26th International Symposium on Spin Physics
A Century of Spin

Development of Electron Beam Study of the Nucleon Axial Vector Form Factor at JLab

Todd Averett (William & Mary), Jim Napolitano (Temple)
Bogdan Wojtsekhowski (JLab), Weizhi Xiong (Shandong Univ.)

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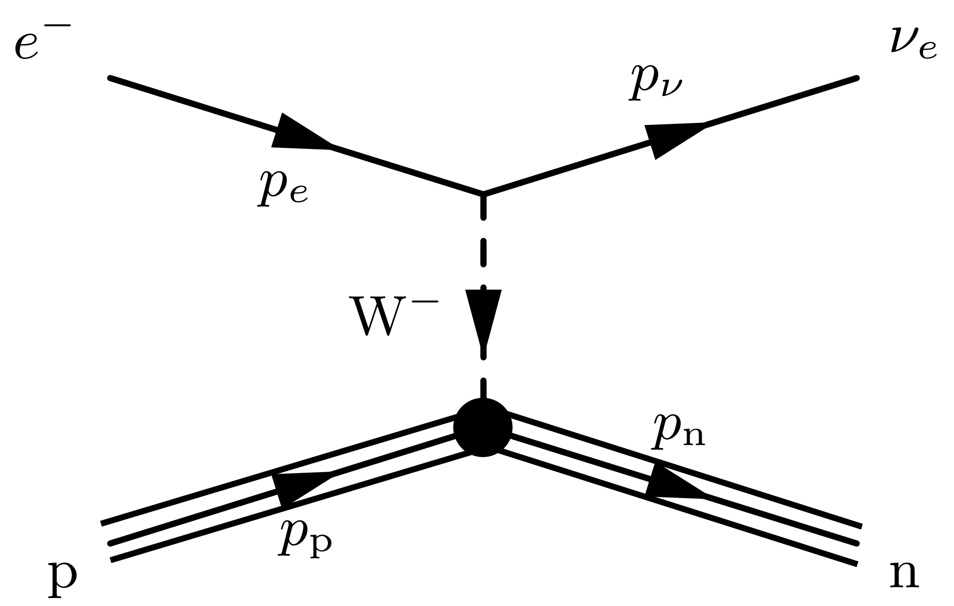
26th International Symposium on Spin Physics

Outline

- Physics motivation
- Experimental concept and design
- Current status and projections
- Summary

The idea has been around a while!

- LOI to PAC 1 (JN) *Not a typo!*
- LOI to PAC 25 (A Deur)
- LOI to PAC 52 (JN and BBW)



Physics Motivation

Charged Weak Current Analog of the Electromagnetic FF's

Vector Interaction

$$\langle p+q\,|\,J_V^{\mu}\,|\,p\rangle = \bar{u}(p+q)\left[F_1(q^2)\gamma^{\mu} + \frac{\kappa}{2m}F_2(q^2)i\sigma^{\mu\nu}q_{\nu}\right]u(p)$$

You are very familiar with these form factors.

Axial-Vector Interaction

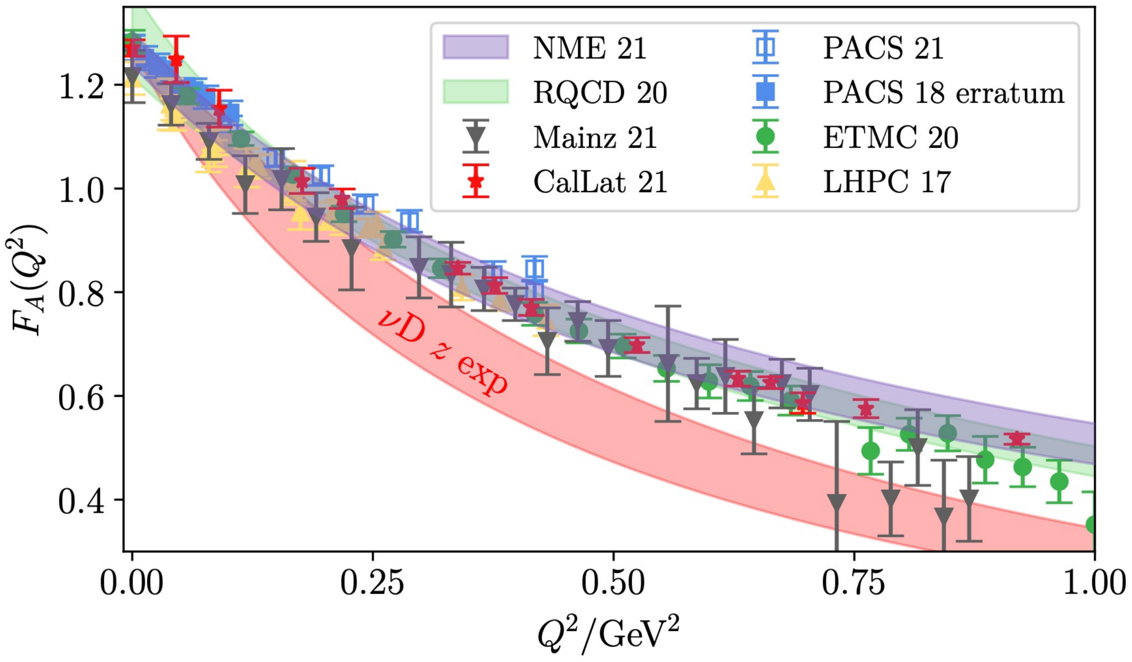
$$\langle p+q\,|\,J_A^{\mu}\,|\,p\rangle = \bar{u}(p+q)\left[F_A(q^2)\gamma^{\mu}\gamma^5 + F_{PS}(q^2)q^{\mu}\gamma^5\right]u(p)$$

Well measured at zero momentum transfer (beta decay).

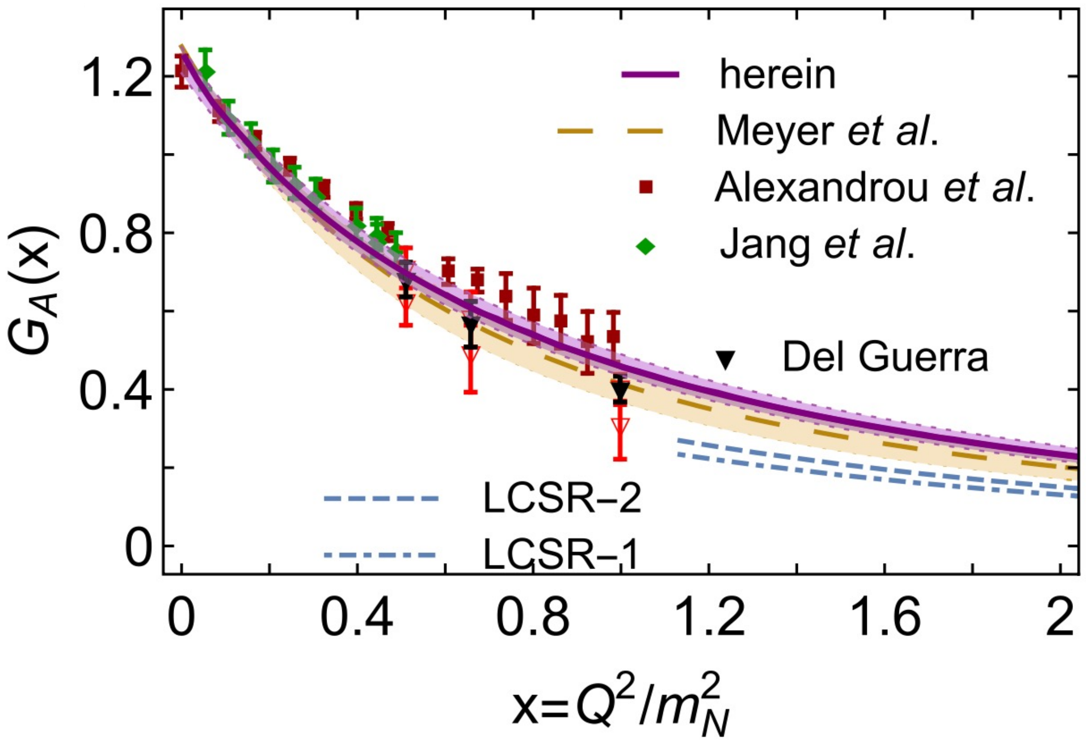
Our goal is to measure $F_A(q^2)$ at finite momentum transfer.

Physics Motivation

- Similar to EMFFs, AVFF is also an essential QCD observable for nucleons
- An important test ground for many theoretical calculations (LQCD, Dyson-Schwinger method…)



A. Meyer, A. Walker-Loud, C. Wilkinson *ARNPS.* 72 (2022) 205-232



C. Chen and C.D. Roberts EPJA 58 (2022) 10, 206

Physics Motivation

(Besides being another fundamental QCD observable!)

- New constraints on Generalized Parton Distributions

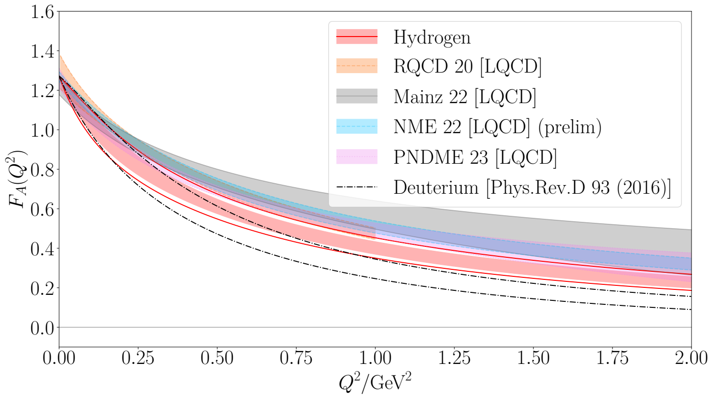
(Peter Kroll)

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

$$+ \; 2\int_0^1 \left[\widetilde{H}^{\bar{u}}(x,\xi,t) - \widetilde{H}^{\bar{d}}(x,\xi,t)\right] dx$$ Sea quarks (small)

- Important input for DUNE and other high energy neutrino experiments

(Aaron Meyer)

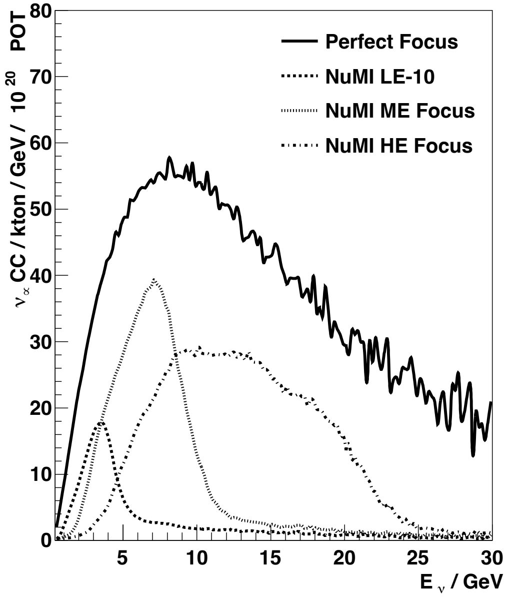


Important constraints on LQCD calculations needed to untangle neutrino oscillations in DUNE.

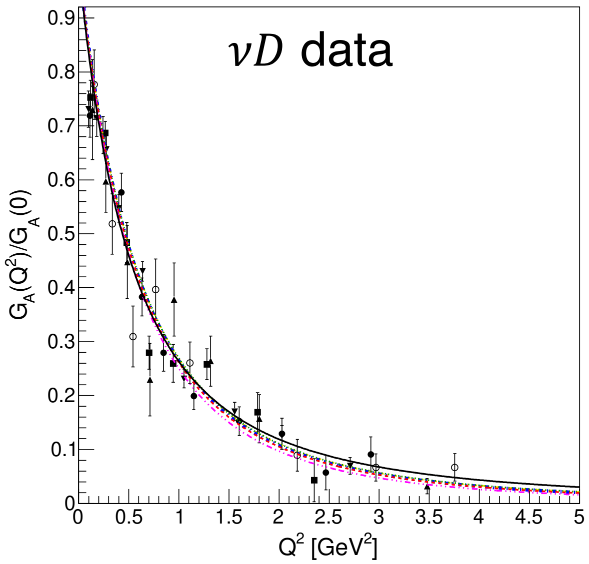
(Even a 25% measurement helps a lot.)

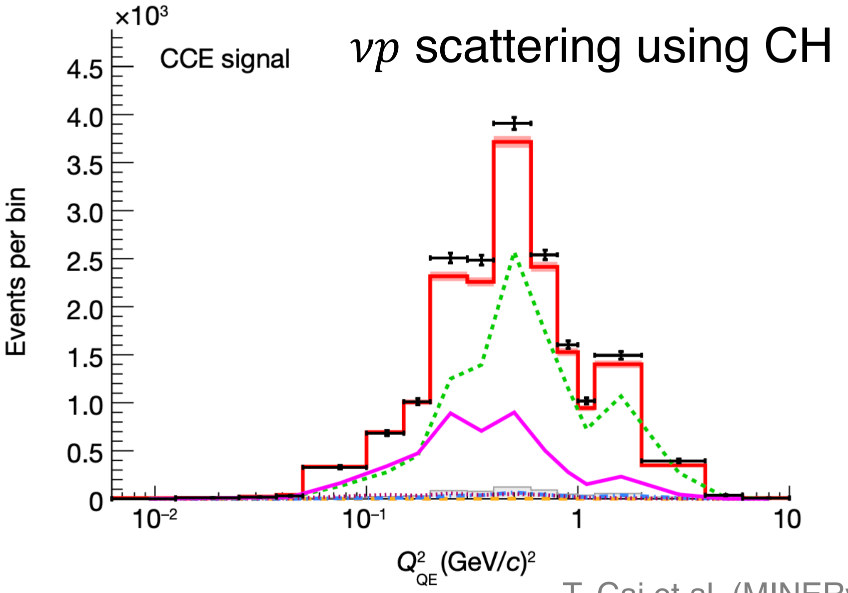
How It Was Measured Before

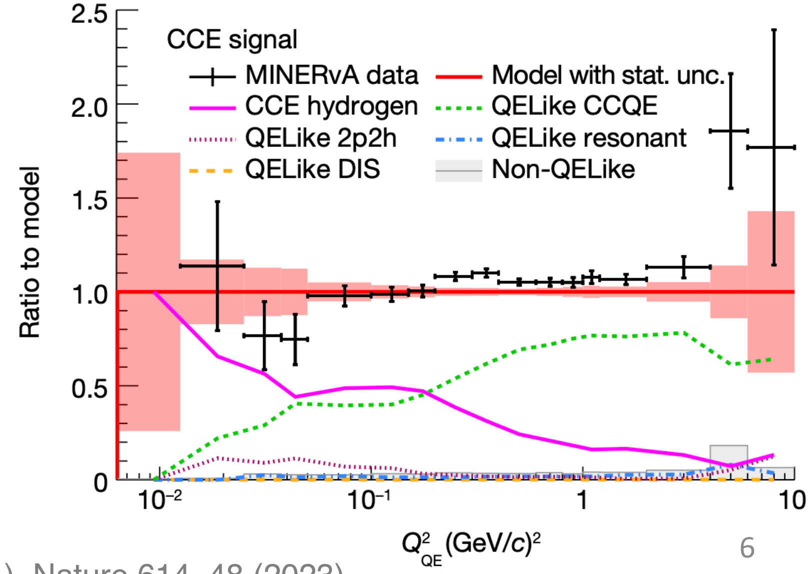
- The natural way to measure $F_A(Q^2)$ is neutrino scattering
  - ➢ νA scattering
  - ➢ νD bubble chamber experiments
  - ➢ νp scattering using plastic scintillator
- Limitations:
  1. Board range neutrino energy
  2. Usually not a free proton (nuclear effect)
  3. Large systematics



Phys. Rev. D 93, 113015 (2016)





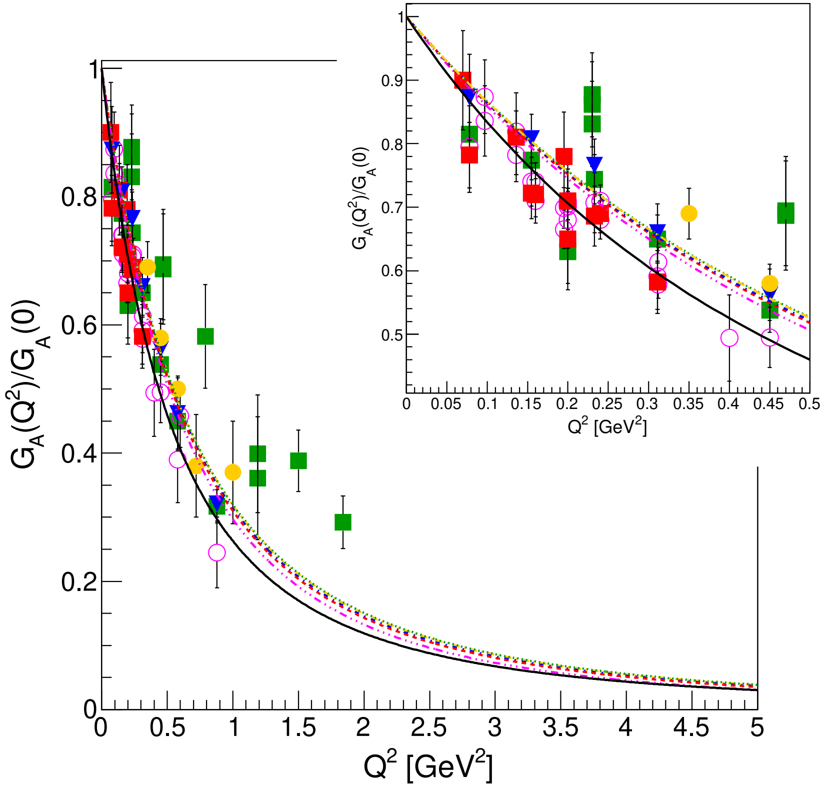


T. Cai et al. (MINERvA), Nature 614, 48 (2023)

How It Was Measured Before

- Another model dependent method is pion eletroproduction near threshold
  - Need to assume partially conserved Axial current model (PCAC)
- Results with large uncertainties, and disagree at high Q^2

Phys. Rev. C 101, 025501 (2020)



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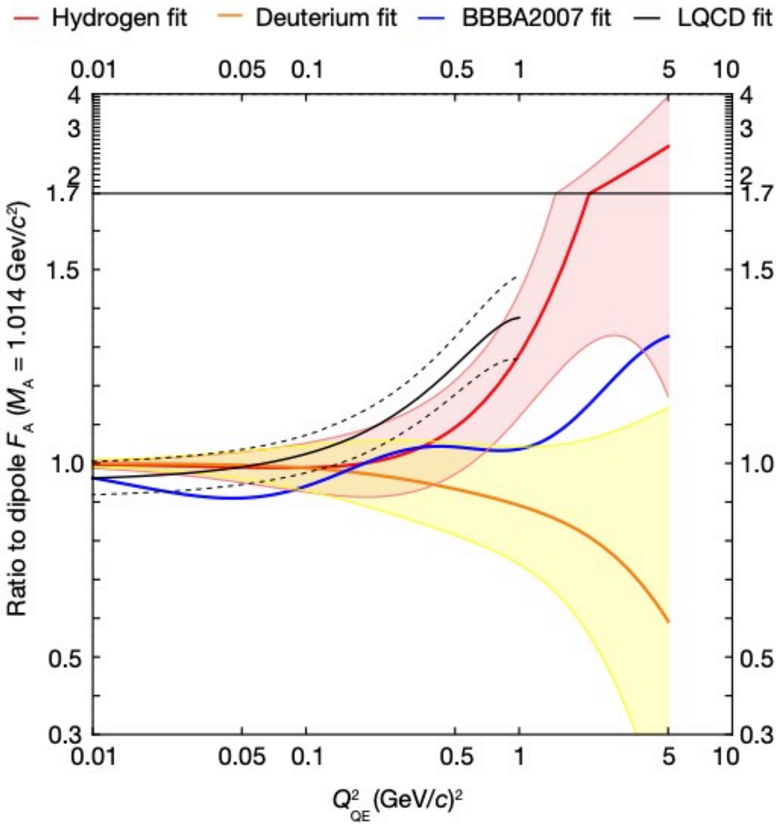
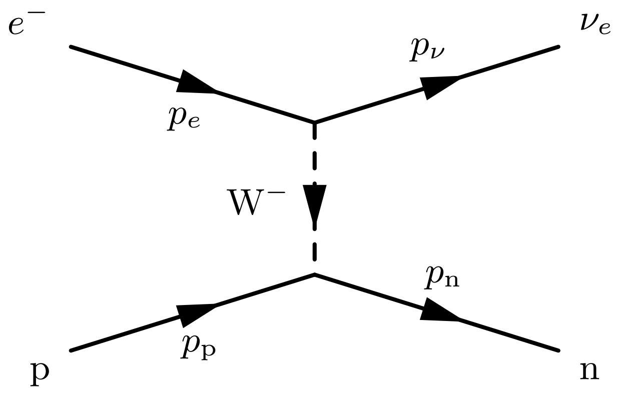


Experimental Concept



- Is it possible to measure this using electron beam?
  - ➢ free proton target, no nuclear effect
  - ➢ no model dependency
  - ➢ high precision lepton beam, compared to neutirno beam

- No hope in detecting the neutrino obviously, but we can still capture the neutron

- Reaction kinematic close to elastic ep kinematic, that means at a given scattering angle:
  - Neutron kinetic energy is fixed
  - Neutron from this reaction has the largest kinetic energy

- For neutrons of interested, recon ebeam should equal beam energy
- **Nice and easy!**

$$E^{rec}_{beam} = \frac{E_n - (M_p^2 + M_n^2)/2M_p}{1 + (P_n \cos\theta_n - E_n)/M_p},$$

Experimental Concept

- In reality this is quite difficult…
  - Charge current cross section: $$\frac{d\sigma}{d\Omega_{\nu,lab}}|_{e+p\to\nu+n} = 1.35 \times 10^{-39}\ \mathrm{cm}^2/\mathrm{sr}$$
- Meanwhile, background rates from other channels:
  - Elastic ep cross section: $$\frac{d\sigma}{d\Omega_{lab}}|_{e+p\to e+p} = 1.4 \times 10^{-32}\ \mathrm{cm}^2/\mathrm{sr}$$
  - Pion electro and photo-production rate ($ep\to e\pi^+n$, $\gamma p\to\pi^+n$, $ep\to e\pi^+\pi^0 n\ldots$), should be even higher than elastic ep
  - What about aluminum cell window, quasi-elastic en, pion production in Al?

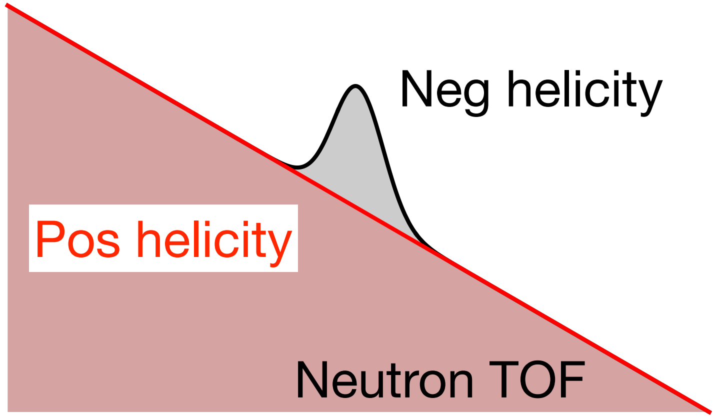
Experimental Concept

1. Need to measure the neutron angle and kinetic energy with high precision!
   - Neutron time-of-flight, can reach about **1% resolution for T with 100ps resolution**, possible! (BAND detector in Hall B JLab)
   - Hadronic calorimeter, resolution ~50%/sqrt(E), **used for suppress low E bg.**

2. Need large acc. veto detector (0.4 sr) to reject backgrounds (pion production, elastic ep…)
   - *p* and *e* are co-planer, with constrained kinematics
   - for neutrons from pion production, *n* and *π* are also co-planer, with constrained kinematics

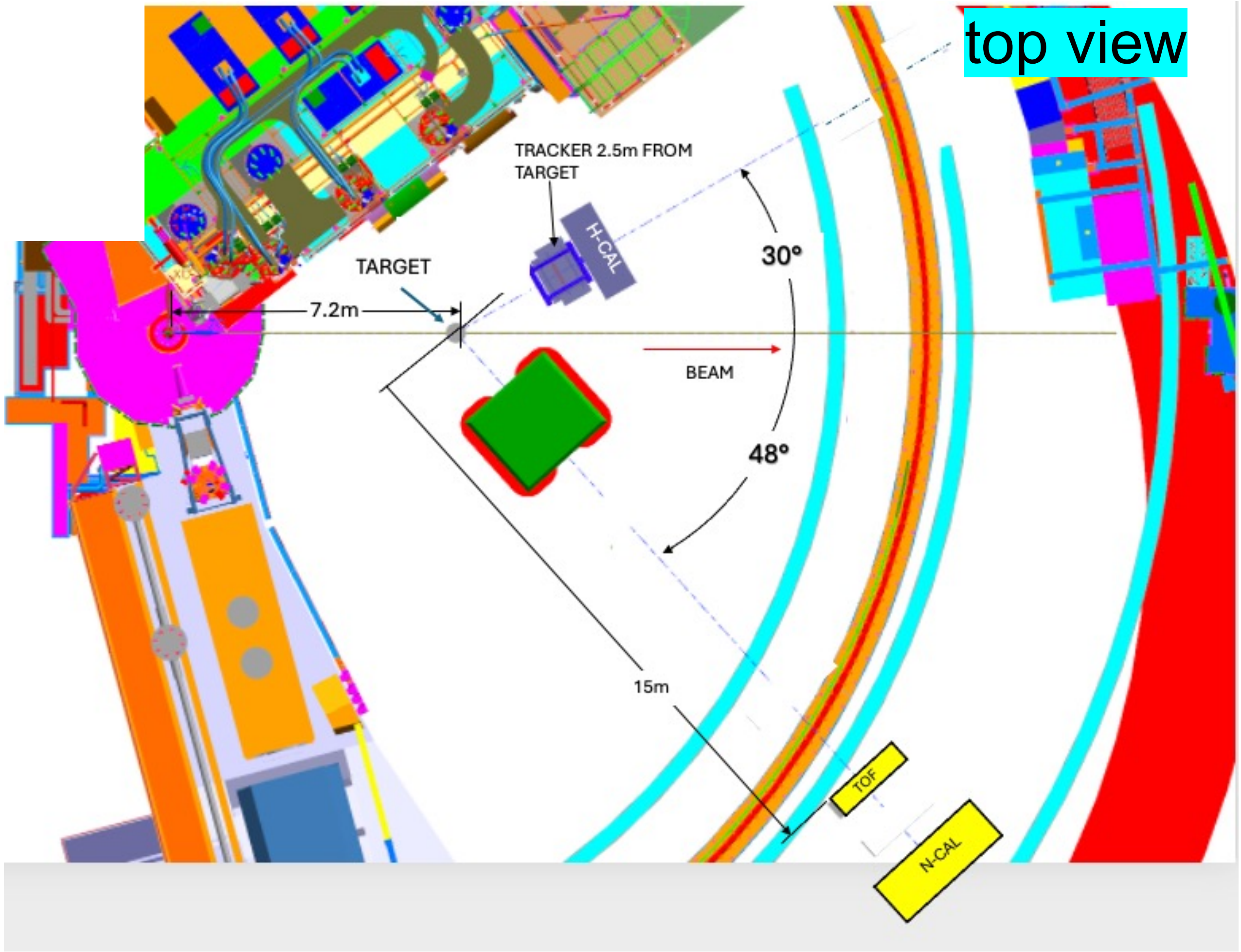
3. Need carefully designed shielding to block Al windows
4. **Only left handed *e* can produce signal!**

The primary challenge is to reduce the backgrounds from electromagnetic processes (10^7 larger than our signal) so that background subtraction yields a statistically useful signal.



Experimental Setup

Jefferson Lab Hall C



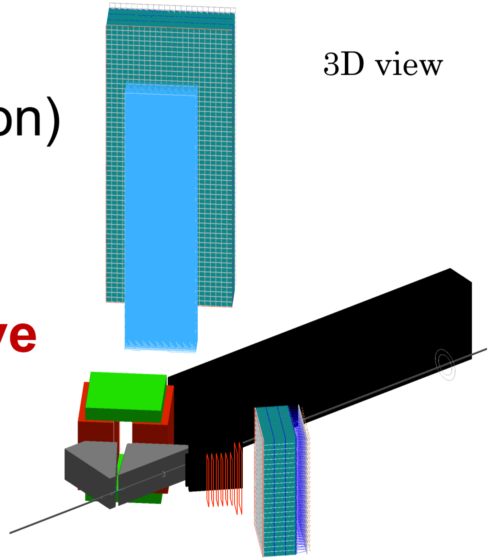
- E=2.2 GeV, 120μA, P=85%
- 10cm LH2 target (*pure; low D2)*

- θ_n=48° so $Q^2 = 1 GeV^2$
- T_n = 525 MeV, v/c=0.77
- 15m to TOF, 65 ns, $\Delta\Omega$=75 msr
- Expect to get σ_{TOF}=100 ps

- $\theta_\nu = 30^\circ = \theta_e$
- $E_e = 1.67$ GeV

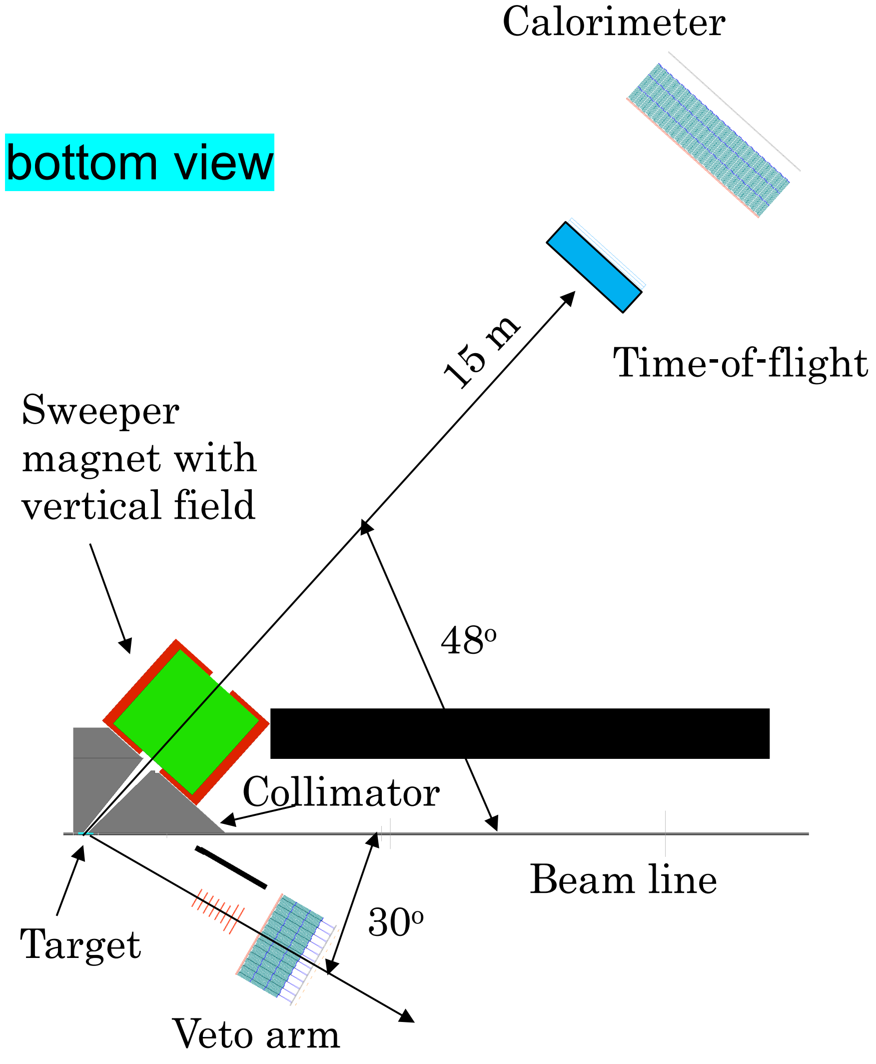
Experimental Setup

- Neutron arm:
  - Center at **48°**
  - Sweeper magnet
  - 1540 6cm x 6cm x 200cm long scintillator bars for nTof
  - Large NCal 2.5m downstream of nTof
- Veto arm
  - Center at **30°**
  - Used as veto detector to reject elastic and pion production events
  - Calorimeter HCal
  - GEM trackers (only for calibration)
- LH2 target:
  - 25cm long LH2 with **10cm active**
  - Al cell, windows 150um each
  - W shielding, block cell windows



3D view

bottom view

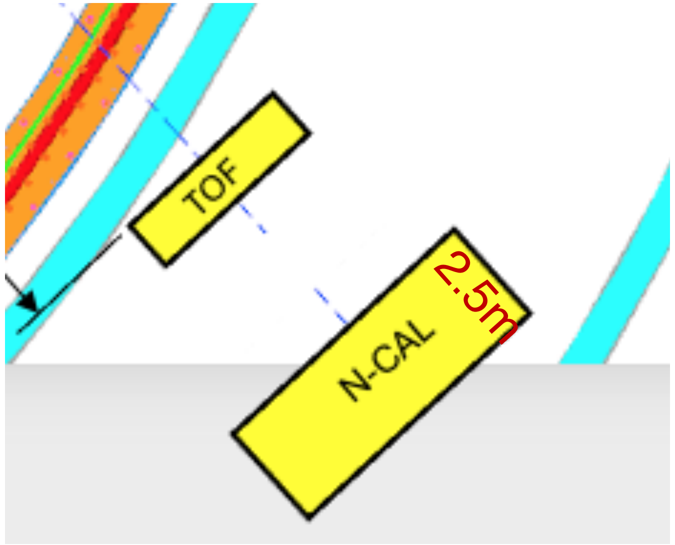


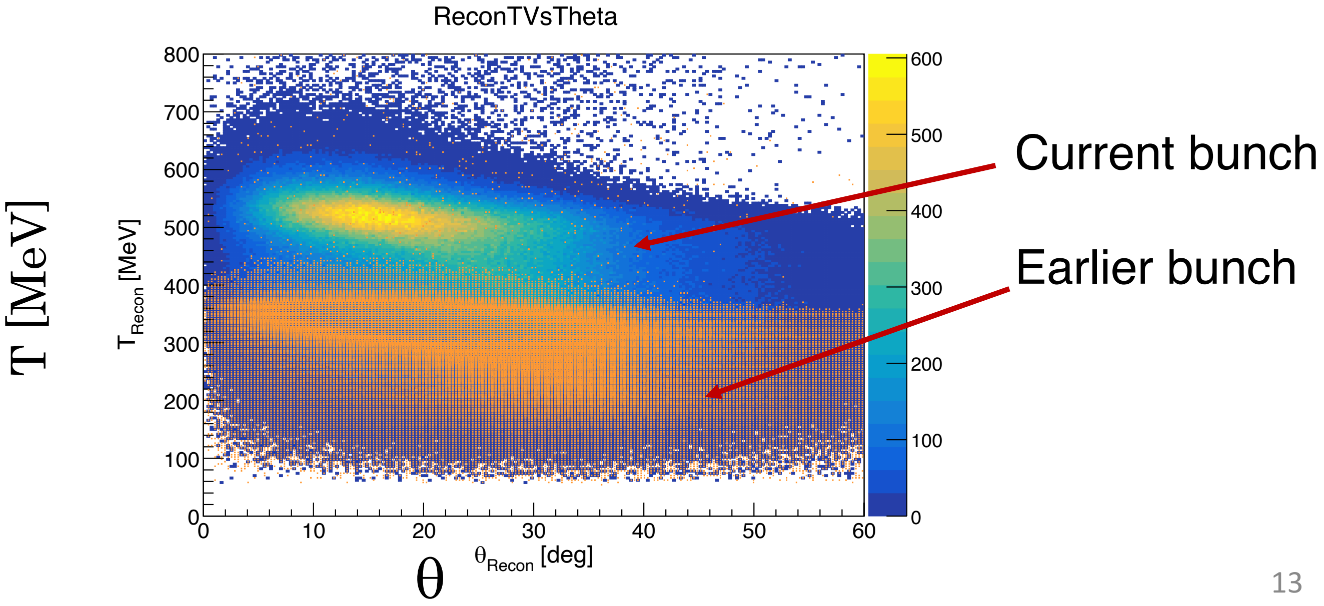
Using NCal + TOF to Determine Beam Bunch

- JLab beam has bunch interval, 2ns, 4ns, 8ns, 16ns…
- How do we know what bunch the neutron is coming from?
  - ➢ n we want to detect arrives at ~65ns (T = 529MeV)
  - ➢ at 8ns later, the neutron still has ~350MeV, 16ns later still ~250MeV…
  - ➢ ~60% energy resolution of calorimetry cannot reject events from out-of-time bunches!

➢ Solution: move NCal 2.5m downstream, and measure beta using TOF and NCal

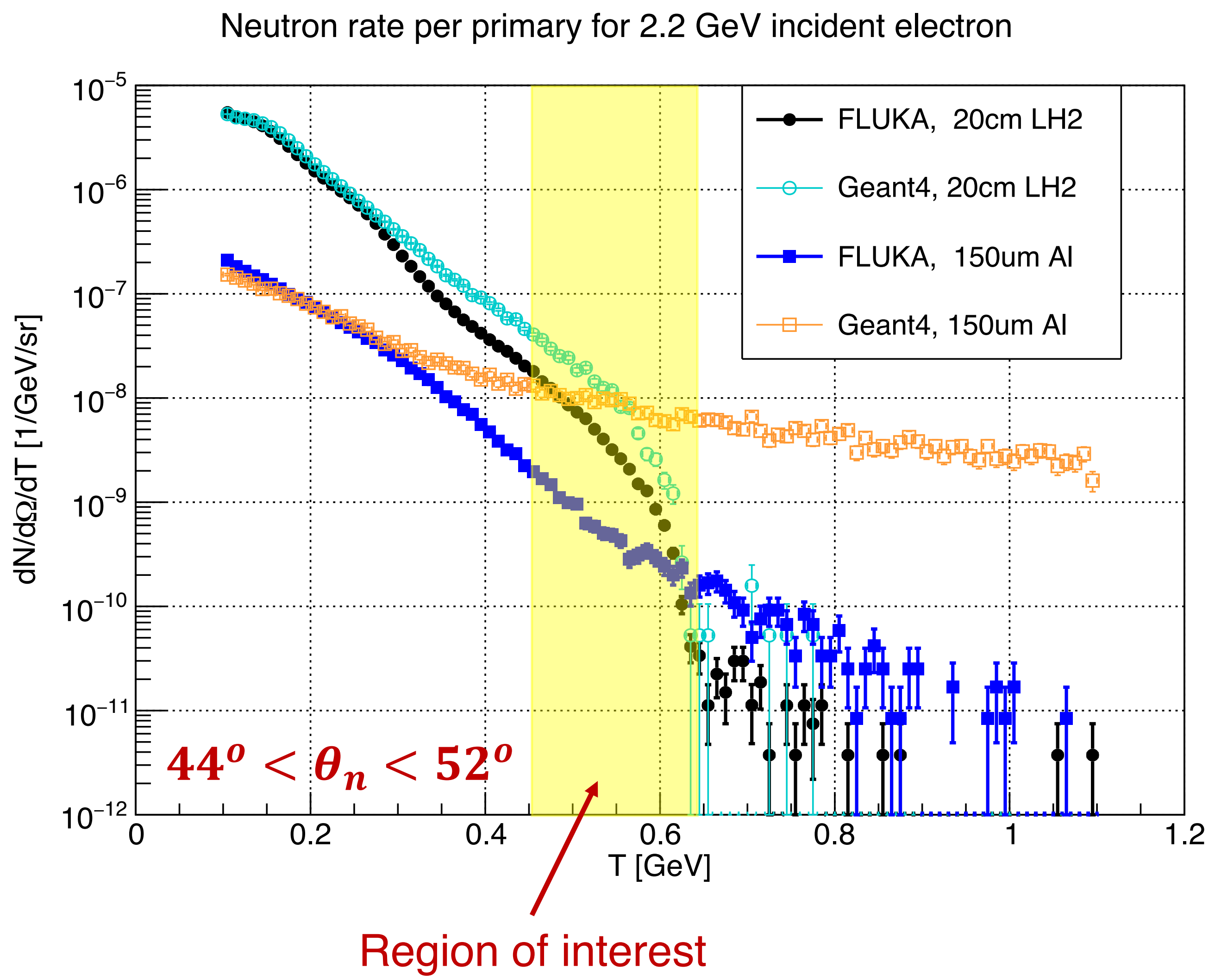
➢ Preliminary estimation: efficiency ~25%





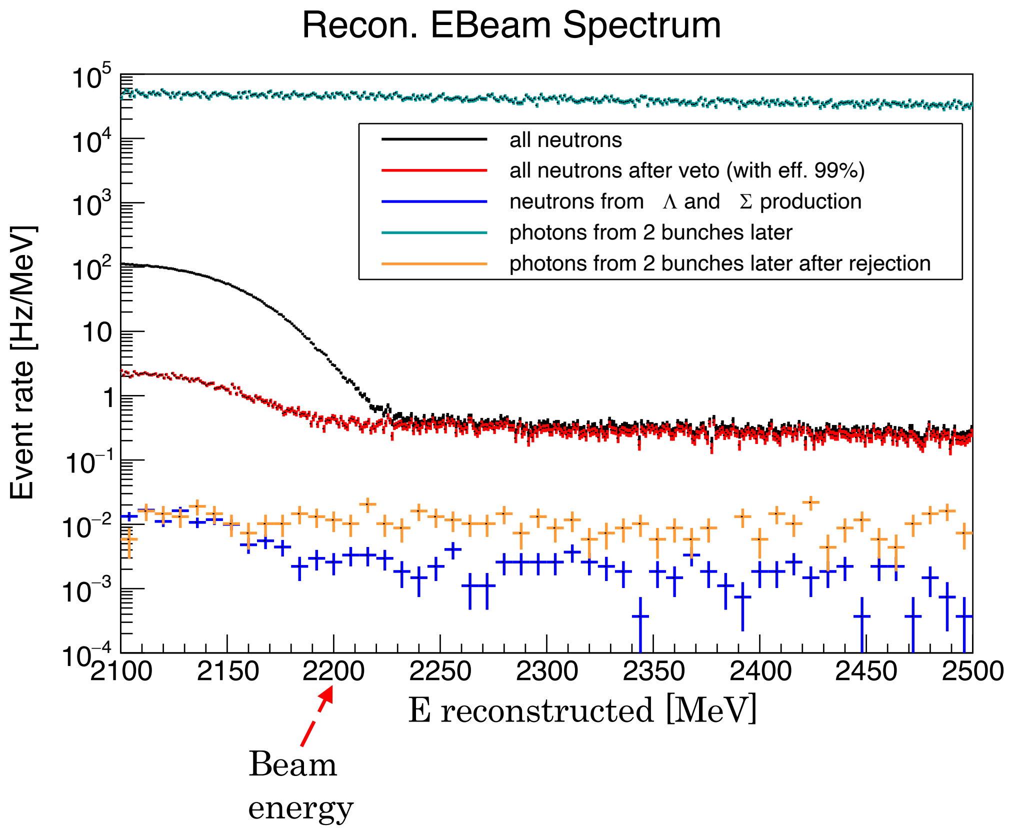
Simulation Comparison between G4 And FLUKA

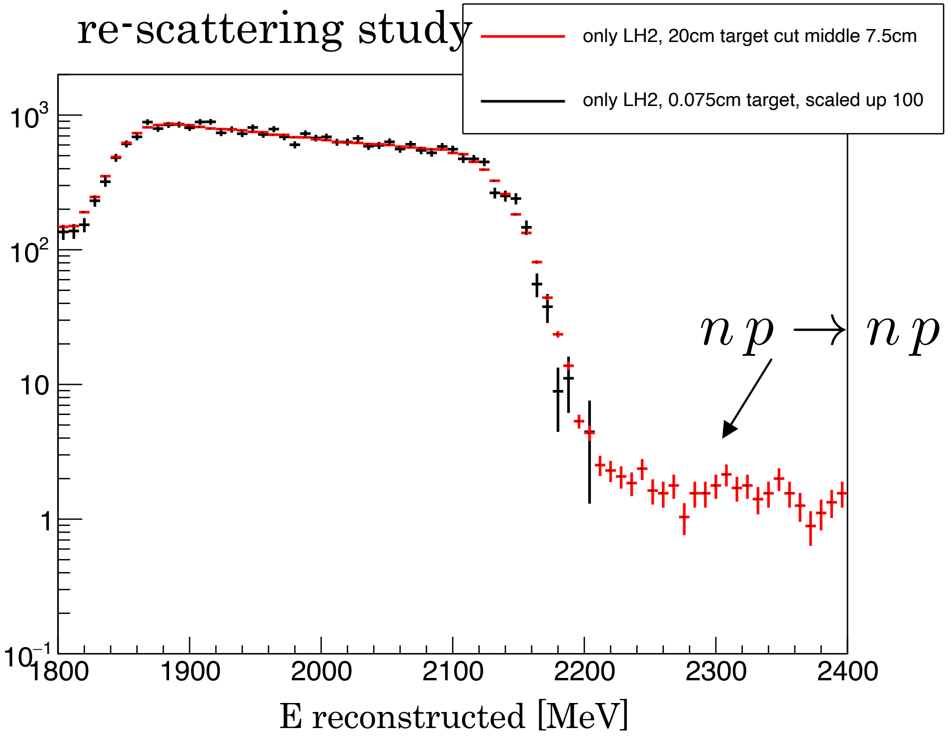
- Geant4 produce about ~2 times more neutron background from LH2 than FLUKA
- 10 times more neutrons from aluminum
- Currently in progress of resolving this discrepancy
- Taking the G4 rate for conservative estimate for now



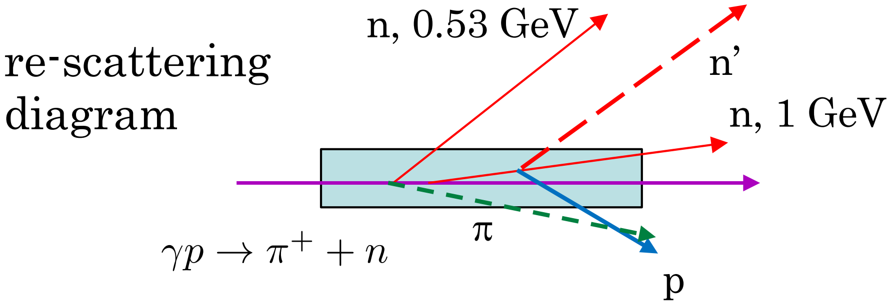
Simulation

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

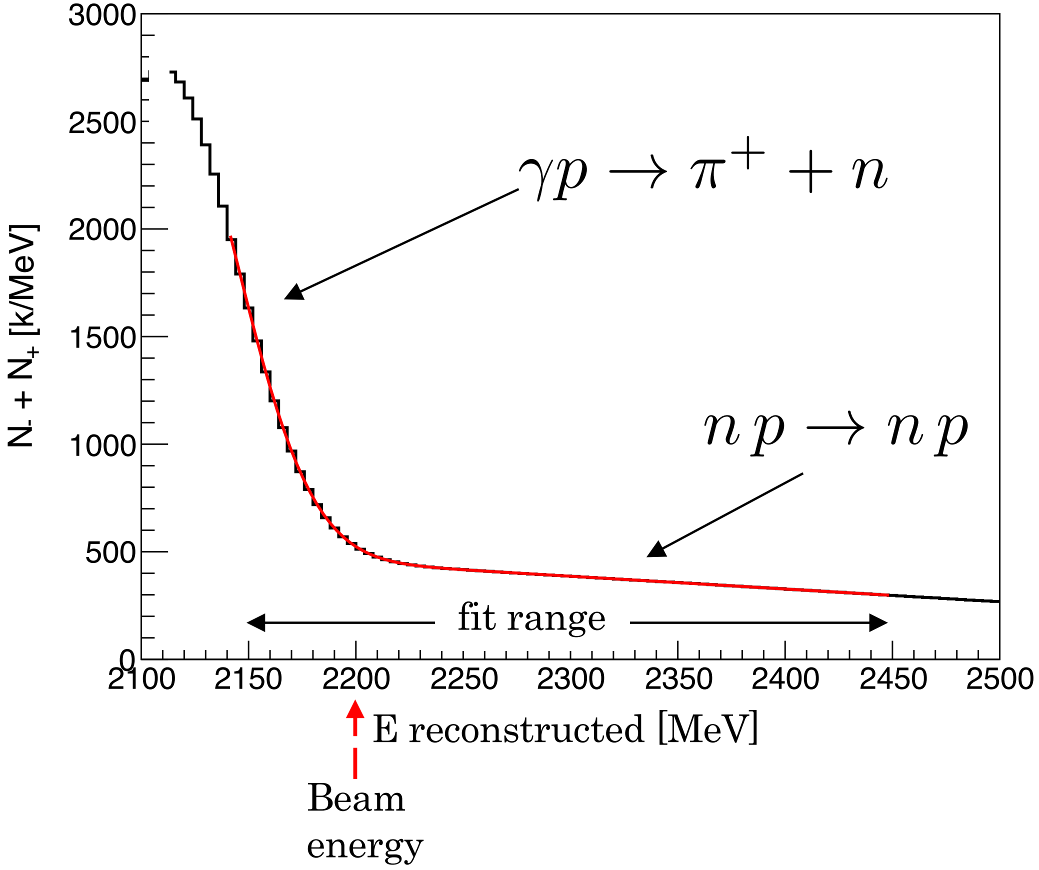


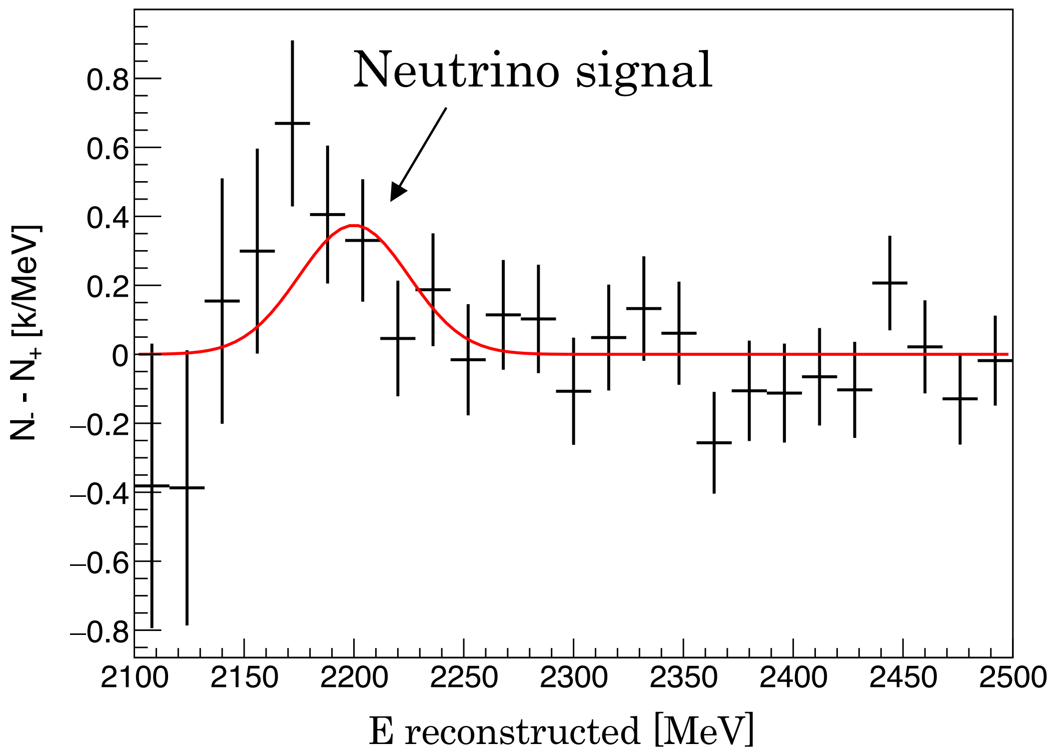


$$E_{reconst} = \frac{E_n - (M_p^2 + M_n^2)/2M_p}{1 + (P_n \cos\theta_n - E_n)/M_m}$$



Simulation





Fit function has three components:

1. Signal (gaussian shape)
2. Background (gaussian tail)
3. Background (linear)

50 days of data taking, 120 μA

(N^- - N^+) bin-by-bin analysis

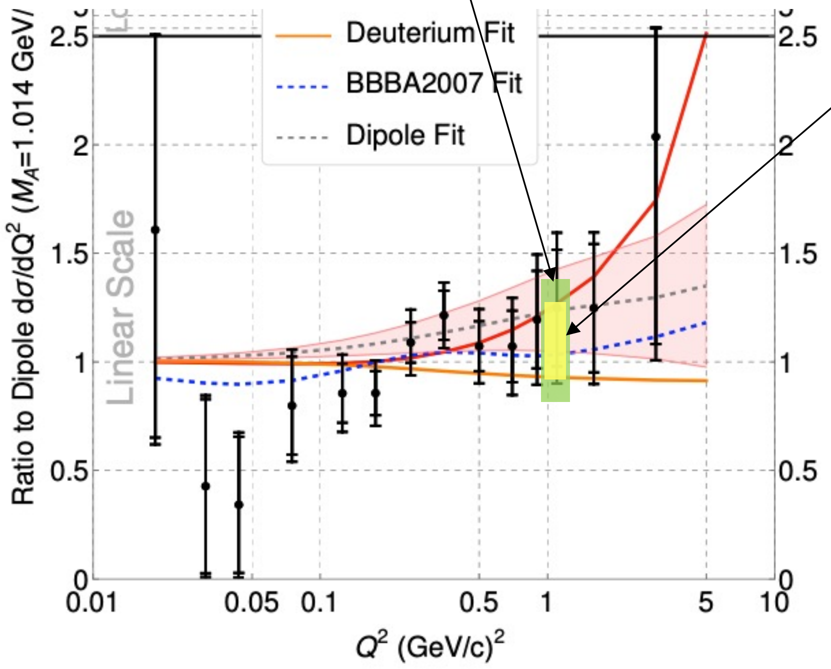
Signal = 19k +/- 6.5k events

Simulation

- Assume 50 PAC days of data taking, with 10cm active LH2 target and 120 uA current
- Current conservative estimate gives overall 35% uncertainty
- Time resolution < 50ps possible quite possible (detector development at USTC, CERN, INFN, JLAB, EIC…), gives 25% accuracy

Current conservative estimate (Geant4 rate + 100ps time reso.)

Geant4 rate + 50ps time reso., 25% accuracy



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

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

Summary

- A ”new” method to measure axial form factor using polarized electron beam
  - ➢ Free proton target, no nuclear effect
  - ➢ no model dependency
  - ➢ high precision lepton beam, compared to neutirno beam

- Projected result: 34% statistical uncertainty + 5% systematic uncertainty, with 50 PAC days running at 120uA @ 2.2 GeV at JLab

- Still working on various potential improvements (and problems)
  - Uncertainty largely dominated by pion production background (single and multi pions)
  - Geant4 gives significantly more neutrons than FLUKA, **need beam test for background measurement**
  - Optimization of collimators, target cell, TOF, and neutron efficiency

- Further improvement quite possible!
- Essential to have short test run for neutron bg rate and time reso.
- Any suggestion and ideas are very welcomed, thank you for your attention!

Backup

Particle rate on TOF

- Sweeper magnet
  - ➢ 1Tm, 2m tall aperture
  - ➢ Sweep away charged particles
- Simulation shooting 2.2GeV electron beam at target
- Particle flux measured in front of TOF and NCal
- Significant reduction of particle rate at high energy region with magnet turned on