The LHC and Beyond

Jack Gunion
U.C. Davis

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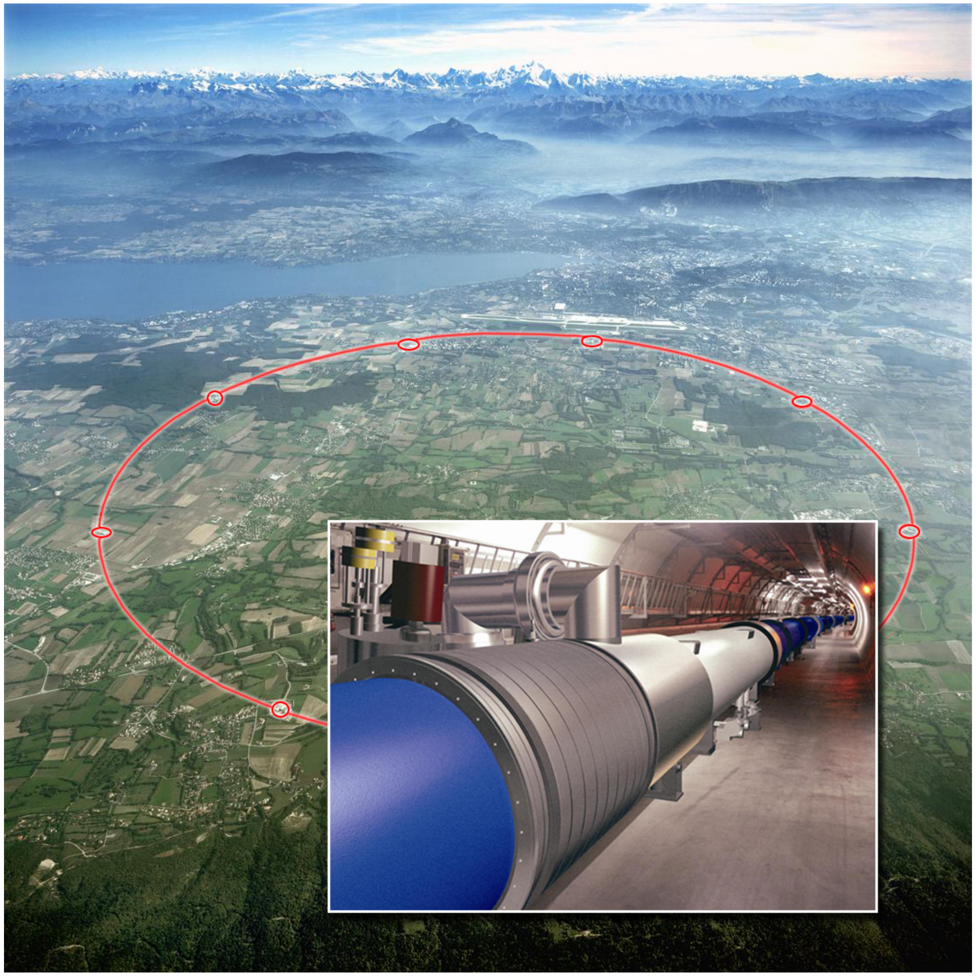
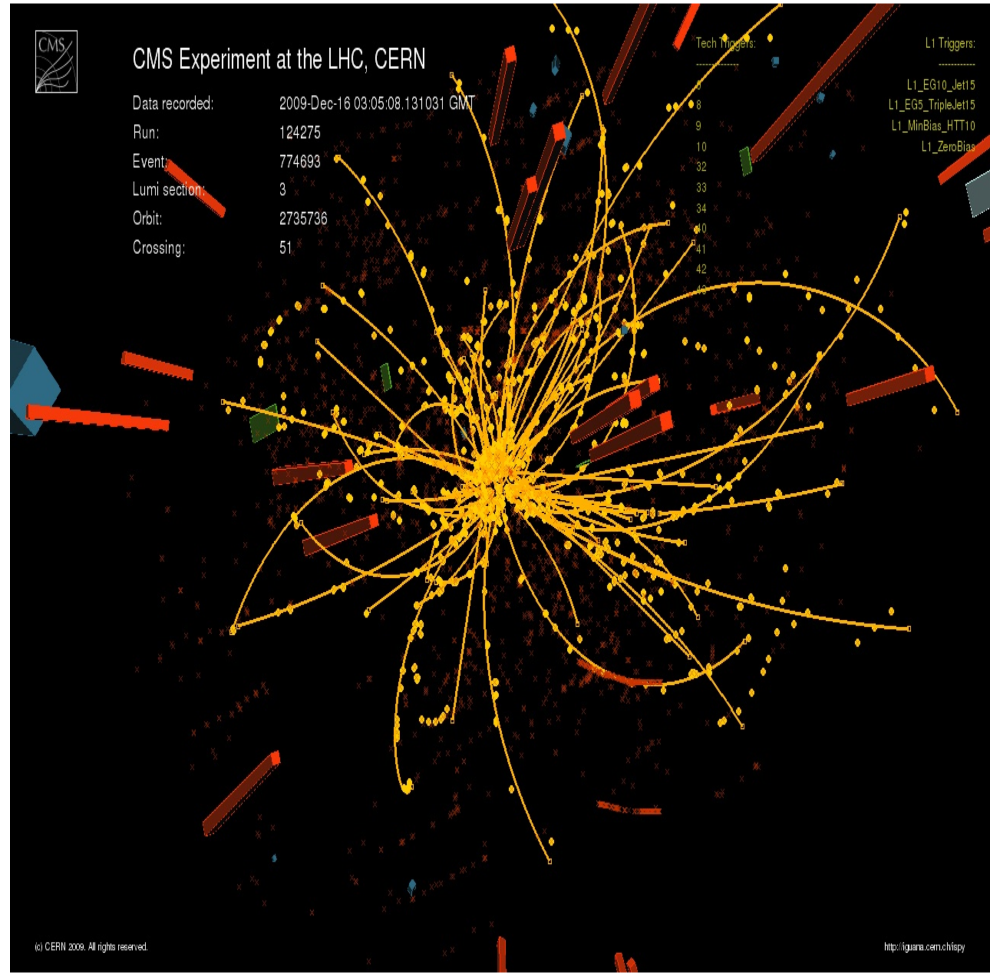
LHC Status and Status of Experiments (CMS)





The LHC is back!! **Collisions have been recorded by all detectors. Jets and muons are clearly seen.**

High Pt Dijet Candidate
Run 123596, Event 6732761

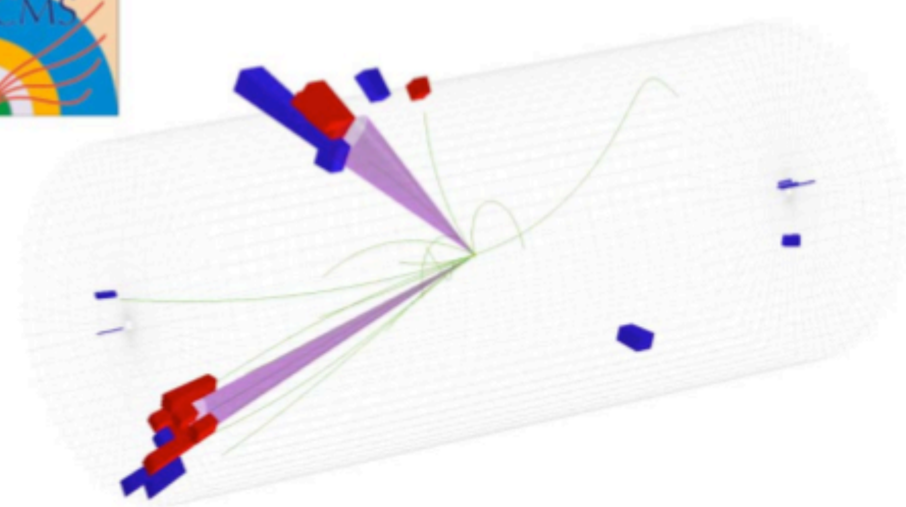
Anti – KT with cone size R=0.5

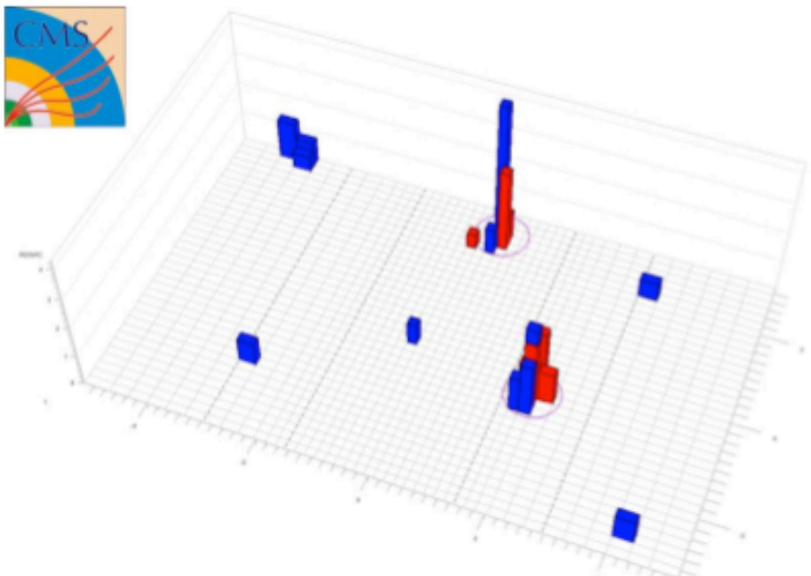
Jet1: Raw pT = 12 GeV, Corr pT = 24 GeV, PF pT = 16 GeV, phi = -0.69, eta = 1.96, EMF = 0.66

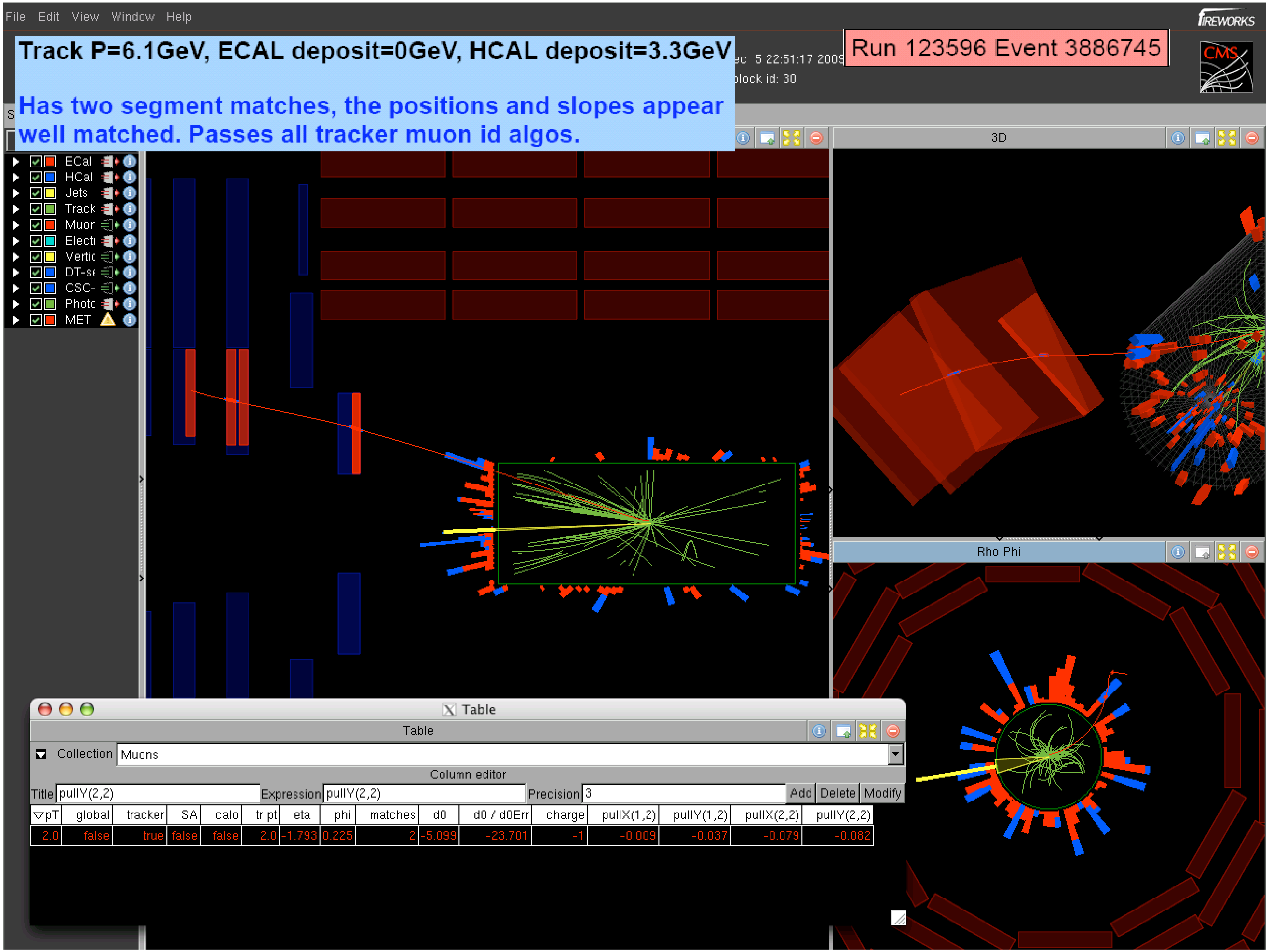
PF constituents: Jet 2: 6 charged hadrons, 6 photons, 1 neutral hadron

Jet2: Raw pT = 11 GeV, Corr pT = 23 GeV, PF pT = 19 GeV, phi = 2.48, eta = 0.27, EMF = 0.50

PF constituents: : 6 charged hadrons, 7 photons, 0 neutral hadron






File Edit View Window Help
FIREWORKS
Track P=6.1GeV, ECAL deposit=0GeV, HCAL deposit=3.3GeV
Has two segment matches, the positions and slopes appear well matched. Passes all tracker muon id algos.
Run 123596 Event 3886745
3D
Rho Phi
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HCal
Jets
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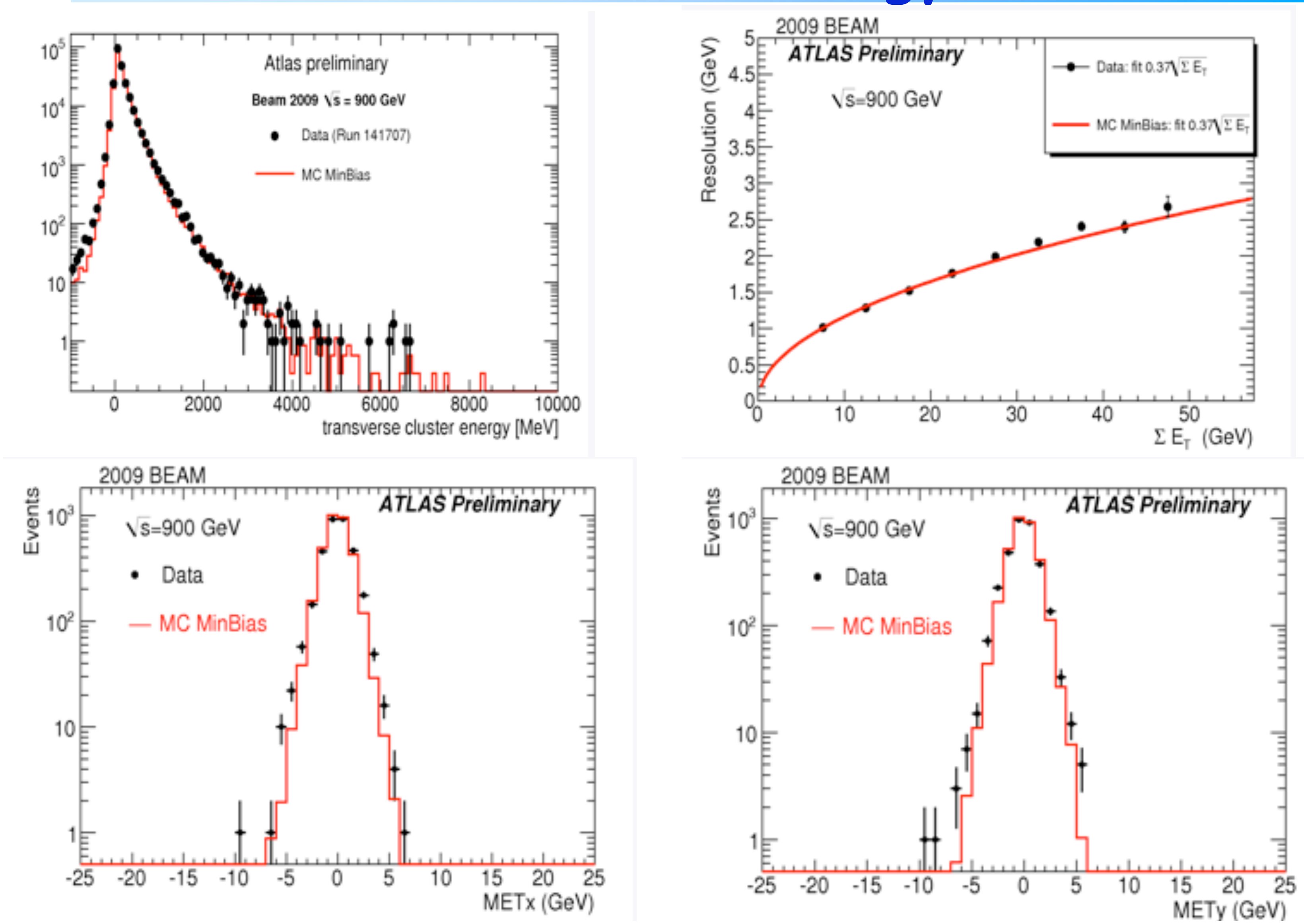
Column editor
Title pullY(2,2) Expression pullY(2,2) Precision 3 Add Delete Modify
pT global tracker SA calo tr pt eta phi matches d0 d0 / d0Err charge pullX(1,2) pullY(1,2) pullX(2,2) pullY(2,2)
2.0 false true false false 2.0 -1.793 0.225 2 -5.099 -23.701 -1 -0.009 -0.037 -0.079 -0.082

The detectors are amazingly well-understood (thanks to the Cosmic Ray runs – "CRAFT"): Monte Carlo=data at low p_T *and* at low $\not{E}_T$.

ATLAS: Transverse Energy and MET



Will the LHC answer all, some, or none of the Big Questions from "The Quantum Universe" — IT DEPENDS

1. **What is the electroweak symmetry breaking mechanism?**
2. **Are there undiscovered symmetries and physical laws?**
3. **Can we understand dark energy?**
4. **Are there extra dimensions of space?**
5. **Do all the forces become one?**
6. **Why are there so many kinds of particles?**
7. **What is dark matter? Can it be made in the laboratory?**
8. **What are the tiny neutrino masses telling us?**
9. **How did the universe come to be? How do we understand inflation?**
10. **What happened to the antimatter?**

The problems, questions and solutions all have to do with quantum physics, especially virtual quantum loops. Most often the solutions to problems related to virtual quantum loops suggest and/or require answers to more than one of the above questions simultaneously.

SM Status

- We all expect it is a low-energy ($i.e.$ $E < few \times 100~\mathrm{GeV}$) effective theory. Reasons will emerge as we go on.

  But, anthropic ideas suggest that an alternative view is possible: that the SM vacuum was just THE one choice among the many (10^{500} in string theory) vacua that was able to support our form of life.

  Are there parallel Universes?

  In the extreme, this anthropic view would suggest that the only new particle the LHC will see is the Higgs boson.

  How far can we go without needing to resort to the anthropic principle?

- Since the SM is a renormalizable theory it is highly predictive and predictions agree amazingly well with all available data after adding neutrino mass.

- Dropping anthropic principle, we expect corrections from higher E scales:

TeV scale (LHC!)
Unification scale M_U (if there is unification)
Planck scale $M_{\rm Pl}$

Indeed, viewed as a low-E effective theory, the SM is far from satisfactory.

The QCD portion of the theory is in excellent accord with data, but the Higgs sector/electroweak symmetry breaking leads to all sorts of conceptual problems.

- Now that the LHC is working (although not at full E or $\mathcal{L}$ for a while), we anxiously await
  - Clarification of electroweak symmetry breaking.
  - Evidence for new physics at the TeV scale.
  - Direct detection of the Dark Matter particle(s).
  - Discoveries that clarify flavor/neutrino physics.

  We have been waiting for a long time: the LHC experimental results are badly needed!

Higgs/Electroweak symmetry breaking

This was not actually on the Big Question list, but was after all the reason the LHC was built and designed to have an energy of $\sqrt{s} = 14$ TeV and possibility of achieving $L = 300$ fb^{-1} (after a number of years of operation).

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

Vacuum energy
$V_{0exp} \sim (2.10^{-3}\ \mathrm{eV})^4$

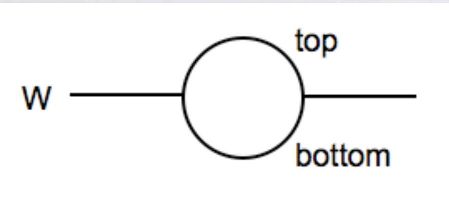
Origin of quadratic divergences.
Hierarchy problem

Possible instability depending on m_H

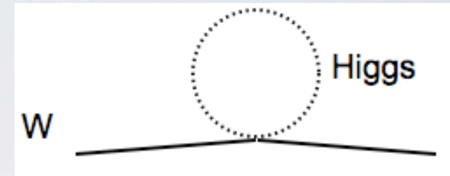
The flavour problem: large unexplained ratios of Y_{ij} Yukawa constants

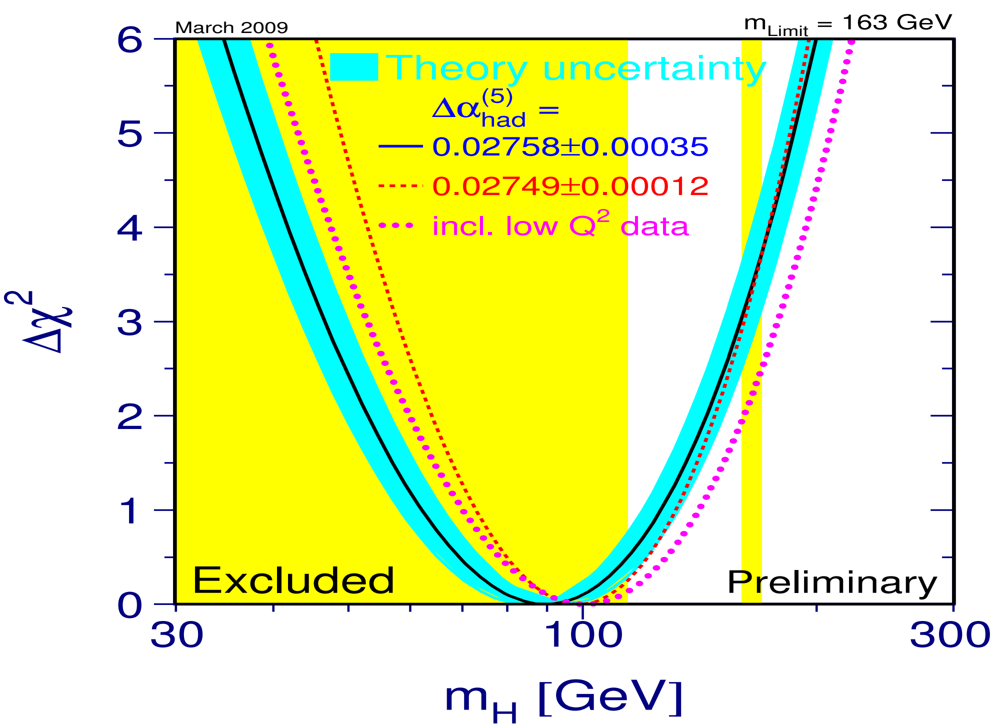
There are two big issues for the SM Higgs sector arising from **Quantum Loops**. These have led us to many alternative models.

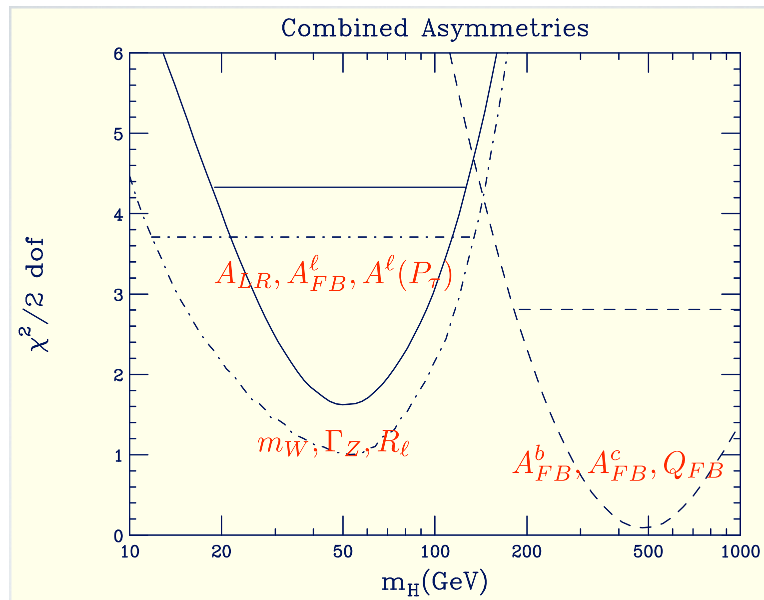
Loop Issue I: Precision Electroweak (PEW) consistency. *i.e.* effects from loop corrections to m_W and m_Z and related.



$$m_W = m_W^{tree} + c_1 m_{top}^2 + c_2 \log(m_H^2)$$







At the χ^2 minimum the usual SM Higgs fit has CL of only 0.14. The problem lies in the inconsistency of leptonic FB asymmetries and hadronic FB asymmetries.

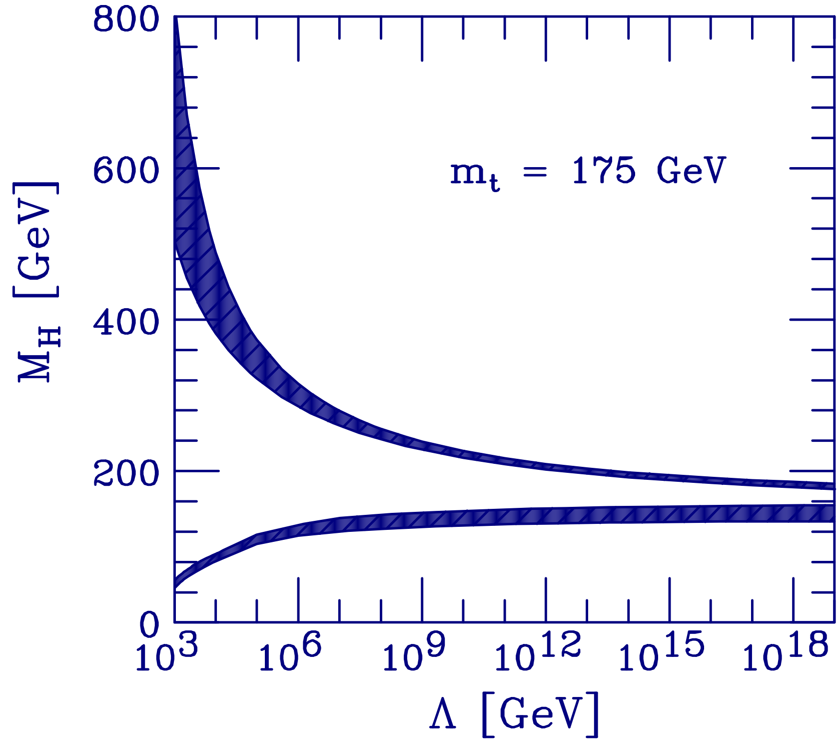
Throwing out the FB-hadronic gives CL=0.78, but χ^2 minimum is at $m_{h_{\rm SM}} \sim 50~{\rm GeV}$ with 95% CL upper limit of $m_{h_{\rm SM}} \leq 105~{\rm GeV}$.

Tension: $m_{h_{\rm SM}} < 105~{\rm GeV}$ contradicts LEP limit unless the h with SM-like WW, ZZ couplings has extra decays to which LEP was not very sensitive. Main candidates: $h \to \ \geq 4\tau$ ($m_h^{LEP} > 86~{\rm GeV} \stackrel{ALEPH}{\rightarrow} 105~{\rm GeV}$), $h \to \ \geq 4j$ ($m_h^{LEP} > 82~{\rm GeV}$). (LEP indicates lower limit from LEP data.)

Ideal Higgs: $82~{\rm GeV} < m_h < 105~{\rm GeV}$, maybe $m_h \sim 98~{\rm GeV}$ with $B(h \to b\overline{b}) \sim 0.1-0.2$ (vs. normal $0.8-0.9$), to explain LEP 2.3σ excess, and $B(h \to 4\tau, 4j, \ldots) \geq 0.7$ to escape LEP $Z + b's$ limits.

Very generic possibility for extra decays: $h \to aa$ with $B(h \to aa) \geq 0.7$, with $m_a < 2m_B$ so that $a \to \tau^+\tau^-, c\overline{c}, gg, s\overline{s}$, leaving $B(h \to b\overline{b}) \sim 0.15-0.2$.

Since the SM is a renormalizable theory, the SM Higgs picture could be valid up to $M_{\rm Pl}$. Two constraints derive from RGE (loop) calculations:



- the Higgs self coupling should not blow up below scale Λ; $\Rightarrow$ upper bound on $m_{h_{\rm SM}}$ as function of Λ.
- the Higgs potential should not develop a new minimum at large values of the scalar field of order Λ; $\Rightarrow$ lower bound on $m_{h_{\rm SM}}$ for given Λ.

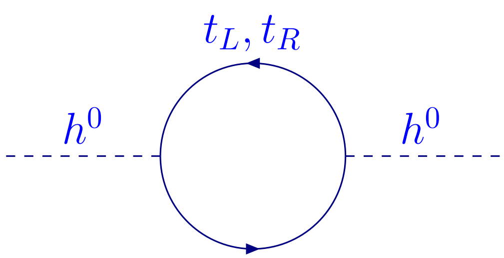
These two constraints imply that the SM can be valid all the way up to $M_{\rm Pl}$ if $130 \lesssim m_{h_{\rm SM}} \lesssim 180~{\rm GeV}$. But, this range is inconsistent with PEW $m_{h_{\rm SM}} \leq 105~{\rm GeV}$ constraint.

Note: If $m_{h_{\rm SM}} \leq 105$ GeV, $\Lambda \lesssim 10$ TeV is required.

What could the new physics at scale Λ be?

Loop Issue II: Hierarchy/Quadratic Divergence Problem

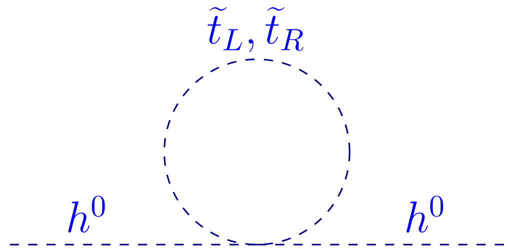
$$\mathcal{L}_{Yukawa} = -\frac{y_t}{\sqrt{2}} H^0 \bar{t}_L t_R + h.c. \quad \text{with } H^0 = v + h^0 \text{ and } m_t = \frac{y_t v}{\sqrt{2}} \Rightarrow \quad (1)$$

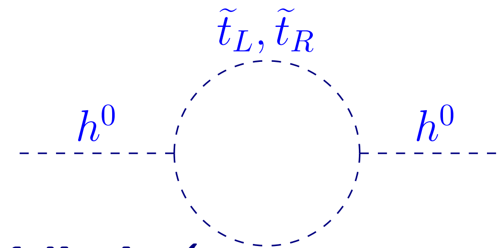


$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\left[\Lambda^2 - 3m_t^2 \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \ldots\right]$$

If $\Lambda \sim M_U$, then a huge cancellation is required between the bare mass-squared for the h^0 and this 1-loop correction in order that the Higgs have mass below ~ 1 TeV (as required by WW scattering unitarity). This is the naturalness or hierarchy problem.

The SUSY solution to this is to cancel away the quadratic (and logarithmic) Λ^2 dependencies using stop loops.





The cancellation will be total in the exact SUSY limit ($m_t = m_{\widetilde{t}_L} = m_{\widetilde{t}_R}$ and h^0 couplings to $\widetilde{t}_{R,L}$ as predicted by SUSY) and one would find

$$m_h^2 \leq m_Z^2 \cos^2 2\beta \,, \tag{2}$$

There will be a finite 1-loop residual if SUSY is broken by $m_{\widetilde{t}_L}, m_{\widetilde{t}_R} > m_t$, as required by experimental limits on superpartners.

SUSY is very attractive for many reasons:

- **It is the unique extension of the usual space-time symmetry.**
- **It provides a natural framework for elementary scalar fields (Higgses esp.)**
- **If $m_{\rm SUSY} < 1~{\rm TeV} \Rightarrow$ coupling constant unification, if only 2 doublets.**
- **It solves hierarchy problem if $m_{\rm SUSY} < 1~{\rm TeV}$.**

- Electroweak symmetry breaking occurs "automatically" via RGE evolution of soft-SUSY-breaking parameters from M_U.

- If R-parity is conserved, LSP is a natural Dark Matter candidate.

Minimal vs. Next-to-Minimal Supersymmetric Model

- SUSY can solve the electroweak finetuning (EWFT) problem (getting m_Z right without finetuning parameters at M_U) if $m_{\rm SUSY} < 500~{\rm GeV}$.

  But, then $m_h \lesssim 100~{\rm GeV}$, so there is tension with the LEP limit, $m_h > 114~{\rm GeV}$, applicable in the case of the Minimal Supersymmetric Model (MSSM) which has two-doublets of Higgses but no singlets.

- The NMSSM is even more attractive.

  It solves the μ problem via $W \ni \lambda \widehat{S}\widehat{H_u}\widehat{H_d}$ when scalar component of $\widehat{S}$ acquires vev: $s = \langle S \rangle$.

  The singlet a is naturally very light and $B(h \to aa) > 0.7$ is typical. $\Rightarrow$ can have Ideal Higgs $m_h \lesssim 100~{\rm GeV}$ scenario with no EWFT problem.

Indeed, there are many alternatives for the Higgs sector:

- Stand alone scalar sector with of one doublet, more doublets, additional singlets. HP=bad; unification possible (e.g. 2HDM+1 (Y=0) triplet).
- Higgses of SUSY. HP=good, EWFT=bad in MSSM; EWFT=good in NMSSM. Unification = good.
- Multi-singlet NNNN...MSSM models provide even more flexibility without altering any of good features of MSSM.
- Composite (of fermions, of WW, ...) Higgs. HP=ok; unification=?
- Pseudo-Goldstone boson of an enlarged symmetry. HP=delayed to $\Lambda > 10~\mathrm{TeV}$; unification=?
- A manifestation of extra dimensions (5th component of gauge boson, an effect of orbifolding or of boundary conditions ...). HP=ok, unification possible.
- A combination of the above.

Possibilities for the LHC

1. **No Higgs, no $W_L W_L$ resonances:**

   $W_L W_L, \ldots$ scattering becomes strong at $\sqrt{s_{WW}} \sim 800~\mathrm{GeV}$. Can unitarize in adhoc way (e.g. T-matrix, ...) but no one has demonstrated that consistency with PEW is possible.

   No hint of what might follow above $1~\mathrm{TeV}$. $\Rightarrow$ return to strong interaction theories?

2. **No Higgs, but construct model with $W_L W_L$ resonances.**

   Can be made consistent with PEW constraints (Dominici et. al.) without necessarily having any resonances with low enough mass to be seen at LHC (need to make use of extra dimensional 5d brane).

   $W_L W_L$ scattering could be perturbative but you would not know why.

   LHC problem: At the LHC it is hard to tell if $W_L W_L$ scattering is strong or not because of very large $W_T W_T$ scattering background.

Beyond LHC (BLHC) solutions: 1) Study strong WW sector and/or see resonances by increasing LHC energy and/or luminosity (SLHC with $L \geq 1000~\mathrm{fb}^{-1}$). 2) Build ILC,CLIC with $\sqrt{s_{ee}} > 2~\mathrm{TeV}$.

3. **No Higgs, unitarize WW scattering with extra W_k and Z_k resonances exchanges.**

   Models identifying W, Z excitations with KK modes in extra dimensional approach have been constructed.

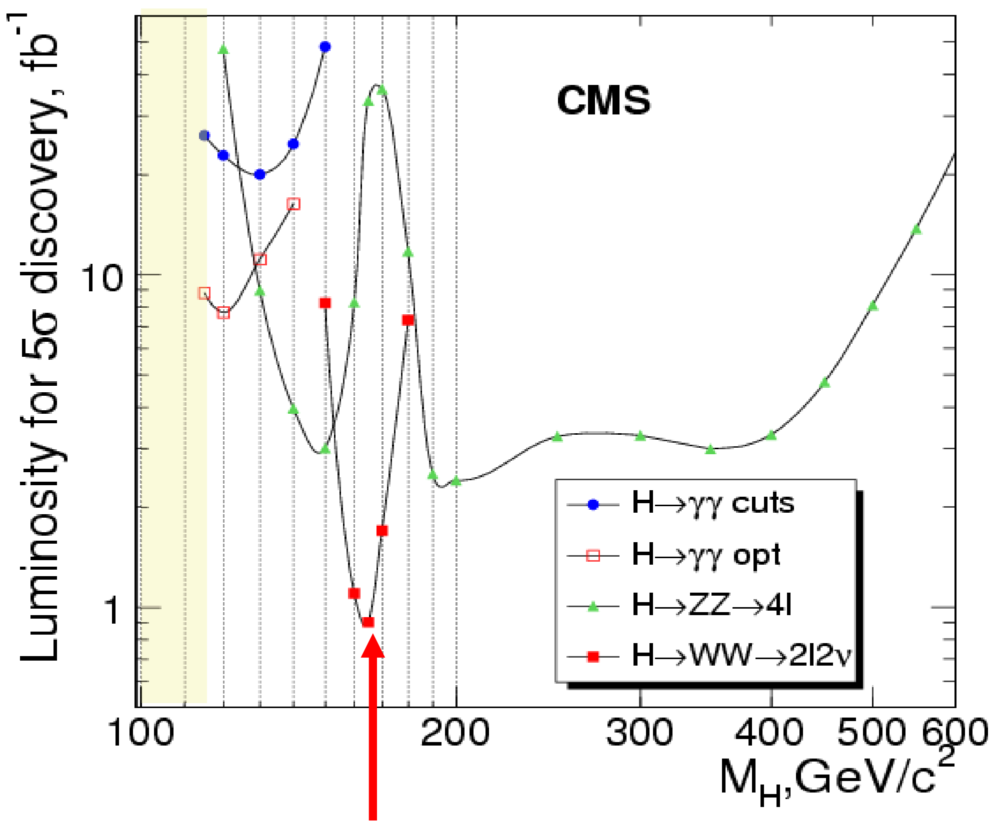
   Resonances must have fairly low masses to solve unitarity problem, **but then PEW constraints are very problematical.** At best can get very marginal consistency using warping in extra dimension.

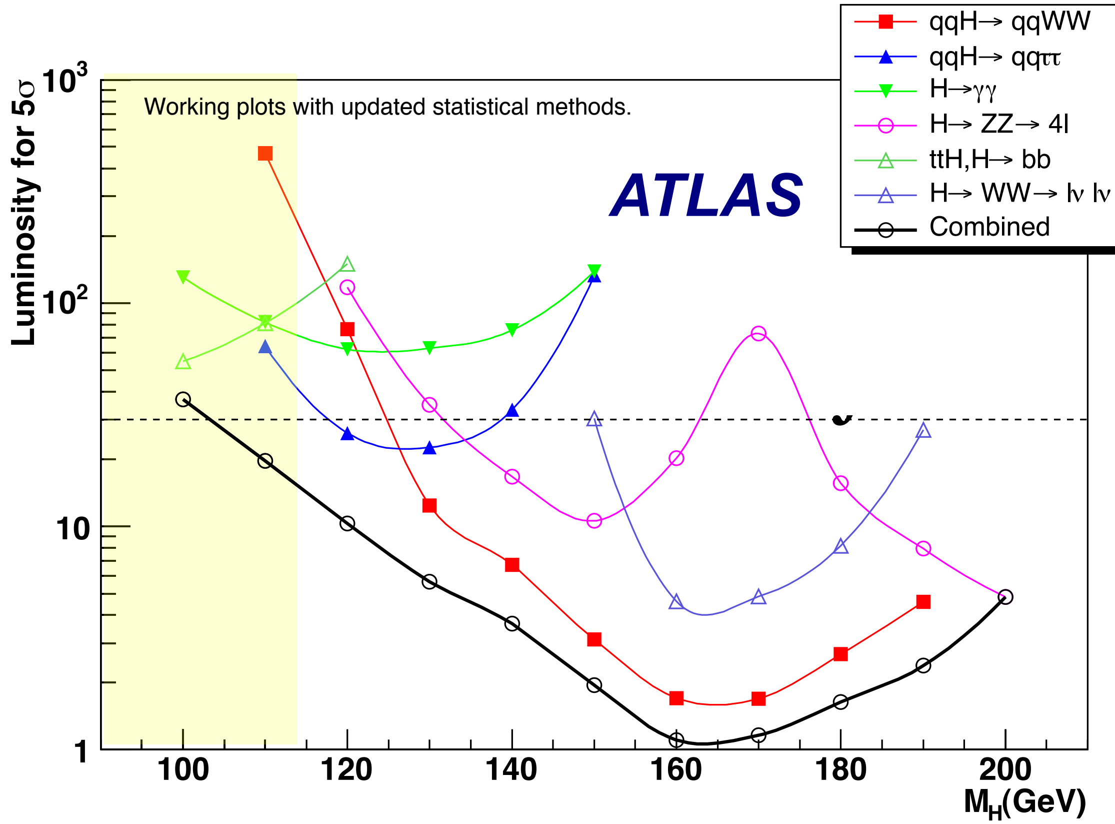
   No LHC problem: will see all the W, Z excitations fairly easily.

4. **SM Higgs.**

   Certainly no worse than the above models, and has the advantage of "no hastle" consistency with combined PEW data set if $m_{h_{\rm SM}}$ close to $114~\mathrm{GeV}$.

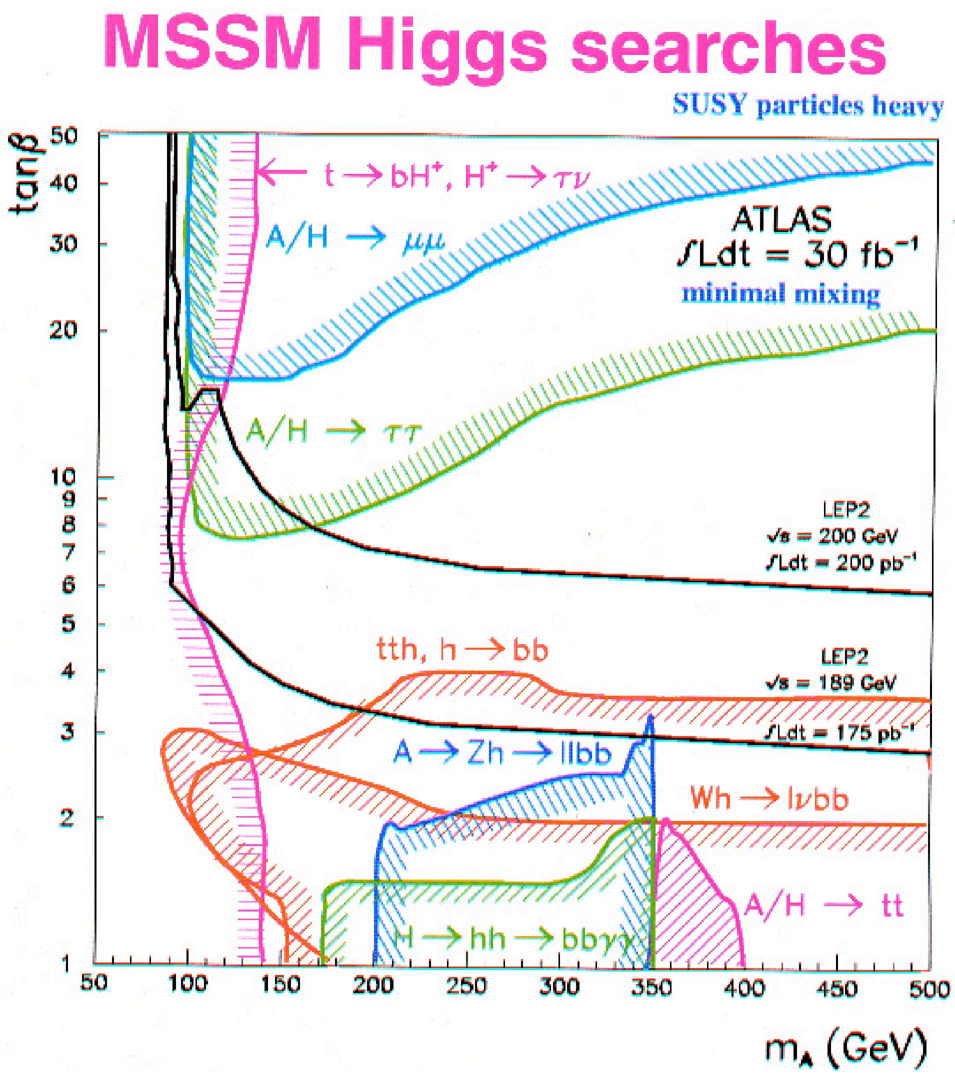
LHC Discovery Modes have been proven: $\sqrt{s} = 14~\mathrm{GeV}$ plots are below.

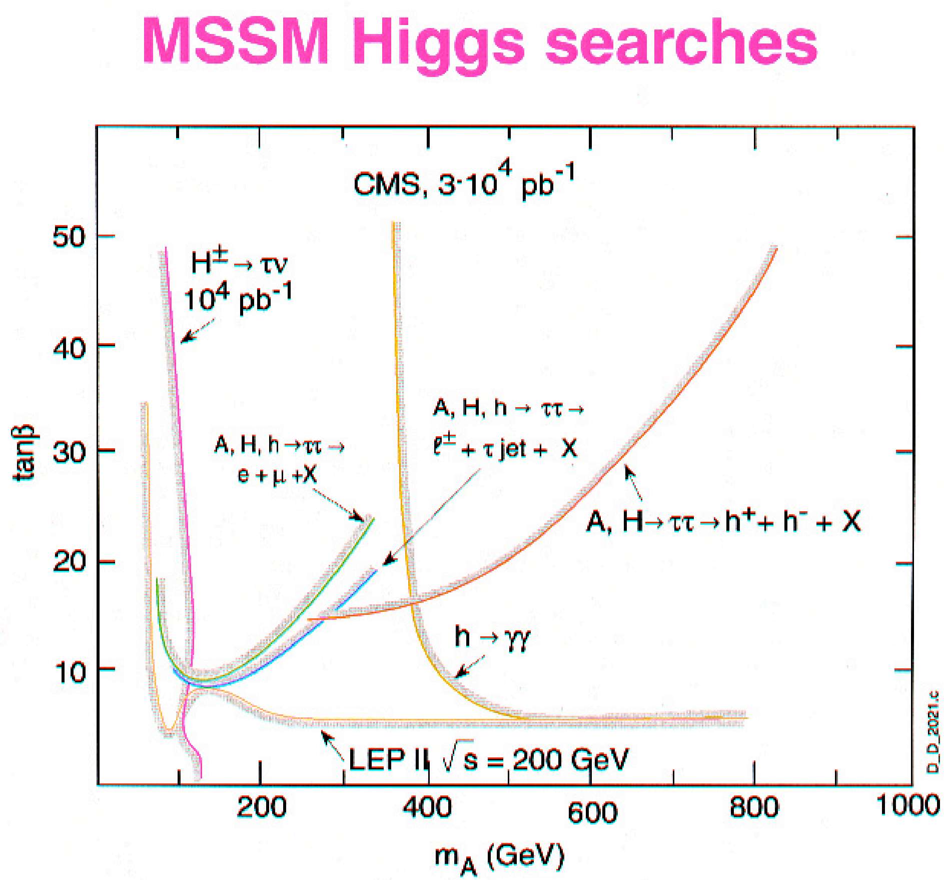




5. MSSM Higgs

At LHC, use mixture of SM-like modes. Will at least see light h and maybe also heavier $H, A, h^{\pm}$.





LHC Problem: There is a large h-only window where it is not easy to distinguish h from $h_{\rm SM}$.

BLHC Solution: Go to SLHC? Build ILC/CLIC with $\sqrt{s} > 2m_{A^0}, 2m_{h^\pm}$.

MSSM Problem: In MSSM, LEP implies must have $m_h > 114~{\rm GeV}$, which yields large EWFT and is not "Ideal" for PEW.

Solution=go to NMSSM.

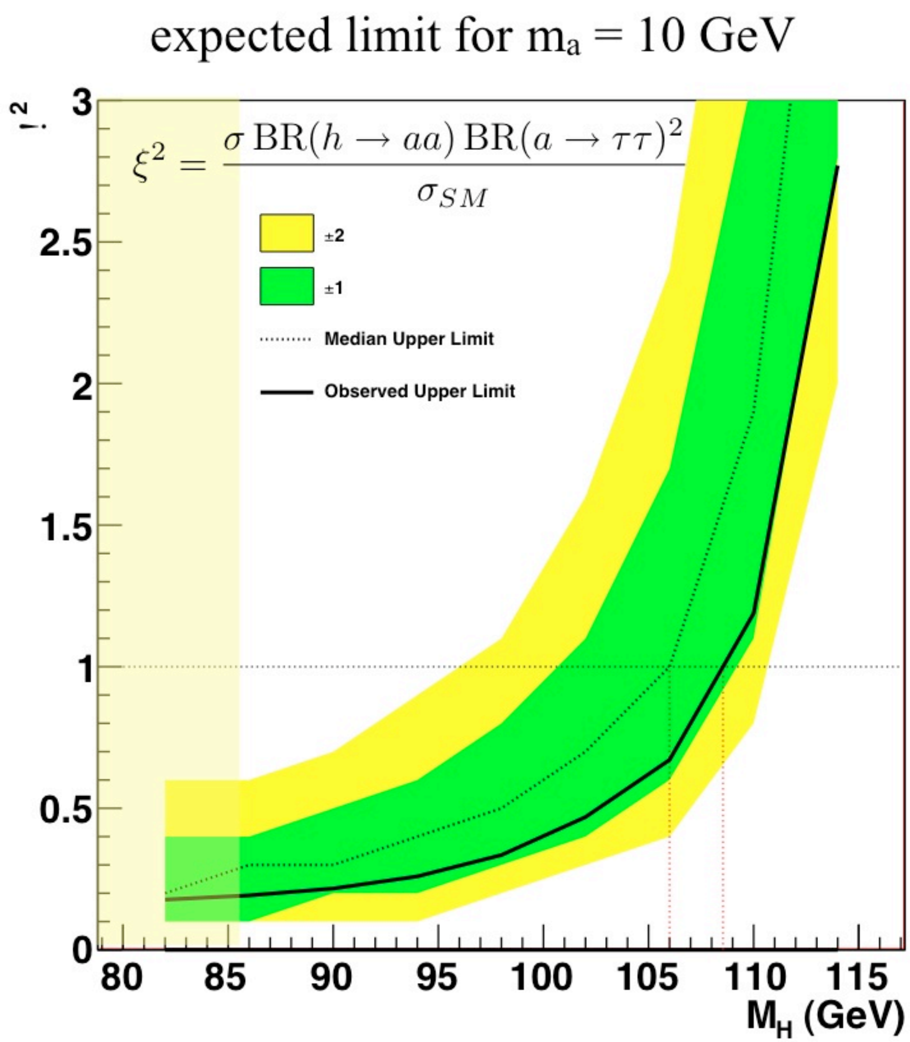
6. NMSSM Higgs

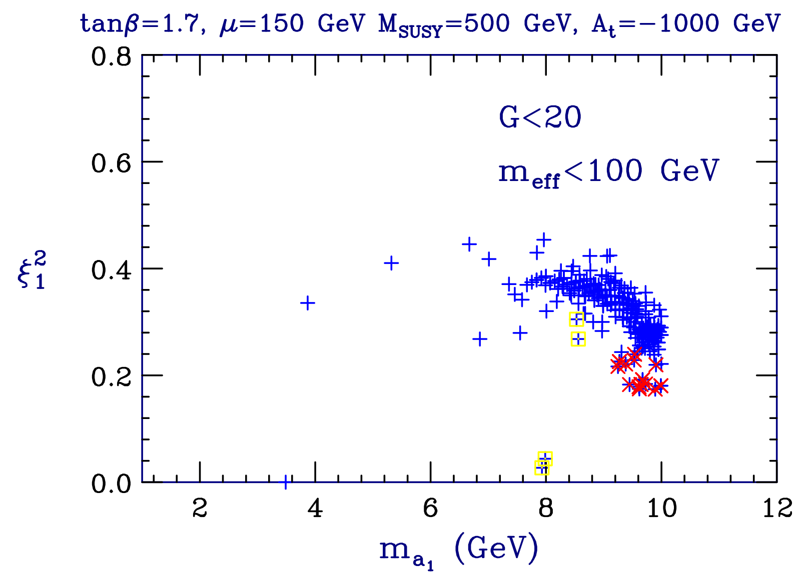
It is very natural for singlet-like a to have $m_a < 2m_B$ and for $B(h \to aa) > 0.7$, provided m_a is close to $2m_B$.

This evades old LEP searches if $m_h \gtrsim 86~{\rm GeV}$.

But, new ALEPH limit on $e^+e^- \to Zh$ with $h \to 4\tau$ creates tension if $\tan\beta \gtrsim 3$.

If $\tan\beta < 3$, then $a \to \tau^+\tau^-, gg, c\overline{c}$ mixture that allows escape from latest ALEPH results.





LHC problem: **Not clear that an h with such a mixture of decays can be seen at the LHC.**

$\Rightarrow$ **Lots of SUSY at LHC, but no Higgs detection.**

Beyond LHC Solution: Build ILC, CLIC and detect the h that couples to ZZ, WW independent of how it decays by looking for peak in M_X in $e^+e^- \to ZX$ reaction.

7. NNNN...MSSM Higgs

- In general can add many singlets to the 2 doublets of the MSSM without spoiling any of good MSSM properties (unifcation, RGE EWSB, ...).
- These will in general all mix with one another and with the doublet Higgs fields as in the NMSSM.

  $\Rightarrow$ a spectrum of eigenstates with complicated decays to SM particles and to lower mass Higgs pairs.

  $\Rightarrow$ this spectrum can have ZZ coupling density $\rho(m)$ down to rather low xs$m$ distributed in such a way as to give $m_{eff}^{PEW} \sim 50~\mathrm{GeV}$ and still evade all LEP limits.

  LHC Problem:

  Hard to detect the Higgs even in NMSSM case. Here we have additional complications related to state overlap within resolution, ...

  Specific realization of "Worst Case" scenario (JFG+Espinosa).

BLHC Solution:

ILC/CLIC can detect even a broad spectrum enhancement in the M_X distribution coming from $e^+e^- \to ZX$. Need at least $L \sim 1000~\mathrm{fb}^{-1}$, but PEW requires all states with good ZZ coupling be light $\Rightarrow$ lower $\sqrt{s} \sim 250~\mathrm{GeV}$ ideal.

8. **Buried Higgs Models.**

   Can introduce extra symmetry to make Higgs of SUSY a pseudo-Goldstone-Boson which decays to aa with $a \to 2j$ only (Csaki et al.).

   Can break R-parity (losing dark matter) and have $h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to 3j + 3j$ (Carpenter et al.).

   Higgs in these models will be essentially impossible to see at the LHC. $\Rightarrow$ ILC,CLIC as above.

   But, superparticles will be seen easily.

9. **Model with a SM-like Higgs, that has no HP but also no observable LHC other than the SM-like Higgs?**

Originally, this appeared to be the motivation behind the Twin Higgs models.

In these models, the Higgs sector is duplicated by a twin Higgs sector which has no SM couplings.

To cure the HP, there is a heavy top quark partner in the twin (or hidden) sector that must have some SM couplings to cancel the top loop quadratic. But, it can be made to decay only to hadrons, in which case it may not be seen at the LHC because of backgrounds.

However, the twin/hidden sector Z_H will inevitably be detectable if the HP is satisfactorily resolved (requiring not too heavy Z_H).

E.G., ATLAS study $\Rightarrow$ will see the $Z_H \to e^+e^-, \mu^+\mu^-$ with modest L.

Table 2: Required integrated luminosity to reach a signal significance of 5σ.

$m(Z_H)$ (GeV)	N_{signal} in 10 fb^{-1}	N_{bkg} in 10 fb $^{-1}$	5σ luminosity (fb $^{-1}$)
1196	1123	6	0.04
1495	464	7	0.10
2407	43	1	1.1
3587	2	0	15

To my knowledge, there is no model that can both cure the Hierarchy Problem and avoid any new LHC physics beyond a SM-like Higgs boson.

If true, only an anthropic solution to the hierarchy problem can possibly avoid dramatic new physics at the LHC.

10. Little Higgs theories

This is a kind of model where Λ^2 HP first appears only at 2 loops because of extra symmetries.

The non-perturbative regime starts at $\Lambda \sim 10$ TeV. $\Rightarrow$ ultraviolet completion for the theory is unclear.

Extra tricks, including at least T-parity, needed to solve PEW constraints.

Lots of LHC signals, such as new T quark partner to the t quark.

11. Higgs=$\overline{\psi}\psi$ condensate

In this case, there are no fundamental scalars, but these models need a very strong binding force: $\Lambda_{new} = 10^2\Lambda_{QCD}$. Technicolor is an example.

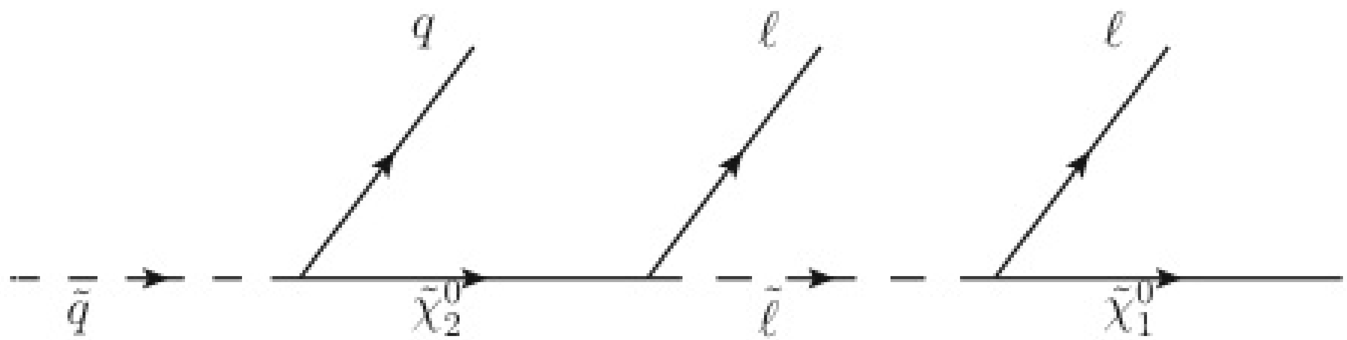
These models have great difficulty with PEW constraints, but keep returning in new forms (walking technicolor).

At the LHC, one would expect new resonances aside from the Higgs, such as the techni-rho, to be highly visible.

SUSY particles and Dark Matter

If R-parity is conserved in SUSY, then SUSY events will be distinguished by having large $\not{E}_T$.

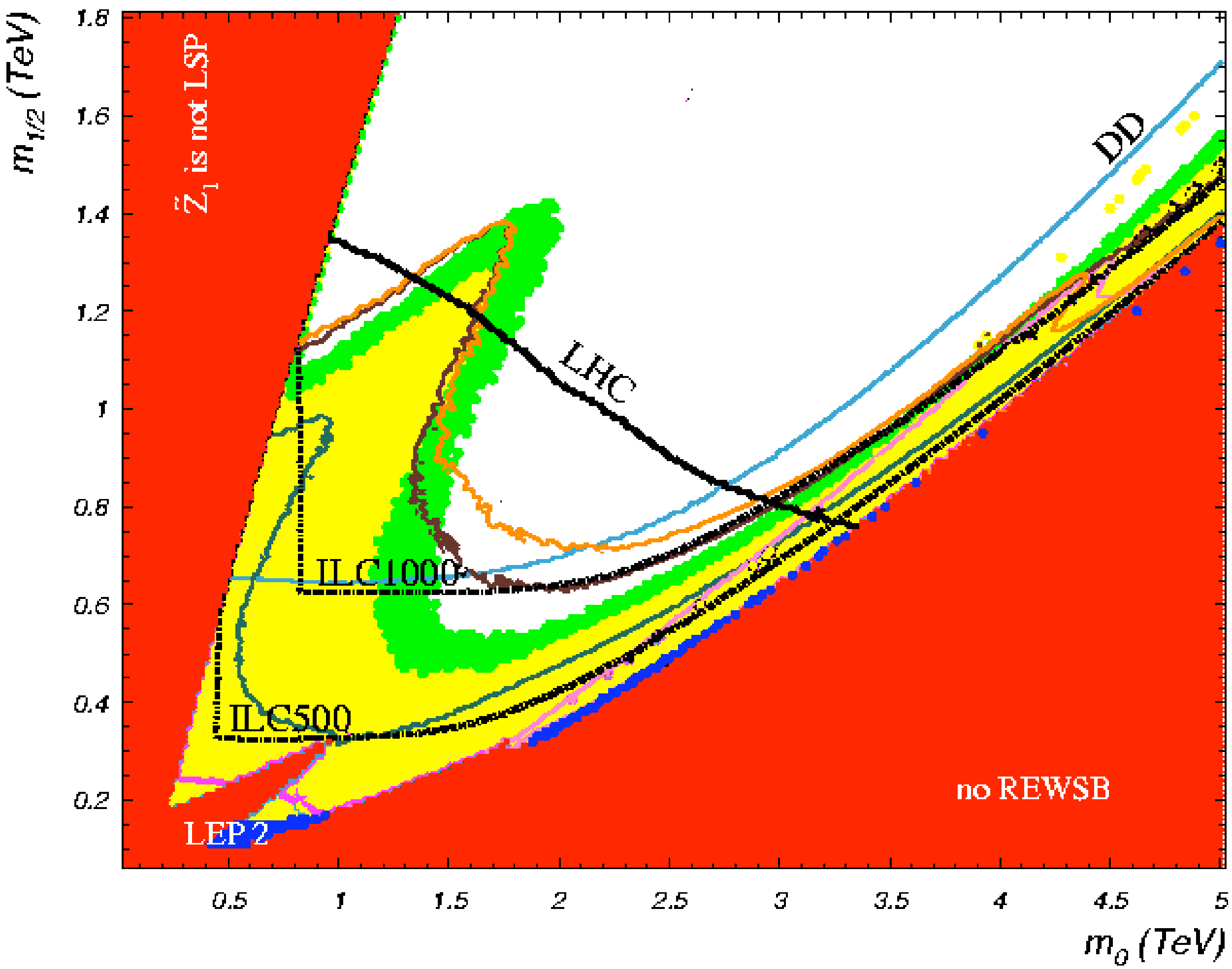
For example, in the mSUGRA class of models, many events will contain two decay chains of the type



By and large the LHC will be able to detect such SUSY events (over background) for any mass scale appropriate to solving the Hierarchy Problem.

An example from Baer in mSUGRA is the figure below, which is for high $\tan\beta = 55$ where Yukawa unification is possible.

mSUGRA : $A_0 = 0$, $\mu > 0$, $\tan\beta = 55$, $m_t = 172.6$ GeV



- $0 < \Omega h^2 < 0.094$
- $0.094 < \Omega h^2 < 0.129$
- LEP2 : $m_{\tilde{W}1} < 103.5$ GeV
- $m_h = 110$ GeV
- $\sigma(\tilde{Z}_1 p) = 2 \times 10^{-9}$ pb
- $\Phi^{sun}(\mu) = 40\ \mathrm{Km^{-2} yr^{-1}}$
- $\Phi(\gamma) = 10^{-10}\ \mathrm{cm^{-2} s^{-1}}$
- $d\Phi/dEd\Omega(\bar{p}) = 9.3 \times 10^{-9}\ \mathrm{GeV^{-1} cm^{-2} s^{-1} sr^{-1}}$
- $d\Phi/dEd\Omega(e^+) = 7.1 \times 10^{-9}\ \mathrm{GeV^{-1} cm^{-2} s^{-1} sr^{-1}}$
- $d\Phi/dEd\Omega(\bar{D}) = 3.0 \times 10^{-12}\ \mathrm{GeV^{-1} cm^{-2} s^{-1} sr^{-1}}$

There, the contour marked "LHC", which corresponds to $m_{\widetilde{g}} \sim 3$ TeV when $m_{\widetilde{q}} \sim m_{\widetilde{g}}$ or $m_{\widetilde{g}} \sim 1.8$ TeV when $m_{\widetilde{q}} \gg m_{\widetilde{g}}$, will be accessible at the LHC with $L = 100~\mathrm{fb}^{-1}$.

The green region shows where dark matter abundance agrees with experiment within errors.

LHC problems:

The LHC does not cover all of the so-called hyperbolic branch/focus point region where the $\widetilde{\chi}_1^0$ has a large higgsino component that facilitates early universe annihilation via $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to WW, ZZ$ and thereby makes $\Omega h^2 < 0.129$ possible.

Nor does it cover the A-funnel region, where the A Higgs facilitates $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ annihilation.

BLHC non-solution

The ILC/CLIC will require very large $\sqrt{s}$ to cover the entirety of the green region.

BLHC solution

However, direct detection (DD, blue line) by Xenon experiment will cover the HB/FP region.

Also shown are contours indirect WIMP detection rates using high-energy ν detection at IceCube or via detection of γ's, $e+$'s or $\overline{p}$'s arising from neutralino annihilation in the galactic core.

These latter cover most of the A-funnel region that lies beyond the LHC reach.

Other SUSY Models that have dark matter

- **Models with gravitino LSP.**
- **Models with axino LSP.**
- **non-mSUGRA models with close degeneracy of, for example, $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_1^0$ when both are wino-like (AMSB, ...).**

  A long life-time for the $\widetilde{\chi}_1^{\pm}$ is a possibility, but such a $\widetilde{\chi}_1^{\pm}$ would be easily seen as a heavily ionizing track. This is not a likely scenario.

  Can even have $m_{\widetilde{g}} \sim m_{\widetilde{\chi}_1^0} \sim m_{\widetilde{\chi}_1^{\pm}}$ for generic non-universal gaugino masses.

  LHC Problem:

Degeneracies of this type can make SUSY more difficult to detect, lowering the mass reach somewhat.

BLHC Solution:

Not a problem at ILC: a) use $\widetilde\chi_2^0\widetilde\chi_1^0$ production; b) use photon tag, e.g. $e^+e^- \to \gamma\widetilde\chi_1^+\widetilde\chi_1^-$.

- Models in which the $\widetilde g$ is the LSP (non-universal gaugino masses, JFG+Chen+... or very nearly stable (split SUSY, Dimopoulos et al.).

  If early universe annihilation not "strong-interaction-like" (as some would argue, Wacker et al.) then so many $\widetilde g$'s survive till now that we would have known (heavy isotopes, ...).

  In either case, many special features at LHC.

  The $\widetilde g$ passes through the detector as a $\widetilde g - q$ color singlet (so-called R-hadron), charge exchanging with the material in the detector, and behaving like a "bowling ball" with little energy deposit.

  – If charged states last long enough will see heavily ionizing tracks.

– If only neutral R-hadrons are long lasting in the detector (mass splitting between charged and neutral states large) then the $\widetilde{g}$ will carry away unseen energy $\Rightarrow \not\!\!E_T$.

Either way, we will get a reasonable LHC signature and will discovery this type of SUSY (JFG+Baer+CHen, Wacker et al.)

In case gluinos (more properly, neutral R-hadrons) have a long life-time, should search for $\widetilde{g}$'s that decay long after the event that made them.

$\Rightarrow$ if lifetime not too long then experiments can look for late decays during beam-off down time. There are such plans at ATLAS and CMS.

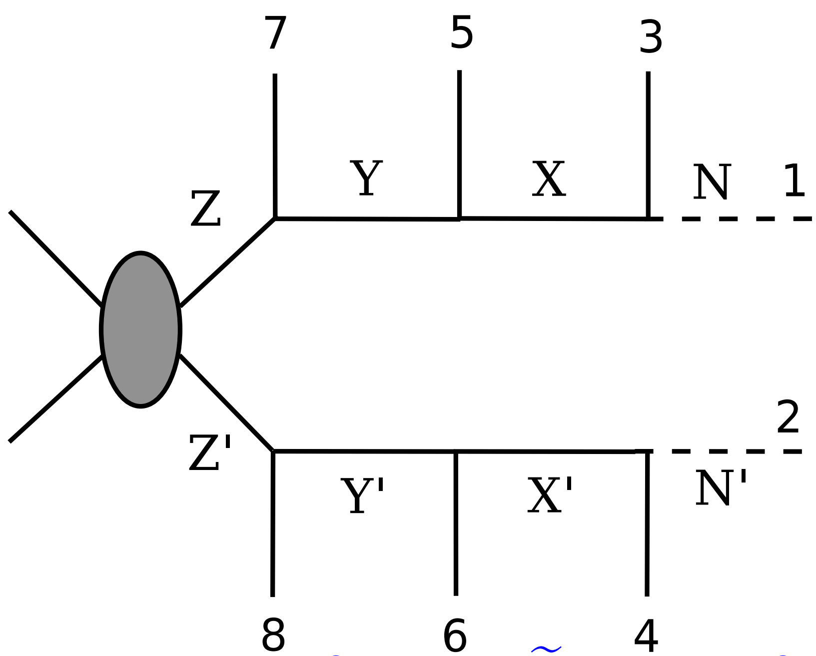
$\Rightarrow$ If the $\widetilde{g}$'s have quite long life time and became entrapped in the detector material, then could grind up the detectors after LHC end and look for heavy isotopes.

Dark Matter Properties

Of course, if we see missing energy at the LHC, we will want to check that it comes from a pair of particles such as a pair of $\widetilde{\chi}_1^0$'s.

And, to check that it is the dark matter particle, we will want to determine its mass, spin and other properties.

For a typical mSUGRA point (SPS1a' for those who know) LHC events will often look like



$(Z = \widetilde{q},\ Y = \widetilde{\chi}_2^0,\ X = \widetilde{\ell},\ N = \widetilde{\chi}_1^0)$

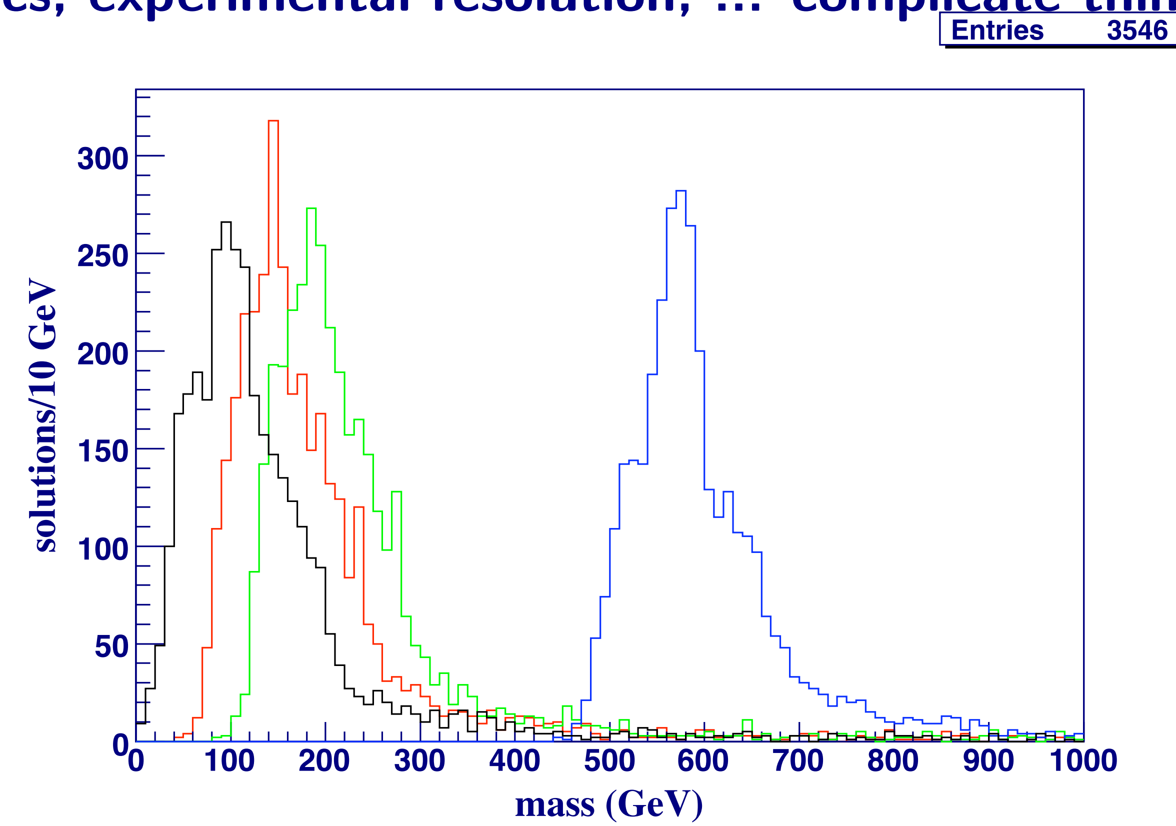
Potential LHC Problem:

Can we get a good determination of $m_{\widetilde{\chi}_1^0}$ when there are two invisible particles per event?

LHC Solution:

For the above 2 chain topology, can use full kinematic information and solve for all unknown masses using just 2 events.

Combinatorics, experimental resolution, ... complicate things somewhat.



But, with just 50 events we get good results (JFG, Cheng, Han, McElrath).

With more L, we can determine all masses, including $m_{\widetilde{\chi}_1^0}$, to within about $\mathbf{2-3}$ GeV.

The $MT2$ techniques (Barr, Lester ...) also do a good job of determining masses.

Once masses are known, we can then determine the spin of the LSP (1/2 in SUSY) by looking at angular distributions/correlations.

Is something BLHC needed?

ILC/CLIC will do better on masses, but only using detailed energy scanning, which eats up luminosity that might be used for maximum energy running.

SUSY Models without Dark Matter

- R-parity can be violated.

  If in the leptonic couplings, then SUSY will be easily discovered using multi-lepton signals even though there is no $\not\!\!E_T$.

  If R-parity is violated in the baryonic coupling, then discovery will depend to a large extent on energetics of the leptons that come from $\widetilde\chi_1^\pm \to \ell\nu\widetilde\chi_1^0$. (It will be difficult to use the 3 jets from each $\widetilde\chi_1^0$ given QCD backgrounds.)

  If leptons are energetic, as in mSUGRA where $m_{\widetilde\chi_1^\pm} \sim 2m_{\widetilde\chi_1^0}$, then can use the like-sign di-lepton signal from $\widetilde g\widetilde g$ pair production where each $\widetilde g \to qq\widetilde\chi_1^\pm$.

  LHC Problem:

  However, if AMSB or similar SUSY-breaking applies, with $m_{\widetilde\chi_1^\pm} \sim m_{\widetilde\chi_1^0}$, these leptons are soft and we must rely on leptons from $\widetilde\chi_2^0 \to Z^{(*)}\widetilde\chi_1^0$ and similar.

This will weaken reach.

BLHC Solution

At ILC/CLIC, can directly produce $e^+e^- \to \widetilde\chi_1^0 \widetilde\chi_1^0 \to 3j + 3j$, and, since backgrounds are small, reconstruct the $3j$ masses.

Extra Dimensions

- **String theory suggests ED at $M_{\rm Pl}$.**
- **Could ED be larger and have impact below $M_{\rm Pl}$?**

Exciting Possibilities

- **Coupling unification (maybe not gauge group unification) associated with ED at M_U.**
- **ED as a solution, or part of the solution, of the Hierarchy Problem at $\sim$ TeV.**
- **Electroweak symmetry breaking could arise via an ED mechanism (e.g. boundary conditions on branes) even below $\sim$ TeV.**
- **Fermion mass hierarchies, including CKM and neutrino mixings, could have ED origin.**

Many exciting potential LHC signatures.

These are model dependent. Below is a list of some possibilities.

- **KK modes.**

  If a number, δ ($\delta \geq 2$), of extra dimensions are curled up to size $R \sim 1/M$, with $M \sim \mathrm{TeV}$, then $\Rightarrow$ resonances at TeV masses, $m_{KK} \sim n/R \sim nM$.

  These will provide very clear LHC signals in 2 particle final states so long as $M \lesssim 3~\mathrm{TeV}$.

  The width of the KK resonances will provide additional information about the nature of the extra dimensions.

- In δ universal extra dimensions, Higgs can mix with graviscalar states of the ED theory.

  $\Rightarrow$ very large invisible width of the SM-like Higgs.

  LHC Problem:

  Hard to separately determine δ and M, the latter being the inverse size of the extra dimensions.

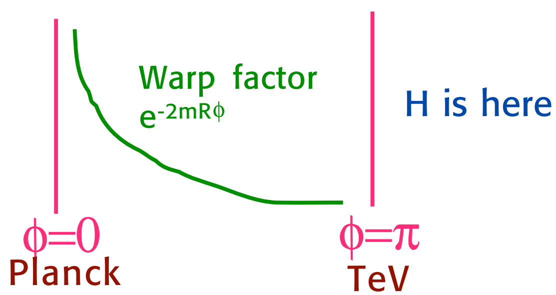
LHC Solution:

Examine the Higgs invisible decays at a variety of LHC energies.

BLHC Solution:

Go to ILC/CLIC and examine Higgs invisible decays at a variety of energies.

- Warping as solution to Hierarchy Problem.



$$ds^2 = e^{-2mR|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - R^2\phi^2$$

All SM particles probably in bulk except for Higgs.

There is a radion = quantum fluctuation of field that stabilizes the separation between the $M_{\rm Pl}$ and TeV branes.

$\Rightarrow$ Higgs-radion mixing that would observably affect light Higgs properties and give a 2nd Higgs like state.

Also, Fermion Yukawas could differ due to different wave functions for different fermions in 5th dimensions. For example, the more overlap with H located on the TeV brane, the heavier the particle.

- **(mini) Black hole or excited string state production is possible at the LHC.**

Theoretical Exotica

1. **Unparticles**

   These are not particles in the usual sense since there is no isolated pole. Rather there is a kind of continuum of poles (like a cut in comlex plane).

   The unparticles can, however, mix with the normal H creating a spectrum with a pole buried in a continuum.

   The result is not unlike the the "worst case" scenario as in NMSSM in terms of having a $\rho(m)$ spectral density in $g^2_{ZZh}(m)$ sense, but with one important difference:

   the unparticle states, being invisible, imply that most of the Higgs in the spectrum have large invisible branching ratio.

   $\Rightarrow$ LEP constraints don't allow m_{eff}^{PEW} as low as $50~\mathrm{GeV}$.

2. **Quirks:**

A new strongly interacting theory (Luty) in which the quirks could be produced at the LHC, separate by macroscopic scales, but never escape from one another.

$\Rightarrow$ **they would be pulled back together and would slowly radiate away their energy due to the associated acceleration and possibly periodic partial annihilation.** $\Rightarrow$ **low energy photon fuzz.**

3. **...**

There are many not totally crazy ideas out there. Theorists have had too long to think without data.

Flavor/neutrino physics

The LHC will certainly shed light, but much of this physics is poorly understood. As a result, we cannot be sure what we might see.

LHC Possibilities

- Rare L violating decays in B-physics (e.g. $B \to \mu^+\mu^-$)

- Rare FCNC top quark decays $t \to c \ldots$.

- Evidence for low-scale see-saw explanation of neutrino masses. $m_\nu \sim km_{dirac}^2/M$ where M is scale of L non-conservation and can be small if k is small.

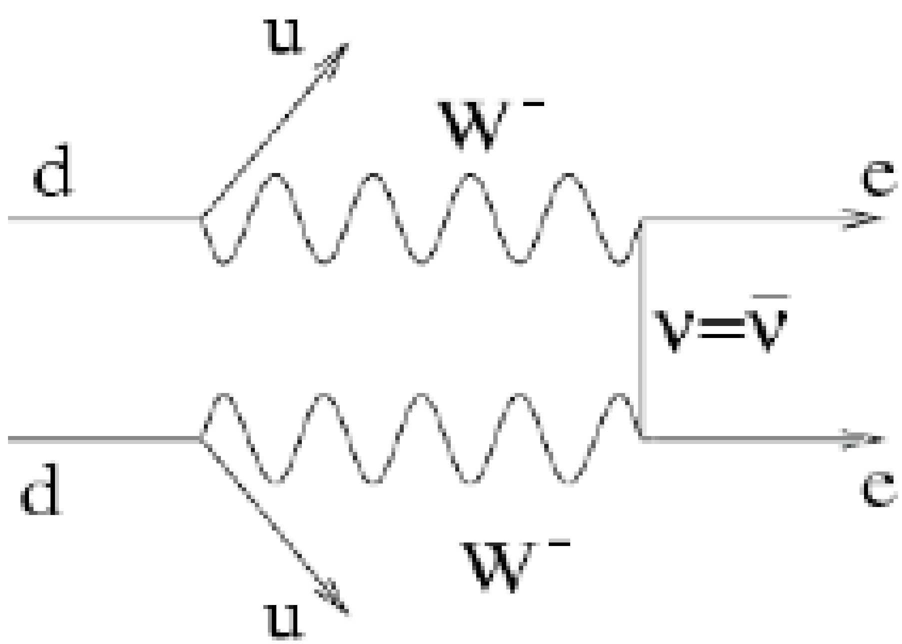
- Evidence for Right-Left symmetric model W_R, Z_R that are part of triplet Higgs source for neutrino masses.

BLHC experiments abound

These include:

- $\mu \to e\gamma$ **(MUCOOL)**

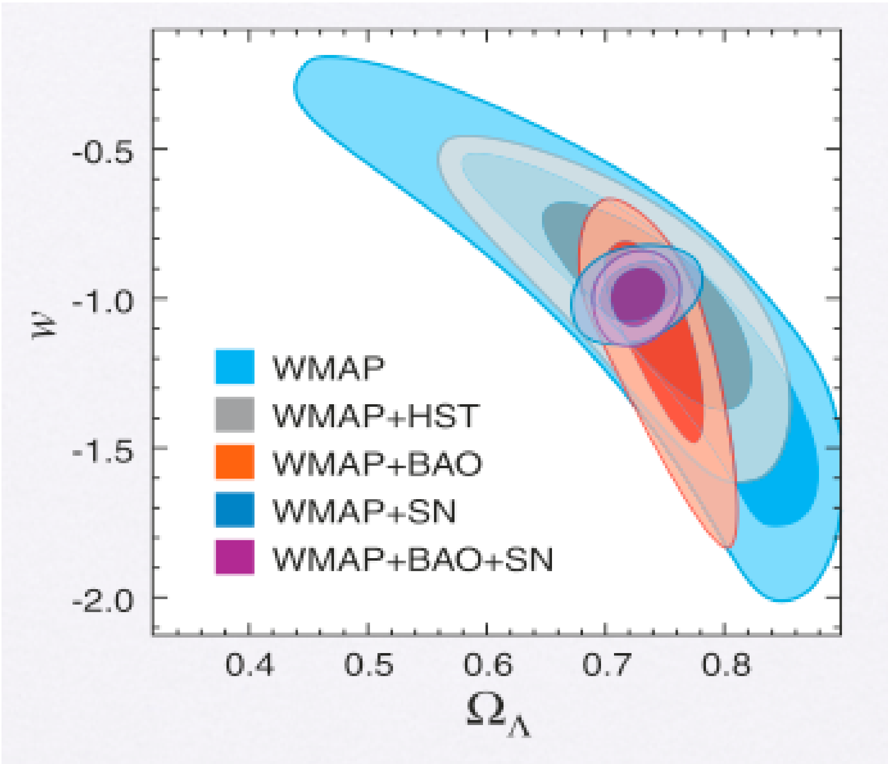
- **Neutrinoless double beta decay ($0\nu\beta\beta$) would provide a proof of L non-conservation.**

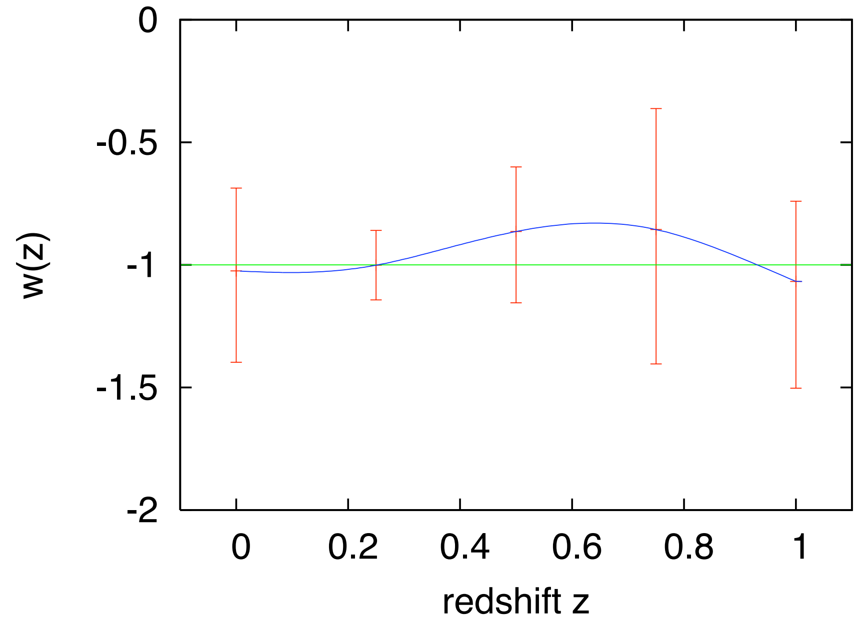


$0\nu\beta\beta$ = dd -> uue^-e^-

Dark Energy

Looking more and more like a cosmological constant.





Some models predict variation of w with z; plot containing data from WMAP+UNION+BAO+WL+ISW+LSS shows 2σ constraints. No sign of variation.

Are there viable alternatives that the LHC would possibly expose?

- **Could use combination of axion-photon mixing ($w = -1/3$) and network of domain walls ($w = -2/3$) to get $w = -1$.**

  LHC problem:

  Will never directly see either the axion needed nor (of course) the domain walls.

  BLHC solution:

  Searches are underway for γ conversion to axion in high-Q resonant cavities (ADMX experiment).

- **Quintessence field, ϕ? why has cosmological constant become relevant to expansion just now when radiation, .. dominated earlier.**

  Is there experimental access to the quintessence field through neutrino phenomenology because of coupling of ϕ via ν_R?

It is hard to be optimistic that the LHC can shed light on Dark Energy.

This is a case where the very small value of the cosmological constant, $\rho_\Lambda \sim (2 \times 10^{-3}\ eV)^3$, creates a huge hierarchy/finetuning problem.

In quantum field theory, $\rho_\Lambda \sim (\Lambda_{cutoff})^4$.

If SUSY is broken at a TeV, then $\rho_\Lambda \sim (m_{\rm SUSY})^4 \sim 10^{59} \rho_{obs}$.

It seems very possible that the anthropic argument is needed.

- **Possibly our Universe is just one of the infinitely many continuously created from the vacuum by quantum fluctuations.**
- **Different physics in the different Universes emerges according to the multitude of string theory solutions ($\sim 10^{500}$).**
- **We live in a very unlikely Universe, namely the one that allows our existence.**

Conclusions

1. **It is possible that the LHC will not find the Higgs particle.**

   But, if the hierarchy problem is at all relevant then the LHC will find something else.

2. **It is possible that the LHC will only find the Higgs particle but no other new physics.**

   This is technically possible within renormalizable SM framework, but requires ignoring hierarchy.

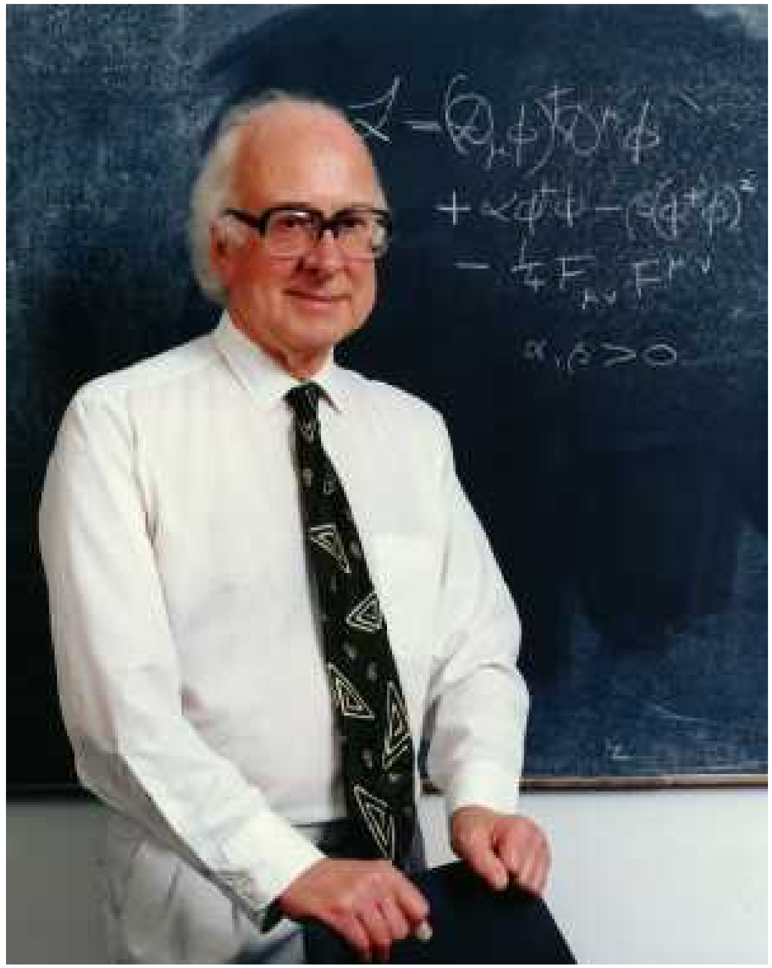
3. **It is possible that the LHC will only see strong WW scattering, but hard to imagine given PEW constraints.**

   LHC will study the strongly-interacting WW sector and provide details of how PEW works out.

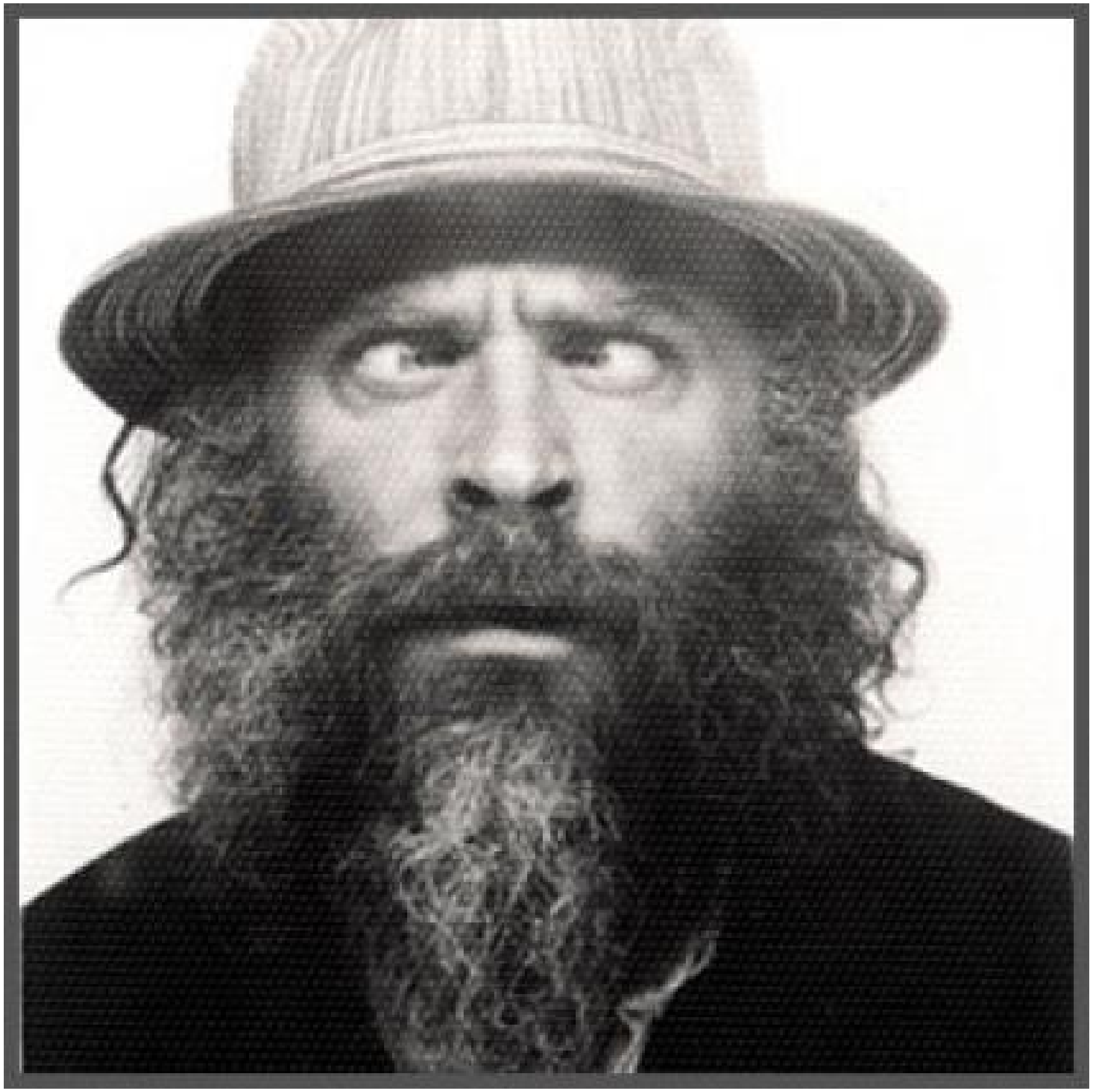
4. Unitarity for WW implies we must find at least one of the above.

We really should not count on knowing what the Higgs "looks like". It could be ...

Priestly, highly orthodox



Ornery/ mean, highly heretical



singer Daniel Higgs

Beautiful but unorthodox

singer Rebekah Higgs

Or, will the LHC bury the Higgs?

In fact, there is even a “buried Higgs” model.

All we can do now is wait (we don't need more wrong theories).