Measuring the Nucleon Axial-Vector FF and $p \rightarrow \Delta^0$ Transition FF with SBS

Todd Averett (William & Mary), Jim Napolitano (Temple)

Bogdan Wojtsekhowski (JLab), Roberto Perrino (INFN), Yi Yu (Duke),

Weizhi Xiong (Shandong Univ.)

SBS Collaboration Meeting

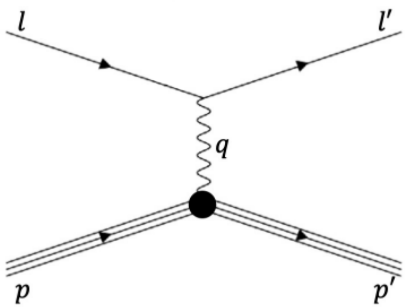
March. 2nd – 4th 2026

Introduction

Charged Weak Current Analog of the Electromagnetic FF's

Vector Interaction

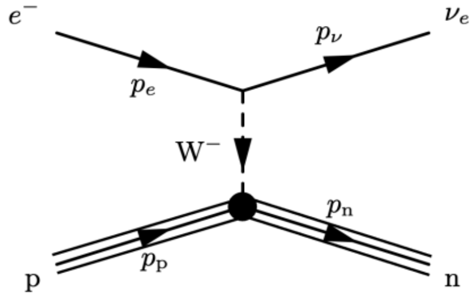
$$\langle p+q\,|\,J_V^\mu\,|\,p\rangle = \bar{u}(p+q)\left[F_1(q^2)\gamma^\mu + \frac{\kappa}{2m}F_2(q^2)i\sigma^{\mu\nu}q_\nu\right]u(p)$$



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

(Besides being another fundamental QCD observable!)

- New constraints on Generalized Parton Distributions

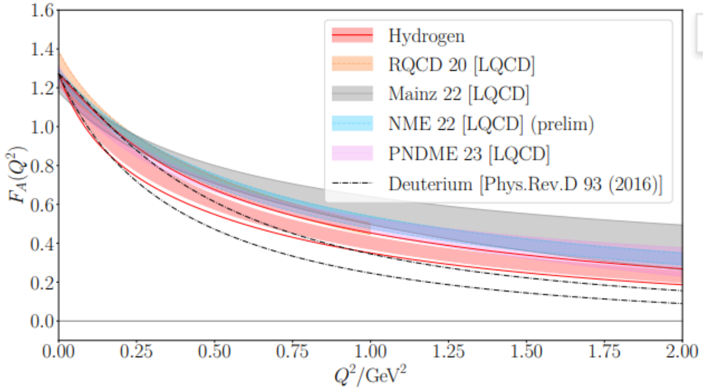
(Peter Kroll)

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

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

- Important input for DUNE and other high energy neutrino experiments

(Aaron Meyer)



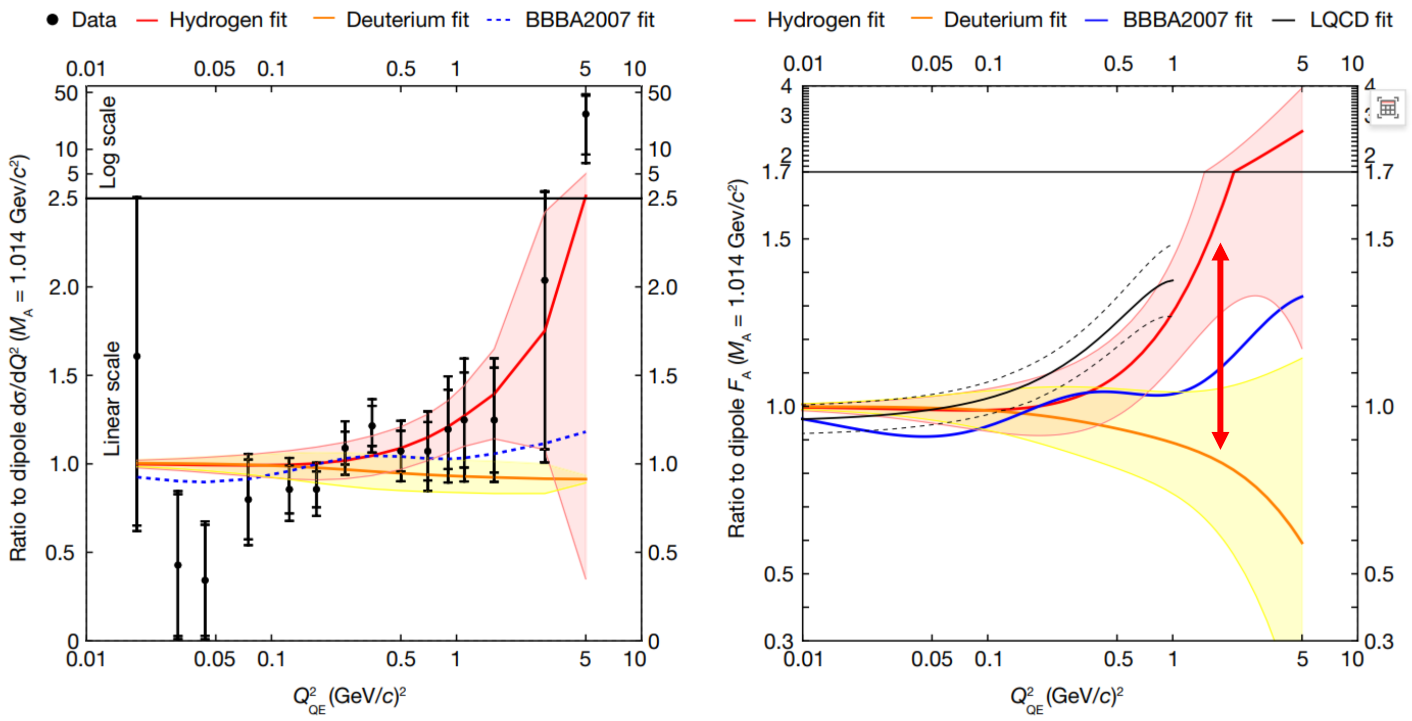
Important constraints on LQCD calculations needed to untangle neutrino oscillations in DUNE.

(Even a 25% measurement helps a lot.)

How It Was Measured Before

- Typically measured with neutrino scattering (νA, νD, νp in plastic scintillator)
  - Results typically with larger uncertainty:
    - ➢ Board range of beam energy
    - ➢ Non-trivial nuclear effect

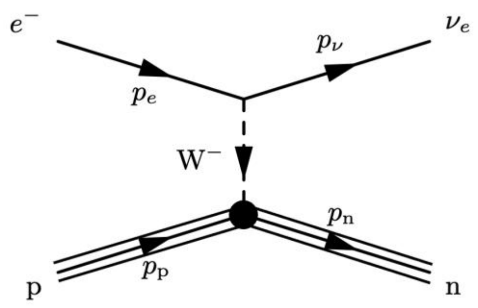
T. Cai et al. (MINERvA), Nature 614, 48 (2023)



- 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

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
  - expected statistic per year ~50 times higher @ Q^2 = 1GeV^2



- 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

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

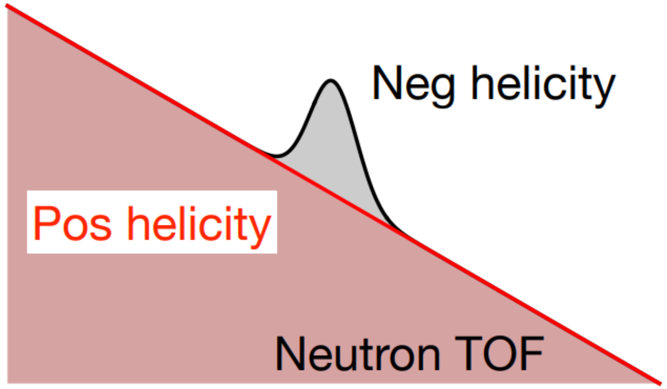
Experimental Concept

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 to reject backgrounds (pi production, elastic ep…)
   - *p* and *e* are co-planer, with constrained kinematics
   - for neutrons from pion production, *n* and *π* are also co-planer if n has high enough kinetic energy

3. Need carefully designed shielding and cell to reduce background from 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.

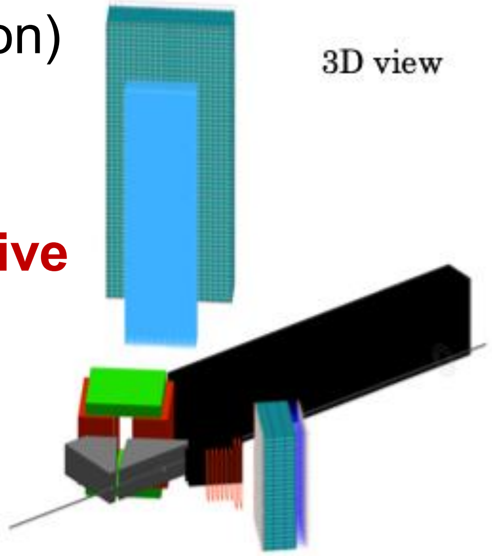


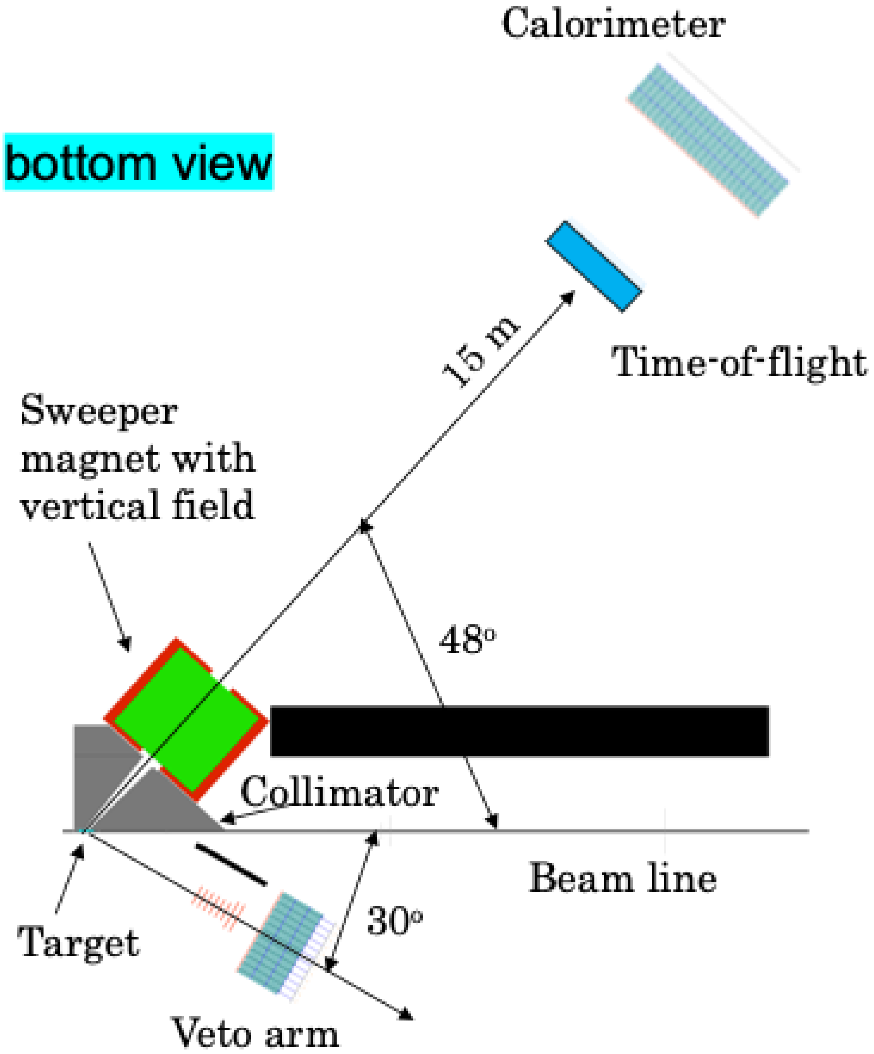
Experimental Setup

- Neutron arm:
  - ➢ Sweeper magnet
  - ➢ 1540 6cm x 6cm x 200cm long scintillator bars for nTof
  - ➢ Large NCal 2.5m downstream of nTof

- Veto arm
  - ➢ 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**
  - ➢ W shielding, block cell windows





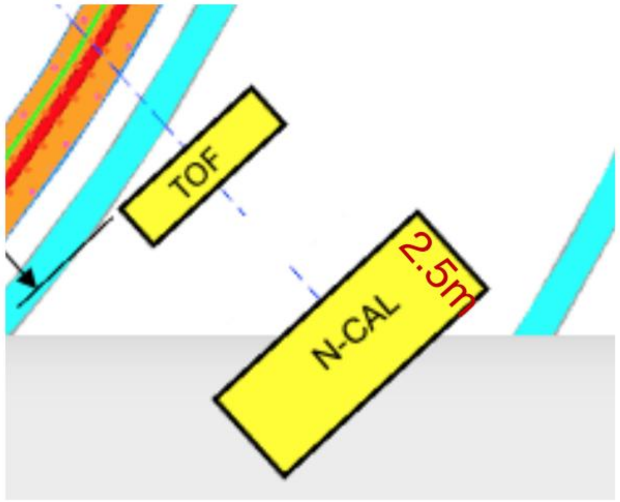
Using NCal + TOF to Determine Beam Bunch

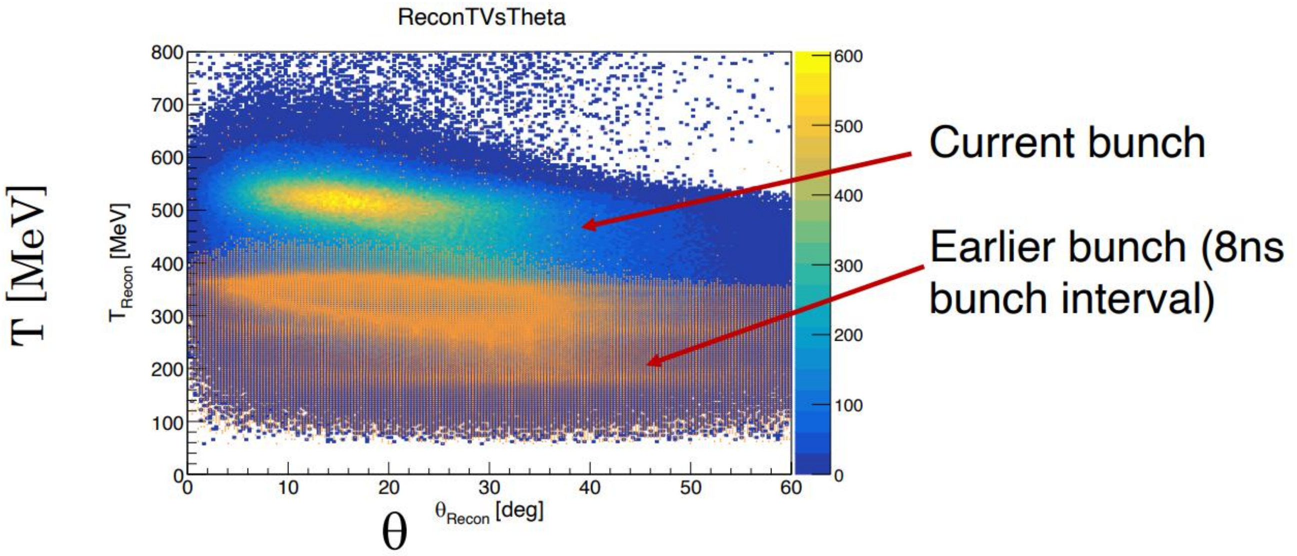
- Only detectable particle is neutron, detected using TOF
- At T_n~500MeV: $\Delta T_n \pm$ 200MeV ⇒ Δt ~10-15ns, larger than typically bunch spacing
- 350MeV *n* from 8ns earlier bunch arrive the same time as 525MeV *n* from current bunch
  - ➢ ~60% energy resolution of calorimetry cannot reject events from out-of-time bunches!

➢ Development of bunch identification technique for high-luminosity requirement

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

➢ Preliminary estimation: efficiency ~25%

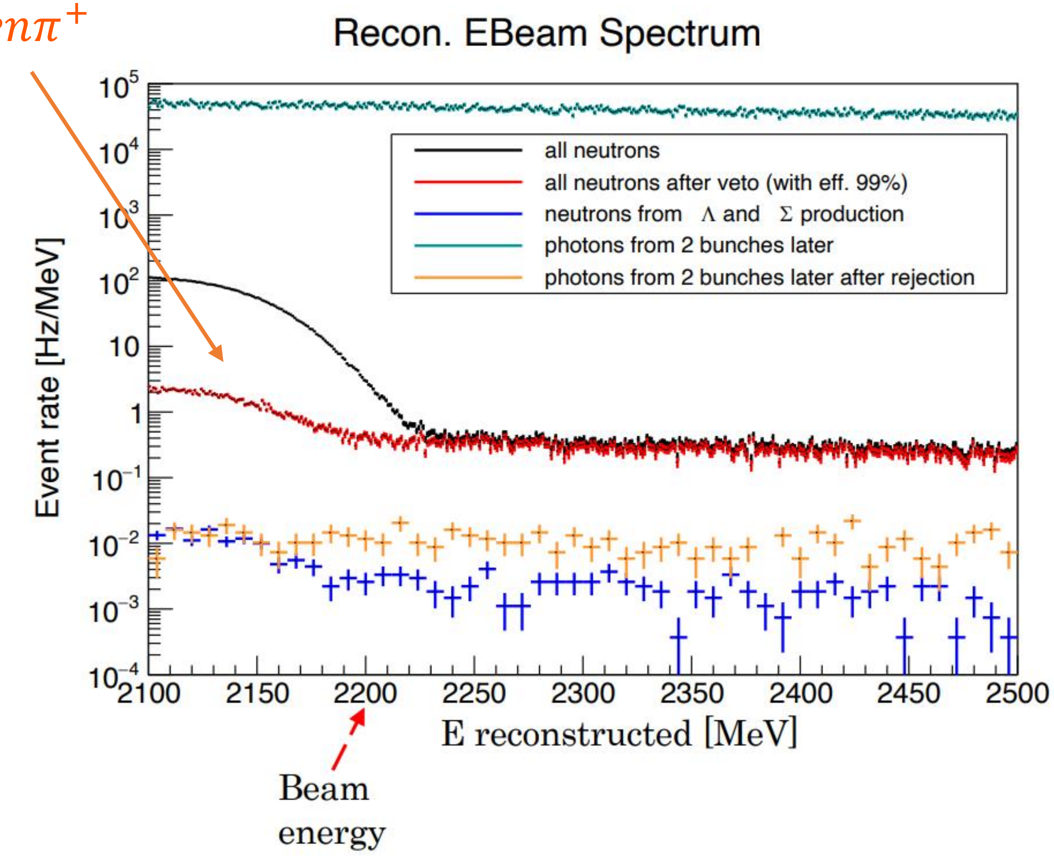


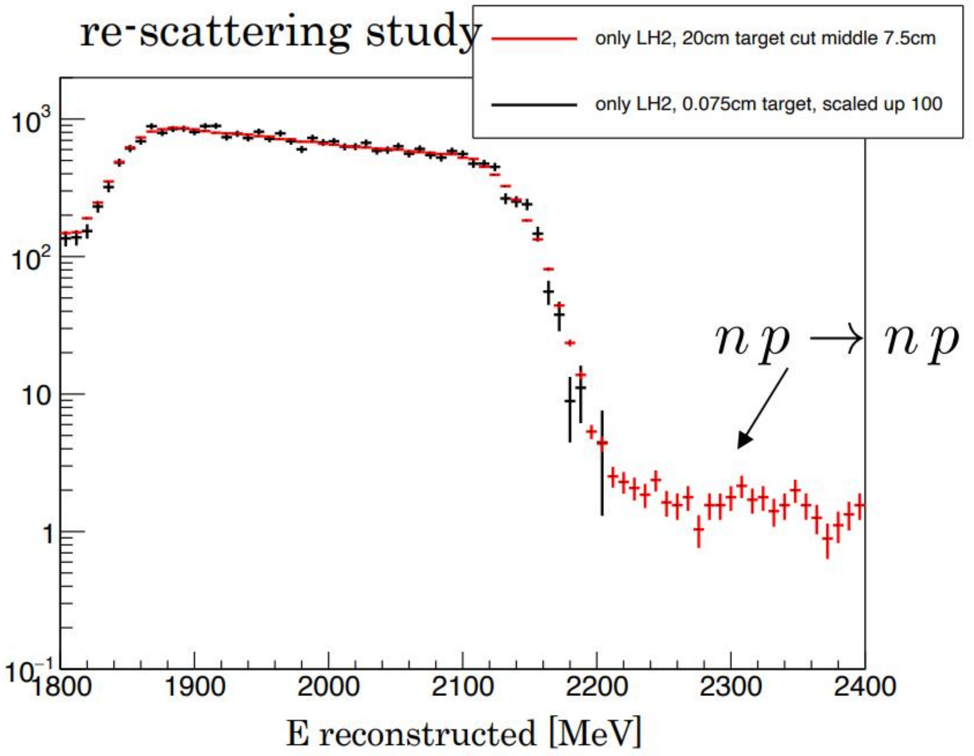


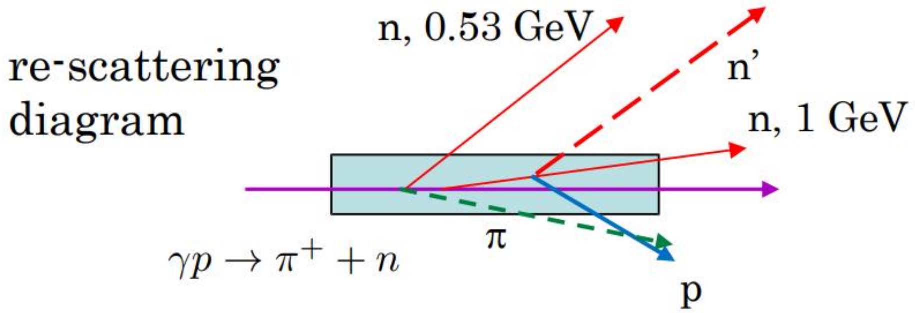
Simulation with 2.2 GeV Beam

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

Domiated by $ep \rightarrow en\pi^+$



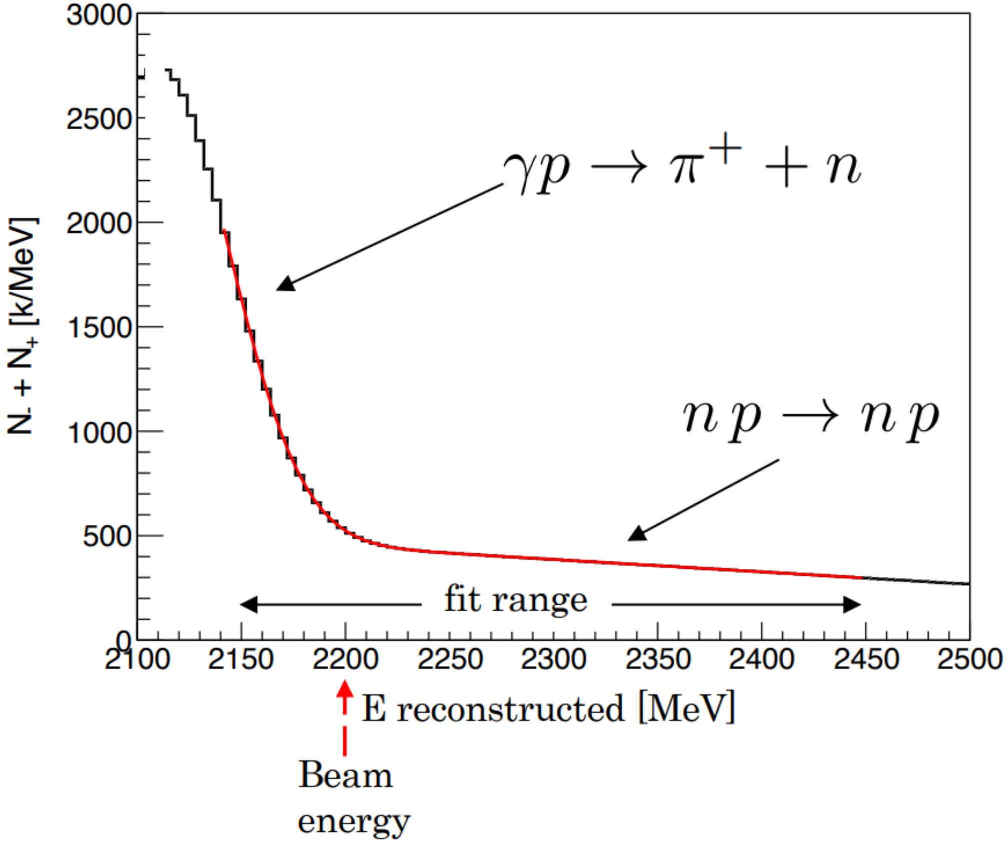




$$E_{reconst} = \frac{E_n - (M_p^2 + M_n^2)/2M_p}{1 + (P_n \cos\theta_n - E_n)/M_m}$$

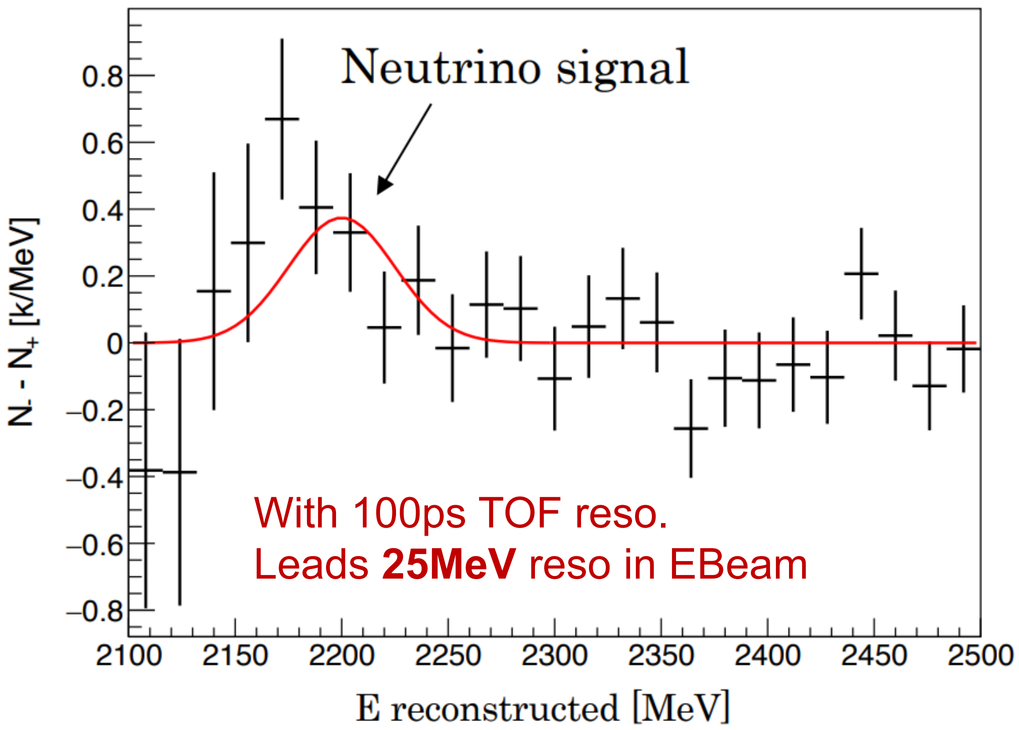
Simulation with 2.2 GeV Beam

Fitting method



Fit function has three components:
1. Signal (gaussian shape)
2. Background (gaussian tail)
3. Background (linear)

Bin-by-bin subtraction method



50 days of data taking, 120 μA

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

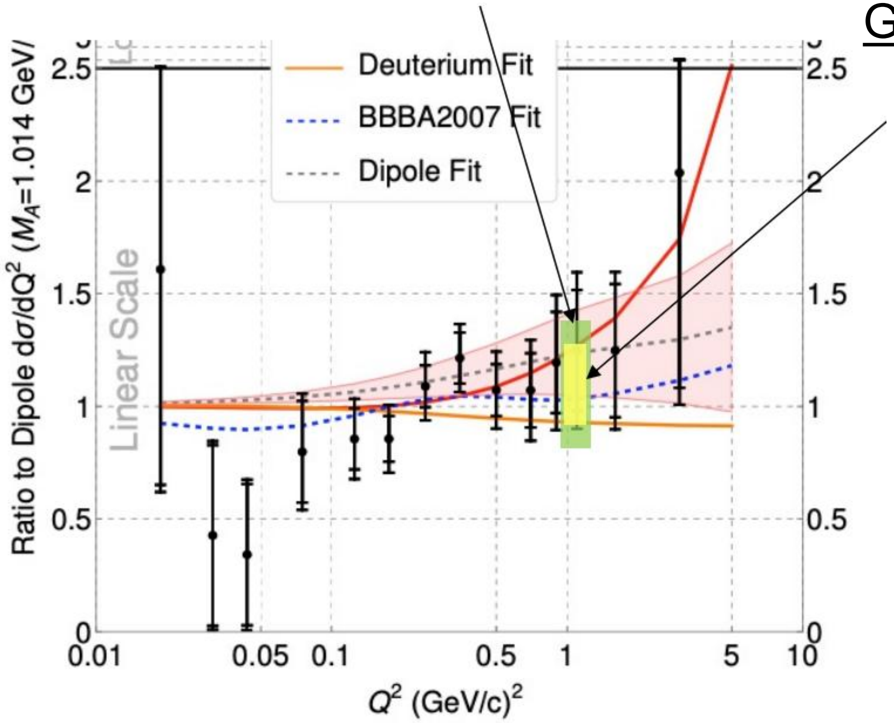
Signal = 19k +/- 6.5k events

Simulation with 2.2 GeV Beam

- 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

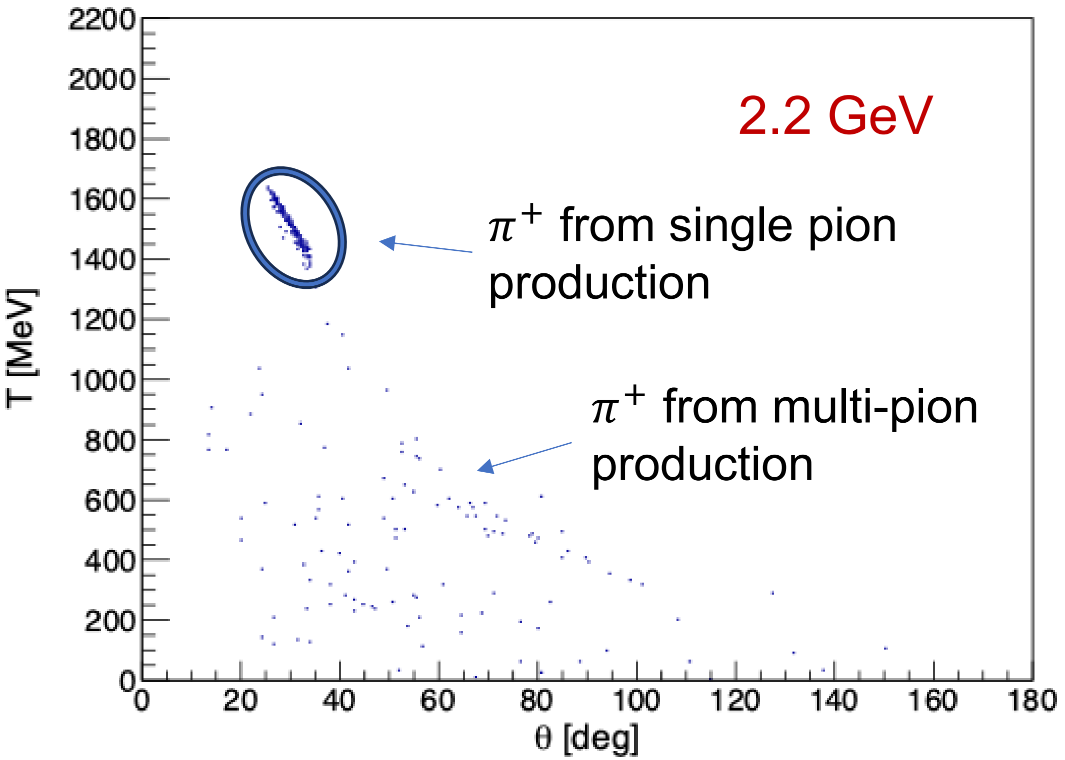


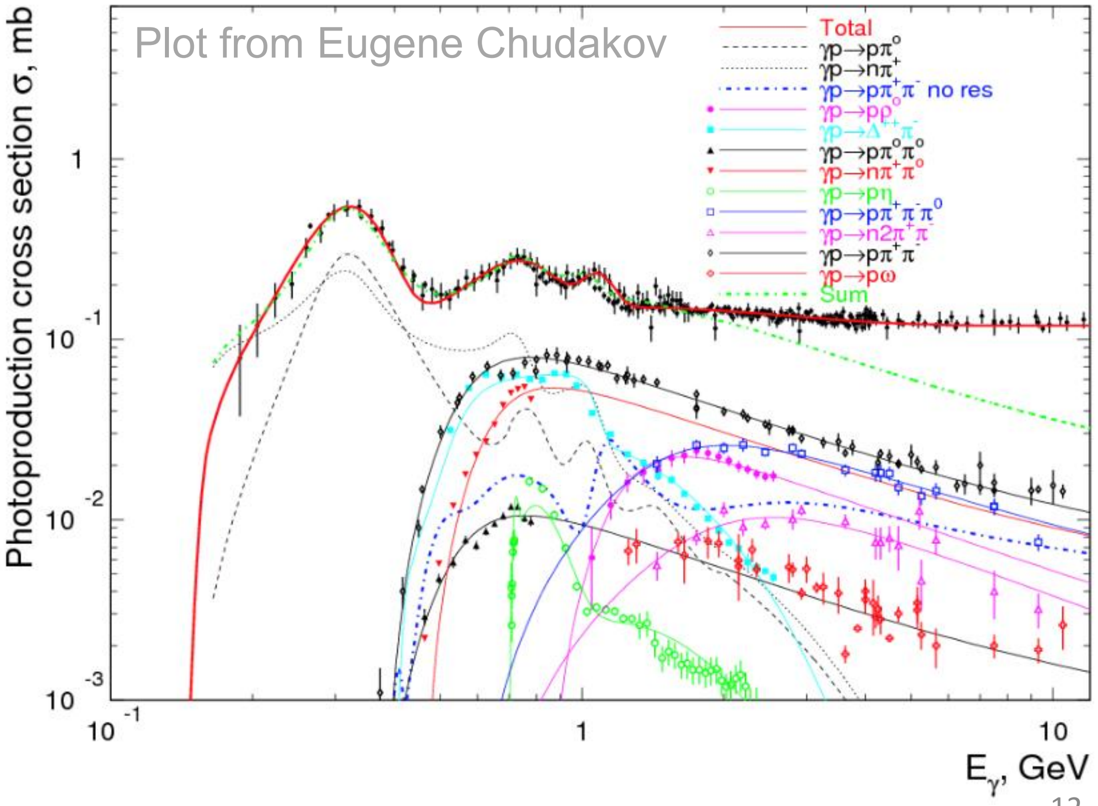
Event type	Rate Hz, all cuts 310 MeV range	Total events	Asymmetry events	Accuracy, contr. frac
p(e,n)υ	0.0044	19k	1.0	
$\Lambda + \Sigma$	0.23	1M	~0.03	0.06
$\pi^+ + n$	34.5	150M	$< 10^{-6}$	< 0.01
Detector syst.	efficiency, $\Delta\Omega$, ...			0.05
Statistics				0.34
Stat. + syst.				0.35

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

Further Improvement

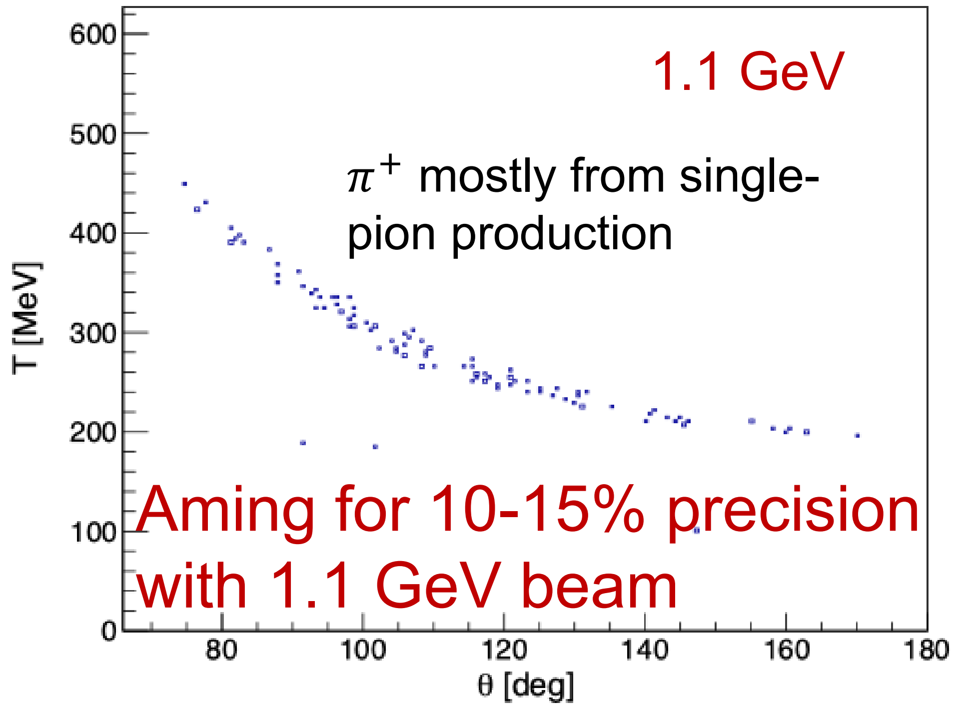
- We recognize even with 25% accuracy, the measurement is not impressive
- At 2.2 GeV beam energy, a major issue is the multi-pion production
- However, there are still things we can improve: Use of lower beam energy, detector development, shielding design…

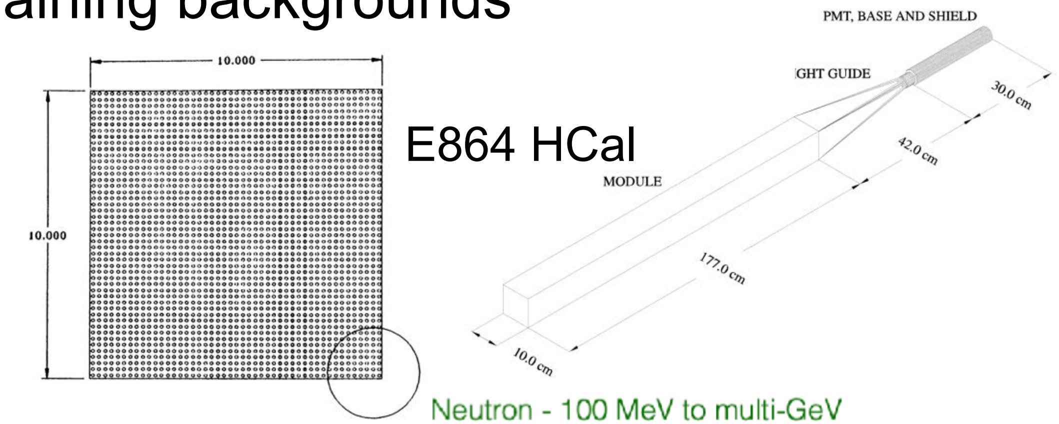


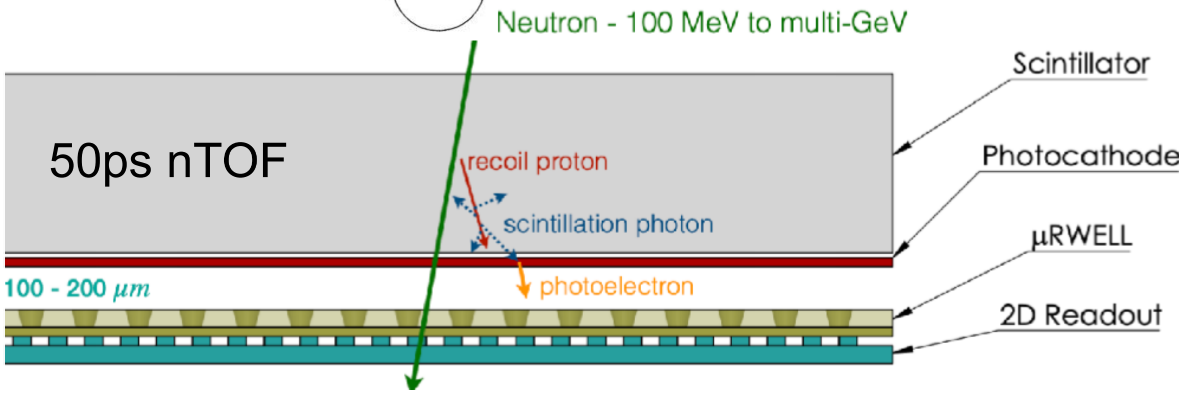


Further Improvement

- With 1.1 GeV beam, EBeam reso. 5 times better than 2.2 GeV
- At 30 deg neutron angle, $Q^2 \sim 1 GeV^2$, signal rate about the same
- 1.1 GeV beam energy has significant advantage in reducing multi-pion and Λ production
- Single-pion production can be easily vetoed
- Hardware developing: 50ps neutron TOF and ~400ps NCal based on E864-type HCal
- Optimized shielding allow to reduce remaining backgrounds

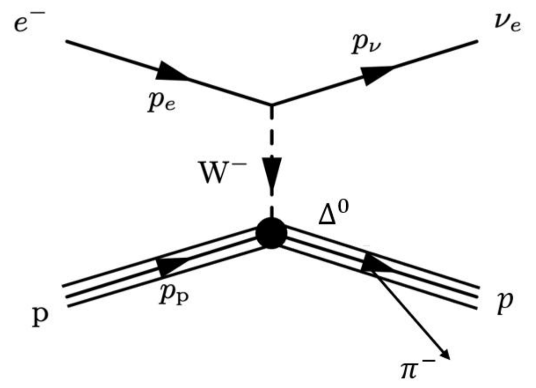






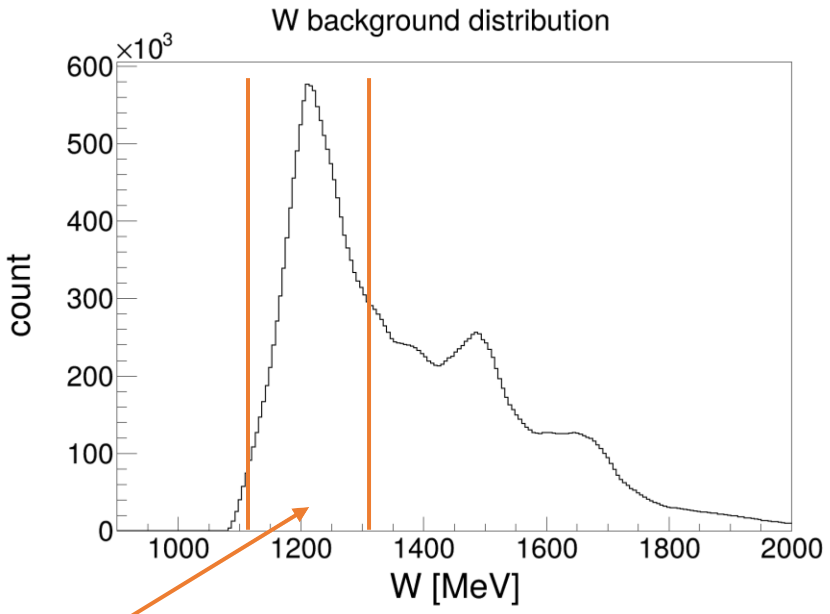
Possibility of Measuring tAVFF using $ep \rightarrow v_e \Delta^0 \rightarrow v_e p \pi^-$

- Lessons learned from the AVFF study:
  1. Excellent Ebeam resolution is essential!
  2. Re-scattering background is serious problem
  3. Shielding cell windows is highly non-trivial (shielding produces backgrounds too)



- $\Delta^0 \rightarrow p\pi^-$ gives two charged particles in the final state:
  - ➢ Better resolution (mom., angles, timing), can reconstruct vertex positron

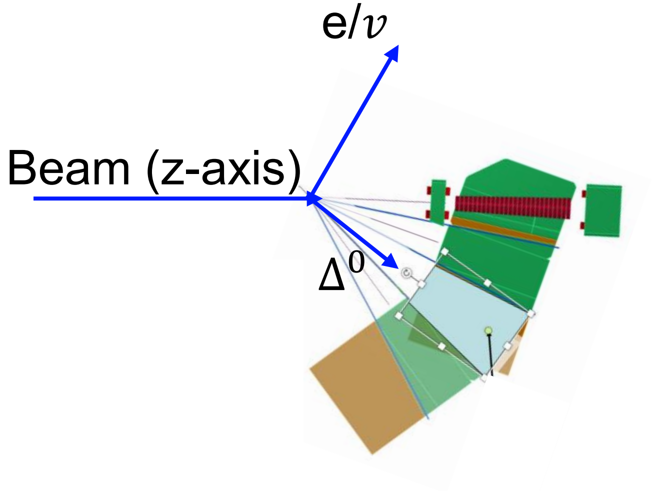
- Use Hall B genKYandOnePion generator to study the Δ^0
  - The generator is for $ep \rightarrow e\pi^+ n$, only used to study kinematics



These events from Δ^0 kinematic studies

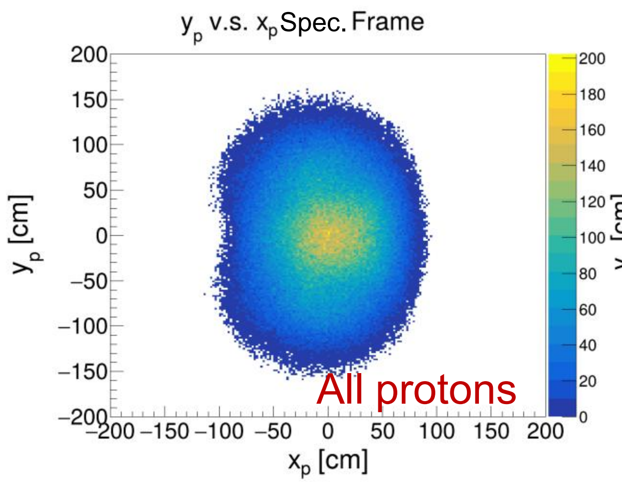
Acceptance for $\Delta^0 \rightarrow p\pi^-$

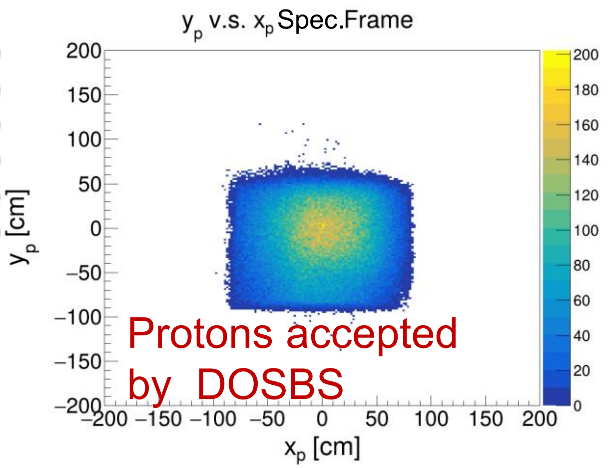
- With 2.2 GeV beam, Δ^0 @ Q^2 = 1.3 GeV^2 has around 1500 MeV momentum, $\theta_\Delta \sim 28^o$, $\theta_e \sim 47^o$
  - ➢ Decayed p and π^- has ~ 800 MeV momentum, with large opening angle, need large acc. Spectrometer such as DOSBS (will be presented by Bogdan in this afternoon)
  - ➢ So far, best way seems to be putting DOSBS exactly at the Δ^0 scattering angle
  - ➢ Getting ~12% acceptance for Δ^0

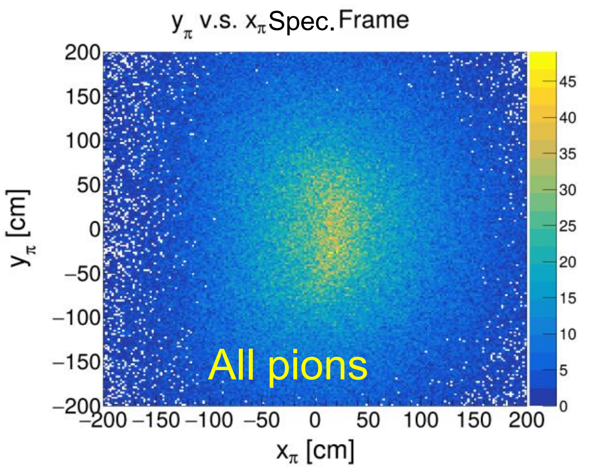


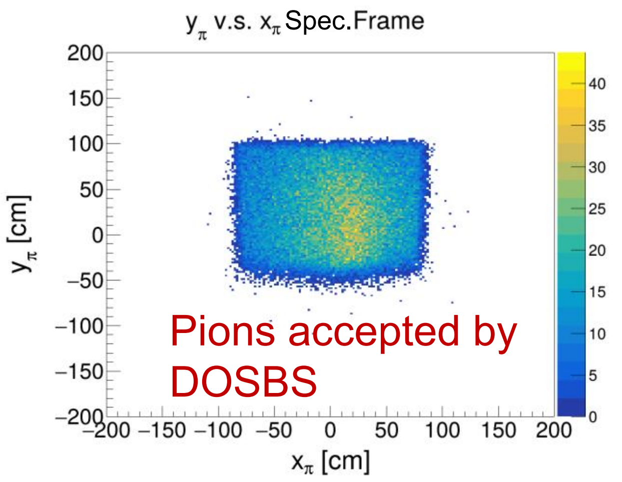
Assuming $\theta_{e'}$ from 37 to 57 deg, $|\varphi_{e'}| < 27^o$

Coordinates shown in spectrometer frame (z-axis along center of DOSBS)







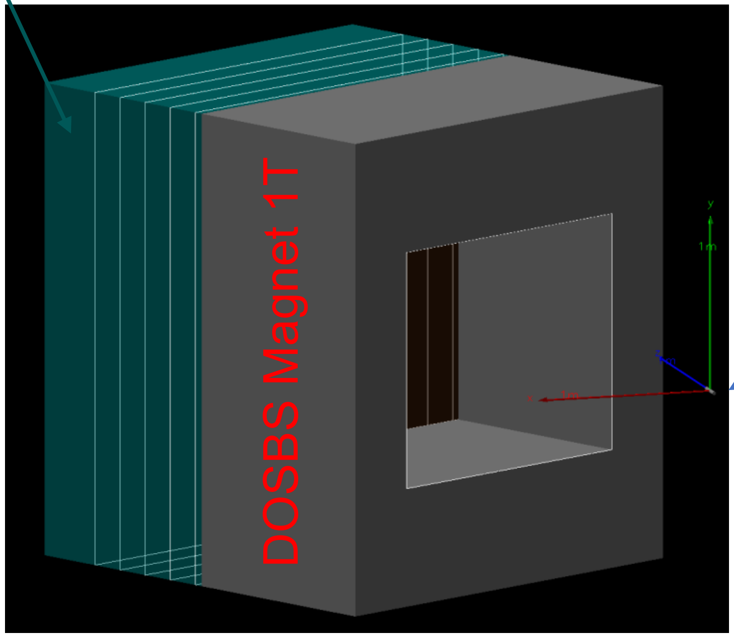


Detector Setup And Resolution

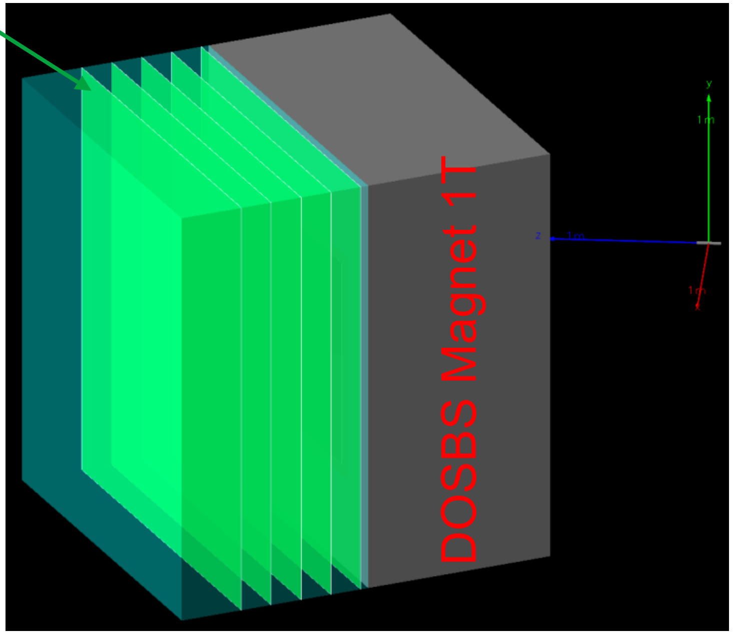
- Decayed p and π^- has ~ 800 MeV momentum, large multiple scattering effect, need to reduce material
  - Need to replace GEMs with low-mass MWDC ($X_0 < 0.1\%$)
  - Vacuum chamber from target to back of DOSBS, thin Kapton window (0.2-0.5mm thickness)
  - ^{4}He bags between MWDC
- A Simple G4 program to estimate the resolution

20cm thickness ^{4}He bags, 5 bags in total

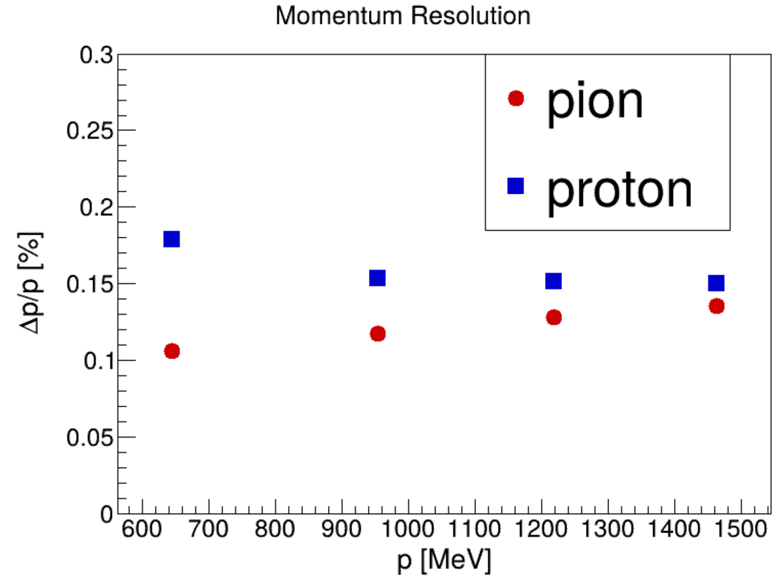
5 MWDC ($X_0 \sim 0.03\%$), 20cm separation, 100um pos resolution

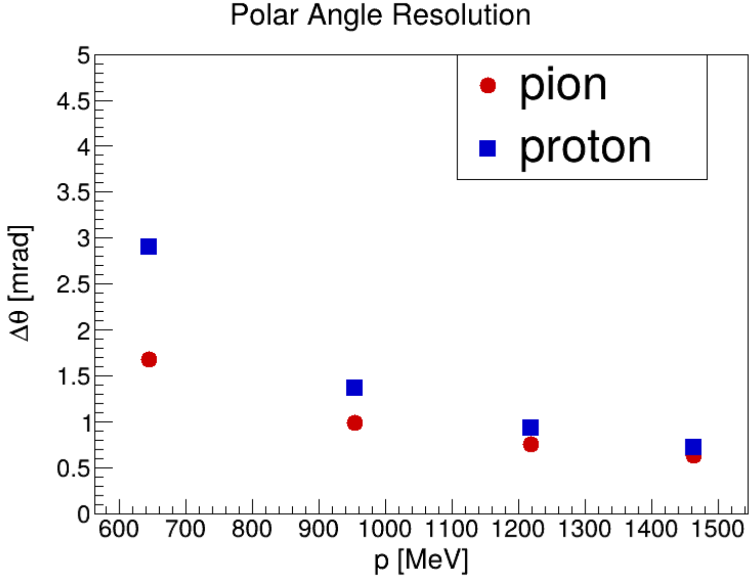


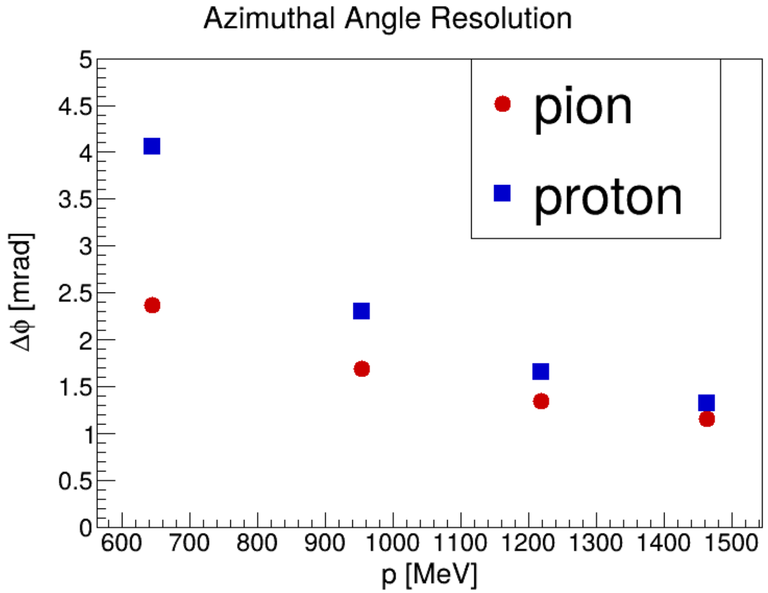
Target: 15cm LH2,
100um Al windows,
100um Al wall

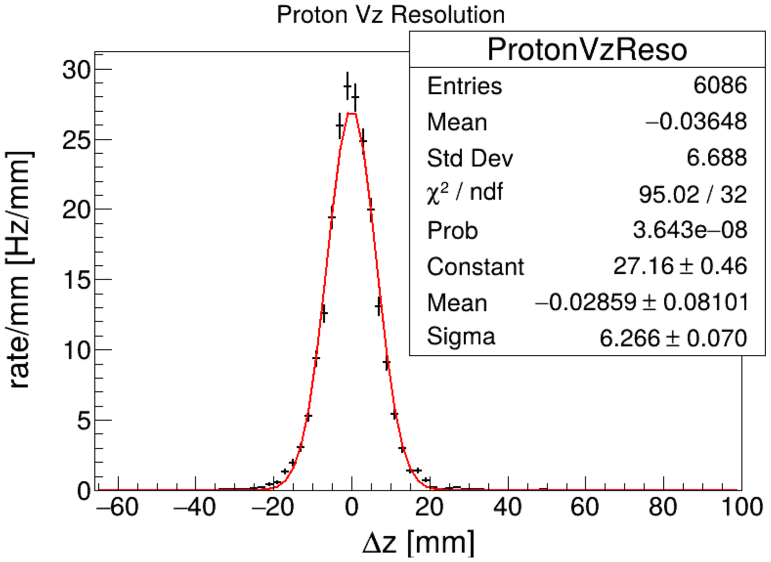


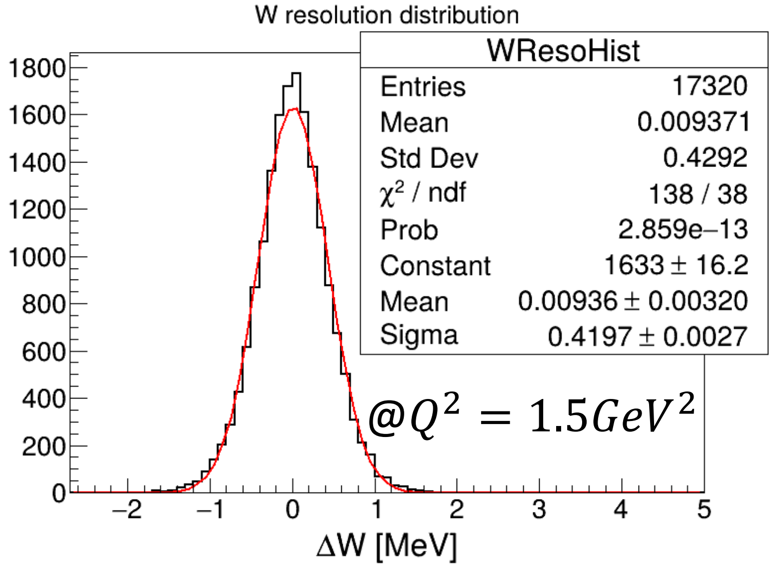
Detector Setup And Resolution

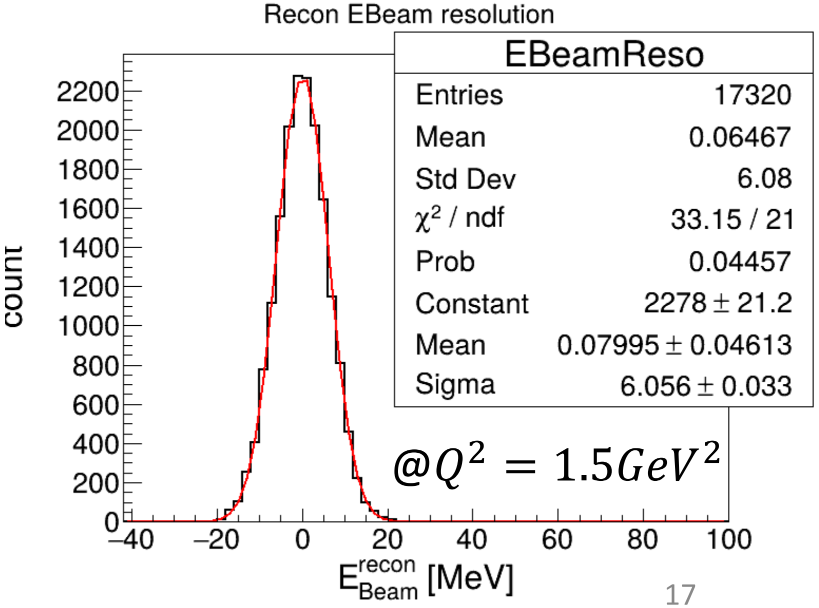






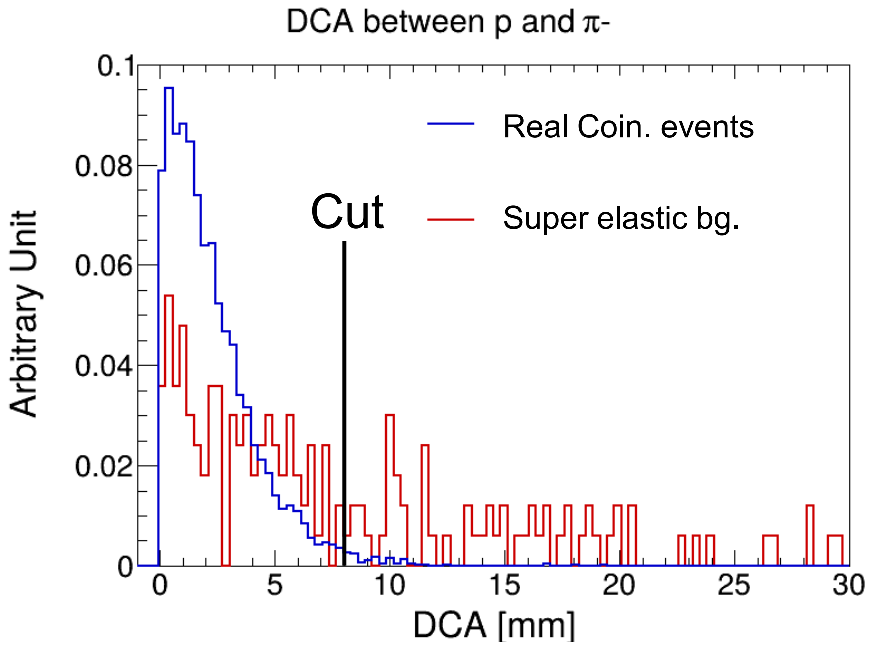


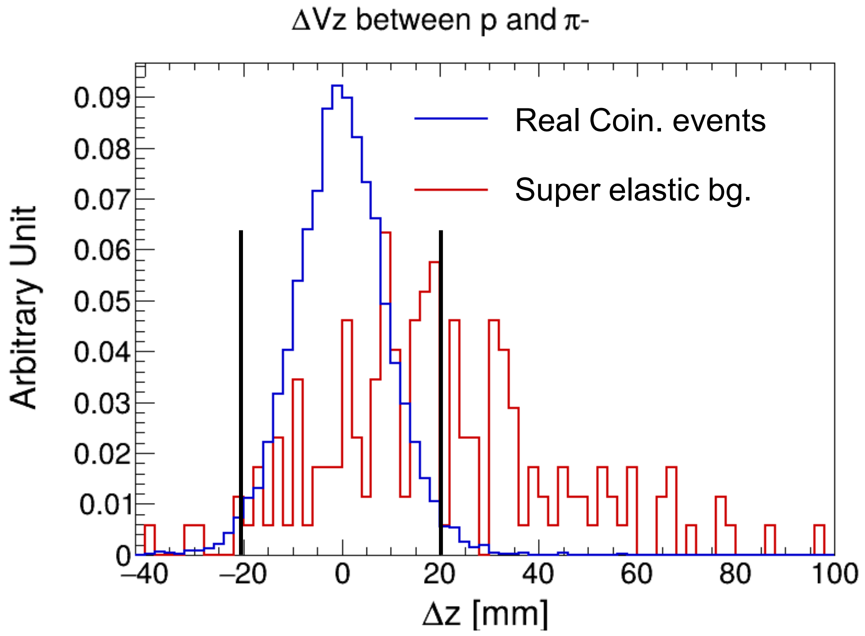


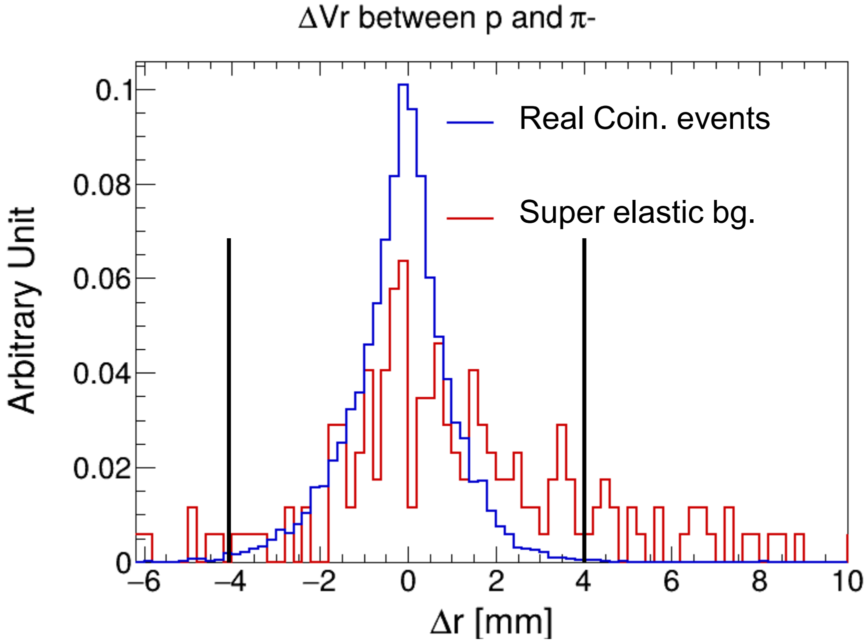


Coincidence Vertex Cut

- With 2 charged tracks, we can do coincidence vertex to reject re-scattering events
  - Something we cannot do previously with neutrons
  - Super elastic background tend to be much wider than events with real coincident vertex







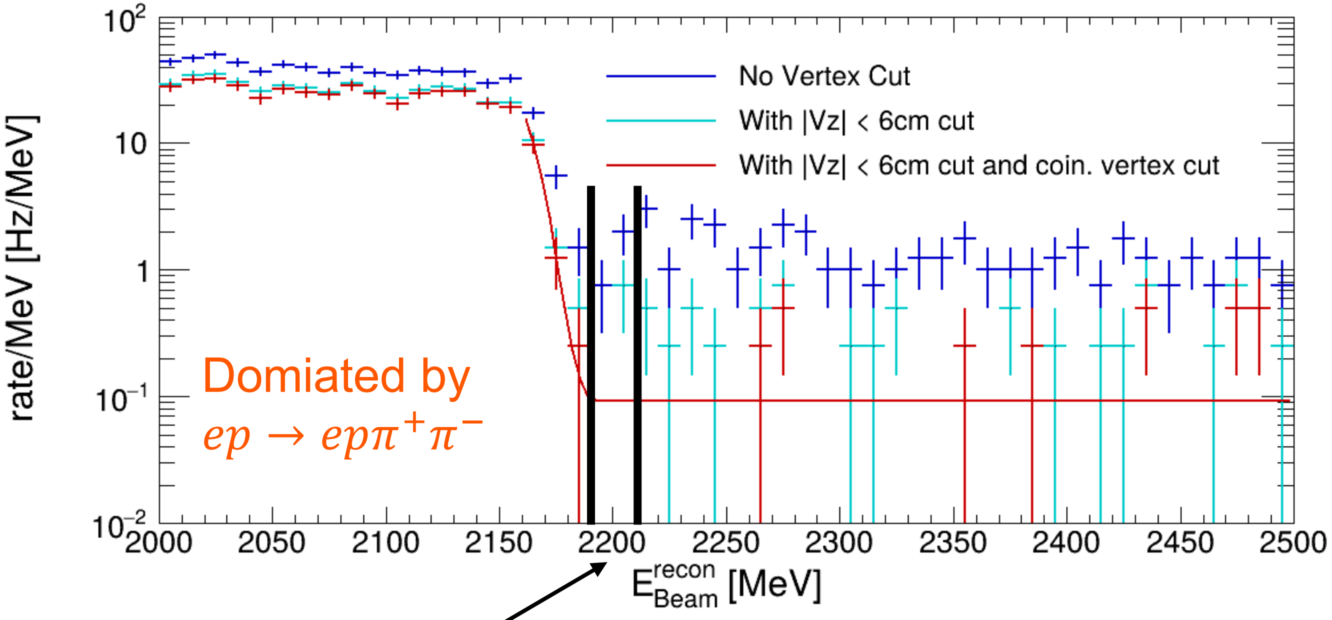
Reconstructed Ebeam Distribution

- Ebeam can be reconstructed using formula

$$E^{rec}_{beam} = \frac{2M_P\tilde{E}_\Delta - M_P^2 - \tilde{m}_\Delta^2}{2M_P + 2(\tilde{p}_\Delta \cdot \cos(\tilde{\theta}_\Delta) - \tilde{E}_\Delta)}$$

Var with ~ from recon

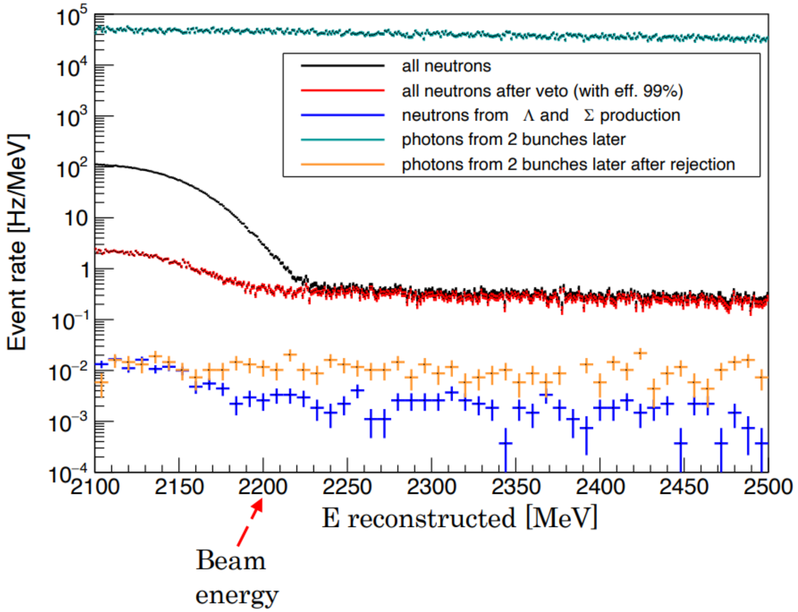
- EBeam resolution ~7MeV
- Background rate under signal: 0.09Hz/MeV
- Using a simplified BOT simulation, only target, cut on particle angles and momentum (for now)



Our signal will be mostly here

From $ep \to \nu_e n$ study

- Ebeam resolution: ~25 MeV
- Background rate under signal: ~0.4Hz/MeV



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
  - ➢ higher stat. per year of running, but very significant amount of background

- Goal: 10-15% stat. uncertainty, <5% syst. uncertainty, with 2 months running at 120uA @ 1.1 GeV at JLab

- Still working on various potential improvements (and problems)
  - Optimization of shielding, target cell, TOF, and neutron efficiency, beam energy

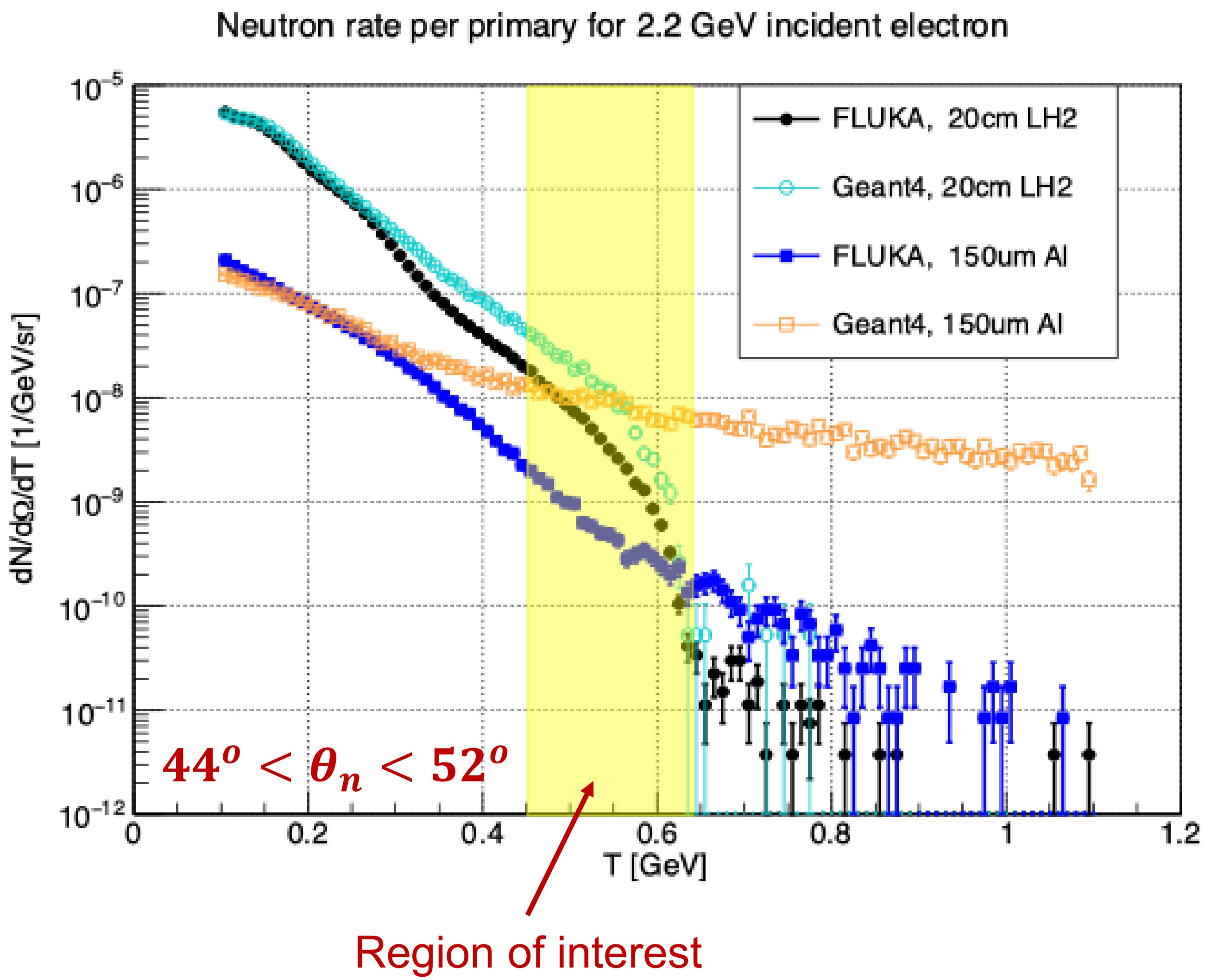
- Exploited the possibility of measuring $\Delta^0 \rightarrow p\pi^-$ AV transition FF using DOSBS setup
  - ➢ Results look promising, aiming for LOI in 2026 and proposal in 2027

Special thanks to Pavel Degtiarenko for suggesting the idea of tAVFF and agree to join the LOI

Backup

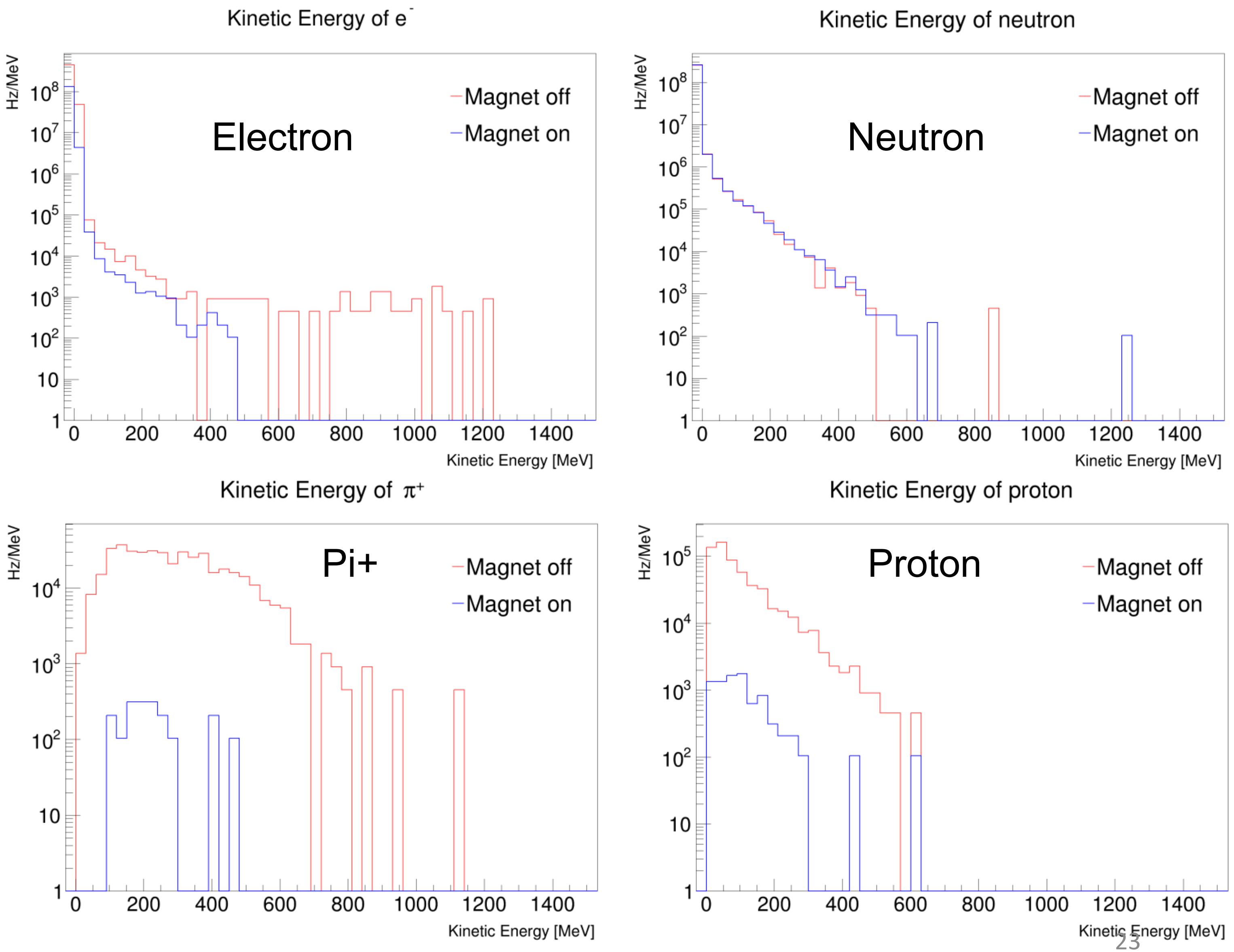
Simulation Comparison between G4 And FLUKA

- 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
- Some beam test results would be useful



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



Trigger logic and analysis steps

Rates:

1. Large amplitude signal in the calorimeter (NCAL) (100 MeV) — 25 MHz
   - Removed low energy neutrons and most prompt photons
2. Veto if the signal in veto arm (HCAL) above 650 MeV — 0.25 MHz
3. Time-of-flight system hit correlated in time/position with NCAL
   - Record the event if TOF/NCAL within 10 ns and 0.25 m^2 — 25 kHz
4. TOF vs. NCAL time for the beam bunch identification
   - Remove event if incorrect beam bunch
5. Beam energy reconstruction
6. Helicity correlated signal at 2200 MeV

Introduction - Elastic CC Cross Section Formalism – P. Kroll

Cross Section for unpolarized electron scattering

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

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

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

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

$$\text{where, } F_{1,2}^{(3)}(t) = F^p_{1,2}(t) - F^n_{1,2}(t)$$

$$F_A^{(3)}(t)$$

- Axial Vector Form Factor
- 50% of cross section

Polarized beam:

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

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

$m =$ nucleon mass

$t = -Q^2$

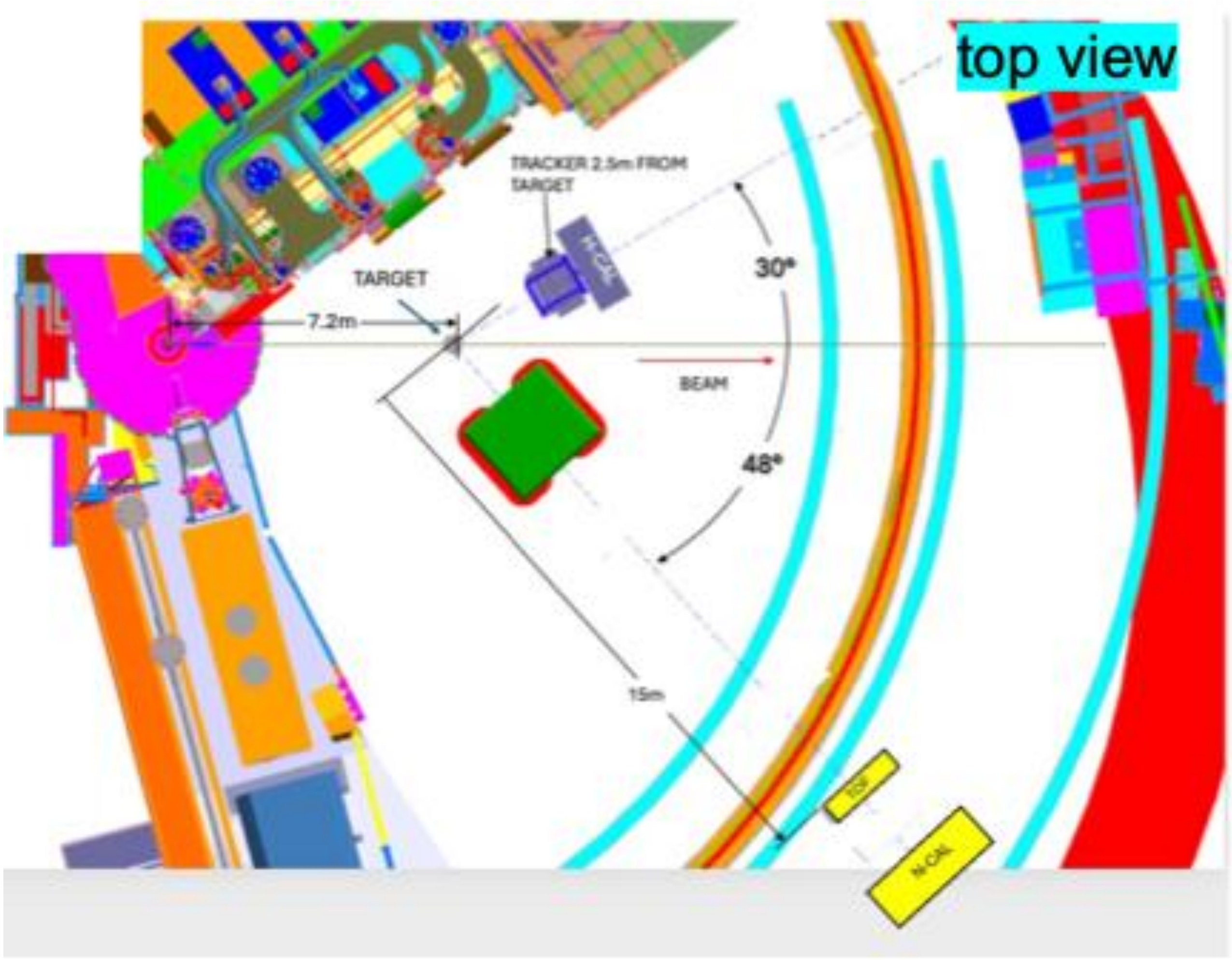
$s = (p_e + p_p)^2$

Experimental Concept

- In reality this is quite difficult…
  - Charge current cross section: $$\frac{d\sigma}{d\Omega_{\nu,lab}}\Big|_{e+p\rightarrow\nu+n} = 1.35\times10^{-39}\ \mathrm{cm}^2/\mathrm{sr}$$
- Meanwhile, background rates from other channels:
  - Elastic ep cross section: $$\frac{d\sigma}{d\Omega_{lab}}\Big|_{e+p\rightarrow e+p} = 1.4\times10^{-32}\ \mathrm{cm}^2/\mathrm{sr}$$
  - Pion electro and photo-production rate ($ep\rightarrow e\pi^+n$, $\gamma p\rightarrow\pi^+n$, $ep\rightarrow e\pi^+\pi^0n$…), should be even higher than elastic ep
  - What about aluminum cell window, quasi-elastic en, pion production in Al?

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

List of New Technology/Development

1. Using TOF + NCal for neutron bunch identification under high luminosity
2. Thin window LH2 target cell
3. High time-resolution TOF and NCal
4. Shielding design
5. Geant4/FLUKA validation

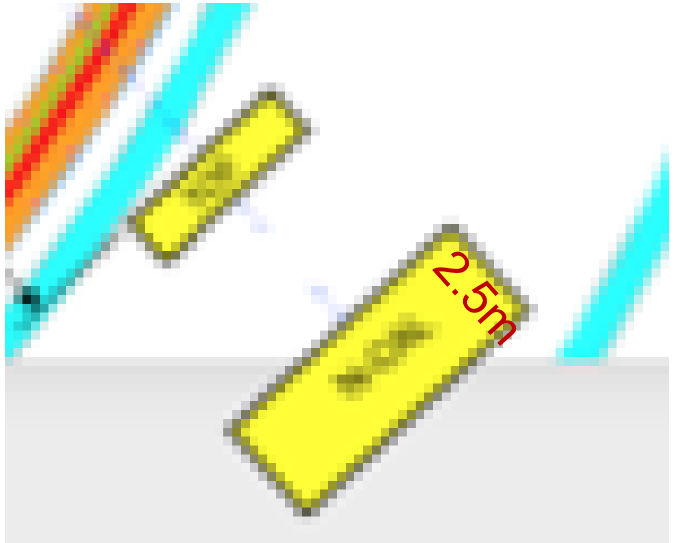
High resolution neutron spectrometer (50 ps) and experimental program based on it

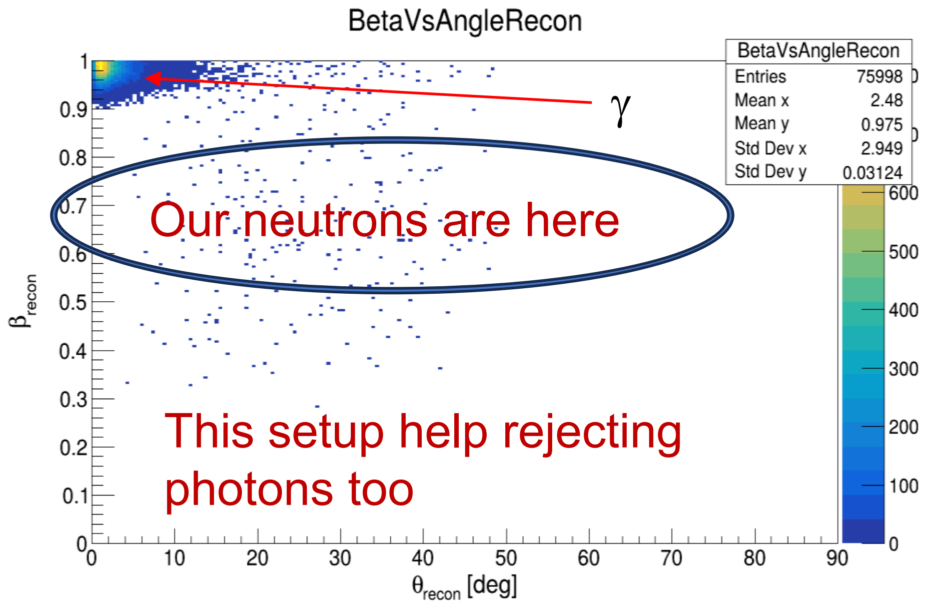
- Wide Angle Compton Scattering from neutron
- Neutron polarizabilities (real and virtual)
- Deuteron two-body split: D(γ,pn)
- Neutron Form Factors: GMn, GEn and TPE
- Axial Vector Form Factor
- Neutral pion photoproduction from neutron
- Positive pion photoproduction from proton

Using NCal + TOF to Determine Beam Bunch

- Only detectable particle is neutron, detected using TOF
- At T_n~500MeV: $\Delta T_n \pm$ 200MeV ⇒ Δt ~10-15ns, larger than typically bunch spacing
- 350MeV *n* from 8ns earlier bunch arrive the same time as 525MeV *n* from current bunch
  - ~60% energy resolution of calorimetry cannot reject events from out-of-time bunches!

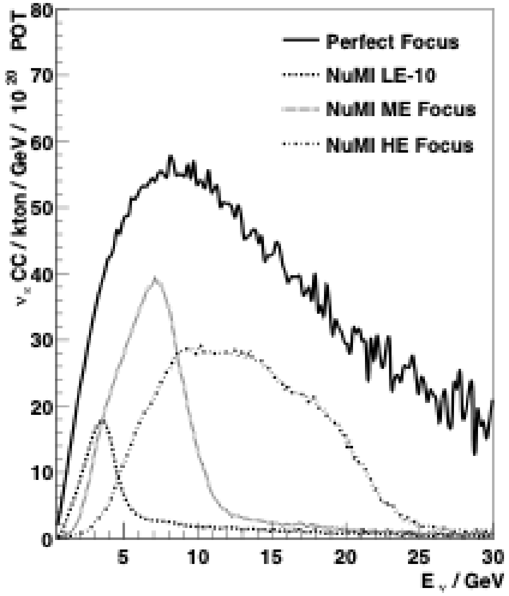
- Development of bunch identification technique for high-luminosity requirement
- Solution: move NCal 2.5m downstream, and measure beta using TOF and NCal
- Preliminary estimation: efficiency ~25%



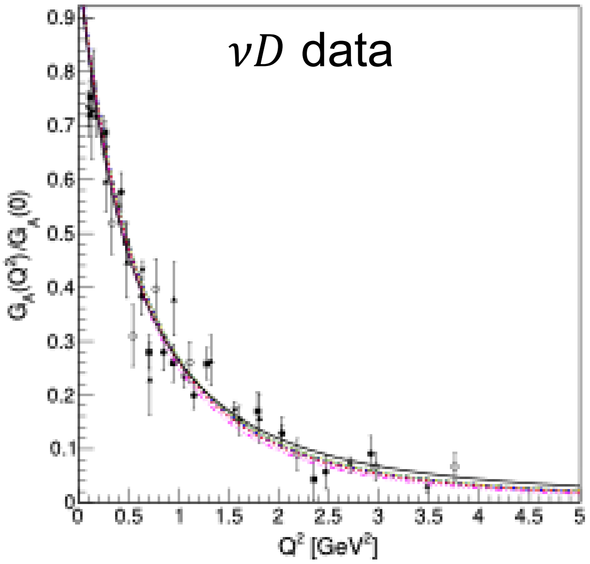


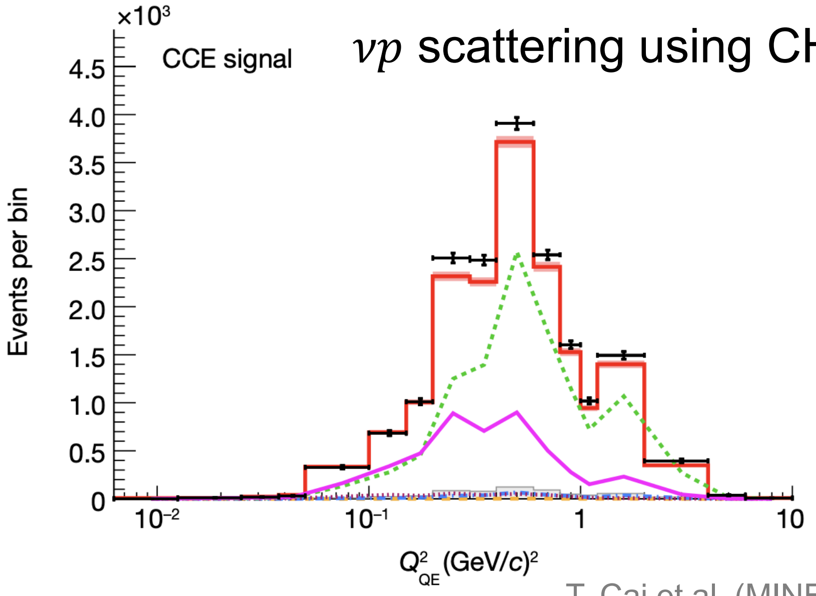
How It Was Measured Before

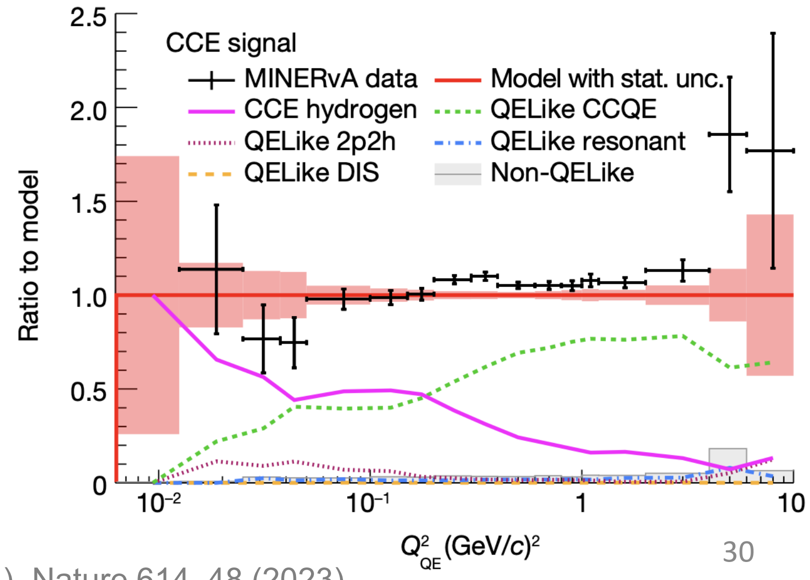
- The natural way to measure $F_A(Q^2)$ is neutrino scattering
  - ➢ νA scattering
  - ➢ νD bubble chamber experiments
  - ➢ νp scattering using plastic scintillator
- Limitations:
  1. Board range neutrino energy
  2. Usually not a free proton (nuclear effect)
  3. Large systematics



PRC 101 (2020) 2, 025501



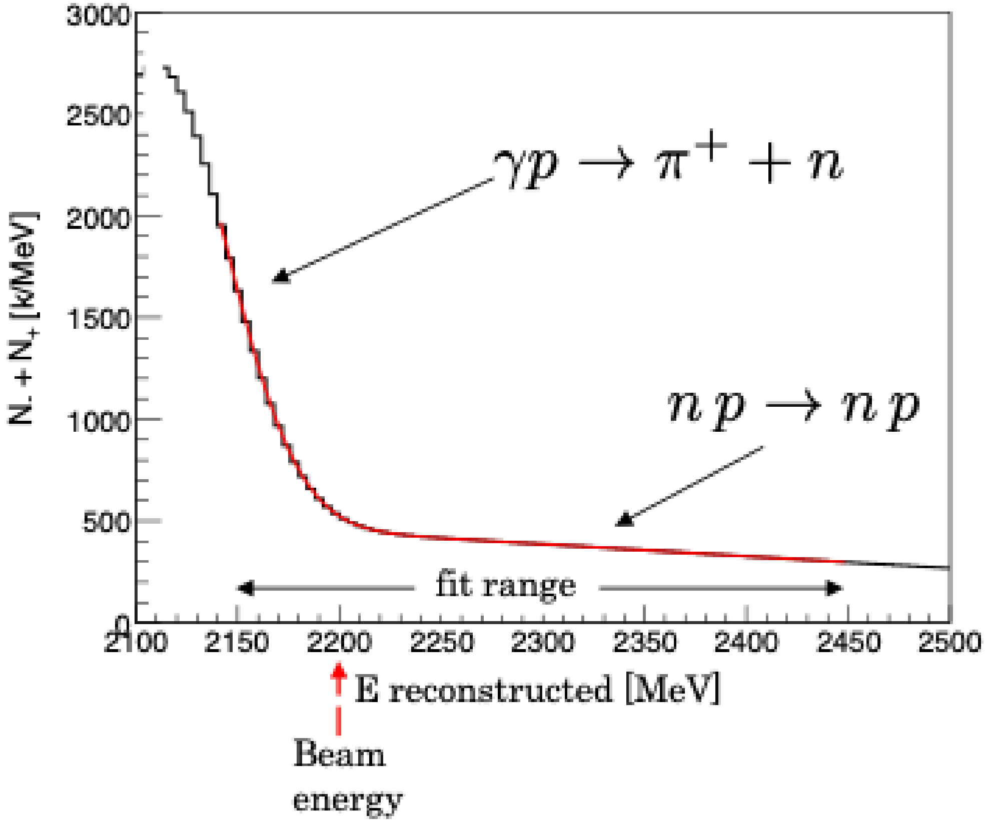




T. Cai et al. (MINERvA), Nature 614, 48 (2023)

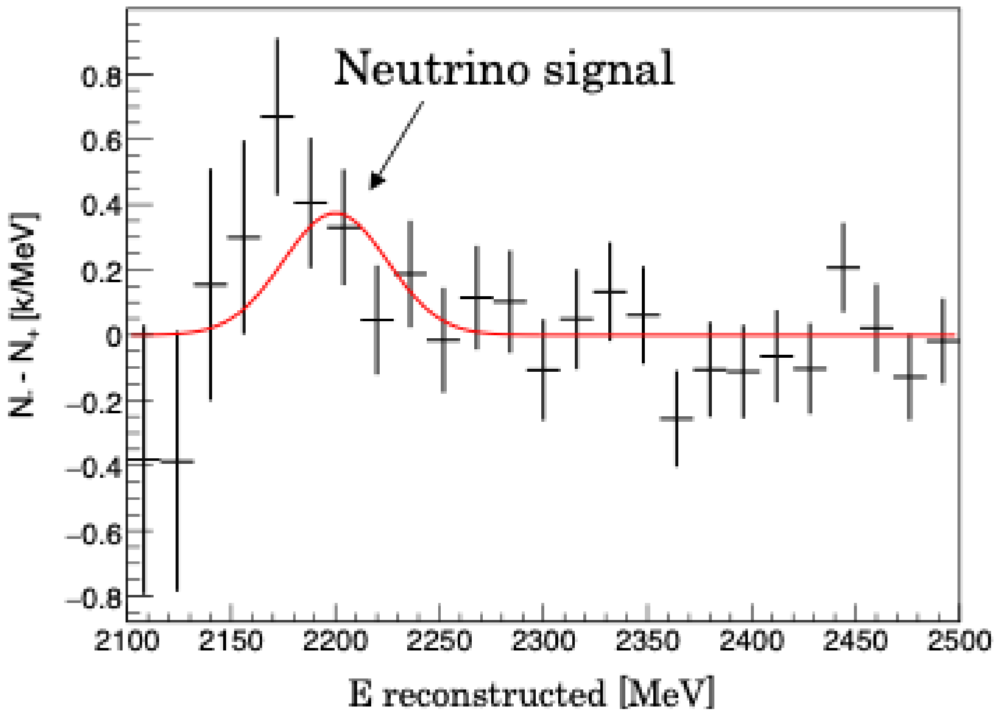
Simulation

Fitting method



Fit function has three components:
1. Signal (gaussian shape)
2. Background (gaussian tail)
3. Background (linear)

Bin-by-bin subtraction method



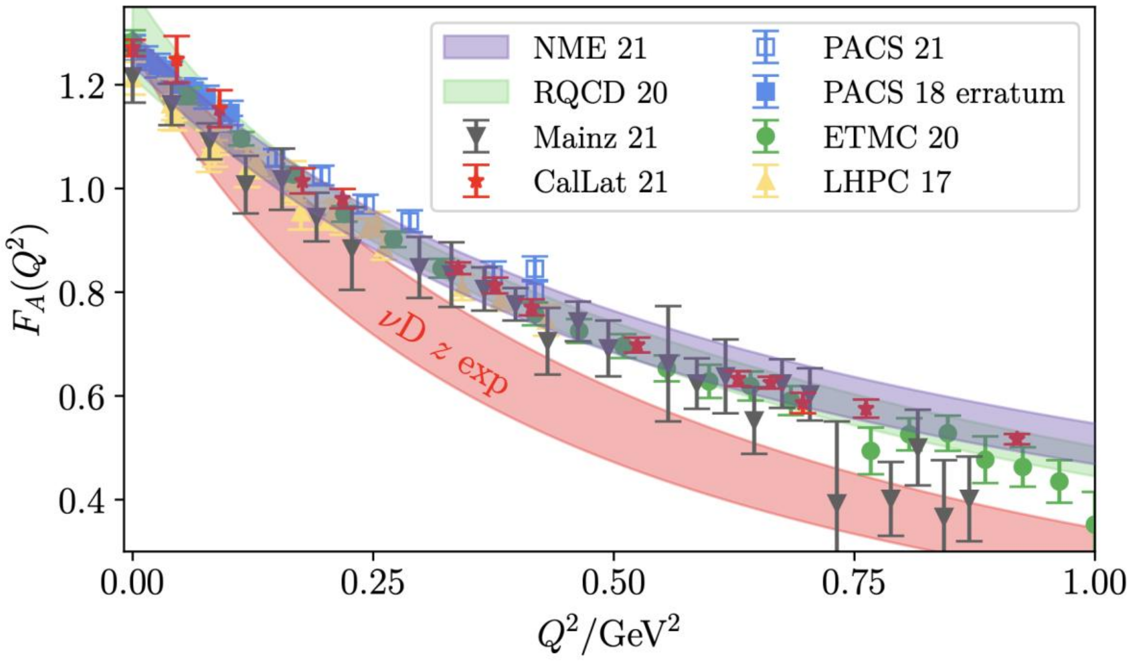
50 days of data taking, 120 μA

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

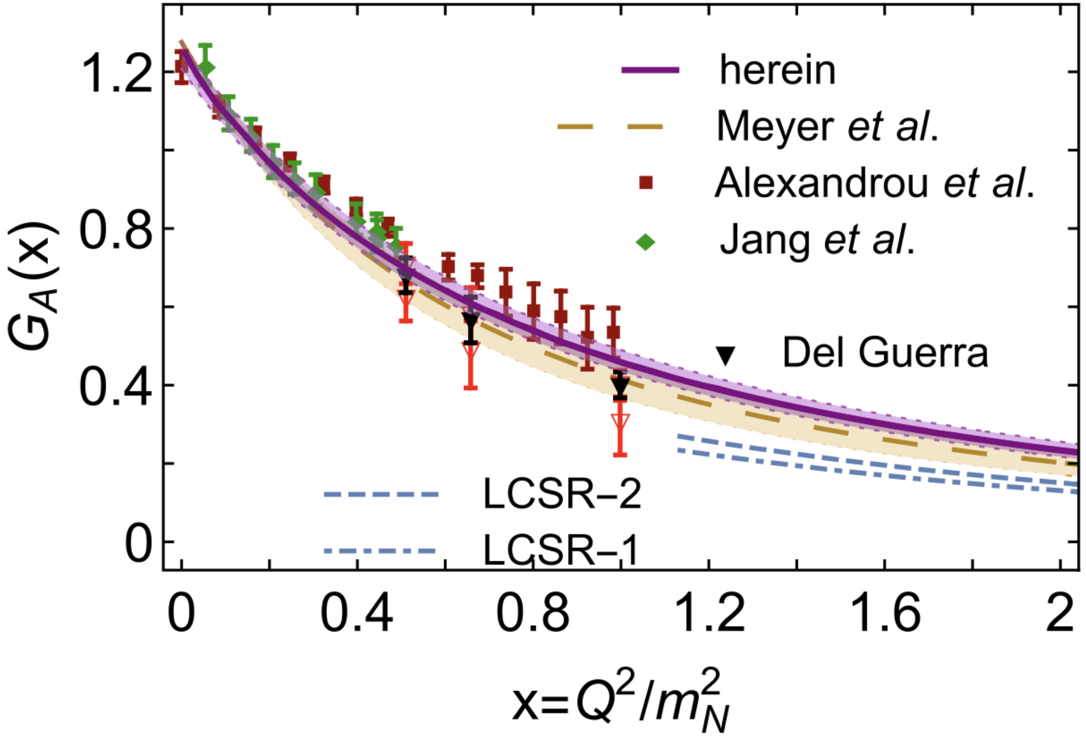
Signal = 19k +/- 6.5k events

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