Directly Probing the Proton's Axial Vector Form Factor via Electron-to-Neutrino Transitions

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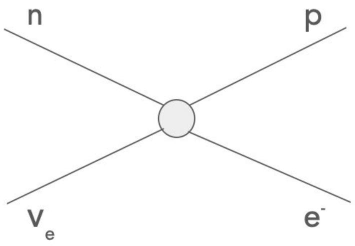
INFN

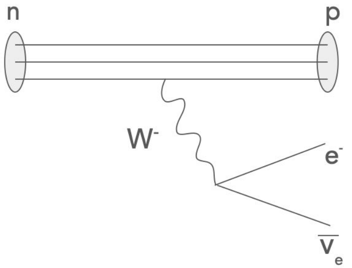
Jefferson Lab
Thomas Jefferson National Accelerator Facility

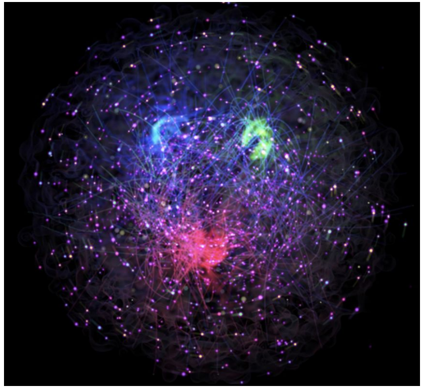
Preamble - From point-like to structured interaction - Form Factors



The coupling constant g_A = 1.2753 ± 0.0013 (PDG average, 2025) which measures the **strength of the axial-vector part of the weak interaction** responsible for **β-decay** has been a **very well established** and precise "universal constant" for a long time.

However, this pointlike parameter **does not provide any useful information on the Q^2>0** dynamics of weak processes, which is **eagerly desired** for the interpretation of the **past and future neutrino experiments** results.





In addition, **the knowledge of the Axial Vector Form Factor at Q^2>0 provides a complementary insight into the hadron dynamics**, namely spin distributions, to put useful **constraints upon the complex modeling of the nucleon structure** in the QCD framework.

Nucleon structure and dynamics

Power of Lepton-Nucleon Scattering Probe

Electron-nucleon elastic scattering

- has long since revealed the **electromagnetic structure** of the nucleon
- distribution of charge, magnetization successfully modeled by **EM form factors (EMFF)**: $G^{p,n}_{E,M}(Q^2)$
- experimental **knowledge of EMFF extremely accurate** owing to Q^2-wide campaign of measurements (GEp-V latest at JLab/Hall A, Aug. 2025)

Neutrino-nucleon elastic scattering

- only probe able to **directly access the axial structure** of the nucleon, related to spin
- axial distributions inside the nucleon also modeled by the **axial-vector form factor (AVFF)** and an induced pseudo-scalar FF):

$$F_A(Q^2) \qquad F_P(Q^2)$$

- **AVFF poorly known experimentally**
- ν-beams access to AVFF severely affected by large indetermination in ν energy and by the need to use nuclear targets

Underlying formalism fully developed and established (V-A)

C.H. LLEWELLYN SMITH, PHYSICS REPORTS, 3, No. 5(1972) 261-379

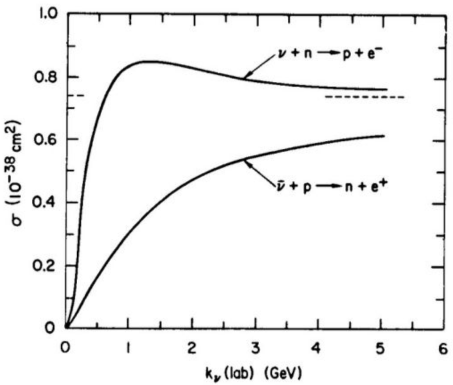
$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu n \to l^- p \\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right],$$

A, B, C combination of V, A contributions

$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\left(1-\frac{Q^2}{4M^2}\right)|\xi F_V^2|^2 + \frac{4Q^2}{M^2}\mathrm{Re}F_V^{1*}\xi F_V^2 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right],$$

$$B(Q^2) = \frac{Q^2}{M^2}\mathrm{Re}F_A^*(F_V^1 + \xi F_V^2),$$

$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{4M^2}|\xi F_V^2|^2\right)$$



Nucleon structure/dynamics impact

The AVFF F_A

- The **least known of the nucleon form factors**
- **Extends the knowledge of the nucleon dynamics poorly accessible through EM probes** (spin distribution).
- **Test of novel lattice QCD modeling.**
- **Constraints on GPDs**

(P. Kroll)

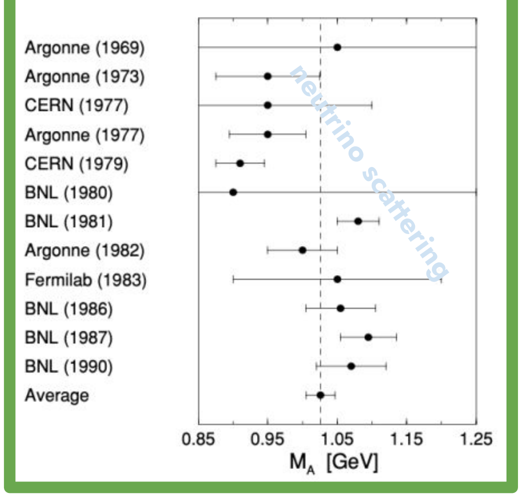
$$F_A^{(3)}(t) = \int_0^1\left[\widetilde{H}_v^u(x,\xi,t) - \widetilde{H}_v^d(x,\xi,t)\right]dx + 2\int_0^1\left[\widetilde{H}^{\bar{u}}(x,\xi,t) - \widetilde{H}^{\bar{d}}(x,\xi,t)\right]dx$$

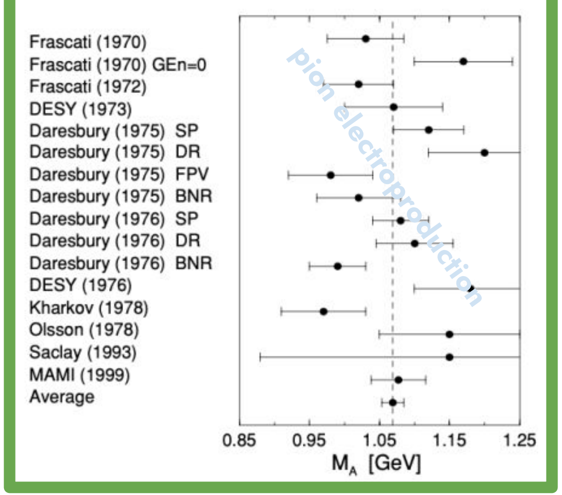
Still, existing measurement from (anti)neutrino QE scattering: **scarce** (mostly bubble chamber on D_2 target)+**statistically limited** +largely **affected by model dependent systematics (mostly nuclear effects).**

AVFF impact on neutrino oscillation experiments physics

G. Bani et al., JHEP05 (2020)126

Neutrino oscillation experiments (DUNE) strongly need factorization of <u>nucleon-level</u>, <u>nuclear-level</u> and <u>neutrino flux</u> for accurate event rate predictions.



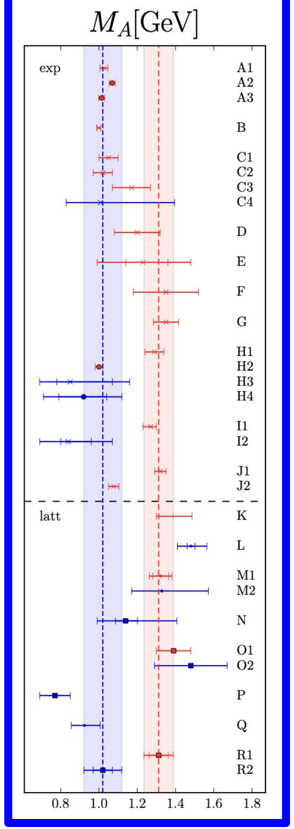


V. Bernard et al., J.Phys.G:NPP 28 (2002) R1

Dipole-ansatz (arbitrary):

$$F_A(Q^2) = \frac{F_A(0)}{(1+Q^2/M_A^2)^2}$$

Extended review of existing measurements interpreted in terms of the only <u>axial mass as a parameter</u>, display great deal of scattered values for M_A and a <u>neat tension</u> between a dipole shaped F_A and z-expansion analysis.

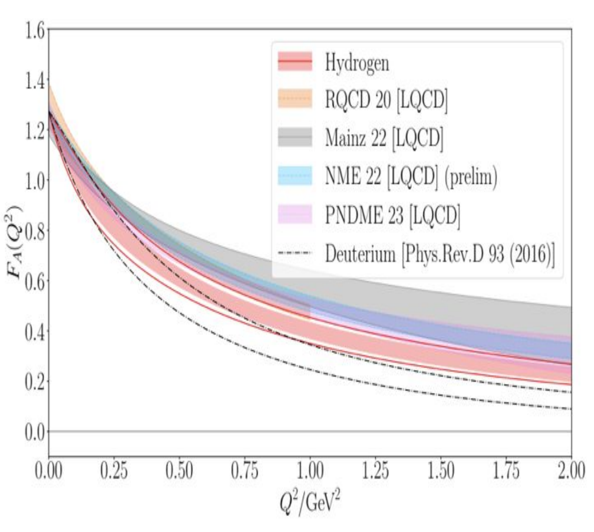


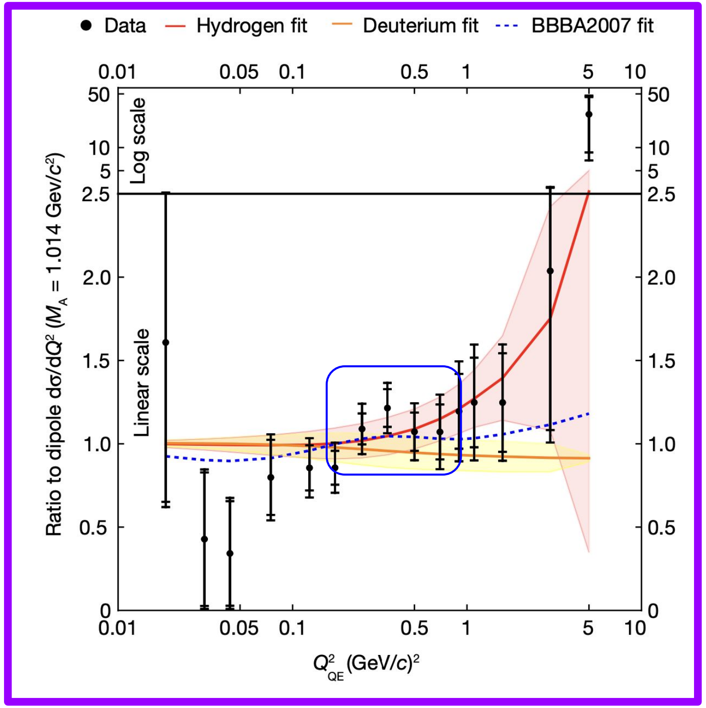
AVFF is a prominent source of uncertainty at the nucleon-level

Theory:

LQCD calculations **display a significant spectrum of uncertainty** (Meyer, deuterium fit).

A.Meyer et al., PRD93 (2016) 113015





T. Cai et al., Nature, 614 (2023) 48

Experiment:

Recent results from direct antineutrino + H (Minerva) also show significant deviations and uncertainties if compared to the dipole ansatz and ab-initio calculations.

Therefore constraints from elementary target data are critical to neutrino experiments precision.

Even one single point with <25% accuracy useful!

A direct, independent precision measurement highly desirable.

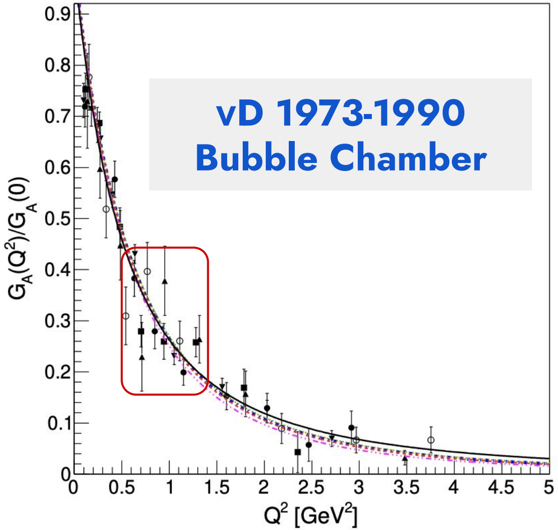
Current experimental knowledge of the AVFF

νA QE scattering
νD bubble-chamber experiments
νp elastic scattering in plastics

Affected by:

Broad range of neutrino energy
Not a free proton (nuclear effect)
Large systematics

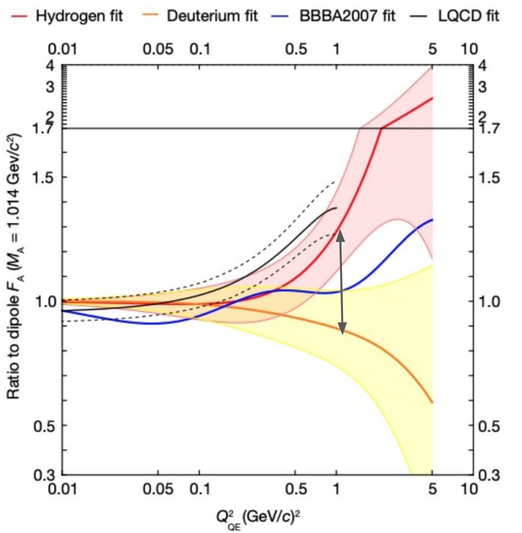
Meyer et al., PRD 93 (2016) 113015



νD 1973-1990 Bubble Chamber

νp elastic scattering in plastics (Minerva, red curve)

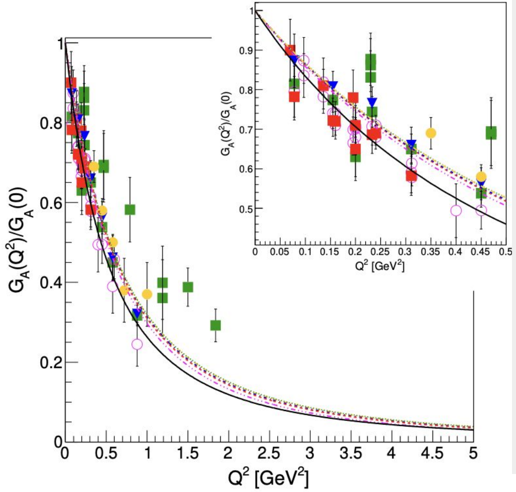
T. Cai et al., Nature, 614 (2023) 48



- **Manifest tension with old deuterium data**
- **Decent agreement with LQCD**

AVFF from pion electro-production

Megias et al. PRC 101 (2020) 025501



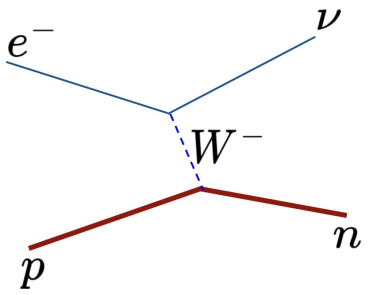
In summary, the **knowledge status of the AVFF does not seem different from that described 20 years ago** [despite progress in νN, μ-capture, eπ, G. Ricciardi, F. Vissani et al., JHEP 08 (2022) 212].

The CCE scattering approach (inverse β-decay)

Mastery and long standing success of the lepton-hadron interaction probing technique has a straightforward suggestion.

Perform an "elastic-wise" electron-proton scattering experiment and forget about the neutrino, look for <u>kinematically closed</u> neutron production (originally J. Napolitano, 1981, JLab PAC1).

$$e^- + p \longrightarrow n + \nu$$



In this process, the **AVFF** naturally appears in the matrix element of the hadronic current, accompanied by an induced *pseudo-scalar* term, which turns out suppressed by mass factor in the cross-section

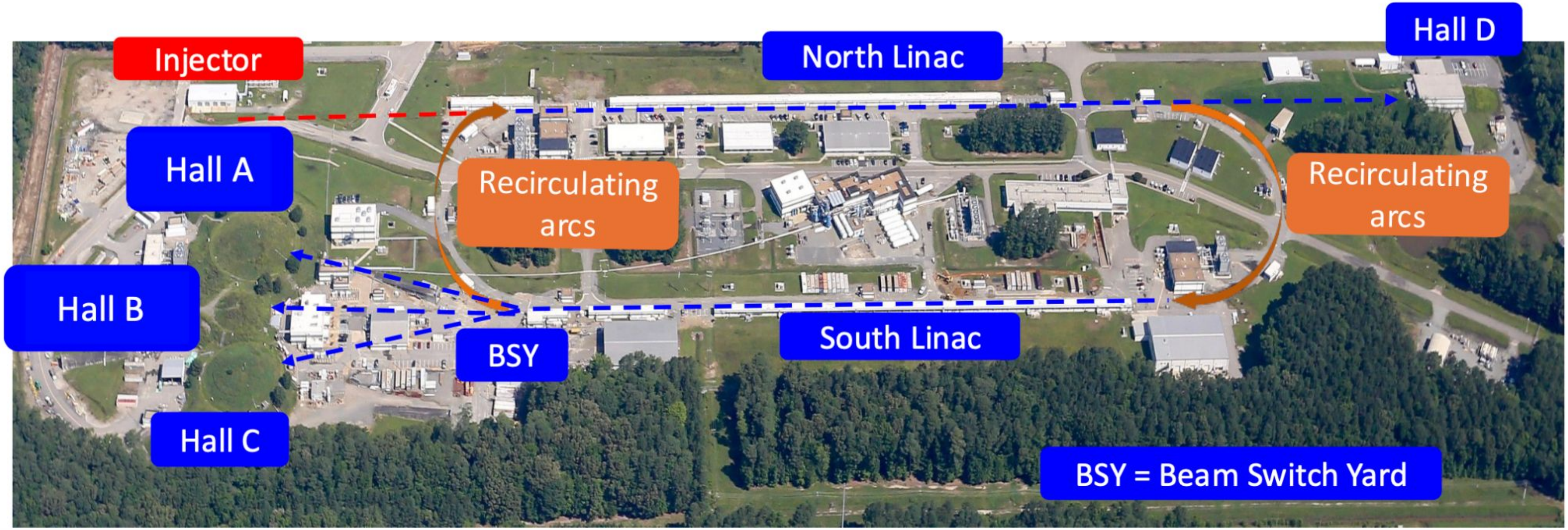
$$\langle n|A_\mu^+(0)|p\rangle = \bar{u}_{S_n}(\vec{p}_n)\left(\gamma_\mu\gamma_5 F_A(q^2) + i\frac{q_\mu\gamma_5 F_P(q^2)}{m_\pi}\right)u_{S_p}(\vec{p}_p)$$

Get a ***bonus*** with highly **polarized electron beam**! The lepton current mediated by the W introduces a **sharp helicity dependence**, which can be **explicitly factorized in the cross section** and allows one to use beam **asymmetry** to filter neutrino events out of the electromagnetic ones (e.g. pion production).

$$\left.\frac{d\sigma_{pn}}{dQ^2}\right|_\lambda = (1-\lambda)\left.\frac{d\sigma_{pn}}{dQ^2}\right|_{unp}$$

$$\lambda = \pm 1 \left\langle \begin{matrix} right\ handed \\ left\ handed \end{matrix} \right.$$

Jefferson Lab is the place!



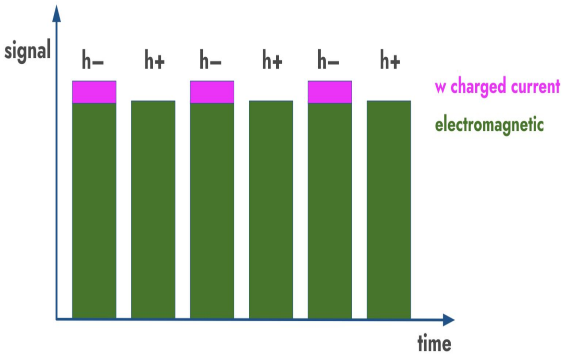
- **JLab** accelerator facility in Newport News, Virginia, U.S.A.
- Delivers up to 11 GeV **electron beam** to Halls A, B, C and D (12 GeV)
- **High polarization** (>80%), **high intensity** beam (~100uA)

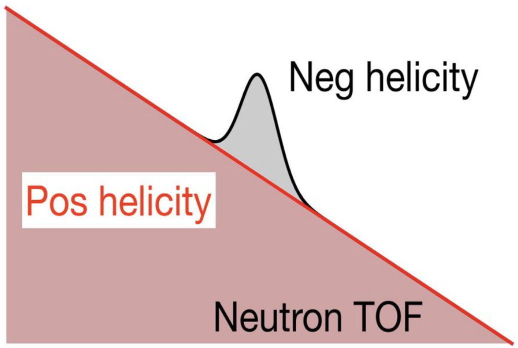
Experimental Strategy

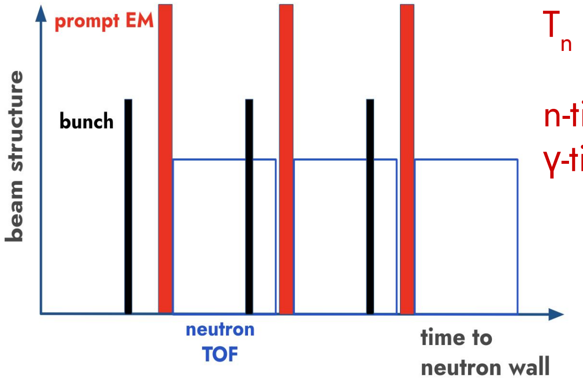
- Detect only the neutron in the 2-body final state $e^- + p \longrightarrow n + \nu$
- Identify neutron with time-of-flight + calorimeter
- Magnetically suppress charged particles
- Subtract background from elastic ep, π-production, other sources

Subtract the residual background by **using the right handed electrons (h+) through observed asymmetry**

$$A_{obs} = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+} = \frac{A_\nu N_\nu + A_{ep} N_{ep}}{N_\nu + N_{ep}}$$







d = 15 m
T_n = 500 MeV

n-time = 66 ns
γ-time = 50 ns

tuning the beam time structure to cope with prompt β=1 background (~16 ns earlier than neutron), 16 or even 32 ns spacing

To aim at statistical significance, we are challenged to suppressing EM backgrounds 10^7 higher than our signal!

Proposed experimental setup and purpose

Beam-Target:

- ➔ Electron beam: 2.2 GeV - 75 uA - 85% pol
- ➔ Target: 20-40 cm LH2
- ➔ Beamtime projected: 500-700 h

Neutron arm:

- ➔ Neutron kinematics: θ_n=48° - T_n=525 MeV - Q^2=1 GeV^2
- ➔ Neutron TOF: distance 15 m - solid angle 75 msr
  - ◆ TOF time resolution: 100 ps
  - ◆ detection efficiency >30%

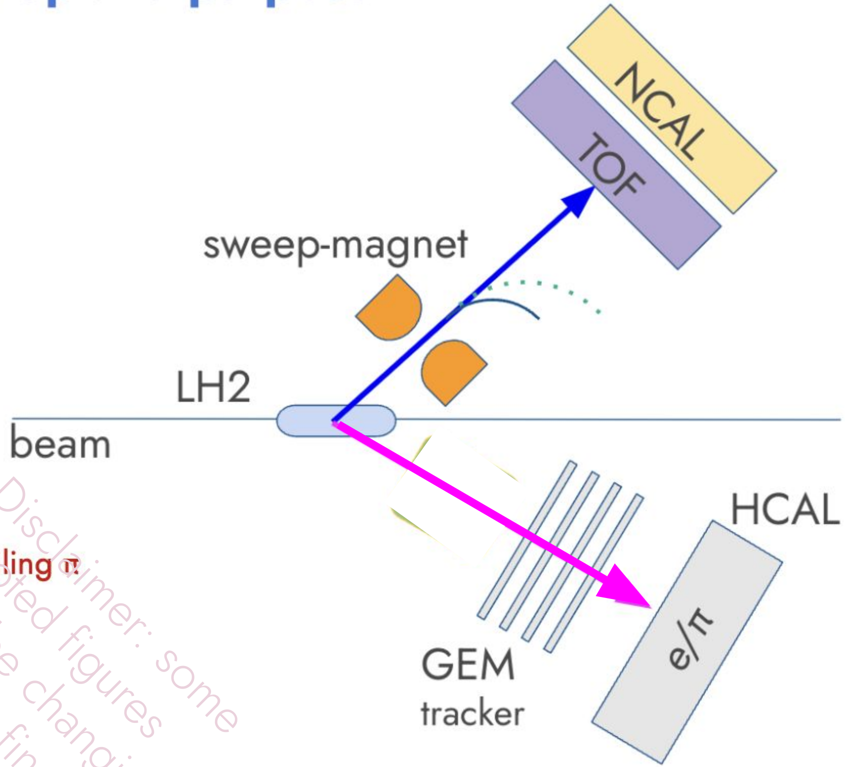
Veto arm:

- ➔ SBS/GEM for precision calibration, e/π detection
  - ◆ neutron background from π production through recoiling π

Expected results on N_{vn}:

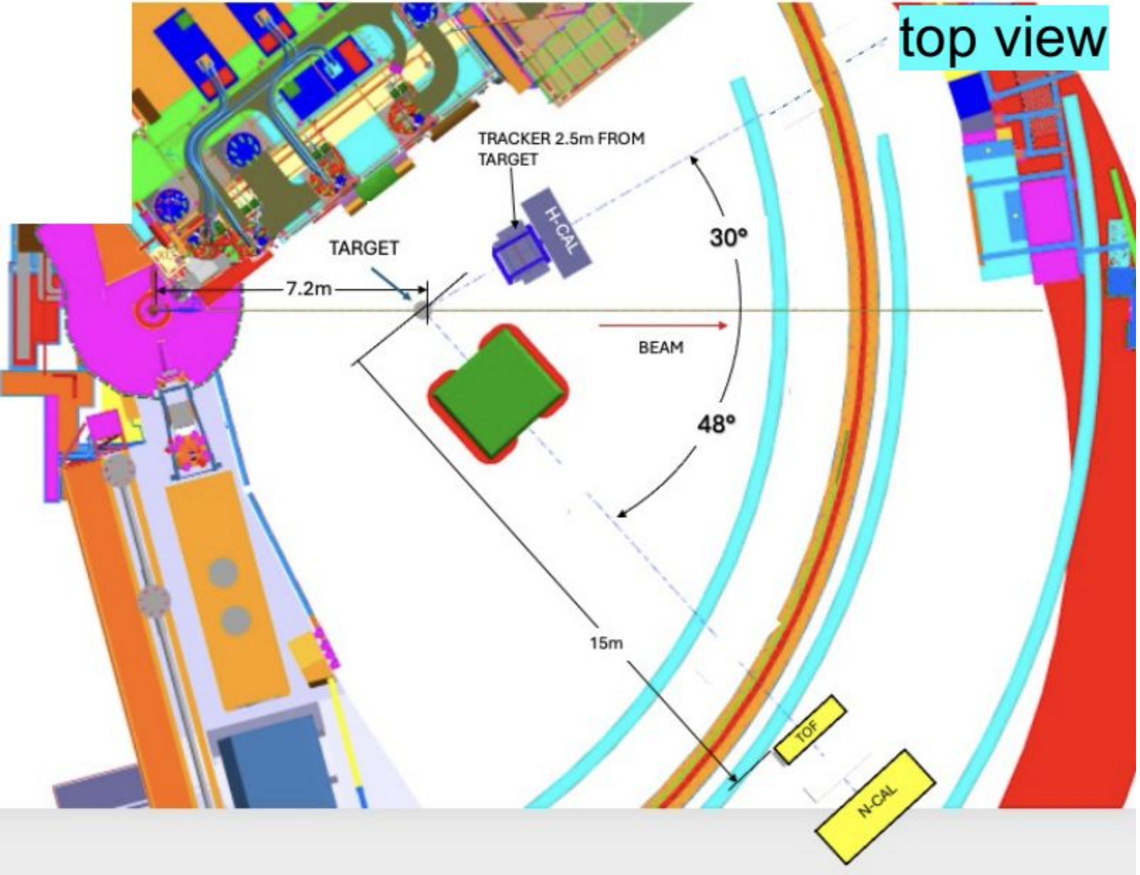
- ➔ Overall background rate after all suppressions ~2 Hz
- ➔ N_{vn} signal rate ~ 30 cts/h ~ 0.01 Hz
- ➔ Statistical precision on F_A ~ 15-25%

Disclaimer: some quoted figures may be changing with MC fine tuning



The initial purpose of the proposed experiment is to **proof the principle at Q^2=1 GeV^2**.
Success would open up a **campaign of systematic** measurement of **Q^2 dependence**.

Implementation at JLab/Hall C



Signal

$$e^- + p \longrightarrow n + \nu$$

background

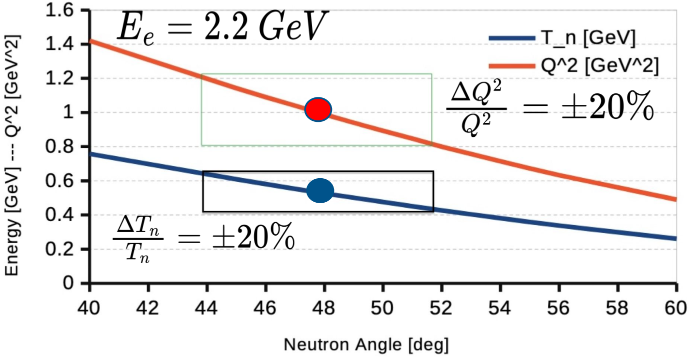
$$\vec{\gamma} + p \rightarrow \vec{n} + \pi^+$$
$$\vec{e}^- + p \rightarrow e^- + \vec{p}$$
$$\vec{\gamma} + p \rightarrow \vec{\Lambda} + K^+$$

- ➔ LH2 Target 7.2 m downstream
- ➔ 15 m away n-TOF 65 ns/100 ps
- ➔ VETO arm: HCAL+GEM calibration
- ➔ NCAL 2.5 m away from TOF for enhanced beam bunch identification

New equipment highlight:

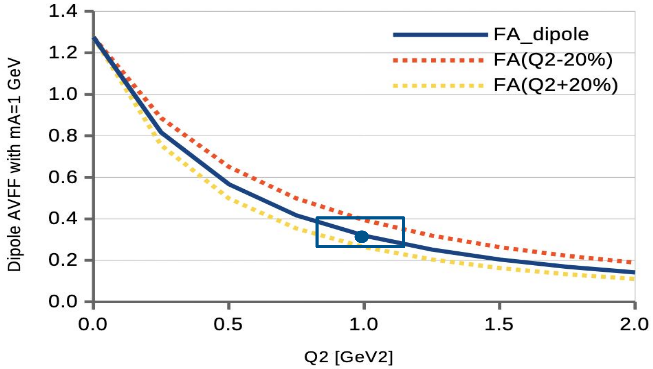
The neutron TOF counter

Energy and squared momentum acceptance



In this acceptance range:

- dipole FF variation ~15 %
- cross section by factor ~1.5

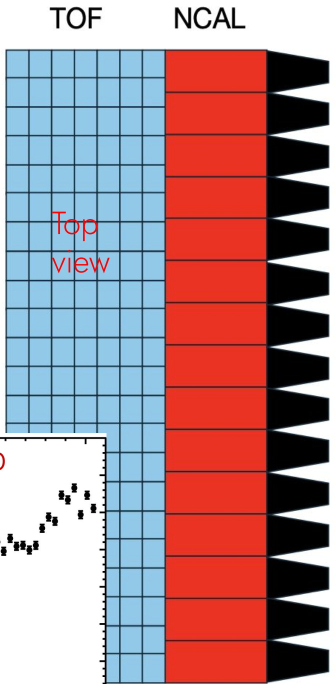


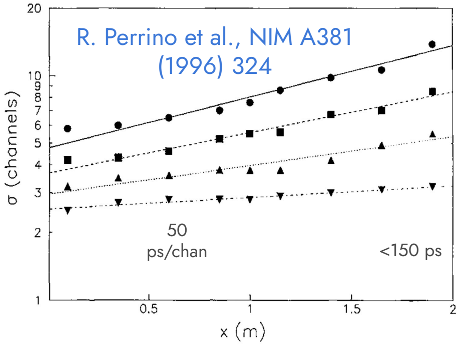
Single counter:

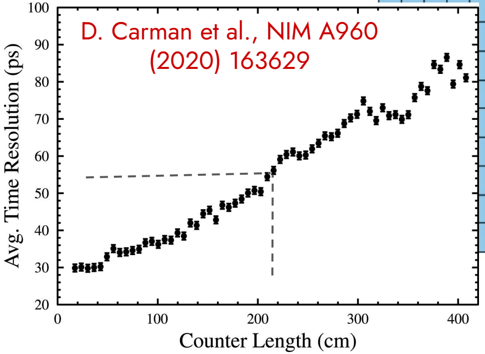
- BC408 6x6x200 cm (W x H x L)
- Readout by PMTs at both ends
- Based on CLAS12 forward TOF (σ_t<100 ps)

Full neutron wall:

- 11 horizontal layers (66 cm depth)
- 140 single counter/layer (8 m)
- ~2000 PMTs

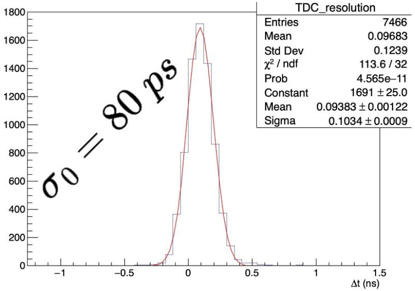




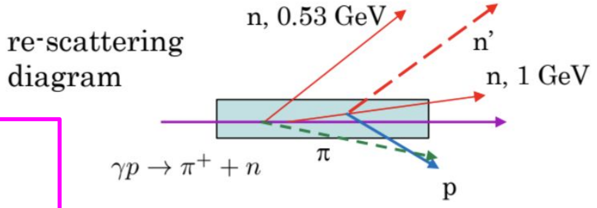


Ongoing R&D [JLab, INFN]

Scintillator: EJ-200 200x6x6 cm^3 PMT: Hamamatsu R13089



Geant4-based full Monte Carlo results

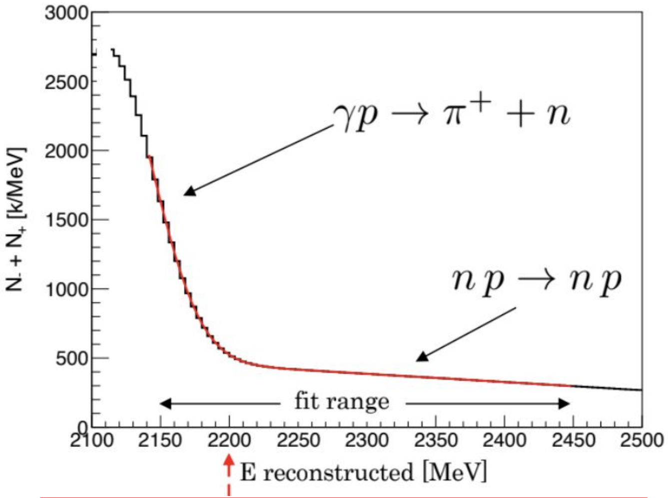


Beam energy reconstruction for closed kinematics after triggers:

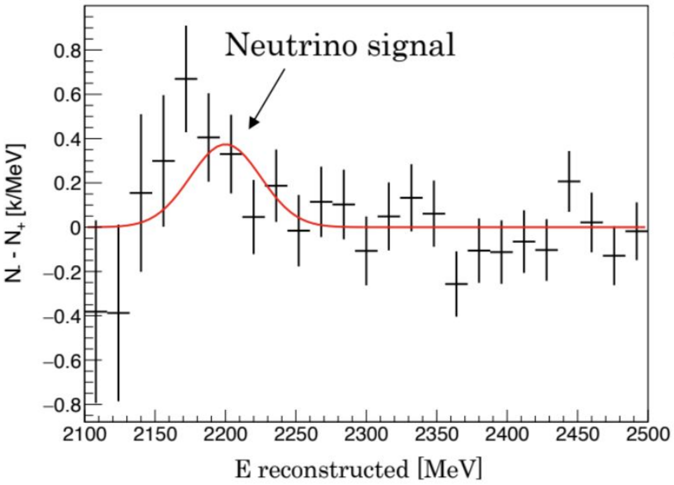
Threshold >100 MeV in NCAL	25	MHz
Veto if signal in VETO arm (HCAL) > 650 MeV	0.25	MHz
NCAL correlated TOF hit in 10 ns window	25	kHz
[Event removal if TOF-NCAL bunch identification mismatch]		

50 days of data taking, 10 cm LH2, 120 μA

$$E_{reconst} = \frac{E_n - (M_p^2 + M_n^2)/2M_p}{1 + (P_n \cos\theta_n - E_n)/M_m}$$



Full signal+backgrounds spectrum



Helicity correlated counts

Projected results:

Signal (events) = 19 k ± 6.5 k

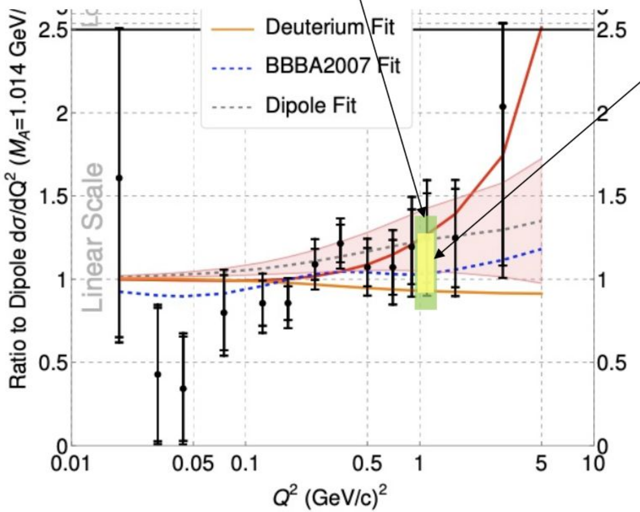
$\delta F_A/F_A$ ~ 34% (stat)

(comparable to Minerva)

Expected impact on AVFF at Q^2=1 (GeV/c)^2

GEANT4 rate - 100 ps time_resolution

G4 rate 50 ps σ_t



50 days of data taking, 10 cm LH2, 120 μA

Event type	Rate Hz, all cuts 310 MeV range	Total events	Asymmetry events	Accuracy, contr. frac
p(e,n)υ	0.0044	19k	1.0	
$\Lambda + \Sigma$	0.23	1M	~0.03	0.06
$\pi^+ + n$	34.5	150M	$< 10^{-6}$	< 0.01
Detector syst.	efficiency, $\Delta\Omega$, ...			0.05
Statistics				0.34
Stat. + syst.				0.35

$$F_A/F_{A,Dipole} = 1 \pm 0.34(stat) \pm 0.08(syst) \text{ at } Q^2 = 1\,(\text{GeV/c})^2$$

Current (JLab PAC53 - Proposal PR12-25-009, 2025) estimates point to overall 35% accur.

<50 ps TOF detector developments (USTC, JLab, INFN, CERN, ...) pointing to 25% accur.

35% recognized as not sufficient for a striking progress wrt high detector cost → PAC53: proposal deferred

Route 1: Lower beam energy; detector improvement; shielding optimization (multi-pion prod is main bother)

Route 2 - the resilient one :-): Investigate alternative reaction, e.g. two-step transition + smart charged final state $p(\vec{e}, \Delta^0 \to p + \pi^-)\nu_e$

$ep \to \nu_e \Delta^0 \to \nu_e p \pi^-$ / Access tAVFF

Big experimental advantage from:

- **charged final state (high efficiency);**
- **hi-res tracking, vertexing;**
- **invariant mass cut** $\Delta^0 \to p\pi^-$

No Neutrons!

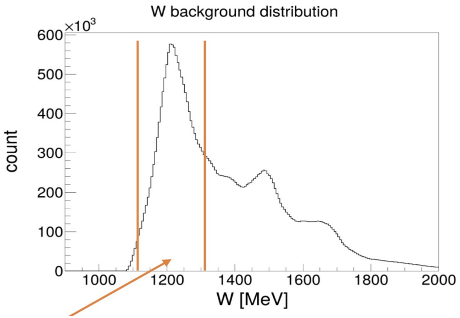
Develop SBS spectrometer variant:

HR-DOSBS (Double Open SBS)

Same tactics of End-point Energy Reconstruction Method:

$$E_{beam}^{rec} = \frac{E_\Delta - (M_p^2 + M_\Delta^2)/2M_p}{1 + (P_\Delta \cos\theta_\Delta - E_\Delta)/M_p}$$

Owing to HR DOSBS, expected δE~7 MeV
Cut of 2σ suppresses most background (e.g. 2π, etc.)



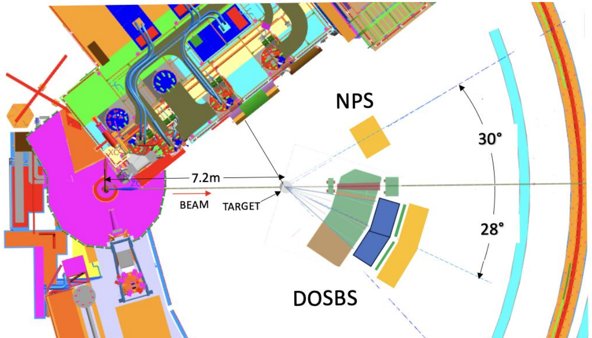
Used exploratory event generator: Hall B genKYandOnePion

$ep \to \nu_e \Delta^0$

Formalism & x-sect fully developed

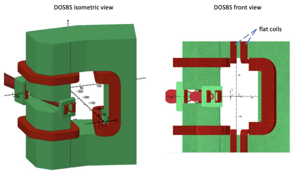
(P. Kroll, doi:10.1103/PhysRevD.107.054009)

Hall C proposed set-up



Key equipment: **the DOSBS**

The Calibration Arm
NPS



The Delta Arm
DOSBS Low-Mass MWDC+TOF+HCAL

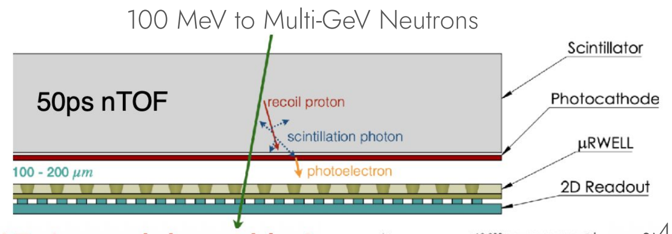
Letter-of-Intent LOI12-26-009 PAC54: 100 days for x-sect at 1–2 (GeV/c)2 with relative statistical accuracy 26%

Outlook - Current Plan of AVFF Collaboration

Aim at 10-15% accuracy with 1.1 GeV e-beam

Technology Development

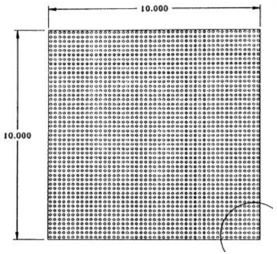
- < 50 ps Time-of-Flight
- TOF+NCal neutron bunch id @ hi-lumi
- Thin window LH2 target cell
- High time-resolution TOF and Ncal
- Shielding design
- Geant4/FLUKA validation



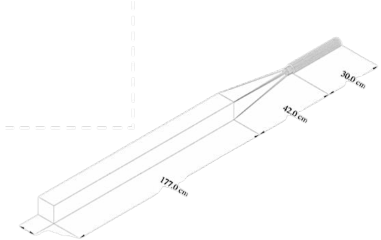
Need of prototype test for

> neutron background

> neutron timing



~400 ps NCAL (after BNL E864 HCAL)



50 ps TOF Neutron Spectrometer opens up to Wide-range Experimental Program

- Axial Vector Form Factor
- Wide-Angle Compton Scattering from neutron
- Deuteron break-up D(e/γ,pn)
- Neutron Form Factors: GMn, GEn and TPE (Two Photon Exchange)
- Neutral pion photoproduction from neutron
- Positive pion photoproduction from proton

Goal 1:

Pursue revised direct measurement of AVFF with new technology: 10-15% stat. uncertainty, <5% syst. uncertainty, with 2 months running at 120uA @ 1.1 GeV at JLab

Goal 2:

Preparation of Full Proposal for PAC55/2027 on the alternative/complementary transition-AVFF measurement through the reaction $ep \to \nu_e \Delta^0$

A Proposal to Jefferson Lab PAC53

The Nucleon Axial-Vector Form Factor from the $p(\vec{e}, n)\nu_e$ Reaction

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> 25 Institutions > 60 authors

https://www.jlab.org/exp_prog/proposals/25/PR12-25-009.pdf

A Letter-of-Intent to Jefferson Lab PAC54

Neutrino production in the Nucleon-Delta $p(\vec{e}, \Delta^0 \to p + \pi^-)\nu_e$ Reaction

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No need to say …

Welcome all possible sinergy from intersection with Neutrino Community