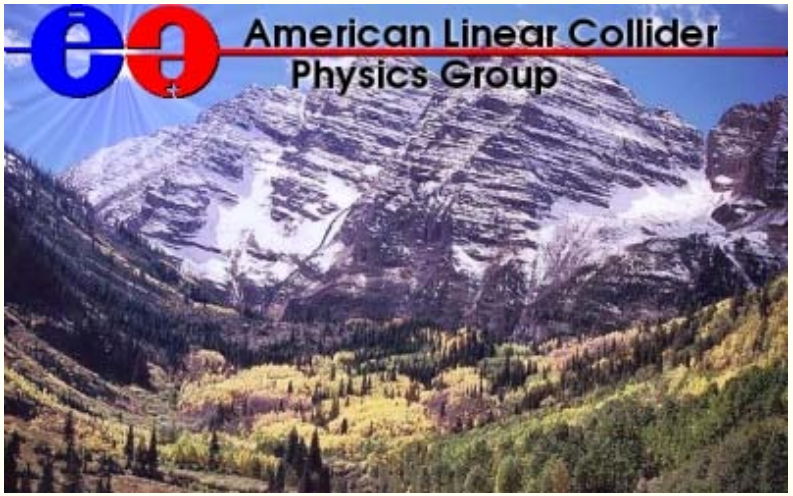
SUSY WG summary: ILC-LHC-Cosmology

Alexander Belyaev

Michigan State University



2005 International Linear Collider Physics and Detector Workshop
and Second ILC Accelerator Workshop
Snowmass, Colorado, August 14-27, 2005

Thank you all, who has contributed to SUSY WG!

Mond, Aug 15

Joe Lykken	"HEPAP LHC/ILC report"
Peter Zerwas	"ILC: Physics Scenarios"

Tue, Aug16

Alexander Belyaev	"SUSY at ILC"
David Rainwater	"ILC/LHC Introduction"
Genevieve Belanger	"ILC/Cosmology"

Wed, Aug17

Georg Weiglein	"Indirect Sensitivities on the scale of SUSY"
Jan Kalinowski	"SPA studies"
Caroline Milstene	"Analysis of Stop Quark with Small Stop-Neutralino Mass Difference at a Linear Collid
Ayres Freitas	"Studying light sneutrinos at the ILC and physical implications"
Joseph Proulx	"Update on Slepton and Gaugino Mass Resolution Studies"
W. Smith	"Physics capabilities of LHC and SLHC"
Shrihari Gopalakrishna	"B-physics and Linear Collider signatures of light Stop and Sbottom"
Yeong Gyun Kim	"Probing the Majorana Nature and CP Properties of Neutralinos"
Werner Porod	"Correlations between neutrino physics and collider physis in the bilinear model"

Fri, Aug 19

Marco Battaglia	"Detector and simulation issues of SUSY searches at ILC"
Sonja Hillert	"Physics potential of vertex detector as function of beam pipe radius"
Sven Heinemeyer	"FeynHiggs"
Csaba Balazs	"Electroweak baryogenesis in the MSSM"
Jose A.R. Cembranos	"Collider signatures of SuperWIMP warm dark matter"

Mon, Aug 22

Tadas Krupovnickas	"The Challenges of Focus Point at the LHC and LC"
Alexander Belyaev	"Implications of non-universal SUGRA models at ILC"
Howard Baer	"Scenarios for SUSY CDM and the ILC"
Wim de Boer	"Why the EGRET excess of diffuse galactic gamma rays points towards heavy scalar
Stefan Hesselbach	"CP-odd and T-odd Asymmetries in Chargino and Neutralino Production and Decay
Gudrid Moortgat-Pick	"The physics case for the polarization of both beams at the ILC"
Gudrid Moortgat-Pick	"Impact of forward-backward asymmetries for constraining heavy virtual particles"
Zhiqing Zhang	"Analysis of two challenging SUSY DM scenarios at ILC"
Albert de Roeck	"Non-universal scalar Masses/Gravitino DM benchmarks"

Thank you all, who has contributed to SUSY WG!

Mon, Aug 23

Kyle Cranmer	"Higgs at the (S)LHC"
Scott Snyder	"Performance of (S)LHC of e/gamma/mu/tau"
Peter Loch	"Performance of (S)LHC of Jets and ETmiss"
Albert de Roeck	"SUSY and BSM"
Georg Weiglein	"LHC-ILC interplay"
Stefan Hesselbach	"Identifying the NMSSM by combined LHC-ILC analyses"
Dirk Zerwas	"SUSY parameter determination"
Jose A.R. Cembranos	"Branon phenomenology: Search for Extra Dimensions Dark Matter"
Wim de Boer	"Dark Matter not so dark anymore?"
Csaba Balazs	"Supersymmetric origin of matter"
Ayres Freitas	"Analyzing the stop co-annihilation region"
Shinya Kanemura	"Electroweak baryogenesis and quantum corrections to the triple Higgs boson coupli
Michael Peskin	"LHC and ILC Cosmology predictions from Scans of the MSSM Parameters"
Francois Richard	"Dark Matter with heavy scalars at the ILC"
Maxim Perelstein	"Dark Matter at Colliders: a Model-Independent Approach?"
Jim Alexander	"Dark matter and precision measurements in the focus point region"
Jack Gunion	"Dark Matter from Light Neutralinos and CP-odd Higgs Bosons in the NMSSM and the I

Wed, Aug 24

Juergen Reuter	"Multi-particle event generators for the MSSM"
Philip Bechtle	"SUSY Parameter Measurements with Fittino"
Werner Porod	"Progress Report on SPheno"
Howard Baer	"Progress Report on ISAJET"
Alexander Belyaev	"Progress Report on IsaTools"
Genevieve Belanger	"Progress Report on MicrOmegas"
Howie Baer	"Constraints on SUSY parameters from present data"
Dave Cline	"Direct Dark Matter Detection"
Marco Battaglia	"Can the Relic Density be determined at colliders?"
Kaustubh Agashe	"Xtra Dimensional models and cosmology"

SUSY WG:

Jan Kalinowski, Kiyotomo Kawagoe , Alexei Safonov, Seong Youl Choi, Alexander Belyaev

Exciting topics has been defined/studied, some are in progress

- *Physics goals: to understand the best ILC potential(s) for SUSY physics*
  - *ILC discovery potential in LHC and beyond regions*
  - *SUSY precision measurements within mSUGRA and beyond, including non-universal scalar, higgs and gaugino SUGRA models*
  - *link to cosmology, DM search, LHC-ILC connections*
  - *SUSY benchmarks* **(Jan Kalinowski)**
  - *flavor, CPV, RPV SUSY physics* **(Werner Porod)**
- *SUSY tools* **(Alexei Safonov)**
  - *develop and compare*
  - *what we have and what we need?*
  - *importance of coherent efforts*
- *Detector capabilities simulation issues* **(Kiyotomo Kawagoe)**
  - *agree on LCC + new benchmark points, need people for simulations!*
  - *requirements from physics and feedback from detector studies*

ILC discovery potential in LHC and beyond regions

- *Focus Point(Hyperbolic Branch region)*

ILC discovery potential in LHC and beyond regions

Focus Point(Hyperbolic Branch region)

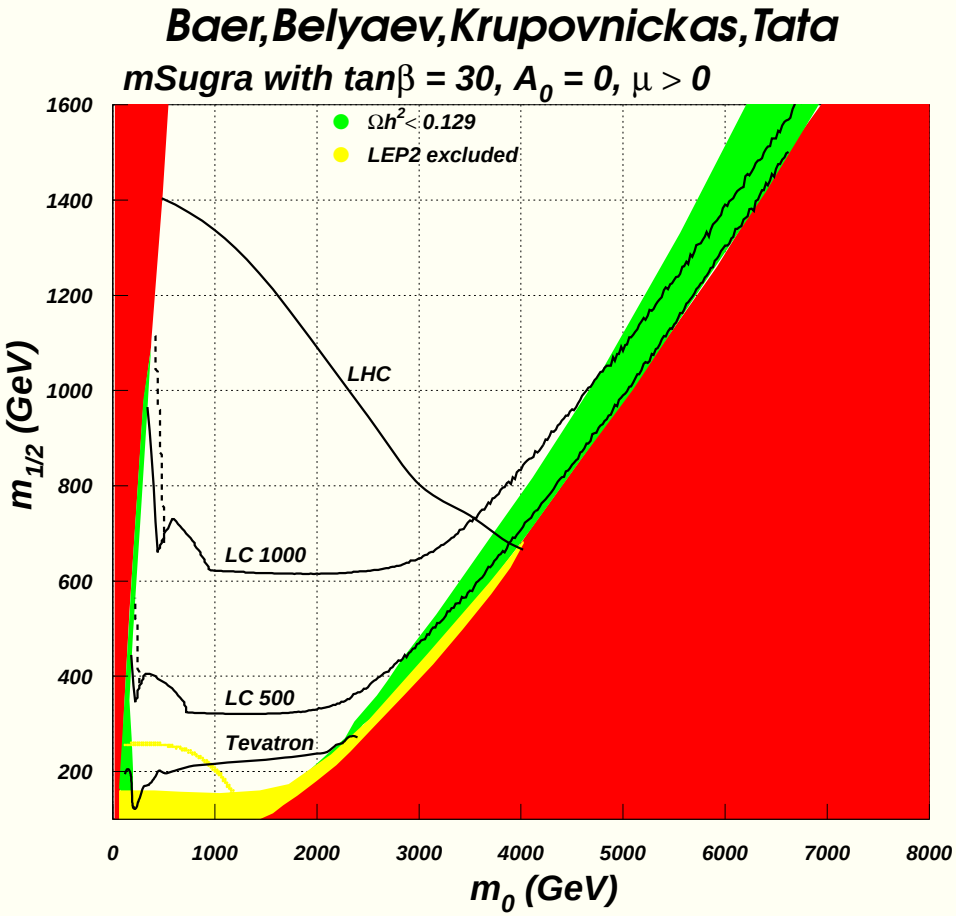
Chargino pair production in the far HB/FP region

Cuts:

- 1 lepton + 2 jets
- 20 GeV $< E_{visible} <$ 100 GeV
- $\cos(\phi_T(j,j)) > -0.6$
- $m(l j_{near}) > 5$ GeV
- $|\cos(\theta(j))| < 0.8$ (both jets)

The background was generated with the modified ISAJET 7.69, including all $2 \to 2$ SM processes and $\gamma\gamma \to c\bar{c}, b\bar{b}$ with bremsstrahlung and beamstrahlung.

H. Baer, A. Belyaev, T. K. and X. Tata, JHEP 0402:007,2004.



ILC discovery potential in LHC and beyond regions

Focus Point(Hyperbolic Branch region)

Baer,Belyaev,Krupovnickas,Tata

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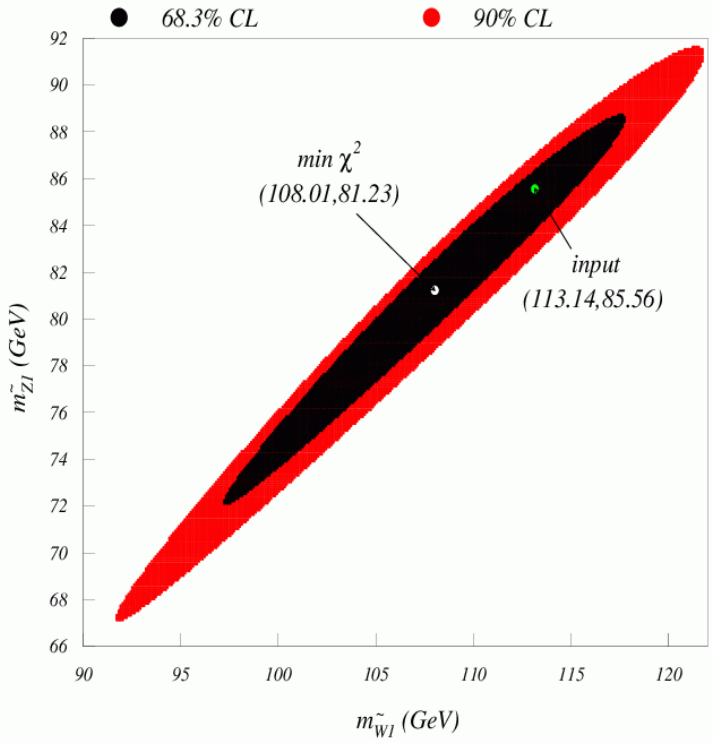


Fits to $m_{\tilde{Z}_1^0}$ and $m_{\tilde{W}_1^\pm}$ for a FP case study $m_0 = 2500$ GeV, $m_{1/2} = 300$ GeV, $\mu > 0$ and $m_t = 175$ GeV.

H. Baer, A. Belyaev, T. K. and X. Tata, JHEP 0402:007,2004.

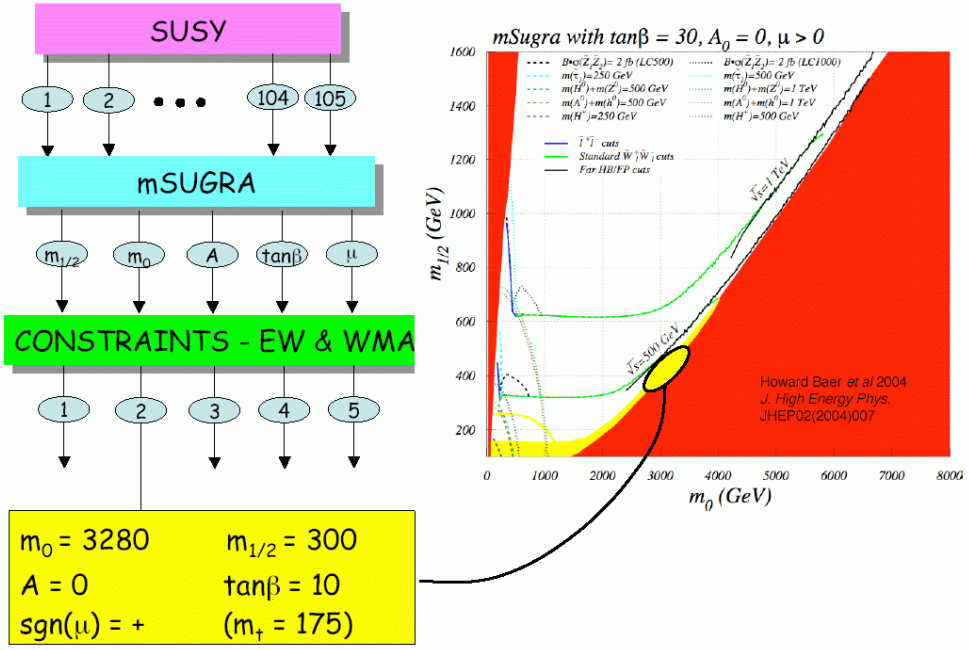
ILC discovery potential in LHC and beyond regions

ILC discovery potential in LHC and beyond regions

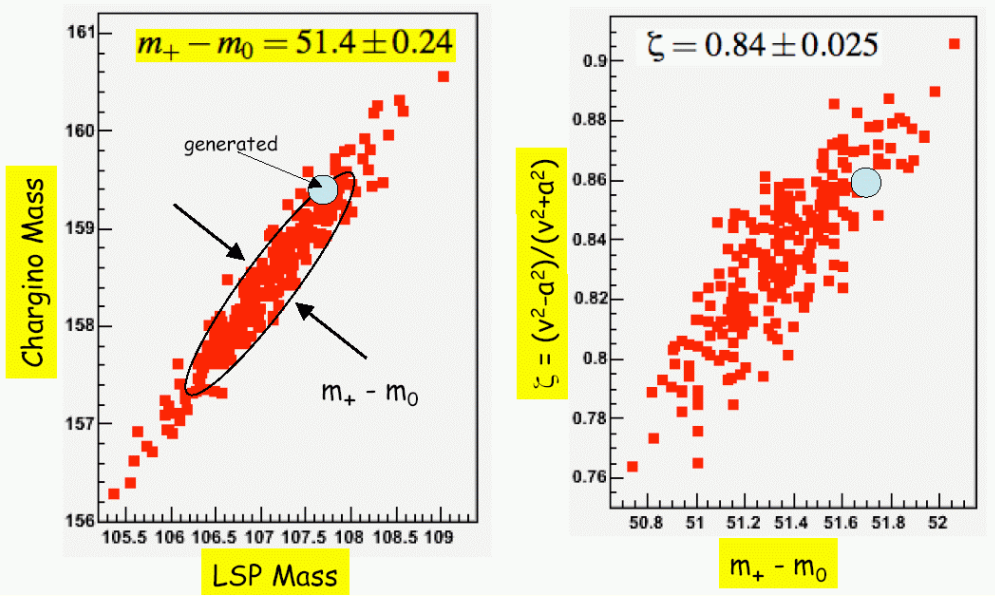
Focus Point(Hyperbolic Branch region) studies

Jim Alexander's and Marco Battaglia's talks

Focus Point Benchmark LCC-2



Simultaneous fit for dΓ/dM & dΓ/dE

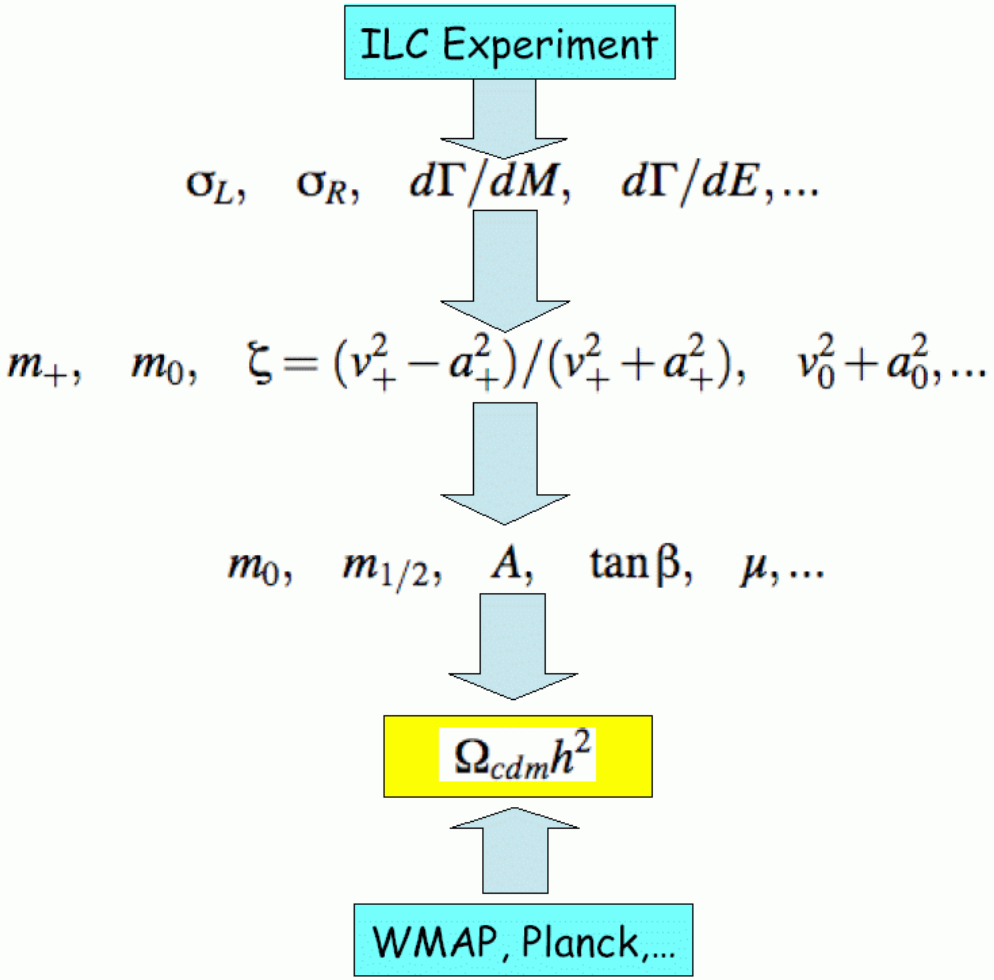


ILC discovery potential in LHC and beyond regions

- **Determination of Dark Matter density from the collider studies**

Jim Alexander's and Marco Battaglia's talks

Cosmological Connections



ILC discovery potential in LHC and beyond regions

- **Challenging DM scenarios at ILC: $\tilde{\tau}$-$\widetilde{Z}_1$ and $\widetilde{W}_1$-$\widetilde{Z}_1$ degeneracy**

Zhiqing Zhang

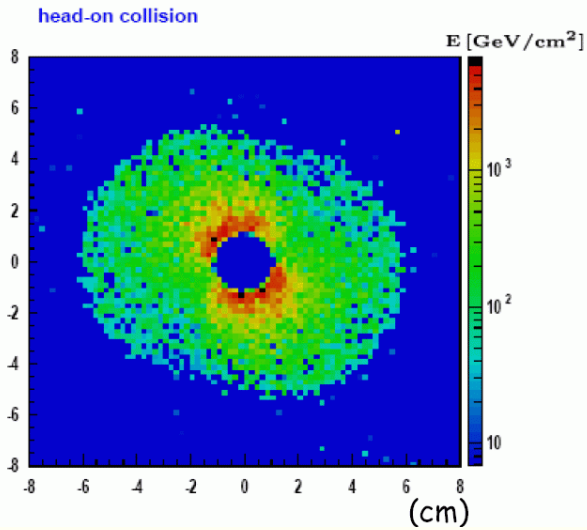
ILC discovery potential in LHC and beyond regions

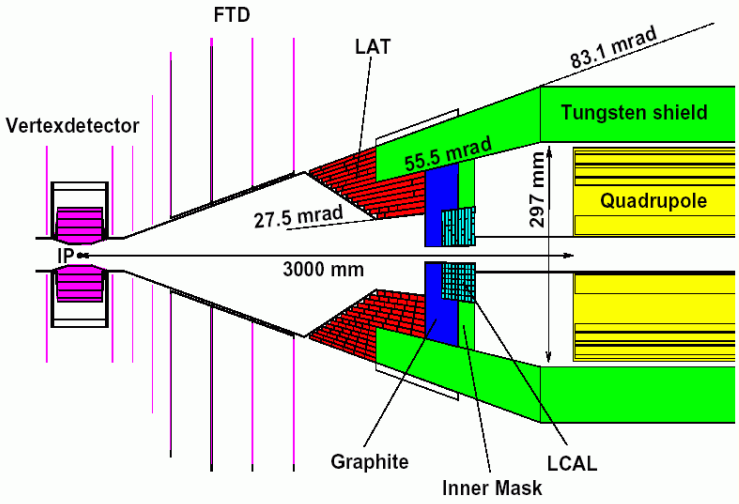
- *Challenging DM scenarios at ILC: $\tilde{\tau}$-$\tilde{Z}_1$ and $\widetilde{W}_1$-$\tilde{Z}_1$ degeneracy*

Zhiqing Zhang

Vetoing Against Energetic e^+/e^- from $\gamma\gamma$ out of Huge Number Soft Beamstrahlung Background

- e^+/e^- from ee→eeff: Few e's per event but energetic
- **Beamstrahlung background:** Huge number e,γ/event but soft
  e.g. the energy density/event in LCAL @ z=3.7m simulated by K. Buesser





real challenge: missing energy and very soft final state, big SM backgrounds; tag of low angle electrons - ***also in Marco Battaglia's talk***

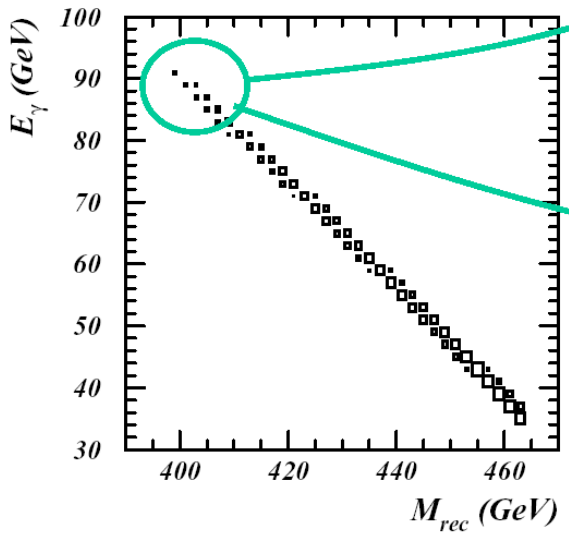
ILC discovery potential in LHC and beyond regions

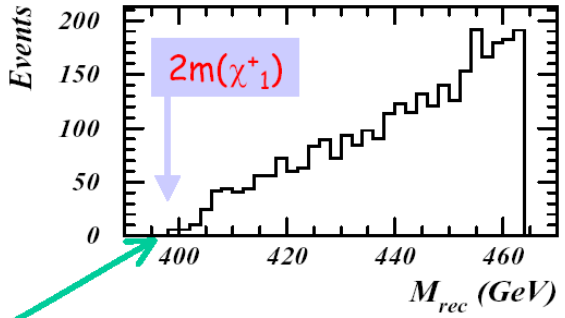
- **Challenging DM scenarios at ILC: $\tilde{\tau}$-$\tilde{Z}_1$ and $\widetilde{W}_1$-$\tilde{Z}_1$ degeneracy**

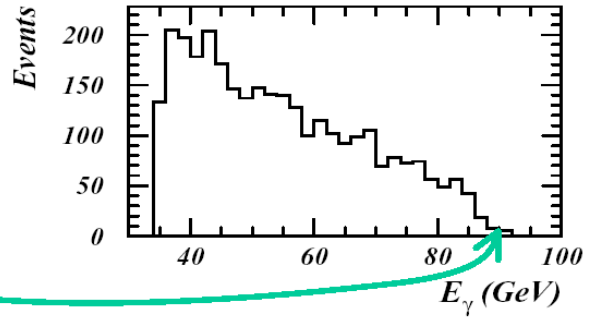
Zhiqing Zhang

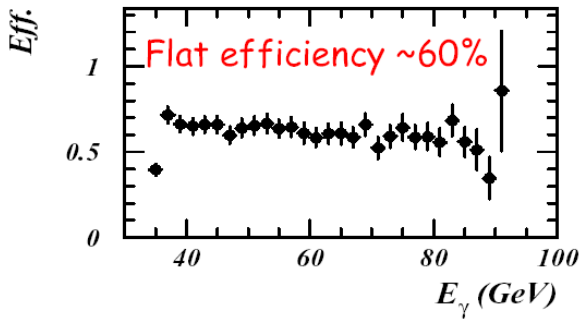
Towards Mass Determination

ISR γ energy versus recoil mass:
$M^2_{rec}=s-2s^{1/2}E_\gamma$







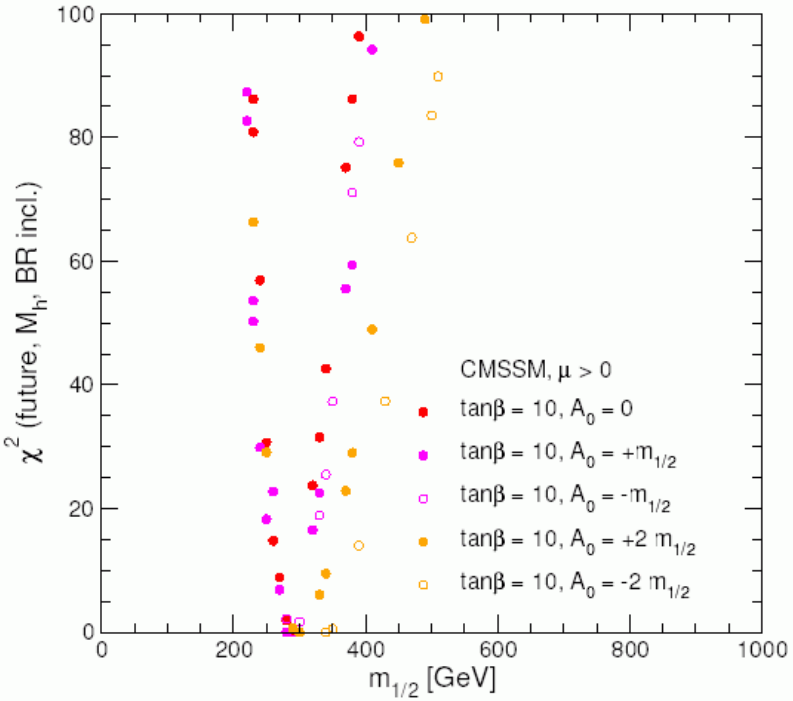


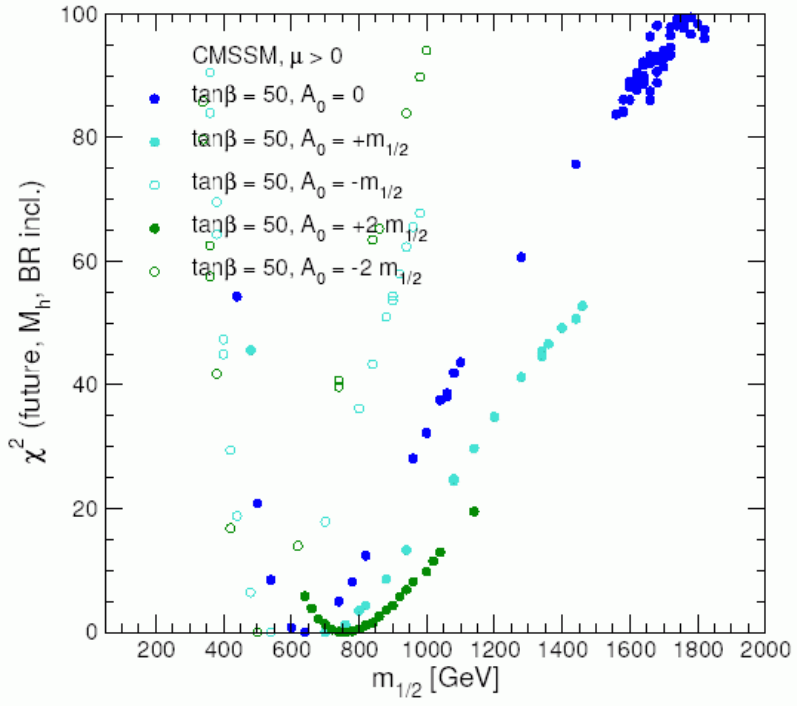
χ^2 analysis of mSUGRA parameter space

χ^2 analysis of mSUGRA parameter space

Georg Weiglein

χ^2 fit in CMSSM with CDM constraints: M_W, $\sin^2\theta_{\rm eff}$, $(g-2)_\mu$, $\mathrm{BR}(b\to s\gamma)$, M_h, $\mathrm{BR}(h\to b\bar{b})/\mathrm{BR}(h\to WW^*)$, ILC precison





⇒ Great increase in sensitivity

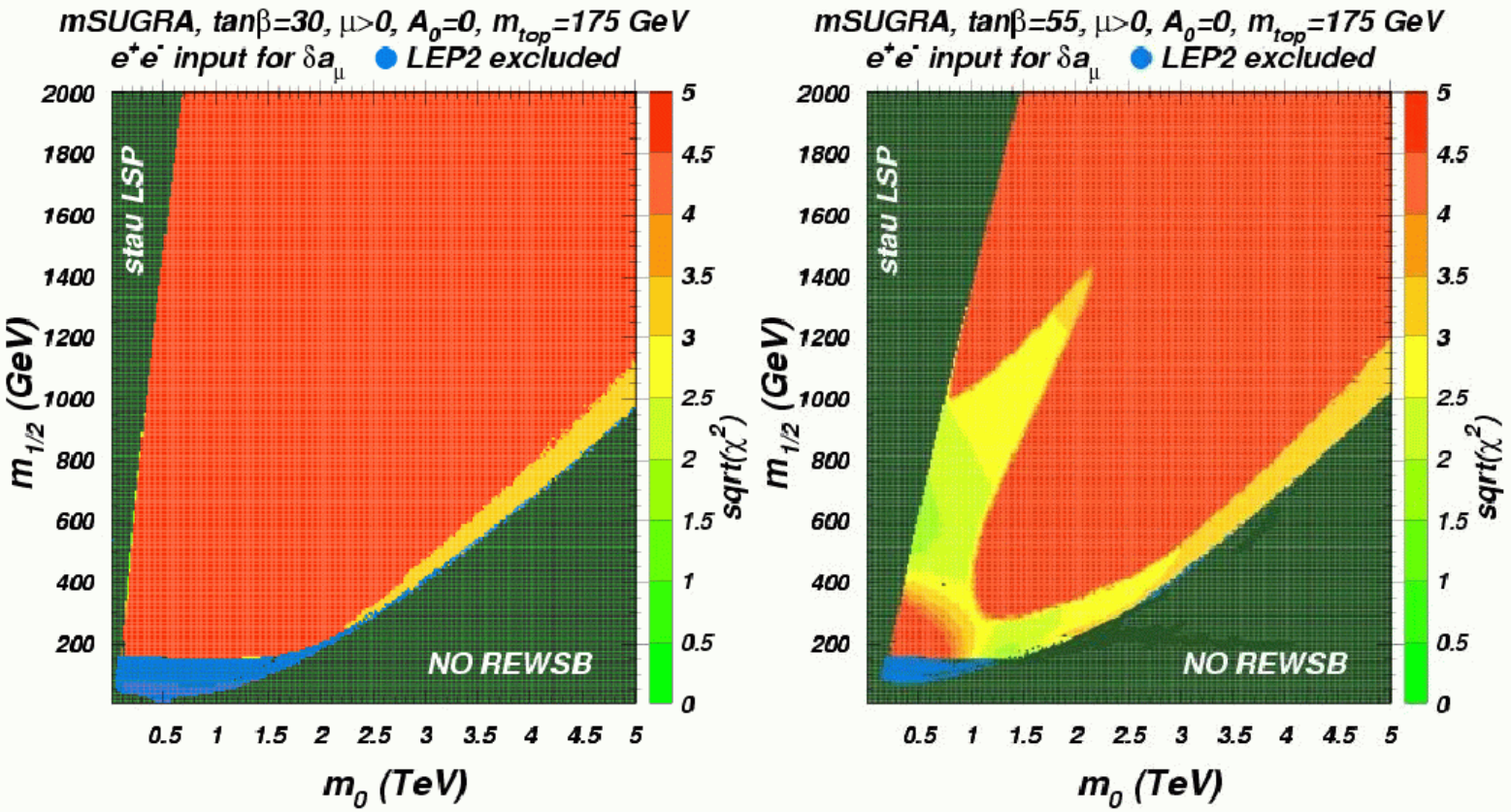
⇒ tight constraints on particle masses

χ^2 analysis of mSUGRA parameter space

Baer,Belyaev talks

mSUGRA: $\chi^2 = \chi^2_{\delta a_\mu} + \chi^2_{\Omega h^2} + \chi^2_{b\to s\gamma}$

Baer,Belyaev,Krupovnickas,Mustafayev, hep-ph/0403214



Δa_μ favors light second generation sleptons, while $BF(b \to s\gamma)$ prefers heavy third generation: **hard to realize in mSUGRA model.**

also in hep-ph/0508169 by Ellis,Heinemeyer,Olive,Weiglein; see Georg's talk

Non-universal SUGRA scenarios

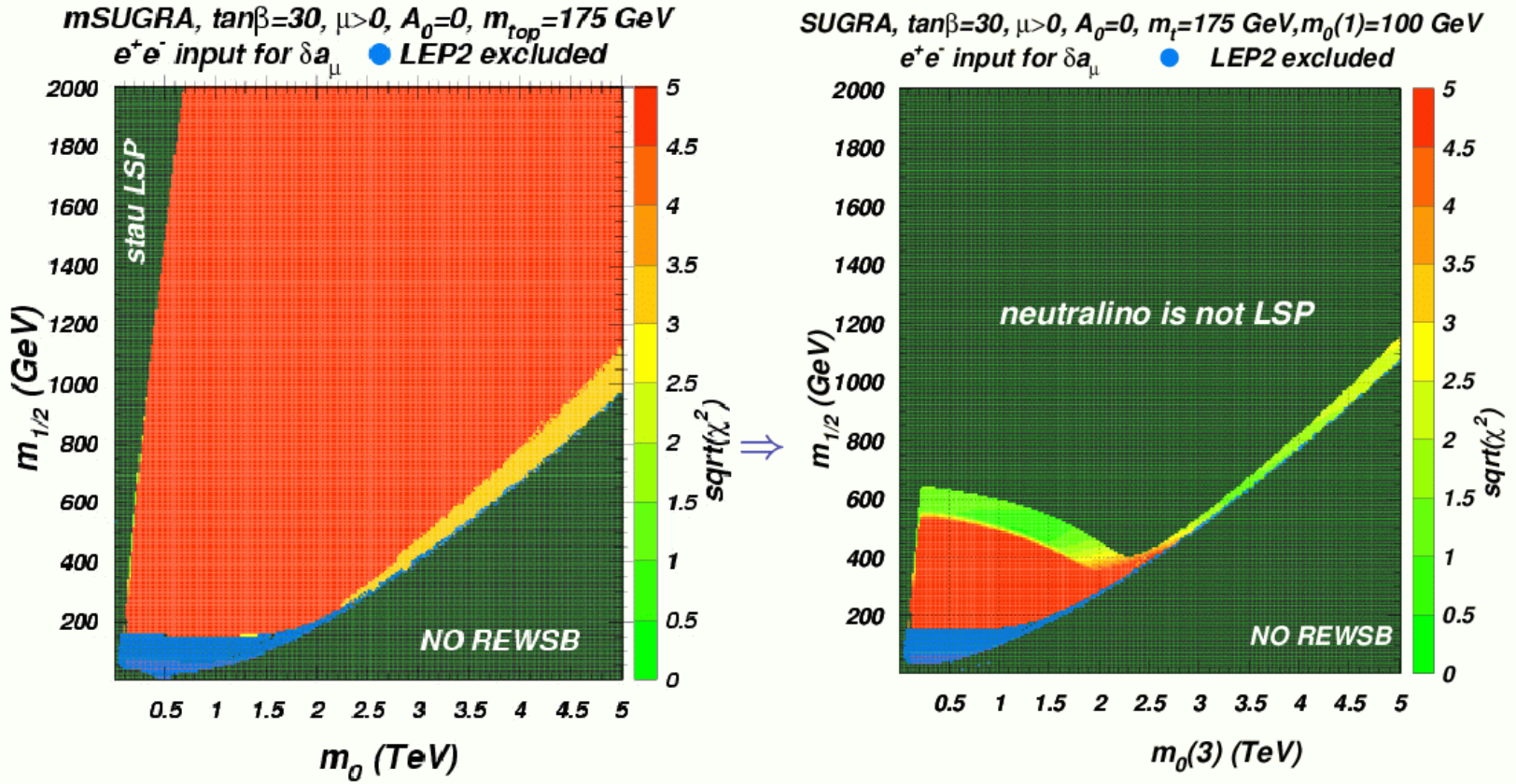
Non-universal SUGRA scenarios

reconciliation of $BF(b \to s\gamma)$ and $(g-2)$ **Baer,Belyaev,Krupovnickas,Mustafayev**

Normal Mass Hierarchy(NMH) in SUGRA

- **one step beyond universality solves the problem!**

$$m_0, m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu) \Longrightarrow m_0^{1,2}, m_0^3,\ m_H,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$$



- $B_H^0 - B_L^0 = \Delta m_B$ **mass splitting bound is safe**

SUGRA with non-universal Higgs Mass (NUMH1)

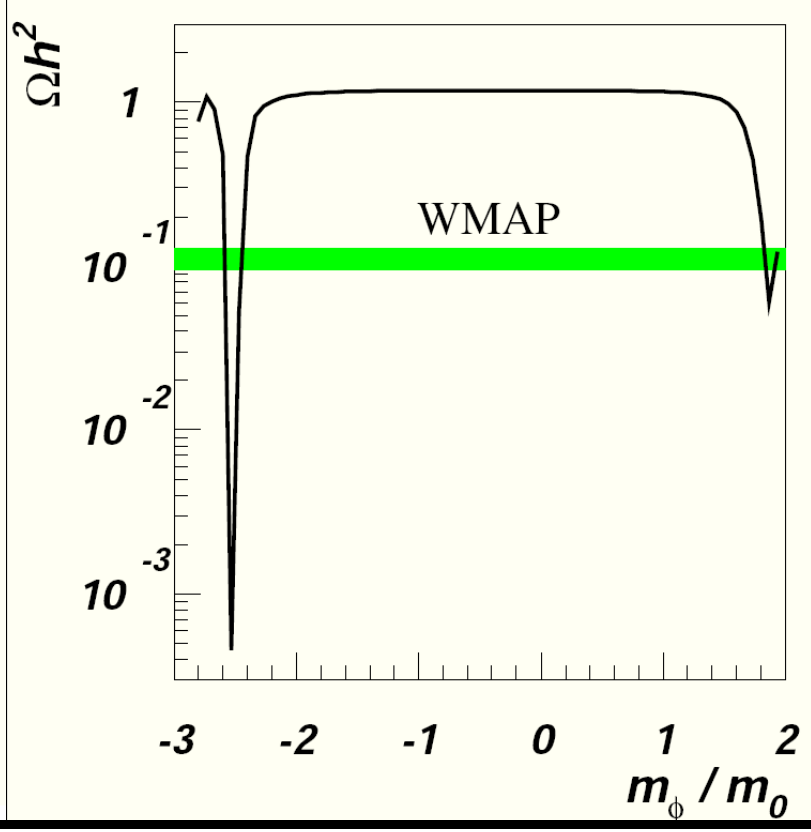
Baer,Belyaev,Mustafayev,Profumo,Tata

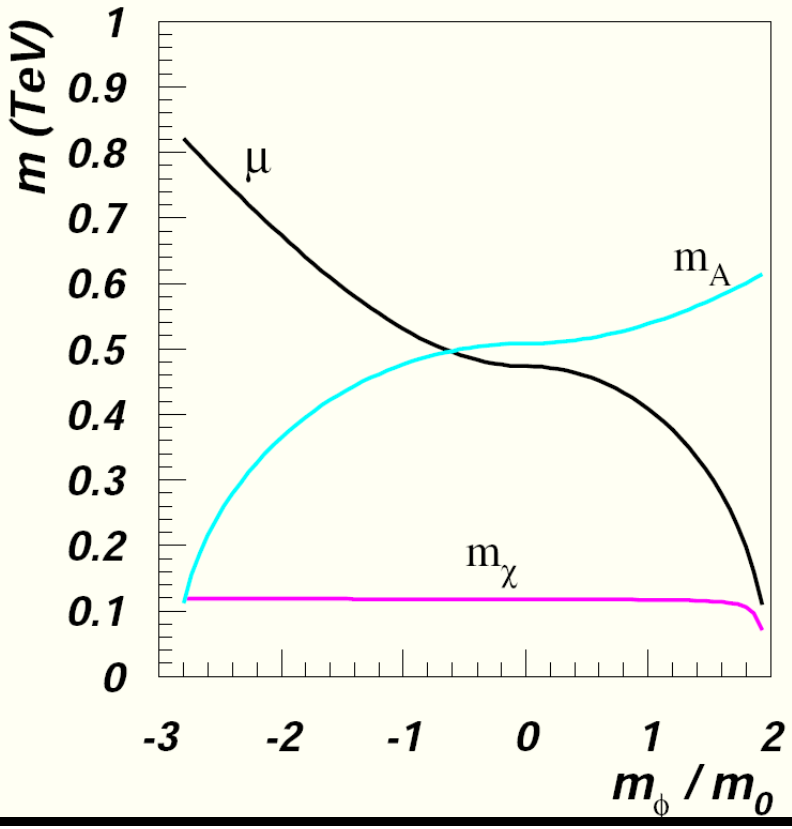
$m_{H_u}^2 = m_{H_u}^2 = m_\phi^2 \neq m_0$ **(NUHM1)**

motivated by $SO(10)$ **SUSY GUTs: matter** $\in \hat{\psi}(16)$, $\hat{H}_{u,d} \in \hat{\phi}(10)$

- μ **becomes small for** $m_\phi > m_0 \Rightarrow$ **FP! can be reached even for low** m_0
- M_A **decrease down to** $2m_{\tilde{Z}_1}$ **for** m_ϕ **going down** $\Rightarrow$ **Funnel for low** $\tan\beta$**!.**

m_0=300GeV, $m_{1/2}$=300GeV, tanβ=10, A_0=0, μ>0, m_t=178GeV

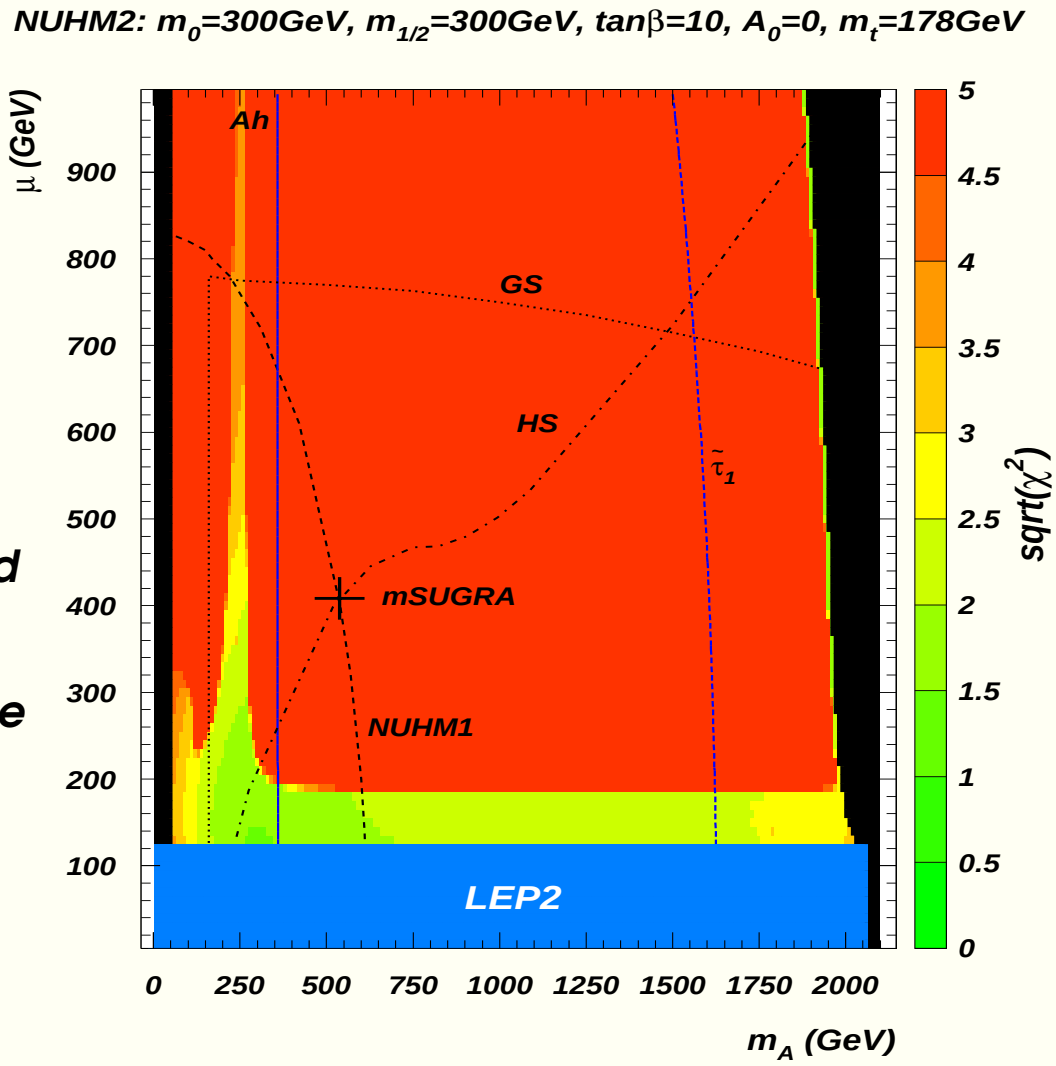




SUGRA with two non-universal Higgs Masses (NUMH2)

Baer,Belyaev,Mustafayev,Profumo,Tata

- $m^2_{H_u} \neq m^2_{H_u} = m^2_\phi \neq m_0$ *motivated by* $SO(5)$ *SUSY GUTs:* $\hat{H}_u \in \hat{\phi}(5)$ *while* $\hat{H}_d \in \hat{\phi}(\bar{5})$
- $m^2_{Hu},\ m^2_{Hd} \Leftrightarrow \mu,\ m_A$
- *See also* ***Berezinsky et al; Arnowitt and Nath; Ellis, Olive, Falk and Santoso; De Roeck,Ellis,Gianotti,Moortgat,Olive,Pape***
- $m_A \sim 250 GeV$ *- funnel region*
- *Small* μ *- HB/FP region*



$S \gg 0$: $\tilde{\tau}_R,\ \tilde{e}_R,\ \tilde{\mu}_R$ *are suppressed,* $\tilde{u}_R,\ \tilde{c}_R,\ \tilde{t}_R$ *are enhanced*

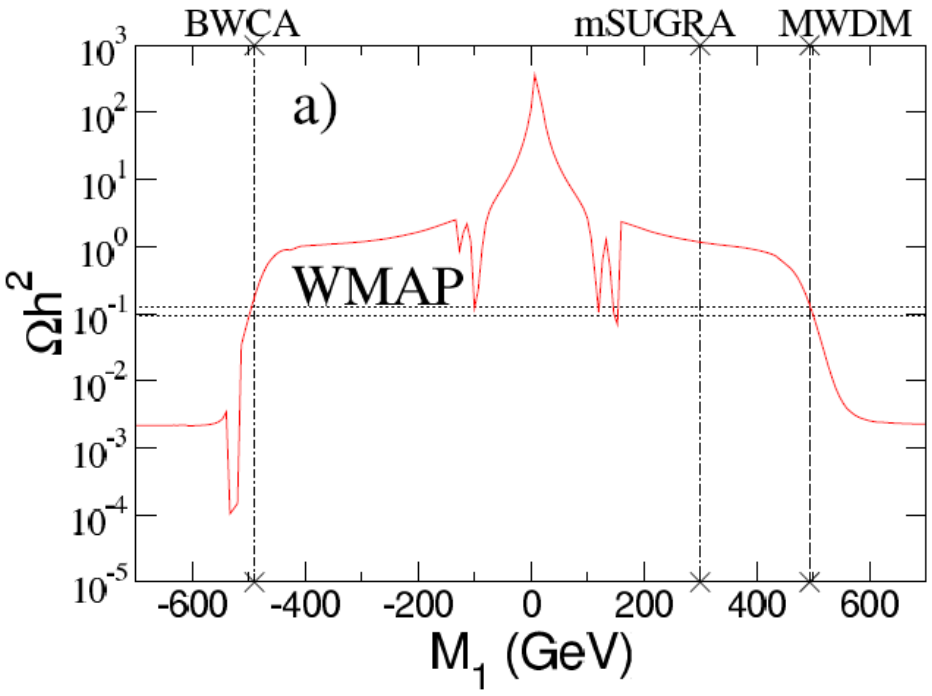
$S \ll 0$: $\tilde{\tau}_R,\ \tilde{e}_R,\ \tilde{\mu}_R$ *are enhanced,* $\tilde{u}_R,\ \tilde{c}_R,\ \tilde{t}_R$ *are suppressed*

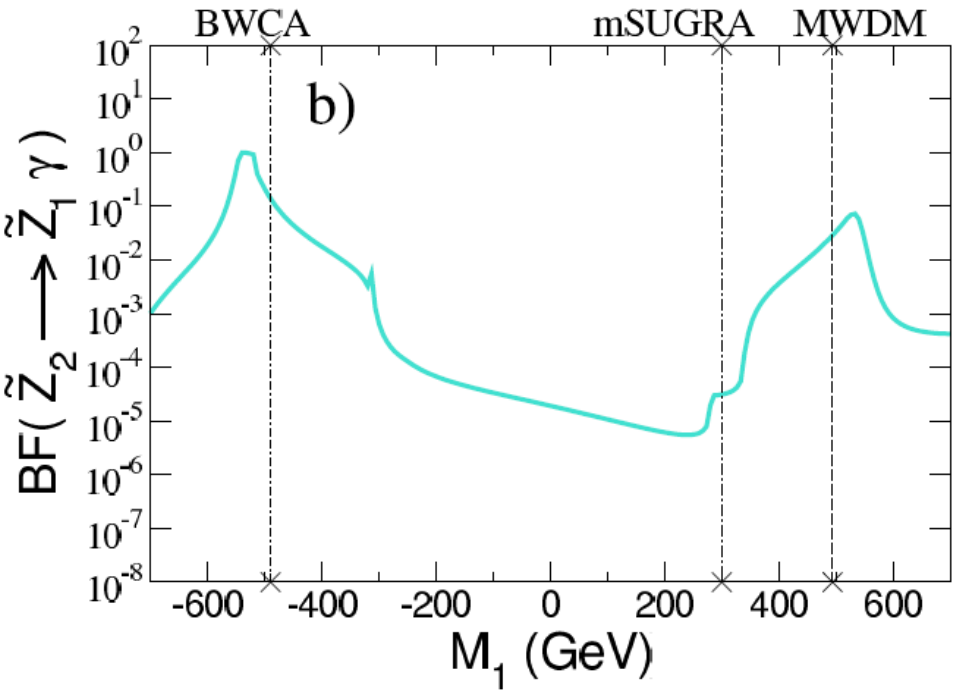
SUGRA with two non-universal gaugino masses(NUMH2)

$M_1 \neq M_2 \neq M_3$: **Baer,Krupovnikas,Mustafayev,Park,Profumo,Tata**

- motivation: SUSYGUTs where gauge kinetic function transforms non-trivially
- $M_2 \sim M_1$ at M_{GUT}: mixed wino dark matter (MWDM)
- $M_2 \simeq -M_1$ at M_{GUT}: bino-wino co-annihilation (BWCA)

m_0=300 GeV, $m_{1/2}$=300 GeV, tanβ=10, A_0=0, μ>0, m_t=178 GeV

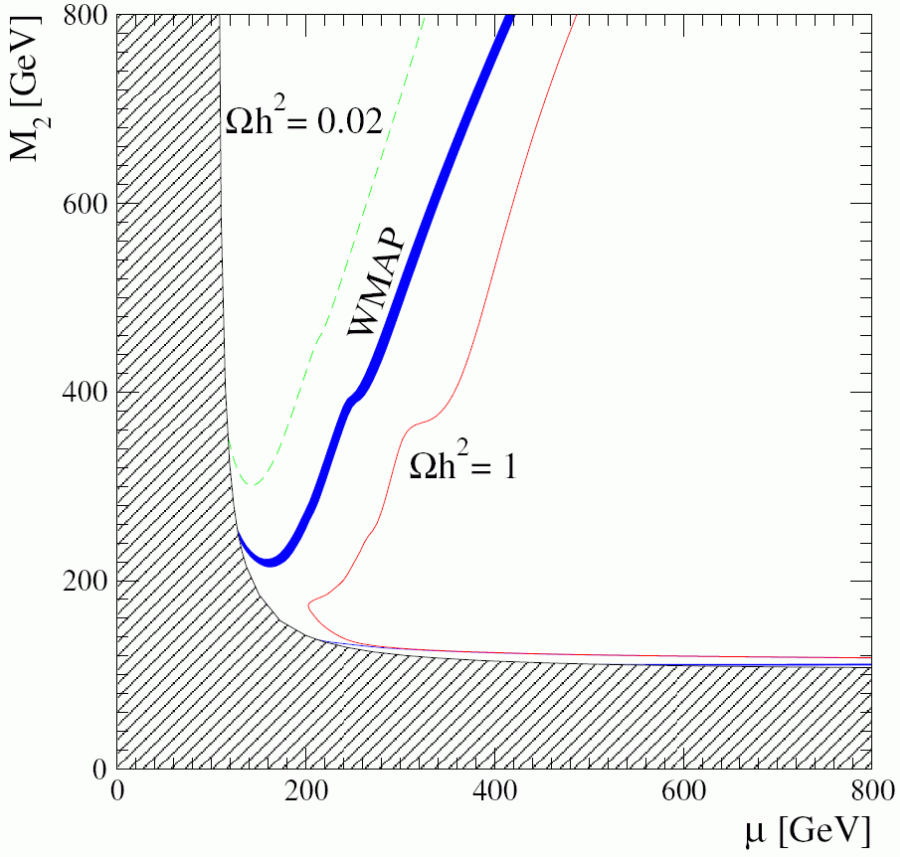


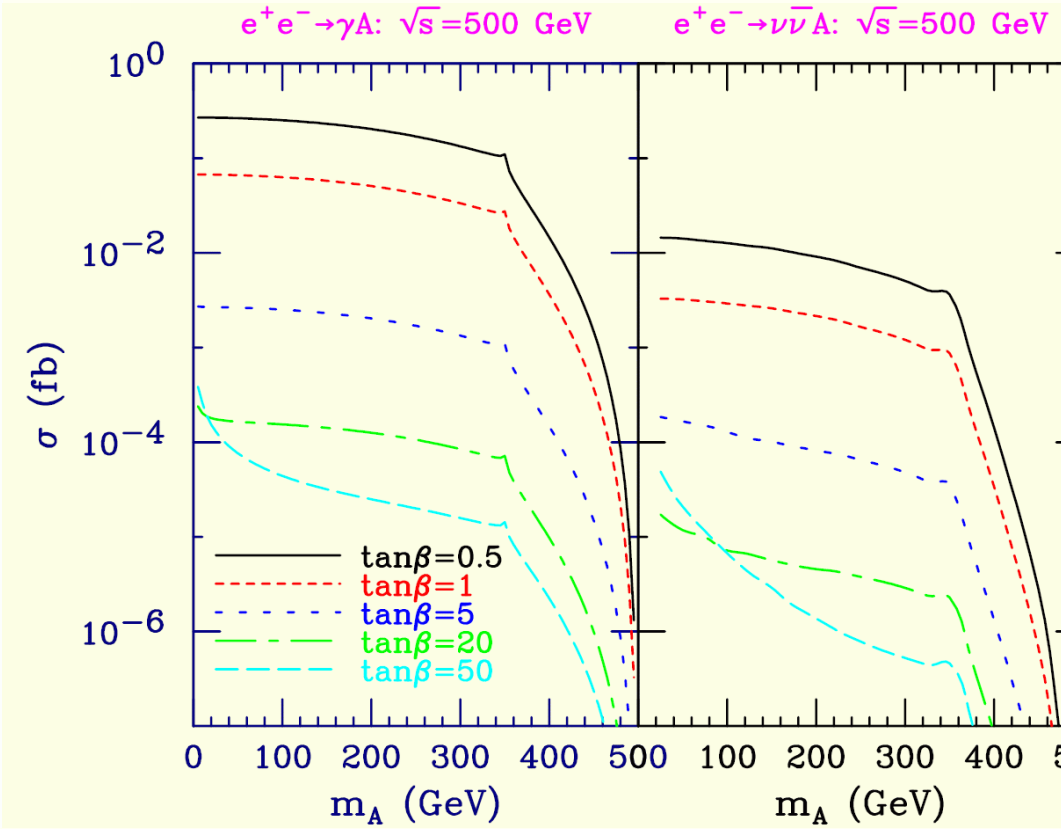


SUGRA beyond MSSM – NMSSM with extra singlet SF $\hat{S}$

Gunion et al; Belanger et al

- ***motivation: introduce μ via SUSY breaking***
- ***spectrum: 3 neutral Higgses, 2 pseudoscalars, 5 neutralinos***





- ***precision measurements at*** ***Stefan Hesselbach***

Back to motivations from cosmology – main questions to answer

Genevieve Belanger, review talk

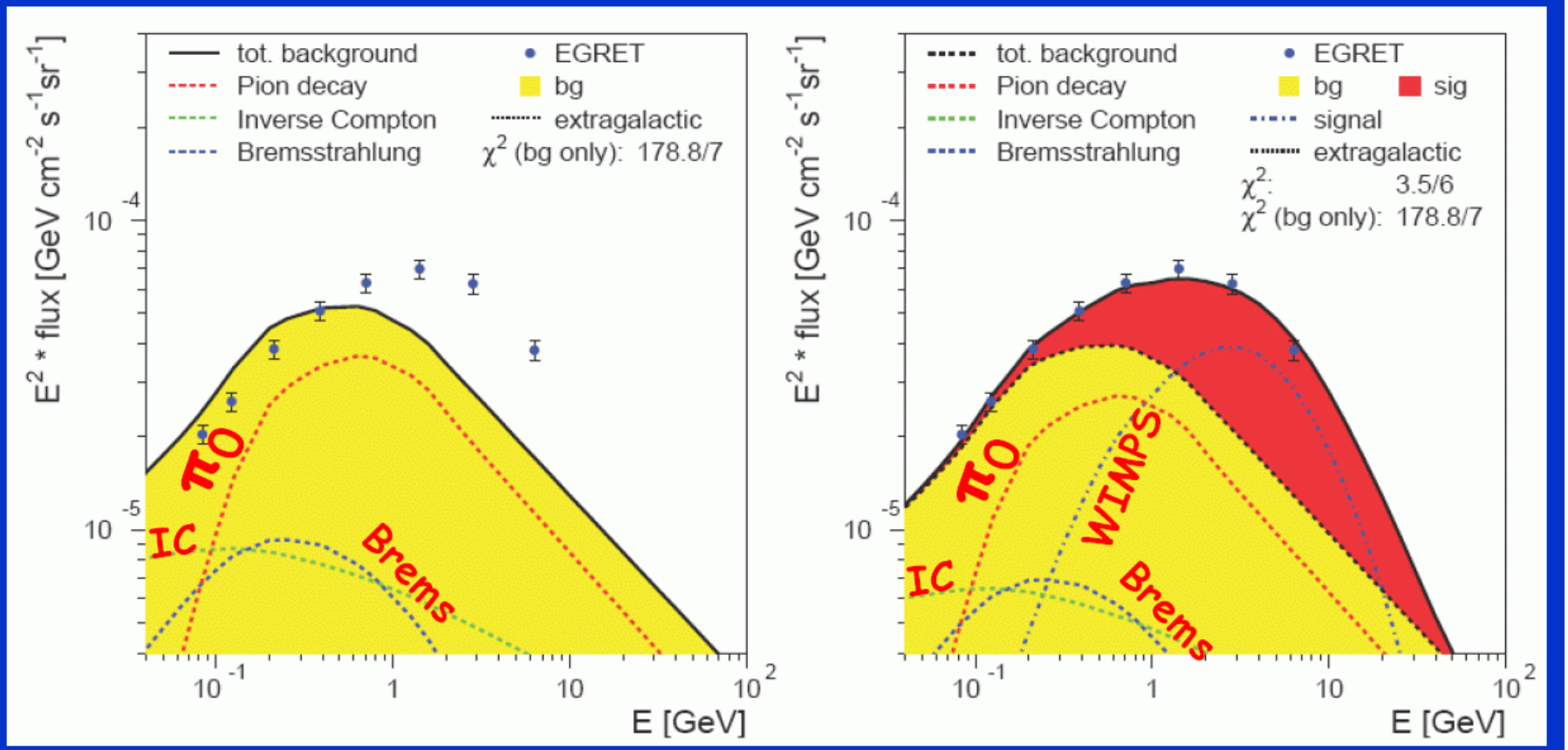
- Dark matter
  - Related to physics at weak scale
  - New physics at weak scale can also solve EWSB
  - Many possible solutions
- Dark energy
  - Related to Planck scale physics
  - NP for dark energy might affect cosmology and dark matter
- Baryon asymmetry
  - New physics at weak scale could also explain baryon asymmetry of the universe, eg. electroweak baryogenesis and MSSM with CP violation
  - Leptogenesis may be connected to some higher scale

Direct/Indirect DM search

Interpretation of Egret γ-ray excess in GeV region

Wim De Boer

The EGRET excess of diffuse galactic gamma rays without and with DM annihilation



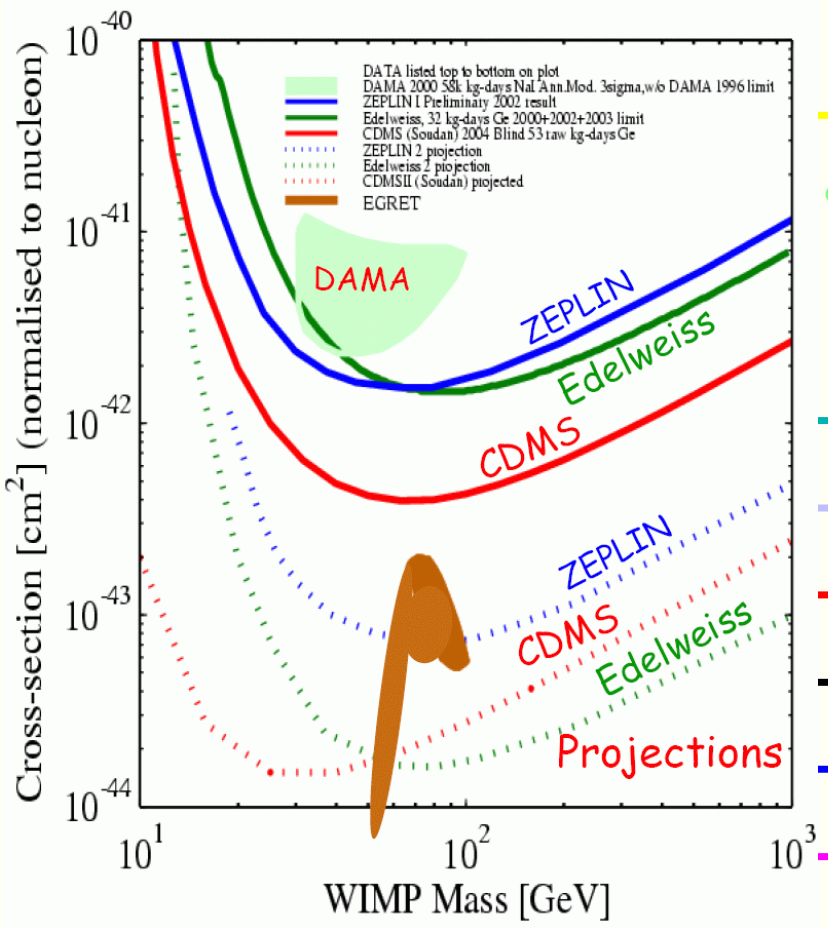
Fit only KNOWN shapes of BG + DMA, i.e. 1 or 2 parameter fit
NO GALACTIC models needed. Propagation of gammas straightforward

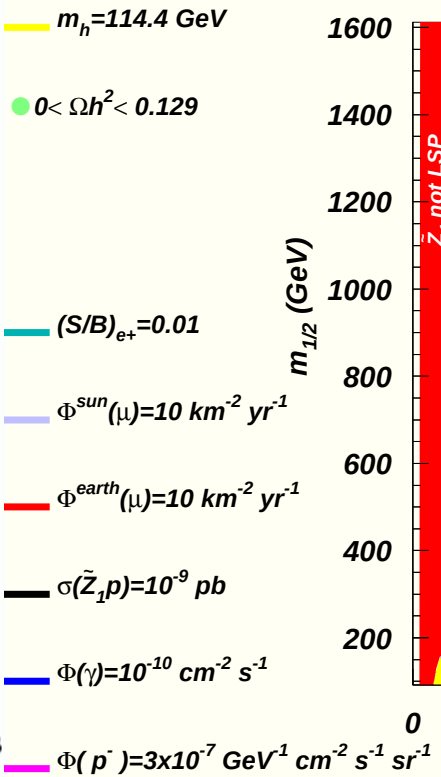
Gamma ray flux measured towards Galactic center

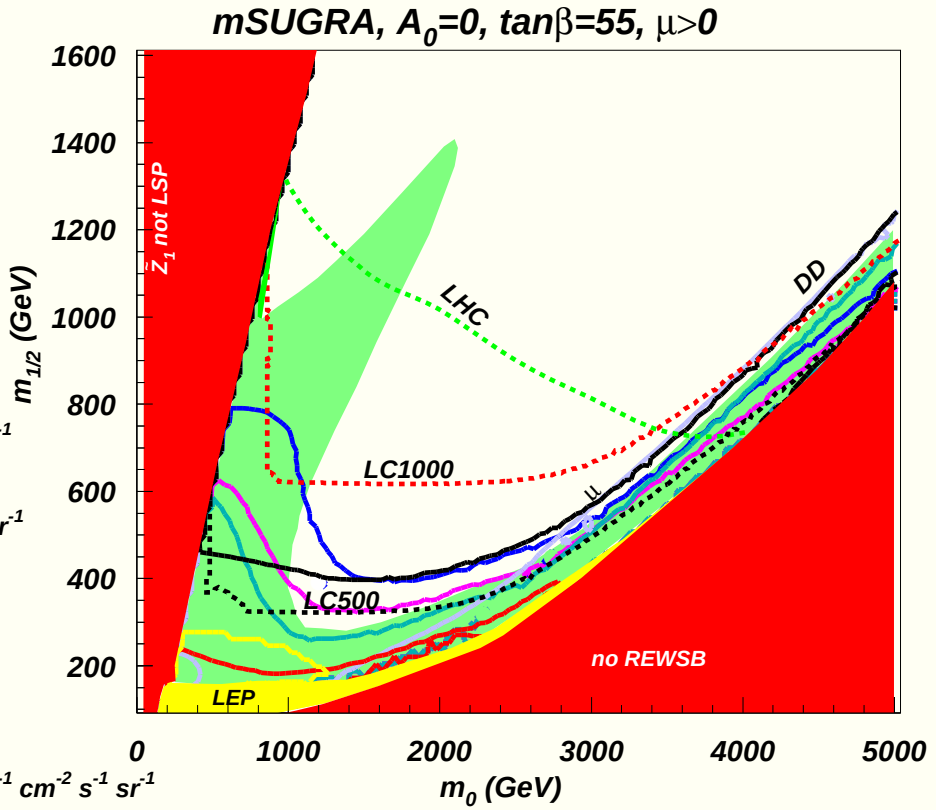
Direct/Indirect DM search

- **Great Potential for CDM searches**

Dave Cline; Wim De Boer; Baer,Balazs,Belyaev,Krupovnikas,O'Farrill







- **FP region will be covered by stage 3 DM search experiments**
- **ILC is to understand what has been observed**

Theoretical ideas on various DM sources

Gravitino DM, LHC/ILC search

Jose A.R. Cembranos; Albert de Roeck

- Gravitino LSP has extremely weak interactions SUPERWIMP-> irrelevant during thermal freeze-out
- NLSP freeze-out as usual (can be slepton, neutralino..) and Ω can be ~0.1
- NLSP eventually decay to SM+gravitino
- $\Omega_G = m_G/m_{NLSP}\ \Omega_{NLSP}$
- Relic density naturally of right order

Wrapped Xtra-Dim (Randall-Sundrum) DM

Kaustubh Agashe

- GUT model with matter in the bulk
- Solving baryon number violation in GUT models → stable Kaluza-Klein particle
- Example based on SO(10) with Z3 symmetry: LZP is KK right-handed neutrino

Branons

Jose A.R. Cembranos

Massive branons could offer an alternative explanation for the observed DM abundance and recent measurements of $(g-2)_\mu$

Universal extra-dimensions DM

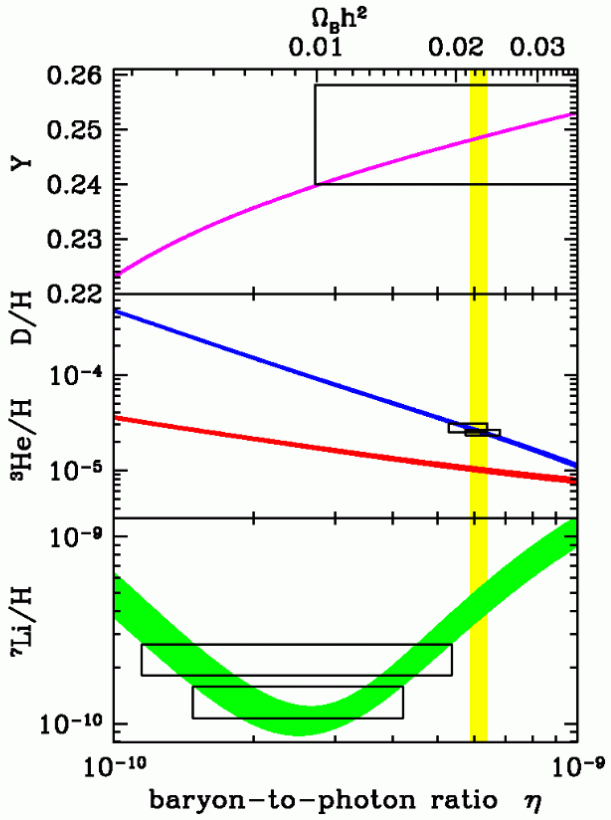
Maxim Perelstein

Baryon asymmetry of the Universe

- Small excess of particles over antiparticles in the universe
- Both Big Bang Nucleosynthesis (BBN) and measurements of CMB agree

$$\eta \equiv \frac{n_B}{n_\gamma} = \begin{cases} 3.4 - 6.9 \times 10^{-10}, & \text{BBN} \\ 5.9 - 7.3 \times 10^{-10}, & \text{CMB} \end{cases}$$

- Conditions to create an excess
  - Baryon number violation
  - C and CP violation
  - Out of thermal equilibrium
  - Non-vanishing B-L
- *Need physics Beyond the SM*



- ***EW baryogenesis*** *is one of the solutions. Collider phenomenology comes into play.*

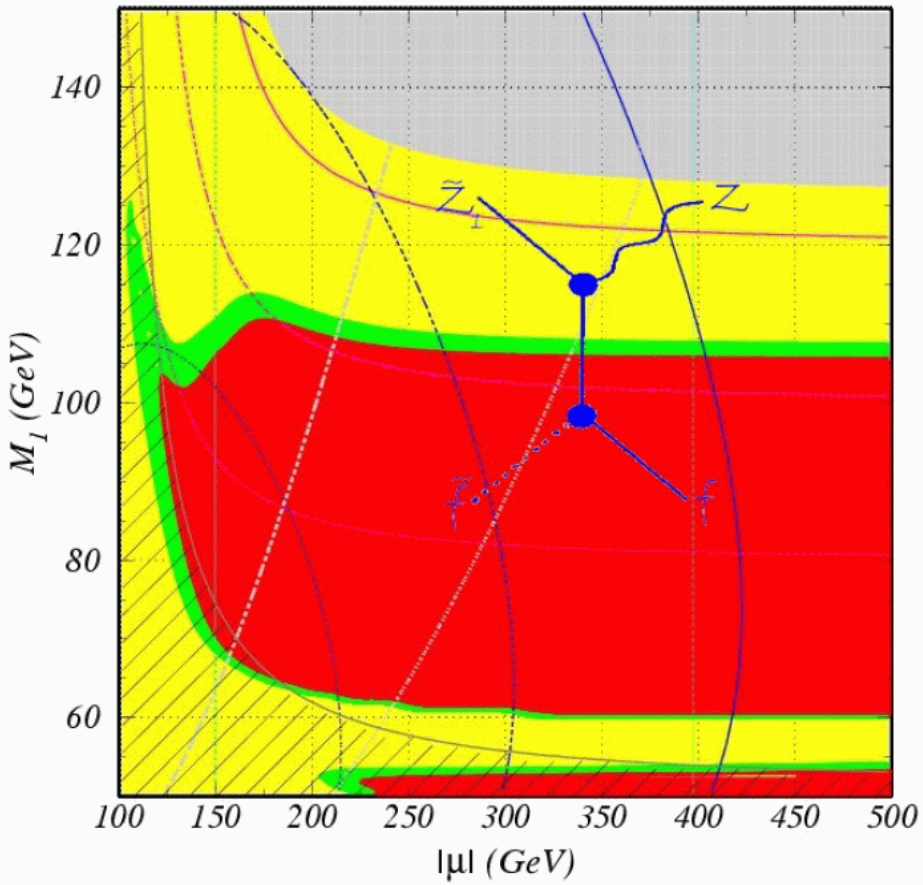
EW baryogenesis – parameter space

- *requires strong EW phase transition pf the 1st order*
- *quantum corrections to triple Higgs-boson coupling are important*

  Shinya Kanemura
- *analysis of the parameter space*

  Csaba Balazs in coll with Carena,Seco,Quiros,Wagner

  light stop, CPV, heavy (1,2) scalars



Input parameters:

$\tan\beta = 7$, $m_A = 1000$ GeV, $Arg(\mu) = 1.571$

$M_2 = M_1 g_2^2/g_1^2$, $Arg(M_1) = Arg(M_2) = 0$, $M_3 = 1$ TeV

$m_{U3} = 0$ GeV, $m_{Q3} = 1.5$ TeV, $X_t = 0.7$ TeV

m_{L3}, m_{E3}, $m_{D3} = 1$ TeV

$m_{L1,2}$, $m_{E1,2} = 10$ TeV

$m_{Q1,2}$, $m_{U1,2}$, $m_{D1,2} = 10$ TeV

Legend:

$m_{t1} > m_{Z1}$ $\quad$ $m_{W1} < 103.5$ GeV

$\Omega h^2 > 0.129$ $\quad$ $\Omega h^2 < 0.095$

$0.095 < \Omega h^2 < 0.129$

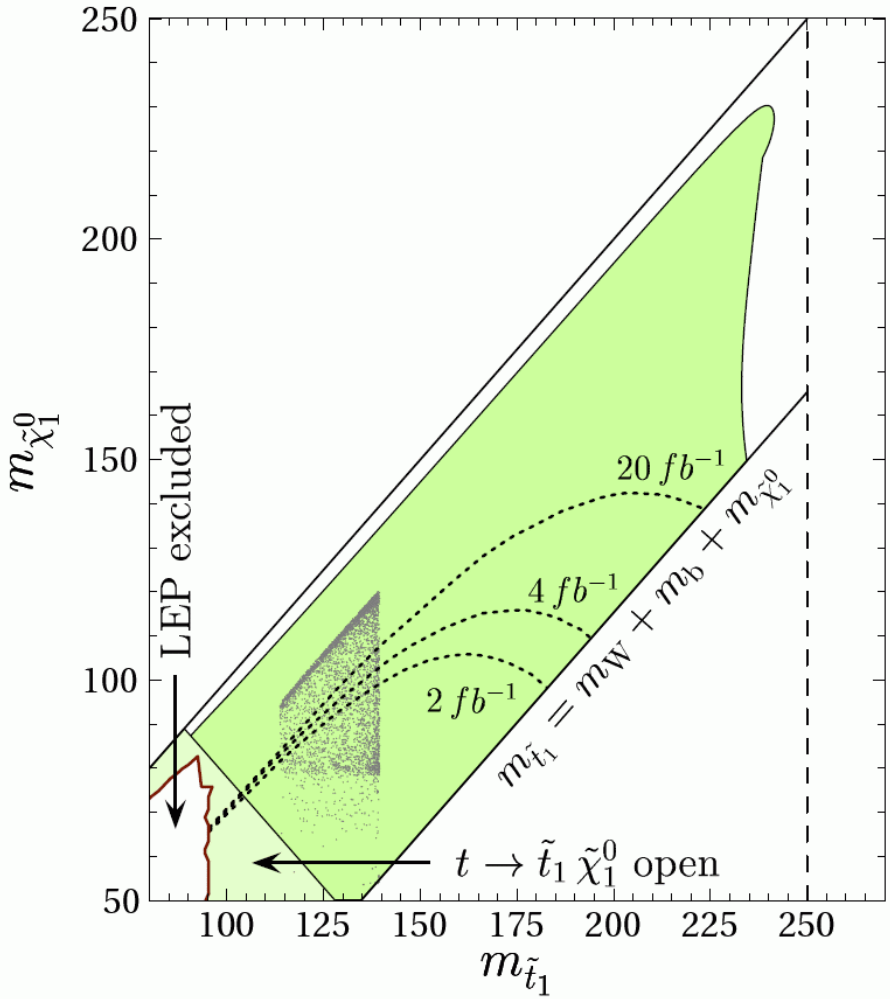
σ_{si} = 3E-08 3E-09 3E-10 pb

m_{Z1} = 120 100 80 GeV

d_e = 1E-27 1.2E-27 1.4E-27 e cm

EW baryogenesis – collider searches

talks by Ayres Freitas and Caroline Milstene in coll with Finch,Sopczak,Nowak



From simulations:

Background numbers B and signal efficiencies ϵ with theor. cross-section σ yields signal number $S = \epsilon\sigma$

Green region: $\dfrac{S}{\sqrt{S+B}} > 5$

Light green:
decay $t \to \tilde{t}_1 \tilde{\chi}_1^0$ open
(not yet studied)

Detection of light stops possible for $\Delta m \sim \mathcal{O}(5\text{GeV})$

Cover complete co-annihilation region

- ***benchmark points, parameter measurements at ILC, CDM prediction***

LHC-ILC-cosmology connections, precision measurements

Joe Lykken, Michael Peskin, David Rainwater, Georg Weiglein, Peter Zerwas

- *LHC is a discovery machine , unless we are in the upper FP region, where ILC does the job*
- *ILC would play a major role in understanding what has been discovered: spins, coupling, theory parameters, DM prediction.*
- *Relic density prediction requires very precise determination of underlying parameters*
- *ILC is necessary to identify DM candidate*

LHC-ILC interplay

Parameter	"True" value	ILC Fit value	Uncertainty (ILC+LHC)	Uncertainty (LHC only)
$\tan\beta$	10.00	10.00	0.11	6.7
μ	400.4 GeV	400.4 GeV	1.2 GeV	811. GeV
X_τ	-4449. GeV	-4449. GeV	20.GeV	6368. GeV
$M_{\tilde{e}_R}$	115.60 GeV	115.60 GeV	0.27 GeV	39. GeV
$M_{\tilde{\tau}_R}$	109.89 GeV	109.89 GeV	0.41 GeV	1056. GeV
$M_{\tilde{e}_L}$	181.30 GeV	181.30 GeV	0.10 GeV	12.9 GeV
$M_{\tilde{\tau}_L}$	179.54 GeV	179.54 GeV	0.14 GeV	1369. GeV
X_t	-565.7 GeV	-565.7 GeV	3.1 GeV	548. GeV
X_b	-4935. GeV	-4935. GeV	1284. GeV	6703. GeV
$M_{\tilde{u}_R}$	503. GeV	503. GeV	24. GeV	25. GeV
$M_{\tilde{b}_R}$	497. GeV	497. GeV	8. GeV	1269. GeV
$M_{\tilde{t}_R}$	380.9 GeV	380.9 GeV	2.5 GeV	753. GeV
$M_{\tilde{u}_L}$	523. GeV	523. GeV	10. GeV	19. GeV
$M_{\tilde{t}_L}$	467.7 GeV	467.7 GeV	3.1 GeV	424. GeV
M_1	103.27 GeV	103.27 GeV	0.06 GeV	8.0 GeV
M_2	193.45 GeV	193.45 GeV	0.10 GeV	132. GeV
M_3	569. GeV	569. GeV	7. GeV	10.1 GeV
$m_{A_{run}}$	312.0 GeV	311.9 GeV	4.6 GeV	1272. GeV
m_t	178.00 GeV	178.00 GeV	0.050 GeV	0.27 GeV
χ^2 for unsmeared observables: 5.3×10^{-5}				

$\Rightarrow$ most of the Lagrangian parameters can hardly be constrained by LHC data alone

$\Rightarrow$ precise determination of SUSY parameters only possible with LHC $\oplus$ ILC

from Georg's talk

ILC precision measurement studies

- ***Ayres Freitas:***
  "Studying light sneutrinos at the ILC and physical implications"
- ***Joseph Proulx:*** *"Update on Slepton and Gaugino Mass Resolution Studies"*
- ***Stefan Hesselbach:***
  "CP-odd and T-odd Asymmetries in Chargino and Neutralino Production and Decay"
- ***Gudrid Moortgat-Pick:***
  "The physics case for the polarization of both beams at the ILC"
  "Impact of forward-backward asymmetries for constraining heavy virtual particles"
- ***Dirk Zerwas:*** *"SUSY parameter determination"*
- ***Francois Richard:*** *"Dark Matter with heavy scalars at the ILC"*

Concluding remarks

- *many very exciting directions have been defined and problems studied*
- *we have done a big progress in understanding/defining benchmarks* **(Jan Kalinovski's talk)** *, SUSY tools* **(Alexei Safonov's talk)** *and detector and simulation issues* **((Kiyotomo Kawagoe's talk)**
- *ILC is necessary tool to understand SUSY, and DM in particular*
- *minimization of the time gap between LHC and ILC is very important*
- *in spite of unknown fate of ILC we are very active – this is the main source of making ILC become true*
- ***let us keep up our progress!***