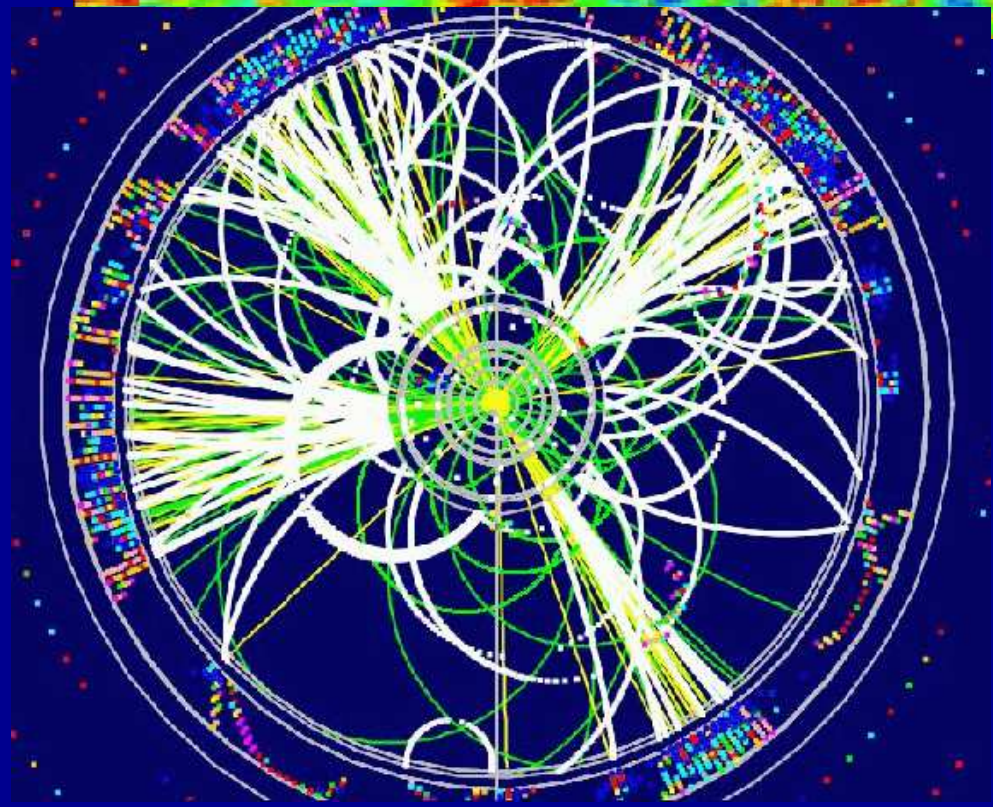
Study of CDM−inspired cMSSM Scenarios at a 1 TeV Linear Collider



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Introduction

✧ LC Physics and Cosmology connection becoming an important argument for sharpening the Linear Collider case;

✧ Offers an important opportunity to re-consider the LC potential for detailed exploration of New Physics responsible for CDM to define benchmark scenarios to optimise the detector design;

✧ This study represents a preliminary survey of the capabilities and experimental implications in slepton and Higgs analyses of CDM-inspired cMSSM scenarios;

✧ initiated as part of the activity of the US LC-Cosmo group and now becoming also embedded in the ALCPG Detector Design Study;

✧ Consider $\sqrt{s} = 0.5$ TeV and 1 TeV and including `Circe` beamstrahlung, events generated with `Pythia 6.205+Isajet 7.67`, detector simulation with `Brahms`, `Lelaps` and Fast Simulation; analysis with `JAS-3` LCD Software;

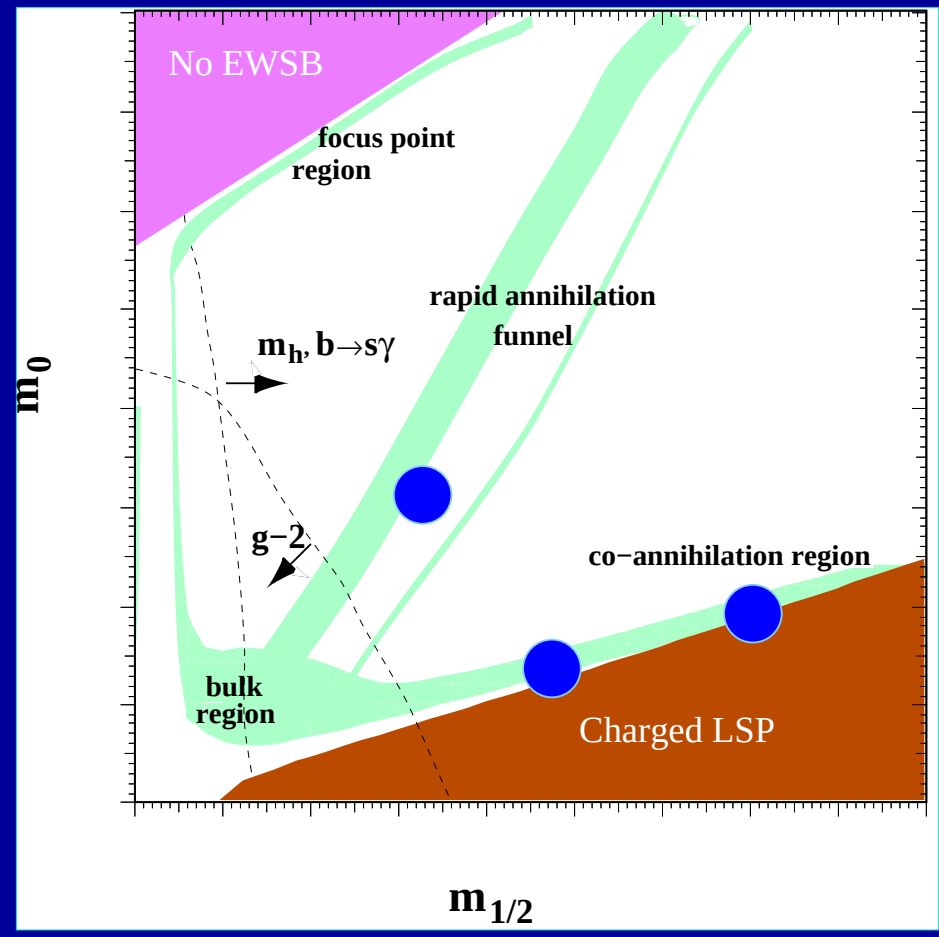
Post-LEP & WMAP cMSSM

✧ cMSSM regions compatible with LEP and WMAP CDM constraints in **co-annihilation** $(\chi\tilde{\ell})$, **rapid annihilation** $(\chi\chi \to A)$ and **focus point** regions;

✧ LC potential in testing CDM nature requires to follow reach and accuracy along these regions for different values of $(m_{1/2}, \tan\beta)$ and study experimental issues;

✧ This study addresses phenomenology along **co-annihilation tail** and in **rapid annihilation funnel**;

✧ Checking consistency of cMSSM with cosmology data requires precise determinations of $M_{\tilde{\ell}} - M_{\chi_1^0}$ or M_χ/M_A and $\tan\beta$ at LC.



Slepton Signatures in the post-WMAP cMSSM Parameter Space

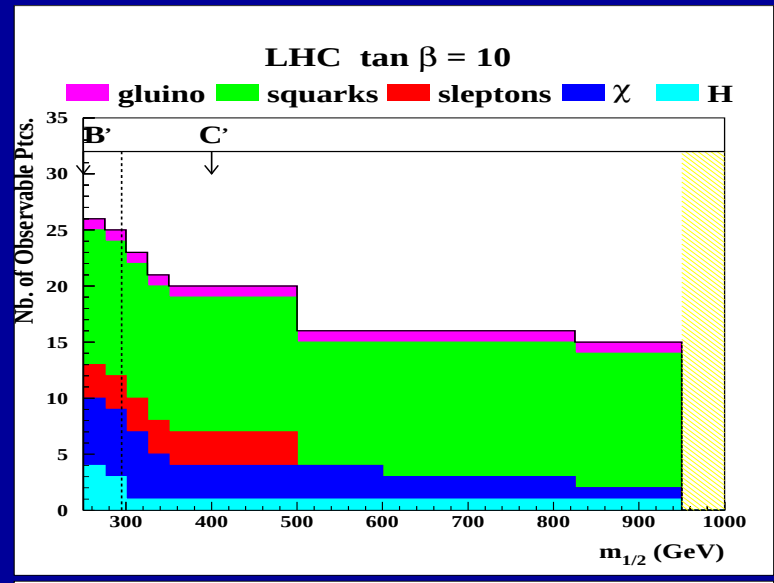
✧ Slepton reconstruction at LC crucial for determining SUSY masses complementing the LHC reach;

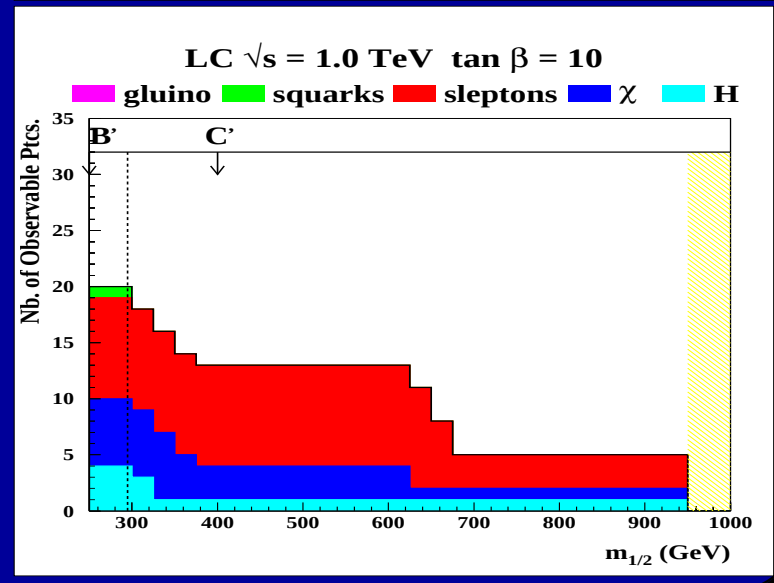
✧ Testing SUSY nature of DM confronting cosmology data, crucial to accurately measure $M_{\tilde{\ell}} - M_{\chi}$ in co-annihilation region and $M_{\tilde{\tau}} - M_{\chi}$ in annihilation funnel.

✧ Distinctive $2\ \ell\ +\ E_{missing}$ signature offers clean selection and fit to E_{ℓ} spectrum provides $M_{\tilde{\ell}}$ vs. M_{χ} reconstruction, τ tagging important;

✧ Typical LC mass accuracy in bulk region
$\delta M_{\tilde{\ell}}/M_{\tilde{\ell}} \simeq 0.3\ \%$ $\quad \delta M_{\chi}/M_{\chi} \simeq 0.2\ \%$

✧ Co-Annihilation and funnel regions present new challenges requiring detailed study of LC capabilities.



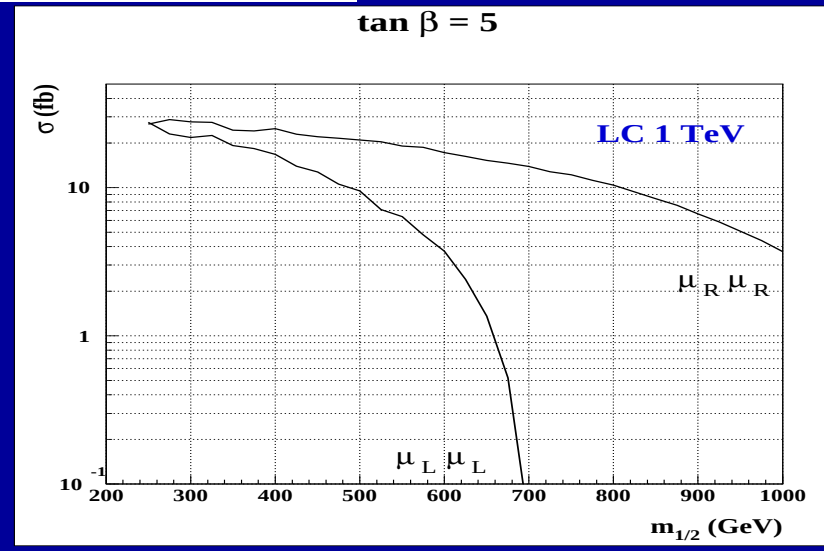


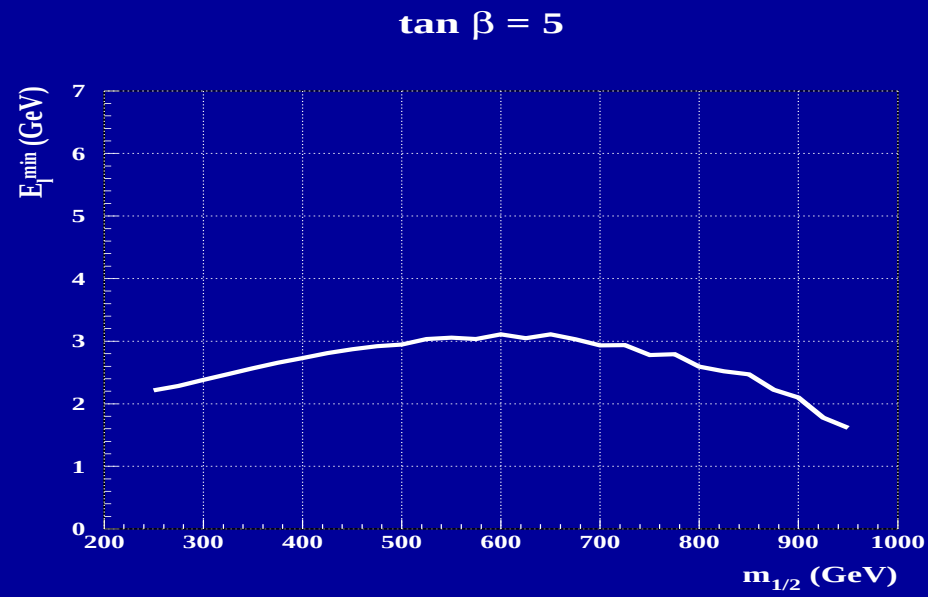
Slepton Signatures in the co-Annihilation Region

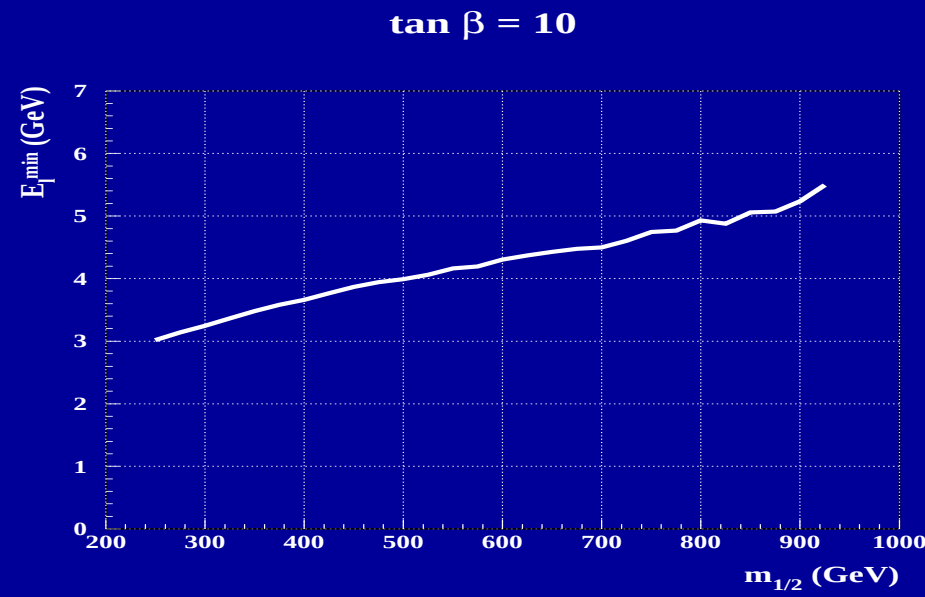
✧ Highest reach in $m_{1/2}$ from $e^+e^- \to \tilde{\ell}_R^+\tilde{\ell}_R^-$: LC at $\sqrt{s}$=1 TeV covers upper limit in $m_{1/2}$ for $\tan\beta =$ 5 - 10 with $\sigma(e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-) = \mathcal{O}$(1-10 fb);

✧ along WMAP line $\tilde{\ell}_R$ becomes nearly degenerate with χ_1^0: tuning E_{beam} for sizeable σ softens E_ℓ^{min}:

$$E_\ell^{min} = \frac{1}{2} M_{\tilde{\ell}} \left(1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\ell}}}\right) \gamma \left(1 - \sqrt{1 - \frac{M^2_\ell}{E^2_{beam}}}\right);$$







✧ Lepton id. critical at lower endpoint due to:

1. Intrinsic Momentum Cut-off
2. $\gamma\gamma \to \mathrm{hadrons}$ Background

✧ Momentum cut-off p_t^{min} defined by radius R_{det} of ECal, HCal and Muon Chambers and solenoidal field B:

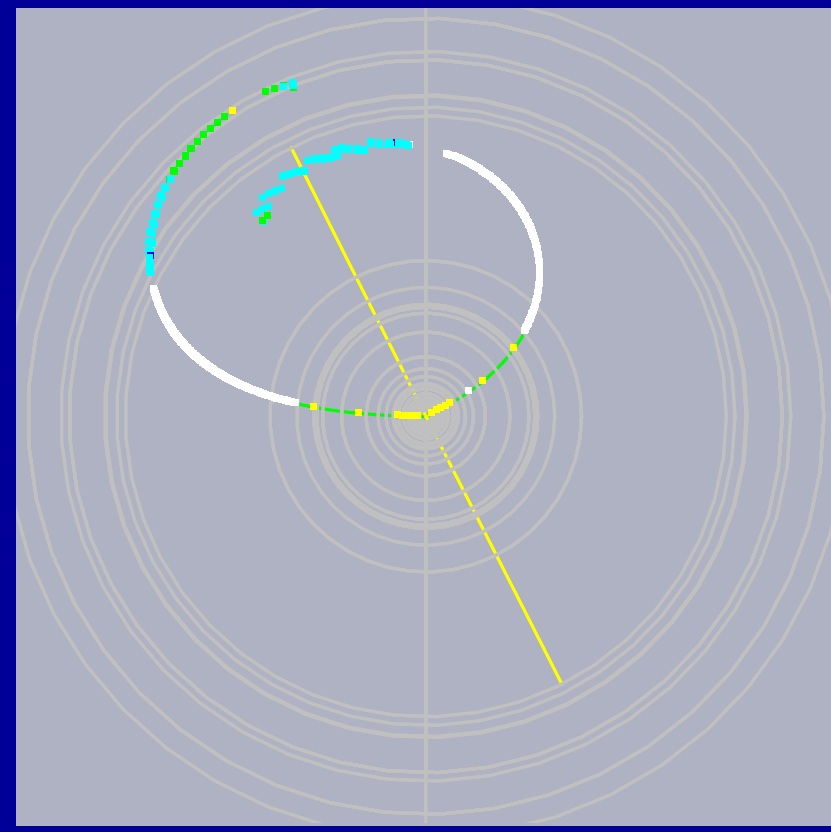
$$p_t^{min}[\mathrm{GeV}] = \frac{R_{det}[\mathrm{m}]}{0.3B[\mathrm{Tesla}]}$$

	Large Det
B [Tesla]	4
	p_t^{min} (GeV)
μ μCh	4.2
μ HCAL	2.0
e ECAL	1.5
e dE/dx	0.7

✧ $\gamma\gamma \to \mathrm{hadrons}$ bkg becomes relevant if only one lepton can be tagged

Wired Display of $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$ at 1 TeV at lower endpoint

$\tan\beta = 5,\ m_{1/2} = 600,\ m_0 = 118$

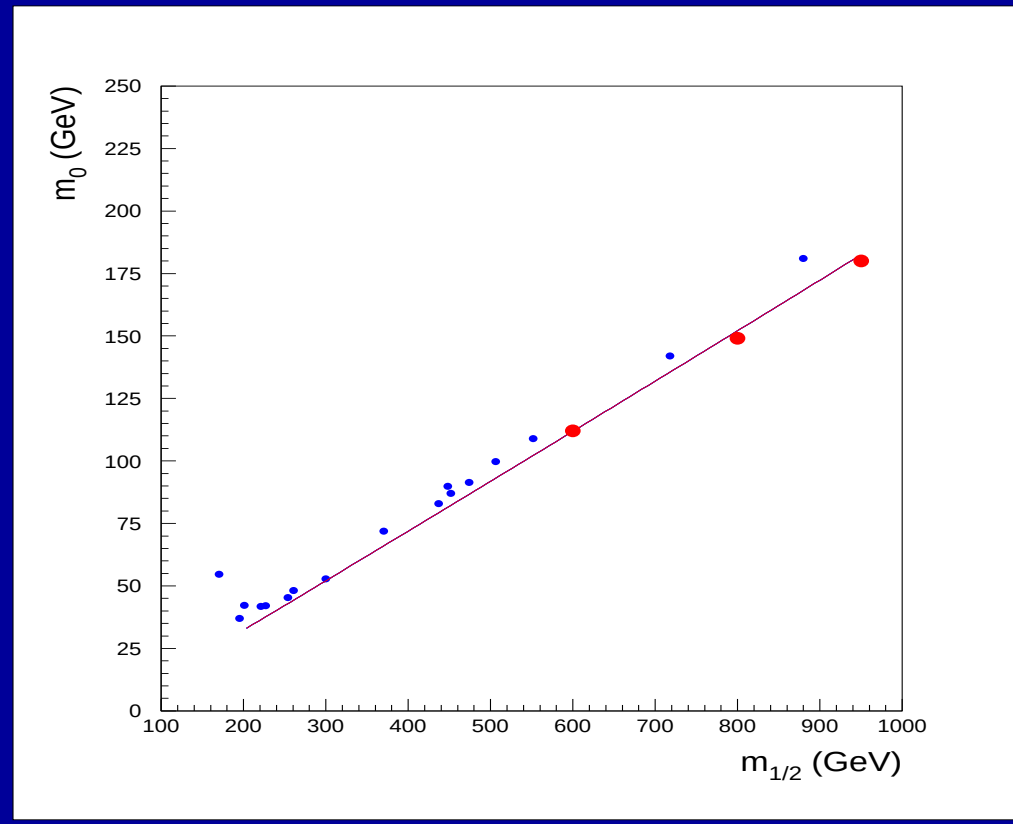


Benchmarking the co-Annihilation Tail

- Study co-annihilation tail with Micromegas and SSARD;
- define 3 study points at $\tan\beta = 5$ to track the slepton phenomenology at 1 TeV LC;

MASSES AT STUDY POINTS

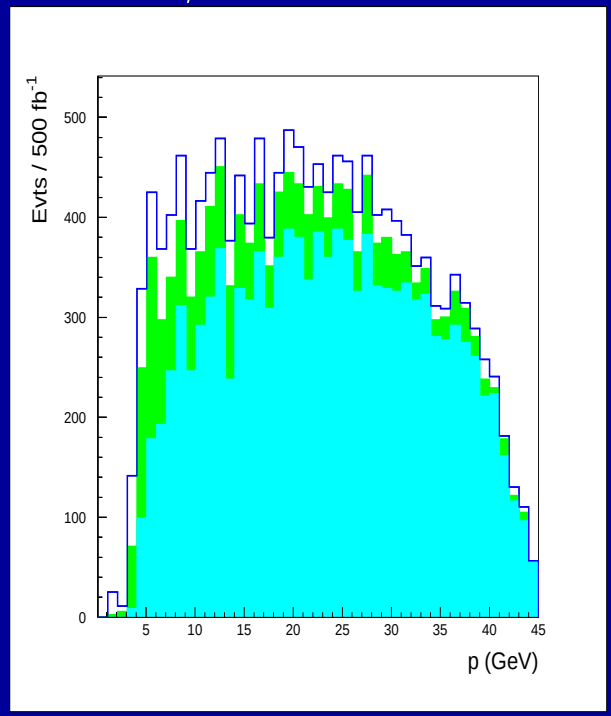
$m_{1/2} = 600$	$m_0 = 114$
$M_{\tilde{\ell}_L} =$	428 GeV
$M_{\tilde{\ell}_R} =$	255 GeV
$M_{\chi_1^0} =$	243 GeV
$m_{1/2} = 800$	$m_0 = 149$
$M_{\tilde{\ell}_L} =$	564 GeV
$M_{\tilde{\ell}_R} =$	335 GeV
$M_{\chi_1^0} =$	329 GeV
$m_{1/2} = 950$	$m_0 = 182$
$M_{\tilde{\ell}_L} =$	668 GeV
$M_{\tilde{\ell}_R} =$	397 GeV
$M_{\chi_1^0} =$	394 GeV



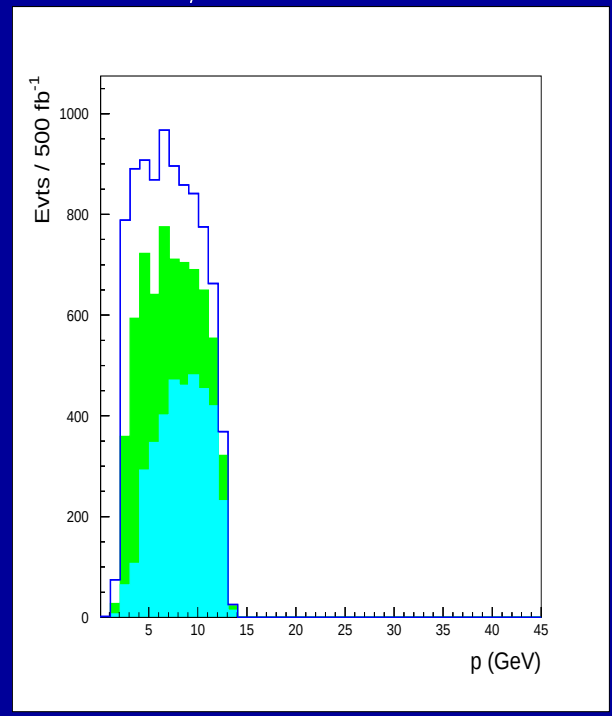
Lepton Momentum

LEPTON MOMENTUM SPECTRUM IN
$e^+e^- \to \tilde{\ell}_R^+\tilde{\ell}_R^- \to \ell^+\chi_1^0\ell^-\chi_1^0$ AT 1 TeV FOR $\tan\beta = 5$ ($\ell = e, \mu$)

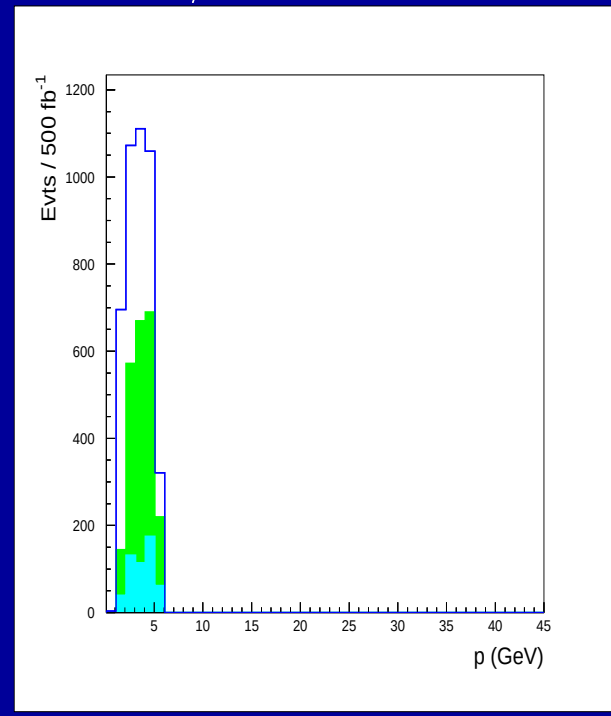
$m_{1/2} = 600$ GeV



$m_{1/2} = 800$ GeV



$m_{1/2} = 950$ GeV



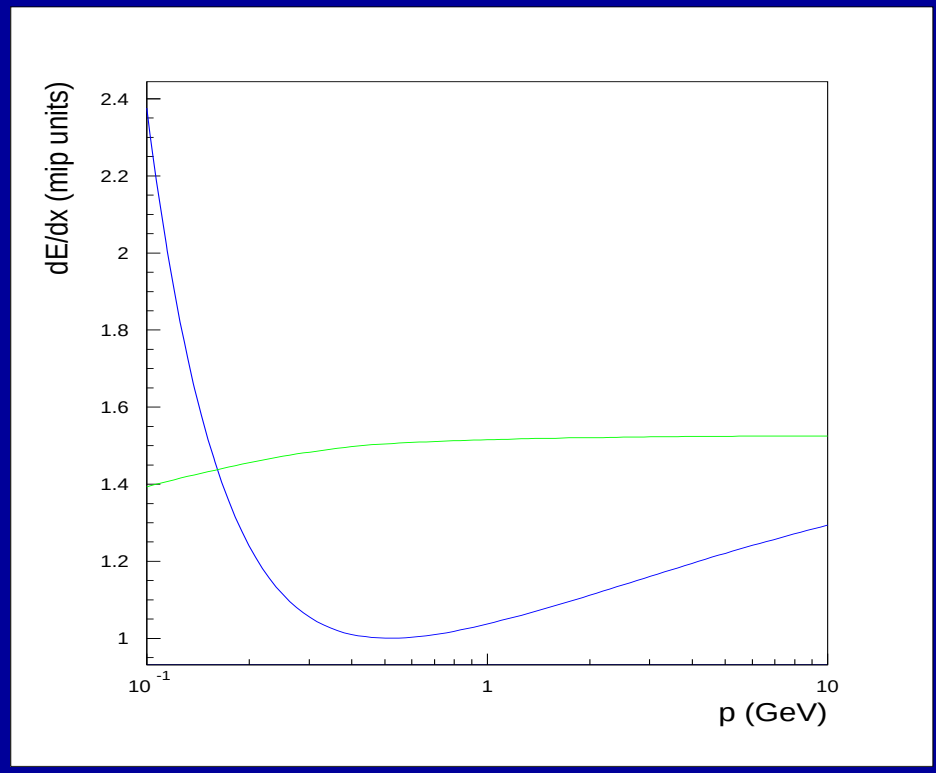
✧ Lepton ld momentum acceptance cuts into lower endpoint for $m_{1/2} > 500$ GeV.

Electron Id with dE/dx in TPC

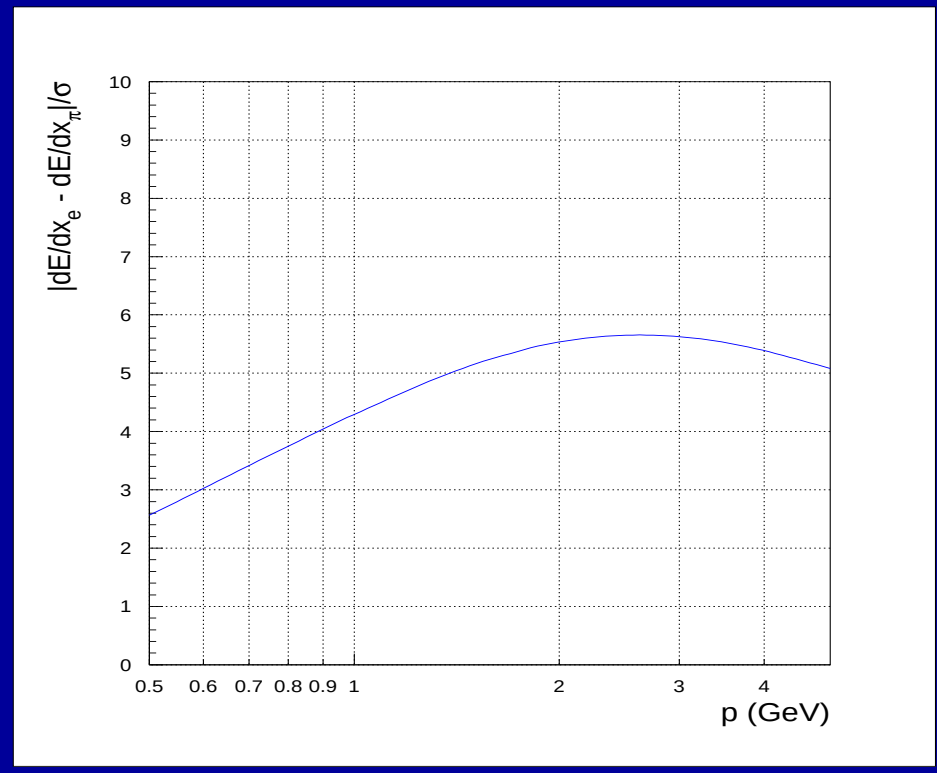
✧ dE/dx in TPC useful to recover low-momentum electrons:

$$\sigma(dE/dx) = 0.045 \times \sqrt{\frac{1.68[\mathrm{m}]}{0.3B[\mathrm{T}]p_t[\mathrm{GeV}]}}$$

dE/dx vs. p



$|dE/dx_e - dE/dx_\pi|/\sigma$

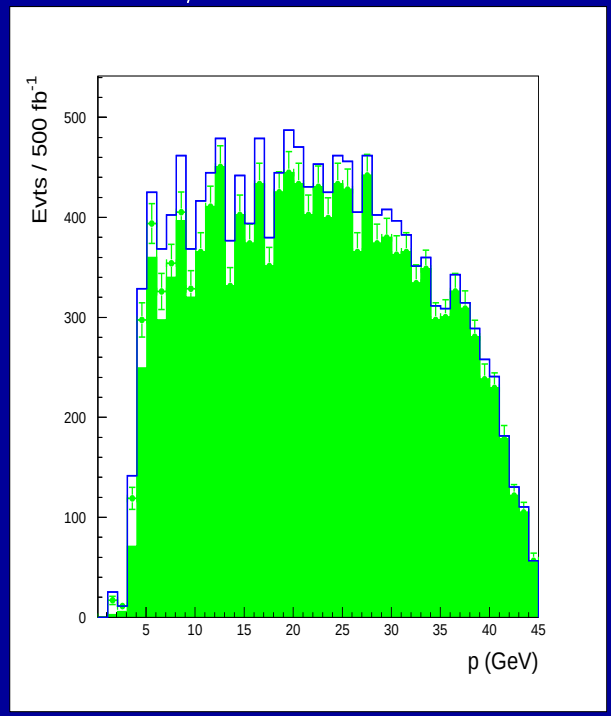


✧ TPC with 200 samplings and 4.5% resolution should ensure $> 4\sigma$ e/π separation over the interesting momentum window.

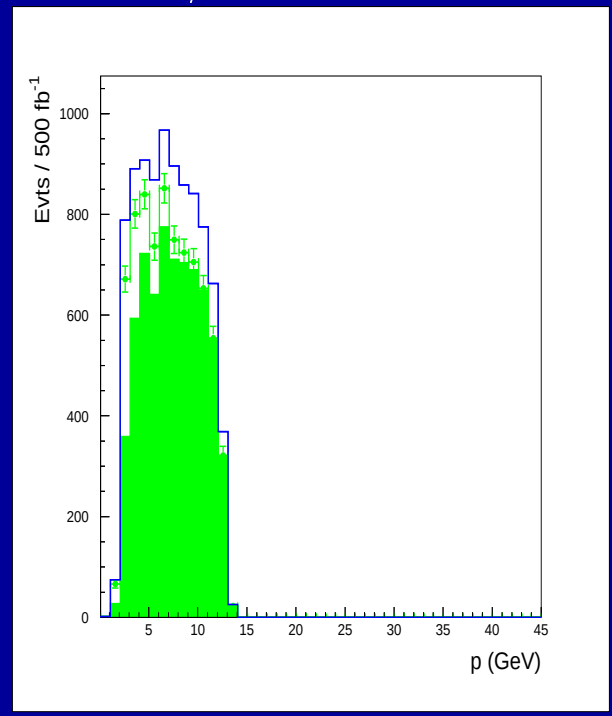
Electron Momentum

Electron Momentum Spectrum in
$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^- \to e^+\chi_1^0 e^-\chi_1^0$ at 1 TeV for $\tan\beta = 5$ (with dE/dx Id)

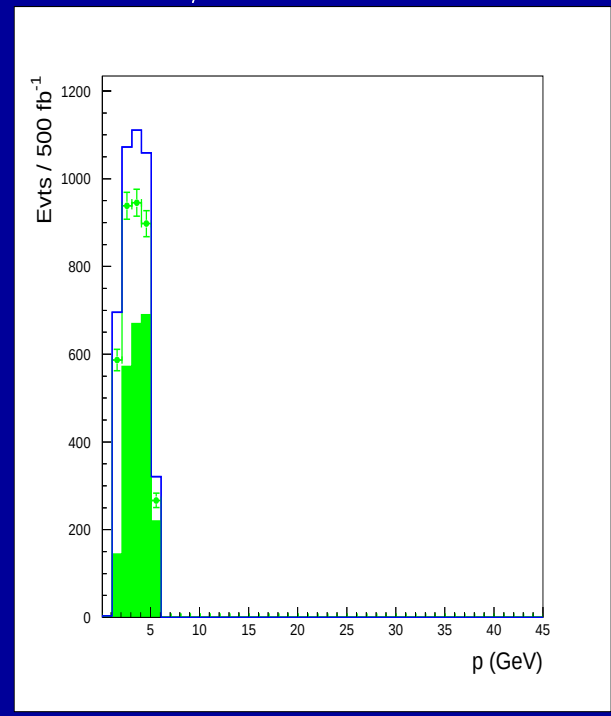
$m_{1/2} = 600$ GeV



$m_{1/2} = 800$ GeV



$m_{1/2} = 950$ GeV

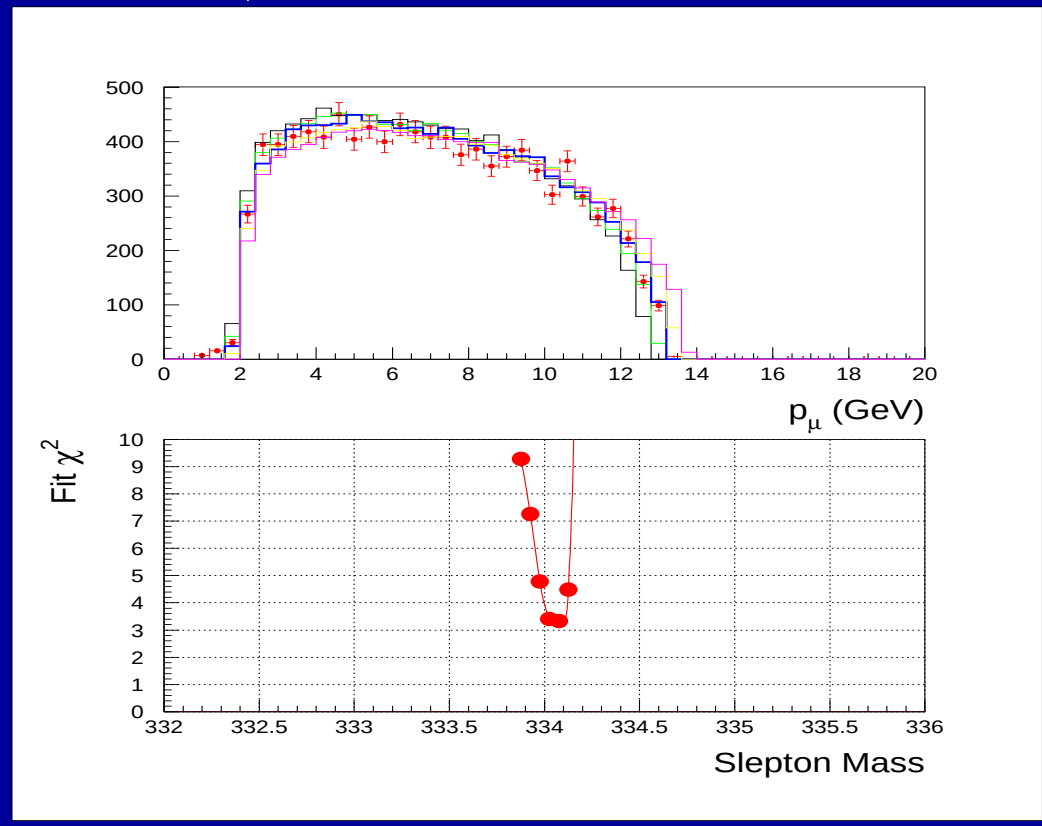


- Electron dE/dx Id recovers sensitivity to lower endpoint almost to upper $m_{1/2}$ edge.

Slepton Mass Fit

- Extract $\tilde{\ell}_R$ mass from χ^2 fit to full lepton momentum distribution;
- include beamstrahlung and momentum resolution effects;
- impose χ_1^0 mass (will add as syst. uncertainty);

$m_{1/2} = 800$ GeV, $\sqrt{s} = 1$ TeV



Preliminary Slepton Mass Accuracy at 1 TeV for 500 fb^{-1}

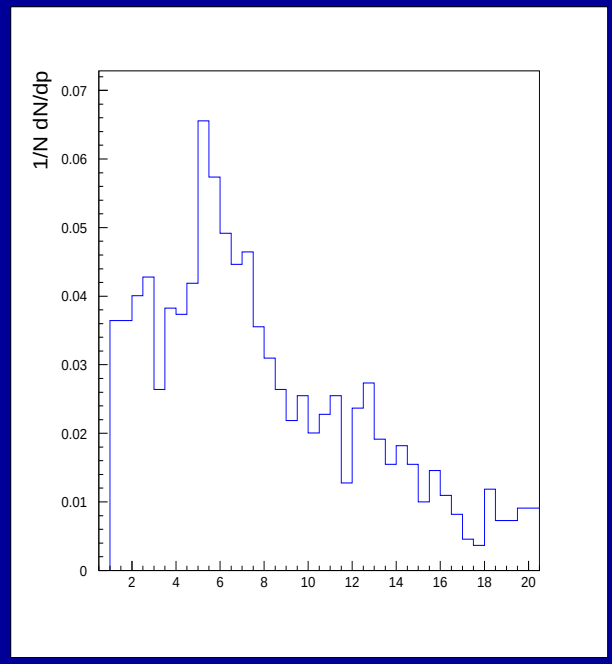
$m_{1/2}$ (GeV)	$\delta M_{\tilde{\ell}_R}$ (GeV)
600	0.07
800	0.10
950	0.06

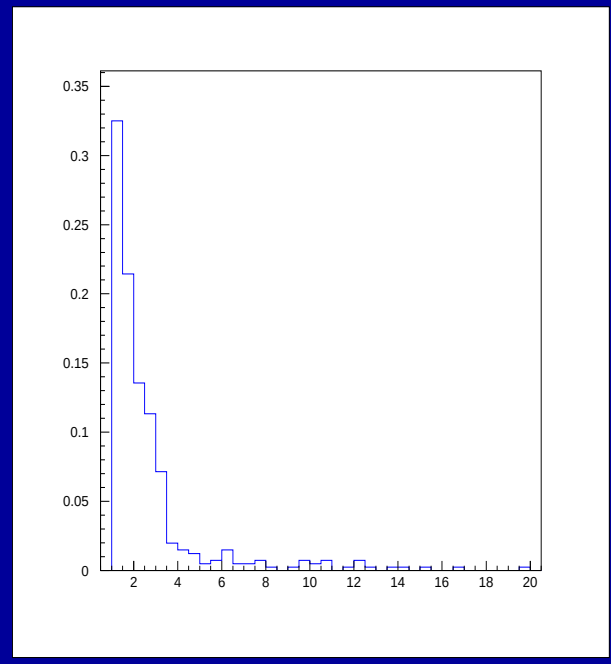
$e^+e^- \to \tilde{\tau}\tilde{\tau}$

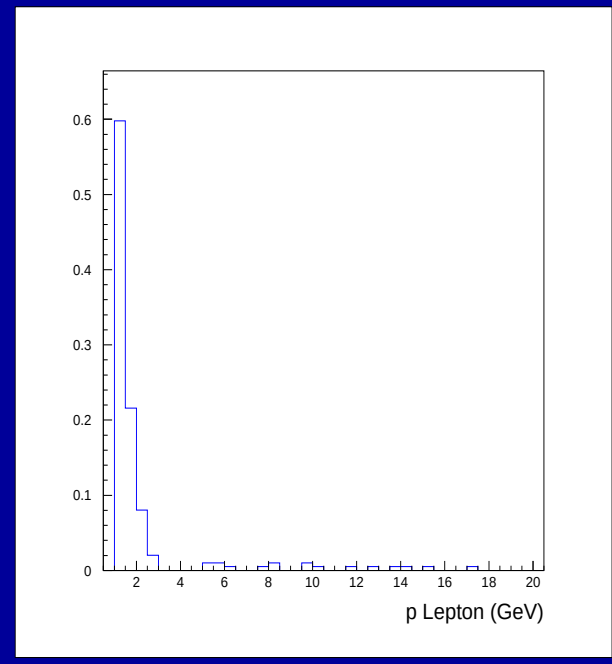
✧ Soft lepton spectrum also affects reconstruction of stau decays;

LEPTON MOMENTUM SPECTRUM IN
$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^- \to \ell^+ X \chi_1^0 \ell^- X \chi_1^0$ AT 1 TeV FOR $\tan\beta = 5$

$m_{1/2} = 600$ GeV	$m_{1/2} = 800$ GeV	$m_{1/2} = 950$ GeV
$M_{\tilde{\tau}_1} = 253.6$ GeV	$M_{\tilde{\tau}_1} = 332.3$ GeV	$M_{\tilde{\tau}_1} = 396.8$ GeV
$M_{\tilde{\tau}_2} = 428.0$ GeV	$M_{\tilde{\tau}_2} = 563.7$ GeV	$M_{\tilde{\tau}_2} = 668.4$ GeV





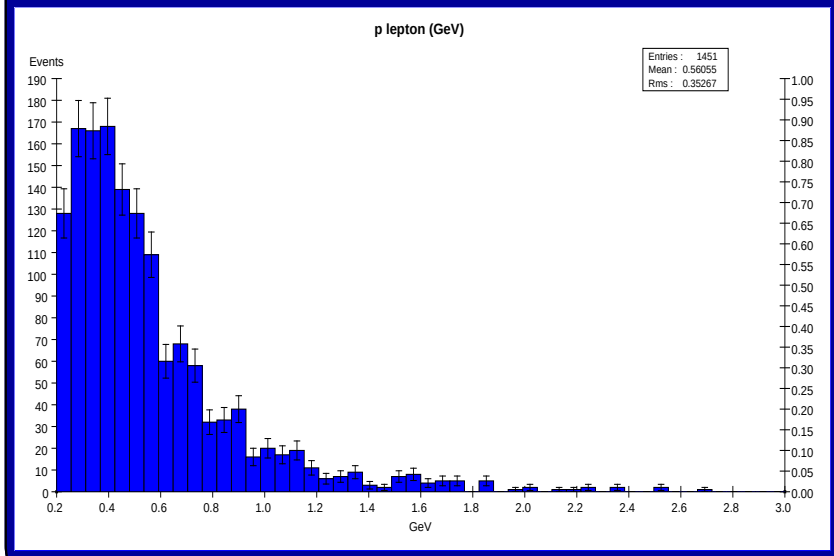


$\gamma\gamma \to$ hadrons **Background**

- Estimate rate from $\gamma\gamma \to$ hadrons background

	TESLA 0.8 TeV	NLC 1.0 TeV
$\mathcal{L}$ (fb BX^{-1})	2.7×10^{-9}	1.3×10^{-9}
$N_{\gamma\gamma}$ BX^{-1}	0.40	0.27
$N_{\gamma\gamma}$ 500 fb^{-1}	0.75×10^{11}	1.05×10^{11}

- $\gamma\gamma \to$ hadrons sample for NLC at 1 TeV;
- Suppress $\gamma\gamma \to$ hadrons bkg using event shape and kinematical variables;
- Assume $\epsilon(\pi \to \ell) \simeq 0.10$ at low p



Evts/500 fb^{-1}	1.5 - 2.5 GeV	2.5 - 5 GeV
$2\ \ell\ +\ E_{missing}$	$\sim$ 22k	$\sim$ 7 k
$1\ \ell\ +\ E_{missing}$	$\sim$ 16M	$\sim$ 1.5 M

- Important to tag fwd electrons down to small angles to suppress $\gamma\gamma \to$ hadrons.

The A^0 Annihilation Funnel

✧ In rapid annihilation $\chi\chi \to A^0$ funnel, Ω_{CDM} controlled by $R = 2M_\chi/M_A$ and $\tan\beta$;

✧ estimate required accuracy on M_A, M_χ;

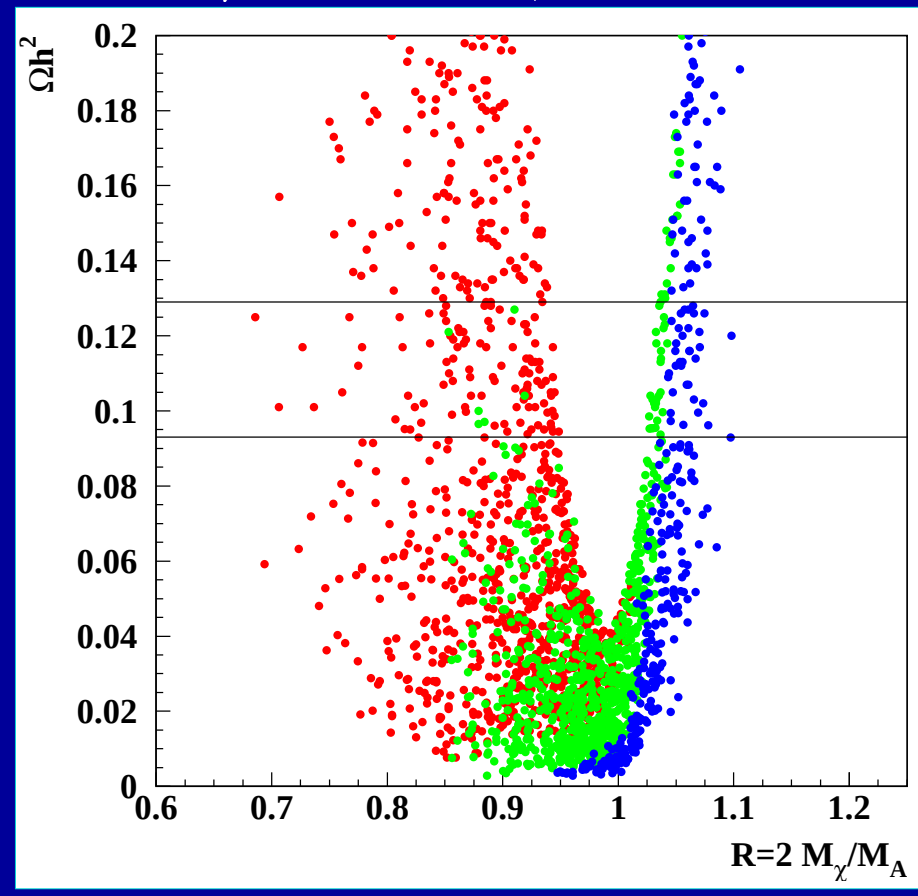
✧ Scan of $(m_0,\ m_{1/2},\ \tan\beta)$ with `Micromegas`, imposing $M_h > 111.5$ GeV and $0.093 < \Omega_{CDM}h^2 < 0.129$ to determine $\Delta\Omega_{CDM}/\Delta R$ (agrees with sc DarkSusy);

$$\Delta\Omega_{CDM}/\Delta R = 2 \text{ - } 5$$

$$\frac{\delta R}{R} = 2\frac{\delta M_\chi}{M_\chi} \oplus \frac{\delta M_A}{M_A}$$

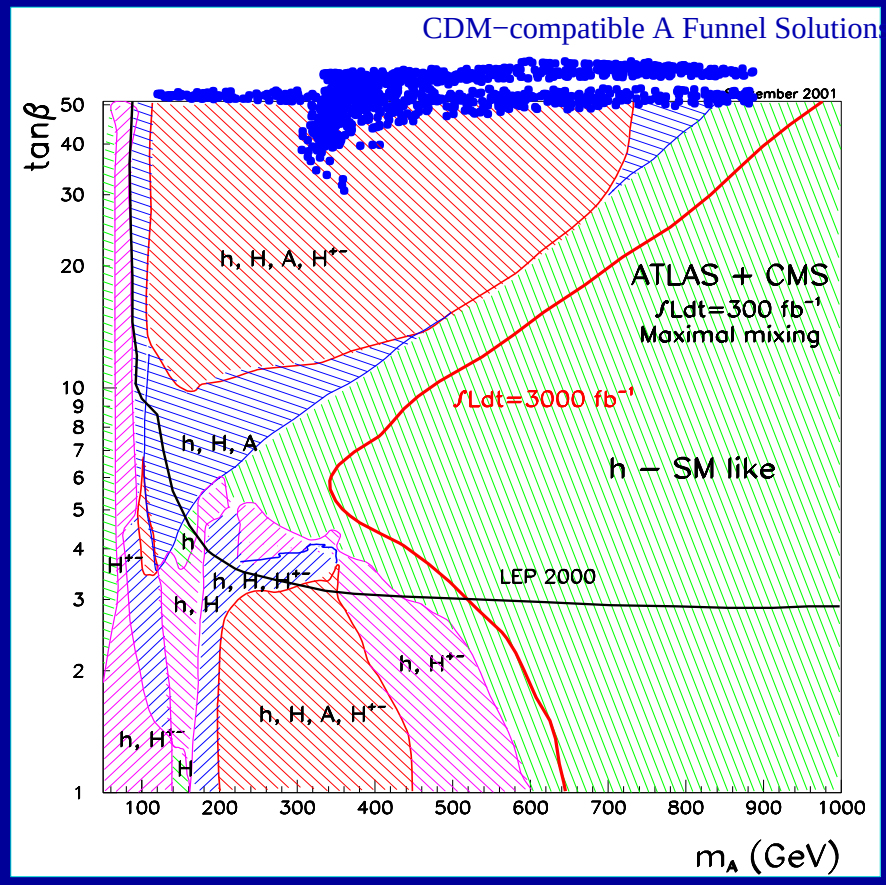
$\to$ must determine M_χ and M_A to $\mathcal{O}(0.5\%)$ or better to ensure Ω_{CDM} accuracy comparable to next generation of satellites (PLANCK), assuming theory uncertainty $\simeq \mathcal{O}(1\ \%)$.

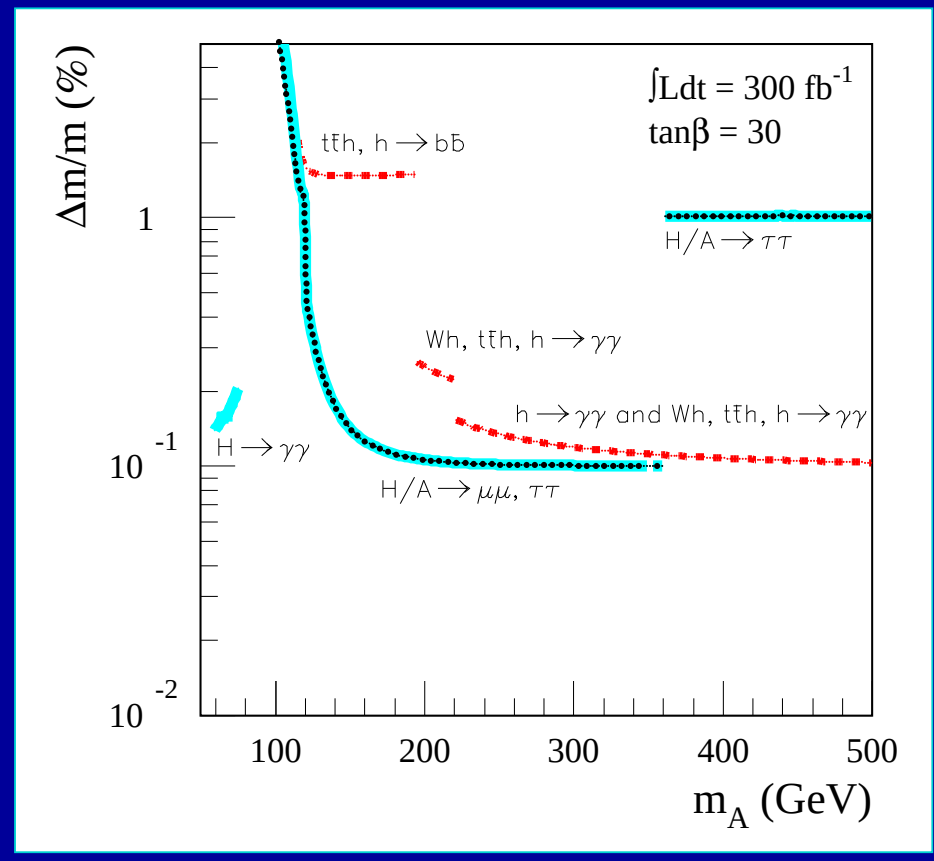
$\Omega_{CDM}h^2$ VS. $2M_\chi/M_A$
FOR $\mu > 0$ IN $\tan\beta \pm 1$ SLICES



The A Boson at the LHC

✧ Cosmologically interesting region within sensitivity of heavy Higgs search at the LHC:





✧ M_A Mass determination accuracy at LHC critically depends on accessibility to $A^0 \to \mu^+\mu^-$ channel which is at the borderline for part of CDM-favoured region.

The LC-Cosmo Study Point LCC4

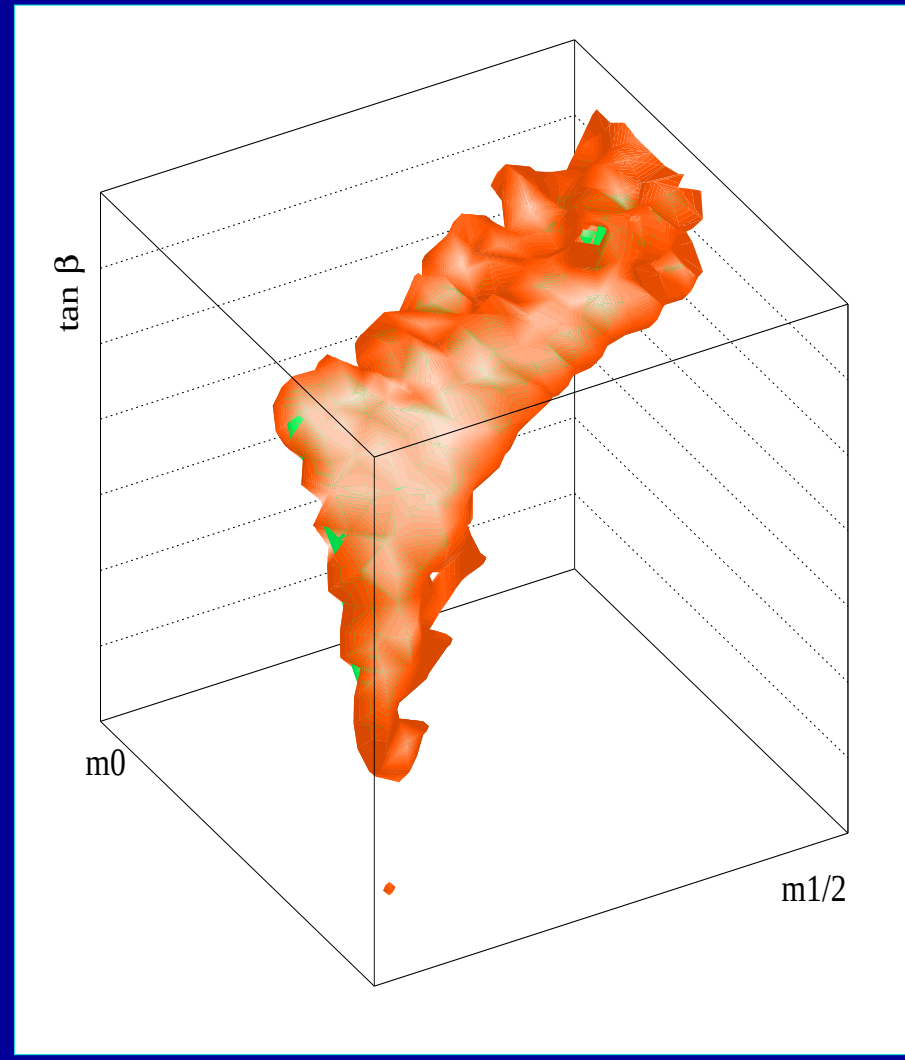
m_0=340.00 GeV $m_{1/2}$=400.00 GeV $\tan\beta$=51
A=0 $Sgn(\mu)$=+1 M_{top}=178 GeV

	Mass (GeV)
M_{h^0}	119
M_{A^0}	419
$M_{\chi_1^0}$	160
$M_{\tilde{\tau}_1}$	187

Analysis strategy

- Determine at 0.5 TeV:
  $M_{\tilde{\tau}_1}$ by threshold scan and $\Delta M = M_{\tilde{\tau}_1} - M_\chi$
  by $\tilde{\tau}_1 \to \tau\chi$ jet kinematics to extract M_χ
- Estimate at 0.5 TeV:
  M_A using $\frac{\mathrm{BR}(h^0\to b\bar{b})}{\mathrm{BR}(h^0\to W^+W^-)}$, $\frac{\mathrm{BR}(h^0\to b\bar{b})}{\mathrm{BR}(h^0\to c\bar{c})}$
- Determine 1.0 TeV:
  M_A with $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$.

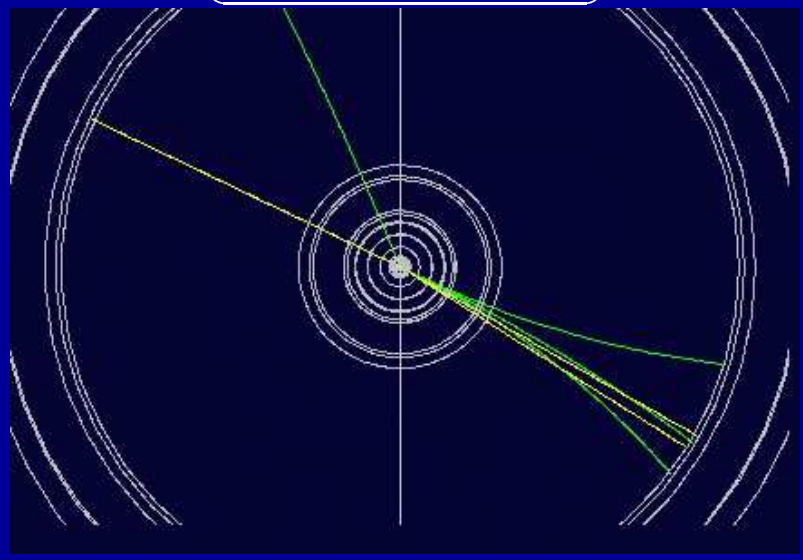
Micromegas SCAN FOR $Sgn(\mu)$=+1



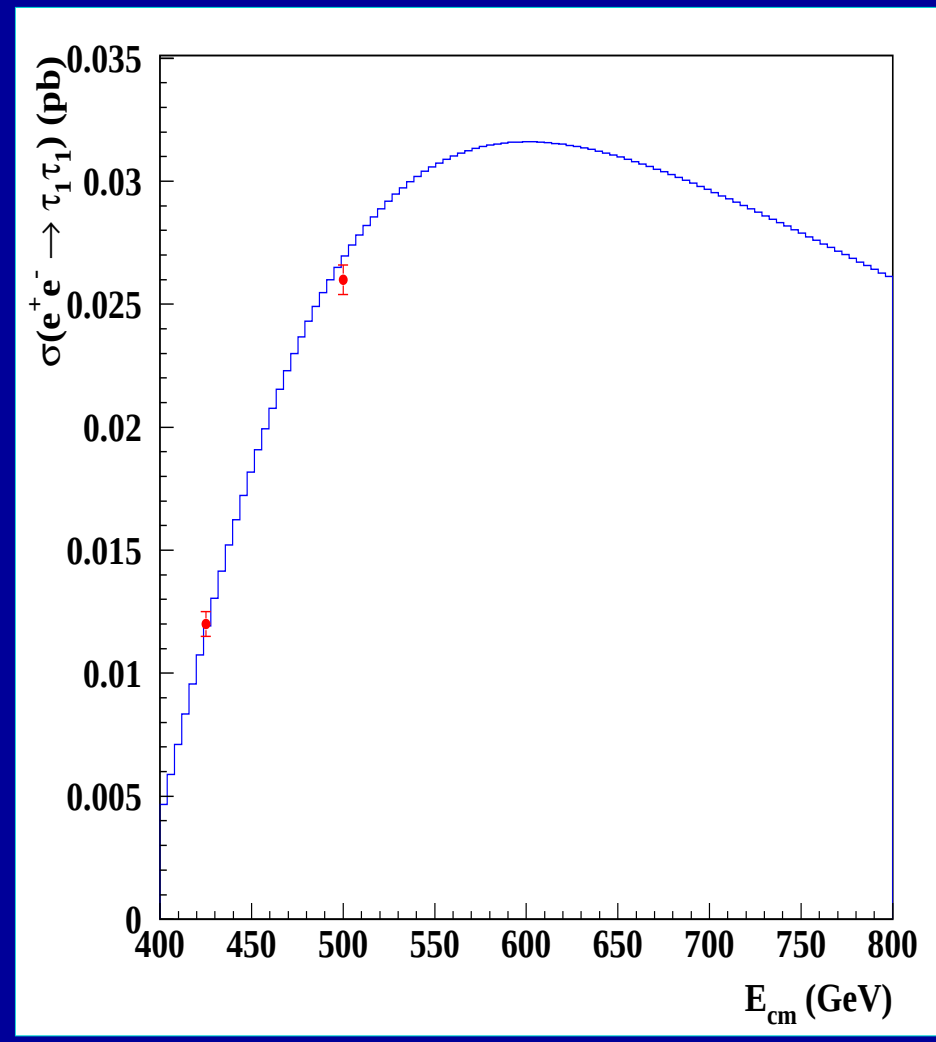
$e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$ at 0.5 TeV

- Extract M_χ from $\tilde{\tau}_1 \to \tau\chi$, which is accessible at $\sqrt{s}$=0.5 TeV;
- Threshold scan to determine $M_{\tilde{\tau}_1}$: $\frac{\Delta\sigma}{\Delta M_{\tilde{\tau}_1}}$=0.6 fb/GeV
- Irreducible SM Bkg $e^+e^- \to \tau\tau\nu\nu$ $E_{missing} >$ 350 GeV $\sigma_{SM} \simeq$ 6.5 fb
- 2 point scan: 425 GeV - 500 GeV with 200 + 300 fb^{-1}

$$\delta M/M \simeq 0.5\ \%$$



THRESHOLD SCAN FOR LCC-4



✧ Use $\tilde{\tau}_1\tilde{\tau}_1$ production to determine $\Delta M = M_{\tilde{\tau}_1} - M_\chi$;

✧ Tag τ jets using multiplicity and lepton content and pair with charge;

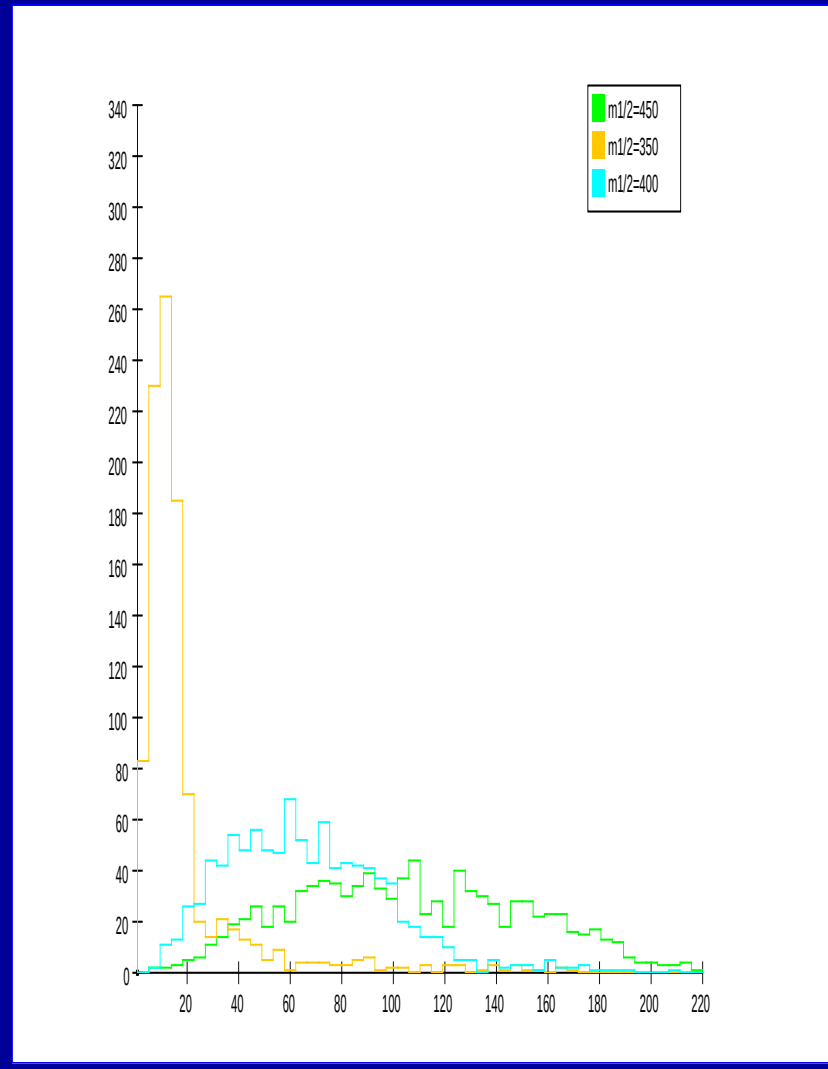
✧ Reject SM bkg with combination of cuts on $E_{missing}$, θ_{JJ} and shape variables;

✧ Define estimator for ΔM from $M_{JJE_{missing}}$ and fit data to templates for different ΔM values;

$$\delta\Delta M \simeq 1 \text{ GeV}$$

$$\delta M_\chi / M_\chi \simeq 1 \ \%$$

✧ May also use $e^+e^- \to \chi_1^0\chi_2^0$ but $\sigma \simeq 1$ fb.



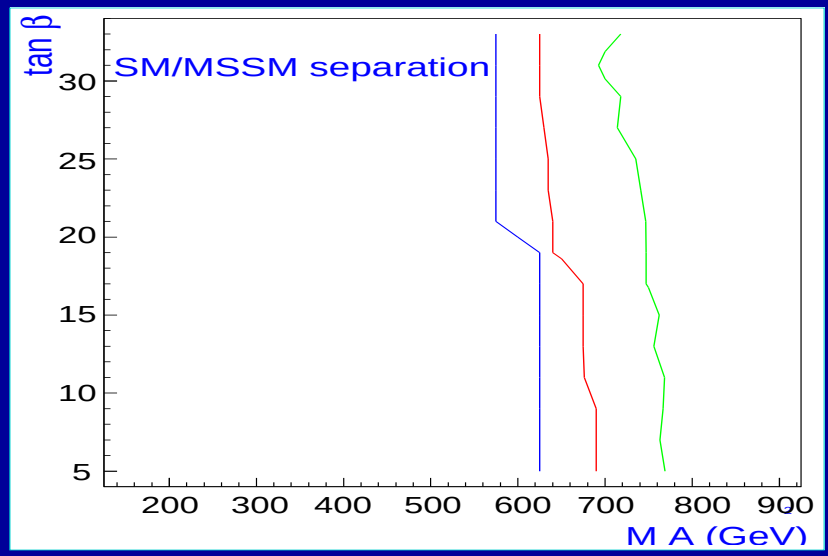
$h^0 \to f\bar{f}$ at 0.5 TeV

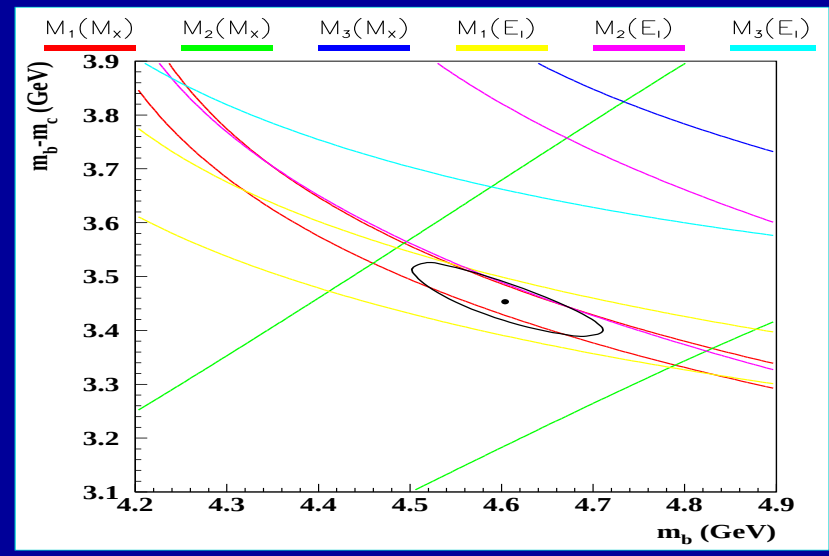
✧ Beyond LHC, the 0.5 TeV LC data would show that the Higgs sector is non minimal through precise measurements of h^0 branching fractions and may already provide some constraints on the A^0 mass;

✧ in particular $R_{bW} = \frac{\mathrm{BR}(h^0 \to b\bar{b})}{\mathrm{BR}(h^0 \to W^+W^-)}$ has a sensitivity of 0.02 GeV^{-1};

✧ underlying heavy quark mass uncertainties are significantly reduced using moments of spectral distribution in s.l. b decays from B-factory and CDF data to $\delta \mathrm{B}R(h \to b\bar{b})/\mathrm{B}R < 1\%$ and $\delta \mathrm{B}R(h \to c\bar{c})/\mathrm{B}R < 10\%$;

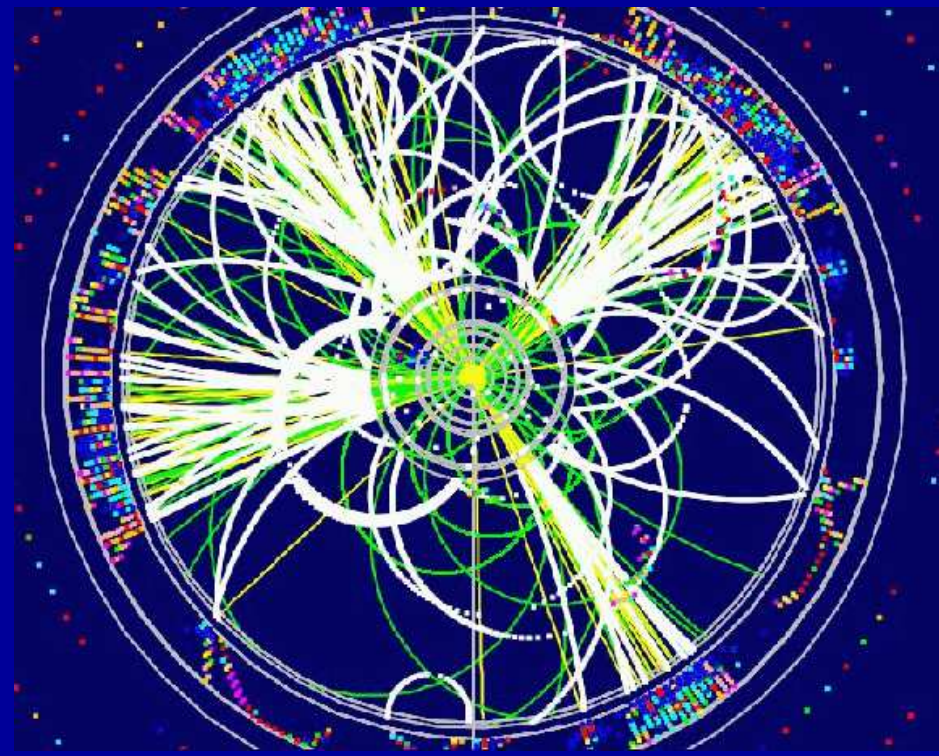
✧ Combined analysis of h^0 branching fractions should give $(M_A \pm 15)$ GeV;

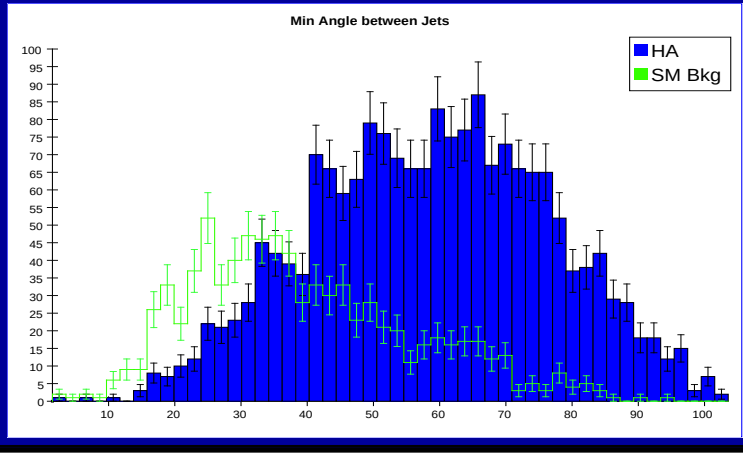


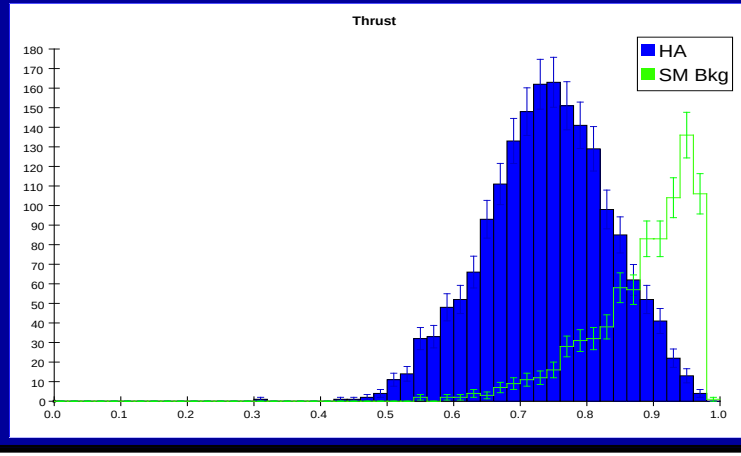


$e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$ at 1 TeV

- ✧ Select hadronic events with no significant $E_{missing}$ and force 4-jet reconstruction;
- ✧ reject background with selection on discriminant based on Φ_{jj}, y_{34}, $Thrust$ and $M_{jj1} - M_{jj2}$ cuts;
- ✧ apply parametric b-tagging for di-jet and kinematic fit;
- ✧ Consider SM $e^+e^- \to Z^0Z^0$, W^+W^- and $b\bar{b}b\bar{b}$ (5 fb) and inclusive SUSY background.





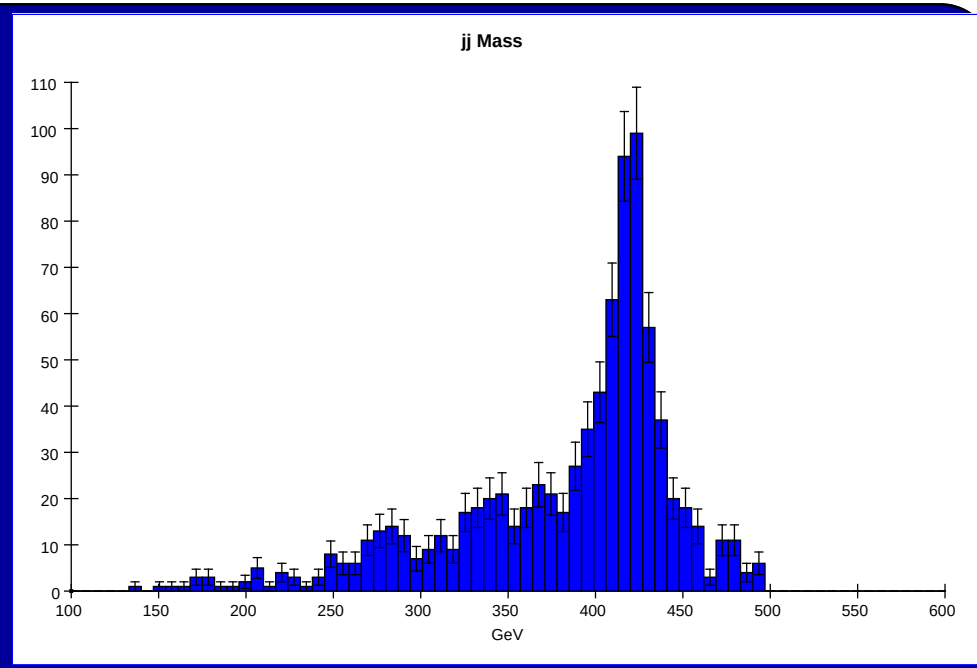


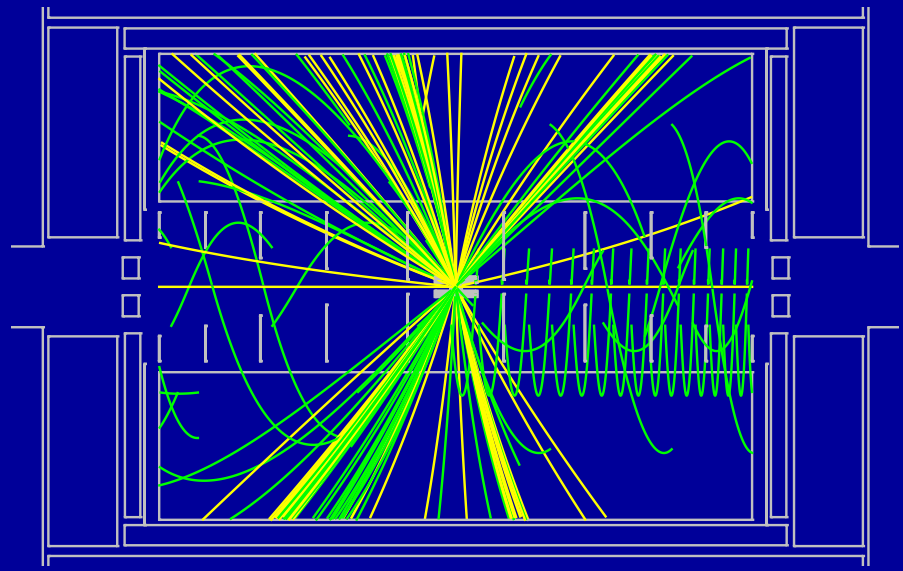
✧ Obtain $\epsilon_{signal} \simeq 0.30 \simeq \delta M \simeq = 1.5$ GeV

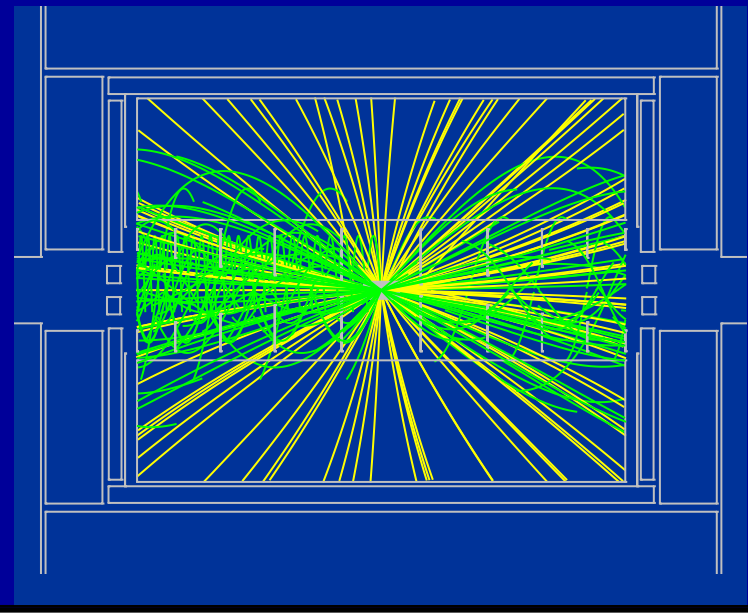
$$\boxed{\delta M/M = 0.5\ \%}$$

with fast simulation,
preliminary results using `Lelaps` agree;

✧ Need to include full 4-f background and overlay $\gamma\gamma \to \mathrm{hadrons}$ events which may distort jet reconstruction significantly.







Conclusions

✧ CDM-inspired cMSSM presents important challenges for experimentation at LC;

✧ typical LC $\mathcal{O}(0.1\ \%)$ accuracy on slepton masses appears realisable along co-annihilation tail;

✧ but co-annihilation region at small $M_{\tilde{\ell}} - M_{\chi_1^0}$ characterised by low lepton momenta which requires to extend acceptance of lepton Id, in particular at low $\tan\beta$ and careful study of $\gamma\gamma$ Bkg rejection;

✧ Achieving few $\%$ precision on predicting Ωh^2 from SUSY measurements requires accuracies of $\mathcal{O}(0.5\ \%)$ for individual masses;

✧ complete analyses of benchmark points along co-annihilation tail and in the annihilation funnel will clarify the LC impact on testing CDM nature in a quantitative way and underline their implications on detector design.
