Sleuthing

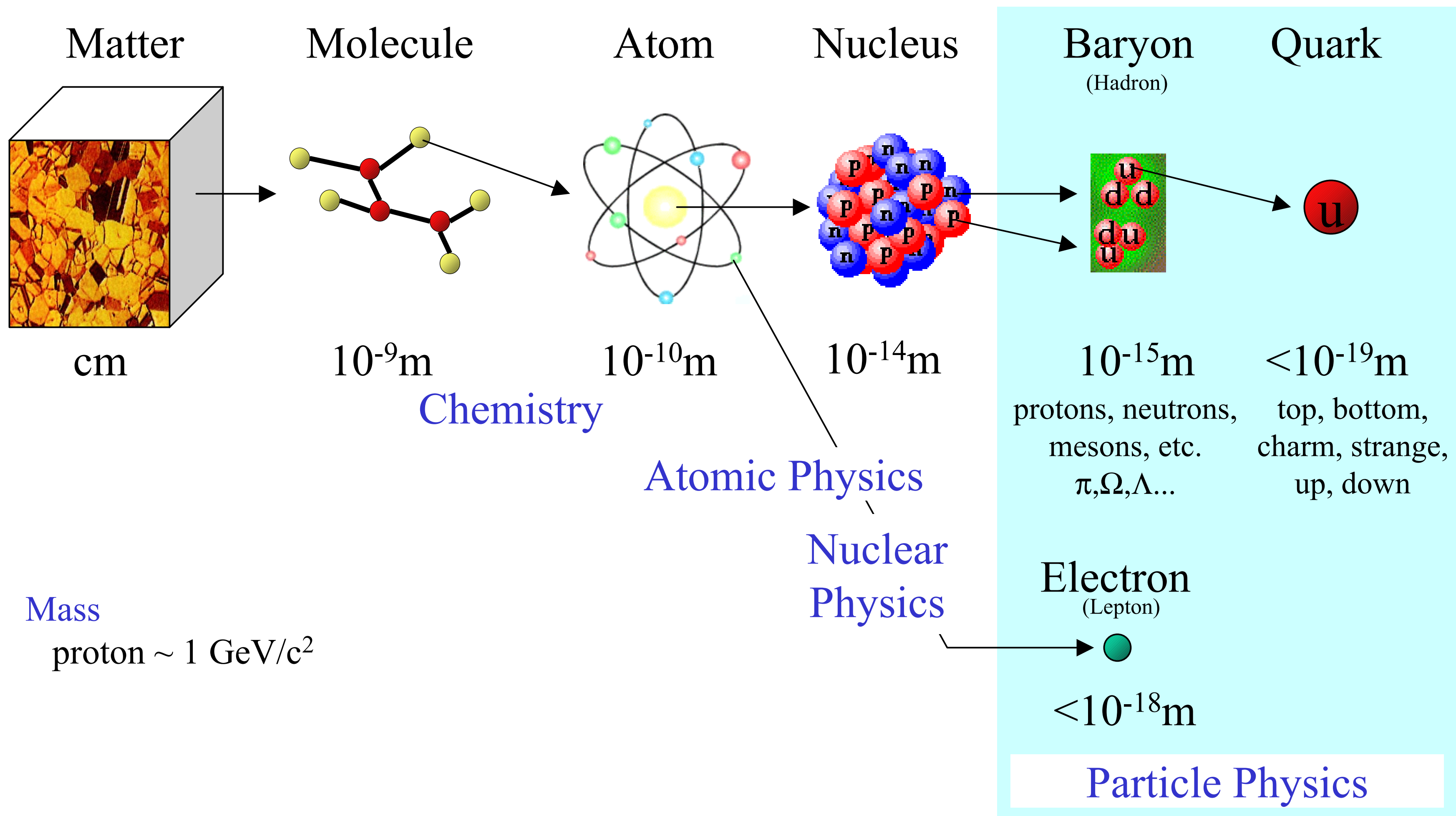
for physics beyond the Standard Model

The state of high energy physics

The nature of the problem

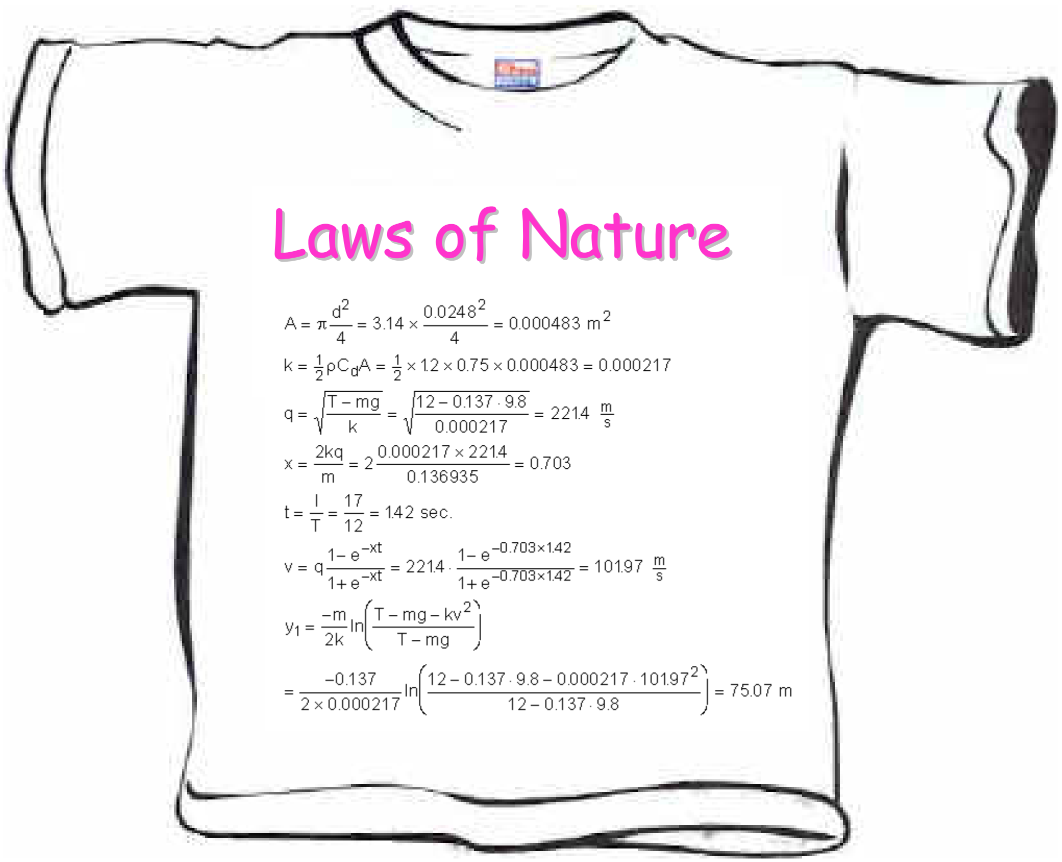
Sleuth

Bruce Knuteson
Berkeley/Chicago



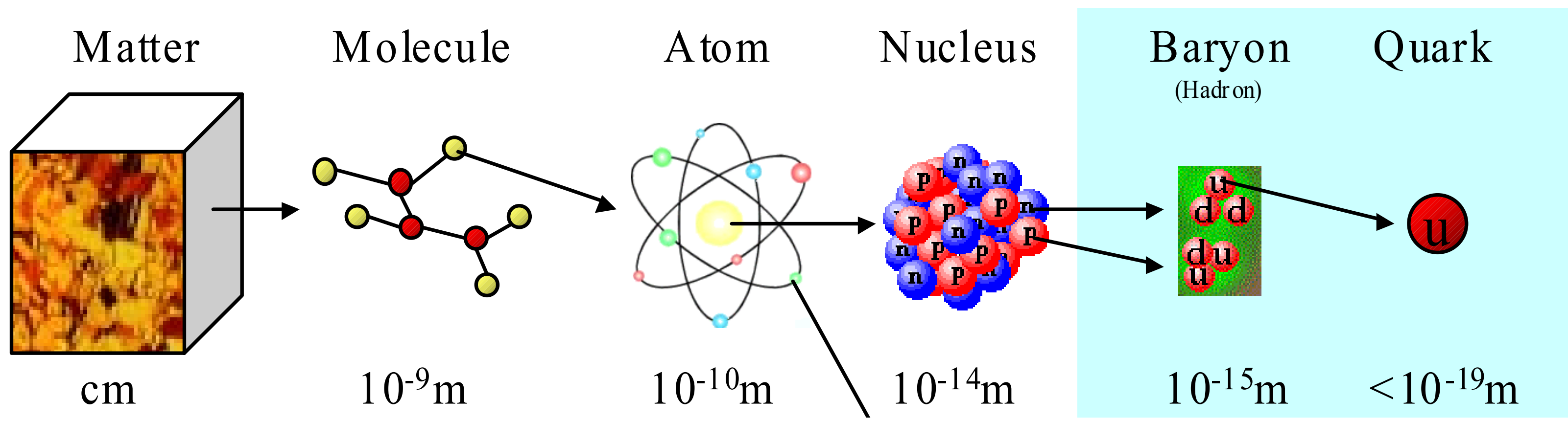
Mass
proton ~ 1 GeV/c^2

What are the goals of particle physics?

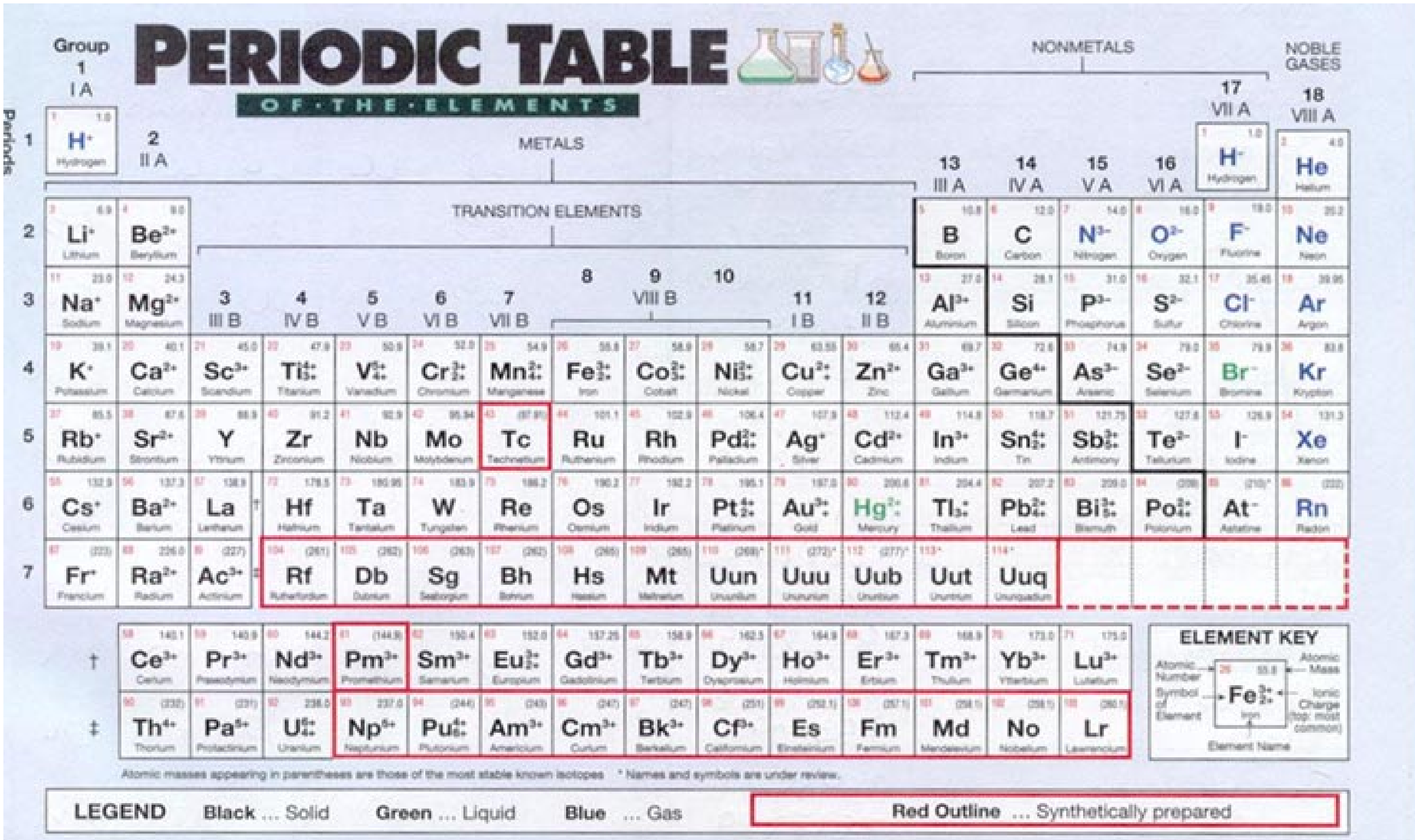


We try to express these laws in terms of
fundamental actors ("things", "objects")
matter
and their (inter)actions ("behaviors")
forces

What is taken to be "fundamental" depends crucially on scale



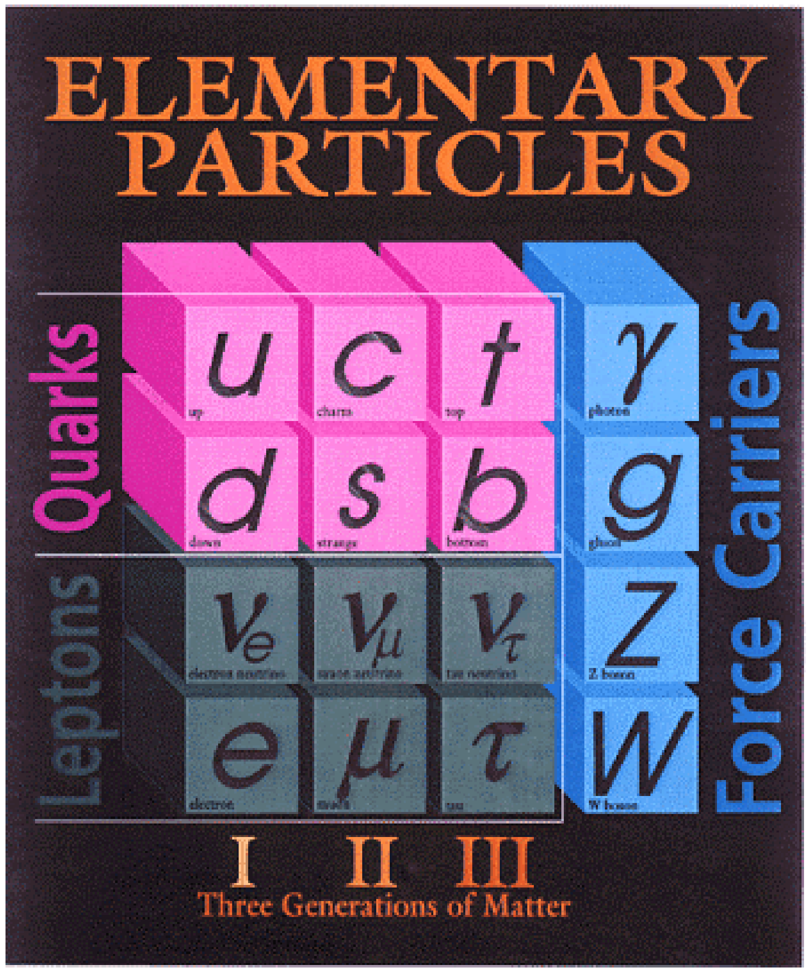
At scales of ≈ 1 nm, we have a large cast . . .



(Periodicity hints at an underlying simplicity?)

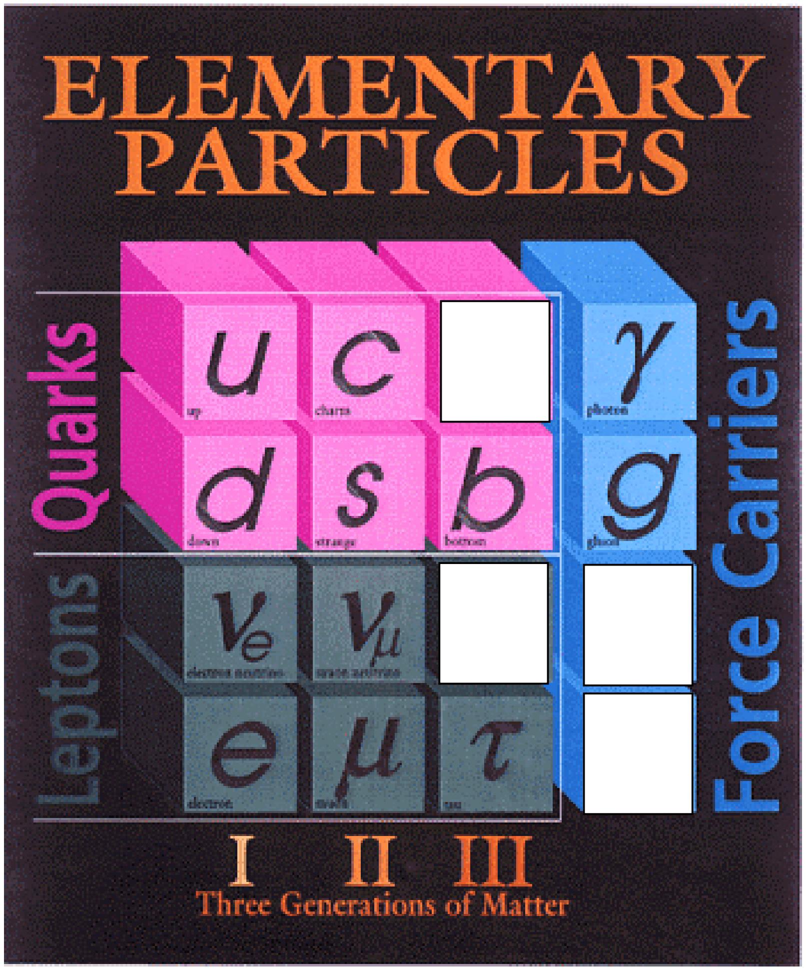
At scales of ≈ 1 am, we have a different picture

The Standard Model



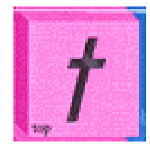
(Periodicity hints at an underlying simplicity?)

In 1980, the Standard Model looked like this:

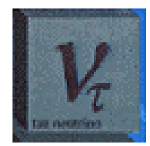


But there was strong evidence favoring the existence of 

(Discovered at CERN in 1983)

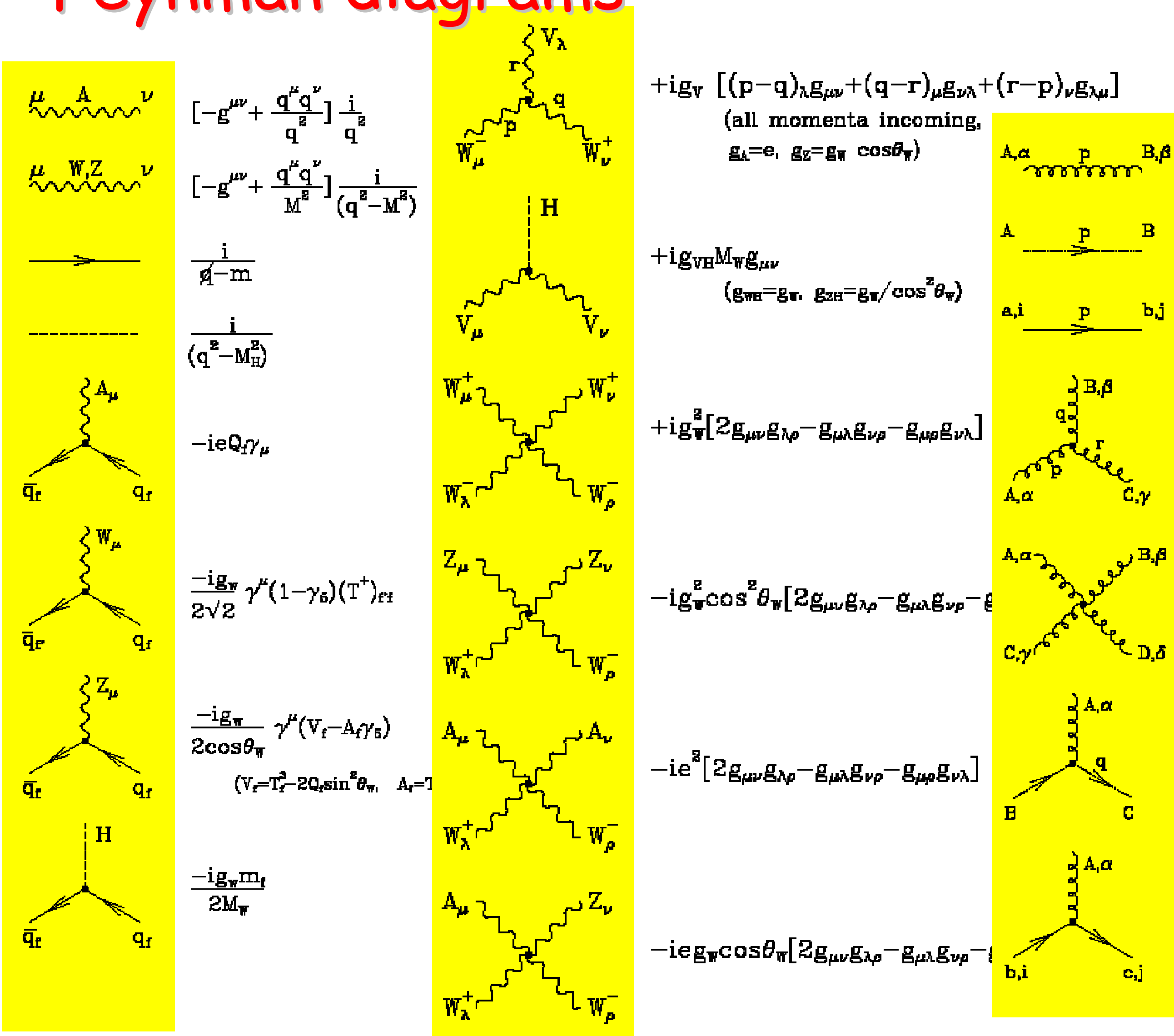
as well as 

(Discovered at Fermilab in 1995)

and 

(Direct observation at Fermilab in 2000)

We can understand interactions with Feynman diagrams



So . . . is that it? Are we done?

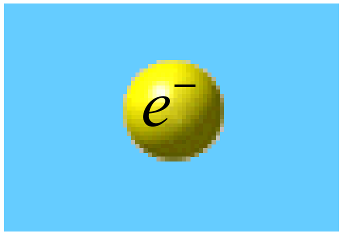
After all, if the next "interesting" distance scale is much smaller than we can ever hope to probe experimentally, what's the point?

The chances that the next interesting distance (energy) scale is "right around the corner" must be tiny, right?

Wrong!

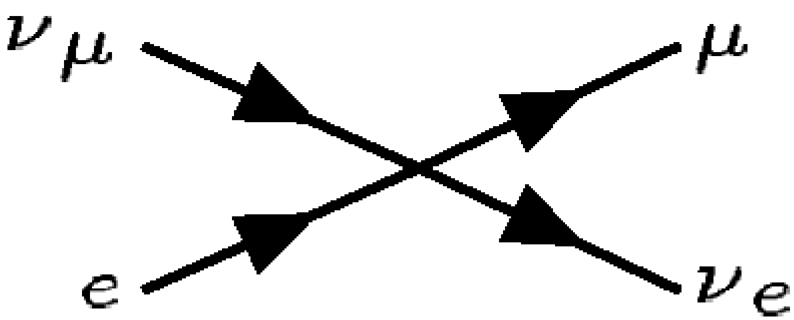
There must be something more than the model I have just described, because this model makes unphysical predictions at energy scales of $\approx$ 1 TeV

(In much the same way that classical electrodynamics predicts its own demise with an infinite electron self-energy)



Let's see how this happens . . .

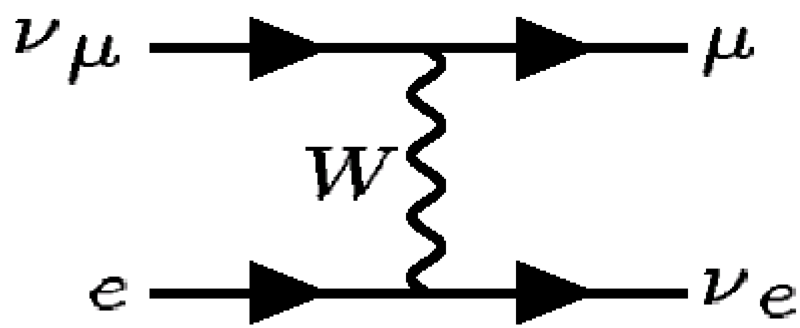
Fermi theory of the 1930's



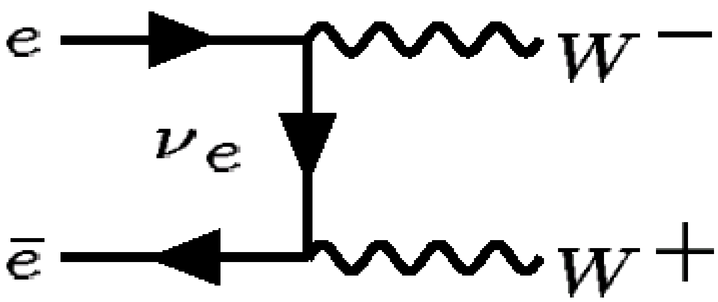
This process violates unitarity at high energies

What do we do?

Modify the diagram to cancel the divergence



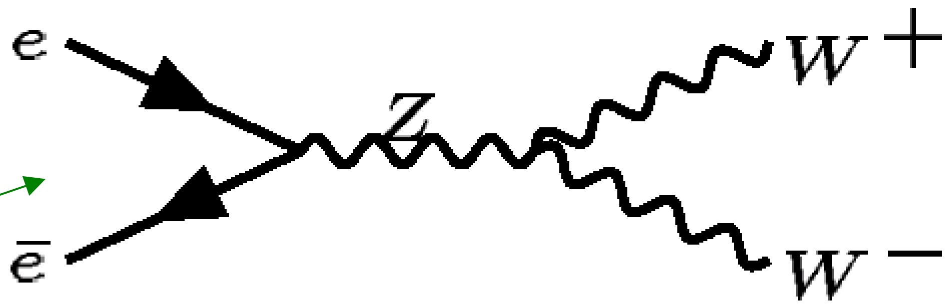
the W boson



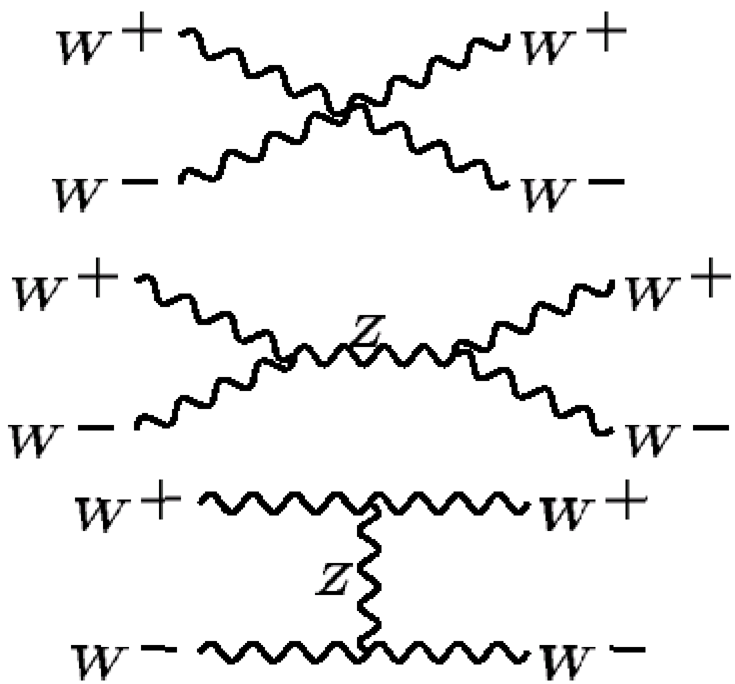
But now this process violates unitarity at high energies!

What do we do?

Introduce another diagram that cancels the divergence



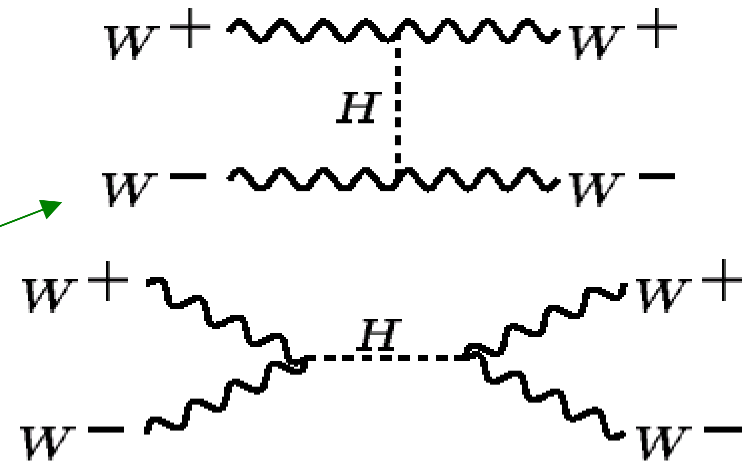
the Z boson



But now these processes violate unitarity at high energies!

What do we do?

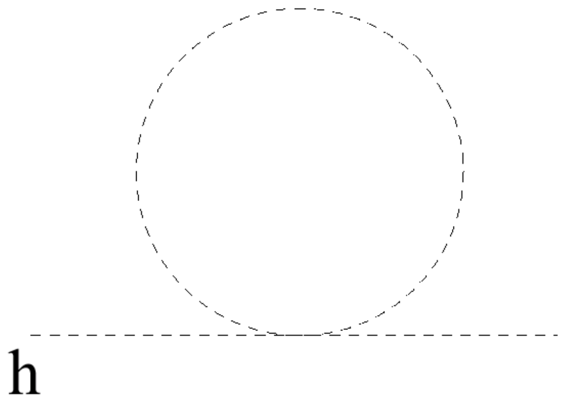
Introduce other diagrams to cancel the divergence



the Higgs boson

Thus far we have no direct evidence for the Higgs boson*

but let's keep going:



If the Higgs exists, this process violates unitarity at high energies unless a parameter is "unnaturally" fine-tuned ("fine-tuning problem")

What do we do?

Introduce other diagrams to cancel the divergence without fine-tuning →

- supersymmetry
- strong dynamics
- extra dimensions

Logically, the possible options now are:

a) A Higgs-like field does not exist

  $\rightarrow \exists$ other interesting physics at $\approx$ 1 TeV

b) A Higgs-like field does exist

  i) A parameter is tuned to 1 part in 10^{16}

    $\rightarrow$ No need for new physics at $\approx$ 1 TeV

  ii) The parameter is not tuned to 1 part in 10^{16}

    $\rightarrow \exists$ other interesting physics at $\approx$ 1 TeV

(Hence the excitement!)

The Fermilab Tevatron Collider

1992-95

Run 1: 100 pb^{-1}, 1.8TeV

Major detector upgrades ← now

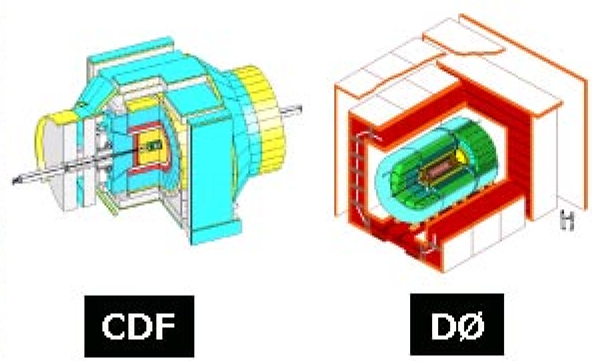
2001-03

Run 2a: 2 fb^{-1}, 1.96 TeV

Short shutdown to install new silicon

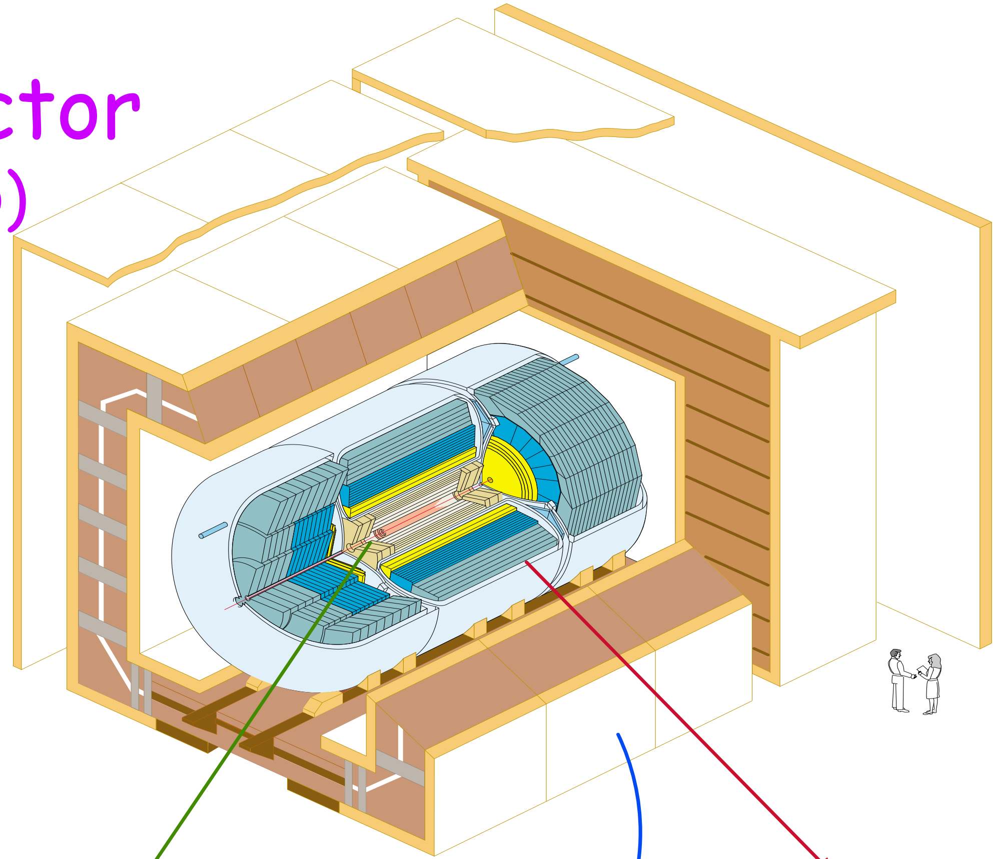
2003-07(?)

Run 2b: ~ 15 fb^{-1}



Run I detector
(1992-1995)

- Multipurpose detector
  - central tracking
  - muon spectrometer
  - U-LAr sampling calorimeter



TRACKING

σ(vertex)=6 mm
$\sigma(r\phi)$ = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)

MUON

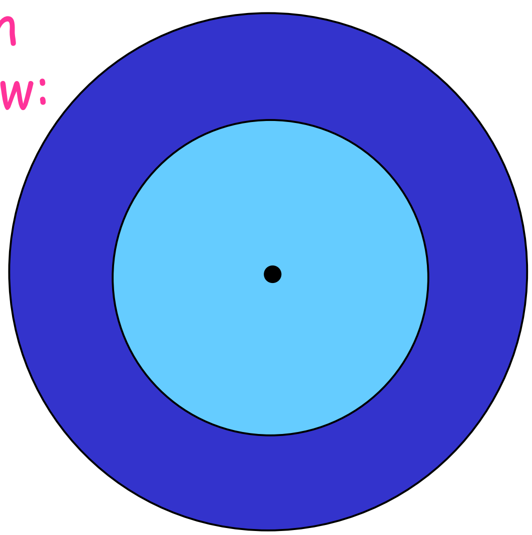
$|\eta| < 3.3$

$\frac{\delta p}{p} = 0.2 \oplus .003p$

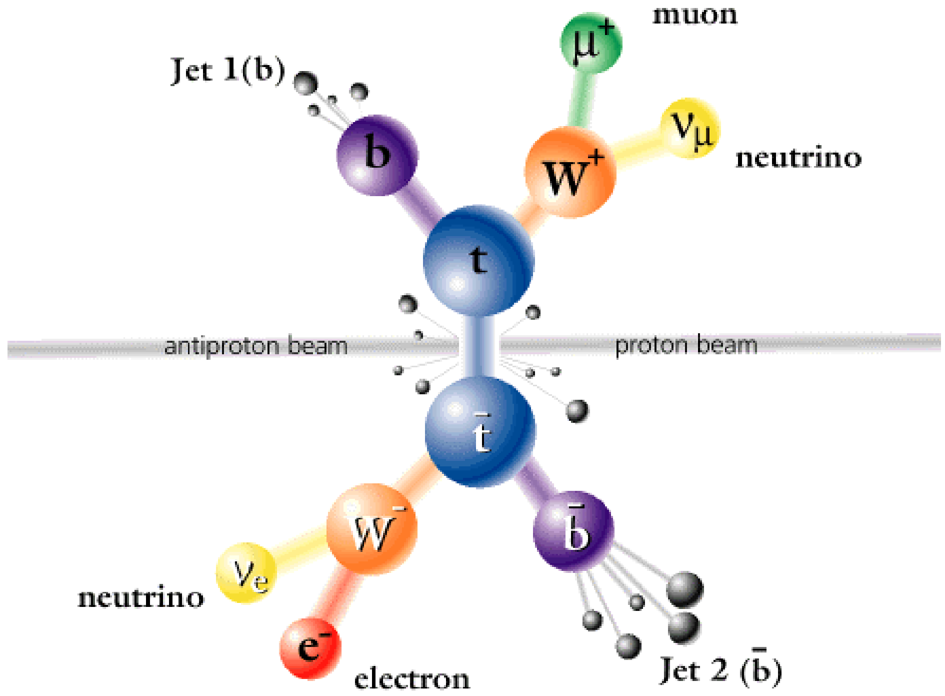
CALORIMETRY

$|\eta|<4$
$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
$\sigma(EM) = 15\%/\sqrt{E}$
$\sigma(HAD) = 50\%/\sqrt{E}$

Cartoon end view:



A cartoon collision (an “event”)



10^{-16} m

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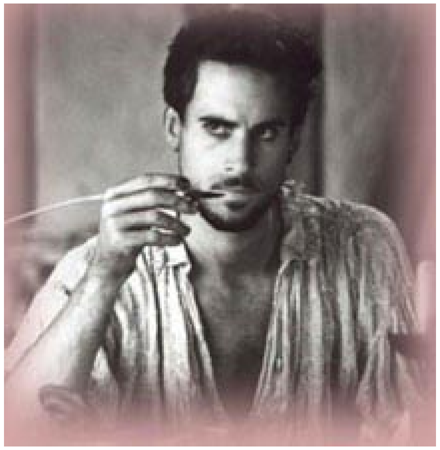
The nature of the problem

Sleuth



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
q[05uy 98ragj a’reoigjfda’ogj98areujgalkjvb ouvba-e09r6n ba[u765bn
45eojrgt;oishp9v8 tu-q0968n-96-439u6 0-b 8n1u6nb 0=5b
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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
09ytpi[45wiy’p52i[0ih0][rshhjgfh 0[9renub0[48nw[0v vc m54w\ \ wnb 1[42
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ggjb ;;lfdshk;hg b;h sp ugbvoirehgorh0-gh-o[4[2whw[ohg pohspohgo gr8n0
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 the document is defined as

$$\sum_{monkey\ phrases} (\#\ \text{of English majors who identify the phrase with Shakespeare})$$

3) 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.

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

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.

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

The state of high energy physics

The nature of the problem

Sleuth

Consider the most recent major discoveries in high energy physics:

- W, Z bosons CERN 1983
- top quark Fermilab 1995
- tau neutrino Fermilab 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)

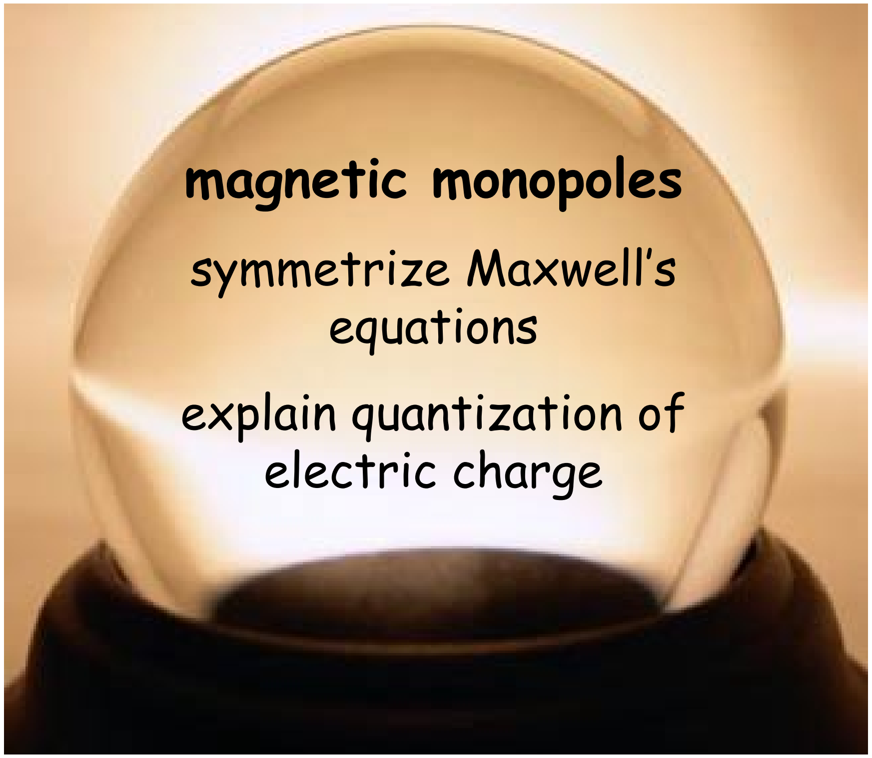
you were willing to bet even odds that the particle existed

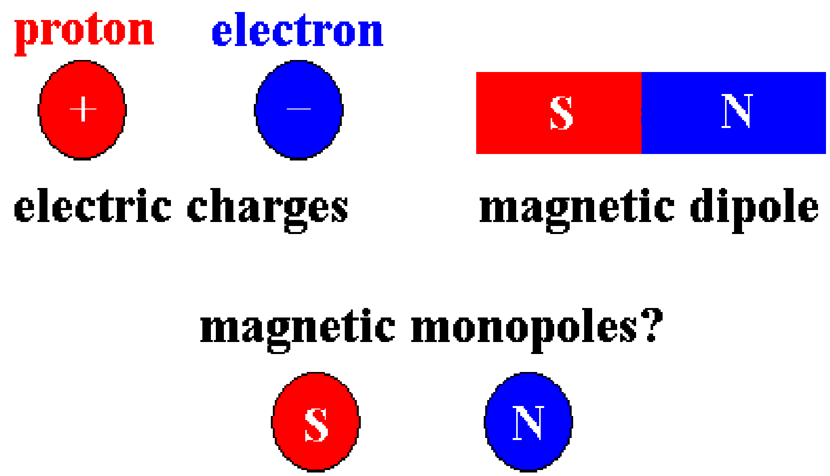
We are now in a qualitatively different situation

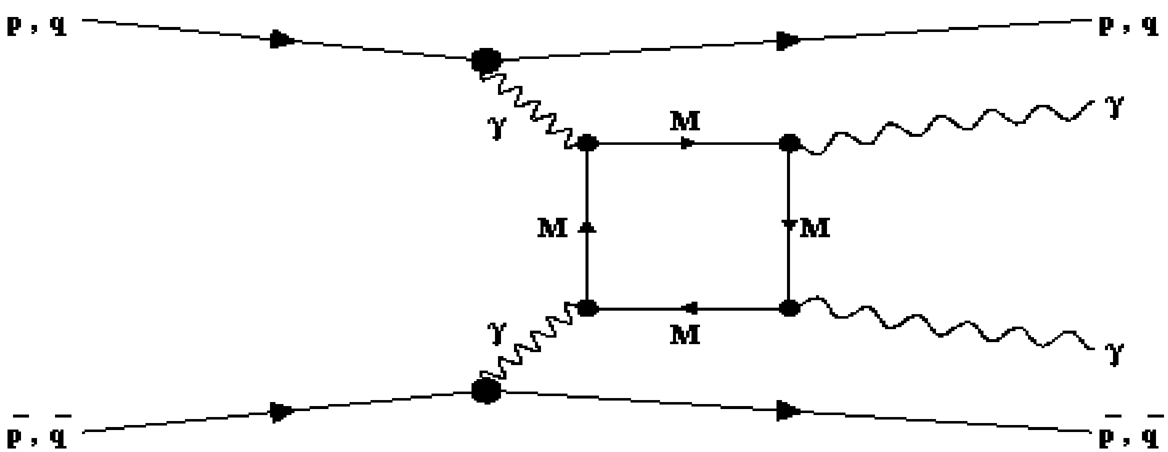
the chance that any particular model on hep-ph is correct is naively ≈ 1/18,948

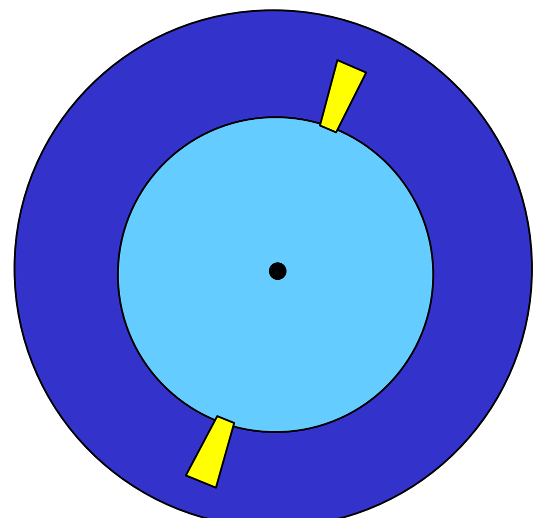
Have you chosen the right one?

(Are you willing to bet your career on it?)

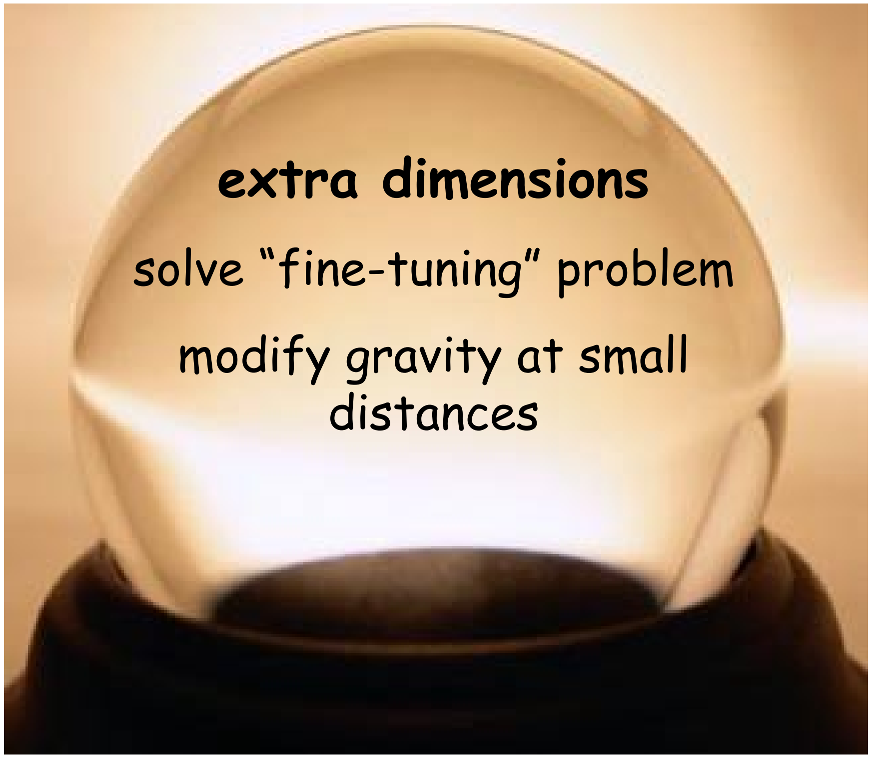

magnetic monopoles
symmetrize Maxwell's equations
explain quantization of electric charge

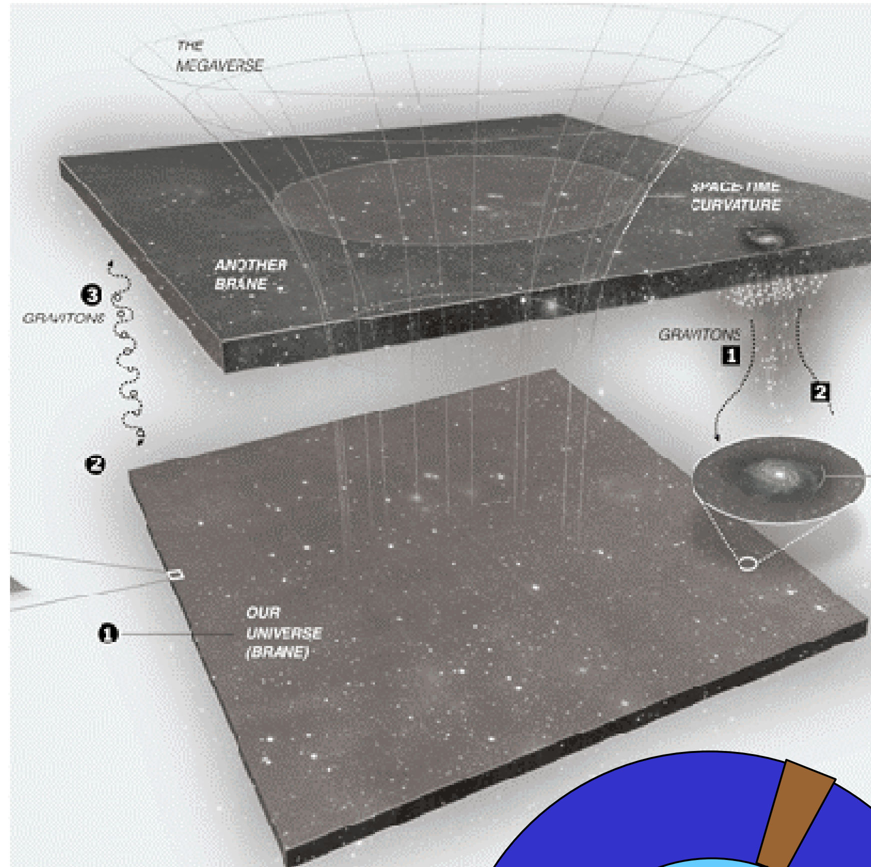

proton
electron
+
−
S
N
electric charges
magnetic dipole
magnetic monopoles?
S
N

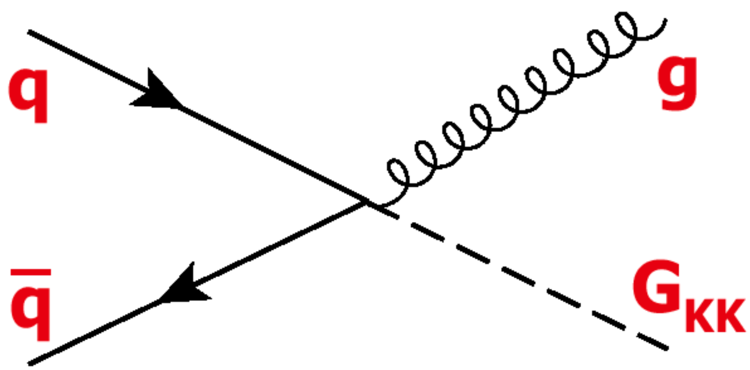

p , q
p , q
γ
M
γ
M
M
γ
M
γ
p̄ , q̄
p̄ , q̄

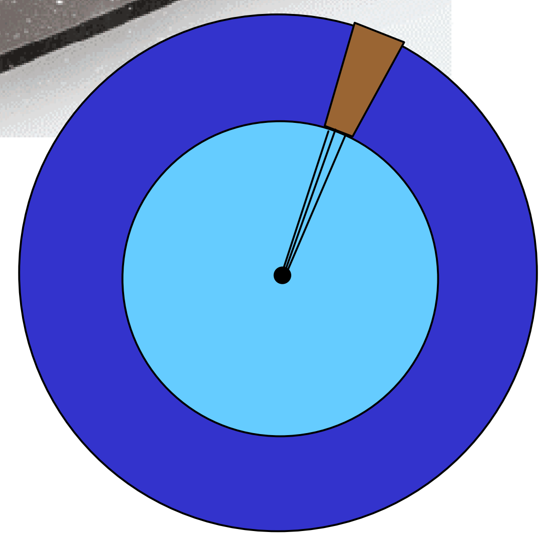


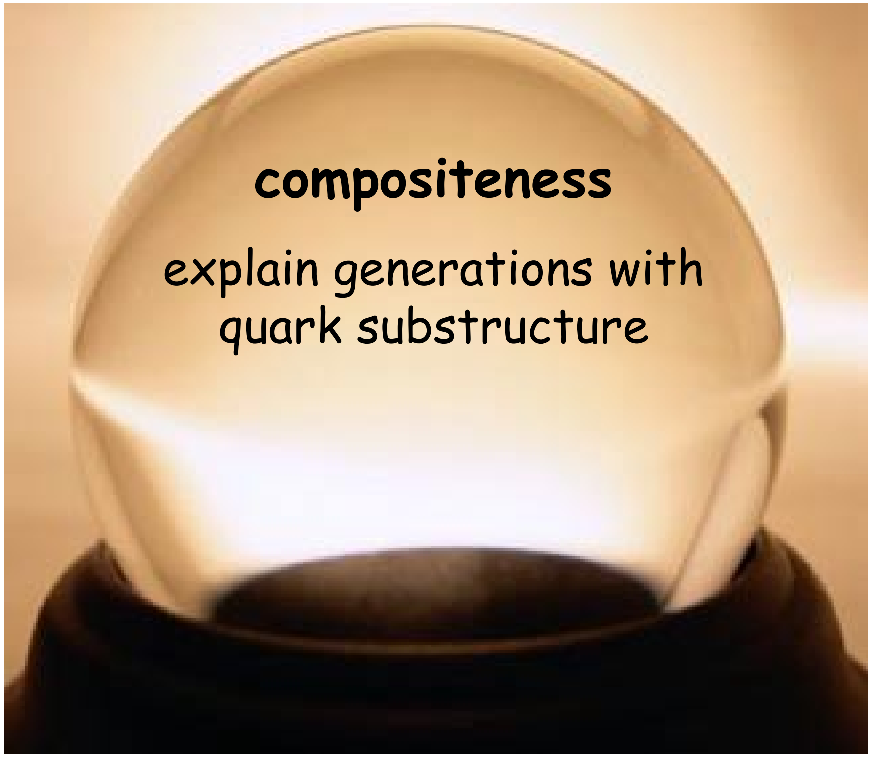
Possible new phenomena

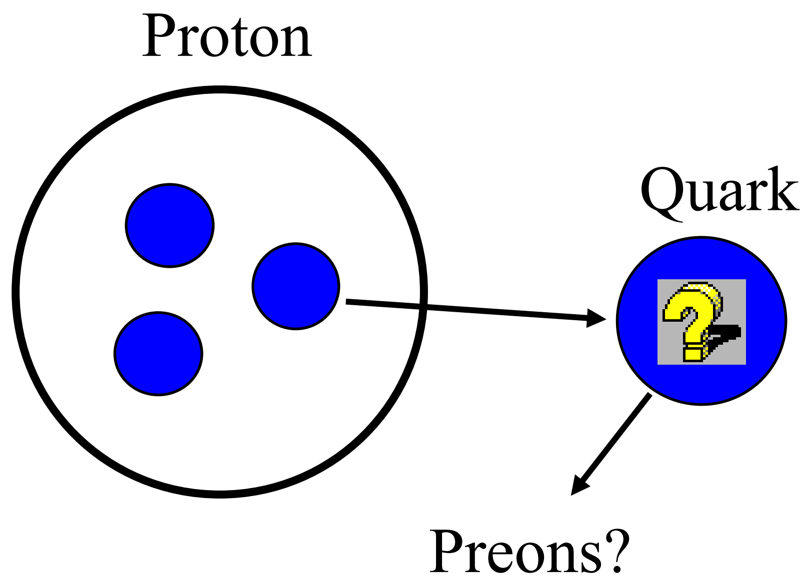


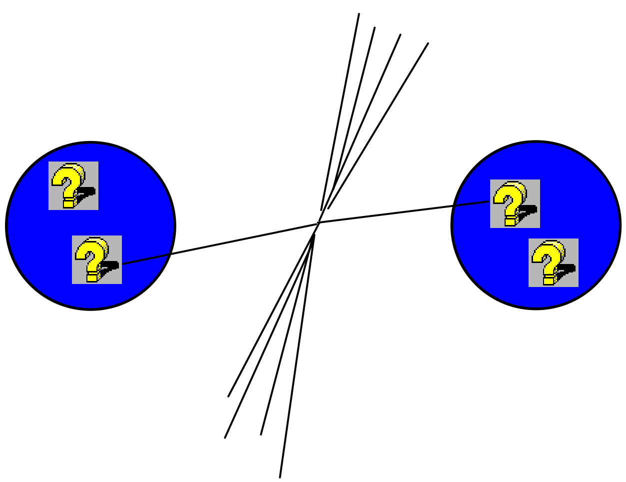


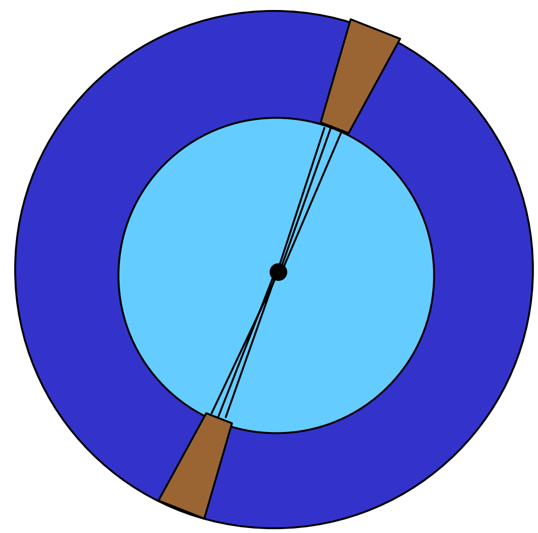


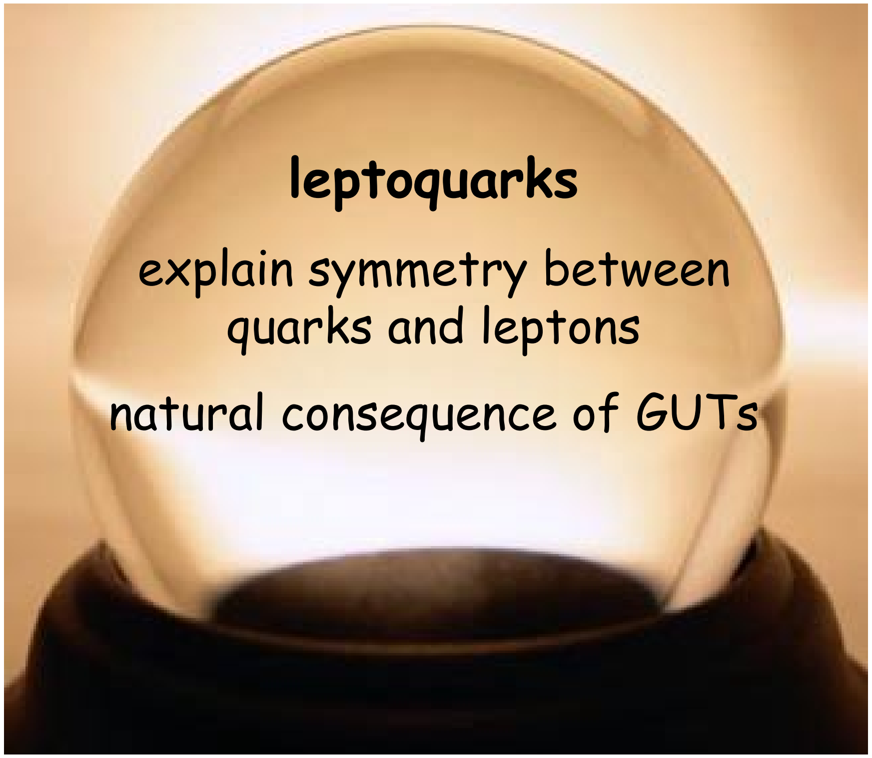



compositeness
explain generations with quark substructure

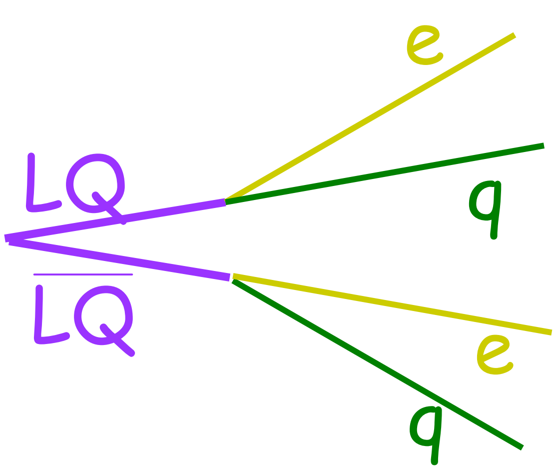

Proton
Quark
Preons?

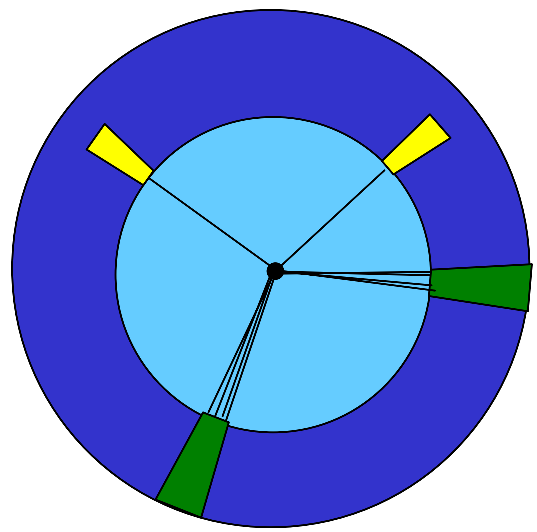




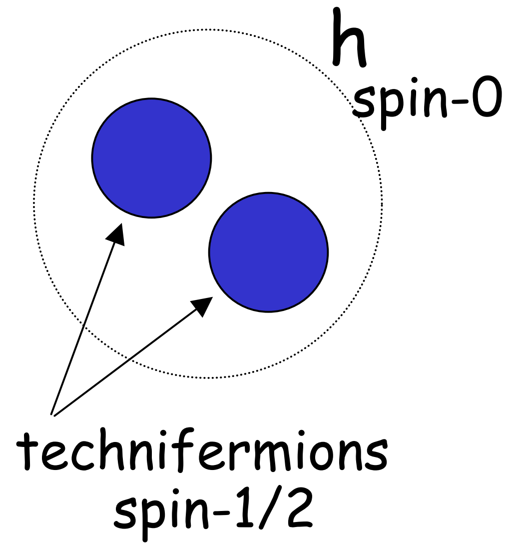

leptoquarks
explain symmetry between quarks and leptons
natural consequence of GUTs


Lepto[redacted]
Quarks
Three Generations of Matter
I
II
III


LQ
$\overline{LQ}$
e
q
e
q




technicolor
explain the Higgs as a fermion condensate
solve the "fine-tuning" problem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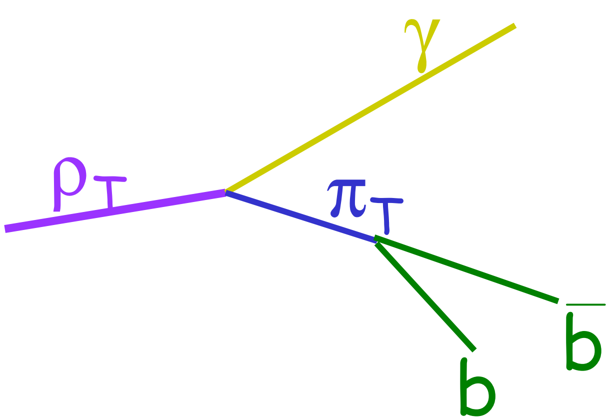
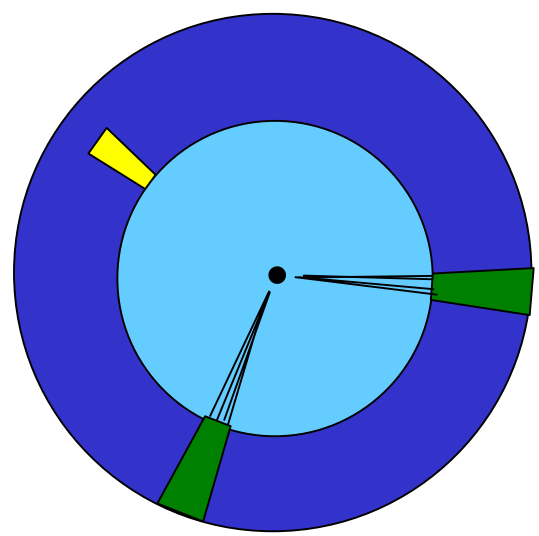
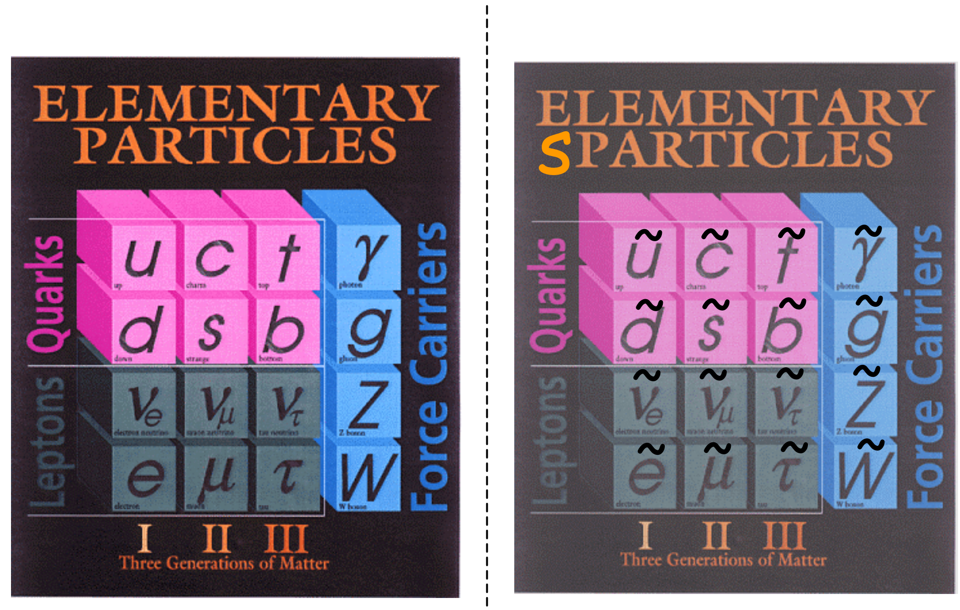
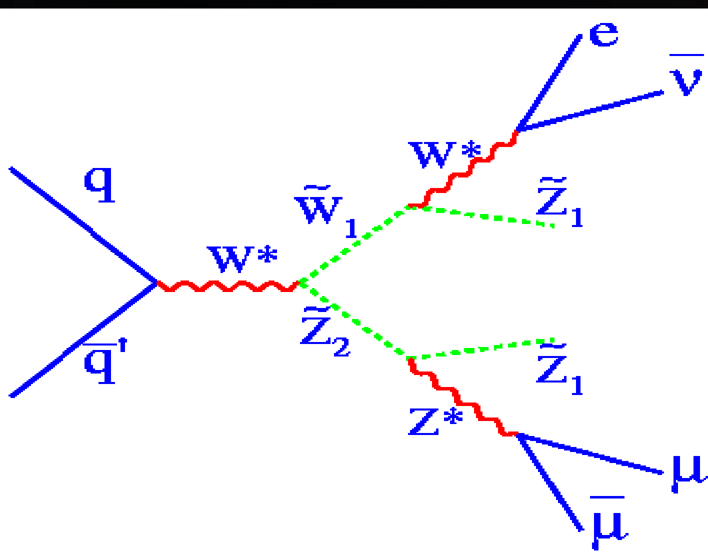
technifermions
spin-1/2

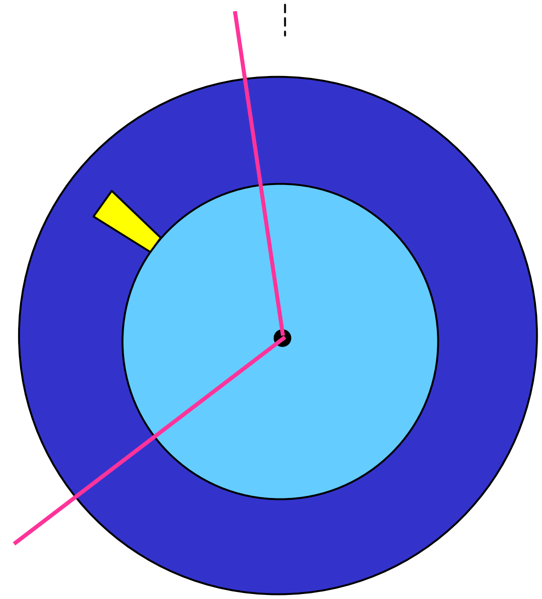

γ
ρT
πT
b
b̄

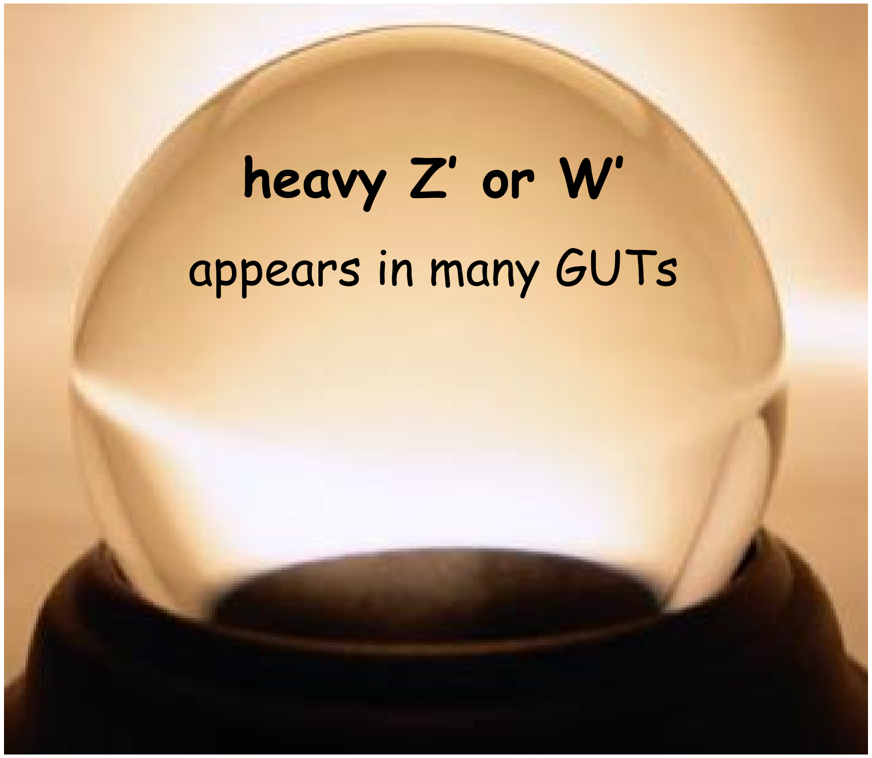



supersymmetry
introduce a symmetry between fermions and bosons
solve the "fine-tuning" problem


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u c t γ
d s b g
νe νμ ντ Z
e μ τ W
I II III
Three Generations of Matter
ELEMENTARY SPARTICLES
Quarks
Leptons
Force Carriers
ũ c̃ t̃ γ̃
d̃ s̃ b̃ g̃
ν̃e ν̃μ ν̃τ Z̃
ẽ μ̃ τ̃ W̃
I II III
Three Generations of Matter

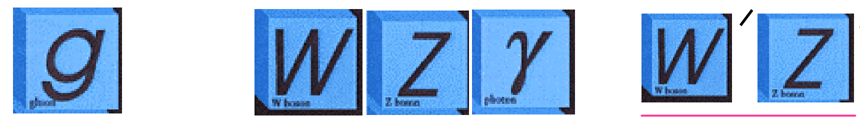

q
q̄'
W*
W̃1
Z̃2
W*
Z̃1
Z̃1
Z*
e
ν̄
μ
μ̄

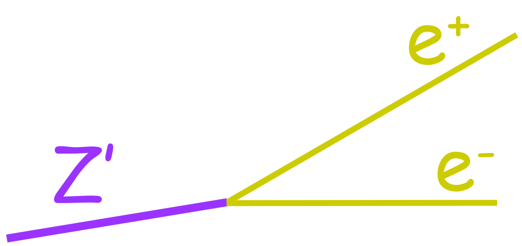


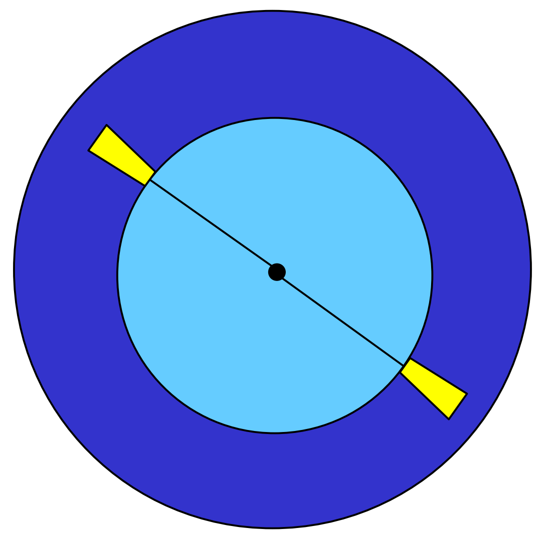


The gauge symmetry of the standard model is:

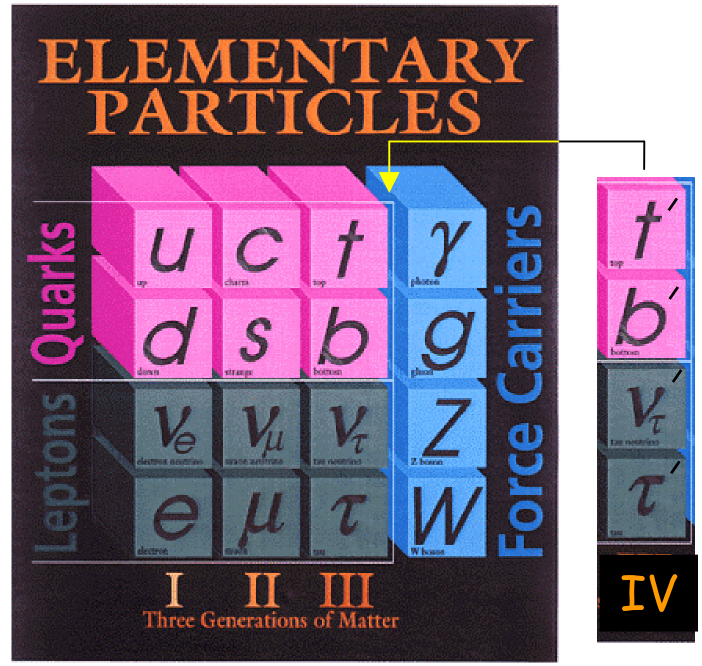
$$SU(3)_{color} \times SU(2)_L \times U(1)_Y \times SU(2)_R \times \ldots$$

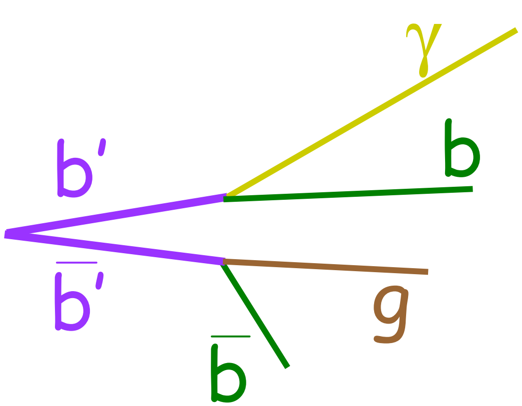


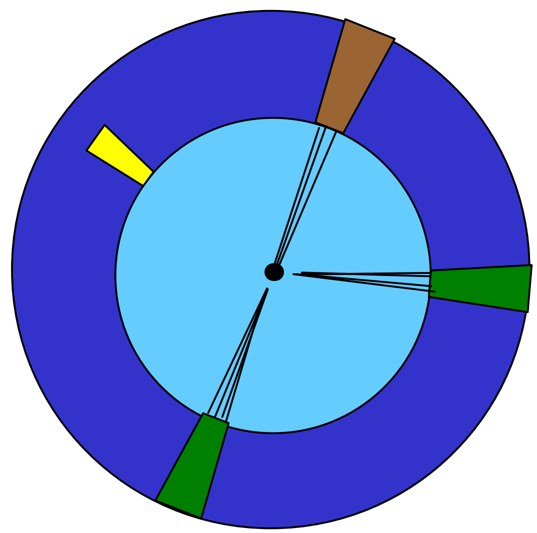




Possible new phenomena





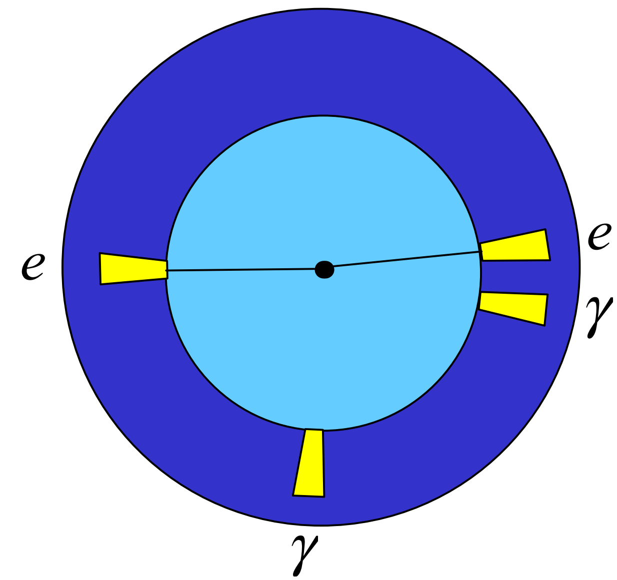


CDF $ee\gamma\gamma\not{E}_T$ Candidate Event

Another related issue:

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

After all, the probability of seeing exactly those events is zero!



How excited should we be?

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

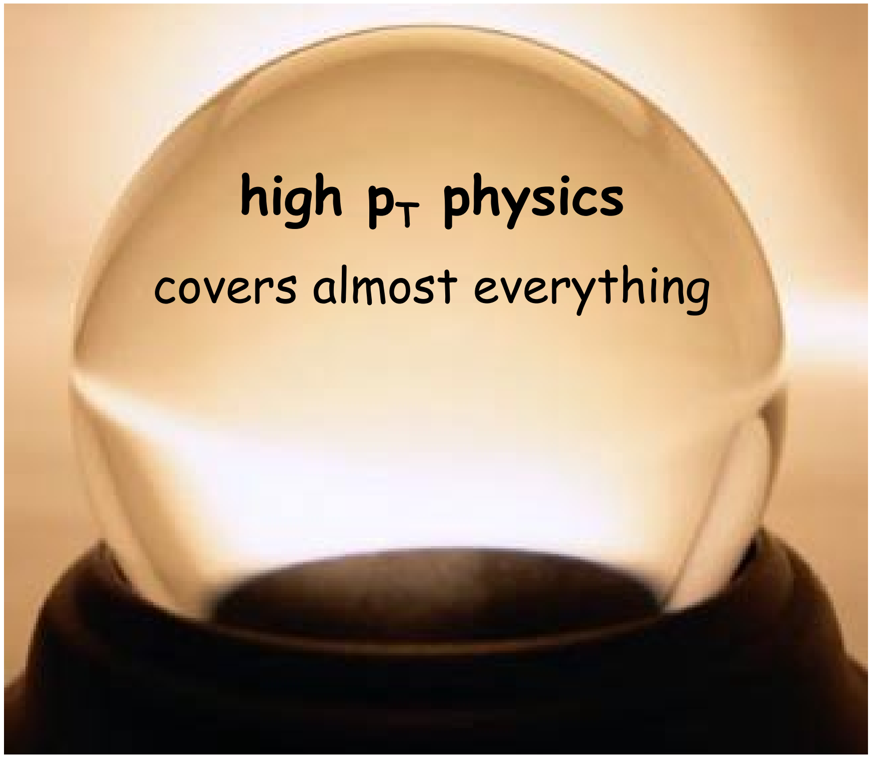
Steps:

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



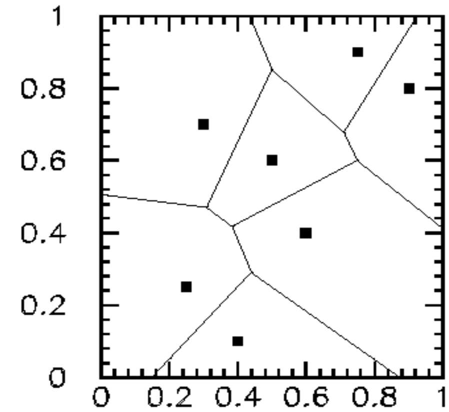
2) Define a (low-dimensional) variable space

Transverse momenta (p_T) of final state objects

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

For each final state . . .

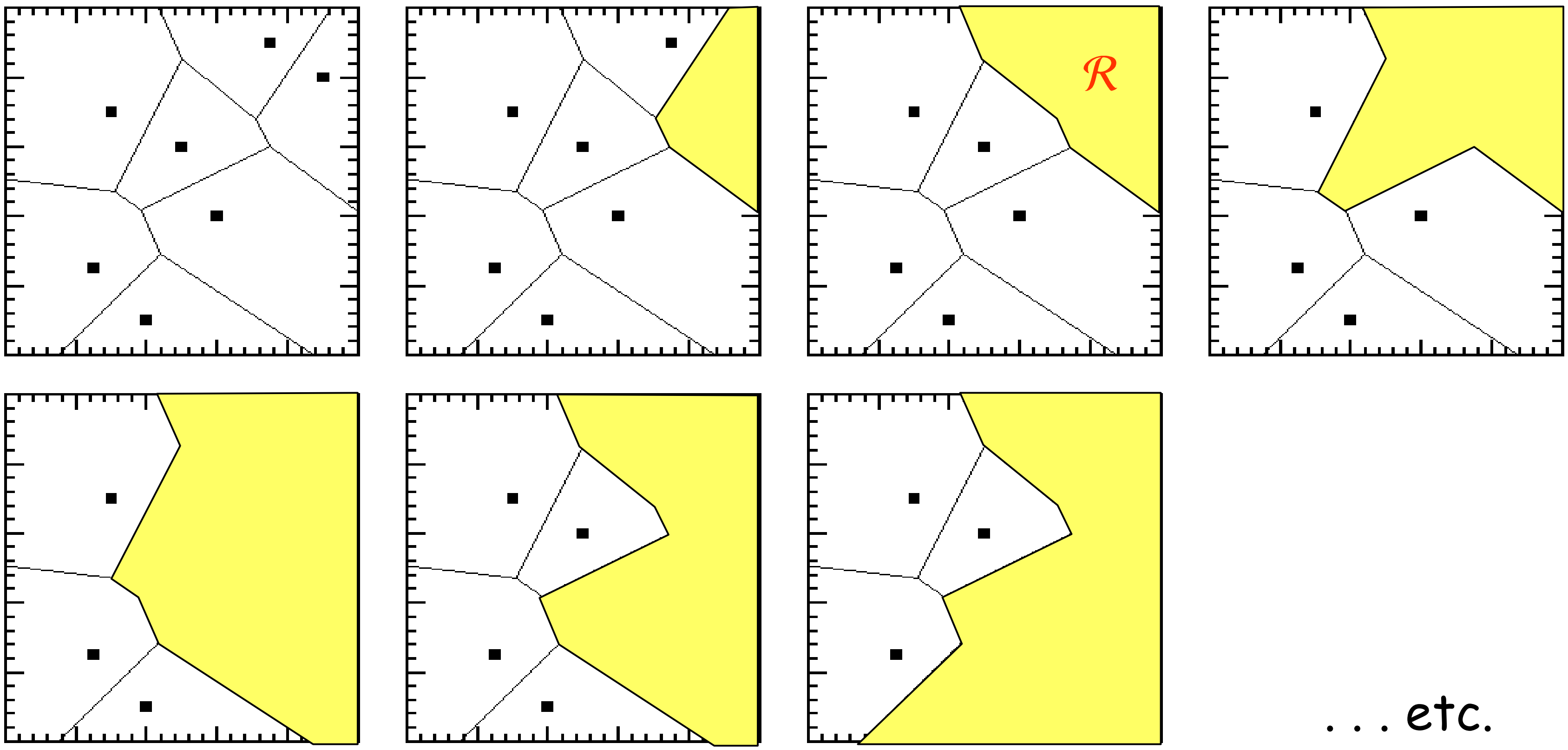
Input: 1 data file, estimated backgrounds



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

We search the space to find the region of greatest excess, $\mathcal{R}$



. . . etc.

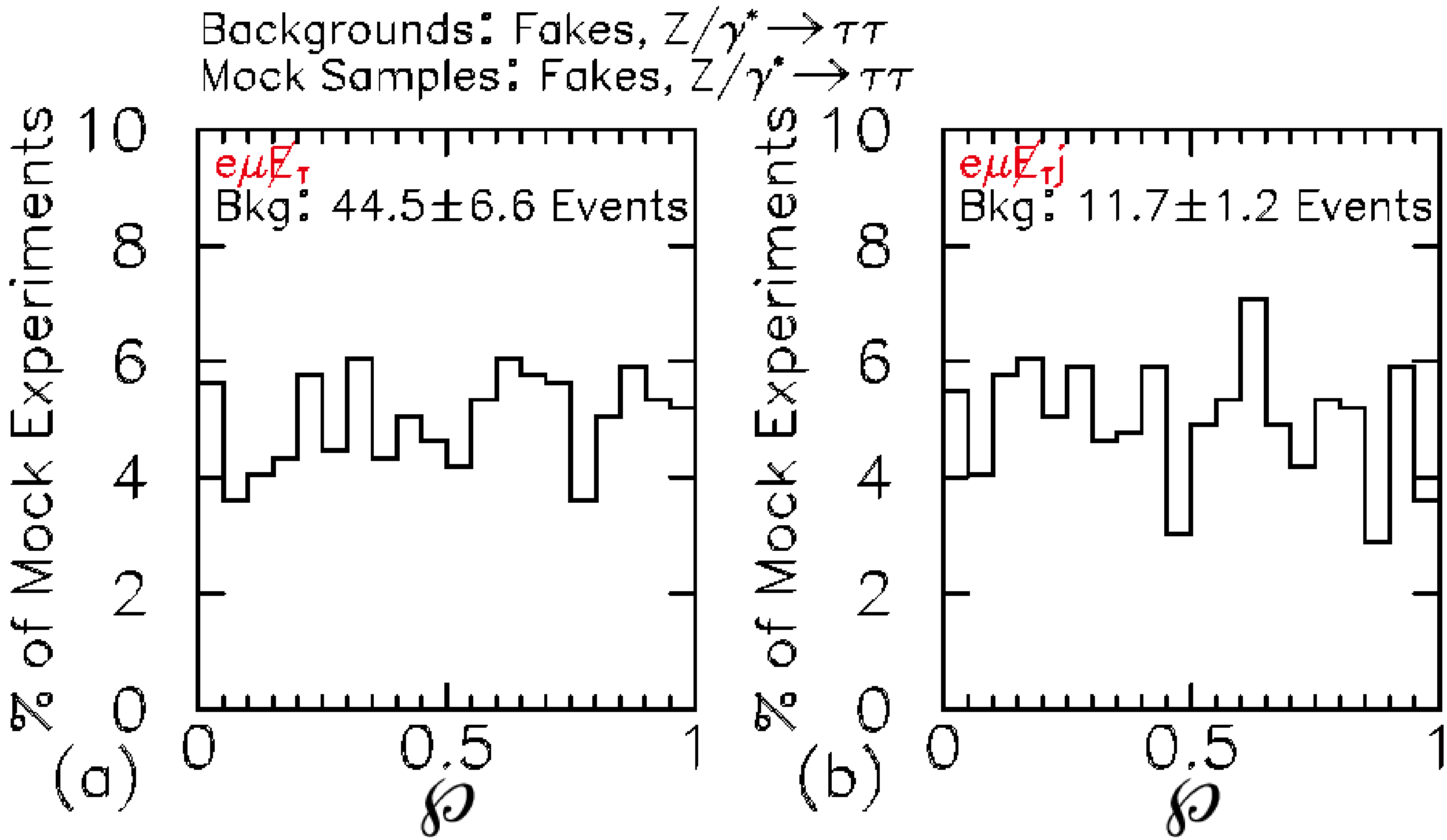
[Analogous to finding the most interesting monkey phrase.]

Perform many hypothetical similar experiments

- generate "data samples" from the background distributions
  - Allow numbers of events from each background source to vary according to statistical and systematic errors
- find the most interesting region in each pseudo sample
  - Use same searching algorithm as for the actual data
- compare the most interesting region in each pseudo sample with $\mathcal{R}$
- Determine $\mathcal{P}$, the fraction of *hypothetical similar experiments* in which you see something more interesting than $\mathcal{R}$

[Analogous to finding the fraction of normal monkeys that would have produced a document as interesting as the one produced by the Shakespeare monkey.]

If a data sample contains background only, $\mathcal{P}$ should be a random number distributed uniformly in the interval (0,1)



If a data sample contains evidence of new physics, we should find $\mathcal{P}$ to be small (close to zero).

$\mathcal{P}$ can be written in terms of standard deviations by solving

$$\mathcal{P} = \frac{1}{\sqrt{2\pi}} \int_{\mathcal{P}_{[\sigma]}}^{\infty} e^{-t^2/2} \, dt$$

for $\mathcal{P}_{[\sigma]}$

Thus $\mathcal{P} = 0.001$ corresponds to ≈ 3 σ . . . and so forth

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?

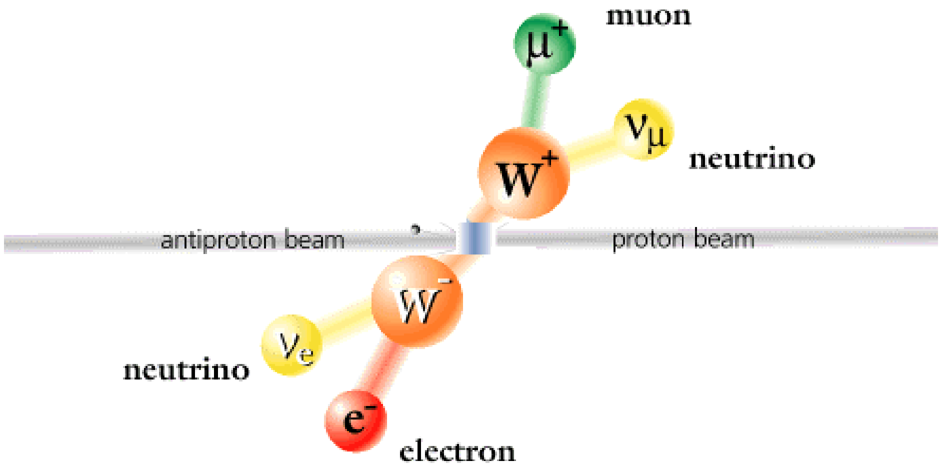
How *sensitive* is Sleuth to new physics?

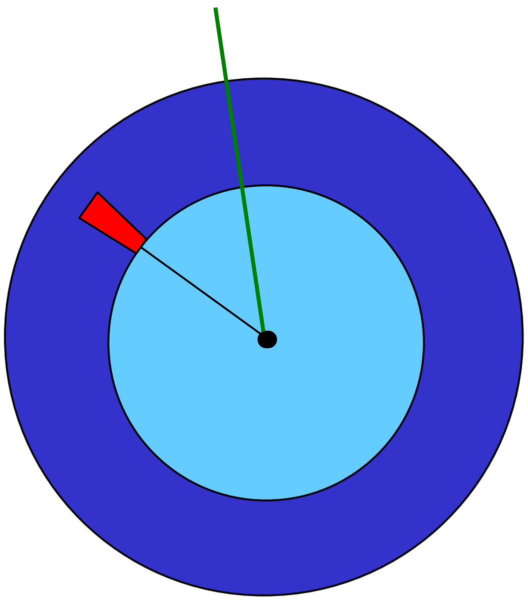
Impossible to answer, in general

(Sensitive to *what* new physics?)

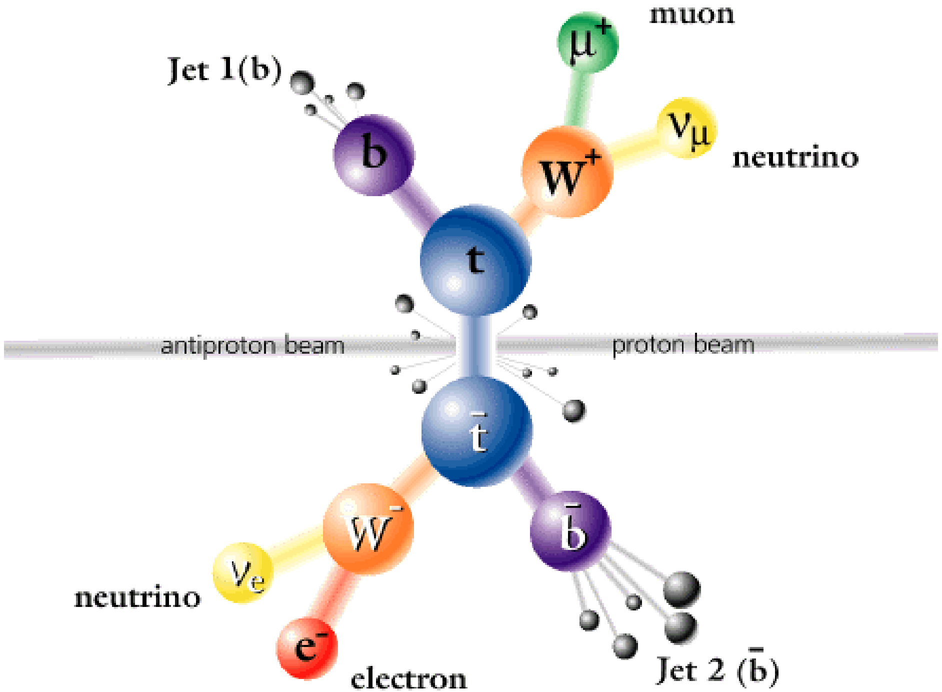
But we can provide an answer for specific cases

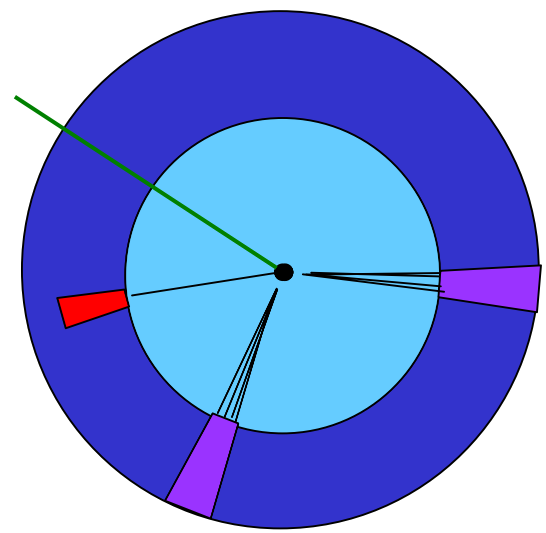
How “sensitive” is Sleuth to $WW \rightarrow e\mu \not{E}_T$?





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 $t\bar{t}$

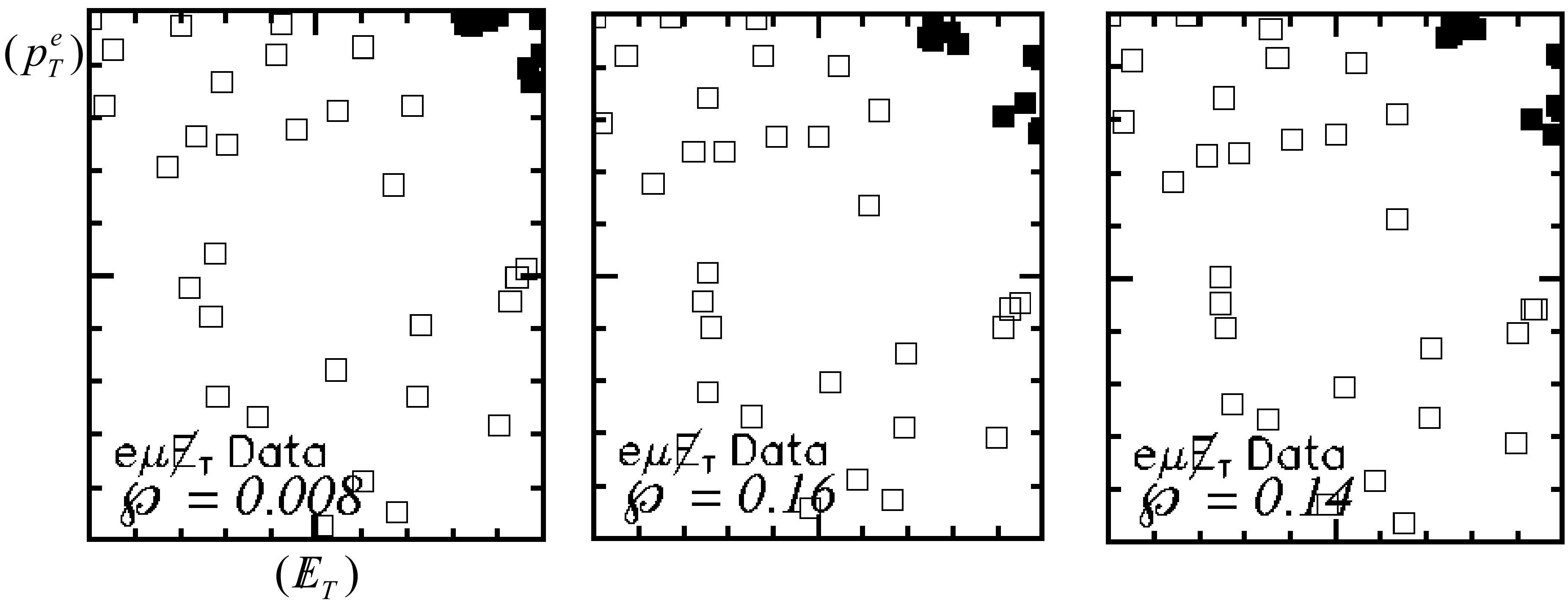
(We've given ourselves a difficult test)

Let the backgrounds include

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

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

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



Let the backgrounds include

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

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

3)
- 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 $t\bar{t}$

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

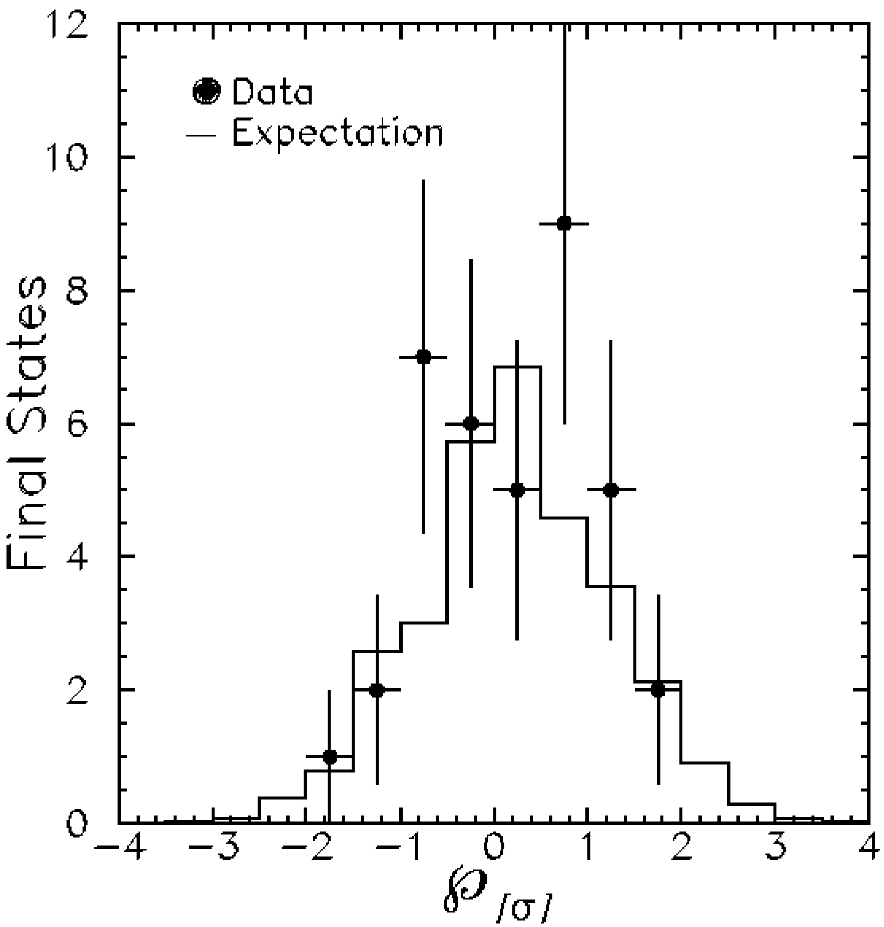
Excess corresponding (presumably) to $t\bar{t}$

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

Sleuth — 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 $(+1.08\sigma)$
$e\mu \not{E}_T j$	0.45 $(+0.13\sigma)$
$e\mu \not{E}_T\ 2j$	0.31 $(+0.50\sigma)$
$e\mu \not{E}_T\ 3j$	0.71 (-0.55σ)
W+jets-like	
$W\ 2j$	0.29 $(+0.55\sigma)$
$W\ 3j$	0.23 $(+0.74\sigma)$
$W\ 4j$	0.53 (-0.08σ)
$W\ 5j$	0.81 (-0.88σ)
$W\ 6j$	0.22 $(+0.77\sigma)$
$e\not{E}_T\ 2j$	0.76 (-0.71σ)
$e\not{E}_T\ 3j$	0.17 $(+0.95\sigma)$
$e\not{E}_T\ 4j$	0.13 $(+1.13\sigma)$
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 $(+1.75\sigma)$
$ee\not{E}_T\ 2j$	0.68 (-0.47σ)
$ee\not{E}_T\ 3j$	0.36 $(+0.36\sigma)$
$ee\not{E}_T\ 4j$	→ 0.06 $(+1.55\sigma)$
$\mu\mu\ 2j$	0.08 $(+1.41\sigma)$
$(\ell/\gamma)(\ell/\gamma)(\ell/\gamma)X$	
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 $(+0.74\sigma)$
$e\gamma\gamma$	0.66 (-0.41σ)
$e\gamma\gamma j$	0.21 $(+0.81\sigma)$
$e\gamma\gamma\ 2j$	0.30 $(+0.52\sigma)$
$W\gamma\gamma$	0.18 $(+0.92\sigma)$
$\gamma\gamma\gamma$	0.41 $(+0.23\sigma)$
$\tilde{\mathcal{P}}$	→ 0.89 (-1.23σ)

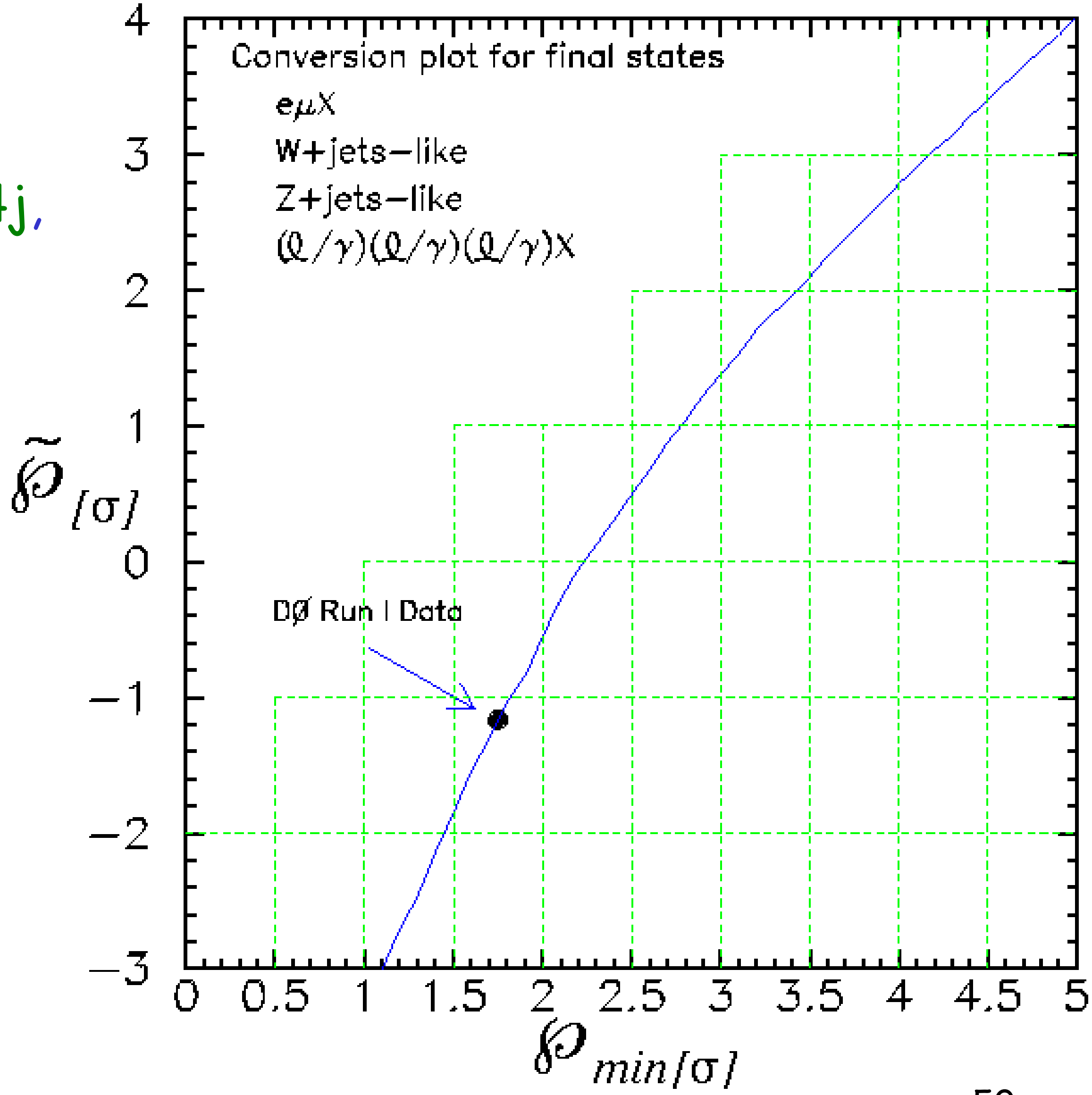
We find

$\mathcal{P}_{min}$ = 0.04 (+1.7σ)

from the final state ee 4j,

corresponding to

$\tilde{\mathcal{P}}$ = 0.89 (-1.2σ)



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
- **Sleuth** finds no evidence of new physics in DØ data
- **Sleuth** has the potential for being a very useful tool
  - Run II of the Tevatron (Fermilab, 2001)
  - Large Hadron Collider (CERN, 2006)?
  - Other fields of research?

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