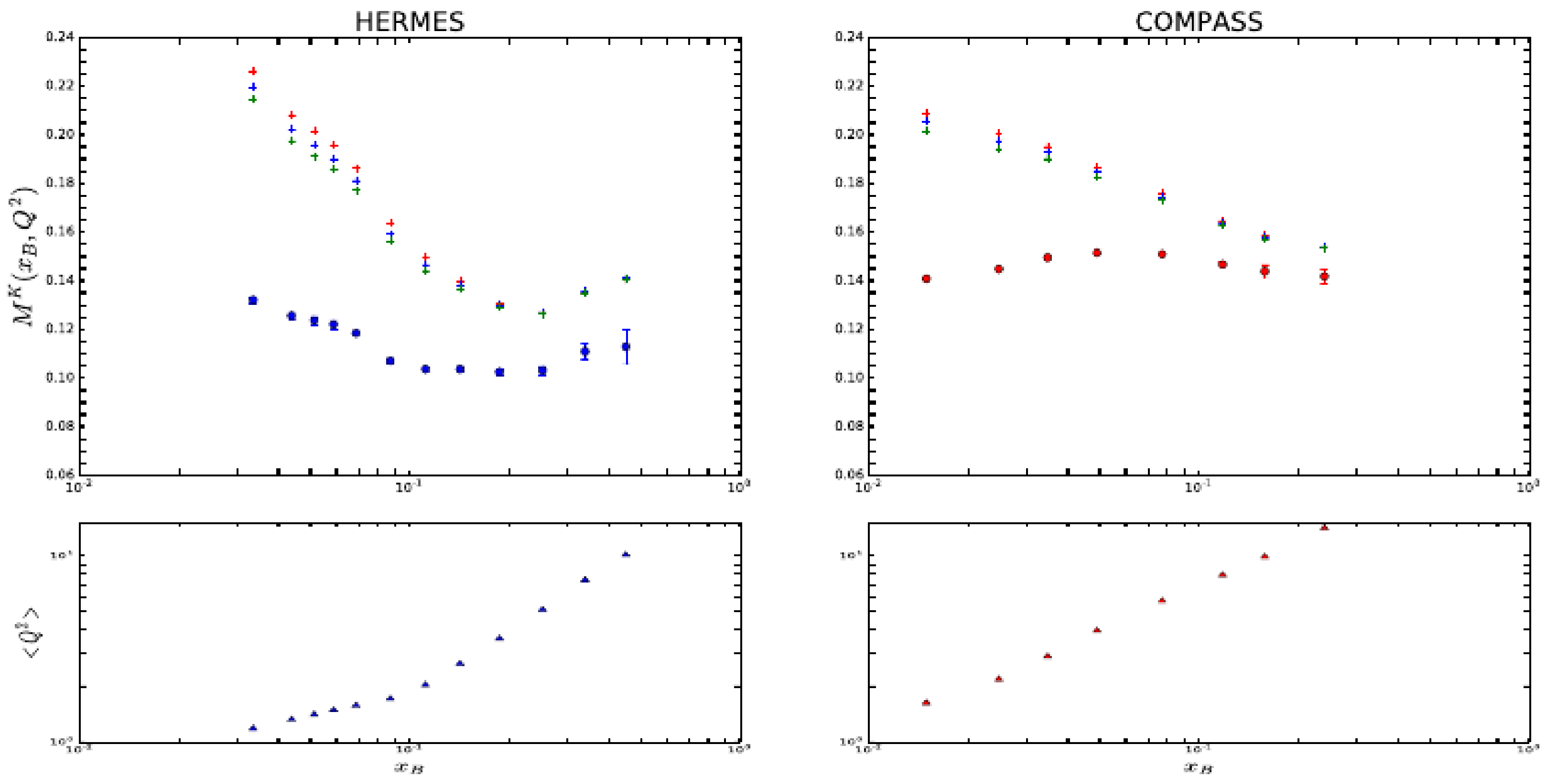
Fragmentation function systematics

- PDF: CTEQ14
- FFs: DSS (dashed lines), HKNS(dashed-dotted lines), KKP(dotted lines)
- Data (dots) vs. Theory (Bjorken limit, Albino prescription, Our prescription)



Fragmentation function systematics

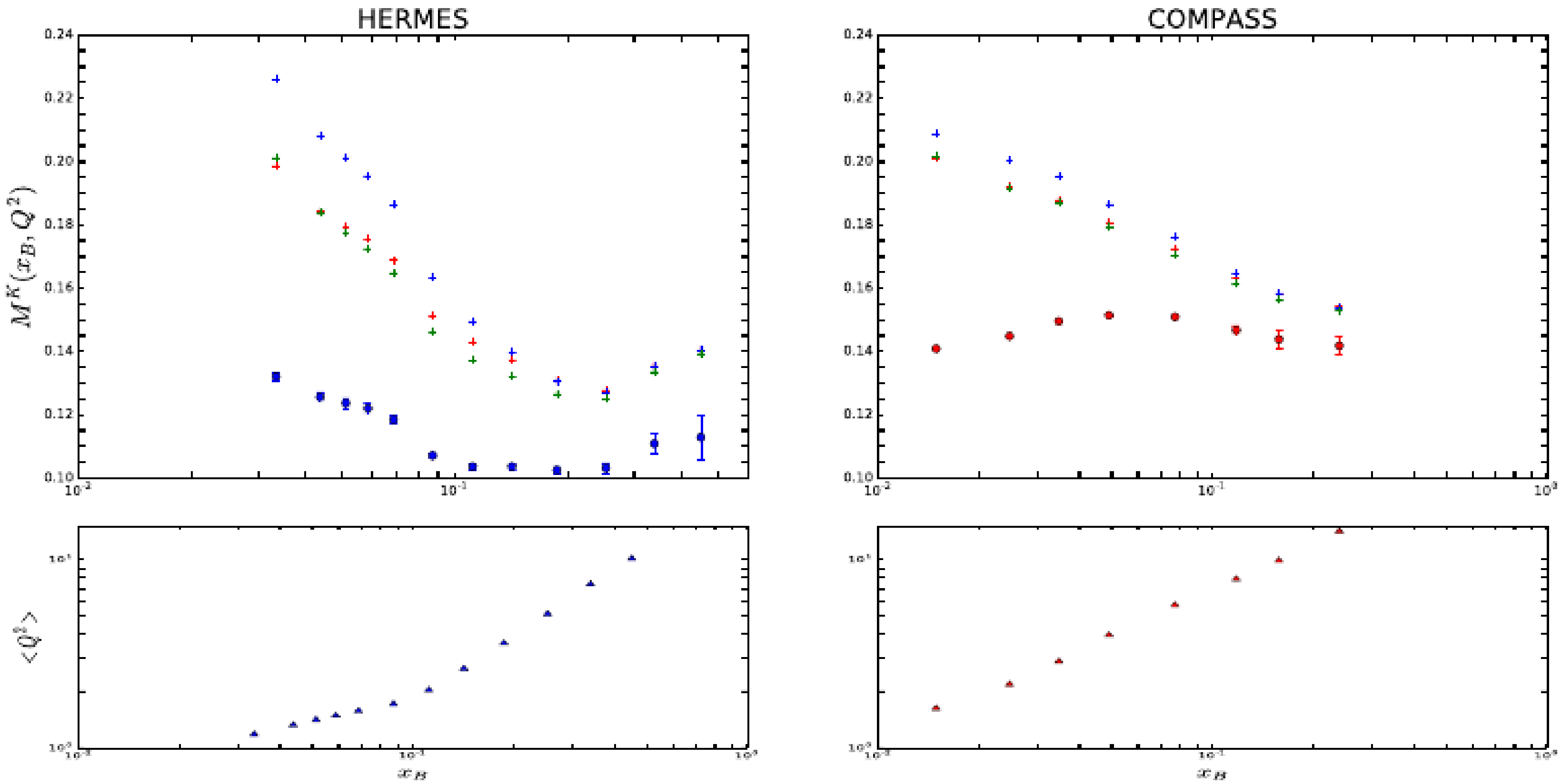
- Parton Level Multiplicities: $M^{K(0)}_{exp} = M^{k}_{exp} \left. \frac{M^{K(0)}}{M^{K}} \right|_{Theory}$
- Exp. Data (dots) vs. "Partonic" Data (Cross) (DSS, KKP, HKNS)



HMCs "removed" data stable

Fragmentation function systematics

- Parton Level Multiplicities: $M^{K(0)}_{exp} = M^{k}_{exp} \frac{M^{K(0)}}{M^{K}}\Big|_{Theory}$
- Exp. Data (dots) vs. "Partonic" Data (Cross) (CT6L, CT14, GJR08)



COMPASS vs. HERMES

Experimental Data

HMC removed data

HMC effects for kaons may be very large, obscure parton dynamics (at first sight)

HERMES & COMPASS in rough agreement when HMCs taken into account

(still, what about HERMES L-shaped result, that persists also in pion data?)

→ **data become directly comparable to parton model**