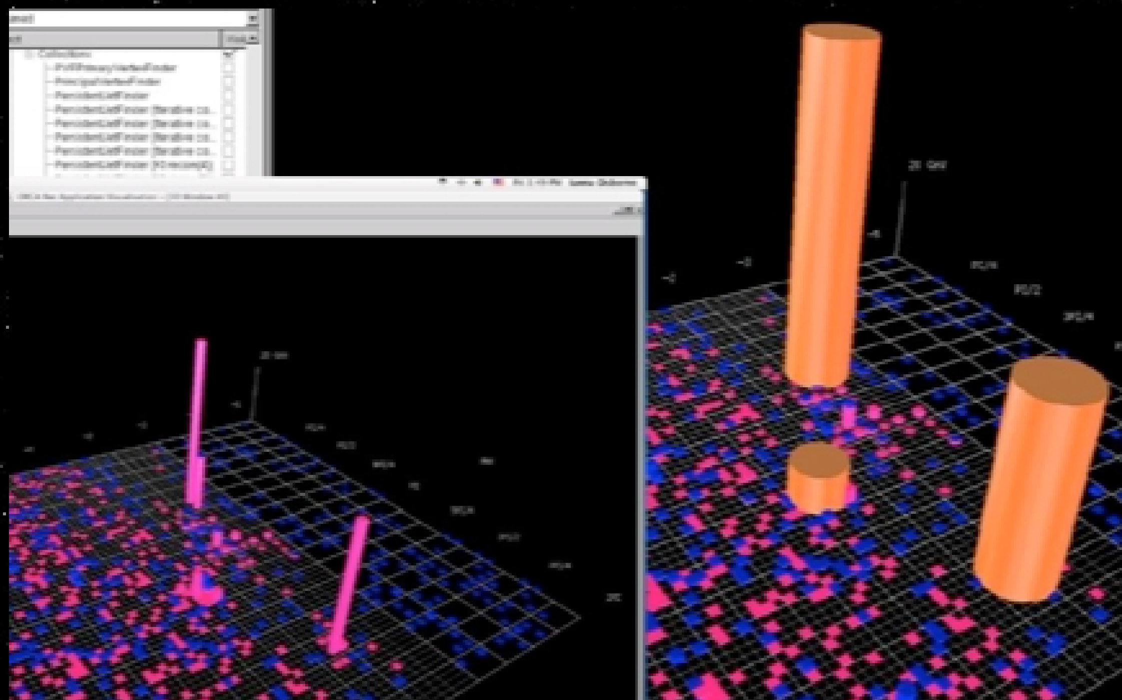
is particle physics ready for the LHC?



Joe Lykken
Fermi National Accelerator Laboratory

Hinchliffe's theorem:

when a title is in the form of a question,
the answer is always "no"

outline

- countdown to the Large Hadron Collider
- is it new physics?
  - “clean” signatures
  - how to discover supersymmetry
  - missing energy
- what kind of new physics?
  - is it supersymmetry, or is it little Higgs?
  - hidden supersymmetry
  - is that bump a $\mathbf{Z}'$, or is it 11 dimensional M-theory?
- how the LHC will change everything

this is a special time in particle physics

- urgency: provocative discoveries lead to profound questions
- connections: questions appear to be related in fundamental but mysterious ways -> big ideas are in play
- tools: we have the experimental tools, technologies and strategies needed to tackle these questions

conclusion:

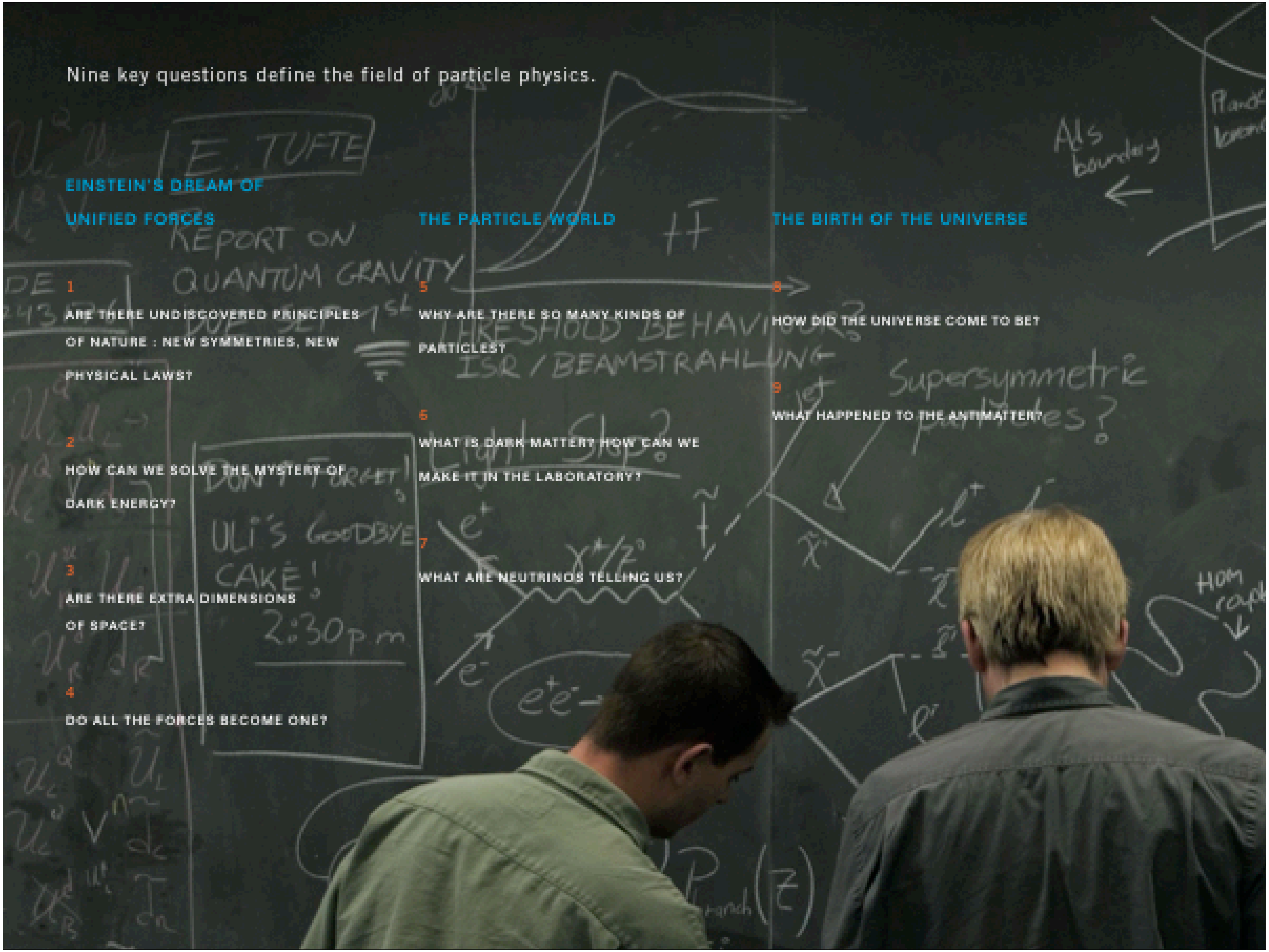
we are seeing a scientific revolution in the making

Large Hadron Collider

turns on July 1, 2007

- a 27 km particle accelerator at CERN
- colliding beams of protons at 14 TeV total energy
- 7 times the energy and 50 times the luminosity of the Fermilab Tevatron

- the largest and most ambitious scientific project ever attempted
- e.g. requires 30,000 tons of 8.4 Tesla dipole magnets cooled to 1.9 degrees K by 90 tons of liquid helium
- e.g. 40 MHZ collision rate = 1 Terabyte/sec raw data rate from the CMS and ATLAS particle detectors



Nine key questions define the field of particle physics.

EINSTEIN'S DREAM OF UNIFIED FORCES

1
ARE THERE UNDISCOVERED PRINCIPLES OF NATURE : NEW SYMMETRIES, NEW PHYSICAL LAWS?

2
HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

3
ARE THERE EXTRA DIMENSIONS OF SPACE?

4
DO ALL THE FORCES BECOME ONE?

THE PARTICLE WORLD

5
WHY ARE THERE SO MANY KINDS OF PARTICLES?

6
WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

7
WHAT ARE NEUTRINOS TELLING US?

THE BIRTH OF THE UNIVERSE

8
HOW DID THE UNIVERSE COME TO BE?

9
WHAT HAPPENED TO THE ANTIMATTER?

a universe full of Higgs?

the Standard Model conjectures:

- the existence of a Higgs field
- the Higgs field permeates the entire universe
- W and Z react to the Higgs field and get mass
- the matter particles (quarks and leptons) also get mass this way

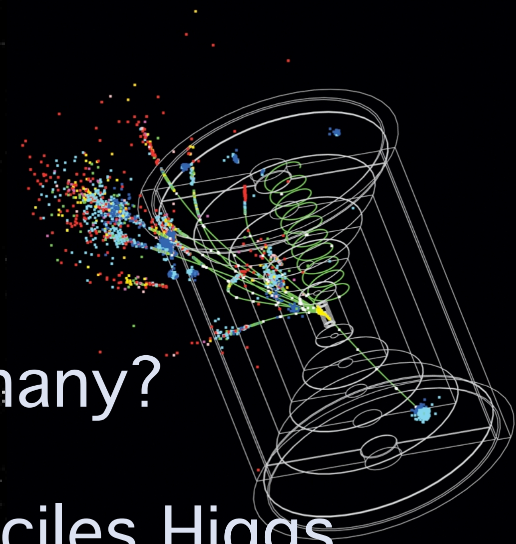
these are bold conjectures!

Higgs vs the quantum vacuum

Problems:

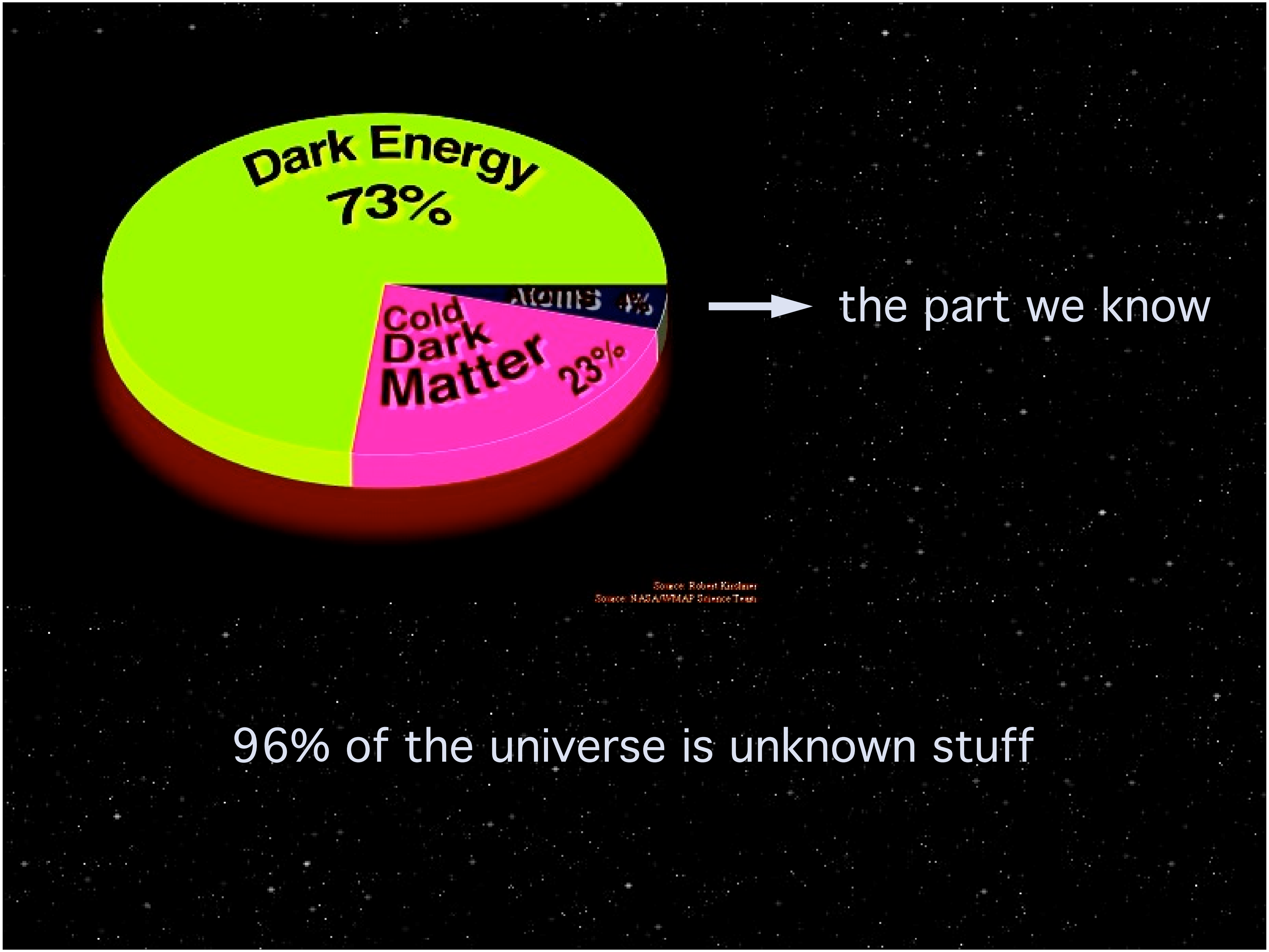
- if there is a Higgs field, there should also be a Higgs particle - we haven't found it yet
- a Higgs field doesn't seem to be consistent with a quantum vacuum
- some important new physics is missing in this story!

questions for the LHC:



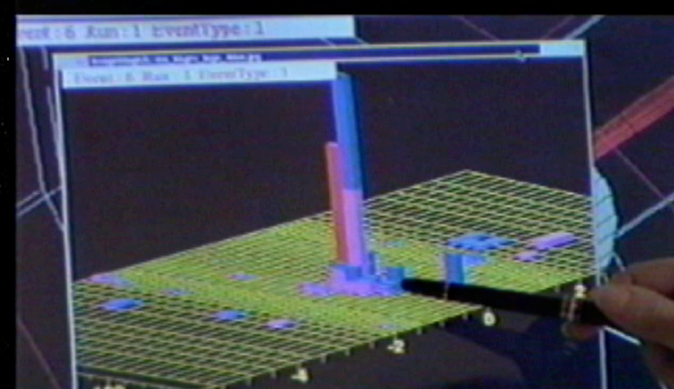
- is there a Higgs? what kind? how many?
- what is the new physics that reconciles Higgs (or something like it) with the quantum vacuum?

supersymmetry? new forces? extra dimensions? none of the above?

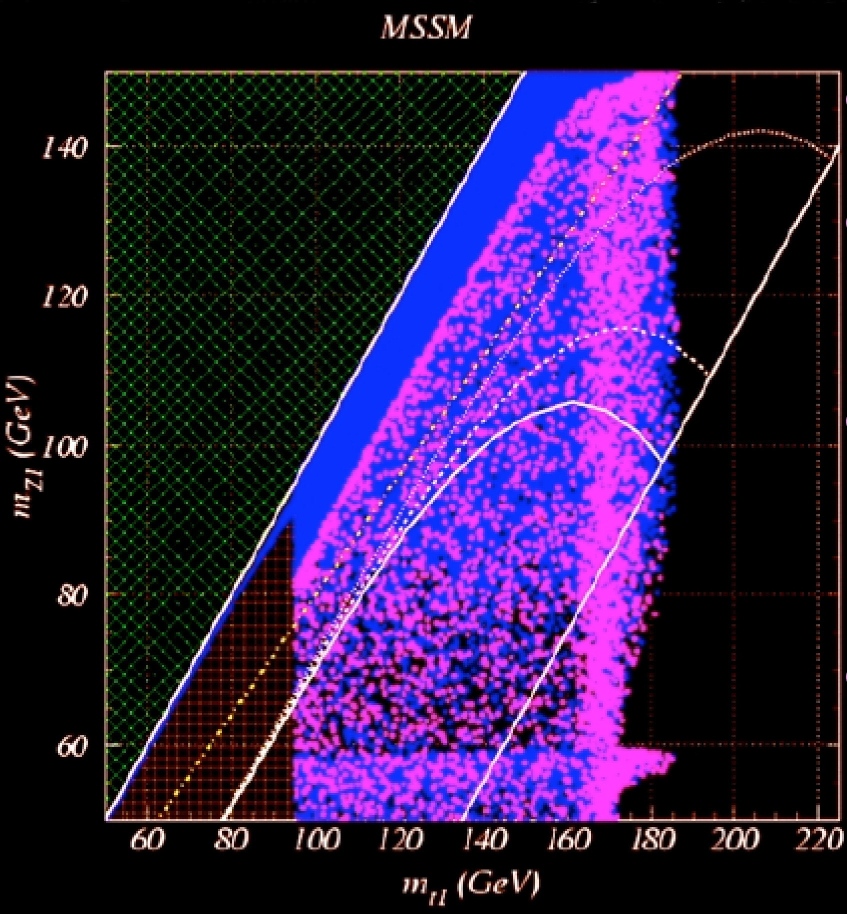

Dark Energy
73%
Cold Dark Matter
23%
Atoms 4%
the part we know
Source: NASA/WMAP Science Team
96% of the universe is unknown stuff

dark matter at the LHC:

- a natural explanation for part/all of the dark matter is weakly interacting thermal relic particles with mass 0.1 - 1 TeV.
- the LHC would certainly produce such particles
- they could then be detected as “missing energy”, just as we do for neutrinos



the neutralino of supersymmetry is a natural dark matter candidate



- scanning over different models
- magenta points produce exactly the right amount of dark matter!
- inside white lines means supersymmetry will be seen at Tevatron!
- for most magenta points, CDMS will also see neutralinos from the galactic halo!

(Balazs, Carena, Wagner 2004)

accelerator challenges

- the LHC accelerator design (to compete with the SSC!) pushes the envelope in several areas:
- 30,000 tons of 8.4 Tesla dipoles cooled to 1.9 degrees K by 90 tons of liquid helium
- 2808 proton bunches (each direction), with 100 billion 7 TeV protons per bunch
- Beam energy of 300 Megajoules = 120 Kg TNT, enough to melt ~ a ton of copper

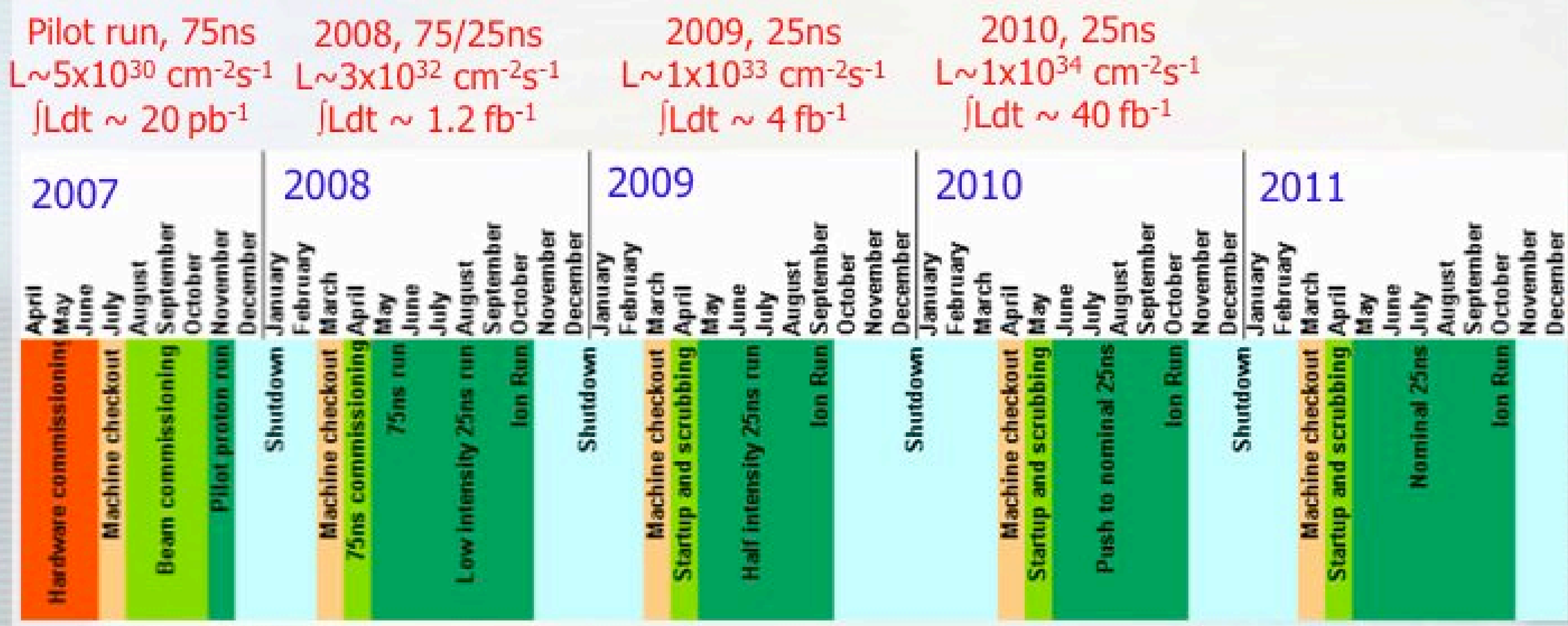
beam safety is a critical issue

What CDF was surprised by and reacted to

- Very Serious (CDF)
  - Fast beam loss (risk was known – but reinforced by experience)
  - Damage to silicon from low doses (100's of rads) at high rate (100 nsec) [particular failure mode not reproduced in tests]
  - (note: CDF shields D0 from proton halo)
- Serious (CDF and D0)
  - Damage to various electronics in collision hall due to SEB (single event burnout) or similar single events ← abnormally high losses
- Annoying (CDF)
  - Example: Beam induced background in missing E_T trigger ← halo scraping upstream of CDF

The LHC Start-Up

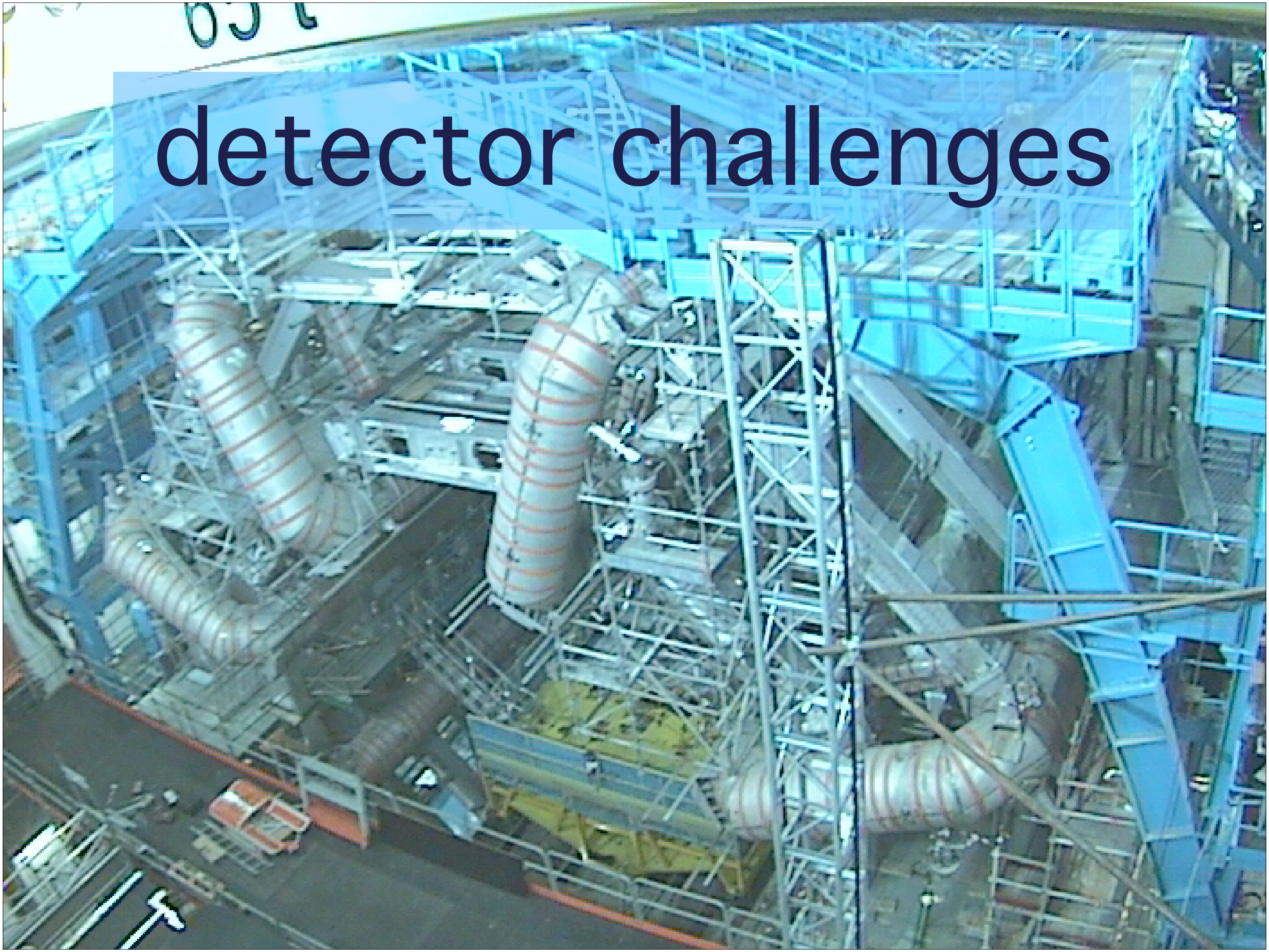
- Physics running: 140 days/year
- ATLAS/CMS running: ~100 days/year
- Typical efficiency for physics: 40%
- Effective ATLAS/CMS running time/year: ~1000 hours ~ 4×10^6 s ~ 4×10^{38} cm^{-2} = 4×10^{14} b^{-1} = 400 pb^{-1} @ 10^{32}cm^{-2}s^{-1}
- Note that the schedule below [R. Bailey, LHCAC, 6/5/05] is "all goes well" scenario



what is the message to theorists?

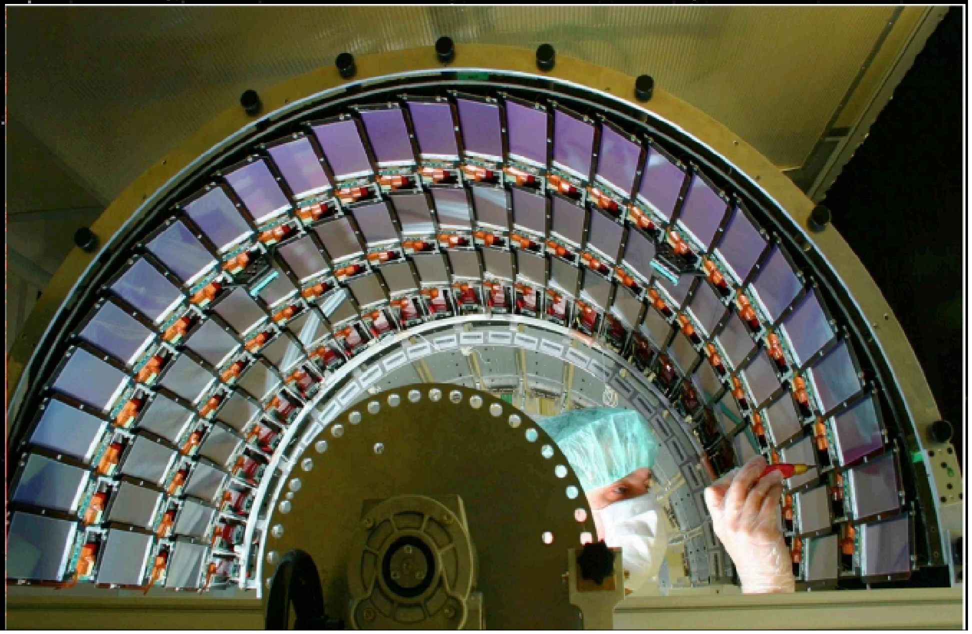
- LHC startup will be slow and gradual
- the discoveries announced in 2009-2010 will be made from data sets with $<\sim \mathbf{10}\ \mathrm{fb}^{-1}$ not the $\mathbf{30-100}\ \mathrm{fb}^{-1}$ that you see in all the studies

detector challenges



detector challenges

- new detectors with new technologies
- new environment: higher energy + luminosity
- calibration, alignment, and integration of many big subsystems



trigger and reconstruction challenges

- 40 MHZ collision rate = 1 Terabyte/sec raw data
- only 5 events out of a billion will be a Higgs
- all the reconstructed physics objects are new kinds of beasts: e.g. for a 35 GeV CMS electron, 44% of its energy is in bremsstrahlung

what is the message to theorists?

- initial LHC discoveries will come from simple “inclusive” experimental signatures

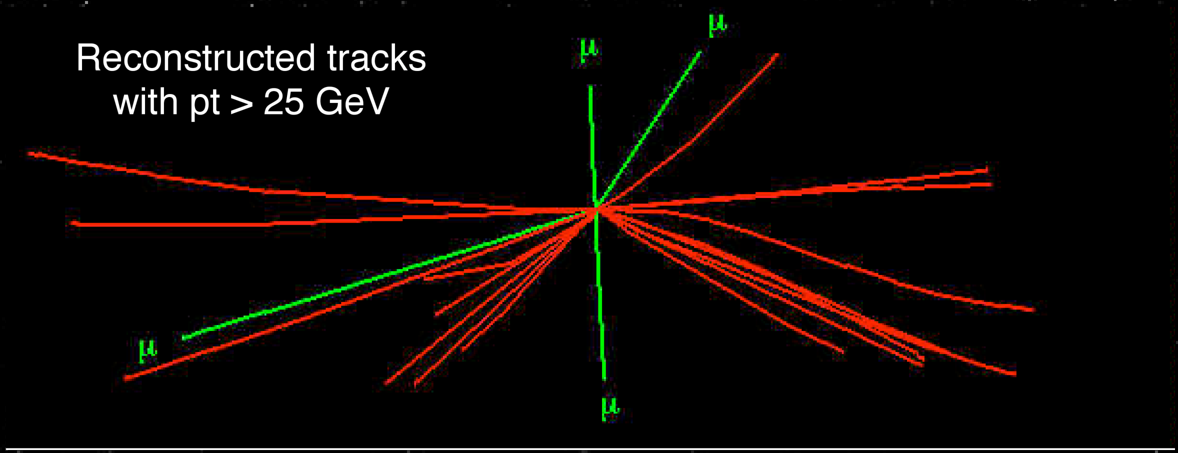
is it new physics?

Standard Model cross sections at LHC are huge:

- total inelastic: ~ 0.1 barns
- inclusive bbar: ~ 500 microbarns
- inclusive W and Z: ~ 100 nanobarns
- inclusive top: 0.89 nanobarns
- Z + 2 jets, with Z decaying to neutrinos: ~ 200 pb
- compare this to 1 TeV supersymmetry: ~ 3 pb

“clean” signatures at LHC

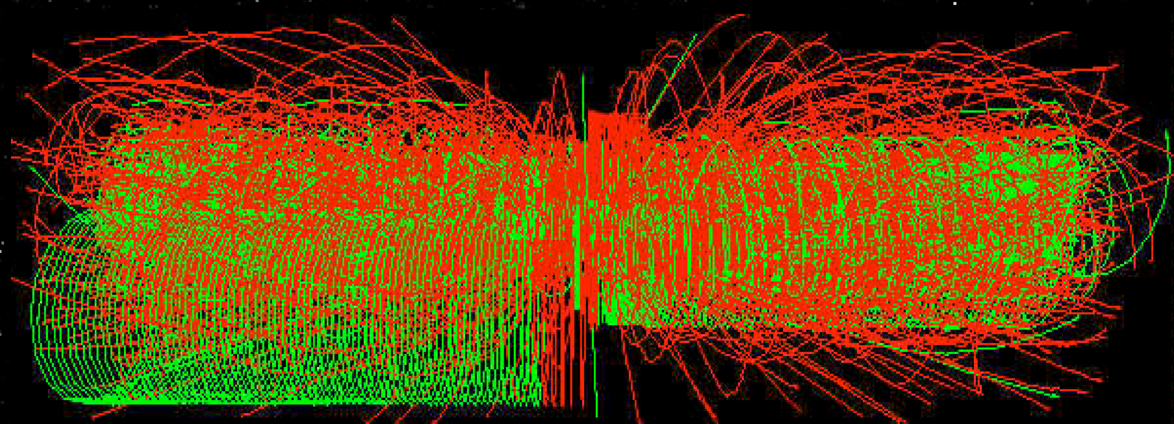
- every new physics event, no matter how clean, will have 20 - 50 additional collision events laid on top of it, plus an underlying event from the proton remnants



golden event: $\mathrm{gg} \to \mathrm{h} \to \mathbf{ZZ} \to \mu^+\mu^-\mu^+\mu^-$

“clean” signatures at LHC

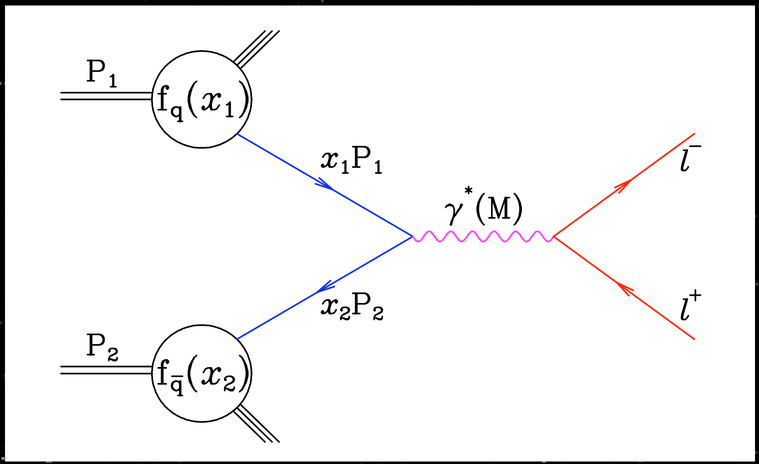
- the extra junk is soft, but adds a total of about 1 TeV to the event

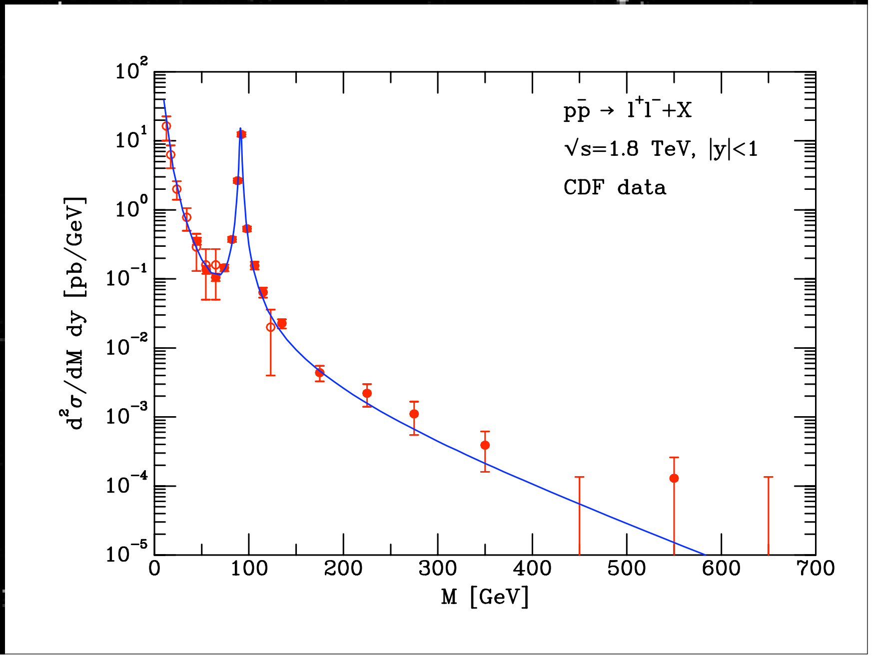


golden event: $gg \rightarrow h \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$

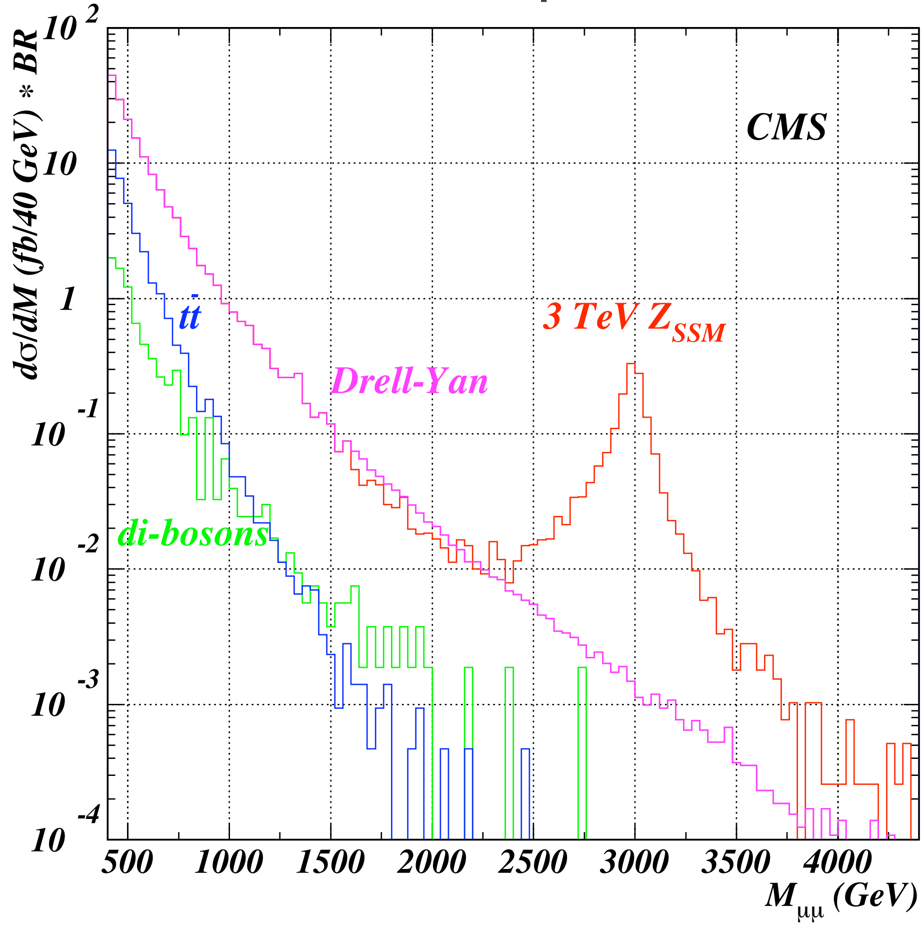
clean signatures: Drell-Yan

- production of electron or muon pairs is well-understood theoretically and computed at next-to-next-to-leading order in QCD
- theory and data agree very well





look for new particles as resonances in ee or mumu production



ask Bob Cousins

for a 1.5 TeV Z' with SM-like couplings, produce ~30 events per fb-1 after cuts

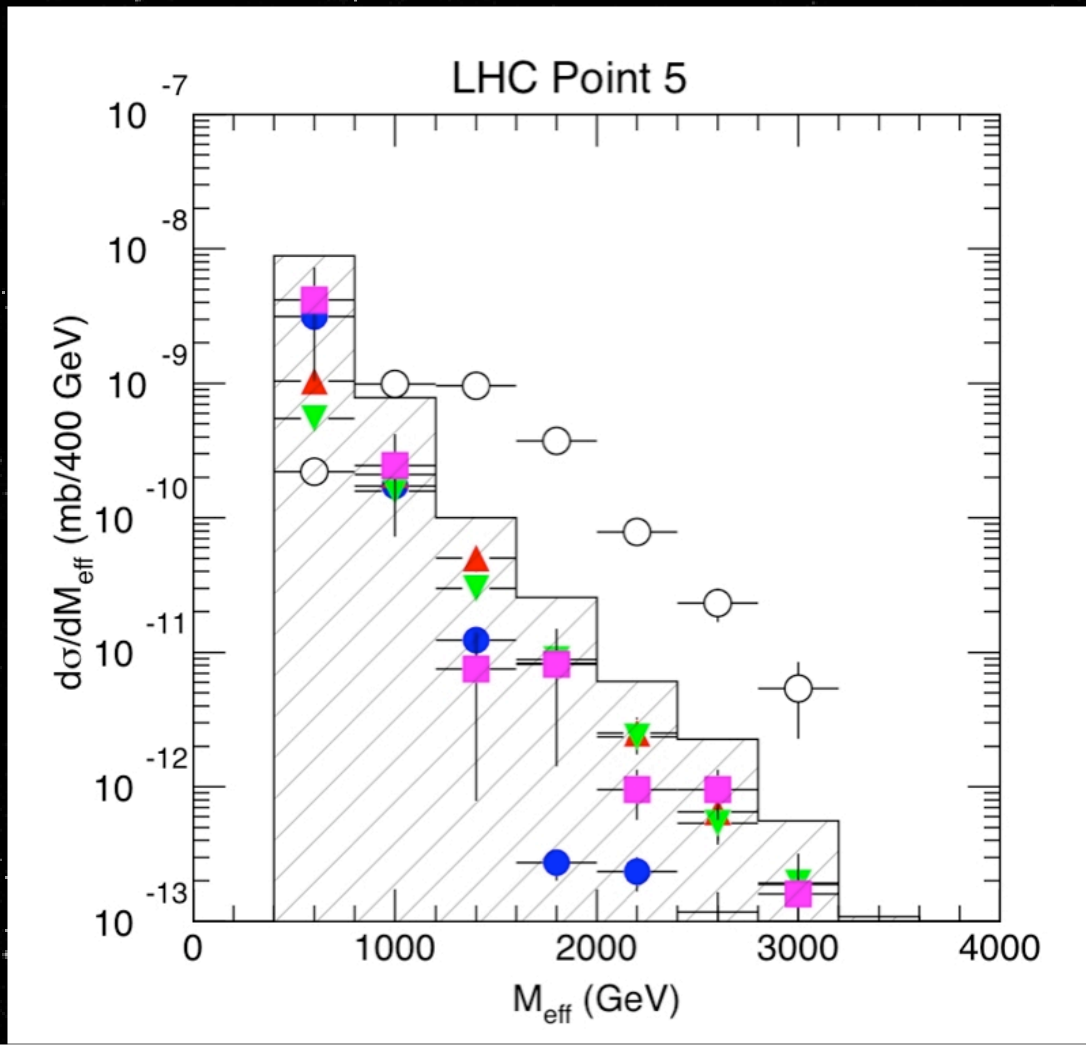
discovering supersymmetry

- the dominant production of superparticles at LHC is through pairs of gluinos and squarks
- their cascade decays produce high energy jets and large "missing energy" from neutralinos
- a simple discriminant for supersymmetry searches is the effective mass defined as

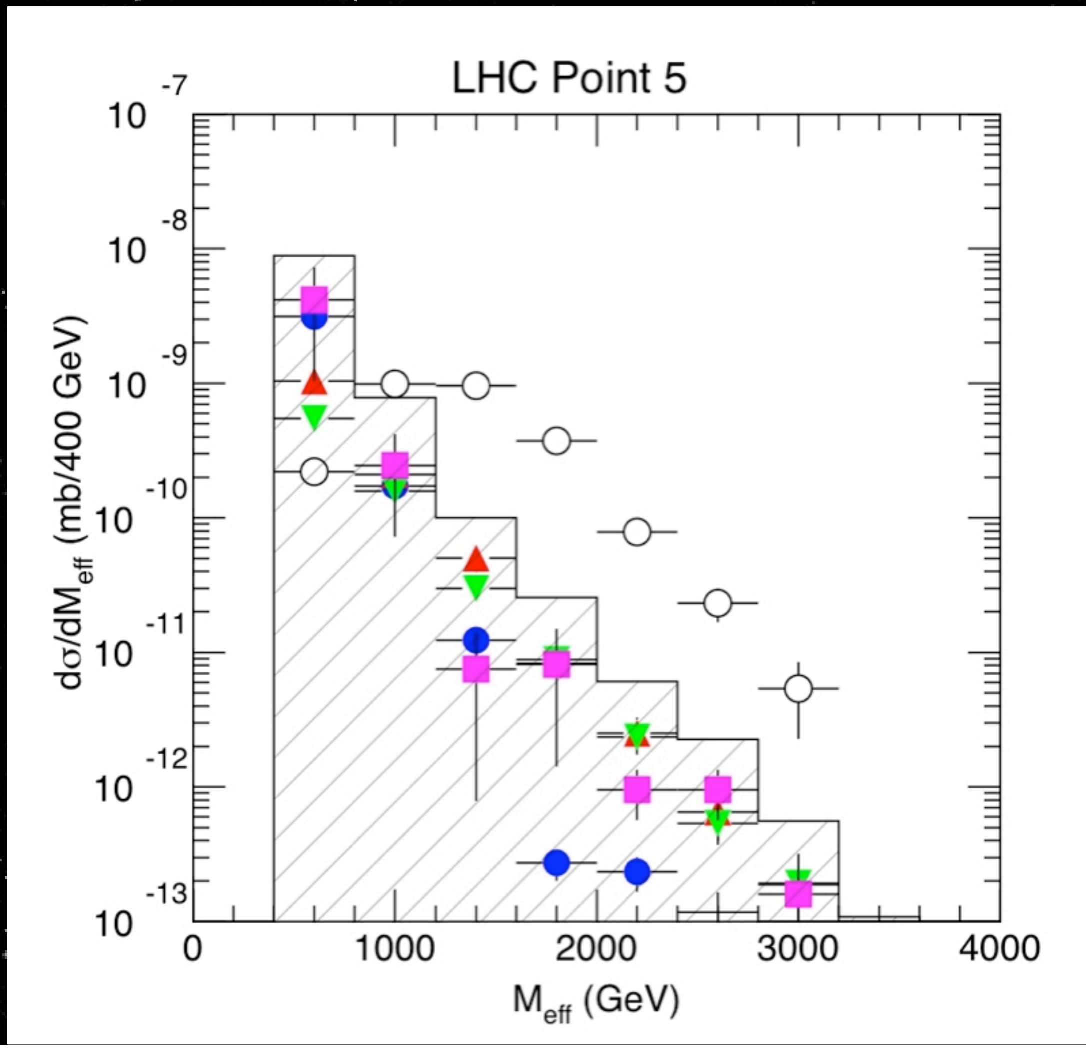
$$\mathbf{M_{eff} = E_T^{miss} + \sum_{i=1}^{4} P_T^{jet}}$$

- an excess of events with large $\mathbf{M_{eff}}$ could be the initial discovery of supersymmetry

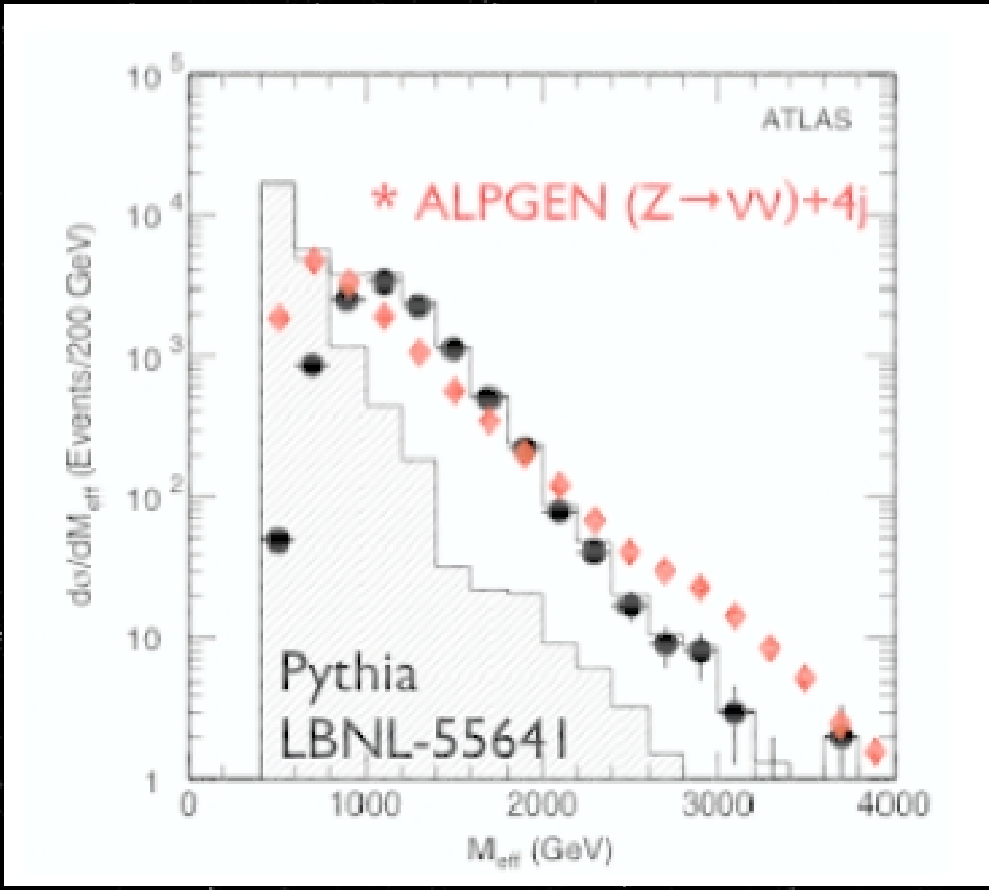
- this strategy is backed up by this famous plot from the ATLAS TDR
- for 8 years, was used to make the case that LHC can discover supersymmetry after “a few weeks of running”



the only problem is:
this plot is completely wrong



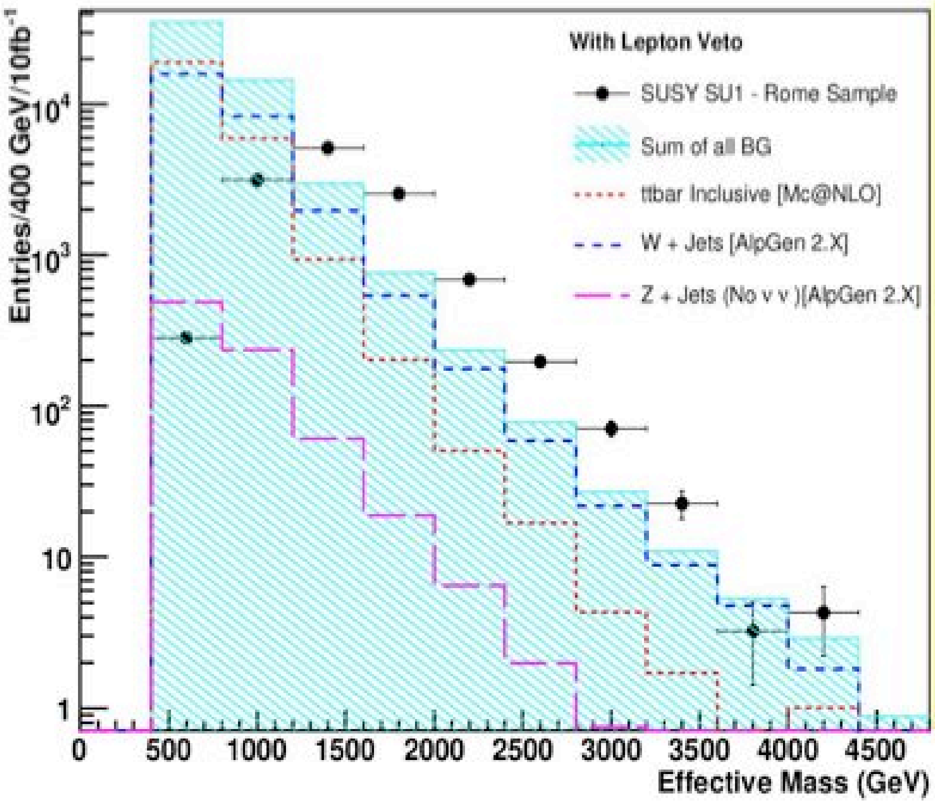
- at LHC, supersymmetry channels have large SM backgrounds from top, Z+jets, and W+jets
- showering Monte Carlos like Isajet and Pythia underestimate these backgrounds by up to a factor of ten in the signal region
- this was forgotten until recently, when better QCD theory tools became available



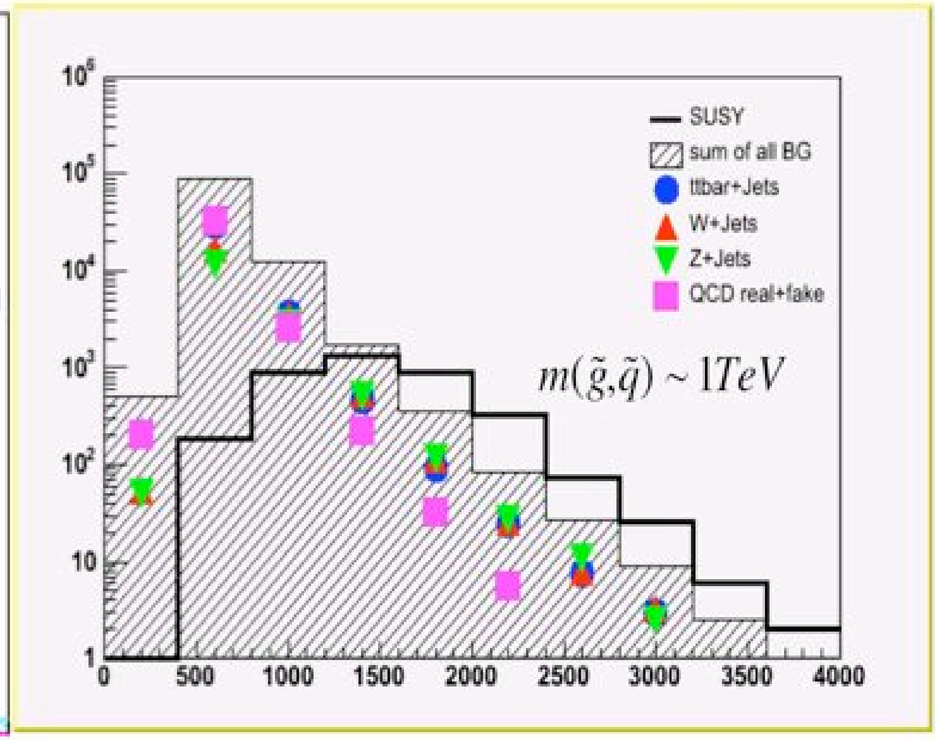
ask Zvi Bern

Comparisons with Other studies [0 lepton mode]

this study



S. Asai et. al.



Differences in Generator Version (AlpGen)

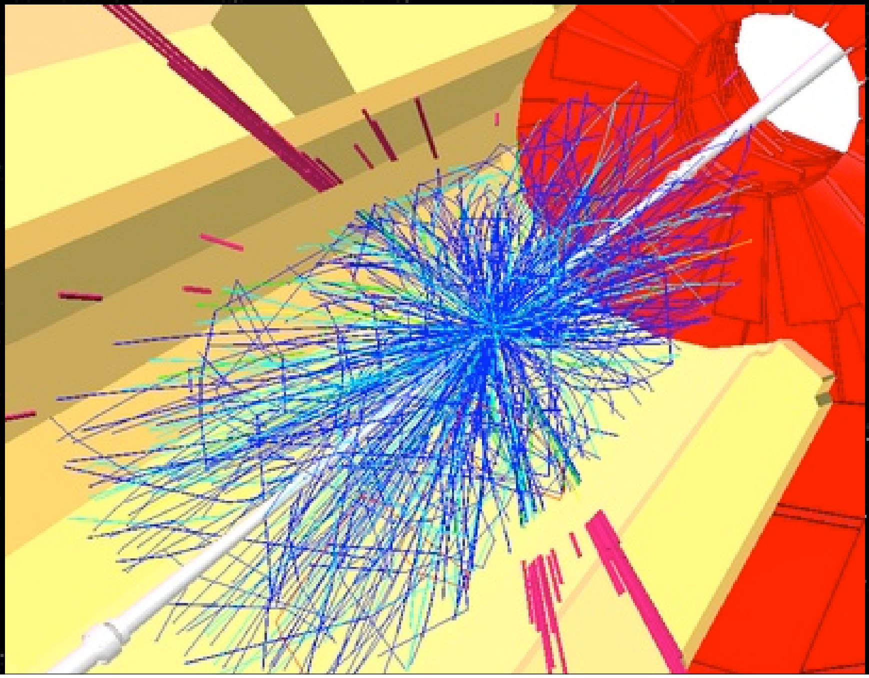
ME + PS matching prescriptions

Selection cuts and Scale choice

Matching presciption, Matching at Pt ~ 20 GeV Vs 40 GeV ??

how to discover supersymmetry?

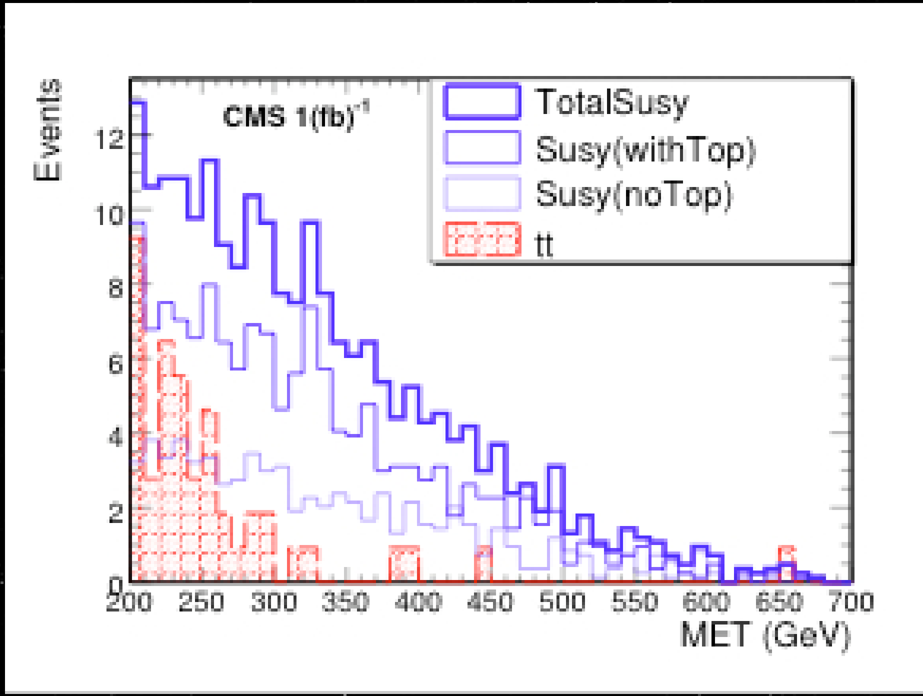
- can enhance the SUSY signal by requiring leptons
- but now we have to understand a lot: multijets, missing energy, leptons, jets faking leptons, ...
- and the search strategies become more dependent on which supersymmetry model Nature has chosen



how to discover supersymmetry?

- CMS is exploring a “self-calibrating” approach, where first you understand your large data sample of top quarks
- then you look for an excess of events in this data sample with large missing energy
- these would come from superpartner particles decaying into top quarks plus neutralinos plus other junk

discovery of supersymmetry in 2008?



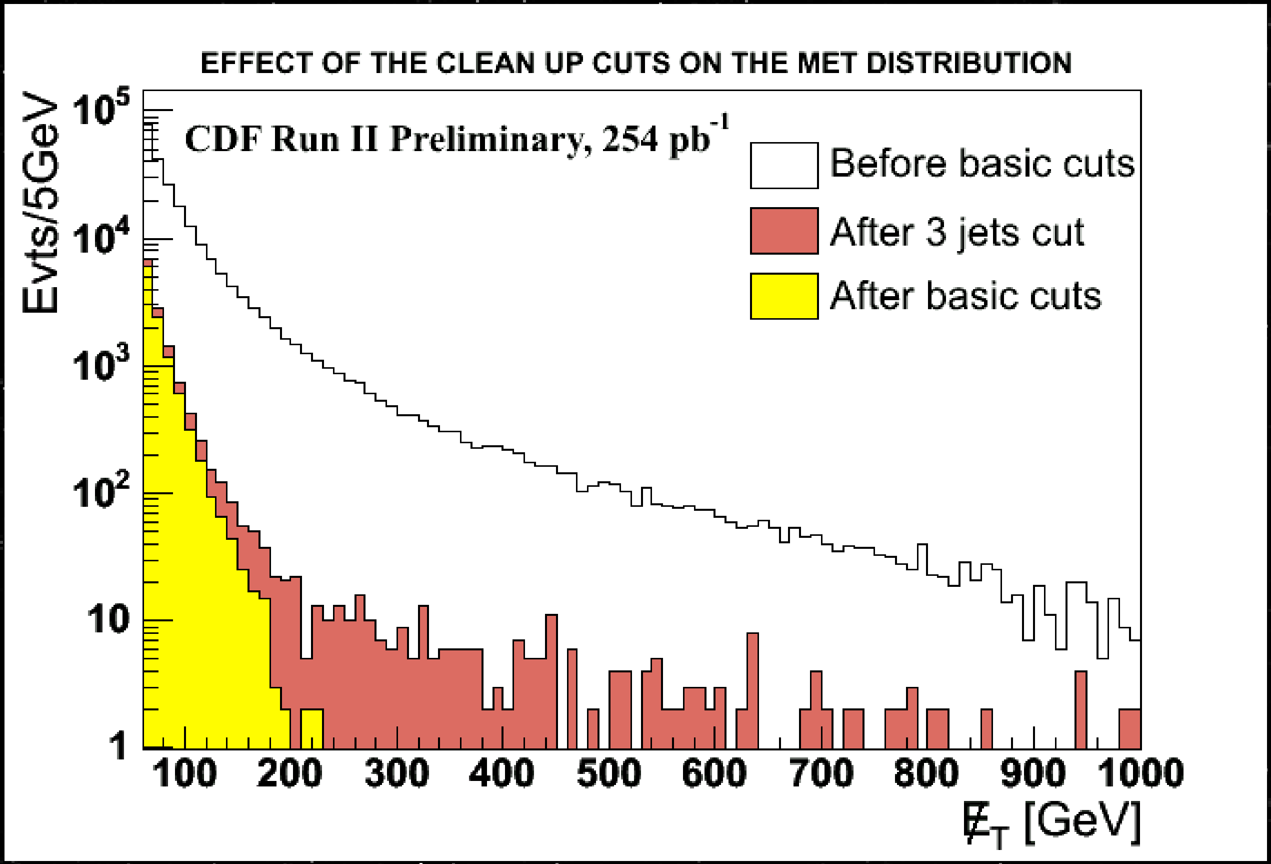
- Caveat: missing energy, the best discriminator between supersymmetry and SM, is also one of the most challenging physics objects

missing energy signatures

- ANY beyond the Standard Model theory which incorporates weakly interacting dark matter will have missing energy signatures
- so do many models of large or warped extra dimensions, for reasons that have nothing to do with dark matter

see e.g. JL hep-ph/0503148,
JL and Randall, hep-th/9908076

not for amateurs



- missing energy + multijets among the most challenging searches at Tevatron Runs I and II

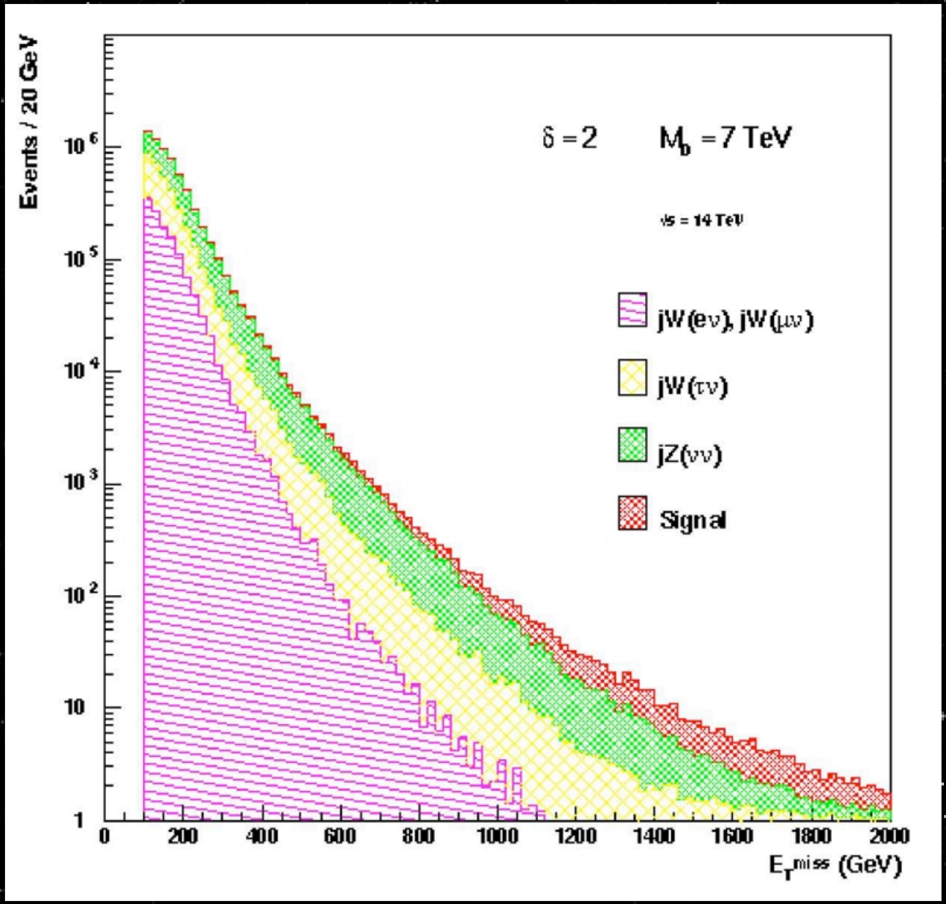
ask Jay Hauser

"beware the monojet, my son"

- monojet searches are even more difficult (ask Carlo Rubbia)
- at the Tevatron, the *Run I* monojet analyses were not completed until 2003/2004
- but monojet searches are essential for probing extra dimensions

signals in many models of extra dimensions are smooth excesses over SM backgrounds, e.g.

production of massive gravitons produces an excess of collision events with large missing energy

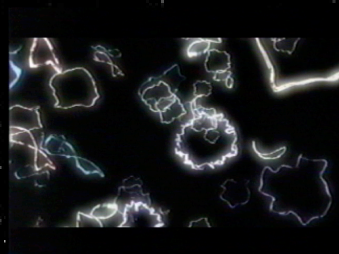


Hinchliffe and Vacavant, hep-ex/0005033

what kind of new physics?

- I just showed you an example where a smooth excess over SM backgrounds constitutes the discovery of extra dimensions of space
- or does it?
- experimenters can write neutral papers with titles like "observation of excess events in channel X"
- but there will be great urgency to put a label on the new physics

the big picture (we think)

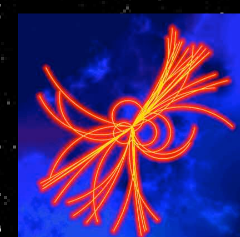


string unification

supersymmetry → *extra dimensions*

broken / *hidden*

new TeV scale physics



+ *neutrinos, cosmology, rare processes, astrophysics, etc*

all BSM models look alike

- the existence of dark matter, plus the cosmological assumption that it is a thermal relic, implies ~TeV mass stable WIMPS
- electroweak precision data implies that all new heavy particles associated with electroweak symmetry breaking are either
  - multi-TeV
  - conspiratorial
  - pair-produced (implying a conserved charge or parity)

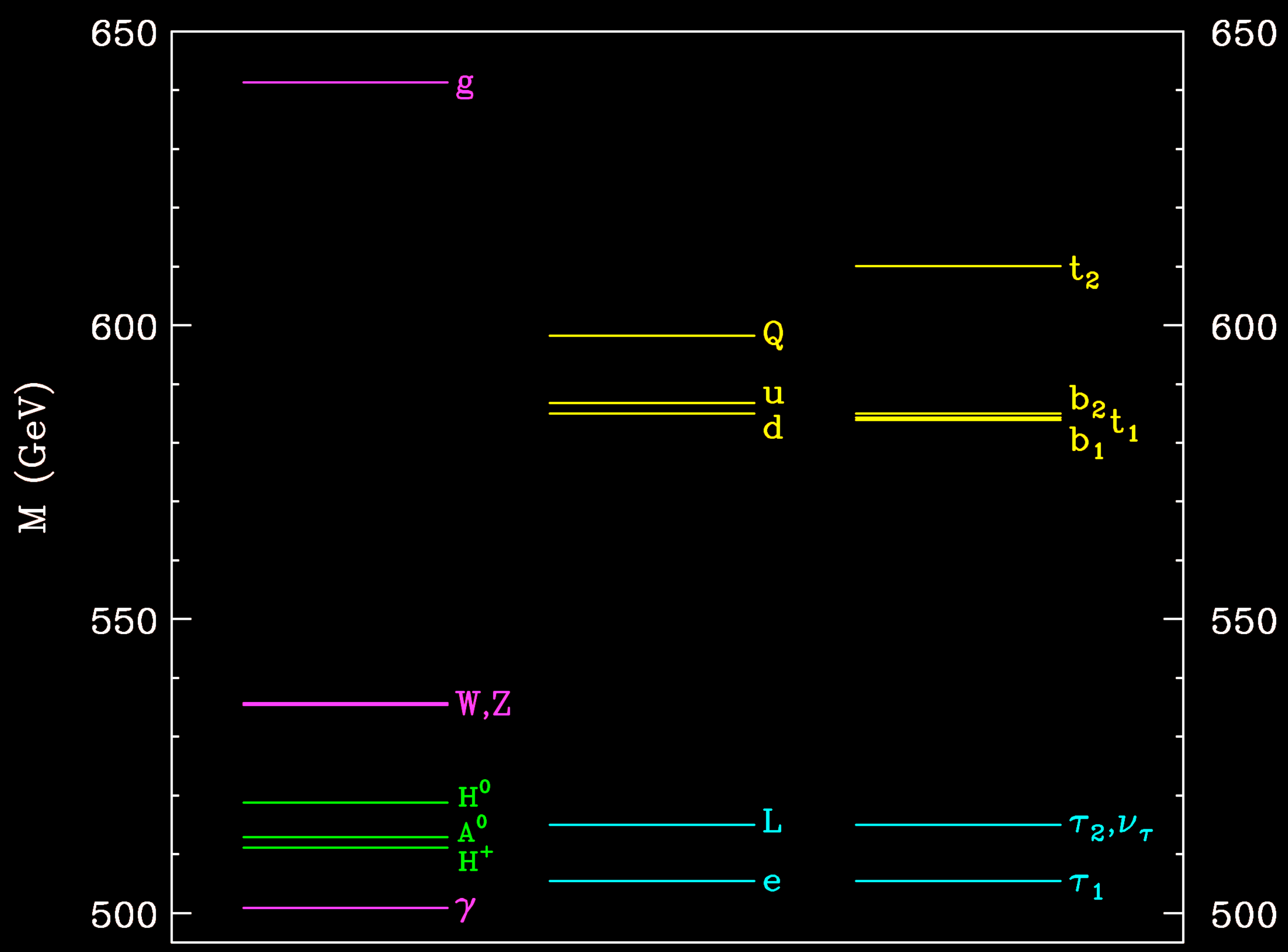
all BSM models look alike

- so nowadays several BSM models have LHC signatures which are similar to supersymmetry
- and non-SUSY-like models need to make most of the new particles multi-TeV, reducing the number of distinct signals accessible at the LHC
- the many varieties of SUSY models also present look-alike problems in their LHC phenomenology

“confusion scenarios”

- Michael Peskin’s name for different kinds of new heavy particles whose decay chains result in the same final state
- For example, in many SUSY models the squarks are heavier than the second-lightest neutralino, which is heavy than the sleptons, which are heavier than the lightest neutralino
- The same pattern occurs in UED (Universal Extra Dimensions), for the masses of the lightest Kaluza-Klein partners

lowest KK modes of UED look like SUSY!



Cheng, Matchev, Schmaltz, hep-ph/0205314

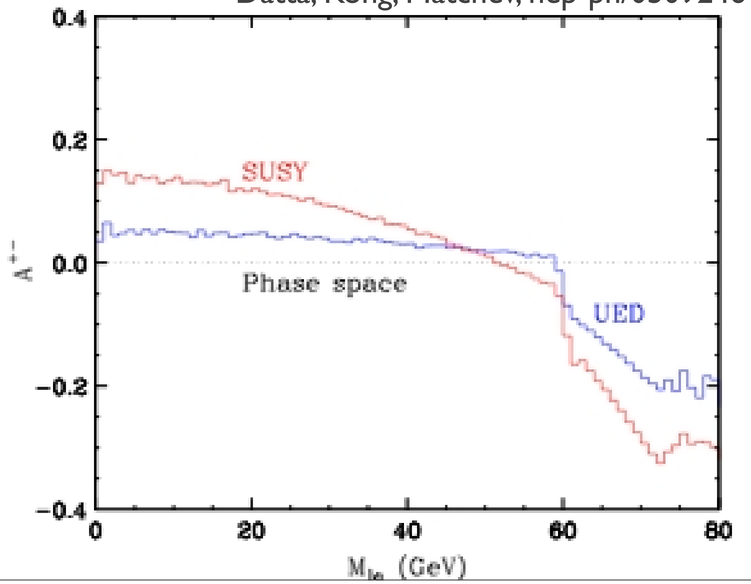
is it SUSY, or is it the 5th dimension?

- how do we tell these scenarios apart?
- the UED partners have a very specific mass pattern, but this is an artifact of insufficiently creative model-building
- there are only two robust ways of discriminating:
  - superpartners and KK partners differ in spin
  - there is a 2nd, 3rd, ... set of KK partners lurking up at higher masses

is it SUSY, or is it the 5th dimension?

- the most recent study by Matchev et al indicates that the second set of UED Kaluza-Klein modes could be discovered at LHC in early (10 fb-1) running, if 1/R <= 750 GeV
- but discriminating the spins looks hopeless, even with 100 fb-1

Datta, Kong, Matchev, hep-ph/0509246



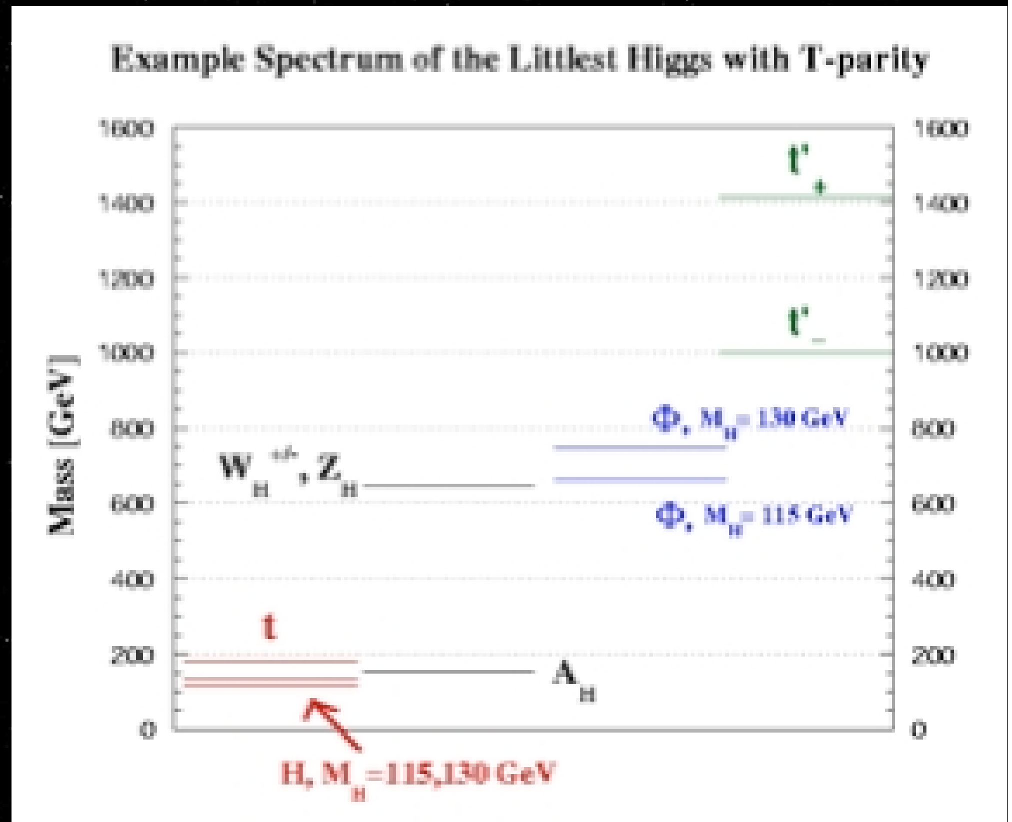
is it supersymmetry, or is it little Higgs?

- in the little Higgs models, heavy partners of the W, Z, Higgs, and top provide new loop diagrams that keep the Higgs light, without SUSY and with all the other new physics pushed up to 10 TeV
- little Higgs models have problems with the EW precision data, unless we invoke a conserved "T-parity"
- then the partners have to be pair-produced, and the lightest one is a good dark matter candidate

Cheng and Low, hep-ph/0308199

is it SUSY, or is it little Higgs with conserved T-parity?

- the heavy partners of top will be strongly pair-produced at LHC
- they decay to W's, Higgs, and the LTP, which shows up as missing energy
- looks like heavy stops in SUSY, except for the spin

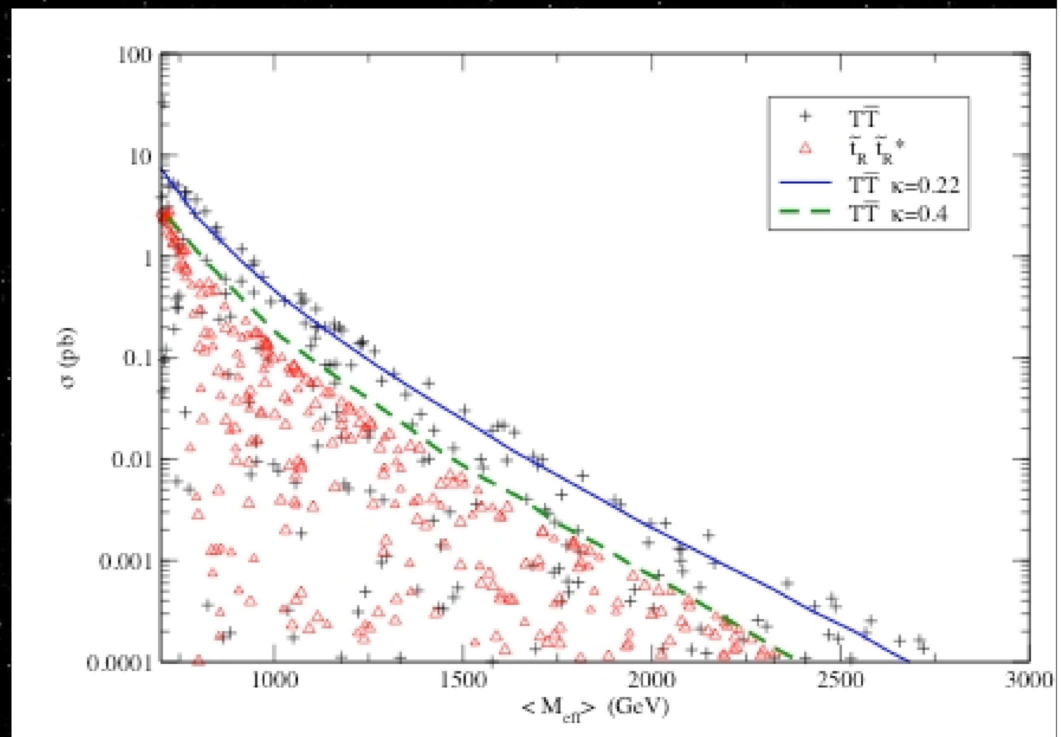


Hubisz and Meade, hep-ph/0411264

is it SUSY, or is it little Higgs with conserved T-parity?

- all other things being equal, having spin 1/2 versus spin 0 buys you about a factor of 3 in the production cross section

- but all other things are not necessarily equal



Cheng, Low and Wang, hep-ph/0510225

hidden supersymmetry

- another likely scenario is that there is SUSY, but important parts of the superpartner spectrum are hard to see at LHC
- at Les Houches 05 LHC Workshop we did a case study...

baryogenesis and stops

- electroweak baryogenesis is the simplest way to explain the excess of matter over antimatter
- also want to get right amount of dark matter
- supersymmetry does all this naturally provided:
- lightest stop mass <~ 170 GeV
- stop-neutralino mass difference 20-30 GeV

Balazs, Carena, Menon, Morrissey, Wagner, hep-ph/0412264 signatures of light stops at LHC

$$\mathbf{pp} \to \tilde{\mathbf{t}}_1\tilde{\mathbf{t}}_1 \to \mathbf{cc}\tilde{\chi}_1^0\tilde{\chi}_1^0$$ (impossible to see)

$$\mathbf{pp} \to \tilde{\mathbf{t}}_1\tilde{\mathbf{t}}_1 \to \mathbf{bbW^*W^*}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$\mathbf{pp} \to \tilde{\mathbf{g}}\tilde{\mathbf{g}} \to \mathbf{tt}\tilde{\mathbf{t}}_1\tilde{\mathbf{t}}_1 \to \mathbf{ttcc}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$\mathbf{pp} \to \tilde{\mathbf{g}}\tilde{\mathbf{g}} \to \mathbf{tt}\tilde{\mathbf{t}}_1\tilde{\mathbf{t}}_1 \to \mathbf{ttbbW^*W^*}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$\mathbf{pp} \to \tilde{\mathbf{g}}\tilde{\mathbf{g}} \to \mathbf{tt}\tilde{\mathbf{t}}_1\tilde{\mathbf{t}}_1 \to \mathbf{ttbcW^*}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Same-sign tops giving same-sign leptons

G.L. Kane and S. Mrenna, hep-ph/9605351

R. Demina, J. Lykken, K. Matchev, A. Nomerotski hep-ph/9910275

"Among the remaining SUSY particles, gluinos have the largest production cross section, and they can decay to stop pairs.

Since the stops are invisible, the signature is similar to the leptonic channels of top pair production. The crucial difference from t-t production is that because of the Majorana nature of the gluino, half of the time the top quarks will have the same sign."

Cross sections, event numbers: SM processes

	tb	tqb	$\bar{t}b$	$\bar{t}qb$	ZZ	ZW	WW	$t\bar{t}$	$Zb\bar{b}$	All
σ, pb	0.212*	5.17*	0.129*	3.03*	18(NLO)	26.2	70.2	886(NLO)	232(NLO)*	
N1	2,120	51,700	1,290	30,300	180,000	262,000	702,000	8,860,000	2,320,000	
N2	112	1,798	71	1,067	256	727	39.7	142,691	12,924	160,000

main contribution into background

- ▷ Other process
  - ▷ generated with CompHEP

	WWW	ZWW	ZZW	ZZZ	$WWWW$	$ZWWW$	$ZZWW$	$ZZZW$	$ZZZZ$
σ, pb	0.129	0.0979	0.0305	0.00994	0.000574	0.000706	0.000442	0.000572	0.0000161
N1	1,290	979	305	99.4					
N2	<15	<10	<3	<1					

	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}WW$	$t\bar{t}ZW$	$t\bar{t}ZZ$
σ, pb	0.556	0.65	neg.	neg.	neg.
N1	5,560	6,500			
N2	<200	<200			

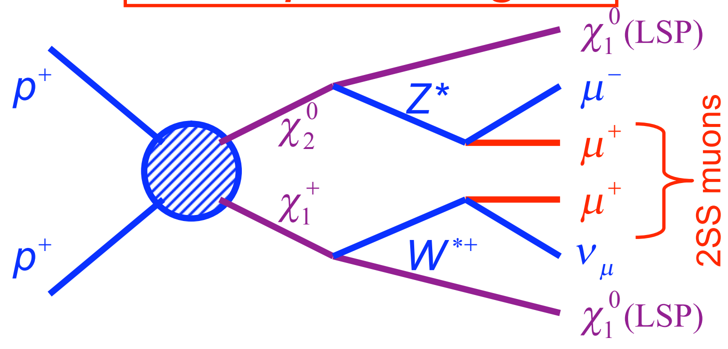
(grey box) - negligible contribution

all but $t\bar{t}W$, $t\bar{t}Z$ are negligible

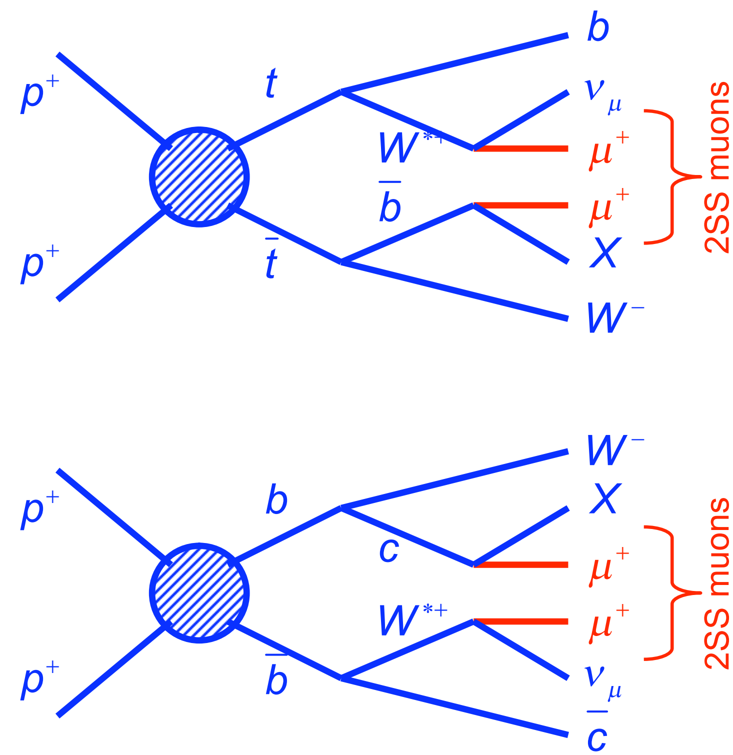
- ▷ Notations:
  - ▷ N1 – total number of expected events for integral luminosity of $10fb^{-1}$
  - ▷ N2 – number of events after pre-selection (two same sign muons, P_T>10 GeV)

Same-sign dimuons signal + backgrounds

example of signal



examples of background



- Handles for separation:
  - dimuons with same signs
  - isolation
  - cut on vertices
  - $\not{E}_t$
  - number of jets
- CDF and DØ successfully killed considered backgrounds

generator-level muons, pt >10 GeV, |eta| < 2.4
from Pythia t-tbar production
numbers = LHC 10 fb-1= 8,860,000 t-tbar pairs

single muon	OS dimuons	SS dimuons	tri-muons	4 muons
2,339,000	228,400	117,300	24,900	500

require muon pt > 15 GeV:

2,028,900	155,300	68,100	11,500	100

apply isolation cut: remove muons within 30 degs of any >15 GeV "jet object"

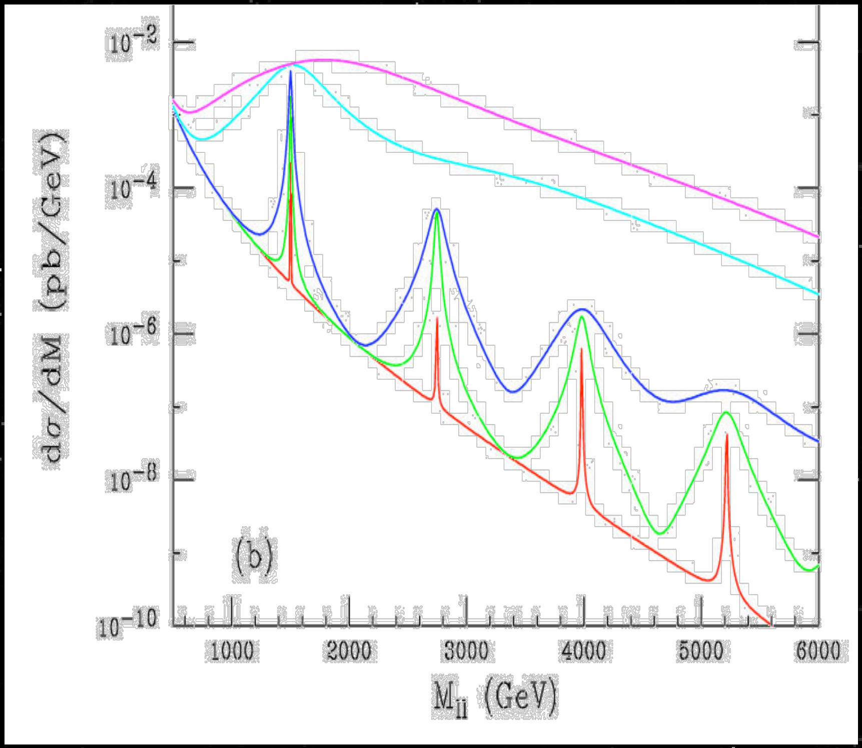
single muon	OS dimuons	SS dimuons	tri-muons	4 muons
955,100	38,100	900	~100	~0

is it a Z', or is it M-theory?

- discovery of a heavy dilepton resonance will be interpreted as a Z'.
- discovery of more than one resonance in the same channel will be interpreted as extra dimensions
- are they spin one, or are they spin two gravitons?
- if they are gravitons $\longrightarrow$ warped extra dimensions
- what kind of warped extra dimensions?

- the smoking gun is the mass ratios
- if they are 1, 1.83, 2.66, 3.48, this is locally AdS(5), as you would get from D3 branes of 10d Type IIB strings
- if they are 1, 1.64, 2.26, 2.88, this is what you would get from M5 branes of 11d M-theory

Bao and JL, hep-ph/0509137



Davoudiasl, Hewett, Rizzo

outlook

what we could know by 2015:

- what “Higgs” really is
- there is supersymmetry
- one of the constituents of dark matter
- there is a new fundamental force
- there are extra spatial dimensions
- or: the theorists were all wrong!