A few follow-up comments

- Model with <H> and <S>
  - *$\phi_1 \rightarrow \phi_2\, \phi_2 \rightarrow$ (bb)(bb), (bb)($\tau^+\tau^-$), ($\tau^+\tau^-$)($\tau^+\tau^-$), AND (bb)($\gamma\gamma$)*
  - Apparently (ATLAS TDR) the latter is by far the best.
    - (Thanks Matt Bowen – see his upcoming paper with J Wells)

- Resonant repeaters
  - I talked about reconstructing a repeater as a 2→ 1 resonance
  - If the mass of the repeater is too high to produce, a gradual deviation of the scattering cross-section from SM prediction will still be seen (cf. compositeness as tentative explanation of deviations of dijet cross-section at Tevatron Run I)
- Flavor and repeaters
  - *SM: leptons come from W → u,c;e,μ,τ ; Z → uu,cc;dd,ss,bb;ee,$\mu\mu$,$\tau\tau$*
  - *u,c,d,s;e,μ light generation repeaters can shift the typical quark/lepton balance (happens a lot in SUSY, but also elsewhere)*
  - *Separation between light and heavy generation repeaters, or absence of light generation repeaters, will change e:μ:τ ratios*
  - *etc.*

Extra Fermionic Dimensions

- Can we do better? Can we move Λ , where the Little Higgs is strongly coupled, much higher than 10 TeV?
- Is there a weakly coupled model valid up to the Planck scale with a light Higgs and no hierarchy problem?
- *Yes! Extra fermionic dimensions do the trick*.

- This is also called "supersymmetry". *I will not study this model in detail – see Polesello 2006 SLAC summer school lectures, Luty TASI 2004 lectures, and many other reviews*

- Just as with ordinary bosonic dimensions, there is a tower of states for each standard model particle
- But there are some key differences
  - There need be only one repeater for each particle
  - The spin of the repeater differs from the original's spin by 1/2
  - Every particle in the SM *must* have a repeater at scales that cannot differ too much from the weak scale

Or "Supersymmetry" (SUSY)

- This means we have to add about thirty new particles:
  - Gluons → gluinos (spin ½)
  - 2 Higgs doublets → charged, 2 neutral Higgsinos (spin ½)
  - Photon,W,Z → photino(?), Wino, Zino (spin ½)
  - Quarks → squarks (spin 0)
  - Leptons, neutrinos → sleptons, sneutrinos (spin 0)
  - Gravitons → gravitinos (spin 3/2)

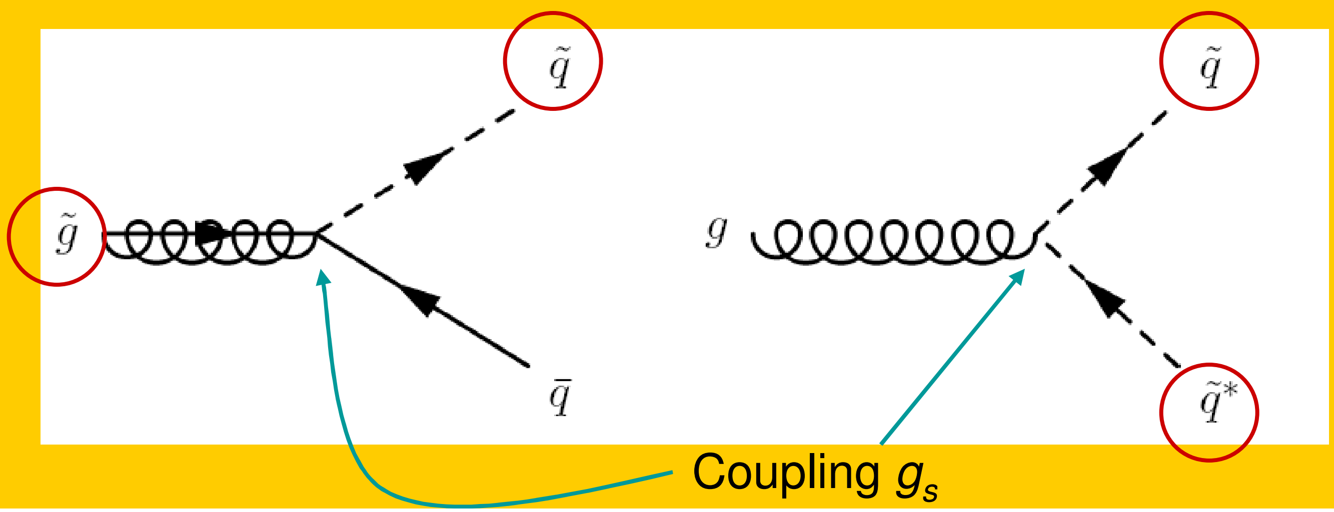
- But it's a bit more complicated than this, unfortunately…
- Were SUSY exact, all particles and superpartners would have equal masses
- But SUSY is spontaneously broken, so the *masses* are unknowns
- And many of the particles have same quantum numbers, so they *mix*
  - charged Higgsino, Wino → 2 charginos
  - neutral Higgsinos, photino(?), → 4 neutralinos

- Also we have two Higgs doublets → h^0 H^0 A^0 H^+ H^-

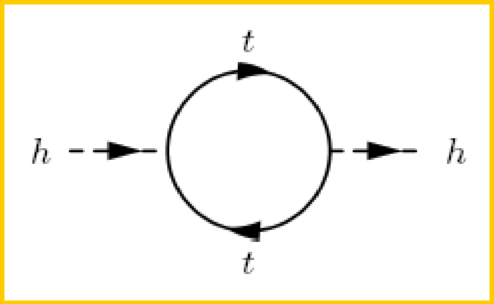
- *Altogether something like 100 new parameters!* (Many are well-constrained by experiment, but plenty are not.)

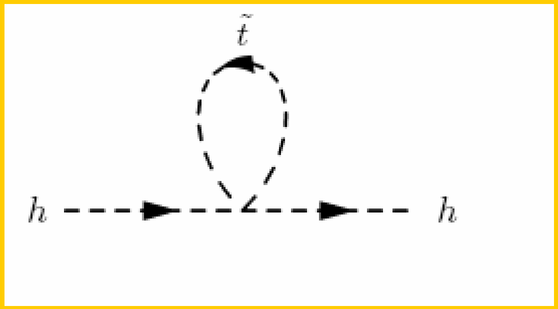
SUSY interactions

- As with models like extra dimensions, take any SM 2→1 process and replace SM particles with repeaters –
- but *unlike previous cases,*
  - coupling constant must be **exactly** the same
  - must replace *two* SM particles with repeaters, never one.
- This last condition is simply Lorentz invariance:
  - Replace two fermions with two bosons ok
  - Replace a fermion with a boson and a boson with a fermion ok
  - Replace one fermion with one boson ***not ok***
- *Some other 4-boson interactions too, see SUSY review for details.*



What's so good about SUSY?

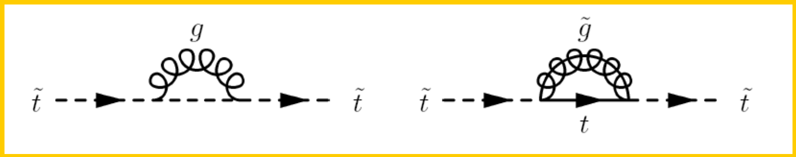




- Just as in little Higgs, the one-loop corrections to the Higgs boson mass cancel between the original and the repeater
- In this case there is a conspiracy of couplings and Bose vs. Fermi statistics
- But --- amazing --- cancellation of M^2 corrections to m_h^2 works **to all loops**!!! … as long as all particles have repeaters…
- More precisely, if all repeaters are at 1 TeV, then corrections to m_h^2 are small.
- *Why do we need all SM repeaters light in a SUSY model?*

Why light superpartners?

- We need the top squark to be light to cancel the top correction to the Higgs mass
- But the top squark, like the Higgs, is a ***scalar*** – this is what makes SUSY different from the other models with repeaters…
- And its mass also gets ***additive corrections*** of order M^2 from a gluon loop…
- …unless there is a gluino whose mass is of order a TeV … or so …



- The presence of light scalars requires *all repeaters be light* in order to avoid extreme fine-tuning in some part of the theory.
- But not *that* light… The loops come with coupling constants and loop factors!
- To be precise: if repeaters for *W,Z,h,t,[b]* are below 1 TeV, and other repeaters are not *too* high, then corrections to m_h^2 are small.
- It is possible that most of the other repeaters *could* be too heavy to see at the LHC –

The More Minimal Supersymmetric Standard Model
hep-ph/9607394 Cohen, Kaplan, Nelson

Other good things about SUSY(?)

- Since SUSY is (in simple scenarios) weakly-interacting, it does not generate large shifts in electroweak observables.
  This is true. Note, however, that it is also true that most simple SUSY models are themselves now becoming a bit fine-tuned; generally, theorists expected that we would have seen some supersymmetric particles and the Higgs by now, in simple scenarios.

- The gauge couplings unify better with SUSY partners
  This is true. [Note it does not imply Grand Unification of Three Forces! In string theory, gauge coupling unification without GUTs is typical.]

- "SUSY provides a candidate for dark matter" ?
  Not really true – actually the logic is rather different, see below.

- "SUSY required by string theory" ?
  Not true – certainly not <u>TeV-scale</u> SUSY-breaking.

- In any case, a *minimal* SUSY model is not required! And so the phenomenology may not look at all like standard SUSY models that have received most study, even if SUSY is at the weak scale.

But SUSY is not so predictive

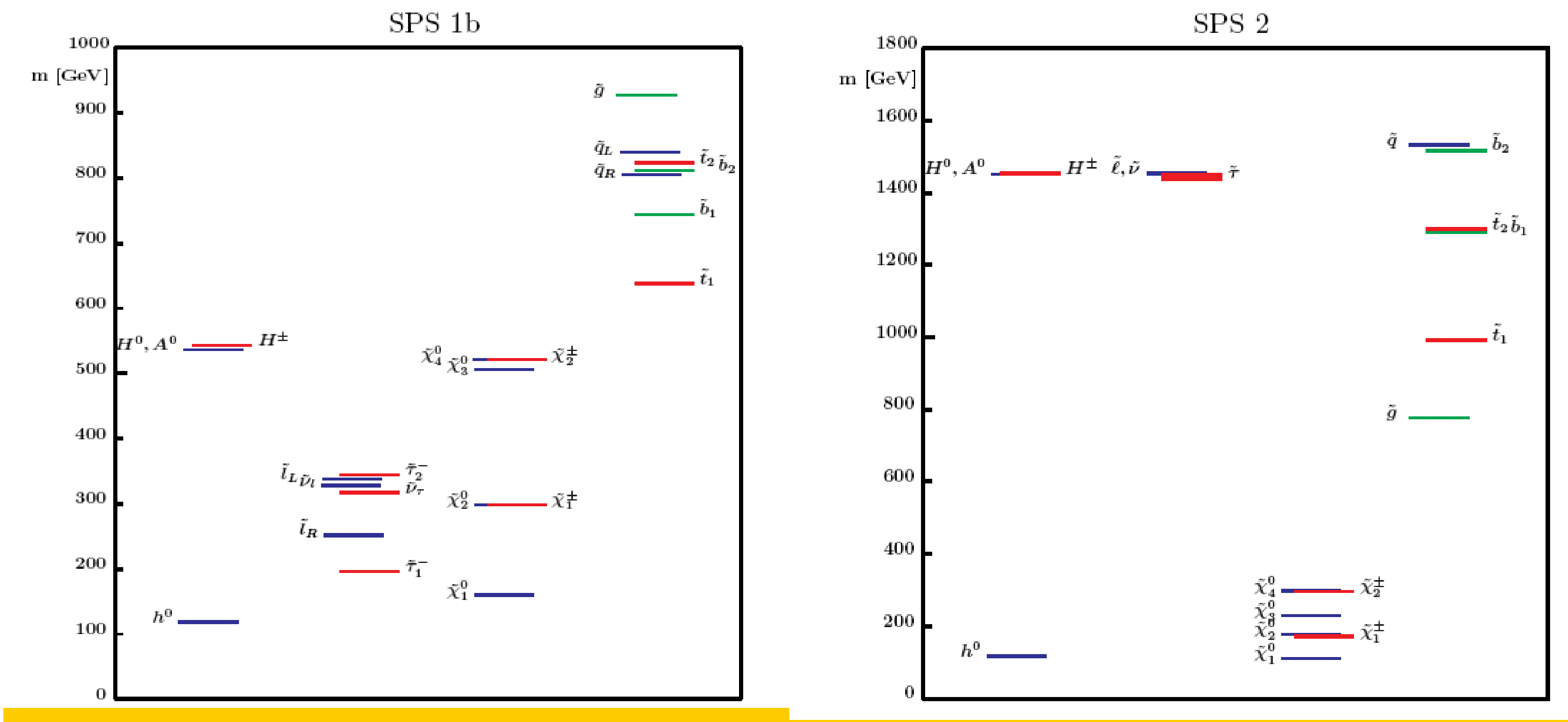
- As we saw, SUSY, as a solution to the hierarchy problem, predicts at least some superpartners will be found at the LHC

- But with 100 new parameters, we are not able to make any many predictions for LHC physics unless we try to guess how these parameters are determined

- The “mechanism” of SUSY breaking is not known; many possibilities:
  - Gauge mediation
  - Hidden sector mediation
  - Gaugino mediation
  - Anomaly mediation
  - Minimal Supergravity??? See below.

- Different mechanisms predict different ***relations*** among these many parameters, but rarely predict any one parameter; we theorists have no idea which of these many mechanisms to prefer.

Some SUSY spectra



Supersymmetric Benchmarks with Non-Universal Scalar Masses

A. De Roeck, J. Ellis, F. Gianotti, F. Moortgat, K. A. Olive and L. Pape

Supersymmetric spectra in NUHM and GDM benchmarks calculated with ISASUGRA 7.69

Spectra depend on program

Model	α	β	γ	δ	ϵ	ζ	η
$m_{1/2}$	293	370	247	750	440	1000	1000
m_0	206	225	328	500	20	100	20
$\tan\beta$	10	10	20	10	15	21.5	23.7
sign(μ)	+	+	+	+	+	+	+
A_0	0	0	0	0	-25	-127	-25
m_t	178	178	178	178	178	178	178
Masses							
$\lvert\mu\rvert$	375	500	325	920	569	1186	1171
h^0	115	117	115	122	119	124	124
H^0	267	328	241	1159	626	1293	1261
A^0	265	325	240	1152	622	1285	1253
$H^\pm$	278	337	255	1162	632	1296	1264
χ_1^0	113	146	95	310	175	417	417
χ_2^0	215	282	180	600	339	805	804
χ_3^0	380	503	332	925	574	1192	1176
χ_4^0	400	518	352	935	587	1200	1184
$\chi_1^\pm$	215	283	180	601	340	807	806
$\chi_2^\pm$	399	518	352	935	587	1200	1184
$\tilde{g}$	711	880	619	1691	1026	2191	2191
e_L, μ_L	299	351	378	713	306	684	677
e_R, μ_R	216	241	328	572	171	387	374
ν_e, ν_μ	287	340	368	703	290	669	662
τ_1	213	239	315	565	153	338	319
τ_2	300	352	378	712	309	677	670
ν_τ	287	340	365	700	288	660	653
u_L, c_L	674	826	636	1604	935	1991	1998
u_R, c_R	661	808	629	1550	902	1911	1908
d_L, s_L	679	831	642	1606	938	1993	1990
d_R, s_R	652	797	621	1544	899	1903	1900
t_1	492	622	453	1219	710	1545	1553
t_2	662	800	611	1486	900	1842	1840
b_1	609	752	558	1456	852	1807	1804
b_2	641	785	603	1516	883	1851	1846

Table 4: *Proposed NUHM and GDM benchmark points and mass spectra (in GeV), as calculated using* ISASUGRA 7.69 *[21] and adapting the input parameters to give the best match to the* SSARD *[20] spectra shown in Table 2, as described in the text.*

All these models have degenerate heavy Higgs bosons, well-split neutralinos, gluino-squark near-degeneracy

Notice these input parameters do not correspond closely to any physical masses.

mSUGRA – a digression

- **Minimal Supergravity ???**
- Good news: only 4 (5) parameters
- Bad news:
  - Not supergravity (was once thought to be)
  - In fact, not a theory
  - At best a scenario; mainly a fairly arbitrary parameter reduction scheme
  - Few realistic models naturally reduce to these parameters
  - Potentially deeply misleading for LHC phenomenology
- Unfortunately, for historical reasons, the vast majority of studies for supersymmetry are based on it.
- Beware studies that limit themselves to this scheme; their conclusions are potentially deeply misleading about what SUSY will actually look like, or how constrained it will be.
- *But that's not what's really bad about this scheme.*

- **Worse news: the 5 parameters are parameters in the effective Lagrangian at $M = M_{GUT} \sim 10^{16}$ GeV**

How not to use data

- Data → GUT-scale Theory is a bad idea
  - Many theoretical assumptions must be made.
  - Very difficult to use or interpret results; constantly have to run couplings down to TeV in one theory, then back up in another theory.
  - Limits on masses and couplings in Lagrangian correspond poorly to constraints on physical masses and couplings.
  - Tiny variations in Lagrangian parameters can make large variations in physical quantities, and vice versa.
  - Even one additional nonminimal particle can *completely* change the results.

- I strongly encourage you to push your colleagues to avoid publishing data <u>*exclusively*</u> in this format!

How to use data

- Data → TeV-Scale Theory ← High-Scale Theory is a much better idea
  - Experimentalists can perform the first step without adopting nearly as many theoretical assumptions about unmeasurable quantities
  - Relatively easy for different theorists, or experimentalists, to convert from their favorite High-scale theory to TeV scale theory
  - Limits on masses and couplings in Lagrangian correspond well to constraints on physical masses and couplings.
  - Tiny variations in Lagrangian parameters can only make small variations in physical quantities.
  - One additional nonminimal particle is much less likely to change the results substantially

- Data published in this form is far easier to interpret and far more usable for the community; it properly captures what we actually know from data with far less theoretical bias

Another way to use data?

Something to think about in the early days of LHC:

- Data → Fragment of TeV-Scale Theory →
  Complete TeV-Scale Theory ← High-Scale Theory

  - Experimentalists can perform the first step with even fewer assumptions about unmeasured quantities
  - A fragment of a theory need not be fully consistent, need not be renormalizable, etc, but still makes predictions, can be run through Monte Carlos, and will be useful in trying to figure out the complete theory
  - A good place for theorists and experimentalists to work together (since a useful fragment of a theory can only be designed once the data comes in and a signal is detected)

An example of a partial theory is given in our Summer 2005 LHC Olympics analysis

Testing SUSY

Need to see ALL the superpartners

- *Unfortunately, we're not likely to see them all at LHC*

Need to measure coupling constant relations that SUSY predicts

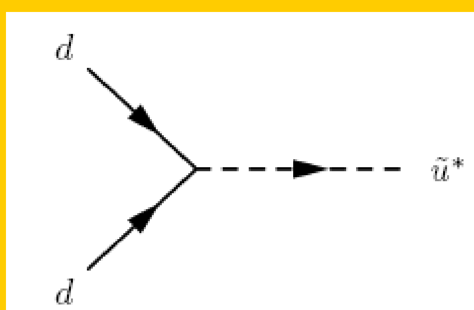
- *Unfortunately, because of mixing among states, coupling constants get mixed up with mixing angles; so this too is a really tough thing to do at the LHC*

- Only in very special circumstances, and usually with some experimentally-unjustifiable assumptions, can SUSY be verified at the LHC

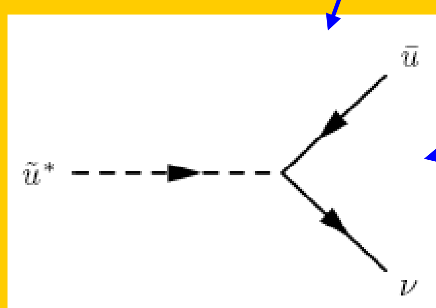
- ***But discovery of TeV-scale <u>scalar</u> <u>repeaters</u> of quarks and leptons will be profoundly suggestive.*** *Other models can fake this, of course, but not easily.*

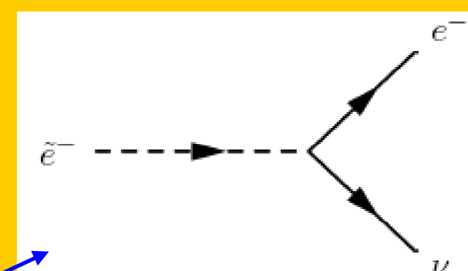
Some Additional Interactions

- Earlier, we did not exhaust the list of possible important interactions in SUSY, because of new *scalar* states – can't arise with same-spin repeaters.
- New baryon-number- and lepton-number-violating interactions *with one superpartner and two SM particles* are possible in SUSY, not in other models.
- These lead to lethal proton decay. This is bad.

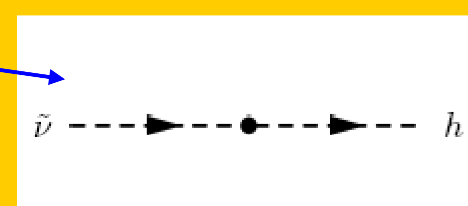


Violates B





Violates L



Some Additional Interactions

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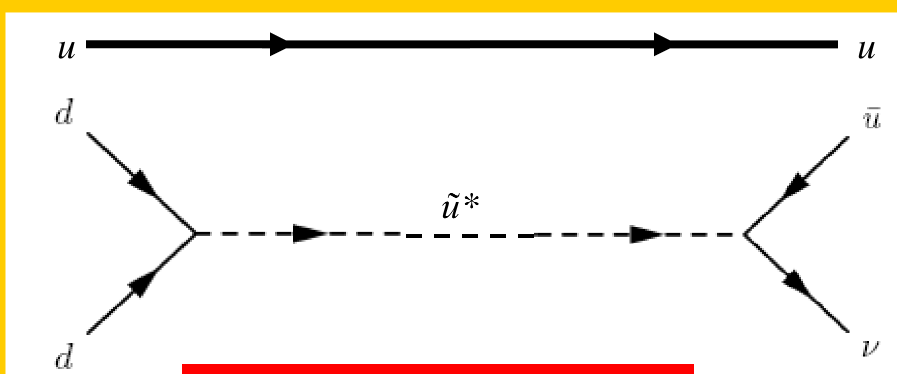
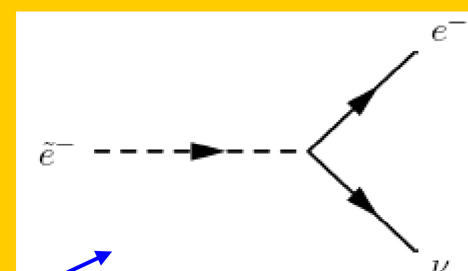
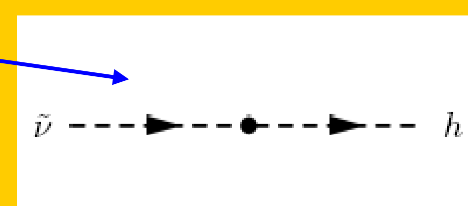


$p \rightarrow \pi^0\ \nu$



Violates L



Forbid These Interactions

- This leads people to often *(but not always)* introduce a new global symmetry on top of supersymmetry: this is called "R-parity" for historical reasons, or "matter parity", which is a less fancy word for the same thing.

- Effectively, it gives all standard model particles a charge of +1, and all superpartners a charge of -1.

- This then requires that *all interactions must have two or zero superpartners*, never one. It forbids all the interactions on the previous page.

- This requirement has very big consequences:
  - ***Superpartners must be produced in pairs.***
  - ***A superpartner cannot decay to standard model particles alone,*** enhancing the likelihood of cascade decays.
  - ***The lightest superpartner must be stable***
    - (but it might not be a standard model superpartner – it might be the gravitino, or a right-handed sneutrino, or some new object)

- ***Without R-parity, none of these facts are true of SUSY models!***

New Global Symmetries

R-parity implies:

- No superpartners can be resonantly produced; 2→1 can't happen. ***Superpartners must be produced in pairs.***
- Once produced, ***a superpartner cannot decay to standard model particles alone***. If a superpartner decays, another superpartner comes out in its decay products, often leading to cascade decays.
- Also, the ***lightest superpartner must be stable*** (but it might not be a standard model superpartner)

- This motivates us to consider more generally the phenomenological consequences of *global symmetries that are not carried by SM particles.*
- We'll consider
  - Effects of exact new global symmetries: exact conservation laws
  - Effect of tiny violation of new global syms: conservation laws barely violated
  - Effect of small violation of new global syms: conservation laws somewhat violated
  - Etc.

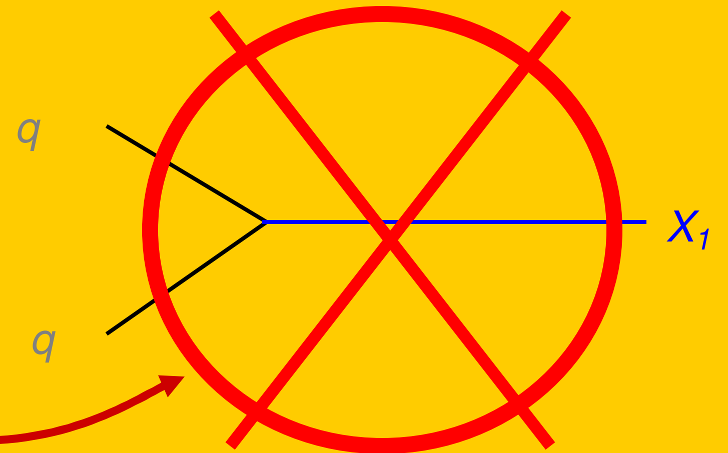
And effects of new weakly-coupled sectors that also carry the global symmetry

A New Exact Global Symmetry

Suppose we have new particles $\boldsymbol{X_1, X_2, X_3, X_4, \ldots X_n}$
(Let's order them by mass, X_1 the lightest, X_n the heaviest)
All carry a new global X-charge

- In any SM collision,
  - initial state is global-neutral…so
  - the final state is also global-neutral… therefore
- X_i can't be resonantly produced; cannot have

  $q\, q \rightarrow X_1$

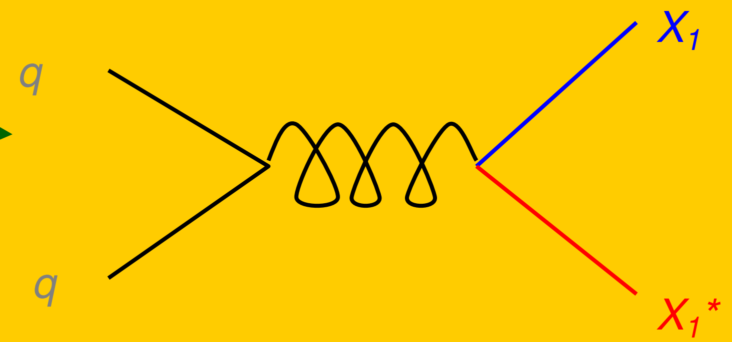


- Instead they must be produced in pairs,

  e.g. $q\, q \rightarrow X_1\, X_1^*$

  $q\, q \rightarrow X_1\, X_2$

  (if X_1, X_2 have opposite global charge)

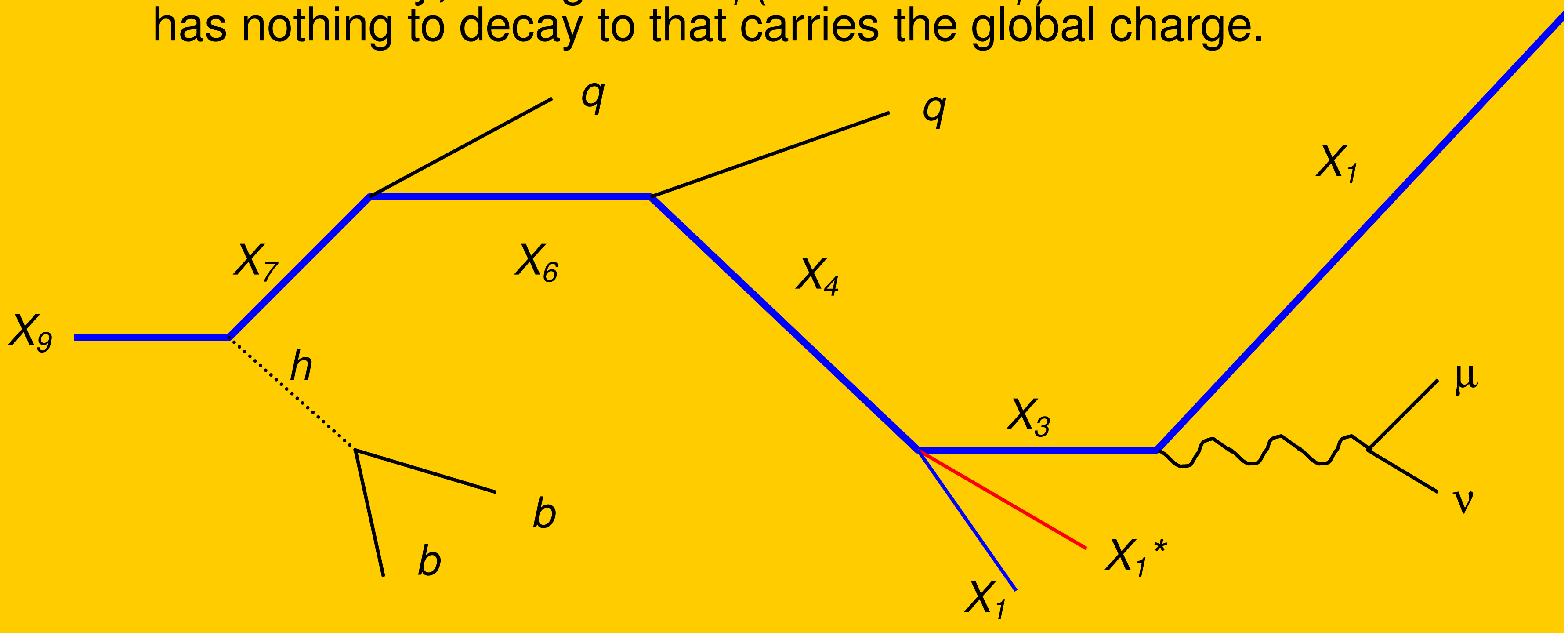


- *Special case if (as with R-parity)*
- *symmetry takes $X_i \rightarrow -X_i$, $X_k \rightarrow -X_k$*

  Then can have
  - $q\, q \rightarrow X_i\, X_i$
  - $q\, q \rightarrow X_i\, X_k$

Conserved charge!

- Once produced, an X_i cannot decay to standard model particles alone: when an X_i decays, at least one X_k $(k < i)$ comes out in its decay products.
- If some X_i don't decay immediately to X_i , then ***cascade decays ensue***.
- As a corollary, the lightest X_i (the "LXP" X_1) must be ***stable***. It has nothing to decay to that carries the global charge.



Consequence of stability

- So X_1 (the lightest particle carrying X-charge, or "LXP") is stable
  - But the LXP would have been produced abundantly in the early universe *(right?)*
  - And so there would be plenty of them around today *(right?)*
  - So the LXP can't be electrically charged or carry color since we have very strong constraints on stable charged or colored particles from searches for heavy atoms *(right?)*
- ***EXERCISE: carefully investigate how robust these arguments actually are.***

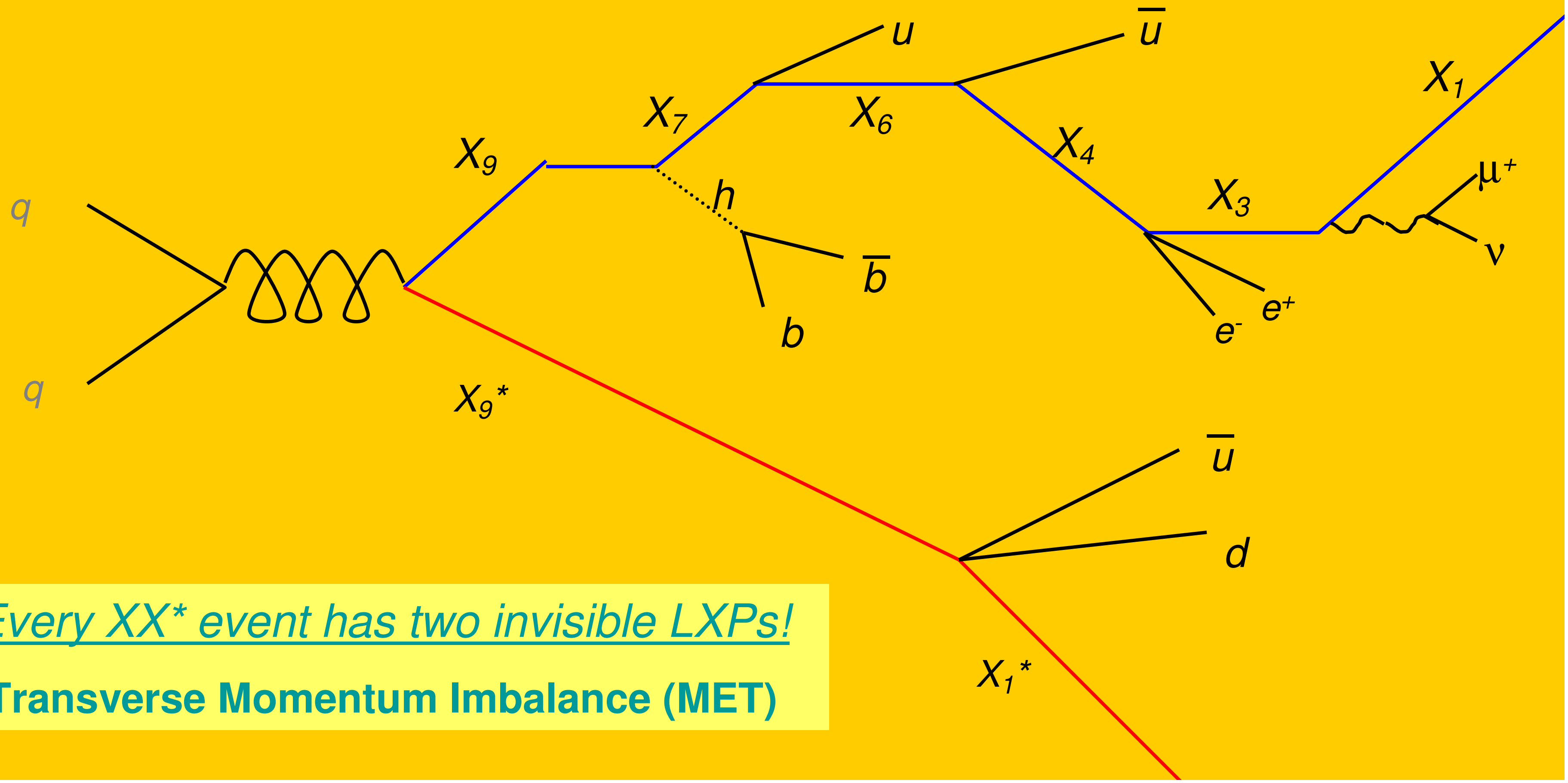
- So therefore it must be *(right?)* that the LXP is electrically-neutral and color-neutral, so that it interacts very weakly with ordinary matter, at best comparable to a neutrino, perhaps even more weakly.

- **Let's just accept this argument and assume the LXP is weakly- or very-weakly interacting.**

- ***This makes it a potential dark matter candidate: a WIMP.***

- What about collider implications?

A Pair of Invisible Particles !



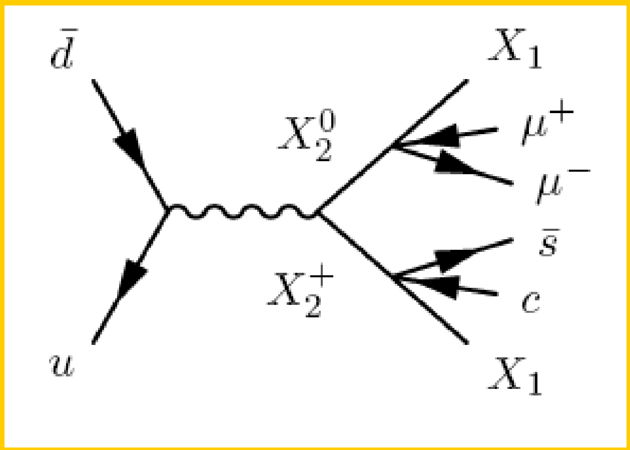
<u>*Every XX* event has two invisible LXPs!*</u>

Transverse Momentum Imbalance (MET)

Collider consequences

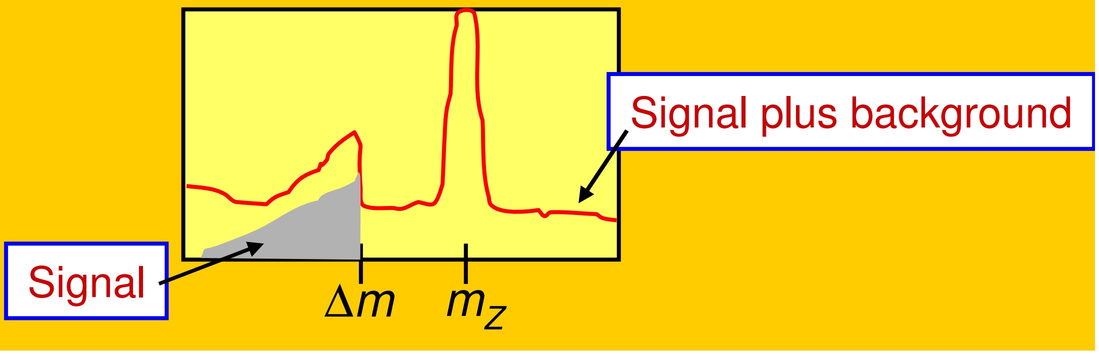
- MET (because the LXP is invisible, and two are produced in every event)
- Greater possibility of cascade decays (since the *X* particles don't decay immediately to light SM particles)
- No resonances to be built from SM particles; no invariant mass plots will show a peak
- Will see only kinematic endpoints and edges from three-body decays, multiple two-body decays, etc. with a missing particle

Example:



$q\,q \rightarrow \mu^+\mu^-\, j\, j$ + MET

The invariant mass of the $\mu^+\mu^-$ pair from the ***three body decay*** *$X_2 \rightarrow \mu^+\mu^- X_1$ will have a kinematic endpoint at $\Delta m = m_2 - m_1$*



Collider consequences

- MET (because the LXP is invisible, and two are produced in every event)
- Greater possibility of cascade decays (since the *X* particles don't decay immediately to light SM particles)
- No resonances to be built from SM particles; no invariant mass plots will show a peak
- Will see only kinematic endpoints and edges from three-body decays, multiple two-body decays, etc. with a missing particle

- **Notice these are characteristics often said to be those of SUSY. They are not!**

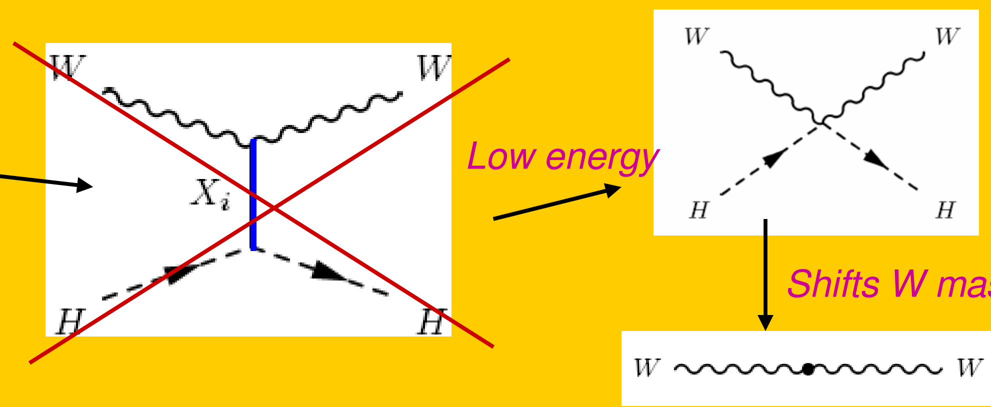
- They are consequences of a conserved global symmetry – R-parity, in SUSY case.
  - *If you remove R-parity and keep supersymmetry, you lose these features*
  - *If you keep R-parity and remove supersymmetry, you keep these features.*
  - *If you take little Higgs or extra dimensions and add a corresponding "T-parity" or "KK-parity", you can get the same features!!*

- *Ah, but don't you get extra repeaters that are globally-neutral that you can find in little Higgs and extra dimensional models, to distinguish them from SUSY?*
  - There need be no globally-neutral repeater states in e.g. extra dimensions
  - There could be R-parity-even repeaters in SUSY models too; not required, but not forbidden

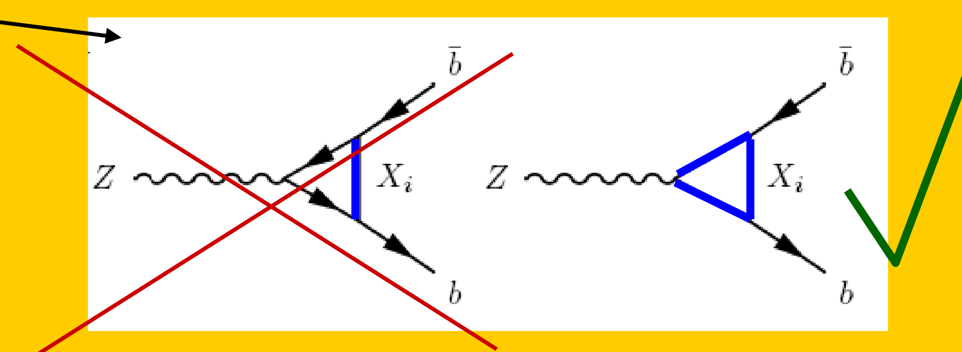
Effect on quantum corrections

The global symmetry is also partly responsible for the small corrections to electroweak precision measurements.

- Suppression of higher-dimension operators



- Suppression of loops
- Thus the success of SM predictions for electroweak observables suggests that a global symmetry as well as weakly-interacting physics is present in TeV physics beyond the standard model



Suppressed by heavy mass

Revised consequences

Given any new exact conserved global symmetry:

- ***Globally-charged particles must be produced in pairs.***
  - *Corrections to electroweak predictions must involve pairs of globally-charged particles, and tend to be loop-suppressed and mass-suppressed.*
- ***Globally-charged particles cannot decay to standard model particles alone***.
  - *The lightest globally-charged particle (LXP) must be stable*
  - *Because the LXP is presumably neutral and weakly-interacting,*
    - *It is a dark-matter candidate.*
    - *Every event in which globally-charged particles are produced has (at least) two LXPs in the final state, giving an MET signal.*
  - *No resonances to be built from SM particles; no invariant mass plots will show a peak*
  - *Will see only kinematic endpoints and edges from three-body decays, multiple two-body decays, etc. with a missing particle*

- **These are all characteristics often said to be those of SUSY.**
- **They are not!**

There's more

- So we have good reasons to expect a **new global symmetry** along with weakly-interacting TeV-scale physics – which may or *may not* involve SUSY.
- Our reasons to expect SUSY are strong, but not as strong as is sometimes suggested.

There's still much more left to say:

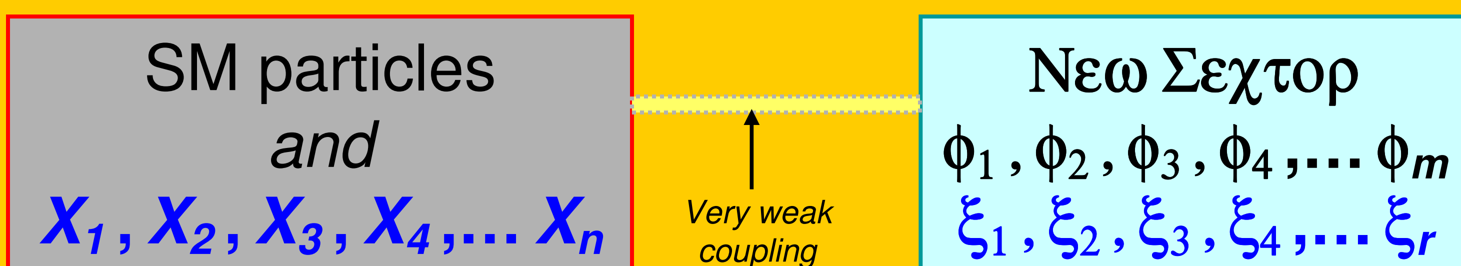
- Our global symmetry need not have the above-described collider physics, even if it is exactly conserved!
- And most of its good features survive even if it is ***not*** exactly conserved; however, its collider phenomenology may be very different.
- I will now explore these statements with some care; the range of different and interesting phenomena which may arise is striking and worthy of your thoughtful consideration.

An ultra-weakly coupled sector

- Suppose that the standard model and the particles ***$X_1, X_2, X_3, X_4, \ldots X_n$*** carrying the new global charge all couple to each other with weak-interaction strength or stronger

- But in addition there is another sector containing
  - particles $\phi_1, \phi_2, \phi_3, \phi_4, \ldots \phi_m$ neutral under the new global charge
  - particles $\xi_1, \xi_2, \xi_3, \xi_4, \ldots \xi_r$ charged under the new global charge

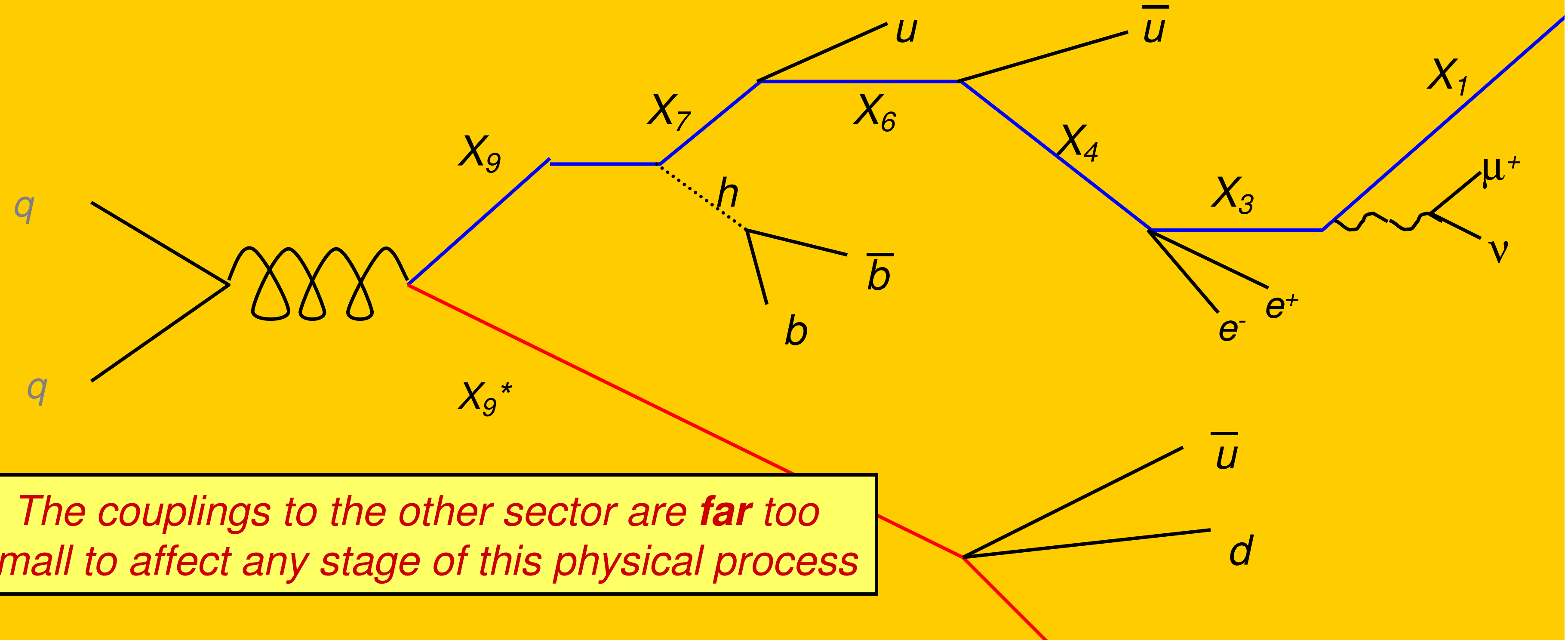
- These particles may couple to each other rather strongly, but they couple to SM particles and the ***X_i*** ultra-weakly (much more weakly than the weak interactions)



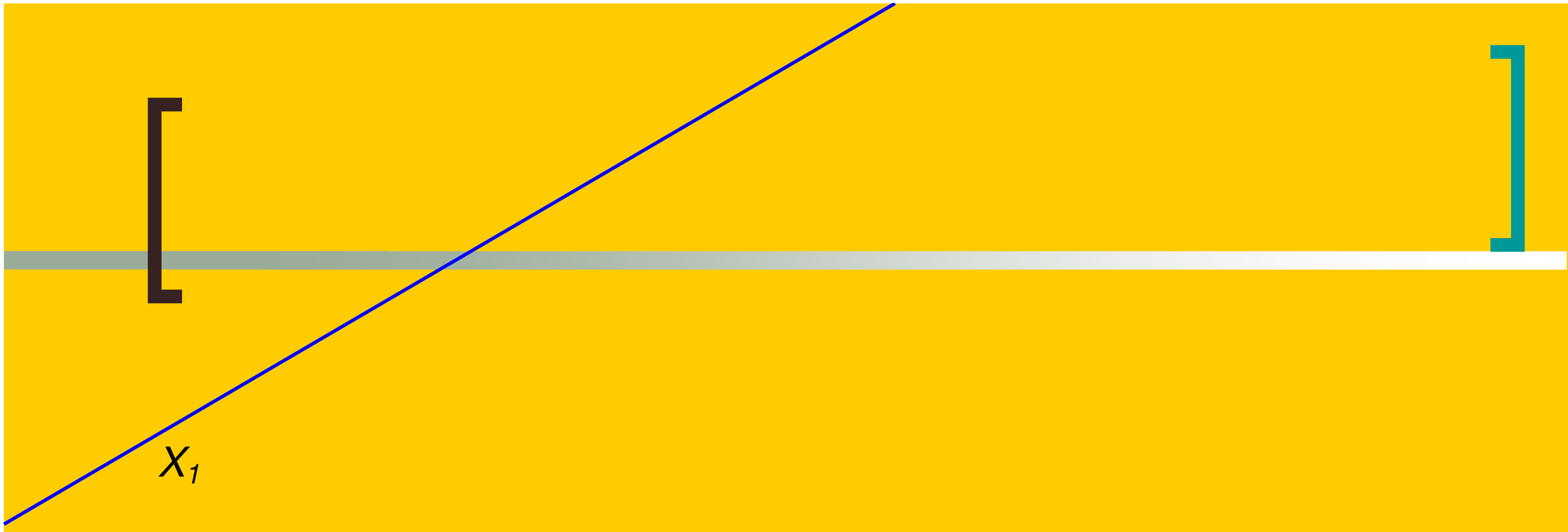
Simple case first: one ξ

Νεω Σεχτορ
ξ_1

- Suppose the new sector consists only of one globally-charged particle ξ_1 (or `ξ' for short)
- Suppose also that ξ is lighter than $\boldsymbol{X_1}$, so that although $\boldsymbol{X_1}$ is the LXP in the sector containing the SM (the `LsXP'), the true LXP is ξ
- Remember the two sectors are ultra-weakly coupled to one another
- Now let us revisit the process we considered earlier:

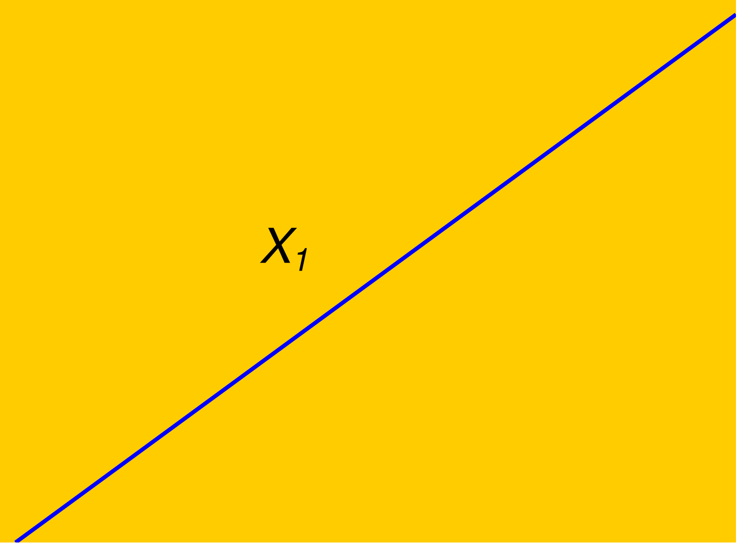


*The couplings to the other sector are **far** too small to affect any stage of this physical process*

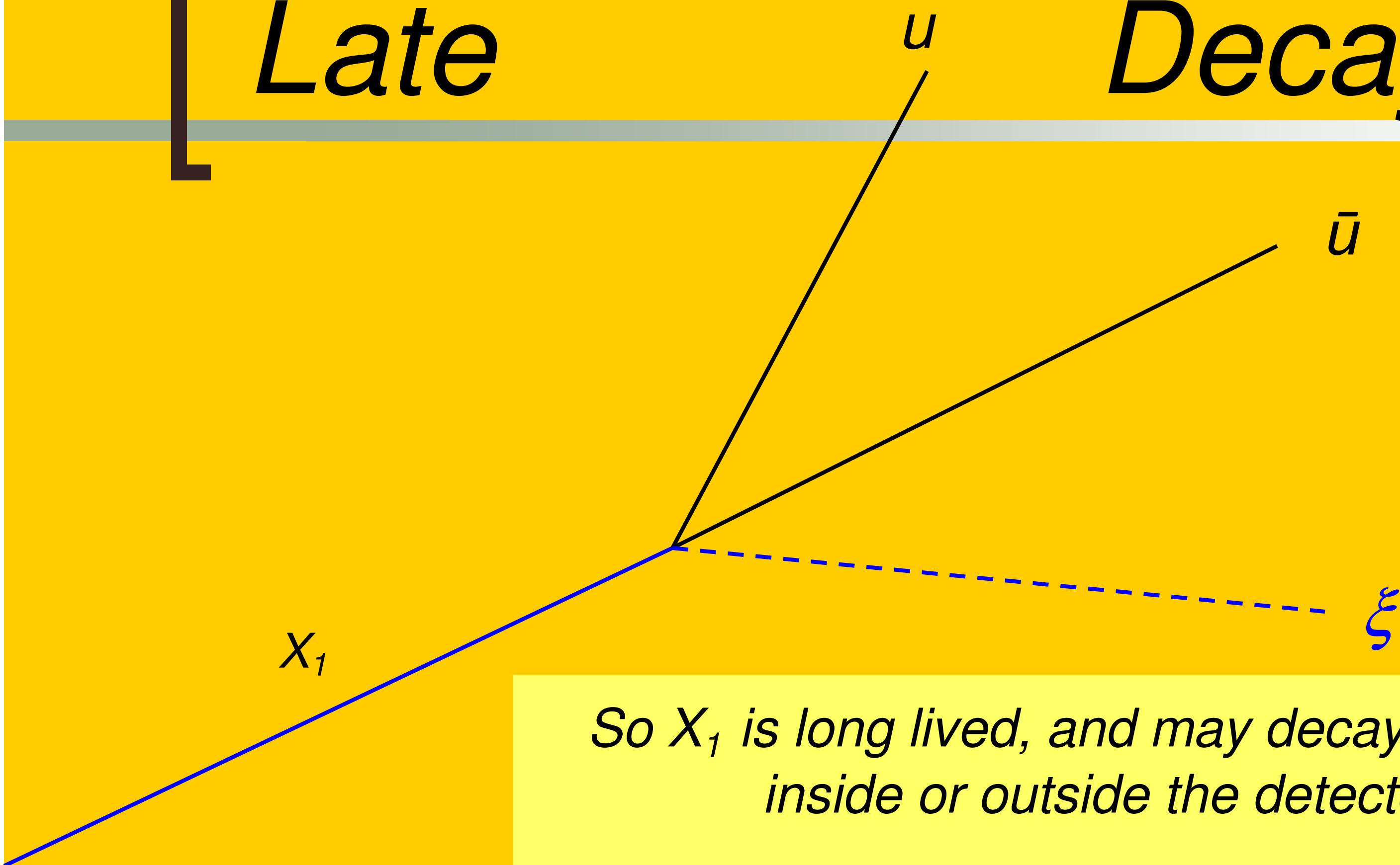


… so nothing happens …

… … … until … …



Late Decays



So X_1 is long lived, and may decay anyplace inside or outside the detector.

An example:

Gauge Mediated Supersymmetry Breaking

The global symmetry is R-parity
and
ξ is the gravitino, the true LSP

Implications

- Of course, if the X_1 lifetime is longer than a few nanoseconds, its decay occurs outside the detector and clearly there's no change from the infinite-lifetime case; still get MET, exactly as before…
- *Oh, wait a second.*
- Remember this argument?

> •So the lightest *X* (the "LXP") must be stable
> •But the LXP would have been produced abundantly in the early universe
> •And so there would be plenty of them around today
> •So the LXP can't be electrically charged (heavy atoms) or carry color (heavy nuclei) on which we have very strong constraints
> •So therefore it must be that the LXP is electrically-neutral and color-neutral, so that it interacts very weakly with ordinary matter, at best comparable to a neutrino, perhaps even lighter.

- It fails now, so the conclusion fails too.
- If the X_1 lifetime is short compared to the age of the universe, it can be electrically charged and/or it can carry color.
- *Caution: if its decays release too much energy it may be ruled out, by direct detection or by effects on nuclei abundances, so the lifetime might have to be short compared to 1 second.*

Implications

- ~~Of course, if the X_1 lifetime is longer than a few nanoseconds, its decay occurs outside the detector and clearly there's no change from the infinite lifetime case; still get MET, otherwise nothing…~~

- Of course, if the X_1 lifetime is longer than a few nanoseconds, it appears stable to the LHC detectors, but since it need not be weakly-interacting, every event may give MET or it may contain two (or more)
  - Effectively-stable charged particles
  - Effectively-stable charged and colored particles
  - Effectively-stable neutral and colored particles
- Stable charged colorless objects behave somewhat like odd muons.
- Stable colored objects have more interesting interactions with matter, including possibly charge exchange and intermittent tracks.
- Studies of and searches for stable colored particles that decay long after stopping in the detector have recently been performed.

(If the X_1 is stable and charged, it must be heavy enough not to have not been produced and seen at LEP or Fermilab.)

More implications

- On the other hand, if the X_1 lifetime is short compared to picoseconds, then its decays are prompt, and what we detect is **two sets** of whatever decay products are generated when X_1 decays to ξ .
- These could be easy to see or very hard to detect, depending on what they are

- Consider the implications of new physics arising with

  - *Two photons in every event*
  - *Two muons in every event*
  - *Two taus in every event*
  - *Two top quarks in every event*
  - *Two b jets in every event*
  - *Two Z bosons in every event*
  - *Two off-shell Z bosons in every event*
  - *Two Higgs bosons in every event*
  - *Four leptons in every event*
  - *Four top quarks in every event*

plus

- a reduced amount of MET (from the two ξ particles)
- possibly some hard jets and leptons from cascade decays of the original *X* particles produced.

All of these are possible and some are even reasonable. The hard ones deserve some serious and careful thought.

Still more implications

- If X_1 lifetime is in the range of pico- to nanoseconds, may decay anywhere in the detector.

  Could be easy to see or very hard to detect, depending on where it decays and what it decays to.

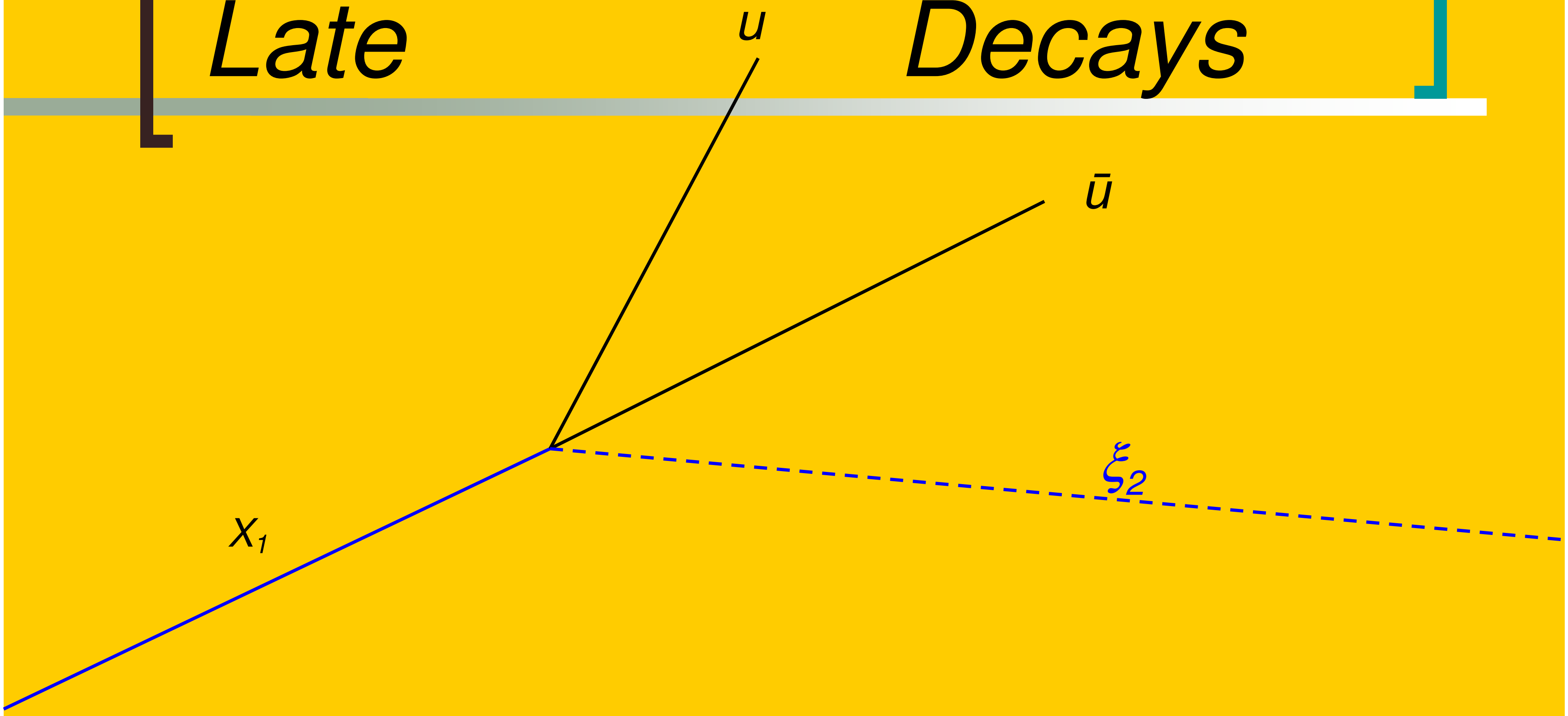
- Consider the implications of
  - *Two photons appearing from nowhere in every event*
  - *Two muons appearing off a charged track in every event (track with a kink)*
  - *Two taus appearing off a charged track in every event (track with a kink or spray)*
  - *Two off-shell Z bosons appearing from nowhere in every event (jet-pairs, muon-pairs, electron-pairs out of empty space)*
  - *Two Higgs bosons appearing from nowhere in every event (jet-pairs from empty space)*
  - *Two pairs of top quarks appearing from nowhere in every event (good lord!)*

- Clearly the difficulties are enormously variable, depending on whether the decay is
  - Within the beampipe (where tracking and vertexing work)
  - Somewhere in the tracker (the tracking may fail but the calorimeter works)
  - Somewhere in the calorimeter or muon chamber (heaven knows what will happen)
- Triggering can be a big issue! As are cosmic backgrounds, effects of detector material…
- *No general systematic study of this kind of signal has ever been undertaken for any of the Tevatron or LHC detectors, as far as I am aware.* Only a few cases have been studied, and less than five analyses published.

Larger new sectors

- This is what can happen if the ultra-weakly coupled sector has **one** particle
- If it has more than one particle, so that decays within the new sector can occur, then the range of possible signals becomes much larger
- Suppose there are **three** particles in the new sector,
  - ξ_1 , ξ_2 that carry global charge, and
  - ϕ that doesn't carry it
- And suppose the interactions *among* these particles are ***strong***.
  - (They are weakly coupled to the SM, remember, but they need not be weakly coupled to each other.)

Late Decays

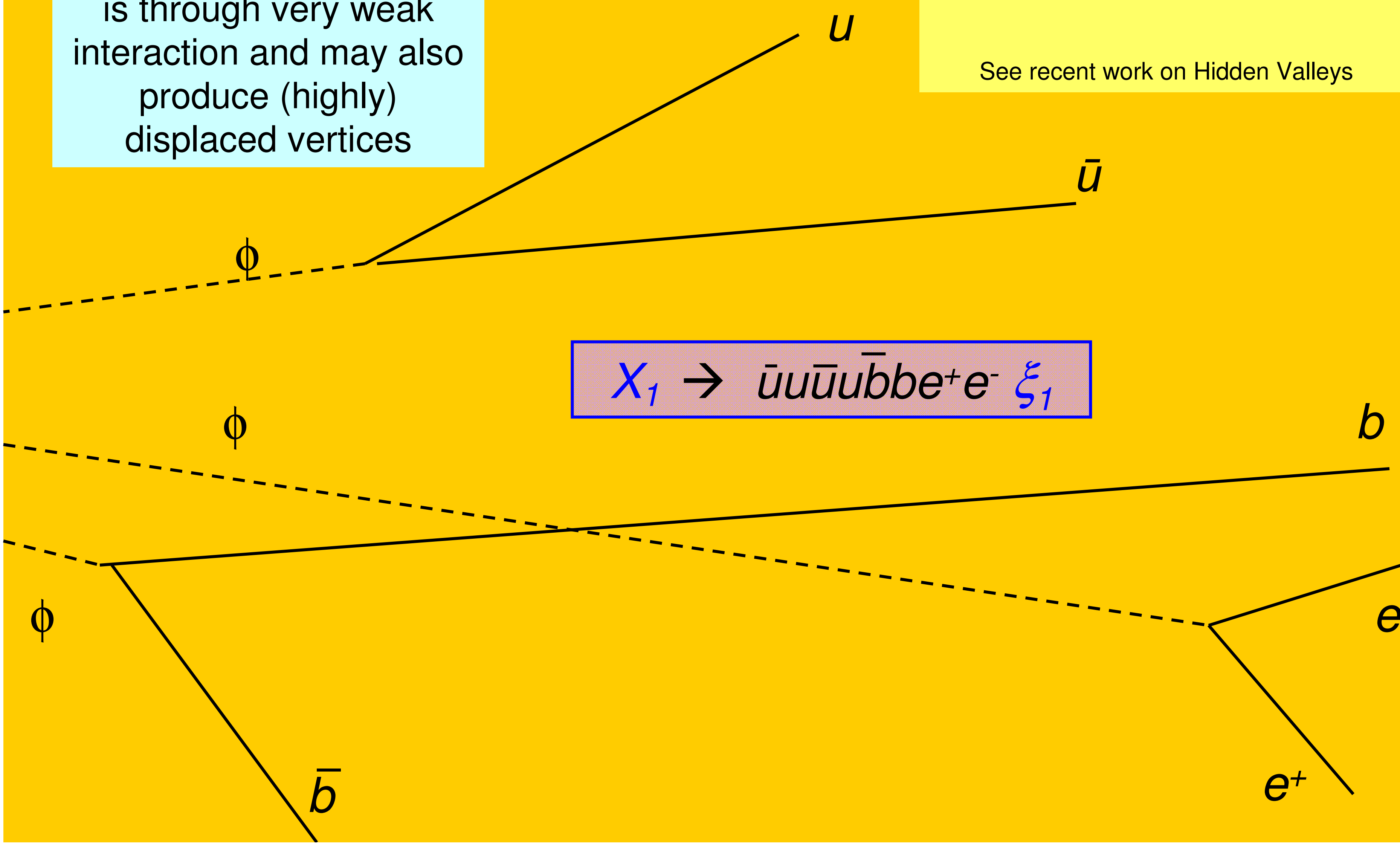


ξ_2
ϕ
ϕ
ϕ
ϕ
ξ_1

ϕ decay to SM particles is through very weak interaction and may also produce (highly) displaced vertices

Yes, this is wacky! But it happens in some models!

See recent work on Hidden Valleys



$X_1 \rightarrow \bar{u}u\bar{u}u\bar{b}be^+e^-\ \xi_1$

Re-Revised consequences

Given any new exactly conserved global symmetry:

- ***Globally-charged particles must be produced in pairs.***
  - *Corrections to electroweak predictions must involve pairs of globally-charged particles, and tend to be loop-suppressed and mass-suppressed.*
- ***Globally-charged particles cannot decay to standard model particles alone*.**
  - *The lightest globally-charged particle (LXP) must be stable*
  - *Because the LXP is presumably neutral and weakly-interacting,*
    - *It is a dark-matter candidate.*
  - *But the lightest globally-charged particle in the standard model sector (LsXP) may not be the LXP*
    - *The LsXP need not be neutral or weakly-interacting*
    - *The LsXP decay to the LXP may be prompt, or occur in the detector at a macroscopic distance, or occur well outside the detector*
  - *Every event in which globally-charged particles are produced has (at least) two LsXPs in the final state, and possibly the decay products of the LsXPs if they decay visibly inside the detector*
  - *If most of the decay products of the LsXP are visible, there may be only a little MET.*
  - *No resonances to be built from SM particles, though resonances from SM particles combined with a metastable visible LsXP are possible*
  - *If LsXP decays promptly with considerable MET, see only kinematic endpoints and edges from three-body decays, multiple two-body decays, etc. with a missing particle*

An important lesson

What we learn from this is the following:

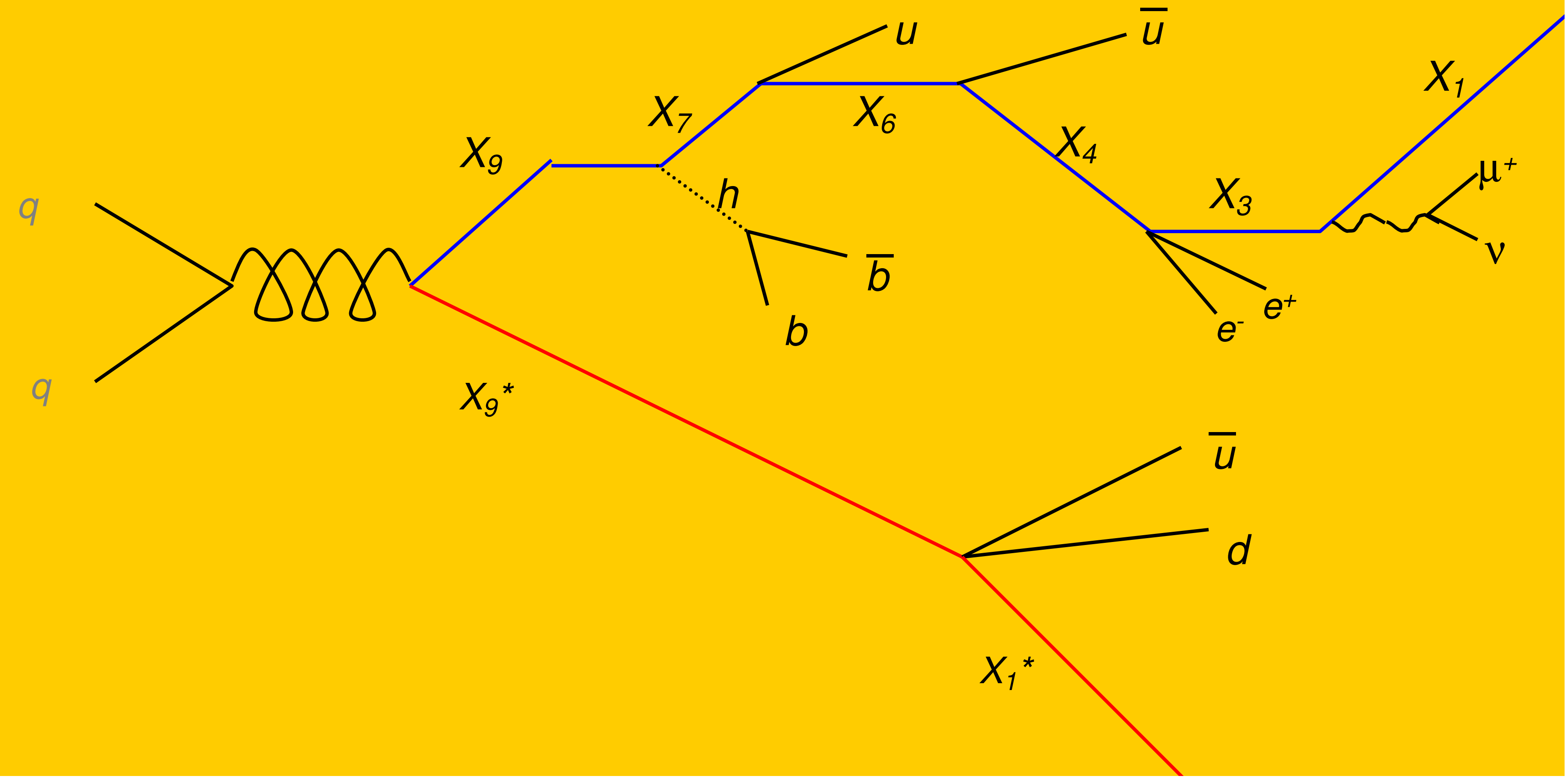
- Even if the most optimistic theorists are right and
  - *Supersymmetry is truly the solution to the hierarchy problem*
  - *R-parity is true and stabilizes a dark matter candidate*

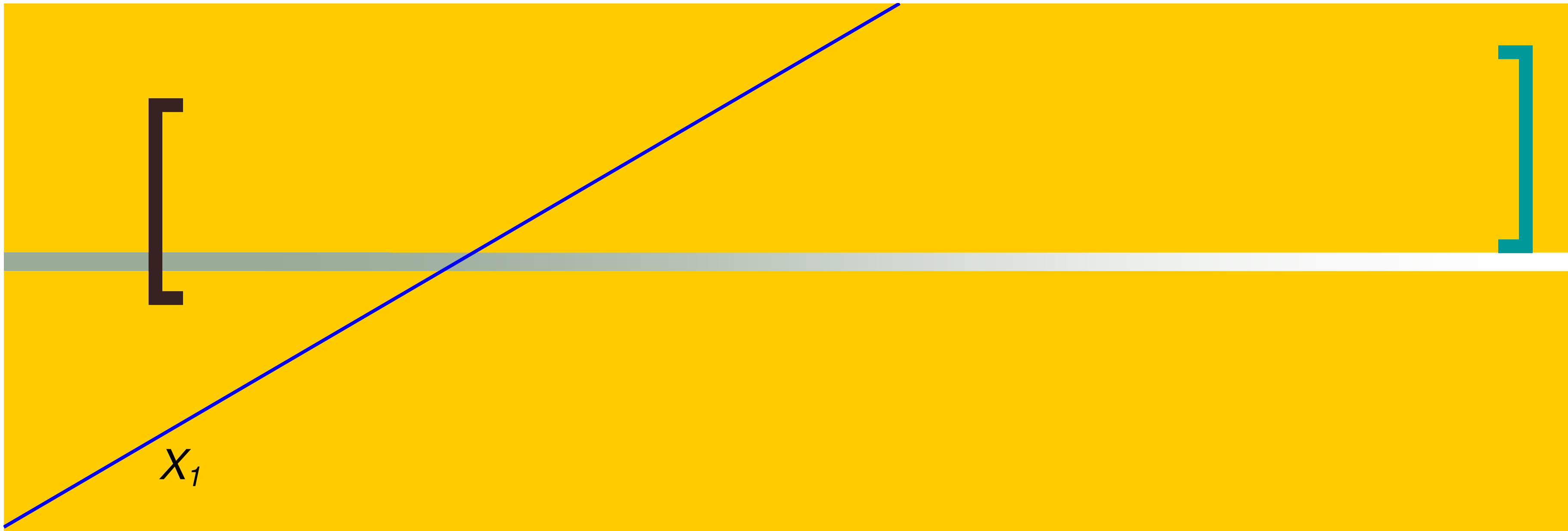
the phenomenology of supersymmetric models may differ wildly from the standard high-pT jets and leptons plus MET search.

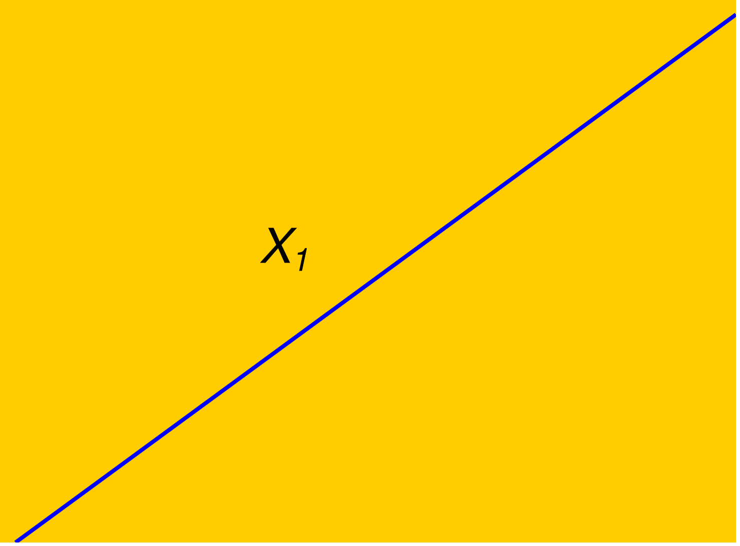
and it will be a long road from the discovery of an R-parity-like global symmetry to an actual claim of having found supersymmetry.

If not exactly conserved?

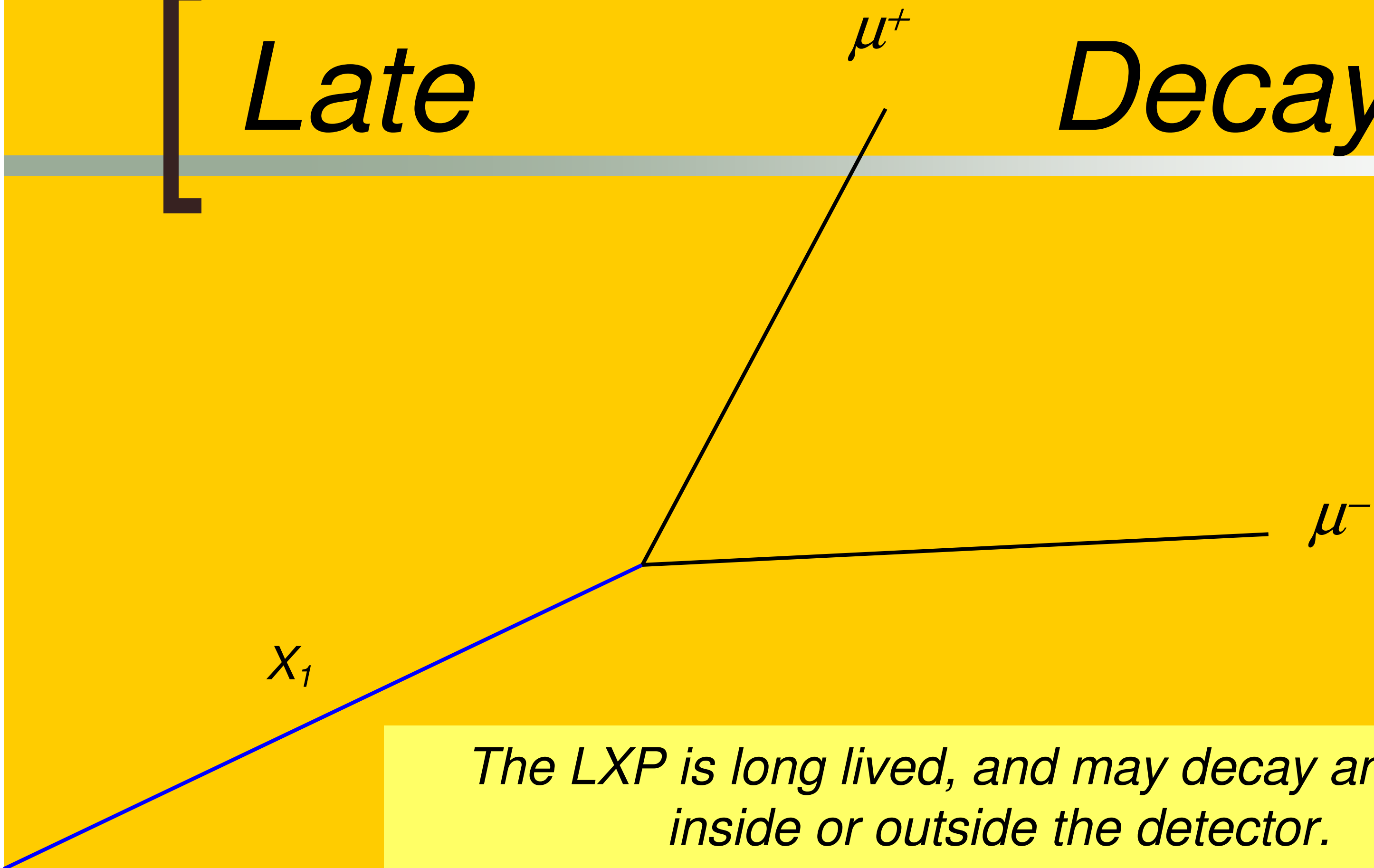
Ok, let's forget about extra sectors and instead consider the possibility that the global symmetry is violated by a tiny amount




X_1


X1

Late Decays



The LXP is long lived, and may decay anyplace inside or outside the detector.

Because the symmetry is not conserved, it will be able to decay to standard model particles only!

If its decay products are all visible, it can be reconstructed as a final-state resonance!

Consequences

very slightly false, but true for all practical purposes

Given any new global symmetry with tiny violations :

- ***Globally-charged particles must* be produced in pairs.***
  - *Corrections to electroweak predictions must involve pairs of globally-charged particles, and tend to be loop-suppressed and mass-suppressed.*
- ***Globally-charged particles cannot* decay to standard model particles alone.***
  - *The lightest globally-charged particle (LXP) IS NOT stable*
    - *It is NOT a dark-matter candidate.*
    - *It may decay entirely or in part to SM particles*
    - *It may decay promptly, or do so at a macroscopic distance from the beampipe, or appear stable*
  - *Every* event in which globally-charged particles are produced has (at least) two LXPs in the final state, and possibly the decay products of the LXPs, if they decay visibly inside the detector*
  - *If all the decay products of the LXP are visible, there will be no MET.*
  - *The LXP, and all particles that decay visibly to the LXP, can be reconstructed as resonances, as long as the LXP is*
    - *metastable and visible, or*
    - *has decays in the detector to all-visible SM particles*

- This is typical phenomenology of SUSY models with R-parity violation, which typically has to be small to avoid other problems. It will also be typical of many other models.
- In extra dimensions and Little Higgs models with new global symmetries, the global symmetry is mainly needed for the small corrections to electroweak physics, but serves no other critical purpose. The violations might not be that small… so let's consider…

Consequences

Given any new global symmetry with moderate violations:

- ***Globally-charged particles must be mostly produced in pairs.***
  - *Corrections to electroweak predictions must involve pairs of globally-charged particles, and tend to be loop-suppressed and mass-suppressed.*
  - *Resonant production of globally-charged particles might be visible, with low production rates.*
- ***Globally-charged particles cannot often decay to standard model particles alone.***
  - *The lightest globally-charged particle (LXP) IS NOT stable*
    - *It is NOT a dark-matter candidate.*
    - *It will decay promptly to SM particles*
  - *Most events in which globally-charged particles are produced have the decay products of two LXPs in the final state*
  - *If all the decay products of the LXP are visible, there will be no MET.*
  - *The LXP, and all particles that decay visibly to the LXP, can be reconstructed as resonances, as long as the LXP has decays in the detector to all-visible SM particles*

We're almost back to cases with no global symmetry at all

Summary Table

Global Sym-metry?	Resonant Produc-tion of X-charged particles	Resonant decay of X-charged particles	Cascade decays	L(s)XP pairs	MET	Quasi-stable visible L(s)XP	Macro-scopic L(s)XP decay	Prompt L(s)XP decay	Electro-weak corrections	Dark matter candidate
None	**Yes**	**Yes**	**Atypical**	**No**	**Atypical**	**No**	**No**	**Yes**	**Large**	**No**
Violated by moderate effects	**Rare**	**Likely, if LXP decay visible**	**Maybe**	**Usually**	**Maybe**	**No**	**No**	**Yes**	**Small**	**No**
Violated by tiny effects	**No**	**Yes, if LXP or its decay visible**	**Typical**	**Yes**	**Depends on LXP decay**	**Maybe**	**Maybe**	**Maybe**	**Small**	**No**
Exact, but with LXP in new sector	**No**	**Yes, if LsXP visible**	**Typical**	**Yes**	**Depends on LsXP decay**	**Maybe**	**Maybe**	**Maybe**	**Small**	**Yes**
Exact, SM sector only	**No**	**No**	**Typical**	**Yes**	**Always**	**No**	**No**	**No**	**Small**	**Yes**

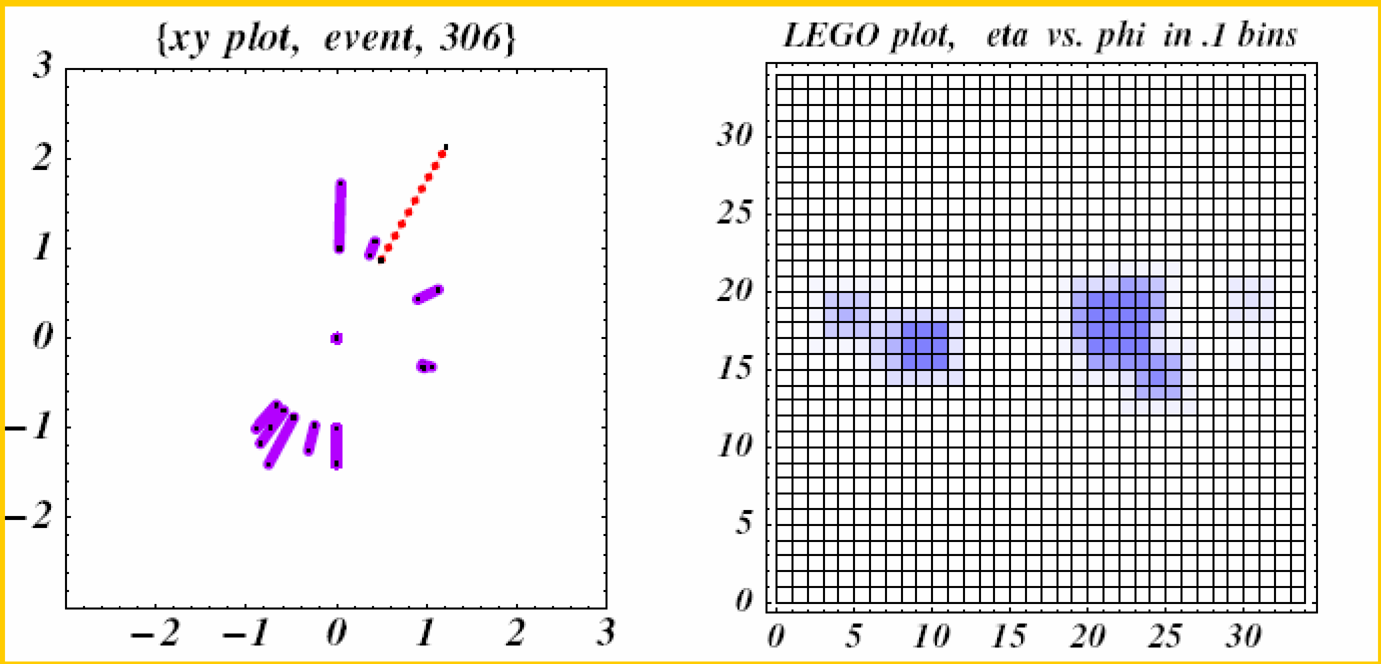
Exotica – one slide!

- Can't look for everything!!
- Stuff that would be found with searches for more classic beyond-the-standard-model physics need not be worried about right now
  - *A new exotic thing that produces same-sign muons and MET would be found in SUSY searches [and called "supersymmetry", but that's ok.]*
- Need to gather phenomena that would be missed by standard searches
- Need to develop methods for searching for many of these phenomena at once using a small and relatively efficient set of preliminary searches
- Follow up hints with more detailed study
- Possible directions
  - Weird combinations of objects in a single event (same sign muons, two photons and jets)
  - Resonances decaying to a strange combination of objects (such as $\mu^+ j\ j$)
  - Particles of small fractional charge (tracks with few hits and weak curvature – very hard!)
  - Magnetic monopoles or dyons (tracks with wrong shape)
  - Strange things accompanying MET (fat blobby super-jets, cluster of four taus)
  - Events with many long-lived particles simultaneously produced (multiple displaced vertices)
  - Events with many partons simultaneously produced (strange energy deposition, odd track patterns, some MET and multiple b jets and/or leptons.)
  - Kinematic features within set of weird-looking events (light muon-pair resonance produced only in rare events with fat blobby jets)

Summing up

- The Higgs sector is very sensitive to and is easily affected by new physics.
- The Hierarchy Problem makes theorists uncomfortable, probably (but not certainly) with good reason, and motivates new physics at a TeV.
- Quantum gravity at the TeV scale would have many strange effects; four-dimensional quantum field theory would start breaking down badly (though in ways that could initially be mimicked by physics from other new sectors.)
- Models that attempt to solve or mitigate the hierarchy problem (TeV Extra Dims, Technicolor, Little Higgs, SUSY, etc.)
  - Tend to produce repeaters at or below TeV, especially for the W, Z, Higgs and heavy quarks – everything that couples strongly to the Higgs boson. *Loopholes exist! This is a tendency, not a theorem.*
  - Sometimes they produce repeaters for other particles, and often they produce exotic states
- Success of electroweak precision tests suggest a new global symmetry is waiting to be discovered among new particles at the TeV scale or below. Candidates include but are not limited to R-parity in a SUSY model. Phenomenology depends crucially on whether this symmetry is exact or only approximate, and to what degree.
  - Exact symmetries tend to give what is traditionally but incorrectly called "SUSY signals"
  - Approximate symmetries can change these signals dramatically, as can new sectors that are very-weakly-interacting with the standard model.
- Many new exotic objects, or ordinary objects with exotic behavior, can be imagined and deserve at least passing consideration; in some cases they are easy to detect, in other cases very challenging.
- In all cases, collider phenomenology is *very* sensitive to additional particles that are not present in minimal models.

Good Luck!!!!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LEGO plot, eta vs. phi in .1 bins
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