Run Scenario for the Linear Collider

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. In what order should runs be made, and what provisions are necessary for calibrations. What would we do if we are not in a New Physics = Susy world?

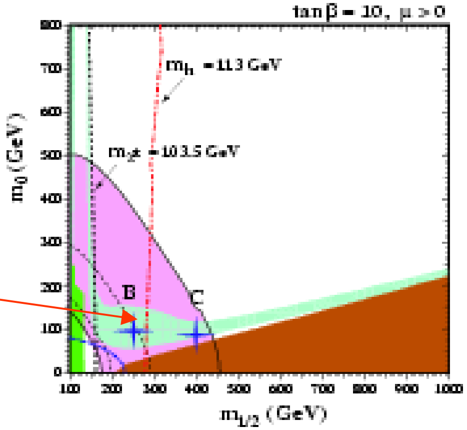
c.f. hep-ph/0201177
but details here are changed

Assumptions

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

☆ Use mSUGRA benchmark: **Snowmass E2 Group #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.

We assume 1000 fb^{-1} = 1 ab^{-1} luminosity acquisition (500 GeV equivalent).
Assume electron (not positron) polarization of ±80%

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

Run Plan considerations

- Higgs studies are best optimized around 350 GeV
- $\bar{t}t$ Scan at 350 GeV is desired for top quark properties
- Getting Susy particle masses using kinematic end points favors operation at largest available energy
- Desired scans of sparticle pair thresholds depend sensitively on the model; often thresholds overlap. Choose appropriate polarization.
- Exploration of unexpected physics needs highest available 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 can trade luminosity for higher energy ($\chi_1^\pm \chi_2^\mp$ threshold > 500 GeV in SM2 Susy benchmark).
- Need calibration runs (at Z) relatively early
- Studies demanding high performance of Collider to be done later (e.g. Giga Z with e^+ polarization; WW scan with precise E_{beam} control …

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. Quote σ's for 80% L or R polarization.

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)
$\tilde{\nu}_e\tilde{\nu}_e^*$	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 500 GeV run (for "end point" mass determinations). Scans at some 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-	M_Z	L/R	10	45	calibrate with Z's
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	60	75	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

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

End point masses – comments

For: $\tilde{A} \rightarrow \tilde{B} + C$

(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.

The traditional end point method:

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

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

Making an box distribution mass measurement requires:

1. A given final state (& e^- polarization) should be fed by only 1 dominant reaction
2. Two body decay with C a stable observable SM particle.

Neither of these conditions are generally true for benchmark SM2 with large BRs into τ's and ν_τ

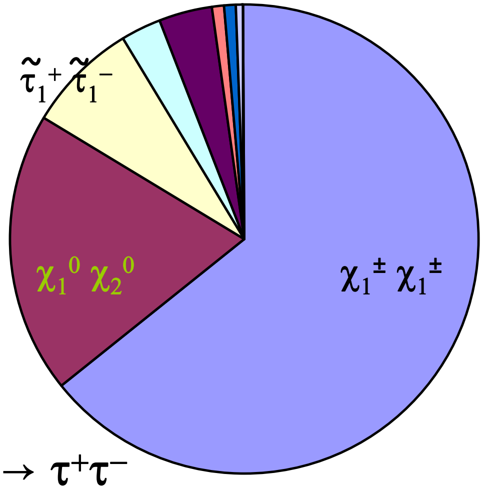
However, it is not necessary to have a 'box' distribution for determining mass – any known distribution will do. But if there are not sharp edges, the precision is lower. (Recall that the top quark mass was measured to within 4% in semileptonic decays with a broad mass distribution (using templates) with only about 40 events and S/B ~ 1/2.

3. To get δM for 'end point' masses here, I have scaled from the studies of the Colorado group (Snowmass '01), or used estimates for the $\tau\tau$ channels from preliminary studies and some guesswork.

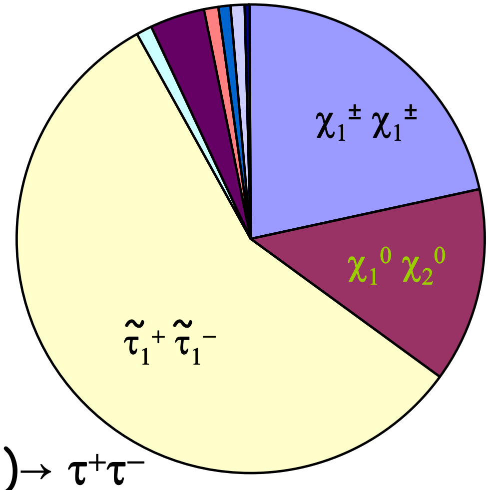
The reaction overlap problem

Among all-leptonic (& missing energy) decays of sparticle pairs, $\tau\tau$ is the dominant final state. It is fed by 9 different sparticle pair reactions !

(and moreover the taus are not stable, so the "end points" of the observed final state (1 prong $\pi^\pm$,$\rho^\pm$ etc.) are washed out.



e^+e^- (left)→ $\tau^+\tau^-$
152K evnts

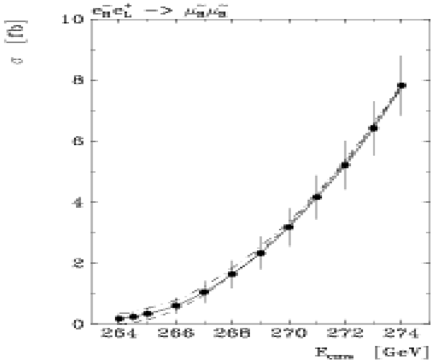


e^+e^- (right)→ $\tau^+\tau^-$
52K evnts

Discussion of how to address this problem in Susy/Higgs parallel session.
More detailed study of extracting multiple masses from several reactions is needed.

Threshold scans for sparticle masses

- Martyn & Blair (hep-ph/9910416) studied the mass precision available from scans near 2-body thresholds. For p-wave threshold $\sigma \sim \beta^1$, while for s-wave, $\sigma \sim \beta^3$.



- Martyn-Blair used 10 points – perhaps not optimal. Strategy should depend on # events $\delta(\sigma BR)/\sigma BR$, backgrounds and β-dependence. Mizukoshi et al. (hep-ph/0107216), Blair (Snowmass) found that 2-point scans could be optimal. Cahn (Snowmass) did analytic study of mass precision from scans vs N = # pts, spaced at ΔE and found little improvement for N>3, particularly for p-wave.

- One needs to allocate scans carefully – tradeoff between luminosity at 500 GeV (end points and searches) and use of lower energy (reduced luminosity). Do only those scans that give the most restrictive information on Susy model parameters. (In SM2, get some scans 'for free' as thresholds overlap.)

We scaled the δm's from existing studies by the ratio of $\sqrt{\sigma(500\ \text{GeV}) * \mathcal{L}t}$. (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 on that score)

★ 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

Mass precisions obtained 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**
$\tilde{\tau}_2$	--	1.1	**1.1**
$\tilde{\nu}_e$	~1	--	**~1**
$\tilde{\nu}_\mu$	7 ??	--	**7 ??**
$\tilde{\nu}_\tau$	--	--	**--**
$\tilde{\chi}_1^0$	0.07	--	**0.07**
$\tilde{\chi}_2^0$	~1 - 2	0.12	**0.12**
$\tilde{\chi}_3^0$	8.5	--	**8.5**
$\tilde{\chi}_4^0$	--	--	--
$\tilde{\chi}_1^\pm$	~1 - 2	0.18	**0.18**
$\tilde{\chi}_2^\pm$	4	--	**4**

Assuming we live in mSUGRA (as for benchmark SM2), what are the Susy parameter errors ?

- δm_0 mainly from $\tilde{e}_R$, $\tilde{\mu}_R$ masses
- $\delta m_{1/2}$ mainly from $\chi_1^\pm$, $\chi_2^\pm$ masses
- δA_0 mainly from $\tilde{\tau}_1$, $\tilde{\tau}_2$ masses
- $\delta\tan\beta$ mainly from $\chi_1^\pm$, χ_1^0 masses

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

Parameter	SM2
m_0 (GeV)	100±0.08
$m_{1/2}$ (GeV)	250±0.20
A_0 (GeV)	0±13
$\tan\beta$	10±0.47

Higgs, top quark parameter errors

Higgs:

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

adding WW → $H\nu\nu$ will help for Hff couplings

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

Relative errors on Higgs parameters (%)

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

Top Quark:

Threshold scan near 350 GeV. Scale errors from TESLA TDR and Snowmass Book. Statistical errors small compared with systematic errors.

Errors on top quark parameters

M_{top}	150 MeV (0.09%)
Γ_{top}	≈70 MeV (7%)

Absolute Calorimeter Calibration

The program requires good calibration of calorimeter energies – for measurement of Higgs mass, sparticle 'end point' masses.

To get to $\delta M_{Higgs}/M_{Higgs}$ = 0.3 per mille level calibration is difficult! The ZH event sample itself gives 6 per mille accuracy from the Z hadronic decays. Doing a separate calibration at < 1 per mille and transferring it to the Higgs will be hard! But what is the physics point of this accuracy? Is more time/luminosity on calibrating warranted?

The best sparticle mass determination ($\tilde{e}_R$) is 0.1 per mille; more typical precisions are ≥ 1 per mille. But what need is there to get the absolute Susy masses to this precision? If the sparticle masses are known ***relatively*** to high precision, what is the harm if all are off by a common scale factor of ≤ 1% ?

(Threshold measurements place stringent constraints on the knowledge of the beam energies, but that is a separate issue. The most difficult case is WW needing $\delta E/E \sim 1 \times 10^{-4}$; tt threshold requires $\sim 1 \times 10^{-3}$.)

Relative Calibration at the Z

For a 2 fb^{-1} exposure at the Z (11 fb^{-1} equivalent at 500 GeV), we have 3.6M $Z \rightarrow ee$ (or $\mu\mu$) and 76M $Z \rightarrow$ hadrons. What calibration accuracies do these offer?

Assuming a calorimeter with 10^6 EM 'towers' and 5×10^4 HAD towers, with a given electron or hadron depositing energy into a 4 tower cluster

and $\delta E/E = 0.15/\sqrt{E} \oplus 0.005$ (EM) ; $\delta E/E = 0.4/\sqrt{E} \oplus 0.01$ (HAD)

We obtain about 28 electrons in every possible calorimeter EM cluster area and 24K hadrons in each HAD cluster area.

$\delta M = \sigma_M/\sqrt{N}$ and $\sigma_M/M = \delta E/E$ at $E = M_Z$

This should yield relative statistical error on the Z mass for each cluster of

3.8 per mille (EM) and 0.3 per mille (HAD)

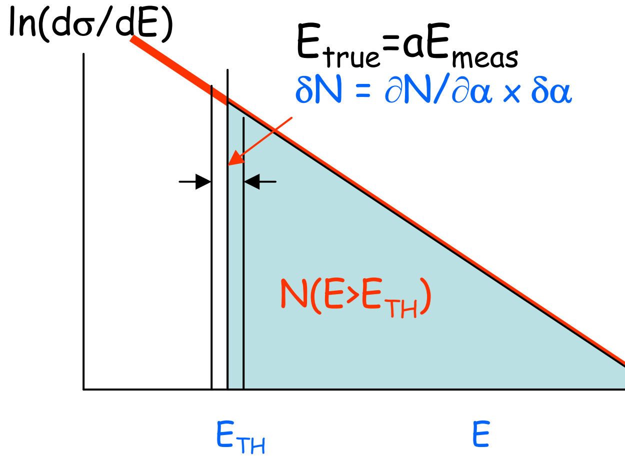
These can be taken as the accuracy of the relative calibration of different cluster areas in the calorimeter

These are small compared to the intrinsic energy resolution smearing, so should produce small effect on the mass determination errors for Susy.

⇨ **Put 4 such Z calibration runs into the first 1 ab^{-1} Run Scenario.**

In situ relative Calibration using Energy Flow

It is widely understood that Bhabha events provide a useful continuous calibration sample. An alternative used in hadron colliders is Energy Flow – the number of events above some fixed energy threshold. For a ring of 'cells' at fixed cosθ, variable ϕ, the variation in $N(E > E_{th})$ gives the relative calibration of the energy scale.



If, in some 'cell' of the calorimeter, $dN/dE \approx Ae^{-BE}$, and if $E_{true} = \alpha\, E_{meas}$, one can show that for N events in the 'cell', the error on α is: $\delta\alpha = (1/BE)\, 1/\sqrt{N}$ and the optimum threshold for measuring α is $E_{Th}=2/B$

For each 10 fb^{-1} at full energy, with $E_{Threshold}$ = 5 GeV, can get 1% calibration in each of 200 ϕ and 20 cosθ bins (used inclusive particle spectra at 1 TeV from T. Barklow) – a very useful cross check of the calibration from the Z invariant mass at lower energies, and for both EM and hadronic.

[In 2 fb^{-1} at the Z we have about 5000 particles (π, γ) in each of 4000 bins, yielding a precision on the energy scale α of about 8 per mille.]

In situ relative calibration of the ϕ rings at different cosθ can be done using a calibration from Z's.

Order of energies if SM2 Susy

Recall: We will know Higgs mass, and if there is Susy,from LHC/Tevatron

1. In first year, if 500 GeV is available, I would go there – in 10 fb^{-1} have ~ 700 ZH events, and a first take on Susy particles. If not, running at 350 GeV for Higgs would be the choice (~1500 ZH in 10 fb^{-1}). If not, run at M_Z for calibration and high event statistics commissioning.
2. Go to 500 GeV as soon as possible for ~ 80 fb^{-1} (2x ultimate error on end pt. Masses). This should give good $\tilde{e}_{L/R}$, $\tilde{\mu}_{L/R}$, $\tilde{\chi}_1^0$ masses and reasonable estimates of $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, $\tilde{\tau}_1$ masses.
3. Scan at 285 GeV ($\tilde{\mu}_L$, $\tilde{\mu}_R$), 350 GeV (tt, $\tilde{e}_L\tilde{e}_R$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$)
4. Complete the 500 GeV run for best precision on end point masses and disentangling the $\tau\tau$, $\tau\tau\tau\tau$ final states.
5. Scan at 270 GeV ($\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\tau}_1\tilde{\tau}_1$) .
6. e^-e^- scan at 285 GeV for precise $\tilde{e}_R$ mass.
7. 580 GeV e^+e^- for $\chi_1^+\chi_2^-$ study.

What if New Physics is not Susy?

We will know if we are in this world from LHC!

There are two avenues for observing new phenomena in Non-Susy scenarios:

1. **New states or cross-section deviations at large energy**
2. **Deviations from SM precision observables**

Possible Runs:	**L_{equiv}:**
To look for new phenomena at high mass, we would want substantial running at 500 GeV	500 fb^{-1}
Would want some running at highest accessible energy (~600 GeV) to examine energy dependence of new signals (e.g. if large extra dimensions. Trade luminosity for energy)	150
Will want the full Giga Z sample, with polarized e^+. About 20 fb^{-1} needed (100 fb^{-1} equiv. at 500 GeV). Would want late, when systematic errors and $\mathcal{P}(e^+)$ are well understood.	100
Likely to want $\gamma\gamma$ at maximum energy (orthogonal view of $\Delta\kappa$, λ for TGCs, heavy Z′, sensitivity to large extra dimensions …)	150
WW threshold scan, after beam energy is well understood	80
tt threshold scan	20

Complementarity of LC and LHC

The term 'complementarity' is thought to be politically incorrect – rather, 'How does the LC enhance the investment in the LHC and vice versa'

1. Knowledge of LC parameters will allow reanalysis of LHC data to extract new information:

- $m(\chi_1^0)$ from LC improves LHC $m(\tilde{g})$ & $m(\tilde{q})$;
- LC measurement of tanβ ⇒ improved LHC $M(H/A/H^\pm)$;
- $\Delta\kappa,\lambda$ at LC ⇒ better WW/ZZ anomalous production at LHC.

Note that if LC information comes after LHC turned off, it is very difficult to resuscitate the full data set and analysis machinery.

2. LC measurements may dictate new LHC conditions; for example

- if LC sees extra dimensions, LHC might want to run at several energies below 14 TeV to get information on number of EDs
- LC data could drive the LHC machine upgrade – $\mathcal{L}$ vs. E_{cm}
- LC data could dictate detector upgrades; e.g. Roman pots for diffractive Higgs; replace crystal EMCAL with TOF/gamma pointing detector; improve τ ID if high tanβ Susy; improve HadCAL to improve $M(\tilde{g})$

…

Conclusions

- Even for the physics rich scenarios of Susy benchmark SM2 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, or non-Susy –model. The optimum run plan varies strongly as models or model parameters vary.

- For both Susy, and for non-Susy worlds, it remains very likely that higher energy will be needed to complete the mass determination and fix the Susy breaking mechanism, or delineate the alternate EWSB mechanism.