Can the Relic Dark Matter Density be determined at the ILC ?

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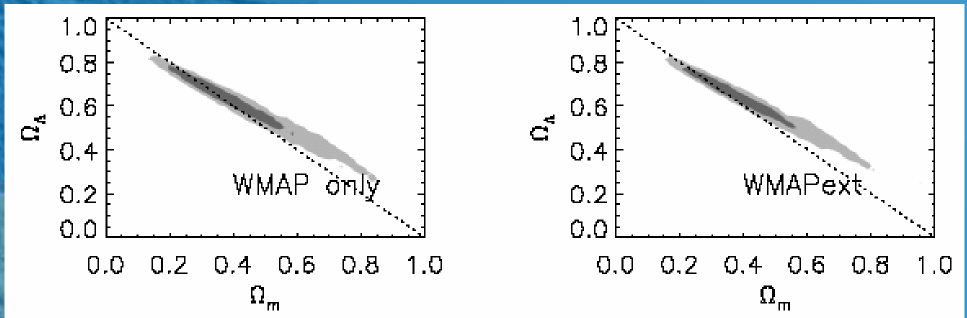
Contributions by J. Alexander, E. Baltz,
B. Dutta, J. Feng, T. Kamon, M. Peskin

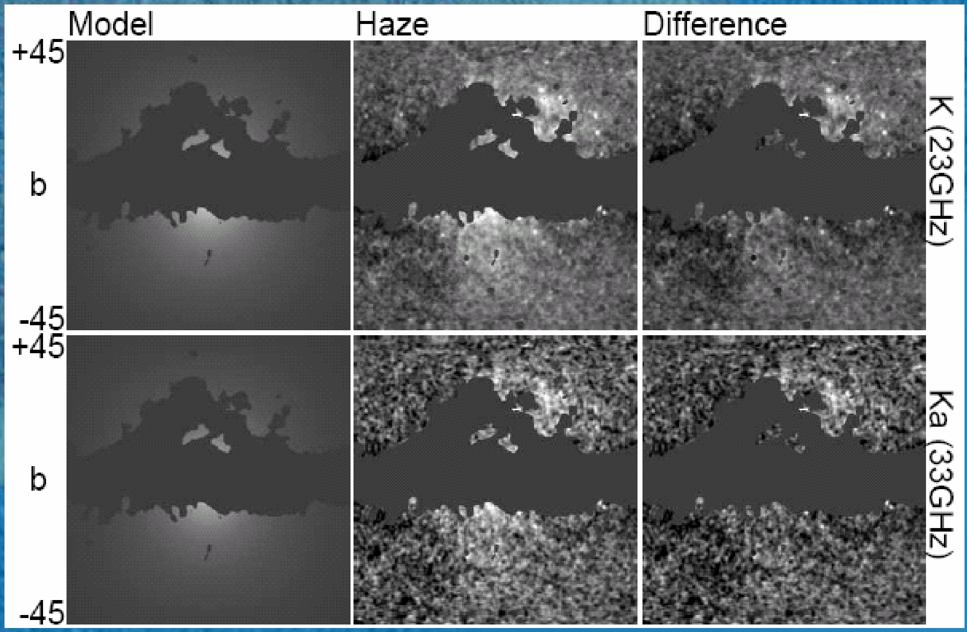
CMB data from WMAP provides precise determination of relic Dark Matter density, result further corroborated by data on supernovas and galaxy clusters;



$0.087 < \Omega_{CDM}\, h^2 < 0.129$

EGRET data from Compton Gamma Ray Observatory show excess of γ **emission** in Inner Galaxy, which may be interpreted as signal from DM annihilation;

Analysis of subtracted WMAP spectrum at different frequencies shows excess microwave emission interpretable as **synchrotron emission** from energetic e^+e^- pairs produced in DM annihilation near galactic center:



Finkbeiner, **astro-ph/0409027**

Data consistent with ~100 GeV particle annihilation with $<\sigma v> = 2 \times 10^{-26}\ cm^3\ s^{-1}$

Systematic study of ILC reach promoted by **White Paper on ILC-Cosmo Connections** (M.B., J.Feng, N.Graf, M.Peskin, M.Trodden Editors)

Point	m_0	$m_{1/2}$	$\tan\beta$	A_0	$M(t)$	$M(\chi_1^0)$
LCC 1	100	250	10	-100	178.	96.1
LCC 2	3280	300	10	0	175.	107.7
LCC 3	210	360	40	0	178.	142.5
LCC 4	380	420	53	0	178.	169

Compute RGEs with Isajet 7.69 and estimate dark matter density from Isajet spectrum and couplings with MicrOMEGAS 1.3 and DarkSUSY 4.0

Point	DarkSUSY 4.0	MicroMEGAS 1.3
LCC 1	0.193	0.193
LCC 2	0.108	0.110
LCC 3	0.059	0.057
LCC 4	0.113	0.106

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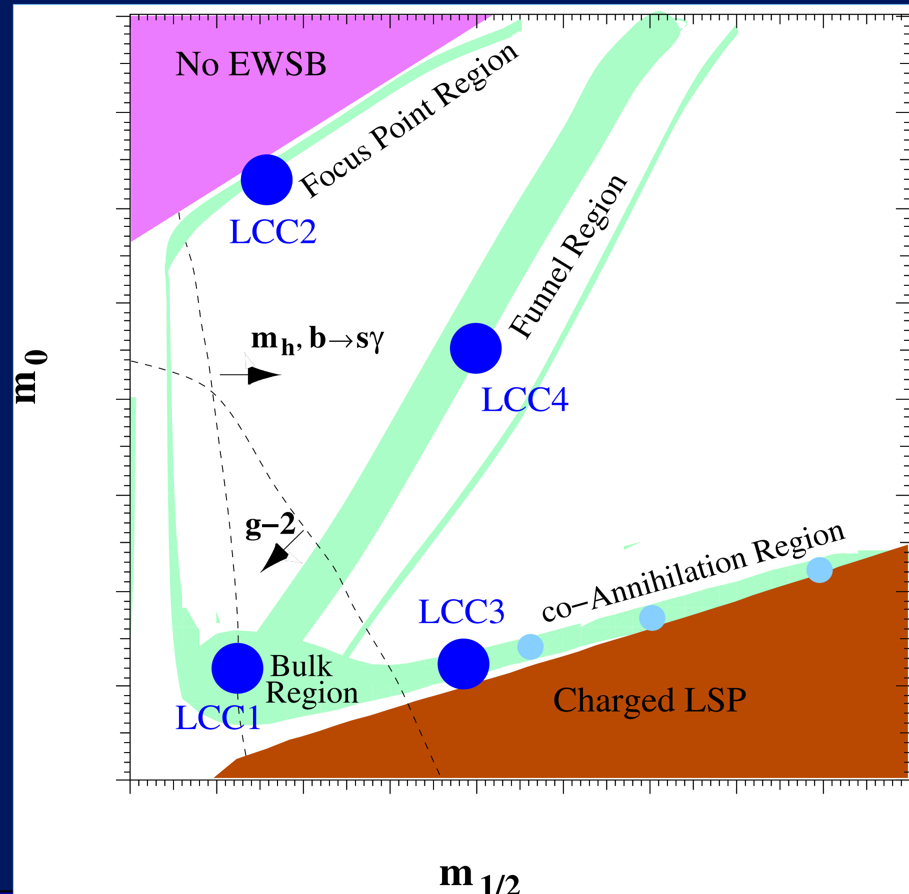
SUSY models analysis simplified within cMSSM: dimensionality of parameter space reduced by one ($m_{1/2} \leftrightarrow m_0$): four regions emerge:

Cosmologically interesting cMSSM Regions and Benchmark points for the ILC-Cosmo White Paper



LHC Sensitivity

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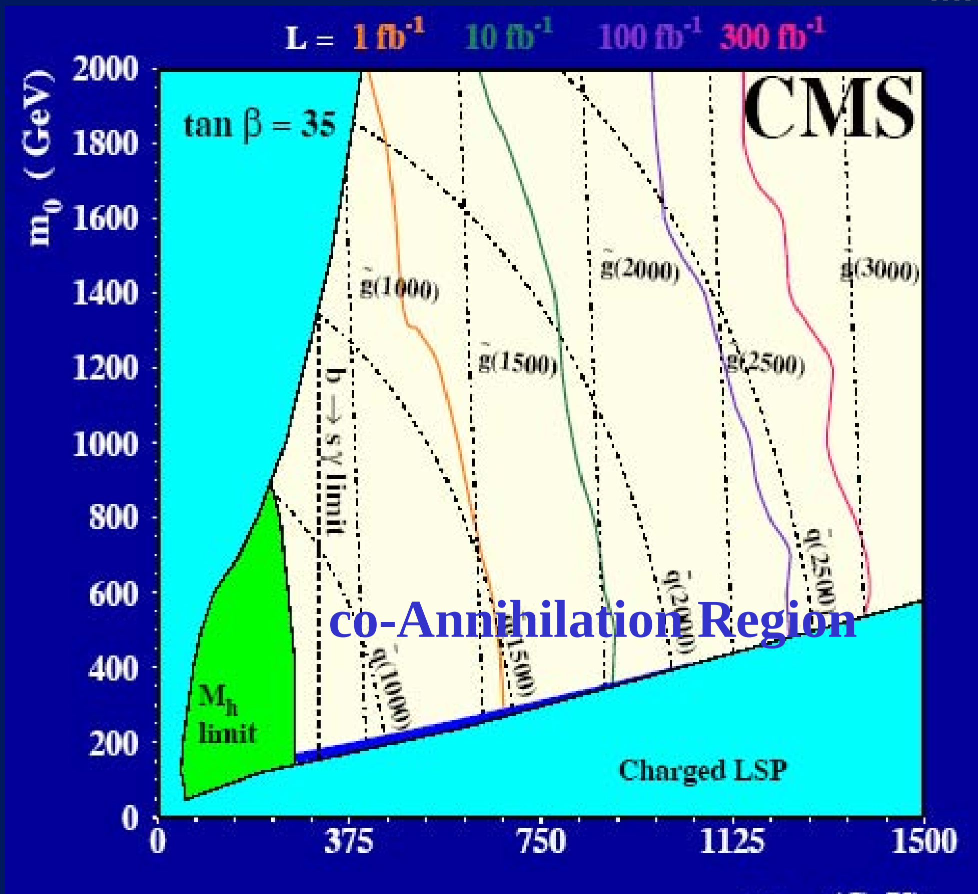
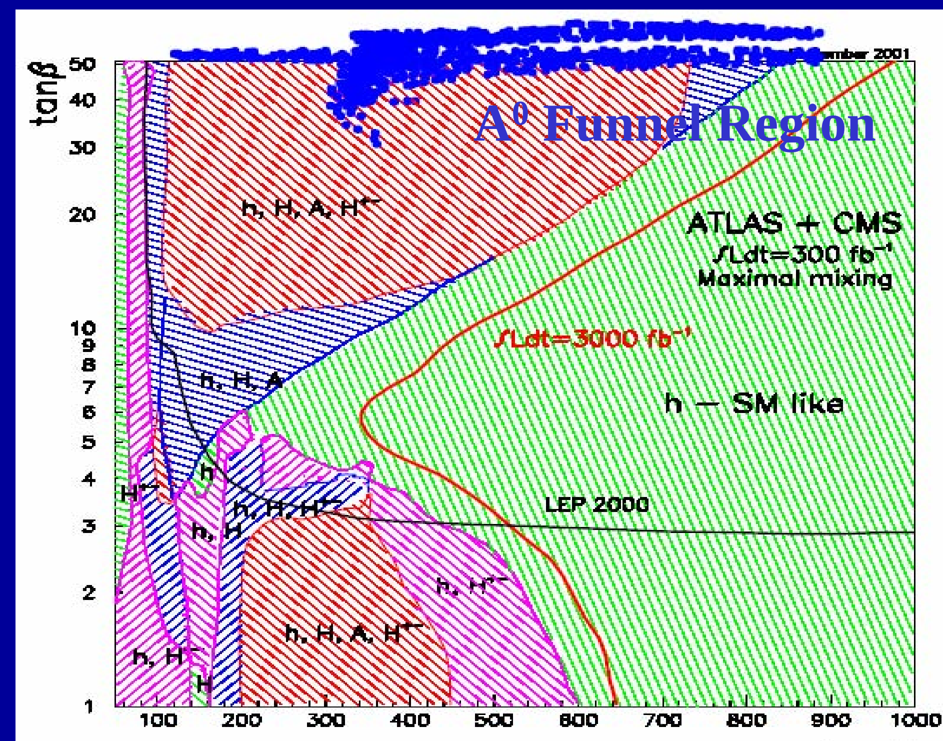
LHC sensitivity almost saturates the available phase space in the WMAP compatible cMSSM region:

Inclusive SUSY Sensitivity in Jets + E^T_{miss}



modified from S. Abdullin

Higgs Bosons Sensitivity in M_A-tan β



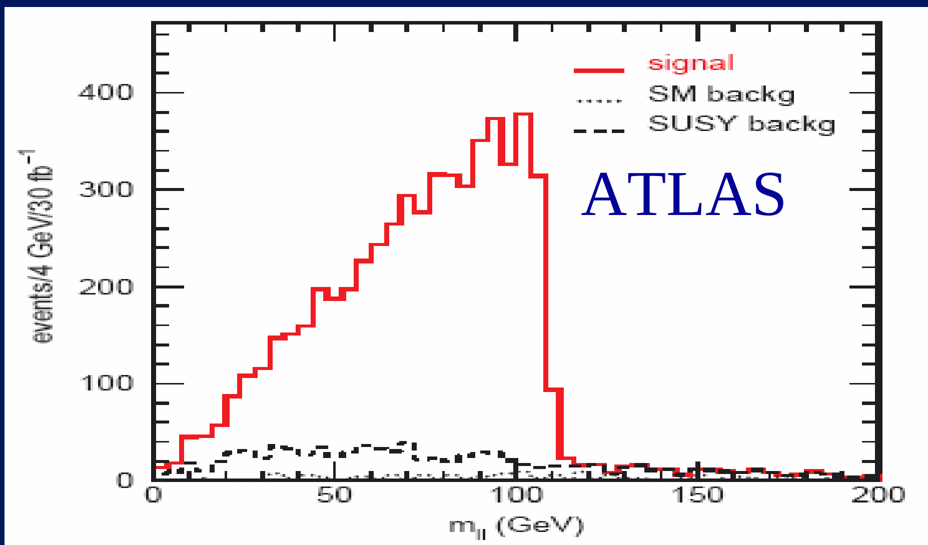
M.B., Hinchliffe, Tovey + ATLAS

LHC reach limited towards high end of Focus Point Region where strongly interacting superpartners become too heavy to be produced.

LHC Measurements

Availability of decay chains with multi-leptons, lepton+jets topologies allows to determine masses from kinematical endpoints (but significant correlations from sensitivity to mass differences):

$$\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}^\pm\ell^\mp \to q\ell^\pm\ell^\mp\tilde{\chi}_1^0$$

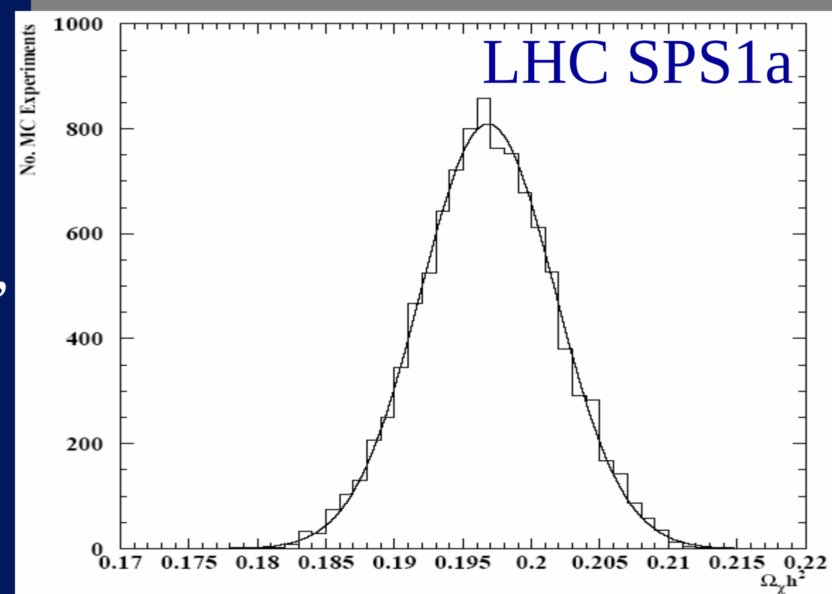


$$M_{\ell^+\ell^-}^{\max} = \frac{\sqrt{\left(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2\right)\left(m_{\tilde{\ell}}^2 - m_{\chi_1^0}^2\right)}}{m_{\tilde{\ell}}}$$

$$M_{\ell_1 q}^{\max} = \frac{\sqrt{\left(m_{\chi_2^0}^2 - m_{\tilde{\ell}}^2\right)\left(m_{\tilde{q}}^2 - m_{\chi_2^0}^2\right)}}{m_{\chi_2^0}}$$

Predictions of DM relic density can be obtained, in a model-dependent way, to good numerical accuracy in some regions by reconstructing cMSSM parameters from observed endpoints:

SPS1a: $\delta\Omega/\Omega$ = **0.025** (stat.) 300 fb^{-1}



Polesello, Tovey, **hep-ph/0403047**

Bulk Point LCC1

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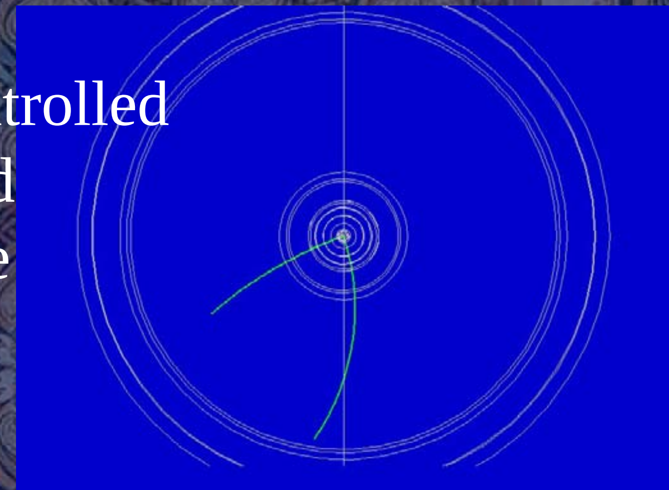
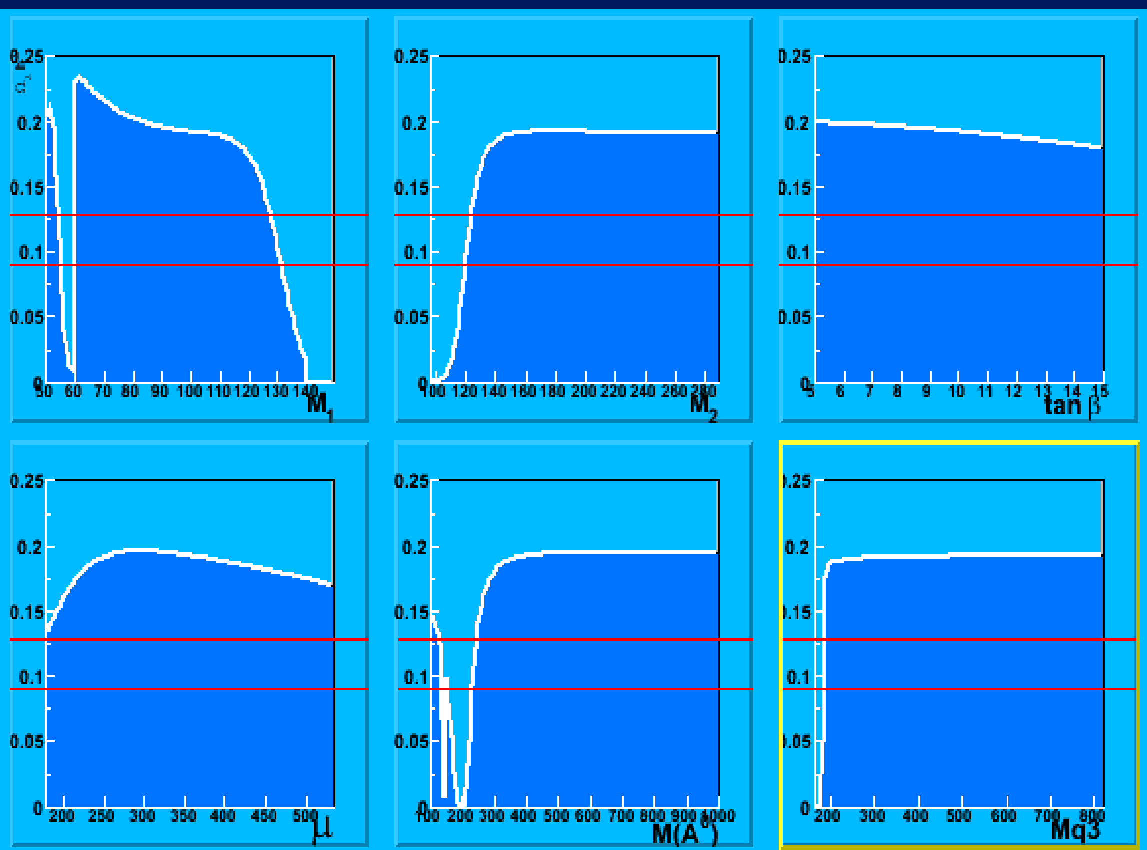
In bulk region LSP mostly bino and DM density controlled by annihilation to leptons via slepton exchange: need to determine LSP and slepton masses but also ensure no other mechanisms contribute.





	value	δ(LHC)	δ(ILC)
$M(\tilde{\chi}_1)$	96.1	$\pm$ 4.8	$\pm$ 0.05
$M(\tilde{e}_R)$	143.0	$\pm$ 4.8	$\pm$ 0.05
$M(\tilde{\mu}_R)$	143.0	$\pm$ 4.8	$\pm$ 0.2
$M(\tilde{\tau}_R)$	133.2	$\pm$ 5-8	$\pm$ 0.3
$M(\tilde{e}_L)$	202.1	$\pm$ 5.0	$\pm$ 0.2
$M(\tilde{\mu}_L)$	202.1	$\pm$ 5.0	$\pm$ 0.5
$M(\tilde{\tau}_L)$	206.1	?	$\pm$ 1.1
$M(\tilde{\chi}_2) - m(\tilde{\chi}_1)$	80.3	$\pm$ 0.08	$\pm$ 2
$M(A)$	393.6	$M(A) > 200$	$M(A) > 220$

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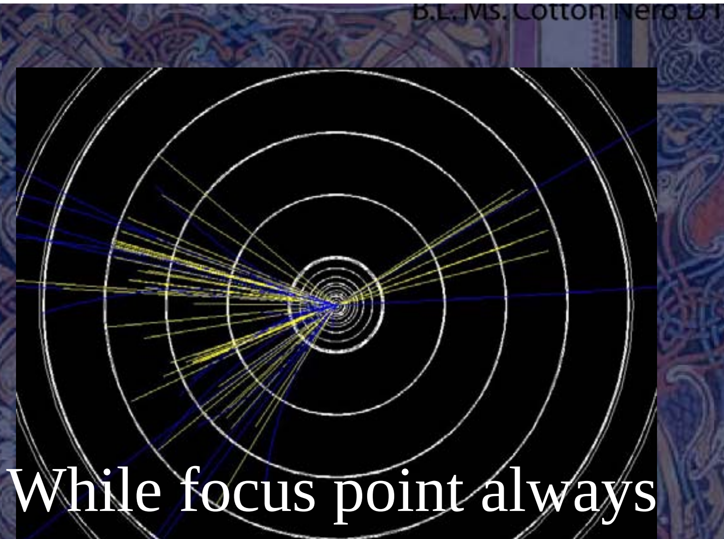
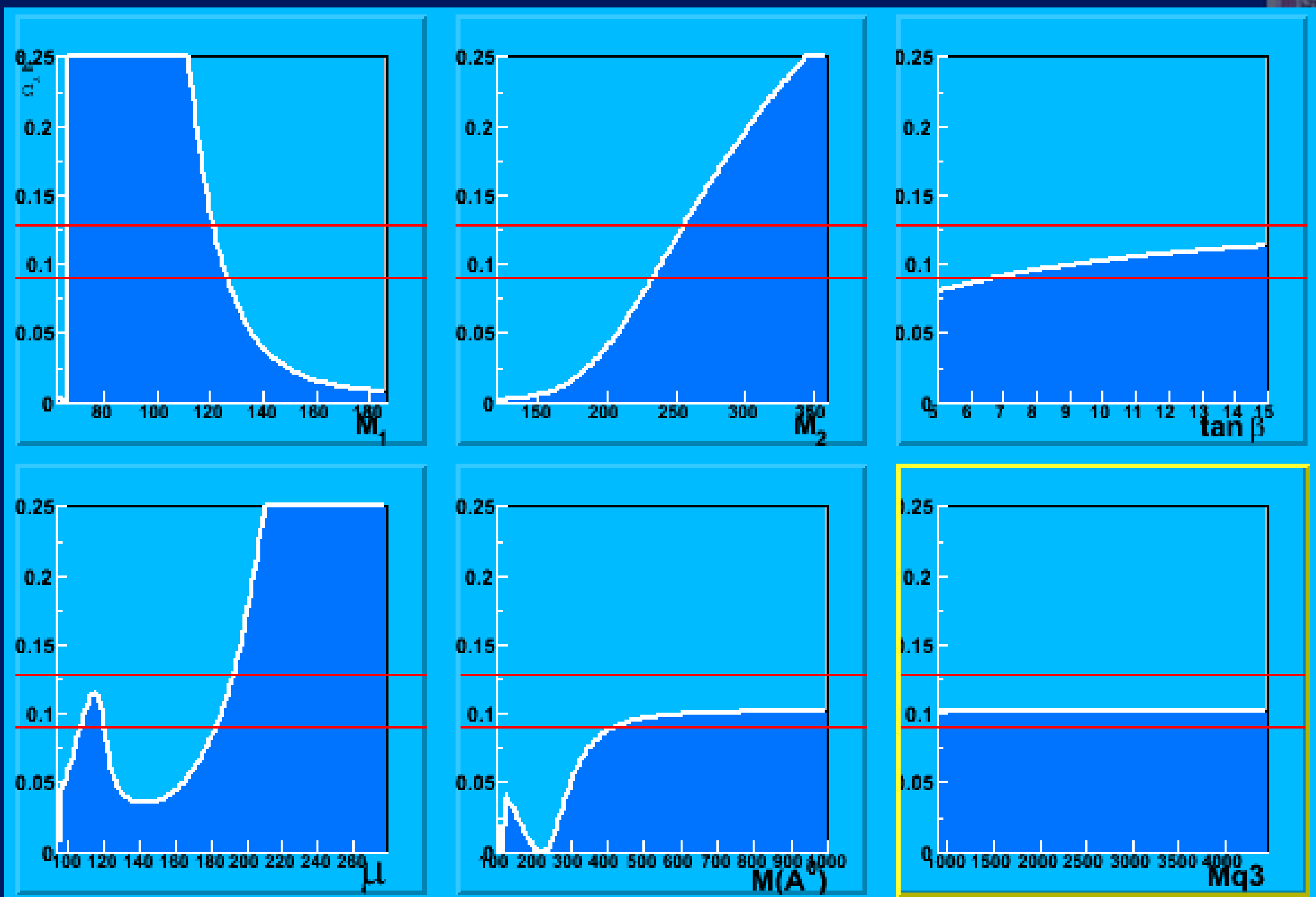
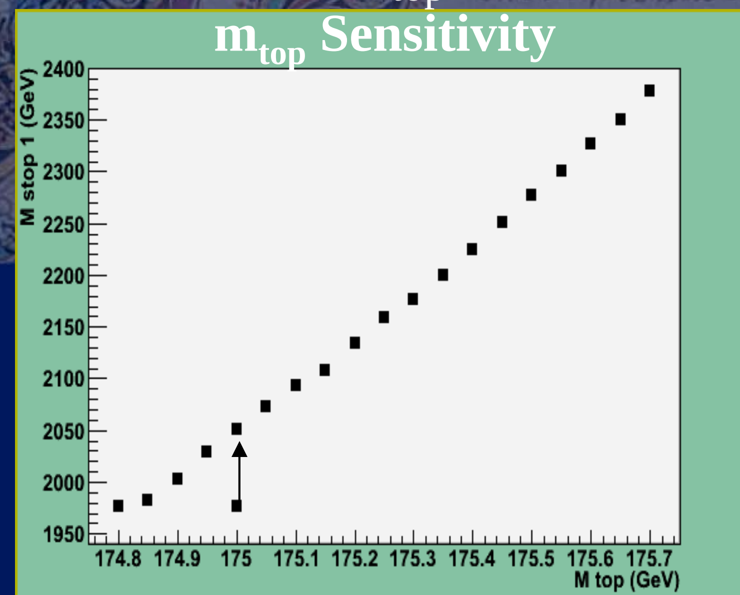
Focus Point LCC2

In focus point DM density controlled by LSP annihilation to WW and ZZ , large mass splitting between gauginos and sfermions:





While focus point always present, its localization in terms of m_0, $m_{1/2}$ depends crucially on m_{top}

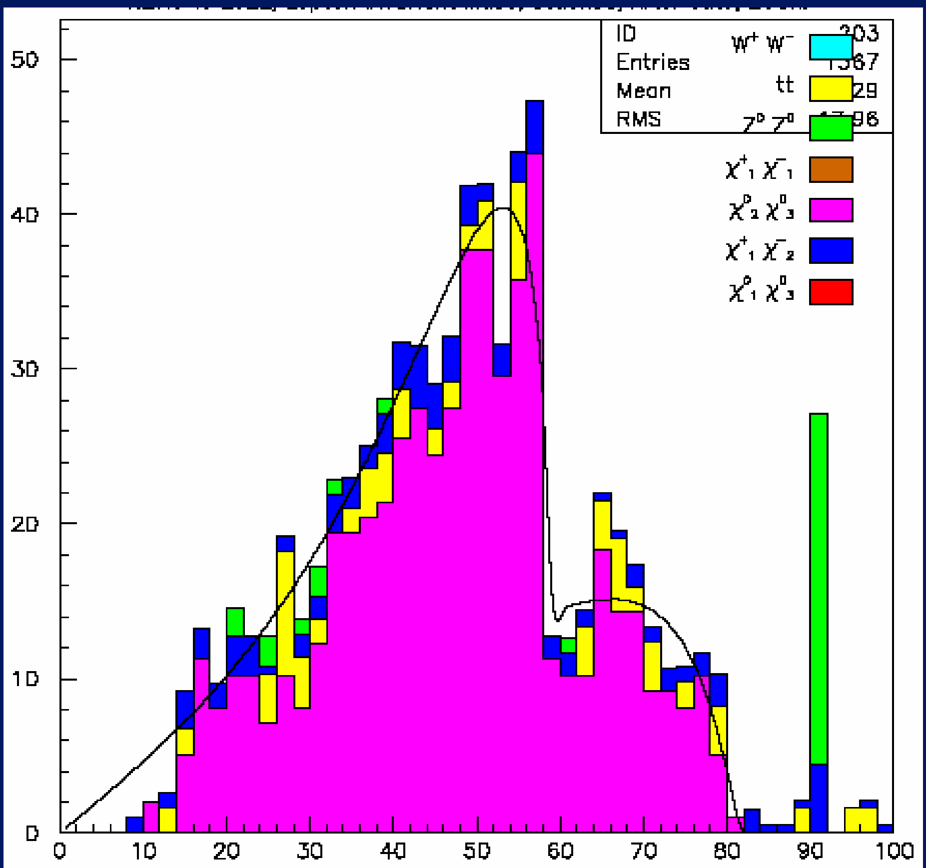


ILC Measurements at LCC2

Study of Focus Point at 0.5 TeV is based on five main reactions:

e+e- $\rightarrow \chi^+_1\chi^-_1$, $\chi^+_1\chi^-_2$, $\chi^0_1\chi^0_3$, $\chi^0_2\chi^0_3$, $\chi^0_3\chi^0_4$

Determine mass differences from endpoint of ll and jj distributions and use kinematics to fix masses:



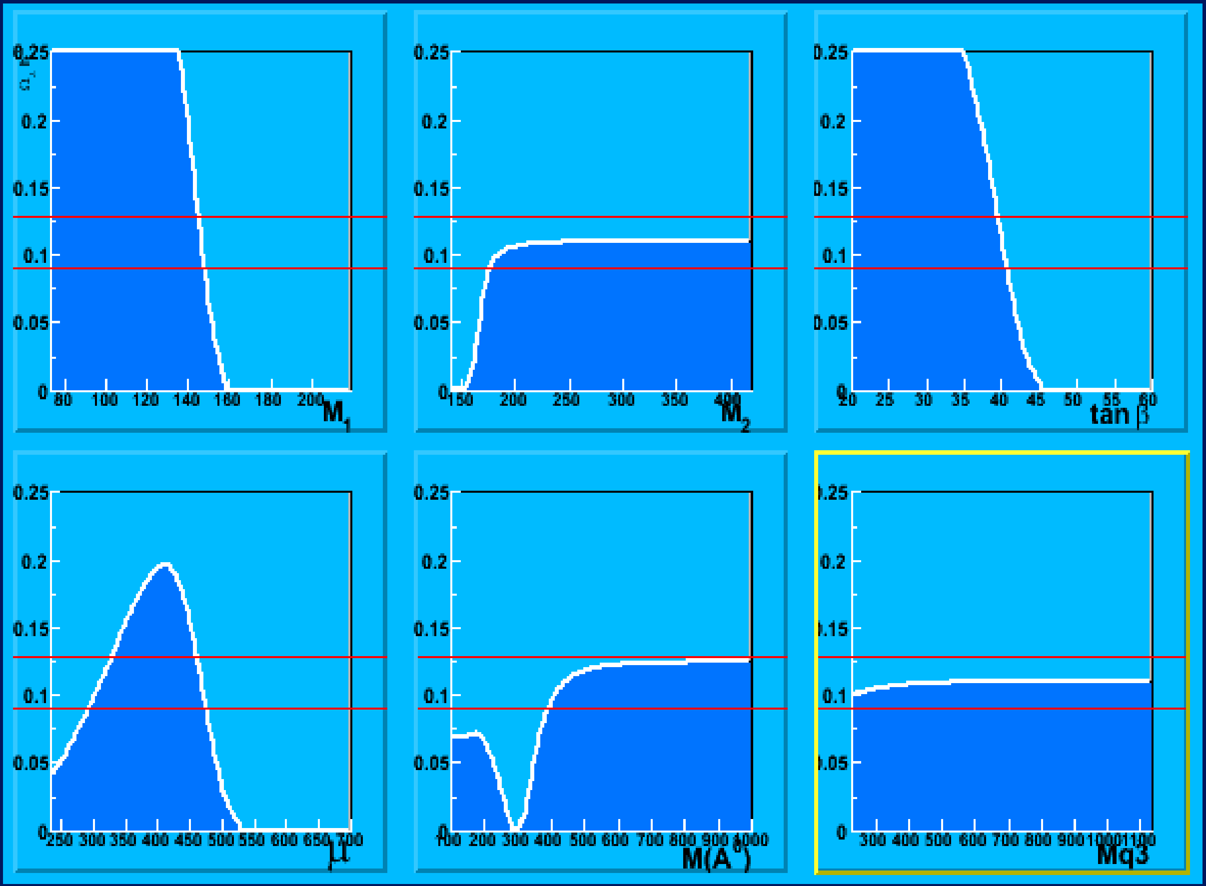
Alexander *et al.* **ll Inv. Mass (GeV)**

Availability of polarised beams provides additional observables for establishing properties of gauginos;

	value	δ(ILC)
$M(\tilde{\chi}_1)$	107.7	$\pm$ 0.7
$M(\tilde{\chi}_2) - M(\tilde{\chi}_1)$	58.6	$\pm$ 0.4
$M(\tilde{\chi}_3) - M(\tilde{\chi}_1)$	82.3	$\pm$ 0.3
$M(\tilde{\chi}^+_1) - M(\tilde{\chi}_1)$	143.0	$\pm$ 0.3
$\sigma(e^-e^+ \rightarrow \tilde{\chi}^+_1\chi^-_1)$ (-0.8/+0.6)		$\pm$ 7.7%
$\sigma(e^-e^+ \rightarrow \tilde{\chi}^+_1\chi^-_1)$ (+0.8/-0.6)		$\pm$ 10.5%
$\sigma(e^-e^+ \rightarrow \tilde{\chi}^0_2\chi^0_3)$ (-0.8/+0.6)		$\pm$ 3.8%
$\sigma(e^-e^+ \rightarrow \tilde{\chi}^0_2\chi^0_3)$ (+0.8/-0.6)		$\pm$ 4.5%
$M(\tilde{\ell})$	3270	
$M(\tilde{q})$	3300	
$M(A)$	3242.2	>220

co-Annihilation Point LCC3

DM density controlled by stau-LSP mass splitting and μ: sensitivity to small ΔM depends on γγ background rejection:



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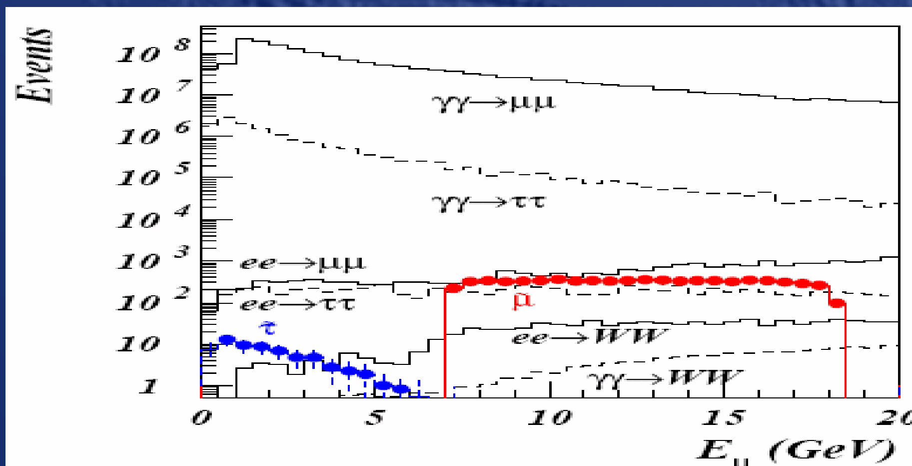
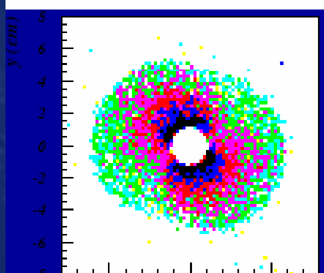
	value	δ(ILC)
$M(\tilde{\tau}_1) - M(\tilde{\chi}_1)$	9.5	$\pm$ 1.0
$M(\tilde{\tau}_1)$	151	$\pm$ 0.5
$M(\tilde{\chi}_1^0)$	142	$\pm$ 0.1
$M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$	80.3	$\pm$ 0.5
$M(\tilde{\chi}_3^0) - M(\tilde{\chi}_1^0)$		$\pm$ 2.0
$M(\tilde{\chi}_2^+) - M(\tilde{\chi}_1^+)$		$\pm$ 2.0
$M(\tilde{\chi}+_1)$, $M(\mu_R)$	274	$\pm$ 0.7
$M(\tilde{e}_R)$, $M(\tilde{\mu}_R)$	252	$\pm$ 1.0
$M(\tilde{e}_R) - M(\tilde{\chi}_1^0)$		$\pm$ 1.0
$M(\tilde{\tau}_2) - M(\tilde{\chi}_1)$		$\pm$ 1.1
$M(A)$		$M(A) > 450$

ILC Measurements at LCC3

At 0.5 TeV production of $\tau_1\tau_1$ and $\chi_1\chi_2$ resulting in $\tau\tau$ $E_{missing}$ final state;

Important to reject $\gamma\gamma$ bkg ee $\rightarrow$ ee$\tau\tau$ by low angle electron tagging:

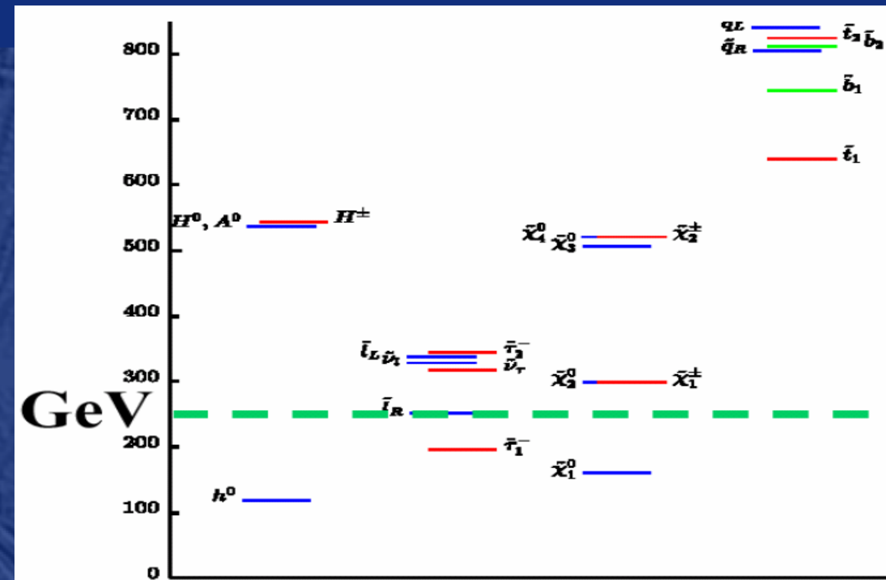




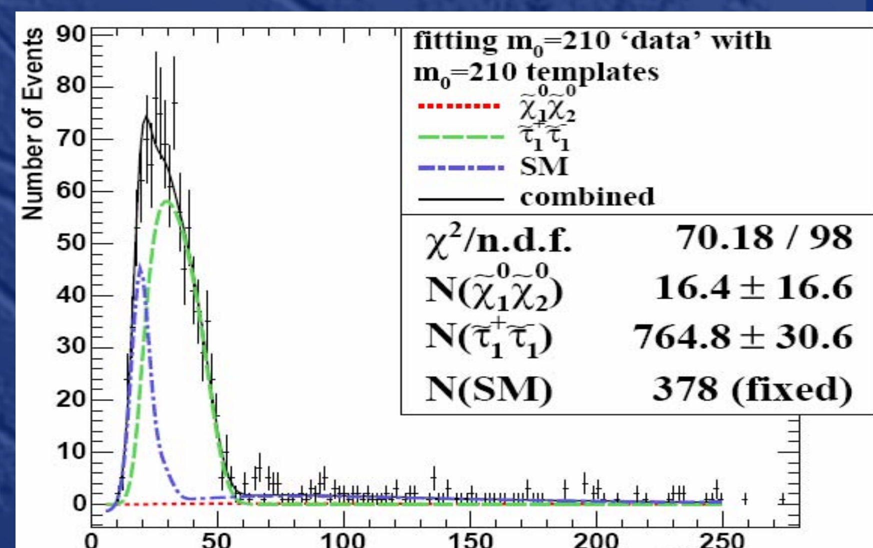
Very Fwd. calorimetric coverage controls minimum reachable ΔM:

ΔM accuracy at ILC = 10%

At LHC worst accuracy and feasibility critically depends on fake jet rate.



Determine $M(\tau_1)$ - $M(\chi_1^0)$ from distribution of $M(j_1j_2E_{missing})$



Dutta, Kamon, SUSY05

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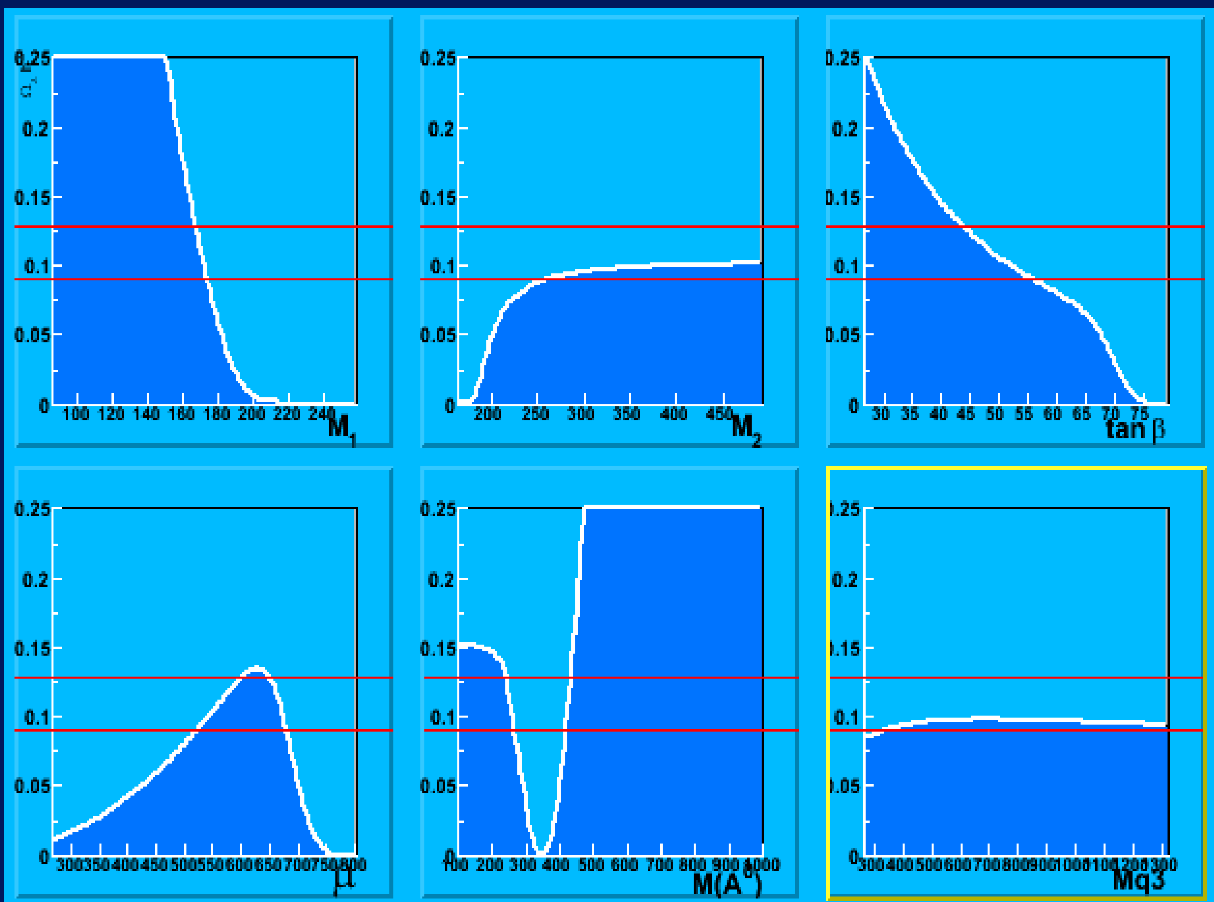
A^0 Funnel Point LCC4

DM density controlled by M(A)/2M(χ), Γ(A) and μ requires intensive program of measurements from 0.35 TeV to 1.0 TeV:



	value	δ(LC)
$M(\tilde{\tau}_1)$	198	± 0.9
$M(\tilde{\tau}_1) - M(\tilde{\chi}_1^0)$	29	± 1.0
$M(\tilde{\chi}_1^0)$	169	± 1.4
$M(\tilde{\chi}_1^+)$	327	± 0.6
$M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$	158	± 1.8
$M(\tilde{\chi}_3^0) - M(\tilde{\chi}_1^0)$		± 2.0
$M(\tilde{\chi}_2^+) - M(\tilde{\chi}_1^+)$		± 2.0
$M(A^0)$	419	± 0.8
$\Gamma(A^0)$	18	± 1.2

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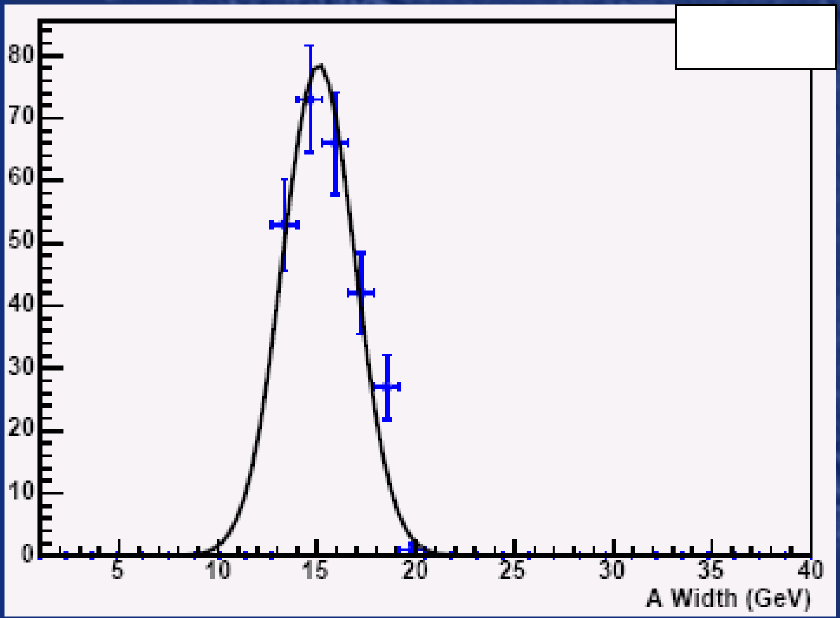
ILC Measurements at 0.5 TeV

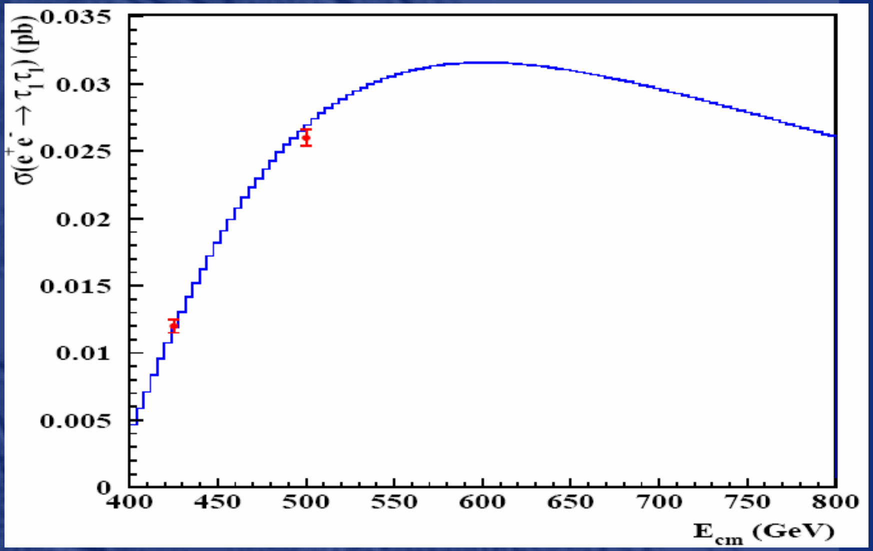
Determine $M(\tau_1)$ and $M(\tau_1) - M(\chi_1^0)$ from stau threshold scan and stau decays;

Estimate $\Gamma(A^0)$ from precise determination of $BR(h^0 \rightarrow bb)$ at 0.35/0.5 TeV;

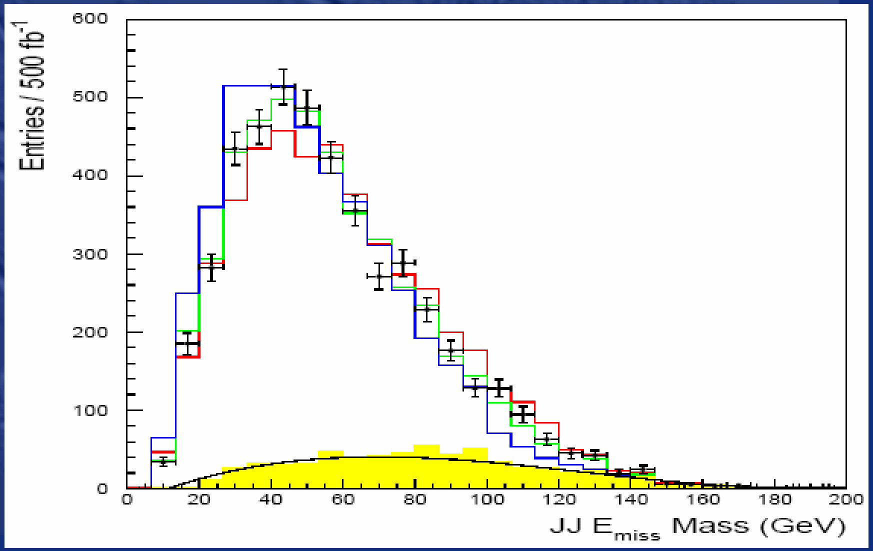
$$\Gamma(A^0) = \frac{BR(h^0 \to b\bar{b})}{BR(A^0 \to b\bar{b})} \times \Gamma(h^0) \times \tan^2\beta$$



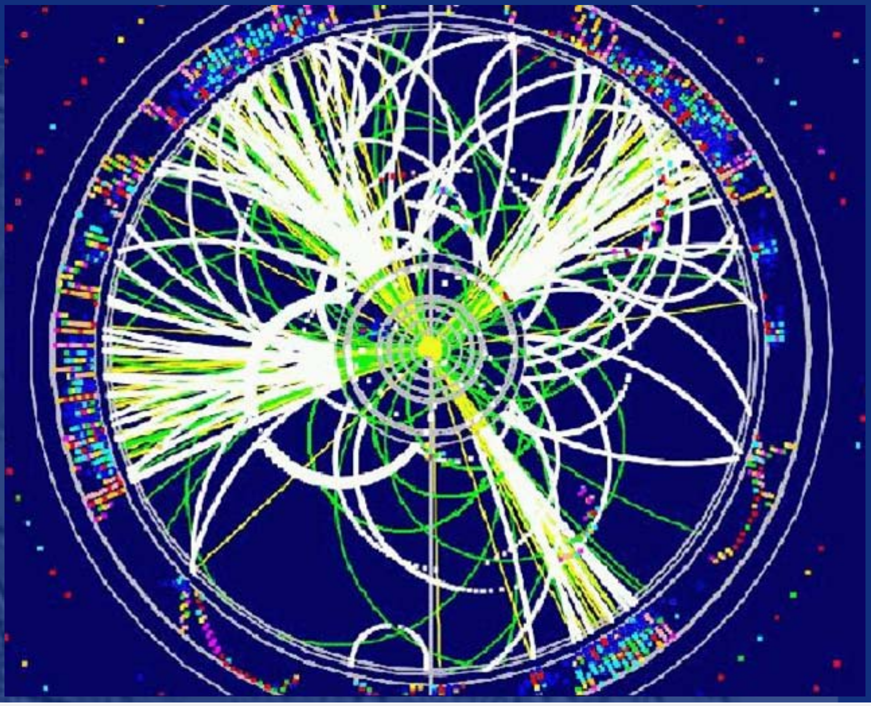
Stau Threshold Scan



$M(j_1j_2E_{missing})$



ILC Measurements at 1 TeV



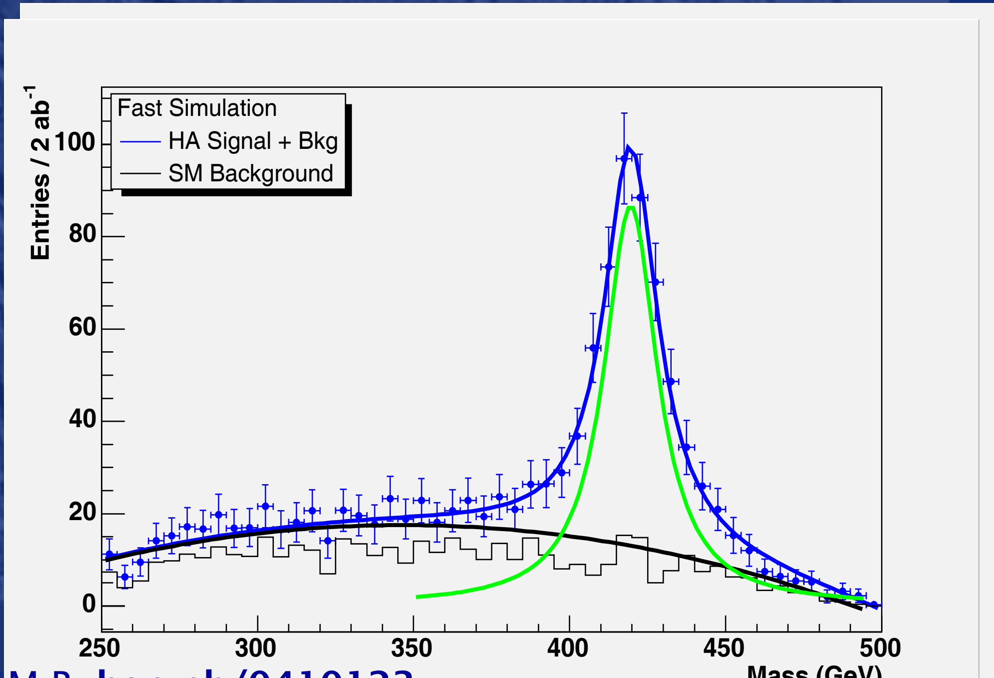
Determine M_A from $e^+e^- \rightarrow H^0A^0$ reconstruction in 4-b jet events at 1 TeV;

Apply 4C constraints and determine M_A and Γ_A from 5-par fit to M_{jj} spectrum using $BW \oplus Gauss$ signal + quadratic background term:

	5-par Fit
$M(A)$ (GeV)	418.9±0.8
$\Gamma(A)$ (GeV)	16.1±2.7
$M(H) - M(A)$ (GeV)	1.4 (Fixed)

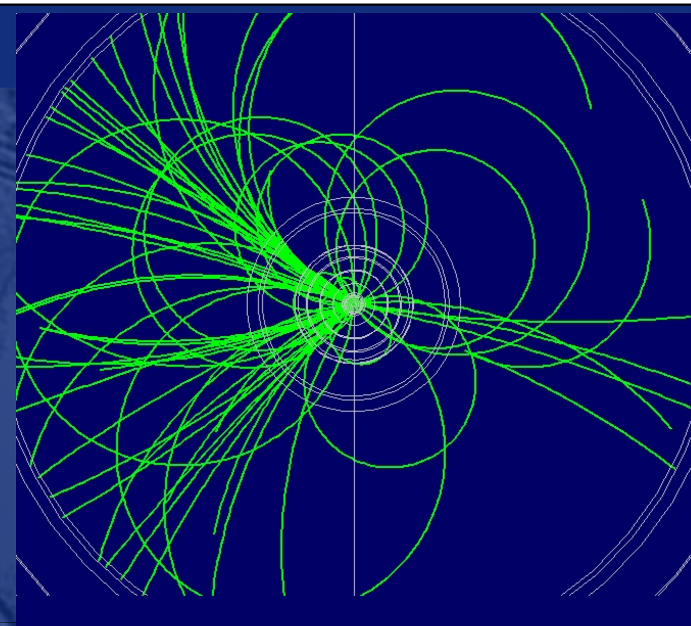
Determine $M(\chi_3)$-$M(\chi_1)$ from Z energy distribution in $\chi_3 \rightarrow \chi_1 Z$ decays in $\chi_3\chi_2$ events to fix μ value;

At LHC M(A) measurable to 2 GeV but difficuly to control Γ(A) and μ.



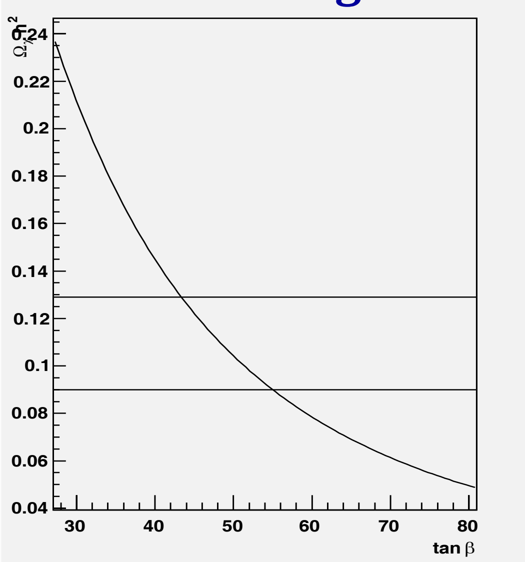
M.B. hep-ph/0410123

Constraining tan β at 1 TeV

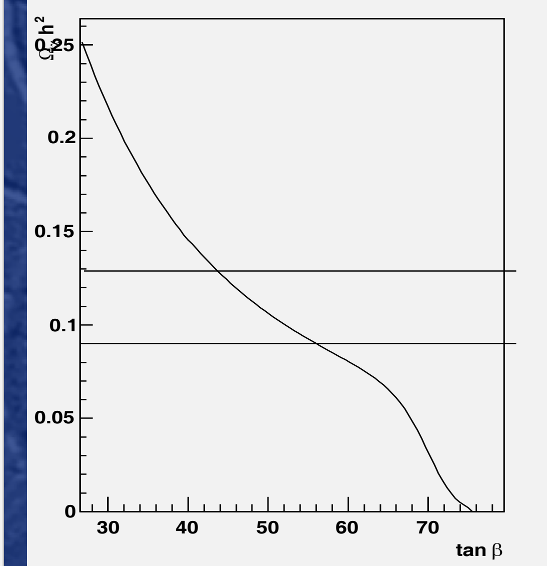


Points at large tan β, such as LCC3 and LCC4 and EGRET compatible region have large sensitivity on tan β;

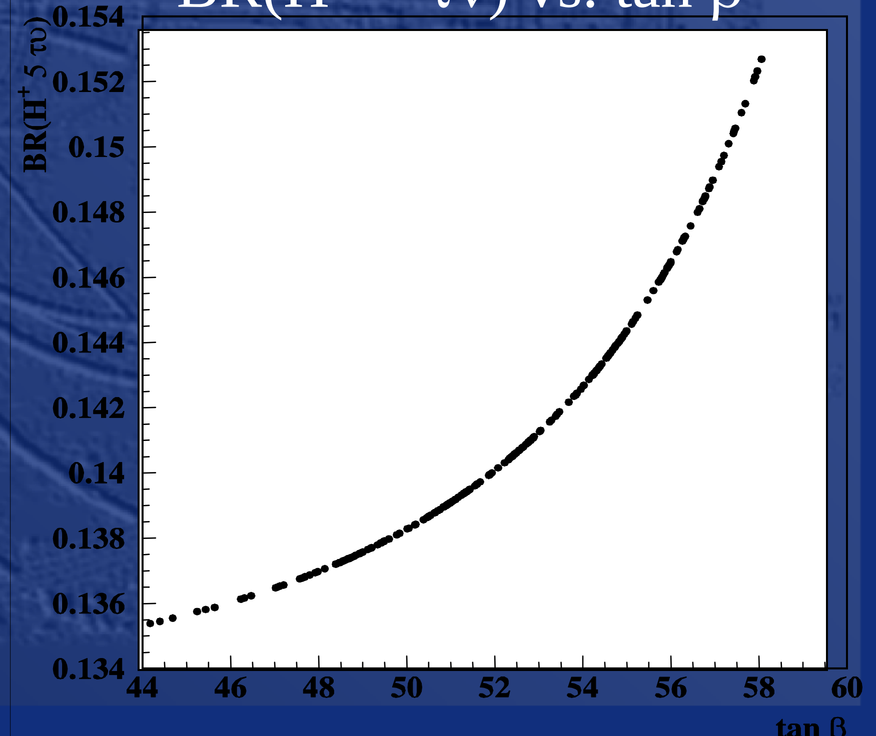
EGRET Region



LCC 4 Point



BR(H^+ →τν) vs. tan β



e+e- →H+H- →tbτν sensitive to tan β process produced with typical cross section of ~ 2 fb at 1 TeV giving BRs accuracy of O(3-6%).

Flat Scans

Perform model-independent MSSM scans around each LCC point;

Extract MSSM parameters from cMSSM inputs and vary MSSM parameters in uncorrelated way over ranges consistent with > 3σ from anticipated accuracies;

Compute DM relic density at each MSSM point and constructed *pdf* by weighting by $\Pi_J \; erf(\frac{\delta_j}{\sqrt{\sigma_j}})$

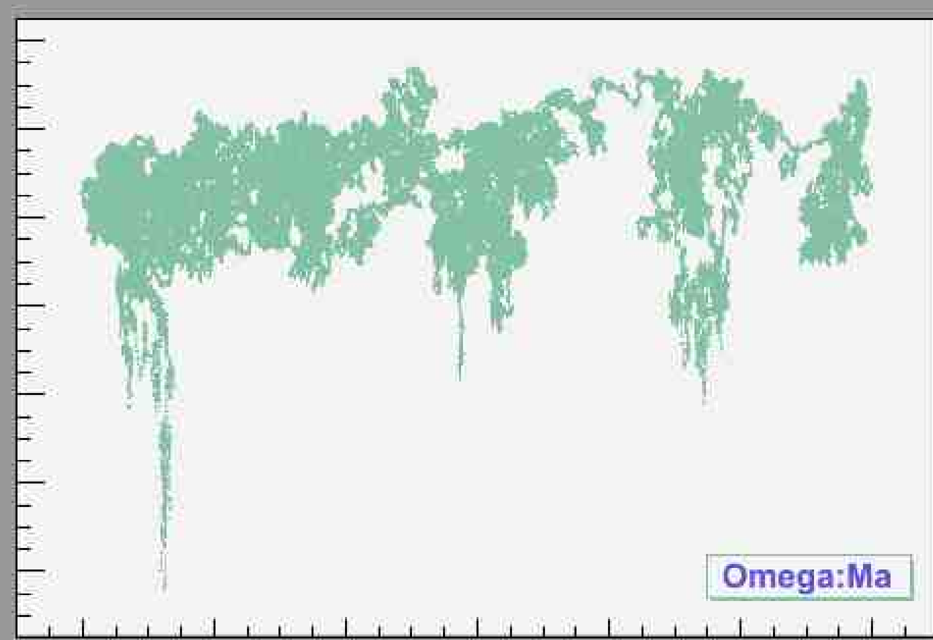
Extract uncertainty on DM density prediction by width of resulting *pdf* distribution.

Parameter	LCC 1	LCC 2	LCC 3	LCC 4
$\tan\beta$	± 10	± 5	± 4	± 10
M_1	± 30	± 10	± 5	± 10
M_2	± 30	± 10	± 5	± 5
M_3	± 30	± 10	± 5	± 5
A_m	±150	±150	±150	± 150
A_l	±150	±150	±150	± 150
A_b	±150	±150	±150	± 150
A_t	±150	±150	±150	± 150
$Ml1$	± 15	± 10	± 4	± 5
$Mr1$	± 15	± 10	± 4	± 5
$Ml3$	± 15	± 10	± 4	± 5
$Mr3$	± 15	± 10	± 4	± 5
Mqu	± 10	± 10	± 10	± 10
Mqd	± 10	± 10	± 10	± 10
$Mq3$	± 10	± 10	± 10	± 10
μ	±150	±150	±150	± 100
M_A	± 100	± 50	± 5	± 4
M_{top}	± 1	± 1	± 1	± 1

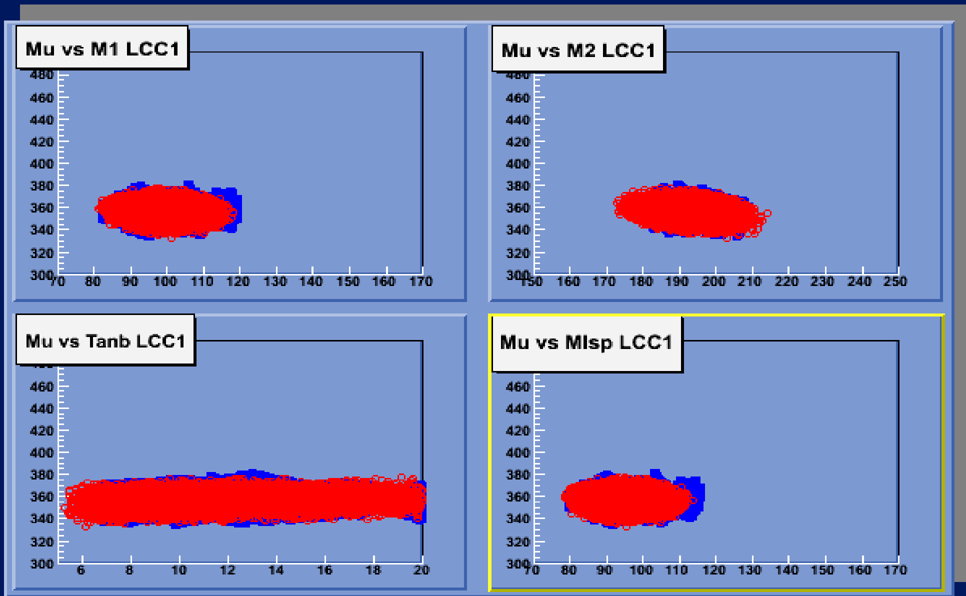
Markov Chain Scans

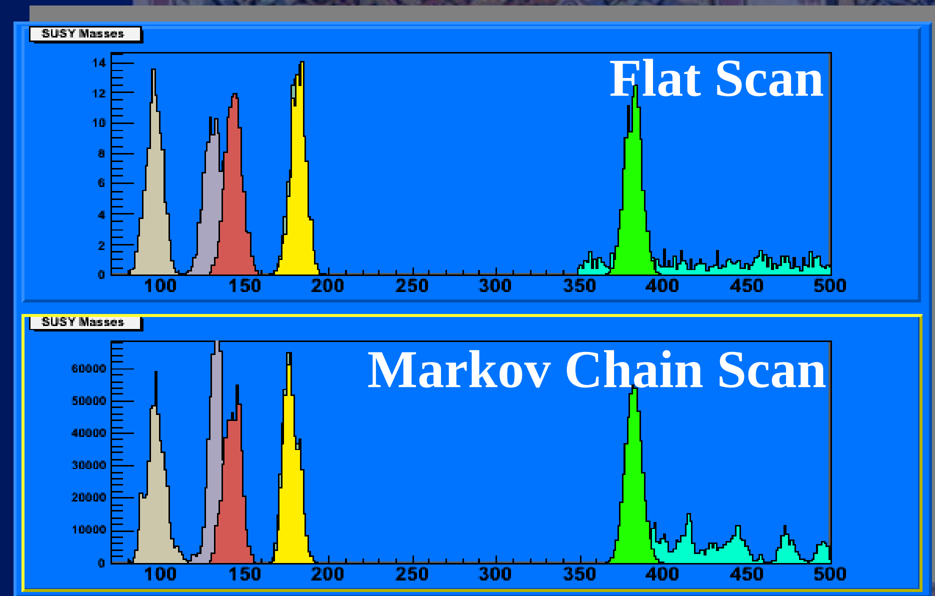
Scan MSSM multi-parameter phase space using Markov Chain Monte Carlo technique: given a point *i* advance to new point *i*+1 if i) $\mathcal{L}(i+1)/\mathcal{L}(i)$ or ii) > rndm() where $\mathcal{L}$ defined by SUSY measurements and anticipated accuracies; (Berg, **cond-mat/0410490** and Baltz, Gondolo **hep-ph/0407039**)

Markov Chain technique is more effcient and has better statistical weight of relevant regions; but reaching into topologically disconnected regions may be problematic;

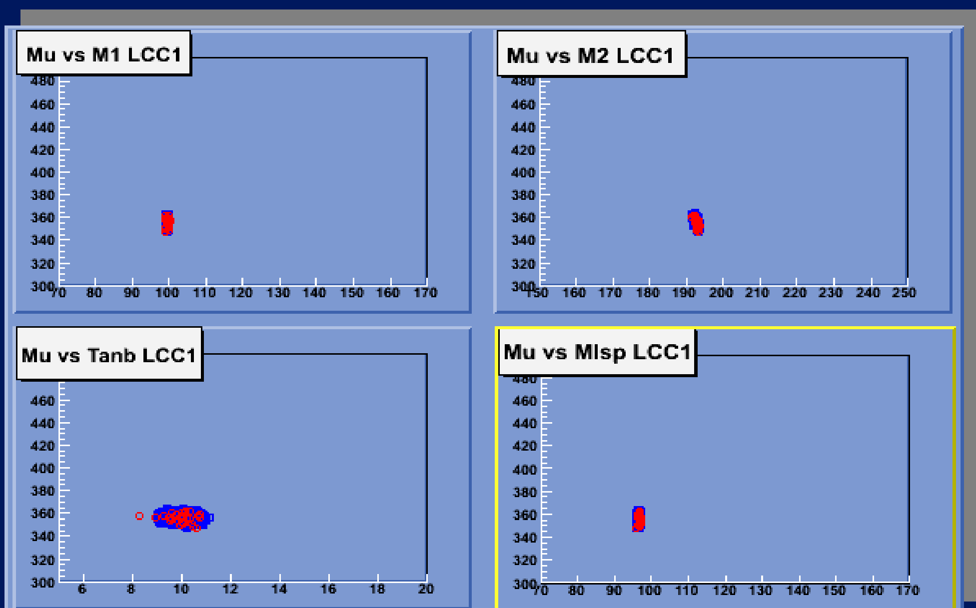


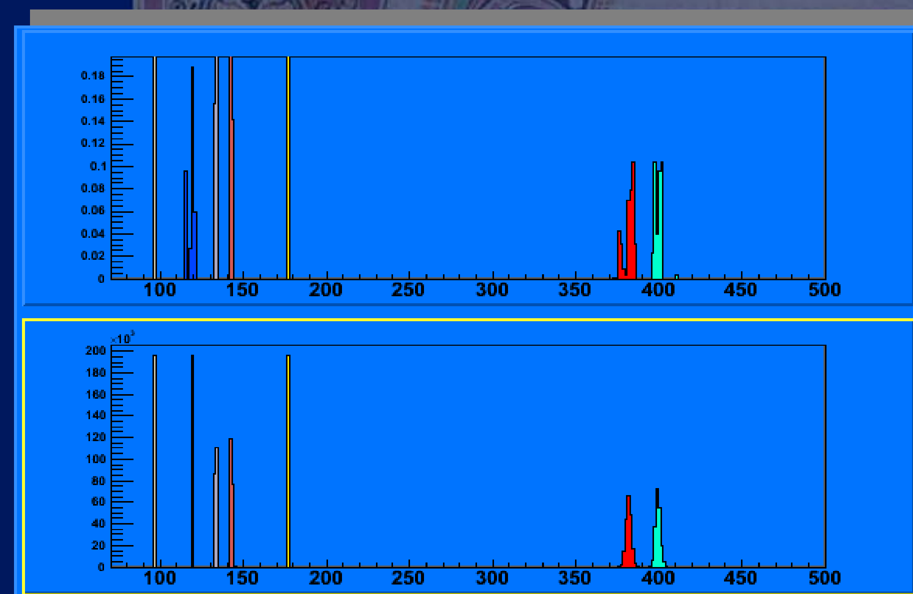
Selected Parameter Regions at LHC and ILC





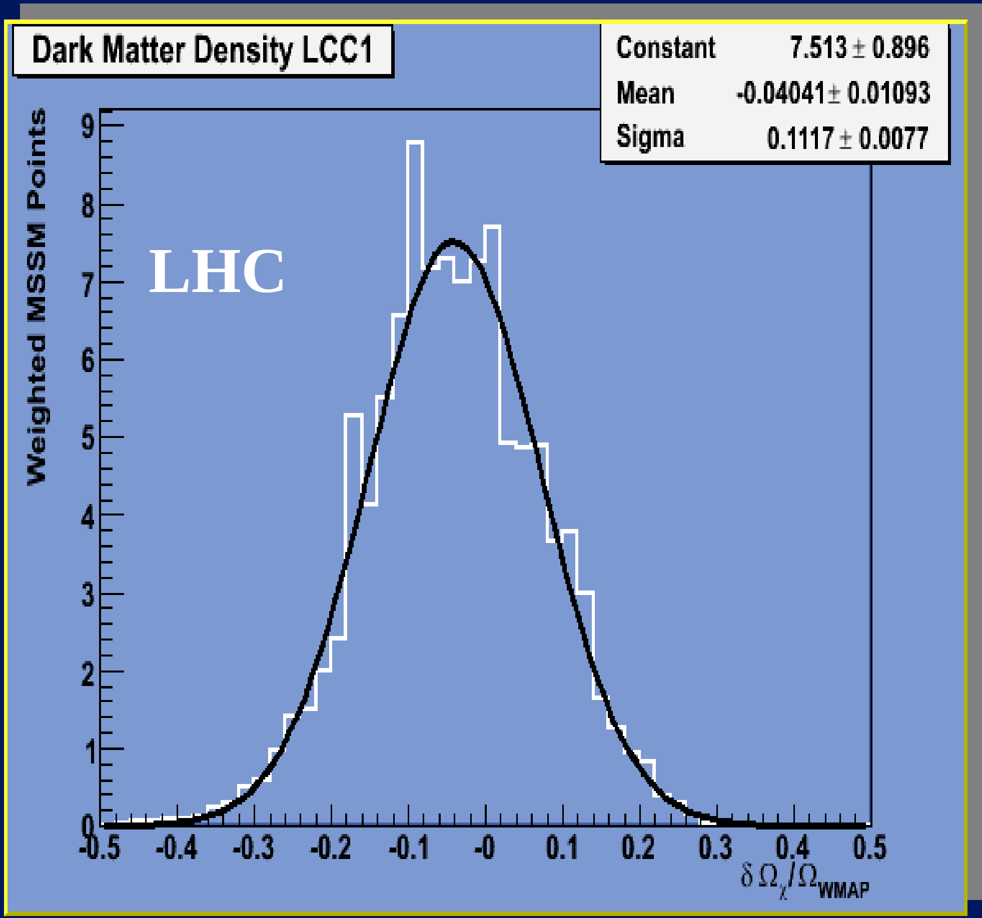
LHC

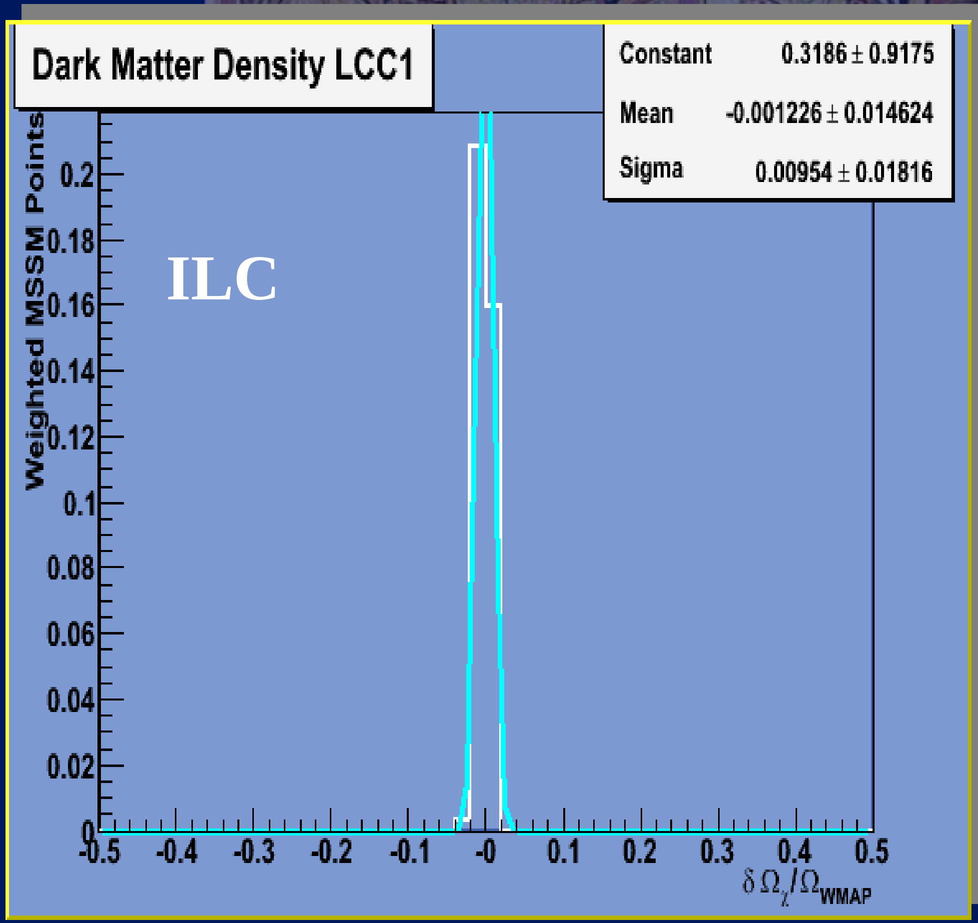




ILC

A Comparison on DM density accuracy at LHC and ILC in Bulk Region





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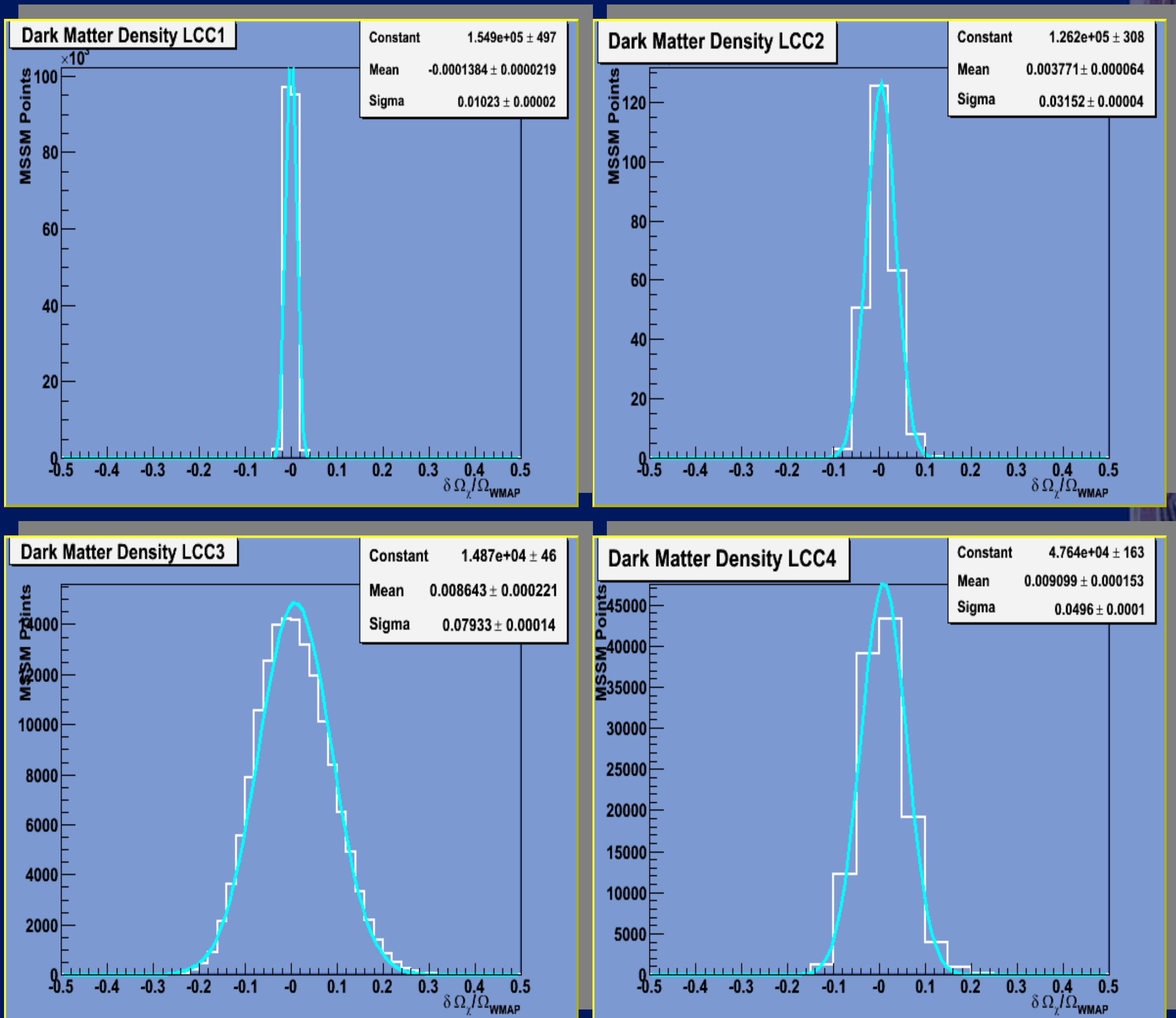
ILC Accuracy on Dark Matter
(Preliminary)



Relative Accuracy $\delta\Omega/\Omega$ (Preliminary)

Flat Scan

LCC1 0.009	LCC2 0.035
LCC3 0.060	LCC4 0.046

Markov Chain Scan

LCC1 0.010	LCC2 0.032
LCC3 0.075	LCC4 0.049

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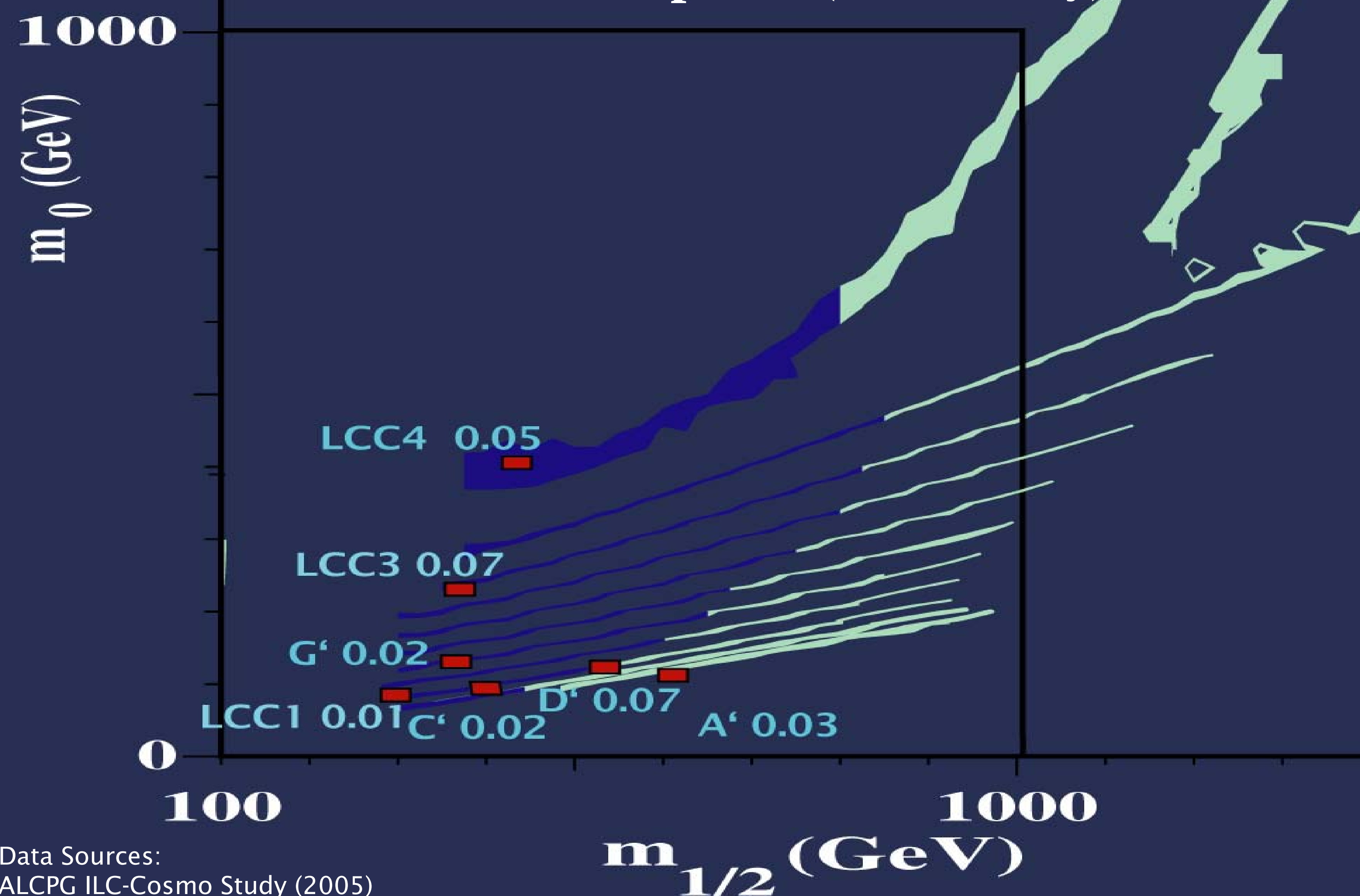
δΩ/Ω ILC Accuracy within MSSM on cMSSM plane (Preliminary)



Data Sources:
ALCPG ILC-Cosmo Study (2005)
and Bambade *et al.* hep-ph/0406010

If Lightest Neutralino responsible for observed Dark Matter density in the Universe, **expect important signals to be detected at LHC**;

But to fully understand the role of the newly discovered particles in determining the Dark Matter and its impact on the history of the Universe, the **accuracy provided by the ILC** in studying its microscopic properties and those of the other relevant particles is **crucial**;

A sample of scenarios, widely different in terms of phenomenology and requirements shows that the ILC has the capabilities to promote the study of SUSY Dark Matter to an accuracy competitive to that of present and future satellite CMB data.