Review of Cosmology and the Linear Collider

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LC-Cosmology working group

★ Convenors
- M. Battaglia, J. Feng, N. Graf, M. Peskin, M. Trodden
- see http://www.physics.syr.edu/~trodden/lc-cosmology/

★ Call to arms!
- Europe, Japan contingent
- Belanger, Djouadi, Okada, …
Construction

★ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$

★ matter content: 3 generations quarks and leptons

\[
\begin{pmatrix}
u \\ e \\
\end{pmatrix}
\]

★ Higgs sector $\Rightarrow$ spontaneous electroweak symmetry breaking:

\[
\phi = \begin{pmatrix}
\phi^+ \\
\phi_0
\end{pmatrix}
\]

★ Yukawa interactions $\Rightarrow$ massive quarks and leptons

★ 19 parameters

★ good-to-excellent description of (almost) all accelerator data!
Data not described by the SM

- neutrino masses and mixing
- baryogenesis $\eta \sim 10^{-10}$ (matter anti-matter asymmetry)
- cold dark matter
- dark energy

★ Note astro/cosmological origin of all discrepancies!
Neutrino masses

Data on neutrino masses/ mixings

★ Solar $\nu$ oscillations (Homestake to SNO)
  - SNO: Standard Solar Model works, but $\nu$s oscillate!
  - $|m_{\nu_2}^2 - m_{\nu_1}^2| \sim 7 \times 10^{-5}$ eV$^2$

★ Atmospheric oscillations (SuperK): ($\nu_\mu \rightarrow \nu_\tau$?)
  - $|m_{\nu_2}^2 - m_{\nu_3}^2| \sim 3 \times 10^{-3}$ eV$^2$

★ large mixing angles

★ WMAP gives upper absolute mass limit:
  - $\sum_i m_{\nu_i} < 0.71$ eV

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How to explain?

A few of many models

★ Dirac $\nu$ masses? (inelegant)

★ Bilinear $R$-violation in SUSY? (Valle, Diaz, Porod, ⋅ ⋅ ⋅)

★ Add gauge singlet RHN to SM fermion content
  – large Majorana mass allowed
  – completes a generation in $\psi(16)$ of $SO(10)$
  – easily accommodated in $SO(10)$ SUSY GUT
  – see-saw mechanism $\Rightarrow$ light $\nu_L$
  – heavy $N_R \sim 10^9 – 10^{15}$ GeV
  – mechanism for baryogenesis via leptogenesis
  – LFV: $\mu \rightarrow e \gamma$, $\tau \rightarrow \mu \gamma$ (Rückl)

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Baryogenesis:

what gives rise to matter-antimatter asymmetry?

★ SM not adequate to describe baryogenesis
★ Beyond the SM physics needed:
  ● EW baryogenesis
    * can work in SUSY
    * need strong first order EW phase transition
    * needs $m_h < 105 - 118$ GeV, $m_{\tilde{t}_1} < m_t$
  ● Affleck-Dine baryogenesis
    * need flat directions in scalar potential
    * scalar fields carrying baryon number
    * naturally implemented in SUSY theories
  ● GUT baryogenesis
    * baryogenesis at $Q = M_{GUT}$ washed out below $M_{GUT}$ by sphaleron effects? (but pre-heating?)
leptogenesis: (Fukugita, Yanagida)

- out-of-equilibrium asymmetric decays of $N, \tilde{N}$ in early universe generates lepton-antilepton asymmetry
- EW sphaleron effects convert lepton asymmetry into baryon asymmetry
- naturally implemented in $SO(10)$ SUSYGUTs
- test via LFV: $e^+e^- \rightarrow \tilde{\ell}_1^+ \tilde{\ell}_1^- \rightarrow e^+ \mu^- + 2\tilde{Z}_1$
Testing leptogenesis at a LC:

(HB, Balazs, Mizukoshi, Tata)

★ Add $\hat{N}_i^c$ to MSSM: $\hat{N}^c \ni (\tilde{\nu}_R^\dagger, \psi_{N^cL})$

★ $\hat{f} = f_{MSSM} + f_\nu \epsilon_{ij} \hat{L}^i \hat{H}^j_u \hat{N}^c + \frac{1}{2} M_N \hat{N}^c \hat{N}^c$

★ $\mathcal{L}_{soft} = \mathcal{L}_{MSSM} - m_{\tilde{\nu}_R}^2 |\tilde{\nu}_R|^2 + \left[ A_\nu f_\nu \epsilon_{ij} \hat{L}^i \hat{H}^j_u \tilde{\nu}_R^\dagger + \frac{1}{2} B_\nu M_N \tilde{\nu}_R^2 + h.c. \right]$

★ RGEs of MSSM modified to contain terms with $f_\nu$

★ $f_{\nu_3} = f_t$ in $SO(10)$

★ large $f_\nu$ acts to suppress 3rd gen. sleptons compared to 1st and 2nd!

★ $\frac{d}{dt} (2\Delta_L - \Delta_R) = \frac{4}{16\pi^2} f_\nu^2 (m_{\tilde{\tau}_L}^2 + m_{\tilde{\nu}_R}^2 + m_{H_u}^2 + A_\nu^2)$
  • $\Delta_L = m_{\tilde{\nu}_L}^2 - m_{\tilde{\tau}_L}^2$; $\Delta_R = m_{\tilde{\nu}_R}^2 - m_{\tilde{\tau}_R}^2$

★ correct for stau mixing

★ need to measure 1st/3rd gen. slepton masses to 2 – 3% to test
Evidence for dark matter in the universe

★ binding of galactic clusters (Zwicky, 1930s)
★ galactic rotation curves
★ large scale structure formation
★ gravitational lensing
★ inflation ⇒ \( \Omega = \rho/\rho_c = 1 \)
★ anisotropy in cosmic microwave background (WMAP)
★ surveys of distant galaxies via supernovae (DE)
★ Big Bang nucleosynthesis
  - \( \Omega_A \simeq 0.7 \)
  - \( \Omega_{CDM} \simeq 0.25 \)
  - \( \Omega_{baryons} \simeq 0.045 \) (dark baryons \( \sim 0.040 \))
  - \( \Omega_\nu \simeq 0.005 \)
Cosmic $\mu$-wave background anisotropies (COBE to WMAP)
Dark matter versus dark energy

Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Candidates for cold dark matter

- axions (Sikivie)
- gravity mediated SUSY with $R$-parity
  - lightest neutralino $\tilde{Z}_1$ (Goldberg; Ellis, Hagelin, Nanopoulos, Olive and Srednicki)
  - gravitino $\tilde{G}$ (superWIMP) (Feng, Rajaraman, Takayama)
- UED: lightest KK-odd boson e.g. $B_1$ (Servant, Tait)
- little Higgs scalar DM: (Birkedal, Wacker)
- SUSY $Q$-balls: (Kusenko, Shaposhnikov)
- branons: (Cembranos, Dobado, Maroto)
Neutralino dark matter

★ Why $R$-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin)

★ In thermal equilibrium in early universe

★ As universe expands and cools, freeze out

★ Number density obtained from Boltzmann eq’n
  
  $\frac{dn}{dt} = -3Hn - \langle\sigma v_{\text{rel}}\rangle(n^2 - n_0^2)$

  ★ depends critically on thermally averaged annihilation cross section times velocity

★ many thousands of annihilation/co-annihilation diagrams

★ equally many computer codes
  
  ★ Neutdriver (Jungman; not maintained)
  
  ★ DarkSUSY: (Gondolo, Edsjo, Ullio, Bergstrom, Schelke, Baltz)
• Micromegas (Belanger, Boudjema, Pukhov, Semenov)
• SSARD: (Ellis, Falk and Olive)
• IsaRED: (HB, Balazs, Belyaev)
• Drees/ Nojiri code
• Roszkowski code
• Arnowitt/ Nath code
• Lahanas/ Nanopoulos code
• Bottino/ Fornengo et al. code
• ⋯ (I am sure I am omitting many...)
Main mSUGRA regions consistent with WMAP

- bulk region (low $m_0$, low $m_{1/2}$)
- stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\tilde{Z}_1}$)
- HB/FP region (large $m_0$ where $|\mu| \to$ small)
- $A$-funnel ($2m_{\tilde{Z}_1} \simeq m_A, m_H$)
- $h$ corridor ($2m_{\tilde{Z}_1} \simeq m_h$)
- stop co-annihilation region (particular $A_0$ values $m_{\tilde{t}_1} \simeq m_{\tilde{Z}_1}$)
Relic density of neutralinos in mSUGRA model

- $0.3 < \Omega h^2 < 1.$
- $\Omega h^2 < 0.1$
- $0.1 < \Omega h^2 < 0.3$
- Excluded by theory

$m_0$ (GeV) vs. $m_{1/2}$ (GeV)

- $\tan\beta = 10, \mu > 0$
- $\tan\beta = 45, \mu < 0$

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Sparticle reach of all colliders and relic density

$m_{\text{Sugra with } \tan\beta = 30, A_0 = 0, \mu > 0}$

$0 \leq \Omega h^2 < 0.129$

● LEP2 excluded

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Sparticle reach of all colliders and relic density

$m_{Sugra}$ with $\tan\beta = 45$, $A_0 = 0$, $\mu < 0$

$\Omega h^2 < 0.129$

LEP2 excluded

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Group activities: 6 simulation points

★ bulk region (Battaglia)
  • \((m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu) = 57 \text{ GeV}, 250 \text{ GeV}, 0, 10, +1)\)

★ HB/FP region (Alexander, Matchev, students)
  • \((m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu) = 3280 \text{ GeV}, 300 \text{ GeV}, 0, 10, +1)\)

★ \(\tilde{\chi}^0\)co-ann. region (Arnowitt, Dutta, Kamon, Khotilovich)(Banbade, Berggren, Martyn, Richard, Zhang)
  • \((m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu) = 213 \text{ GeV}, 360 \text{ GeV}, 0, 40, +1)\)

★ A funnel (Battaglia)
  • \((m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu) = 340 \text{ GeV}, 400 \text{ GeV}, 0, 51, +1)\)

★ light stop (Strube, Lu, Graf)
  • \((m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu) = 600 \text{ GeV}, 200 \text{ GeV}, -1300 \text{ GeV}, 30, +1)\)
Goals of exercise:

- determine mass, spin etc. of DM particle
- determine $\Omega_{CDM} h^2$ from LC measurements?
Conclusions

Strong motivations for physics BSM from astro/cosmology!

★ $\nu$ mass $\Rightarrow$ SUSYGUTSs?!

★ baryogenesis ($\Rightarrow$ SUSY)

★ LC possible test of leptogenesis via precision slepton mass measurements

★ neutralino dark matter
  - bulk region
  - stau co-annihilation
  - HB/FP region: mixed higgsino/bino LSP
  - $A$ annihilation funnel

★ Depending on what is found, can determine neutralino annihilation mechanism in early universe!