Strangeness in the nucleon
cold dark matter in the universe
and neutrino scattering off liquid Ar

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Outline: What, Why, How

- What is Δs anyway?
  - Strangeness and the spin of the nucleon 101
- Why do we need to know?
  - Direct detection of cold dark matter
  - Neutralino LSP as the cold dark matter candidate
  - Neutralino-nucleon elastic scattering
- How we can do something about it
  - Measuring Δs in neutrino-nucleon scattering
  - Why a liquid Argon TPC detector

A Crash Course on the Spin of the Nucleon

How does the spin of the nucleon arise from the angular momenta of its constituent quarks and gluons?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$

Almost all information so far comes from polarized deep-inelastic lepton-nucleon scattering

For longitudinally polarized beam and target: $A_{\|} = D(A_1 + \eta A_2)$

D = fraction of beam polarization carried by virtual photon

A_1, A_2 related to spin-dependent structure functions: $A_1 = \frac{g_1 - \gamma^2 g_2}{F_1}$

A_2 small ($|A_2| \leq \sqrt{R}$) <u>and</u> kinematically suppressed

g_2 higher-twist and also kinematically suppressed: $\gamma^2 = Q^2/\nu^2$

$$A_1 \approx g_1/F_1$$

Ratio of spin-dependent and -dependent structure functions

Spin-Dependent Structure Function

g_1 related to net quark polarizations (helicity distributions)

$$\Delta q = \left(q^+ - q^-\right) + \left(\overline{q}^+ - \overline{q}^-\right)$$

(polarization relative to parent nucleon spin)

$$g_1(x, Q^2) = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x, Q^2)$$

Function of Bjorken-x (momentum fraction of "struck" quark) and (minus) 4-momentum transfer Q^2

Similar expression for F_1, with unpolarized distributions (sums)

Total net spin carried by all quarks: $\Delta\Sigma = \Delta u + \Delta d + \Delta s$

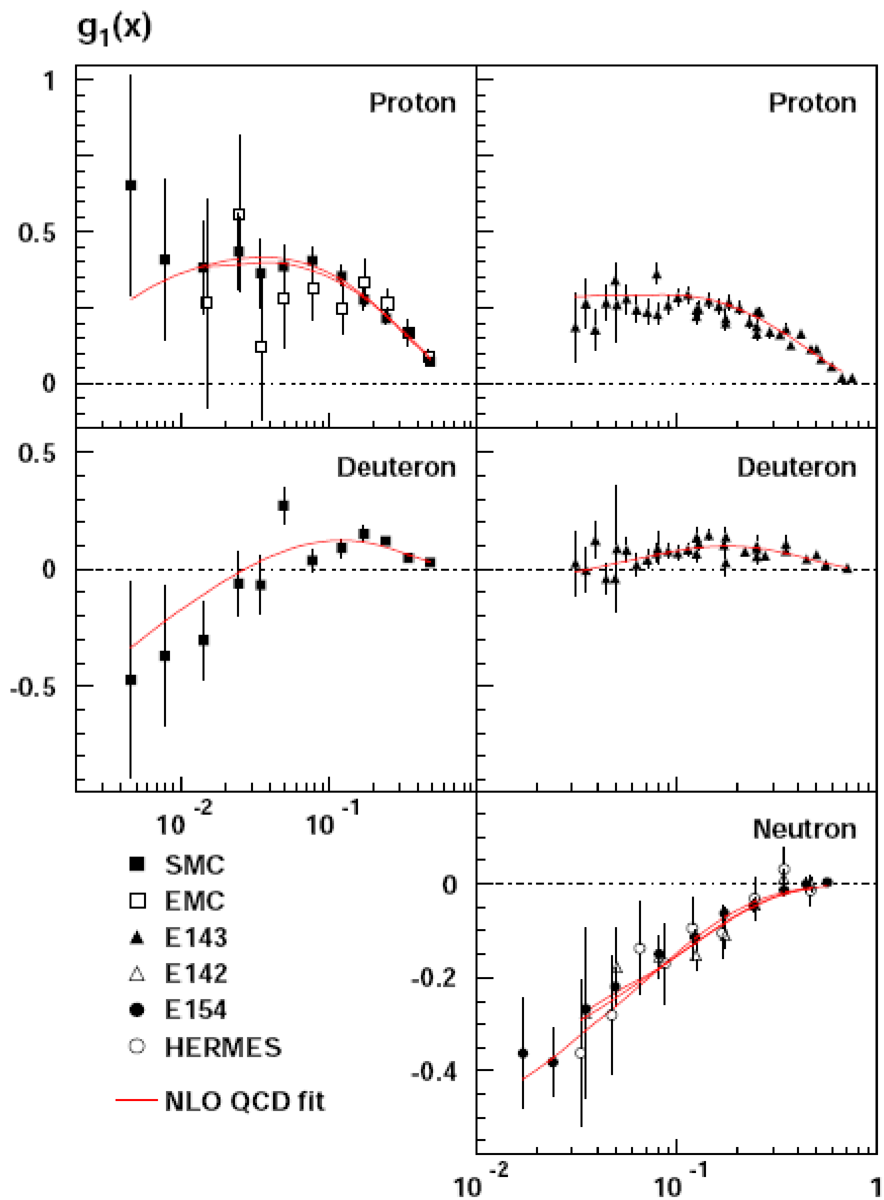
(Integrated over all x, from 0 to 1)

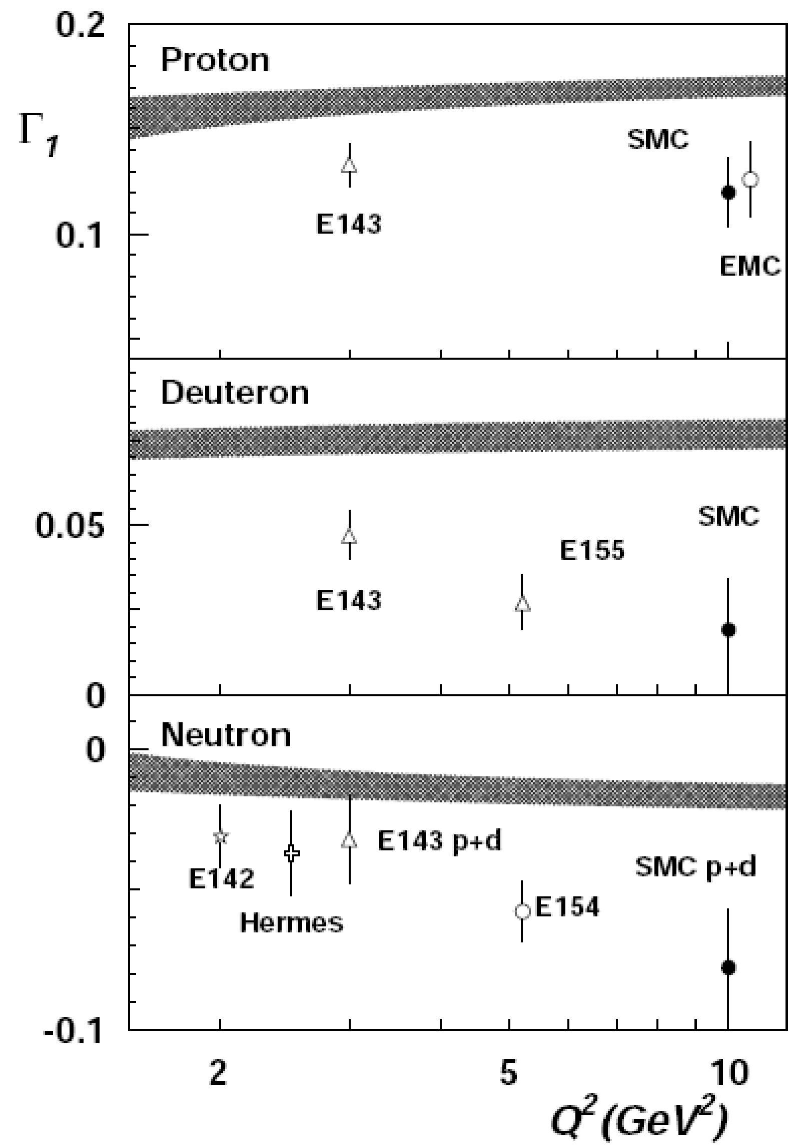
Use $\Gamma_1(Q^2) = \int_0^\infty g_1(x, Q^2)\mathrm{d}x$ (extrapolate to unmeasured regions)

Two equations: measurements on protons and neutrons

One additional assumption is needed to extract all three quark contributions to the nucleon spin

Measurements of g_1 and its First Moment





Axial Matrix Elements

We can define new combinations corresponding to SU(3) λ-matrices

$$\begin{aligned}\Delta q_3(x,Q^2) &= \Delta u(x,Q^2) - \Delta d(x,Q^2),\\ \Delta q_8(x,Q^2) &= \Delta u(x,Q^2) + \Delta d(x,Q^2) - 2\Delta s(x,Q^2)\end{aligned}$$

as well as the sum of *u*, *d*, and *s* ("singlet"),
or the corresponding integrals (over *x*)

$$a_3 \equiv \Delta u - \Delta d$$

$$a_8 \equiv \Delta u + \Delta d - 2\Delta s$$

$$a_0 \equiv \Delta u + \Delta d + \Delta s = \Sigma$$

In the limit $Q^2 \to \infty$ these are matrix elements of axial quark operators $\overline{q}\gamma^\mu\gamma^5 q$ between nucleon states, *e.g.*

$$a_3 = < N|\overline{u}\gamma^\mu\gamma^5 u - \overline{d}\gamma^\mu\gamma^5 d|N > = \frac{g_A}{g_V}$$

the ratio of axial and vector coupling constants in neutron decay
(Bjorken Sun Rule, confirmed from measurements of g_1 of the proton and neutron)

Flavor SU(3) and Strange Quark Polarization

Similar relationship obtained fc a_8 assuming flavor SU(3) symmetry in baryon octet decays

$$a_8 = \frac{1}{3}(3F - D)$$

The SU(3) couplings are obtained from hyperon decays

This provides the third equation to solve for Δu, Δd, Δs

$$\begin{aligned} \Delta u &= 0.84 \pm 0.03 \\ \Delta d &= -0.43 \pm 0.03 \\ \Delta s &= -0.09 \pm 0.03 \end{aligned}$$

Strange sea quarks are polarized opposite to the nucleon spin!
(Also known as the violation of the Ellis-Jaffe Sum Rule)

Caveats:

1) Flavor SU(3) symmetry is not exact
   Probably small contribution to uncertainty
2) QCD complicates relationship between $\Delta\Sigma$ and a_0
   Due to axial anomaly, quark and gluon polarizations mix

MSSM LSP as the Cold Dark Matter Candidate

Neutralino: Lowest-mass linear combination of gauginos

$$\chi = Z_{\chi 1}\tilde{B} + Z_{\chi 2}\tilde{W} + Z_{\chi 3}\tilde{H}_1 + Z_{\chi 4}\tilde{H}_2$$

Direct searches rely on elastic scattering of neutralinos with ordinary matter (detectors) and need knowledge of the cross sections within a supersymmetric model

Neutralino-nucleon coupling: four-fermion interactions like
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ (spin-dependent) and
$\bar{\chi}\chi\bar{q}q$ (spin-independent)

Most general effective Lagrangian

$$\mathcal{L} = \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}_i\gamma_\mu(\alpha_1 + \alpha_2\gamma^5)q_i + \alpha_3\bar{\chi}\chi\bar{q}_i q_i + \alpha_4\bar{\chi}\gamma^5\chi\bar{q}_i\gamma^5 q_i + \alpha_5\bar{\chi}\chi\bar{q}_i\gamma^6 q_i + \alpha_6\bar{\chi}\gamma^5\chi\bar{q}_i q_i$$

All but 2 and 3 are velocity-dependent and can be neglected for slow dark matter

Spin-Dependent Neutralino-Nucleon Elastic Scattering

Note: The same quark operators appear as in polarized lepton-nucleon deep-inelastic scattering

Cross section $$\sigma_2 = \frac{32}{\pi} G_F^2 m_r^2 \Lambda^2 J(J+1)$$

where $\Lambda = \frac{1}{J}(a_p \langle S_p \rangle + a_n \langle S_n \rangle)$ with $a_p = \sum_i \frac{\alpha_{2i}}{\sqrt{2} G_F} \Delta_i^{(p)}, \qquad a_n = \sum_i \frac{\alpha_{2i}}{\sqrt{2} G_F} \Delta_i^{(n)}$

Expectation values for proton (neutron) spins in a nucleus are given by the nuclear shell model

Examples for typical detector materials

$^{73}\mathrm{Ge} \quad \langle S_{p,n} \rangle = 0.011, 0.491$ (single unpaired neutron)
$^{19}\mathrm{F} \quad \langle S_{p,n} \rangle = 0.415, -0.047$ (single unpaired proton)

The net quark polarizations enter in the spin-dependent cross section

The uncertainty in Δs affects

Interpretation of experimental limits

Choice of detector material for future experiments

Spin-Independent Cross Section

$$\sigma_3 = \frac{4m_r^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

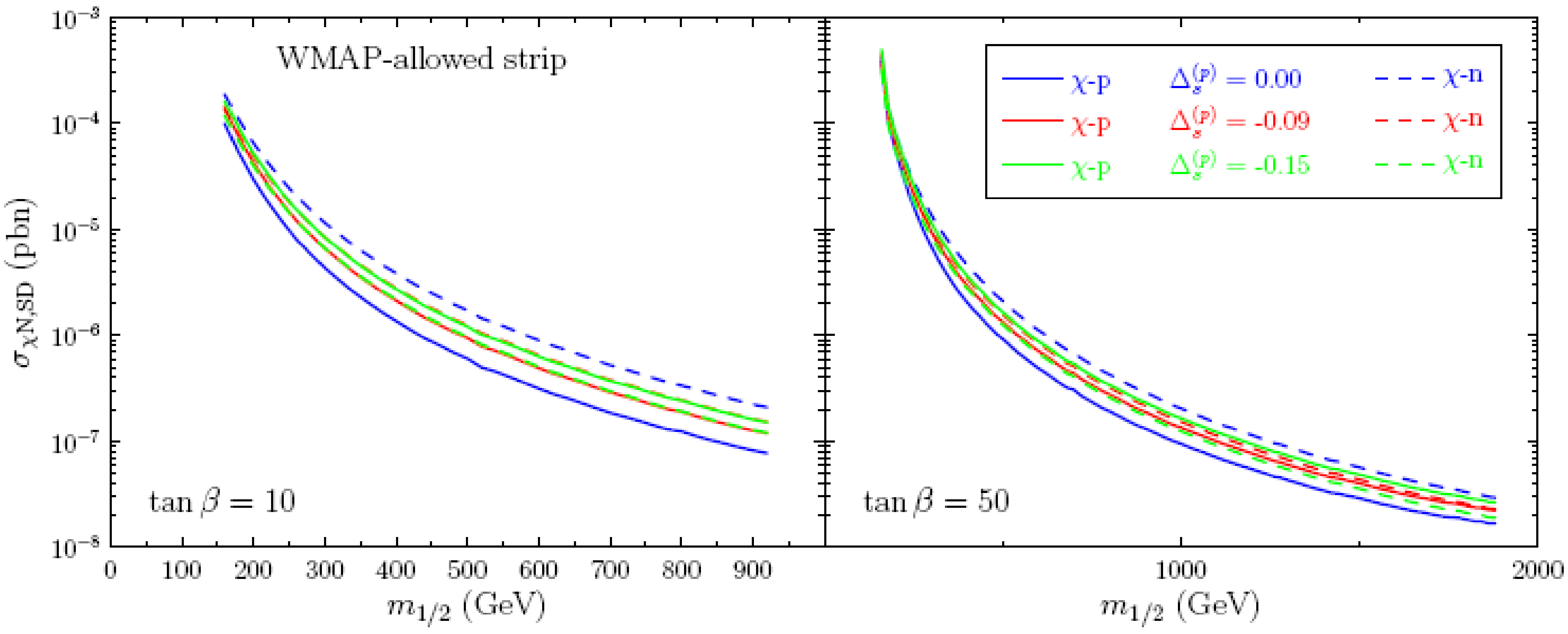
A few comments

- Spin-independent cross section for scattering off nucleons about 100-1000 times smaller than spin-dependent one
- But greatly enhanced for heavy nuclei (coherent scattering proportional to square of number of nucleons)
- Cross section involves scalar matrix element: pion-nucleon sigma term —— resulting in much larger uncertainty

Spin-Dependent Cross Section

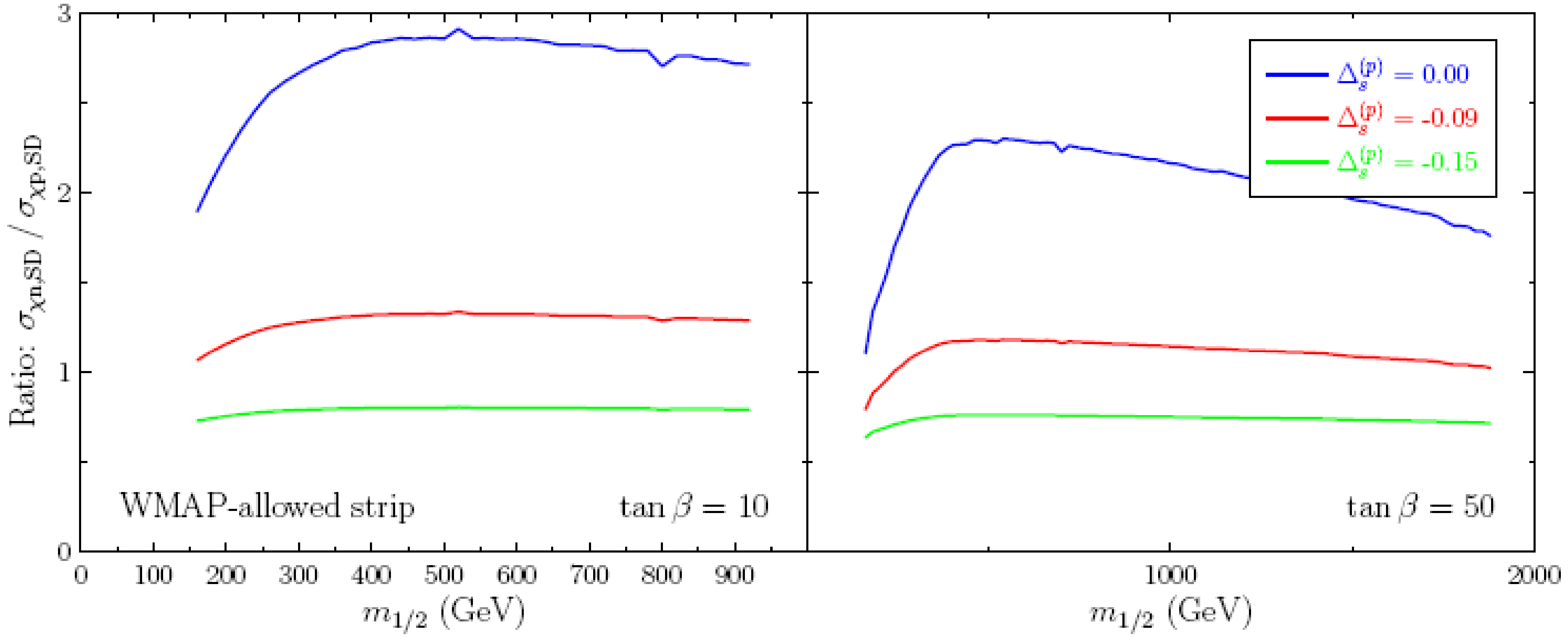
Constrained MSSM: supersymmetry-breaking parameters m_0, $m_{1/2}$ universal at input GUT scale (tanβ = ratio of Higgs vev's)

Plots shown for (m_0, $m_{1/2}$) combinations consistent with WMAP results on cold dark matter density (assumed dominated by neutralino)



p (*n*) cross section increases (decreases) with more negative Δ*s*

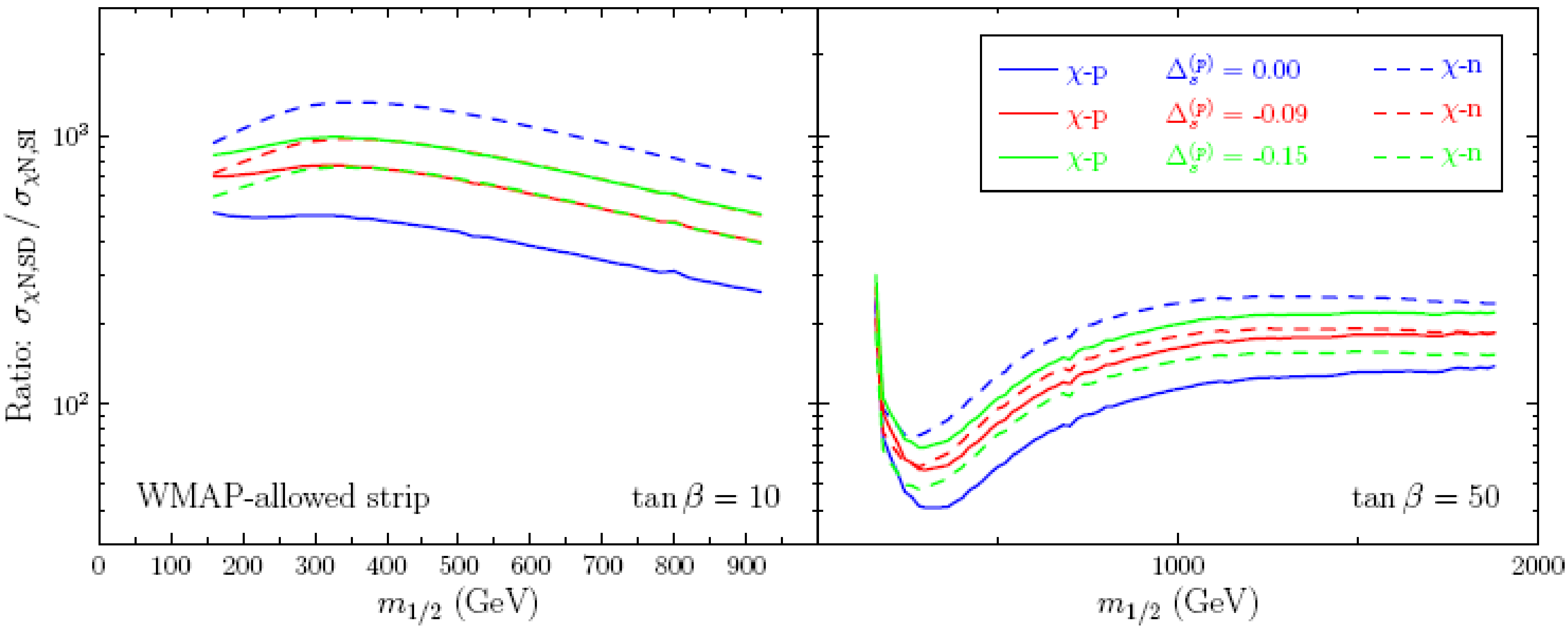
Neutron-to-Proton Cross-Section Ratio



p, *n* cross sections about equal for preferred value of Δ*s* from DIS

But much larger *p* cross section if Δ*s* = 0

Spin-Dependent and -Independent Cross Sections



Elastic Neutrino-Proton Cross Section

Elastic np scattering dominated by axial form factors at low Q^2

$$\frac{d\sigma}{dQ^2}(\nu p \to \nu p) \xrightarrow[Q^2 \to 0]{} \frac{G_F^2}{128\pi}\frac{M_p^2}{E_\nu^2}\left[\left(-G_A^u + G_A^d + G_A^s\right)^2 + \left(1 - 4\sin^2\theta_W\right)^2\right]$$

In terms of measured form factors

$$\frac{d\sigma}{dQ^2}(\nu p \to \nu p) = \frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}\left(A \pm BW + CW^2\right) \qquad \begin{matrix} + & \nu \\ - & \bar{\nu} \end{matrix}$$

with

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

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

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

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

Dependence on strange form factors is buried in the weak (Z) form factors.

Strange Axial Form Factors from νp Scattering

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

Combination of first two terms known at $Q^2 = 0$ from *n* decay ($g_A = 1.2695 \pm 0.0029$) and at higher Q^2 if dipole form is assumed:

$$G_A^{\mathrm{CC}} = G_A^u - G_A^d = \frac{g_A}{\left(1 + Q^2/M_A^2\right)^2}$$

Neutrino-proton elastic-scattering cross section at $Q^2 = 0$ measures G_A^s related to Δs measured in DIS (strange contribution to proton spin at large Q^2)

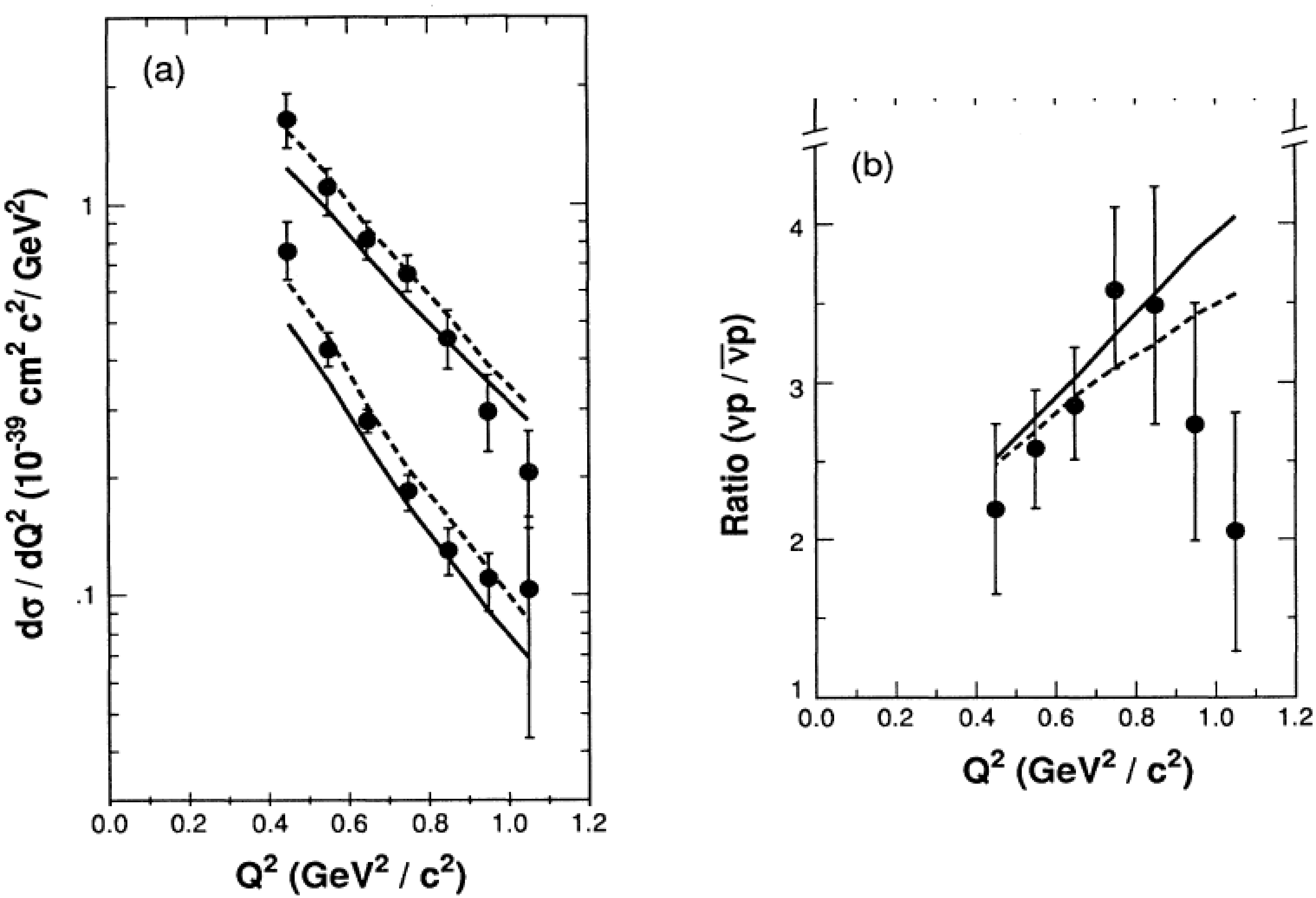
M_A determined from fits, but result very sensitive to value of M_A and dipole assumption is not well established

Originally, E734 announced $G_A^s = -0.15 \pm 0.07$ [Ahrens *et al*, *PRD* 35, 785 (1987)], in agreement with DIS

More detailed analysis showed sensitivity to assumptions

Fits to E734 Elastic νp Scattering Data

Garvey, Louis, and White, PRC 48, 761 (1993)

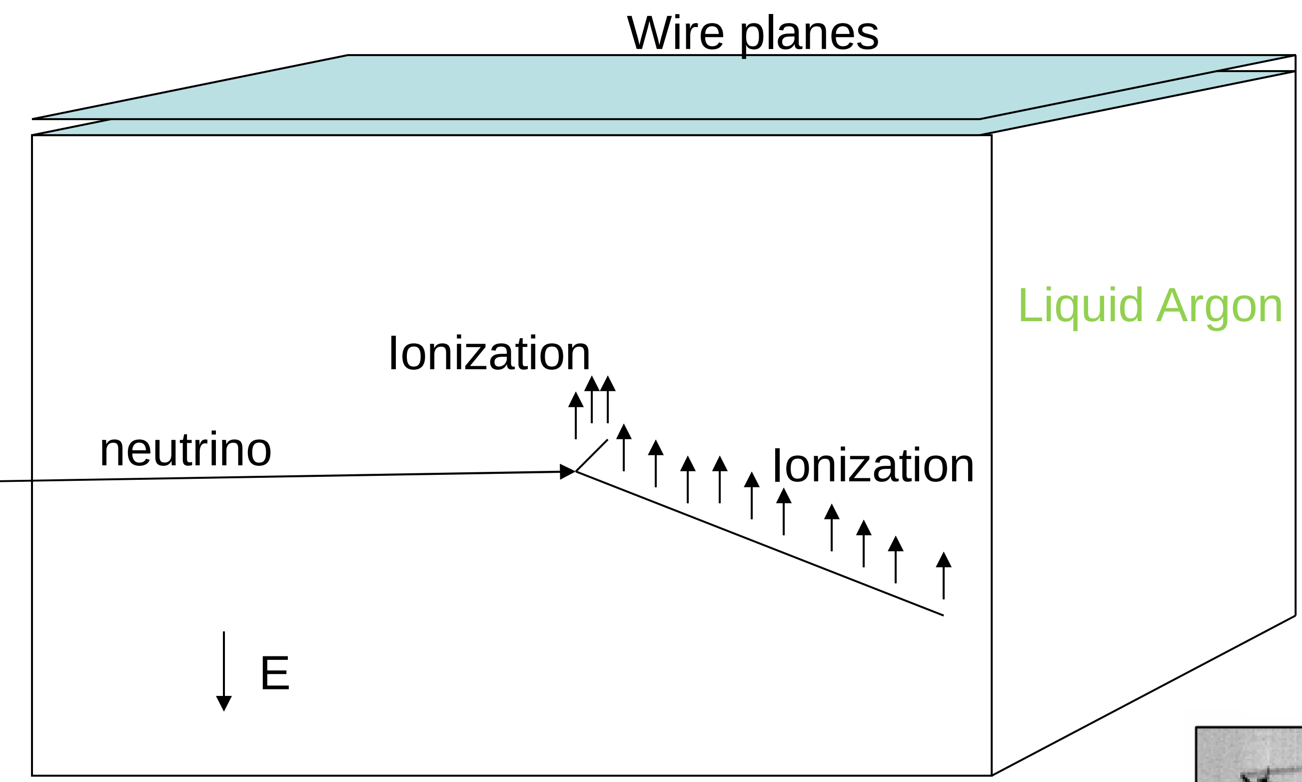


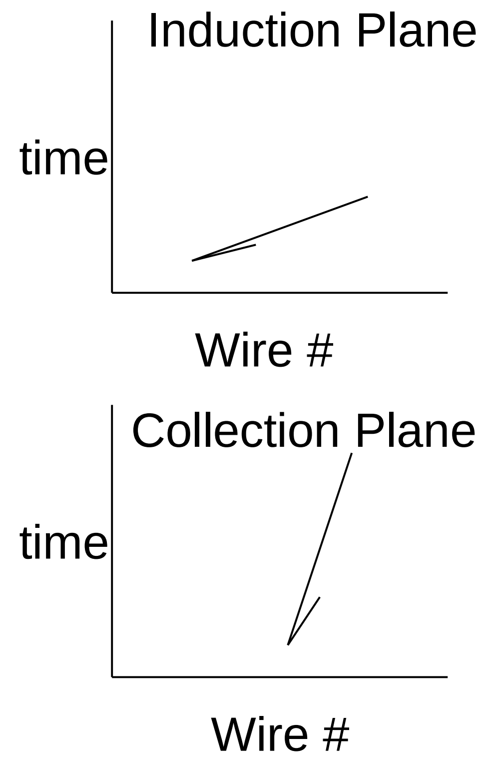
Reasonable fits can be obtained with G_A^s either zero (solid line) or negative (dashed line): G_A^s = -0.21±0.10

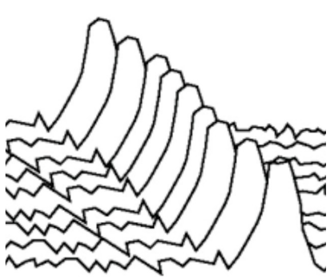
How the Neutrino Data Can be Improved

- Improve measurements of cross sections in general, especially at low Q^2
- Make improved determination of axial dipole form factor
- Better measurements of neutrino vs. antineutrino elastic cross sections
- Measure charged-to-neutral current cross-section ratio
- Measure cross-section ratio from protons, neutrons
  - Both sensitive to the axial strange form factor

The LArTPC technique

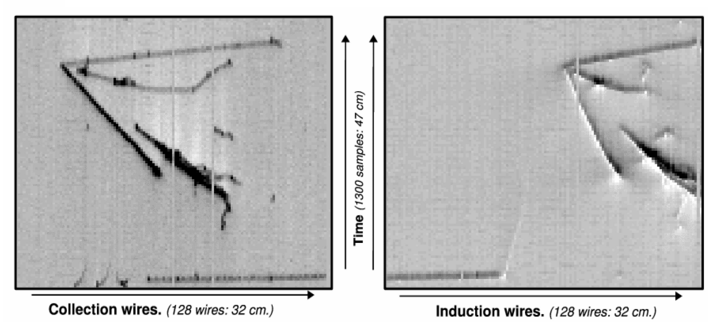






Wire pulses in time give the drift coordinate of the track

Scintillation light can give t_0



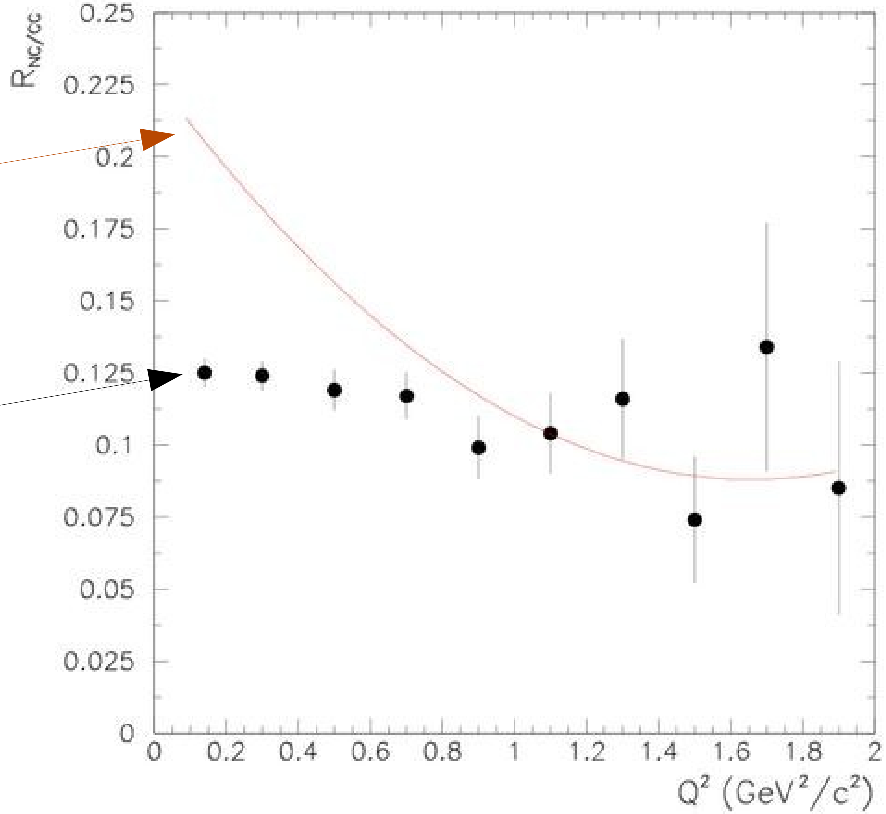
ICARUS 50L in WANF neutrino beam

induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

• *J. Spitz, FNAL Users' Meeting, June 4, 2009*

NC/CC (Quasi-)Elastic Scattering Ratio

- Measure R(NC/CC)≡σ(νp→νp)/σ(νn→μ$^-$$p$)
  - Very similar final states
- Advantages of an LAr TPC
  - Good proton identification
  - Possibility of identifying primary νn vertices from deposited energy
  - Proton recoil momentum measured down to 40 MeV
    - Q^2≈0.08 GeV^2/c^2
    - Minimize uncertainties from extrapolation to zero

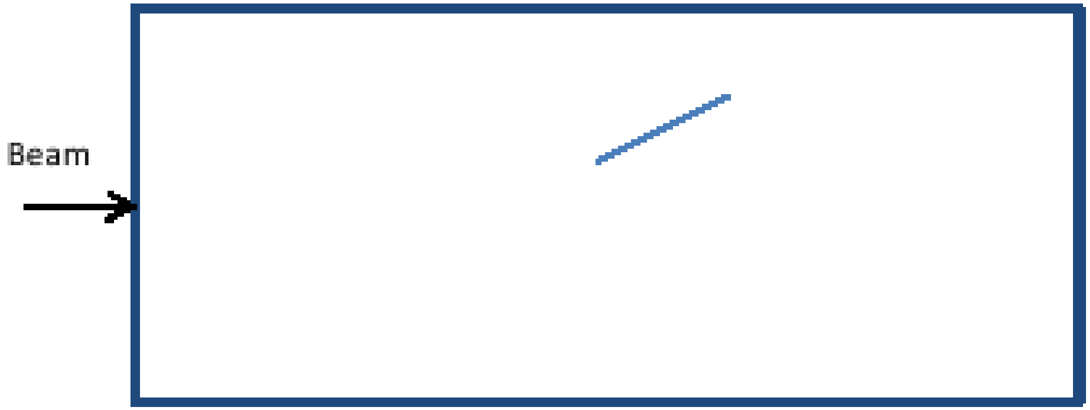


- Global fit to form factors
  - Elastic eN scattering and PVAS + BNL 734
  - Work in progress (S. Pate, priv. comm.)

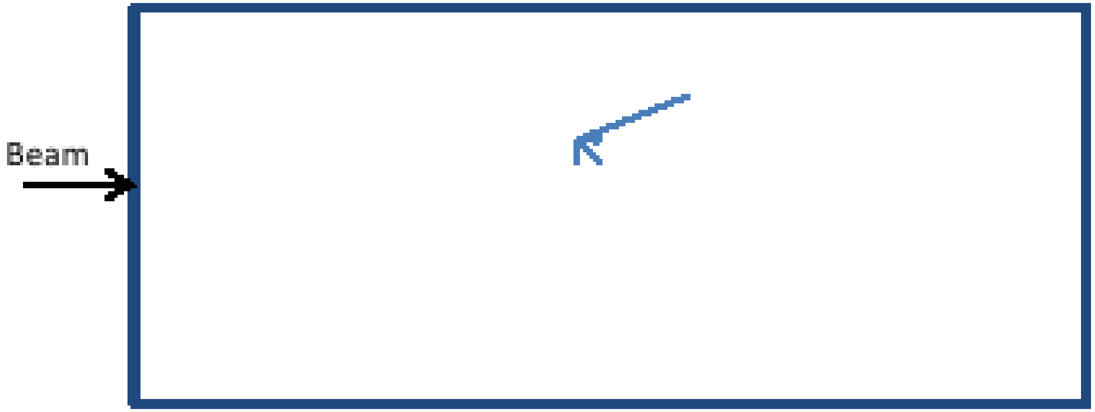
- *NUANCE* Monte Carlo
  - Default form factors
  - Generator-level only (no FS interactions)
  - 70-ton fiducial volume LAr
  - 1 yr nominal run
  - 2×10^{20} POT

Event Discrimination in LAr

Single proton visible



Proton visible w/ nuclear debris



- *J. Spitz, Internal MicroBooNE Note, March 2009*

Conclusions

- We need a better determination of Δs
- We may be able to do it with a large liquid-Argon TPC in the Fermilab BNB within the next few years

Backup Slides

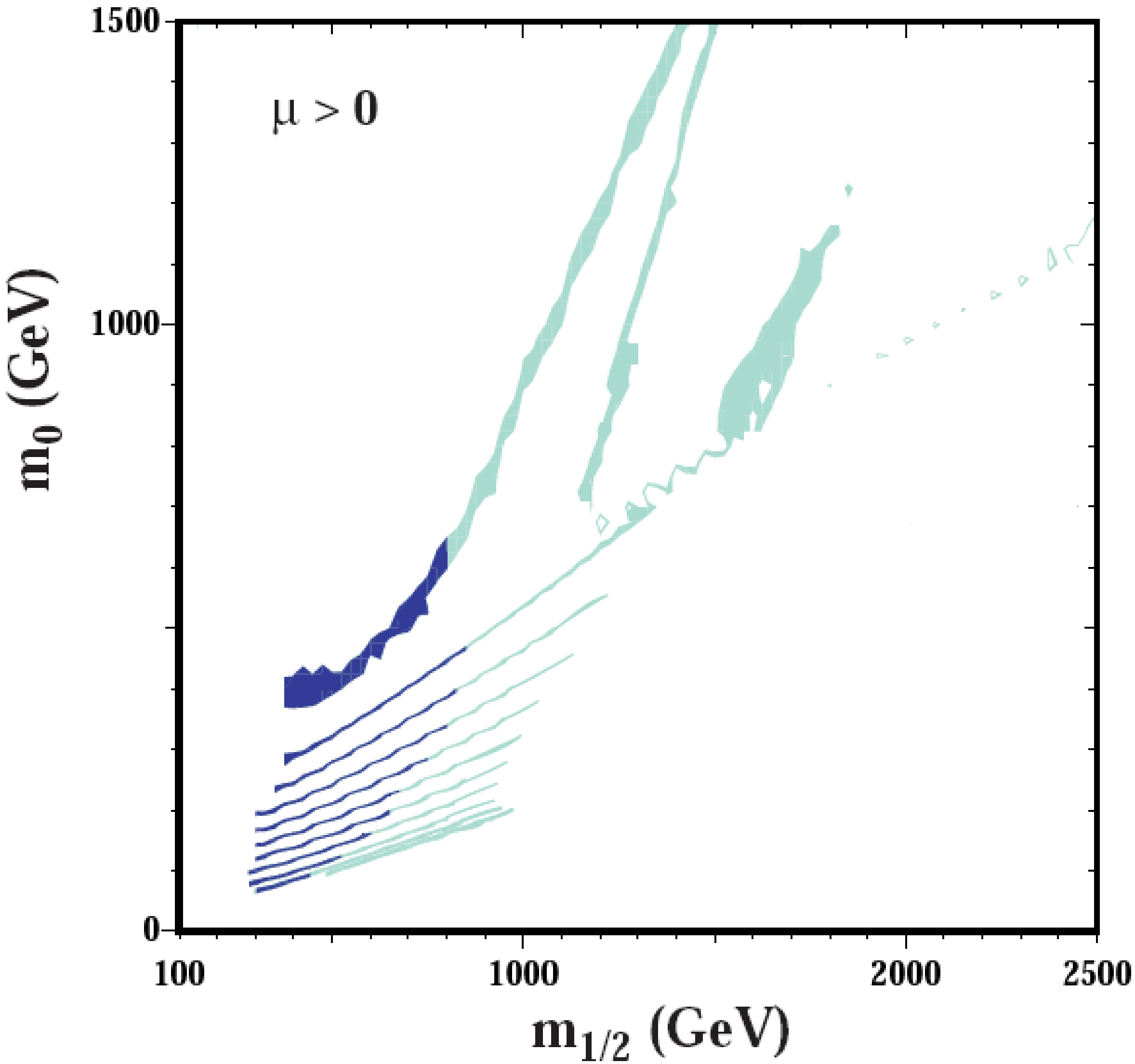


Figure 2: *The strips display the regions of the* $(m_{1/2}, m_0)$ *plane that are compatible with* $0.094 < \Omega_\chi h^2 < 0.129$ *and the laboratory constraints for* $\mu > 0$ *and* $\tan\beta = 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55$. *The parts of the strips compatible with* $g_\mu - 2$ *at the 2-σ level have darker shading.*

$$\alpha_{2i} = \frac{1}{4(m_{1i}^2 - m_\chi^2)}\left[\left|\eta_{11}^*\left(\frac{Y_i}{2}g'Z_{\chi 1} + gT_{3i}Z_{\chi 2}\right) + \frac{\eta_{12}^* g m_{q_i} Z_{\chi 5-i}}{2m_W B_i}\right|^2 + \left|-\eta_{12}^* e_i g' Z_{\chi 1}^* + \frac{\eta_{11}^* g m_{q_i} Z_{\chi 5-i}^*}{2m_W B_i}\right|^2\right]$$
$$+\frac{1}{4(m_{2i}^2 - m_\chi^2)}\left[\left|\eta_{21}^*\left(\frac{Y_i}{2}g'Z_{\chi 1} + gT_{3i}Z_{\chi 2}\right) + \frac{\eta_{22}^* g m_{q_i} Z_{\chi 5-i}}{2m_W B_i}\right|^2 + \left|-\eta_{22}^* e_i g' Z_{\chi 1}^* + \frac{\eta_{21}^* g m_{q_i} Z_{\chi 5-i}^*}{2m_W B_i}\right|^2\right]$$
$$-\frac{g^2}{8m_Z^2\cos^2\theta_W}(|Z_{\chi_3}|^2 - |Z_{\chi_4}|^2)T_{3i}$$

$$\alpha_{3i} = -\frac{1}{2(m_{1i}^2 - m_\chi^2)}\mathrm{Re}\left[\left(\frac{\eta_{11}^* g m_{q_i} Z_{\chi 5-i}^*}{2m_W B_i} - \eta_{12}^* e_i g' Z_{\chi 1}^*\right) \times \left(\eta_{11}^*\left(\frac{Y_i}{2}g'Z_{\chi 1} + gT_{3i}Z_{\chi 2}\right) + \frac{\eta_{12}^* g m_{q_i} Z_{\chi 5-i}}{2m_W B_i}\right)^*\right]$$
$$-\frac{1}{2(m_{2i}^2 - m_\chi^2)}\mathrm{Re}\left[\left(\frac{\eta_{21}^* g m_{q_i} Z_{\chi 5-i}^*}{2m_W B_i} - \eta_{22}^* e_i g' Z_{\chi 1}^*\right) \times \left(\eta_{21}^*\left(\frac{Y_i}{2}g'Z_{\chi 1} + gT_{3i}Z_{\chi 2}\right) + \frac{\eta_{22}^* g m_{q_i} Z_{\chi 5-i}}{2m_W B_i}\right)^*\right]$$
$$-\frac{g m_{q_i}}{4m_W B_i}\left[\mathrm{Re}\left(\delta_{1i}[gZ_{\chi_2} - g'Z_{\chi_1}]\right) C_i D_i \left(-\frac{1}{m_{H_1}^2} + \frac{1}{m_{H_2}^2}\right) + \mathrm{Re}\left(\delta_{2i}[gZ_{\chi_2} - g'Z_{\chi_1}]\right)\left(\frac{D_i^2}{m_{H_2}^2} + \frac{C_i^2}{m_{H_1}^2}\right)\right]$$

For up (down) quarks:

$B_i = \sin\beta(\cos\beta)$

$C_i = \sin\alpha(\cos\alpha)$

$D_i = \cos\alpha(-\sin\alpha)$

δ_{1i} is $Z_{\chi 3}$ $(Z_{\chi 4})$

δ_{2i} is $Z_{\chi 4}$ $(-Z_{\chi 3})$