Rethinking the LHC - ILC Connection

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Linear Collider
Workshop of the Americas
September 2009

Within two months, beams will be injected into the LHC again, and the LHC experimental program will begin.

If the models of new physics that we are discussing at this meeting are correct, the first signs of that new physics will be discovered at the LHC.

The discoveries could begin as early as the fall of 2010.

When physics beyond the Standard Model becomes a reality, it will be much clearer to our colleagues and to the public what the ILC is for and why is it needed.

This will be the moment when the ILC is approved for construction - or not.

We need to begin thinking now about the precise form that our arguments for the ILC will take.

Last fall, Sakue Yamada constituted a Physics Panel in the LOI Common Task Groups to discuss this issue and other issues connected to ILC physics (e.g. detector benchmarking)

The current members of this Panel are:

Tim Barklow (SLAC)
Stewart Boogert (Rutherford)
Seong Youl Choi (Chonbuk)
Klaus Desch (Bonn)
Keisuke Fujii (KEK)
Yuanning Gao (Tsinghua)
Heather Logan (Carleton)

Klaus Moenig (DESY)
Andrei Nomerotski (Oxford)
Michael Peskin (SLAC)
Aurore Savoy-Navarro (Paris)
Georg Weiglein (Durham)
Jae Yu (Texas-Arlington)

ILD SiD convener

This talk will have two parts.

1. I will give my own analysis of the timeline for discoveries at the LHC and give a list of discoveries that could be made as early as the first run in 2010.

I will outline the case that these discoveries require the ILC. I will address the question of how the mass seen at the LHC is related to the energy required at the ILC.

2. I will present some suggestions from the Panel of new ILC physics analyses that we ought to have in place to respond to early LHC discoveries.

We will add to this list as the LHC discovery reach increases and as the actual results from the LHC become apparent.

To begin, I would like to recall the elements of the ILC physics case as we made it in 2001.

We argued that,

> Whatever would be found at the LHC,
> the next machine should be the ILC.

If the LHC discovers that electroweak symmetry breaking results from a new spectroscopy such as supersymmetry,

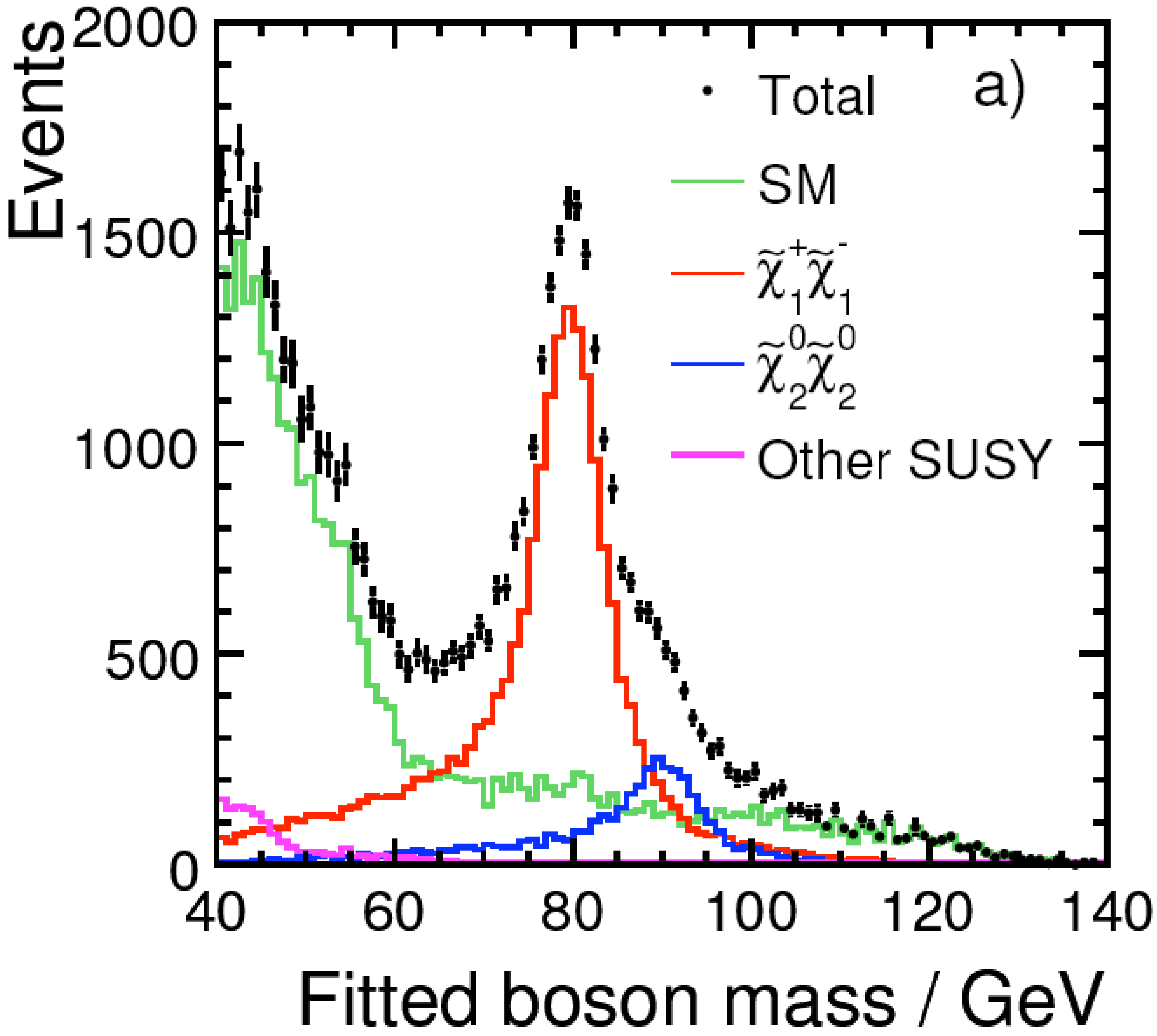
the ILC is needed to determine the model unambiguously by measuring the masses, couplings and spins of new particles.

If the LHC discovers that electroweak symmetry breaking results from strong interactions in the Higgs sector,

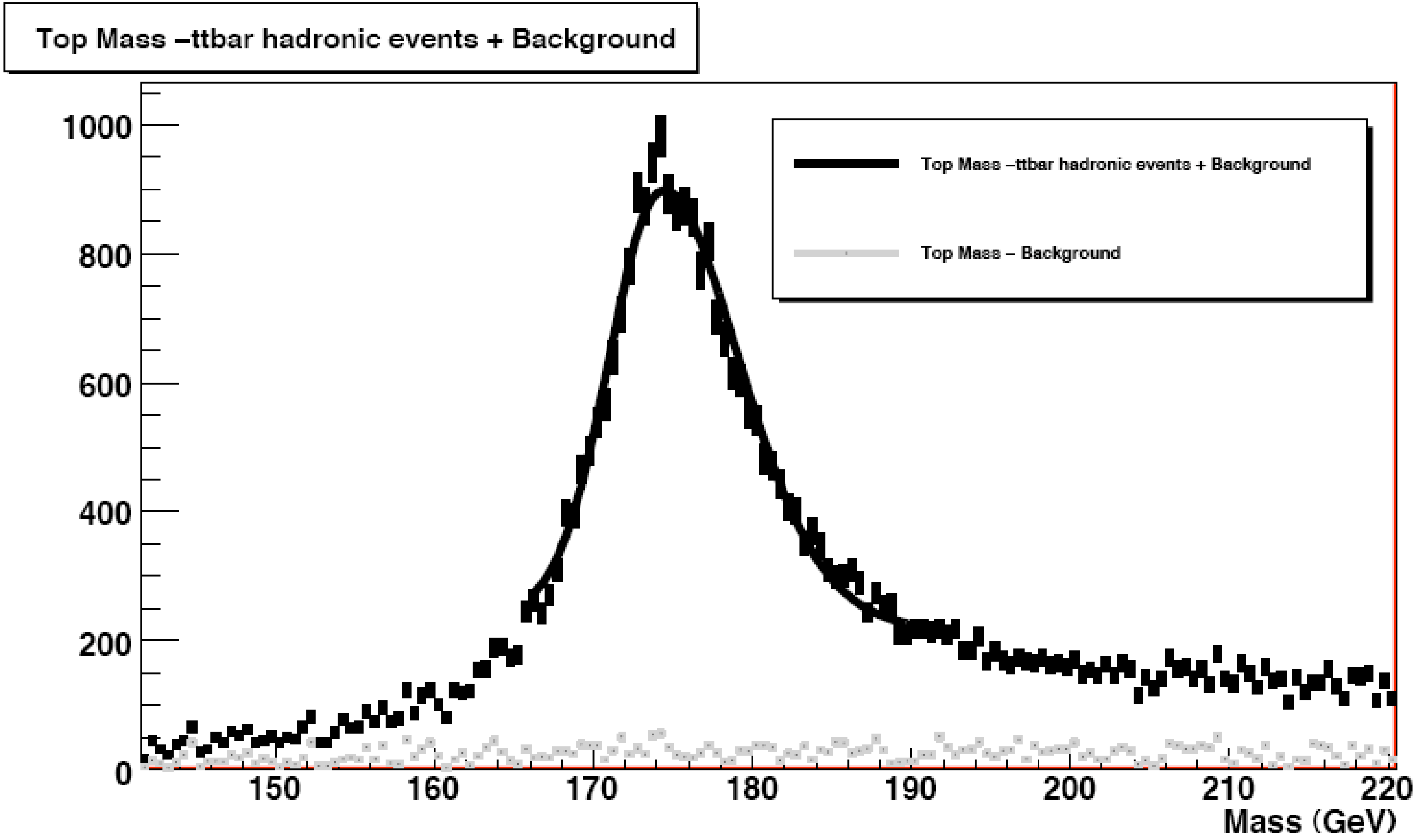
the ILC is needed to measure these strong interactions through W and top processes.

If the LHC discovers a minimal Higgs boson and nothing else,

the ILC is needed to check precisely that this particle indeed generates all masses of quarks, leptons, and gauge bosons.


Events
2000
1500
1000
500
0
40
60
80
100
120
140
Fitted boson mass / GeV
a)
Total
SM
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
$\tilde{\chi}_2^0\tilde{\chi}_2^0$
Other SUSY

ILD
LOI


Top Mass –ttbar hadronic events + Background
1000
800
600
400
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170
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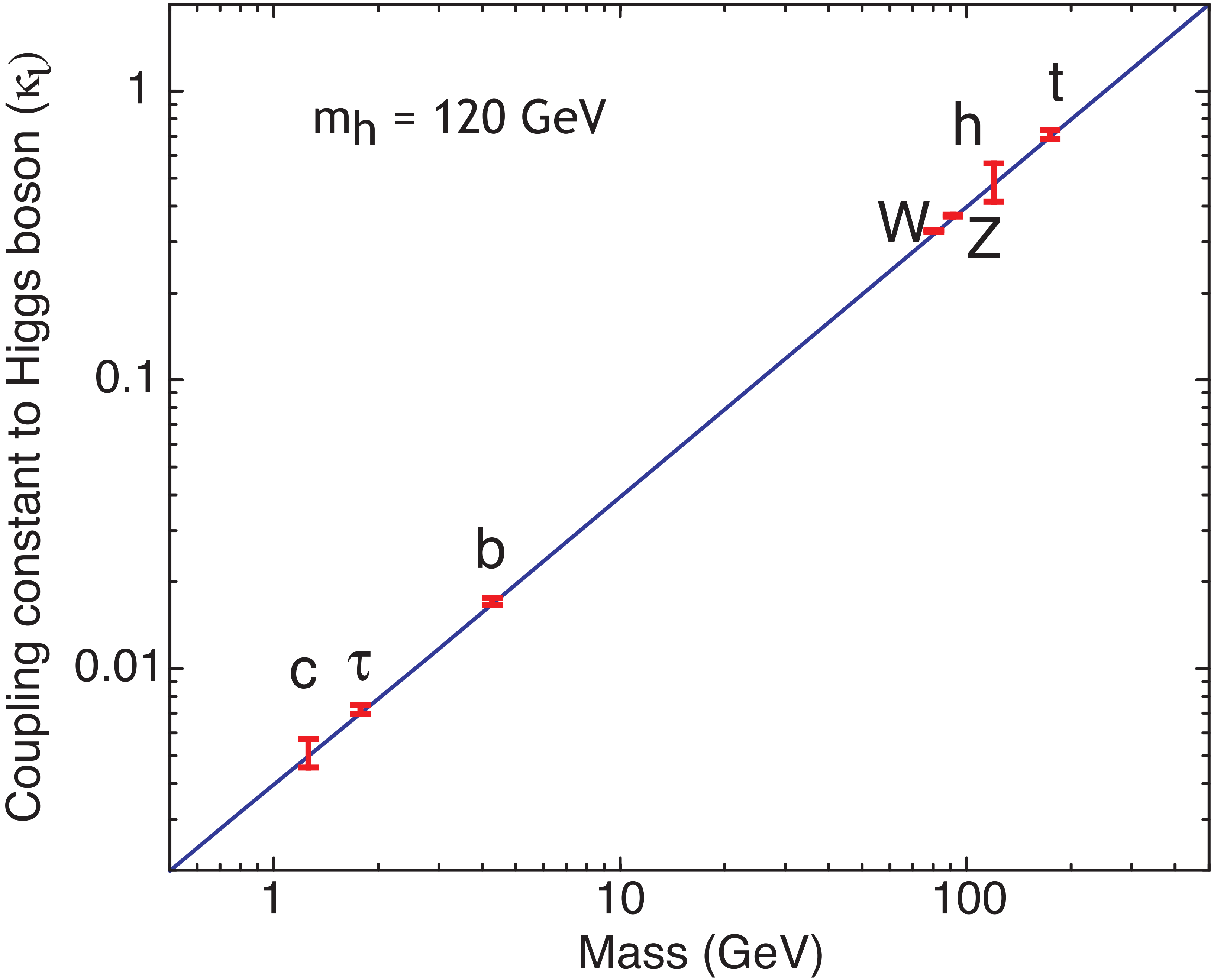
220
Mass (GeV)
Top Mass –ttbar hadronic events + Background
Top Mass – Background

SiD LOI



ACFA LC study

This is an excellent argument, and it is still correct !

However, obviously, it has not got us the ILC.

There are no serious alternatives for the next major high-energy physics facility

The VLHC, even the muon collider, are beyond the horizon.

Our problem is that, for a facility of the cost of the ILC, our colleagues and our funders wonder whether the cost will be justified by the science it will produce.

We must prove that new physics exists to be addressed at the ILC, and that this physics raises questions that the ILC can answer.

My conclusion is that the ILC must be motivated by specific Tevatron or LHC discoveries. We must have an argument that what is found at the hadron colliders leads directly to a need for the ILC.

In this talk, I will concentrate mainly on LHC.

For this, we need to study the LHC timeline, think about what new phenomena might be observed, and be prepared to show how the ILC addresses those issues.

To begin, here is a rough version of the currently projected LHC timeline ...

	July	LHC	
8 TeV	2010	3 pb^{-1}	min bias, QCD
	2011	300 pb^{-1}	$\tilde{q}$ at 600 GeV, MET at 2σ, l+l+ at 3σ Z’ at 1.5 TeV stable $\tilde{l}$- at 200 GeV
14 TeV	2012	1 fb^{-1}	$\tilde{q}$,$\tilde{g}$ at 1 TeV, MET, ll, lll at 5σ Higgs at 300 GeV in ZZ
	2013	10 fb^{-1}	Higgs at 140 GeV in ZZ*
	2014	30 fb^{-1}	Higgs at 120 GeV in $\gamma\gamma$ $t\bar{t}$ resonance at 3 TeV
	2015	100 fb^{-1}	strong WW scattering unexpected Q at 2 TeV
	2016	200 fb^{-1}	strong ZZ scattering unexpected Q at 3 TeV

On this schedule, a Higgs boson in the region prefered by electroweak symmetry breaking probably would not be discovered until 2013.

The Tevatron might find evidence for a light Higgs boson. However, this will need to be confirmed and clarified at the LHC.

I conclude that the precision Higgs physics -- though a very important ILC physics topic -- will not be the driver to justify the ILC in 2012.

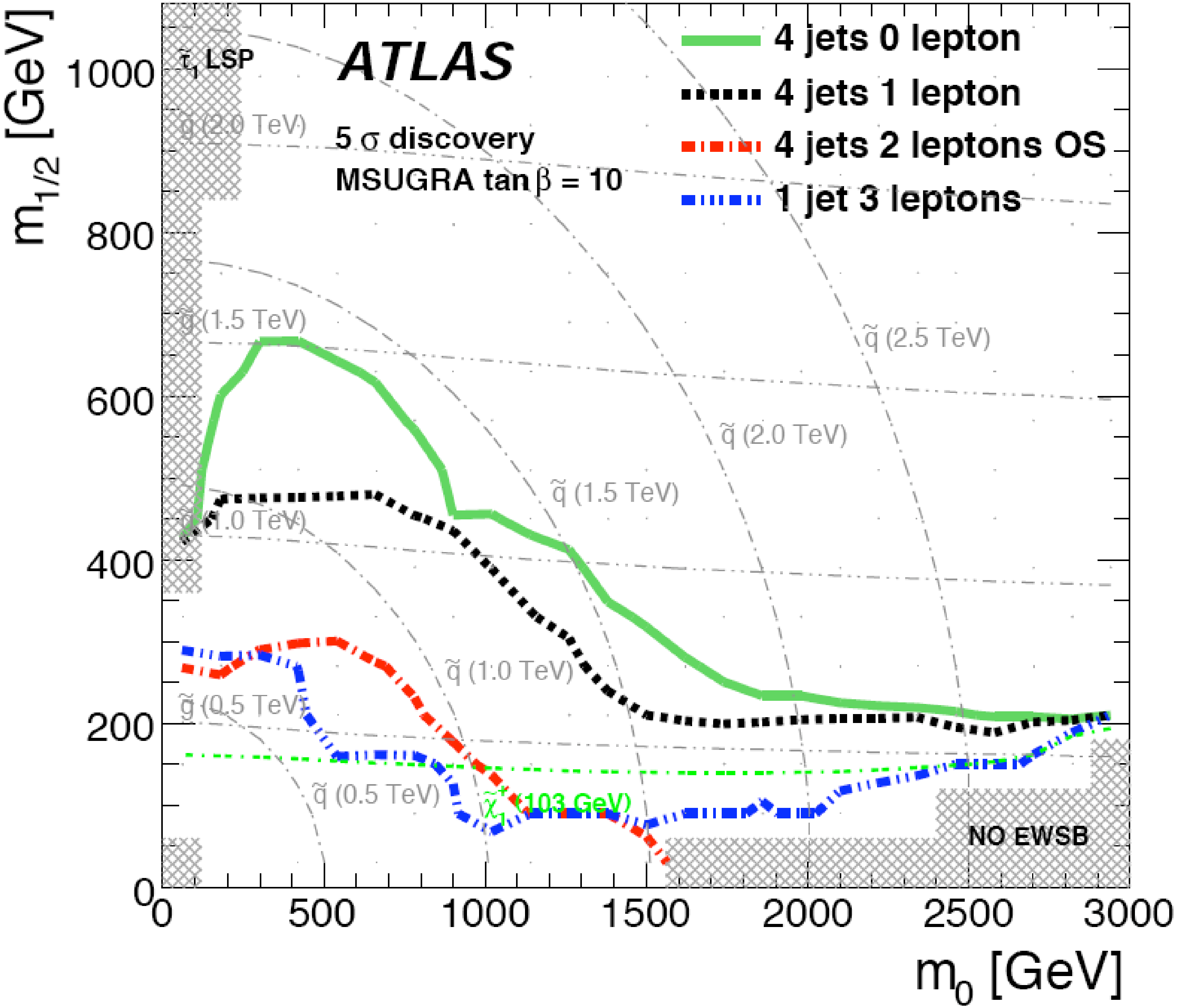
On the other hand, more exotic physics discoveries are possible at the LHC before 2012 and could drive the case for the ILC.

It is especially interesting to ask,

What new phenomena could the LHC discover in the 2010 run, optimistically, 300 pb-1 at 8 TeV ?

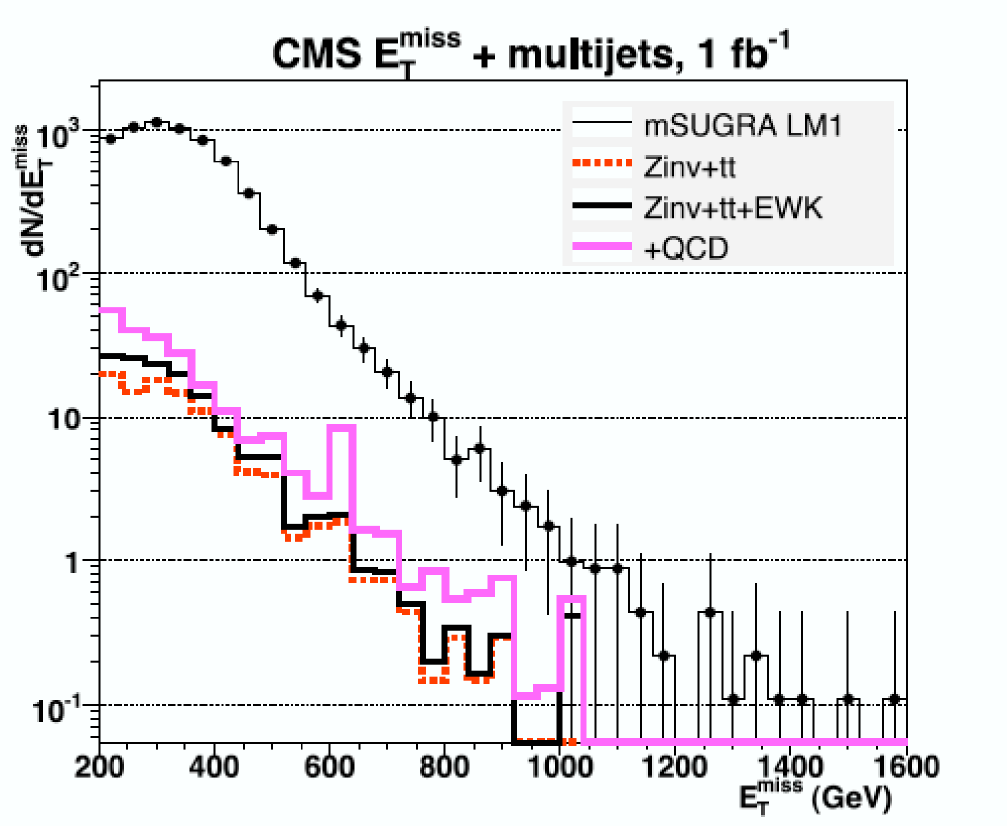
What can the ILC do to advance the physics uncovered there ?

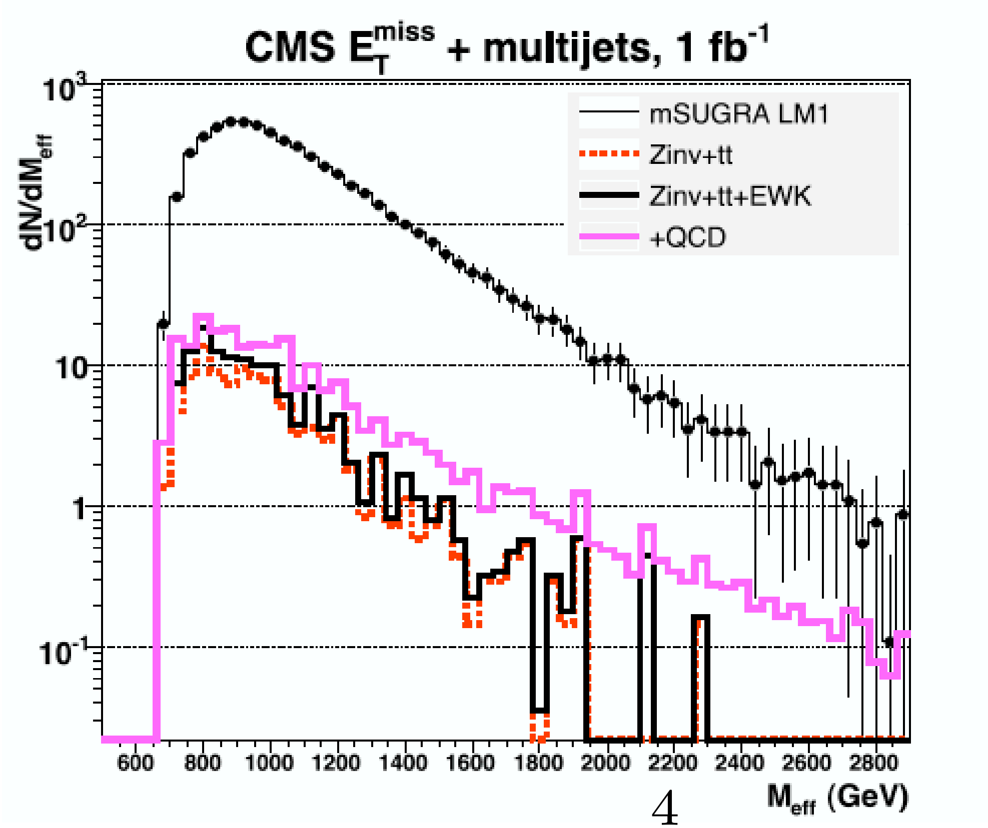
1. Supersymmetry, or another new spectroscopy, with quark and gluon partners at 500 - 600 GeV.



contours
for 1 fb-1

$$m(\tilde{g}) = 600\ \mathrm{GeV}$$



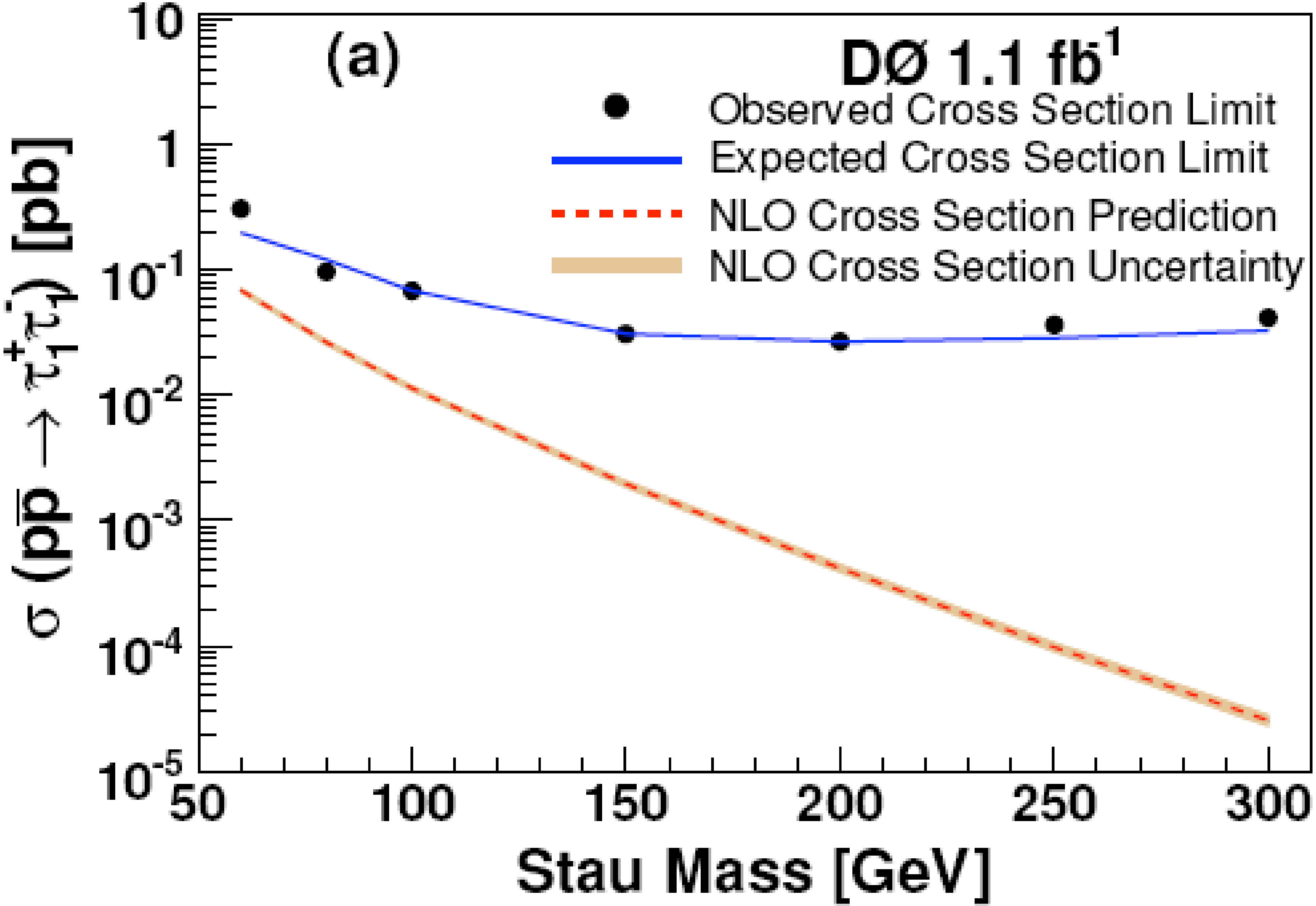


$$\not{E}_T$$

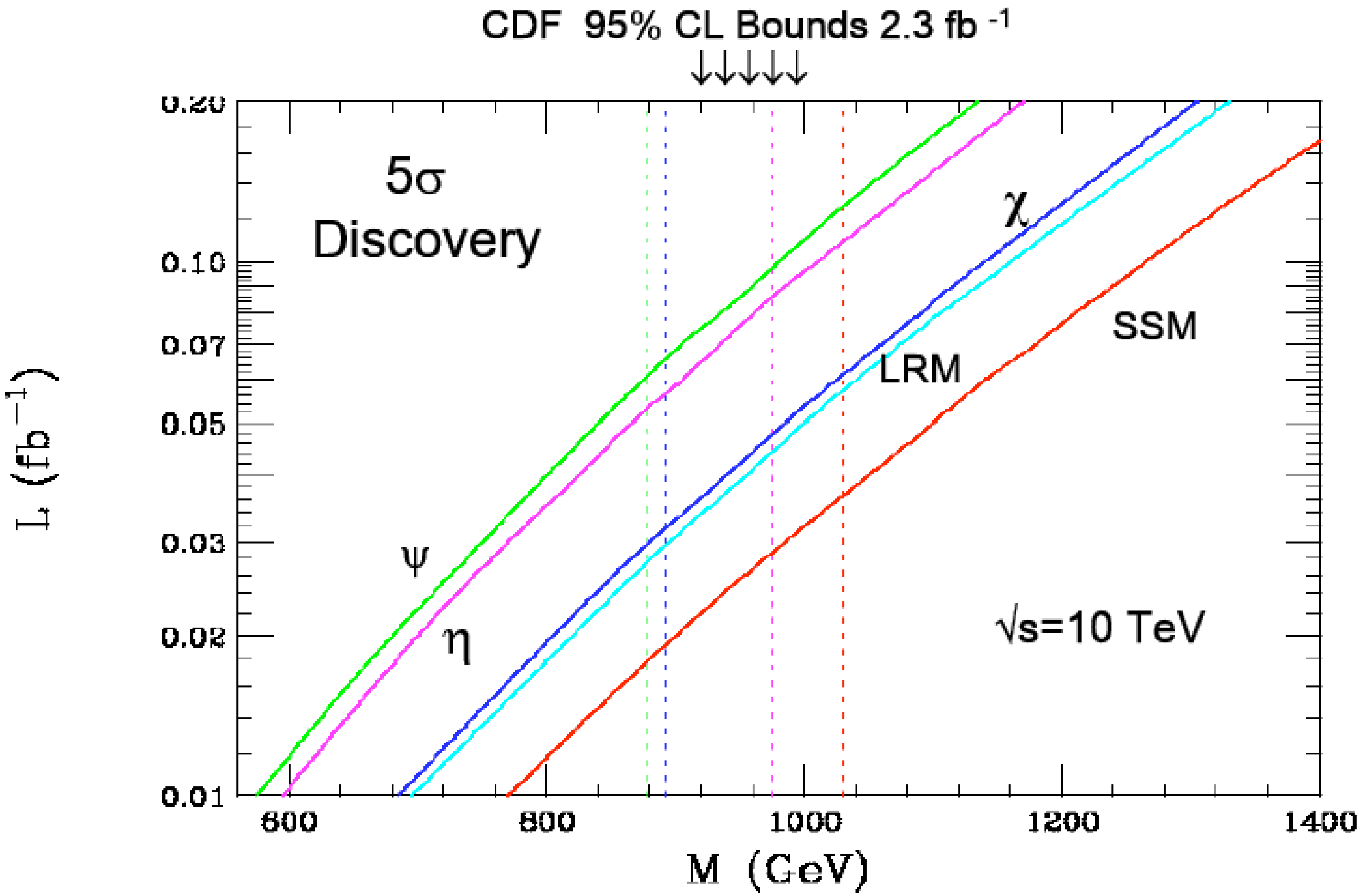
$$M_{\mathrm{eff}} = \not{E} + \sum_i^4 E_{Ti}$$

Yetkin and Spiropulu

2. Supersymmetry with quasi-stable sleptons.

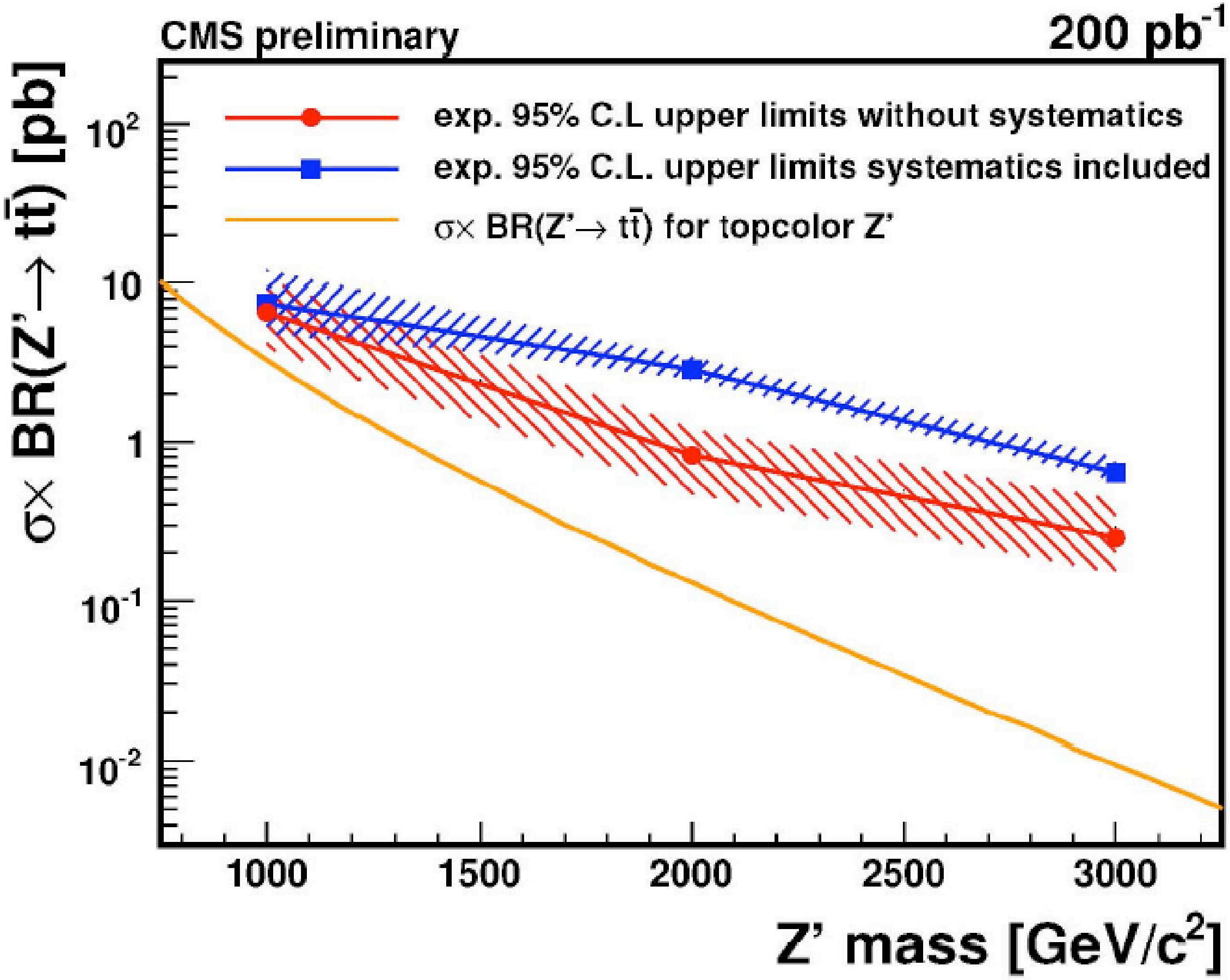


3. A Z-prime at 1 - 1.5 TeV



Rizzo

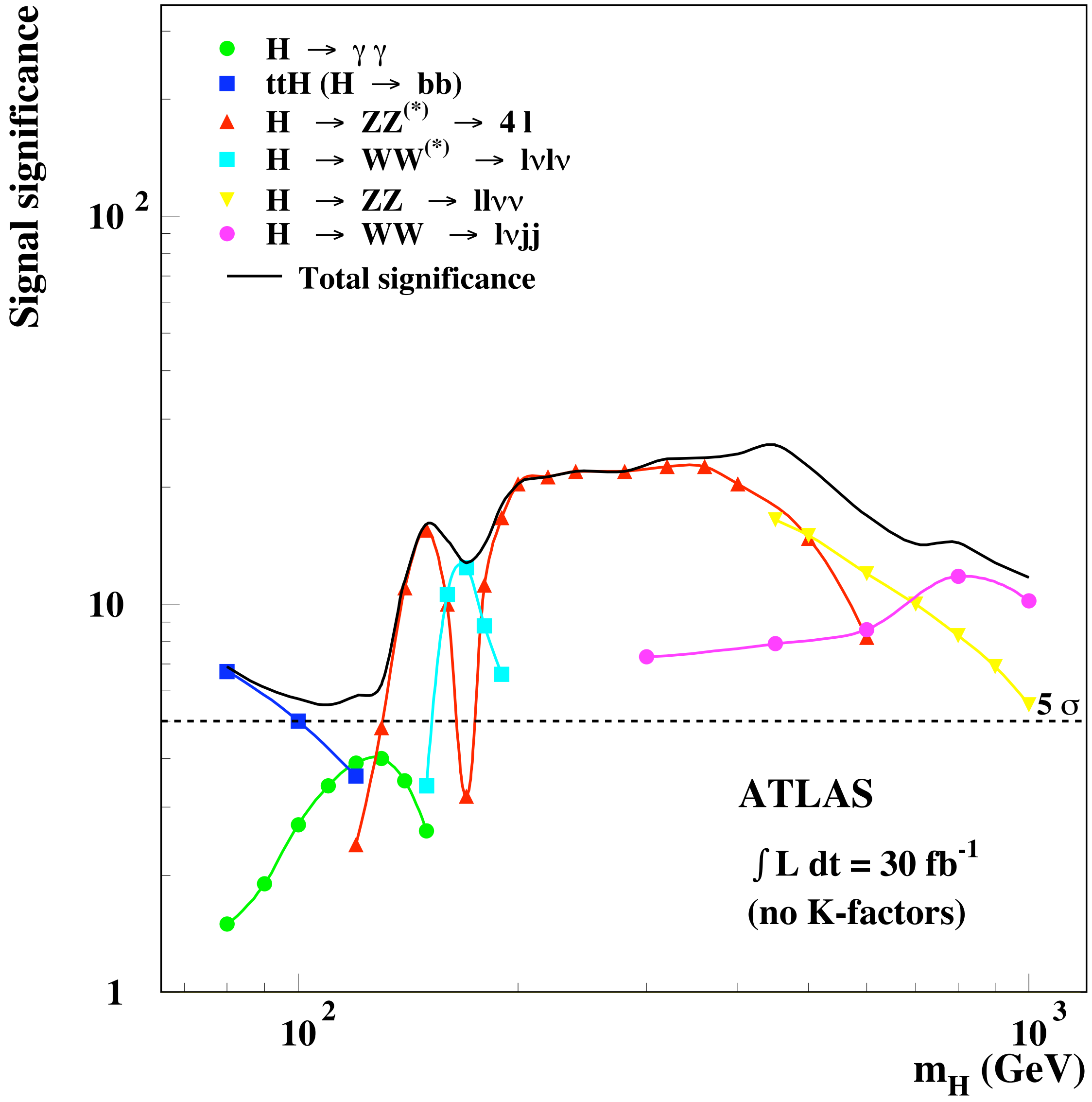
4. A top-antitop quark resonance at 1 - 1.5 TeV.

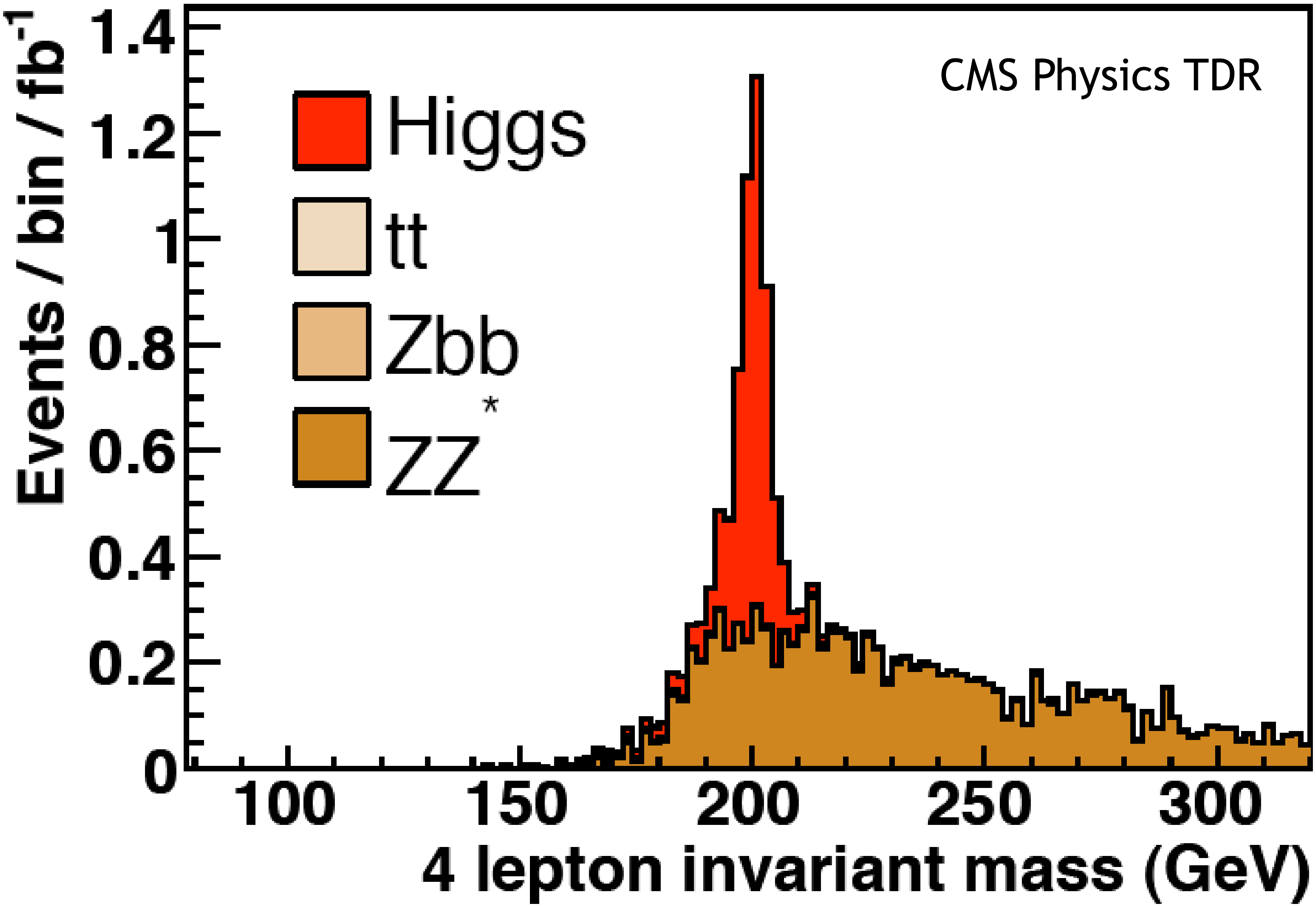


at 10 TeV

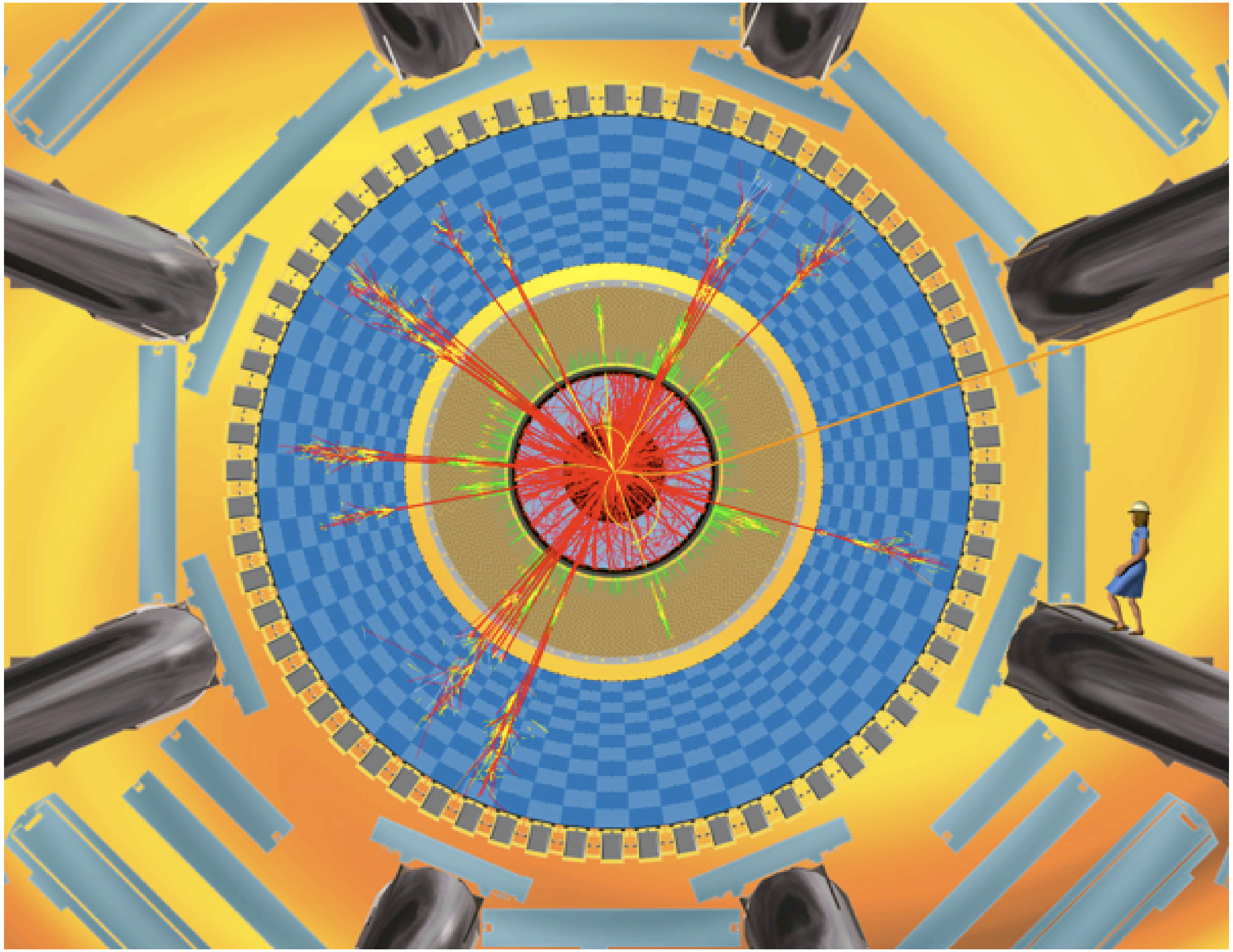
courtesy N. Hadley

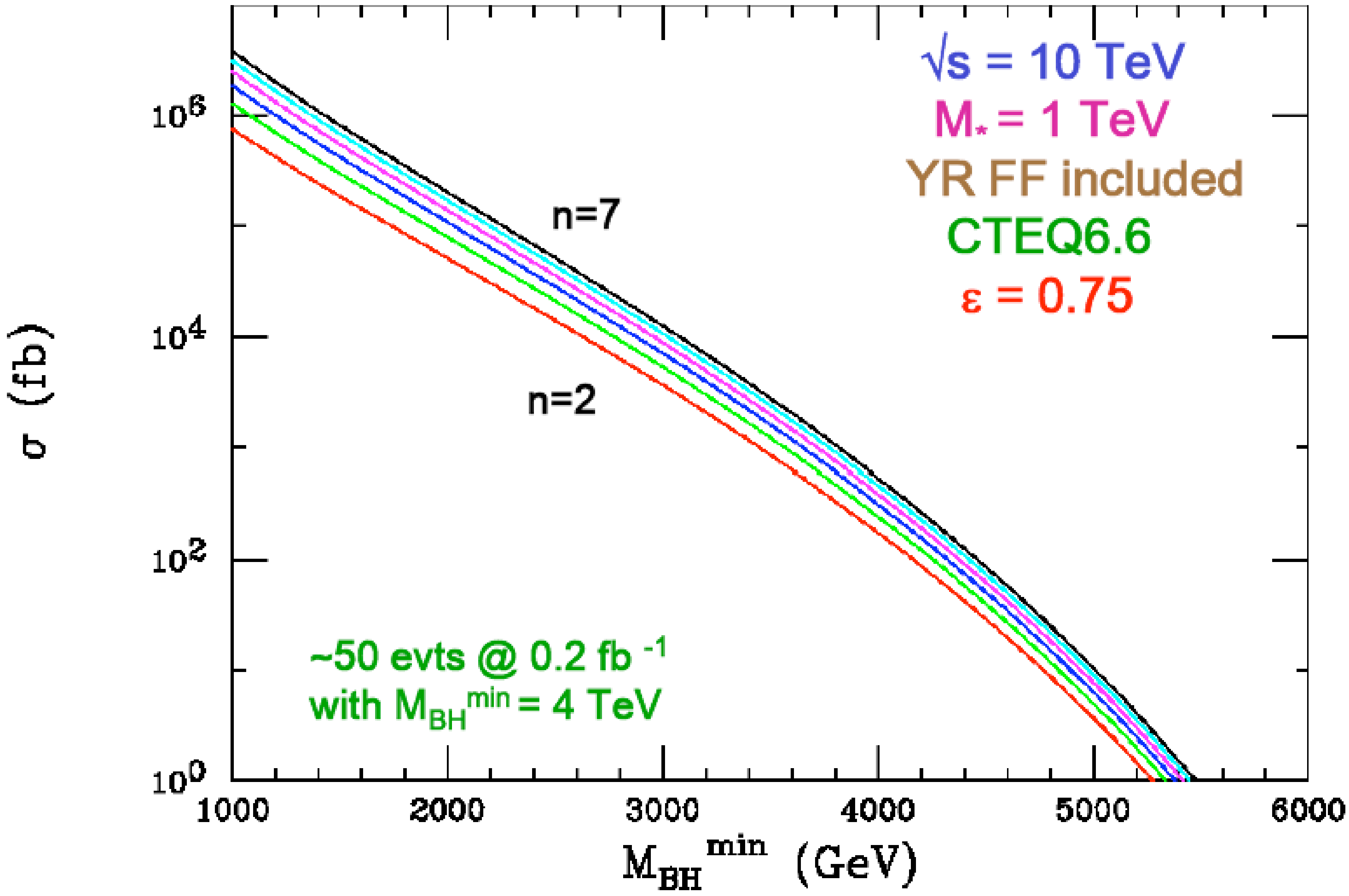
5. A Higgs boson with mass 200 GeV.




CMS Physics TDR
Higgs
tt
Zbb
ZZ*
Events / bin / fb^{-1}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
100
150
200
250
300
4 lepton invariant mass (GeV)

6. Black holes !




√s = 10 TeV
M* = 1 TeV
YR FF included
CTEQ6.6
ε = 0.75
n=7
n=2
~50 evts @ 0.2 fb -1
with M_BH^min = 4 TeV
σ (fb)
10^0
10^2
10^4
10^6
1000
2000
3000
4000
5000
6000
M_BH^min (GeV)

Rizzo

One often hears that

“we need the LHC to set the energy scale for the ILC”.

Thinking about these possible discoveries, you see that this is not a useful way to analyze the LHC-ILC connection.

All of these models have interesting physics at e+e- CM energies above 1 TeV,

but

All of the models have important observables that are measured at 500 GeV and below.

It is a truism in high-energy physics that

1. Higher energy is always better.
2. Technologies of the future will give us higher energy.

To advocate for the ILC,
we will need to argue that we cannot wait !

That is,

The specific phenomena found at the LHC urgently require new measurements that can only be made at an e+e- collider and are possible at 500 GeV.

I would like to analyze the specific discovery scenarios that I have just reviewed from this point of view.

What information will we not obtain from the LHC ?

How can e+e- experiments answer these questions ?

What (minimum) e+e- energy is needed ?

What quality of answers will the ILC give ?

For those discoveries that we can anticipate, we ought to have ILC analyses ‘in the bank’ so that we can immediately make clear to the broader HEP community how relevant ILC is.

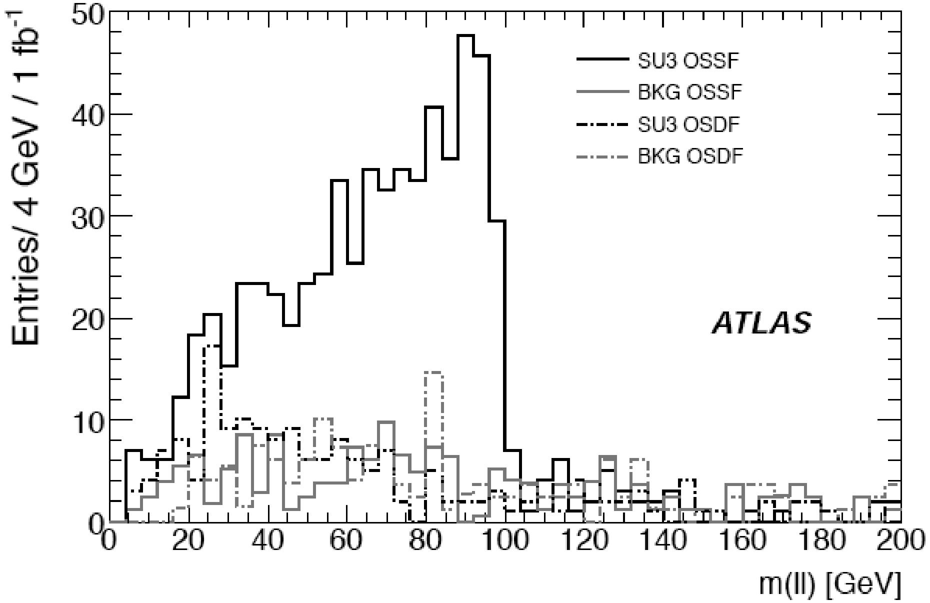
This leads to suggestions for physics analyses that should have high priority in the next year.

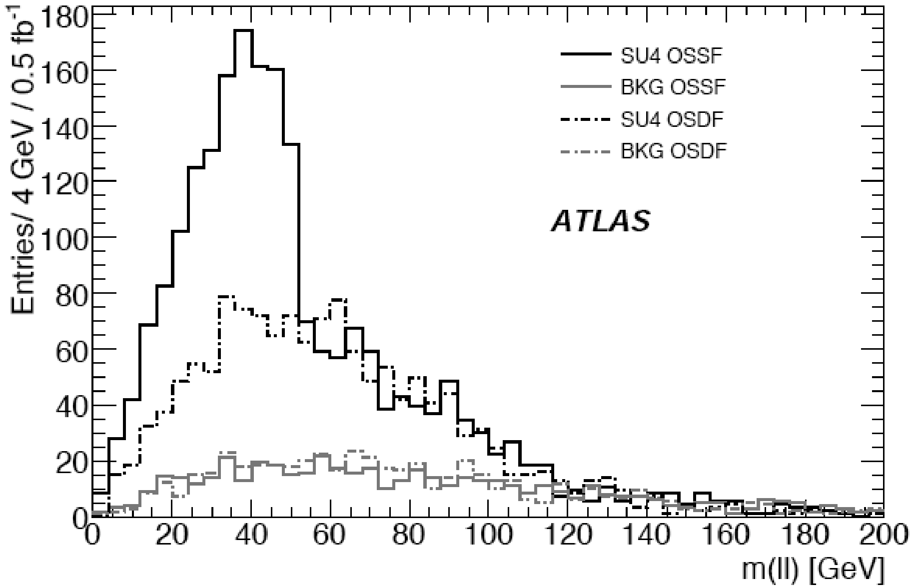
The LOIs have given us an excellent set of tools for carrying out these analyses. In turn, these analyses give new tests relevant for detector benchmarking.

Let’s now discuss the scenarios in turn:

1. Supersymmetry, or another new spectroscopy, with quark and gluon partners at 500 - 600 GeV.

In this scenario, it is likely that the LHC will be able to provide us a great deal of information on the mass spectrum of the new particles. In many models, specific kinematic features such as dilepton endpoints can be located to percent accuracy.





Assembling these pieces of information, we will be able to obtain the masses of the major states in the spectrum (W,q,g partners) to about 10% accuracy.

However, this only begins the study of the new particle sector.

Why is it there ? What is it for ? Does it unify with the particles of the Standard Model ? Does it in fact solve the mystery of electroweak symmetry breaking.

The answers to these questions require the detailed couplings of the new particles, and Higgs sector quantities such as $\tan\beta$. These are very difficult to obtain at the LHC.

A particularly clear and pressing question is that of dark matter.

If new particles at the LHC decay to missing transverse energy, the lightest new particle will be a natural candidate for WIMP dark matter. We should obtain the mass to about 10% from the LHC, and this might allow a rough check against masses obtained to lower accuracy in direct or indirect detection.

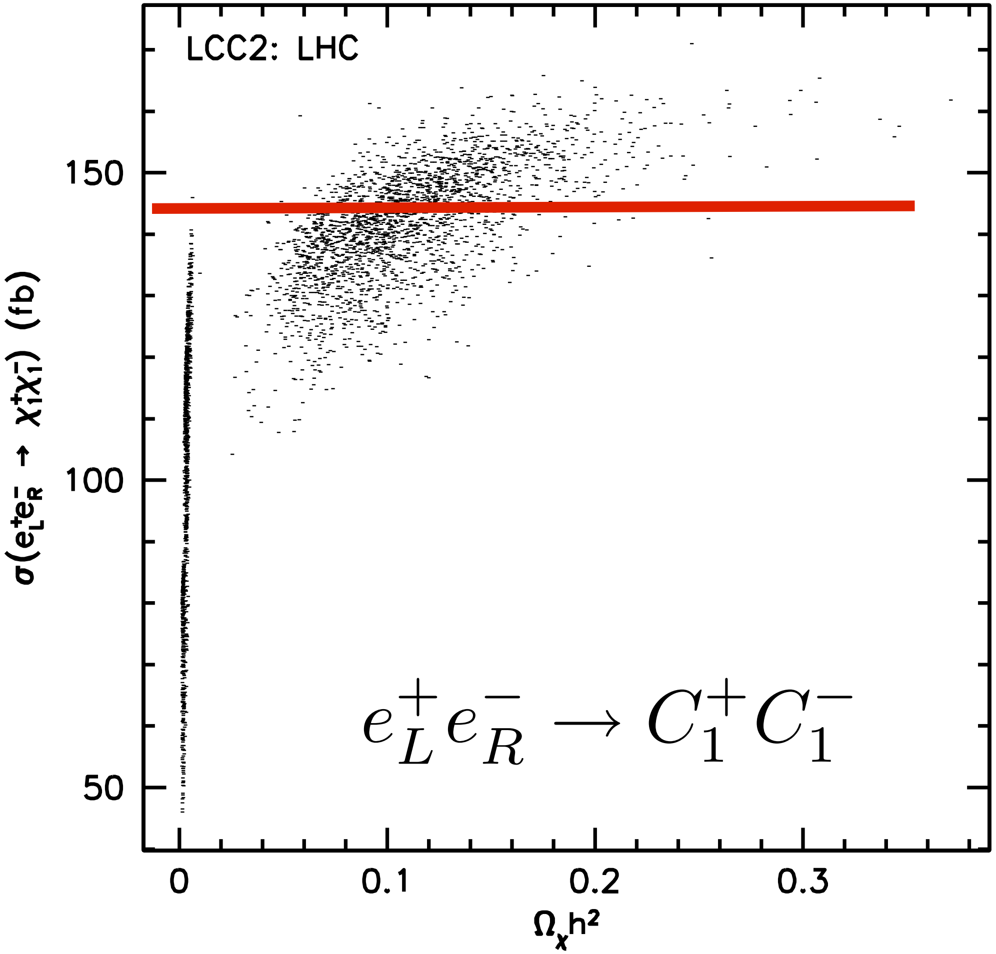
To go further, we must predict the dark matter abundance and direct detection cross sections from collider data. These are determined by complex calculations that require information on the helicity-dependent gauge and Higgs couplings.

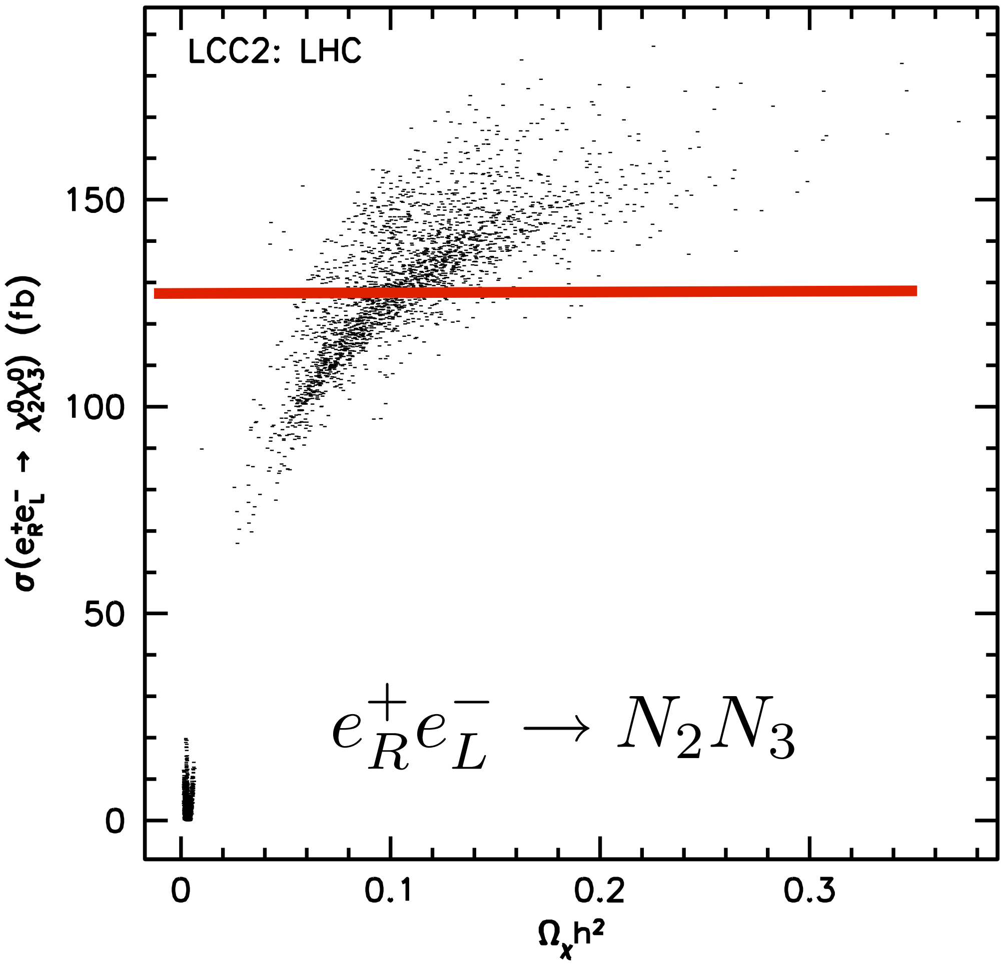
It is known that polarized cross sections such as

$$\sigma(e^-_L e^+_R \to \chi^+_1 \chi^-_1)$$

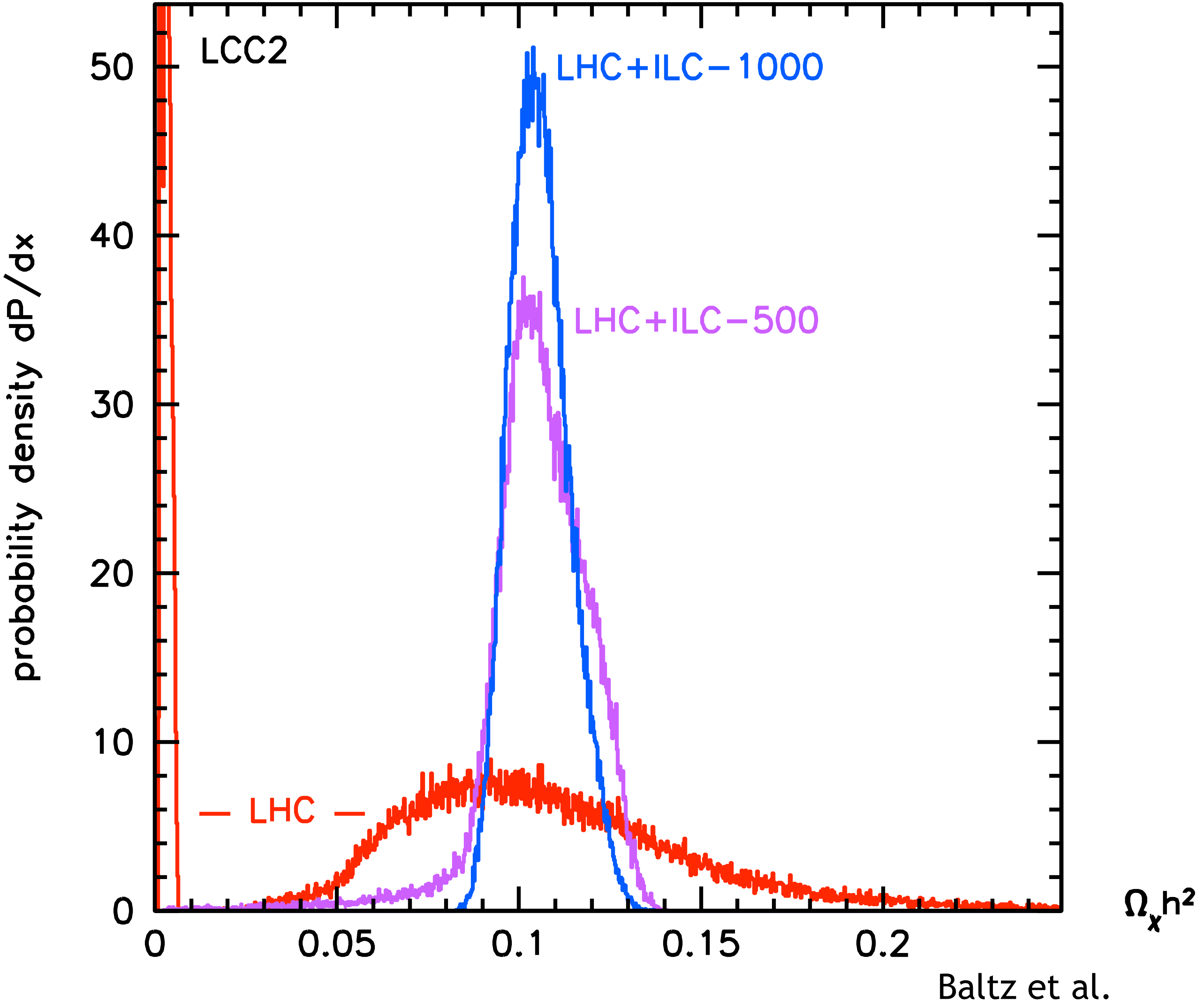
can provide this information.   In the LOIs, it is shown that such cross section can be measured with ~1% accuracy at the ILC.

The LHC will give us the mass of the lightest new particle with electroweak charge. Typically, this mass is much less than the mass of the primary colored particle produced at the LHC. The pair-production of that particle can already give us precise information on the WIMP couplings and might well decide the identity of the dark matter particle.


LCC2: LHC
$e_L^+ e_R^- \to C_1^+ C_1^-$
$\sigma(e_L^+ e_R^- \to \chi_1^+ \chi_1^-)$ (fb)
150
100
50
0
0.1
0.2
0.3
$\Omega_\chi h^2$


LCC2: LHC
$e_R^+ e_L^- \to N_2 N_3$
$\sigma(e_R^+ e_L^- \to \chi_2^0 \chi_3^0)$ (fb)
150
100
50
0
0
0.1
0.2
0.3
$\Omega_\chi h^2$

Baltz et al.

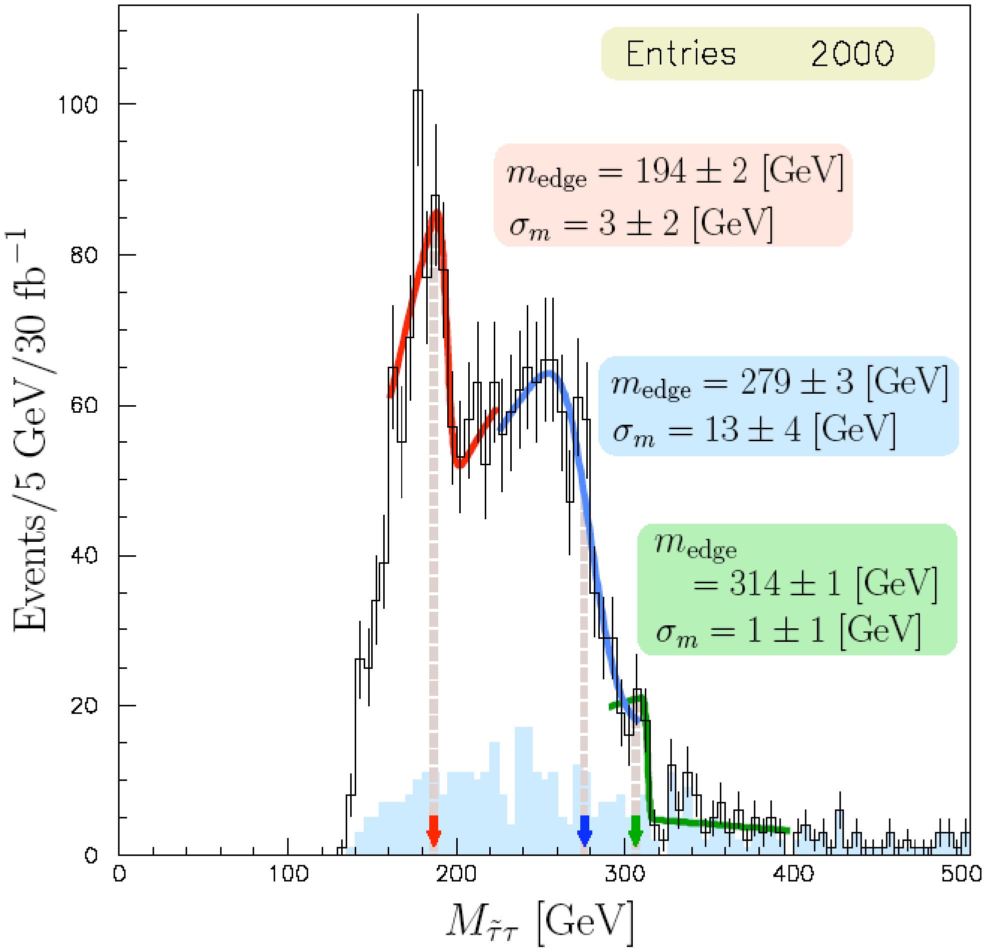

LCC2
LHC+ILC−1000
LHC+ILC−500
— LHC —
probability density dP/dx
0
10
20
30
40
50
0
0.05
0.1
0.15
0.2
$\Omega_\chi h^2$
Baltz et al.

2. Supersymmetry with quasi-stable sleptons.

In this scenario, a stable slepton appears as a track in the LHC detectors. Often, this track is triggered on by the muon system and its momentum is measured precisely.

This allows kinematic reconstruction of neutralinos in the LHC environment.

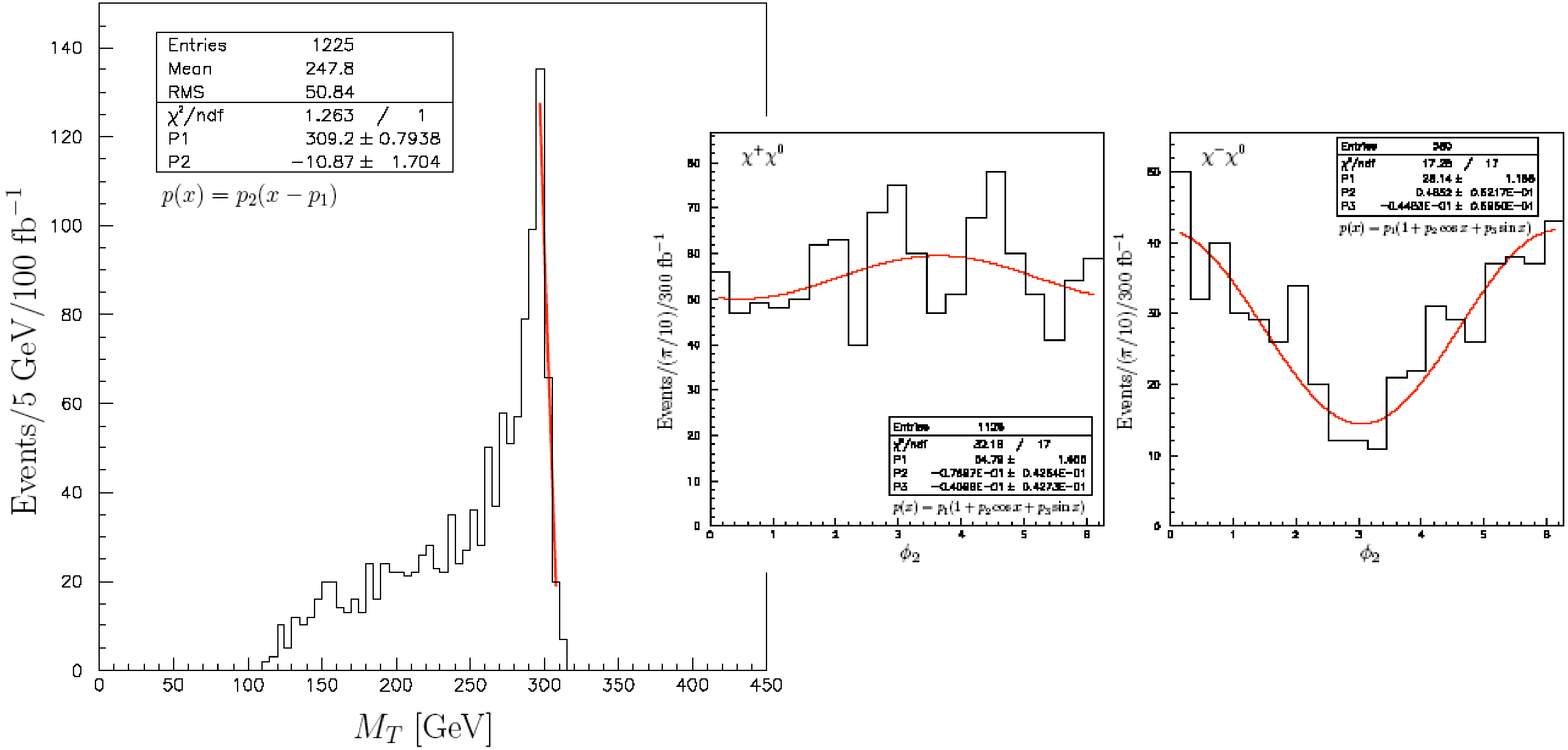
Ibe-Kitano



In a recent paper, Kitano has argued that, in these scenarios, the study of

$$q\bar{q} \to \chi^+\chi^0$$

at the LHC allows not only a precise chargino mass but also spin and coupling measurements.



Still, it will be compelling to perform experiments at the ILC to push this study to the next level.

Using $e^+e^- \to \widetilde{\ell}^+\widetilde{\ell}^-, \chi^+\chi^-$, we can study

precise cross section and angular distribution,
specification of the SM quantum numbers of the slepton

decay properties of $\widetilde{e}$, $\widetilde{\mu}$ to the stable slepton.

capture of a sample of stable sleptons and study of their decay

Using $e^+e^- \to \chi^+\chi^-$, we can study

precision (part-per-mil) determination of SUSY parameters,
including $\tan\beta$.

There is no study of a scenario of this type at the ILC. Such a study ought to be done using the LOI frameworks.

3. A Z-prime at 1 - 1.5 TeV

Many models of new physics contain new gauge bosons or other resonances in mass region of a few TeV. The LHC will observe such resonances in $q\overline{q} \to \ell^+\ell^-$, obtaining the mass and the forward-backward asymmetry. It might also be possible to distinguish the contributions to the cross section from u and d quarks.

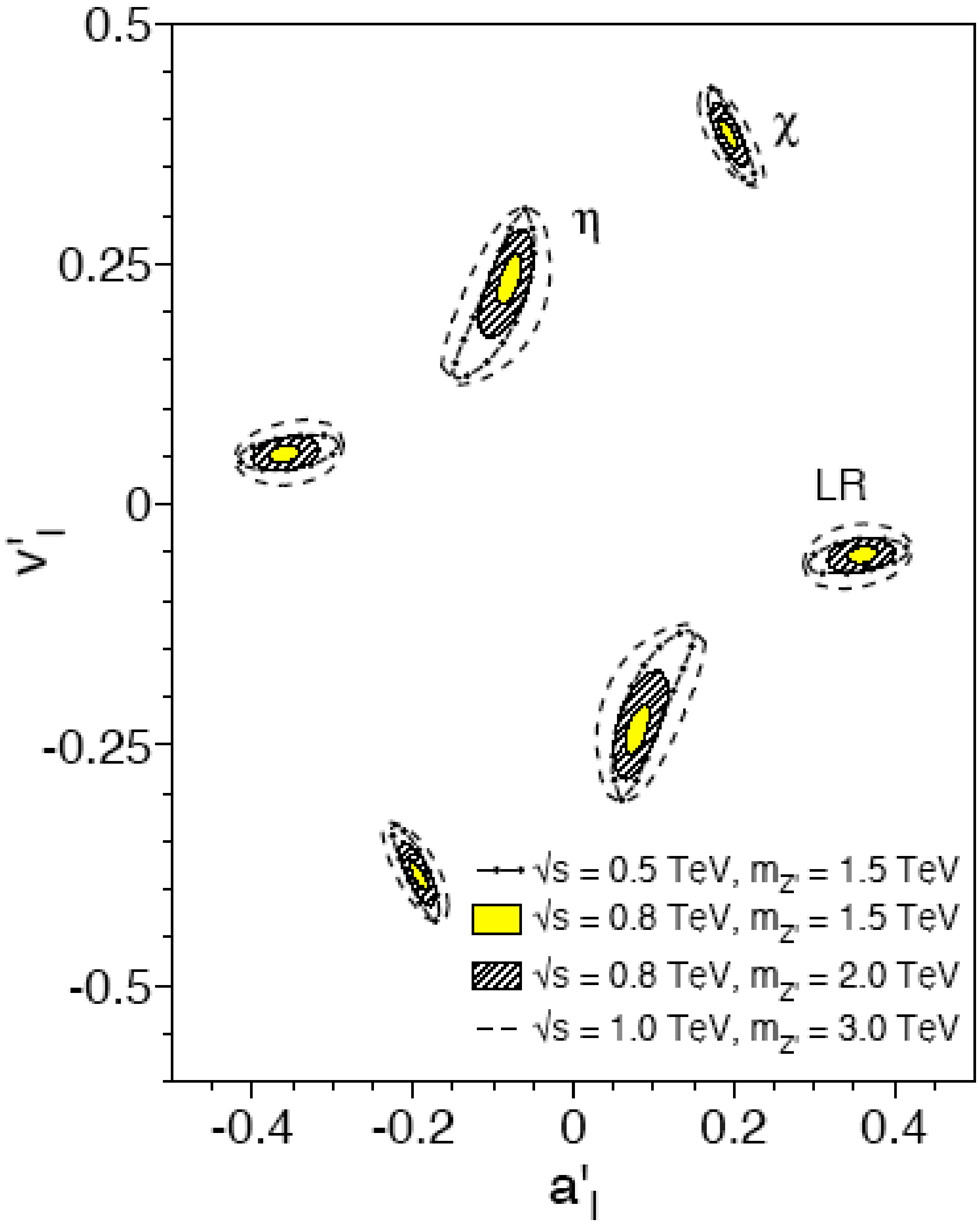
This is will leave many questions to be explored at e+e- colliders. We would like to know the precise couplings of the Z' to the L- and R- components of all species of quarks and leptons.

Ideally, we would like to go to the Z' resonance. However, if there is no technology available for this, we can learn a great deal through polarized $e^+e^- \to f\overline{f}$ at the highest available energy.

For example, for $e^-_L e^+_R \to f_L \overline{f}_R$, the Z' adds an amplitude

$$\frac{g_{eL} \cdot g_{fL}}{s - m_Z^2 + i m_Z \Gamma_Z}(1 + \cos\theta)$$

which interferes with the Standard Model pair-production amplitude. Using the mass from the LHC, we can use the polarized forward and backward cross sections to obtain all of the Z' couplings.


0.5
0.25
0
-0.25
-0.5
v'_l
-0.4
-0.2
0
0.2
0.4
a'_l
χ
η
LR
√s = 0.5 TeV, m_Z' = 1.5 TeV
√s = 0.8 TeV, m_Z' = 1.5 TeV
√s = 0.8 TeV, m_Z' = 2.0 TeV
√s = 1.0 TeV, m_Z' = 3.0 TeV

Riemann

These ILC capabilities were studied extensively with fast simulation. The process $e^+e^- \to \tau^+\tau^-$ was studied in the LOIs, mainly emphasizing the capability for tau polarization.

Another set of reactions that needs to be revisited is

$$e^+e^- \to b\overline{b}\ ,\ c\overline{c}$$

Recently, the LCFI group has presented new methods for $b/\overline{b}/c/\overline{c}$ discrimination based on vertex charge. It would be very useful to have a full study of the application of these methods to the determination of the b,c couplings of a Z', done in the LOI frameworks.

Vertex charge measurement in the forward direction, which is important to this study, is likely to be affected by machine backgrounds. A study of this effect should be part of the accelerator design optimization.

4. A top-antitop quark resonance at 1 - 1.5 TeV.

Despite the large amount of information that we have on the top quark from the Tevatron, the status of this quark is still unclear. The top quark is the heaviest quark and therefore the one most strongly coupled to electroweak symmetry breaking. Is the top quark

weakly coupled to a weakly-interacting Higgs sector ?

weakly coupled to a strongly-interacting Higgs sector ?

composite and strongly-interacting under new forces?

The discovery of a $t\bar{t}$ resonance at the LHC, or at the Tevatron, will eliminate the first of these possibilities and pose a sharp question between the other two.

For the QCD strong interactions, we understood the composite structure of meson and baryons by measuring their coupling to pointlike currents.

For the top quark, the composite structure would be manifest in the form factors of vector and axial vector currents:

$$e A_\mu \, \bar{t}\gamma^\mu [F_{LA}(Q^2) P_L + F_{RA}(Q^2) P_R] t$$
$$+ \frac{e}{c_w s_w} Z_\mu \, \bar{t}\gamma^\mu [F_{LZ}(Q^2) P_L + F_{RZ}(Q^2) P_R] t$$

These form factors are constrained at $Q^2 = 0$ to be

$$F_{LA}(0) = F_{RA} = \frac{2}{3} \quad F_{LZ}(0) = (\frac{1}{2} - \frac{2}{3}\sin^2\theta_w) \quad F_{RZ}(0) = \quad ?$$

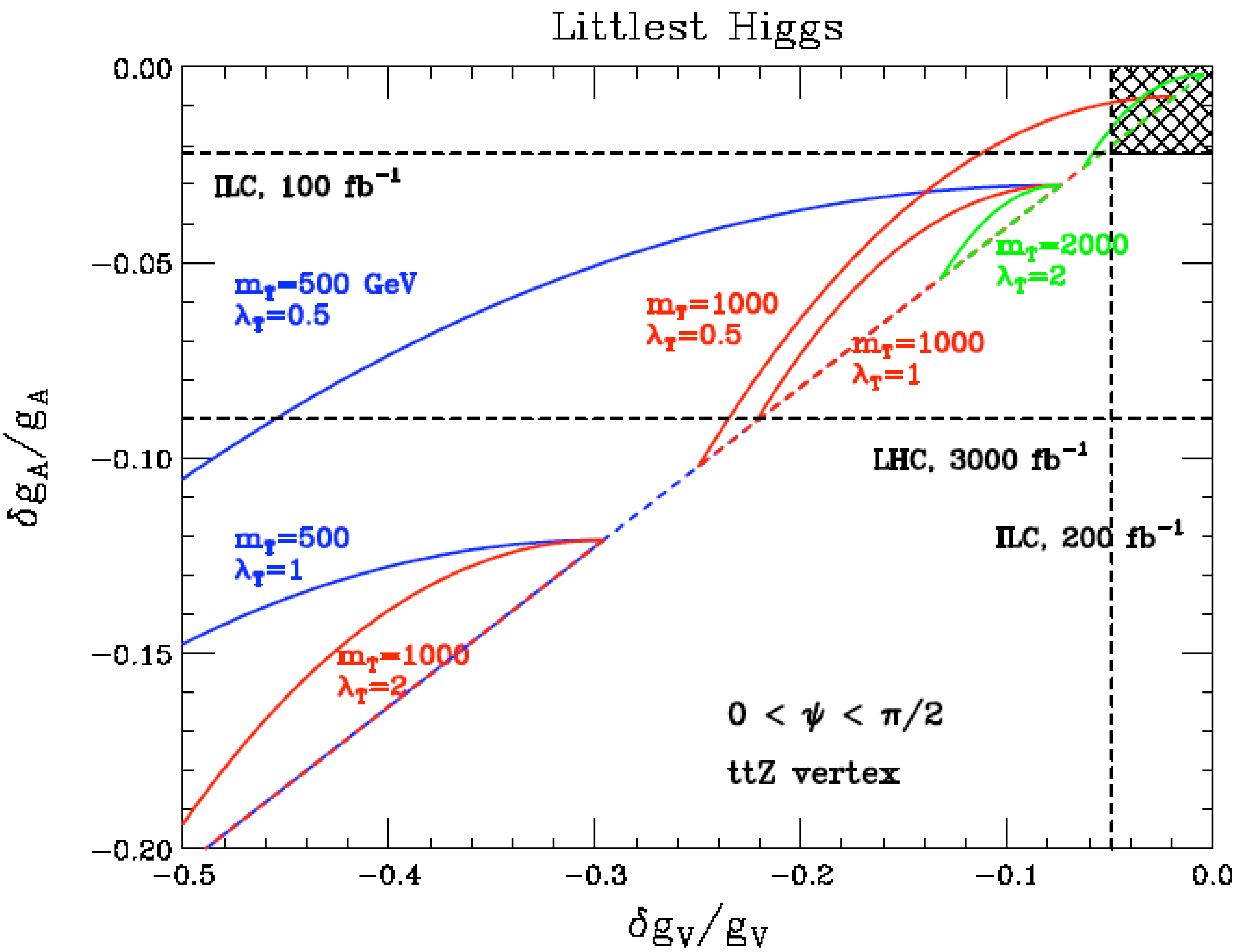
At the top quark theshold, we measure them at

$$Q^2 = 4m_t^2 \ , \ Q^2/m_R^2 = 0.1$$

The LOIs studied the reaction $e^+e^- \to t\bar{t}$ at 500 GeV, concentrating on the measurement of m_t and the top decay properties.

It would be very useful to continue this study in the LOI frameworks, focusing on the forward-backward asymmetry with polarized beams.

This should establish the ability of the ILC to measure the four top quark form factors at the few-percent level.



Berger, Petriello, Perelstein

5. A Higgs boson with mass 200 GeV.

Most ILC studies have been done for light Higgs bosons. If the Higgs boson mass is above 170 GeV, the properties of the Higgs are different, and less favorable to the ILC. The dominant decay modes are

$$h^0 \to W^+W^-, Z^0Z^0$$

The decay $h^0 \to Z^0Z^0$ is observable at the LHC in a way that allows full spin analysis. The Higgs decays to light fermions and boson become rare decay modes, eg. $BR(h^0 \to b\bar{b}) \sim 2 \times 10^{-3}$

Still many issues will remain after the LHC program:

Are there other Higgs bosons, or does h^0 give 100% of SM masses ?

Does h^0 have a substantial branching fraction to invisible modes ?

Does h^0 couple to quarks and leptons ? With what values ?

Some of these questions will be answered by ILC running at 350 or 500 GeV to study the reaction $e^+e^- \to Z^0 h^0 \ , \ h^0 \to WW, ZZ$

However, the harder and more interesting questions, which involve the HIggs-fermion couplings, require higher energy, 800 GeV to 1 TeV.

Barklow has shown that the $hb\bar{b}$ coupling of a 200 GeV Higgs can be measured to 5% accuracy in the 2 jet + (missing) analysis of

$$e^+e^- \to \nu\bar{\nu}h^0 \ , \ h^0 \to b\bar{b}$$

Gay has shown that the $ht\bar{t}$ coupling of a 200 GeV Higgs can be measured to 20% accuracy in the l + (missing) + 8 jet analysis of

$$e^+e^- \to t\bar{t}h^0 \ , \ h^0 \to WW, ZZ$$

Both studies were the first of their kind, using only fast-simulation tools. They should be repeated in the LOI frameworks. Gay's study, in particular, would benefit greatly in statistics if additional channels, including the 10-jet final state, could be included.

6. Black holes !

Black hole production at LHC will be a signal that the scale where quantum gravity becomes important to particle physics is as low as a few TeV. At this scale, gravity will be a strong interaction.

This requires that, somehow, a series of new reactions that involve gravity in an essential way turn on between LEP/Tevatron energies and TeV energies.

It will be important to understand this transition as precisely as possible. This can be done through the ILC study of

$$e^+e^- \to \gamma + G$$

and the identification of effects from gravitational (and also superstring) resonances in

$$e^+e^- \to f\overline{f}$$

Quick summary of the above:

We recommend that the following processes be studied in the LOI frameworks in preparation for a possible LHC discovery in 2010:

$$
\begin{aligned}
&500\ \text{GeV}: \\
&\qquad e^+e^- \quad\rightarrow\quad b\bar{b}, c\bar{c} \qquad \sigma, A_{FB} \text{ for each } P_e \\
&\qquad e^+e^- \quad\rightarrow\quad t\bar{t} \qquad \sigma, A_{FB} \text{ for each } P_e \\
&\qquad e^+e^- \quad\rightarrow\quad \chi^+\chi^-, \chi^0\chi^0,\ \chi \rightarrow \nu, \ell + \text{stable } L \\
&\ 1\ \text{TeV} \quad : \\
&\qquad e^+e^- \quad\rightarrow\quad \nu\bar{\nu}h^0,\ h \rightarrow b\bar{b} \quad m_h = 200\ \text{GeV} \\
&\qquad e^+e^- \quad\rightarrow\quad t\bar{t}h^0,\ h^0 \rightarrow WW, ZZ \quad m_h = 200\ \text{GeV}
\end{aligned}
$$

Many of these reactions provide new, interesting benchmarks for the ILC detectors.

Prof. Yamada has asked our group to suggest a list of benchmarks for the evaluation of the LOI detectors at 1 TeV.

It would be very useful for the CLIC studies, which will use the LOI detector models, to examine the same reactions that the ILC groups analyze at 250 GeV, 500 GeV, 1 TeV. This will allow more direct comparisons for detector optimization and understanding of the effects of the CLIC time structure and beam backgrounds on physics measurements.

We will offer a official list of suggestions later in the fall. But I would like to make a few observations now.

First, the two processes that we have suggested for 1 TeV

$$e^+e^- \to \nu\overline{\nu}h^0,\ t\bar{t}h^0 \text{ with } m_h = 200 \text{ GeV}$$

exercise the capabilities for hadron calorimetry

The also address new issues that are important at 1 TeV:

complexity of events, jet combinatorics
forward peaking of t channel (W-exchange) reactions

Second, it would be useful for physics reasons to repeat some of the analyses we have suggested under other conditions at higher energy or lower Higgs mass:

$$\begin{aligned} e^+e^- &\to \tau^+\tau^-,\ b\bar{b},\ c\bar{c} \\ e^+e^- &\to \nu\overline{\nu}h^0,\ h^0 \to \mu^+\mu^- \quad m_h = 120 \text{ GeV} \end{aligned}$$

all at 1 TeV. These stress tracking and heavy flavor ID under the 1 TeV conditions.

Third, we cannot help but notice that the same SUSY point studied in the LOI has more interesting physics at 1 TeV:

$$e^+e^- \quad\rightarrow\quad \chi_2^+\chi_2^-, \chi_3^0\chi_4^0,\ \chi \rightarrow W, Z, h + \chi_1^+, \chi_2^0$$

These may be interesting processes for 1 TeV benchmarking. They also make the point that, at ILC, we learn interesting things at 500 GeV, and additional interesting things at 1 TeV.

Finally, we emphasize that more work is needed on the precision Higgs case for a light Higgs. In particular, the triple Higgs coupling was discussed for the LOI study, but the work was not done.

The precision Higgs physics is a core capability of the ILC.
Whatever specific LHC discovery motivates the ILC, it will be an important point for the ILC that it allows precise measurements over the complete spectrum of Higgs boson couplings.

Our discussions of 1 TeV benchmarks are still going on. We are eager to receive your comments and suggestions.

To conclude, I return to the main point of this lecture:

To see the ILC approved, we will need specific physics discoveries at the LHC or the Tevatron. We will need to build a case that these disoveries raise urgent questions about physics, and that the ILC can answer these questions.

We need to pay attention to the capabilities of the LHC, anticipate discoveries that can be made there, and demonstrate the ILC capabilities relevant to those observations.

The physics case for the ILC is strong. When the LHC begins running, and when it makes its first discoveries, this will put the Terascale physics front and center in high-energy physics.

We have been doing well in the course of "Physics of the ILC". This is the final exam. We can ace it. We need to be prepared.