Q&A for Fermion Generations II (experiment) -- EDITING

[slide 14]
What differentiates, experimentally, an electronic neutrino and a muonic neutrino that allowed the muonic neutrino to be discovered ?

In short, the charged weak interactions. It's the same idea that allows neutrino flavours to be identified in neutrino mixing measurements. For example, if you have a muon neutrino with enough energy and you put a target in its path, there's a chance it will interact like (nu_mu + d -> mu- + u) and then the muon produced identifies it; for an electron neutrino, you'd get an electron.

[slide 34]
Aren't the experimental limits on >3 generations from H->yy/gg loops and CKM unitarity measurements thrown out the window if there is an extended Higgs sector, e.g. if additional fermion generations couple to a different Higgs doublet? Or would one split hairs and not call this an additional generation?

One of my theory colleagues would be able to give you a more complete answer, but in short: yes, if you change the structure of the couplings, you can probably evade some or all of the limits. (You have to be a little bit careful of indirect effects from loop processes.) This is why I was expressing things in terms of limits on the number of SM-like fermion generations.

That might sound a bit hopeless -- if you can dodge limits, what have we even learned? -- but dodging all limits simultaneously is a much harder problem. (And remember, you don't want the model of NP to decouple totally from the SM, otherwise you aren't helping to solve any of the puzzles that motivate looking for NP in the first place.)

[slide 37]
(i) Why and how can we directly measure the top mass, but not the other quarks masses?
(ii) About the top quark, we know it can't exist in a bound state, but we also know that all observed particles should be neutral in terms of color charge... Is the top quark an exception in this case?

This is driven by the extremely short top lifetime. There are two timescales in competition: if you make a top quark, does it decay first, or does it hadronise first? For all of the other quarks, the lifetime scale is a lot longer. For the top, the scales are flipped: the top will [or is very likely to] decay first, and then the decay products hadronise. It's still not totally trivial to measure the mass (since the width is finite, you have to handle the lineshape carefully) but that particular problem goes away.

(Aside: Why is the top lifetime so short? Basically because it's heavy. This not only means it has lots of phase space to decay, but also when it decays the W can be on-shell or close to it, in which case you don't have the usual weak-vs-EM suppression. And because it's the heavier quark in its doublet, the CKM coefficient for the decay, Vtb, is basically 1 so it's not CKM-suppressed either.)

It is often said top is too short-lived to hadronise. Still, its lifetime is only about 10% of the typical hadronisation time. Does this mean certain (a few %) top quarks still manage to hadronise before they decay? In that case, can we see top hadrons in experiment? How would they decay? B hadron + a real W? Have there been searches for this?

[Aside: if there's a factor of 10 between the two timescales, that means an expected hadronisation rate of one in e^10 ~ 2x10^4, rather than one in 10. But the hadronisation timescale is a bit order-of-magnitude so maybe one shouldn't over-interpret that.]

I don't have a very detailed answer for you, I'm afraid, other than that no top hadrons are known experimentally. (Probably a good starting point is the top quark PDG review, which does note that you might get some hadron/resonance-like features under certain conditions; someone from ATLAS/CMS might be able to give more detail.) But I can try and give you my hand-wavy intuition.

At some level it comes down to what is meant by a hadron. Quarks are produced in qqbar pairs, so our newly created top quark begins life in a QCD field, near to other coloured objects. But when we talk about a hadron, we mean something more than that: we mean that the quarks have formed a system that is colour neutral, localised, and (speaking a little loosely) shows bound or resonant behaviour. If you think of a K* resonance, for example, it's going to fall apart rapidly into a kaon and a pion, but it is not merely a kaon and pion in proximity: it is a state with well-defined quantum numbers, associated with a pole in the scattering amplitude.

Now I move well outside my area of competence, so take what I write with a big pinch of salt:

Even though the top lifetime is very short, I think you could in principle calculate what a top bound state might look like (though actually doing the calculation might be a different story, and I have my doubts about what it means to define the field for such a short-lived particle). The phase space would be so huge that I suspect its decays would be functionally indistinguishable from an unhadronised top quark, i.e. "b-quark jet + W", and I'm guessing its width would also be comparable (being dominated by the top weak decay). So what you'd be looking for is small modifications to the broad top lineshape. That's something that has been scrutinised as part of top mass measurements, so perhaps that could be recast into limits on contributions on top hadron production.

[slide 46]
The paper linked for pi->mu+nu_e is from bubble chamber in 1982. Can short baseline neutrino beam experiments be sensitive to this process?

My neutrino colleagues might have something to add here, but in principle I don't see why not. (Could even be that they've effectively done it, but expressed the results in different terms. The limit I quoted is the one currently shown in the PDG.) It for sure would be nice to have a stricter limit here.

Are there actual models predicting BNV in 3rd generation which avoid proton decay limits? Also, it looks like the proton decay constrains Delta B = 1, neutron oscillations constrain Delta B = 2, but have there been limits on Delta B = 3 processes?

There has been at least one model of BNV published which [by its authors' calculations] avoids the proton decay limit but allows BNV in heavier baryons (see Phys.Lett.B 721 (2013) 82 and Phys.Rev.D 85 (2012) 036005). In that particular case, the model adds a six-fermion operator with strictly flavour-diagonal couplings (i.e. exactly two fermions from each generation), so that proton decay is badly loop-suppressed but you can do stuff like Xib0 oscillations. I would guess, but don't know for sure, that other models of NP that have non-generic flavour couplings (e.g. NP that couples only to third-generation fermions seems like an obvious candidate).

About DeltaB=3 limits: The motivation is a bit less obvious -- I think you'd have to have a very complicated 9-fermion operator. That's not by itself a deal-breaker -- experimentalists like to look for all kinds of weird final states on the off-chance -- but once you require charge and energy conservation there are not so many options. Decays of light and strange baryons wouldn't do it. You could just about do it in charm, but experimentally it'd be tough (you either have neutrons in the final state or you start with a Xic/Omegac, for which the production rate is limited). With their larger phase space beauty decays would work (e.g. Lb -> pbar pbar pi+ pi+, or B0 -> p p p pi- pi- pi-)

but I can't think of a search off-hand and I don't see anything promising from a peek at the PDG. So I'm not aware of any current limits.

(On the other hand, DeltaL=3 should be easier. Obvious one is D+ -> mu+ mu+ mu+ pi- pi-. I don't see any current limits, but there's no reason it couldn't be done.)

[end]