The origin of matter in the nMSSM

or

Why do we need the ILC?

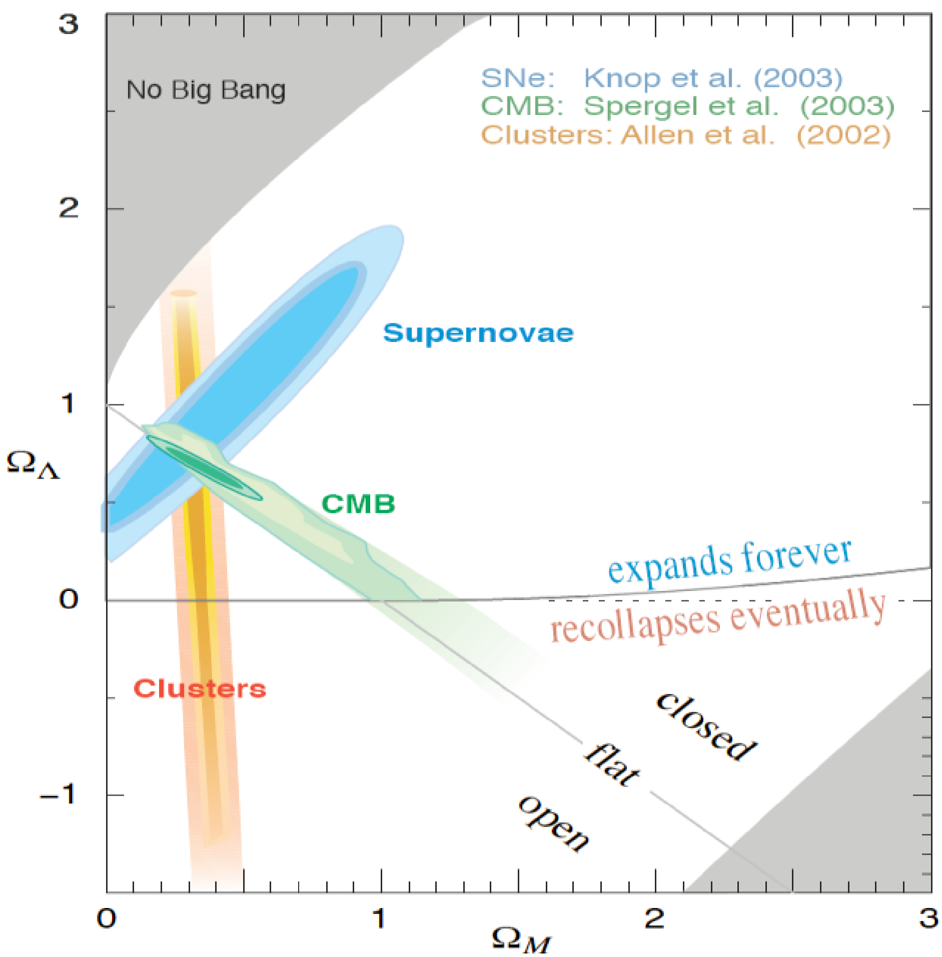
- Origin of matter in the MSSM
- Origin of matter in the nMSSM
- Need for the ILC

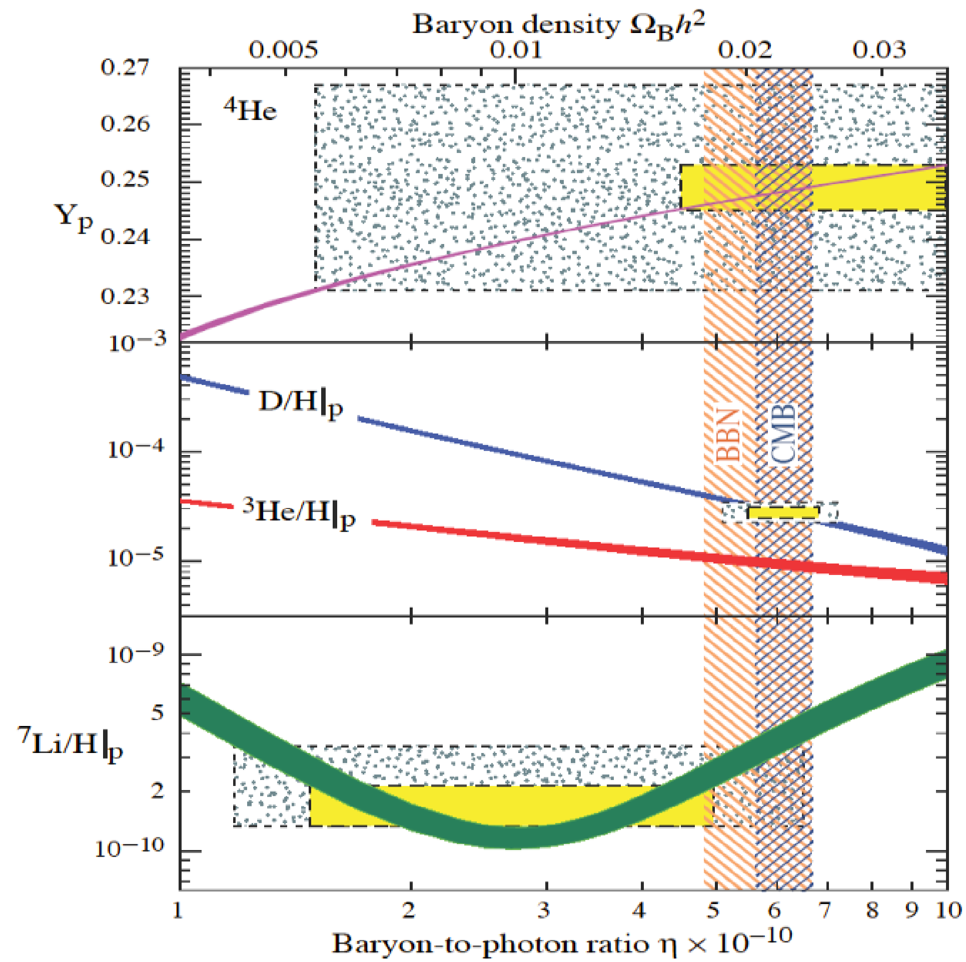
C.Balázs, M.Carena, A. Freitas, C.Wagner hep-ph/0606nnn

C.Balázs, M.Carena, A. Menon, D.Morrissey, C.Wagner PRD71 075002 (`05)

C.Balázs, M.Carena, C.E.M.Wagner PRD70 015007 (`04)

The matter content of the universe





$\Omega_{CDM} = 0.27 \pm 0.04$ $\Omega_B = 0.044 \pm 0.001$

Unexplained by the standard models

Baryons in the MSSM

— Electroweak baryogenesis

• explains Ω_B • constrains MSSM parameter space

— EW phase transition strongly 1st order → a light stop & higgs

$m_{\tilde{t}_1} < m_t$, $m_{\tilde{t}_2} \gtrsim 1$ TeV,

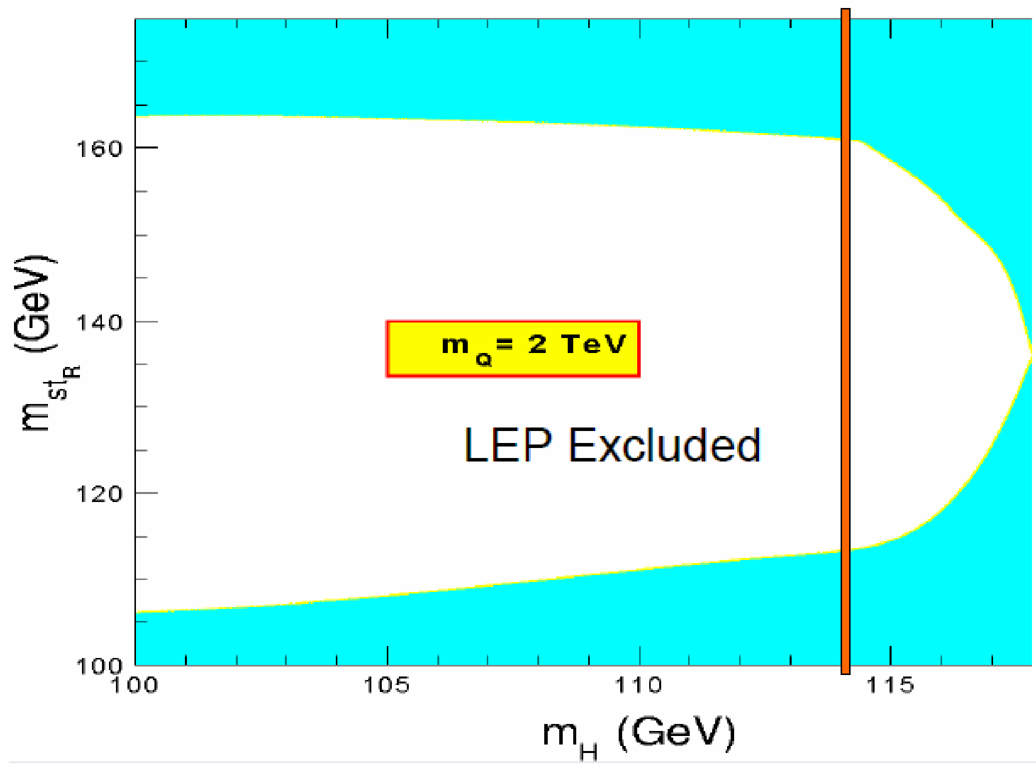
$0.3 < |X_t| / m_{\tilde{Q}_3} < 0.5$,

$m_h \lesssim 120$ GeV

— Enough CP̸ → light charginos & μ

$M_2, \mu \lesssim 500$ GeV,

$\mathrm{Arg}(M_2 \mu) \gtrsim 0.1$

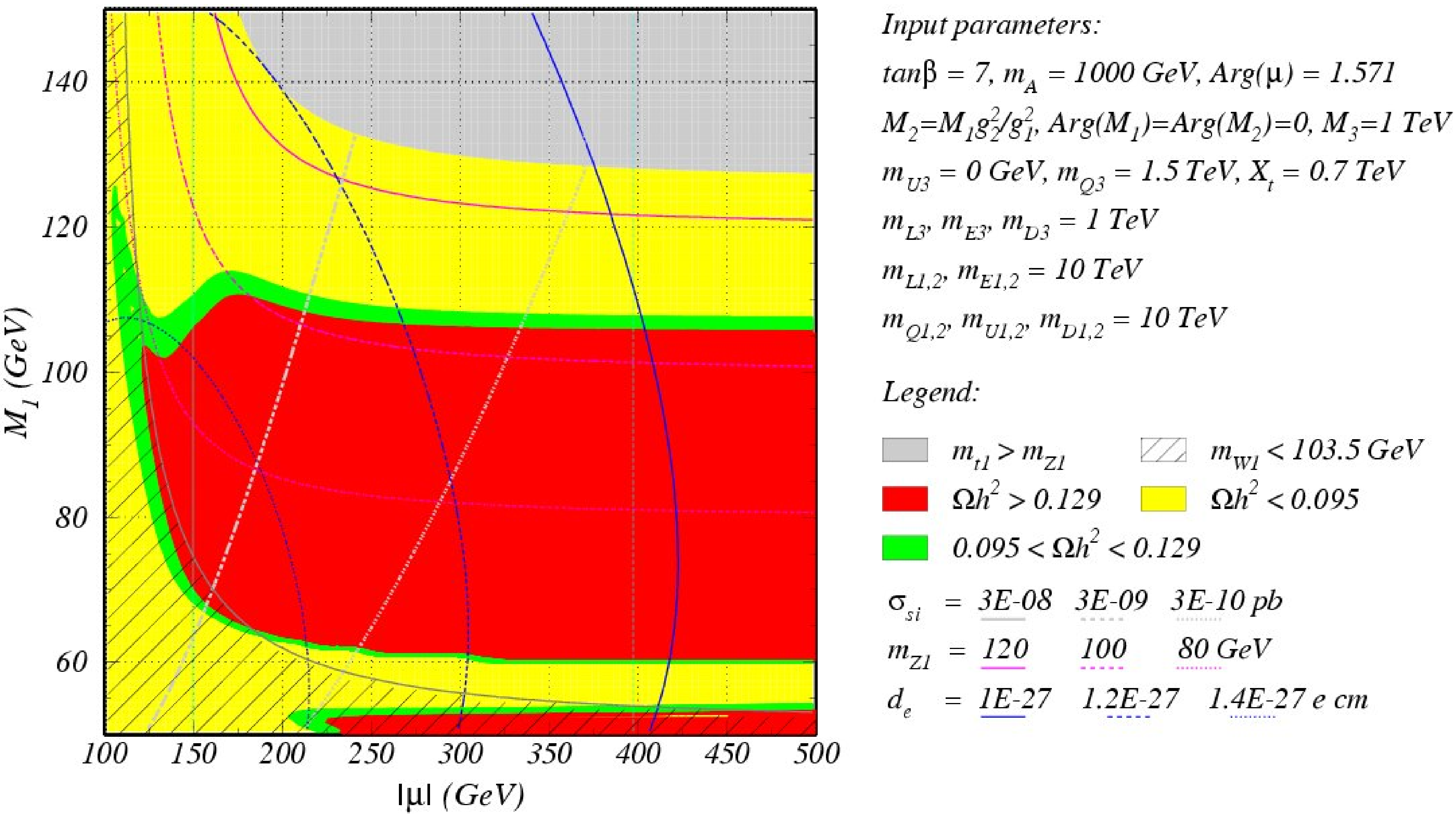


Carena, Seco, Quiros, Wagner 2002

— EDM limits → heavy 1st & 2nd generation scalars

All matter in the MSSM

– Ω_B & Ω_{CDM} simultaneously predicted in MSSM



Balázs, Carena, Menon, Morrissey, Wagner 2005

nMSSM

— Discreet symmetries of super- & Kahler potential

$$Z_5^R, Z_7^R \subset U(1)_{R'} \quad \text{where} \quad R' = 3R + PQ$$

to prevent domain walls and large tadpoles

- Superpotential

$$W = W_{MSSM} + \lambda \hat{S} H_1.H_2 + \frac{m_{12}^2}{\lambda} \hat{S}$$

- Scalar potential

$$V = V_{MSSM} + m_S^2 |S|^2 + t_S(S + h.c.) +$$
$$a_\lambda(S H_1.H_2 + h.c.)$$

- New parameters

$$v_S, \lambda, a_\lambda, m_S, m_{12}, t_S$$

nMSSM

— Solves μ problem naturally

$$W = W_{MSSM} + \lambda \hat{S} H_1.H_2 + \frac{m_{12}^2}{\lambda} \hat{S}$$

- $\mu = \lambda \langle S \rangle = \lambda v_S$ set by EW scale

— Alleviates fine tuning in Higgs/stop sector

$$m_h^2 \leq m_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{g^2} \sin^2 2\beta \right)$$

- tree level lightest Higgs mass limit relaxed

— Tree level cubic term of scalar potential

$$V = V_{MSSM} + m_S^2 |S|^2 + t_S (S + h.c.) + a_\lambda (S H_1.H_2 + h.c.)$$

assists a strongly 1^{st} order EW phase transition

Baryons in the nMSSM

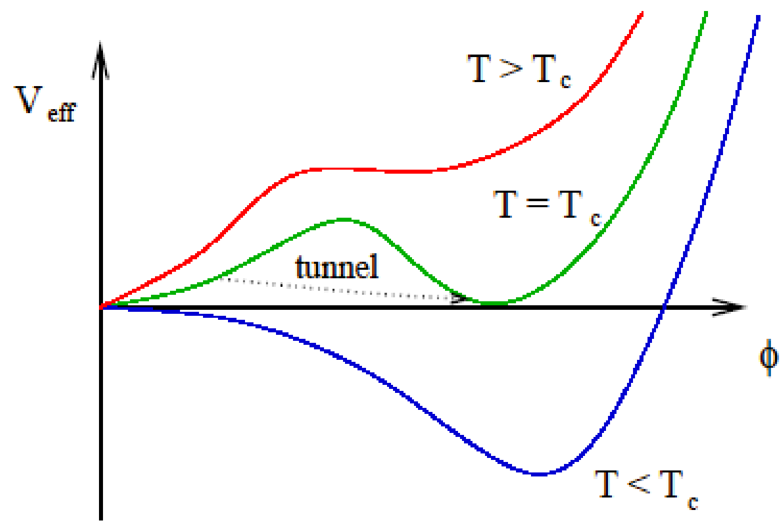
— Measured $\eta_B \leftrightarrow$ strongly 1st order EWPT $\leftrightarrow$ large OP

$$\phi_c/T_c \gtrsim 1$$

- strength of EWPT $\leftrightarrow$ minimum of finite T eff. potential

$$V_{eff}(\phi,T) = (-\mu^2+\alpha T^2)\phi^2 - \gamma\, T\, \phi^3 + \frac{\lambda}{4}\phi^4 + \ldots$$

- V_{eff} minimal for $0 < \phi$ if
  $\frac{\phi_c}{T_c} \sim \frac{\gamma}{\lambda} \rightarrow \gamma$ determines OP
- γ generated by
  SM : bosonic loops $\rightarrow \gamma \sim g^3$
  MSSM : sc. loops $\rightarrow \gamma \sim y^3$
  nMSSM : tree level $\rightarrow \gamma \sim a_\lambda$



- MSSM: light stop induces strongly 1st order EWPT
  nMSSM: no need for light stop

Dark matter in nMSSM

— Neutralinos

$$\mathcal{M}_{\tilde{Z}} = \begin{pmatrix} M_1 & . & . & . & . \\ 0 & M_2 & . & . & . \\ -c_\beta s_W m_Z & c_\beta s_W m_Z & 0 & . & . \\ s_\beta c_W m_Z & -s_\beta c_W m_Z & \lambda v_S & 0 & . \\ 0 & 0 & \lambda v_2 & \lambda v_1 & 0 \end{pmatrix}$$

- unification assumption: $M_2 = \alpha_2/\alpha_1 \, M_1$
- EWBG: low $\tan\beta$
- typical lightest neutralino: mostly singlino

$$m_{\tilde{Z}_1} \sim 2\lambda v_1 v_2 v_S / (v_1^2 + v_2^2 + v_S^2) \lesssim 60 \text{ GeV}$$

- complex phase: $\lambda = |\lambda| e^{i\phi_\lambda}$

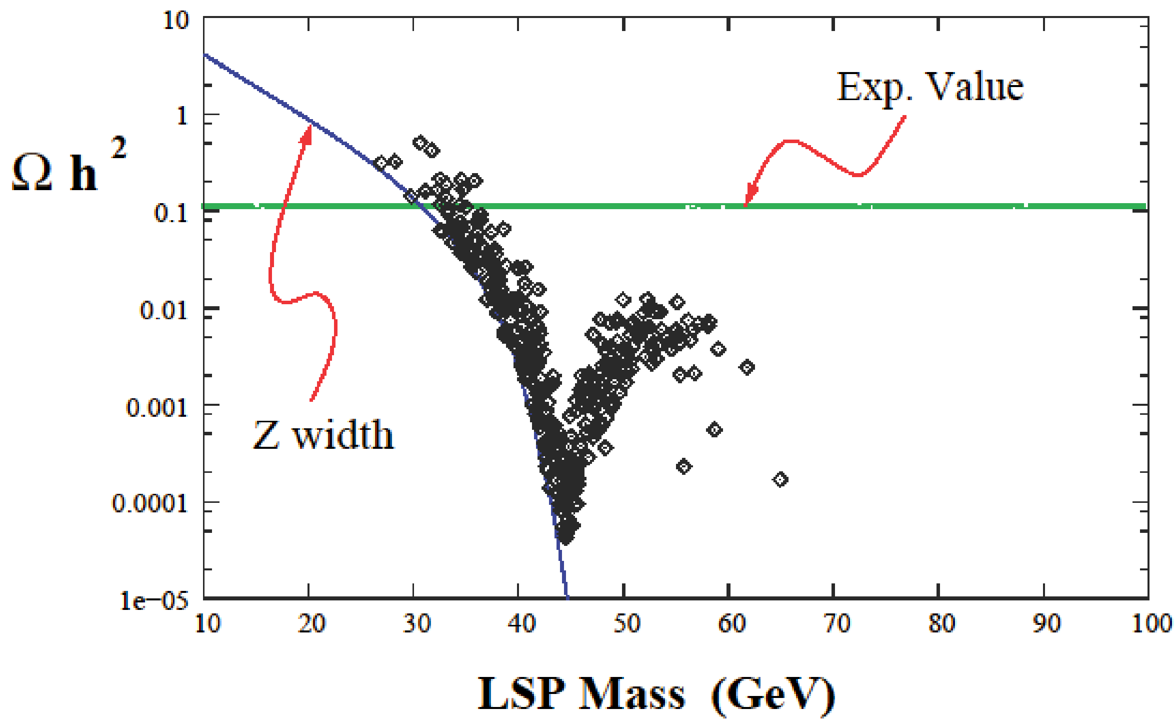
All matter in nMSSM

— Neutralino relic density

- $\tilde{Z}_1$ light $\rightarrow$

  no coannihilations

  dominant annihilation channel: $\tilde{Z}_1 \tilde{Z}_1 \rightarrow Z \rightarrow 2x$



Menon, Morrissey, Wagner 2004

Aside: Higgs sector

$$H_1 = \begin{pmatrix} v_1 + (\phi_1 + i\, a_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\, a_2)/\sqrt{2} \end{pmatrix}$$

$$S = v_S + (\phi_S + i\, a_S)/\sqrt{2}$$

- $6 - 1 = 5$ neutral physical Higgses

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} = O^S \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_S \end{pmatrix} \qquad \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = O^P \begin{pmatrix} A^0 \\ a_S \end{pmatrix}$$

- lightest Higgs (~ 115 GeV) decay modes

$$Br(S_1 \to b\bar{b}) = 8\% \qquad Br(S_1 \to \tilde{Z}_1 \tilde{Z}_1) = 91\%$$

- LHC: detection via WBF & Zh production

  mass determination via ratio of WBF & Zh prod

Benchmark scans

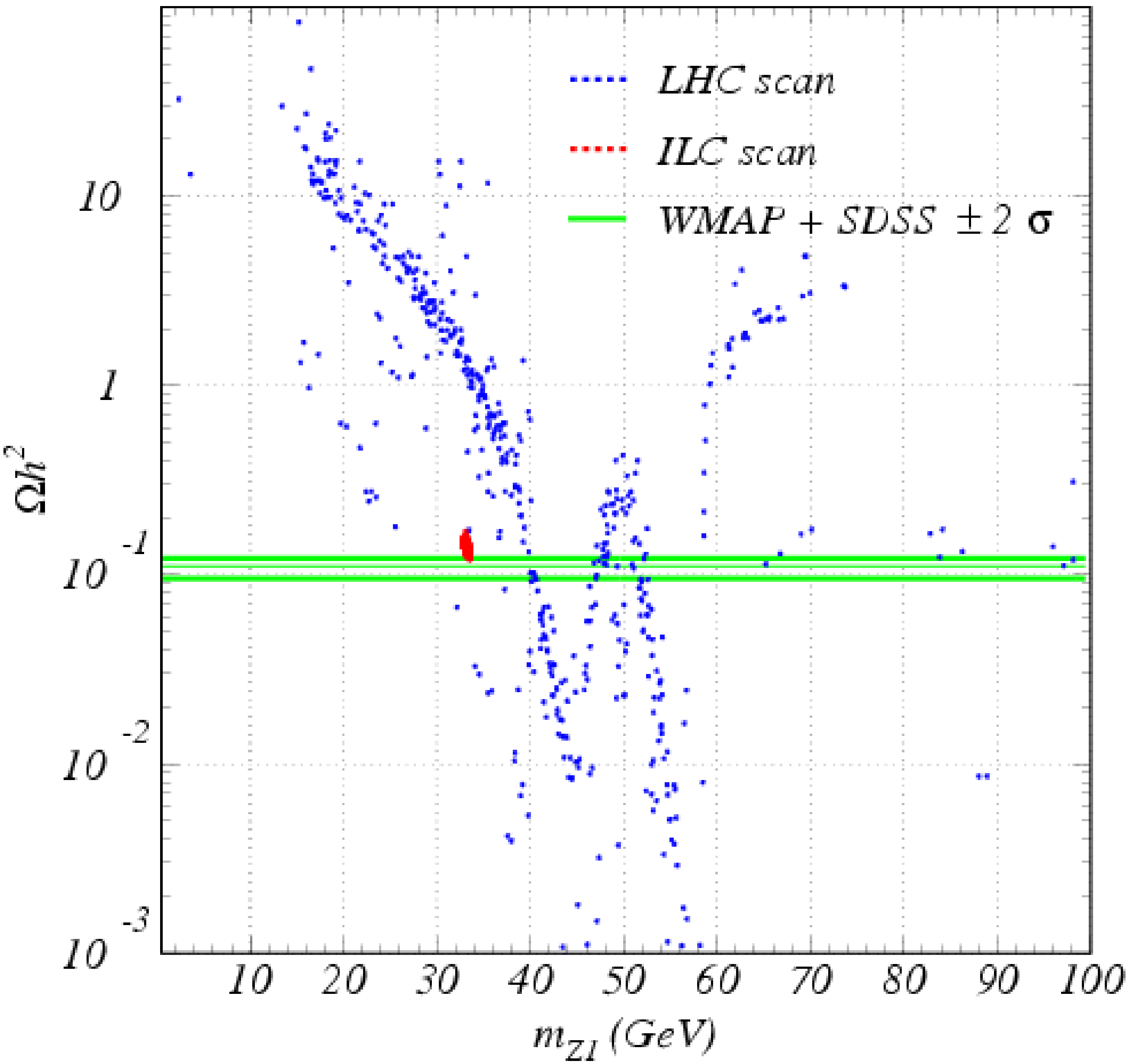
— Benchmarks

	$\tan\beta$	λ	v_s	a_λ	m_a	M_2	ϕ_λ
A	1.70	0.619	-384	373	923	245	0.14
B	1.99	0.676	-220	305	914	418	2.57
C	1.10	0.920	-276	386	514	462	2.38
			GeV	GeV	GeV	GeV	

— "Scan"

- generate LHC & ILC events (tree & parton level w/ BGs, jet broadening, ...)
- construct appropriate invariant mass distributions
- reconstruct masses (couplings) from distributions
- determine central values and precision

Need for the ILC



Need for the ILC

– Typical production/decay chain:

squarks/gluinos →

charginos/neutralinos →

leptons/jets

- typical invariant mass spectra (lumi 300 fb^{-1})

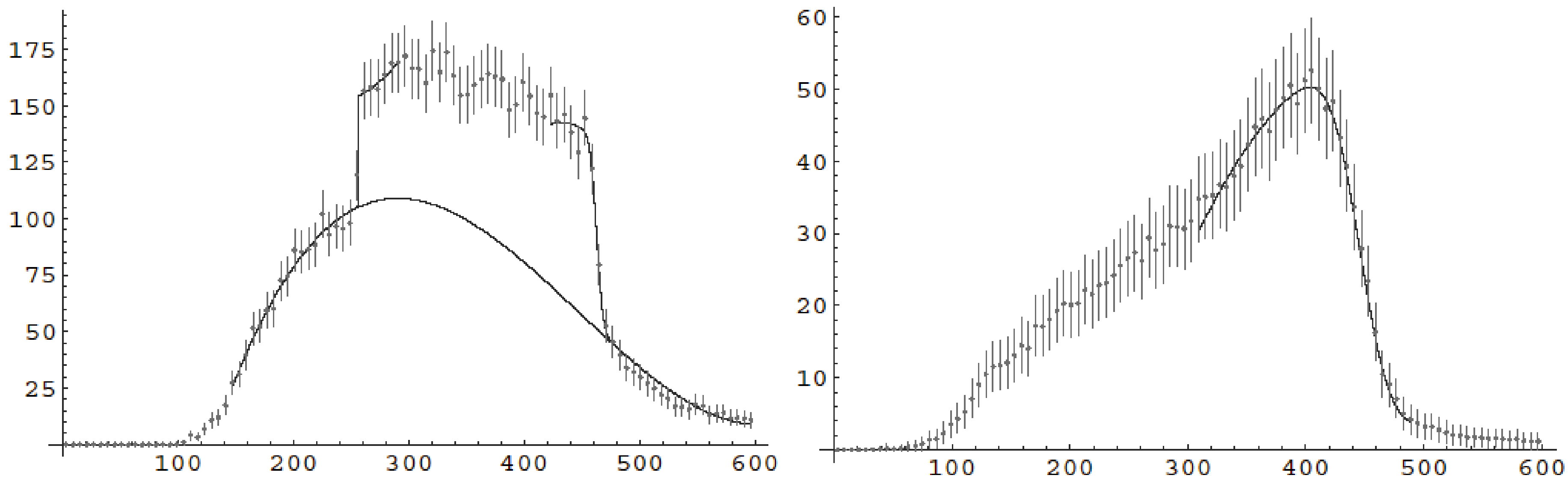


Figure 2: *Fits to m_{jll} distribution for $\tilde{\chi}^0_3$ and $\tilde{\chi}^0_2$ production at LHC.*

Need for the ILC

- four kinematic (mass) edges → four mass parameters

$$m_{ll,max} = m_{\tilde{Z}_2} - m_{\tilde{Z}_1} = 73.5 \pm 0.6 \text{ GeV}$$

$$m^2_{jll,max,2} = (m^2_{\tilde{Z}_2} - m^2_{\tilde{Z}_1})(m^2_{\tilde{b}_1} - m^2_{\tilde{Z}_2})/m^2_{\tilde{Z}_2} = 447.0 \pm 20.0 \text{ GeV}$$

$$m^2_{jll,min,3} = f(m_{\tilde{Z}_1}, m_{\tilde{Z}_3}, m_{\tilde{Z}_2}, m_{\tilde{b}_1}) = 256.2 \pm 7.0 \text{ GeV}$$

$$m^2_{jll,max,3} = f(m_{\tilde{Z}_1}, m_{\tilde{Z}_3}, m_{\tilde{Z}_2}, m_{\tilde{b}_1}) = 463.5 \pm 9.0 \text{ GeV}$$

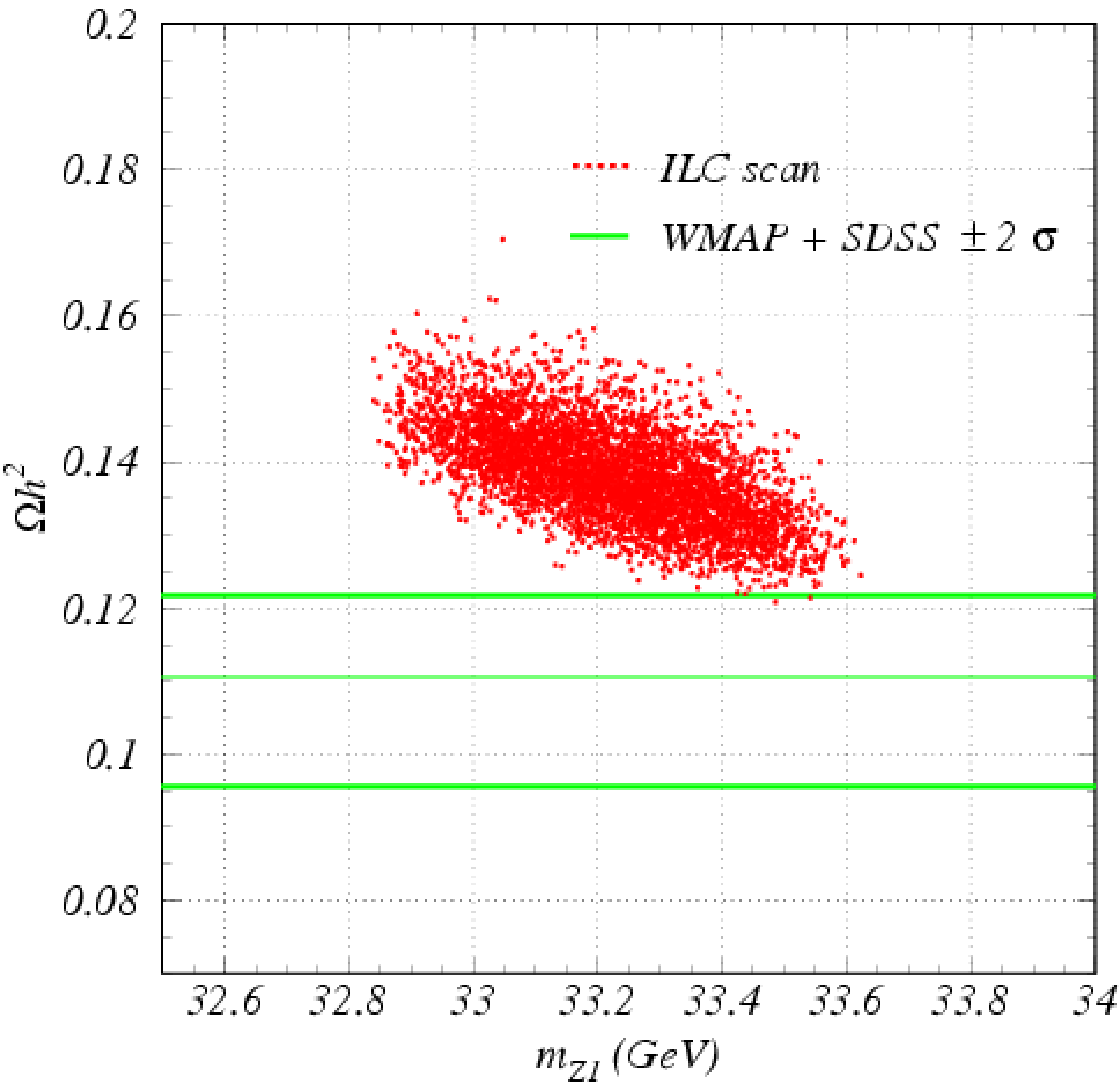
- individual masses

$$m_{\tilde{Z}_1} = 33^{+32}_{-18} \text{ GeV} \qquad m_{\tilde{Z}_2} = 107^{+33}_{-18} \text{ GeV}$$

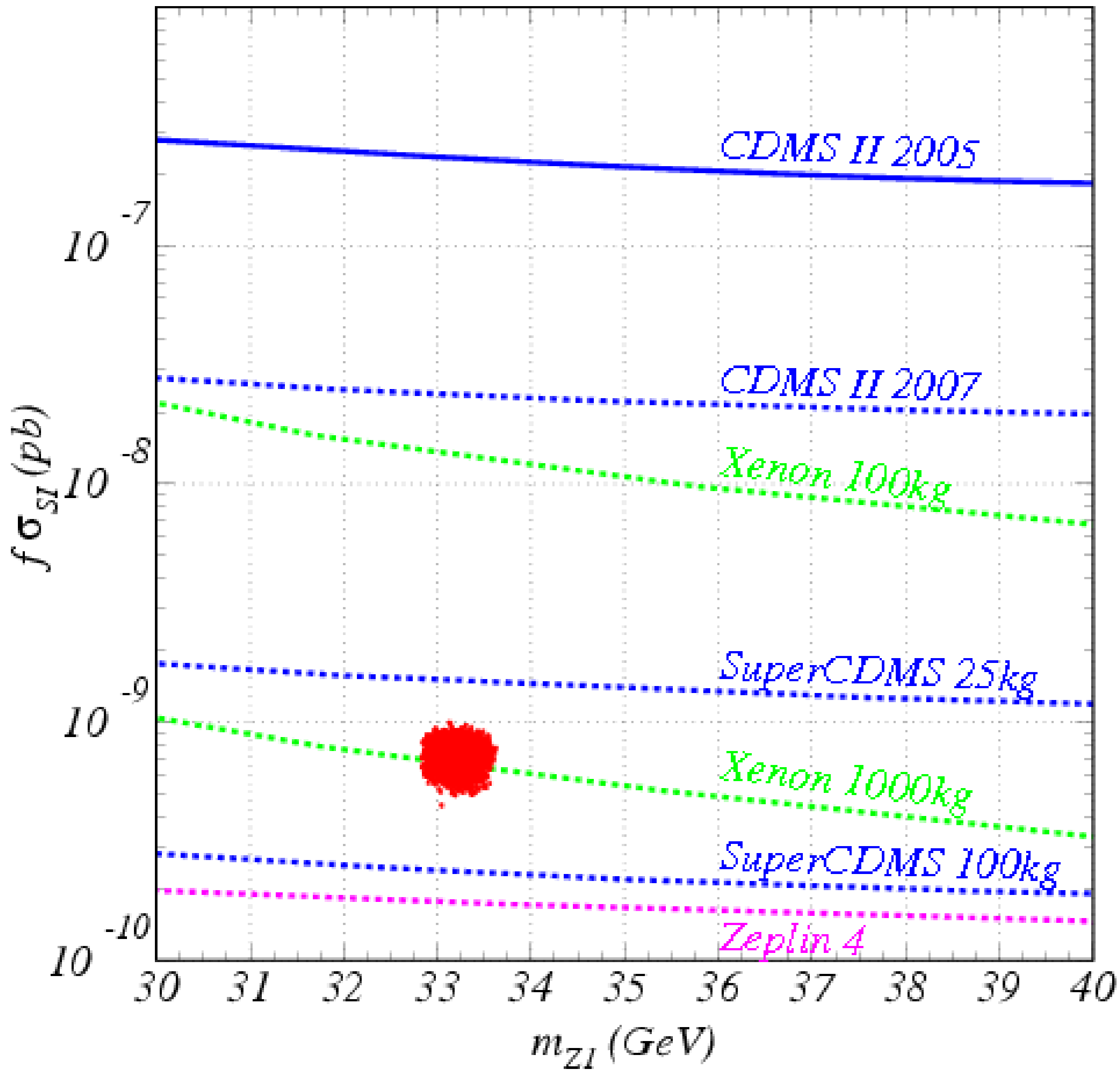
$$m_{\tilde{Z}_3} = 181^{+20}_{-10} \text{ GeV} \qquad m_{\tilde{b}_1} = 499^{+30}_{-17} \text{ GeV}$$

- absolute precision is reasonable but $\tilde{Z}_1$ is very light!

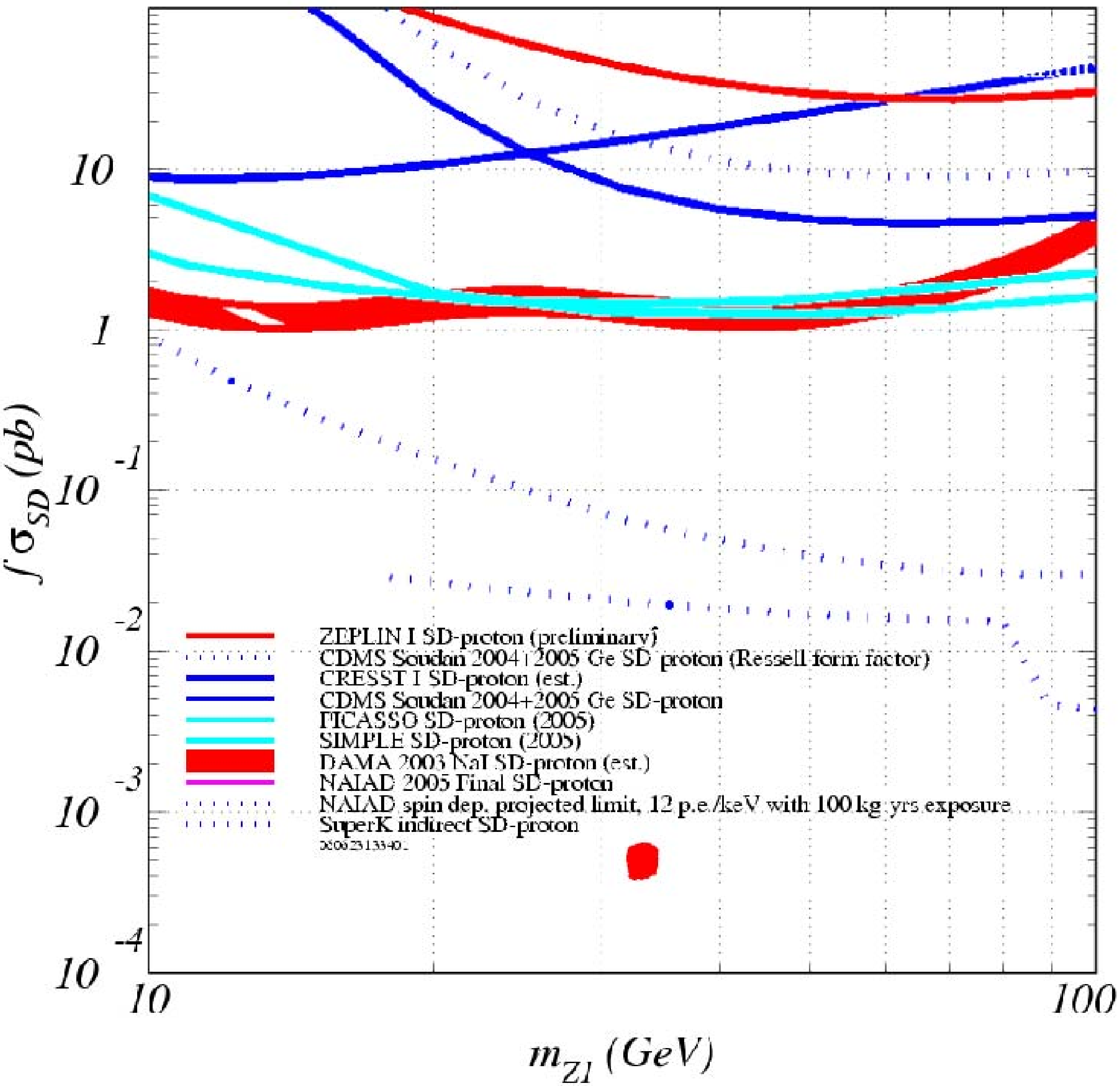
Need for the ILC



Direct detection



(in)Direct detection



Conclusions

nMSSM improves on MSSM: no μ problem, no (less) fine-tuning, less constrained spectrum

Electroweak baryogenesis less constrained in nMSSM due to tree level cubic contribution to scalar potential

All matter in the Universe can be simultaneously generated in the nMSSM

ILC precision is critical for determining astrophysical parameters: relic density, WIMP-nucleon scattering, ...