Impact of collider data on uncertainties in relic density

B. Allanach, G. Belanger, F. Boudjema, A. Pukhov

- **Introduction**
- **Coannihilation scenarios in mSUGRA and MSSM**
- **Focus point and funnel region**
- **Some remarks beyond mSUGRA**

LC-Cosmology

- Cosmology (relic density of dark matter) strongly constrains SUSY models, in particular, in mSUGRA, points to specific scenarios for SUSY searches at colliders
- With WMAP :

  $.094 < \Omega h^2 < .128$ (2 sigma)
- PLANCK expects precision of 2%
- LHC will test SUSY Dark Matter hypothesis (can also have some LSP signal from direct detection experiments), with precision measurements of SUSY parameters at LHC/LC can one match the precision of the relic density measurement by WMAP/PLANCK hence consistency check on cosmological model

- In mSUGRA one must appeal to very specific mechanisms to reach agreement with WMAP. The main reason

The LSP is mostly bino

- A bino LSP annihilates into fermion pairs through
  - t-channel exchange of right-handed slepton

- The coupling is U(1) strength annihilation cross section for neutralino pairs is not efficient enough too much relic density

Need rather fine adjustment of parameters to meet WMAP

Need very precise determination of parameters for an accurate prediction of relic density

- In mSUGRA the only possibilities : coannihilation, Higgs resonance, or Higgsino LSP (in focus point)

- In more general MSSM:
  - Coannihilation can also occur (not necessarily with stau/stop)
  - Higgs funnel regions are also found (even at low tanbeta)
  - In addition to scenarios with Higgsino LSP, also possible to have wino LSP: Examples: AMSB, dilaton-dominated/moduli-dominated, non-universal SUGRA ....

- **In the WMAP favoured region of mSUGRA the relic density is very sensitive to**
  - Δ *M(NLSP-LSP)*

    μ
  - *MA-2M* χ

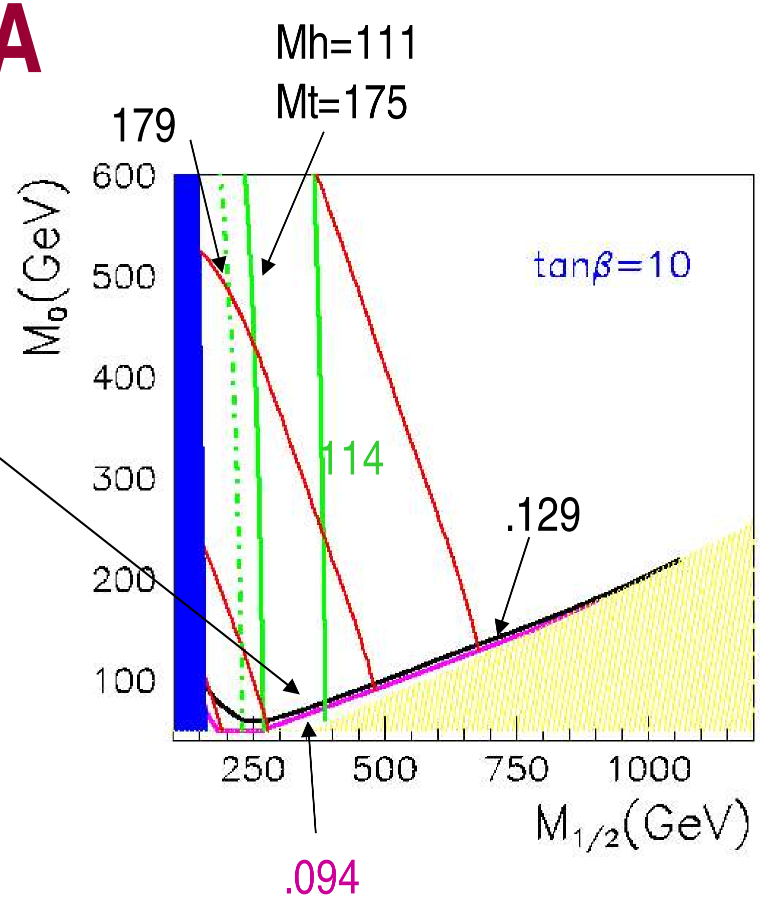
- **How precisely do the physical parameters (MSSM/SM) need to be measured at LHC+LC colliders to have prediction for Ω h^2 competitive with WMAP/PLANCK**

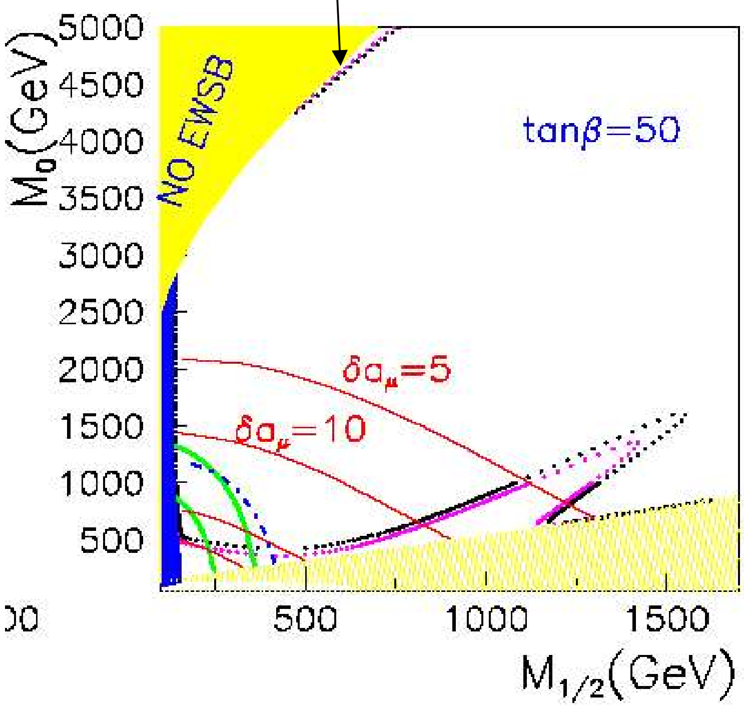
  Consistency check on cosmological model

- **Two cases:**
  - **mSUGRA: expect also strong dependence on SM parameters that affect the SUSY spectra, eg. mt, mb …**
  - **pmSUGRA : take mSUGRA spectrum then change weak scale parameter and recalculate mass spectrum WITHOUT imposing mSUGRA or electroweak symmetry breaking condition**
- **Input parameters :** ***Susy Les Houches Accord (P.Skands et al..)***
  - *Pole masses, mixing matrices …*
  - *These parameters are taken from SUSY spectrum calculator code (softSUSY)*
  - *Relic density computed with micrOMEGAs_1.3*

mSUGRA

- Hardly any "Bulk" region
- Coannihilation with stau
- Higgs resonance
- Higgsino LSP: focus point





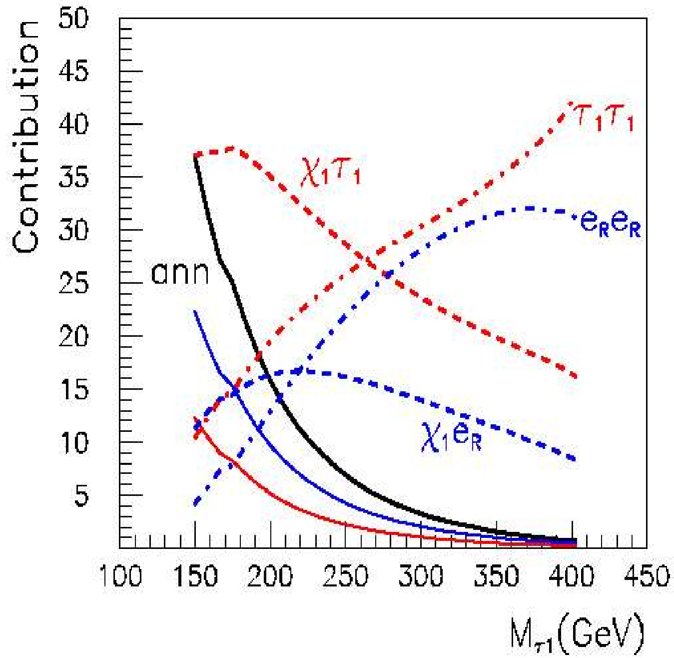
Coannihilation region

tan =10, A=0 μ>0

- Almost degenerate stau-LSP
- Dominant annihilation channel -> tau pairs
- As one increases M_{LSP} coannihilation channels become dominant
- $h^2 \sim 1/(\ _{eff} v)$
- Coannihilation processes are suppressed by factor

$$\exp^{-\Delta M/T_f}$$

  – h^2 very sensitive to Δ M



Slope:

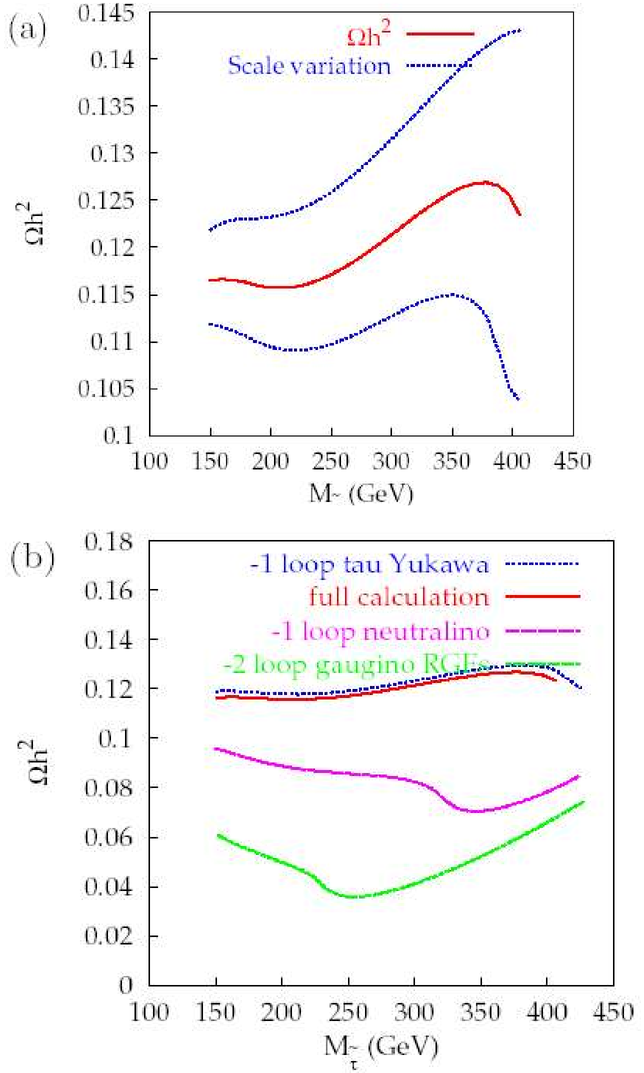
$$\frac{m_0}{\mathrm{GeV}} = 20.3333 + 0.134\frac{M_{1/2}}{\mathrm{GeV}} + 5.0667 \times 10^{-5}\left(\frac{M_{1/2}}{\mathrm{GeV}}\right)^2 .$$

mSUGRA: coannihilation

- **Scale dependence**
  - Estimate of present theoretical uncertainties from higher order effects in calculation of physical spectrum
  - In SoftSusy vary M(susy)

    ½<M'/M<2
  - Δ : 5-20%

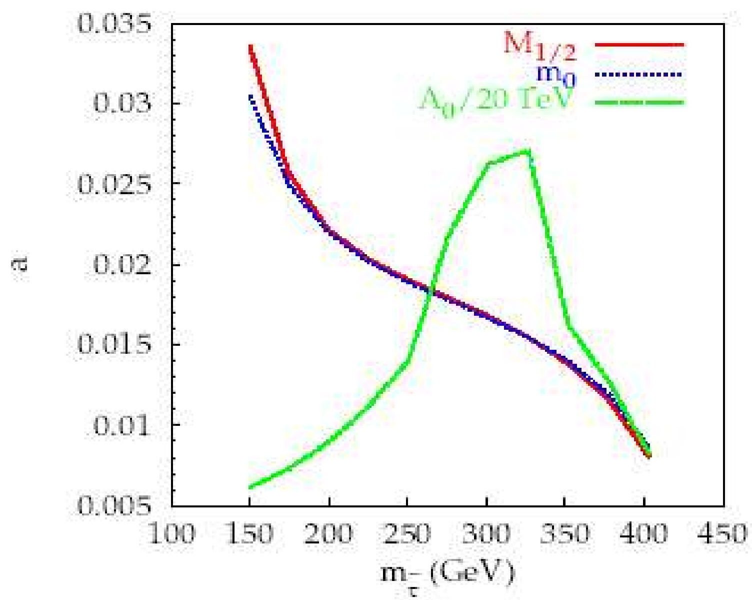
- **Important higher-order corrections are those that affect mass of stau and LSP**
  - One-loop threshold corrections to neutralino masses
  - Two-loop terms in RGE of gaugino masses
  - Neglected higher-order corrections should be suppressed 1/100??



mSUGRA: Coannihilation

- Precision on various parameters to get prediction of relic density with 10% uncertainty (WMAP)
  (roughly scale by a factor 5 for PLANCK)

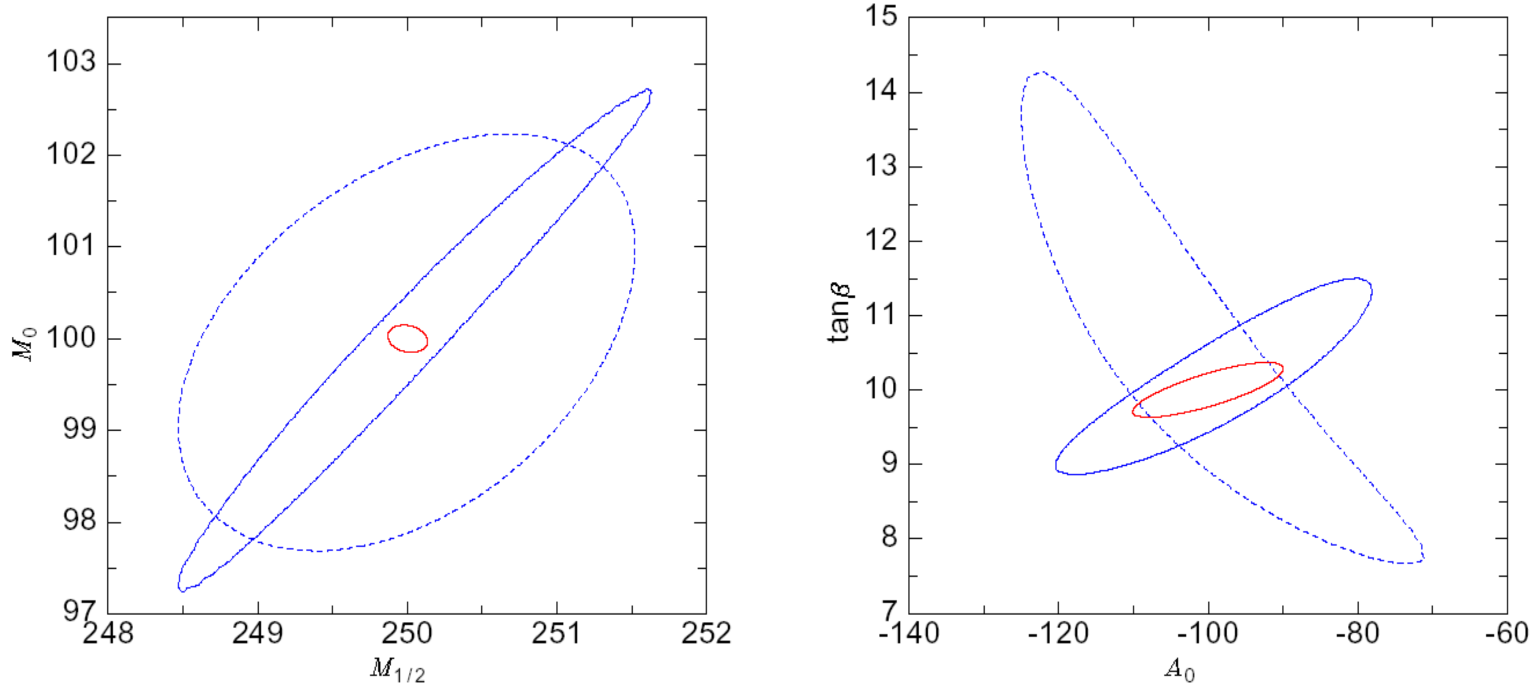
- Need a precision of 3% on M0-M1/2 (1% at higher masses)
  - Comparable to LHC on SPS1A
  - No need of accurate measurement of mstau or Δ M when assuming mSUGRA
  - Too meet precision of PLANCK need LC
- Δ (A0)~200GeV



$$r = \frac{d \ln \Omega}{d \ln \Delta M}.$$

a= 0.1/r (WMAP)

$\tan\beta = 10,\ M_0 = 200\ GeV,\ M_{1/2} = 250\ GeV,\ A_0 = -100,$
$sign(\mu) = 1$ (1 σ errors)



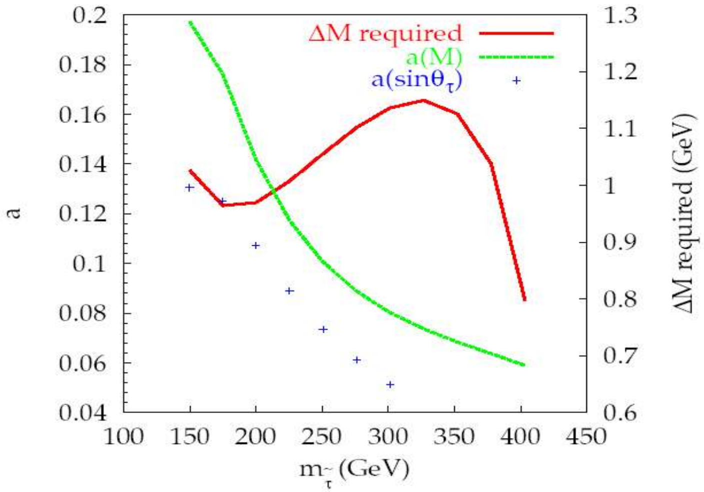
"LHC", experimental errors
"LHC", experimental errors + todays theoretical error (scale dep.)
"LHC+LC", experimental errors

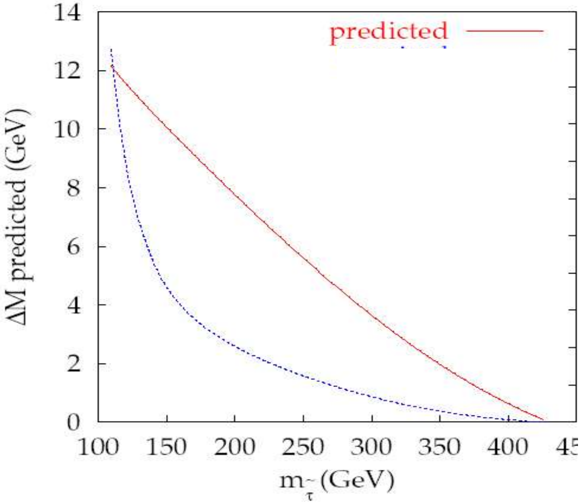
Allanach et al, hep-ph/0403133

pmSUGRA: coannihilation

- Mass difference (NLSP-LSP) is crucial parameter
  - For relic density prediction at 10% need to know to 1 GeV
  - For PLANCK ~.2GeV
- LC can make precise measurements of sleptons with small ∆ M (Zhang et al, LCWS), Martyn(LCWS)

- To have accurate prediction of relic density in this scenario need also to know precisely the cross-section
  - Precision required on absolute mass scale (keeping ∆ M constant) 10-20%
  - Precision required on mixing angle: 5-10%





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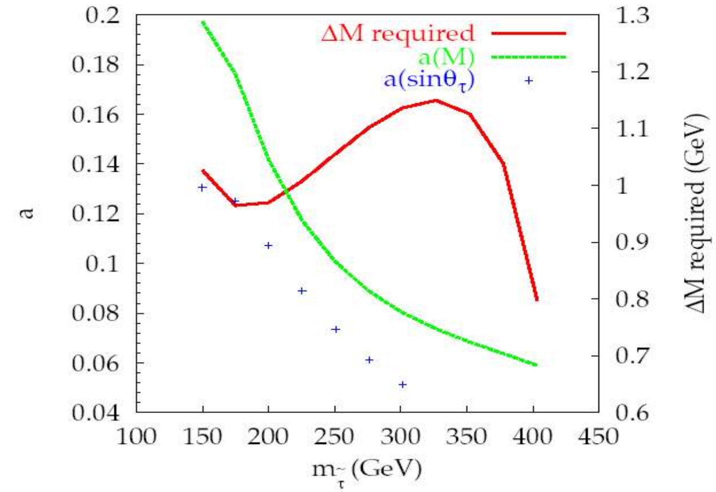

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Strategy one: (L=500fb^{-1})

Scenario		A	C	D	G	J
ΔM	(GeV)	7	9	5	9	3
Ecm	(GeV)	505	337	440	316	660
σ	(fb)	0.216	0.226	0.279	0.139	1.35
Efficiency	(%)	13.6	17.3	8.5	17.2	1.4
δm_{stau}	(GeV)	0.42	0.15	0.40	0.12	>1.0
$\delta\Omega h^2$	(%)	3.1	1.6	5.0	1.6	>14*

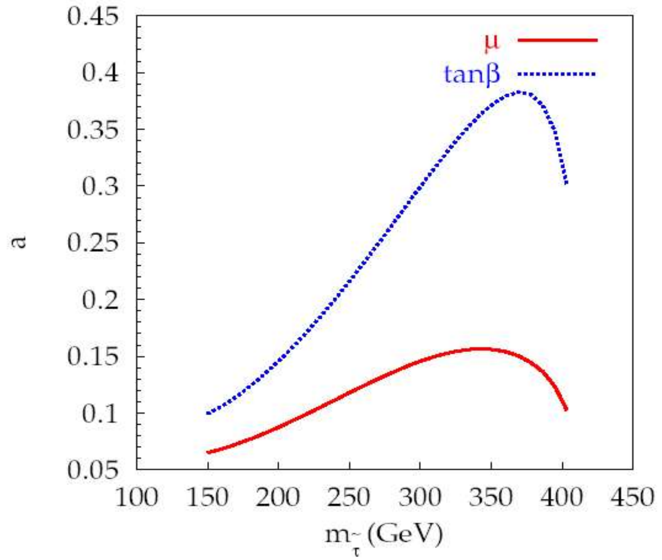
pmSUGRA: coannihilation …

- **Cross-sections also depend on MSSM parameters of neutralino/gaugino sector.**

- **In region relevant for LC500, WMAP level of accuracy requires**
  - **μ ~ 5-10% level**
  - **tan ~ 10-20% level**

- **In MSSM, SFitter/Fittino forSPS1A find**

  μ ~2% (LHC) 1%(LC)
  - **tan ~ 40% (LHC) 15%(LHC+LC)**



Error on determination of **tan** might limit the accuracy to which the relic density can be predicted

Issue specially for PLANCK

The focus point region

Sfermions are heavy : difficult for LHC

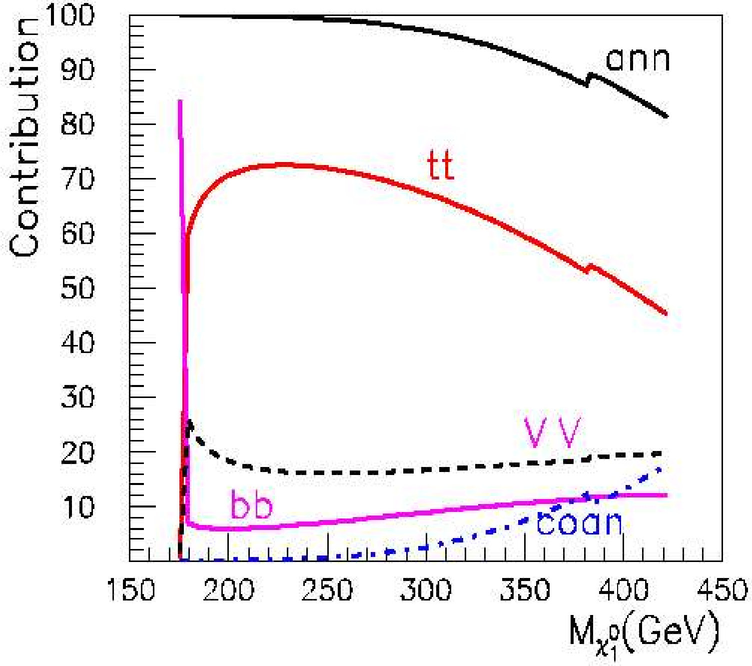
Potential for LC in gaugino/Higgsino sector

With new value for top quark focus point region is pushed to very high values of M0 for intermediate tan ,
consider tan =50

LSP has Higgsino component
μ is important parameter for relic density

Coannihilation with charginos and/or heavier neutralinos are important but do not give the main contribution when h^2~0.1

tan =50, A=0 μ>0

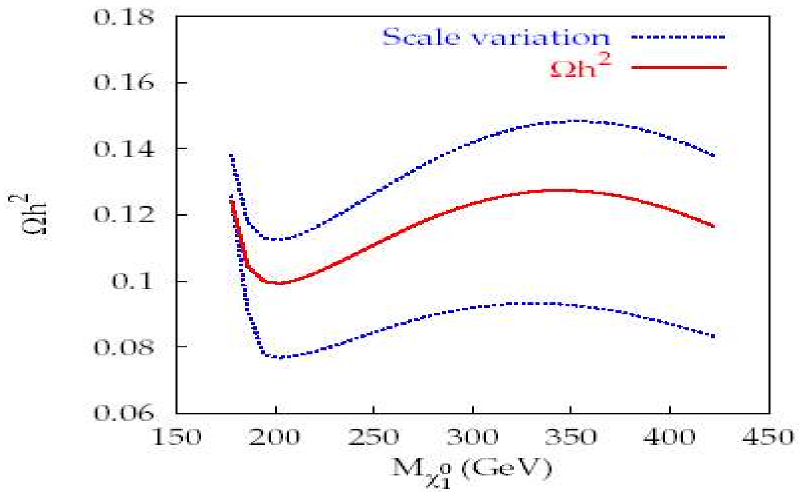


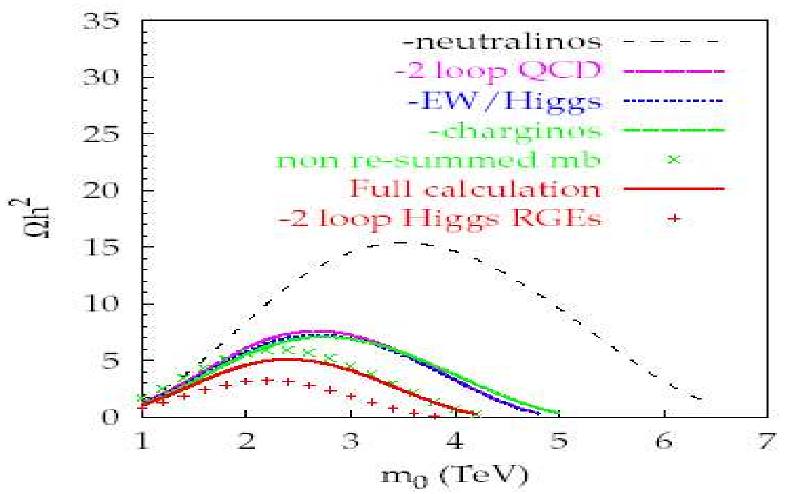
$$\frac{m_0}{\mathrm{GeV}} = 3019.85 + 2.6928\frac{M_{1/2}}{\mathrm{GeV}} - 1.01648 \times 10^{-4}\left(\frac{M_{1/2}}{\mathrm{GeV}}\right)^2 .$$

mSUGRA: focus point

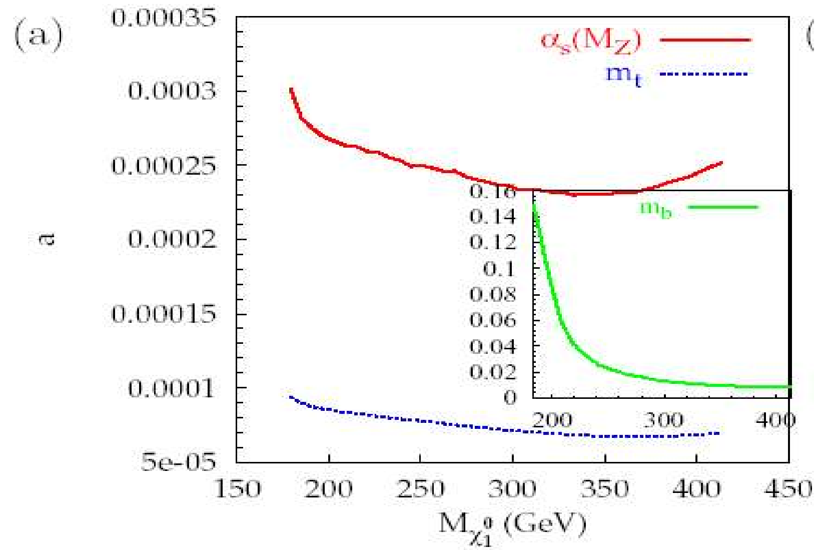
- Scale dependence
  - In SoftSusy vary M(susy)

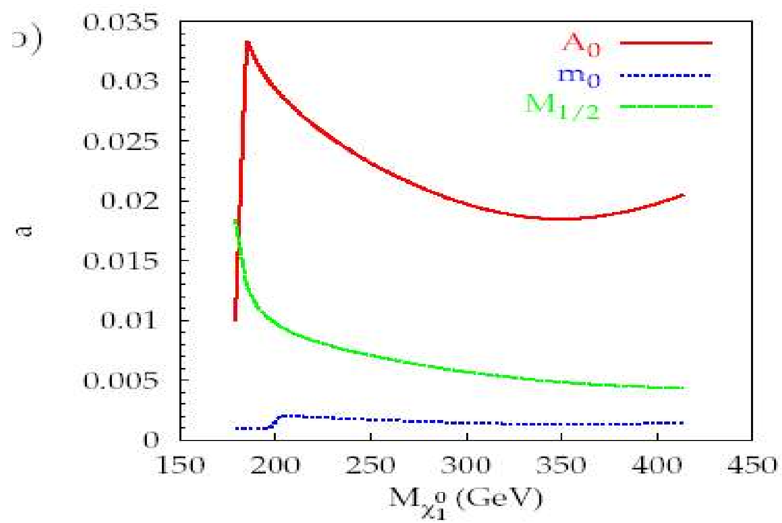
    ½<M'/M<2
  - Δ : up to 30%
  - Indicates large theoretical uncertainties
- Sensitivity to higher-order effects in RGE's: high sensitivity to h_t (see approximations in calculation of mt(mt) (DR)) in particular:
  - One-loop neutralino corrections
  - Two-loop QCD
  - One-loop electroweak and Higgs corrections
  - One-loop chargino corrections





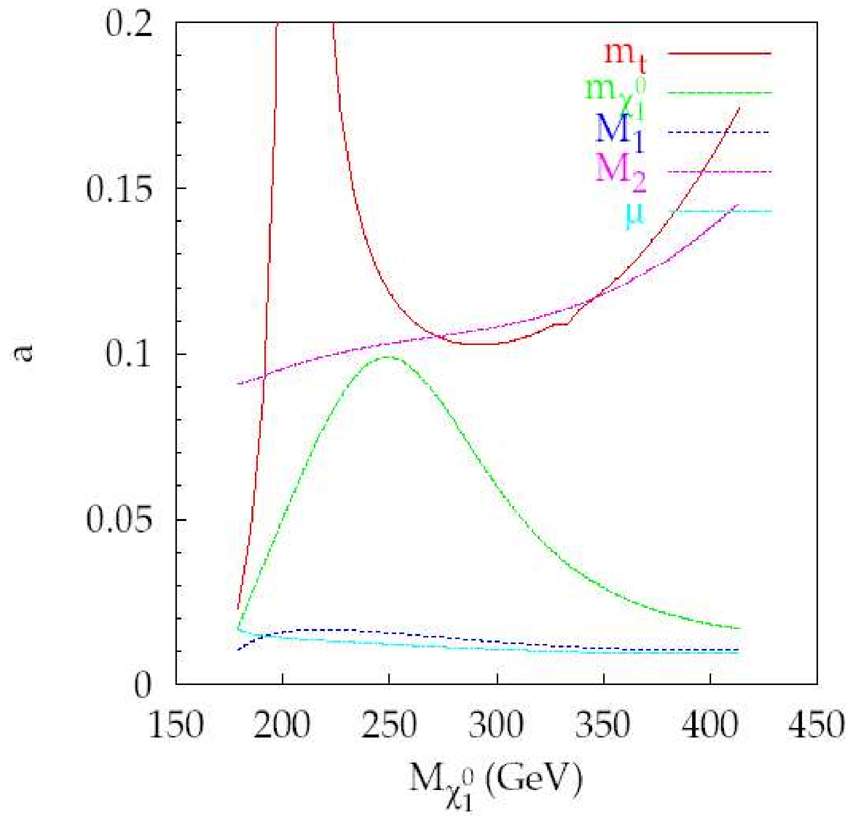
- **Precision on various parameters to get prediction of relic density with 10% uncertainty (WMAP)**
- **Huge sensitivity to**
  - **Mt (20MeV)**
    - **Expect 30MeV (exp) 100Mev(th)**
  - **$_s$(0.025%)**
    - **Affects extraction of ht from mt**
  - **Mb(mb) (1-15%)**
    - **Precision on mb(mb) is limited by non understood non perturbative corrections ~0.05**
- **msUGRA inputs must be known to few permil ($M_{1/2}$-M_0), A_0 to 200GeV**
  - **Hopeless for M_0 since all scalars are too heavy for LHC/LC**





pmSUGRA: focus point

- Situation is much better in pmSUGRA by assuming the spectrum to be measured
  - Dependence on top yukawa for calculating spectrum drops out
  - Mt dependence only in the cross-section, sensitive only near threshold (0.5GeV required for WMAP)
- Most important parameters are the ones that determine the Higgsino content of LSP –also determines couplings to Higgs/Z
  - μ,M1~% level
  - LSP mass ~5-10% level
  - Mb is known well enough for PLANCK accuracy

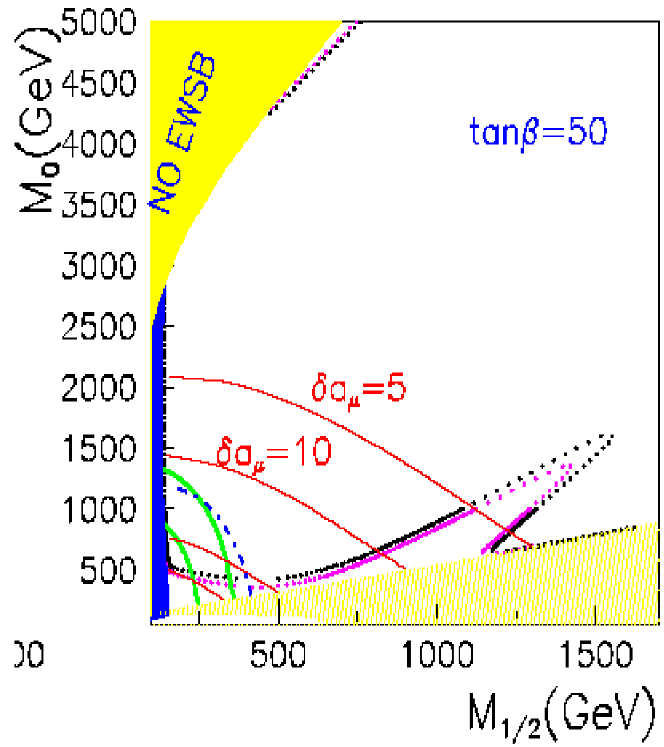


Need ILC
Means per-mil level for PLANCK
can this be done at ILC??

Heavy Higgs annihilation

- Heavy Higgs resonance (funnel)
  - Heavy Higgs enhanced coupling to b quarks
  - Large width
  - Acceptable relic density if
    - $M(LSP)-M_A/2 \sim {}_A$
- Main annihilation channel into bb pairs
- Most of Heavy Higgs annihilation region at large tan is not accessible to LC500 (or LHC).
- Even at low $M_{1/2}$, important contribution of diagram with heavy Higgs exchange (as well as slepton exchange) possible far from resonance even if M (LSP)<200GeV
  - Constraint from b->s important
  - What are relevant parameters and how precisely should they be measured to get precise estimate of relic density (MA 300-400GeV)

Mt=175

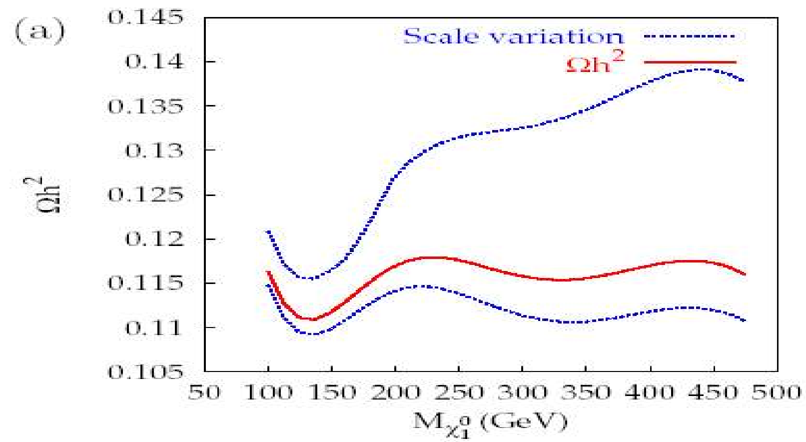


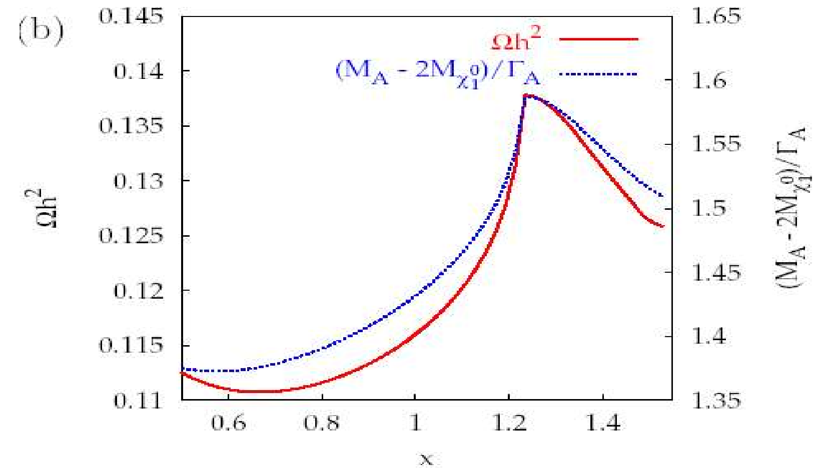
mSUGRA: Higgs funnel

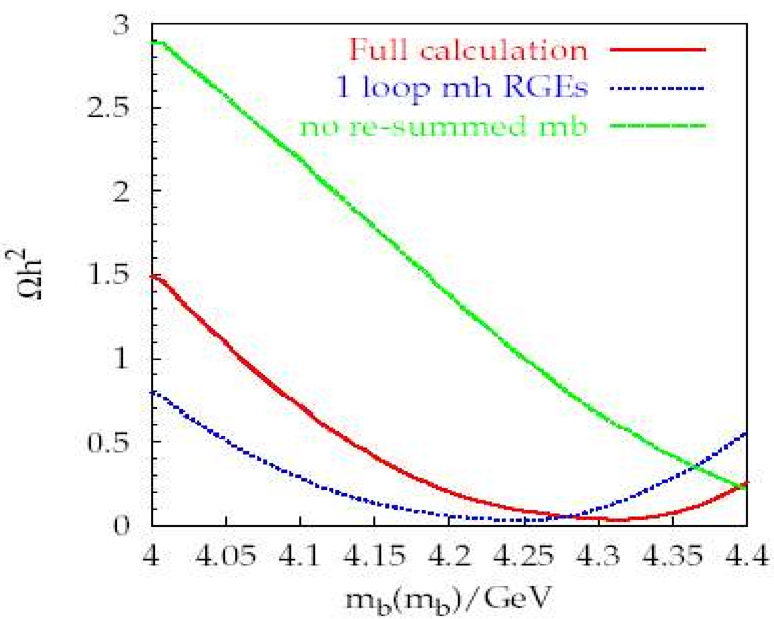
tan =50, A0=0, μ >0

- Again strong scale dependence (5-20%)
- Perfect correlation between shift in relic density and $(M_A\text{-}2M_{LSP})/\ \ _A$
  - For m0=1000, $M_{1/2}$=1100GeV
- Resummation of large tan SUSY correction to $\Delta\ ^b$ is essential

(through impact on M_A)







$M_0=814-2.2M_{1/2}+.0033M_{1/2}^2-1.1\ 10^{-6}M_{1/2}^3$

(p)mSUGRA: Higgs funnel

- **In mSUGRA: strong dependence on mt, mb(mb), $_s$ but not as bad as focus point region**
  - **With Δ mt =.8GeV can predict h^2 with 10% precision**
    - **ILC accuracy enough even for PLANCK**
  - **Mb(mb) dependence can be controlled by measuring the A width**
    - **Need per-mil precision**
- **Main problem is** tan , shifts in tan induce shifts in MA / M(LSP) , 10%accuracy on would require %level on tan

Precise predictions of relic density within this mSUGRA scenario not possible . Much more reliable predictions after determination of MSSM parameters

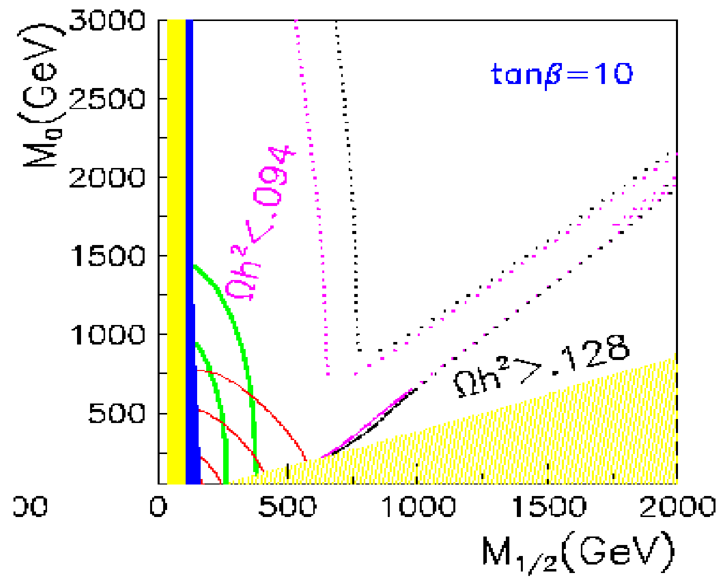
- **In pmSUGRA, since MA is kept constant, mt, mb(mb), $_s$ dependence is weak**
  - **Most important parameter is ($2M_{LSP}$-MA), this quantity can be measured at per-mil level at LHC/LC**
  - **The A width is not an important parameter (far enough from resonance)**
  - **Also need to know μ**, tan

Some remarks

- mSUGRA inspired models might seem too restrictive but even in other scenarios relic density from WMAP often imposes coannihilation /Higgs funnel/ Higgsino LSP Results presented are relevant for more general MSSM models
- Other cases not considered yet
  - stop NLSP, e.g. in mSUGRA with large A0
    - Mass difference should be critical parameter for relic density prediction (Δ M~30-50GeV)
  - Wino LSP :
    - scenario that cannot be realized in mSUGRA
    - much easier to satisfy relic density constraint if LSP not bino,
    - One example: changing the gaugino mass relations at GUT scale
    - Important to also consider such scenario

- M1~1.8M2 at GUT scale
  M1~M2 at weak scale

$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow$ WW



GB, Boudjema, Cottrant, Pukhov, Semenov hep-ph/0407218

Summary

- We have examined the requirements for measurements of MSSM parameters to make reliable predictions for the relic density
- Theoretical uncertainties in mSUGRA (scale dependence) are too high as compared to WMAP precision, especially in focus point and Higgs funnel need to include higher order effects
- Experimental information necessary is demanding within mSUGRA, sufficient accuracy can be reached at LHC/LC in coannihilation region, m_t is problem in focus point.
- Situation is better if after having determined roughly the SUSY scenario at LHC one directly measures the MSSM parameters
- ILC essential for precision measurement of NLSP-LSP mass difference in coannihilation region (can even be competitive with PLANCK precision)
- In focus point region, need high precision determination of μ .
- At large tan need precise determination of ($MA-2M_{LSP}$) LC

Relic density and MSSM parameters

- With expected precision from hadron Collider **Δ Mt=1-2 GeV, prediction for can vary by more than one order of magnitude**

- With expected precision from LC Δ mt=0.1GeV still large corrections to h^2 (up to 100%)

- Need to improve on theoretical predictions

- **In terms of MSSM parameters rather than mSUGRA, prediction for h^2 more stable (recall measuring μ few per-mil is needed to match PLANCK accuracy)**