F2(p,n,d) at the EIC

- flavor separation at largish x -

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Hampton U. and Jefferson Lab

Large-x at the EIC

JLab, October 4th, 2016

Overview

- **A PDF landscape**
- **State of the art at large *x*: the CJ15 fit**
  - NUCL/HEP symbiosi
- **Why EIC ?**
- **Simulations with F2(p) F2(d) and F2n(p-tagged)**
  - u/d flavor separation
  - Bound nucleon structure
  - Gluons
- **Final thoughts**
  - What else can we do at EIC?

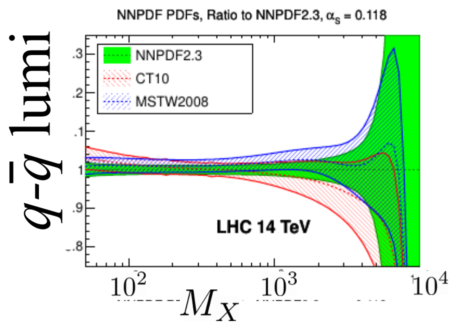
A PDF landscape

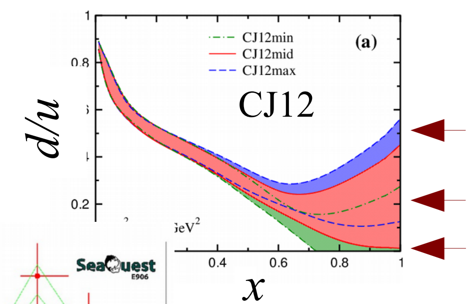
*Accardi, **PoS DIS2015 001** – "PDFs from protons to nuclei"*

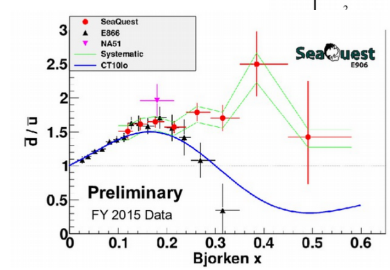
Why PDFs ?

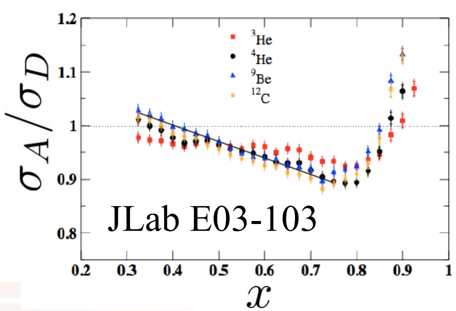
Accardi – Mod.Phys.Lett. A28 (2013) 35
Forte and Watt – Ann.Rev.Nucl.Part.Sci. 63 (2013) 291

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

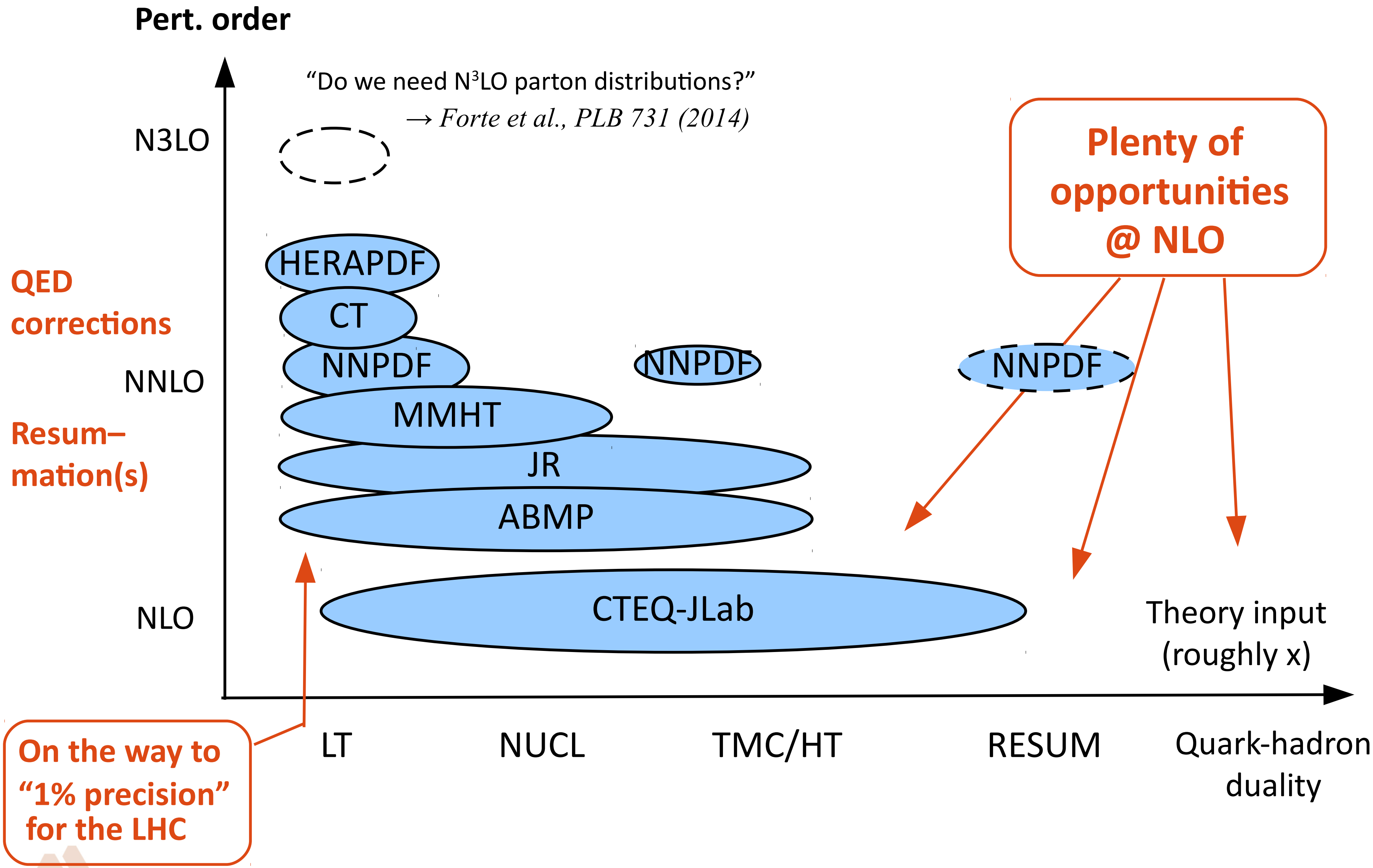




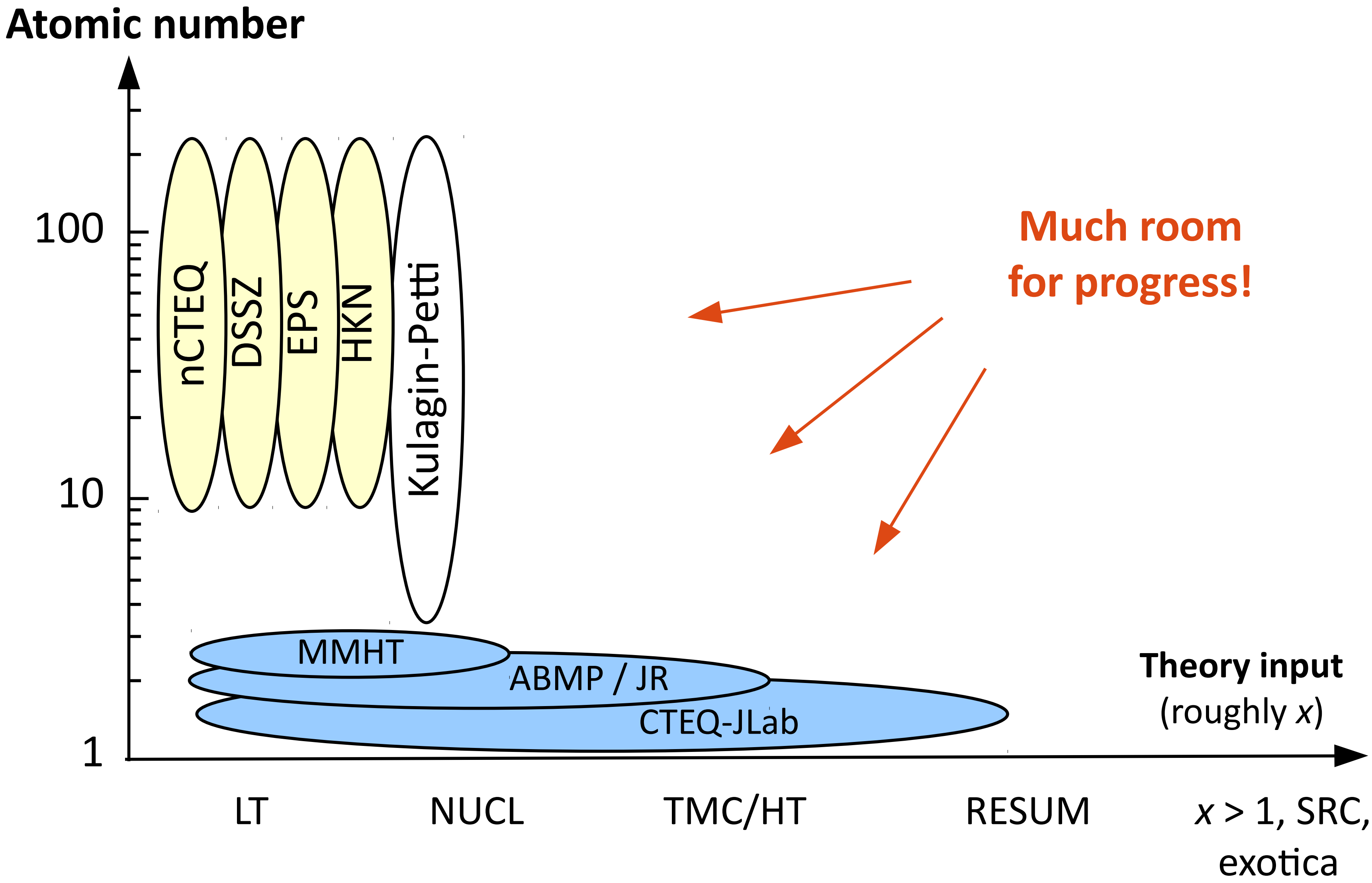




A PDF landscape

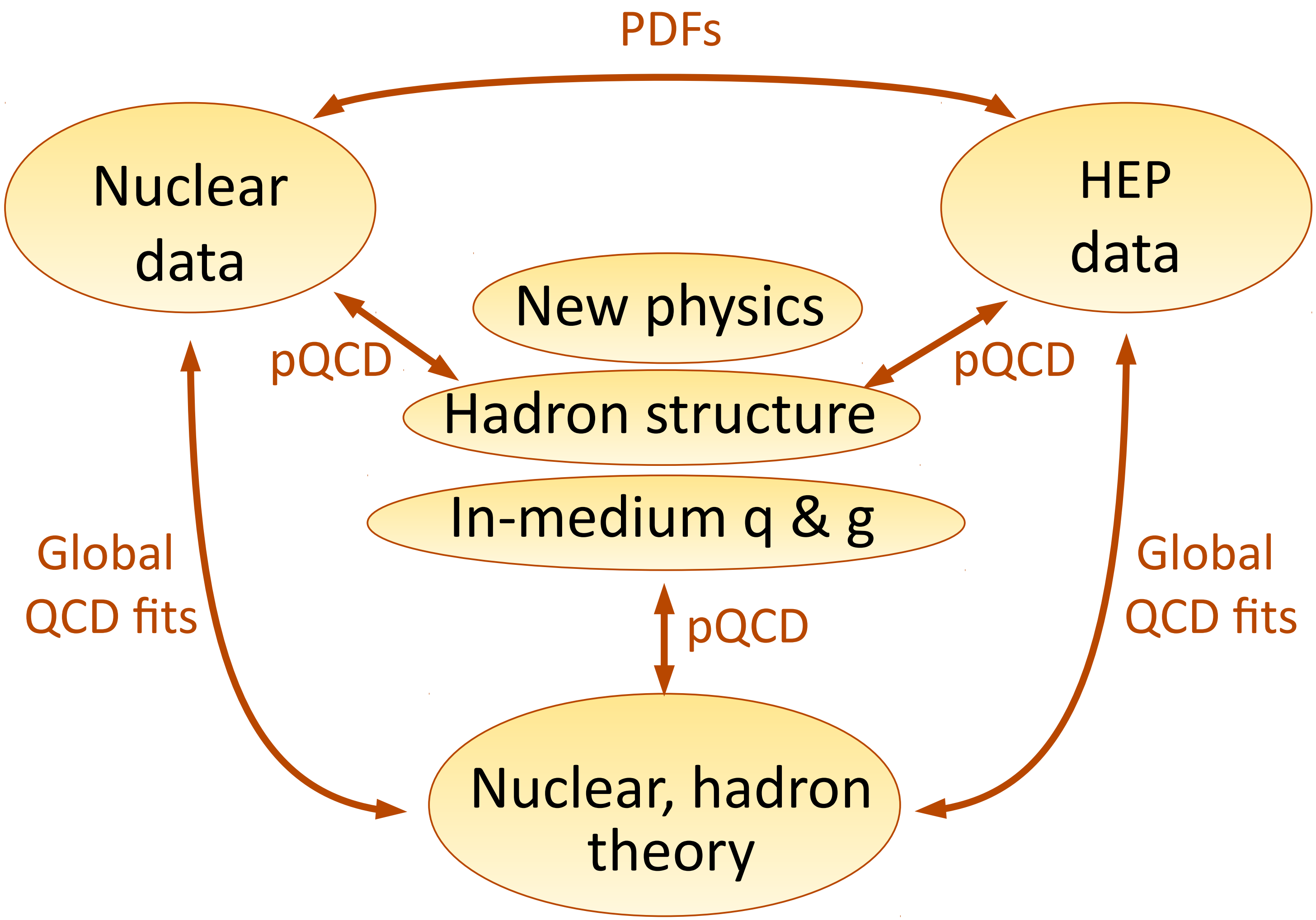


A nPDF landscape



Needs the betrothal of HEP and NUCL

- A global approach across subfields



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, et al. (2015 & 2016)*

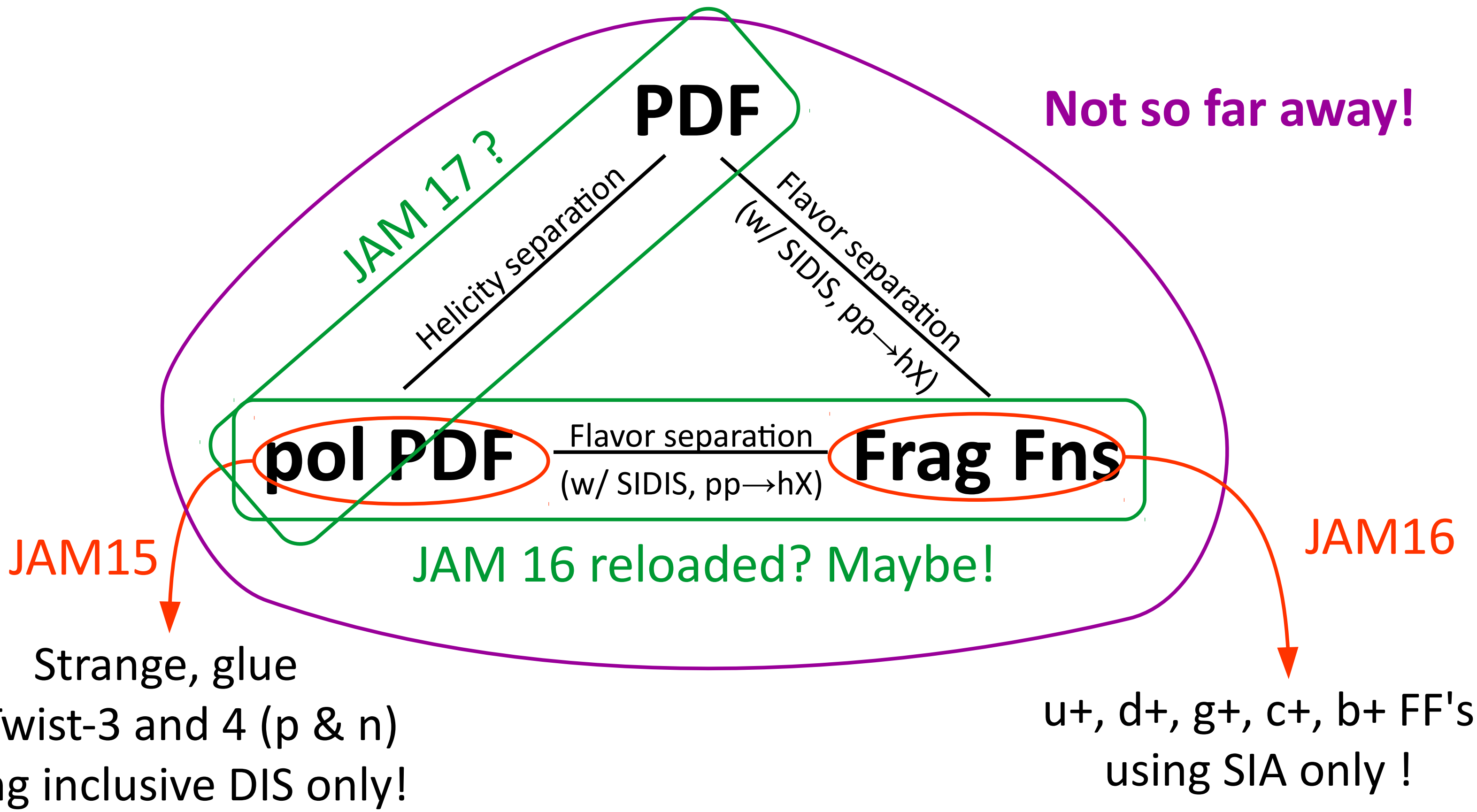
  Large number of parameters, trustable uncertainty estimates

- Self organizing maps → *Liuti et al.*

Iterative Monte Carlo approach

N.Sato at al [JAM], ***PRD93 (2016) 074005*** *and* ***arXiv:1609.00899***

- 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

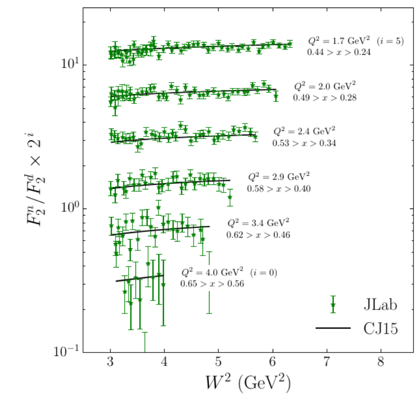
PDFs available on: `www.jlab.org/cj` *&* `LHAPDF`

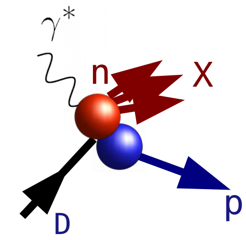
The CJ15 fit at a glance

	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

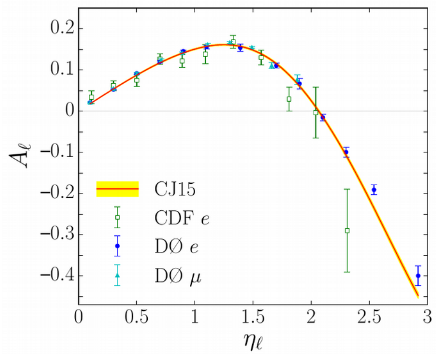
New in CJ15

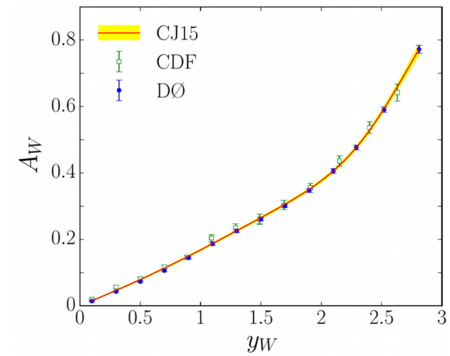


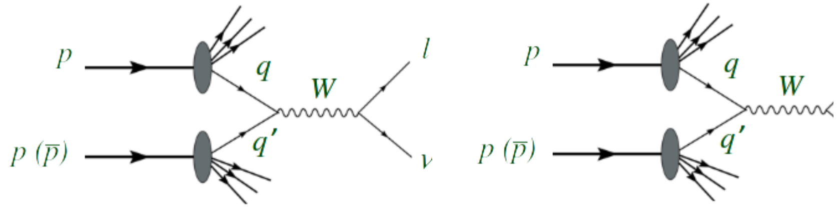


- s-ACOT scheme for heavy flavors

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

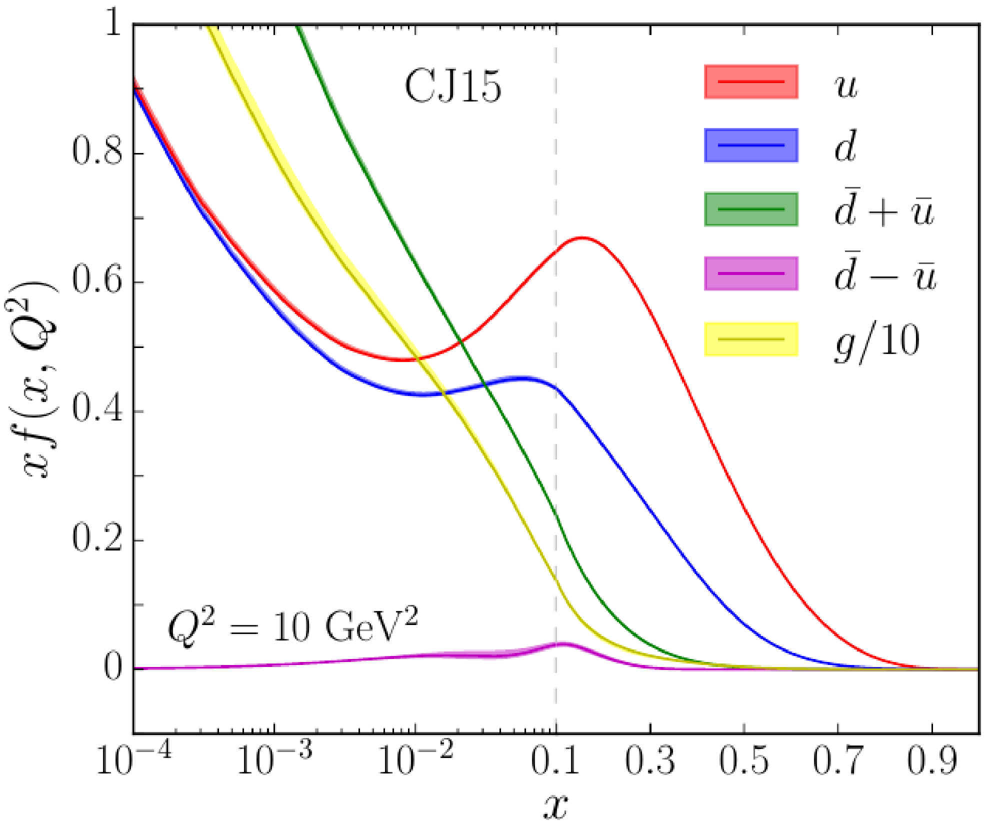






- **New off-shell nucleon treatment in deuteron targets (DIS <u>and DY</u>)**
  - Parametrized vs. modeled → absorbs wave function uncertainty

CJ15 - PDFs



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

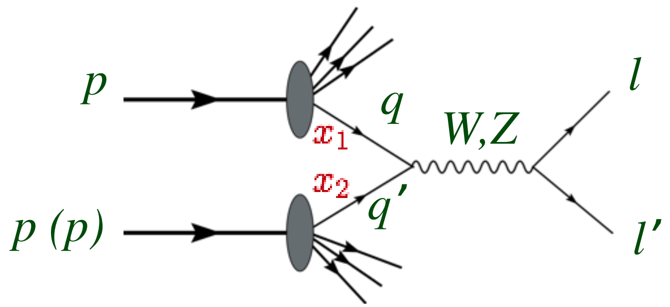
$$\Delta\chi^2 = 2.71$$

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

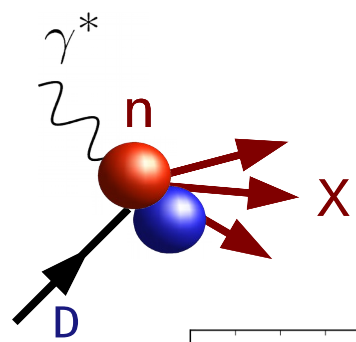
- NLO fit gives $\chi^2/\mathrm{datum} = 1.04$
- LO fit much worse – cannot accommodate Q^2 dependence of data

NUCL / HEP symbiosis

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

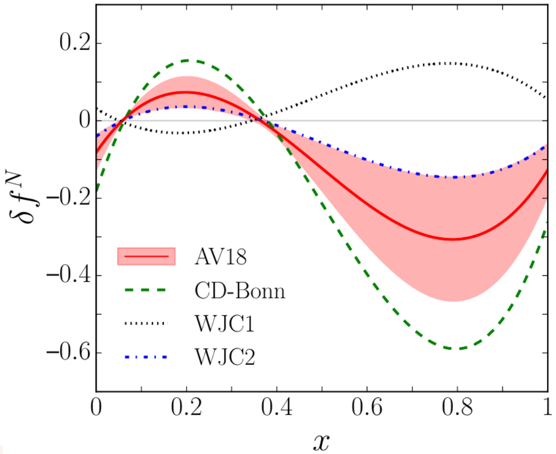


$$A_W(y) \approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)}$$



- 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	χ^2 NLO	χ^2 NLO (OCS)	χ^2 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
	⋮	⋮	⋮	⋮	⋮	⋮
Drell-Yan	E866 (pp) [29]	121	148	**139**	139	145
	E866 (pd) [29]	129	207	**145**	143	158
	⋮	⋮	⋮	⋮	⋮	⋮
χ^2/datum			1.33	**1.04**	1.04	1.09

NUCL / HEP symbiosis

Observable	Experiment	# points	χ^2			
			LO	NLO	NLO (OCS)	NLO (no nucl)
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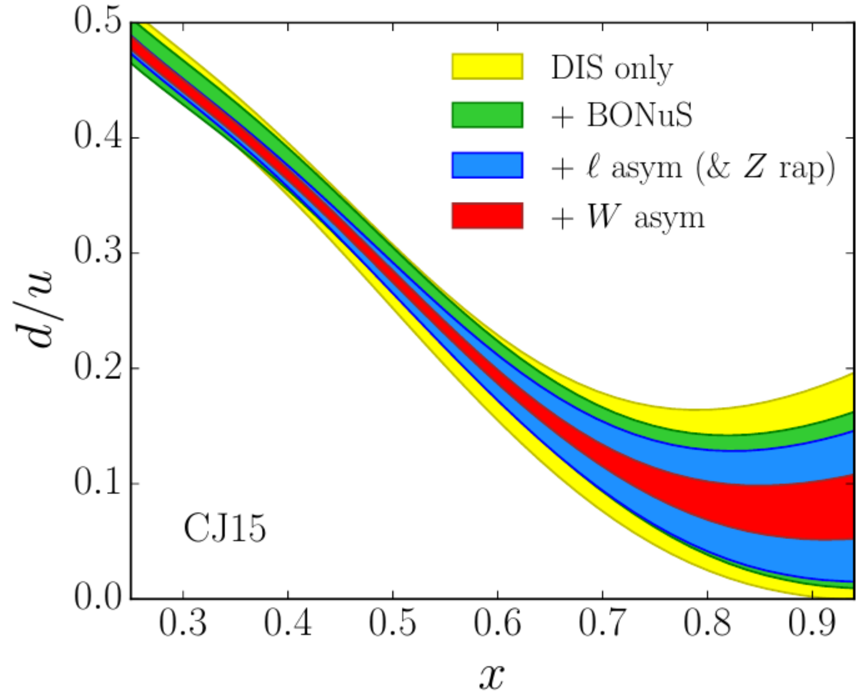
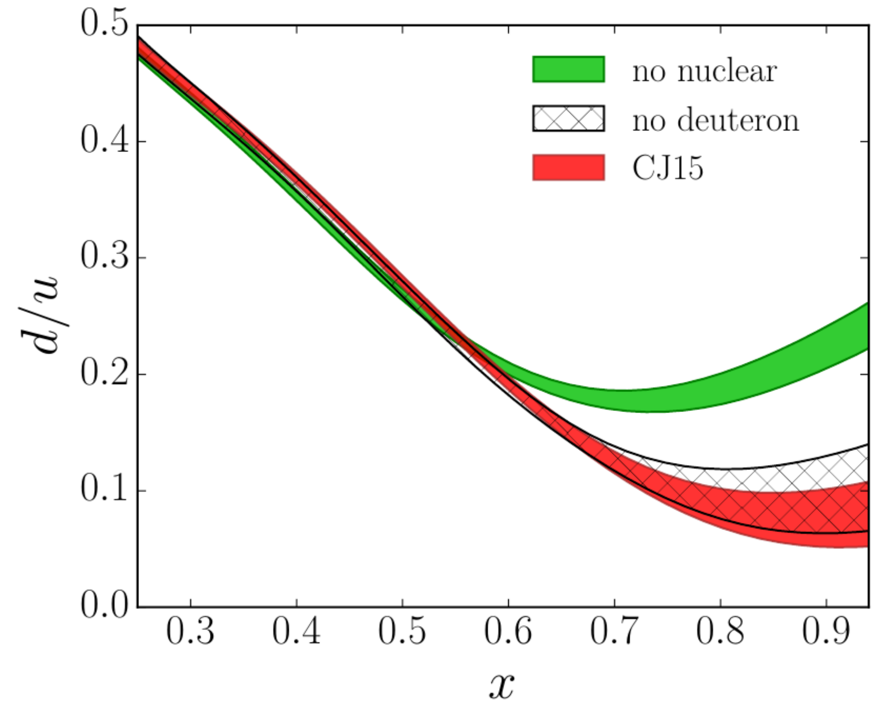
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26

- If one ignores 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: d/u ratio

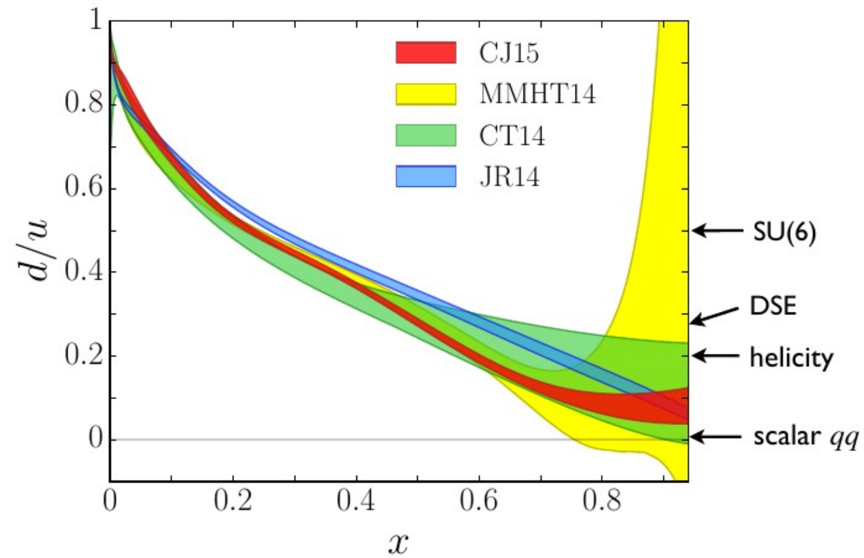




- **d-quark determined by p+p⟶W+X**
- **Nuclear corrections dominant at large x**
  - SLAC(d)'s statistical power used to fit the off-shell function...
  - ... and to improve d/u flavor separation, esp. at x<0.3 (see backup)

Hadronic physics output: 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 $a_2^d = a_2^u$)

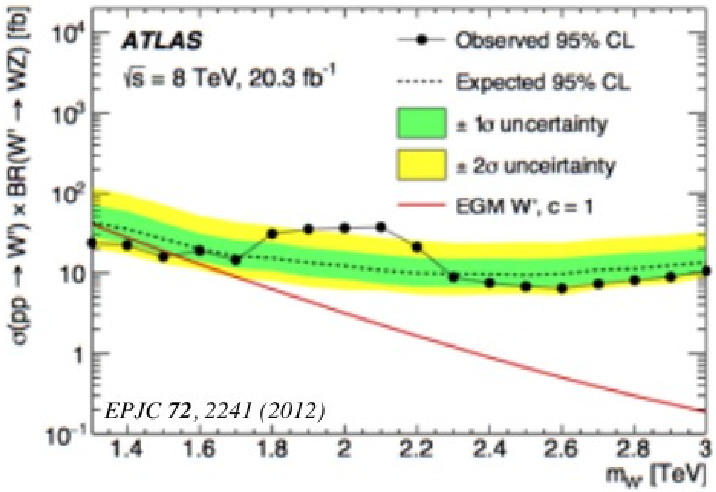
MMHT14: fitted deuteron corrections
standard *d* parametrization
→ "UNDERCONSTRAINED"

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

HEP output: BSM searches

- Observation of new physics signals requires accurate determination of QCD backgrounds, which depend on PDFs
  - ***e.g.*, heavy W' boson production at LHC**



- $3.4\,\sigma$ excess in WZ diboson channel at ~ 2 TeV
- extended gauge model $W' \to WZ$ with $M < 1.5$ TeV excluded at 95% c.l.

  - For W'^- production the parton luminosity is

$$\mathcal{L}_{W'^-} \sim x_1 x_2 \big[\cos^2\theta_C \big(d(x_1)\bar{u}(x_2) + s(x_1)\bar{c}(x_2) \big) + \sin^2\theta_C \big(s(x_1)\bar{u}(x_2) + d(x_1)\bar{c}(x_2) \big) \big] + (x_1 \leftrightarrow x_2)$$

$$\sim d(x_1)\bar{u}(x_2) \quad \text{at large rapidity } y_{W'}$$

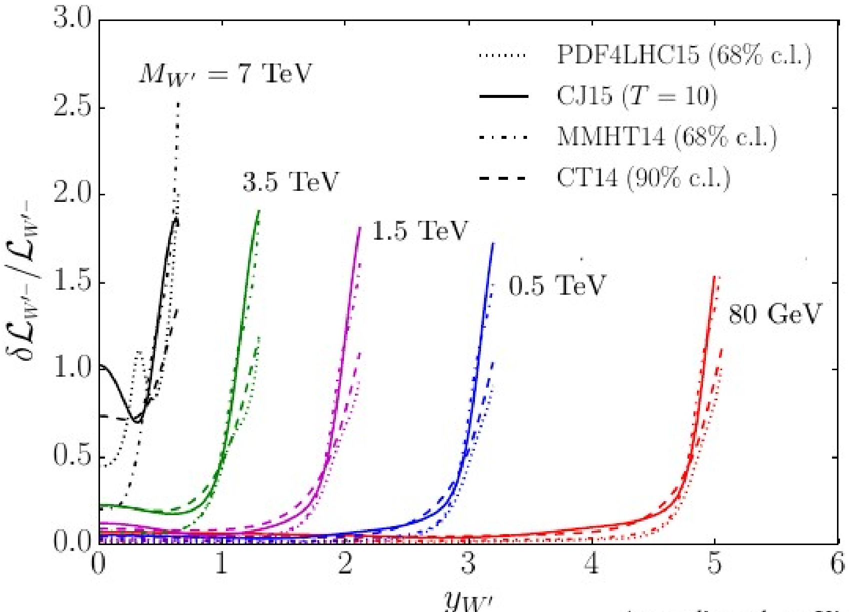
$$x_{1,2} = \frac{M_{W'}}{\sqrt{s}} e^{\pm y_{W'}}$$

HEP output: BSM searches

- Observation of new physics signals requires accurate determination of QCD backgrounds, which depend on PDFs

  - **Large-*x* uncertainties scale with masses**

relative uncertainty in luminosity

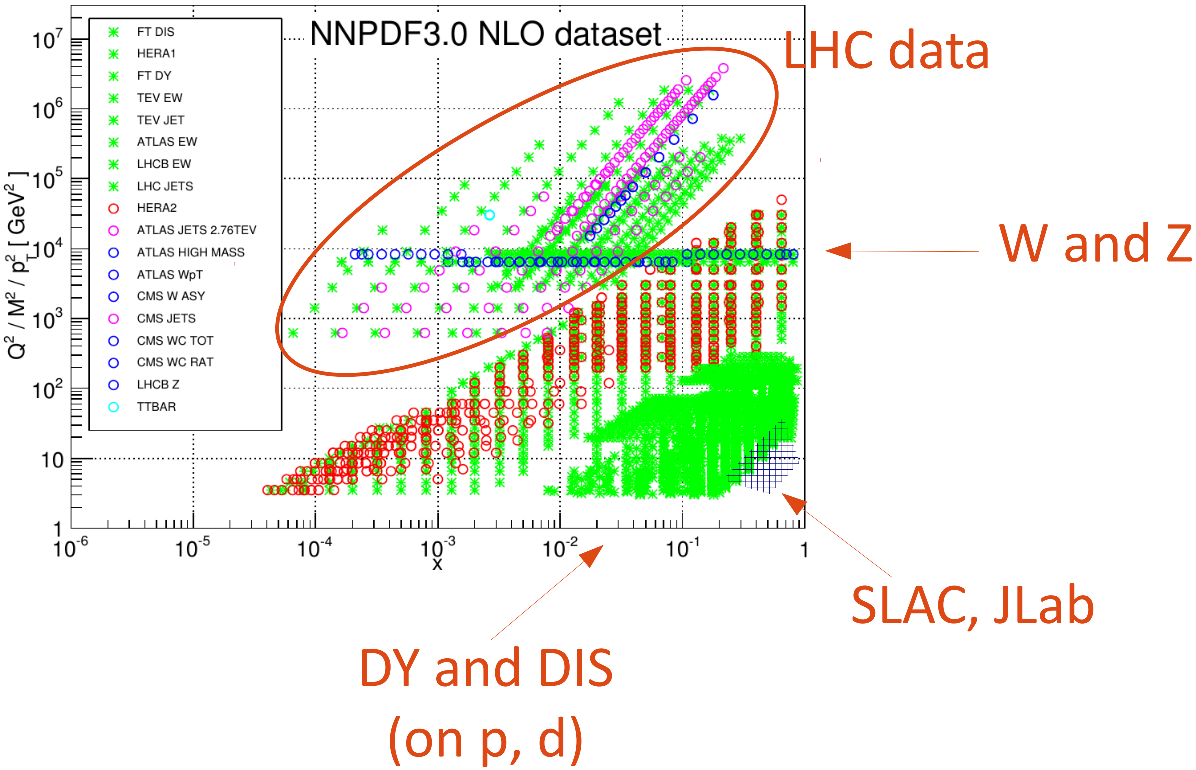


Accardi et al., arXiv:1603.08906

  - **PDF uncertainty is small at low *x*, rises dramatically at large *y* for all $M_{W'}$**

Why EIC?

1 - Data coverage for PDF fits



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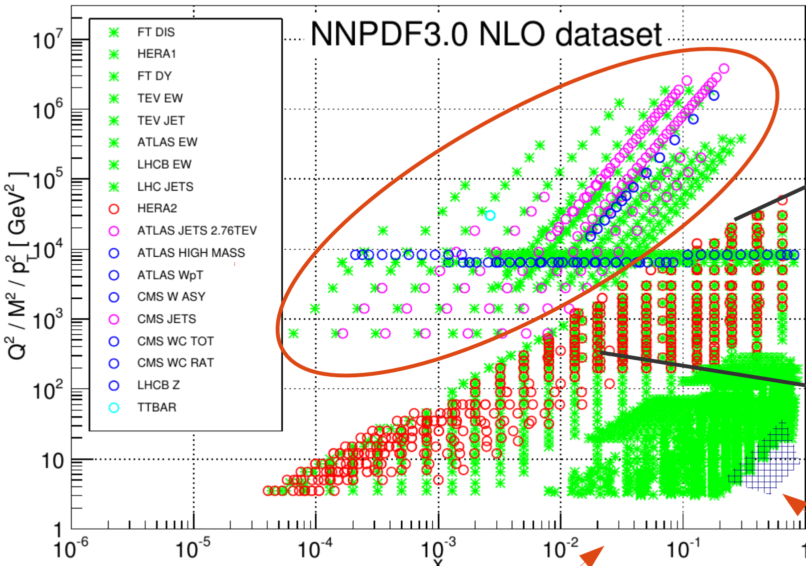
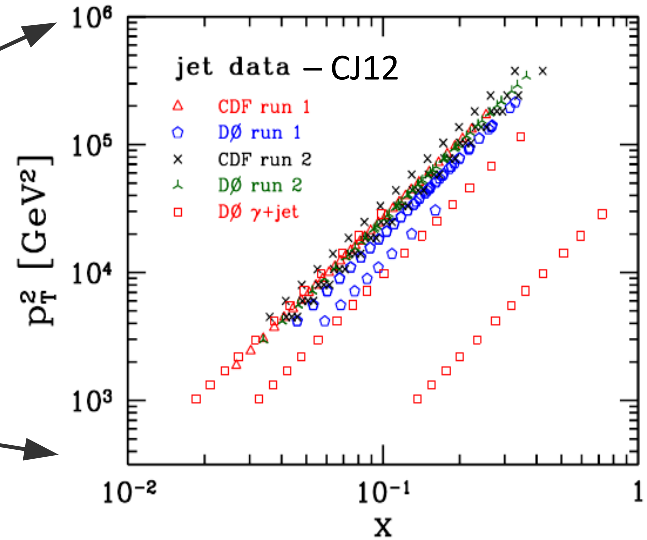


LHC data

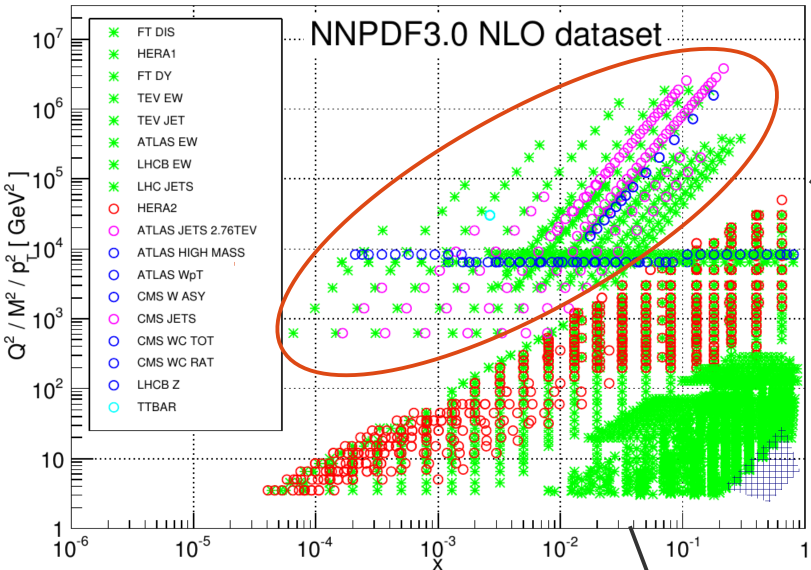
Tevatron Jets



SLAC, JLab

DY and DIS
(on p, d)

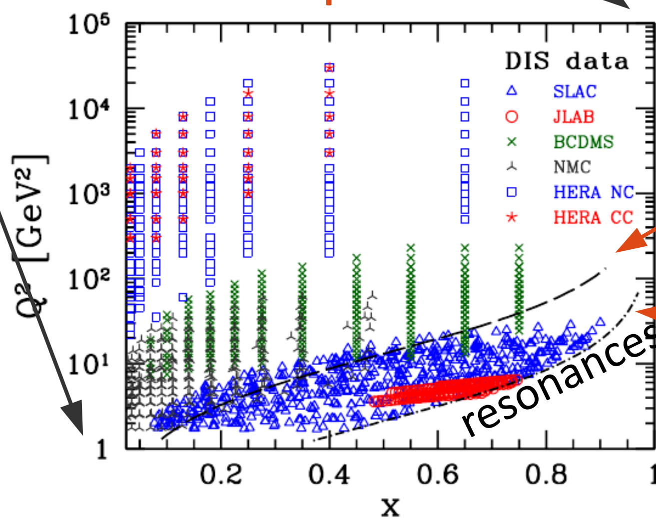
1 - Data coverage for PDF fits



LHC data

Scant large-x coverage in DIS !

DIS – prot. & deut.

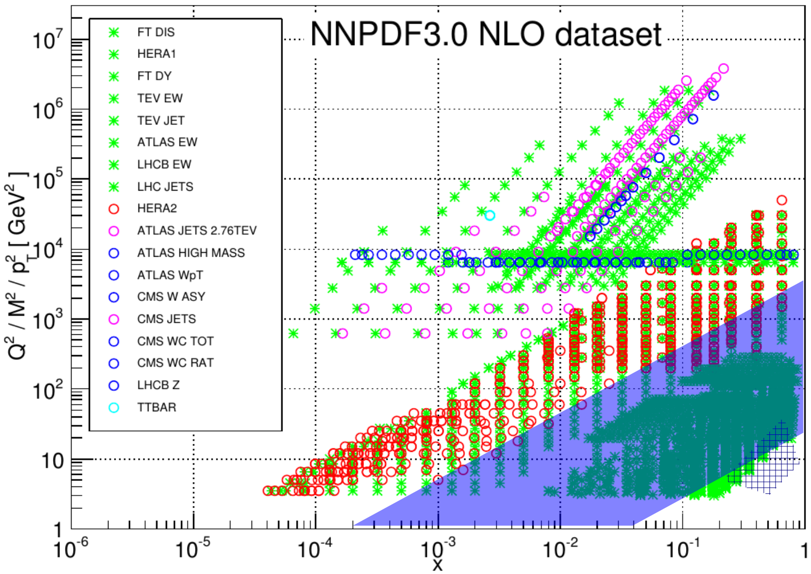


standard cut
$W^2 \gtrsim 14\ \mathrm{GeV}^2$

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

– CJ12

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

- **Unique at the EIC**
  - "Easy" spectator tagging in DIS
    - Quasi-free neutron targets ← this talk
  - 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)

Preliminary simulations
- impact of EIC on d,u,g -

In collaboration with:

- R. Ent, C. Keppel, K. Park, R. Yoshida (JLab),
- M. Wing (UC London)

Can EIC help?

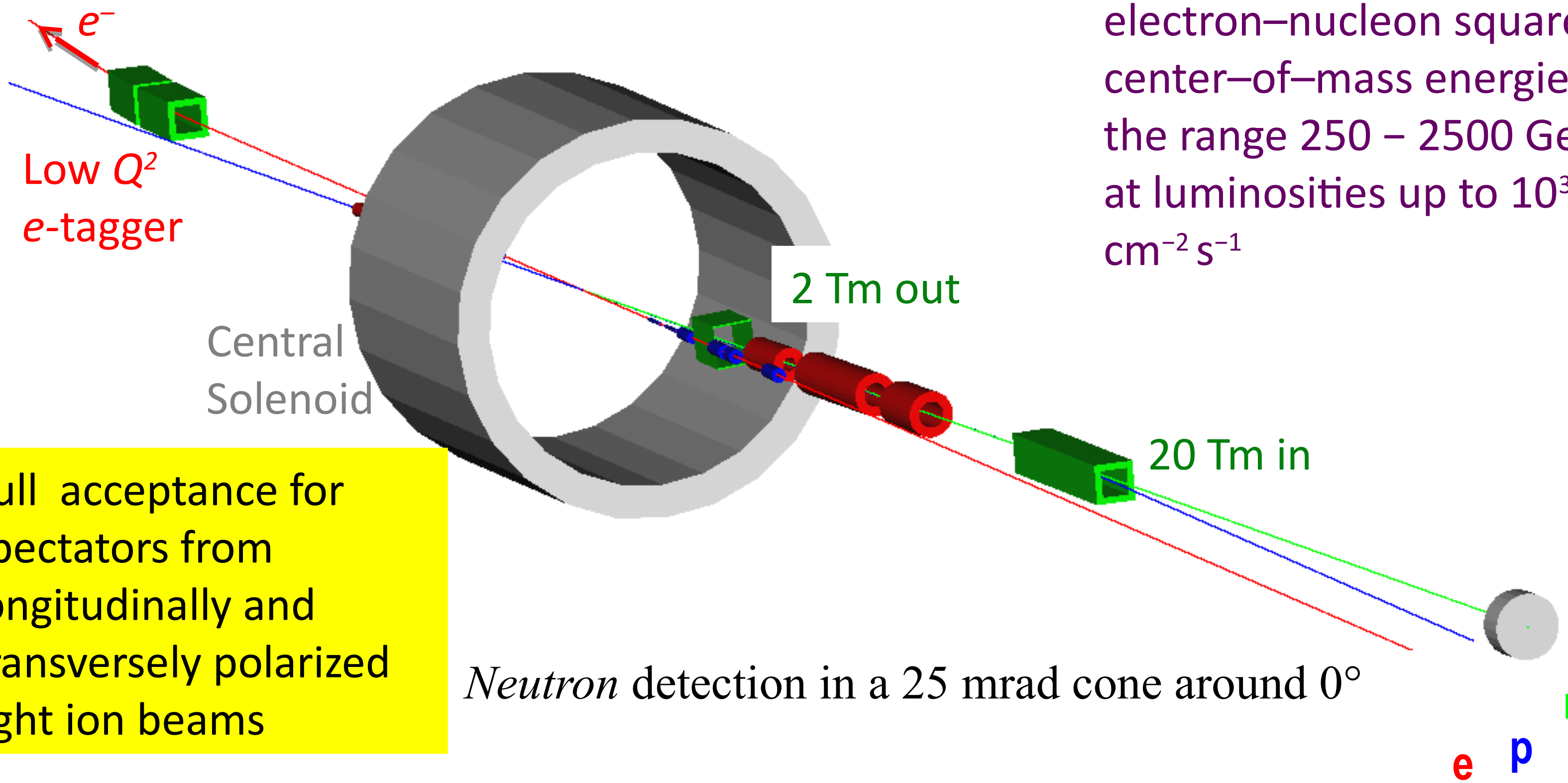
- Flavor separation, nuclear corrections with F2(p) and F2(d)
  - "bread and butter", but: how large in x, what precision?
  - What impact on PDFs ?

- d-quarks wtithout nuclear corrections: F2(n)
  - possible with planned EIC spectator tagging capabiities

- Gluons through scaling violation
  - require range in both x, Q2
  - not currently possible at large x without the EIC
  - Don't forget jets!

- To begin investigating possibilities, we used rough projected data kinematics and uncertainties, and the "CJ" global PDF fit…

Tagged structure functions at the EIC



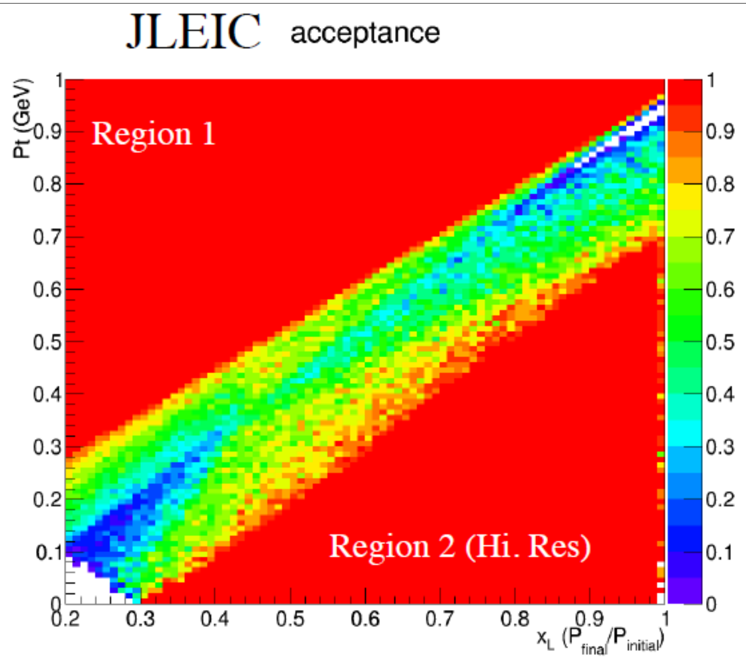
The JLEIC design provides electron–nucleon squared center–of–mass energies in the range 250 – 2500 GeV^2 at luminosities up to 10^{34} cm^{-2} s^{-1}

- Full acceptance for spectators from longitudinally and transversely polarized light ion beams

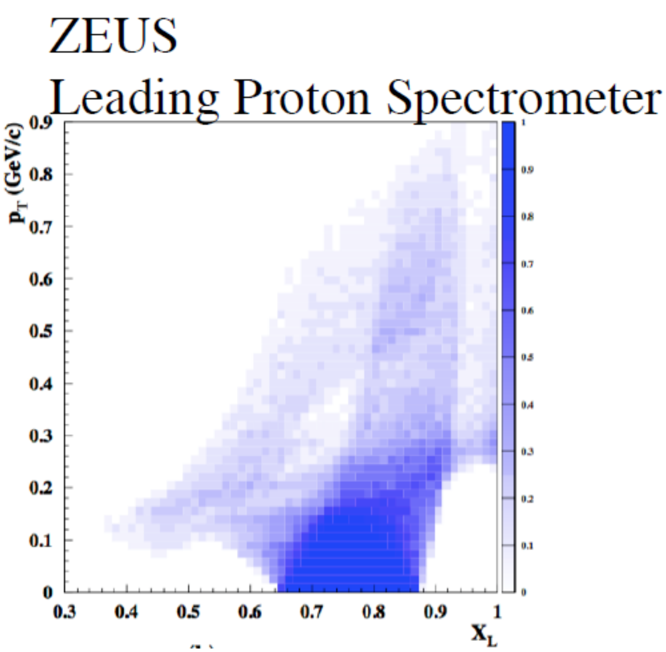
Neutron detection in a 25 mrad cone around 0°

EIC: full acceptance for forward physics

Example: acceptance for p' in e + p → e' + p' + X



Zhiwen Zhao (Duke)



Acceptance in diffractive peak (X_L>~.98)

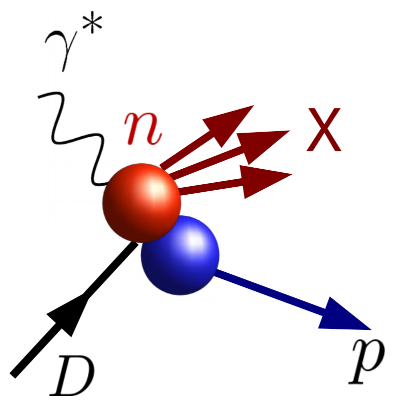
ZEUS: ~2%

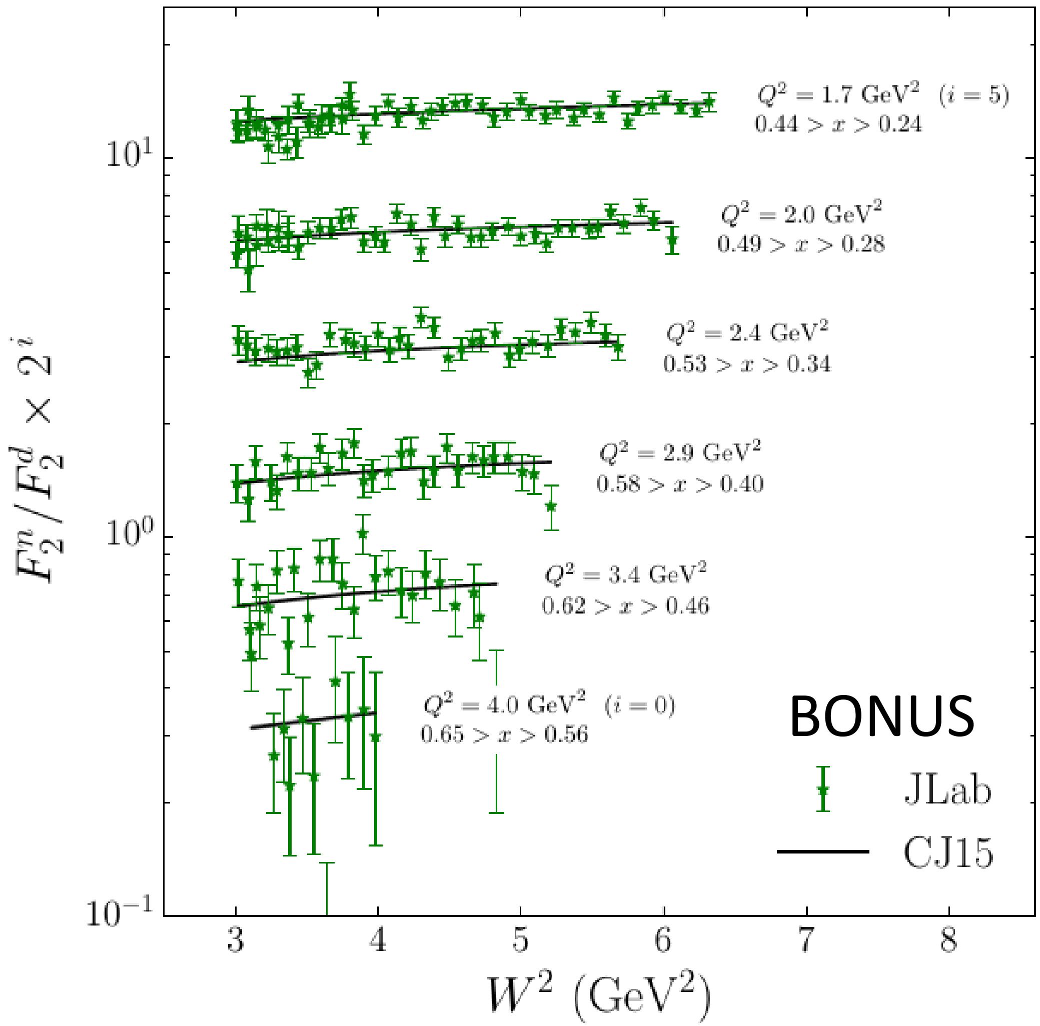
JLEIC: ~100% (also covers much higher X_L than ZEUS)

Huge gain in acceptance for forward tagging to measure F_2^n and diffractive physics!!!

Spectator tagging at Jlab: quasi-free neutrons

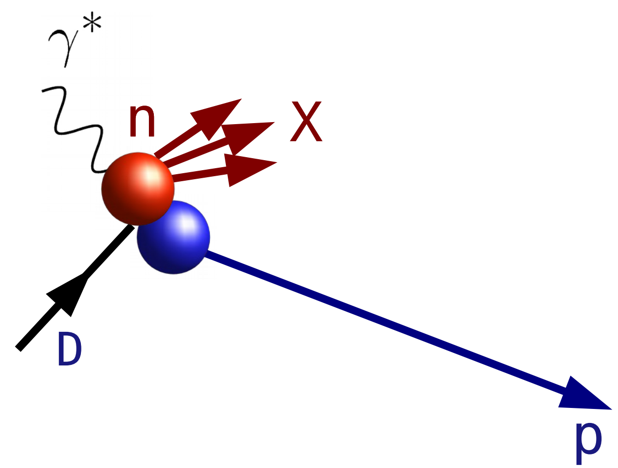
N.Baillie et al., PRL 108 (2012) 199902

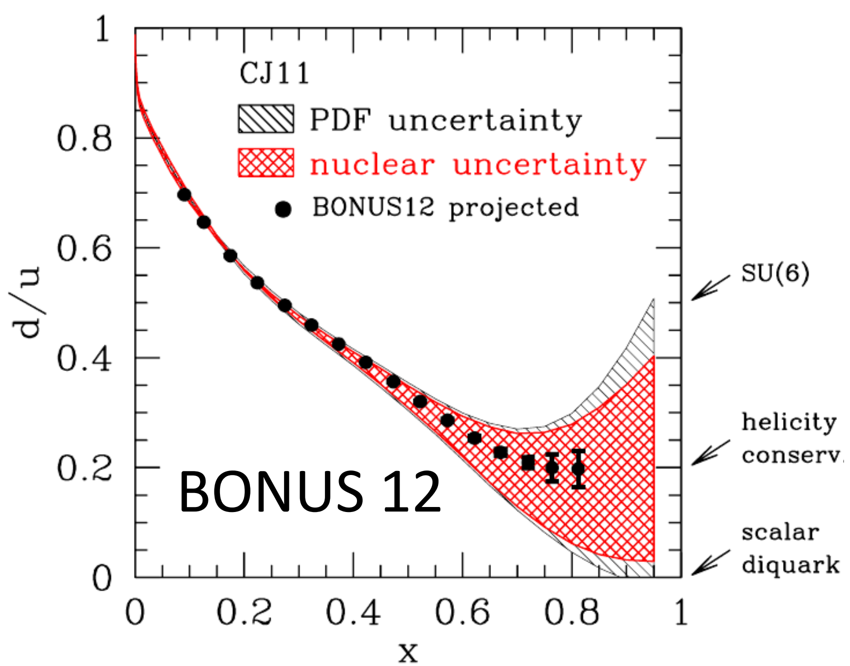


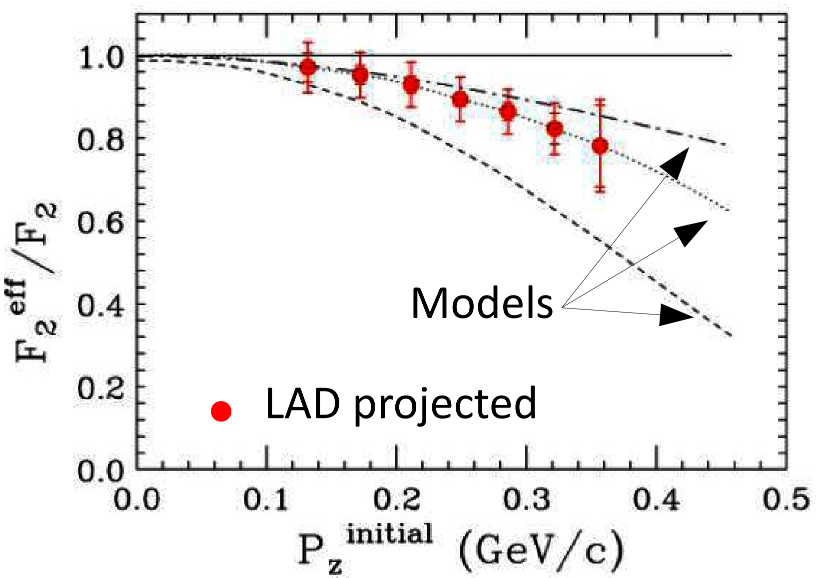


Spectator tagging at JLab12

- Neutron off-shellness depends on on spectator momentum:
  - Slow: nearly on-shell (BONUS12)
  - Fast: more and more off-shell (LAD)

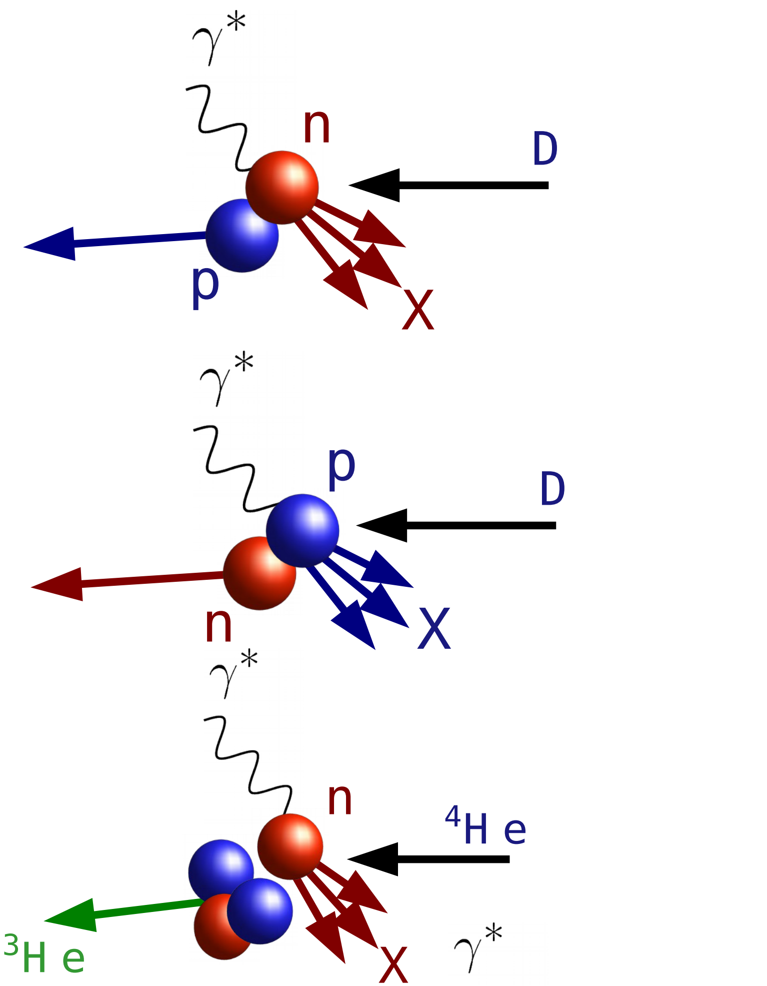






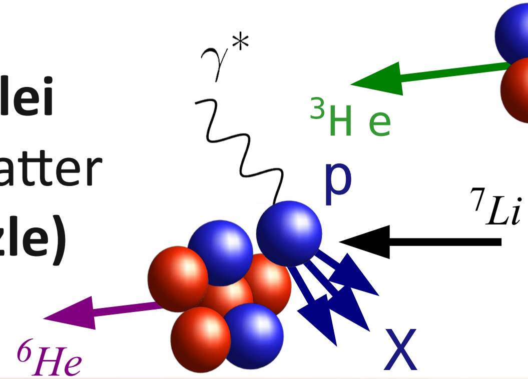
Spectator tagging at EIC: even better!

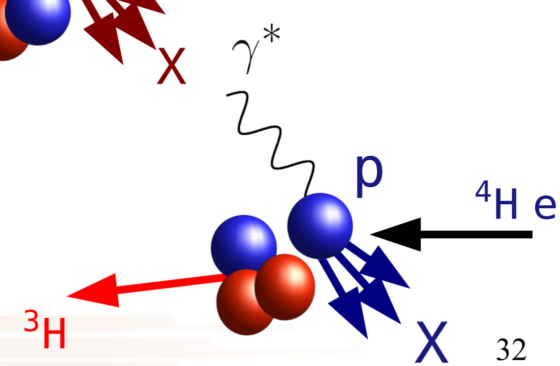
- measure **neutron F_2** in D target
  - flavor separation



- measure **proton F_2** in D target
  - **Unique at colliders**
  - Compare off-shell to free proton
  - Establish nuclear effects
  - Validate on-shell extrapolation techniques

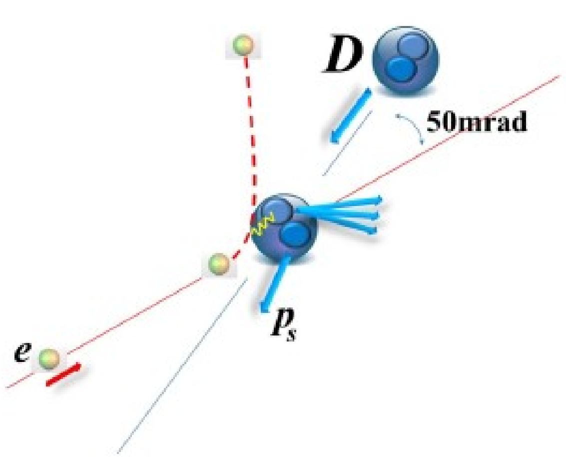
- **proton, neutron in light nuclei**
  - embedding in nuclear matter **(a piece of the EMC puzzle)**

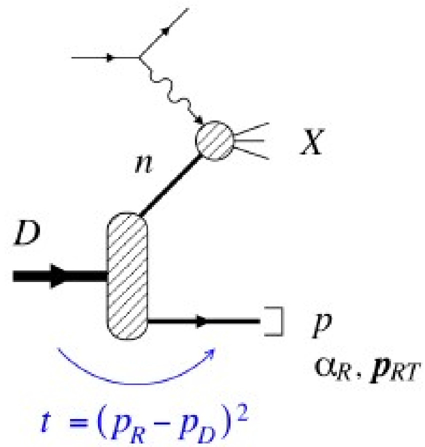


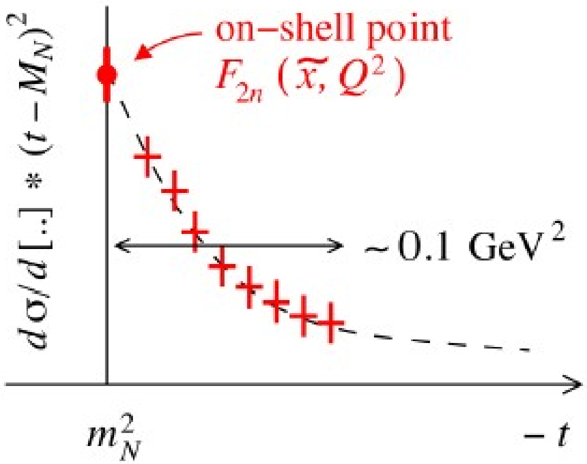


(Tagged) neutron structure extrapolation in t

JLab LDRD project 2014/15 – C.Weiss et al. – www.jlab.org/theory/tag/



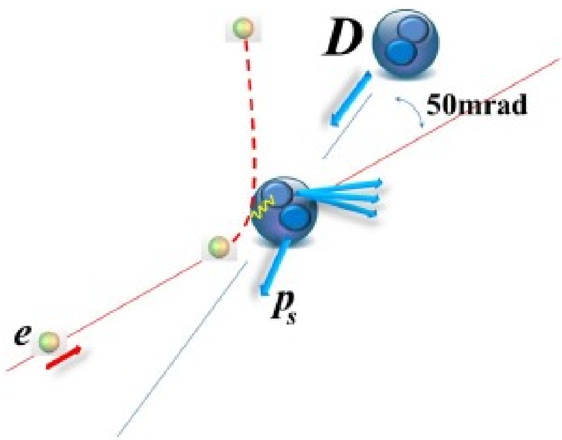


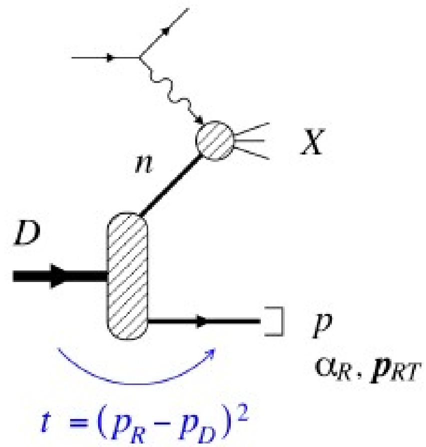


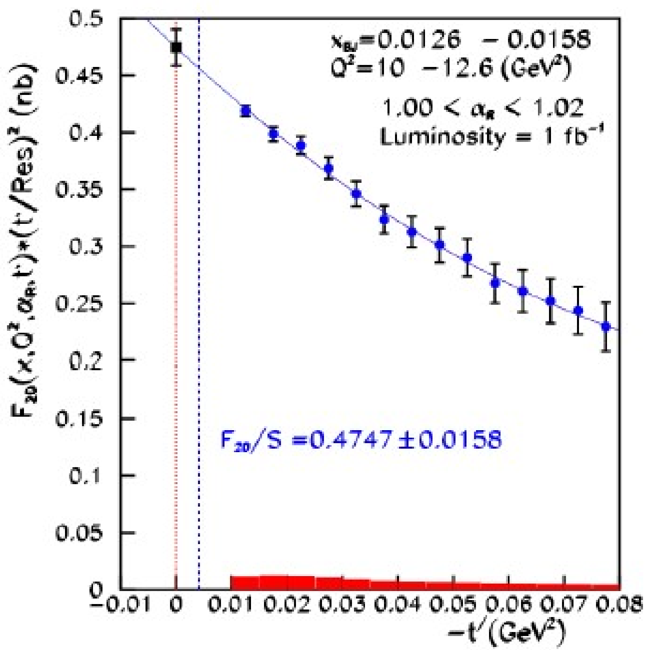
- t resolution better than 20 MeV, < fermi momentum
  - Resolution limited/given by ion momentum spread
  - Allows precision extraction of F2n neutron structure function

(Tagged) neutron structure extrapolation in t

JLab LDRD project 2014/15 – C.Weiss et al. – www.jlab.org/theory/tag/







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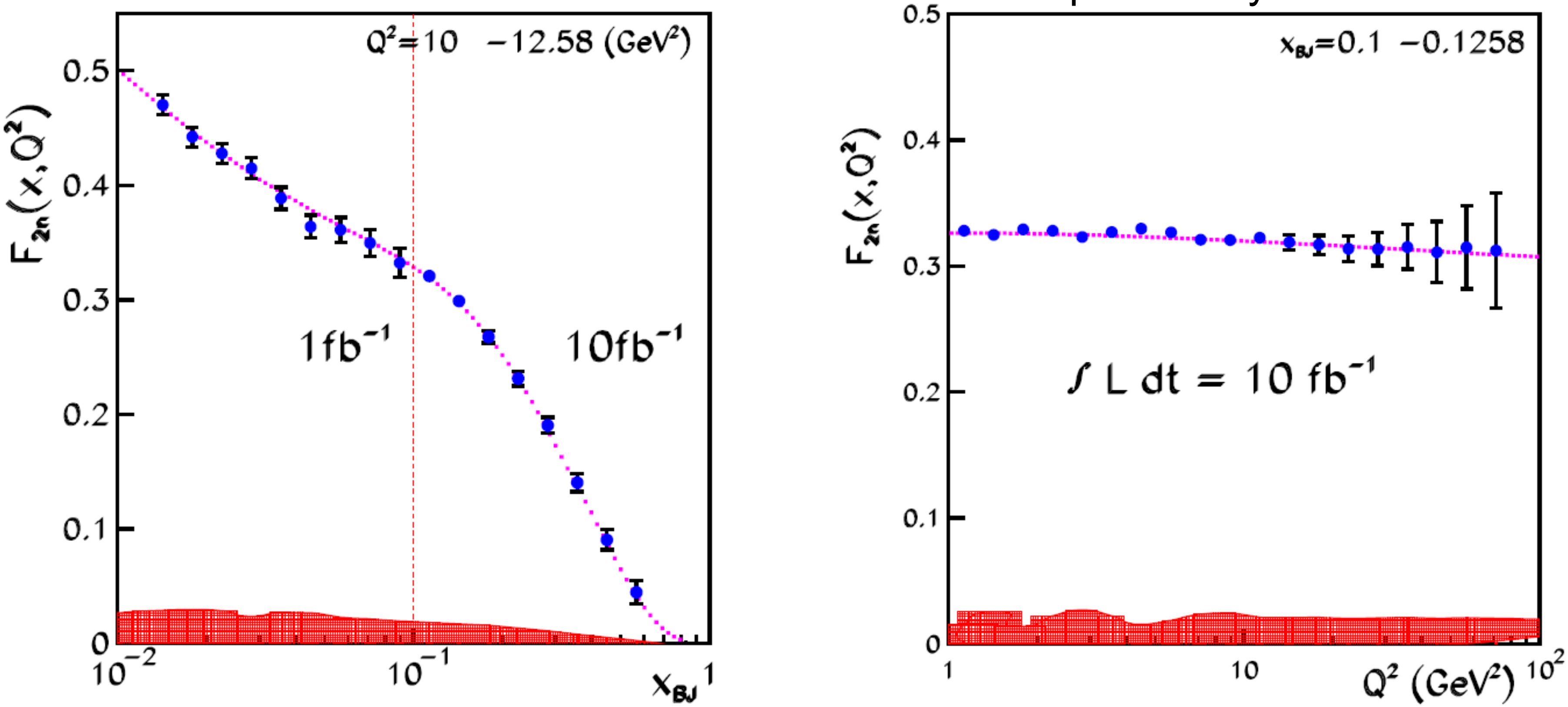
Preliminary examples (courtesy Kijun Park)
Uncertainties include on-shell neutron extrapolation systematics



- 1 year of EIC @ luminosity of 10^{32} gives about 1 fb^{-1}
- 1 year of EIC @ luminosity of 10^{33} gives about 10 fb^{-1}
- 1 year of EIC @ luminosity of 10^{34} gives about 100 fb^{-1} ←

Projected data (so far) and impact on PDFs

So far, JLEIC 10x100 GeV^2 projections in bins $0.1 < x < 0.9$ for:

- ✓ F_2^p
- ✓ F_2^n from deuterium with tagged proton spectator
- ✓ F_2^d

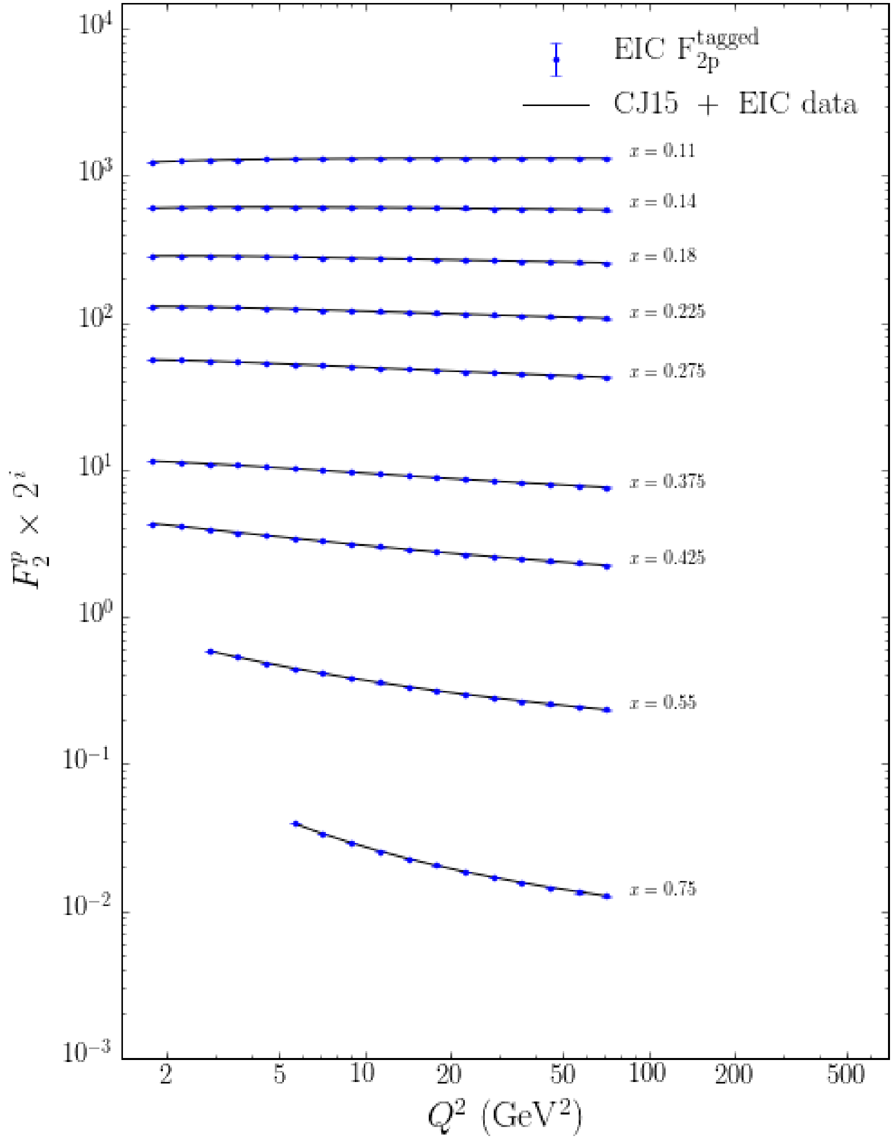
- *Assume 1% systematic uncertainty*
- $W^2 > 3.5$ GeV^2 and $Q^2 > 1.69$ GeV^2 (standard CJ15 cuts)

Finally,

- fit projected data along rest of CJ15 data sets
- examine impact on d, u, g

- ***A simple study so far (first results from this summer)…***

Can EIC help?

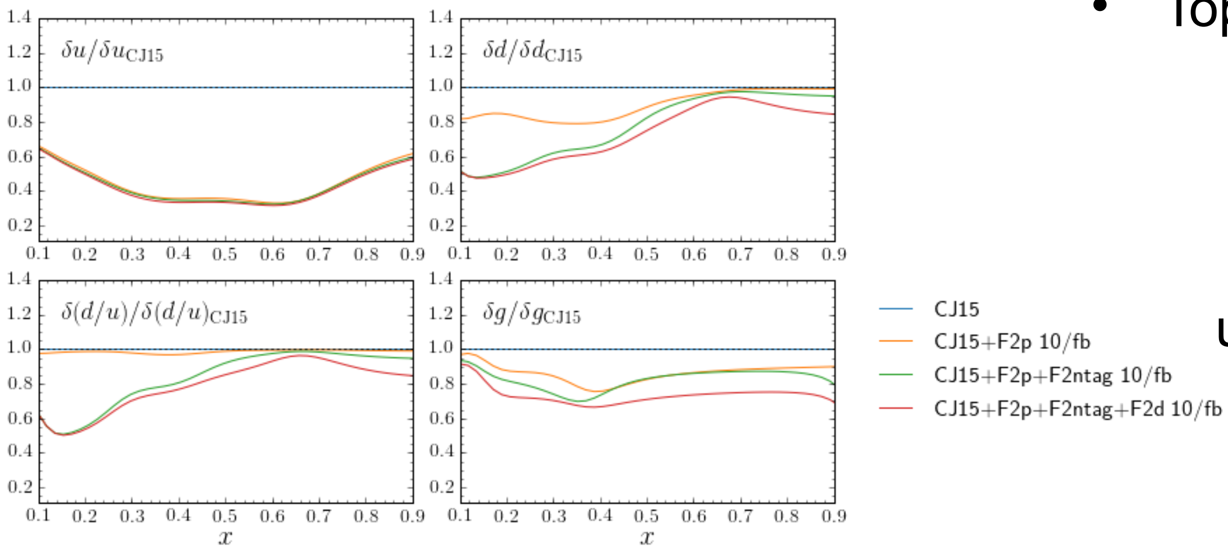


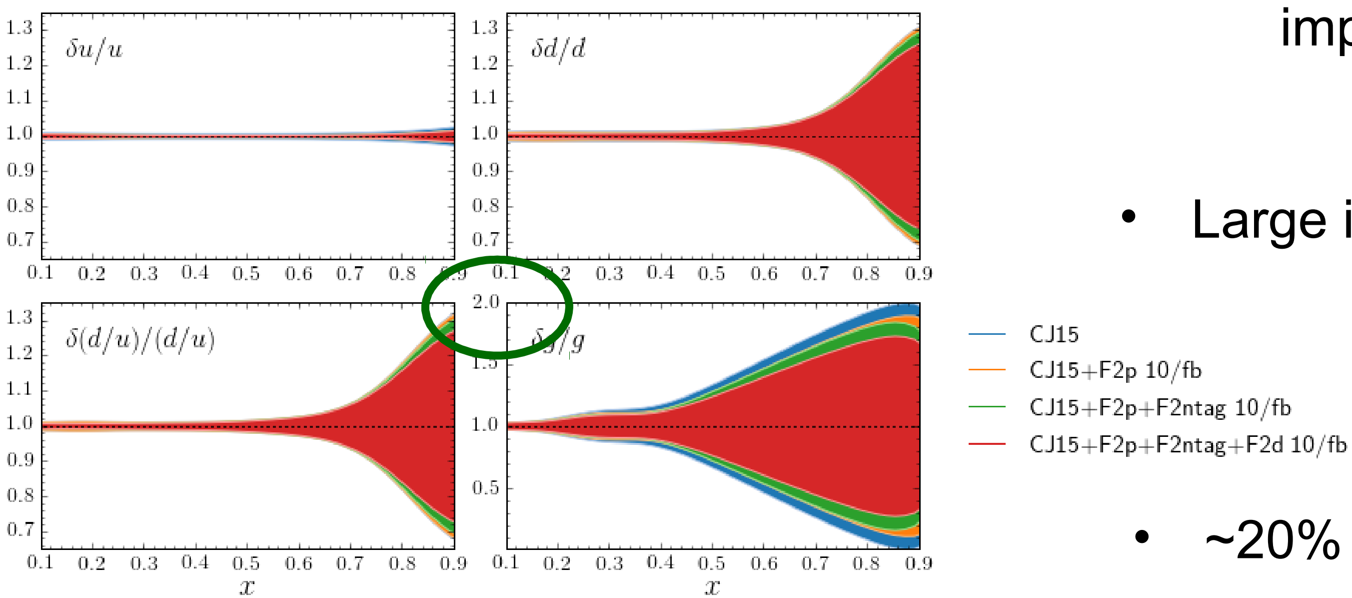
Compressed scale makes it somewhat difficult to see the experimental and fit uncertainties

Currently no cut in y:

- would loose a little bit in the high Q^2 range from y<ymax,
- would loose some low Q^2 at large x from a y_min cut, → impact on gluon fits ?
- requires more careful simulations, evaluation of systematic uncertainties

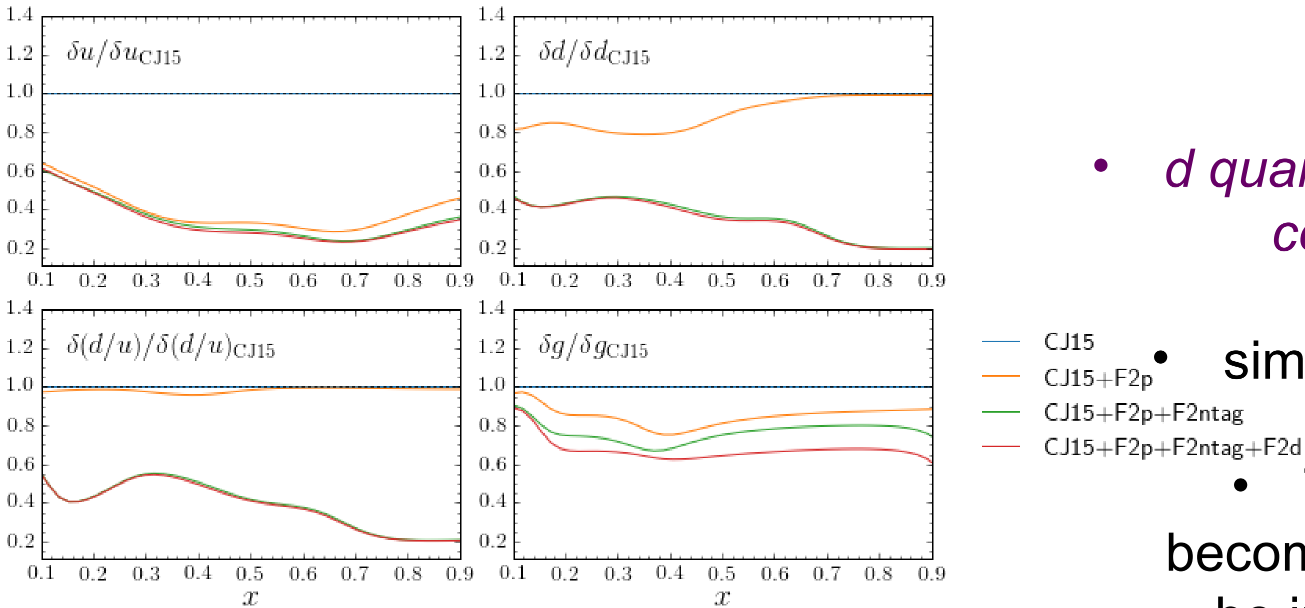
10/fb luminosity

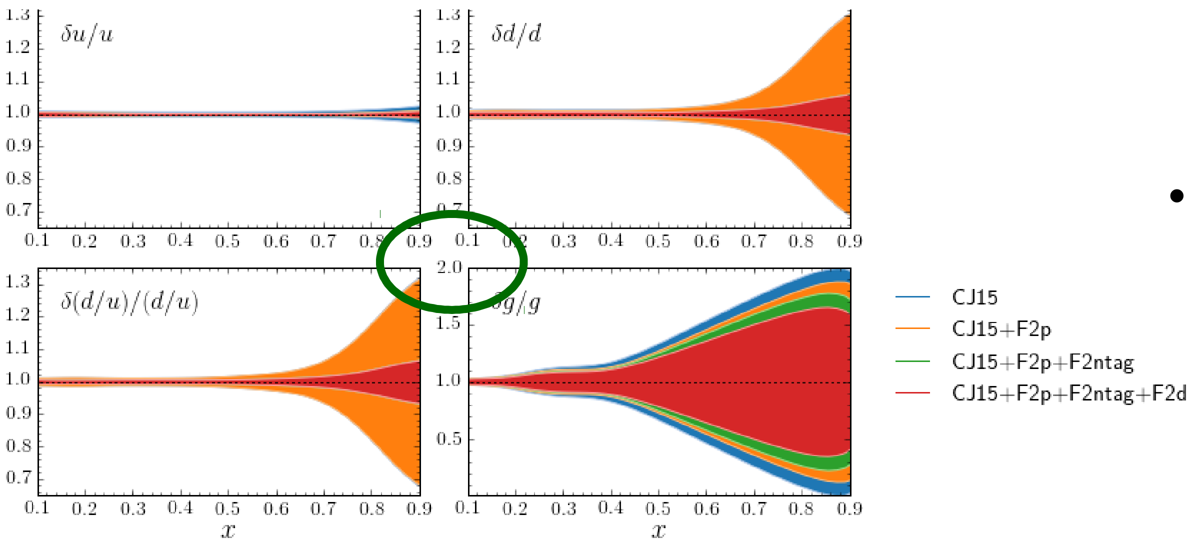




- Top: improvement in relative PDF uncertainties compared to CJ15
- Bottom: relative uncertainties compared to CJ15
- Improvement in u impressive, but already small uncertainty
- Large improvement in d(x), ~50%
- d/u tracks d
- ~20% improvement in g(x)

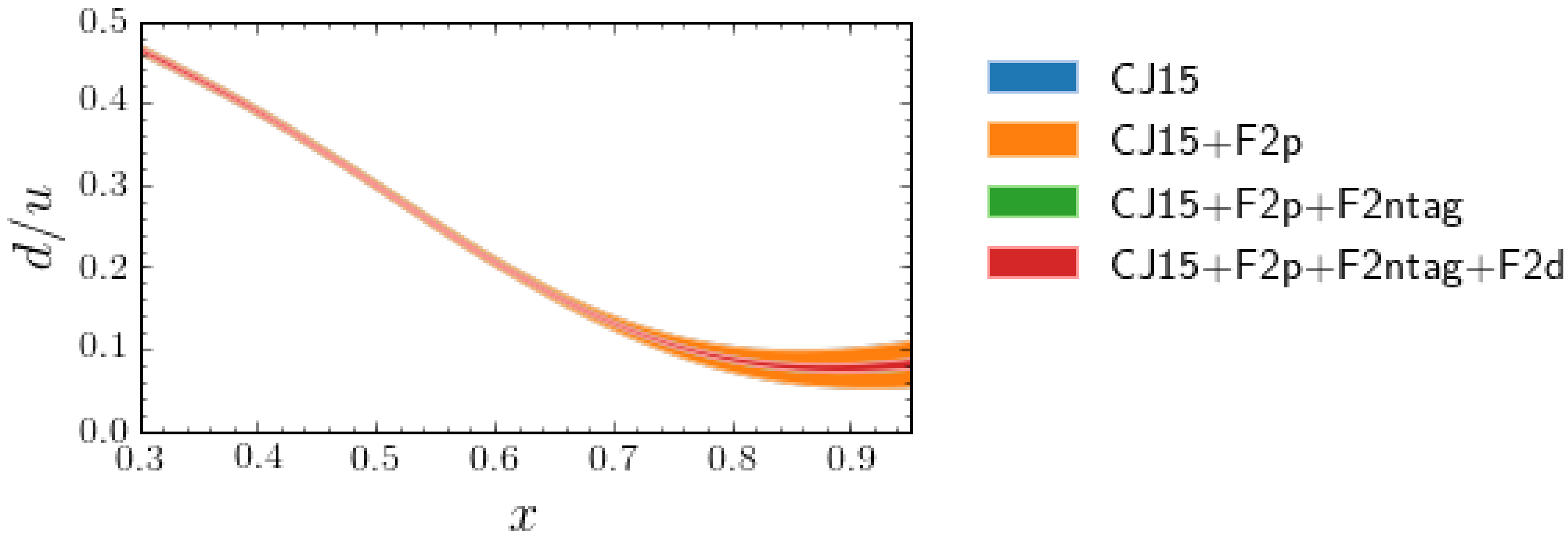
100/fb luminosity





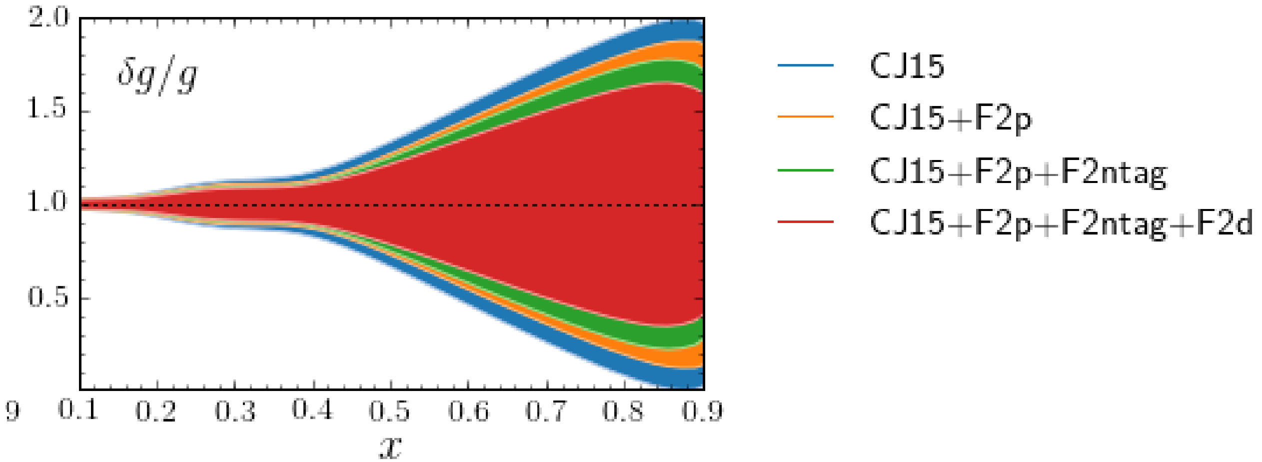
- *d quark precision will become comparable to current u!!*
- similar improvement in g(x)
- The u quark uncertainty becomes less than ~1%; may be important for large mass BSM new particles.
- With d quark nailed by F_2^n, fitting F_2^d data will explore details of nuclear effects

Improved d/u precision is good news



- The d-quark goes from a few 10% to ~1% percent level
- Resolve long-standing mystery of d/u at large x,
  → Can explore in detail fundamental models nucleon structure
- D/(p+n) in one experiment for the first time –
  → unprecedented handle on nuclear medium modifications
  → can quantitatively address interplay of hard scattering and (soft) nucleon dynamics
- Facilitate accurate neutron excess/isoscalar corrections
  - Important also for neutrino physics and nuclear PDFs

Improved *gluon* precision is also good news



- **Gluons improve by a bit less than 10% *per data set included*,** seemingly independent of luminosity

  – Gluons are accessed by the F_2 shape in Q^2, so precision of each data point is not very important; lever arm in Q^2 matters most

- Energy scans at, say, 3+100 and 6+100 may improve up to 80%
  – and also provide direct access of gluons thorugh F_L.

- Need more work to confirm above

Some final thoughts

EIC has big potential

- EIC has excellent potential for
  - **u, d, g flavor determination at large x** ⟷ hadronic structure, BSM
  - Revolutionizing **nuclear structure studies using hard probes**

  Needs more work, realistic systematics, grid optimization, y cuts, ...

- For discussion later: what's best to use in a QCD fit:
  - QCD cross sections at many energies
  - or, experimental extraction and fit of FL ?

- How much glue and strange can one get from QCD evolution w/o utilizing directly sensitive data (*i.e.*, on day 0, before E-scan?)
  - IMC analysis by JAM indicates non negligible info can be etracted if advanced techniques utilized in fits

What else can we dream of doing at the EIC?

- **Isospin violations**
  - Play free n from BONUS/EIC vs. free p from D0, RHIC W-asym.
- **Strangeness from PVDIS**
  - Strange quarks are quaint: LHC vs fixed target; HERMES SIDIS; ...
- **Intrinsics charm**
  - Positive signal only from (contested) EMC data
  - Take new and better data with EIC !
- **Large leverage in A – from light to heavy**
  - Combined PDF / nPDF fits
  - Study propagation of charm in cold nuclei using nu+A dimuon data
- **Polarized and unpolarized data at large Q2 from same machine**
  - Another combined fit $\longleftrightarrow$ helicity separation
- ...

Time for discussion!