Beyond the Standard Model

Frank Deppisch

f.deppisch@ucl.ac.uk

University College London

Part I – The Standard Model

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

The Standard Model

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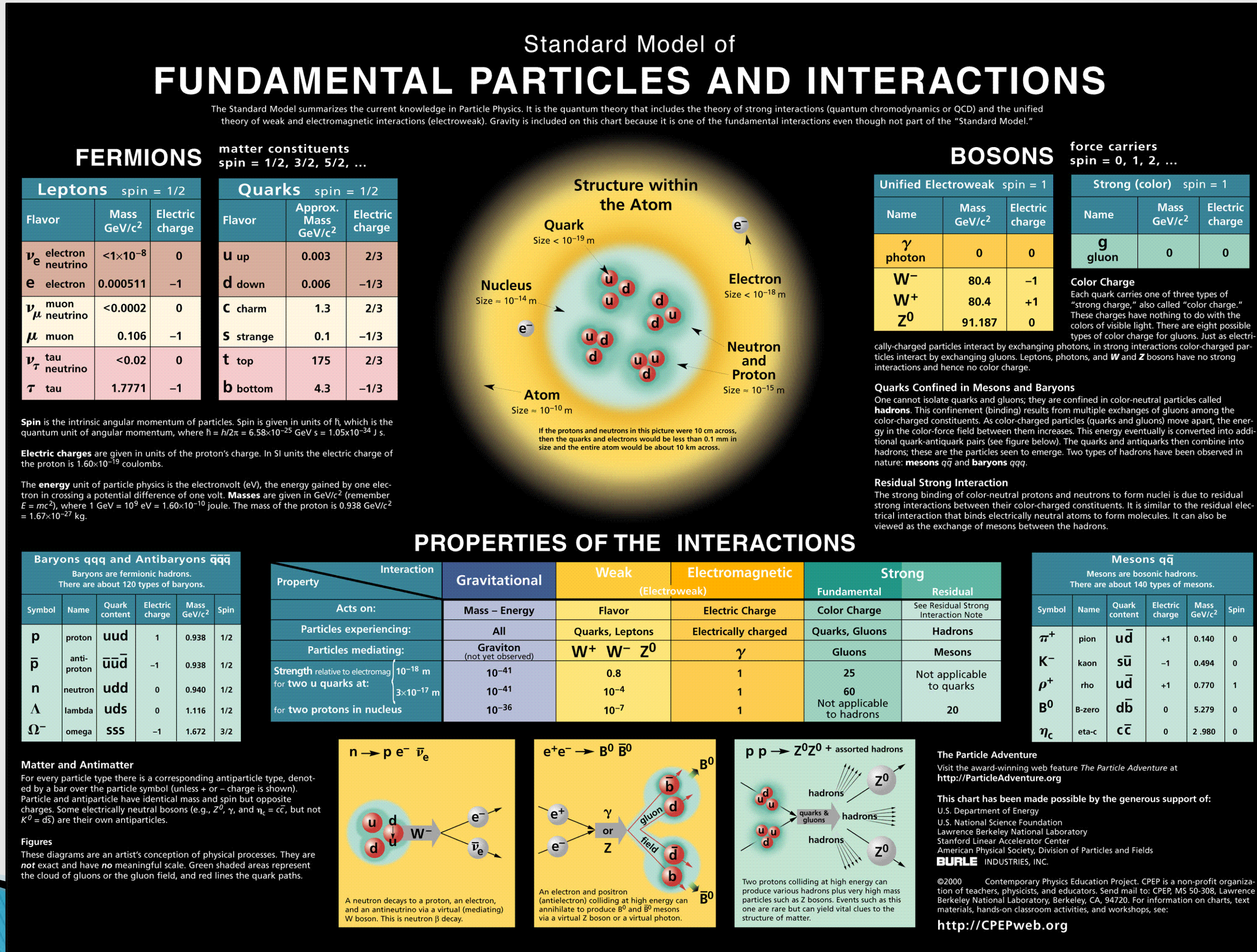

Standard Model of

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 = 1.05×10^{-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.

Structure within the Atom

Quark Size < 10^{-19} m

Nucleus Size ≈ 10^{-14} m

Electron Size < 10^{-18} m

Neutron and Proton Size ≈ 10^{-15} m

Atom Size ≈ 10^{-10} m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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.

$n \rightarrow p\, e^-\, \bar{\nu}_e$

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

$e^+e^- \rightarrow B^0\, \bar{B}^0$

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.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons

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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BURLE INDUSTRIES, INC.

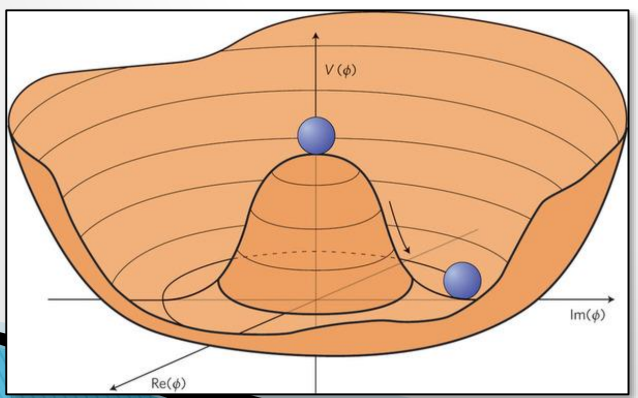
http://CPEPweb.org

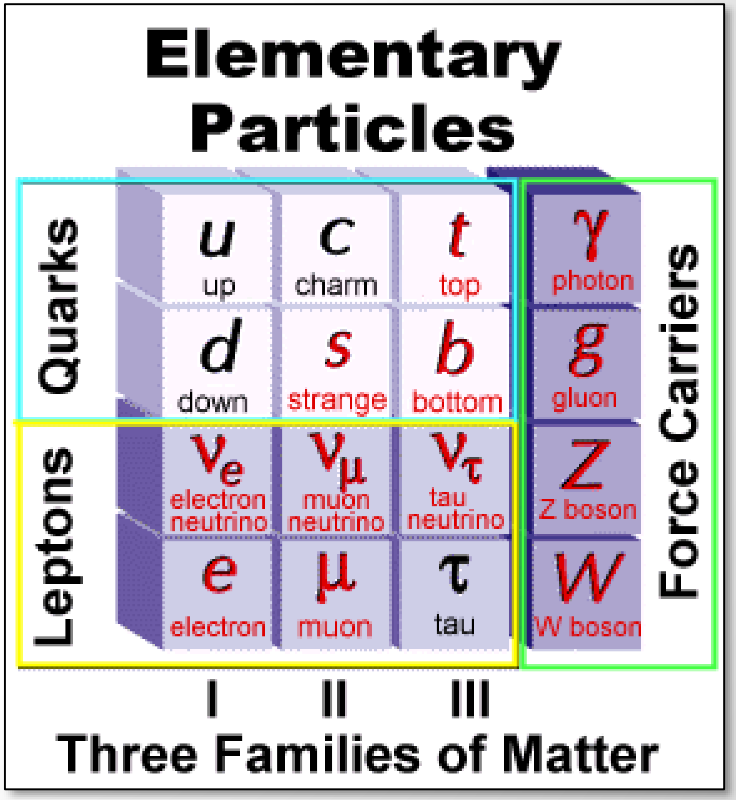
The Standard Model

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

$$\boxed{SU(3) \times SU(2) \times U(1)_Y}$$

- Spontaneously broken via Higgs Mechanism





The Standard Model

- Lagrangian

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

- 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

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- Lagrangian

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

- 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

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

- Yukawa Sector explicitly

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

- Freedom to rotate in flavour space

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

  - 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

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- Lagrangian

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

- Higgs Potential

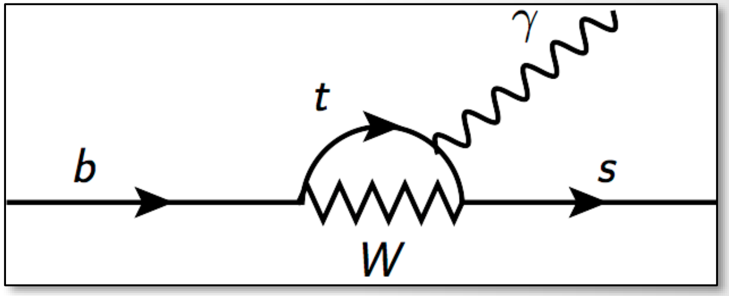
$$\boxed{V(H) = -\mu^2 H^+ H + \frac{\lambda}{4}(H^+ H)^2}$$

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

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

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 $\approx$???
    - Electroweak scale $\approx 10^2$ GeV and neutrino scale $\approx 10^{-2}$ eV (or $\approx 10^{14}$ GeV)
    - Electroweak scale $\approx (10^2\ \mathrm{GeV})^4$ and cosmological constant $\approx (10^{-3}\ \mathrm{eV})^4$
  - 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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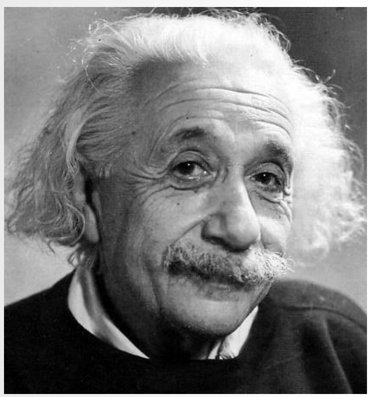
- First Goal: Falsification of Standard Model
- But so far it works nicely! (apart from above short-comings)
- Two approaches to look for signs of new physics

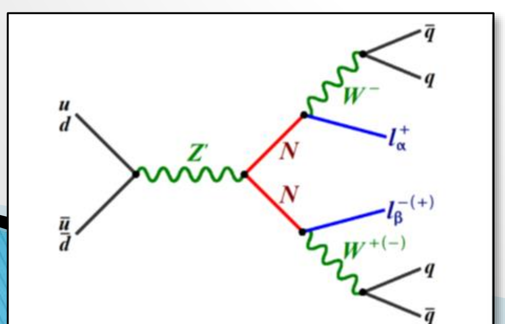


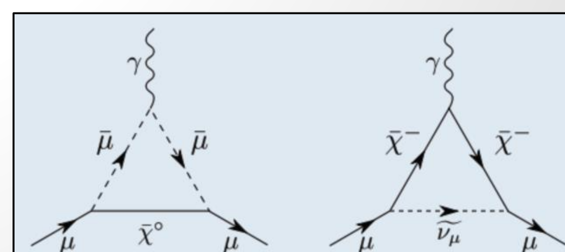
$$E = mc^2$$

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

Provide enough energy to create real heavy particles

Try often enough to see effect of virtual heavy particles





Avenues to BSM Physics

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- 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
    - Direct Dark Matter searches
    - Rare decays
  - Astrophysics
    - Cosmic microwave background
    - Cosmic rays
    - Large scale structure
      - Supernovae

Avenues to BSM Physics

- 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

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- 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?
- Beyond QFT: String Theory
- Summary
- Further Reading
- Exercises and Solutions

Gauge Unification

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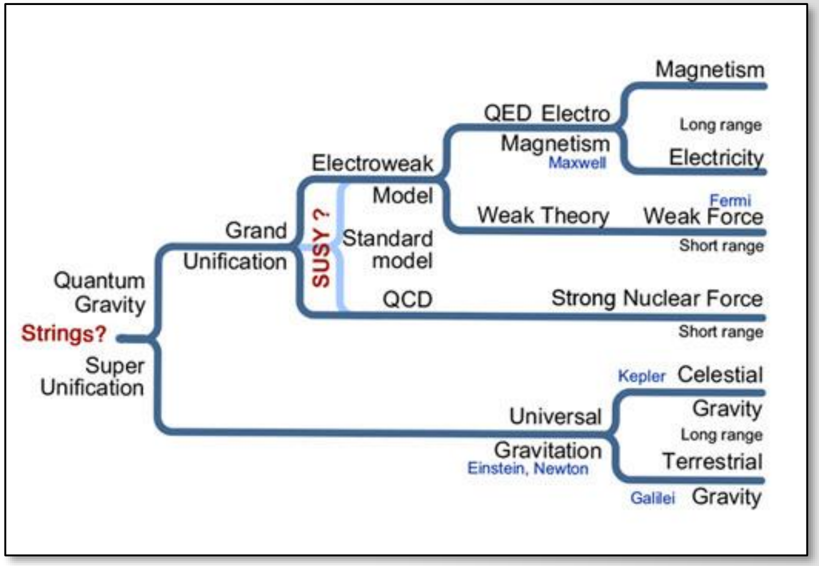
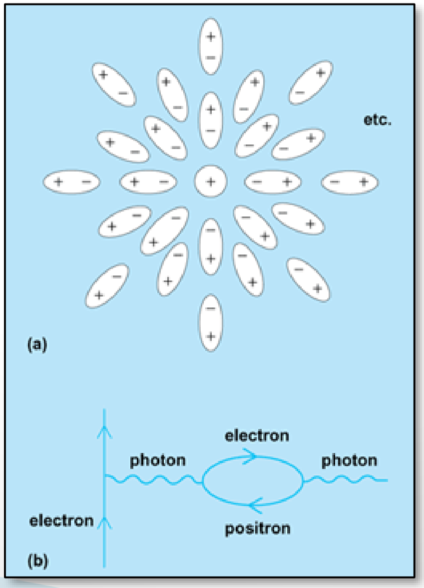
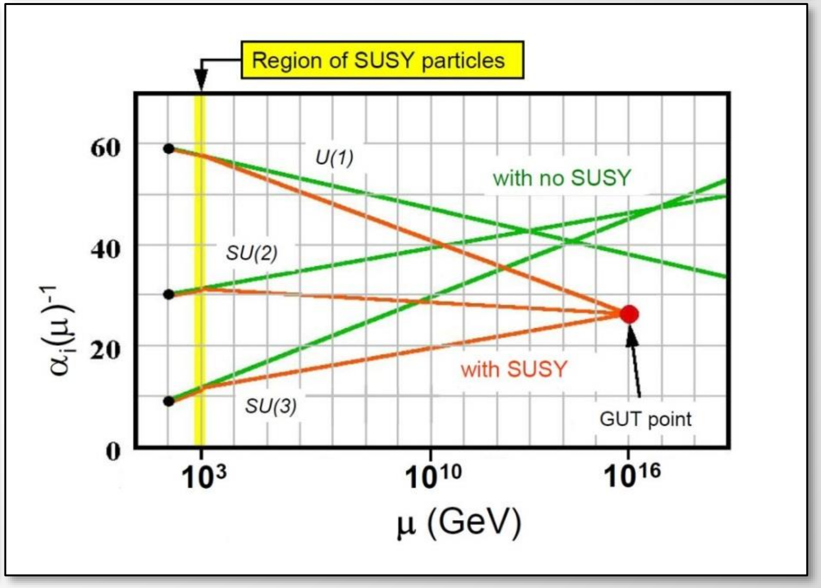
- Apply success of spontaneously broken gauge theory to other gauge symmetries / larger particle content
- Three forces in SM are different but very similar
- Do they have a common origin at high energies?
- Ultimate Goal: Unification to one force = Grand Unified Theories
  - "Shielding" due to quantum 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 $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$
  - 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

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

Gauge Unification

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- Gauge (adjoint) representations

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

- 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

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

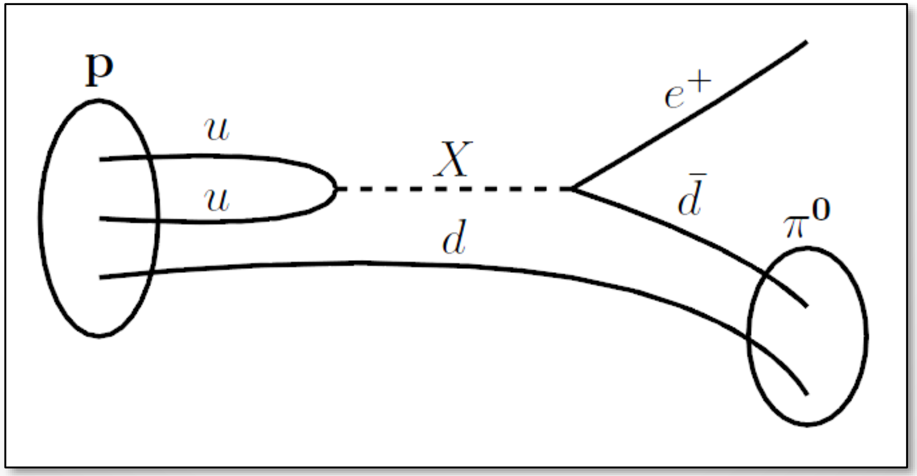
- Properties
  - Unification to one gauge group / coupling
    - Does not exactly work with observed SM gauge couplings (requires SUSY)
    - Partial unification around $\Lambda \approx 10^{15}$ GeV
  - Partial Yukawa coupling unification
    - Does not really work for SM masses
  - Neutrino masses are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

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

- 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

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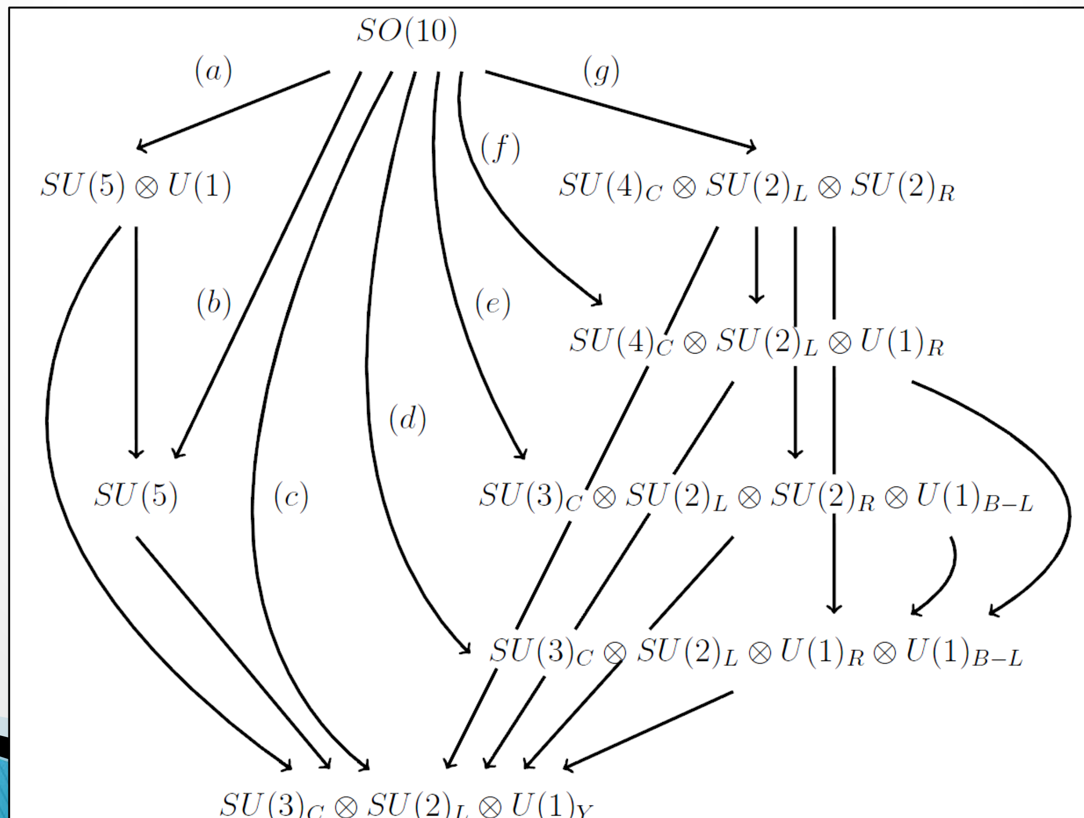
- Example: SO(10)
  - All fermions (of one generation) including right-handed neutrino unified in one 16-plet

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

  - Large number of possible gauge breaking chains

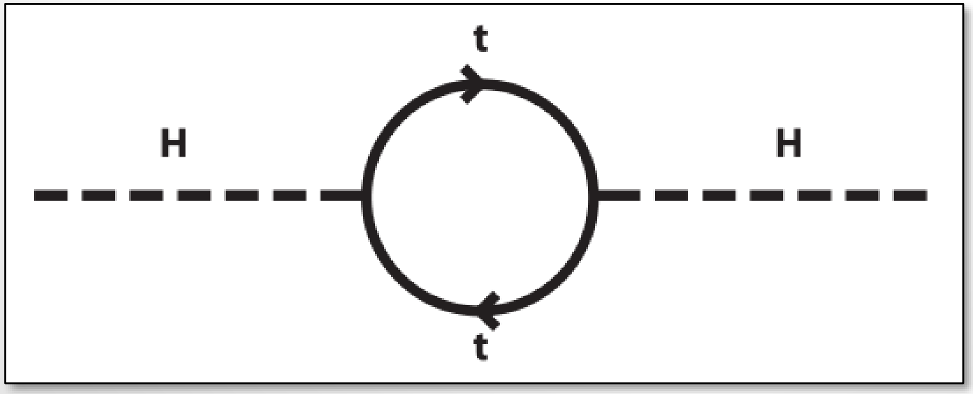


Naturalness

- 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

- 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

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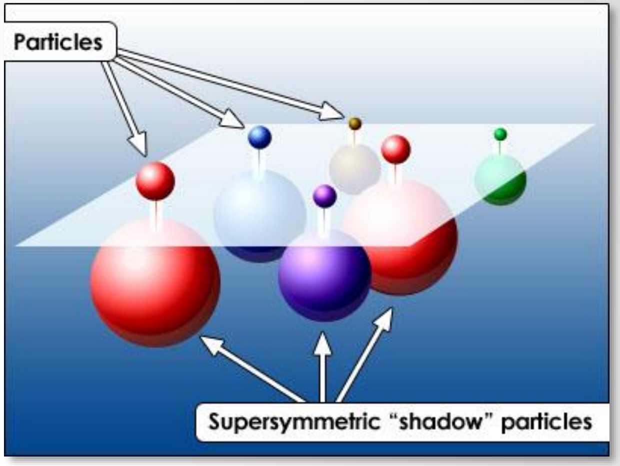
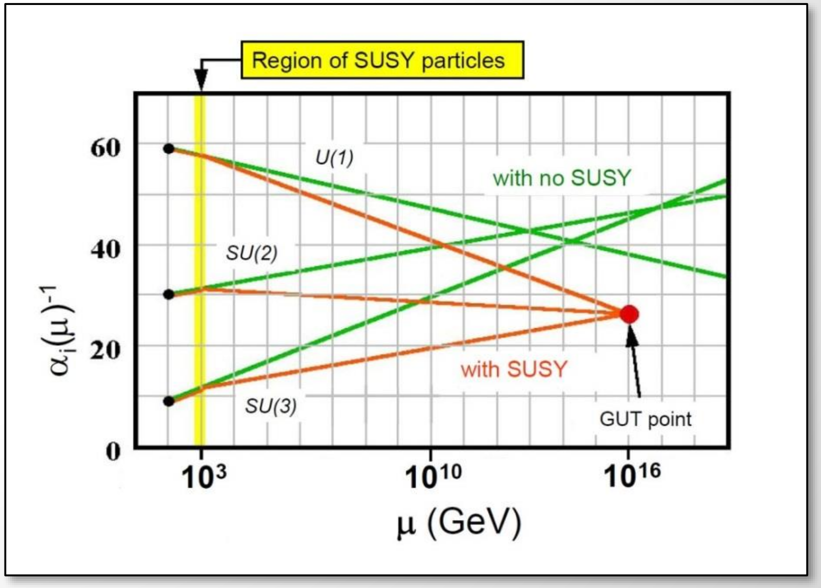
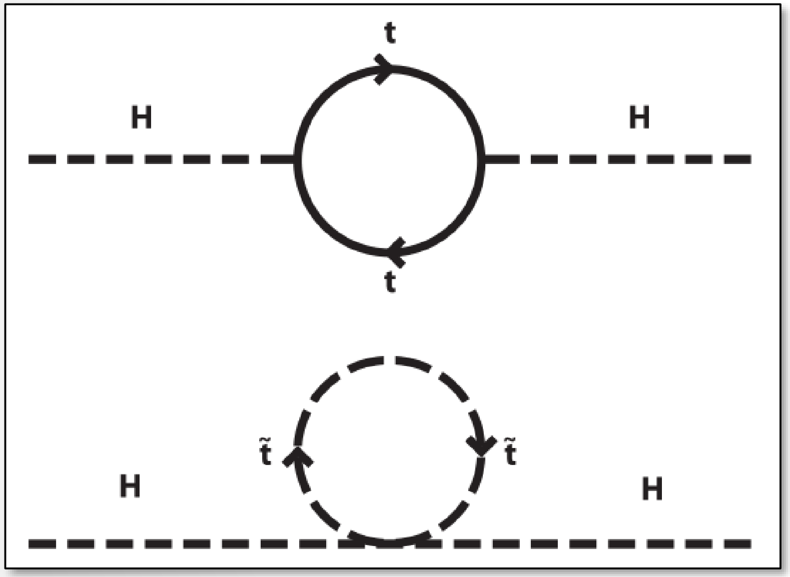


- Most popular extension of Standard Model
- Predicts symmetry between bosons and fermions
- Unifies force with matter particles
- May explain why Higgs mass is 125 GeV
- Deep theoretical advantages
  - Maximal symmetry of a Quantum Field Theory is Poincare x Gauge x Supersymmetry
  - Supersymmetry is 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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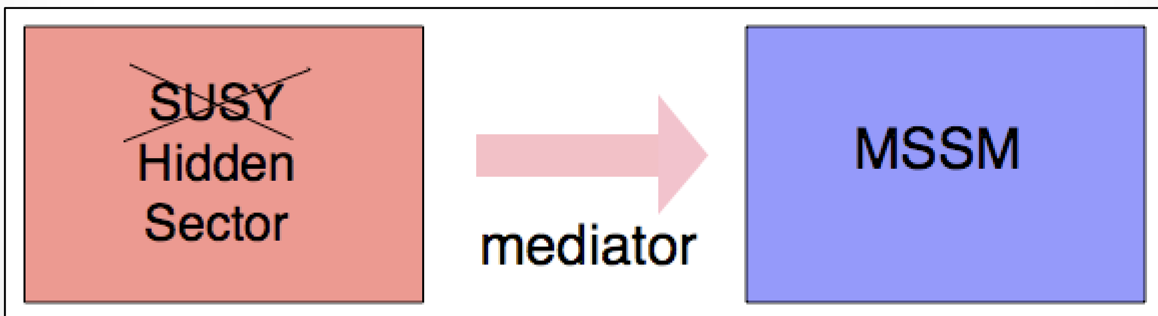
- The MSSM
  - Minimal supersymmetric version of the Standard Model

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

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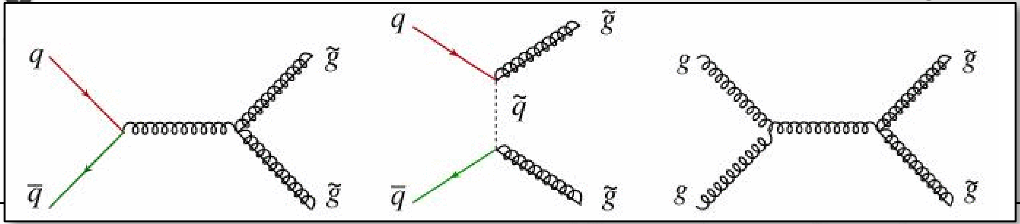
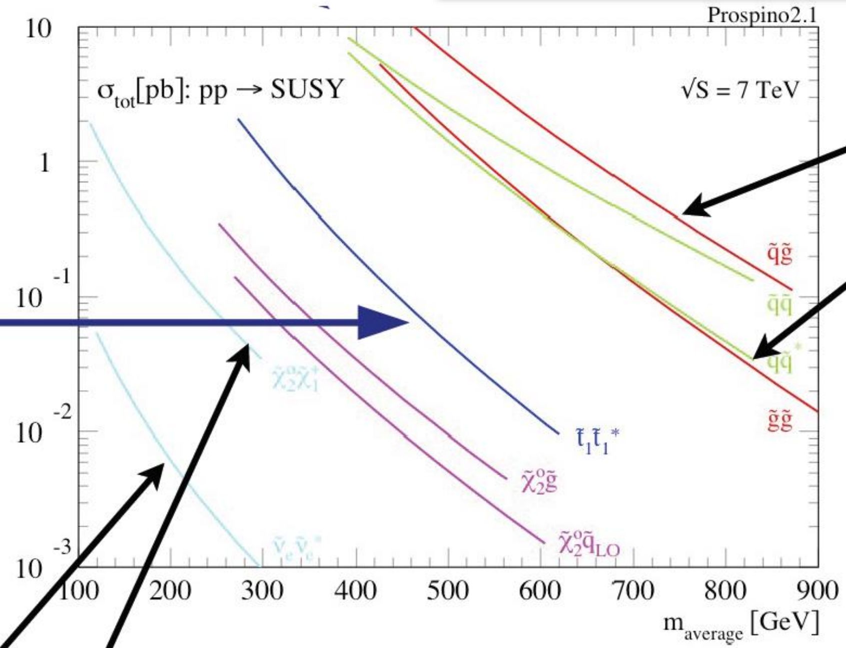
- Large number of free parameters
  - Look at simplified scenarios
    - e.g. SUSY breaking parameters unify at GUT scale $\approx 10^{16}\,\mathrm{GeV}$ (mSUGRA)
- Lightest SUSY particle (LSP) made stable via introduction of a "$\mathbb{Z}_2$“ symmetry called R-parity
  - Assigns −1 to SUSY particles 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



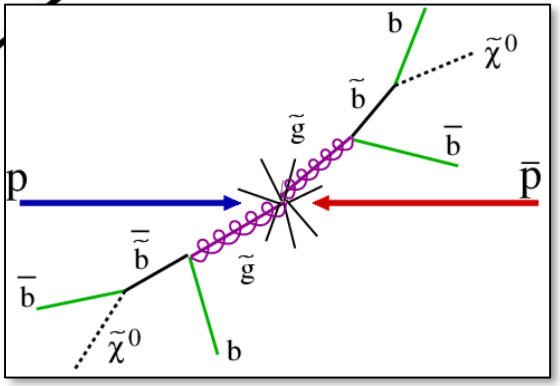


All searches so far rely on producing gluinos and/or 1st, 2nd gen. squarks, different decay channels

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: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

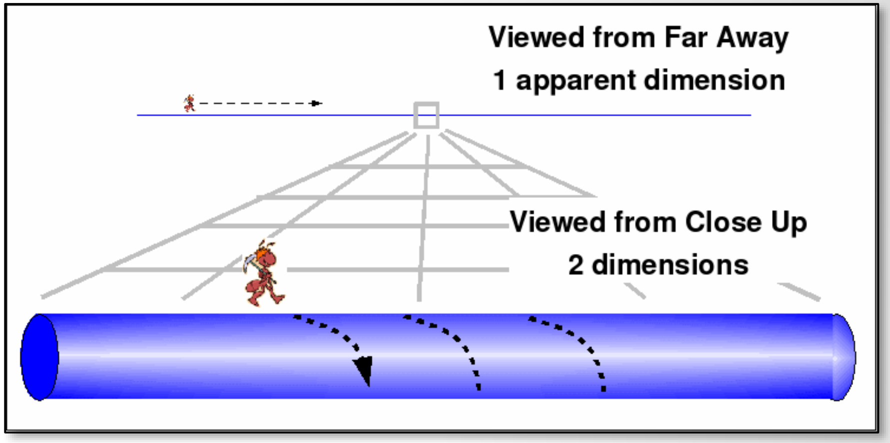
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm \to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

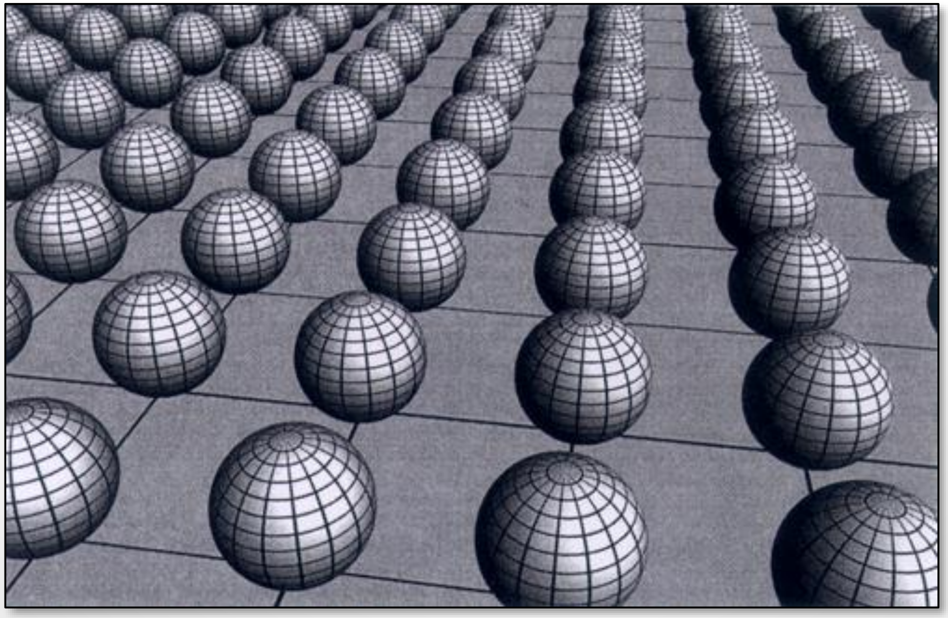
10^{-1} 1 **Mass scale [TeV]**

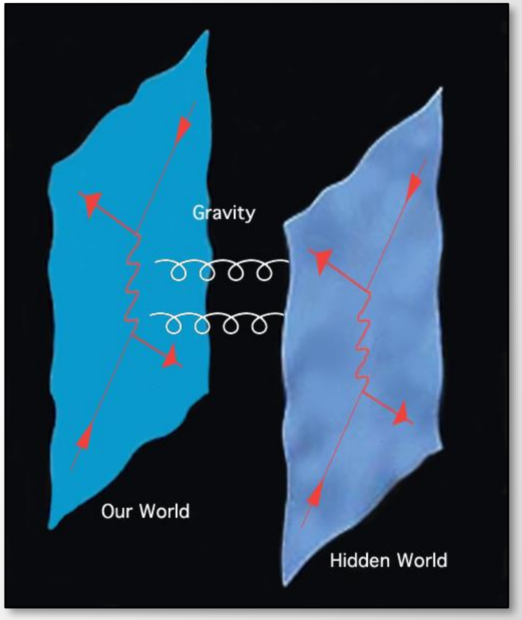
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

Extra Dimensions

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







Extra Dimensions

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- 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

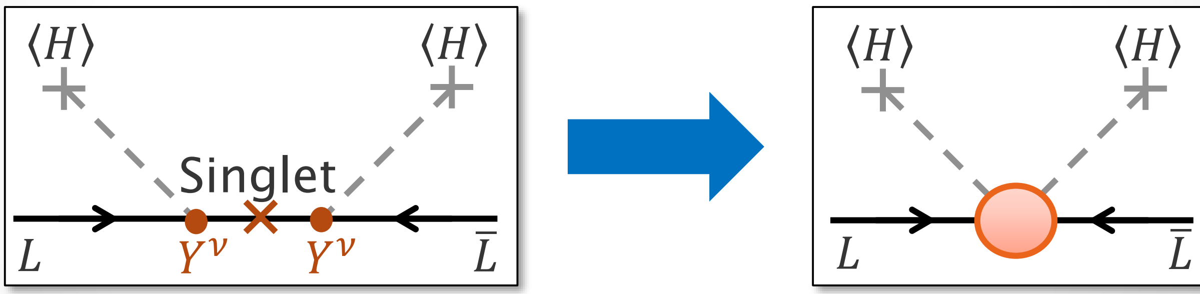
- Technicolor, Composite Higgs
  - Higgs is composite bound state (analogous to mesons in QCD)
  - New strong force around the TeV scale
  - Non-perturbative, difficult to calculate
- Little Higgs
  - Introduce global symmetry that forces Higgs mass = 0, and slightly break it
- Axions
  - Strong CP problem: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

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

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

Effective Field Theories

- 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

- Examples
  - Dimension-5 operator (only possibility)

    $\boxed{\mathcal{O}_5 = 1/2\,(\bar{L}_i \cdot H)(H^+ \cdot L_j)^c}$ $\longrightarrow$ Neutrino Majorana masses

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

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

    - Four Lepton

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

    - Two Lepton-Two Quark

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

Neutrino Masses

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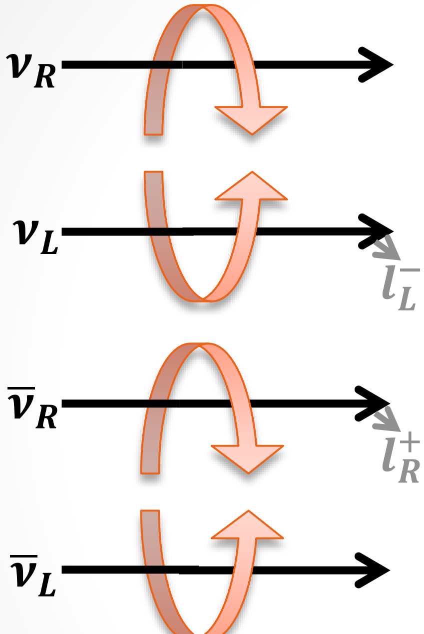
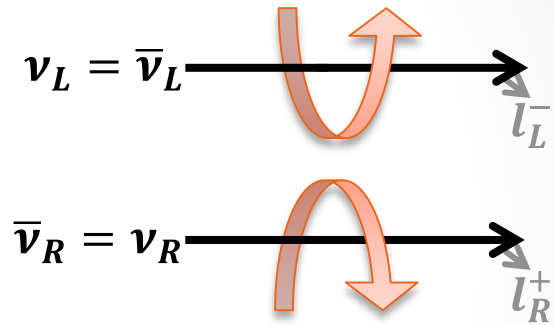
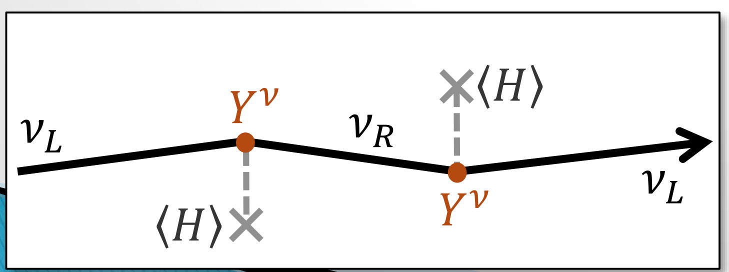
- Two possibilities to define neutrino masses

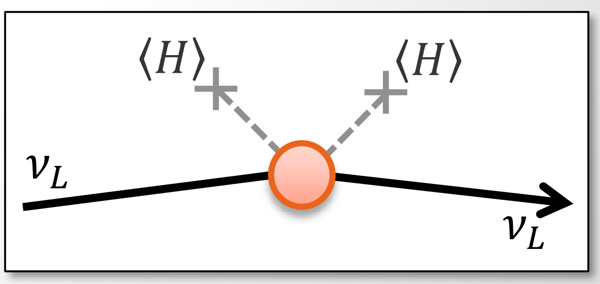




Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs

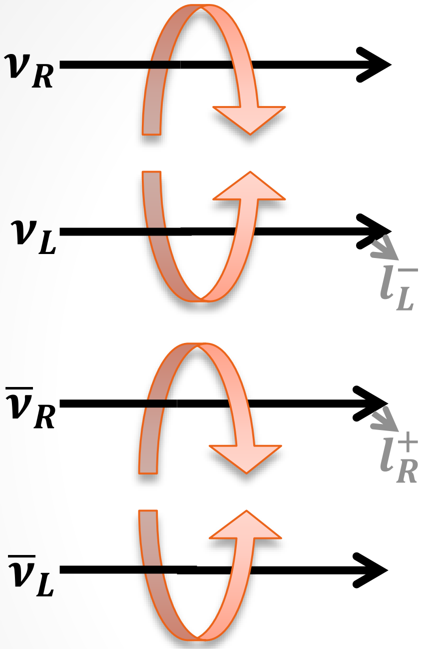


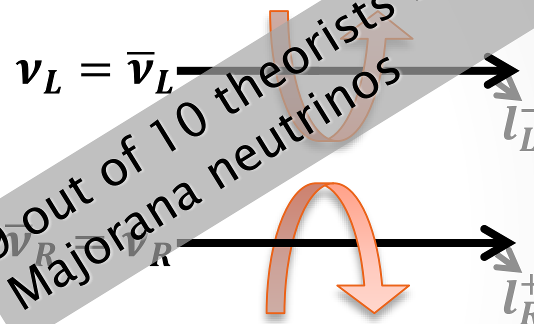
Majorana mass, using only a left-handed neutrino → Lepton Number Violation



Neutrino Masses

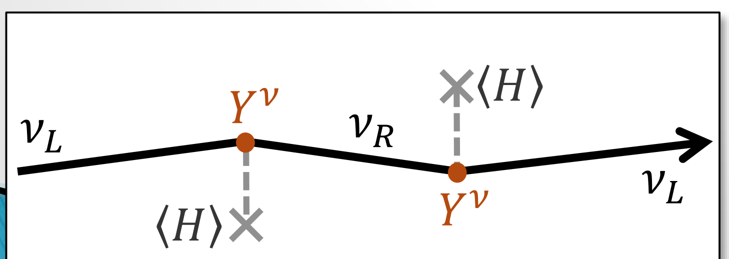
- Two possibilities to define neutrino masses



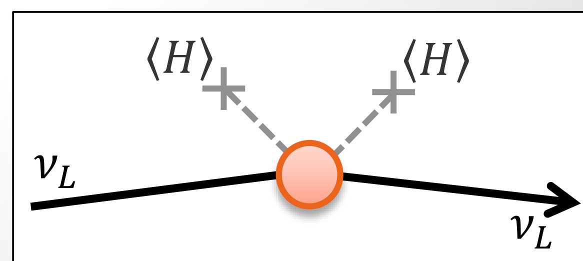


9 out of 10 theorists recommend Majorana neutrinos

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



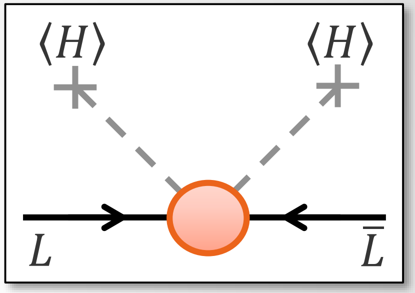
Majorana mass, using only a left-handed neutrino → Lepton Number Violation



Majorana Neutrino Masses

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

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

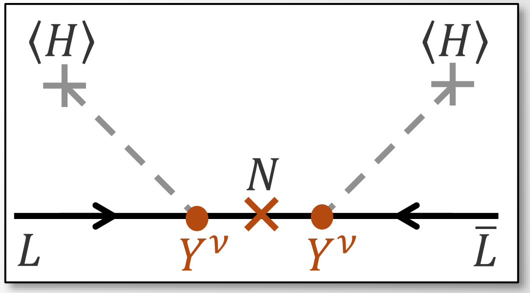


- Seesaw Mechanism
  - Add right-handed neutrinos N_i to SM, $M_N \approx 10^{14}$ GeV

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

- Light neutrino mass

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



Dark Matter

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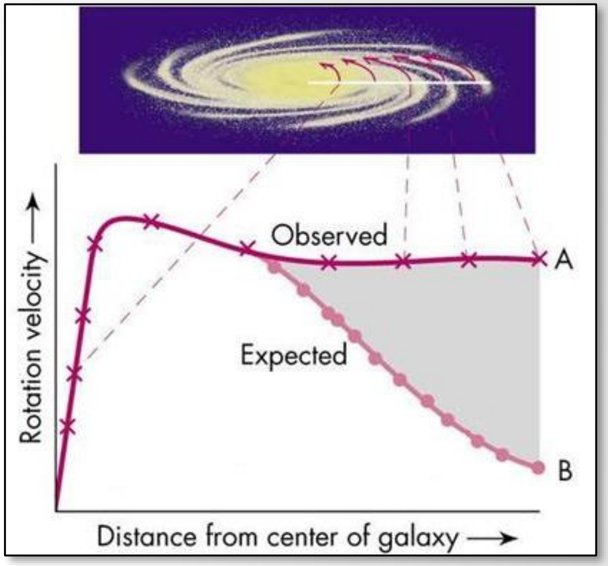
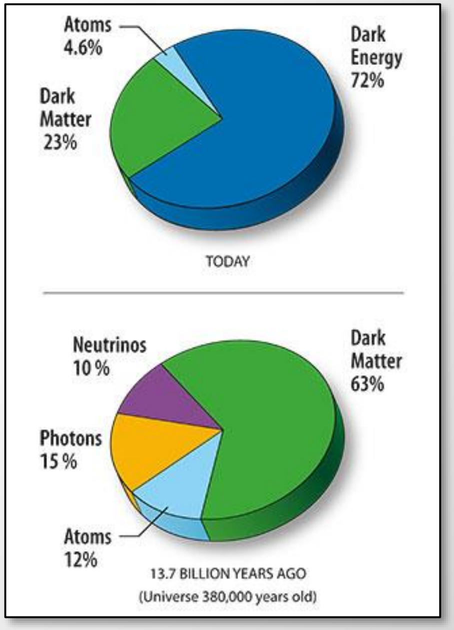
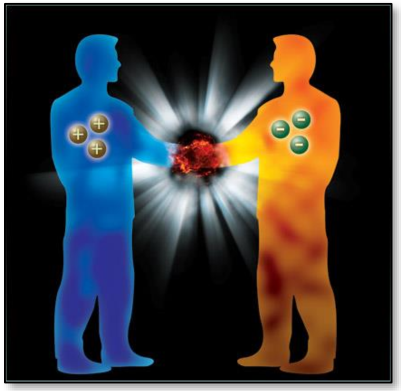
- There must be more mass than we can see
  - Galaxies rotate "too fast"
  - Motion of Galaxy clusters
  - Universe Structure Formation
- What is it?
  - ~~Brown Dwarfs? Gas? Dust? Black Holes?~~
  - Less than 20% is "normal" matter
  - Should be heavy, (quasi)-stable, non-baryonic, neutral
  - Most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

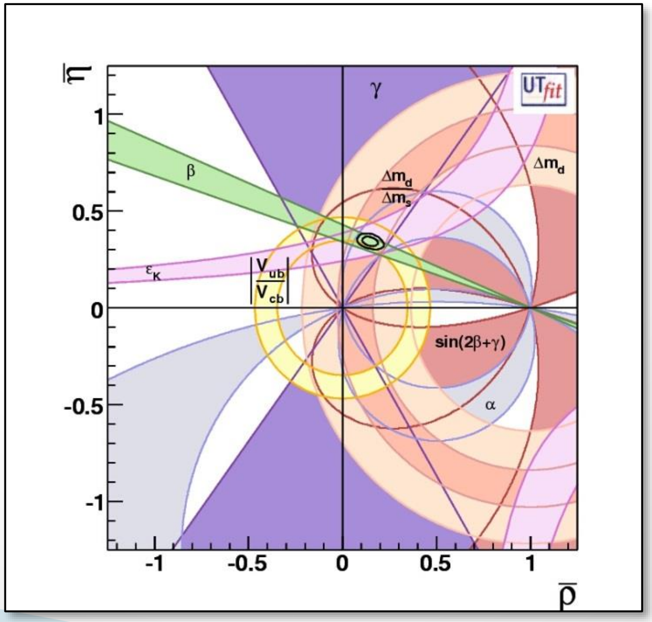


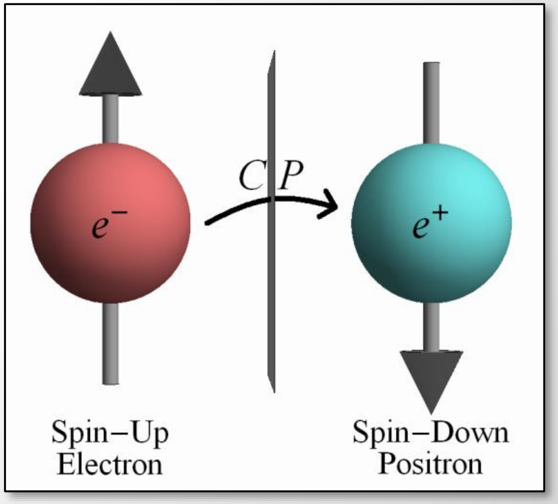


Matter–Antimatter Asymmetry

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







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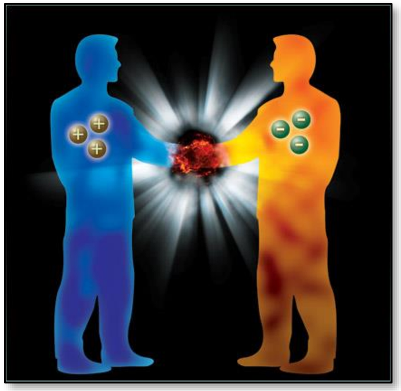
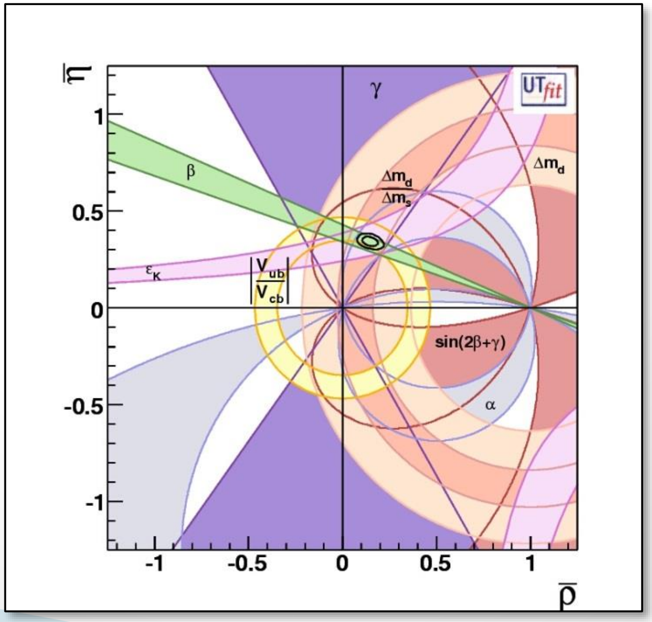
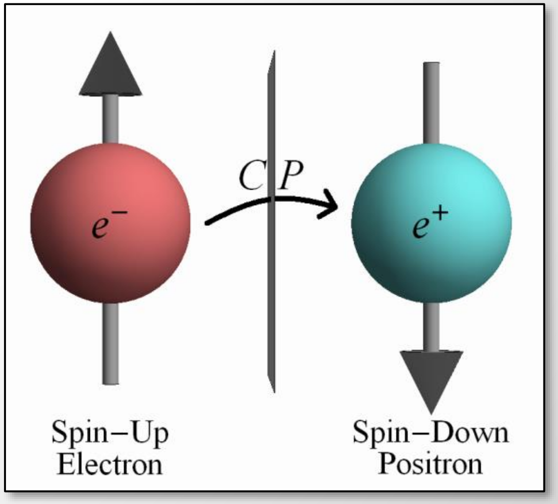
Matter–Antimatter Asymmetry

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

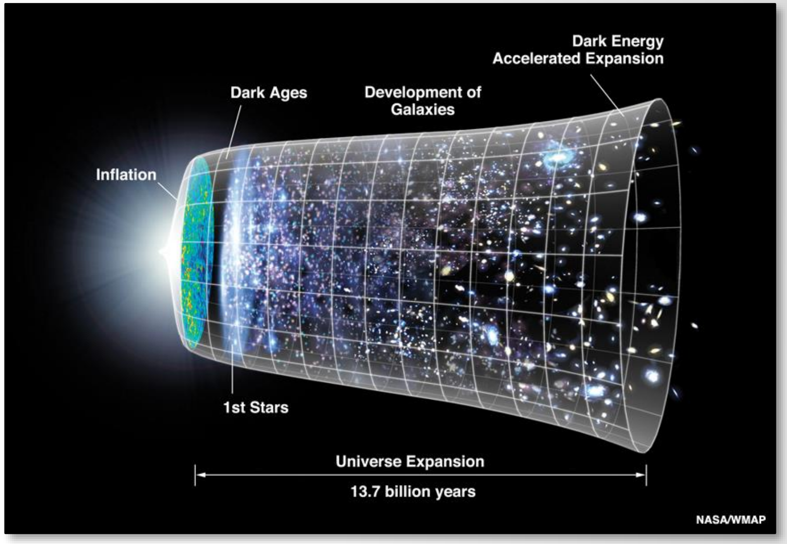


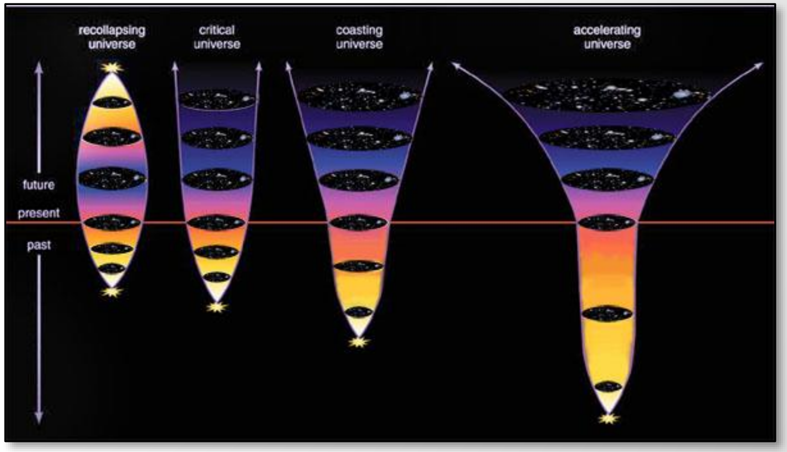




Dark Energy

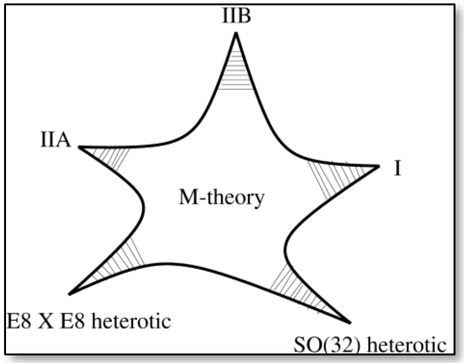
- Inflation predicts a rapid exponential expansion in the early Universe
- Universe seems to be currently accelerating in its expansion
- Not possible with only matter and radiation present
- QFT vacuum energy leads to exponential expansion but
  - Observed cosmological constant $= (10^{-3}\ \mathrm{eV})^4$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

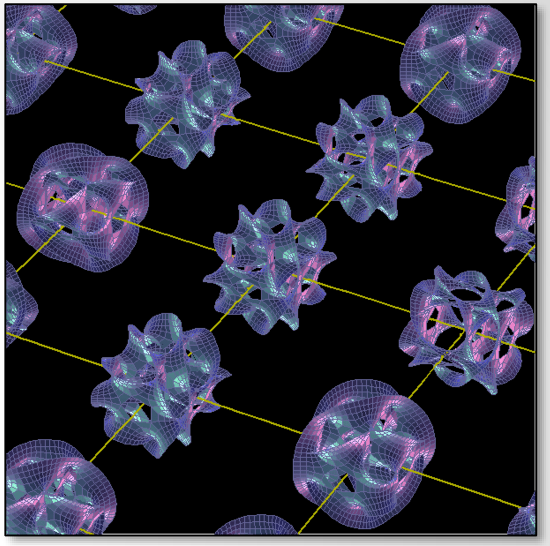


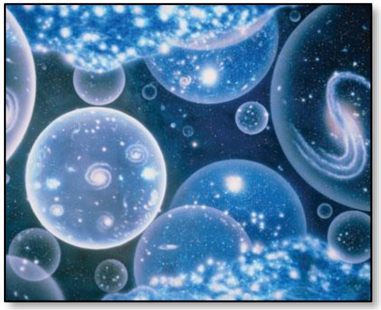


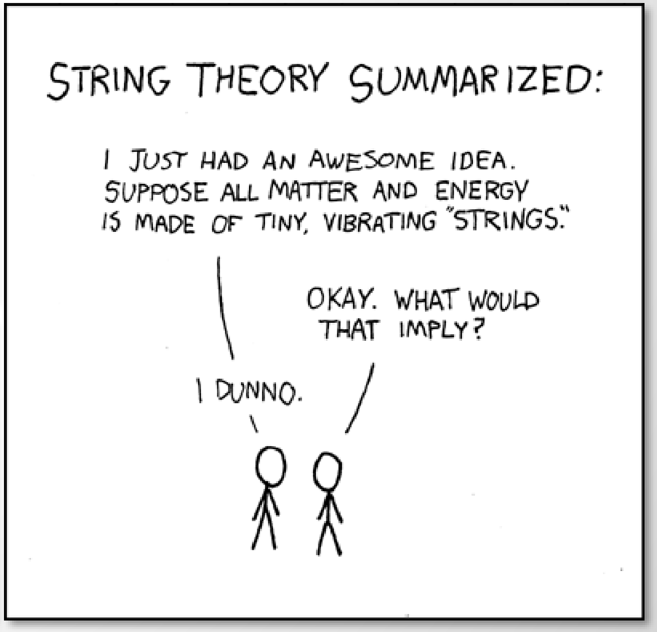
String Theory

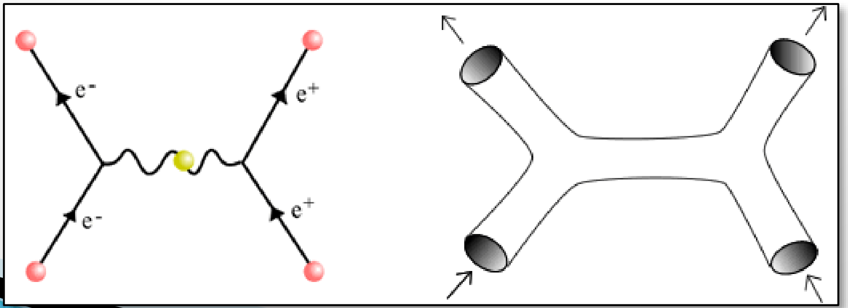
- Particles as Vibrations of Strings
- Quantum Gravity
- Requires
  - Supersymmetry
  - Extra Dimensions
- Structure strongly constrained
- $\sim 10^{500}$ possible vacua!
  - Landscape of Multiverses











Summary – Part II

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There are a
lot of models

Summary – Part II

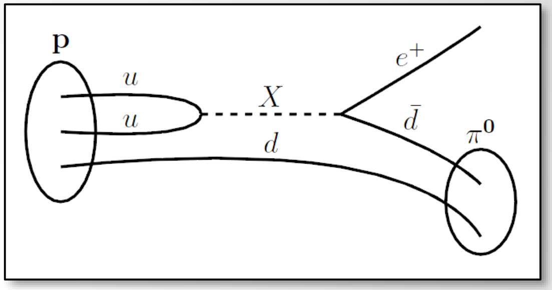
- There are a lot of models
- Some are better than others (potentially solve more problems of the SM)
- But there is no clear preference at the moment
- Searches for New Physics should probably best be driven by experimental signatures
- Very different models can have very similar signatures
  - Missing 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"

Further Reading

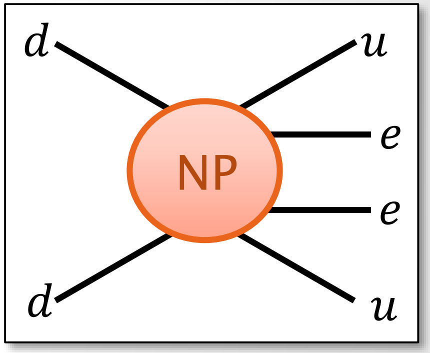
- I only list two books that cover a range of BSM physics frameworks. More detailed treatments of specific BSM models can be found in dedicated literature
  - "Unification and Supersymmetry: The Frontiers of Quark-Lepton Physics", Third Edition, Rabindra N. Mohapatra, Springer
    - Very theoretical 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)

A few exercises

Back-of-the-envelope estimation



- 1) Estimate the half life for the proton decay shown in GUT models.
  - Given the current limit $T^{1/2} >\approx 10^{34}$ y, what is the constraint on the GUT scale?



- 2) Estimate the half life for neutrinoless double beta decay via the effective operator shown. (The phase space is not so simple here as the decay takes place inside a nucleus, e.g. ${}^{76}_{32}\text{Ge} \to {}^{76}_{34}\text{Se} + 2e^-$. Try to find out how much kinetic energy the electrons acquire.)
  - Given the current limit $T^{1/2} >\approx 10^{25}$ y, what is the constraint on operator scale?
- 3) Estimate the branching ratio of the lepton flavour violating decay $\mu \to e\gamma$ via the operator $\bar{L}_i \sigma^{\mu\nu} e_j^c H^+ F_{\mu\nu}$.
  - Given the current limit $Br(\mu \to e\gamma) <\approx 10^{-13}$, what is the constraint on the operator scale?

Spoiler Alert: Solutions Ahead

1) The heavy gauge boson X mediates the decay between 4 fermions, i.e. the effective operator is of dimension 6. In the Lagrangian it would appear as (symbolically)

$$\frac{c}{\Lambda_{GUT}^2}\, uude$$ (c: collects coupling factors in the UV model - dimensionless)

$\Rightarrow$ Decay Rate: $\Gamma \approx |M|^2 dPS \approx \left(\frac{c^2}{\Lambda_{GUT}^2}\right)^2 dPS$

Estimate phase space dPS through dimensional analysis, neglecting positron and pion mass compared to proton mass m_p

$$\Rightarrow \Gamma \approx \frac{c^4}{\Lambda_{GUT}^4}\, m_p^5$$

$\Rightarrow$ Decay half life $T_{1/2}$

$$\frac{1}{T_{1/2}} \approx \frac{c^4}{\Lambda_{GUT}^4} m_p^5$$

Use $m_p \approx 1\,\text{GeV}$, set $c \approx 1$ (order one couplings)

$$T_{1/2} \gtrsim 10^{34}\,y, \qquad 6.6 \times 10^{-16}\,s = (eV)^{-1}$$

$$\Rightarrow \Lambda_{GUT} \gtrsim 10^{14}\,\text{GeV}$$

2) The decay is mediated by an effective 9-dimensional operator connecting 6 fermions,

$$\frac{c}{\Lambda_{0\nu\beta\beta}^5}\, uuddee$$

$\Rightarrow$ Decay rate: $\Gamma \approx \frac{c^2}{\Lambda_{0\nu\beta\beta}^{10}}\, dPS$

The phase space is not so easy to estimate here as the decay happens within a heavy nucleus to 2 electrons and a lighter but still heavy nucleus $\rightarrow$ look up the mass difference Δm between nuclei $\rightarrow$ energy available to electrons $\Delta m = Q + 2m_e$. The Q-value gives the kinetic energy released to the electrons

$$\Rightarrow \quad \Gamma \approx \frac{c^2}{\Lambda_{0\nu\beta\beta}^{10}}\, Q^{11}$$

$\Rightarrow$ Decay half life

$$\frac{1}{T_{1/2}} \approx \frac{c^2}{\Lambda_{0\nu\beta\beta}^{10}} Q^{11}$$

Use $Q \approx 3\,\text{MeV}$, $c = 1$

$$T_{1/2} \gtrsim 10^{25}\,y$$

$$\Rightarrow \Lambda_{0\nu\beta\beta} \gtrsim 100\,\text{GeV}$$

3) The relevant operator is 6-dimensional,

$$\frac{c}{\Lambda_{LFV}^2} \bar{L}_\mu \sigma^{\mu\nu} e^c H^\dagger F_{\mu\nu}$$

This operator mediates $\mu \to e\gamma$ once H acquires a vacuum expectation value v,

$$\frac{cv}{\Lambda_{LFV}^2} \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu}$$

$$\Rightarrow \text{Decay rate: } \Gamma_{\mu \to e\gamma} \approx \frac{c^2 v^2}{\Lambda_{LFV}^4} m_\mu^3$$

Phase space, neglecting m_e

Write in terms of branching ratio and total decay rate Γ_μ

$$\Gamma_{\mu \to e\gamma} = Br(\mu \to e\gamma) \times \Gamma_\mu$$

$$\Rightarrow \quad \frac{Br(\mu \to e\gamma)}{\overline{T}_{1/2}} = \frac{c^2 v^2}{\Lambda_{LFV}^4} m_\mu^3$$

total μ half life

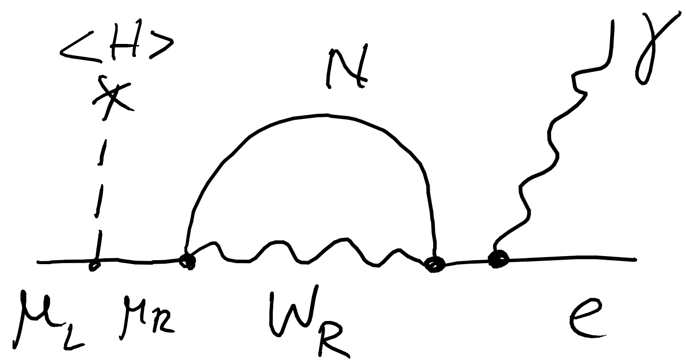
Use $m_\mu \approx 0.1$ GeV, $c = 1$, $v \approx 100$ GeV

$\overline{T}_{1/2} \approx 2 \times 10^{-6}$ s, $Br(\mu \to e\gamma) \lesssim 10^{-13}$

$$\Rightarrow \Lambda_{LFV} \gtrsim 7 \times 10^5 \text{ GeV}$$

A few embellishments:

- This operator cannot be generated at tree level, i.e. heavy particles in BSM models must run in loops (see example left with right-handed W_R boson and heavy neutrino N)
  $\Rightarrow$ extra loop suppression $\approx \frac{1}{16\pi^2}$



- The photon must couple via an electromagnetic coupling e
  $\Rightarrow$ can write: $c = e \cdot c'$

- In many cases, the Higgs coupling to the muon gives the main contribution,
  $\Rightarrow$ $c' = y_\mu c''$ ← μ Yukawa coupling

Including all modifications would give

$$\Gamma_{\mu \to e\gamma} \approx \frac{e^2 c''^2}{(16\pi^2)^2} \frac{\overbrace{y_\mu^2 v^2}^{m_\mu^2}}{\Lambda_{LFV}^4} m_\mu^3$$

$$\approx \frac{e^2 c''^2}{(16\pi^2)^2} \frac{m_\mu^5}{\Lambda_{LFV}^4}$$