

# Progress and Opportunities for nuclear PDFs & the EIC

POETIC25 – FIU – Miami

Peter Risse



**nCTEQ**

nuclear parton distribution functions

# Structure of nuclei

- ▶ Nuclear binding energy  $\sim 1\%$  of mass
- ▶ First approximation:  
nuclei consist of free protons & neutrons

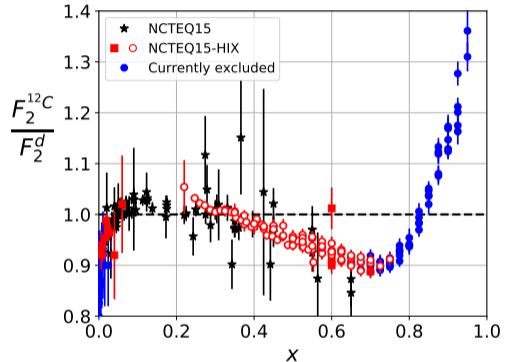
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$\Rightarrow$  **does not work**



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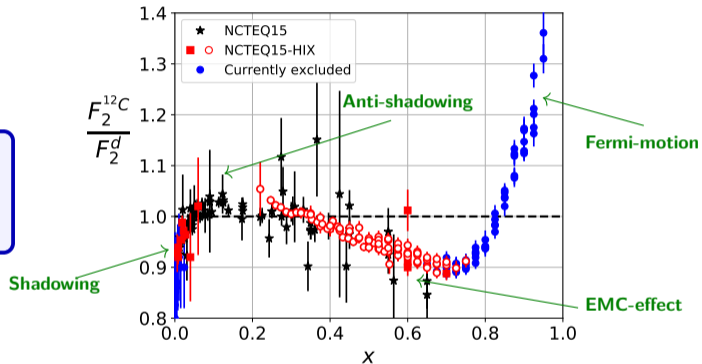
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- ▶ Cross-sections in nuclear collisions are modified
- ▶ Can we translate these modifications into universal quantities?

$\Rightarrow$  **nuclear PDFs**



# Theoretical foundation and assumptions

- Natural theoretical framework: **Collinear Factorization**

DIS-like Process

$$d\sigma_{lA \rightarrow lX} = \sum_i^{q, \bar{q}, g} f_i^{(A, Z)} \otimes d\hat{\sigma}_{il \rightarrow l'X}$$

DY-like Process

$$d\sigma_{pA \rightarrow l\bar{l}X} = \sum_{i,j}^{q, \bar{q}, g} f_i^p \otimes f_j^{(A, Z)} \otimes d\hat{\sigma}_{ij \rightarrow l\bar{l}X}$$

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- ▶ Assumptions

Averaged proton/neutron with isospin symmetry

$$f_i^{(A,Z)} = \frac{Z}{A} f_i^{p/A} + \frac{A-Z}{A} f_i^{n/A} \quad \text{where} \quad \begin{aligned} u^{n/A}(x) &= d^{p/A}(x) \\ d^{n/A}(x) &= u^{p/A}(x) \end{aligned}$$

**Problems:**

- ▶ difficult flavor separation
- ▶ need more isospin-asymmetric nuclei

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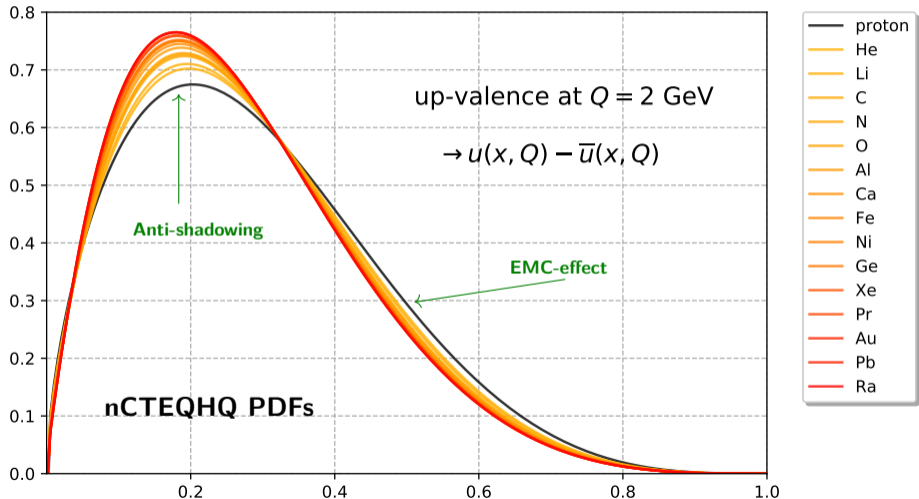
**Problems:**

- ▶ difficult flavor separation
- ▶ need more isospin-asymmetric nuclei

Neglect contributions from  $x > 1$

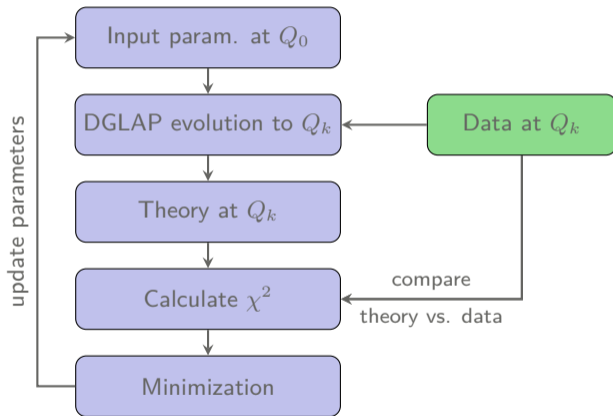
- ▶ DGLAP evolution equations
- ▶ free proton PDFs sum rules
- ▶ under investigation at JLab/EIC

# Nuclear modification: free proton vs bound proton

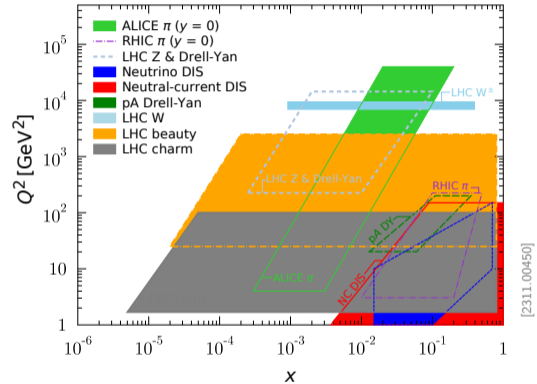
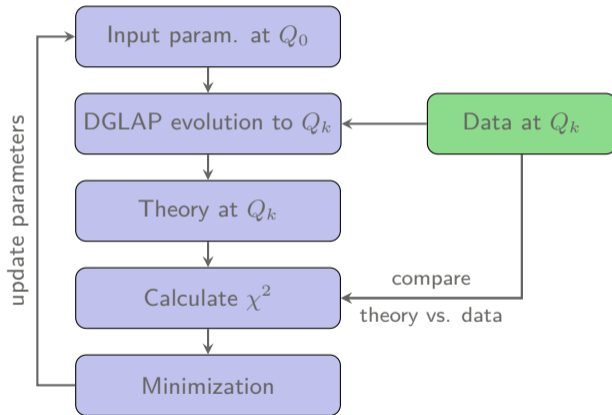




# Methodology and experimental data



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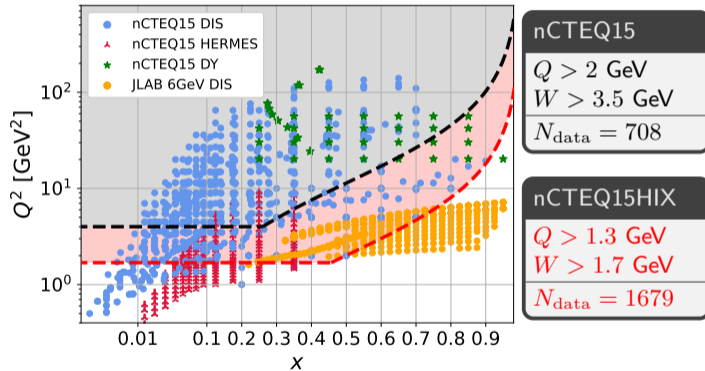


- ▶ utilized data points:  $\mathcal{O}(3000)$
- ▶ experimental precision lower than for proton

# Enlarged kinematic cuts

Kinematic variables:

$$Q^2 \quad \& \quad W^2 = Q^2 \frac{1-x}{x} + M_N^2$$



[PRD 103, 114015 (2021)]

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Kinematic variables:

$$Q^2 \quad \& \quad W^2 = Q^2 \frac{1-x}{x} + M_N^2$$

Requires proper treatment of:

- ▶ deuteron corrections

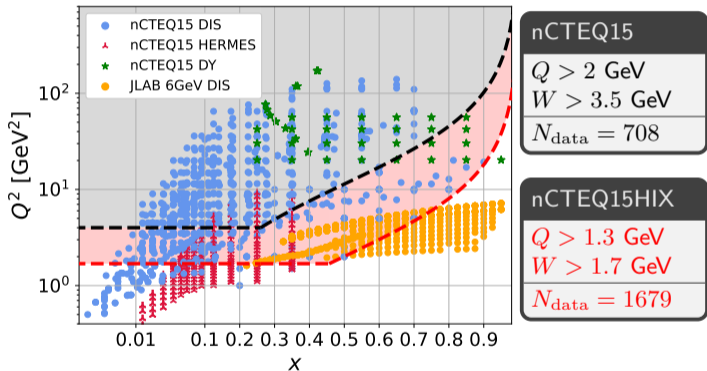
[PRD 93, 114017 (2016)]

- ▶ target mass corrections (TMCs)

[Prog.Part.Nucl.Phys. 136 (2024) 104096]

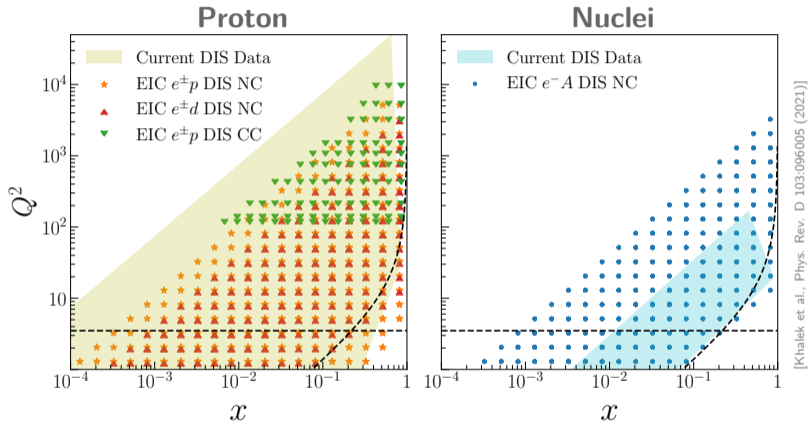
- ▶ higher twist effects

[PRD 93, 114017 (2016)]



[PRD 103, 114015 (2021)]

# EIC: projected neutral current DIS data



► kinematic coverage more than doubles

► “EIC will be the nuclear HERA”

# Comparison of available nPDFs

	KSASG20 PRD 104, 034010	TUJU21 PRD 105, 094031	EPPS21 EPJC 82, 413	nNNPDF3.0 EPJC 82, 507	nCTEQ15HQ PRD 105, 114043
$IA$ NC DIS	✓	✓	✓	✓	✓
$\nu A$ CC DIS	✓	✓	✓	✓	
$pA$ Drell-Yan	✓		✓	✓	✓
$\pi A$ Drell-Yan			✓		
RHIC dAu $\pi$			✓		✓
LHC $pPb$ $\pi, K$					✓
LHC $pPb$ $W/Z$		✓	✓	✓	✓
LHC $pPb$ dijet			✓	✓	
LHC $pPb$ HQ			✓ GMVFNS	✓ FO+PS(rew)	✓ ME fit
LHC quarkonium					✓ ME fit
LHC $pPb$ $\gamma$				✓	
Kinematic cuts	$Q > 1.3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 1.3$ GeV $W > 1.8$ GeV $p_T^{HQ} > 3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 2$ GeV $W > 3.5$ GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335	2410	2077	2188	1496
No free param.	9	16	24	256 (NN)	19
$\chi^2/\text{dof}$	1.06(1.05)	0.94(0.84)	1.00	1.10	0.86
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
$\Delta\chi^2$ tol.	20 (68% CL)	50	35	N/A	35
Proton baseline	CT18	custom	CT18A	~NNPDF4.0	~CTEQ6.1
$Q_0$ ini. scale	1.3 GeV	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV
No flavours	3	4	6	6	5
Deuteron treat.	fitted	fitted	free	fitted	free
QCD order	NLO & NNLO	NLO & NNLO	NLO	NLO	NLO
HQ scheme	FONLL	FONLL	S-ACOT	FONLL	S-ACOT

[2311.00450]

# EPPS21 parametrization

## Bound Proton

$$f_i^{p/A}(x, Q_0^2) = R_i^{p/A}(x, Q_0^2) f_i^p(x, Q_0^2)$$

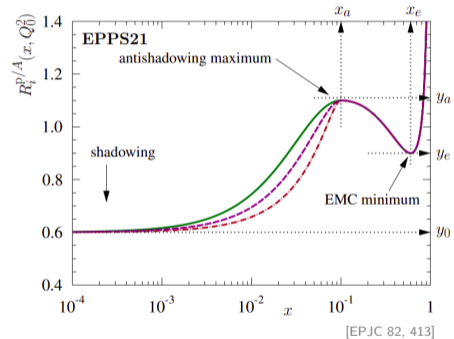
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## with Nuclear ratio

$$R_i^{p/A}(x, Q_0^2) = \begin{cases} a_{0i} + a_{1i}(x - x_{ai}) \left[ e^{-x a_{2i}/x_{ai}} - e^{-a_{2i}} \right], & x \leq x_{ai} \\ b_{0i} x^{b_{1i}} (1 - x)^{b_{2i}} e^{x b_{3i}}, & x_{ai} \leq x \leq x_{ei} \\ c_{0i} + c_{1i} (c_{2i} - x) (1 - x)^{-\beta_i}, & x_{ei} \leq x \leq 1, \end{cases}$$





# EPPS21 parametrization

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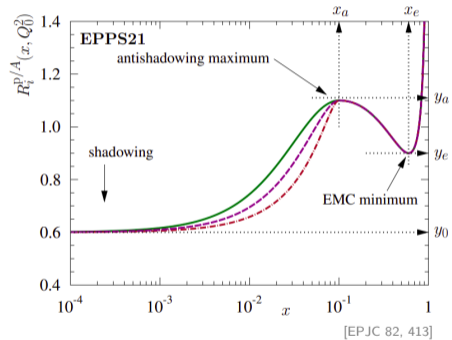
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## and $A$ -dependence through scaling

$$R_i^{p/A}(x, Q_0^2) = 1 + \left[ R_i^{p/A_{\text{ref}}}(x, Q_0^2) - 1 \right] \left( \frac{A}{A_{\text{ref}}} \right)^{\gamma_i}, \quad \gamma_i > 0, \quad A_{\text{ref}} = 12$$



# nNNPDF3.0 parametrization

## Bound Proton

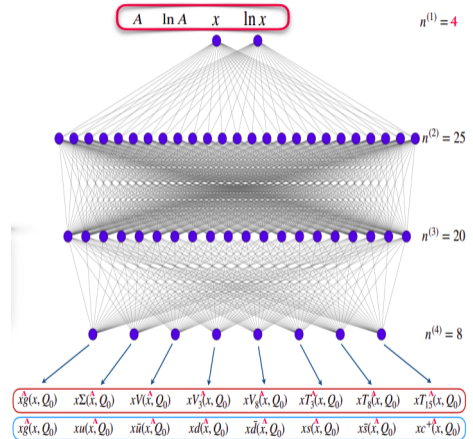
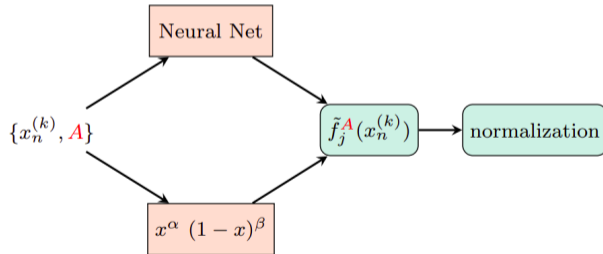
$$x f_k^A(x, Q_0; \theta) = \eta_k^A x^{1-\alpha_k^A} (1-x)^{\beta_k^A} \text{NN}_k^A(x, Q_0; \theta)$$

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## Neural Network with explicit $A$ -dependence



[T. Rabemananjara]

# nCTEQ parametrization (incl. an update for the upcoming release)

## Proton baseline



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## Proton baseline



## PDF parametrization:

$$\begin{aligned}
 x f_i(x, Q_0^2) &= \mathbf{c}_0 x^{\mathbf{c}_1} (1-x)^{\mathbf{c}_2} \left( 1 + \mathbf{c}_3 \sqrt{x} + \mathbf{c}_4 x + \mathbf{c}_5 \sqrt{x^3} \right) & i = u_v, d_v, g, \bar{u} + \bar{d}, s + \bar{s} \\
 \bar{d}/\bar{u}(x, Q_0) &= \mathbf{c}_0 x^{\mathbf{c}_1} (1-x)^{\mathbf{c}_2} + 1 + \mathbf{c}_3 x (1-x)^{\mathbf{c}_4} & Q_0 = 1.3 \text{ GeV}
 \end{aligned}$$

# nCTEQ parametrization (incl. an update for the upcoming release)

## Proton baseline

$$\begin{array}{ccc} \text{CTEQ6M} & \Rightarrow & \text{CJ15} \\ \text{[PRD 75,054030 (2007)]} & & \text{[PRD 93, 114017 (2016)]} \end{array}$$

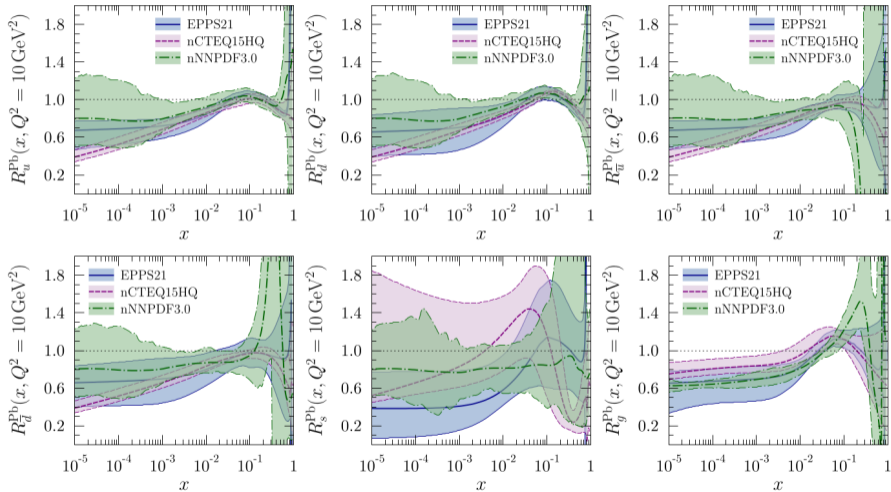
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with updated  $A$ -dependence:

$$\begin{array}{ccc} \text{Currently:} & c_k(A) \equiv p_k + a_k \left( 1 - A^{-b_k} \right) & \\ & \Downarrow & \\ \text{Future:} & c_k(A) \equiv p_k + a_k \ln(A) + b_k \ln^2(A) & \end{array}$$

# Nuclear ratio of EPPS21 vs. nNNPDF3.0 vs. nCTEQ15HQ



[2311.00450]

**What else can the EIC do for nPDFs?**

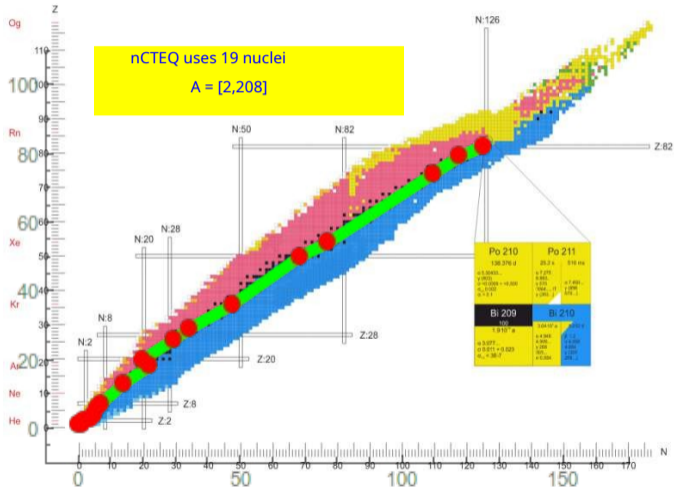


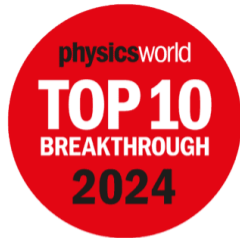
# Nuclei currently included

**Periodic Table of the Elements**

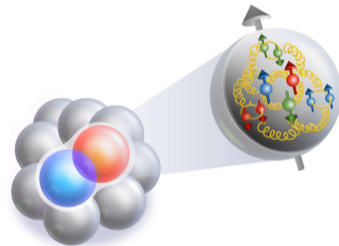
1 IA H Hydrogen 1.008	2 IIA Be Beryllium 9.012																	18 VIII He Helium 4.003					
3 Li Lithium 6.941	4 Be Beryllium 9.012																	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 III Al Aluminum 26.982	14 IV Si Silicon 28.086	15 V P Phosphorus 30.974	16 VI S Sulfur 32.066	17 VII Cl Chlorine 35.453	18 VIII Ar Argon 39.948											36 Kr Krypton 83.801					
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.833	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 83.801						
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.413	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29						
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.384	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon [222]						
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium [unknown]	114 Fl Flerovium [289]	115 Uup Ununpentium [unknown]	116 Lv Livermorium [293]	117 Uus Ununseptium [unknown]	118 Uuo Ununoctium [unknown]						

# Isotope chart






















## Short Range Correlations & nuclear PDFs



### Modification of Quark-Gluon Distributions in Nuclei by Correlated Nucleon Pairs

A.W. Denniston <sup>1,\*</sup> T. Ježo <sup>2,†</sup> A. Kusina <sup>3</sup> N. Derakhshanian <sup>3</sup> P. Duwentäster <sup>2,4,5</sup>  
 O. Hen <sup>1</sup> C. Keppel <sup>6</sup> M. Klasen <sup>2,7</sup> K. Kovarik <sup>2</sup> J.G. Morfin <sup>8</sup> K.F. Muzakka <sup>2,9</sup>  
 F.I. Olness <sup>10</sup> E. Piassetzky <sup>11</sup> P. Risse <sup>2</sup> R. Ruiz <sup>3</sup> I. Schienbein <sup>12</sup> and J.Y. Yu. <sup>12</sup>

## New SRC-motivated parametrization

Modeling of short-ranged nuclear structure suggests separation of single nucleons from SRC nucleon pairs.



Translation to parton model

$$f_i^A(x, Q_0) = \frac{Z}{A} \left[ (1 - C_p^A) f_i^p(x, Q_0) + C_p^A f_i^{p, SRC}(x, Q_0) \right] \\ + \frac{N}{A} \left[ (1 - C_n^A) f_i^n(x, Q_0) + C_n^A f_i^{n, SRC}(x, Q_0) \right]$$

$$f_i^{p/n}(x, Q_0)$$

free nucleon PDFs

**A-independent**

$$C_p^A, C_n^A$$

fraction of nucleon in SRC pairs

**A-dependent**

$$f_i^{p, SRC}(x, Q_0), f_i^{n, SRC}(x, Q_0)$$

modified nucleon in SRC pair

**A-independent**

## Quality of the fit

$\chi^2/N_{\text{data}}$	DIS	DY	$W/Z$	JLab	$\chi_{\text{tot}}^2$	$\frac{\chi_{\text{tot}}^2}{N_{\text{DOF}}}$
traditional	0.85	0.97	0.88	0.72	1408	0.85
baseSRC	0.84	0.75	1.11	0.41	1300	0.80
pnSRC	0.85	0.84	1.14	0.49	1350	0.82
$N_{\text{data}}$	1136	92	120	336	1684	

- ▶ three fits: one with traditional parametrization, two fits SRC inspired

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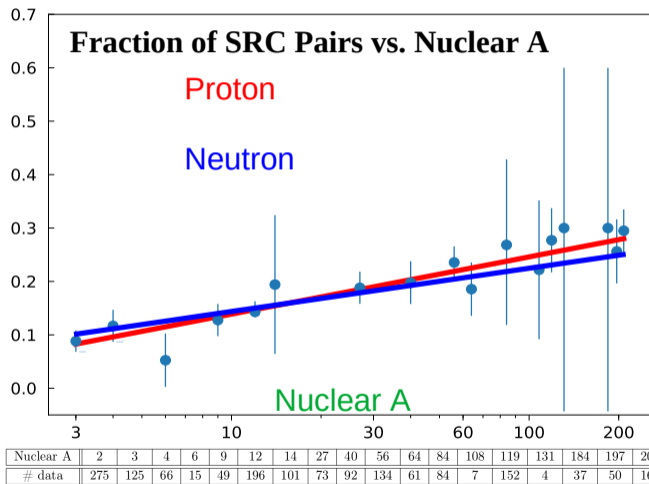
- ▶ three fits: one with traditional parametrization, two fits SRC inspired
- ▶ **better overall** quality for the SRC inspired fit
- ▶ particularly pronounced for high- $x$  JLab data
- ▶ worse description of *W/Z* data, which probe lower  $x$ -values



## SRC fractions

Fit **proton** & **neutron** fractions independently: baseSRC

- ▶ both **proton** and **neutron** fraction have simple logarithmic  $A$ -dependence
- ▶  $C_p^A$  &  $C_n^A$  unconstrained for nuclei with sparse data



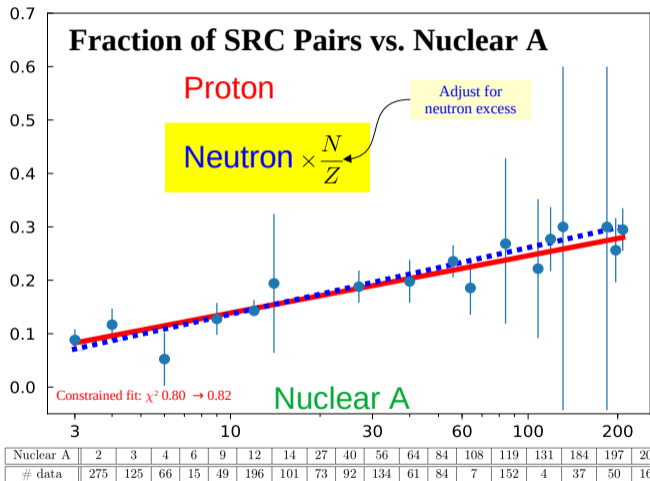
# SRC fractions adjusted for neutron excess

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- ▶ both **proton** and **neutron** fraction have simple logarithmic  $A$ -dependence
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New fit with  $C_n^A = Z/N C_p^A$ : pnSRC

- ▶ **neutron** fractions adjusted for excess
- ▶ better agreement with **proton** fractions
- ▶ small  $\chi^2/N_{\text{DOF}}$  increase, but less parameters to fit!



**Thank you!**

# Preliminary results: $A$ -dependence

