Astroparticle Physics at Colliders

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Bonn University
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  - Scalar fields can get large vevs due to these fluctuations
  - At least one model maybe testable at the LHC!
History (cont.d)

- **Reheating**: (Re-)populates Universe with particles.
  
  Re-heat temperature $T_R$ not known: $T_R \gtrsim 3$ MeV (BBN)
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- Some models make predictions for colliders!
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  - May have some connection to collider physics (sphalerons)
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- Energy density of the Universe begins to be dominated by (dark) matter
History (cont.d)

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  - In models with dynamical Dark Energy (“quintessence”): Can affect dynamics of BBN, creation of Dark Matter, . . .
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- SUSY can also play crucial role in re–heating Allahverdi et al., hep–ph/0505050, 0512227, 0603244
3 Dark Energy

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- In models with large extra dimension: LHC may be black hole factory; “cosmon” should be produced in bh decay
4 Baryogenesis

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Some models work at rather low temperature: can be tested at colliders! Will discuss two such models.
Leptogenesis with degenerate neutrinos

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If $M_2 - M_1 \ll M_1$: effective CP violation enhanced: Can have $M_1 \sim \text{TeV}$! Pilaftsis 1997/9; Pilaftsis & Underwood 2004
Leptogenesis (cont.d)

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If $M_{N_{1,2}} \lesssim 500$ GeV: may see CPV at LHC! Bray et al., hep-ph/0702294
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**Other scenarios with low-scale leptogenesis:** Grossman, Kashti, Nir, Roulet 2004; Hambye et al. 2003; Raidal, Strumia, Turzynski 2004
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- Does not work in SM: cross–over (no phase transition) for $m_H \gtrsim 60$ GeV!
Baryogenesis (cont.d)

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- Determination of $\phi_{\mu}$ in relevant region of parameter space
5 Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)
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$\Omega$: Mass density in units of critical density; $\Omega = 1$ means flat Universe.

$h$: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$
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- Cosmic Microwave Background anisotropies (WMAP) imply $\Omega_{DM} h^2 = 0.105^{+0.007}_{0.013}$

Spergel et al., astro-ph/0603449
Density of thermal DM

Decoupling of DM particle $\chi$ defined by:

$$n_\chi(T_f)\langle v\sigma(\chi\chi \rightarrow \text{any})\rangle = H(T_f)$$

$n_\chi$: $\chi$ number density $\propto e^{-m_\chi/T}$

$v$: Relative velocity

$\langle \ldots \rangle$: Thermal average

$H$: Hubble parameter; in standard cosmology $\sim T^2/M_{\text{Planck}}$
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Gives average relic mass density

$$\Omega_\chi \propto \frac{1}{\langle v\sigma(\chi\chi \rightarrow \text{any})\rangle}$$

Gives roughly right result for weak cross section!
Assumptions

\( \chi \) is effectively stable, \( \tau_\chi \gg \tau_U \): partly testable at colliders
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Thermal WIMPs at colliders: Generalities

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- Hence can generally only test models with “Überbau” of heavier, strongly interacting new particles decaying into $\chi$
- Such particles exist for best–motivated $\chi$ candidates: SUSY, Little Higgs, universal extra dimension
SUSY Dark Matter

Conditions for successful DM candidate:

- Must be stable \( \Rightarrow \chi = \text{LSP} \) and \( R \)–parity is conserved
  (if LSP in visible sector)
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And the winner is . . .
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$$\chi = \tilde{\chi}^0_1$$

(or in hidden sector)
\( \tilde{\chi}_1^0 \) relic density

To predict thermal \( \tilde{\chi}_1^0 \) relic density: have to know

\[
\sigma(\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \text{SM particles})
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In general, this requires knowledge of almost all sparticle and Higgs masses and of all couplings of the LSP!
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Neutralino mass matrix in the MSSM:

$$M_0 = \begin{pmatrix}
M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\
0 & M_2 & -M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\
-M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & -\mu \\
M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & -\mu & 0
\end{pmatrix}$$
\( \tilde{\chi}_1^0 \) relic density

To predict thermal \( \tilde{\chi}_1^0 \) relic density: have to know

\[
\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \text{SM particles})
\]

In general, this requires knowledge of almost all sparticle and Higgs masses and of all couplings of the LSP!

Neutralino mass matrix in the MSSM:

\[
M_0 = \begin{pmatrix}
M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\
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\end{pmatrix}
\]

\( \rightarrow \) Can determine decomposition of \( \tilde{\chi}_1^0 \) by studying \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^0, \tilde{\chi}_3^0 \).
\( \tilde{\chi}_1^0 \) annihilation in the MSSM

\[ m_{\tilde{f}_L}, m_{\tilde{f}_R}, \theta_{\tilde{f}} : \text{Needed for } \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow f \bar{f} \]
$\tilde{\chi}_1^0$ annihilation in the MSSM

1. $m_{\tilde{f}_L}, m_{\tilde{f}_R}, \theta_{\tilde{f}}$: Needed for $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow f \bar{f}$

2. $m_h, m_H, m_A, \alpha, \tan \beta$: Needed for $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow f \bar{f}, VV, V\phi, \phi\phi$ ($V$: Massive gauge boson; $\phi$: Higgs boson).
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- For many masses: lower bounds may be sufficient

- If coannihilation is important: final answer depends exponentially on mass difference

- Parameters in Higgs and squark sector are also needed to predict \( \tilde{\chi}_1^0 \) detection rate, i.e. \( \sigma(\tilde{\chi}_1^0 N \rightarrow \tilde{\chi}_1^0 N) \)
Impact on particle physics (mSUGRA)

Parameter space is constrained by:

- Sparticle searches, in particular $\tilde{\chi}_1^\pm$, $\tilde{\tau}_1$ searches at LEP: $\sigma < 20$ fb
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- Simple CCB constraints (at weak scale only)
mSUGRA, $m_t = 178$ GeV, $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$

All constraints except DM included

$\tilde{\tau}_1$ is LSP

$h$ is too light

$\tilde{\chi}_1^+ \text{is too light}$
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Predicting $\Omega_{\tilde{\chi}_1^0} h^2$ from LHC data

The precision with which $\Omega_{\tilde{\chi}_1^0} h^2$ can be predicted strongly depends on SUSY parameters: black Battaglia et al., hep–ph/0602187
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Based on spectrum information only!
Any mSUGRA parameter set can have the right DM density if LSP is in hidden or invisible sector. It could be:

- **The axino** Covi et al., hep-ph/9905212
Hidden Sector Dark Matter

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- Detection of hidden sector DM seems impossible: Cross sections are way too small!
Nonstandard cosmology

Can either reduce or increase density of stable $\tilde{\chi}_1^0$
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- **Increase**: through increase of $H(T_f)$; or through non-thermal $\tilde{\chi}_{1}^{0}$ production mechanisms.
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None of these mechanisms in general has observable consequences (except DM density).

If $\tilde{\chi}_1^0$ makes DM: Can use measurements at colliders to constrain cosmology!
Dark Energy: Difficult to probe at colliders; perhaps some possibilities if $D > 4$
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- **Dark Matter**:
  - Many models can be tested at colliders, some cannot
  - SUSY WIMPs: Relic density often depends very sensitively on parameters: need very accurate measurements in collider experiments!