Course Philosophy and Plan

- Experimentalist-oriented research seminar
  - Think like a working experimentalist
    - What are the interesting problems?
    - What are the basic aspects of the theory that provide a framework for understanding what is useful to measure?
    - What can we go out and measure, and, most importantly, how do we do it?
  - Mishmash of interesting topics -- incoherent, but interesting
  - Focus on basic understanding and picking out important science points.
    Take a 200-level course for detailed derivations.
- Not a typical course!
  - Not problem-set driven
  - Not 1-way! Need lots of discussion! Like research group seminar
  - I've picked topics that I personally want to learn more about, and I don't claim a great deal of expertise in them

Topic Choice

- Focus is on "new physics"
- Three kinds of topics we will cover
  - "Nonperturbative" new physics -- manifests itself in new particles, new phenomena, etc. that we can go out and search for.
    - Dark matter
    - Neutrino oscillations
  - "Perturbative" new physics -- precision measurements that can show up hints of new physics in "old" measurements, many not using conventional techniques
    - Electron and neutron electric dipole moments
    - Muon g-2
    - neutrino magnetic moment
    - precision gravity measurements
  - Particles in astrophysics
    - Not really "new physics", but trying to understand extremely energetic astrophysical phenomena through techniques of particle physics.

Standard Model Review

- Fundamental Matter Fields: spin-1/2 fermions
  - quarks and charged leptons appear to be Dirac fields
  - massiveness of these fields and observed behavior implies there are right-handed and left-handed particles and antiparticles

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2				Quarks spin = 1/2			
Flavor		Mass GeV/c^2	Electric charge	Flavor		Approx. Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0	u	up	0.003	2/3
e	electron	0.000511	–1	d	down	0.006	–1/3
ν_μ	muon neutrino	<0.0002	0	c	charm	1.3	2/3
μ	muon	0.106	–1	s	strange	0.1	–1/3
ν_τ	tau neutrino	<0.02	0	t	top	175	2/3
τ	tau	1.7771	–1	b	bottom	4.3	–1/3

  - massiveness of neutrinos has been established; but has not been established whether they are Dirac or Majorana particles (Majorana: particle is its own antiparticle, lives in 2-element Weyl spinor, not 4-element Dirac spinor)

Standard Model Review

- Fundamental Global (Noether) Symmetries of Fermionic Lagrangian
  - U(1) complex phase symmetry: any field can be rotated by a complex phase and the Lagrangian is left unchanged
  - SU(2) weak isospin symmetry:
    - Left-handed fermionic fields appear to live in SU(2) doublets aligned with their interactions via the weak force. Rotations by SU(2) matrices leave the Lagrangian unchanged. These pairings imply that elements of a SU(2) doublet are connected by an interaction.
      - u_L and d_L are the two components of a 2-element spinor and connected via beta decay: $n \rightarrow p + e^- + \text{anti-}\nu_e$ is fundamentally $d_L \rightarrow u_L + e_L^- + \text{anti-}\nu_{eR}$
      - Similarly for leptons: μ^-_L and $\nu_{\mu L}$ are a doublet, as seen in muon decay $\mu^-_L \rightarrow \nu_{\mu L} + e^-_L + \text{anti-}\nu_{eR}$
    - Right-handed fields are singlets under this rotation -- i.e., u_R and d_R don't rotate into each other, and thus are not subject to the interaction.
    - The distinction between *L* and *R* fields is lost in most cases since Dirac mass terms connect them (propagating states are mixtures of *L* and *R*). But there may yet be a distinction for neutrinos (are there ν_R?)
  - SU(3) strong symmetry
    - Quarks are labeled by *color* (red, green, blue) and form multiplets under SU(3) rotations, meaning the different colors are connected by strong interactions. All leptons are SU(3) singlets.

Standard Model Review

- Global symmetries are made into local (gauge) symmetries
  - i.e., allow the "rotation angle" of these rotations to be position dependent, and require that Lagrangian remain invariant
  - Requires introduction of new fields with specific transformation properties under the symmetries to cancel the terms that appear due to derivatives of the spatial dependence of the rotation parameter:
    - U(1) x SU(2) give four fields: the γ, the Z^0, and the $W^{\pm}$.
    - SU(3) gives the 8 gluon fields, g
    - The fields are all Lorentz 4-vectors and also have nontrivial rotation under U(1), SU(2), and SU(3) (except the photon): the vector gauge bosons.
  - Their appearance in the Lagrangian makes it clear these are the fields that "mediate" interactions, meaning that every time there is a term in the Lagrangian that has fields of two different kinds, these additional fields are also there.
  - Mass terms not gauge invariant unless introduced via Higgs mechanism
    - Introduce scalar Higgs field with potential that makes its expectation value nonzero.
    - Higgs couplings to other particles ("Yukawa couplings") then imply mass when H takes on nonzero vev.
  - Neutrino sector still unsettled, but neutrino oscillations can be accomodated in slightly modified SM

Standard Model Review

- Origin of mass
  - Normal fermionic and gauge boson mass terms do not satisfy gauge symmetries.
    - But they have to be there -- we know all fermions and the Z^0 and $W^{\pm}$ are massive.
  - Higgs mechanism allows introduction of gauge-invariant mass terms.
    - Introduce scalar Higgs field with potential that makes its expectation value nonzero.
    - Introduce terms that include Higgs and other particles: these couple the Higgs to the other particles ("Yukawa couplings").
    - These Yukawa couplings are easily made gauge-invariant.
    - Expand H above vev: the constant term yields mass terms that are gauge-invariant (due to additional gauge properties of H) and the 1st-order terms yield interactions between the Higgs and other particles.
  - Neutrino sector still unsettled, but neutrino oscillations can be accomodated in slightly modified SM; just need to know whether neutrinos are Dirac or Majorana measure the "mixing matrix" -- relation between weak-isospin states and freely propagating states.

Review of Spinors

- Non-relativistic spin-1/2 particles described by Pauli spinors (Ph125):

$$\phi = \begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix}$$

- One can't write a relativistically covariant Lagrangian using only Pauli spinors; Dirac was forced to expand to 4-component (Dirac) spinors:

$$\psi = \begin{pmatrix} c_{+\uparrow} \\ c_{+\downarrow} \\ c_{-\uparrow} \\ c_{-\downarrow} \end{pmatrix}$$

- He wrote a Lagrangian

$$\mathcal{L}_{Dirac} = \overline{\psi}\left(i\gamma^\mu \partial_\mu - m\right)\psi$$

with $\quad \gamma^0 = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & -\mathbf{1} \end{pmatrix} \quad \gamma^i = \begin{pmatrix} \mathbf{0} & \sigma_i \\ -\sigma_i & \mathbf{0} \end{pmatrix} \quad \overline{\psi} = \psi^\dagger \gamma^0$

$$\mathbf{1} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \mathbf{0} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \quad \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Review of Spinors

- The resulting equation of motion is the Dirac equation

$$(i\gamma^\mu \partial_\mu - m)\,\psi = 0$$

- Solutions to Dirac equation include E > 0 and E < 0; E > 0 only has c_+ components, E < 0 only c_- components; interpreted as particles and antiparticles.

Review of Spinors

- From SM point of view, more sensible to work in helicity basis.
  - Gamma matrices are only defined by anticomm relations:

$$\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu} \qquad g^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$$

  - So pick a different representation:

$$\gamma^0 = \begin{pmatrix} \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} \end{pmatrix} \qquad \gamma^i = \begin{pmatrix} \mathbf{0} & -\sigma_i \\ \sigma_i & \mathbf{0} \end{pmatrix}$$

  - Define:

$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & -\mathbf{1} \end{pmatrix}$$

$$P_L = \frac{1}{2}(1 - \gamma^5) = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix} \qquad P_R = \frac{1}{2}(1 + \gamma^5) = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}$$

  P_L and P_R clearly project top and bottom components of spinors in this rep, so write

$$\psi = \begin{pmatrix} \phi_R \\ \phi_L \end{pmatrix}$$

Review of Spinors

- Rewrite Dirac equation in this helicity representation assuming plane-wave solution $\psi(x^\mu) = \Psi e^{-ip_u x^\mu}$:
  - Dirac equation $(\gamma^\mu p_\mu - m)\,\Psi = 0$
  - Write in block form using Pauli matrices

$$\begin{pmatrix} -m & p_0 + \vec{\sigma}\cdot\vec{p} \\ p_0 - \vec{\sigma}\cdot\vec{p} & -m \end{pmatrix} \begin{pmatrix} \Phi_R \\ \Phi_L \end{pmatrix}$$

  - And write out as equations:

$$-m\Phi_R + (p_0 + \vec{\sigma}\cdot\vec{p})\,\Phi_L = 0$$
$$(p_0 - \vec{\sigma}\cdot\vec{p})\,\Phi_R - m\Phi_L = 0$$

  - Clearly, mass mixes the top and bottom halves of the Dirac spinor in this basis.
  - If particle is massless, no mixing, and $\vec{\sigma}\cdot\vec{p} = p_0$ or $\vec{\sigma}\cdot\vec{p} = -p_0$
  - Also, for massless particles, $|p_0| = |\vec{p}|$, so these massless states are pure helicity states: spin either completely along momentum direction or completely opposite. Hence the L and R labeling: they are left and right-handed states. (c.f. photon)
- So: Dirac fermions naturally split into L and R states, and mass terms mix these states.

Standard Model Lagrangian

- Fermion kinetic and mass terms

$$\mathcal{L}_{kin} = \sum_{f=1}^{n} \left[\bar{\nu}^f \, i\partial\!\!\!/ \, \nu^f + \bar{e}^f \left(i\partial\!\!\!/ - m_E^f\right) e^f + \bar{u}^f \left(i\partial\!\!\!/ - m_U^f\right) u^f + \bar{d}^f \left(i\partial\!\!\!/ - m_D^f\right) d^f\right]$$

  - massless Dirac fermion kinetic energy term $\partial\!\!\!/ = \gamma^\mu \partial_\mu$, γ^μ are Dirac matrices
  - masses are from zeroth order term in expansion of Yukawa couplings to Higgs about vacuum expectation value (see later slide)
    - Not manifestly invariant under SU(2) rotations, but presence of Higgs vev in *m* fixes it
  - assumes neutrinos are Dirac particles (unproven) and massless (wrong)
  - f = index over 3 generations
- Global symmetries → Local symmetries
  - $\partial_\mu \rightarrow D_\mu = \partial_\mu$ + terms include *A*, *W*, *g* fields to cancel the terms that appear when we apply local symmetry transformations under U(1), SU(2), SU(3)
  - Results in interactions of gauge fields and fermions

Standard Model Lagrangian

- Fermion-EM and fermion-neutral weak gauge boson interaction terms

$$\mathcal{L}_{em} = e \sum_{f=1}^{n} \left(-\bar{e}^f \, \gamma_\mu \, e^f + \frac{2}{3} \bar{u}^f \, \gamma_\mu \, u^f - \frac{1}{3} \bar{d}^f \, \gamma_\mu \, d^f \right) \, A^\mu$$

$$\begin{aligned} \mathcal{L}_n \;\; &= \;\; \frac{e}{4 \cos\theta_W \sin\theta_W} \sum_{f=1}^{n} \Big[\bar{\nu}^f \, \gamma_\mu (1 - \gamma_5) \, \nu^f + \bar{e}^f \, \gamma_\mu \left(-1 + 4 \sin^2\theta_W + \gamma_5 \right) \, e^f \\ &+ \;\; \bar{u}^f \, \gamma_\mu \left(1 - \frac{8}{3} \sin^2\theta_W - \gamma_5 \right) \, u^f + \bar{d}^f \, \gamma_\mu \left(-1 + \frac{4}{3} \sin^2\theta_W + \gamma_5 \right) \, d^f \Big] \, Z^\mu \end{aligned}$$

  - Couplings to photon based on particle electric charge, so no neutrinos in EM
  - Left-handed projection op $P_L = 1 - \gamma_5$ picks left-handed states
  - *Z* interacts with L and R *e*, *u*, and *d*, though unequally, because what we see is after a rotation away from a pure left-right basis
    - start with *B* and $W^0, W^{+/-}$; L and R pcles interact differently with B (different charges Y_L and Y_R) and only L pcles interact with $W^0, W^{+/-}$ (depending on SU(2) isospin).
    - But then construct linear superposition *A* of *B* and W^0 so L and R pcles have same interaction strength with photon *A* ($Q_L = Q_R$). Final interaction strength with *Z* is thus a linear combination of Y_L , Y_R and SU(2) isospin. Since L and R have different SU(2) isospin and different Y_L , Y_R, we have that L and R don't interact equally with Z.
    - ν is special: its Y_L, Y_R and SU(2) isospin imply R interaction with Z has zero coupling

Standard Model Lagrangian

- Fermion-charged weak gauge boson interaction terms

$$
\begin{aligned}
\mathcal{L}_c \;&=\; \frac{g}{2\sqrt{2}}\left[\sum_{f=1}^{n}\bar{\nu}^f\,\gamma^\mu(1-\gamma_5)\,e^f + \sum_{f,g=1}^{n}\bar{u}^f\,\gamma^\mu(1-\gamma_5)\,V_{fg}\,d^g\right]W^+_\mu \\
&+\; \frac{g}{2\sqrt{2}}\left[\sum_{f=1}^{n}\bar{e}^f\,\gamma^\mu(1-\gamma_5)\,\nu^f + \sum_{f,g=1}^{n}\bar{d}^f\,\gamma^\mu(1-\gamma_5)\,V^*_{fg}\,u^g\right]W^-_\mu
\end{aligned}
$$

  - Pairings into SU(2) isospinors is clear: *u*-*d* pairing, ν-e pairing
  - Completely left-handed because the original $W^{+/-}$ that interact only with L particles are not modified in any way.
    - V matrices are the quark mixing matrices (Cabibbo-Kobayashi-Maskawa, CKM): SU(2) interaction is with weak eigenstates, which are not the same as mass eigenstates (~ neutrino oscillation).
    - Doesn't affect mass and neutral interactions because V is unitary and because of pairing of quarks into SU(2) isospinors: it's a clever cancellation mechanism, called the GIM mechanism (no flavor-changing neutral currents; predicted the charm quark)
- (SU(2) matrices not explicit in above; they have already been applied and the terms split apart)

Standard Model Lagrangian

- Gauge Boson Kinetic Terms

$$
\begin{aligned}
\mathcal{L}_{YM} \quad = \quad & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}W^{+}_{\mu\nu}W^{\mu\nu}_{-} \\
& + ig\sin\theta_W \left(W^{+}_{\mu\nu}W^{\mu}_{-}A^{\nu} - W^{-}_{\mu\nu}W^{\mu}_{+}A^{\nu} + F_{\mu\nu}W^{\mu}_{+}W^{\nu}_{-}\right) \\
& + ig\cos\theta_W \left(W^{+}_{\mu\nu}W^{\mu}_{-}Z^{\nu} - W^{-}_{\mu\nu}W^{\mu}_{+}Z^{\nu} + Z_{\mu\nu}W^{\mu}_{+}W^{\nu}_{-}\right) \\
& - \frac{g^2}{2}\left(2g^{\mu\nu}g^{\rho\sigma} - g^{\mu\rho}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\rho}\right) \\
& \left[W^{+}_{\mu}W^{-}_{\nu}(A_\rho A_\sigma \sin^2\theta_W + Z_\rho Z_\sigma \cos^2\theta_W + 2A_\rho Z_\sigma \sin\theta_W\cos\theta_W) - \frac{1}{2}W^{+}_{\mu}W^{+}_{\nu}W^{-}_{\rho}W^{-}_{\sigma}\right]
\end{aligned}
$$

$$
F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu; \quad Z^{\mu\nu} = \partial^\mu Z^\nu - \partial^\nu Z^\mu; \quad W^{\mu\nu}_{\pm} = \partial^\mu W^\nu_{\pm} - \partial^\nu W^\mu_{\pm}
$$

- Remember $F^{\mu\nu}$ from EM? It gives $E^2 - B^2$ in Lagrangian, which gives rise to all the derivatives of *E* and *B* in Maxwell's equations.
- These terms are necessary for dynamics in the gauge fields.
- General principle:
  Any term that is not expressly disallowed by symmetry requirements is allowed.

Higgs Terms

- Mass terms break gauge invariance
  - Mass terms for SU(2) gauge bosons break U(1) and SU(2) invariance because they add terms under gauge transformation (are not U(1) and SU(2) rotation invariant)
  - Mass terms for fermions break SU(2) invariance because they couple L and R
- Add new particle H that couples to everything and provides mass coefficients in gauge-invariant manner
  - H needs to be complex SU(2) isodoublet (isospin 1/2) to give enough dof to make Z^0 and $W^{+/-}$ massive
  - It has a potential energy V(H) that sets its vacuum expectation value; we expand around that vev to get real dof of H. 0th order terms of the Taylor expansion provide mass coefficients.
  - Include interactions between H and fermions and gauge bosons
  - Need Higgs kinetic terms

V(H)

$$\mathcal{L}_{Higgs} = \frac{1}{2}\,\partial^\mu H\,\partial_\mu H + \left(m_W^2\,W^{\mu +}W^-_\mu + \frac{1}{2}\,m_Z^2\,Z^\mu Z_\mu\right)\left(1+\frac{H}{v}\right)^2 - \frac{1}{2}\,m_H^2\,H^2 - \lambda v H^3 - \frac{1}{4}\lambda H^4$$

$$\mathcal{L}_{Yukawa} = -\frac{H}{v}\sum_{f=1}^{n}\left(m_D^f\,\bar{d}^f d^f + m_U^f\,\bar{u}^f u^f + m_E^f\,\bar{e}^f e^f\right)$$

QCD Lagrangian

- Less and more complicated
  - SU(3) gauge invariance requires introduction of 8 fields and more complicated SU(3) rotation matrices
  - But none of the complications of mass generation: fermion masses generated by Higgs, gluons are massless

$$L_{\rm QCD} = -\frac{1}{4} F^{(a)}_{\mu\nu}\; F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q\; \gamma^\mu\; (D_\mu)_{ij}\; \psi^j_q$$

$$F^{(a)}_{\mu\nu} = \partial_\mu\; A^a_\nu - \partial_\nu\; A^a_\mu - g_s\; f_{abc}\; A^b_\mu\; A^c_\nu\;,$$

$$(D_\mu)_{ij} = \delta_{ij}\; \partial_\mu + i g_s\; \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu\;,$$

SU(3) matrices

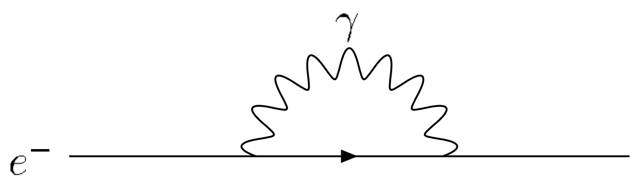
sum over a, b, c indices are implicit

Problems with the Standard Model

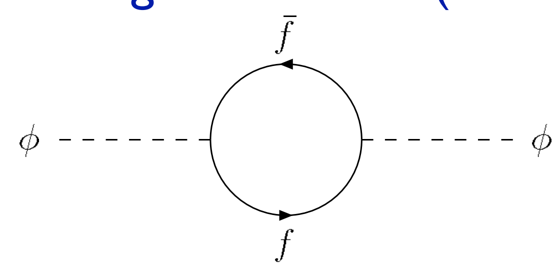
- Too many free parameters
  - There are 13 free masses in the SM without Higgs. Higgs mechanism makes these mass terms gauge-invariant, but still leaves 13 undetermined Yukawa couplings and a couple more parameters to describe the Higgs potential.
  - There are three different gauge boson coupling strengths to the matter fields (EM, weak, and strong) that do not unify at any energy scale if one only assumes SM.
  - Quark and lepton mixing matrices, including complex phases (CP violation)

Problems with the Standard Model

- Hierarchy problem: why are all the masses not M_{Pl}?
  - All particles are subject to radiative corrections to their masses (virtual loop diagrams) with loops running up to some cutoff scale Λ (= M_{Pl}?)
  - For fermions, these diagrams are divergent as $\log(\Lambda/m)$, where Λ is the cutoff energy for these loops; a single renormalization removes such divergences to all orders.



  - For gauge bosons, masslessness is protected by gauge invariance (γ and g), and massive bosons are kept light by single renorm of log corrections (I think).
  - Scalars have quadratic divergences that must be renormalized separately at each order of expansion.



  - If the Higgs goes up to M_{Pl}, then Yukawa couplings pull everyone else up.

New Physics?

- So, we hope there is some physics beyond the Standard Model that explains these problems
  - Really need a fix the hierarchy problem
  - Would be awfully nice to unify all the gauge couplings
  - Would be a bonus to explain all the masses
- How?
  - Direct searches for new particles
  - New phenomena: e.g., neutrino oscillations
  - Precision measurements of well-known phenomena that may have corrections from new particles in higher-order diagrams
  - Both can be pursued at accelerators and in non-accelerator experiments

Topic Choice

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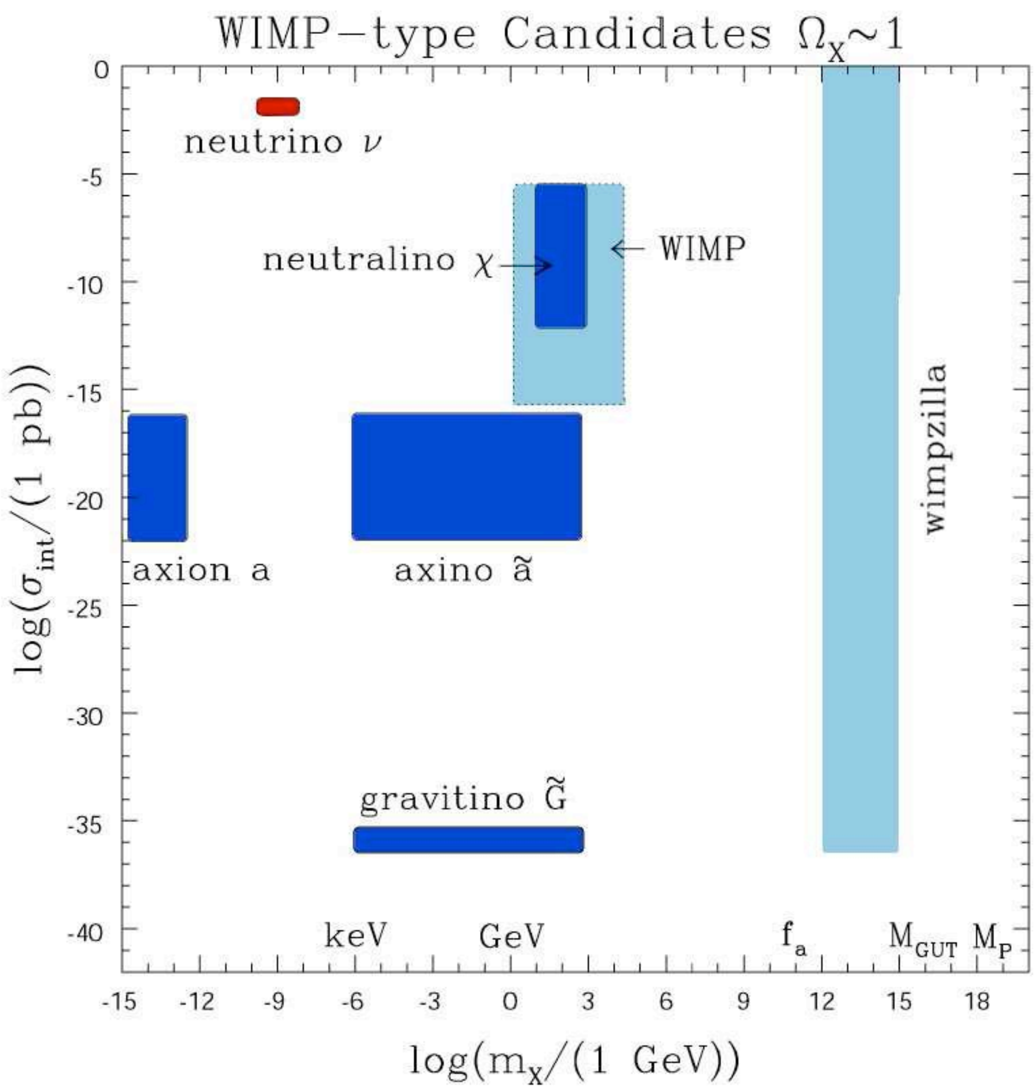
    - Dark matter
    - Neutrino oscillations
  - “Perturbative” new physics -- precision measurements that can show up hints of new physics in “old” measurements, many not using conventional techniques
    - Electron and neutron electric dipole moments
    - Muon g-2
    - neutrino magnetic moment
    - precision gravity measurements
  - Particles in astrophysics
    - Not really “new physics”, but trying to understand extremely energetic astrophysical phenomena through techniques of particle physics.

Dark Matter

- Surprising inventory of the universe:
  - 4% baryons
  - 23% non-baryonic dark matter
  - 73% "dark energy"
- Zoo of particle physics candidates
  - neutrinos, neutralinos, axions, axinos, gravitinos, primordial black holes, Q-balls, strange quark nuggets, mirror particles, CHArged Massive Particles (CHAMPs), self interacting dark matter, D-matter, cryptons, superweakly interacting dark matter, brane world dark matter, heavy fourth generation neutrinos...



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Dark Matter

- “Favored” Particle Dark Matter Candidates
  - new massive electroweak-scale particle (Weakly Interacting Massive Particle, WIMPs), e.g., neutralino from supersymmetry
    - like a massive neutrino with M ~ 100 GeV, produced thermally in the early universe
  - massive sterile neutrino produced from oscillations of non-sterile neutrinos
    - few keV mass, in some sense predicted by seesaw mechanism
  - axion
    - created to solve strong-CP-violation problem (need to set coefficient of CP-violating strong-force Lagrangian terms to zero, make the parameter dynamical)
  - axino
    - if you have an axion and supersymmetry, then you have a spin-1/2 axino, mass ~ neutralino
  - gravitino
    - spin-3/2 light, very weakly interacting prospect
  - extra-dimensional particles
    - weak interactions because they live in the higher-dimensional bulk

Detecting Dark Matter

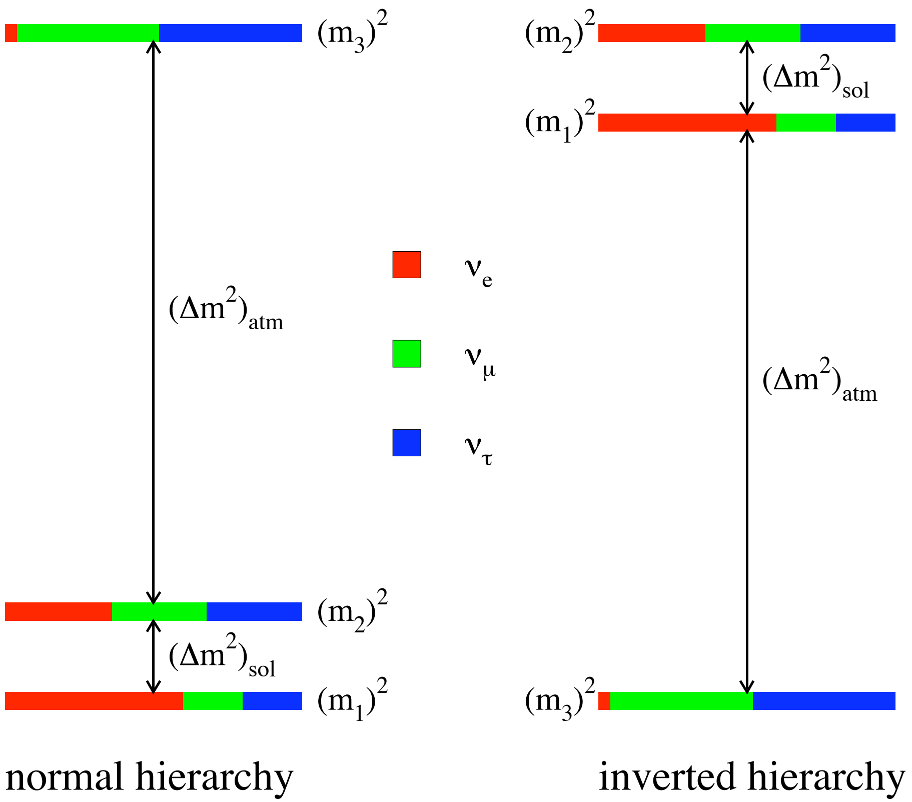
- "Favored" Particle Dark Matter Candidates
  - WIMP
    - Rare-event neutralino-scattering experiments
    - key signatures: scattering on nuclei, annual and diurnal modulation due to Earth's motion through galactic halo
  - massive sterile neutrinos
    - β decay spectrum endpoint shape
    - searches in decays of massive particles produced in collider/fixed-target experiments
    - $\beta\beta$-0ν decay
    - astrophysical evidence: X-rays, pulsar kicks, large-scale-structure power spectrum
  - axion
    - Primakoff conversion ($a + B \rightarrow \gamma$) in cavity with detection by low-noise RF receiver or Rydberg atom
    - astrophysical searches for axion decay or conversion in high-B regions
  - axino, gravitino, extra-dim particles
    - Largely undetectable?

Neutrino Oscillations

- Basic idea:
  - neutrinos are produced in weak-interaction eigenstates -- diagonal under weak interaction
  - neutrinos propagate in mass eigenstates -- those states that are diagonal under interactionless neutrino Hamiltonian
  - If there is a neutrino mass term, it's possible for these two sets of eigenstates to be different
- Oscillations
  - Just like Ph12a beat phenomenon: if you start a coupled oscillator system in a state that is not an eigenstate of the "propagation" Hamiltonian, energy sloshes between the "propagating modes"
  - Initial weak eigenstate gets turned into a state that is not a weak eigenstate: probability of detecting a different neutrino species is nonzero

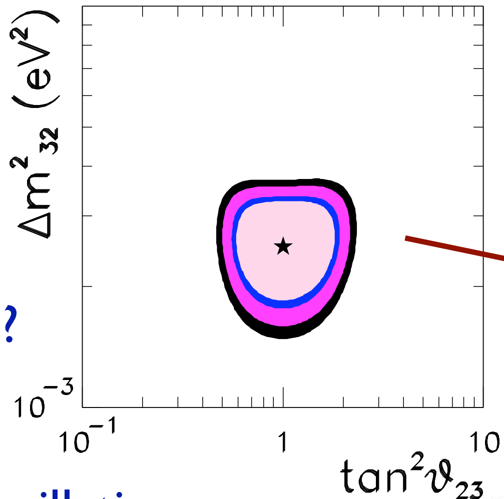
Neutrino Oscillations

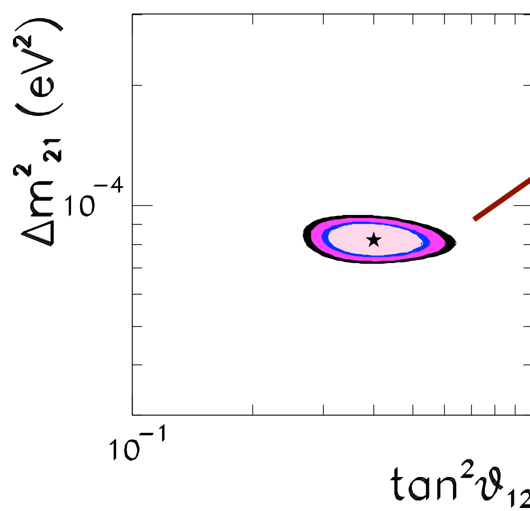
- Well established in the last decade
- Simple scheme:
  - two Δm^2 dominate
  - 1-2 leads primarily to ν_e-ν_μ oscillation
    - initially detected in solar ν_e disappearance
    - now confirmed by KamLAND reactor anti-ν_e disappearance
    - Requires "matter-enhancement" of oscillation in Sun
  - 2-3 mainly gives ν_μ-ν_τ oscillation
    - atmospheric (cosmic ray shower) ν_μ disappearance
    - K2K, MINOS: create ν_μ at accelerator, they disappear on the way to detector

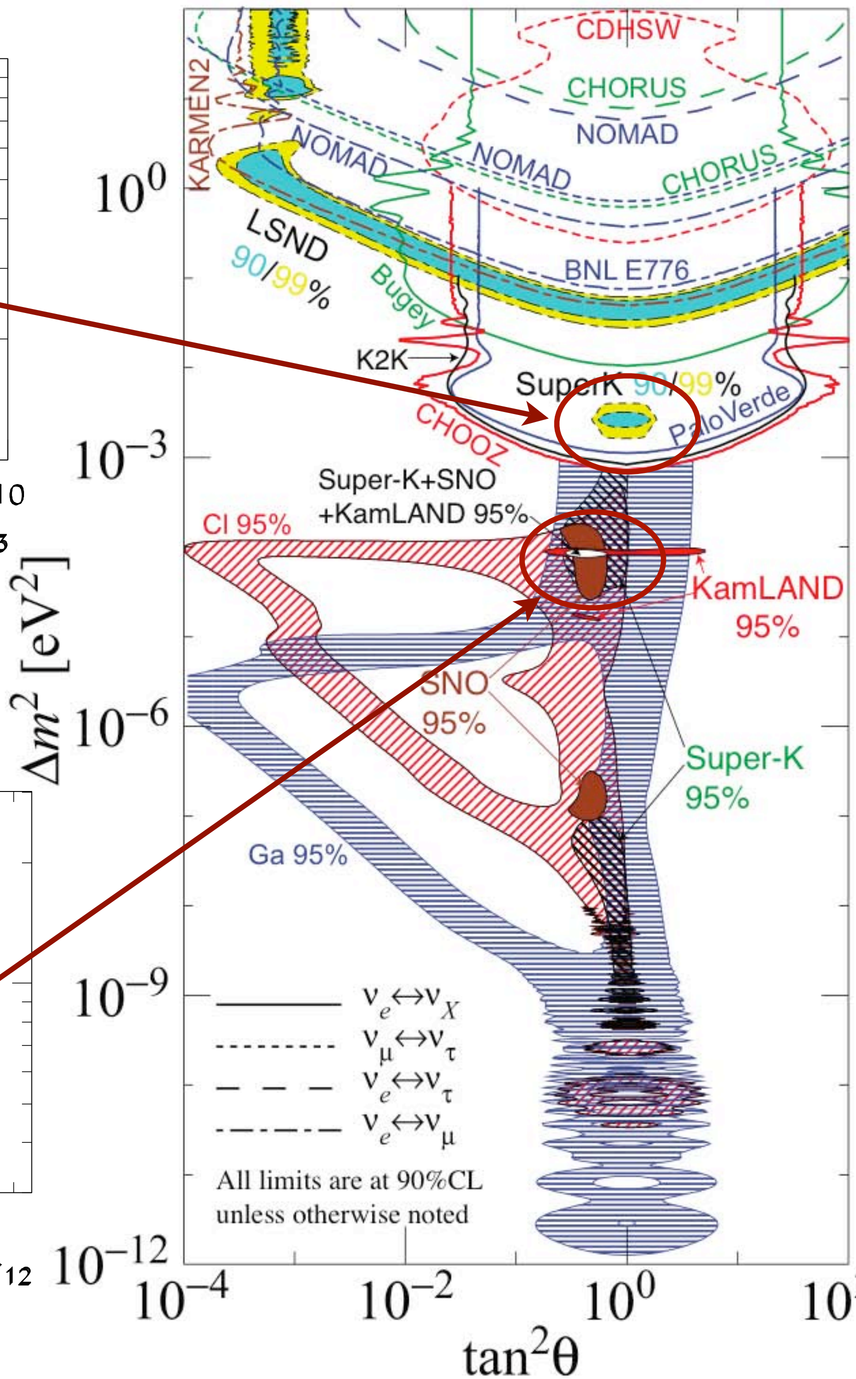


Neutrino Oscillations

- PDG summary of results
- But:
  - what about LSND? Suggests fourth (or more) sterile generation with oscillations with ν_μ
  - Being tested by MiniBoone
  - Other reasons to believe in sterile neutrinos
- Next:
  - measure 1-3 mixing to close the loop
  - CP violation in neutrino mixing?

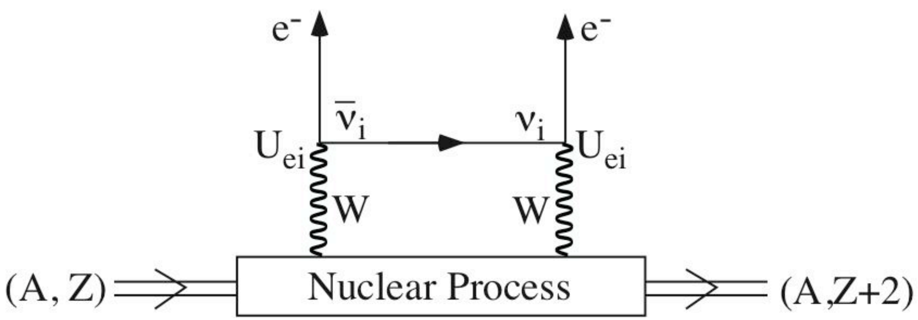






Double-Beta Decay

- Neutrino oscillations lead us to ask: how to implement neutrino mass
  - Standard model with massless ν has no ν_R and anti-ν_L, only ν_L and anti-ν_R.
  - But now we need to introduce neutrino mass
  - Dirac mass term: does not allow mixing of ν_R and ν_L: $\mathcal{L}_D = -m_D \overline{\nu}_L \nu_R + h.c.$
  - Majorana mass term does allow mixing: $\mathcal{L}_M = -m_R \overline{\nu_R^c} \nu_R + h.c.$
- How do we know which? $\beta\beta$-0ν decay
  - Majorana term allows the following process: simultaneous beta decay of two neutrons in a nucleus
  - Only possible with Majorana mass term
  - Detectable as very sharp peak due to all decay energy going into two e^- (as opposed to continuous β-decay-like spectrum of $\beta\beta$-2ν decay)



- Major efforts going into this area
  - Majorana: Ge high-resolution spectrometers
  - EXO: Liquid xenon

Electric Dipole Moments

- EDMs in point particles are inherently P and T violating
  - EDM is $\mathbf{D} = \int \mathbf{x}\rho(\mathbf{x})d^3x$
  - By this defn, EDM is clearly odd under P (moment flips direction) and even under T (no change in x or charge density)
  - But our theory of fundamental particles only assigns particles mass, charge, and spin; spin is the only vector, so EDM $\propto$ spin
  - But spin is T-odd and P-even.
- Holds for composite particles too (neutrons, protons, deuterons, etc.): intraparticle interactions would have to violate P and T to create an EDM if constituent particles do not have them.
- P invariance well-known in weak interaction, but T-breaking → CP-violation, which is existent but very small in SM
- Moreover, need to get the CP violation into the particle-γ interaction, so requires high-order diagrams (see next page)

E.g., Electron Electric Dipole Moments

- Communicating CP violation from quark sector
  - Need to go to three-loop diagrams
  - Even these fail when summed; need gluon corrections to quarks to get nonzero effect
- CP violation in lepton sector
  - Possible if CP violation in neutrino sector
  - But 1-loop and 2-loop diagrams all cancel: need 3-loop diagrams
  - But new physics (new particles) can change this. Generically:

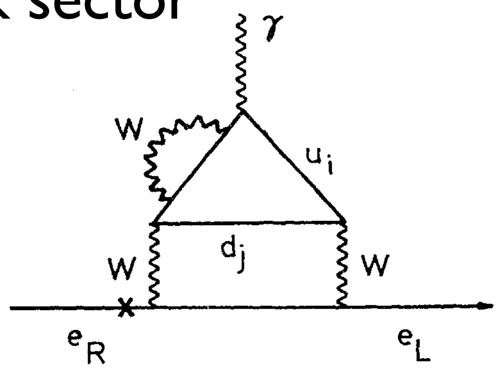


FIG. 1. An example of a three-loop quark contribution to the electron-photon vertex in the Standard Model. The cross denotes a mass insertion.

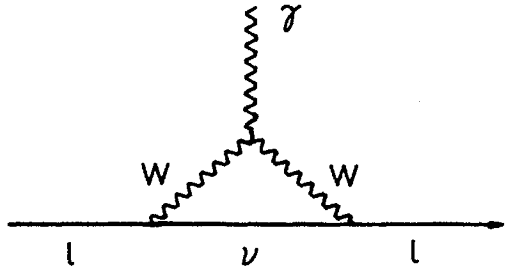


FIG. 2. One-loop Standard Model contribution to the lepton-photon vertex.

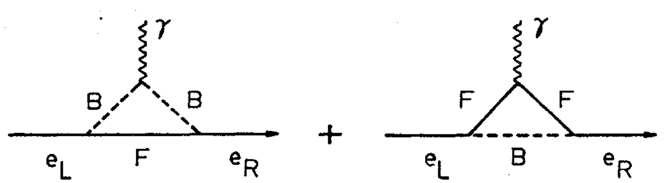
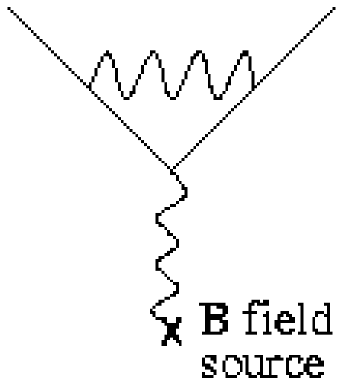


FIG. 3. Generic one-loop diagrams that can generate a nonzero EDM of the electron. *F* denotes a fermion and *B* denotes a boson of spin zero or one.

g-2

- Gyromagnetic ratio: $\mu = g\,(q/2m)\,S$ with
  - S = angular momentum
  - q = charge
  - m = mass
  - g = gyromagnetic ratio
- g = 1 for a classical charged sphere
- g = 2 for spin-1/2 particles to zeroth order
- Corrections in particle-γ interaction push g away from 2. SM first-order correction is just QED-based.
- Clearly, higher-order corrections, esp. those involving new particles, can also affect g-2.
- Muon g-2 is more sensitive to new physics because there is more energy sloshing around for creation of virtual particles in the vertex

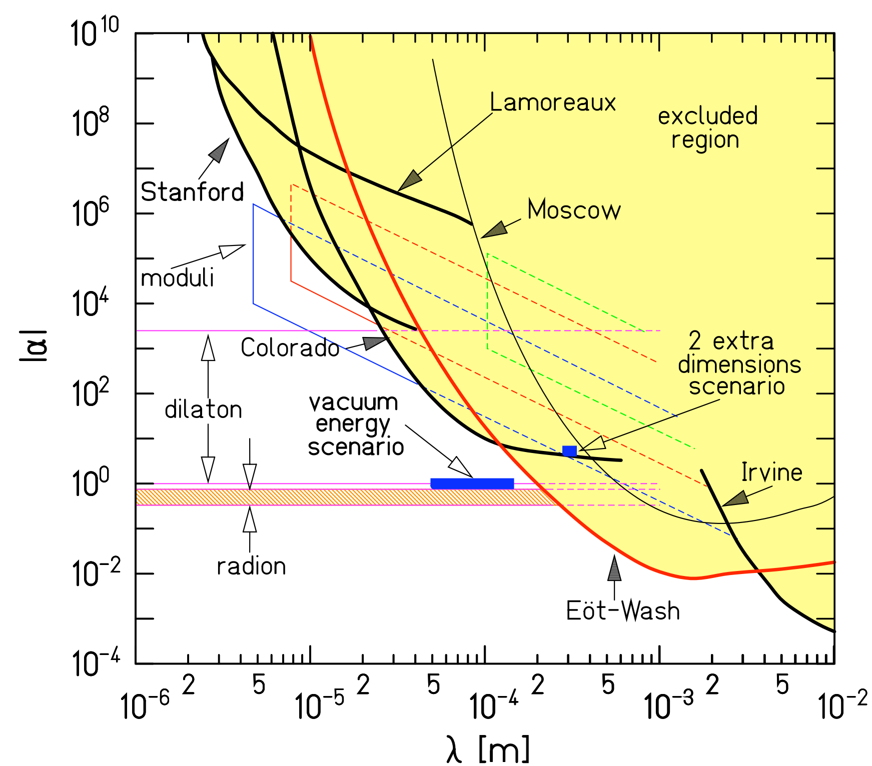


Extra Dimensions and Precision Gravity

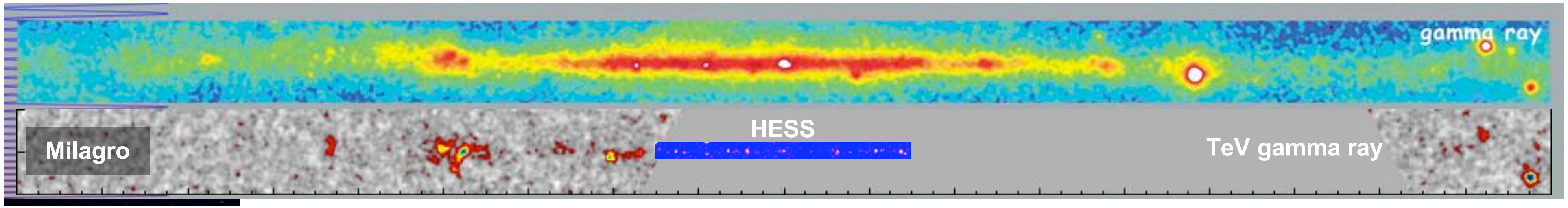
- Solving the hierarchy problem with extra dimensions:
  - extra dimensions of μm-to-mm size may explain weakness of gravity: gravity lives in all dimensions, other particles and forces live only in 3 spatial dimensions
  - brings Planck scale down to ~TeV scale: gravity is weak not because the coupling constant is weak, but because there is so much volume for its flux to live in
  - Trades hierarchy problem for problem of deciding on size of extra dimensions
- And various and sundry additional theories
- Experimentally:
  - can test by making high-precision measurements of gravity on μm-to-mm scales
  - Parameterize corrections as

$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 + \alpha \exp\left(-r/\lambda\right)\right]$$

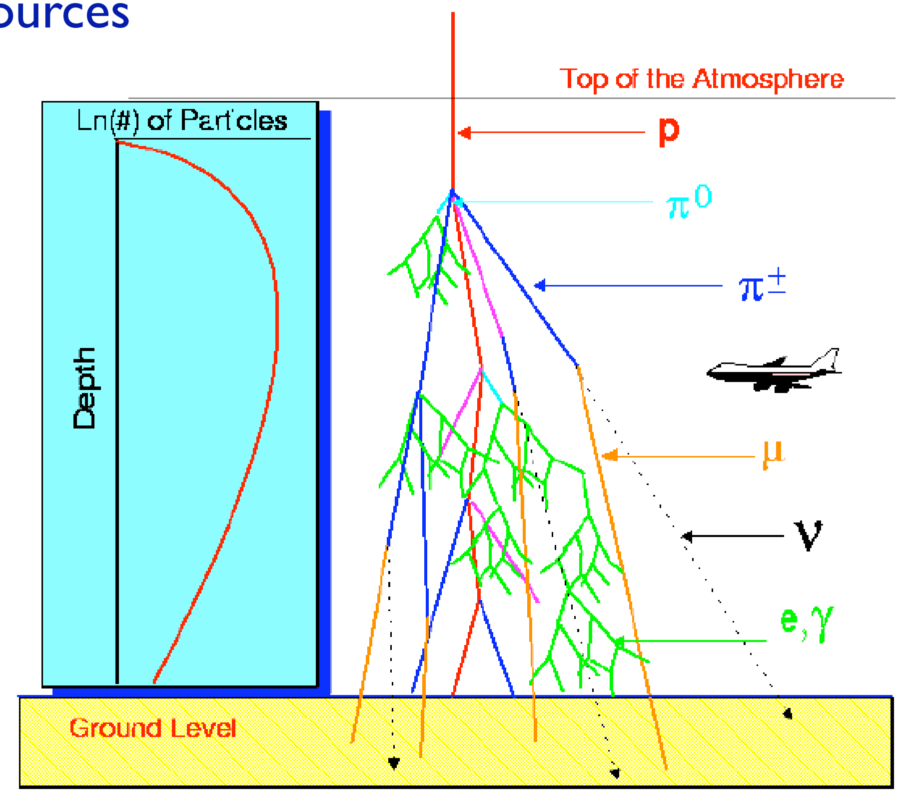
  - Some old: torsion balances
  - Some new: nanoresonators, etc.



TeV Gamma-Ray Astronomy



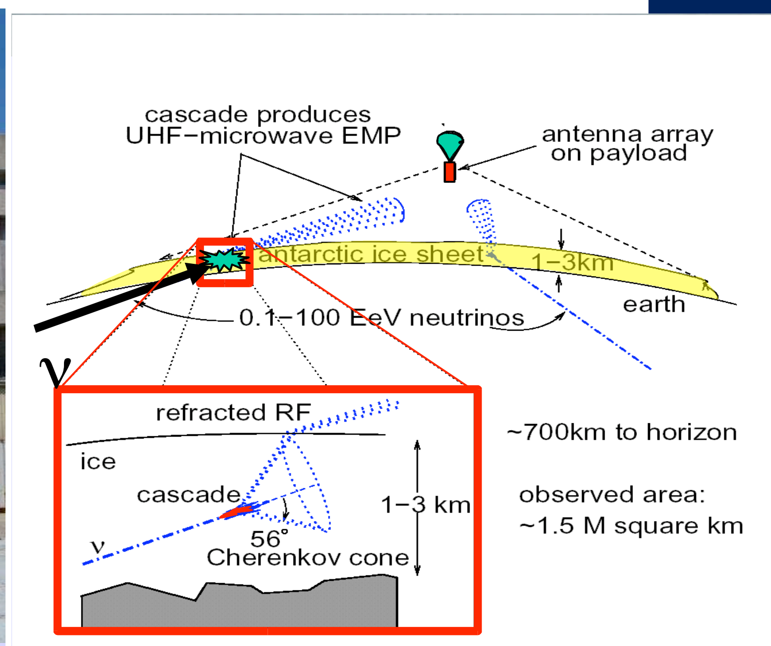
- Sources
  - Very energetic “astrophysical” photon sources
    - pulsar nebulae and supernova remnants: synchrotron photons (high B fields) + inverse compton scattering off very energetic electrons (shock accel?)
    - active galactic nuclei: inverse compton scattering from relativistic particles in AGN jets
    - diffuse production: $p + X \to \pi + Y \to \gamma\gamma$
  - *Dark matter annihilation to $\gamma\gamma$ and γZ*
  - *Primordial black hole evaporation*
- Techniques
  - Air Cerenkov
  - Ground air shower

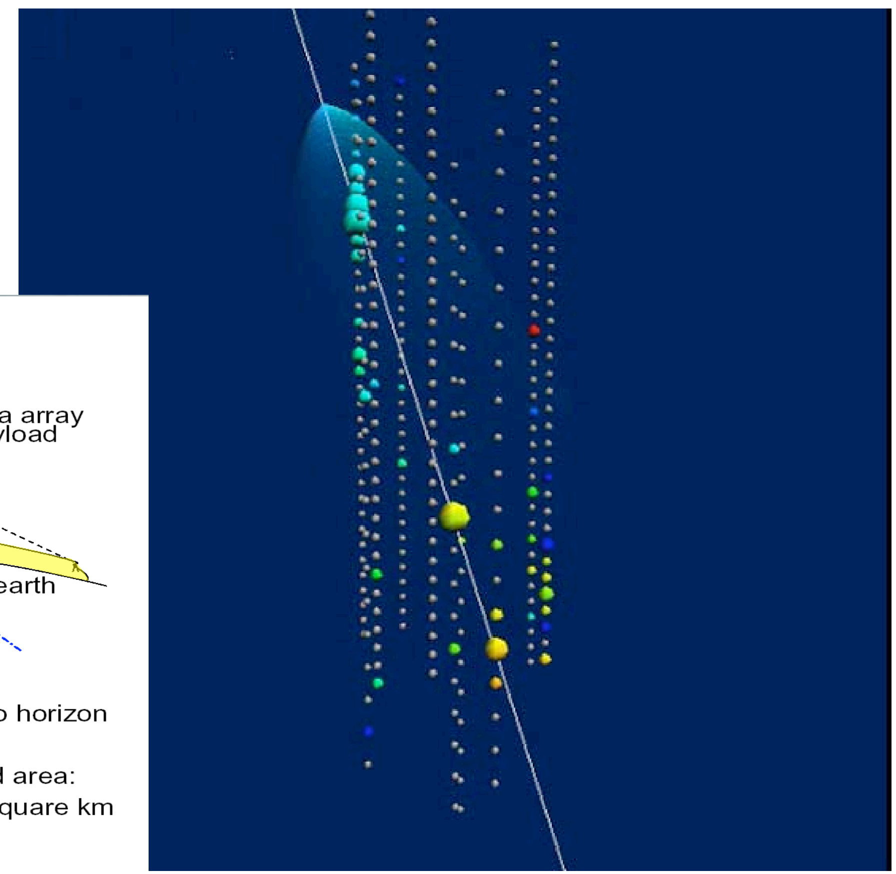


Extensive Air Showers

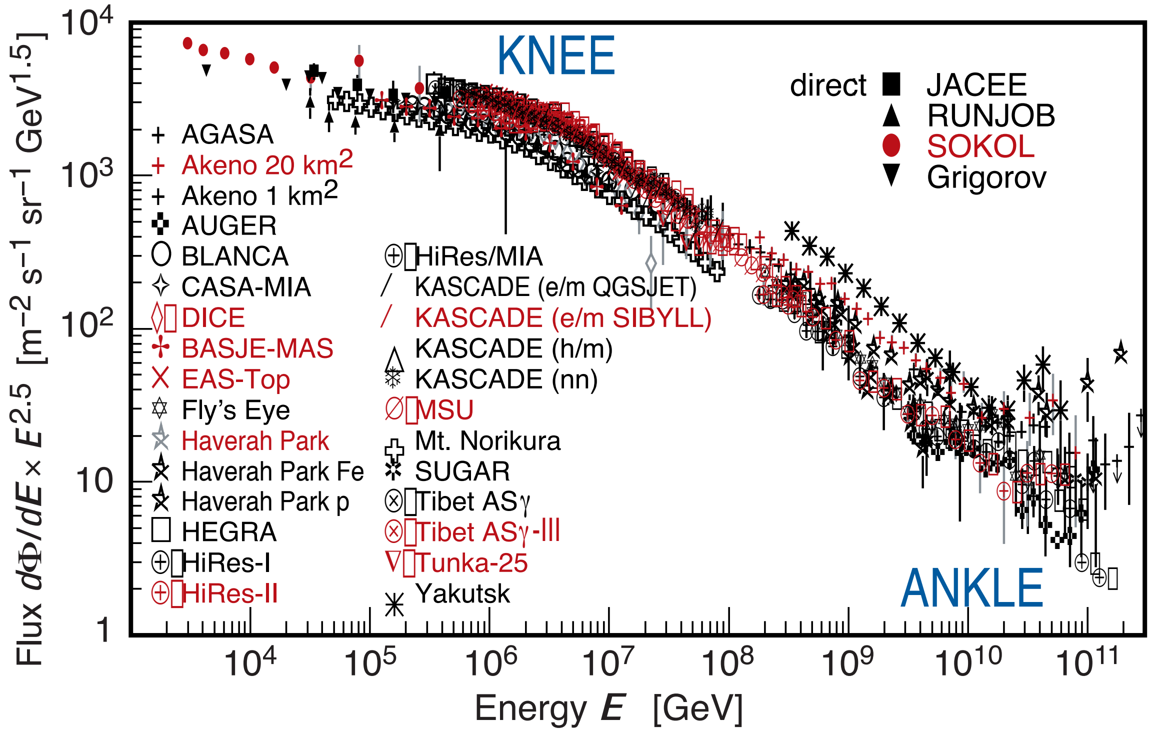
Neutrino Astronomy

- Similar sources, esp. $\pi \rightarrow \mu + \nu_\mu$
- Low interaction cross-section, so more penetrating view of sources
- Detection by charged-current scattering $\nu_\mu + X \rightarrow \mu + Y$ and track the final-state μ via the particle shower it creates
  - Ice optical Cerenkov (AMANDA, IceCube)
  - Water optical Cerenkov (ANTARES)
  - Ice radio Cerenkov (ANITA, RICE)
  - Radio Cerenkov in the moon





Ultra-High-Energy Cosmic Rays



- Cosmic rays (protons and nuclei) extend up to very high energy
- There should be a cutoff due to interaction with CMB CIRB
- Some events have been seen above the cutoff (2, 3.2 x 10^{11} GeV)
- Maybe can use for astronomy?
  - At most energies, cosmic rays have gyroradius comparable to galaxy and so lose memory of source direction
  - But protons at such high energies have very gyroradius >> galaxy: may point back to sources, can identify
  - Some hints of anisotropy in existing measurements

Ultra-High-Energy Cosmic Rays

- Pierre Auger Observatory
  - 1600 surface stations on 1.5 km spacing
    - detect charge particle air shower
    - provides good direction measurement
  - 4 N_2 fluorescence detectors
    - shower excited fluorescence by N2 molecules in atmosphere
    - provides good energy measurement