Measuring Dark Matter at Colliders

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Outline of talk

• Cosmological Dark Matter $\longleftrightarrow$ LHC/LC Physics

• Why we need to measure Dark Matter at Colliders
  - The Importance of Being Correct

• A Model-Independent Approach
  - Seeing the Invisible

• Why knowing all of the masses is important
  - What You Don't Know Will Be Held Against You!

• Measuring Sleptons at the LHC
  - Knowing What We Don't Know

• Summary
Why Do We Care?

• Dark matter makes up most of the mass of the universe.
• Direct discovery of dark matter will tell us rather little.
  – Won't know how many dark matter candidates there are.
  – Won't know if dark matter is directly related to the weak scale and EWSB.
• These questions are best answered by colliders
Related Research

- H. Baer, and collaborators
- B. Dutta, and collaborators
- M. Battaglia, and collaborators
- J. Feng, and collaborators
- M. Peskin, and collaborators
- B.C. Allanach, G. Belanger, F. Boudjema, A. Pukhov
- W. de Boer, and collaborators
- T. Moroi, and collaborators
- Many others!
Dark Matter

✦ We know dark matter exists! (WMAP, Astrophys. J. Suppl. 148, 175 (2003))

\[ 0.094 \leq \Omega_{dm} h^2 \leq 0.129 \]

✦ Discovery – 1933 (Fritz Zwicky)

✦ Galactic rotation


✦ Cosmic Microwave Background
Dark Matter

★ We know dark matter exists! (WMAP, Astrophys. J. Suppl. 148, 175 (2003))

\[ 0.094 \leq \Omega_{dm} h^2 \leq 0.129 \]

★ It's likely a particle (scales like matter with universal expansion)

★ Can't be protons, neutrons or electrons \[ \Omega_{\text{matter}} \approx 0.3 \]

★ non-relativistic (from structure formation)

★ We have a good idea how it got here:

★ A stable particle in the early universe...

★ Very hot!

★ Everything in thermal equilibrium, \( n_{\text{DM}}(T) \) is known.

★ \( \Gamma(DM \; DM \rightarrow SM \; SM) = \Gamma(SM \; SM \rightarrow DM \; DM) \)

★ \( T \) decreases, unstable particles decay
\[ T < m_{DM}, \quad n_{eq}(T) \sim e^{-m_{DM}/T} \]

- Equilibrium density decreases quickly!
- Interaction rate also drops, \( \Gamma \sim n(T) \langle \sigma v \rangle \)
- Dark matter drops out of thermal equilibrium.
  - Called “Freeze-out”
  - Details governed by Boltzmann equation:
    \[ \dot{n} + 3Hn = -\langle \sigma v \rangle \left( n^2 - n_{eq}^2 \right) = -\Gamma n + \Gamma_{eq} n_{eq} \]
  - Freeze-out: when interaction rate \( \ll \) universal expansion rate

- After freeze-out, dark matter co-moving number density is fixed.

- Dark matter: interaction rate in early universe fixes present number density
Dark Matter

★ Interaction Rate: just particle physics!

★ To get $0.094 \leq \Omega_{\text{dm}} h^2 \leq 0.129$, we need $\sigma(DM \rightarrow SM) \approx 1 \text{ pb}$

This is just the Weak Scale, so

$$\sigma(DM \rightarrow SM) \approx \alpha_{EW}^2 / M_{EW}^2$$

★ WIMP!

Connections between DM and LHC/LC Physics

- We know dark matter exists!
  \[ 0.094 \leq \Omega_{\text{dm}} h^2 \leq 0.129 \]

- Explanations of the weak scale (SUSY, Ex. Dim., little Higgs, etc.) → left-over symmetries
  - leaves stable weak-scale particle
  - perfect DM candidate!

- Correct answer for \( \rho_{\text{DM}} \)
  \[ \sigma(\text{DM DM} \to \text{SM SM}) \approx \text{weak scale} \]

- WIMP!

Dark Matter and LHC/LC physics... made for each other!
The Importance of Being Correct

• Imagine CDMS II sees something, what do we know?
  - All of the dark matter?
    • Astrophysical Uncertainties
      - Halo model? Caustics?
    • Turning $\sigma_{\text{scat}}$ into $\sigma_{\text{ann}}$ (then $\Omega_{\text{DM}} h^2$)?

• To *know* that we have the dark matter particle:
  - enough measurements to calculate annihilation cross section
    • Direct detection $\rightarrow$ not nearly enough
  - Making and measuring dark matter at colliders
    • Absolutely essential
Seeing the Invisible

- Cosmology: $\Omega_{DM} h^2$

$$\Omega_{DM} h^2 \approx \frac{1}{\langle \sigma v \rangle}$$

- Collider signature?
  - Build a DM collider?
  - No! Crossing symmetry:
  - But we don't collide 'SM+SM'
  - we can collide 'e^+e^-' 

- Model-independent!
Seeing the Invisible

- Hmm... $e^+ e^- \rightarrow nothing$ might be hard to detect!

- Add a photon!
  - Soft or Collinear – SM calculable!
    - Collinear works best

$$\frac{d \sigma (e^+ e^- \rightarrow 2DM + \gamma)}{dx \, d \cos \theta} \approx \frac{\alpha}{\pi} \frac{1 + (1 - x)^2}{x} \frac{1}{\sin^2 \theta} \hat{\sigma} (e^+ e^- \rightarrow 2DM)$$

Here $x = 2E_\gamma / \sqrt{s}$

Universal SM factor

![Graph showing the relationship between $d\sigma/dE_\gamma$ and $E_\gamma$](image)
• 500 GeV LC, 500 fb$^{-1}$

• Cuts
  
  - $\sin \theta > 0.1$
    
    • detector acceptance
  
  - $p_T > 7.5$ GeV
    
    • eliminates Bhahba
  
  - $\frac{\sqrt{s}}{2}\left(1 - \frac{8M_x^2}{s}\right) \leq E_y \leq \frac{\sqrt{s}}{2}\left(1 - \frac{4M_x^2}{s}\right)$
  
  - Systematics?

  - Polarization?

Experimentally challenging, but not out of the question!
What you don't know **WILL** be held against you!

- $\Omega_{DM} h^2$ depends on any particle involved in $\chi \chi \rightarrow $ SM SM
- Hope to measure them all?
- Coannihilation?
- Maybe only a few are important?
- mSUGRA
  - 5 parameters:
    $\left( M_0, M_{1/2}, A_0, \tan(\beta), \text{sgn}(\mu) \right)$
mSUGRA: Bulk Point

\[ m_0 = 57, \ m_{1/2} = 250, \ A_0 = 0, \ \tan\beta = 10, \ \text{sgn}(\mu) = +1 \]
• 3 light sleptons and lightest neutralino

- What else is important? Let's see...

Plots for $\tilde{\tau}_L$, $\tilde{e}_R$, $\tilde{\mu}_R$ are similar
mSUGRA: Focus Point Region

$m_0 = 3280$, $m_{1/2} = 300$, $A_0 = 0$, $\tan\beta = 10$, $\text{sgn}(\mu) = +1$
• Focus Point – lightest neutralino is dark matter, scalars very heavy
  - Relic density -> –ino sector, *nothing else*

• -ino masses and couplings
  - \( \Delta m_{\chi_1^0} \leq 1.6 \text{GeV} \)
  - \( \Delta (m_{\chi_2^0} - m_{\chi_1^0}) \leq 0.3 \text{GeV} \)
  - \( \Delta (m_{\chi_3^0} - m_{\chi_1^0}) \leq 0.5 \text{GeV} \)
  - 500 GeV LC (J. Alexander, *et. al.*, preliminary)

• Lower bound on scalar masses (~500 GeV)
  - How? (LHC?)

• Limit on \( \Omega_{DM} h^2 \)? Not yet for focus point...
Knowing what We Don't Know

- Rough idea of particle masses is essential for $\Omega_{\text{DM}} h^2$
  - lower bounds just as crucial as mass measurements
- Heavy Sleptons (above LC reach): how do we tell mass?
- If we can't, we only know: $\text{LC} < m < \infty$
- Sleptons at the LHC? Can that be done?
  - Let's see...
Sleptons at the LHC and LC

- **LHC** — We'll mainly make squarks and gluinos. Sleptons will be made through cascade decays mostly.

- **LC** — Sleptons can be made directly!

\[ \tilde{q} \rightarrow q + \tilde{l}^+ + \nu_e + \bar{\nu}_e \]

\[ \chi_2 \rightarrow \tilde{l} + \chi_1 \]

\[ \text{e}^+ \rightarrow Z + \tilde{l}^+ \]

\[ \text{e}^- \rightarrow Z + \tilde{l}^- \]
Slepton masses at the LHC through $\chi_2$ decay.

- Sleptons - cascade decays at the LHC

- Useful information - from the endpoint of the $m_\ell\ell$ distribution (see, for example, I. Hinchliffe and F. Paige, PRD 61:095011, 2001):
  - 3-body decays (virtual slepton/Z): kinematic endpoint of $m_\ell\ell$ gives $(m_{\chi_2} - m_{\chi_1})$
  - 2-body decays: kinematic endpoint of $m_\ell\ell$ gives: $((m_{\chi_2}^2 - m_{\text{slep}}^2)(m_{\text{slep}}^2 - m_{\chi_1}^2)/m_{\text{slep}}^2)^{1/2}$

- Just the endpoints? What about the shape of the distribution? Can that tell us anything?
  - Yes, can discriminate between 3-body and 2-body decay.
  - Can even measure slepton masses!
Invariant Mass Distributions and the Slepton Mass

Slepton mass values: black - infinite, blue - 300 GeV

Aha! The shapes are quite different, even for the same endpoint value!
Distribution Shapes in mSUGRA

- For a fixed endpoint value of 59 GeV, we get line segments in the \((M_0, M_{1/2})\) plane:

Kolmogorov-Smirnov in mSUGRA
(point with $M_0 \sim 300$ GeV)

- Black star – taken to be experimental result.
- Red dot – templates that can be ruled out at the 95% confidence level.
- Yellow dot – templates that can't be ruled out at the 95% confidence level.

What can we learn from this?

- High-mass points ($M_0 > 1$ TeV) can often be distinguished from low-mass points, and a lower limit on the value of $M_0$ can be determined.

- For low-mass 3-body decay points, the $M_0$ value can be bracketed (sometimes quite nicely).

- For 2-body decay points (with a real slepton), the value of $M_0$ can be bracketed, and they can be clearly distinguished from 3-body decay points.
Summary

• Dark Matter and LHC/LC physics: Intimately connected?
  – Great reason to be *very* excited if you are a particle/astro physicist!

• Cosmological dark matter predicts model-independent collider signature
  – Certainly possible for SUSY and UED (challenging!)

• A convincing case for specific dark matter particle
  – Requires verifying $\Omega_{DM} h^2$ through collider measurements
  – The irrelevant becomes relevant (heavy sleptons, for instance)
  – Cosmological precision on $\Omega_{DM} h^2$ possible in mSUGRA bulk region

• work ongoing in the focus point
Summary

- Slepton mass determinations are possible at the LHC through neutralino decays, even for heavy virtual sleptons.
  - Needs backgrounds and cuts (currently in progress).
  - These shape analyses will also undoubtably be useful in making measurements at a future linear collider.

- Lots of exciting, relevant work to be done!

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