Low Energy Tests of High Energy Theory: An Overview

Marjorie Shapiro

Jan 24, 2025

Outline

- Why expect new physics?
- What are the important unanswered questions?
- What theories might answer these questions?
- What experimental measurement can confront these theories?

  NB: This talk only covers a small subset of the interesting measurements

Unanswered Questions

- With discovery of the Higgs, SM looks complete
- Aside from ν-mass data appears consistent with SM
- But, there are many unanswered questions:
  - What is Dark Matter?
  - Where did all the antimatter go?
  - Why is the EW scale so low (relative to Planck scale)?
  - Why 3 generations?
  - Do all the forces unify?
  - What about gravity?

Answers to these questions lie outside the SM

Searching for the new: What should we look for?

- Many extensions to the SM have been proposed
- Before LHC turn-on weak-scale SUSY was by far the most popular
- Absence of evidence for SUSY has changed the landscape
  - Searches continue, but must explore a wider range of possibilities
- Perhaps it is better to view theoretical models as sign-posts that indicate possible signatures for new physics
- In the past many of the most important discoveries were totally unexpected and not based on theoretical models
  - Michaleson-Morley
  - Discovery of the muon
  - Parity and CP violation

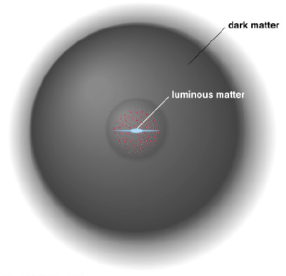
Any time we can search for new phenomena with signficantly better precision than past measurements, we should do so!

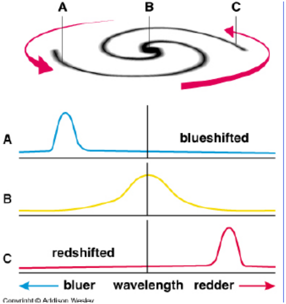
Searching for the new: How should we look?

- Possible strategies include:
  - Creation of new particles in high energy collisions
    - Not the topic of this semester's 290e
  - Direct observation of new particles that exist around us
    - eg Dark Matter searches
  - Searches for violations of global symmetries such as
    - Lepton flavor violation
    - Unexpected sources of P or CP violation
  - Precision measurements sensitive to loop corrections from new particles
    - eg $g-2$ of the μ or e
  - Searches for new or unexplained phenomena
    - Tests of GR
    - Time dependence of fundamental constants
- Use the unanswered questions as a springboard for discussion
  - BSM extensions provide possible explanations
  - These theories suggest experimental strategies
- Measurements can be interpreted using different models and often address more than one question

Question #1: What is Dark Matter?

- Strong evidence exists that there is matter in Universe that doesn't shine
- Distribution of this matter is different from the luminous stuff
- Many independent observations using different techniques
- Among the most important are:
  - Study of rotation curves in galaxies and in clusters of galaxies
  - Measurements of temperature of hot gas in clusters
  - Gravitational lensing
  - Baryon acoustic oscillations





Is it a particle? What kind?

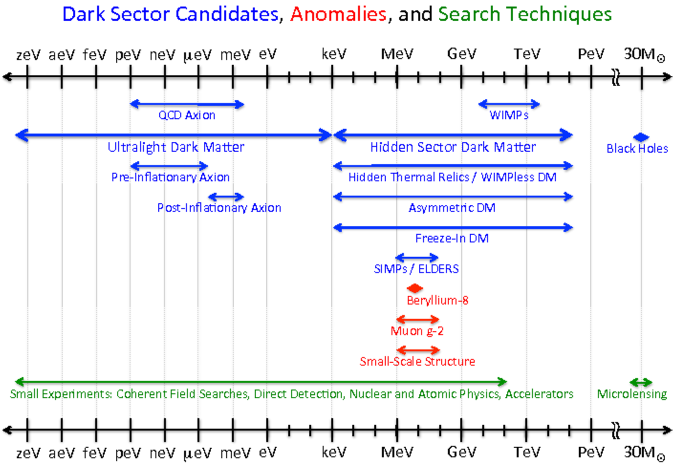
- BBN suggests that the DM is non-relativistic
- Gravitational lensing searches rule out massive dark baryonic DM
- A common model: Assume particles in thermal equilibrium
  - DM particles can annihilate and can pair produce
  - Freeze out occurs when annihilation rate ≈ expansion rate
  - Can calculate DM density

$$\Omega_X \propto \frac{1}{\sigma v} \propto \frac{M_X}{g_X^4}$$

  - Using observed DM density if $m_X \sim 100$ GeV and $g_x \sim 0.6$ then the predicted $\Omega_X \sim 0.1$
  - Weakly interacting particles with masses in the 100 GeV range give about the right Ω: *The WIMP Miracle*
- One possible WIMP particle: SUSY LSP

Many experimental searches for such WIMPs, not limited to SUSY scenarios

But WIMPs are not the only possibility



arXiv:1707.04591FERMILAB-CONF-17-282-AE-PPD-T

Dan will cover this topic in his talk Feb 7

Question #2: What drives the Universe's matter-antimatter asymmetry?

- The universe is made largely of matter with very little antimatter

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-9}$$

Why is this the case?

- Matter dominance occured during early evolution of the Universe
- Assume Big Bang produces equal numbers of B and $\overline{B}$
- At high temperature, baryons in thermal equilibrium with photons

$$\gamma + \gamma \leftrightarrow p + \overline{p}$$

- Temperature and mean energy of photons decrease as Universe expands
  - Forward reaction ceases
  - Baryon density becomes low and thus backward reaction rare
  - Number of B and $\overline{B}$ becomes fixed

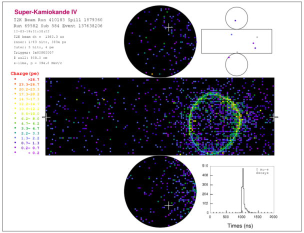
  "Big-Bang" baryogenesis
- Need a mechanism to explain the observed matter-antimatter asymmetry

The Sakharov Conditions

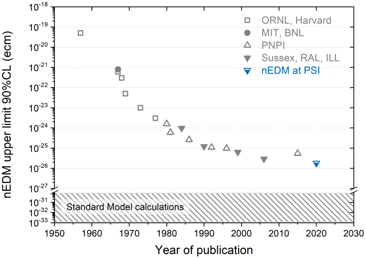
- Sakharov (1967) showed that 3 conditions needed for a baryon dominated Universe
    1. A least one B-number violating process so $N_B - N_{\overline{B}}$ is not constant
    2. C and CP violation (otherwise, for every reaction giving more B there would be one giving more $\overline{B}$)
    3. Deviation from thermal equilibrium (otherwise, each reaction would be balanced by inverse reaction)
- Is this possible?
    - Options exist for $\#1$
    - $\#3$ will occur during phase transitions as temperature falls below mass of relevant particles (bubbles)
    - $\#2$ is an active area of research
        - CP violation in SM comes from imaginary phase in CKM matrix
        - CKM phase well measured in K and B decays: Resulting CP violation not large enough
        - Many BSM sources of CP violation proposed, but still no experimental evidence for any of them
        - Searches for CP violating effects in any and all systems are interesting, as long as they have adequate sensitivity

Some examples of measurements sensitive to BSM CP Violation

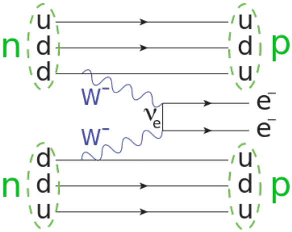
ν-Oscillations



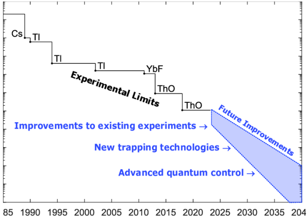
Neutrino EDM



New phases if ν are Majorana

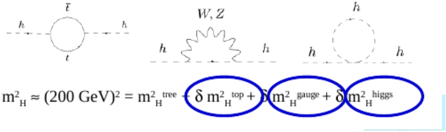


Electron EDM

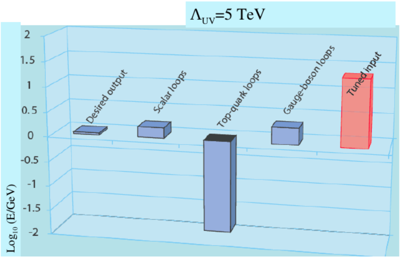


Question #3: The Hierarchy Problem

- Why is the EWK scale so low?
- Assume no new physics up to a scale Λ
  - Suppose that scale is M_{Planck}
  - Radiative corections force Higgs mass up: $m_h \sim M_{Planck}$
- Need "finetuned" cancellation between diagrams
- Can be solved by presence of new particles at TeV scale
  - Tuning already $\sim 1\%$ for $\Lambda \sim 10$ TeV



$$m^2_H \approx (200\ \text{GeV})^2 = m^2_{H}{}^{\text{tree}} + \boxed{\delta m^2_{H}{}^{\text{top}}} + \boxed{\delta m^2_{H}{}^{\text{gauge}}} + \boxed{\delta m^2_{H}{}^{\text{higgs}}}$$



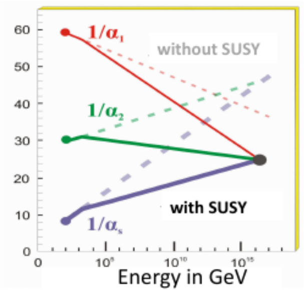
Possible Solutions to the Hierarchy Problem

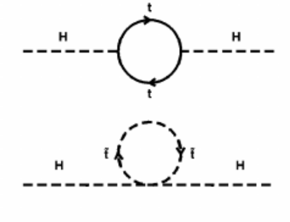
- Solution #1: a composite Higgs
  - Higgs a bound state (eg due to new extra strong interaction)
- Solution #2: Supersymmetry (SUSY)
  - Partner for every SM particle with spin that differs by $\frac{1}{2}$
- Solution #3: "little Higgs"
  - Ultimate theory with scale well above EW scale with Higgs as "pseudo goldstone boson." Effective theory valide up to ~ 10 TeV or higher
- Solution #4: Extra Dimensions
  - Brings Planck scale down to EW scale
  - Gravity propagates in all dimensions, SM in 3

All these solutions demand presence of new particles

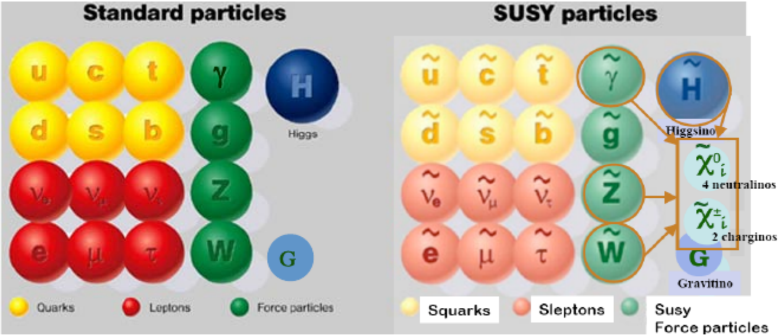
How SUSY can solve the some problems of SM

- Each SM particle gets a partner differing in spin by 1/2
- Unification of forces possible
  - SUSY changes running of coupling constants
- Dark matter candidate exits
  - Lightest neutral partner of gauge bosons (or higgs)
- Little fine-tuning required
  - Cancellation of fermion and sfermion loops
  - SUSY particle masses must not be too high for this to work ($\approx$ TeV scale)



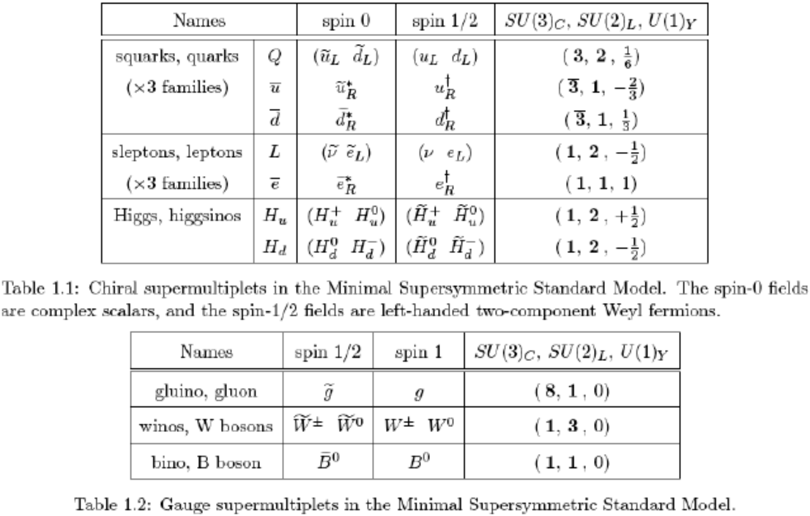


Supersymmetry: Overview



- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squark, selectron, smuon, ...): spin 0
    - **gauginos** (chargino, neutralino, gluino,...): spin 1/2

Supersymmetry: The Particles



Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\, \mathbf{2}\,,\, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\, \mathbf{1},\, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\, \mathbf{1},\, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\, \mathbf{1},\, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, -\frac{1}{2})$

Table 1.1: Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\, \mathbf{1}\,,\, 0)$
winos, W bosons	$\widetilde{W}^\pm \;\; \widetilde{W}^0$	$W^\pm \;\; W^0$	$(\,\mathbf{1},\, \mathbf{3}\,,\, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\, \mathbf{1}\,,\, 0)$

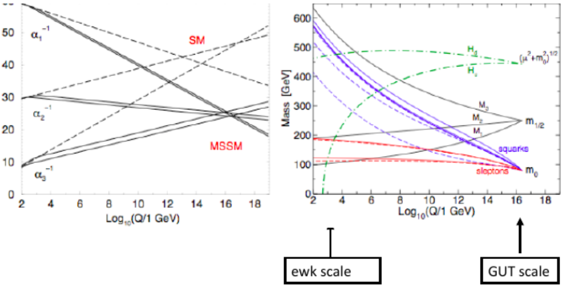
Table 1.2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

SUSY Breaking

- If SUSY was a good symmetry, the particles and sparticles would have the same mass
- We have not seen selectrons, squarks, etc, so if they exist their masses must be large
  - SUSY must be a broken symmetry
- Not clear what mechanism breaks SUSY. Many possibilities
  - Phenomenology changes drastically depending on mechanism for SUSY breaking
  - Breaking occurs in some "hidden sector" that does only couples very weakly to "visible sector" of SM and SUSY particles

Lot's of options for new physics in the SUSY breaking mechanism

How the SUSY particles develop their different masses

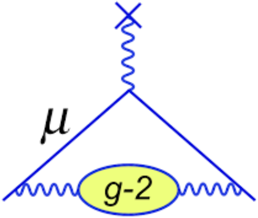


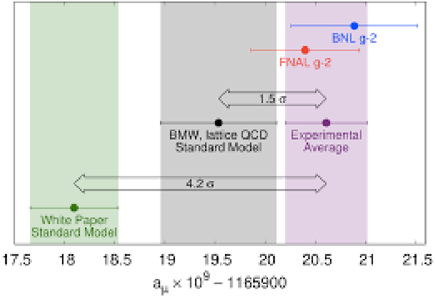
- Depends on SUSY breaking mechanism. This is one example.
- Assume Grand Unified (GUT) scale where all spin 0 sparticles have one mass and all spin 1/2 sparticles has one mass
- Masses evolve with scale (use renormalization group equations to calculate the running of the masses)
- Weakly coupled particles are the lightest

How do we search for SUSY?

- Precision measurements of SM Observables
  - eg, $g-2$ of the muon
- Enhancement in rare decays
  - eg $\mu \to e\gamma$
- Observation of a Dark Matter candidate with the right properties
  - eg WIMP
- Direct production at colliders
  - Eg the LHC

Muon $g-2$ and SUSY



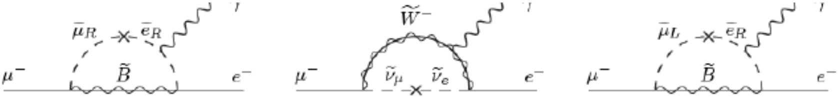


- Exquisite experimental precision

$$a_\mu = 0.00116592059(22)$$

- Experimental resul 5.1σ from 2020 SM theory predictions
- However, new lattice calculations much closer to experiment
- Theoretical issues must be resolved before any conclusion can be drawn

Rare Decays: $\mu \to e\gamma$



(a) (b) (c)

Figure 6.6: Some of the diagrams that contribute to the process $\mu^- \to e^-\gamma$ in models with lepton flavor-violating soft supersymmetry breaking parameters (indicated by ×). Diagrams (a), (b), and (c) contribute to constraints on the off-diagonal elements of $\mathbf{m}^2_{\bar{\mathbf{e}}}$, $\mathbf{m}^2_{\mathbf{L}}$, and $\mathbf{a}_{\mathbf{e}}$, respectively.

$$\mathrm{Br}(\mu \to e\gamma) \;=\; \left(\frac{|m^2_{\tilde{\bar{\mu}}_R^* \tilde{\bar{e}}_R}|}{m^2_{\tilde{\bar{\ell}}_R}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{\bar{\ell}}_R}}\right)^4 10^{-6} \times \begin{cases} 15 & \text{for } m_{\tilde{B}} \ll m_{\tilde{\bar{\ell}}_R}, \\ 5.6 & \text{for } m_{\tilde{B}} = 0.5 m_{\tilde{\bar{\ell}}_R}, \\ 1.4 & \text{for } m_{\tilde{B}} = m_{\tilde{\bar{\ell}}_R}, \\ 0.13 & \text{for } m_{\tilde{B}} = 2 m_{\tilde{\bar{\ell}}_R}, \end{cases}$$

- Experimental limit from MEG at PSI $BR < 1.2 \times 10^{-11}$
- Mu2e at FNAL plans improvement of 4 orders of magnitude
- Experiments also proposed or underway at PSI and in Japan

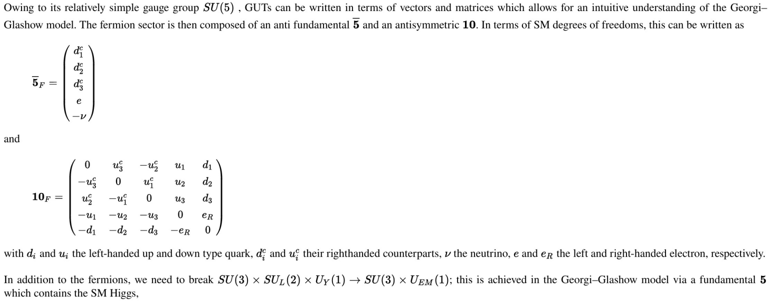
Question #4: Is there a simple theory that unifies all the SM forces?

- SM built on the gauge group $SU(3) \times SU(2)_L \times U(1)$
  - 19 parameters: 3 coupling constants, 9 charged fermion masses, 4 CKM parameters, Higgs mass and quartic coupling, and θ_{QCD}
  - No fundamental explanation of why the number of quark and lepton families are the same
- One possible solution: Embed the SM group into a larger group where quarks and leptons exist within the same multiplets
  - Larger group $\Rightarrow$ more gauge bososn
  - These bosons mediate new interactions, eg between leptons and quarks
  - If these bosons are heavy, effect on current measurements small
  - Boson masses must be generated dynamically (as were those of the W and Z) to ensure gauge invariance
- At high energy, theory has a smaller number of parameters than the SM
  - Running of couplings and masses from high to low energy introduces splittings
- Many choice of gauge group and fermion representation possible

  Simplest option: minimal SU(5), the Georgi-Glashow model, has been ruled out due to its prediction of a proton lifetime of $< 10^{31}$ years

Minimal SU(5)

- Although minimal SU(5) experimentally excluded, it provides a simple example of how GUTs work
- Gauge group: SU(5)
- Fermion representation: $\mathbf{10}$ and $\overline{\mathbf{5}}$ multiplets for each generation



Owing to its relatively simple gauge group $SU(5)$, GUTs can be written in terms of vectors and matrices which allows for an intuitive understanding of the Georgi–Glashow model. The fermion sector is then composed of an anti fundamental $\overline{\mathbf{5}}$ and an antisymmetric $\mathbf{10}$. In terms of SM degrees of freedoms, this can be written as

$$\overline{\mathbf{5}}_F = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix}$$

and

$$\mathbf{10}_F = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e_R \\ -d_1 & -d_2 & -d_3 & -e_R & 0 \end{pmatrix}$$

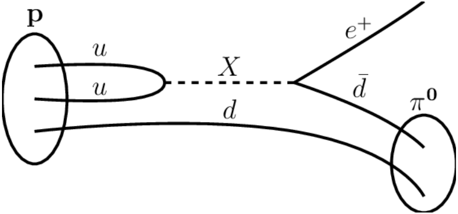
with d_i and u_i the left-handed up and down type quark, d_i^c and u_i^c their righthanded counterparts, ν the neutrino, e and e_R the left and right-handed electron, respectively.

In addition to the fermions, we need to break $SU(3) \times SU_L(2) \times U_Y(1) \rightarrow SU(3) \times U_{EM}(1)$; this is achieved in the Georgi–Glashow model via a fundamental $\mathbf{5}$ which contains the SM Higgs,

- SU(5) has 24 generators, so there 12 new gauge bosons (called X and Y bosons)
- Larger groups and/or introduction of SUSY increases the number of new boson fields

GUTs and proton decay

- Proton decay mediated by exchange of X bosons
- In SU(5), dominant decay mode: $p \to e^+\pi^0$



- In other GUTs, alternative decay modes possible (eg involving kaons)
- In general, because quarks and leptons are in the same multiplets, the new bosons will mediate proton decay
  - High mass of the new bosons is why the lifetime is long

$$\tau \propto \frac{1}{M_x^2}$$

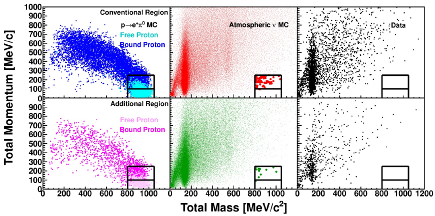
Searching for proton decay

- Long lifetime of proton means we need lots of matter to see any decays
- Large detectors such as those build to study solar and atmospheric ν are ideal
- Most stringent limits $\ell + \pi^0$ modes come from Super-K
- Limits at 90% cl

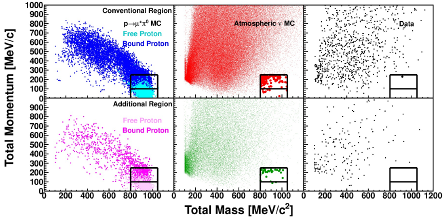
$$\begin{aligned} \tau/BR(p \to e^+\pi^0) &> 2.4 \times 10^{34}\ \mathrm{yr} \\ \tau/BR(p \to e^+\pi^0) &> 1.6 \times 10^{34}\ \mathrm{yr} \end{aligned}$$

- Next generation ν-oscillation experiments will push the limits down (or observe something)

$$p \to e^+\pi^0$$



$$p \to \mu^+\pi^0$$



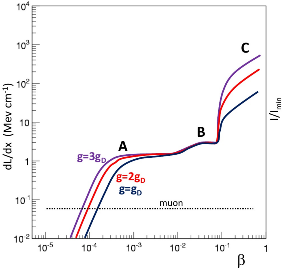
GUTs and monopoles

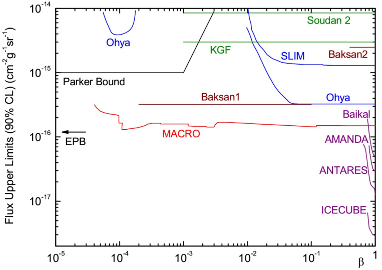
- “Topological defects” in broken GUTs can produce monopoles
- Experimental observation would rely on detecting their energy loss in matter
- Searches performed both at accelerators and in matter
- These searches also sensitive to other sources of highly ionizing particles
  - eg, massive particles with low velocity but high momentum
  - Sensitive to very heavy Dark Matter

GUTs and monopoles

TABLE I: Flux upper limits for GUT and Intermediate Mass Monopoles from different experiments, assuming $g = g_D$.

Experiment (Ref)	Mass Range (GeV/c^2)	β range	Flux Upper Limit ($cm^{-2}\ s^{-1}\ sr^{-1}$)	Detection Technique
AMANDA II Upgoing [69]	$10^{11} - 10^{14}$	$0.76 - 1$	$(8.8 - 0.38) \times 10^{-16}$	Ice Cherenkov
AMANDA II Downgoing [69]	$10^{8} - 10^{14}$	$0.8 - 1$	$(17 - 2.9) \times 10^{-16}$	Ice Cherenkov
IceCube [71]	$10^{8} - 10^{14}$	$0.8 - 1$	$(5.6 - 3.4) \times 10^{-18}$	Ice Cherenkov
Baikal [68]	$10^{7} - 10^{14}$	$0.8 - 1$	$(1.83 - 0.46) \times 10^{-16}$	Water Cherenkov
ANTARES [70]	$10^{7} - 10^{14}$	$0.625 - 1$	$(9.1 - 1.3) \times 10^{-17}$	Water Cherenkov
MACRO [63]	$5 \times 10^{8} - 5 \times 10^{13}$	$> 5 \times 10^{-2}$	3×10^{-16}	Scint.+Stream.+NTDs
MACRO [63]	$> 5 \times 10^{13}$	$> 4 \times 10^{-5}$	1.4×10^{-16}	Scint.+Stream.+NTDs
Soudan 2 [66]	$10^{8} - 10^{13}$	$> 2 \times 10^{-3}$	8.7×10^{-15}	Gas drift tubes
OHYA [64]	$5 \times 10^{7} - 5 \times 10^{13}$	$> 5 \times 10^{-2}$	6.4×10^{-16}	Plastic NTDs
OHYA [64]	$> 5 \times 10^{13}$	$> 3 \times 10^{-2}$	3.2×10^{-16}	Plastic NTDs
SLIM [62]	$10^{5} - 5 \times 10^{13}$	$> 3 \times 10^{-2}$	1.3×10^{-15}	Plastic NTDs
SLIM [62]	$> 5 \times 10^{13}$	$> 4 \times 10^{-5}$	0.65×10^{-15}	Plastic NTDs
Induction, combined [9]	$> 10^{5}$	any	4×10^{-13}	Induction





Annu. Rev. Nucl. Part. Sci. 2015. 65:279

Question #5: What about gravity?

- Spin-2 nature of graviton has precluded its inclusion into the SM
- Need to use string theory at energy scales where gravity becomes strong
- Can ask whether their are new interactions that modify Einstein's equatios
- Tests include
  - Fifth force tests (deviations from $1/r^2$)
  - Equivalence principle tests
  - Studies involving gravitational waves

We'll hear more from Shimon Kolkowitz in a few weeks

Conclusions

- Good reasons to believe there is physics beyond the Standard Model
- May possible extensions exist
- To cover the possibilities, a wide variety of techniques are needed
- Lot's of room for clever ideas and new strategies
- This semester should give everyone lots to think about

Sign-up for you half hour talk