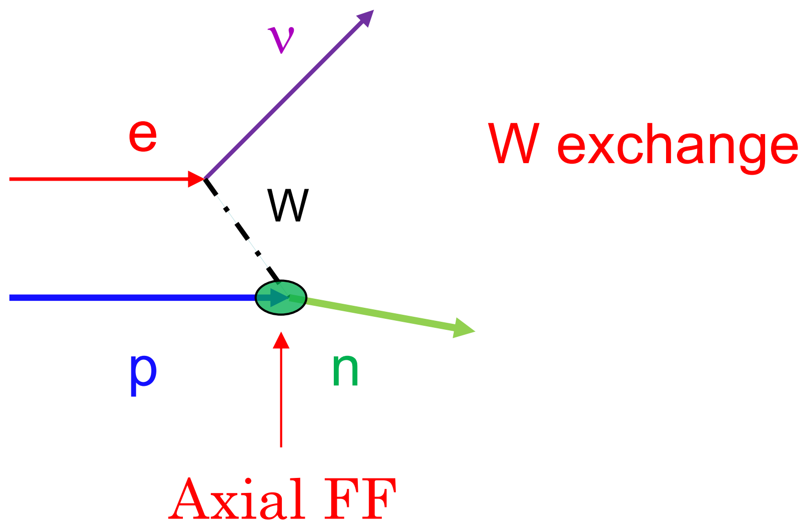
Jefferson Lab
Thomas Jefferson National Accelerator Facility

# Weak Axial-vector Form Factor


B. Wojtsekhowski, JLab

in collaboration with

P. Degtiarenko, A. Deur, J. Golak,
D. Jones, C. Keppel, E. King, J. Napolitano

# Charge current experiments for DIS

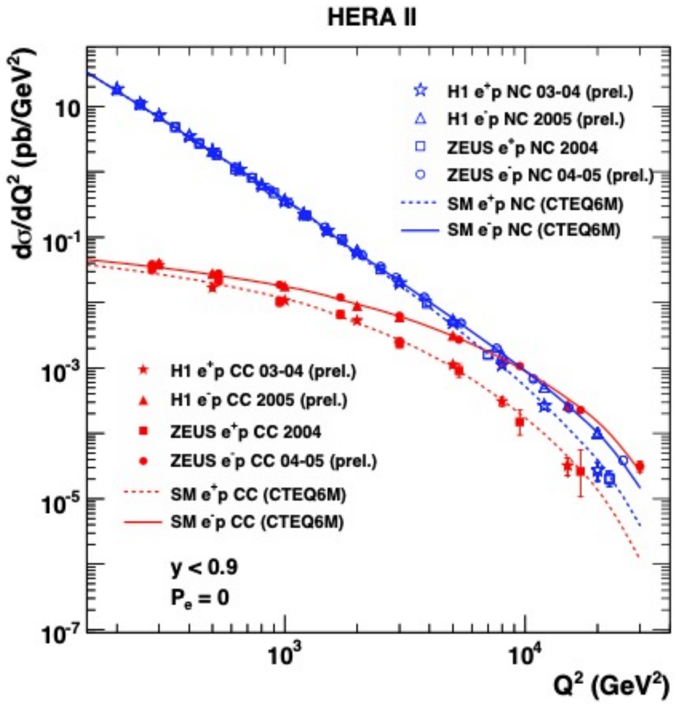
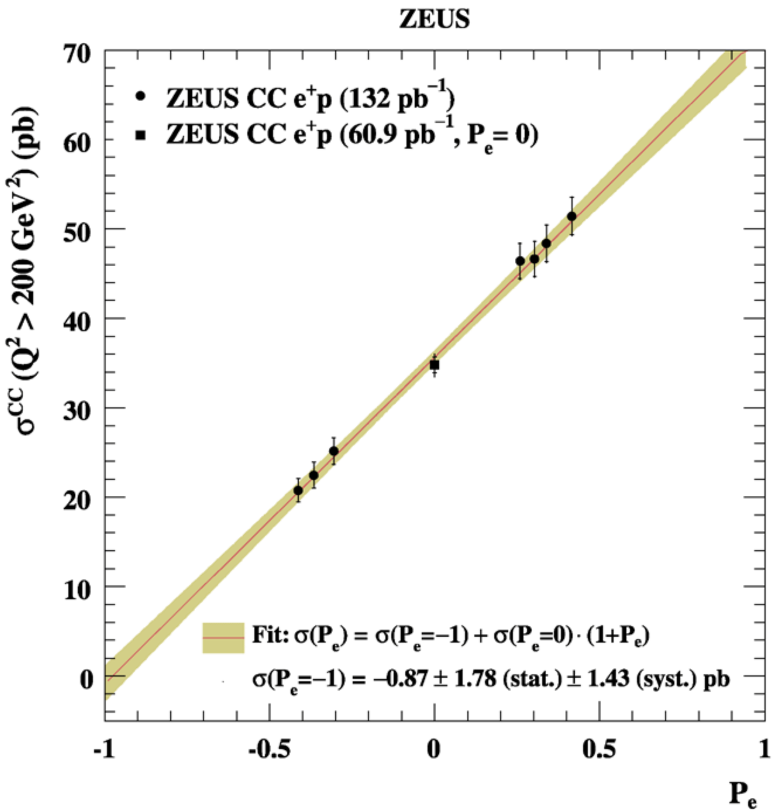



**Figure 1.** Unpolarised $e^{\pm}p$ NC and CC single differential cross sections, $d\sigma/dQ^2$.




## 3. Polarised CC cross sections

The longitudinal polarisation has a particularly strong effect on the CC cross sections, as they are predicted to be linearly dependent on the polarisation, independently of kinematic variables:

$$\sigma_{CC}^{e^{\pm}p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^{\pm}p}(P_e = 0). \qquad (4)$$

PHYSICAL REVIEW D VOLUME 28, NUMBER 3 1 AUGUST 1983

# High-energy quasielastic $\nu_\mu n \to \mu^- p$ scattering in deuterium

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa,
A. Yamaguchi, K. Tamai, T. Hayashino, Y. Otani, H. Hayano, and H. Sagawa

vector-current (CVC) hypothesis are also assumed to simplify the formulation. Reported values of the axial-vector mass $M_A$ range between 0.65 and 1.07 GeV; the weighted average is somewhat smaller than, but consistent with, the mass value $M_A \sim 1.15$ GeV obtained from electroproduction experiments.[5] These results, as well as the absolute cross section for the quasielastic reaction, are consistently described by the formulation of the $V-A$ theory in the low-ener $\nu_\mu n \to \mu^- p$ there has been no experi-

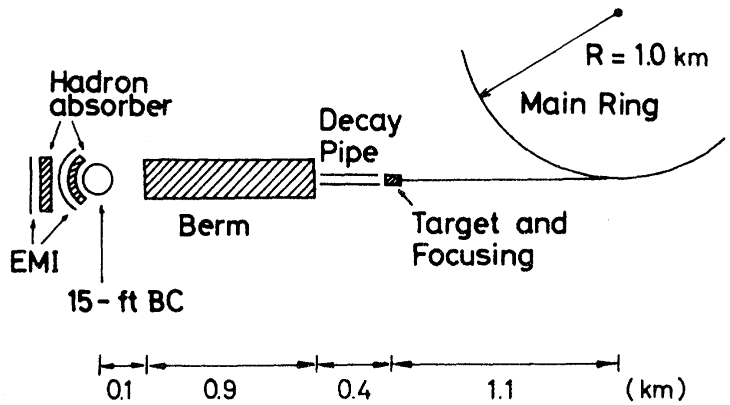



FIG. 1. Schematic layout of the neutrino beam line and the bubble chamber with two-plane external muon identifiers (EMI).

from this experiment have been published elsewhere.[6–10]

## II. EXPERIMENTAL DETAILS

### A. Neutrino beam and bubble chamber

The wide-band neutrino beam was produced by 350-GeV/$c$ protons striking a 33-cm-long beryllium oxide target. Figure 1 shows the schematic layout of the neutrino beam line. Secondary particles with positive charge were focused by a horn magnet pulsed to a maximum current of 80 kA. The neutrinos were produced from $\pi^+$ and $K^+$ decays in flight in a 400-m-long decay pipe. With the exception of neutrinos, almost all particles which pass through this decay pipe are absorbed in the 900-m-long earth berm and iron shield. Thus at the end of the berm, a beam consisting primarily of $\nu_\mu$ emerged. The contamination of the neutrino flux by antineutrinos is estimated by a Monte Carlo simulation[11] to be about 14%. The neutrino flux has a maximum at 20 GeV and extends above 200 GeV with an average energy of 27 GeV. A total of 328 000 pictures was taken with $4.9 \times 10^{18}$ extracted protons, averaging about $1.5 \times 10^{13}$ protons per pulse. A detailed study of this flux is given in Ref. 10.

Article

# Measurement of the axial vector form factor from antineutrino–proton scattering

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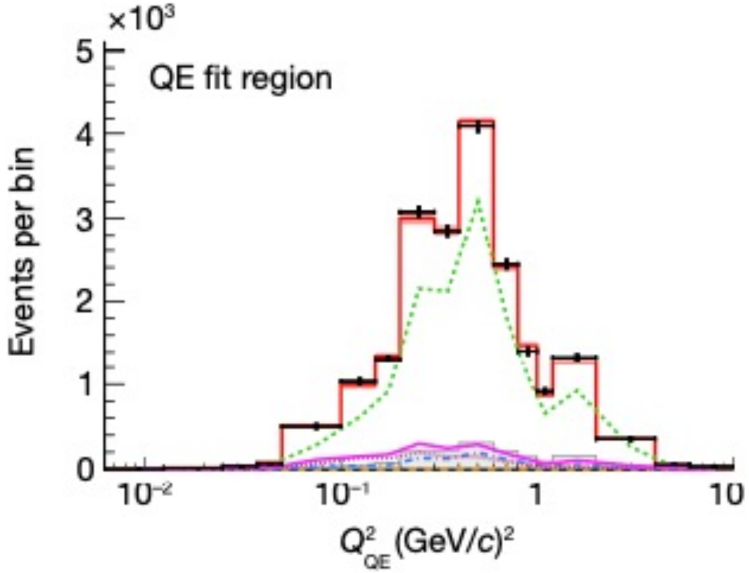
T. Cai[1,2]✉, M. L. Moore[1,26], A. Olivier[1], S. Akhter[3], Z. Ahmad Dar[3,4], V. Ansari[3], M. V. Ascencio[5,27], A. Bashyal[6,28], A. Bercellie[1], M. Betancourt[7], A. Bodek[1], J. L. Bonilla[8], A. Bravar[9], H. Budd[1], G. Caceres[10,29], M. F. Carneiro[6,10,30], G. A. Díaz[1], H. da Motta[10], J. Felix[8], L. Fields[11], A. Filkins[4], R. Fine[1,31], A. M. Gago[5], H. Gallagher[12], S. M. Gilligan[6], R. Gran[13], E. Granados[8], D. A. Harris[2,7], S. Henry[1], D. Jena[7], S. Jena[14], J. Kleykamp[1,32], A. Klustová[15], M. Kordosky[4], D. Last[16], T. Le[12], A. Lozano[10], X.-G. Lu[17,18], E. Maher[19], S. Manly[1], W. A. Mann[12], C. Mauger[16], K. S. McFarland[1]✉, B. Messerly[20,33], J. Miller[21], O. Moreno[4,8], J. G. Morfín[7], D. Naples[20], J. K. Nelson[4], C. Nguyen[22], V. Paolone[20], G. N. Perdue[1,7], K.-J. Plows[18], M. A. Ramírez[8,16], R. D. Ransome[23], H. Ray[22], D. Ruterbories[1], H. Schellman[6], C. J. Solano Salinas[24], H. Su[20], M. Sultana[1], V. S. Syrotenko[12], E. Valencia[4,8], N. H. Vaughan[6], A. V. Waldron[15,25], M. O. Wascko[15], C. Wret[1], B. Yaeggy[21,34] & L. Zazueta[4]



# The CC proposal history at JLab

1988 LOI to PAC3 by J. Napolitano

2003 LOI to PAC25 by A. Deur

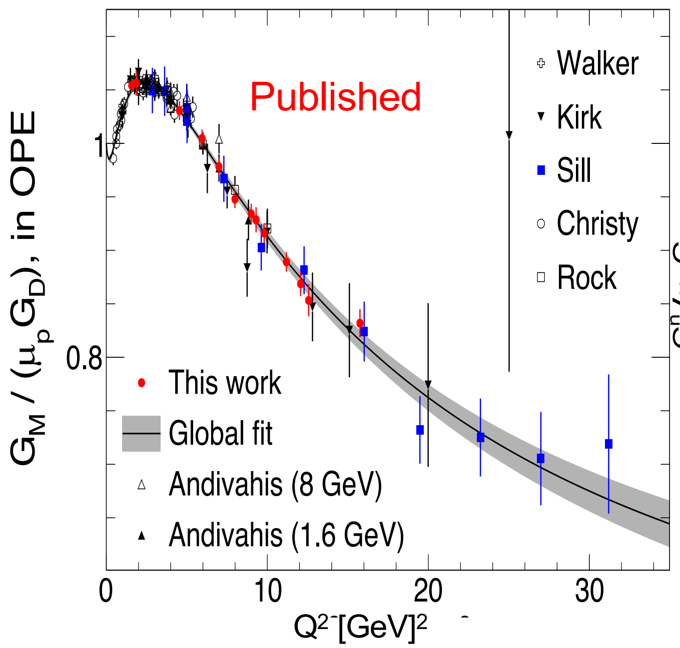
2023 LOI to PAC51 by D. Dutta

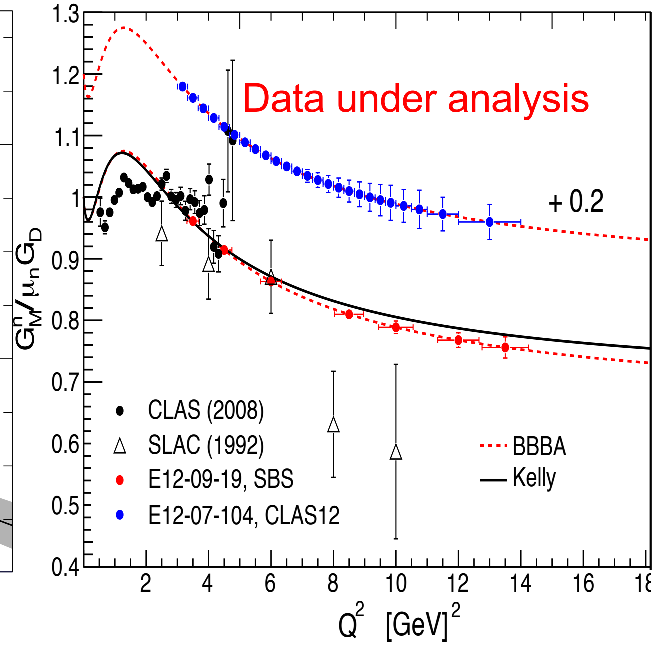
The LOI 1988 is missing in PAC3 report, discovered just recently

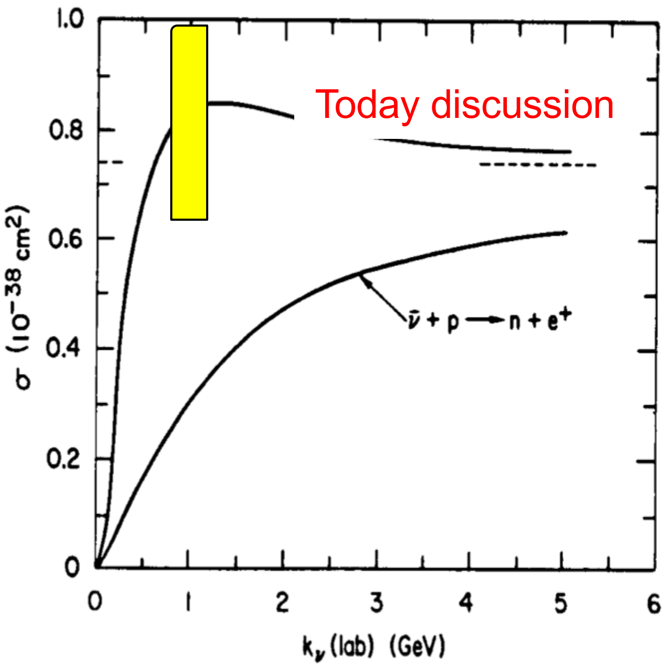
The LOI 2003 had the focus on $Q^2 \sim$ 1-3 $GeV^2$. Interest is very large, some questions about how to proceed, was not updated to proposal

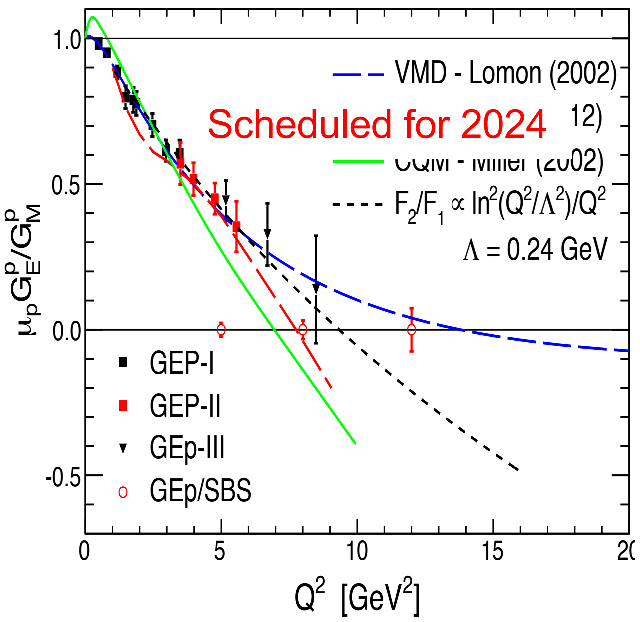
The LOI 2023 proposed a different idea (for low $Q^2$) based on TDIS proton detector and the reaction with a positron beam:
$e^+ + d \to p + p + \nu$

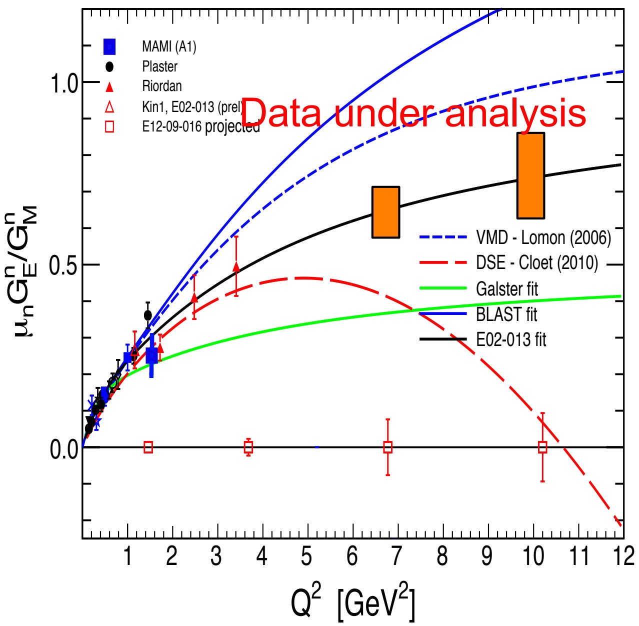
# The nucleon elastic FFs

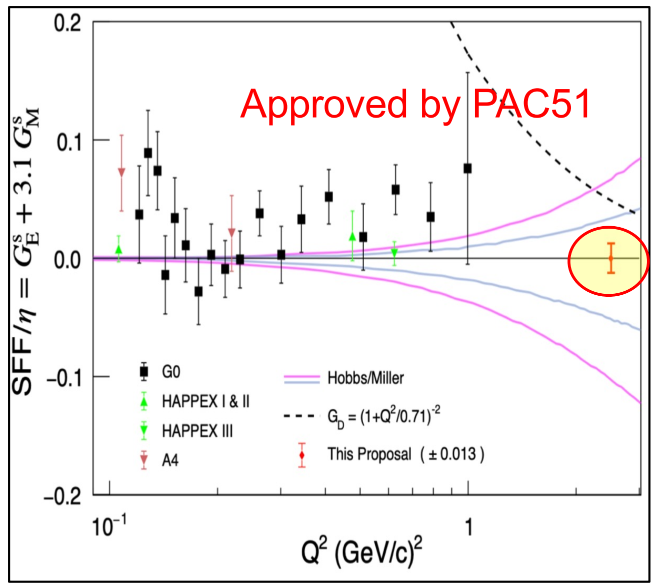


# Cross section calculation

NEUTRINO REACTIONS AT ACCELERATOR ENERGIES *

C.H. LLEWELLYN SMITH
*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA*

Received 30 August 1971

$$F_A(Q^2)=F_A(0)/(1+Q^2/M_A{}^2)^2\,, \qquad (6)$$

where the value of $F_A(0)=-1.23\pm0.01$ is taken from $\beta$-decay experiments.[16]

From these assumptions, the differential cross section for the quasielastic reaction can be expressed in terms of only one parameter, $M_A$, as

$$\frac{d\sigma}{dQ^2}=\frac{G^2M^2\cos^2\theta_C}{8\pi E_\nu{}^2}\left[A(Q^2)+B(Q^2)\frac{(s-u)}{M^2}+C(Q^2)\frac{(s-u)^2}{M^4}\right], \qquad (7)$$

where $s-u=4ME_\nu-Q^2-m_\mu{}^2$, and $M=(M_n+M_p)/2$. The values of the Fermi constant and of the Cabibbo angle are taken to be $G=1.166\,32\times10^{-5}$ GeV$^{-2}$ and $\cos\theta_C=0.9737$, respectively (see Ref. 16). The structure

$$M_A=1.03\pm0.04 \text{ GeV}\,,$$

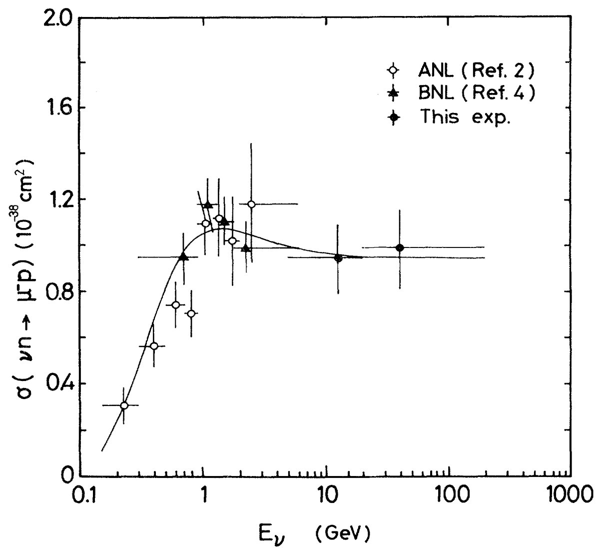



FIG. 10. Quasielastic cross section $\sigma(\nu_\mu n\to\mu^-p)$ as a function of $E_\nu$. The data points from this experiment and Ref. 4 are calculated from Eq. (7) using the $M_A$ values in Table I. The curve is derived from Eq. (7) with $M_A=1.05$ GeV.

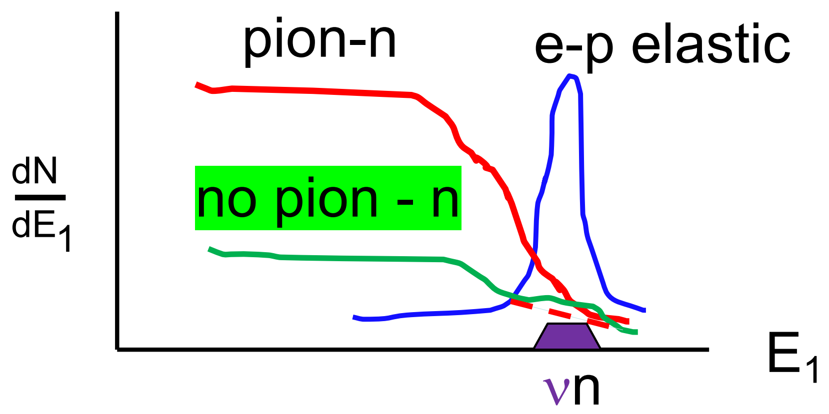
# Challenges in the study of $e + p \rightarrow \nu + n$ process

- Cross section for the weak process is of ~ $10^{-39}$ $cm^2/sr$
- Pion photo-production cross section ~ $10^7$ of the weak one
- Proton rate from electron elastic e-p ~ $10^6$ of the weak one

# The key is a lepton initial energy

$$E_1 = (E_n - m) / \left[1 + \frac{P_n \cos\theta_n - E_n}{m}\right]$$

Reconstructed using the momentum and angle of the neutron



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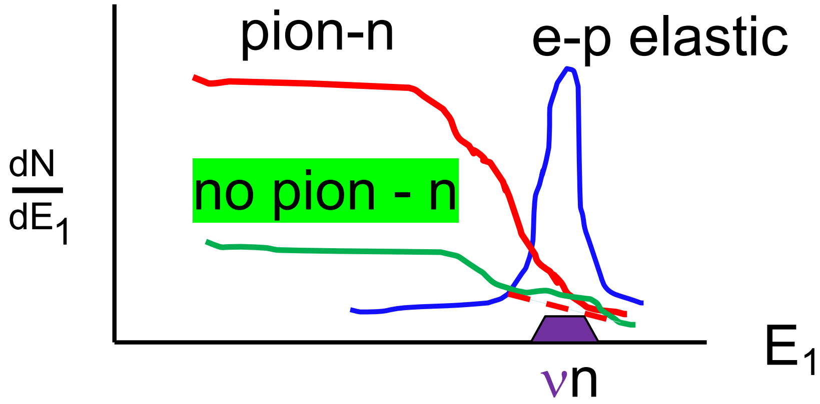



$$E_1 = (E_n - m_n + m_\pi^2/2m_n) / \left[1 + \frac{P_n \cos(\theta_n) - E_n}{m_n}\right]$$

# Proposed solution for the e + p --> ν + n experiment

1. High momentum resolution neutron detector

2. High angular resolution neutron detector

3. Reconstruction of the incident energy to at least 1%

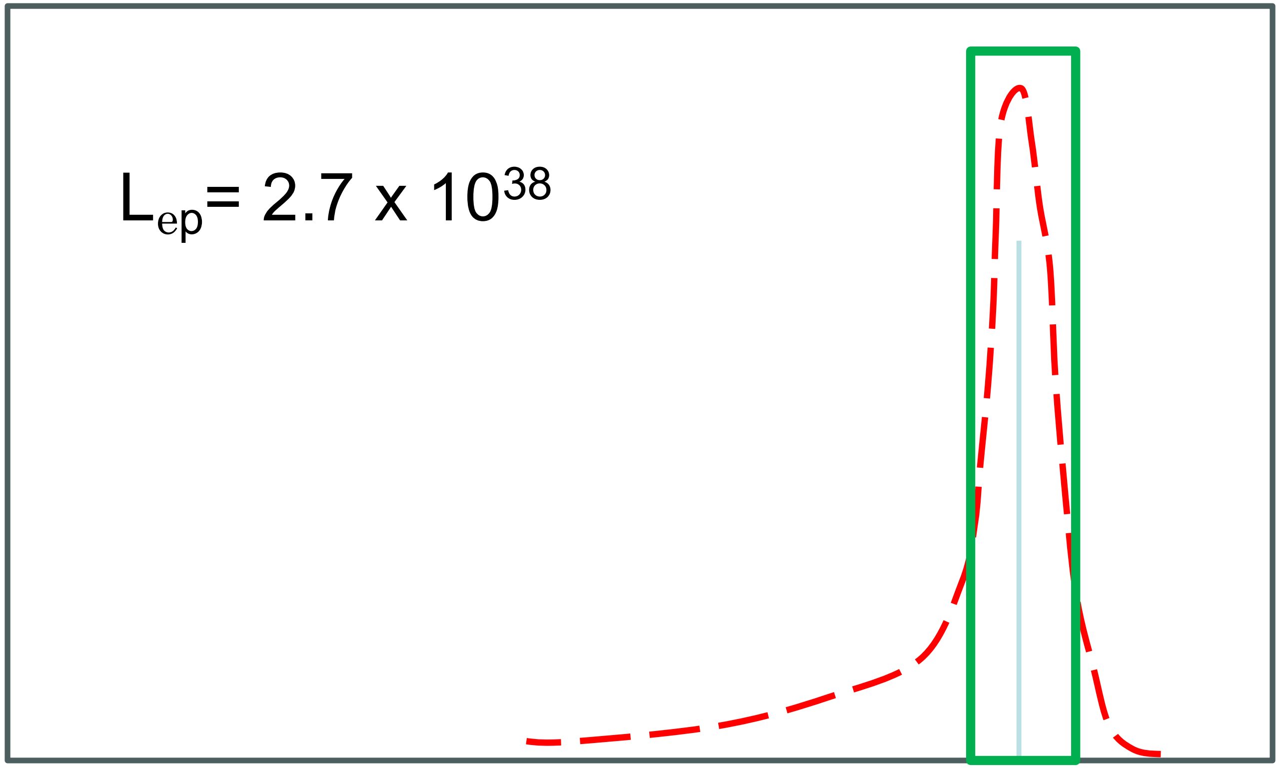
4. High efficiency of the charge particle spectrometer as a veto

5. Analysis of the distribution (3.) shape

6. Determination of the extra rate at the elastic “peak”

7. Beam helicity effect is 100% for e p --> ν n

H(e,e'p)




$\sigma_p$ = 0.5%

event rate at 30 deg,

50 msr ~ 190 kHz

E = 2.2 GeV

$Q^2$ = 1 $GeV^2$

Electron initial energy from a spectrometer event rate at (degrees) 30-e / 48-h

Electrons ~ 190 kHz

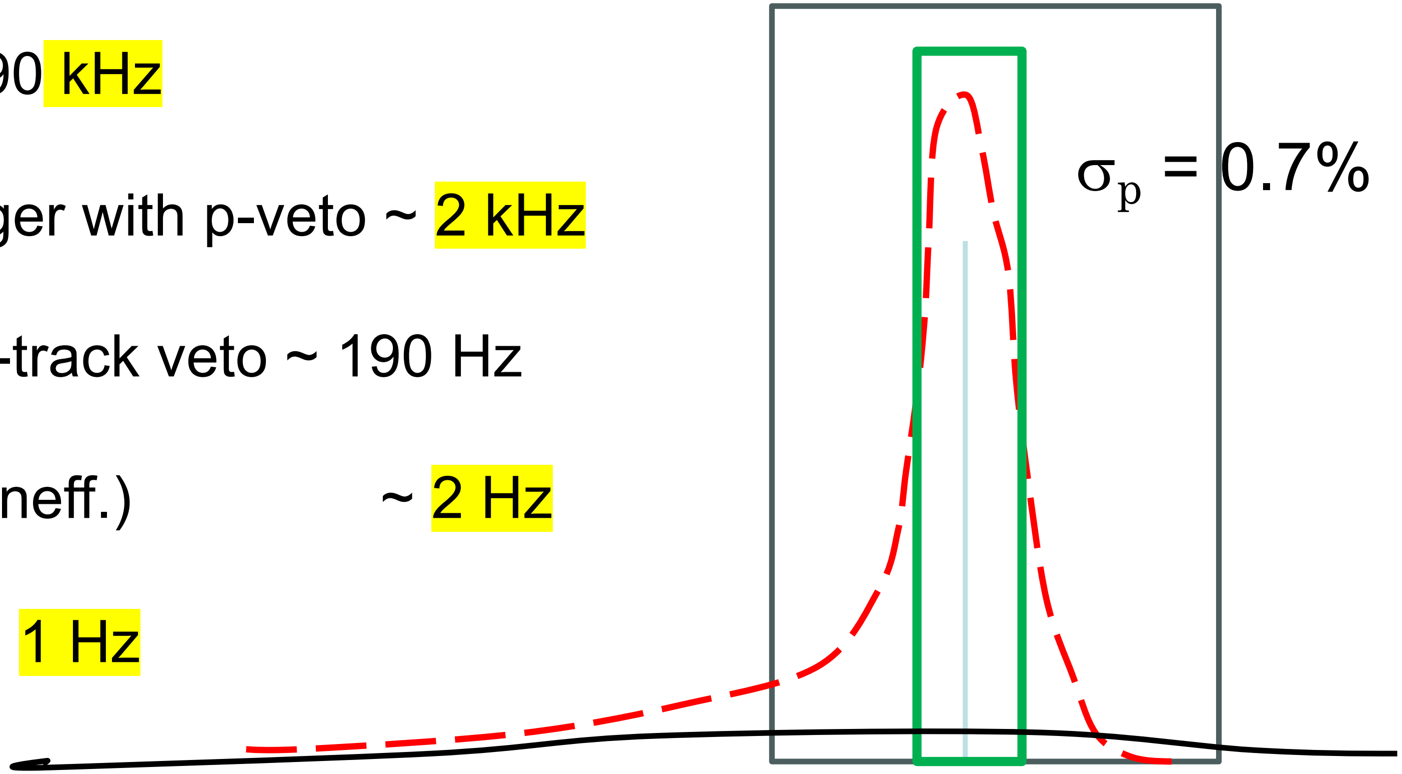
E-shower trigger with p-veto ~ 2 kHz

Off-line with e-track veto ~ 190 Hz

+ p-veto (1% ineff.) ~ 2 Hz

+ 50% n-eff. ~ 1 Hz

H(e, n \no p \no e’)

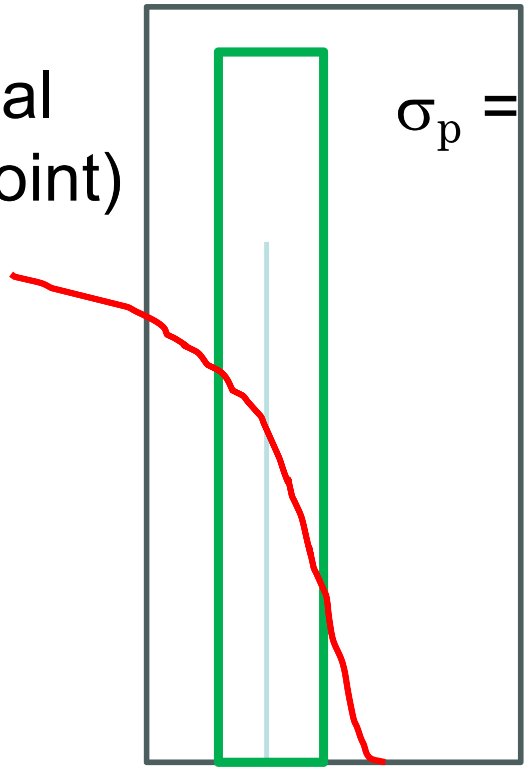



Electron initial energy from $T_p$ and $\theta_p$

Pion rate calculation:

$H(e,\pi^+n)$

$L_{\gamma p}= 6.3 \times 10^{34}$ (both real and q-real photons in 1.4% interval at end-point)



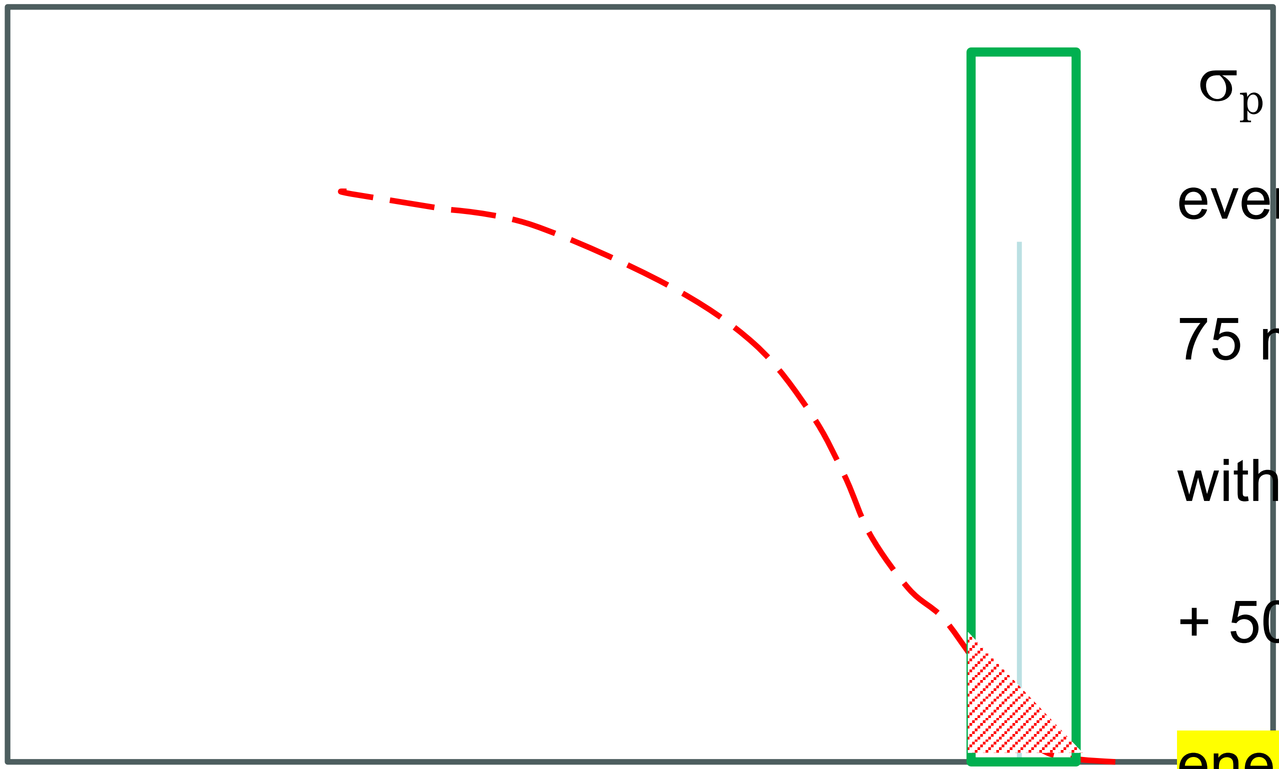
$\sigma_p = 0.5\%$

$d\sigma/d\Omega_{\pi\,(cms)} = 0.5 \times 10^{-30}\ cm^2/sr$
(CLAS arXiv:0903.1110) =>

Rate in 50 msr (lab solid angle)
is 400 Hz

Photon energy from a pion E, $\theta$ in the spectrometer

## H(e,n \no $\pi^+$)



$\sigma_p$ = 0.7%

event rate at 48 deg,

75 msr (neutron) 400 Hz

with $\pi$-veto ~ 20 Hz

+ 50% n-eff. ~ 10 Hz

energy shift effect => 5 Hz

Photon energy from $T_n$ and $\theta_n$ (assuming CC process)
It has 40 MeV (~ 2%) shift due to the pion mass effect

$$E_1 = (E_n - m_n + m_\pi^2/2m_n)/\left[1 + \frac{P_n \cos(\theta_n) - E_n}{m_n}\right]$$

Factor ~ 2 in the rate reduction

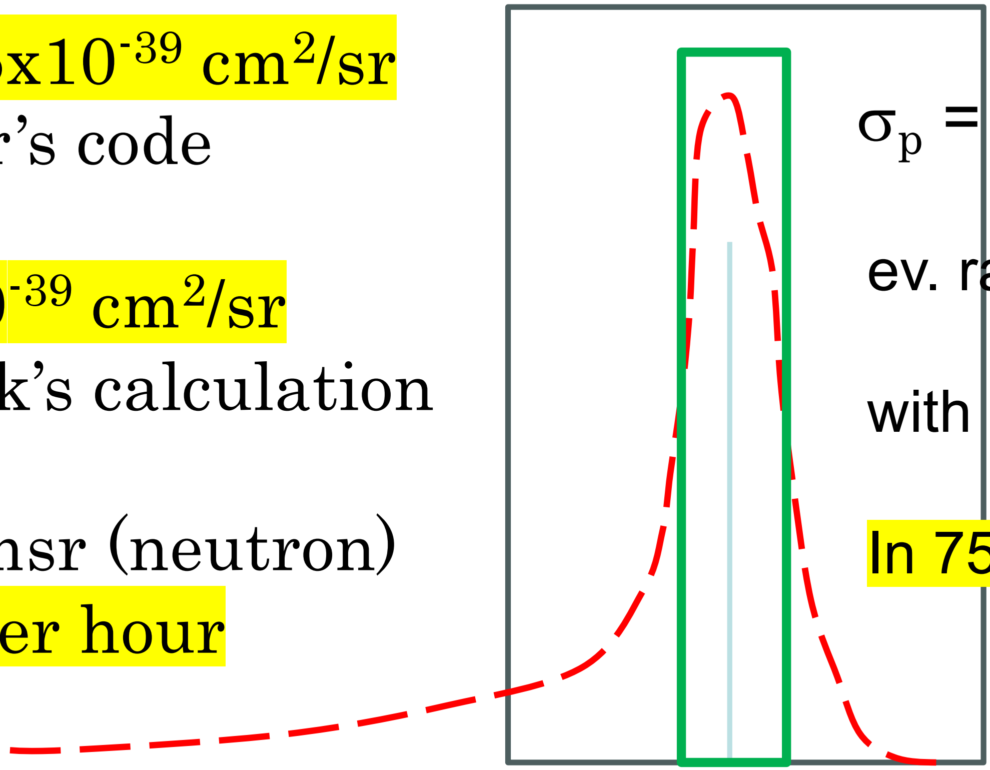
$L_{ep}$= 2.7 x $10^{38}$

$d\sigma/d\Omega_\nu$ = $2.5\times10^{-39}$ $cm^2/sr$
from A.Deur's code

Used $1.1\times10^{-39}$ $cm^2/sr$
from J.Golak's calculation

Rate in 75 msr (neutron)
is 54 per hour

H(e,n)ν



$\sigma_p$ = 0.7%

ev. rate at 48 deg,

with 50% n-efficiency

In 75 msr ~ 27 per hour

Electron energy from $T_n$ and $\theta_n$ (assuming CC process)

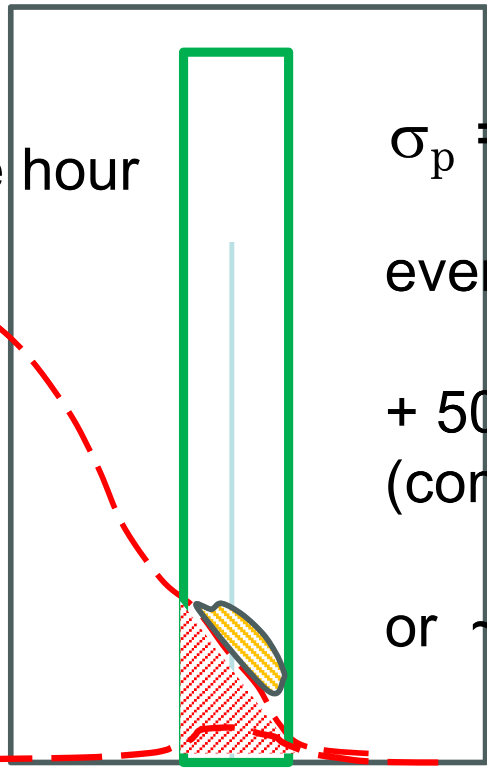
## H(e,n \no e') + H(e,n \no $\pi^+$ )

At $Q^2$ = 1 $GeV^2$

S/B ~ 27x0.85 / 21600 in one hour
($A_s$ = 1, $P_e$ = 0.85)

Beam helicity asymmetry
A = 1.1x$10^{-3}$
500 hours data taking run

A = 11x$10^{-4}$ +/- 3x$10^{-4}$



$\sigma_p$ = 0.7%

event rate at 48 deg,

+ 50% n-eff. ~ 6 Hz
(combined ep, $\gamma\pi$)

or ~ 21600 per hour

Electron energy from $T_n$ and $\theta_n$ (for CC process)

# Weak Proton Form Factor at 1 $GeV^2$

## Estimation of the experiment parameters:

- Beam energy 2.2 GeV with a 10-cm long LH2 target
- Electron/pion/neutrino angle 30 degrees, $p_e$ = 1.7 GeV/c
- Recoil proton/neutron 48 degrees, $p_n$ = 1.1 GeV/c

- $\pi$+ in SBS; efficiency ~ 90%+5% ($\mu$ are forward) – need MC

- Electron detection efficiency 99.9%; solid angle 50 msr – need MC

- Neutron: huge solid angle 75 msr; at 15 m distance: 2 m x 8 m

- For 1% $dE_1/E_1$ using $E_1 = (E_n - m)/\left[1 + \frac{P_n \cos\theta_n - E_n}{m}\right]$

  angular resolution $\delta\theta$ ~ 6 mrad => 8 cm coordinate
  time resolution dt => 0.11 ns

# Weak Proton Form Factor at 1 $GeV^2$

- Beam energy 2.2 GeV with a 10-cm long LH2 target
- Electron/pion/neutrino angle 30 degrees, $p_e$ = 1.7 GeV/c
- Recoil proton/neutron 48 degrees, $p_n$ = 1.1 GeV/c

- $\pi$+ in SBS; efficiency ~ 90%+5%? ($\mu$ are forward) – need MC

- Electron detection efficiency 99.9%; solid angle 50 msr – need MC

- Neutron: huge solid angle 75 msr; at 15m distance: 2m x 8m

- For 1% $dE_1/E_1$ using $E_1 = (E_n - m) / \left[1 + \frac{P_n \cos\theta_n - E_n}{m}\right]$

Projected result A = $11 \times 10^{-4}$ +/- $3 \times 10^{-4}$

Weak process cross section 1.1 +/- 0.3 x $10^{-39}$ $cm^2/sr$

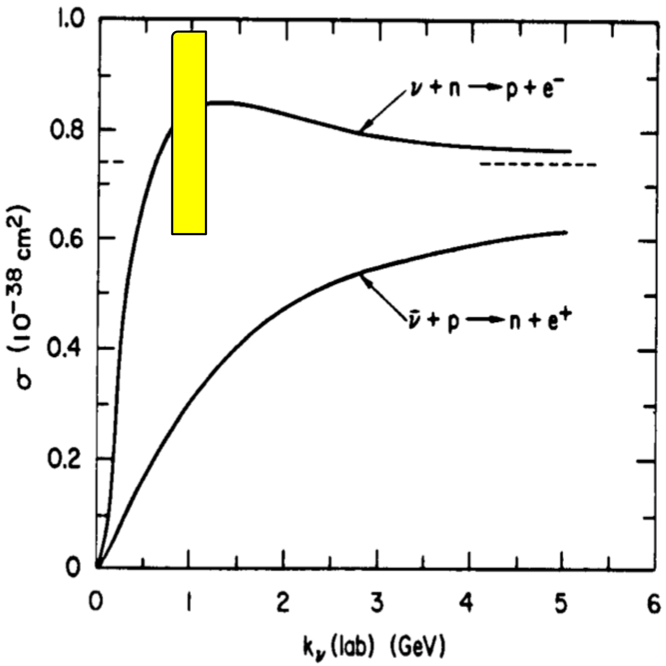
False asymmetry is below $10^{-5}$ , as it was MC for sFF: A in e,e'p due to the recoil proton side polarization and the detector as an analyzer

# Proton Axial-vector Form Factor at 1 GeV$^2$

Projected result A = 11x10$^{-4}$ +/- 3x10$^{-4}$

Weak process cross section 1.1 +/- 0.3 x 10$^{-39}$ cm$^2$/sr

After 500 hours data taking



# Modern ToF system CLAS12

*D.S. Carman, L. Clark, R. De Vita et al.*

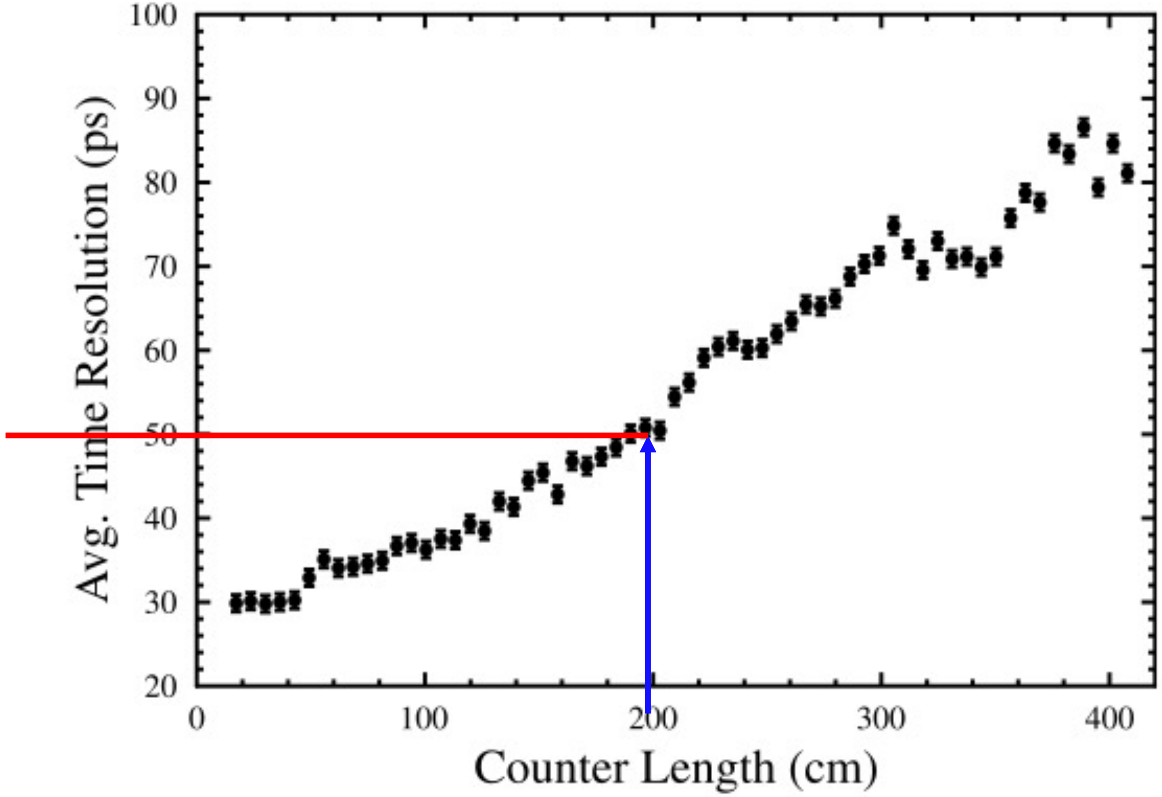



**Fig. 14.** Measurements of the time resolution (ps) vs. counter length (cm) achieved for the FTOF panel-1b system averaged over the six counters of a given length belonging to each CLAS12 Forward Carriage sector. These data were acquired on the bench using cosmic rays. Full details are included in Ref. [11].

# Modern ToF system CLAS12

| Parameter | Design Value |
|---|---|
| **Panel-1a** | |
| Angular Coverage | $\theta = 5^\circ \rightarrow 35^\circ$, $\phi: 50\%$ at $5^\circ \rightarrow 85\%$ at $35^\circ$ |
| Counter Dimensions | $L = 32.3$ cm $\rightarrow 376.1$ cm, $w \times h = 15$ cm $\times$ 5 cm |
| Scintillator Material | BC-408 |
| PMTs | EMI 9954A, Philips XP2262 |
| Design Resolution | 90 ps $\rightarrow$ 160 ps |
| **Panel-1b** | |
| Angular Coverage | $\theta = 5^\circ \rightarrow 35^\circ$, $\phi: 50\%$ at $5^\circ \rightarrow 85\%$ at $35^\circ$ |
| Counter Dimensions | $L = 17.3$ cm $\rightarrow 407.9$ cm, $w \times h = 6$ cm $\times$ 6 cm |
| Scintillator Material | BC-404 (#1 $\rightarrow$ #31), BC-408 (#32 $\rightarrow$ #62) |
| PMTs | Hamamatsu R9779 |
| Design Resolution | 60 ps $\rightarrow$ 110 ps |
| **Panel-2** | |
| Angular Coverage | $\theta = 35^\circ \rightarrow 45^\circ$, $\phi: 85\%$ at $35^\circ \rightarrow 95\%$ at $45^\circ$ |
| Counter Dimensions | $L = 371.3$ cm $\rightarrow 426.1$ cm, $w \times h = 22$ cm $\times$ 5 cm |
| Scintillator Material | BC-408 |
| PMTs | Photonis XP4312B, EMI 4312KB |
| Design Resolution | 145 ps $\rightarrow$ 160 ps |

e 1: Table of parameters for the scintillators, PMTs, and counters for the FTOF
›anel-1b, and panel-2 arrays.

# Backup slides

# Weak Proton Form Factor at 2 $GeV^2$

## Estimation of the experiment parameters:

- Beam energy 4.4 GeV with a 10-cm long LH2 target
- Electron/pion/neutrino angle 21 degrees, $p_e$ = 3.4 GeV/c
- Recoil proton/neutron 43 degrees, $p_n$ = 1.7 GeV/c

- $\pi$+ in SBS; efficiency ~ 96%+3% ($\mu$ are forward) – need MC

- Electron detection efficiency 99.9%; solid angle 50 msr – need MC

- Neutron: huge solid angle 135 msr; at 15 m distance: 4m x 8m

# Luminosities

$L_{ep}$= 2.7 x $10^{38}$ for 10 cm LH2 x 100 $\mu$A

Photon flux estimate:

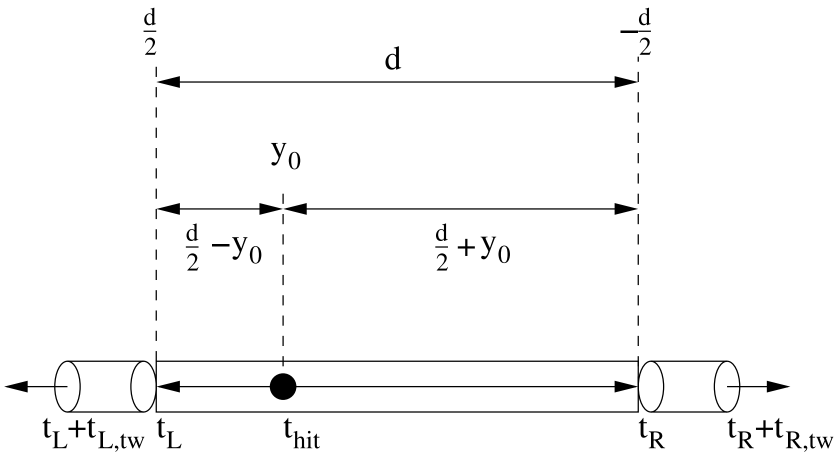
Quasi real: $I_e$ x 0.013 x $dE_\gamma/E_e$ x 0.75 (Budnev-1975)

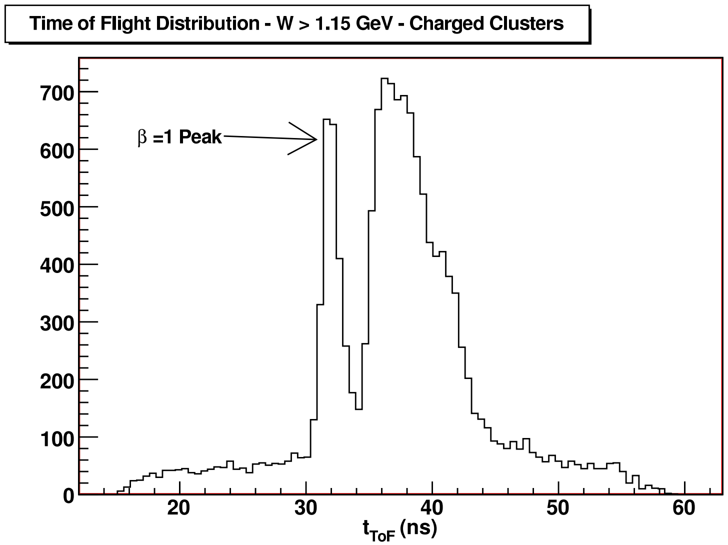
Real: $I_e$ x 0.007 x $dE_\gamma/E_e$ ( 10cm LH2 / 2 / 735cm )

$I_e$ x (0.013 x 0.014 x 0.75 + 0.007x 0.014)

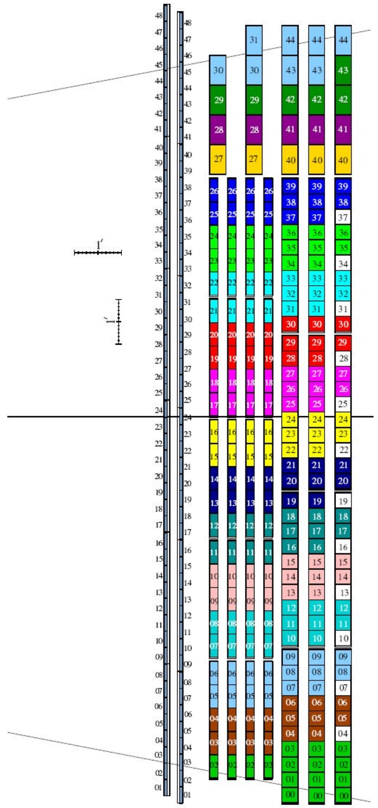
$L_{\gamma p}$= 6.3 x $10^{34}$

# Time-of-flight

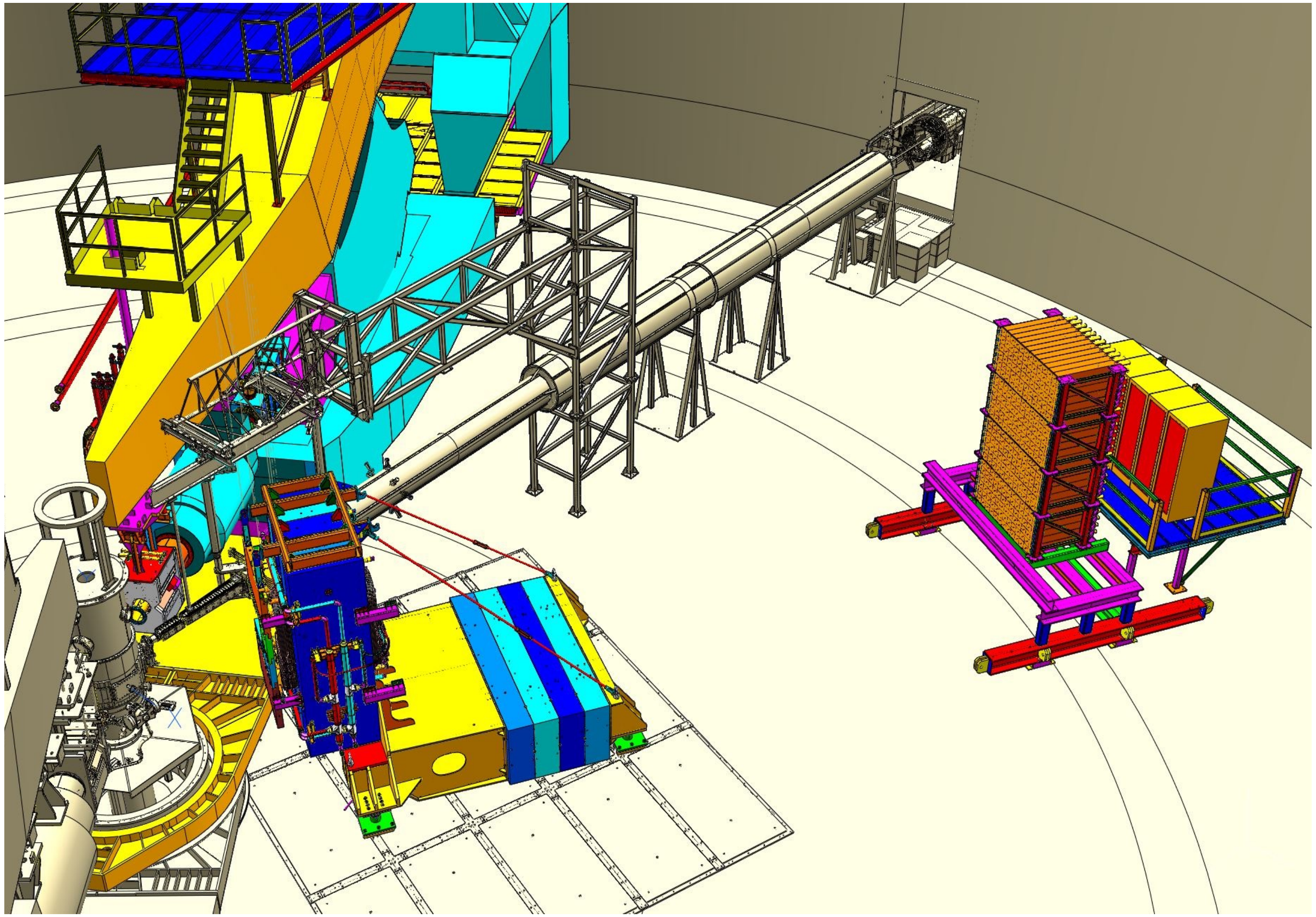


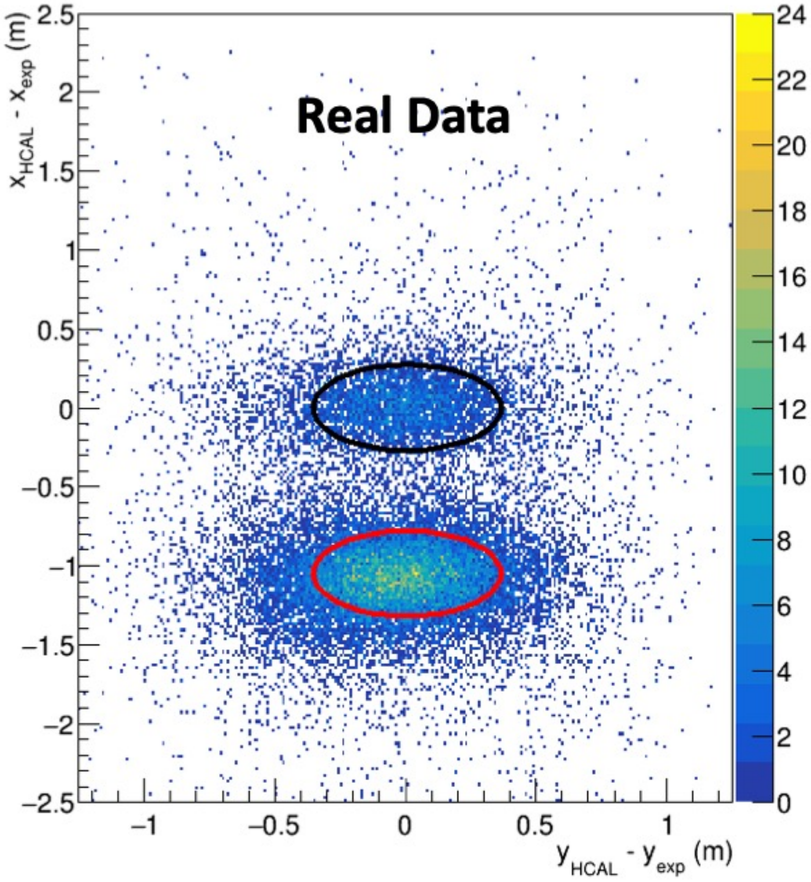

GEn-I “Big Hand”

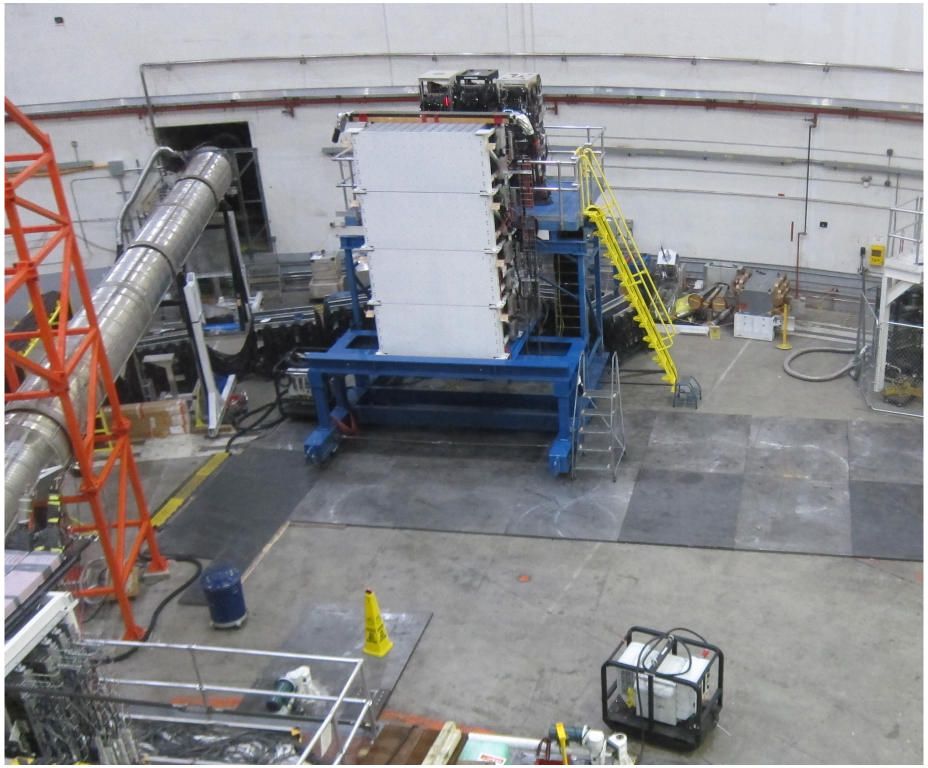


# SBS neutron arm – Hadron Shower Calorimeter



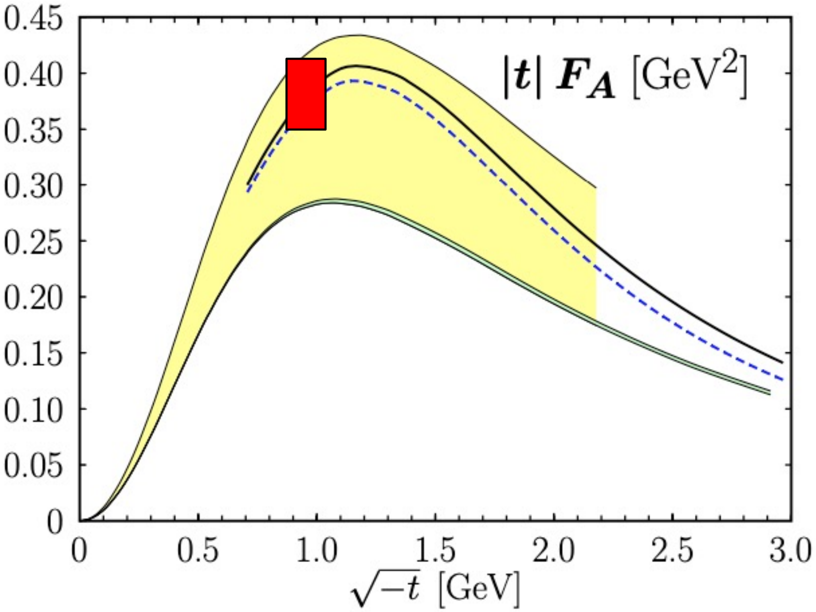
# SBS neutron arm



# Isovector axial FF and GPD $\tilde{H}$

M. Diehl, P. Kroll arXiv:1302.4604; hep-ph>arXiv:1703.05000




JLab - Wide Angle Compton Scattering:

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha_{em}^2}{s^2}\left[-\frac{u}{s} - \frac{s}{u}\right]\left\{\frac{1}{2}\left(R_V^2(t) + R_A^2(t)\right) - \frac{us}{s^2+u^2}\left(R_V^2(t) - R_A^2(t)\right)\right\}$$

$$K_{LL} = 2\frac{-t}{s-u}\frac{R_A}{R_V}\frac{1+\eta\kappa_T}{1+\kappa_T^2}\left[1 + \frac{t^2}{(s-u)^2}\frac{R_A^2}{R_V^2}\frac{1}{1+\kappa_T^2}\right]^{-1}$$