Physics of the 'Terascale'

M. E. Peskin
2006 Program Review

In the 1990's, high-energy physics experiments explored the energy scale of the W and Z bosons. The result was a striking and precise confirmation of the predictions of the Standard Model.

Now, after many years, we are about to begin the exploration of a qualitatively higher energy scale at the LHC.

This energy region has been called the `Terascale'.

HEPAP subpanels and the recent EPP2010 report have highlighted the Terascale as a step of great promise for particle physics.

Is it plausible that the Standard Model can be valid to percent accuracy at the 100 GeV scale and be violated dramatically at the Terascale?

For better or worse, yes.

In any model with the property of 'decoupling'

new particles have vectorlike coupling to SU(2) x U(1)

the corrections to electroweak predictions are of the order of

$$\frac{\alpha}{4\pi}\frac{m_Z^2}{M^2}$$

Even in complex models such as supersymmetry, these can be small effects.

Models w.o. decoupling (e.g. technicolor) are already excluded.

Is there really direct evidence for physics at the Terascale ?

It is possible that the LHC energy region contains a scalar Higgs boson and no other new particles.

But, we have major unanswered questions in particle physics that would naturally be addressed at the Terascale.

Electroweak symmetry breaking:

The model with one Higgs boson does not explain why SU(2) x U(1) is broken. Models that predict (not just parametrize) SU(2) x U(1) breaking are complex, with families of new particles. The scale that must be explained is

$$\langle \varphi \rangle = 246 \text{ GeV}$$

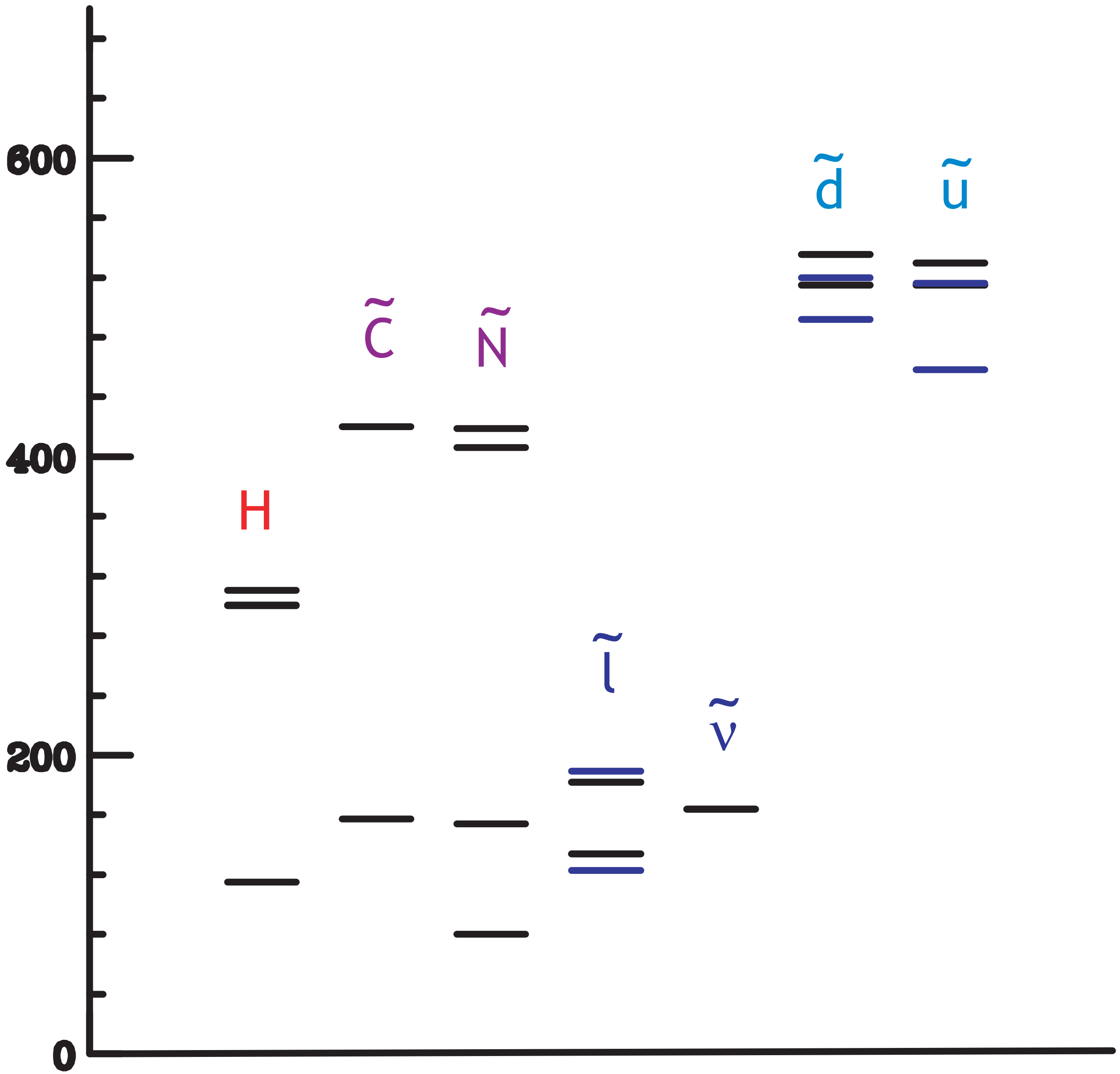
Cosmic dark matter:

80% of the matter in the universe is not accounted for by the Standard Model. If this matter is a new neutral stable particle that was produced thermally in the early universe, the annihilation cross section of this particle is

$$\langle \sigma v \rangle = 1 \text{ pb} = \frac{\pi \alpha^2}{8 m^2} \quad \text{for } m = 100 \text{ GeV}$$

This is no time for minimal expectations. These phenomena are likely to be part of a new big picture of fundamental physics.

a typical spectrum of supersymmetric particles:



If these ideas are correct, we have much to do in the next 15 years. We should already be organizing ourselves to take advantage of the opportunities that will be presented.

1. Prove that the Standard Model is violated at the LHC.

2. Measure the masses of new particles produced at the LHC.

3. Detect dark matter particles in the galaxy; show that these particles have the mass seen at the LHC.

4. Definitively measure the spins and quantum numbers of new particles. Identify the new qualitative picture of particle physics.

5. Measure the parameters of the new Lagrangian precisely.

6. Determine the cross sections of dark matter particles. Combine HEP and astrophysical data to measure the dark matter structure of the galaxy.

The experiments that we anticipate for the next 15 years -- LHC, ILC, and dark matter searches and surveys -- can carry out this program.

The SLAC Theory Group has played an important role over the past decade in formulating this program as a unified whole, developing its theoretical framework, and arguing for the resources that will be needed.

As you will hear this afternoon and tomorrow, the SLAC PPA Division has realigned itself to pursue all of the experimental aspects of this program.

The HEP experiments will not be done at the SLAC Linac.

It doesn't matter. SLAC will have a key role in the future of particle physics.

I have a few minutes left to talk about the SLAC Theory Group.

What are we doing today to advance this program?

What do we need to prove that the Standard Model is violated at the LHC ?

If we understand the Standard Model exactly, and if the LHC experiments perform as advertised, this should be simple.

Neither assumption is likely to be correct. But we need to prepare as well as we can, both theoretically and phenomenologically.

Since the early 90's, Lance Dixon, working with Zvi Bern and David Kosower, has been a leader in developing the precise predictions of higher-order perturbative QCD.

About 2 years ago, this program received an impetus from Witten's observation that QCD amplitudes are simplified in twistor space.

In the past year, Bern, Dixon, Kosower, Carola Berger, and Darren Forde have developed these observations into a technology for multi-jet QCD at one-loop order (NLO).

This group has just published compact analytic expressions for

$$\text{parton} + \text{parton} \to n \ \text{partons}$$

for $\Delta h \geq (n-4)$ and arbitrarily large n at NLO.

We also need to understand how the important processes for new physics signatures can be constrained by experimental observations.

observable	SM source	control reaction
σ(multi-jet)	higher-order QCD	p_T balanced 2, 3 jet events
$\not{E}_T$ w. > 2 jets	$Z \to \nu\bar{\nu}$	$Z \to \ell^+\ell^-$
	$t\bar{t}$ w. $\ell \to 0$	observed $t\bar{t} \to \ell + 4j$
$\ell+ \not{E}_T$	W + jets	Z + jets
$\ell^+\ell^+$	$t\bar{t}$, W^+W^+	1-lepton $t\bar{t}$
$\ell^+\ell^- + \not{E}$	$Z+$ jets, ZZ, WZ	Z + jets
$Z^0 + \not{E}$	$Z+$ jets, ZZ, WZ	Z + jets
b + multi-jets	c + jets, b in QCD	$b\bar{b}$ w. 2 jets
$b + \not{E}_T$	$t\bar{t}$, $t\bar{t}$ + jets	balanced $t\bar{t}$
multiplet b jets	QCD multi-c, b	multijet w. c

We are studying in simulations: How exactly is column B constrained by column C? What other ingredients must be considered ?

We are studying how models of new physics beyond the Standard Model actually appear at the LHC.

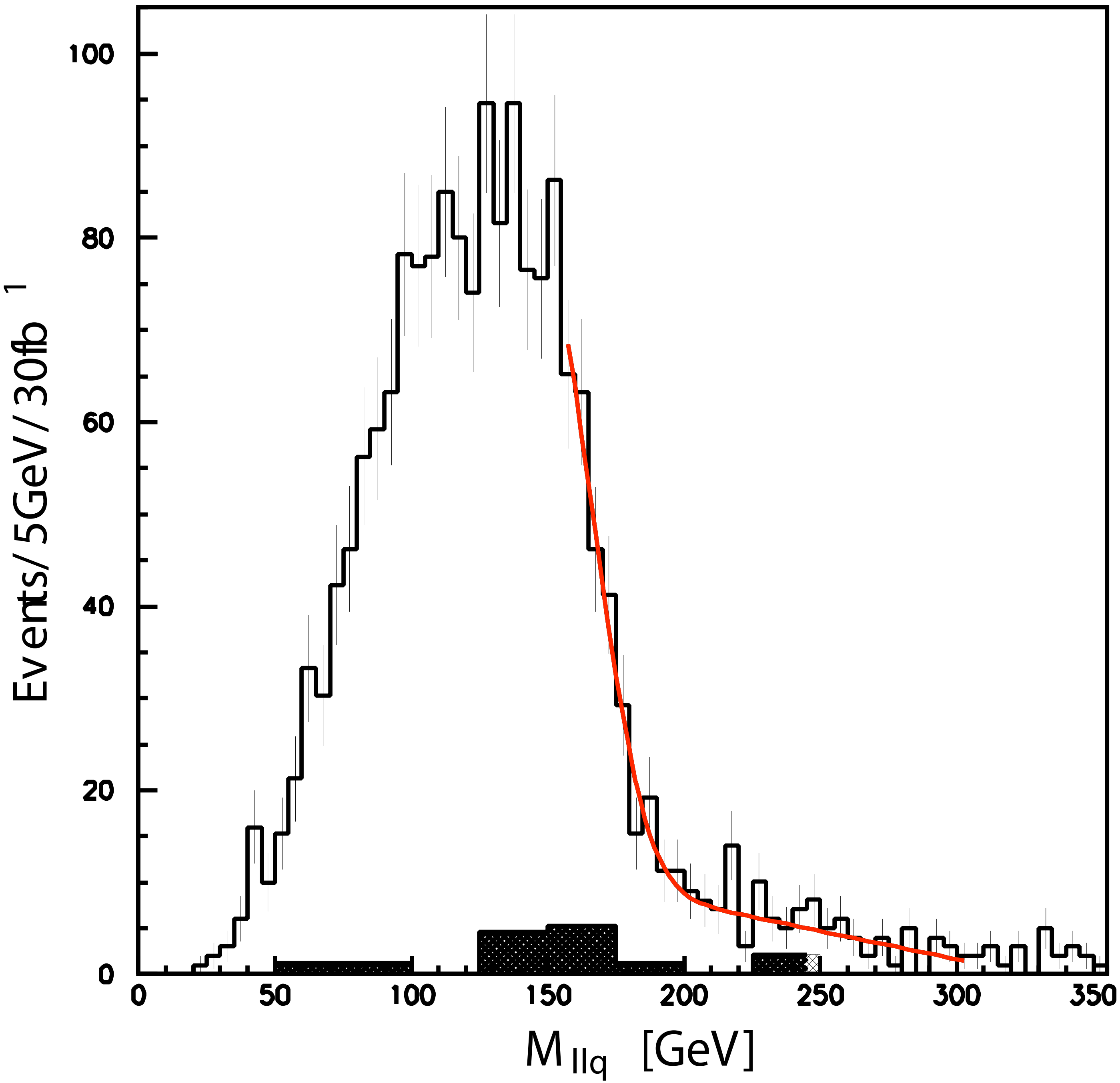
Our studies include:

new variants of supersymmetry (Kitano)

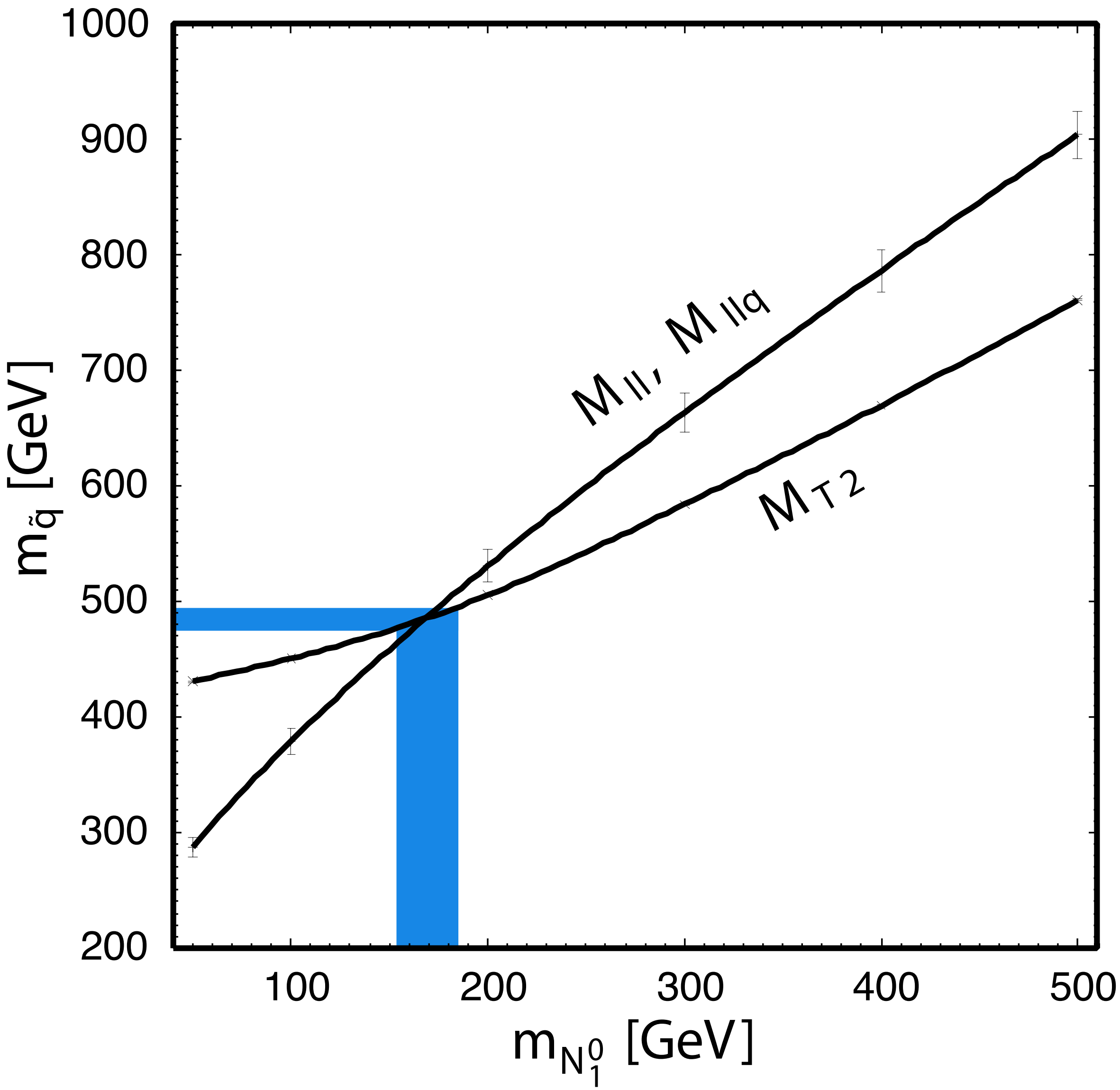
'twin Higgs' models (Harnik)

'Universal Extra Dimensions' - phenomenology w. spin (Davenport, Peskin, Ruderman)

Randall-Sundrum and other models with warped extra dimensions (Lillie, Hewett, Rizzo)

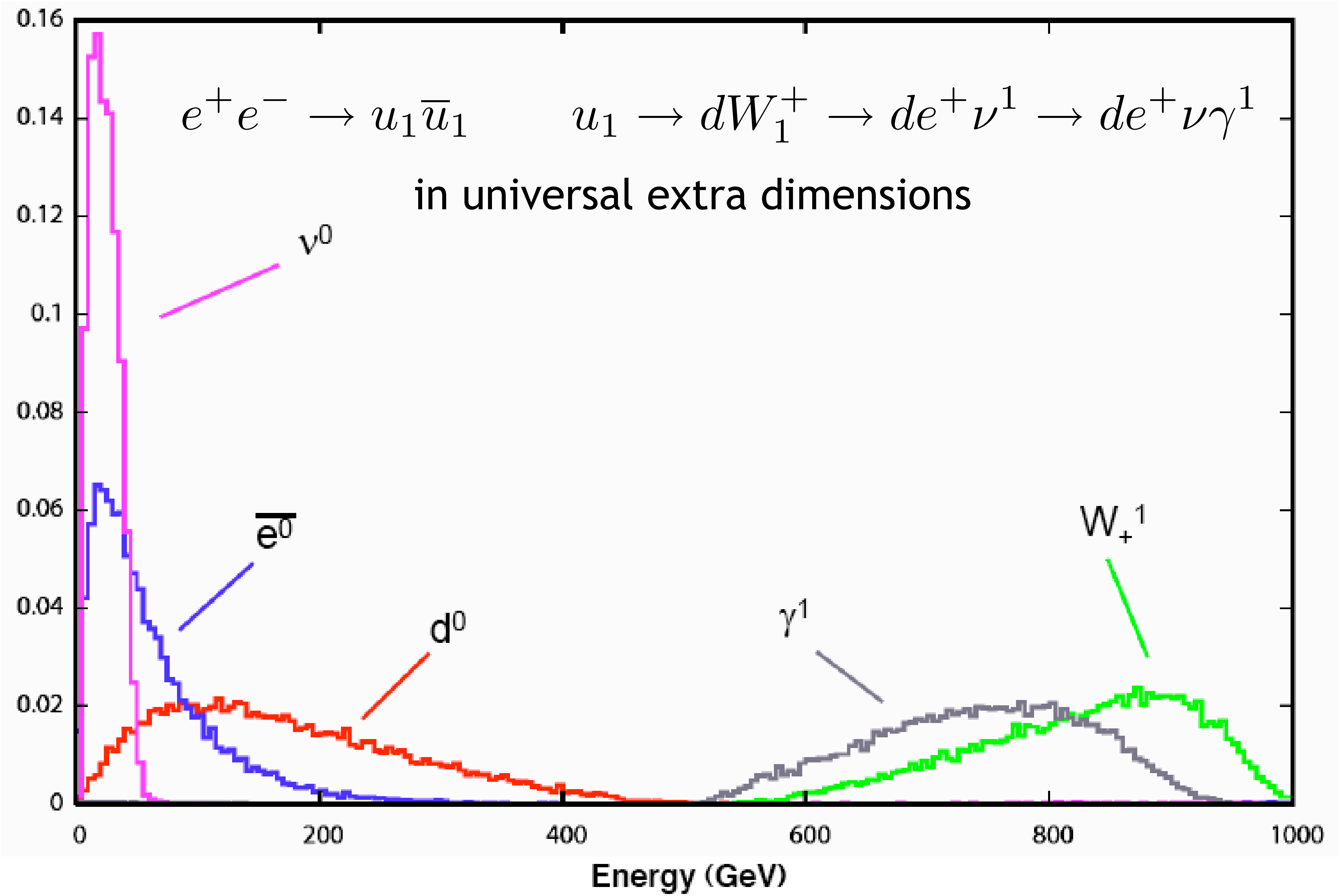


Kitano-Nomura



$$m_{N_1} = 169 \pm 17 \text{ GeV} \quad m_{\tilde{q}} = 486 \pm 11 \text{ GeV}$$

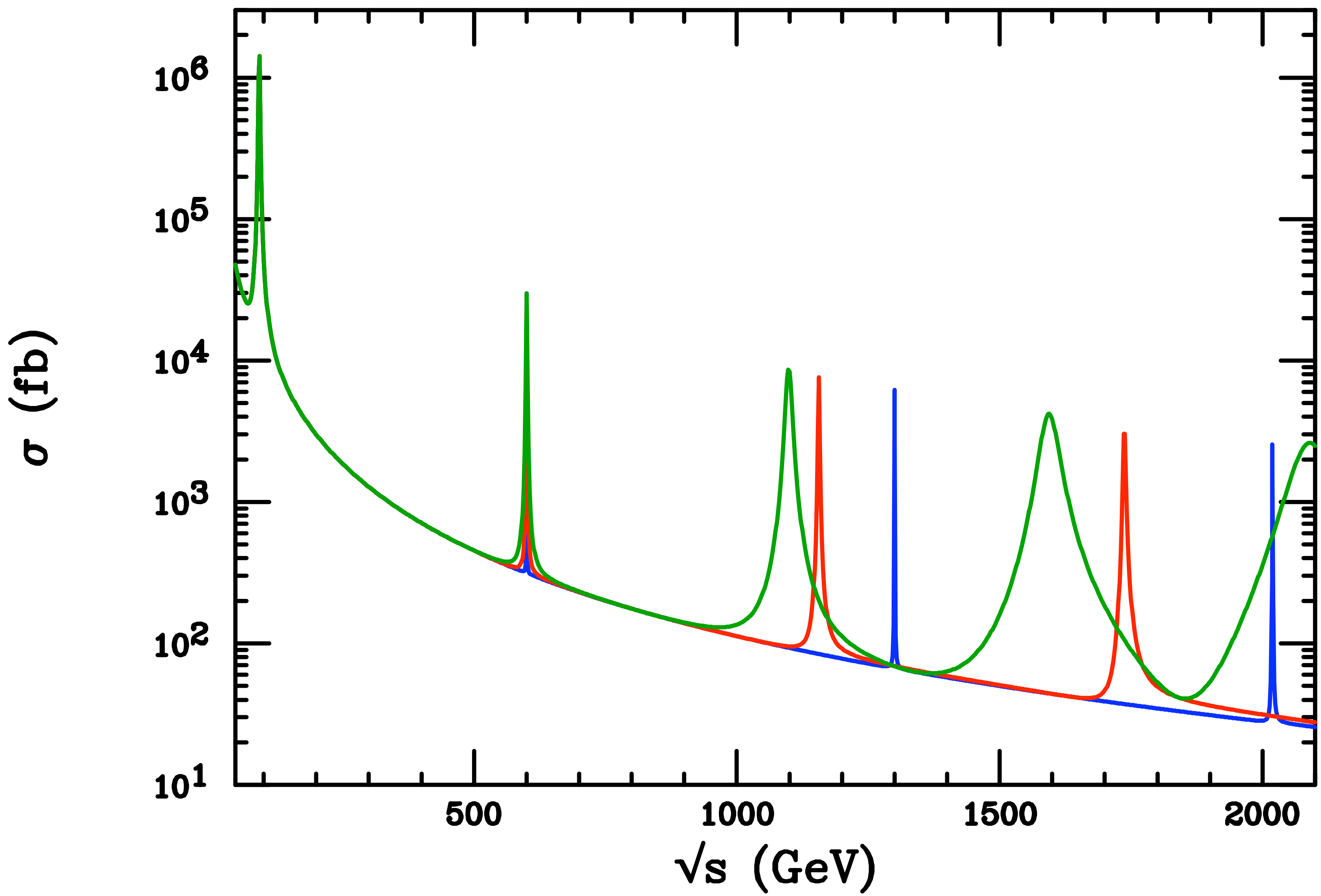
Kitano-Nomura



$e^+e^- \to u_1\overline{u}_1 \qquad u_1 \to dW_1^+ \to de^+\nu^1 \to de^+\nu\gamma^1$
in universal extra dimensions
ν^0
$\overline{e^0}$
d^0
γ^1
W_+^1
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
200
400
600
800
1000
Energy (GeV)

Ruderman

graviton resonances in warped extra dimensions



Davoudiasl-Lillie-Rizzo

Ted Baltz will describe our work on the connection between high-energy collider physics and the dark matter problem.

I expect that the exploration of the Terascale will be subtle and full of surprises. The progress will be made by young theorists who can confront the data with original and inventive ideas.

Why should such young people come to SLAC ?

Other the past few years, we have been developing in our group all of the resources that these people will need in the LHC era. We have experts on the capabilities of the experiments, event modeling and simulation, perturbative QCD, model building in all varieties, and connections to cosmology, and the connections of supersymmetric and extra-dimensional models to string theory and quantum gravity.

SLAC has a long tradition of close collaboration between theory and experiment. A part of this is the Bjorken+Drell tradition in which the theorists who work with experimenters are same ones who deal with deep fundamental ideas.

Is such close collaboration possible in an era where experiments are done at one accelerator in the world ?

We believe that the answer is yes.

We would like to provide a model for how this can be done.