Precision νDIS at the Forward Physics Facility

CATCH22(+2), Dublin, Ireland

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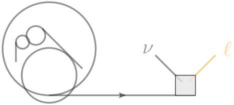
1 May 2024



thank you for the invitation!

gov.ie News Department

Press release

Minister Harris announces Ireland has been successful in next phase of CERN application

From Department of Further and Higher Education, Research, Innovation and Science
Published on 19 December 2023
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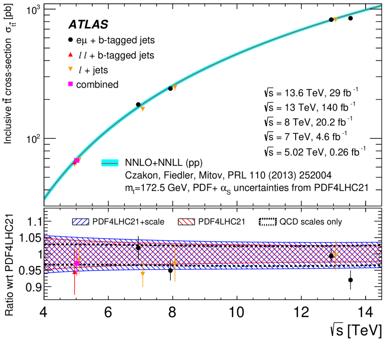
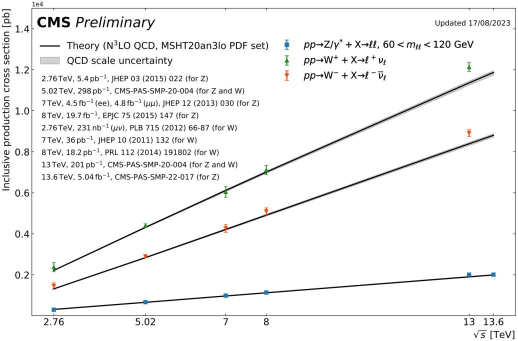
Minister for Further and Higher Education, Research, Innovation and Science Simon Harris has announced that Ireland has been successful in the next step to join the European Organization for Nuclear Research, CERN, one of the world's largest and most respected centres for scientific research.

CERN considered Ireland's application last week and agreed to send a taskforce to Ireland to assess its application. The taskforce will produce a report on Ireland's fulfilment of the criteria for Associate Membership. After reviewing this report, it is likely that CERN Council will make a final decision on Ireland's application for Associate Membership in June of 2024.

presently, we in an era of precision hadron collisions

for the next 15+ years ('40s) we will be guided by high-energy, high-precision hadron-hadron collision data (ion-ion data, too!)





The high-luminosity program has a **robust and exciting portfolio** for Standard Model measurements and new physics searches

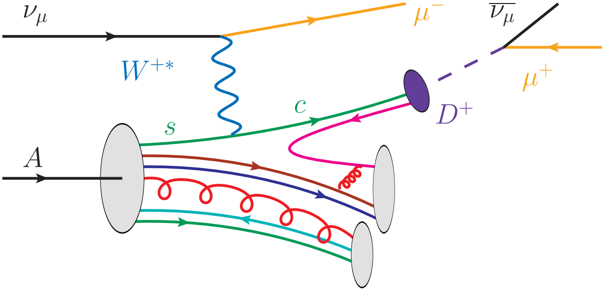
ongoing discussions on future programs at CERN (FCC!), e.g., European Strategy Update ('20); Snowmass ('21) [2209.14872];

new! SOI between USA and CERN "*expresses intention by the United States to collaborate on FCC-ee*" (April'24)

while the present era ends in the 2040s,

we are already entering another precision era

an era of precision deep-inelastic scattering (DIS)



Several νDIS and $e^{\pm}$DIS programs already collecting data:

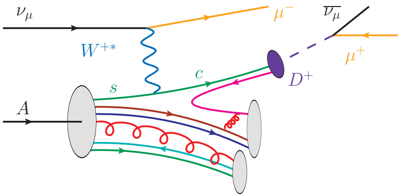
- Fermilab (short-baseline ν)
- JLab (12 GeV CEBAF)
- CERN (FASER/SND experiments)

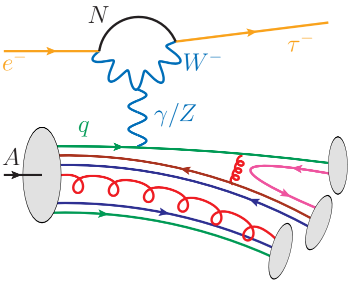
with more planned for '20s-'50s:

- BNL (EIC) ✓
- LBNF (DUNE) ✓
- CERN (Forward Physics Facility)

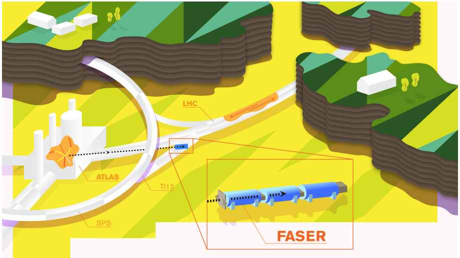
with various agendas:

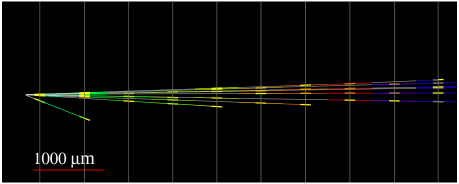
- precision ν oscillations
- precision hadronic structure
- QCD at the extremes
- search for LFV
- search for feably coupled phys.





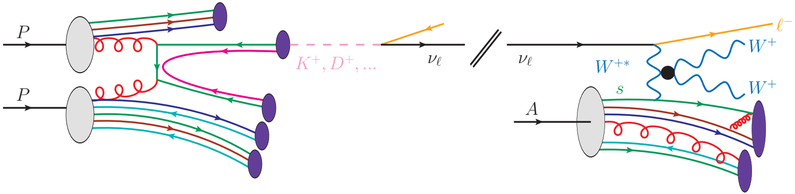
In the past few years, the LHC has been established as an intense (laboratory) source of TeV-scale neutrinos (ν) **(a remarkable expt. achievement!)**





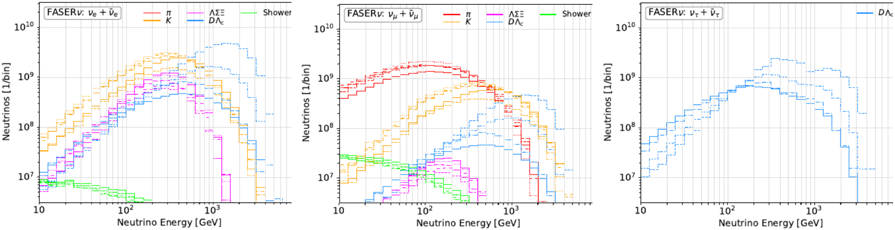
Candidate LHC neutrino event from FASER's pilot run

New programs (FASER, SND@LHC) **now collecting ν-nucleus scattering data**

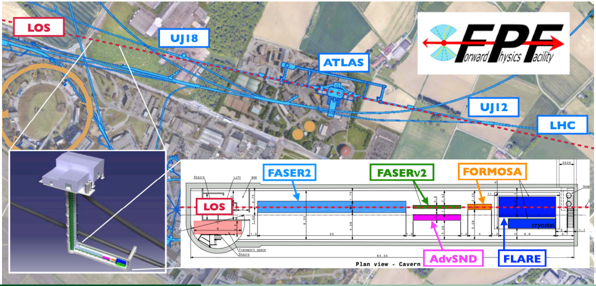


ν **fluxes** from LHC **(a) are large** and **(b) span $1-4$ TeV in energy**

Kling & Nevay (PRD'21)



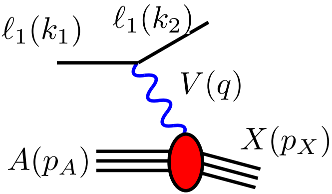
Detectors at the the Forward Physics Facility, a proposed cavern alongside ATLAS, can see $\mathcal{O}(10^6)$ TeV-scale νDIS events [2203.05090]; Feb'24 meeting

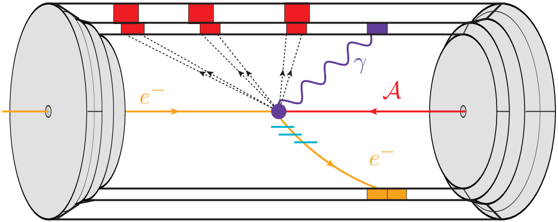


precise data demands precise predictions from theory

how to do this?

by learning from the LHC program





Accelerator-based scattering experiments are counting experiments:

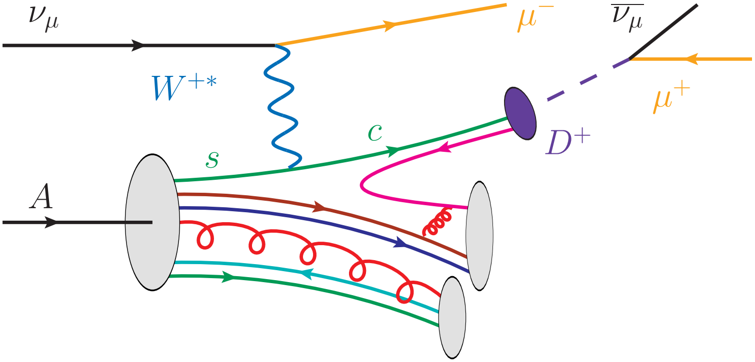
- **count** # of candidate signal events, e.g., $1e^{\pm} + X$ satisfying criteria
- **estimate** # of background events from data-driven control region
- **calculate** statistical significance

Theory needed to estimate number (and unc.) of signal and bkg events:

$$\underbrace{N_{\text{candidates}}}_{\text{hep/nucl−ex}} = \underbrace{\mathcal{L}(\text{data!})}_{\text{accelerators}} \times \underbrace{\sigma(\text{scattering likelihood})}_{\text{hep/nucl−th/ph}}$$

Formally, inclusive **DIS** of $\ell \in \{\ell^{\pm}, \nu, \overline{\nu}\}$ off **nucleons** can be described by the **Collinear Factorization Theorem**

Collins, Soper ('87); Collins ('11)

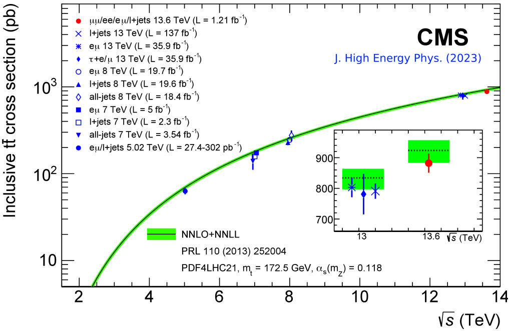


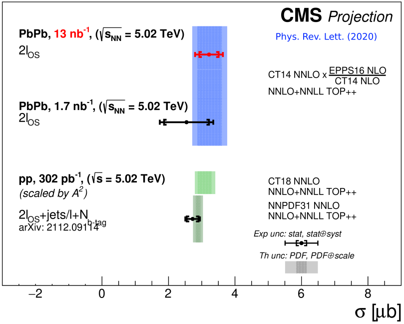
$$d\sigma(\nu\mathcal{A} \to \ell X) = \underbrace{\sum_{k,X_n}}_{inclusive} \underbrace{\Delta_{kk'}}_{\text{shower/RGE}} \otimes \underbrace{f_{k'}}_{\text{PDF}} \otimes \underbrace{d\hat{\sigma}_{\nu k' \to X_n}}_{\text{hard scattering}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{\text{NP}}^{2+k}}{Q^{2+k}}\right)}_{\text{interesting bit!}}$$

1. improving (nuclear) parton distribution functions

Major effort to use low- and high-energy scattering data to constrain $f_k^{\mathcal{A}}$

e.g., JLAB, FNAL, CERN





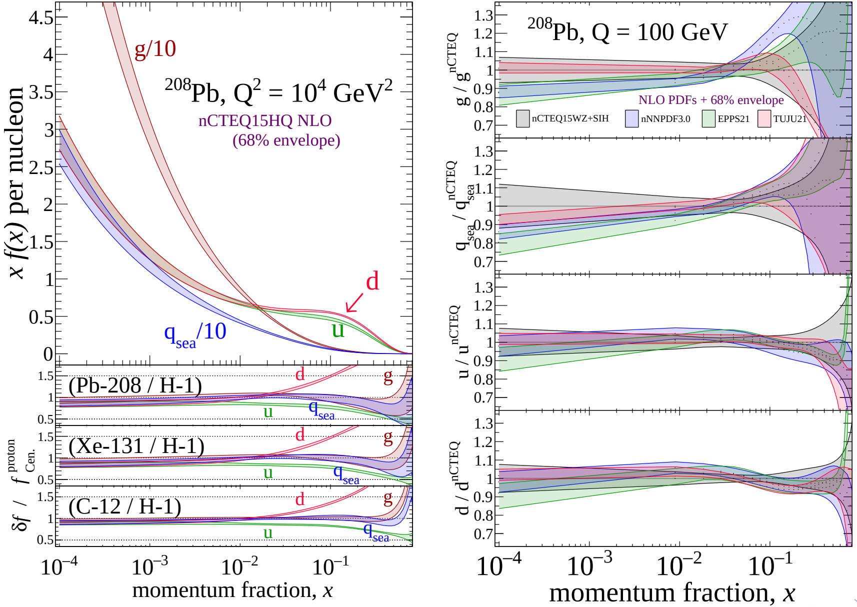
– $\mathcal{O}(5\%)$ uncertainties for q, g, γ content of **proton** driven by W/Z, $t\bar{t}$, dijet data from the Large Hadron Collider (LHC) leadership by CTEQ/CT, NNPDF, M*HT

– $\mathcal{O}(20\%)$ uncertainties for **nuclei** driven by ℓ/ν-DIS + new LHC data

many activities by nCTEQ, nNNPDF, EPPS, TUJU, DSSZ collaborations

(L) nuclear PDFs vs energy fraction carried by parton **(R)** PDF ratios

w/ Fuks, Marougkas†, Sztandera† [2024.xxx]



2. improving the interesting bit

$$d\sigma(\nu\mathcal{A}\to\ell X) = \underbrace{\sum_{k,X_n}}_{inclusive} \underbrace{\Delta_{kk'}}_{\text{shower/RGE}} \otimes \underbrace{f_{k'}}_{\text{PDF}} \otimes \underbrace{d\hat{\sigma}_{\nu k'\to X_n}}_{\text{hard scattering}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{\rm NP}^{2+k}}{Q^{2+k}}\right)}_{\text{interesting bit!}}$$

Importance of “subleading” (aka power) corrections

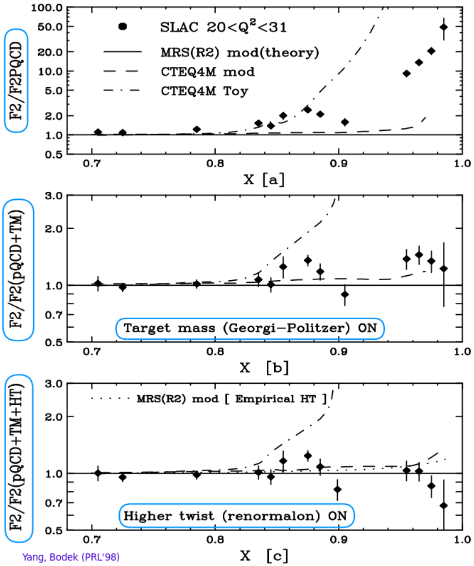
$\mathcal{O}\left(\frac{\Lambda_{\rm NP}^{2+k}}{Q^{2+k}}\right)$ corrections increasingly important at **small** Q^2**, large** x!

“target mass corrections” (TM) $\rightarrow$

Georgi, Politzer ('76,'76)

“renormalon” corrections” (HT) $\rightarrow$

Dasgupta, Webber ('91)



Yang, Bodek (PRL'98)

in extreme kinematics, necessary:

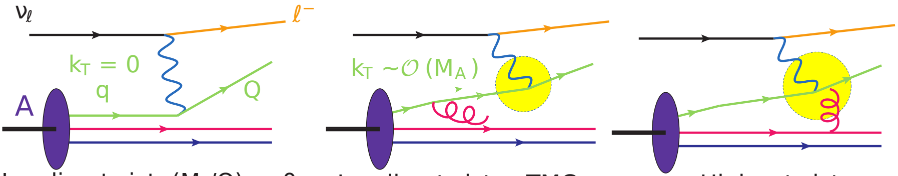
– describe DIS data

– extend validity of Fact. Thm.

– extract PDFs from structure fns.

$\mathcal{O}\left(\frac{\Lambda_{\rm NP}^{2+k}}{Q^{2+k}}\right)$ corrections have several origins (kinematical and dynamical)

Georgi, Politzer ('76,'76); Ellis, Furmanski, Petronzio ('82,'82); Dasgupta, Webber ('91); lots more



Leading twist, $(M_A/Q) \to 0$ | Leading twist + TMCs | Higher twist

For DIS on protons, **target mass corrections (TMCs)** incorporated by replacing $F_i^{A\ \text{(No TMC)}} \to F_i^{A\ \text{(TMC)}}$ in cross sections:

Georgi, Politzer ('76,'76); Ellis, Furmanski, Petronzio ('82,'82); lots more; Kretzer, Reno ('02,'03); Schienbein, et al [0709.1775]

$$\frac{d^2\sigma^{\rm NC}}{dx\,dy} = x(s - M^2)\,\frac{d^2\sigma^{\rm NC}}{dxdQ^2} = \frac{4\pi\alpha^2}{xyQ^2}\left[\frac{Y_+}{2}\ \sigma^{NC}_{\rm Red.}\right]$$

$$\sigma^{NC}_{\rm Red.} = \left(1 + \frac{2y^2\varepsilon^2}{Y_+}\right)F_2^{\rm NC} \mp \frac{Y_-}{Y_+}\,xF_3^{\rm NC} - \frac{y^2}{Y_+}F_L^{\rm NC}$$

not obvious that $\mathcal{O}\left(\frac{\Lambda_{\rm NP}^{2+k}}{Q^{2+k}}\right)$ power corrections for protons

are same for **arbitrary nuclei** [1]

[1] for many reasons, including questions of original derivation's correctness [Collins ('84)]

TMCs for protons (p) and nuclei $(\mathcal{A})$ are almost identical

TMCs for DIS on nuclei

RR, Olness, Schienbein, et al [nCTEQ], [Prog.Part.Nucl.Phys ('24)]

$$\tilde{F}_1^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A}{\xi_A r_A}\right)\tilde{F}_1^{A,(0)}(\xi_A) + \left(\frac{M_A^2 x_A^2}{Q^2 r_A^2}\right)\tilde{h}_2^A(\xi_A) + \left(\frac{2M_A^4 x_A^3}{Q^4 r_A^3}\right)\tilde{g}_2^A(\xi_A)\,,$$

$$\tilde{F}_2^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A^2}{\xi_A^2 r_A^3}\right)\tilde{F}_2^{A,(0)}(\xi_A) + \left(\frac{6M_A^2 x_A^3}{Q^2 r_A^4}\right)\tilde{h}_2^A(\xi_A) + \left(\frac{12M_A^4 x_A^4}{Q^4 r_A^5}\right)\tilde{g}_2^A(\xi_A)\,,$$

$$\tilde{F}_3^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A}{\xi_A r_A^2}\right)\tilde{F}_3^{A,(0)}(\xi_A) + \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_3^A(\xi_A)\,,$$

$$\begin{aligned}\tilde{F}_4^{A,\mathrm{TMC}}(x_A) = &\left(\frac{x_A}{\xi_A r_A}\right)\tilde{F}_4^{A,(0)}(\xi_A) - \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^2}\right)\tilde{F}_5^{A,(0)}(\xi_A) + \left(\frac{M_A^4 x_A^3}{Q^4 r_A^3}\right)\tilde{F}_2^{A,(0)}(\xi_A)\\ &+ \left(\frac{M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_5^A(\xi_A) - \left(\frac{2M_A^4 x_A^4}{Q^4 r_A^4}\right)\left(2 - \xi_A^2 M_A^2/Q^2\right)\tilde{h}_2^A(\xi_A)\\ &+ \left(\frac{2M_A^4 x_A^3}{Q^4 r_A^5}\right)\left(1 - 2x_A^2 M_A^2/Q^2\right)\tilde{g}_2^A(\xi_A)\,,\end{aligned}$$

$$\begin{aligned}\tilde{F}_5^{A,\mathrm{TMC}}(x_A) = &\left(\frac{x_A}{\xi_A r_A^2}\right)\tilde{F}_5^{A,(0)}(\xi_A) - \left(\frac{M_A^2 x_A^2}{Q^2 r_A^3 \xi_A}\right)\tilde{F}_2^{A,(0)}(\xi_A)\\ &+ \left(\frac{M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_5^A(\xi_A) - \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^4}\right)\left(1 - x_A\xi_A M_A^2/Q^2\right)\tilde{h}_2^A(\xi_A)\\ &+ \left(\frac{6M_A^4 x_A^3}{Q^4 r_A^5}\right)\tilde{g}_2^A(\xi_A)\,,\end{aligned}$$

$$\tilde{F}_6^{A,\mathrm{TMC}}(x_A) = \left(\frac{x_A}{\xi_A r_A^2}\right)\tilde{F}_6^{A,(0)}(\xi_A) + \left(\frac{2M_A^2 x_A^2}{Q^2 r_A^3}\right)\tilde{h}_6(\xi_A)\,.$$

Rescaling

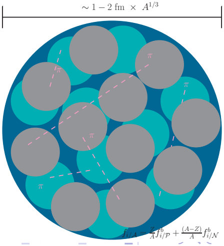
Interestingly, TMCs have particular kinematical dependence:

$$\frac{x_A}{\xi_A} \quad \text{or} \quad \left(\frac{x_A^2 M_A^2}{Q^2}\right)$$

Define "average (nucleon) kinematics": $M_N \equiv M_A/A$ **and** $x_N \equiv A x_A$

$$\frac{x_A}{\xi_A} = \frac{x_N}{\xi_N} \quad \text{or} \quad \left(\frac{x_A^2 M_A^2}{Q^2}\right) = \left(\frac{x_N^2 M_N^2}{Q^2}\right)$$

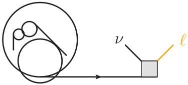
Consequence: TMCs take on **universal, A-independent form** matches intuitive picture of nuclei being collection of A nucleons →



summary and conclusion

We are entering an era of precision DIS that strongly complements the ongoing hadron program

- **ongoing efforts** to improve theory predictions
- **theory improvements** applicable to programs at CERN, US labs
- **lots not covered,** so see new (pedagogical) review JPPNP ('24) [2301.07715]
- **advert:** 3-year TH postdoc on νDIS@CERN opening this fall



Thank you!

backup

the dark secret of ν scattering experiments

in practice, νDIS needs nuclear targets

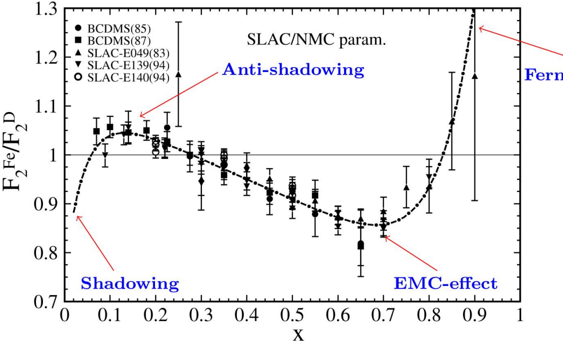
1. ν only interact through weak force: targets must be bigger ($\mathcal{O}(10)$tons) and denser (Ar,Fe,Pb) $\implies$ more nuclear

2. fact of life: nuclear dynamics impact hadronic structure

Plotted: $\frac{F_2^{\rm iron}}{F_2^{\rm deuteron}}$ for ℓ-DIS

For non-expert, QED (γ) contribution to F_2:
$F_2(\xi) \approx \sum_{i\in\{q,\overline{q},g\}} Q_i^2 \ \xi \ f_i^A(\xi)$,

Q_i=electric charge of i

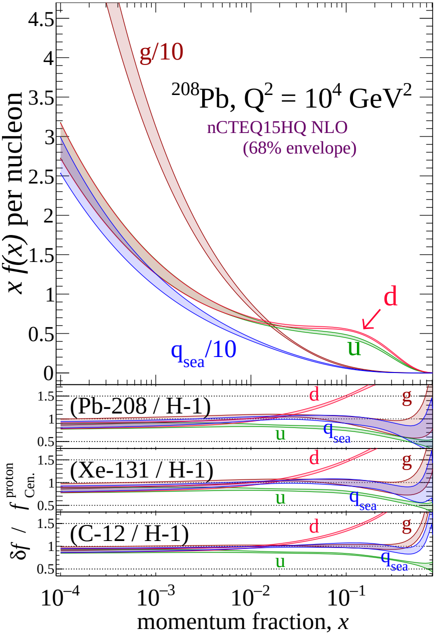


Schienbein, et al [0710.4897]

Plotted: PDF of avg. nucleon in ^{208}Pb vs (avg) energy fraction carried by parton

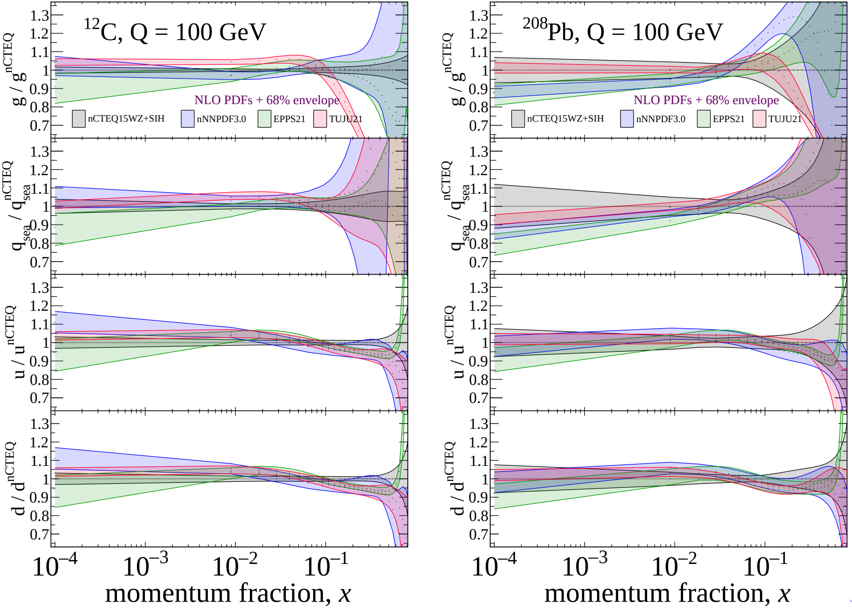
- huge g content (always easy to make more g)
- $q_{\rm sea}$, d, and u content converge for $x \lesssim 10^{-2}$ (dominated by $g^* \to q\bar{q}$ splitting)
- densities smaller (larger) than proton for $x \lesssim 10^{-2} (x \gtrsim 10^{-2})$
- qualitatively different from proton
- smaller $\mathcal{A}$ are more proton-like

w/ Fuks, Marougkas†, Sztandera† [2024.xxx]→



Plotted: Ratios of nuclear PDFs vs (avg) energy fraction carried by parton

w/ Fuks, Marougkas†, Sztandera† [2024.xxx]



running numbers

running the numbers

we use NLO PDFs (nCTEQ15) to build str. fns. At LO, these are

$$F_1^{\nu A} = (d + s + \bar{u} + \bar{c}), \qquad F_1^{\bar{\nu} A} = (u + c + \bar{d} + \bar{s})$$

$$F_2^{\nu A} = 2x\,(d + s + \bar{u} + \bar{c}), \qquad F_2^{\bar{\nu} A} = 2x\left(u + c + \bar{d} + \bar{s}\right)$$

$$F_3^{\nu A} = +2\,(d + s - \bar{u} - \bar{c}), \qquad F_3^{\bar{\nu} A} = -2\left(u + c - \bar{d} - \bar{s}\right)$$

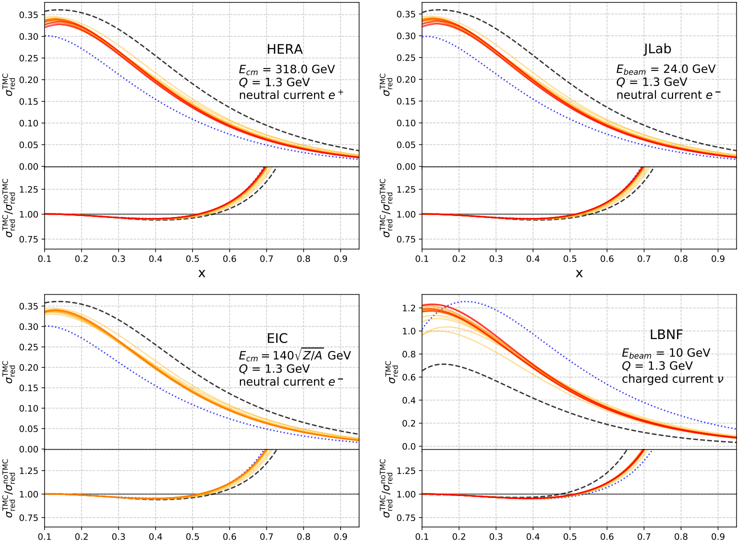
$$F_2^{l^\pm A} = x\frac{1}{9}\left[4(u + \bar{u}) + (d + \bar{d}) + 4(c + \bar{c}) + (s + \bar{s})\right]$$

for many targets

Symbol	A	Z	Symbol	A	Z	Symbol	A	Z	Symbol	A	Z
H	1	1	Be	9	4	Ca	40	20	Xe	131	54
D	2	1	C	12	6	Fe	56	26	W	184	74
^{3}He	3	2	N	14	7	Cu$_{\rm iso}$	64	32	Au	197	79
He	4	2	Ne	20	10	Kr$_{\rm iso}$	84	42	Au$_{\rm iso}$	197	98.5
Li	6	3	Al	27	13	Ag$_{\rm iso}$	108	54	Pb$_{\rm iso}$	207	103.5
Li	7	3	Ar	40	18	Sn$_{\rm iso}$	119	59.5	Pb	208	82

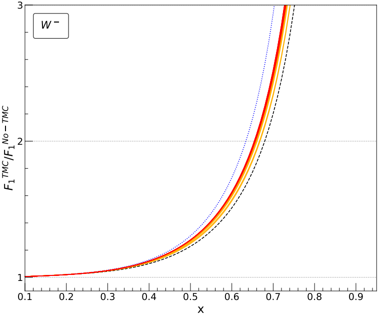
reduced cross sections for many nuclear targets

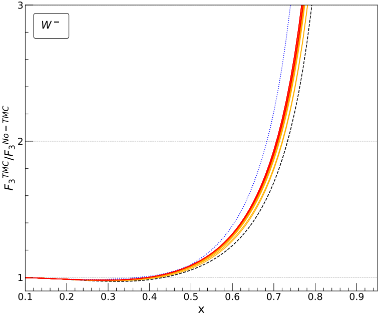
Plotted: (upper) reduced cross sections with nTMCs; (lower) ratio to w/o



ratio of F_i^{TMC} / $F_i^{\mathrm{no\ TMC}}$

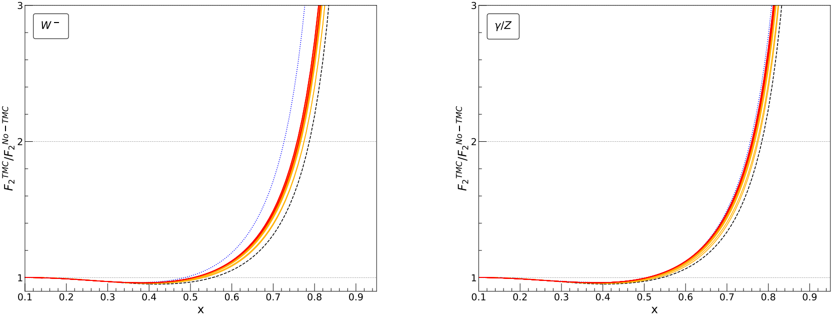
Plotted: ratio for (L) $F_1^{W^-}$ and (R) $F_3^{W^-}$ at $Q = 1.5$ GeV





Can you spot the ^{1}H and ^{2}D curves?

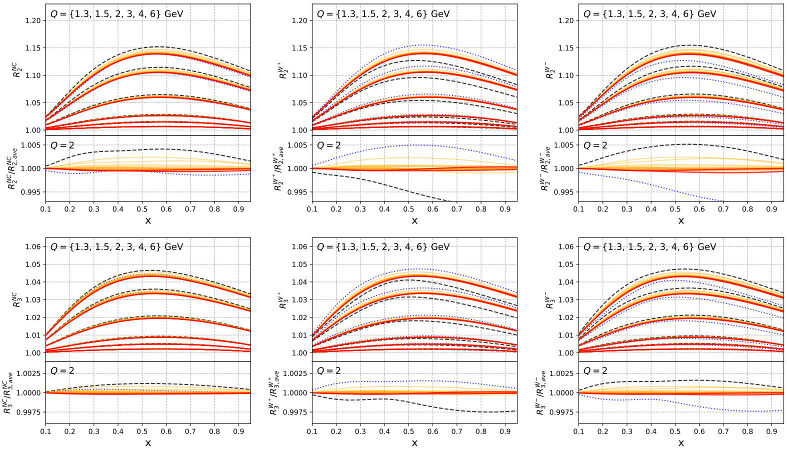
Plotted: ratio for (L) $F_2^{W^-}$ and (R) $F_2^{\gamma/Z}$ at $Q = 1.5$ GeV



Can you spot the ^{1}H and ^{2}D curves?

ratio of F_i^{TMC} / $F_i^{\mathrm{leading\ TMC}}$

Plotted: ratio for (L) $F_i^{Z/\gamma}$, (C) $F_i^{W^+}$, (R) $F_i^{W^-}$ for $i = 2$ (upper) and $i = 3$ (lower)



remarkable uniformity! (good enough to fit! ☺)