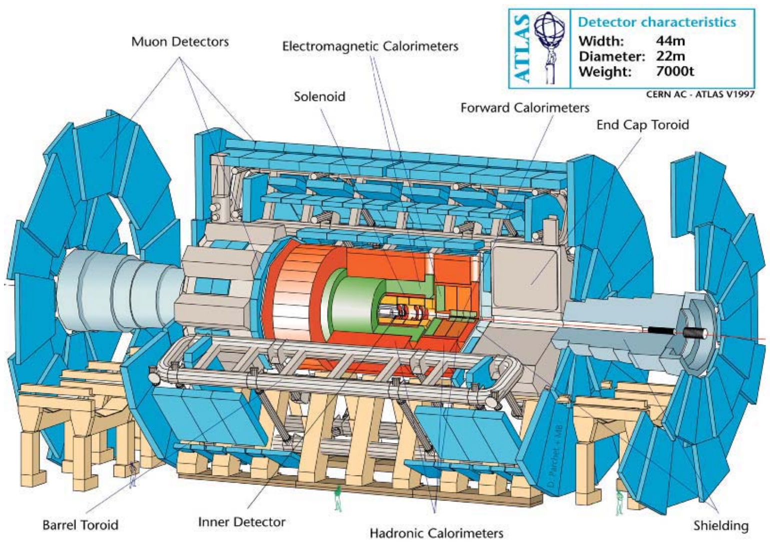
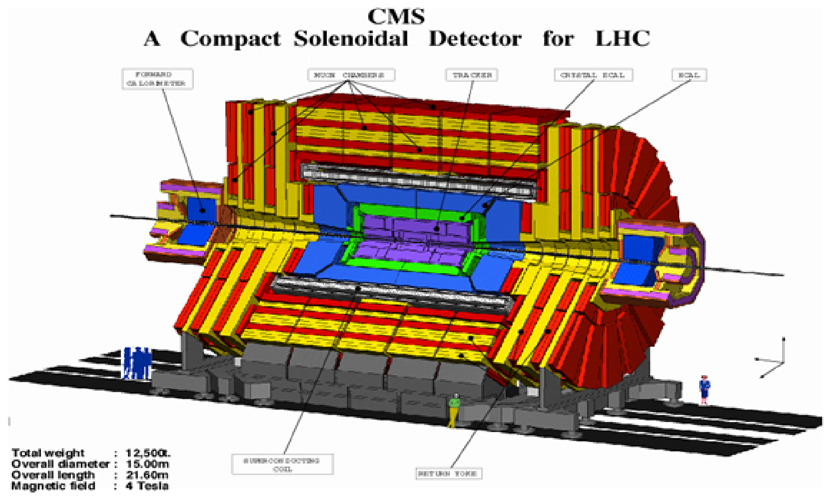
The LHC and the Road Ahead



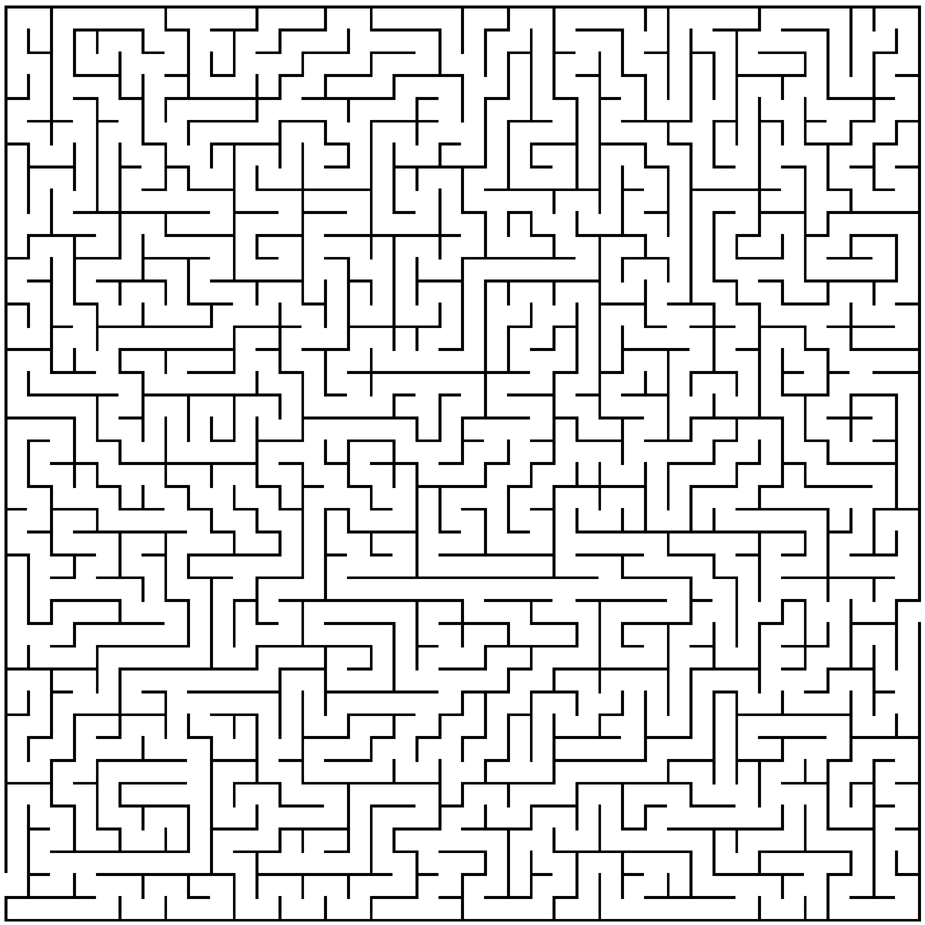


T. Rizzo, Sendai, 3/3/08

DISCLAIMER

The views expressed on these slides are mine & mine alone

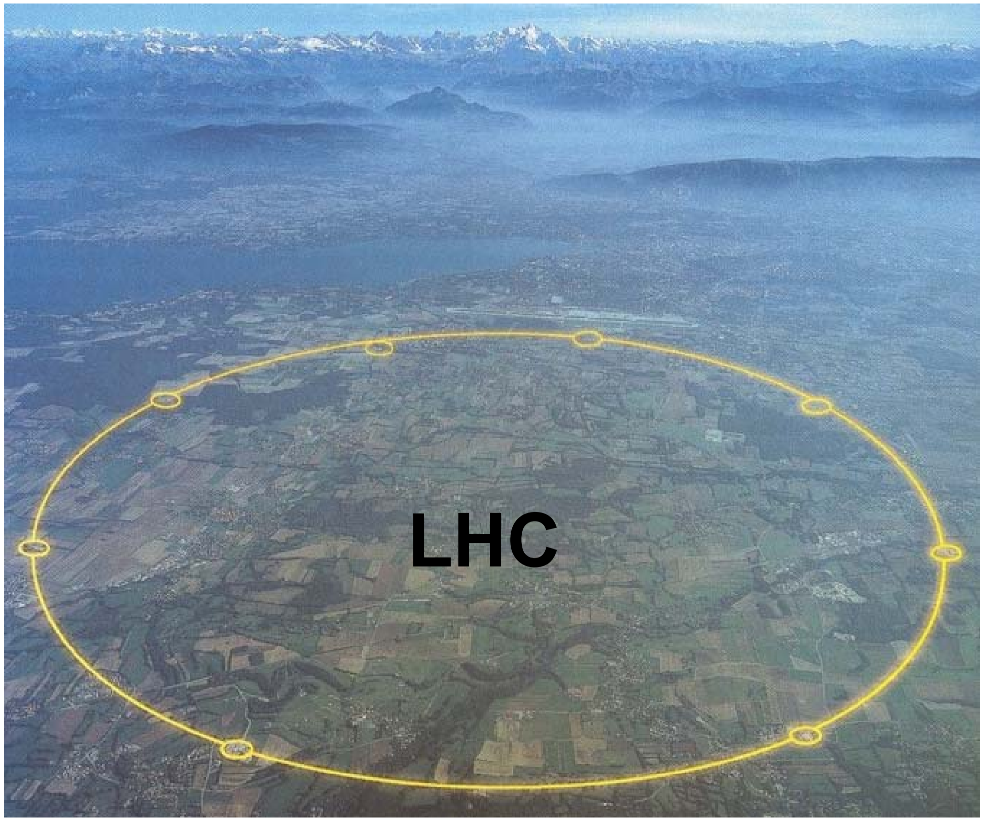
To begin a journey, one needs to start at the beginning



We are here →

← **Our goal: to understand the physics at the Terascale**

The journey is difficult…but fortunately we will have some help on the way…

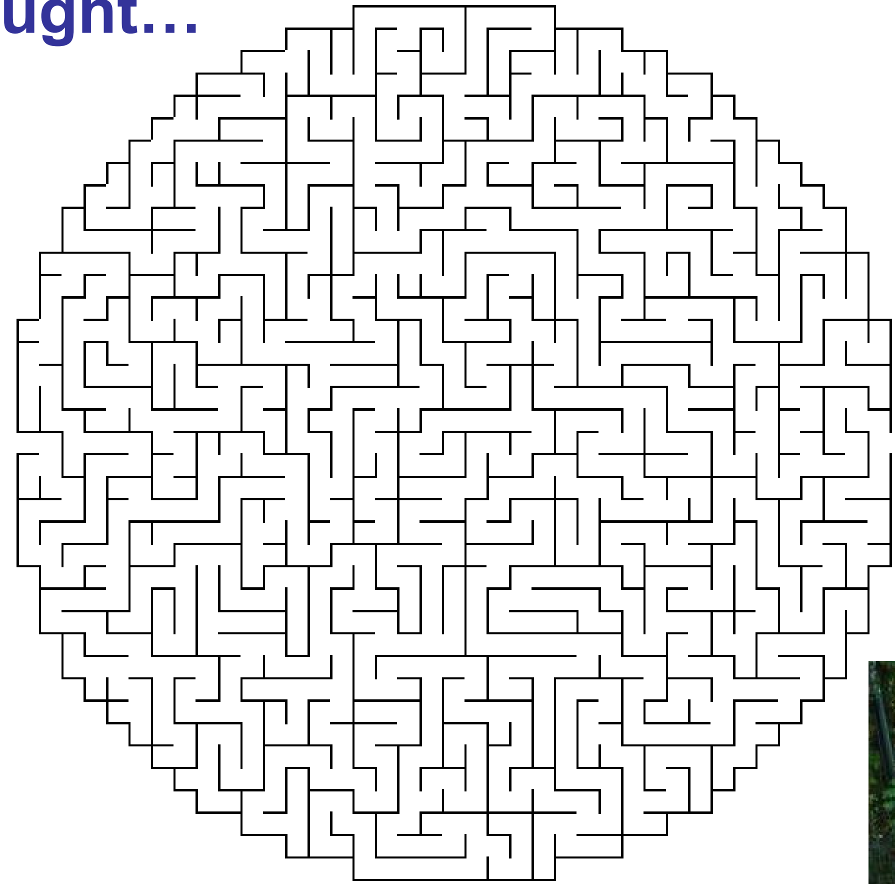


For the next decade or so, the LHC will be pointing us in the right direction….

Although the LHC can tell us many things…

…maybe even that our path is shaped differently than we originally thought…

We are here →



← Our goal: to understand the physics at the terascale

..the LHC can't tell us *everything* we need to know !

To get there, we all agree, we *need* a linear collider…

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Physics interplay of the LHC and the ILC☆

The LHC/ILC Study Group

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doi:10.1016/j.physrep.2005.12.003

But only the data from the LHC can tell what the energy requirements of this machine must be..

If the new physics is accessible below 0.5-1 TeV, the ILC could take us there.

If not, some other machine, e.g., CLIC or a μ-collider may be necessary.

Either way we need to be ready…accelerator research is critical!

Strategies
TeV Scale Lepton Collider

- Assuming LHC reveals the new physics we all anticipate,
  - **We will want complementary lepton collider for precision measurements**

- Time scales dictate vigorously investing toward that goal now
  - **If LHC physics justifies a < 1 TeV machine, ILC can be ready to become construction project as the next big HEP machine (GDE)**
  - **If LHC physics demands a > 1 TeV machine, CLIC may be the answer with a longer time scale, depending on "feasibility" (Tor)**
  - **The alternative muon collider is also a long term possibility, if "FEASIBLE" (Neutrino Sessions)**

So a series of workshops have started last April at Fermilab to address the implications of early LHC data for the future…

http://conferences.fnal.gov/ilc-lhc07

The LHC Early Phase for the ILC

April 12 - 14, 2007

Working Groups

- Working Group I
- Working Group II
- Working Group III
- Working Group IV
- Working Group Convenors
- Home Page

WG I: Only one state, SM-like Higgs boson, at the early stage of LHC
Convenors: Howard Haber, Laura Reina, Alexei Raspereza, Markus Schumacher

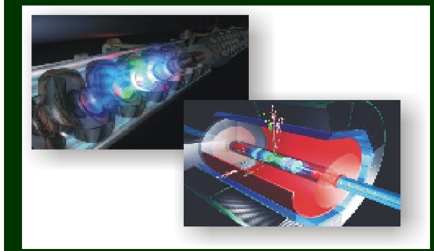
WG II: No Higgs boson at the early stage of the LHC
Convenors: Tim Barklow, Jack Gunion, Wolfgang Kilian

WG III: BSM: Leptonic resonances and Multi-Gauge-Boson signals
Convenors: Tao Han, Sabine Riemann, Tom Rizzo

WG IV: BSM: Missing energy (+nothing, leptons, jets) and everything else
Convenors: Filip Moortgat, Jose Santiago, James Wells, Graham Wilson

Working groups were set up in a signal-based manner…

LHC for ILC: WG3 - Lepton Resonances and Multi-Gauge Bosons



Conveners:

Kevin Black
Tao Han
Sabine Riemman
Thomas Rizzo

Charge

We plan to study three classes of possible scenarios of results observed in the initial LHC runs:
i) the detection of only one state with properties that are compatible with those of a Higgs boson
ii) no experimental evidence for a Higgs boson at the early stage of LHC;
iii) the detection of new states of physics beyond the Standard Model.
For the purpose of this workshop `early LHC data' should be understood as an integrated luminosity of about 10 fb-1.

A wide variety of talks were presented by theorists as well as by LHC & ILC experimenters…

Contribution List | Time Table

Friday, 13 April 2007

10:00		
	[20] **Introduction** by Black KEVIN (Harvard University) (Hornet's Nest (WH8X): 10:30 - 10:40)	slides
	[21] **Resonances in Universal Extra Dimensions** by Dr. Kyoungchul KONG (FNAL) (Hornet's Nest (WH8X): 10:40 - 11:00)	slides
11:00	[22] **Discoveries through ILC precision measurements** by Sabine RIEMANN (Institut fuer Hochenergiephysik Zeuthen) (Hornet's Nest (WH8X): 11:00 - 11:20)	slides
	[23] **Using top quarks to probe the Randall-Sundrum model** by Dr. Lillie BENJAMIN (University of Chicago) (Hornet's Nest (WH8X): 11:20 - 11:40)	slides

Contribution List | Time Table

Friday, 13 April 2007

13:00		
	[24] **Search for Extra Dimensions and Leptoquarks in Early LHC data** by Greg LANDSBERG (Brown University) (Hornet's Nest (WH8X): 13:30 - 13:50)	slides
14:00	[25] **New (and Not So New) Z' Gauge Bosons and the LHC/ILC Connection** by Dr. Tim TAIT (ANL) (Hornet's Nest (WH8X): 13:50 - 14:10)	slides
	[26] **New and old gauge boson discoveries in early LHC data** by Gustaaf BROOIJMANS (Physics Dept., Pupin Physics Lab. - Columbia University) (Hornet's Nest (WH8X): 14:10 - 14:30)	slides
	[27] **Using object correlations to extract new physics from the LHC** by Prof. Scott THOMAS (Rutgers University) (Hornet's Nest (WH8X): 14:30 - 14:50)	
15:00	[28] **Discussion Session** by Dr. Thomas RIZZO (SLAC) (Hornet's Nest (WH8X): 14:50 - 15:30)	slides

This series will soon continue…

``The LHC Early Phase--Shaping the Future of Terascale Exploration'' will take place at CERN, Summer 2008

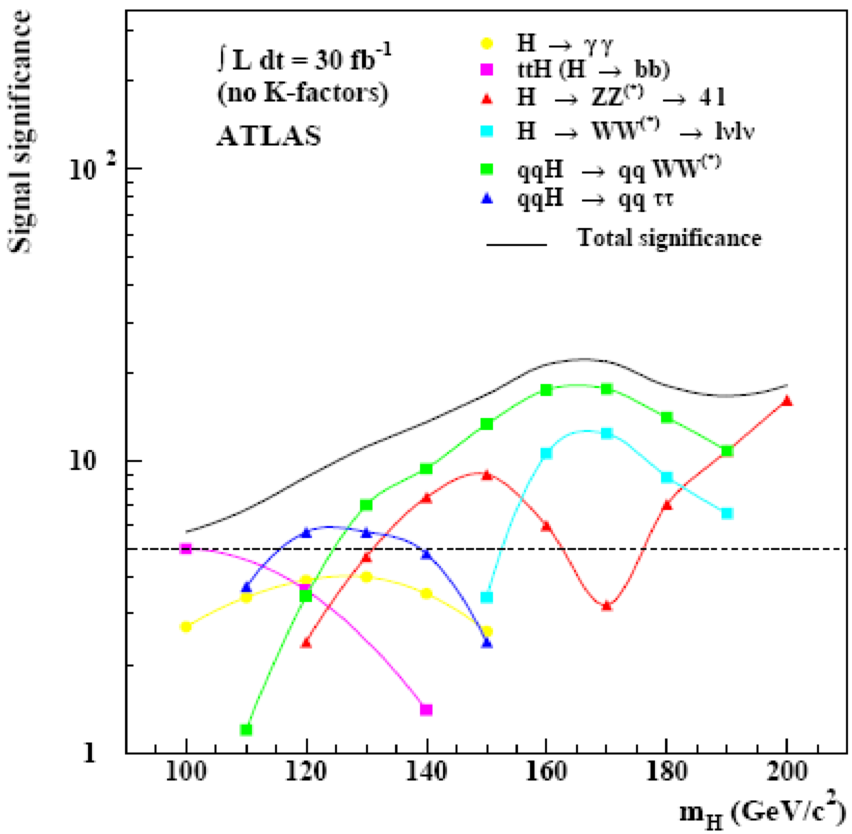
``With the knowledge of about 10 fb^-1 of data analyzed at the LHC, should we go ahead in constructing a new major facility at the high-energy frontier -- and if yes, which one and with what specifications -- or should we wait?

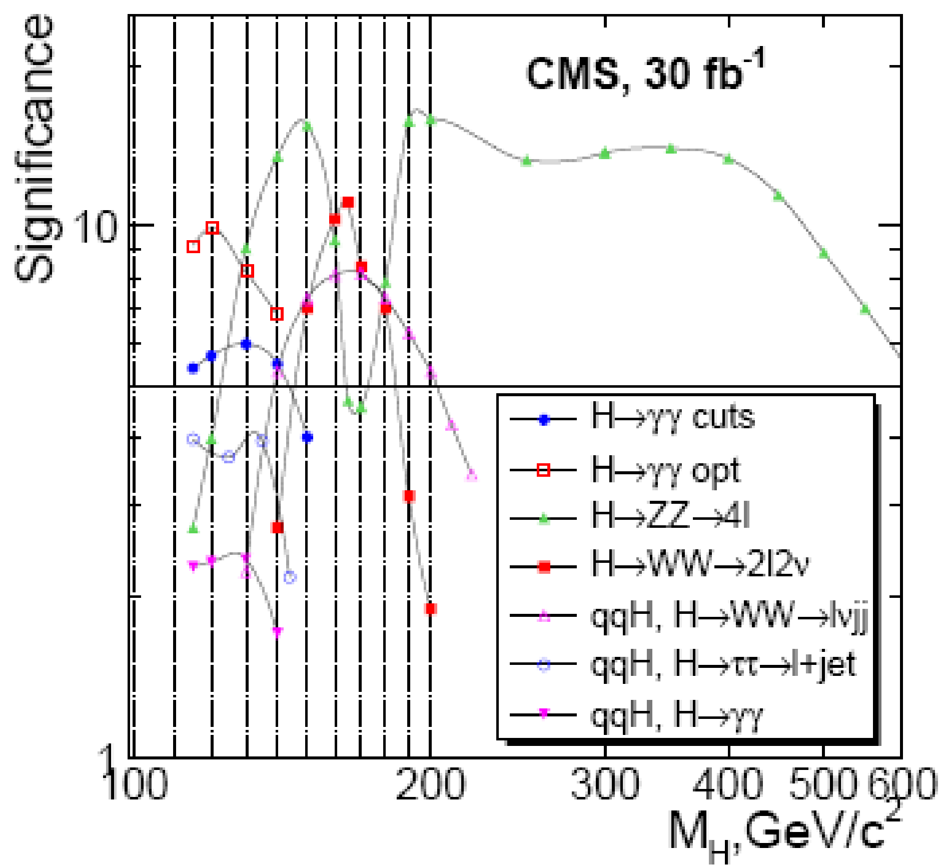
What are the *critical* measurements necessary to make this decision????''

These are highly non-trivial questions and input from all is welcome!

Let's turn to two sample physics scenarios demonstrating the LHC/LC interconnection...

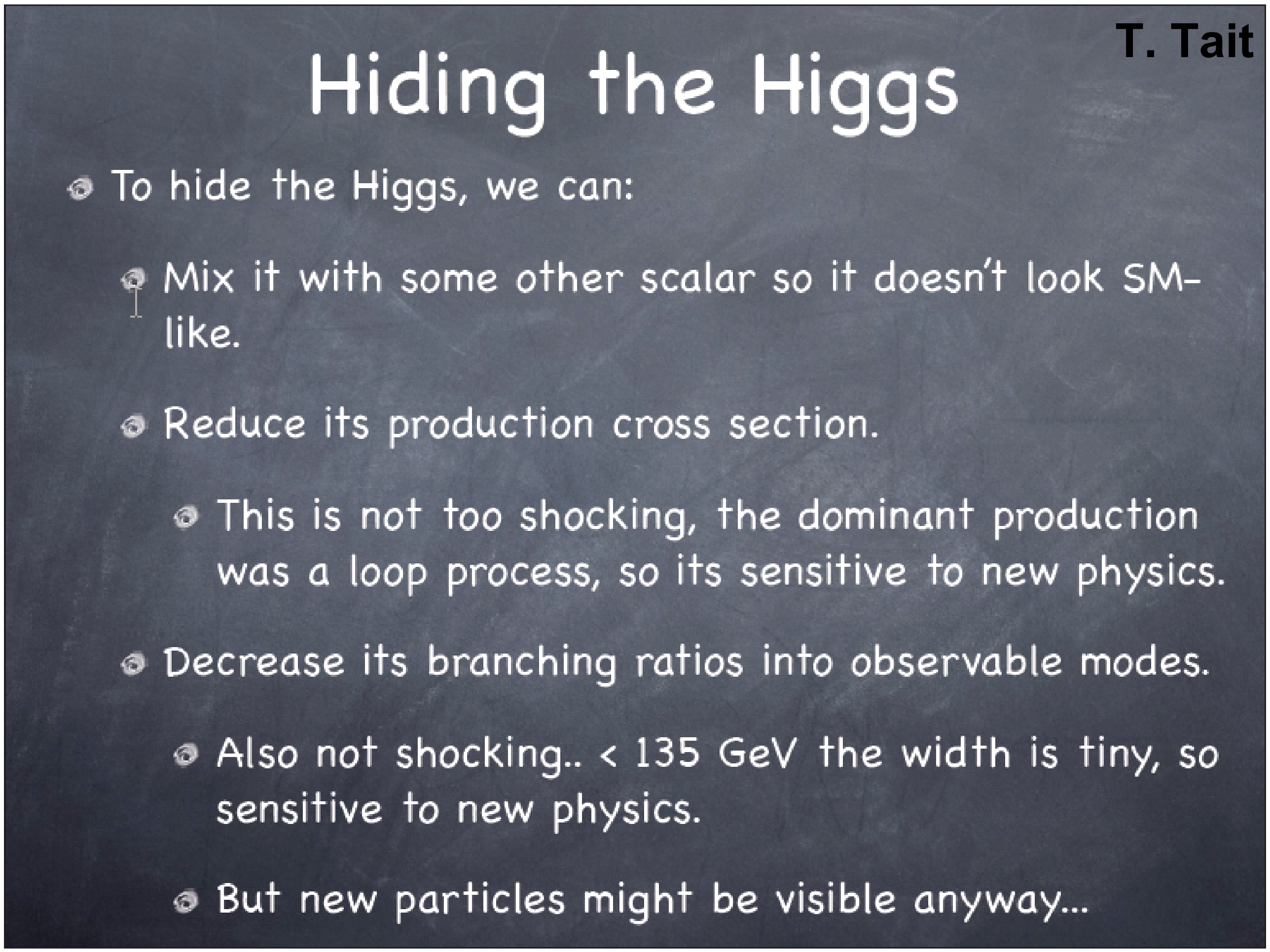
→ **Studies show that if there is a SM/MSSM-like Higgs boson it will be found at the LHC…**





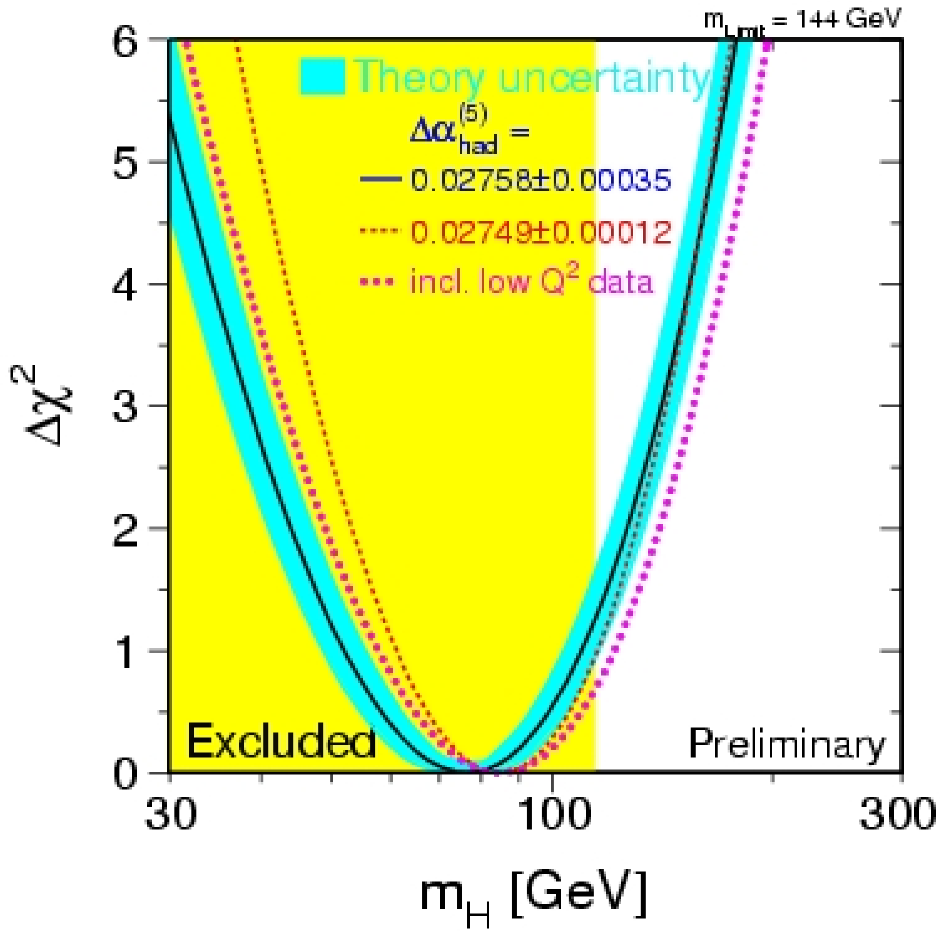
But what if no Higgs OR strong WW scattering is seen? Could the Higgs have somehow been missed…not only at the LHC but also at LEP & the Tevatron?? It would need to have non-standard properties..

There are several possibilities…#



See, e.g., T. Tait & C. Wagner at the Fermilab LHC/ILC meeting

As we all know, there is some indication that the Higgs is light which is consistent with the usual SUSY picture…



LEPEWWG

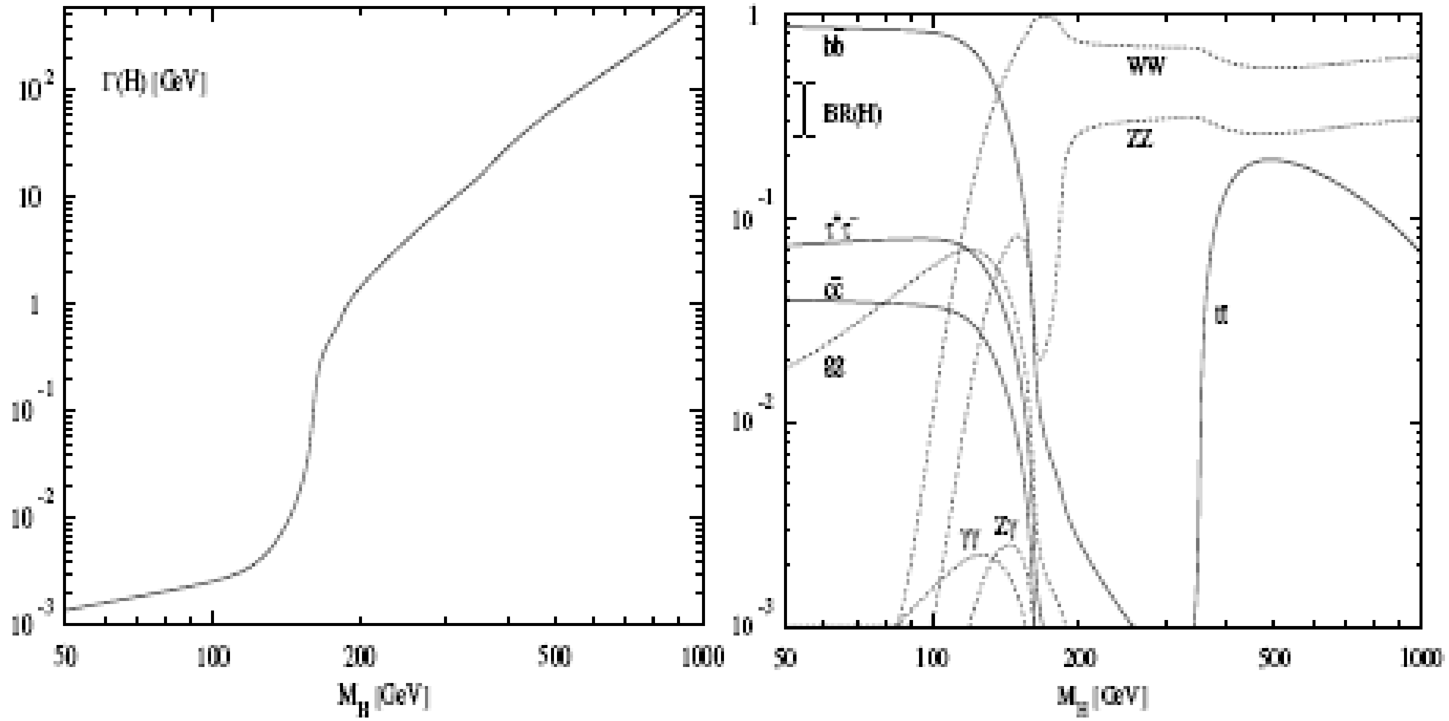
But one observes that the SM-like Higgs is quite narrow for masses less than ~130-140 GeV…

Thinking within the SUSY context….

Hiding the SUSY Higgs

- Zeroth order: m_h < 130 GeV : The MSSM is covered!
  - So no Higgs means no MSSM.
- First order: The MSSM could allow for a new decay mode like H -> super-partners. (More on that later).
  - We could also consider the two Higgs doublet model effects, but that probably won't change our conclusions.
- Second order: It could be SUSY, but it might not be the minimal model. The strong assumptions that made the MSSM minimal were actually in the Higgs sector, so it wouldn't be too shocking if that was where the model might break down.

T. Tait



For example: Can there exist states into which the Higgs can dominantly decay, substantially weakening present constraints & allowing the Higgs to avoid easy detection at LHC?? Recall b-quark Yukawa's are tiny!

A SUSY/MSSM possibility, $H \to \chi\chi$, is unlikely in the conventional DM, bino-like LSP scenario. But we can go beyond MSSM to the NMSSM, which has other nice properties, where a completely new scenario opens up due to the existence of a light, singlet CP-odd scalar, `a_1'.

NMSSM Case

- Higgs spectrum includes three CP-even scalars and two CP-odd scalars
- A light, mainly singlet CP-odd scalar may fulfill all required properties, namely $\chi \equiv a_1$ →2b's
- If its mass is larger than $2\ m_\tau$ but smaller than $2\ m_b$ dominant decay mode

$$h \to a_1 a_1 \to 4\ \tau' s$$

Dermisek, Gunion
Chang, Fox, Weiner
Graham, Pierce, Wacker

- Such a Higgs may have escaped detection at LEP. Branching ratio of decay into bottom quarks reduced. If of order 0.1 may explain LEP small excess at 100 GeV **(The LEPII limit is then only ~90 GeV)**
- Detectability at the LHC difficult (see Ellwanger et al, **hep-ph/0503203; T.Han et al., in preparation)** **(Les Houches Higgs report)**
- Possible signal at the Tevatron with 6 fb-1 ? (see Graham et al, **hep-ph/0605162)**

Reduced fine-tuning can occur in the NMSSM while also solving the mu-problem

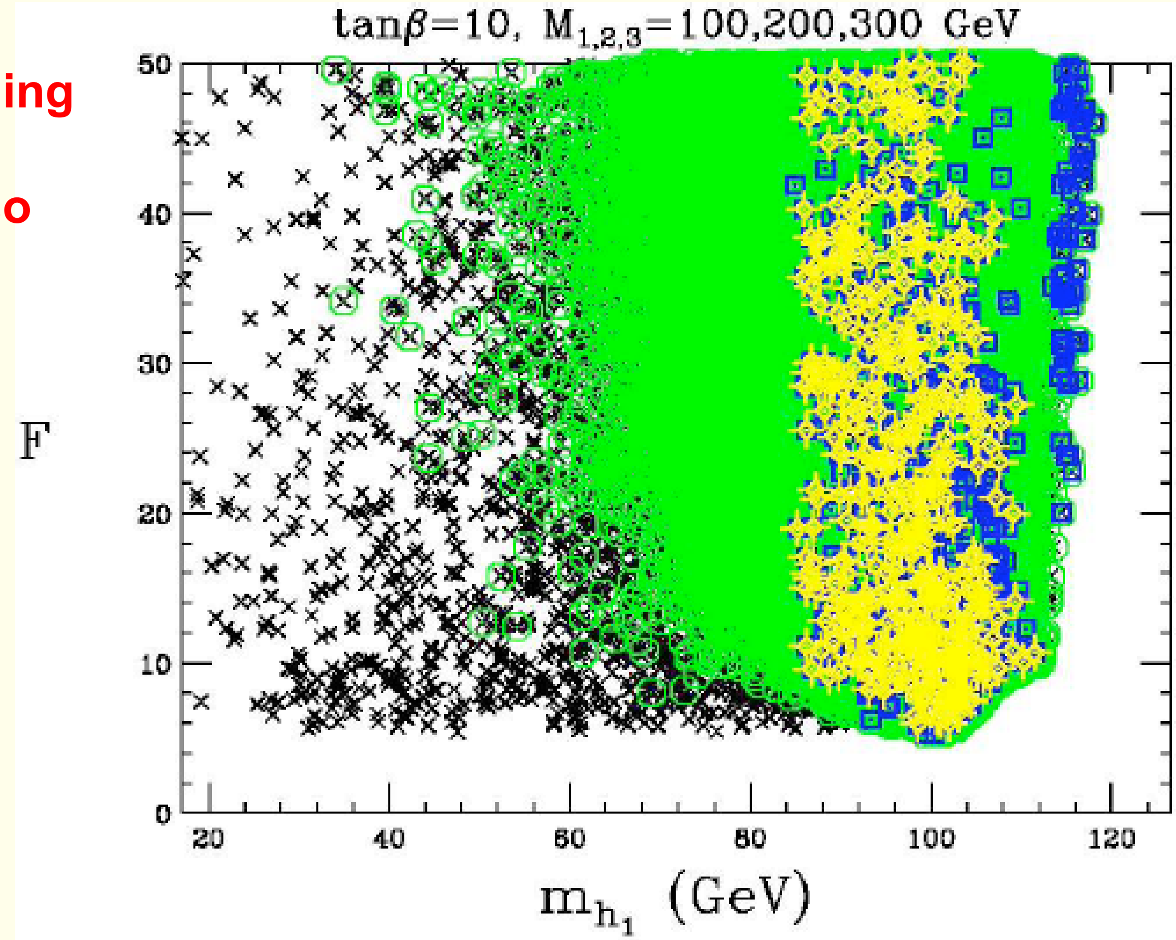


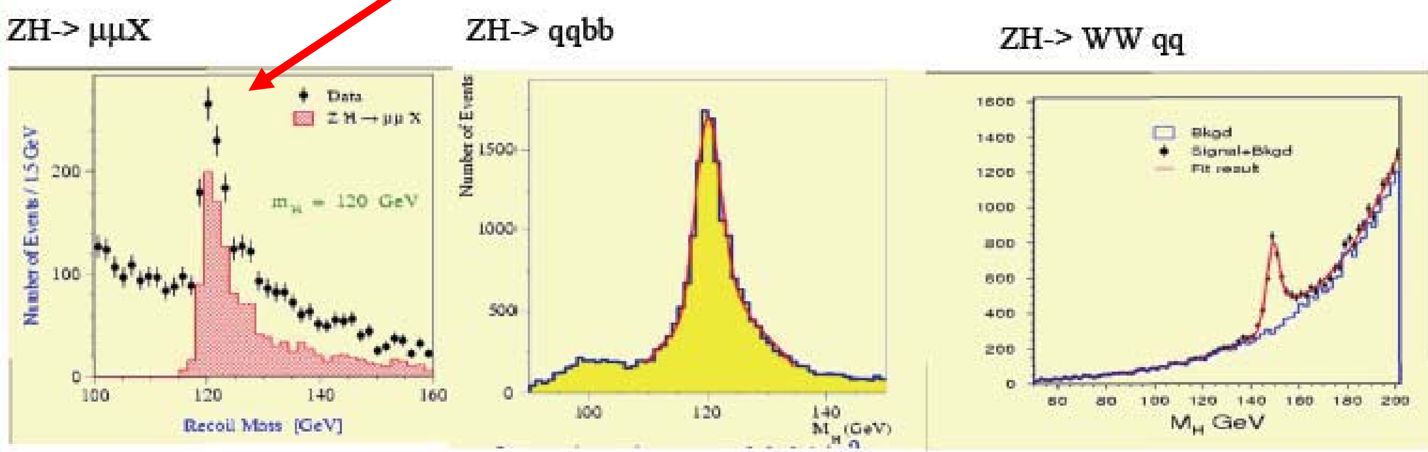
Figure 9: *F vs. m_{h^0} in the NMSSM for $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Large yellow crosses are fully consistent with LEP constraints. See earlier Dermisek + JFG refs.*

– A large majority of the yellow crosses have $B(h_1 \to b\bar{b}) \sim 0.1$ or so

Of course at the ILC, the recoil technique can find the Higgs in this mass range *no matter how* the Higgs boson decays...

Higgs at the ILC

Determination of mass and width of the Higgs:
most favorable (light Higgs) ee->Z->ZH



Clear signals in many channels:

mass		width:
M(Higgs)	ΔM	
120 GeV	40 MeV	to 5-10%
150 GeV	70 MeV	
180 GeV	90 MeV	

General SUSY Study

Another analysis[#] , the beginning of a long term project whose ultimate goals include a large scale survey of the MSSM parameter space for the LHC and future lepton colliders:

First Round Goals:

- Study in as realistic a way as possible the capability of the ILC to examine the physics of a large number of random points (242) in MSSM parameter space. Such a large-scale study of points *not* tied to a specific model, e.g., MSUGRA, has never been done.
  → We don't know how SUSY is broken so an analysis which is as model-independent as possible is extremely valuable

- Examine the capability of the ILC to distinguish (162) pairs of points in parameter space which lead to essentially identical, so called `degenerate', signatures at the LHC.

[#]C.F. Berger, J.S. Gainer, J.L Hewett, B. Lillie and TGR 0711.1374 & 0712.2965

How :

- Pick one of the models[@]. Simulate SUSY signal events with PYTHIA and CompHEP feeding in Whizard/GuineaPig generated beam spectrum for ILC

- Add the SM backgrounds: all 2 -> 2, 4 & 6 ($e^+ e^-$, γe & $\gamma\gamma$) full matrix element processes (1016) produced by Tim Barklow

- Pipe this all through the java-based SiD fast detect simulation org.lcsim (vanilla version)

- Assuming E_{cm}=500 GeV, L=500 fb^{-1} with P_{e-} =80%, analyze after appropriate generalized, i.e., *model-independent* cuts are applied.. this is highly non-trivial requiring many iterations

→→ ADD lots (and lots) of time…& >1 CPU century

[@] To connect w/ LHC we use the models of Arkani-Hamed etal., hep-ph/0512190

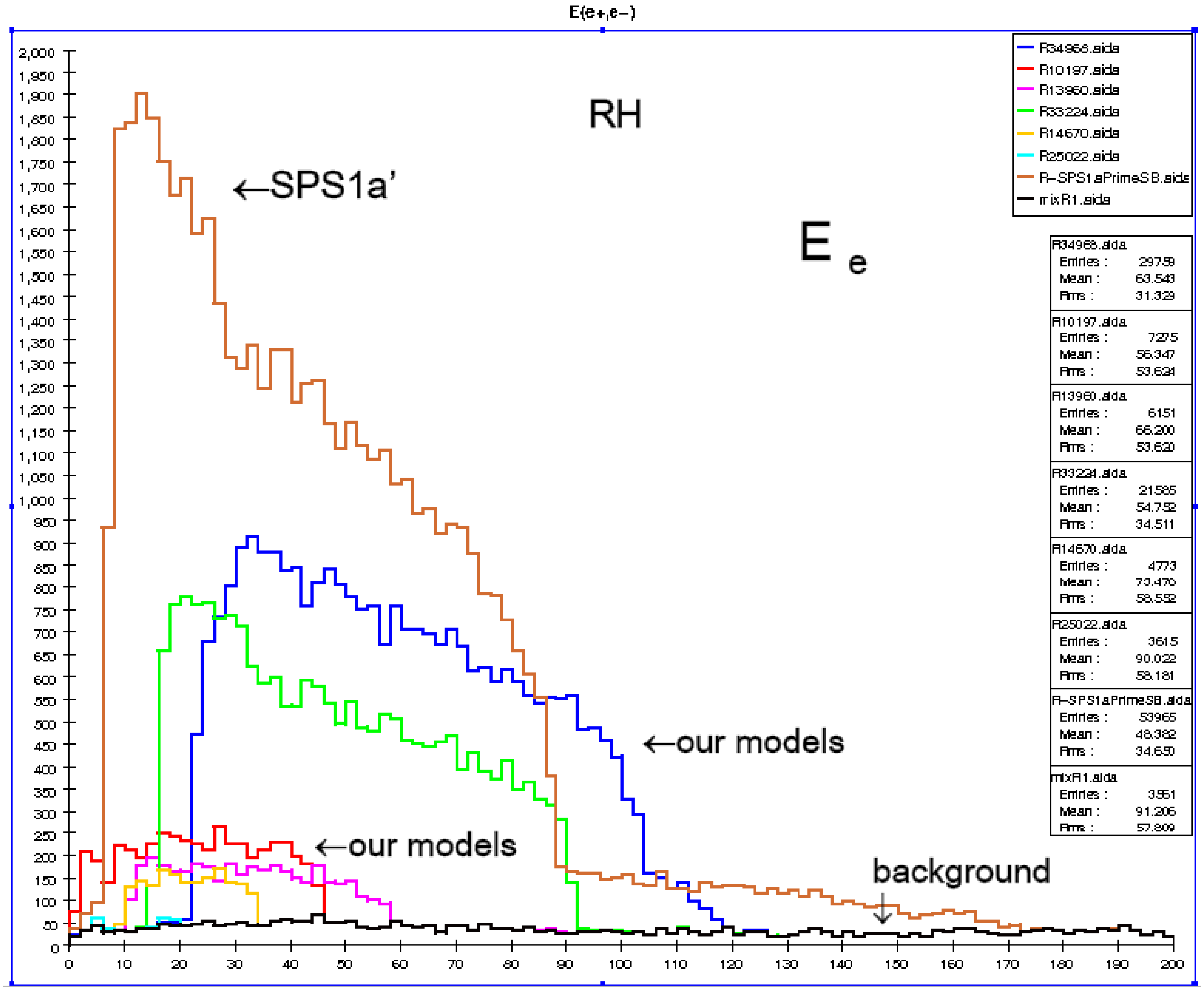
Kinematic Accessibility (≠ Observability)

Final State	500 GeV	1 TeV
$\tilde{e}_L^+\tilde{e}_L^-$	9	82
$\tilde{e}_R^+\tilde{e}_R^-$	15	86
$\tilde{e}_L^\pm\tilde{e}_R^\mp$	2	61
$\tilde{\mu}_L^+\tilde{\mu}_L^-$	9	82
$\tilde{\mu}_R^+\tilde{\mu}_R^-$	15	86
Any selectron or smuon	22	137
$\tilde{\tau}_1^+\tilde{\tau}_1^-$	28	145
$\tilde{\tau}_2^+\tilde{\tau}_2^-$	1	23
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$	4	61
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$	11	83
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$	18	83
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	53	92
Any charged sparticle	85	224
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$	7	33
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	180	236
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ only	91	0
$\tilde{\chi}_1^0 + \tilde{\nu}$ only	5	0
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	46	178
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	10	83
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	38	91
$\tilde{\chi}_2^0\tilde{\chi}_3^0$	4	41
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	2	23
Nothing	61	3

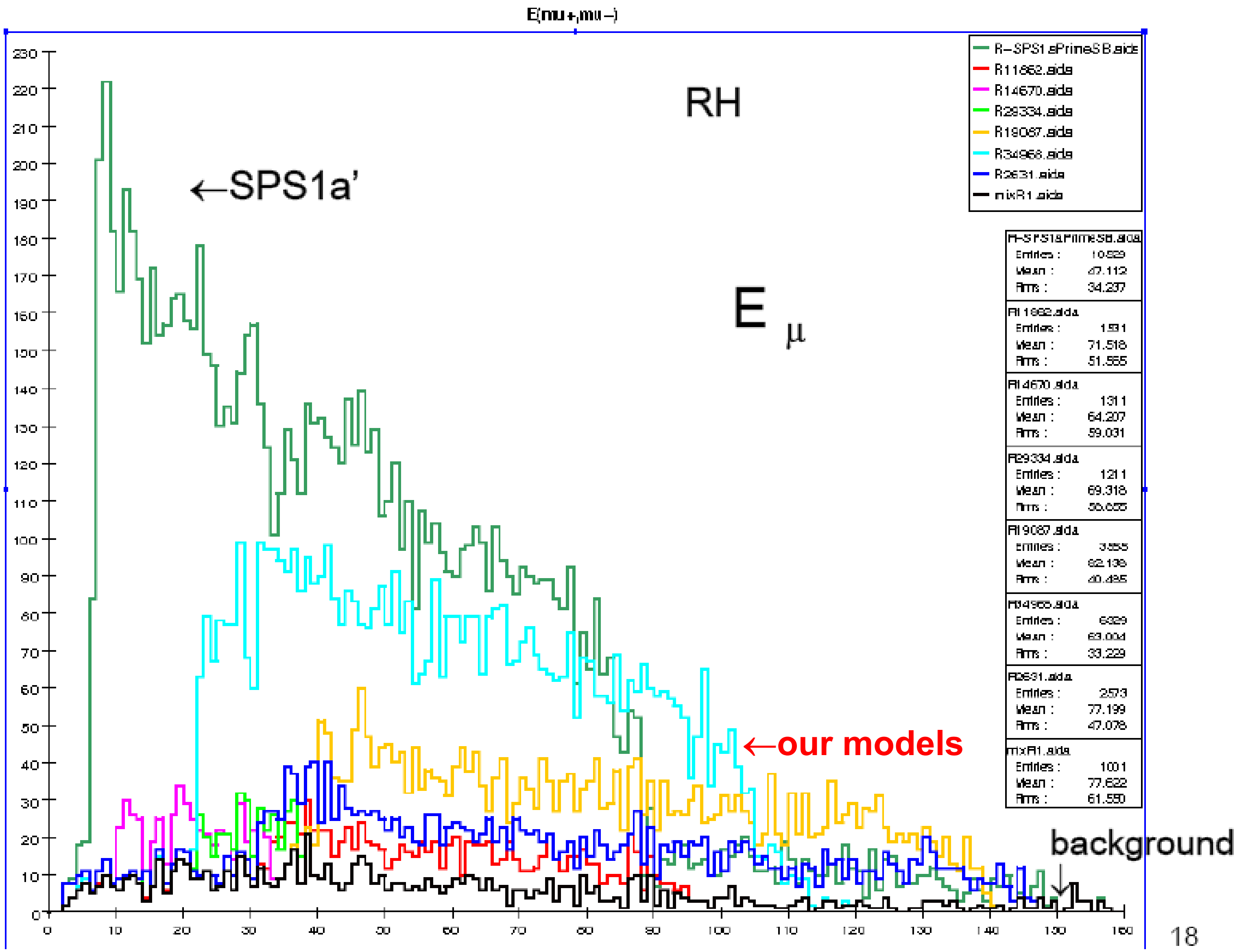
Out of 242 models at 500 GeV, 61+91+5=157/242 ~ 65% have no trivially observable signal at the ILC…the percentage will be a bit higher after some further investigation as discussed later. But this fraction is *much* smaller at 1 TeV, ~ 7%.

This is a strong argument for 1 TeV as soon as possible!

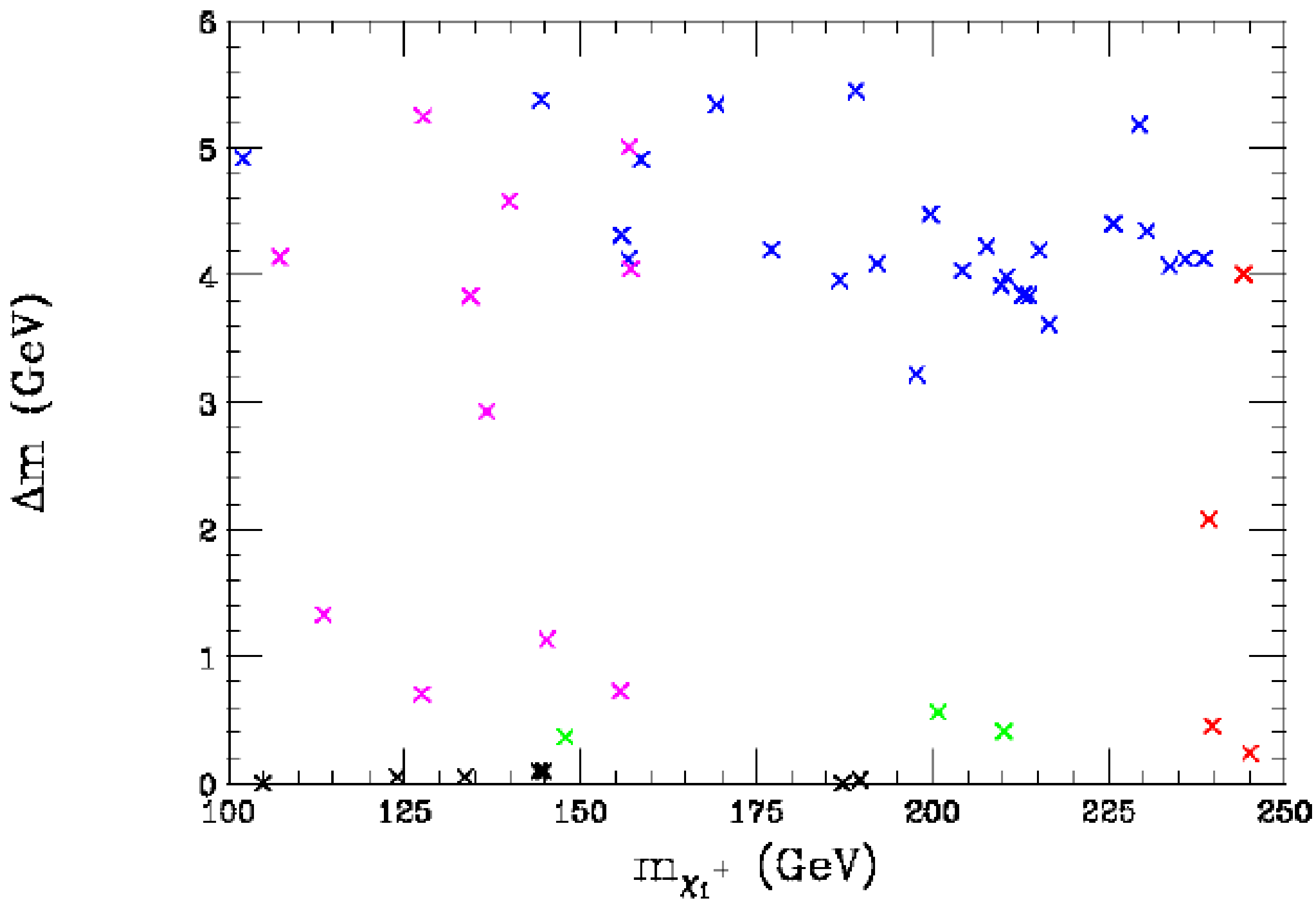
Selectron production @ 500 GeV



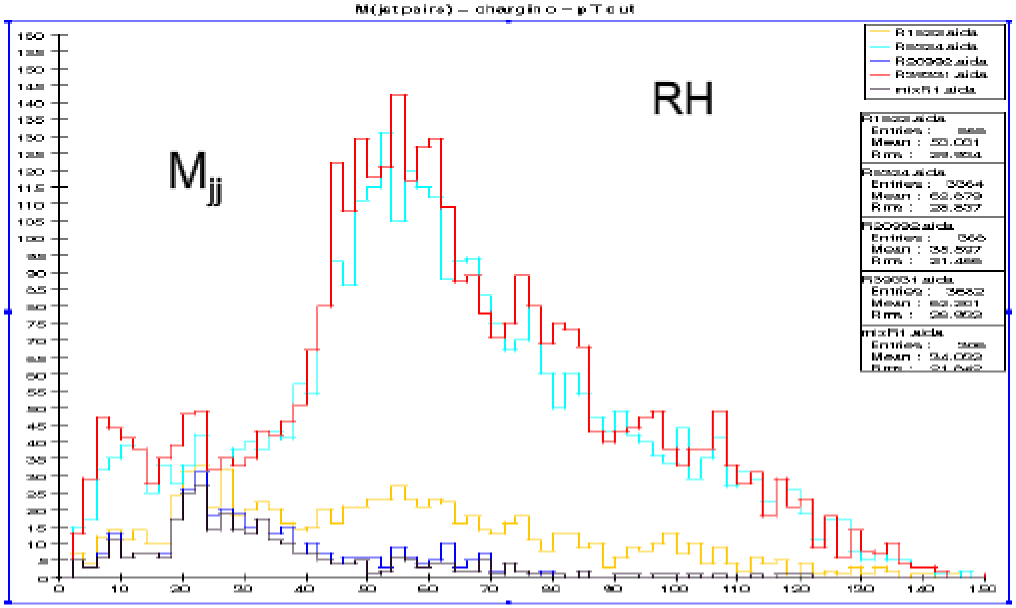
Smuon Production @ 500 GeV

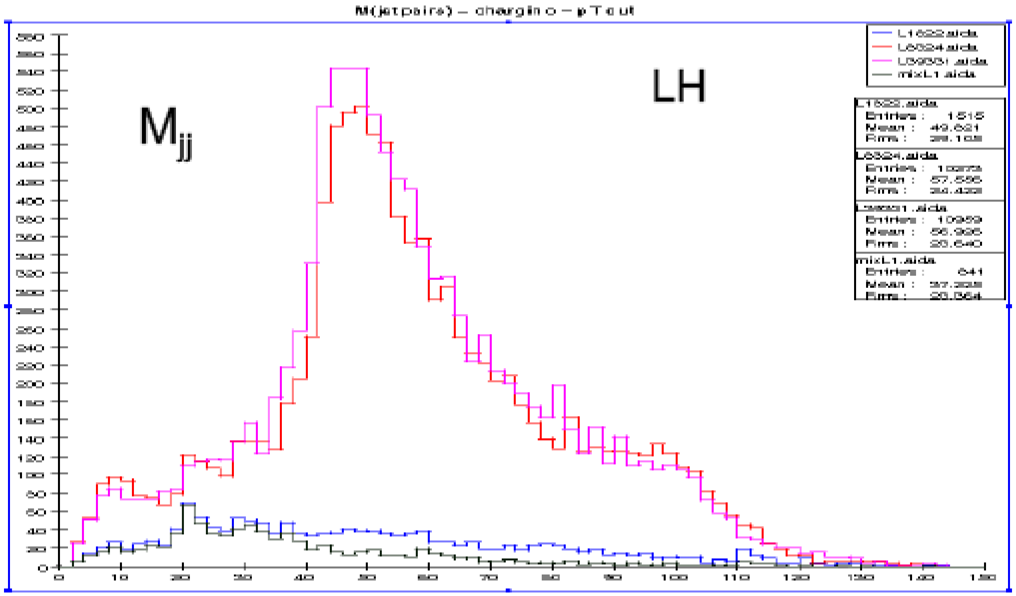


Charginos are seen in many different analyses…



Green = radiative only
Black = stable only
Blue = off-shell W
Magenta = off-shell W & radiative
Red = missed





Chargino 4-jet+Missing Energy Analysis

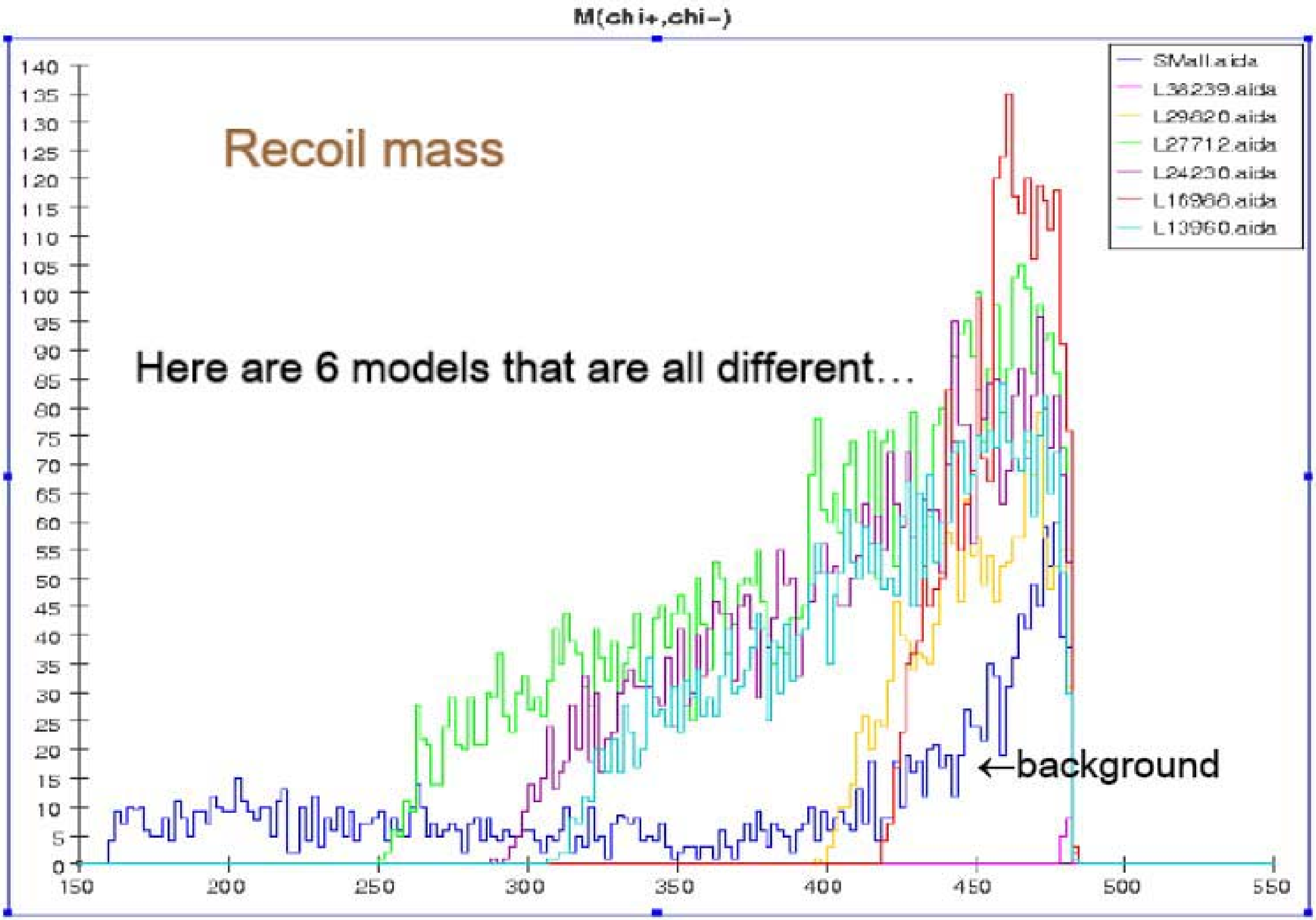
AFTER p_T CUT…

Much cleaner!

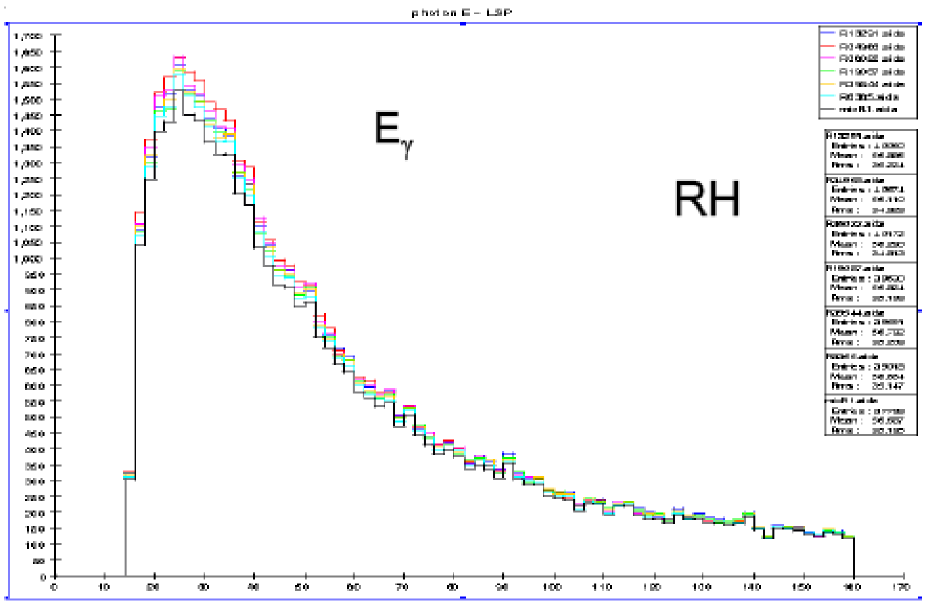
2 real + 2 fake models

Seeing a signal does not mean discovery of the particle being searched for…

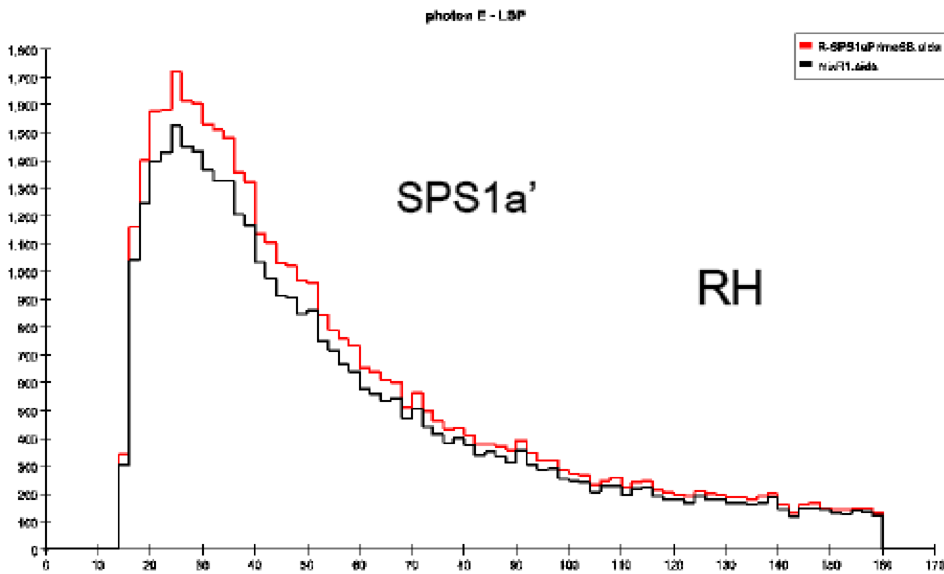
Small Δm ~ 1 GeV, Charginos: soft hadrons + photon tag



Photon + Missing Energy Analysis



Photon tagging is quite efficient.. we see this final state for 17/242 models. Sneutrino pollution is important in some cases.



S/B can be substantially increased here by using positron polarization.

SPS1a' produces a rate far larger than all our models but is contaminated by sneutrino production

After all this, our first goal is collect our results and determine just how many models lead to a visible signal at the 500 GeV ILC…

Particle	Number Visible
$\tilde{e}_L$	8/9
$\tilde{e}_R$	12/15
$\tilde{\mu}_L$	9/9
$\tilde{\mu}_R$	12/15
$\tilde{\tau}_{1,2}$	21/28
$\tilde{\nu}_{e,\mu}$	0/11
$\tilde{\nu}_\tau$	0/18
$\tilde{\chi}_1^\pm$	49/53
$\tilde{\chi}_1^0$	17/180
$\tilde{\chi}_2^0$	5/46

We do this by performing a likelihood ratio analysis based on Poisson statistics and require a significance greater than 5 to claim observability.

R=L(S+B1,B2)/L(B1,B2)

Sig=(2 log R)$^{1/2}$ > 5

This is done individually for each of our analysis histograms…

The Final Score

Visibility: We see

78/85 models w/ at least one charged sparticle
17/96 models w/ neutral sparticles only
82/161 models w/ any accessible sparticle
82/242 of all models

Distinguishability:

57(63)/72 pairs w/ at least one charged sparticle at 5(3)σ
0/90 pairs where `neutral only' models are compared
57(63)/162 of all pairs at 5(3)σ

Summary

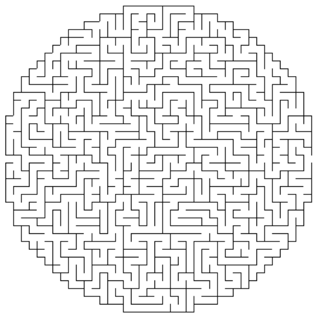
The LHC finally turns on *this year* and opens up the Terascale for exploration… though we can speculate, what it will find is (a known!) unknown… but we should prepare to be surprised.

It is clear (to me) that, more than likely, no matter what is found at the LHC there will be an important future need for a LC, operating at some $\sqrt{s}$, to elucidate these discoveries. The number of examples are legion.

Of course to solidify this claim to others we need to wait until at least the LHC first round data becomes available in ~2010 (????)

We should think deeply about which measurements are necessary to make this choice firm.…

Let's have the *audacity* to work as hard as possible to keep our eyes on the physics of the Terascale & let the data point the way ahead.



BACKUP SLIDES

A Few Comments on AKTW Model Generation

- There are certainly other ways one could have chosen to generate a set of models: parameter ranges, prior `tilts', etc... We are studying these alternatives now.

- These models satisfy the LEPII constraints as well as the Tevatron naïve squark and gluino bounds but not, e.g., WMAP, g-2, $b \rightarrow s\gamma$, direct dark matter searches, Higgs search constraints, precision electroweak data, etc…

- To be specific and to deal with LHC distinguishability issues we will use these models for our study.

- We are now making our own *much* larger model set satisfying all the known constraints. This requires *many* different codes to talk to each other & lots of time for code testing & development & for actual model generation.

- Recall there is major filtering required: generate 10^8 models to get a few thousand (??)

LHC Inverse Problem

→ Generate blind SUSY data and map it back to parameters in the fundamental Lagrangian

- Generated *many* models within MSSM for 10 fb^{-1} @ LHC (Pythia 6.324). Here a `model' = a particular parameter space point…
- For 15 parameters:

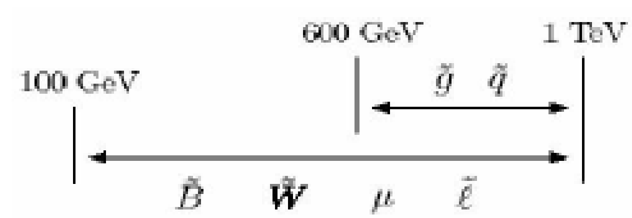
Inos : $M_1,\ M_2,\ M_3,\ \mu$

Squarks : $m_{Q_{1,2}},\ m_{U_{1,2}},\ m_{D_{1,2}},\ m_{Q_3},\ m_{\tilde{t}_R},\ m_{\tilde{b}_R}$ + tan β

Sleptons : $m_{L_{1,2}},\ m_{E_{1,2}},\ m_{L_3},\ m_{\tilde{\tau}_R}$

w/ flat priors…

Within the constraints:



$2 < \tan\beta < 50$

…and keeping the 1st two scalar generations degenerate

- Used ~1800 LHC MSSM `Observables'
  - Rate counting, kinematic distributions,…
- NO SM Backgrounds! (so the REAL world is far worse!)

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

ANALYSES :

To cover all the possibilities many simultaneous analyses are required:

(i) Selectron/smuon/stau pairs → SM analogues + missing E

(ii) Radiative neutralino (LSP) pairs using tagging γ's

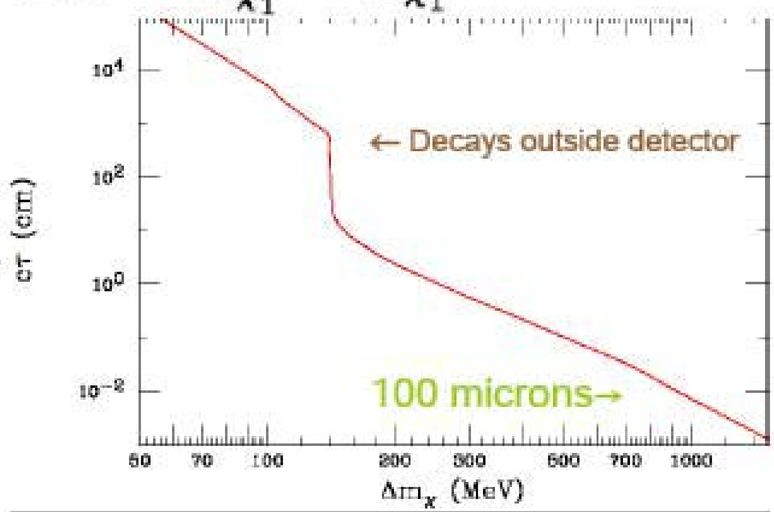
(iii) $\chi_2^0 \chi_1^0$ → missing E + Z/H (jj /l^+l^-)

(iv) Sneutrino pairs → (4jets+ lepton pair/6jets) + missing E , +....

(v) $\chi_1^+ \chi_1^-$: analyses will depend on the

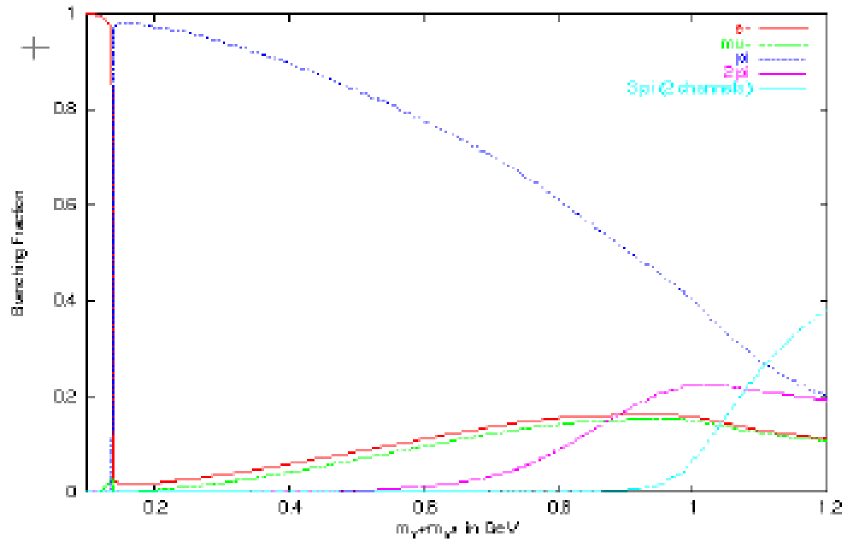
Critical parameter for charginos: $\Delta m = m_{\chi_1^\pm} - m_{\chi_1^0}$

(a) → if $\Delta m < m_\pi$ we need to do a stable charged particle search ..



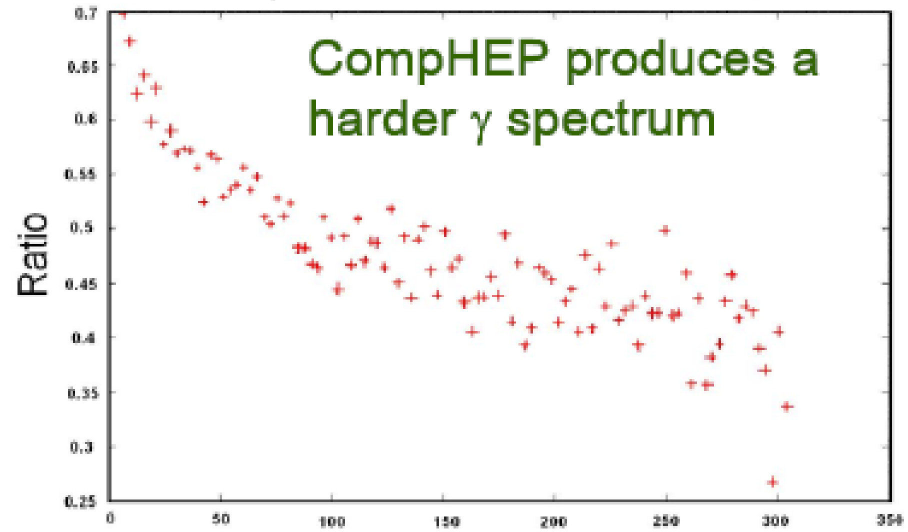
Analyses Continued :

(b) When $m_\pi < \Delta m < \sim 1$ GeV the chargino decays to soft hadrons which we tag by a hard photon. A full matrix element calculation is important here...



Δm

PYTHIA σ / CompHEP σ for associated hard γ production



pT(γ) in GeV

(c) For larger Δm, we look for chargino decays through real or virtual W's or through smuons which lead to (4j/jj+μ/μμ)+ missing E final states. There are multiple sub-analyses here depending on the specific final state and W virtuality.

Now for some results…..

All ee,γe,γγ → 2,4,6 processes w/ full matrix elements included, e.g.,

Table 12:

Process Class	Initial state	Final state
44(a)	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; u \; \bar{u} \; \mu^- \; \mu^+$
	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; u \; \bar{u} \; \tau^- \; \tau^+$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; u \; \bar{u} \; e^- \; e^+$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; u \; \bar{u} \; \tau^- \; \tau^+$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; u \; \bar{u} \; e^- \; e^+$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; u \; \bar{u} \; \mu^- \; \mu^+$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_e \; e^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_e \; e^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_e \; e^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_\mu \; \mu^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_\mu \; \mu^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_\mu \; \mu^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_\tau \; \tau^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_\tau \; \tau^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$u \; \bar{u} \; \nu_\tau \; \tau^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; \mu^- \; \mu^+ \; d \; \bar{d}$
	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; \tau^- \; \tau^+ \; d \; \bar{d}$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; e^- \; e^+ \; d \; \bar{d}$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; \tau^- \; \tau^+ \; d \; \bar{d}$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; e^- \; e^+ \; d \; \bar{d}$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; \mu^- \; \mu^+ \; d \; \bar{d}$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_e \; e^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_e \; e^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_e \; e^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_\mu \; \mu^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_\mu \; \mu^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_\mu \; \mu^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_\tau \; \tau^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_\tau \; \tau^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$d \; \bar{d} \; \nu_\tau \; \tau^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; \mu^- \; \mu^+ \; s \; \bar{s}$
	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; \tau^- \; \tau^+ \; s \; \bar{s}$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; e^- \; e^+ \; s \; \bar{s}$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; \tau^- \; \tau^+ \; s \; \bar{s}$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; e^- \; e^+ \; s \; \bar{s}$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; \mu^- \; \mu^+ \; s \; \bar{s}$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_e \; e^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_e \; e^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_e \; e^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_\mu \; \mu^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_\mu \; \mu^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_\mu \; \mu^+ \; \tau^- \; \bar{\nu}_\tau$

Table 13:

Process Class	Initial state	Final state
44(b)	$e^- \; e^+$	$s \; \bar{s} \; \nu_\tau \; \tau^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_\tau \; \tau^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$s \; \bar{s} \; \nu_\tau \; \tau^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; c \; \bar{c} \; \mu^- \; \mu^+$
	$e^- \; e^+$	$\nu_e \; \bar{\nu}_e \; c \; \bar{c} \; \tau^- \; \tau^+$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; c \; \bar{c} \; e^- \; e^+$
	$e^- \; e^+$	$\nu_\mu \; \bar{\nu}_\mu \; c \; \bar{c} \; \tau^- \; \tau^+$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; c \; \bar{c} \; e^- \; e^+$
	$e^- \; e^+$	$\nu_\tau \; \bar{\nu}_\tau \; c \; \bar{c} \; \mu^- \; \mu^+$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_e \; e^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_e \; e^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_e \; e^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_\mu \; \mu^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_\mu \; \mu^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_\mu \; \mu^+ \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_\tau \; \tau^+ \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_\tau \; \tau^+ \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$c \; \bar{c} \; \nu_\tau \; \tau^+ \; \tau^- \; \bar{\nu}_\tau$
45	$e^- \; e^+$	$b \; \bar{b} \; u \; \bar{d} \; s \; \bar{c}$
	$e^- \; e^+$	$b \; \bar{b} \; c \; \bar{s} \; d \; \bar{u}$
46	$e^- \; e^+$	$b \; \bar{b} \; u \; \bar{d} \; d \; \bar{u}$
	$e^- \; e^+$	$b \; \bar{b} \; c \; \bar{s} \; s \; \bar{c}$
47	$e^- \; e^+$	$b \; \bar{b} \; u \; \bar{d} \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$b \; \bar{b} \; u \; \bar{d} \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$b \; \bar{b} \; u \; \bar{d} \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$b \; \bar{b} \; c \; \bar{s} \; e^- \; \bar{\nu}_e$
	$e^- \; e^+$	$b \; \bar{b} \; c \; \bar{s} \; \mu^- \; \bar{\nu}_\mu$
	$e^- \; e^+$	$b \; \bar{b} \; c \; \bar{s} \; \tau^- \; \bar{\nu}_\tau$
	$e^- \; e^+$	$b \; \bar{b} \; \nu_e \; e^+ \; d \; \bar{u}$
	$e^- \; e^+$	$b \; \bar{b} \; \nu_e \; e^+ \; s \; \bar{c}$
	$e^- \; e^+$	$b \; \bar{b} \; \nu_\mu \; \mu^+ \; d \; \bar{u}$
	$e^- \; e^+$	$b \; \bar{b} \; \nu_\mu \; \mu^+ \; s \; \bar{c}$
	$e^- \; e^+$	$b \; \bar{b} \; \nu_\tau \; \tau^+ \; d \; \bar{u}$
	$e^- \; e^+$	$b \; \bar{b} \; \nu_\tau \; \tau^+ \; s \; \bar{c}$