Potpourri:
DM and Physics BSM at HE Colliders

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Fermilab, February 17, 2004
Cast of characters

- Senior personnel
  - K. Matchev (UF, Cornell), (Anton, DOB August 2003)

- Postdocs
  - A. Birkedal (UF, Cornell), (Austin, DOB July 2003)
  - A. Datta (UF), (TBA, EDC April 2004)

- Graduate students
  - K.C. Kong (UF), (TBA, EDC June 2004)
  - C. Group (UF, 0.5 FTE, with R. Field)

- Undergraduate students
  - J. Blender (Cornell), REU student at UF, Summer 2003
Many motivations for new physics, but... dark matter is our best evidence for new physics BSM: $\Omega_{DM} = 0.23 \pm 0.04$.

Questions to ask theorists:

Who is the dark matter in your theory/model and can you calculate its relic abundance?

How can we test this theory at the Tevatron/LHC/NLC?

- WIMPs: motivated by both particle and astrophysics.
  - Predicted in many particle physics scenarios BSM.
  - Give the right order of magnitude $\Omega_{DM}$.

$$\Omega_{DM} h^2 \sim 0.1 \left( \frac{\sigma_{EW}}{\sigma_{ann}} \right)$$

Is this simply a coincidence?

- Potentially observable signals in DM detection expts.

$$\chi \rightarrow \chi \rightarrow SM$$
New physics models with DM WIMPs

- **Recipe for BSM dark matter**
  - invent a model with new particles
  - invent a symmetry which guarantees a stable new particle
  - fudge parameters until the lightest new stable particle is neutral and has the correct relic density

- **Three generic examples of new physics with a DM WIMP**
  - supersymmetry: DM = lightest superpartner.
  - extra dimensions: DM = lightest Kaluza-Klein mode.
  - Little Higgs: DM = LPOP, LZOP? (billion, gatesino, ...)

- **Intro, discovery prospects**
- **How can we distinguish the different scenarios?**
  - in astroparticle physics experiments
  - at high energy colliders

- **How well can we test cosmology at the LHC/NLC?**

- **What does WMAP say about collider signals?**

- **Outreach**
Model summary

<table>
<thead>
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<th>Model</th>
<th>SUSY</th>
<th>UED</th>
<th>Little Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM particle</td>
<td>LSP</td>
<td>LKP</td>
<td>LTP</td>
</tr>
<tr>
<td>Spin</td>
<td>1/2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Symmetry</td>
<td>$R$-parity</td>
<td>KK-parity</td>
<td>$T$-parity</td>
</tr>
<tr>
<td>Mass range</td>
<td>50-200 GeV</td>
<td>600-800 GeV</td>
<td>400-800 GeV</td>
</tr>
</tbody>
</table>
Supersymmetry

- Supersymmetry is an extra dimension theory with new anticommuting coordinates $\theta_\alpha$:

$$\Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha\theta_\alpha$$

- SUSY relates SM particles and their superpartners ($\phi \leftrightarrow \psi$)
  - quarks, leptons $\leftrightarrow$ squarks, sleptons
  - gauge bosons: $g, W^\pm, W^0_3, B^0$ $\leftrightarrow$ gauginos: $\tilde{g}, \tilde{w}^\pm, \tilde{w}^0, \tilde{b}^0$
  - Higgs bosons: $h^0, H^0, A^0, H^\pm$ $\leftrightarrow$ higgsinos: $\tilde{h}^\pm, \tilde{h}^0_u, \tilde{h}^0_d$

- The superpartners have
  - spins differing by 1/2
  - identical couplings
  - unknown masses (model-dependent)

- Discovering new particles with those properties IS discovering supersymmetry
  - The superpartners are charged under a conserved $R$-parity
    - SM particles: $R = +1$
    - superpartners: $R = -1 \implies$ stable LSP (DM?).
  - No tree-level contributions to precision EW observables
**SUSY WIMPs**

- The lightest neutralino $\tilde{\chi}_1^0$ is a mixture of $\tilde{b}^0$, $\tilde{w}^0$, $\tilde{h}_u^0$, $\tilde{h}_d^0$:

  $$\tilde{\chi}_1^0 = a_1 \tilde{b}^0 + a_2 \tilde{w}^0 + a_3 \tilde{h}_u^0 + a_4 \tilde{h}_d^0$$

- Gaugino fraction $R_\chi$ of the LSP:

  $$R_\chi \equiv |a_1|^2 + |a_2|^2 \approx |a_1|^2.$$

  Feng, KM, Wilczek (2000)

- Focus point region: large $m_0$, mixed LSP.

- Coannihilation region: small $m_0$, $\tilde{\tau} - \tilde{\chi}_1^0$ degeneracy.
Universal Extra Dimensions

Appelquist, Cheng, Dobrescu, hep-ph/0012100

- Universal Extra Dimensions is an extra dimension theory with new \textit{bosonic} coordinates \( y \) (spanning a circle of radius \( R \)):

\[
\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \phi^n(x^\mu) \cos(ny/R) + \chi^n(x^\mu) \sin(ny/R)
\]

- Each SM field \( \phi \) (\( n = 0 \)) has an infinite tower of Kaluza-Klein (KK) partners \( \phi^n \) and \( \chi^n \) with
  - identical spins
  - identical couplings
  - unknown masses of order \( n/R \)

- Remnant of \( p_5 \) conservation: KK-parity \((-1)^n\)
  - \( KK = +1 \) for even \( n \) and \( KK = -1 \) for odd \( n \).
  - lightest KK partner at level 1 (LKP) is stable.
    \[
    \begin{align*}
    P_3 & \rightarrow P'_3 P_0, P_2 P_1, P_1 P_0; \\
    P_2 & \rightarrow P'_2 P_0, P_1 P_1, P_0 P_0; \\
    P_1 & \rightarrow P'_1 P_0.
    \end{align*}
    \]

- No tree-level contributions to precision EW observables
The KK modes at each KK level $n$ are extremely degenerate:

$$m_n^2 = \left( \frac{n}{R} \right)^2 + m_0^2$$

Cheng, KM, Schmaltz, hep-ph/0204342

- The radiative corrections are crucial for phenomenology, e.g.

$$e_1 \rightarrow \gamma_1 e_0 ?$$

$$m_{e_1} - (m_{\gamma_1} + m_{e_0}) \sim -R^{-1} \left( \frac{m_e}{R^{-1}} \right) \sim -R^{-1} 10^{-6}$$

- Lots of stable (charged, colored) heavy particles...
Impact of radiative corrections on discovery signatures

- Higgs searches
  - \( gg \rightarrow h, h \rightarrow \gamma\gamma \) at LHC.
  - \( m_h, \lambda_b \) corrections in MSSM.

- Anomaly mediation (wino mass splitting determines charged wino lifetime)

Cheng, Dobrescu, KM, hep-ph/9811316

\[ \Delta m_\chi (1\text{-loop}) \]
\[ \delta(\Delta m_\chi) \text{ (exact)} \]
\[ \delta(\Delta m_\chi) \text{ (approx)} \]
\[ \Delta m_\chi \text{ (tree level)} \]

- Universal extra dimensions
Including radiative corrections, the mass spectrum of level 1 KK modes looks something like this:

Cheng, KM, Schmaltz, hep-ph/0204342

- Mimics supersymmetry: prompt decays!
- Seems difficult to discover at the LHC, but...
- $W^\pm_1$, $Z_1$ have pure leptonic branchings!
- $\sin^2 \theta_W \approx 0 \implies \gamma^1 \approx B^1$, similar to $\tilde{B}$ in SUSY.
The KK Weinberg angles

- Mass matrix for the neutral gauge bosons

\[
\begin{pmatrix}
\frac{n^2}{R^2} + \frac{1}{4}g_1^2 v^2 + \hat{\delta}m^2_{B_n} & \frac{1}{4}g_1 g_2 v^2 \\
\frac{1}{4}g_1 g_2 v^2 & \frac{n^2}{R^2} + \frac{1}{4}g_2^2 v^2 + \hat{\delta}m^2_{W_n}
\end{pmatrix}
\]

- The Weinberg angle $\theta_n$ at KK level $n$

\[
\gamma_n = \cos \theta_n B^0_n + \sin \theta_n W^0_n \approx B^0_n.
\]

Cheng, KM, Schmaltz, hep-ph/0204342
KK dark matter relic density


\[ \Omega h^2 = 0.16 \pm 0.4 \]

Unlike supersymmetry: no helicity suppression

\[ \Omega h^2 = \frac{1.04 \times 10^9 \text{ GeV}^{-1}}{M_P \sqrt{g_*}} \frac{x_F}{a + 3b/x_F}; \quad x_F = \frac{M_{KK}}{T_F} \]

\[ a = \frac{\alpha_1^2}{M_{KK}^2} \frac{380\pi}{81}; \quad b = -\frac{\alpha_1^2}{M_{KK}^2} \frac{95\pi}{162}. \]

Unlike supersymmetry: coannihilation lowers the bound
Little Higgs models

- The hierarchy problem in the SM

\[ h \quad \lambda \quad h \quad h \quad \lambda_t \quad h \]

- Introduce new particles at TeV scale to cancel the one-loop quadratic divergences

\[ h \quad -\lambda \quad h \quad h \quad -g^2 \quad h \quad -\lambda_t/(2f) \quad h \]

- Conserved $T$-parity (Cheng, Low hep-ph/0308199)
  - $T = +1$ for SM particles, $T = -1$ for new particles.
  - the lightest $T$-odd particle is stable.
  - No tree-level contributions to precision EW observables
If the lightest $T$-odd particle is a scalar, it can be a mixture of an SU(2)-triplet $\phi^0_3$ and an SU(2)-singlet $\eta^0_1$:

$$N_1 = \cos \theta_{\eta \phi} \eta^0_1 + \sin \theta_{\eta \phi} \phi^0_3$$

Birkedal-Hansen, Wacker hep-ph/0306161

- The absence of helicity suppression requires large masses for the WIMP case.
- For 150 GeV $< m_{N_1} < 350$ GeV, annihilation into $t\bar{t}$ and $hh$ is very efficient.
SUSY discovery reach at colliders

• The estimated Tevatron trilepton leach in Run II

KM, D. Pierce (1999)

• When do we know we have seen supersymmetry?
  • Many superpartners: can we count squark, slepton species?
  • Spins?
  • Couplings? \( \sigma \times BR \), confusion, PDF uncertainty...

\[ \text{(a) tan}\beta=5 \]
\[ \text{(b) tan}\beta=35 \]

L=30 fb\(^{-1}\)
L=10 fb\(^{-1}\)
L= 2 fb\(^{-1}\)
Sparite count

Battaglia et al., hep-ph/0306219

Post-WMAP Benchmarks

- Squarks are difficult to count:
  - can be mistaken for gluinos
  - $\tilde{q}_R$ decays mostly give jets
  - Many more 1st gen. $\tilde{q}$’s than 2nd gen. $\tilde{q}$’s.
Outreach I: PDF uncertainties

Bourilkov, Group, KM 2004

- The LHAPDF interface is designed to work with pdf sets
  - Fermi2002 (100)  (Giele, Keller, Kosower)
  - CTEQ6 (40)  (Pumplin et al, hep-ph/0201195)
- LHAPDF has been interfaced with PYTHIA 6.2 and HERWIG
- 100k events per pdf member on the UF CMS PC farm.

Botje, hep-ph/9912439
PDF uncertainties: gluino production

- Example: gluino production at the LHC

![Graph showing gluino production at the LHC](image)

- $q\bar{q} \rightarrow \tilde{g}\tilde{g}$ agree (sort of)
- Large discrepancy in $gg \rightarrow \tilde{g}\tilde{g}$ (?)
PDF uncertainties: CTEQ6 vs Fermi

- Compare the PDF uncertainties at typical values of $x_{\text{max}} = \max\{x_1, x_2\}$ and $x_{\text{min}} = \min\{x_1, x_2\}$.
- Averages: $0.01 < \langle x_{\text{min}} \rangle < 0.1$ and $0.1 < \langle x_{\text{max}} \rangle < 0.3$

Goal: estimate PDF uncertainties in Higgs and sparticle production at the Tevatron and the LHC.
Collider phenomenology of UED

- Allowed dominant transitions

  - KK gluon: \( B(g_1 \rightarrow Q_1Q_0) \simeq B(g_1 \rightarrow q_1q_0) \simeq 0.5 \).
  - Singlet KK quarks: preferentially \( q_1 \rightarrow \gamma_1 q_0 \)
  - Doublet KK quarks:
    \[
    B(Q_1 \rightarrow W_1^\pm Q_0') \sim 65\% \quad B(Q_1 \rightarrow Z_1 Q_0) \sim 33\%
    \]
  - KK W- and Z-bosons: only leptonic decays!
  - KK leptons: 100% directly to the LKP.
  - At hadron colliders we want: strong production, weak decays!
UED signature: $4\ell \mathbb{H}_T$

- Arises from inclusive $Q_1 Q_1$ production: $Q_1 \rightarrow Z_1 \rightarrow \ell^\pm \ell^\mp \gamma_1$
- Tevatron triggers
  - Single lepton $p_T(\ell) > 20$ GeV, $\eta(e) < 2.0$, $\eta(\mu) < 1.5$.
  - Missing energy $\mathbb{E}_T > 40$ GeV.
- Tevatron cuts
  - $p_T(\ell) > \{15, 10, 10, 5\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\mathbb{E}_T > 30$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- Main background: $ZZ \rightarrow \ell^\pm \ell^\mp \tau^+ \tau^- \rightarrow 4\ell \mathbb{E}_T$. Not a problem.
- LHC cuts (pass the single lepton trigger)
  - $p_T(\ell) > \{35, 20, 15, 10\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\mathbb{E}_T > 50$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- LHC backgrounds: multi-boson, $t \bar{t} Z$, fakes, etc.
Assumption: 50 events/year (100 fb$^{-1}$).
UED discovery reach at the Tevatron and LHC

- Discovery reach in the $Q_1 Q_1 \to 4\ell \not{E}_T$ channel.

Cheng, KM, Schmaltz, hep-ph/0205314

Typical signatures include:

- soft leptons, soft jets, not a lot of $\not{E}_T$
- a lot of missing mass (LHC can’t measure it)
- $B(Q_1 \to 2\ell \not{E}_T + X) \sim \frac{1}{9}$. In principle, channels with $W_1$’s can also be used – less leptons, but more often.
Bosonic or fermionic supersymmetry?

- Can you tell SUSY from UED?
- Yes. Tenth Conference on String Phenomenology in 2011. 
  J.Ellis hep-ph/0208109
- Look for the higher KK levels: e.g. $g_2$ resonance.
- Single production of KK level 2 is suppressed (involves 
  KK-number violating couplings).

\[ q_0 \quad g_2 \quad q_1 \quad q_0 \]
\[ q_0 \quad g_2 \quad q_1 \quad q_0 \]
\[ q_0 \quad g_2 \quad q_0 \quad q_0 \]

$\sim 55\% \quad \sim 35\% \quad \sim 10\%$

- $g_2$ appears a high mass dijet resonance. $Z'$?
- Pair production? Typically the rate is too small.
Looking for KK level 2: $Z_2$ resonance

- $Z_2$ appears promising: $Z_2 \to Q_1 Q_1$ and $Z_2 \to Q_2 Q_0$ are closed. Lots of hard leptons? No! $Z_2 \to Q_0 Q_0$ wins over $Z_2 \to \ell_0 \bar{\ell}_0$.
- $Z_2$ branching fractions:

![Branching Fractions Graph]

- $Z_2$ also a high mass dijet resonance. $Z'$? $g_2$?
- $Z_2$ may also appear as a dilepton resonance, but $B(Z_2 \to \ell^+ \ell^-) \sim 1\%$.
Looking for KK level 2: $\gamma_2$ resonance

- $\gamma_2$ appears most promising. All $\gamma_2 \to f_2 f_0$ and $\gamma_2 \to f_1 f_1$ decays are closed. Every $\gamma_2$ decay dumps a lot of energy.
- $\gamma_2$ branching fractions:

<table>
<thead>
<tr>
<th>$\gamma_2 \to uu, cc$</th>
<th>$\gamma_2 \to dd, ss, bb$</th>
<th>$\gamma_2 \to tt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-2}$</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $\gamma_2$ also a high mass dijet resonance. $Z'$? $g_2$? $Z_2$?
- In all cases the natural width is negligible compared to the detector dijet mass resolution.
LHC reach for level 2 KK modes

- Inclusive search for high-mass dijet/dilepton resonances
- Recycle existing LHC analyses for $Z'$ searches
- Rescale the background to account for the narrow width
- Reach for $R^{-1}$ in GeV, assuming $100 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>KK mode</th>
<th>$jj$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_2$</td>
<td>350</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>worse</td>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>worse</td>
<td>350</td>
<td>400</td>
</tr>
</tbody>
</table>

- Can we discriminate the $Z_2$ and $\gamma_2$ resonances?
- Confusion: Supersymmetry plus one or more $Z'$?
UED implementation in COMPHEP

- **Why COMPHEP?**
  - Spin correlations accounted for.
  - Automated: ideal for new models which are straightforward generalizations of the Standard Model (UED, little Higgs).
  - Once the Feynman rules are defined, any final state signature can be studied.
  - It already has SUSY.
  - It is interfaced to PYTHIA.
  - The experimentalists know how to deal with it.

- **What we have done so far:**
  - Level 1 is fully implemented with correct 1-loop masses. Approximation: $Z_1 \approx W_1^3$, $\gamma_1 \approx B_1$. Widths: reasonable guess, but can be recalculated with COMPHEP.
  - Level 2 fully implemented ($Z_2 \approx W_2^3$, $\gamma_2 \approx B_2$, $\ell_2$) with the correct widths.
UED phenomenology: Lepton colliders

- The importance of the level 2 widths.

\[ e^+ \xrightarrow{\gamma, Z} e^- \]
\[ \mu_1^+ \xrightarrow{\gamma_2, Z_2} \mu_1^- \]

- Comparative study of SUSY and UED at LCs under way.

Datta, Kong, KM (preliminary)
SUSY versus UED at a LC

- The spin information is encoded in the angular distributions!

\[ e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad \text{SUSY} \]
\[ e^+e^- \rightarrow \mu_1^+\mu_1^- \rightarrow \mu^+\mu^-\gamma_1\gamma_1 \quad \text{UED} \]

\[ \frac{d\sigma}{d\cos \theta} \sim 1 - \cos \theta^2 \quad \frac{d\sigma}{d\cos \theta} \sim 1 + \cos \theta^2 \]

Datta, Kong, KM (preliminary)

- Significant difference in the total cross-section as well!
- The masses can be extracted from the \( E_\mu \) distribution.
- Threshold scan would confirm the spins.
Outreach II: event generators online

- **SUPERSIM flow chart** (Blender, Group, KM)

```
SUPERSIM Home

HERWIG  ISAJET  PYTHIA

ISASUGRA/ISAWIG  General MSSM

ISAWIG Decay Table  ISASUGRA Output

Run HERWIG Events  Run ISAJET Events  Run PYTHIA Events

HERWIG Output  ISAJET Output  PYTHIA Output

Detector Simulation

Cut Selection

Plots
```
Outreach III: ADD in AMEGIC++

- Run I: bootleg version of PYTHIA with real graviton production added as an external process (Lykken,KM, 1999)
- The full ADD model recently implemented in AMEGIC++.
  - Real graviton production
  - Virtual exchange (3 conventions)
  - New Feynman rules included

Gleisberg,Krauss,KM,... hep-ph/0306182
- Spin-independent cross-sections for the 13 benchmark points of Battaglia et al. hep-ph/0106204.

- No lower limit: cancellations are possible.
- **Spin-dependent** cross-sections for the 13 benchmark points of Battaglia et al. hep-ph/0106204.

Ellis, Feng, Ferstl, KM, Olive hep-ph/0110225

- Far below sensitivity of near-term future experiments.
• As usual, spin-dependent and spin-independent cross-sections.

Cheng, Feng, KM, hep-ph/0207125

• The signals are enhanced near the $s$-channel resonance:
  \[ \sigma \sim (m_{q^1} - m_{B^1})^{-2}. \] Unnatural in SUSY, guaranteed here.
  
Cheng, Feng, KM, hep-ph/0207125
Servant, Tait, hep-ph/0209262
Majumdar, hep-ph/0209277

• Constructive interference: lower bound!
MSSM: Positron signal

- Both the shape and the normalization of the background are uncertain:
- Hard positrons come from $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow WW$ and $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ZZ$.

Ellis, Feng, Ferstl, KM, Olive hep-ph/0110225

- The signal is typically a small fraction of the background, and the shape is not very characteristic.
- Annihilation into fermion pairs is **not** helicity suppressed.

\[ B(B^1 B^1 \rightarrow e^+ e^-) = 20\% \]

- There is a bump! The positrons are monoenergetic at birth. Some smearing from propagation through the galaxy.

AMS-II will be able to measure high-\(p_T\) positrons!
Can we test cosmology at the LHC/NLC?

- LCWG: Connections to Astrophysics and Cosmology (2003)
- The charge:
  - Assume the LHC has already “discovered” SUSY and performed the expected measurements of SUSY masses etc.
  - How well can we predict the neutralino relic density based on the LHC results?
  - How much do we benefit from the NLC?
- Our approach: (Birkedal,KM 2004)
  - What are the relevant model parameters?
  - How well can the LHC and NLC determine those?
  - What is the expected uncertainty in $\Omega_{DM} h^2$?
- We necessarily have to choose a model (benchmark point)
  point B: $m_0 = 57$, $M_{1/2} = 250$, $A_0 = 0$, $\tan \beta = 10$, $\mu > 0$.
  - Typical for any benchmark set
  - Similar points discussed in the LHC literature
What are the relevant parameters?

- Point B: neutralinos annihilate through $t$-channel sfermion exchange. Need to measure squark, slepton masses.
- Squarks are heavy $\implies$ small effect on $\Omega h^2$
- Right-handed sleptons are most important:

\[
\begin{align*}
M_{\tilde{\chi}^0} &\approx R \\
M_{\tilde{\chi}^0} &\approx 0.1 \\
M_{\tilde{\chi}^0} &\approx 15 \text{ GeV} < 30 \text{ GeV}. \text{ Unobservable at LHC?}
\end{align*}
\]

- $M_{\tilde{\ell}_R} - M_{\tilde{\chi}^0_1} = 15 \text{ GeV} < 30 \text{ GeV}$. Unobservable at LHC?
- $M_{\tilde{\ell}_L} > M_{\tilde{\chi}^0_2} \implies \tilde{\ell}_L$ will not be produced in cascades.
What about irrelevant parameters?

- Constraining the irrelevant parameters is also important!
- The Higgs pole $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow H^0, A^0$ appears at small $m_A$.

However, $m_A < 200$ GeV would have been discovered...
More irrelevant parameters

- The size of $\mu$ determines the gaugino-higgsino mixing.

Birkedal,KM Preliminary

- How well can we trust the relic density codes?
• LHC: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{q}_L$ to within 10%.

• NLC: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\ell}_L, \tilde{\ell}_R$ to within 2%. Everything else above 250 GeV.
Recent new ideas in particle physics lead to novel alternatives for dark matter candidates. SUSY DM? Not so fast...

Extra dimensions also yield natural dark matter candidates, with calculable rates for detection.

Little Higgs theories, with certain assumptions, also have a dark matter candidate.

The usual question: how do we discover these models?

How do we tell the difference?

How do we uncover the identity of the dark matter?

How will we know we have found the dark matter at the LHC?