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Beyond the Standard Model

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Part I – The Standard Model

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- Symmetries and content
- A few select properties
- Outstanding issues
- Avenues to BSM physics
- Summary

The Standard Model

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Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

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

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

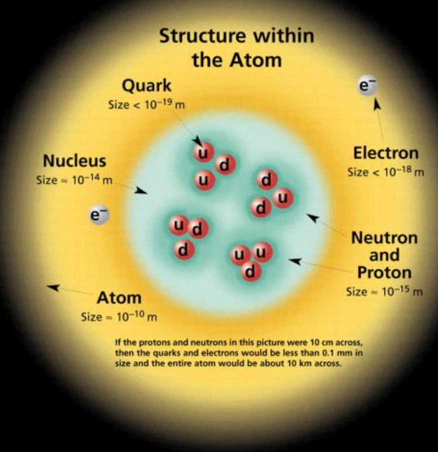
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

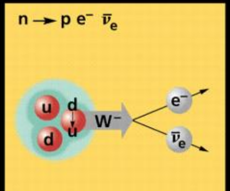
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

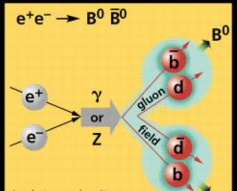
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

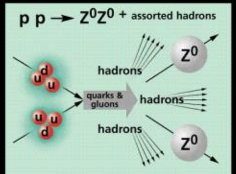
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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The Standard Model

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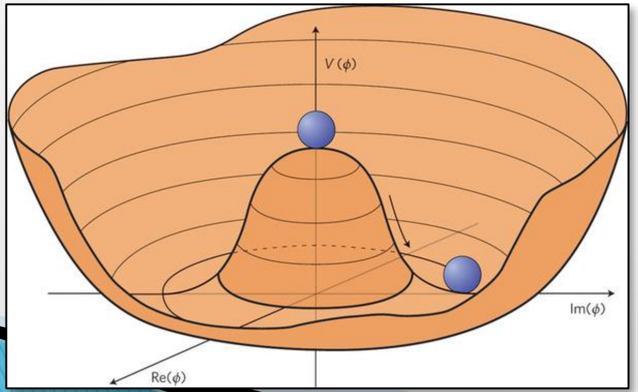
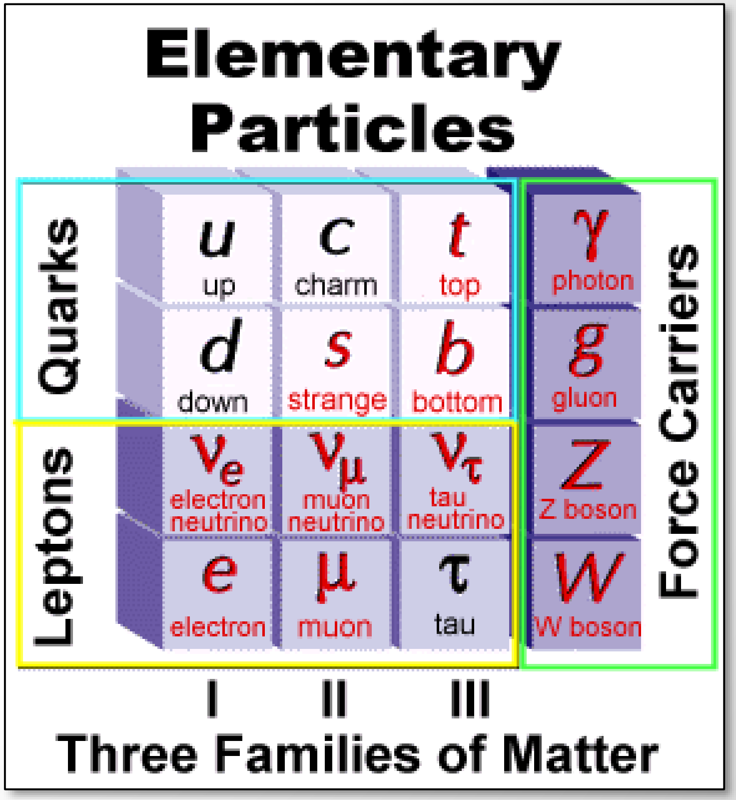
- (Special) Relativistic Quantum Theory
- Point-like particles as excitations of fields
- Three Forces are transmitted by carrier particles
- Internal Gauge symmetry

$$SU(3) \times SU(2) \times U(1)_Y$$

- Spontaneously broken via Higgs Mechanism





The Standard Model

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- Lagrangian

$$L = i\bar{\psi}_i \bar{\sigma}^\mu D^\mu \psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + Y_{ij}\psi_i\psi_j H^{(c)} + h.c. + |D_\mu H|^2 - V(H)$$

- Re-normalizable gauge theory based on

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

- One scalar Higgs field $H \equiv (1,2,-1/2)$
- Fermion content
  - in terms of *chiral Weyl* fermions to account for the fact that left/right-handed parts couple differently
  - (times 3 for generations)

ψ_i	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	3	2	+1/6
u^c	$\bar{3}$	1	−2/3
d^c	$\bar{3}$	1	+1/3
L	1	2	−1/2
e^c	1	1	+1

The Standard Model

- Lagrangian

$$L = i\bar{\psi}_i\bar{\sigma}^\mu D^\mu\psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a,\mu\nu} + Y_{ij}\psi_i\psi_j H^{(c)} + h.c. + |D_\mu H|^2 - V(H)$$

- Gauge Sector
- Gauge Symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Three gauge couplings
- Global symmetry $U(3)^5$ (rotation in generations space per fermion species)

The Standard Model

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- Lagrangian

$$L = i\bar{\psi}_i \bar{\sigma}^\mu D^\mu \psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + \boldsymbol{Y_{ij} \psi_i \psi_j H^{(c)}} + h.c. + |D_\mu H|^2 - V(H)$$

- Yukawa Sector explicitly

$$L \ni Y^u_{ij} Q_i H^c u^c_j + Y^d_{ij} Q_i H d^c_j + Y^e_{ij} L_i H e^c_j + h.c.$$

- Freedom to rotate in flavour space

$$L \ni y^u_i Q_i H^c u^c_i + y^d_i U^{CKM}_{ij} Q_i H d^c_j + Y^e_{ij} L_i H e^c_j + h.c.$$

  - Diagonal terms y lead to fermion masses after EWSB, $m = y\langle H \rangle$
  - Mismatch of rotations of Q, u^c, d^c source of quark flavour and CP violation

The Standard Model

- Lagrangian

$$L = i\bar{\psi}_i\bar{\sigma}^\mu D^\mu \psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a,\mu\nu} + Y_{ij}\psi_i\psi_j H^{(c)} + h.c. + |\boldsymbol{D_\mu H}|^2 - \boldsymbol{V(H)}$$

- Higgs Potential

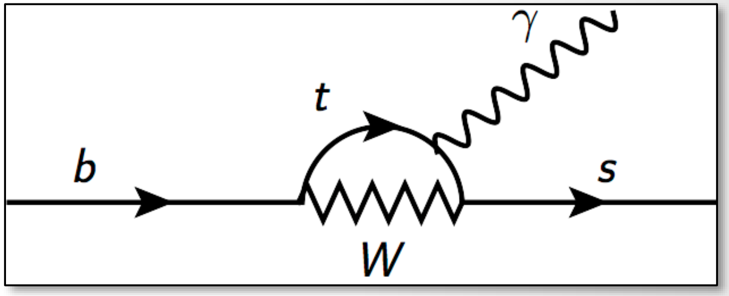
$$V(H) = -\mu^2 H^+ H + \frac{\lambda}{4}(H^+ H)^2$$

  - From Higgs observation and other measurements: $\mu \approx 90$ GeV, $\lambda \approx 0.13$
  - Higgs acquires vacuum expectation value leading to EWSB

$$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_e$$

The Standard Model

- CKM mixing matrix only source of flavour and CP violation
  - No tree level 'FCNC' (Flavour Changing Neutral Currents)
    - Z couples diagonally to all fermions
  - Suppressed FCNC at loop level
  - Suppression of CP violation (CPV requires three generations of non-degenerate quarks)



- Higgs sector invariant under $SO(4)$
  - Breaks to a global 'custodial' $SU(2)$ symmetry
  - Strong constraint on BSM models that do not have this symmetry
- Accidental Symmetries
  - Baryon number symmetry $U(1)_B$
  - Lepton flavour/number symmetry $U(1)_e \times U(1)_\mu \times U(1)_\tau \ni U(1)_L$
  - Proton is stable

Outstanding Issues in the Standard Model

- Experimental/Observational
  - No neutrino masses (Oscillations)
  - No candidate for Dark Matter (Astrophysics and Cosmology)
  - Origin of Matter-Antimatter asymmetry unexplained (Cosmology)
  - Inflation is unexplained (Cosmology?)
  - **It explains almost all observations to well!!!**
- Theoretical
  - Naturalness of large hierarchies
    - Electroweak scale $\approx 10^2$ GeV and Planck scale $\approx 10^{18}$ GeV
    - Electroweak scale $\approx 10^2$ GeV and scale of new BSM physics ≈ ???
    - Electroweak scale $\approx 10^2$ GeV and neutrino scale $\approx 10^{-2}$ eV (or $\approx 10^{14}$ GeV)
    - Electroweak scale $\approx (10^2 \text{ GeV})^4$ and cosmological constant $\approx (10^{-3} \text{ eV})^4$
  - No explanation for Dark Energy
  - Gravity is not included

Outstanding Issues in the Standard Model

- Metaphysical / Fine-tuning?
  - Origin of structure
    - Why are there 3 generations (hierarchically ordered)? 3 gauge couplings? 3+1 dimensions?
  - What is the origin of all the different constants
  - Why is CP violation so small?
    - Strong CP problem
  - Why are electric charges quantized?
    - Charges of U(1) symmetries are a priori arbitrary

Avenues to BSM Physics

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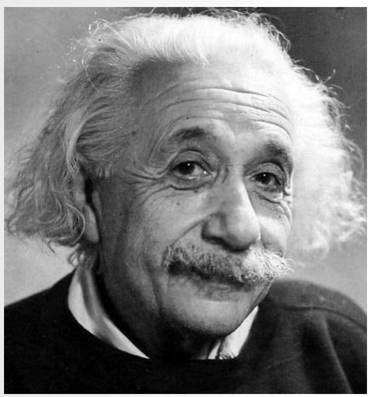
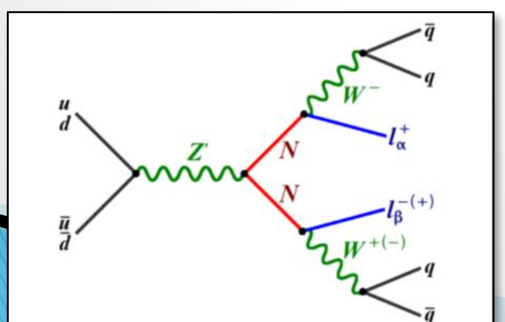
- First Goal: Falsification of Standard Model
- But so far it works nicely! (apart from above short-comings)
- Two approaches to look for signs of new physics



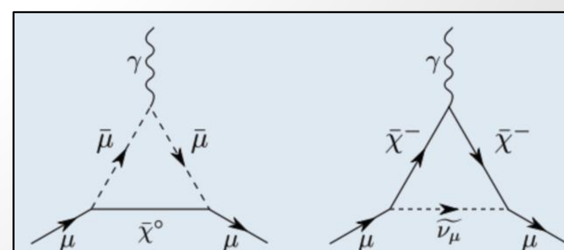
$$E = mc^2$$

Provide enough energy to create real heavy particles



$$\Delta E \cdot \Delta t \geq \hbar/2$$

Try often enough to see effect of virtual heavy particles



Avenues to BSM Physics

- Experimental
  - Accelerator based
    - High-energy such as LHC
      - Discovery of Higgs and determination of properties
      - Discovery/Exclusion of new heavy states
      - Searches for missing energy processes (Dark Matter)
    - Lower energy / high luminosity
      - Precision measurements
      - Observation/Limits on rare processes
  - Non-accelerator based
    - E.g. direct Dark Matter searches, neutrino oscillations, proton decay
  - Astrophysics
    - Cosmic microwave background
    - Cosmic rays
    - Large scale structure
    - Supernovae

Avenues to BSM Physics

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- Theoretical / Phenomenological
  - Discovery of new structures in Quantum Field Theories and Effective Field Theories
    - Symmetries
  - Extensions of Quantum Field Theory
    - String theory
  - Better understanding of the Standard Model
  - Construction of improved BSM models
  - More precise and general predictions in BSM models
  - Improved analysis of experimental results
    - Simplified Models

Summary – Part I

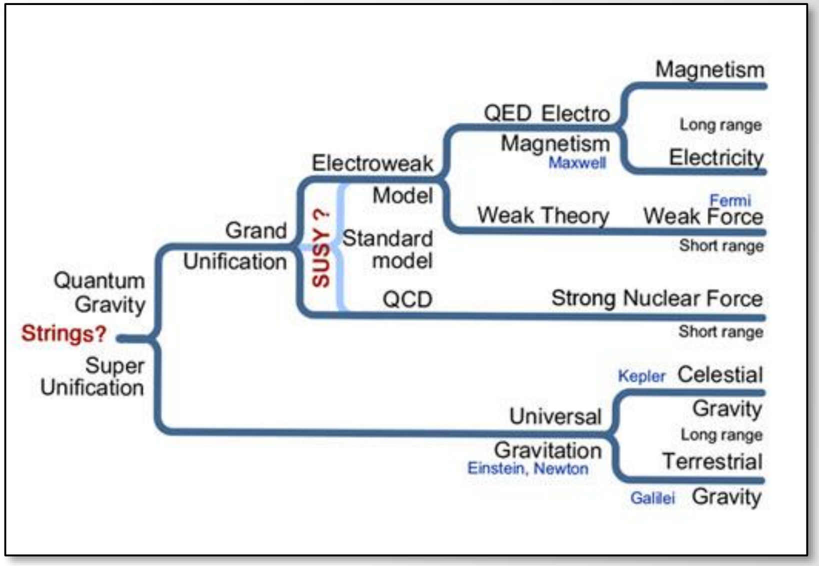
- The Standard Model is an outstanding success
- Established as a renormalizable gauge Quantum Field Theory that is spontaneously broken
  - Prototype for many BSM models
- Fully self-consistent, apart from potential fine-tuning, albeit not very beautiful
- Neutrino masses only immediate hint for new physics
  - As we will see can be accommodated pretty easily
- Dark Matter strongest hint that there is another state out there
- Naturalness has been the strongest theoretical argument for new physics and motivation to search the "Terascale"

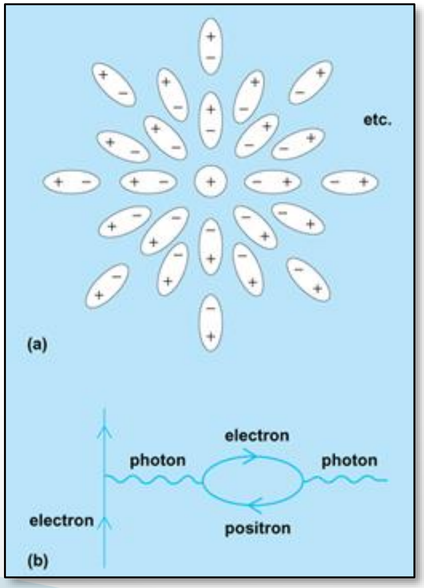
Part II – BSM Landscape

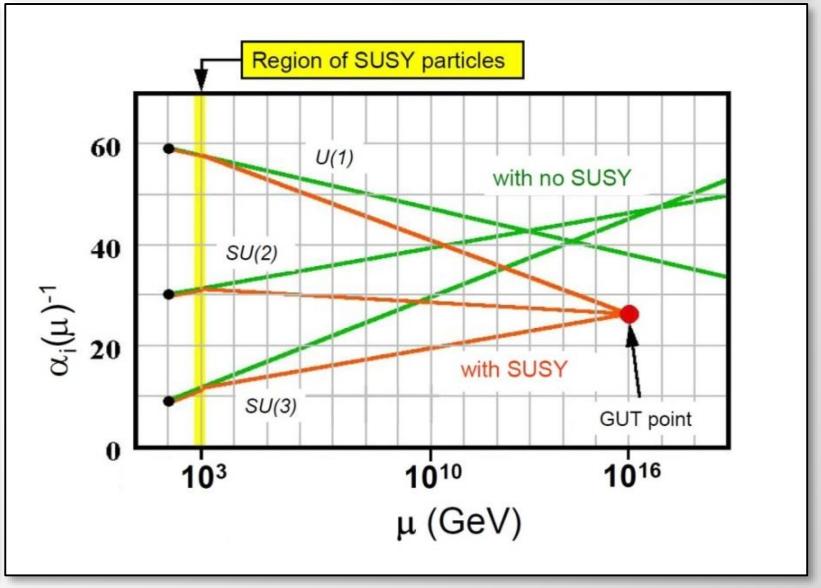
- Gauge Unification
- Naturalness Problem
- Supersymmetry
- Extra Dimensions
- Other models
- Mapping the Landscape: Effective Field Theories
- What about
  - Neutrino Masses?
  - Dark Matter?
  - the Matter–Antimatter Asymmetry?
  - Dark Energy?
- Summary
- Further Reading

Gauge Unification

- Apply success of spontaneously broken gauge theory to other gauge symmetries / larger particle content
- Three forces in SM are different but very similar
- Do they have a common origin at high energies?
- Ultimate Goal: Unification to one force = Grand Unified Theories
  - "Shielding" due to quantum fluctuations at different energies







Gauge Unification

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- Same principle as in SM
  - Choose a gauge group (that contains the SM gauge group)
  - Assign particle fields (SM + exotics) to irreducible representations of gauge group
  - Choose Higgs representation(s) and scalar potential such that the gauge symmetry breaks spontaneously
- Example $SU(5) \to SU(3) \times SU(2) \times U(1)$
  - Fermion representations

$$\bar{\mathbf{5}} \leftrightarrow \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix}_L , \quad \mathbf{10} \leftrightarrow \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}_L ,$$

breaking to SM representations

$$\bar{\mathbf{5}} \to \{\bar{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}\} \oplus \{\mathbf{1}, \mathbf{2}^*, \text{-}\tfrac{1}{2}\},$$
$$\mathbf{10} \to \{\mathbf{3}, \mathbf{2}, \tfrac{1}{6}\} \oplus \{\bar{\mathbf{3}}, \mathbf{1}, \text{-}\tfrac{2}{3}\} \oplus \{\mathbf{1}, \mathbf{1}, 1\}.$$

Gauge Unification

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- Gauge (adjoint) representations

$$\mathbf{24} \to \{\mathbf{8},\mathbf{1},0\} \oplus \{\mathbf{1},\mathbf{3},0\} \oplus \{\mathbf{1},\mathbf{1},0\} \oplus \{\mathbf{3},\mathbf{2},\tfrac{1}{6}\} \oplus \{\bar{\mathbf{3}},\mathbf{2},-\tfrac{1}{6}\}.$$

- Higgs representations
  - One 24-plet Σ, breaking $SU(5) \to SU(3) \times SU(2) \times U(1)$
  - One 5-plet, containing the SM Higgs

$$\mathbf{5} \to (\mathbf{3},\mathbf{1},-\tfrac{1}{3}\} \oplus (\mathbf{1},\mathbf{2},\ \tfrac{1}{2}\}.$$

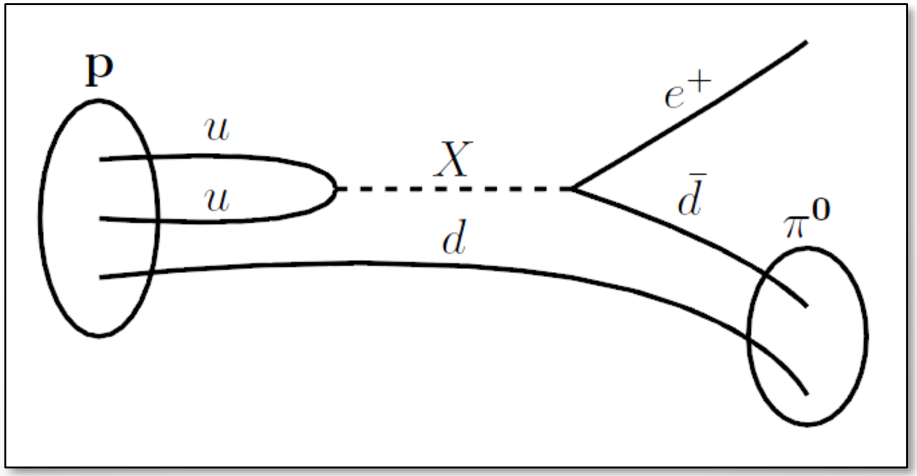
- Properties
  - Unification to one gauge group / coupling
    - Does not exactly work with observed SM gauge couplings (requires SUSY)
    - Partial unification around $\Lambda \approx 10^{15}$ GeV
  - Partial Yukawa coupling unification
    - Does not really work for SM masses
  - Neutrino masses are not incorporated

Gauge Unification

- Lack of 'Doublet–Triplet' splitting of the 5–Higgs
  - Fine–tuning required to make SM triplet heavy and SM doublet light

$$\mathbf{5} \to (\mathbf{3}, \mathbf{1}, -\tfrac{1}{3}\} \oplus (\mathbf{1}, \mathbf{2}, \ \tfrac{1}{2}\}.$$

- Proton decay
  - Mediated by heavy GUT scale gauge bosons



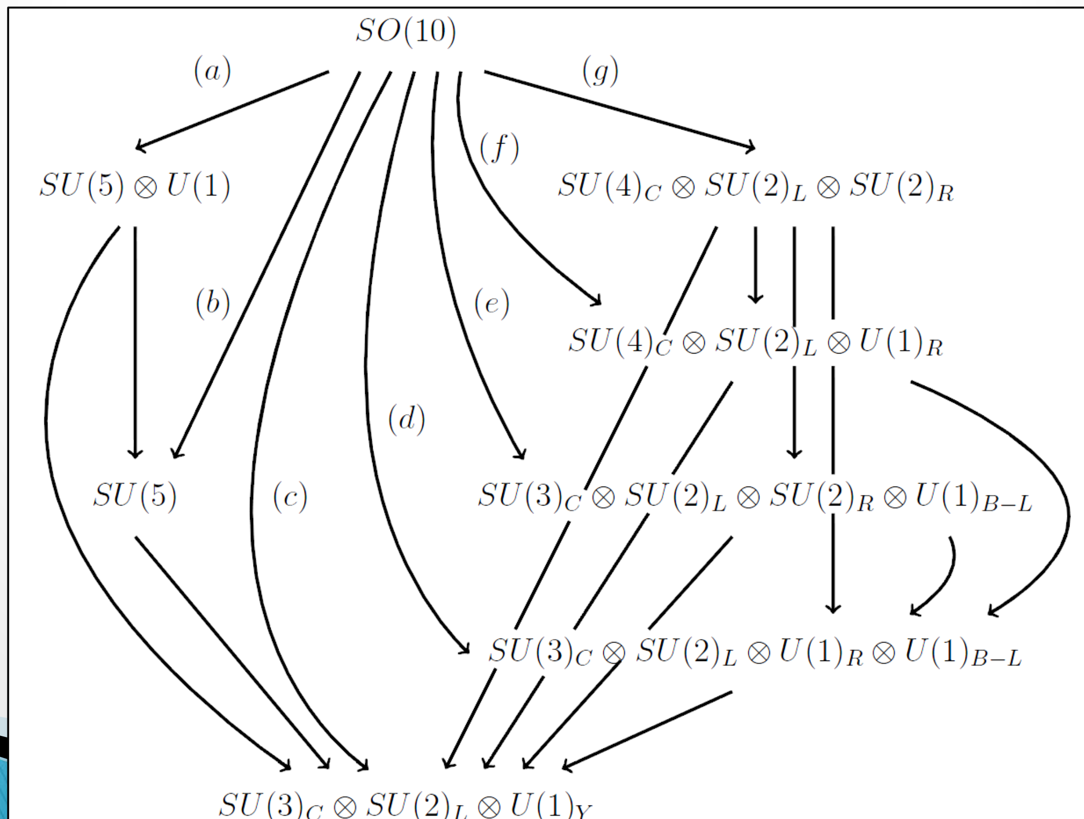
  - Experimental limit $T^{1/2} > 10^{34}$ y (Super–Kamiokande)
    - Requires $\Lambda_{GUT} > 10^{16}$ GeV (rules out minimal SU(5) model)

Gauge Unification

- Example: SO(10)
  - All fermions (of one generation) including right-handed neutrino unified in one 16-plet

$$\mathbf{16} = \{u_1^c, d_1^c, d_1 u_1, \nu^c, e^c, d_2, u_2, u_2^c, d_2^c, d_3, u_3, u_3^c, d_3^c, e, \nu\}_L,$$

  - Large number of possible gauge breaking chains



Naturalness

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- Generic BSM approach
  - View SM as an effective theory, valid up to a certain scale Λ_{NP}
  - At this scale, it is replaced by a new underlying theory
- General Naturalness principle
  - The SM should not be too sensitive to physics at Λ_{NP}
  - In other words: Different scales should decouple
  - In some sense necessary to do any science
    - E. g. physics at LHC should not depend on the weather on Saturn

Naturalness

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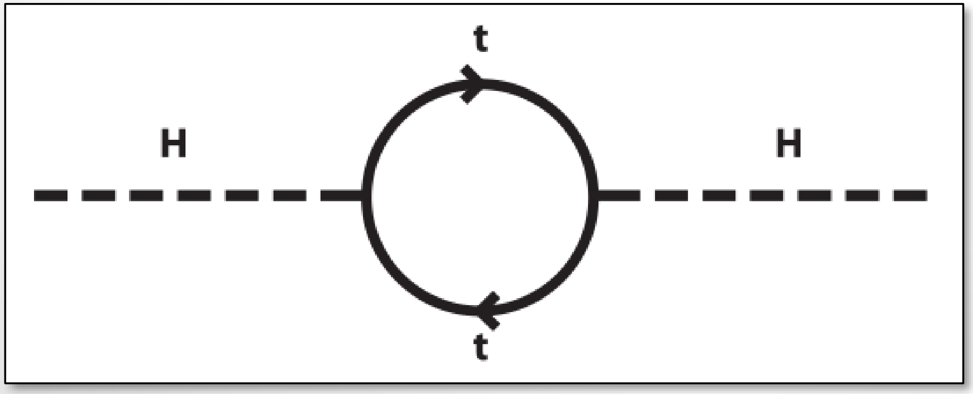
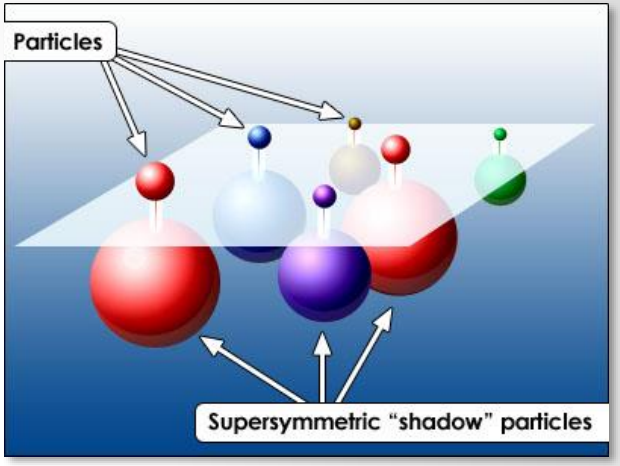
- Connection to symmetries: t'Hooft Principle
  - "A parameter in a theory should only be small if the theory becomes more symmetric as the parameter goes to zero"
  - Example: Lepton and quark Yukawa couplings; if zero, the SM Lagrangian would have a global $SU(3)^5$ symmetry
- Does not apply to Higgs mass
  - would be "naturally" of the order $m_H \approx \Lambda_{NP}$
- Quantum corrections to Higgs mass

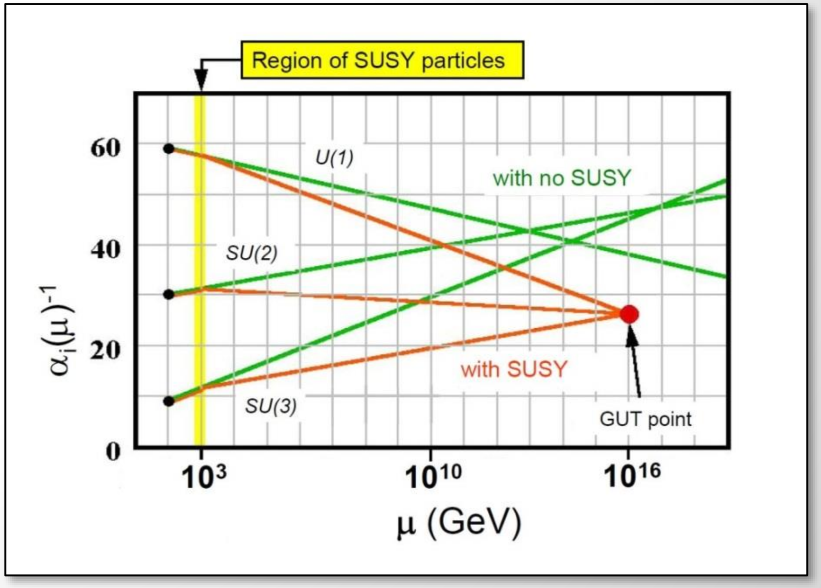


$$\delta m_H^2 \approx -\frac{y_t^2}{8\pi^2}\Lambda_{NP}^2$$

Supersymmetry

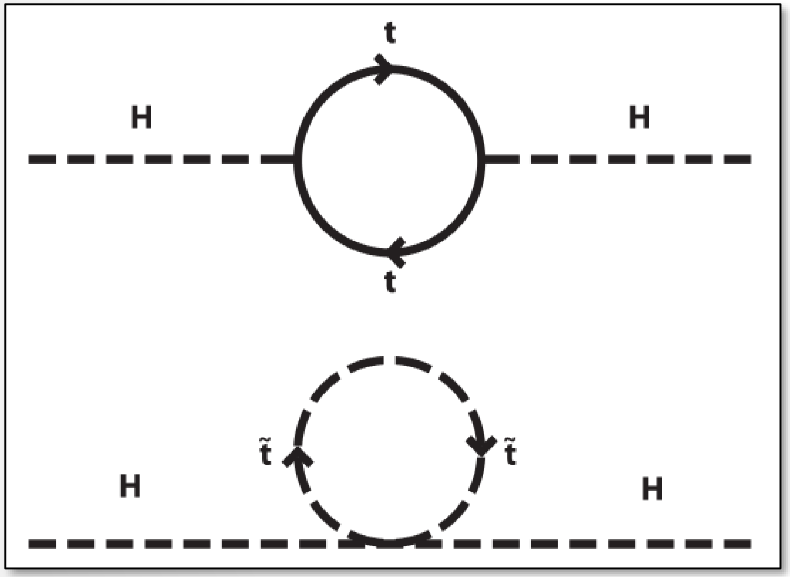
- Most popular extension of Standard Model
- Predicts symmetry between bosons and fermions
- Unifies force with matter particles
- May explain why Higgs mass is 125 GeV
- Deep theoretical advantages
  - Maximal symmetry of a Quantum Field Theory is Poincare x Gauge x Supersymmetry
  - Supersymmetry is needed for a quantum theory of gravity





Supersymmetry

- Solution to naturalness problem
  - Cancellation of quantum corrections to Higgs mass



$$\delta m_H^2 \approx -\frac{y_t^2}{8\pi^2}\Lambda_{NP}^2 + 2\frac{\lambda_{\tilde{t}}}{16\pi^2}\Lambda_{NP}^2$$

$$\lambda_{\tilde{t}} = y_t^2$$

Supersymmetry

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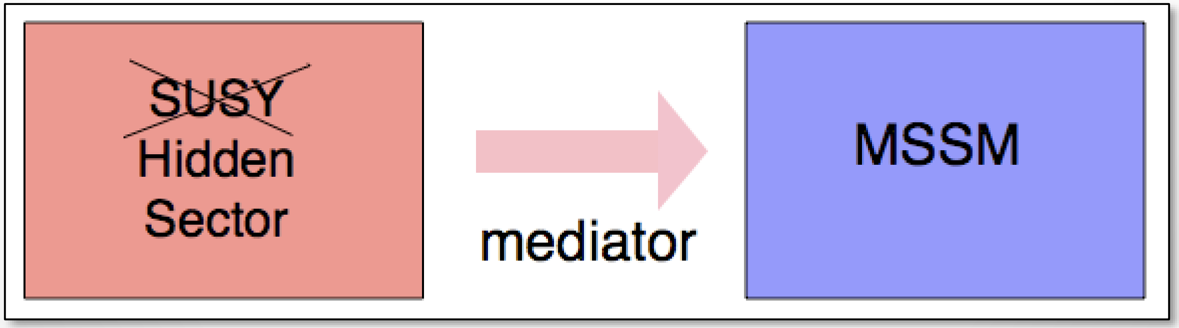
- The MSSM
  - Minimal supersymmetric version of the Standard Model

Superfield	$s=0$	$s=\frac{1}{2}$	$s=1$	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
$\hat{Q}_i$	$(\tilde{Q}_i)_L$	Q_i	-	$\{3, 2, \frac{1}{6}\}$
$\hat{u}_i^c$	$(\tilde{u}_i^c)_L$	u_i^c	-	$\{\bar{3}, 1, -\frac{2}{3}\}$
$\hat{d}_i^c$	$(\tilde{d}_i^c)_L$	d_i^c	-	$\{\bar{3}, 1, \frac{1}{3}\}$
$\hat{L}_i$	$(\tilde{L}_i)_L$	L_i	-	$\{1, 2, -\frac{1}{2}\}$
$\hat{e}_i^c$	$(\tilde{e}_i^c)_L$	e_i^c	-	$\{1, 1, 1\}$
$\hat{H}_u$	H_u	$\tilde{H}_u$	-	$\{1, 2, \frac{1}{2}\}$
$\hat{H}_d$	H_d	$\tilde{H}_d$	-	$\{1, 2, -\frac{1}{2}\}$
$\hat{G}$	-	$\tilde{G}$	G_μ	$\{8, 1, 0\}$
$\hat{W}$	-	$\tilde{W}$	W_μ	$\{1, 3, 0\}$
$\hat{B}$	-	$\tilde{B}$	B_μ	$\{1, 1, 0\}$

Supersymmetry

- SUSY can not be exactly realized in nature as we do not see partners of the SM particles
  - SUSY must be broken but not too much to spoil the nice parts
- SUSY breaking in a hidden sector
  - mediated to the visible sector (MSSM) via gravitational or gauge interactions



  - Effective description: “Soft SUSY breaking Lagrangian”

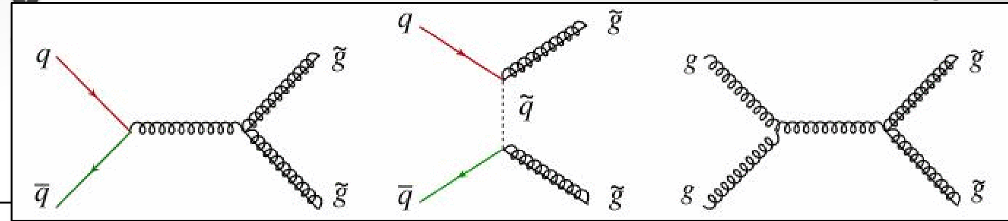
$$\begin{aligned}\mathcal{L}_{soft} = & -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}\right) \\ & - \left(A_u\tilde{u}^c\mathbf{y}_u\tilde{Q}H_u - A_d\tilde{d}^c\mathbf{y}_d\tilde{Q}H_d - A_e\tilde{e}^c\mathbf{y}_e\tilde{L}H_d + \text{c.c.}\right) \\ & - \tilde{Q}^*\mathbf{m}_Q^2\tilde{Q} - \tilde{L}^*\mathbf{m}_L^2\tilde{L} - \tilde{u}^{c*}\mathbf{m}_u^2\tilde{u}^c - \tilde{d}^{c*}\mathbf{m}_d^2\tilde{d}^c - \tilde{e}^{c*}\mathbf{m}_e^2\tilde{e}^c \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (B_0\mu H_u H_d + \text{c.c.})\,.\end{aligned}$$

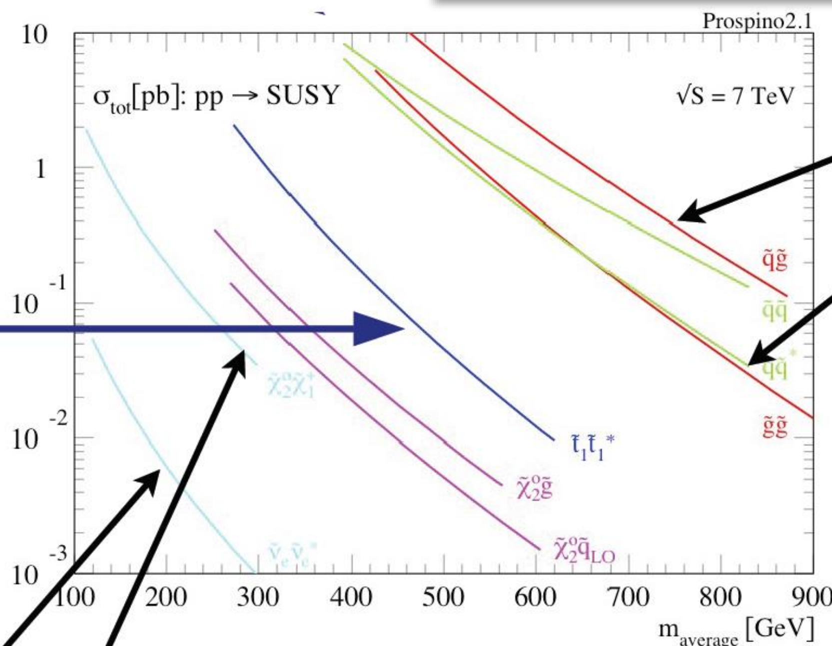
Supersymmetry

- Large number of free parameters
  - Look at simplified scenarios
    - e.g. SUSY breaking parameters unify at GUT scale $\approx 10^{16}\ \mathrm{GeV}$ (mSUGRA)
- Lightest SUSY particle (LSP) made stable via introduction of a "$\mathbb{Z}_2$" symmetry called R-parity
  - Assigns -1 to SUSY particles and $+1$ to SM particles
  - Ensures proton stability
  - Makes the LSP a potential Dark Matter candidate
  - Generic signature at colliders: Missing energy as LSP escapes

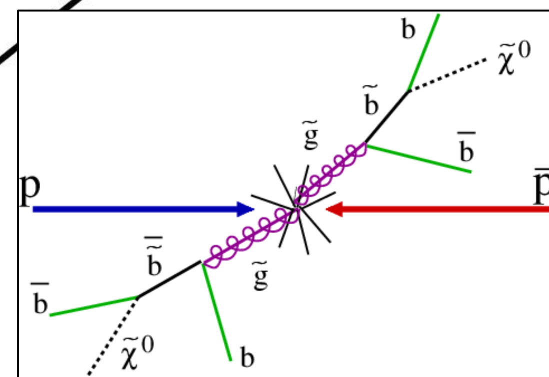
Supersymmetry

- Production at the LHC





All searches so far rely on producing gluinos and/or 1st, 2nd gen. squarks, different decay channels



Stops have small cross sections:

$\sigma(\tilde{t}\tilde{t}^*) \approx 30$ fb

at 500 GeV

Chargino/neutralino (e.g. higgsino) cross sections are even smaller

Plot credit: H. Bachacou talk at LP-11

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[fb^{-1}]$	Mass limit ($\sqrt{s}$ = 7, 8 TeV / $\sqrt{s}$ = 13 TeV)		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.85 TeV (7, 8 TeV)	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	$\tilde{q}$ 1.35 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV (13 TeV)	$m(\tilde{q})-m(\tilde{\chi}^0_1)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.86 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.83 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$<400 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}^0_1)+m(\tilde{g}))$	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	13.2	$\tilde{g}$ 1.7 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	2 e,μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 1.6 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV (13 TeV)		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV (13 TeV)	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV (7, 8 TeV)	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV (7, 8 TeV)	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.37 TeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	3.2	$\tilde{b}_1$ 840 GeV (13 TeV)	$m(\tilde{\chi}^0_1)$<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	1 b	Yes	13.2	$\tilde{b}_1$ 325-685 GeV (13 TeV)	$m(\tilde{\chi}^0_1)$<150 GeV, $m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_1)$+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 117-170 GeV (7, 8 TeV); 200-720 GeV (13 TeV)	$m(\tilde{\chi}^\pm_1)=2m(\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 90-198 GeV (7, 8 TeV); 205-850 GeV (13 TeV)	$m(\tilde{\chi}^0_1)$=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 90-323 GeV (13 TeV)	$m(\tilde{t}_1)-m(\tilde{\chi}^0_1)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	13.3	$\tilde{t}_2$ 290-700 GeV (13 TeV)	$m(\tilde{\chi}^0_1)$<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$ 320-620 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-335 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$ 140-475 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 355 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	1407.0350
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 715 GeV (7, 8 TeV)	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 425 GeV (7, 8 TeV)	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 270 GeV (7, 8 TeV)	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$ 635 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_2)=m(\tilde{\chi}^0_3)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^0_2)+m(\tilde{\chi}^0_1))$	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$ 115-370 GeV (7, 8 TeV)	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$ 590 GeV (7, 8 TeV)	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$ 270 GeV (7, 8 TeV)	$m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^\pm_1$ 495 GeV (7, 8 TeV)	$m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV (13 TeV)		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 537 GeV (7, 8 TeV)	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 440 GeV (7, 8 TeV)	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$ 1.0 TeV (7, 8 TeV)	7 <$c\tau(\tilde{\chi}^0_1)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}^0_1$ 1.0 TeV (7, 8 TeV)	6 <$c\tau(\tilde{\chi}^0_1)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV (13 TeV)	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.45 TeV (7, 8 TeV)	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}^\pm_1$ 1.14 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 450 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)>0.2\times m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.08 TeV (13 TeV)	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.55 TeV (13 TeV)	$m(\tilde{\chi}^0_1)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	13.2	$\tilde{g}$ 1.3 TeV (13 TeV)	$m(\tilde{t}_1)$<750 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 410 GeV; 450-510 GeV (13 TeV)		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV (7, 8 TeV)	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV (7, 8 TeV)	$m(\tilde{\chi}^0_1)$<200 GeV	1501.01325

Extra Dimensions

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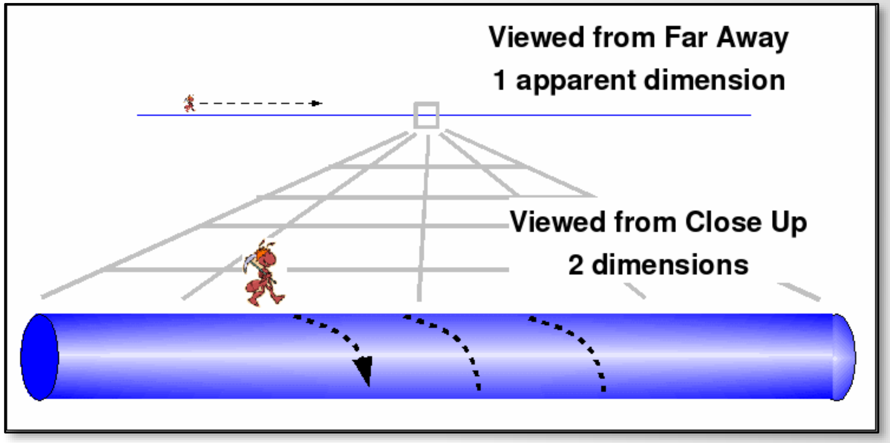
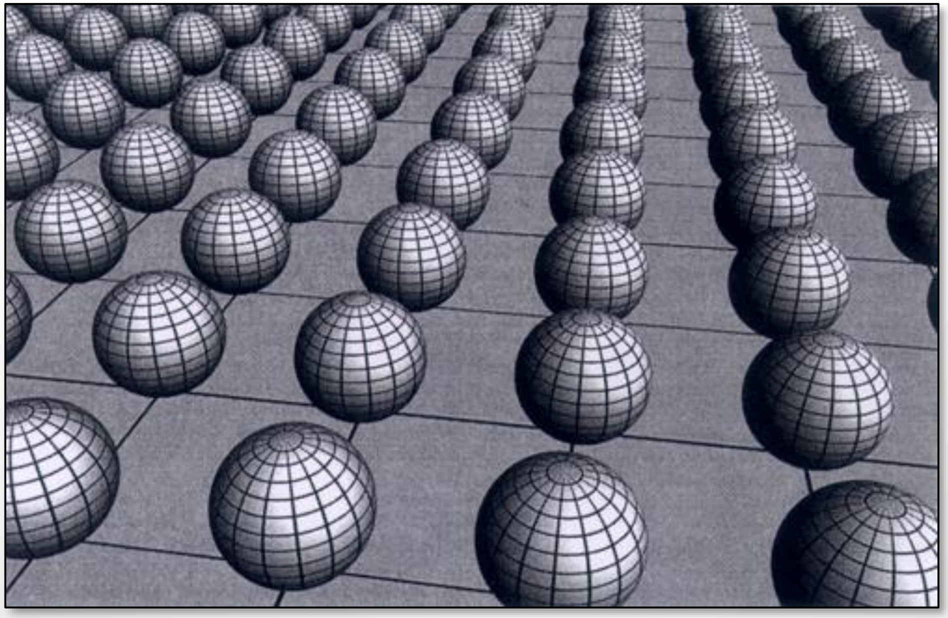
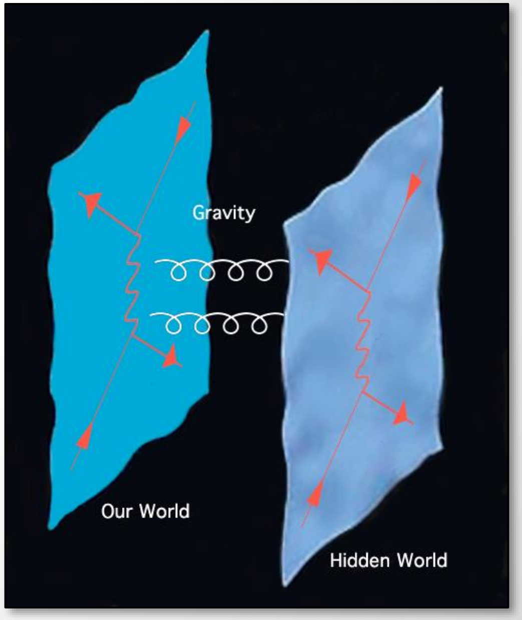
- Are there more than 3 space dimensions?
  - Possibly wrapped up
  - We are stuck on a 3D subspace







Extra Dimensions

- Potential solutions to the hierarchy / naturalness problem
  - There is no hierarchy – ADD / Large extra dimensions
    - SM is on a 4D "brane" inside larger dimensional space
    - Gravity is diluted as permeates all dimensions

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \ (r \ll R).$$

    - The large Planck scale is only effective, true Planck scale is near EW scale

$$M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n.$$

$$R \sim 10^{\frac{30}{n}-17} \mathrm{cm} \times \left(\frac{1\mathrm{TeV}}{m_{EW}}\right)^{1+\frac{2}{n}}$$

  - Gauge symmetry is broken as part of the compactification of an extra dimensions (near the EW scale)
    - Kaluza-Klein modes cancel corrections to Higgs mass

Other models out there

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- Technicolor, Composite Higgs
  - Higgs is composite bound state (analogous to mesons in QCD)
  - New strong force around the TeV scale
  - Non-perturbative, difficult to calculate
- Little Higgs
  - Introduce global symmetry that forces Higgs mass = 0, and slightly break it
- Axions
  - Strong CP problem: Explain absence/smallness of CP-violating term in SM Lagrangian

$$L_\theta = \frac{\theta}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}G^{\mu\nu}G^{\rho\sigma}$$

  - Light particles with small couplings
- Hidden Valley models
  - Light particles with suppressed couplings to SM

Effective Field Theories

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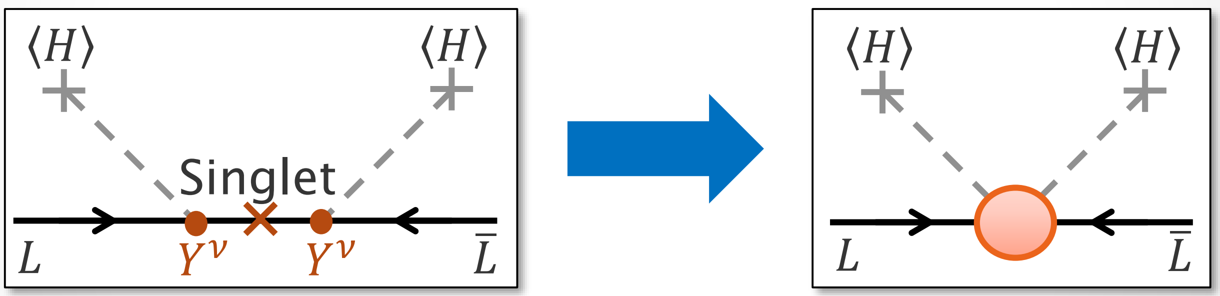
- The Standard Model is re-normalizable and contains only operators in the Lagrangian of dimension 4 or less
- Physics at higher scales introduces effective higher-dimensional operators
  - "Integrate out" heavy particles



- Parametrize in terms of effective operators O_n^i at with dimensions $n = 5, 6, 7, \ldots$ suppressed by powers of New Physics scale Λ_{NP}^{4-n}

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}}\mathcal{L}_5 + \frac{1}{\Lambda_{\text{NP}}^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_n = \sum_i C_n^i \mathcal{O}_n^i(\text{SM fields}) + h.c.$$

  - Operators O_n^i are constructed out of SM fields and invariant under Lorentz and SM gauge transformations

Effective Field Theories

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- Examples
  - Dimension-5 operator (only possibility)

$$\mathcal{O}_5 = (\bar{L}_i \cdot H)(H^+ \cdot L_j)^c$$ → Neutrino Majorana masses

  - Dimension-6 operators mediating charged lepton flavour violation
    - Two Lepton-Higgs-Photon

$$\mathcal{O}_6(ll\gamma H) = \bar{L}_i \sigma^{\mu\nu} e_j^c H^+ F_{\mu\nu}$$ → $\mu \to e\gamma$ etc., $g-2$, EDMs

    - Four Lepton

$$\mathcal{O}_6(llll) = (\bar{L}_i \gamma^\mu L_j)(\bar{L}_k \gamma^\mu L_l), \text{ etc.}$$ → $\mu \to eee$ etc., NSIs in neutrino oscillations

    - Two Lepton-Two Quark

$$\mathcal{O}_6(llqq) = (\bar{L}_i \gamma^\mu L_j)(\bar{Q}_k \gamma^\mu Q_l), \text{ etc.}$$ → $\mu \to e$ conversion in nuclei, Meson decays

Neutrino Oscillations

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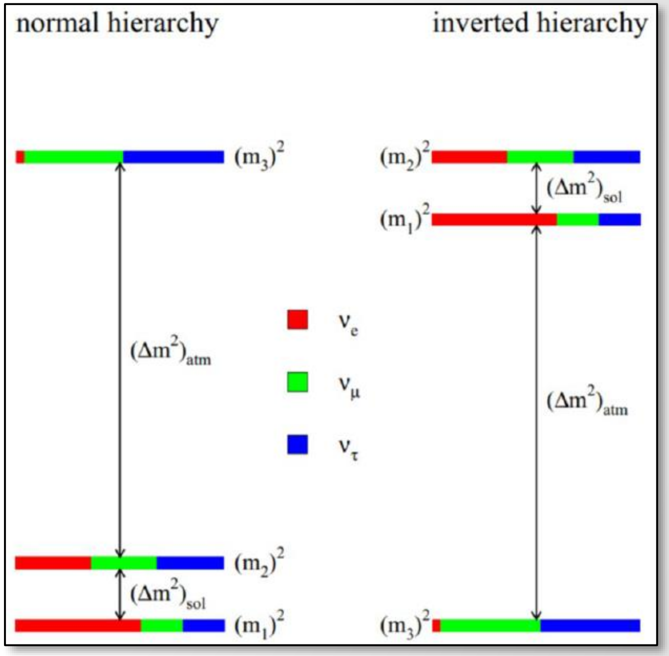
- Neutrino interaction eigenstates different from mass eigenstates
  - Neutrino flavour can change through propagation → LFV

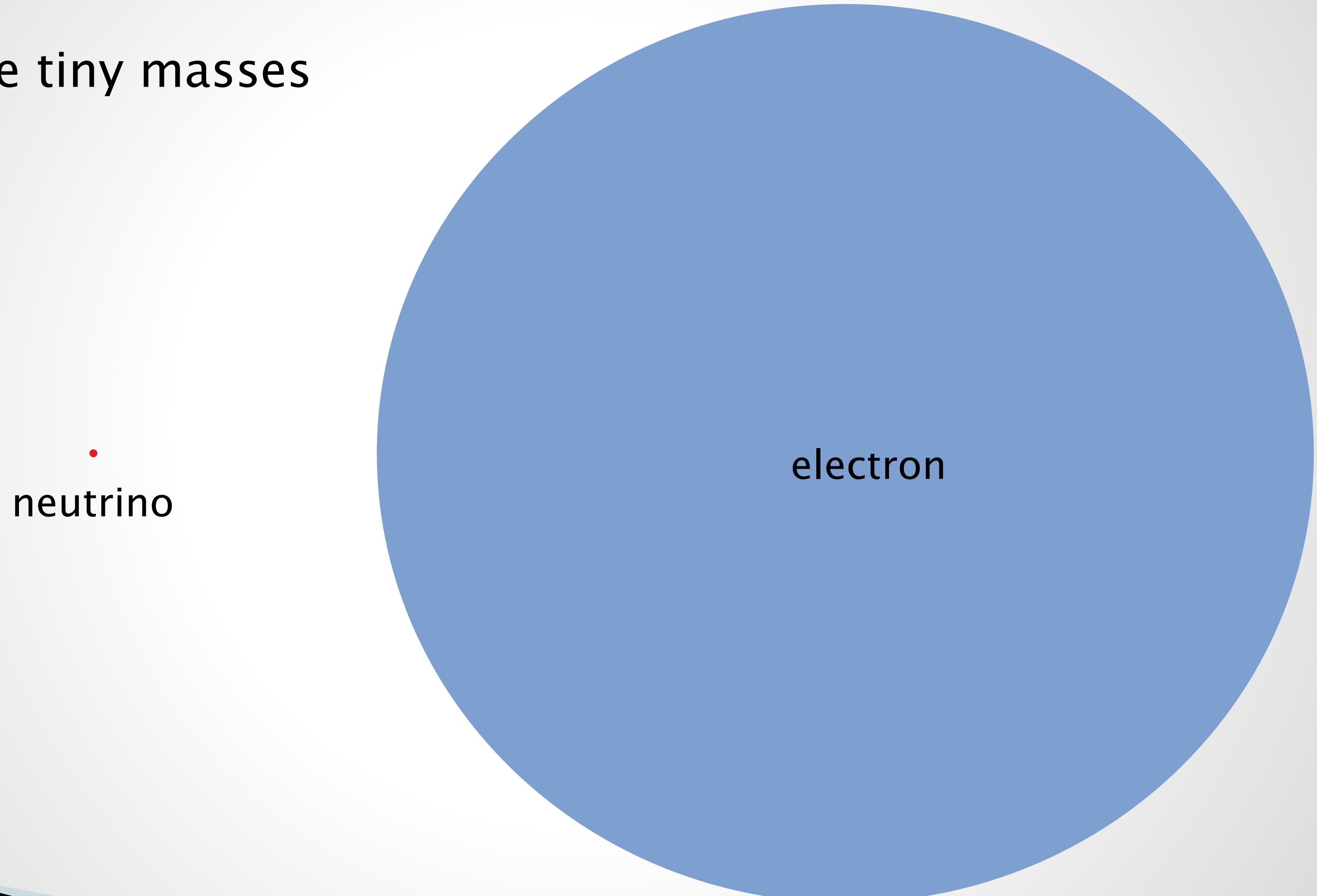
$$\nu_i = U_{\alpha i}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i(0)$$
$$\Longrightarrow P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$



- Solar Neutrino Oscillations
  - Large Mixing
- Atmospheric Oscillations
  - ≈ Maximal Mixing
- Reactor and Accelerator Neutrinos
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.021$
- Experimental Unknowns and Anomalies
  - CP Violation? Sign of Δm_{23}? Sterile Neutrinos?

Neutrinos

- Have tiny masses



Neutrino Masses

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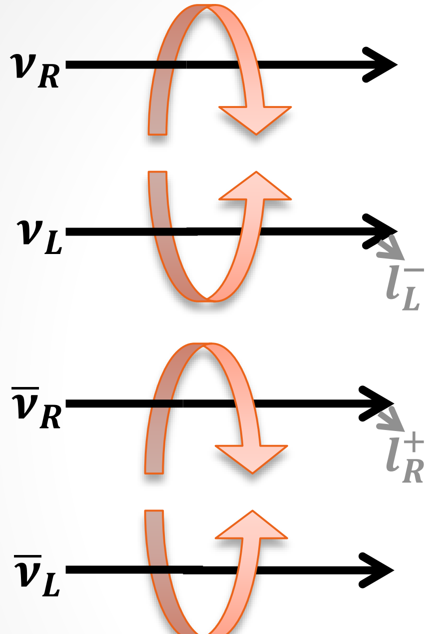
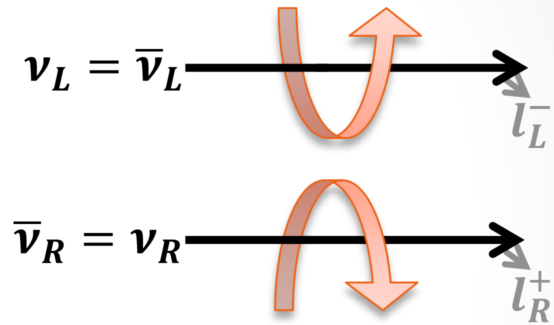
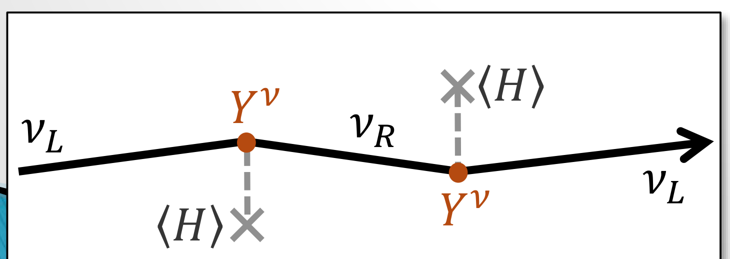
- Two possibilities to define neutrino masses

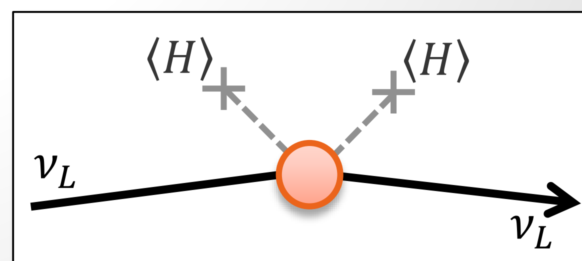




Dirac mass analogous to other fermions but with $m_\nu/\Lambda_{EW} \approx 10^{-12}$ couplings to Higgs

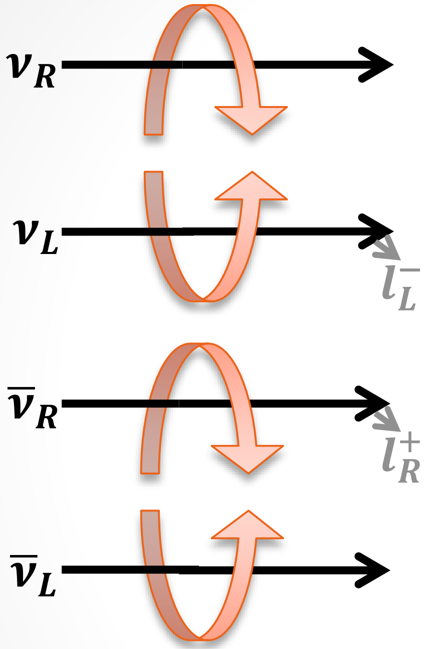


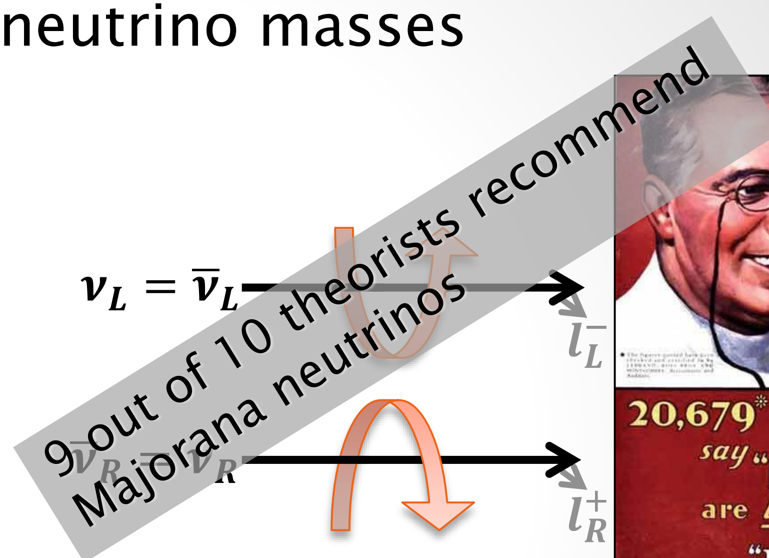
Majorana mass, using only a left-handed neutrino → Lepton Number Violation



Neutrino Masses

- Two possibilities to define neutrino masses





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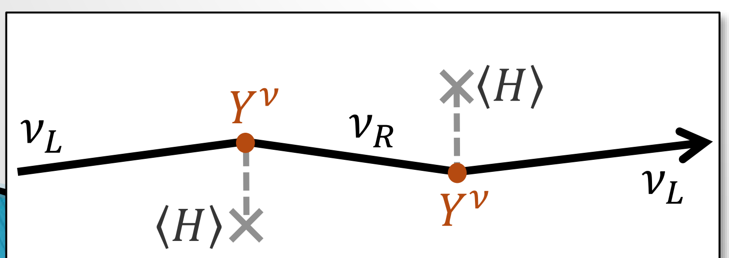

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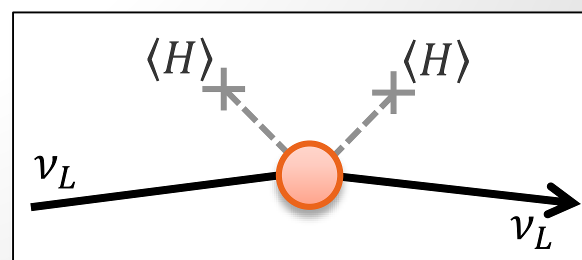

Neutrinoless Double Beta Decay

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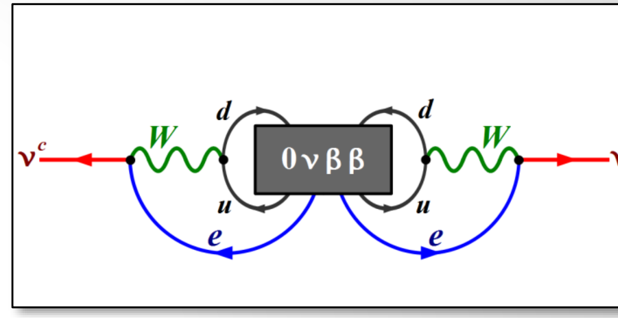
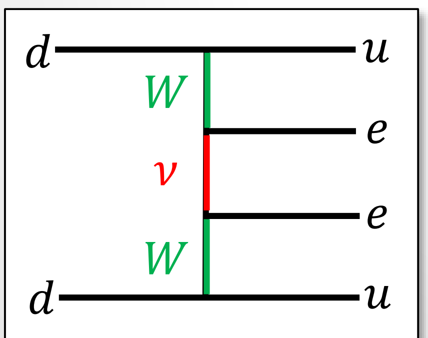
- Process $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- Uncontroversial detection of $0\nu\beta\beta$ of utmost importance
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles (Schechter & Valle '82)



$$\delta m_\nu \approx \frac{1}{(16\pi^2)^4} \frac{\text{MeV}^5}{M_W^4} \approx 10^{-23}\text{eV}$$

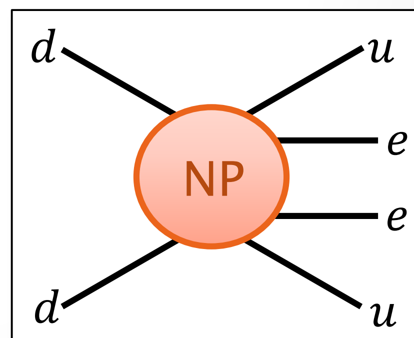
- Which mechanism triggers the decay?

Light Neutrino Exchange



$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\,\text{y} \rightarrow m_{\beta\beta} \approx 0.1\text{ eV}$$

General Effective Operator



$$\frac{\bar{u}\bar{u}\bar{e}\bar{e}dd}{M_{LNV}^5}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\,\text{y} \rightarrow M_{LNV} \approx 1\text{ TeV}$$

Absolute Neutrino Mass

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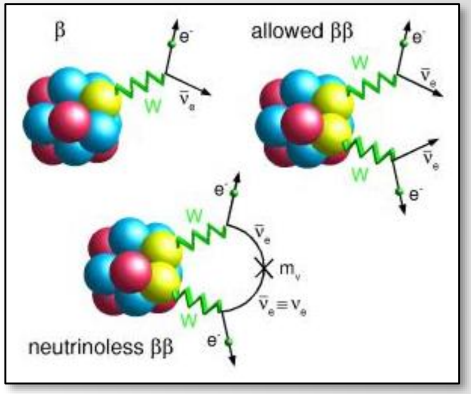
- Energy Endpoint in Beta Decay

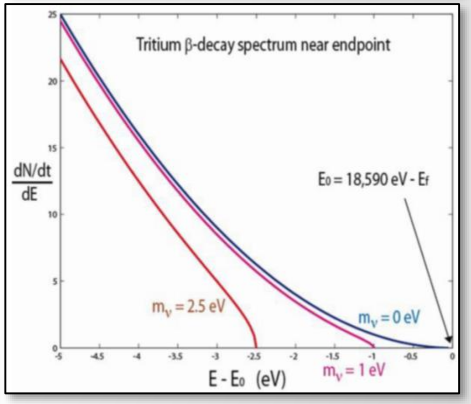
$$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_{\nu_i}^2 < (2.2\ \text{eV})^2$$

$\approx (0.2\ \text{eV})^2$ (KATRIN, 2018)



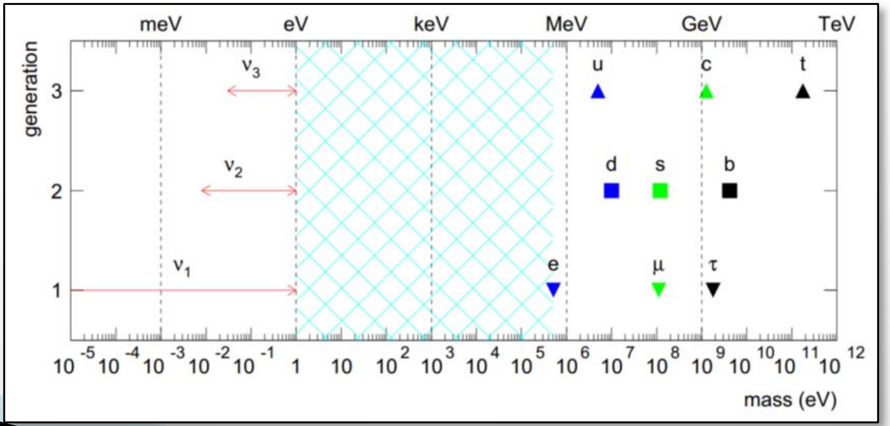
- Neutrinoless Double Beta Decay

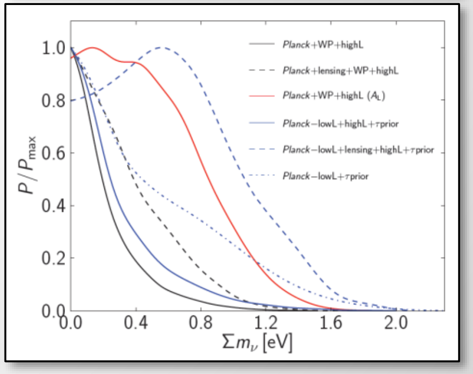
$$m_{\beta\beta} = |\Sigma_i U_{ei}^2 m_{\nu_i}| < 0.2 \cdots 1.0\ \text{eV}$$



- Impact on Large Scale Structure

$$\Sigma = \Sigma_i m_{\nu_i} < 0.3 \cdots 1.0\ \text{eV}$$





Lepton Flavour versus Lepton Number Violation

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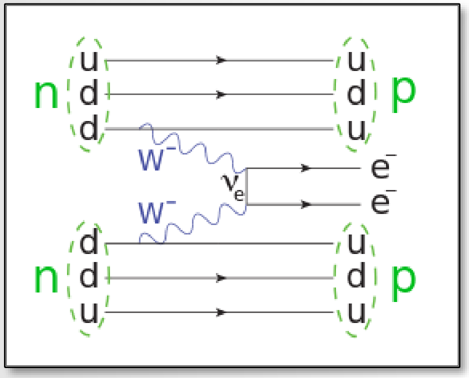
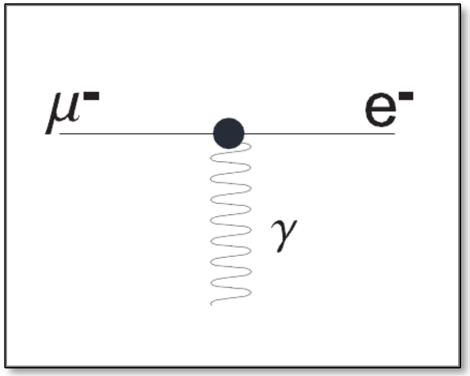
Neutrinoless double beta decay



$\Delta L_e = 2, \Delta L_\mu = 0, \Delta L = 2$

Lepton Number Violation

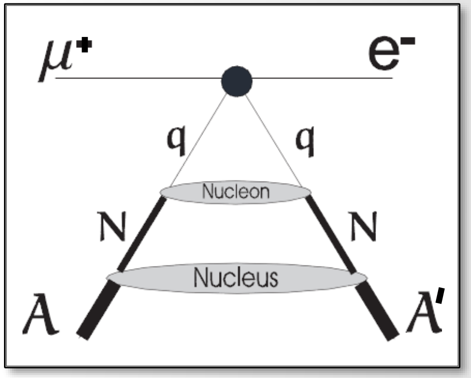
$\mu^- \to e^- \gamma$



$\Delta L_e = 1, \Delta L_\mu = -1, \Delta L = 0$

Lepton Flavour Violation

$\mu^+ \to e^-$ conversion in nuclei



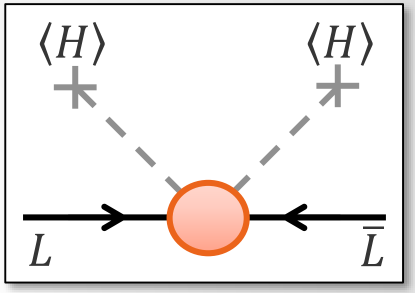
$\Delta L_e = 1, \Delta L_\mu = 1, \Delta L = 2$

Lepton Flavour Violation + Lepton Number Violation

Majorana Neutrino Masses

- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond the SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H\rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

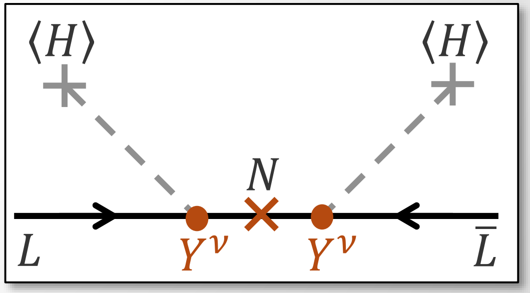


- Seesaw Mechanism
  - Add right-handed neutrinos N_i to SM, $M_N \approx 10^{14}$ GeV

$$\mathcal{L} \supset Y_{ij}^\nu \bar{N}_i \;\; L_j \cdot H - \frac{1}{2} M_{ij} \bar{N}_i \;\; N_j^c \xrightarrow[\mu \ll M_N]{} \frac{1}{2}(Y_{ki}^\nu M_{kl}^{-1} Y_{lj}^\nu)(\bar{L}_i^c \cdot H)(H^T \cdot L_j)$$

- Light neutrino mass

$$m_\nu \approx 0.1 \text{ eV}\left(\frac{Y_\nu \langle H\rangle}{100 \text{ GeV}}\right)^2 \left(\frac{10^{14} \text{ GeV}}{M}\right)$$



Heavy Sterile Neutrinos
Experimental Searches

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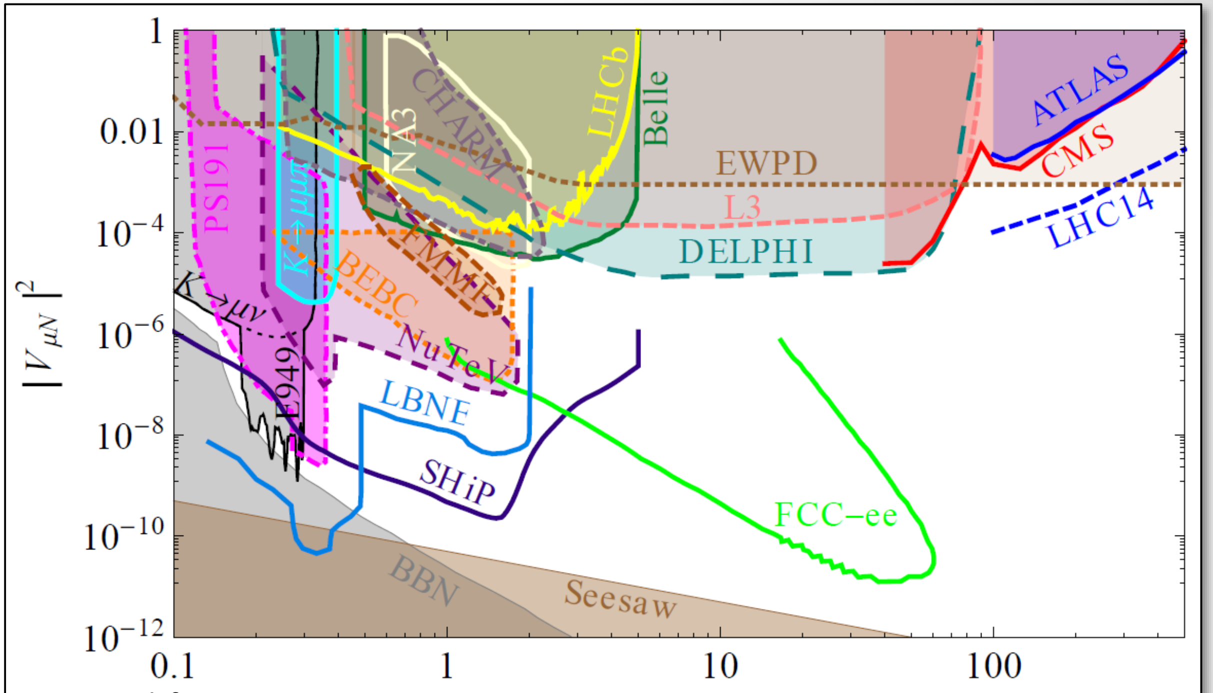
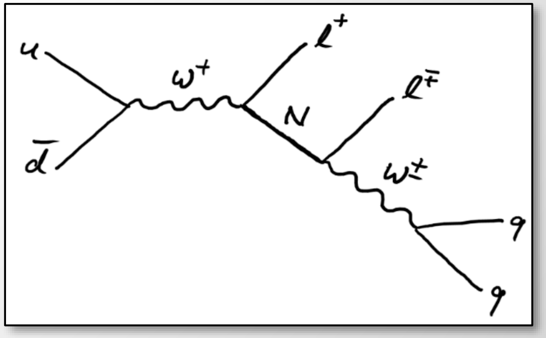
- Constraints on coupling to leptons $|V_{lN}|$
- Neutrinoless Double Beta Decay
  - GERDA
  - stringent for pure Majorana N
- Peak Searches in Meson Decays
  - $\pi, K \to e\nu$
  - Belle
- Beam Dump Experiments
  - e.g. PS191, CHARM
  - LBNE
- LNV Meson Decays
  - $K \to ee\pi$
  - SHiP
- Z Decays
  - LEP: L3, Delphi
  - FCC-ee
- Electroweak Precision Tests
  - EWPD: Fit of electroweak precision observables, lepton universality observables



FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019



Dark Matter

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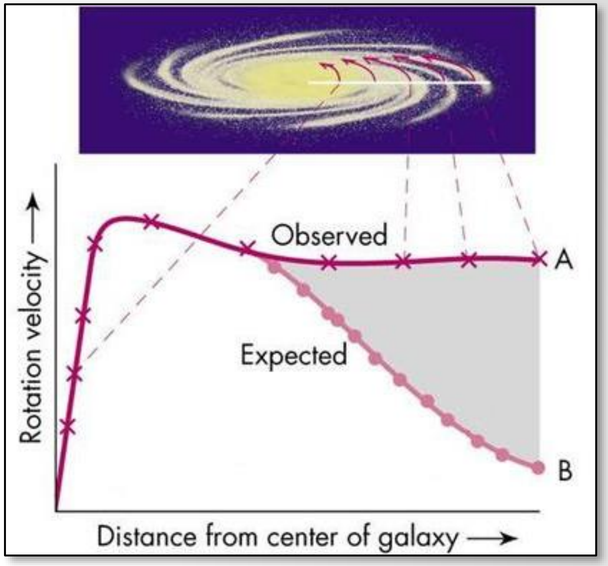
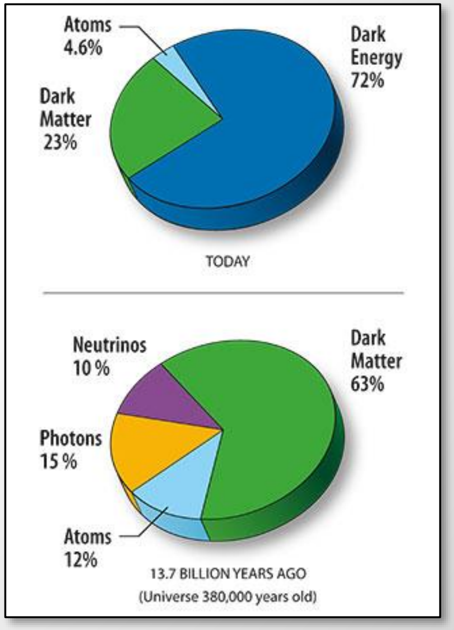
- There must be more mass than we can see
  - Galaxies rotate "too fast"
  - Motion of Galaxy clusters
  - Universe Structure Formation
- What is it?
  - ~~Brown Dwarfs? Gas? Dust? Black Holes?~~
  - Less than 20% is "normal" matter
  - Should be heavy, (quasi)-stable, non-baryonic, neutral
  - Most popular:
    WIMPs
    "Weakly Interacting Massive Particles"
    For example: Neutralinos in the MSSM





Matter–Antimatter Asymmetry

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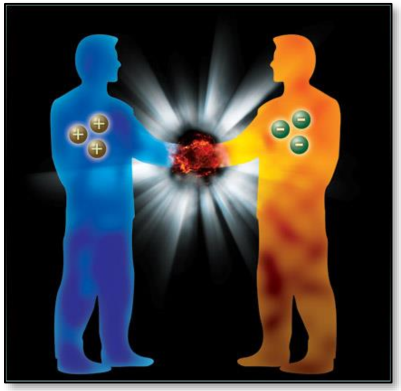
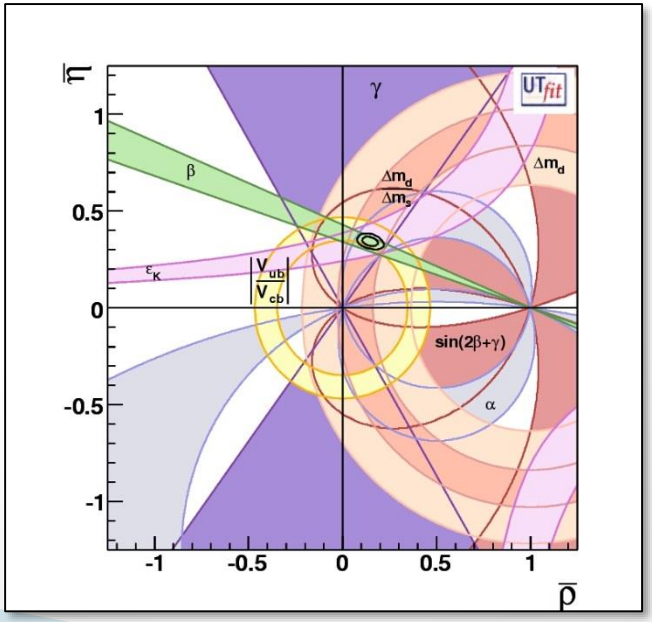
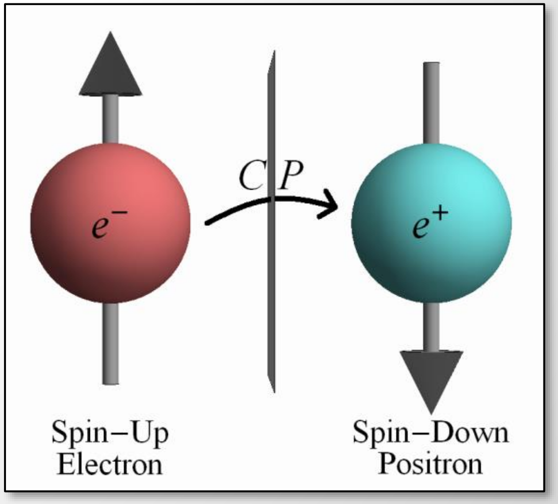
- What happened with all the antimatter?
- If perfectly balanced, it would have annihilated to nothing
- Particles and Anti-Particles need to behave slightly differently

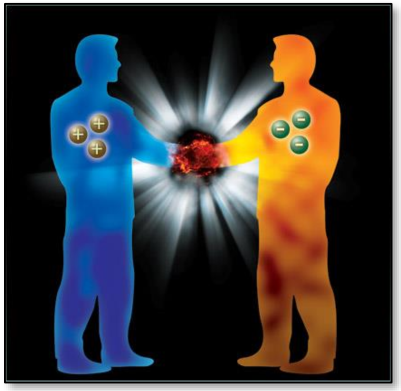


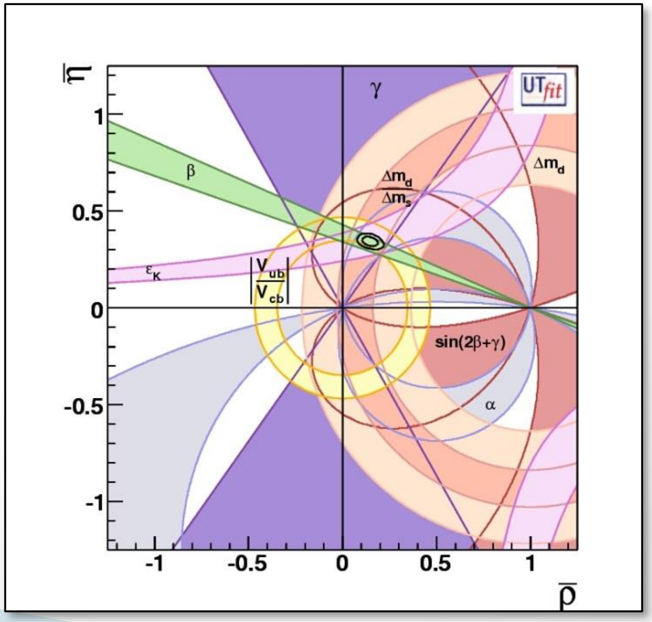


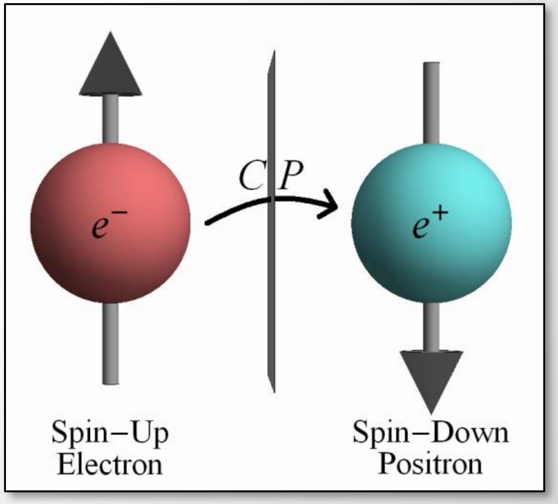


Matter–Antimatter Asymmetry

- Models have to satisfy Sakharov conditions:
  - Baryon number violation
  - C violation
  - CP violation
  - Departure from thermal equilibrium



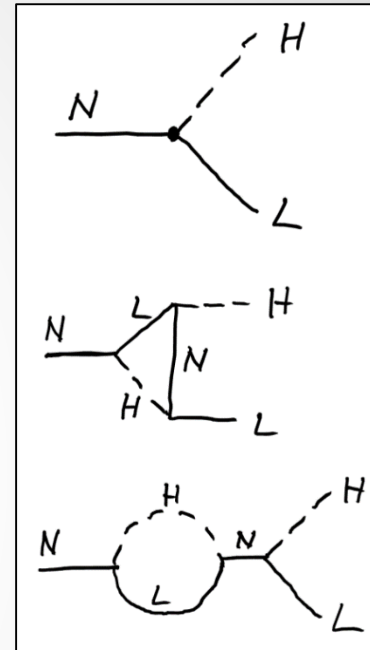


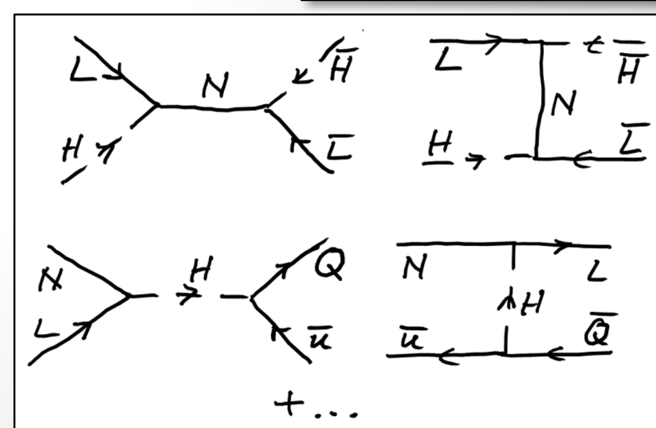


Matter–Antimatter Asymmetry

- Example: Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Solve Boltzmann equation(s) for number density of (leptons – antileptons)
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

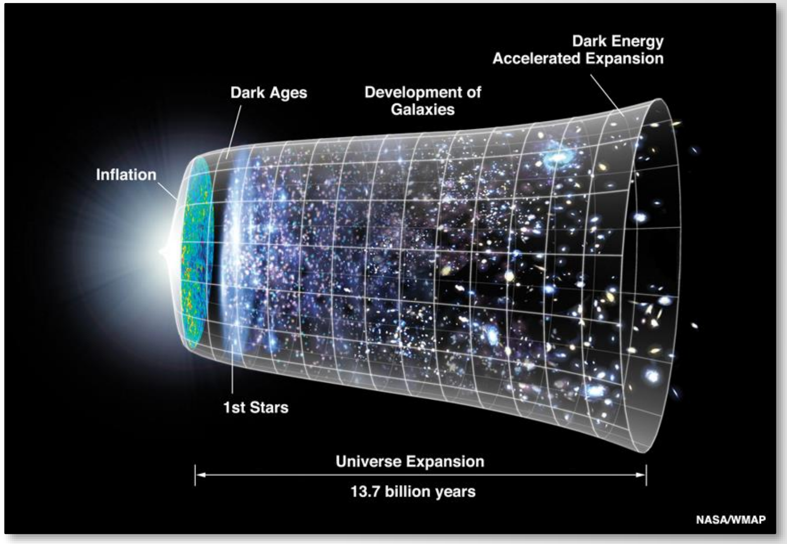
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$

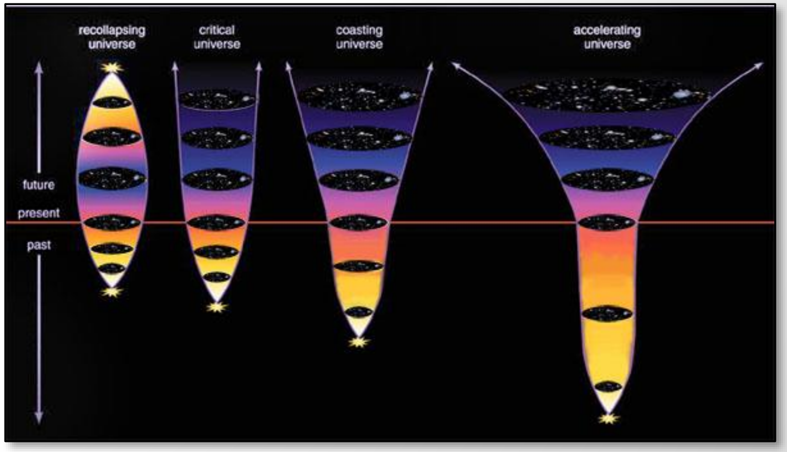




Dark Energy

- Inflation predicts a rapid exponential expansion in the early Universe
- Universe seems to be currently accelerating in its expansion
- Not possible with only matter and radiation present
- QFT vacuum energy leads to exponential expansion but
  - Observed cosmological constant $= (10^{-3}\ \text{eV})^4$
  - Naïve estimate $= \Lambda_{Pl}^4 \approx (10^{18}\ \text{GeV})^4$
  - Lowest estimate $= \Lambda_{EW}^4 \approx (10^{2}\ \text{GeV})^4$
    - → Predictions are 'slightly' off





Summary – Part II

There are a
lot of models

Summary – Part II

- There are a lot of models
- Some are better than others (potentially solve more problems of the SM)
- But there is no clear preference at the moment
- Searches for New Physics should probably best be driven by experimental signatures
- Very different models can have very similar signatures
  - Missing energy signatures in SUSY and Extra-Dimensional models (production of gravitons escaping the detector)
- Description in terms of Effective Field Theories provides a convenient way to do BSM physics “model-independently”
  - Without clear sign of New Physics, stronger emphasis on model-independent analyses (EFTs, simplified models)

Further Reading

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- I only list two books that cover a range of BSM physics frameworks. More detailed treatments of specific BSM models can be found in dedicated literature
  - "Unification and Supersymmetry: The Frontiers of Quark-Lepton Physics", Third Edition, Rabindra N. Mohapatra, Springer
    - Very theoretical and requires good knowledge of group theory
    - Provides a concise, insightful and detailed look into BSM gauge theories, supersymmetry and connections to string theory
  - "Beyond the Standard Model of Elementary Particle Physics", Yorikiyo Nagashima, Wiley-VCH
    - Quite recent and covers a wide range of frameworks (GUTs, SUSY, EDs, Axions)
    - Does not go very deep into theory but covers the phenomenology well, with many plots from original research papers
    - Includes cosmology and astrophysics (DM, Dark Energy)