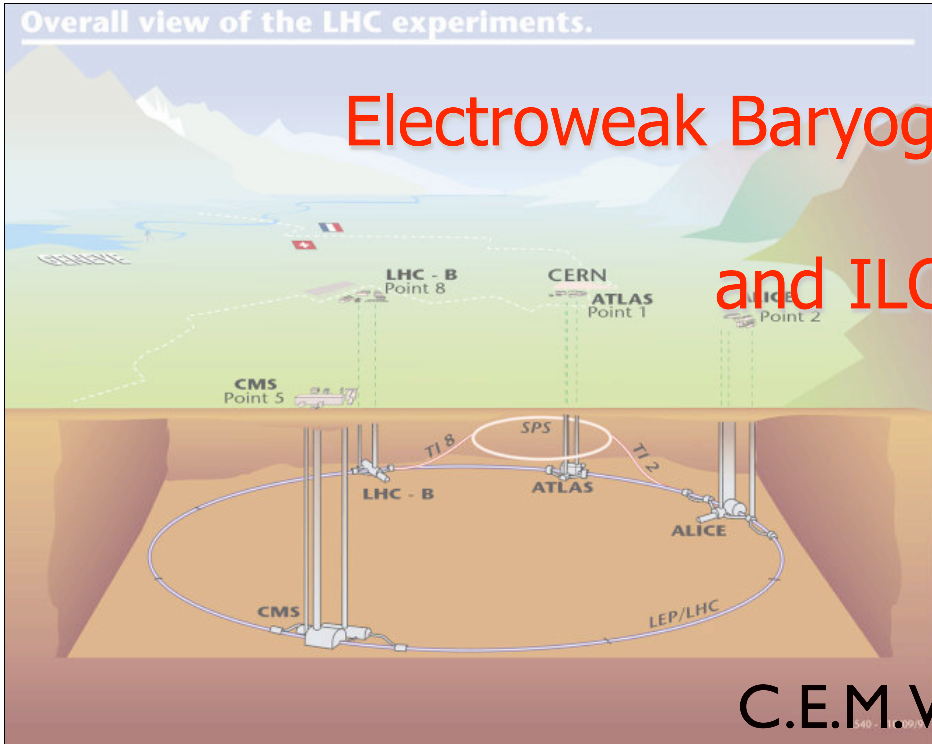
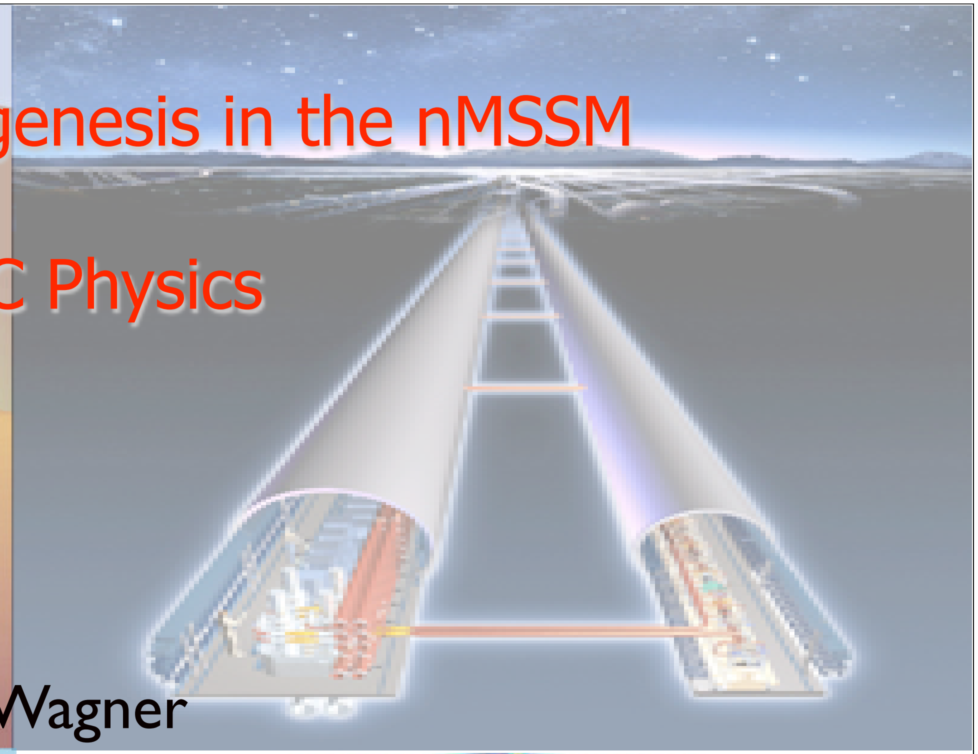
Electroweak Baryogenesis in the nMSSM

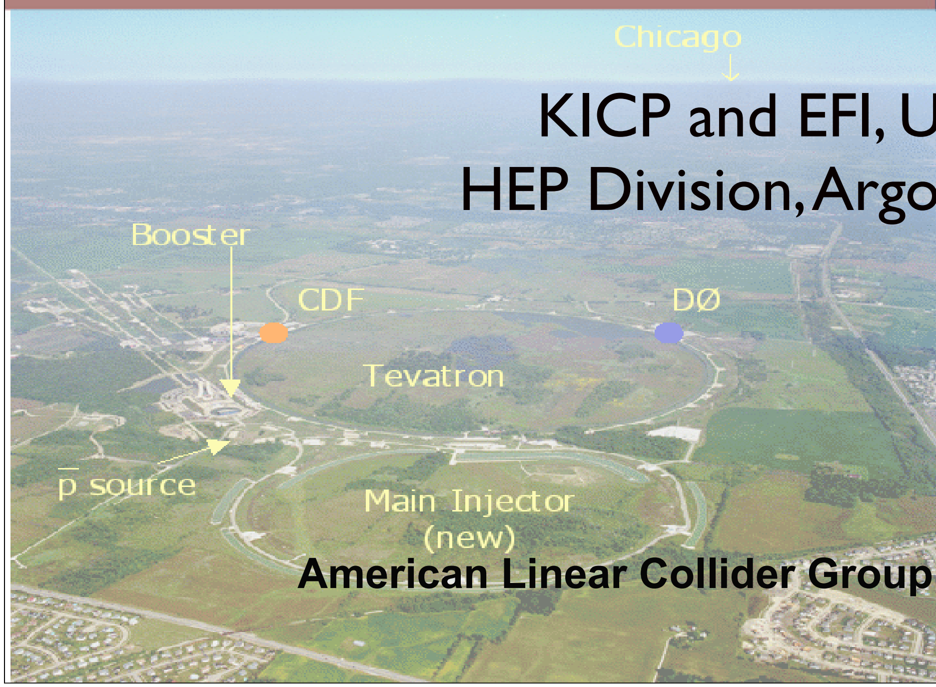
and ILC Physics

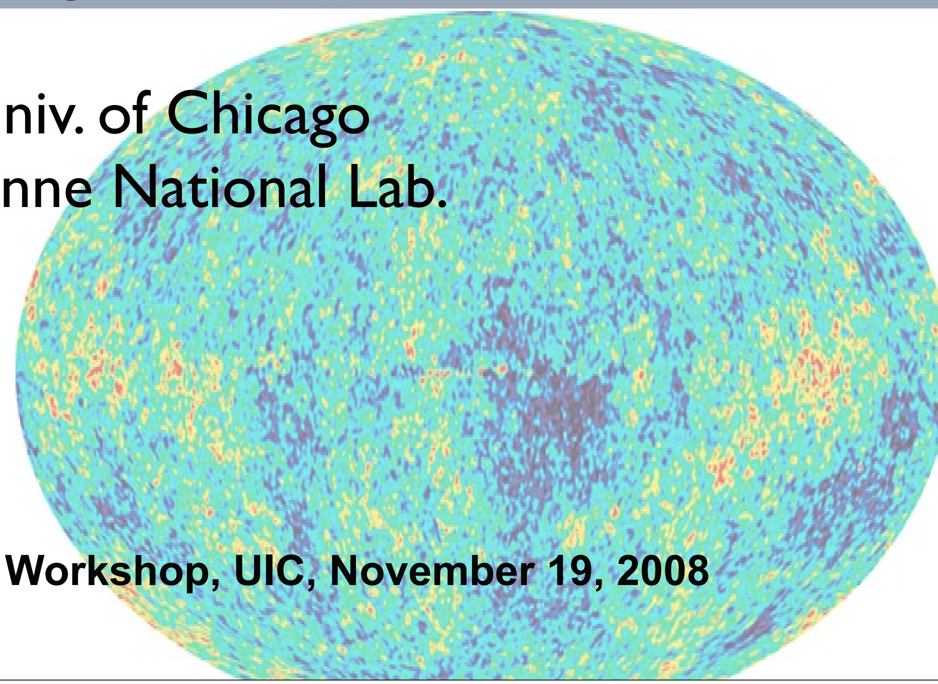




C.E.M. Wagner

KICP and EFI, Univ. of Chicago
HEP Division, Argonne National Lab.





American Linear Collider Group Workshop, UIC, November 19, 2008

Based on the works :

A. Menon, D. Morrissey and C.W.; Phys. Rev. D70:035005, 2004.

C. Balazs, M. Carena, A. Freitas and C.W., **arXiv:0705.0431, JHEP0706 (2007) 066**

Tao Liu and C.W., JHEP0806:073, 2008

Open questions in the Standard Model

- Source of Mass of fundamental particles.
- Nature of the Dark Matter, contributing to most of the matter energy density of the Universe.
- Origin of the observed asymmetry between particles and antiparticles (Baryon Asymmetry).
- Dark Energy, Quantum Gravity and Unified Interactions.

Baryogenesis at the weak scale

- Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them :
- Baryon number violation: Anomalous Processes
- C and CP violation: Quark CKM mixing
- Non-equilibrium: Possible at the electroweak phase transition.

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s}\ \exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}}\exp\left(-\frac{\mathrm{E_{sph}(T_c)}}{\mathrm{T_c}}\right)\right)$$

$$\boxed{\mathbf{E_{sph}} \propto \frac{\mathbf{8\pi\, v}}{\mathbf{g}}}$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

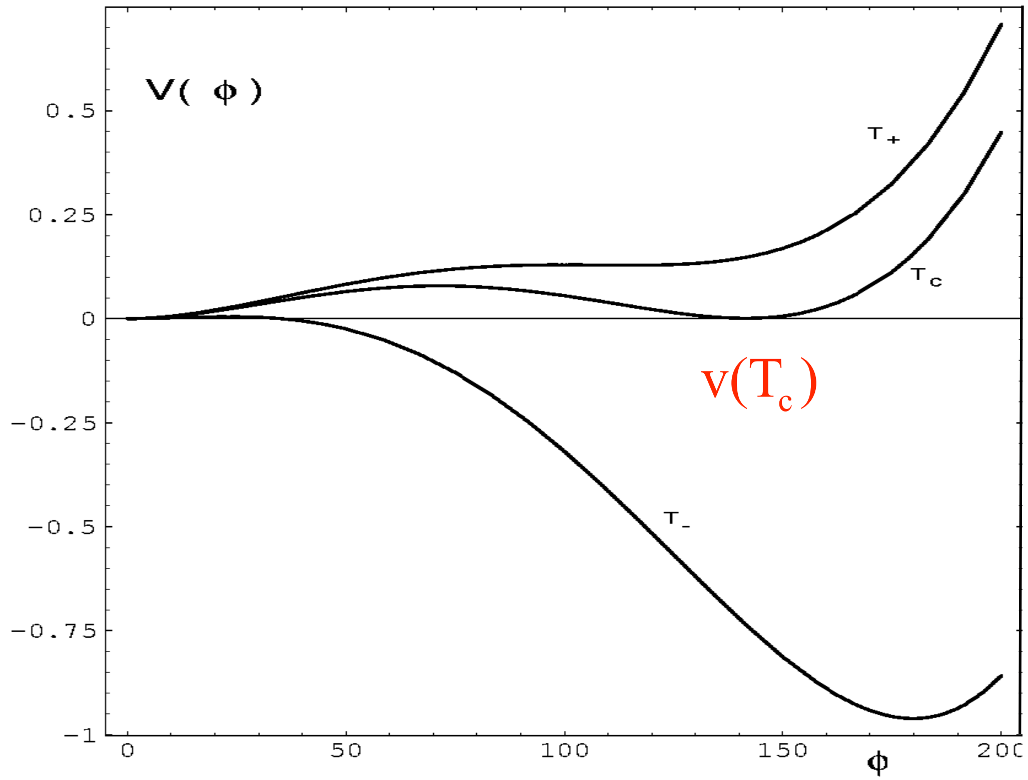
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

$$\frac{\mathrm{v}(T_c)}{T_c} > 1$$

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition



Finite Temperature Higgs Potential

$$V(T) \;=\; D(T^2 - T_0^2)\phi^2 - E_B T\phi^3 + \frac{\lambda(T)}{2}\phi^4$$

D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

E receives contributions proportional to the sum of the cube of all light boson particle couplings

$$\frac{\mathrm{v}(\mathrm{T_c})}{\mathrm{T_c}} \approx \frac{\mathrm{E}}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{\mathrm{m_H^2}}{\mathrm{v}^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

$$\frac{\mathrm{v}(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H \quad < 40\ \text{GeV.}$$

Electroweak Baryogenesis in the SM is ruled out

Electroweak Baryogenesis in the nMSSM

A. Menon, D. Morrissey and C.W., PRD70:035005, 2004
C. Balazs, M. Carena, A. Freitas, C.W., JHEP0706 (2007) 066

See also Kang, Langacker, Li and Liu, hep-ph/0402086.
Barger et al ’04

Early work in this direction:

M. Pietroni ‘93
Davies et al. ‘96
Huber and Schmidt ‘00

Electroweak Symmetry Breaking and the μ Problem

- Negative values of the soft supersymmetry breaking mass parameter induce electroweak symmetry breaking. The total Higgs masses receive a SUSY contribution

$$\mu^2 + m_{H_i}^2$$

- Electroweak symmetry breaking therefore demands a relation between these two contributions

$$\mu^2 + \frac{M_Z^2}{2} = \frac{m_{H_d}^2 - \tan^2\beta \, m_{H_u}^2}{\tan^2\beta - 1}, \qquad \tan\beta = \frac{v_u}{v_d}$$

- Therefore, μ must be of the order of the SUSY breaking parameters
- Also, the mixing term $(B_\mu H_u H_d + h.c.)$ appearing in the potential

$$\sin 2\beta = \frac{2B_\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2}$$

must be of the same order. Is there a natural framework to solve the flavor problem, inducing weak scale values for μ and B_μ ?

Singlet Mechanism for the generation of μ

- A natural solution would be possible by introducing a singlet

$$W = \lambda S H_u H_d + h_u Q U H_u + \ldots$$

- This alllows to replace the μ-term by the vacuum expectation value of the singlet field S,

$$\mu = \lambda v_S$$

- This model, however, preserves a Peccei Quinn symmetry

$$\widehat{Q} : -1, \qquad \widehat{U}^C : 0, \qquad \widehat{D}^C : 0, \qquad \widehat{L} : -1, \qquad \widehat{E}^C : 0, \qquad \widehat{H}_u : 1, \qquad \widehat{H}_d : 1, \qquad \widehat{S} : -2,$$

- Therefore, once the Higgs acquire v.e.v.'s there is an unacceptable massless Goldstone in the spectrum. The Peccei Quinn symmetry must be then broken

Singlet Mechanism for the generation of μ in the NMSSM

- One could break the symmetry by self interactions of the singlet

$$W = \lambda S H_u H_d - \frac{\kappa}{3} S^3 + h_u Q U H_u + \ldots$$

- No dimensionful parameter is included. The superpotential is protected by a Z3 symmetry, $\phi \rightarrow exp(i2\pi/3)\phi$
- This discrete symmetry would be broken by the singlet v.e.v. Discrete symmetries are dangerous since they could lead to the formation of domain walls: Different volumes of the Universe with different v.e.v.'s separated by massive walls. These are ruled out by cosmology observations.
- One could assume a small explicit breakdown of the Z3 symmetry, by higher order operators, which would lead to the preference of one of the three vacuum states. That would solve the problem without changing the phenomenology of the model.

(See Tao Liu's talk this afternoon)

Tadpoles in the NMSSM

- The NMSSM construction then, assumes the existence of small Z3 breaking terms that solve the domain wall problem.
- One possible construction in supergravity theories is to break the Z3 symmetry by the same sector that breaks supersymmetry.
- However, in general this also leads to the generation of tadpole terms for the singlet, $\mathcal{L}_{\rm soft} \supset t_S\, S \sim \frac{1}{(16\pi^2)^n}\, M_{\rm P}\, M_{\rm SUSY}^2\, S$, where n is the number of loops at which it is generated.
- If a large tadpole is generated, it would shift the v.e.v. of S to large values, reintroducing the mu problem. Therefore, in this case n should be larger than 5.
- One could imagine that the operators present do not lead to large tadpoles. More reassuring would be to find a way of eliminating them.
- Three natural solutions: Gauge the PQ symmetry (UMSSM) or find alternative symmetries that ensure large n (MNSSM or nMSSM) or break SUSY at lower energies.

Minimal Extension of the MSSM (nMSSM)

Dedes et al. , Panagiotakopoulos, Pilaftsis'01

- Superpotential restricted by Z_5^R or Z_7^R symmetries

$$W = \lambda S H_1 H_2 + \frac{m_{12}^2}{\lambda} S + y_t Q H_2 U$$

- No cubic term. Tadpole of order cube of the weak scale, instead

- Discrete symmetries broken by tadpole term, induced at the sixth loop level. Scale stability preserved

- Similar superpotential appears in Fat-Higgs models at low energies

Harnik et al. '03

$$V_{soft} = m_1^2 H_1^2 + m_2^2 H_2^2 + m_S^2 S^2 + \left(t_s\, S + h.c. \right)$$
$$+ \left(a_\lambda S H_1 H_2 + h.c. \right)$$

Electroweak Phase Transition

Defining $\phi^2 = \mathbf{H}_1^2 + \mathbf{H}_2^2$, $\tan\beta = \frac{\mathbf{v}_1}{\mathbf{v}_2}$

- In the nMSSM, the potential has the approximate form:

(*i.e.* tree-level + dominant one-loop high-T terms)

$$V_{eff} \simeq (-m^2 + A\,T^2)\phi^2 + \tilde{\lambda}^2\phi^4 + 2t_s\phi_s + 2\tilde{a}\,\phi_s\phi^2 + \lambda^2\phi^2\phi_s^2$$

with $\tilde{a} = \frac{1}{2}\,a_\lambda \sin 2\beta$, $\tilde{\lambda}^2 = \frac{\lambda^2}{4}\sin^2 2\beta + \frac{\bar{g}^2}{2}\cos^2 2\beta.$

- Along the trajectory $\frac{\partial V}{\partial \phi_s} = 0$, the potential reduces to

$$V_{eff} = (-m^2 + A\,T^2)\phi^2 - \left(\frac{t_s + \tilde{a}\,\phi^2}{m_s^2 + \lambda^2\phi^2}\right) + \tilde{\lambda}^2\phi^4.$$

Non-renormalizable potential controlled by m_s. Strong first order phase transition induced for small values of m_s.

Parameters with strongly first order transition

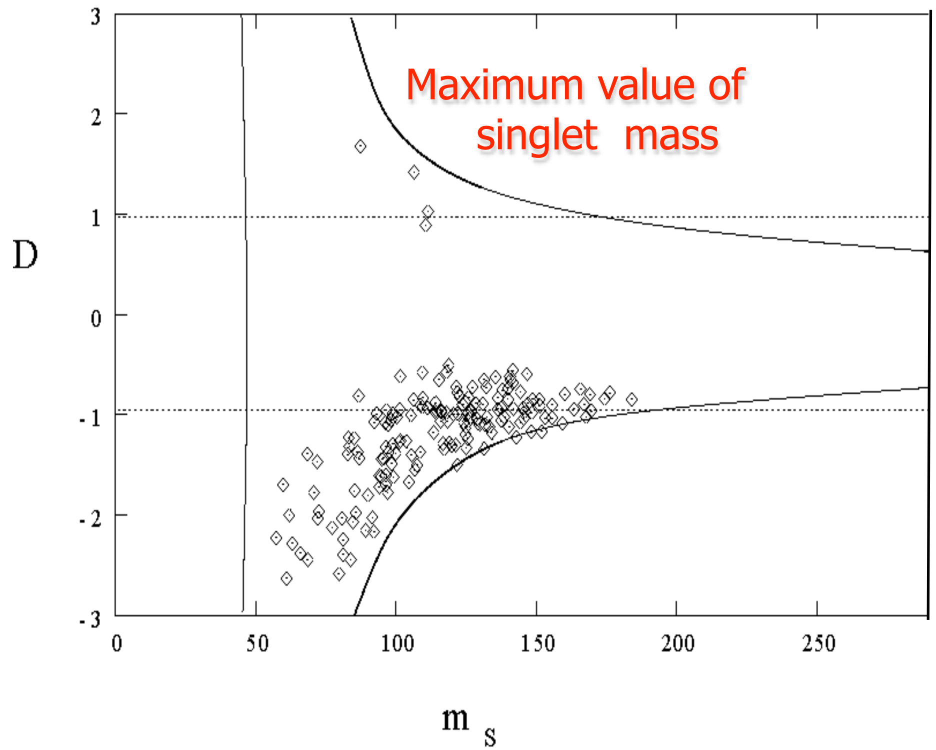
- All dimensionful parameters varied up to 1 TeV

- Small values of the singlet mass parameter selected

$$D = \frac{1}{\tilde{\lambda}\, m_S^2} \left\| \frac{\lambda^2 t_S}{m_S} - m_S\, a_\lambda \cos\beta \sin\beta \right| \geq 1$$

Menon,Morrissey,C.W.'04

- Values constrained by perturbativity up to the GUT scale.



Neutralino Mass Matrix

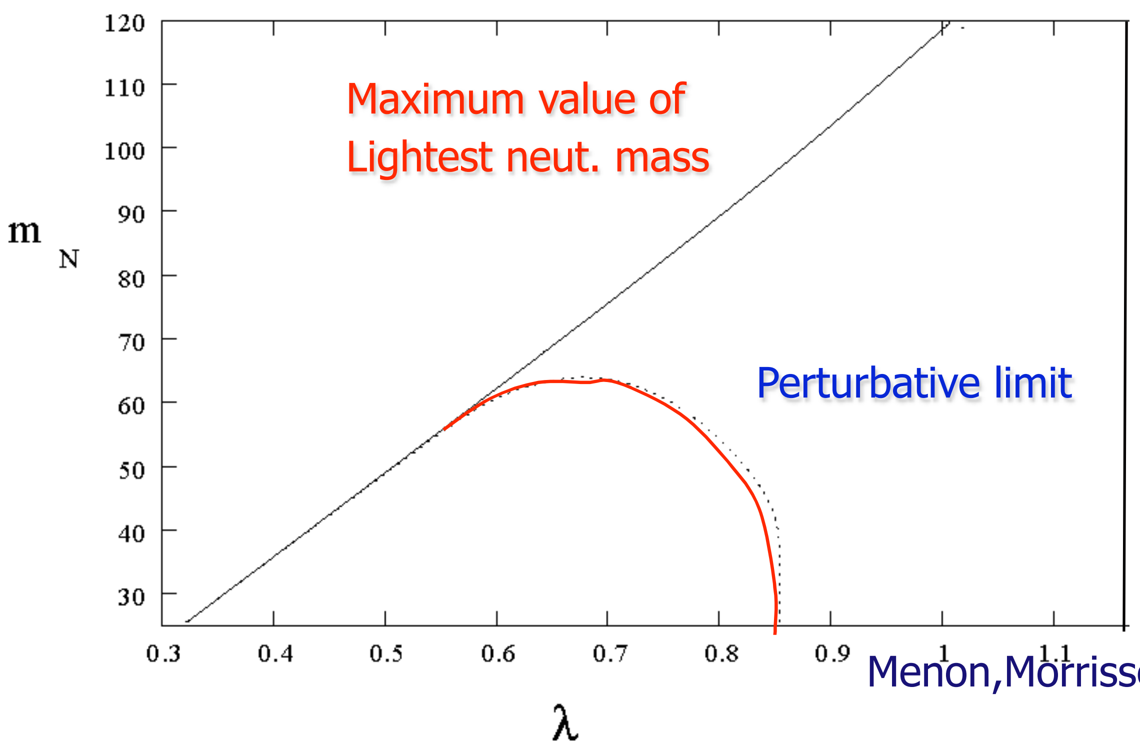
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_\mathrm{W} M_\mathrm{Z} & s_\beta s_\mathrm{W} M_\mathrm{Z} & 0 \\ 0 & M_2 & c_\beta c_\mathrm{W} M_\mathrm{Z} & -s_\beta c_\mathrm{W} M_\mathrm{Z} & 0 \\ -c_\beta s_\mathrm{W} M_\mathrm{Z} & c_\beta c_\mathrm{W} M_\mathrm{Z} & 0 & \lambda v_\mathrm{s} & \lambda v_2 \\ s_\beta s_\mathrm{W} M_\mathrm{Z} & -s_\beta c_\mathrm{W} M_\mathrm{Z} & \lambda v_\mathrm{s} & 0 & \lambda v_1 \\ 0 & 0 & \lambda v_2 & \lambda v_1 & \kappa \end{pmatrix},$$

In the nMSSM, $\kappa = 0$.

Upper bound on Neutralino Masses

$$m_1 = \frac{2\lambda\, v \sin\beta\ x}{(1+\tan^2\beta + x^2)} \qquad \text{with} \quad x = \frac{v_s}{v_1}$$

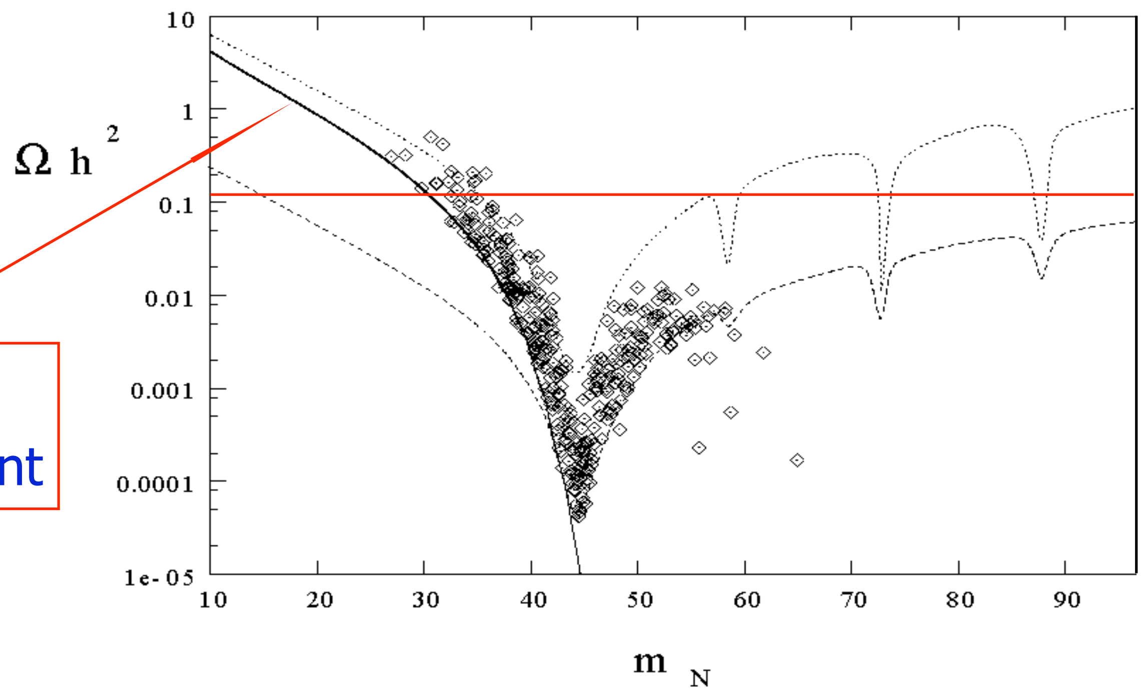
Values of neutralino masses below dotted line consistent with perturbativity constraints.



Menon,Morrissey,C.W.'04

Relic Density and Electroweak Baryogenesis

Region of neutralino masses selected when perturbativity constraints are imposed.
Z-boson and Higgs boson contributions shown to guide the eye.



Z-width constraint

Lightest neutralino masses of about 30--35 GeV (mainly singlino) are required to satisfy the dark matter density constraints

Menon,Morrissey,C.W.'04

CP-Violating Phases

The conformal (mass independent) sector of the theory is invariant under an R-symmetry and a PQ-symmetry, with

	$\hat{H}_1$	$\hat{H}_2$	$\hat{S}$	$\hat{Q}$	$\hat{L}$	$\hat{U}^c$	$\hat{D}^c$	$\hat{E}^c$	$\hat{B}$	$\hat{W}$	$\hat{g}$	W_{nMSSM}
$\mathrm{U(1)_R}$	0	0	2	1	1	1	1	1	0	0	0	2
$\mathrm{U(1)_{PQ}}$	1	1	-2	-1	-1	0	0	0	0	0	0	0

These symmetries allow to absorve phases into redefinition of fields. The remaining phases may be absorved into the mass parameters. Only physical phases remain, given by

$$\arg(m_{12}^* t_\mathrm{s} a_\lambda), \longleftarrow \text{Higgs Sector}$$

$$\arg(m_{12}^* t_\mathrm{s} M_i), \quad i = 1, 2, 3, \longleftarrow \text{Chargino-Neutralino Sector}$$

$$\arg(m_{12}^* t_\mathrm{s} A_\mathrm{u}), \quad (3 \text{ generations}), \longleftarrow \text{S-up sector}$$

$$\arg(m_{12}^* t_\mathrm{s} A_\mathrm{d}), \quad (3 \text{ generations}), \longleftarrow \text{S-down sector}$$

Choice of CP-violating Phases

- We will assume phases in the (universal) gaugino mass parameters
- This choice leads to signatures in electric dipole moments similar to those ones present in the MSSM
- Choosing the phase in the Higgs sector, however, may lead to a realistic scenario. It is an open question if this can be tested.

  Huber, Konstantin, Prokopec, Schmidt'06
- Hard to realize this scenario with only phases in the squark sector.

Information from LHC/ILC

Balazs, Carena, Freitas, C.W. ‘07

Higgs Spectrum

- New CP-odd and CP-even Higgs fields induced by singlet field (mass controled by $\mathbf{m_S^2}$)
- They mix with standard CP-even and CP-odd states in a way proportional to λ **and** $\mathbf{a_\lambda}$
- Values of λ restricted to be lower than 0.8 in order to avoid Landau-pole at energies below the GUT scale.
- As in the MSSM, upper bound on Higgs that couples to weak bosons
- Extra tree-level term helps in avoiding LEP bounds.

$$\mathbf{m_h^2 \leq M_Z^2 \cos^2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loop corrections}}$$

Espinosa,Quiros ’98; Kane et al. ;98

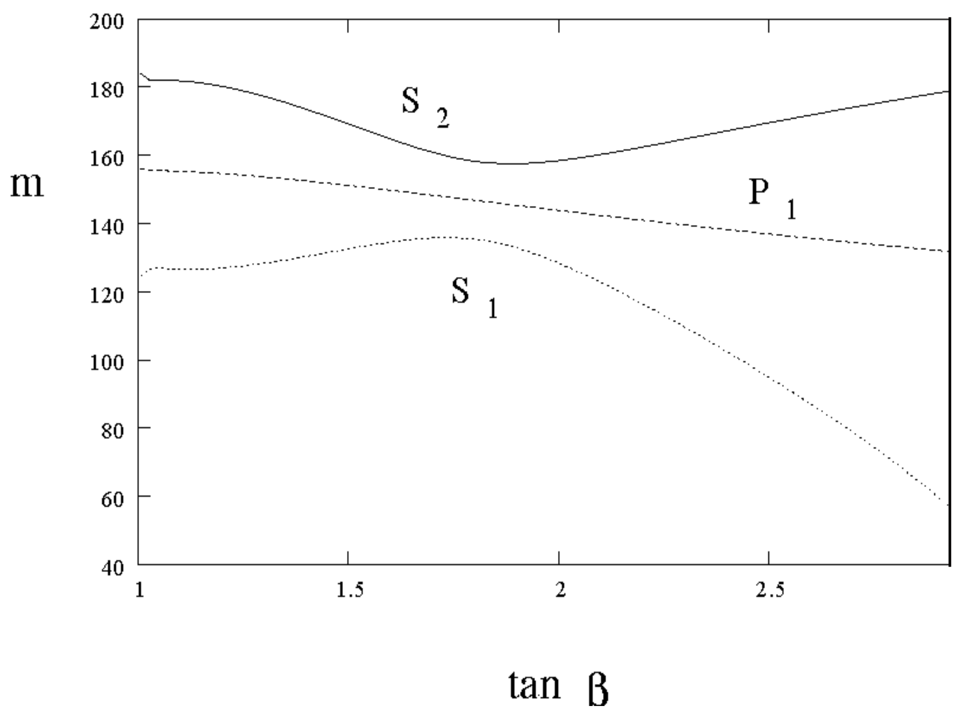
Light Higgs boson masses

- Even in the case in which the model remains perturbative up to the GUT scale, lightest CP-even Higgs masses up to 130 GeV are consistent with electroweak Baryogenesis.

$M_a = 900\,\mathrm{GeV}$ $\quad v_S = -300\,\mathrm{GeV}$

$a_\lambda = 350\,\mathrm{GeV}$ $\quad t_S^{1/3} = 150\,\mathrm{GeV}$

$\lambda = 0.7$



Menon,Morrissey,C.W.'04

Higgs Searches

- Invisibly decaying Higgs may be searched for at the LHC in the Weak Boson Fusion production channel.
- Defining

$$\eta = \mathrm{BR}(H \to \mathrm{inv.}) \frac{\sigma(\mathrm{WBF})}{\sigma(\mathrm{WBF})_{\mathrm{SM}}}$$

- The value of η varies between 0.5 and 0.9 for the lightest CP-even Higgs boson.
- Minimal luminosity required to exclude (discover) such a Higgs boson, with mass lower than 130 GeV:

$$L_{95\%} = \frac{1.2\ \mathrm{fb}^{-1}}{\eta^2} \quad , \qquad L_{5\sigma} = \frac{8\ \mathrm{fb}^{-1}}{\eta^2}$$

Higgs Working Group, Les Houches’01

(see also Davoudiasl,Han,Logan, hep-ph/0412269)

- Lightest CP-odd and heavier CP-even has much larger singlet component. More difficult to detect.

Searches for Supersymmetric particles

Balazs, Carena, Freitas, C.W. ‘07

- Light chargino and neutralino spectrum dictated by condition of generation of baryon asymmetry and dark matter.
- We assume the presence of gluinos with masses dictated by gaugino mass unification, as well as not very heavy third generation squarks. We choose them to have masses of about 500 GeV.
- The LHC may be able to determine the chargino and second neutralino masses, as well as the lightest neturalino mass with some precision. The presence of one Higgs decaying invisibly provides further information.
- A 500 GeV ILC will allow to measure four of the five neutralino masses, as well as the chargino masses. It will also verify the existence of two light CP-even Higgses, which decay mainly invisibly.

Benchmark Scenario. Chargino and Neutralino Properties

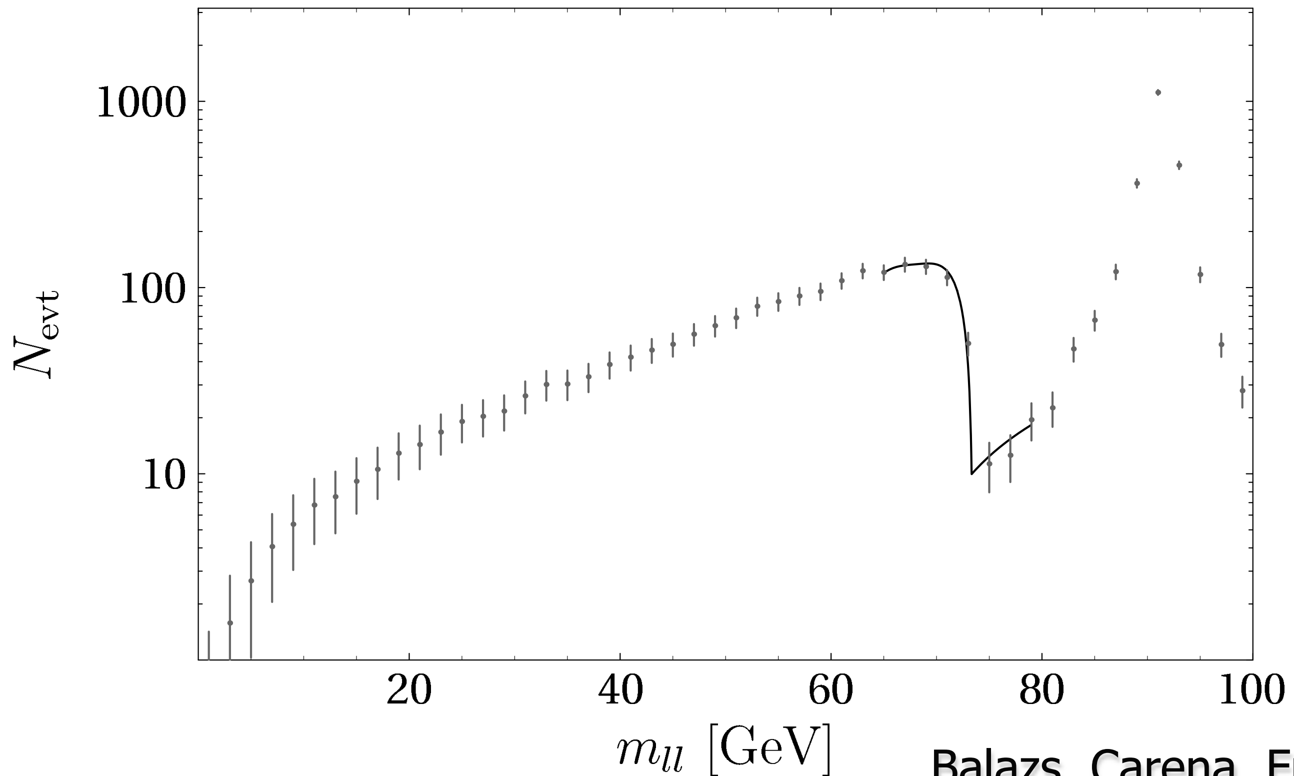
Sparticle	Mass m [GeV]	Width Γ [GeV]	Decay modes	
$\tilde{\chi}_1^0$	33.3	—	—	
$\tilde{\chi}_2^0$	106.6	0.00004	$\tilde{\chi}_2^0 \to Z^* \tilde{\chi}_1^0$	100%
$\tilde{\chi}_3^0$	181.5	0.09	$\tilde{\chi}_3^0 \to Z \tilde{\chi}_1^0$	74%
			$\to S_1 \tilde{\chi}_1^0$	26%
			$\to P_1 \tilde{\chi}_1^0$	0.4%
$\tilde{\chi}_4^0$	278.0	1.5	$\tilde{\chi}_4^0 \to Z \tilde{\chi}_1^0$	11%
			$\to Z \tilde{\chi}_2^0$	22%
			$\to Z \tilde{\chi}_3^0$	1%
			$\to W^\pm \tilde{\chi}_1^\mp$	43%
			$\to S_1 \tilde{\chi}_1^0$	7%
			$\to S_1 \tilde{\chi}_2^0$	0.2%
			$\to S_2 \tilde{\chi}_1^0$	8%
			$\to P_1 \tilde{\chi}_1^0$	7%
			$\to P_1 \tilde{\chi}_2^0$	0.7%
$\tilde{\chi}_1^\pm$	165.0	0.136	$\tilde{\chi}_1^+ \to W^+ \tilde{\chi}_1^0$	100%
$\tilde{\chi}_2^\pm$	319.5	2.0	$\tilde{\chi}_2^+ \to W^+ \tilde{\chi}_1^0$	32%
			$\to W^+ \tilde{\chi}_2^0$	1%
			$\to W^+ \tilde{\chi}_3^0$	34%
			$\to Z \tilde{\chi}_1^+$	29%
			$\to S_1 \tilde{\chi}_1^+$	5%
			$\to P_1 \tilde{\chi}_1^+$	0.3%

Sbottoms and Gluinos

$\tilde{b}_1$	498.8	6.6	$\tilde{b}_1 \to b\tilde{\chi}_1^0$	0.5%
			$\to b\tilde{\chi}_2^0$	12%
			$\to b\tilde{\chi}_3^0$	12%
			$\to b\tilde{\chi}_4^0$	0.1%
			$\to b\tilde{\chi}_5^0$	5%
			$\to t\tilde{\chi}_1^-$	57%
			$\to t\tilde{\chi}_2^-$	15%
$\tilde{b}_2$	503.3	12.5	$\tilde{b}_2 \to b\tilde{\chi}_1^0$	0.6%
			$\to b\tilde{\chi}_2^0$	4%
			$\to b\tilde{\chi}_3^0$	9%
			$\to b\tilde{\chi}_4^0$	0.2%
			$\to b\tilde{\chi}_5^0$	7%
			$\to t\tilde{\chi}_1^-$	56%
			$\to t\tilde{\chi}_2^-$	23%
$\tilde{g}$	730	6.6	$\tilde{g} \to b\tilde{b}_1$	35%
			$\to b\tilde{b}_2$	34%
			$\to t\tilde{t}_1$	18%
			$\to t\tilde{t}_2$	13%

$$pp \to \tilde{g}\tilde{g}, \qquad \tilde{g} \to b\tilde{b}^* \text{ or } \bar{b}\tilde{b} \to b\bar{b}\tilde{\chi}_2^0 \qquad \tilde{\chi}_2^0 \to Z^*\,\tilde{\chi}_1^0$$

$$m_{ll,\max,2} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \qquad m^2_{jll,\max,2} = \frac{1}{m^2_{\tilde{\chi}_2^0}}(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0})(m^2_{\tilde{b}} - m^2_{\tilde{\chi}_2^0})$$



Balazs, Carena, Freitas, C.W. '07

Using similar methods for $\tilde{\chi}_3^0$, one obtains $(\mathcal{L} = 300\ \mathrm{fb}^{-1})$

$$m_{\tilde{\chi}_1^0} = 33^{+32}_{-17.5}\ \mathrm{GeV}, \quad m_{\tilde{\chi}_2^0} = 106.5^{+32.5}_{-17.5}\ \mathrm{GeV}, \quad m_{\tilde{\chi}_3^0} = 181^{+20}_{-10}\ \mathrm{GeV}, \quad m_{\tilde{b}} = 499^{+30}_{-17}\ \mathrm{GeV}$$

Selection Cuts

- At least three jets with transverse momentum $p_t^{\text{jet}} > 150, 100, 50\,\text{GeV}$.
- Missing energy $\not{E} > \max(100\text{ GeV}, 0.2M_{\text{eff}})$ with $M_{\text{eff}} \equiv \not{E} + \sum_{i=1}^{3} p_{t,i}^{\text{jet}}$.
- Two isolated leptons with $p_t^{\text{lep}} > 20, 10\,\text{GeV}$.

- Top production background may be removed by substracting pair of leptons with the same flavor from the ones with different flavor

$$|m_{ll} - M_{\text{Z}}| < 10\,\text{GeV}$$

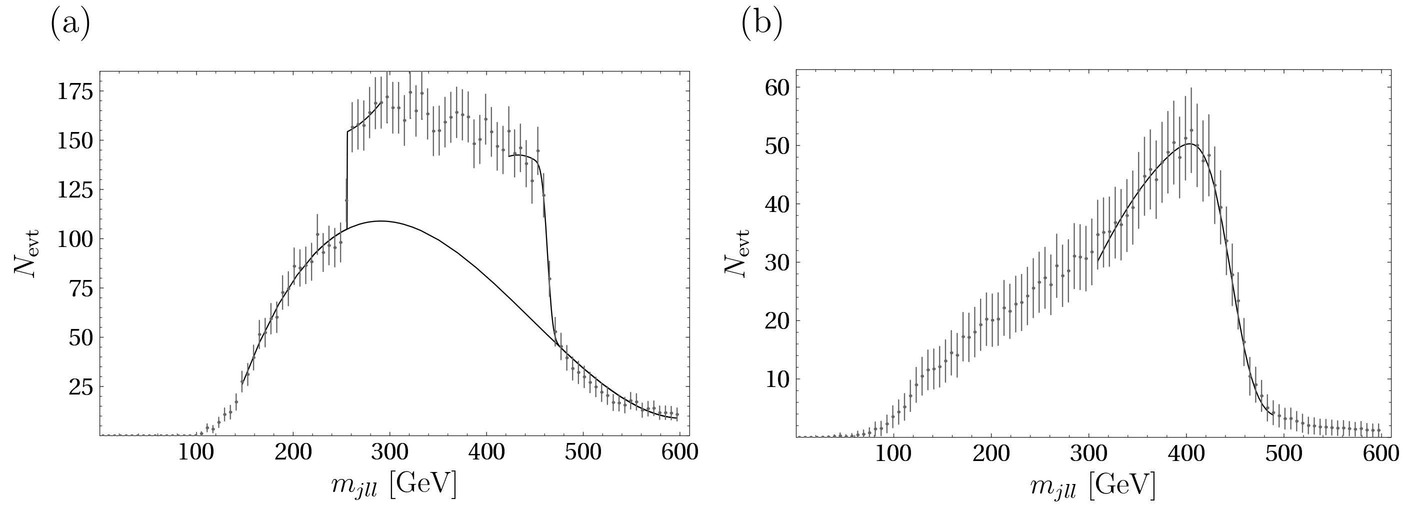


Figure 2: *Fits to the m_{jll} distribution for (a) $\tilde{\chi}_3^0$ and (b) $\tilde{\chi}_2^0$ production at the LHC.*

$$m^2_{jll,\max,3\,(\min)} = \frac{1}{2m^2_{\tilde{\chi}_3^0}}\Big[m^2_{\tilde{\chi}_1^0}m^2_{\tilde{\chi}_3^0} - m^4_{\tilde{\chi}_3^0} - m^2_{\tilde{\chi}_1^0}m^2_{\tilde{b}} + m^2_{\tilde{\chi}_3^0}m^2_{\tilde{b}} + m^2_{\tilde{\chi}_3^0}M_Z^2 + m^2_{\tilde{b}}M_Z^2$$
$$\underset{(+)}{-}(m^2_{\tilde{\chi}_3^0} - m^2_{\tilde{b}})\sqrt{\lambda(m^2_{\tilde{\chi}_1^0}, m^2_{\tilde{\chi}_3^0}, M_Z^2)}\Big].$$

$$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc.$$

The nMSSM at the ILC

At the ILC, one can use

- Chargino pair production
- Lightest chargino threshold scans
- Neutralino $(\tilde{\chi}_2^0\tilde{\chi}_4^0)$ $(\tilde{\chi}_3^0\tilde{\chi}_4^0)$ production
- Higgs production provides a good determination of CP-even Higgs masses
- Assume that 500 fb^{-1} are spent with (50% and 80% pol.) $P(e^+)/P(e^-) = \text{left/right and right/left each}$

Chargino and Neutralino Production Cross Section

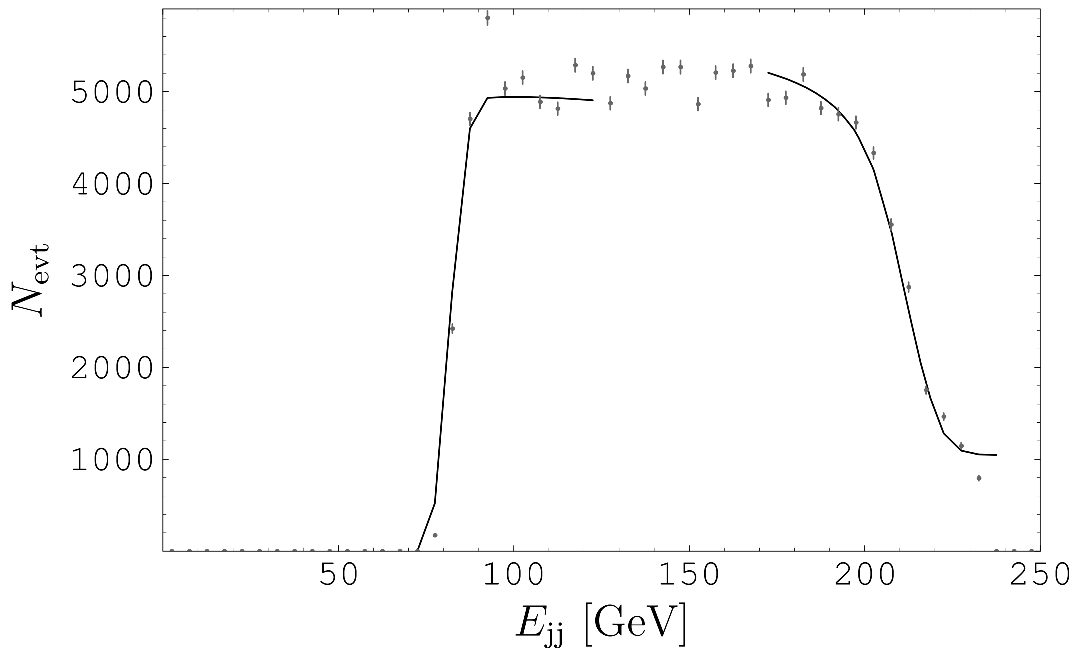
Due to the relatively light spectrum these chargino and neutralino cross sections at a 500 GeV ILC acquire sizable values

$e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$	$\tilde{\chi}_i^0 = \tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_5^0$
$\tilde{\chi}_j^0 = \tilde{\chi}_1^0$	2.0	5.4	3.7	3.9
$\tilde{\chi}_2^0$	0.4	0.6	16.2	0.1
$\tilde{\chi}_3^0$		0.1	32.8	—
$\tilde{\chi}_4^0$			—	—
$\tilde{\chi}_5^0$				—
$e^+e^- \to \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp$	$\tilde{\chi}_i^\pm = \tilde{\chi}_1^\pm$	$\tilde{\chi}_2^\pm$		
$\tilde{\chi}_j^\mp = \tilde{\chi}_1^\mp$	594	32.2		
$\tilde{\chi}_2^\mp$		—		

Jets from Chargino Production

Information on the mass difference of the lightest chargino and neutralino may be obtained form the energy distributin of the jets proceeding from chargino decay $\tilde{\chi}_1^{\pm} \to \chi_1^0 W^{\pm}$

$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to W^+ W^- \, \tilde{\chi}_1^0 \, \tilde{\chi}_1^0 \to jj \, l^{\pm} + \not{E}$$



$$\Delta R = \sqrt{(\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2} < 0.3$$

$$p_t \; > \; 12\,\mathrm{GeV}, \;\; \not{E} \; > \; 100\,\mathrm{GeV}$$

$$|m_{jj} - M_{\rm W}| < \; 10 \text{ GeV}$$

$$m_{l,\rm miss} > 150\,\mathrm{GeV}$$

$$P(e^+)/P(e^-) = \mathrm{right/left}.$$

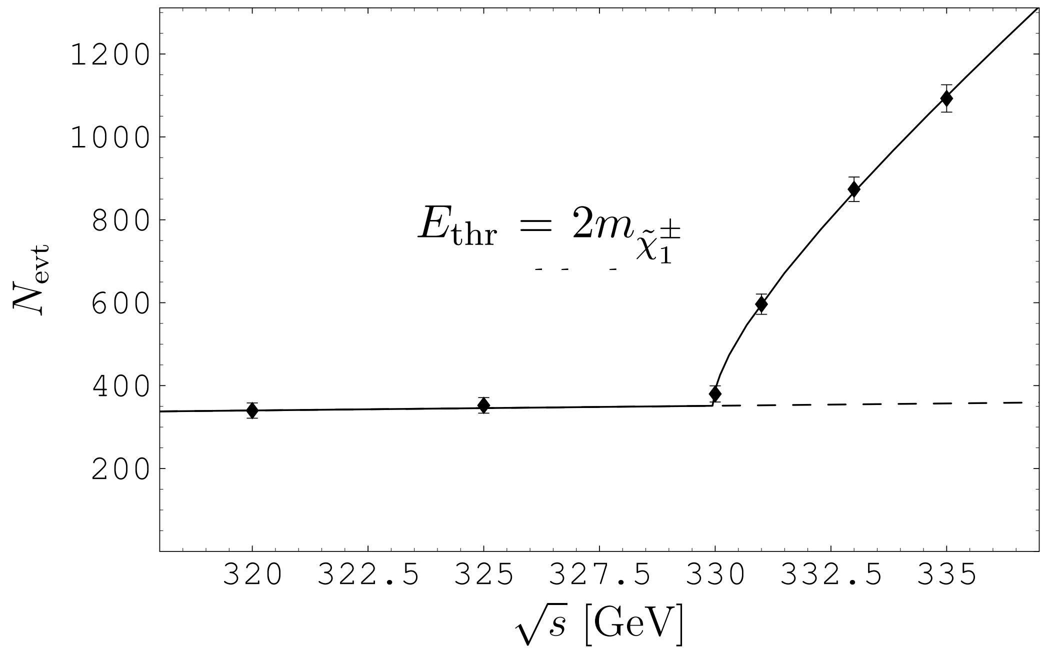
(increases both signal and bckgd.)

$$E_{\rm min,max} = \frac{1}{4m^2_{\tilde{\chi}_1^{\pm}}} \left[(m^2_{\tilde{\chi}_1^{\pm}} - m^2_{\tilde{\chi}_1^0} + M^2_{\rm W}) \sqrt{s} \mp \sqrt{\lambda(m^2_{\tilde{\chi}_1^{\pm}}, m^2_{\tilde{\chi}_1^0}, M^2_{\rm W}) (s - 4m^2_{\tilde{\chi}_1^{\pm}})} \right].$$

Threshold Scan for Chargino Pair Production

$$P(e^+)/P(e^-) = \text{right/left}.$$

$10\,\text{fb}^{-1}$ luminosity is spent per point, amounting to total of $60\,\text{fb}^{-1}$.



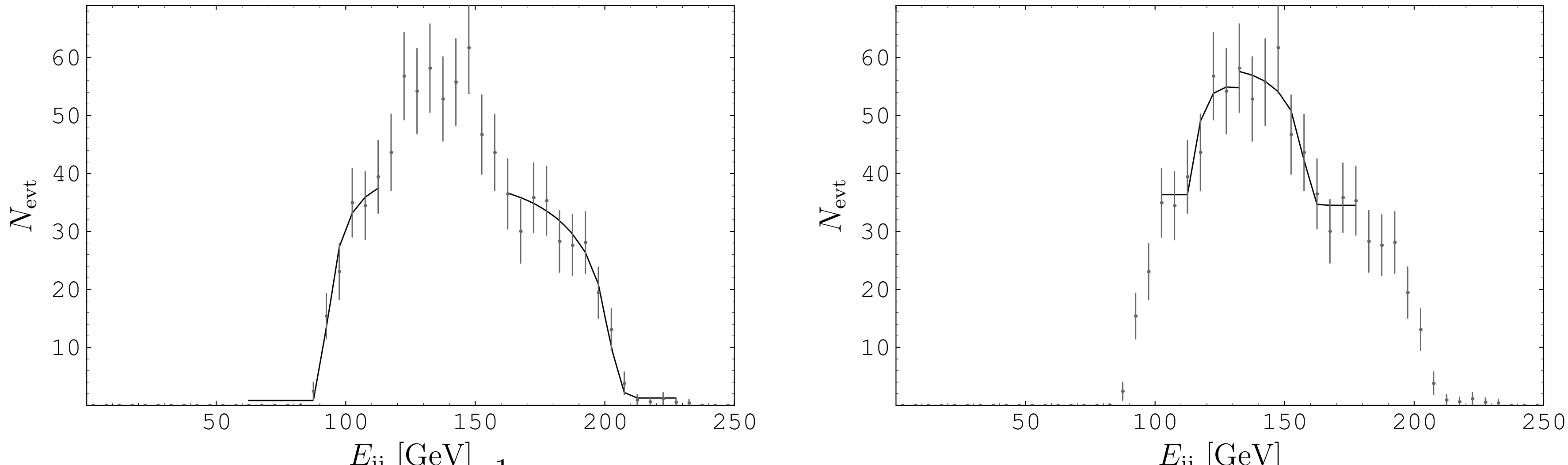
$m_{\tilde{\chi}_1^\pm} = 164.98 \pm 0.05$ GeV. $\quad m_{\tilde{\chi}_1^0} = 33.3^{+0.4}_{-0.3}$ GeV

Production of Neutralinos: $e^+e^- \to \tilde{\chi}^0_3\,\tilde{\chi}^0_4$

$$e^+e^- \to \tilde{\chi}^0_3\tilde{\chi}^0_4 \to ZZ\,\tilde{\chi}^0_1\,\tilde{\chi}^0_1 \to 4j + \not{E}.$$

$p_t > 12\,\mathrm{GeV},\ \not{E} > 100\,\mathrm{GeV}$ $\qquad P(e^+)/P(e^-) = \mathrm{left/right}$

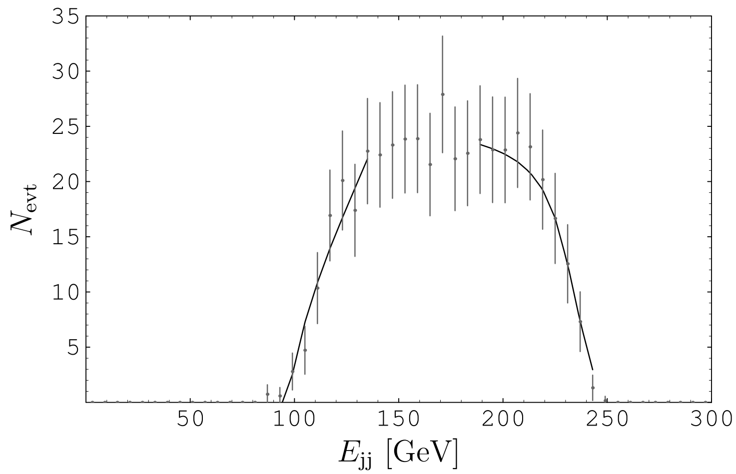
$|m_{j_1j_2} - M_Z| < 10\,\mathrm{GeV}$ and $|m_{j_3j_4} - M_Z| < 10\,\mathrm{GeV}$.

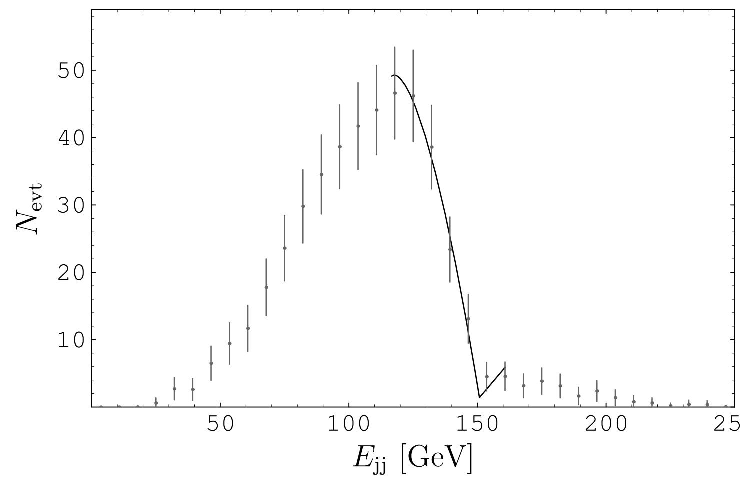


$$E_{\min,\max,3} = \frac{1}{4m^2_{\tilde{\chi}^0_3}\sqrt{s}}\Big(m^4_{\tilde{\chi}^0_3} - m^2_{\tilde{\chi}^0_3}m^2_{\tilde{\chi}^0_4} + m^2_{\tilde{\chi}^0_3}M_Z^2 - m^2_{\tilde{\chi}^0_4}M_Z^2 + m^2_{\tilde{\chi}^0_3}s + M_Z^2 s - m^2_{\tilde{\chi}^0_1}(m^2_{\tilde{\chi}^0_3} - m^2_{\tilde{\chi}^0_4} + s) \mp \sqrt{\lambda(m^2_{\tilde{\chi}^0_3}, m^2_{\tilde{\chi}^0_1}, M_Z^2)\,\lambda(m^2_{\tilde{\chi}^0_3}, m^2_{\tilde{\chi}^0_4}, s)}\Big)$$

$$E_{\min,\max,4} = \frac{1}{4m^2_{\tilde{\chi}^0_4}\sqrt{s}}\Big(m^4_{\tilde{\chi}^0_4} - m^2_{\tilde{\chi}^0_3}m^2_{\tilde{\chi}^0_4} + m^2_{\tilde{\chi}^0_4}M_Z^2 - m^2_{\tilde{\chi}^0_3}M_Z^2 + m^2_{\tilde{\chi}^0_4}s + M_Z^2 s - m^2_{\tilde{\chi}^0_1}(m^2_{\tilde{\chi}^0_4} - m^2_{\tilde{\chi}^0_3} + s) \mp \sqrt{\lambda(m^2_{\tilde{\chi}^0_4}, m^2_{\tilde{\chi}^0_1}, M_Z^2)\,\lambda(m^2_{\tilde{\chi}^0_3}, m^2_{\tilde{\chi}^0_4}, s)}\Big)$$

Production of Neutralinos: $e^+e^- \to \tilde{\chi}_2^0\, \tilde{\chi}_4^0$





$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_4^0 \to ZZ^*\, \tilde{\chi}_1^0\, \tilde{\chi}_1^0 \to 4j + \not{E}$$

$p_t > 50\,\text{GeV},\qquad P(e^+)/P(e^-) = \text{left/right},\qquad M_Z - m_{j_3j_4} > 10\,\text{GeV}$

$\not{E} > 100\,\text{GeV},\qquad |m_{j_1j_2} - M_Z| < 10\,\text{GeV}$

$$E_{\max,2} = \frac{m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_4^0} - 2m^2_{\tilde{\chi}_1^0}\sqrt{s} + s}{2\sqrt{s}},$$

$$E_{\min,\max,4} = \frac{1}{4m^2_{\tilde{\chi}_4^0}\sqrt{s}}\Big(m^4_{\tilde{\chi}_4^0} - m^2_{\tilde{\chi}_2^0}m^2_{\tilde{\chi}_4^0} + m^2_{\tilde{\chi}_4^0}M_Z^2 - m^2_{\tilde{\chi}_2^0}M_Z^2 + m^2_{\tilde{\chi}_4^0}s + M_Z^2 s$$
$$- m^2_{\tilde{\chi}_1^0}(m^2_{\tilde{\chi}_4^0} - m^2_{\tilde{\chi}_2^0} + s) \mp \sqrt{\lambda(m^2_{\tilde{\chi}_4^0}, m^2_{\tilde{\chi}_1^0}, M_Z^2)\,\lambda(m^2_{\tilde{\chi}_2^0}, m^2_{\tilde{\chi}_4^0}, s)}\Big).$$

Combination of Channels

- One can also use the heaviest chargino,

$$e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp \to Z\, W^+ W^-\, \tilde{\chi}_1^0\, \tilde{\chi}_1^0 \to 4j\, l^\pm + \not{E}\,.$$

- Combining all sparticle channels, one may determine the neutralino-chargino spectrum.

- The heaviest neutralino is out of reach

$$m_{\tilde{\chi}_2^0} = 106.6^{+1.1}_{-1.3}\ \text{GeV}, \qquad m_{\tilde{\chi}_3^0} = 181.5 \pm 4.9\ \text{GeV}, \qquad m_{\tilde{\chi}_4^0} = 278.0^{+2.5}_{-3.5}\ \text{GeV}.$$

$$m_{\tilde{\chi}_1^0} = 33.3^{+0.4}_{-0.3}\ \text{GeV}, \qquad m_{\tilde{\chi}_1^\pm} = 164.98 \pm 0.05\ \text{GeV}, \qquad m_{\tilde{\chi}_4^0} = 319.5^{+5.5}_{-4.3}\ \text{GeV}.$$

Higgs Mass Matrix

For large values of m_A

$$M^2_{\mathrm{S}_{1,2}} = \begin{pmatrix} M_{\mathrm{Z}}^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta & v(a_\lambda \sin 2\beta + 2\lambda^2 v_{\mathrm{s}}) \\ v(a_\lambda \sin 2\beta + 2\lambda^2 v_{\mathrm{s}}) & m_{\mathrm{s}}^2 + \lambda^2 v^2 \end{pmatrix} + \Delta M^2_{\mathrm{S}_{1,2}}$$

$$\Delta M^2_{\mathrm{S}_{1,2}} \equiv \begin{pmatrix} \Delta_{S11} & \Delta_{S12} \\ \Delta_{S21} & \Delta_{S22} \end{pmatrix} \approx \begin{pmatrix} \Delta_{S11} & 0 \\ 0 & 0 \end{pmatrix}, \qquad \text{with} \;\; \Delta_{S11} \approx \frac{3}{8\pi^2} \frac{m_{\mathrm{t}}^4}{v^2} \log \frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_{\mathrm{t}}^4}.$$

Hence, by measuring both Higgs bosons one can already determine

$$M_{S1}^2 < m_{\mathrm{s}}^2 + \lambda^2 v^2 < M_{S2}^2.$$

Knowledge of the stop masses provides additional information

Higgs Bosons Detection

- Two Higgs Bosons with relevant couplings to the Z, which can be reconstructed from its lepton decays
- Higgs bosons have large invisible width
- Kinematic mass peaks may be reconstructed from the recoil of the Z
- Based on previous studies, we can estimate the precision in the determination of Higgs properties

Garcia-Abia et al.'00, Battaglia, Desch '01, Schumacher'03

$$\delta M_{S1} \approx 130 \text{ MeV}, \qquad \delta M_{S2} \approx 185 \text{ MeV}.$$

$$BR[S_1 \to b\bar{b}] = (8 \pm 0.7)\%, \qquad BR[S_1 \to \text{inv.}] = (91 \pm 3)\%,$$
$$BR[S_2 \to b\bar{b}] = (2 \pm 0.3)\%, \qquad BR[S_2 \to \text{inv.}] = (79 \pm 5)\%,$$
$$BR[S_2 \to W^+W^-] = (17 \pm 1.5)\%.$$

Information after 500 GeV ILC run

Balazs, Carena, Freitas, C.W. '07

- From measurements in the neutralino and chargino sectors (masses and cross sections)

$$
\begin{aligned}
M_1 &= (122.5 \pm 1.3)\ \mathrm{GeV}, & |\kappa| &< 2.0\ \mathrm{GeV}, & m_{\tilde{\nu}_\mathrm{e}} &> 5\ \mathrm{TeV}, \\
M_2 &= (245.0 \pm 0.7)\ \mathrm{GeV}, & \tan\beta &= 1.7 \pm 0.09, & m_{\tilde{e}_\mathrm{R}} &> 1\ \mathrm{TeV}. \\
|\lambda| &= 0.619 \pm 0.007, & |\phi_\mathrm{M}| &< 0.32, & & \\
v_\mathrm{s} &= (-384 \pm 4.8)\ \mathrm{GeV}, & & & &
\end{aligned}
$$

- From measurements in the Higgs sector (two CP-even Higgs bosons) combined with the information above (assuming stop masses of order 500 GeV).

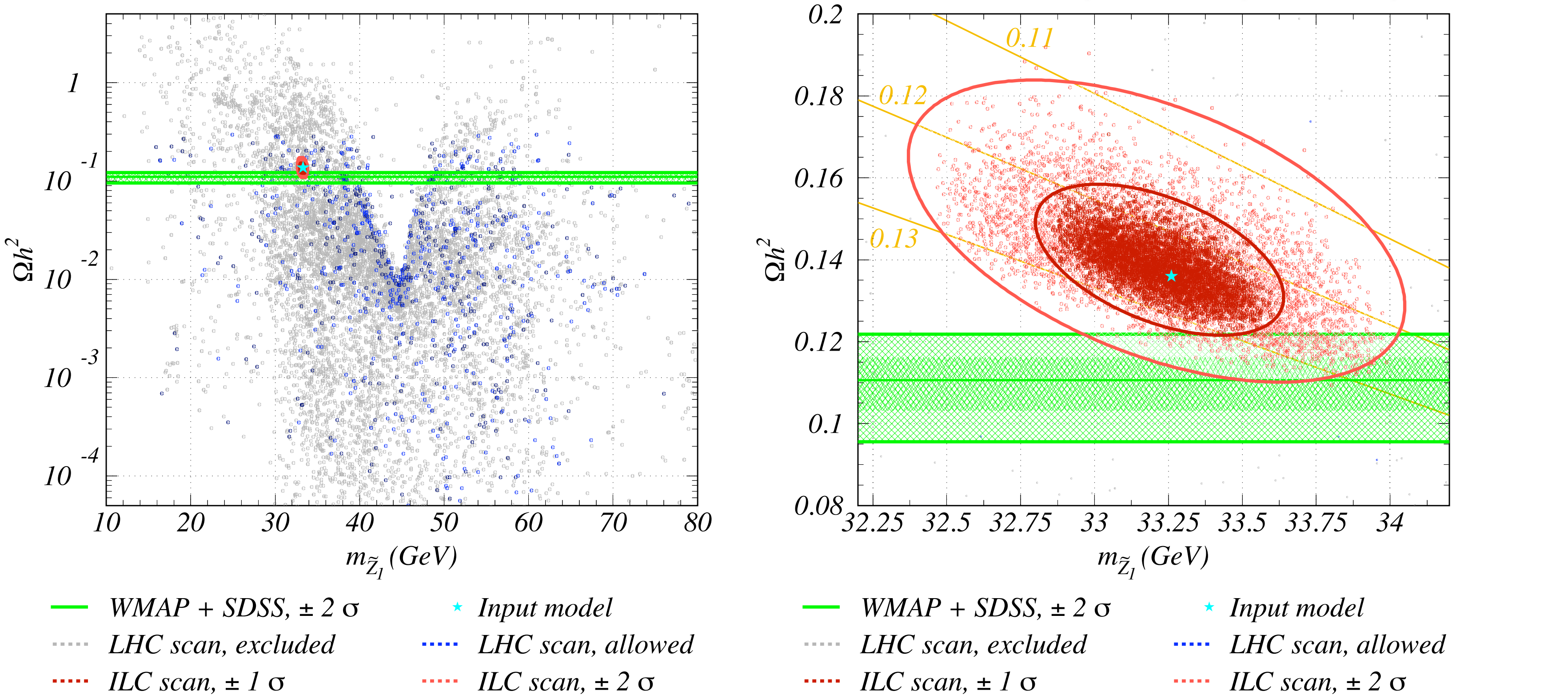
$$
\begin{aligned}
a_\lambda &= (373^{+17}_{-21})\ \mathrm{GeV}, & m_\mathrm{s} &= (106 \pm 18)\ \mathrm{GeV}, \\
t_\mathrm{s}^{1/3} &= (156^{+25}_{-39})\ \mathrm{GeV}, & |D| &\sim 1.0 \pm 0.65.
\end{aligned}
$$

$$
m_\mathrm{s}^2 = -a_\lambda v_1 v_2 / v_\mathrm{s} - t_\mathrm{s}/v_\mathrm{s} - \lambda^2 v^2
$$

Dark Matter Density Determination

From the information obtainable at the ILC/LHC, one can determine the dark matter density

Balazs, Carena, Freitas, C.W. '07



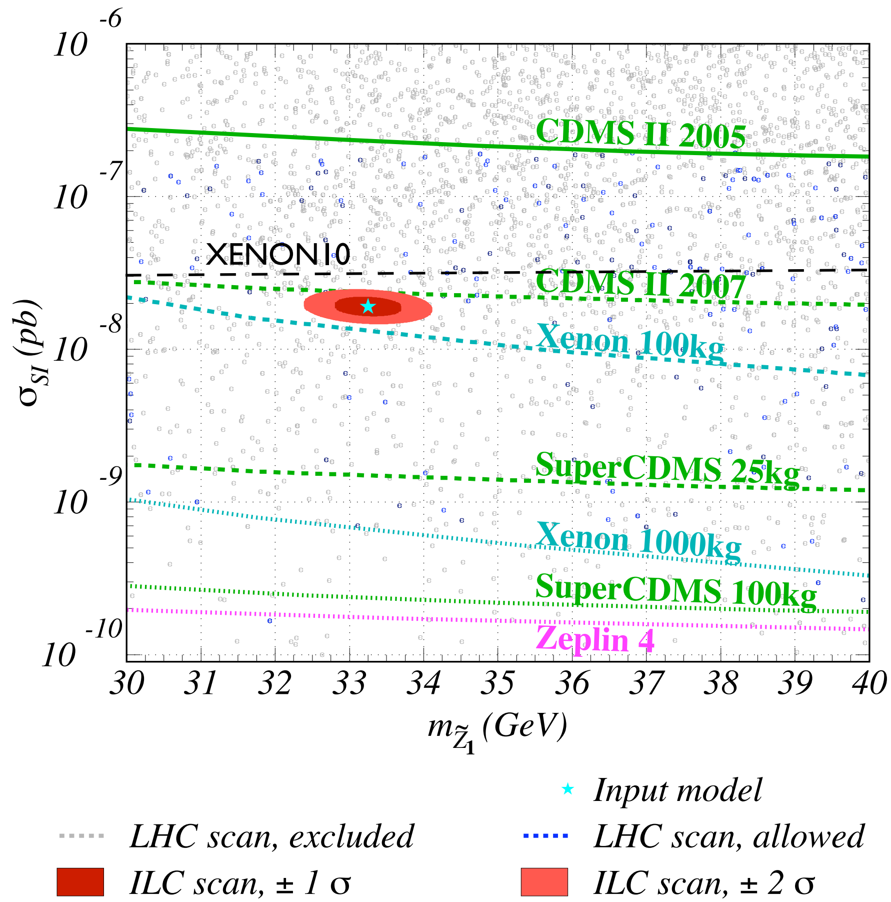
Conclusions

- Electroweak Baryogenesis provides an attractive and testable dynamical framework for the generation of the matter-antimatter asymmetry.
- nMSSM provides a natural scenario for the generation of electroweak symmetry breaking, without domain wall problems.
- Origin of Dark Matter and Baryogenesis may explained in a natural way in this model, provided singlet mass is small.
- Invisible decaying Higgs signature of this model, as well as an extended and light neutralino sector.
- ILC will provide the necessary measurements to test this scenario.
- Direct dark matter detection rate well predicted, and about to be tested in the near future.

[4]Note that the rejection of the two-photon and $e^{\pm}$-γ background depends crucially on an excellent coverage of the detector at low polar angles, so that energetic fermions with low transverse momentum can be vetoed. The results of ref. [7] are based on the detector design of the TESLA study [57], with low beam crossing angle, muon detectors extending to 65 mrad, and endcap calorimeters extending to 27.5 mrad. Although for the current ILC detector R & D several changes in the details of this setup are discussed, the planned ILC detector designs are expected to reach a similar photon-induced background rejection [58]. However, we also want to point out that the simulation of the photon-induced background in ref. [7] with PYTHIA [59] has unquantified and possibly large theoretical uncertainties.

Direct Dark Matter Detection

- Since dark matter is mainly a mixing betwen singlinos (dominant) and Higgsinos, neutralino nucleon cross section is governed by the new, λ -induced interactions, which are well defined in the relevant regime of parameters



- Next generation of direct dark matter detection will probe this model

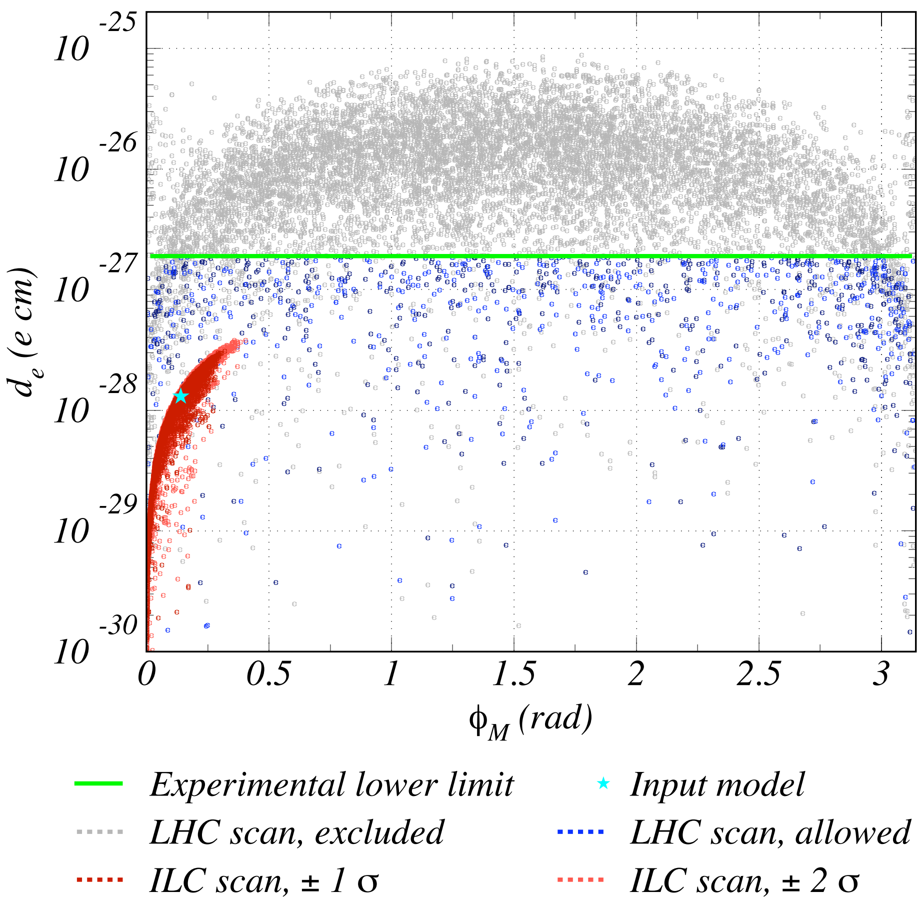
Barger,Langacker,Lewis,McCaskey, Shaughnessy,Yencho'07

Balazs,Carena, Freitas, C.W.'07

Electric Dipole Moments. Heavy Sleptons

Low values of $\tan\beta$ and heavy CP-odd scalars suppress the electric dipole moments

Balazs, Carena, Freitas, C.W. '07



Generation of μ :Giudice-Masiero mechanism

- Assume exact Peccei-Quinn symmetry forbidding μ
- Then, introduce higher dimensional operators in Kahler function

$$\Delta\mathcal{L} = \int d^4\theta \; H_u H_d \left(c_1 \frac{X}{M} + c_2 \frac{X^\dagger X}{M^2} \right) + h.c.$$

- where $X = X + F_X \theta^2$ is the SUSY breaking chiral superfield. Then,

$$\mu = \frac{c_1 F_X}{M}, \qquad B_\mu = \frac{c_2 F_X^2}{M^2}$$

- But in theories of gauge mediation, as we have seen

$$\frac{B_\mu}{\mu} \simeq \frac{F_X}{M} \simeq 100 \text{ TeV}$$

- It is therefore required that c_2 is suppressed. Different alternatives have been proposed to make it work. I will concentrate on a slightly different strategy.

CP-Violation sources

- Another problem for the realization of the SM electroweak baryogenesis scenario:

- Absence of sufficiently strong CP-violating sources

- Even assuming preservation of baryon asymmetry, baryon number generation several order of magnitues lower than required

$$\Delta_{CP}^{max} = \left[\sqrt{\frac{3\pi}{2}}\frac{\alpha_W T}{32\sqrt{\alpha_s}}\right]^3 J \frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)}{M_W^6}\frac{(m_b^2-m_s^2)(m_s^2-m_d^2)(m_b^2-m_d^2)}{(2\gamma)^9}$$

$$J \equiv \pm Im[K_{li}K_{lj}^* K_{l'j}K_{l'i}^*] = c_1 c_2 c_3 s_1^2 s_2 s_3 s_\delta$$

γ : Quark Damping rate

Gavela, Hernandez, Orloff, Pene and Quimbay'94

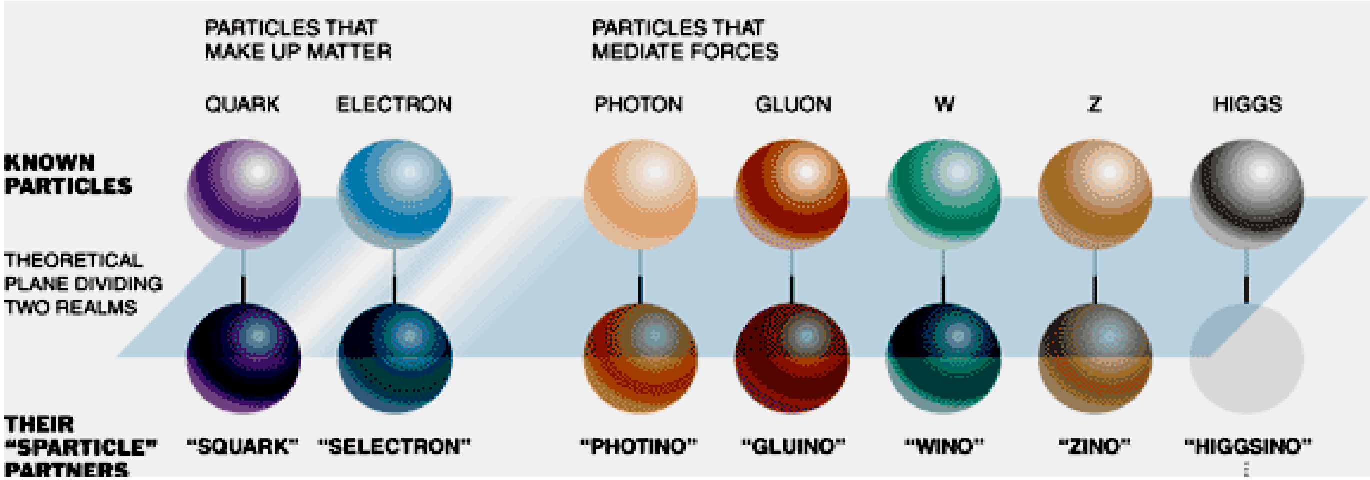
Electroweak Baryogenesis

and

New Physics at the Weak Scale

Supersymmetry

fermions bosons



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

Two Higgs Doublets necessary: $\tan\beta = \frac{v_2}{v_1}$

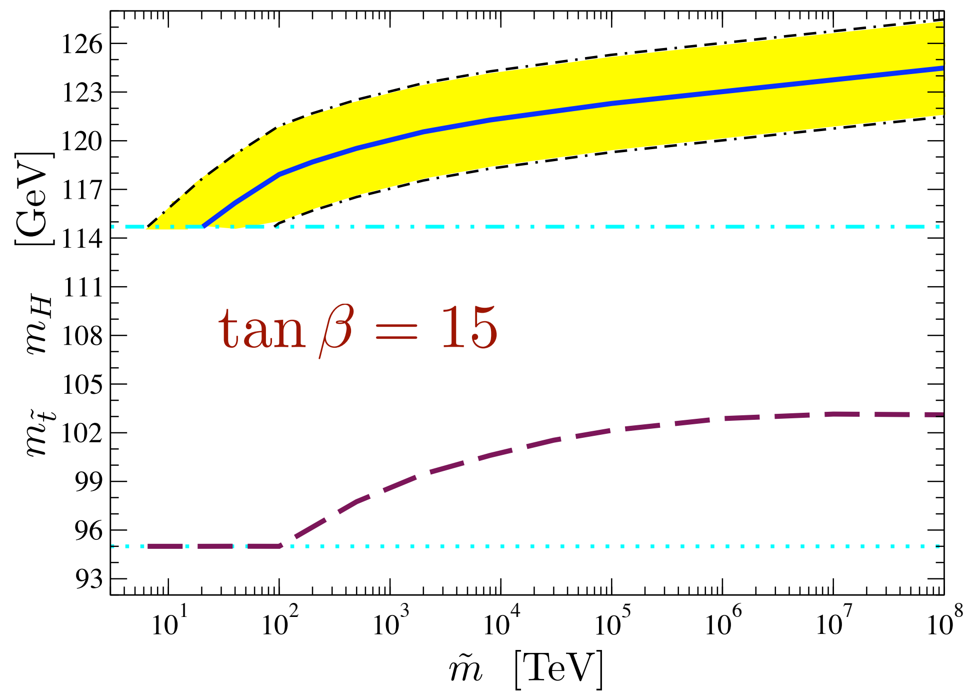
MSSM: Limits on the Stop and Higgs Masses to preserve the baryon asymmetry

Suficciently strong first order phase transition to preserve generated baryon asymmetry:

• Higgs masses up to 125 GeV

• The lightest stop must have a mass below the top quark mass.

See M. Carena's talk



- Moderate values of $\tan\beta$, $\tan\beta \geq 5$ preferred in order to raise the Higgs boson mass.

  Heavier stop must be very massive

M. Carena, M. Quiros, C.W. '98

M.Carena, G. Nardini, M.Quiros, C.W.'08

Baryon Number Violation at finite T

- Anomalous processes violate both baryon and lepton number, but preserve B – L. Relevant for the explanation of the Universe baryon asymmetry.

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

$$\Gamma(\Delta B \neq 0) \propto A\,T \exp\left(-\frac{E_{sph}}{T}\right) \qquad \mathbf{E_{sph}} \propto \frac{8\pi\,\mathbf{v}}{\mathbf{g}}$$

Klinkhamer and Manton ’85, Arnold and Mc Lerran ’88