Sleuthing
for physics beyond the Standard Model

The nature of the problem

Sleuth

Results

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The nature of the problem

Most searches follow a well-defined set of steps:

- Select a model to be tested
- Find a measurable prediction of the model differing as much as possible from the prediction of the Standard Model
- Check those predictions against the data

This approach becomes problematic if the number of competing candidate theories is large . . . and it is!

Is it possible to perform some kind of "generic" search?

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The first sign of new physics will come from:

- ☐ Heavy gauge bosons
- ☐ Technicolor
- ☐ Large extra dimensions
- ☐ Leptoquarks
- ☐ Supersymmetry
- ☐ Fourth generation fermions
- ☐ Compositeness
- ☐ Something else

The values of the 105 MSSM parameters are:

$$W_{\rm MSSM} = \bar{u}\mathbf{y_u}QH_u - \bar{d}\mathbf{y_d}QH_d - \bar{e}\mathbf{y_e}LH_d + \mu H_u H_d \,.$$

$$\begin{aligned}\mathcal{L}^{\rm MSSM}_{\rm soft} = & -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B}\right) + \text{c.c.}\\ & -\left(\tilde{\bar{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \tilde{\bar{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \tilde{\bar{e}}\,\mathbf{a_e}\,\widetilde{L}H_d\right) + \text{c.c.}\\ & -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \tilde{\bar{u}}\,\mathbf{m^2_{\bar{u}}}\,\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\,\mathbf{m^2_{\bar{d}}}\,\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\,\mathbf{m^2_{\bar{e}}}\,\tilde{\bar{e}}^\dagger\\ & - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.\end{aligned}$$

$$y_u = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix}\quad y_d = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix}\quad y_e = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix}$$

$$a_u = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix}\quad a_d = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix}\quad a_e = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix}$$

$$m_{\widetilde{Q}} = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix} m_{\widetilde{L}} = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix} m_{\tilde{\bar{u}}} = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix} m_{\tilde{\bar{d}}} = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix} m_{\tilde{\bar{e}}} = \begin{pmatrix}\square & \square & \square\\ \square & \square & \square\\ \square & \square & \square\end{pmatrix}$$

$$\square\,\mu \quad \square\,M_1 \quad \square\,M_2 \quad \square\,M_3 \quad \square\,m^2_{H_u} \quad \square\,m^2_{H_d} \quad \square\,b$$

The nature of the problem

“model”

The word “model” can connote varying degrees of generality

generality

1 - A special case of a class of models with definite parameters
  mSUGRA with $M_{1/2}=200$, $M_0=220$, $\tan\beta=2$, $\mu<0$

2 - A special case of a class of models with unspecified parameters
  mSUGRA

3 - A class of models
  SUGRA

4 - A more general class of models
  gravity-mediated supersymmetry

5 - An even more general class of models
  supersymmetry

6 - A set of even more general classes of models
  theories of electroweak symmetry breaking

Most new physics searches have generality $\approx 1\frac{1}{2}$ on this scale

We are shooting for a search strategy with a generality of ≈ 6 . . . .

The nature of the problem

Another related issue:

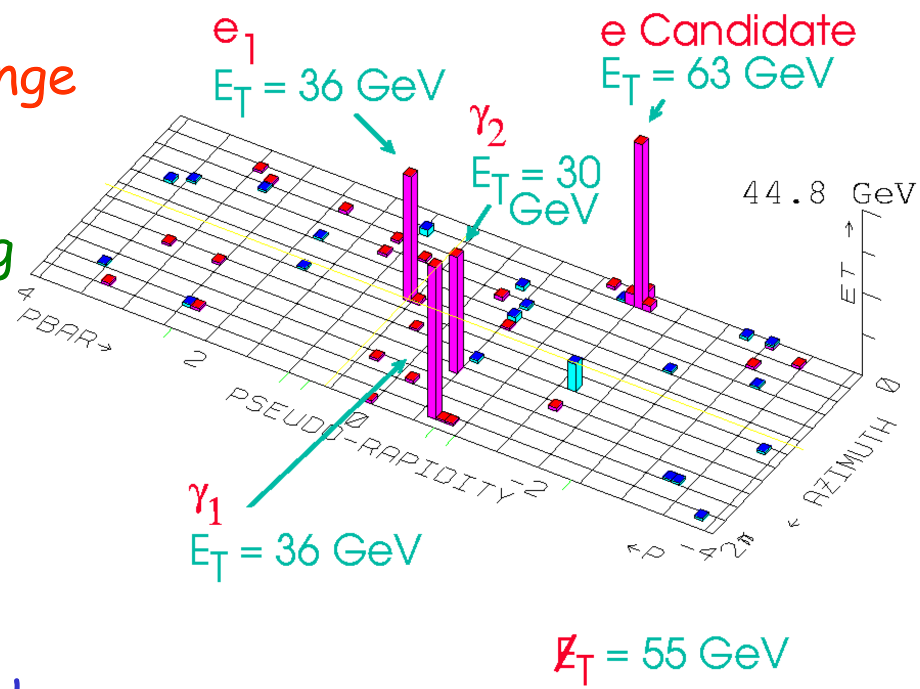
How do we quantify the "interestingness" of a few strange events *a posteriori*?

After all, the probability of seeing <u>exactly</u> those events is zero!

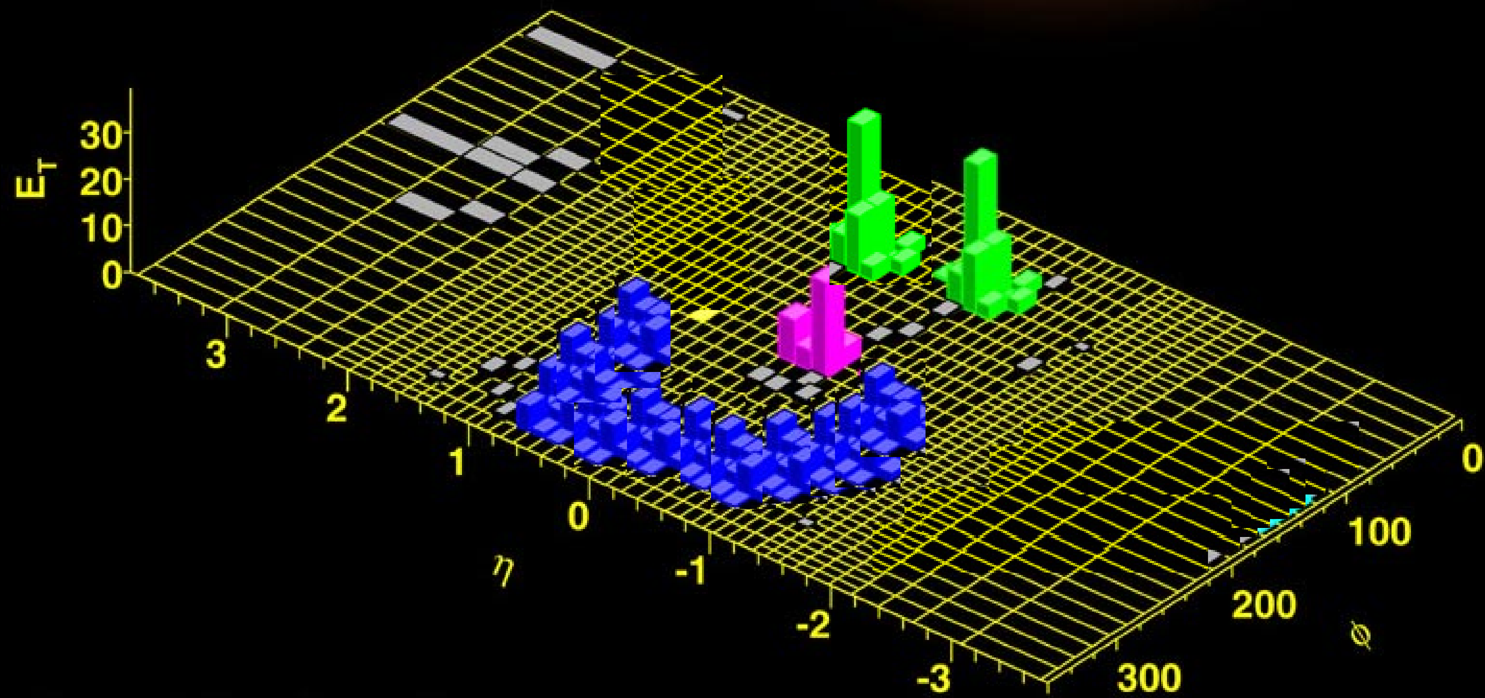
How excited should we be?

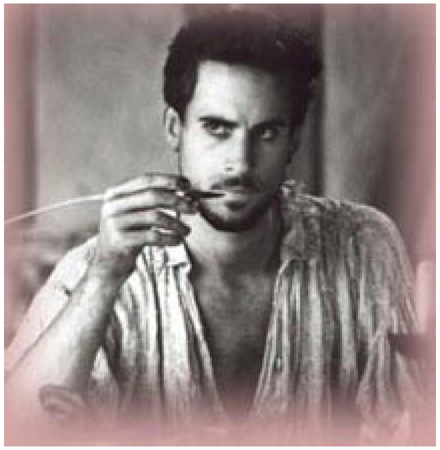
How can we possibly perform an unbiased analysis after seeing the data?

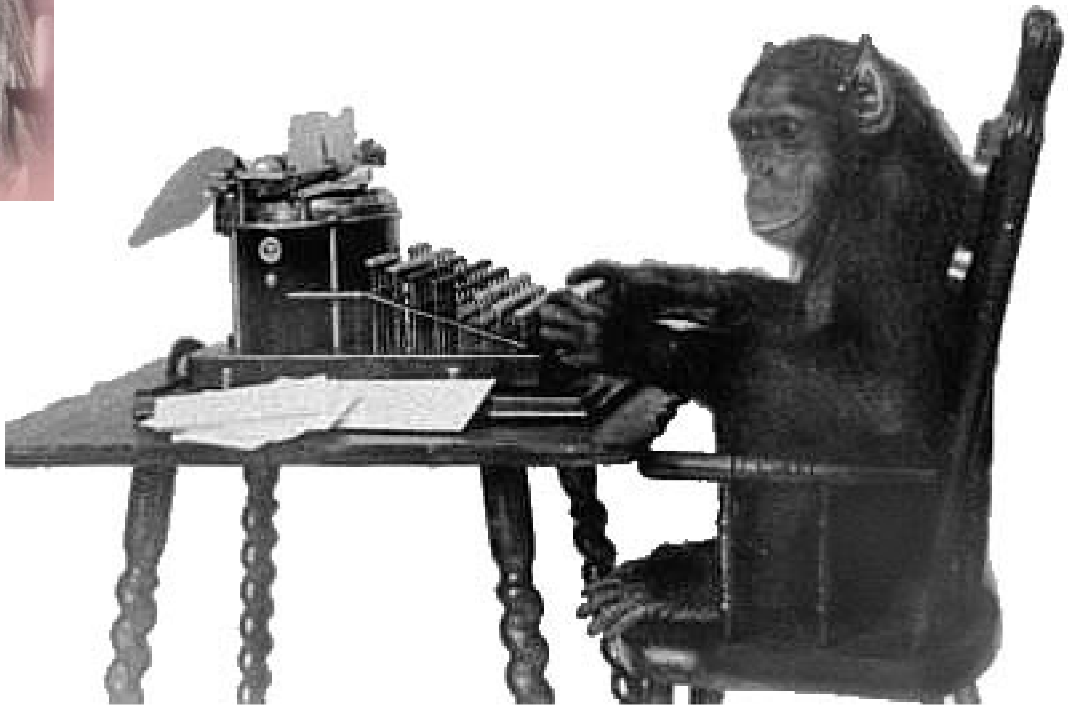
CDF $ee\gamma\gamma\not{E}_T$ Candidate Event



CDF smiley face candidate event







Suppose you inserted Shakespeare's brain into a monkey, and then set him at a typewriter . . .

The monkey produces lots of gibberish, and then on page 52 you see this:

tahtkl ;alkgh hk;fdsah kah ;ahg;kjfdhg;lk h;ka o;itreahg; ogha;lkg ha;rlg
ha;ll;kg a;lkg a;lkg ;lakd g;ldafghalkhglakjglj raeoithoireqhoqyoqyg
[requyt9u45yqt54qyygqortqhg ;oirthgwqoi upqo5yht ;qoi4hy ;q45hy
iuqhgq;oit ;oqhyto[45qhy4o5qhyq’oh o uqo54yq’o45
yhohy;oyr;oyuq54o;y54h;yh4o hyj ;irthoiq54;yhq45o yhq4’oiyh ‘oqiyhj ‘oiyh
j’oirthj ‘oih’oirth oqjoryhjqt’orhjy ‘qtroyjtq ‘orjy’oq45uyo[45q uy’q4oi5jy ‘oithj
‘ohsg’oihj’ohu’oirtwhj woirhjn’ogih ;oishsroihg trs;oi hg984qu5
y9845yhoirshg h h shgjbhsj gjh;slhj ;hjsoj h;ortsjh ;lhj;sortihjy ;hj ;lrtshj
oshjs;oihj lkhlish ligy yuser oigjfdlkg jfdnvlkdnvmzco;irjehptoiqwureot
qre09ut 9843t 43oq utqoifdg;hgsutg45hjoig4thg4poig984twg2oi4 jgo;i2
h4oi5thj4[toi uh45qu yj bv09 096b7w4[06bn86vbn\ 43q-nbq6v[q306bnv 45
6bi\ ]456nb q5b8n q5 6ub[0q53b [0q-nb 0-yqu45yovn60963qtnv [3b 05nv4viu
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vridlkfj lkdsvsirdhv h4tv 598y t9ryuta;eorur09[neuab o[eauvt urevyb
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yu45qypouo nboureaov r;osuc ;o To be or not to be, that is the question. ms
opsu;ortroirt huybporsnu60uy5b[u45wvpn0u45womn po45wv5y5w4v riesj;lr
uyto;ist u0[ew987b60[42u [0qiu]tae 8-6b86\ 45y4qa56b[w5 ub;ljgfb go;su
b[u6yuy45 hjw r[phj[0j2u09 uhj’r sjto hu[04iuy5’hrtowj h’fs
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fsunbp9u05eb6un [5s r]tbn]\ 45qb6n 42nb portsuunboipbuy oigsfdjoihgv02e
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9[78uyo[ihh0[8hs[fhu o[gu8u]s\ rtu8ytrs8[yip78uytp[b8nt8nb7[rt87n[7n8[rn7

To be or not to be, that is the question.

Amazing!

But is this a breakthrough in neuroscience, or just a statistical accident?

The problem now is finding the right question to ask:

What is the probability that the monkey:

would have produced this phrase in ≤ 52 pages?

would have produced this phrase in the time limit of the experiment?

would have produced a well-known phrase in the time limit . . . ?

would have produced any Shakespeare phrase in the time limit . . . ?
possibly with a misspelling or two

would have produced any Elizabethan-era phrase . . . ?
or would have performed any number of non-typewriter-related actions reminiscent of Shakespeare

(Shakespeare never used a typewriter)

At issue is the *trials factor* --
how many equally interesting things could have happened, but didn't?

This is nearly impossible to assess after seeing the data

But what if we had made the notion of "interesting" rigorous ***before*** *we had performed this experiment?*

E.g.,

1) The monkey is allowed to write exactly 100 pages
2) The "interestingness" ("Shakesperianness") of a phrase is defined as the number of English majors who identify the phrase with Shakespeare
3) The "interestingness" of the document is defined as the interestingness of the most interesting phrase $\mathcal{R}$
4) The relevant quantity is the fraction $\mathcal{P}$ of normal monkeys that would produce a document more interesting than the Shakespeare monkey's document.

Set a bunch of normal monkeys to the same task.

What does this have to do with high energy physics?

Lots.

Although we are almost certainly on the verge of finding something, we have only vague ideas of what that something might be.

The present paradigm of selecting a particular model and testing its predictions against the data is woefully inadequate — the space of possibilities has simply grown too large.

# of articles in the last 5 years
on hep-ph: 18,948
on hep-ex: 2,299

Is it possible to perform some kind of "generic" search?

Consider the most recent major discoveries in high energy physics:

• W, Z bosons	CERN	1983
• top quark	Fermilab	1995
• tau neutrino	Fermilab	2000
• Higgs boson?	CERN	2000

In all cases the predictions were "definite" (apart from mass)

- couplings known (quantum numbers)
- cross section known (how much signal)
- final states known (what the signal looks like)
- you were willing to bet even odds that the particle existed

We are now in a qualitatively different situation

- the chance that any particular model on hep-ph is correct is naively ≈ 1/18,948

Have you chosen the right one?
(Are you willing to bet your career on it?)

The nature of the problem

desiderata

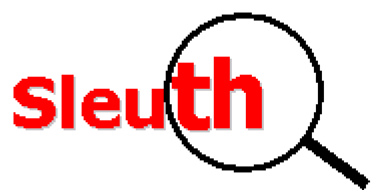
What characteristics would an ideal analsysis strategy have?

Emphasize an understanding of the data (rather than what the data have to say about a particular model)

Provide a systematic method for analyzing the entire data set (leaving no stone unturned!)

Construct an approach that keeps attention focused on the most promising channels (rather than optimizing cuts for a signal that does not exist)

Allow for surprises . . .



The nature of the problem

Sleuth

Results

Steps:

1) We consider exclusive final states

We assume the existence of standard object definitions

These define e, μ, τ, γ, j, b, $\not{E}_T$, W, and Z

All events which contain the same numbers of each of these objects belong to the same final state

Why exclusive final states?

Most previous analyses have been performed on inclusive final states

($\gamma\gamma X$, $\gamma b \not{E}_T X$, $\mu\gamma X$, $e \not{E}_T jjX$, . . .)

But:

- The presence of an extra object in an event often qualitatively changes the probable interpretation of the event

$$e \not{E}_T b\bar{b} \quad \leftarrow \quad Wh$$

- The presence of an extra object in an event generally changes the variables that one would want to use to characterize the event

$$e\mu \not{E}_T \quad \leftarrow \quad \text{don't want to use } p_T^j$$

- Allowing inclusive final states leaves an ambiguity in definition

$$e\mu \not{E}_T jjX\ ? \quad e\mu \not{E}_T X\ ? \quad eX\ ?$$

Our goal is a rigorous prescription — need to specify!

ee at?

(to be overlayed)

jjj xxxx

(to be overlayed)

Consequences?

- We expect a signal to appear in one box
  Final states are not combined (as was done for top, for example)

$$\binom{100}{2} \approx 5000$$

- Philosophy: We label an event as completely as possible, as long as we have sufficient confidence in that label

  Call an electron an electron
  Call Z boson a Z boson
  Call a charm quark a jet

- If the signal turns out to be exotic (eee, $ee\gamma\gamma\not{E}_T$, . . .), this simple idea of exclusive final states may be all you need

2) Define variables

What is it we're looking for?

The physics responsible for EWSB

What do we know about it?

Its natural scale is a few hundred GeV

What characteristics will such events have?

Final state objects with large transverse momentum

What variables do we want to look at?

p_T's

Why not invariant masses?

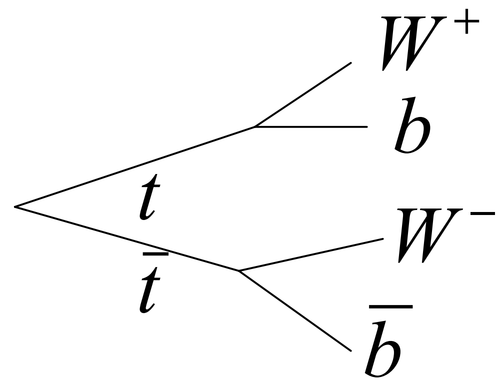
Because they are exceptionally poor variables for a generic search

Consider $e\mu\not{E}_T jj$

The obvious invariant mass to consider is m_{jj}

(even more so if the final state is $e\mu\not{E}_T bb$)

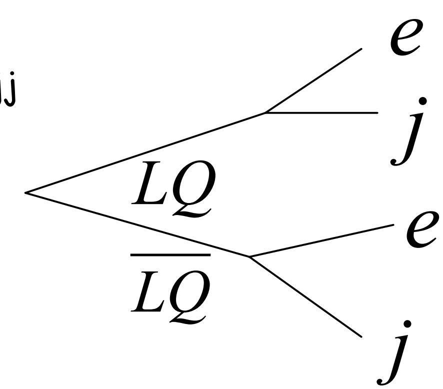
But you would have missed top!



Consider $eejj$

The obvious masses to consider are m_{ee} and m_{jj}

Lose sensitivity to leptoquarks



Consider $e\not{E}_T jjjj$

What invariant masses should we consider?

m_{j1j2} m_{j1j3} m_{j1j4} m_{j2j3} m_{j2j4} m_{j3j4}

$m_{e\not{E}j1}$ $m_{e\not{E}j2}$ $m_{e\not{E}j3}$ $m_{e\not{E}j4}$ m_{j1j2j3} m_{j1j2j4} m_{j1j3j4} m_{j2j3j4}

$m_{j1j2j3j4}$ $m_{e\not{E}j1j2j3j4}$ $m_{e\not{E}j1j2}$ $m_{e\not{E}j1j3}$ $m_{e\not{E}j1j4}$ $m_{e\not{E}j1j2j3}$ . . .

Why not invariant masses?

Because we do not know what mass to expect

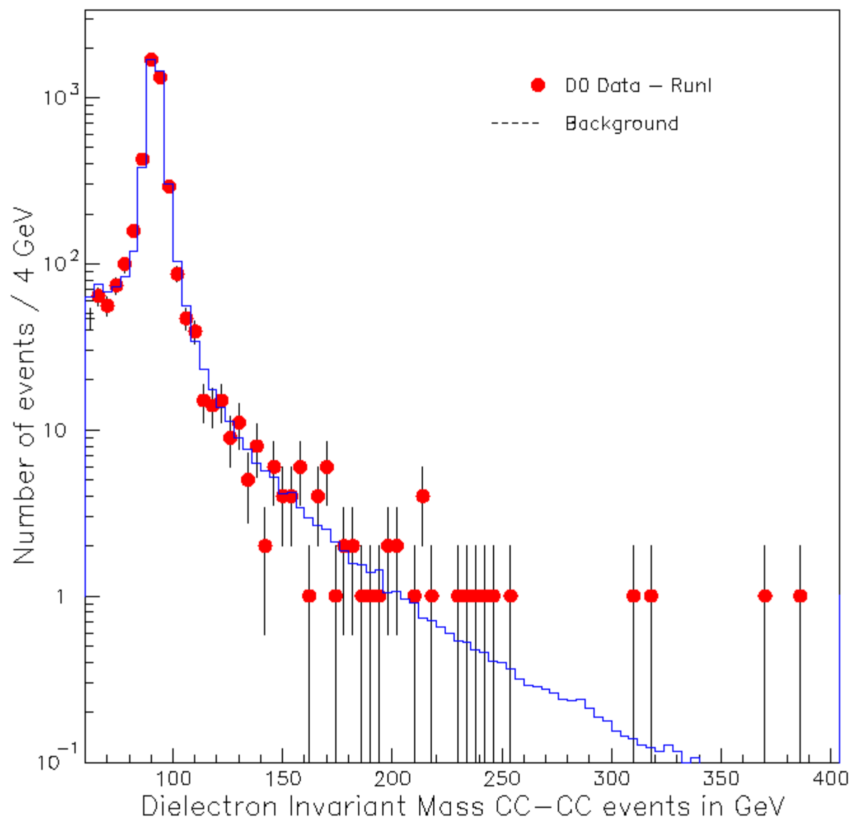
Consider ee (the simplest case):

Where do we expect a peak?

Of what width?

Consider all possibilities?

→ Enormous trials factor !



In short, invariant masses suffer from:

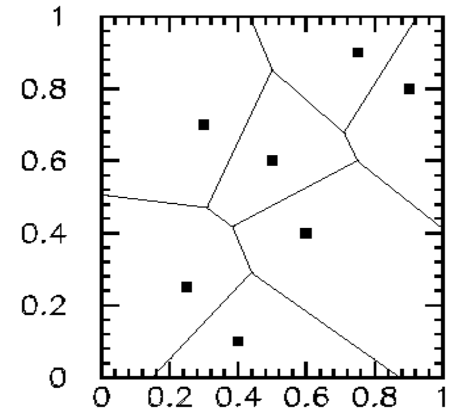
- Combinatorics
- Unknown peak position
- Having to guess correctly which mass(es) to use
- Having to define (and justify) variables one final state at a time

Step 2: Variables

If the final state contains	Then consider the variable
1 or more lepton	$\sum p_T^{\ell}$
1 or more γ/W/Z	$\sum p_T^{\gamma/W/Z}$
1 or more jet	$\sum p_T^{j}$
missing E_T	$\not{E}_T$

(adjust slightly for idiosyncrasies of each experiment)

3) Search for regions of excess (more data events than expected from background) within that variable space



For each final state . . .

Input: 1 data file, estimated backgrounds

- transform variables into the unit box
- define regions about sets of data points
  - Voronoi diagrams
- define the "interestingness" of an arbitrary region
  - the probability that the background within that region fluctuates up to or beyond the observed number of events
- search the data to find the most interesting region, $\mathcal{R}$
- determine $\mathcal{P}$, the fraction of *hypothetical similar experiments* (hse's) in which you would see something more interesting than $\mathcal{R}$
  - Take account of the fact that we have looked in many different places

Output: $\mathcal{R}$, $\mathcal{P}$

The nature of the problem

Sleuth

Results

If the data contain no new physics, Sleuth will find $\mathcal{P}$ to be random in (0,1)

If we find $\mathcal{P}$ small, we have something interesting

If the data contain new physics, Sleuth will *hopefully* find $\mathcal{P}$ to be small

If we find $\mathcal{P}$ large, is there no new physics in our data?

or have we just missed it?

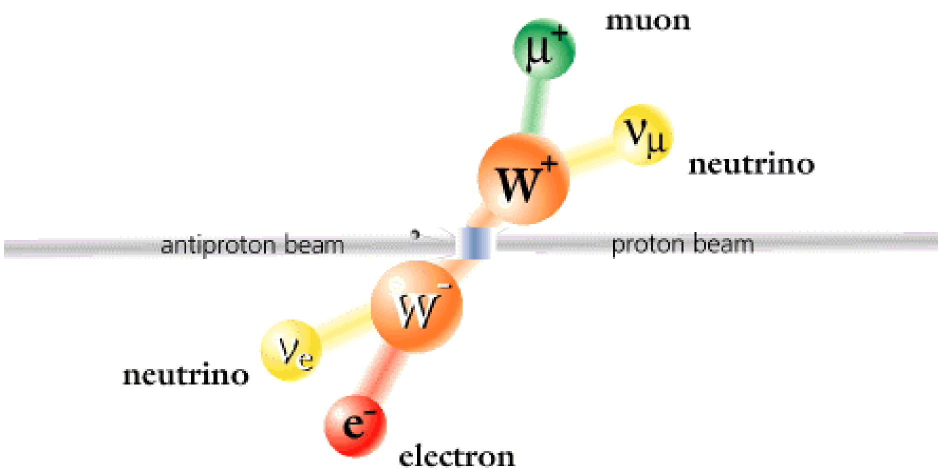
How *sensitive* is Sleuth to new physics?

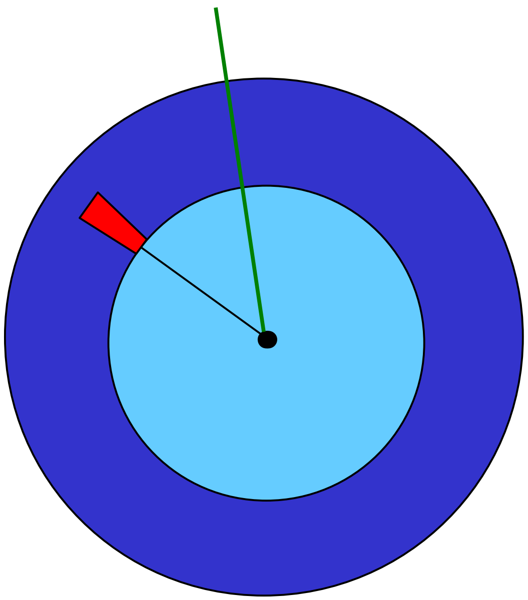
Impossible to answer, in general

(Sensitive to *what* new physics?)

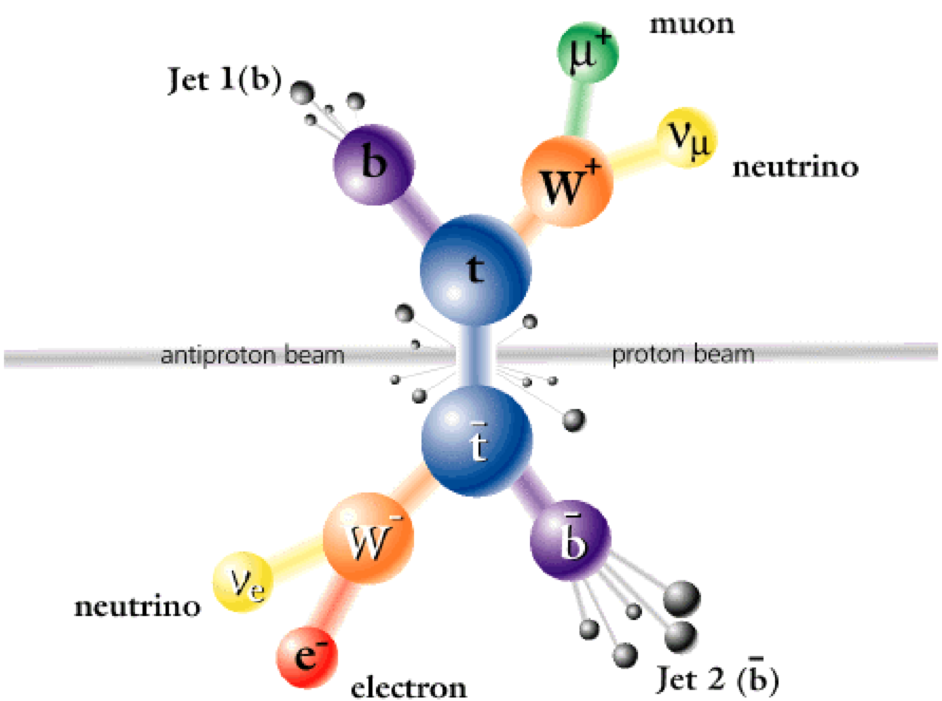
But we can provide an answer for specific cases

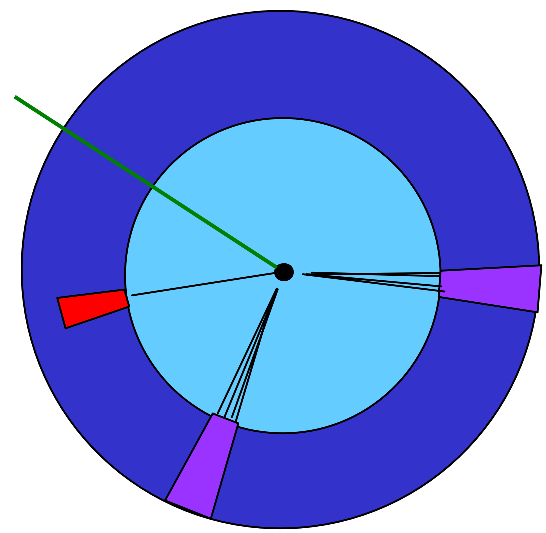
How "sensitive" is Sleuth to $WW \to e\mu \not{E}_T$?





How "sensitive" is Sleuth to $t\bar{t} \rightarrow e\mu \not{E}_T jj$?





To put $t\bar{t}$ in context:

DØ's top discovery PRL (1995, 50 pb^{-1}):

all channels: 17 events with 3.8 ± 0.6 expected — a 4.6σ "effect"

eμX alone: 2 events with 0.12 ± 0.03 expected — a 2.5σ "effect"

DØ's top cross section PRL (1997, 125 pb^{-1}):

all channels: 39 events with 13.7 ± 2.2 expected

eμX alone: 3 events with 0.21 ± 0.16 expected — a 2.75σ "effect"

Sleuth should never be more sensitive than a dedicated search,

so ≈ 2.75σ is an upper bound on our sensitivity to $t\bar{t}$

(We've given ourselves a difficult test)

Sensitivity check: $t\bar{t}$ in $e\mu X$

Let the backgrounds include

1)
- fakes
- $Z \to \tau\tau$
- WW
- $t\bar{t}$

DØ data

Data Set	$\mathcal{P}$
$e\mu\not{E}_T$	2.4σ
$e\mu\not{E}_T j$	0.4σ
$e\mu\not{E}_T jj$	2.3σ
$e\mu\not{E}_T jjj$	0.3σ
Combined	1.9σ

Excesses corresponding (presumably) to WW and $t\bar{t}$

2)
- fakes
- $Z \to \tau\tau$
- WW
- $t\bar{t}$

DØ data

Data Set	$\mathcal{P}$
$e\mu\not{E}_T$	1.1σ
$e\mu\not{E}_T j$	0.1σ
$e\mu\not{E}_T jj$	1.9σ
$e\mu\not{E}_T jjj$	0.2σ
Combined	1.2σ

Excess corresponding (presumably) to $t\bar{t}$

3)
- fakes
- $Z \to \tau\tau$
- WW
- $t\bar{t}$

DØ data

Data Set	$\mathcal{P}$
$e\mu\not{E}_T$	1.1σ
$e\mu\not{E}_T j$	0.1σ
$e\mu\not{E}_T jj$	0.5σ
$e\mu\not{E}_T jjj$	-0.5σ
Combined	-0.6σ

No evidence for new physics

Sensitivity check: $t\bar{t}$ in W+jets

To put $t\bar{t}$ in context:

DØ's top cross section PRL (1997, 125 pb^{-1}):

ℓ+jets w/o btag: 19 events observed (9 in e+jets, 10 in μ+jets)
8.7 ± 1.7 events expected — a 2.6σ "effect"

ℓ+jets w/ btag: 11 events observed (5 in e+jets, 6 in μ+jets)
2.5 ± 0.5 events expected — a 3.6σ "effect"

The lesson: b-tagging is crucial for top in this channel

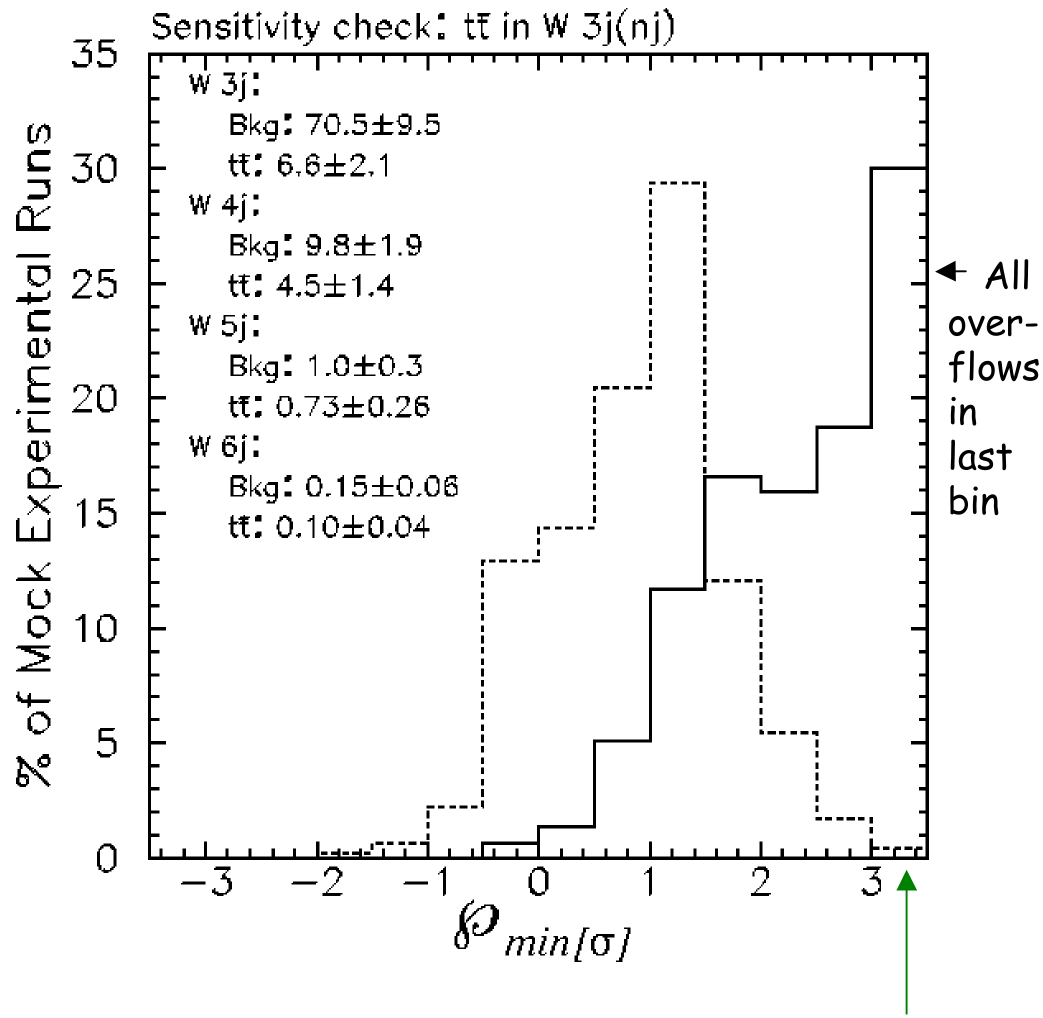
We have put Sleuth at a large disadvantage by choosing to not identify b's

(Again, we've given ourselves a difficult test)

Improved detectors and standard b-tagging tools will allow us to define Sleuth final states with bottom in Run II

Sensitivity check: $t\bar{t}$ in Wjjj(nj)

Could Sleuth have found $t\bar{t}$ in the lepton+jets channel?



Sleuth finds $\mathcal{P}_{min}$ > 3σ in 30% of an ensemble of mock experimental runs

Results

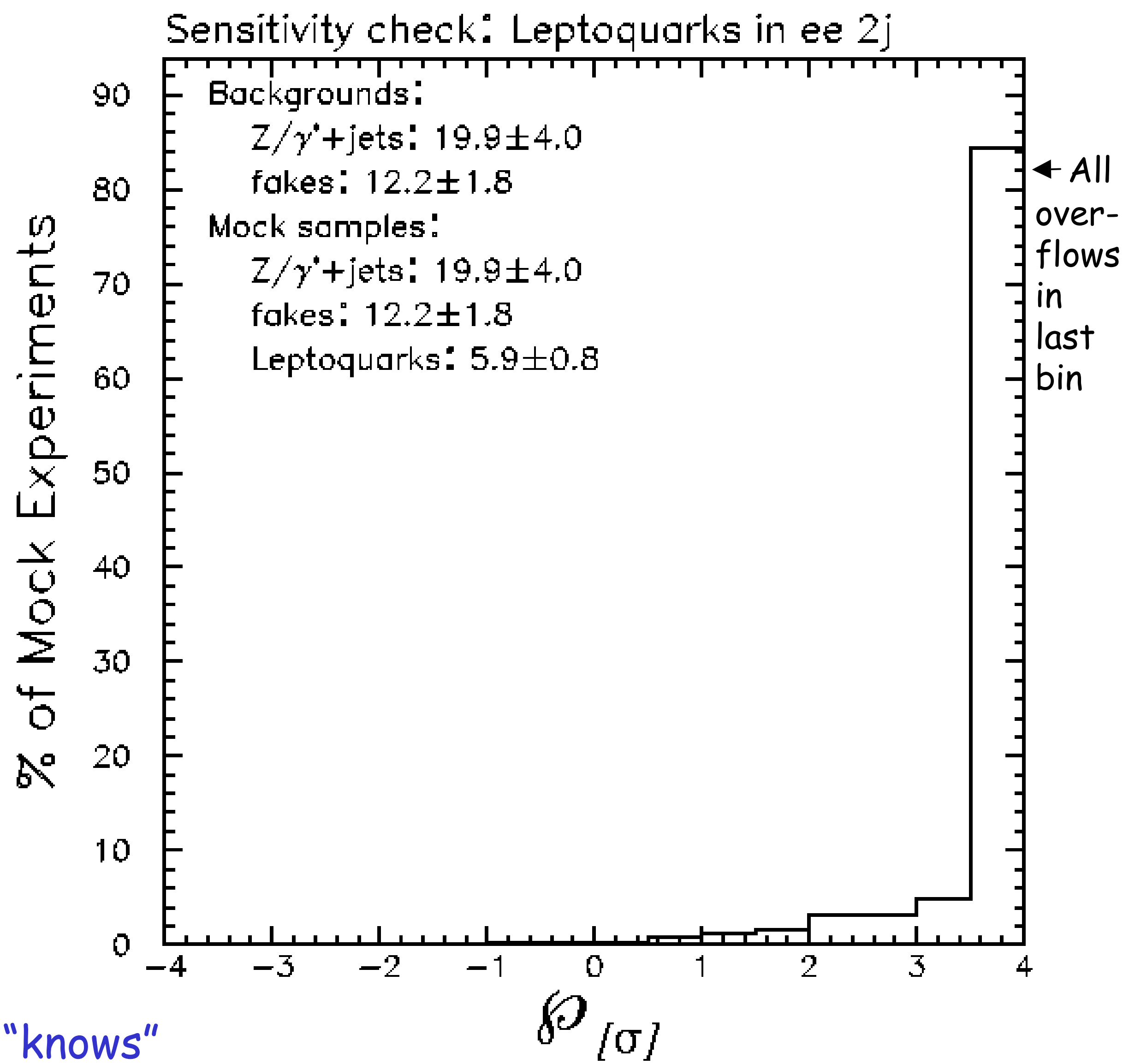
Sensitivity check: Leptoquarks in eejj

We can run mock experiments with hypothetical signals, too

What if our data contained leptoquarks?

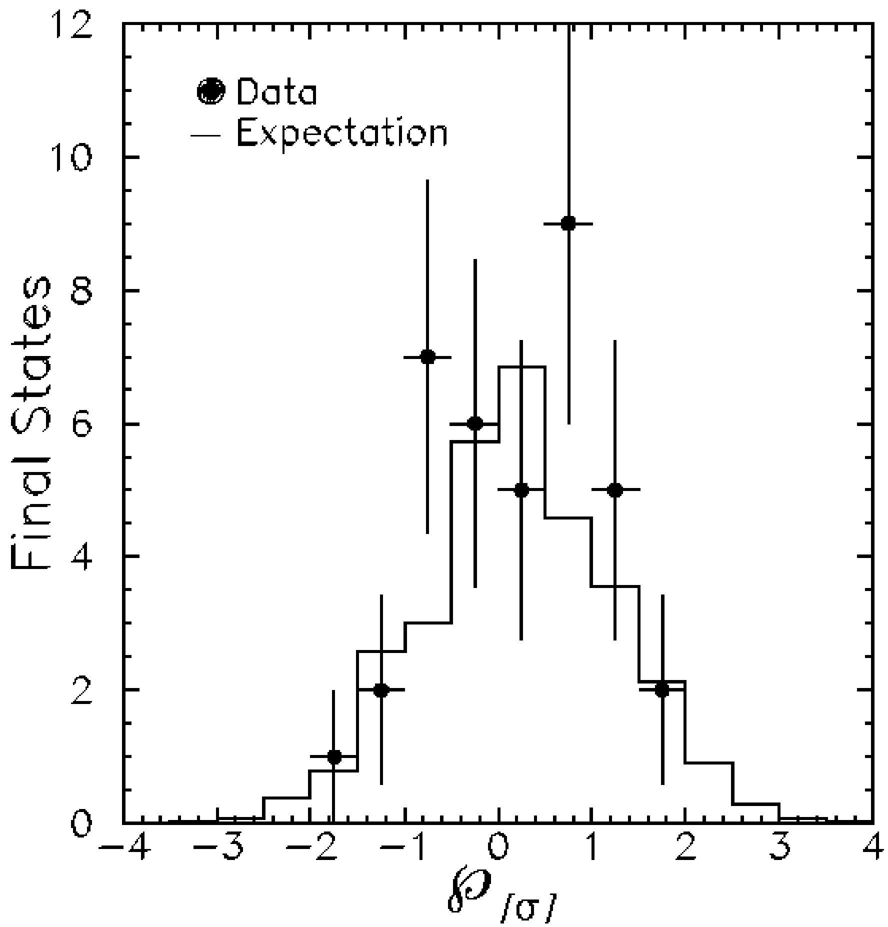
(Assume scalar, β = 1, m_{LQ} = 170 GeV)

Sherlock finds $\mathcal{P}$ > 3.5σ in > 80% of the mock experiments



(Remember that Sherlock "knows" nothing about leptoquarks!)

Results DØ data



Results agree well with expectation

No evidence of new physics is observed

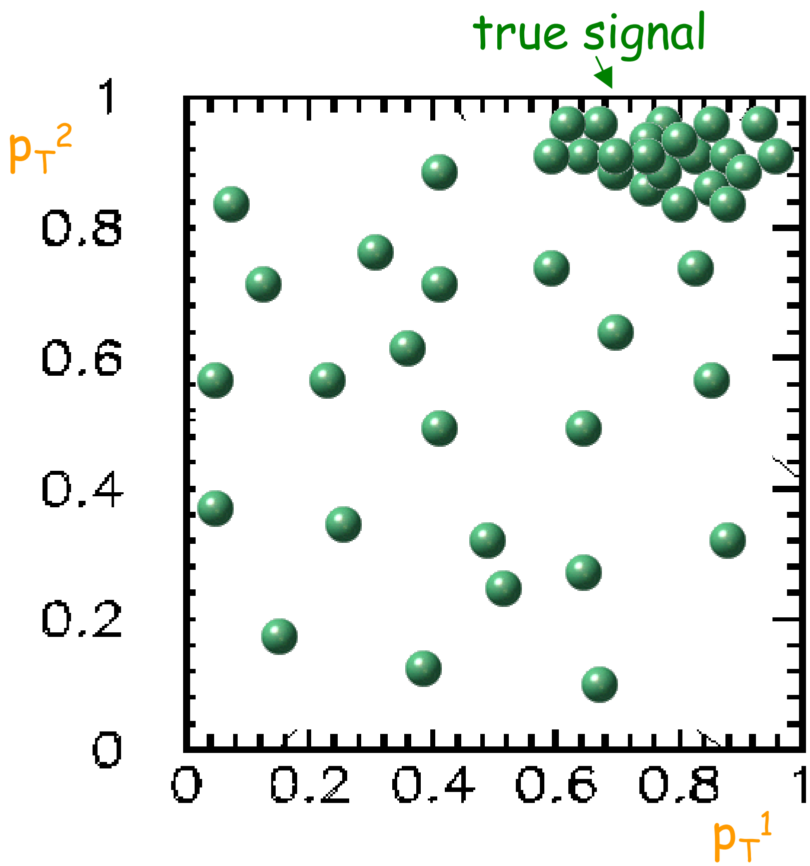
Data set	$\mathcal{P}$
$e\mu X$	
$e\mu \not{E}_T$	0.14 (+1.08σ)
$e\mu \not{E}_T j$	0.45 (+0.13σ)
$e\mu \not{E}_T\, 2j$	0.31 (+0.50σ)
$e\mu \not{E}_T\, 3j$	0.71 (−0.55σ)
W+jets-like	
$W\, 2j$	0.29 (+0.55σ)
$W\, 3j$	0.23 (+0.74σ)
$W\, 4j$	0.53 (−0.08σ)
$W\, 5j$	0.81 (−0.88σ)
$W\, 6j$	0.22 (+0.77σ)
$e\not{E}_T\, 2j$	0.76 (−0.71σ)
$e\not{E}_T\, 3j$	0.17 (+0.95σ)
$e\not{E}_T\, 4j$	0.13 (+1.13σ)
Z+jets-like	
$Z\, 2j$	0.52 (−0.05σ)
$Z\, 3j$	0.71 (−0.55σ)
$Z\, 4j$	0.83 (−0.95σ)
$ee\, 2j$	0.72 (−0.58σ)
$ee\, 3j$	0.61 (−0.28σ)
$ee\, 4j$	0.04 (+1.75σ)
$ee\not{E}_T\, 2j$	0.68 (−0.47σ)
$ee\not{E}_T\, 3j$	0.36 (+0.36σ)
$ee\not{E}_T\, 4j$	0.06 (+1.55σ)
$\mu\mu\, 2j$	0.08 (+1.41σ)
$(\ell/\gamma)(\ell/\gamma)(\ell/\gamma)X$	
eee	0.89 (−1.23σ)
$Z\gamma$	0.84 (−0.99σ)
$Z\gamma j$	0.63 (−0.33σ)
$ee\gamma$	0.88 (−1.17σ)
$ee\gamma\not{E}_T$	0.23 (+0.74σ)
$e\gamma\gamma$	0.66 (−0.41σ)
$e\gamma\gamma j$	0.21 (+0.81σ)
$e\gamma\gamma\, 2j$	0.30 (+0.52σ)
$W\gamma\gamma$	0.18 (+0.92σ)
$\gamma\gamma\gamma$	0.41 (+0.23σ)
$\tilde{\mathcal{P}}$	0.89 (−1.23σ)

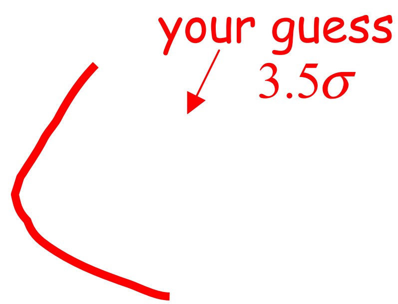
The nature of the problem

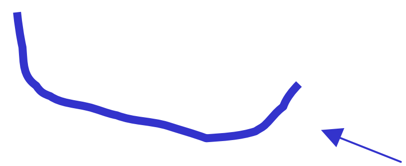
If we continue to pursue specific searches, how might a discovery look?

Remember that you will guess wrong

But let's say that you are very lucky and guess close




your guess
3.5σ

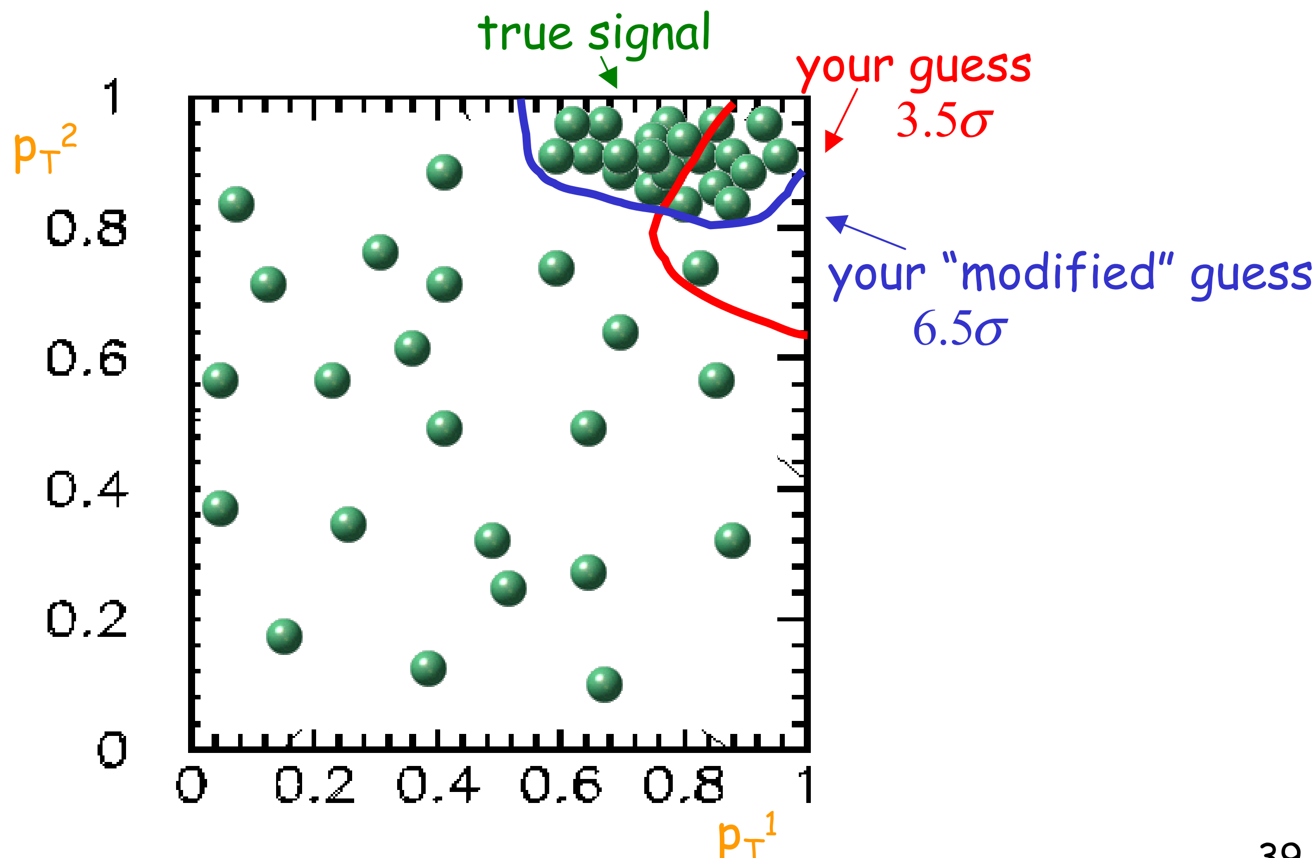


(to be overlayed)

The nature of the problem

How do you interpret this? Would anybody believe you?

Moral: Any "successful" dedicated search is almost bound to end up in a set of highly sculpted cuts, since your original guess is bound to be wrong.



The nature of the problem — the bane of dedicated searches

Compare this to the following scenario:

"Our analysis method was prescribed before data-taking began

The method produces one number ($\widetilde{\mathcal{P}}$) — "the fraction of hypothetical similar experimental runs that would have produced something more interesting than the most interesting thing observed"

We find $\widetilde{\mathcal{P}} = 5\sigma$ (or whatever)"

Which do you find to be the more convincing line of reasoning?

Conclusions

- **Sleuth** is a quasi-model-independent search strategy for new high p_T physics
  - Defines final states and variables
  - Systematically searches for and quantifies regions of excess
- **Sleuth** allows an *a posteriori* analysis of interesting events
- **Sleuth** appears sensitive to new physics . . .
- . . . but finds no evidence of new physics in DØ data
- **Sleuth** has the potential for being an extremely useful tool
  - **Looking forward to Run II!**

hep-ex/0006011 PRD
hep-ex/0011067 PRD
hep-ex/0011071 PRL