Probing the proton Axial Vector Form Factor with an inverse β−decay experiment

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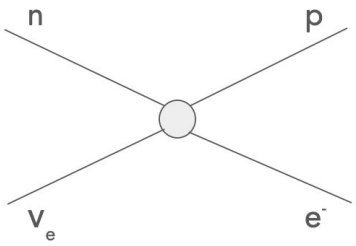
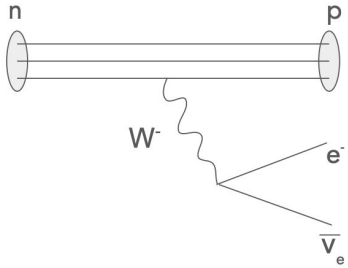
on behalf of the AVFF Collaboration

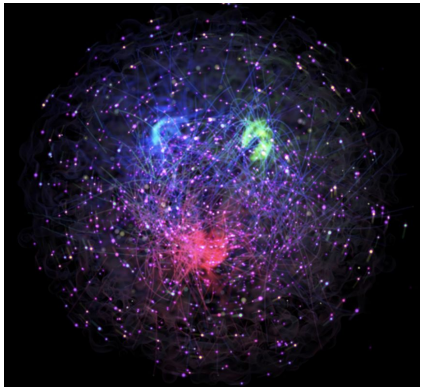
Preamble



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.



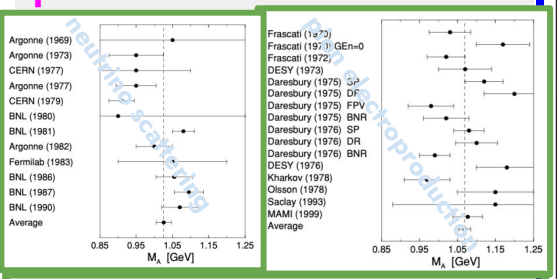
However, this pointlike parameter **does not provide any useful information on the $Q^2>0$** dynamics of weak processes, which is **eagerly desired** for the interpretation of the **past and future neutrino experiments** results.



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 to the complex modeling of the nucleon structure** in the QCD framework.

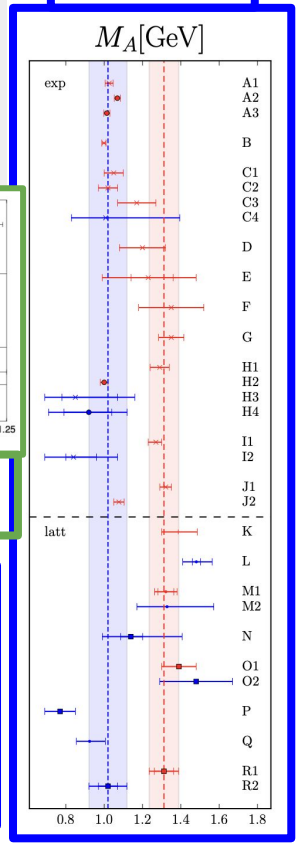
Neutrino physics impact

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



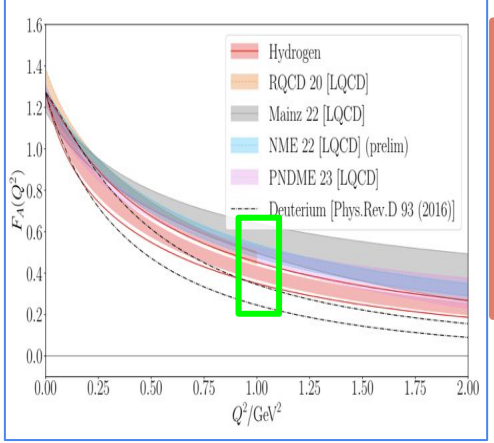
V. Bernard et al., J.Phys.G:NPP 28 (2002) R1

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

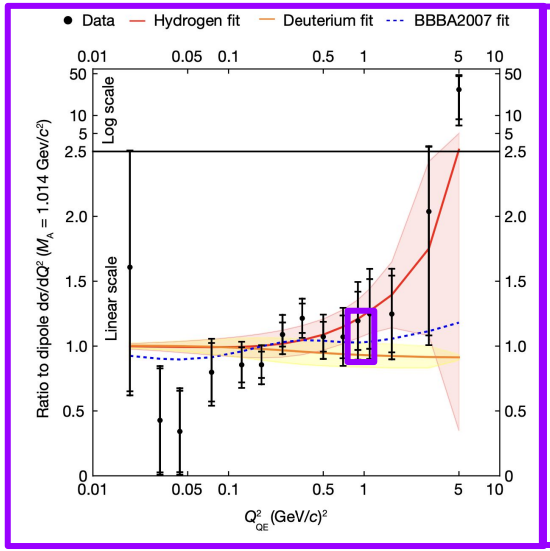


Extended review of existing measurements interpreted in terms of only the axial mass as a parameter, display great deal of scattered values for M_A and a neat tension between a dipole shaped F_A and z-expansion analysis.

AVFF is a prominent source of uncertainty.
Meyer reported **results on deuterium** and compared to many LQCD calculations **showing a significant spectrum of uncertainty**.



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



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

Recent direct antineutrino + H (from 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. A direct, independent precision measurement highly desirable.

Nucleon structure and dynamics

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)**: $G_{E,M}^{p,n}(Q^2)$
- 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

Theory fully developed and established (V-A)

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

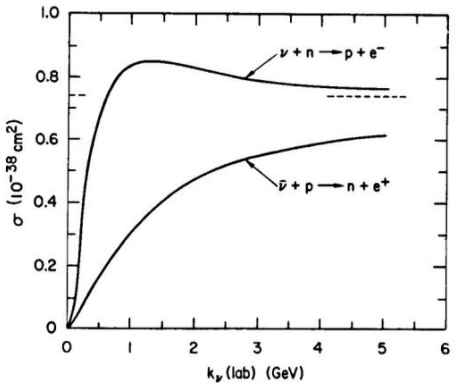
$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu n \to l^- p\\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right],$$

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 by EM probes** (spin distribution).
- **Test of novel lattice QCD modeling**.
- **Constraints on GPDs**

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

(P. Kroll)

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).**

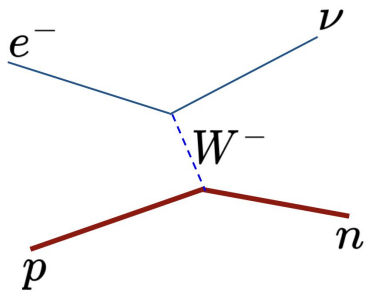
In summary, the **knowledge status of the AVFF does not seem different from that described 20 years ago** [despite progress in νN, μ-capture, eπ, G. Ricciardi et al., JHEP 08 (2022) 212].

The inverse β-decay approach

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 kinematically closed neutron production (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 count neutrino events out of the electromagnetic ones (e.g. pion production).

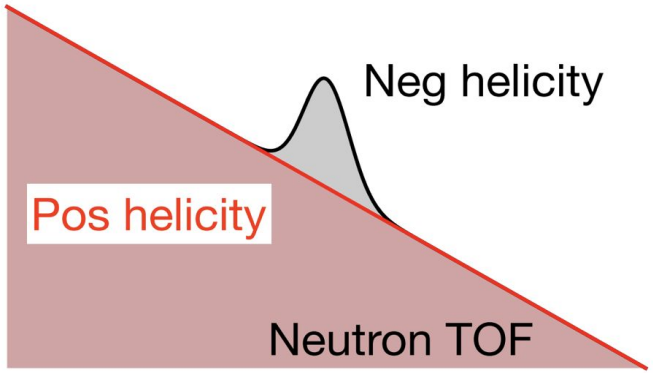
$$\left.\frac{d\sigma_{pn}}{dQ^2}\right|_\lambda = (1-\lambda)\left.\frac{d\sigma_{pn}}{dQ^2}\right|_{unp}$$

$$\lambda = \pm 1 \begin{cases} right\ handed \\ left\ handed \end{cases}$$

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

Then:
Subtract the residual background by **using the right handed electrons data**



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

Devised experiment key physics numbers summary:

Kinematics: E_{beam} = 2.2 GeV, θ_n = 48 deg, Q^2 = 1 $(GeV/c)^2$
Signal cross section: 1.35 x 10^{-39} cm^2/sr
ep cross section: 1.4 x 10^{-32} cm^2/sr
Other backgrounds (πn): ~10^{-29} cm^2/sr

Beam Polarization > 85%
Beam Current > 100 uA

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:

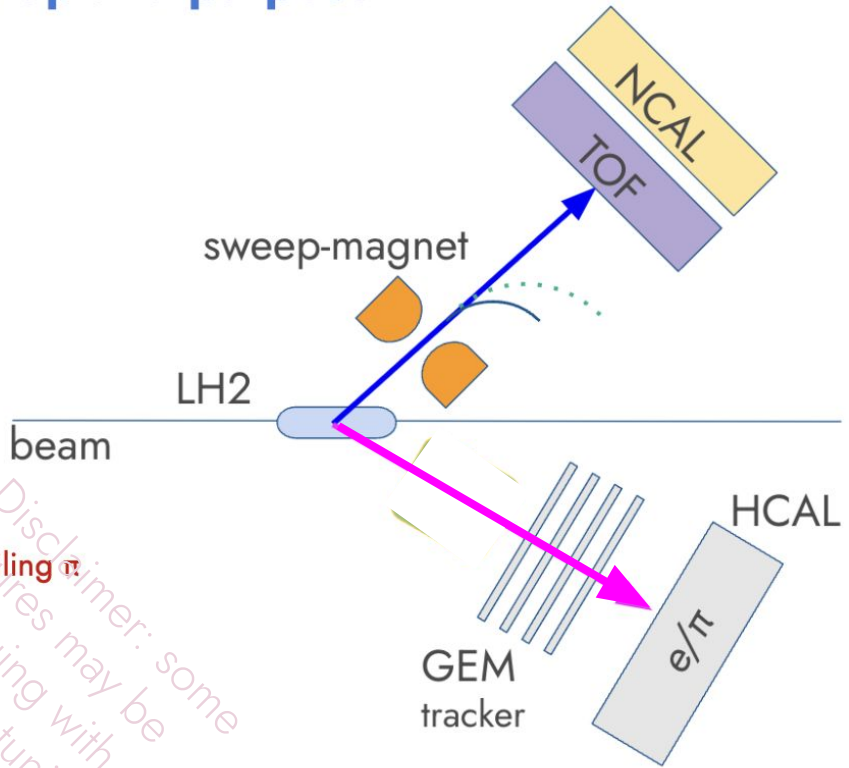
- Neutron kinematics: θ_n=48° - T_n=525 MeV - Q^2=1 GeV^2
- Neutron TOF: distance 15 m - solid angle 75 msr
  - TOF time resolution: 100 ps
  - detection efficiency >30%

Veto arm:

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

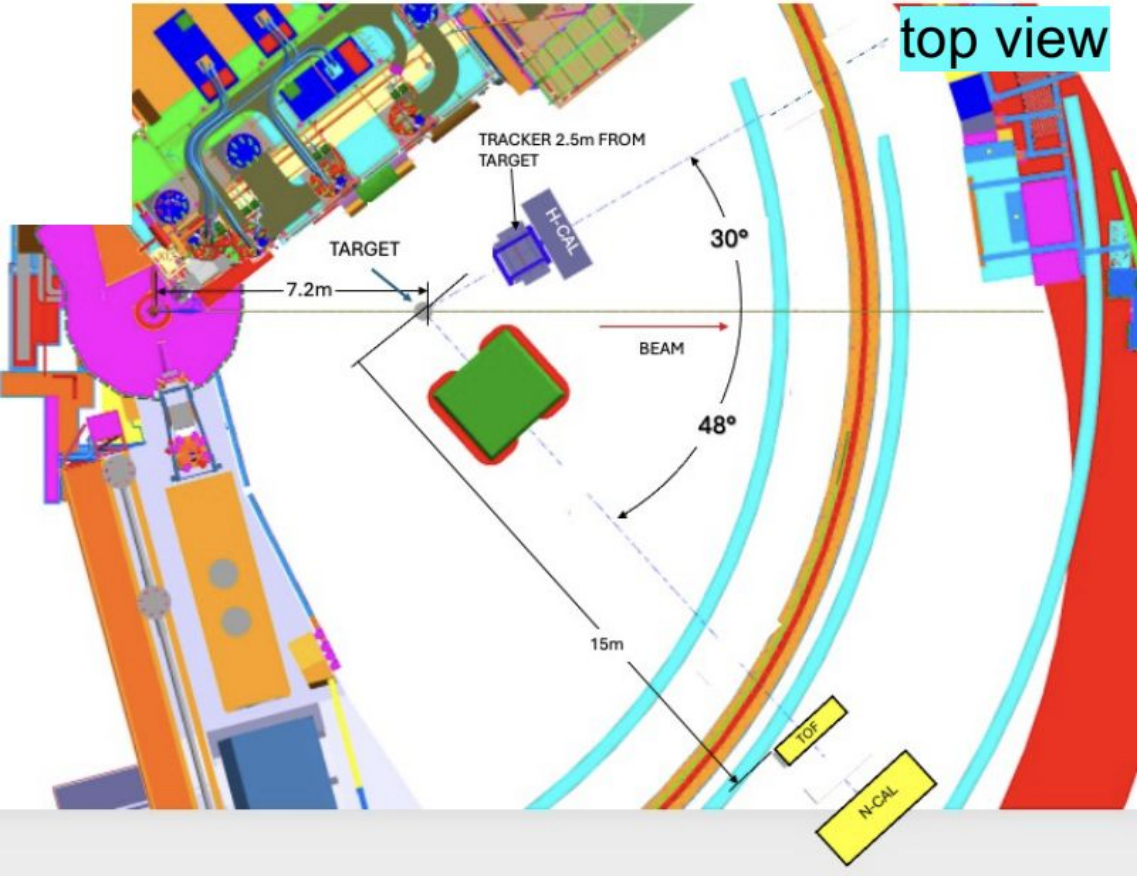
Expected results on N_{vn}:

- 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%



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

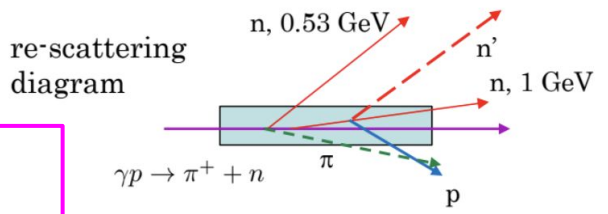
$$e^- + p \longrightarrow n + \nu$$

background

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

- ➔ 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

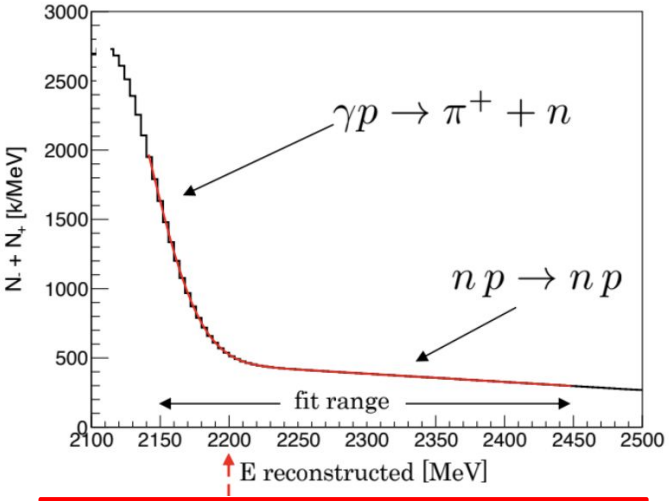
Geant4-based full Monte Carlo results



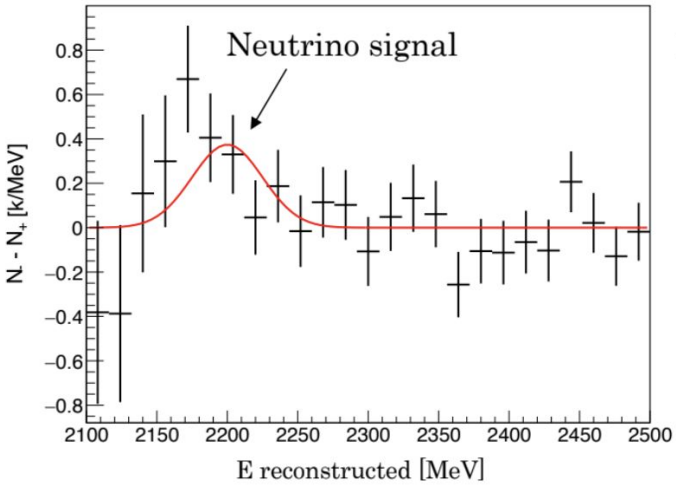
Beam energy reconstruction for closed kinematics after triggers cascade:

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



Full signal+backgrounds spectrum



Helicity correlated counts

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

Projected results:

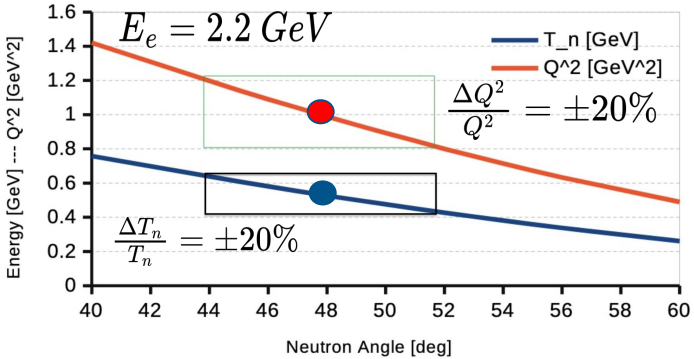
Signal (events) = 19 k ± 6.5 k

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

(comparable to Minerva)

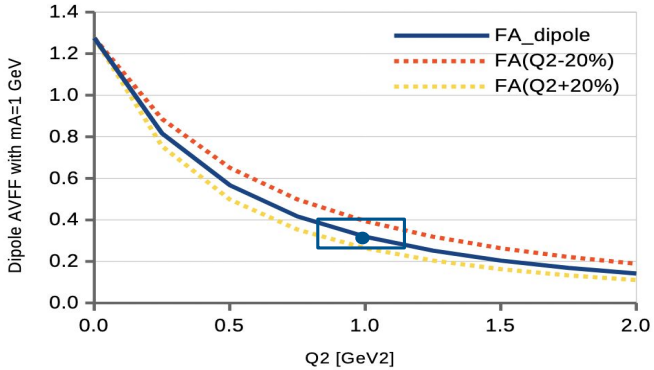
New equipment highlight: # The neutron TOF counter

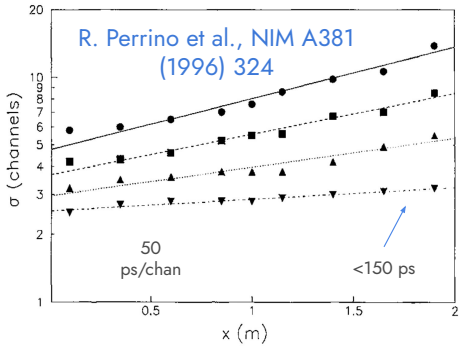
Energy and squared momentum acceptance

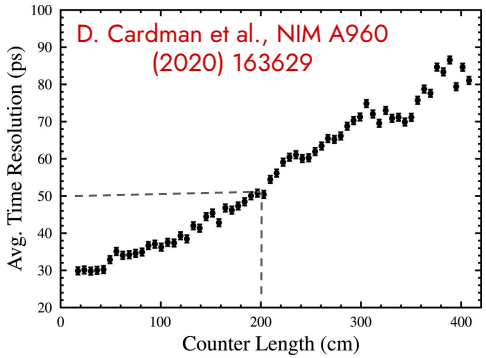


In this acceptance range:

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





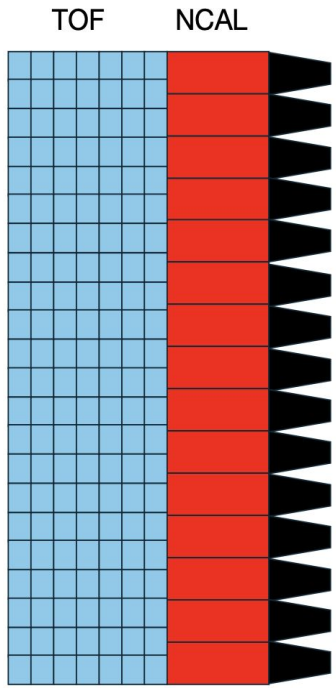


Single counter:

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

Full neutron wall:

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



Summary & Outlook

- A model independent **extraction of** the proton **Axial-Vector Form Factor** has definitely **manifold interests**
- Past and future **neutrino experiments** need **fundamental ingredient** to cope with event rate uncertainties
- **Insight of the nucleon dynamics** from EMFF would be complemented with the least known AVFF, providing constraints on GPDs
- To this extent, a **novel experiment** (first of its kind) of **inverse β-decay** has been **devised at JLab** at Q^2=1 $(GeV/c)^2$ with a highly polarized electron beam on liquid hydrogen target
- The experiment (PR12-25-009) will use a **2.2 GeV polarized electron beam**, a **high resolution time-of-flight** detector with a **neutron calorimeter**, and an **electron/pion veto** arm made from the available detectors.
- Last July, JLab PAC53 has deferred the approval to allow **planning crucial background studies** with a purposed **validation beam-test**, **exploration of TOF resolutions to 50-70 ps** in order to push accuracies $\delta F_A/F_A$ below the ones from neutrinos