A Model Independent Approach to LHC Phenomenology

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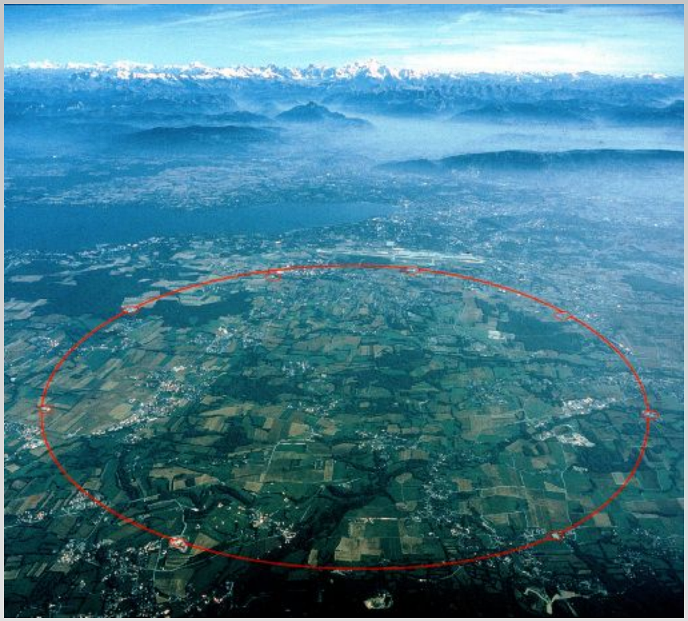
Based on: hep-ph/0601124 P.M, M. Reece

Outline For Talk

- Motivation for Model Independent Studies
- Ways to go about such studies
- Partners of the top quark @ LHC
  - Mass Determination
  - Spin Determination
- Conclusions/Future Studies…

What is this talk about?...



THE FUTURE OF HIGH ENERGY PHYSICS ARRIVES IN APPROXIMATELY:

1 year and 6 months from today!

(with some caveats on the definition of arrival…)

Possible Discoveries… Finishing the Standard Model and Beyond:

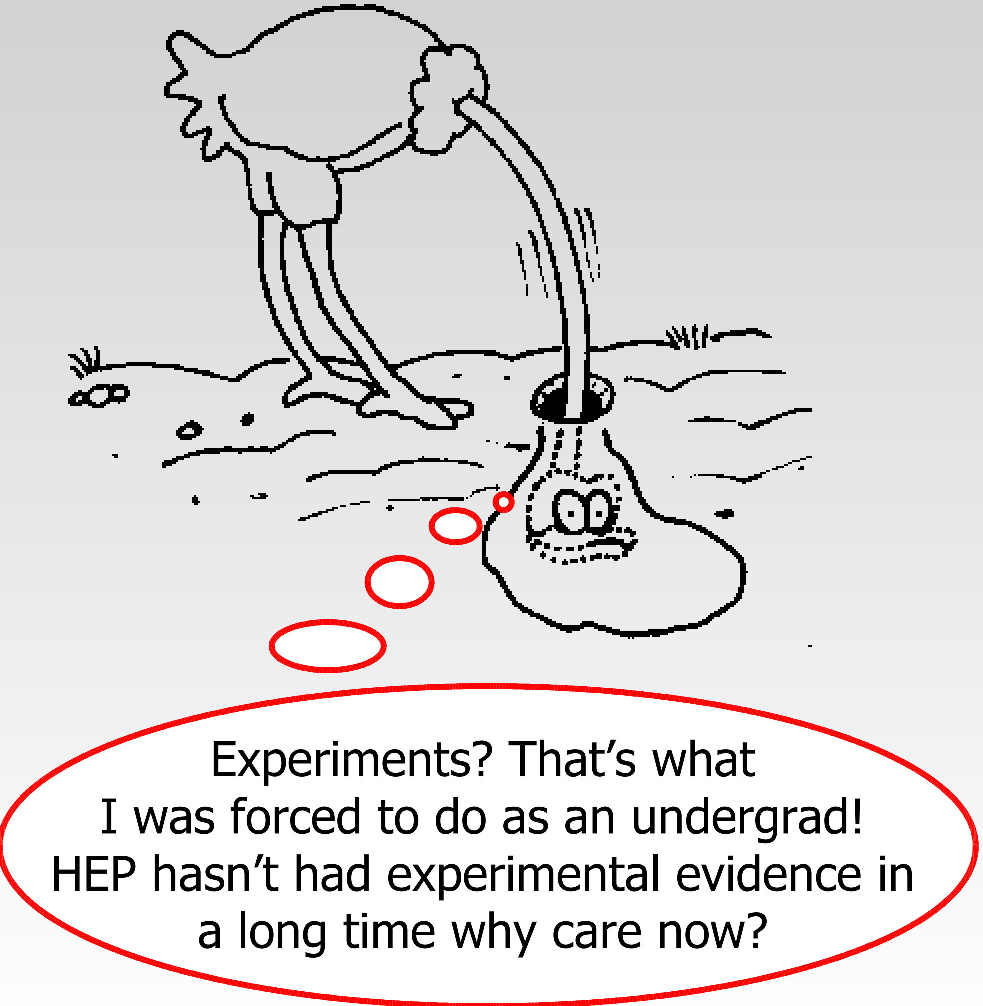
- Something responsible for unitarizing WW scattering
- Mechanism for Electroweak Symmetry Breaking
- Supersymmetry, extra dimensions, strong dynamics…
- Dark Matter Explanation

What do we do in the meantime??

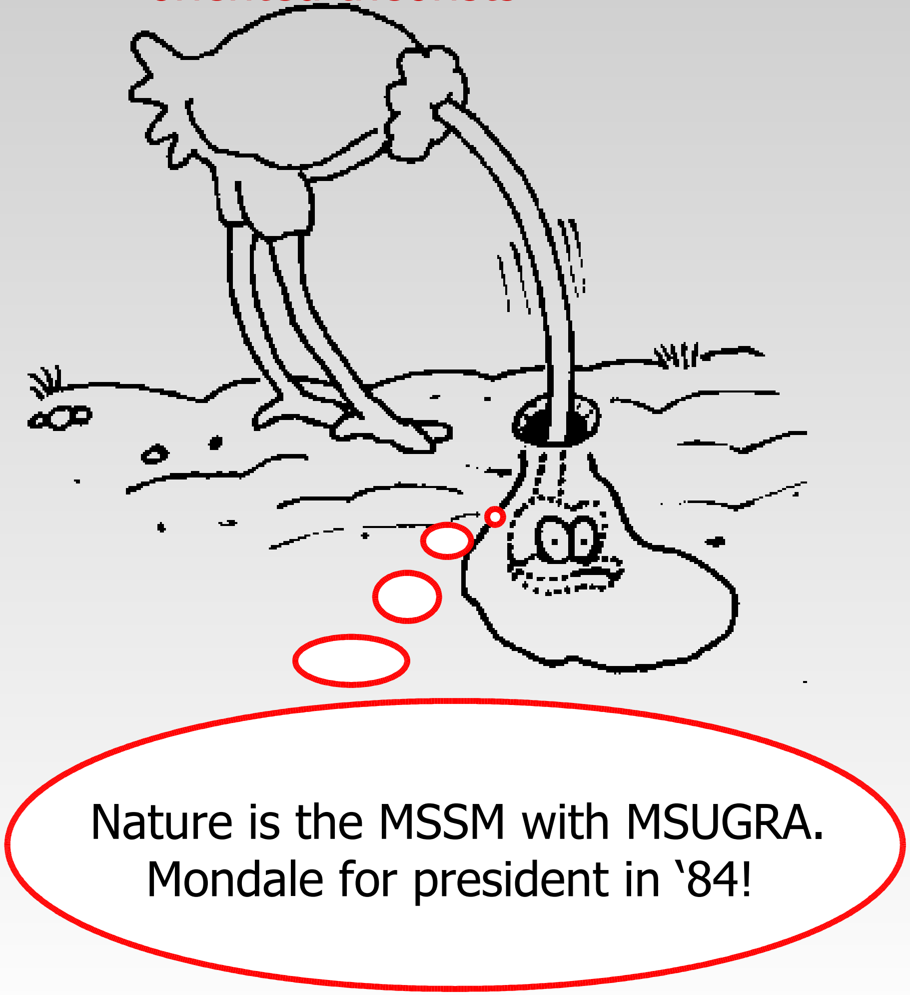
Keep the status quo for BSM theory (for the most part)?

Many good ideas… but there are other options

<u>Some</u> more theoretically oriented theorists



<u>Some</u> more experimentally oriented theorists



Where has it got us so far?
Brief Overview of
Collider Phenomenology for LHC

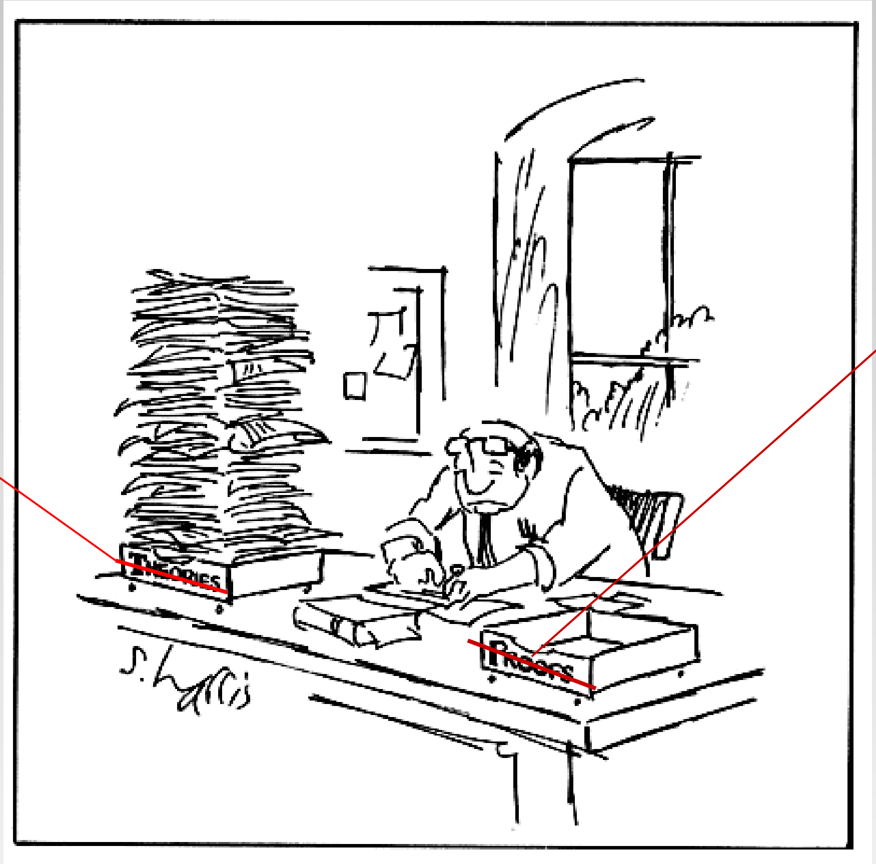
Physics Topic	Status (Run, Walk or Crawl)
Standard Model and Higgs	**Run/Walk/Crawl**
Supersymmetry	**Walk**
Other Models… (for the most part)	**Crawl**

For good reasons sometimes…

Model Dependent Phenomenology

Can Seem Daunting!

possible
models



experimental
evidence

Also magnified
by number of
parameters per model

For instance more than
100 parameters in MSSM

Very important as it can lead to new signatures or complications of existing ones!

Recent Examples: R-parity, T-parity, KK-parity ???
Long Lived Gluinos…

Model Dependent Phenomenology

What we really are interested in is the inverse problem

from data to the space of models and parameters

????

MODEL(S) ←———————— **DATA**

There can be many degeneracies…

Often when looking at data=f(model) picking it in “nice” regions

Example: Leptons Everywhere!!!

Can get lost playing with the global picture of a model

More and more theorists are starting to take this problem more seriously…

LHC -

Can try other approaches…
Model Independent

Quite possible we haven't found the right model!
(I/we can hope…)

"But don't you see, Gershon - if the particle is too small and too short-lived to detect, we can't just take it on faith that you've discovered it."

Analyze possibilities at the LHC in a model independent fashion to learn about what we can possibly figure out from the LHC and develop new techniques

Model Independent Phenomenology

What if we aren't so lucky as to have been more clever than nature herself so far…

If our attempts at phenomenology are restricted to only models
that have been written down so far we could be leaving out lots of interesting possibilities

Our focus sometimes can also become too broad

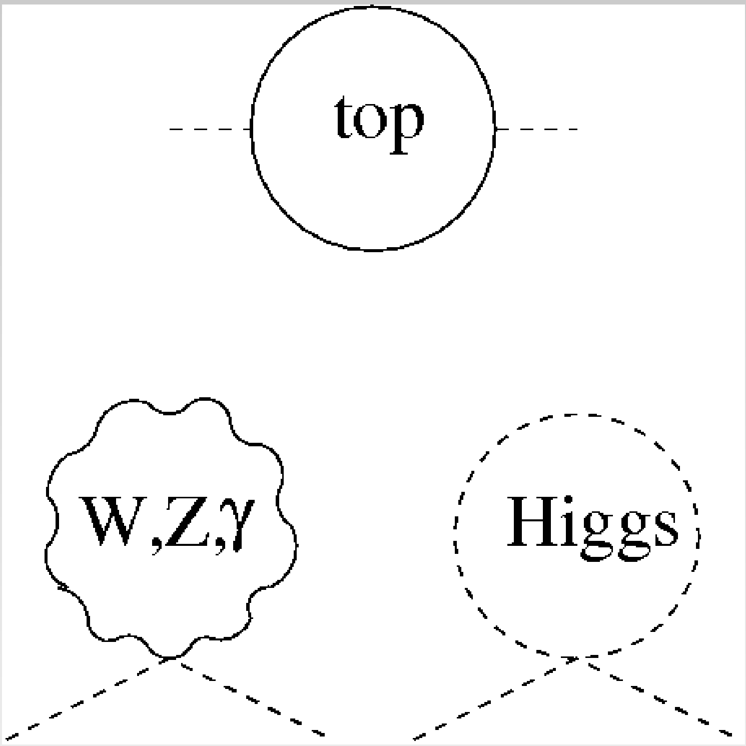
We can attempt to prepare for the LHC using
model independent signature based studies

Sounds great and all… but what should we look at?

Can start thinking about every possible signature but that is just… well you know

Need some sort of guiding principle… naturalness for instance

Naturalness Motivation



Top $\sim \lambda_t^2 \Lambda^2$ Biggest!

Gauge $\sim g^2 \Lambda^2$

Higgs $\sim \lambda^2 \Lambda^2$

$$m_h^2 \sim \Lambda^2$$

Supersymmetry: Stops, Gauginos, Higgsinos

Little Higgs: Same Spin Partners

May or may not be the way nature works…

Naturalness Motivation

Assumptions: weakly coupled extension of SM, naturalness in EFT

↓

predictions for what "types" of new physics

Higgs mass in the SM gets its largest divergence from the top quark

↓ naturalness

A reasonable first prediction for TeV scale is some colored partner of top quark responsible for canceling top loop divergence

Many models give examples of these "top partners"

Two options for the spin: T'(the top partner) could be a fermion or scalar

Additional Assumptions

Experimentalists can find a resonance, so don't waste time there!

Assume we have some Z_2 parity under which T′ is odd and there exists some neutral LPOP N (Dark Matter Motivation)

We assume only two types of couplings to the SM

$$t\bar{T}'N \qquad g T'\bar{T}'$$

(additional coupling to gluons if T′ is a scalar)

Furthermore we assume only a RH coupling to SM top quarks → **Not testing coupling to Higgs**

Model independent possibilities:

- T′ scalar → N fermion
- T′ fermion → N scalar
- T′ fermion → N gauge boson

What is the signal at the LHC?

$$pp \longrightarrow T'\bar{T}' \longrightarrow t\bar{t}NN$$

which is:

$$pp \longrightarrow t\bar{t} + MET$$

YIKES!!!!

Nevertheless we proceed…

Only two parameters for our study: $m_{T'}, m_N$

Assume that tT'n coupling is ~e
as long as width is calculated appropriately
this doesn't enter in as a separate parameter

What do we wish to address?

- Significance (can we see this?)
- Can we measure any properties of T′ and N?
  - Mass determination
  - Spin determination

tools? ~~CompHEP~~, ~~Pythia~~, ~~Herwig~~, MadGraph

What all do we look at?

"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them!"

Lots of Missing Energy!

Typically the questions of spin determinations is a resounding no at the LHC

Mass determination… (maybe)

Significance

Signal has three channels we can look at based on how the W's decays

$$pp \rightarrow t\bar{t} + NN \rightarrow b\bar{b}jjjj + NN$$ Hadronic

$$pp \rightarrow t\bar{t} + NN \rightarrow b\bar{b}l\nu jj + NN$$ Semileptonic

$$pp \rightarrow t\bar{t} + NN \rightarrow b\bar{b}l^+l^-\nu\nu + NN$$ Fully leptonic

NOT THE ONLY BACKGROUNDS

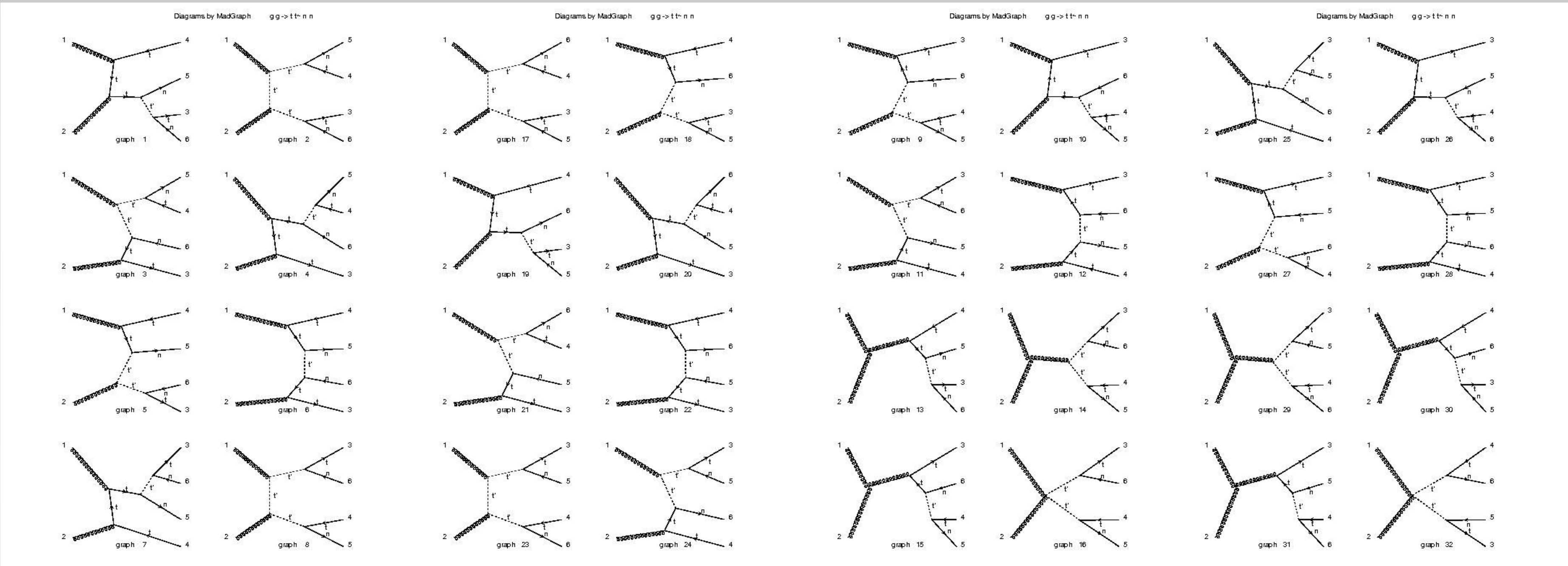
Thus the backgrounds will be:

Hadronic $$pp \rightarrow t\bar{t}Z \rightarrow b\bar{b}jjjj\nu\nu$$

Semileptonic and Fully leptonic $$pp \rightarrow t\bar{t}$$ With appropriate decays of the W's

Significance

We do a **tree-level** analysis with Madgraph for the various cases



(gratuitous display of diagrams in gluon production channel to illustrate the reason for using Madgraph)

HUGE background in the leptonic and semileptonic channels

$$\sigma(pp \to t\bar{t}) \sim 600\,\text{pb}$$

Hadronic channel much more reasonable

Gain additional kinematic info

$$\sigma(pp \to t\bar{t}Z) \sim 1\,\text{pb}$$

Not only us in this channel (Baur et al. other reasons)

Significance in hadronic channel

Cuts:

$MET > 100$ GeV

$E_T > 100$ GeV Hardest jet

$E_T > 40$ GeV All jets

$|\eta| < 2.5$ All jets

$\Delta R > .4$ All jets

Guarantees events will be triggered on

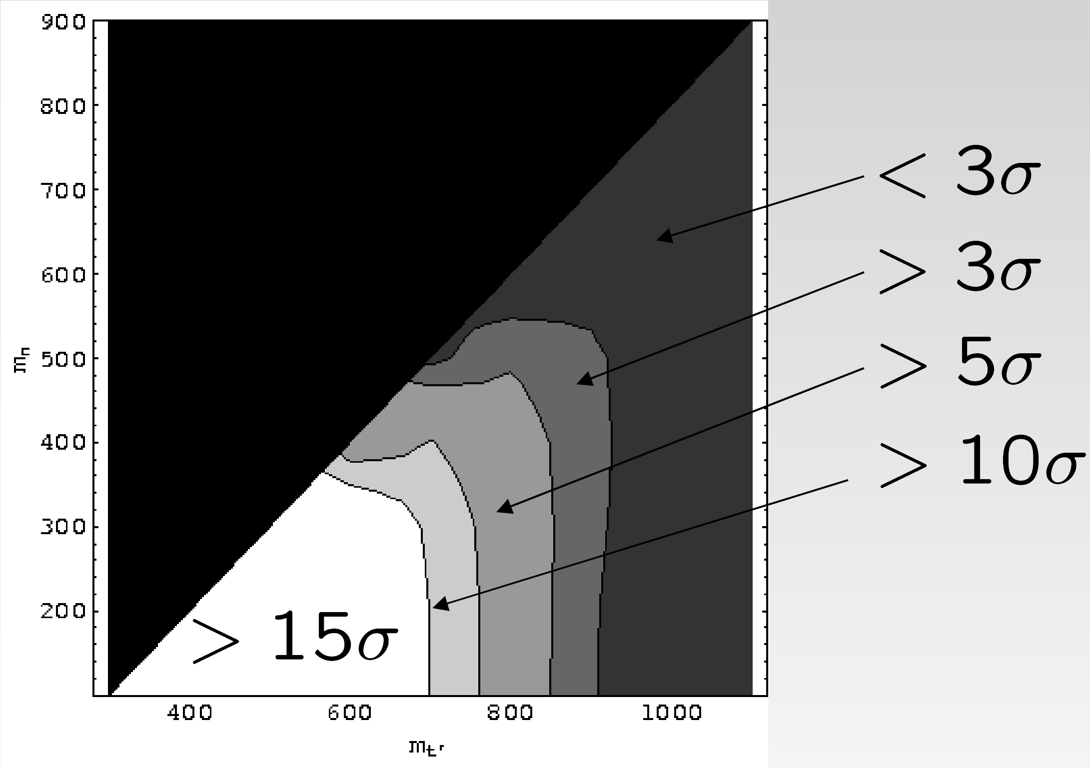
Defining Significance as: $\frac{S}{\sqrt{B}}$

$$60 \text{ Gev} < M_{jj} < 100 \text{ Gev}$$

$$150 \text{ Gev} < M_{bjj} < 190 \text{ Gev}$$

$$H_T > 500 \text{ GeV}$$

Fermion T'



10 fb^{-1}

Can discover easily!!

<u>Included an Efficiency of ~ .18</u>

2 b tags ~ .3

τ veto all non b-jets~ .6

Calculated SM backgrounds

Channel	Generator	$\epsilon_{b\tau}$	σ
$t\bar{t}Z\ (Z \to \nu\nu)$	MadGraph	0.18	0.32 fb
$t\bar{t}j \to \tau jjjb\bar{b} + \text{MET}$	MadGraph	0.011	0.09 fb
$t\bar{t}jj \to \tau\tau jjb\bar{b} + \text{MET}$	MadGraph	0.0006	$< 10^{-5}$ fb
$Wb\bar{b} + 3j\ (W \to \tau\nu)$	Alpgen	0.01	< 0.009 fb
$W + 5j\ (W \to \tau\nu)$	Alpgen	3.5×10^{-6}	$< 10^{-5}$ fb
$Zb\bar{b} + 4j\ (Z \to \nu\nu)$	Alpgen	0.18	< 0.022 fb
$Z + 6j\ (Z \to \nu\nu)$	Alpgen	$6. \times 10^{-5}$	< 0.013 fb

b tag efficiency ~ .6, factor of 100 rejection of light quark and gluon jets and 10 on charm

tau veto: hadronically decaying tau fakes light jet ~ 5%
light jet reconstructs to a tau ~ 10 %

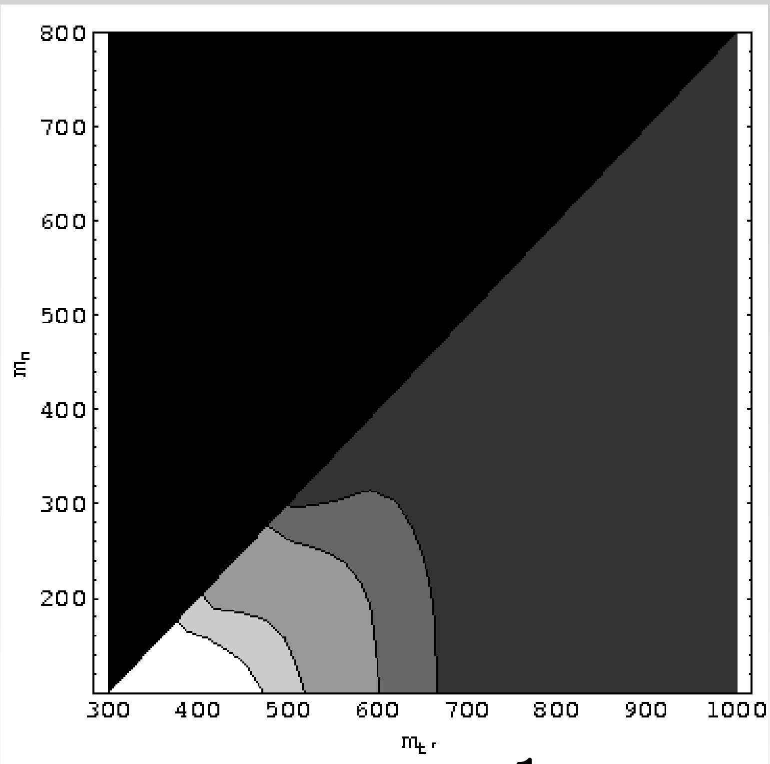
Investigated Jet Energy Mismeasurement in PGS

A MORE REALISTIC DETECTOR SIMULATION SHOULD BE DONE
ESTIMATES WE MAKE CONSERVATIVE TO WARRANT SOMEONE DOING THIS

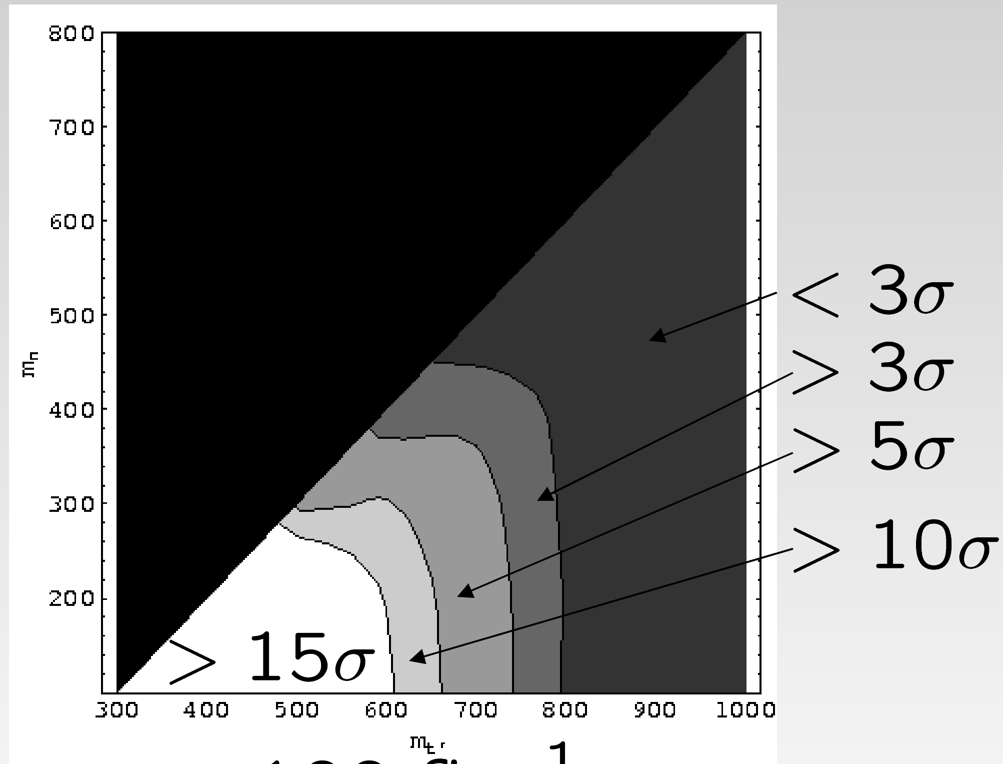
Significance in hadronic channel

Same cuts and efficiency used

Scalar T′



$10\ \mathrm{fb}^{-1}$

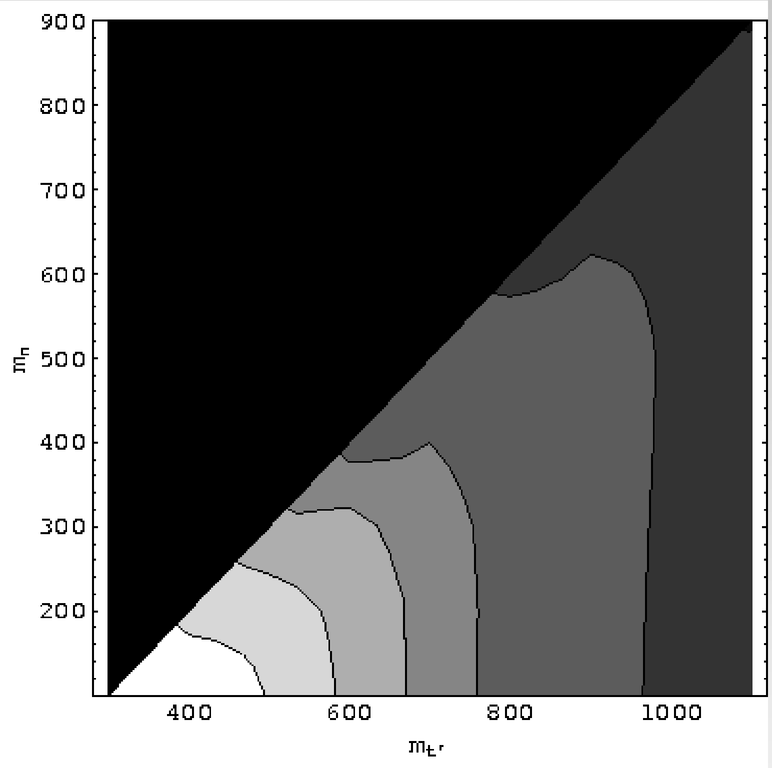


$100\ \mathrm{fb}^{-1}$

Can discover almost as easily!!

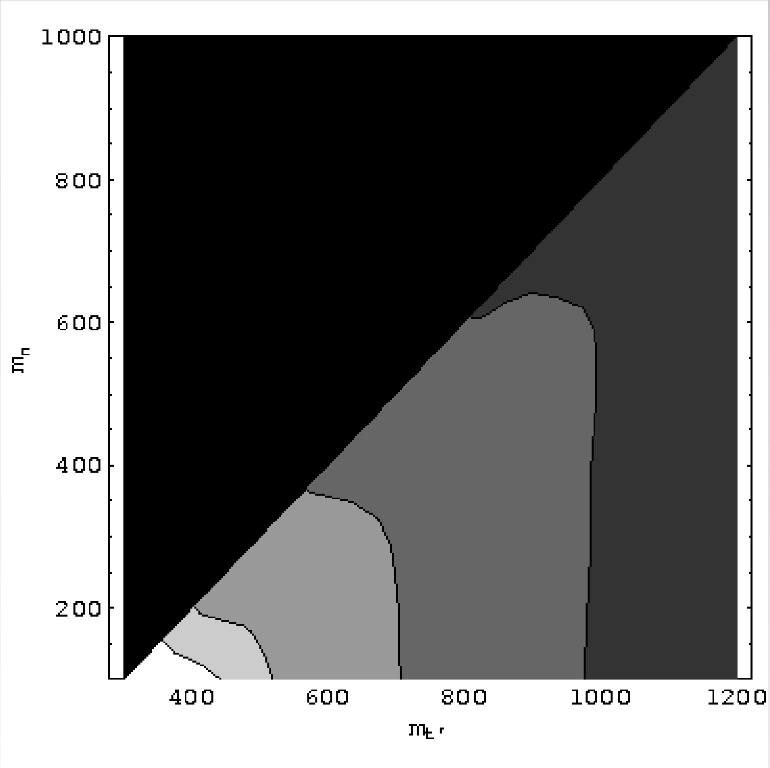
Signal to Background

Fermion T′



Contours of S/B = 40,20,10,5,1

Scalar T′



Contours of S/B =10,5,1,0.1

Scalar >1 T'~750 GeV
Fermion >1 T'~950 GeV

Mass determination

So now that we can find something what are its properties?

- Two massive objects escaped detection
- Don't know the mass of N
- Don't know the mass of T'
- Don't know the initial energy of the collision and boost to CMS

Uphill battle…

What observables might shed some light?

$$MET$$

Perhaps peak correlates with N mass?

$$M_{eff} = MET + \sum_{i=1}^{4} p_T^i$$

Peak is supposed to correlate
With the mass of lightest colored particle

$$H_T = \sum_i p_T^i + MET$$

Other possible combinations of momenta, perhaps they have a different dependence on the masses of T' and N

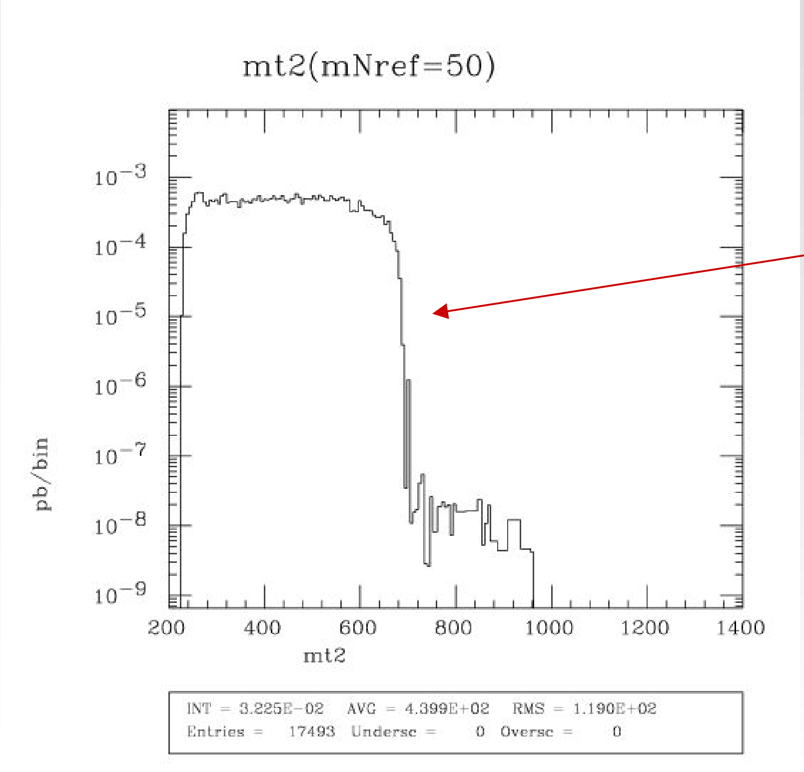
More "sophisticated" observable Cambridge MT2

transverse mass introduced for W decays but only 1 object contributes to MET

Real problem is how to break up missing p_T for the two N's

$$m_T^2(p_T^t, p_T^N, m_N) \equiv m_t^2 + m_N^2 + 2(E_T^t E_T^N - p_T^t \cdot p_T^N)$$

$$m_{T2}^2(\chi) = \min_{\not{q}_T^{(1)} + \not{q}_T^{(1)} = \not{p}_T} [\max\{m_T^2((p_T^{t(1)}, \not{q}_T^{(1)}; \chi), m_T^2((p_T^{t(2)}, \not{q}_T^{(2)}; \chi)\}]$$



Lester, Summers hep-ph/9906349
Barr,Lester, Stephens hep-ph/0304226

Edge corresponds to the mass of the parent particle

Really useful if you know the mass of the particle that is escaping detection!

What do we find?

In the end all these variables have roughly the **same dependence** on the masses of T' and N!

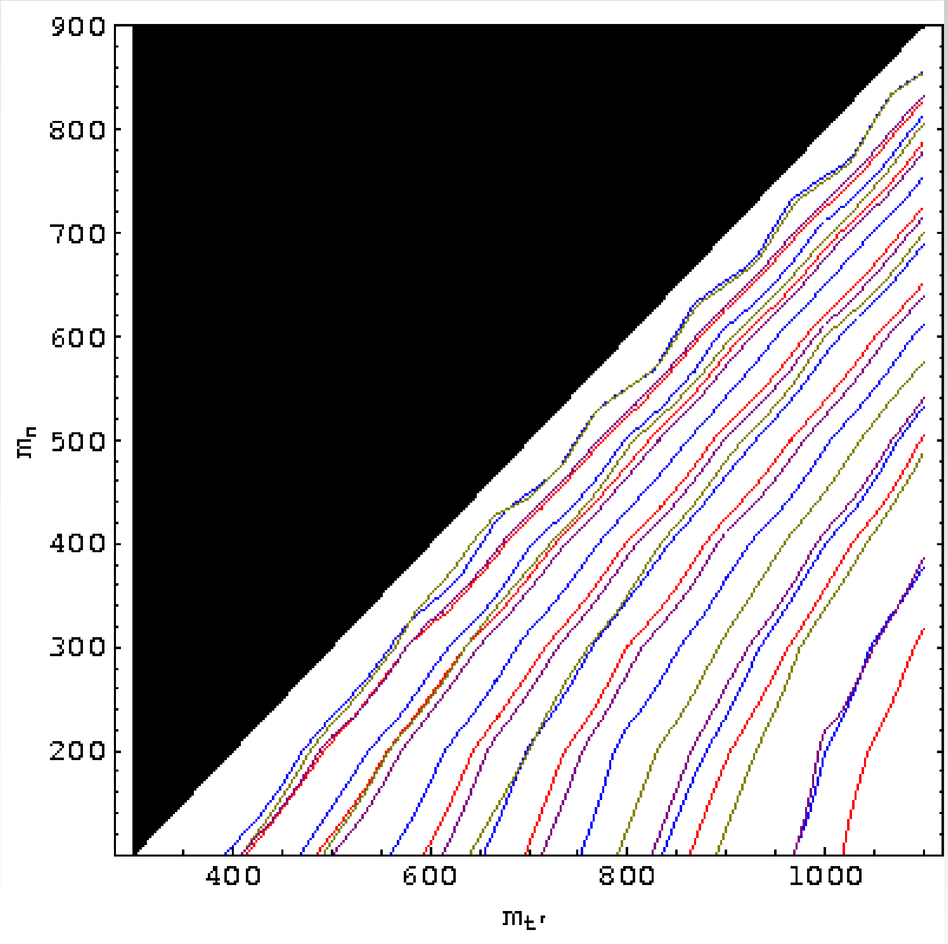
$< M_{eff} >$, $< MET >$, $< H_T >$, edge of M_{T2}

Easy to understand since the objects we measure always depend on the mass DIFFERENCE

Dispels the myth of M_{eff}

(needs large mass difference)

Alas we still don't have the masses!



Mass determination

Need something else…

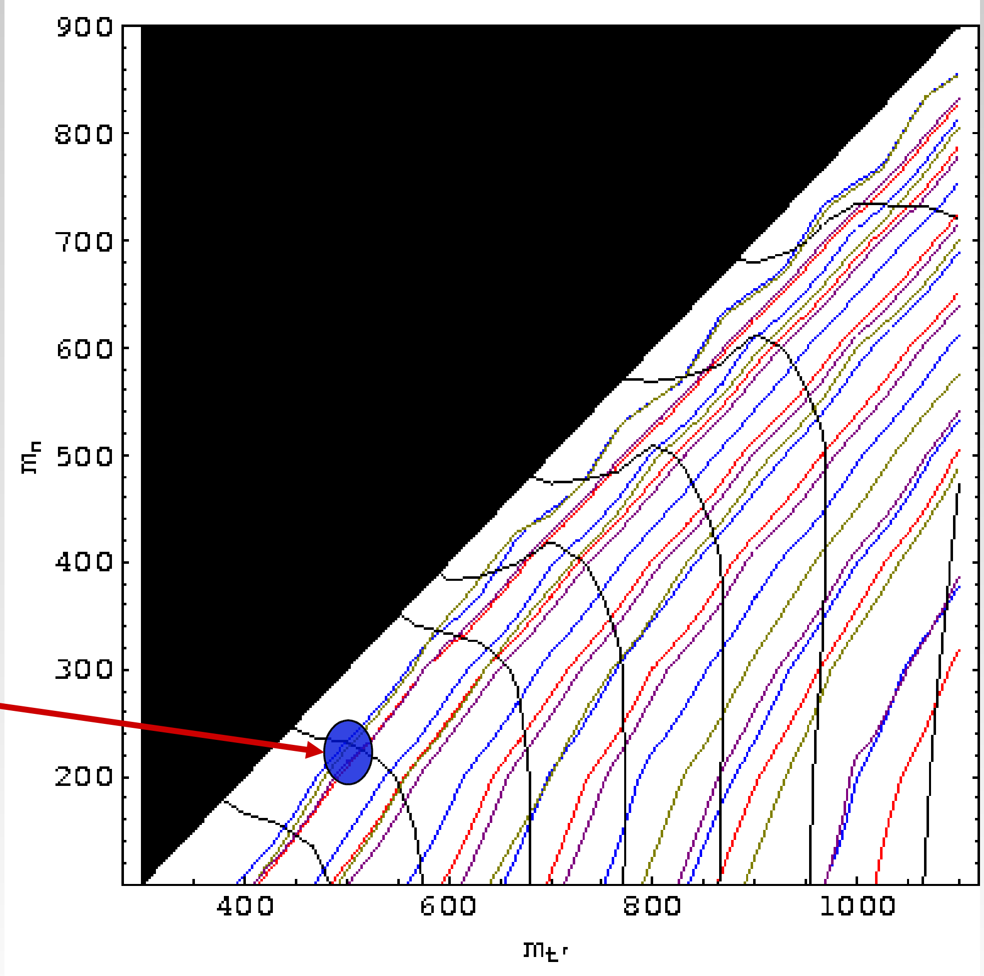
All the usual kinematic variables had the same slope in the T′-N masses

Cross section really depends on the mass of initial particle

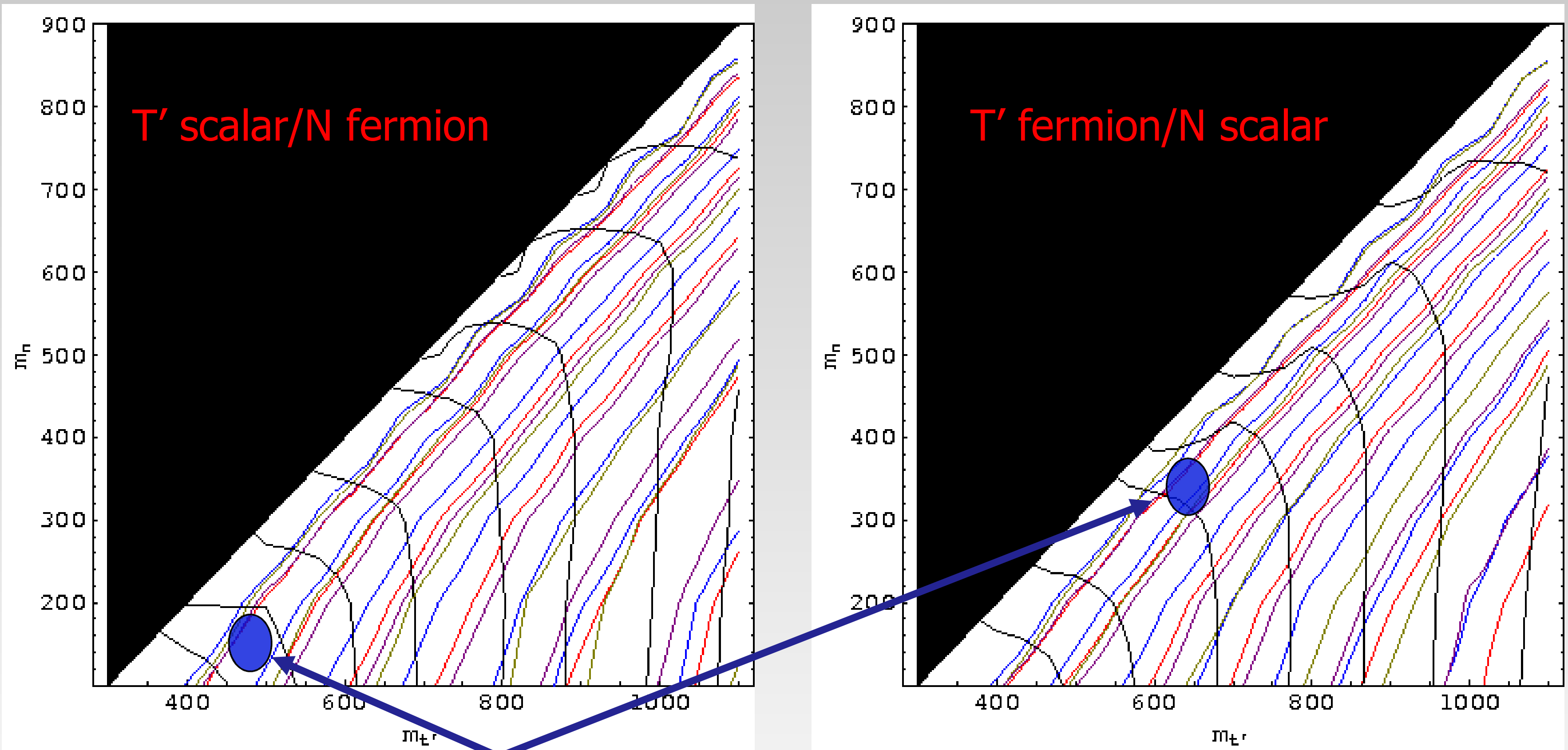
Can get masses of T′ and N!

(**for a given spin**)

Cross section error doesn't throw mass dependence off badly



Spin info STILL needed to break degeneracy



For a given scalar T′ point there is a fermion T′ with the same cross section and kinematic observables!

(Converse not true always as fermions have larger cross section)

<u>So we can find them, and find there masses up to some degeneracy due to spin!</u>

How are spins usually determined?

- Get some governments to pay for ILC
  - Hope it is within mass reach!
  - Angular Distributions
  - Threshold Scans
- At the LHC??
  - Spin correlations (very very difficult)
  - M_{eff} + Cross section (this doesn't work necessarily)
  - Barr Analysis
    - Charge Asymmetry Not Applicable
    - More recent work will touch on in a bit…
  - Something new!!

What do we do? Something new...

We can reconstruct the momenta of the two top quarks in the all hadronic channel

$p^Z_{t_1}, p^Z_{t_2}$ are the z components of momenta of the top quarks in the lab frame

$$N_+ \equiv \text{Number of events where } p^Z_{t_1} p^Z_{t_2} > 0$$

$$N_- \equiv \text{Number of events where } p^Z_{t_1} p^Z_{t_2} < 0$$

Define a "Beam Line Asymmetry"

$$BLA \equiv \frac{N_+ - N_-}{N_+ + N_-}$$

Basically how often are the tops in the same direction

Sensible in that there are really two different mass scales for the spins!

CAN ALSO BE REFORMULATED IN TERMS OF RAPIDITY(will come back to this)

Direction Asymmetry

Again we can reconstruct the momenta of the two top quarks

p_t^1, p_t^2 are the three momenta of one of the top quarks in the lab frame

$$N_+ \equiv \text{Number of events where } .9 > \frac{p_t^1 \cdot p_t^2}{|p_t^1||p_t^2|} > .5$$

Similarly for N_

Define a "Direction Asymmetry"

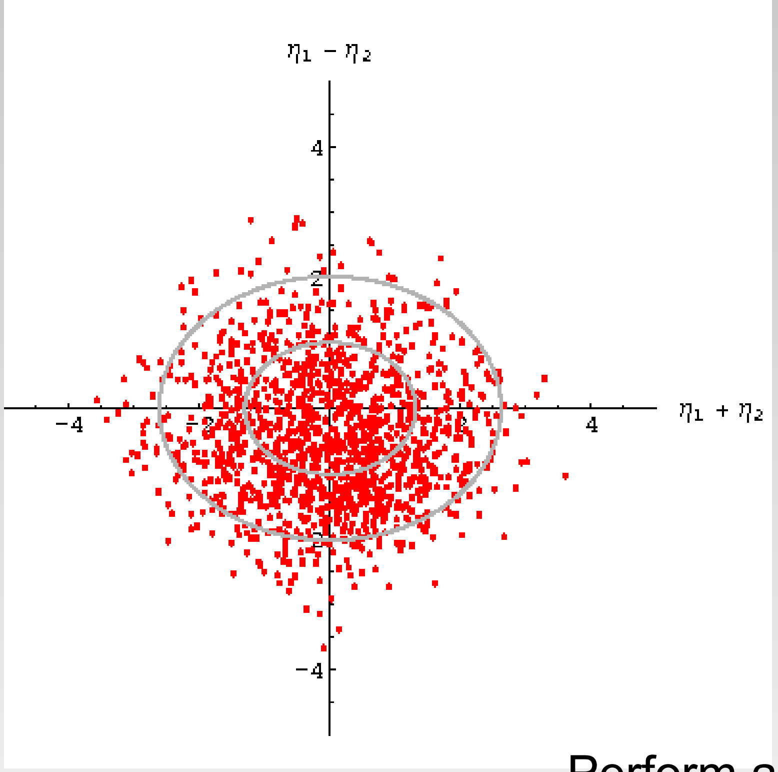
$$D \equiv \frac{N_+ - N_-}{N_+ + N_-}$$

Hard to do more without knowing the right frame...

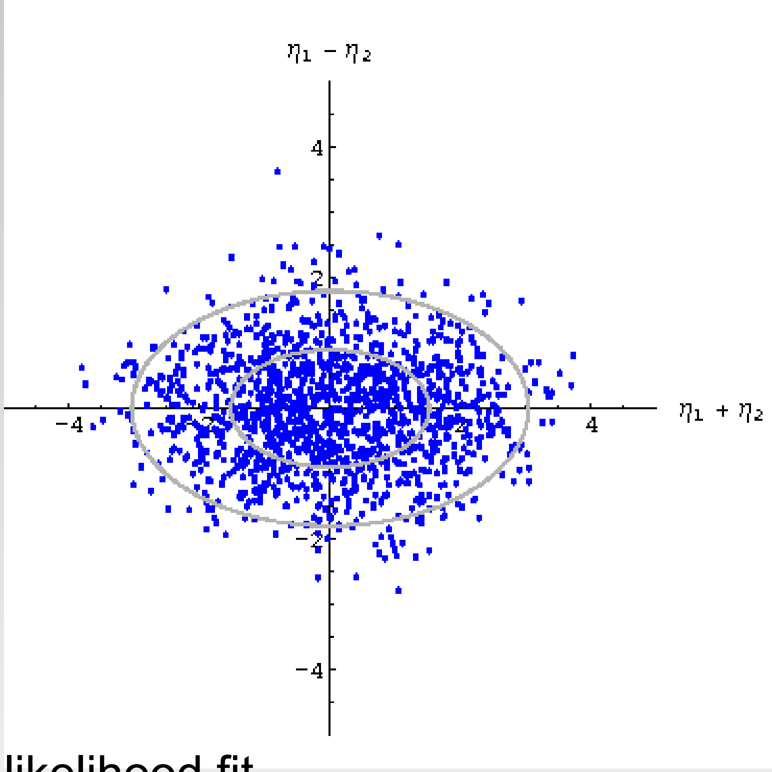
Pseudorapidity Correlations

Example Points For A Given Degeneracy

Fermion



Scalar



Perform a log likelihood fit

$$-2\log\mathcal{L} \quad \mathcal{L} = \Pi_i P(\eta_{+i}, \eta_{-i})$$

$$P(\eta_+, \eta_-) = \frac{C}{\sigma_+\sigma_-}\exp\left(-\frac{\eta_+^2}{2\sigma_+^2} - \frac{\eta_-^2}{2\sigma_-^2}\right)$$

Boost dependent axis measures "mass" possibly more

Boost invariant axis possibly more a measure of spin correlation

Results of these asymmetries

Example Points

Spin (t', N)	$(m_{t'}, m_N)$	$\langle H_t \rangle$	σ	BLA	DA	σ_+	σ_-
(F,S)	(550,300)	781	5.1	0.22	-0.43	1.40	1.05
(S,F)	(390,115)	786	5.0	0.31	-0.25	1.59	0.94
(F,V)	(550,300)	779	5.2	0.22	-0.46	1.39	1.03
(F,S)	(600,350)	775	3.3	0.16	-0.44	1.38	1.15
(S,F)	(415,165)	777	3.1	0.32	-0.34	1.57	0.82
(F,V)	(600,350)	785	3.4	0.20	-0.46	1.37	1.00
(F,S)	(700,400)	865	2.0	0.16	-0.40	1.31	1.01
(S,F)	(500,150)	874	2.1	0.26	-0.32	1.52	0.90
(F,V)	(700,400)	857	2.1	0.16	-0.45	1.30	1.08
(F,S)	(700,500)	695	0.51	0.19	-0.66	1.27	1.03
(S,F)	(515,315)	742	0.44	0.36	-0.55	1.40	0.75
(F,V)	(700,500)	690	0.50	0.17	-0.64	1.20	0.94

Further points studied

Doesn’t distinguish spins of N

Does distinguish T’ fermion/scalar

How Much Luminosity?? Good Question…

Spin (t', N)	$(m_{t'}, m_N)$	$\langle H_t \rangle$	σ	BLA	DA	σ_+	σ_-
(F,S)	(700,400)	865	2.0	0.16	-0.40	1.31	1.01
(S,F)	(500,150)	874	2.1	0.26	-0.32	1.52	0.90
(F,V)	(700,400)	857	2.1	0.16	-0.45	1.30	1.08

Errors scale like $\sim \frac{1}{\sqrt{N}}$

Ignoring background which is a factor of 5 smaller…

To separate σ_+ after 300 inverse fb you are 5 sigma apart

To separate σ_+ after 1200 inverse fb you are 10 sigma apart

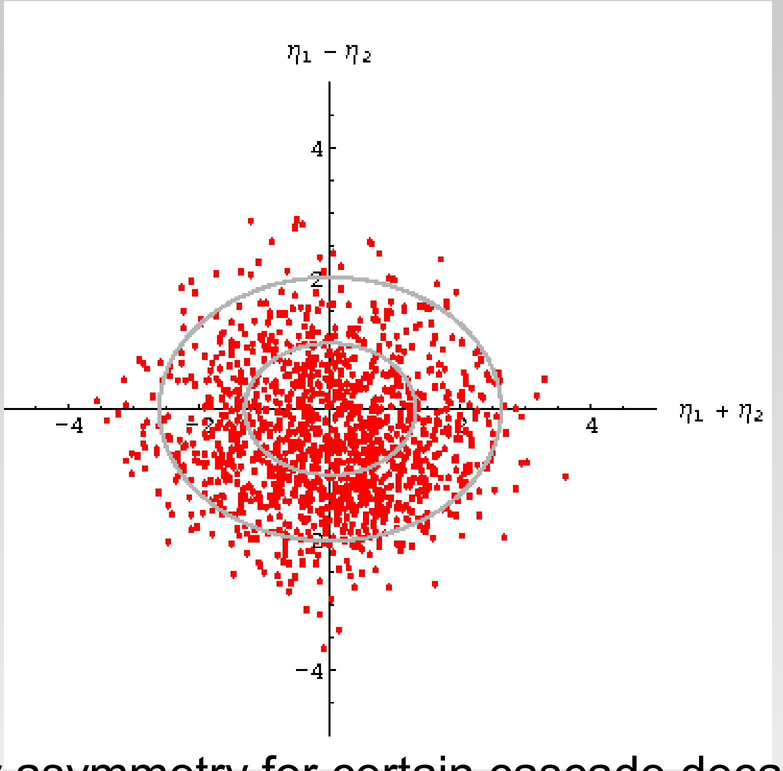
ROUGH ESTIMATE ONLY (commensurate with all other suggested methods)

LHC may be more feasible for spin determination than ILC depending on masses!

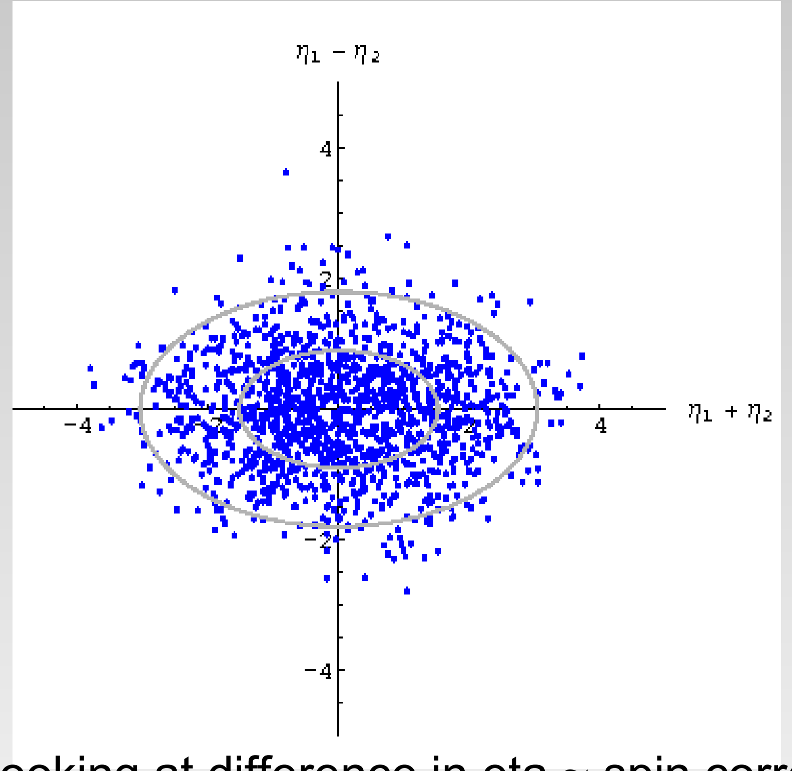
Pseudorapidity Correlations

Comparison to other methods…

Fermion



Scalar



Barr asymmetry for certain cascade decays looking at difference in eta ~ spin correlation

Top spin correlation $$\frac{dN_{R,L}}{d\cos\theta_i^*} = \frac{1}{2}(1 + h_i \cos\theta_i^*)$$

Hard to deconvolute spin correlation **Function of particles, masses, spins!**

Barr method doesn't take into account degeneracy

starting point is same mass

Top Partner Summary

Starting with a model independent ansatz motivated by naturalness

- We can find this signal over a large range of masses (hadronic channel)
- We can determine masses of both T′ and N up to a discrete choice of spin
  - Degeneracy often not accounted for
- We can determine spin of T′ using new asymmetries and correlations
  - Any other study of spin at LHC has to have a different starting point or understand how to measure masses
- Only SM backgrounds accounted for but non-SM backgrounds can be accounted for easily in this framework

Other Scenarios for Model Independent Studies

- Places where most useful
  - Not lots of different channels for new physics
  - Particular channels that are “expected”
- Straightforward top partner extensions…
- Partners of gauge bosons?
- Testing Higgs couplings model independently

Lots of interesting possibilities how far can it be stretched??