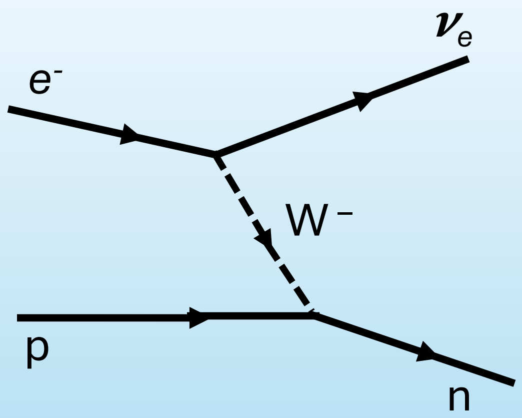
Axial-Vector Form Factor (AVFF) Proposal Update

T. Averett, *William & Mary*, 2-Oct-2024

- Half-day meeting designed to pull together ideas and collaboration
  - 14-Sept-2024

  - J. Napolitano – Overview
  - A.Meyer – Theory Perspective
  - W. Xiong –Simulation
  - D. Carman – CLAS12 High Res. TOF
  - T. Averett – Proposal Overview

  - https://indico.jlab.org/event/878/



Weak CC "Elastic Scattering"

$$p(\vec{e},n)\nu$$

- Never Measured

$$\frac{d\sigma}{dQ^2} \propto G_E(Q^2),\ G_M(Q^2),\ G_A(Q^2)$$

In a nutshell, obtain the nucleon axial-vector FF in elastic by precise neutron detection.

Elastic CC Formalism for our Reaction – P. Kroll

Unpolarized Cross Section

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}\frac{1}{(s-m^2)^2}\left(\frac{G\cos\theta_C}{\sqrt{2}}\right)^2 8\Big\{(s-m^2)^2(F_1^{(3)2} + \underline{F_A^{(3)2}})$$

$$+\,t\Big[sF_1^{(3)2} - \frac{(s-m^2)^2}{4m^2}F_2^{(3)2} + (s-2m^2)\underline{F_A^{(3)2}}$$

$$-2(s-m^2)(F_1^{(3)} + F_2^{(3)})\underline{F_A^{(3)}}\Big]$$

$$+\,\frac{1}{2}t^2\Big[|F_1^{(3)} + F_2^{(3)} - \underline{F_A^{(3)}}|^2 - \frac{s}{2m^2}F_2^{(3)2}\Big]\Big\}$$

where, $F_{1,2}^{(3)}(t) = F_{1,2}^{p}(t) - F_{1,2}^{n}(t)$ $\quad m$ is the nucleon mass

Polarized beam:

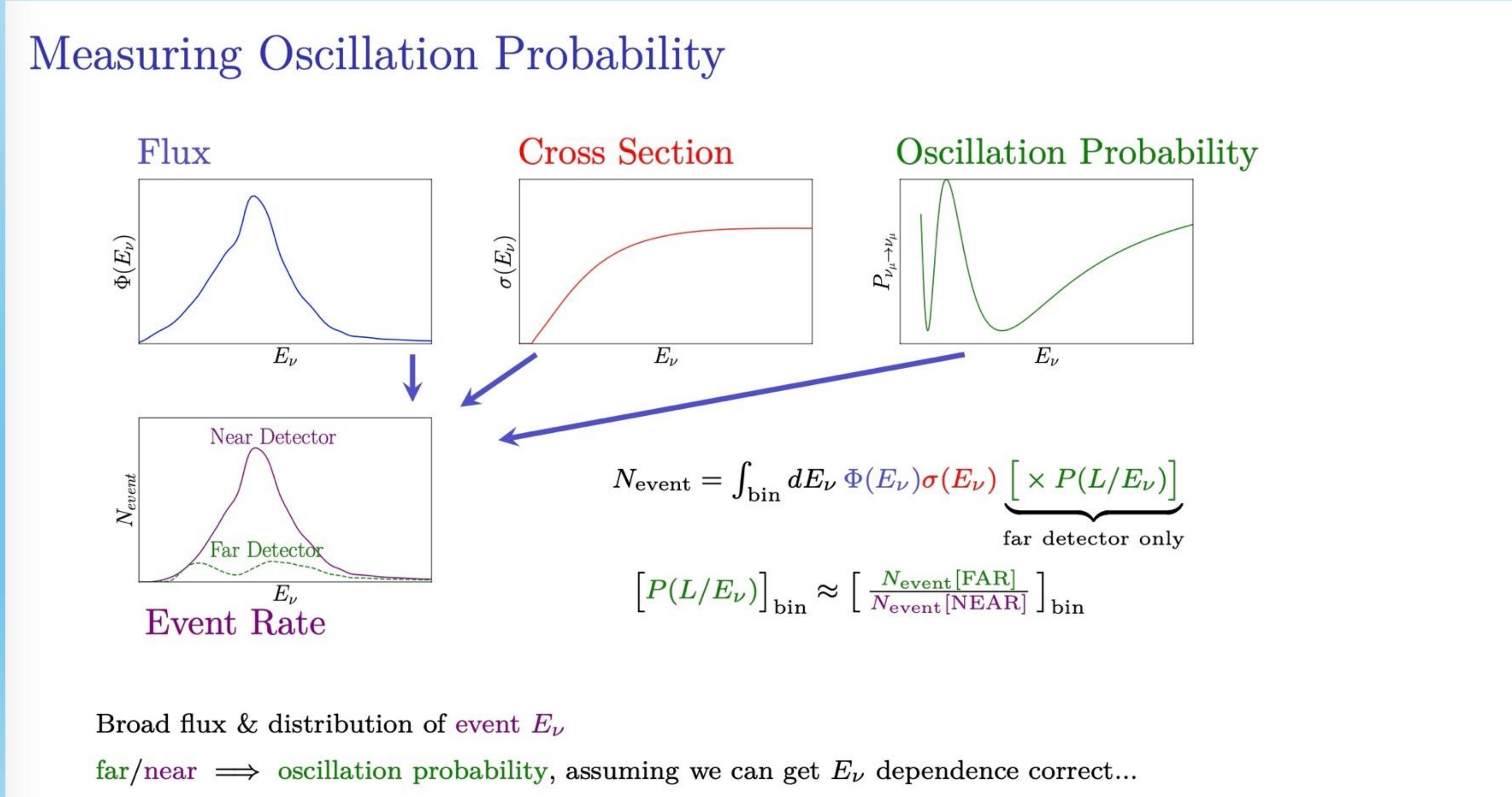
$$\frac{d\sigma(-)}{dt} = 2\frac{d\sigma}{dt}$$

$$\frac{d\sigma(+)}{dt} = 0$$

Connection to GPDs $\quad F_A^{(3)}(t) = \int_0^1 \left[\tilde{H}_v^u(x,\xi,t) - \tilde{H}_v^d(x,\xi,t)\right]dx + 2\int_0^1 \left[\tilde{H}^{\overline{u}}(x,\xi,t) - \tilde{H}^{\overline{d}}(x,\xi,t)\right]dx$

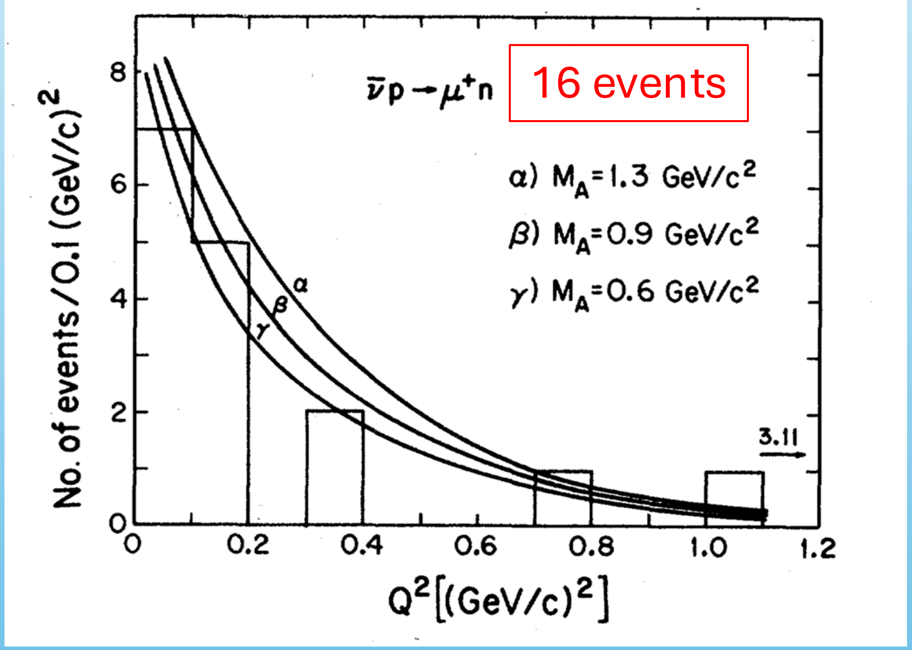
Motivation: Determine cross section and G_A with precise Q^2 = 1 GeV^2 via ep -> νn

- Goals –
  - Cross section poorly know
  - Dipole assumption not justified – not consistent with QCD
  - Compare to precise LQCD calculations
  - New GPD constraint
  - Reduce systematics in neutrino oscillation experiments



- World Weak Elastic Data:
  - All p→n data* are QE from bubble chambers in 1970-80s using $\nu + \mathrm{d} \longrightarrow \mu + \mathrm{n}$
  - Modern neutrino factories use $\nu + \mathrm{A} \longrightarrow \mu + \mathrm{N}$ - nuclear corrections
  - Inelastic Data → meson production, messy
  - * 16 bubble chamber events in 1980
  - * 2023 MINERvA - see slide 7

$$\nu + \mathrm{p} \longrightarrow \mu + \mathrm{n}$$



Fanourakis *et al.*, PRD 21, 1980

- Issues:
  - Poor statistics
  - Neutrino energy spectrum is broad Q^2 → 0.5 – 6 GeV^2
  - Nuclear corrections

World Data for M_A from quasielastic* scattering

*except elastic in CC in 1980, and NC in 1987

Assume Dipole, extract M_A :

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

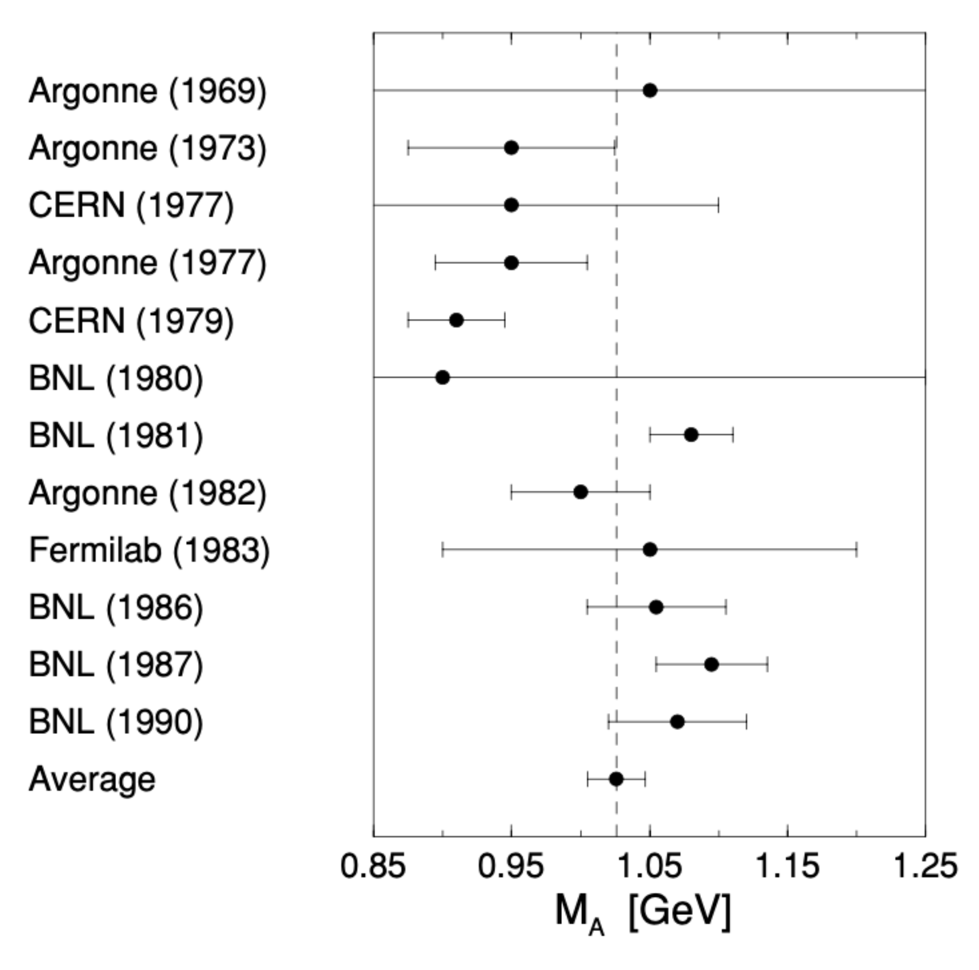
$$F_A(0) = g_A = -1.2723$$

Well-known from neutron beta decay

One free parameter, $M_A = 0.9^{+0.4}_{-0.3}\ \mathrm{GeV}^2$

CC $\nu p \rightarrow \nu n$

NC $\nu p \rightarrow \nu p$



Summary
J. Phys. G: Nucl. Part. Phys. 28 R1

• *The Axial Form Factor Extracted from Elementary Targets*
Talk by Aaron S. Meyer LLNL

PRD 93, 113015 (2016)

- **Why do we even assume the axial form factor is dipole-like?**

- **No reason a priori to expect $F_A \sim F_D$, inconsistent with QCD**
- **Cross section precision cannot distinguish between models**

- Reanalysis of historical data from deuterium bubble chambers $\mathrm{d}(\nu_\mu, \mu^- \mathrm{pp}_s)$
  - 3 expts, low statistics, flux uncertainty, nuclear correction

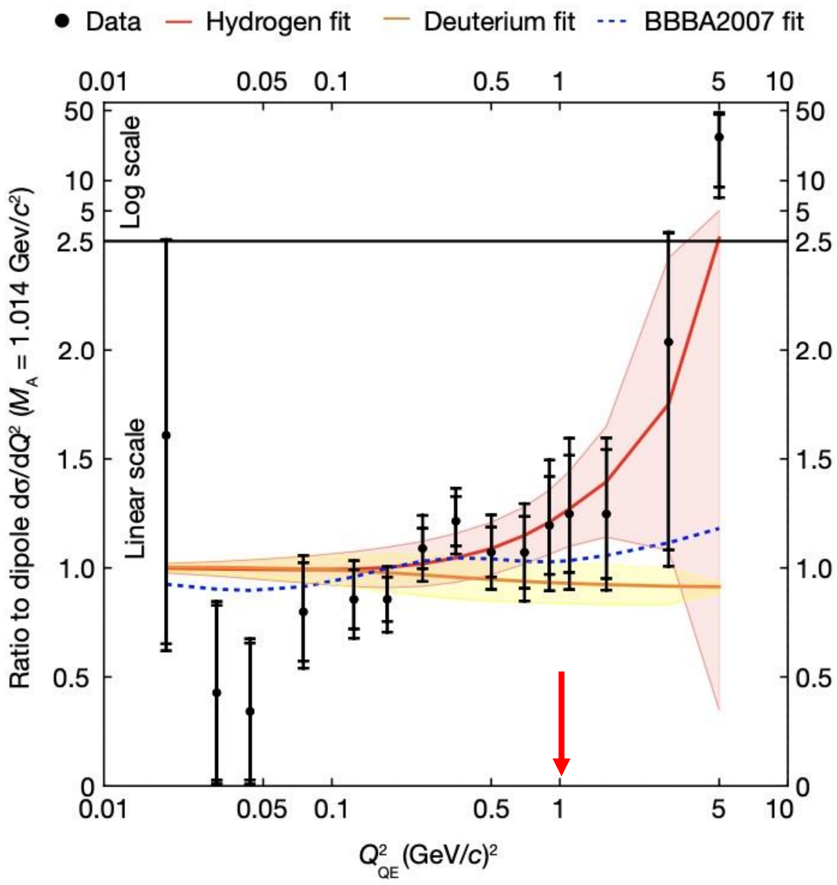
- Reanalysis assumes F_A comes from QCD-motivated, model independent z – expansion formalism, also used for EM FFs => proton radius as $Q^2 \to 0$

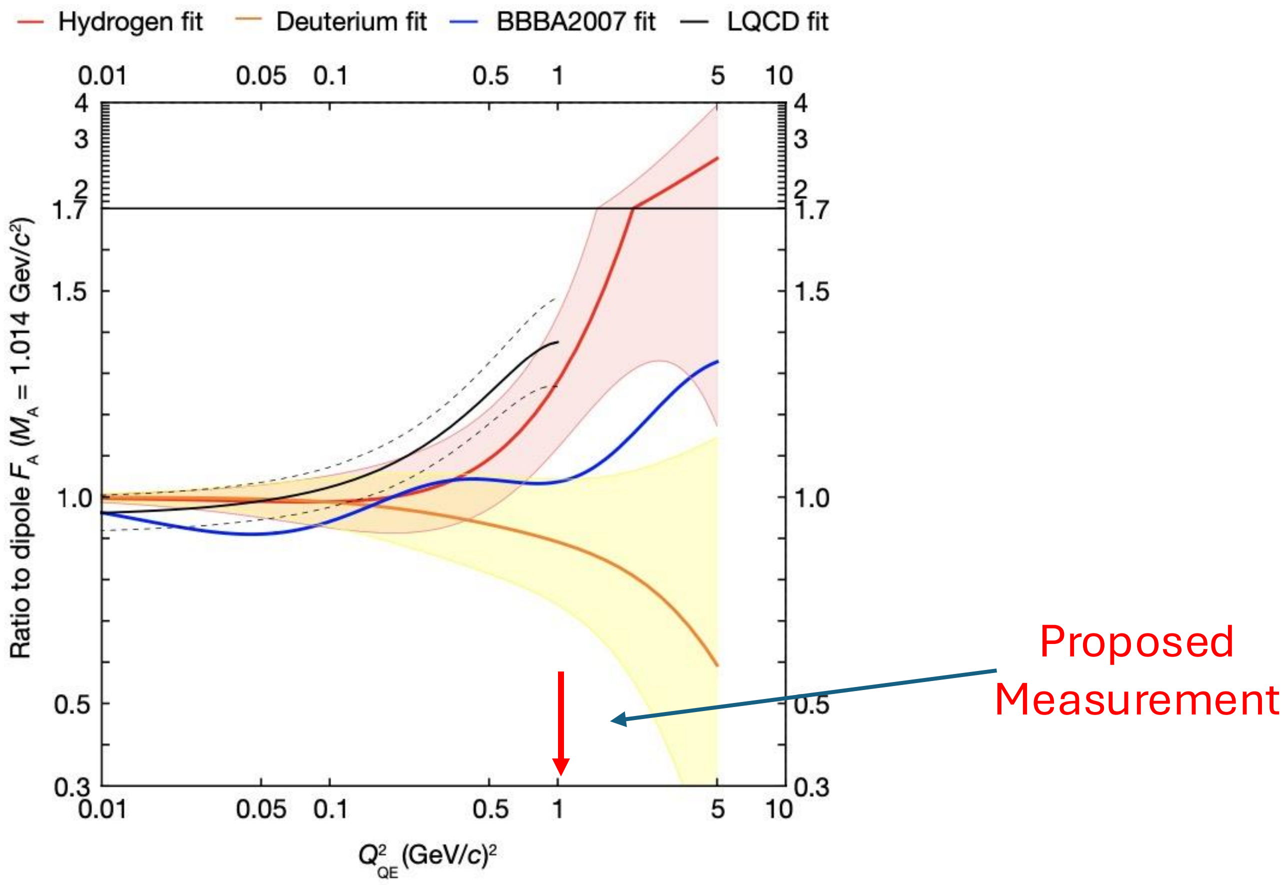
- → Meyer Conclusion: Dipole ansatz has led to ~ 10x underestimated uncertainty in F_A

- Why impt? 50% of cross section comes from F_A ???

2013 MINERvA Results from M. Kordosky

$$\nu + p \longrightarrow \mu + n$$



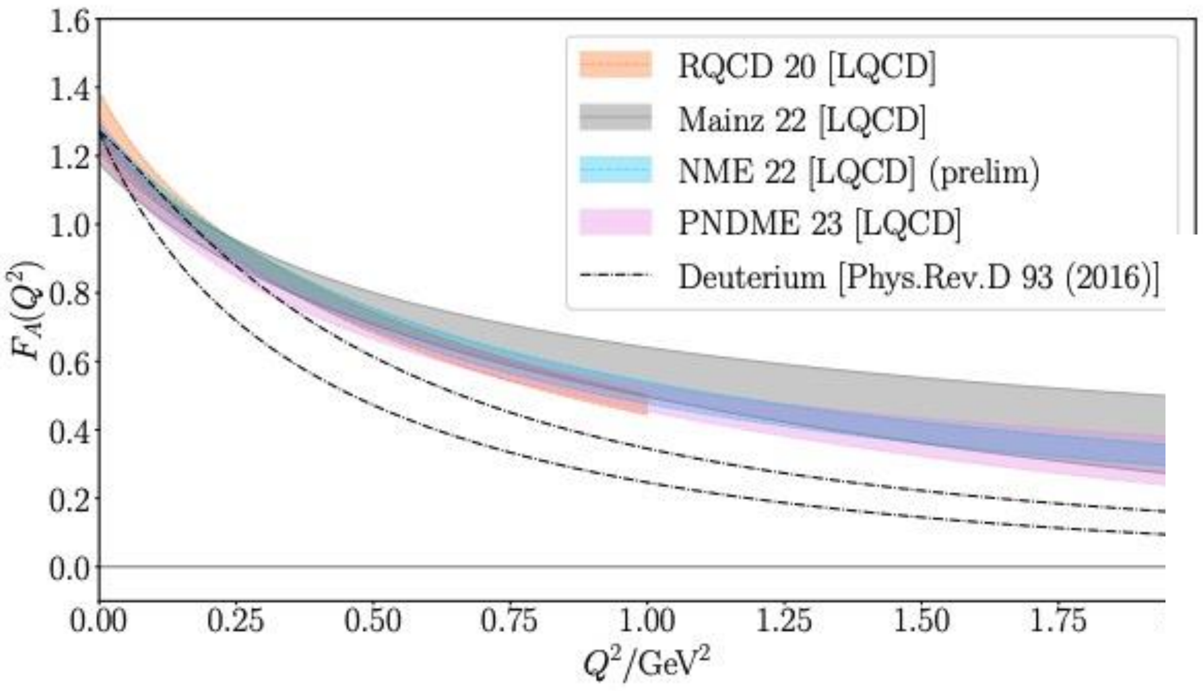


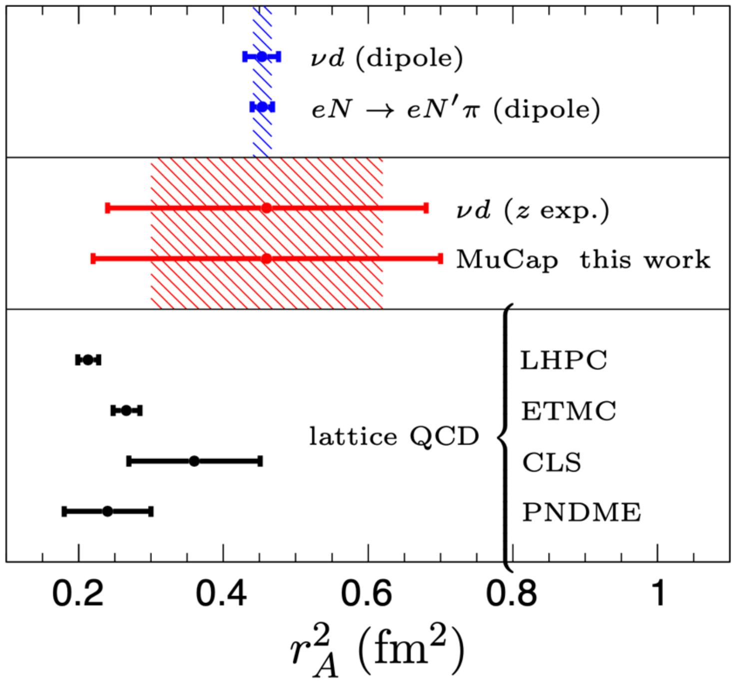
Black dots -- MINERvA cross section data ratio to xsec predicted by dipole FF

Red = proton fit using z-expansion
Orange = deuteron fit using z-expansion
Black = LQCD

T. Cai *et al.*, Nature 614 2023

Axial Form Factor from LQCD





LQCD results maturing:

- Many results, all physical M_π: *independent "data" & different methods*
- Small systematic effects observed (expectation: largest at $Q^2 \to 0$)
- Subject to nontrivial consistency checks from PCAC

LQCD prediction of slow Q^2 falloff, situation unlikely to change drastically

Experimental Overview

$$\mathrm{p}(\vec{e},\mathrm{n})\nu$$

- 10 cm LH2 target
- 100 uA beam – longitudinally polarized → 100% asymmetry
- 500 hours, E = 2.2 GeV, Q^2 = 1 GeV^2
- Hadron arm + pion veto Arm (SBS)

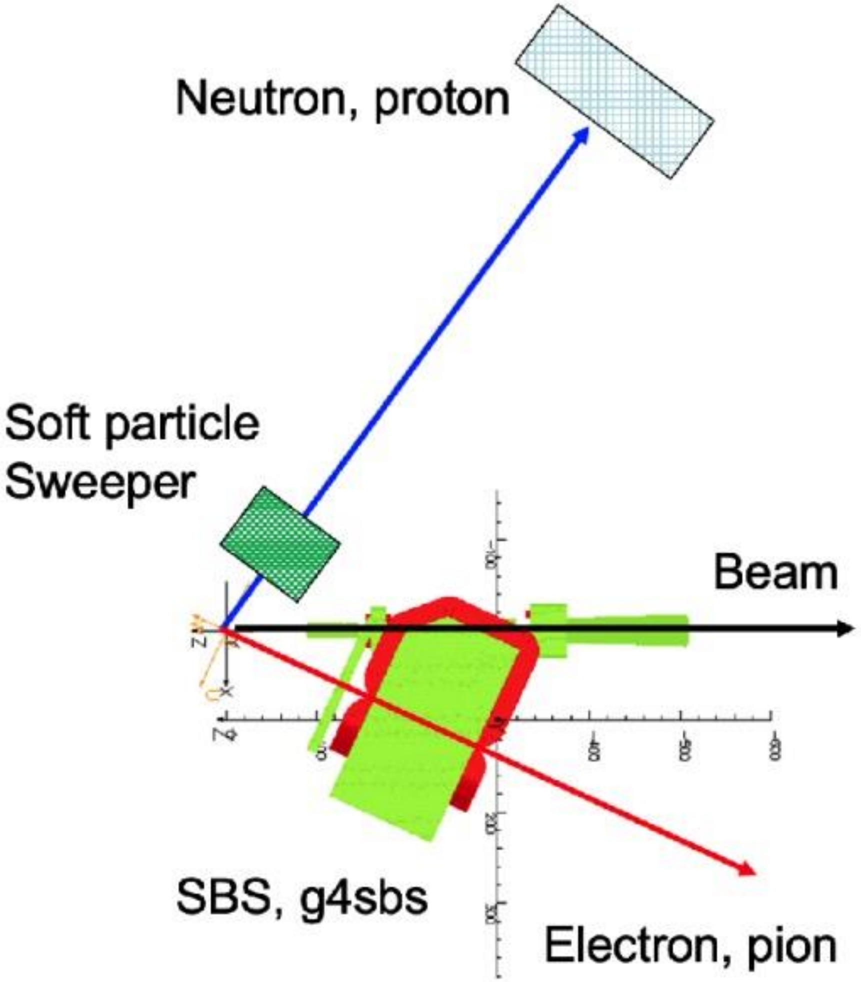
Three processes for neutron production

$$e + p \longrightarrow \nu + n \quad \text{weak CC elastic} \qquad \frac{d\sigma}{d\Omega} \sim 10^{-39} \ \ \mathrm{cm}^2/\mathrm{sr}$$

$$e + p \longrightarrow e + p \quad \text{EM elastic} \qquad \frac{d\sigma}{d\Omega} \sim 10^{-32} \ \ \mathrm{cm}^2/\mathrm{sr}$$

$$\gamma + p \longrightarrow \pi^+ + n \quad \text{pion photoproduction} \qquad \frac{d\sigma}{d\Omega} \sim 10^{-31} \ \ \mathrm{cm}^2/\mathrm{sr}$$

Letter of Intent to PAC 52 (Summer 2024)



Key Assumptions

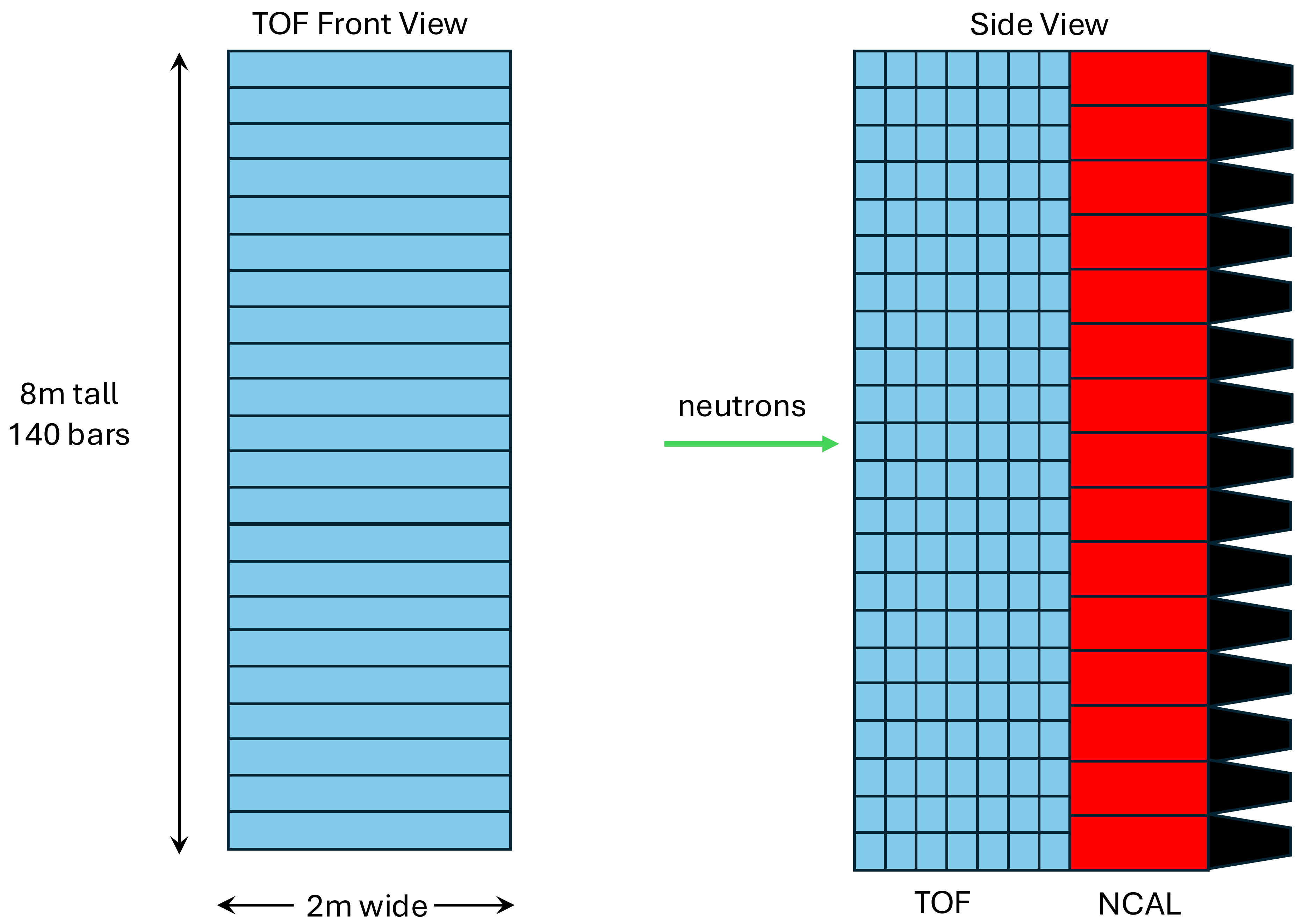
- A 500-hour data taking run with a beam on a 10-cm-long LH2 target in Hall C.
- A 100 μA electron beam at 2.2 GeV energy with a high degree of circular polarization.
- SBS to veto events from the processes with the final state electron or pion.
- A large size high efficiency neutron detector with time resolution better than 100 ps at a distance of 15 m from the target (75 msr).
- A magnet covering the neutron arm acceptance to sweep out charged particles.

Two goals:

- High Rate requires high online background rejection to get DAQ rates manageable
- High offline rejection of non-weak processes

- Primary Detector: Horizontal sweeper magnet → 7 layer TOF → Hadron Calorimeter (NCAL)
  - Protons, electrons and low energy charged particles horizontally off of NCAL
  - Online: NCAL trigger on n → constrain TOF hit location → timing cuts
- Veto Spectrometer: SBS → GEMs → HCAL
  - Offline rejection of pi-n coincidence events

Neutron Arm – TOF followed by Neutron Calorimeter



TOF: 980 Scin. bars
6cm x 6cm x 2m
100 ps time res.

NCAL: Fe/Scin. stacks
HCAL design

DAQ: VETROC, FADC

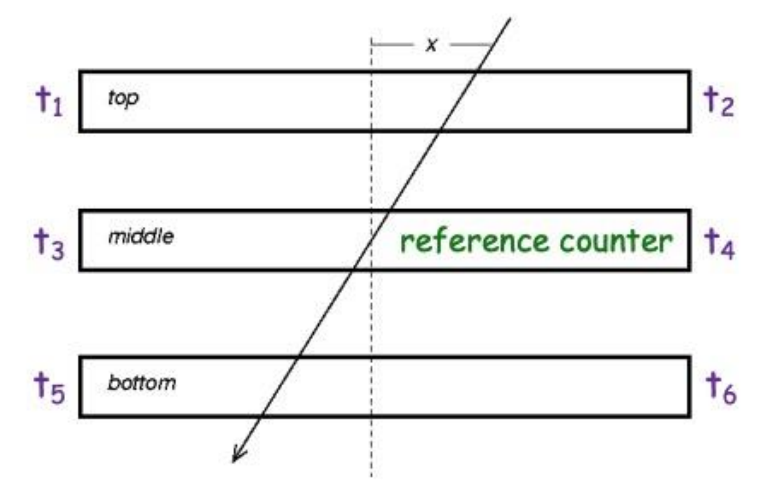
TRIGGER: NCAL

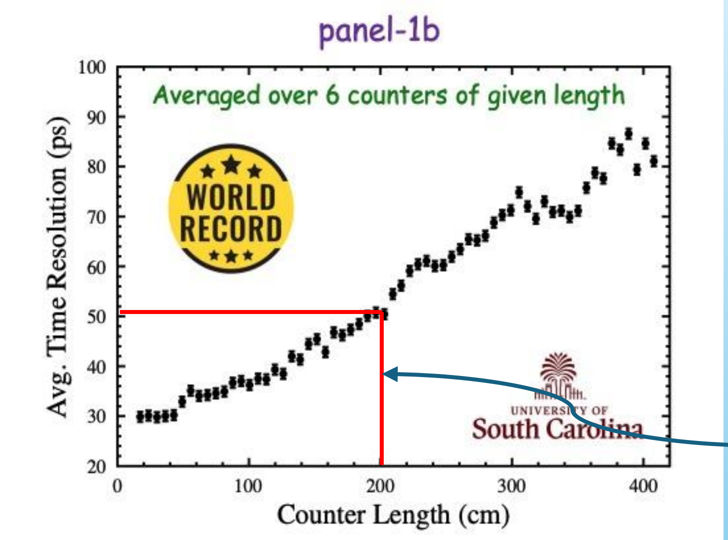
Non-weak neutron VETO: TOF , beam timing and geom.

CLAS12 FTOF Detector Talk – Daniel S. Carman

NIM A 960 (2020)163629

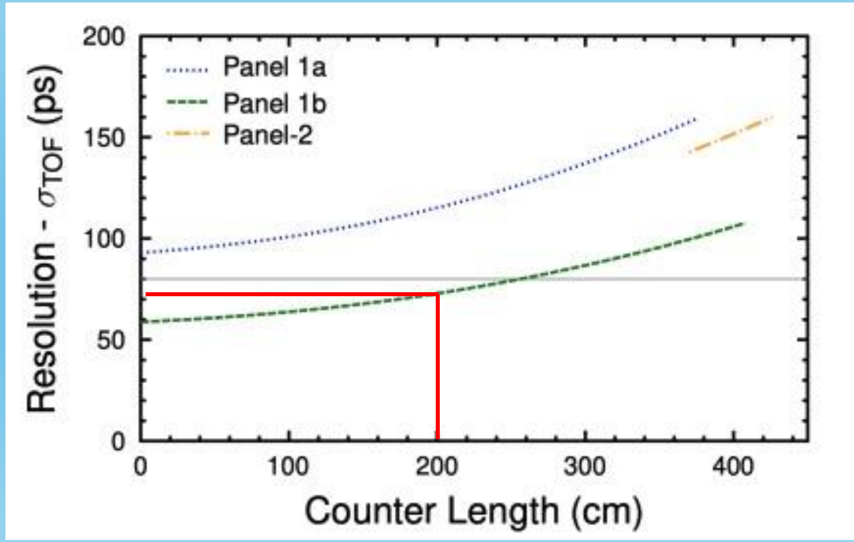
- CLAS12 FTOF Panel-1b is basis for our TOF design → we require 100 ps resolution





Intrinsic Time Resolution on test bench

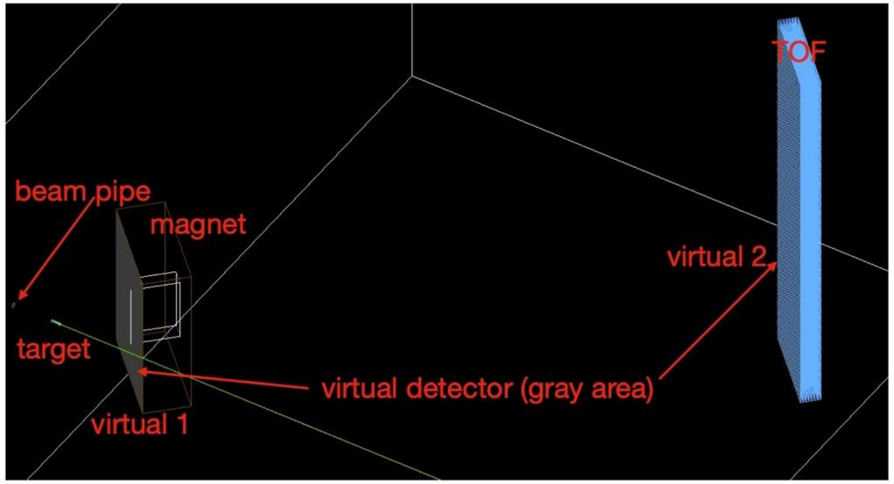
Our TOF, 2 m

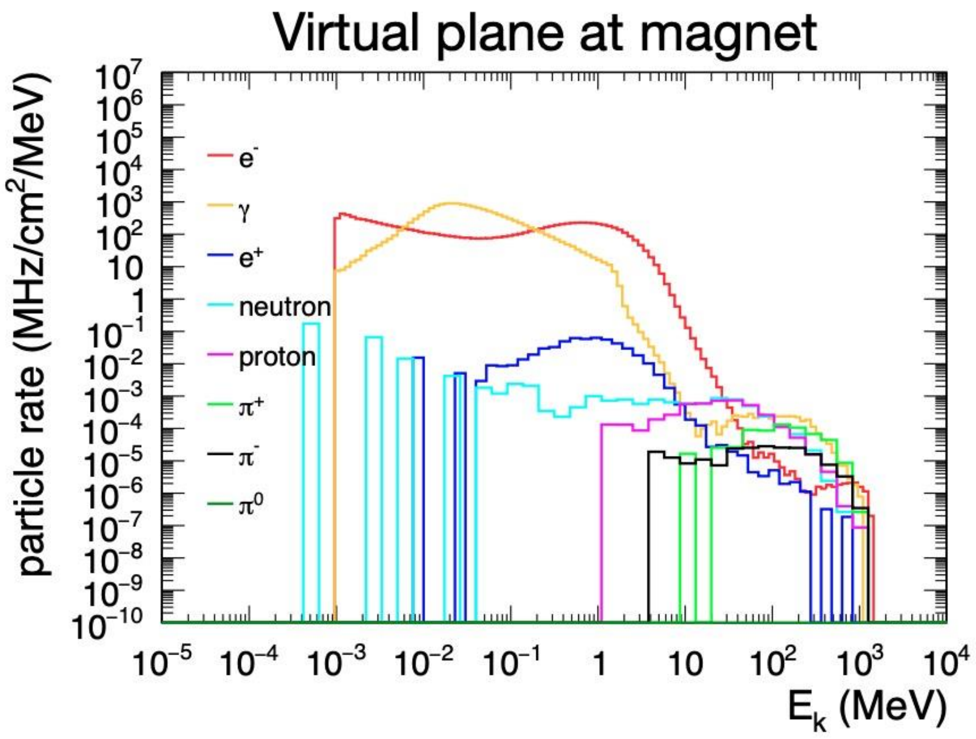


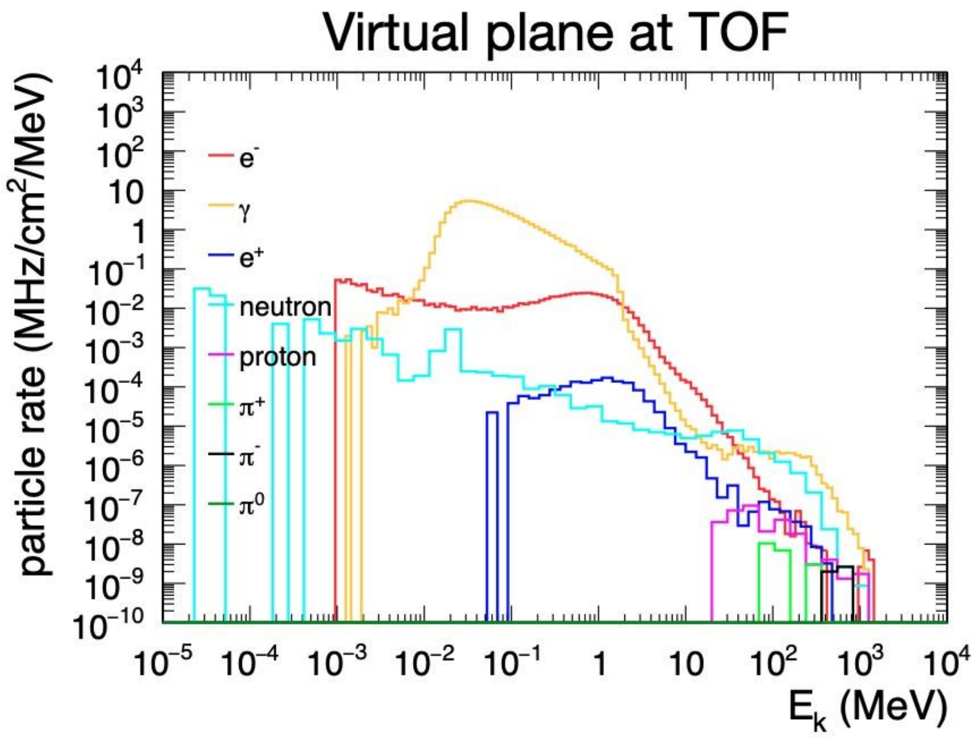
Effective Time Resolution, in-situ

GEANT4 Simulation of Neutron Arm
Weizhi Xiong, Yi Yu, Shangdong Univ., China

Virtual Plane 1 – front of sweeper magnet
Virtual Plane 2 - TOF







- All detectors are placed in air

- NCAL trigger rate with 50 MeV threshold

  - Protons,electrons will be deflected off of NCAL
  - Neutron rate ~ 800 kHz – simulation
    - Reduce non-correlated 400 kHz rate to 1 kHz using TOF and NCAL event position correlation
    - Expect position-correlated event 200 kHz rate
      - Reduce to 20 kHz using timing cut with beam bunch
  - DAQ rate ~ 20 kHz

Offline Rejection

- Accidental rate:
  - Assume 10 ns time window, 1000 bars, 1 MHz per bar – GEANT4 simulation
  - Accidental rate per trigger = $10^{-8} * 10^{3} * 10^{6}$ = 10 accidental TOF hits per NCAL trigger

- Remaining 10 accidental in TOF at 1 kHz
- Additional 90% pi-n rejection from pion coincidence in VETO arm
- Reduce time window 10 ns --> 1 ns (offline time res = 0.1 ns), factor of 10
- 100 Hz event rate
- Final rejection using neutron energy cut based on 100 ps TOF resolution → 4 Hz pion related

Final Numbers

- Expected *vn* rate 50 events/hour => 0.014 Hz
- 50% neutron efficiency in TOF => 0.007 Hz
- Accidental 4 Hz => 2 Hz
- Asymmetry $A = \frac{(2 + 0.007) - 2}{(2 + 0.007) + 2} = 0.0018$
- 500 hours at 2 Hz => N = 8.6 x 10^7

$$\frac{dA}{A} = \frac{0.00018}{0.001} \rightarrow 18\%$$

36% uncertainty in F_A

Status:

- PAC response to LOI (paraphrased): A unique opportunity to measure the axial-vector FF, the least well-known nucleon FF. Of considerable importance for accelerator-based neutrino oscillation experiments. The PAC encourages the proponents to proceed to a full proposal after the above issues (full simulation, detector details, cost) are addressed. Need a full Monte Carlo simulation. If this method of extracting the axial-vector form factor proves successful, the PAC notes that this could become part of a larger measurement campaign. In particular, a measurement of the Q2 dependence of the axial-vector form factor would be of great interest to the neutrino scattering community.
- Currently - Weekly simulation meetings
- In place: Accurate cross section formalism/estimation from Peter Kroll
- Qty = 7 CLAS12 – type scintillators + PMTs being tested in BW lab
- Proposal in progress – TDA, BW
- Upon approval – MRIs for TOF and NCAL xxM$??
- JOIN US in measuring a channel never before explored !!!!