Elastic Neutrino-Nucleon Scattering

Argonne, July 2002

C. J. Horowitz

Elastic Neutrino Scattering

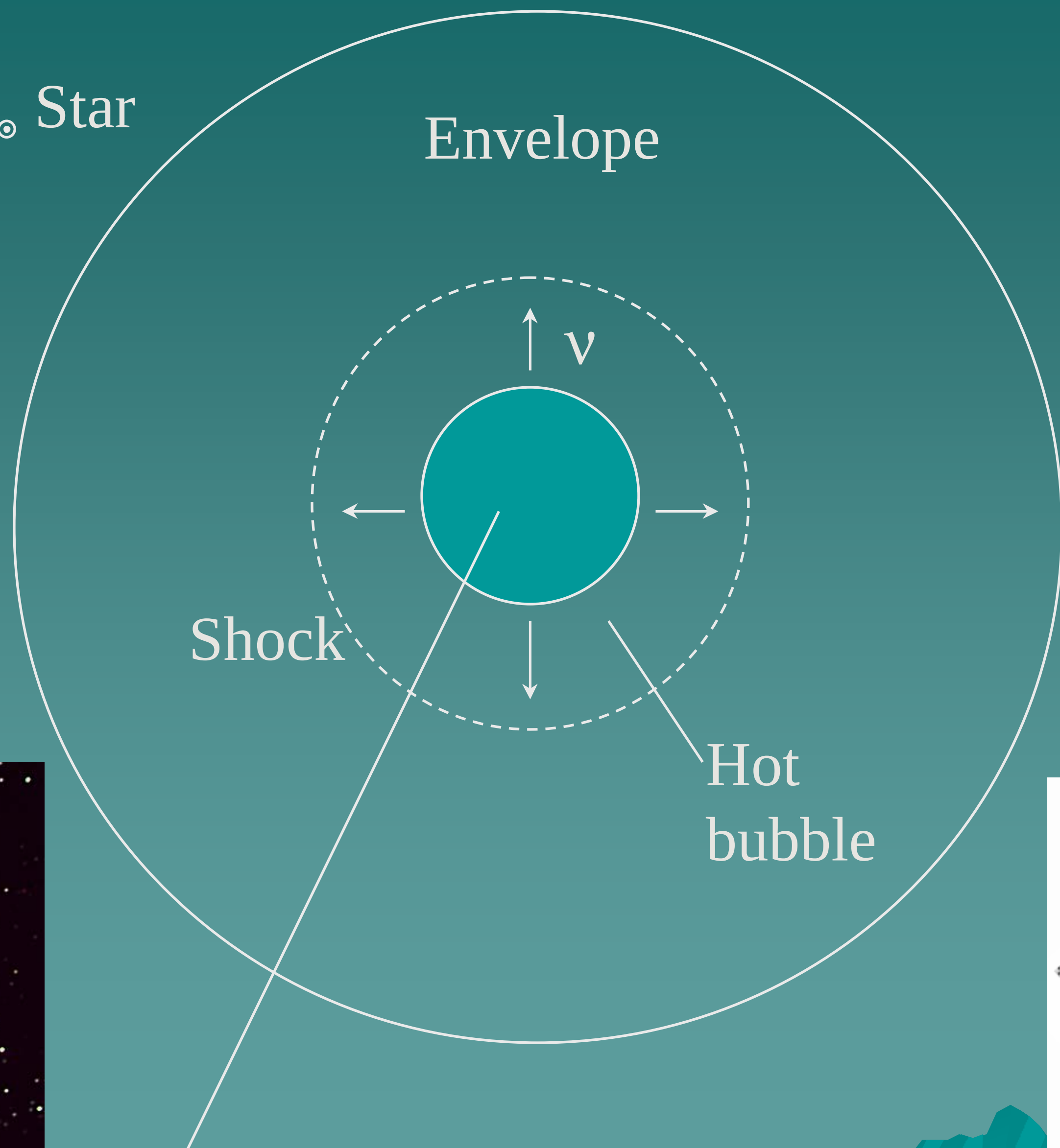
- Nothing in.
- Nothing out.
- Nothing happens.

Neutrino Elastic Scattering

- Supernovae
  - Introduction
  - Opacity dominated by ν-n elastic
  - Detection via ν-p and ν-A elastic
- Strange quark content of nucleon
  - Parity violating electron scattering
  - Contributions to nucleon spin
- Past ν-p elastic measurements
- Future exp: controlling systematics

Core collapse supernova

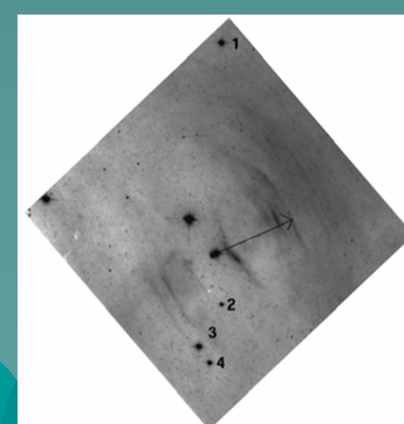
>8M$_\odot$ Star



Proto-neutron star: hot, e rich

July 5,
1054

Crab nebula



Opacity Dominated by ν-n Elastic

- Energy transport mostly by ν_x ($\equiv \nu_\mu, \nu_\tau$) because twice as many as ν_e and ν_x without charged currents, have longer mean free path.
- Opacity of ν_x mostly from ν-n elastic.
- Incorrect elastic cross sec caused Oak Ridge simulation to explode when it did not with correct one.
- Uncertainty in ν-n cross sec from strange quarks very relevant for SN simulations.

Detecting Supernova ν

- Important to measure total energy radiated in neutrinos. This is binding E of proto-neutron star ~3/5 GM^2/R.
- Astrophysicists very interested in mass of proto-neutron star. Compactness, M/R, important for SN mechanism, ν driven wind and nucleosynthesis.
- Benchmark for ν osc. measurements.
- Most E in ν_x because twice as many as ν_e.

Need to Measure ν_x

- 20 anti-ν_e detected from SN1987A via anti-ν + p $\rightarrow$ n + e^+.
- To measure energy of ν_x need two-body final states: ν-e, ν-p or ν-A elastic.
- ν_x-e has small cross sec, swamped by background from ν_e-e.
- ν-p elastic may be possible in Kamland [J. Beacom].
- ν-A has very large cross section.

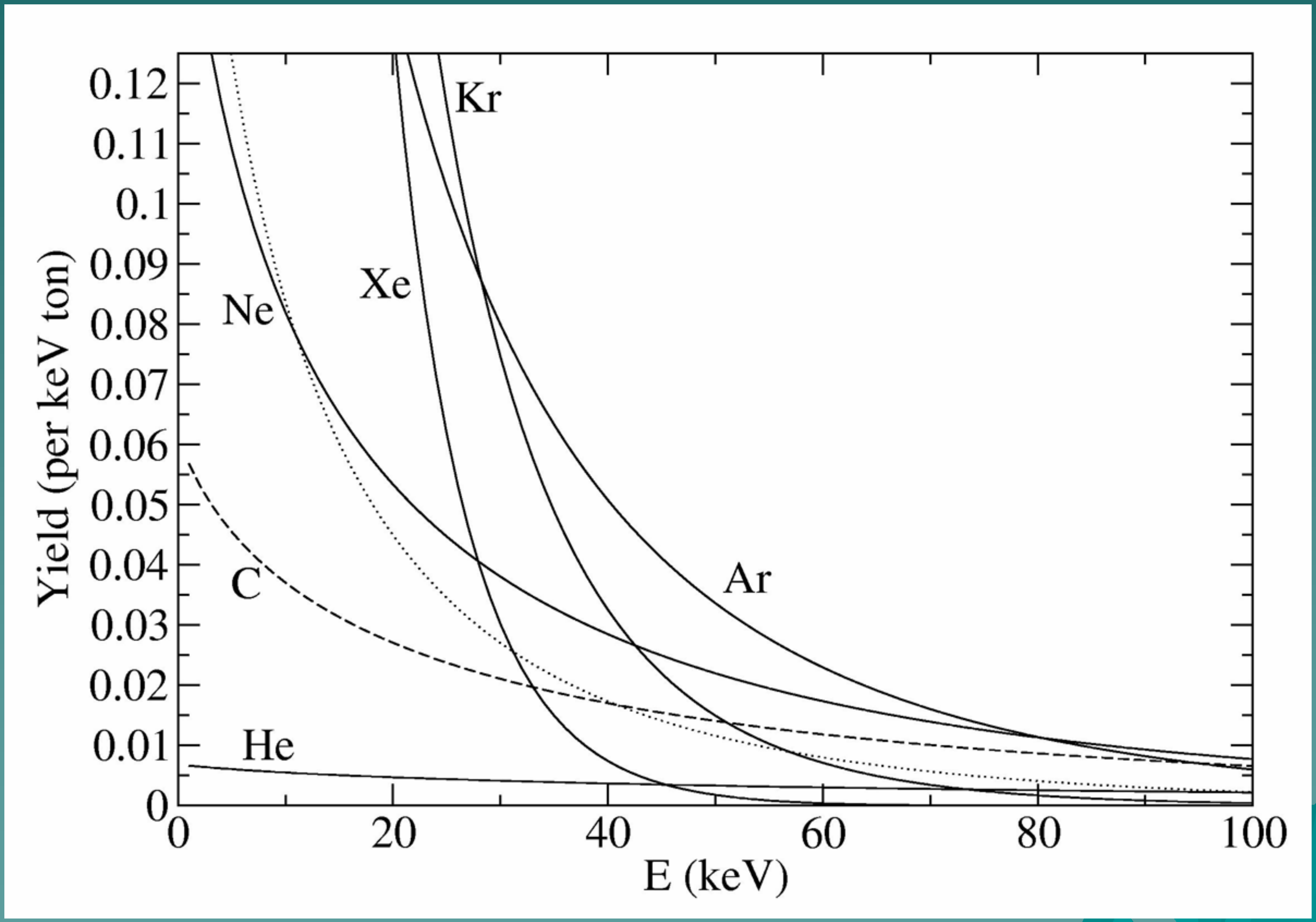
Underground Laboratory

- Underground lab. will facilitate low background, low threshold, large mass experiments.
- Detecting low energy solar ν, dark matter, and supernovae via ν-A elastic scattering are complimentary.
- Backgrounds for SN $\ll$ solar ν or dark matter [Events in known ~10 sec. interval with ~ half in first sec.]

CLEAN (D. McKinsey)

- Liquid Ne scintillator (≈ 100 tons) for low energy solar ν via ν-e scattering.
- Liquid is self cleaning of radioactive impurities for low backgrounds and thresholds.
- Coherent ν_x-Ne cross sec gives yields up to 4 events / ton for SN at 10 kpc ($\geq$ 20 times anti-ν_e+p in H_2O).
- Should yield large very clean ν_x signal.

Recoil Spectrum



Strange quark content of nucleon

$$\langle f \,|\, J_\mu^H \,|\, i\rangle = \bar{u}_f(p')\left[\gamma_\mu F_1(Q^2) + i\frac{\sigma^{\mu\nu}}{2M_p} q^\nu F_2(Q^2) + \gamma_\mu\gamma_5 G_A(Q^2)\right] u_i(p)\,,$$

- Three form factors
- F_1^s, F_2^s, G_a^s
- Low Q limits:
  - $F_1^s(0)=0$, dF_1^s/dQ^2 → strangeness radius ρ_s,
  - $F_1^s=(\rho_s+\mu_s)\, Q^2/4M^2$ for small Q^2
  - $F_2^s(0)=\mu_s$ strange magnetic moment,
  - $G_a^s(0)=\Delta s$, fraction of nucleon spin carried by s

Assume good isospin

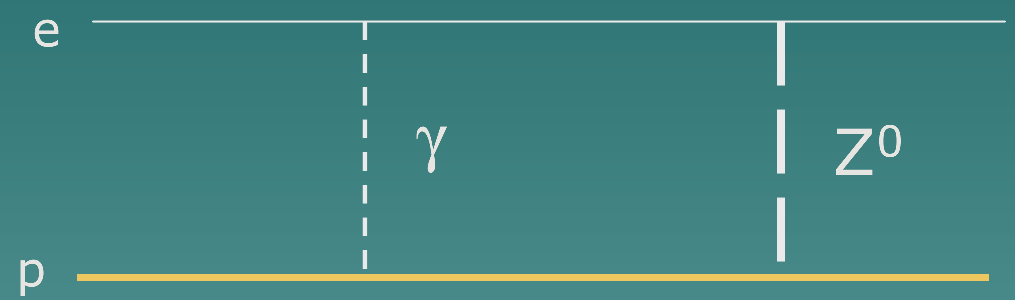
- Assume strange quarks in proton same as in neutron: s is isoscalar.
- Three observables: E+M form factor of proton, neutron and parity violating weak from factor of proton: allows separation of u, d, and s contribution.
- Without assuming isospin, can't separate d from s, even in principle, because they have same E+M and weak charge.

Parity Violating Electron Scattering

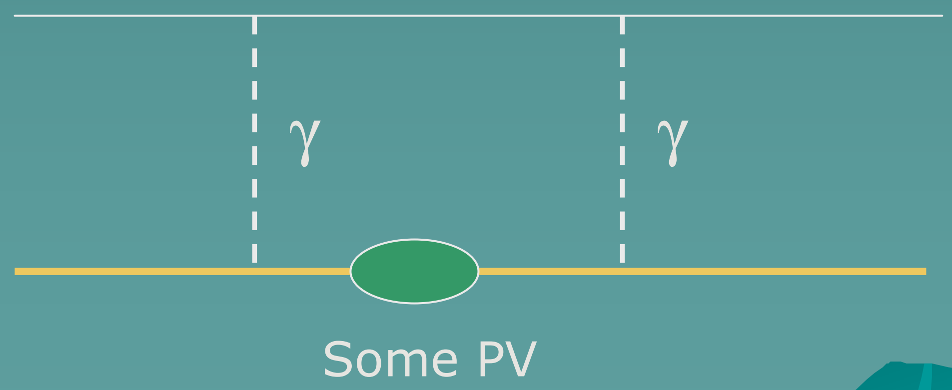
- Measure asymmetry in cross section of right handed versus left handed electrons. $A \approx 1$ ppm
- Sensitive to interference between Z^0 and γ exchange.
- Forward angles: F_1^s, back angles F_2^s
- Little sensitivity to G_a^s because of small vec. weak coupling of electron (and radiative corrections). PV can't get Δs!

Radiative Corrections

- Lowest order matrix elem. Squared

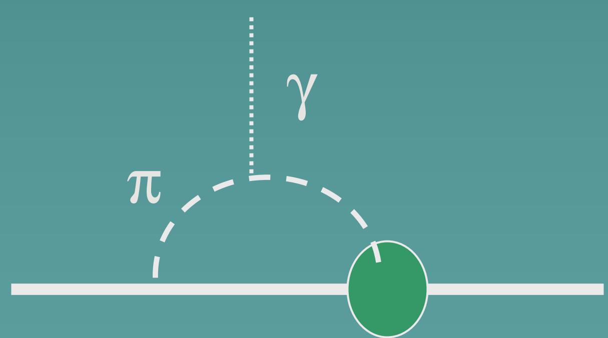


- Radiative correction



Radiative Corrections

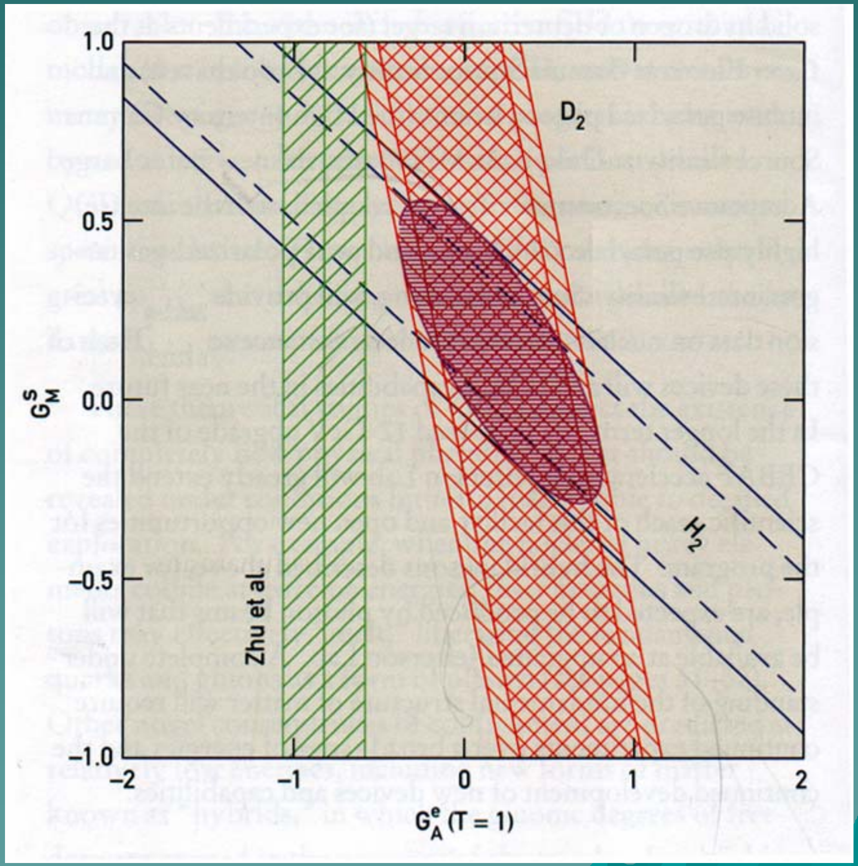
- Parity violation admixture in either initial or final wave function. Nucleon need not have good parity.
- Parity violating coupling of photon to nucleon (anapole moment).



Example: photo couples to pion loop which has parity violating weak coupling to nucleon

Sample Results

- PV on H and D give both radiative corrections and μ_s.
- $G_M{}^s$ (or μ_s) consistent with zero put large errors.
- Radiative corrections much larger then expected.



HAPPEX

- Forward angle exp. at Jefferson Lab Hall A, Q^2=0.5 Gev^2.

$$G_E^s(-0.48) + 0.39 G_M^s(-0.48) = +0.023 \pm 0.034 \pm 0.022 \pm 0.026.$$

- Errors: stat., syst. and E+M form factors
- SAMPLE:

$$G_M^s(Q^2 = 0.1) = (+0.14 \pm 0.29\,(\text{stat.}) \pm 0.31\,(\text{syst.}))\ \text{n.m.}.$$

Other PV Experiments

- G_0 will measure PV from H and D at front and back angles over large Q^2 range.
- A4 in Germany, PV from H at intermediate angles.
- HAPPEX II: PV from H at more forward angle Q^2=0.1 GeV^2.
- Low Q^2 ^{4}He experiment isolates F_1^s
- Elastic PV from Pb will measure neutron radius. [Weak chage of n $\gg$ p].
- Q_{weak} PV from H at low Q^2 as standard model test. Also PV e-e exp. at SLAC.

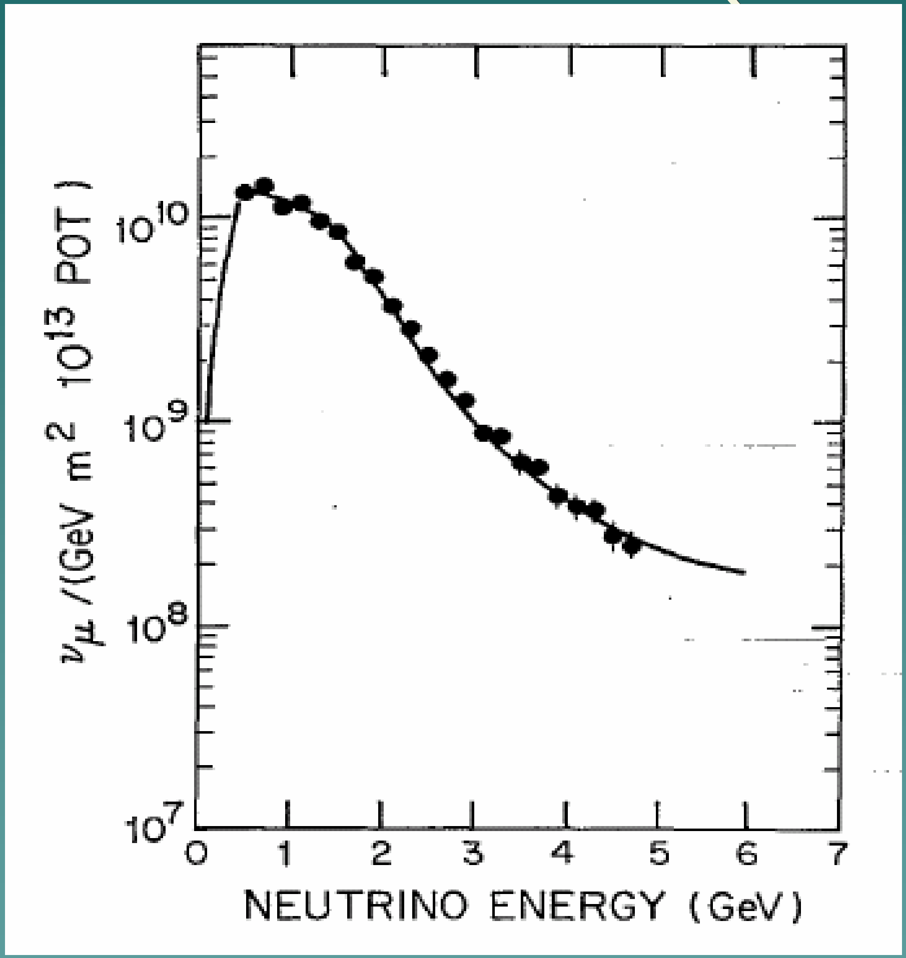
Bring Me the Head of a Strange Quark

- Can one measure μ_s with accuracy much better than ± 0.3 ?
- Can one find a significantly nonzero strange quark signal with PV??
- It may be very hard to improve significantly on the systematic errors of SAMPLE and G_0.

Neutrino-Nucleon Elastic Scattering

- Measure both Δs and μ_s
- Radiative corrections small.
- Past experiments (BNL, LSND)
- Present (BOONE)
- Future ratio experiments very promising.

BNL Exp. With 170 ton detector in wide band beam (1986)



BNL cross sections

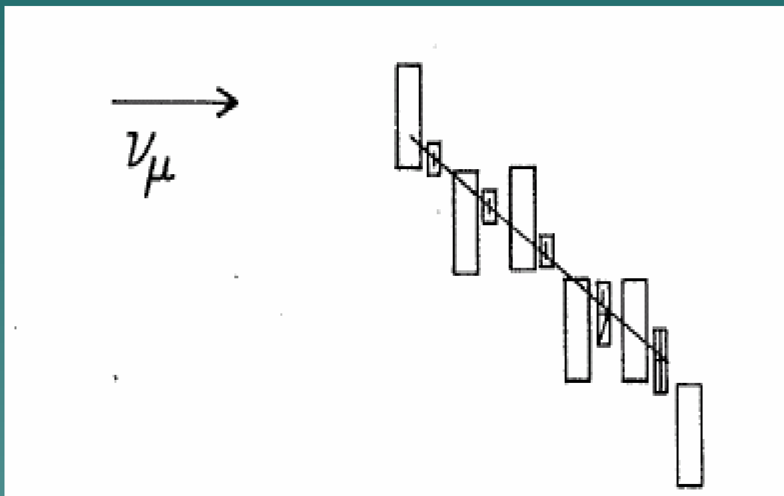
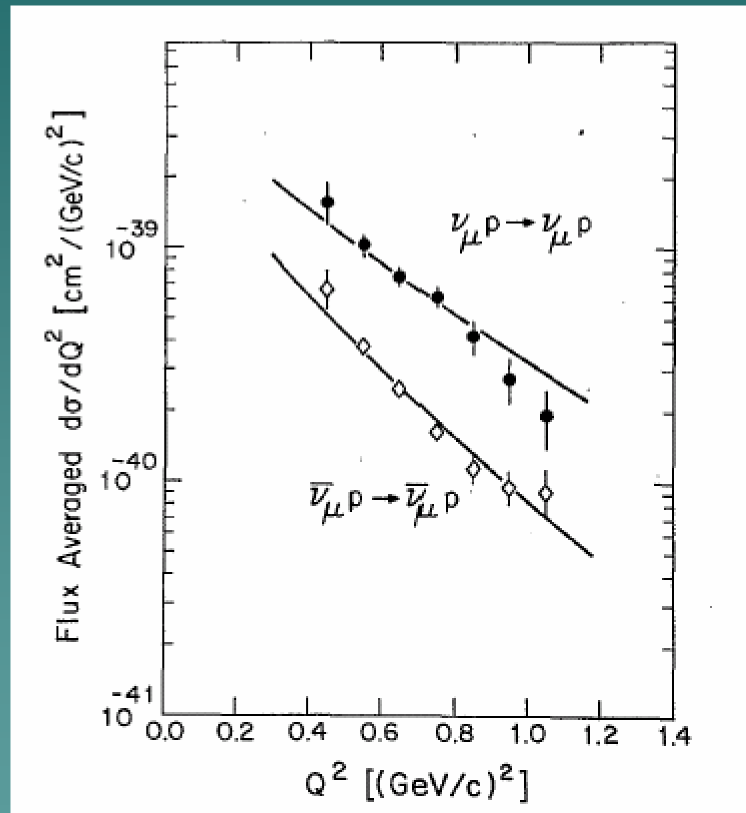


FIG. 5. The side view of a typical elastic-scattering candidate. The large boxes represent scintillator cells and the smaller boxes PDT cells hit. The best fit to the PDT drift positions (shown inside the PDT cells) is drawn on the event.



Energy of recoil gives Q^2, this + angle gives E_ν

$$G_A(Q^2) = \frac{1}{2}\frac{g_A(0)}{(1+Q^2/M_A{}^2)^2}(1+\eta)$$

$\Delta s = -1.26\eta$

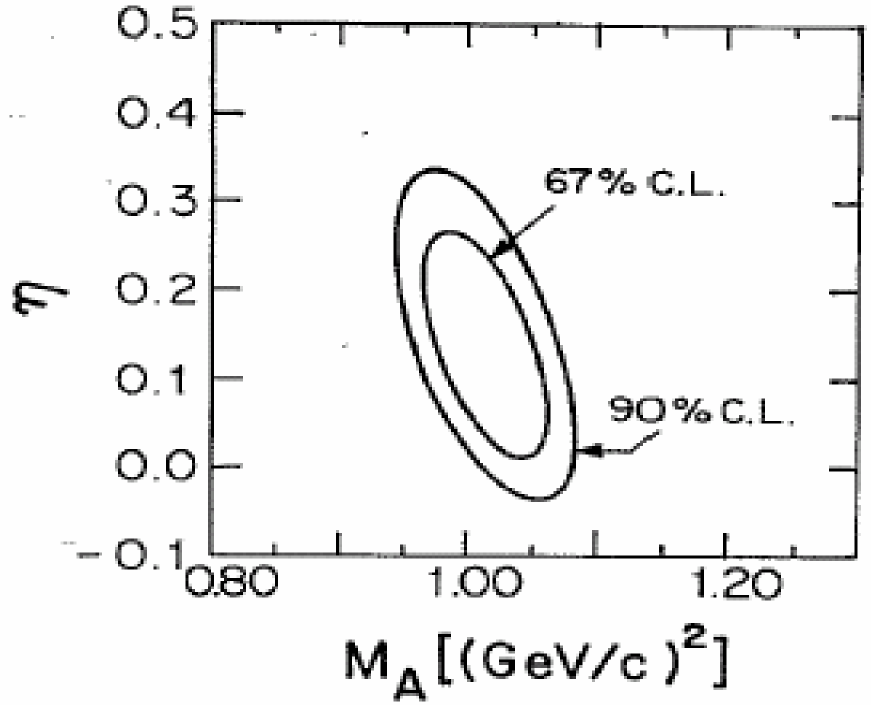
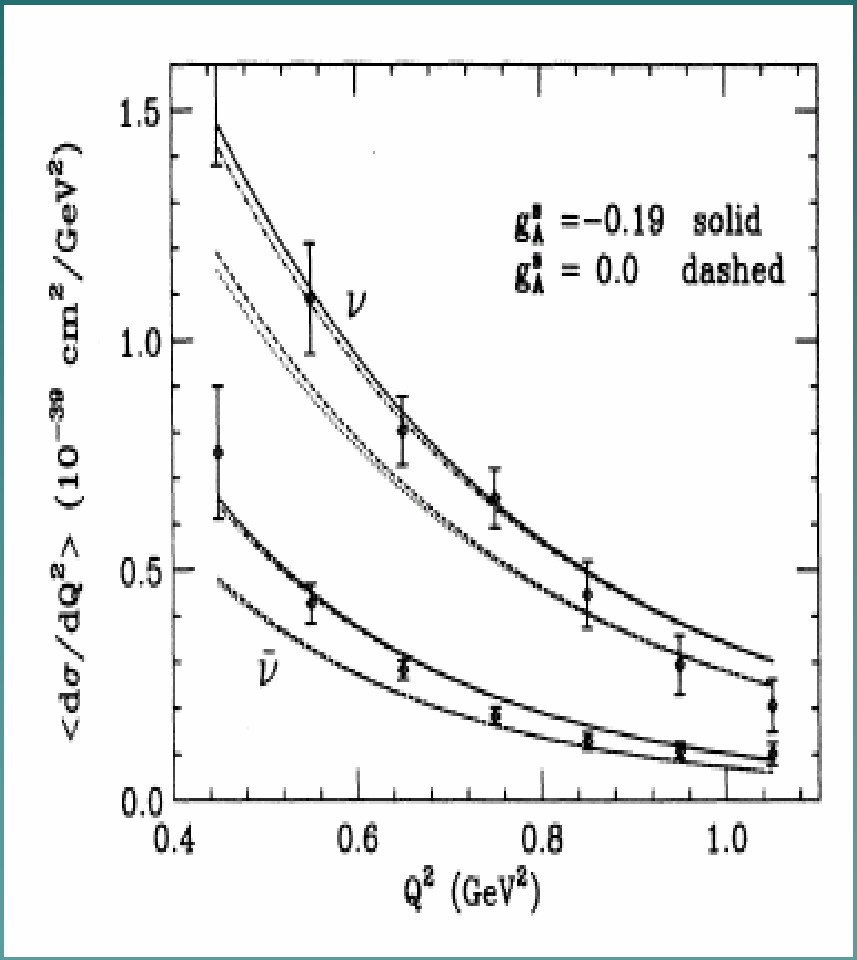
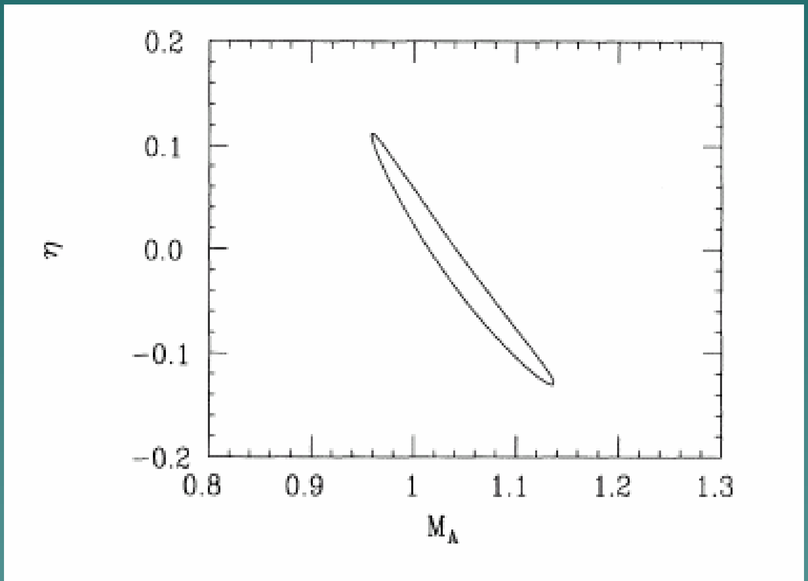


FIG. 37. Simultaneous fit of $d\sigma/dQ^2$ for the neutrino and antineutrino elastic-scattering samples in M_A, η space with $\sin^2\theta_W$ fixed at 0.220. M_A has been constrained to the world-average value.

CJH+S. Pollock, PRC48('93)3078





Rel. Mean Field Calculations compared to BNL data.

Δs or η strongly correlated with M_A.

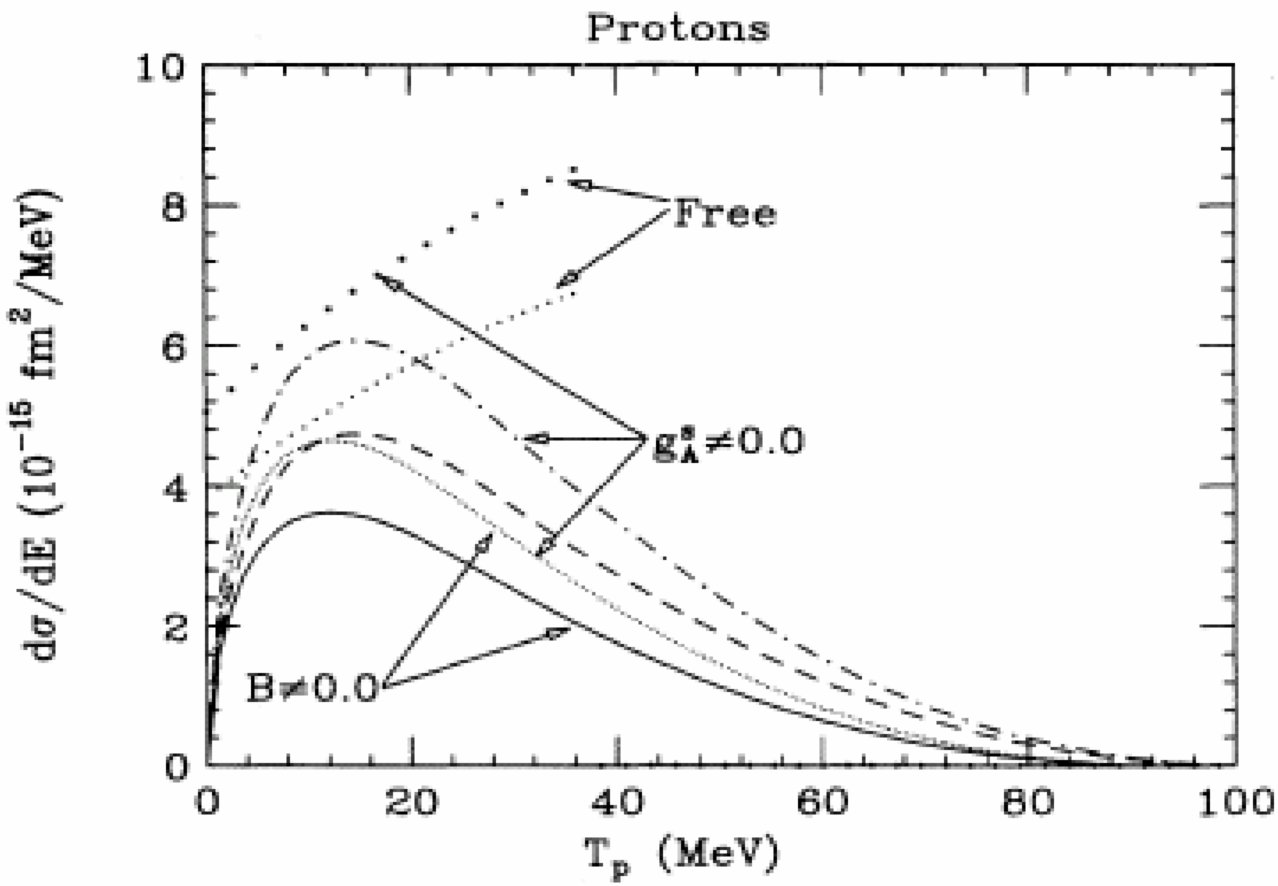
Sensitivity to Parameters

TABLE I. Differential cross section averaged over the BNL neutrino spectrum [9] and logarithmic derivatives with respect to various parameters for proton and neutron knockout at $Q^2 = 0.75\ \mathrm{GeV}^2$.

	ν		$\bar{\nu}$	
	p	n	p	n
$\left\langle \frac{d\sigma}{dQ^2} \right\rangle$ [a]	0.65	0.58	0.23	0.16
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial M_A}$ [b]	2.27	1.63	3.63	1.88
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial g_A^s}$	-1.02	0.98	-1.60	1.11
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial \mu_s}$	-0.25	0.26	0.16	0.06
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial \rho_s}$	0.0	0.03	0.02	0.13

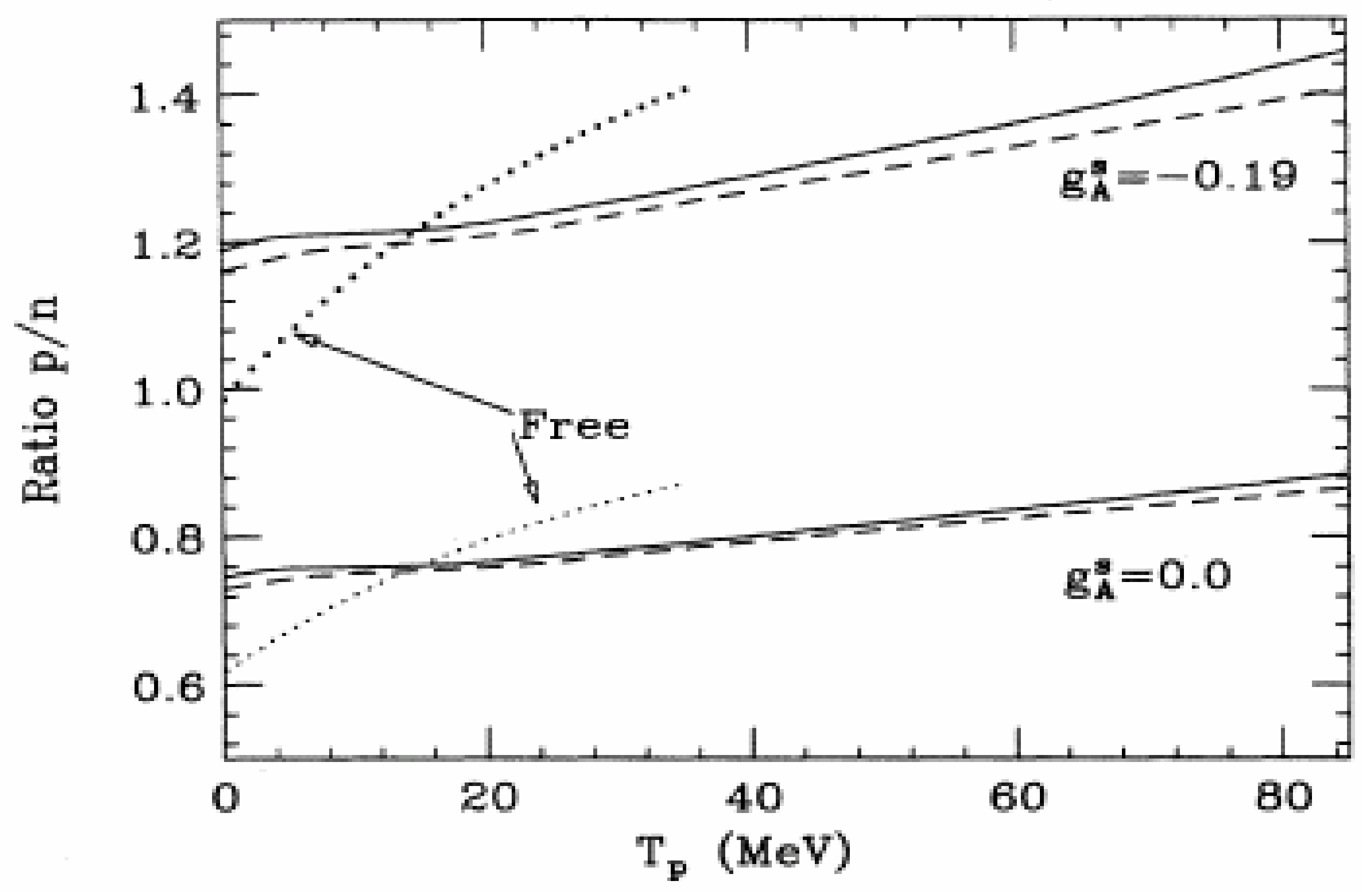
[a] $10^{-39}\ \mathrm{cm}^2/\mathrm{GeV}^2$.
[b] GeV^{-1}.

E_ν=150 MeV



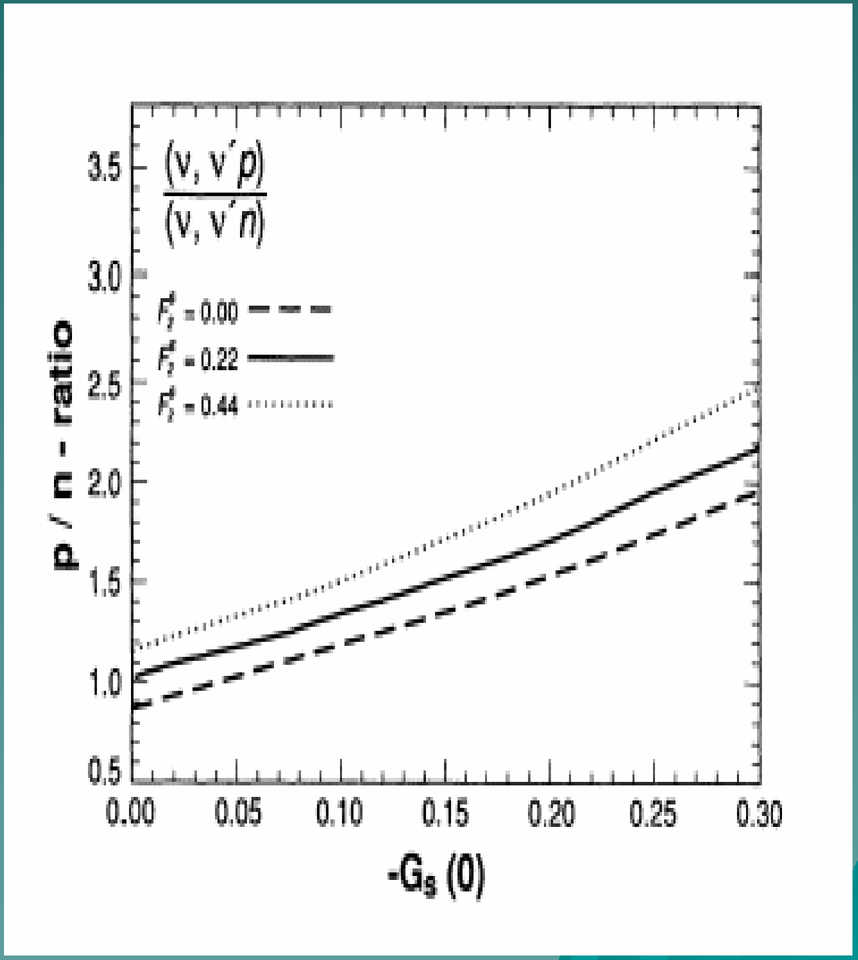
Protons
Free
$g_A^s \neq 0.0$
B≠0.0
dσ/dE (10^{-15} fm^2/MeV)
T_p (MeV)
0
2
4
6
8
10
20
40
60
80
100

Ratio of p/n sensitive to Δs



Garvey, Kolbe, Langanke and Krewald

- Continuum RPA calculation averaged over LSND's decay in flight ν beam.
- Ratio very sensitive to Δs, some sensitivity to μ_s.



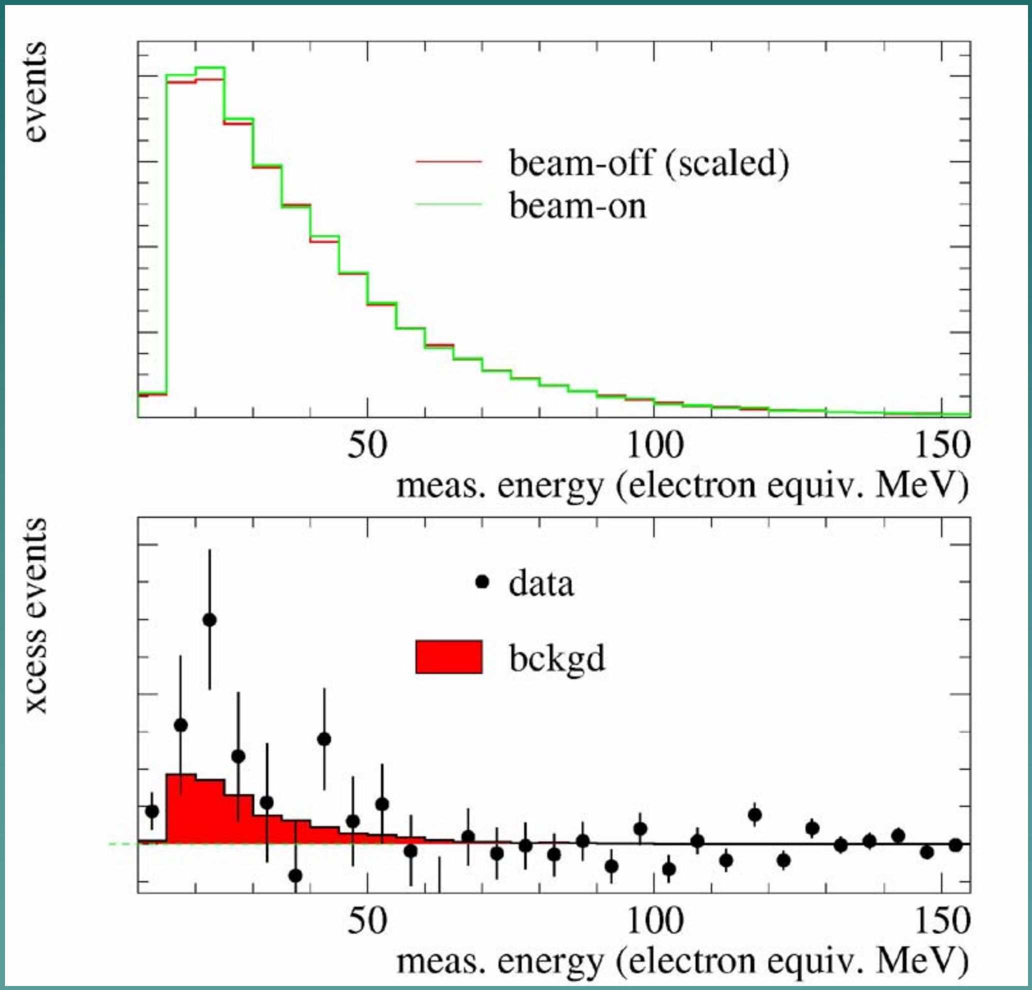
Low E Sensitivity to Parameters

TABLE II. Differential cross sections and logarithmic derivatives with respect to various parameters for a 150 MeV neutrino to knockout a 30 MeV neutron or proton.

	ν		$\bar{\nu}$	
	p	n	p	n
$\frac{d\sigma}{dE_p}$ [a]	0.79	0.64	0.48	0.32
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial M_A}$ [b]	0.23	0.18	0.28	0.19
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial g_A^s}$	−1.22	1.21	−1.58	1.48
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial\mu_s}$	−0.11	0.11	0.13	−0.12
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial\rho_s}$	0.0	0.0	0.0	0.0

[a] 10^{-15} $\mathrm{fm}^2/\mathrm{MeV}$.
[b] GeV^{-1}.

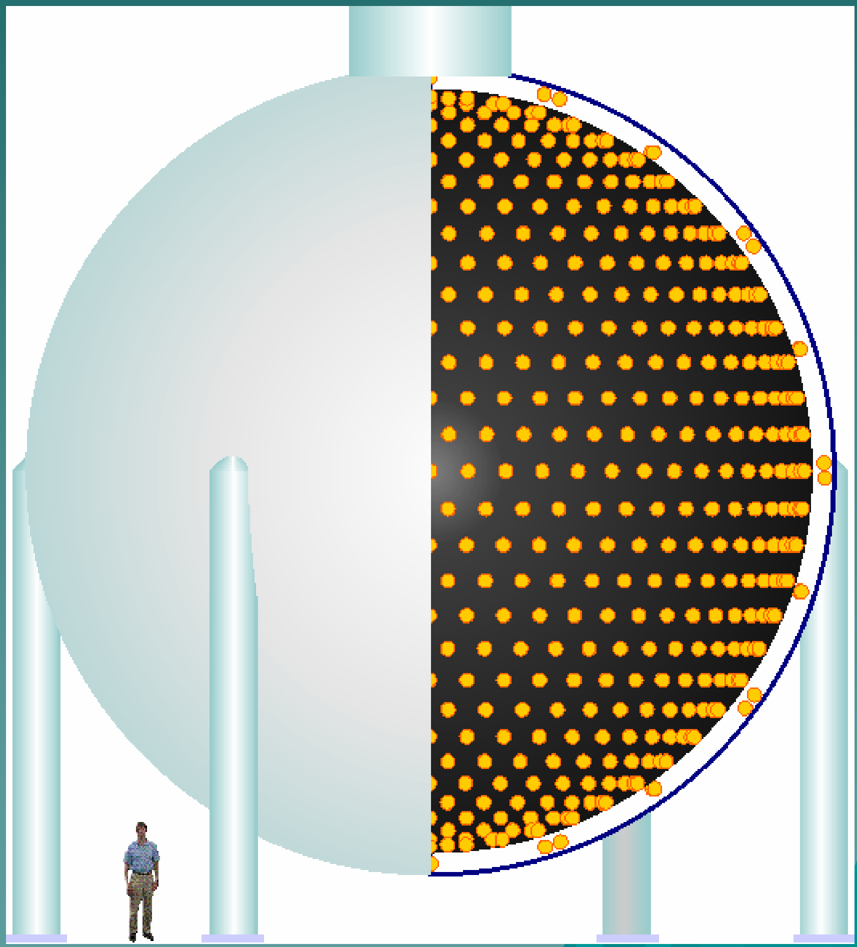
LSND had background problems



Rex Tayloe

Mini Boone

- In $<E_\nu> \approx$ 800 MeV beamline.
- Large tank of mineral oil (Both Cerenkov and scint. Light).
- Will try and measure ratio of neutral to charged current.
- However lack of segmentation will limit precision.



A Future ν-p Elastic Experiment

- Physics goals are compelling:
  - $G_a^s(Q^2)$ and Δs.
  - F_2^s or μ_s independent of PV radiative correcections.
- Very attractive ν fluxes at beam lines for long baseline ν-osc. experiments (NUMI, BOONE, KeK…)

Need to control systematic errors!

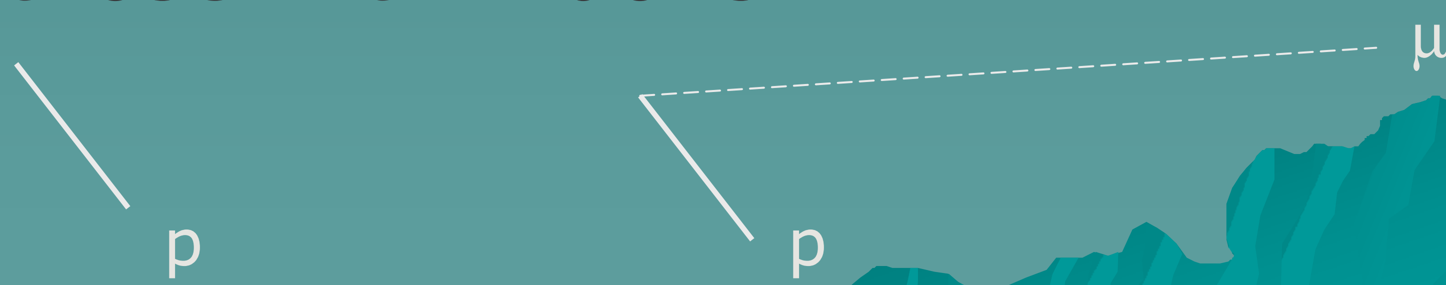
- Beam flux and spectrum (measure a ratio)
- Theory errors from:
  - M_A (lower Q^2, measure M_A, look at a ratio),
  - μ_s (lower Q^2, also measure with anti-ν).
- Detector efficiencies, backgrounds.
- Inelastic contributions: Pions! (good particle id, segmented detector, lower beam energy)
- Nuclear structure ($Q^2 \geq 0.5$ Gev^2)
- Two-body contributions to rxn. Mechanism.

Possible ratio measurements

- Ratio of ejected neutrons to protons
  - Very sensitive to Δs.
  - Insensitive to beam flux.
  - Insensitive to "isoscalar" distortions.
  - Worry about neutron detection efficiency and two-body corrections to reaction mechanism.
  - At high Q^2, neutron detection hard.

Ratio of Neutral to Charged Currents

- Ratio of protons from: $\nu + p \rightarrow \nu + p$ to protons from: $\nu + n \rightarrow \mu^- + p$.
- Note, both are quasielastic scattering from an N=Z nucleus such as ^{12}C.
- Very simple observable: ratio of protons of a given E without muons to those with muons.



Example: E_ν=0.8 GeV, Q^2=0.5

- $R \approx 0.14$
- Assume $G_a^s = \Delta s/(1+Q^2/M_A^2)^2$
- Error in extracted Δs
  - 5% measurement of R 0.04
  - $\pm$0.03 GeV uncer. in M_A 0.01
  - $\pm$0.3 uncer. in μ_s 0.07
  - $\pm$2 uncer. in ρ_s 0.002

- 5% ratio sensitive to Δs at $\pm$0.04
- Determine one combination of Δs and μ_s from ν and another from anti-ν.

Experimental Considerations

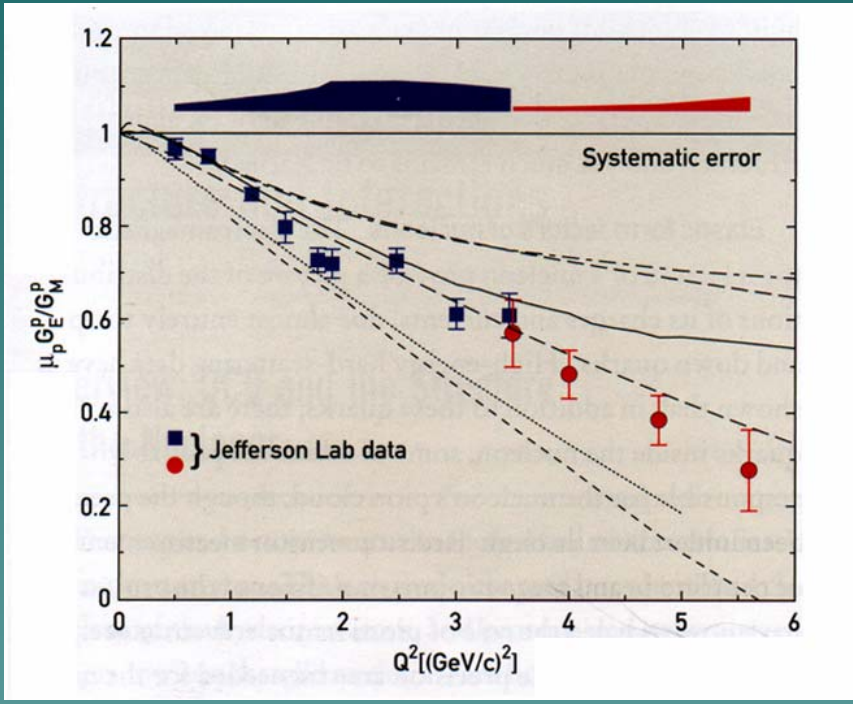
- Many systematics, such as absolute flux, cancel in ratio.
- Need to know spectrum but ratio only weakly depends on E_ν.
- Need to identify pions to separate elastic from inelastic events. [This may require a segmented detector.]
- Want large acceptance for muons.

Ratio of Nucleon to Nucleus Elasitc

- Consider a CH_2 target.
- ν-C elastic cross section is large and accurately known. Makes very good beam monitor.
- Measure ratio of ν-p to ν-C elastic events.
- Need to see low energy C recoils.

Measurement of Axial Form Factor

- Needed to control systematic errors for extraction of Δs.
- Accurate determination of M_A possible with charged current quasielastic events.



- ❑ Search for non dipole behavior? Look at large Q2 range: 0.5-2+GeV2. How to control systematic errors??

A Future ν-p Elastic Experiment

- Physics goals are compelling:
  - $G_a^s(Q^2)$ and Δs.
  - F_2^s independent of PV radiative correc.
  - $G_a(Q^2)$ and Axial mass M_A.
- Very attractive ν fluxes at beam lines for long baseline ν-oscillation exp.
- Measuring ratio of neutral to charged currents is simple and controls many systematic errors.