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Lecture 4 - Beyond the Standard Model (BSM)

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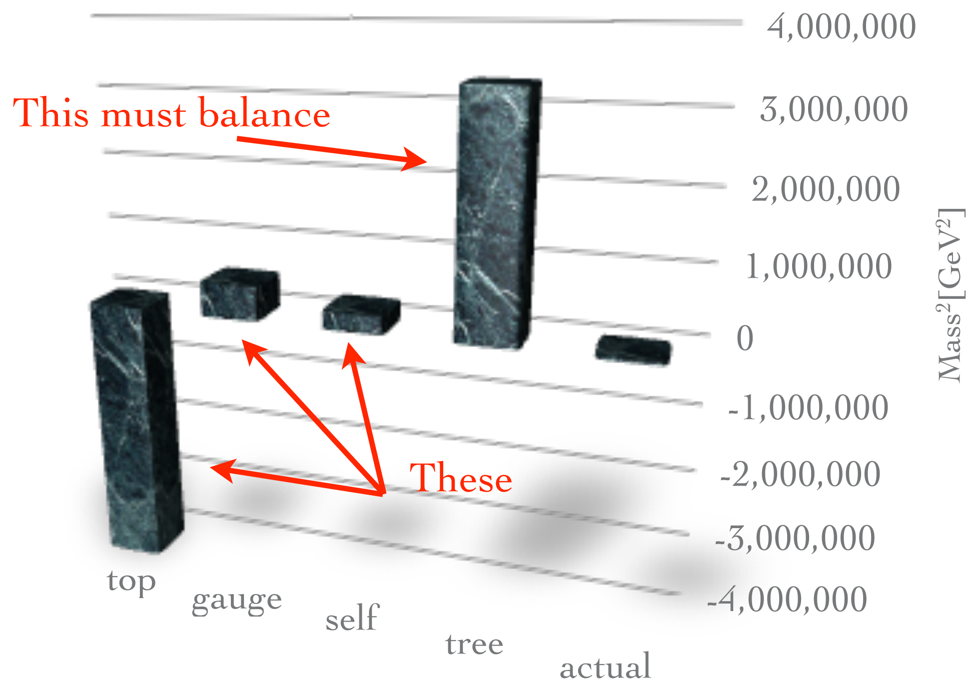
Recall the Hierarchy Problem

- In order to avoid the significant fine-tuning required to cancel the quadratic divergences of the higgs mass, some new physics is required (below ~10 TeV)

$$m_H^2 \approx (200\ GeV)^2 = m_H^{2\ tree} + \delta m_H^{2\ top} + \delta m_H^{2\ gauge} + \delta m_H^{2\ self}$$

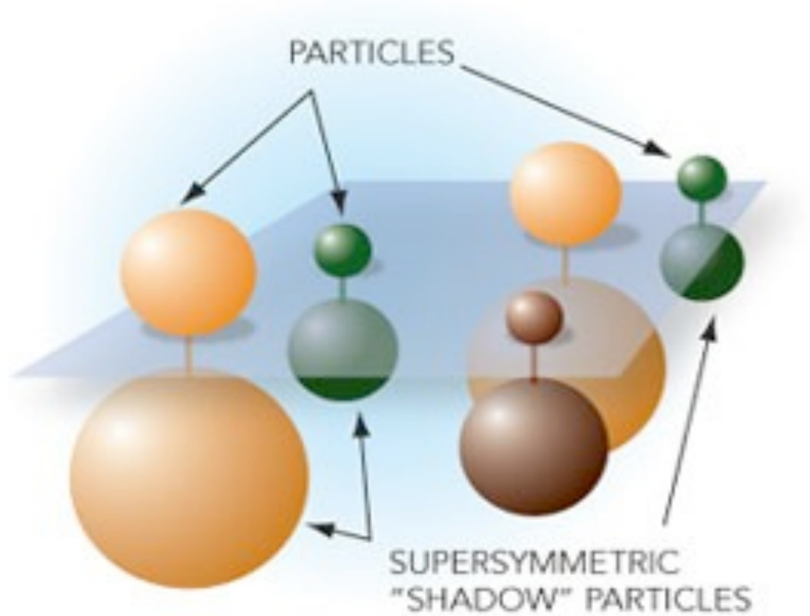
- Dreaming up what this new physics might be has kept theorists busy for the last 30 years

- In this lecture, we'll take a look at some of the more plausible scenarios (and a few that aren't that plausible) that they've come up



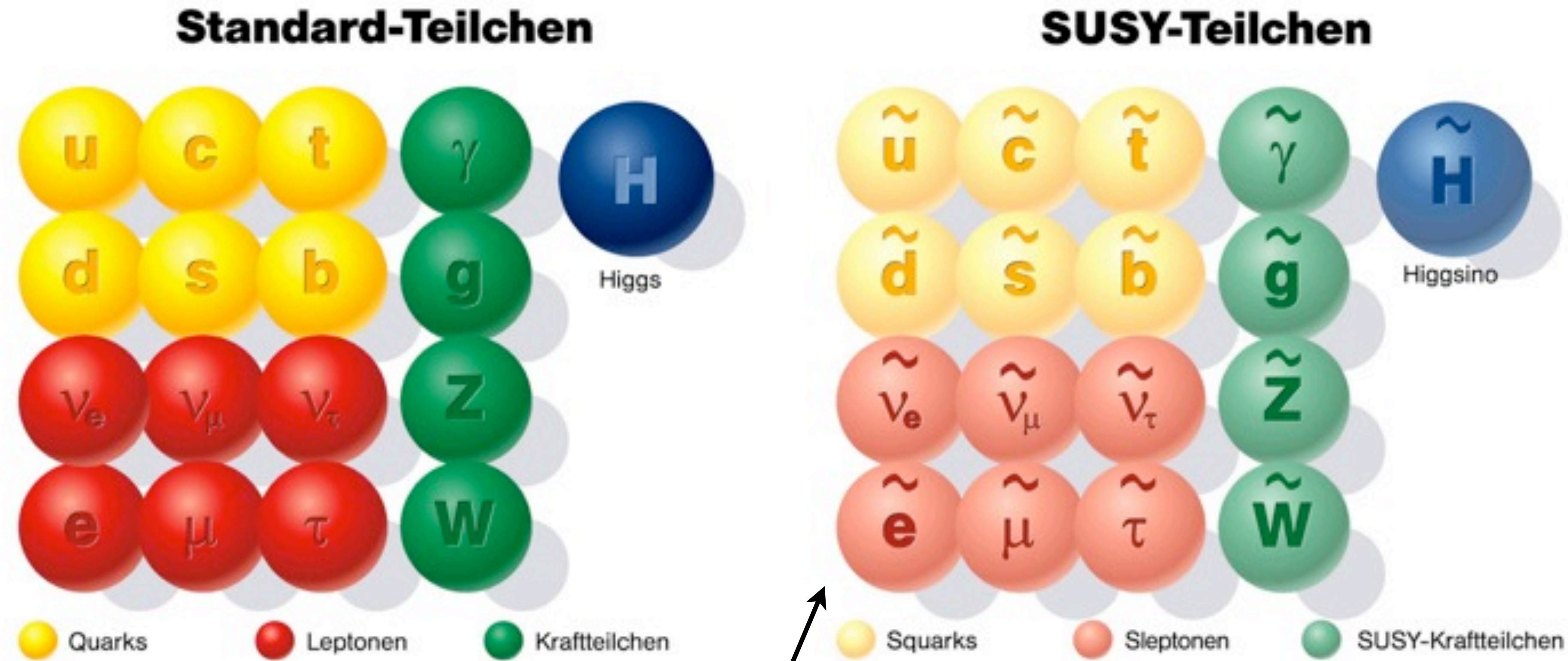
Supersymmetry

- One favoured idea to solve the hierarchy problem is supersymmetry (SUSY)
    - Supersymmetry is a symmetry between fermions and bosons
    - Thus, to make the SM lagrangian supersymmetric requires each bosonic particle to have a fermionic superpartner and vice-versa
- These contribute with opposite sign to the loop corrections to the higgs mass providing cancellation of the divergent terms!



$$\delta m^2{}_H + (-\delta m^2{}_H) = 0$$

SUSY particle spectrum (in German)



Only slight problem, none of these have been observed!

R-Parity and Proton Decay

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- SUSY allows for proton decay to occur via $p \rightarrow e^{+}\pi^{0}$
- The lifetime is predicted to be very short $\tau_p \sim 6 \times 10^{-13}\ \mathrm{sec}(\frac{m_{\tilde{s}}}{1\ \mathrm{TeV}})^4 \frac{1}{\lambda'^4}$
- But proton decay experiments have established that $\tau_p > 1.6 \times 10^{33}$ yrs
- To rectify this situation. it is commonly supposed that there must be a new discrete symmetry called R-parity which is conserved
  - All SM particles have even R-parity (R = 1)
  - All SUSY particles have odd R-parity (R= -1)

$$R = (-1)^{2S+3B+L}$$

- Hence, protons can not decay in R-parity conserving SUSY models

Lightest Supersymmetric Particle (LSP)

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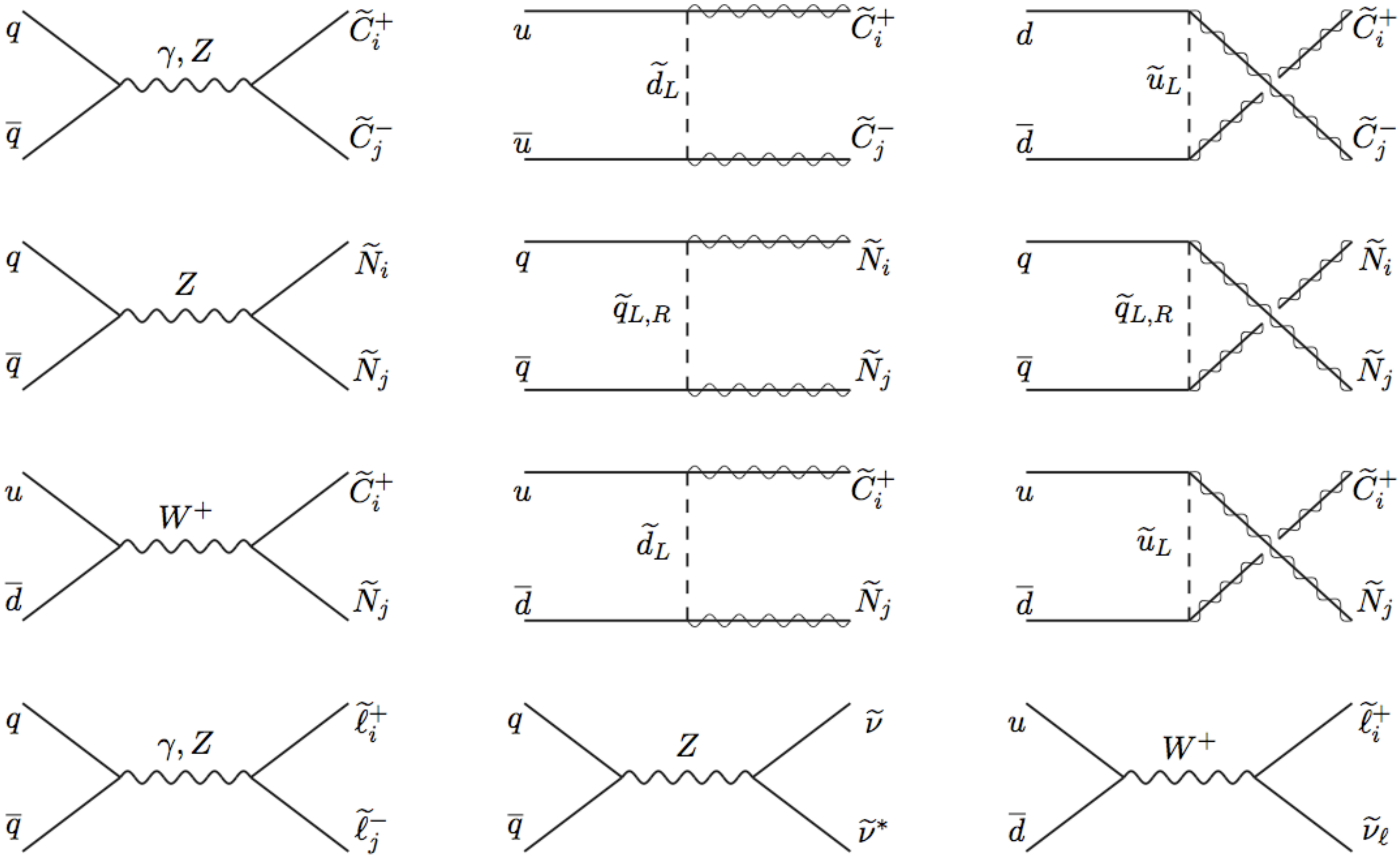
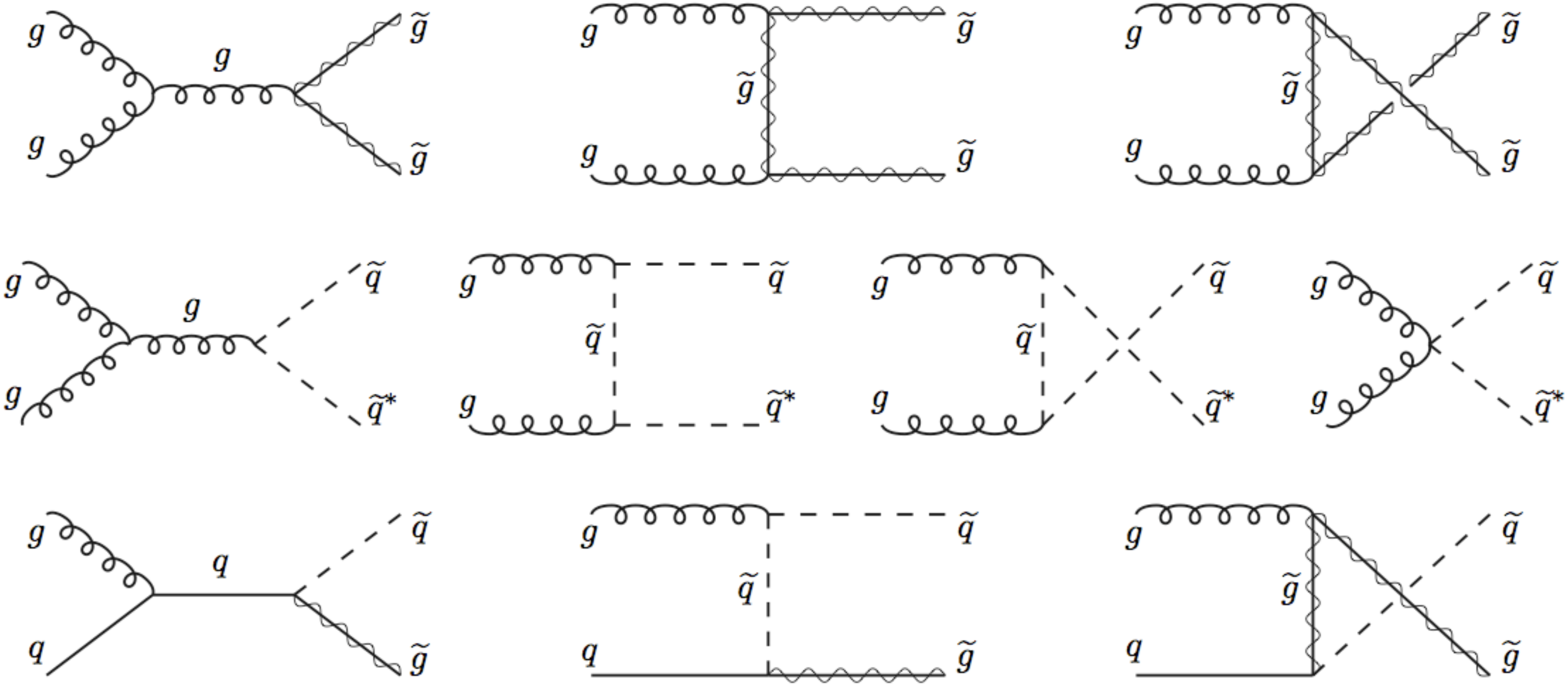
- An immediate consequence of R-parity conservation is that the LSP (whatever that may be) is stable (since its decay would be R-parity violating)
    - The LSP would thus make a very good dark matter candidate if it is neutral and non-strongly interacting
        - This is why many models are popular in which the LSP is the lightest neutralino, chi_1_0
        - This also has the effect that whenever SUSY particles are produced they always cascade down to the massive but stable LSP (which shows up only as missing energy - the canonical SUSY signature)
- Another consequence which affects the phenomenology is that you can only produce (or annihilate) superparticles pairwise
    - In practice this means that each vertex diagram must have two “twiddles” on it

Some examples to get the hang of it



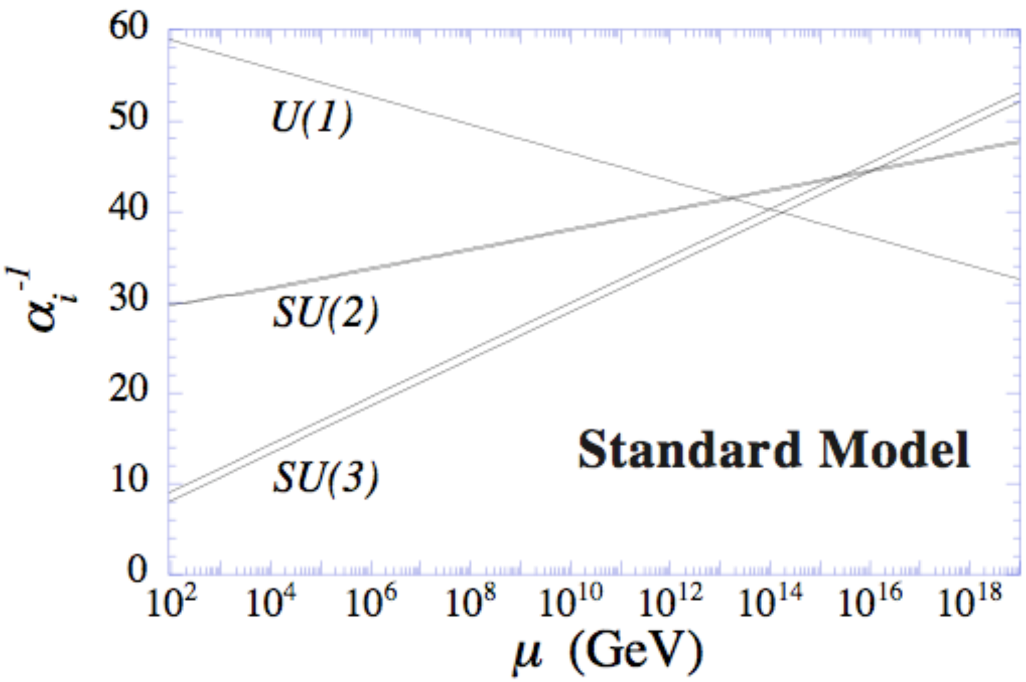
More Examples

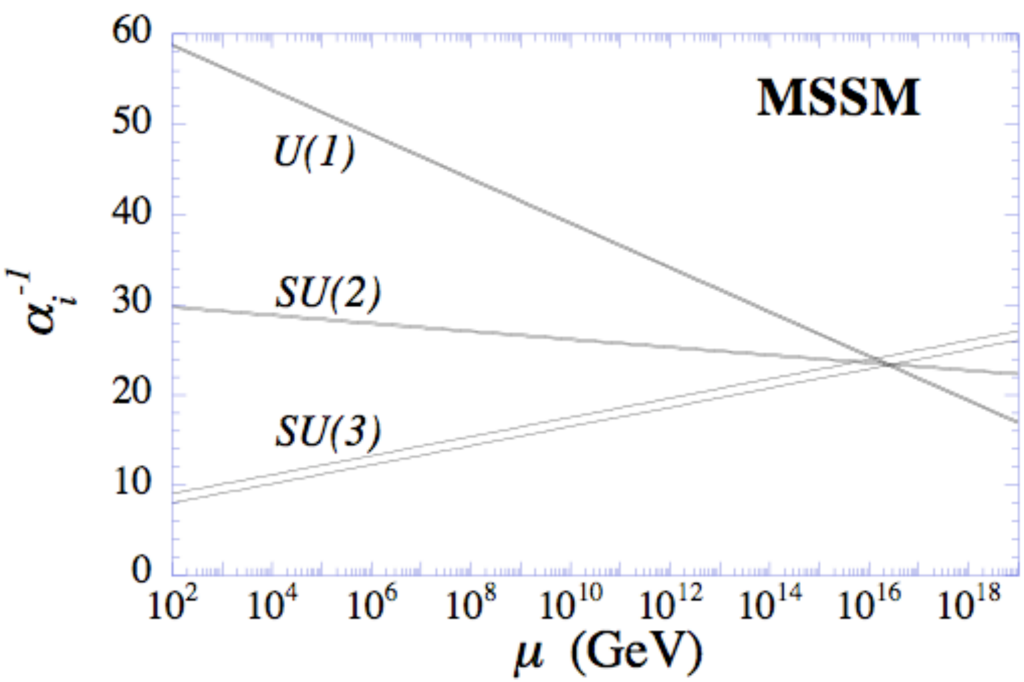


- These come from S. Martin's SUSY primer - a good resource
  http://arxiv.org/pdf/hep-ph/9709356v4

Grand Unification?

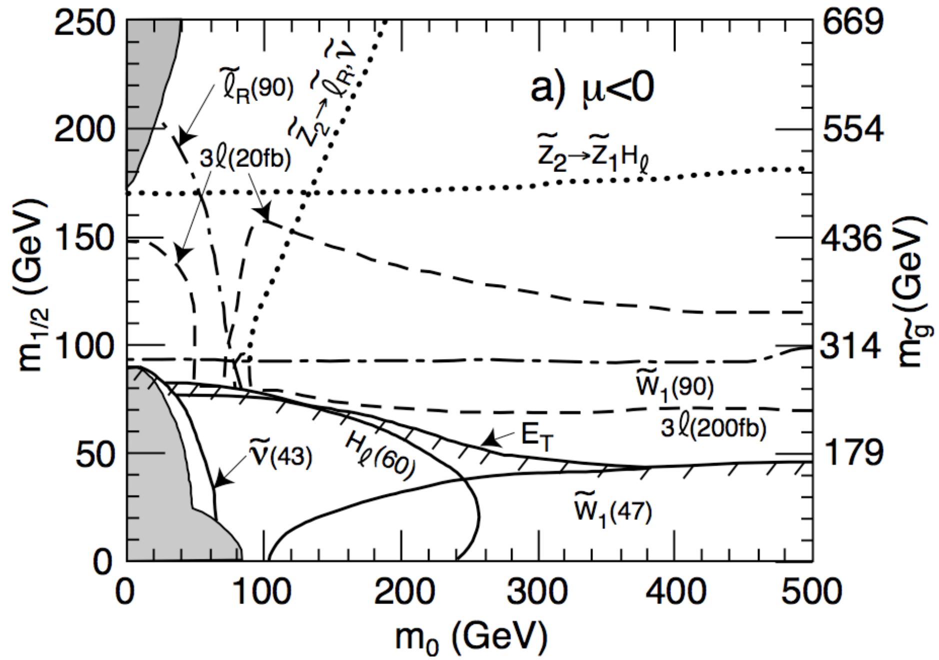
- Another theoretical consideration which makes SUSY is desirable gauge-coupling unification





SUSY Phenomenology

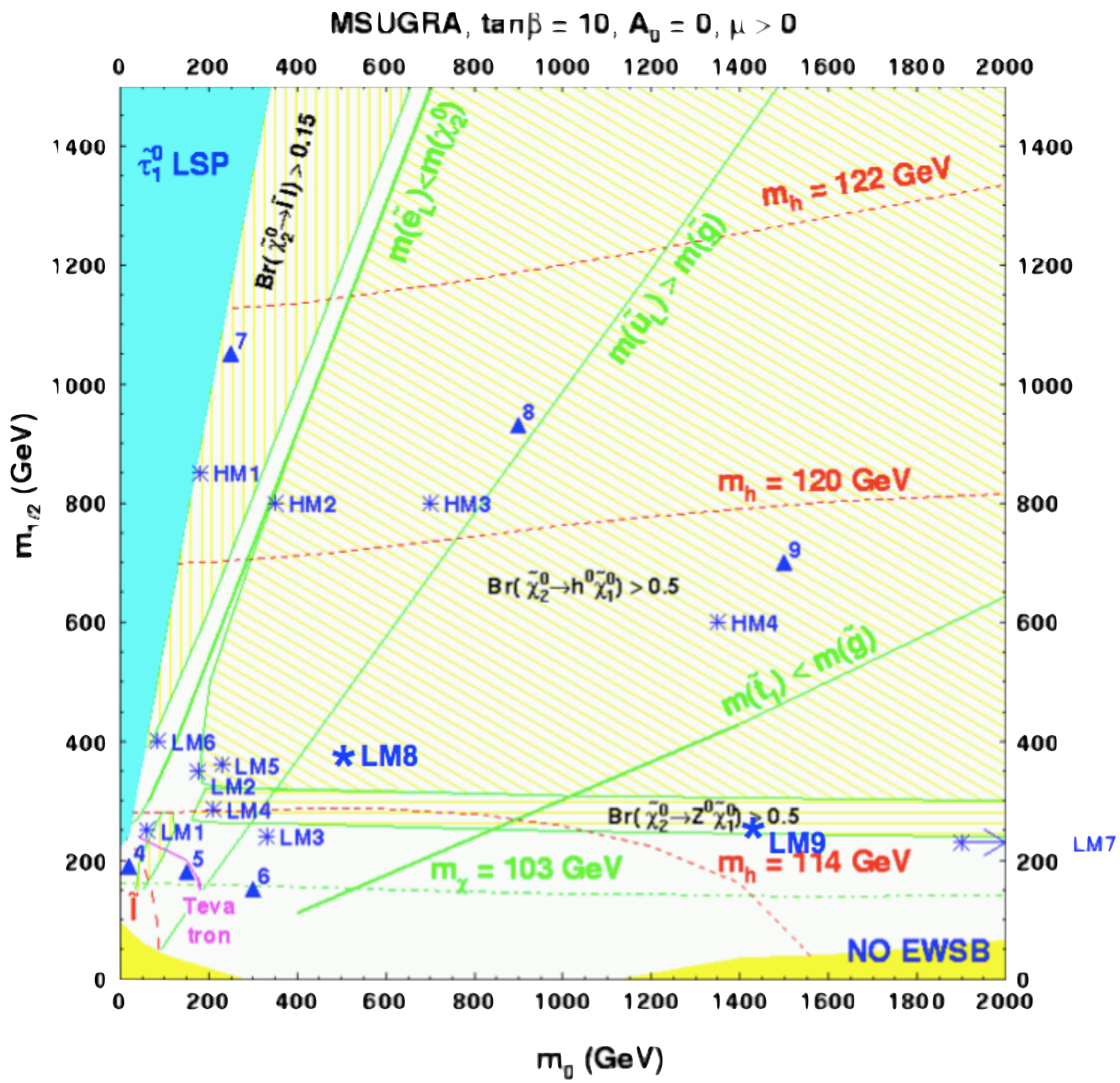
- There are a very large (>100) number of free parameters in the MSSM (where “M” is for “Minimal” by the way!)
  - E.g. none of the masses are predicted
- This makes it impossible to make any phenomenological predictions without making further assumptions to constrain these parameters
- The ways in which this are done are (way) too numerous to go into here - but I will list some of the more popular tricks:
  - Impose boundary conditions at a higher energy scale then evolve phenomenology down to the weak scale via RGE (e.g. mSUGRA)
  - Constraints related to the way SUSY is broken - it has to be afterall, since we don’t observe the symmetry intact (e.g. GMSB)



An example of a plot in such a constrained parameter space (mSUGRA) where there are “only” 5 parameters

Even confined to mSUGRA, things are complex

- In order to make SUSY studies more tractable, LHC experiments have agreed to examine 13 points in mSUGRA space
  - 9 at low mass (LM1->LM9)
  - 4 at high mass (HM1->HM4)
- Covering a representative sampling of experimental signatures & topologies



Example of mSUGRA evolution

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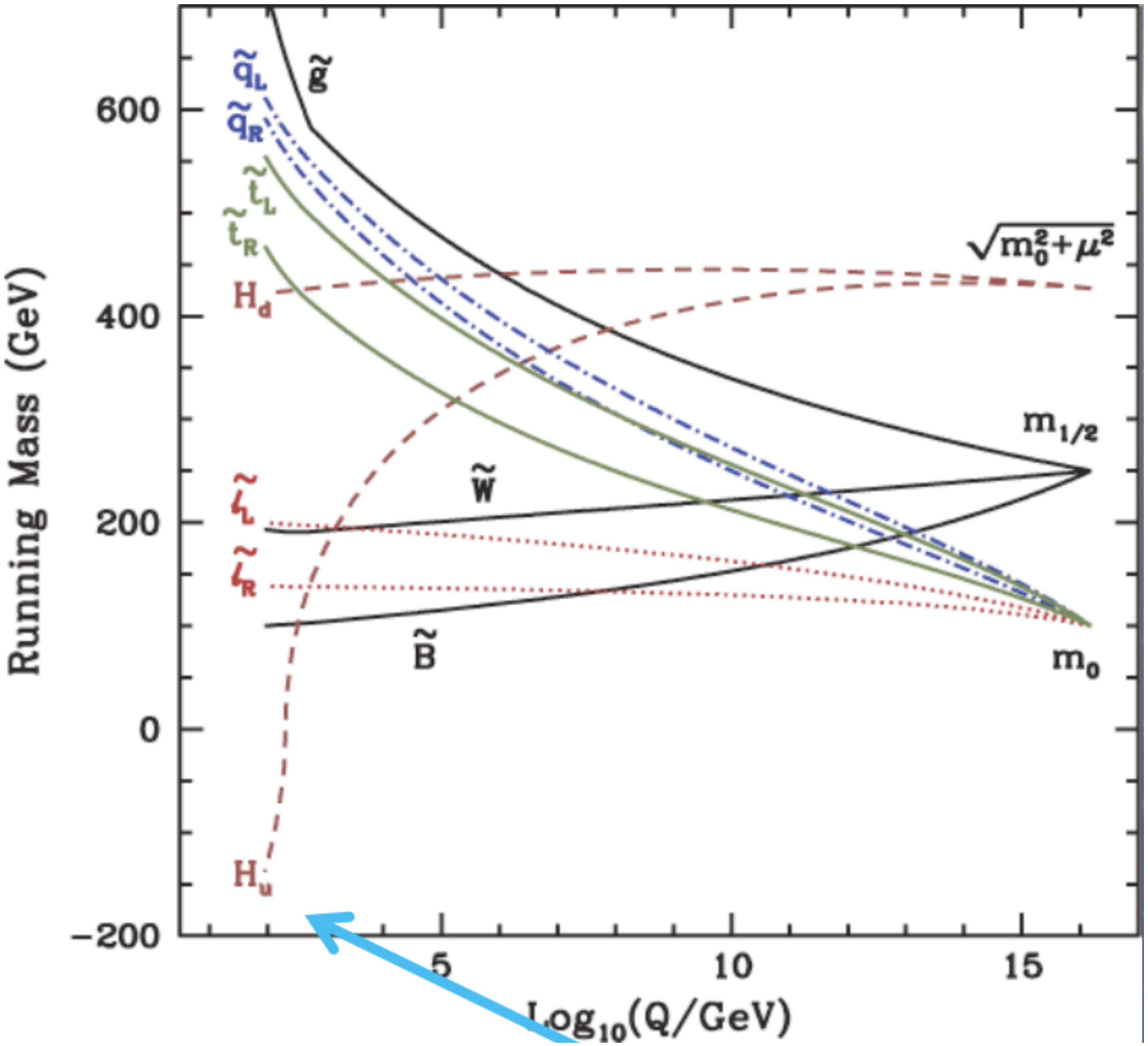


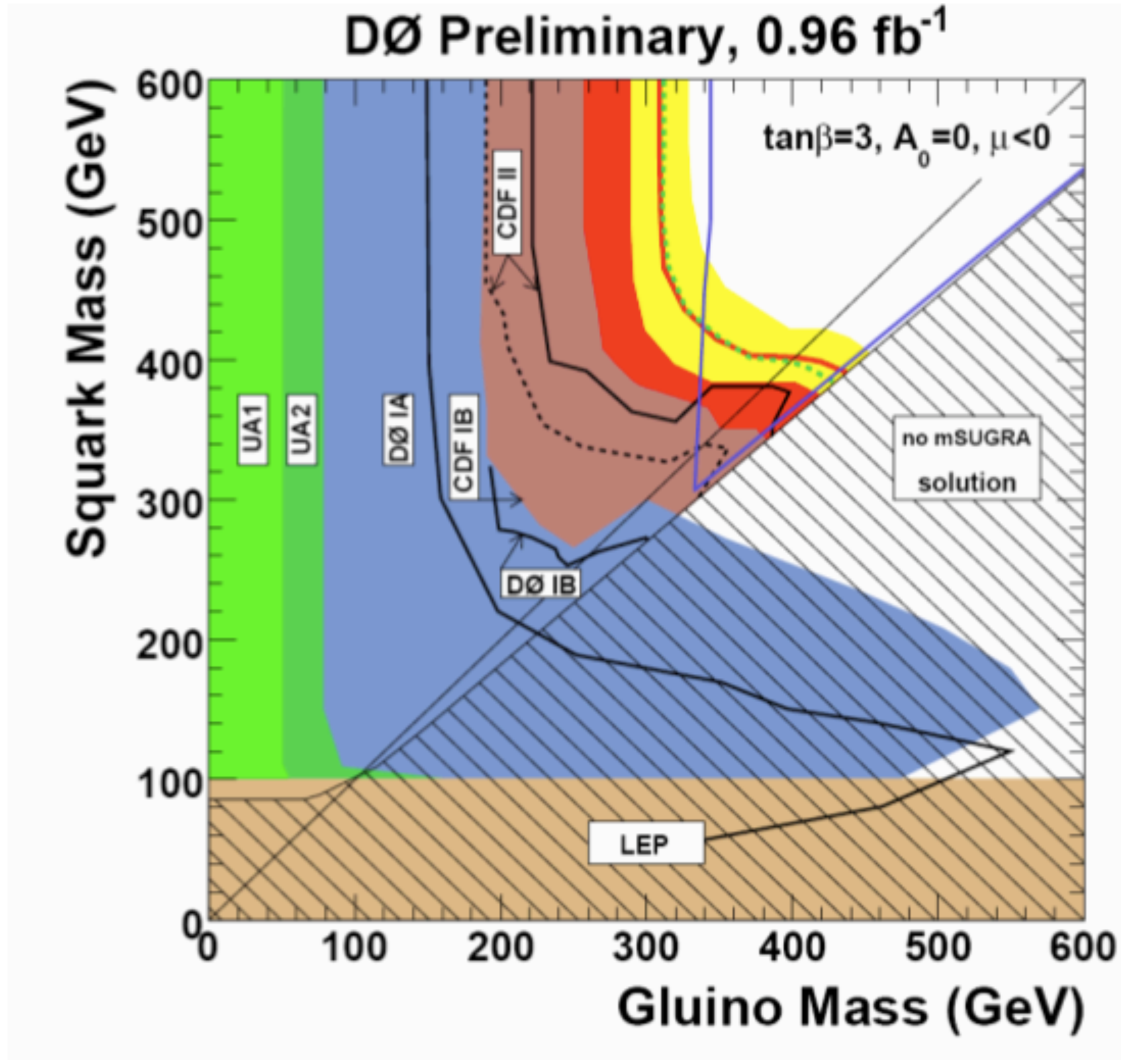
- Generally valid features of evolving from GUT scale
  - Gauge couplings increase SUSY masses
  - Yukawa couplings decrease them

State of the Search for SUSY

- Experiments have been looking for evidence of SUSY ever since it was proposed more than 30 years ago

- LEP and (more recently) the Tevatron have set the most stringent limits to date on sparticle masses. Roughly speaking these are:

  - m_sleptons/charginos > ~ 95 GeV
  - m_LSP(neutralino) > ~ 45 GeV
  - m_gluino > ~290 GeV
  - m_squark > ~375 GeV



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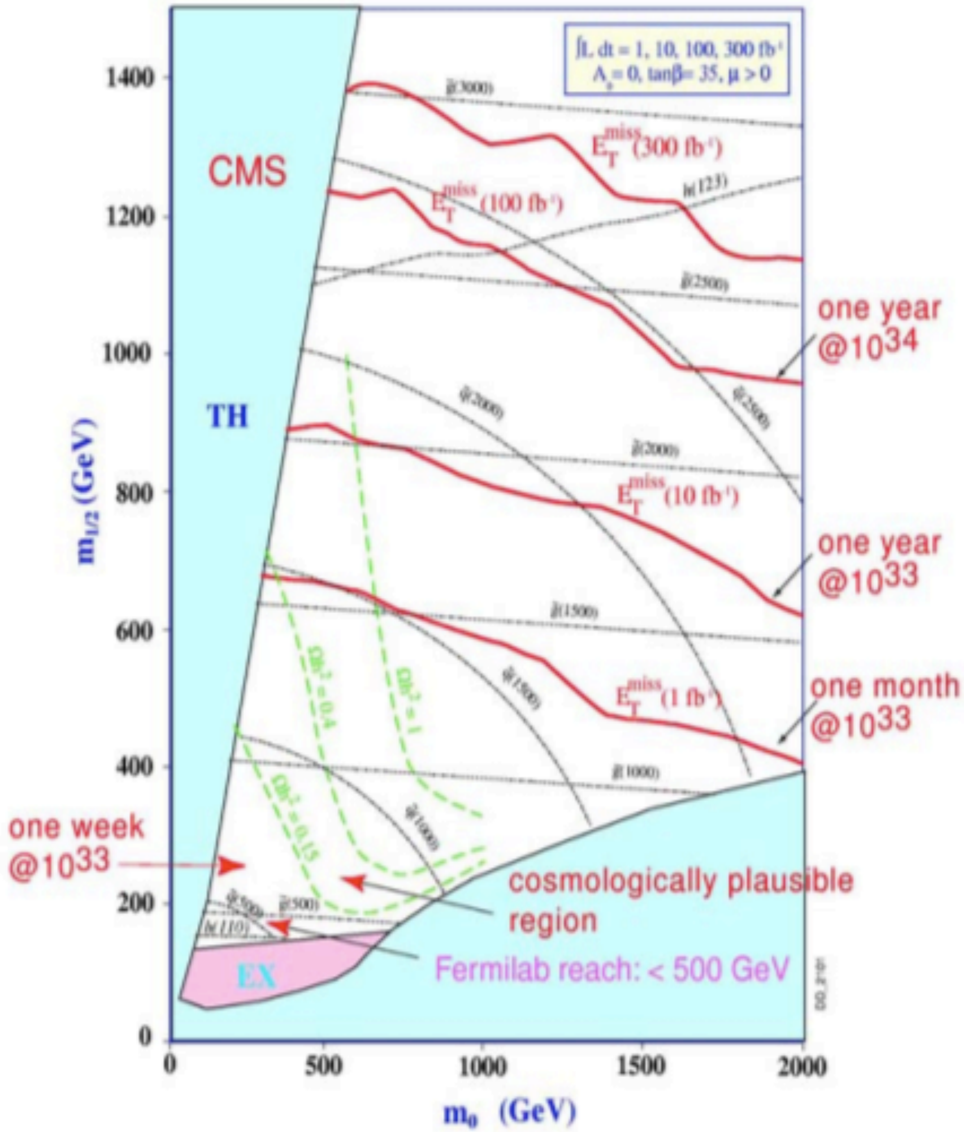
Searching for SUSY at LHC

- As mentioned, previous experiments have not found any evidence as of yet (and they are running out of time to do so)

- However, if any of the more common variants of SUSY do exist, the LHC will find it

    - It may take longer than this probably overly optimistic plot at right suggests, but SUSY should be found relatively quickly in one or more modes

        - Plot is for multijets + missing E_T



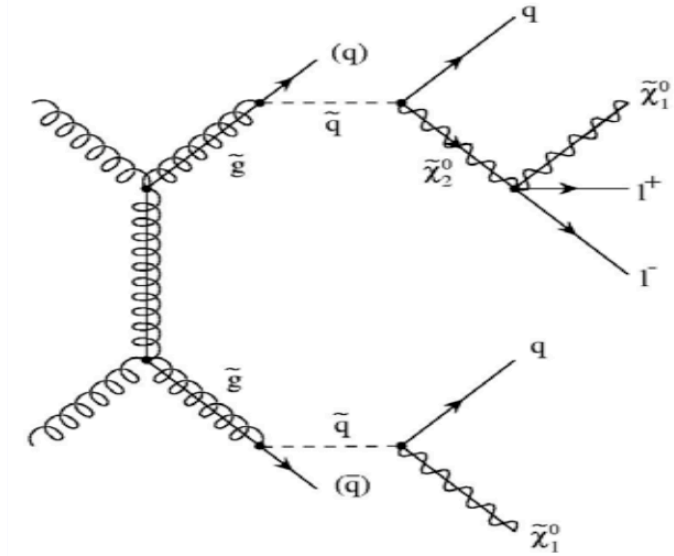
Example LHC Search Mode - Squark/ Gluino Production

- These particles are strongly produced and thus have cross-sections comparable to QCD processes (at the same mass scale)

- Will produce an experimental signature of multi-jets + leptons + missing

- A useful variable is the effective mass

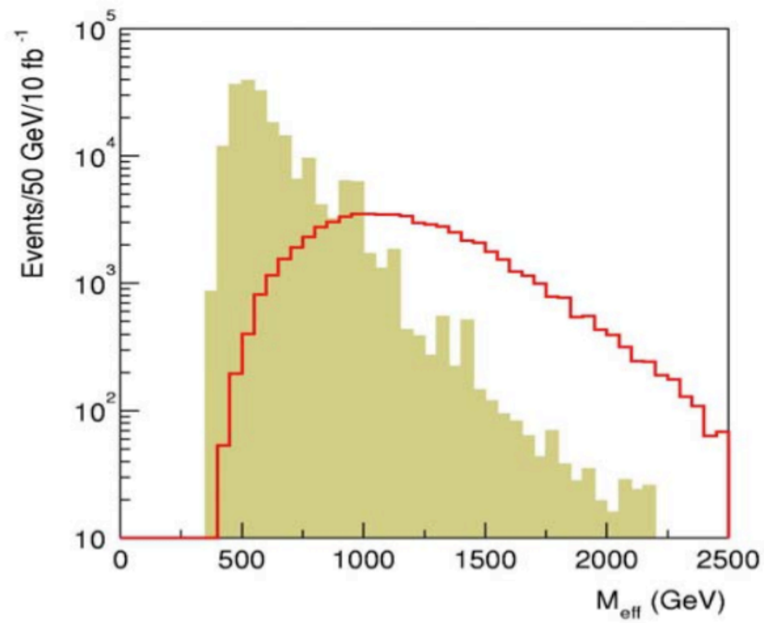
- Typical selection $n_{jet} > 4$, $E_T > 100,50,50,50$, 2 leptons $E_T > 20$ GeV, MET >100 GeV



LHC reach for Squark- and Gluino masses:

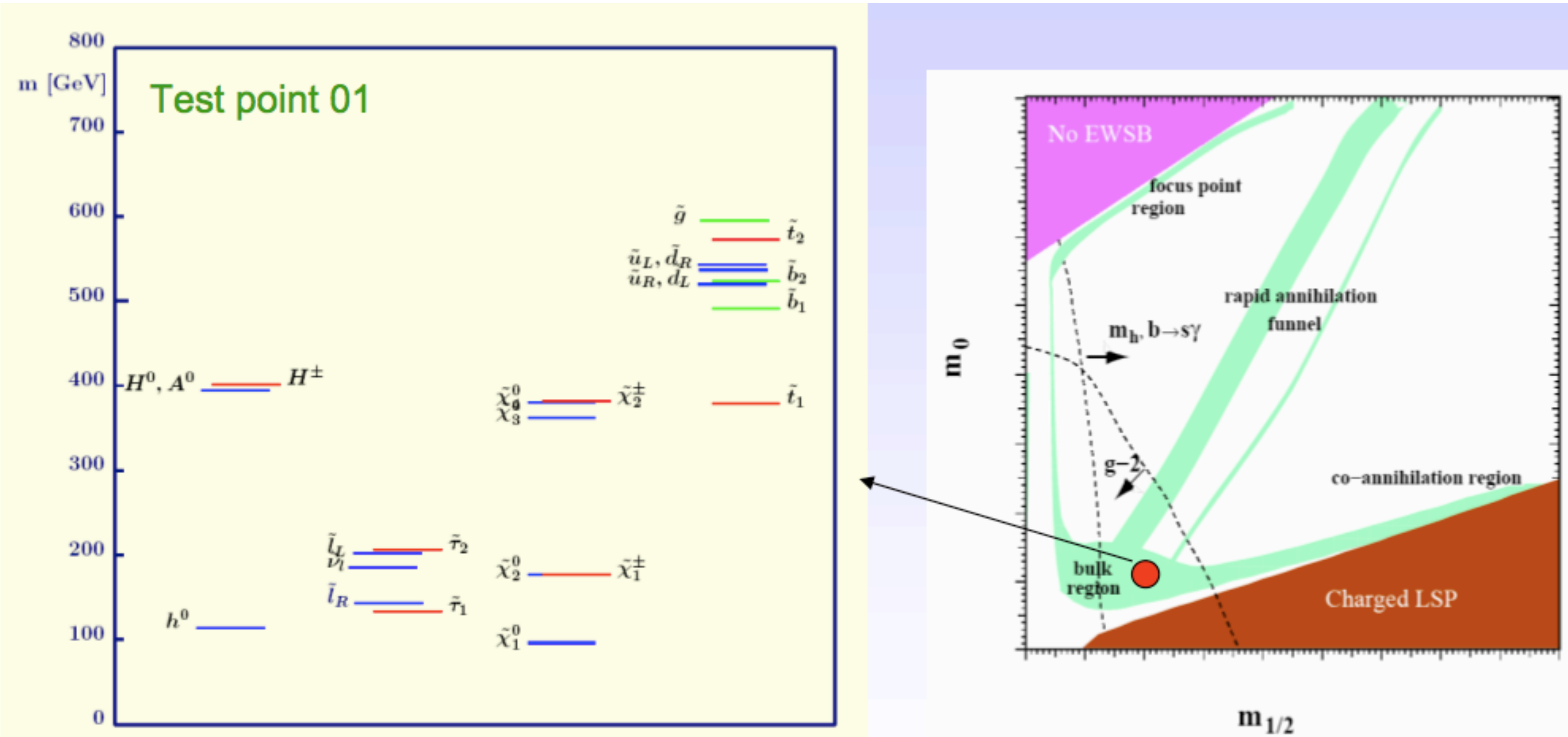
1 fb^{-1}	⇒	M ~ 1500 GeV
10 fb^{-1}	⇒	M ~ 1900 GeV
100 fb^{-1}	⇒	M ~ 2500 GeV

TeV-scale SUSY can be found quickly !

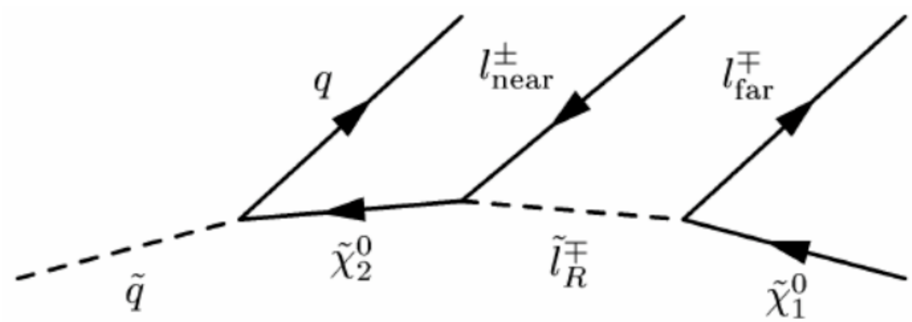


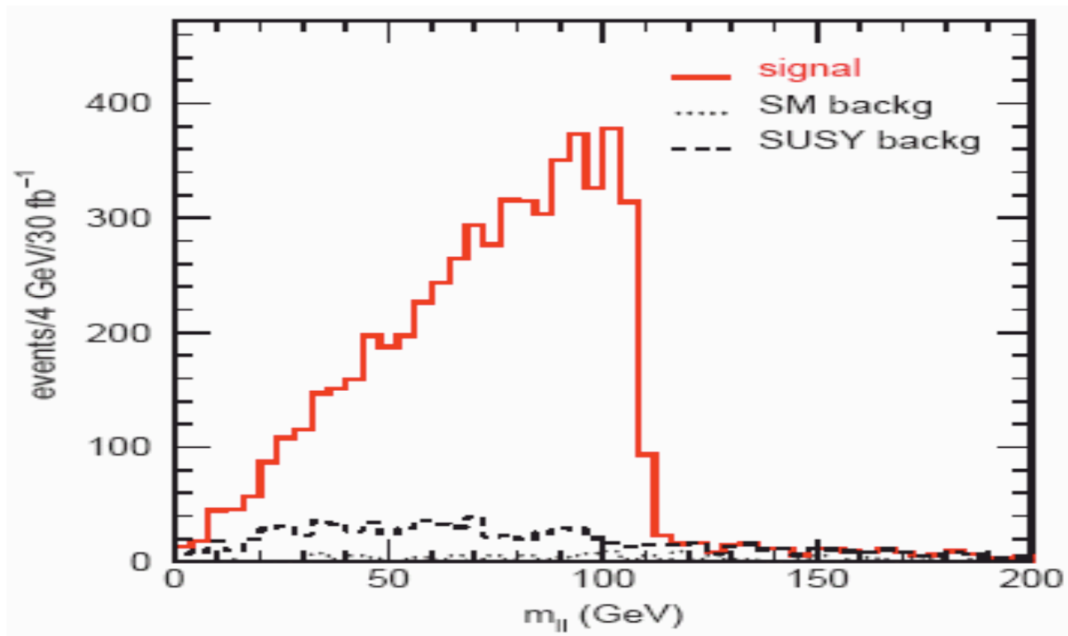
Can the underlying model be disentangled?

- This will not be easy … something that will help is to map out the SUSY mass spectrum



How can we measure SUSY masses?





- One strategy is to measure the endpoint of cascade decays
- By combining enough such measurements, maybe the mass spectrum can be measured

$$m^{max}_{\ell^+\ell^-} = \frac{\sqrt{(m^2_{\chi^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\chi^0_1})}}{m_{\tilde{\ell}}}$$

Signature Based Searches

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- If one were to ennumerate all the possible SUSY search modes that anyone has studied it would be quite a long list

- A more practical way which the experiments have organised their searches is in terms of signatures (e.g. at CMS):

    - MET + jets @ LM1, MET > 200 GeV
    - Muons + MET + jets @ LM1, MET > 130 GeV
    - Same sign di-muons @ LM1, MET > 200 GeV
    - Opposite sign dileptons @ LM1, MET > 200 GeV
    - Di-taus @ LM2, MET > 150 GeV
    - Higgs + X @ LM5, MET > 200 GeV
    - Z^0 + X @ LM4, MET > 230 GeV
    - Top + leptons + X@ LM1, MET > 150 GeV

Note: All signatures require MET

A word about MET

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- You don't measure missing E_T, you calculate it as a vector sum over the energy measured in the calorimeter

$$E_T^{miss} = -\sum E_T$$

- Ideally if E_T^{miss} is nonzero it is due to a physics (a neutrino, or more interestingly a neutralino)
  - But often it is due to more mundane things (e.g. a particle going in a crack bewteen calorimeter cells)
- This causes the object, usually a jet, to be mismeasured and give apparent E_T^{miss}
- These cases are (usually) easily identifiable because the E_T^{miss} is either along, or opposite, the jet's axis
- In the start of an experiment, though, there can be other sources (e.g. beam related) which may be harder to identify
- In any case, at least at startup, E_T^{miss} may not be all that reliable an indicator of SUSY

SUSY Higgs Sector

- Electroweak symmetry breaking in the MSSM proceeds exactly as in the SM with one important difference, two higgs doublets of complex scalar fields are needed
  - Thus, there are 8 d.o.f. instead of 4
- Both of these doublets, have non-zero vev's which break the $SU(2)_L \otimes U(1)_Y$ symmetry
  - The ratio of these vev's is called tanβ
- The EWSB process again uses up 3 d.o.f., giving them to the longitudinal components of $W^\pm$, Z^0 as before
  - This leaves 5 d.o.f. which become the five Higgs bosons on the MSSM
  - h^0, H^0, $H^\pm$, A^0

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}$$

$$\Phi_1^{min} + \delta\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 + H_1 \end{pmatrix}$$

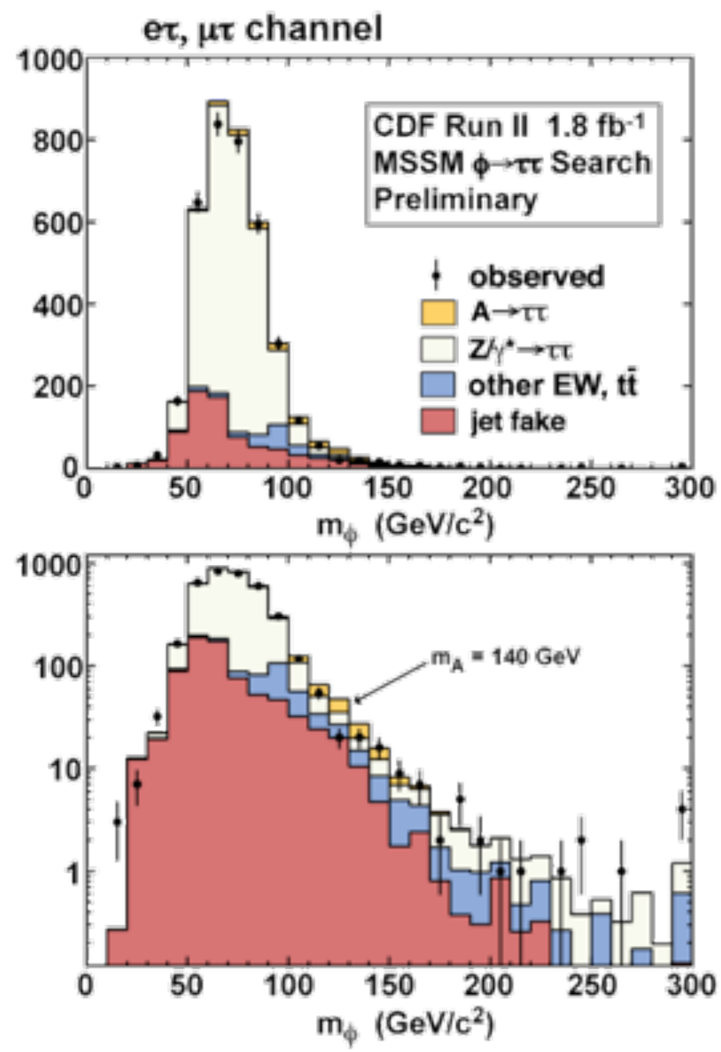
$$\Phi_2^{min} + \delta\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 + H_2 \\ 0 \end{pmatrix}$$

$$v = \sqrt{v_1^2 + v_2^2}$$

$$\tan\beta \equiv v_2/v_1$$

Will these Higgs be Easier or Harder to Find?

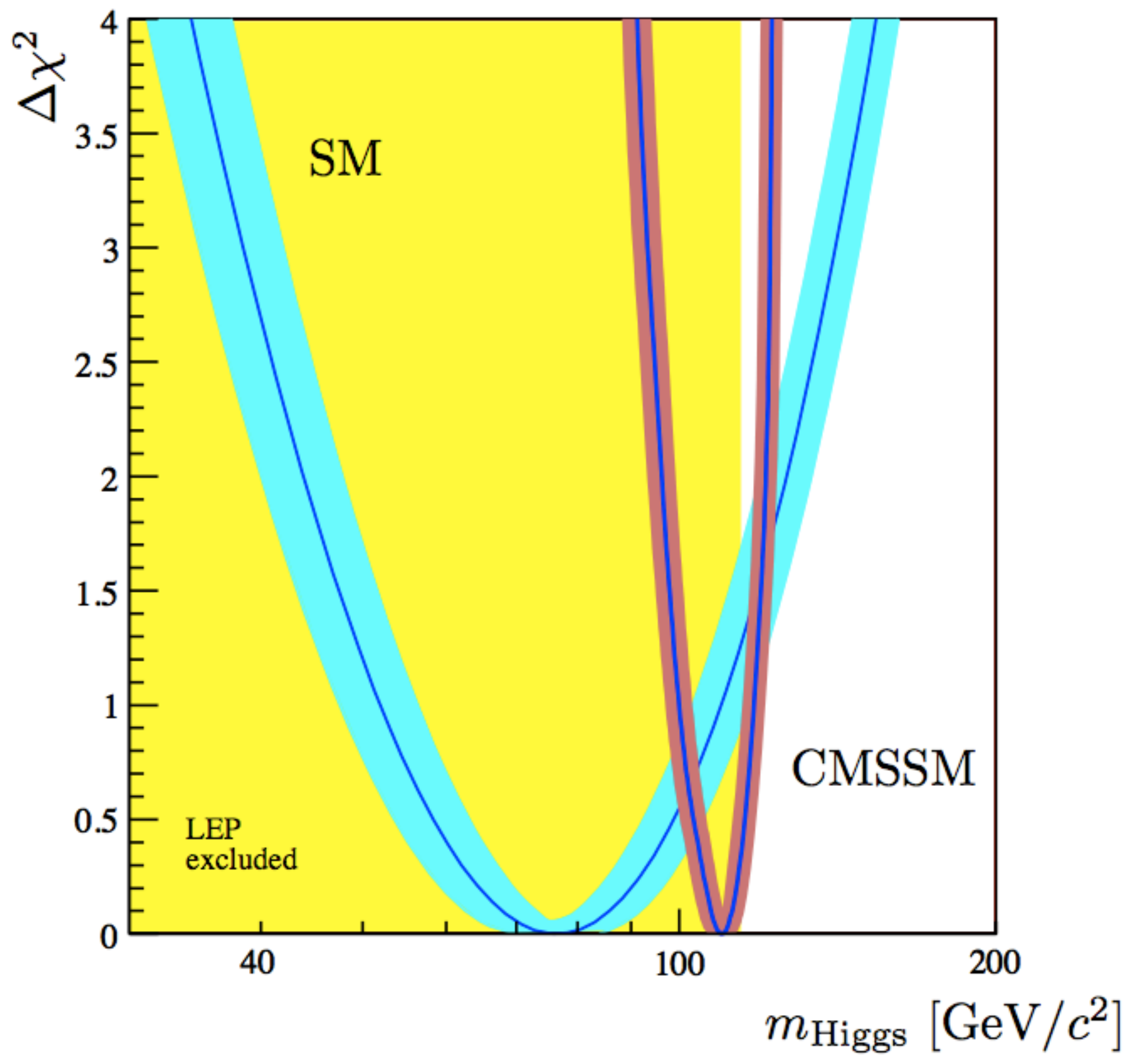
- Well, it depends …
- Firstly, in nearly all models, the lightest neutral SUSY Higgs needs to be pretty light (m_h < ~130 GeV)
- Secondly the phenomenology is sensitive to SUSY parameters, e.g. tanβ
  - If tanβ is large, couplings to down-type fermions are enhanced and the role of b's and τ's become increasingly important
  - Production cross-sections are enhanced by $(\tan\beta)^2$
  - This can make for very large event rates, even at the Tevatron (hence the flurry of blog induced rumours about A→ τ τ at CDF last year that you might have heard about)



There is no excess @ CDF

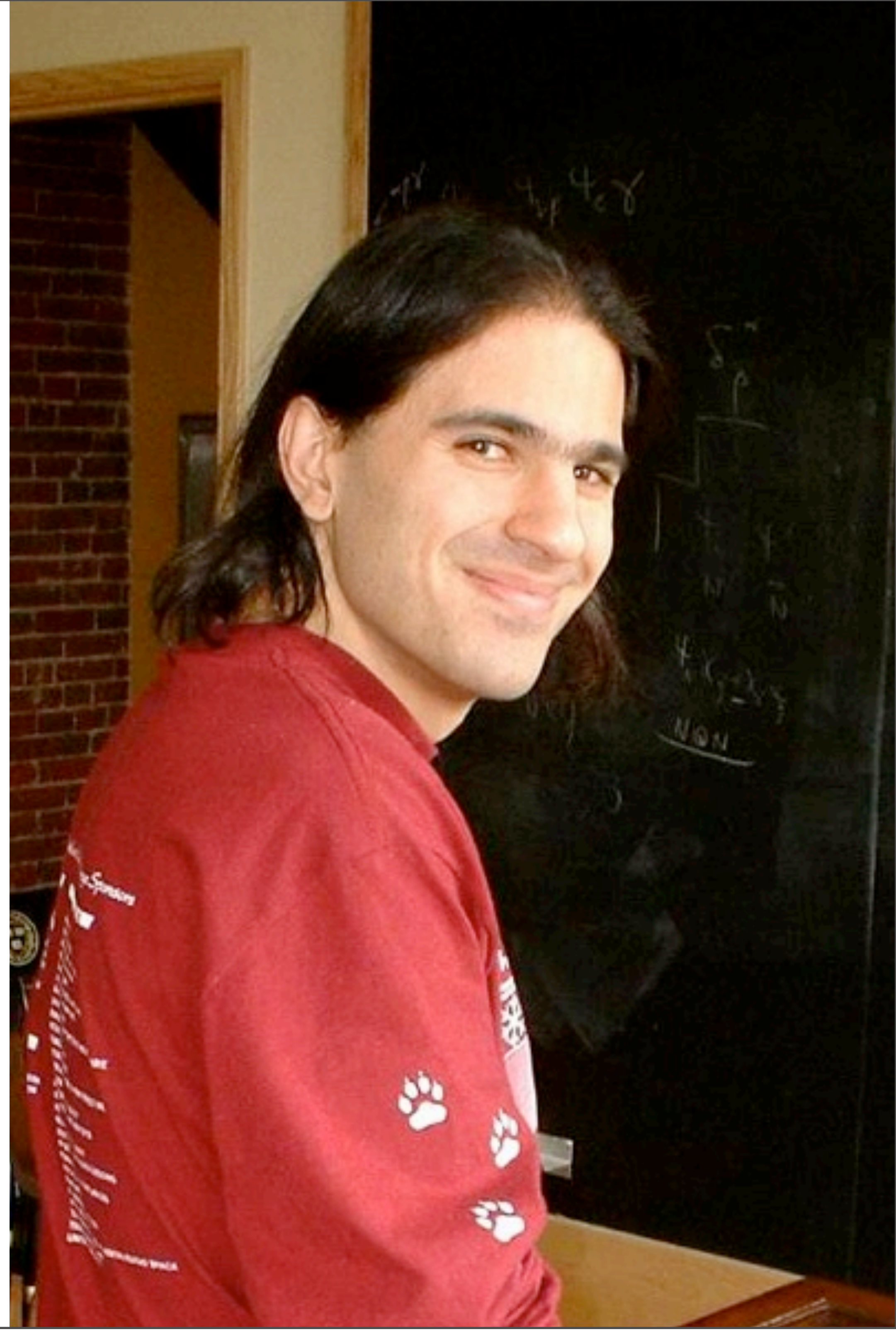
What do the measurements say about SUSY Higgs?

- A plot from a recent paper (arXiv:0707.3447v2) I thought was interesting
- In what they call the CMSSM (C is for constrained), which I think is the same as mSUGRA, they obtain the following fit to all electroweak, flavour physics, and cold-dark matter search
- The preferred value for the hightest higgs is
  - $m_h \sim 110 \pm 10$ GeV



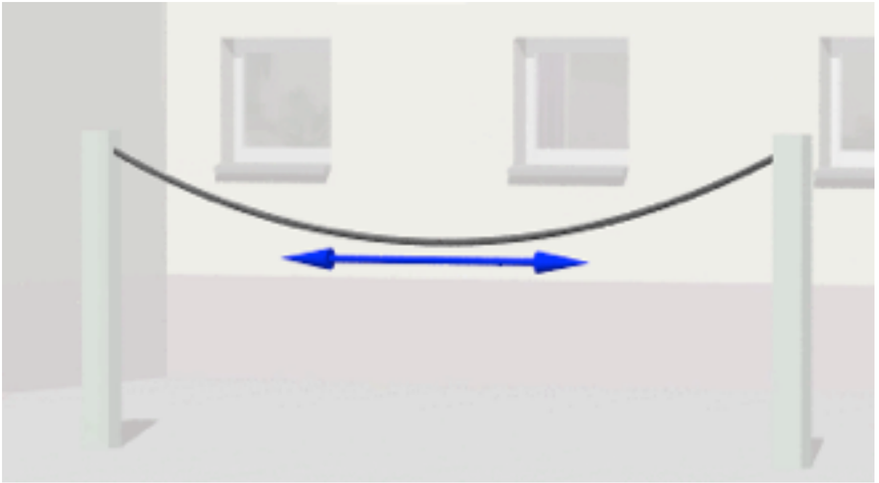
Alternative Solutions to the Hierarchy Problem

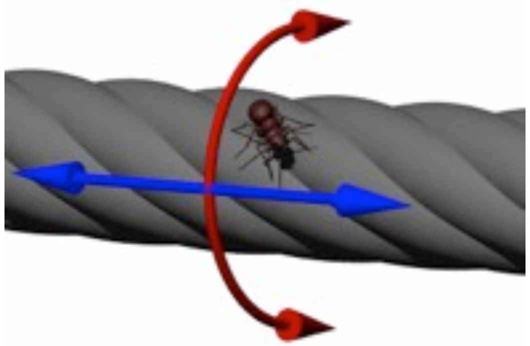
- SUSY is not the only way to address the hierarchy problem
- In the last 10 years, several viable alternatives have emerged
- The most important of them (at least it seems to me) have originated from Nima Arkani-Hamed (pictured at right)
  - Extra-dimensions
  - Little Higgs
  - Split Susy (which doesn't solve the hierarchy problem so much as ignore it)



“Large” Extra-Dimensions (ADD)

- In the late 1990’s Akani-Hamed, Divali, & Dimopolous wrote a paper suggesting that their might be numerous “large” extra spatial dimensions which affect gravity below scales of ~1 mm
- This was possible because while electroweak interactions have been probed down $1/M_{EW}$
- Gravitational interactions (had) been only studies to ~1 cm
- It is certainly possible that there exist more spatial dimensions than x,y,z but that we haven’t (gravitationally) noticed them yet and which will appear when we look

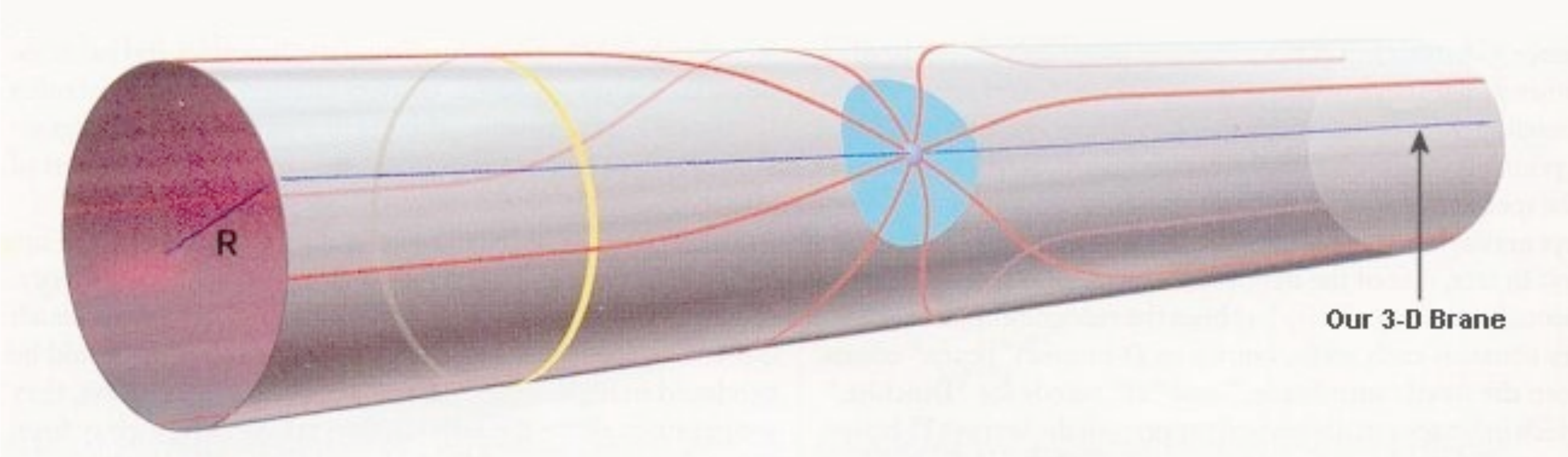




What would ADD extra dimenions look like? Why is gravity affected?

- For r << R, gravity behaves as if it were 4+n dimensonal (field lines spread out uniformly throughout the bulk) and will be stronger

- For r ≥ R gravitational field lines are deformed since they are confined to the 4 dimensions (represented by a 3-D cylinder in the picture below)



SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.

How do extra dimensions solve the Hierarchy problem?

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- Remember the hierarchy problem is that if one computes the quadratic corrections to the higgs mass, cut off at a scale $\Lambda_{cutoff} \sim M_{Pl}$ the fine tuning required to get an ~100 GeV Higgs is extreme

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, (r \ll R)$$

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} R^n} \frac{1}{r}, (r \gg R)$$

- This is because M_{Pl} is a big number

$$M_{Pl}^2 \sim M_{Pl(4+n)}^{n+2} R^n$$

- Extra-dimensions (n of them, of radius R) simply make M_{Pl} a smaller number

$$R \sim 10^{\frac{30}{n} - 17} \mathrm{cm} \times (\frac{1\mathrm{TeV}}{m_{EW}})^{1+\frac{2}{n}}$$

- This is because 4+n dimensional gravity is much stronger than 4 dimensional diluted version

How can ADD extra dimensions be detected?

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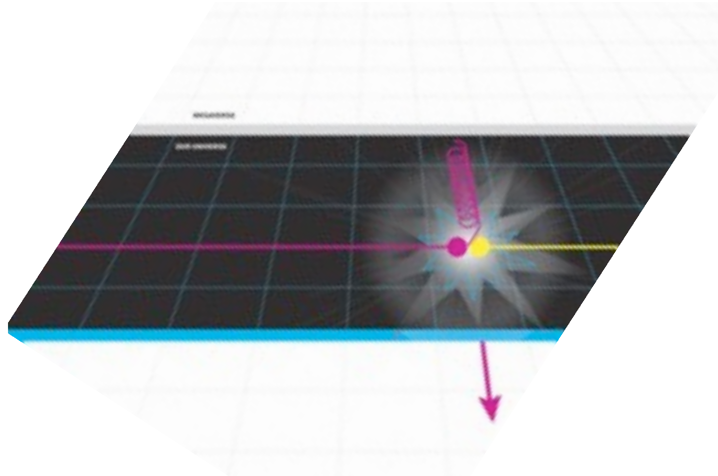
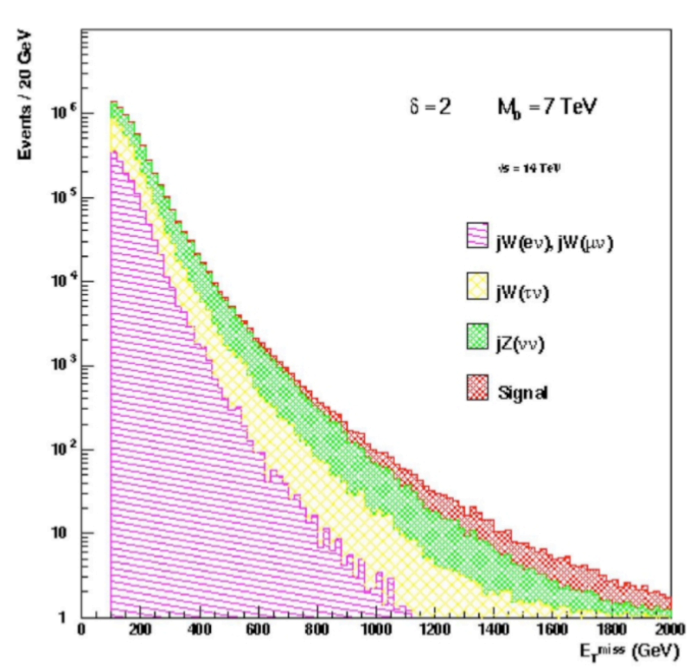
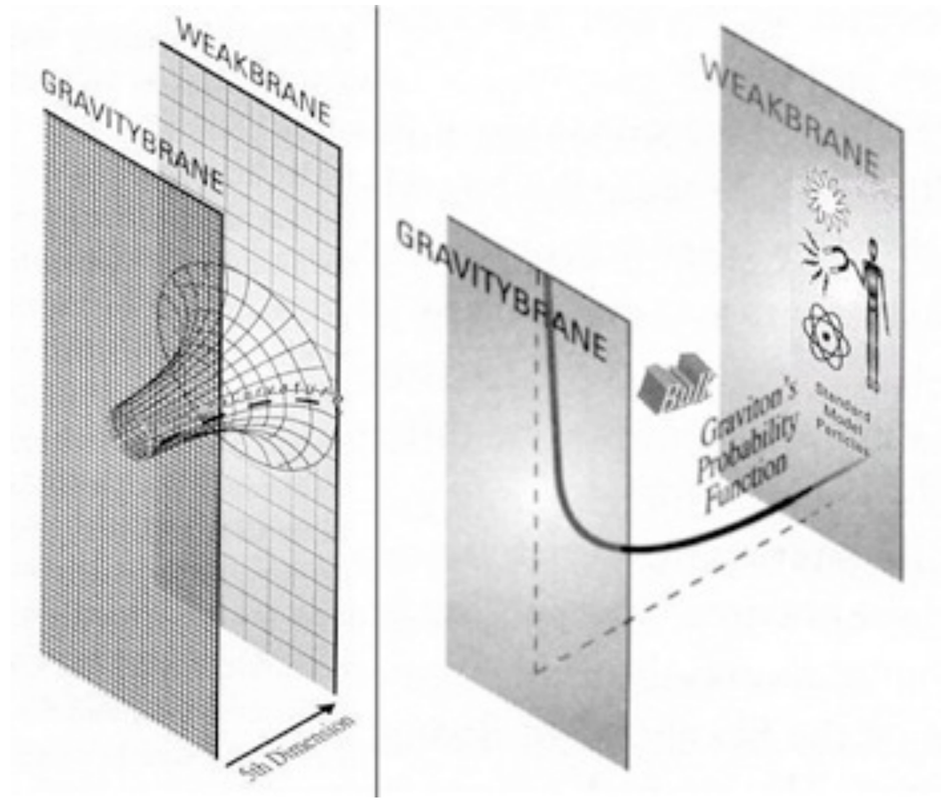
- Increasingly precise tabletop experiments can measure deviations from Newtonian gravity at small scales (current limits are < 10-100 μm)
- Colliders can search for evidence of extra-dimensions too
- Gravitons can escape into the extra dimensions and appear as missing energy at the LHC
  - Search for an overall excess of $E^{miss}{}_T$
  - Or as an excess of monojet + $E^{miss}{}_T$ events





“Warped” Extra-Dimensions

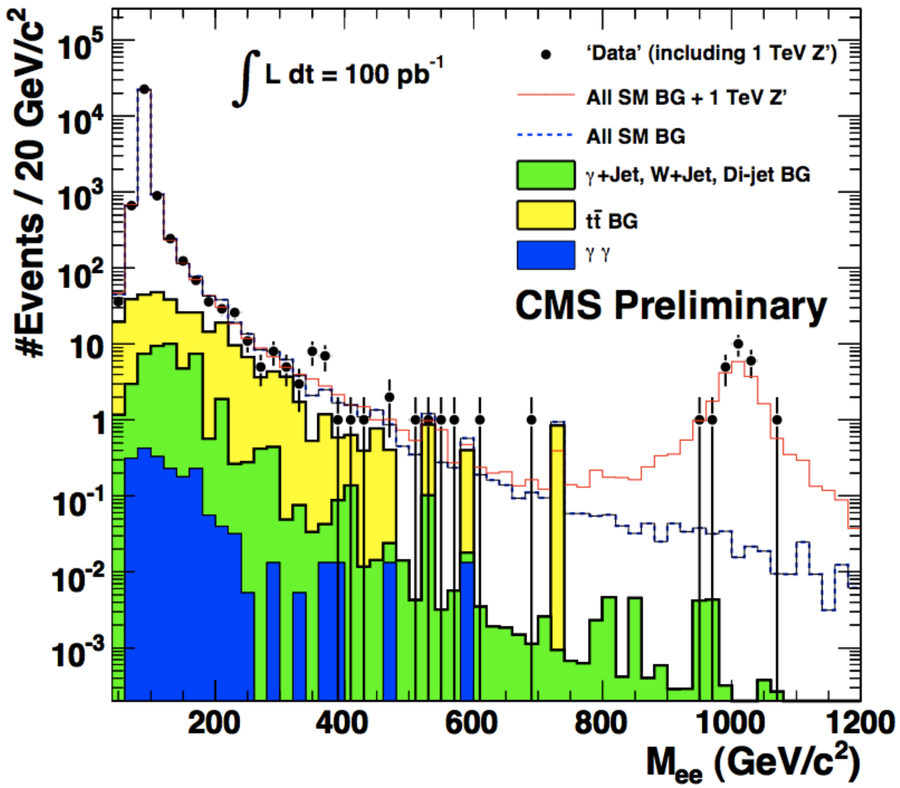
- Sometime after ADD, Randall-Sundrum proposed another very interesting extra dimensional model
- In this theory, there is but one extra-dimension
- In this theory, the 4-D space-time metric is multiplied by a “warp” factor which is a rapidly changing function of the additional dimension
- Gravity is weak on the “weak brane” where SM fields are confined but increases in strength exponentially in the extra dimension (since space-time is accordingly “warped”)

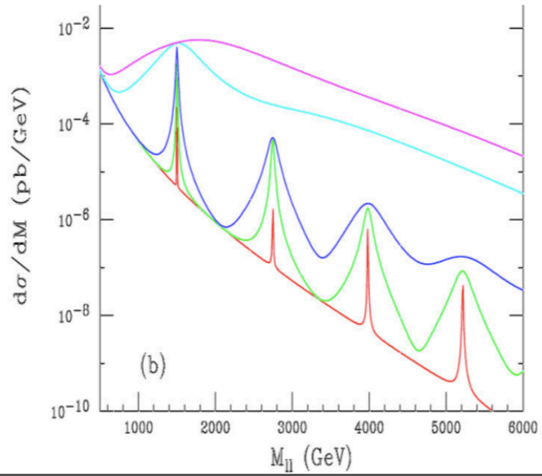


$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^{\nu} + r_c^2 d\phi^2$$

Detecting Randall-Sundrum Gravitons

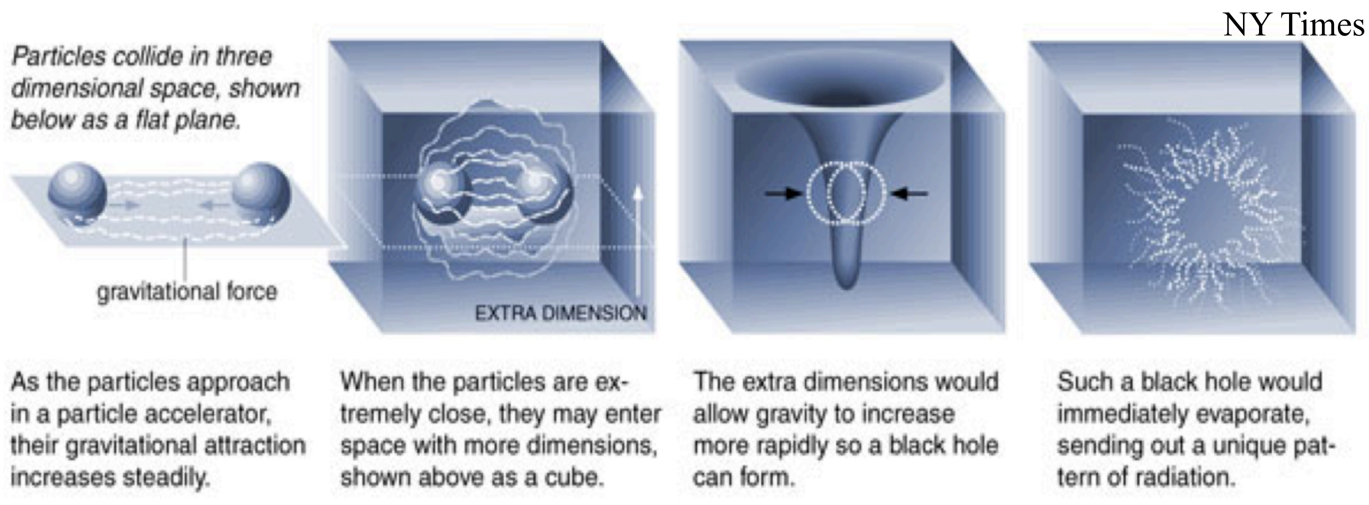
- RS gravitons will appear as a narrow resonance above background in the high mass region of the dileption invariant mass spectrum
- Fairly easy signature to observe, difficulty will be in distinguishing whether this is a new gauge boson (Z') or RS gravitons
    - If more than one resonance observed in same channel, more likely extra-dimensions
    - Only way to know for sure is to measure the spin (gravitons have spin = 2)





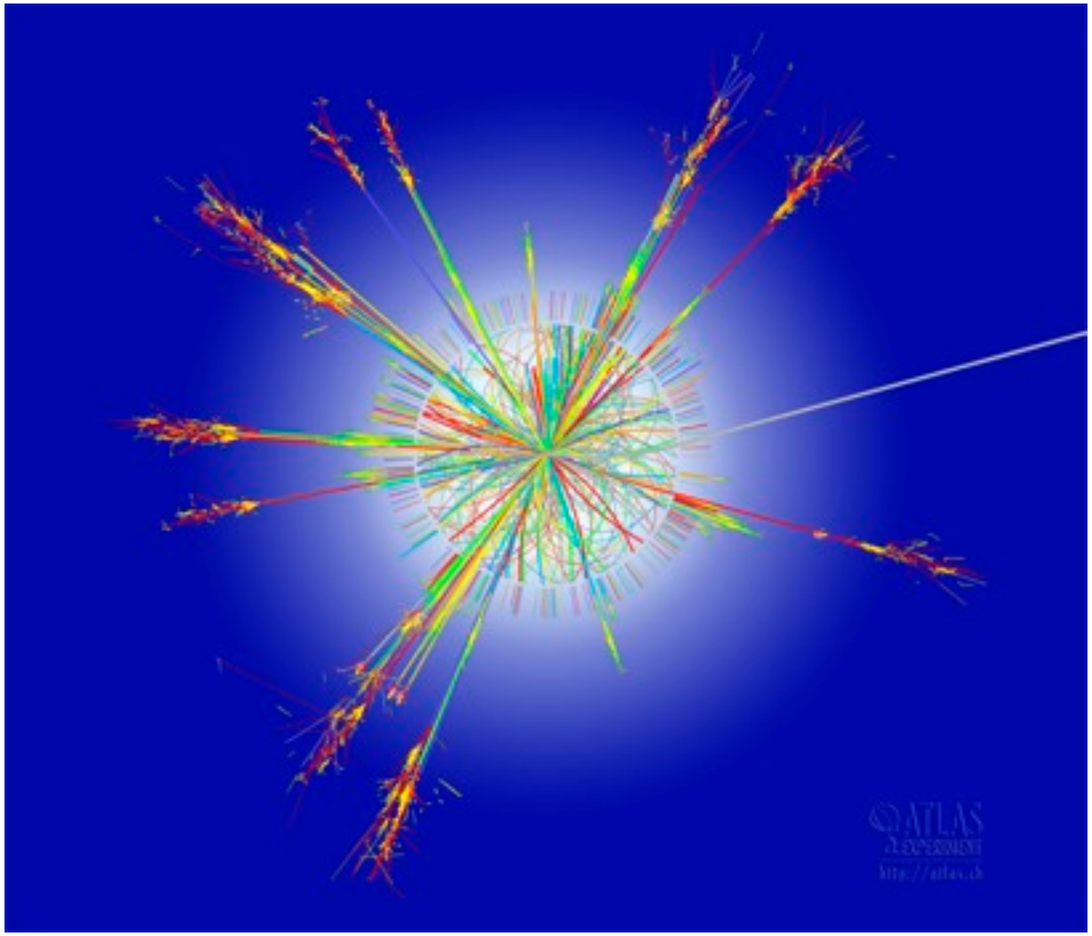
Micro Black Holes

- M_{Pl} is that energy/length scale at which gravitational interactions become important
- Normally in collider physics, we assume this scale is 10^{19} GeV and thus we can completely the gravitational interaction of the colliding particles
- But if, due to extra-dimensions $M_{Pl} \sim M_{EW}$ (i.e. gravity is much stronger at these scales then we thought) then gravitational interactions will be important
- In fact, at length scales below $1/M_{Pl}$, gravity will dominate, and a micro-black hole will form



Detecting Micro-Black Holes

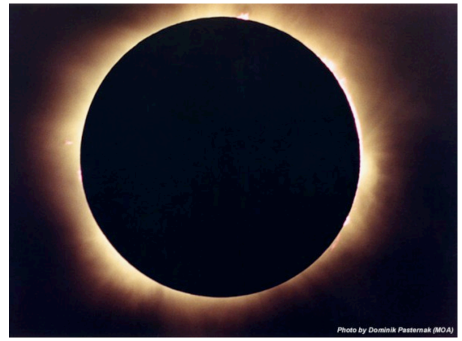
- These micro black holes will rapidly evaporate via Hawking radiation
- This radiation is a thermal process, not a QFT one, so the decays will be unlike anything we are used to in a particle physics experiment
    - Black holes will have a temperature (related to their mass and energy) and they will radiate like a "black body"

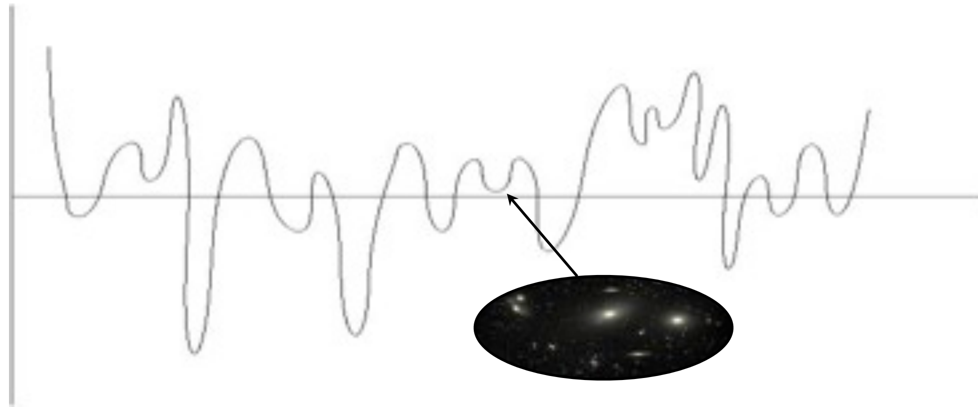


Democratic decays to all sorts of particle at the same time - look for combinations with essentially no SM analouge

The String Theory Landscape

- What if the fine-tuning of the hierarchy problem (actually more importantly that of the cosmological constant) was just a coincidence (like the apparent sizes of the sun and moon)?
    - Which is statistically reasonable given the number of celestial objects in the universe
- The same statistical argument could apply for these fine-tunings if there were enough universes
- The string theory “landscape” provides such a possibility
- Theories based on these ideas are called split susy models and they have interesting, observable consequences for the LHC





IT TURNS OUT THERE MAY BE > 10^{100} VACUA, MORE THAN ENOUGH!

Stopped Gluinos

- Gluinos could be copiously produced with rates approaching 1 Hz

$$gg \rightarrow \tilde{g}\tilde{g}$$

- If long-lived, they will hadronize

$$\tilde{g}q\bar{q} \quad \tilde{g}qqq \quad \tilde{g}g$$

- If then charged, they will ionize

- Some will come to rest inside CMS

- When they decay (hours, days, months later), will be highly distinctive

$$\tilde{g} \rightarrow q\bar{q}(q') + \tilde{\chi}^0(\tilde{\chi}^{\pm})$$

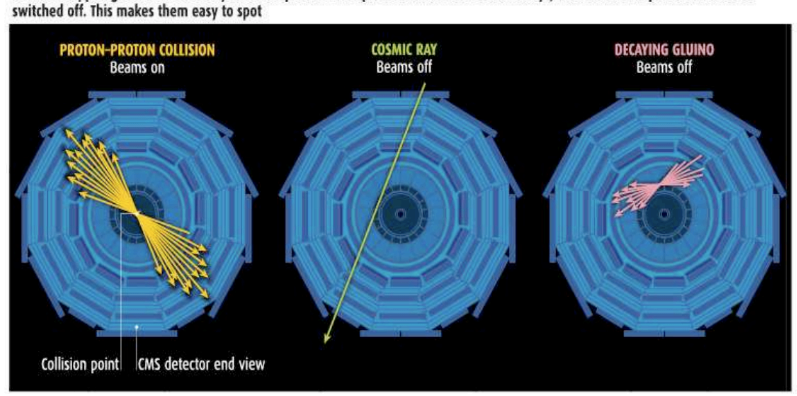
Chris Hill at the University of Bristol in the UK works on one of the LHC's particle detectors, called the Compact Muon Solenoid

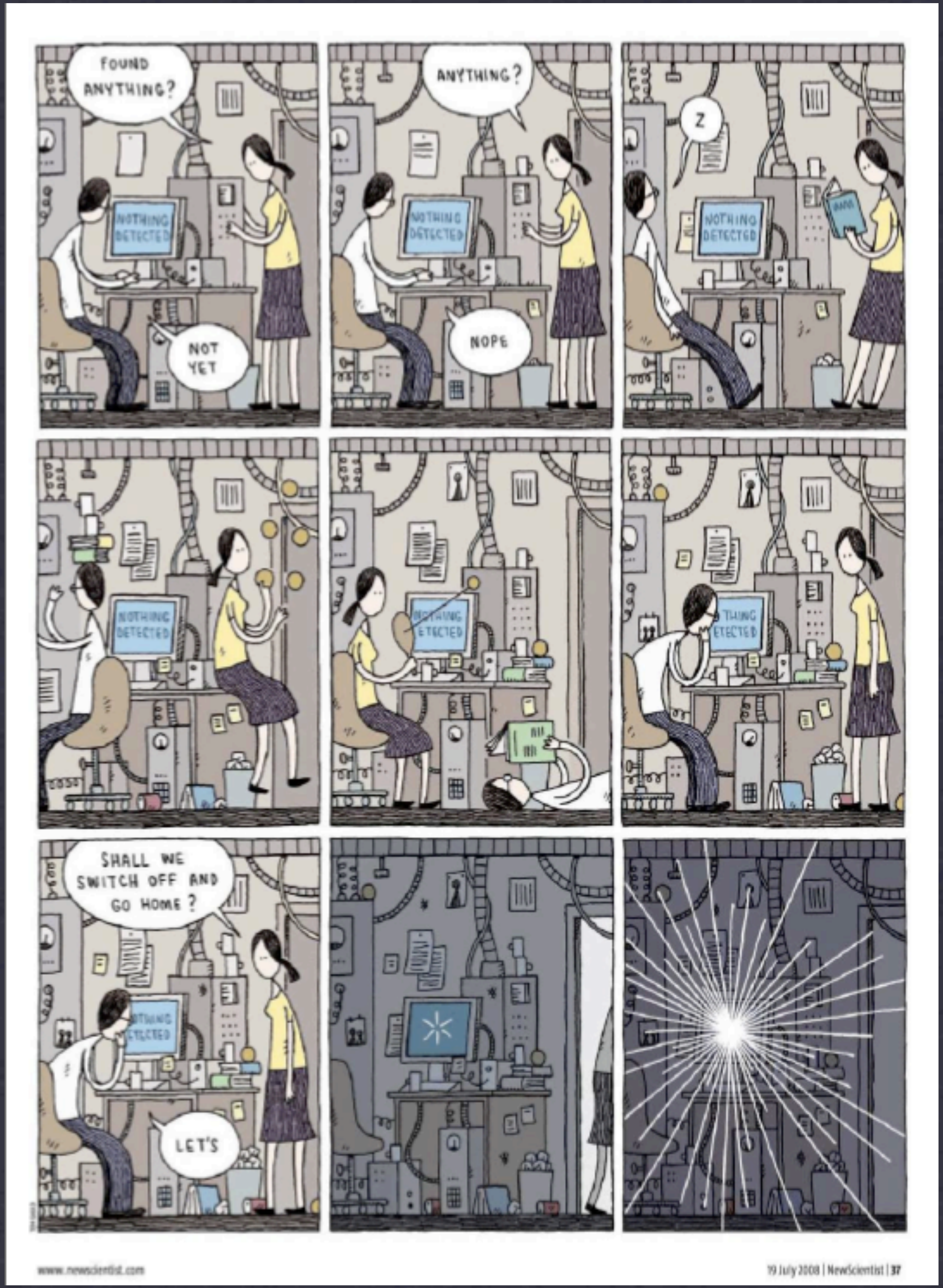
"The best time to see a gluino go bang is when the LHC is switched off"

(CMS). His interest was piqued when he read a paper about stopped gluinos, and decided to work out how to spot them. "It occurred to me that the absolute best time to look for these things was when nothing else was going on," he says.

STOP THAT GLUINO

Detectors at the Large Hadron Collider identify particles from the distinctive pattern of tracks and splashes of energy they leave behind. Stopped gluinos leave a very different pattern from proton collisions and cosmic rays, even when the proton-beams are switched off. This makes them easy to spot




FOUND ANYTHING?
NOT YET
ANYTHING?
NOPE
Z
NOTHING DETECTED
SHALL WE SWITCH OFF AND GO HOME?
LET'S
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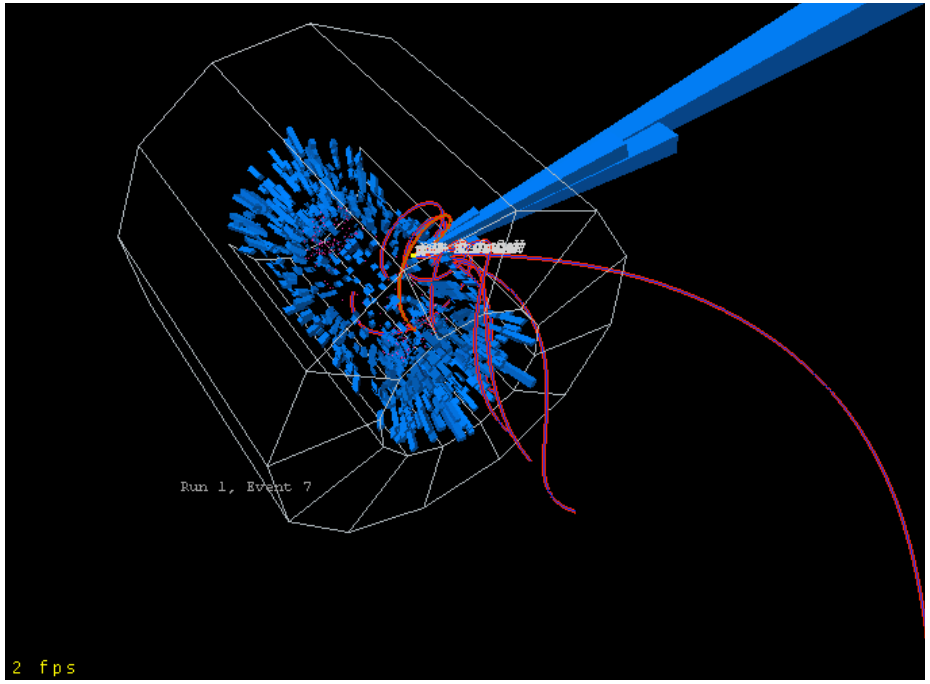
Simulated Stopped Gluino Decay

- These stopped gluinos will go off like time bombs … their decays will be spectacular
- Because we will look when the LHC is off, the detector should not record anything
- As you can see from the simulated event at right these things will be easy to find - **a discovery could come in the first weeks of datataking, before most other searches get started!**

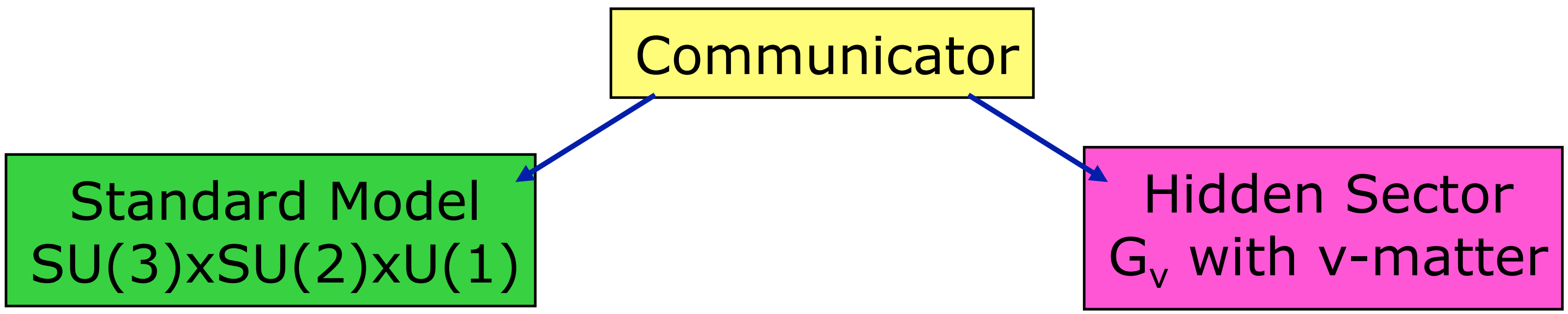


And now for some even weirder stuff …
Hidden Valleys, Quirks, and Unparticles

(Slides shamelessly stolen from a nice talk given recently at Heidelberg LHC Physics Workshop by Matt Strassler, Rutgers)

Hidden Sectors at the LHC

- A scenario:
  - **Not a Model, or even a Class of Models**
  - **A Very Large Meta-Class of Models**
- Basic minimal structure



Hidden Sectors

- a collection of SM-neutral fields (1, 10, 100,…)
- very weak interactions with (light) SM fields,
- arbitrary self-interactions (maybe strong)

- Common in string theory, extra dimensions, supersymmetry breaking
- Reasonable to expect, given that there is dark matter

Of course, they are often inaccessible at LHC: too weakly coupled or too heavy

But if accessible, a hidden sector can **drastically** alter LHC pheno, so we must prepare!

Very few constraints on hidden sectors

- Cosmological constraints are easily evaded without altering LHC signals
- LEP, Tevatron constraints are relatively weak (it's hidden!)

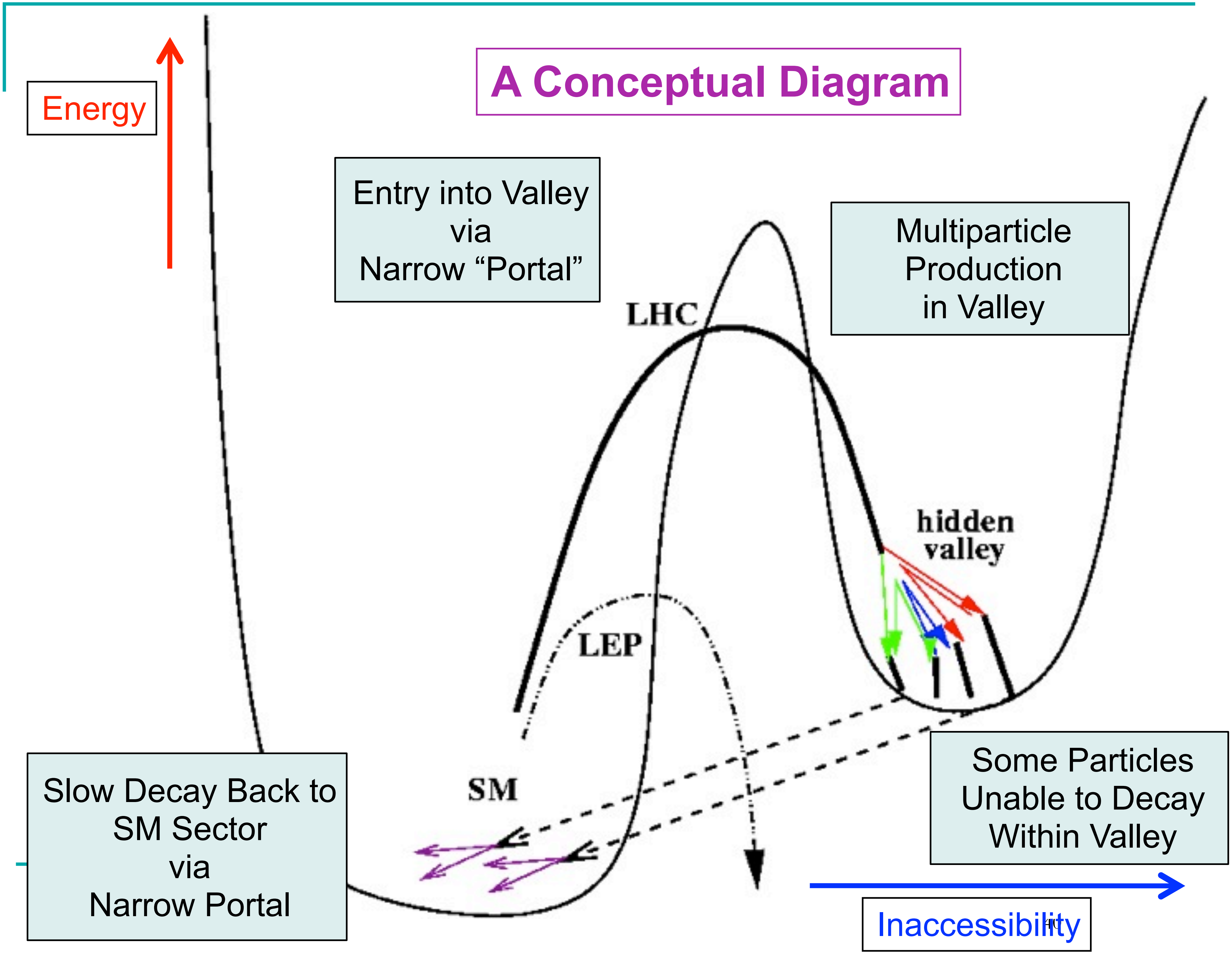
Thus hidden sectors are easily added to SM, MSSM, ExDim, **higgs**,

- Without fouling anything up theoretically
- Without violating any existing experimental constraints
- **But** totally changing the LHC experimental signatures

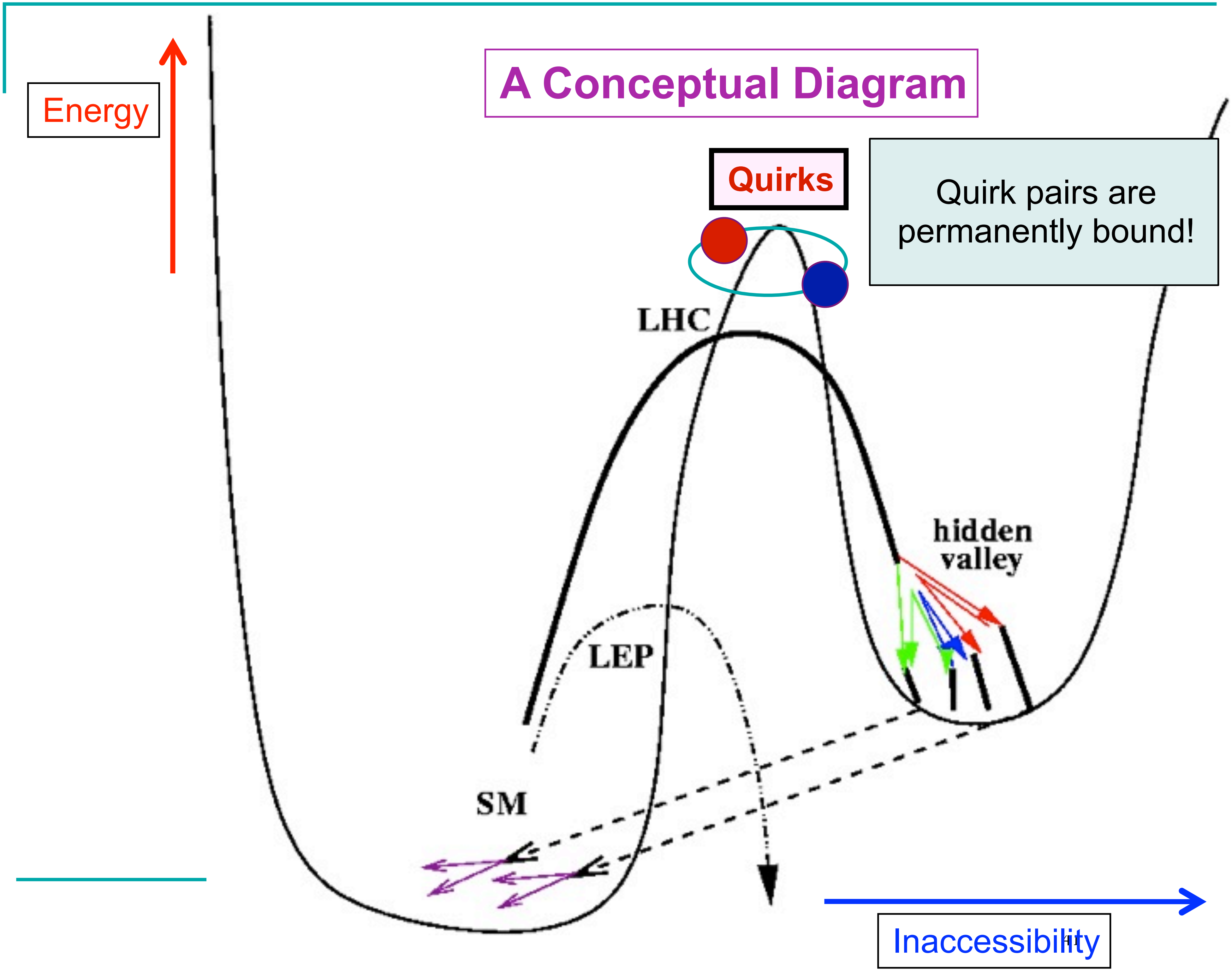
Hidden Sectors

- Various non-hidden extensions of SM have been considered
  - More elaborate Higgs sector
  - New vectorlike matter
  - New abelian gauge groups

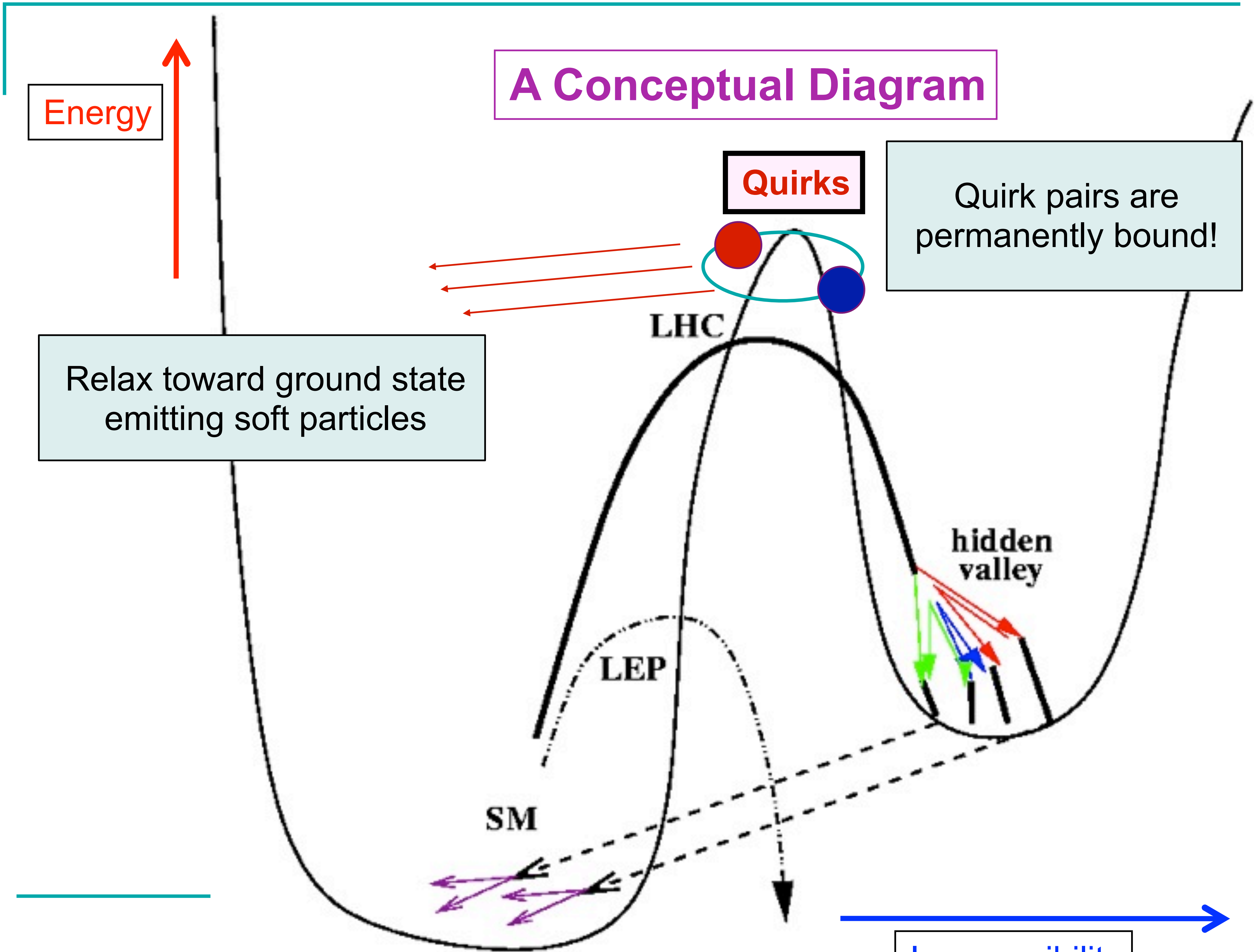
- Coupling them to new hidden-sector dynamics can give entirely new signatures
  - Matter with new dynamics (e.g "quirks", "colored unparticles")
  - Badly distorted Higgs (e.g. "unHiggs")
  - Badly distorted Z', etc.
  - Very exotic decay modes of Higgs, Z', etc.

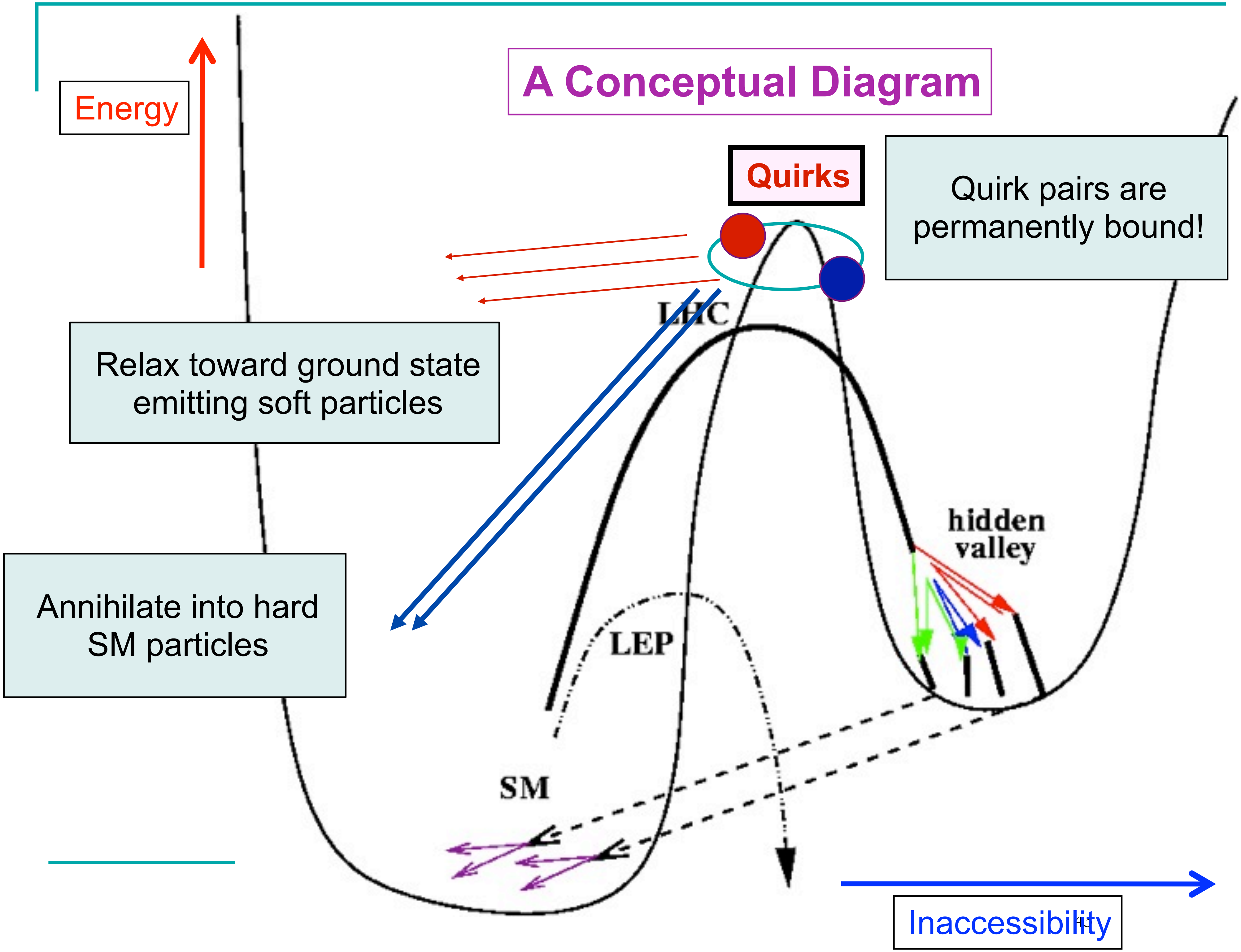

A Conceptual Diagram
Energy
Entry into Valley
via
Narrow “Portal”
LHC
Multiparticle
Production
in Valley
hidden
valley
LEP
SM
Slow Decay Back to
SM Sector
via
Narrow Portal
Some Particles
Unable to Decay
Within Valley
Inaccessibility

A Conceptual Diagram

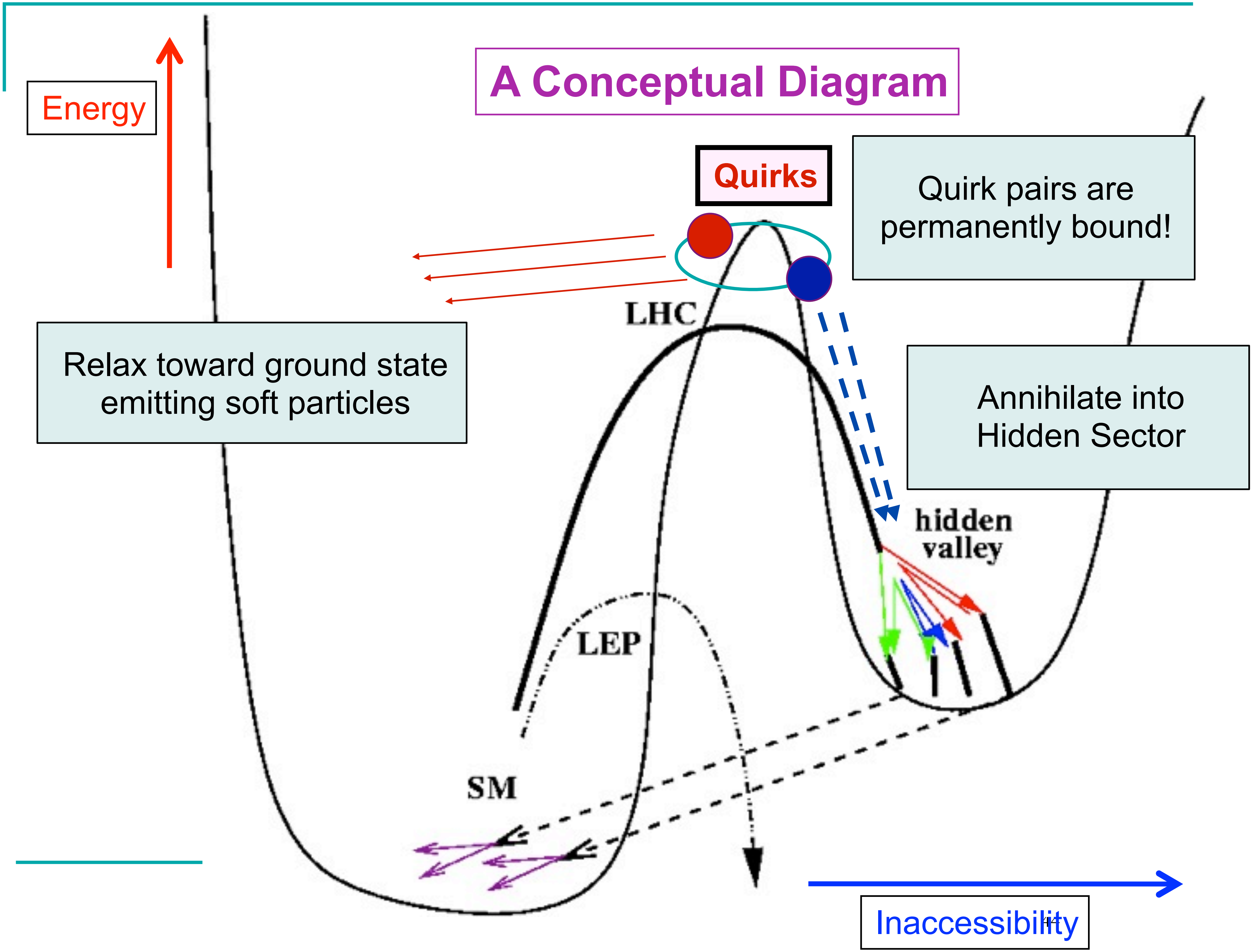


A Conceptual Diagram



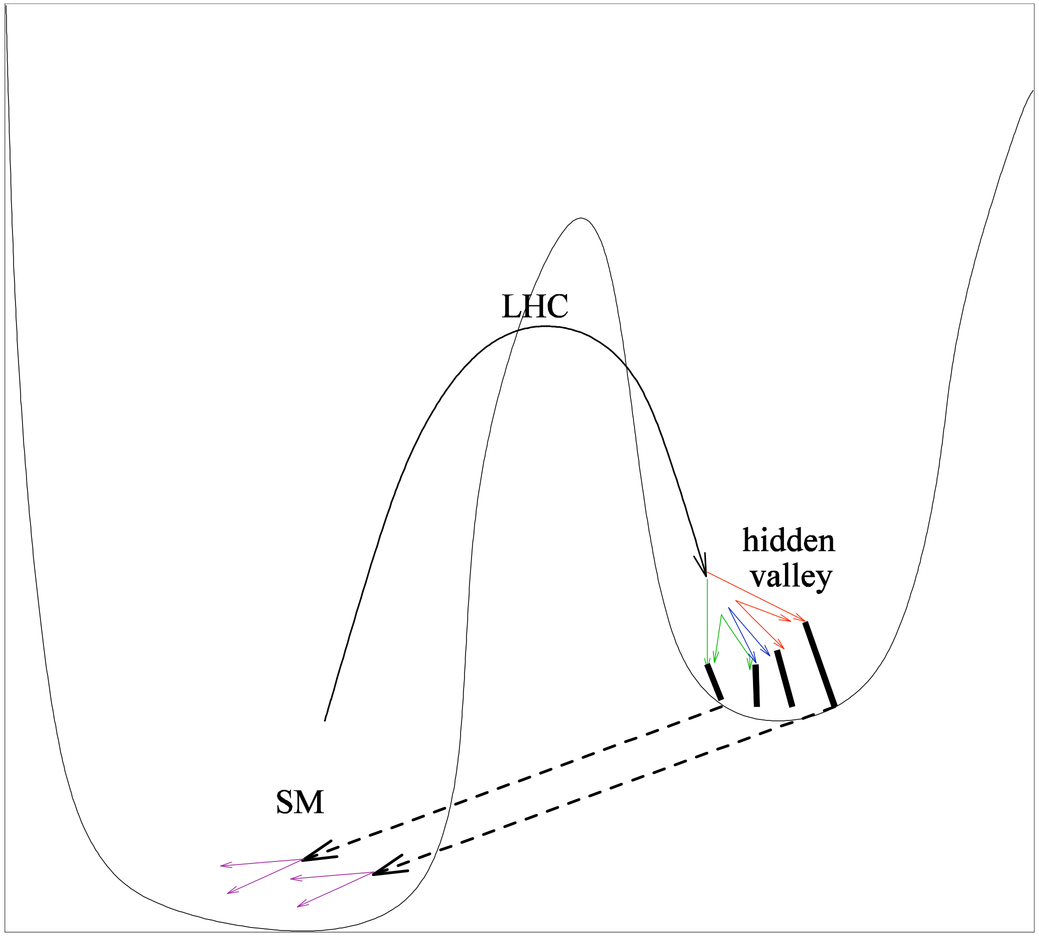

A Conceptual Diagram
Energy
Quirks
Quirk pairs are permanently bound!
LHC
Relax toward ground state emitting soft particles
hidden valley
Annihilate into hard SM particles
LEP
SM
Inaccessibility

A Conceptual Diagram



Hidden Valleys, Unparticles, Etc.

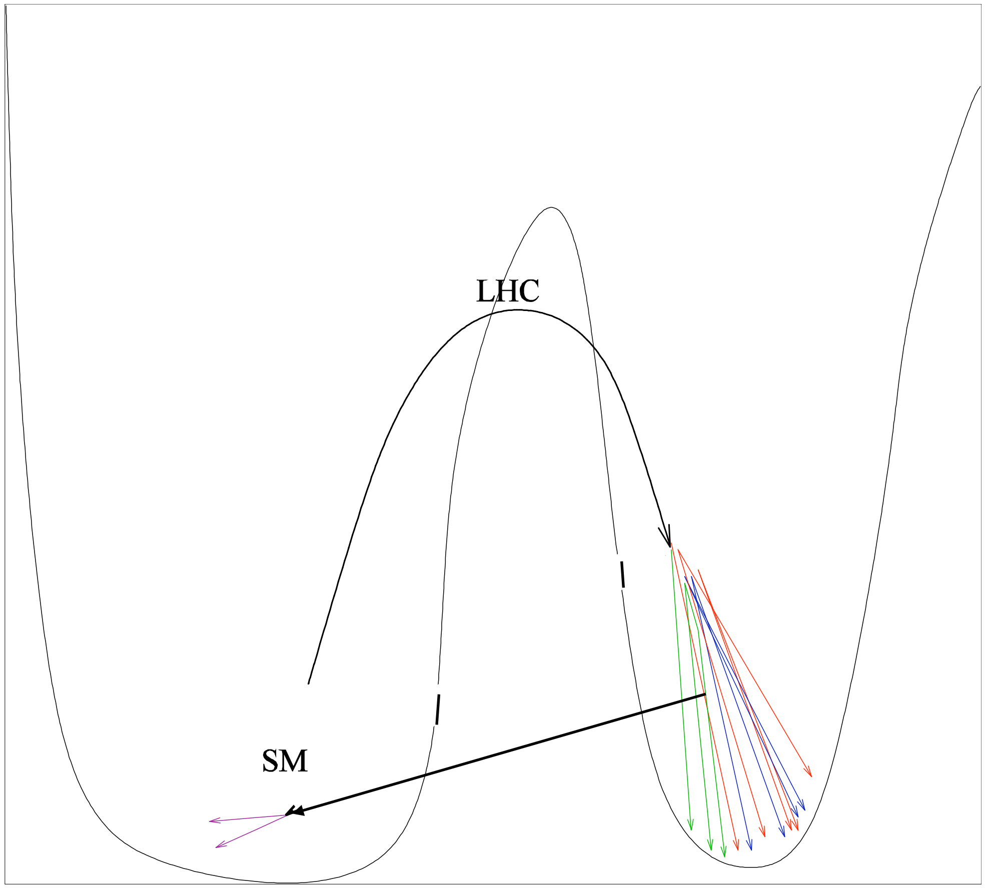
MJS-Zurek 2006



Hidden Valleys, Unparticles, Etc.

Lower mass gap ➔

invisible (almost) to LHC



Hidden Valleys, Unparticles, Etc.

Lower mass gap ➔

invisible (almost) to LHC

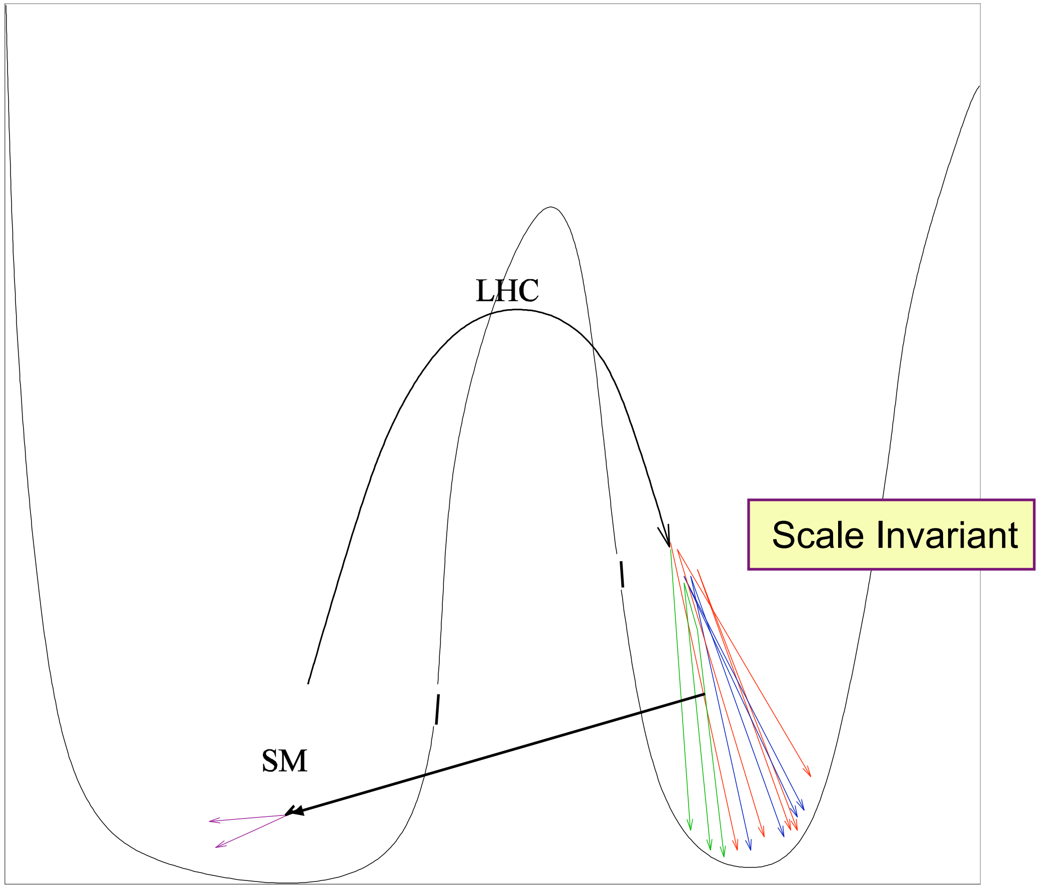
Conformal Dynamics

well above mass gap

➔ “unparticles”

(unusual kinematic distributions in inclusive distributions)

Georgi 2007



Hidden Valleys, Unparticles, Etc.

Lower mass gap ➔

invisible (almost) to LHC

Conformal Dynamics

well above mass gap

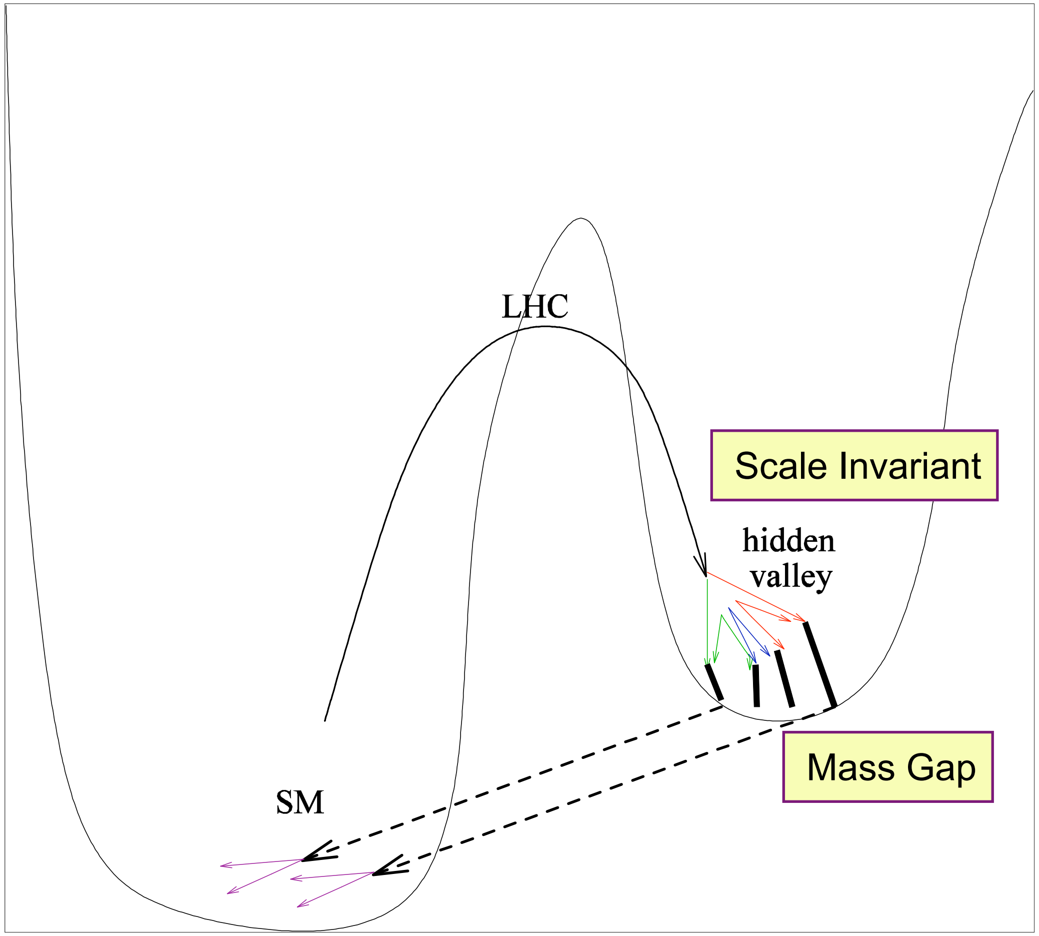
➔ "unparticles"

(unusual kinematic distributions in inclusive distributions)

Conformal Dynamics above

Mass Gap below

unparticle AND hidden valley



Hidden Valleys, Unparticles, Etc.

Lower mass gap ➔

invisible (almost) to LHC

Conformal Dynamics

well above mass gap

➔ "unparticles"

(unusual kinematic distributions in inclusive distributions)

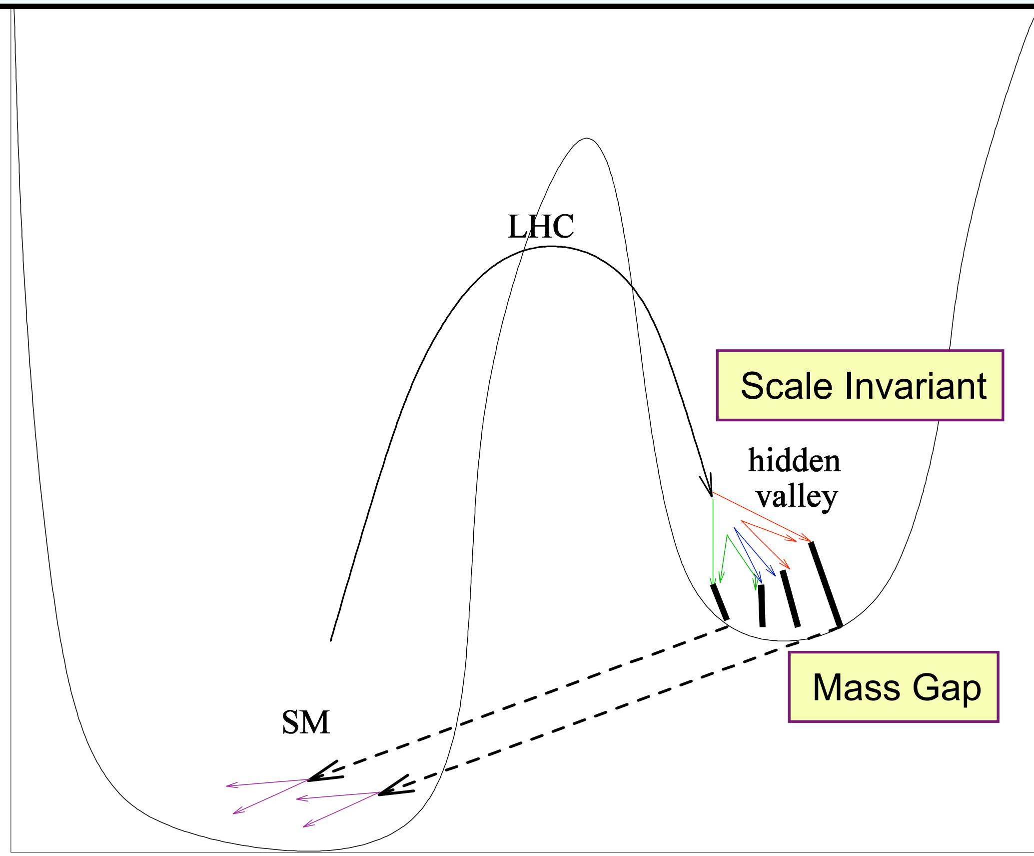
Conformal Dynamics above

Mass Gap below

unparticle AND hidden valley

Both Hidden Valley and Unparticle phenomenology may be simultaneously present.

But HV phenomenology appears in exclusive measurements: 2010
Testing for scale invariance requires inclusive ones – hard!! 2015



Summary

- We expect new physics at the LHC due to hierarchy problem
- SUSY is the canonical solution to hierarchy problem, but there are many alternatives
- Extra-dimensions are perhaps the most exciting of these, and should be detectable at the LHC if they are accessible
  - The real challenge might be knowing that it is ED and not SUSY, this would be a nice problem to have
  - Black holes are a bit of a long shot, but if produced it would be very interesting as we would then be able to directly study quantum gravity (particle physics as we know it would end though ...)
- Split susy is an interesting alternative to the alternatives
- Hidden Valleys, Quirks, Unparticles are other exotic possibilities we must be prepared for