Searches for Physics Beyond the Standard Model
A Theoretical Perspective

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SLAC

APS April Meeting
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The Plan

Motivations for Physics Beyond the Standard Model

New Hints from Dark Matter

Possible Interpretations

Implications for the LHC
The hierarchy

\[ \frac{G_{\text{Newton}}}{G_{\text{Fermi}}} = 10^{-32} \]

\[ M_{\text{Planck}} = G_{\text{Newton}}^{\frac{1}{2}} = 10^{19} \text{ GeV} \]

\[ M_{\text{weak}} = G_{\text{Fermi}}^{\frac{1}{2}} = 10^{3} \text{ GeV} \]

Separated by $10^{16}$
The Hierarchy Problem
Big numbers adding up to something small

If $\Lambda \gg M_{W\pm}$: a delicate fine-tuning

Hints that $\Lambda \sim M_{W\pm}$
Naturalness

Primary motivation for new theories

$10^{15}\,\text{TeV}$

Gauge Hierarchy Problem

Dynamics stabilizing Higgs mass

$M_P$

$M_W$

Dynamics predict new particles & resonances

Tevatron & LHC are directly testing different theories of naturalness
Supersymmetry
Doubles Standard Model particles

Fermion $\leftrightarrow$ Boson
Quark $\rightarrow$ Squark
Gluon $\rightarrow$ Gluino
Lepton $\rightarrow$ Slepton
Photon $\rightarrow$ Neutralino

Susy particles at TeV scale
Proton stability linked to LSP stability
Natural DM candidate
Stabilizes the Higgs vev automatically

Adds 100+ new parameters
Leads to benchmark based searches
Gauge Coupling Running

\[ V(r) = \frac{\alpha(r)}{r} \]

\[ \alpha^{-1}(r) \sim \alpha_0^{-1} + \beta \log r \]

Counts charged particles

All 3 couplings run

If couplings were unified at short distances

\[ \alpha \text{ and } \sin^2 \theta_w \implies \alpha_s \]
Gauge coupling unification

\[ \alpha^{-1} \]

\[ \sin^2 \theta_w \]

\[ E (\text{GeV}) \]

\[ E_{\text{GUT}} \]
Gauge coupling unification

powerful hint at an organizing principle

MSSM

\[ \alpha^{-1} \]

\[ \sin^2 \theta_w \]

\[ E \text{ (GeV)} \]

\[ E_{\text{GUT}} \]
LSP Dark Matter
Lightest supersymmetric particle stable

Annihilation cross section determines DM abundance

$$\sigma(\chi^0\chi^0 \rightarrow \text{SM}) \sim \frac{\alpha^2}{m^2_{\chi}}$$

Fixes DM Mass (w/o hierarchy problem!) $$\Rightarrow m_{\chi} \sim 100 \text{ GeV}

WIMP Miracle

LSP: an early Universe relic and could be DM
Motivations for New Physics haven’t changed

Hierarchy Problem

Gauge Coupling Unification

Dark Matter

Same story was told in 1991...

I still find it compelling!
Anomalies in Indirect & Direct Detection

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
<th>Energy Range</th>
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<tr>
<td>DAMA</td>
<td>NaI annual modulation experiment</td>
<td></td>
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All won’t be DM signals
If one is, could change expectations for colliders
Anomalies in Indirect & Direct Detection

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INTEGRAL

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DAMA & Inelastic Dark Matter

Consistency with other experiments narrows possibilities

(CDMS & XENON10)

Tucker-Smith, Weiner (2001)
Chang, Kribs, Tucker-Smith, Weiner (2008)

Multiple, near-degenerate states

$$\delta m \sim 100 \text{ keV}$$

$$m_{dm} + \delta m \rightarrow \chi_2$$

$$m_{dm} \rightarrow \chi_1$$

Nuclear Recoil Spectrum

Tucker-Smith, Weiner (2001)
Chang, Kribs, Tucker-Smith, Weiner (2008)
Distinctive Recoil Spectrum

Low recoil energies are suppressed

\[ v_{\text{min}}(E_R) \approx \frac{1}{\sqrt{2mE_R}} \left( \frac{mE_R}{\mu} + \Delta \right) \]

\[ (E_R)_{\text{peak}} \approx \frac{\mu(\Delta m)}{m} \]

Chang, Pierce, Weiner (2008)
A New Vector Boson

Explanation to DAMA requires inelastic transitions dominating elastic ones

Scalars couple to everything

Vectors change labels

\[ h \phi^\dagger \phi \leftrightarrow h (\phi_1^2 + \phi_2^2) \]
\[ A_\mu \phi^\dagger i \overleftarrow{\partial}^\mu \phi \leftrightarrow A_\mu \phi_1 \overleftarrow{\partial}^\mu \phi_2 \]
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Choices for how to couple

Standard Model \[\Rightarrow\] vector boson \[\Rightarrow\] Dark Matter

DM has weak charge
SM has new gauge charge
Photon and Dark Photon Mix
A New Vector Boson

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Photon & Dark Photon Mixing

\[ \mathcal{L} = (F_{\text{sm}}^{\mu \nu})^2 + (F_{\text{dm}}^{\mu \nu})^2 + \epsilon F_{\text{dm}}^{\mu \nu} F_{\text{sm}}^{\mu \nu} + M^2 A_{\text{dm}}^2 \]

EM Field strength in gauge invariant

Nothing forbids \textit{kinetic} mixing \quad \text{(Holdom (1986))}

SM charged under new DM force
DM neutral under SM forces

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GUT-scale particles


\[ \epsilon \sim 10^{-3} \]
DAMA is a Weak Scale Cross section

\[ \sigma \sim \frac{\epsilon^2 \alpha_{dm} \alpha_{sm}}{M_{A_{dm}}^4} \sim \frac{\alpha_{sm}^2}{M_{W^\pm}^4} \]

\[ M_{A_{dm}} \sim \epsilon \frac{1}{2} M_{W^\pm} \sim \mathcal{O}(1 \text{ GeV}) \]

Very light state!

Can directly produce Dark Photon

Best Machines are High Intensity, Low Energy
BaBar, Belle, KLOE, CLEO-c, BESIII

Essig, Schuster, Toro (2009)
PAMELA

An excess in $r_{e^+e^-} = \frac{\phi(e^+)}{\phi(e^-)}$

Rising towards 100 GeV

Could be DM annihilation

$\sigma_{\text{Pamela} \nu} \gg \sigma_{\text{Freeze out} \nu}$

DM already annihilated!

Need an enhancement in annihilation rate

A large rate to electrons

A small rate to hadrons
Annihilating to a new light vector

Constraints on usual annihilations

\[
\begin{align*}
\chi^0 & \rightarrow W^+ \\
\chi^0 & \rightarrow W^- \\
\chi^0 & \rightarrow \text{hadrons} \\
\chi^0 & \rightarrow \text{positrons, anti-Protons}
\end{align*}
\]

Dark Photon acts as new long range force

\[
\sigma_{\text{Pamela}} \nu \propto \frac{1}{\nu}
\]

Increases cross section when DM is cold!

\[
\begin{align*}
\chi^0 & \rightarrow A_{dm} \\
\chi^0 & \rightarrow \text{electrons} \\
\chi^0 & \rightarrow \text{positrons}
\end{align*}
\]

Hints that there might be a Dark Sector

Must give mass to dark photon

Must generate $\delta m_{dm}/m_{dm} \sim 10^{-6}$

Alves, Behbahani, Schuster, JW (2009)

Standard Model \hspace{1cm} \longleftrightarrow \hspace{1cm} \text{Dark Sector}

$q$ \hspace{1cm} $\bar{q}$

cascade decay

dark photon

$\ell\bar{\ell}$ \hspace{1cm} $\ell\bar{\ell}$ \hspace{1cm} $\ell\bar{\ell}$

$\ell\bar{\ell}$

$\chi^0$ \hspace{1cm} $\chi^0$

$\chi^0$

$\ell\bar{\ell}$

\{“lepton jets”\}


leptons + MET

Light particles in cascade: boosted final states

“Hidden Valley”-like

Strassler, Zurek (2006)
Hints at Dark Matter are not MSSM-like

Supersymmetric Standard Model could still be there
(now have SM & DM hierarchy problem!)

Dark Matter Production could look like

<table>
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<tr>
<th>Standard Model</th>
<th>Susy</th>
<th>Dark Sector</th>
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Cheung, Ruderman, Wang, Yavin (2009)
Morrissey, Zurek (2009)
Bottom of susy spectra matters for searches

Neutralino may not be stable
Lightest SSM particle could be charged or colored
R-parity violation -- Lots of Jets & no MET

If LSP is stable, MET could be rare

How robust are the searches to small perturbations?
Look inside existing susy searches and vary assumptions
Most BSM searches based on Susy
Susy carries a lot of baggage from 28 years of study

SOFTLY BROKEN SUPERSYMMETRY AND SU(5)

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Received 2 June 1981

Here we explore a simpler alternative possibility—that the supersymmetry is broken explicitly, but softly, by terms of dimension less than four in the lagrangian. We add to the lagrangian (not to $v$) the following SU(5) invariant mass terms, all of the order of a TeV:

1. a positive mass squared term for the matter bosons;
2. a mass for the Higgs fermions (and their SU(5) partners);
3. a Majorana mass for the gauge fermions;
4. a negative mass squared term for the boson fields in the $\Sigma$ supermultiplet;
5. a mixed (with positive and negative eigenvalues) mass squared matrix for the Higgs bosons.
mSugra has 5 parameters

Only 2 are relevant for collider searches

![Diagram showing many relations between masses, driven by an ansatz, not consistency.]

Tuning searches to mSugra, limits applicability to other models.
mSugra Caveats

Gaugino mass running is multiplicative:

\[ m_{\tilde{B}} : m_{\tilde{W}} : m_{\tilde{g}} \quad 1 : 2 : 7 \]

\[ \tilde{g} \rightarrow \tilde{B} + q \bar{q} \]

Always have very hard jets

What if \( m_{\tilde{B}} : m_{\tilde{g}} \sim 1 : 1.5 \)?

Jets become softer
Challenge to increase S/B, but possible!

In non-Susy theories, mass splittings may be different

\[ m_{\tilde{B}} \simeq m_{\tilde{W}} \simeq m_{\tilde{g}} = m_{\frac{1}{2}} + \Delta_i m \]
Tevatron Sensitivity Plot

Tevatron's existing searches don't cover $m_{\tilde{g}} \sim 120$ GeV but potential sensitivity.

$\tilde{g} \rightarrow \chi_1^0 + jj$

$\tilde{g} \rightarrow \chi_2^0 + jj$

$\rightarrow \chi_1^0 + jj + jj$

Alwall, Le, Lisanti, JW (2008)
Results from DM experiments change LHC expectations

If DM is not the LSP:
search philosophy for BSM may be ineffective

Should scrub searches of irrelevant theoretical assumptions

Is the full mSugra framework needed
to search for Jets + MET?

Possible to cut away a visible signal
(e.g. additive vs multiplicative renormalization)

Excess baggage usually avoidable
Search for simplified models
More robust against small changes in spectra

Alwall, Schuster, Toro (2008)

Dark matter may be pointing to novel final states!
Dark Matter

Supersymmetry

Compositeness

???

Hierarchy Problem