

Impact of precision measurements for dark matter constraints

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



Overview

- Convert SUSY measurements into dark matter test
 - Turn LHC+LC measurements into precise SUSY parameters
 - Predict $\Omega_X h^2$ on basis of parameter determination
- Which precision is sufficient to be competitive with cosmo?
 - Planck/WMAP 2013: $\Omega_X h^2 = 0.120 \pm 0.003$
- Which tools and theory level are required for matching?
 - In order to calculate $\Omega_X h^2$ one requires all SUSY parameters
 - With LHC results: calculate $\Omega_X h^2$ mainly in CMSSM *Nojiri et al. '05*
 - Add-on's @ LC: extend CMSSM *Moroi et al. '05* to pMSSM studies *Baltz et al. '06*
 - tunable tools (polarization, threshold scans, ISR method)
 - high precision measurements (up to quantum level)
 - *Evaluate $\Omega_X h^2$ using parameters from $X^+ X^-$ @ NLO*

Strategy

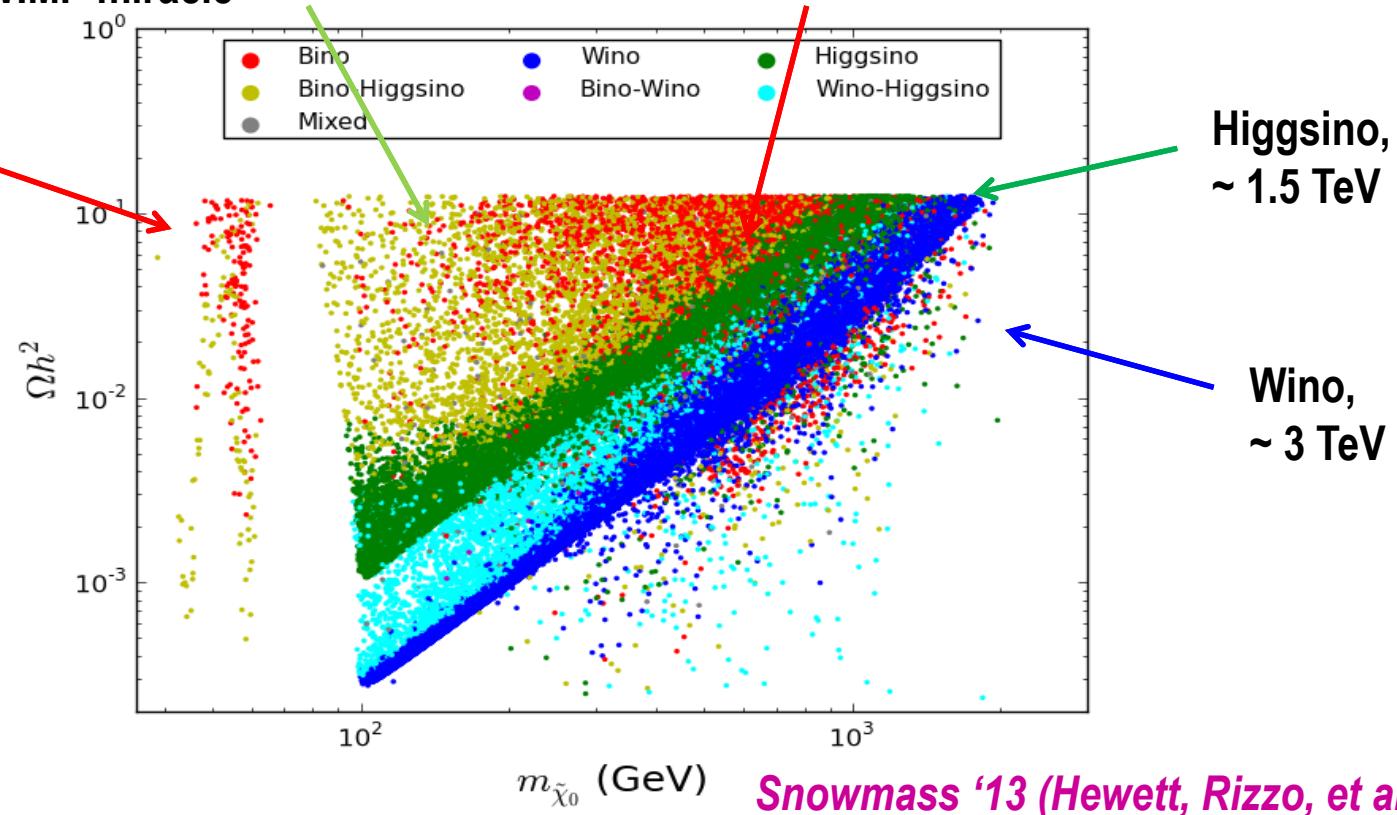
- Studied process: $e^+e^- \rightarrow X^\pm_1 X^\mp_1$
 - Input : measured masses of $X^\pm_1, X^0_{1,2}$, via continuum or threshold
 - Measured polarized cross sections at 350 and 500 GeV
 - Measured A_{FB} of this process
- Determine fundamental parameters: $M_1, M_2, \mu, \tan\beta$
 - Fine, very 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)
 - Determine parameters fitting loop-corrected observables
 - Fit sensitive to heavier virtual particles (m_{stop}, m_A)

Interplay: DM and mixing

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”



Delineation: chosen scenarios

- In the MSSM $\Omega_\chi h^2$ depends strongly on region
 - $m_{\chi_{01}} \sim \mu$ (focus point)
 - $m_{\chi_{01}} \sim m_\tau$ (stau coannihilation)
 - $m_{\chi_{01}} \sim M_A$ (funnel)
- Chosen scenarios
 - Examples from almost all characteristics regions
 - Not all scenarios fulfill all bounds
 - kept as demonstration only
 - Tricky phenomenology: both highly degenerated as well as very heavy particles
 - New scenario: ‘best fit’ only preliminary results, apologies...

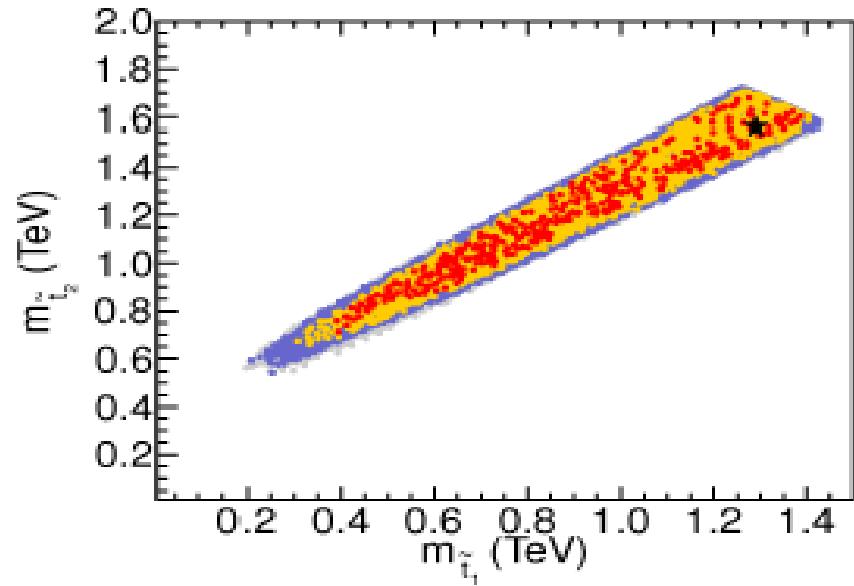
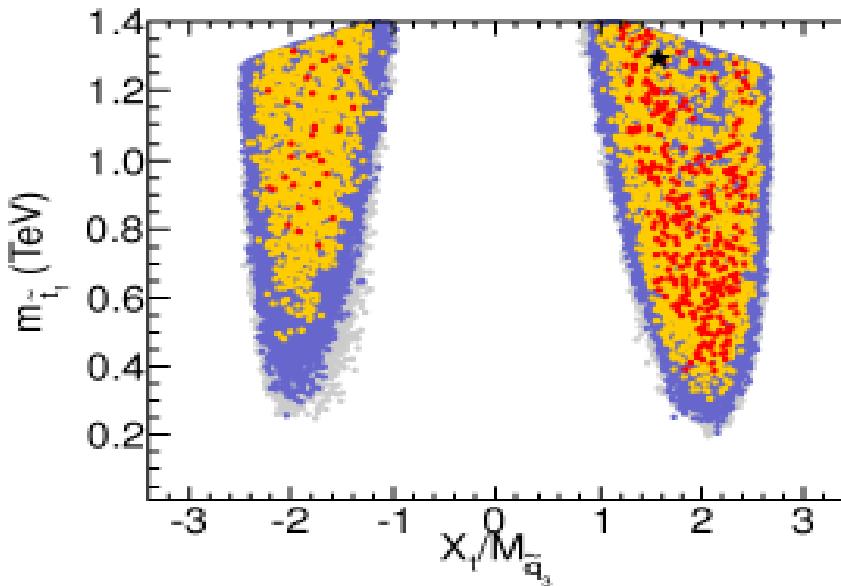
Examples

- **Scenario 1: Focus point region**
 - Heavy sleptons (m_{se_1} 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: ‘Best fit’ scenario**
 - ‘Mastercode’ best fit: ‘degenerated’ M_1, M_2 , heavy sfermions
 - Respecting all bounds
 - $\Omega_\chi h^2$ too small, but strongly sensitive to fundamental parameters!

Impact of stop mixing on light Higgs

- MSSM fit, preferred values for stop masses

Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein, Zeune



- Rather large $X_t = A_t - \mu \cot \beta$
- Large stop mixing required
 - Best fit prefers heavy stops beyond 1 TeV
 - But good fit also for light stops down to ≈ 300 GeV

Strategy: fundamental SUSY parameters from $e^+e^- \rightarrow \chi^+_1 \chi^-_1$

- In the past: parameter determination at LC
 - Extracted from $\sigma_{L,R}^\pm$ polarized cross sections at $\sqrt{s}=350$ and 500 GeV, masses $m\chi^\pm_1$ and $m\chi^0_{1,2}$ with 500 fb⁻¹

M_1	SUSY Parameters				Mass Predictions		
	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

$$59.45 \leq M_1 \leq 60.80 \text{ GeV}, \quad 118.6 \leq M_2 \leq 124.2 \text{ GeV}, \quad 420 \leq \mu \leq 770 \text{ GeV}$$

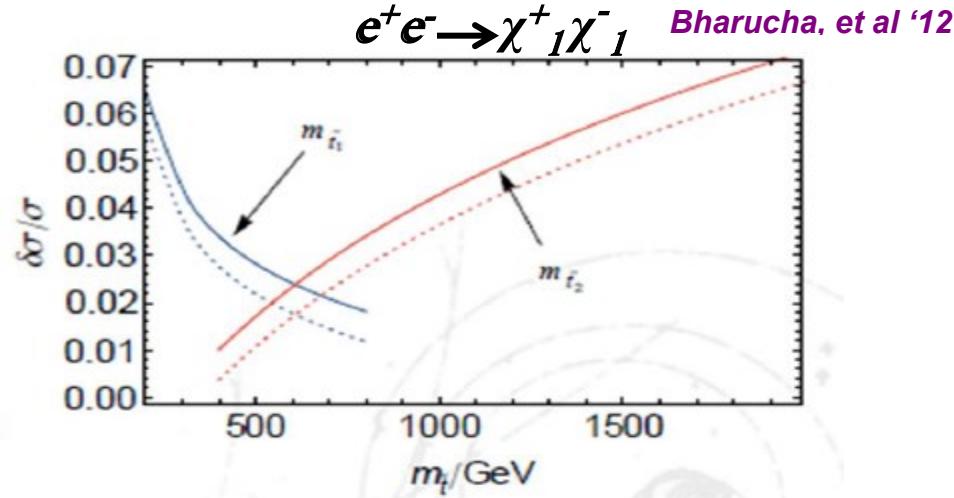
$$1900 \leq m_{\tilde{\nu}_e} \leq 2120 \text{ GeV}, \quad m_{\tilde{e}_L} \geq 1500 \text{ GeV}, \quad 11 \leq \tan \beta \leq 60.$$

- Now: incorporate loop-contributions

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

- However: Loop effects known to be relevant

- Sensitivity to parameters arising from loops, e.g. stop- and Higgs sector



- But: Strategies for parameter determination still applicable?
 - Known that SUSY loop effects might be large
 - $\Delta\sigma_{\text{exp}} \sim \Delta\sigma_{\text{NLO}}$: apply loop-corrected polarized $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ cross sections at $\sqrt{350}$ and 500 GeV
 - Apply loop-corrected A_{FB} at both energies
 - Assume light chargino/neutralino masses have been measured
 - at continuum measurement versus threshold scan
- Apply fit to: $M_1, M_2, \mu, \tan\beta, \cos\Theta_t, m_{t1}, m_{t2}$ and m_ν, M_A

Fit results@Loop Level

- Scenario 1: Focus point region

$M_1 = 123 \text{ GeV}$

$M_2 = 250 \text{ GeV}$

$\mu = 182 \text{ GeV}$

$\tan\beta = 10$

$m_{l,r} = 1500 \text{ GeV}$

$m_{q1,2} = 1500 \text{ GeV}$

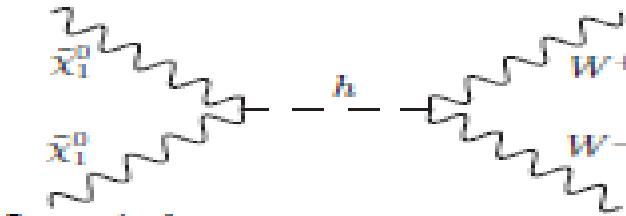
$M_{l3,e3} = 800,400 \text{ GeV}$

$A_{f1,2} = 650 \text{ GeV}$

$M_A = 1000 \text{ GeV}$

$M_3 = 700 \text{ GeV}$

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



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

Fit results@Loop Level

- Scenario 1: Impact of loops and assumed uncertainties

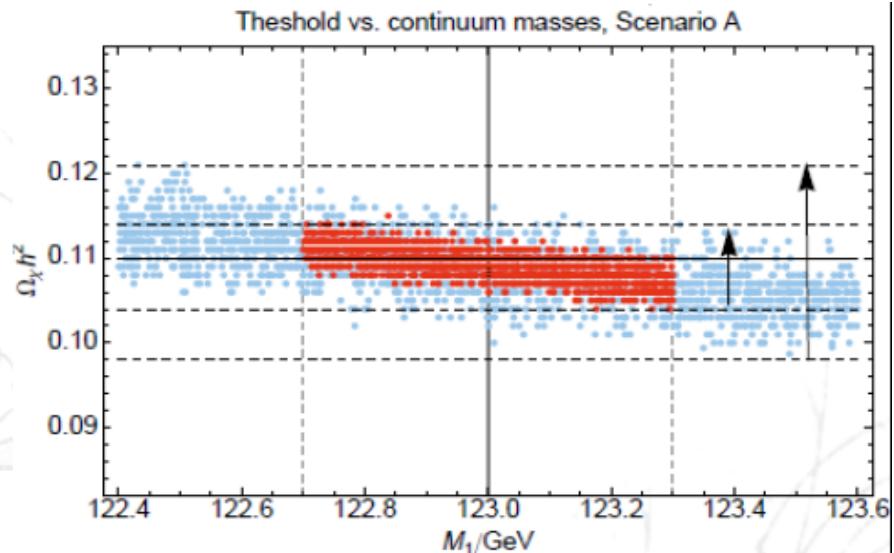
Observable	Tree value	Loop corr.	Error exp.	Error th.
$m_{\tilde{\chi}_1^\pm}$	149.6	—	0.1 (0.2)	—
$m_{\tilde{\chi}_2^\pm}$	292.3	—	0.5 (2.0)	—
$m_{\tilde{\chi}_1^0}$	106.9	—	0.2	—
$m_{\tilde{\chi}_2^0}$	164.0	2.0	0.5 (1.0)	0.5
$m_{\tilde{\chi}_3^0}$	188.6	-1.5	0.5 (1.0)	0.5
$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)_{(-0.8, 0.6)}^{350}$	2347.5	-291.3	8.7	2.0
$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)_{(0.8, -0.6)}^{350}$	224.4	7.6	2.7	0.5
$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)_{(-0.8, 0.6)}^{500}$	1450.6	-24.4	8.7	2.0
$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)_{(0.8, -0.6)}^{500}$	154.8	12.7	2.0	0.5
$A_{FB}^{350}(\%)$	-2.2	6.8	0.8	0.1
$A_{FB}^{500}(\%)$	-2.6	5.3	1.0	0.1

Fit results@Loop Level

- **Scenario 1: Focus point region**

Parameter	Scenario A
M_1	123 ± 0.3 (0.6)
M_2	250 ± 0.6 (1.6)
μ	182 ± 0.4 (0.7)
$\tan \beta$	10 ± 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 ± 24 (20)
$M_{e_{1,2}}$	1500 ± 500

- 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

$M_1 = 105 \text{ GeV}$

$M_2 = 211 \text{ GeV}$

$\mu = 181 \text{ GeV}$

$\tan\beta = 11$

$m_1 = 180 \text{ GeV}$

$m_{e1,2} = 125 \text{ GeV}$

$m_{q1,2} = 1500 \text{ GeV}$

$m_{e3} = 106 \text{ GeV}$

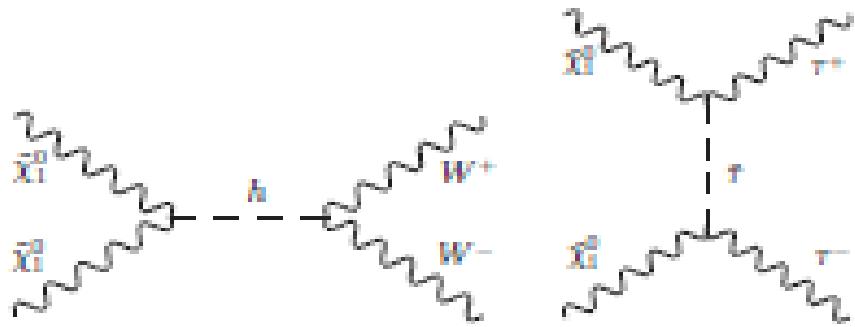
$m_{q3} = 450 \text{ GeV}$

$A_{f1,2} = -1850 \text{ GeV}$

$M_A = 500 \text{ GeV}$

$M_3 = 1500 \text{ GeV}$

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



- Largest contributions to annihilation cross section:
 - WW (24%)
 - Stau stau (23%)
 - $\mu^+\mu^-$ (10%)
 - e^+e^- (8%)
 - bb (7%)

Fit results@Loop Level

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

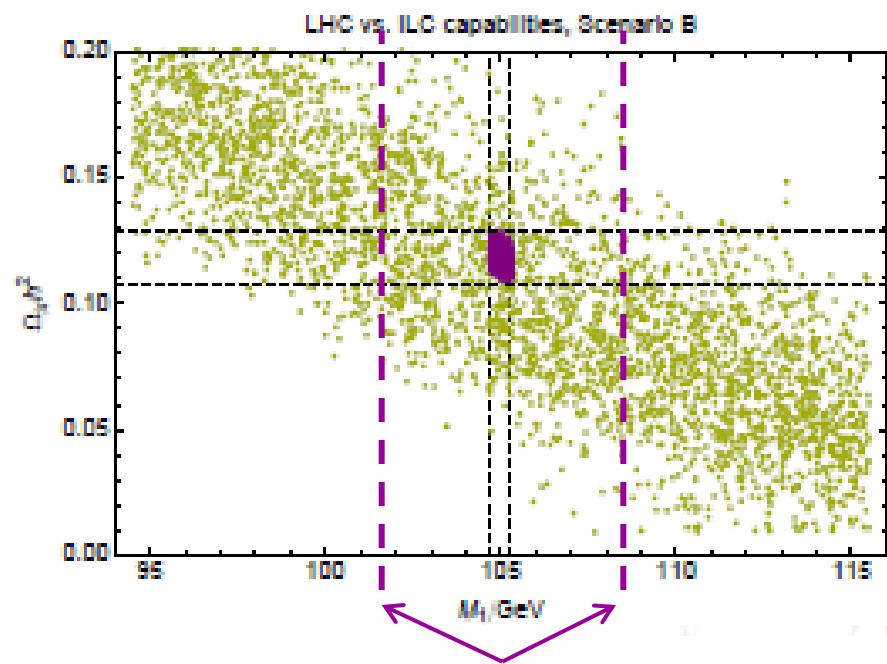
Observable	Tree value	Loop corr.	Error exp.	Error th.
$m_{\tilde{\chi}_1^\pm}$	139.3	—	0.1	—
$m_{\tilde{\chi}_2^\pm}$	266.2	—	0.5	—
$m_{\tilde{\chi}_1^0}$	92.8	—	0.2	—
$m_{\tilde{\chi}_2^0}$	148.5	2.4	0.5	0.5
$m_{\tilde{\chi}_3^0}$	189.7	-7.3	0.5	0.5
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{400}_{(-0.8,0.6)}$	709.7	-85.1	4.5	—
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{400}_{(0.8,-0.6)}$	129.8	20.0	2.0	—
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{500}_{(-0.8,0.6)}$	560.0	-70.1	4.5	—
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{500}_{(0.8,-0.6)}$	97.1	16.4	2.0	—
$A_{FB}^{400}(\%)$	24.7	-2.8	1.4	0.1
$A_{FB}^{500}(\%)$	39.2	-5.8	1.5	0.1

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

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

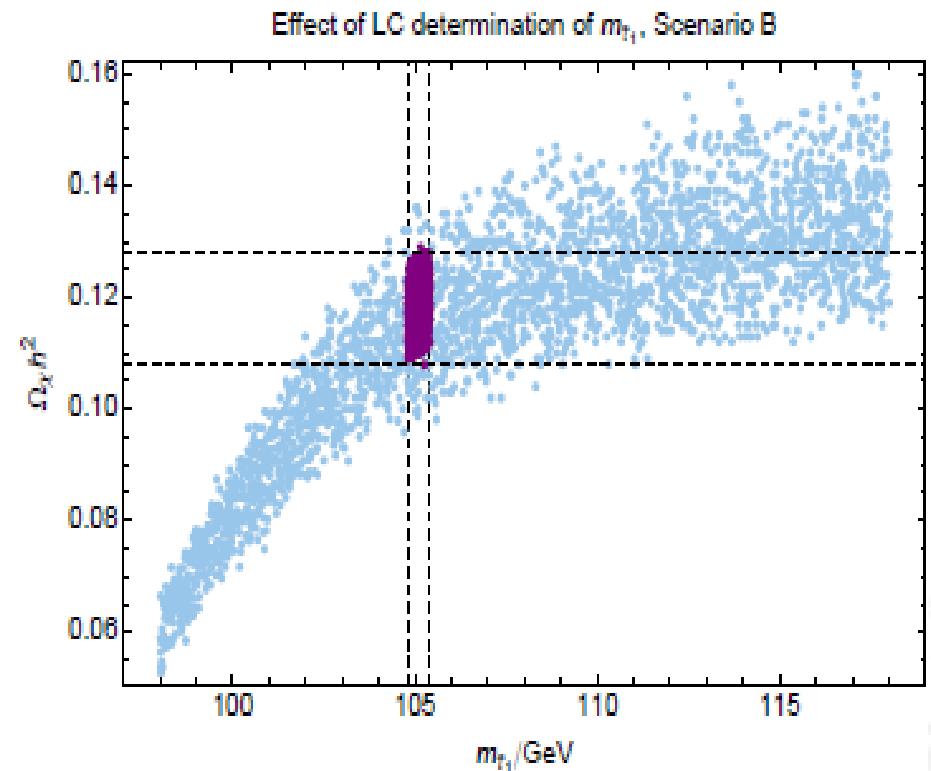


Fit results@Loop Level

- 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

- Effect of stau precision measurement at the LC



Fit results@'best fit'

- **Mastercode: 'best fit' results**
 - *pMSSM10 parameter space*

*de Vries, Bagnaschi, Buchmüller,
Cavanaugh, Citron, et al '15*

$M_1 = 170 \text{ GeV}$

$M_2 = 170 \text{ GeV}$

$\mu = 550 \text{ GeV}$

$\tan\beta = 37.6$

$m_{l,r} = 440 \text{ GeV}$

$m_{q1,2} = 2880 \text{ GeV}$

$m_{q3} = 4360 \text{ GeV}$

$A_f = 790 \text{ GeV}$

$M_A = 2070 \text{ GeV}$

$M_3 = 2600 \text{ GeV}$

$$X^0_1 = 0.98B - 0.16W + 0.11h_1 - 0.04h_2$$

- **Dark matter too small:**

$$\Omega_X h^2 = 4.24E-02$$

*Micromegas 4.1.8
Belanger 2013*

- **Largest contributions to annihilation cross section:**
 - WW (99%)

However: how sensitive is $\Omega_X h^2$ to parameters in this case?

LC assumptions

preliminary

- **Challenging scenario:**

- $m_{\chi_1^0} = 164 \text{ GeV}$
- $m_{\chi_2^0} = 170 \text{ GeV}$
- $M_{\chi_1^\pm} = 165.5 \text{ GeV}$

→ *LSP and lightest chargino very close in mass*

estimates: $\Delta m = 0.5 \text{ GeV}$

cross sections at 350 GeV, 500 GeV: $\varepsilon \sim 15 \%$

conservative estimate with ref. to similar ‘degenerated’ scenarios with full detector simulations

Berggren et al. ‘13)

- **So far only at tree level (still under work)**

- No surprises expected,...but stay tuned, please

Fit results@'best fit' ‘preliminary’

- Since only ‘tree-level’: *Bharucha, GMP, Rolbiecki ‘15*

$$M_1 = 170.0 \pm 0.6 \text{ GeV}$$

$$M_2 = 169.9 \pm 0.8 \text{ GeV}$$

$$\mu = 549.2 \pm 40.0 \text{ GeV}$$

$$m_\nu = 435.0 \pm 1.9 \text{ GeV}$$

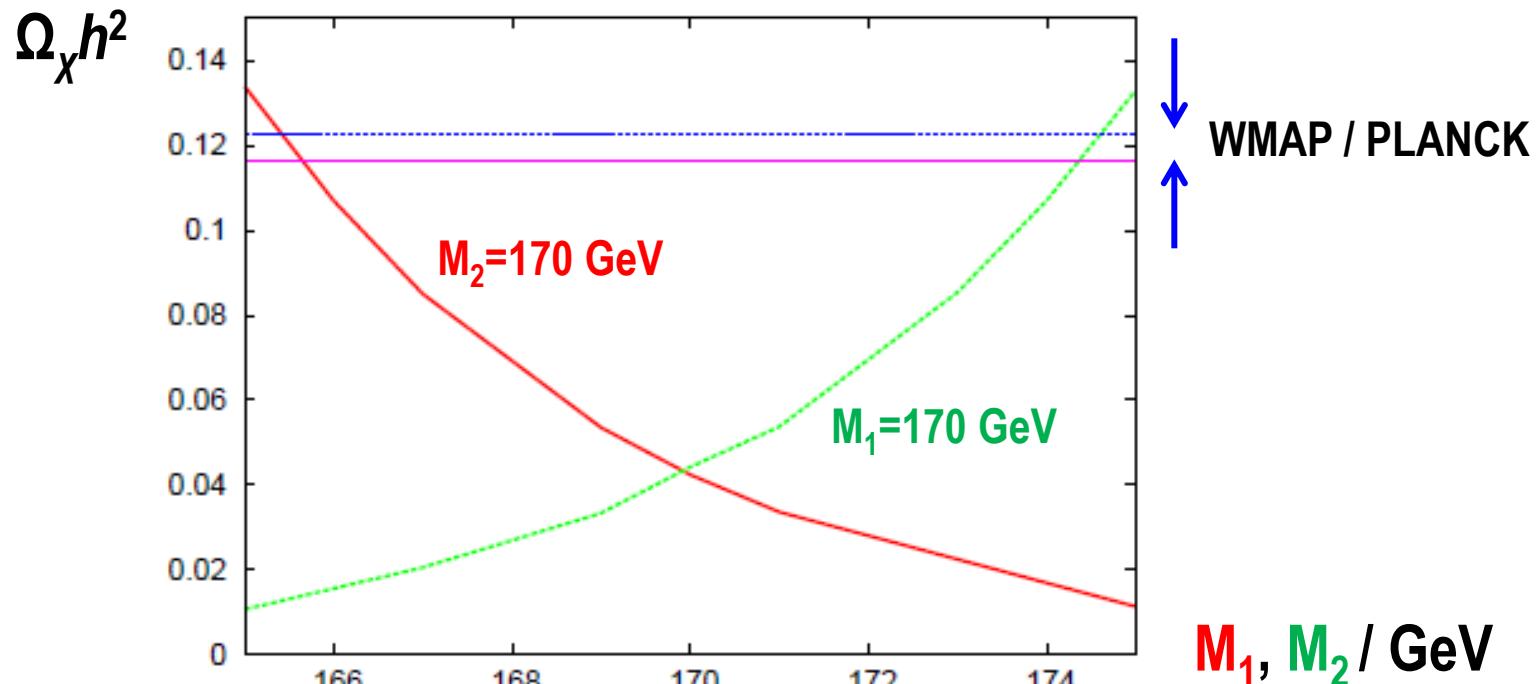
- Within these bounds:

M1=169:	$\Omega_\chi h^2 = 5.35 \text{ E-02}$
171:	=3.36 E-02
M2=169:	=3.33 E-02
171:	=5.37 E-02
$\mu = 509:$	=3.64 E-02
589:	=4.75 E-02

Impact on DM

preliminary

- Since $M_1 \sim M_2$:
→ abrupt changes in mixing character expected



- Very sensitive to M_1, M_2 : precision required!

Conclusions

- Precise predictions ~10% (due to parametric uncertainties) for $\Omega_X h^2$ 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, χ^\pm) production
- Extract parameters $M_1, M_2, \mu, \tan\beta, m_{stop1}$, 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