QUESTIONS ABOUT THE QUANTUM UNIVERSE

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DEFINING THE PHYSICS CASE FOR PROJECT X

"I shall not today attempt further to define [pornography]. But I know it when I see it"
- U.S. Supreme Court Justice Potter Stewart

- ➡ Identify the big long-range questions that drive this science.
- ➡ Connect the big questions to what Project X experiments could actually do.
- ➡ Don't have to show that these expts can answer the big questions, but show how they could play an essential role in a larger long-term world-wide program.
- ➡ This is discovery science, so don't have to guarantee that Nature will put the gold where we can find it.
- ➡ Demonstrate timeliness, cost-effectiveness, synergies.

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THIS TALK

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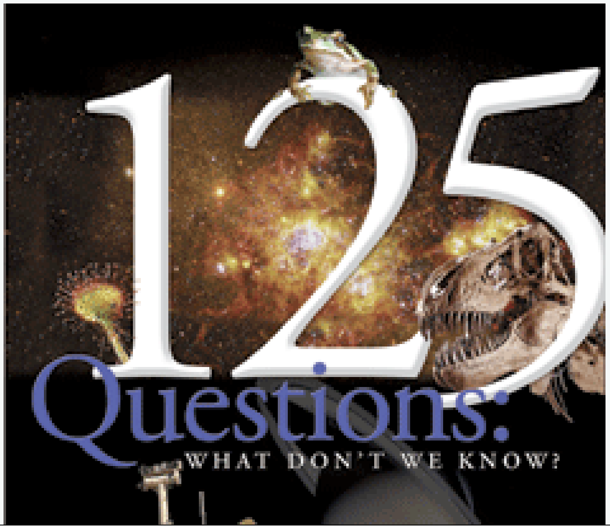
PHYSICS FIRST

- The physics should drive Project X, not vice-versa
- A good starting point is to organize the discussion around the 9+1 great questions from the *Quantum Universe* report
- Note these correspond to questions 1, 5, 26, 27, 32, 33, 34, 36, and 37 of the top 125 questions in all of science, according to *Science*.



THE BIG QUESTIONS

0. What is the origin of mass for fundamental particles?
1. Are there undiscovered principles of nature: new symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

Based on “The Quantum Universe,” HEPAP 2004

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1. Are there undiscovered principles of nature: new symmetries, new physical laws?

7. What are neutrinos telling us?

➡ Neutrinos provide direct access to physics beyond the Standard Model, the only laboratory-accessible direct access that we have had so far.

➡ The existence of neutrino mass and mixings already implies breaking of a symmetry (neutrino flavor) and points towards new symmetries (unification), and other new breaking of symmetries (charged lepton flavor violation and lepton CP violation)

➡ Neutrinos have already surprised us. They may very well surprise us again. Neutrino science is the exploration of the unknown

1. Are there undiscovered principles of nature: new symmetries, new physical laws?

7. What are neutrinos telling us?

➡ We expect the LHC experiments to discover new principles of nature that are directly manifest at Terascale energies

➡ As with the Standard Model, a *broad long range* experimental program will be required to demystify this new science. This must certainly require precision experiments with quarks and leptons

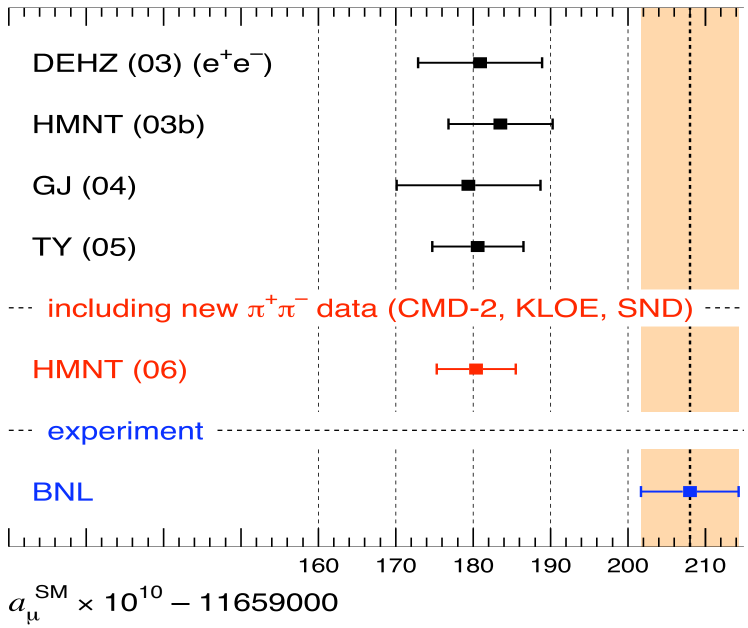
➡ Precision physics is itself a tried and true method of revealing new symmetries and violations of symmetries that imply new phenomena

the promise and the pitfalls

2. The anomalous magnetic moment of the muon

$$a_\mu \equiv (g-2)_\mu/2$$

Overview about the current experimental and SM (theory) result:
[*g-2 Collaboration, hep-ex/0602035*] $\to$ T



$$a_\mu^{\rm exp} - a_\mu^{\rm theo,SM} \approx (28 \pm 8) \times 10^{-10} \quad : \ 3.4\,\sigma$$

4. Do all the forces become one?

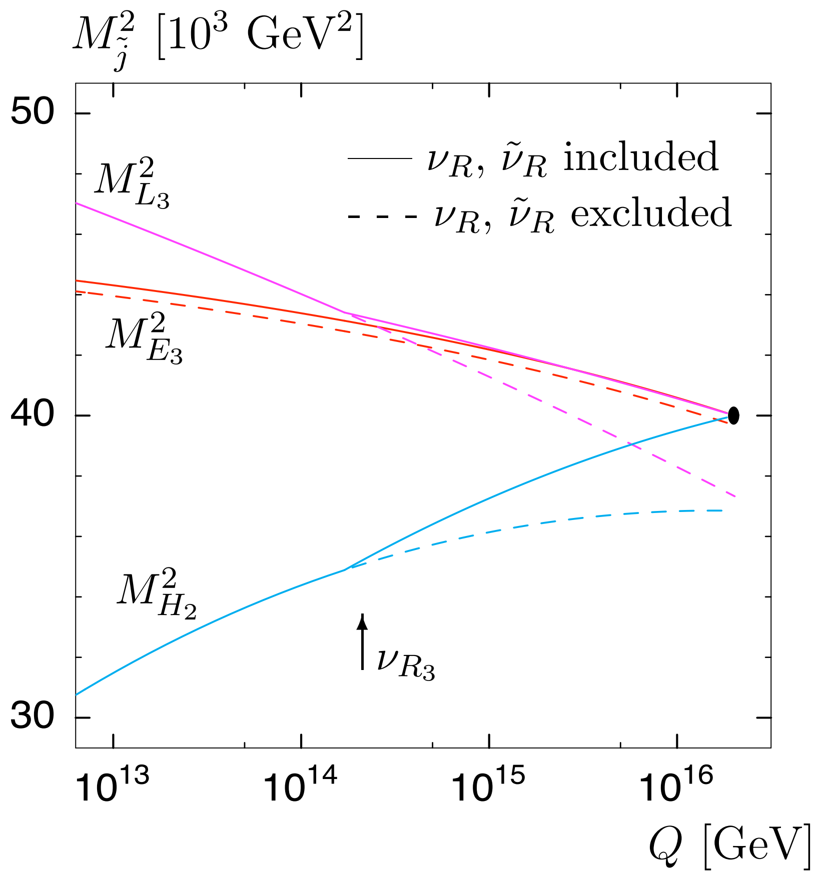
5. Why are there so many kinds of particles?

- ➡ Flavor physics is unification physics
- ➡ Quarks talk to each other via their mass-giving mechanism and via the weak interactions
- ➡ Neutrinos talk to each other via their mass-giving mechanism and via the weak interactions
- ➡ Quarks and leptons appear to know about each other, since they cancel each other's gauge anomalies

4. Do all the forces become one?

5. Why are there so many kinds of particles?

- ➡ The discovery of any new Terascale physics at LHC will raise flavor questions that are (most likely) not themselves accessible at LHC
- ➡ The discovery of supersymmetry at LHC will raise questions about unification that are (most likely) only crudely accessible at LHC



G. Blair, W. Porod, P. Zerwas, 2002
G. Kane, P. Kumar, D. Morrissey, M. Toharia, 2006

Example: effect of the superheavy neutrinos on SUSY matter unification

4. Do all the forces become one?

5. Why are there so many kinds of particles?

- ➡ Supersymmetry + a neutrino see-saw implies charged lepton flavor violation. If we verify all three experimentally, we are revealing key aspects of the unified origins of matter
- ➡ This is very exciting!
- ➡ Caveat: we do not know how to make *all* the measurements that would be required to verify a detailed unification theory at ~10^16 GeV
- ➡ But we *do* know how to make a series of measurements that will tell us if we are on the right track, and discriminate between many different scenarios

4. Do all the forces become one?

5. Why are there so many kinds of particles?

NEWSFLASH:

➡ We now know that new sources of heavy quark flavor or CP violation at sub-TeV energies are constrained to be small

➡ Even a couple years ago this was not obvious! (B_s mixing, B -> tau + nu). From a theory point of view it is quite surprising

➡ We have discovered that the quark sector, which includes the unknown Terascale physics of electroweak symmetry breaking, is either Minimally Flavor Violating or close to it

IMPLICATIONS OF AN ALMOST-MFV WORLD

➡ Measuring small deviations from MFV will be of great importance, since these can tell us about things like (i) the SUSY breaking scale, (ii) flavor symmetries related to unification, (iii) compositeness, extra dimensions, etc.

➡ Such measurements will be directly complementary to the central physics program of the LHC

➡ Future quark flavor experiments had better focus on modes with small theoretical uncertainties, and had better achieve experimental precision comparable to those small theory errors

➡ More $ for lattice gauge theory!

A few comments:

I) The MFV hypothesis is far from being verified

To prove MFV from data we need to

- observe some deviation form the SM in FCNCs
- observe the CKM pattern predicted by MFV [within same type of FCNCs]

$$A_{FCNC} = C_{CKM} \; [\, F_{SM} + \Delta_{new} \,]$$

$\Delta F = 2$ processes are in principle good candidates to prove MFV, but so far we are limited by theoretical (Lattice) uncertainties

Best $\Delta F=1$ candidates to proof/disproof the MFV hypothesis:

$B_{d,s} \to l^+ l^-$ & $K_{u,d} \to \pi\nu\nu$

8. How did the universe come to be?

9. What happened to the antimatter?

- ➡ Some new phenomena in the very early universe produced an excess of baryons/leptons
- ➡ One scenario for this, electroweak baryogenesis, will be tested (eliminated?) at LHC and ILC
- ➡ Another scenario for this, leptogenesis, is strongly suggested by the same ideas that link neutrinos to unification

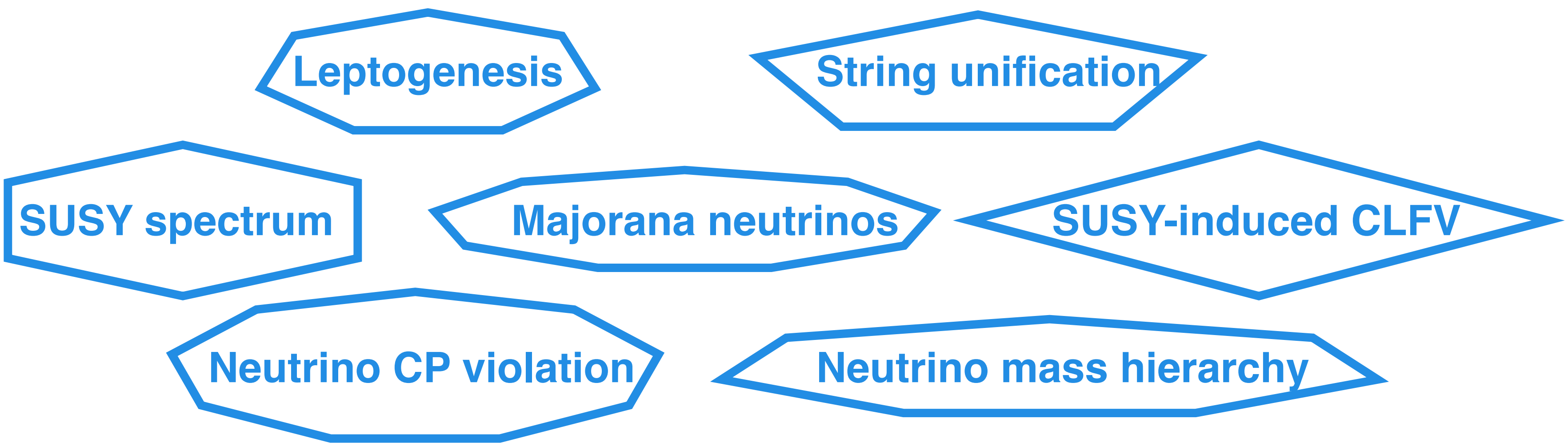
8. How did the universe come to be?

9. What happened to the antimatter?

- ➡ Caveat: we do not know how to make *all* the measurements that would be required to verify a detailed leptogenesis theory at ~10^9 to 10^15 GeV
- ➡ But we *do* know how to make a series of measurements that will tell us if we are on the right track, and discriminate between many different scenarios
- ➡ We should not be shy about pushing this as a major priority for particle physics, with equally important ties to cosmology

DO WE ALL COME FROM NEUTRINOS?

- Neutrino discoveries make leptogenesis seem an increasingly likely possibility
- Leptogenesis is tied up with the even bigger question of unification
- The discovery of SUSY + verification of the neutrino see-saw would provide an obvious source for lepton flavor violation (CLFV), as well as a telescope to unification scale
- Can we put all the pieces of this story together?



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