CTEQ-JLab global QCD analysis

Alberto Accardi

Hampton U. and Jefferson Lab

CTEQ-Jefferson Lab Collaboration

HiX 2019

Kolympari, Crete, Aug 18th, 2019

HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

Jefferson Lab

Overview

- **The CJ15 global QCD analysis**
- **d/u and off-shell corrections at large x**
- **F2 neutron extraction**
  - Non-singlet p-n moment
- **Systematics of off-shell and d/u extraction**
- **Summary and the future**

REFERENCES:

* Accardi, **PoS DIS2015 (2015) 001** – "PDFs from protons to nuclei"

* Accardi et al, **PRD 93 (2016) 114017** – the CJ15 global fit

The CJ15 global QCD analysis

Global QCD analysis

data

- DIS: p, d
- p+p(pbar) $\rightarrow l^+l^-$, $W^\pm$, Z
- p+p(pbar) $\rightarrow$ jets, γ+jet

theory

- pQCD at NLO
- Factorization & universality
- Large-x, low-Q^2, **nuclear corr.**

fit

- Parametrize PDF at Q_0, evolve to Q
- Minimize χ^2

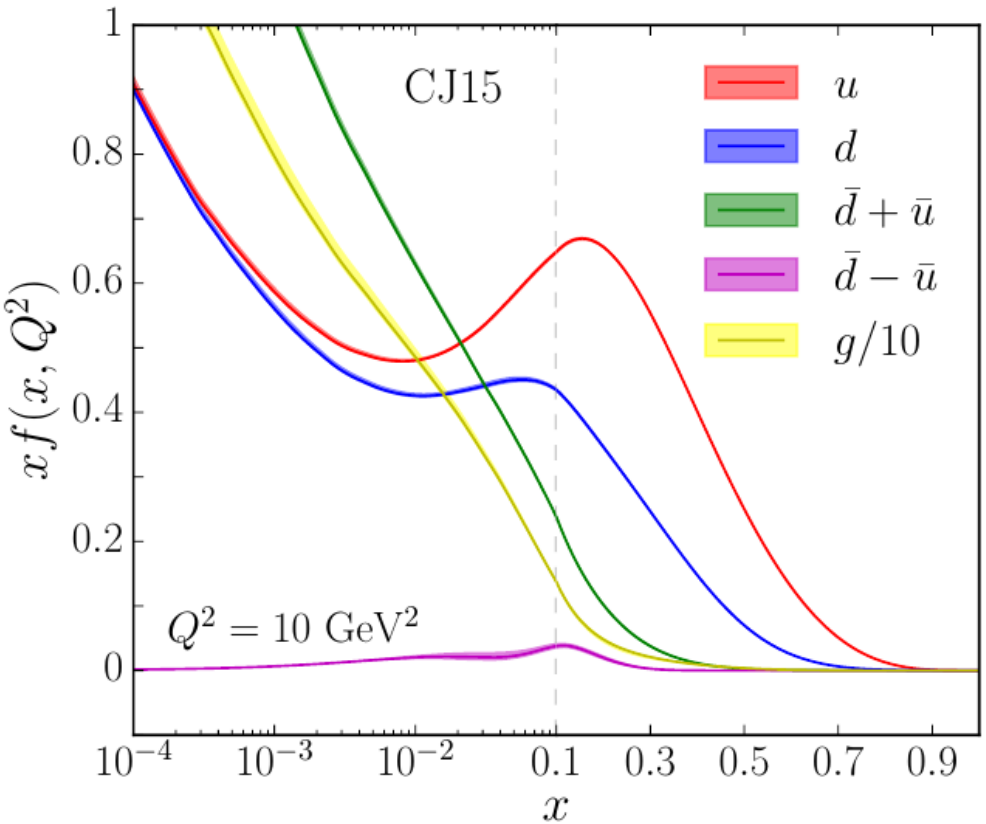
PDFs

F_2(n)
W',Z', Higgs / any hard obs.
Nuclear dynamics

The CTEQ-JLab global analysis

- **Collaborators:**
  - **Theory:** A.Accardi, I.Fernando, W.Melnitchouk, J.Owens, N.Sato
  - **Experiment:** C.Keppel, Shujie Li, 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**
  - **Accardi, Brady, Melnitchouk, Owens, Sato, PRD 93 (2016) 114017**
    - www.jlab.org/cj
    - Included in LHAPDF

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)

- Fitted with $\chi^2/\text{datum} = 1.04$
- LO fit much worse – cannot accommodate Q^2 dependence of data

35+ years of unpolarized global PDF fits

	JLab & BONUS	HER MES	HERA I+II	Tevatron W,Z	LHC	ν+A di-μ	Large-*x* treatment: Nucl. & offsh	HT TMC	Flex *d*	low-W DIS
CJ15 *	✓✓	✓	✓	✓	*in prog.*	✗	✓✓	✓	✓	✓
CT18			✓	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.1			✓		✓	✓		TMC only		
JR14	✓				✓	✓	✓	✓		
ABMP16/AKP				✓ ¤¤	✓	✓	✓/✓	✓	(✓)	✓
HERAPDF2.0			✓	¤						

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

35+ years of unpolarized global PDF fits

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MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
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JR14	✓				✓	✓	✓	✓		
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HERAPDF2.0			✓	¤						

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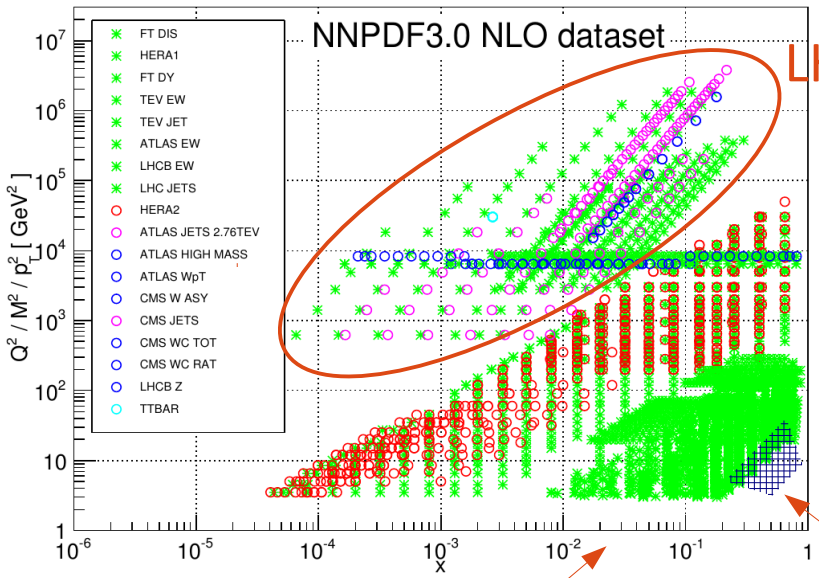
Extraction of large-x d/u and off-shell deuteron effects

Data coverage for PDF fits



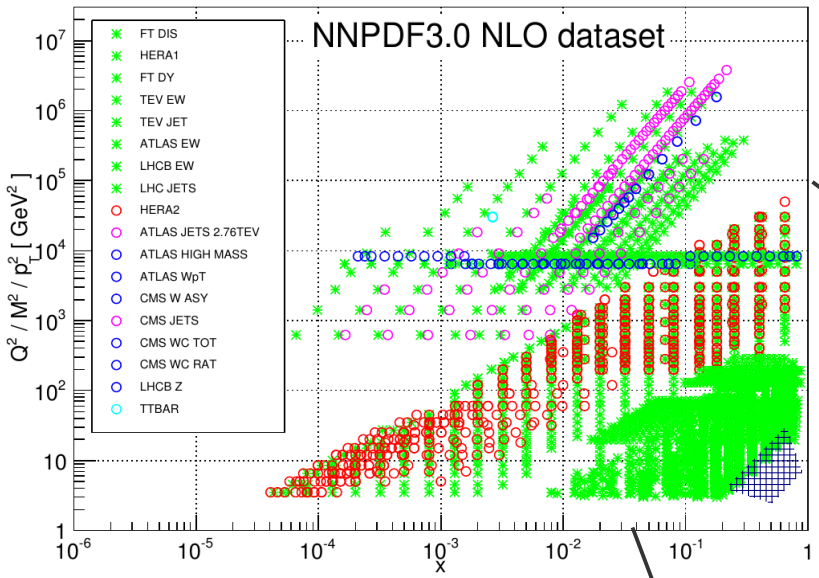
LHC data (soon to be included in CJ fits)

W and Z

SLAC, JLab

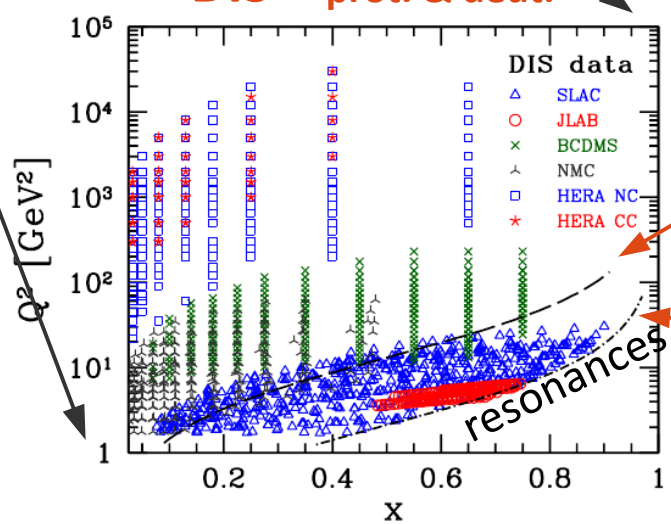
DY and DIS
(on p, d)

Data coverage for PDF fits



Large-x coverage in DIS:
mostly SLAC
Jlab limited kinematically
(but full Jlab 6 sets being investigated)

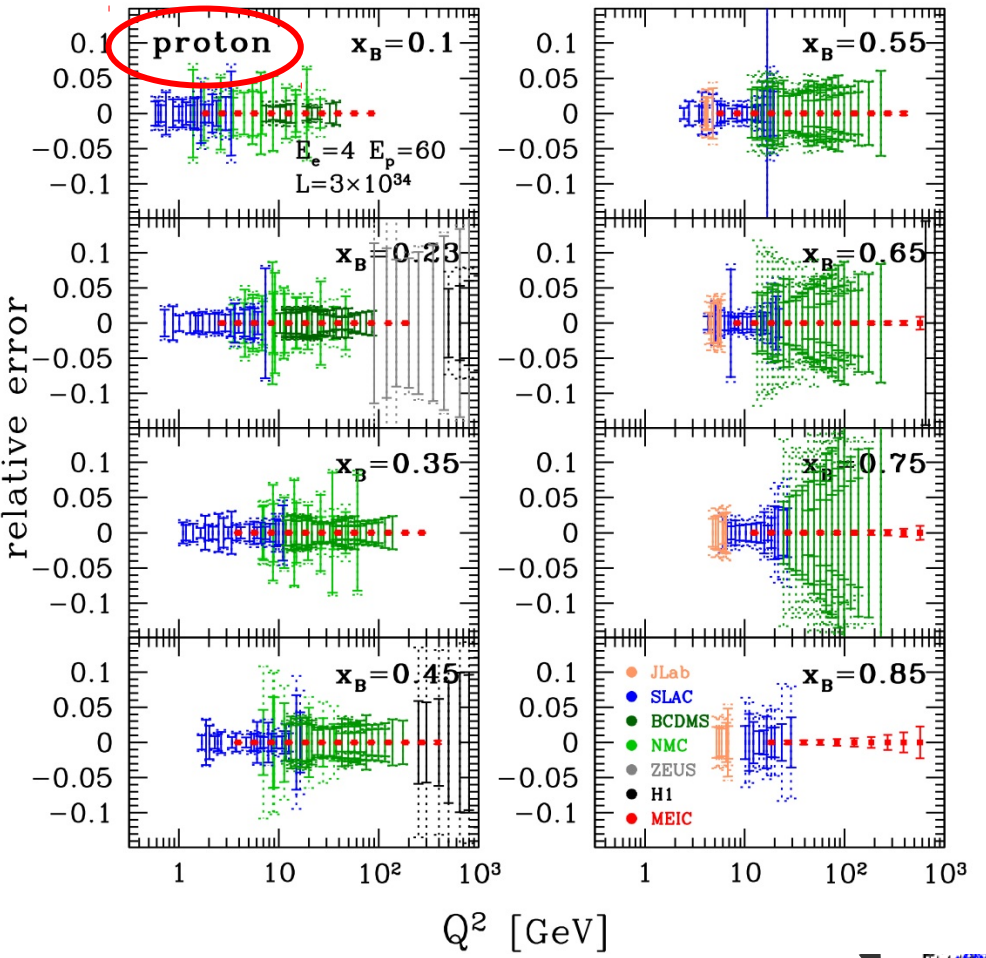
DIS – prot. & deut.



standard cut
$W^2 \gtrsim 14\ \mathrm{GeV}^2$

CJ15
$W^2 \gtrsim 3.5\ \mathrm{GeV}^2$

...and uncertainties



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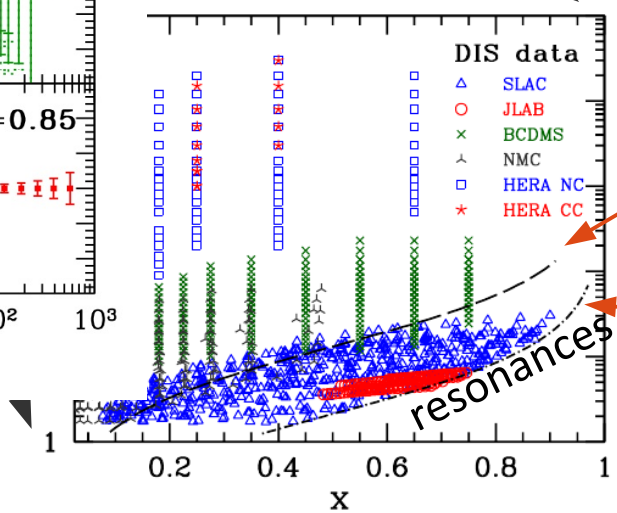

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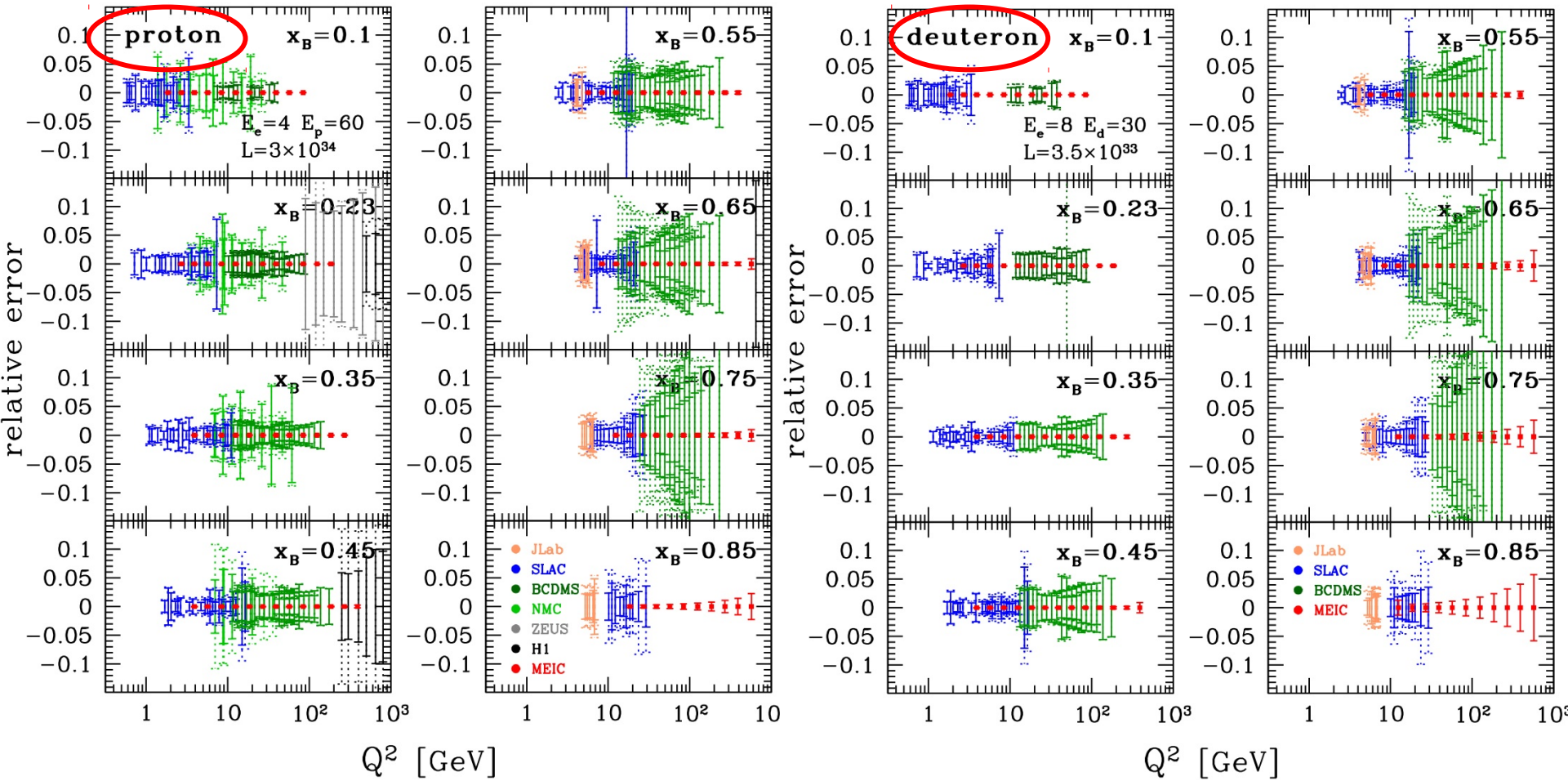
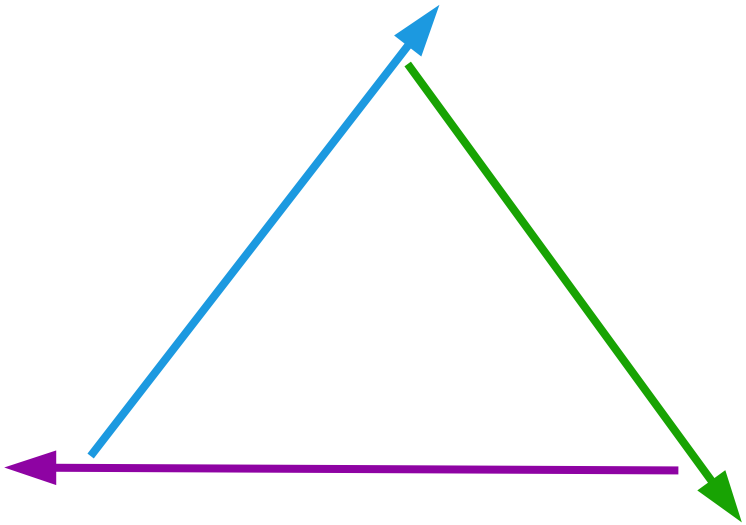


Interplay of observables



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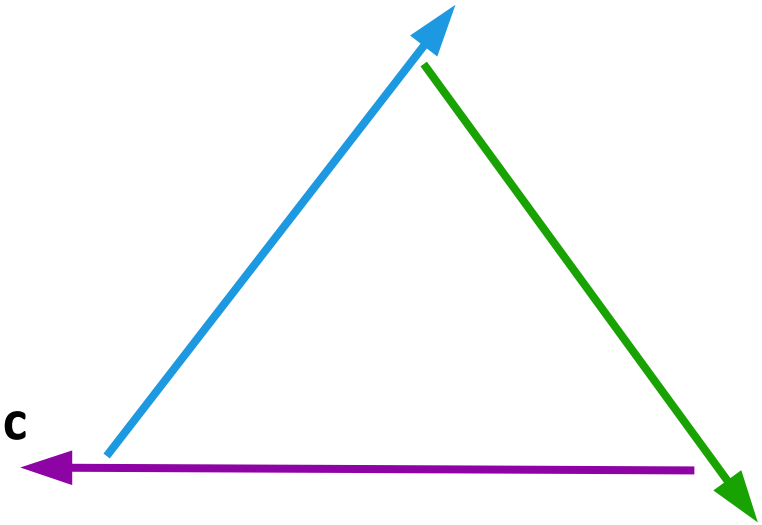
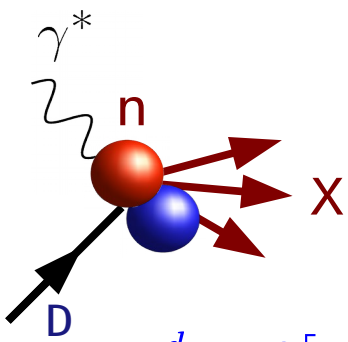
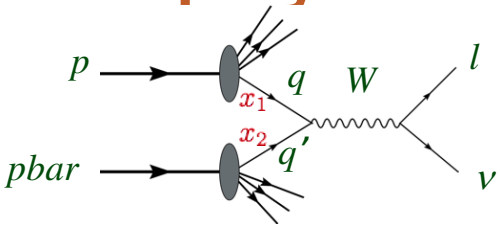


Deep inelastic deuterium

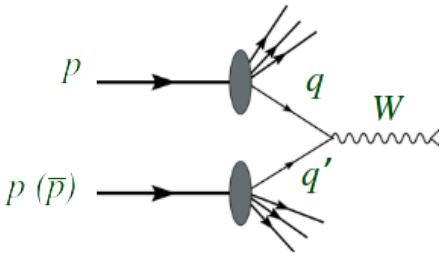


$$F_2^d \propto \mathcal{S}\left[4xu_{\rm off}(x) + xd_{\rm off}(x)\right]$$

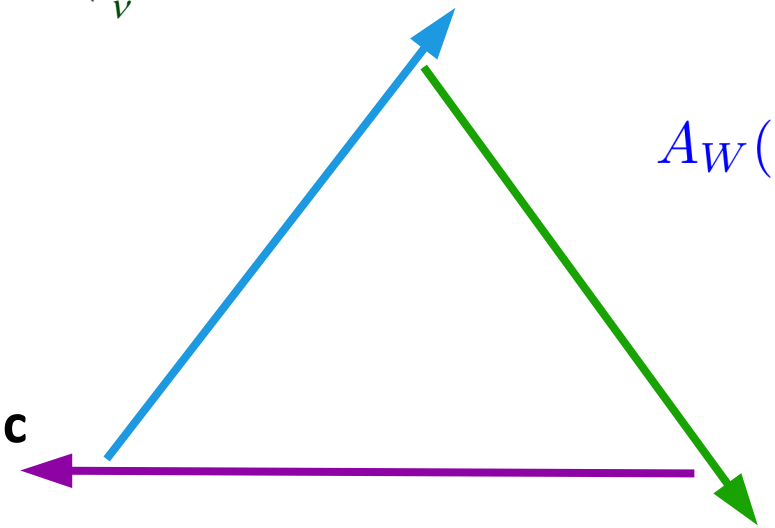
Interplay of observables



D0, CDF asymmetries



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



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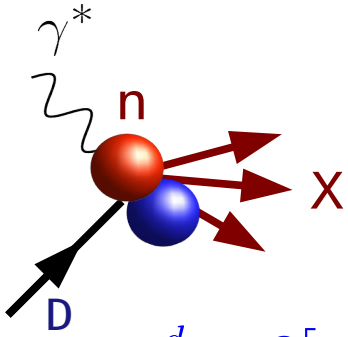

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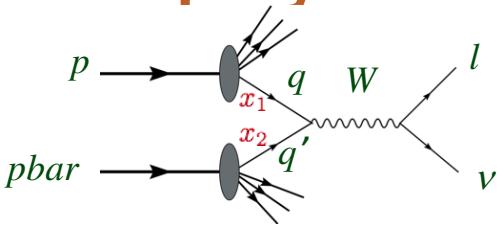

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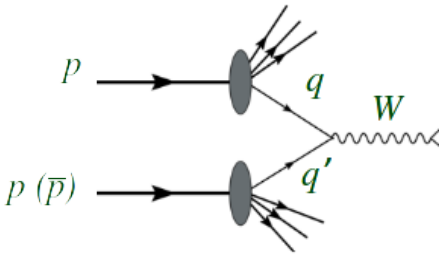

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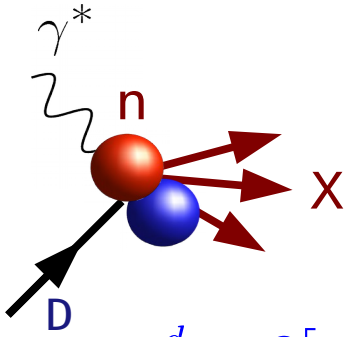

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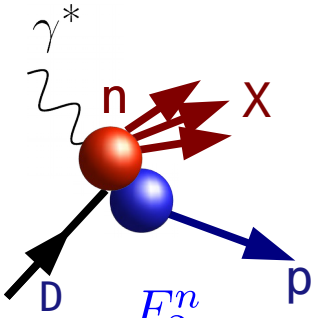
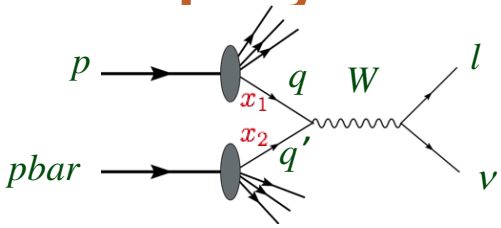
"BONuS" tagged neutron target



$$\frac{F_2^n}{F_2^d} \propto xu(x) + 4xd(x)$$

Interplay of observables



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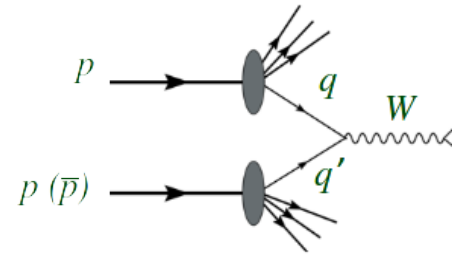


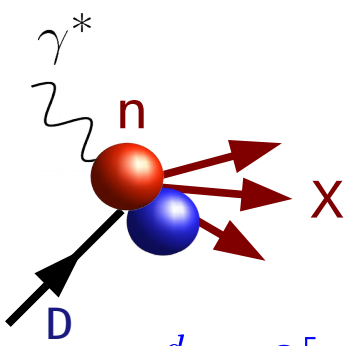
$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$

d/u

&

Offshell dynamics

Deep inelastic deuterium



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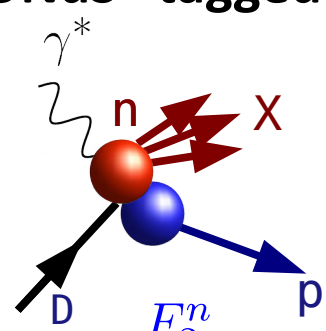

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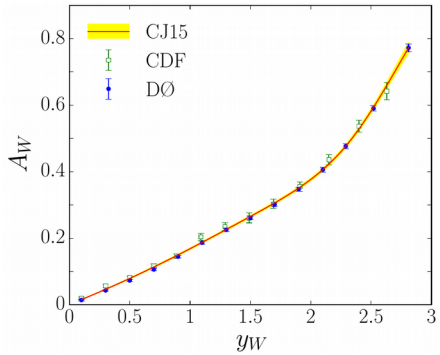
Interplay of observables

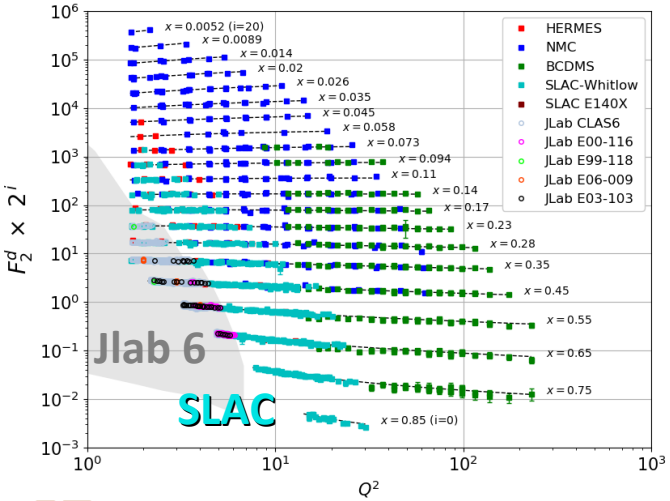
D0, CDF asymmetries



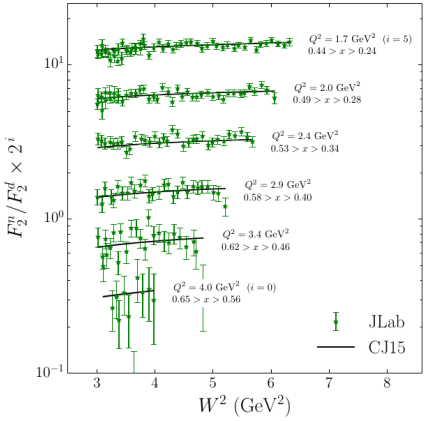
d-quark at largest x
on proton targets

d/u
&
Offshell dynamics

Deep inelastic deuterium

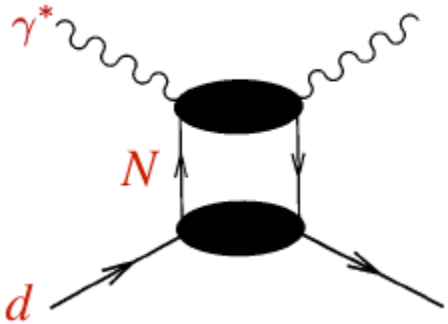


"BONuS" tagged neutron target



Deuteron corrections

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



$$F_{2d}(x,Q^2) = \int \frac{dz}{z}\, f_{N/d}(z,p^2)\, F_{2N}^{TMC+HT}(x/z,p^2,Q^2)$$

nucleon momentum distribution in d ("smearing function")

Str. fn. in bound (off-shell nucleon)

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

momentum fraction of d carried by N

$\longrightarrow$ 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

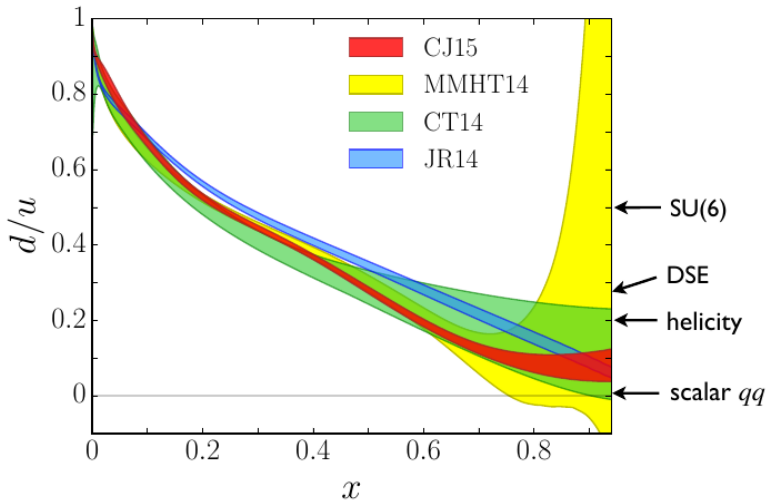
$$\tilde{q}^N(x,p^2) = q^N(x)\left[1 + \frac{(p^2-M^2)}{M^2}\,\delta q^N(x)\right]$$

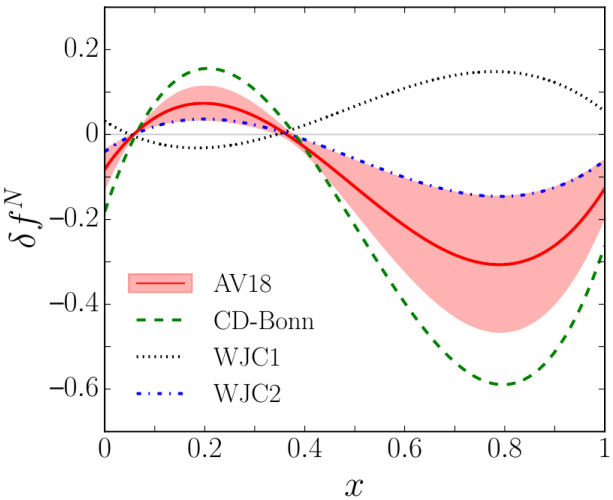
$$\boxed{\delta q^N = C_N(x-x_0)(x-x_1)(1+x-x_0)} \qquad \int_0^1 dx\, \delta q^N(x)\Big(q^N(x) - \bar{q}^N(x)\Big) = 0$$

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 <u>other</u> data:
  - Test "EMC effect" models (of course)
  - On the lattice: "nucleon response to external color field"
  - …

Interplay of observables

D0, CDF asymmetries

– Dominant constraint on d(x)
– **data up to x ~ 0.7**
– Not much dta, but very precise
– Dominantt constraint from D0 W
→ need cross checks

d/u

&

Offshell dynamics

Deep inelastic deuterium

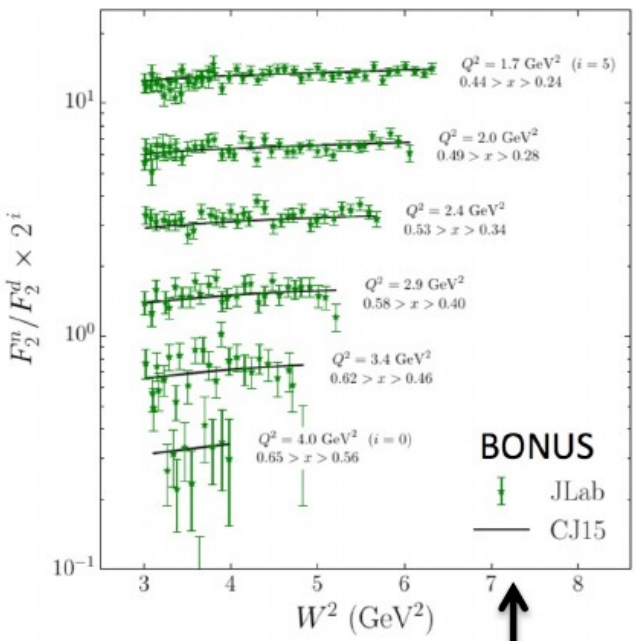
– Large body of data from multiple experients
– **data up to x ~ 0.9**
– Mainly constrains off-shell (and helps with *d/u* uncertainty)

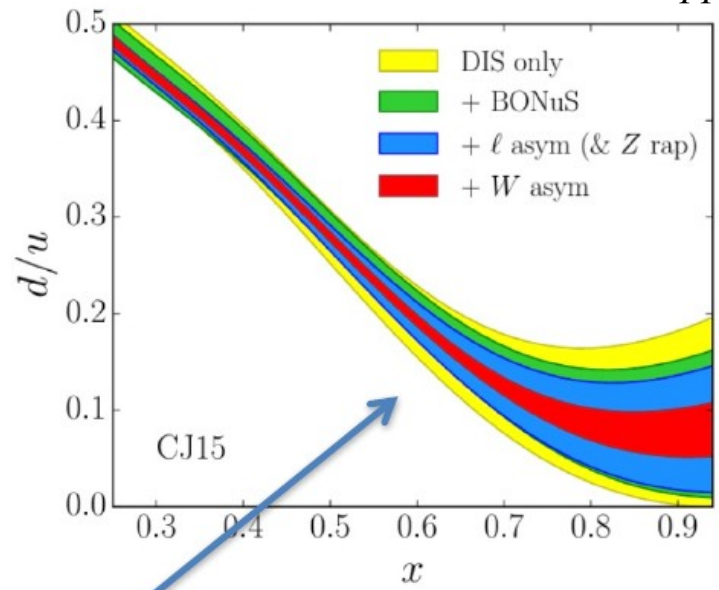
"BONuS" tagged neutron target

– Nearly model-independent neutron data
– Data obtained in 6 GeV Jlab era at low W, Q
– Loss of precision for large *x* DIS

Interplay of observables

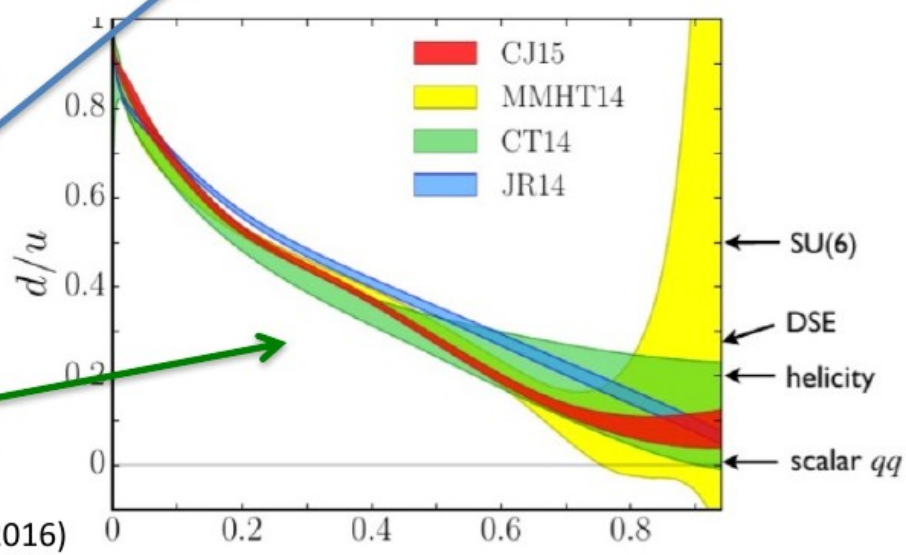
Keppel, DIS 2019 talk





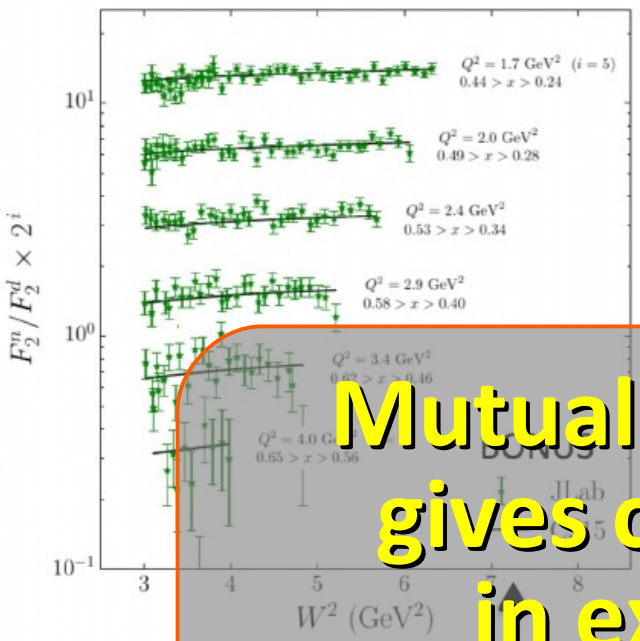
CJ15

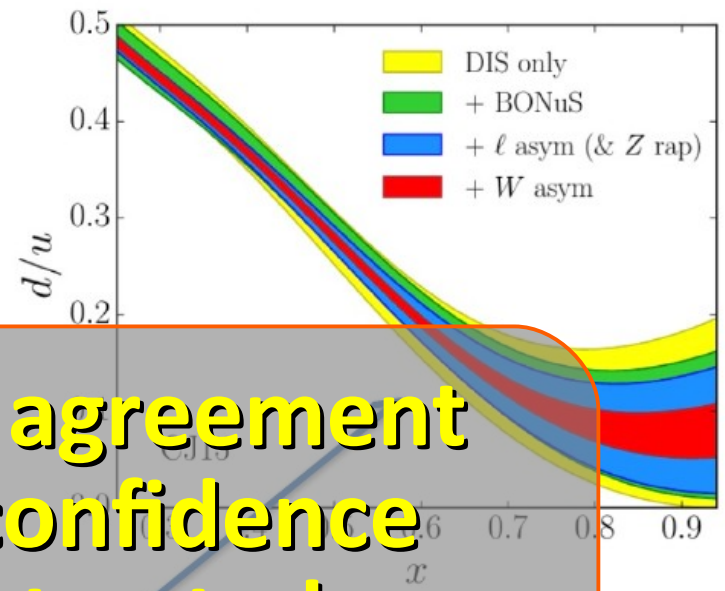
- BONuS data well fit by CJ
- Effect of adding BONUS (also W, l asymmetries from D0)
- **Substantial reduction in d/u uncertainty at large x!**



A. Accardi, et al., Phys. Rev. D **93** 114017 (2016)

Interplay of observables

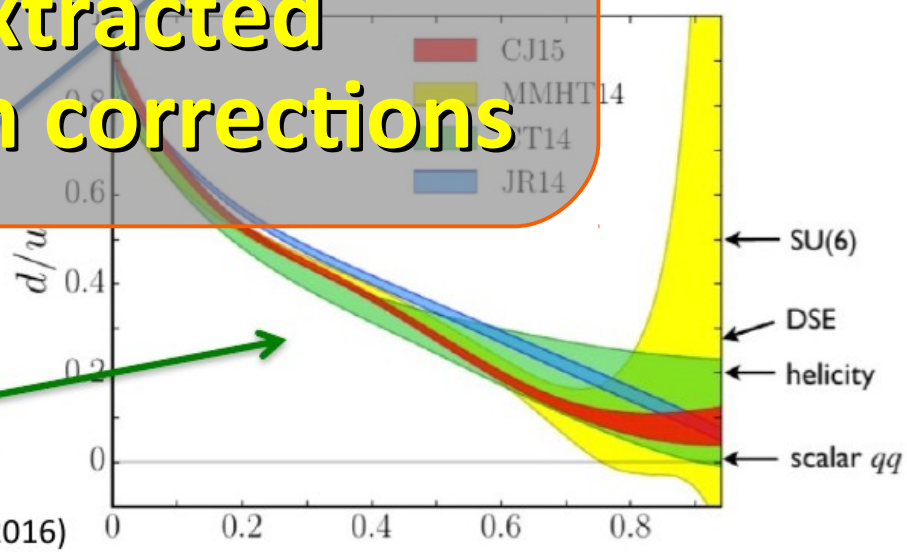




CJ15

Mutual agreement gives confidence in extracted deuteron corrections

- BONuS data [illegible]
- Effect of adding BONUS (also W, l asymmetries from D0)
- **Substantial reduction in d/u uncertainty at large x!**



A. Accardi, et al., Phys. Rev. D **93** 114017 (2016)

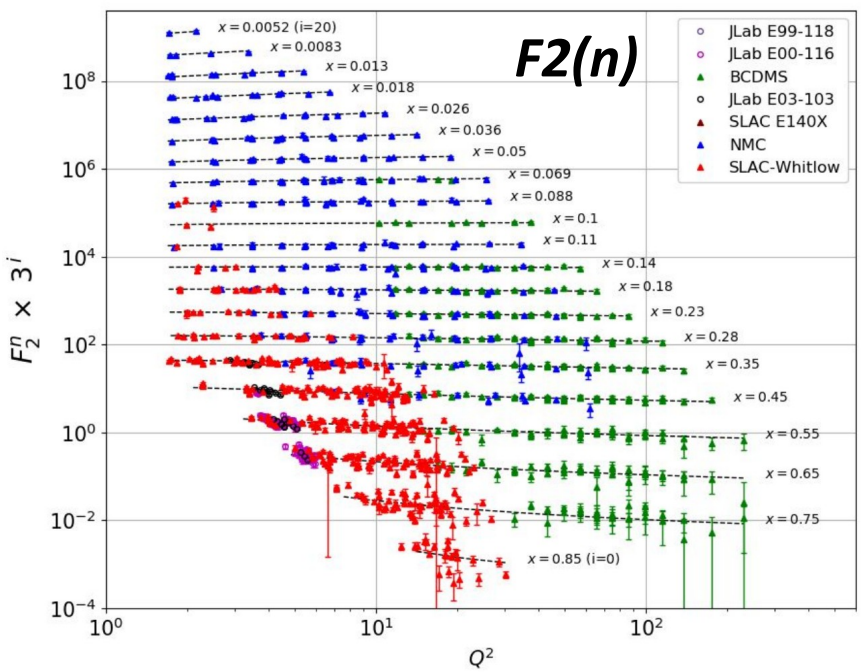
Extraction of “free neutron” DIS data

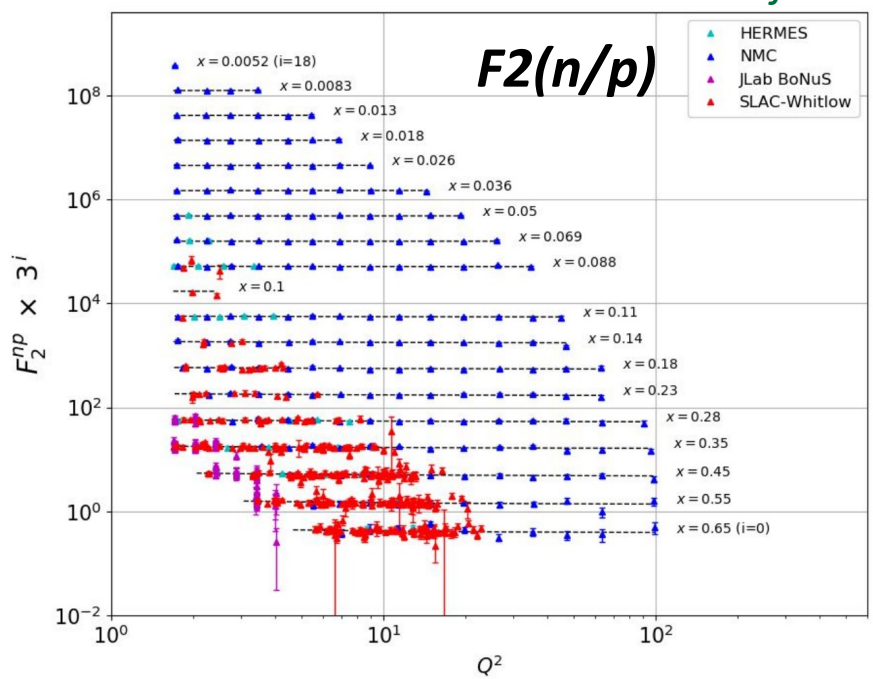
Application: Neutron DIS "data"

CJ + Shujie LI + G&I Niculescu
to appear soon

- **F2(neutron) extraction**
  - Take F2(p) & F2(d), and either F2(d/p) or F2(n/d) data
  - Apply CJ15 nuclear corrections
  - *Extract **F2(n) and F2(n/p)***
    - → *Use, e.g, for **"pure" A/(p+n) "EMC" ratios***

Plots: Shujie Li





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  - ...and ***F2(p-n)***

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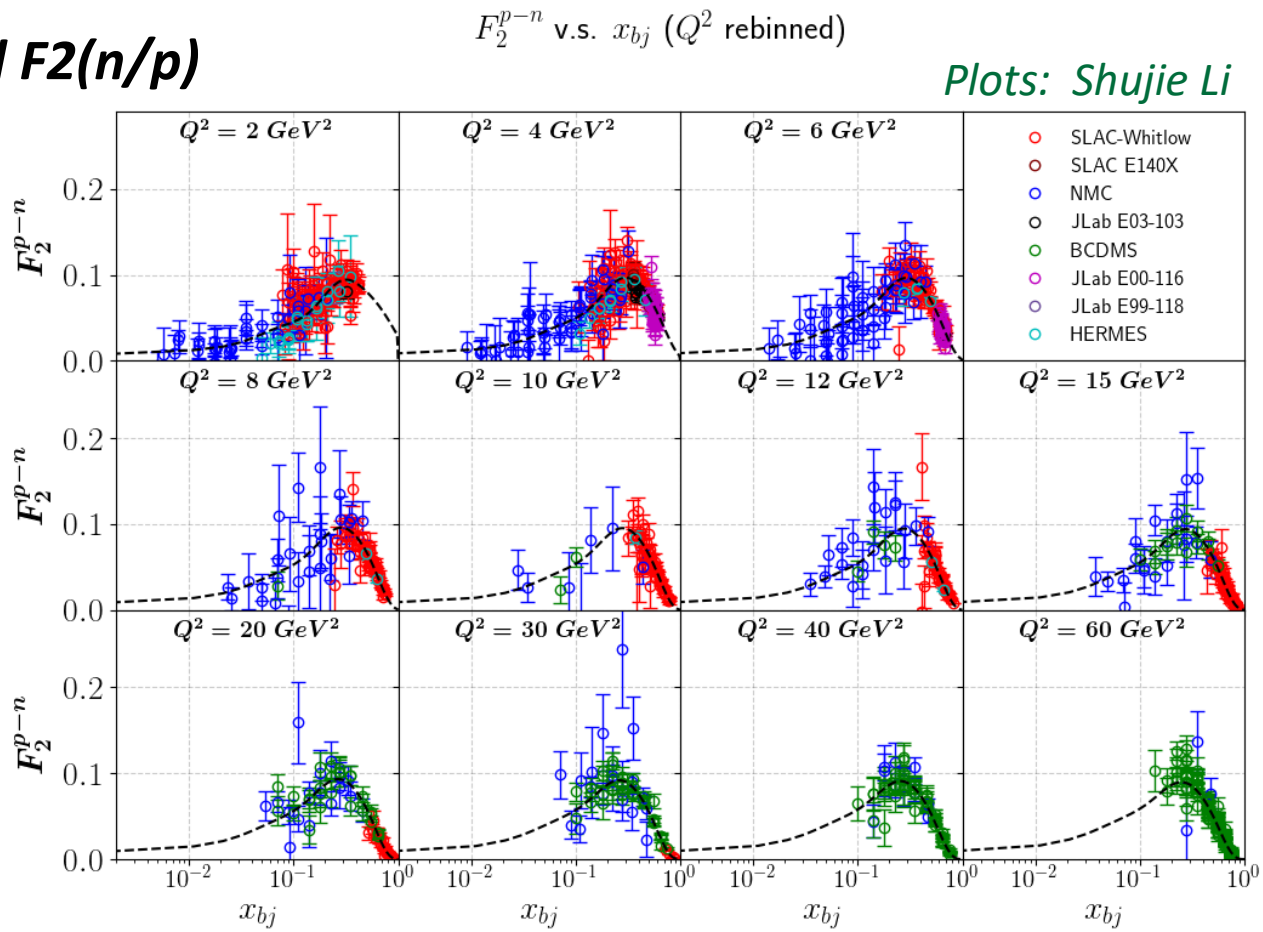

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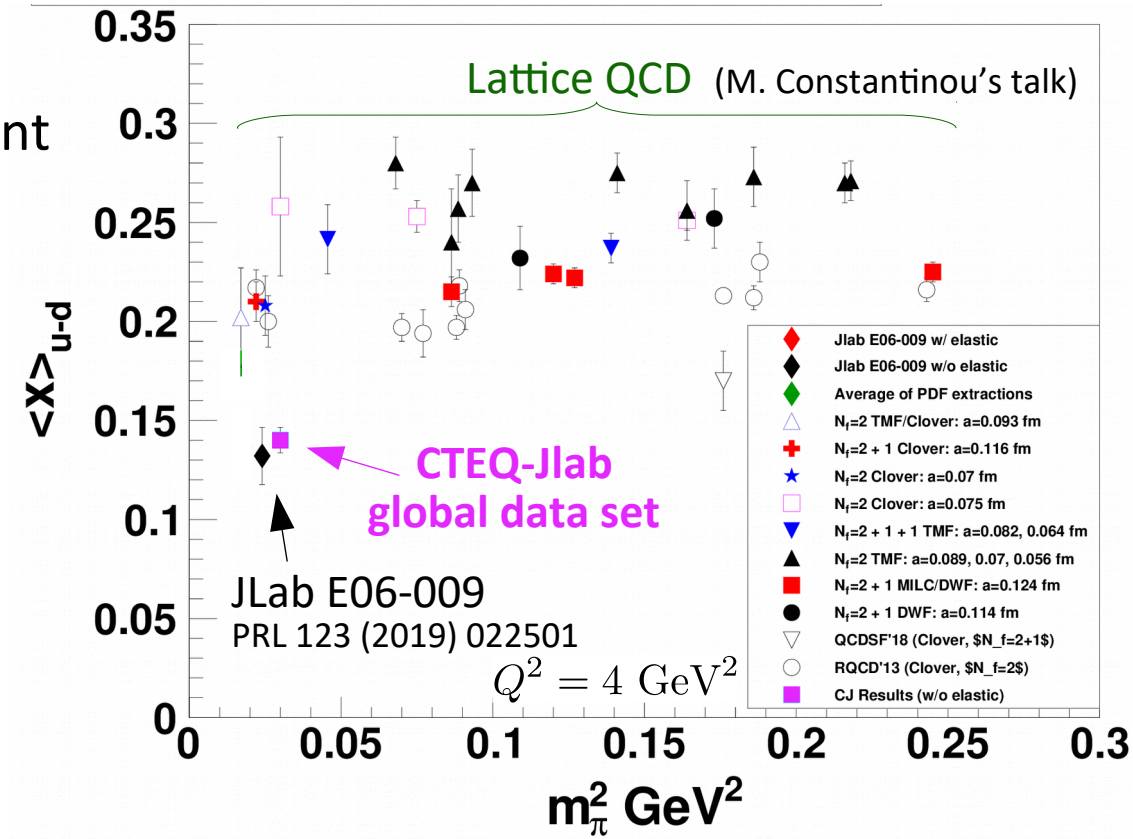
  - Take F2(p) and either F2(d), F2(d/p), or F2(n/d) data
  - Apply CJ15 nuclear corrections
  - *Extract **F2(n) and F2(n/p)***
  - ...and ***F2(p-n)***
  - ...and nonsinglet moment



Application: Neutron DIS "data"

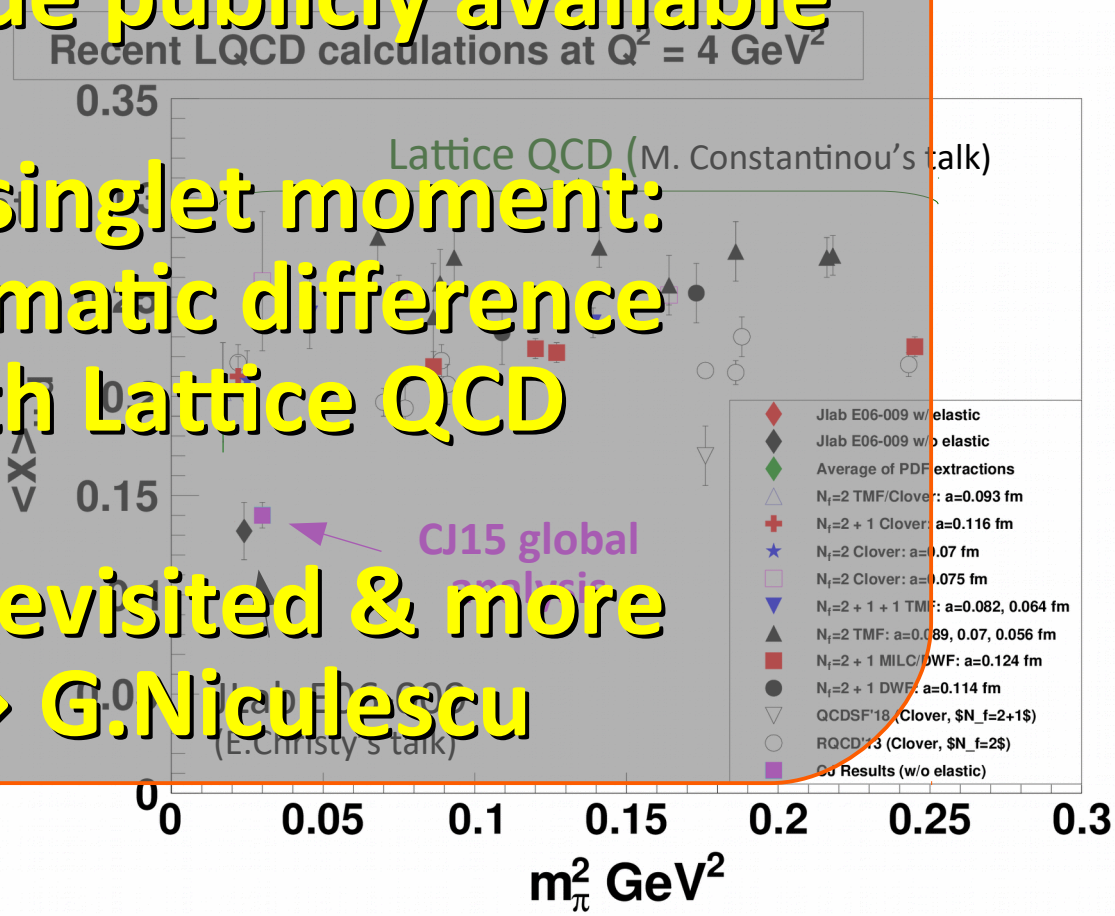
CJ + Shujie LI + G&I Niculescu
to appear soon

- **F2(neutron) extraction**
  - Take F2(p) and either F2(d), F2(d/p) or F2(n/d) data
  - Apply CJ15 nuclear corrections
  - *Extract **F2(n) or F2(n/p)***
  - ...and ***F2(p-n)***
  - ...and nonsinglet moment

"free neutron" data to be made publicly available

Non-singlet moment: systematic difference with Lattice QCD

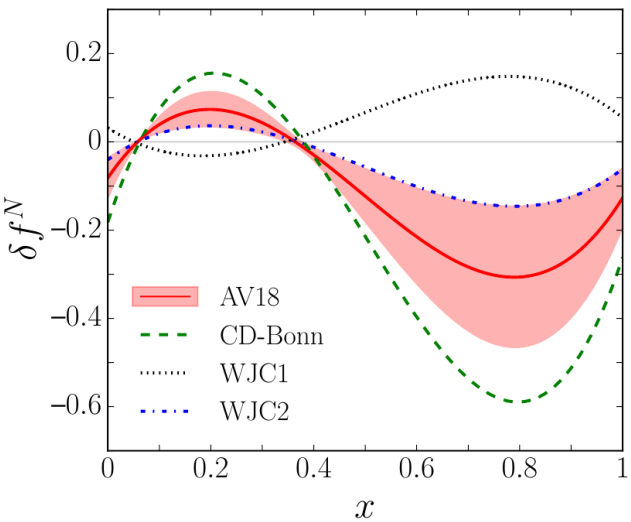
GSR revisited & more → G.Niculescu

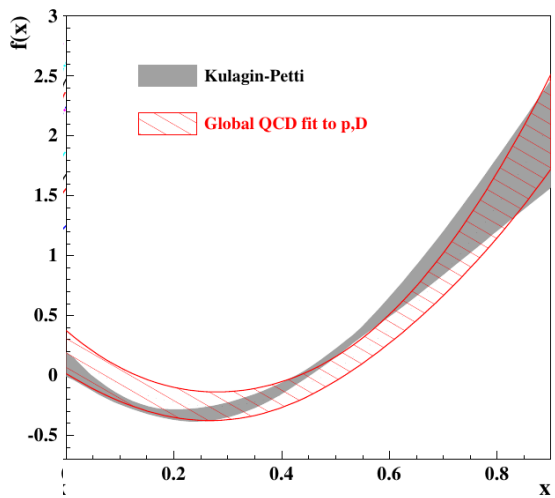


Systematics: compare to ABKM/AKP

Off-shell function

- **Compare to Alekhin-Kulagin-Petti (2017)**
  - Same functional form (but different normalization)





Kulagin, Petti (e+A fits), NPA 765 (2006) 126

Alekhin + KP (e+d global fits) PRD96 (2017) 054005 (Note: Paris ~ AV18 wave fn.)

  - Different shape and size ?!?
- But:
  - Extended d-quark (CJ15) vs. conventional (AKM)
  - Use real W asymetry vs. decay lepton W → l + (n) asymmetry
  - …

Off-shell function (and *d/u*)

CJ + I.Fernando

- **CJ study of data set and parametrization dependence**
  - Use / remove W-asymmetry
  - Use extended or conventional d-quark

$$d_{CJ15}(x) = N\Big(x^a(1-x)^b p(x) + c\,x^d\,u(x)\Big)$$

Quark sum rule

Mixes in some *u* quark

$$\Longrightarrow \quad \boxed{d/u \underset{x\to 1}{\longrightarrow} cN \neq 0, \infty}$$

  - Generalize off-shell parametrization:

Try with and w/o

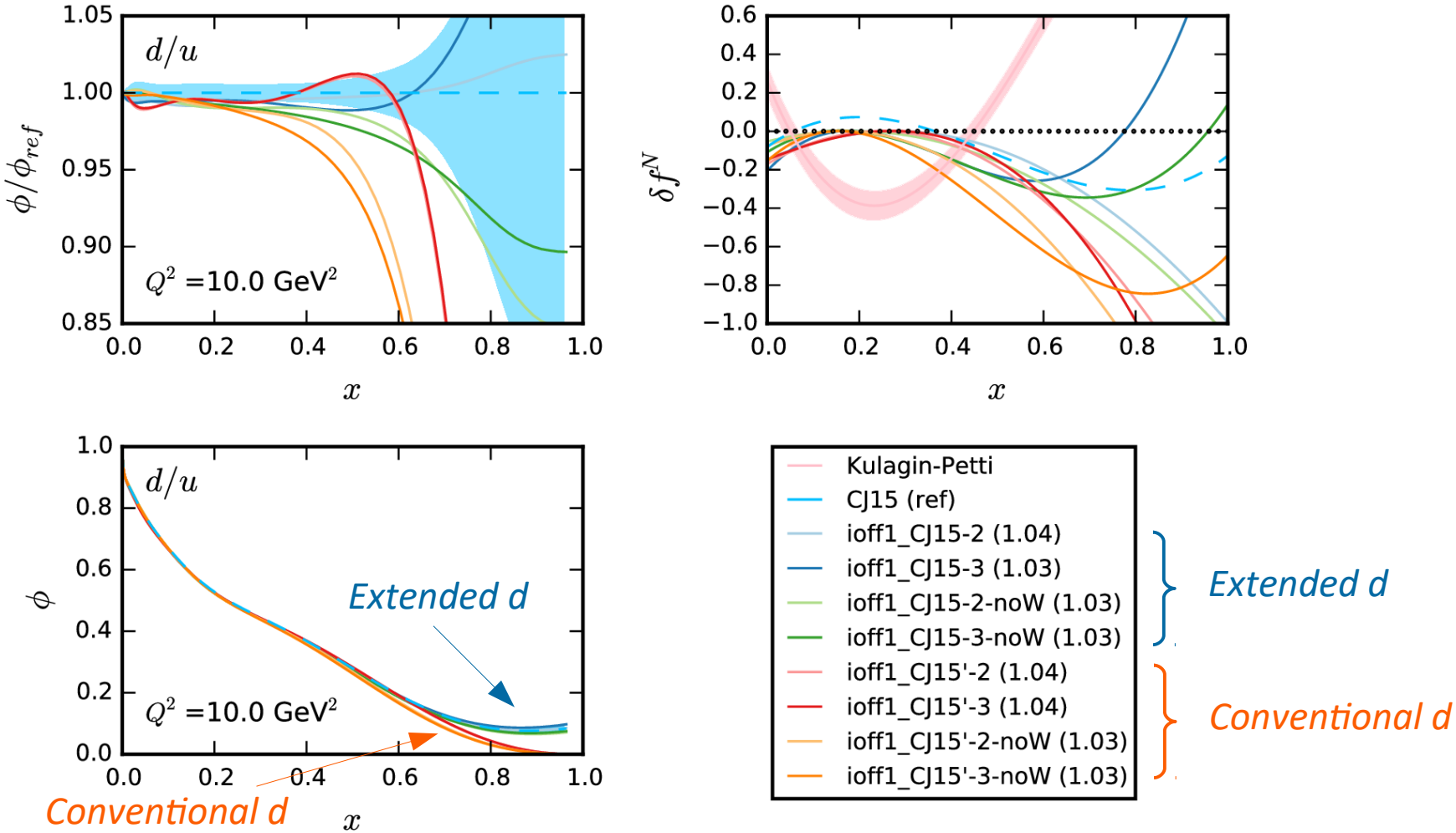
$$\delta f(x) = N(x-x_1)(x-x_3)(x-x_3)$$

Off-shell function (and *d/u*)

CJ + I.Fernando

- **CJ study of data set and parametrization dependence**

Initial conditions: pure CJ15

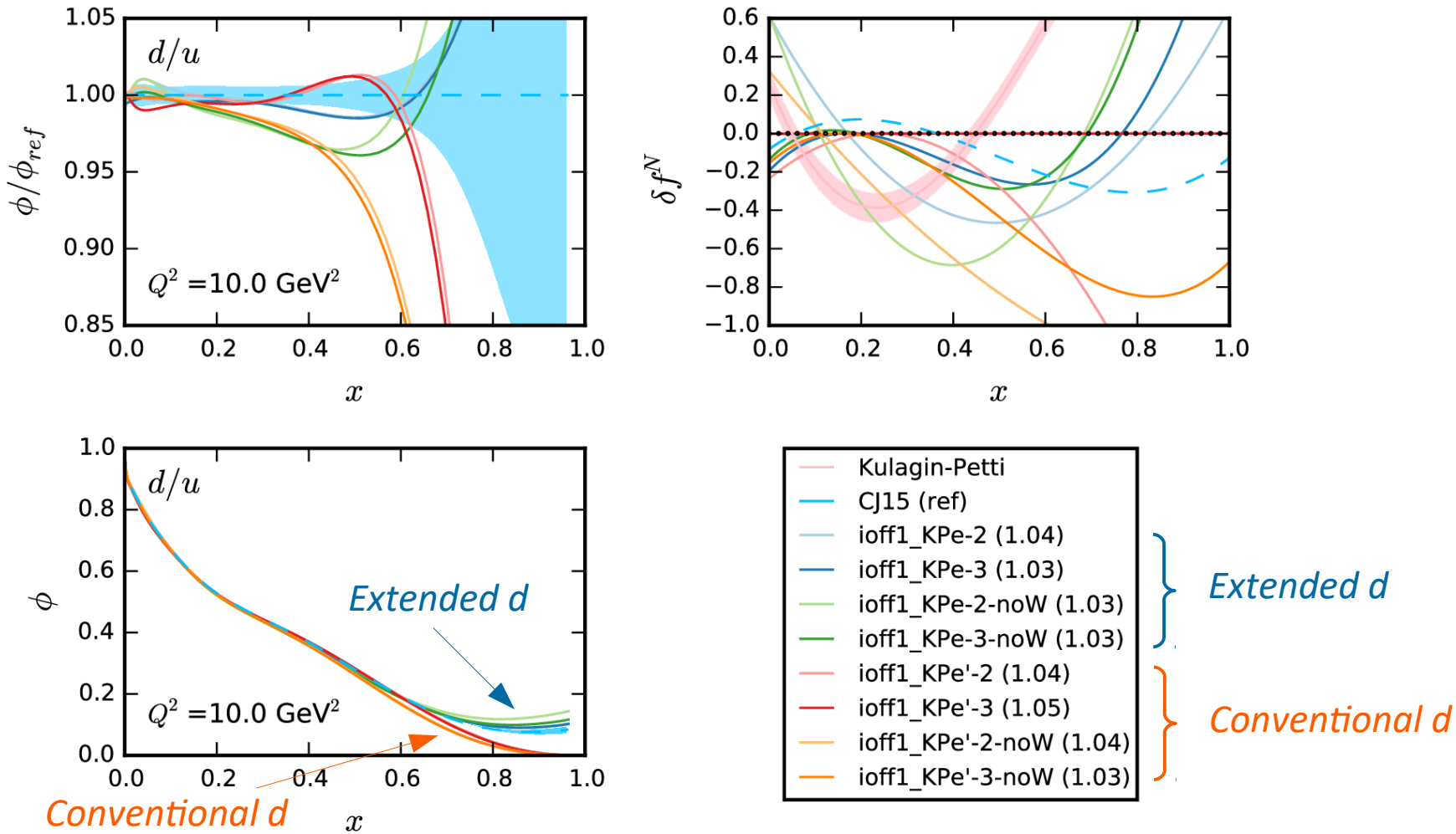


Off-shell function (and *d/u*)

CJ + I.Fernando

- **CJ study of data set and parametrization dependence**

Refitted initial cond,: fixed KP off-shell, with W data



Off-shell function (and *d/u*)

CJ + I.Fernando

- Conclusions:
  - **CJ15 d/u is robust** against
    - use of W asymmetry
    - offshell parametrization
  - **Off-shell function strongly correlated to d-quark**
    - becomes large, ~O(AKP), with conventional *d* parametrization
  - **Sign change in CJ off-shell *δf***
    - was an artefact of overconstrained parametrization
    - would likely reappear if including pion cloud effects

Off-shell function (and *d*/*u*)

CJ + I.Fernando

- ...and finally:
  - **Concavity is rather robustly downward!**

Off-shell function (and *d*/*u*)

CJ + I.Fernando

- ...and finally:
  - **Concavity is rather robustly downward!**

Is there a relative sign change
in definition/implementation of δf ?

Off-shell function (and *d/u*)

CJ + I.Fernando

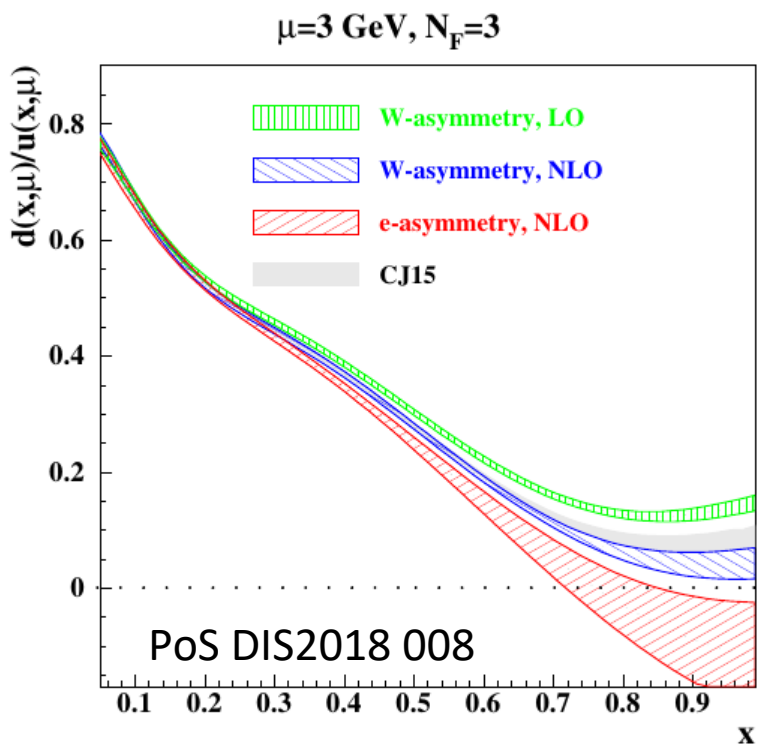
- ...and finally:
  - **Concavity is rather robustly downward!**

Is there a relative sign change
in definition/implementation of δf ?

Or maybe a local minimum
when limiting δf to a 2nd order
polynomial
(but without much effect on d/u) ???

d/u ratio

- ABKMP suggest our d/u ratio driven by lack of NLO effects in W-asy
  - even if K-factor ~ 1



d/u ratio

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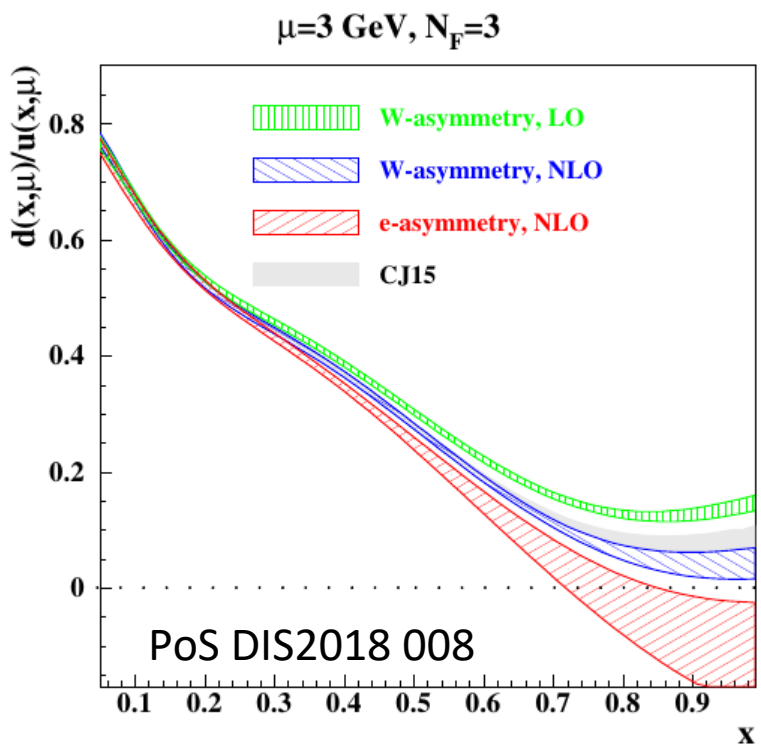
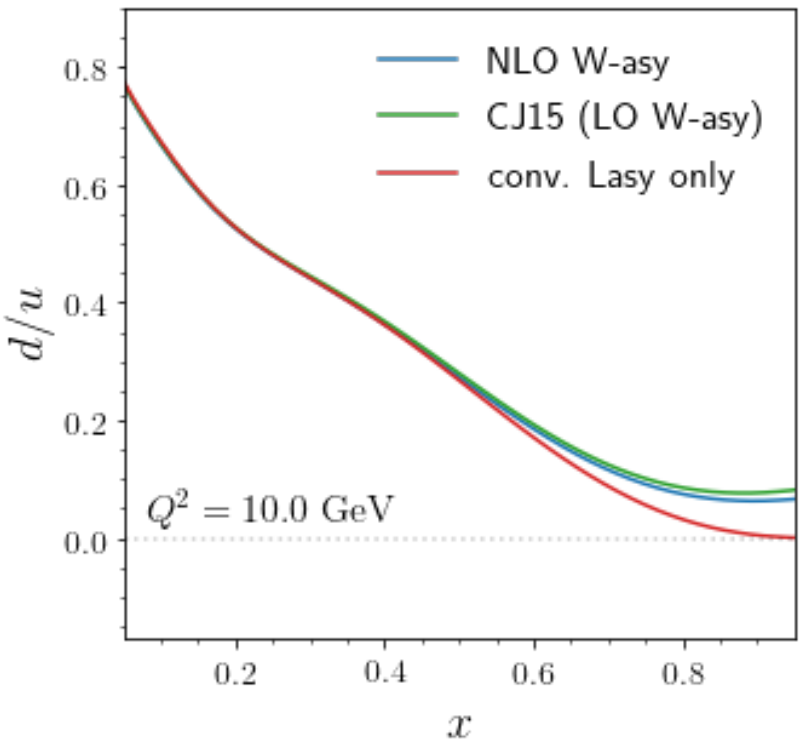


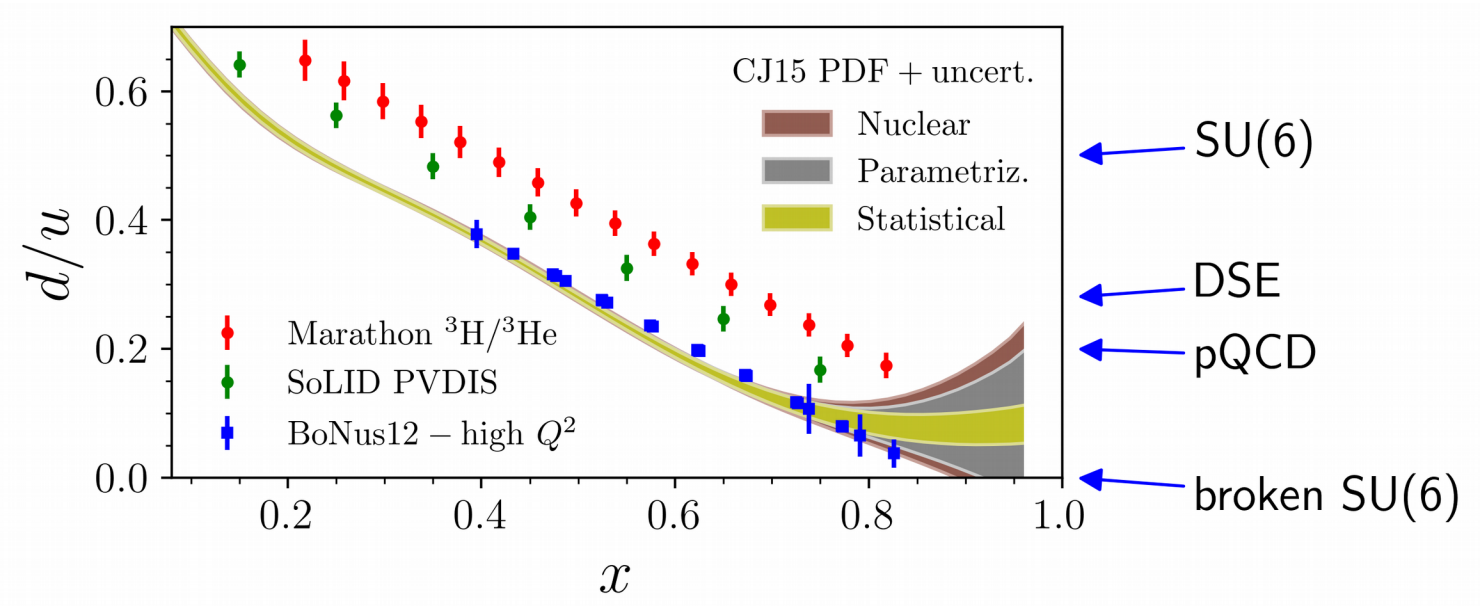


- But:
  - **CJ15 ratio robust against order of perturbation theory in W-asy**

Summary and future

Summary: controlled PDFs at large x

- **CJ15 provides the most controlled large-x PDF fit on the market**
  - ABMP16 / AKM "next best" choice, provides systematic benchmark

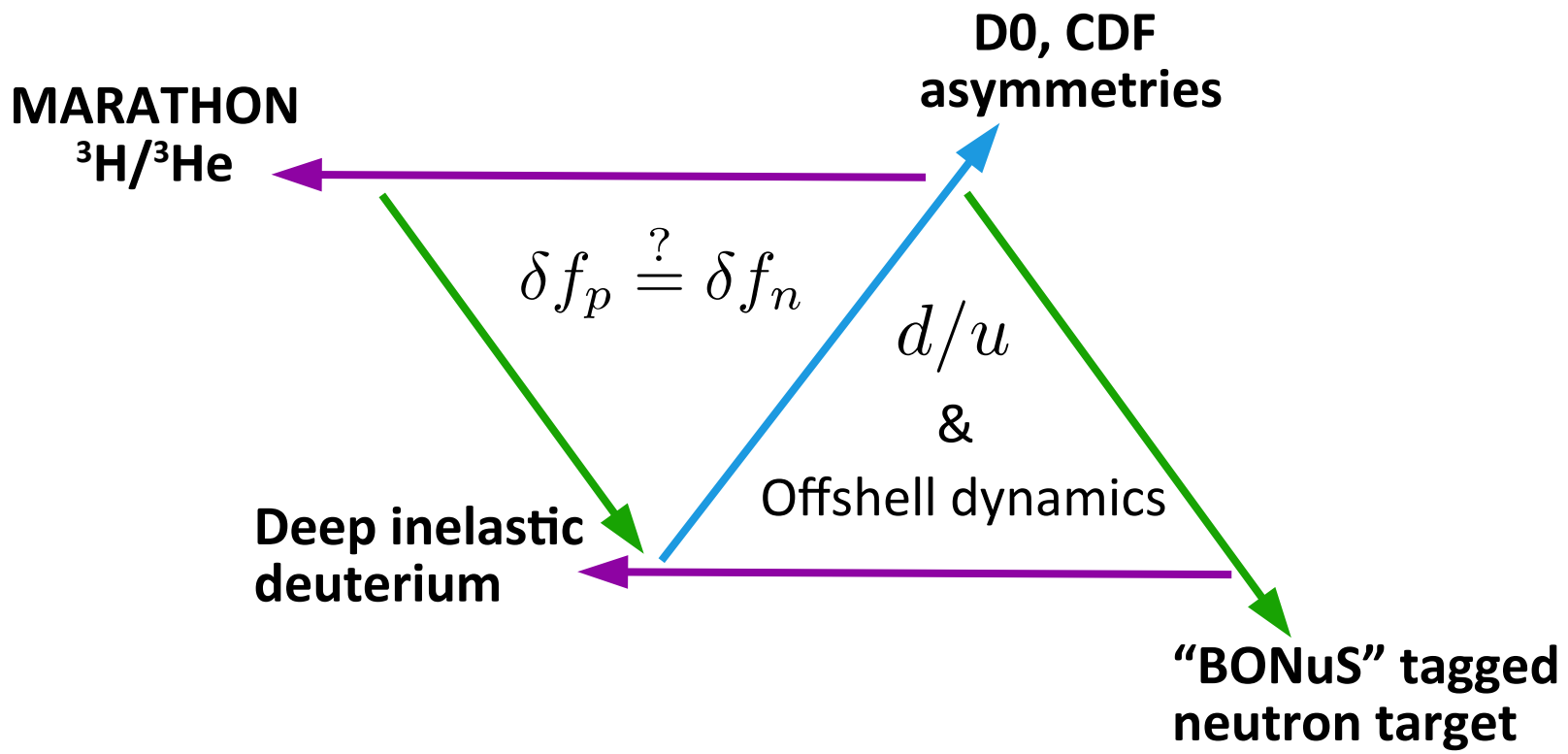


- Further progress needs **precise nucleus-free "control observables"...**
  - W asymmetry: RHIC, LHC *(working on it w/ Sanghwa Park, Xiaxian Jing)*
  - BoNus12, Marathon*, SoLID PVDIS
- **...and more p, d DIS**

** see F.Hauenstein and M. Petratos talks*

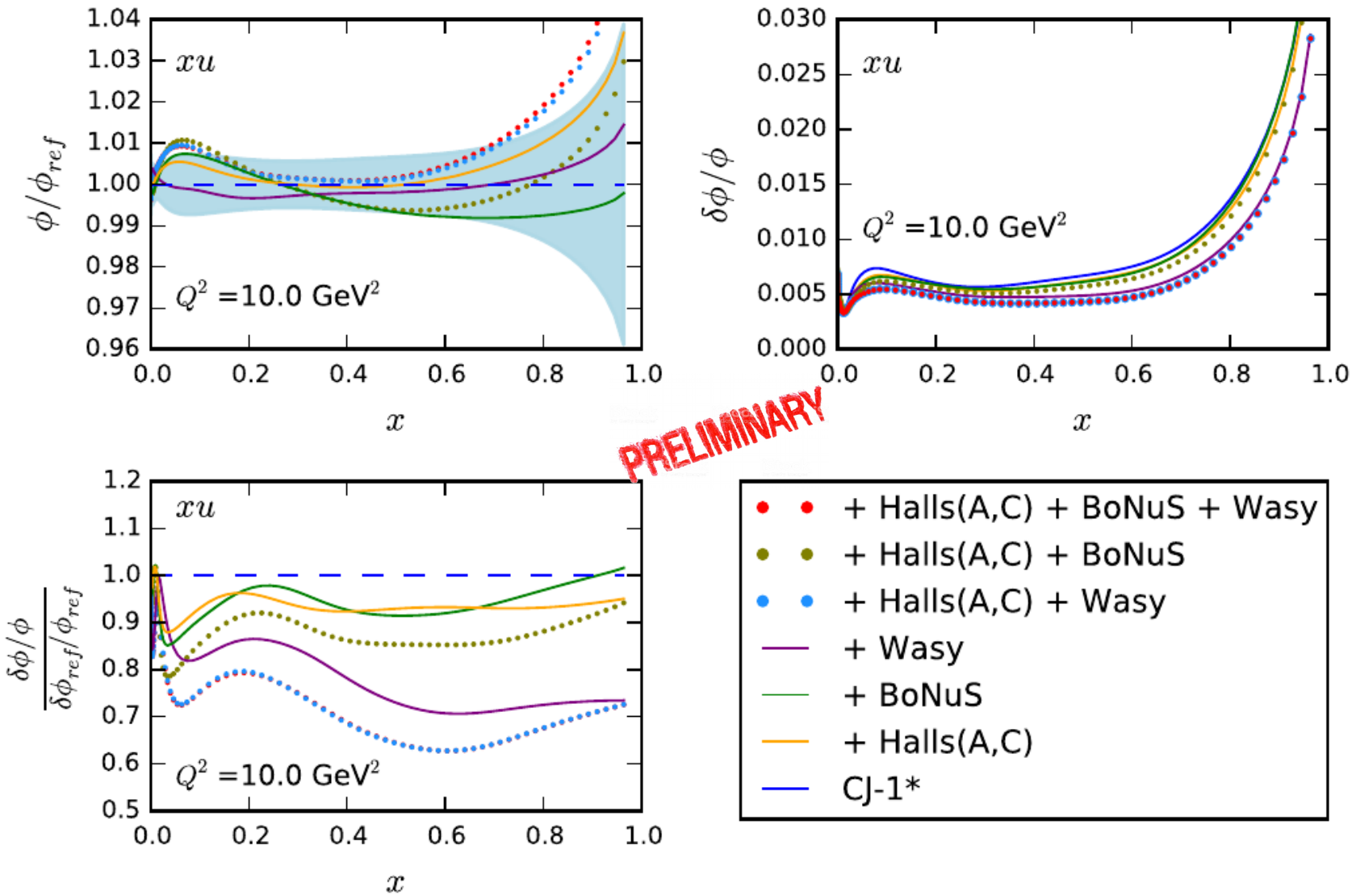
The Marathon parallelogram

- Can extend the CJ15 triangle to a parallelogram
  - Verify if off-shell protons ~ off-shell neutrons → *cf. W.Melnitchouk's talk*



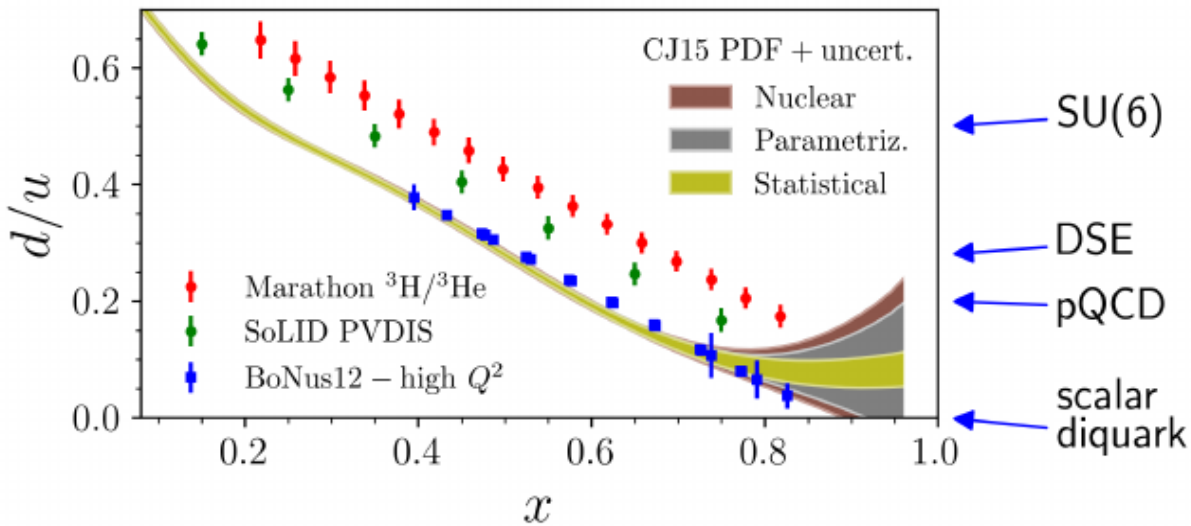
More p, d DIS → Jlab 6

CJ + I.Fernando + F.Araiza-Gonzalez



Probing the Valence Regime at JLab12

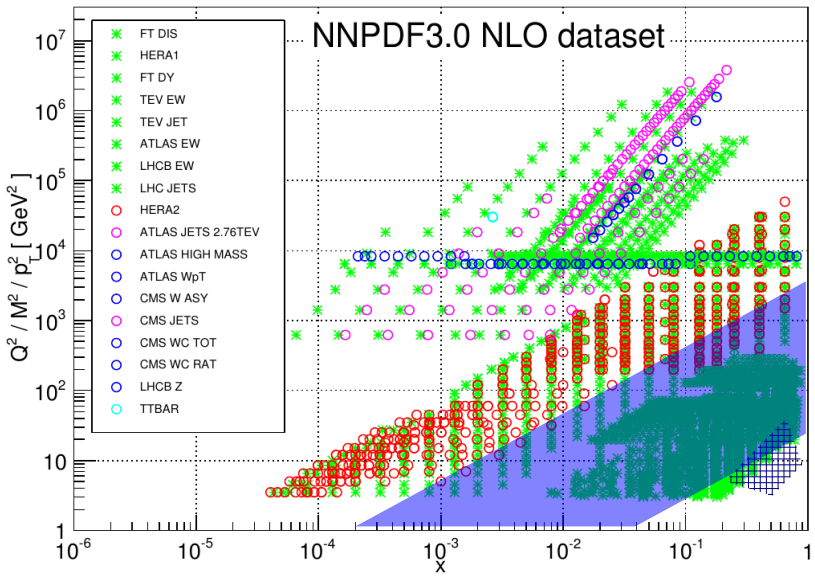
Keppel, DIS 2019 talk



- New generation of experiments at JLab at 12 GeV will access the regime where valence quarks dominate
- First experiments *COMPLETED!*
  - ✓ Hall C $F_2^{p,d}$ → *S. Malace's talk*
  - ✓ Hall A ^{3}H/^{3}He → *Hauenstein & Petratos talks*
- BONUS12 to run this Fall
- PVDIS (further future) on p target
- Dedicated effort to extract valence PDFs
  - "CJ", (CTEQ-Jefferson Lab) – and also "JAM" (polarized PDF, SIDIS) collaborations
- Also SeaQuest Drell-Yan experiment E906 at FNAL focused on high x sea

Expect significant improvement in large x PDFS in next 1-2 years!!

Enters the EIC



- Interpolates fixed target and HERA
- Large Q^2 leverage
  - More evolution at large x
  - Better separation of LT and HT
- High luminosity → large x capabilities

→ EIC2 project under way
(Hobbs, AA, Furletova, Yoshida)

- **Unique at the EIC**
  - "Easy" spectator tagging in DIS
    - Quasi-free neutron targets; neutron tagging → check vs real free p
    - Strong PID capabilities → F_2^c, F_2^{cc}, ...
  - High luminosity → CC, PVDIS → d/u, strange quarks, dbar/ubar, ...
  - Unpolarized & polarized scattering (also light ions)

Backup

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

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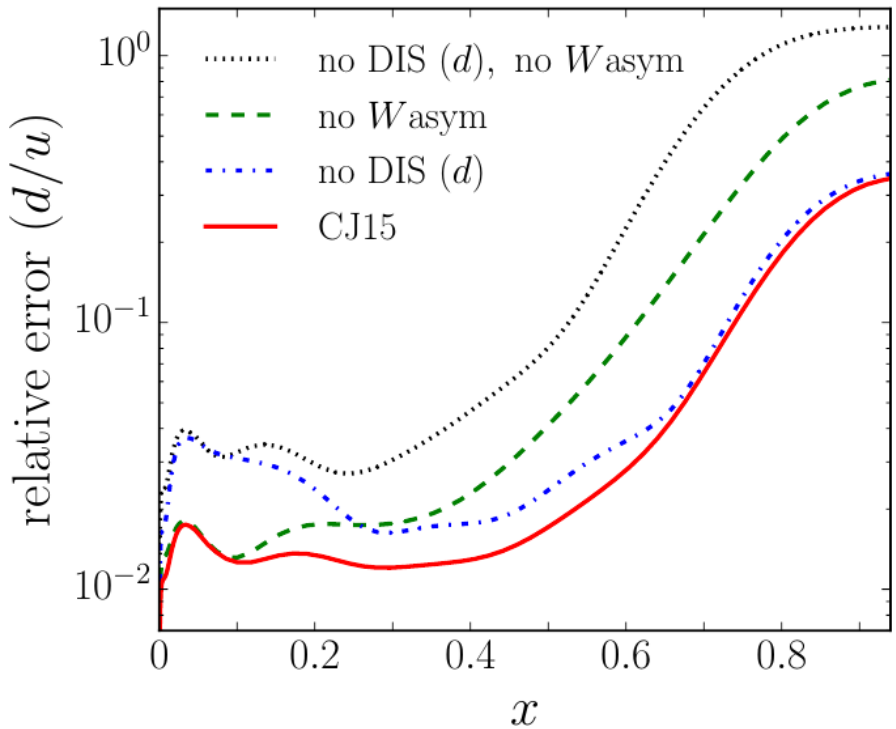
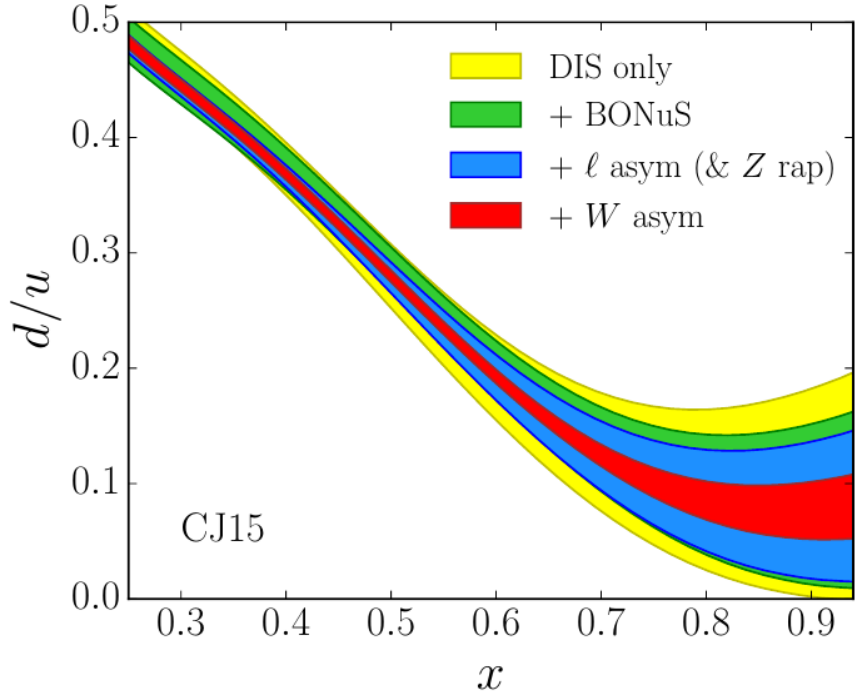
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26

- 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**

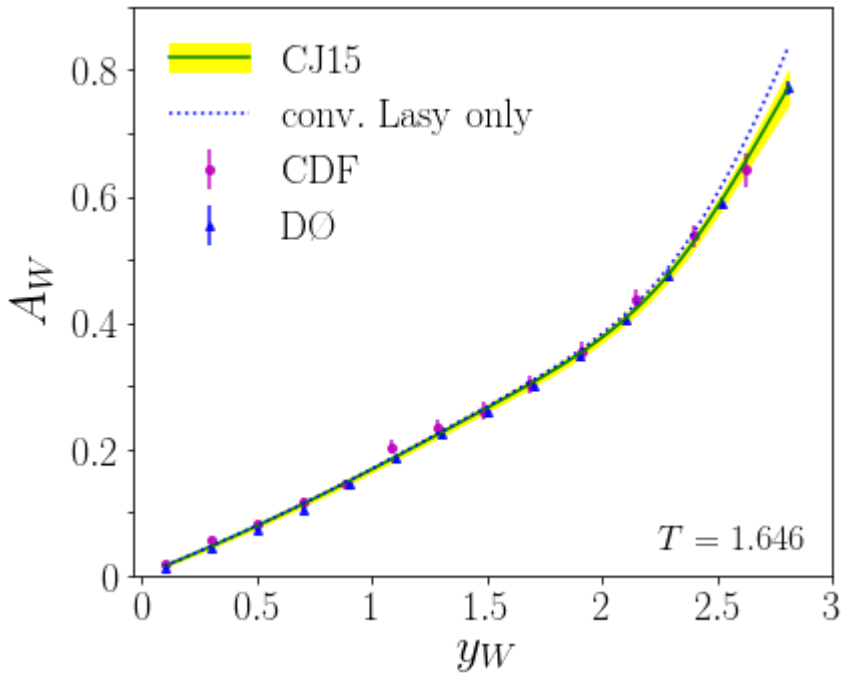
What fits what?

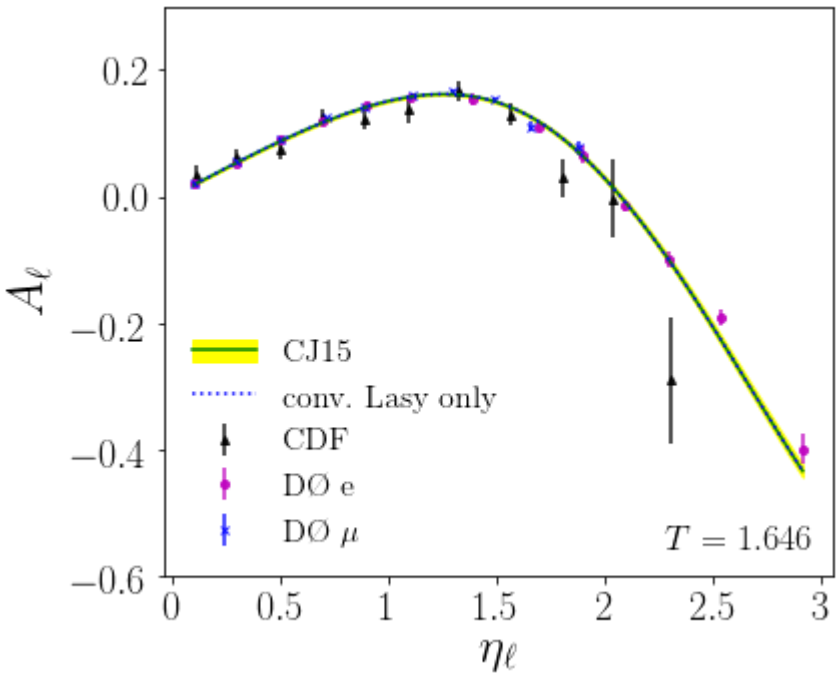




- **Large x > 0.3:**
  - D0's W-asymmetry determines the d-quark
  - SLAC(d)'s statistical power used to fit the off-shell function
- **Moderate x < 0.3:**
  - SLAC(d) enables precise d/u flavor separation

CJ15 vs. W-asymmtrey and W→l asymmetry data

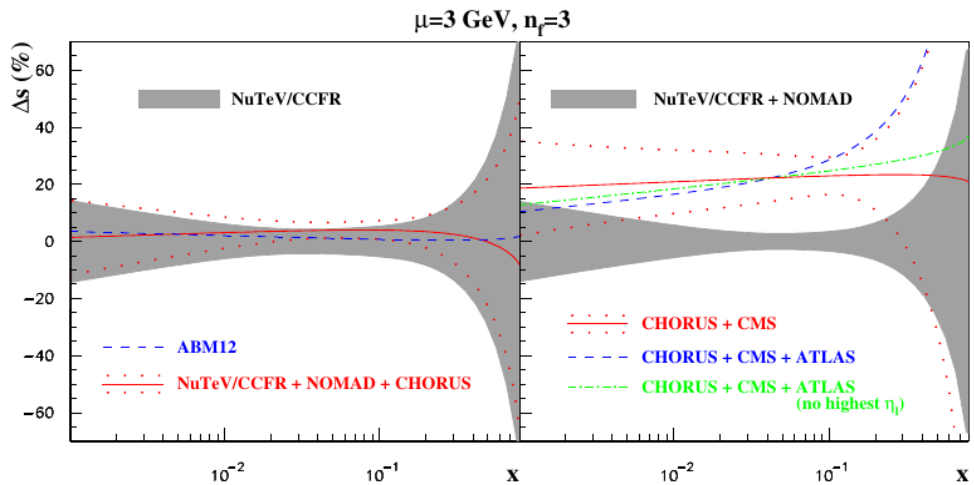




- W→l asymmetry well described in both standard or no-Wasy CJ15 fits!
  - Another proof that W-asy reaches to larger x than L-asy

Example 2: strange strange quarks

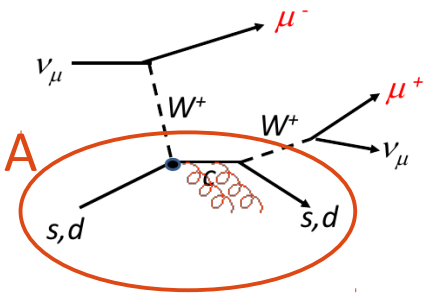
- **ν+*A* → dimuons** *vs.* ***p+p* → *W+c* at LHC** *Alekhin et al., arXiv:1404.6469*



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

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

FSI ?



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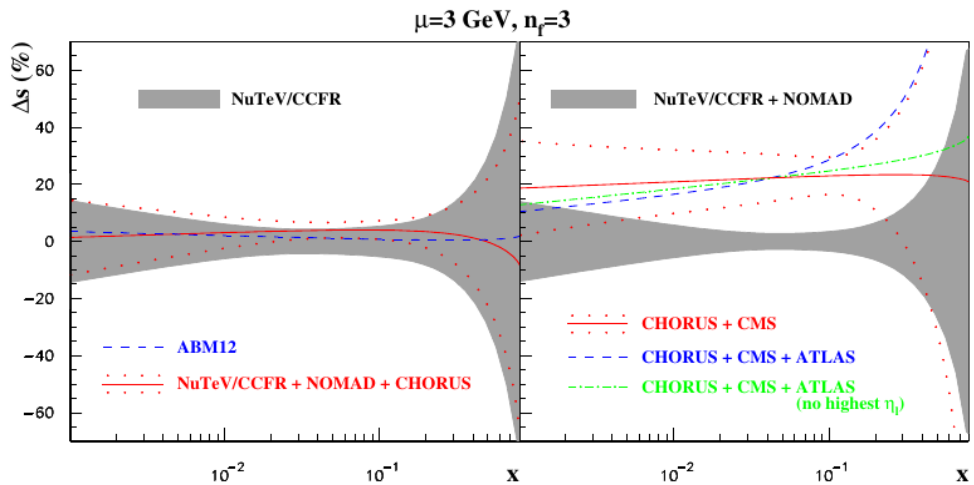

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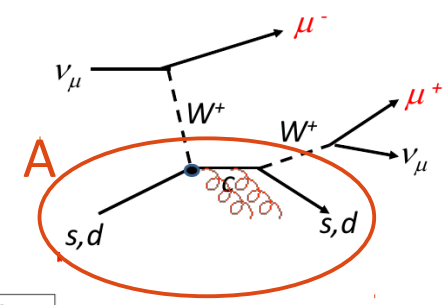
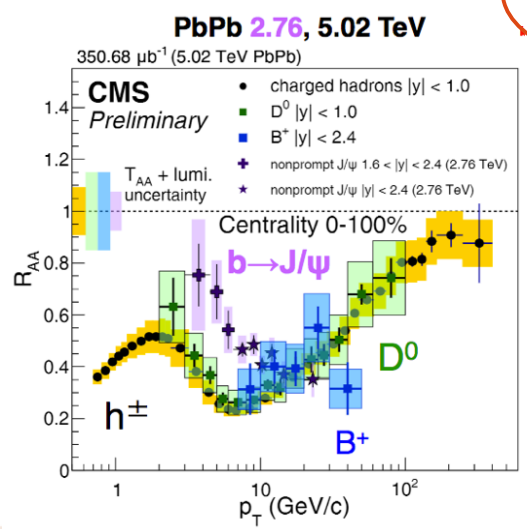
FSI ?



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

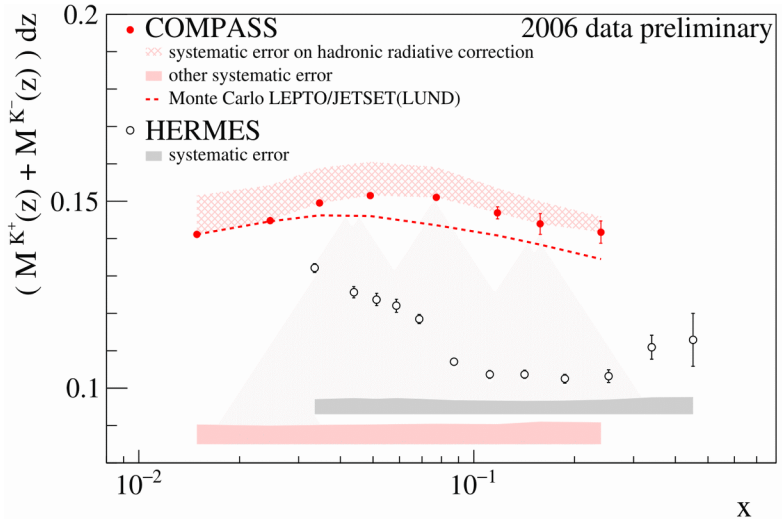
$$R^h_{AA} = \frac{\left(dN^h/d^2p_T\right)_{AA}}{N_{col} \times \left(dN^h/d^2p_T\right)_{pp}}$$



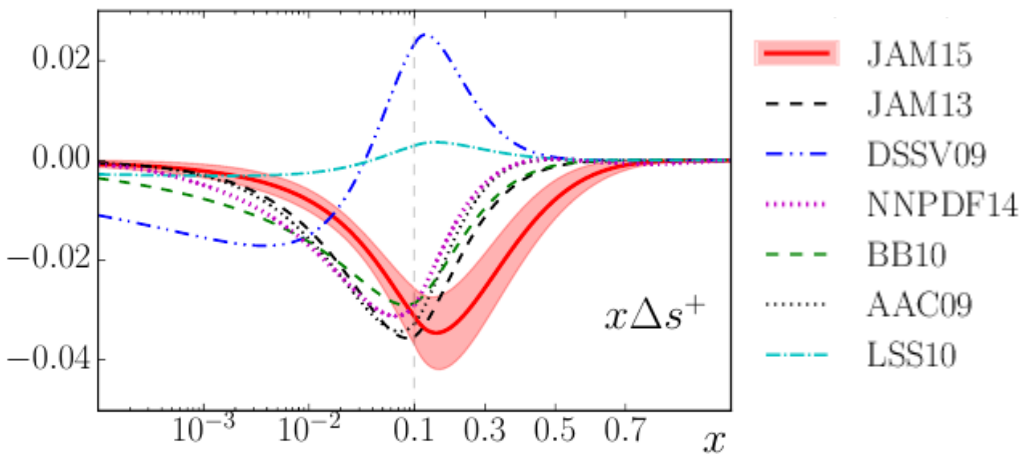
Yen-Jie ,
Quark Matter 2017

Example 2: strange strange quarks

- **s : large or small?**
  - Possibly, large Hadron Mass effects
    Guerrero, Accardi, PRD 97 (2018)
  - Extraction of s(x) strongly affected by **kaon <u>systematic</u> uncertainty**



- **Δs : positive or negative?**
  - Depends on **kaon FF used in SIDIS calculations!**
    LSS, PRD 84&91

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

  - What about the unpol s ?