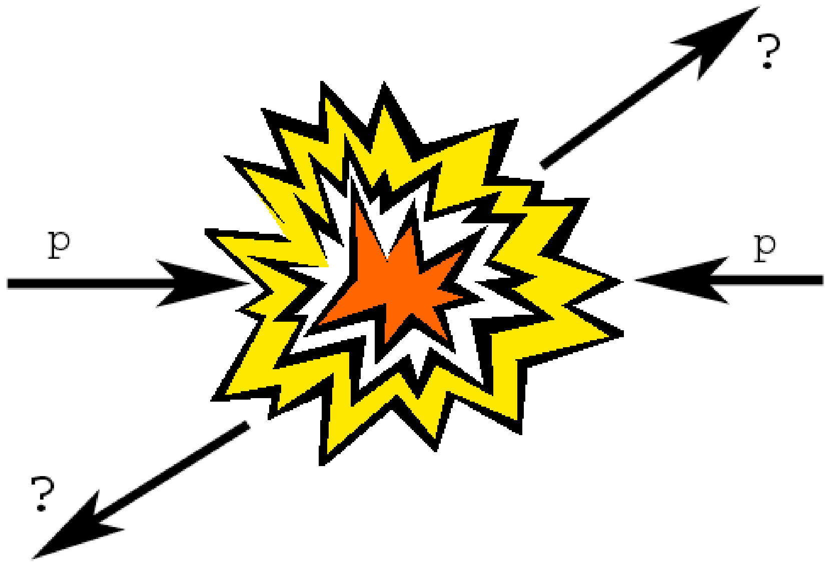
LHC Olympics: A Theorist's Adventures in Collider Physics



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Introduction
Triumphs of the Standard Model

- The Standard Model of particle physics has been around for nearly 30 years now.
- The predictions of the SM have been tested to great accuracy in collider experiments.
- Collider experiments have so far not revealed any direct (or indirect) evidence for physics beyond the SM.

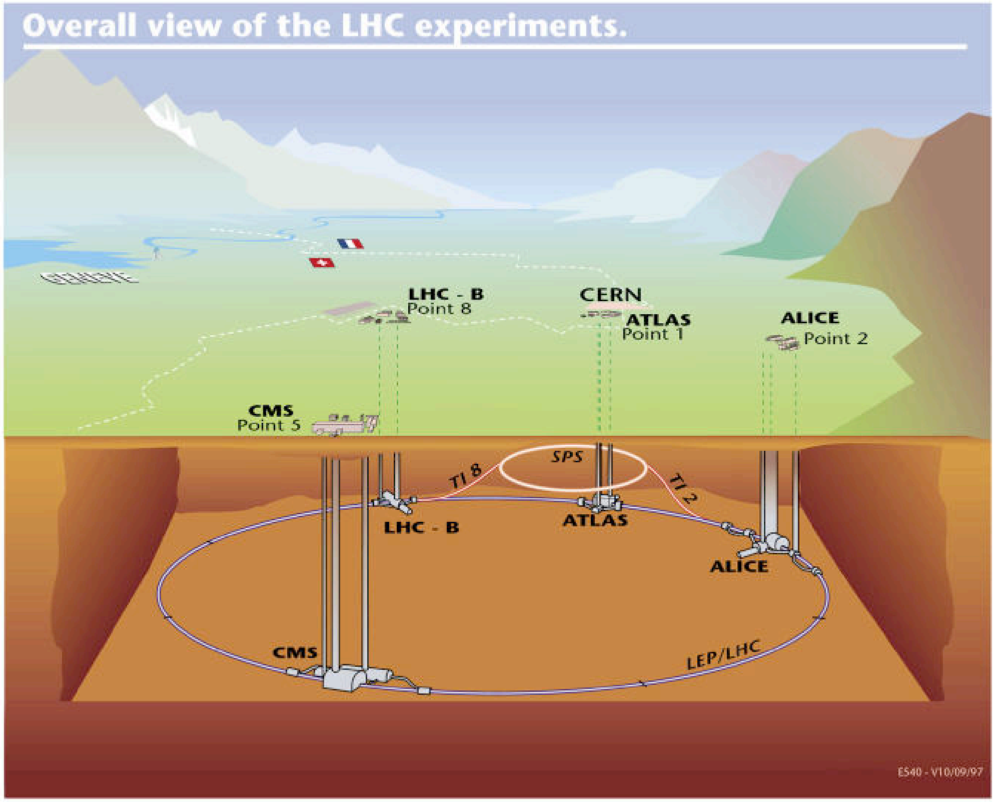
Introduction
Why Look Further?

- We have yet to see the final piece of the SM, the electroweak-symmetry breaking sector.
- We have encountered phenomena that cannot be explained by the SM alone, like DM, DE, matter-antimatter asymmetry, the horizon problem and neutrino masses.
- 'Lofty' considerations of naturalness (gauge hierarchy problem, CC problem) or symmetry (flavor structure) lead us to expect BTSM physics.
- Most natural (or even unnatural) models of BTSM physics contain new particles at the TeV scale.

Introduction
The LHC - The Next Big Thing

Introduction
The LHC - Facts

- The LHC is a pp collider with a CM energy of 14 TeV and a (final) luminosity of 10^{34} cm^{-2}s^{-1} or 100 fb^{-1}yr^{-1}.
- The two main detectors are ATLAS and CMS.



Introduction
The Past, the LHC, the Future?

Colliders	$\sqrt{s}$ (GeV) (GeV)	$\mathcal{L}$ ($\mathrm{cm^{-2}s^{-1}}$)	$\delta E/E$	f (kHz)	polar.	L (km)
LEP I	M_Z	2.4×10^{31}	$\sim 0.1\%$	45	55%	26.7
SLC	~ 100	2.5×10^{30}	0.12%	0.12	80%	2.9
LEP II	~ 210	10^{32}	$\sim 0.1\%$	45		26.7
	(TeV)			(MHz)		
ILC	$0.5 - 1$	2.5×10^{34}	0.1%	3	80, 60%	14-33
CLIC	$3 - 5$	$\sim 10^{35}$	0.35%	1500	80, 60%	33-53

TABLE I: Some e^+e^- colliders and their important parameters: c.m. energy, instantaneous peak luminosity, relative beam energy spread, bunch crossing frequency, longitudinal beam polarization, and the total length of the collider. The parameters are mainly from PDG [4], ILC working group reports [14], and a recent CLIC report [15].

Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ ($\mathrm{cm^{-2}s^{-1}}$)	$\delta E/E$	f (MHz)	#/bunch (10^{10})	L (km)
Tevatron	1.96	2.1×10^{32}	9×10^{-5}	2.5	p: 27, $\bar{p}$: 7.5	6.28
HERA	314	1.4×10^{31}	0.1, 0.02%	10	e: 3, p: 7	6.34
LHC	14	10^{34}	0.01%	40	10.5	26.66
SSC	40	10^{33}	5.5×10^{-5}	60	0.8	87
VLHC	$40 - 170$	2×10^{34}	4.4×10^{-4}	53	2.6	233

TABLE II: Some hadron colliders and their important parameters [4]: c.m. energy, instantaneous peak luminosity, relative beam energy spread, bunch crossing frequency, number of particles per bunch, and the total length of the collider. For reference, the cancelled SSC and a recently discussed future VLHC [16] are also listed.

Introduction
The LHC - Scenarios

- (Most optimistic) We detect a smoking gun signature which strongly points to a particular model (a KK tower, long lived gluinos etc) This would give very strong incentives for future research.
- We discover new physics but cannot tell what it is. This would still give an incentive for a future collider, possibly a linear collider in the right energy range.
- We have a few sigma events here and there, but no discovery level signatures. In this case we are likely to keep running the LHC, with increased luminosity.
- (Most pessimistic) We see nothing but the SM (say with a single doublet Higgs). In this scenario it is not clear whether any new collider would be built in a foreseeable future.

Introduction
Why a Theorist Should Have Data Analysis Skills

- In the most optimistic scenario we do not have to work too hard, in the most pessimistic scenario there is not a lot we can do.
- For the other scenarios we will likely have a LONG time before the next collider. If the LHC data is all we have, we have to extract each last piece of information from it. Theorists may notice something that the experimentalists have overlooked.
- In any case once the LHC turns on, the field of phenomenology will be shifted towards collider physics and it does not hurt to start building up one’s skills today.

Introduction
What Have Theorists Been Doing?

- So far the field of phenomenology has thought about collider physics in one direction. “Here is my model, and here are some interesting signatures of it, so somebody please look for those in your experiment”
- There are a LOT of models out there.
- The signatures of different models are not necessarily distinguishable.
- When the LHC turns on, the real question we face will be ‘Here is the data. What is the physics behind it?’ We need to start working on *this* question.
- The LHC is not a precision machine. We will need to get smart in order to identify new physics.

Introduction
What Have Experimentalists Been Doing?

- So far, experimentalists have taken a rather specific approach towards the analysis of new data.
- There have been extensive studies of benchmark points (SPS 1a etc) and their local neighborhoods in parameter space. Even then there is significant degeneracy.
- We really need a much broader and model independent framework to tell between entirely different kinds of new physics.
- (Entre nous) We are told that the ATLAS group did once have a black-box challenge. We hear they have not done very well. It may be up to us theorists to save the day.

LHC Olympics – What *is* it?

- Right now three groups (Harvard, Michigan and Seattle) are generating black-boxes of different kinds of BTSM physics. Our goal is to try to extract the maximal amount of information from the black-boxes, and also analyze our own ‘white-box’.
- More groups are thinking of joining in.
- For those who wish to participate without going through the pain of coding their own analysis program, the Harvard group has made a Mathematica analysis package called ‘Chameleon’ publicly available online, together with a tutorial prepared by Philip Schuster and Natalia Toro. The Harvard blackbox site is http://www.jthaler.net/olympics
- We do not intend to do the experimentalist’s job, but we do hope that combining a theorist’s broad model building intuition with familiarity of the specific methods and difficulties of collider physics will enable us to devise signatures that will help in revealing the nature of BTSM physics. It will likely be a long road made up of numerous short stages.

Hadron Colliders vs. $e^+ e^-$ Colliders 1

- An $e^+ e^-$ collider has the advantages that we are to a very good approximation in the CM frame (good control over kinematics + maximum available energy),
- We can calculate the SM background very well,
- The initial state is uncharged under the global symmetries of the SM (lepton # etc) so one can create particle antiparticle pairs easily,
- One can (at least partly) polarize the beams to look for chiral couplings, forward-backward asymmetries etc.
- The disadvantages are: Electrons synchrotron-radiate a LOT. It is difficult to get them to high energies. (Linear collider? Lower luminosity)
- The initial state couples to a spin 1 particle so resonant production of spin 0 (Higgs) or spin 2 (gravitons) is suppressed.

Hadron Colliders vs. $e^+ e^-$ Colliders 2

- Some advantages of hadron colliders: Protons are heavy and so do not synchrotron radiate as much, leading to higher achievable CM energies. Storage rings help with luminosity.
- Very large cross sections due to QCD.
- qq, qg, gg initial states allow for resonant production of different spin states.
- The down sides are: The hard scattering happens between partons so we utilize only a fraction of the available CM energy and we are not in the CM frame, thereby losing a lot of kinematical information.
- We cannot calculate with QCD to high accuracy and very large backgrounds tend to overwhelm any interesting signals.
- The proton is a complicated bound system, and we need to know parton distribution functions to high accuracy in order to calculate cross sections.

Particle Detectors – In a Nutshell

- Closest to the beam we have vertex detectors, then a charged particle tracking chamber, then EM calorimeters, hadronic calorimeters and finally muon chambers on the outside.

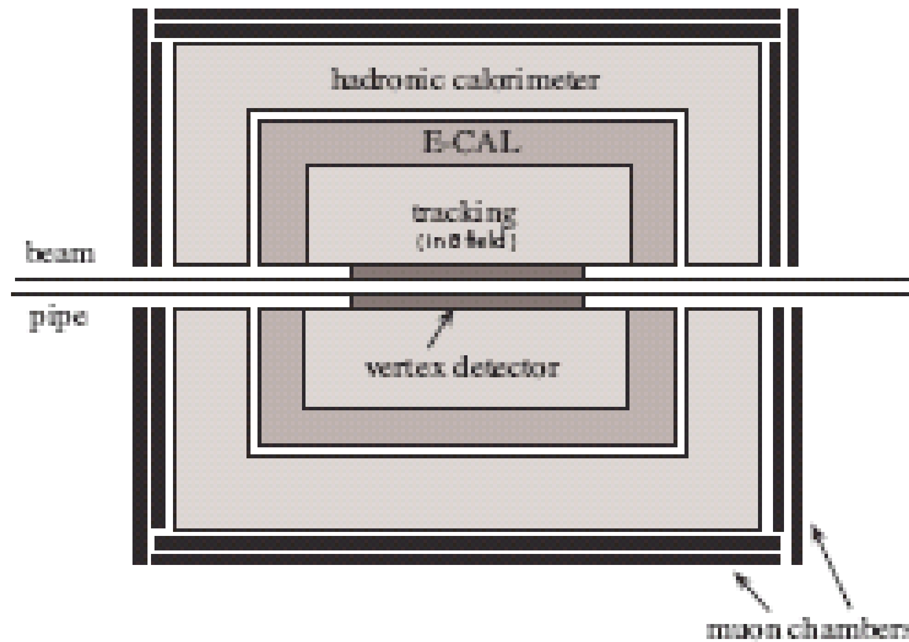
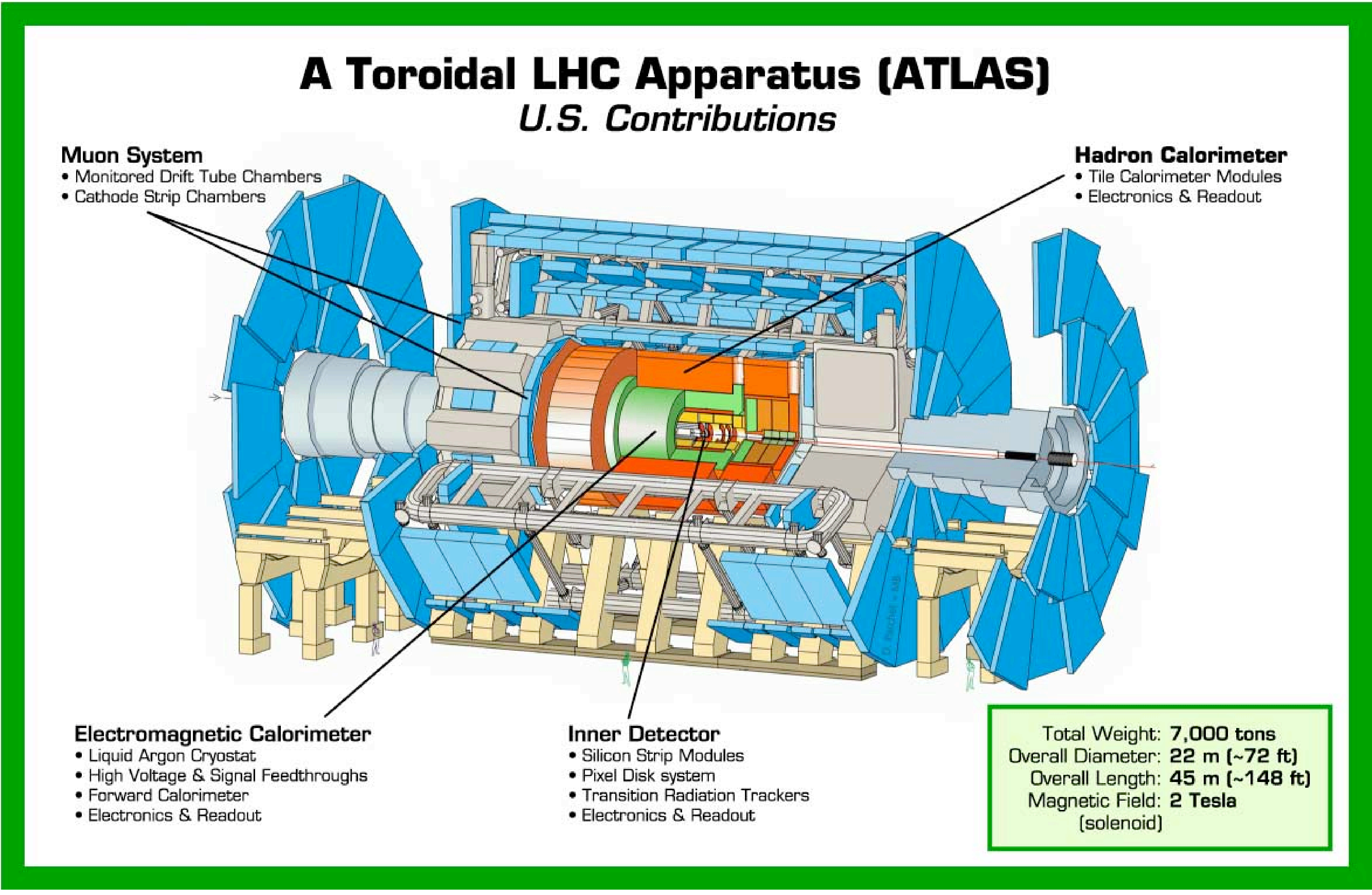


FIG. 7: Modern multi-purpose detector at colliders.

Particle Detectors – The Real Thing



Particle Detection

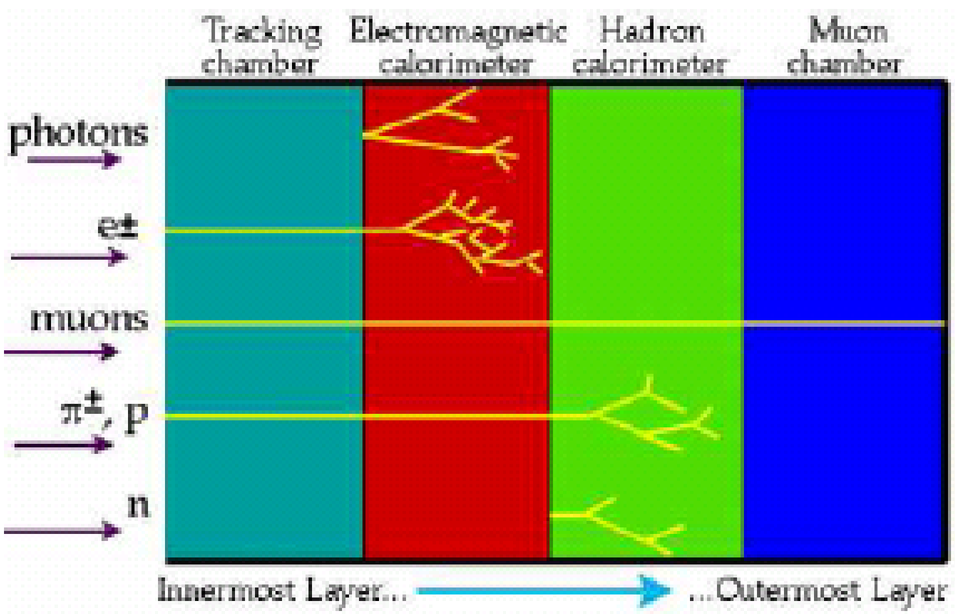


FIG. 8: Particle signatures left in the detector components.

- Charged particles show up in the tracking chamber.
- Electrons and photons deposit their energy in the EM calorimeters.
- Strongly interacting particles deposit their energy mostly in the hadronic calorimeters
- Ideally, only muons make it beyond the calorimeters and can be detected in the muon chambers.

What Do We See?

- We 'see' particles with life-times of T>10^{-10} s, including n, Λ, K^0, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$.
- We do NOT see short lived particles like π^0 , Z , $W^{\pm}$,t…
- We can reconstruct displaced vertices for particles with life-times of order 10^{-12} s, like $B^{\pm,0}$, $D^{\pm,0}$, $\tau^{\pm,0}$.
- Particles that do not interact strongly or electromagnetically and that are long lived will escape the detector, thereby reducing the kinematical information available. This can be a ν, the LSP in SUSY scenarios with R-parity etc.

Leptons	Vetexing	Tracking	ECAL	HCAL	Muon Cham.
$e^{\pm}$	$\times$	$\vec{p}$	E	$\times$	$\times$
$\mu^{\pm}$	$\times$	$\vec{p}$	$\surd$	$\surd$	$\vec{p}$
$\tau^{\pm}$	$\surd\times$	$\surd$	$e^{\pm}$	$h^{\pm};\ 3h^{\pm}$	$\mu^{\pm}$
ν_e, ν_μ, ν_τ	$\times$	$\times$	$\times$	$\times$	$\times$
Quarks					
u, d, s	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$c \to D$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$b \to B$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$t \to bW^{\pm}$	b	$\surd$	$e^{\pm}$	$b + 2$ jets	$\mu^{\pm}$
Gauge bosons					
γ	$\times$	$\times$	E	$\times$	$\times$
g	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$W^{\pm} \to \ell^{\pm}\nu$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}'$	$\times$	$\surd$	$\surd$	2 jets	$\times$
$Z^0 \to \ell^+\ell^-$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}$	$(b\bar{b})$	$\surd$	$\surd$	2 jets	$\times$

TABLE III: What the elementary particles in the SM look like in detectors.

A Theorist’s Data

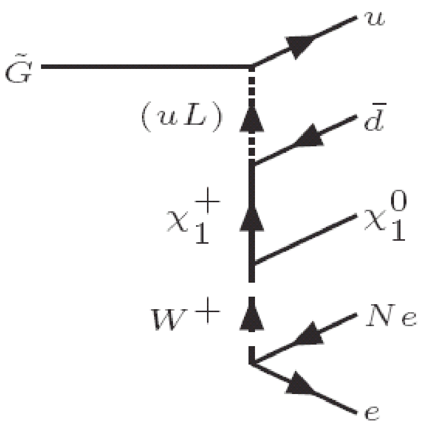
- We generate events using the program PYTHIA developed by Sjostrand, Lonnblad, Mrenna and Skands.
- We pipe the generated events into the ‘Pretty Good Simulator’ for a detector (PGS) developed by John Conway.
- An event looks like this
- #typ eta phi pt jmas ntrack btag
- 1 1 -1.278 2.857 25.49 1.00 1.0 0.0
- 2 1 -0.842 4.947 49.05 -1.00 1.0 0.0
- 3 4 -0.354 2.444 267.25 11.21 8.0 0.0
- 4 4 -0.344 3.896 120.54 9.01 9.0 0.0
- 5 4 2.250 4.937 39.44 0.00 0.0 0.0
- 6 4 0.495 5.882 50.28 7.72 7.0 0.0
- 7 4 0.865 0.939 27.65 2.59 4.0 0.0
- 8 4 0.688 2.269 16.37 4.09 4.0 0.0
- 9 6 0.000 6.180 249.38 0.00 0.0 0.0

Analysis

- We look at ‘inclusive signatures’. These can be things as simple as counting the number of different types of particles in events, or calculating the invariant mass from a subset of particles in the event.
- Last year Jesse Thaler and Liantao Wang at Harvard have prepared an analysis software package for MSSM models.
- By scanning a large number of SUSY models they have found a large degeneracy (work to be published soon), meaning we would have to introduce more diverse signatures to distinguish between these models.
- In the end we are hoping to come up with signatures to distinguish between many different BTSM scenarios, not only SUSY.

Basic SUSY Phenomenology

- In SUSY with R-Parity, the LSP is stable and can be a neutralino, (bino or higgsino-like, depending on the spectrum) or a gravitino (among other possibilities). It will carry away missing energy.
- In a hadron collider the first supersymmetric particles to be produced would be squarks or gluinos, depending on which is kinematically favorable, and these will start the decay chain.
- A possible gluino decay chain may look like this and is virtually impossible to reconstruct.



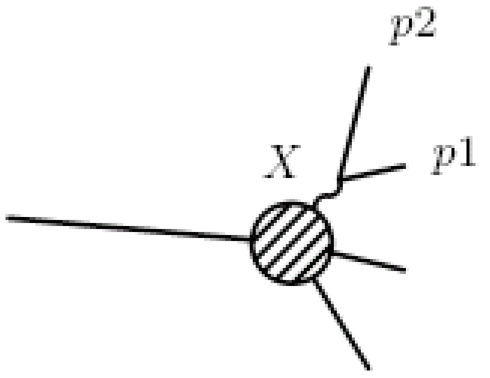
More SUSY Phenomenology

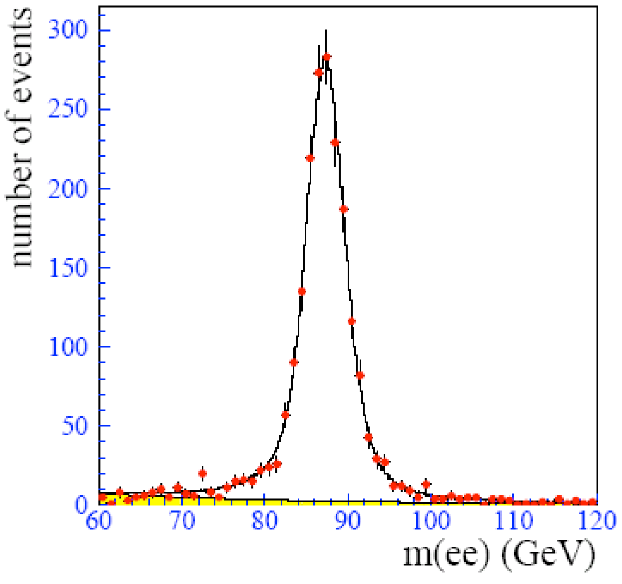
- In almost all scenarios of SUSY breaking, the colored sparticles are significantly heavier than uncolored ones due to RG evolutions of masses. This holds for gluinos vs. other gaugions as well as squarks vs. leptons. The stop is usually the lightest squark.
- Left handed sparticles are usually lighter than right handed ones because of the SU(2) contribution to their mass RGE's.
- Usually gluinos are heavier than squarks so squarks decay into charginos/ neutralinos + quarks. Gluinos decay into a squark and a quark.
- Sleptons decay into charginos/neutralinos and a lepton.
- For $\mu > M_{1,2}$ the lighter chargino and neutralino will be wino and bino-like. Otherwise there will be mixing between gauginos and higgsinos.
- Charginos and neutralinos usually decay either into lighter chargino/ neutralinos + gauge bosons (higgs) or into a sfermion + fermion. Sleptons are kinematically favored over squarks. If none of these channels are available they will decay through off shell intermediate states. If the gravitino is the LSP, the NLSP (assuming it is a neutralino) will decay to it via emission of a photon.

Kinematics Worth Looking At

The Bump

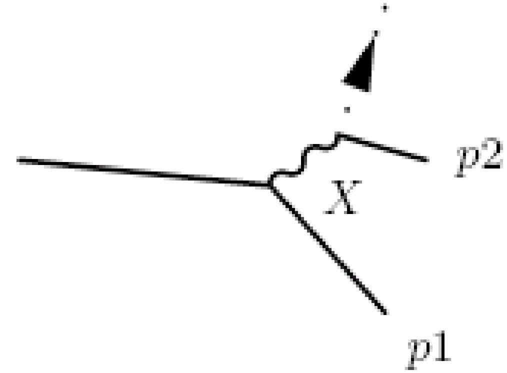
- The most obvious thing to look for is a peak in the invariant mass distribution. This points with certainty to the resonant production of an intermediate on-shell particle.

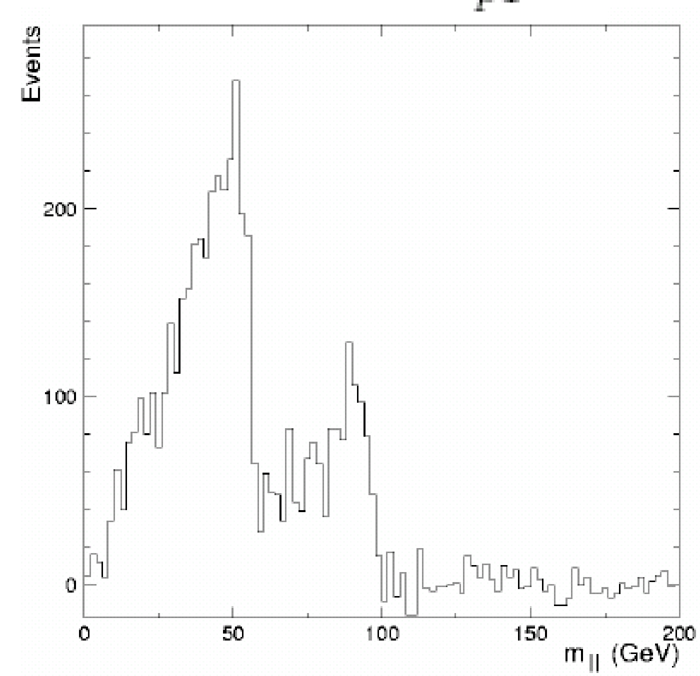




Kinematics Worth Looking At
The Edge

- In three body decays with an intermediate on-shell particle one of whose decay products is invisible, one expects the invariant mass of the two visible particles to have an edge (shoulder)



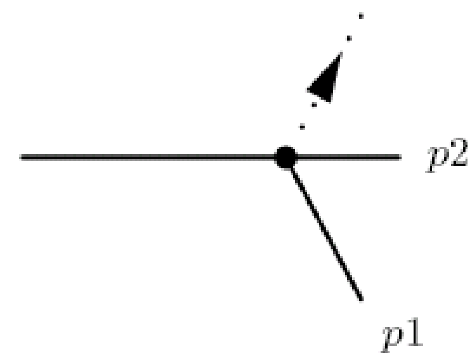


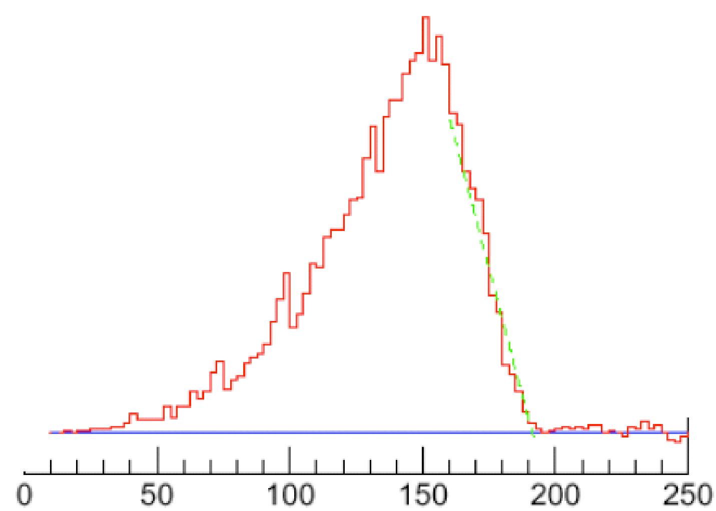
$$(m_{p1}+m_{p2})^2_{max} = \frac{(m_{in}^2 - m_{inter}^2)(m_{inter}^2 - m_{unseen}^2)}{m_{inter}^2}$$

Kinematics Worth Looking At

The Endpoint

- In three body decays with an off-shell intermediate particle (or no intermediate particle at all) one expects the invariant mass distribution of two of the final particles to have an endpoint.





[redacted] m + [redacted] m [redacted] in - [redacted]

A Sample Analysis

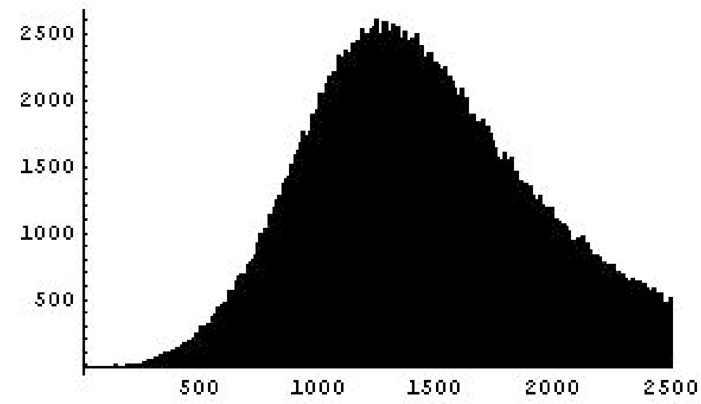
- The participants of the LHC Olympics have agreed not to present solutions to existing blackboxes before our upcoming meting on February 9th, which means that I cannot talk about what we have found in the other groups' boxes so far.
- So to give you a taste of the kind of analysis we are doing I have prepared a blackbox analysis of my own (I have asked Jesse Thaler to make up a 'presentable' blackbox without telling me the contents). The purpose of the following few slides is to demonstrate what one can do quite a bit with even very basic analysis.

Analysis - Cuts

- Any ‘real’ data is bound to come with a LOT of SM processes. To see any signal at all one tries to put cuts on events and particles that will eliminate most of the background.
- In the following (unless explicitly stated otherwise) I will be using an event veto for missing pt less than 125 GeV and 25 GeV cuts on the particle level.
- About 320000 events survive these cuts with an integrated luminosity of 40 fb^{-1} , which is consistent with a cross section of 8 pb (or more - cuts). This is a large enough cross section to make us suspect a strong coupling to the new physics sector. The primarily produced particles are probably charged under color.

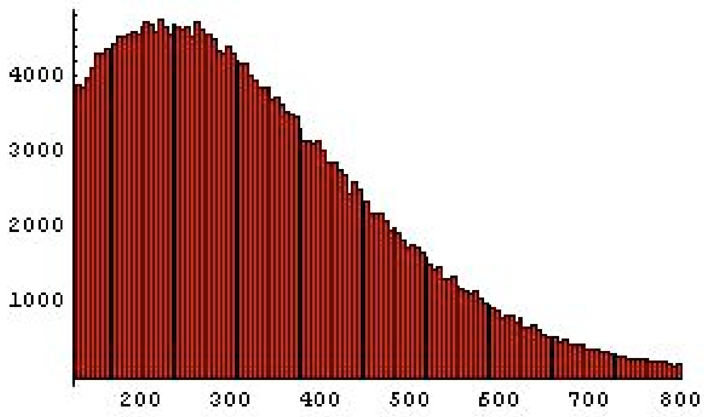
Analysis
Total Invariant Mass

- First thing one can look at: The total invariant mass of all particles in the event.
- This is not only very rough, but also ambiguous, not only have we cut particles out, we also have to assign a random (by default zero) rapidity to the missing pt.
- Yet, this can still give us a clue as to what energy scales contain new physics.
- Here, the majority of events seem to have a CM energy of roughly 1.5 TeV.
- In a SUSY scenario this might point to pair production of particles with masses of around 700-800 GeV.



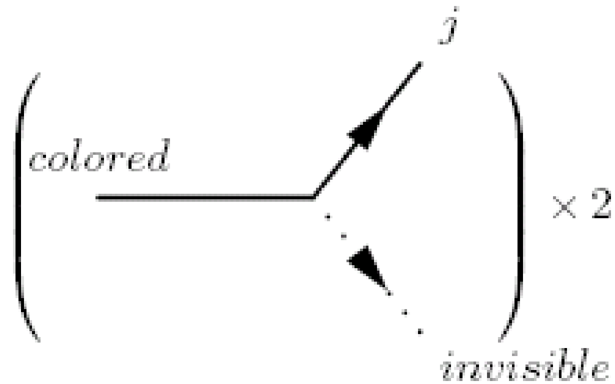
Analysis
Missing pt

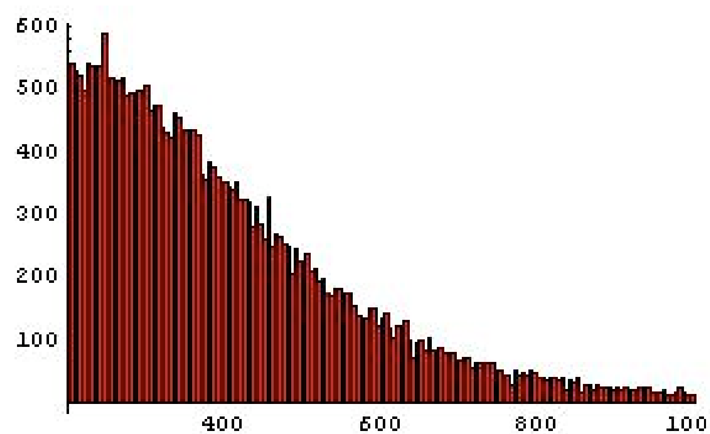
- There is a large amount of missing pt in most events.
- We appear to have at least one metastable invisible particle. Such a particle must be neutral under color and EM.
- This, combined with the large cross section points to more than one new type of particle.
- Our best guess at this stage: At least one colored particle that decays to at least one type of invisible particle.



Analysis
Primary Products

- If the primary products are color charged, the first decay product is likely to be a jet.
- Let us consider the following process:
- We plot jet-pt in events with 2 jets and nothing else.
- We seem to have an approximate endpoint at 700 GeV. This would roughly correspond to the mass difference between the primary products and the invisible particles.
- In a SUSY scenario we might make a guess of squarks/gluinos at roughly 800 GeV and the lightest neutralino at roughly 100 GeV.



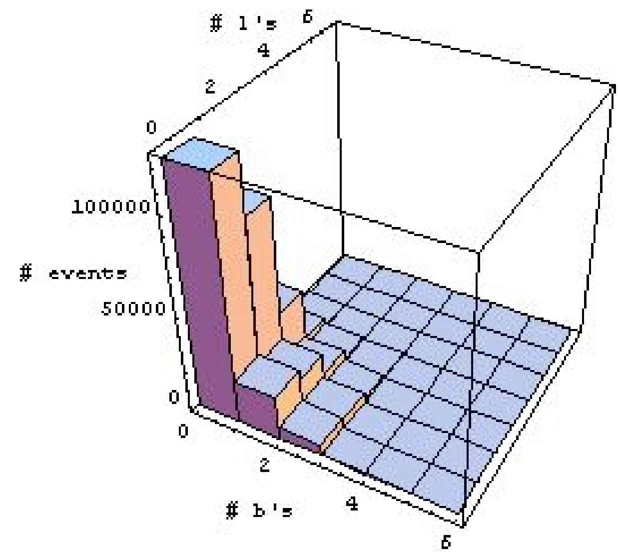


Analysis
Counting Leptons

e−	e+	μ−	μ+	τ−	τ+
22054	30116	19379	25975	9432	11765

Number of leptons per event	0	1	2	3	4	5	6	7
Number of events	153905	118721	42720	7308	659	17	3	0

- We have a large number of leptons in the events. This may mean that we have intermediate states with nonzero lepton number which can go on shell. In a SUSY scenario this means that we are producing on shell sleptons. If this hypothesis is correct, it should be visible in dileptons.
- Taking into account the sensitivity of the detector to lepton species and the triggering efficiencies, these numbers are consistent with (at least approximate) flavor universality.
- In fact the R (to the closest jet) distribution is comparable to one in a t-tbar-sample, also a hint towards universal coupling.
- We find no obvious correlation or anti-correlation between the number of leptons and the number of b jets. This means that we are not producing a large number of top quarks.

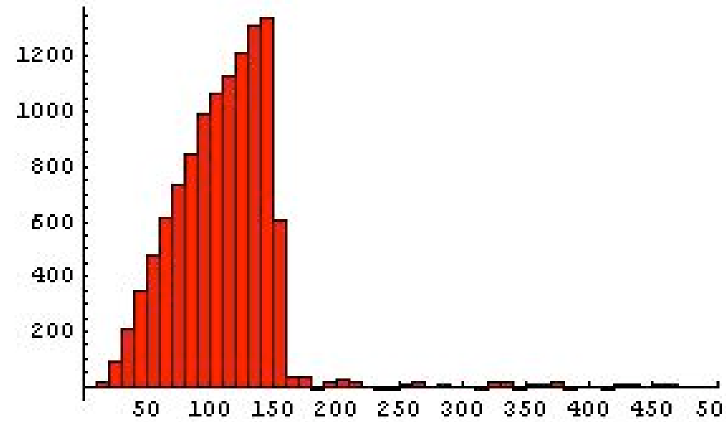


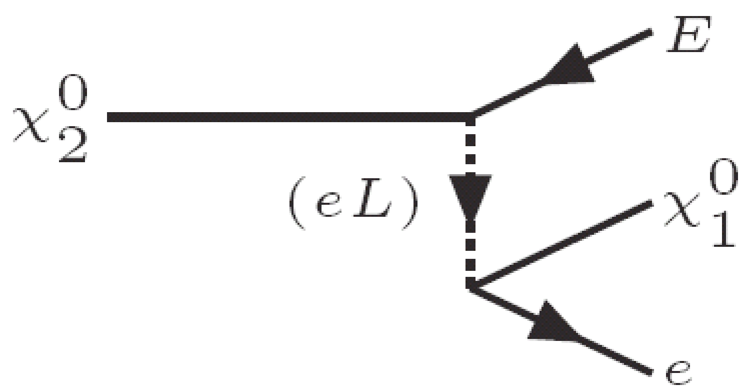
Analysis

Dileptons

	$\tau-$	$\mu-$	e−	e+	$\mu+$	$\tau+$
$\tau-$	182	665	801	1866	1595	1294
$\mu-$	0	512	1165	3033	7511	1515
e−	0	0	721	9642	2999	1722
e+	0	0	0	1380	2318	1297
$\mu+$	0	0	0	0	1043	1158
$\tau+$	0	0	0	0	0	301

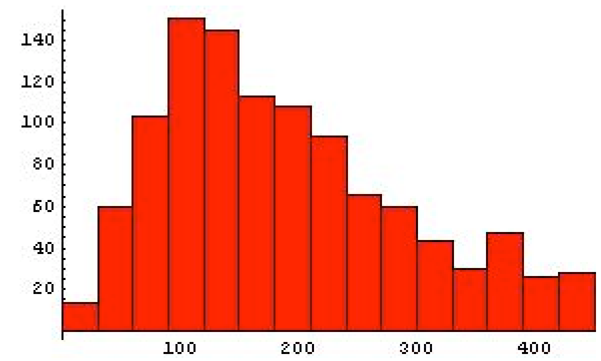
- We find a strong preference for opposite sign same flavor dileptons (Z's?) and also OSDF dileptons (two decay cascades that are charge correlated giving off $W^+ W^-$, in a SUSY scenario this may point to squarks being the primary particles to be produced)
- A flavor subtracted dilepton invariant mass distribution has a very distinct edge at 150 GeV. This is consistent with an on shell intermediate state with nonzero lepton number. If this is a SUSY scenario then we are most likely seeing the slepton edge.

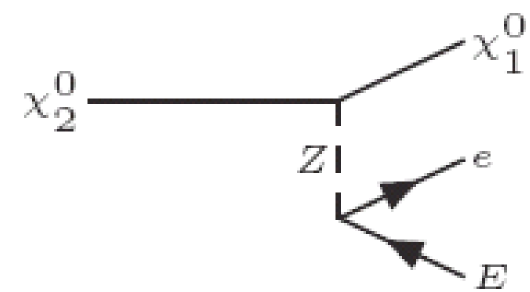




Analysis
Z's

- In OS dilepton events that reconstruct a Z, we plot the 3-momentum of the Z.
- Most Z's seem to have momenta of 100-200 GeV, however there may be a peak at 400 GeV. In a SUSY scenario this could correspond to a ~ino mass difference (χ4->χ1 for instance).
- There appear to be a good number of Z's produced. (In SUSY this would indicate that there is at least one ~ino mass difference above the Z mass.)





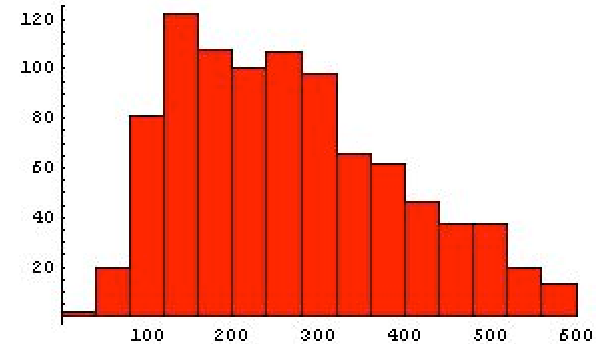
Analysis
Counting b jets

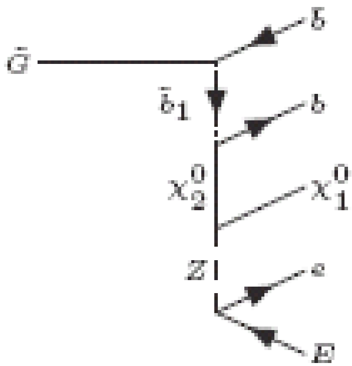
Number of tagged b's per event	0	1	2	3	4	5	6
Number of events	257195	51047	13857	1106	122	6	0

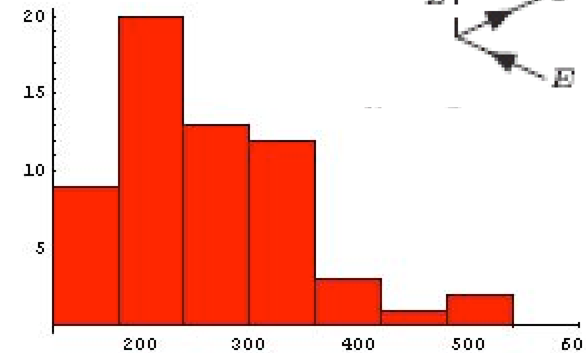
- One can count b-jets
- With a b-tagging efficiency of about 50% this is not a surprising number of b-jets. In fact it is not hard to believe that the colored primary particles are decaying more or less equally into all quark flavors.
- We find no obvious peak in bb events at low energies, if there is a Higgs, it is not visible in this channel.
- So far everything appears to be consistent with SUSY. Let us look for a bb OS dilepton edge coming from gluinos.

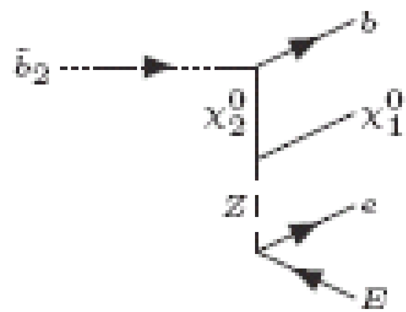
Analysis
b-Edges

- In bb OS dilepton events we plot the bb invariant mass. There appears to be an edge at 300 GeV. This suggests that the decay chain starts with a gluino which can decay to squarks.
- In the same events where the dileptons reconstruct a Z we plot the invariant mass of the Z and the softer b. There is an edge at 350 GeV.





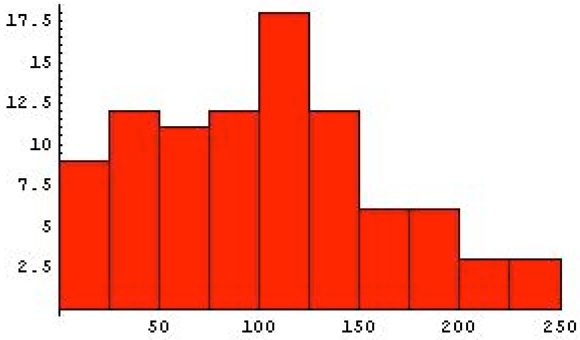




Analysis
Photons

Number of photons per event	0	1	2	3
Number of events	316714	6511	108	0

- We do not find a large number of photons.
- In a SUSY scenario this disfavors gauge mediation. We would then likely have a neutralino as the LSP.
- In diphoton events we plot the invariant mass of the two photons. There appears to be a small peak around 120 GeV. This could be h->γγ.



Analysis
Conclusions So Far

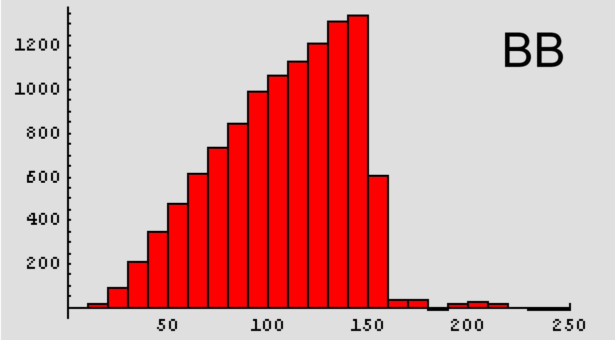
- Everything is consistent with a SUSY scenario with a neutralino LSP.
- The cascades probably start with a gluino. From the mpt and minv plots we make a rough guess for Mg~800 and $M\chi_1$~150.
- From the peak at Z's we guess $M\chi_4$~550 and for having on shell Z's we try $M\chi_2$~350.
- To match the slepton edges we find ML~250.
- From the bb edge we find MB~675.
- Finally all this is consistent with the location of the bZ edge.
- We may have a Higgs at around 120 GeV.
- It is not clear at this point where the last neutralino state is, generically it will be nearly degenerate with one of the other ones (assuming there is no large mixing between the gauginos and the higgsinos) at approximately μ. In fact it is rather generic for SUSY scenarios with flipped M1,M2 and μ to give near degenerate signatures and it is an interesting question in general how one might tell them apart. For the moment we will take μ>M2>M1.

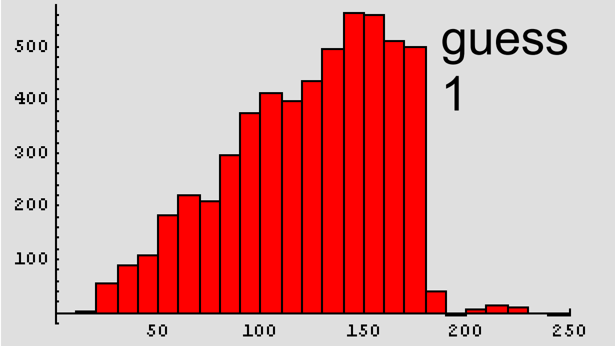
Analysis
Towards an Answer : Model Simulation

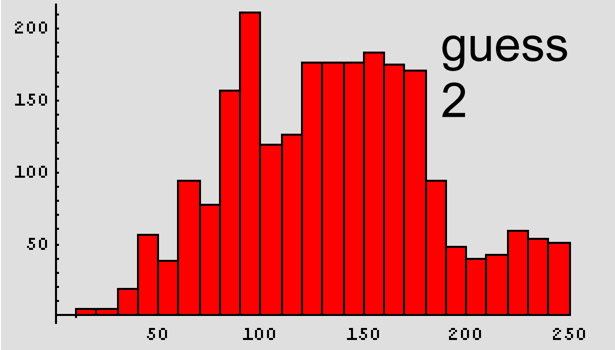
- Now we simulate our best guess model and compare with the black box. An important check on our guess is the total cross section.
- We find that our guess has a cross section that is within 5% of the correct one. Also all counts are within a few $N^{1/2}$.
- We also find good agreement in all plots. The edge in the dileptons is about 10 GeV too high. The Higgs peak in diphotons is visible but a little too low.
- In the next step of the analysis we would further tune our MSSM input parameters to account for these discrepancies and simulate a better guess. I will cut off this sample analysis here as we have done the 'easy' part of the work and come up with a pretty good answer, the rest would be harder work to try and eliminate all small discrepancies.
- There still remains the question of breaking the larger degeneracy of the ~ino mass hierarchy. For this we simulate a second guess model, this time with $M2>\mu>M1$.

Analysis
Breaking the Degeneracy?

- In our second guess, the dilepton edge shape is different from the blackbox. The branching ratio of heavy ~ino to Z + lighter ~ino is too large.
- Also, the total number of leptons is too low and there are discrepancies in the b-jet numbers and the bb-plot.
- Furthermore, the higgs peak in the diphoton plot for guess2 is too high.
- All in all, our first guess seems to be a better fit to the blackbox than the second one.
- However, it is possible that shifting the input parameters around a little we might get the second guess to look better, we may have simply gotten lucky for the first guess.
- Finally, we have not tried all possible mass hierarchies, M1 need not be the smallest one.







Analysis
The Answer Revealed

- It turns out that our first guess was quite close to the actual answer (with the various ~ino masses within 50 GeV of where they should be), the more important shortcomings of our preliminary analysis are:
- The blackbox contained a left-right split SUSY scenario. In hindsight it is not surprising that we missed this information as it is hidden in the jet plots and buried under a lot of combinatorics. It is doubtful whether the LHC has a chance of observing such a splitting.
- We have made a good start in trying to break the ~ino ‘flipping’ degeneracy however I would not claim at this stage that we have determined a unique answer. In fact it remains in general an interesting question how one can break this particular degeneracy in more general scenarios (for instance when the sleptons cannot go on shell). We were able to make some progress in this direction when there are ~ino mass splittings less than m_Z , and one can observe edges in dilepton plots and measure branching ratios.

Analysis
Closing Comments

- One needs a more realistic background for our results to be of real value. We currently have t-tbar and diboson background samples, we would also like to have a W/Z+jets sample.
- Triggering issues in the real detector need to be taken into account in our studies. Recent versions of PGS already incorporate a rough imitation of LHC triggers.
- Still, all in all one can learn a good deal by very simple analysis.

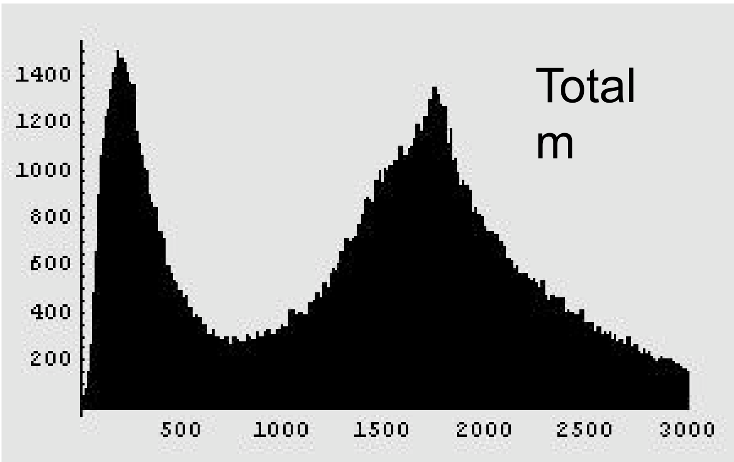
The Harvard Blackbox, Our Best Kept Secret

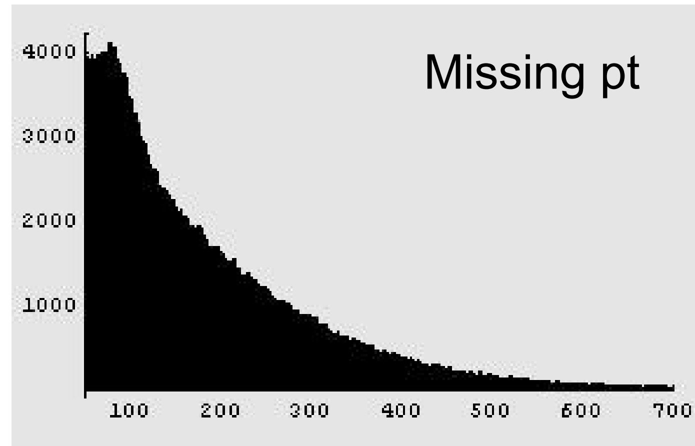
- The black-box building team includes: Jesse Thaler, Liantao Wang, C.K., Tom Hartman, Matt Baumgart and Cliff Cheung.
- Here follows a preliminary look into our black box. This is also available online on the Harvard LHC Olympics site.

Analysis
Harvard Blackbox - Cuts

- In the following we throw away:
- Leptons or photons with pt<25 GeV or $|\eta|$ >2
- Jets with pt<50 GeV or $|\eta|$>3
- Missing energy less than 50 GeV.

Analysis
Harvard Blackbox – A First Look





in a total of 384393 events:

total lepton count (e-,e+,mu-,mu+,tau-,tau+): 19768 21244 14823 15858 12096 13169

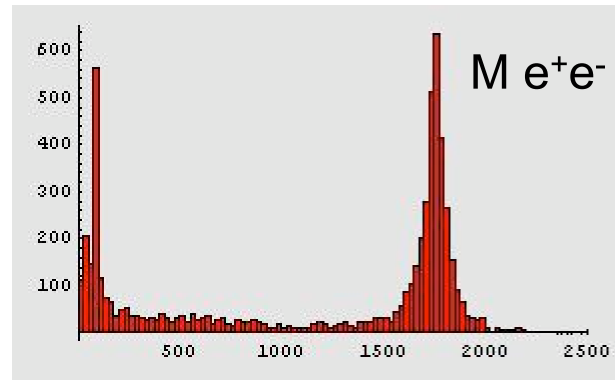
single lepton count (e-,e+,mu-,mu+,tau-,tau+): 11293 12555 7893 8818 8115 9079

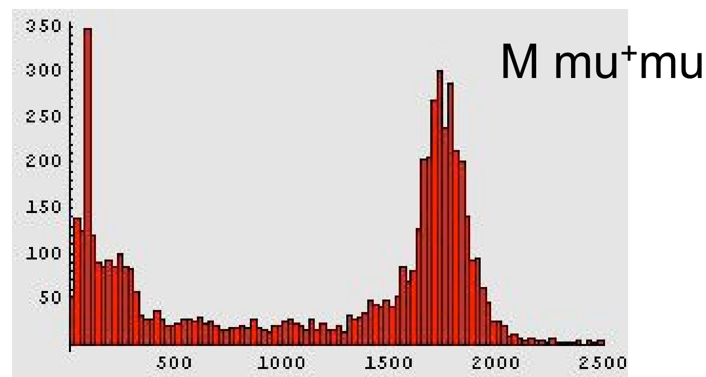
lepton counts	307485	57753	18315	787	51	2	0	0	0	0	0	0	0	0	0	0	0
b jet counts	312466	56263	13639	1825	190	10	0	0	0	0	0	0	0	0	0	0	0
jet counts	66457	46023	42845	52179	68022	56487	32758	13757	4423	1140	259	39	2	1	0	0	1
photon counts	118124	174473	90970	812	14	0	0	0	0	0	0	0	0	0	0	0	0

dilepton count table	tau-	mu-	e-	e+	mu+	tau+
tau-	90	164	229	801	654	1638
mu-	0	63	155	587	4869	646
e-	0	0	141	5920	540	784

Analysis
A Closer Look on Leptons

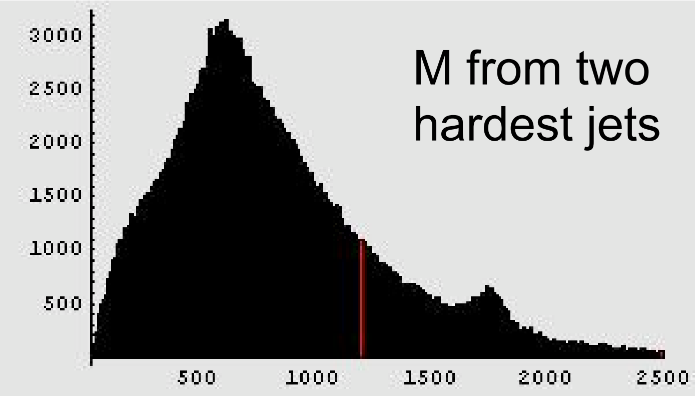
- Opposite sign dileptons seem to be favored.
- Aha!

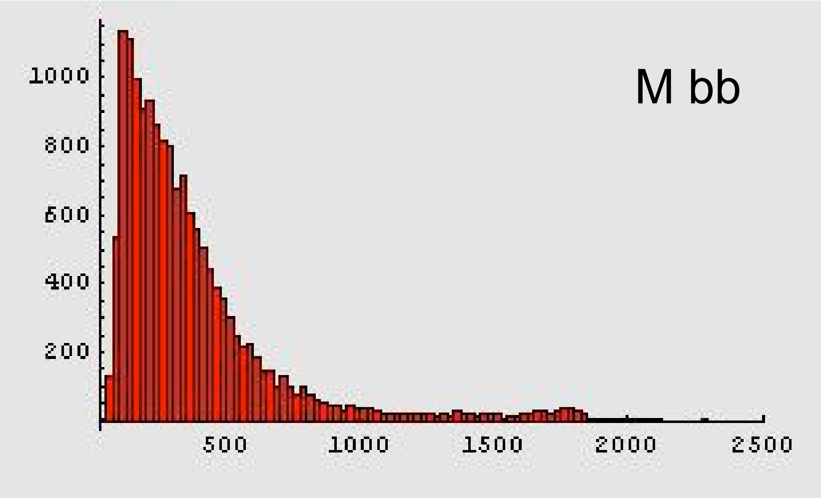


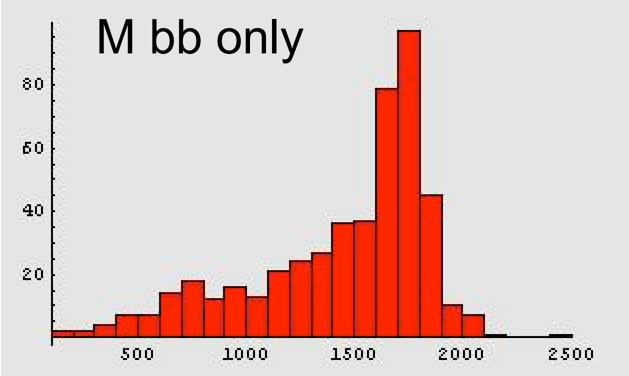


Analysis
A Closer Look at Jets

- Let us look at the invariant mass of the two hardest jets.
- bb jets…
- bb jets with nothing else in the event.
- Aha…



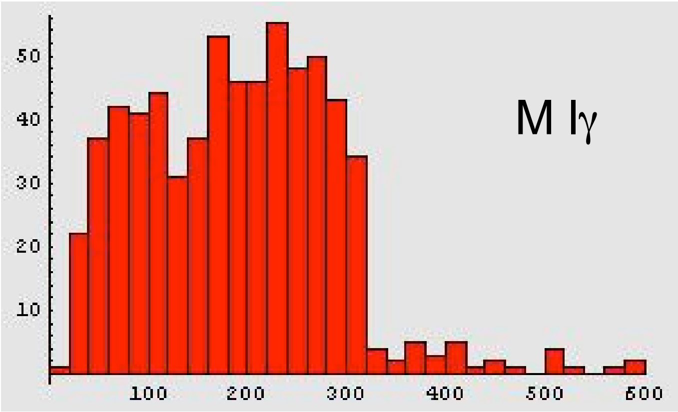


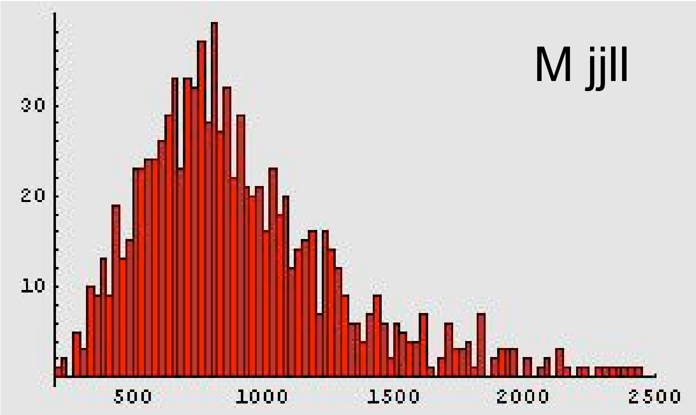


Analysis
A Closer Look at Photons

- There are a lot of diphoton events. Let us look at the dilepton distribution in these events.
- Opposite sign dileptons seem to be favored. If we pair photons and electrons using R-cuts and plot photon-lepton invariant mass we find
- Finally, let us plot the invariant mass from the dileptons and the two hardest jets (for the audience: what could this be reconstructing?)

	tau-	mu-	e-	e+	mu+	tau+
tau-	16	40	61	98	89	126
mu-	0	19	37	131	356	83
e-	0	0	22	518	114	107
e+	0	0	0	35	51	57
mu+	0	0	0	0	26	49
tau+	0	0	0	0	0	17

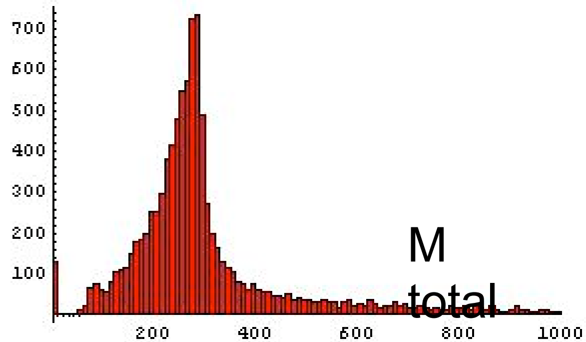




Analysis
Harvard Blackbox – What Have We Seen?

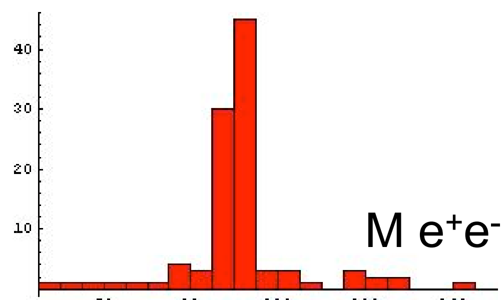
- About 400000 events for 40fb^{-1} events.
- Large number of events reconstruct to about 1.8 TeV (and there appears to be a peak around 400-500 GeV also).
- A lot of missing pt in many events.
- There are a lot of diphoton events
- Very distinct peak in opposite sign dilepton events at around 1.8 TeV.
- Also a peak in jets (and b jets) there, but less distinct.
- Diphoton events seem to favor opposite sign dileptons.
- In diphoton events, there is a distinct edge in photon lepton invariant mass (around 300 GeV) and a broad peak in dijet dilepton invariant mass (around 900 GeV)
- Now, let us find out who is still awake…

Challenge 1



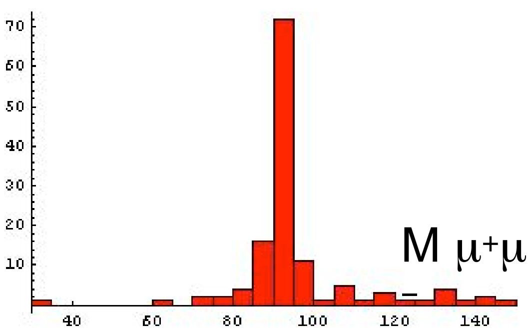
	τ+	μ+	e+	e-	μ−	τ−
τ+	47	14	10	88	93	190
μ+	0	1	1	48	147	91
e+	0	0	1	114	53	92
e-	0	0	0	0	0	14
μ−	0	0	0	0	0	19
τ−	0	0	0	0	0	53

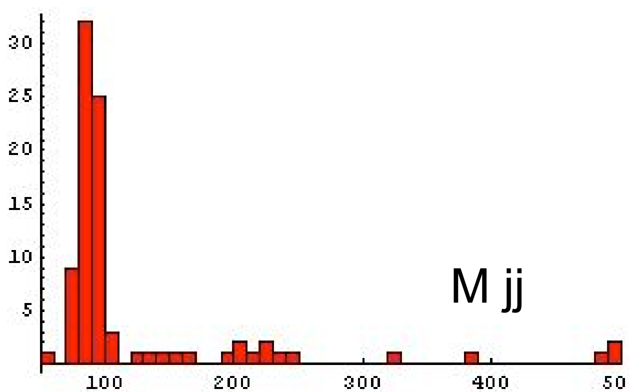
Dileptons

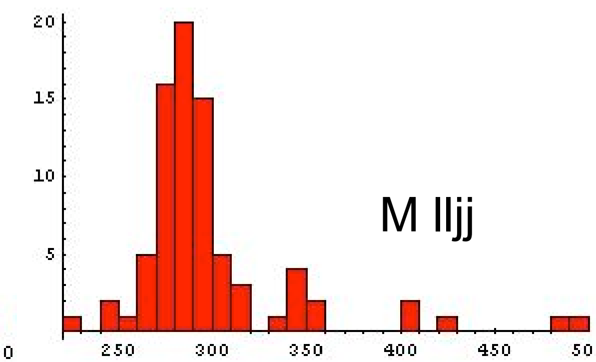


Number of jets in dilepton events

{{103, 0}, {62, 1}, {83, 2}, {10, 3}, {3, 4}}



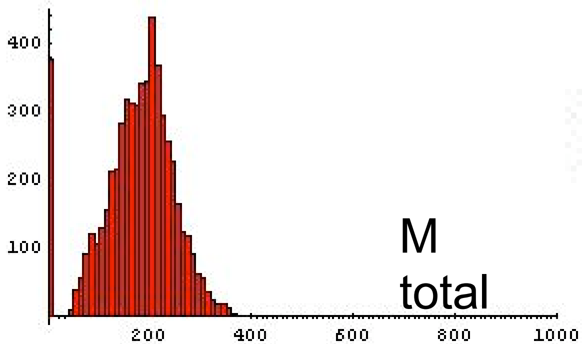




Challenge 2

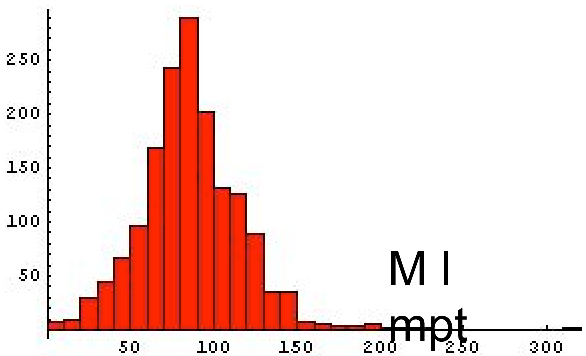
e-	e+	μ−	μ+	τ−	τ+

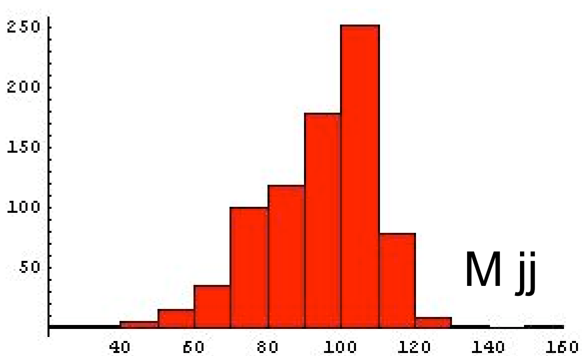
{323, 329, 308, 340, 391, 425}

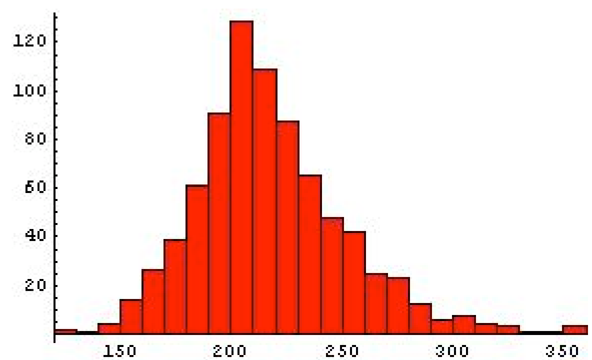


Leptons per event

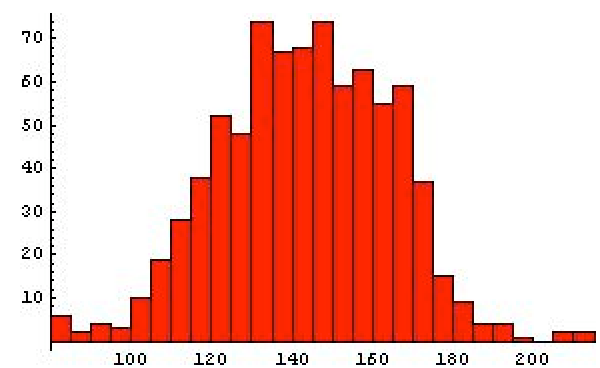
{{3908, 0}, {1606, 1}, {211, 2}, {28, 3}, {1, 4}}





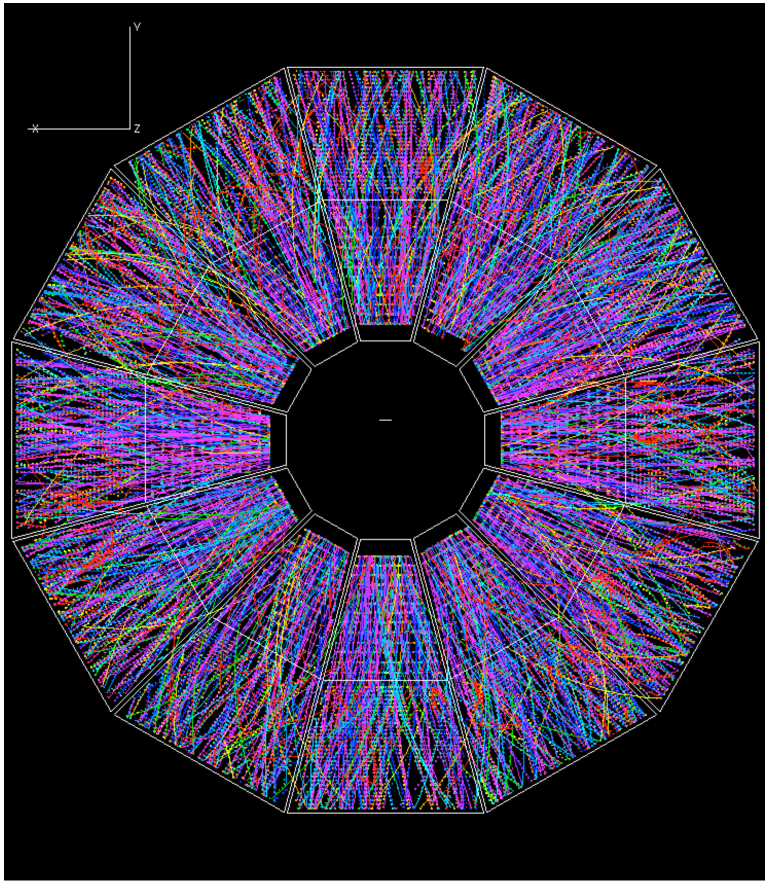


M jjl mpt



Final check : M jjl

Challenge 3



- A plethora of particles with essentially a thermal spectrum…

We Are Only Just Getting Started

- We have only recently started looking at the black-boxes from the other groups. For newcomers, hardly any previous experience is required. Anyone is welcome to join.
- You can start by generating and analyzing your own white-box as a training run until you feel comfortable enough with the analysis.
- It is time to be original and come up with interesting ideas. There are many interesting questions to be answered. (Can you tell the spin of a top partner, can you distinguish between a neutralino vs a higgsino LSP etc)
- We ultimately aim to go beyond SUSY (which means beyond PYTHIA) and simulate other models (Little Higgs? Extra dimensions?)
- For graduate students, what you learn in this project can come in very handy in a couple of years, especially in looking for jobs. (It can also get you a ticket to Geneva within the coming year)

Conclusions

- Genuine new data is coming in a few years.
- It is very likely to contain new physics.
- There is no established way of looking for the type of physics contained in new data.
- It is the time to come up with basic ideas that might distinguish between different models.
- The field is young and much can be done in a short time.
- The LHC Olympics is open for all who want to develop their data-analyzing skills.