Decoupling the Neutrino Interaction through Polarization: What Electron–Ion Collider Can (at least) Do for Neutrino Physics





Guang Yang (Brookhaven National Lab)

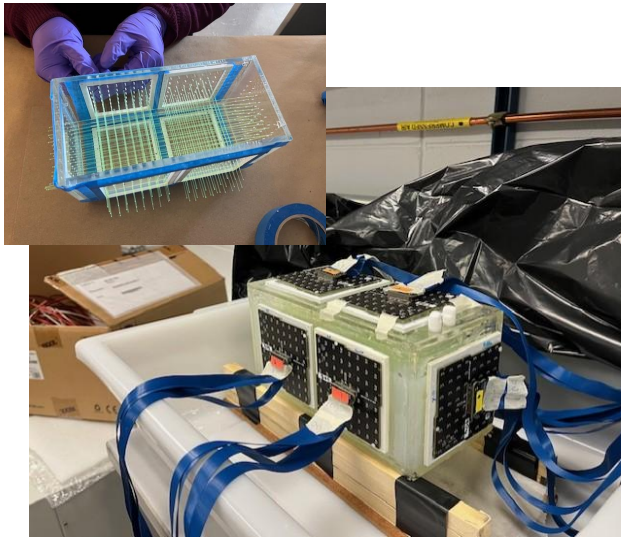
October 2026

NNN-2026 Seoul, Korea

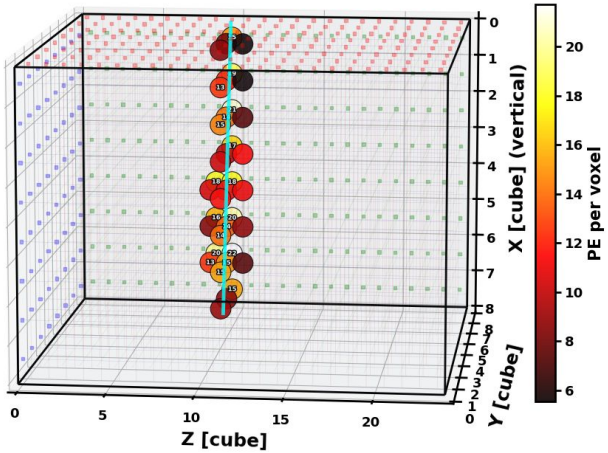
*Special thanks to **Milind Diwan, Minfang Yeh and Gabriella Carini***

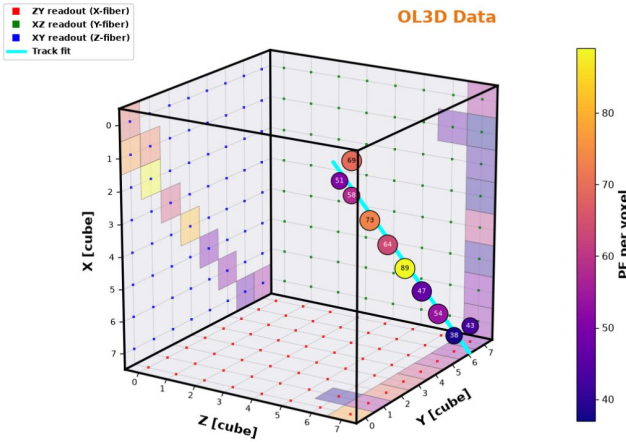
Who am I

- I try to be an experimentalist (the detector guy)
- I am actively running three novel complex (and fun) detectors
- I want to do KOTO-II, DAMSA, FASER, PICO …
- I am in CPAD, DRD2, DRDCalo …



All done by me, Praveen Kumar, Hoahui Che and Sasmit Gokhale

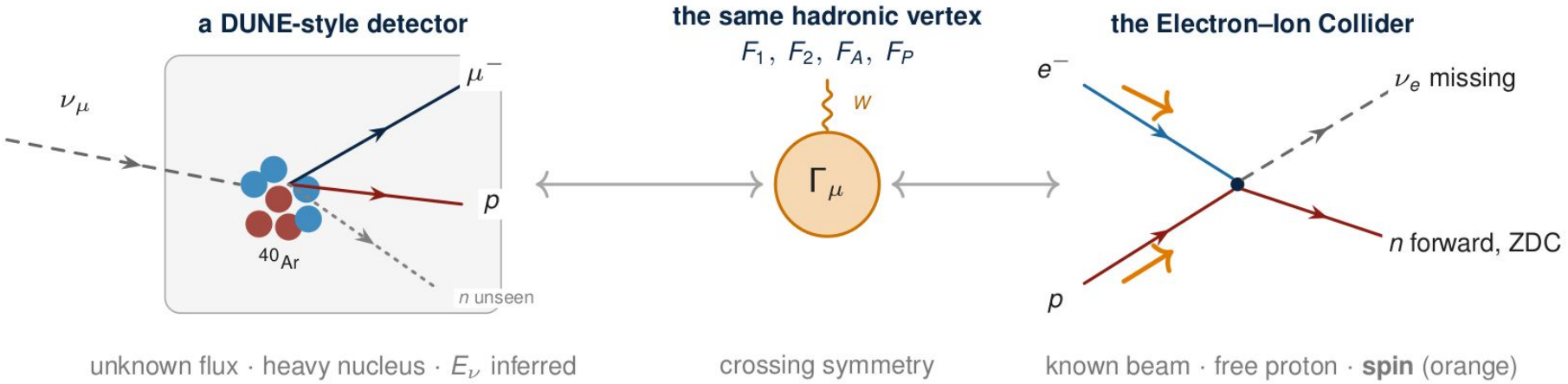




Colliding electron with proton and ions

Why collider in this room: DUNE's reaction and the EIC reaction contain the same W–nucleon vertex.

- The collider offers what a neutrino beam cannot: a known beam energy, a free proton, and spin on both beams. That is enough to measure the pieces of the vertex that neutrino data leave open.



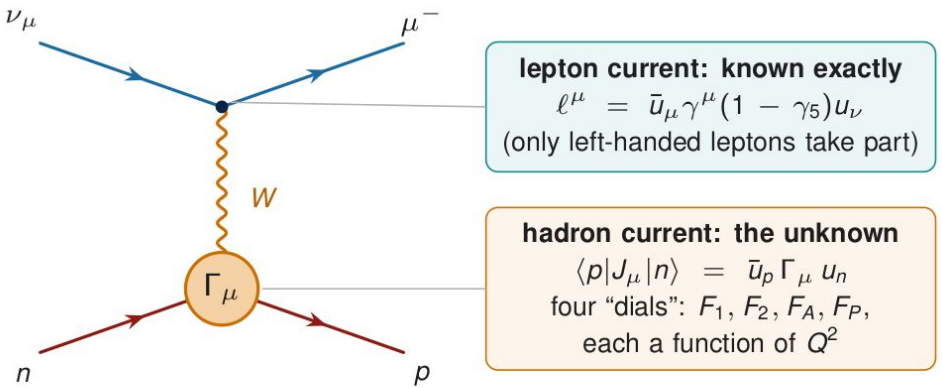
Neutrino experiments

Before you can perform any neutrino oscillation measurements, three questions needed asks:

- **How often?** events = flux × cross section × targets. The flux can be separated measured given the independence of the target.
- **With what shape?** $d\sigma/dQ^2$, how the rate falls with the momentum transfer Q^2. This shape is set by the nucleon's form factors and fixes $\sigma(E\nu)$.
- **What comes out?** $E\nu$ is reconstructed from the visible particles. It can be bias, e.g. every unseen neutron makes the event look 50–200 MeV less energetic than it was.

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * T_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

Form factor



$$\text{amplitude} = \frac{G_F V_{ud}}{\sqrt{2}} \ell^\mu \langle p|J_\mu|n\rangle$$

The form factor is fourier transform of the density of the nuclear system.
A nucleon has three quarks, so the simplest model is dipole form.
EM part is very precise. Axial part is difficult.

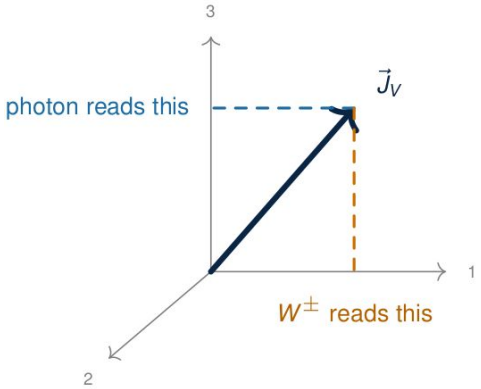
The weak interaction is a product of two currents at one point, with one universal strength GF. The lepton side is calculable; everything unknown sits in the hadron side.

$$\Gamma_\mu = \underbrace{\gamma_\mu F_1 + \frac{i\sigma_{\mu\nu} q^\nu}{2M} F_2}_{\text{vector: charge, magnetism}} + \underbrace{\gamma_\mu \gamma_5 F_A + \frac{q_\mu}{M} \gamma_5 F_P}_{\text{axial: spin}}$$

Each coefficient can depend only on the one invariant available, Q^2.

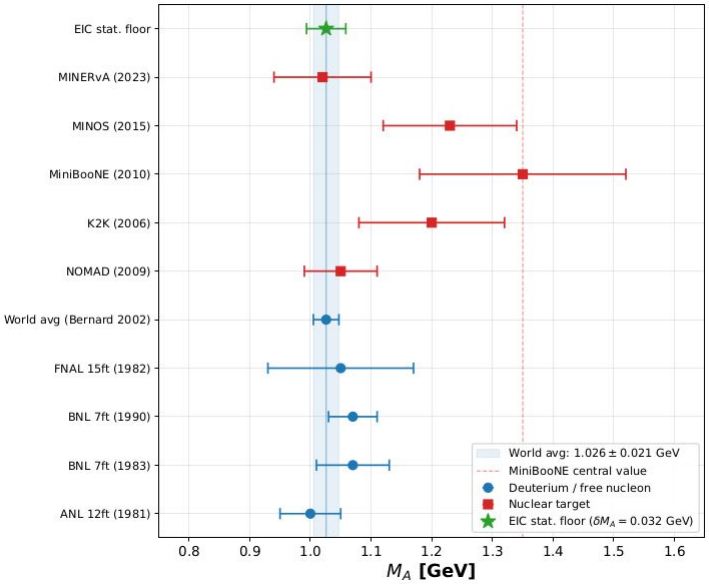
Rate ~ square and sum over spins.
dσ/dQ^2 is a known factor times a quadratic form in F1 , F2 , FA.

Form factor continue



$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

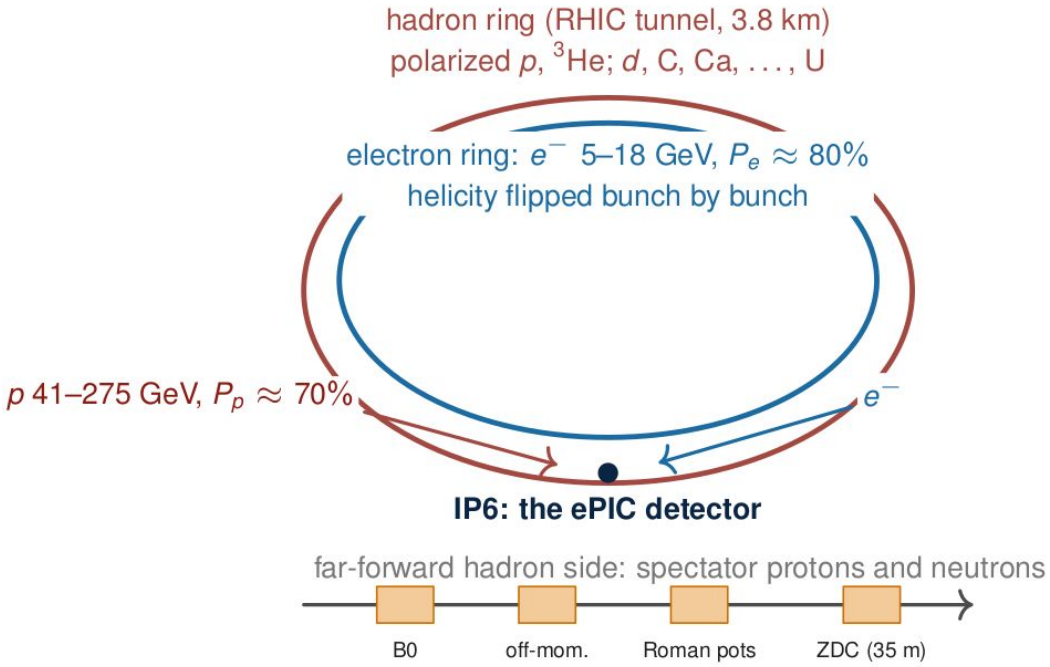
$$g_A = F_A(0) = 1.2723 \pm 0.0023$$



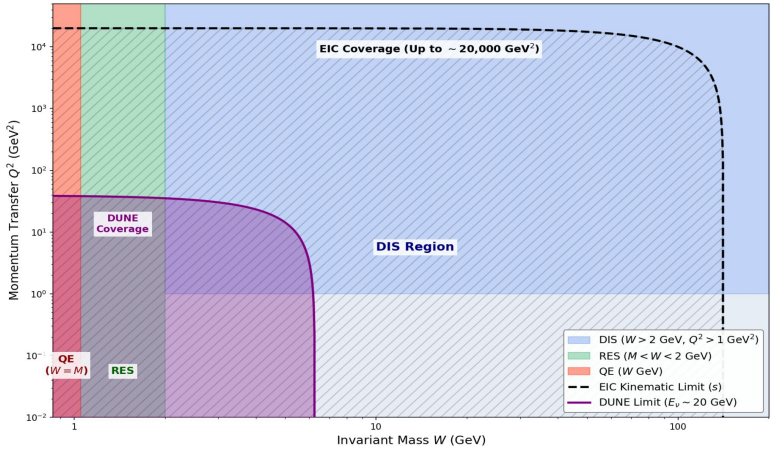
Two assumptions

- The weak vector current and the isovector electromagnetic current are two components of one vector in isospin space.
- Ignore the pion field for electron scattering

EIC kinematics



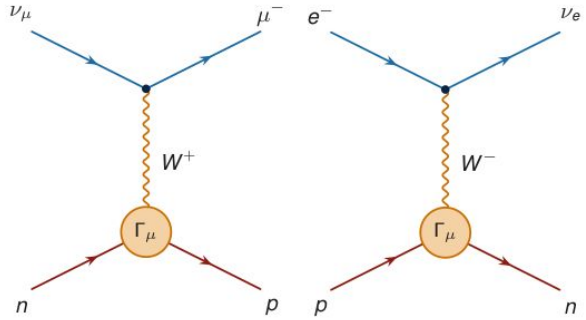
Parameter (as assumed in [1])	**Value**
$E_e \times E_p$ (maximum)	18×275 GeV, $\sqrt{s} = 141$ GeV
same collision, proton at rest	a 10.5 TeV electron beam
integrated luminosity	500 fb^{-1}
polarization e / p	80% / 70%, measured to 1%
luminosity uncertainty	2%



Beam polarization

Both electron and proton/ion can be polarized and kept at 80%/70% level.

Combination of the two side polarization can give us a new degree looking into the weak interaction.





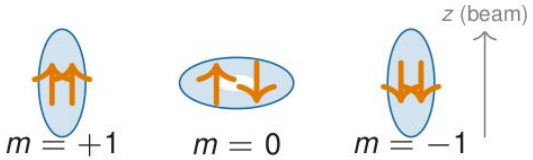
8 up, 2 down:
$P = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow) = 60\%$



left-handed (LH): spin against motion

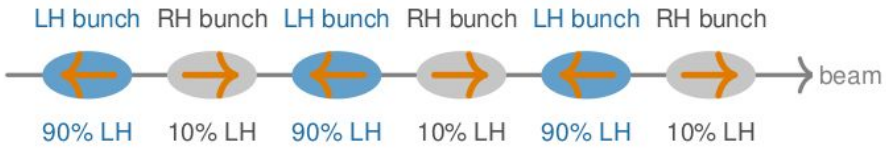


right-handed (RH): spin along motion

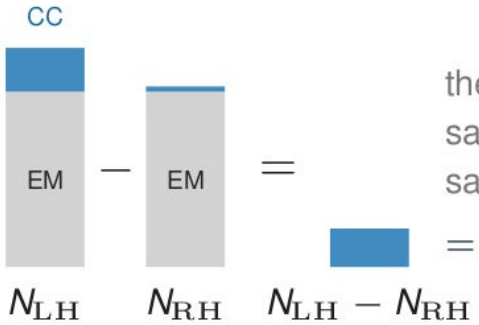


Spin-$\frac{1}{2}$ beams (e, p, ^{3}He): one number, $P = (N_\uparrow - N_\downarrow)/N$; "longitudinal" means along the beam; for a moving particle the sign is its *helicity*.
Spin-1 beams (d): three sub-states, so *two* numbers: the vector polarization $P_z = n_+ - n_-$ (which way) and the **tensor polarization** $P_{zz} = n_+ + n_- - 2n_0$ (spins *aligned along* the axis, $m = \pm 1$ "cigar", versus *across* it, $m = 0$ "doughnut"). $P_{zz} = +1$: no $m = 0$; $P_{zz} = -2$: only $m = 0$.

Background removal



orange = spin; beam moves to the right;
LH = spin against the motion ($P_e = 0.80$)



the EM part cancels:
same detector, same time,
same luminosity, same cuts

$= P_e\, N_{\rm CC}$

Weak interaction couples left-handed neutrino or right-handed antineutrino to nucleon.

This fact helps to reduce EM background.

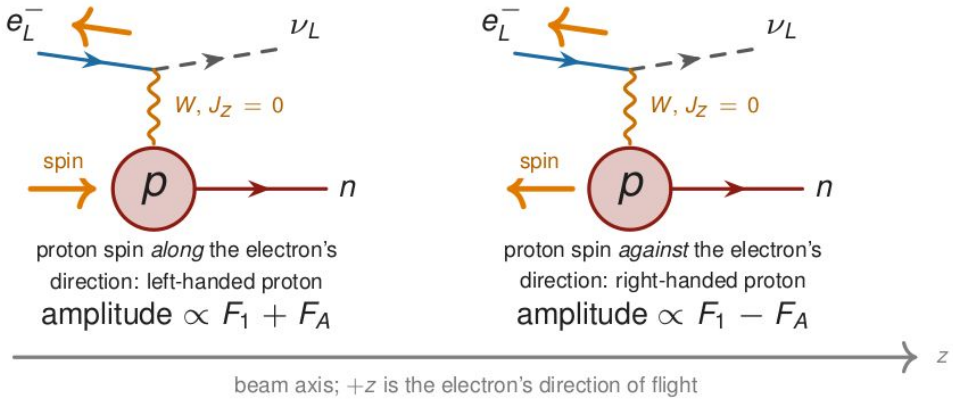
$$N_{\rm LH} = \frac{1+P_e}{2} N_{\rm CC} + N_{\rm EM}, \qquad N_{\rm RH} = \frac{1-P_e}{2} N_{\rm CC} + N_{\rm EM},$$

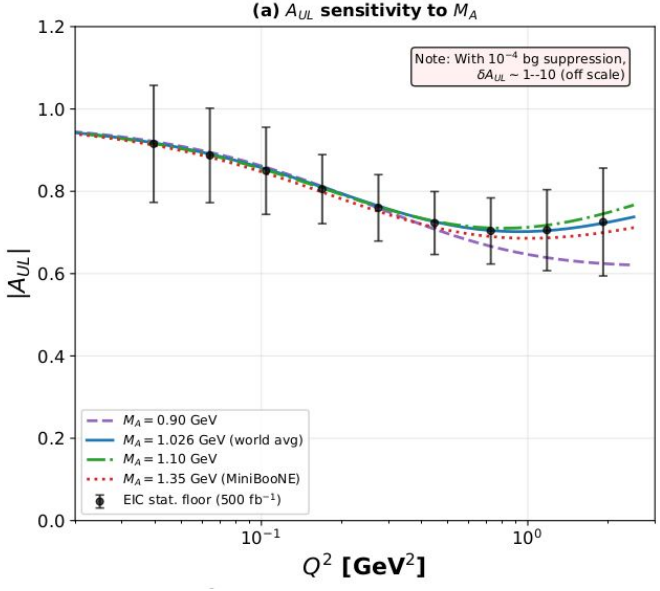
$$N_{\rm CC} = \frac{N_{\rm LH} - N_{\rm RH}}{P_e}, \qquad \delta N_{\rm CC} = \frac{\sqrt{N_{\rm LH} + N_{\rm RH}}}{P_e}.$$

Axial form factor extraction

$$\sigma(\uparrow) \propto (F_1 + F_A)^2 + \tau F_2^2, \quad \sigma(\downarrow) \propto (F_1 - F_A)^2 + \tau F_2^2$$

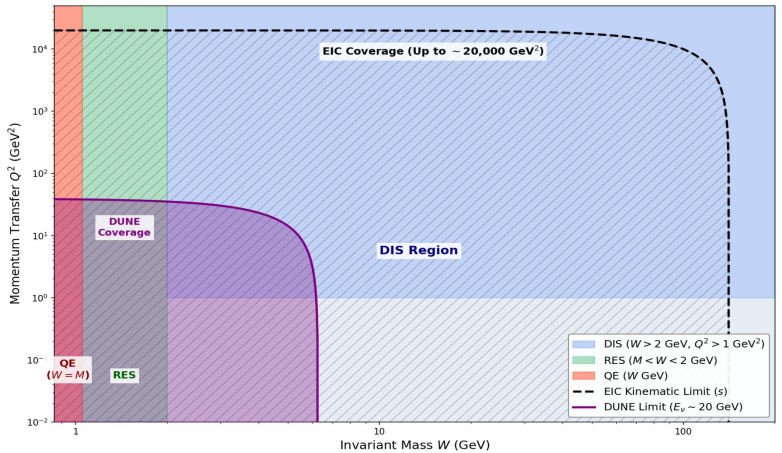
$$A_{UL} = \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} = \frac{2F_1 F_A}{F_1^2 + F_A^2 + \tau F_2^2} \xrightarrow{Q^2 \to 0} 0.97 \ \ (g_A = 1.27)$$

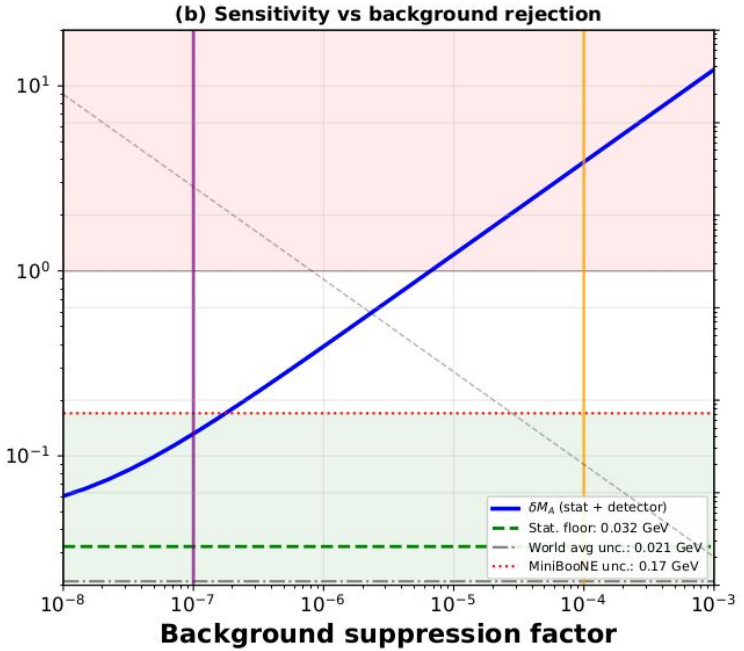




Background accounting

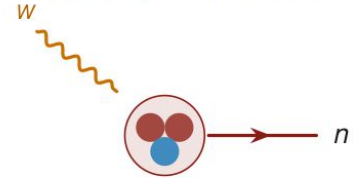
scenario (Table IV of [1])	δM_A [GeV]	
statistical floor, ∼2,200 events	**0.032** (3%)	shape: 98% of the information
background suppression 10^{-7}	**0.14**	competitive (MiniBooNE ±0.17)
today's baseline 10^{-4}	≈ 4	**unfeasible** ($S/B \approx 3 \times 10^{-4}$)
systematics, total (at 10^{-7})	0.019	bg subtraction, ZDC scale



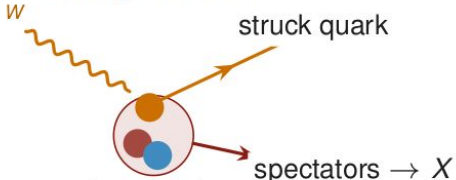


Deep inelastic evaluation

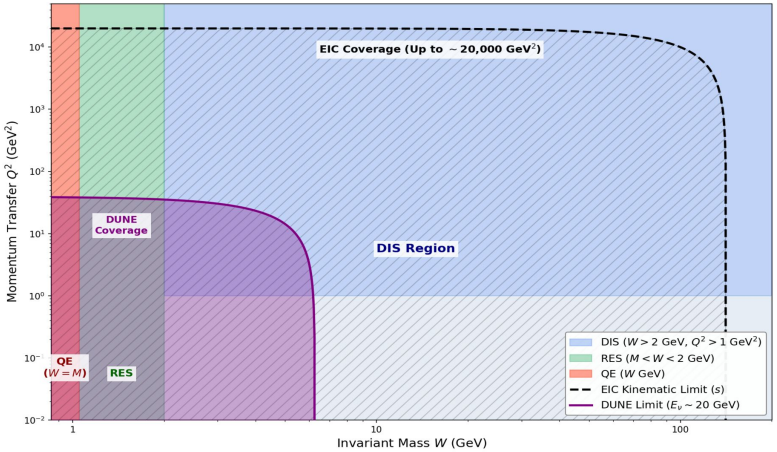
elastic ($x = 1$):
the whole proton recoils



deep inelastic ($x < 1$):
one quark is hit



x = share of the proton's momentum carried by the struck quark



$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2\, s}{4\pi}\left[Y_+ F_2(x) \pm Y_-\, xF_3(x)\right]$$

$$F_2 = 2x(q+\bar{q}), \quad xF_3 = 2x(q-\bar{q})$$

quasi-elastic: the whole proton answers — $C = \frac{1}{4}(F_A^2 + F_1^2 + \tau F_2^2)$

deep inelastic: sum over quarks, weight $2x$ — $\frac{1}{2}F_2(x)$

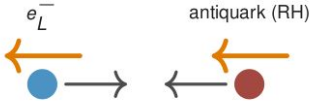
Handed! ← $\pm F_A\, G_M$ / $\pm xF_3(x)$

Deep inelastic evaluation



grey: motion; orange: spin

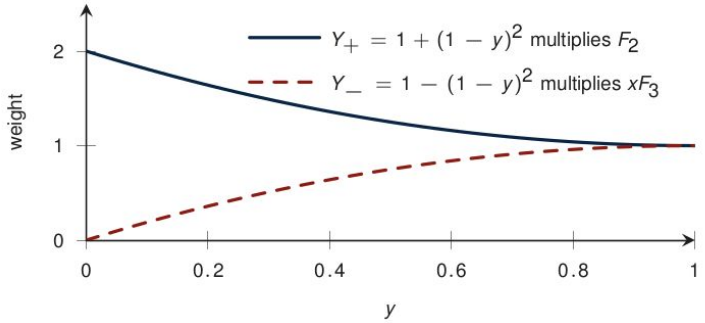
spins opposite: $J_z = -\frac{1}{2} + \frac{1}{2} = 0$
any angle allowed: flat in y

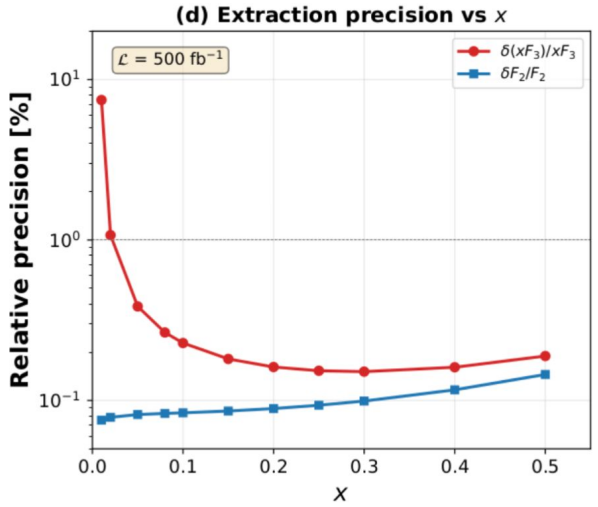


spins parallel: $J_z = -\frac{1}{2} - \frac{1}{2} = -1$
backward forbidden: $(1-y)^2$

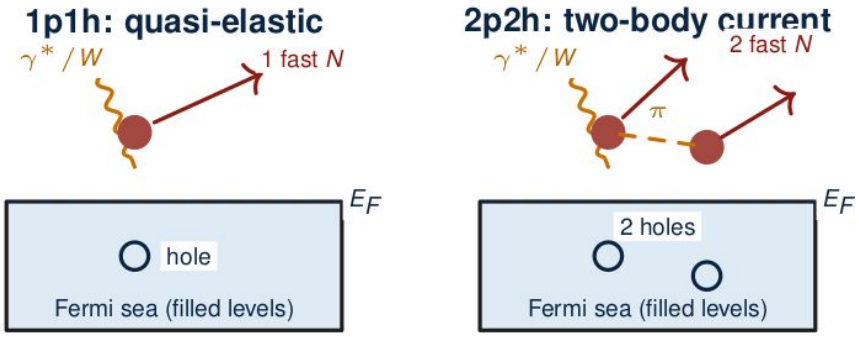
$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2\, s}{4\pi}\left[Y_+ F_2(x) \pm Y_-\, xF_3(x)\right]$$

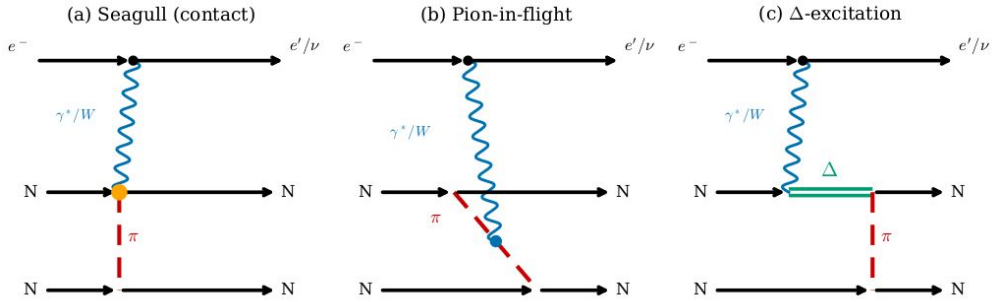
	$\delta(xF_3)/xF_3$
NuTeV [24], iron (nuclear corrections)	5–10%
CHORUS [25], lead	$\sim$ 10%
EIC, free p, statistical ($x > 0.05$)	$< 1\%$
EIC, free p, realistic	**2–5%**





Two-particle two-hole (higher Q^2)





$$X(Q^2) \equiv \frac{\sigma_{\text{meas}}(Q^2) - \sigma_{\text{IA}}(Q^2)}{\sigma_{\text{IA}}(Q^2)},$$

electron scattering
photon couples to the **vector** current only
excess = V

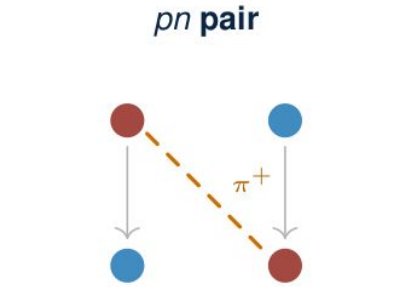
→

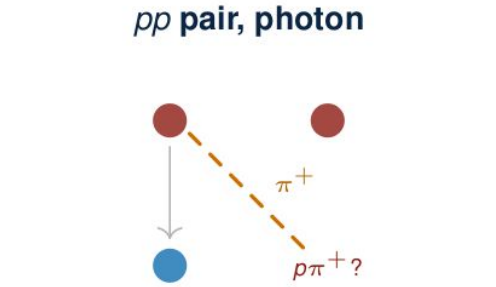
charged current
W couples to **vector + axial**
excess = $V + A$

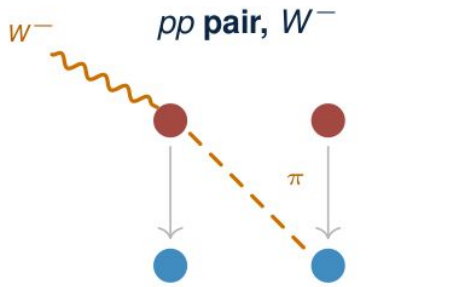
→

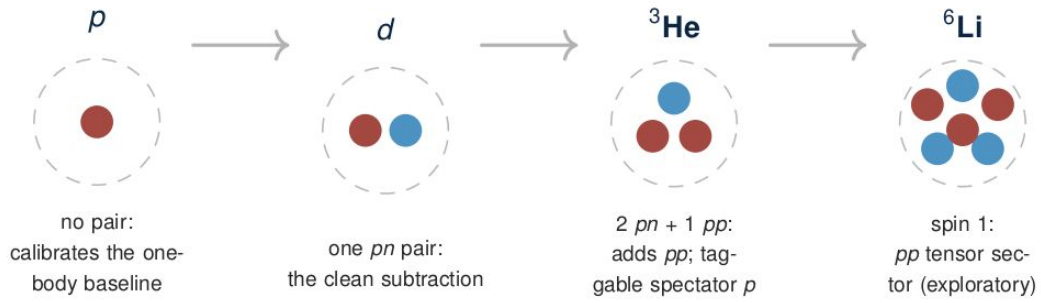
subtract
same nucleus, same Q^2, same dip window
$(V + A) - V = A$

Isospin decomposition







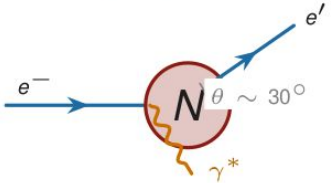


$$A_{ij}(Q^2) = (V+A)_{ij}(Q^2) - V_{ij}(Q^2),$$

$$X(^3\mathrm{He}) = f_{pn}\, V_{pn} + f_{pp}\, V_{pp},$$

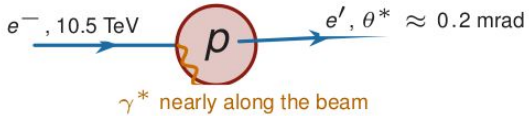
Fixed-target + Collider

fixed target (JLab, 2.2 GeV)



angle and energy can be varied: ε from 0 to 1 (L/T separation); helicity terms $\propto \tan(\theta/2) \approx 0.4$

collider, seen in the proton's rest frame



the angle cannot be varied: $\varepsilon = 1$ to 10^{-8}, no L/T lever arm; helicity terms $\propto \tan(\theta^*/2) \sim 10^{-4}$

fixed target (JLab, polarized d, ^{3}He targets): the L/T separation, the double-spin responses, the parity-violating cross-check [36].

collider: the unpolarized vector excess, the four tensor responses, the CC excess ($V + A$), and the CC target-spin asymmetry (parity-odd by itself, so it survives).

Response	Requires	Measures
	Collider observables	
R^L	unpolarized	charge response (IA)
R^T	unpolarized	vector pn current
R^L_{20}	P_{zz}	D-state + charge MEC
R^T_{20}	P_{zz}	Δ sign test
R^{TT}_{22}	P_{zz}	quadrupole / mechanism
R^{TL}_{21}	P_{zz}	L–T tensor interference
	Fixed-target observables	
$R^{T'}_{\mathrm{EM}}$	P_e, P_z	spin-flip interference
$R^{TL'}$	P_e, P_z	L–T spin-flip

Conclusion

Neutrino experiments have to deal with interaction cross sections and face major uncertainties.

Electron scattering experiments are effective resources to help.

Polarizing both lepton and nucleon can decompose degenerate effects.

Would be interesting to exhaustively utilize the heavy nuclei scattering data in future EIC.





Editors' Suggestion

Constraining neutrino-nucleon form factors with charged-current scattering at the Electron-Ion Collider

Guang Yang[1] and Praveen Kumar[1,2]

[1]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*University of Alabama, Tuscaloosa, Alabama 35487, USA*

(Received 19 April 2026; accepted 21 May 2026; published 22 June 2026)

Next-generation neutrino oscillation experiments such as the Deep Underground Neutrino Experiment require percent-level knowledge of neutrino-nucleon interaction cross sections. The nucleon axial form factor $F_A(Q^2)$, parametrized by the axial mass M_A, is the dominant source of uncertainty in the quasielastic channel, and the parity-violating structure function xF_3 is poorly constrained on free nucleons. We propose using charged-current (CC) electron-proton scattering at the Electron-Ion Collider (EIC) to address both problems simultaneously. The measurement exploits three key features of the EIC: (1) helicity-selective electron bunches provide *in situ* electromagnetic background rejection; (2) a longitudinally polarized proton target enables extraction of $F_A(Q^2)$ through the target-spin asymmetry A_{UL}; and (3) the y-distribution leverage in CC deep inelastic scattering (DIS) separates F_2 and xF_3 on a free proton, without nuclear corrections. Using a Fisher information analysis at $\sqrt{s} = 141$ GeV with 500 fb^{-1} of integrated luminosity, we project the Cramér-Rao statistical floor of $\delta M_A \approx 0.03$ GeV (3%). Incorporating first-order realistic detector effects, such as zero-degree calorimeter acceptance, Q^2 smearing (5%), and background noise from helicity subtraction, the projected sensitivity is severely background-limited due to the small signal-to-background ratio ($S/B \approx 3 \times 10^{-4}$) in the elastic channel. Achieving competitive sensitivity ($\delta M_A \approx 0.14$ GeV) would require $\sim 10^{-7}$ background suppression, 3 orders of magnitude beyond current projections. The CC DIS y distribution provides subpercent extraction of $xF_3^{W^-}$ over $0.05 < x < 0.5$, representing the most robust electroweak measurement in the near term.