A New Proposal to Measure the Nucleon Axial Vector Form Factor at Jefferson Lab

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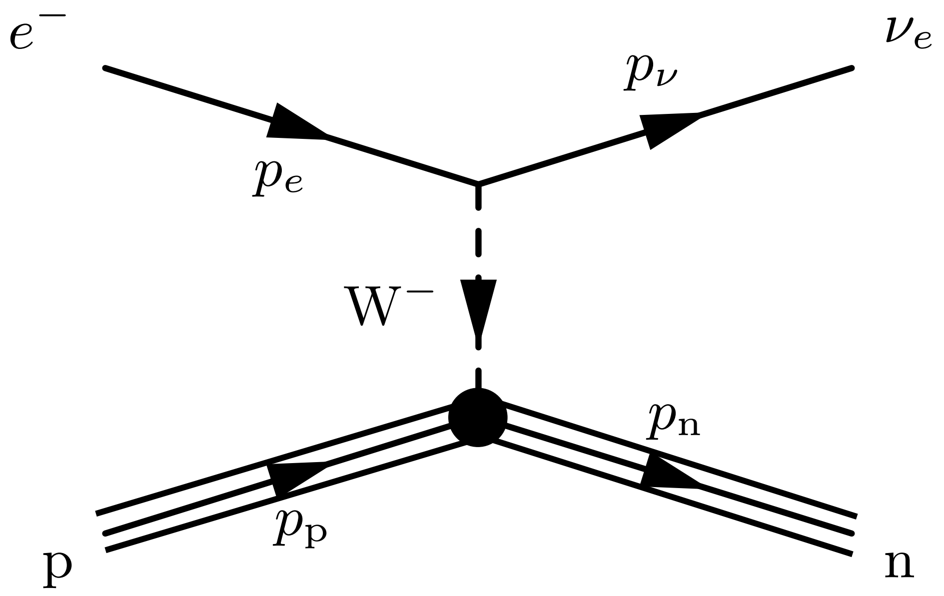
June 17th -18th 2025

JLab Hall A/C Collaboration Meeting

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 Background

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

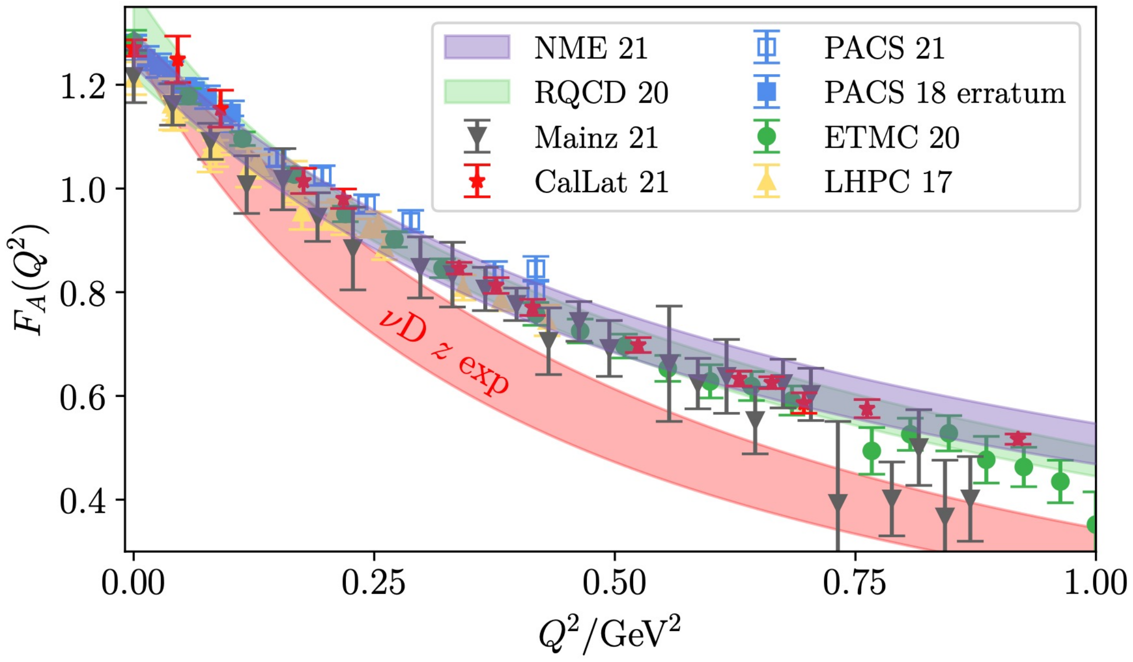
$$\langle p+q\,|\,J_A^\mu\,|\,p\rangle = \bar{u}(p+q)\left[F_A(q^2)\gamma^\mu\gamma^5 + F_{PS}(q^2)q^\mu\gamma^5\right]u(p)$$

Well measured at zero momentum transfer (beta decay).

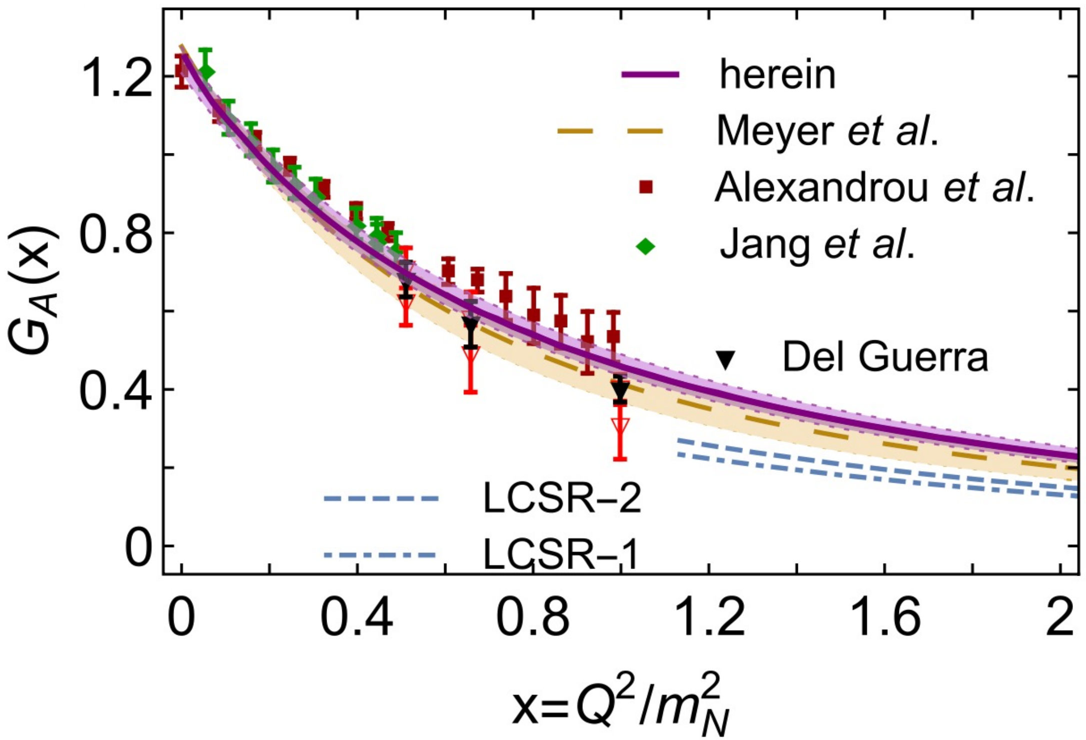
Our goal is to measure $F_A(q^2)$ at finite momentum transfer.

Physics Background

- 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 Background

(Besides being another fundamental QCD observable!)

- New constraints on Generalized Parton Distributions

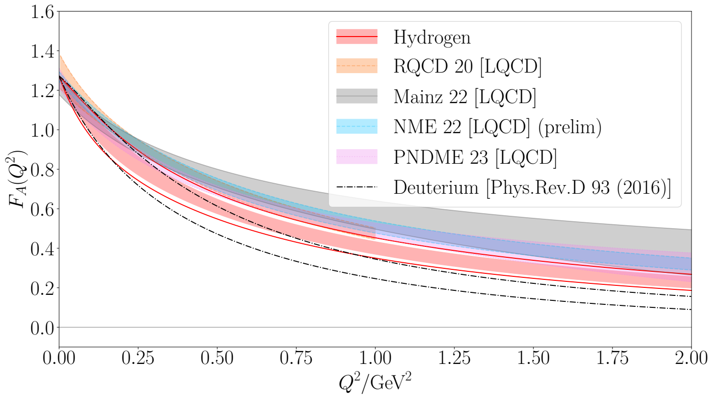
(Peter Kroll)

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

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

- Important input for DUNE and other high energy neutrino experiments

(Aaron Meyer)

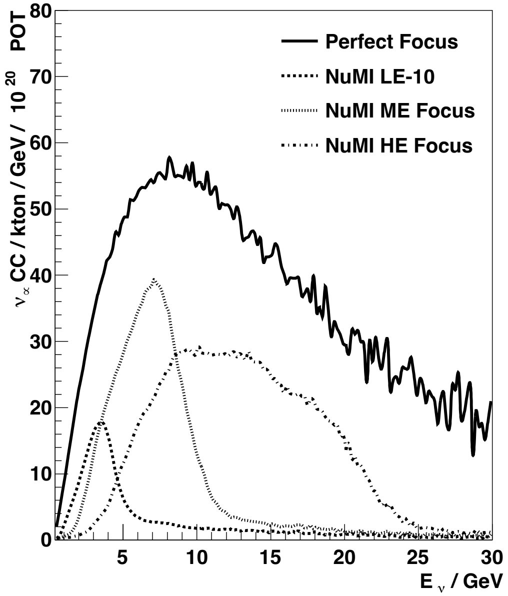


Important constraints on LQCD calculations needed to untangle neutrino oscillations in DUNE.

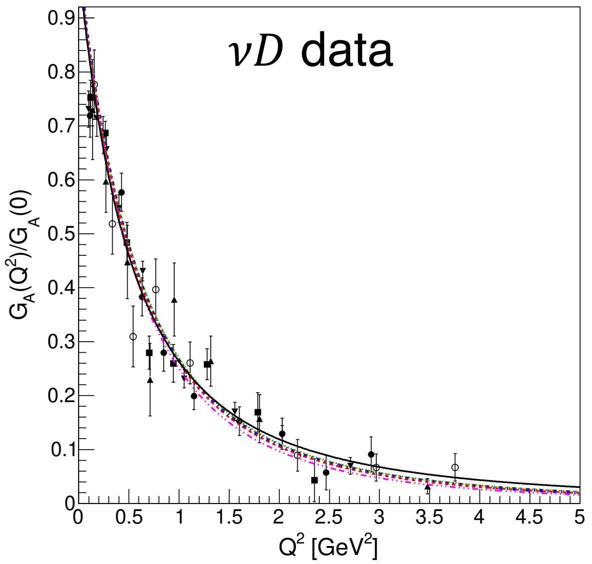
(Even a 25% measurement helps a lot.)

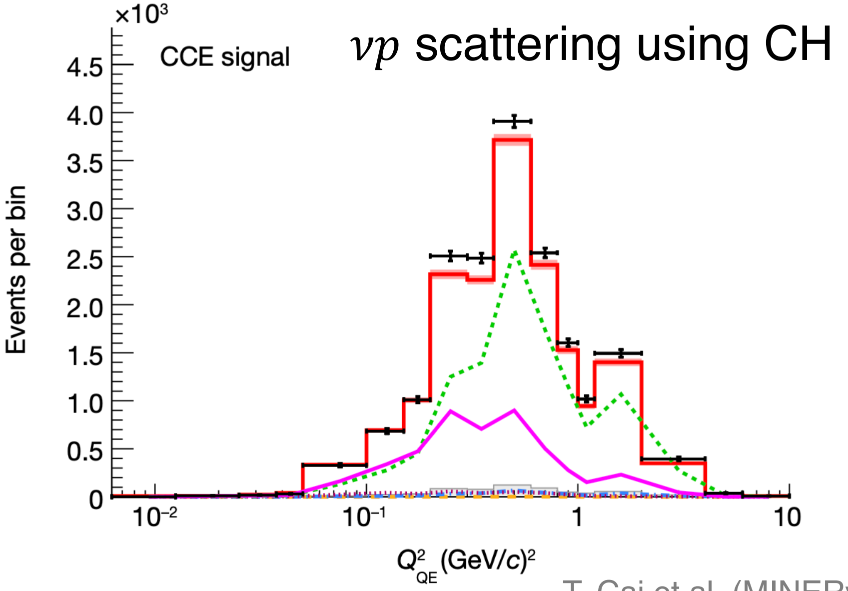
How It Was Measured Before

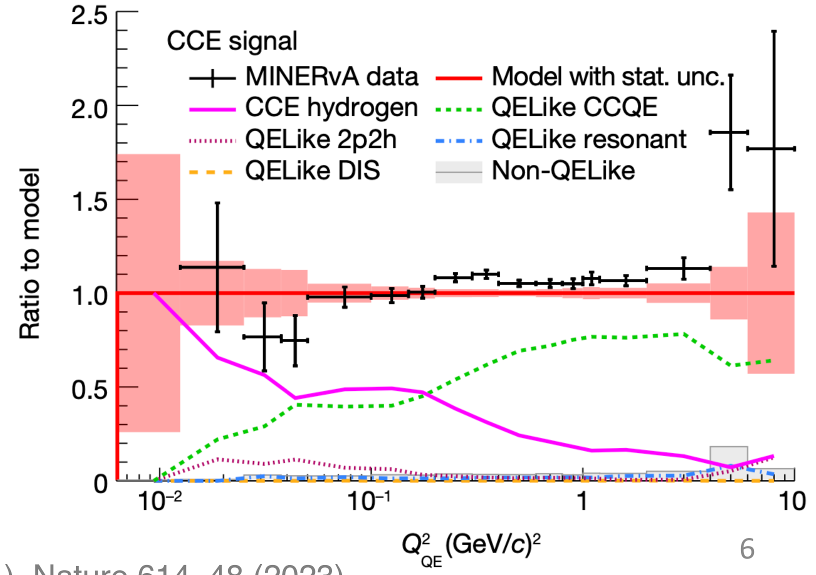
- The natural way to measure $F_A(Q^2)$ is neutrino scattering
  - ➢ νA scattering
  - ➢ νD bubble chamber experiments
  - ➢ νp scattering using plastic scintillator
- Limitations:
  1. Board range neutrino energy
  2. Usually not a free proton (nuclear effect)
  3. Large systematics



Phys. Rev. D 93, 113015 (2016)





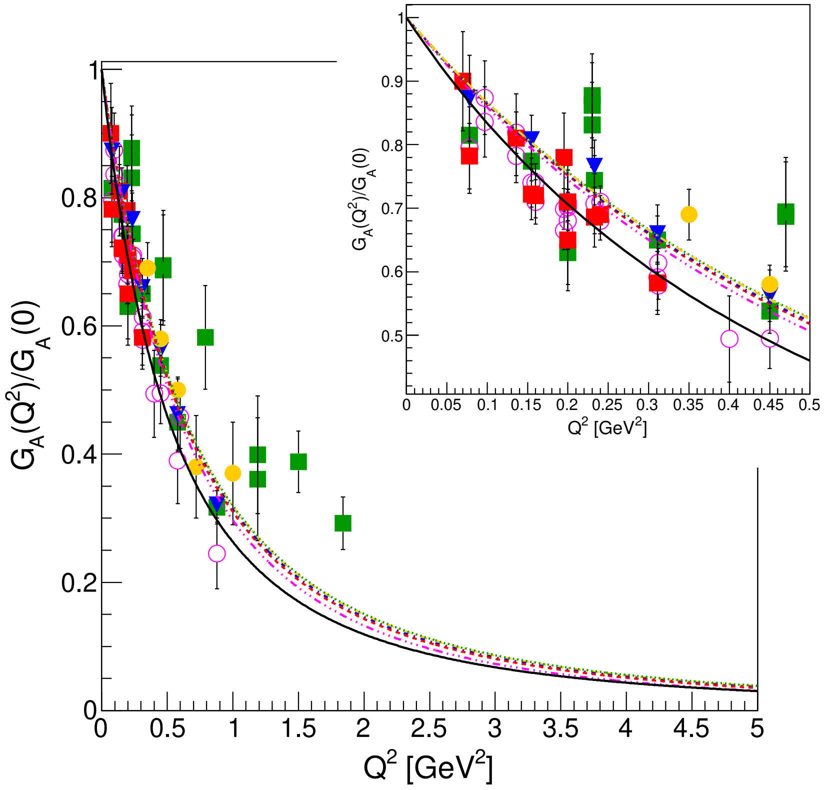


T. Cai et al. (MINERvA), Nature 614, 48 (2023)

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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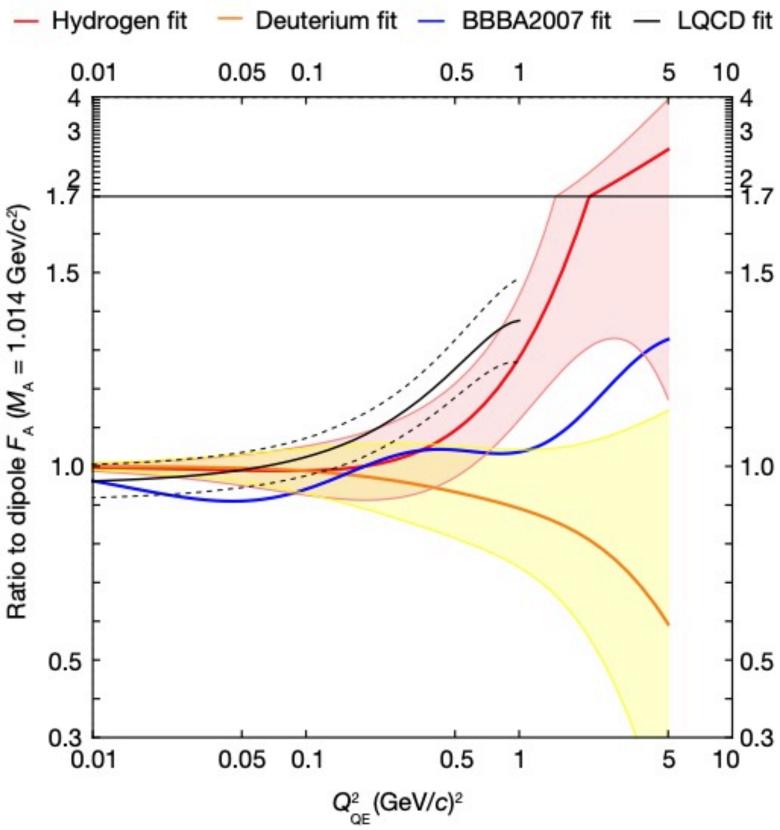
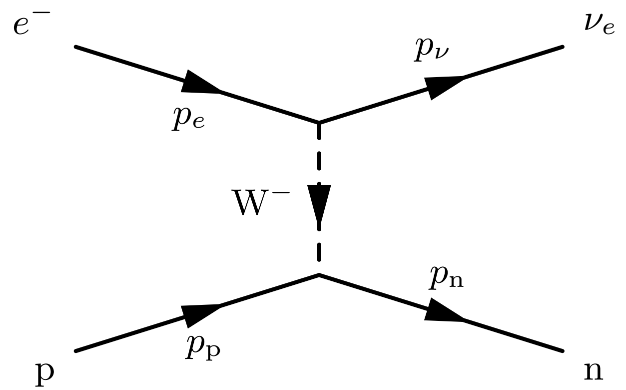


Experimental Concept



- 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 ($ep\to e\pi^+ n$, $\gamma p\to\pi^+ n$, $ep\to e\pi^+\pi^0 n$…), should be even higher than elastic ep
  - What about aluminum cell window, quasi-elastic en, pion production in Al?
  - …

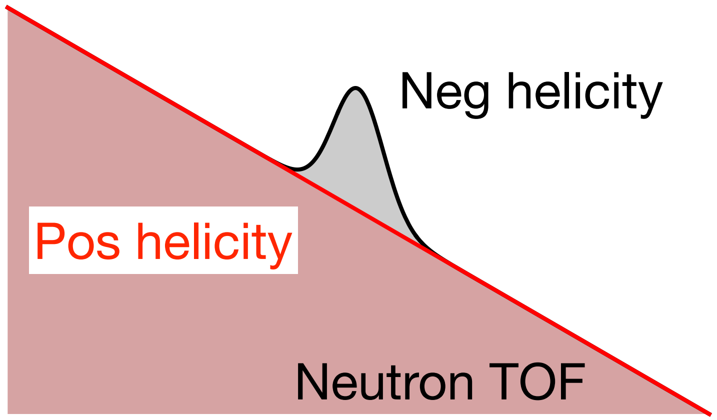
Experimental Concept

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.**

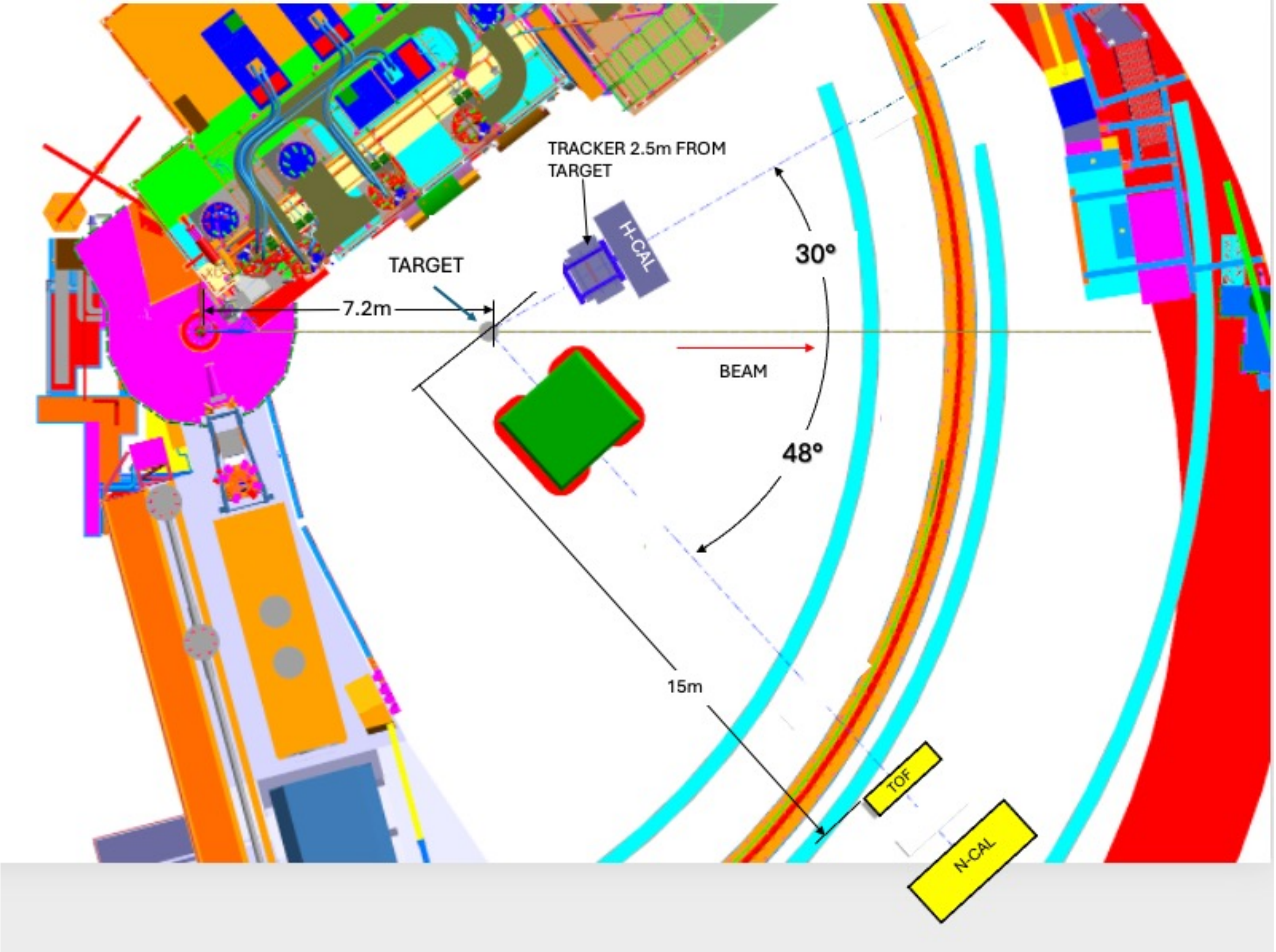
2. Need large acc. veto detector (0.4 sr) to reject backgrounds (pion production, elastic ep…)
   - *p* and *e* are co-planer, with constrained kinematics
   - for neutrons from pion production, *n* and *π* are also co-planer, with constrained kinematics

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.



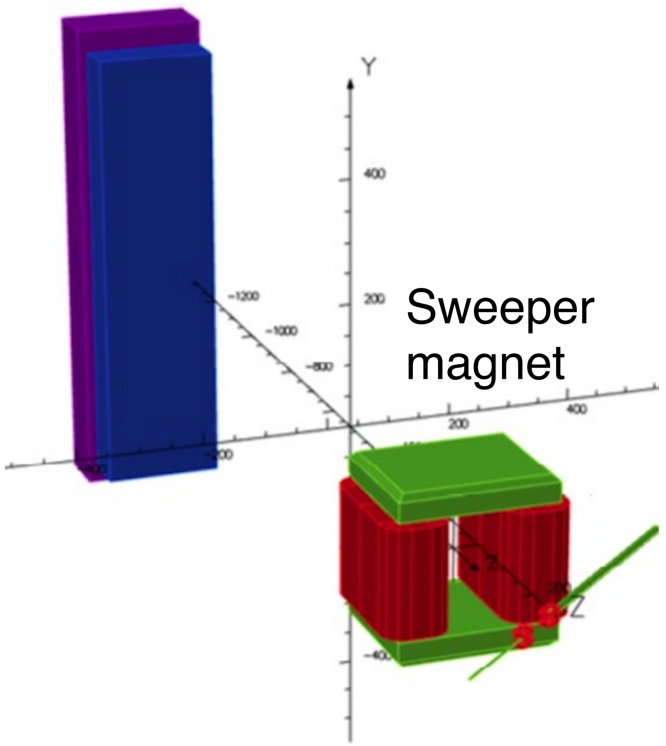
Experimental Setup

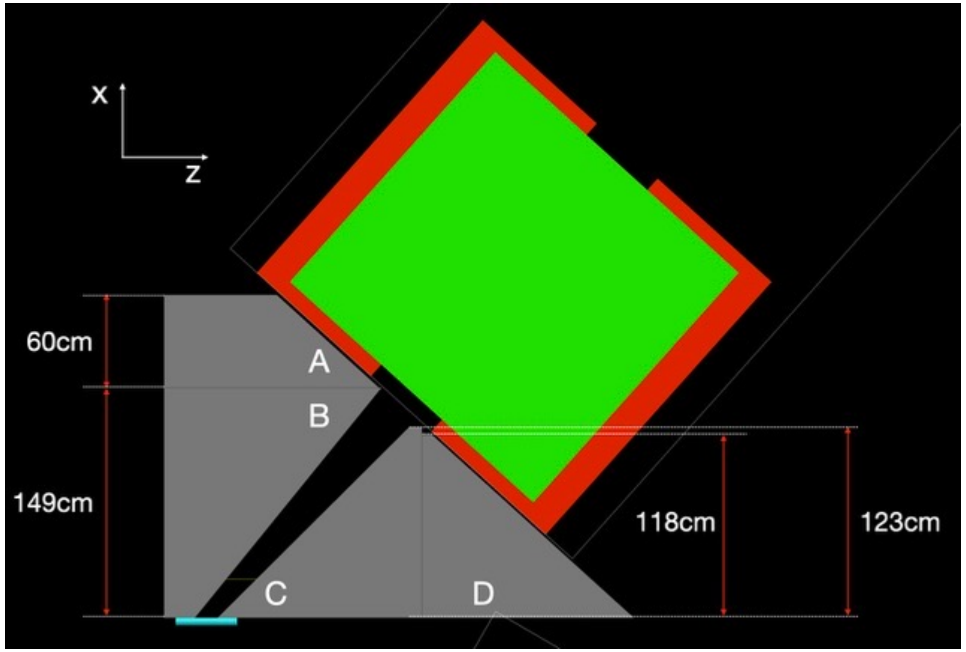


- E=2.2 GeV, 120μA, P=85%
- 10cm LH2 target (*pure; low D2)*
- θ_n=48° so $Q^2 = 1 GeV^2$
- T_n = 525 MeV, v/c=0.77
- 15m to TOF, 65 ns, $\Delta\Omega$=75 msr
- Expect to get σ_{TOF}=100 ps
- $\theta_\nu = 30^\circ = \theta_e$
- $E_e = 1.67$ GeV

Experimental Setup

- A 17.5m long new neutron arm will be built and essembled
  - New large sweeper magnet to get rid of charged particle (2m tall aperture)
  - New TOF scintillator array for neutron timing measurement (11 layers)
  - Hadronic calorimeter (potentially use existing EMCal from STAR and/or BNL-E864, may need modifications)
  - W shielding blocks to shield target windows





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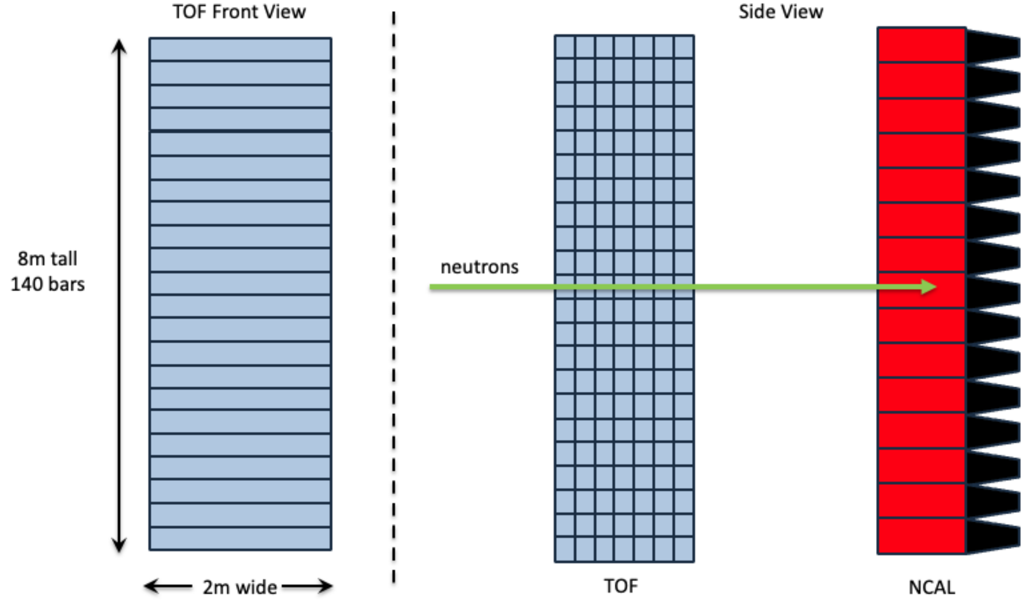
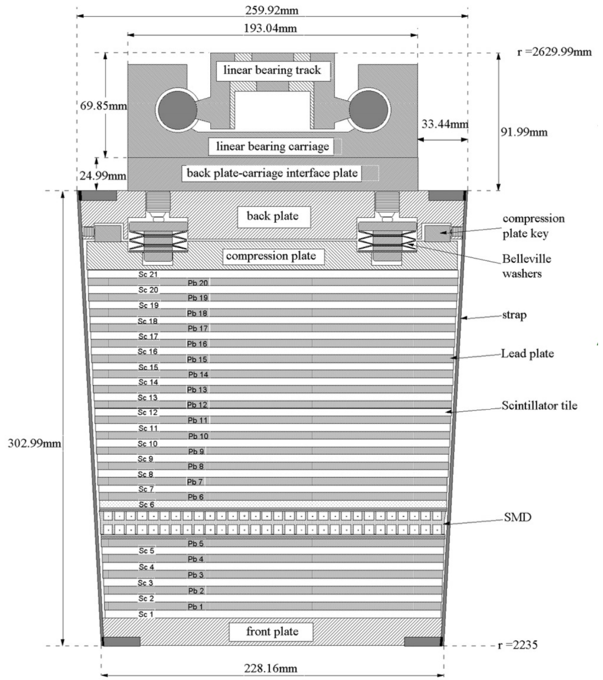
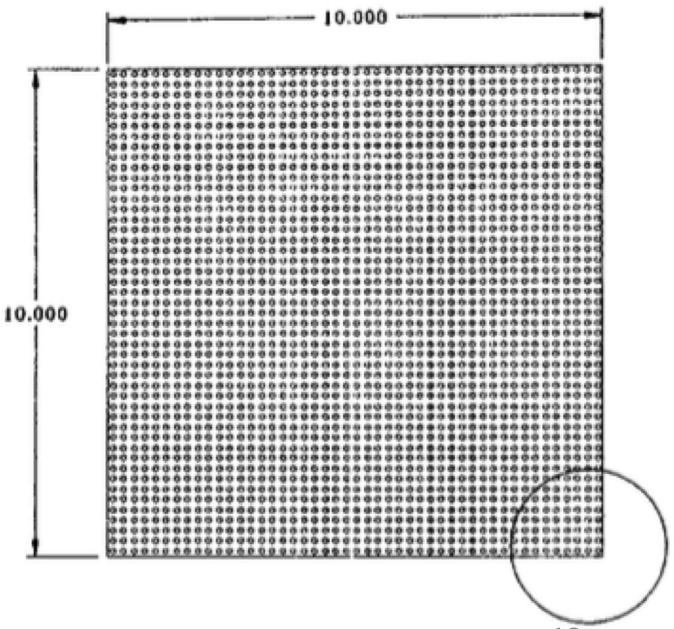
Scintillator TOF



STAR TOF



BNL-E864 calorimeter

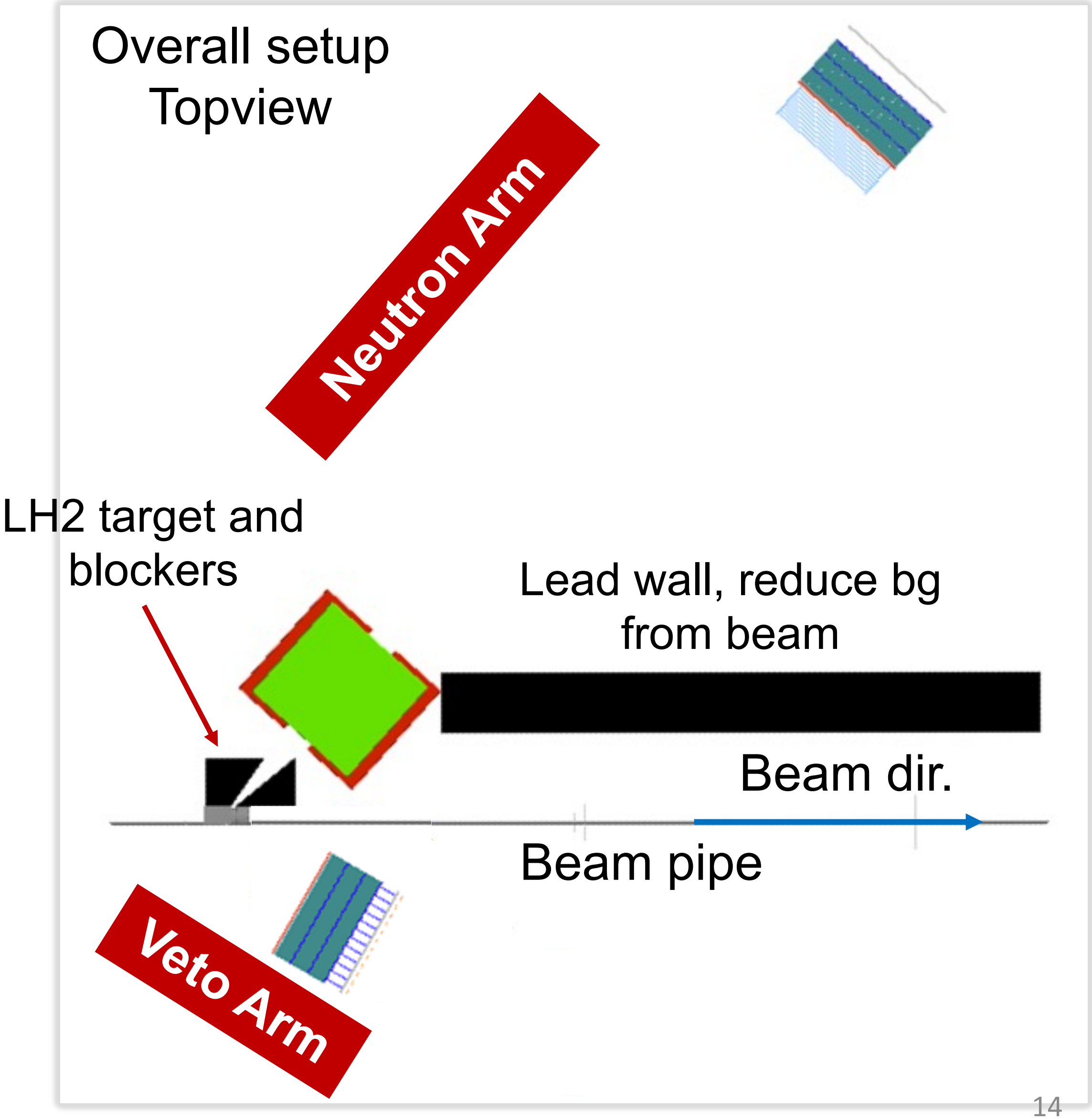


G4 Simulation

- Simulation based on G4SBS

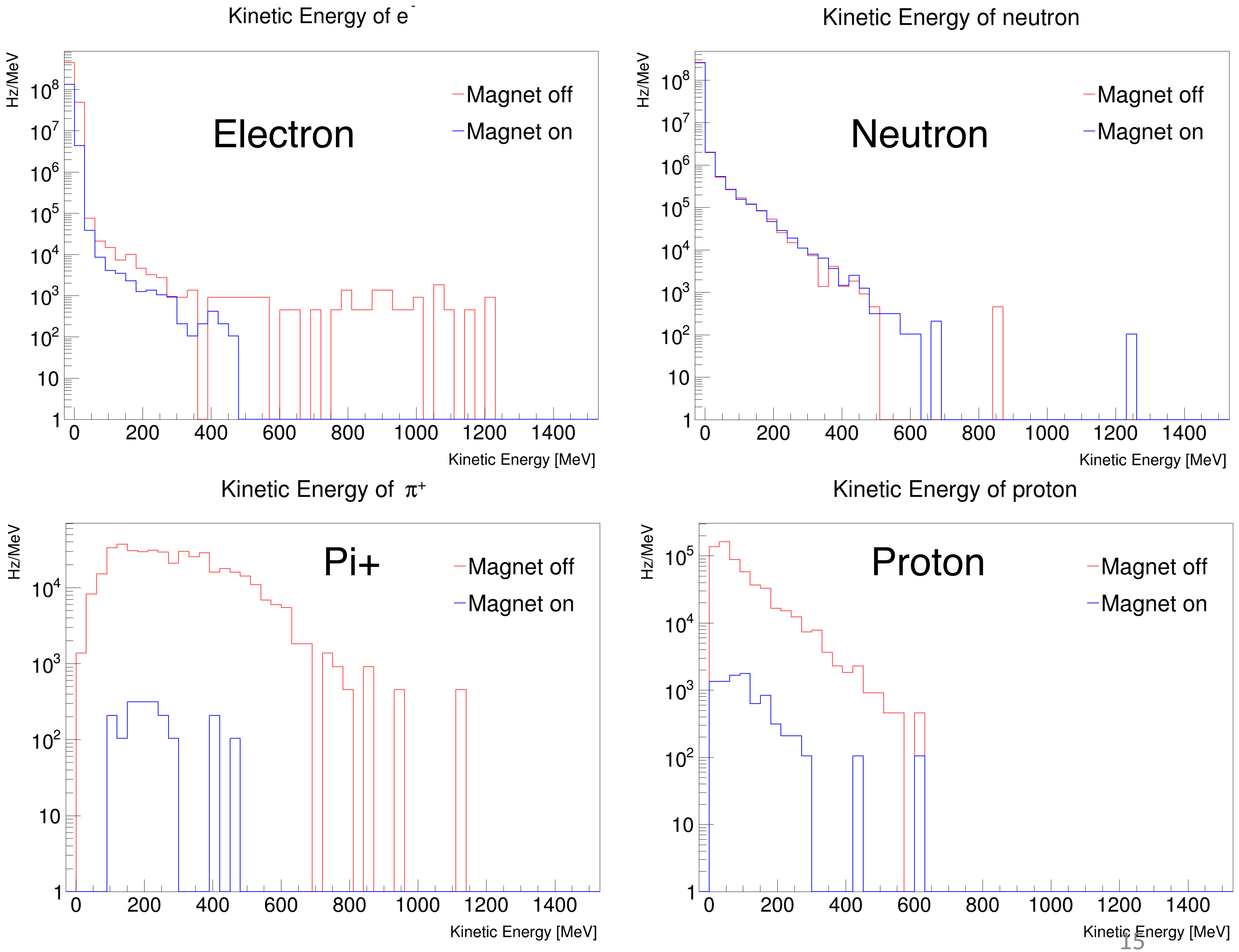
- LH2 target:
  - ➢ 25cm long LH2 with **10cm active**
  - ➢ Al cell, windows 150um each
  - ➢ W shielding, block cell windows

- Veto arm
  - ➢ Center at **30**°
  - ➢ Used as veto detector to reject elastic and pion production events
  - ➢ Calorimeter HCal
  - ➢ ~4m from target (0.4 sr), much larger then N-arm acc.
  - ➢ GEM trackers (only for calibration with 1uA)



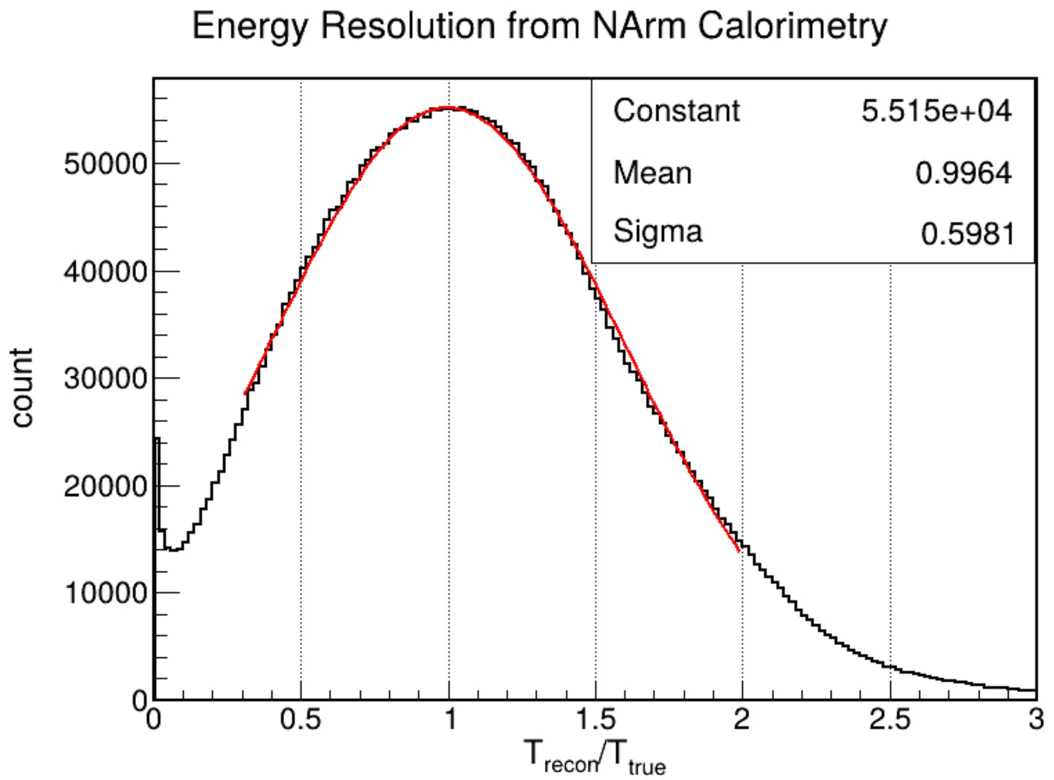
Particle rate on TOF

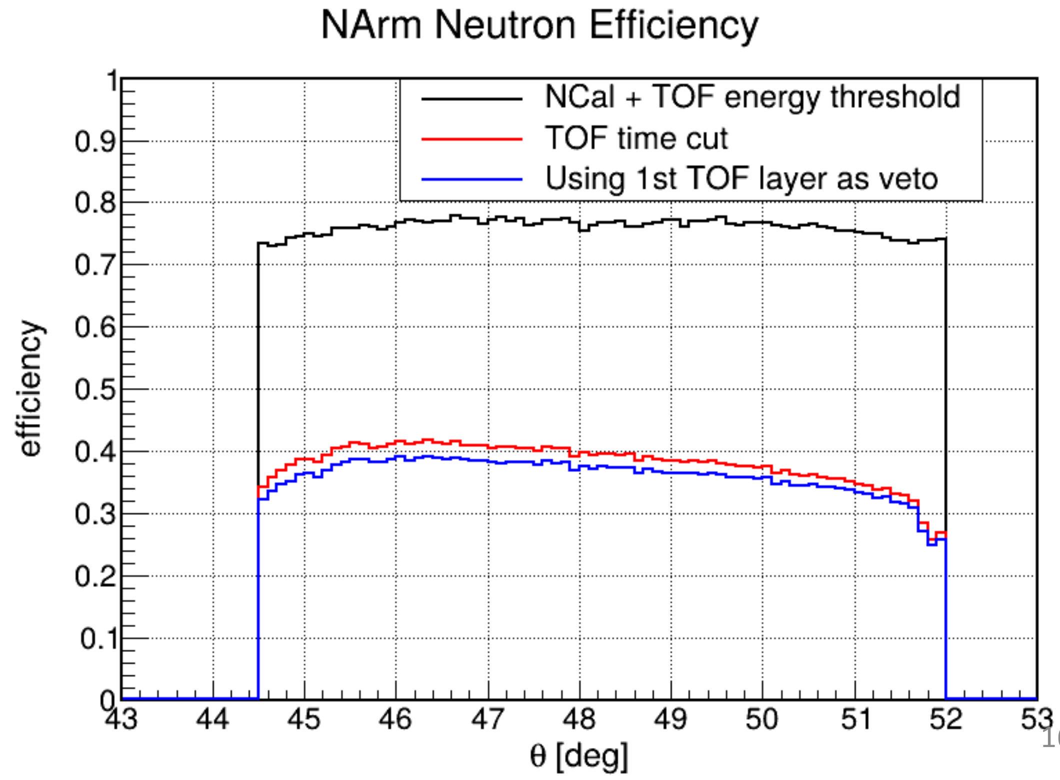
- Sweeper magnet
  - 1Tm, 2m tall aperture
  - Sweep away charged particles
- Simulation shooting 2.2GeV electron beam at target
- Particle flux measured in front of TOF and NCal
- Significant reduction of particle rate at high energy region with magnet turned on



Neutron Detection Efficiency

- Neutron energy resolution **~60%** using energy deposition (edep) in NCal and TOF
- Neutron detection efficiency **~40%,** when requires:
    1. Reconstructed kinetic energy > 100MeV using NCal and TOF edep
    2. TOF edep threshold 3MeV
    3. 10ns time window for Ncal, 0.5ns time window for TOF
    4. 1st layer of TOF used as veto for charged particle background





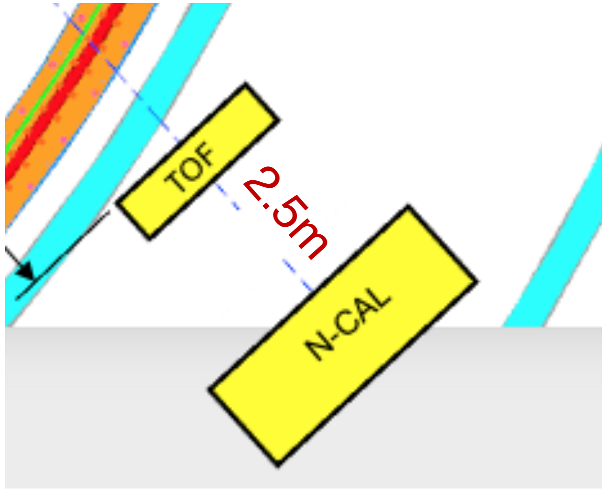
Using NCal + TOF to Determine Beam Bunch

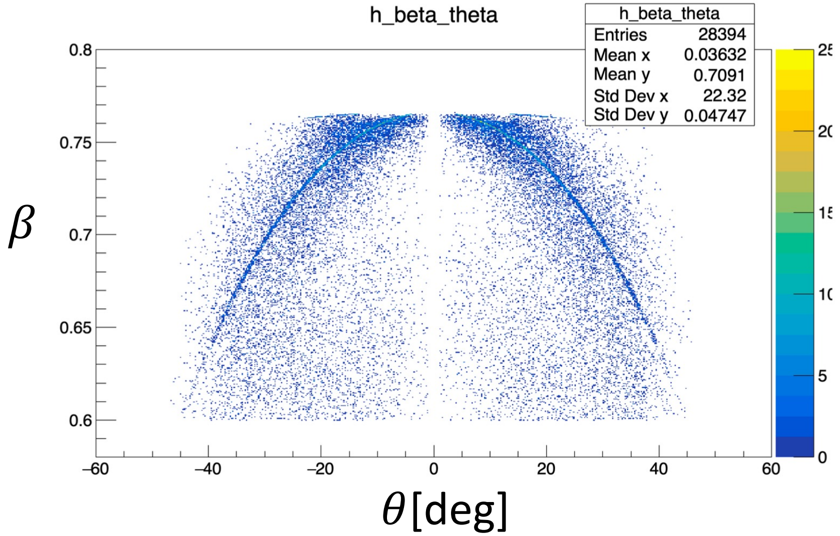
- So how do we know what bunch the neutron is coming from?
- JLab beam has bunch interval, 2ns, 4ns, 8ns, 16ns…
- **BUT!:**
    - ➢ n we want to detect arrives at ~65ns (T = 529MeV)
    - ➢ at 8ns later, the neutron still has ~350MeV, 16ns later still ~250MeV…
    - ➢ ~60% energy resolution of calorimetry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

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

➢ Simplified idea: using elastic/QE n-p scattering

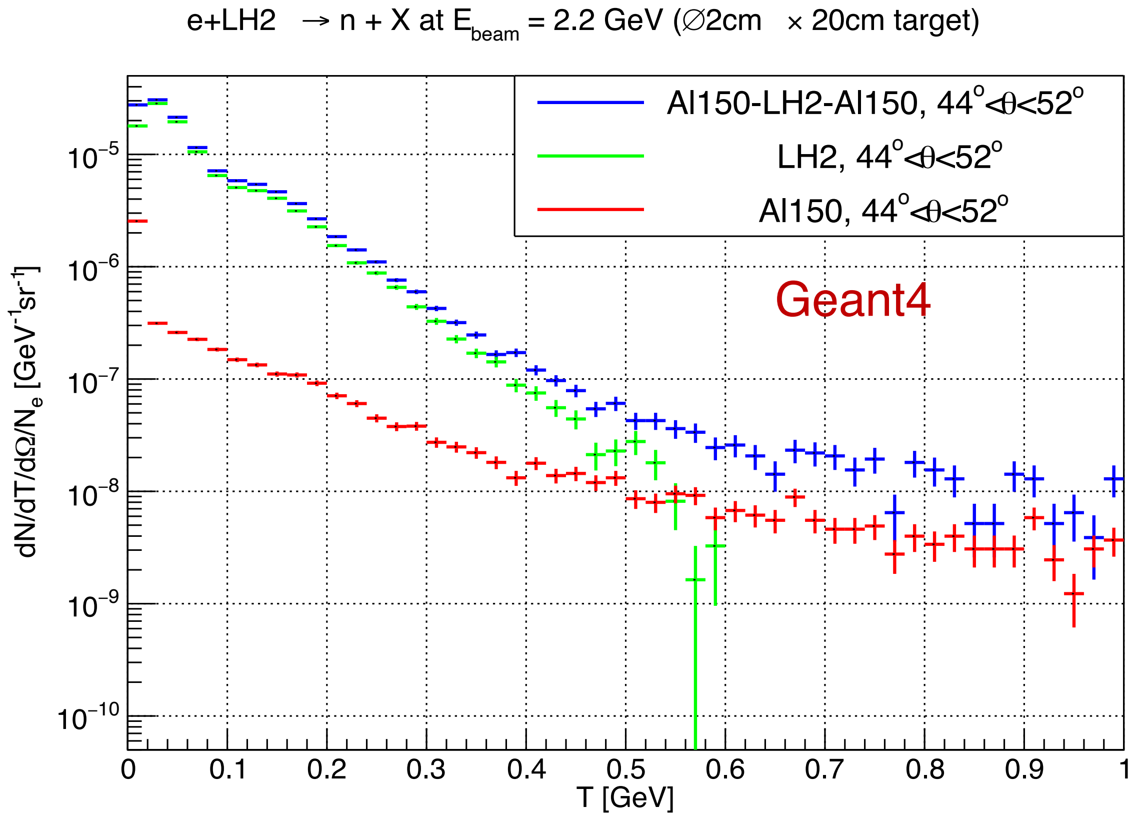
➢ Preliminary estimation: efficiency drops from ~40% to ~25%



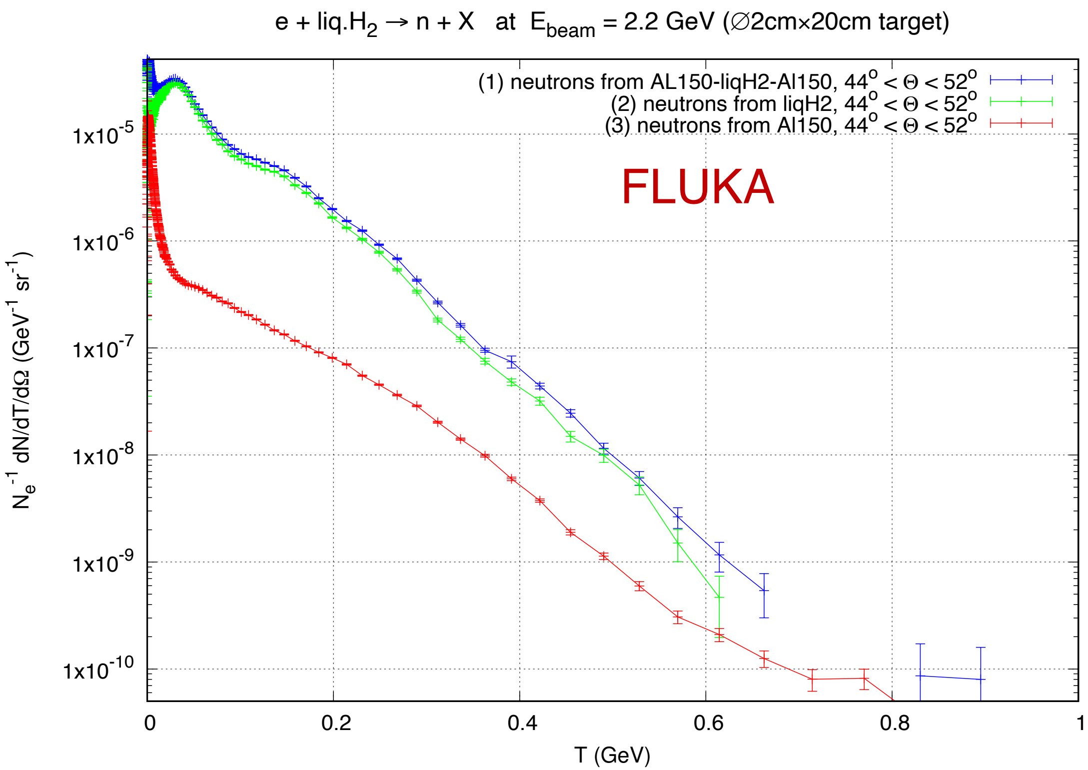


Simulation Comparison between G4 And FLUKA

- Geant4 produce about ~2 times more neutron background from LH2 than FLUKA, 10 times more neutrons from aluminum, some beam test?

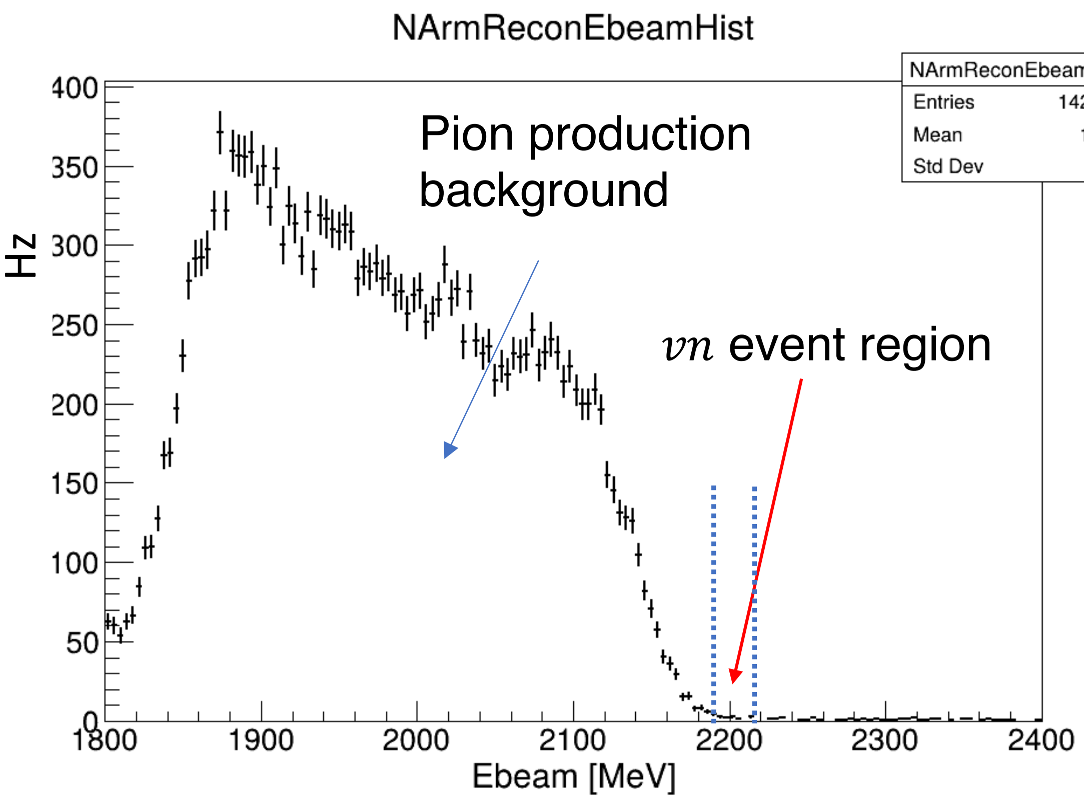


Using this for current studies

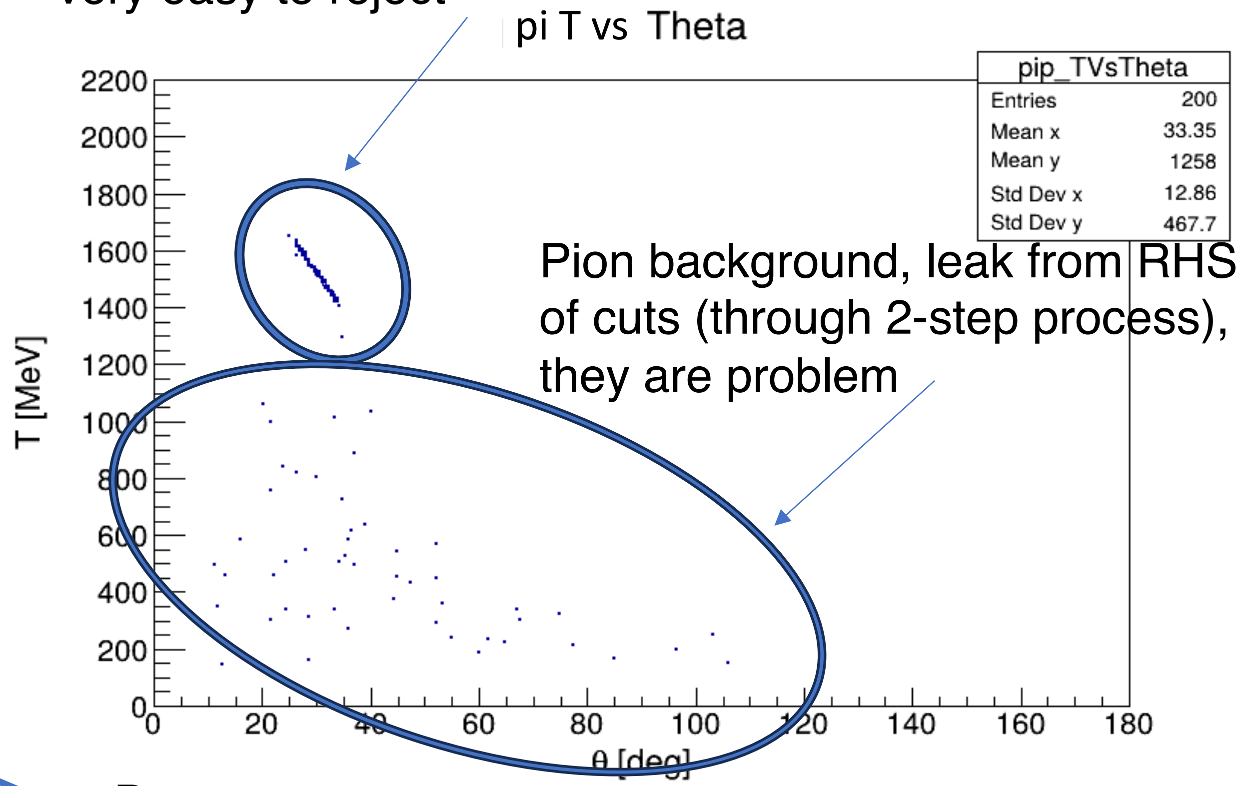


Simulation

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

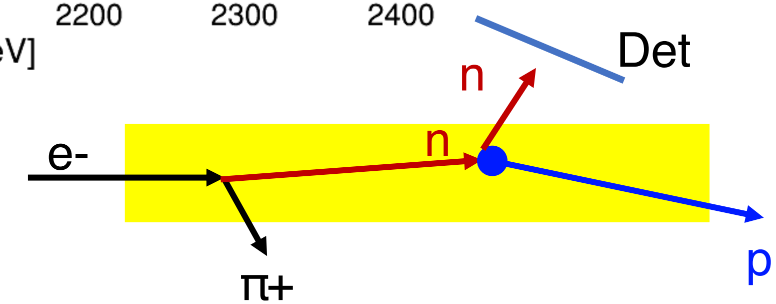


Single pion background, leak from LHS of cuts (through resolution), well within SBS acceptance, very easy to reject



Pion background, leak from RHS of cuts (through 2-step process), they are problem

2-step process



Beam Time and Rates

- Level-0 trigger:
  - NCal + TOF energy > 100 MeV
  - 25 MHz for entire NCal
- Level-1 trigger:
  - Hit position match (0.25m^2) and rough time cut (10ns) between NCal and TOF
  - 0.25 MHz
- Level-2 trigger:
  - Tigher geometric cut (15cm x 15cm)
  - 25 kHz, well within DAQ limit

Request Beam Time

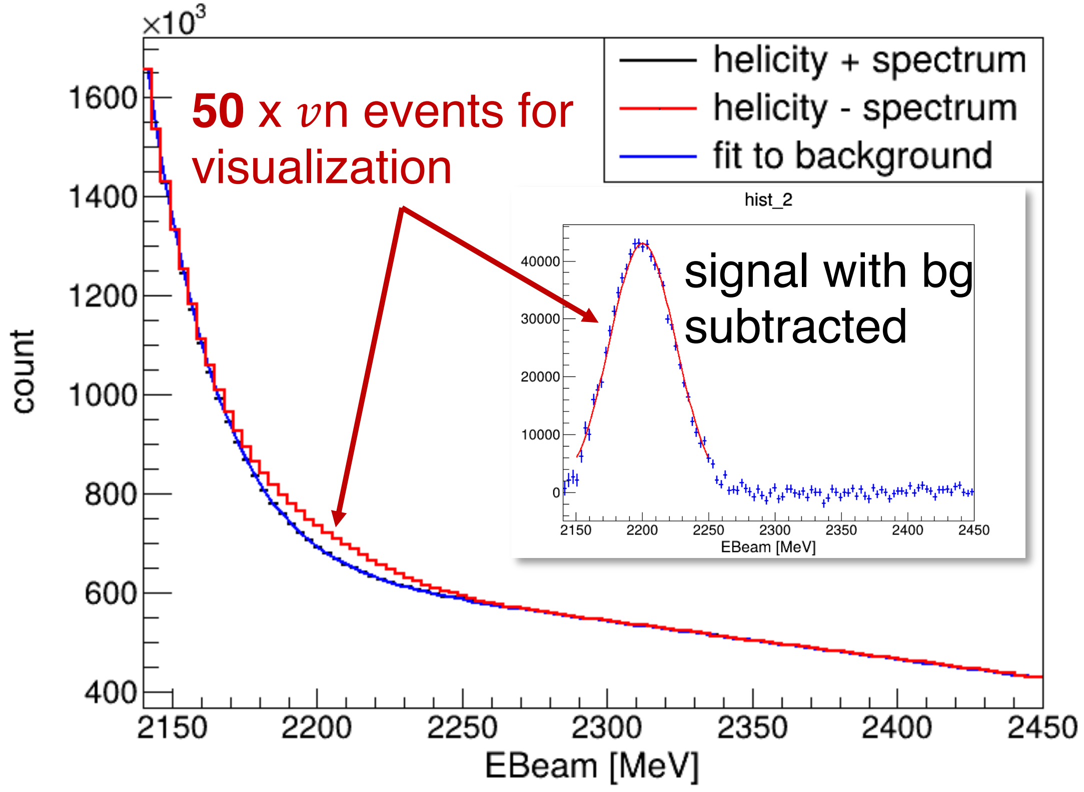
	Target	Beam energy, GeV	Beam, μA	Time, days
Calibration	LH2/LD2	2.2	1	2.5
Production	LH2	2.2	120	50
Beam polarization	Moller	2.2	1	2.5
Total requested time				55

Background rate after cut and veto

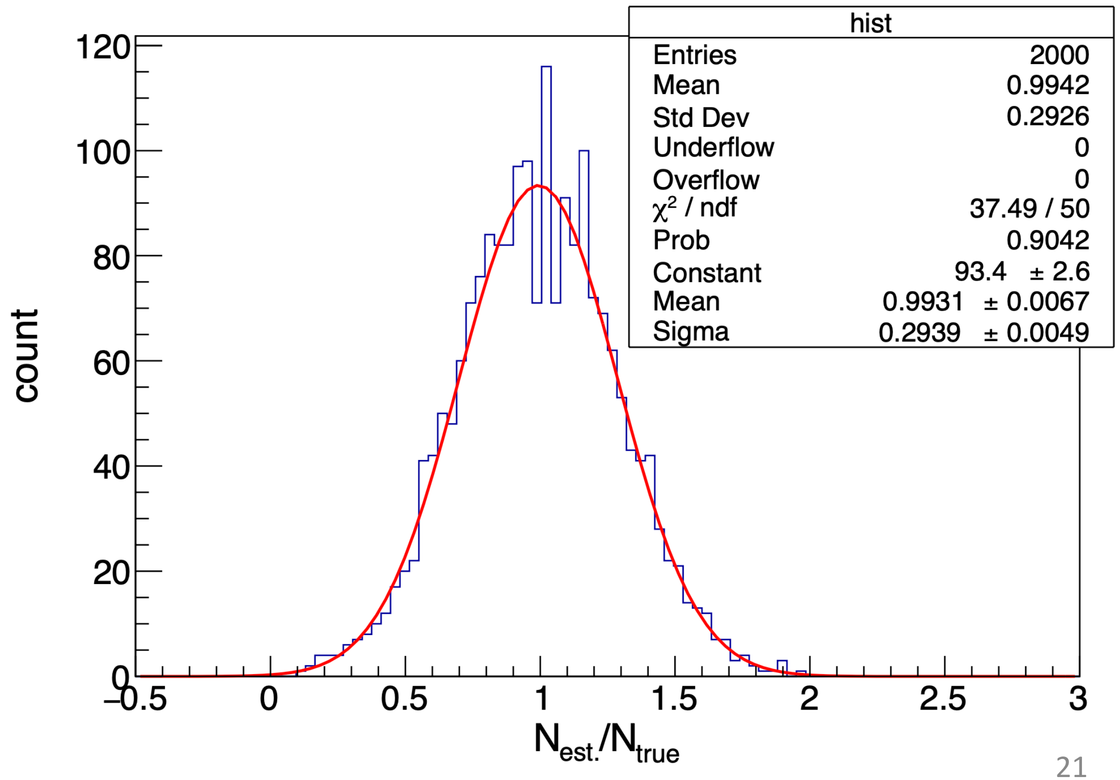
Background Source	Rate [Hz]
Neutrons from elastic ep	0.02
Quasi-elastic from Al window	0.22
Single pion production from LH2	0.81
Pion production form Al window	0.16
Neutrons from 2-step process	12.5

Projected Results

- Final estimation of neutrino events obtained by fitting the EBeam spectrum
- Helicity + spectrum well described by Gaussian + Linear function
- Helicity – spectrum can be described by two Gaussian (one for signal) + Linear function
- Preliminary estimation gives ~29% for the stat. uncertainty



# of recon over # of true νn events for 1000 trials



Tantative Plan for Short Test Run

- Test run can be realized mostly based on
  - existing apparatus (E864 Cal., SHMS, W-based collimator, proton veto plane)
  - Two new TOF planes (~22 high reso. counters)

- Need PAC endorsement for short test run to demonstrate:
  1. Neutron time resolution with 2m long scintillator counters
  2. Neutron backgrounds from different sources (two-step processes, Al cell windows, bg helicity asymmetry...):

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: 29% statistical uncertainty + 5% systematic uncertainty, with 50 PAC days running at 120uA @ 2.2 GeV at JLab
  - Already submitted to JLab PAC this year

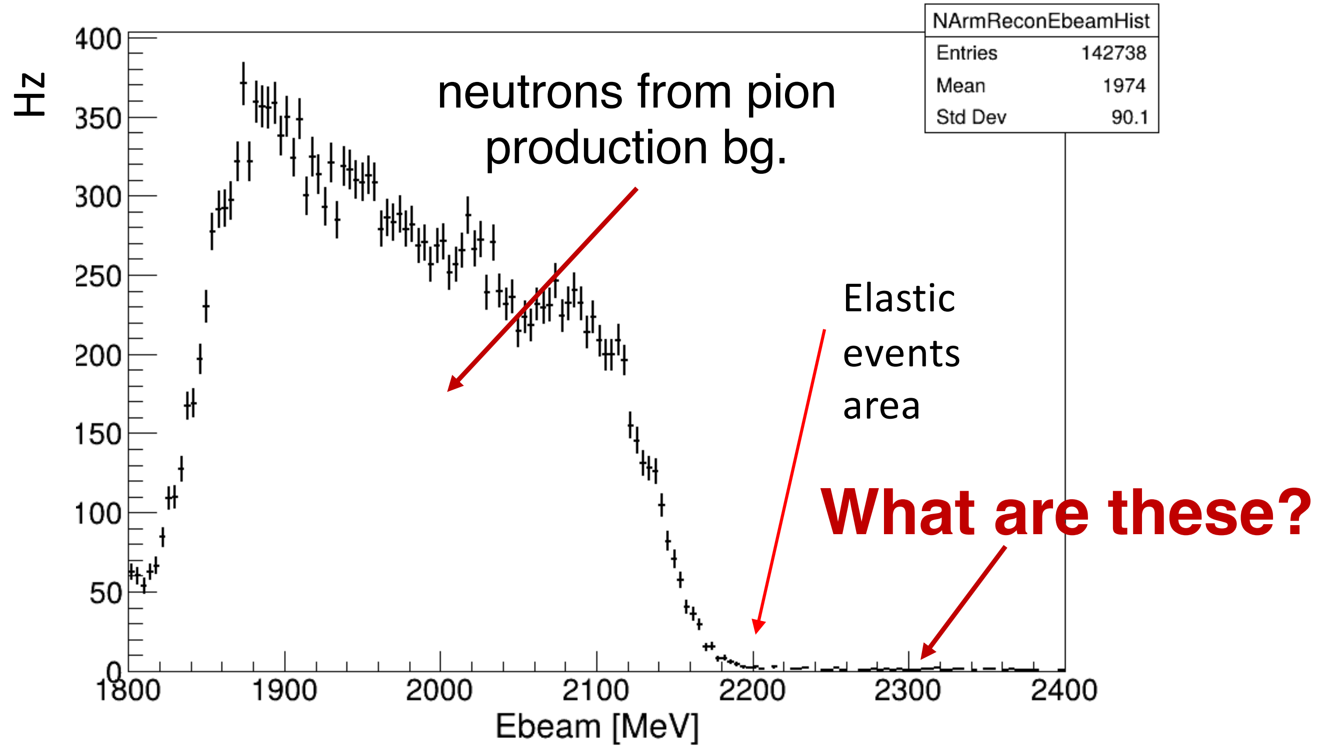
- Still working on various potential improvements (and problems)
  - Uncertainty largely dominated by pion production background (single and multi pions)
  - Geant4 gives significantly more neutrons than FLUKA, **need beam test for background measurement**
  - Optimization of collimators, target cell,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

- 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

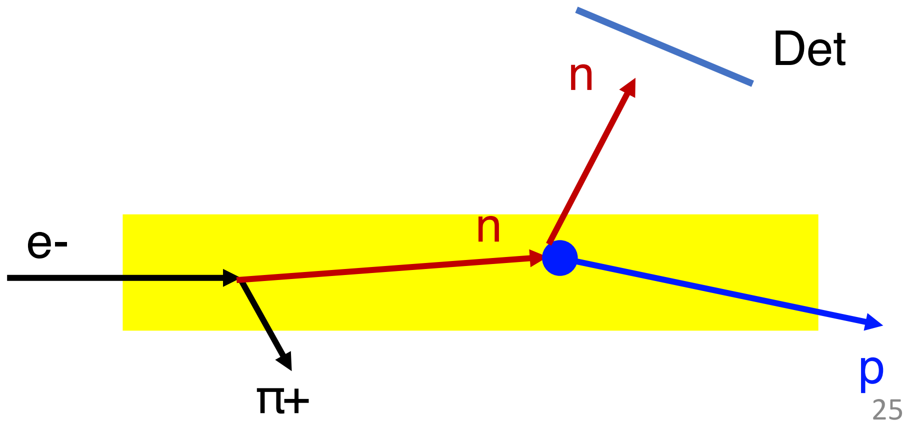
What Challenge We Are Facing Right Now?

- In principle, elastic neutrons should have the highest T and E_{beam}^{rec} at a given angle, why there are super-elastic events?
- This is one of the main background! Very difficult to veto



They are mostly come from two step process (based on current studies):

1. A high energy neutron produced with very small angle
2. This neutron scatters with another proton in LH2
3. Scattered neutron bounces into detector



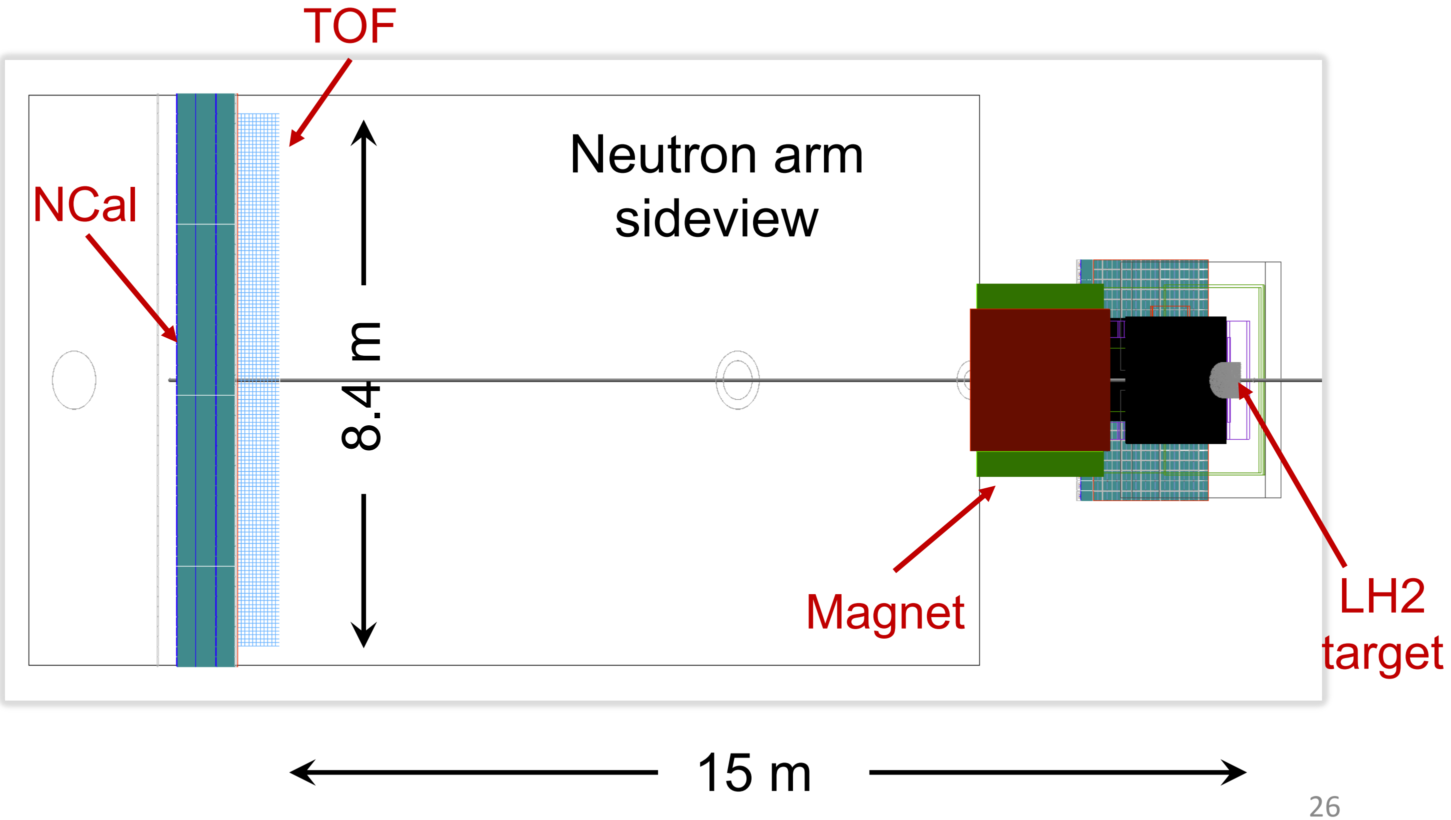
G4 Simulation

- Additional neutron arm for neutron detector, center **48°**, arm at 15m
  1. Arm made of Sweeper magnet, neutron TOF, and neutron calorimeter (NCal)
  2. Coverage: $44° < \theta < 52°, -20° < \varphi < 20°$

- Sweeper magnet:
  - 1Tm, 2m tall aperture

- TOF:
  - 11 layers of scint. bars
  - 140 bars per layer
  - Bar dim. 6cm x 6cm x 200cm
  - Expected t reso. ~100ps

- NCal:
  - Fe+Scint. Calorimeter, Similar to HCal in SBS arm, or use existing calorimeters



Systematics for the cross section value (relative)

Beam polarization	85%	<2%
Luminosity	3.1×10^{38} Hz/cm^2	2%
Neutron arm solid angle	70 msr	1-2%
Neutron detection efficiency	0.25	2-3%
Overall systematics		<5%

	Target	Beam energy, GeV	Beam, μA	Time, days
Calibration	LH2/LD2	2.2	1	2.5
Production	LH2	2.2	120	50
Beam polarization	Moller	2.2	1	2.5
Total requested time				55

Quantity	Variable	Value
Nucleon mass (proton)	m	0.938 GeV
Beam energy	E	2.20 GeV
(Total 4-momentum)^2	s	5.01 GeV^2
-(4-momentum transfer)^2	$-t = Q^2$	1.00 GeV^2
Energy transfer	$\nu = E - E_\nu$	0.53 GeV

Neutron/Proton

Scattering angle	θ_n	48.0°
Energy	E_n	1.47 GeV
3-momentum	p_n	1.13 GeV
Kinetic energy	E_k	0.53 GeV
Beta	β	0.77
Time-of-flight (15 m)	t_n	65.0 ns

Neutrino/Electron

Scattering angle	θ_ν	30.0°
Energy	E_ν	1.67 GeV