A Model Independent Approach to the LHC Olympics Data

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Prologue 1

This prologue was added after the talk as a guide to the reader.

- The analysis below is of the LHC Olympics' first black box, which consists of a signal with a ~ 35 pb cross-section and large missing energy in essentially all events; integrated luminosity is 2 fb^{-1}. See the LHC Olympics webpage.
- The sample has crude modelling of detector effects; all Pythia-generated events are passed through a version of PGS (by John Conway) modified a bit to apply to LHC detectors (by Steve Mrenna)
- *At this stage in the Olympics, there is no background; this is to keep the exercise manageable for a wider variety of theorists. Over time, this will change.* To keep the following analysis minimally realistic, only events with missing transverse momentum (MET) greater than 125 GeV were used in the analysis below.

Prologue 2

- Most or all of the analysis techniques used here could be applied to a sample with much harder MET cuts and jet-energy cuts, requiring of course a larger integrated luminosity. For such a sample, most or all of the same conclusions could be drawn. This is the main reason, in our view, why this study is probably useful despite its limitations.
- However, it should be emphasized that this is a work in progress and we do not believe we have extracted all the information which is present in the data set. Nor have we had time to perform important cross-checks at present.
- A version of this talk — corrected as need be, and supplemented by additional studies — will eventually be posted on our websites; mine is at http://www.phys.washington.edu/~strasslr .
- Comments are more than welcome! We are still learning.

Prologue 3

Here is a summary of the steps in the analysis.

- a brief consideration of a $t\bar{t}$ sample as a reality-check.
- the MET in the sample is plotted; it has a long tail above 125 GeV, where a cut is placed. [We also apply $p_T > 25$ GeV cuts to all objects.]
- a visible mass plot shows the rough energy scale of the dominant process(es) is of order 1 TeV or below; the events are consistent with pair production of colored particles whose decay products include invisible particles.
- b-tagging information indicates that at least half of the events in the signal (and possibly all) contain 4 b quarks.

Prologue 4

- examination of dilepton events shows that the two leptons are completely uncorrelated in both flavor and sign, which
  - excludes a Higgs as a dominant source of the bs.
  - is consistent with the absence of dilepton kinematic endpoints.
  - means that the two leptons are emitted independently, through the independent decays of two real [i.e. not complex] particles.
- But charge conservation then requires that either electric charge is being hidden in jets or it is disappearing in low-p_T leptons.
  - The first case cannot be excluded but is unlikely from the model-building point of view.
  - The second is very natural; it merely requires that the light invisible particles be part of a degenerate multiplet (as in anomaly mediated SUSY models, light Higgsino models, and many others.)

Prologue 5

- A search, in events with high p_T leptons, for low-p_T leptons whose charge is anti-correlated with the charges of high-p_T leptons, is carried out, but no discovery is made [note this is described in more detail near the end of the analysis.] This implies the degeneracy of the invisible particles is small.
- Working hypotheses are developed; these predict a $b\bar{b}$ kinematic endpoint and the presence of top quarks in many events.
  - A kinematic endpoint in $b\bar{b}$ is found, using quiet events; still preliminary but looks promising.
  - A search for top quarks using multiple methods is partially successful but difficult to interpret.

Prologue 6

- Two models, based on one of the working hypotheses (gluinos with $m \sim 450$ GeV and light degenerate gauginos or Higgsinos with $m \sim 150$ GeV), are simulated and found to match the data reasonably well on several crude measures. This is extremely preliminary at the time of this conference; the specific models chosen are not carefully chosen and are currently inconsistent, but their dominant signal (gluino production and decay) is not very sensitive to these problems.
- Some possible methods for detecting and studying the degenerate invisible particles and for distingushing between gaugino-LSP and Higgsino-LSP scenarios are discussed.

A Work In Progress

- All Results Extremely Preliminary! Please do not use yet.
- Work of Steve Ellis, Matt Bowen, MJS from 6/28 – 7/18
- Many ambiguities in the analysis could surely be removed with additional work.
- Thanks also to Steve Mrenna and David Rainwater for useful discussions.

Our Philosophy and Methodology:

- We tried to be as realistic as possible (very difficult) and not cheat.
- We tried to be as model-independent as possible and not assume supersymmetry or any other specific framework until absolutely necessary.

At the end of June, a usable signal sample and a corresponding $t\bar{t}$ sample became available and we started looking at them.

First question: can we understand the $t\bar{t}$ sample?

- Can we see reasonable numbers of all three flavors of leptons?
- Can we estimate detection rates and fake rates for the three leptons?
- Can we understand b tagging (remember charm quarks are also tagged sometimes and gluons/light-quarks are mistagged.)
- Do we see anything profoundly wrong with the data set?

We did find problems but only with handfuls of events; still needs a look if we ever do something like this again.

Start with leptons

$t\bar{t}$ sample - 500,000 events, no MET cut

Single Leptons with $p_T > 25$ GeV

[If you don't put any p_T cut, then the μs outnumber es by 35 percent.]

$$\begin{bmatrix} e^- & e^+ & \mu^- & \mu^+ & \tau^- & \tau^+ \\ 25220 & 25011 & 28397 & 28582 & 20058 & 20280 \end{bmatrix}$$

(hadronic τs; leptonic τs end up in e/μ sample.)

Officially $(1/9)(6/9) \times 500,000 = 37000$.

Why are these numbers so small? Acceptance in η? p_T? Isolation cuts? Other issues? Not sure.

Effective efficiency = efficiency×acceptance×isolation ~ 60 percent.

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$t\bar{t}$ sample — 500,000 events, no MET cut

Single Lepton

(hadronic τs; leptonic τs end up in e/μ sample.)

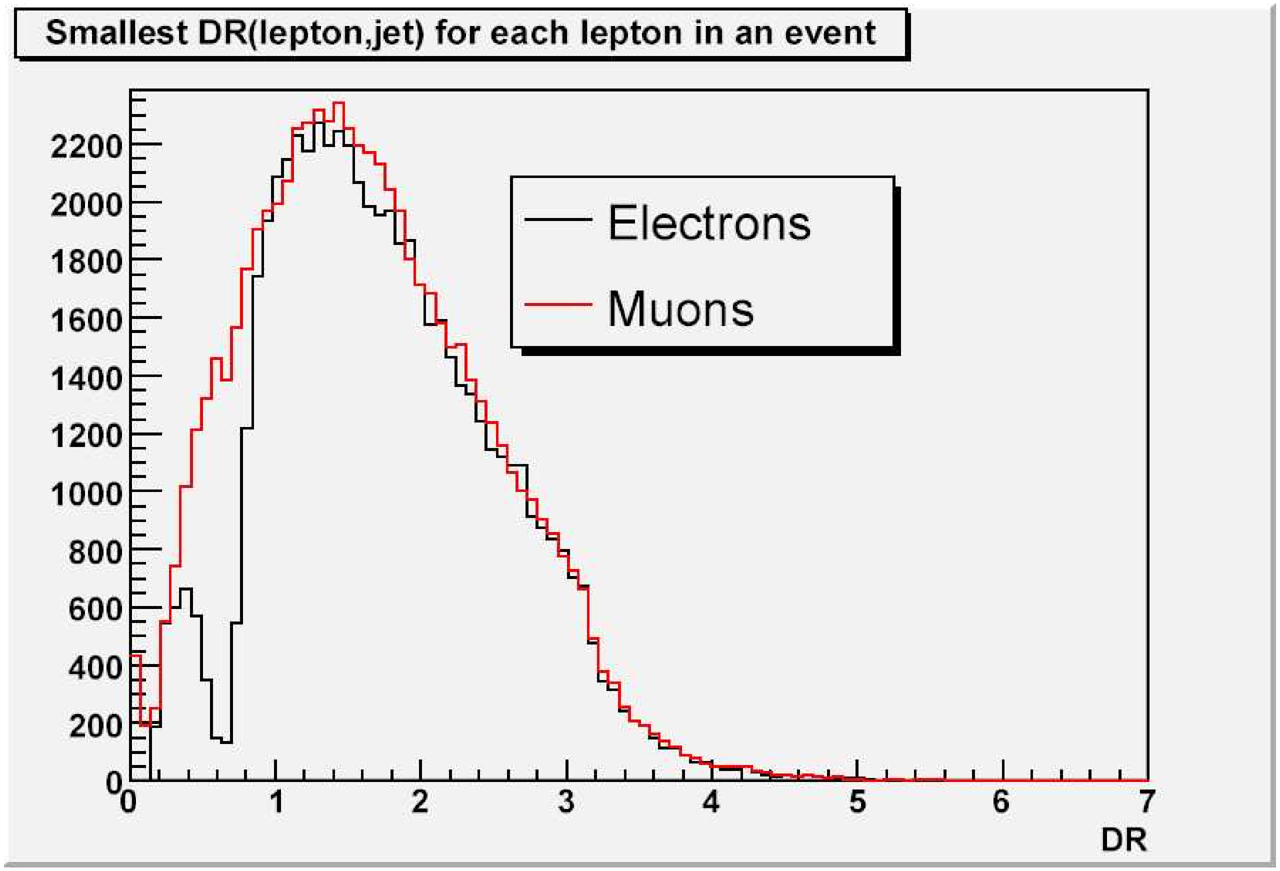
$$\begin{bmatrix} e^- & e^+ & \mu^- & \mu^+ & \tau^- & \tau^+ \\ 25220 & 25011 & 28397 & 28582 & 20058 & 20280 \end{bmatrix}$$

Why are e and μ so differnt?

- slightly higher intrinsic efficiency
- μ isolation cut less severe
- μs produced by b, c quarks; a few are isolated

Have not explored in detail.

Separation between e or μ and nearest jet in $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



The effect of the isolation criteria needs a study (NET)

Look at dilepton pairs

$$\left[\begin{array}{ccccccc} & \tau^- & \mu^- & e^- & e^+ & \mu^+ & \tau^+ \\ \tau^- & 363 & 456 & 410 & 1414 & 1754 & 1252 \\ \mu^- & & 25 & 20 & 2289 & 2609 & 1728 \\ e^- & & & 0 & 2066 & 2338 & 1467 \\ e^+ & & & & 4 & 15 & 383 \\ \mu^+ & & & & & 22 & 452 \\ \tau^+ & & & & & & 359 \end{array}\right]$$

Notice all the fake hadronic τs (consistent with probability ~ 0.5 percent per jet)

Notice all the same-sign dimuons (muons from heavy quark decays)

Very few electrons are not real.

Also 502 trilepton events (most from fake τs, some from isolated μs from bs.)

b tagging:

Again, b tagging is very complicated

Steve M. gave us the formula for b tagging for a jet with given p_T and η; it saturates at 60 percent.

for non-b,c : min(.0001*etj,.01) [etj in GeV];
for c, 0.173*tanh(etj/42.08)*1.1;
for b, 0.57*tanh(etj/36.05)*1.1.
The additional factor of 1.1 accounts for using soft-lepton information.

Won't go through the analysis here, but the average b tagging rate on the $t\bar{t}$ sample is clearly lower, more like $40 - 45$ percent

(To get this right, need to include fact that charm has nonzero tagging rate and half the $t\bar{t}$ events have charm jets.)

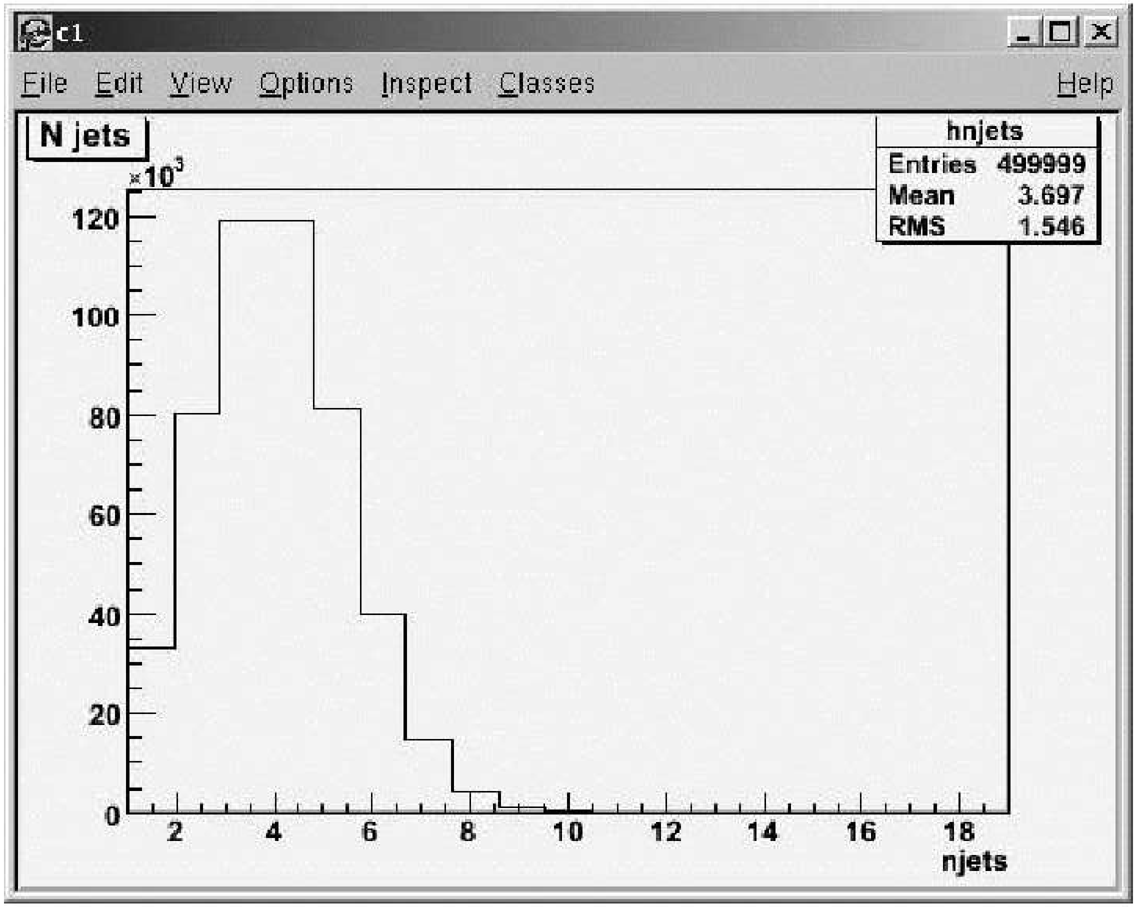
Have not checked whether this is working right.

No possibility of establishing the tagging rate to better than a few percent — important later.

Can we see the W and the top quark?

An obvious question, but for reasons that will become clear soon, I will not address this now.

How about counting jets? — should be events with up to 6 jets.



hnjets

Entries 499999

Mean 3.697

RMS 1.546

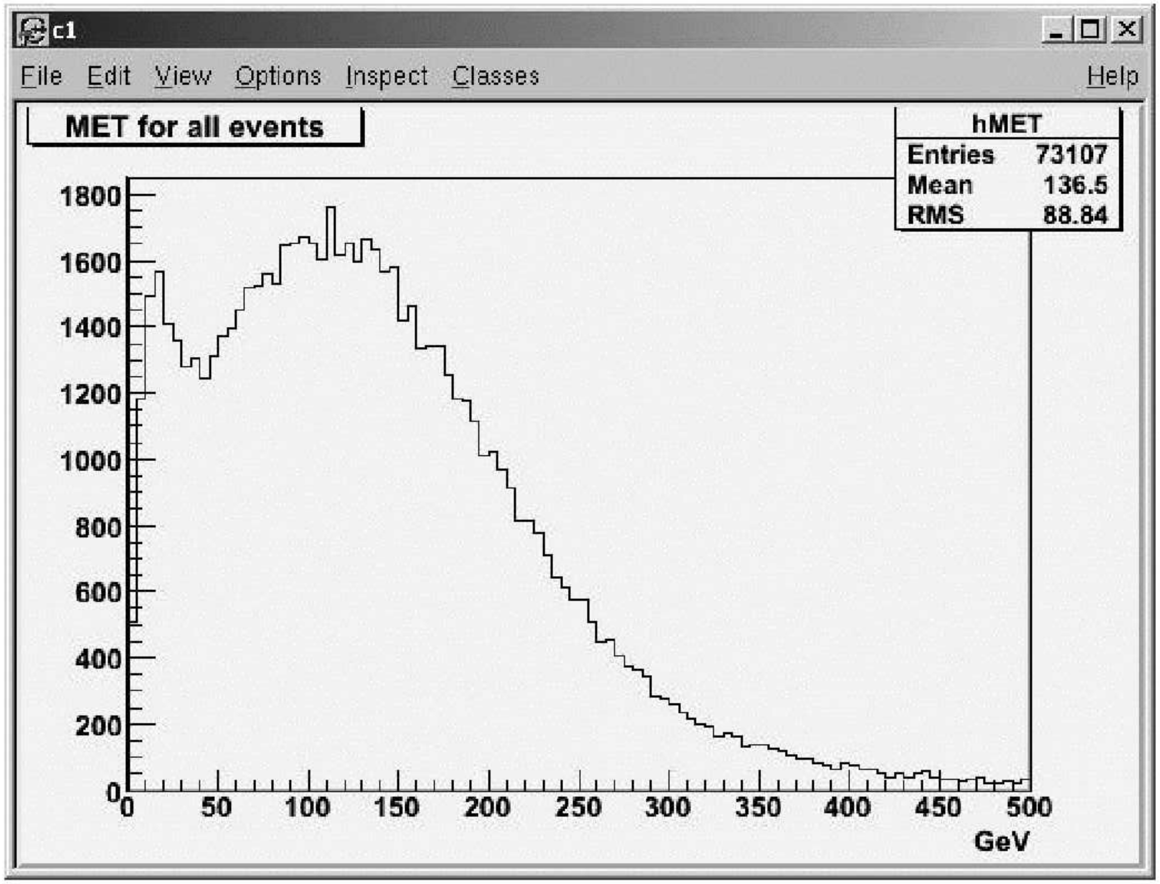
Let's turn to the signal data set. Some initial comments:

- In our view, a study without backgrounds is totally unrealistic.
- A study in which much of the data would be undetectable at LHC is worse than unrealistic — it is profoundly misleading.
- We do not want to be misled. (We do not want to mislead you either.)
- But we are not given a background. [It is not easy to generate the backgrounds at LHC; the dynamic range of production processes is enormous; minimum 10^8 events required!!! cf. Atlas data challenge, Hinchliffe] What are we to do?

A study without backgrounds is basically a study of a signal which can be purified to nearly 100 percent purity. This is almost inconceivable, because the standard model does almost everything sometimes.

But this particular data set does allow at least a rough attempt at honesty.

If you make a plot of the MET in the signal data set



So we see there's a very large missing energy signal!

But of course there's a very large missing energy background at LHCm from mismeasurements and from neutrinos from τs, Zs, $t\bar{t}$...

If we use all this data, it will be completely unrealistic.

For this reason, we tie one arm behind our backs.

Our analysis is done with a cut of $MET > 125$ GeV.

This is high enough to remove most standard model and detector background, though perhaps not quite high enough (but higher would leave no data.)

This removes half the data; 73000 events → 37000 events.

We only loosen this cut when it is clearly justified to so.

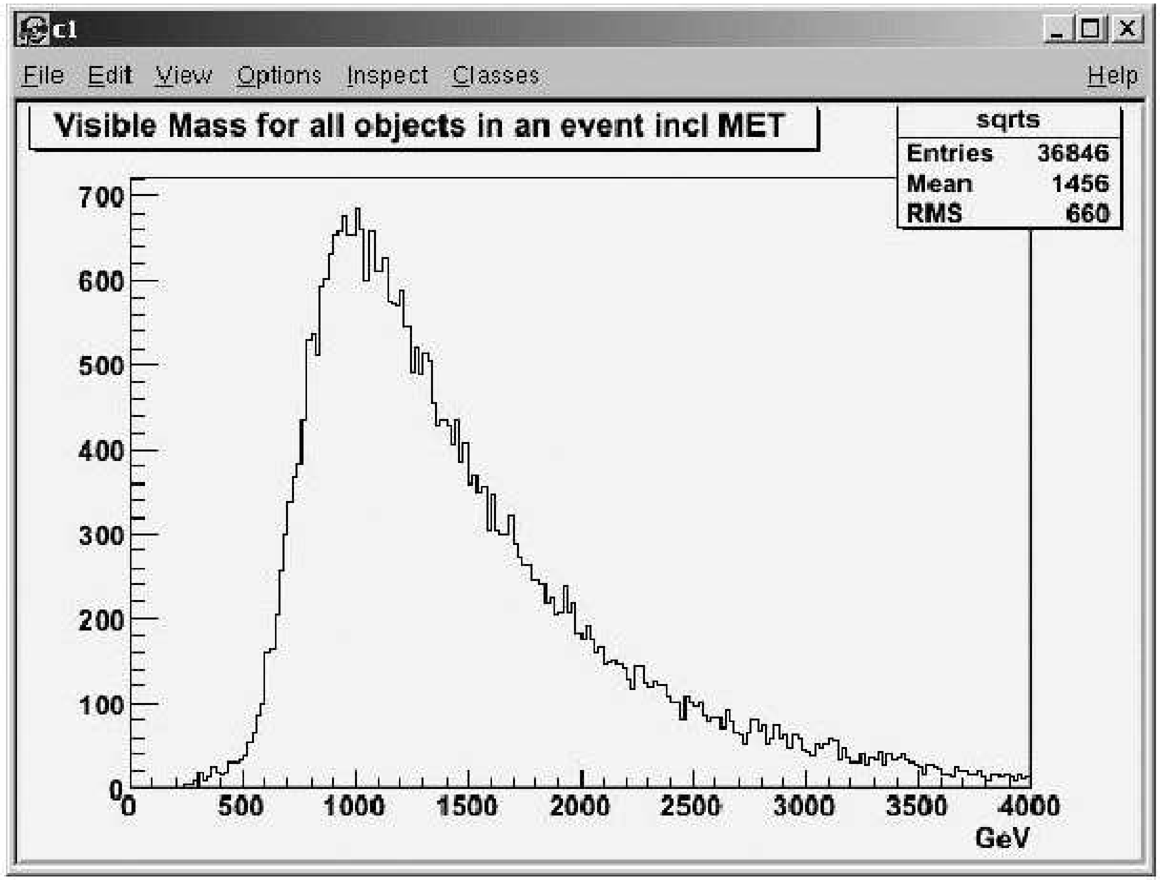
We also put a universal p_T cut of 25 GeV on all objects (jets, leptons of all flavors) in order to avoid fakes, energy mismeasurements, etc.

Again, we loosen this cut only when it is clearly justified to do so.

Ok, with these cuts, the first question we should ask is about basic kinematics.

Sum all four-momenta of all objects (putting MET vector at $\eta = 0$)

Construct invariant mass, no corrections applied to anything:



This tells us that we are producing something at a center of mass energy of order (but below) 1 TeV *(actually it could be higher if energy is lost in neutral massive particles, but constrained)* and that there is no second large production process at a higher energy.

We have searched for a second mass scale using various tricks, but as of yet have not found one. Higher mass scales are clearly present but there may be insufficient data to separate them out. (NET)

Are we producing a single particle or two?

If we have a gg, gq, or other parton-pair resonance — we should see a sharper visible-mass plot and huge number of 2-jet + no MET events; we don't. ×

So we are producing at least two particles; most likely (but not necessarily) they are two particles of the same mass.

From the size of the cross-section (something of order 30 pb) and the mass scale (1 TeV or less) we know that this is a cross-section which requires a large-coupling — such as we would expect from a QCD-like coupling strength. Most likely we are producing colored particles, possibly many flavors.

So — our best guess so far [BGSF] is pair-production of at least one type of colored particle.

We are also producing something invisible and metastable; otherwise there would be many events in the visible-mass peak with little or no MET. Such an object must carry neither color nor electric charge.

Either this object is produced directly (but then why is the cross-section so big?) or it is produced indirectly via decays of the produced particles. The latter seems more likely.

Is there one such particle or two?

- If there are two, one for each produced particle, then higher visible-mass events need not have higher MET.
- If there is one, higher visible-mass events should have higher MET.
  ×

BGSF: pair-production of at least one type of colored particle, each of which decays to at least one invisible particle.

We'll call this invisible particle the LIP (light invisible particle.)

Now let's look at types of events:

How many events with k *b*-tagged jets?

$$\begin{bmatrix} \text{k tags} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \#\text{ events} & 7184 & 12449 & 11436 & 4879 & 844 & 53 & 1 & 0 \end{bmatrix}$$

WHOA! that's a huge number of 4-*b*-tagged events!

Where are they all coming from? Can't be coming from charm, tagging efficiency is too low. must be real *b*'s.

Given the tagging efficiency for *b*s, how many four-*b* events are actually in the sample?

Well, out of about 37000 events, given 844 four-b-tagged events

- tagging $\sim$ 40 percent, then about 33000 four-b events.
- tagging $\sim$ 45 percent, then about 20500 four-b events.
- tagging $\sim$ 50 percent, then about 13500 four-b events.
- tagging $\sim$ 60 percent, then about 6500 four-b events.

So if you use Mrenna's original numbers blindly, instead of the $t\bar{t}$ data, you could be off by a factor of 5.

If you use the $t\bar{t}$ data to get the tagging fraction to five percent, you have a 50 percent error bar on the number of four-b events.

But the signal surely does not have the same intrinsic η and p_T distribution for its four b's that the two bs in the $t\bar{t}$ data have, so even a perfect measurement of the $t\bar{t}$ tagging function is not enough.

You must have a model, and a very accurately calibrated detector simulation, to calculate the number of b's generated from the number of b's measured.

But any reasonable measure says that at least half the events in this sample of 37,000 events have four b quarks produced.

Now, where are all these b quarks coming from?

Directly produced b's? t's? h^0? H^+? something else?

They are not coming from neutral standard-model-like Higgs bosons.

If they were, then if there are N $h \to b\bar{b}$ events there will be about $N/12$ as many $\tau^+\tau^-$ pairs as Higgs bosons.

Even with 40 percent efficiencies for the τs to decay hadronically and be detected there should be $N/25$ extra τ events (compared to e or μ) and there should be $N/75$ extra $\tau^+\tau^-$ events (compared to $\tau^+\tau^+$ or e^+e^- or τ^+e^-.) And this is extremely conservative.

As we will see, this is completely excluded; roughly $N < 5000$. So the Higgs might play a role, but it is not a dominant effect.

Confirmation: no large $b\bar{b}$ mass peaks in the data, though there are hints of one at around 120 GeV; statistics too low at present to allow separation.

Similar arguments disfavor charged higgs.

Ok, do we have top quarks in the data sample? Possibly. We do have leptons.

Leptons:

$$\begin{bmatrix} e^- & e^+ & \mu^- & \mu^+ & \tau^- & \tau^+ \\ 1366 & 1412 & 1845 & 1760 & 1045 & 1104 \end{bmatrix}$$

Notice that the ratio of leptons to events is smaller here than in $t\bar{t}$.

Should we conclude, that there cannot be a $t\bar{t}$ pair in every event?

The ratio of muons to electrons is higher, the ratio of taus to electrons is comparable.

Should we conclude, from the fact that the μ/e ratio is higher here, that we have flavor universality violation?

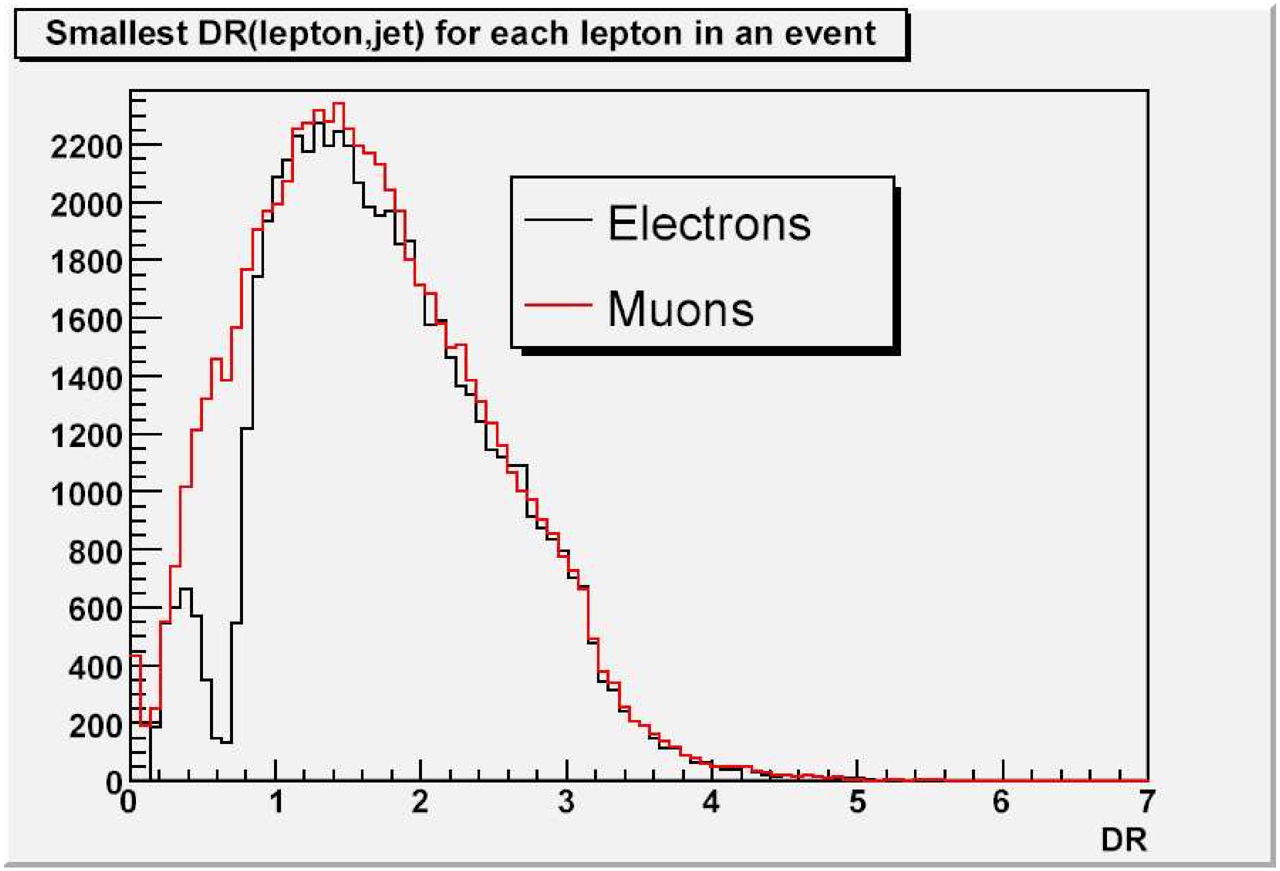
Not necessarily.

- Many more b quarks $\Rightarrow$ many more μs, some will be isolated.
- Many more jets $\Rightarrow$ harder to isolate leptons.
- η dependence of leptons determined by unknown η dependence and spins of their sources.

In fact, there is evidence against flavor violation .

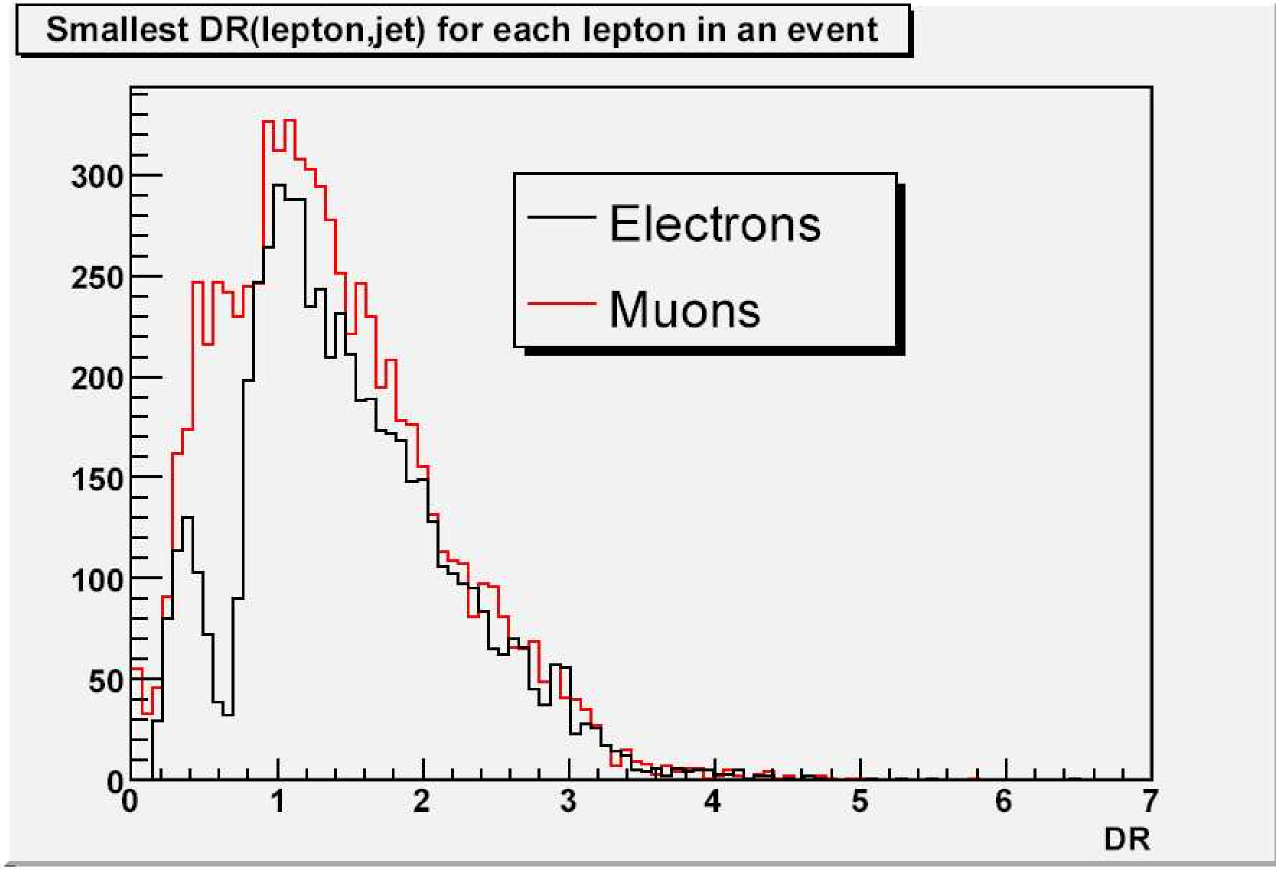
Separation between e or μ and nearest jet in $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$...

in $t\bar{t}$



Separation between e or μ and nearest jet in $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$...

in the signal



So everything is consistent with flavor universality, to a few percent.

$$\begin{bmatrix} e^- & e^+ & \mu^- & \mu^+ & \tau^- & \tau^+ \\ 1366 & 1412 & 1845 & 1760 & 1045 & 1104 \end{bmatrix}$$

Notice also there are no charge asymmetries.

However, the small fraction of events with leptons does indeed suggest that the fraction of events with $t\bar{t}b\bar{b}$ plus unseen neutral particles is probably not 1, though it might be as big as 0.5 or so.

There cannot be a large number of events with $t\bar{t}t\bar{t}$; we would see far more leptons (and we'll see another problem in a minute.)

It is important to understand whether leptons are correlelated, anticorrelated, or uncorrelated with b-tagged jets and with untagged jets.

This helps rule out many possibilities.

For example, if bs are anticorrelated with leptons, then the leptons cannot be coming from $t \to \ell\nu b$.

If the b's are correlated with the ℓs, then there must be a class of events which produce neither bs nor ℓs.

Suffice it to see that we see no correlation or anticorrelation.

Does this mean all events have 4 b's? or does it mean that even in events with fewer b's, we are just as likely to find leptons as in events with 4 bs? We don't know.

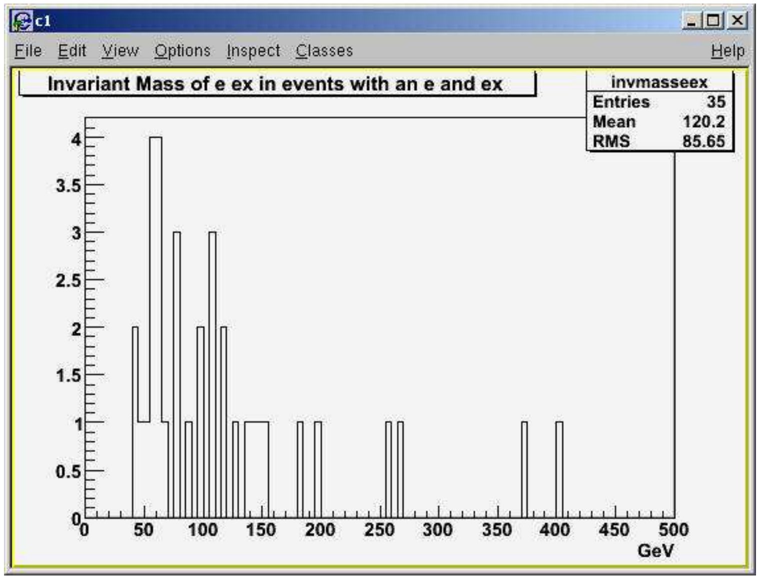
Now let's look at dilepton events.

As everyone knows, the first things you always look for (in SUSY or anything else) are kinematic endpoints and for Z bosons in the invariant masses of lepton pairs.

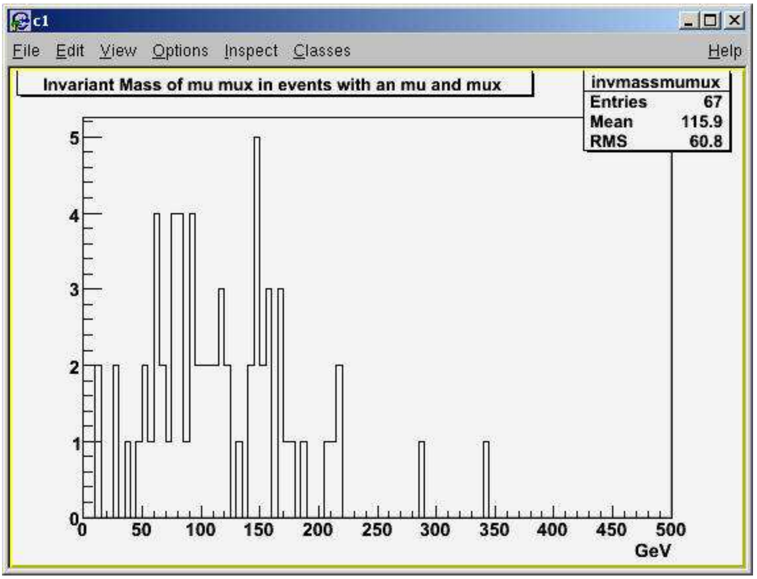
Now let's look at dilepton events.

As everyone knows, the first things you always look for (in SUSY or anything else) are kinematic endpoints and/or Z bosons in the invariant masses of lepton pairs.

But there aren't any.



invmasseex	
Entries	35
Mean	120.2
RMS	85.65



invmassmumux	
Entries	67
Mean	115.9
RMS	60.8

Let’s count the lepton pairs:

$$\begin{bmatrix} & \tau^- & \mu^- & e^- & e^+ & \mu^+ & \tau^+ \\ \tau^- & 19 & 43 & 39 & 35 & 55 & 25 \\ \mu^- & & 36 & 56 & 51 & 66 & 50 \\ e^- & & & 21 & 34 & 51 & 27 \\ e^+ & & & & 21 & 61 & 35 \\ \mu^+ & & & & & 25 & 43 \\ \tau^+ & & & & & & 21 \end{bmatrix}$$

Total dilepton events: 814 ; # trilepton events (e,mu,tau): 25

trilepton events with ditau: 12 ; # events with (e,mu,tau)>3: 0

No charge asymmetries.

No same-flavor/opposite-sign preference (so few Zs , Z^*/γ^*s)
[* means “off-shell”]

No opposite-sign preferences! (few $t\bar{t}$ or $h \rightarrow W^+W^-$)

In fact, flavor and charge of the two leptons are completely uncorrelated!

To get two leptons of two independent charges and flavors, we must have two leptons independently being emitted in the decay of two independent real particles.

Note this is consistent with not seeing any lepton pair kinematic endpoints.

This would be consistent with two gluinos, each of which manages to emit one lepton; the gluino has no preference for one charge over another since it is a Majorana particle.

It would also be consistent with squark pairs with each $\tilde{q}$ *decaying only to* $q\chi^0$, *the* χ^0 *being a neutralino which similarly decays to a lepton of either sign.*

But in either case, we have a problem.

Our problem: We have a real particle decaying to a charged lepton.

Where did the charge go?

We have

$$\text{real} \rightarrow b\bar{b}\ell^{\pm}\ \text{LIP} + ????$$

There are two possibilities.

- the charge is being emitted in two jets, such as $u\bar{d}$.
- the charge is being hidden in low-energy particles (quarks or leptons) that lie below the $p_T > 25$ GeV cut, and possibly below detection thresholds.

To do the first, must add something leptophobic to the model, in channel which cannot decay via a W or H^+ ($\Rightarrow$ leptons). This requires that the particle which is decaying to the two jets is an electroweak singlet. *I don't think this can be done in SUSY, given the data.*

To detect it, we need to find a way to see the two jets. This could be very difficult.

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$$\text{real} \to b\bar{b}\ell^{\pm}\ \text{LIP} + ????$$

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- the charge is being hidden in low-energy particles (quarks or leptons) that lie below the $p_T > 25$ GeV cut, and possibly below detection thresholds.

The second is very natural, if the LIP is actually one of an electroweak multiplet of LIPs, which can easily be degenerate.

For instance, this happens in SUSY if $M_2 \ll M_1, \mu$ (anomaly mediated models, with triplet gaugino LSPs) or $\mu \ll M_1, M_2$ (Higgsino LSP models, with 2 doublet higgsino LSPs.)

Could the LIPs carry lepton number? (e.g. degenerate slepton and sneutrino)

No; if lepton-number electroweak-doublet LIPs were produced in every event, this would lead to far more easy-to-see leptons (an average of one per event) than are seen.

Degenerate lepton-number-carrying doublets that are not LIPs will also give far too many easy-to-see leptons.

So we exclude this; the leptons we see come with a neutrino, and lepton number is not carried off by a LIP

This makes it likely that a W^* of very low mass provides the lepton or quarks that carry off the missing charge.

So — let us hypothesize that for every visible lepton there is a very low-mass W^* which will sometimes give us a hard-to-see lepton.

More precisely, assume many events have four W's or W^*s, two with high mass and two with low mass, two with positive charge and two with negative charge, charges assigned at random.

In this case, we could rule this scenario *in* if we could detect very low p_T leptons which are *anticorrelated* in sign with the ones that we detect at high p_T.

We have done a search for such leptons and found none, so we cannot confirm this scenario. But this could change with higher statistics; something to watch. More on this later.

The possibility that the charge disappears via a leptophobic process remains unsettled.

What now?

Let's take stock:

We are most likely producing a pair of particles which carry color, and are either themselves real or decay almost always to real particles.

Along the way they probably emit two b quarks but not via Higgs and almost never via two top quarks.

The cross-section for these particles is of order 30 pb. This is consistent with a color octet of mass of order 300-500 GeV or with a number of color triplets of this mass scale. We cannot lower the mass scale (the visible mass plot) nor can we trivially raise it (since this would decrease the cross-section — though we could compensate by producing multiple similar particles.)

Either we have degenerate LIPs with degeneracy less than a few GeV, or we have a leptophobic decay mode that allows charge to be stored only in hadrons.

We'll return to the question of detecting the LIPs later in the talk.

Without doing a single computation, we have ruled out mSUGRA in most (all?) of its parameter space.

In mSUGRA $M_1 < M_2 < M_3$, so the LIPs must be Higgsinos in the regime $\mu \ll M_1 < M_2 < M_3$; but our production process must then be gluino production (in which case $M_3 \sim 400$ GeV and M_2 and M_1 are too small to give degenerate Higgsinos) with

$$\tilde{g} \to b\bar{b}\chi_0, t\bar{b}\chi^-$$

or squark production with $M_3 > M_2 > m_{\tilde{q}} > M_1 > \mu$, with

$$\tilde{q} \to q\tilde{B}, \tilde{B} \to b\bar{b}\tilde{H}^0, t\bar{b}\tilde{H}^-$$

but this cannot be done in mSUGRA since the squarks would be pulled by renormalization up to the gluino mass scale, which by assumption is well above 1 TeV...

Moreover, there is nothing preventing a decay of the form $\tilde{B} \to hH^0$ (and we'll see that kinematics does not forbid it) and we have very strong constraints on the number of tau pairs; this disfavors this kind of model.

Of course, we do not want to assume supersymmetry right now. We have not in any sense verified it.

We have two natural starting points to explore.

1) Pair production of color octet particle "G", decaying to LIPs "N^0" (possibly more than one) and "$C^\pm$", via $G \to b\bar{b}N^0$ and $G \to t\bar{b}C^-$ [and its charge conjugate.]

2) Production of multiple sets of color-triplet quark-number-carrying particles Q decaying to a real particle R^0 and from there to the LIPs, via $Q \to qR^0$ and either $R^0 \to b\bar{b}N^0$ or $R^0 \to t\bar{b}C^-$ [and its charge conjugate].

More elaborate scenarios are certainly possible but let's stick with these.

In either case, it is crucial to verify that there are actually top quarks in the sample, and to measure the kinematic endpoint from the $G \to b\bar{b}N^0$ decay or the $R^0 \to b\bar{b}N^0$ decay.

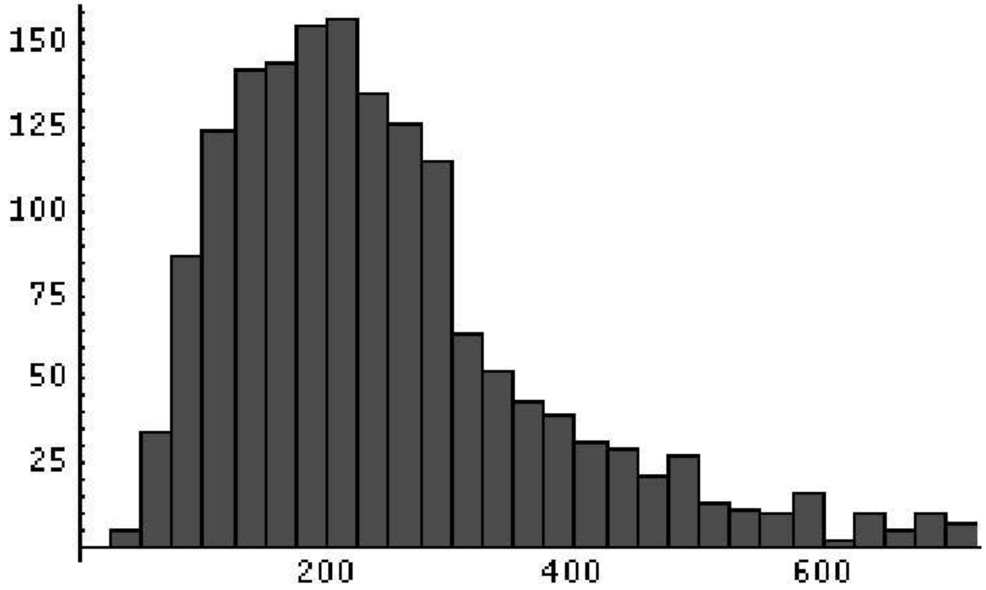
We'll do the latter first.

To seek a kinematic endpoint from $G \to b\bar{b}N^0$ or $R^0 \to b\bar{b}N^0$ we select events which are especially quiet (at least two b-tagged jets and at most 4 jets total with $p_T > 25$.)

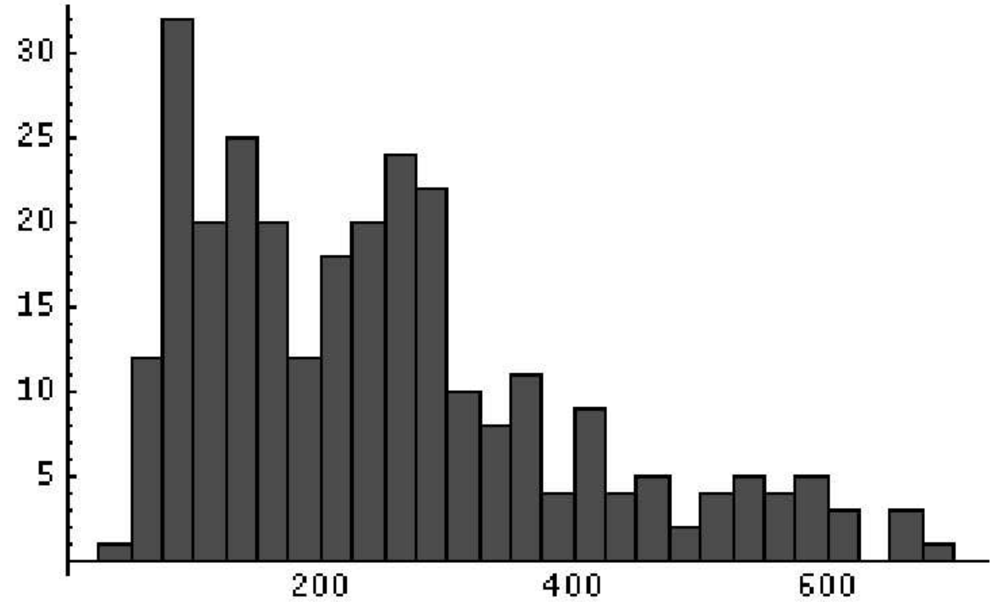
... and plot the invariant mass of the b-jet pairs ...

To seek a kinematic endpoint from $G \to b\bar{b}N^0$ or $R^0 \to b\bar{b}N^0$, we select events which are especially quiet (at least two b-tagged jets and at most 4 jets total with $p_T > 25$.)

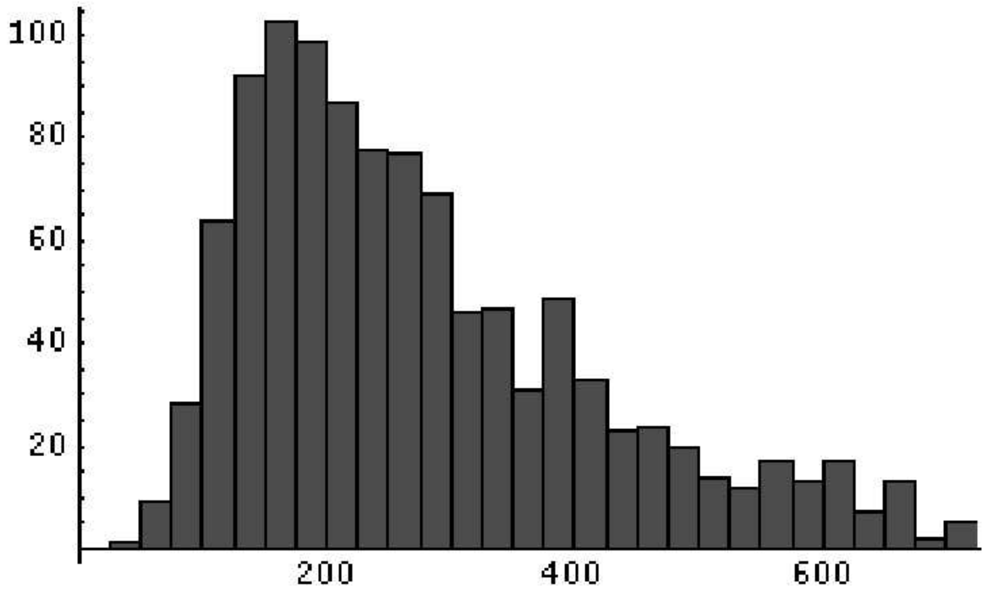
... and plot the invariant mass of the b-jet pairs ...



Similarly in quiet events in untagged jets



and in quiet events one tagged jet and one untagged jets



So there appears to be a mass splitting between G and N^0 or R^0 and N^0 of about 300 GeV. This could still go away; we would feel much better if we could see this in more subsamples. If it is real, it could be measured more precisely with more work and/or more data.

This now explains why we don't get $t\bar{t}$ even though we have $t\bar{b}$ and $b\bar{b}$; the mass splitting is smaller than $2m_t$. So we don't have to explain this dynamically.

Now let us confirm that there are actually top quarks in the sample, because if there are none, we must seek another source of leptons.

How does Tevatron do this? Since $t \to Wb$ and $W \to \ell\nu$ or jj, take "lepton+jets" events $t\bar{t} \to (\ell\nu b)(jjb)$ Take the events with one lepton and two tagged jets and two untagged jets.

Then use Missing Energy and constraint $(p_\ell + p_\nu)^2 = m_W^2$ to get two possible values for $\vec{p}_\nu$ and thus two values for $\vec{p}_W$ for the leptonic top. Combine with one of the b jets to get the best value of the top mass.

Then take the other two jets and see if they make a W. If they do, combine them with the other b and measure the invariant mass.

This works, to a point. Additional jets are often radiated, and jets are occasionally lost, and charm is occasionally tagged.

But this method relies crucially on the fact that the only missing momentum ("MET") comes from a neutrino.

Since the signal is dominated by events with MET from other sources, this method is useless; the leptonically-decaying W cannot be reconstructed.

How else can we find top quarks?

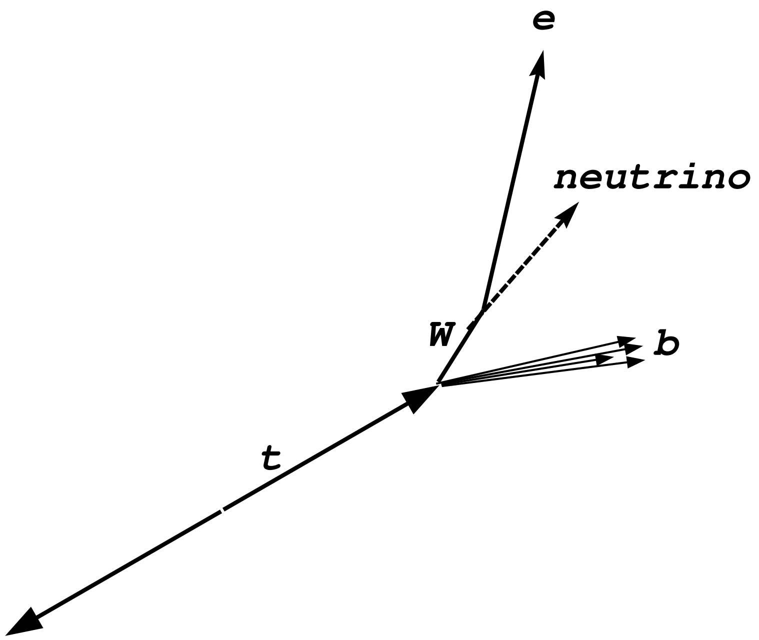
(1) Leptonically decaying top quarks, guess where the neutrino went.

(2) Hadronically decaying top quarks, full reconstruction of the mass despite huge combinatoric backgrounds.

Can either of these work?

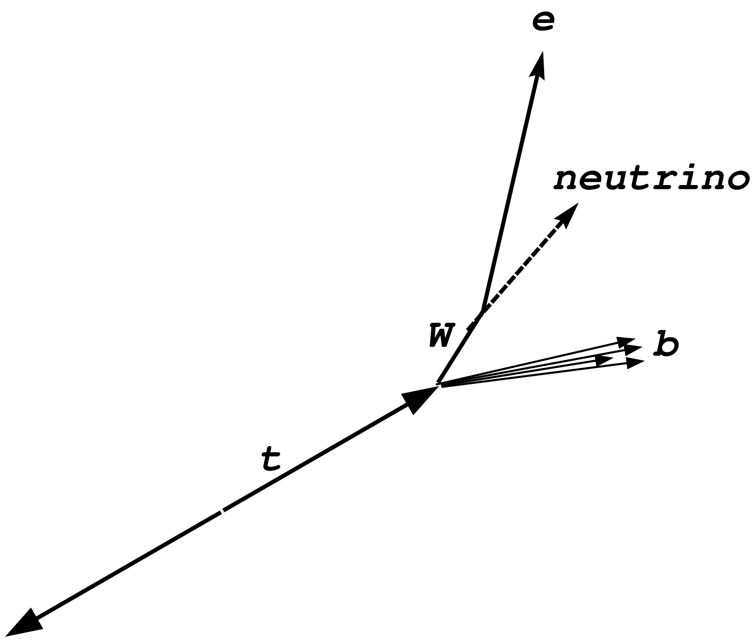
Clearly, we must test any method on the $t\bar{t}$ sample; if it doesn't work there it won't work anywhere.

Leptonically-decaying top quarks:



If a top is highly boosted, then its W will also be highly boosted, and the corresponding lepton and neutrino will likewise be highly boosted.

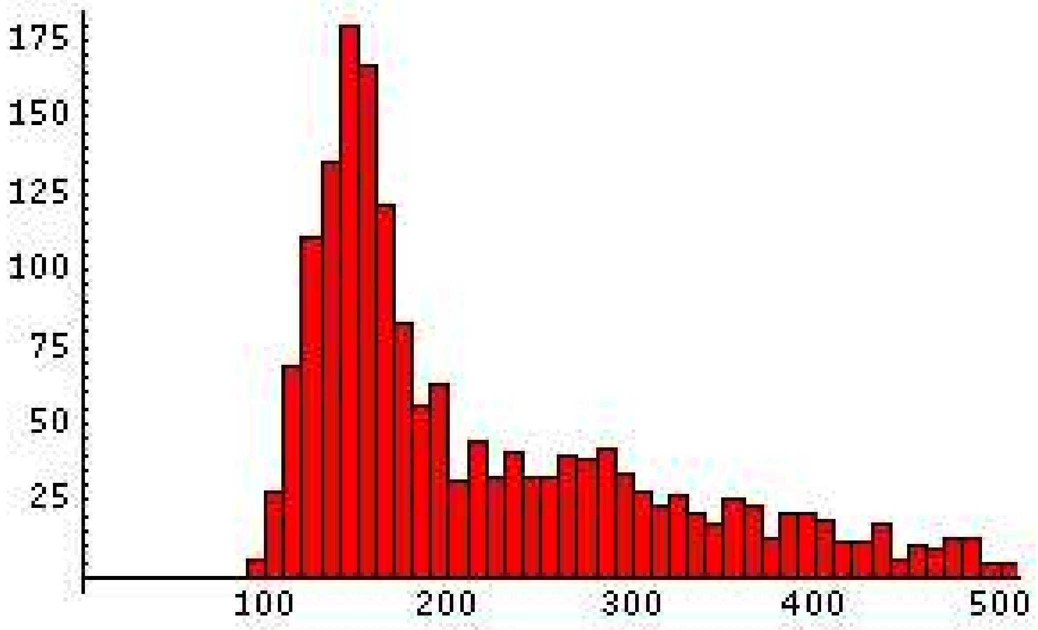
Leptonically-decaying top quarks:



If the lepton is especially highly boosted, it tends to be travelling in the same direction of the W and have about the same momentum of the W boson itself... roughly.

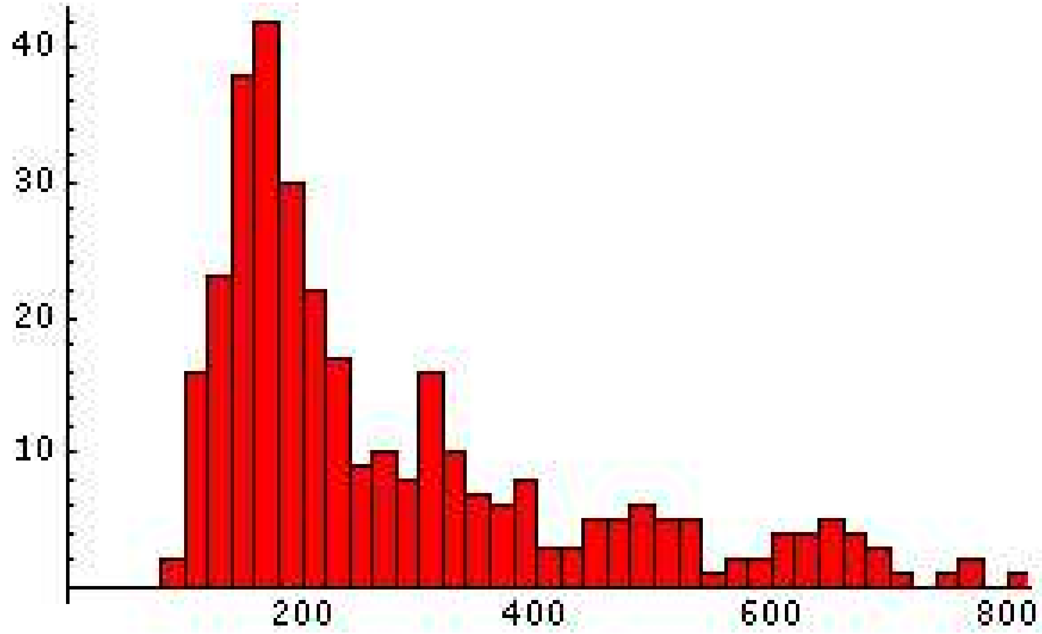
So take high visible-mass $t\bar{t}$ events, replace the electron with a W, same momentum, mass of 80 GeV; combine with all b-tagged jets in event and form invariant mass.

In the $t\bar{t}$ sample events, demanding lepton $p_T > 125$ GeV, we see the top as a very clear peak:



Good to know there really are top quarks there.

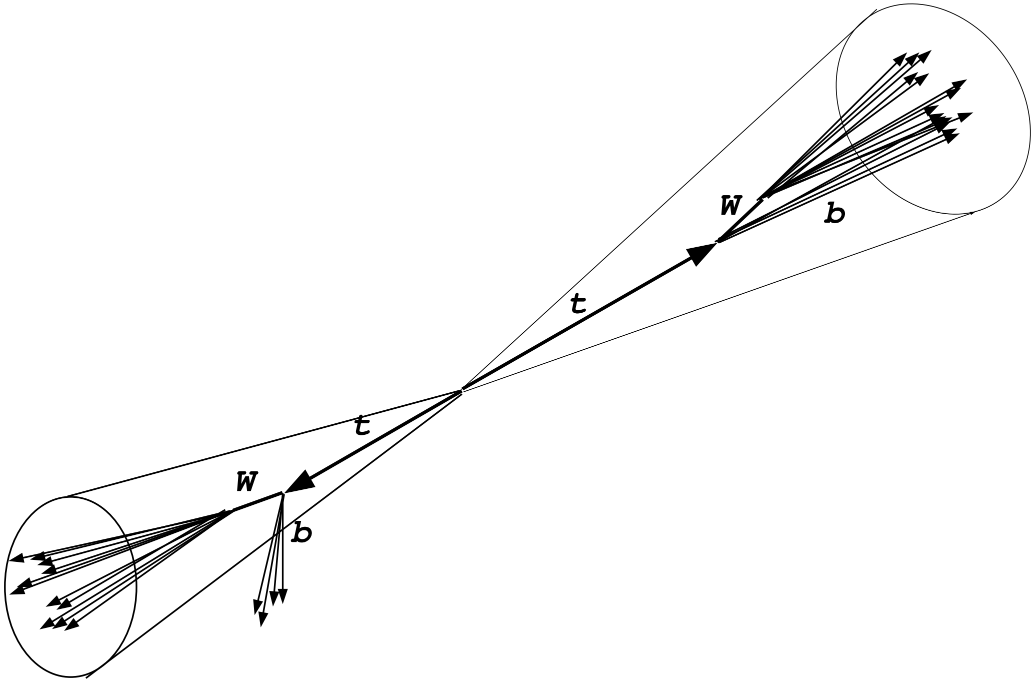
In the new data, demanding visible mass greater than 1200 GeV and lepton $p_T > 150$ GeV, we see...



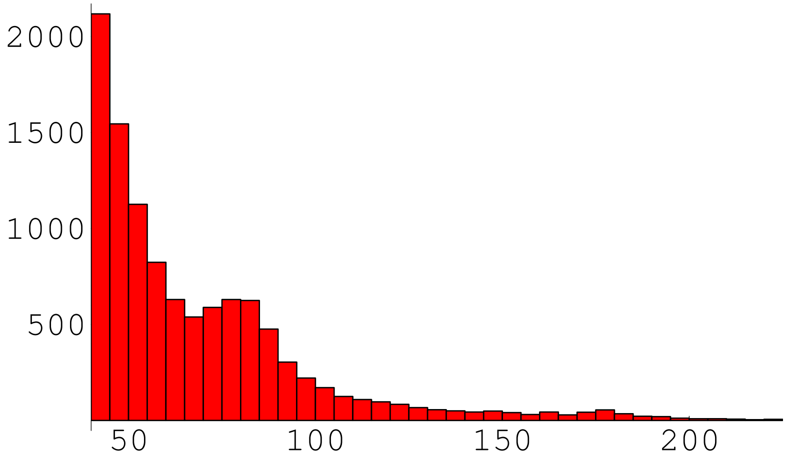
so there are *some* top quarks in the sample. Of course, this doesn't tell us how many; it only puts a very weak lower bound.

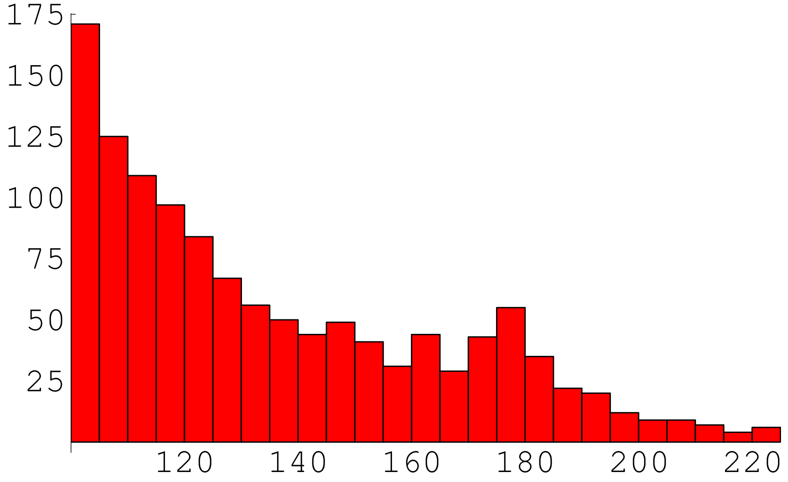
What about hadronically decaying top quarks?

Here we use a similar trick. In the extreme limit, a boosted W boson or top quark may form a single massive jet:

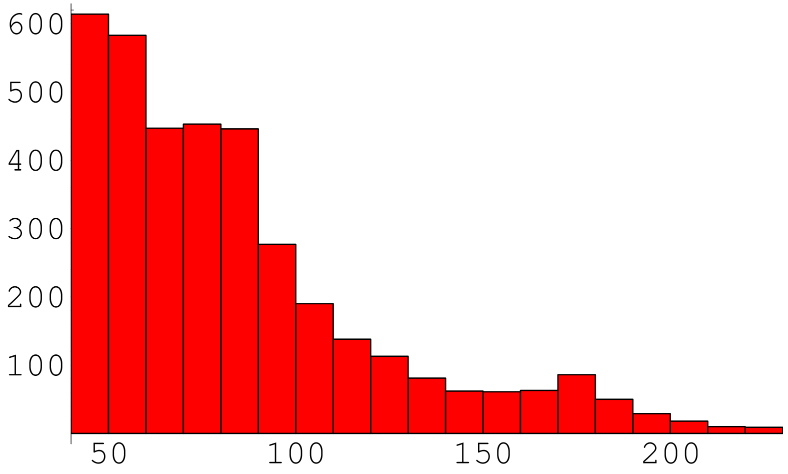


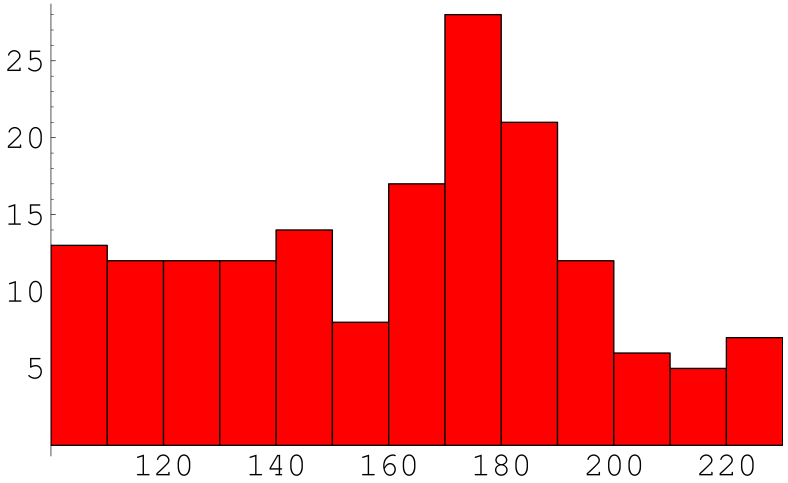
So we should see W and t if we make a plot of masses of individual jets, as given in a sample of 55,000 tops.





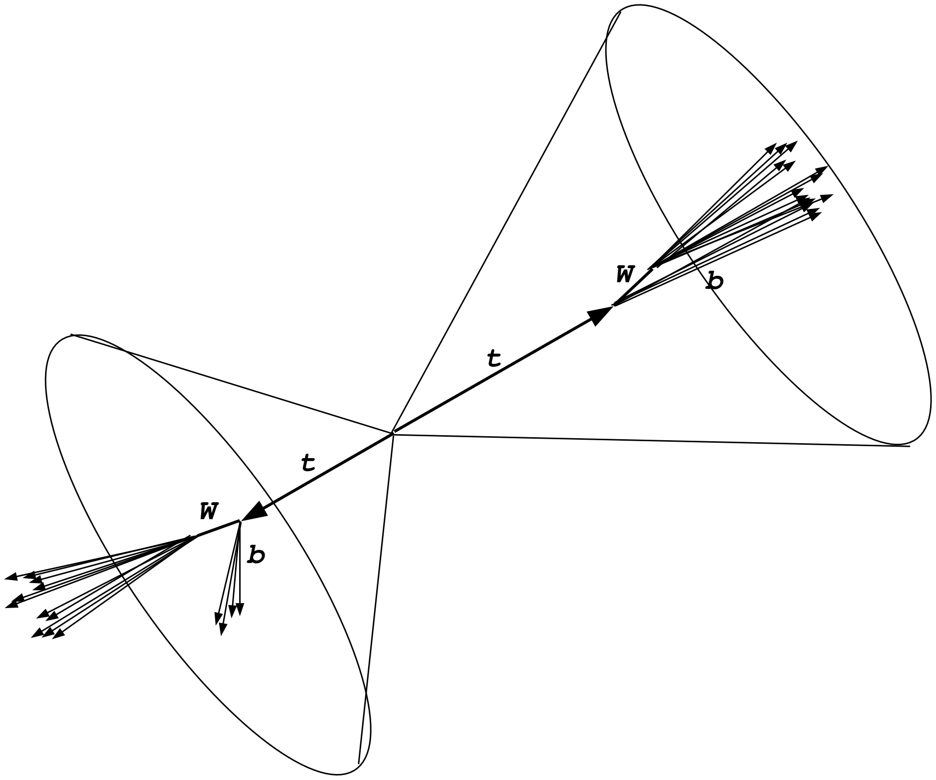
We can enhance this by looking at jets with at least 25 or 35 charged tracks.





But we don't see anything so dramatic in the signal. Is this because there aren't that many top quarks? or is it because there are so many other jets that they wash out the effect? Can the effect be teased out intelligently?

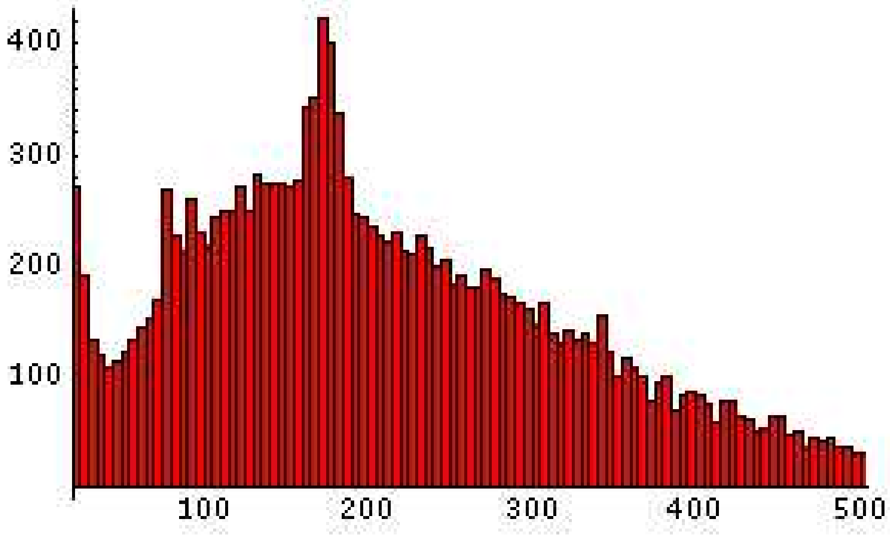
The other thing we can do is widen our conesize, from $\Delta R = 0.7$ as Steve Mrenna used [with specific jet merging which can make the size larger] to be 90 degrees, or 120 degrees, or even 180 degrees across.



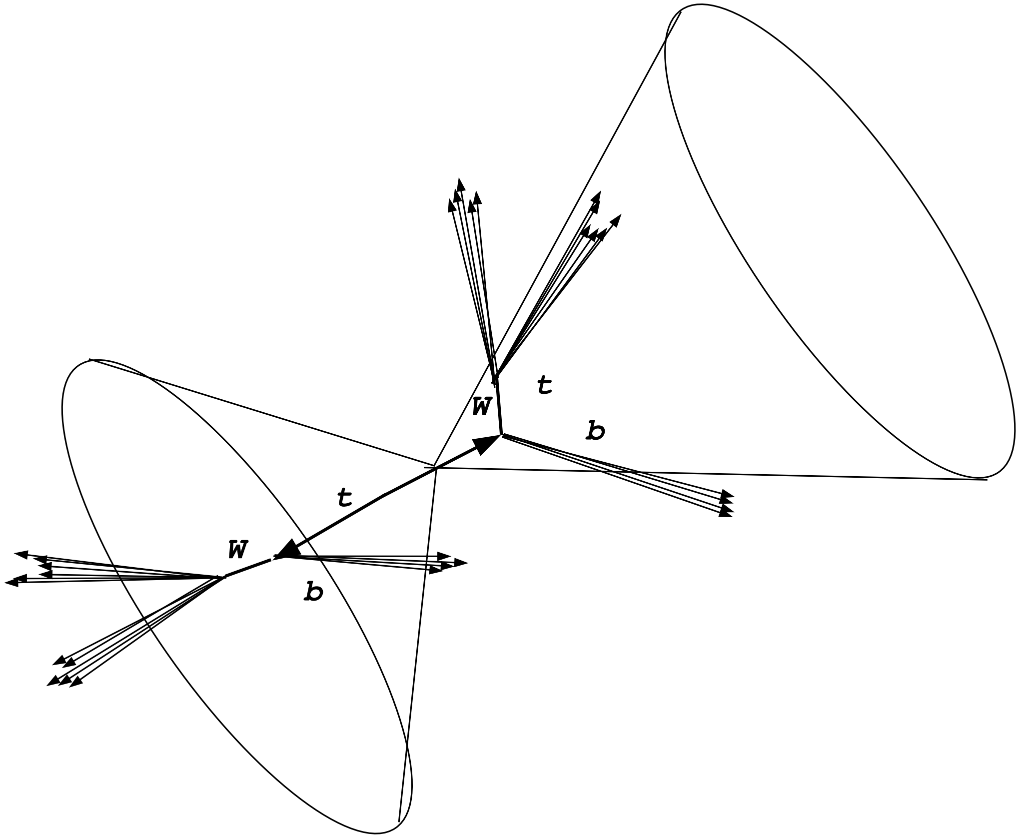
As the figure makes clear, we really want to have the t and $\bar{t}$ be back-to-back; so boost to the rest frame of the $t\bar{t}$ event as best we can.

- take events which are high above threshold (so $v_t \sim 1$)
- reconstruct rest frame of visible system
- determine whether event is highly distorted along an axis
- orient cones along this axis
- take invariant mass inside each cone

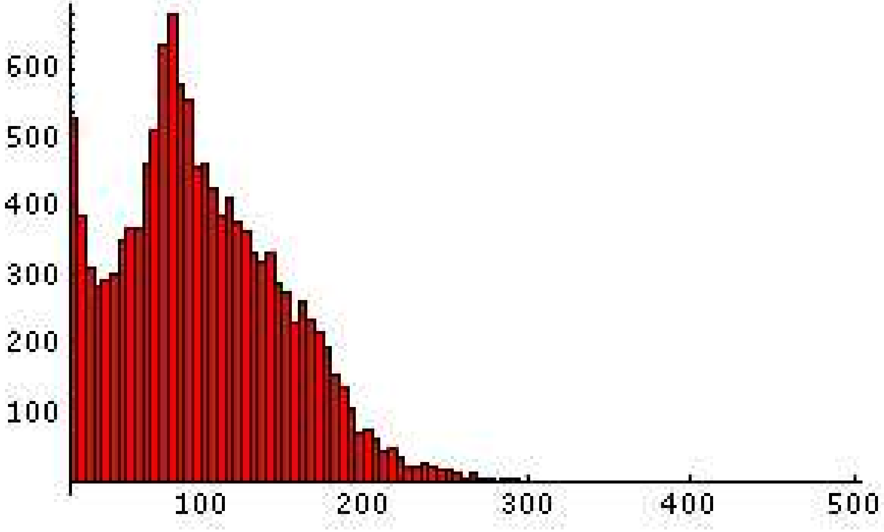
For entire hemisphere,



How about the W boson itself? Here we can work with events which are not high above threshold but which also are distorted in some way, for instance,



We repeat the same exercise for lower visible-mass events and find



Can we see Ws and ts in the signal? Here there is more difficulty because the center-of-mass frame is harder to construct (because of the missing energy whose z-component is not known) and because there are more jets which tend to leak into any given cone.

Smaller cones should work better.

Jet mass plot sees the W a little bit, not the t. (Hmm.)

Wedge-cone plots see the W but only with difficulty; 90 degree cone, demand no b-tagged jets inside cone

But the top quark is another matter; it is quite hard to see.

Why?! Is it absent? or is this just not an effective method for seeing hadronic top in this kind of sample? This requires a study... (NET)

Well, to determine this, and many other things, we will finally have to write down some candidate models to get a feel for how all this stuff works.

[The models we will use later show slightly stronger signals, but to understand this will require many more studies (NET)]

What kind of models might we explore?

Again, we either have G, t, b, Ns and Cs playing a role, or we have Qs, R, t, b, Ns and Cs, at a bare minimum. Of course there could be much more.

The kinematic endpoint in the $b\bar{b}$ invariant mass strongly constrains our scenario with the Qs, which must now must have mass of at least 350-400 GeV to be consistent with current limits on N and C. A 30 pb rate is very large if the Qs are produced by $q\bar{q} \rightarrow Q\bar{Q}$ or $gg \rightarrow Q\bar{Q}$ and the Qs have a mass of 400 GeV.

Of course, in supersymmetry, and in other models of similar type, this is easier to accomplish, since the production is via G exchange! we can have $ud \rightarrow UD$, for instance, which has a much higher rate than $u\bar{u} \rightarrow S\bar{S}$. So this production process could still be consistent with a 400 GeV mass scale.

As of today I have a very preliminary report that the total cross-section if all u, d, s, c squarks at this mass scale is less than the observed cross-section; so this model can probably be discarded.

But if we identify our electroweak singlet R^0 with the $\tilde{B}$, we expect the decay $\tilde{B} \rightarrow h\tilde{H}^0$, which is kinematically allowed; if large this would cause problems with τ pairs and with our sharp kinematic endpoint. Also if top and bottom squark pairs produced (especially if $\tan\beta$ is *large, as may be necessary to keep the Higgsinos sufficiently degenerate) we will get* $t\bar{t}\tilde{H}\tilde{H}$ *events, leading to flavor-correlated leptons.*

Still, there appears to be a loophole here... it deserves more study.

The simplest classes of models, however, are those with a G at 400-500 GeV and LIPs N and C which are 300 GeV lighter.

The simplest effective theory for the majority of the observed data set would be of the form

$$\mathcal{L} \sim \text{gauge kinetic terms} + \gamma_b G b\bar{b} N^0 + \gamma_t G b\bar{t} C^+ + c.c.$$

where the dimensions of the coefficients γ depend on the spin of G and N/C and chiral structure of the model (e.g. t_L vs. t_R.)

We can tune γ_b/γ_t (only the ratio is observable, since all we measure are the G branching fractions) to get the observed number of leptons. Then we can check whether this model is consistent with the data.

In a supersymmetric version of this model, we can roughly determine the mass of the gluino G from its cross-section. [question – can we constrain the spin?]

Of course we do not know the cross-section [need to know effect of cuts, requires a study; also need NLO calculation and simulation!] and can only estimate it to within a factor of 2 or 3. But this is enough to pin down the mass to within 20 percent or so, because of the steeply-falling parton luminosities at LHC.

This then fixes the mass of a gluino at about 460 GeV and of N^0, C^+ at about 160 GeV, with an additive error bar on both masses of 50 GeV.

There are two classes of supersymmetric models of this type, which I will term the “gaugino” type and “higgsino type”.

Gaugino type: LIPs are Winos; $M_2 < M_1, M_3, \mu$.

Higgsino type: LIPs are Higgsinos; $\mu < M_3, M_1, M_2$

Crudely:

In the first case we need μ very large (if $\tan\beta \sim 1$) or $\mu >$ 400 GeV or greater (if $\tan\beta > 10$). A 400 GeV higgsino could affect the data if $\tilde{g} \to b\bar{b}\tilde{H}$ sometimes.

In the second case we need M_1, M_2 large (if $\tan\beta \sim 1$) and M_1 >400 GeV or greater (if $\tan\beta > 10$). A 400 GeV Bino could affect the data if $\tilde{g} \to q\bar{q}\tilde{B}$ sometimes.

We can now build “straw man” models of this class and see if they roughly agree with the data, or if they fail badly for a clear reason.

We do this by getting the cross-section roughly right, then adjusting the branching fraction to top quarks (by moving top/bottom squark masses around) until we get the correct number of leptons.

The Durham, Idaho models – neither optimized nor vetted – both have inconsistencies at present– ultrapreliminary!!!!

Our Higgsino Model

$$M_1 = 800\ ;\ M_2 = 800\ ;\ M_3 = 366\ ;\ \mu = 130\ ;\ \tan\beta = 13\ ;$$

$$m_{\tilde{q}} = m_{\tilde{\ell}} \gg 1000\ ;\ m_{\tilde{t}_1} = 875\ ;\ m_{\tilde{b}_1} = 925$$

Our Gaugino Model (ruled out for several reasons)

$$M_1 = 800\ ;\ M_2 = 180\ ;\ M_3 = 366\ ;\ \mu = 320\ ;\ \tan\beta = 1.5\ ;$$

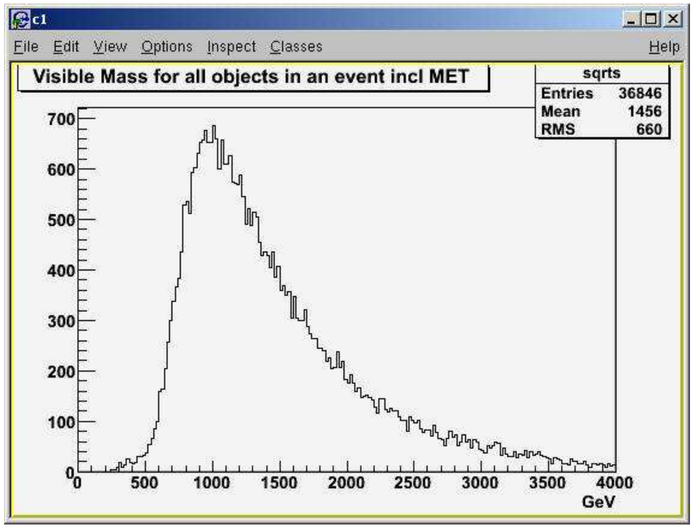
$$m_{\tilde{q}} = m_{\tilde{\ell}} \gg 1000\ ;\ m_{\tilde{t}_1} = 428\ ;\ m_{\tilde{b}_1} = 988$$

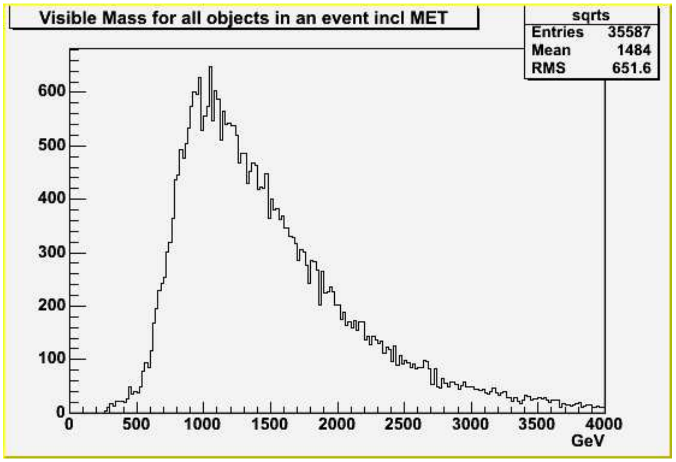
(all numbers in GeV)

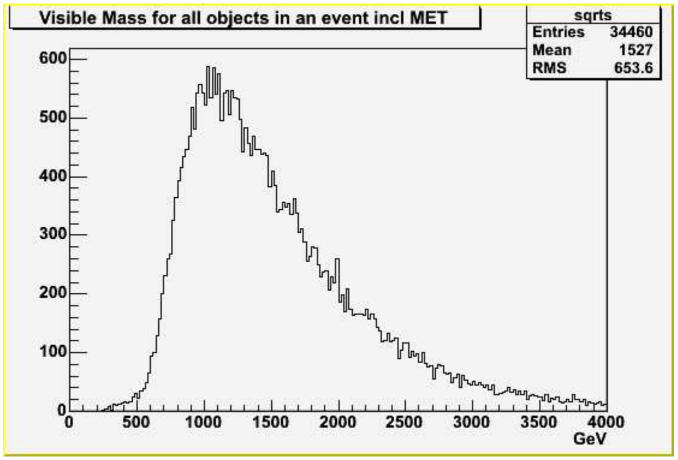
Branching fraction to tb+LSP is 80 percentish; so 50 percent of events decay to $ttbb$.

These are generated using Pythia and run through our version of PGS (which we have *not* had time to cross-check by generating a $t\bar{t}$ sample!!)

Plots of Visible Mass







Lepton information: Higgsino Model

After MET cut: 34460 events

$$\begin{bmatrix} e^- & e^+ & \mu^- & \mu^+ & \tau^- & \tau^+ \\ 1319 & 1405 & 1776 & 1841 & 881 & 927 \end{bmatrix}$$

$$\left[\begin{array}{ccccccc} & \tau^- & \mu^- & e^- & e^+ & \mu^+ & \tau^+ \\ \tau^- & 18 & 44 & 39 & 34 & 46 & 26 \\ \mu^- & & 33 & 53 & 44 & 82 & 42 \\ e^- & & & 16 & 43 & 47 & 34 \\ e^+ & & & & 19 & 48 & 35 \\ \mu^+ & & & & & 35 & 42 \\ \tau^+ & & & & & & 15 \end{array}\right]$$

Total dilepton events: 795; # trilepton events: 14;

trilepton events with ditau: 3; # events with (e,mu,tau)>3: 0

Lepton information: Signal

After MET cut: 36846 events

$$\begin{bmatrix} e^- & e^+ & \mu^- & \mu^+ & \tau^- & \tau^+ \\ 1366 & 1412 & 1845 & 1760 & 1045 & 1104 \end{bmatrix}$$

$$\begin{bmatrix} & \tau^- & \mu^- & e^- & e^+ & \mu^+ & \tau^+ \\ \tau^- & 19 & 43 & 39 & 35 & 55 & 25 \\ \mu^- & & 36 & 56 & 51 & 66 & 50 \\ e^- & & & 21 & 34 & 51 & 27 \\ e^+ & & & & 21 & 61 & 35 \\ \mu^+ & & & & & 25 & 43 \\ \tau^+ & & & & & & 21 \end{bmatrix}$$

Total dilepton events: 814; # trilepton events: 25;

trilepton events with ditau: 12; # events with (e,mu,tau)>3: 0

Lepton information: Gaugino Model

After MET cut: 35587 events

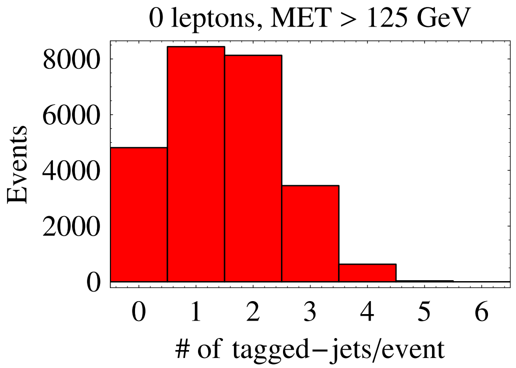
$$\begin{bmatrix} e^- & e^+ & \mu^- & \mu^+ & \tau^- & \tau^+ \\ 1406 & 1270 & 1814 & 1771 & 1016 & 997 \end{bmatrix}$$

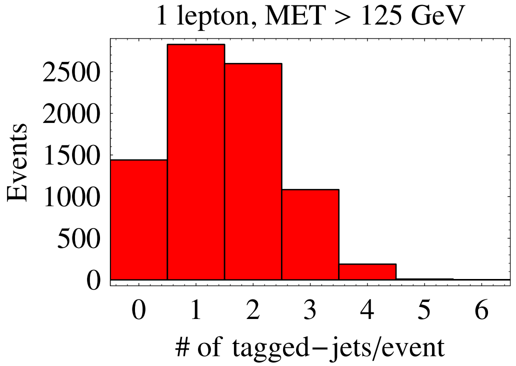
$$\begin{bmatrix} & \tau^- & \mu^- & e^- & e^+ & \mu^+ & \tau^+ \\ \tau^- & 15 & 36 & 37 & 31 & 40 & 19 \\ \mu^- & & 42 & 44 & 41 & 69 & 39 \\ e^- & & & 16 & 37 & 38 & 23 \\ e^+ & & & & 17 & 46 & 28 \\ \mu^+ & & & & & 38 & 47 \\ \tau^+ & & & & & & 11 \end{bmatrix}$$

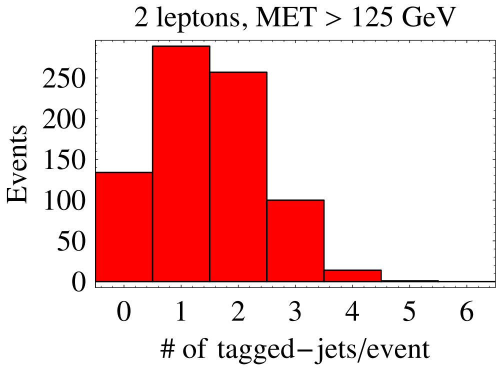
Total dilepton events: 714; # trilepton events: 24;

trilepton events with ditau: 7; # events with (e,mu,tau)>3: 0

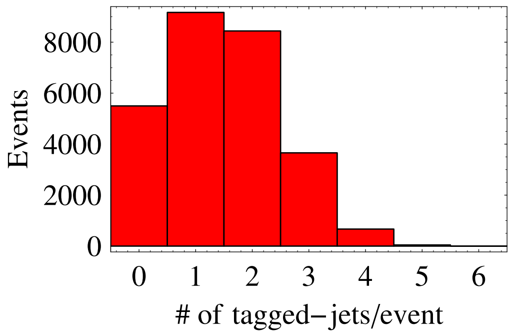
For k leptons, # events with n tagged jets: Higgsino Model

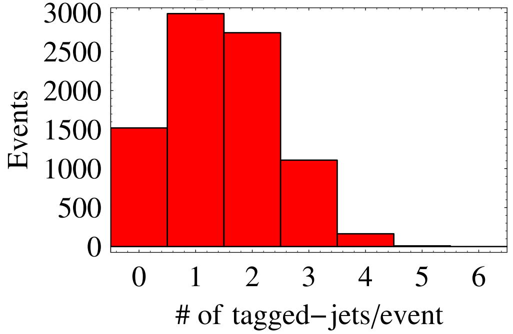

0 leptons, MET > 125 GeV

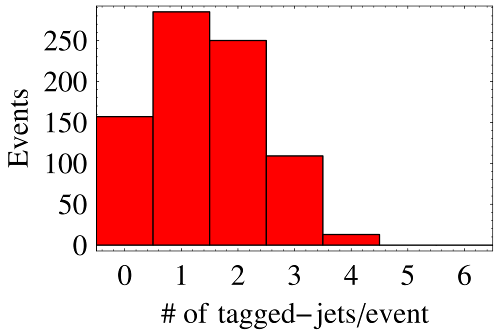

1 lepton, MET > 125 GeV


2 leptons, MET > 125 GeV

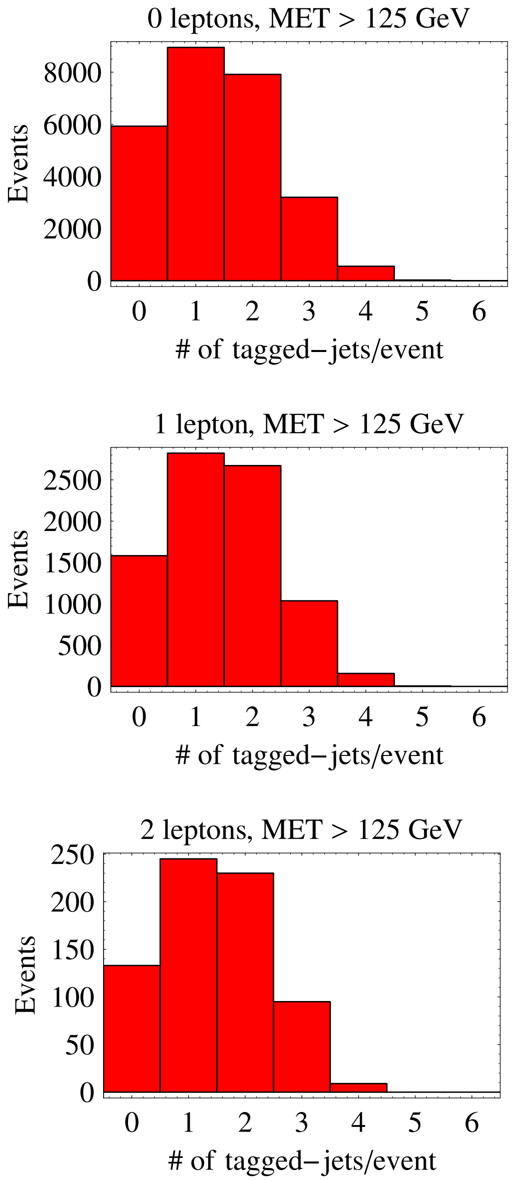
For k leptons, # events with n tagged jets: Signal


0 leptons, MET > 125 GeV

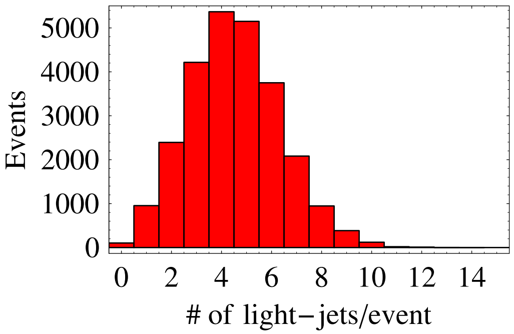

1 lepton, MET > 125 GeV

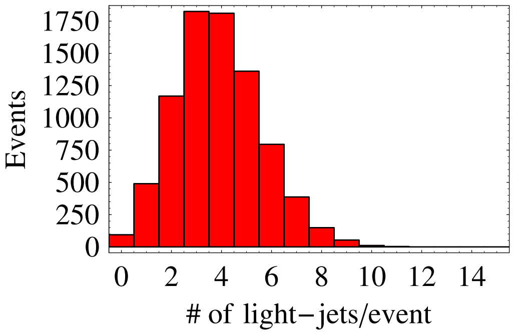

2 leptons, MET > 125 GeV

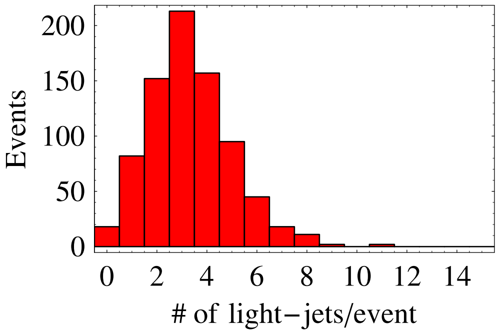
For k leptons, # events with n tagged jets: Gaugino Model



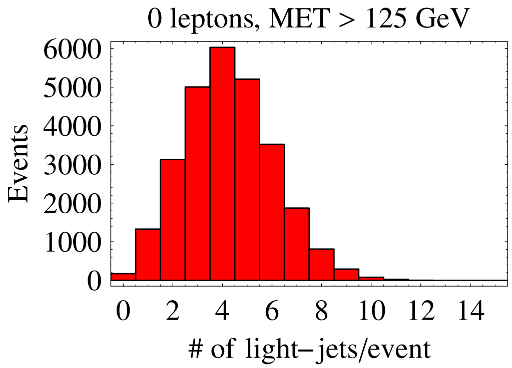
For k leptons, # events with n untagged jets: Higgsino Model

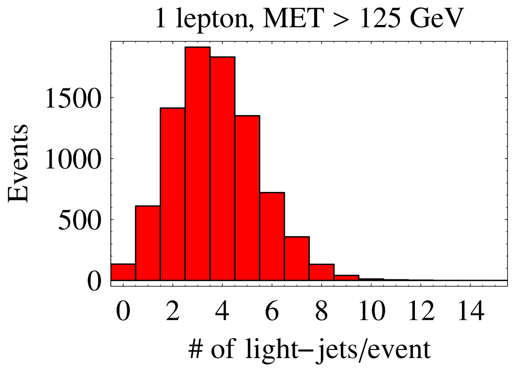

0 leptons, MET > 125 GeV

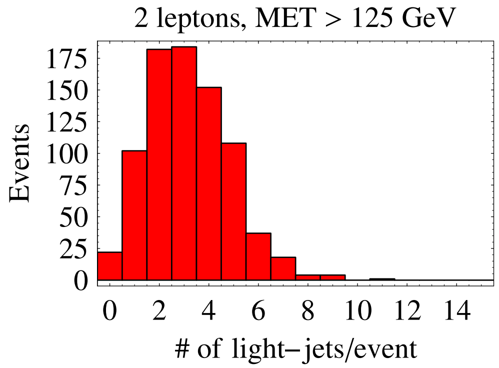

1 lepton, MET > 125 GeV


2 leptons, MET > 125 GeV

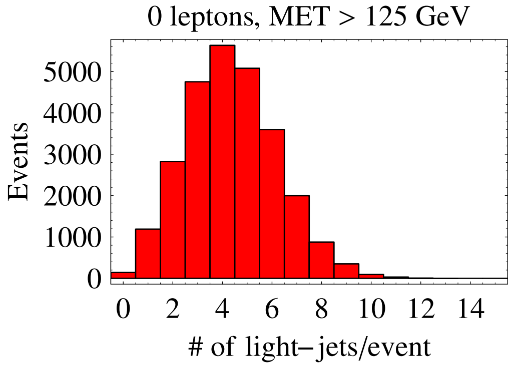
For k leptons, # events with n untagged jets: Signal

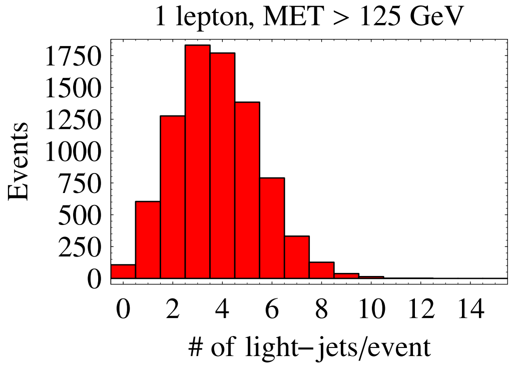


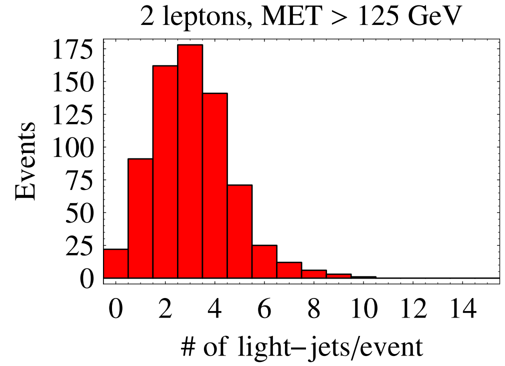




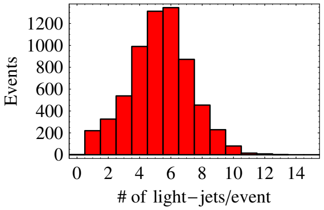
For k leptons, # events with n untagged jets: Gaugino Model

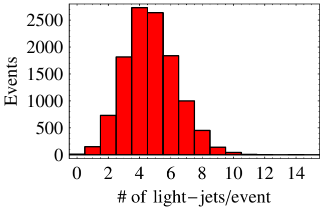

0 leptons, MET > 125 GeV

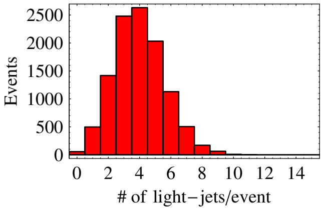

1 lepton, MET > 125 GeV

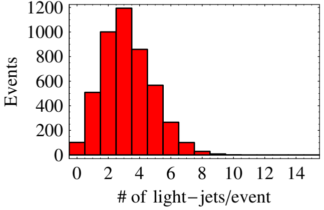

2 leptons, MET > 125 GeV

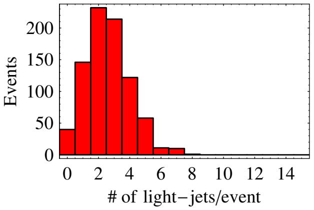
For k b-tags, # events with n untagged jets: Higgsino Model


0 tags, MET > 125 GeV

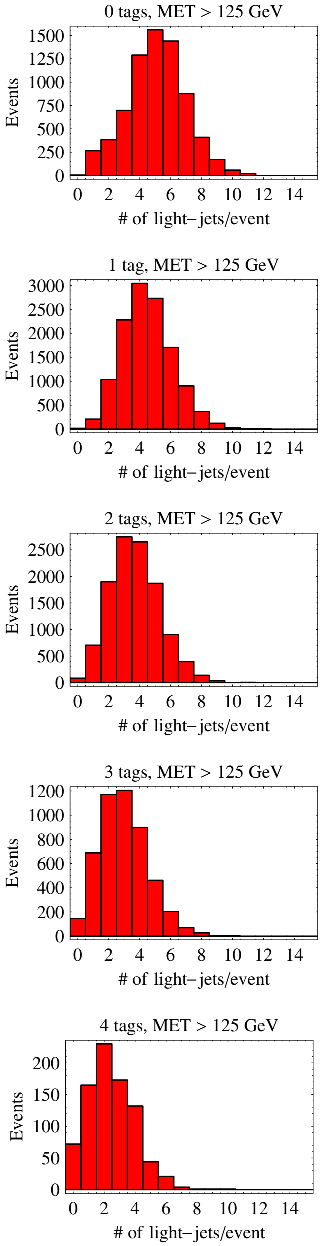

1 tag, MET > 125 GeV


2 tags, MET > 125 GeV

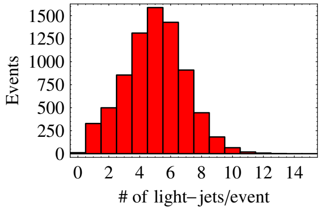

3 tags, MET > 125 GeV

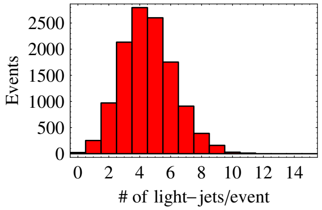

4 tags, MET > 125 GeV

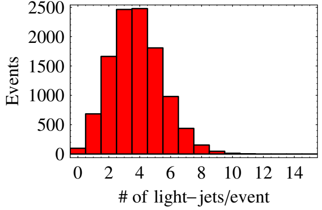
For k b-tags, # events with n untagged jets:Signal

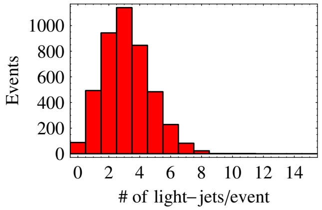


For k b-tags, # events with n untagged jets: Gaugino Model


0 tags, MET > 125 GeV


1 tag, MET > 125 GeV


2 tags, MET > 125 GeV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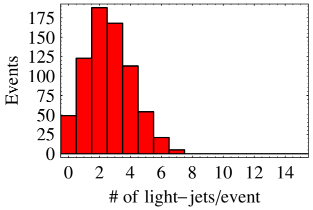

4 tags, MET > 125 GeV

Now, we still haven't directly verified that there are degenerate LIPs, or determined how degenerate they are.

How can we do this?

If the LIPs decay to τs, and are not too degenerate, in the 10-20 GeV range, we may well be able to see muons, or, if they decay always via τs, we may eventually be able to see one-prong (hadronic and/or leptonic) decays of the τs.

But this is very hard, and will have to fight large fake rate.

However, for single leptons, there is a charge anticorrelation against high p_T leptons.

When pairs are produced in a $N_2^0 \rightarrow N_1^0 \tau^+ \tau_-$ decay, we also have a correlation.

We have searched for low p_T leptons...

First we consider same-sign dilepton events from the earlier sample, where each ℓ has $p_T > 25$ GeV, and ask, in the subsample of this set where a third lepton is observed with $10 < p_T < 25$ GeV, is the charge of the third lepton anticorrelated with the same-sign dileptons?

We see no effect.

Next we lower the lower p_T cut to 3 GeV (unrealistically low at LHC) and look at muons.

We see a 1.5 sigma effect on 52 $p_T < 25$ GeV muons.

Finally we look at events with a single lepton; some of these may have only one high-mass W^* and one low-mass W^* of the opposite sign. In this case we might see a signal consisting of one high-p_T lepton of one sign and a low-p_T lepton tending to be of the other sign.

We don't see anything here either.

This puts limits on the splitting between the charged LIP and the neutral LIP of a few GeV.

Additionally, if we have two neutral LIPs (as with Higgsinos = 2 doublets), then we might have LIP2 $\rightarrow \ell_i^+ \ell_j^-$ LIP1

A search for opposite-sign muons at low invariant mass revealed nothing. But the decay could be via $\tau^+\tau^-$, hard to see.

So we have limits on possible degenerate LIPs, but no detection.

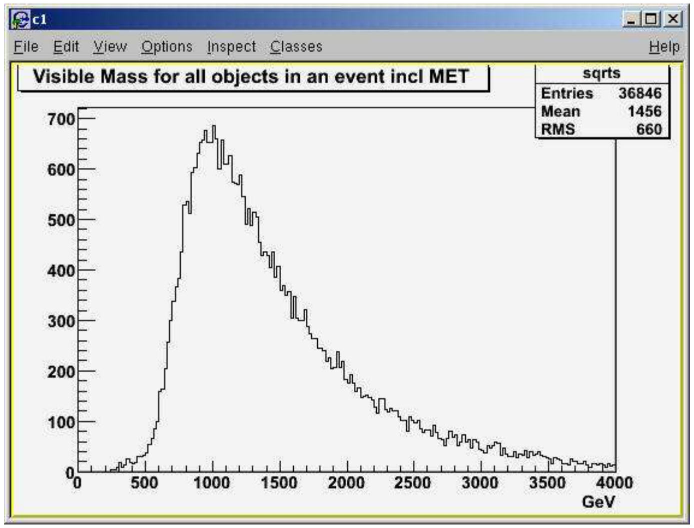
If the LIPs are extremely degenerate, the charged LIP could be metastable, looking like a muon; but we'd see the charge correlation in our muon sample.

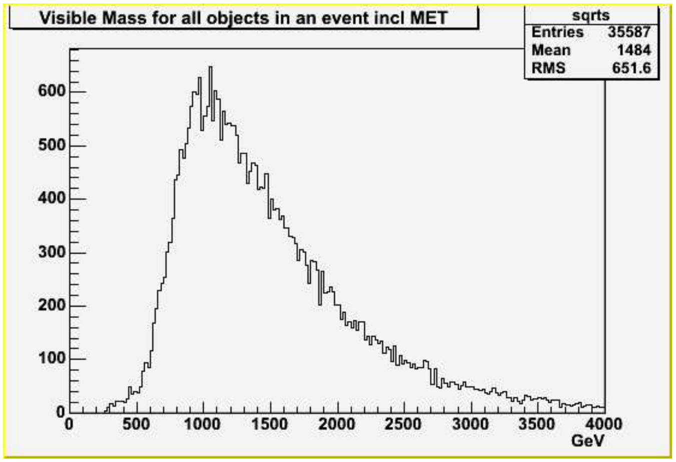
They may be somewhat less degenerate and then be long-enough lived that a few will leave a short track in the detector. This is a long shot and of course PGS will not see this.

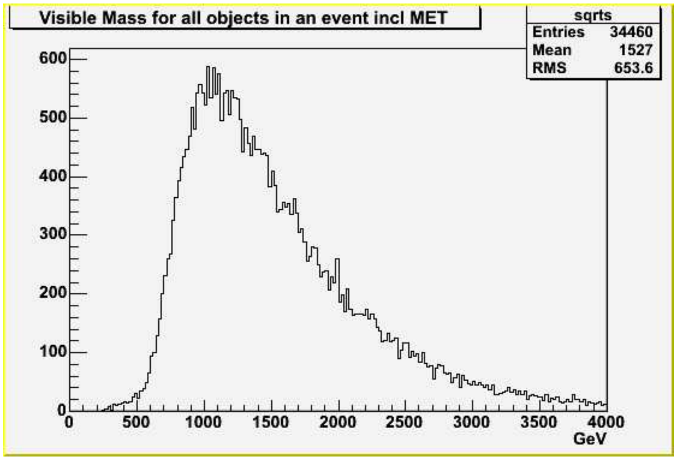
If the splitting between them is 1 to 10 GeV, it may be extremely difficult to detect these particles through their decays.

Can we detect that they are being produced?

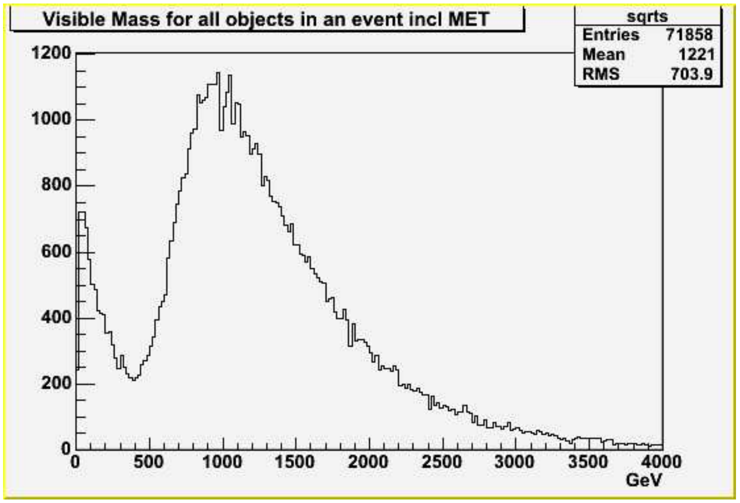
Recall our visible-mass plots in the presence of our 125 GeV MET cut.

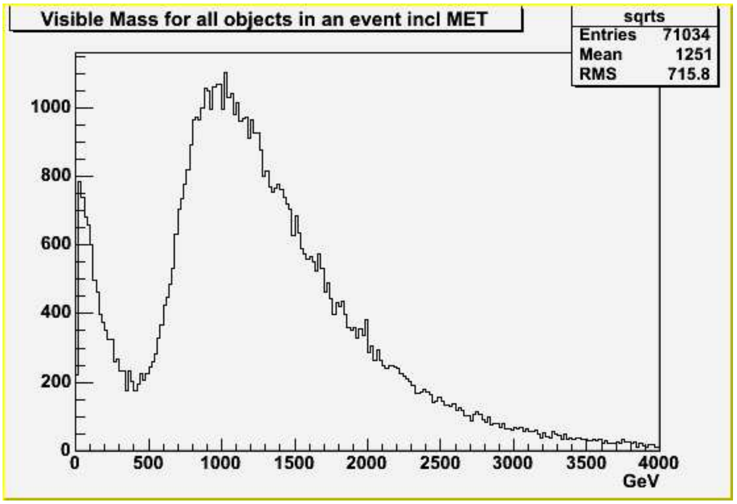






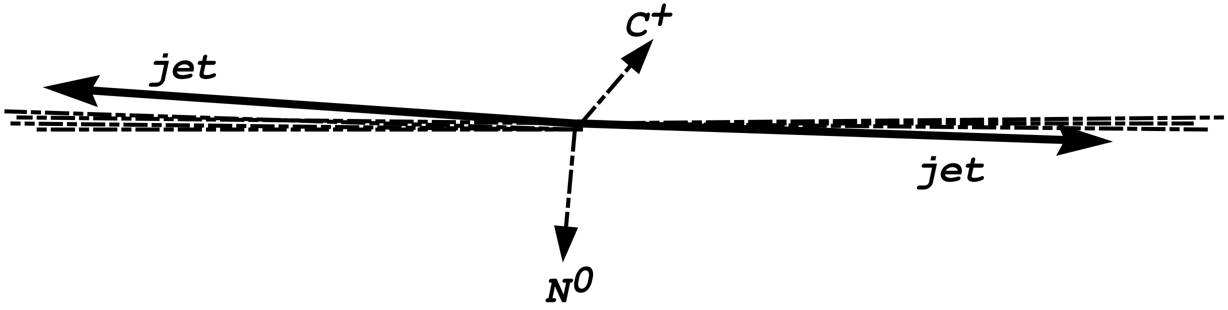
If you don't have the MET cut, you see, in our models, what happens with the production of the degenerate LSPs. We get low visible-mass events consisting of jets from initial state radiation, plus nothing; no leptons, no b's, low MET.



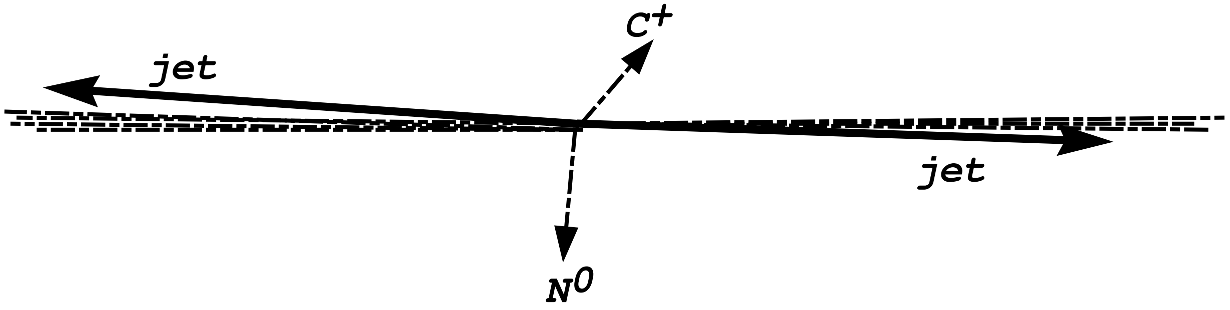


Many of these are Rapidity Gap Events!

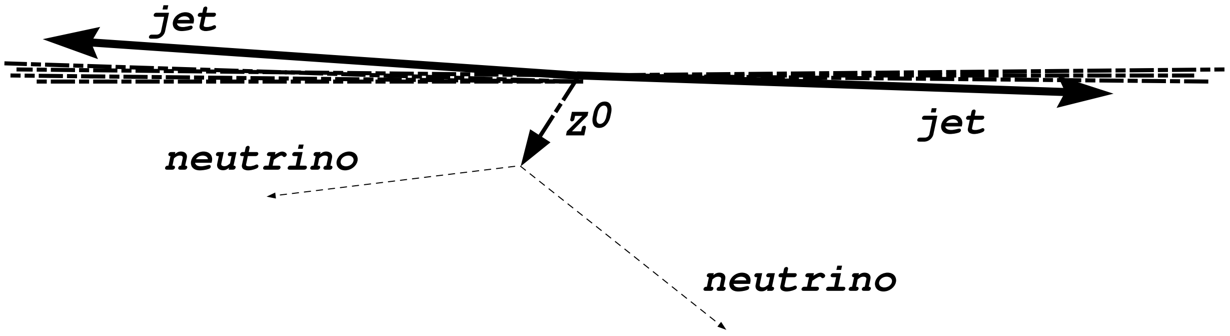
A rapidity-gap event:



A rapidity-gap event:



Unfortunately there is a huge background from $Z \rightarrow \nu\nu$



though this is measurable using $Z \rightarrow \mu^+\mu-$ and could be subtracted with pretty good accuracy, if the signal were large enough *and triggering were very well understood.*

But with MET$>$ 125 GeV, there are essentially no events left.

[Not invisible if you were to cheat!!]

Is there a possibility of detecting an excess of rapidity gap events (perhaps with very soft leptons in the central region between the jets) with sufficiently high integrated luminosity and clever cuts?

This requires a signal-to-background study of the highest quality and we cannot address it in the present context.

Another possible detection method:

$q\bar{q} \to GN^0$, $q\bar{q} \to GC^+$

But some better understanding of the model is needed before these events can be identified; in particular, the event rate is low.

How can we determine whether the Gaugino model or the Higgsino model is closer to the truth, or rule both out completely?

$q\bar{q} \to GN^0$, $q\bar{q} \to GC^+$ moderately large in the Gaugino model and highly suppressed in the Higgsino model; but high statistics needed

Another possible technique for distinguishing these models, which cannot be applied here, is that the chiral structure of the $Gt\bar{b}C^-$ coupling is different in the two models, affecting spin polarizations and lepton energy and angle distributions. *But we cannot study this using Pythia, which throws this information away!* Must use Herwig or even SMadgraph.

A key difference:

- the Gaugino model requires that the $\tilde{t}$ be lighter than the $\tilde{b}$ (in fact the $\tilde{t}$ is lighter than the $\tilde{g}$ in our best model!) and that both be much lighter than the other $\tilde{q}$; otherwise $\tilde{g} \to q\bar{q}\tilde{W}^0$ will be unsuppressed and we won't get enough b-quark jets.
- the Higgsino model only requires that neither $\tilde{t}$ nor $\tilde{b}$ be too heavy compared to the other squarks, and that their relative masses be consistent with $\tan\beta$ (which we will be hard-pressed to measure but which cannot be too close to 1 to avoid Higgsino degeneracies, unless M_1 is very large.)

So measuring the squark masses would help a lot. This may already be possible in this data set; we simply haven't had time to look. It may be that there is insufficient statistics currently.

On the other hand, it seems that both models are somehow wrong. Not only are the number of jets smaller in the signal than in the models, the top quark peaks in the signal appear too weak for the top quark to be plausibly responsible for all leptons (assuming our PGS simulation matches the detector!)

So probably the leptons are not all coming from top quarks, and we need a richer model where fewer jets are sometimes produced.

[Note that the fact that the signal has a smaller number of jets than the models suggests both that the $Q \to qR$ model discussed earlier, and the possibility that the missing charge disappears into jets, is disfavored, though not forbidden if the jets have very low p_T.]

One possibility; our G model is right except that there is also a real particle R^0 in this model too.

Then in addition to

$G \to b\bar{b}N^0$, $G \to t\bar{b}C^-$

we have a certain number of events of the form

$G \to q\bar{q}R^0$, $R^0 \to W^+C^-$.

This makes sense only if we can suppress $R^0 \to Z^0N^0$ which is often the case; it may be that $R^0 \to b\bar{b}N^0$ is preferred, or even $R^0 \to h^0N^0$, perhaps explaining our Higgs signal. [And maybe we do need a few Z^0s too...?]

It may also be necessary to suppress the $R^0 \to t\bar{b}C^-$ decay; but this would happen if $m_R - m_C < 200$ GeV.

Either our Gaugino model or our Higgsino can accommodate this change, I believe.

This slightly more complicated set of straw-man models requires more investigation and is left for the future.

This is all fun, but...

- Pythia does this wrong, both the matrix elements and the radiation of jets, so all this matching is useless when it is taken to be too detailed; the simulation of the model is not the same as the true model.
- In the real world, the detector simulation and the detector will be different, and hard to match.
- PGS is nothing like a real LHC detector; there is no guarantee that CMS and Atlas will behave anything like what we've seen here, so don't take these results seriously.
- All techniques used here are more difficult with backgrounds; determining the leptons are uncorrelated in the presence of Z plus jets and $t\bar{t}$, and detecting the presence or absence of top quarks and W bosons in the presence of W plus jets and $t\bar{t}$, requires cutting much harder – MET $>$ 400 is used in the recent Rome Atlas studies. Need much more data to get a pure sample.

- In the real world, one of the largest uncertainties is triggering efficiencies. The present exercise completely ignored this issue! A perilous situation.
- Optimizing requires studies; but Pythia and PGS give wrong answers; so how should theorists study and help optimize? Can they?
- Degeneracy of different phenomena is part of life at LHC; how shall we characterize the data?
- This whole exercise is both too easy and too hard; if the data are this clear, the experimentalists will not need theorists to extract the information. And no theorist has the tools to do this data extraction correctly.
- The real problem is that the data might be much more ambiguous than this, barely standing up above backgrounds; then theorists will really be necessary... so we think the Olympiad should concentrate on such situations.