What Can Experiment Tell String Theory?

A Small Talk of More Questions than Answers...

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Introduction

What kinds of discoveries could we conceivably make at high-energy accelerators in the next 5 years? The list (below) is **remarkably** different from what I would have made 5 years ago- there has been an amazing revolution in the expectations of observable effects at the TeV scale. This is due to the proposal of Arkani-Hamed, Dimopoulos (an ex-UC student!), and Dvali that a possible solution to the *hierarchy problem* is that there are large extra dimensions, which could have observable effects at the electro-weak scale.

What this means to an experimentalist is a much richer set of possibilities- in addition to (in order of approximately decreasing cross-section) soft particle production, QCD hard scattering, b and c quark flavor production, electroweak production of photons, Drell-Yan lepton pairs, W and Z bosons, and top quark production, there may be effects of gravity and geometry. These may involve supersymmetry, new bosons, etc.- the range of possibilities has grown from the (boring) MSSM to all kinds of fantastic (precisely?) possibilities.

Quick Glossary

- *The Electroweak Scale*: $M_{EWK} \simeq G_{Fermi}^{-1/2} \simeq 300$ GeV (Often taken as 0.1-1 TeV by theorists for whom $10 \approx 1$ in $\sqrt{s}$.)
- *The Planck Scale*: $M_{Planck} \simeq G_{Newton}^{-1/2} \simeq 10^{19}$ GeV
- *The Hierarchy Problem*: Why is the $M_{EWK} << M_{Planck}$, and what keeps it small wrt radiative corrections?
- *The Standard Model (SM)*: $SU(3) \times SU(2) \times U(1)$- the strong and electroweak gauge interactions.
- *Supersymmetry Breaking*: Whatever it is that makes the super-partners (assuming they exist) heavy.
- *Tevatron Run I*: The data-taking from 1992-95; $\sqrt{s} = 1.8$ TeV, $\int Ldt = 100 pb^{-1}$.
- *Tevatron Run IIa*:The data-taking from 2002-2005? $\sqrt{s} = 1.96$ TeV, $\int Ldt = 2000? pb^{-1}$.
- *Tevatron Run IIb*:The data-taking from 2005? $\sqrt{s} = 1.96$ TeV, $\int Ldt = 13000? pb^{-1}$.
- *CDF, D0*: The two big (new!) detectors at Fermilab.
- *LHC, Atlas, CMS*:LHC: $\sqrt{s} = 14$ TeV; expect 10 fb^{-1} in 2007?; 100 fb-1 in 2009? Atlas, CMS: The two much bigger detectors at CERN.
- *Jet* A cluster of energy detected in a calorimeter.
- *Electron* A narrow cluster of energy in a calorimeter with a single track pointing to it, usually of momentum $p > E/2$.
- *Muon* A track that penetrates the calorimeter and leaves much less energy than its momentum there.
- *Photon* A narrow cluster of energy in a calorimeter with no track pointing at it.
- *Missing Transverse Energy ($\not{E}_t$)* The imbalance in momentum transverse to the beam direction (indicative of neutral penetrating particles).

What Could We Find?
(Outline of talk)

- *Black Holes*
- *Large Extra Dimensions*:
- *Gravitons*:
- *Supersymmetry - measure mass scale, spectrum, breaking*:
  - *Gravitinos*:
  - *Supersymmetric Quarks and Gluons*:
  - *Supersymmetric Gauge Particles*:
  - *Multiple Neutral Higgs Bosons*:
  - *Charged Higgs Bosons*:
- *New Gauge Bosons (new Gauge Groups)(e.g. Z')*:
- *4th Generation Quarks or Leptons*:
- *Excited Leptons*:
- *Lepton Number Violation*:

Black Holes

TeV-scale gravity may allow the production of black holes in particle collisions [1]

- The production cross is (?) is purely geometrical:

$$\sigma_{ij \to bh(s)} \sim \pi r_h^2(\sqrt{s}) \tag{1}$$

  where i and j are incoming partons with a cm energy of $\sqrt{s}$, and r_h is the Schwarzschild radius of a black hole of mass $M_{bh} = \sqrt{s}$.

- The radius of a black hole in N (large) dimensions is[2]

$$r_h \sim \frac{1}{M_P} \left[\frac{M_{bh}}{M_P} \right]^{1/n+1} \tag{2}$$

  where M_P is the 'reduced Planck mass' which we are assuming is on the order of a TeV, corresponding to the strength of gravity but in the higher dimensional space.

- This cross-section is **large** if any of this is true- e.g. if $M_P = 1$ TeV, n=5, $\sigma = 740pb$ (!). This is 100 times the top quark cross-section of 6 pb.

- At the LHC the rates estimated by folding in the parton momentum distribution functions are also large for $M_P = 1$ TeV; at a luminosity of 30 fb^{-1}/yr the LHC would make approximately one per second.

[1] see, e.g., Argyres, Dimopoulos and March Russell, hep-th/9808138; Giddings and Thomas, hep-ph/0106219; Dimopoulos and Landsberg, hep-ph/106295; Giddings, hep-ph/0110127

Black Holes- continued

What are the signatures of black hole decay?[2]

- Decay is governed by the Hawking temperature

$$T_h = C \times M_P \left(\frac{M_P}{M_{bh}} \right)^{1/(n+1)} \tag{3}$$

where n is the number of extra dimensions and C is a constant of order one:

$$C = \frac{n+1}{(4\sqrt{\pi}} \left(\frac{n+2}{8\Gamma((n+3)/2)} \right)^{1/(n+1)} \tag{4}$$

For example, for n=5, C=1.17

- The average multiplicity of the decay products is low, as the average energy per decay product is approximately the Hawking temperature:

$$\langle N \rangle \sim \frac{1}{2} \left(\frac{M_{bh}}{T_h} \right) \tag{5}$$

For example, for n=4 dimensions, $\langle N \rangle = 5$ for $\frac{M_P}{M_{bh}} \approx 4$,
$\langle N \rangle = 10$ for $\frac{M_P}{M_{bh}} \approx 7$.

- The black hole decay should be 'democratic', i.e. it decays to all fermionic and bosonic states with equal statistical weight. For example, the ratio of hadrons to leptons should be 5:1, as (3 colors $\times$ 5 quark generations)/(3 lepton generations) = 5.

The consequence is that the predicted signature is a large number (e.g. > 4) of very high p_T objects, and has many configurations that are *very* rare in the Standard Model such as multiple high pt photons and leptons and jets.

[2] Dimopoulos and Landsberg, hep-ph/106295; I'm not even on thin ice here.

An Inclusive Black Hole Search Method?

The experimental signatures of black hole decay may depend on the details of the space: different models have different sectors in the bulk, for example (e.g. there are models with the SM fields in the bulk, rather than just gravity as in the original ADD proposal).

But, perhaps one could do a 'disappearance' experiment, rather than an appearance experiment to perform a search that is independent of *any* details of the model.

Consider the spectrum in invariant mass of a hard QCD process, such as dijet or multijet production. Above the threshold for making a black hole the spectrum should turn sharply down, with a slope set only by the invariant-mass resolution (i.e. the production should go to zero).

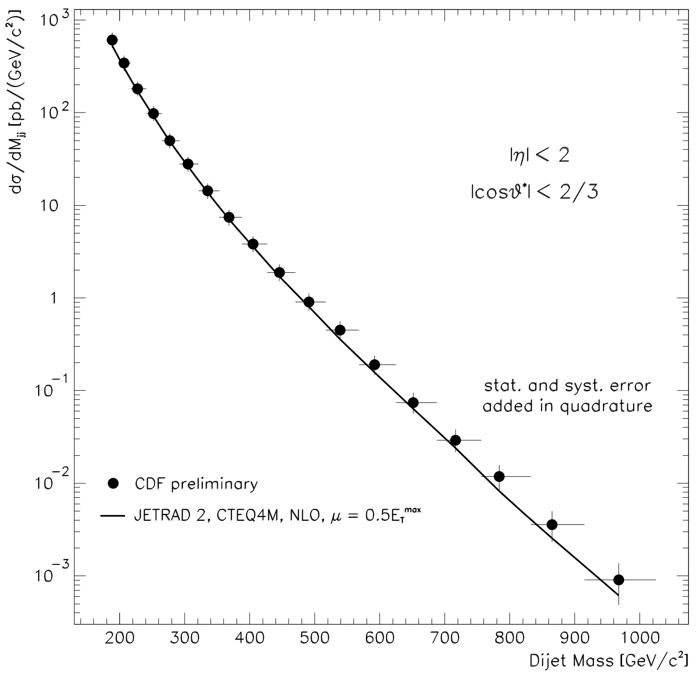


Figure 1: The invariant mass of dijet events from CDF Run I data. The spectrum shows no cutoff up to $\approx$ 1 TeV due to a black-hole threshold opening up.

An Inclusive BH Search Method Continued

Just for fun, look at CDF multi-jet events with very high invariant mass [3]

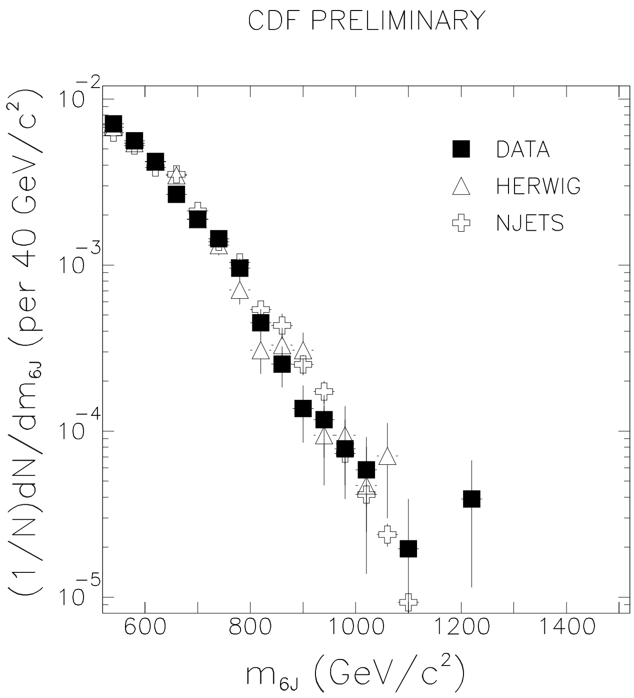


Figure 2: The invariant mass of sixjet events from CDF Run I data.

Joe- maybe it does turn up at the end?[4].

[3] However, this is also an illustration that one has to be careful- some of the highest mass events come from collisions with forward jets, and may not be a single hard-scatter at small impact parameters such that you would form a black hole. How much is initial-state radiation (from other incoming partons and how much is final-state radiation (which is part of the $\sqrt{s}$ of the scatter is a detailed MC question.

[4] This is a joke

Large Extra Dimensions (LED's)

There can be measurable effects of large extra dimensions less striking than black hole production. For example, in the model where gravity is in the bulk and the SM in 4D, one can excite Kaluza-Klein excitations in the bulk, which are invisible to us.[5]

Peter Onyisi has just finished a CDF analysis looking for this, tagged by the (em) radiation of an initial-state photon from an incoming charged parton:

$$\bar{p}p \to \gamma + \not{E}_t \tag{6}$$

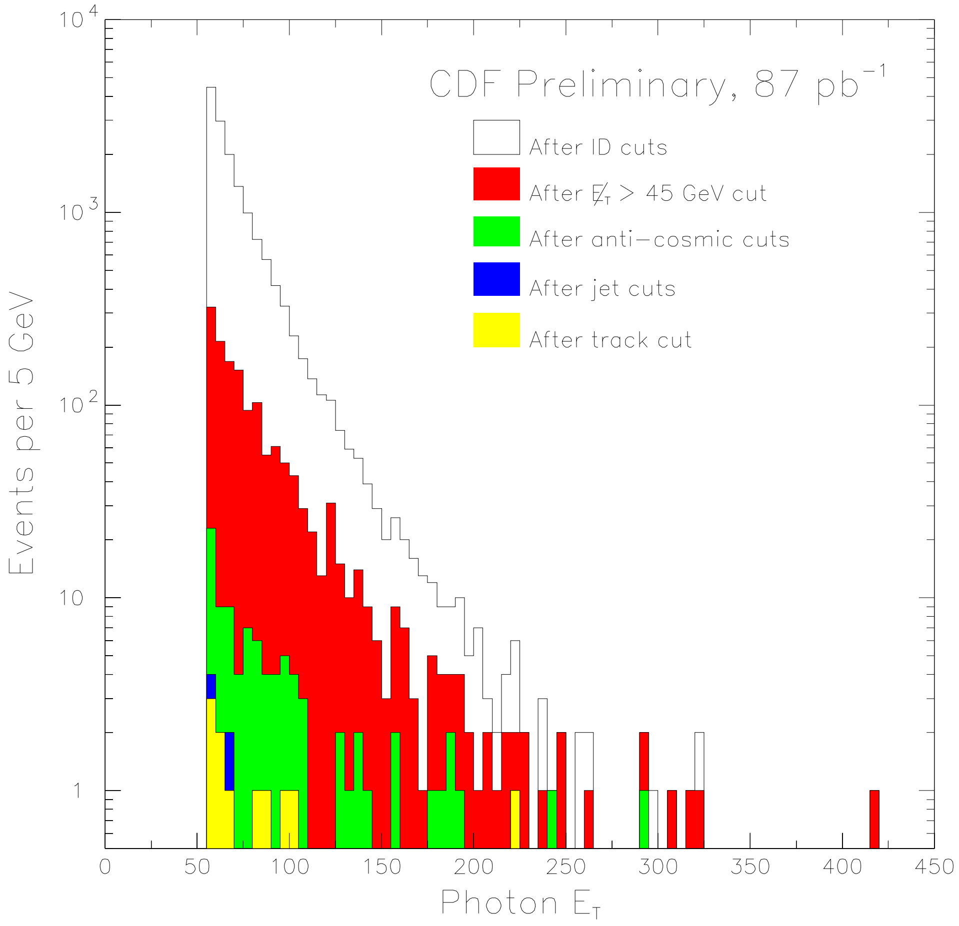


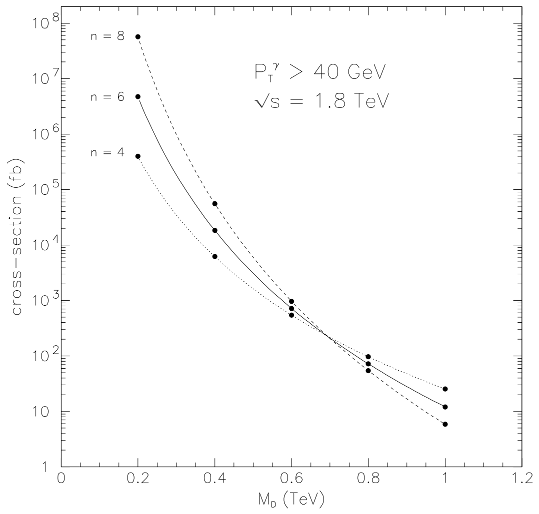
Figure 3: The spectrum of photon E_T from CDF Run I data.

[5]This is a very difficult reaction to observe in beams of 10^{12} particles: $\bar{p}p \to$ nothing!

Large Extra Dimensions, cont.

(Peter Onyisi)

Predicted Cross-sections, and Observed #'s of Events:



Cosmic rays	6.3 ± 2.0
$Z^0\gamma \to \nu\bar{\nu}\gamma$	3.2 ± 1.0
$W \to e\nu$	0.9 ± 0.1
Prompt diphotons	0.4 ± 0.1
$W\gamma$	0.3 ± 0.1
Non-QCD Background	11.0 ± 2.2
QCD Background	0.9
Total observed	11

Figure 4: Left:The predicted cross-section for KK excitations making the signature $\gamma + \not{E}_t$ at CDF; n is the number of large extra dimensions. Right: the numbers of expected SM events and the number observed.

Peter uses the Giudice, Rattazzi, Wells[6] (GRW) formalism:

Results:

$$n = 4: \; M_D \geq 549 \text{ GeV}$$
$$n = 6: \; M_D \geq 581 \text{ GeV}$$
$$n = 8: \; M_D \geq 602 \text{ GeV}$$

Best limits from LEP:

$n = 4$: 840 GeV (DELPHI)

$n = 6$: 580 GeV (DELPHI)

$n = 8$: 411 GeV (L3)

[6] hep-ph/9811291 v2

It would be wonderful if it said

ANYTHING!

Measuring the Particle Mass Spectrum

Even in 4 dimensions there are so many free parameters that the only strategy I subscribe to is to look for physics beyond the Standard Model, and then characterize the mass spectrum[7]

What could we learn? Some examples:

1. Supersymmetry exists
2. The SUSY-breaking scale
3. The mechanism of the breaking (e.g. Super-gravity or some gauge-mediated breaking)
4. The source of the breaking (e.g. is there a hidden sector?)
5. The character of the LSP
6. New conserved/partially-conserved quantities, e.g. R-parity, B-L,...
7. Details of the Higgs 'sector', possibly shedding light on CP viol.
8. Other 'soft' parameters, such as those governing the splitting of the two stop squark states, mixing angles, phases, etc.
9. Something more about flavor than we know now.

[7] For a theoretical summary, see Carena, Culbertson, Eno, Frisch, and Mrenna, Rev.Mod.Phys. 71 (1999) 937-981; hep-ex/9712022

To get some sense of possibilities, consider some recent CDF SUSY analyses:

1. Maria Spiropulu's Analysis - $\not{E}_t + Jets$
2. Jeff Berryhill's Analysis - $\gamma + e/\mu + X$
3. Ray Culbertson's Analysis - $\gamma + b + X$
4. Peter Onyisi's Analysis - $\gamma + \not{E}_t$

I. Search for Gluinos/Squarks in $\not{E}_t + Jets$

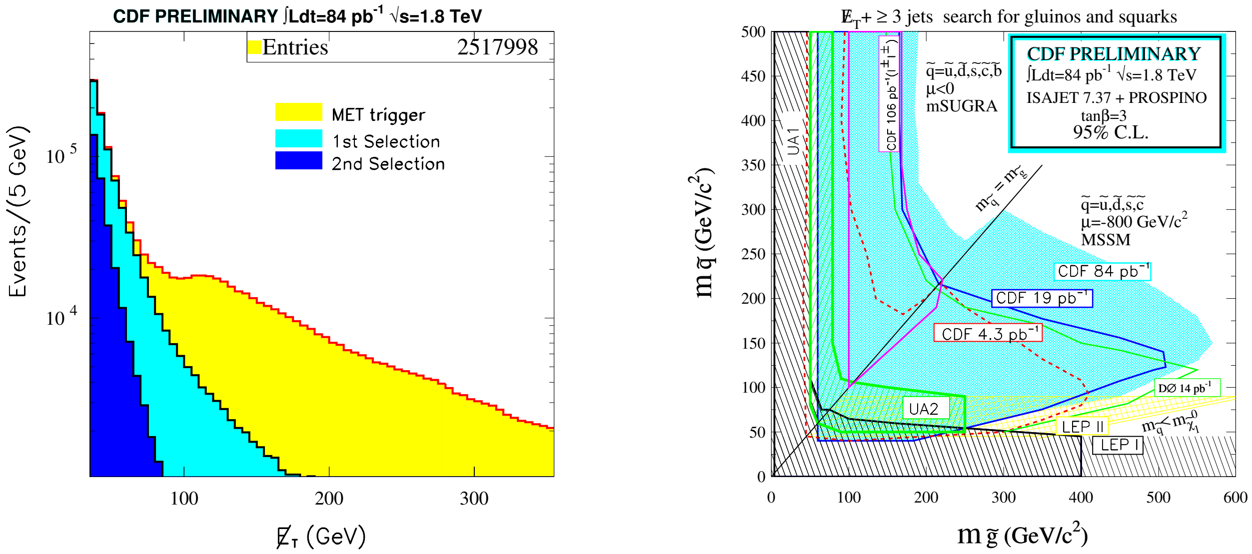


Figure 5: Left: the spectrum in missing E_T raw and after the 2 sets of cuts to remove backgrounds. Right: The (gaudy) excluded values of the squark mass (ordinate) and gluino mass (abcissa) in the mSugra model (upper part of plane) and the CMSSM (lower part of plane).

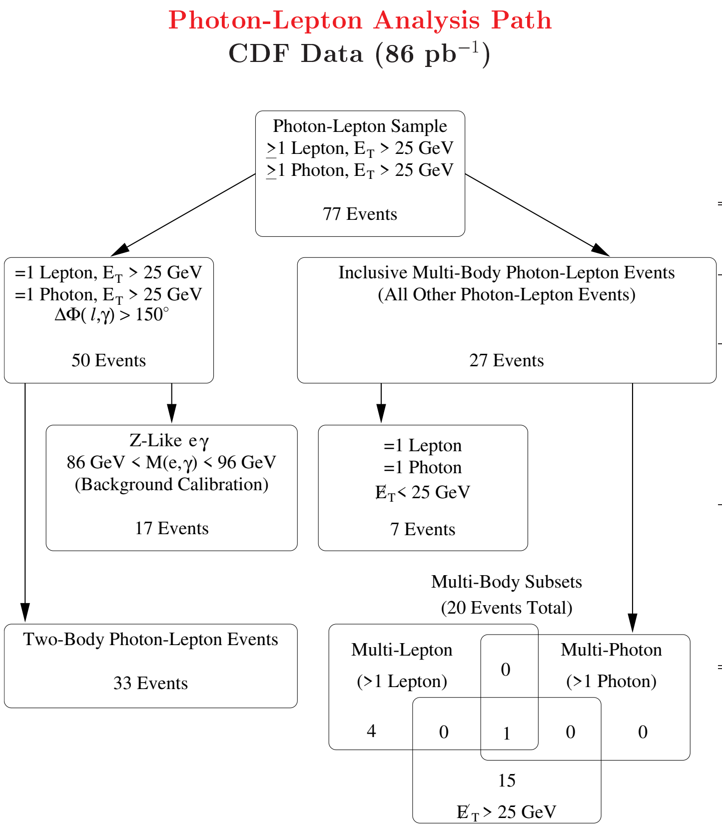
For large m_{squark} the limit on m_{gluino} is $m_{gluino} >$ 195 GeV

For $m_{gluino} = m_{squark}$ the limit is $m_{squark/gluino} >$ 300 GeV

For $m_{gluino} = 150$ the limit on m_{squark} is $m_{squark} >$ 560 GeV

II. Search for $\gamma + e/\mu + X$

A signature-based search, motivated by the $ee\gamma\gamma\not{E}_t$ event, for a high-p_T photon + a high E_T electron or muon, + anything. A subset is $\gamma + e/\mu + \not{E}_t$; for this the dominant SM process is the (rare) $W+\gamma$and $Z^0+\gamma$ high-order ewk processes. Note- this is an example of a mode in which a democratically-decaying TeV black-hole would show up like a sore thumb (so to speak). Also a gauge-mediated SUSY channel.



Photon-Lepton Results
CDF Data (86 pb^{-1})

Category	μ_{SM}	N_0	$P(N \geq N_0 \vert \mu_{SM})$ %
All $\ell\gamma X$	–	77	–
Z-like $e\gamma$	–	17	–
Two-Body $\ell\gamma X$	24.9 $\pm$ 2.4	33	9.3
Multi-Body $\ell\gamma X$	20.2 $\pm$ 1.7	27	10.0
Multi-Body $\ell\ell\gamma X$	5.8 $\pm$ 0.6	5	68.0
Multi-Body $\ell\gamma\gamma X$	0.02 $\pm$ 0.02	1	1.5
Multi-Body $\ell\gamma\not{E}_T X$	7.6 $\pm$ 0.7	16	0.7

Figure 6: Left: the data flow after requiring one high p_T lepton and one high p_T photon. Right: The comparison of the expected (SM) and observed numbers of events, and the associated probabilities.

Search for $\gamma + e/\mu + X$ Continued:

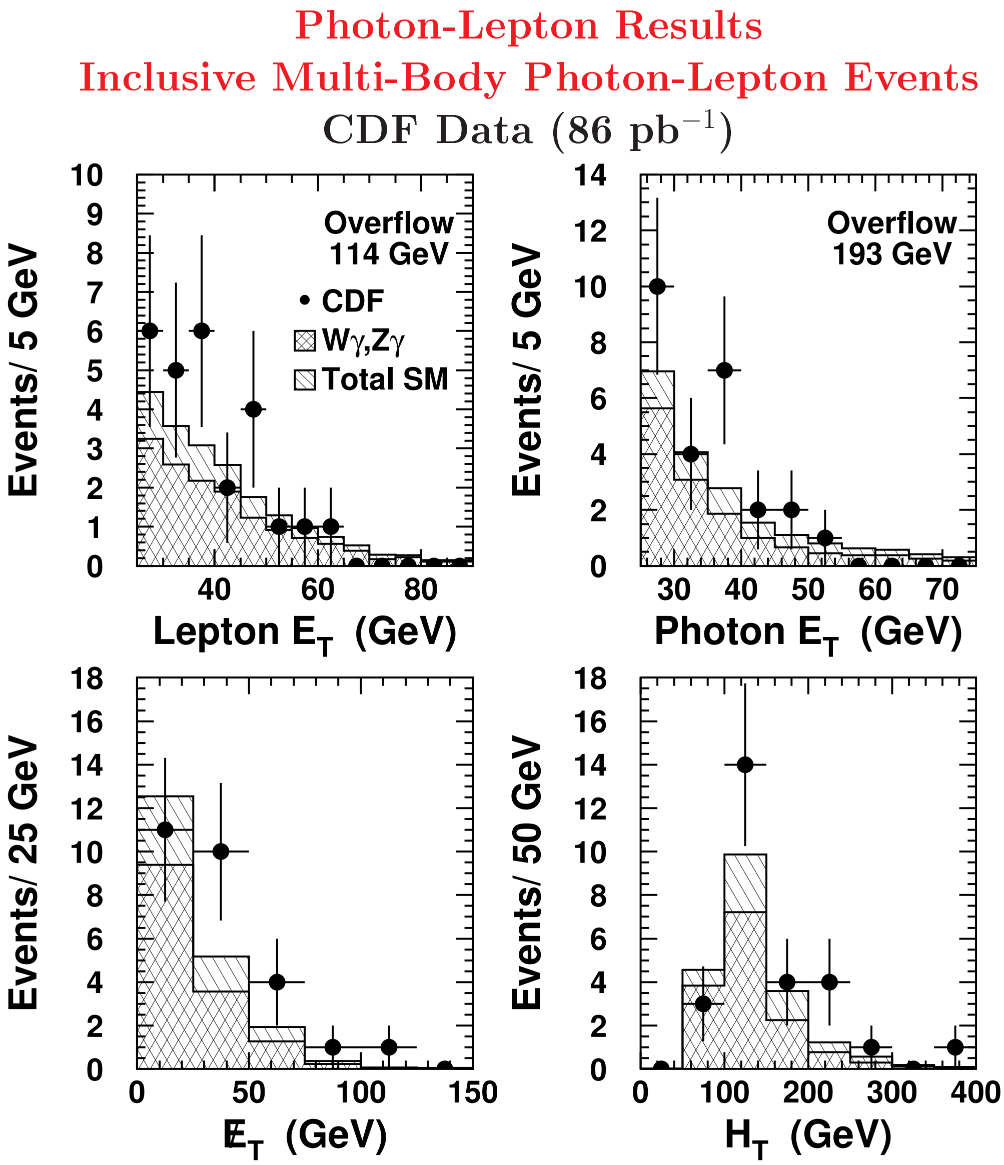


Figure 7: A comparison of various kinematic quantities in the $\gamma + e/\mu + \not{E}_t + X$ ('multibody') channel with the SM expectations.

Conclusion: have too many $\ell + \gamma + \not{E}_t$ events, but it's statistically not compelling yet. But, we have now set the cuts *for Run II* a priori, and (in principle) have the tools to make the SM predictions.[8]

[8]One interesting thing to note- there's a $\mu\mu\gamma\gamma jj$ event in the sample.

The signature γ+b-quark+$\not\!\!E_t$

Another signature-based search, initally motivated by the possible stop-quark decay.

$$\tilde{\chi}^+\tilde{\chi}^0_2 \rightarrow (\tilde{t}b)(\gamma\tilde{\chi}^0_1) \rightarrow (c\tilde{\chi}^0_1)(\gamma\tilde{\chi}^0_1) \qquad (7)$$

We look for bumps in the mass spectra, and for excesses of events in kinematic regions unpopulated by the SM.

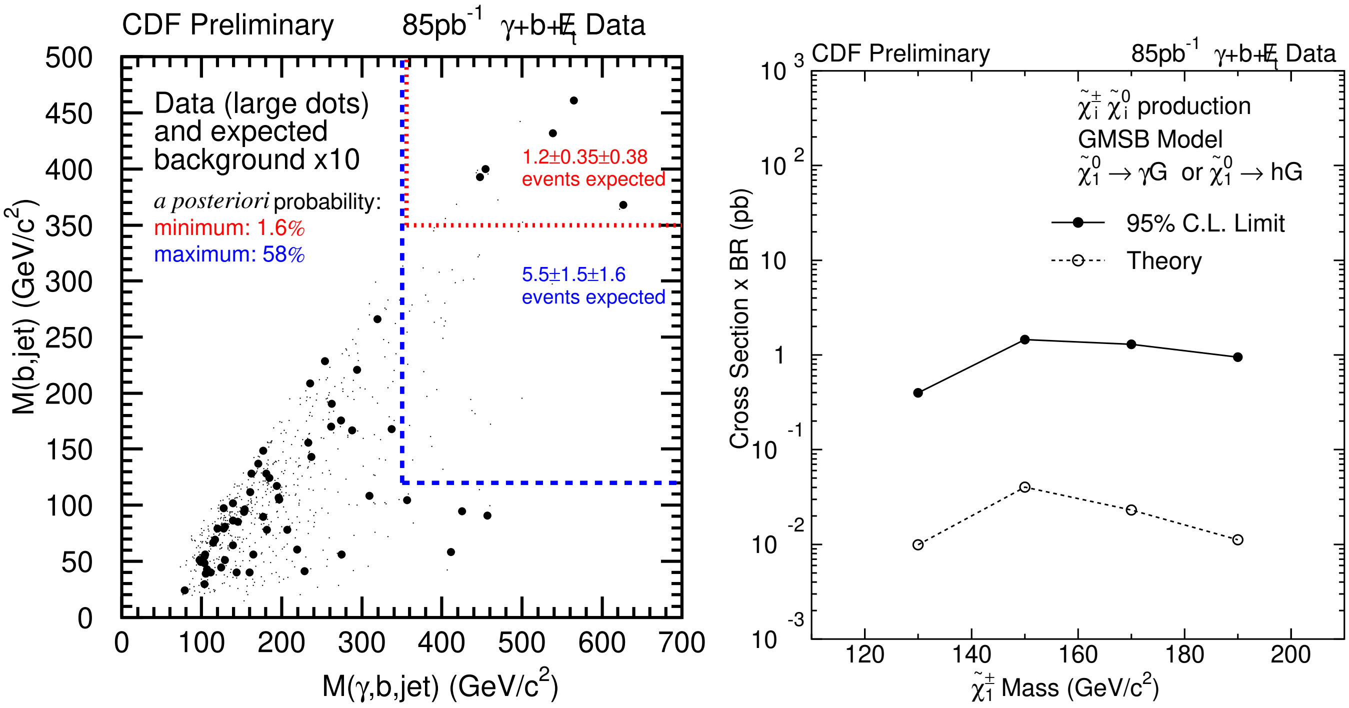


Figure 8: Left: the scatter plot in $\gamma bjet$ 3-body mass vs $bjet$ 2-body mass; Right: The limit vs $\tilde{\chi}^0_1$ mass in a gauge-mediated model in which the gravitino is the LSP and the $\tilde{\chi}^0_1$ is the NLSP. All the squarks and gluinos are very heavy. The b-quark comes from $\tilde{\chi}^0_1 \rightarrow\ h\tilde{G}$, followed by $h \rightarrow b\bar{b}$.

Again, we need (lots) more data to discover the gravitino in this channel. However, because the spectrum is not rapidly falling, and the new detectors have more than twice the acceptance of before, and we are told we will get a factor of 150 more data, it may be of interest.

The Signature $\gamma + \not{E}_t$

(all the work, and even some of the prose, from Peter Onyisi)

We had discussed this in detail above as a signature of LED's: $\bar{p}p$ exciting Kaluza-Klein excitations in the bulk. It is also a SUSY signature for the case of where the gravitino is very light, and all the other sparticles are heavy[9]

The gravitino can couple to SM particles with its goldstino degrees of freedom, with an interaction strength proportional to $1/F^4$. One can thus derive an absolute lower limit on the gravitino mass $m_{3/2}$, and equivalently, the scale $F = \sqrt{3} m_{3/2} M_{\text{Planck}}$ of supersymmetry breaking) through cross section limits on $q\bar{q} \rightarrow \tilde{G}\tilde{G}\gamma$.

$$\boxed{\text{Result: } \sqrt{F} \geq 221 \text{ GeV}}$$

Other limits:

217 GeV (CDF jet + $\not{E}_t$)
217 GeV (DELPHI photon + $\not{E}_t$)
192 GeV (L3 photon + $\not{E}_t$)
190 GeV (OPAL photon + $\not{E}_t$)
186 GeV (ALEPH photon + $\not{E}_t$)

[9] A. Brignole, F. Ferruglio, M. Mangano, F. Zwirner; hep-ph/9801329

The Standard Model Higgs- is it there?

Present Limits:

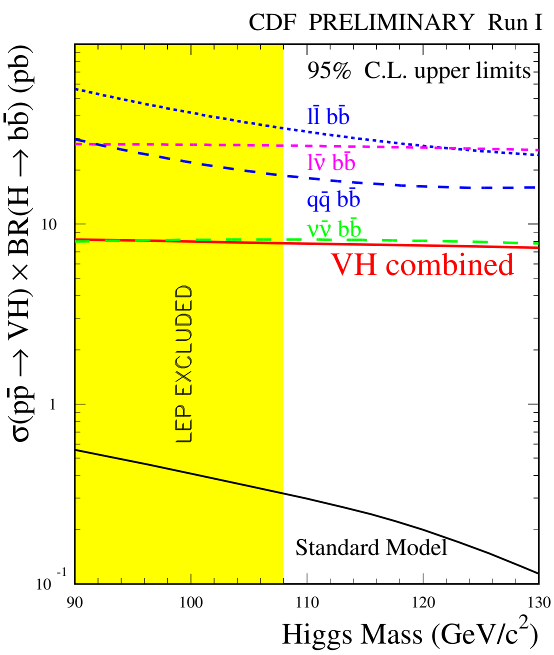


Figure 9:

Estimated Reach in Run II versus Luminosity (Higgs Wk Gp):

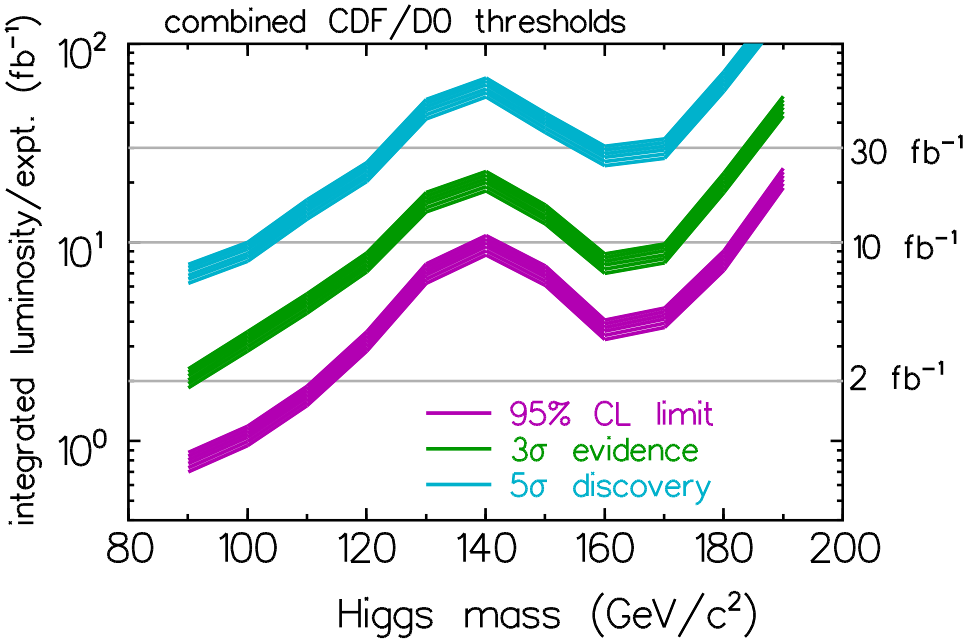
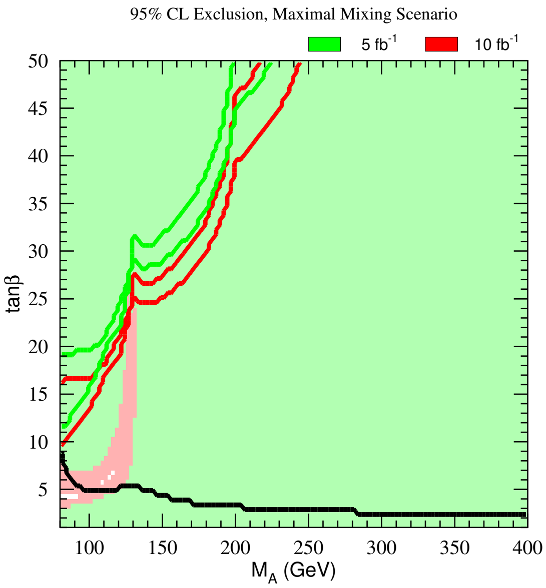


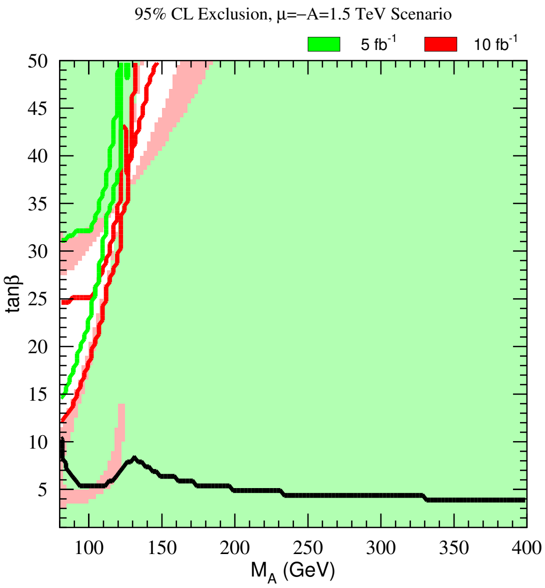
Figure 10:

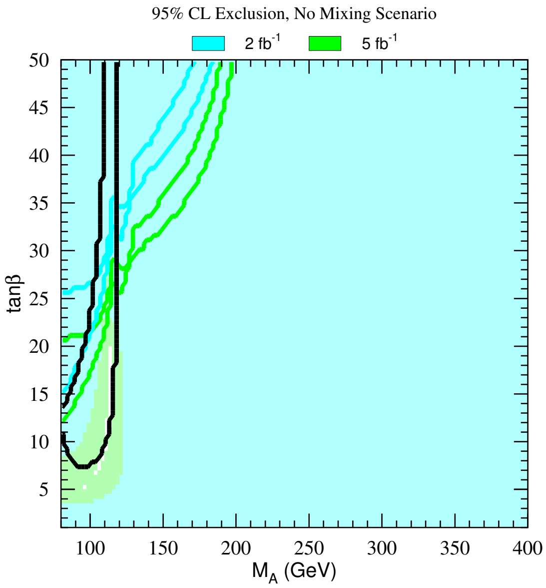
Projections of Reach for MSSM Higgs in Run II:

(Carena, Haber, Mrenna, Wagner)

▷Combine 2 Channels: Solid: $q\bar{q} \to V\phi$, $\phi \to b\bar{b}$, $(\phi = h/A, H/A)$, and Lines: $gg, q\bar{q} \to b\bar{b}\phi$, $(\phi = h/A, H/A)$







95% Exclusion

a) Maximal Mixing

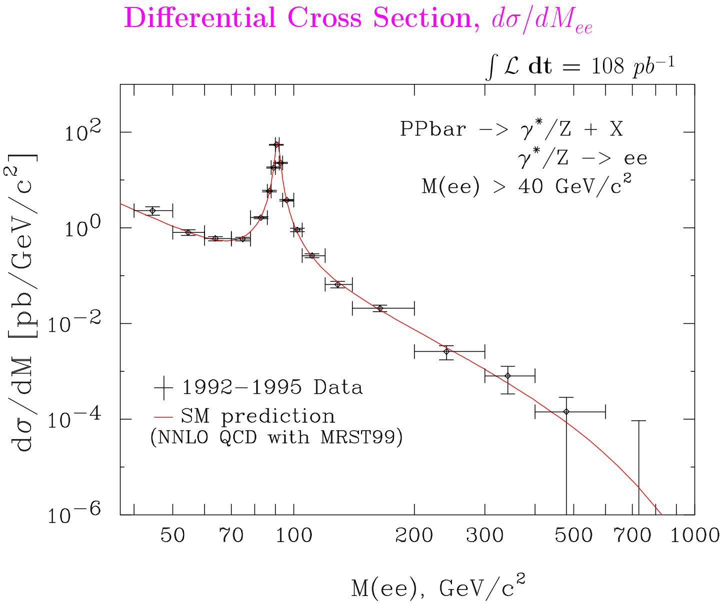
b)'Supressed $V\phi \to Vb\bar{b}$'

c) No Mixing

New Gauge Groups, Particles: e.g. Z-primes

CDF Preliminary

Look for 'bumps' in the invariant mass spectrum:

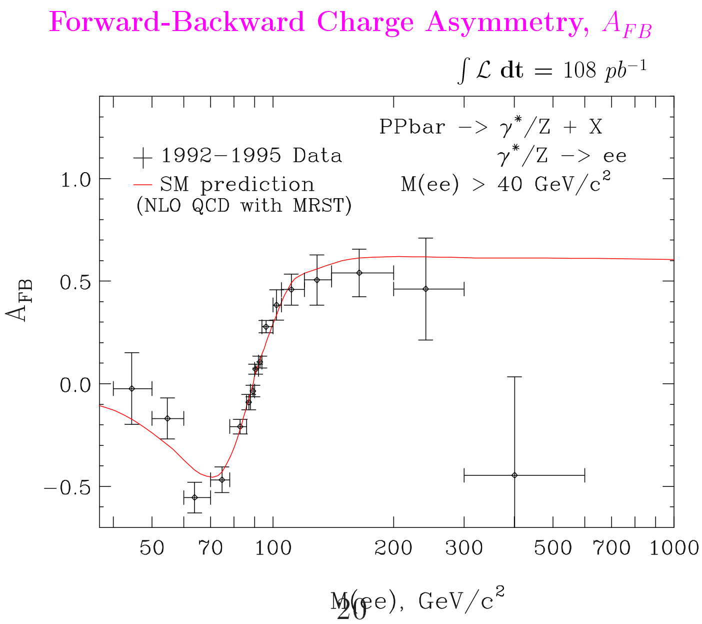


Solid line is NNLO QCD calculation with MRST99 (NLO) PDFs, scaled up by a factor 1.11.

Figure 11:

Can reach much further by looking in the angular distributions for interference (Rosner):

CDF Preliminary



Solid line is NLO QCD calculation with MRST (NLO) PDFs

Figure 12:

New U(1)'s; Z-primes, continued

Present limits from CDF (similar from D0):

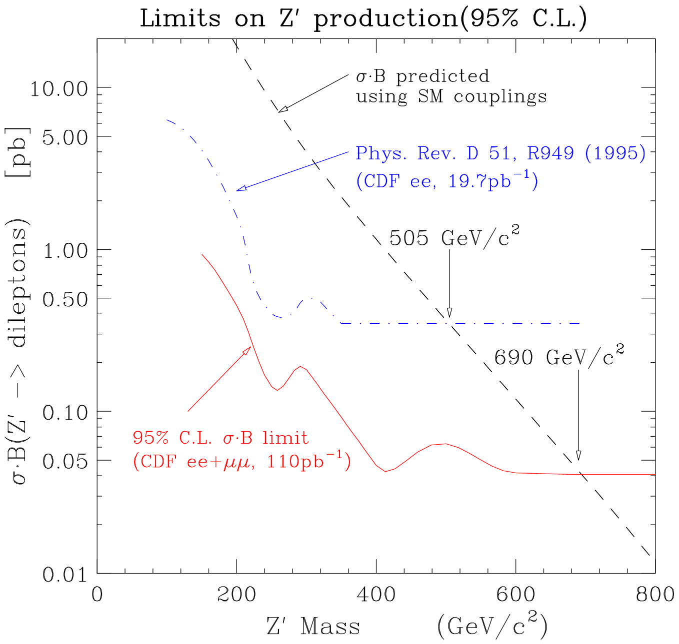


Figure 13:

Our highest mass event (with a 'wrong-sign' asymmetry!):

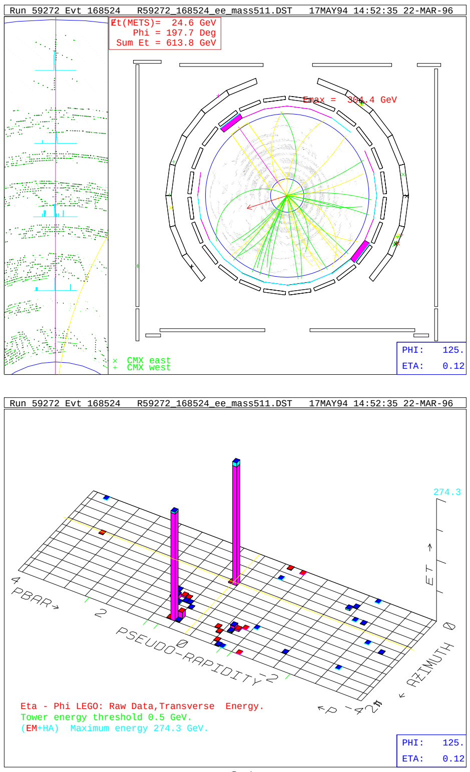


Figure 14:

CONCLUSIONS

Much as the experimental determination of nature summarized by the Standard Model, new phenomena will set boundary conditions on future models and theory. We have proposals that the mass scale of gravity is that of the ewk scale; there are (alternative) proposals that require Supersymmetry to be accessible below a TeV or so. The scenario of a 'desert', with nothing interesting for experimentalists up to the an inaccessible energy, or even the Planck scale, while still possible, seems more and more unlikely.

Among the possibilities that we may find in the next decade, first at Fermilab, and then at the LHC, are:

- Some (unknown!) form of Supersymmetry
- The Higgs or Higgses
- New Gauge Particles and Symmetries
- Large Extra Dimensions
- Black Holes
- The Unexpected...

THE END