Beyond the Standard Model

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Outline

- Why go Beyond the Standard Model
- How to go BSM
- Supersymmetry
- Extra dimensions
- Multi-Higgs models
- Flavour or family symmetries

Questions

- What are we made of?
- What is the origin of the Universe?
- What holds thing together?
- Why is there life?
- What am I doing here?

- The Standard Model and theories beyond are our attempt to answer some of these questions (perhaps not the last one)

Symmetries

- Quantum field theory - combines quantum mechanics and special relativity
- Space-time symmetries: rotations, translations, Lorenz and Poincaré transformations
- Internal symmetries: transformation of the fields in the theory → gauge symmetries
- Global → spacetime momentum, angular momentum, spin
- Local → gauge symmetries
- Continuous symmetries → conserved quantities
  - rotational symmetry angular momentum conservation
  - translational symmetry momentum and energy conservation
- Discrete → charge and parity conjugation CP
- Label and classify particles
- Determine interactions among particles → they must respect the symmetries
- Exact, broken, a little bit broken (softly), hidden

Symmetries

- Modern physics is built on the observation that there are symmetries in Nature (exact or broken)
- Symmetry is a transformation that leaves the system invariant

- QFT is built on space-time symmetries and internal symmetries:

- Space-time symmetries
  transformation acts on coordinate of space-time

$$x^\mu \to \quad x'^\mu(x^\nu) \qquad\qquad \mu,\nu = \{0,1,2,3\}$$

- Internal symmetries
  transformations of the different fields

$$\Phi^a(x) \to T^a{}_b\,\Phi^b(x)$$

$$T^a{}_b = const.$$

symmetry is global

$$T^a{}_b(x)$$

symmetry is local

- Symmetries have as a consequence conserved quantities — Noether’s theorem

- They classify and label particles:
  mass, charge, color, spin, etc

- Invariance under gauge symmetries needs extra gauge bosons, which are the mediators of the interactions, of spin 1

- Invariance under the Poincaré group needs a gravitational field, of spin 2

Accidental Symmetries

- They appear, not imposed $\psi \to \mathrm{e}^{iB\theta}\psi$
- Baryon number
  $B = 1/3$ for quarks, $B = 0$ for leptons
  prevents proton decay
- And the leptonic symmetries:
  zero for the rest

$$\boxed{\begin{aligned} L_e &= L_{\nu_e} = 1 \\ L_\mu &= L_{\nu_\mu} = 1 \\ L_\tau &= L_{\nu_\tau} = 1 \end{aligned}}$$

prevent decays like $\mu \to e\gamma$
also predicts massless neutrinos -
in contradiction with experiment

Broken symmetries

- The SM has also, C, P and T discrete symmetries
- CPT conserved
- P violated in weak interactions, respected in EM and strong
- C violated in weak interactions
- CP violated in weak interactions, not in strong and EM

The Standard Model

- Poincaré symmetry in 4D
- Internal symmetries = gauge symmetries

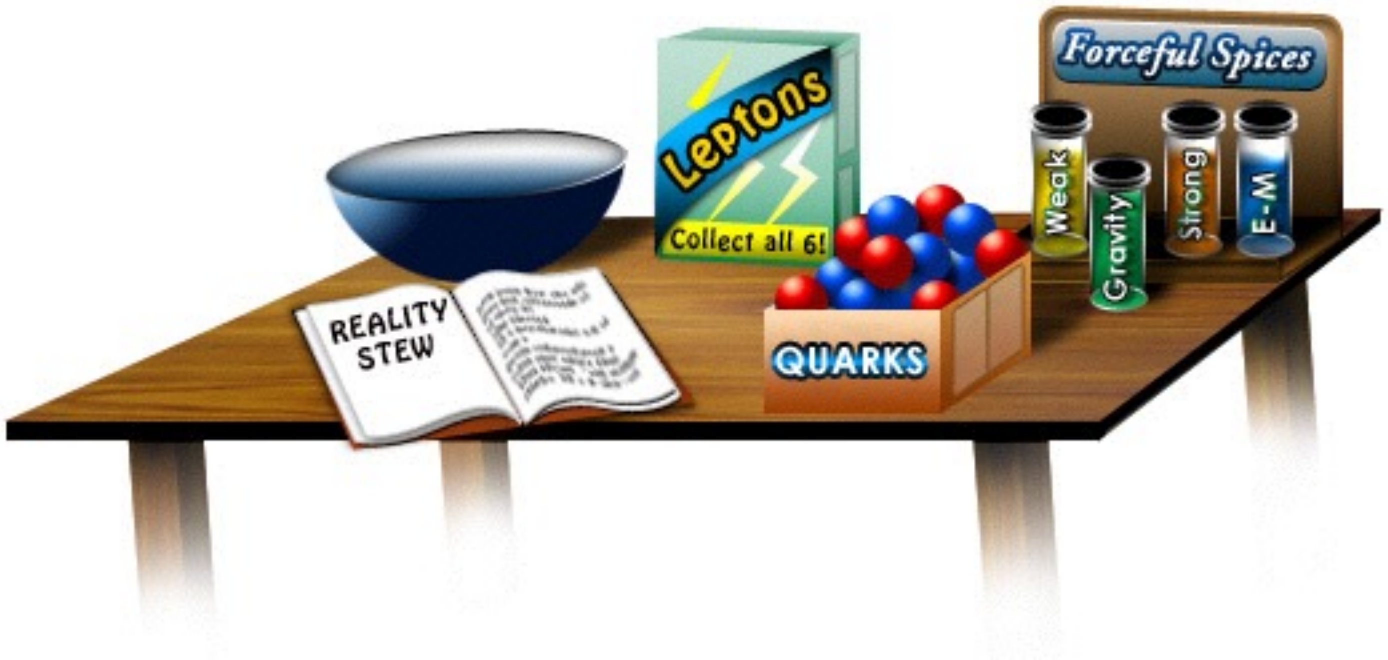
  SU(3) strong interaction

  SU(2)×U(1) electroweak

- Particles acquire mass via the Higgs mechanism → electroweak symmetry breaking

- Gauge fields are bosons
- Matter fields are fermions
- Very different statistics

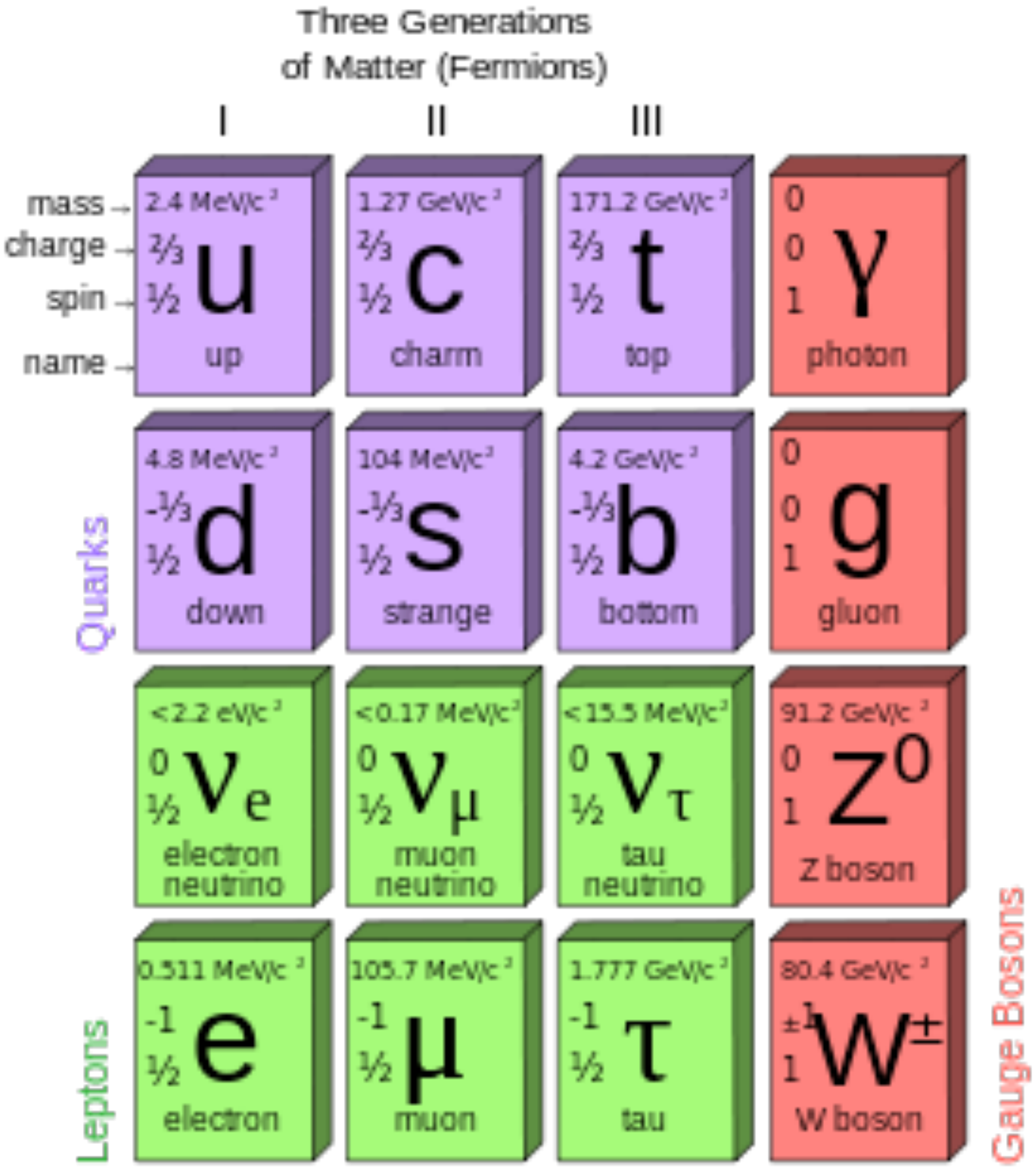
- Standard Model very well tested
- Constructed by an interplay between theory and experiment
- Based on symmetry principles



SM Lagrangian

- Gaugegroup
  $SU(3)_C \times SU(2)_L \times U(1)_Y$

  strong, weak and electromagnetic interactions gauge bosons mediators of force:
  gluons, W±, Z, photons
- Yukawa interactions mediated by the Higgs boson
- Particles acquire mass through the Higgs mechanism

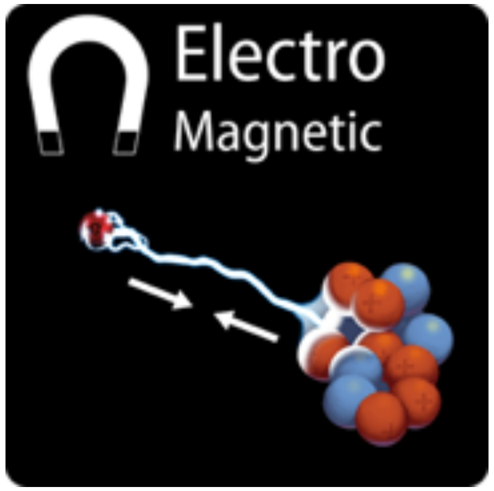


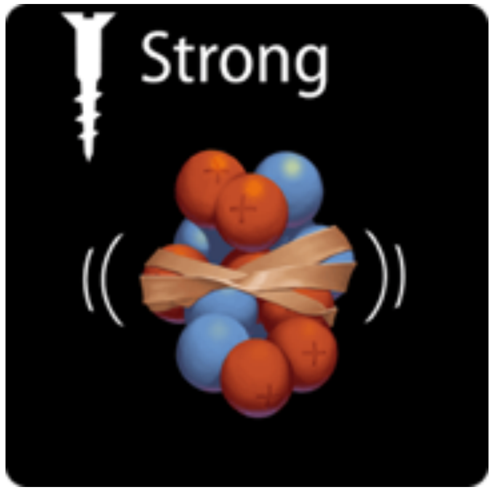
Three Generations of Matter (Fermions)

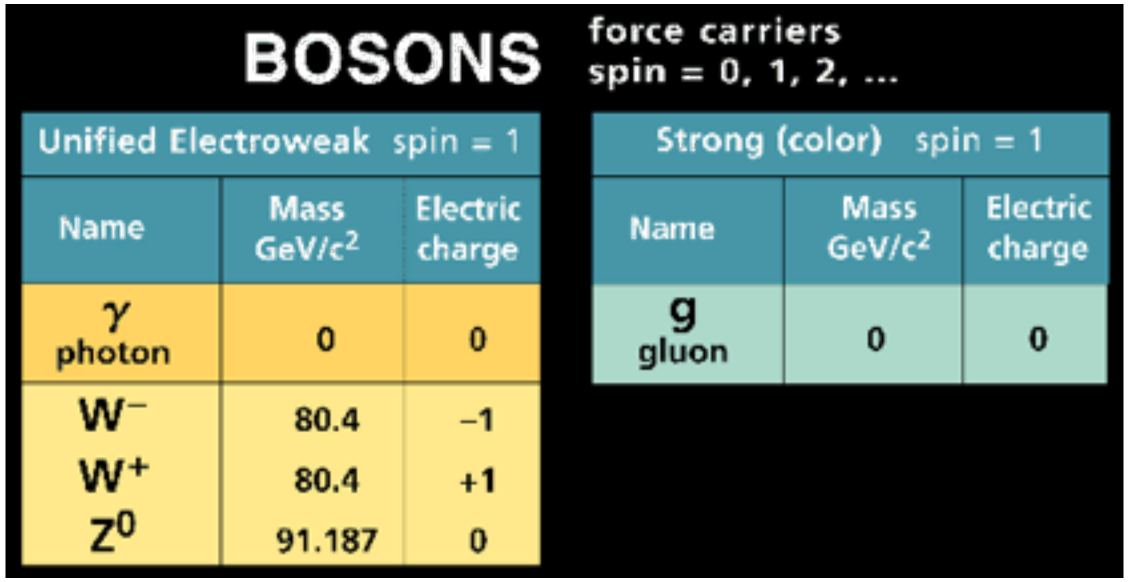
mass →
charge →
spin →
name →

	I	II	III	
Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

Gauge Bosons



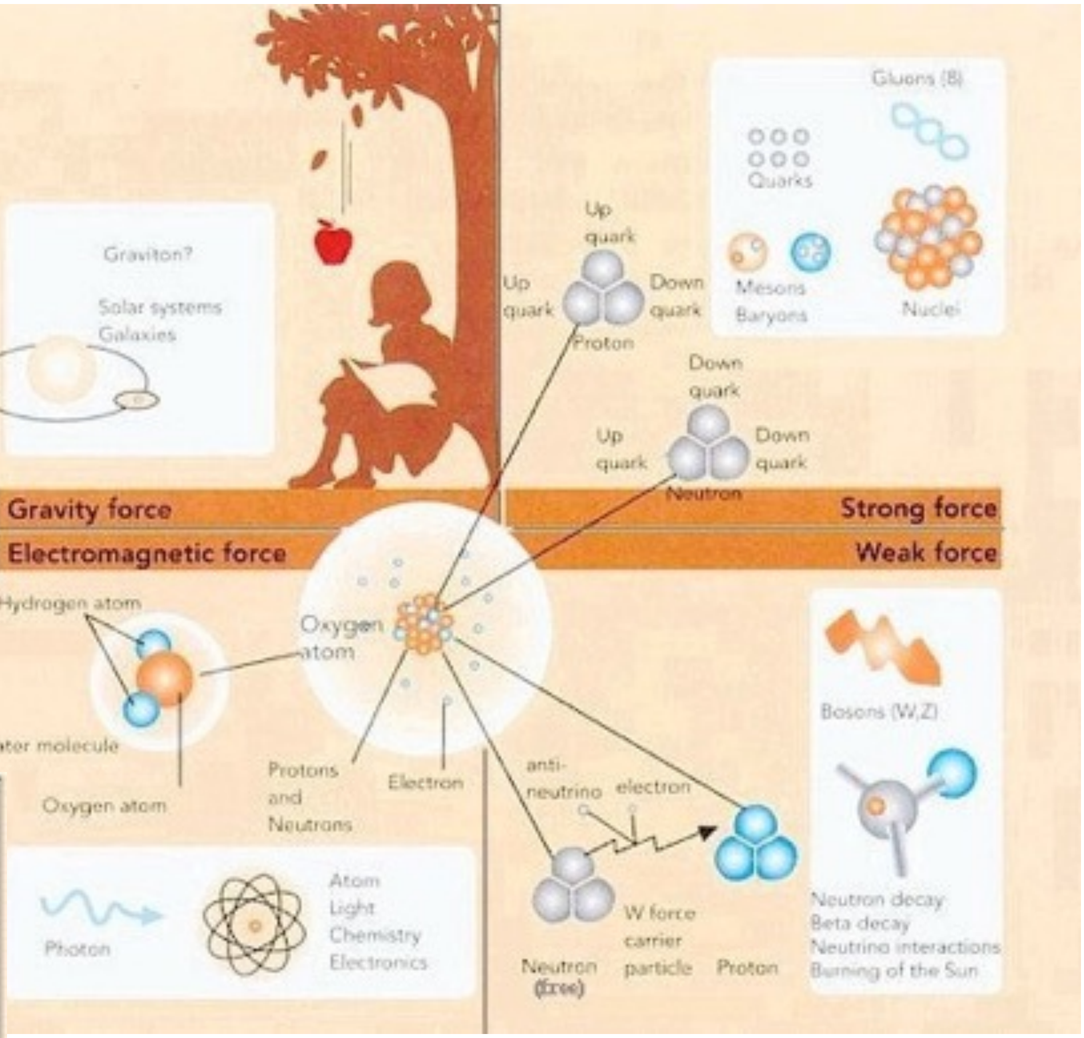


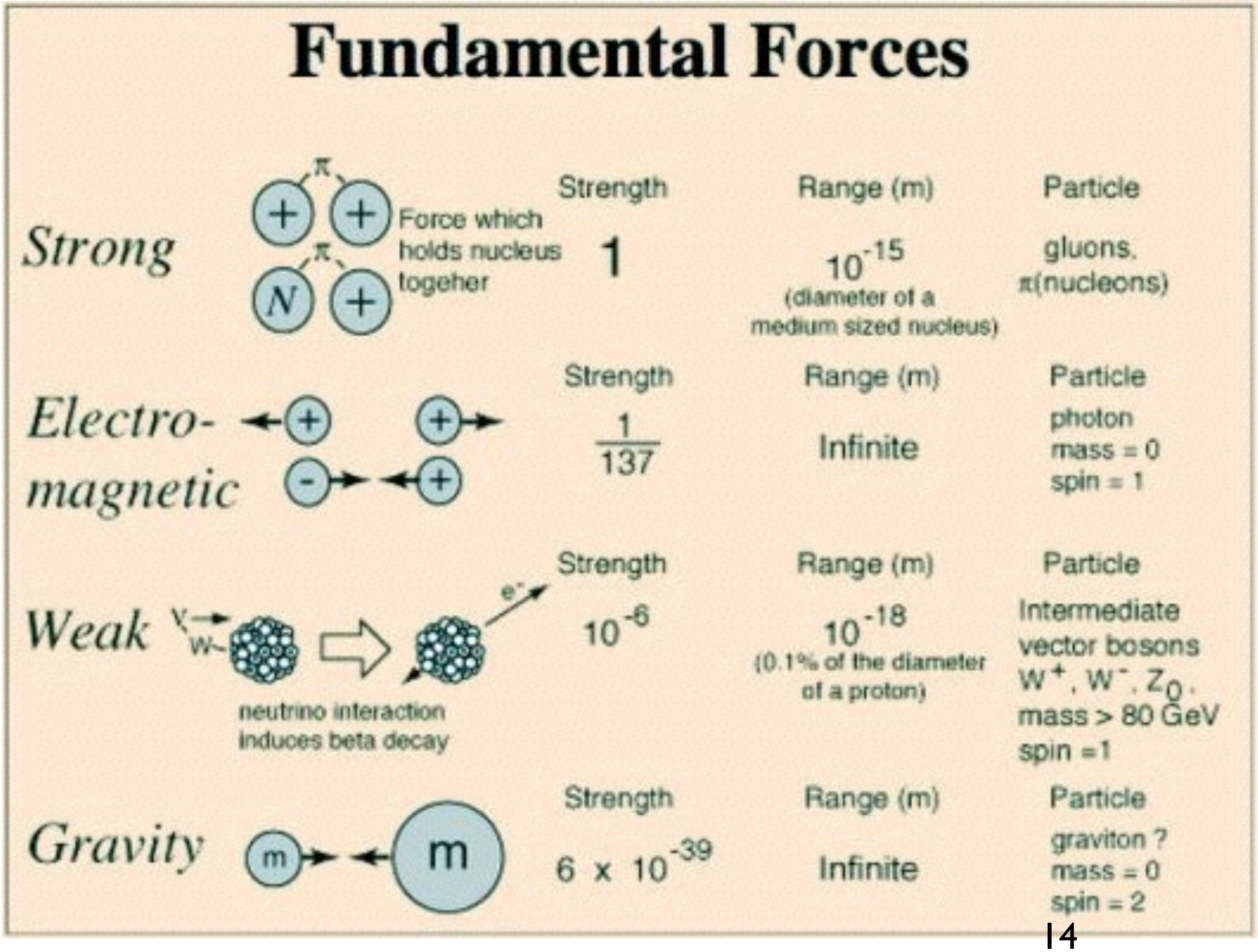


BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	**Mass GeV/c²**	**Electric charge**
γ photon	0	0
W⁻	80.4	−1
W⁺	80.4	+1
Z⁰	91.187	0

Strong (color) spin = 1		
Name	**Mass GeV/c²**	**Electric charge**
g gluon	0	0





Fundamental Forces

		Strength	Range (m)	Particle
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

Why go beyond?

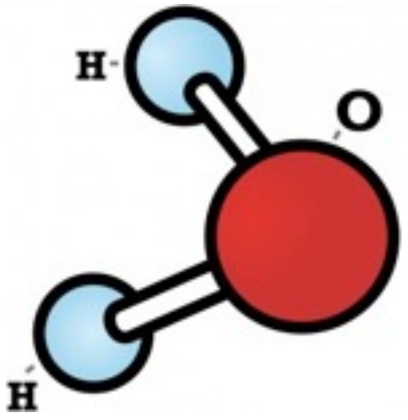
- The hierarchy problem
- Neutrino masses
- Origin of gauge interactions
- Dark matter
- Matter over anti-matter abundance
- Cosmological constant
- Inflation

Higgs sector not natural
Fermion masses vastly different
Origin of electroweak symmetry breaking unknown
Dirac or Majorana neutrinos
Strong CP problem

Not enough CP in SM for Baryogengesis
Value of cosmological constant
Inflation inconsistent with non-zero baryon number
Is DM a particle, then which, is it only one

Symmetry breaking

- Spontaneous symmetry breaking process (spontaneous) through which a system in a symmetry state ends up in a different symmetry state

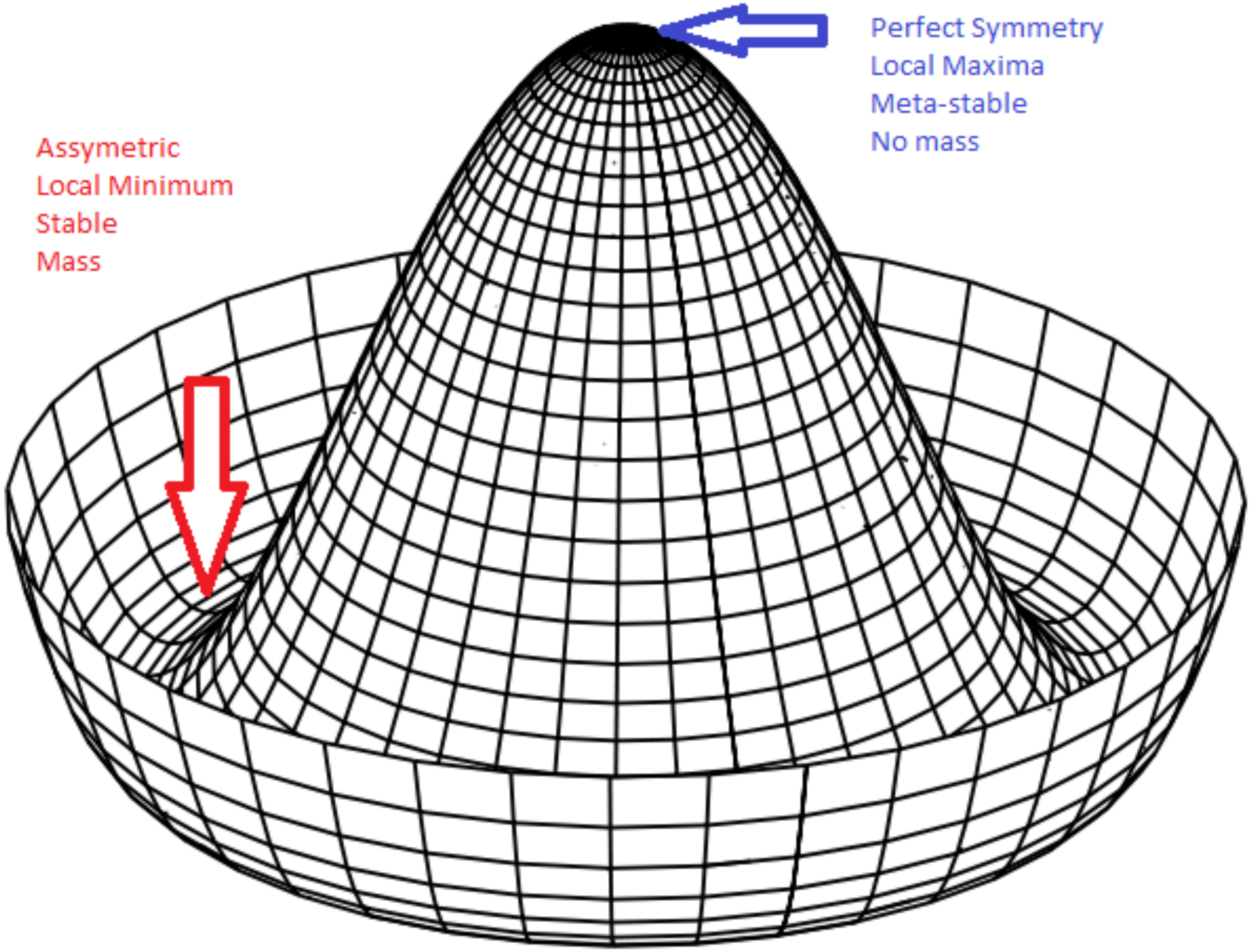


- The Lagrangian obeys certain symmetries, but the minimal energy state does not have the same symmetries

- Explicit symmetry breaking
  Terms in the Lagrangian that do not respect the symmetry

- Associated to phase transitions

Higgs Potential



Higgs Field

- When the electroweak symmetry is broken through the vev v of the Higgs field, gauge bosons and fermions acquire mass

$$M_W = gv/2 \qquad M_H^2 = \lambda v^2$$

$$M_Z = v\sqrt{g^2 + g'^2}/2 \qquad m_f = g_f v/\sqrt{2}$$

- The Higgs fields also acquires a mass

Hierarchy problem

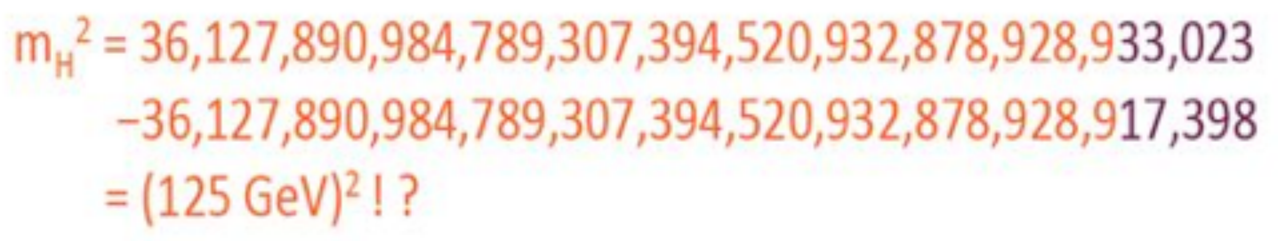
- SM valid to a cut off scale $\mathbf{\Lambda}$
- Higgs mass gets quadratic radiative corrections → diverges

$$\delta m_h^2 \propto \Lambda^2$$

- Fine tuning needed between the bare mass and corrections to get mass ~ 125 GeV

$$M_h^2 \propto M^2(\Lambda^2) - Cg^2\Lambda^2$$

- If $\mathbf{\Lambda}$ is the Planck scale then "some" fine tuning needed....



$m_H^2 = 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}933{,}023$

$-36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}917{,}398$

$= (125\ \text{GeV})^2$! ?

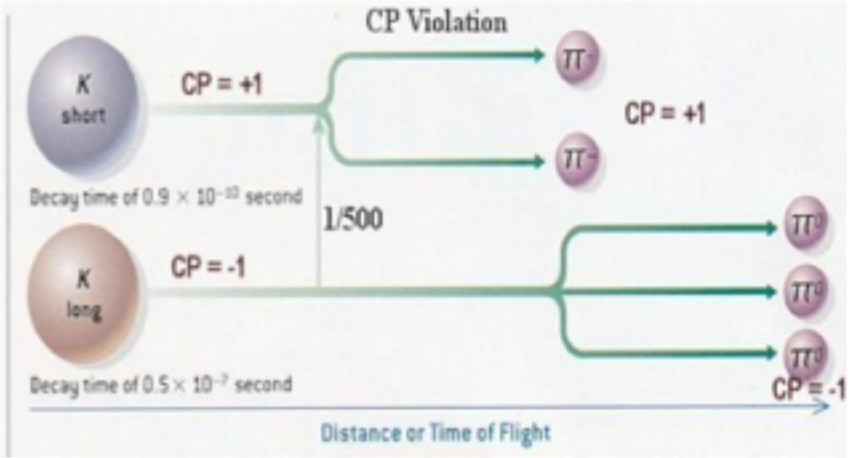
CP violation

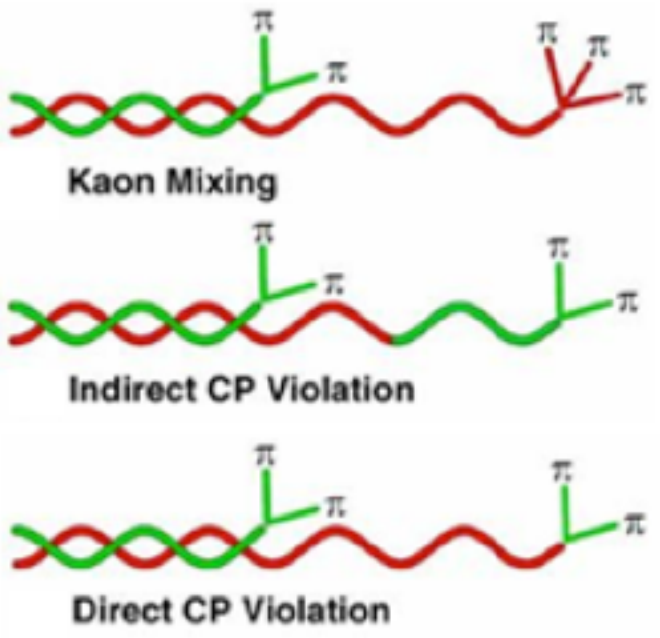
- Complex phase in CKM matrix → three generations
- Processes occur at different rates for particles and anti-particles → CP is violated
- First observed in Kaon-anti Kaon system, now also in decays of B mesons
- Indirect CP violation, CP violation not directly observed, the result of the decays are

$$\bar{N} \to N \neq N \to \bar{N}$$

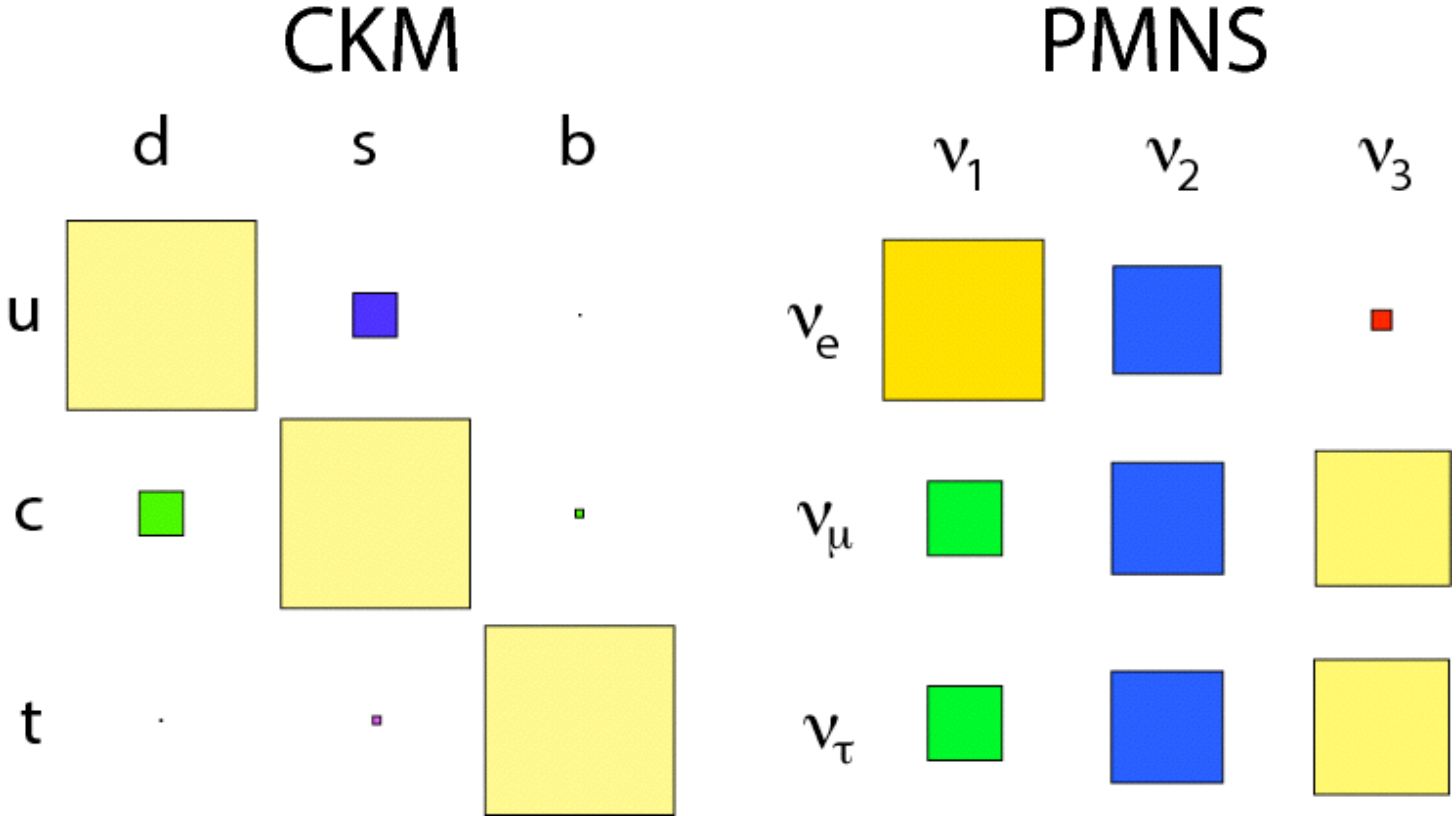
- Direct CP violation

$$\bar{N} \to \bar{f} \neq N \to f$$





PMNS vs CKM



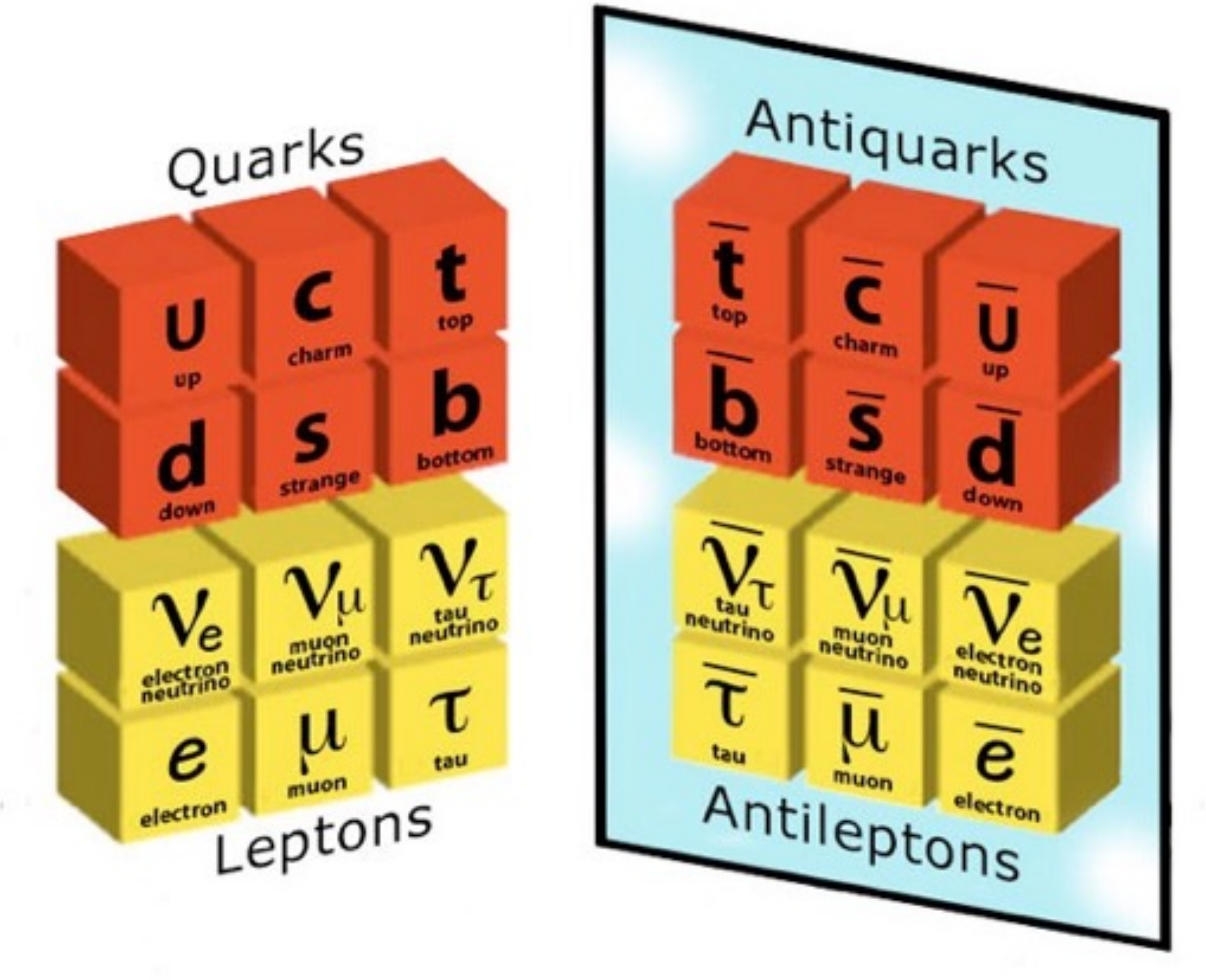
hierarchical

democratic

Anti-matter

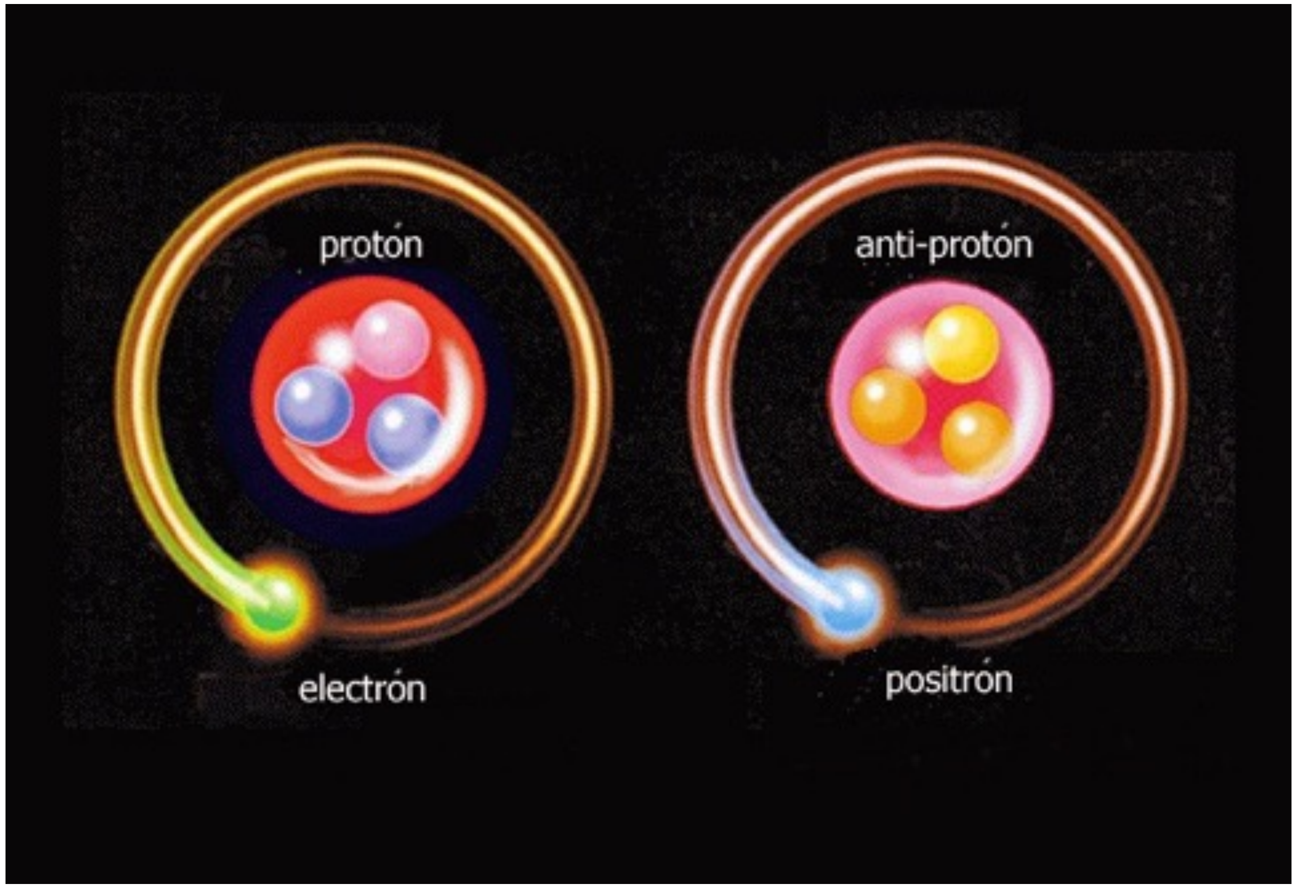
- In the SM there is an anti-matter particle for each matter particle

- When they annihilate they radiate energy, they produce gamma rays, neutrinos, or particle anti-particle pairs



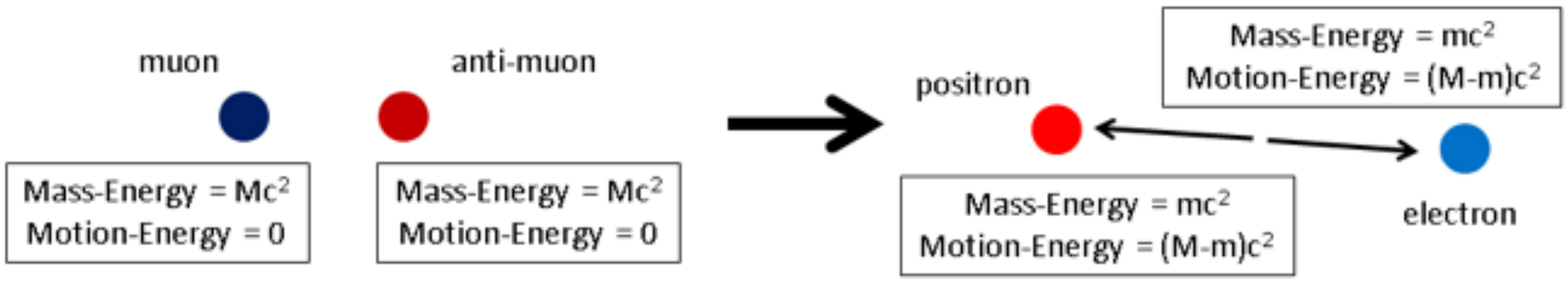
Anti-matter

Our Universe consists mainly of matter

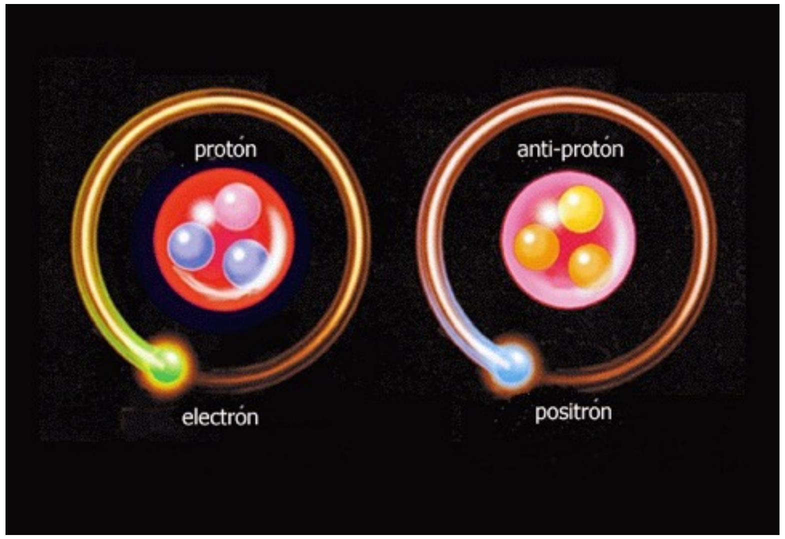


- The Universe made mainly of what we call matter
- We get anti-matter particles from the cosmos, but few

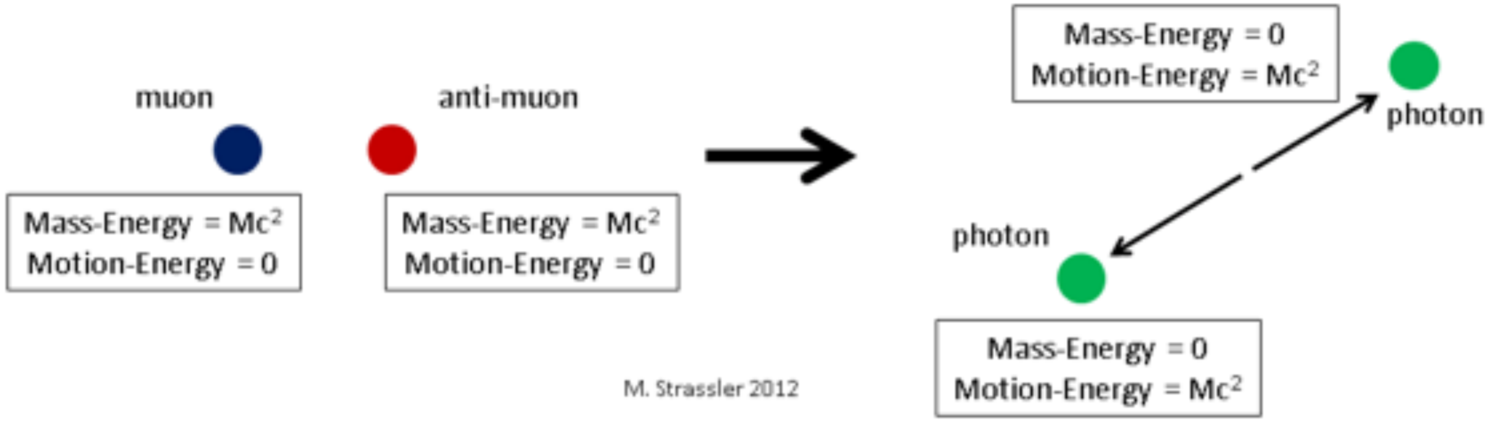
Matter and Anti-matter



M. Strassler 2012



- For every SM model particle there is an anti-particle
- If they meet they annihilate
- It adds a lot more particles to our table...
  but all of them have been observed experimentally



M. Strassler 2012

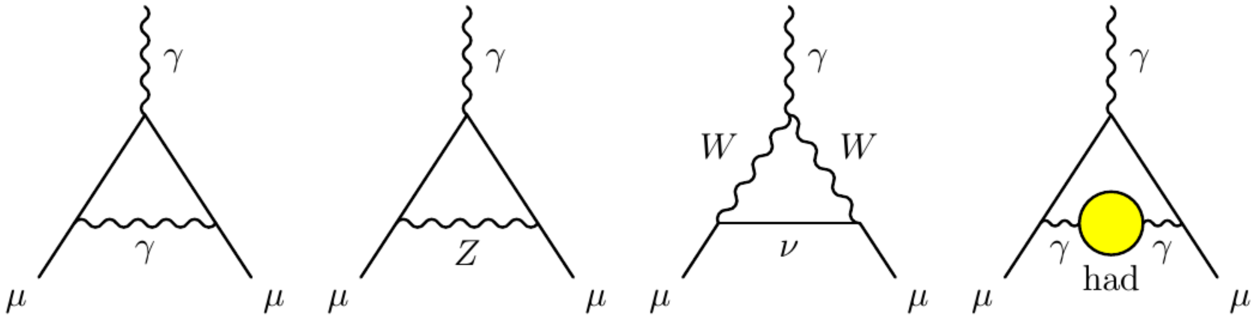
Baryogenesis

- To explain abundance of matter over anti-matter we need more CP violation than in SM
- Sakharov conditions:
    - Baryon number violation
    - Outside thermal equilibrium (or process and its inverse proceed at same rate)
    - CP-violation (or process and its CP mirror would occur at same rate)

g-2

- Interaction between photon and muon, QED corrections to the magnetic moment, in SM

$$g_\mu = 2$$

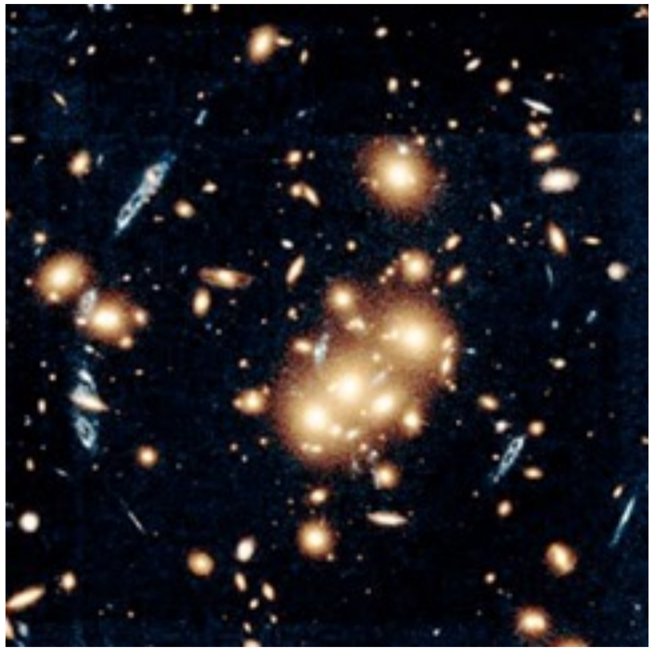


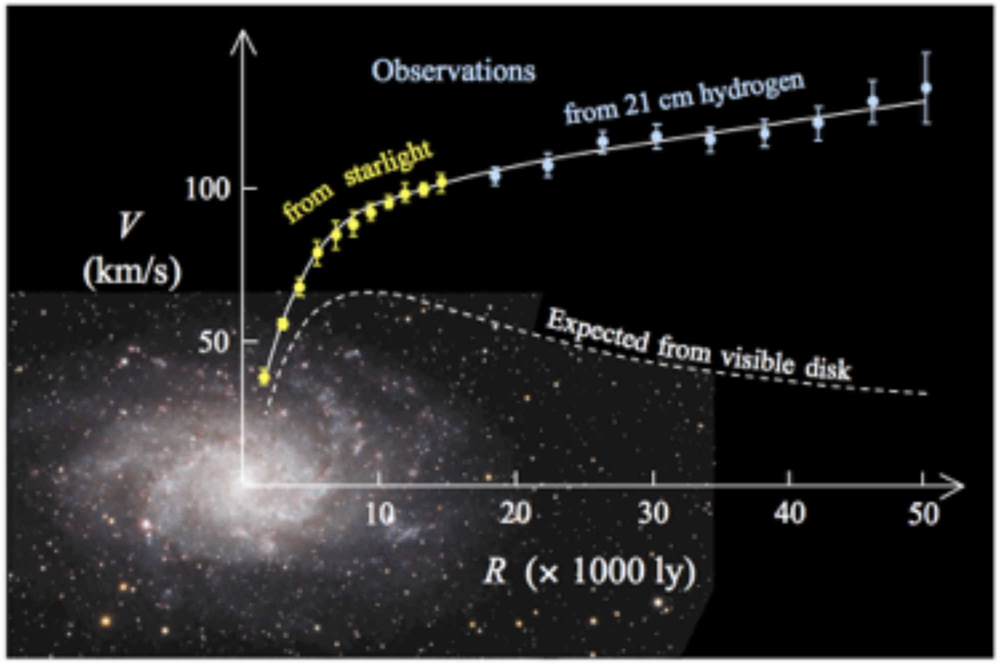
- The experimental value of the anomalous magnetic moment of the muon differs from the SM one...

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 28.8(6.3)(4.9) \times 10^{-10}$$

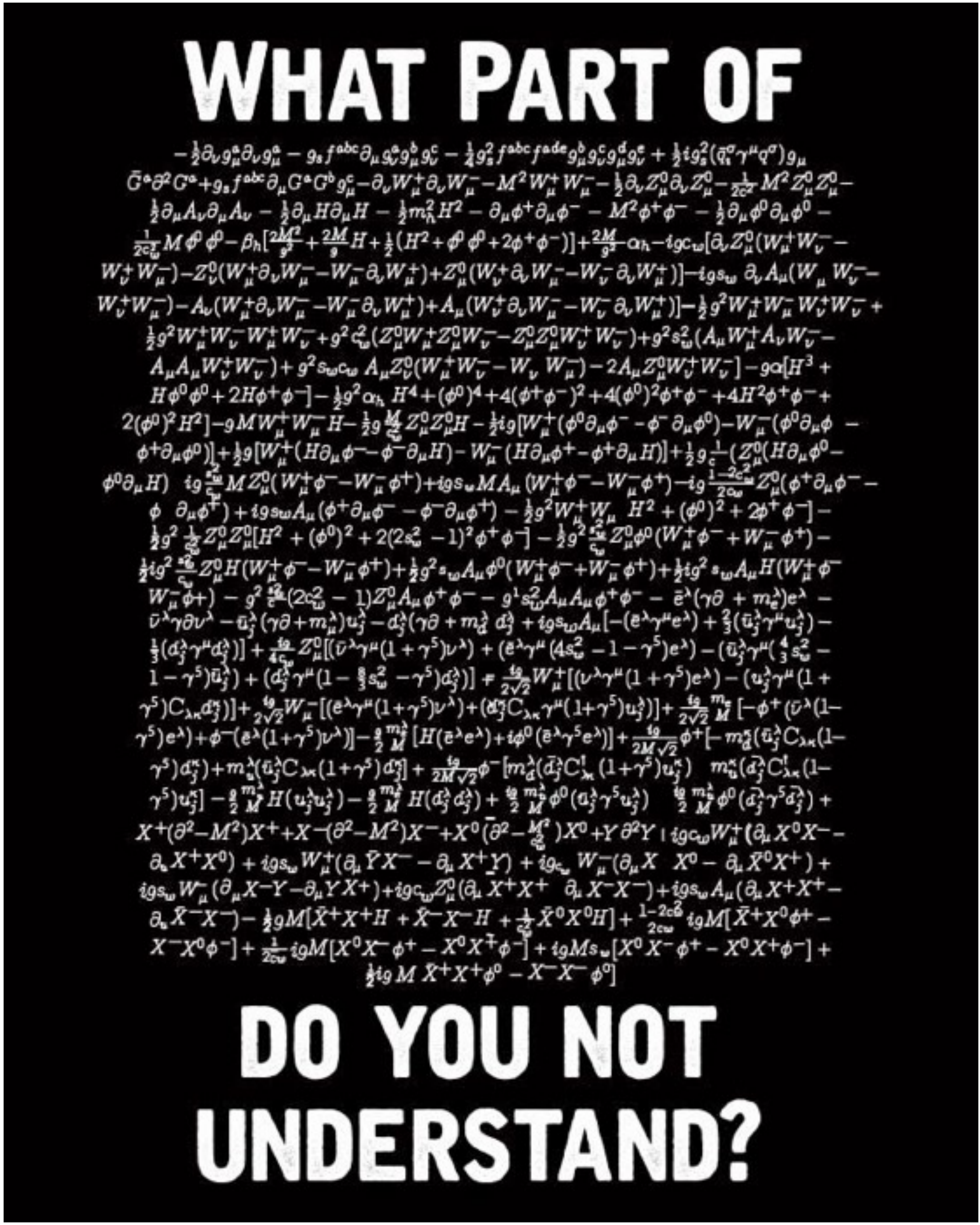
Dark Matter





- There is evidence for dark matter from rotational curves from galaxies, gravitational lensing
- Best solution is a non-interaction (or only weakly) particle
- Is there a dark matter candidate in the SM?
- Neutrinos could be part of DM, but 100% as DM is incompatible with large scale structure formation


STANDARD MODEL
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
LAGRANGIAN


WHAT PART OF
DO YOU NOT UNDERSTAND?


WHAT PART OF
DO YOU NOT UNDERSTAND?

Open questions

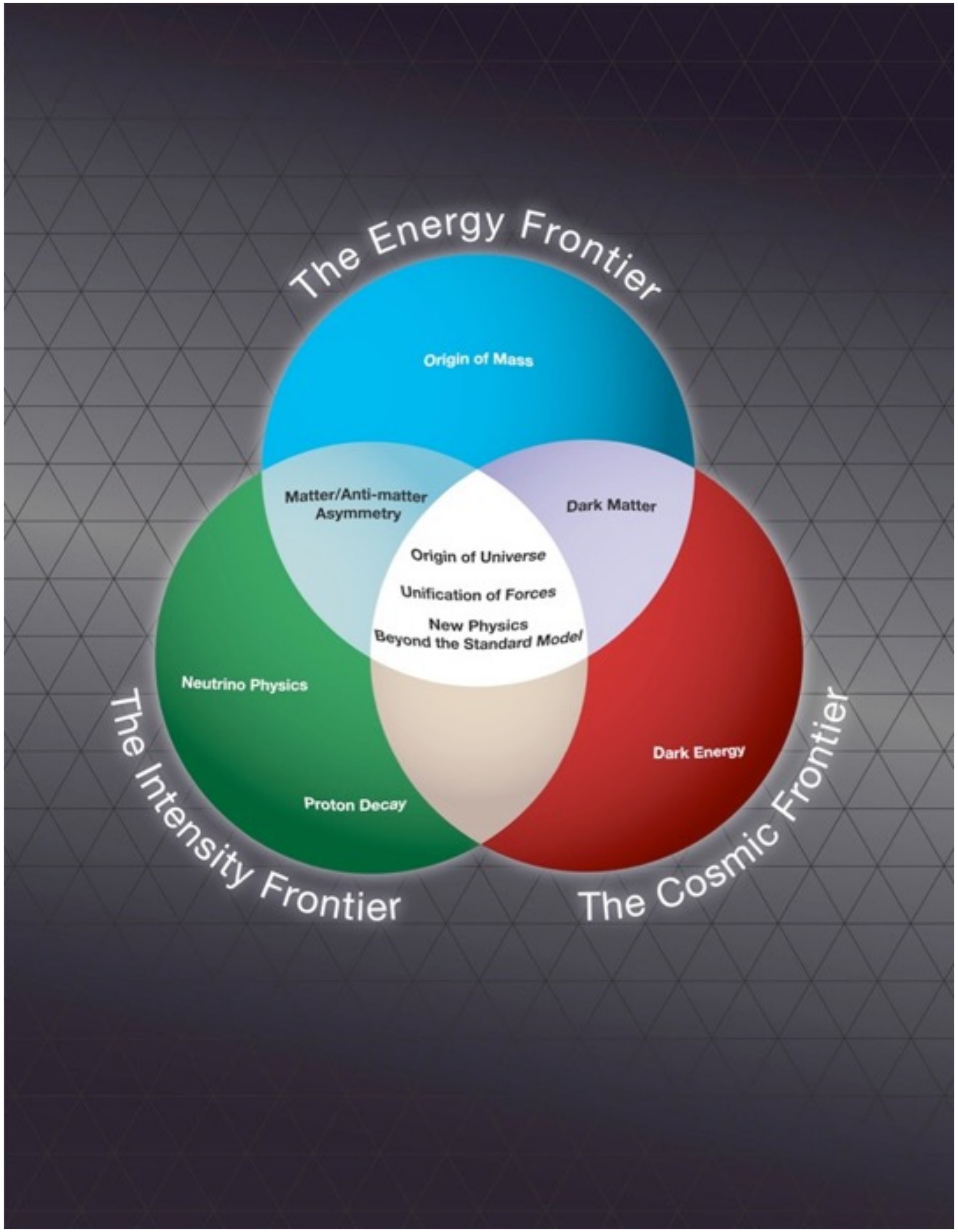
- Are quarks, leptons, Higgs really fundamental?
- Why are there three generations?
- Why the gauge group of the SM?
- Why are the masses of the particles so different?
- Is there only one Higgs?
- What stabilizes the Higgs mass?
- Are there right-handed electroweak interactions?
- Why is the electroweak scale special? What drives the eW symmetry breaking?
- What is the scale of the new physics?
- Are there right handed neutrinos?
- Are the neutrinos Dirac or Majorana?

More open questions...

- What is the origin of the free parameters of the SM?
- Are fundamental particles really point-like?
- What is the origin of CP violation?
- Why is there more matter than anti-matter?
- How are the gauge, Yukawa and Higgs sectors related at a more fundamental level?
- Is there mixing of charged leptons?
- Is there proton decay?
- What happens as we move up in energy? What are the scales of physics?

Beyond the SM

- Evidence of physics BSM are the neutrino masses
- More evidence is the existence of dark matter
  we'll assume it is a particle(s)


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

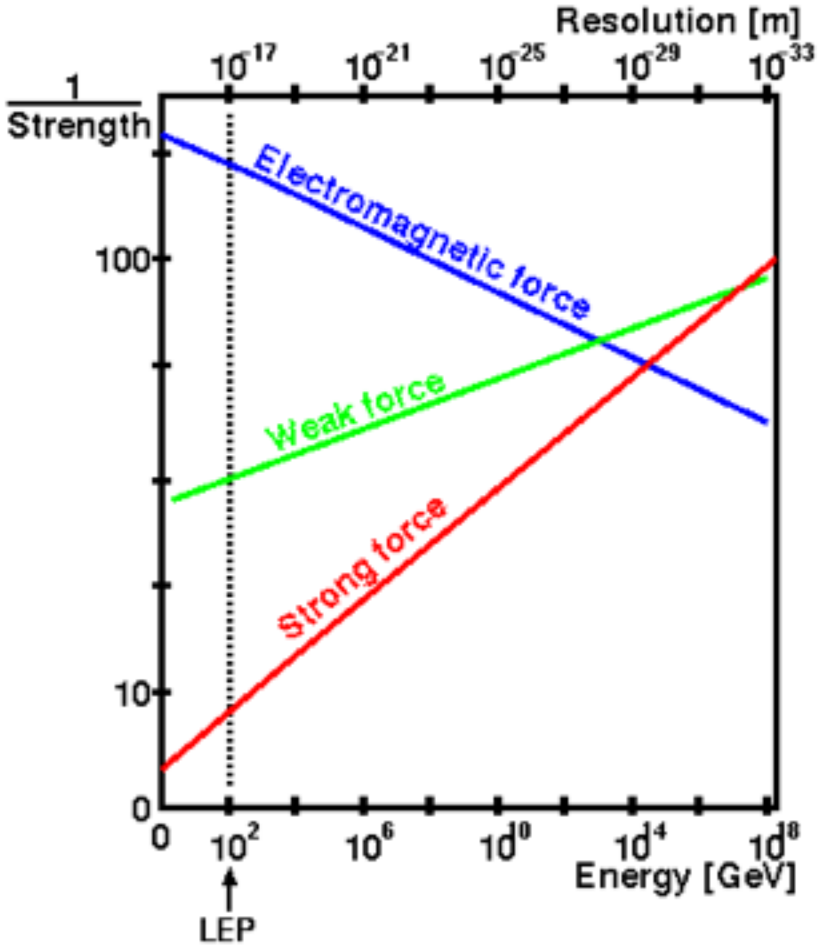
How to proceed?

- Traditional way is to add more symmetries:
  - Gauge symmetries → may imply new interactions and/or particles
  - Symmetry between bosons and fermions
  - Horizontal-family symmetries
  - Left-right symmetries
- Add more particles and/or interactions
- Composite particles
- Particles not point-like
- Add more spatial dimensions
- Combinations of all the above...

Grand Unified Theories GUTS

- Add symmetries:
- Strong, weak and electromagnetic forces are just different realizations of a more fundamental one
- Popular groups:
  $SU(5) \supset SU \times (3) \times SU(2) \times U(1)$
  $SO(10) \supset SU(5)$
  $SO(10) \supset$
  $SU \times (4) \times SU(2)_L \times SU(2)_R$
- Can explain approx mass ratios, fractional charges

- Leptoquarks, proton decay
- Break B symmetry
- Unification not good in SM



SU(5)

- $SU(5)\supset SU\times(3)\times SU(2)\times U(1)$
  SM particles fit nicely, except for right handed neutrinos
- SU(5) broken to SM through the vev of the adjoint 45

$$\bar{5} = \begin{pmatrix} {d^c}_1 \\ {d^c}_2 \\ {d^c}_3 \\ e^- \\ -\nu_e \end{pmatrix} \qquad 10 = \begin{pmatrix} 0 & {u^c}_3 & -{u^c}_2 & -u_1 & -d_1 \\ & 0 & {u^c}_1 & -u_2 & -d_2 \\ & & 0 & -u_3 & -d_3 \\ & & & 0 & -e^c \\ & & & & 0 \end{pmatrix}$$

- SM extrapolated to low energies through RGE's
- $m_e(GUT) = m_d(GUT)$ incompatible with observation
- Too fast rate of proton decay

Charge quantization

- SU(3) and SU(2) have quantised charges, but not U(1)
- Q = Y2 + T3, charge generator is a linear combination of SU(2) and U(1), which are identified with the generators of a GUT, e.g. SU(5)
- Generators of SU(n) are traceless, for down quarks $\Rightarrow$

$$Q(\bar{\nu}_e) + Q(e^+) + 3Q(q) = 0 \Rightarrow Q(q) = -\frac{1}{3}e,$$

- Similarly for up quarks

$$Q_u = Q_d + Q_{e^+} = +\tfrac{2}{3}.$$

Matter content 3 generations

$$\bar{\mathbf{5}} \oplus \mathbf{10} \oplus \mathbf{1}$$

$\bar{5} \to (\bar{3},1)_{\frac{1}{3}} \oplus (1,2)_{-\frac{1}{2}}$ d^c and l

$10 \to (3,2)_{\frac{1}{6}} \oplus (\bar{3},1)_{-\frac{2}{3}} \oplus (1,1)_1$ q, u^c and e^c

$1 \to (1,1)_0$ ν^c

$$24 \to (8,1)_0 \oplus (1,3)_0 \oplus (1,1)_0 \oplus (3,2)_{-\frac{5}{6}} \oplus (\bar{3},2)_{\frac{5}{6}}$$

It also has a 24 irrep, a scalar in the adjoint irrep, acquires vev and breaks SU(5)

$$\frac{Y}{2} = \mathrm{diag}\,(-1/3,-1/3,-1/3,1/2,1/2)$$

- 24 generators, only 12 associated with the SM gauge bosons

1. hypercharge quantization
2. gauge coupling unification
3. proton decay

- Other 12 are called X, Y
  These mediate proton decay,
  They acquire a vev and mass when SU(5) is broken
- The Higgs field is also embedded in a 5 irrep, but adds a coloured triplet. This triplet also has to acquire a heavy mass, to suppress proton decay
- This is called the doublet-triplet splitting it implies a fine-tuning

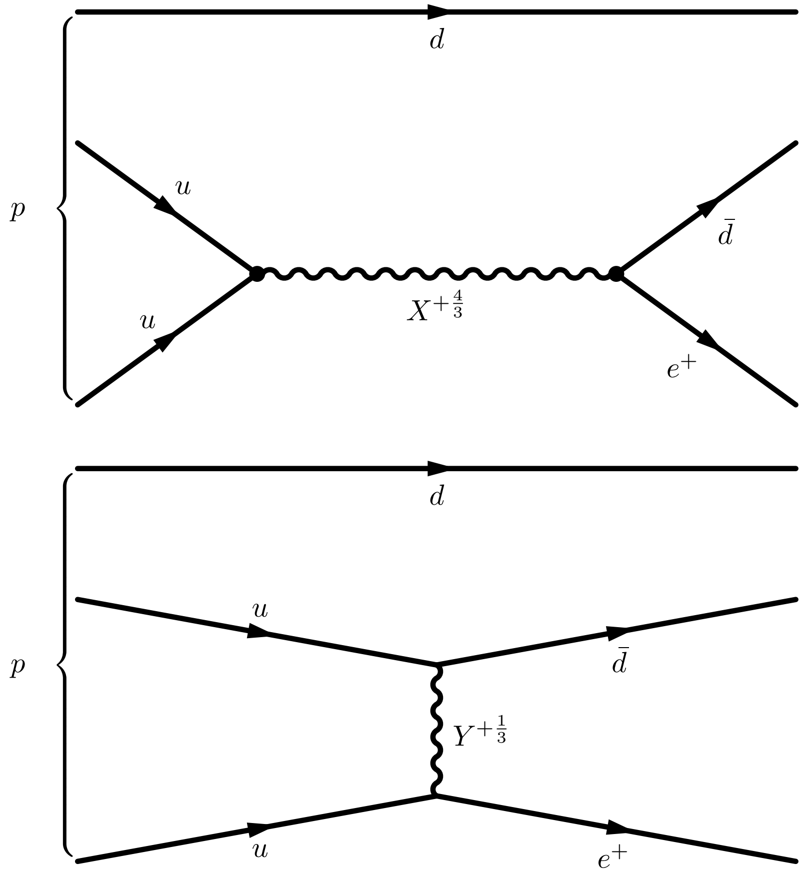
The Higgs in SU(5) can come in the 5 or $\bar{5}$ irreps

$$5 \to (1,2)_{\frac{1}{2}} \oplus (3,1)_{-\frac{1}{3}}$$
$$\bar{5} \to (1,2)_{-\frac{1}{2}} \oplus (\bar{3},1)_{\frac{1}{3}}$$

The triplet part can mediate proton decay

The leptoquarks X,Y can mediate proton decay at an unacceptable rate

The coloured part has to be very heavy to avoid this



$$5 \rightarrow (1,2)_{\frac{1}{2}} \oplus (3,1)_{-\frac{1}{3}}$$
$$\bar{5} \rightarrow (1,2)_{-\frac{1}{2}} \oplus (\bar{3},1)_{\frac{1}{3}}$$

$$< 24_H >= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -3/2 & 0 \\ 0 & 0 & 0 & 0 & -3/2 \end{pmatrix} V$$

The Higgs mass comes from the terms

$$\lambda \ \bar{5}_H \ 24 \ 5_H + \bar{5}_H \ M \ 5_H$$

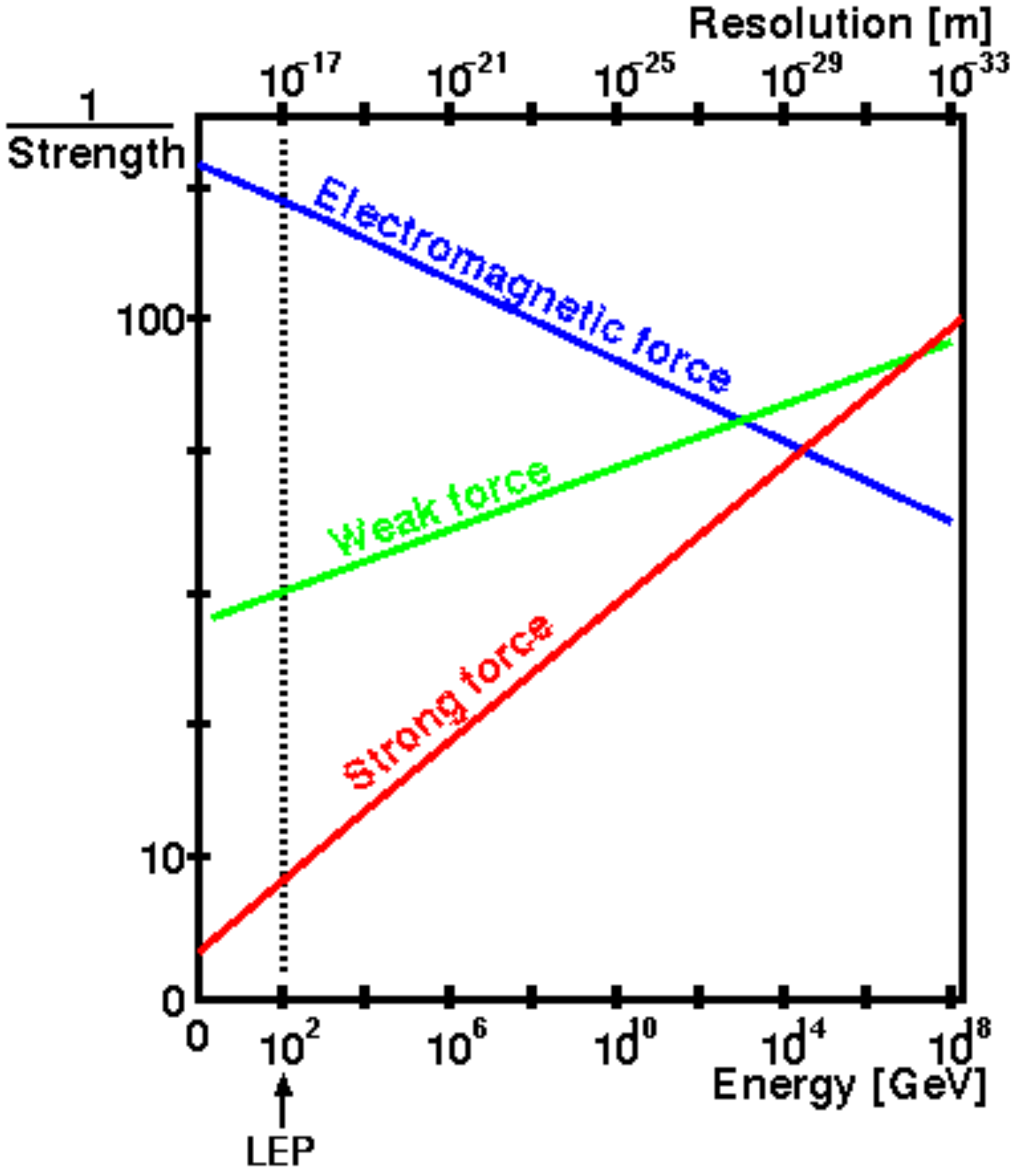
$$M_H = \frac{-3}{2}\lambda V + M \sim O(GUT) \qquad M_H = \frac{-3}{2}\lambda V + M \sim O(M_W)$$

A lot of fine tuning needed to make this work

- Unification scale is ~ 10^{15} GeV (only approximate)
- Renormalizable
- Extends the SM in a minimal way

BUT

- Unacceptable rate of proton decay and other baryon and lepton number violating processes
- Fine tuned — doublet-triplet splitting



SO(10)

$$SO(10) \supset SU(5) \supset SU(3) \times SU(2) \times U(1)$$

$$45 \rightarrow 24_0 \oplus 10_{-4} \oplus \overline{10}_4 \oplus 1_0$$
$$16 \rightarrow 10_1 \oplus \bar{5}_{-3} \oplus 1_5$$
$$16 \rightarrow 10_1 \oplus \bar{5}_{-3} \oplus 1_5$$
$$10 \rightarrow 5_{-2} \oplus \bar{5}_2$$

Two stages of
symmetry breaking

Modifies the unification scale

This affects the proton
lifetime, can be be

Introduces more parameteres

Includes a
right-handed neutrino

SO(10)

- Break SO(10) to the Pati-Salam Group
  $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$
- Four quark colour charges to start with
- More complicated pattern of breaking
- Usually the more simple breaking to SU(5) preferred

$$16 = \begin{pmatrix} \nu_e \\ u_r \\ u_g \\ u_b \\ e^- \\ d_r \\ d_g \\ d_b \\ \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \\ e^+ \\ \bar{u}_r \\ \bar{u}_g \\ \bar{u}_b \\ \bar{\nu}_e \end{pmatrix}_L$$

Supersymmetry

- Add more symmetry
- Coleman-Mandula Theorem:
  S-matrix is a direct product of the Poincaré group and an internal symmetry group.
  Internal and space-time symmetries can only be combined in a trivial way
- Possible to extend the Lie algebras to supergraded algebras, with anti-commutators, whose generators are fermionic operators

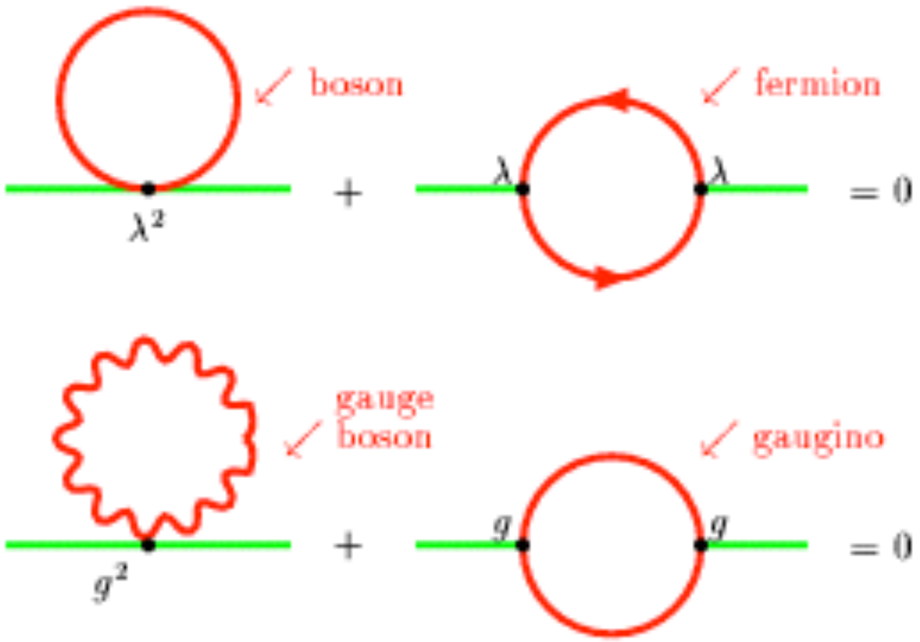
  Symmetry between bosons and fermions

And why SUSY?

- Beautiful, only possible extension of Poincaré group
- It turns out is stabilizes the Higgs mass, realized after it was proposed → solution to the hierarchy problem
- Gives candidates to dark matter
- Good unification of fundamental forces (we'll see later...)
  can extrapolate physics at high scale
- Local supersymmetry → supergravity
- Compatible with precision measurements of the SM not trivial...
- But also not found...

Solution to the hierarchy problem

- If SUSY exact the corrections to the Higgs mass coming from a particle and its superpartner **cancel exactly**



- SUSY broken by soft terms (SSB): superpartner masses are different → the cancellation is not exact
- SSB do not add Λ^2 terms, only log divergences
- The masses should be ~ few TeV

Take these three

- Solution to the hierarchy problem, if SUSY around a few TeV
- Compatible with unification of the gauge couplings if the susy particles are around 1-10 TeV
- If lightest susy particle electrically neutral and stable, only weakly interacting, and of mass ~ few TeV →
  consistent with thermal DM matter
- Remarkable coincidences (but might be just that...)

N=1 Supersymmetry

- To transform bosons into fermions and viceversa, we have the generators of SUSY

$$\left\{Q^{\alpha}, \bar{Q}_{\dot{\beta}}\right\} = 2\sigma^{\mu}_{\alpha,\dot{\beta}} P_{\mu} \qquad \left\{Q^{\alpha}, \bar{Q}_{\dot{\beta}}\right\} = 2\delta_{\alpha,\dot{\beta}} m_a.$$

- Construct an irrep by acting on state that annihilates $\bar{Q}_i$

$$|0\rangle \rightarrow Q_1|0\rangle, Q_2|0\rangle \rightarrow Q_1 Q_2|0\rangle$$

- No more states, since $Q_1 Q_1 = Q_2 Q_2 = 0$
- Two spin zero, two spin 1/2 states obtained ⇒

  matter multiplet

- Starting from a 1/2 spin state ⇒

  two spin 1/2 fermion states
  one spin 1 massive bosonic state
  one spin 0 massive bosonic state
  i.e. two chiral fermions, one massive boson,
  one massive Higgs boson

- Repeating analysis for massless particles ⇒

  states with helicity $h = \lambda \ , \ h = \lambda + 1/2$
  if $\lambda = 1/2 \ \Rightarrow$

  one massless gauge boson and its superpartner fermion

Superpartners

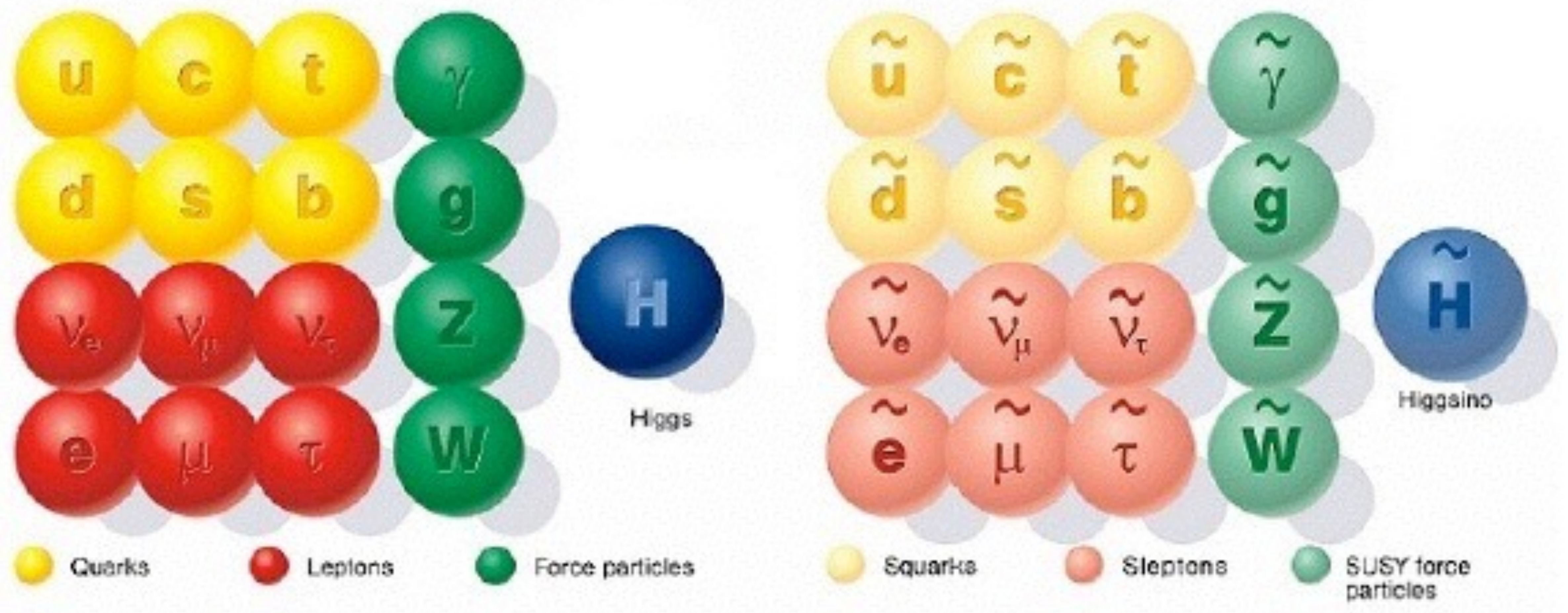
- SUSY relates bosons and fermions, arranged in supermultiplets
- Superpartners have spins differing by 1/2
- $[Q_{\text{SUSY}}, Q_{\text{internal}}]=0$
  Q_{internal} = charge, colour, isospin, etc

We know all SUSY gauge interactions

- quarks $\longleftrightarrow$ squarks
  leptons $\longleftrightarrow$ sleptons
  W, Z $\longleftrightarrow$ Wino, Zino
  photon $\longleftrightarrow$ photino
  gluon $\longleftrightarrow$ gluino
- If the symmetry is exact they are mass degenerate

Predictive power

SUPERSYMMETRY



Standard particles **SUSY particles**

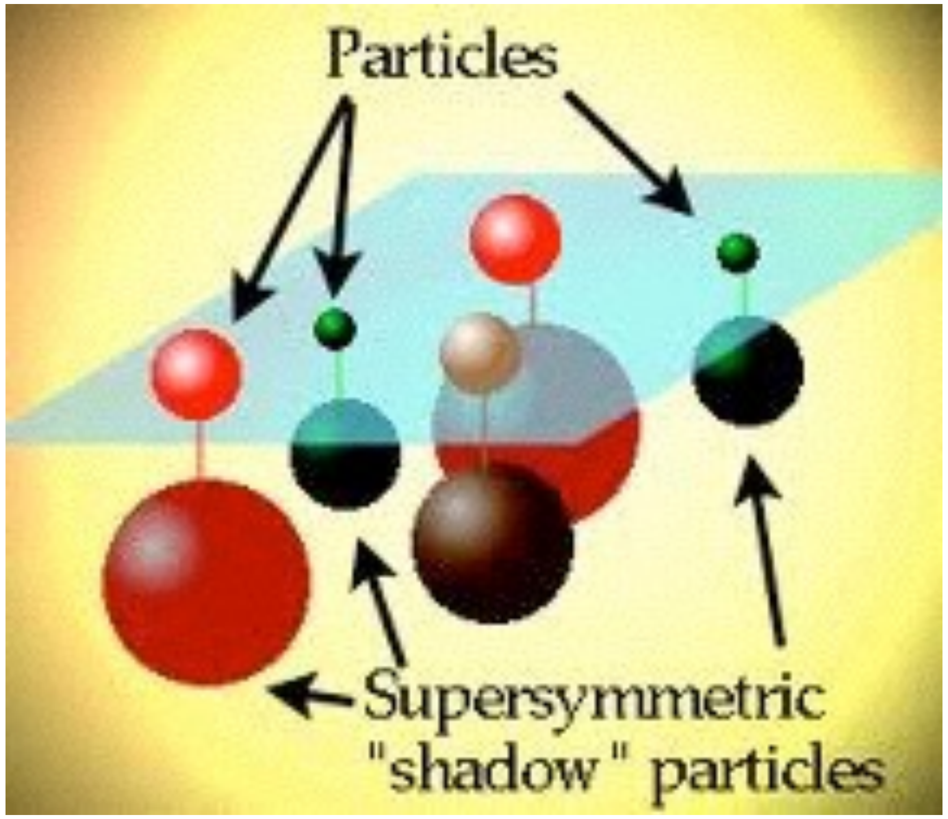
- In a renormalizable SUSY theory masses and interactions are determined by their gauge transformations and the super potential W

$$W \quad = \quad L^i\Phi_i + \frac{1}{2}M^{ij}\Phi_i\Phi_j + \frac{1}{6}y^{ijk}\Phi_i\Phi_j\Phi_k,$$

- Φ_i are the superfields, L_i parameter that is a gauge singlet (absent in the MSSM), M^{ij} is a mass parameter and y^{ijk} are the Yukawa couplings

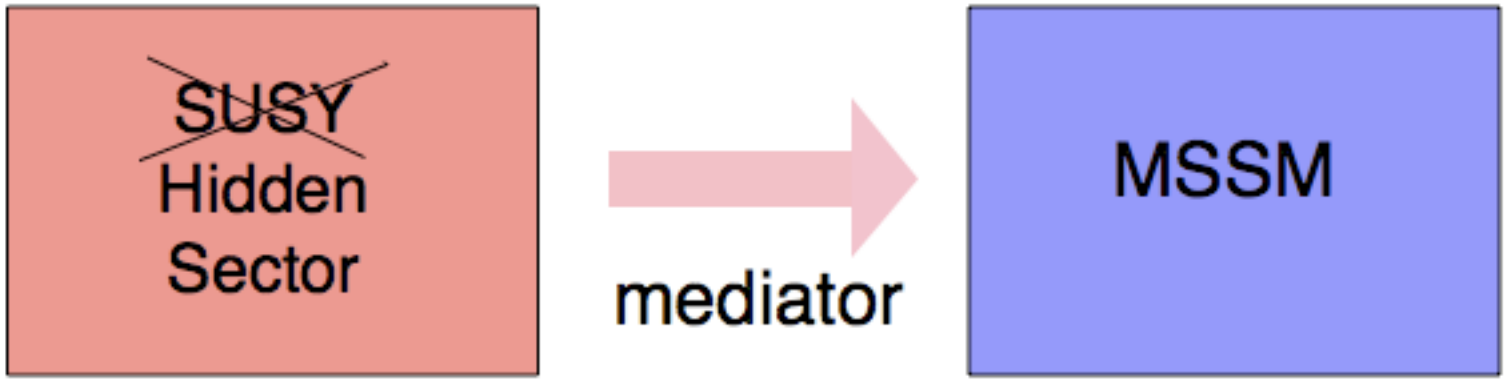
SUSY breaking

- No spartners with masses equal to their partners found so...
- SUSY must be broken
- Soft symmetry breaking → solution to the hierarchy problem
- Soft terms might be related in ways we do not know → dynamical SUSY breaking



SUSY breaking

- Dynamical breaking of SUSY unknown
- Spontaneous symmetry breaking through vevs of F and D terms → bad phenomenology, FCNC, CP violation
- Soft SUSY breaking terms that break susy explicitly: they do not introduce Λ^2 corrections
- Lots of terms than can in principle be there... > 120



Soft breaking terms

- The Lagrangian with soft breaking terms is

$$\mathcal{L}_{\rm soft} \;=\; -\left(\frac{1}{2}M_a\,\lambda^a\lambda^a+\frac{1}{6}a^{ijk}\phi_i\phi_j\phi_k+\frac{1}{2}b^{ij}\phi_i\phi_j+t^i\phi_i\right)+\text{c.c.}-(m^2)^i_j\phi^{j*}\phi_i,$$

- M_a are gauging masses (Wino, Bino, Zino)
- b^{ij} bilinear mass scalar terms
- a^{ijk} trilinear scalar terms
- ϕ_i tadpoles, absent if no gauge singlets
- Free of quadratic divergences

SSB terms

- Can be ~ 120 !!!!
- Not precisely reducing the number of parameters
- But… what we want is to describe Nature
  what is it telling us?
- Imposing absence of FCNC and CP violation
  reduces the number of parameters ~ 30

R parity

- If the spartners are heavy, why don’t they decay?
- SUSY + multiplicative symmetry:

  R parity

$$R = -1^{(3(B-L)+2S}$$

- B = baryonic number, L = leptonic number,

  S = spin
- R = 1 SM, R = -1 SUSY
- SUSY may have exact or broken R:

  very different phenomenology

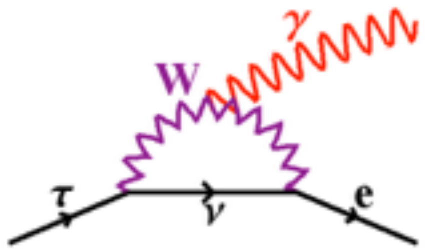
Superpotential and soft breaking terms

- SUSY models, also MSSM, defined through its superpotential
- And its soft breaking terms

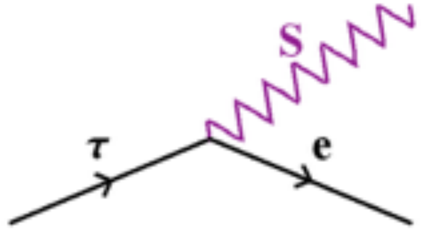
$$W_{\mathrm{MSSM}} = \bar{u}\mathbf{y_u}QH_u - \bar{d}\mathbf{y_d}QH_d - \bar{e}\mathbf{y_e}LH_d + \mu H_u H_d \,.$$

$$\begin{aligned}\mathcal{L}_{\mathrm{soft}}^{\mathrm{MSSM}} \quad = \quad & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \mathrm{c.c.}\right) \\ & -\left(\widetilde{\bar{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\bar{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\bar{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \mathrm{c.c.}\right) \\ & -\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\bar{u}}\,\mathbf{m_{\bar{u}}^2}\,\widetilde{\bar{u}}^\dagger - \widetilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\,\widetilde{\bar{d}}^\dagger - \widetilde{\bar{e}}\,\mathbf{m_{\bar{e}}^2}\,\widetilde{\bar{e}}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \mathrm{c.c.}) \,.\end{aligned}$$

Standard Model FCNC



Beyond–the–SM FCNC



MSSM — Minimal Supersymmetric Standard Model

- N=1 superpotential

$$W_{\rm MSSM} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d \, .$$

- $H_u, H_d, Q, L, \bar{u}, \bar{d}, \bar{e}$ chiral supermultiplets
- $\mathbf{y_u}, \mathbf{y_d}, \mathbf{y_e}$ Yukawa couplings, 3x3 matrices
- μ Higgs mixing term: $\mu (H_U)_\alpha (H_d)_\beta \epsilon^{\alpha\beta}$
- Yukawa part can be rewritten as

$$\overline{u}^{ia}\,(\mathbf{y_u})_i{}^j\,Q_{j\alpha a}\,(H_u)_\beta \epsilon^{\alpha\beta}$$

MSSM

- Superpotential must be analytic in chiral fields
- μ term is unique, terms like $H_u^* H_u$ are forbidden
- $\bar{u} Q H_u$ cannot be replaced by $\bar{u} Q H_d^*$
- → we need two Higgs doublets, also to ensure the absence of gauge anomalies
- The Higgs doublets must have opposite hypercharge Y = ± 1/2

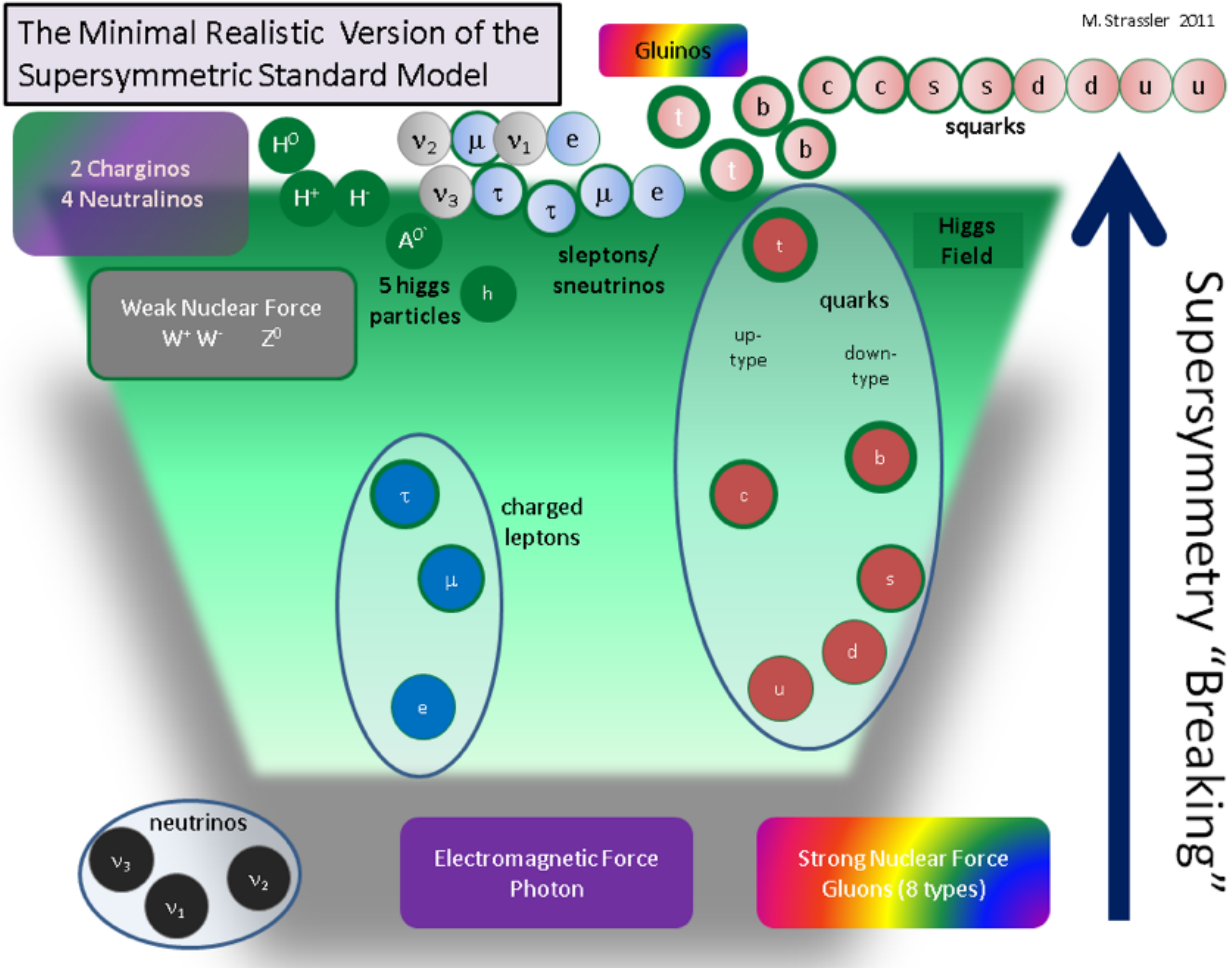
MSSM content

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

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

The Minimal Realistic Version of the Supersymmetric Standard Model

M. Strassler 2011



2 Charginos
4 Neutralinos

Weak Nuclear Force
W$^+$ W$^-$ Z^0

5 higgs particles

sleptons/ sneutrinos

Higgs Field

quarks

up-type

down-type

charged leptons

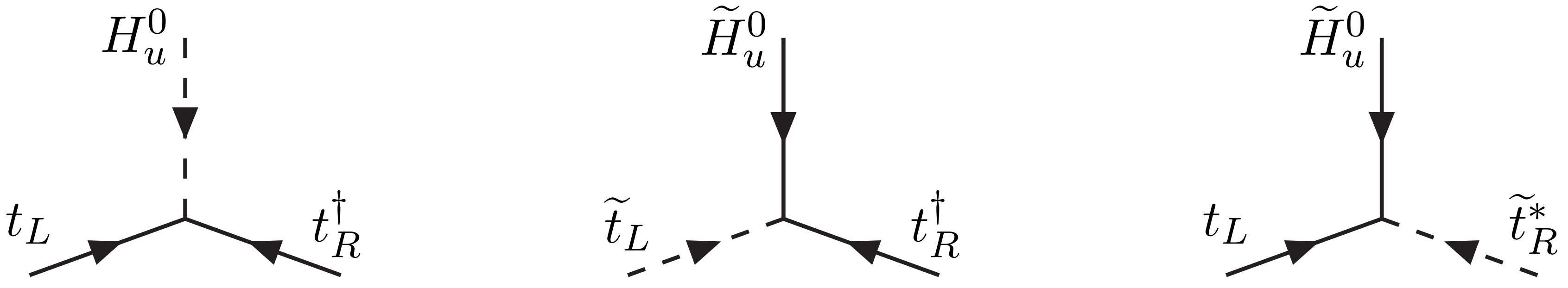
neutrinos

Electromagnetic Force
Photon

Strong Nuclear Force
Gluons (8 types)

Supersymmetry "Breaking"

Yukawa interactions



(a) (b) (c)

(a) Yukawa top interaction $t_L t_R^\dagger H_u$

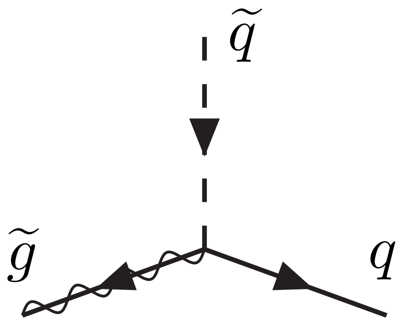
(b) Yukawa stop_L, Higgsino, top_R interaction $\tilde{t}_L t_R^\dagger H_u$

(c) Yukawa top_L, anti-stop_R, Higgsino interaction $t_L \tilde{t}_R^{\dagger *} H_u$

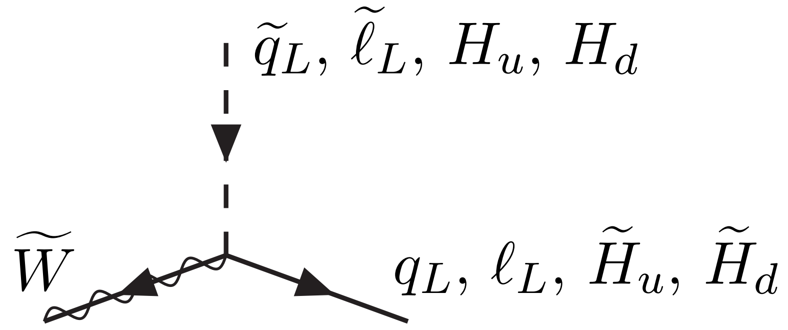
- All have the same coupling y_t

Gauge interactions

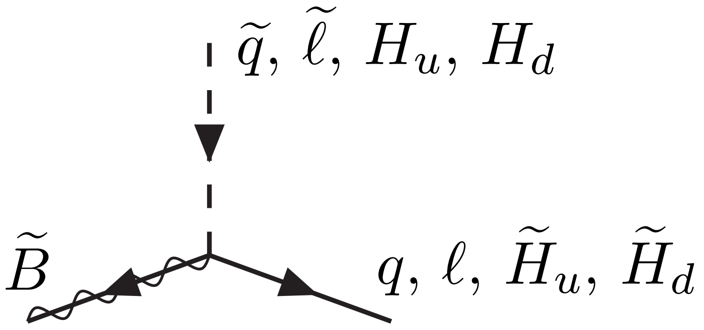
- Except for the third family, they are not very strong
- The ones proportional to gauge couplings dominate
- squark-quark-gaugino



(a)



(b)



(c)

Dimensional couplings

- All proportional to μ term

$$-\mathcal{L}_{\text{supersymmetric Higgs mass}} = |\mu|^2(|H_u^0|^2 + |H_u^+|^2 + |H_d^0|^2 + |H_d^-|^2).$$

$$-\mathcal{L}_{\text{higgsino mass}} = \mu(\widetilde{H}_u^+\widetilde{H}_d^- - \widetilde{H}_u^0\widetilde{H}_d^0) + \text{c.c.},$$

- μ is SUSY version Higgs boson mass
- → It will appear in the minimisation of the potential, and the sparticles masses will depend on it
- Respects SUSY

Soft SUSY Breaking Terms — SSB

- The soft breaking part of the Lagrangian is

$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} \;=\;& -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\ & -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\ & -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\ & - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.\end{aligned}$$

$\mathbf{a}, \mathbf{m^2}$ are 3x3 matrices, in principle over 100 parameters

Universality

- Make some simplifying assumptions → Universality
- Avoids FCNC and CP violating processes

$$\mathbf{m^2_Q} = m^2_Q \mathbf{1}, \quad \mathbf{m^2_{\bar{u}}} = m^2_{\bar{u}} \mathbf{1}, \quad \mathbf{m^2_{\bar{d}}} = m^2_{\bar{d}} \mathbf{1}, \quad \mathbf{m^2_L} = m^2_L \mathbf{1}, \quad \mathbf{m^2_{\bar{e}}} = m^2_{\bar{e}} \mathbf{1}.$$

- Assume a terms proportional to Yukawa couplings

$$\mathbf{a_u} = A_{u0}\,\mathbf{y_u}, \qquad \mathbf{a_d} = A_{d0}\,\mathbf{y_d}, \qquad \mathbf{a_e} = A_{e0}\,\mathbf{y_e},$$

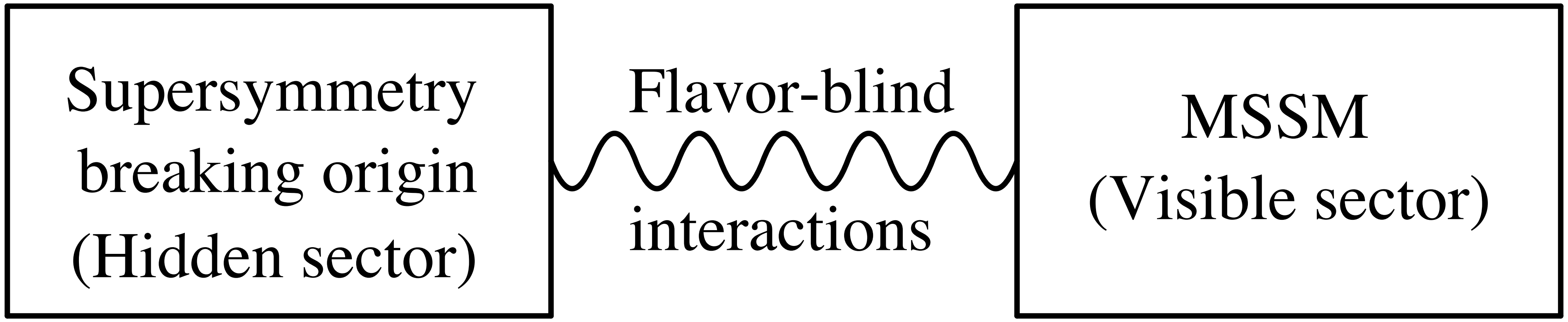
→ only squarks and sleptones of 3rd generation allowed to have large (scalar)^3 couplings

- No extra CP violating phases, only usual CKM one

$$\mathrm{Im}(M_1),\ \mathrm{Im}(M_2),\ \mathrm{Im}(M_3),\ \mathrm{Im}(A_{u0}),\ \mathrm{Im}(A_{d0}),\ \mathrm{Im}(A_{e0}) \ = \ 0$$

Origin of SSB terms?

$$M_1,\ M_2,\ M_3,\ \mathbf{a_u},\ \mathbf{a_d},\ \mathbf{a_e}\ \sim\ m_{\rm soft},$$
$$\mathbf{m^2_Q},\ \mathbf{m^2_L},\ \mathbf{m^2_{\overline{u}}},\ \mathbf{m^2_{\overline{d}}},\ \mathbf{m^2_{\overline{e}}},\ m^2_{H_u},\ m^2_{H_d},\ b\ \sim\ m^2_{\rm soft},$$



Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

MSSM (Visible sector)

SUSY breaking mediated at Planck scale

- SUSY breaking sector connected to SM only through gravitational interactions ⇒ effective Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{soft}} \quad = \quad & -\frac{F}{2M_{\text{P}}} f_a \lambda^a \lambda^a - \frac{F}{6M_{\text{P}}} y^{Xijk} \phi_i \phi_j \phi_k - \frac{F}{2M_{\text{P}}} \mu^{Xij} \phi_i \phi_j - \frac{F}{M_{\text{P}}} n_i^j \phi_j W^i_{\text{MSSM}} + \text{c.c.} \\ & -\frac{|F|^2}{M_{\text{P}}^2} (k_j^i + n_p^i \overline{n}_j^p) \phi^{*j} \phi_i,\end{aligned}$$

- Soft breaking terms given by four parameters

$$m_{1/2} = f\frac{\langle F \rangle}{M_{\text{P}}}, \qquad m_0^2 = (k + n^2)\frac{|\langle F \rangle|^2}{M_{\text{P}}^2}, \qquad A_0 = (\alpha + 3n)\frac{\langle F \rangle}{M_{\text{P}}}, \qquad B_0 = (\beta + 2n)\frac{\langle F \rangle}{M_{\text{P}}}.$$

- This translates into universality relations for soft breaking terms

$$M_3 = M_2 = M_1 = m_{1/2},$$

$$\begin{aligned}
&\mathbf{m^2_Q} = \mathbf{m^2_{\bar{u}}} = \mathbf{m^2_{\bar{d}}} = \mathbf{m^2_L} = \mathbf{m^2_{\bar{e}}} = m_0^2\,\mathbf{1}, \qquad m^2_{H_u} = m^2_{H_d} = m_0^2,\\
&\mathbf{a_u} = A_0\mathbf{y_u}, \qquad \mathbf{a_d} = A_0\mathbf{y_d}, \qquad \mathbf{a_e} = A_0\mathbf{y_e},\\
&b = B_0\mu,
\end{aligned}$$

- Which is clearly desirable from the phenomenology, it avoids FCNC and CP violating terms

Gauge and anomaly mediated soft breaking terms

- In a similar way there may be soft breaking terms mediated by gauge interactions
- Or they might appear due to the violation of superconformal invariance
- This leads to a particular type of soft breaking terms in each case, i.e. specific relations at the GUT scale between the soft breaking terms

Higgs potential

$$\begin{aligned} V &= (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) \\ &\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}$$

- Minimum preserves electromagnetism
- b term, as well as vu and vd are real and positive
  ⇒ no extra CP violation

Potential minimum

- Potential must be bounded from below ⇒

$$2b < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2.$$

- Electroweak symmetry must be broken

$$b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2).$$

if this condition not fulfilled then $H_u^0 = H_d^0 = 0$ is a stable minimum

- If $m_{H_u}^2 = m_{H_d}^2$ the previous conditions cannot be both satisfied

- This happens at tree level in gravity and gauge mediated scenarios

BUT

- Radiative corrections drive $m_{H_u}^2 < m_{H_d}^2$

  $\Rightarrow$ radiative electroweak symmetry breaking

- Works naturally with large y_t so $\Rightarrow$ compatible with phenomenology

- The conditions for a minimum compatible with radiative eW breaking are

$$\begin{aligned} m_{H_u}^2 + |\mu|^2 - b\cot\beta - (m_Z^2/2)\cos(2\beta) &= 0, \\ m_{H_d}^2 + |\mu|^2 - b\tan\beta + (m_Z^2/2)\cos(2\beta) &= 0. \end{aligned}$$

Where $v_u = \langle H_u^0 \rangle, \qquad v_d = \langle H_d^0 \rangle.$

and the vev’s are related to the MZ mass through

$$v_u/v_d = \tan\beta, \qquad v_u = \sin\beta, \quad v_d = \cos\beta$$

$$v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \approx (174\,\mathrm{GeV})^2.$$

- The SM particles acquire their tree level masses through their Yukawa couplings and the vet's

$$m_t = y_t v \sin\beta, \qquad m_b = y_b v \cos\beta, \qquad m_\tau = y_\tau v \cos\beta.$$

Higgs masses

- After SUSY and eW symmetry breaking: 5 physical Higgses
- 8 degrees of freedom, 3 give mass to $W^{\pm}, Z^0$ ⇒ rest are $h^0, H^0, A^0, H^{\pm}$

- Lighter Higgs mass is bounded from above

$$m_{h^0} \; < \; m_Z|\cos(2\beta)|$$

Radiative corrections lift it

$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2}\cos^2\alpha \; y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right) .$$

- The rest of the masses can be arbitrarily large

$$\begin{aligned} m_{A^0}^2 &= 2b/\sin(2\beta) \; = \; 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 \\ m_{h^0,H^0}^2 &= \frac{1}{2}\Big(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 - m_Z^2)^2 + 4m_Z^2 m_{A^0}^2 \sin^2(2\beta)}\Big), \\ m_{H^{\pm}}^2 &= m_{A^0}^2 + m_W^2 . \end{aligned}$$

Neutrinos and charginos

- After electroweak and SUSY symmetry breaking all particles acquire masses
- The higgsinos and gauginos mix with each other
- The neutral states mix among themselves, giving rise to 4 neutral particles - the neutralinos
- The same happens with the charged states, after eW symmetry breaking there are 2 charginos

Neutralinos

- In the gauge-eigenstate basis, $\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$, the mass part in the Lagrangian is

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\widetilde{N}} \psi^0 + \text{c.c.},$$

- With a mass matrix

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} \boxed{M_1} & 0 & -g'v_d/\sqrt{2} & g'v_u/\sqrt{2} \\ 0 & \boxed{M_2} & gv_d/\sqrt{2} & -gv_u/\sqrt{2} \\ -g'v_d/\sqrt{2} & gv_d/\sqrt{2} & 0 & \boxed{-\mu} \\ g'v_u/\sqrt{2} & -gv_u/\sqrt{2} & \boxed{-\mu} & 0 \end{pmatrix}.$$

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}.$$

○ Soft breaking terms

- Neutralino masses

$$\begin{aligned}
m_{\widetilde{N}_1} &= M_1 - \frac{m_Z^2 s_W^2 (M_1 + \mu \sin 2\beta)}{\mu^2 - M_1^2} + \dots \\
m_{\widetilde{N}_2} &= M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \dots \\
m_{\widetilde{N}_3}, m_{\widetilde{N}_4} &= |\mu| + \frac{m_Z^2 (I - \sin 2\beta)(\mu + M_1 c_W^2 + M_2 s_W^2)}{2(\mu + M_1)(\mu + M_2)} + \dots, \\
& \quad |\mu| + \frac{m_Z^2 (I + \sin 2\beta)(\mu - M_1 c_W^2 - M_2 s_W^2)}{2(\mu - M_1)(\mu - M_2)} + \dots
\end{aligned}$$

- Chargino masses

$$\begin{aligned}
m_{\widetilde{C}_1}^2, m_{\widetilde{C}_2}^2 &= \frac{1}{2}\Big[|M_2|^2 + |\mu|^2 + 2m_W^2 \\
& \mp \sqrt{(|M_2|^2 + |\mu|^2 + 2m_W^2)^2 - 4|\mu M_2 - m_W^2 \sin 2\beta|^2} \Big].
\end{aligned}$$

- Squarks and slepton masses

$$\mathbf{m}^2_{\tilde{\mathbf{t}}} = \begin{pmatrix} m^2_{Q_3} + m_t^2 + \Delta_{\tilde{u}_L} & v(a_t^* \sin\beta - \mu y_t \cos\beta) \\ v(a_t \sin\beta - \mu^* y_t \cos\beta) & m^2_{\bar{u}_3} + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix} .$$

$$\mathbf{m}^2_{\tilde{\mathbf{b}}} = \begin{pmatrix} m^2_{Q_3} + \Delta_{\tilde{d}_L} & v(a_b^* \cos\beta - \mu y_b \sin\beta) \\ v(a_b \cos\beta - \mu^* y_b \sin\beta) & m^2_{\bar{d}_3} + \Delta_{\tilde{d}_R} \end{pmatrix} ,$$

$$\mathbf{m}^2_{\tilde{\tau}} = \begin{pmatrix} m^2_{L_3} + \Delta_{\tilde{e}_L} & v(a_\tau^* \cos\beta - \mu y_\tau \sin\beta) \\ v(a_\tau \cos\beta - \mu^* y_\tau \sin\beta) & m^2_{\bar{e}_3} + \Delta_{\tilde{e}_R} \end{pmatrix} .$$

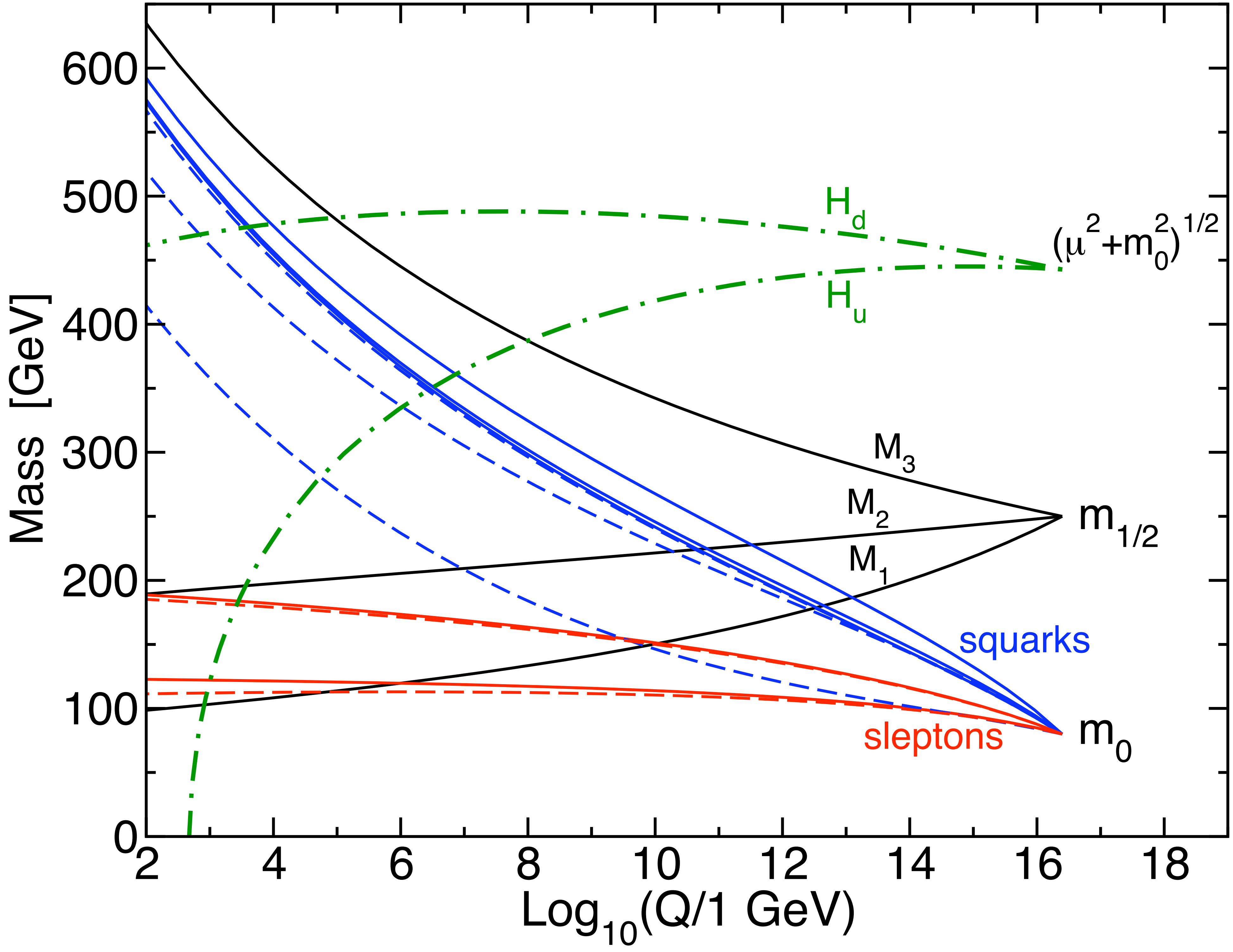
$$\Delta_\phi \;=\; (T_{3\phi} g^2 - Y_\phi g'^2)(v_d^2 - v_u^2) \;=\; (T_{3\phi} - Q_\phi \sin^2\theta_W)\cos(2\beta)\, m_Z^2 ,$$

$$\Delta_{\tilde{d}_L} = (-\tfrac{1}{2} + \tfrac{1}{3}\sin^2\theta_W)\cos(2\beta)\, m_Z^2$$

MSSM mass states

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	-1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	-1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	-1	$\widetilde{B}^0\ \ \widetilde{W}^0\ \ \widetilde{H}_u^0\ \ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	-1	$\widetilde{W}^\pm\ \ \widetilde{H}_u^+\ \ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \ \widetilde{C}_2^\pm$
gluino	1/2	-1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	-1	$\widetilde{G}$	(same)

Evolution of scalars and neutralinos



CMSSM

- MSSM has too many free parameters, even after constraining FCNCs
- Constrained MSSM, inspired by SUSY GUTs and minimal supergravity models mSUGRA
- Assumes universal masses for gauginos, soft scalars at the unification scale

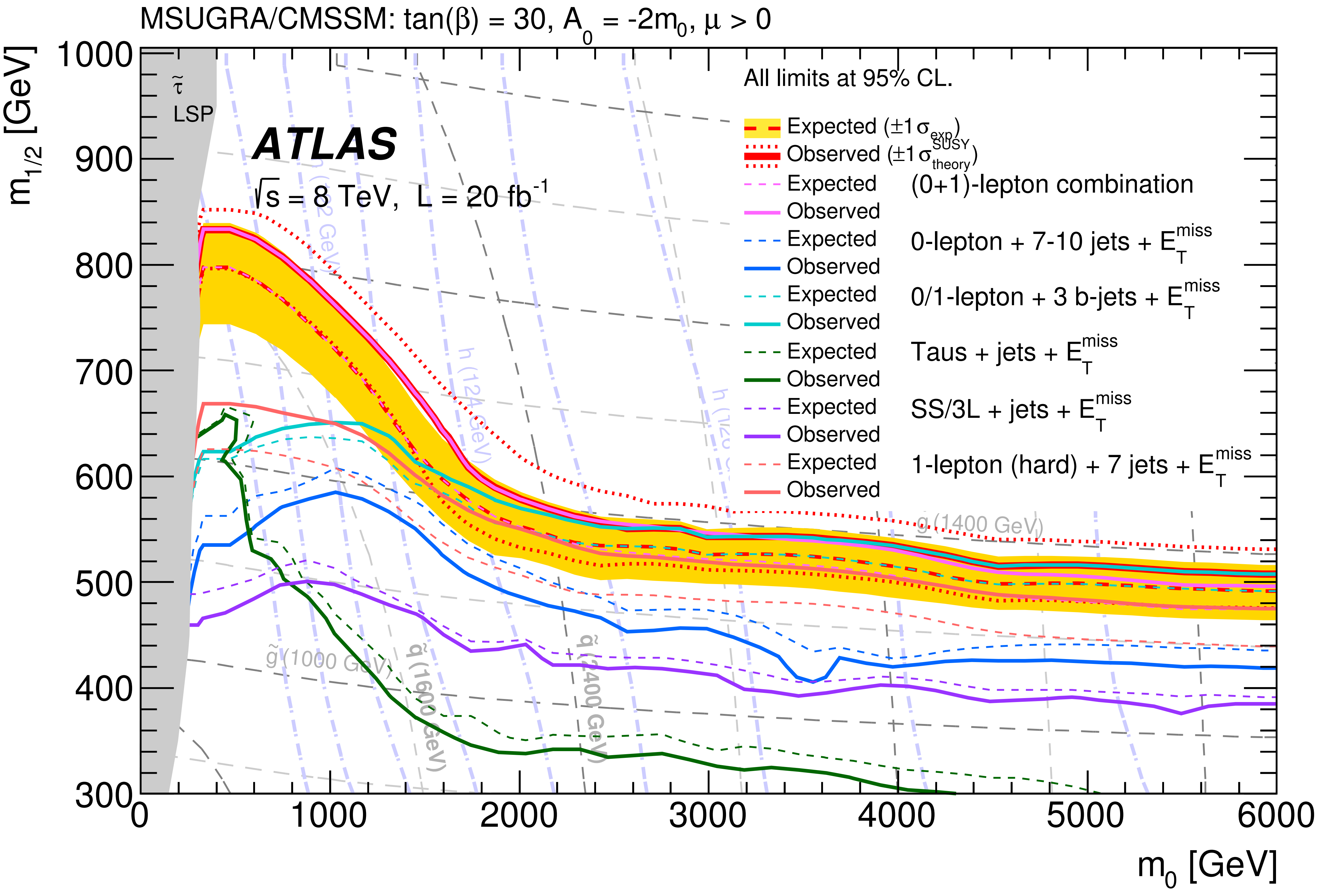
- Has five parameters:

  vu/vd = tan β

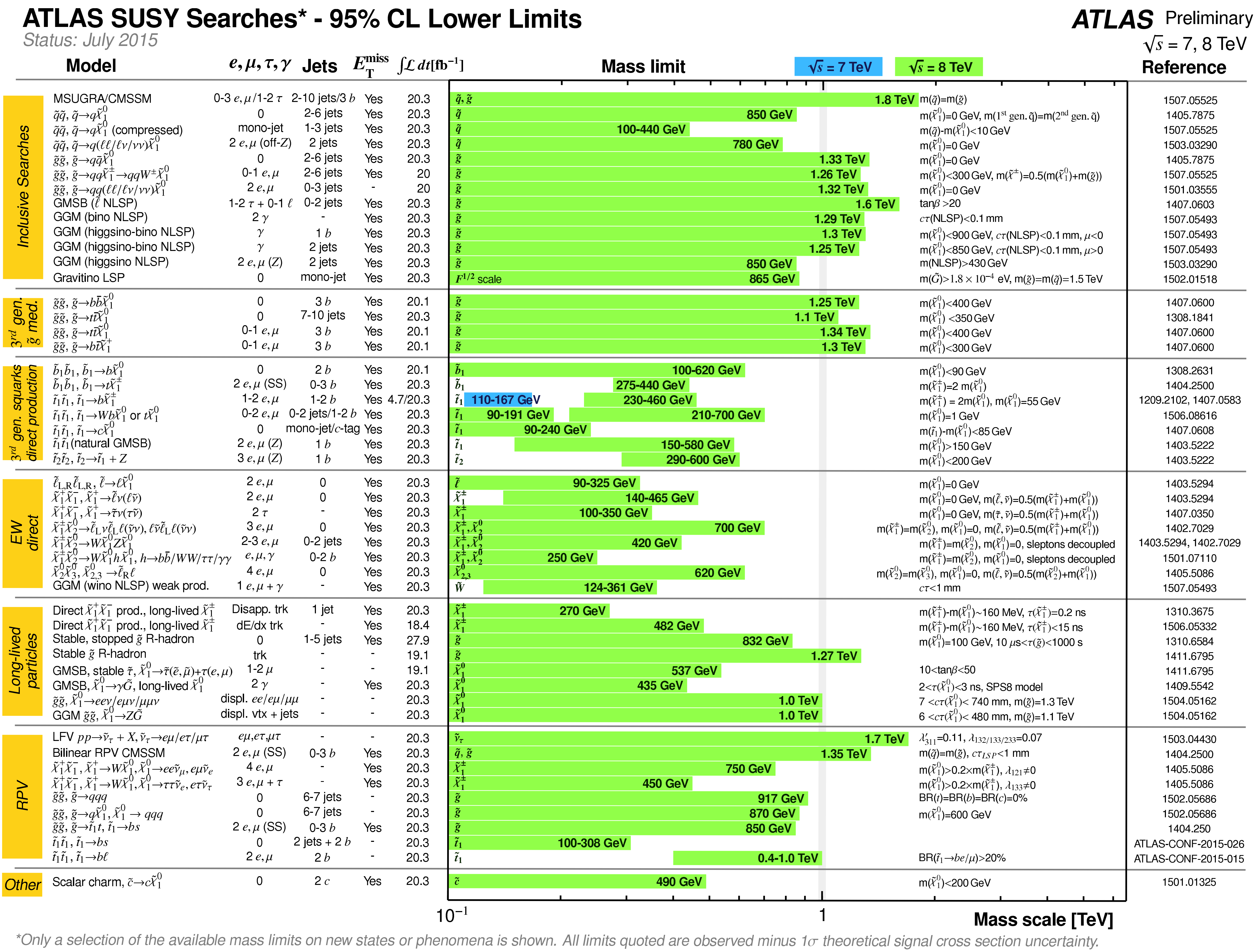
  sign μ

  unified gaugino mass $\mathbf{m}_{1/2}$
  unified scalar mass $\mathbf{m}_0$
  unified trilinear
  scalar terms **A**

- Parts of this model have already been excluded by LHC... others haven't been probed yet



Gluino mass limits from ATLAS (PDG)
masses < 1300 GeV excluded
More sensitivity in LHC to coloured particles — squarks, gluinos



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.8 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$ 100-440 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<10 GeV	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 780 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$ 1.26 TeV	m($\tilde{\chi}_1^0$)<300 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1507.05525
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
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	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 110-167 GeV 230-460 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 210-700 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>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	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
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	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=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	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 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($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu + \gamma$	-	Yes	20.3	$\tilde{W}$ 124-361 GeV	$c\tau$<1 mm	1507.05493
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, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 482 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to q\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 870 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

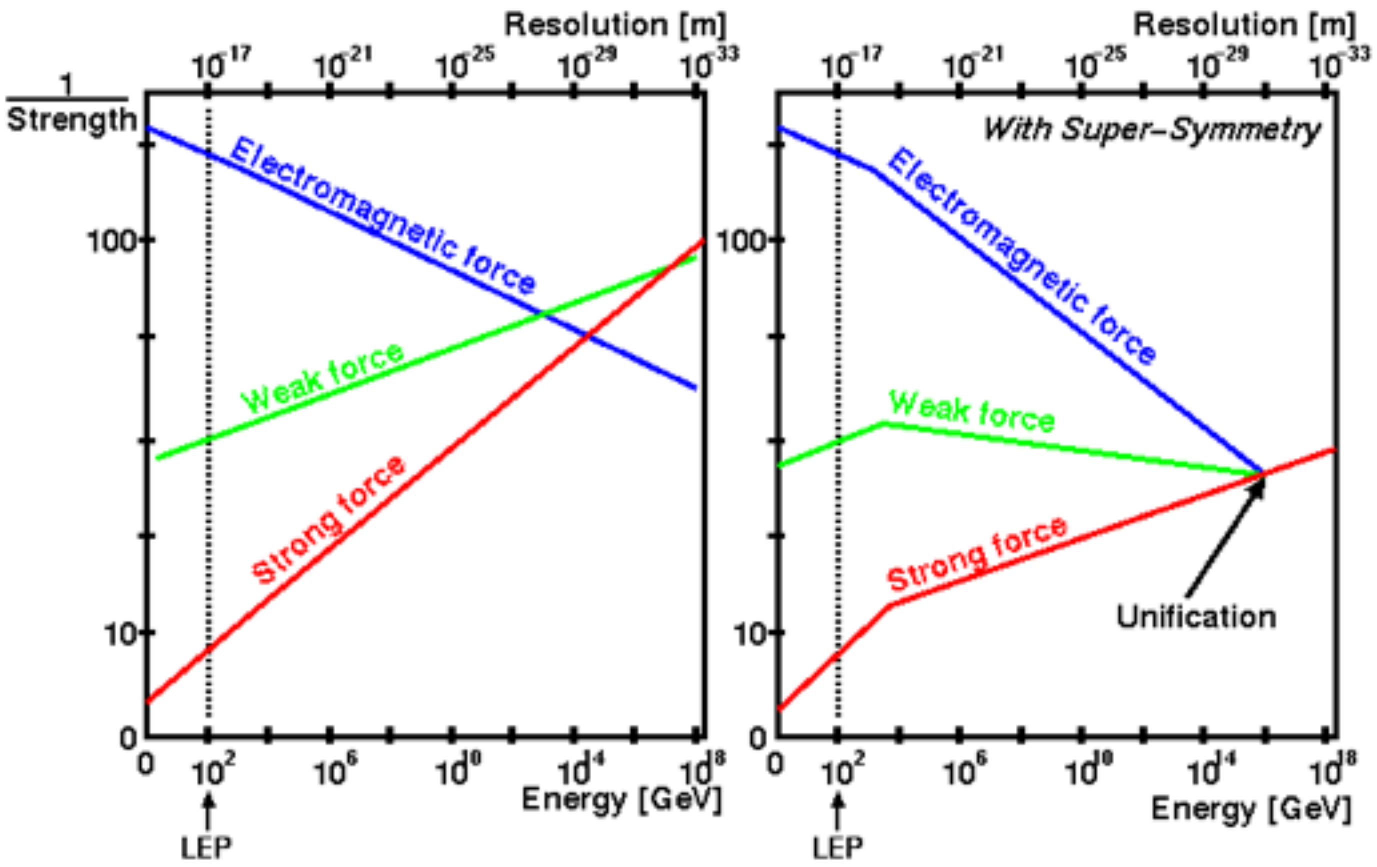
From PDG. Results for CMS similar

so why SUSY?

- Solution to the hierarchy problem
- Several dark matter candidates:
  lightest neutralino, gravitino, axino...
- Compatible with unification of couplings
- Unification of couplings compatible with scales of seesaw mechanism
- R parity can be broken → gravitino as dark matter, neutrino masses in some GUTs
- More models than the CMSSM with different predictions
- Un-natural → might just hide unknown physics → correlations among parameters
- Non-appearance? → reexamine where the expectations came from

SUSY GUTs

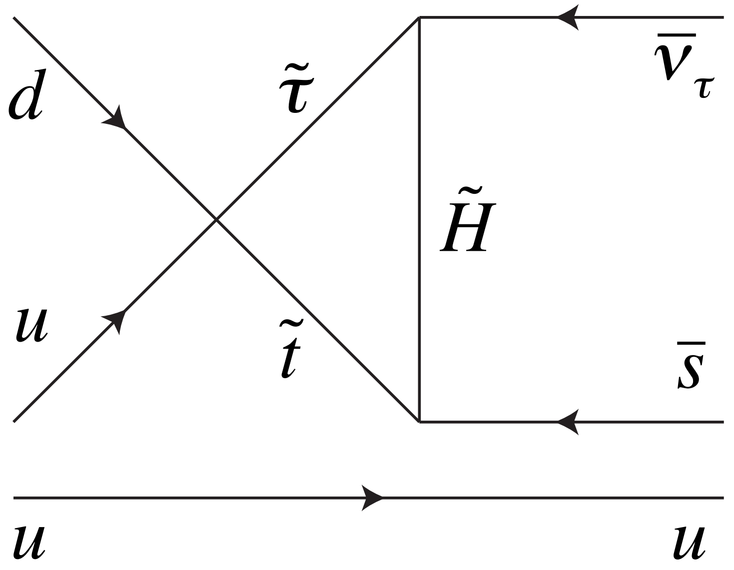
- Add yet more symmetry: combine SUSY and GUTs
- Unification of couplings is good in SUSY GUTs

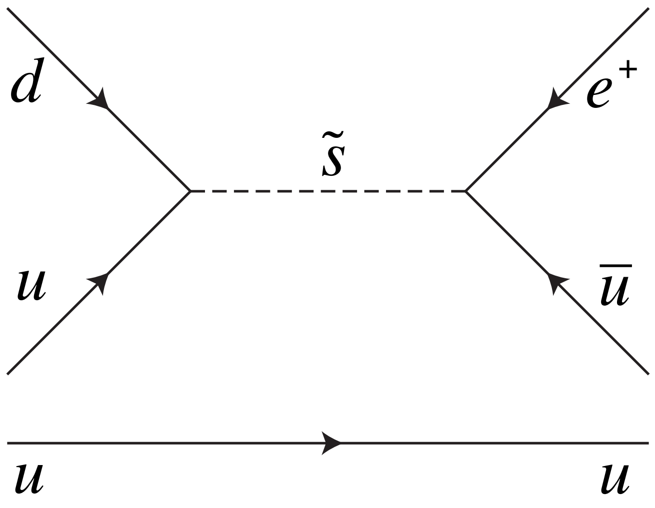


- SU(5) add neutrinos with a U(1), non-renormalizable interactions or R parity violation
- SO(10) has naturally right handed neutrinos, more stages of symmetry breaking
- Some GUT problems alleviated by SUSY relations

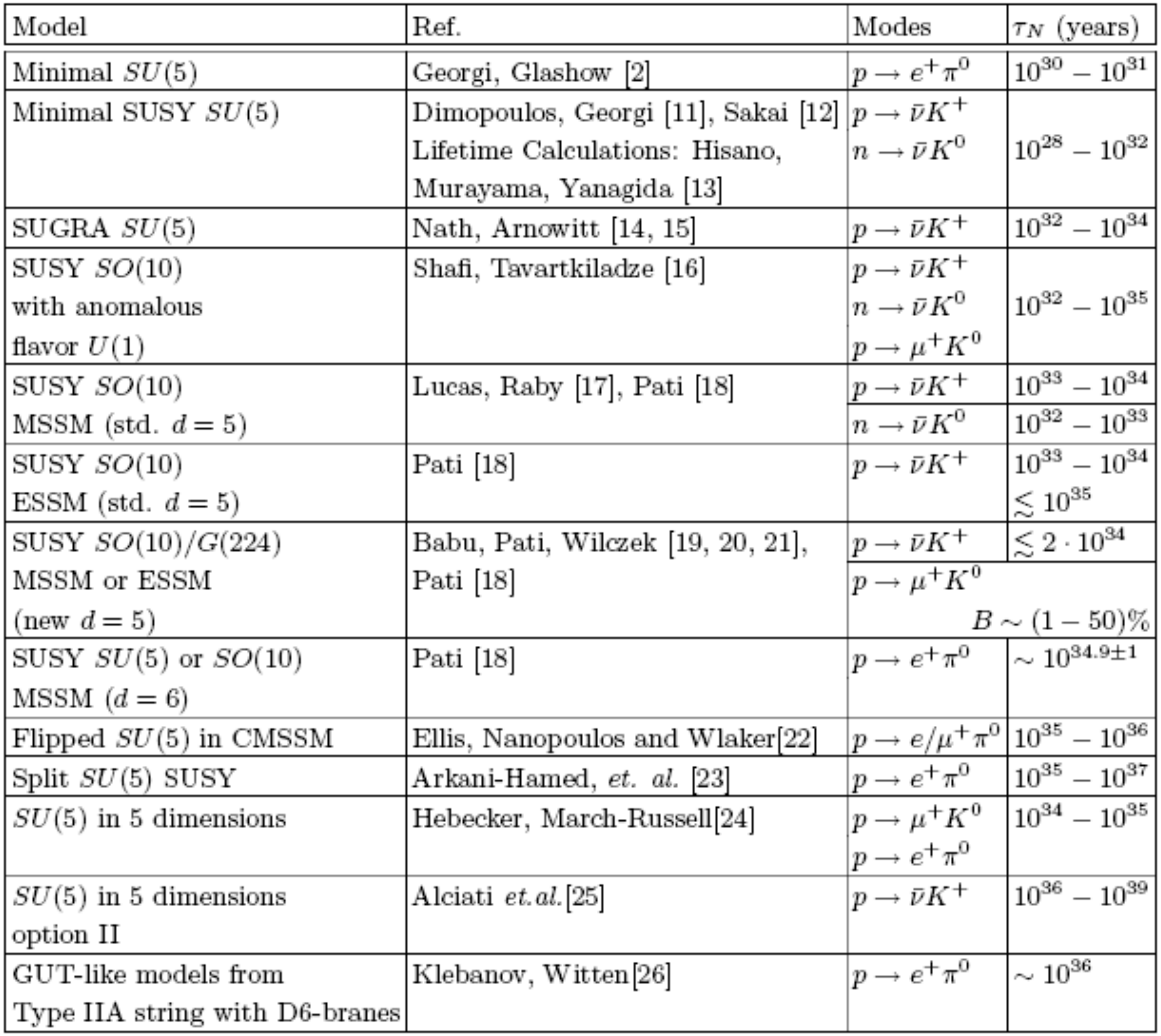
More ways for the proton to decay…

Dimension 5 operators
i.e. QQQL





Dimension 4 operators
$U^C D^C D^C$ or QLD^C
forbidden by R parity



Model	Ref.	Modes	τ_N (years)
Minimal $SU(5)$	Georgi, Glashow [2]	$p \rightarrow e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY $SU(5)$	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \rightarrow \bar{\nu}K^+$ $n \rightarrow \bar{\nu}K^0$	$10^{28} - 10^{32}$
SUGRA $SU(5)$	Nath, Arnowitt [14, 15]	$p \rightarrow \bar{\nu}K^+$	$10^{32} - 10^{34}$
SUSY $SO(10)$ with anomalous flavor $U(1)$	Shafi, Tavartkiladze [16]	$p \rightarrow \bar{\nu}K^+$ $n \rightarrow \bar{\nu}K^0$ $p \rightarrow \mu^+K^0$	$10^{32} - 10^{35}$
SUSY $SO(10)$ MSSM (std. $d = 5$)	Lucas, Raby [17], Pati [18]	$p \rightarrow \bar{\nu}K^+$	$10^{33} - 10^{34}$
		$n \rightarrow \bar{\nu}K^0$	$10^{32} - 10^{33}$
SUSY $SO(10)$ ESSM (std. $d = 5$)	Pati [18]	$p \rightarrow \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d = 5$)	Babu, Pati, Wilczek [19, 20, 21], Pati [18]	$p \rightarrow \bar{\nu}K^+$	$\lesssim 2 \cdot 10^{34}$
		$p \rightarrow \mu^+K^0$ $B \sim (1 - 50)\%$	
SUSY $SU(5)$ or $SO(10)$ MSSM ($d = 6$)	Pati [18]	$p \rightarrow e^+\pi^0$	$\sim 10^{34.9\pm1}$
Flipped $SU(5)$ in CMSSM	Ellis, Nanopoulos and Wlaker[22]	$p \rightarrow e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split $SU(5)$ SUSY	Arkani-Hamed, *et. al.* [23]	$p \rightarrow e^+\pi^0$	$10^{35} - 10^{37}$
$SU(5)$ in 5 dimensions	Hebecker, March-Russell[24]	$p \rightarrow \mu^+K^0$ $p \rightarrow e^+\pi^0$	$10^{34} - 10^{35}$
$SU(5)$ in 5 dimensions option II	Alciati *et.al.*[25]	$p \rightarrow \bar{\nu}K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten[26]	$p \rightarrow e^+\pi^0$	$\sim 10^{36}$

TABLE I: Summary of the expected nucleon lifetime in different theoretical models.

A. Bueno et al. hep-ph/0701101

Current limit ~ 10^{34} years
from super-Kamiokande