NEW PHYSICS & THE LHC FOR BEGINNERS

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August 15, 2006

Plan of the Talk

-- Why expect new physics at the LHC?

-- Some basic hadron collider physics.

-- Detecting new Physics beyond the SM.

-- Is it SUSY?

-- Connecting Data and Theory?

a) LHC Inverse Problem

b) Testing theories against data

Standard Model (SM) – spectacularly successful!

However, has limitations :

a) Hierarchy Problem.

b) Electroweak symmetry breaking.

c) Family structure and Fermion masses.

d) Cosmological challenges.

Therefore, confident that the SM will be extended.

One such popular idea : Supersymmetry (SUSY)

-- Each known particle has a superpartner differing by spin ½ degenerate in mass and related to it by a SUSY transformation.

-- (Chiral) fermions ⟷ scalars
Can solve the hierarchy problem.

-- However, SUSY must be spontaneously broken. If SUSY breaking *soft,* no quadratic divergences reintroduced.

-- Also, superpartner masses lifted to phenomenologically acceptable scales.

--- Have to be between M_z and O(1) TeV to still solve the hierarchy problem ⟶ LOW ENERGY SUPERSYMMETRY

Another motivation for Low Energy SUSY

-- LSP naturally provides for a DM candidate.

-- O(100) GeV scale LSP gives the correct relic density!

Other Approaches to the Hierarchy Problem:

-- Warped Extra Dimensions.
-- Composite Models, etc.

For concreteness, focus on Low Energy SUSY.

All of them predict new physics at the TeV scale

Therefore, expect new physics at the LHC !!

LHC --- LARGE <u>HADRON</u> COLLIDER
(unlike LEP)

<u>CRASH COURSE ON HADRON COLLIDER PHYSICS</u>

Some Basics :

p-p collider -- different from Tevatron ($p\text{-}\bar{p}$ collider)

C.M. energy – 14 TeV (highest energy collider ever built)

Different from a Lepton Collider

-- Unlike a lepton collider, the initial quantum state (id, E, P) of colliding objects (u,d,g) in a hadron collider – not known.

-- So, only a fraction of 14 TeV available to colliding particles (u,d,g).

-- No beam polarization control.

-- LHC a great discovery machine, but perhaps not as good for precision measurements.

Great to have an ILC too! But not available to us for the next 10-15 years.

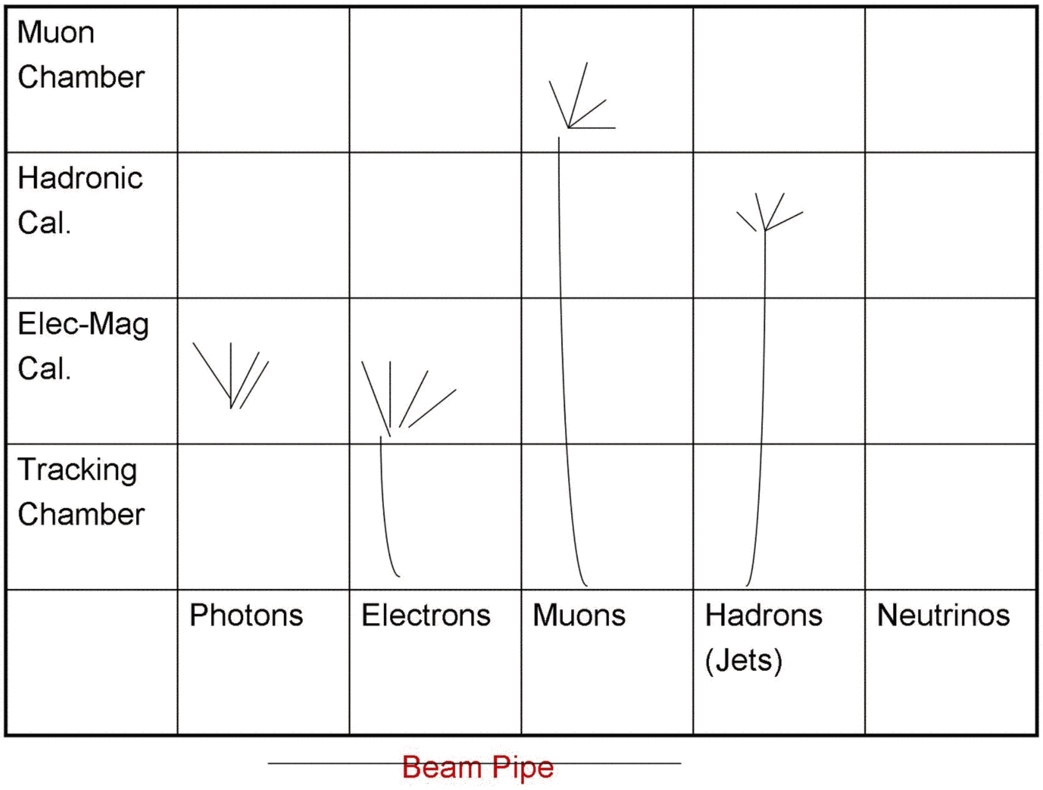
So, focus on what will be available soon (LHC)

Features of Particle Detectors

When two proton beams collide, various processes occur
--- lot of "stuff" produced. Most important ones produced from primary event vertex. Known as "hard" or "prompt".

This "stuff" is then detected by a Particle Detector.

Consists of:
-- Tracking Chamber
-- Electromagnetic Calorimeter (ECAL)
-- Hadronic Calorimeter (HCAL)
-- Muon Chamber



Objects Identified in a Detector

Photons --- Detected as energy in the ECAL, with none in the HCAL, and no track in the calorimeter cell.

Electrons --- Detected as energy in the ECAL, with none in the HCAL, and an isolated track pointing at the calorimeter cell.

Muons --- A muon leaves little energy in the calorimeter. Has a track and travels all the way to the muon chamber outside the calorimeters.

Jets -- Quarks and Gluons confined. Hadronize to form "jets". Cluster of particles detected by the HCAL.

Also possible to identify heavy flavor jets (b or c) --- have a "displaced vertex" (few mm).

Taus – Taus decay 1/3 of the time to e, $\mu + \nu$. Then cannot be distinguished from e,μ. Rest of the time, they decay hadronically. Can be detected by the HCAL.

Missing Transverse Energy – Magnitude of missing transverse momentum in an event. Cannot use $(E, P_{||})$ conservation in a hadron collider. Only P_T conservation used.

Failure of P_T conservation implies existence of neutrinos or other undetectable objects.

(For eg, in the context of SUSY, it may be the LSP)

CUTS and TRIGGERING

When two proton beams cross each other ---10^8 collisions per second !!!

Only about 10^2 per sec can be recorded at present.

Not as bad as it sounds : many of these events just confirm the SM.
(For discovering new physics – SM is the background)

So, have to decide what's interesting beforehand !

Therefore, need to program threshold conditions to decide what's interesting --- known as Triggering

Two stages – Level one (hardware)
Level two (software)

Hardware and software triggers

– designed to restrict to “potentially interesting” events and also reduce the SM background.

For Example –

Leptons – Isolation “cuts” reduce the background significantly.
Different for electron or muon.
Also have to be hard or prompt. (For eg., P_T >10 GeV)

Jets – most common objects in a hadron collider. Impose hard P_T cuts on them to reduce background. (For eg., $P_T > 100$ GeV)

Missing E_T – Impose cut to reduce background. (For eg. $\not{E}_T > 100$ GeV)

Point to take home

Any theoretical model only observable by :

The leptons, photons, jets, $\not{E}_T$ it produces in what **amounts**, what **combinations** and with what **distributions**, such that observable over background.

The background is the SM – so completely predictable.

So, one should try to develop one’s favorite model to the point that one can predict these!

More about this issue later

Detecting Physics Beyond the SM

Two main kinds of signatures at the LHC :

a) **Counting signatures** : Number of events of a particular kind – For eg. Number of events with two +ve charged muons and > 2 jets, etc.

b) **Distribution signatures :** Plot of number of objects or events as a function of a kinematic variable. For eg. the invariant mass (M_{ll}) distribution of OS dileptons

$$M^2_{ll} = (P1_\mu+P2_\mu).(P1^\mu+P2^\mu)$$

If very lucky,

-- may see a nice resonance peak. For eg, if one has an extra U(1), one can observe the Z' peak in the M_{ll} distribution.

-- relatively "easy" to discover new physics.

If not so lucky, (much more probable by definition !)

(for superpartners, essentially guaranteed)

-- Need to study various channels, and look for events *above* those predicted by the SM (the "background" completely calculable).

-- By imposing clever cuts, one can reduce the SM background, so that the signal can be seen.

No clear cut procedure. However, existence of new physics can be shown by comparing to SM.

Example – SUSY signatures beyond the SM

Large Missing E_T -- Typical SUSY models have stable LSPs escaping the detector, giving large Missing E_T (> 100 GeV).

SM --- Missing E_T from neutrinos & mis-measurement of jet energy due to a crack in the detector. Not as large.

Same Sign (SS) Dileptons – Gluinos produced in a susy model -- majorana fermions. Eventually decay equally to +ve and –ve charged leptons.

⇨ PROMPT ISOLATED SS dilepton events.

SM --- No majorana fermions produced with large cross-section. So, essentially no prompt isolated SS dilepton events.

Effective mass Distribution -- (Log Plot)

$$M_{eff} = \sum_i P^i_T + \not{E}_T$$

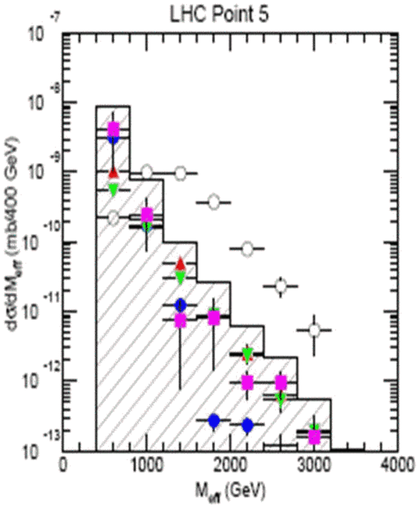


Figure 20-4 M_{eff} distribution for the Point 5 signal (open circles) and for the sum of all Standard Model backgrounds (histogram); the latter includes $t\bar{t}$ (solid circles), $W+$jets (triangles), $Z+$jets (downward triangles), and QCD jets (squares).

Observable above the

SM background typically

→ Possible to detect new Physics beyond the SM

Is It SUSY?

May be Possible to fake *some* SUSY signatures with other

models – like Universal Extra Dimensions, etc.

Looking forward to that challenge.

Expect that *combination* of different signatures will help in distinguishing other models from SUSY , eg.

a) Large $\not{E}_T$.
b) SS dilepton events. *(Datta, Kane, Toharia – hep-ph/0510204)*
c) Trilepton events.
...., etc.

Recently, lot of progress made on measuring spin of particles in cascade decays at the LHC :

-- *L.T. Wang, I. Yavin (hep-ph/0605296)*

-- *C. Athanasiou, C. Lester, J. Smillie, B. Webber (hep-ph/0605286)*

-- *A. Alves, O. Eboli, T. Plehn (hep-ph/0605067)*

……

Done by analyzing angular correlations of particles.

Although more work needs to be done, expect that can distinguish SUSY from other BSM approaches.

Two alternatives for connecting Theory and Data

a) From data to theoretical models.

b) Testing Theories against data.

Talk about both

a) From Data to Theory

LHC Inverse Problem

--- Assuming a signal, how to determine the nature of new physics from LHC Data?
--- Poorly studied until recently.
(Inverse map from signatures to parameters quite challenging)
("Degeneracies" in parameter space – Arkani-Hamed,Kane,Thaler,Wang)

Focus of the "LHC Olympics"

Idea --- create "blackboxes" – models of new physics at collider scales, compute their LHC signatures, and present them in the same format as experimenters would present them in a conference.

Goal --- To unravel these "blackboxes", as well as develop techniques towards unraveling more general and more difficult theoretical models.

“IIIrd LHC Olympics” Workshop at KITP

August 24-25, 2006

At present,

The LHC Inverse Problem – Only discusses how to go from data to low-scale theory.

Want to ultimately connect to underlying microscopic theory, like string theory.

Deeper Inverse Problem – essentially no work on this

To have any chance of doing that, first have to know how to

go from high-scale theory to data.

b) Testing Theories against Data

1) From High-Scale Theory to Low-Scale Theory.

2) From Low-Scale Theory to LHC Signatures.

First address 2) --- *This is how how blackbox models for the LHC olympics are generated.*

Then address 1) --- *How can one connect a string construction to a low scale lagrangian?*

If possible, then can go from a string construction to LHC signatures

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2) From a Low-Scale Model to LHC Signatures

As explained before, to connect any model to data, have to predict signatures measured at the LHC

--- in terms of photons, leptons, jets and $\not{E}_T$.

Therefore, worthwhile to know how to go from a Lagrangian to collider signatures.

TOOLS

1) Low-scale Lagrangian – Compute matrix elements relevant to short-distance processes in collider physics . (Eg. $q + \bar{q} \rightarrow \tilde{g} + \tilde{g}$)

(Parton-level event generation)

Various packages available – CompHEP (CalcHEP), PYTHIA, HERWIG, MADGRAPH, ALPGEN, etc.

2) Short-distance Physics evolved to Long-distance Physics
   -- Hadronization of quarks and gluons into jets of hadrons.
   -- Decays of tau leptons, etc.

So, to predict physics observed at colliders – one has to simulate the whole process for any given model.

Packages available -- PYTHIA, HERWIG.

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3) Detector simulation -- Resulting leptons, photons & jets run through a detector simulation program, to simulate a real detector.

jet reconstruction and lepton identification done at this stage.

For the LHC Olympics – package called PGS used. (originally by John Conway).

Has detector parameters similar to the CMS detector at LHC.

--- The output from PGS is the blackbox data set, used for the olympics.

--- Output contains a list of events with objects in each characterized by type, momentum 4-vector, charge or flavor information, etc.

--- Can construct many counting and distribution signatures from it.

1) From String constructions to Low-scale Lagrangians?

As we know :

-- No non-perturbative or background-independent definition of String Theory.

-- Poor understanding of the full M theory moduli space.

However,

--- Various corners of the M theory moduli space reasonably understood. (at least in the supergravity regime)

--- Recently, lot of progress in moduli stabilization and ~~SUSY~~ in various compactifications.

--- Lot of work done in heterotic and Type II string model-building.

Therefore, one should be hopeful of connecting string theory to the real world (in the SUGRA regime, with some reasonable assumptions)

An Example – Large Volume Type IIB compactifications

(Quevedo et al)

-- Part of Type IIB landscape with all moduli stabilized in the SUGRA regime. Volume quite large. (one kahler modulus (T_b) >> others)

-- Fluxes stabilize the dilaton and complex str. moduli at tree level.

-- Kahler moduli stabilized in general by both non-perturbative effects in W and perturbative effects in K.

$$W = W_0 + \Sigma_i A_i e^{-a_i T_i}$$

$$W_0 \sim O(1)\text{ , no fine-tuning of W.}$$

-- Generically obtain non-susy AdS vacua. ($F_i \neq 0$)

-- Various mechanisms can be used to uplift the AdS min. to a dS one.

At present – no explicit (MS)SM-like matter embedding in these vacua.
However, existence of MSSM-like string embeddings in toroidal type II vacua gives us hope.

Approach -- *Assume* the existence of an MSSM matter embedding with D7 branes, see what predictions it gives.

Since all moduli stabilized, can compute soft SUSY terms.

General structure of soft terms found in –*(Conlon, Quevedo hep-th/0605141)*

--- *$m_{3/2}$ and M_{st} determined by W_0 and volume (V).*
--- *Gauginos generically suppressed relative to the gravitino* ($m_{3/2}$) .
--- *Scalars generically of the same order as the gravitino.*

Scales -- Scale of soft terms set by $m_{3/2}$. Assume $m_{3/2}$.. ~ TeV, to be able to solve the hierarchy problem. This fixes the string scale in these vacua ~ 10^{10}-10^{11} GeV (if do not tune W_0).

⟶ *Standard Gauge unification (at ~10^{16} GeV) not possible in these vacua.*

Dominant contribution to soft SUSY terms depend only on the following "theory" parameters, and can be calculated :

$\{m_{3/2}, n_i\}$; n_i – modular weights, $0 < n_i < 2/3$

With a better understanding of theory, one can fix some (or all) of these.

Analysis valid for any CY 3-fold with one big kahler modulus and many small kahler moduli of roughly similar sizes, admitting a large volume limit, as in *(Conlon, Quevedo, Suruliz hep-ph/0505076)*

-- Vary $m_{3/2}$ and n_i in the appropriate range.

-- Get a "parameter space" of soft terms at the String Scale.

-- RG evolve soft terms to the low scale
(Various packages available -- SOFTSUSY, SuSPECT, SPHENO)
ISAJET, etc

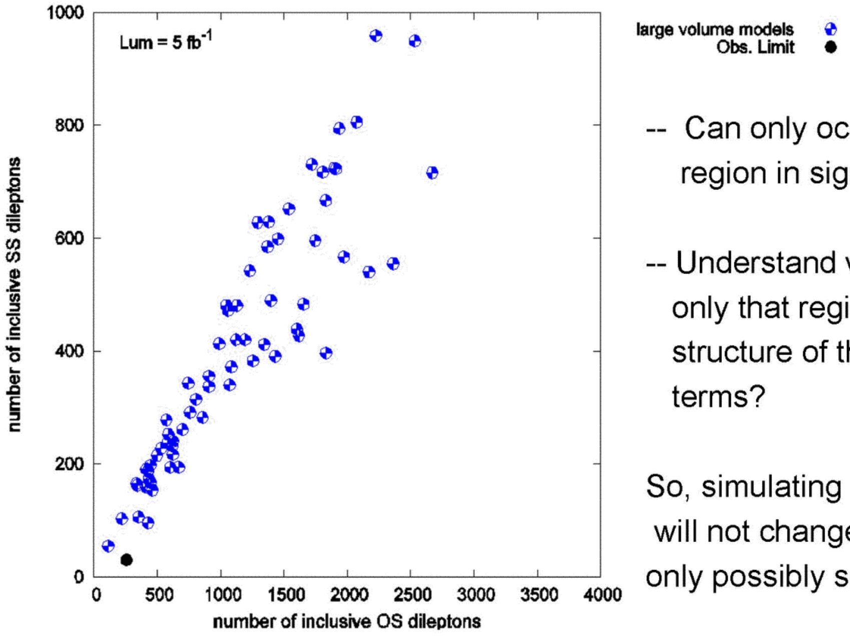
-- Have to impose constraints from experiments and observations.
So, only a subset of the “models” obtained allowed.

Some of these are –

a) Consistent EWSB.
b) Bounds on superpartner masses.
c) Bound on the Higgs mass.
d) Constraints from Flavor and CP physics.
e) Upper bound on the Relic Density.

-- One now has a subset of “models” at the low-scale consistent with all observed data.

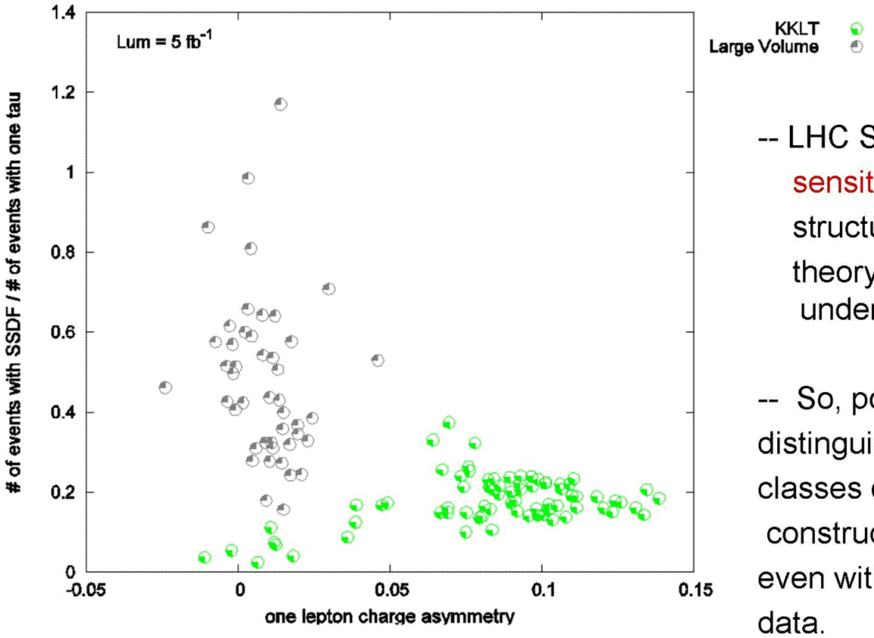
-- Carry out procedure outlined earlier to go to LHC signatures.



-- Can only occupy a finite region in signature space

-- Understand why populate only that region from structure of theory and soft terms?

So, simulating more models will not change main result, only possibly some details.



-- LHC Signatures sensitive to the structure of the theory. Can be understood.

-- So, possible to distinguish different classes of string constructions, even with limited data.

Can help in addressing the deeper Inverse Problem

CONCLUSIONS

-- We are eagerly awaiting the LHC.

-- Expect first results within 2 years from now.

-- Hopefully, the LHC will teach us a lot.