Patrick Stengel

Stockholm University

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1707.02460 with Andrew Davidson, Chris Kelso, Jason Kumar and Pearl Sandick
**Introduction**

Squark mass limits from jets + MET searches

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**Figure:** Simplified models only considering production of light flavor squark pairs, see *CMS 1704.07781*

**Figure:** Use ISR to boost MET and help identify signal events, *ATLAS 1604.07773*
Resurrect “bulk” region by relaxing MFV, allowing light \( \tilde{f} \)

Light flavor squark co-annihilation
- pure \( \tilde{B} \) need sfermions with L-R mixing, nondegenerate masses for s-wave annihilation
- LHC less sensitive for \( m_\chi \simeq m_{\tilde{q}} \gtrsim \mathcal{O}(400 \text{ GeV}) \)
- need \( \tilde{q}^* \tilde{q} \rightarrow gg \), \( \chi \tilde{q} \rightarrow gq \)

Scattering through squark exchange
- enhanced scattering cross section for \( m_\chi \simeq m_{\tilde{q}} \)
- need small mixing angle for consistency with SI limits
- dim-8/spin-dependent operators can dominate
“Simplified” model with singlet DM, squark mediator(s)

\[ \mathcal{L}_{\text{int}} = \sum_{q=u,d,s} \lambda_{Lq}(\bar{\chi}P_L q)\tilde{q}_L^* + \lambda_{Rq}(\bar{\chi}P_R q)\tilde{q}_R^* + h.c. \]

\[
\tilde{q}_L = \tilde{q}_1 \cos \alpha + \tilde{q}_2 \sin \alpha \\
\tilde{q}_R = -\tilde{q}_1 \sin \alpha + \tilde{q}_2 \cos \alpha
\]

Gauge invariance requires squark couplings to SM gauge bosons

\[
\langle \sigma v(\tilde{q}^* \tilde{q} \to gg) \rangle = \frac{7g_s^4 N_{\tilde{q}}}{432\pi m_{\tilde{q}}^2} \left[ N_{\tilde{q}} + \frac{\exp(\Delta m/T)}{3(1 + \Delta m/m_\chi)^{3/2}} \right]^{-2}
\]

- For small \( \Delta m = m_{\tilde{q}} - m_\chi \), QCD processes dominate annihilation
- Temperature at freeze out \( T \simeq m_\chi/25 \) for correct relic density
- Sum over \( N_{\tilde{q}} \) mass degenerate light flavor squarks species
Co-annihilation processes needed to deplete relic density

**Figure:** Relic density contours for benchmarks with a light $d/s$-type squark.
Adding squarks can raise or lower effective $\langle \sigma v \rangle$.

**Figure:** Relic density contours for benchmarks with light $u$-, $d$- and $s$-type squarks.
Relevant operators for squark exchange with $m_{\tilde{q}_1} \ll m_{\tilde{q}_2}$

\[ O_{q1} = \alpha_{q1} (\bar{\chi} \gamma^\mu \gamma^5 \chi)(\bar{q} \gamma^\mu q) \]
\[ O_{q2} = \alpha_{q2} (\bar{\chi} \gamma^\mu \gamma^5 \chi)(\bar{q} \gamma^5 \gamma^\mu q) \]
\[ O_{q3} = \alpha_{q3} (\bar{\chi} \chi)(\bar{q} q) \]
\[ O_{qT2} = \alpha_{qT2} (\bar{\chi} \gamma^\mu \partial_\nu \chi) O_q^{(2)\mu\nu} \]

Scattering enhanced $m_\chi \simeq m_{\tilde{q}_1}$

- $O_{q1}^{*,3,T2}$ spin independent
- $O_{q2}$ spin dependent
- $O_{q2,3,T2}$ velocity independent

\[
\alpha_{q1,2} = \mp \left[ \frac{|\lambda^2_L|}{8} \left( \frac{\cos^2 \alpha}{m_{\tilde{q}_1}^2 - m_\chi^2} \right) + \frac{|\lambda^2_R|}{8} \left( \frac{\sin^2 \alpha}{m_{\tilde{q}_1}^2 - m_\chi^2} \right) \right] \\
\alpha_{q3} = \frac{Re(\lambda_L \lambda_R^*)}{4} (\cos \alpha \sin \alpha) \left[ \frac{1}{m_{\tilde{q}_1}^2 - m_\chi^2} \right] \\
\alpha_{qT2} = \frac{|\lambda^2_L|}{4} \left( \frac{\cos^2 \alpha}{(m_{\tilde{q}_1}^2 - m_\chi^2)^2} \right) + \frac{|\lambda^2_R|}{4} \left( \frac{\sin^2 \alpha}{(m_{\tilde{q}_1}^2 - m_\chi^2)^2} \right) 
\]
$\mathcal{O}_{q3}$ ($\mathcal{O}_{qT2}$) dominates in Xenon at large (small) mixing.

**Benchmark B**

$m_{\tilde{s}_1} = 916$ GeV

**Benchmark E**

$m_{\tilde{u}_1} = m_{\tilde{d}_1} = m_{\tilde{s}_1} = 912$ GeV

**Figure:** Event rate in Xenon-based detector as a function of $\alpha$ for $\mathcal{O}_{q1}$, $\mathcal{O}_{q2}$, $\mathcal{O}_{q3} + \mathcal{O}_{qT2}$, $m_\chi = 900$ GeV. Also show limits from XENON1T (dashed) and projections from LZ-7 (dash-dotted).
Figure: Projected LZ-7 sensitivity for benchmarks $\tilde{u}_1$, $\tilde{s}_1$, $\tilde{u}_1 \tilde{d}_1 \tilde{s}_1$, $\tilde{u}_1 \tilde{u}_2$. 
Light squark co-annihilation

- need \( \tilde{q}\chi \) and \( \tilde{q}\tilde{q} \) initial states to deplete relic density
- small mixing angle requires more general treatment of direct detection
- dim-8 or SD operators can dominate scattering at small \( \alpha \)
- can probe squark masses higher than accessible at LHC

Slepton mediators

- for more “Incredible Bulk”, see 1406.4903
- can look for compressed sleptons at LHC, 1706.05339
- can probe full parameter space at ILC, coming soon
- direct (1608.00642), indirect (1605.03224) detection
Thank you!

Figure: See 1411.2634
LSP is a natural WIMP candidate in the MSSM

R-parity suppresses proton decay
- \[ R = (-1)^{3B+L+2s} \]
- Provides stable WIMP candidate

Neutralino in MSSM
- Mixture of neutral gauginos and higgsinos
- SM interactions depend on specific model
- mSUGRA tightly constrained

Figure: Cosmologically preferred mSUGRA regions are in green with \( A_0 = 0 \) and \( \mu > 0 \). Blue contours denote neutralino masses, see Feng 1003.0904.
Typical mSUGRA/CMSSM scenario with $\tilde{B}$-$\tilde{H}$ admixture

**Relic density with $\tilde{\chi}\tilde{\chi} \rightarrow WW, ff$**
- Assuming gaugino mass unification (at least $M_1 \lesssim M_2$), yields neutralino with small $\tilde{W}$
- Minimal flavor violation eliminates sfermion mixing
- Need $\mu/m_\chi \sim \mathcal{O}(1)$ for $s$-wave
  see e.g. Feng, Sanford 1009.3934

**SI scattering with Higgs exchange**
- Scalar mediated interactions are velocity independent
- Minimal flavor violation guarantees coupling $\sim m_q$
- LHC data and $m_h \simeq 125$ GeV push unified $m_{\tilde{f}} \gtrsim \mathcal{O}(\text{TeV})$
  see e.g. Baer et. al. 1112.3017
Figure: Relic density contours for benchmarks with light $u$–type squarks.
Relic density for $\tilde{u}_1 \tilde{d}_1$

**Figure:** Relic density contours for benchmarks with light $u$- and $d$-type squarks.
Relic density for $\tilde{u}_1 \tilde{u}_2$

Figure: Relic density contours for benchmarks with two light $u$–type squarks.
Figure: Event rate in Xenon-based detector as a function of $\alpha$ for $\mathcal{O}_{q1}$, $\mathcal{O}_{q2}$, $\mathcal{O}_{q3} + \mathcal{O}_{qT2}$, $m_\chi = 900$ GeV. Also show limits from XENON1T (dashed) and projections from LZ-7 (dash-dotted).
The diagrams show the event rate in Fluorine-based detector as a function of $\alpha$ for $O_{q1}$, $O_{q2}$, $O_{q3} + O_{qT2}$, $m_\chi = 900$ GeV. Also show limits from PICO-60L (dashed) and projections from PICO-250L (dash-dotted).
Figure: Event rate in Fluorine-based detector as a function of $\alpha$ for $\mathcal{O}_{q1}$, $\mathcal{O}_{q2}$, $\mathcal{O}_{q3} + \mathcal{O}_{qT2}$, $m_\chi = 900 \text{ GeV}$. Also show limits from PICO-60L (dashed) and projections from PICO-250L (dash-dotted).
Figure: Current XENON1T sensitivity for benchmarks $\tilde{u}_1, \tilde{s}_1, \tilde{u}_1 \tilde{d}_1 \tilde{s}_1, \tilde{u}_1 \tilde{u}_2$. 
Figure: Projected PICO-250 sensitivity for benchmarks $\tilde{u}_1$, $\tilde{s}_1$, $\tilde{u}_1 \tilde{d}_1 \tilde{s}_1$, $\tilde{u}_1 \tilde{u}_2$. 

Projected sensitivity of direct detection at PICO-250
Figure: Current PICO-60 sensitivity for benchmarks $\tilde{u}_1$, $\tilde{s}_1$, $\tilde{u}_1 \tilde{d}_1 \tilde{s}_1$, $\tilde{u}_1 \tilde{u}_2$. 
Can also satisfy relic density with $L-R$ slepton mixing

$$\lambda_L \tilde{\ell}_L \tilde{\chi} P_L \ell + \lambda_R \tilde{\ell}_R \tilde{\chi} P_R \ell$$

$$+ \lambda^*_L \tilde{\ell}_L^* \tilde{\chi} P_L l + \lambda^*_R \tilde{\ell}_R^* \tilde{\chi} P_R l$$

$$\lambda_L = \sqrt{2} g Y_L e^{i\phi/2}$$

$$\lambda_R = \sqrt{2} g Y_R e^{-i\phi/2}$$

$$\begin{bmatrix} \tilde{\ell}_1 \\ \tilde{\ell}_2 \end{bmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} \tilde{\ell}_L \\ \tilde{\ell}_R \end{bmatrix}$$

L-R mixing angle $\alpha$, CP-violating phase $\phi$

Dipole moments constrain mixing
Rule out $\tilde{e}$, constrain $\tilde{\mu}$, allow $\tilde{\tau}$

Figure: Bino relic abundance assuming smuon mixing with $m_\chi = 100$ GeV, $m_{\tilde{\mu}_1} = 120$ GeV and $m_{\tilde{\mu}_2} = 300$ GeV.
Can use ISR to boost MET and help S-B discrimination

$\tilde{\mu}_L$ with $30 \text{ GeV} < \Delta m < 60 \text{ GeV}$
- Can generally satisfy relic density with bino DM
- Do not need monojet for $\Delta m \gtrsim 70 \text{ GeV}$
- Look for OSSF muons, one hard non-b jet and MET

Basic cuts reduce SM background
- $t\bar{t}$ needs one missed jet, both mistagged
- $Z \rightarrow \tau\bar{\tau} \rightarrow \ell^+\ell^- + 4\nu$ reduced by $M_{\tau\tau} > 125 \text{ GeV}$
Angular variables can help reduce remaining backgrounds

Decay products collimated for parents produced above threshold
- $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ leptons collimated, anti-collimated $\not{E}_T$
- $W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ leptons anti-collimated, collimated $\not{E}_T$

$WW$ leptons, MET look like signal
- ISR boost smears collimation, $p_T(j)$ cut cannot be too high
- Less smearing for heavier parents, use rapidity to distinguish parent spin

Figure: Credit J. Kumar
For $p_T(\ell) \ll p_T(j)$, signal MET balanced by $p_T(j)$

**Figure:** $1.0 < p_T(j)/\slashed{E}_T < 1.3$ cut for smaller mass differences
$ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ has leptons recoiling against MET

$\sqrt{s} = 14$ TeV

Figure: $\Delta \phi(\not{E}_T, \ell_1) < 0.6\pi$ helps for intermediate mass differences
$W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ has less anti-collimated leptons

Figure: $\Delta \phi(\ell_1, \ell_2) > 0.5\pi$ suppresses background with lighter parents
\[ \cos \theta_{\ell_1, \ell_2}^* = \tanh(\Delta \eta_{\ell_1, \ell_2}/2) \] depends on parents’ spin.

**Figure:** \( \cos \theta_{\ell_1, \ell_2}^* < 0.5\pi \) suppresses background with spin-1 parents.
Dipole moment contributions from L-R slepton mixing

Figure: Muon electric dipole moment contribution assuming smuon mixing with $m_X = 100$ GeV, $m_{\tilde{\mu}_1} = 120$ GeV and $m_{\tilde{\mu}_2} = 300$ GeV. All unconstrained.

Figure: Muon magnetic dipole moment contribution either fully accounting for measured value (red) or only similar in magnitude (pink).
$M_{\tau\tau}$ suppresses $Z \rightarrow \tau\bar{\tau}$
MET cut helps $t\bar{t}$ background

\[ \sqrt{s} = 14 \text{ TeV} \]

![Graph showing event fraction per GeV](image)

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Window cut on $m_{\ell\ell}$ around $m_Z$
Leading lepton $p_T$

\[ \sqrt{s} = 14 \text{ TeV} \]

- $t\bar{t}jj$
- $ZZjj$
- $WZjj$
- $WWjj$
- $S_{110}^{10}$
- $S_{210}^{10}$
- $S_{310}^{10}$
- $S_{410}^{110}$
- $S_{510}^{110}$
- $S_{610}^{110}$

Event Fraction per GeV ($d\sigma/dE/\sigma$)

$P_T^{ll}$ [GeV]
Subleading lepton $p_T$

$\sqrt{s} = 14$ TeV

Event Fraction per GeV ($d\sigma/dE/\sigma$) vs. $P_{T}^{l_2}$ (GeV)
Primary and secondary cuts

<table>
<thead>
<tr>
<th>Selection</th>
<th>ZZjj</th>
<th>WZjj</th>
<th>WWjj</th>
<th>$S_{30}^{110}$</th>
<th>$S_{40}^{110}$</th>
<th>$S_{50}^{110}$</th>
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</thead>
<tbody>
<tr>
<td>Matched Production</td>
<td>$1.3 \times 10^4$</td>
<td>$4.2 \times 10^4$</td>
<td>$9.5 \times 10^4$</td>
<td>$1.9 \times 10^2$</td>
<td>$1.9 \times 10^2$</td>
<td>$1.9 \times 10^2$</td>
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<tr>
<td>$\tau$-veto</td>
<td>$1.2 \times 10^4$</td>
<td>$4.0 \times 10^4$</td>
<td>$8.9 \times 10^4$</td>
<td>$1.9 \times 10^2$</td>
<td>$1.9 \times 10^2$</td>
<td>$1.9 \times 10^2$</td>
</tr>
<tr>
<td>OSSF muon</td>
<td>$3.2 \times 10^2$</td>
<td>$5.8 \times 10^2$</td>
<td>$5.1 \times 10^2$</td>
<td>$8.1 \times 10^1$</td>
<td>$8.8 \times 10^1$</td>
<td>$8.9 \times 10^1$</td>
</tr>
<tr>
<td>only $1J \ P_T &gt; 30$</td>
<td>$9.4 \times 10^1$</td>
<td>$1.5 \times 10^2$</td>
<td>$1.1 \times 10^2$</td>
<td>$1.6 \times 10^1$</td>
<td>$1.7 \times 10^1$</td>
<td>$1.7 \times 10^1$</td>
</tr>
<tr>
<td>Jet $b$-veto</td>
<td>$8.0 \times 10^1$</td>
<td>$1.4 \times 10^2$</td>
<td>$1.1 \times 10^2$</td>
<td>$1.6 \times 10^1$</td>
<td>$1.7 \times 10^1$</td>
<td>$1.7 \times 10^1$</td>
</tr>
<tr>
<td>$E_T &gt; 100$ GeV</td>
<td>$4.3 \times 10^0$</td>
<td>$7.8 \times 10^0$</td>
<td>$1.7 \times 10^1$</td>
<td>$2.5 \times 10^0$</td>
<td>$3.4 \times 10^0$</td>
<td>$3.8 \times 10^0$</td>
</tr>
<tr>
<td>Jet $P_T &gt; 100$ GeV</td>
<td>$1.4 \times 10^0$</td>
<td>$4.0 \times 10^0$</td>
<td>$1.0 \times 10^1$</td>
<td>$1.8 \times 10^0$</td>
<td>$1.9 \times 10^0$</td>
<td>$1.8 \times 10^0$</td>
</tr>
<tr>
<td>$m_{\ell\ell} \notin M_Z \pm 10$ GeV</td>
<td>$1.0 \times 10^{-1}$</td>
<td>$1.0 \times 10^0$</td>
<td>$8.9 \times 10^0$</td>
<td>$1.6 \times 10^0$</td>
<td>$1.6 \times 10^0$</td>
<td>$1.5 \times 10^0$</td>
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<tr>
<td>$m_{\tau\tau} &gt; 175$ GeV</td>
<td>$2.0 \times 10^{-2}$</td>
<td>$3.3 \times 10^{-1}$</td>
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<td>$9.3 \times 10^{-1}$</td>
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<tr>
<td>$E_T &gt; 175$ GeV</td>
<td>$8.3 \times 10^{-3}$</td>
<td>$9.9 \times 10^{-2}$</td>
<td>$1.3 \times 10^0$</td>
<td>$3.5 \times 10^{-1}$</td>
<td>$3.1 \times 10^{-1}$</td>
<td>$3.2 \times 10^{-1}$</td>
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<tr>
<td>Jet $P_T &gt; 175$ GeV</td>
<td>$6.6 \times 10^{-3}$</td>
<td>$8.7 \times 10^{-2}$</td>
<td>$1.2 \times 10^0$</td>
<td>$3.3 \times 10^{-1}$</td>
<td>$2.6 \times 10^{-1}$</td>
<td>$2.6 \times 10^{-1}$</td>
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</table>
### Tertiary cuts targeted at larger mass gaps

<table>
<thead>
<tr>
<th>Selection</th>
<th>ZZjj</th>
<th>WZjj</th>
<th>WWjj</th>
<th>S_{30}^{110}</th>
<th>S_{40}^{110}</th>
<th>S_{50}^{110}</th>
</tr>
</thead>
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<td>$M_{T2}^{WW} &lt; 1$ GeV</td>
<td>3.9 x 10^{-3}</td>
<td>7.0 x 10^{-2}</td>
<td>8.6 x 10^{-1}</td>
<td>2.8 x 10^{-1}</td>
<td>2.1 x 10^{-1}</td>
<td>2.0 x 10^{-1}</td>
</tr>
<tr>
<td>$0.8 &lt; P_T^j/E_T &lt; 1.8$</td>
<td>3.9 x 10^{-3}</td>
<td>5.6 x 10^{-2}</td>
<td>7.5 x 10^{-1}</td>
<td>2.7 x 10^{-1}</td>
<td>1.9 x 10^{-1}</td>
<td>1.7 x 10^{-1}</td>
</tr>
<tr>
<td>$\Delta\phi(E_T, \ell_1) / \pi &lt; 0.8$</td>
<td>3.9 x 10^{-3}</td>
<td>5.4 x 10^{-2}</td>
<td>7.2 x 10^{-1}</td>
<td>2.6 x 10^{-1}</td>
<td>1.9 x 10^{-1}</td>
<td>1.6 x 10^{-1}</td>
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<tr>
<td>$\Delta\phi(\ell_1, \ell_2) / \pi &gt; 0.5$</td>
<td>2.7 x 10^{-3}</td>
<td>3.1 x 10^{-2}</td>
<td>5.6 x 10^{-1}</td>
<td>2.0 x 10^{-1}</td>
<td>1.6 x 10^{-1}</td>
<td>1.2 x 10^{-1}</td>
</tr>
<tr>
<td>$P_T^{\ell_2} &gt; 40$ GeV</td>
<td>0</td>
<td>1.1 x 10^{-2}</td>
<td>2.3 x 10^{-1}</td>
<td>9.4 x 10^{-2}</td>
<td>8.7 x 10^{-2}</td>
<td>8.4 x 10^{-2}</td>
</tr>
</tbody>
</table>

| Events at $\mathcal{L} = 300$ fb^{-1} | 0.0    | 3.4    | 68.5   | 28.2         | 26.1         | 25.2         |
| $S / B$                                | -      | -      | -      | 0.34         | 0.31         | 0.30         |
| $S / \sqrt{B}$                         | -      | -      | -      | 3.1          | 2.9          | 2.8          |
| Poisson Significance                    | -      | -      | -      | 3.2          | 3.0          | 2.9          |
WIMP miracle predicts new physics at the weak scale

Stable, thermally produced particle will freeze out with relic abundance

$$\Omega_X \sim \frac{1}{\langle \sigma_A v \rangle}$$
largely independent of DM mass, $m_X$

Assuming a weak coupling, dimensionally, the cross section

$$\langle \sigma_A v \rangle \sim \frac{g_{weak}^4}{m_X^2} \left( 1 \text{ or } v^2 \right)$$

$m_X \sim m_{weak}$ will yield the correct $\Omega_{DM}$ for $s$- or $p$-wave annihilation

Figure: See Feng 1003.0904.
Weak scale DM motivated by new physics models

Stabilize gauge hierarchy problem → new weak scale particles
- Lightest new particle protected by discreet symmetry
- Provides WIMP candidate

Neutralino in MSSM
- Mixture of neutral gauginos and higgsinos
- SM interactions depend on specific model
- mSUGRA tightly constrained

Figure: Cosmologically preferred mSUGRA regions are in green with $A_0 = 0$ and $\mu > 0$. Blue contours denote neutralino masses, see Feng 1003.0904.
MSSM parameter space decouples into 3 sectors

- **Heavy sector**: Choose $\mu$, heavy squark masses, and top trilinear couplings to obtain a SM Higgs. Decouple $M_2$, $M_3$ etc. to satisfy LHC.

- **Relic Density sector**: Choose slepton masses and mixings to achieve the dark matter relic abundance. Alternatively, the abundance may be achieved via coannihilations with squarks.

- **Direct Detection sector**: For a given bino mass, neutralino-nucleon elastic scattering cross sections are determined by the light squark masses and mixings.
PDF suppression of 2nd generation squark production

Figure: As $m_{\tilde g}$ falls, $t$-channel gluino exchange becomes important, see Mahbubani et. al. 1212.3328.
Scattering through scalar exchange in non-relativistic limit

\[ \sigma_{SI}^N = \frac{\mu_p^2}{32\pi(2J_X + 1)} \sum_{\text{spins}} \left| \sum_q \frac{B_q^N}{m_X m_q} M_{Xq \rightarrow Xq} \right|^2 \]

\[ B_q^N = \langle N|\bar{q}q|N\rangle = m_N \frac{f_q^N}{m_q} \]

\[ B_p^u = B_d^n = \tilde{\Sigma}_{\pi N} \left[ 1 + (1 - y) \left( \frac{z - 1}{z + 1} \right) \right] \]

\[ B_p^d = B_u^n = \tilde{\Sigma}_{\pi N} \left[ 1 - (1 - y) \left( \frac{z - 1}{z + 1} \right) \right] \]

\[ B_s^p = B_s^n = \tilde{\Sigma}_{\pi N} y, \quad \Sigma_{\pi N} = (m_u + m_d)\tilde{\Sigma}_{\pi N} \]

**Largest uncertainty from strangeness content of nucleon** \[ y = 1 - \sigma_0 / \Sigma_{\pi N} \]

\[ \Sigma_{\pi N} \sim 59 \text{ MeV} \] can be determined from \( \pi\)-N scattering. \( z \approx 1.49 \) and \( \sigma_0 \) can be fit from baryon octet mass differences in chiral pert. theory
Can also calculate $\sigma_0$ on the lattice and predict small $\Sigma_{\pi N}$

<table>
<thead>
<tr>
<th></th>
<th>$y \to 0$</th>
<th>$y = 0.06$</th>
<th>$y \to 1$</th>
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<tr>
<td>$B^p_u = B^n_d$</td>
<td>9.95 (7.59, 12.2)</td>
<td>9.85 (7.51, 12.1)</td>
<td>8.31 (6.34, 10.3)</td>
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<tr>
<td>$B^p_d = B^n_u$</td>
<td>6.67 (5.09, 8.38)</td>
<td>6.77 (5.17, 8.46)</td>
<td>8.31 (6.34, 10.3)</td>
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<tr>
<td>$B^p_s = B^n_s$</td>
<td>0</td>
<td>0.499 (0.380, 0.617)</td>
<td>8.31 (6.34, 10.3)</td>
</tr>
</tbody>
</table>

Table: Can end up with either small $\sigma_0 \lesssim \Sigma_{\pi N}$ or $\sigma_0 \sim \Sigma_{\pi N}$. We assume the central value for $\Sigma_{\pi N}$ of 59 MeV, with the numbers in parentheses indicating the 2$\sigma$ range for $\Sigma_{\pi N}$ (45 MeV, 73 MeV), see Alarcon, Camalich, Oller 1110.3797.

\[
B^N_{q=c,b,t} = \frac{2}{27} \frac{m_N}{m_q} f^N_g, \quad f^N_g = 1 - \sum_{q=u,d,s} f^N_q
\]

Quark loops could couple heavy flavor squarks to gluon content in nucleon

Recall, for squark mixing, we have $\mathcal{M}_{Xq \to Xq} \sim m_q$, so $q = c, b, t$ contributions to $\sigma_{SI}^N$ will be suppressed by $m_q^{-2}$ without MFV couplings.
Calculate cross section and check dipole moments

\[
\sigma_{SI}^N = \frac{\mu_p^2}{4\pi} \left\{ \sum_q g^2 Y_L Y_{Rq} \sin(2\phi_{\tilde{q}}) \left[ \frac{1}{(m_{\tilde{q}_1}^2 - m_X^2)} - \frac{1}{(m_{\tilde{q}_2}^2 - m_X^2)} \right] B_q^N \lambda_q \right\}^2
\]

where \(\lambda_q\) accounts for running from the weak scale. For \(m_X \ll m_{\tilde{q}_1} \ll m_{\tilde{q}_2}\)

\[
\frac{\Delta a}{m_q} \sim \frac{m_X}{16\pi^2 m_{\tilde{q}_1}^2} g^2 Y_L Y_{Rq} \sin(2\phi_{\tilde{q}})
\]

\[
\sigma_{SI}^N \sim (1.1 \times 10^9 \text{ pb GeV}^2) \left( \sum_q \frac{\Delta a_q B_q^N}{m_q} \frac{0.5}{0.5} \right)^2 \left( \frac{m_X}{50 \text{ GeV}} \right)^{-2}
\]

Direct detection already rules out models with \(\Delta a_q (\text{GeV} / m_q) \gtrsim 10^{-9}\)

No contribution to quark EDM and quark MDM limits are relatively weak

LEP constrains current quark moments by checking \(\Gamma_Z\) contributions and LHC constrains chromomagnetic moments; most stringent \(\Delta a_q \lesssim 10^{-5}\)
Assume $m_X = 50$ GeV, maximal mixing and minimal $B_s^N$.

Figure: The grey region is ruled out by LUX, the red region could be ruled out by 300 days of LUX data and the blue region could be probed by LZ-7.
Direct detection with decoupled $m_{\tilde{s}_2}$ and minimal $B_N^s$

**Figure:** Sensitivity in the $(m_X, m_{\tilde{s}_1})$ plane assuming maximal mixing (left) and $(R_N^s, m_{\tilde{s}_1})$ plane with $R_N^s \equiv Y_{Rq}^2 \sin^2(2\phi_{\tilde{q}})(B_q^N)^2 \lambda_{q}^2$ and $m_X = 50$ GeV (right).

$$\sigma_{SI}^N \sim \frac{\mu_p^2 R_{q}^N}{(m_{\tilde{q}_1}^2 - m_X^2)^2}$$

- Enhanced sensitivity near $m_X \simeq m_{\tilde{q}_1}$
- Squark mass reach comparable to LHC
Figure: Sensitivity in the \((m_{\tilde{\chi}}, \sigma_{SI}^N)\) plane with \(m_{\tilde{s}_1} = 2\) TeV and maximal mixing. The dark green band indicates the predicted SI-scattering cross section for \(\sigma_0 = 27\) MeV and allowing the full 2\(\sigma\) range for \(\Sigma_{\pi N}\) of 45 MeV to 73 MeV.