Improving Dark Matter Searches by Measuring the Nucleon Axial Form Factor: perspectives from MicroBooNE

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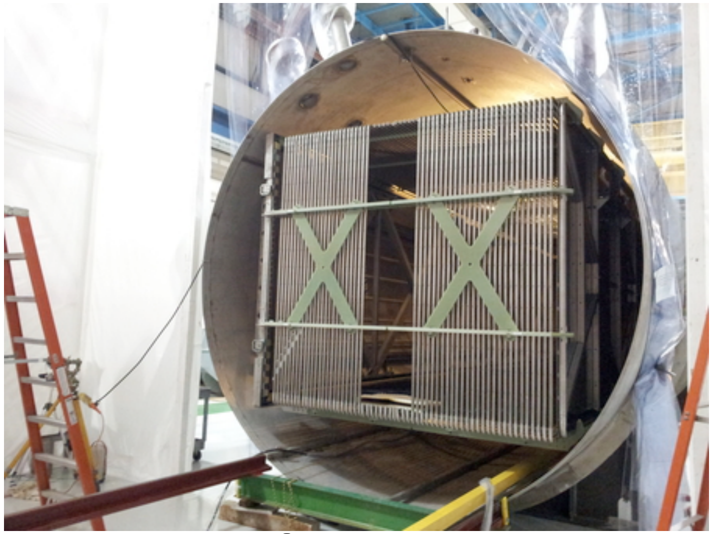
Work with Prof. Vassili Papavassiliou, Prof. Stephen Pate, and Katherine Woodruff of NMSU

MicroBooNE

- See Jonathan Asaadi's talk for more.
- Liquid Argon Time Projection Chamber
  - excellent tracking, calorimetry, and particle ID → low momentum transfer squared (Q^2)
- Measure neutrinos from Fermilab's Booster and NuMI neutrino beams.
- I will show you an interesting measurement we will make with MicroBooNE.



TPC inside LAr cryostat

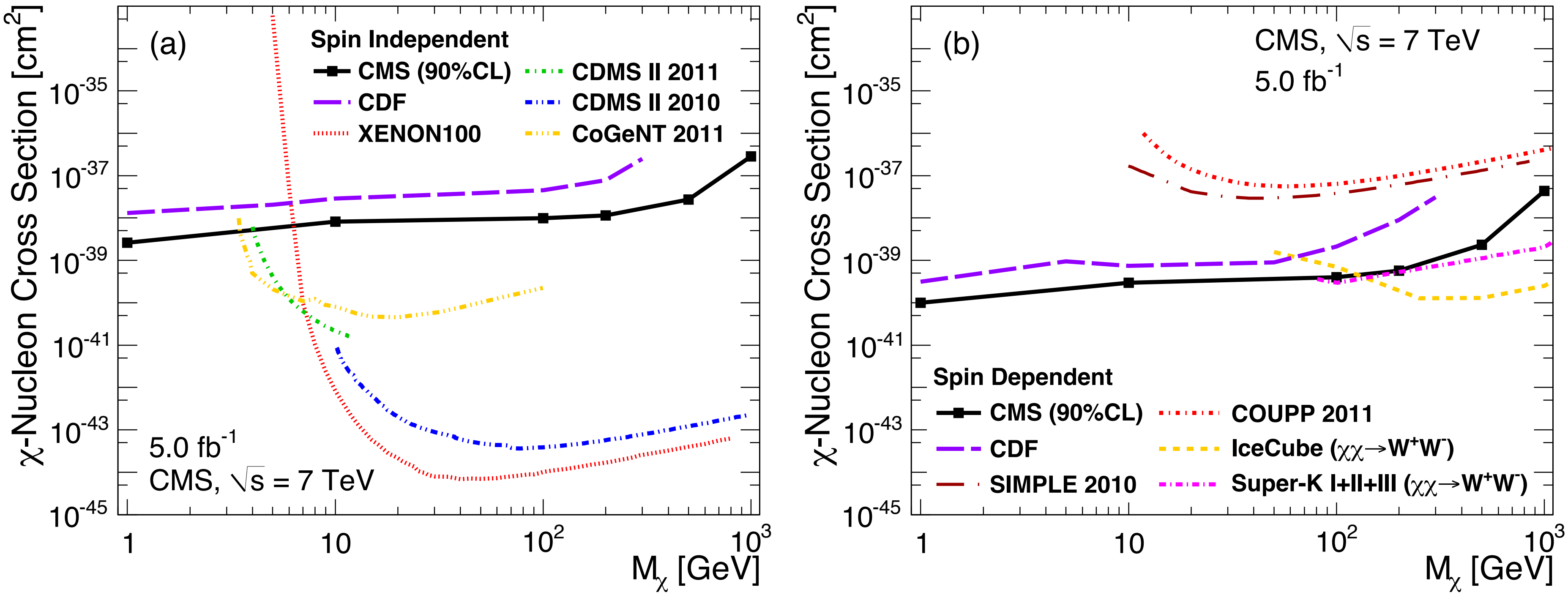
3 planes of wires

Outline

- Why nucleon spin is important for dark matter searches
- Introduction to form factors
- Current global fits
- MicroBooNE as a strange spin detector
- Battle of the Backgrounds

Dark Matter Searches

- Dark Matter may be dependent or independent of spin.

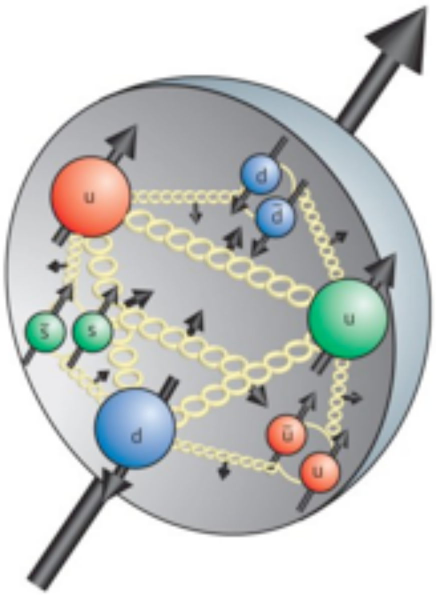


JHEP 1209 (2012) 094

Apologies if your favorite curve is not here!

Motivation

- You may not know, but spin-dependent dark matter (SD-DM) cross-sections suffer from imprecise knowledge of the spin structure of the proton.
  - Specifically, the component of nucleon spin arising from the strange-quark sea, Δs, is not well known.



Summary of the Strange Component of the Nucleon Spin

- Inclusive polarized electron deep inelastic scattering (DIS) experiments consistently indicate $\Delta s < 0$.
  - EMC, SMC, HERMES ($\Delta s = -0.085 \pm 0.017$), COMPASS, SLAC experiments
    Phys. Rev. D75 (2007) 012007

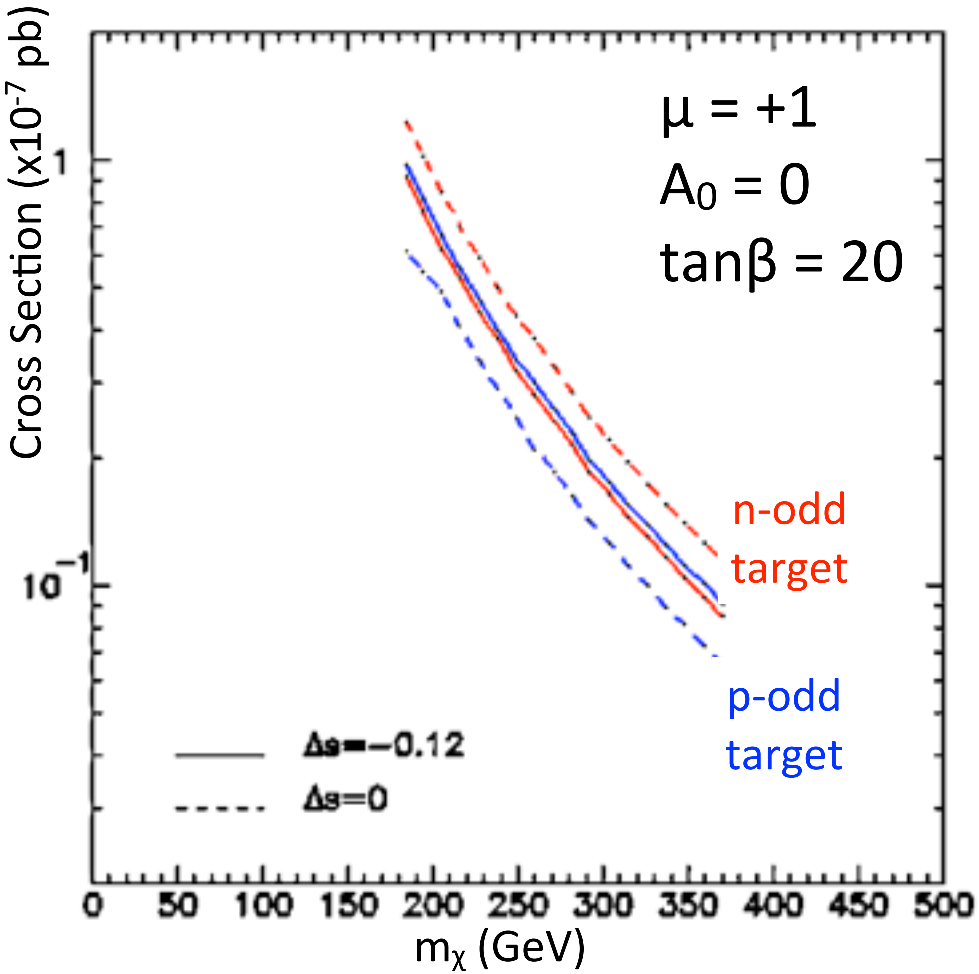
- Semi-inclusive polarized DIS finds Δs is consistent with 0.
  - HERMES ($\Delta s = +0.028 \pm 0.034$) and COMPASS ($-0.01 \pm 0.01$), precision limited.
    Phys. Rev. D71 (2005) 012003
    Phys. Lett. B 693 (2010) 227

- Neutrino scattering experiments are inconclusive so far.
  - BNL-E734 and MiniBooNE. Need to measure lower Q^2.
    Phys.Rev. D35 (1987) 785
    Phys. Rev. D82 (2010) 092005
    Phys. Rev. C 48, 761–765 (1993)
    Nucl.Phys. A651 (1999) 277-286

- A range, $-0.15 < \Delta s < 0$, should be considered when using Δs as input to calculations.

Spin-Dependent Cross Sections

- Assume the Constrained Minimal Super Symmetric Model (CMSSM)
  - consider neutralino cross section.
- For direct SD-DM searches:
  - $\sigma_{\chi\text{-}N}$ can vary from prediction by a factor of 2!
  - If $\Delta s \approx 0$, targets with N_n=odd and N_p=even are strongly preferred
    - e.g. ^{29}Si ^{73}Ge
  - If $\Delta s = -0.12$, targets with N_n=even and N_p=odd are somewhat better
    - e.g. ^{7}Li, ^{19}F, ^{23}Na
- Limits on spin dependent DM may shift by a factor of 2 depending on Δs assumptions.



V. Papavassiliou MicroBooNE-DocDB2810-v1
DarkSUSY: http://www.physto.se/~edsjo/darksusy/
P. Gondolo et al, JCAP 0407 (2004) 008 [astro-ph/0406204]

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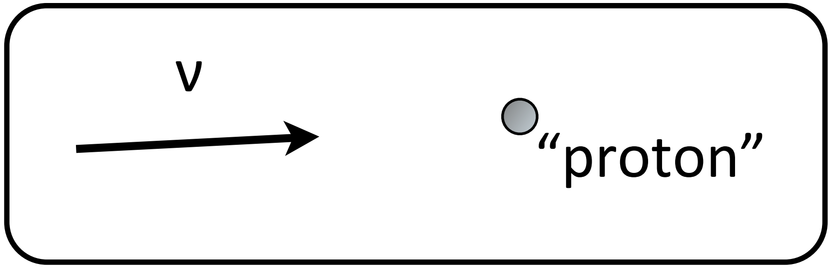
What is a Nucleon Form Factor?

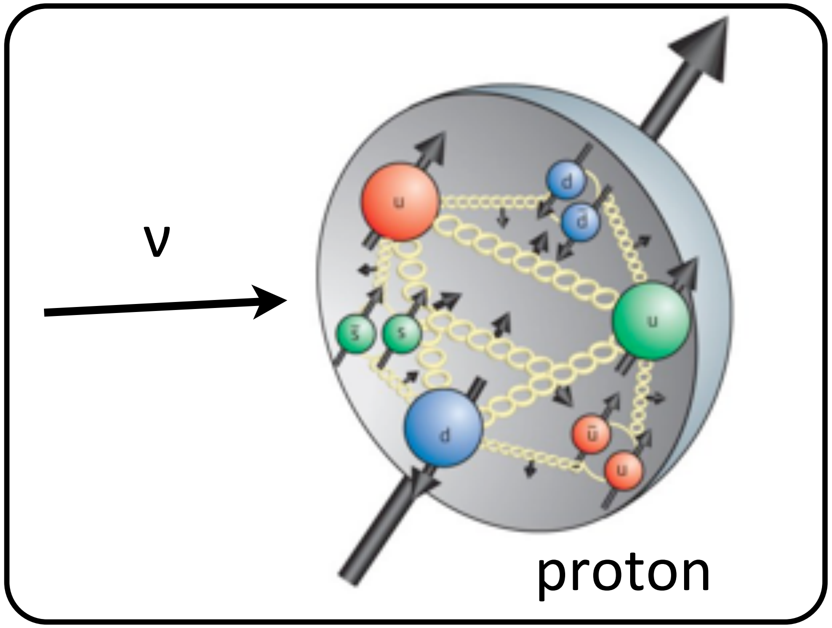
- When an electron or neutrino elastically scatters with a nucleon, it see more than just a simple point particle.

- The structure within the nucleon modifies the elastic cross section.

- This modification is parameterized by form factors.



vs.



Neutral Weak Form Factors

- Neutral weak current

Vector form factors are analogous to electromagnetic form factors, but with weak couplings.

$$J_{\mu}^{NC} = {}_{N}\left\langle p' \left| \mathbf{J}_{\mu}^{NC} \right| p \right\rangle_{N} = \bar{u}(p')\left[\gamma_{\mu} F_{1}^{Z,N}(q^{2}) + i\frac{\sigma_{\mu\nu} q^{\nu}}{2M} F_{2}^{Z,N}(q^{2}) + \gamma_{\mu}\gamma_{5} G_{A}^{Z,N}(q^{2}) + \frac{q_{\mu}}{M}\gamma_{5} G_{P}^{Z,N}(q^{2})\right] u(p)$$

Axial form factor parameterizes amount of parity violation

(Pseudo-scalar form factor, doesn't contribute, so we ignore it.)

Flavor Decomposition of Form Factors

- Write nucleon form factors in terms of contributions from individual quarks, with appropriate couplings.

- Axial form factor (function of Q^2):

well measured from charged-current neutrino reactions and DIS

$$G_A^{Z,p} = \frac{1}{2}\left(-G_A^u + G_A^d + G_A^s\right)$$

MicroBooNE will measure this!

- Strange component to the nucleon spin: $G^s_A(Q^2 \rightarrow 0) \equiv \Delta s$.

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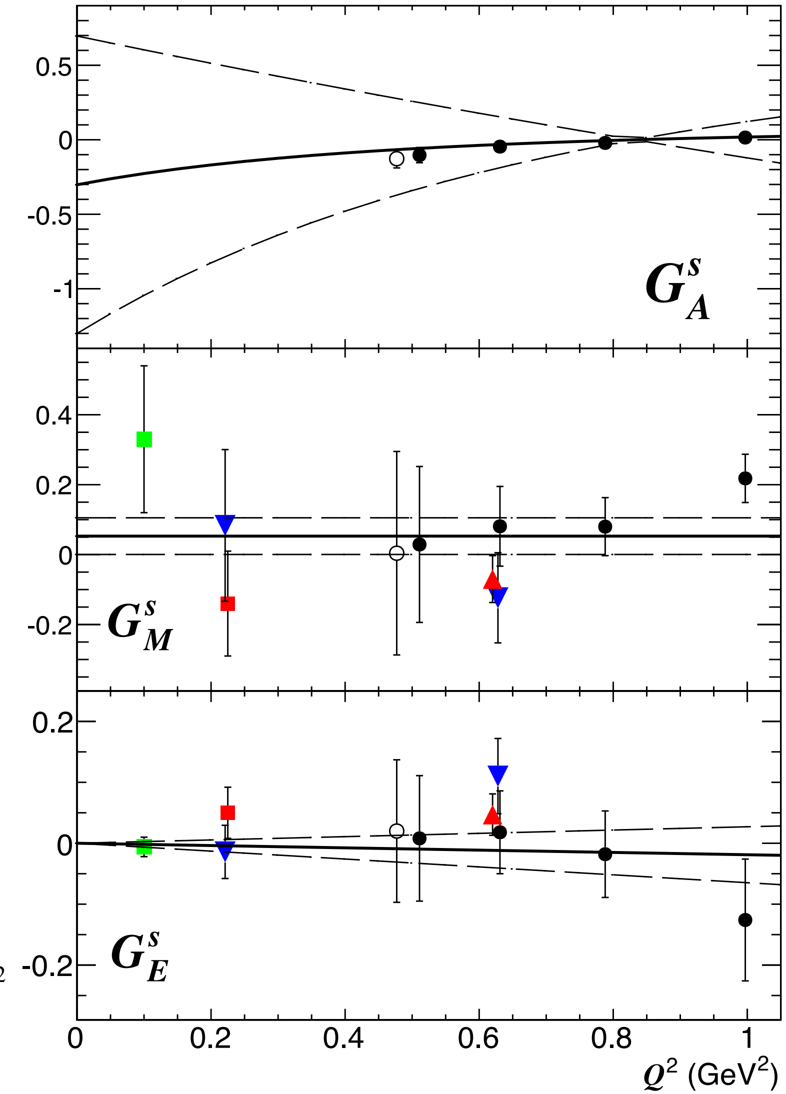
Current Fits & 70% confidence band

- 48 experiments of elastic and quasi-elastic electroweak scattering data compiled by S. Pate and D. Trujillo arXiv:1308.5694.
- In *each bin of Q^2*, the data is simultaneously fit.
- G^S_A uncertainty widens as $Q^2 \rightarrow 0$
  - MicroBooNE can make a big contribution at low Q^2 like BNL-E734 did for higher Q^2.



● G0 (forward ep) + E734 (νp and $\bar{\nu} p$)
○ HAPPEx (forward ep) + E734 (νp and $\bar{\nu} p$)
Pate, Papavassiliou & McKee, PRC 78 (2008) 015207

■ PVA4 (forward and backward ep)
Baunack et al., PRL 102 (2009) 151803

▼ G0 (forward and backward ep, and backward ed)
D. Androic et al., PRL 104 (2010) 012001

■ HAPPEx (forward ep and $e\,^4$He) + G0 (forward ep)
+ SAMPLE (backward ep and ed) + PVA4 (forward ep)
near $Q^2 = 0.1$ GeV^2
Liu, McKeown & Ramsey-Musolf, PRC 76 (2007) 025202

▲ HAPPEx (forward ep) + G0 (forward and backward ep)
at $Q^2 = 0.62$ GeV^2
Ahmed et al., PRL 108 (2012) 102001

arXiv:1308.5694

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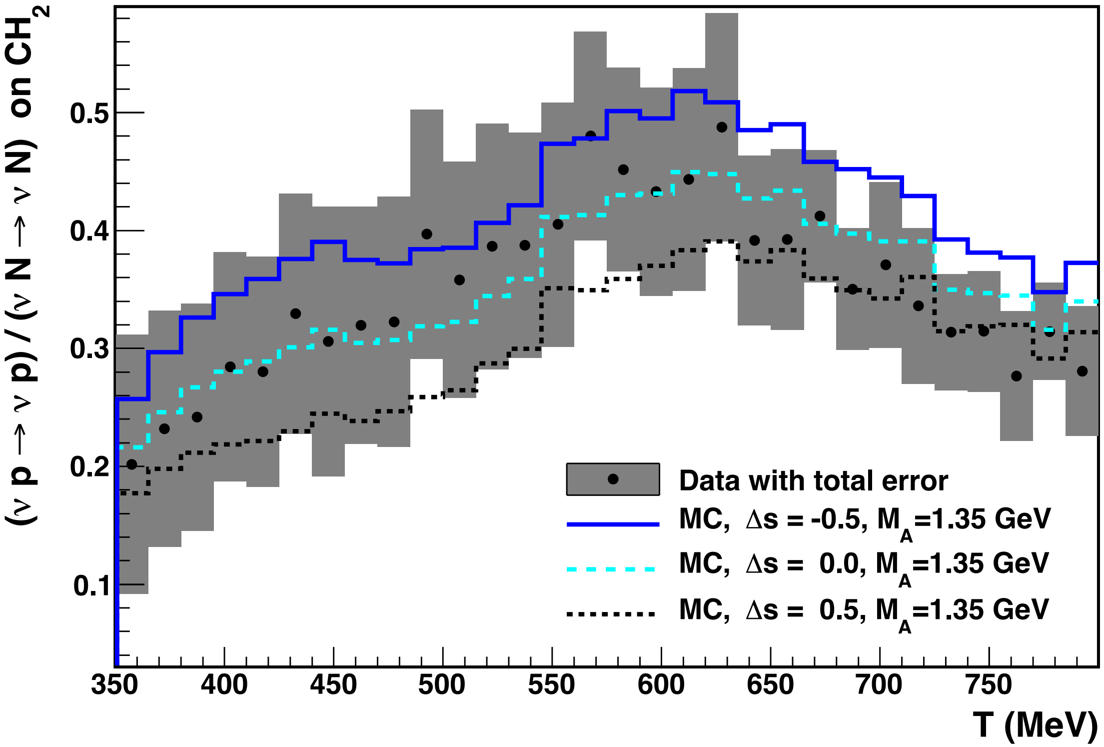
Detecting Strange Spin

- Ratio of neutral current / charged current cross sections (σ_{NC}/σ_{CC}) is sensitive to Δs.
- At MiniBooNE:
  - Measure ratio σ(νp→νp)/σ(νN→μN)
  - See which Δs prediction matches best with the data.

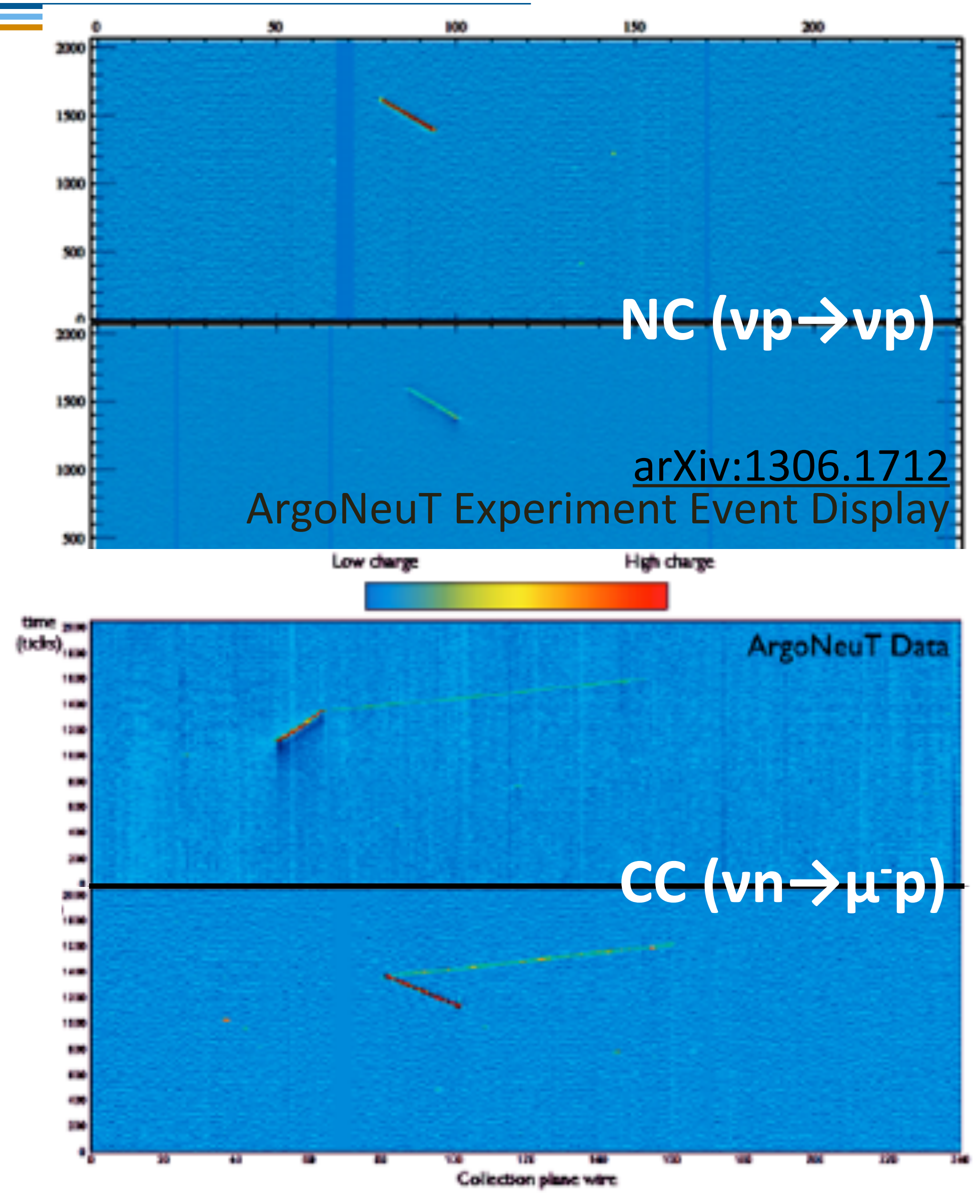


MiniBooNE: Phys. Rev. D 82, 092005 (2010)

- At MicroBooNE:
  - Follow similar procedure, but MicroBooNE will do better (lower Q^2, and improved particle ID).

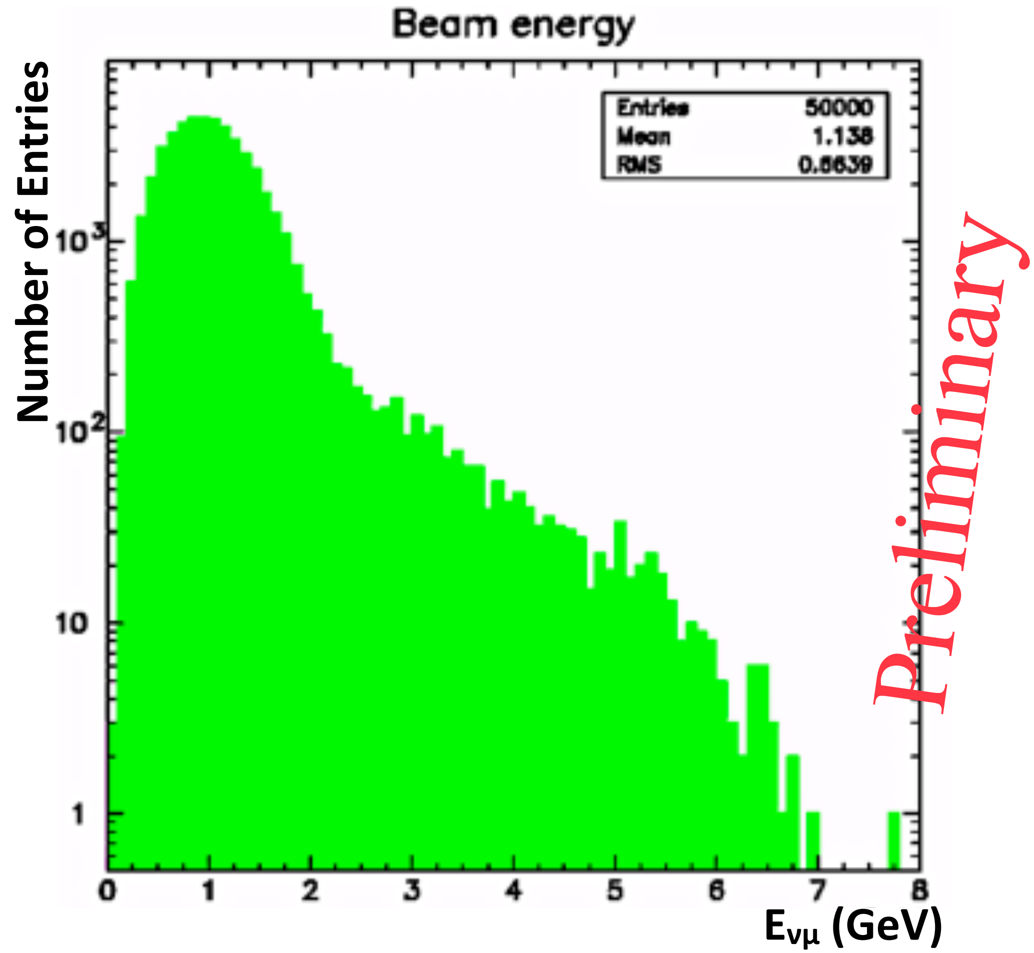
Finding Events

- Example events in ArgoNeuT.
- For MicroBooNE, a conservative Q^2 is considered:
  - minimum track extends over 4 collection wires
  - proton kinetic energy, T_p=40 MeV
  - Q^2=0.08 GeV^2
- We can go even lower in Q^2 if shortest track extends only over 3 wires.



Simple Simulation

- 50k ν-Ar events generated using Nuance v3
  - 2×10^{20} protons on target ~1 year of running
  - 4,343 NC off of n
  - 2,760 NC off of p
  - 22,209 CC off of n



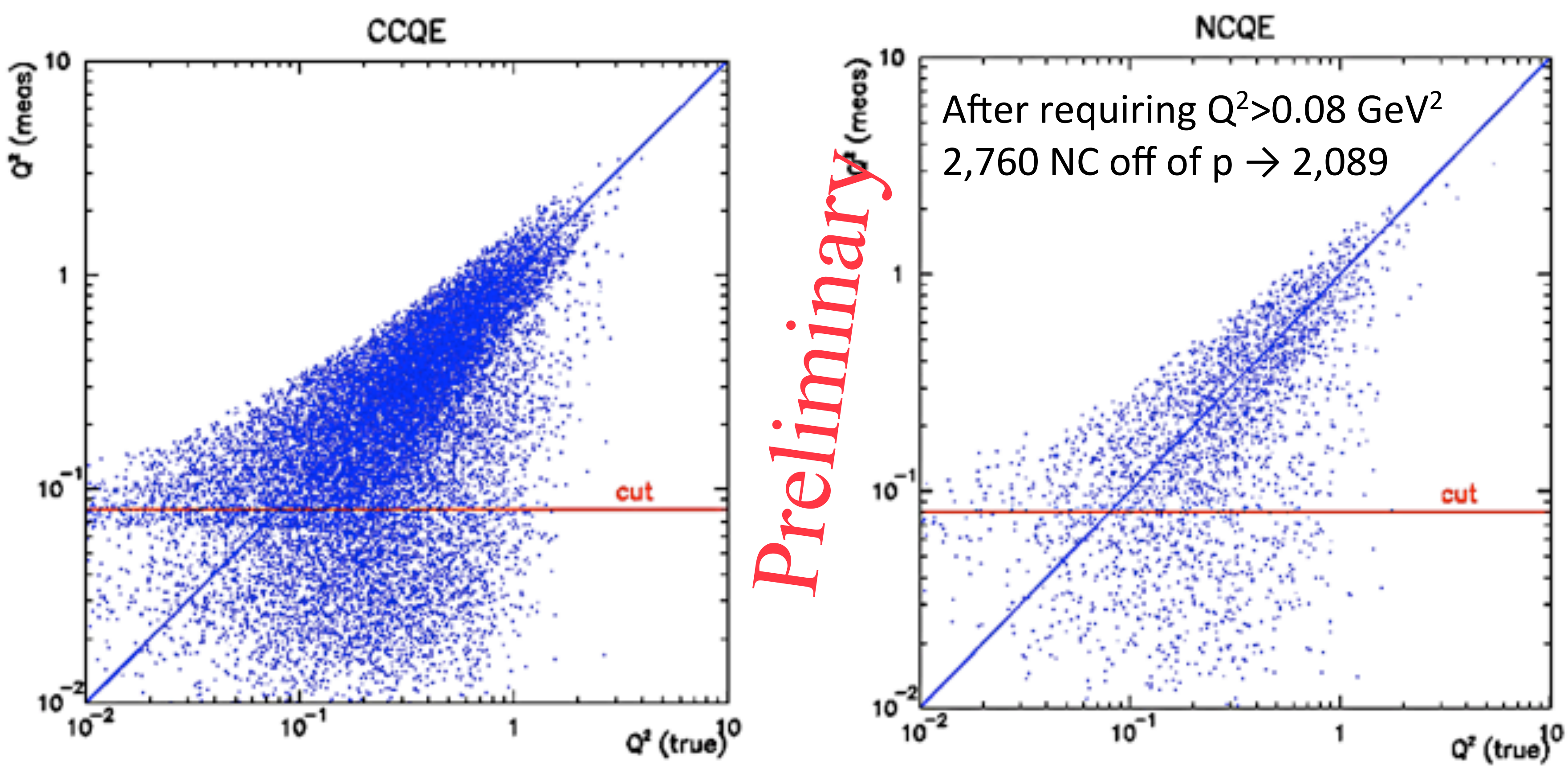
- Booster Neutrino Beam
  - $\langle E_\nu \rangle \sim 1$ GeV

With special thanks to Josh Spitz (Yale) for producing the event N-tuple.

MicroBooNE DocDB 2810-v1

MC ν-Ar Events

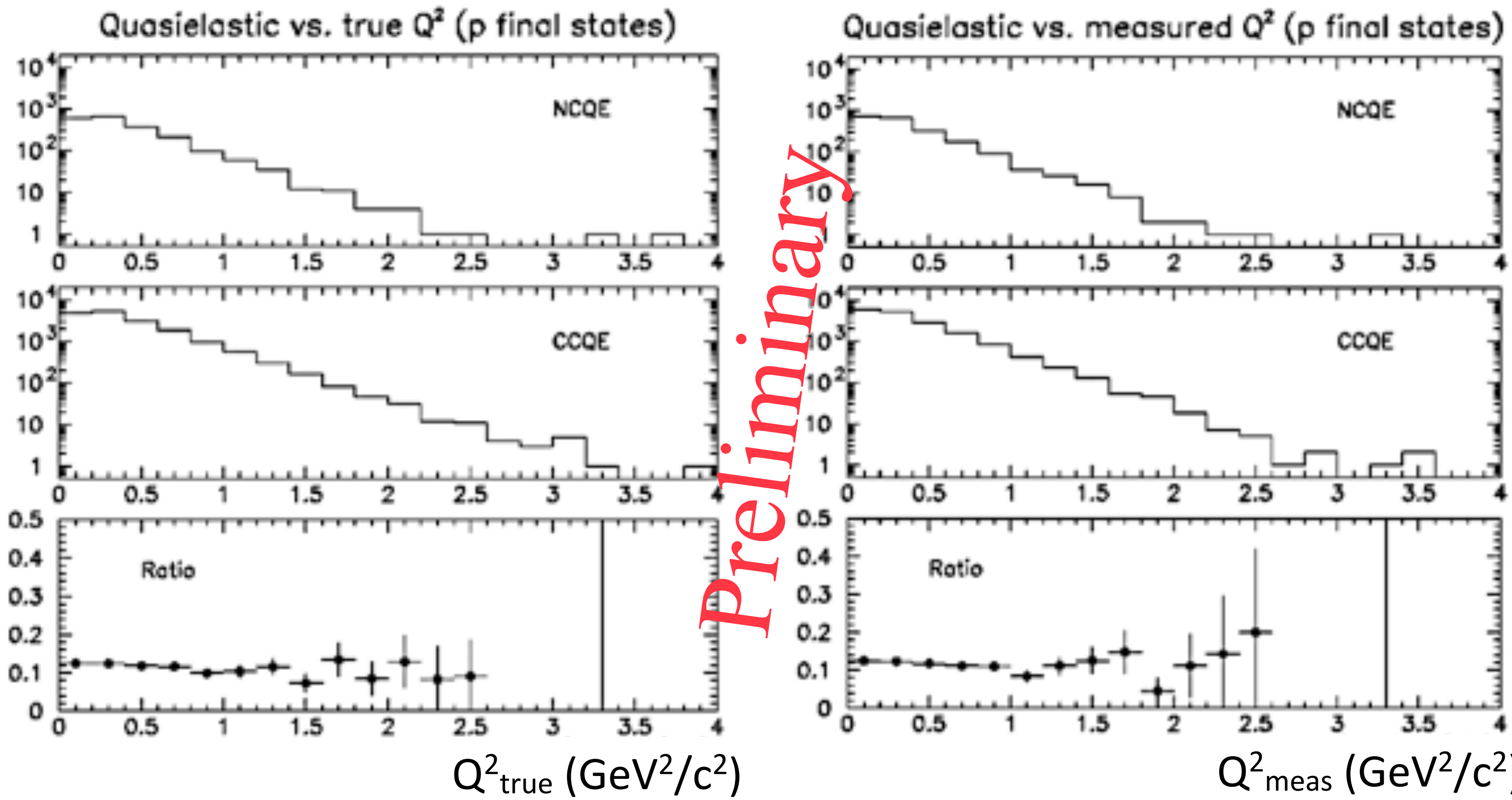
- Apparent vs. True Q^2
  - only nuclear effects (Fermi motion) are considered in Nuance v3



MicroBooNE DocDB 2810-v1

Detecting Strange Spin

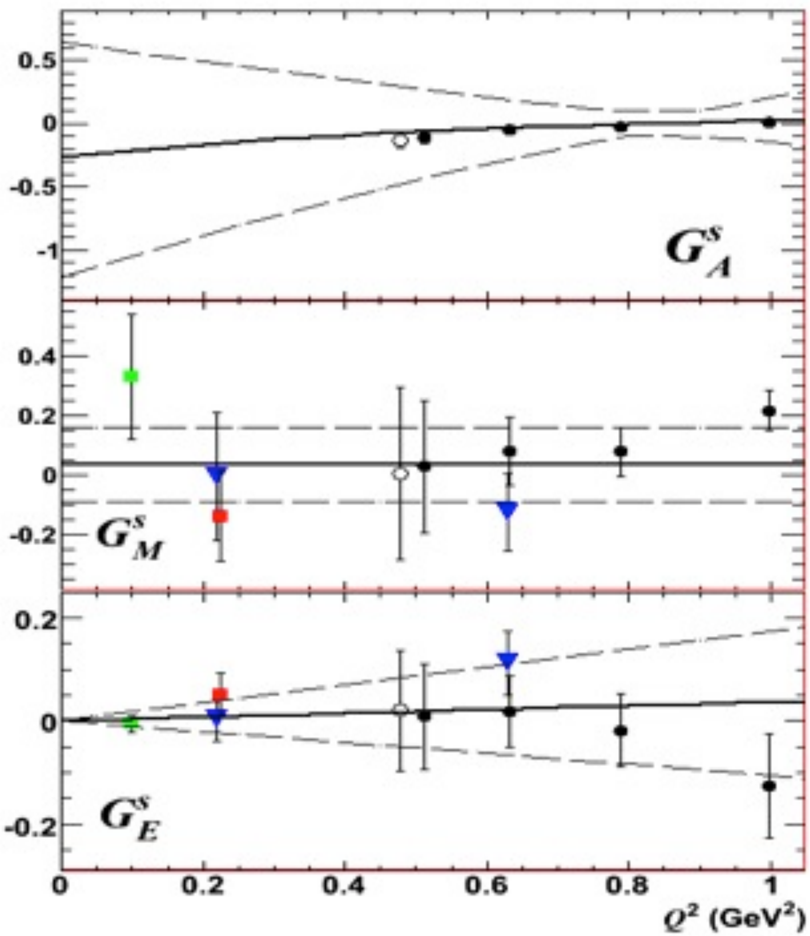
- $\sigma_{NC}/\sigma_{CC} = \sigma(\nu p \rightarrow \nu p)/\sigma(\nu n \rightarrow \mu^- p) = N_p/N_{p+\mu}$ (careful of backgrounds!)

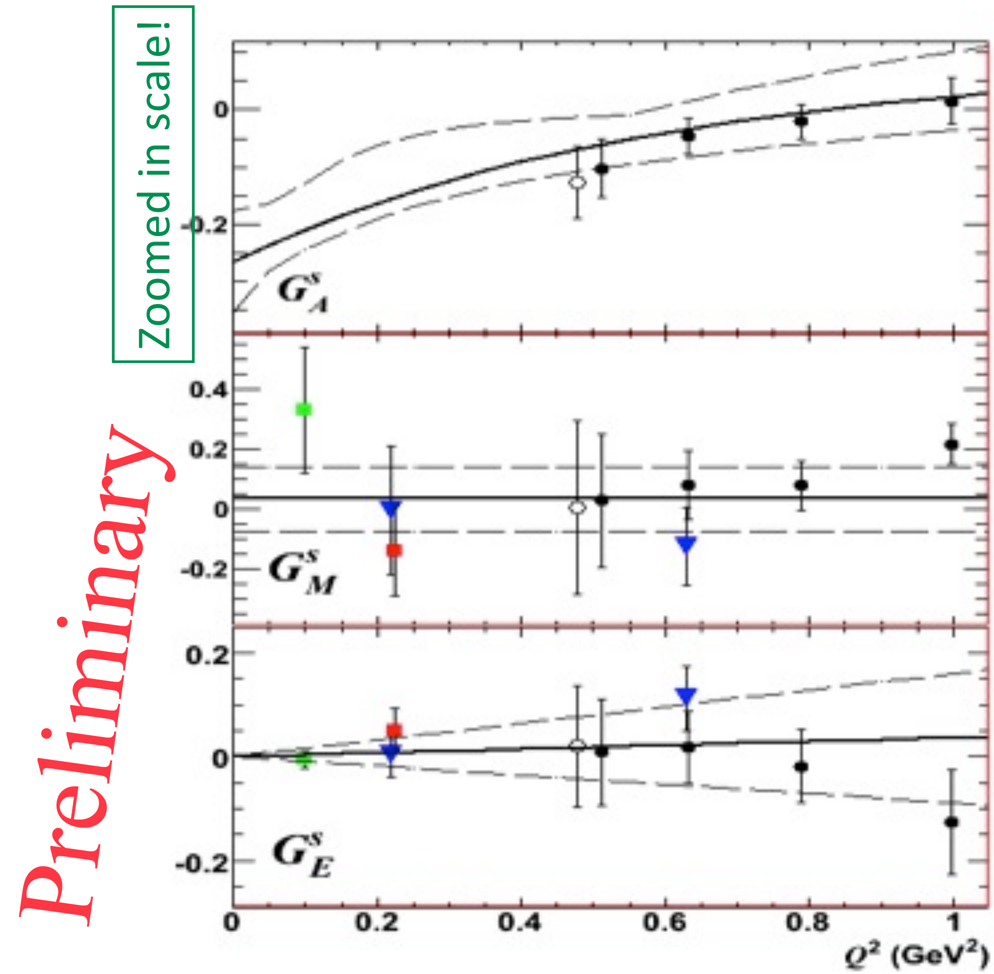


- Some nuclear, detector, and flux effects are common to both NC and CC, so they cancel by taking a ratio.
  - Example: Above, fermi motion does not affect ratio.

Axial FF Fit Uncertainty

- When the simulated MicroBooNE data is folded into the fit (right), the uncertainty in G^S_A can improve by an order of magnitude.





An earlier fit from: arxiv:1012.2991

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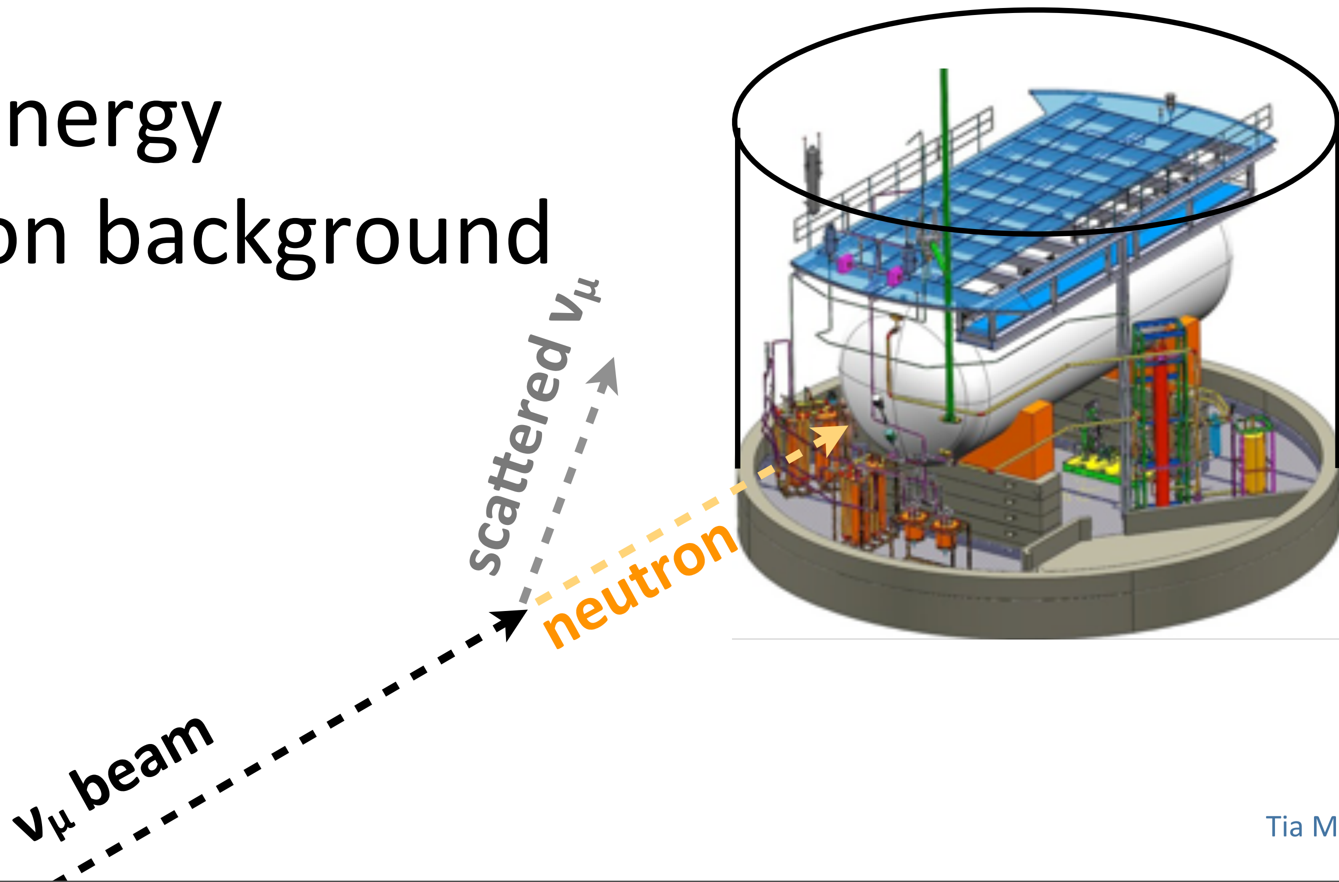
Battle of the Backgrounds

- Many backgrounds for NC and CC will be under study soon.
- Most insidious are the NC backgrounds: neutrons!
  - from upstream scattering in the dirt and cosmic rays

High energy neutron background

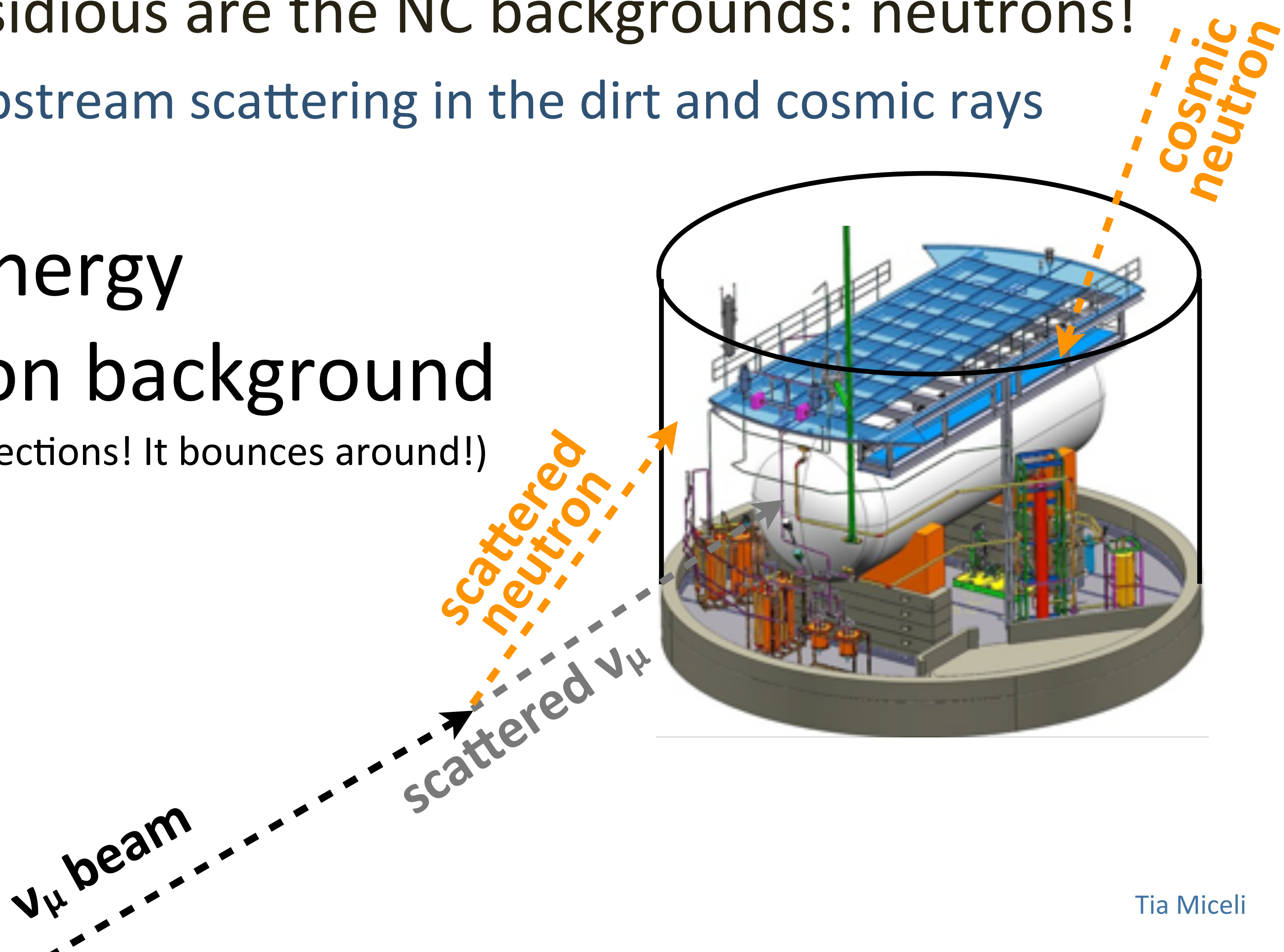


Battle of the Backgrounds

- Many backgrounds for NC and CC will be under study soon.
- Most insidious are the NC backgrounds: neutrons!
  - from upstream scattering in the dirt and cosmic rays

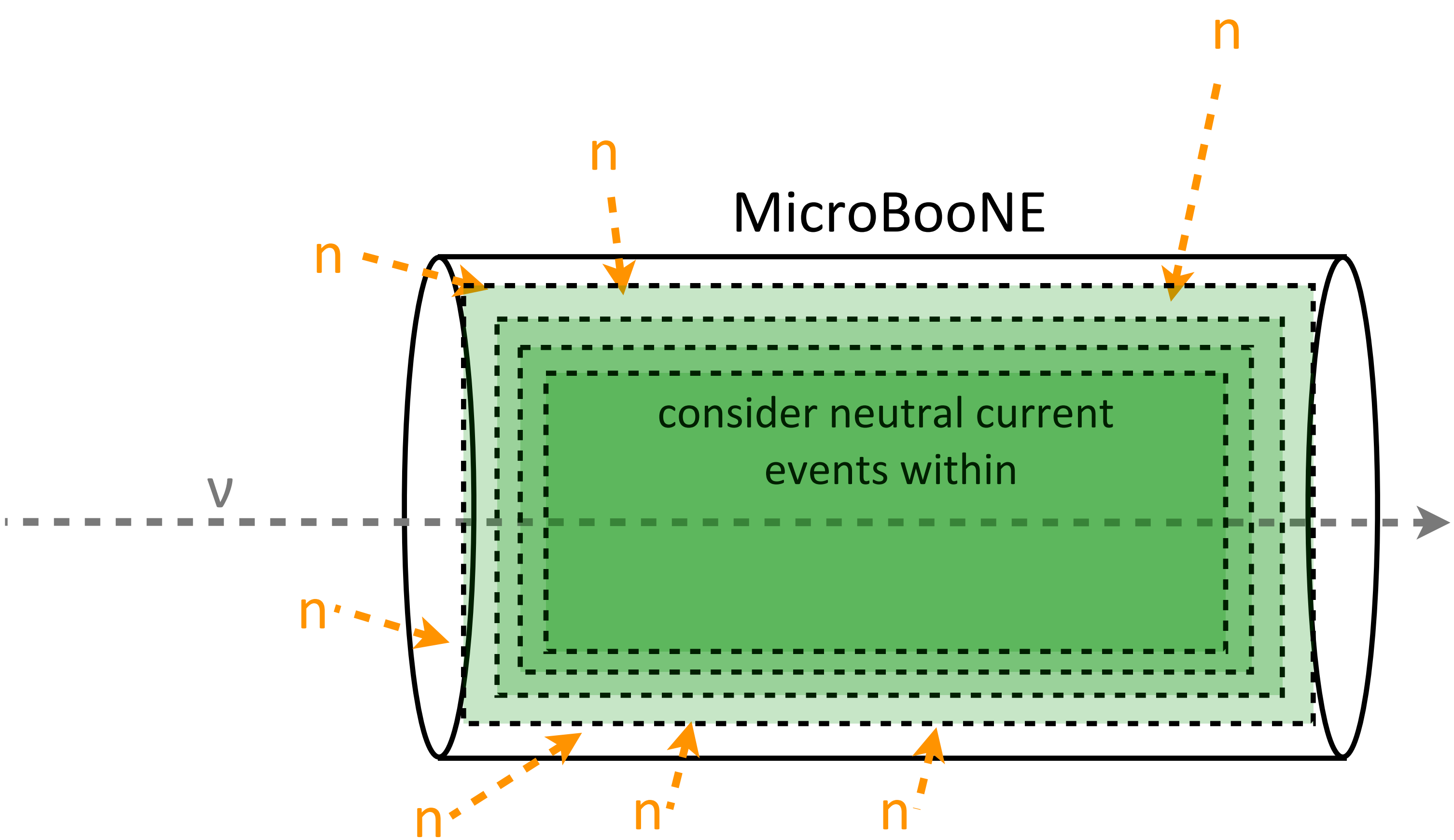
Low energy neutron background

(From all directions! It bounces around!)



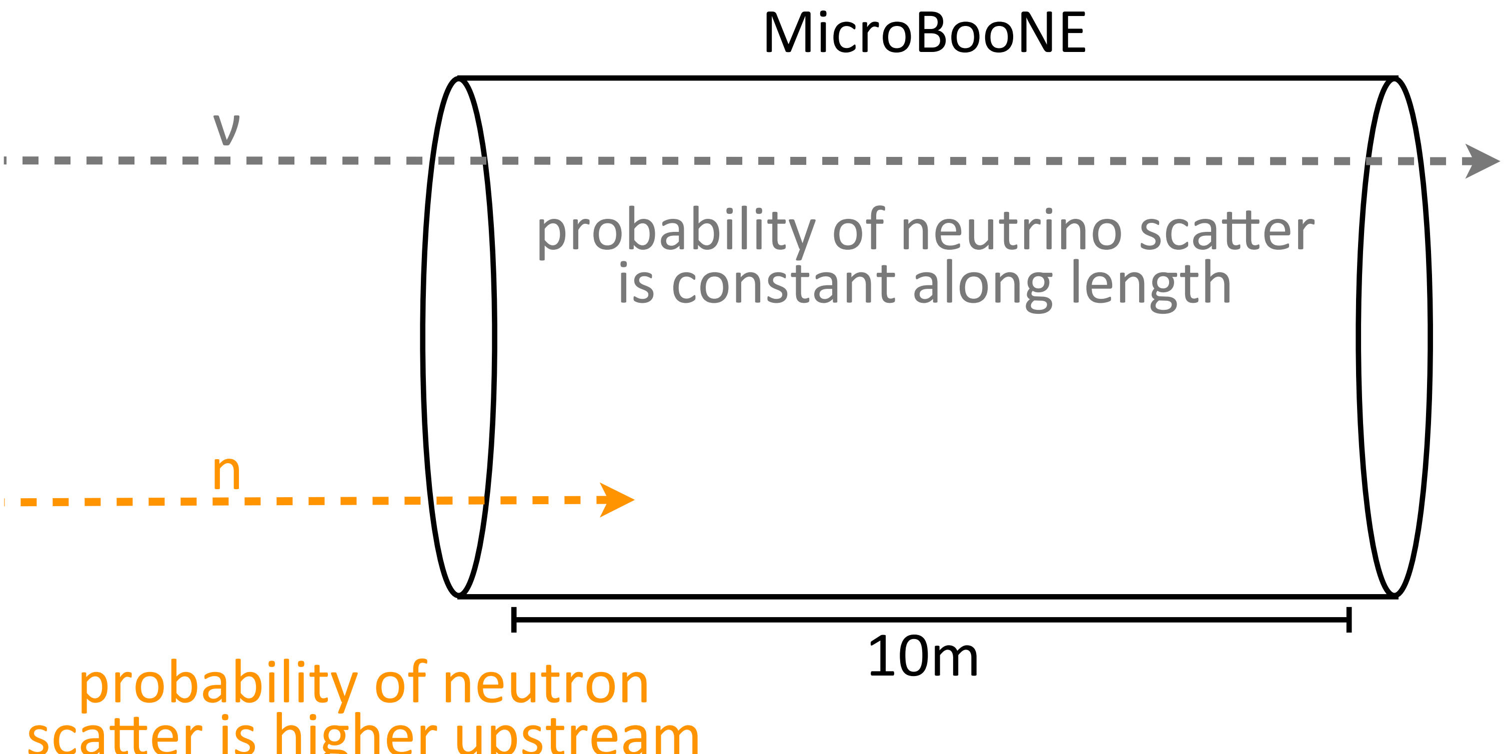
Low Energy Neutron Background

- We will study NC events in various annuli within the detector to define an acceptable fiducial volume. (Data-driven cut and estimate.)



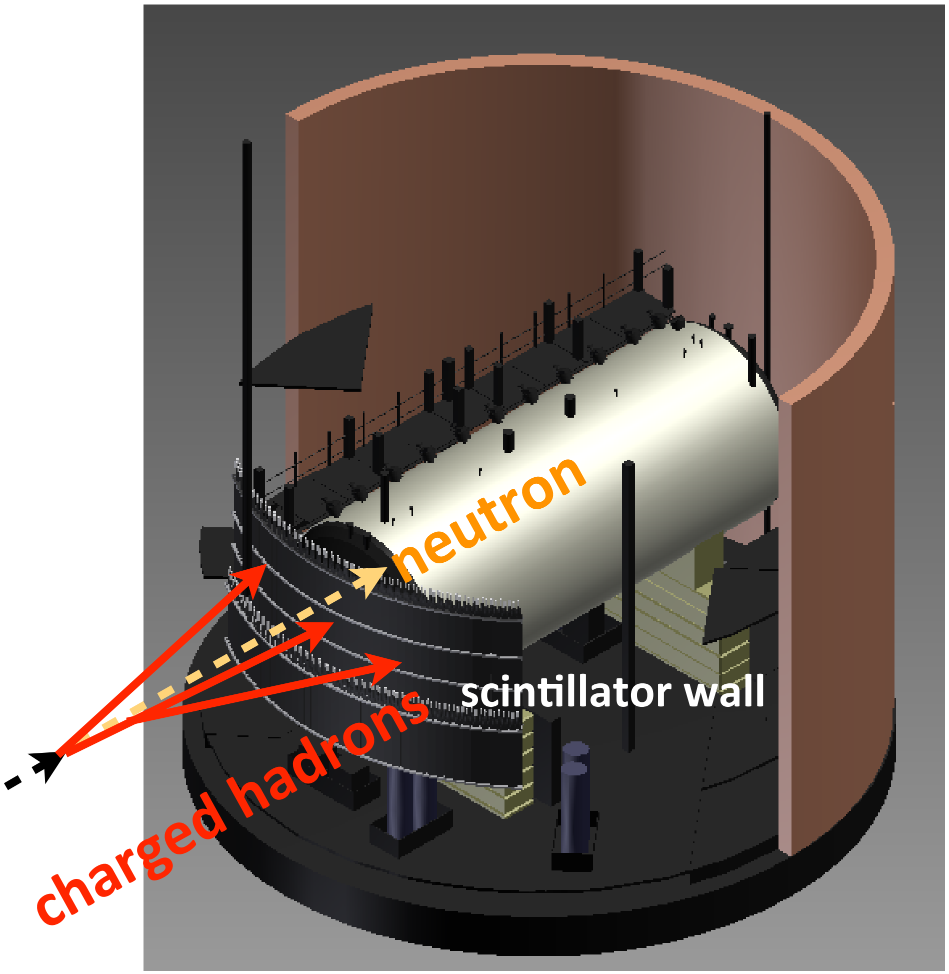
High Energy Neutron Background (1/3)

- We will study the NC event rate as a function of length along the detector to estimate the high energy neutron background. (Data-driven cut and estimate.)



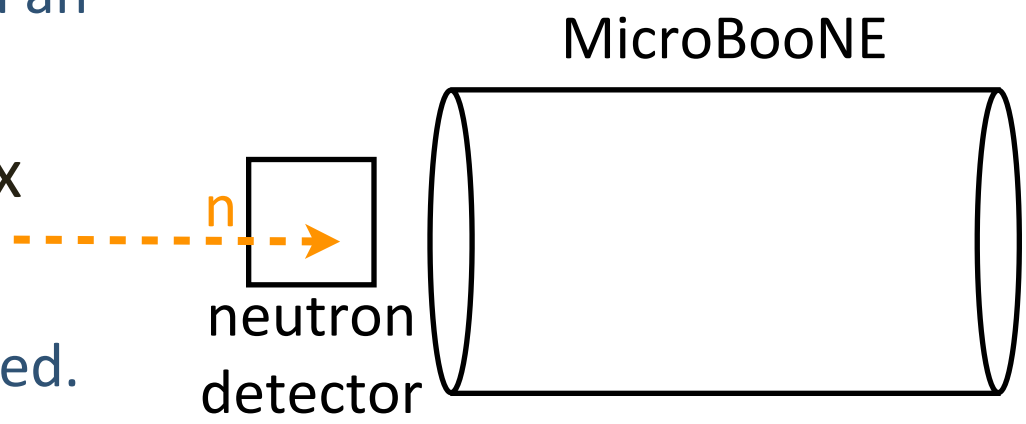
High Energy Neutron Background (2/3)

- If high energy neutron backgrounds are still big
  - Auxiliary detectors may be useful.
  - These are currently under consideration for upgrades.
- Charged scatterers are correlated with neutral production
  - Can veto those events with an auxiliary scintillator wall.



High Energy Neutron Background (3/3)

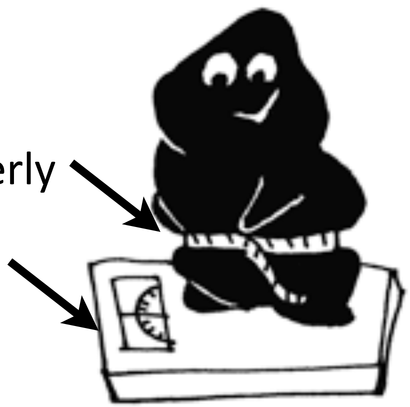
- If high energy neutron backgrounds are still big
  - Auxiliary detectors may be useful.
  - These are currently under consideration for upgrades.
- Charged scatterers are correlated with neutral production
  - Can veto those events with an auxiliary scintillator wall.
- Measure the neutron flux directly in detector hall.
  - Only measure if n is captured.
  - Can't leave detector there.



Conclusions

- MicroBooNE will measure the NC/CC cross section ratio at Q^2 lower than 0.08 GeV^2.
- This cross section ratio will constrain the contribution of the strange-sea quarks to the spin of the nucleon, Δs.
- Δs is an important ingredient that needs to be understood to design good experiments for spin-dependent dark matter.

One's measuring device needs to be properly used and calibrated to get correct data!



Thank you!

Supplementary Slides

CMSSM parameters

- From Nazila Mahmoudi's webpage
- The general MSSM has more than 100 free parameters which makes any systematic study impossible.
- One way to reduce this degree of arbitrariness is to assume universality assumptions at the Grand Unification (GUT) scale.
- A most commonly used example of such model is the CMSSM (or mSUGRA) which assumes at the GUT scale that:
  - all the scalar particles have the same mass: called m0
  - all the gauginos (partners of gauge bosons) have the same mass: called m1/2
  - all the trilinear couplings of the particles are the same: called A0
- and the last free parameter is tan β which is the ratio of the vacuum expectation values of the Higgs doublets.
- The sign of the higgsino mass term μ is also not fixed and can be either positive or negative.

NCQE Cross Section

$$\frac{d\sigma}{dQ^2}(\nu p \rightarrow \nu p) = \frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}\left(A \pm BW + CW^2\right)$$

+	ν
−	$\bar{\nu}$

$$W = 4\left(E_\nu / M_p - \tau\right) \qquad \tau = Q^2 / 4M_p^2$$

$$A = \frac{1}{4}\left[\left(G_A^Z\right)^2(1+\tau) - \left(\left(F_1^Z\right)^2 - \tau\left(F_2^Z\right)^2\right)(1-\tau) + 4\tau F_1^Z F_2^Z\right]$$

$$B = -\frac{1}{4}G_A^Z\left(F_1^Z + F_2^Z\right)$$

$$C = \frac{1}{64\tau}\left[\left(G_A^Z\right)^2 + \left(F_1^Z\right)^2 + \tau\left(F_2^Z\right)^2\right]$$

Motivation

- MicroBooNE will measure the strange axial form factor of the nucleon.
  - Only previous neutrino scattering experiment to say anything competitive about this form factor was BNL's E734 in 1987.
  - MicroBooNE will improve our knowledge of the nucleon spin structure.
- Such nucleons are the target for spin dependent dark matter searches, and this uncertainty is buried within limit setting programs.
- Assuming the CMSSM.
  - Refinement of the spin structure reduces the uncertainties on the spin dependent dark matter cross section.
  - Insight into what type of material to use for spin dependent dark matter experiments.

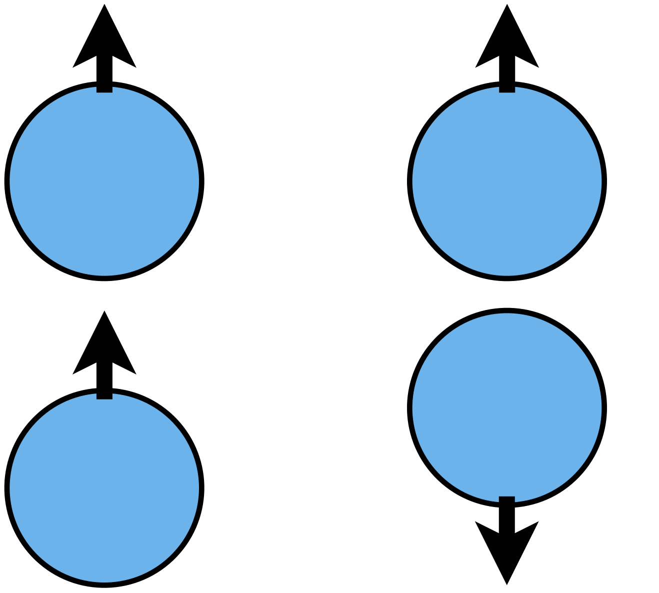
Electromagnetic Form Factors

- Electromagnetic current

$$J_\mu^{EM} = {}_N\langle p' | \mathbf{J}_\mu^{EM} | p \rangle_N = \bar{u}(p')\left[\gamma_\mu F_1^{\gamma,N}(q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2M}F_2^{\gamma,N}(q^2)\right]u(p)$$

for two nucleon states of momentum p and p'. $\left[q^2 = (p'-p)^2\right]$

- Dirac form factor: $F_1^{\gamma,N}$
- Pauli form factor: $F_2^{\gamma,N}$



Electromagnetic Form Factors

- Commonly, we re-write $F_1^{\gamma,N}$ and $F_2^{\gamma,N}$ as a linear combination in the Sach's formulation:

$$G_E^{p,n} = F_1^{p,n} - \tau F_2^{p,n} \qquad G_M^{p,n} = F_1^{p,n} + F_2^{p,n} \qquad \tau = Q^2/4M^2$$

Electric FF **Magnetic FF**

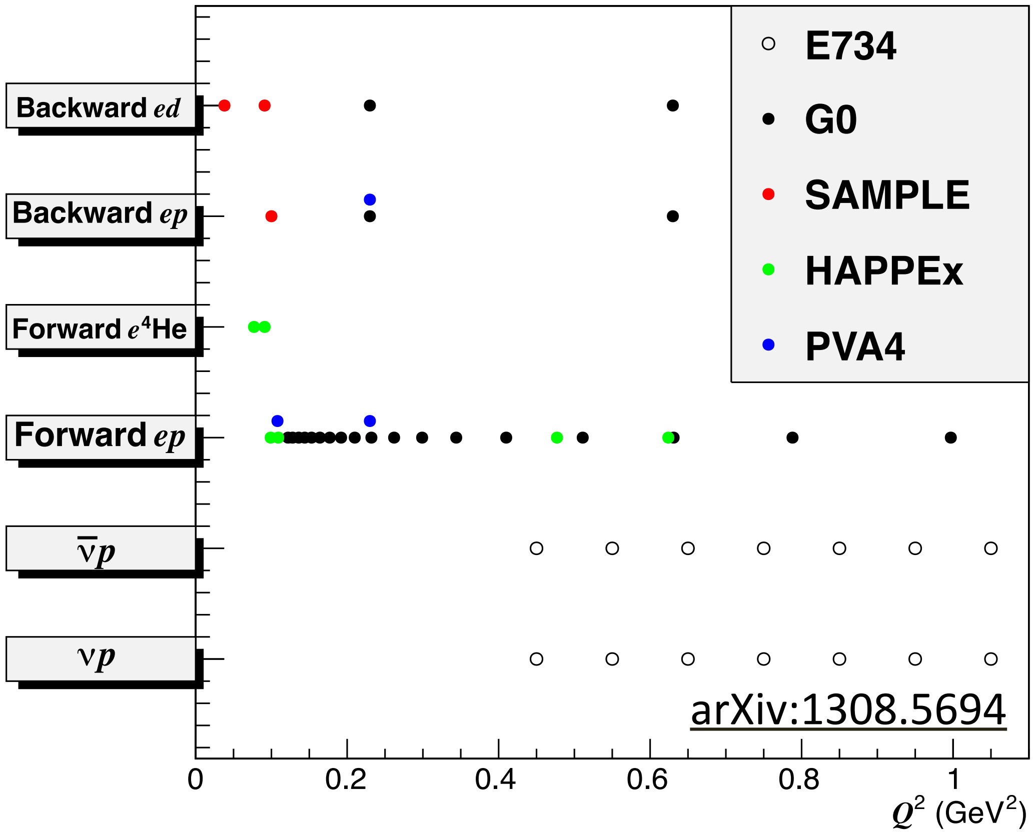
- These are well measured over many years at many laboratories.

Interpreting Strange Form Factors

- G_E^s
  - s and $\bar{s}$ have opposite electric charge
    - sensitive to "s-$\bar{s}$"
  - if s and $\bar{s}$ have same spatial distribution: $G_E^s = 0$
- G_M^s
  - s and $\bar{s}$ have opposite electric charge, so opposite currents
    - sensitive to "s-$\bar{s}$"
  - if s and $\bar{s}$ have same current distribution: $G_M^s = 0$
- G_A^s
  - s and $\bar{s}$ have same axial coupling!
    - sensitive to "s+$\bar{s}$"
  - even if s and $\bar{s}$ have same distributions: can have $G_A^s \neq 0$
  - Strange quark contribution to nucleon spin: $\Delta S = G_A^s(Q^2=0)$

Current Data

- Elastic and Quasi-elastic electroweak scattering data were compiled by S. Pate and D.Trujillo arXiv:1308.5694
- In each bin of Q^2, the data can be simultaneously fit



Dark Matter Uncertainties

- From "Hadronic uncertainties in the elastic scattering of supersymmetric dark matter" Phys. Rev. D 77 (2008) J. Ellis, K Olive, C. Savage.
  - For models of constrained minimal supersymmetry (CMSSM), "Uncertainties in the strange spin contribution Δs... induce 10-15% uncertainties in $\sigma_{\chi N,SD}$..." (the spin dependent dark matter-nucleon cross section)
    - MicroBooNE will improve this!
  - "The large uncertainty in $\sigma_{\chi n,SD}/\sigma_{\chi p,SD}$ induced by Δs for a given model is unfortunate since this ratio may be one of the easiest to determine experimentally."
    - MicroBooNE will measure this!

Parameters for Fit

- $G_E^s = \rho_s \tau$ $\quad \rho_s \equiv \left.\frac{dG_E^s}{d\tau}\right|_{\tau=0}$ $\quad \tau = \frac{Q^2}{4M_N^2}$
- $G_M^s = \mu_s$
- $G_A^s = \frac{\Delta S + S_A Q^2}{\left(1 + Q^2/\Lambda_A^2\right)^2}$
- Parameters of fit are
  - strangeness radius, ρ_s
  - strangeness contribution to the magnetic moment, μ_s
  - strangeness contribution to the spin, ΔS
  - dipole form parameters, Λ_A and S_A