Impact of precision measurements for dark matter constraints

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- Short Intro
- Parameter determination
- Results on DM
- Conclusions

LINEAR COLLIDER COLLABORATION

In the following

Evaluate $\Omega_\chi h^2$ using parameters from $\chi^+_1\chi^-_1$ @NLO:

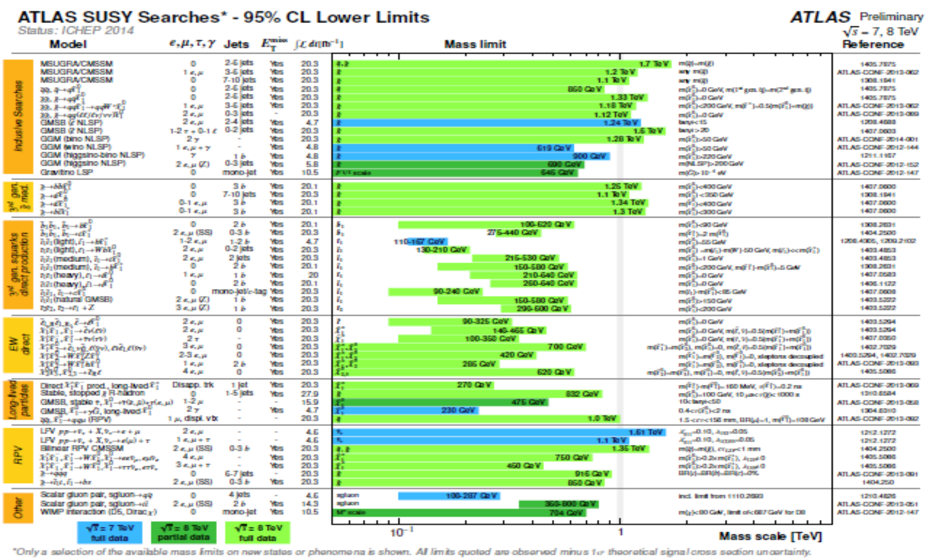
- Our recent NLO analysis showed precise determination of M_1, M_2, $\tan\beta$ + m_{stop1}, $\cos\Theta_t$, M_A possible at LC
- In pMSSM, $\Omega_\chi h^2$ requires ΔX_i, i = 1 to 19
- If combining the parameters $\Delta X_i^{LHC/LC}$, what is the precision in $\Omega_\chi h^2$?

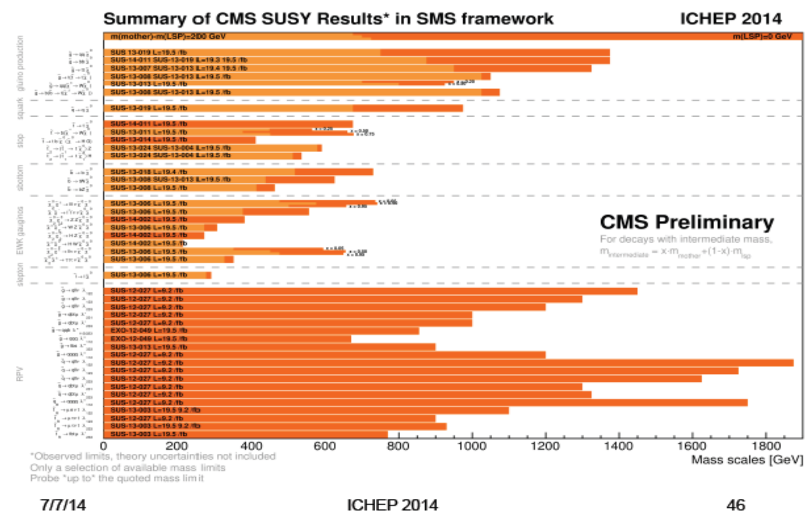
Idea

- Convert SUSY measurements into crucial dark matter test
  - Turn LHC+LC measurements into precise SUSY parameters
  - Predict $\Omega_\chi h^2$ on basis of parameter determination
- Which precision is sufficient to be competitive with cosmo?
  - Remember Planck2013: $\Omega_\chi h^2 = 0.120 \pm 0.003$
- Which tools and theory level are required for matching?
  - In order to calculate $\Omega_\chi h^2$ one requires all SUSY parameters
  - With LHC results: calculate $\Omega_\chi h^2$ in CMSSM
  - escape CMSSM exclusions via pMSSM@LC
- Advantages LC:
  - more tools (polarization, threshold scans,ISR method)
  - higher precision (up to quantum level)

Impact from LHC BSM limits

- **SUSY: still strongly motivated and beautiful, but**
  - so far, no hints of a signal, only rather high exclusion limits in the coloured sector
  - Constrained models (CMSSM,…) + Simpl. Models under tension!





- **Further hints from theory?**

Further SUSY facts

- **Low energy experiments, $(g\text{-}2)_\mu$:**
  - favours rather low SUSY masses in electroweak sector:

$$\delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$$

    - C very model dependent, SUSY/ED ~ O(α/4π …)
  - LHC results prefer rather heavy coloured sector in 1^{st} +2^{nd} generation
  - Way out: rather simple
    - Decouple uncoloured and coloured sector and/or take hybrid models of SUSY breaking
    - Just leave out the constrained minimal models, that's all

Remember: Minimal SUSY contains 105 new parameter… why should nature be too simple ?

Why 'should' light SUSY be preferred?

- **Minimization of 1-loop Higgs Potential:**

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -(m_{H_u}^2 + \Sigma_u^u) - \mu^2$$

- **To keep EWFT ~ 3%:**
  - **rather small μ (~200 GeV) required**
  - **'naturalness'**
  - **Several 'natural' scenarios: light stops and light higgsinos,…**

Papucci,Ruderman,Weiler 2011
Baer,Barger,Huang, Tata, 2012

Strategy

- Studied process: $e^+e^- \longrightarrow \chi^+\chi^-$
  - Input : measured masses of $\chi^\pm$, χ^0, via continuum or threshold
  - Measured polarized cross setions at 350 and 500 GeV
  - Measured A_{FB} of this process
- Determine fundamental parameters: M_1, M_2, μ, $\tan\beta$
  - Fine, very accurate results …. <% level
  - Predict dark matter contribution
  - Well known: loop corrections in SUSY at same level of accuracy
- Apply / evaluate ‘loop’ corrected cross sections (and masses)
  - Fit sensitive to heavier virtual particles (m_{stop}, m_A)
  - Parameters in the range of loop-corrected observables

Status DM searches

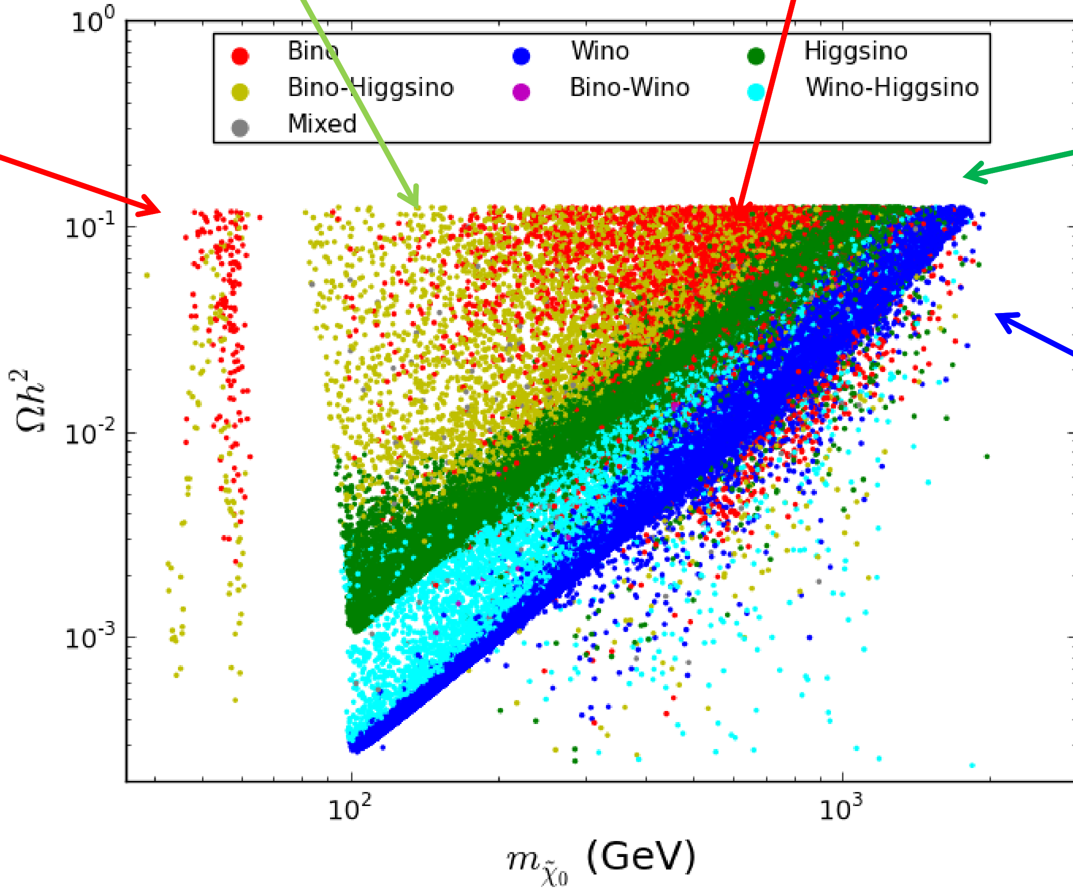
Bino-Higgsino mixture,
Closest case to the
WIMP miracle

Pure Bino needs co-annihilation with other quasi-degenerated SUSY partners

Bino-like that can annihilate through the h or Z "funnels"

Higgsino, ~ 1.5 TeV

Wino, ~ 3 TeV



Snowmass '13 (Hewett, Rizzo, et al.)

Criteria for scenarios

- In the MSSM $\Omega_\chi h^2$ depends strongly on region
  - $m_{\chi 01} \sim m_\tau$ (stau coannihilation)
  - $m_{\chi 01} \sim M_A$ (funnel)
  - $m_{\chi 01} \sim \mu$ (focus point)
- We assume:
  - Assume light Bino/Wino satisfying unification relations
  - Light higgsino satisfying relic density in focus point region
  - Light stops, large A_f, strong mixing in stop sector: Higgs mass
  - Other squarks and gluino heavy due to LHC constraints

Scenarios

- **Scenario 1: Focus point region**
  - Heavy sleptons (m_{sel} accessible in the fit)
  - Charged Higgs (1TeV) - inaccessible: creates uncertainty

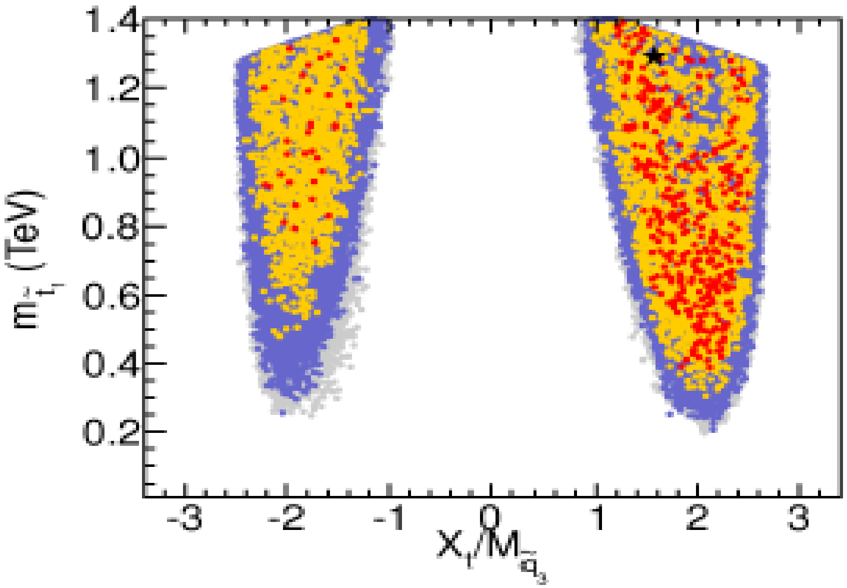
- **Scenario 2: Hybrid (focus point/bulk) region**
  - Light sleptons, accessible at LHC and/or LC(500)
  - Lighter charged Higgs (500 GeV). NLSP is $stau_1$.

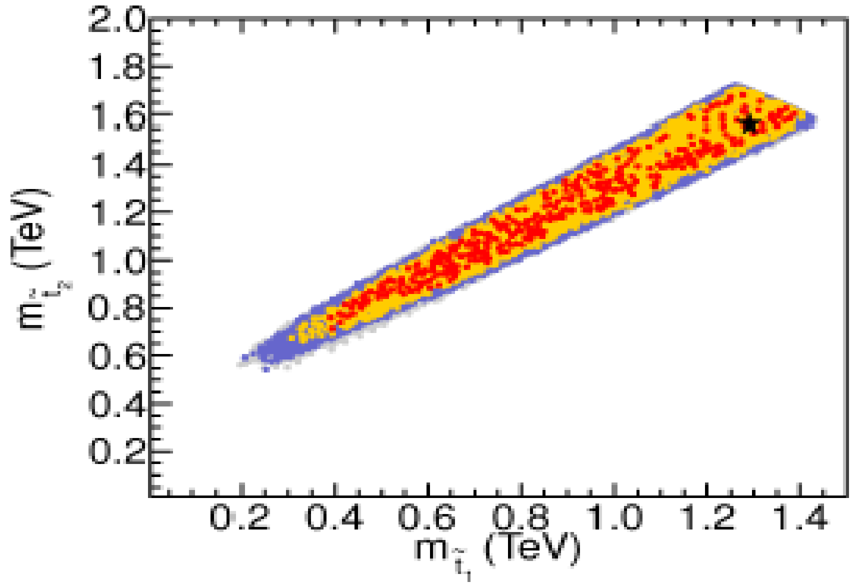
- **Scenario 3: Focus point region**
  - Same characteristics as above, but adjusting dark matter bound

Impact of stop mixing on light Higgs

- **MSSM fit, preferred values for stop masses**

Bechtle, Heinemeyer,Stal,Stefaniak,Weiglein,Zeune





- **Rather large X_t=A_t-μ cot β**

➢ **Large stop mixing required**

Best fit prefers heavy stops beyond 1 TeV

But good fit also for light stops down to ≈300 GeV

LC: Parameters from $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$

- **In the past:** parameter determination at tree level
  - Extracted from $\sigma^{\pm}_{L,R}$ polarized cross sections at $\sqrt{s}$=350 and 500 GeV, masses $m\chi^{\pm}_1$ and $m\chi^0_1$ with 500 fb^{-1}

SUSY Parameters				Mass Predictions		
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5	378.8 ± 7.8	359.2 ± 8.6	378.2 ± 8.1

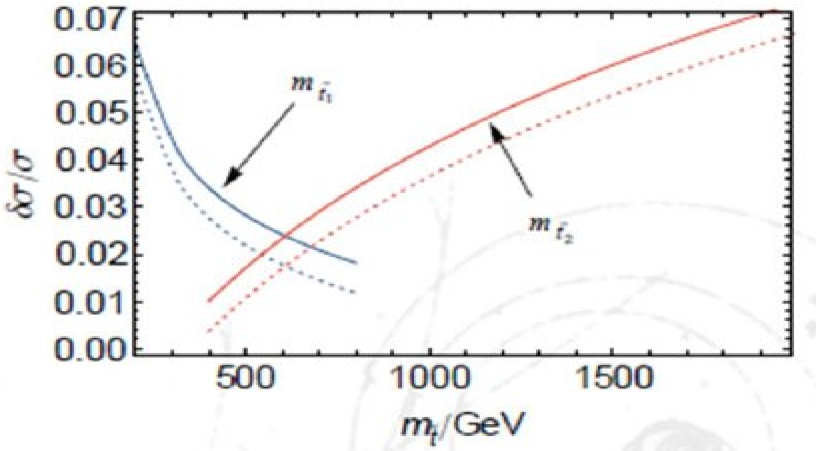
  - If even the sleptons masses ('focuspoint') were too heavy, use in addition A_{FB} of final l or q

$$59.45 \le M_1 \le 60.80 \text{ GeV}, \quad 118.6 \le M_2 \le 124.2 \text{ GeV}, \quad 420 \le \mu \le 770 \text{ GeV}$$
$$1900 \le m_{\tilde{\nu}_e} \le 2120 \text{ GeV}, \quad m_{\tilde{e}_L} \ge 1500 \text{ GeV}, \quad 11 \le \tan\beta \le 60.$$

- **Today:** incorporate contributions from one-loop

LC: Parameters from $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$@NLO

- **However:** Loop effects known to be relevant
  - Sensitivity to parameters arising from loops, e.g. stop- and Higgs sector



Bharucha, Kalinowski, GMP, Rolbiecki, Weiglein ‘12

- **But:** Strategies for parameter determination still applicable?
  - Known that SUSY loop effects might be large
  - $\Delta\sigma_{exp} \sim \Delta\sigma_{NLO}$: apply loop-corrected polarized $\chi^+_1\chi^-_1$ cross sections at $\sqrt{}$350 and 500 GeV
  - Apply loop-corrected A_{FB} at both energies
  - Assume masses of $\chi^\pm_1, \chi^\pm_2, \chi^0_1, \chi^0_2, \chi^0_3$ have been measured
    - via continnum measurement versus via threshold scan

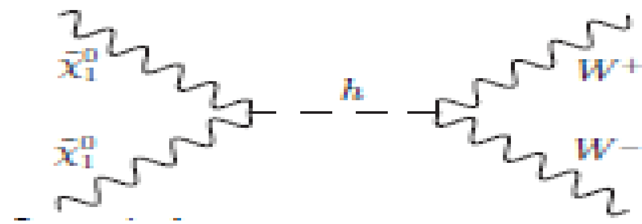
- **Apply fit to: M_1, M_2, μ, $\tan\beta$, $\cos\Theta_t$, m_{t1}, m_{t2} and m_{sneu} (M_A)**

Fit results@Loop Level

- **Scenario 1: Focus point region**

Parameter	Scenario A
M_1	$123 \pm 0.3\,(0.6)$
M_2	$250 \pm 0.6\,(1.6)$
μ	$182 \pm 0.4\,(0.7)$
$\tan\beta$	$10 \pm 0.5\,(1.3)$
m_{A^0}	1000 ± 500
M_3	1000 ± 100
$m_{\tilde{t}_1}$	400 ± 40
$m_{\tilde{t}_2}$	800 ± 80
$\cos\theta_t$	0.46 ± 0.15
$m_{\tilde{b}_1}$	400 ± 40
$\cos\theta_b$	0 ± 0.06
$m_{\tilde{\tau}_1}$	403 ± 40
$m_{\tilde{\tau}_2}$	801 ± 80
$\cos\theta_\tau$	0 ± 0.02
$M_{q_{1,2}}$	1500 ± 500
$M_{l_{1,2}}$	$1500 \pm 24\,(20)$
$M_{e_{1,2}}$	1500 ± 500

$X^0_1 = 0.83B - 0.18W + 0.44h_1 - 0.29h_2$



- **Largest contributions to annihilation cross section:**
  - **WW (68%)**
  - **ZZ (12%)**
  - **hh (7%)**
  - **Zh (6%)**

Fit results@Loop Level

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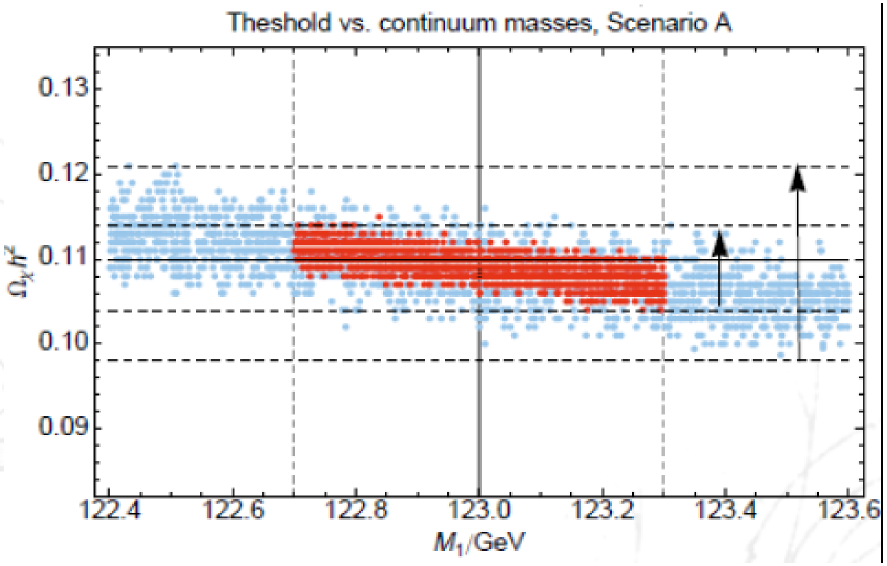
- Obtain fundamental parameters at % level
- Results depend on accuracy of measured masses:
  - If threshold scans used: additional access to stop masses/mixing
  - Analyze uncertainty on relic density

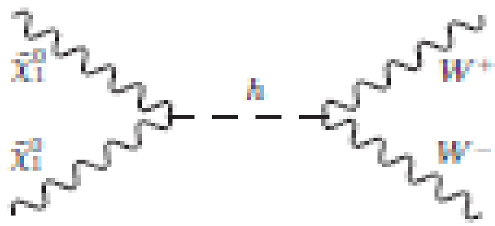


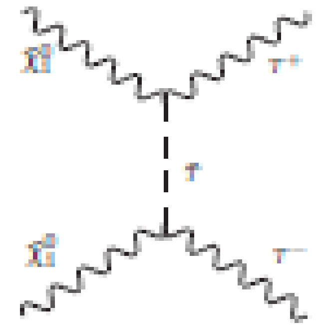
Fit results@Loop Level

- **Scenario 2: Hybrid (focus point/bulk) region**

Parameter	Scenario B
M_1	105 ± 0.3
M_2	211 ± 0.5
μ	181 ± 0.4
$\tan\beta$	11 ± 0.3
m_{A^0}	500 ± 150
M_3	1500 ± 150
$m_{\tilde{t}_1}$	430 ± 43
$m_{\tilde{t}_2}$	1520^{+200}_{-300}
$\cos\theta_t$	$0.15^{+0.08}_{-0.06}$
$m_{\tilde{b}_1}$	450 ± 45
$\cos\theta_b$	0 ± 0.01
$m_{\tilde{\tau}_1}$	105.1 ± 0.3
$m_{\tilde{\tau}_2}$	$191.3^{+14.6}_{-8.6}$
$\cos\theta_\tau$	0.29 ± 0.14
$M_{q_{1,2}}$	1500 ± 500
$M_{l_{1,2}}$	180 ± 40
$M_{e_{1,2}}$	125 ± 5

$X^0_1 = 0.87B - 0.18W + 0.41h_1 - 0.23h_2$





- **Largest contributions to annihilation cross section:**
  - WW (24%)
  - Stau stau (23%)
  - μ+μ- (10%)
  - e+e- (8%)
  - bb(7%)

Fit results@Loop Level

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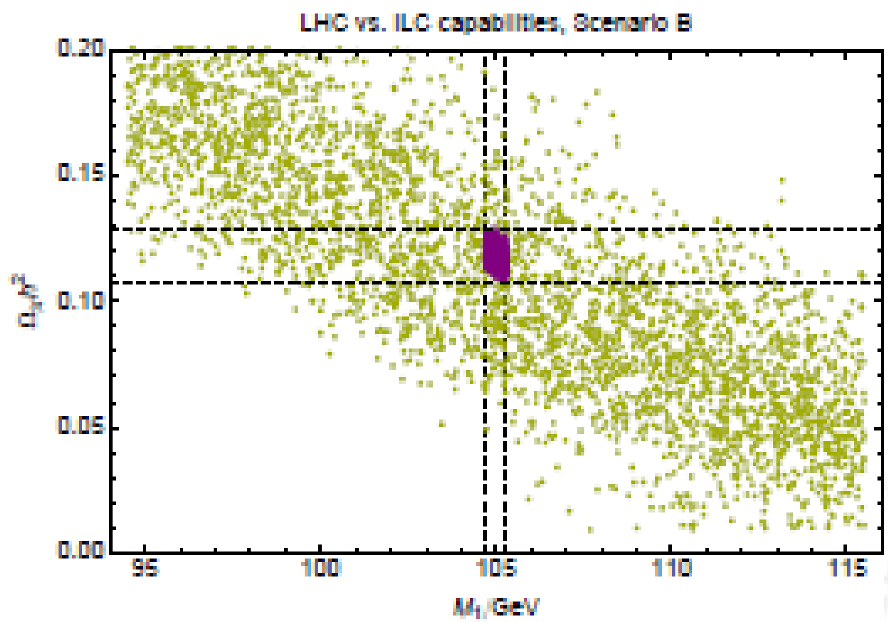
- Obtain fundamental parameters at % level
- **Not only electroweakinos but also sleptons accessible**



Fit results@Loop Level

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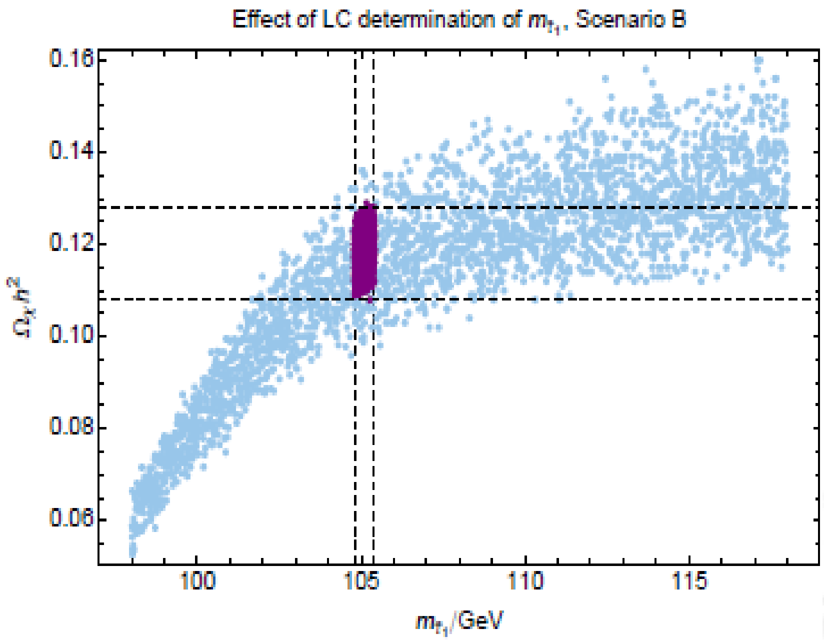
- **Effect of stau precision measurement at the LC**



Fit results@Loop Level

- **Scenario 3: Focus point region (Planck update)**

M_1	146 ± 0.4
M_2	250 ± 1.1
μ	360 ± 0.7
$\tan\beta$	5.8 ± 1.4
m_{A^0}	326 ± 3
M_3	2000 ± 500
$m_{\tilde{t}_1}$	991 ± 100
$m_{\tilde{t}_2}$	3012 ± 500
$\cos\theta$	-0.32 ± 0.15
$m_{\tilde{b}_1}$	1000 ± 100
$\cos\theta$	0 ± 0.06
$m_{\tilde{\tau}_1}$	2000 ± 500
$m_{\tilde{\tau}_2}$	2000 ± 500
$\cos\theta$	0 ± 0.02
$M_{q1,}$	2000 ± 500
$M_{l1,}$	2000 ± 500
$M_{e1,}$	2000 ± 500

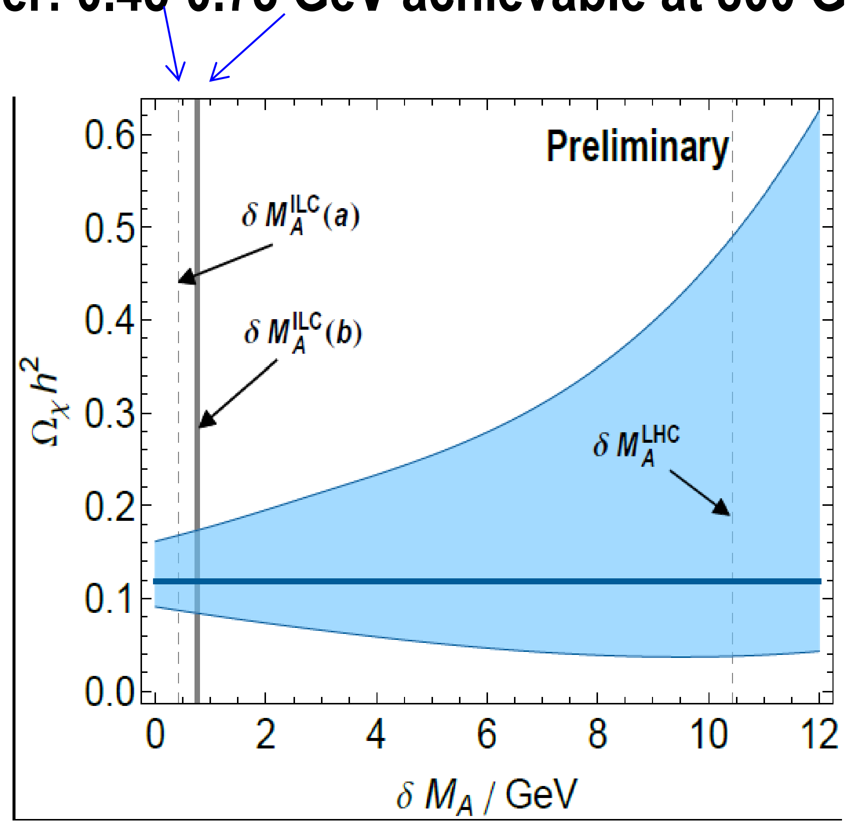
- **Obtain fundamental parameters at % level**
- **Not only electroweakinos but also sleptons accessible**
- **Largest contributions to annihilation cross section:**
  - bb (~78%)
  - l+l- (~10%)
  - hh (~4%)
  - Zh (~3%)
  - WW(~3%)

- **Sensitivity to effects of virtual particles, here: M_A**

Due to Loops: impact of M_A on $\Omega_\chi h^2$

- **Assume Δm_A=0.8 GeV**
  - ILC white paper: 0.45-0.73 GeV achievable at 800 GeV with 500 fb^{-1}

Blue area: uncertainty in $\Omega_\chi h^2$ due to parametric uncertainties



Bharucha '14

➢ ***Parametric uncertainties cause about 10% error in prediction of $\Omega_\chi h^2$***

Conclusions

- Precise predictions ~10% (due to parametric uncertainties) for $\Omega_\chi h^2$ possible via SUSY parameter determination at LC+LHC
- Strategy for parameter determination without assuming a SUSY breaking scheme even at loop level seems applicable:
  - NLO parameter determination up to O(%) level at a LC via (χ^0, $\chi^\pm$) production (only light spectrum)
- Extract parameters M_1, M_2, μ, $\tan\beta$,m_{stop1}, and $\cos\Theta_t$ via fit to NLO predictions for masses, polarized σ's and A_{FB}
- Crucial role: tunable energy, threshold scans, polarization
- Sensitive to heavy virtual particles M_A etc. via loop effects