# CTEQ-Jlab PDFs and d/u ratio at large x


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CTEQ-Jefferson Lab Collaboration


*F2/EMC collaboration meeting*

Jefferson Lab, May 2nd–3rd, 2019

# Overview

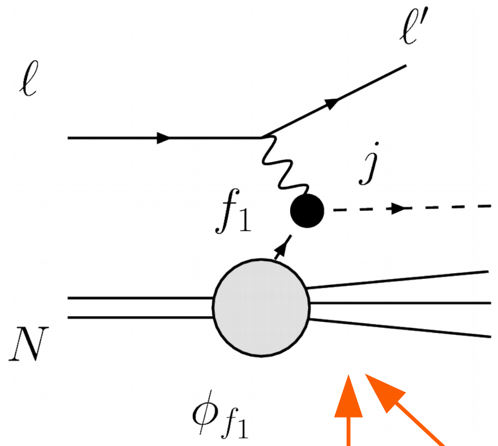
- Basics of QCD global fits and PDF extraction
- The CJ15 global QCD analysis
- d/u ratio at large x
- Summary and the future

REFERENCES:

* Accardi, **PoS DIS2015 (2015) 001** – "PDFs from protons to nuclei"
* Accardi et al, **PRD 93 (2016) 114017** – the CJ15 global fit

# Basics of QCD global fits (of parton distributions)

# Factorization of hard scattering processes



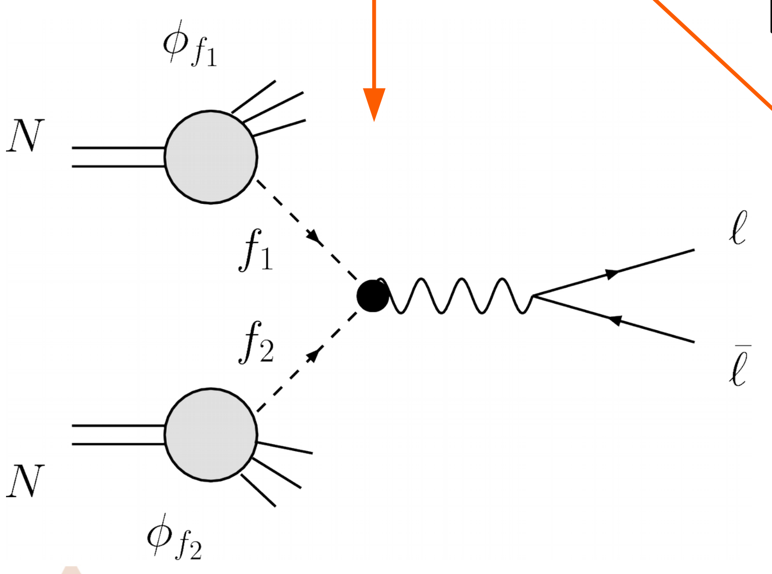

- **perturbative QCD factorization**
  of short and long distance physics

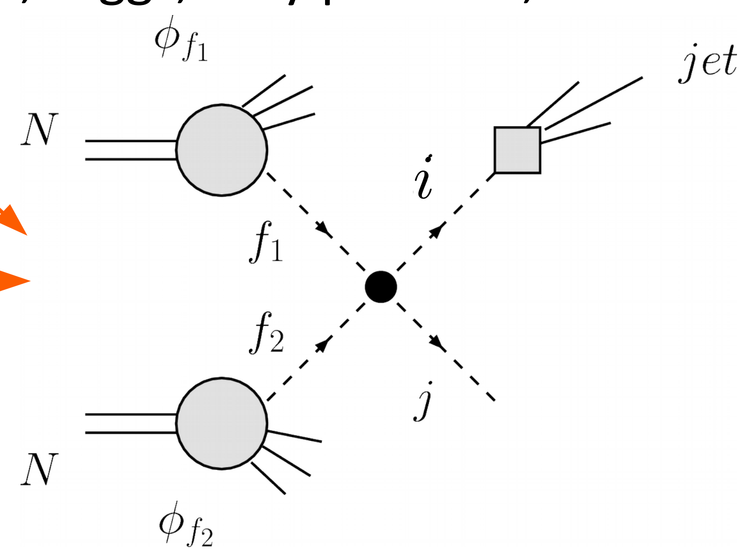
$$d\sigma_{\rm hadron} = \sum_{f_1,f_2,i,j} \phi_{f_1} \otimes \hat{\sigma}^{f_1 f_2 ij}_{\rm parton} \otimes \phi_{f_2}$$

Parton Distribution Fns
(from inclusive DIS)

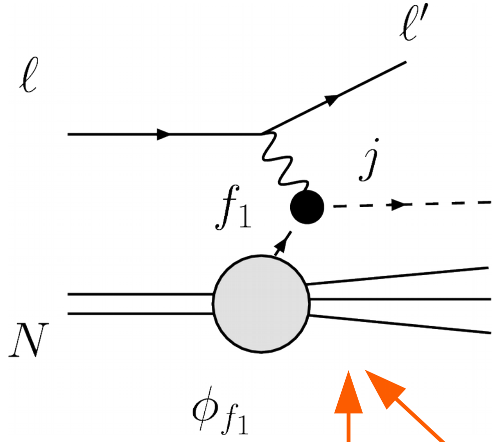
pQCD
cross section

- **Universality:** PDF from DIS describe also
  DY, jets, Higgs, susy particles, Kaluza-Kleins, ...



# Factorization of hard scattering processes




- **perturbative QCD factorization** of short and long distance physics

$$d\sigma_{\text{hadron}} = \sum_{f_1,f_2,i,j} \phi_{f_1} \otimes \hat{\sigma}^{f_1 f_2 ij}_{\text{parton}} \otimes \phi_{f_2}$$

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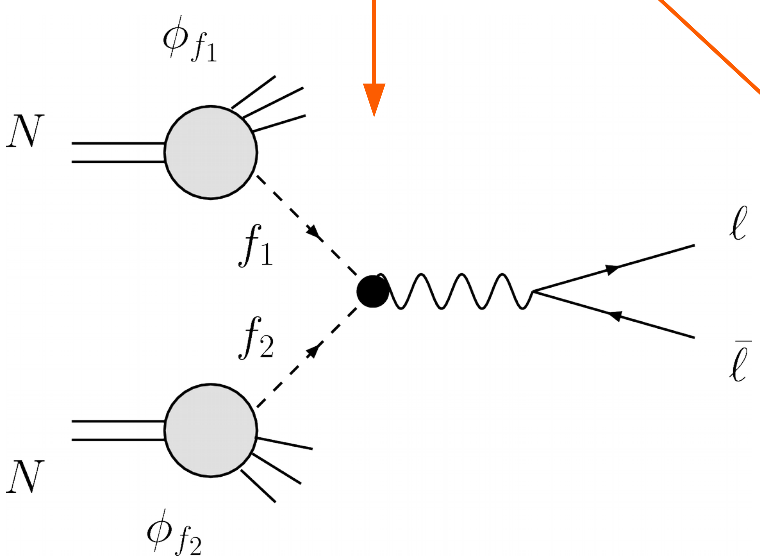
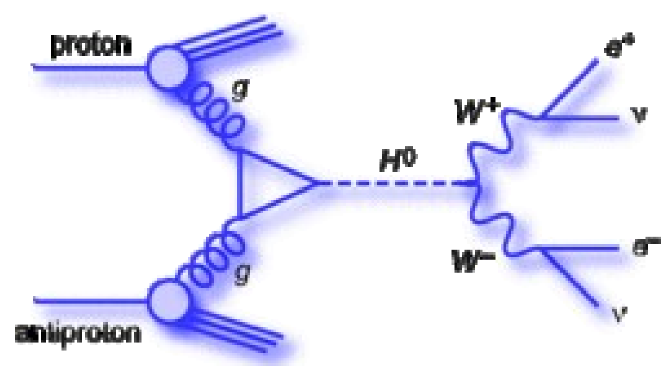


# Global PDF fits

- **Problem**: we need a set of PDFs in order to
  - calculate a particular hard-scattering process (old or new physics)
  - Investigate non-perturbative QCD: quark binding, ….

- **Solution**:
  - Choose data from a set of different, trustable, hard scattering processes
  - Generate PDFs using a parametrized functional form at initial scale $Q_0$; evolve them from $Q_0$ to any $Q$ using DGLAP evolution equations
  - Use the PDF to compute the chosen hard scatterings
  - Repeatedly vary the parameters and evolve the PDFs again
  - Obtain an optimal fit to a set of data.

- **Modern PDF sets**: CTEQ-TEA (CT18), CTEQ-JLab (CJ15), MMHT, NNPDF3.1, ABM16, JR09, HERAPDF1.5

# Global PDF fits

**data**

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

**theory**

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

**fits**

- Parametrize PDF at $Q_0$, evolve to $Q$
- Minimize $\chi^2$

**PDFs**

**$F_2$(n)**

**W, Z / W',Z', Higgs**

(or any other "hard" observable)

# The CJ15 global QCD analysis

# The CTEQ-JLab global analysis

- **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**
  - **Accardi, Brady, Melnitchouk, Owens, Sato, PRD 93 (2016) 114017**
    - www.jlab.org/cj
    - Included in LHAPDF

# Global PDF fits as a tool

- **Test new theoretical ideas**
  - *e.g.*, are sea-quarks asymmetric? Is there any "intrinsic" charm?

- **Phenomenology explorations**
  - *e.g.*, can CDF / HERA "excesses" be at all due to glue/quark underestimate at large *x*? Are there new particles at the LHC?

- **Test / constrain models**
  - *e.g.*, by extrapolating *d/u* at *x=1*
  - Constrain nuclear theory corrections !!

- **Limitations**
  - existing data
  - experimental uncertainty
  - theoretical uncertainty

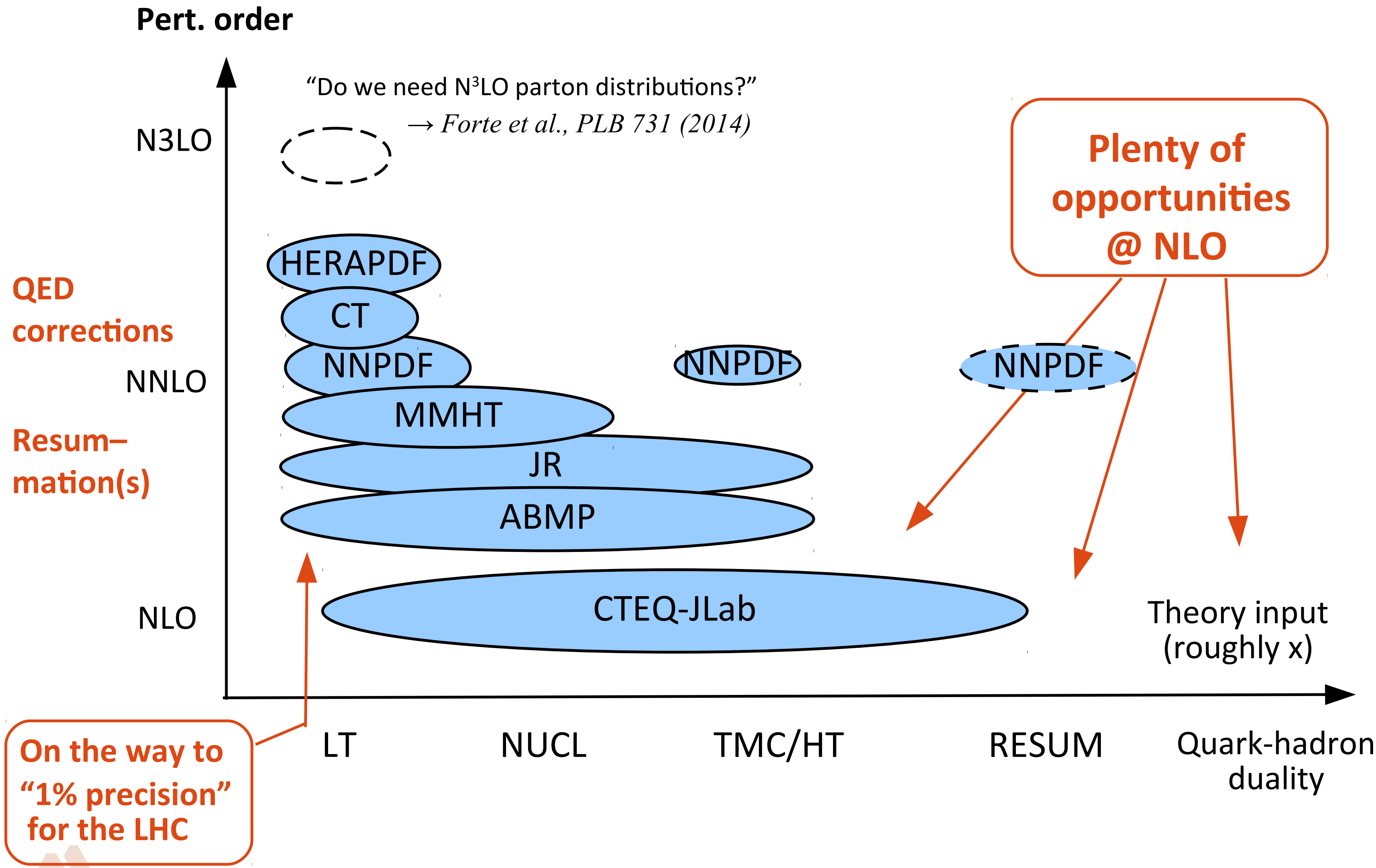
**As a user you should be aware of these**

# 35+ years of unpolarized global PDF fits

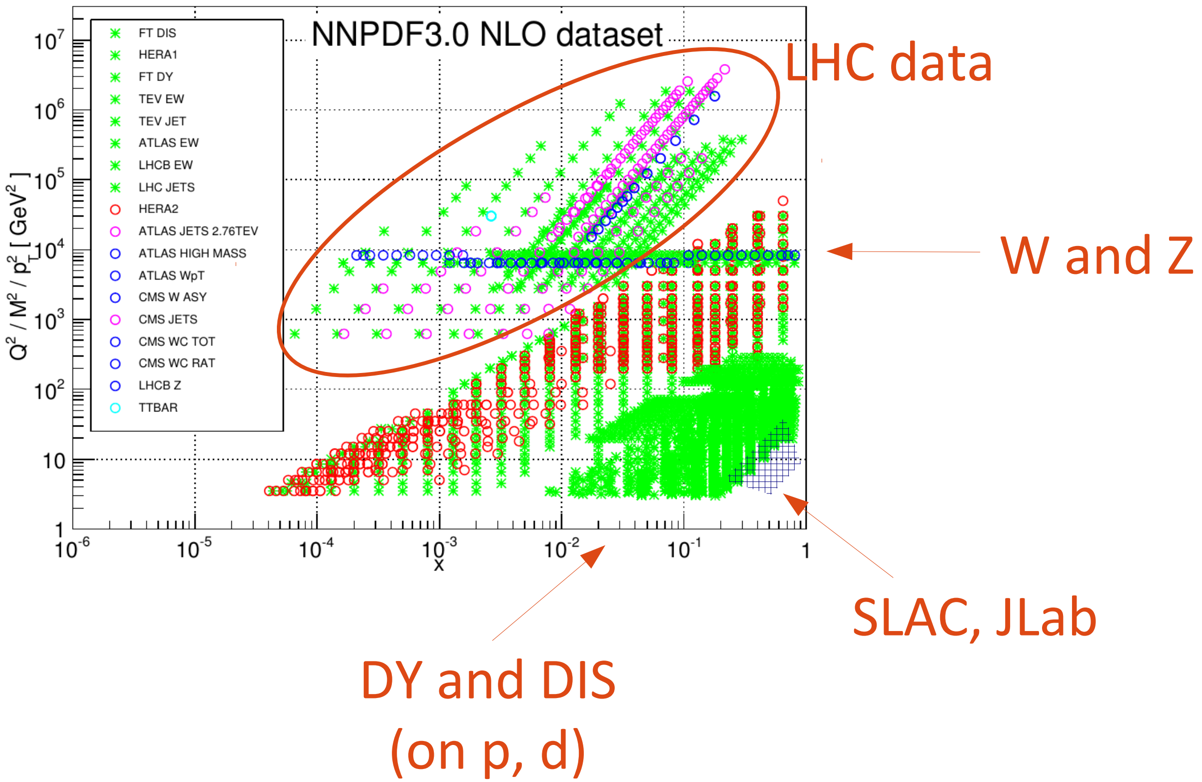
| | JLab & BONUS | HERMES | HERA I+II | Tevatron new W,Z | LHC | ν+A di-μ | Large-*x* treatment: Nucl. | HT TMC | Flex *d* | low-W DIS |
|---|---|---|---|---|---|---|---|---|---|---|
| **CJ15** * | ✓ | ✓ | ✓ | ✓ | *in prog.* | ✗ | ✓✓ | ✓ | ✓ | ✓ |
| CT18 | | | ✓ | ✓ ¤¤ | ✓ | ✓ | | | ✓ | |
| MMHT14 | | | ¤¤¤ | ✓ ¤¤ | ✓ | ✓ | ✓ | | | |
| NNPDF3.1 | | | ✓ | | ✓ | ✓ | | TMC only | | |
| JR14 | ✓ | | | | ✓ | ✓ | ✓ | ✓ | | |
| **ABMP16/17** ** | | | | ✓ ¤¤ | ✓ | ✓ | ✓✓ | ✓ | | ✓ |
| HERAPDF2.0 | | | ✓ | ¤ | | | | | | |

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

# A PDF landscape



# Data coverage for PDF fits



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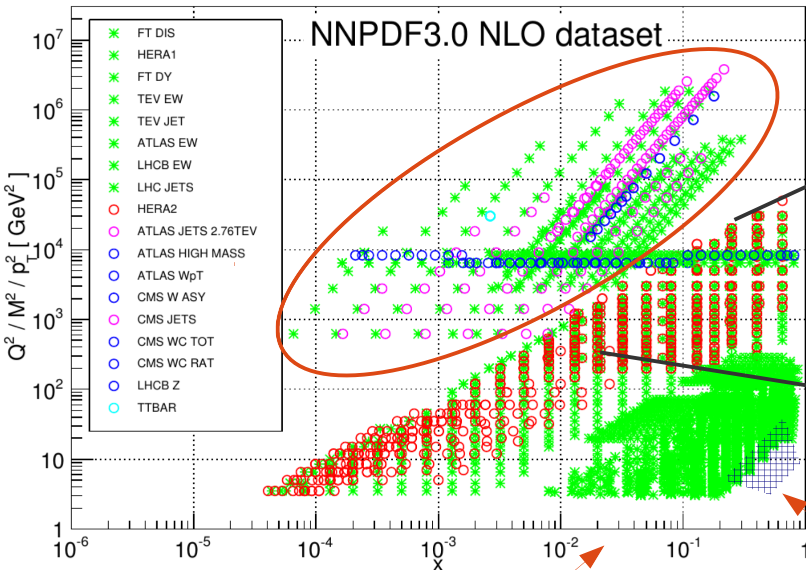
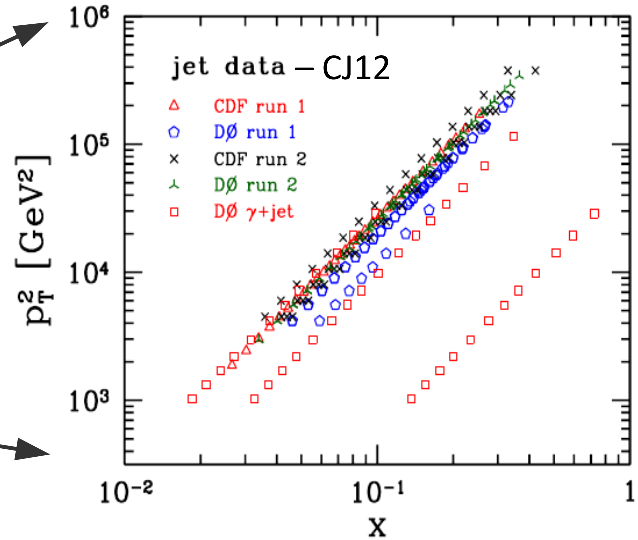



LHC data

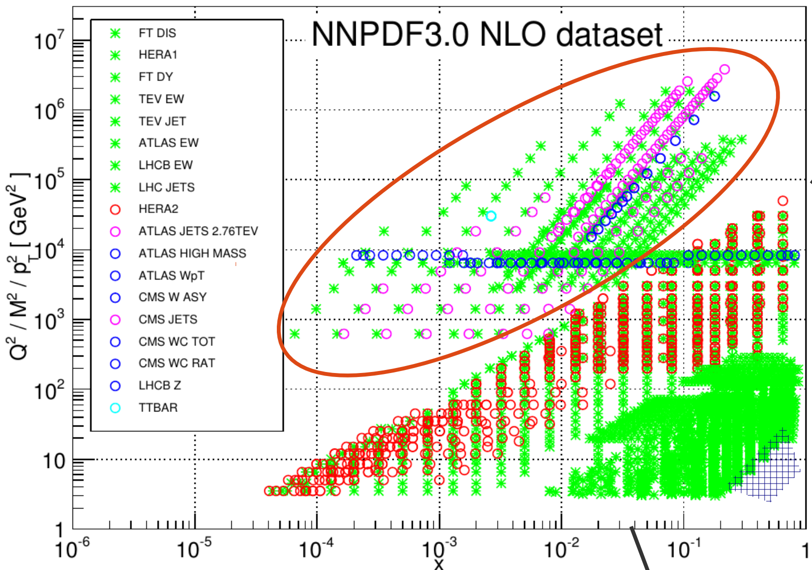
Tevatron Jets




SLAC, JLab

DY and DIS
(on p, d)

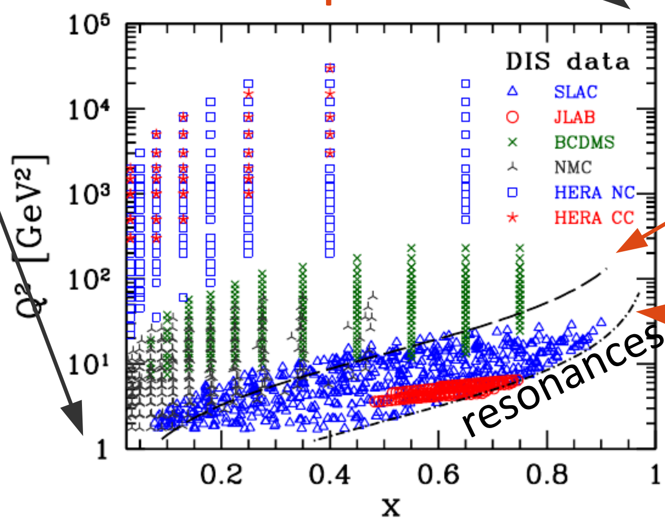
# Data coverage for PDF fits




LHC data

Scant large-x coverage in DIS !

DIS – prot. & deut.

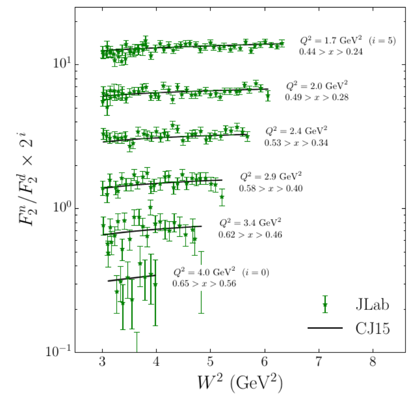


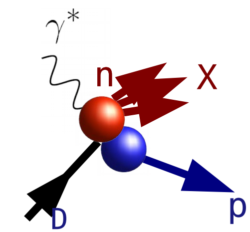

standard cut
$W^2 \gtrsim 14\ \mathrm{GeV}^2$

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

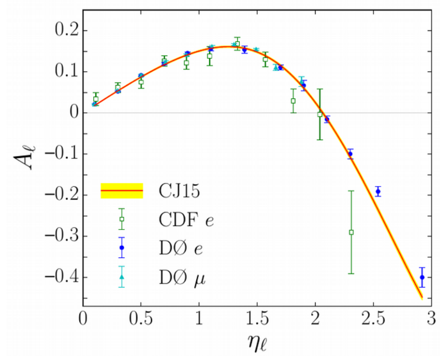
# New in CJ15

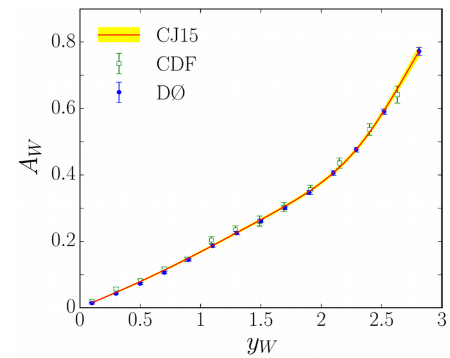
- s-ACOT scheme for heavy flavors

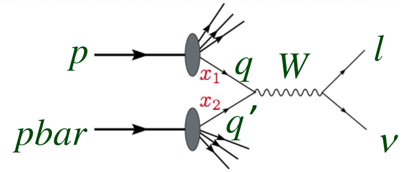


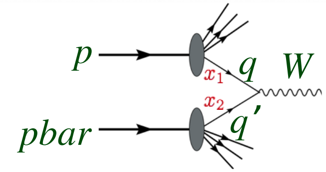




- **New data:**
  - BONUS spectator tagged DIS on neutrons
  - HERA I+II combination
  - HERMES F2
  - High-statistics W-boson charge asymmetries from D0



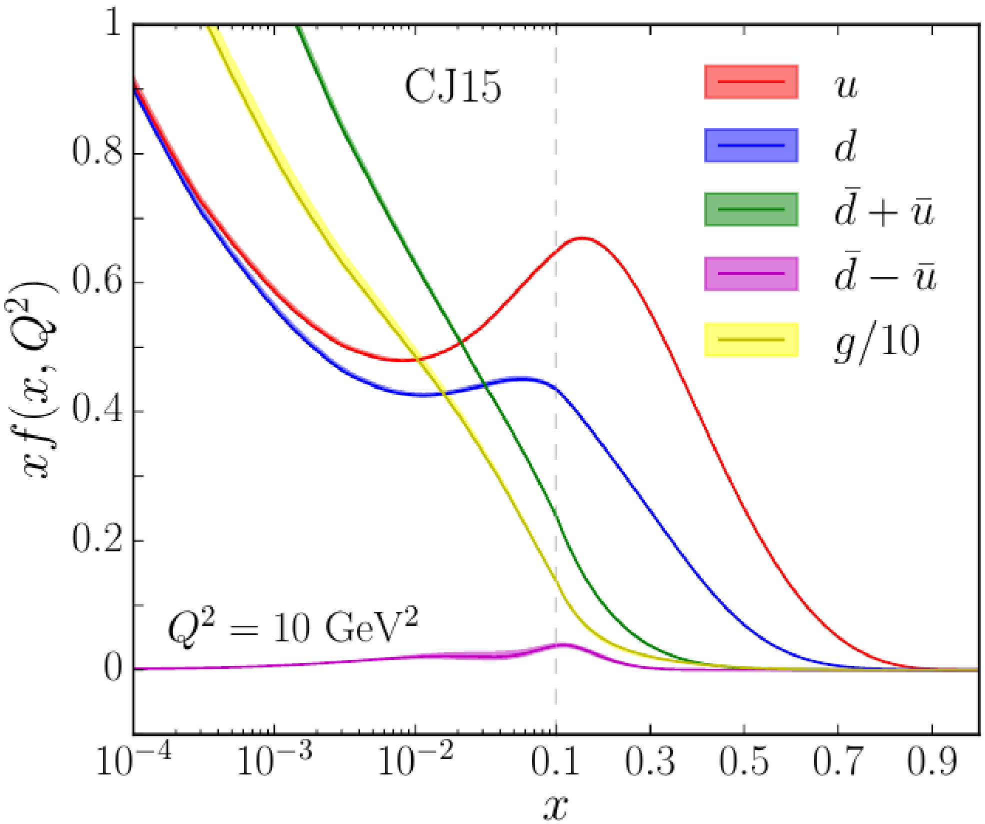




- **New off-shell nucleon treatment in deuteron targets (DIS and DY)**
  - Parametrized vs. modeled → absorbs wave function uncertainty
  - Comparison to extraction from DIS on heavier targets

# CJ15 - PDFs




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

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

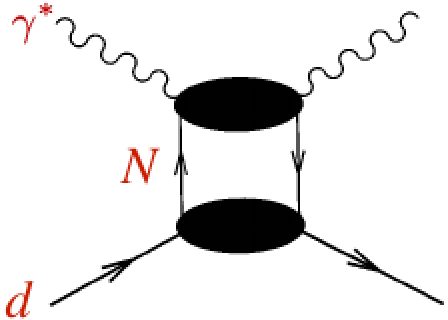
( 90% confidence level
in a perfect, Gaussian world )

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

# d/u extraction
# (and not only)

# Deuteron target: needs nuclear corrections

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




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

nucleon momentum distribution in $d$ ("smearing function")

PDF in bound (off-shell) nucleon

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

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

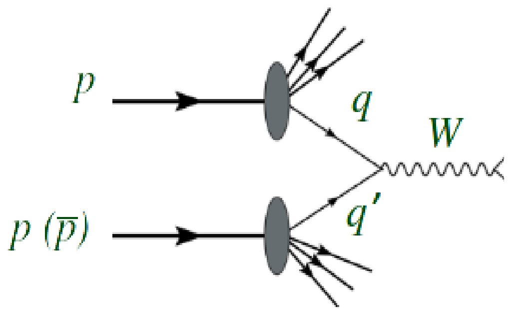
$$\tilde{q}^N(x,p^2) = q^N(x)\left[1 + \frac{(p^2-M^2)}{M^2}\,\delta q^N(x)\right]$$

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

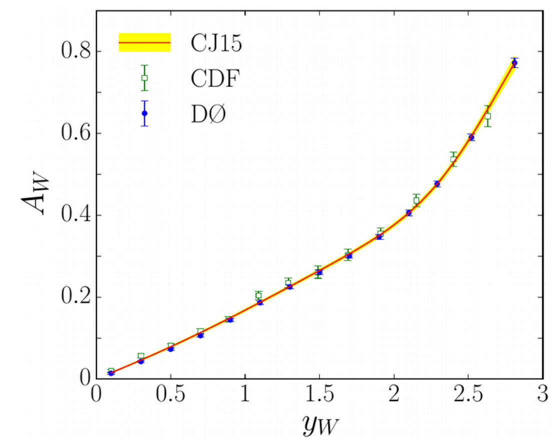
# Tevatron as NUCL facility (!)

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

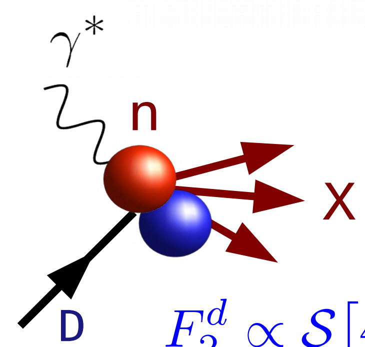
- ***Reconstructed W*** $\longrightarrow$ constrain ***d*-quark at largest x** on proton targets




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




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



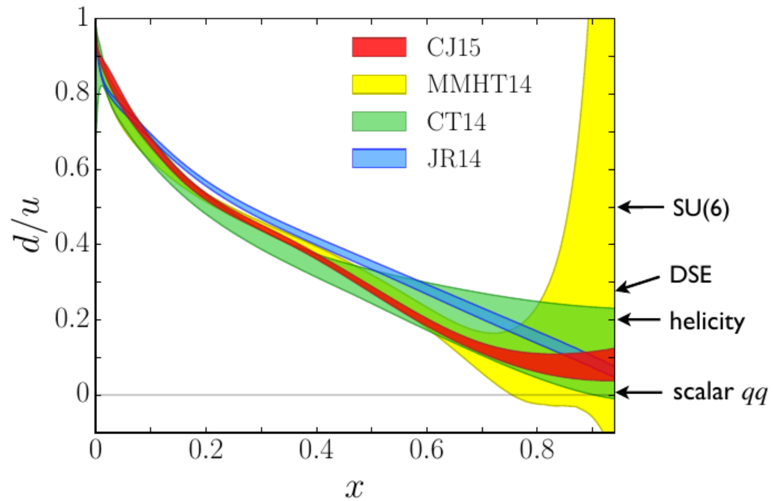

$$F_2^d \propto \mathcal{S}\left[4xu(x) + xd(x)\right]$$

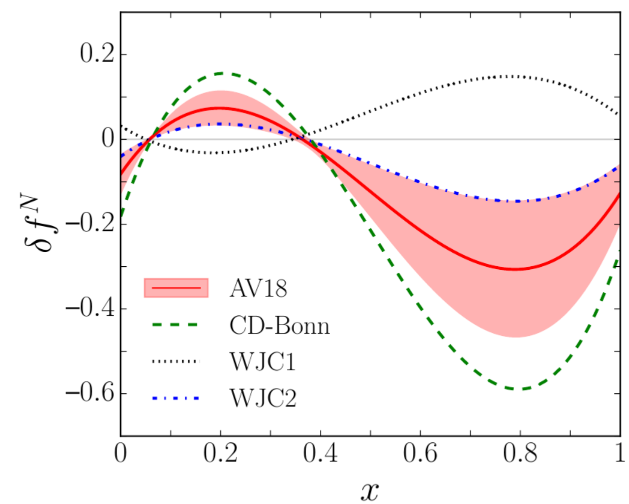
- Currently, mostly a **DØ vs. SLAC(d) interplay**

# 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



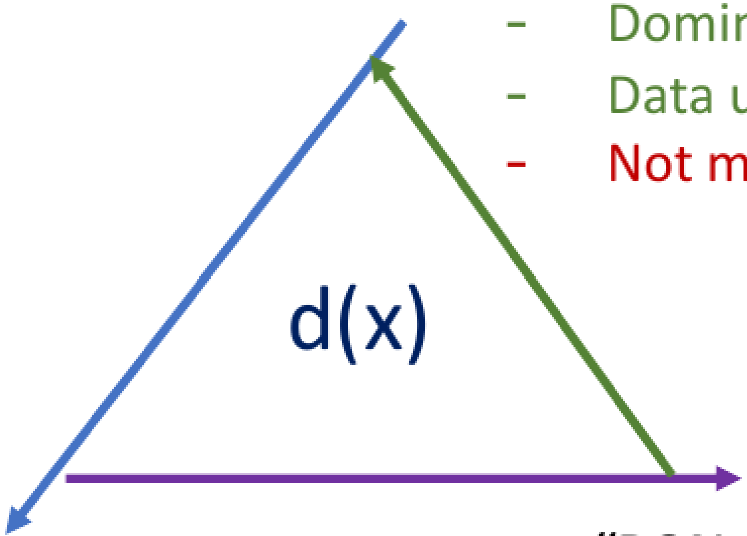

- **Opens novel possibilities**: test nuclear theory ideas against <u>other</u> data:
  - Test "EMC effect" models (of course)
  - On the lattice: "nucleon response to external color field"
  - …

# Interplay of observables

*Keppel, DIS 2019 talk*

**D0, CDF asymmetries**

- Dominant constraint on d(x)
- Data up to x ~ 0.7
- Not much data (~a dozen points)




**Deep inelastic deuterium**

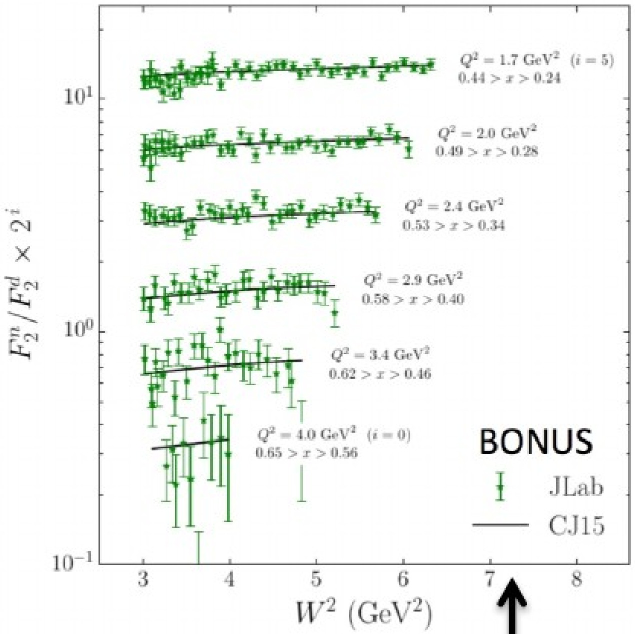
- Large body of data from multiple experiments
- Data up to x ~0.9
- $Q^2$ range for evolution
- Requires deuteron nuclear corrections

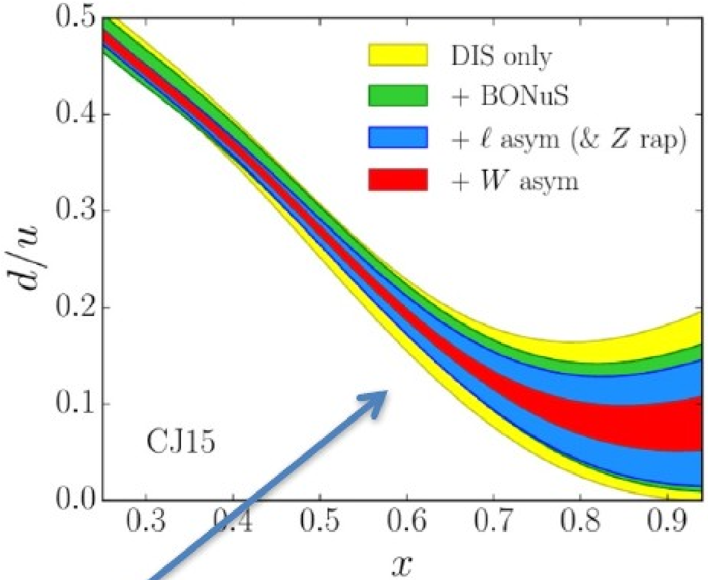
**"BONuS" tagged neutron target**

- Nearly model-independent *neutron* data
- Data obtained in 6 GeV JLab era at low W, Q

# Interplay of observables

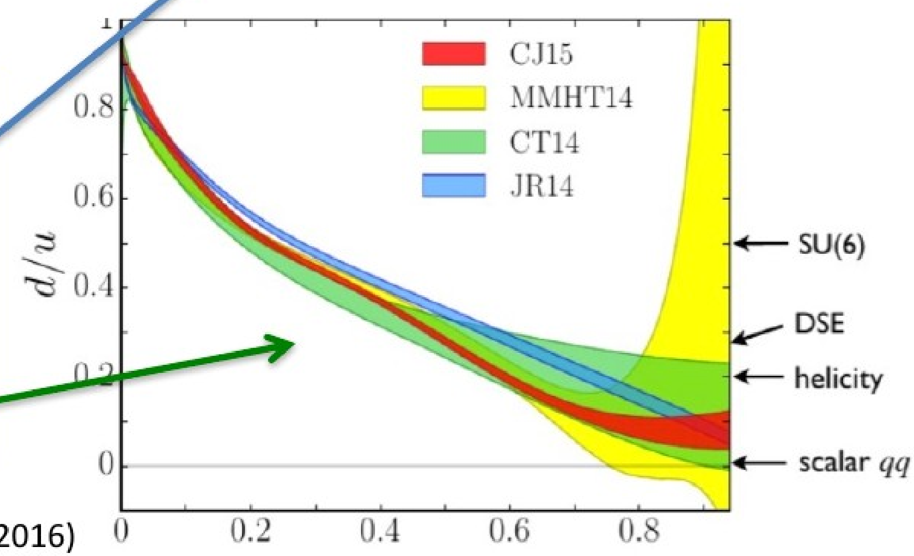
*Keppel, DIS 2019 talk*




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)

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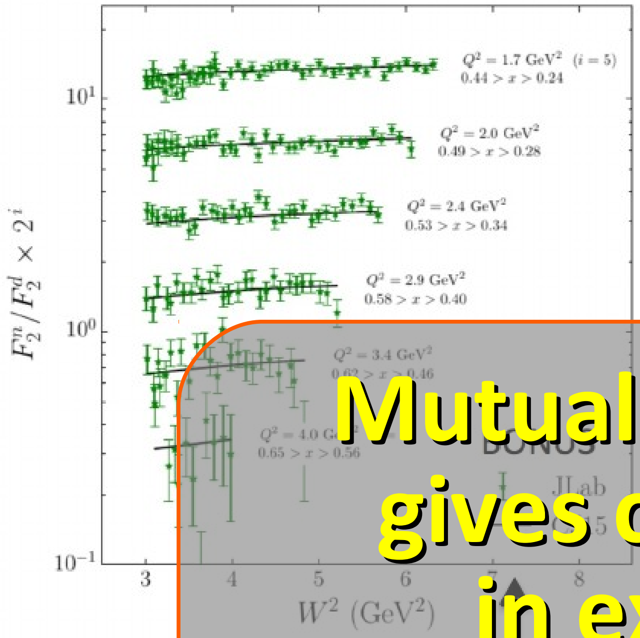


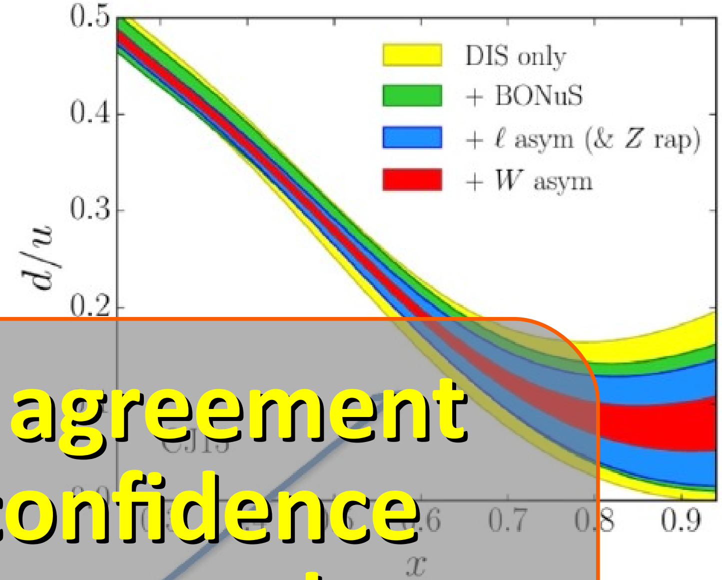


CJ15

Mutual agreement gives confidence in extracted deuteron corrections

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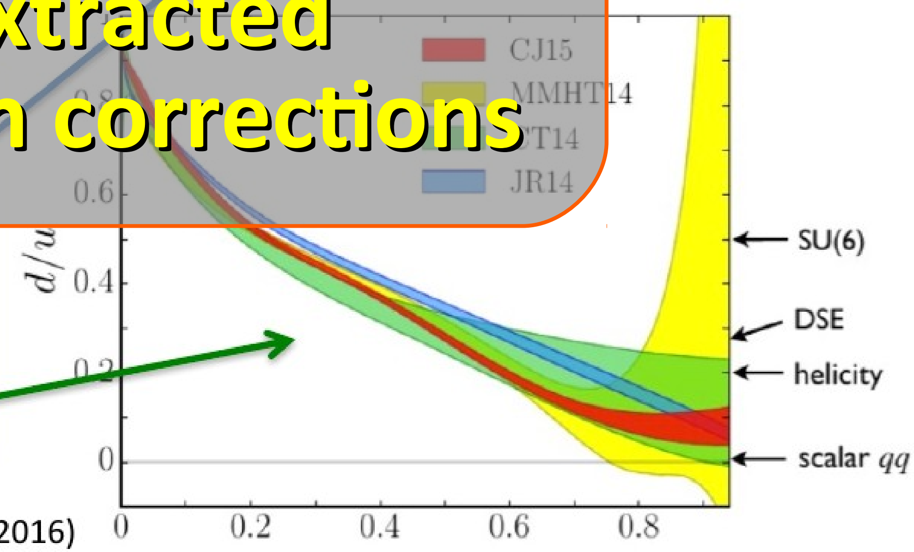
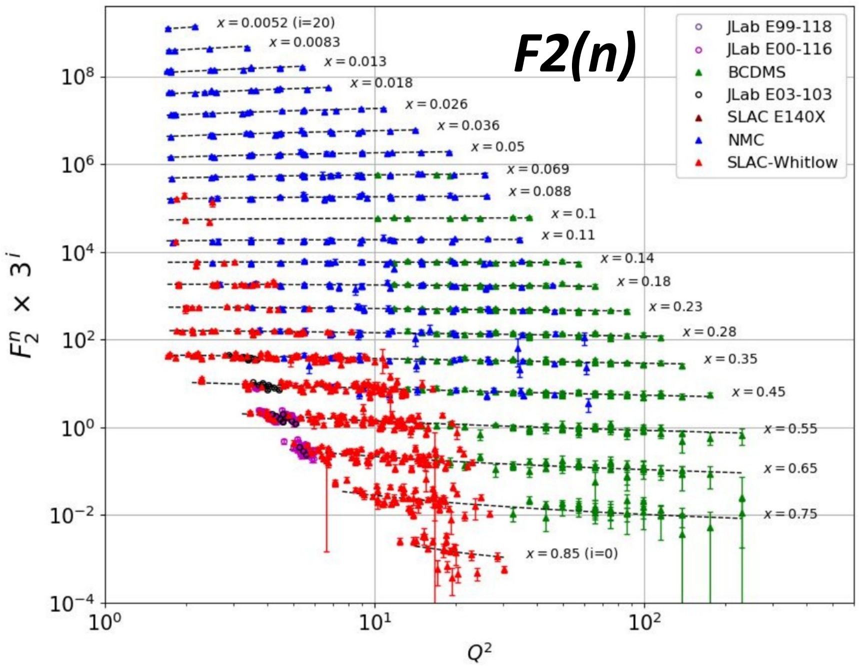
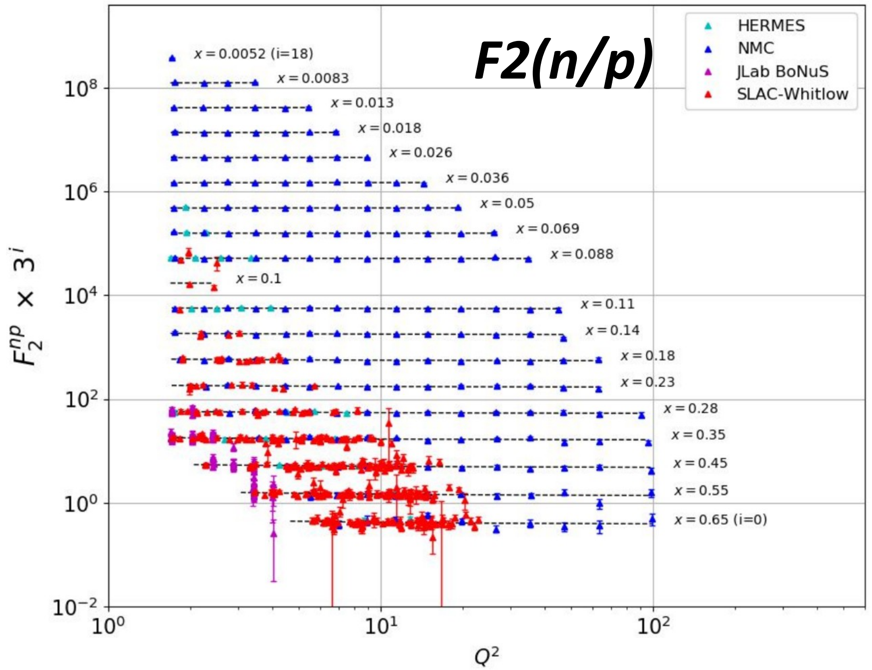



A. Accardi, et al., Phys. Rev. D **93** 114017 (2016)

# Application: Neutron DIS “data”

- **F2(neutron) extraction –** *with Shujie Li*
  - 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)***
    - → *Use, e.g, for **“pure” A/(free nucleons) “EMC” ratios***



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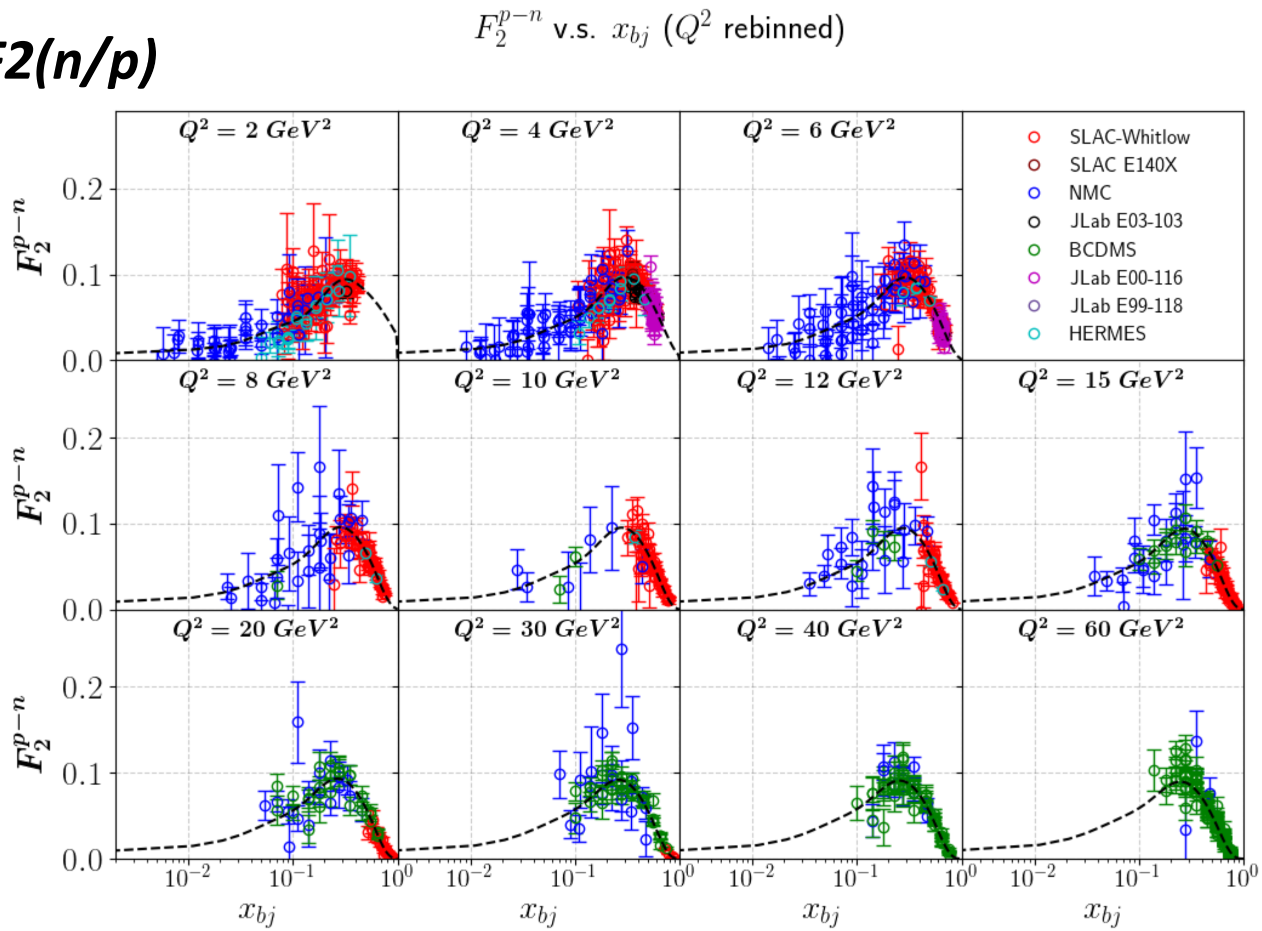
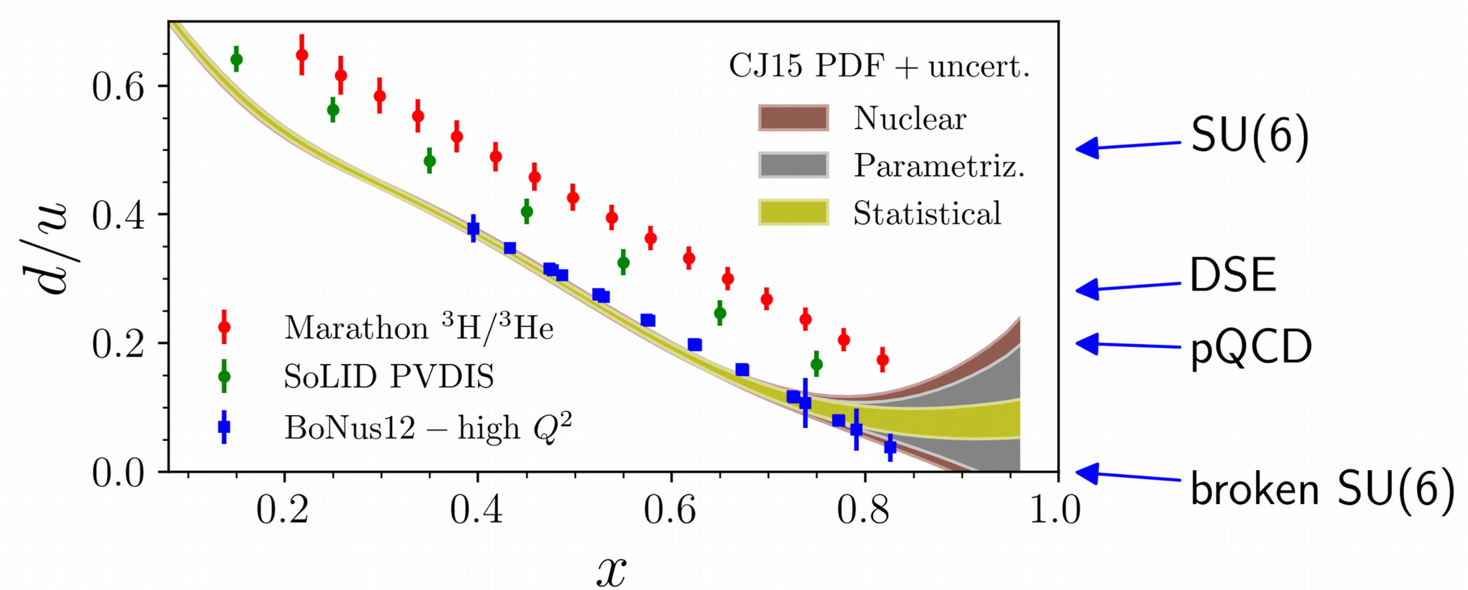
  - And ***F2(p-n)***



# d/u summary and future

# Summary: controlled PDFs at large x

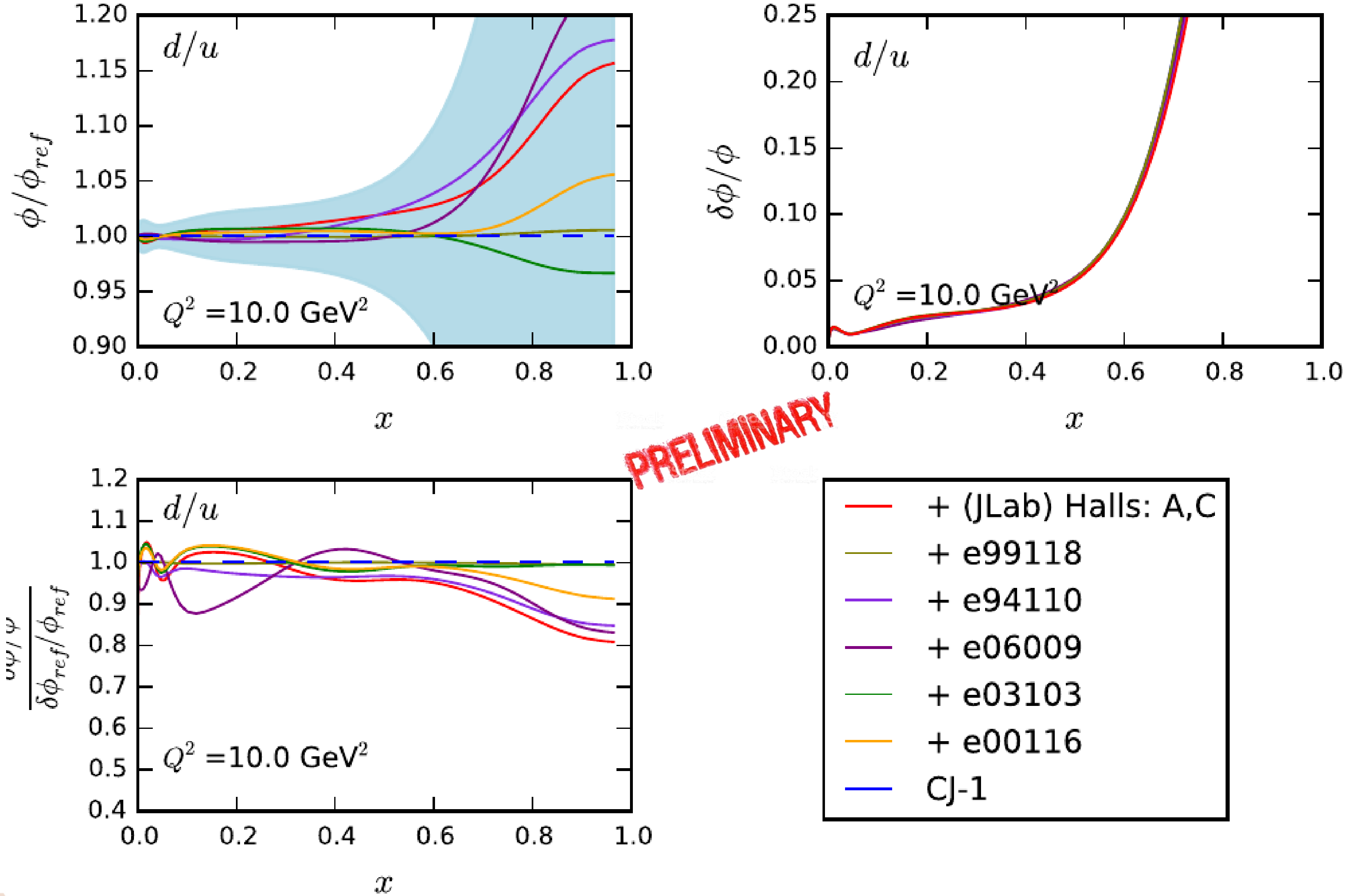
- **CJ15 provides the most controlled large-x PDF fit on the market**
  - ABPM16 next-best choice / benchmark




- Further progress needs **precise nucleus-free "control observables"…**
  - W asymmetry: RHIC
  - BoNus12, Marathon*, SoLID PVDIS
- **…and more p, d DIS**

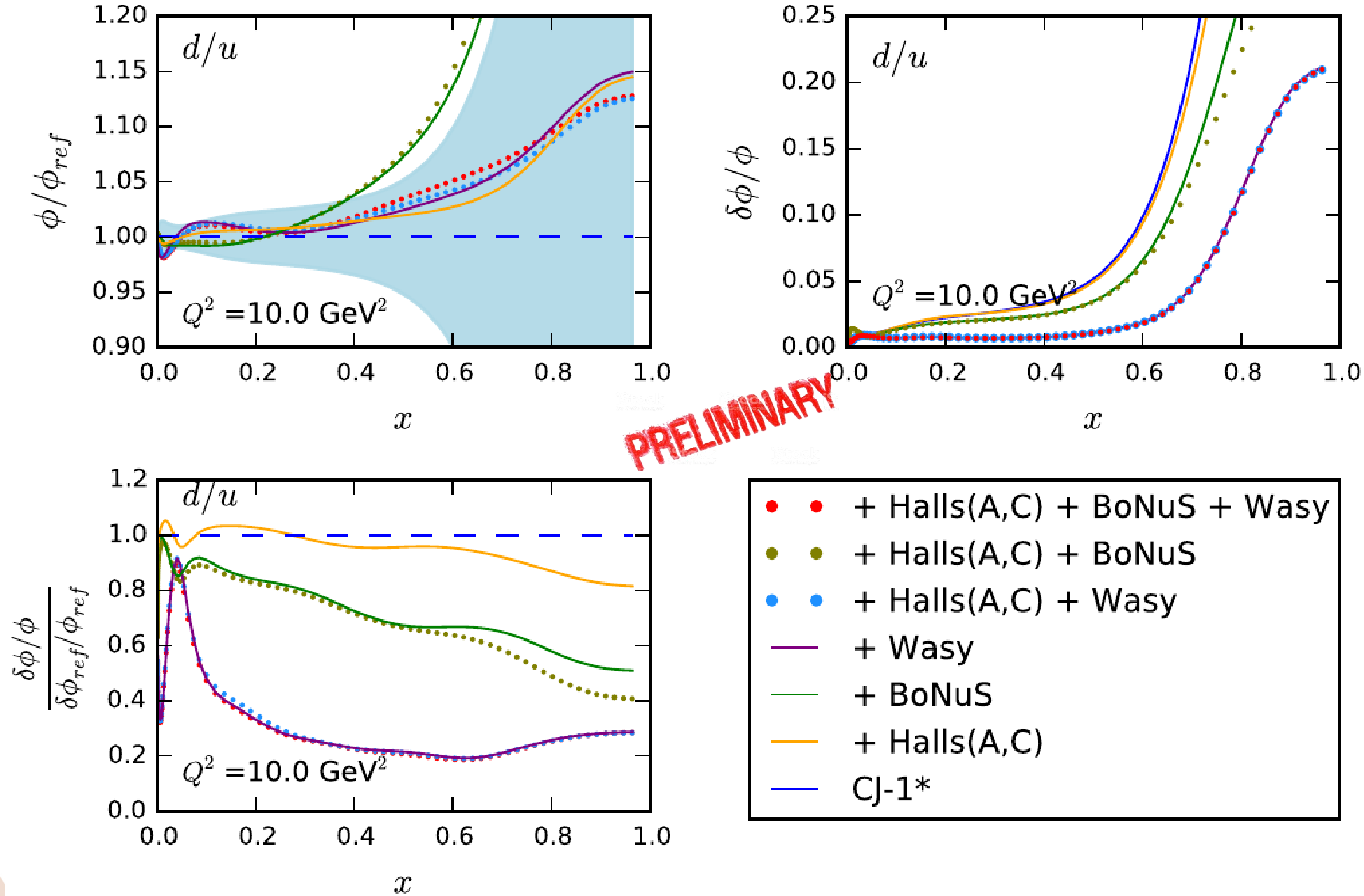
# More p, d DIS → Jlab 6

*CJ + I.Fernando + F.Araiza-Gonzalez*



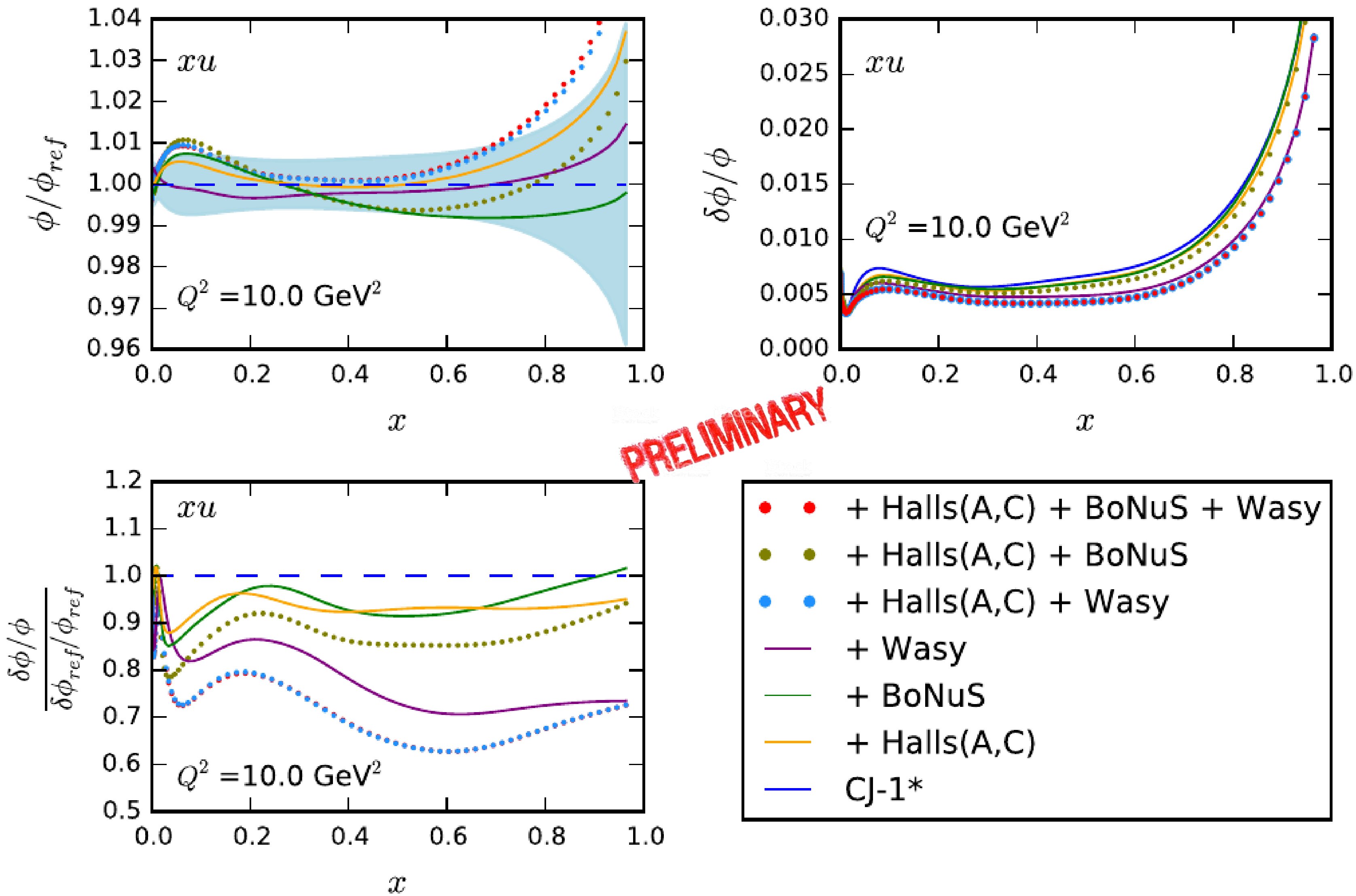
# More p, d DIS → Jlab 6

*CJ + I.Fernando + F.Araiza-Gonzalez*



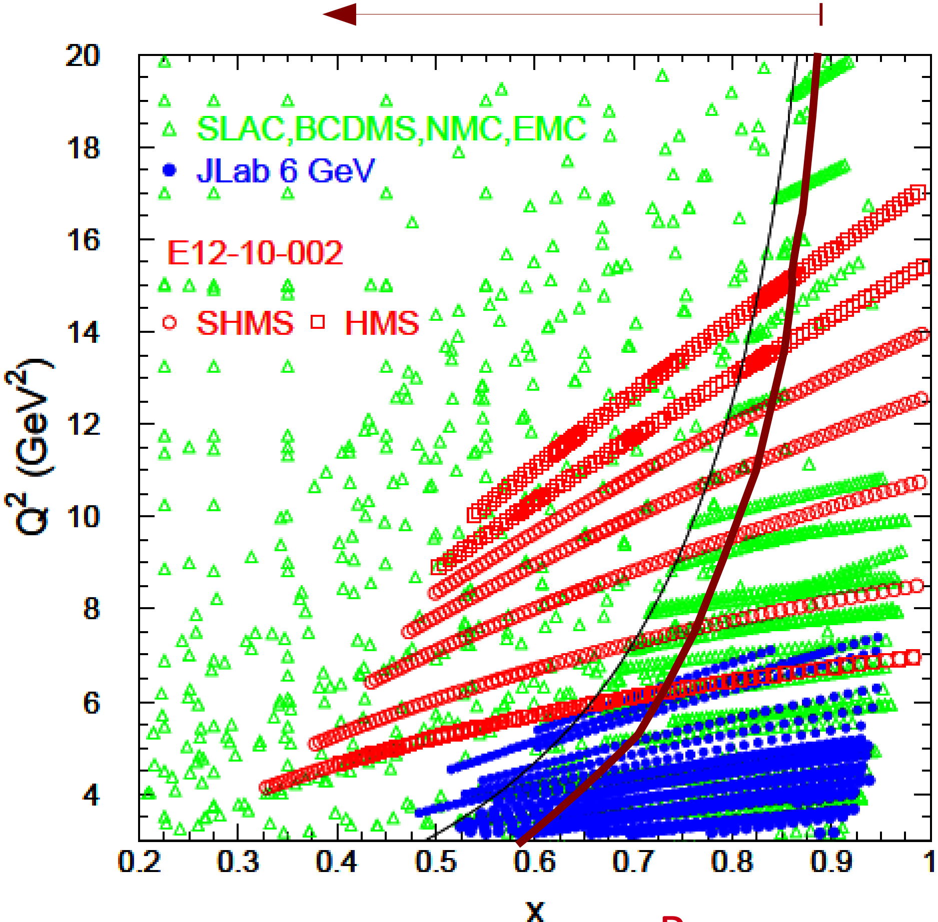
# More p, d DIS → Jlab 6

*CJ + I.Fernando + F.Araiza-Gonzalez*



# More p, d DIS → Jlab 12

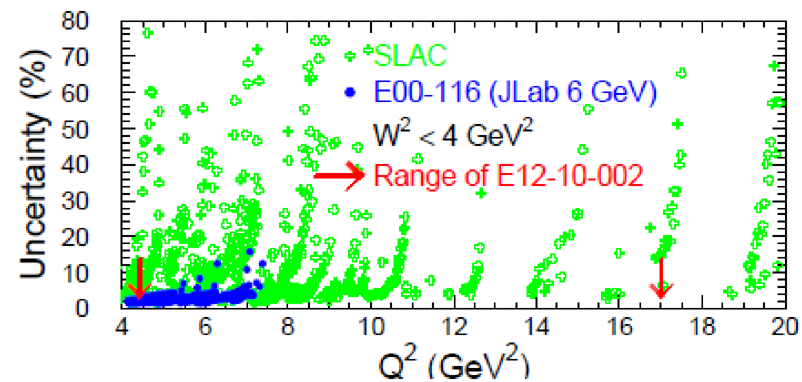
CJ cut: $W^2 > 3\ \mathrm{GeV}^2$




DIS region

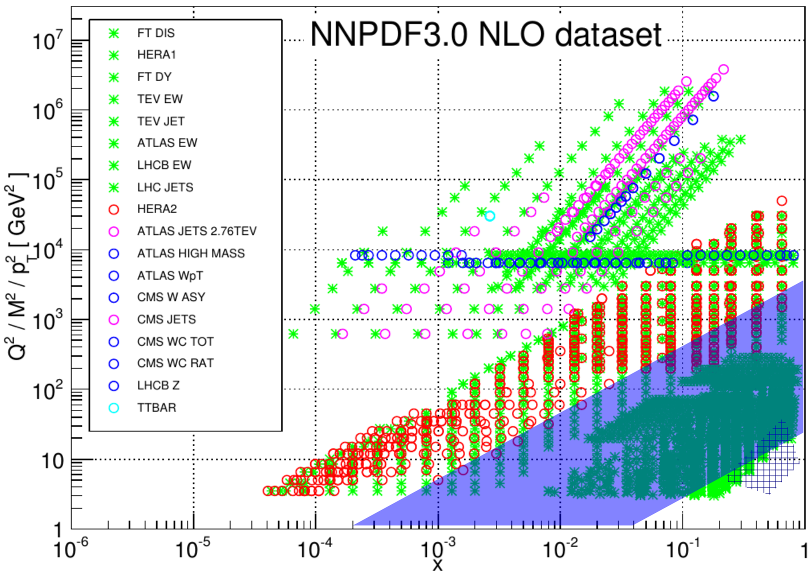
Resonance region

*Jlab12 experiment E12-10-002*




- **JLab 12 GeV**
  - More than double $Q^2$ range
  - Similar precision as JLab **6 GeV** (largely improve cf. **SLAC**)

# Enters the EIC



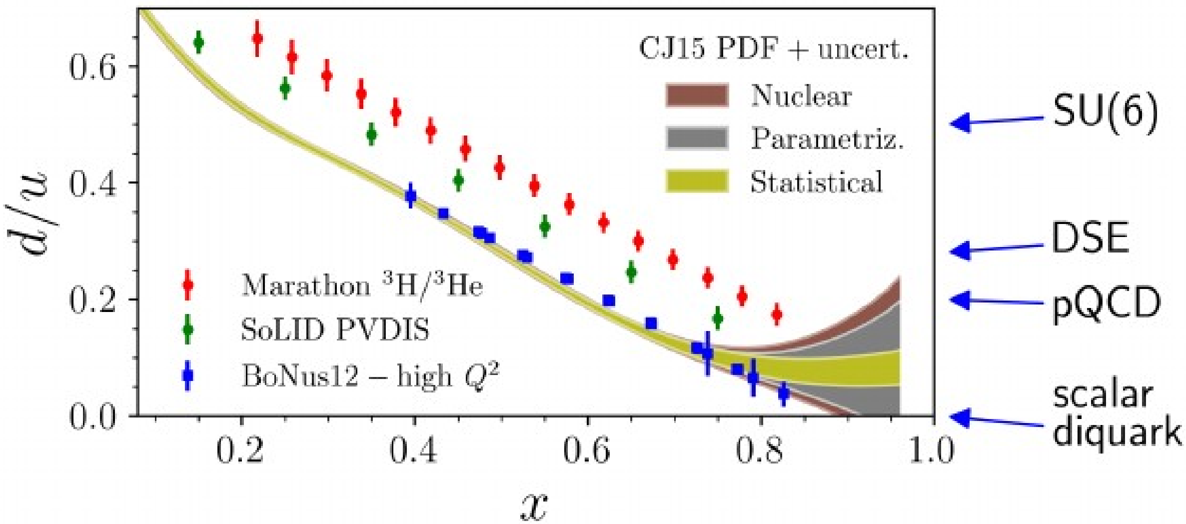

- ❑ Interpolates fixed target and HERA
- ❑ Large $Q^2$ leverage
  - – More evolution at large *x*
  - – Better separation of LT and HT
- ❑ High luminosity → large *x* capabilities

*→ 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)

# 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 $F_2^{p,d}$
  - ✓ Hall A $^3H/^3He$
- 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!!**

# Backup

# NUCL / HEP symbiosis

| Observable | Experiment | # points | $\chi^2$ | | | |
|---|---|---|---|---|---|---|
| | | | 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 ($\mu$) [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 |
| | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| $\chi^2$/datum | | | 1.33 | **1.04** | 1.04 | 1.09 |

# NUCL / HEP symbiosis

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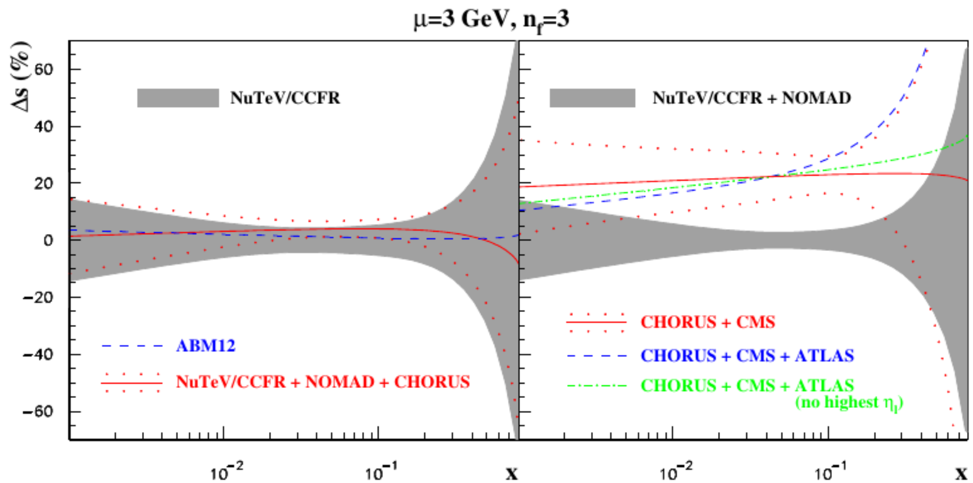
- Ignoring nuclear dynamics, SLAC(d) and D0(W) pull *d* quark in opposite directions
  - **D0 (W) data determine nuclear corrections !!**
  - other asymmetries inconclusive by themselves
  - **BONUS data validate DO(W) analysis**

# Example 2: strange strange quarks

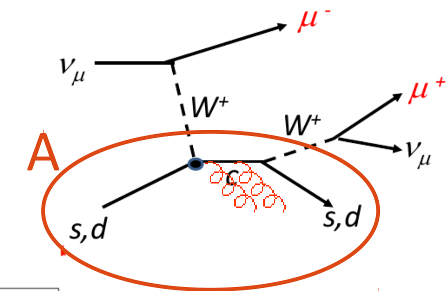
- **$\nu$+*A* → dimuons** *vs.* ***p+p* → *W+c* at LHC** *Alekhin et al., arXiv:1404.6469*




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

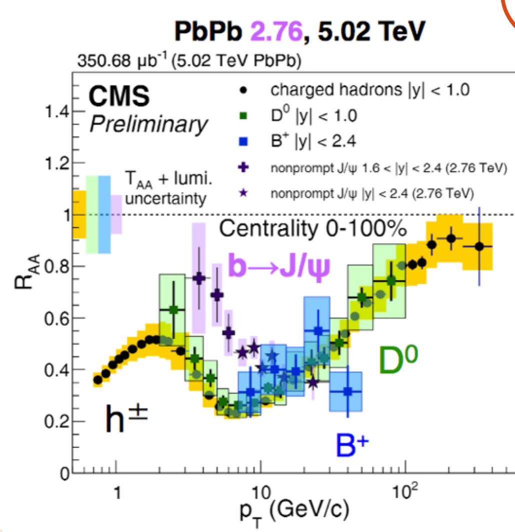
$$\nu\, s_A \to \mu^- \mu^+ \nu_\mu\, s$$

FSI ?




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

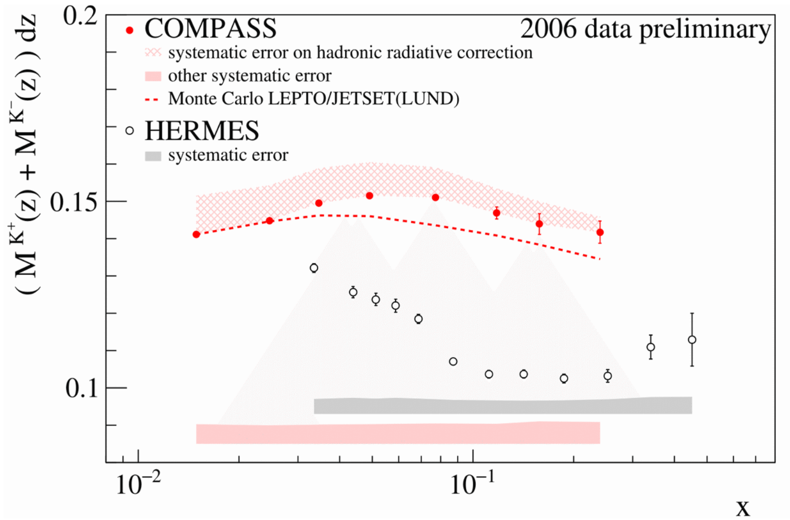
$$R^h_{AA} = \frac{\left(dN^h/d^2p_T\right)_{AA}}{N_{col} \times \left(dN^h/d^2p_T\right)_{pp}}$$




*Yen-Jie , Quark Matter 2017*

# Example 2: strange strange quarks

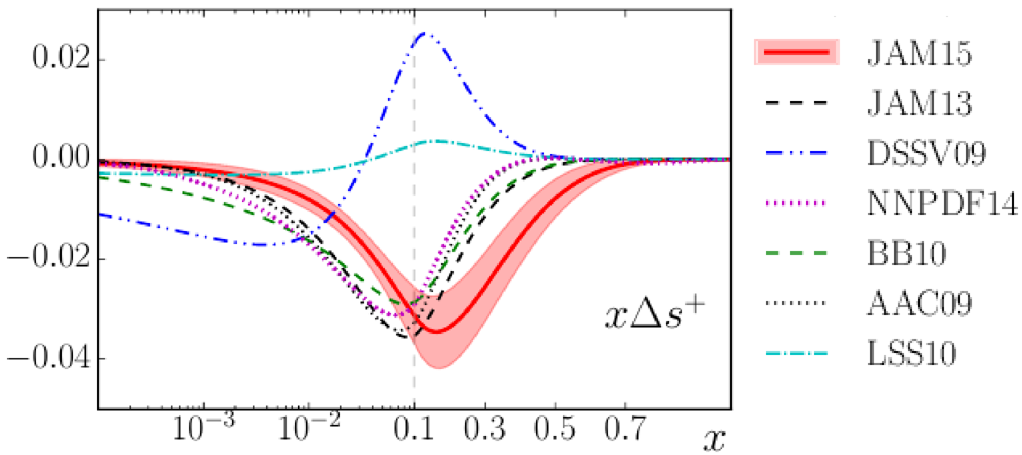
- **s : large or small?**
  - Possibly, large Hadron Mass effects
    *Guerrero, Accardi, in preparation*
  - Extraction of s(x) strongly affected by **kaon <u>systematic</u> uncertainty**




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

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

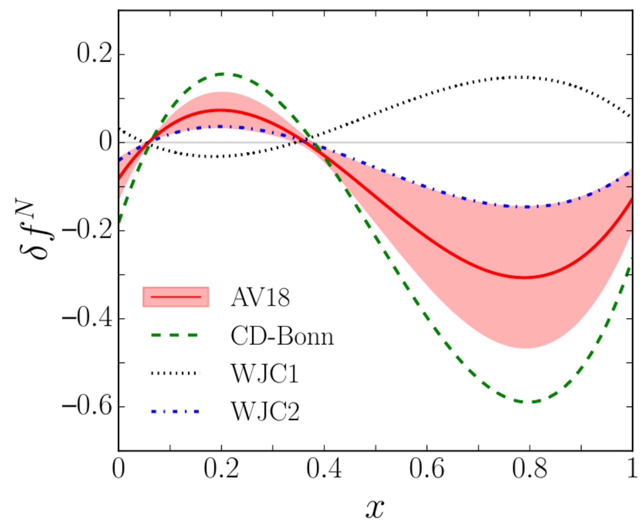
  - What about the unpol s ?

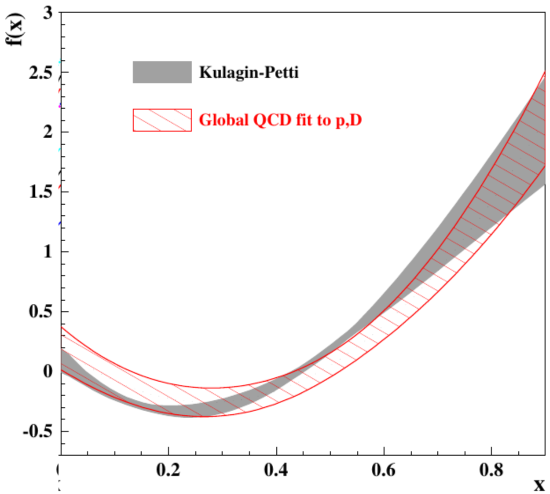


# Appendix:
# Nuclear corrections

# Nuclear physics output

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




*Kulagin, Petti, NPA 765 (2006) 126*

*Alekhin + KP PRD96 (2017) 054005*

- Different shape and size

  → no nuclear universality ?? $\delta f_N$

  → too hard nuclear spectral function at large momentum ??

  → ???