Understanding Supersymmetric Dark Matter at High Energy Particle Colliders

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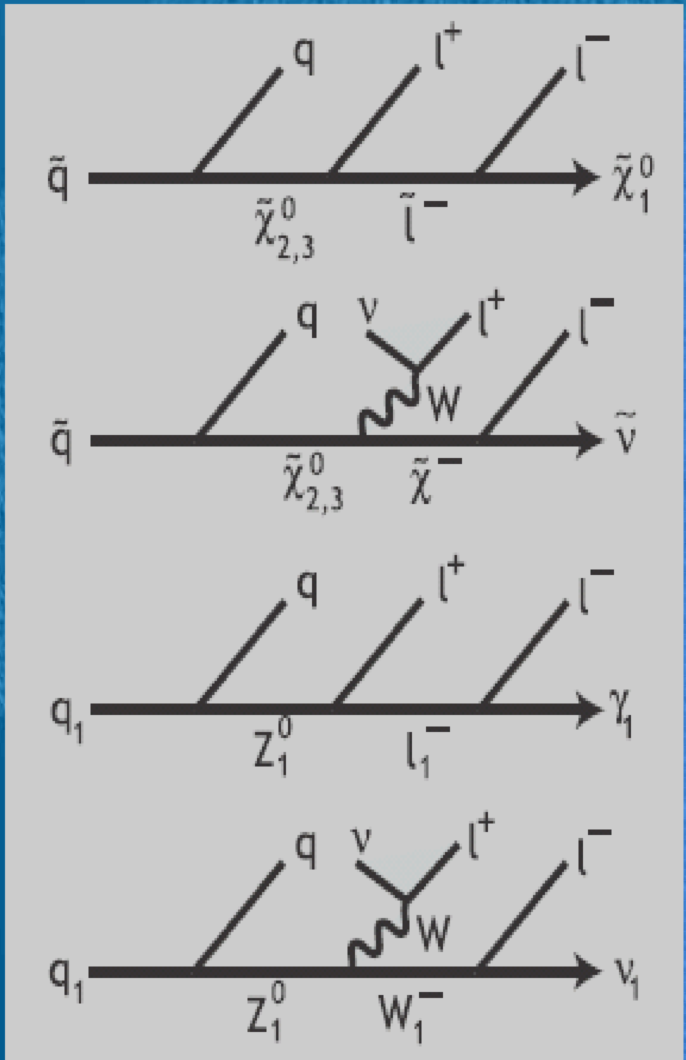
TeVPA 2007 Conference
Venice, August 30, 2007

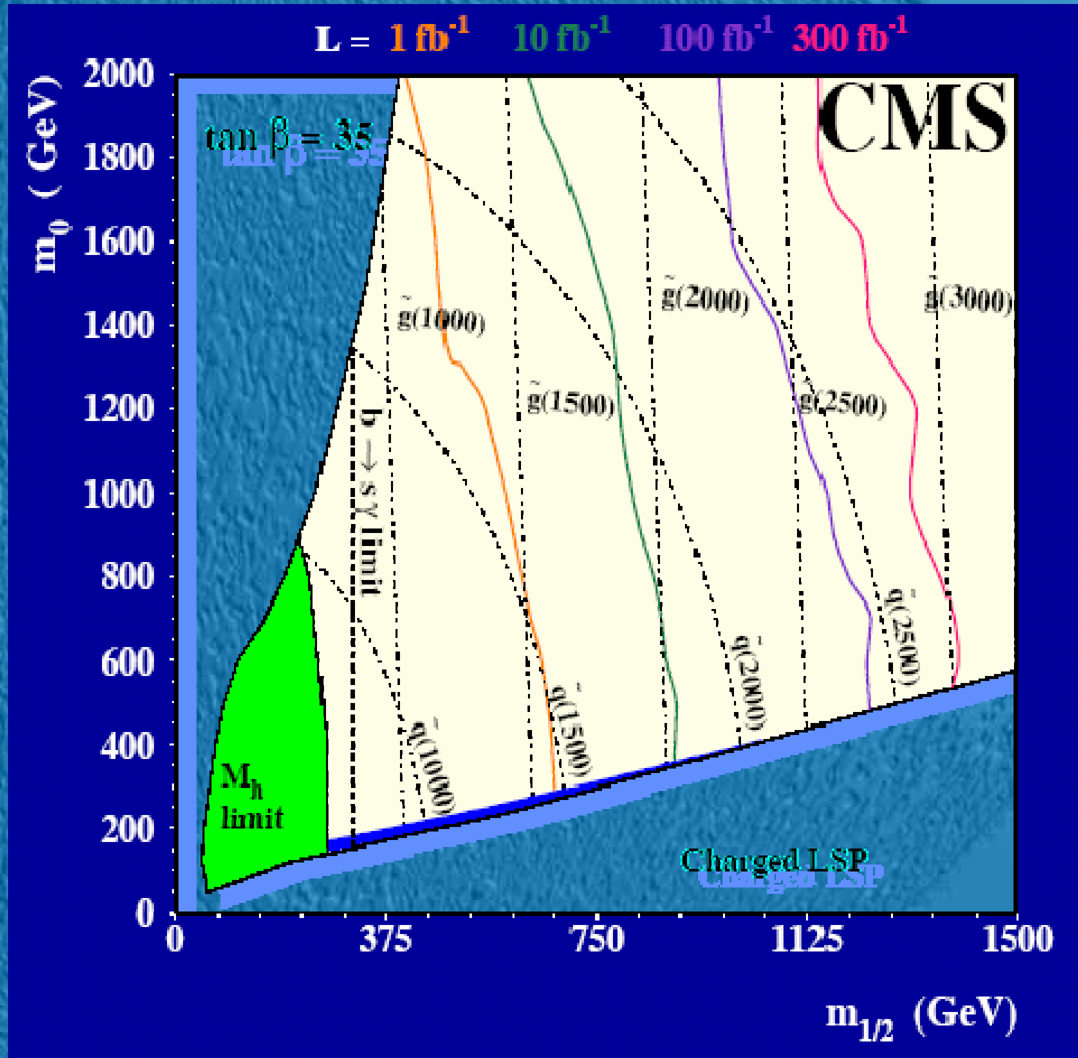
If DM due to WIMPs manifesting New Physics beyond SM, next generation of hadron (LHC, SLHC) and lepton collider (ILC, CLIC) expected to discover direct signal of this NP and perform detailed studies;

Collider data will combine with direct searches and satellite experiments to understand DM properties from microscopic to macroscopic scales;

Supersymmetry offers attractive framework to study opportunities at colliders experiments;

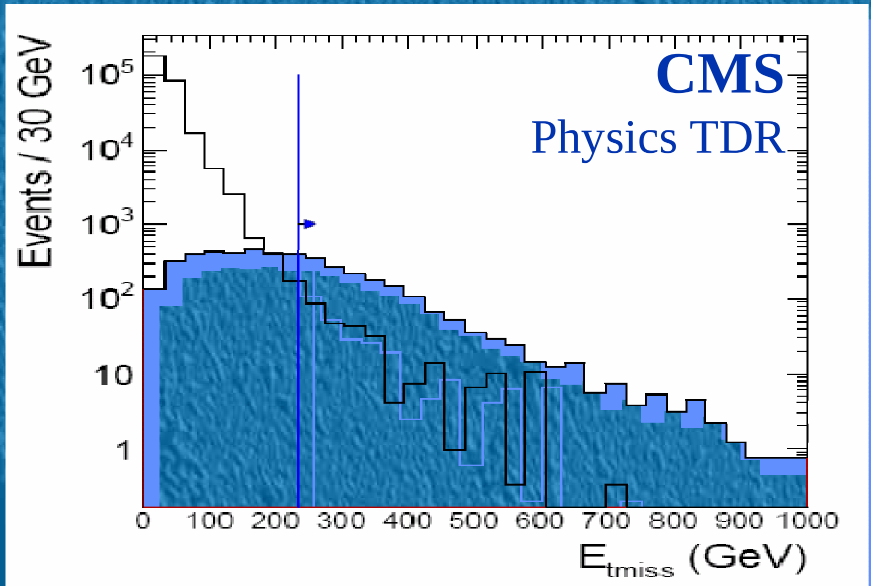
LHC: From SUSY Signals …





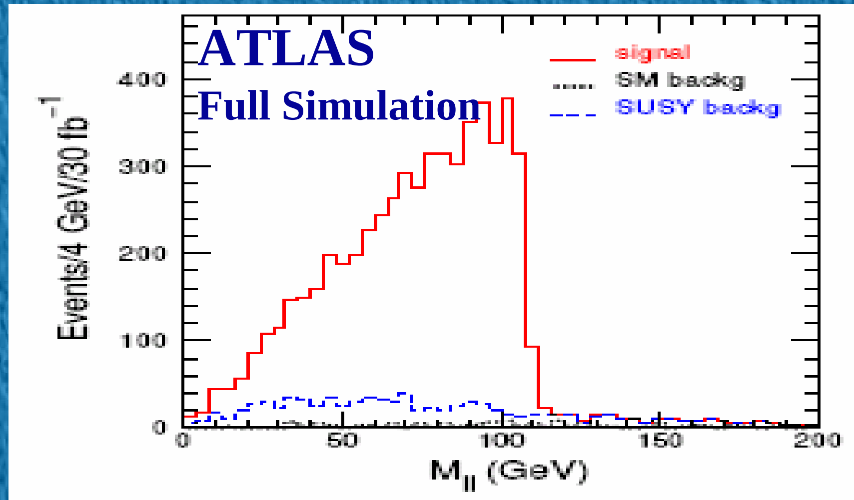
…to SUSY Particle Masses …

LHC discovery reach independent of details of the model: $E_T^{missing}$+ jets and/or isolated leptons sufficient to ensure detection;



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

Availability of decay chains with multi-leptons, lepton+jets topologies allows to determine masses from kinematical endpoints:



$$M^{max}_{\ell^+\ell^-} = \frac{\sqrt{\left(m^2_{\chi^0_2} - m^2_{\tilde\ell}\right)\left(m^2_{\tilde\ell} - m^2_{\chi^0_1}\right)}}{m_{\tilde\ell}}$$

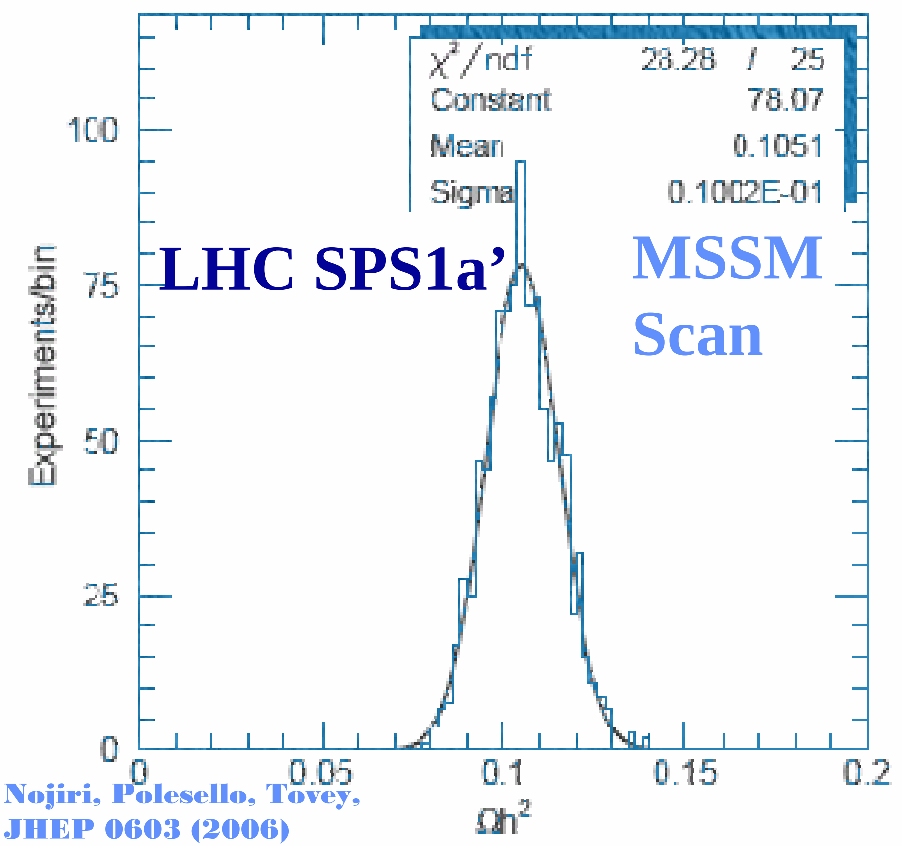
$$M^{max}_{\ell_1 q} = \frac{\sqrt{\left(m^2_{\chi^0_2} - m^2_{\tilde\ell}\right)\left(m^2_{\tilde q} - m^2_{\chi^0_2}\right)}}{m_{\chi^0_2}}$$

…to DM Densities.

Perform tests first within context of specific model (cMSSM) and then reconstruct full decay chain enabling model-independent mass measurements;

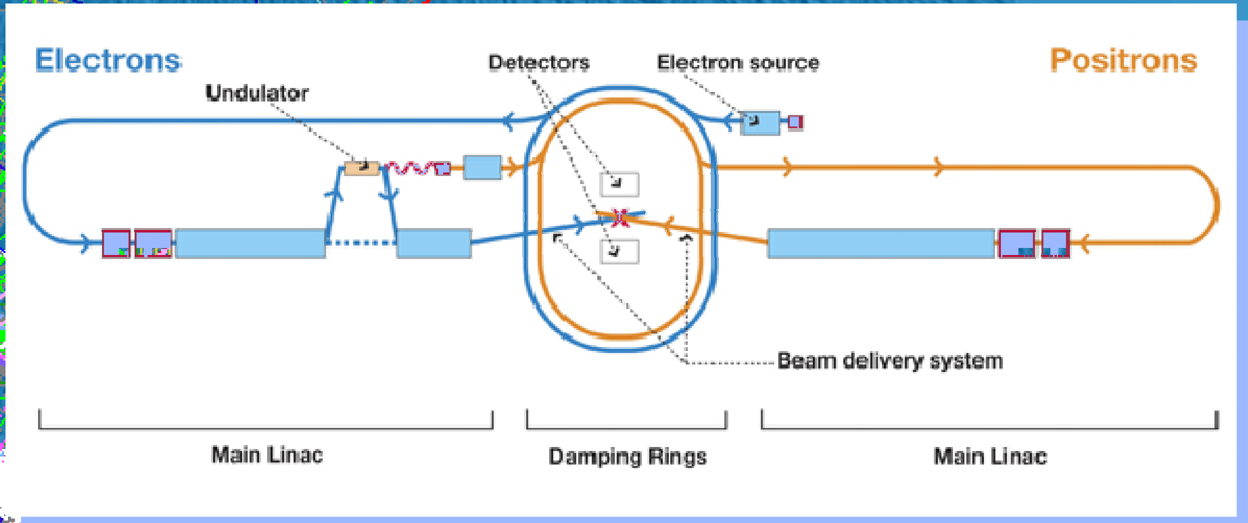
Consistency with DM requires a significant number of measurements which may not be available in generic SUSY scenarios;

Variable	Value (GeV)	Errors Stat+Sys (GeV)	Errors Scale (GeV)	Errors Total
$m_{\ell\ell}^{max}$	81.2	0.03	0.08	0.09
$m_{\ell\ell q}^{max}$	425.3	1.4	2.1	2.5
$m_{\ell q}^{low}$	266.9	0.9	1.3	1.6
$m_{\ell q}^{high}$	365.9	1.0	1.8	2.1
$m_{\ell\ell q}^{min}$	207.0	1.6	1.0	1.9
$m(\ell_L) - m(\tilde{\chi}_1^0)$	92.3	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	315.8	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	62.2	5.0	0.3	5.0



Nojiri, Polesello, Tovey, JHEP 0603 (2006)

Studying NP at Colliders beyond LHC

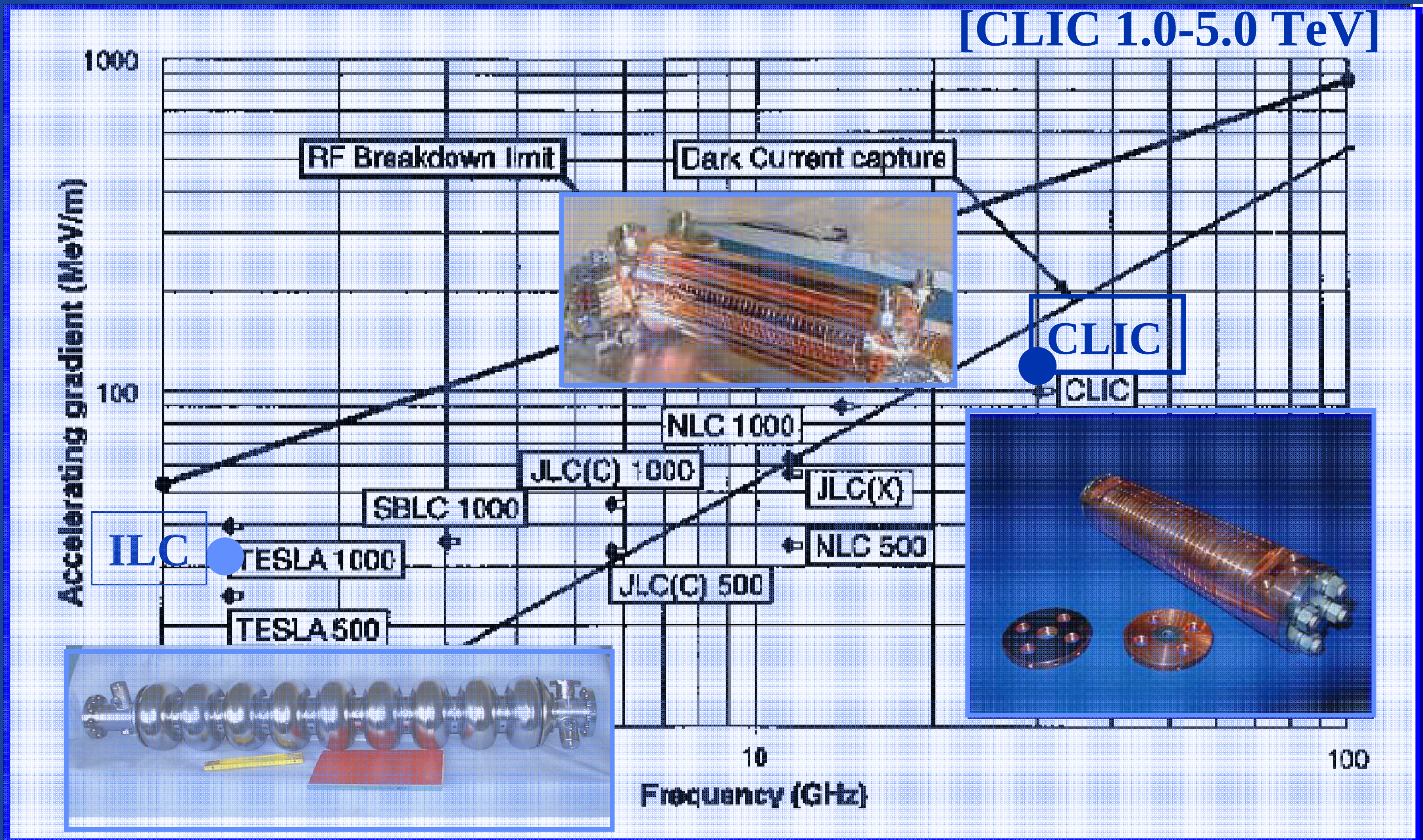


ILC to provide point-like particle collisions from 0.3 TeV up to ~ 1 TeV with tunable centre-of-mass energies, particle species and polarization states;

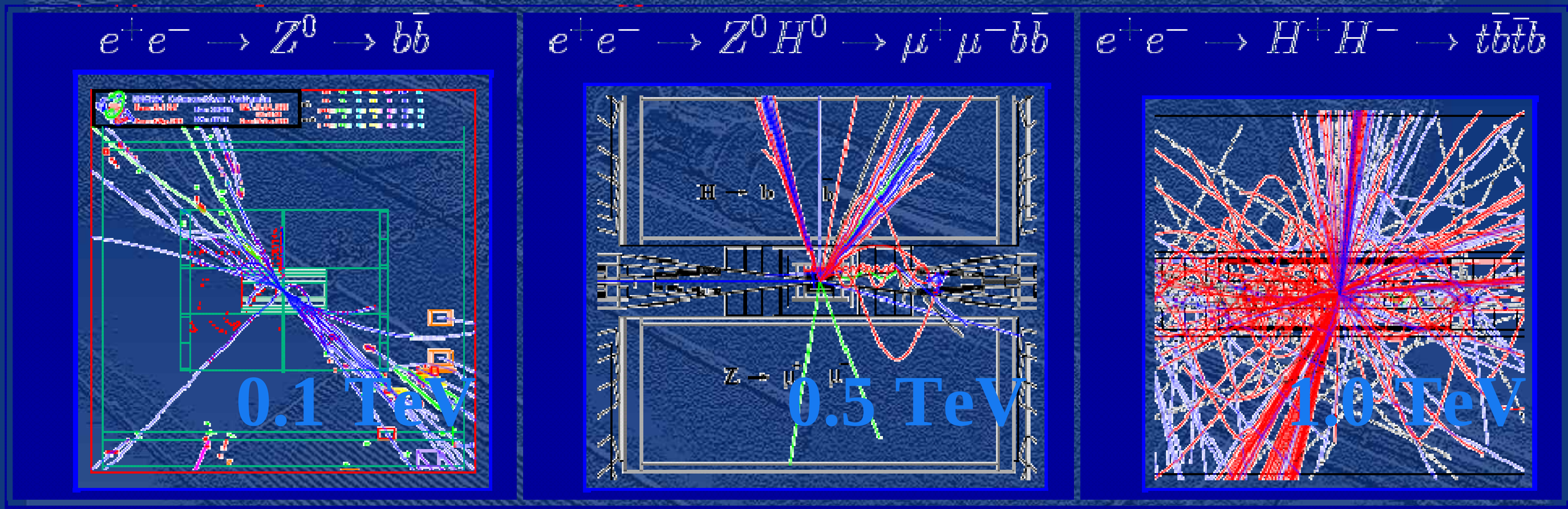
In a farther future, CLIC multi-TeV e^+e^- collider may further push energy frontier up to 3 – 5 TeV.

ILC Energy

Accelerating Gradient vs. RF Frequency: [ILC 0.5 – 1.0 TeV]



ILC has potential to cover widest energy range of any accelerator; Physics program spans from high-precision EW tests of SM to search of new phenomena up to and above the scale accessed by LHC and detailed study of production and decay properties of new particles;



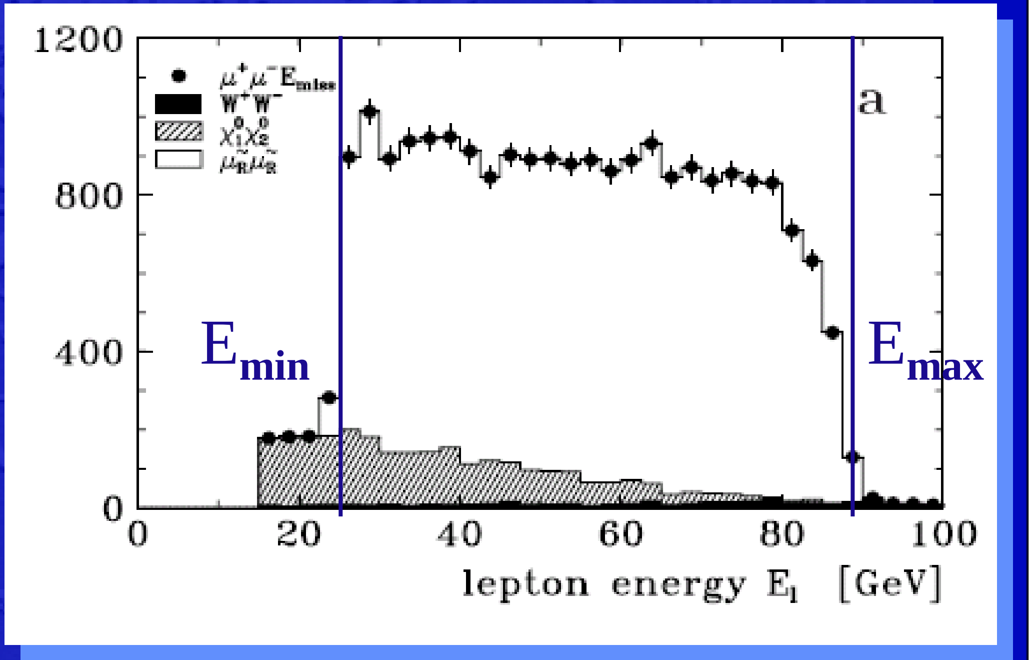
This relies on efficient **identification** of fermion flavours, accurate **reconstruction** of multi-partons and availability of different **beam** particles, energy and polarization **configurations**.

Momentum End Points

In two body decay $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ $E_{squark} = E_{beam}$ if pair produced, χ escapes unobserved and energy of only particle left (q) can be related to mass difference (ratio) between squark particle and LSP :

$$E_{\max,\min} = \frac{E_b}{2}\left(1 \pm \sqrt{1 - \frac{m_{\tilde{q}}^2}{E_b^2}}\right)\left(1 - \frac{M_{\tilde{\chi}_1^0}^2}{m_{\tilde{q}}^2}\right)$$

Method originally introduced for squarks applies also to sleptons $\tilde{\ell}^- \rightarrow \ell^-\tilde{\chi}_i^0$ and allows to determine slepton mass once χ known or determine relation between masses and get LSP mass if slepton can be independently measured;



Accuracy limited by beamstrahlung, not δp/p.

Threshold Scan

Determine signal cross section at threshold as function of centre-of-mass energy, fit data to extract mass and width of pair-produced particles;

Accuracy on particle mass m

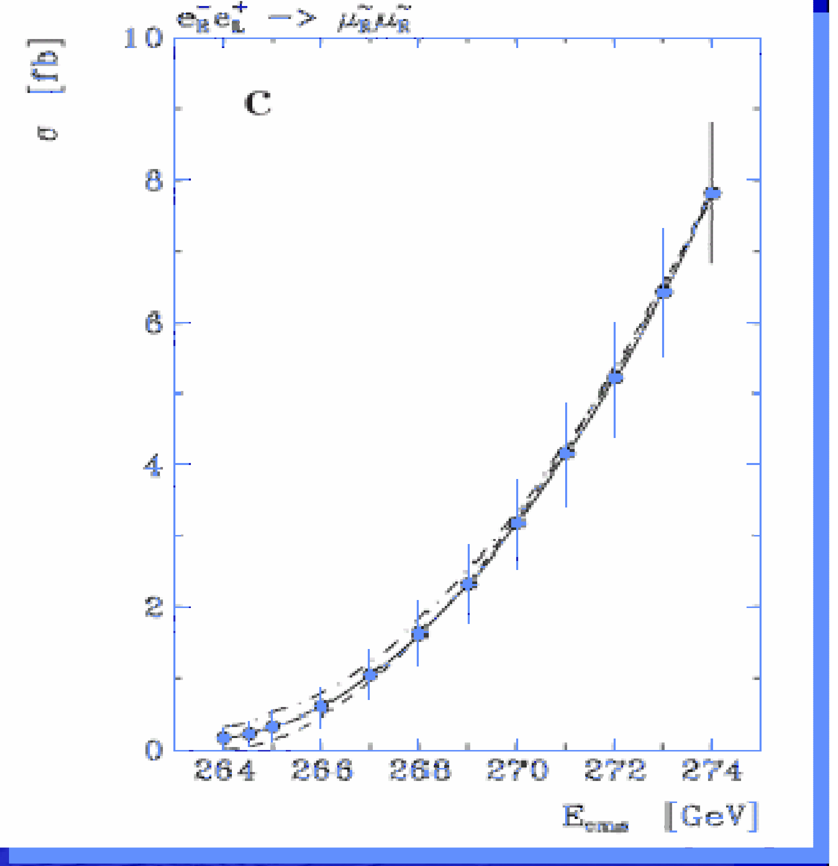
S-wave process = β rise of cross section

$$\delta m \approx \Delta E(1 + 0.36/\sqrt{N})/\sqrt{18 N \mathcal{L} \sigma_u}$$

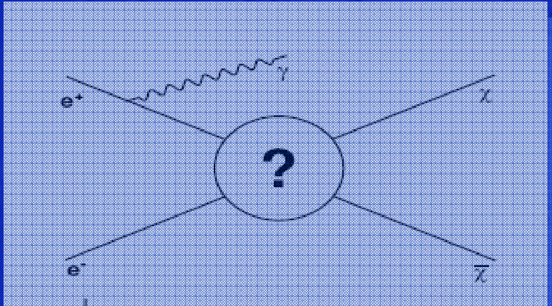
P-wave process = β^3 rise of cross section

$$\delta m \approx \Delta E N^{-1/4}(1 + 0.38/\sqrt{N})/\sqrt{2.6 N \mathcal{L} \sigma_u}$$

Weak dependence of δm accuracy on nb. of scan points N, optimal scan with luminosity concentrated at 2 or 3 points



Model Independent WIMP Detection at ILC



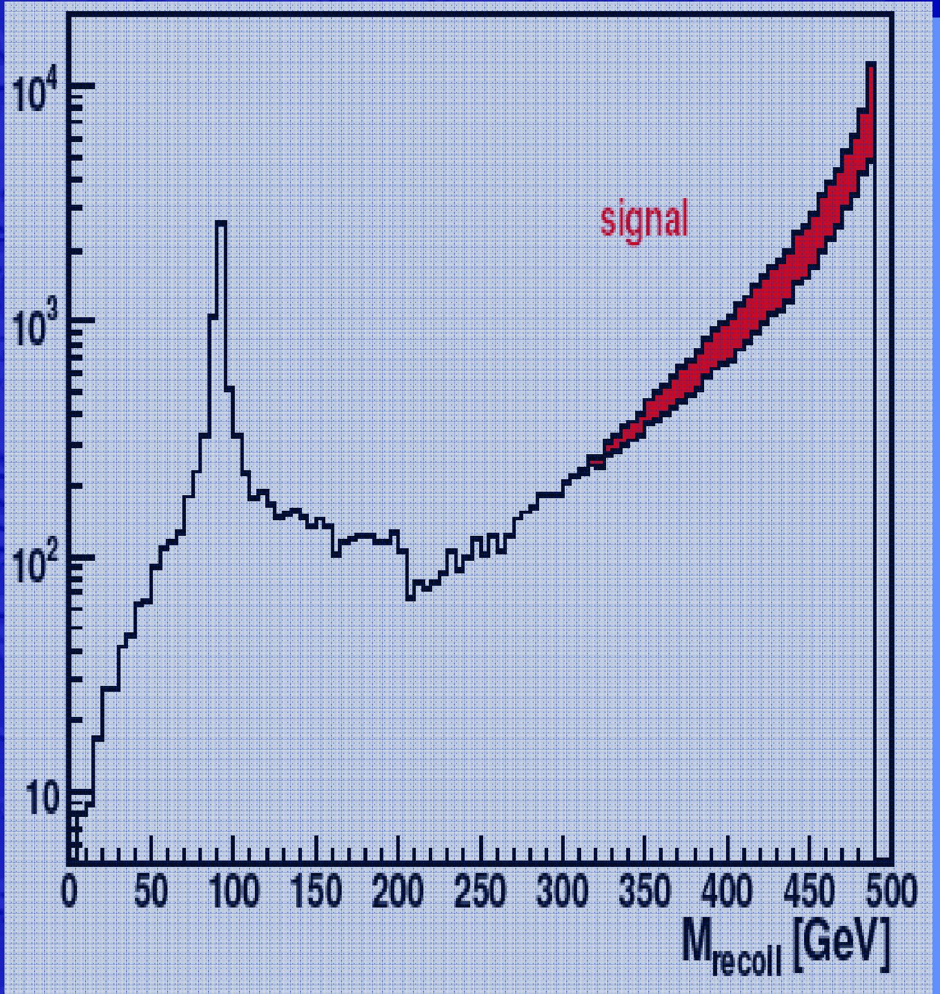
$e^+e^- \longrightarrow \chi\bar{\chi}\gamma$

Irreducible SM $e^-e^+ \rightarrow \nu\bar{\nu}\gamma$ bkg removed by using polarised beams

Analysis performed with full G4 simulation and reconstruction;

$P_{e^-} = 0.8, P_{e^+} = 0.6$:

$M_\chi = 180.5 \pm 0.6$ GeV

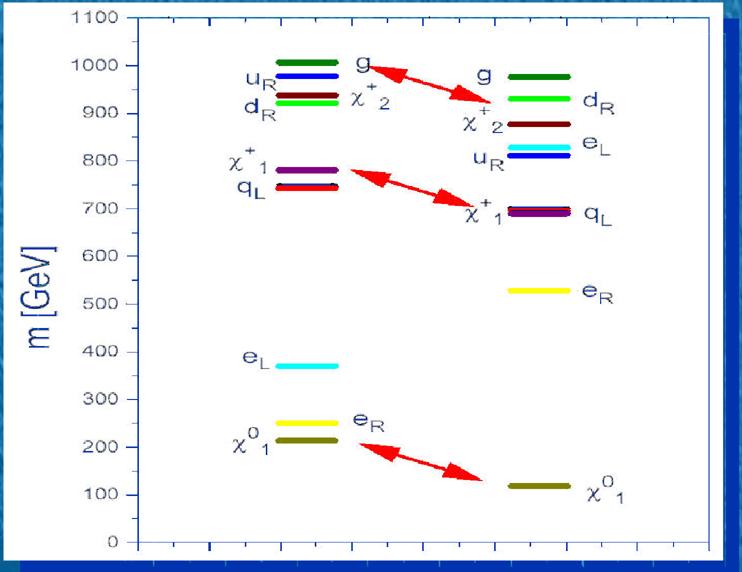


C Bartels, J List

Solving the SUSY Inverse Problem

Resolve the degeneracies arising by reconstructing fundamental parameters from LHC experimental observables;

Arkani-Hamed, Kane, Thaler, Wang, hep-ph/0512190



Study LHC-degenerate models at 0.5 TeV and 1 TeV ILC, started model comparison:

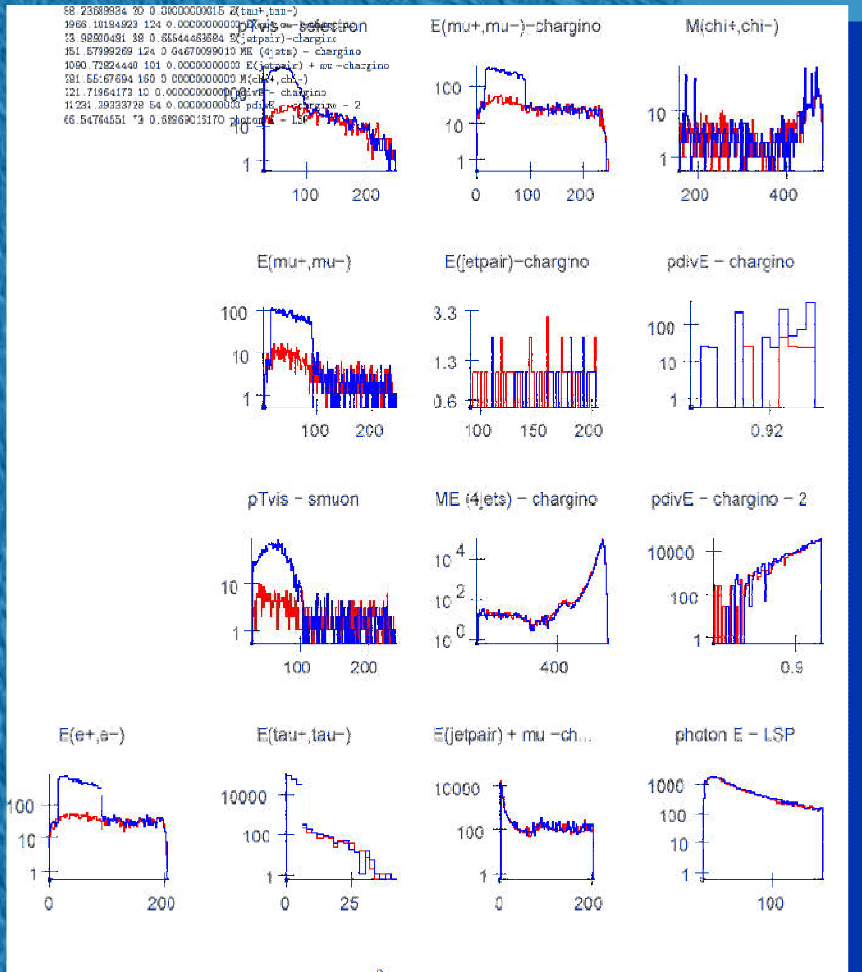


Figure 3: Right 1125 (red) 33224 (blue)

J Hewett, T Rizzo

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

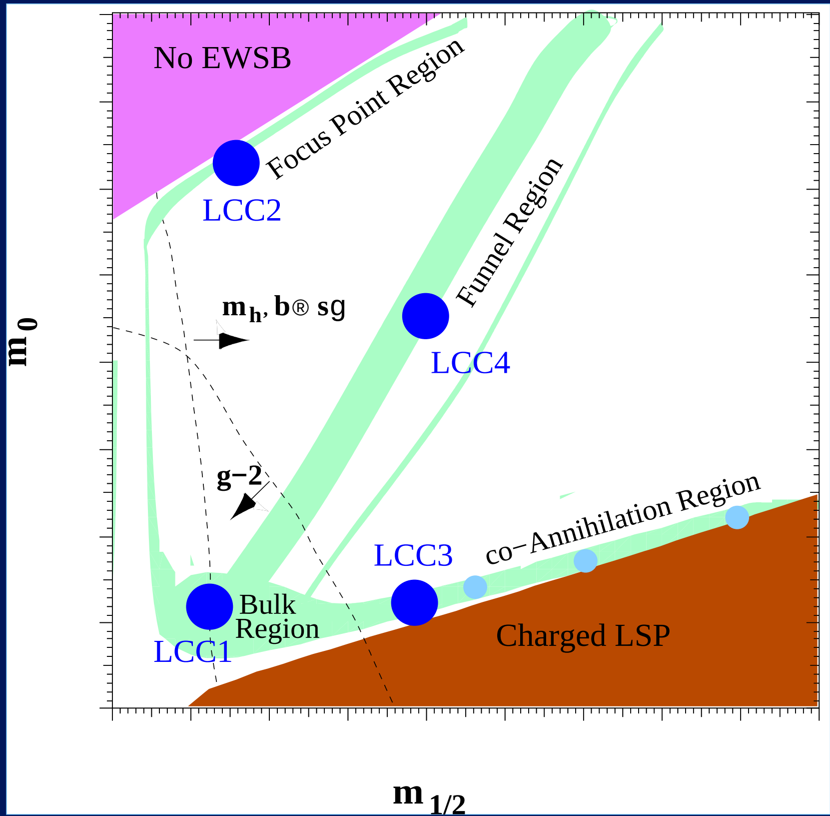
Point	m_0	$m_{1/2}$	$\tan\beta$	A_0	$M(t)$	$M(\chi^0_1)$
LCC 1	100	250	10	-100	178.	96.1
LCC 2	3280	300	10	0	175.	107.7
LCC 3	210	360	40	0	178.	142.5
LCC 4	380	420	53	0	178.	169

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

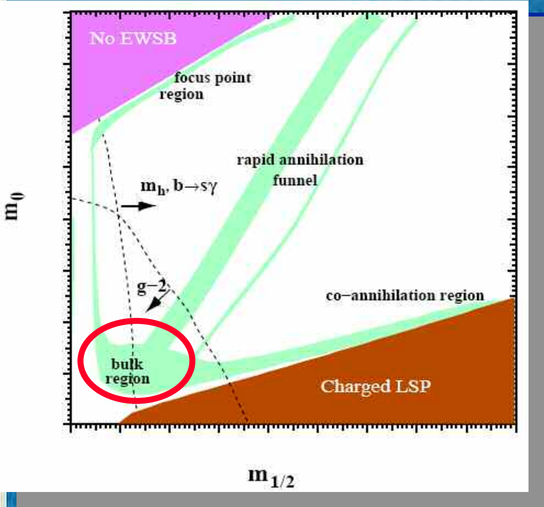
B.L. Ms. Cotton Nero D IV

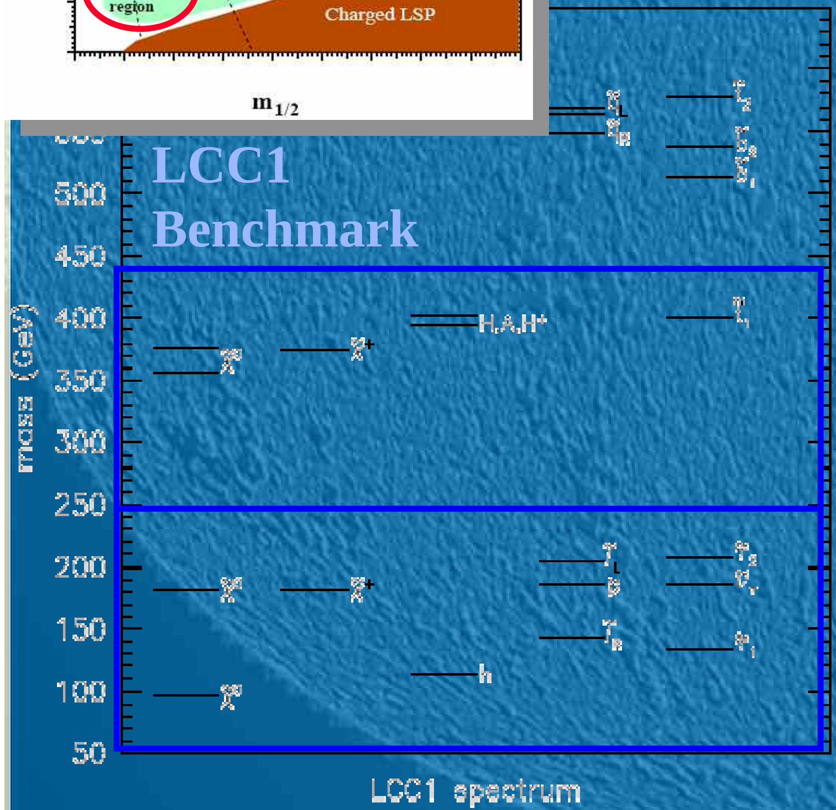
Cosmologically interesting cMSSM Regions and Benchmark points

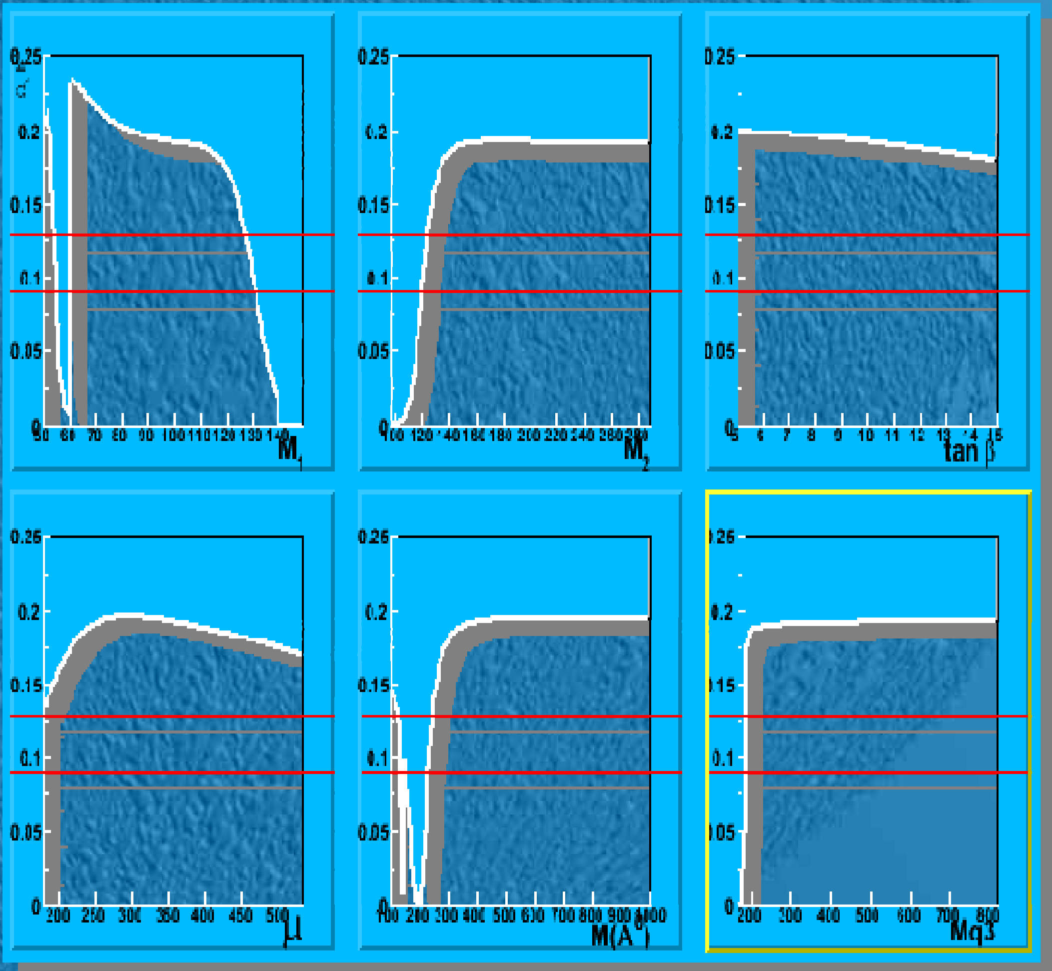


J Ellis, K Olive, MB, M Peskin,...

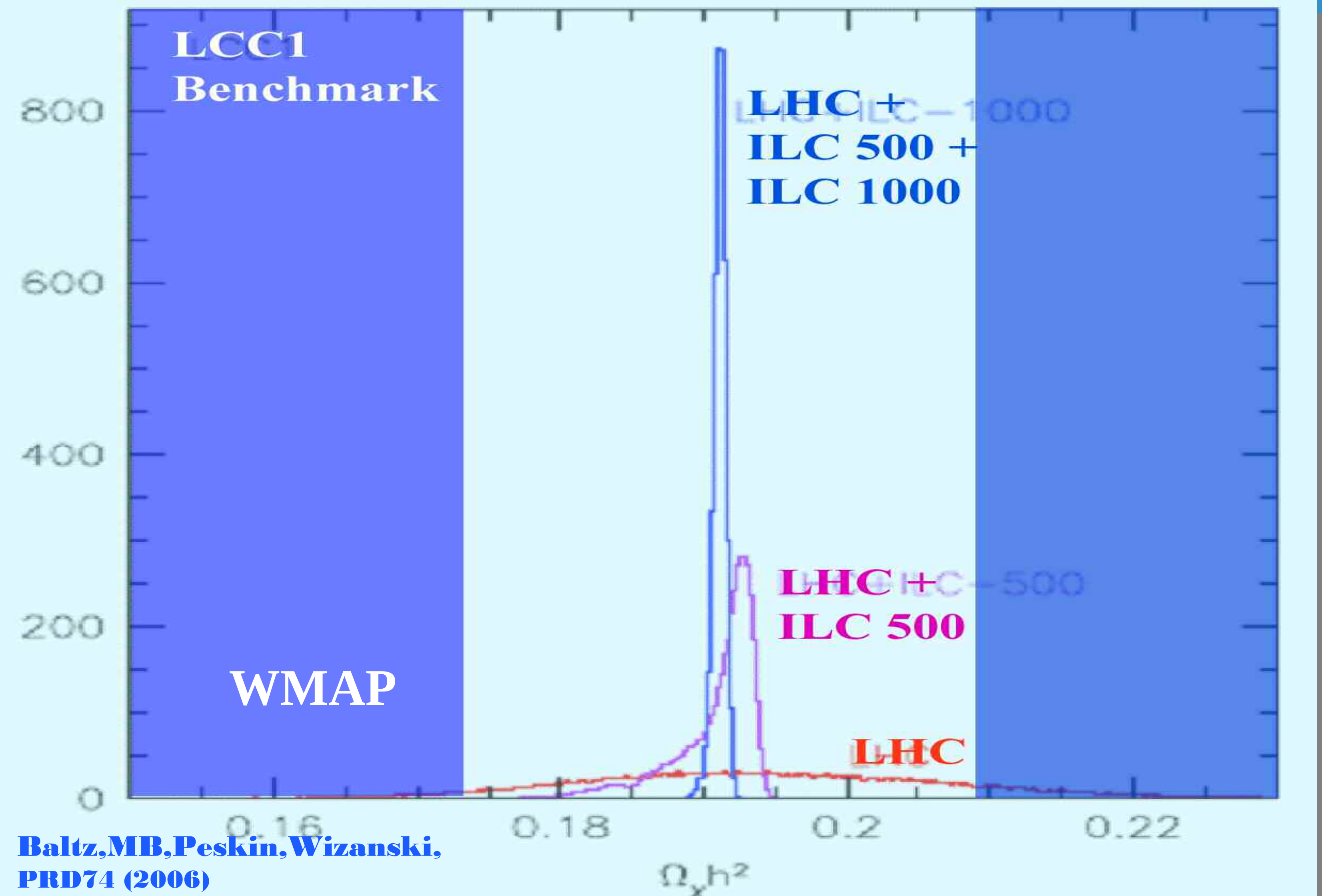
SUSY Bulk Region







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



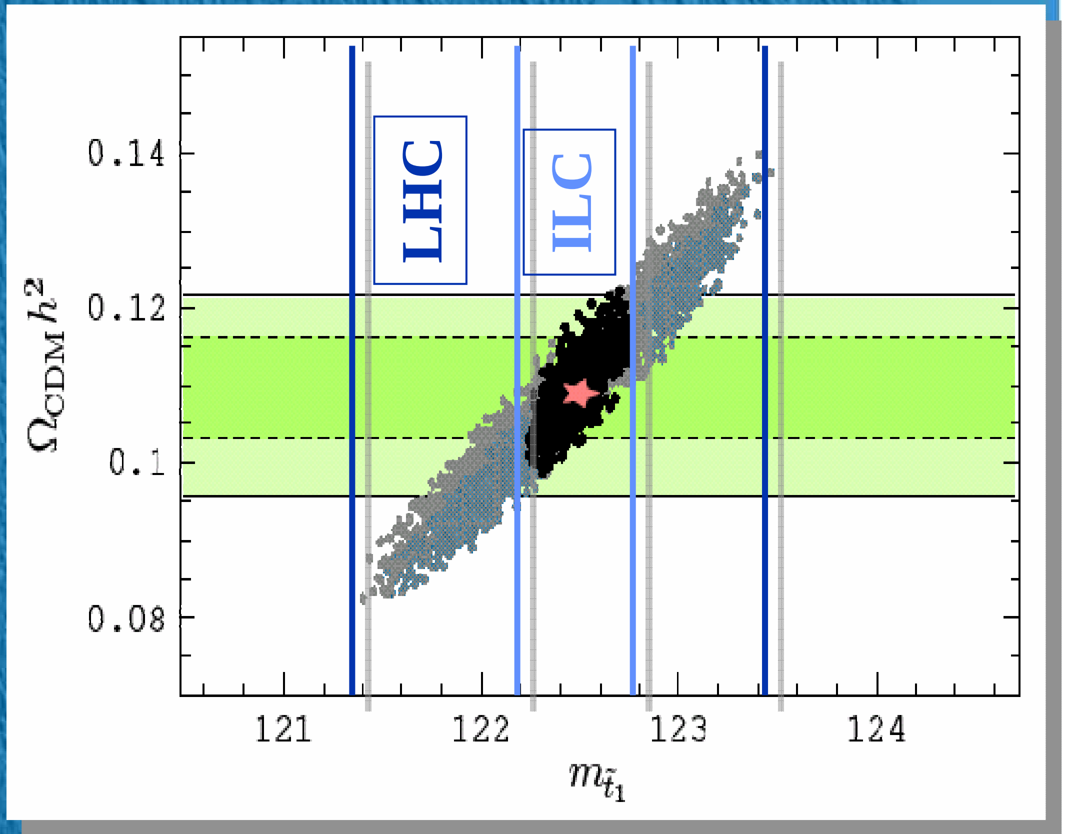
Baltz,MB,Peskin,Wizanski,
PRD74 (2006)

Stop co-Annihilation in Baryogenesis motivated Scenarios

Light scalar top, nearly degenerate with neutralino, provides efficient co-annihilation and evades Tevatron searches due to small E_T.

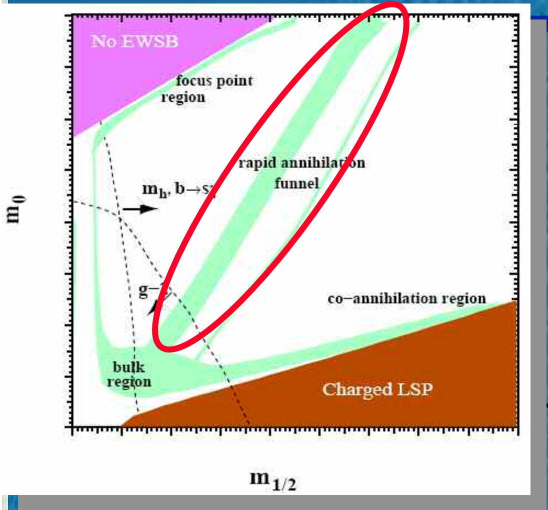
Baryogenesis constraints push towards heavy scalar and introduces CP-violating phase in μ.

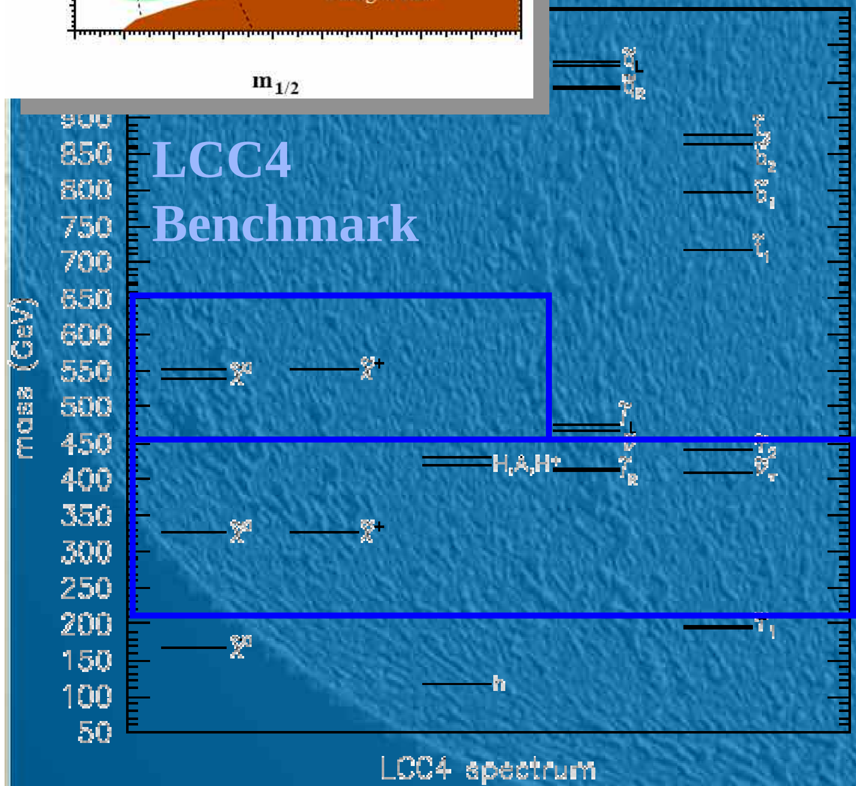
Scenario shares several features characteristic of FP region but requires analysis of real Z^0 and light stops.

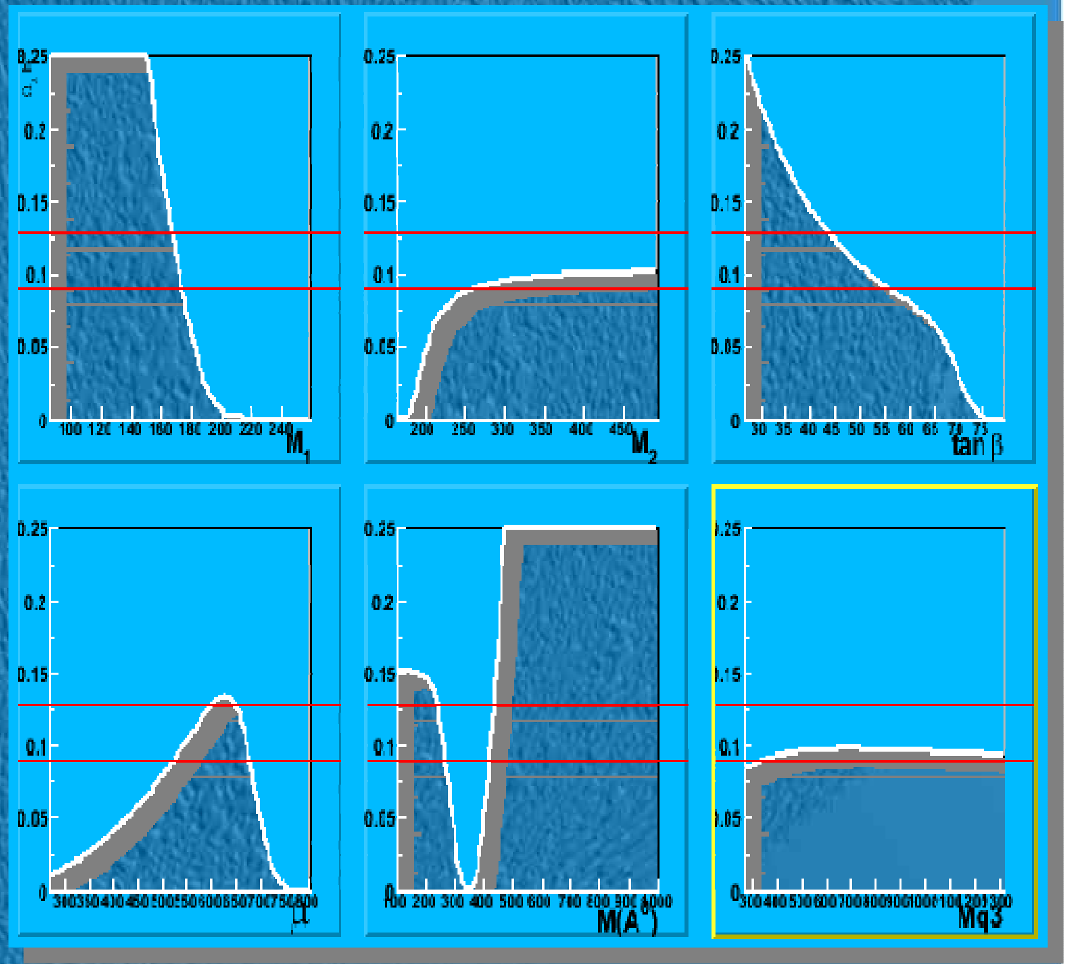


Carena, Freytas, hep-ph/0608255

SUSY A^0 Funnel Region





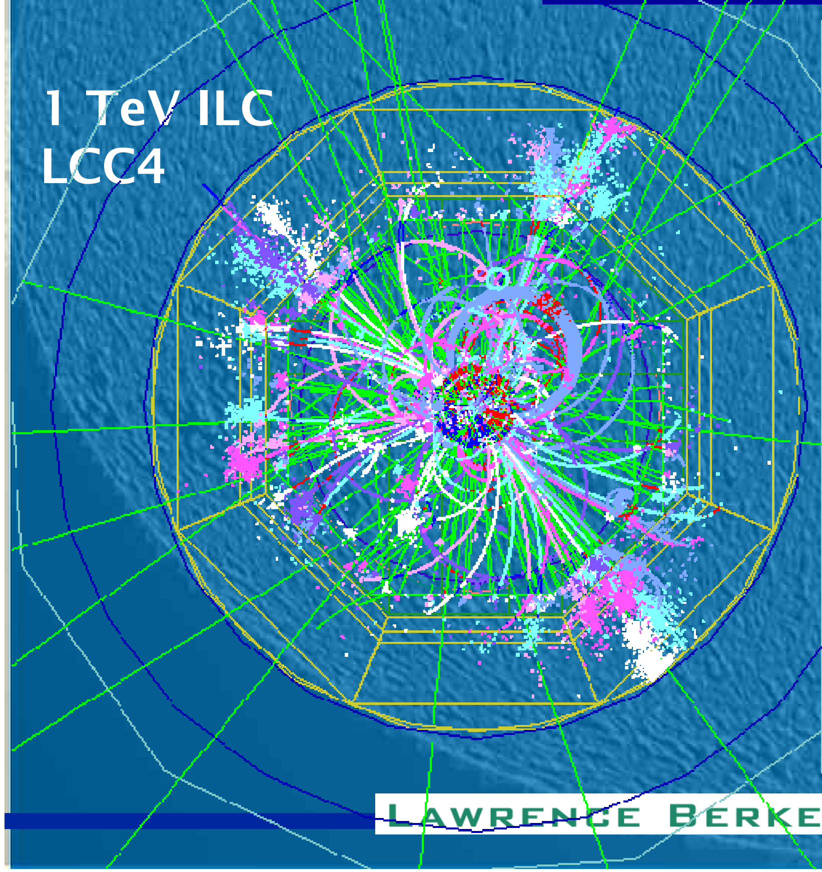


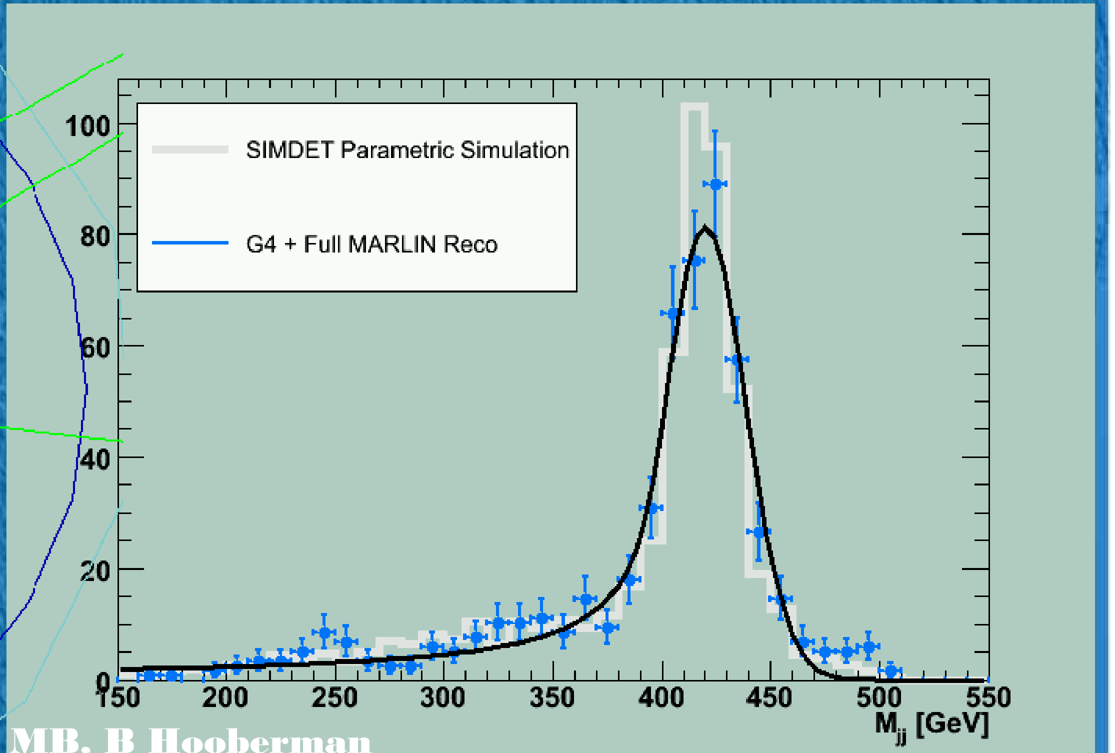
A^0 Funnel Region at ILC 1 TeV

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

	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)

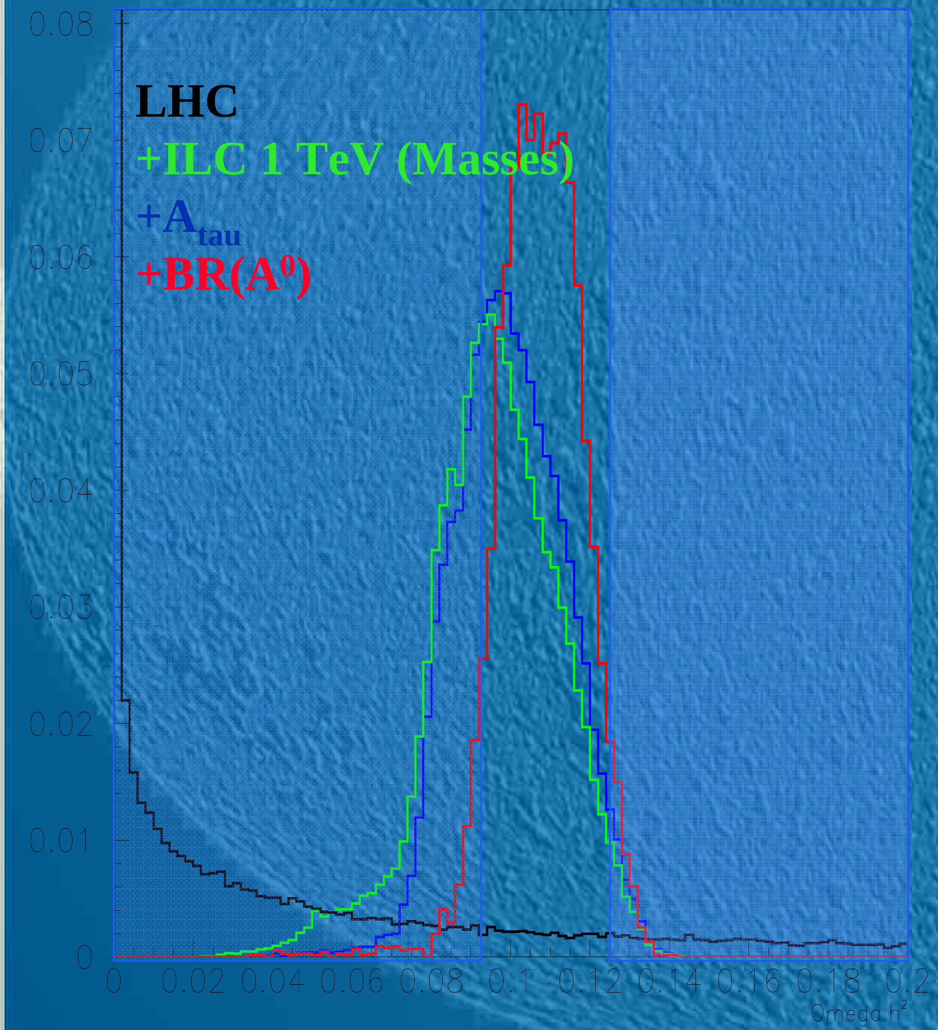
Determine M_A from $e^+e^- \to H^0 A^0$

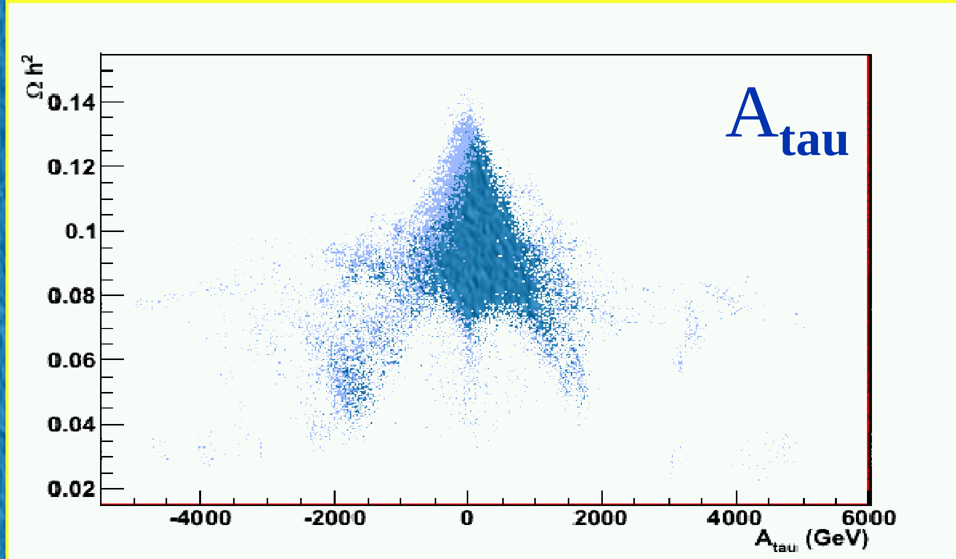


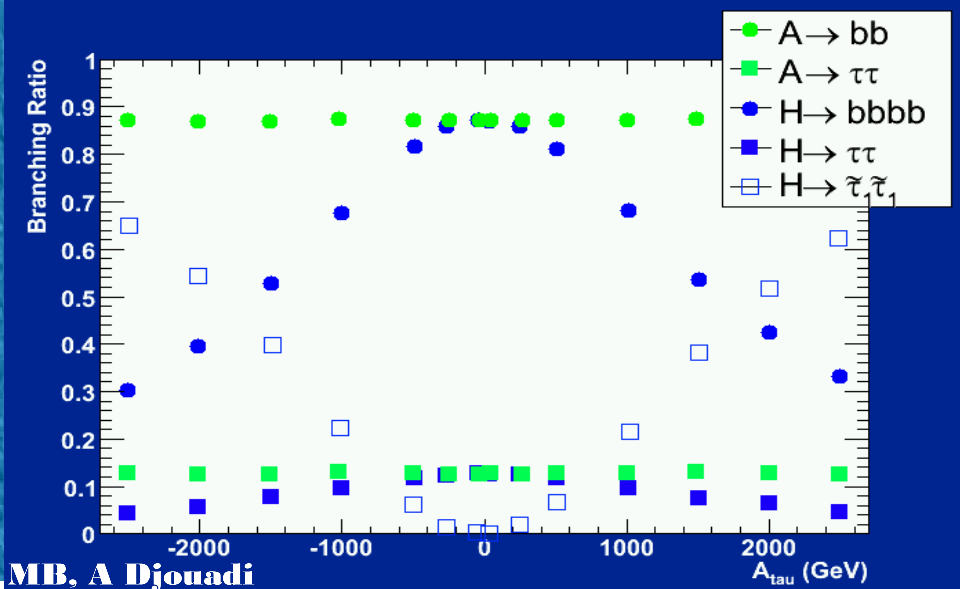


MB, B Hooberman

Further DM Constraints at ILC

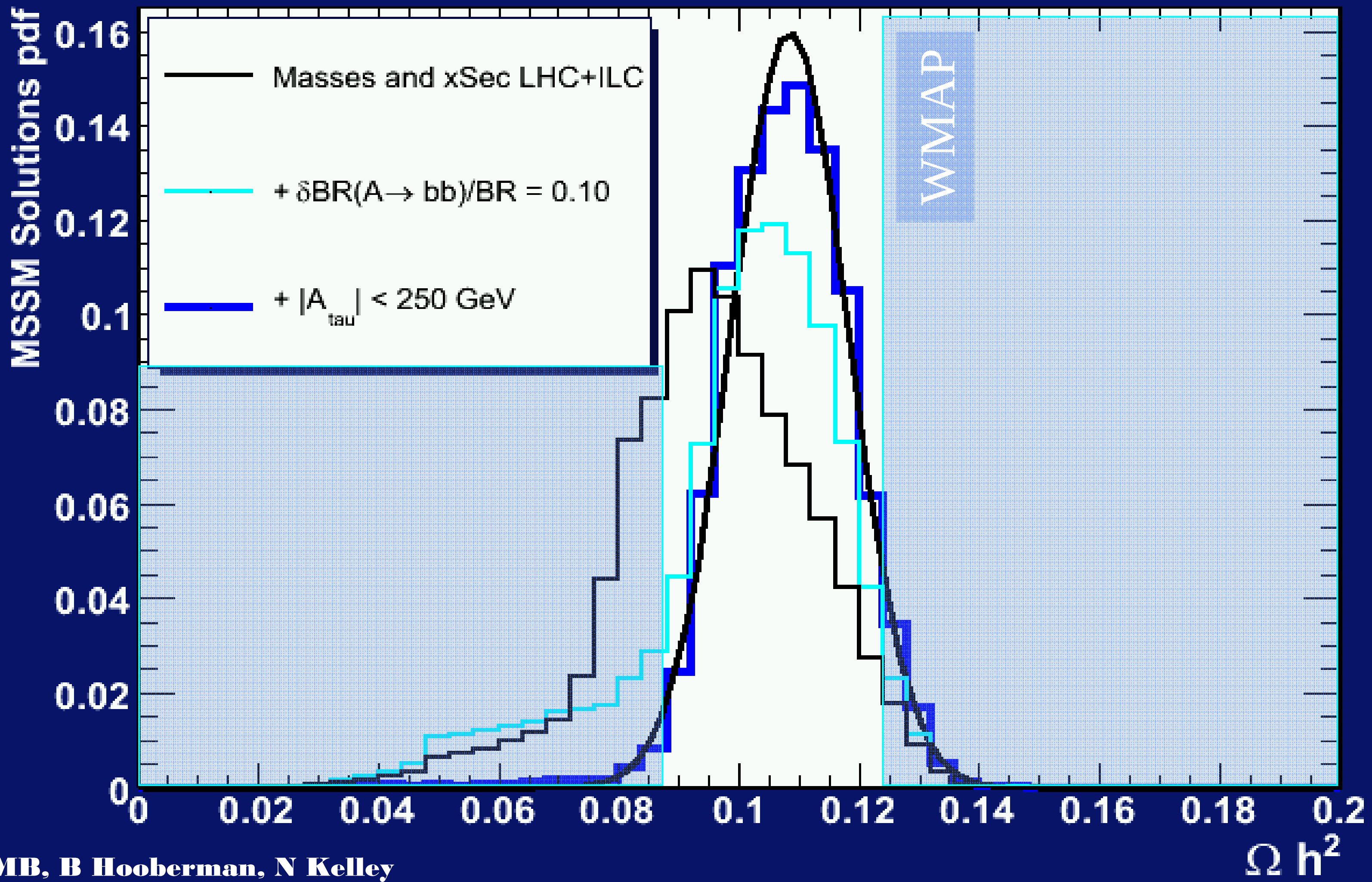






MB, A Djouadi

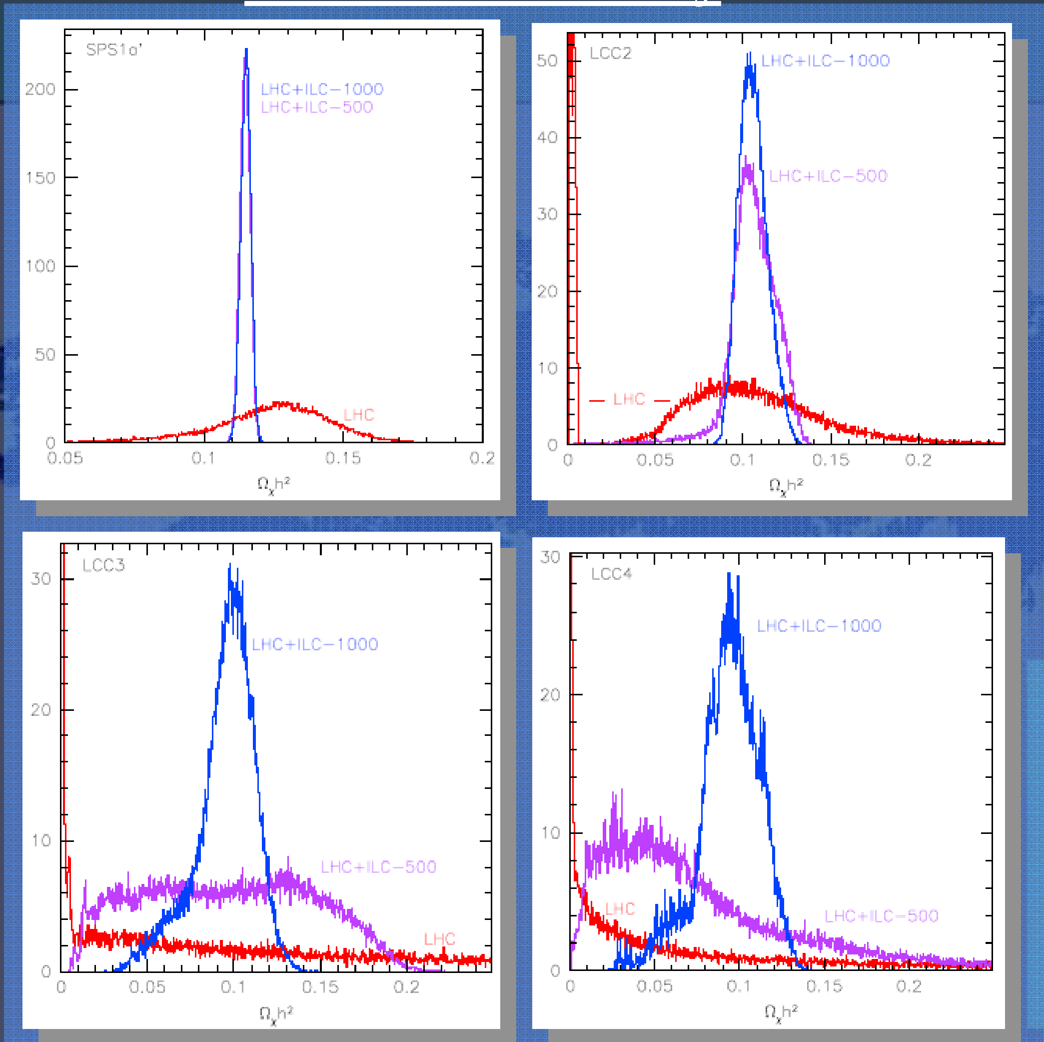
DM density accuracy from ILC in A^0 Funnel Region and WMAP



MB, B Hooberman, N Kelley

Collider Experiments on Dark Matter

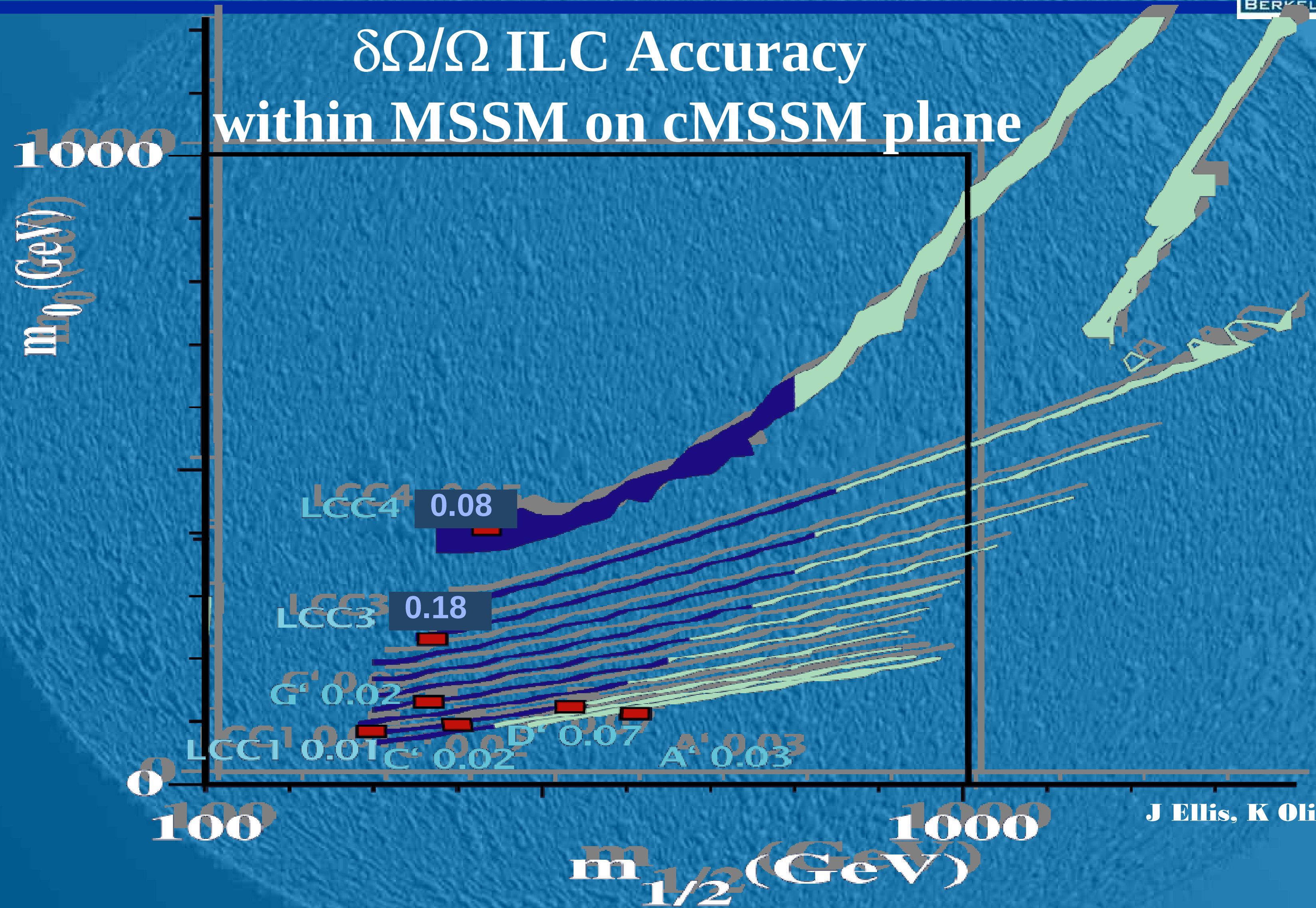
Dark Matter Density



	Ωh^2	LHC	ILC-500	ILC-1000
LCC1	0.192	7.2%	1.8%	0.24%
LCC2	0.109	82.%	14.%	7.6%
LCC3	0.101	167%	50.%	18.%
LCC4	0.114	405%	85.%	19.%
				→0.08

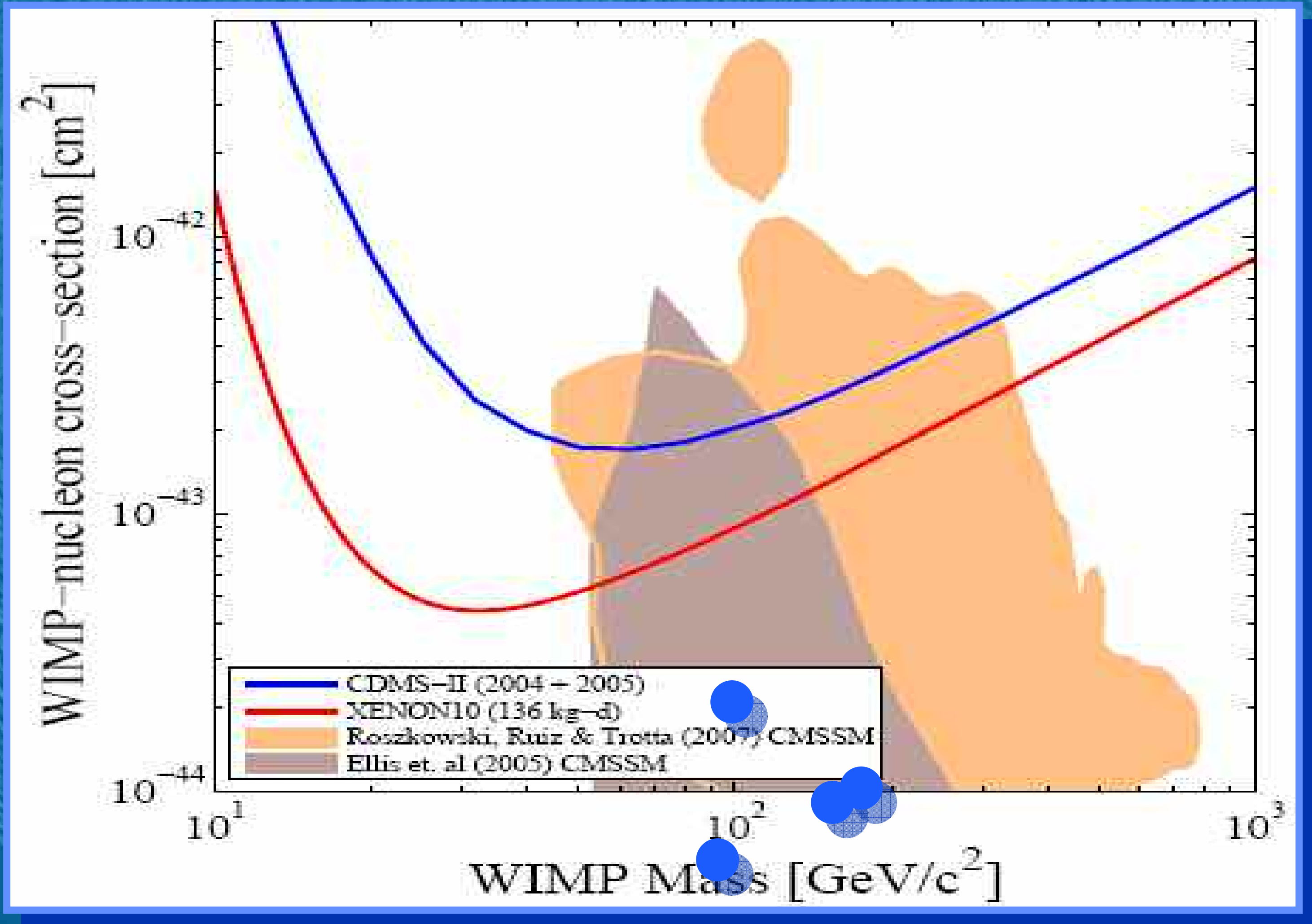
Baltz, MB, Peskin, Wiszanski, PRD74 (2006)

δΩ/Ω ILC Accuracy within MSSM on cMSSM plane



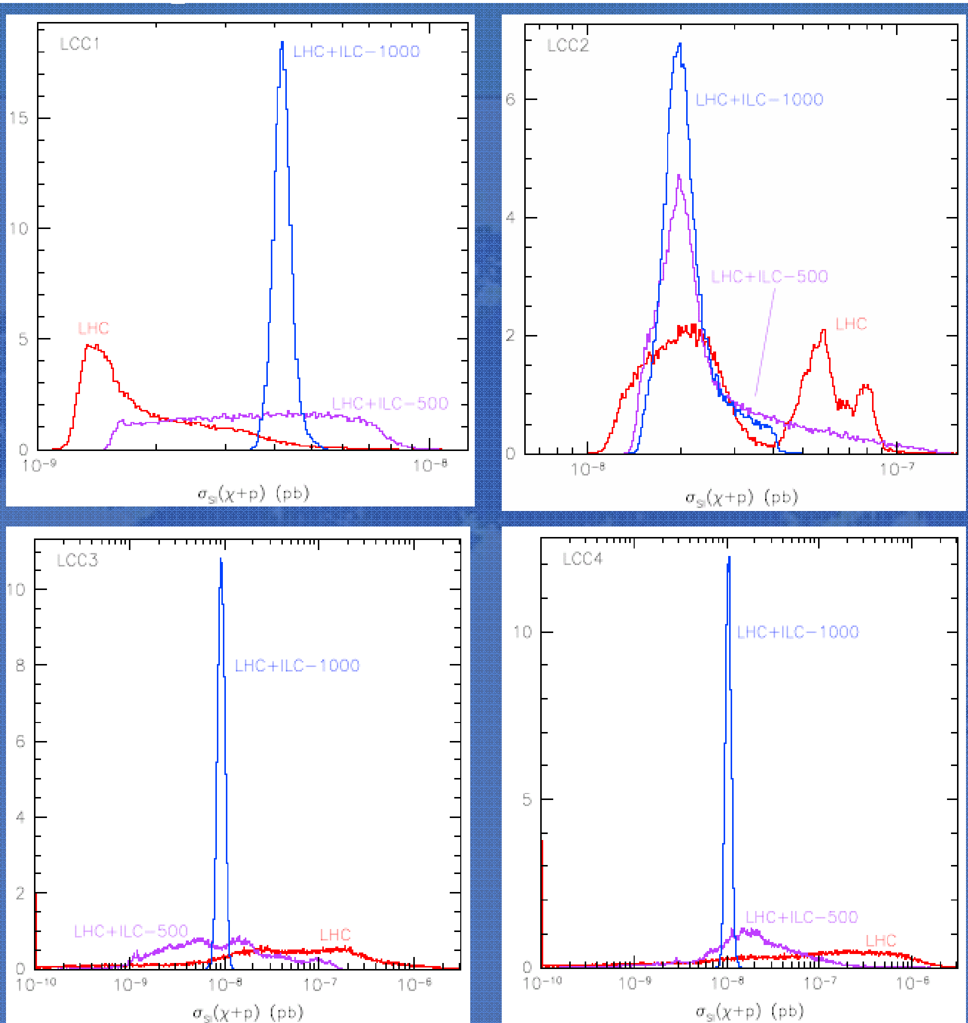
J Ellis, K Olive, MB et al.

ILC and DM Direct Searches



Collider Experiments on Dark Matter

Spin-Independent Neutralino Proton Cross Section

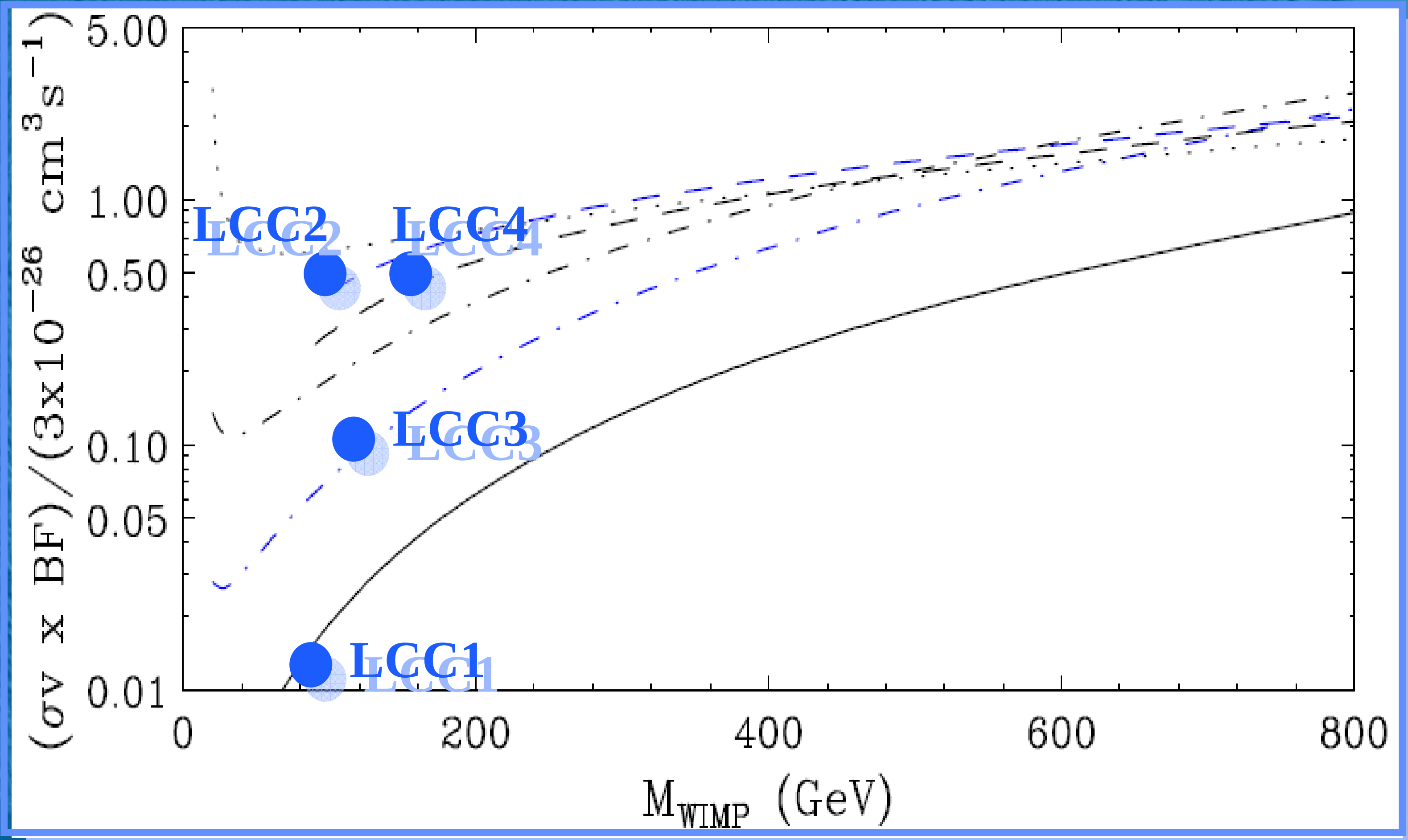


	$\sigma(\chi p)$	LHC	ILC-500	ILC-1000
LCC1	0.418	44.%	45.%	5.7%
LCC2	1.866	62.%	63.%	22.%
LCC3	0.925	184.%	146.%	8.6%
LCC4	1.046	150.%	190.%	7.5%

Baltz, MB, Peskin, Wiszanski, PRD74 (2006)

ILC and DM Satellite Experiments

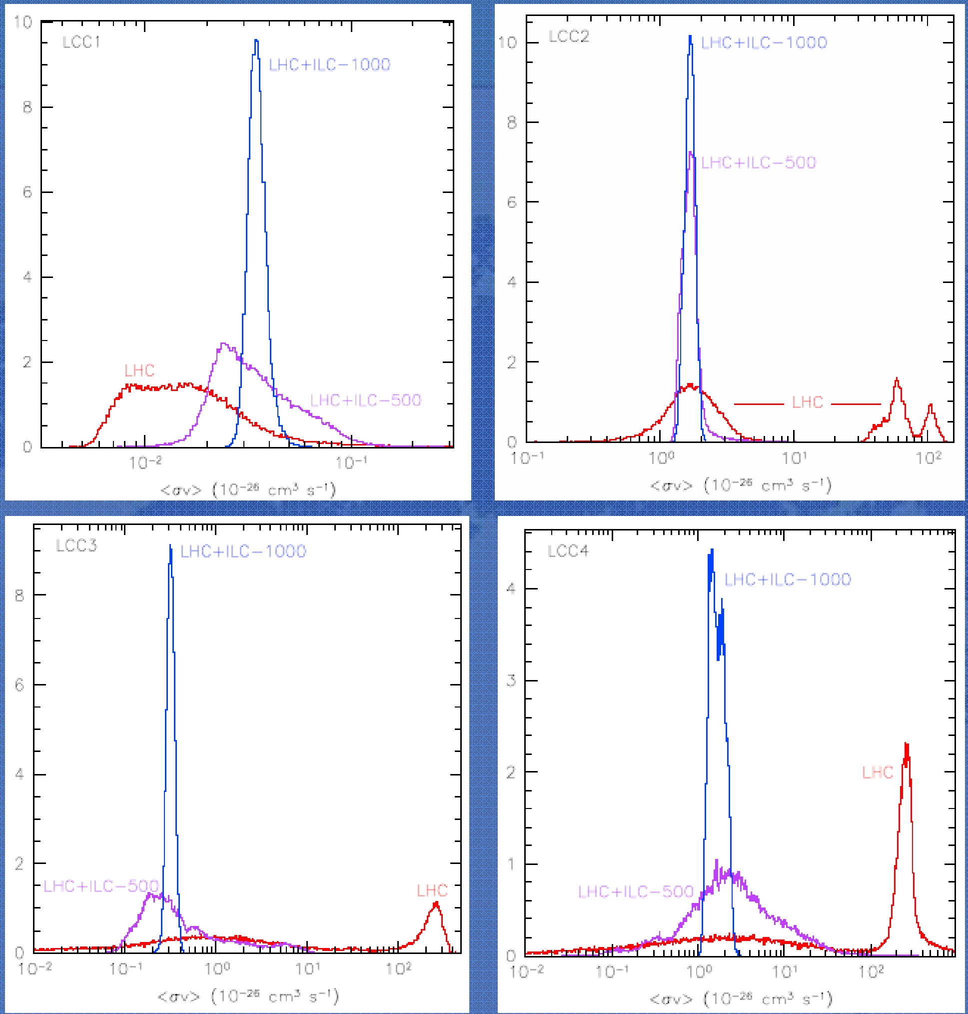
BERKELEY LAB



Hooper, Finkbeiner, Dobler
arXiv:0705.3655 [astro-ph]

Collider Experiments on Dark Matter

Annihilation Cross Section

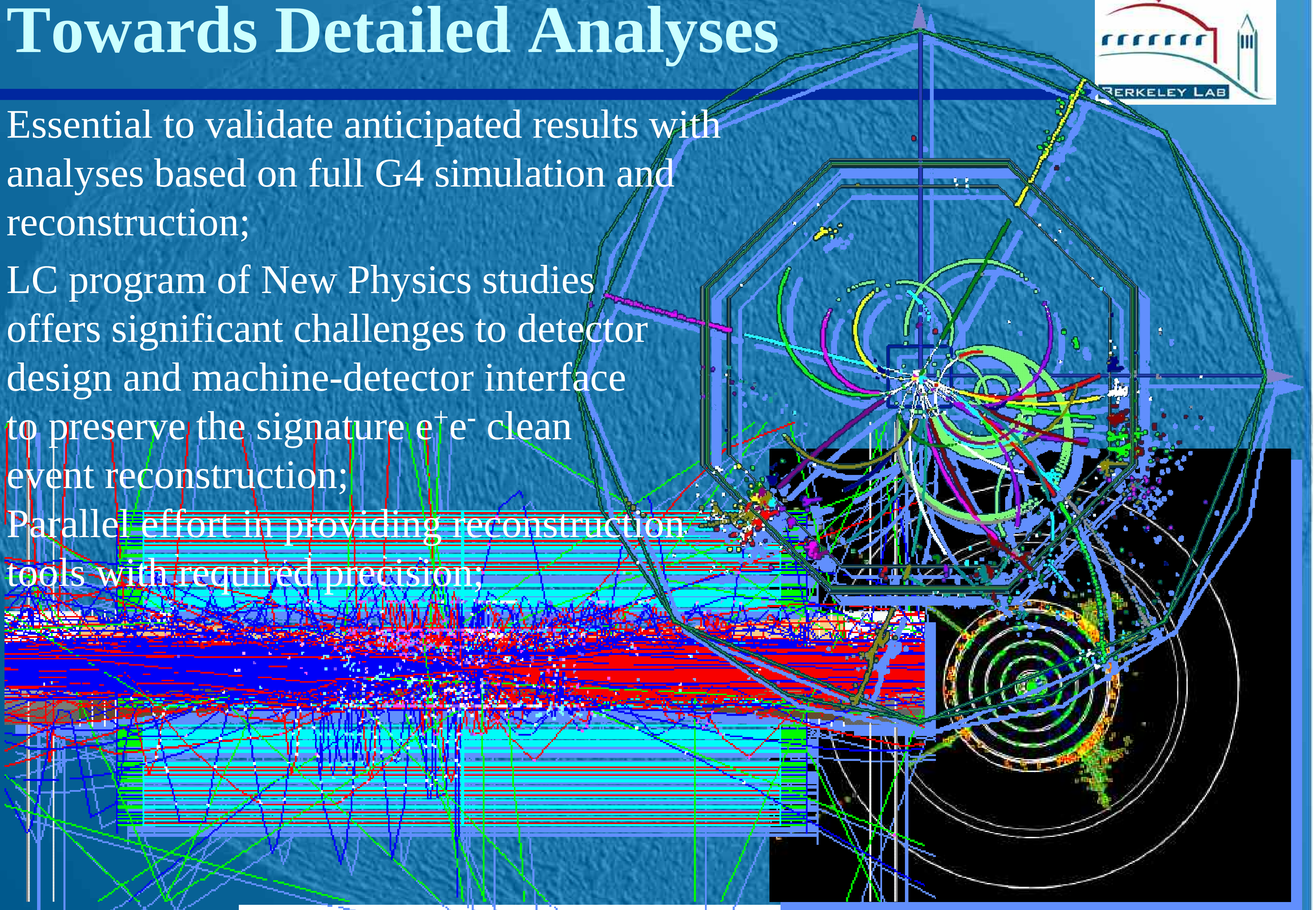


	σv	LHC	ILC-500	ILC-1000
LCC1	0.0121	165.%	54.%	11.%
LCC2	0.547	143.%	32.%	8.7%
LCC3	0.109	154.%	178.%	10.%
LCC4	0.475	557.%	228.%	20.%

Baltz, MB, Peskin, Wiszanski, PRD74 (2006)

Towards Detailed Analyses

- Essential to validate anticipated results with analyses based on full G4 simulation and reconstruction;
- LC program of New Physics studies offers significant challenges to detector design and machine-detector interface to preserve the signature e^+e^- clean event reconstruction;
- Parallel effort in providing reconstruction tools with required precision;



Conclusion

Dark Matter likely to be first signal of New Physics at TeV scale;

Current and future collider experiment programs at Tevatron, LHC and ILC to better define model constraints, discover signature of new phenomena beyond SM and measure them with enough accuracy to test their compatibility with both CMB satellite surveys and ground-based DM searches;

If results would agree, major triumph for both Cosmology and Particle Physics, detailed data on DM particle would enable precise studies of Cosmology;

Detailed event reconstruction, more than maximum centre-of-mass energy is key to obtain accelerator experiment data with accuracy needed to match that of satellite experiments and emphasis the importance of the ILC program complementing the LHC and other experiments.