Run Scenario for a Physics Rich Program at 500 GeV

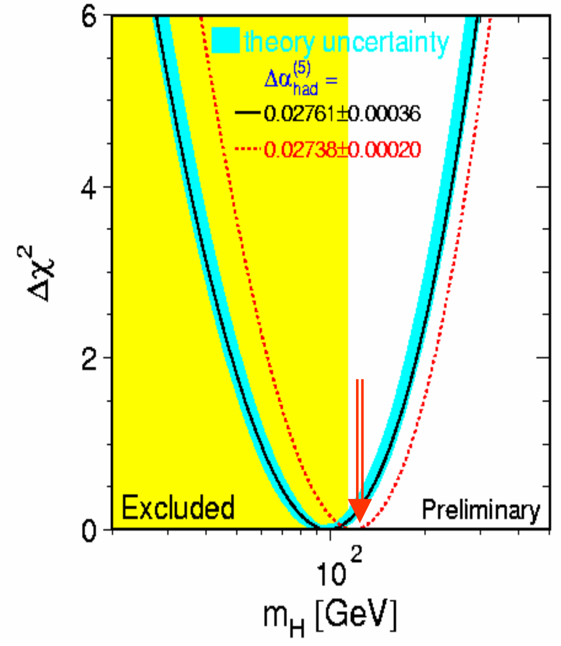
What if Nature presents us with a very rich collection of new physics at the 500 GeV scale? In this delightful case, is the LC capable of encompassing a complete program in a reasonable time?

Construct a realistic Run Scenario and estimate the precision for Higgs, top and Susy parameters.

c.f. hep-ph/0201177

The New Physics Scenario

SM Higgs mass of 120 GeV (or Susy Higgs h^0 in nearly decoupling limit)

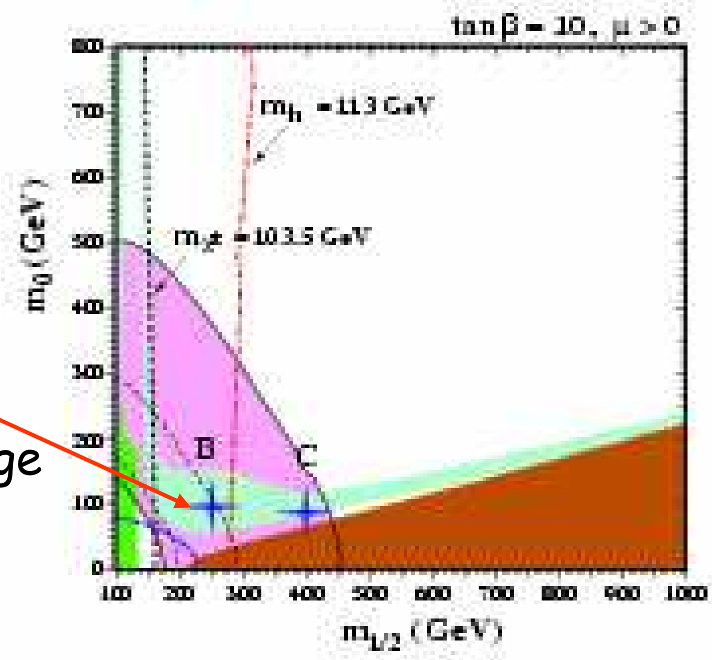


Use mSUGRA benchmark:

Snowmass Group E2, #2 == SM2

(≈ Allanach et al., hep-ph/0202233: 'SPS1a'),
(≈ Battaglia et al. hep-ph/0106204: 'B'):

m_0 = 100 GeV
$m_{1/2}$ = 250 GeV
tan β = 10
A_0 = 0
sgn(μ) = +



This has relatively low mass sparticles, but the large tanβ means that there are dominant τ decays that make life difficult.

(also examined the similar TESLA RR1 mSUGRA point)

Luminosity assumption

We assume 1000 fb^{-1} = 1 ab^{-1} luminosity acquisition if LC runs at 500 GeV. ($\mathcal{L} \sim \sqrt{s}$, so runs at $\sqrt{s} < 500$ GeV 'cost' more. Define $\mathcal{L}_{equiv}$ as the luminosity that would have been acquired in the same length run at 500 GeV.)

Year	1	2	3	4	5	6	7	
($\mathcal{L}_{equiv}$dt)	10	40	100	150	200	250	250	(fb^{-1})

- Note that $\mathcal{L} = 2\mathrm{x}10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ gives 200 fb^{-1} in a 'Snowmass year' of 10^7 sec.

- We assume electron polarization ±80% and no positron polarization (conservative in estimating physics reach).

Run Plans

Considerations:

- Higgs studies are best optimized around 350 GeV

- $t\bar{t}$ Scan at 350 GeV is desired for top quark properties

- Getting Susy particle masses using kinematic end points favors operation at largest available energy

- Scans of sparticle pair thresholds depend sensitively on the model; often thresholds overlap. Threshold ~ β^1 for gaugino pairs, ~ β^3 for sfermions

- Exploration of unexpected new physics places a premium on substantial operation near full energy.

- Special runs may be desired for special purposes – e.g. a threshold scan $e^-e^- \to \tilde{e}_R^- \tilde{e}_R^-$ for best selectron mass precision. Also trade luminosity for added energy to reach $\chi_1^\pm \chi_2^\mp$ (threshold > 500 GeV in SM2 Susy benchmark).

- Run scans with e^- polarization L or R to maximize σBR **(& minimize background)**

SM2 sparticle masses and BR's

particle	M(GeV)	Final state (BR(%))					
$\tilde{e}_R(\tilde{\mu}_R)$	143	$\tilde{\chi}_1^0\, e\,(\mu)$ [100]					
$\tilde{e}_L(\tilde{\mu}_L)$	202	$\tilde{\chi}_1^0\, e(\mu)$ [45]	$\tilde{\chi}_1^\pm \nu_e\,(\nu_\mu)$ [34]	$\tilde{\chi}_2^0 e(\mu)$ [20]			
$\tilde{\tau}_1$	135	$\tilde{\chi}_1^0\, \tau$ [100]					
$\tilde{\tau}_2$	206	$\tilde{\chi}_1^0\, \tau$ [49]	$\tilde{\chi}_1^\pm\, \nu_\tau$ [32]	$\tilde{\chi}_2^0\, \tau$ [19]			
$\tilde{\nu}_e\ (\tilde{\nu}_\mu)$	186	$\tilde{\chi}_1^0\, \nu_e\,(\nu_\mu)$ [85]	$\tilde{\chi}_1^\pm\, e\,(\mu)$ [11]	$\tilde{\chi}_2^0\, \nu_e\,(\nu_\mu)$ [4]			
$\tilde{\nu}_\tau$	185	$\tilde{\chi}_1^0\, \nu_\tau$ [86]	$\tilde{\chi}_1^\pm \tau$ [10]	$\tilde{\chi}_2^0\, \nu_\tau$ [4]			
$\tilde{\chi}_1^0$	96	stable					
$\tilde{\chi}_2^0$	175	$\tilde{\tau}_1\, \tau$ [83]	$\tilde{e}_R\, e$ [8]	$\tilde{\mu}_R\, \mu$ [8]			
$\tilde{\chi}_3^0$	343	$\tilde{\chi}_1^\pm\, W^\mp$ [59]	$\tilde{\chi}_2^0\, Z$ [21]	$\tilde{\chi}_1^0\, Z$ [12]	$\tilde{\chi}_2^0\, h$ [1]	$\tilde{\chi}_1^0\, h$ [2]	
$\tilde{\chi}_4^0$	364	$\tilde{\chi}_1^\pm W^\mp$ [52]	$\tilde{\nu}\nu$ [17]	$\tilde{\tau}_2\tau$ [3]	$\tilde{\chi}_1^0\, Z$ [2]	$\tilde{\chi}_2^0\, Z$ [2]	…
$\tilde{\chi}_1^\pm$	175	$\tilde{\tau}_1\nu_\tau$ [97]	$\tilde{\chi}_1^0\, qq$ [2]	$\tilde{\chi}_1^0\, \ell\nu$ [1]			
$\tilde{\chi}_2^\pm$	364	$\tilde{\chi}_2^0\, W$ [29]	$\tilde{\chi}_1^\pm Z$ [24]	$\tilde{\ell}\nu_\lambda$ [18]	$\tilde{\chi}_1^\pm h$ [15]	$\tilde{\nu}_\ell\, \ell$ [8]	$\tilde{\chi}_1^0\, W$ [6]

SM2 left and right-polarized XS's for selected reactions

Cross sections at 500 GeV,
except as noted

Reaction	σ_L (fb)	σ_R (fb)
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	105	25
$\tilde{\chi}_1^0 \tilde{\chi}_3^0$	4	16
$\tilde{\chi}_1^0 \tilde{\chi}_4^0$	2	4
$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	139	16
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$	310	36
$\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$	37	10 (@580 GeV)

Reaction	σ_L (fb)	σ_R (fb)
$\tilde{\nu}_\varepsilon \tilde{\nu}_\varepsilon^*$	929	115
$\tilde{\nu}_\mu \tilde{\nu}_{\mu*}$	18	14
$\tilde{e}_L^+ \tilde{e}_L^-$	105	17
$\tilde{e}_R^+ \tilde{e}_R^-$	81	546
$\tilde{e}_R^+ \tilde{e}_L^-$	17	152
$\tilde{e}_L^+ \tilde{e}_R^-$	152	17
$\tilde{\mu}_R^+ \tilde{\mu}_R^-$	30	87
$\tilde{\mu}_L^+ \tilde{\mu}_L^-$	38	12
$\tilde{\tau}_1^+ \tilde{\tau}_1^-$	35	88
$\tilde{\tau}_1^\pm \tilde{\tau}_2^\mp$	2	1
$\tilde{\tau}_2^+ \tilde{\tau}_2^-$	31	11

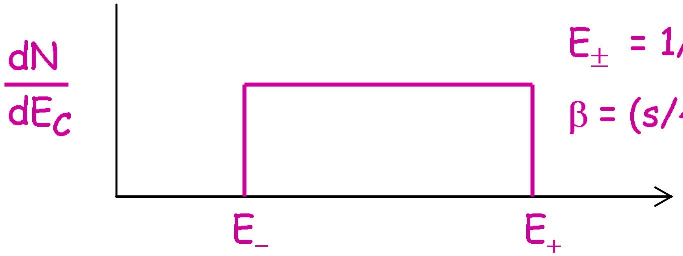
Run Plan for SM2 Susy sparticle masses

Substantial initial run at 500 GeV (for end point mass determinations). Scans at selected thresholds to improve masses. Special e^-e^- run and a run above 500 GeV.

Beams	Energy	Polz'tn	$\mathcal{L}dt$	$(\mathcal{L}dt)_{equiv}$	comments
e^+e^-	500	L/R	335	335	sit at top energy for end point measurements
e^+e^-	270	L/R	100	185	scan thresholds $\tilde{\chi}_1^0\tilde{\chi}_2^0$ (L pol.); $\tilde{\tau}_1\tilde{\tau}_1$ (R pol.)
e^+e^-	285	R	50	85	scan $\tilde{\mu}_R^+\tilde{\mu}_R^-$ threshold
e^+e^-	350	L/R	40	60	scan $t\bar{t}$ thresh; scan $\tilde{e}_R\tilde{e}_L$ thresh (L & R pol.) scan $\tilde{\chi}_1^+\tilde{\chi}_1^-$ thresh. (L pol.)
e^+e^-	410	L/R	100	120	scan $\tilde{\tau}_2\tilde{\tau}_2$ thrsh (L pol); scan $\tilde{\mu}_L\tilde{\mu}_L$ thrsh (L pol)
e^+e^-	580	L/R	90	120	sit above $\tilde{\chi}_1^+\tilde{\chi}_2^-$ thresh. for $\tilde{\chi}_2^\pm$ end pt. mass
e^-e^-	285	RR	10	95	scan with e^-e^- for $\tilde{e}_R$ mass

$\Sigma(\mathcal{L}dt)_{equiv} = 1000\ \mathrm{fb}^{-1}$

End point masses – comments



$E_\pm = 1/2\,(1 \pm \beta)\,(1 - m_A^2/m_B^2)$;

$\beta = (s/4m_A^2 - 1)^{\frac{1}{2}}$

For: $A \to B + C$

(A&B are sparticles; C is observed SM particle). Measuring 2 end points gives ***both*** A and B masses. Statistics, backgrounds, resolutions smear the edges.

- $\tilde{\chi}_1^\pm \to \tilde{\tau}_1 \nu_\tau$ tough for $\tilde{\chi}_1^\pm$ mass, but $\tilde{\nu}_e \to \tilde{\chi}_1^\pm\ e^\pm$ allows getting it (use parent or daughter !)
- $\tilde{\tau}, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ decays mainly to τ's making end point measurements hard. We estimate that use of 1-prong τ's give end point mass to within 1–2 GeV. (There is nothing magic about rectangular box templates for getting masses!)
- $\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z$ is a useful decay for $\tilde{\chi}_2^\pm$ mass but $\tilde{\chi}_2^\pm \tilde{\chi}_1^\mp$ threshold > 500 GeV! Trade off beam current for energy to get above threshold. Get indirect indication of $\tilde{\chi}_2^\pm$ mass from t-channel contribution in $\tilde{\nu}_e \tilde{\nu}_e$ production.
- $\tilde{e}_R$ and $\tilde{e}_L$ states produce multiple end points in $e^+e^- \to e^+e^- + \not{E}$. Nauenberg et al. showed that these may be disentangled cleanly using $(e^+ - e^-)$ distribution differences for both L&R pol.
- SM2 benchmark is special: $\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 Z$ channel is open allowing good measurement of $\tilde{\chi}_3^0$ mass.
- $\tilde{\chi}_1^0 \tilde{\chi}_4^0$ production with $\tilde{\chi}_4^0 \to \tilde{\chi}^0_{1,2} Z$ has insufficient statistics for $\tilde{\chi}_4^0$ mass determination.

- Scale precision from previous studies (Martyn/Blair or Colorado Gp) by $\sqrt{\sigma BR \mathcal{L} \tau}$ for the particular reaction leading to the end point measurement

Unscrambling end point reactions

To make end point mass measurements, we have to know which reaction we are looking at. Is this uniquely possible?

We have info on initial state polarization and specific final state seen.
How many underlying production channels feed each distinct final state?

e.g. $\mu^\pm \tau^\mp \not{E}$ final state from R pol. is fed by $\tilde{\mu}_L\tilde{\mu}_L$ (52%), $\tilde{\nu}_\mu\tilde{\nu}_\mu$ (34%), $\tilde{\chi}_1^0\tilde{\chi}_3^0$ (10%), and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ (4%) channels, and is hard to use for end point studies !

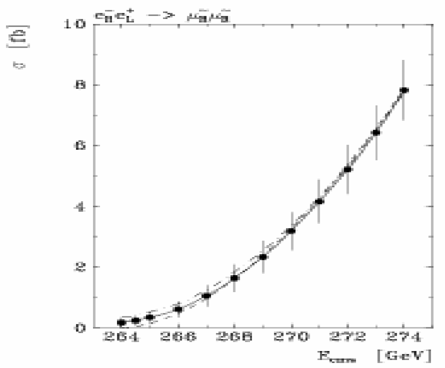
Final state	e^- Pol.	N	dominant reactions	purity	SM particles	sparticle masses
$e^+ e^- \not{E}$	R/L	210K/65K	$\tilde{e}_L\tilde{e}_L$, $\tilde{e}_R\tilde{e}_R$, $\tilde{e}_L\tilde{e}_R$	99/92%	$e^\pm$	$\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\chi}_1^0$
$\mu^+ \mu^- \not{E}$	R	31K	$\tilde{\mu}_R\tilde{\mu}_R$	95%	$\mu^\pm$	$\tilde{\mu}_R$, $\tilde{\chi}_1^0$
$\tau^+ \tau^- \not{E}$	L	152K	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$	56%	$\tau^\pm$	$\tilde{\chi}_1^\pm$, $\tilde{\tau}_1$
$\tau^+ \tau^- \not{E}$	R	49K	$\tilde{\tau}_1\tilde{\tau}_1$	53%	$\tau^\pm$	$\tilde{\chi}_1^0$, $\tilde{\tau}_1$
$e^\pm \tau^\mp \not{E}$	L	88K	$\tilde{\nu}_e\tilde{\nu}_e^*$	65%	$e^\pm$	$\tilde{\chi}_1^\pm$, $\tilde{\nu}_e$
$\mu^+ \mu^- \tau^+ \tau^- \not{E}$	L	2K	$\tilde{\mu}_L\tilde{\mu}_L$	97%	$\mu^\pm$	$\tilde{\mu}_L$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$
$e^+ e^- \tau^+ \tau^- \not{E}$	R	10K	$\tilde{e}_L\tilde{e}_R$	91%	$e^\pm$	$\tilde{e}_L$, $\tilde{\chi}_1^0$, $\tilde{e}_R$
$\tau^+ \tau^- \tau^\pm \mu^\mp \not{E}$	R	8K	$\tilde{\nu}_\mu\tilde{\nu}_\mu$ ($\tilde{\mu}_L\tilde{\mu}_L$)	43(57)%	$\mu^\pm$	$\tilde{\nu}_\mu$, $\tilde{\chi}_1^\pm$

Have a clean channel for all accessible sparticles in SM2, except for $\tilde{\nu}_\tau$, $\tilde{\tau}_2$ and maybe $\tilde{\chi}_2^0$, although some iteration or coupled-channel fits will be needed.

But the situation will be different for each Susy model !!

Threshold scans for sparticle masses

Martyn & Blair (hep-ph/9910416) studied the mass precision available from scans near two-body thresholds (Tesla point RR1). For p-wave threshold (gaugino pairs), $\sigma \sim \beta^1$, while for s-wave (sfermion pairs), $\sigma \sim \beta^3$.



Martyn-Blair used 10 points – probably not optimal. Strategy should depend on # event, $\delta(\sigma BR)/\sigma BR$, backgrounds and β-dependence. Mizukoshi et al. (hep-ph/0107216) studied $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$ thresholds (low σBR and large τ decays) and found that 2 points on the rise and one well above threshold was better. Blair at Snowmass found that 2-point scans could be optimal for δm and Γ (Benchmark SPS1a): can get $\delta\Gamma/\Gamma$ ~ 30% for typical sparticles).

Cahn (Snowmass) did analytic study of mass precision from scans vs N = # pts, spaced at ΔE and found:

$$\delta m \approx \frac{\Delta E}{\sqrt{18\,\mathcal{L}\,\sigma_u}}\left(1 + \frac{0.36}{\sqrt{N}}\right) \text{ (p-wave)}$$

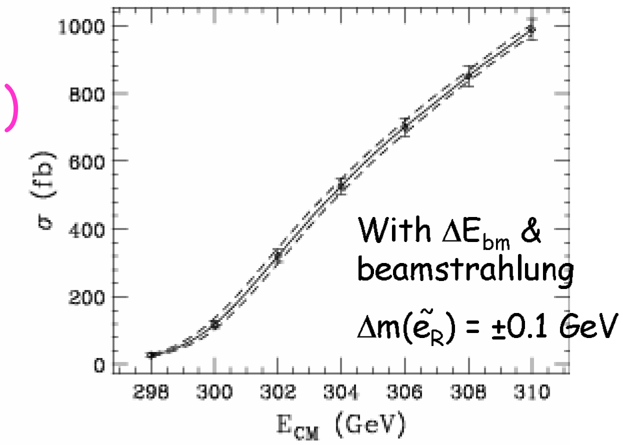
$$\delta m \approx \frac{\Delta E\, N^{-1/4}}{\sqrt{2.6\,\mathcal{L}\,\sigma_u}}\left(1 + \frac{0.38}{\sqrt{N}}\right) \text{ (s-wave)}$$

With $\mathcal{L}$ = total scan luminosity and σ_u = XS at upper end of scan. Good agreement with MC results. **Little improvement for N>3, particularly for p-wave.**

Threshold scans

One needs to allocate scans carefully – there is a trade off between luminosity at 500 GeV (all end points and searches) and use of lower energy (more restricted use of reduced luminosity). Do those scans that give the most restrictive information on Susy model parameters.

For example, Feng & Peskin (hep-ph/0105100) study showed that e^-e^- operation (both beams R polarized) at the $\tilde{e}_R\tilde{e}_R$ threshold (β^1) could give substantially better $\delta m(e_R)$ than the e^+e^- scan (β^3), even after inclusion of beamsstrahlung. We adopt this idea in our run plan.



With ΔE_{bm} & beamstrahlung

$\Delta m(\tilde{e}_R)$ = ±0.1 GeV

In establishing the mass precisions from scans, we have scaled the δm's from existing studies by the ratio of assumed $\sqrt{\sigma(500\ \mathrm{GeV}) * \mathcal{L}t}$. (Probably naïve to ignore details of backgrounds at different benchmarks, and the effect of uncertain σBR's.)

(Used only dominant reaction/polarization, so is conservative)

- Note that for scans, we need not identify particular exclusive decays -- the total visible cross section may be used. But beware overlapping thresholds!

Sparticle mass precision

For run plan indicated for SM2

sparticle	δM_{EP} (end pt)	δM_{TH} (scan)	δM_{COMB} (combined)
$\tilde{e}_R$	0.19	0.02	**0.02 GeV**
$\tilde{e}_L$	0.27	0.30	**0.20**
$\tilde{\mu}_R$	0.08	0.13	**0.07**
$\tilde{\mu}_L$	0.70	0.76	**0.51**
$\tilde{\tau}_1$	~1 - 2	0.64	**0.64**
$\tilde{\tau}_2$	--	0.86	**0.86**
$\tilde{\nu}_e$	0.23	--	**0.23**
$\tilde{\nu}_\mu$	7.0	--	**7.0**
$\tilde{\nu}_\tau$	--	--	**--**
$\tilde{\chi}_1^0$	0.07	--	**0.07**
$\tilde{\chi}_2^0$	~1 - 2	0.12	**0.12**
$\tilde{\chi}_3^0$	8.5	--	**8.5**
$\tilde{\chi}_4^0$	--	--	--
$\tilde{\chi}_1^\pm$	0.19	0.18	**0.13**
$\tilde{\chi}_2^\pm$	4.1	--	**4.1**

The RR1 benchmark mass precisions were worked out in less detail. In general since RR1 has lower τ branching ratios, and smaller sparticle masses, so mass precision should be better than for SM2. There are always idiosyncratic differences – e.g. $\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0$ Z open in SM2 but not RR1.

mSUGRA parameter determination

The ultimate aim of the Susy program at the LC is to determine the character of the Susy breaking (GMSB, mSUGRA, AMSB χMSB, NMSSM, etc.), and illuminate the physics at the unification scale. This will require measurements of the sparticle masses, cross-sections and branching ratios, mixing angles and CP violating observables.

A start on this has been made: G. Blair, *et al.* PRD D63, 017703 ('01);
S.Y. Choi *et al.*, hep-ph/0108117, G. Kane, hep-ph/0008190.

Here we ask the **more restricted question**: Assuming we live in mSUGRA (as for benchmark SM2), what are the Susy parameter errors ?

Mass resolutions quoted for our Run Plan give:

Parameter	SM2	RR1
m_0 (GeV)	100±0.08	100±0.04
$m_{1/2}$ (GeV)	250±0.20	200±0.22
A_0 (GeV)	0±13	0±18
$\tan\beta$	10±0.47	30±05

- δm_0 mainly from $\tilde{e}_R$, $\tilde{\mu}_R$ masses
- $\delta m_{1/2}$ mainly from $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$ masses
- δA_0 mainly from $\tilde{\tau}_1$, $\tilde{\tau}_2$ masses
- $\delta\tan\beta$ mainly from $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$ masses

Conservative, since additional info from $\tilde{t}$, H/A, $\sigma_{L/R}$ will give added constraints on mSUGRA parameters

Higgs, top quark parameter determination

Higgs:

Scale errors from previous studies (TESLA TDR, Snowmass Book) ~ $\surd N_{Higgs}$

Only use $e^+e^- \rightarrow ZH$ sample; adding $WW \rightarrow H$ for Hff couplings will help

Use $e^+e^- \rightarrow \nu\nu W^*W^* \rightarrow \nu\nu H$ XS for λ_{WWH}

#(ZH) in SM2 scenario = 77,000
= # in 550 fb^{-1} at $\sqrt{s}$ = 350 GeV
= # in 1280 fb^{-1} at $\sqrt{s}$ = 500 GeV

Top Quark:

Threshold scan near 350 GeV.

Scale errors from TESLA TDR and Snowmass Book.

Statistical errors small compared with systematic errors.

Use renormalization safe measures of top mass (e.g. 1/2 toponium quasi-bound state mass).

Top width from threshold scan, A_{FB} ($t\bar{t}\gamma$, $t\bar{t}g$, $t\bar{t}H$ interferences)

Threshold behavior of $t\bar{t}$ XS gives rough Yukawa coupling (but much better to go above $t\bar{t}H$ threshold)

Higgs, top quark parameter errors

Relative errors on Higgs parameters (in %)			
parameter	error	parameter	error
M_{Higgs}	0.03 %	Γ_{Tot}	7 %
$\sigma(ZH)$	3	λ_{ZZH}	1
$\sigma(WW)$	3	λ_{WWH}	1
BR(bb)	2	λ_{bbH}	2
BR(cc)	8	λ_{ccH}	4
BR($\tau\tau$)	5	$\lambda_{\tau\tau H}$	2
BR(gg)	5	λ_{ttH}	30

Errors on top quark parameters	
M_{top}	150 MeV (0.09%)
Γ_{top}	≈70 MeV (7%)

Conclusinos

- Even for the physics rich scenarios of Susy benchmarks SM2 (RR1) and low Higgs mass, the Linear Collider can do an excellent job on precision measurements in a reasonable time.

- Runs at the highest energy should dominate the run plan -- to optimize searches for new phenomena, and to get sparticle masses from kinematic end points.

- The details of the run plan depend critically on the exact Susy model -- there is large variation as models or model parameters vary. It will be a challenge to understand the data from LHC and LC well enough to sort out sparticle masses/cross sections and predict the appropriate threshold energies.

- For Susy, it remains very likely that higher energy will be needed to complete the mass determination and fix the Susy breaking mechanism.