# Beyond the Standard Model: the next 20 years

## 3. Beyond the ILC

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In this last lecture, I will discuss prospects for studies of new particles in the era beyond the LHC and ILC.

So far in our discussion, it has been reasonable to think about "generic" new physics models. These are characterized by

new heavy particles in the 100 GeV - 1 TeV mass range

definite chirality assignments, order-1 polarization effects

long decay chains, ending in invisible particles

The phenonemenology associated with different schemes of electroweak symmetry breaking is similar, and the goals for new accelerators are defined by those similarities.

We will see that, at higher energies, the paths diverge.

This point is so important that I should say it in another way.

One often hears the statement:

LHC results are needed to justify and define the ILC.

But the case for colliders in the multi-TeV range is obvious, and we should begin planning for them.

In fact, what the physics models say is just the opposite.

ILC can build its physics case already on physics that we know will be there:

precision study of the top quark

precision study of the Higgs boson

In addition, the ILC should reach the first thresholds for new particles.   This depends on the ‘naturalness’ connection between the heavy particle masses and that requirement that they generate the Higgs potential, which has a 100 GeV energy scale.

I argued in the previous lecture that precision study of the lightest new particles has high scientific value.

Beyond the hundred-GeV mass scale, where is the next logical step ?

This depends on the detailed structure of the physics of electroweak symmetry breaking.   We cannot plan a campaign to explore this without seeing results from the LHC (and maybe also the ILC).

The best we can do today is survey the possibilities.

I will begin such a survey in this lecture.

Let me preface this discussion with a few remarks on accelerators for multi-TeV particle physics. There are three types of proposals, none mature:

pp colliders (e.g., VLHC)

$\mu^+\mu^-$ colliders

$e^+e^-$ colliders (e.g., CLIC)

Despite the fact that I am a theorist, I will try to review them.

The VLHC pp collider was put forward at the 1996 and 2001 Snowmass workshops in the US; the concept is still being studied at a low level at Fermilab. Some key issue are:

difficulty of producing magnets with bending fields above 10 T

To go to 3x LHC, we need new materials beyond $Nb_3Sn$ (high-Tc superconductors ?)

limitations due to synchrotron radiation by the proton beams

Synchrotron power must be extracted from inside the superconducting dipoles.

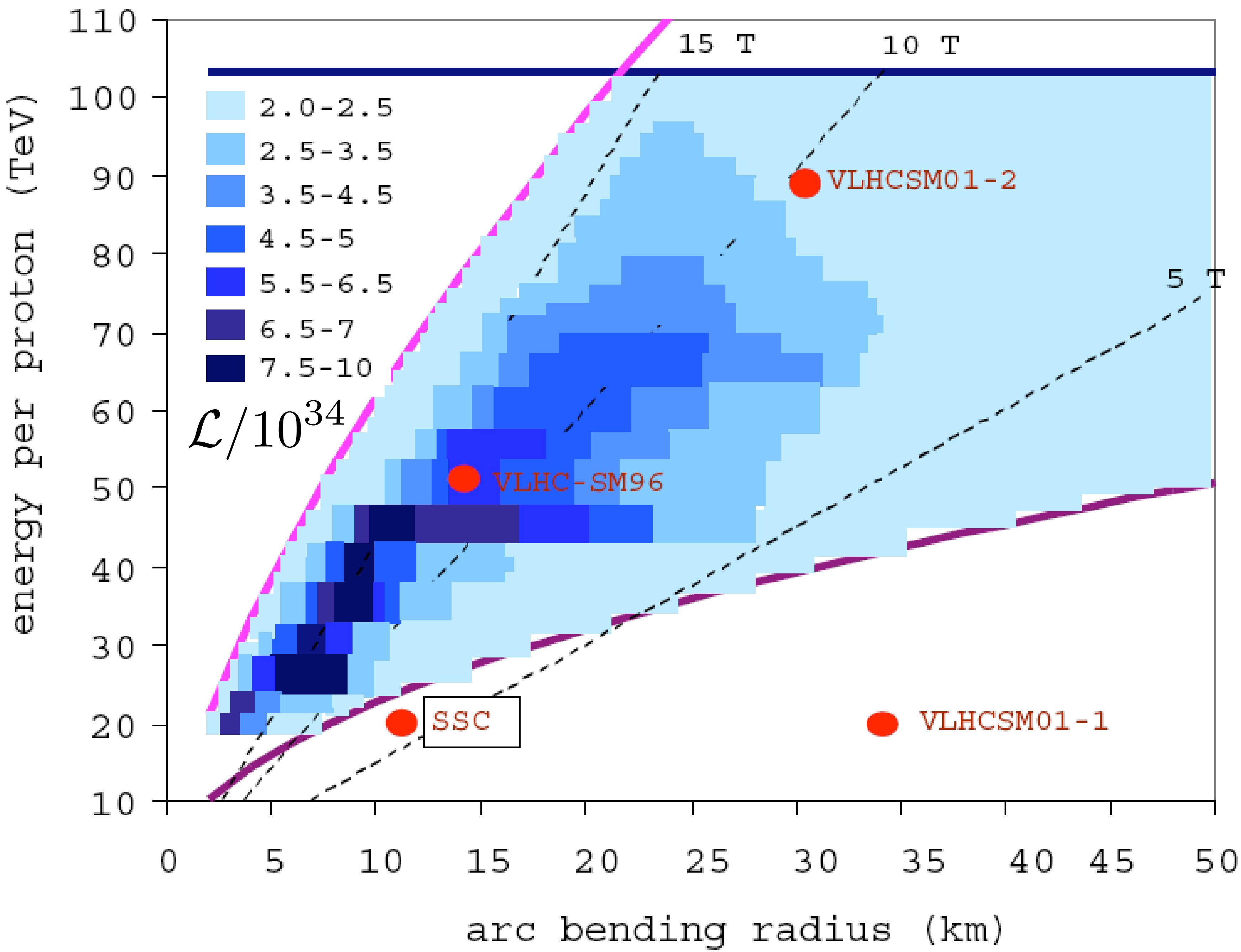
required high luminosity, $\mathcal{L} \sim E_{\rm CM}^2$ , while the pp total cross section remains at the 100 mb level.

The LHC already envisions a luminosity upgrade to $10^{35}/{\rm cm}^2/{\rm sec}$ ; this gives 200 events/crossing.

# VLHC parameters at Snowmass 2001

| | **Stage 1** | **Stage 2** |
|---|---|---|
| Total Circumference (km) | 233 | 233 |
| Center-of-Mass Energy (TeV) | 40 | 175 |
| Number of interaction regions | 2 | 2 |
| Peak luminosity ($cm^{-2}s^{-1}$) | $1 \times 10^{34}$ | $2.0 \times 10^{34}$ |
| Luminosity lifetime (hrs) | 24 | 8 |
| Injection energy (TeV) | 0.9 | 10.0 |
| Dipole field at collision energy (T) | 2 | 9.8 |
| Average arc bend radius (km) | 35.0 | 35.0 |
| Initial number of protons per bunch | $2.6 \times 10^{10}$ | $7.5 \times 10^{9}$ |
| Bunch spacing (ns) | 18.8 | 18.8 |
| $\beta^*$ at collision (m) | 0.3 | 0.71 |
| Free space in the interaction region (m) | $\pm 20$ | $\pm 30$ |
| Inelastic cross section (mb) | 100 | 130 |
| Interactions per bunch crossing at $L_{peak}$ | 21 | 54 |
| Synchrotron radiation power per meter (W/m/beam) | 0.03 | 4.7 |
| Average power use (MW) for collider ring | 25 | 100 |
| Total installed power (MW) for collider ring | 35 | 250 |

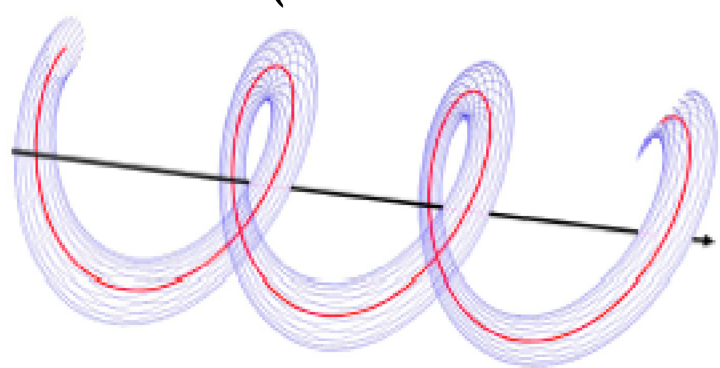
# VLHC parameter space, limited by available magnets, synchrotron power (<10 W/m/beam), events/cross (< 60)



Muon colliders are based on the idea that one might gather muons from intense proton collisions on a target and cool these muons to an emittance that might be acceptable for a storage ring.

Schemes for cooling muons were studied with great enthusiasm in the US in the 90’s, but realistic designs proved to be expensive and inefficient.

But, recently, there is a new idea (Derbenev and Johnson):
`6-D cooling’



employing a helical orbit through an absorbing medium (Li H).

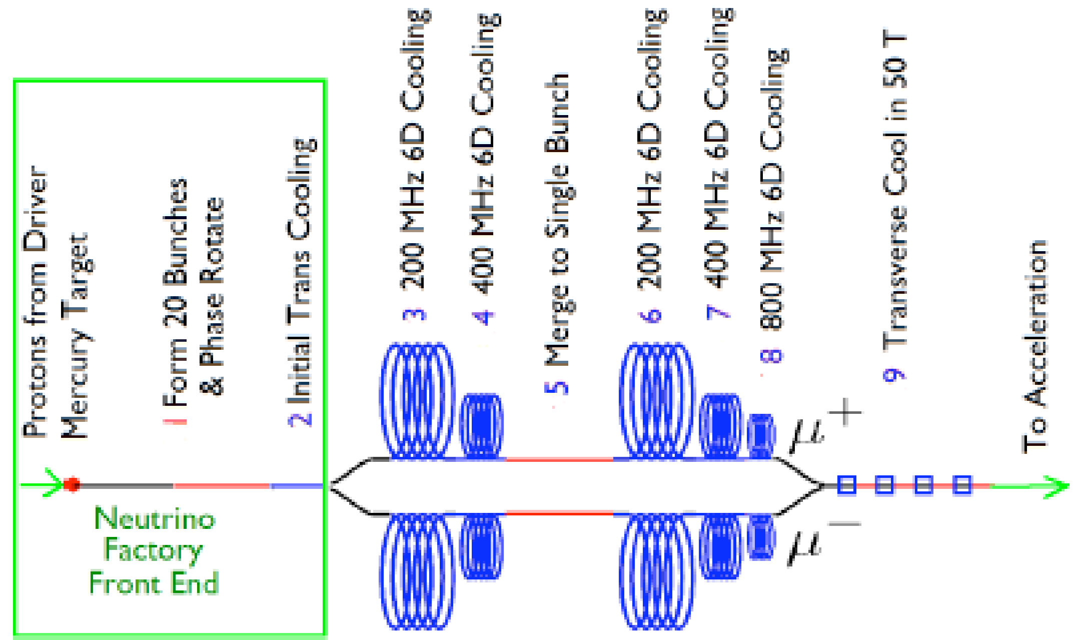
This scheme will be tested in the next few years in a second-generation muon cooling experiment at Fermilab, MANX.

The goal of MANX is a 50% phase space reduction. The eventual collider needs a factor $10^5$ .

Muon colliders also pose severe problems for experimentation. Muons decay in the storage ring, so we expect $\sim 10^6$ 1 TeV electrons and positrons per bunch crossing aimed at the central part of the detector. This makes it very difficult to do vertex detection or to cover forward angles.

parameter table from R. Palmer et al. (2007)

This design requires 50 T solenoids for the final transverses cooling.




| | | | | |
|---|---|---|---|---|
| $E_{\text{c of m}}$ | 1.5 | 4 | 8 | TeV |
| $\mathcal{L}$ | 1 | 4 | 8 | $10^{34}$ cm$^2$sec$^{-1}$ |
| $\Delta\nu$ | 0.1 | 0.1 | 0.1 | |
| $\mu$/bunch | 2 | 2 | 2 | $10^{12}$ |
| $< B_{\text{ring}} >$ | 5.2 | 5.2 | 10.4 | T |
| $\beta^* = \sigma_z$ | 10 | 3 | 3 | mm |
| rms $dp/p$ | 0.09 | 0.12 | 0.06 | % |
| $N_\mu/N_{\mu o}$ | 0.07 | 0.07 | 0.07 | |
| Rep. | 13 | 6 | 3 | Hz |
| $P_{\text{driver}}$ | $\approx$4 | $\approx 1.8$ | $\approx 0.8$ | MW |
| $\epsilon_\perp$ | 25 | 25 | 25 | pi mm mrad |
| $\epsilon_\parallel$ | 72 | 72 | 72 | pi mm rad |

Finally, e+e-.

To go to multi-TeV with a facility of reasonable size, we need high gradient acceleration:

150 MeV/m        factor 5 beyond ILC

This takes us out of the range of superconducting acceleration and back to warm cavities.

There are two problems to be solved:

define the RF power source

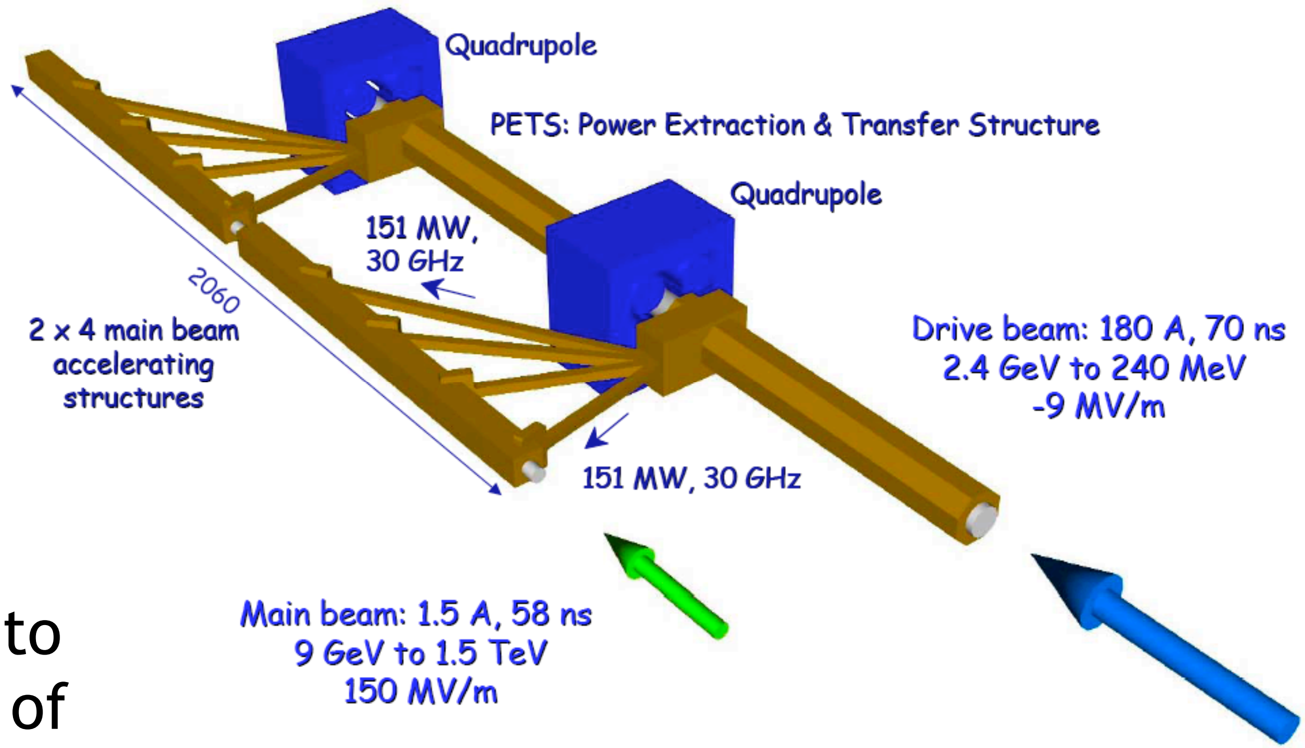
prevent cavities from breaking down after long operation

Also, we need to operate a linear collider above $\mathcal{L} \sim 10^{32}$ before we try to design one that requires $\mathcal{L} \sim 10^{35}$ .

CLIC project at CERN:

proposal of 2-beam acceleration:

high-current low-energy drive beam
frequency-matched cavities,
low-current accelerating beam




In principle, this works at any frequency.

CERN has recently moved to X-band to take advantage of the substantial GLC/NLC experience.

# CLIC parameters at 0.5 and 3 TeV, from 2005 report

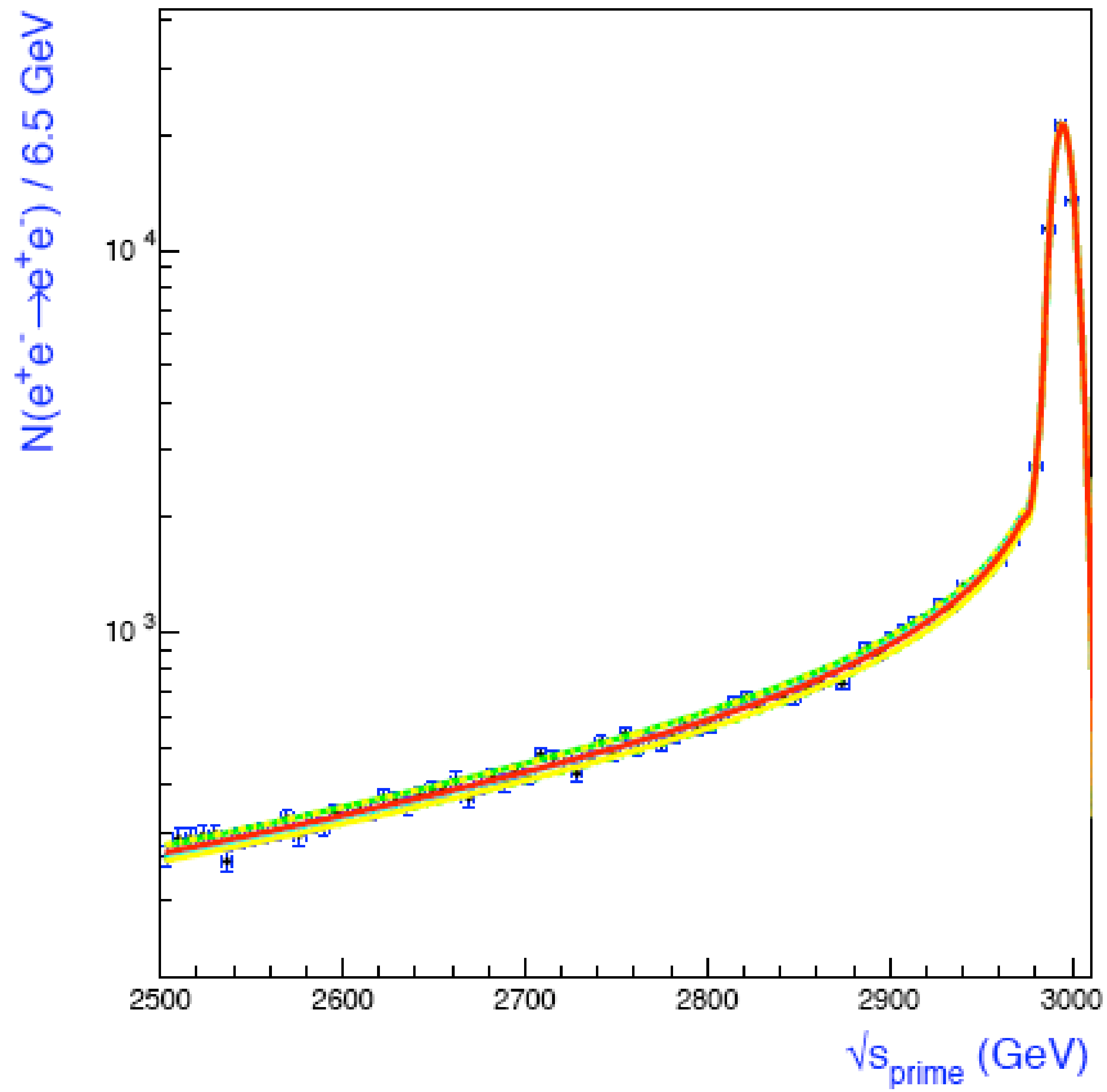
| Collision energy $\sqrt{s}$ (TeV) | 0.5 | 3.0 |
|---|---|---|
| Design luminosity $\mathcal{L}$ ($10^{35}$ cm$^{-2}$s$^{-1}$) | 0.2 | 0.8 |
| Linac repetition frequency (Hz) | 200 | 100 |
| No. of ptcs./bunch $N$ ($10^{10}$) | 0.4 | 0.4 |
| No. of bunches/pulse $n_b$ | 154 | 154 |
| Bunch separation (ns) | 0.67 | 0.67 |
| Bunch length (μm) | 35 | 35 |
| Normalized emittance $\gamma\epsilon_x^*/\gamma\epsilon_y^*$ (m·rad × $10^{-6}$) | 2.0/0.01 | 0.68/0.01 |
| Beam size at collision $\sigma_x^*/\sigma_y^*/\sigma_z^*$ (nm/nm/μm)) | 202/12/35 | 60/0.7/35 |
| Energy spread $\Delta E/E$ (%) | 0.25 | 0.35 |
| Crossing angle (mrad) | 20 | 20 |
| Beamstrahlung $\delta_B$ (%) | 4.4 | 21 |
| Beam power/beam (MW) | 4.9 | 14.8 |
| Gradient unloaded/loaded (MV/m) | 150 | 150 |
| Two-linac length (km) | 5.0 | 28.0 |
| Beam delivery length (km) | 5.2 | 5.2 |
| Final focus length (km) | 1.1 | 1.1 |
| Total site length (km) | 10.2 | 33.2 |
| Total AC power (MW) | 175 | 410 |

CLIC luminosity spectrum (3 TeV)

$\mathcal{L} = 10^{35}$

The expected luminosity spectrum is not as sharply peaked as at ILC, but still sharp enough for e+e- style precision measurement.

beam cross section
60 x 0.7 nm



a difficulty, also inherited from GLC/NLC:

frequent cavity breakdown and eventual self-destruction
at gradients above 100 MeV/m

Tantawi: 'We cannot predict experimental data or
extrapolate on it.'

materials other than Cu may help? (CERN: Mo elements)

standing-wave structures, rethinking RF input, may help ?

may need distributed input, new RF power source ?

My scorecard:

pp colliders : stalled for lack of ideas

$\mu^+\mu^-$ colliders: interesting new ideas, but these are very challenging to implement

$e^+e^-$ colliders: relatively small gap to an interesting machine; new ideas welcome

If we imagine a 40-year lifetime of the ILC lab, the multi-TeV $e^+e^-$ collider would be the next machine in the ILC tunnel.

Remember that the ILC Final Focus, crossing angle anticipate running up to 5 TeV.

When we realize these machines, what physics will we explore ?

Naturally, we follow the new physics discovered at the LHC to higher energies. However, different models have very different extrapolation to high energies.

Most of the differences concern the heavy particles and possible resonance structure associated with their new interactions.

However, I would first like to pick up two topics that we might find in our first encounter with new physics:

heavy stable (s)leptons , new gauge bosons

These objects give distinct signatures at the LHC that can be discovered in very early data, in the actual first 100 pb-1.

Among models of new particle sectors with dark matter, it is possible that the lightest particle is not one with Standard Model quantum numbers but rather a partner of the graviton or another particle with gravitational-strength interactions.

The lightest Standard Model partner will decay to this particle with a long lifetime. In supersymmetry,

$$\tau \sim \frac{1}{G_N} \frac{m_{\widetilde{G}}^2}{m_L^5}$$

We will need to modify the formula given in the previous lecture for the cosmic density of dark matter.

$$\Omega = \frac{1 \text{ pb}}{\langle \sigma_{LL} v \rangle} \cdot \frac{m_{\widetilde{G}}}{m_L}$$

But still this formula implies hundred-GeV-scale dynamics.

If the lifetime satisfies

$$\tau_L > 1\mu\text{sec}$$

this particle will be stable from the viewpoint of LHC detectors.

The graviton partner is a superWIMP with zero cross section for all practical purposes. This is frustrating for astrophysical dark matter searches, but these scenarios can be discovered and tested at the LHC.

Feng, Rajaraman, Su, Takayama

In model of electroweak symmetry breaking, the easiest particle to make light are the partners of the $\gamma$ or the $\tau_R$. The $\tau_R$ is actually preferred, because gammas from the decay of the $\gamma$ partner can disrupt elements formed in primordial nucleosynthesis.

In supersymmetry, the $\widetilde{\tau}_R$ can be made light using terms enhanced at large $\tan\beta$ .

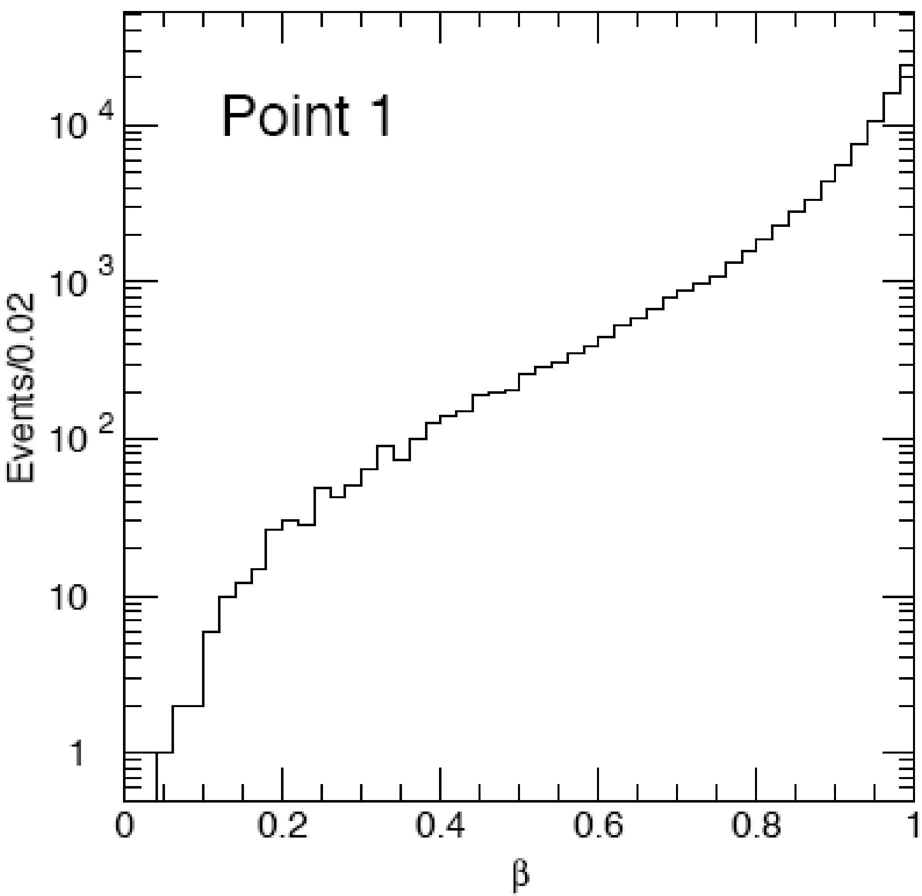
This physics appears naturally in regions of the mSUGRA parameter space and in gauge-mediated supersymmetry breaking.

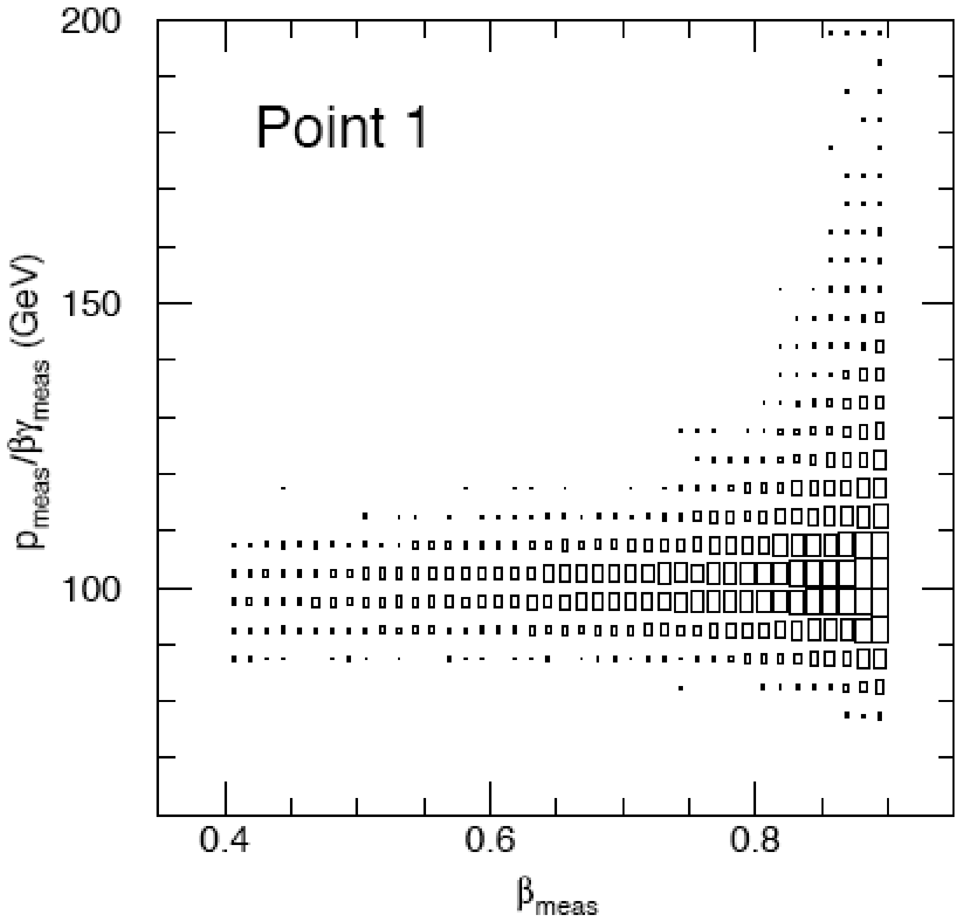
Every supersymmetry events at the LHC contains two apparently stable sleptons !

Kawasaki, Kohri, Moroi

Stable heavy lepton partners appear as muons which are slow but can still be within the time bucket of the muon system.

Using $\beta\ vs.\ p$ , it is possible to measure the mass to 0.1%.



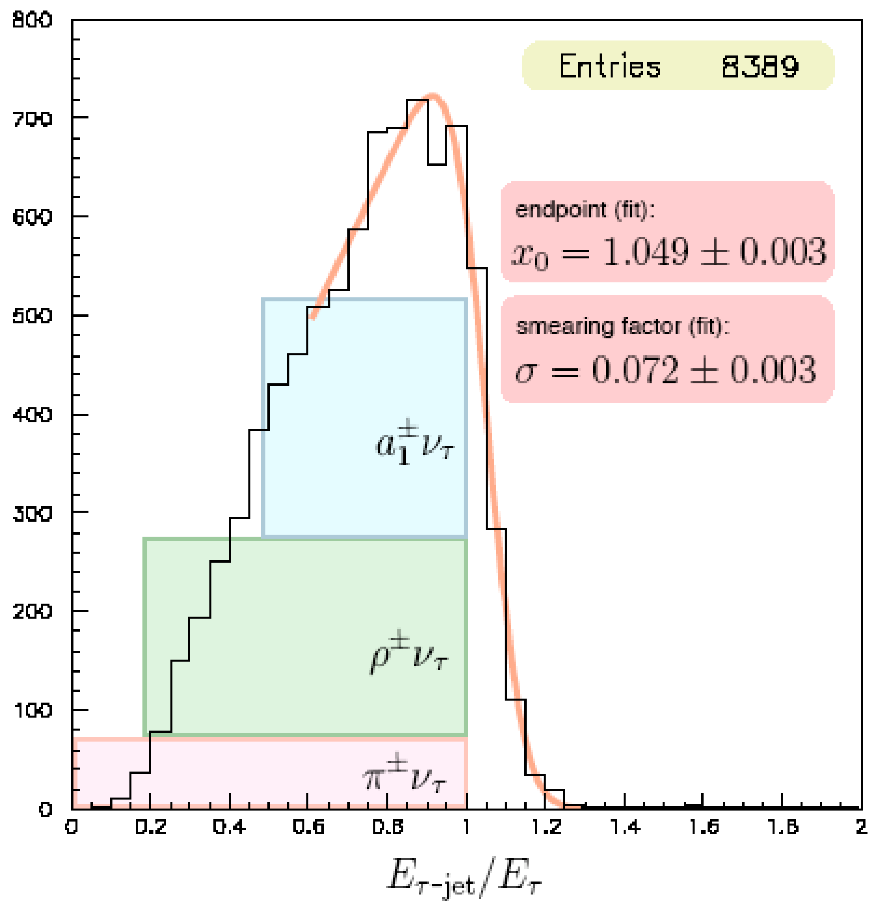

Ambrosanio, Mele, Petrarca, Polesello, Rimoldi

Gauginos decay to the NLSP by

$$\widetilde{\chi}_i^0 \rightarrow \tau^+ \widetilde{\tau}^-$$

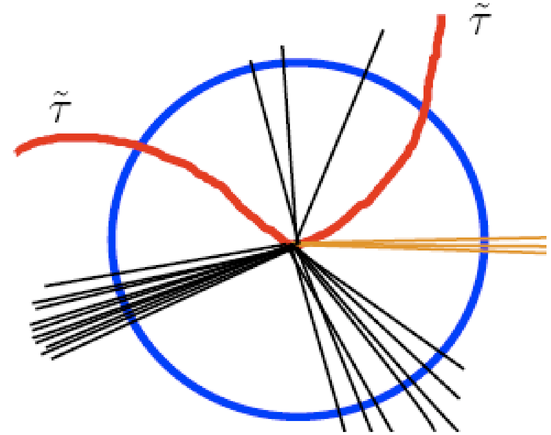
so we can measure the spectrum of gauginos by associating $\tau$ jets with staus. Of course, the $\tau$ is not observed completely. But in hadronic $\tau$ decays, the LHC detectors can see most of the energy.

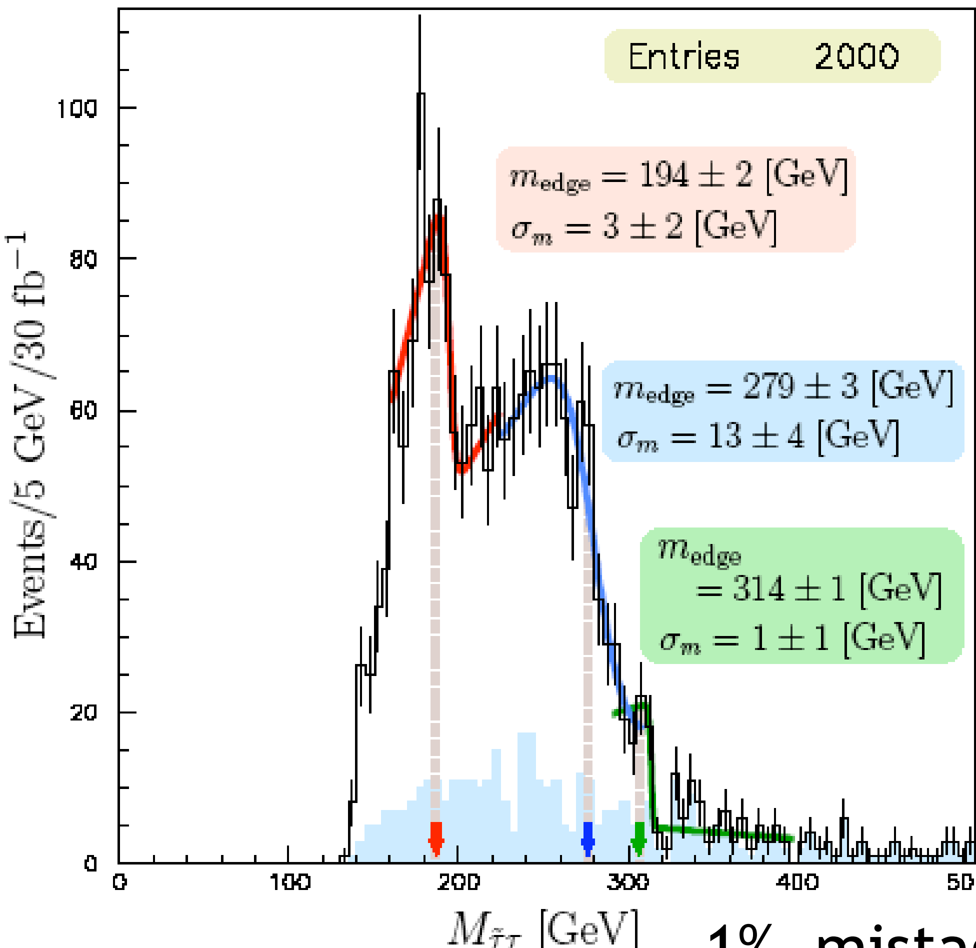
Kitano + Ibe

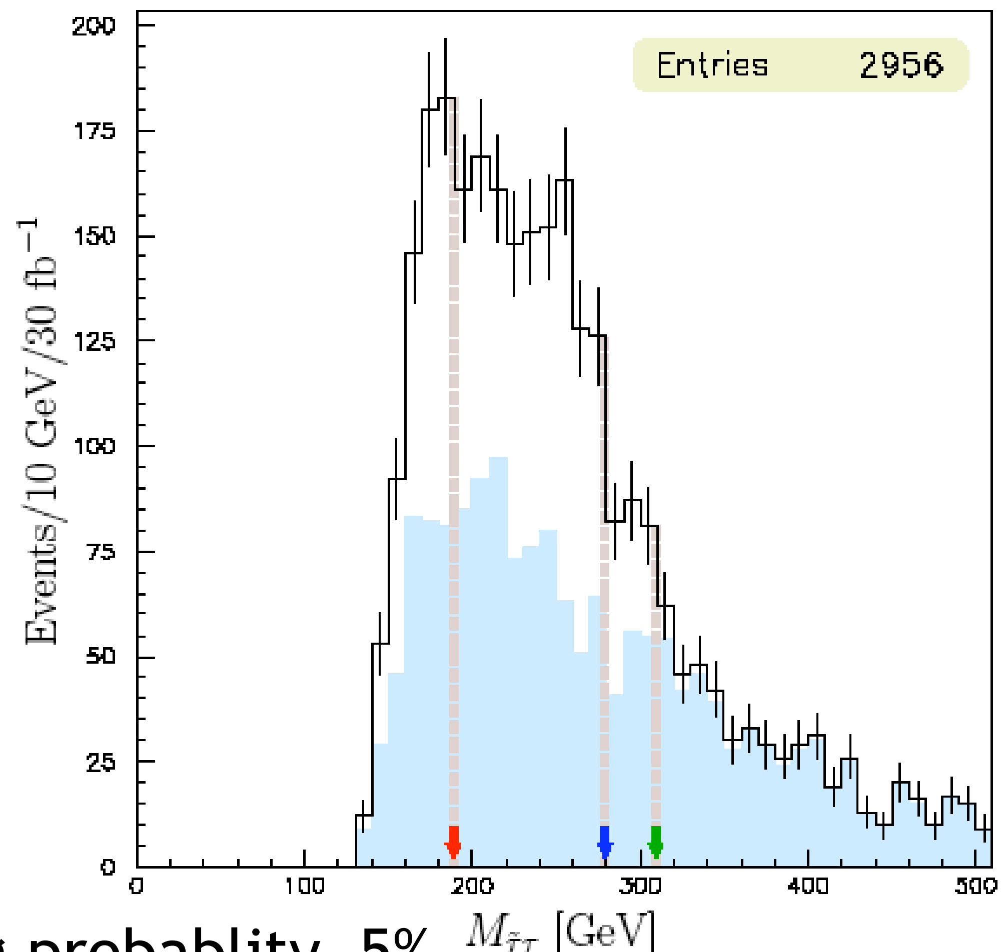



HERWIG + TAOULA + AcerDET

So we can combine stable $\tilde{\tau}$s with $\tau$ jets and look for resonances. Including detector effects, these appear as kinematic edges.



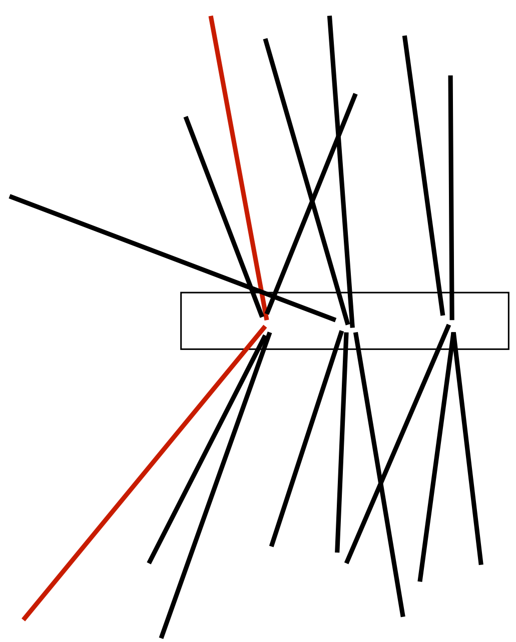




1% mistag probablity 5%

The idea that every supersymmetry event contains stable sleptons might be a bonus for very high energy pp experiments.

A possible strategy would be to trigger only on events with long-lived heavy particles. Their tracks would point back to the production vertex of the new heavy particles. With good z resolution, this would aid the selection and analysis of events in the presence of hundreds of events/crossing.



At LEP and Tevatron energies, we see the gauge group

$$SU(3) \times SU(2) \times U(1)$$

It is likely that the true gauge group in Nature is larger. We know that some gauge bosons get mass at the 100 GeV scale; why not others at the TeV scale ?

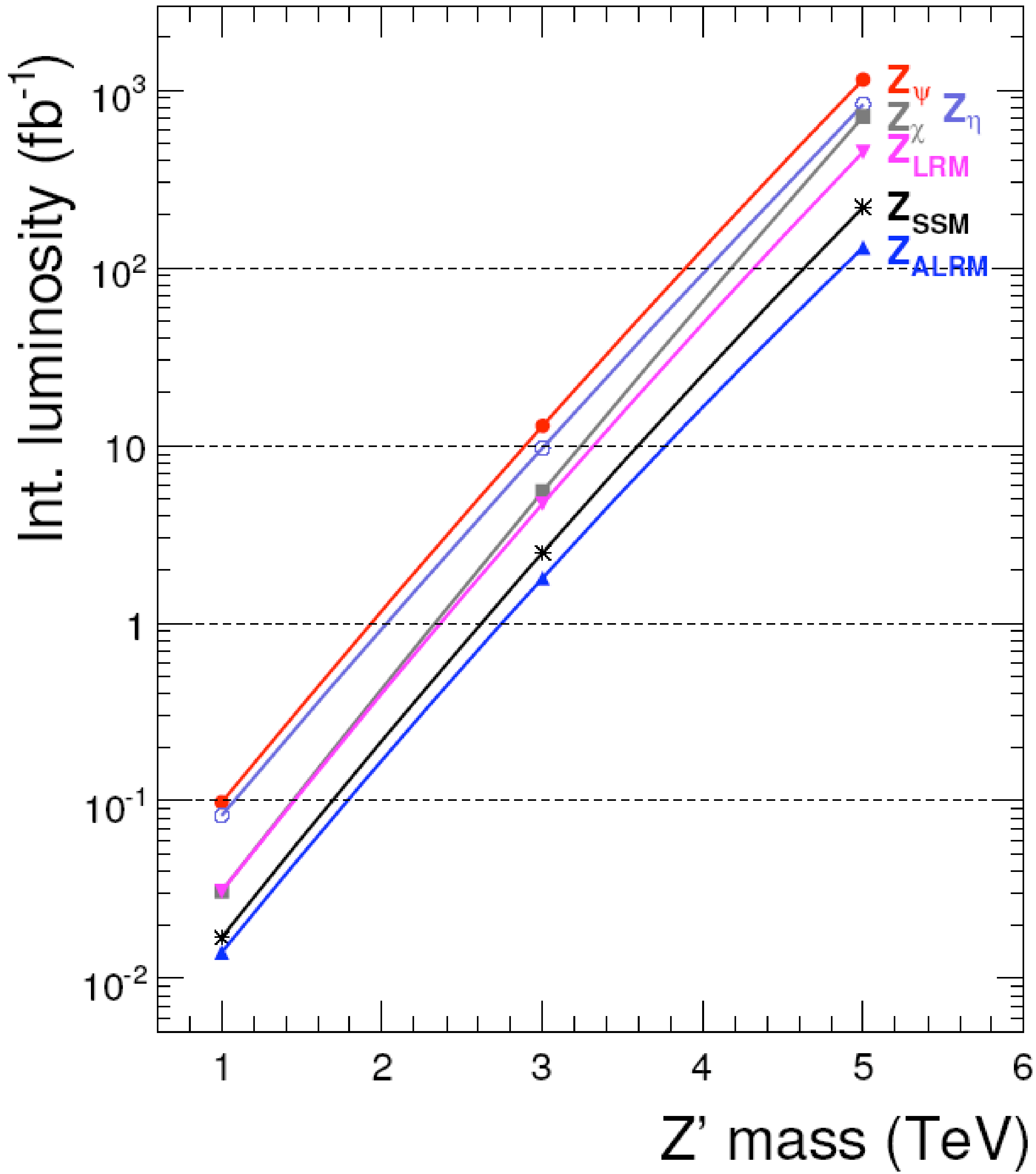
Gauge bosons with mass > $m_Z, m_W$, but obtaining mass from the same physics, appear naturally in models with extended grand unification groups and in superstring models.

Extra-dimensional models predict similar structures, as we will discuss later.

For states visible in

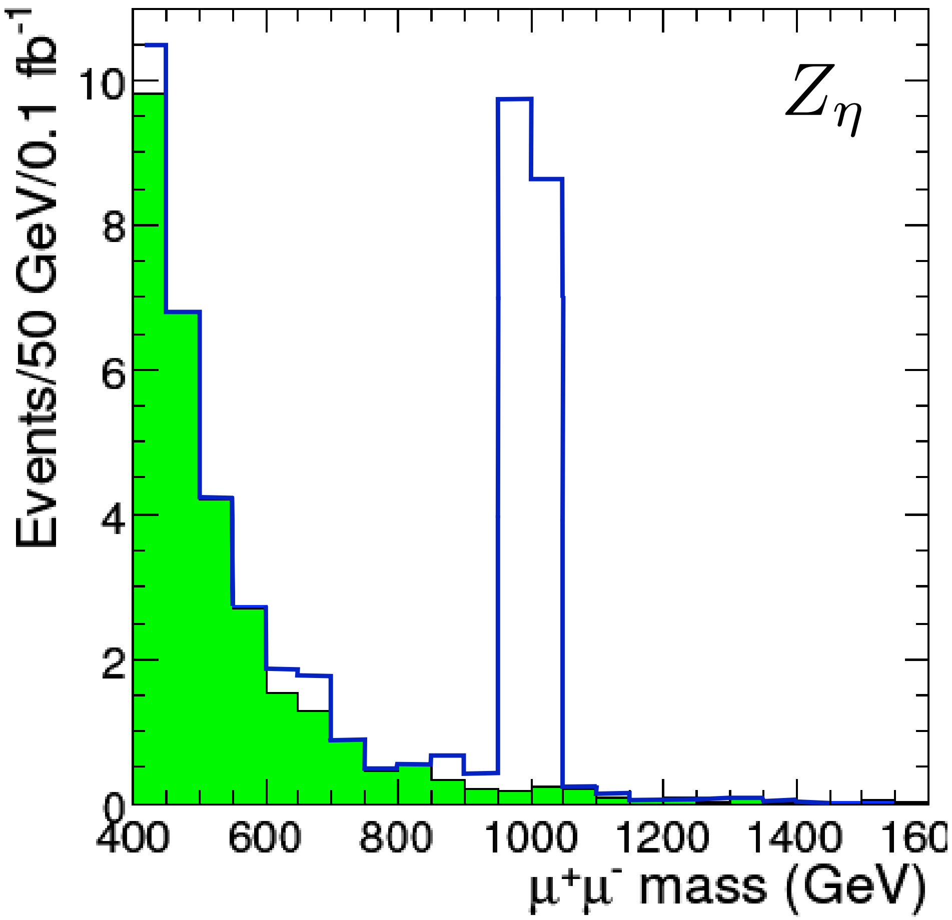
$$pp \to Z' \to \mu^+\mu^-$$

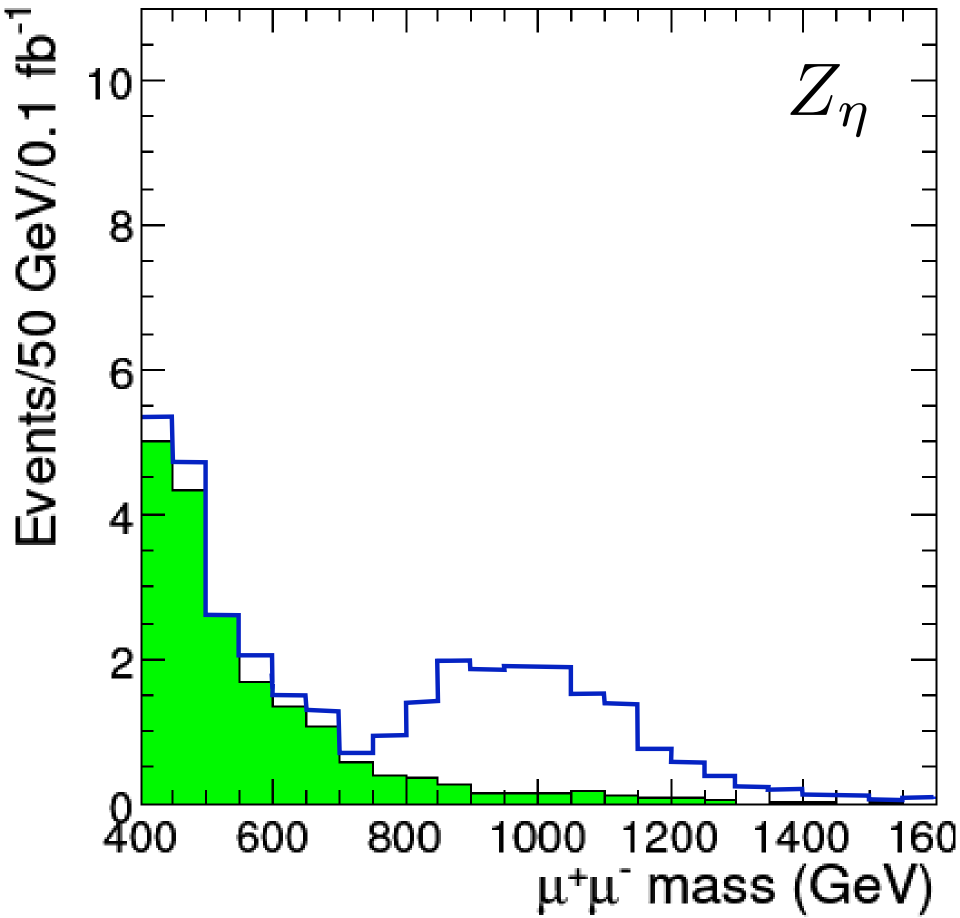
the LHC has exceptional sensitivity at low values of luminosity.




CMS Physics TDR

For low values of mass, these resonances can be discovered even before aligning the muon system.




CMS Physics TDR

Although these resonances might decay only to Standard Model particles, they could decay to new particles.

Strassler and Zurek have proposed that there are entirely new sectors (‘Hidden Valleys’), not coupled to quarks and leptons by any Standard Model interactions, that are accessed through new vector resonances.

Depending on the signature of the ‘hidden’ particles

(jets or leptons with ET > TeV;  long lifetimes;  muliple b jets)

it may be interesting at a high-energy, very high luminosity hadron collider to trigger only on events of this type.

The discovery of new vector resonances would be a tremendous boost for the ILC even if these resonances had masses well above 500 GeV.

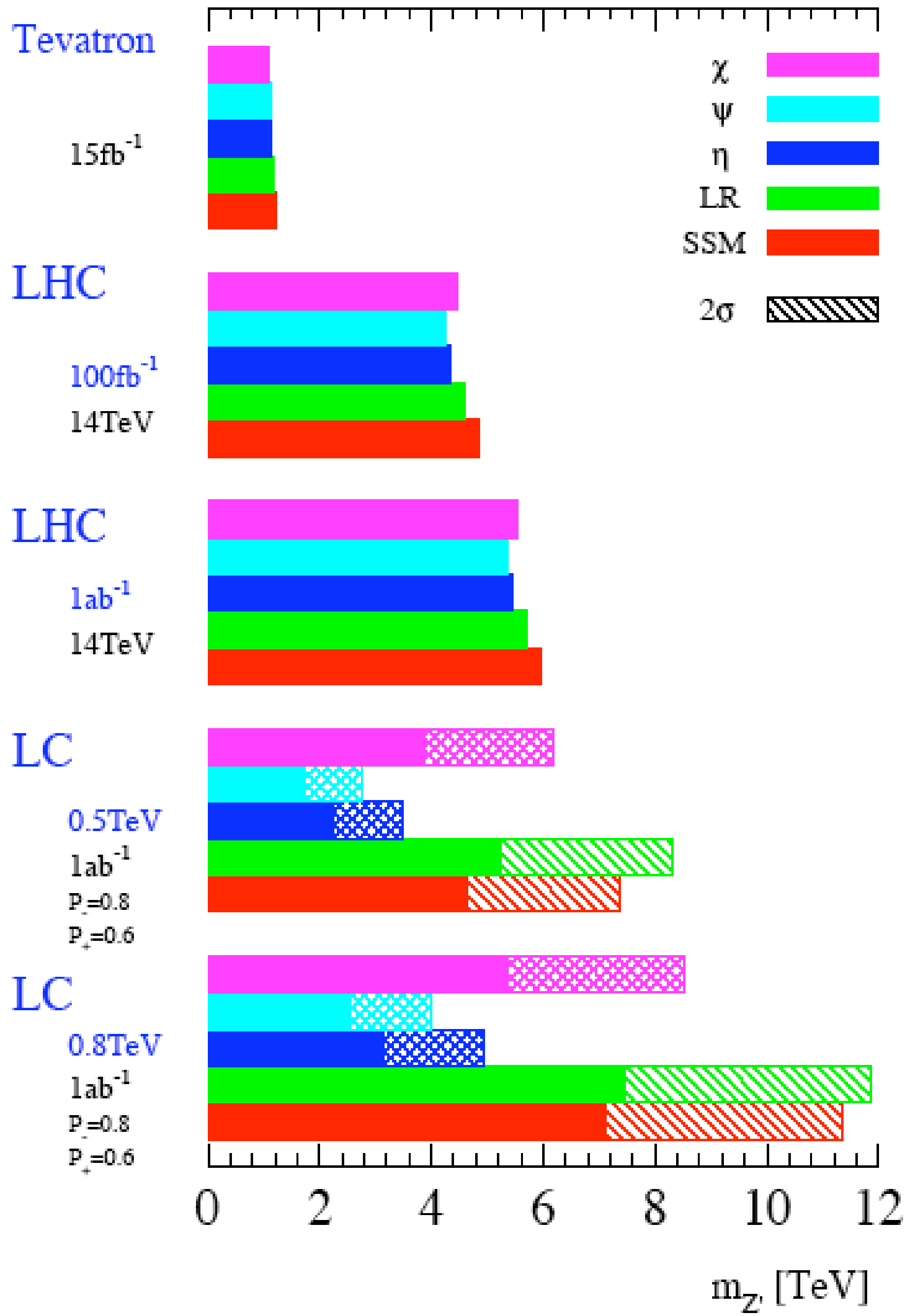
At the LHC, we can measure only a few of the couplings of these resonances to Standard Model particles:

$$\sigma(q\overline{q} \to Z') \cdot BR(Z' \to \ell^+\ell^-)$$
$$A_{FB}(q\overline{q} \to Z' \to \ell^+\ell^-)$$
$$\Gamma(Z')$$

At the ILC, we will see these resonances as interferences in $e^+e^- \to f\overline{f}$ , and every flavor and polarization channel gives new information.

comparison of sensitivity to a new Z resonance

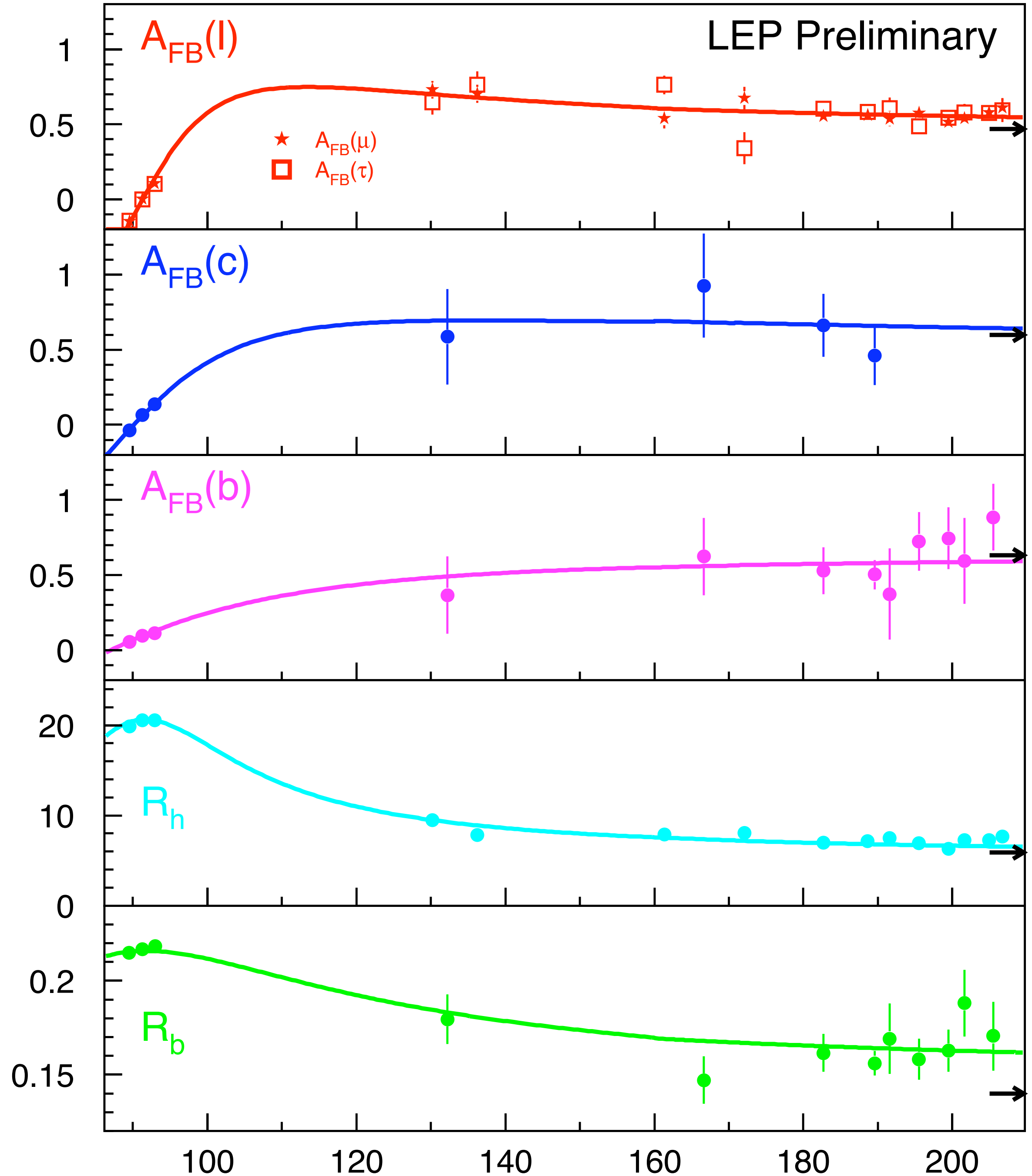
Weiglein et al.



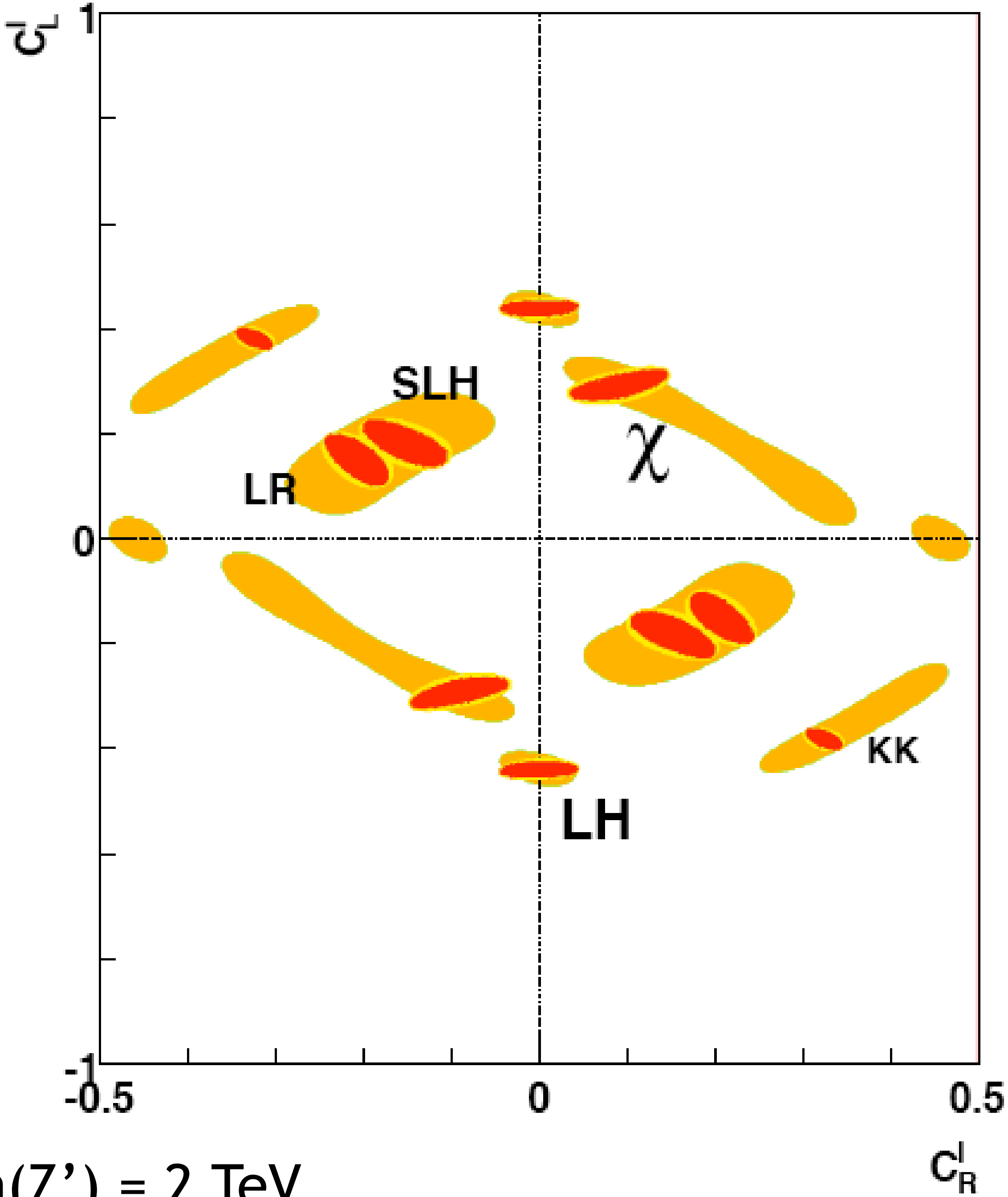
LEP 2 tests of SU(2)xU(1)

for ILC, add

initial-state polarization
efficient b,c tagging
polarization
per mil level of accuracy




data compilation
by Hildreth



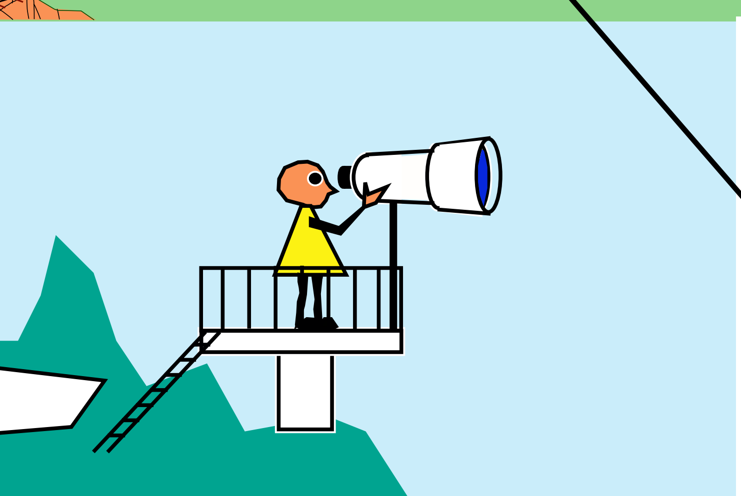

500 GeV, m(Z’) = 2 TeV
1 ab-1, $e^+e^- \to \mu^+\mu^-$

Godfrey, Kalyniak, Tomkins

Let us now proceed in a more systematic way through the high-energy signatures of new physics models.

Begin with supersymmetry.

Do you remember this picture, which used to be hanging in the ATF hall?

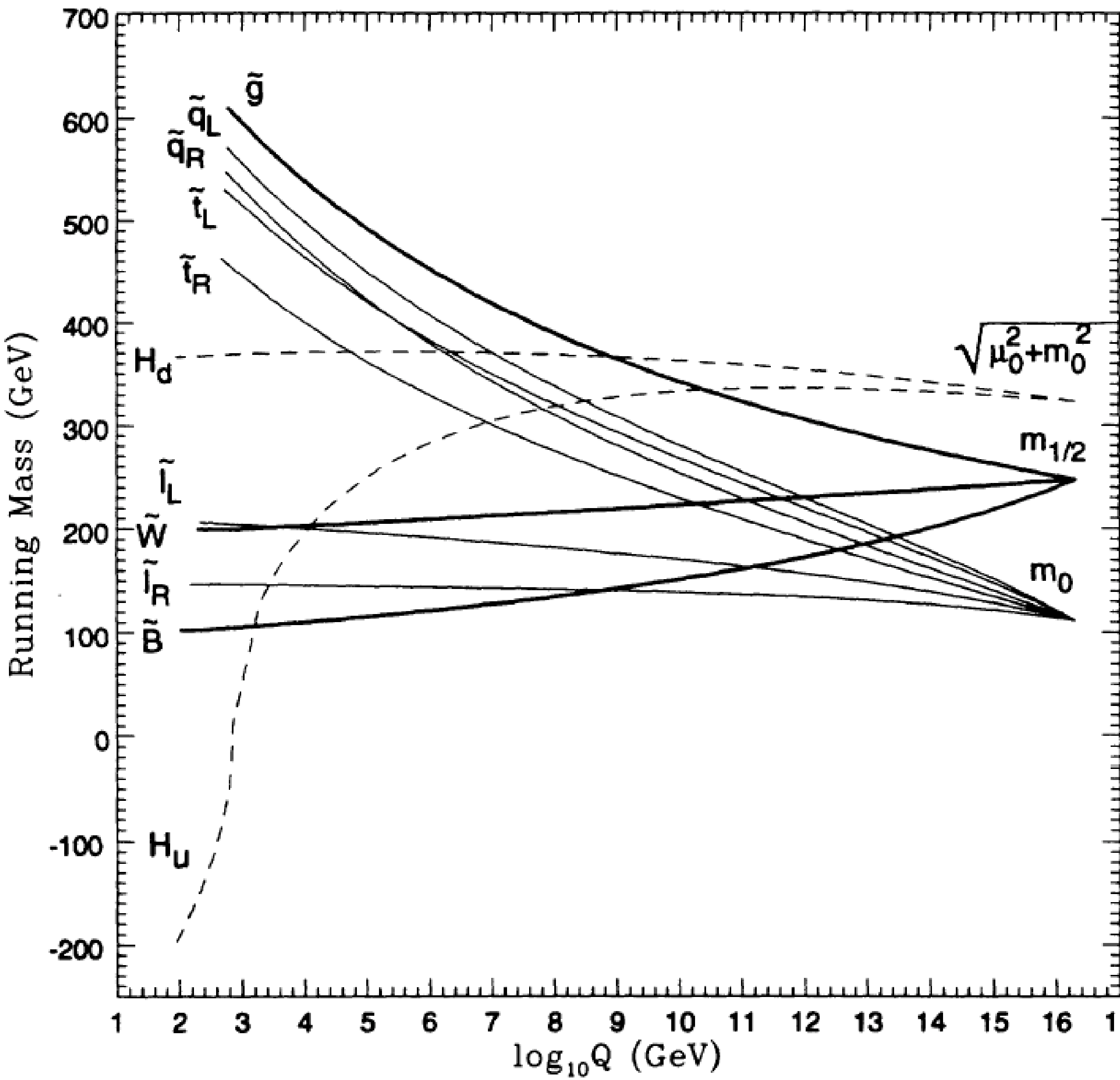
grand desert

supersymmetric land

As I discussed in the first lecture, the mechanism of electroweak symmetry breaking in supersymmetry comes from renormalization group equations. We start at the Planck or GUT scale integrate an differential equation whose variable is $\log Q$ , and eventually find that $m_H^2(Q) < 0$ .

Such a theory can generate deserts of many orders of magnitude in size, with no obvious reference points between the upper and lower scales.

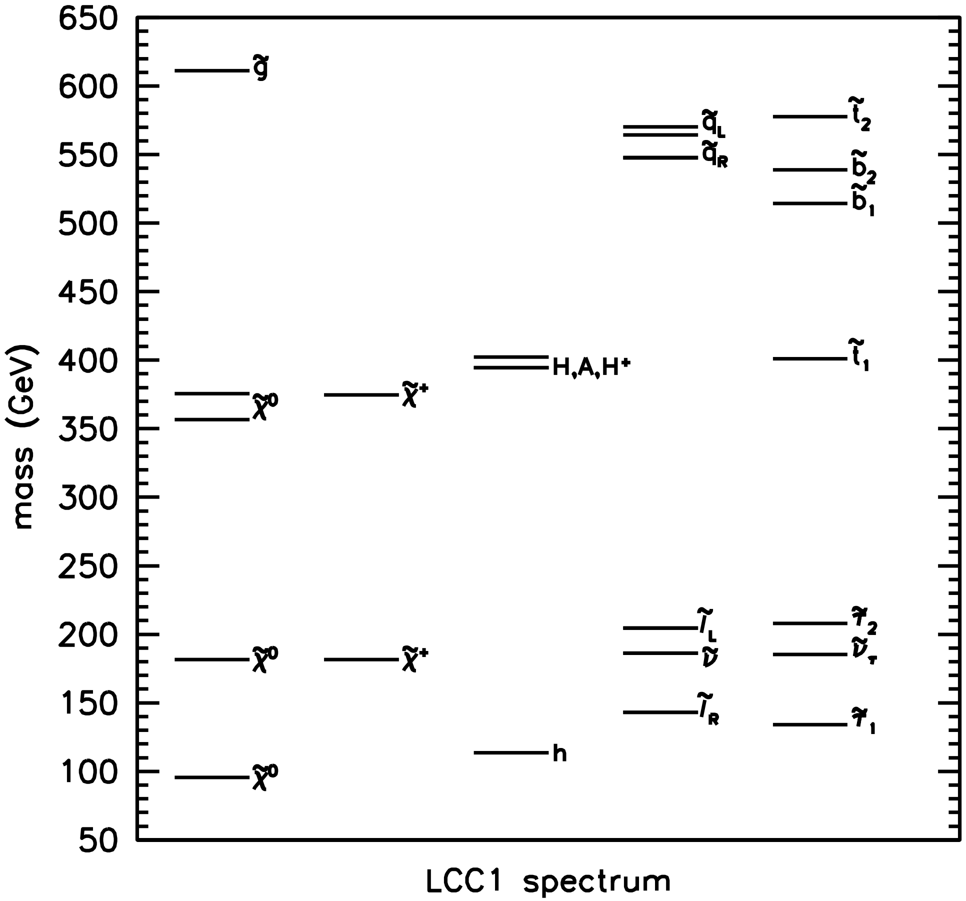
So it is possible in supersymmetry that once that TeV scale physics is over, we will not be able to learn more with accelerators for the foreseeable future.

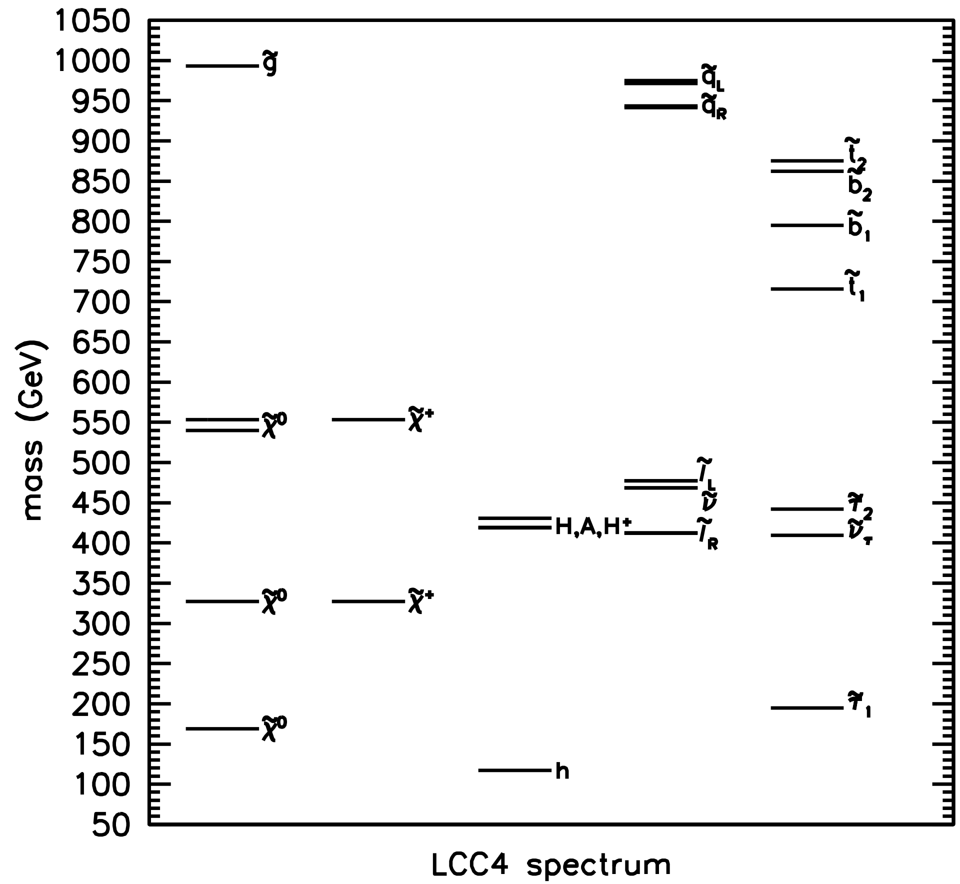



Kane, Kolda, Roszkowski, Wells

But, where does the TeV scale physics end ?

Here are two spectra from our dark matter study:




In a third model, the squarks and sleptons were at 3 TeV.

It is relatively uncommon in realistic supersymmetry models that an e+e- collider at 500 GeV, or even 1 TeV, can reach the squark thresholds.

The current limit from the Tevatron is $m(\widetilde{q}) > 300 \text{ GeV}$ .

But there are important questions to be answered by subjecting the squarks to the same program of precision measurements that I discussed in the previous lecture for sleptons and gauginos.

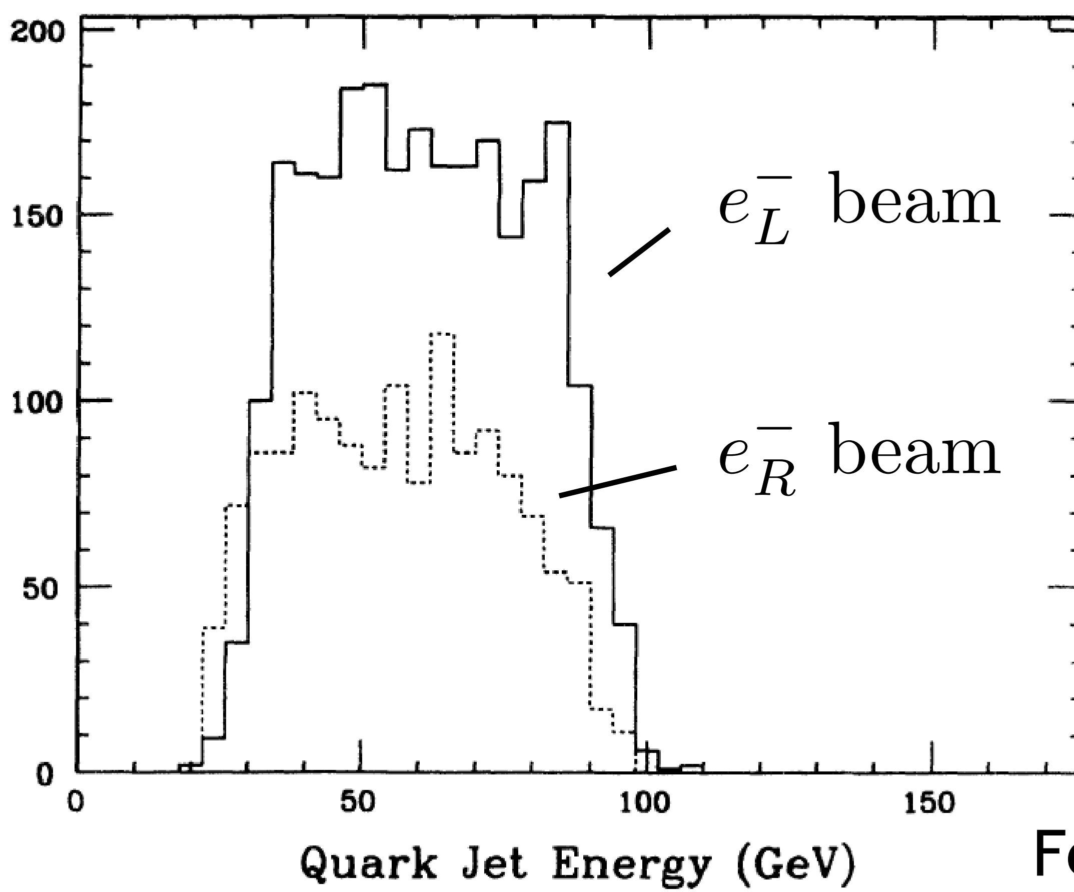
Are squarks with the same electroweak quantum numbers degenerate ?

What are the mass splittings between the squark partners of right- and left-handed quarks ?

Universality at the GUT scale predicts a 5% mass difference.

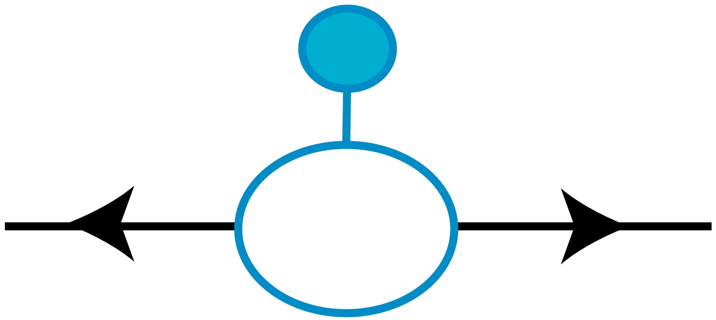
Does each squark decay to quark of a particular flavor, or is there flavor-mixing in squark decay ?

I remind you that it is possible to measure small mass differences between squarks in the LC environment. The QCD physics that converts an emitted quark to a jet is the same for each species and chirality, so we only need to make a precision comparison of jet energies or endpoints.




Feng and Finnell

It is possible that the physics of supersymmetry breaking could be within reach of collider experiments. In gauge mediation, supersymmetry breaking for Standard Model superpartners arises from supersymmetry breaking in a new sector containing particles with couplings to SU(3) x SU(2) x U(1).



There is no reason why this sector cannot be as light as 10 TeV. In that case, the gravitino is light ( < 1 eV), and Standard Model superpartners decay to it promptly. So we will have evidence already at the LHC this sector is light and can be a target of higher-energy accelerators.

Dine, Seiberg, and Thomas have argued that the existence of such a sector at 10 TeV can explain why the Higgs is heavier than expected in the MSSM.

Extra-dimensional models have a fixed scale, the size scale of the extra dimensions. Today, we only know that this scale is close to or above 1 TeV. However, if we find evidence for extra dimensions at the LHC, it will be important to get far above this scale to see the geometrical picture associated with the extra dimensions.

The simplest examples occur when the energy scale of extra dimensions is TeV and SU(3) x SU(2) x U(1) gauge bosons live in the 'bulk', that is, in the higher dimensions.

The quantum states of these gauge bosons have the form

$$f_n(y) e^{-iE_n(k)t + i\vec{k}\cdot\vec{x}}$$

where $f_n(y)$ are solutions of the Laplace equation over the extra dimensions:

$$-\nabla^2 f_n(y) = m_n^2 f_n(y)$$

The energy of this wavefunction is given by

$$E_n(k)^2 = |\vec{k}|^2 + m_n^2$$

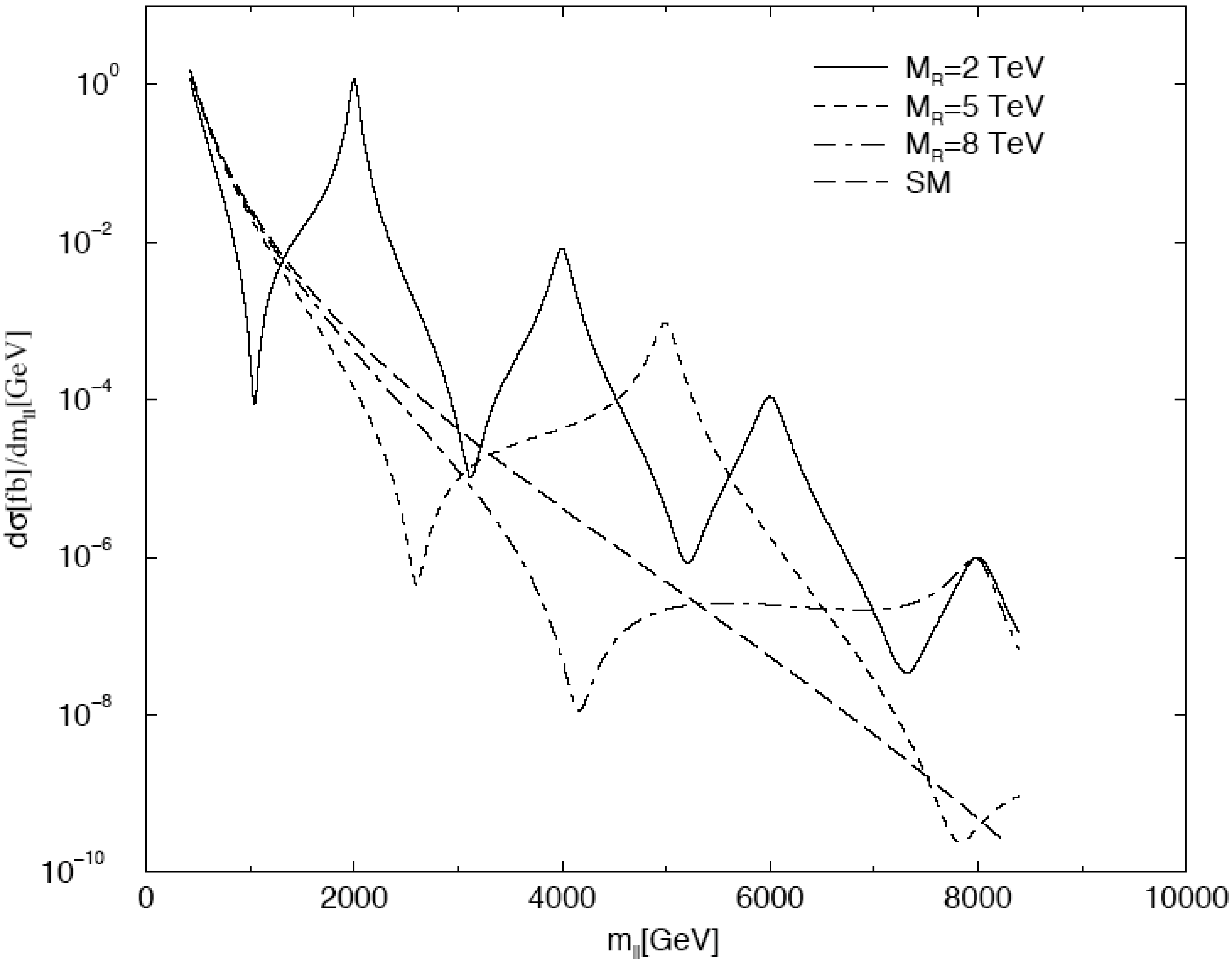
so $m_n$ is the mass of the resonance from the viewpoint of an effective 4-d description. This sequence of resonances is called the 'Kaluza-Klein tower'.

The masses $m_n$ correspond to the Fourier spectrum of waves in the extra dimensions.

Mark Kac asked, "Can you hear the shape of a drum ?"

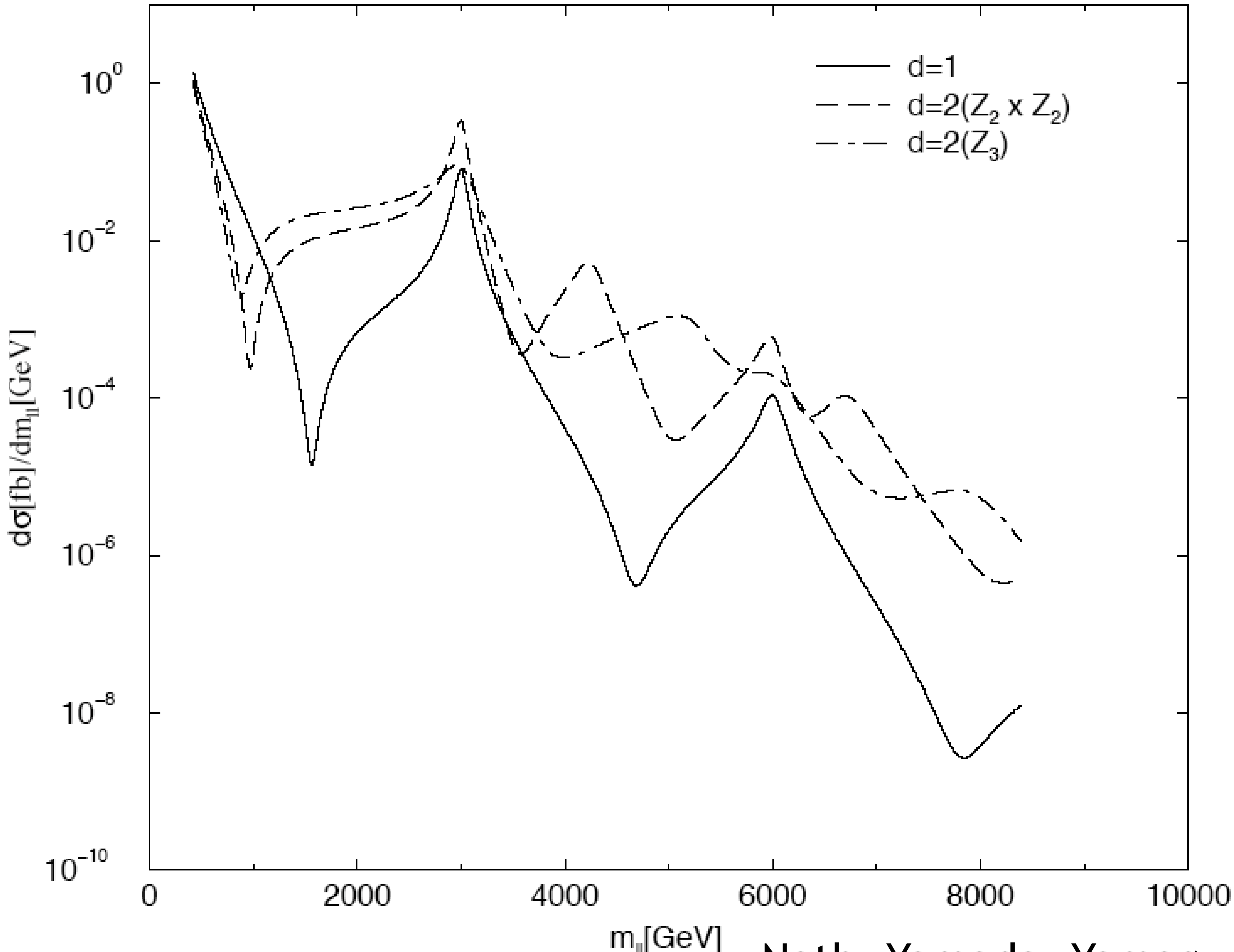
In this model, we will hear the shape of the new dimensions by observing the natural modes as particle resonances.

$pp \to \ell^+\ell^- + X$



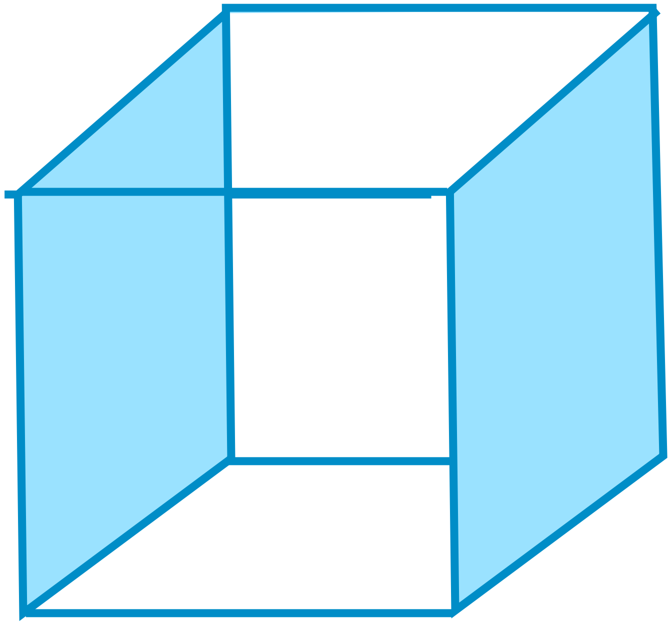

Nath, Yamada, Yamaguchi

$pp \to \ell^+ \ell^- + X$




Nath, Yamada, Yamaguchi

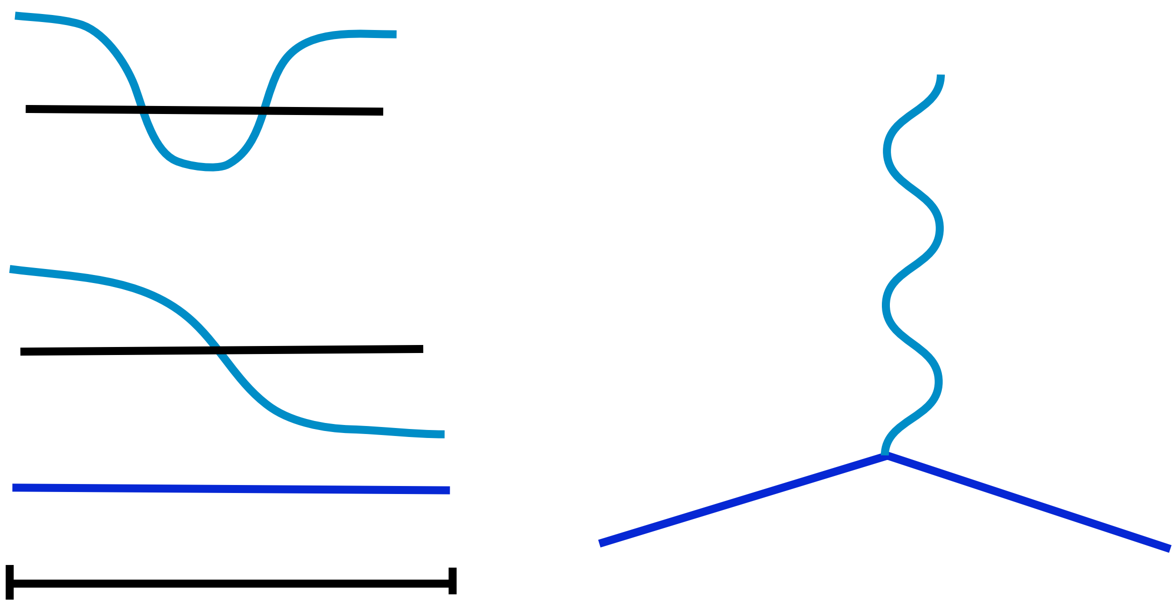
The amplitudes of these resonances depend on whether Standard Model fermions are in the bulk or ‘on the brane’, that is, on a 3-d hypersurface in the large space.



Both possibilities are considered in model-building, and both possibilities can arise from more fundamental approaches such as string theory.

If fermions are on the brane and gauge bosons are in the bulk, the couplings of quarks and leptons to KK resonances are full-strength, $\mathcal{O}(g)$.

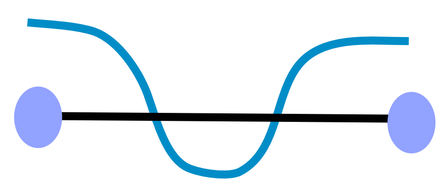
However, if fermions are also in the bulk, these couplings are suppressed. Because we want quarks and leptons to be massless in the first approximation, their wavefunctions are constant in the extra dimensions. The resonances have nontrivial - in fact, orthogonal - wavefunctions.



The transition from the zero-mass wavefunctions to level 1 is forbidden by parity $P_5$ . This is actually a good thing. $P_5$ is the discrete quantum number carried by new particles that keeps the dark matter candidate stable.

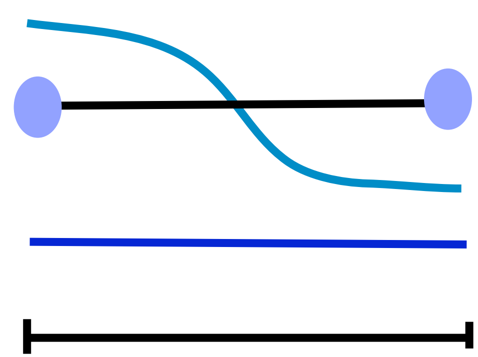
The suppression of the coupling to a level-2 resonance is not absolute. Radiative corrections generate some boundary terms, e.g.,

$$\int_{\partial M} d^3x \; (F_{\mu\nu})^2$$



These permit the 0 -> 2 transitions with suppressed stregth,

$$\mathcal{O}(\epsilon g) \quad \epsilon \sim 0.1 - 0.3$$



For ILC physics, this is not good.  Interference effects of a high-energy resonance, as observed at 500 GeV, are $\mathcal{O}(\epsilon^2)$ .

At a higher energy machine, we will want to carry out experiments at the n = 2 resonance energy.  Then the peak cross section is suppressed by $\mathcal{O}(\epsilon^2)$ .  However, it is no problem; this is still a factor 10 above the standard e+e- annihilation cross section.

On resonance, decays back to light standard model fermions have branching ratios of $\mathcal{O}(\epsilon^2)$.  But branching ratios to particles at the n=1 are $\mathcal{O}(1)$.   We have a KK factory !

So far, I have only discussed flat or smoothly curved extra dimensions. However, some of the most interesting ideas involved warped extra dimensions. This idea starts from anti-de Sitter space in the coordinate system

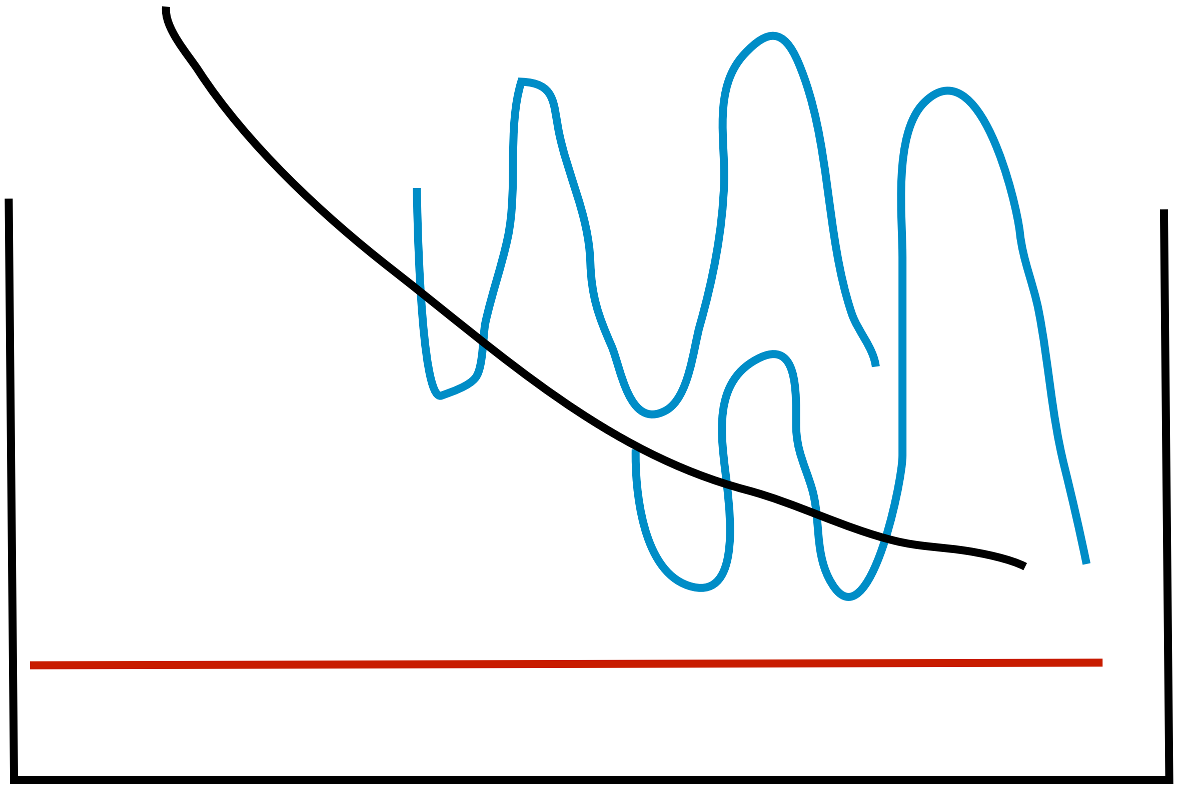
$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

displaying a flat 4-d section whose size is a strong function of the fifth dimension. We represent the universe as a slice from y = 0 (the 'Planck brane') to y = $\pi r_c$ (the 'weak brane').

Randall and Sundrum proposed this as the solution to the problem of the divergent corrections to the Higgs mass. They proposed that the UV cutoff should vary across the fifth dimension, keeping a constant scale in s as distances vary in x. For $k\pi r_c \sim 10$, the cutoff varies from $M_{\rm Pl}$ on the Planck brane to TeV on the weak brane.

The Laplace equation in this geometry has a zero-mode solution that is constant in y, and nonzero-frequency solutions localized near the TeV brane. When these wavefunctions are correctly normalized, the zero-mode couples to particles on the TeV brane with gravitational strength, but the lowest nonzero modes couple with ordinary electroweak strength.

The masses are the zeros of Bessel functions, with n = spin.



With this viewpoint, it is possible to charge ahead into the extra-dimensional phenomenology of the Randall-Sundrum model.

At the minimum, we have the Standard Model on the TeV brane and gravity in the bulk.

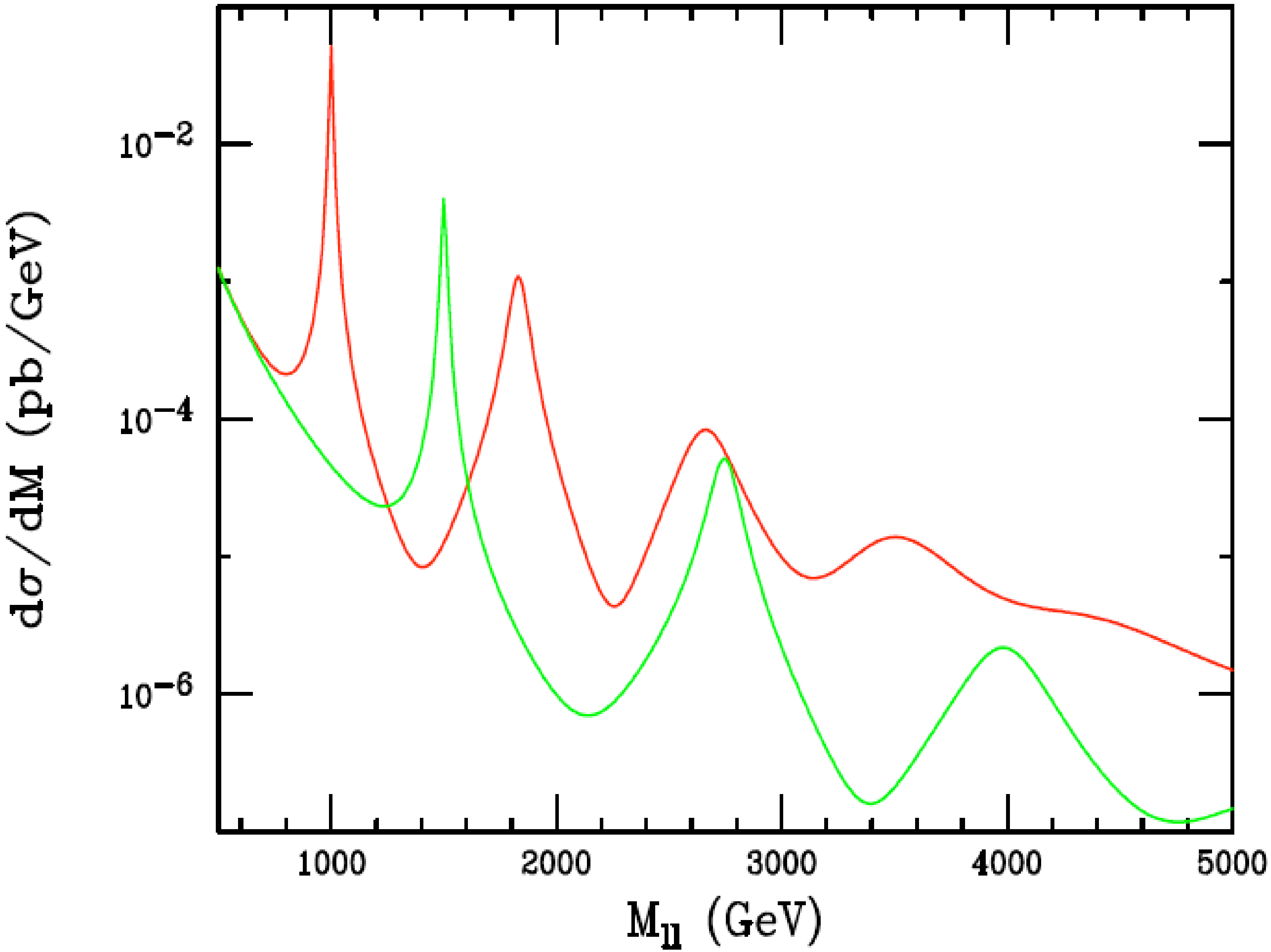
It is interesting to also consider putting the Standard Model in the bulk.  With an appropriate construction, this can lead to a grand unified theory.

We see again both of the considerations from our previous discussion of resonances.  We would like to:

go to high enough energy to see the pattern of resonance masses

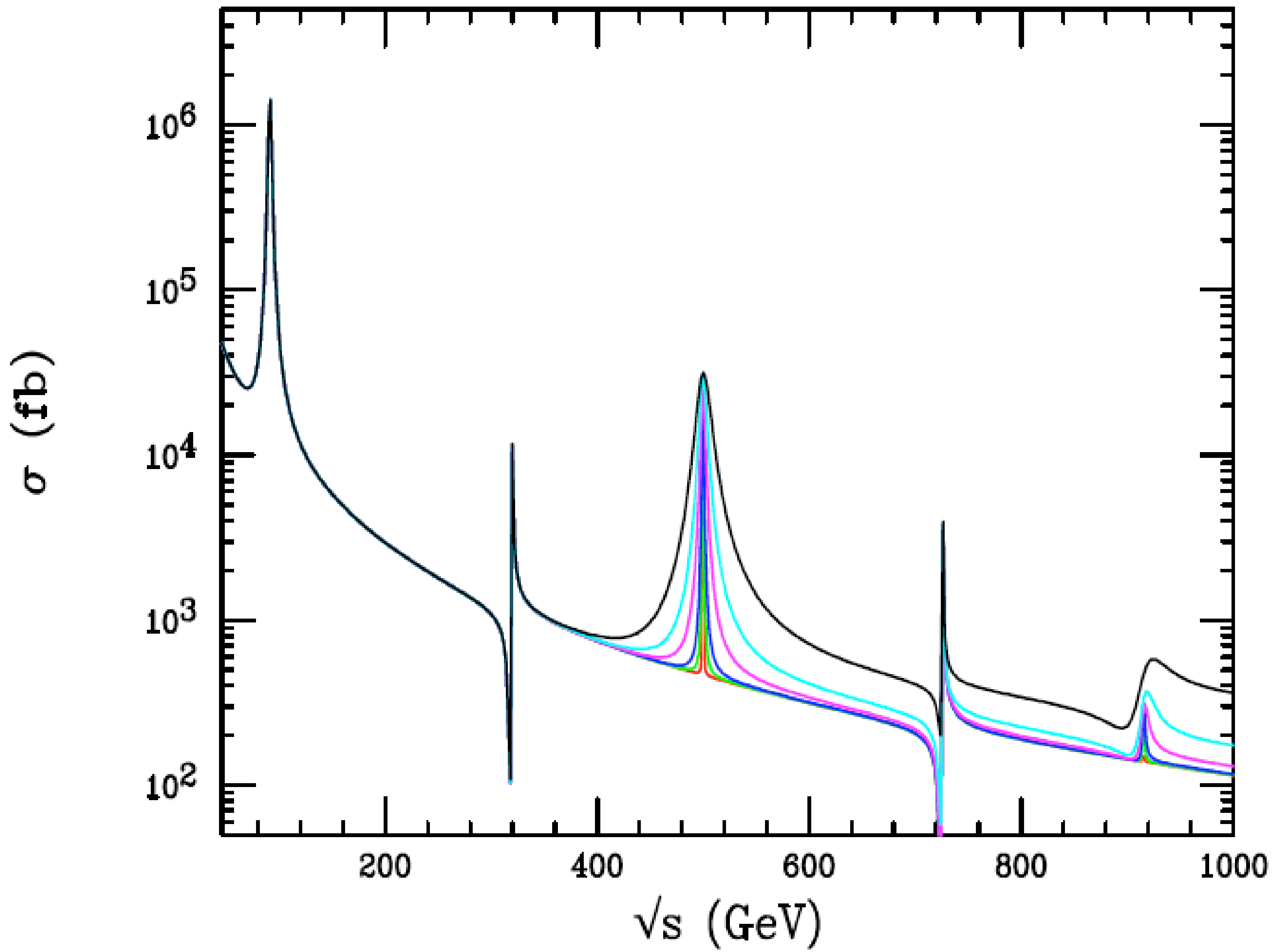
go to individual resonances in e+e- to do KK factory physics

$pp \to \mu^+ \mu^- + X$ graviton resonances



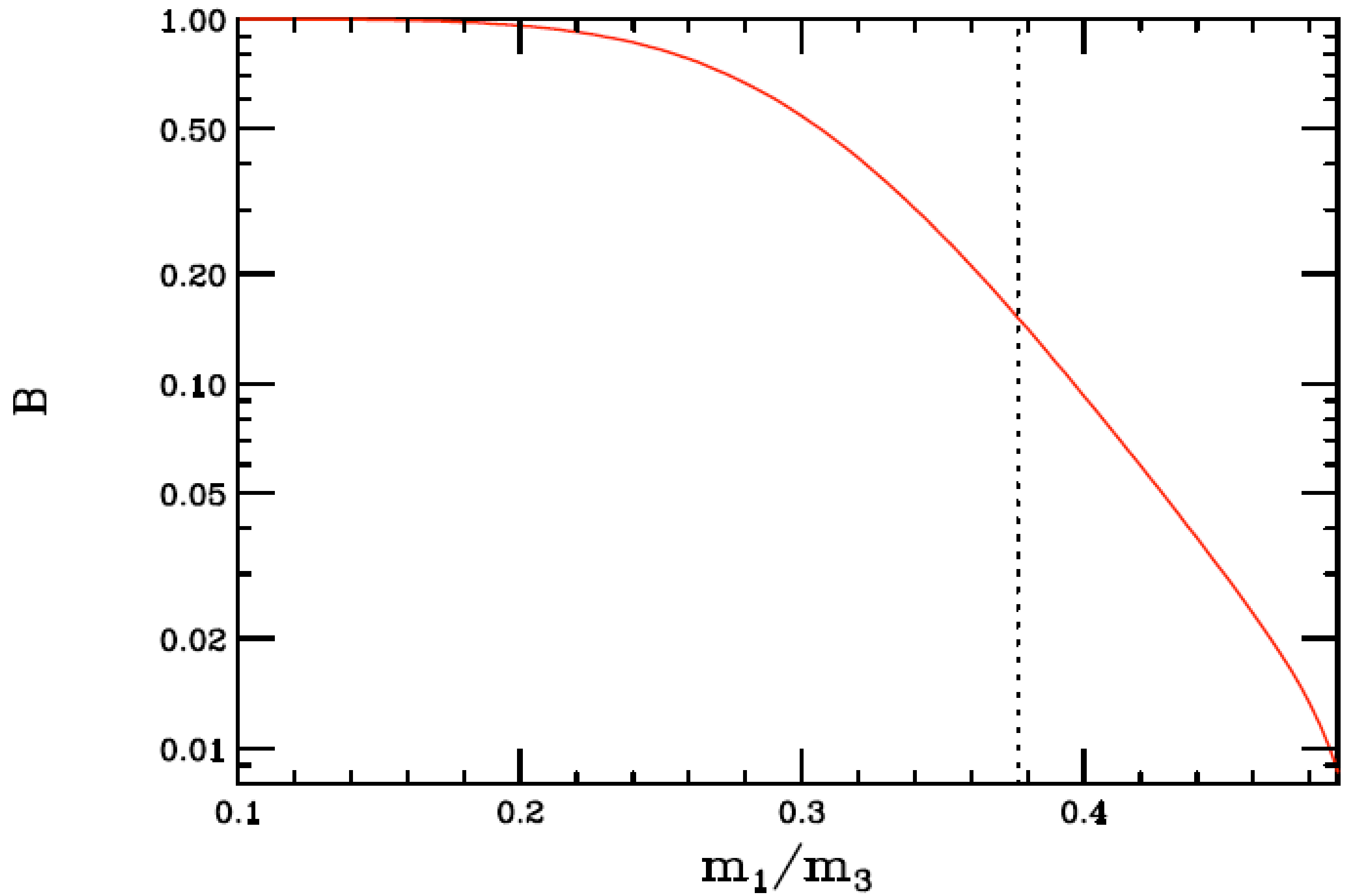

Davoudiasl, Hewett, Rizzo

$e^+e^- \rightarrow \mu^+\mu^-$ showing vector and graviton resonances




Davoudiasl, Hewett, Rizzo

Davoudiasl and Rizzo have looked into ‘graviton factory physics’. The figure shows a prediction for the branching ratio $BR(G^{(3)} \to G^{(1)}G^{(1)})$ . This is a test of the form of the gravitational coupling in the bulk.



This setup provides one interesting opportunity for the ILC.

Fermions in the bulk must be in zero-modes or close to the UV to avoid corrections to precision electroweak predictions. Because of the strong constraint on $BR(Z^0 \to b\bar{b})$, this includes the $(t,b)_L$ doublet.

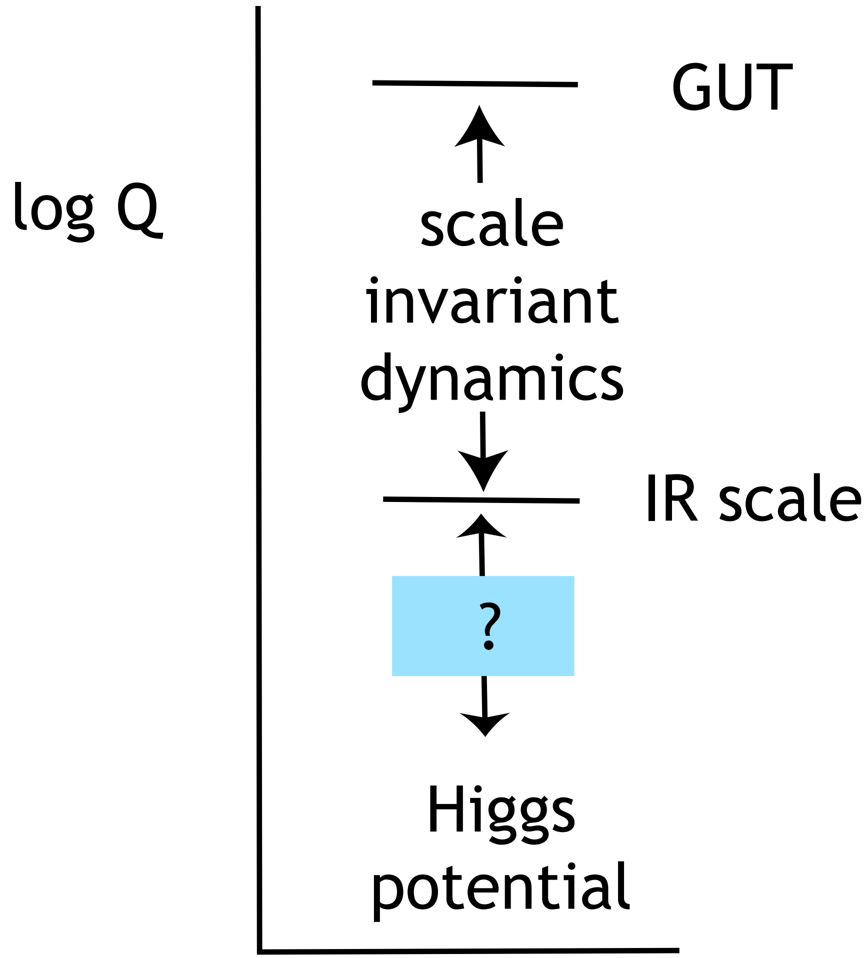
Then, to obtain a large top quark mass, the wavefunction for $t_R$ must be shifted toward the TeV brane. This implies large corrections to the $Z_\mu \bar{t} \gamma^\mu P_R t$ coupling which will be easily observed through the polarization-dependence of the cross section for $e^+e^- \to t\bar{t}$.

There is another reason to be interested in Randall-Sundrum models.

In 1997, Maldacena proposed that 4-d N=4 super-Yang-Mills theory and Type IIB string theory on the 10-d space $AdS_5 \times S^5$ were equivalent theories.   Much evidence has accumulated since then that operator matrix elements in N=4 s-Y-M can be computed by considering these as operators on the boundary of anti-de Sitter space.

An essential part of this construction is the interpretation of shifts in the extra dimension of AdS as scale transformations in the the Yang-Mills theory.

With this construction in mind, it is very interesting to look at the Randall-Sundrum model in a slice of AdS as a model of a new type of strongly interacting 4-d quantum field theory. Physics in the bulk is scale-invariant; the breaking of scale-invariance is modelled by the coupling to the TeV brane.



In this picture, resonances of wave fields in AdS are reinterpreted as the ‘hadronic’ resonances of the strong-interaction theory, according to their spins and SM quantum numbers.

Hopefully, we can generate the instability in the Higgs potential in a natural way.

It is still controversial whether the scale-invariant part of the theory can come all the way down to the TeV scale without upsetting the precision electroweak tests.

It is interesting anyway to try to derive the Higgs potential from the effective low-energy theory of these new strong interactions.

This brings us to ‘Little Higgs’ models.

Arkani-Hamed, Cohen, Nelson, Katz

Here is an idea of a Little Higgs model.

Recall that QCD, with light u,d,s quarks, has a global symmetry SU(3) x SU(3) that is broken to SU(3) by the dynamical generation of the baryon and meson masses.

This symmetry breaking gives 8 Goldstone bosons.

Embed SU(2) x U(1) in this structure, and identify 4 Goldstone bosons with the complex Higgs doublet :

$$\begin{pmatrix} & & \phi^+ \\ & & \phi^0 \\ \phi^- & \phi^0 & \end{pmatrix}$$

At this stage, SU(2) x U(1), should not be broken, and W, Z should be massless. We need to gauge a larger group, e.g. SU(2) x SU(2) x U(1), with the extra gauge bosons getting mass from the strong interaction symmetry breaking.

Because of the SU(3) structure, we also need additional quarks. Most importantly, there is an additional top quark

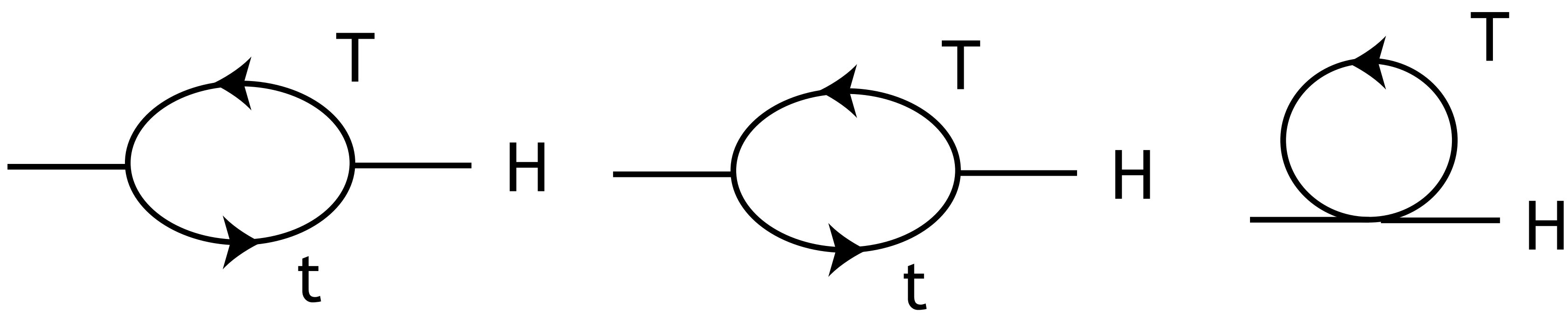
$$\begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} + T_R$$

Choose the scale of the new strong interactions to be 10 TeV. Then the new W, Z, T have TeV-scale masses,

$$m^2 \sim \mathcal{O}(\alpha_w) \cdot (10\ \mathrm{TeV})^2$$

A potential for the Higgs field is generated by radiative corrections. There is a natural cancellation of UV divergences between the old and new W and the old and new top quark.

The contributions from the top quark leave over




$$m_H^2 = -3\frac{\lambda_t^2 m_T^2}{8\pi^2}\log\frac{\Lambda^2}{m_T^2}$$

so we naturally get electroweak symmetry breaking, as promised in the first lecture. If the initial scale was 10 TeV, this is now

$$m_H^2 \sim \mathcal{O}(\alpha_w^2)\cdot(10\ \mathrm{TeV})^2 \sim (100\ \mathrm{GeV})^2$$

The structure of the new physics is interesting:

specific new particles with TeV masses

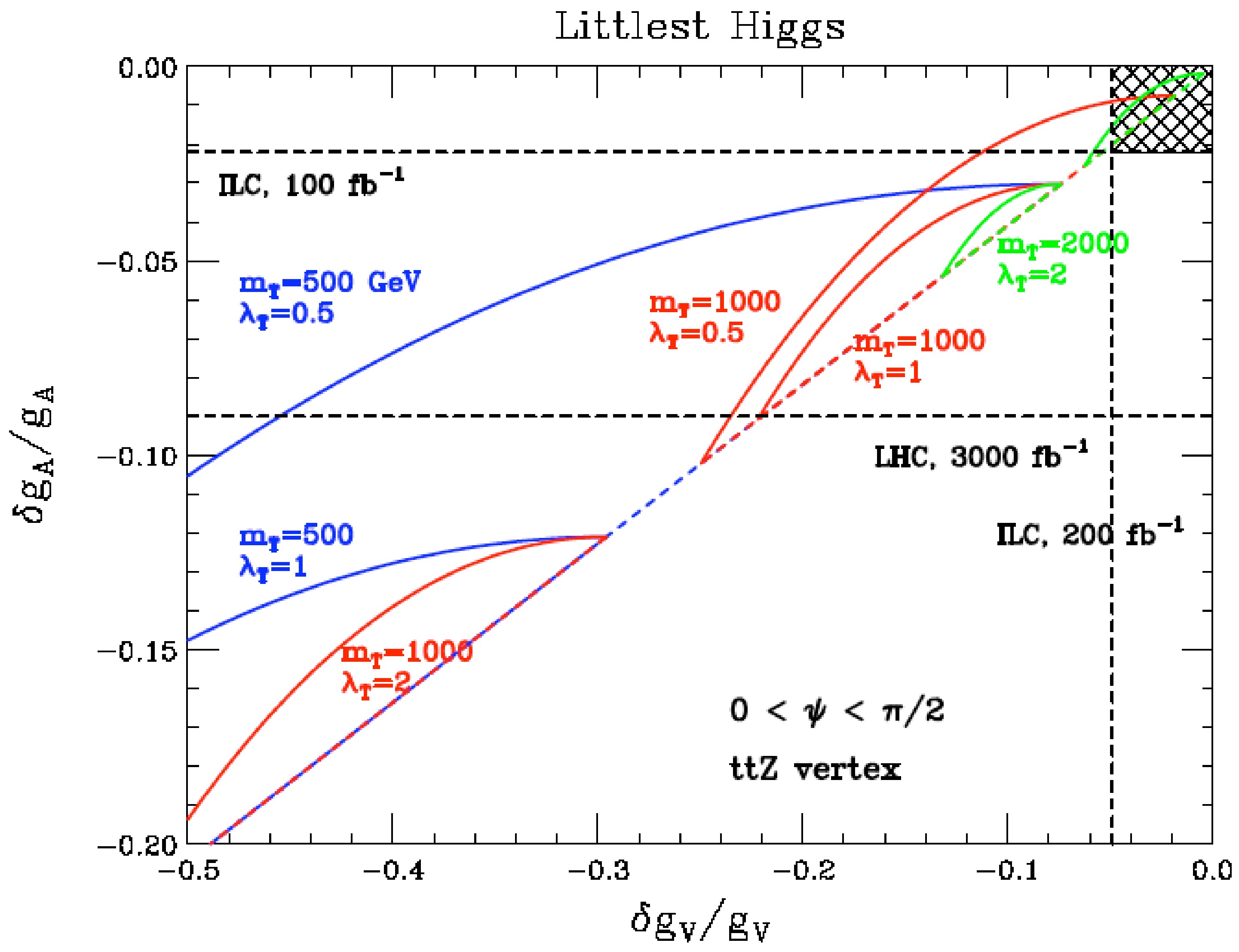
heavy W, Z, T

new strong interactions at 10 TeV

which may be QCD-like or may be a new kind of strong dynamics

These particles provide goals for two generations of new accelerators.

The mixing of t with T corrects the top quark - Z vertices. This effect should already be visible at the ILC.




Berger, Perelstein, Petriello

What are the conclusions of this story ?

In the first lecture, I argued that, at the LHC and ILC, we expect to find a new family of heavy particles.

These particles are needed to provide a dynamical explanation for electroweak symmetry breaking and to provide the particle of cosmic dark matter.

These are generic considerations that cover a wide range of models. Though each model has special features, the phenomenology of all of these models is similar at LHC and ILC.

But beyond ILC, the paths diverge. We might need:

A machine for precision experiments up to 2 TeV, with the grand desert beyond.

A machine for factory physics at new resonances in the TeV region.

A machine to survey resonance masses over a range of 20 TeV or more.

A machine to explore the dynamics of new strong interactions at energies above 10 TeV.

The correct goal depends on what exactly we find at LHC and ILC.

One feature is common:

To reach any of these goals, we need new accelerator technology.    There seem to be especially promising opportunities in the development of e+e- accelerators.

This is attractive, because many of the goals I have listed need the special capabilities of e+e- annihilation.

The ‘final theory’ is not in sight.

We are about to open a new chapter in elementary particle physics. We do not know where this new text will take us.

If history is a guide, it will require tools that we have not yet invented, and it will give us insights that we cannot now imagine.