Electroweak tests and nucleon structure:

Ross D. Young

PacSPIN 2011,
Cairns, Australia
21 June 2011
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Spin searches for “new physics”

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The direct search for dark matter

• “Dark Matter Results from 100 Live Days of XENON100 Data”
arXiv:1104.2549

The New York Times

Particle Hunt Nets Almost Nothing; the Hunters Are Almost Thrilled

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April 13, 2011

Today... convince you this CMSSM blob is too “high”

CMSSM: Constrained Minimal Supersymmetric Standard Model
WIMP-Nucleon cross section

• The Constrained MSSM (CMSSM):

\[ \Delta \chi^2 \]

Using:

\[ \Sigma_{\pi N} = 64 \text{ MeV} \]
**WIMP-Nucleon cross section**

- The Constrained MSSM (CMSSM):

  Using: \( \Sigma_{\pi N} = 64 \text{ MeV} \)

  \( \Sigma_{\pi N} = 45 \text{ MeV} \)

  \( \Rightarrow \) reduction in cross section by factor \( \sim 3 \) to 4
**WIMP-Nucleon cross section**

- The Constrained MSSM (CMSSM):

Using:

\[ \Sigma_{\pi N} = 64 \text{ MeV} \]

\[ \Sigma_{\pi N} = 45 \text{ MeV} \]

\[ \Rightarrow \text{reduction in cross section by factor } \sim 3 \text{ to } 4 \]

Why are we so sensitive to \( \Sigma_{\pi N} \)?
Spin-independent neutralino cross section

- Scalar neutralino–quark contact interaction
  \[ \mathcal{L}_{SI} = \sum_i \alpha_{3i} \bar{\chi} \chi q_i \bar{q}_i \]
  \( \alpha_{3i} \) depend on model (e.g., CMSSM)
  evolved down to low-energy scale

- Cross section \( \sigma_{SI}^p \propto |f_p|^2 \)
Spin-independent neutralino cross section

see eg. Ellis, Olive & Savage, PRD77:065026(2008)

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\[ \frac{f_p}{M_p} = \sum_{q=u,d,s} \tilde{\sigma}_{pq} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_{TG}^p \sum_{q=c,b,t} \frac{\alpha_{3q}}{m_q} \]
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Nucleon scalar quark content \( \bar{\sigma}_{pq} = \frac{m_q}{M_N} \langle N | \bar{q} q | N \rangle \)
Spin-independent neutralino cross section

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\[ \Sigma_{\pi N} = M_N (\bar{\sigma}_{pu} + \bar{\sigma}_{pd}) = \begin{cases} 
  45 \pm 8 \text{ MeV} & \text{Gasser et al. (1991)} \\
  64 \pm 7 \text{ MeV} & \text{GWU (2002)} 
\end{cases} \]

see eg. Ellis, Olive & Savage, PRD77:065026(2008)
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  \]

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\end{cases}
\]

\[
f_{TG}^p = 1 - \sum_{q=u,d,s} \bar{\sigma}_{pq}
\]

Trace anomaly:
Shifman, Vainstein & Zakharov, PLB(1978)
The missing ingredient

- Strangeness scalar content
  \[ \bar{\sigma}_{ps} = m_s \langle N | \bar{s}s | N \rangle / M_N \]
- Commonly used quantity
  \[ \sigma_0 \equiv \hat{m} \langle N | \bar{u}u + \bar{d}d - 2\bar{s}s | N \rangle \]
- Some algebra
  \[ \Rightarrow \bar{\sigma}_{ps} = \frac{m_s}{2\hat{m}} \left( \Sigma_{\pi N} - \sigma_0 \right) / M_N \]
- Use Feynman-Hellmann relation
  \[ m_q \langle N | \bar{q}q | N \rangle = m_q \frac{\partial M_N}{\partial m_q} \]
- First-order breaking in SU(3) baryon masses
  \[ \sigma_0 \simeq \hat{m} \frac{m_{\Xi} + m_{\Sigma} - 2m_{\Sigma}}{m_s - \hat{m}} = 26 \text{ MeV} \]
- With higher-order terms in chiral expansion
  \[ \sigma_0 \simeq 36 \pm 7 \text{ MeV} \]
  \[ \Rightarrow \sigma_{ps} = \left\{ \begin{array}{l} 110 \pm 130 \text{ MeV} \quad [\Sigma_{\pi N}(1)] \\ 350 \pm 120 \text{ MeV} \quad [\Sigma_{\pi N}(2)] \end{array} \right\} \]
## Lattice QCD determination

<table>
<thead>
<tr>
<th></th>
<th>$N$</th>
<th>$\Lambda$</th>
<th>$\Sigma$</th>
<th>$\Xi$</th>
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<tbody>
<tr>
<td>$\bar{\sigma}_B l$</td>
<td>0.050(9)(1)(3)</td>
<td>0.028(4)(1)(2)</td>
<td>0.0212(27)(1)(17)</td>
<td>0.0100(10)(0)(4)</td>
</tr>
<tr>
<td>$\bar{\sigma}_B s$</td>
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<td>0.144(15)(10)(2)</td>
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<td>0.244(15)(12)(2)</td>
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**Diagram:**

- GW: Pavan et al. (2001)
- BM: Borasoy & Meissner (1997)
- YT: Young & Thomas (2009)
- TF: Toussaint & Freeman (2009)

**Notes:**

- Preliminary: for illustration
- Young & Thomas, PRD(2010)

### πN Sigma Term (Expt):
- GW: Pavan et al. (2001)

### Octet Masses & Breaking:
- Gasser (1981)
- BM: Borasoy & Meissner (1997)

### 3-flavour Lattice QCD:
- YT: Young & Thomas (2009)
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### Lattice QCD determination

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**Young & Thomas, PRD(2010)**

**\( \pi N \) Sigma Term (Expt):**
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**Octet Masses & Breaking:**
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**3-flavour Lattice QCD:**
- YT: Young & Thomas (2009)
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*Strange scalar content is small*
2+1-flavour lattice results

Dynamical: $m_u = m_d \& m_s$

Octet baryon masses

- State-of-the-art lattice results approaching the physical domain
Chiral EFT: SU(3) expansion to $m_q^{3/2}$

- Chiral EFT is low-energy effective theory of QCD
- Only way to perform chiral extrapolation consistent with the chiral symmetries and symmetry breaking of QCD

Octet baryon masses

4 free parameters (at this order)

- 1 Overall mass scale
- 3 Linear perturbation in quark masses

Chiral nonanalytic contributions come with *model-independent* coefficients

\[
\begin{align*}
M_0 & \\
\alpha_M, \beta_M, \sigma_M & \\
\end{align*}
\]

Inputs:

\[
g_A = 1.267, D \simeq \frac{3}{5} g_A, F \simeq \frac{2}{5} g_A, C \simeq -2D, f_\pi \simeq 0.087 \text{ GeV}
\]

\[
\pm 15\% \quad \pm 15\% \quad \pm 15\% \quad \pm 5\%
\]
Corrections to the linear expansion

- Poorly converging

\[
\frac{2}{\pi} \int \frac{k^4}{k^2 + m^2} \to m^3
\]
Finite Range Regularization (FRR)

- Suppress ultraviolet contributions to loop integrals from scale beyond the validity of the EFT
- Maintain renormalization such that scale dependence is removed to working order

\[
\frac{2}{\pi} \int \frac{dk}{k^2 + m^2} \rightarrow m^3
\]

FRR

\[
\frac{2}{\pi} \int \frac{k^4 \theta(\Lambda^2 - k^2)}{k^2 + m^2} \rightarrow m^3 \frac{2}{\pi} \arctan \frac{\Lambda}{m}
\]

Donoghue, Holstein & Borasoy, PRD59,036002(1999)
Leinweber et al., PRD61,074502(2000)
Young, Leinweber & Thomas, PPNP 50,399(2003)
Leinweber, Thomas & Young, PRL92,242002(2004)
Lattice results “choose” regularisation scale

- Lattice results prefer a regularisation scale of order 1 GeV (Dipole)

\[ \chi^2 / \text{dof} \]

New development: preferred scale is not input from phenomenology

Young & Thomas, PRD(2010)
**Fit to 8 LHPC points**

\[ m_{s}^{\text{latt}} \sim 1.3 m_{s}^{\text{phys}} \]

Strange quark-mass correction

- Excellent description of lattice results
- Accurate prediction of heavier simulation data
- Reliable correction for lattice simulation quark mass

- \( N \)
- \( \Lambda \)
- \( \Sigma \)
- \( \Xi \)

\[ m_{\pi}^2 \ (\text{GeV}^2) \]

Young & Thomas, PRD(2010)
Fit to 8 PACS-CS points

PACS-CS: 2+1-flavour simulation; different action discretization to LHPC

Correction in strange quark mass demonstrated to be reliable against numerical simulation

As for LHPC, excellent agreement with observed spectrum

PACS-CS have an additional run with a different strange quark mass

Young & Thomas, PRD(2010)
Strange-quark mass dependence

Strangeness sigma term is just local derivative at this point
Sigma terms from lattice QCD
Updated cross sections for benchmark models

Ellis, Olive & Savage PRD(2008)
Strong dependence on sigma term from poorly known strangeness

\[ \bar{\sigma}_{\text{ps}} = \frac{m_s}{2\hat{m}} \left( \Sigma_{\pi N} - \sigma_0 \right) \]

Giedt, Thomas & Young, PRL(2009)
Significant reduction in uncertainty

Cross-section reduced by order of magnitude from XENON100 figure
XENON100

• Shift the “blob” down
XENON100

- Shift the “blob” down
• Shift the "blob" down
Combined global analysis

Sample

HAPPEX-He4

HAPPEX-H

PVA4

Leinweber et al. “Lattice-inspired”

$Q^2 = 0.1 \text{ GeV}^2$

$G^E_S$

$G^M_S$

$68\% \text{ CL}$

$G_0$
PV Electron-Quark Couplings

\[ C_{1(2)q} \]

\[ = C_{1(2)q}^{\text{SM}} \]

new physics

Constrained by low-energy data!

\[ \mathcal{L}_{\text{PV}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_{\mu} \gamma_5 e \sum_q C_{1q}^{\text{SM}} \bar{q} \gamma^\mu q \]

\[ \mathcal{L}_{\text{SM}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_{\mu} \gamma_5 e \sum_q C_{1q}^{\text{SM}} \bar{q} \gamma^\mu q \]
C1q Quark-Vector couplings (electron-axial)

95% CL

SLAC: D DIS
Mainz: Be

APV Tl
APV Cs

C1q Quark-Vector couplings (electron-axial)
PV Asymmetry

- Proton

\[
A_{PV}^{P} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[ \frac{-G_F}{\pi \alpha \sqrt{2}} \right] \varepsilon G_E^{P\gamma} G_Z^{P\gamma} \epsilon' G_M^{P\gamma} \tilde{G}_A^P + \tau \left( G_E^{P\gamma} \right)^2 + \frac{1}{2} \left( 1 - 4 \sin^2 \theta_W \right) \varepsilon' G_M^{P\gamma} \tilde{G}_A^P
\]

Neutral-weak form factors

Assume charge symmetry:

\[
4 G_{E,M}^{PZ} = (1 - 4 \sin^2 \theta_W) G_{E,M}^{P\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^s
\]

- Proton weak charge
- Strangeness

\[
Q_{weak}^{P} = -2(2C_{1u} + C_{1d})
\]
**PV Asymmetry**

- Proton

\[
A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[ -\frac{G_F Q^2}{\pi \alpha \sqrt{2}} \right] \frac{\varepsilon G_{E}^{p\gamma} G_{E}^{pZ} + \tau G_{M}^{p\gamma} G_{M}^{pZ}}{\varepsilon (G_{E}^{p\gamma})^2 + \tau (G_{M}^{p\gamma})^2} - \frac{1}{2} (1 - 4 \sin^2 \theta_W) \varepsilon' G_{M}^{p\gamma} \tilde{G}_{A}^p
\]

Neutral-weak form factors

Assume charge symmetry:

\[
4G_{E,M}^{pZ} = (1 - 4 \sin^2 \theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^s
\]

Proton weak charge \( Q_{weak}^p = -2(2C_{1u} + C_{1d}) \)

**Use data to constrain the parameters of the electroweak theory**
Proton Extrapolation

Proton weak charge

PDG

SM

\( \frac{A^P}{A_{LR}} \)

HAPPEX

SAMPLE

G0

PVA4

Theory estimate for anapole FF

RDY et al., PRL99, 122003 (2007)

\[ Q^2 \text{ (GeV}^2) \]
New update on C1q couplings

RDY et al., PRL99, 122003(2007)
New update on C1q couplings

RDY et al., PRL99, 122003(2007)
New update on C1q couplings

Dramatic improvement in knowledge of weak couplings!

RDY et al., PRL99,122003(2007)
Limits on new physics

• One may be sensitive to a new heavy $Z'$ boson contributing to a new contact interaction

• Imagine a new $Z'$ which has exactly the same couplings to the SM fermions and mass $M_{Z'} \gg M_Z$
  – Simplest Kaluza-Klein excitation from a compact 5th dimension (circle radius $R$)

$$M_{Z_1}^2 = M_Z^2 + \frac{1}{R^2}$$

95% CL

$M_{Z_1} > 1.04 \text{ TeV}$

$R < 2 \times 10^{-4} \text{ fm}$

~200 zeptometres
Model-independent limits

\[ \mathcal{L}_{\text{PV SM}}^{\text{PV}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q}^{\text{SM}} \bar{q} \gamma^\mu q \]

\[ \mathcal{L}_{\text{NP}}^{\text{PV}} = \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_{\nu q}^{\text{PV}} \bar{q} \gamma^\mu q \]

Erler et al., PRD68(2003)
Model-independent limits

\[ \mathcal{L}^{PV}_{SM} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C^{SM}_{1q} \bar{q} \gamma^\mu q \]

\[ \mathcal{L}^{PV}_{NP} = \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h^u_V \bar{q} \gamma^\mu q \]

Full isospin coverage for limits on new physics!

\[ h^u_V = \cos \theta_h \quad h^d_V = \sin \theta_h \]

Data sets limits on \( \frac{g^2}{\Lambda^2} \)

Erler et al., PRD68(2003)
Lower bound on NP scale

\[ \Lambda \leq \frac{g}{\sqrt{2}} \]

95% CL

\[ 0 \leq \theta_h \leq \frac{\pi}{2}, \frac{3\pi}{2} \]

Atomic and others
Lower bound on NP scale

New physics scale $>0.9$ TeV! (from 0.4 TeV)

with PVES
Atomic and others

95% CL
Reminder: Limits on ratio $\frac{\Lambda}{g}$

Weak coupling: eg. new perturbative $Z'$

$g \sim 0.1 \Rightarrow$ low mass limit
(also low yield in colliders)
Reminder: Limits on ratio $\Lambda/g$

Weak coupling: eg. new perturbative $Z'$

$g \sim 0.1 \Rightarrow$ low mass limit
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“Typical” coupling: eg. leptoquarks

$g \sim 1 \Rightarrow$ ball park TeV scale
Reminder: Limits on ratio $\Lambda/g$

Weak coupling: *eg. new perturbative $Z'$*
\[ g \sim 0.1 \implies \text{low mass limit} \]
(also low yield in colliders)

“Typical” coupling: *eg. leptoquarks*
\[ g \sim 1 \implies \text{ball park TeV scale} \]

Strong coupling: *eg. compositeness*
\[ g \sim \sqrt{4\pi} \implies \text{large mass reach} \]
\text{strength of precision tests}
Future: Q-weak Experiment

• Precise measurement of the proton’s weak charge in PVES

\[ Q^p_{\text{weak}} = -2(2C_{1u} + C_{1d}) \]

\[ Q^2 = 0.03 \text{GeV}^2, \ \theta = 8^\circ \]

• At low energy and small scattering angle:

\[ A_{LR} = -\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}} \left[ Q_{\text{weak}} + \beta_A \tilde{G}_A^p \sqrt{Q^2} + \beta_V Q^2 + \ldots \right] \]

\[ \beta_A \propto \theta + O(\theta^3) \]

Anapole uncertainty

Strangeness uncertainty
Impact of $Q$-weak
Impact of Q-weak (assuming SM)
Impact of Q-weak (assuming SM)

Q-weak constrains new physics to beyond 2 TeV

future Q-weak with PVES
Atomic and others

95% CL
What about Q-weak discovery?

Assume Q-weak takes central value of current measurements

\[ \frac{1.5 < \frac{\Lambda}{g} < 2.5 \text{ TeV}}{g} \]