Physics Beyond Standard Model

(mostly supersymmetry)

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Outline

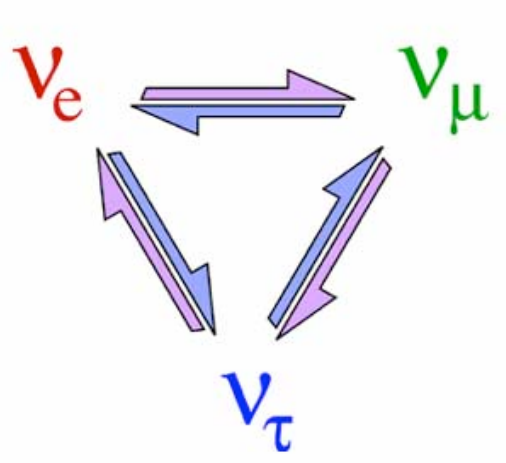
1) Why BSM Physics ?
2) Hierarchy Problem
3) Supersymmetry as a solution
4) The structure of MSSM
5) Soft terms in Different Mediation Schemes

why BSM Physics ?

Phenomenological	Theoretical
neutrino masses	hierarchy problem
dark matter	GUTs/quantum gravity (strings)
leptogenesis/baryogenesis	strong CP

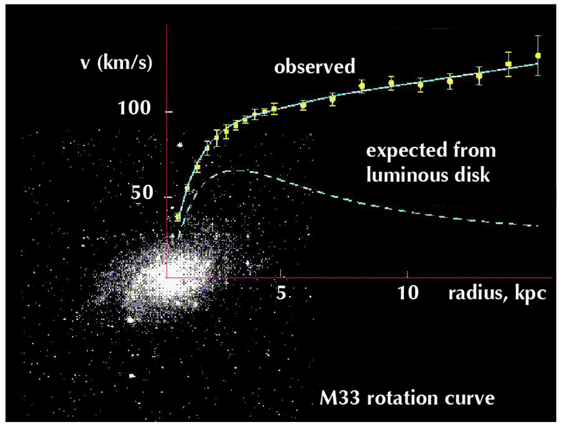
nakaya san's lectures

neutrino masses



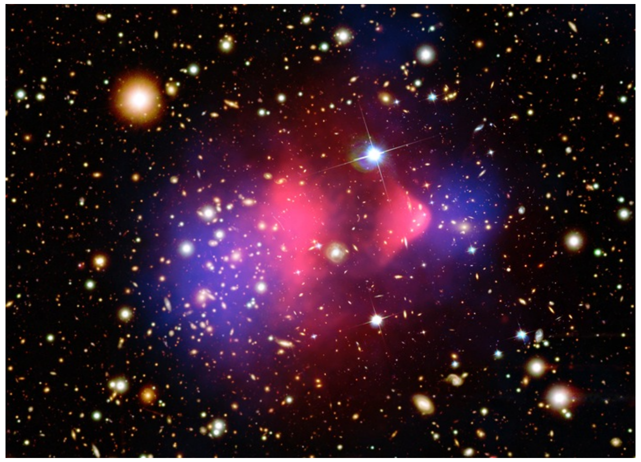
The periodic change of neutrino flavor from one type into another is referred to as neutrino oscillations.

- Super K (atmospheric), SNO (solar), KamLAND, DAYA-BAY (reactor) etc. have put neutrino oscillations on a strong footing.
- Neutrino masses are tiny $\sim 10^{(-5-6)} m_e$
- There are three types of seesaw mechanisms all of which require additional particles at some high scale to generate tiny neutrino masses.
- We still do not know whether neutrinos have Dirac type or Majorana type masses. In either of the case, we expect new symmetries or new phenomena beyond SM.



dark matter

moroi san's lectures

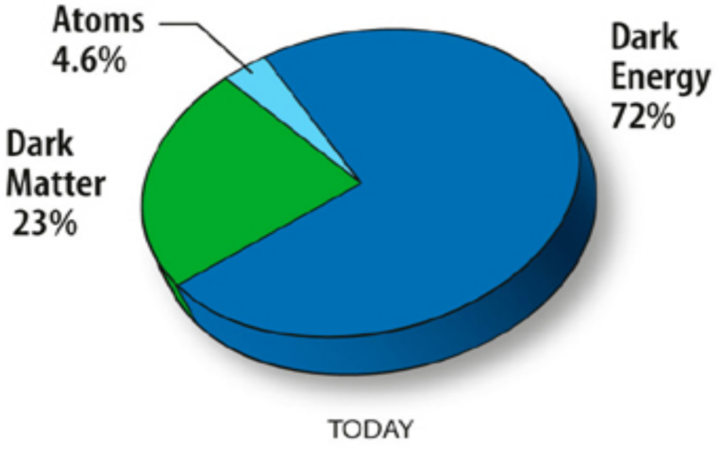


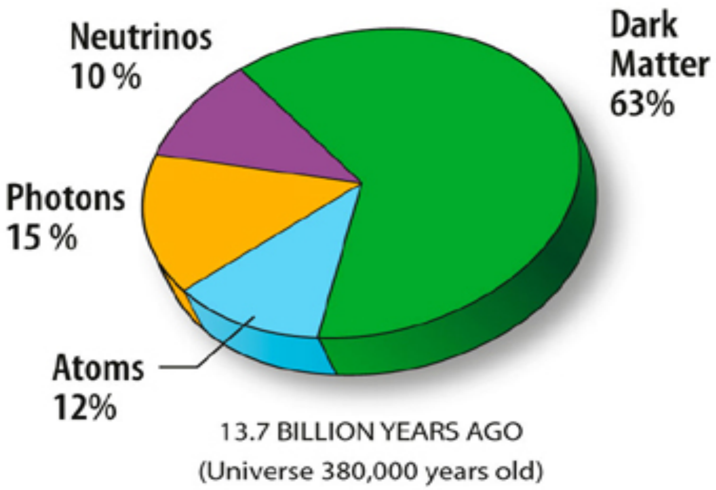
Bullet Cluster: Evidence for Dark Matter

Clear and direct evidence for dark matter at all scales

no particle in SM can be the dark matter

new color and charge neutral, stable and perhaps weakly interacting particles are proposed to be the dark matter





Matter Anti-Matter Asymmetry

moroi san's lectures

- According to Big Bang theory, equal amount of matter and anti-matter was produced in the early universe. However the present universe is dominated by matter.

- A tiny asymmetry in the early universe is sufficient to generate the large asymmetry observed today. $n_b - n_{\bar{b}} \sim 10^{(-10)} n_\gamma$

- Two of the three Sakharov conditions: (C violation, CP violation, B violation), in the Standard Model, B violation is very small. One needs a new source of B or L violation (leptogenesis).

Hierarchy problem

Kaul ’82

murayama

Consider QED :

$$\mathcal{L}_{\mathrm{QED}} = \frac{-1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}\left[i\gamma^{\mu}\partial_{\mu} - ieq_f A_{\mu}) - m_e\right]\psi$$

$$(\Delta m_e) \sim e^2 \ m_e^2 \ ln\Lambda$$

The limit $m_e \to 0$ leads to an enhanced symmetry (chiral symmetry in the theory)

The electron mass is protected from large radiative corrections.

Furthermore there are no large corrections from muon, tau other heavy leptons to the electron mass. Heavy fermions are decoupled.

“natural theories “

Instead consider Yukawa theory:

$$\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - \frac{1}{2}m_S^2\phi^2 + \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m_F)\psi + y\bar{\psi}\psi\phi$$

The correction to the scalar mass term from one loop corrections is given by

$$\delta m_S^2 = -y^2 \int \frac{d^4k}{k^2 - m_F^2} \sim -y^2 m_F^2 \ln\left(\frac{m_F^2}{\mu^2}\right)$$

In the limit $m_F \gg m_S$ these corrections are very large.

Corrections to m_S are not proportional to itself.

they do not go to zero in the limit $m_S \to 0$

there is no enhanced symmetry in that limit.

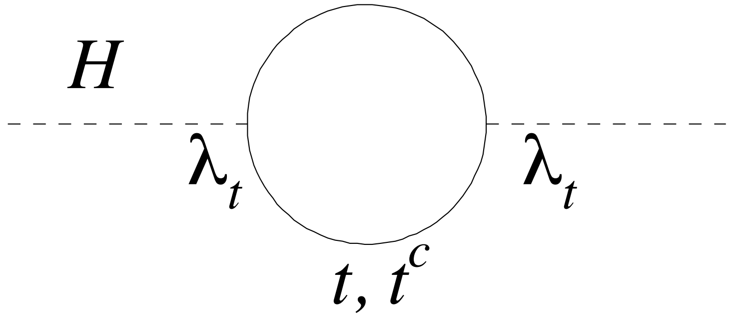
The effects of heavy fermions do not decouple !!

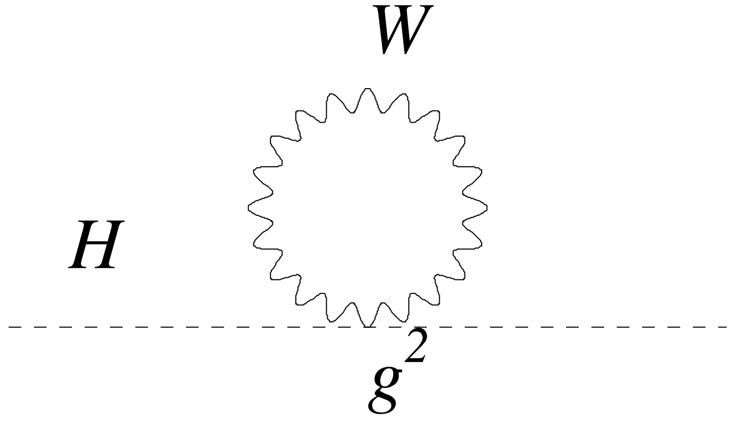
there is no symmetry which protects the
scalar mass from large radiative corrections.

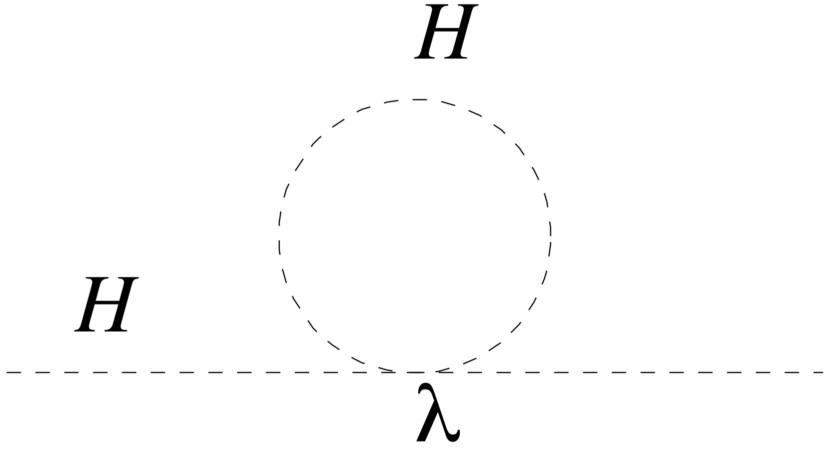
Theories with fundamental scalars are unnatural or fine-tuned.

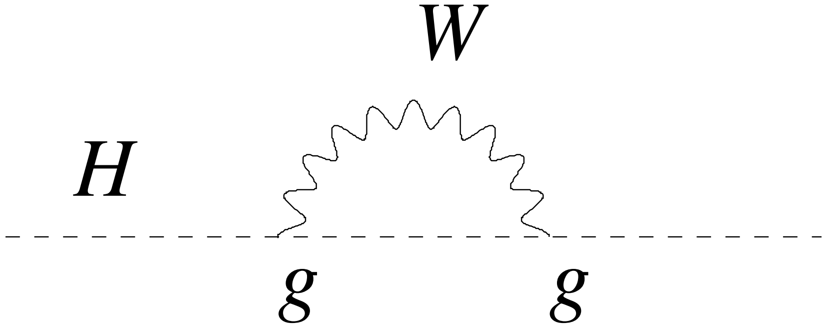
The Standard Model is one such theory

Implications on the Higgs Mass in SM









$$\delta m_H^2 \sim \frac{1}{16\pi^2} M_{\mathrm{GUT}}^2 \text{ or } M_{\mathrm{Pl}}^2$$

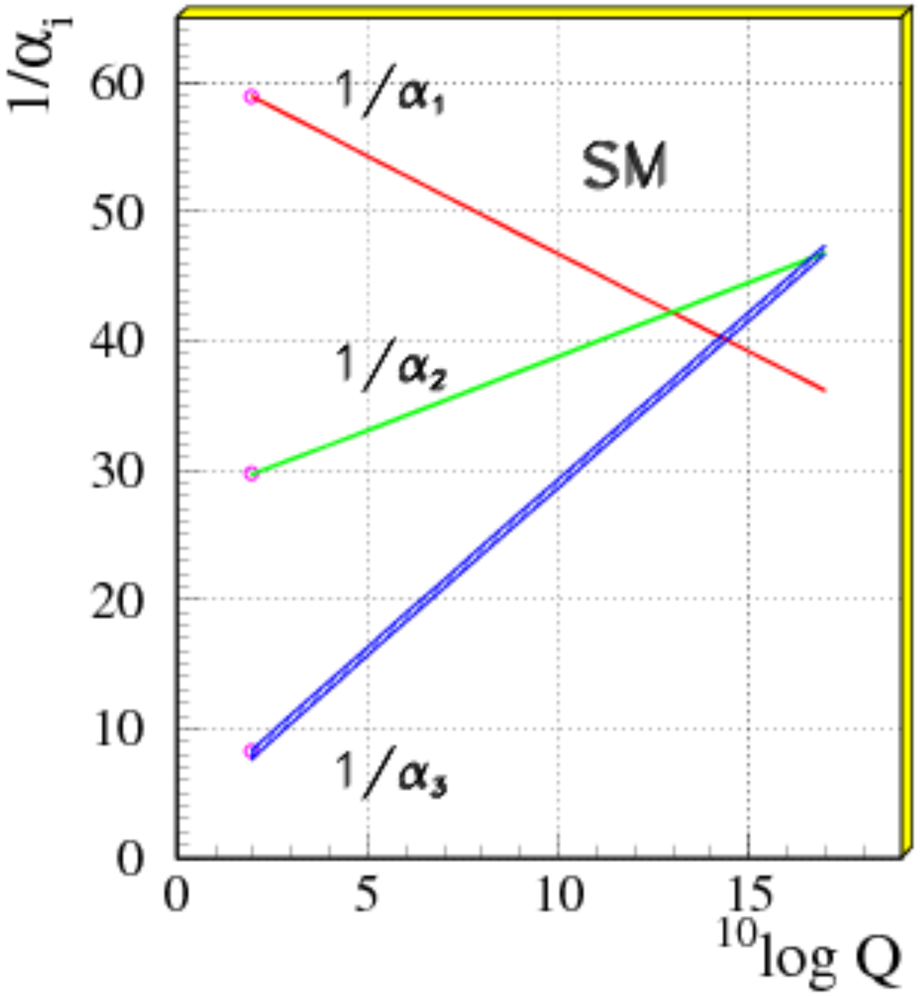
$M_{\rm Planck}$

$$\delta m_h^2 \approx \frac{1}{16\pi^2}\Lambda^2 \approx \frac{1}{16\pi^2}M_{\rm Planck}^2$$

$M_{\rm Weak}$

If SM is an effective theory below Planck
Scale with an elementary scalar, the mass
of such a scalar would be unstable under radiative
corrections

GUTs and Quantum Gravity



Gauge couplings do not unify in SM

Hierarchy problem reappears as Doublet -Triplet splitting problem in GUTs.

The idea of Grand Unification are important after the discovery of neutrino masses

The scale of New Physics

- neutrino masses can be accommodated with new mass scales to the SM from a few TeV to all the way up to GUT scale.

- Dark matter particle mass is not known, it crucially depends on its interaction strength with SM particles. Huge range in mass and other properties like spin etc. is allowed.

- Baryogenesis/leptogenesis can be accommodated by particles of TeV to GUT scale.

- A solution to Hierarchy problem however requires some new physics close to the electroweak scale.

Two Choices

(a) Either the cut-off is low (new physics scale (non-perturbative) like composite scale or extra dimensions etc)

(b) There is some symmetry protecting the Higgs Mass

Supersymmetry is a symmetry which protects the higgs mass but also introduces a new physics scale

How SUSY works

Fermion ↔ Boson

1/2 ↔ 0

1/2 ↔ 1

supermultiplets are form with pairs of particles
transforming by spin 1/2

(0,1/2): Chiral supermultiplet (1/2,1): Vector supermultiplet

same masses and same couplings within the multiplet

The Structure of MSSM

Wess and Bagger, Text Book
Baer and Tata , Text Book
Drees, Godbole, Roy, Text Book
S. P. Martin, Primer hep-ph/9709356

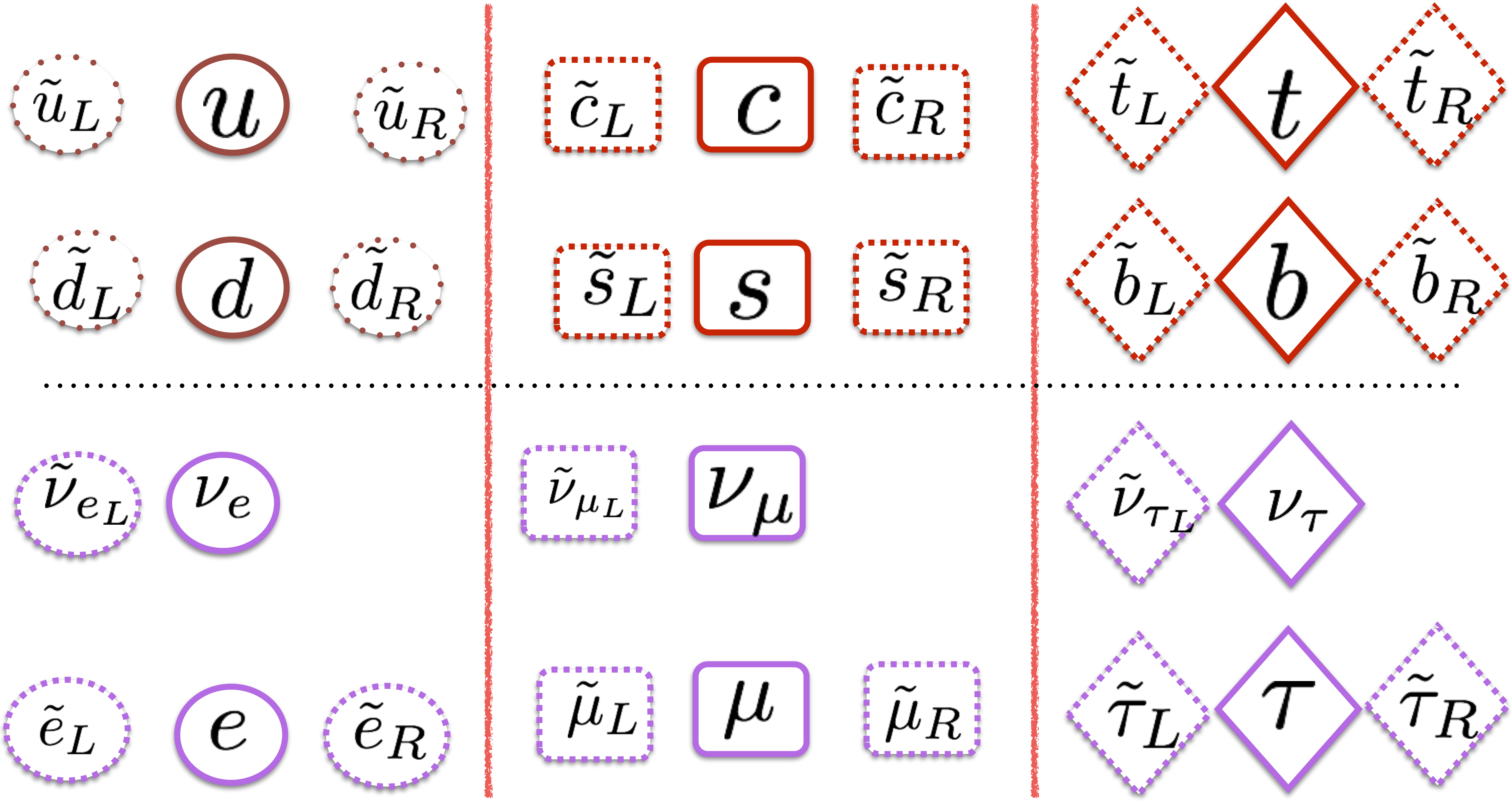
Construction of MSSM

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix} \Longrightarrow \begin{pmatrix}(\nu_e \;\; \tilde{\nu}_e\,) \\ (e,\; \tilde{e}\,)\end{pmatrix}$$

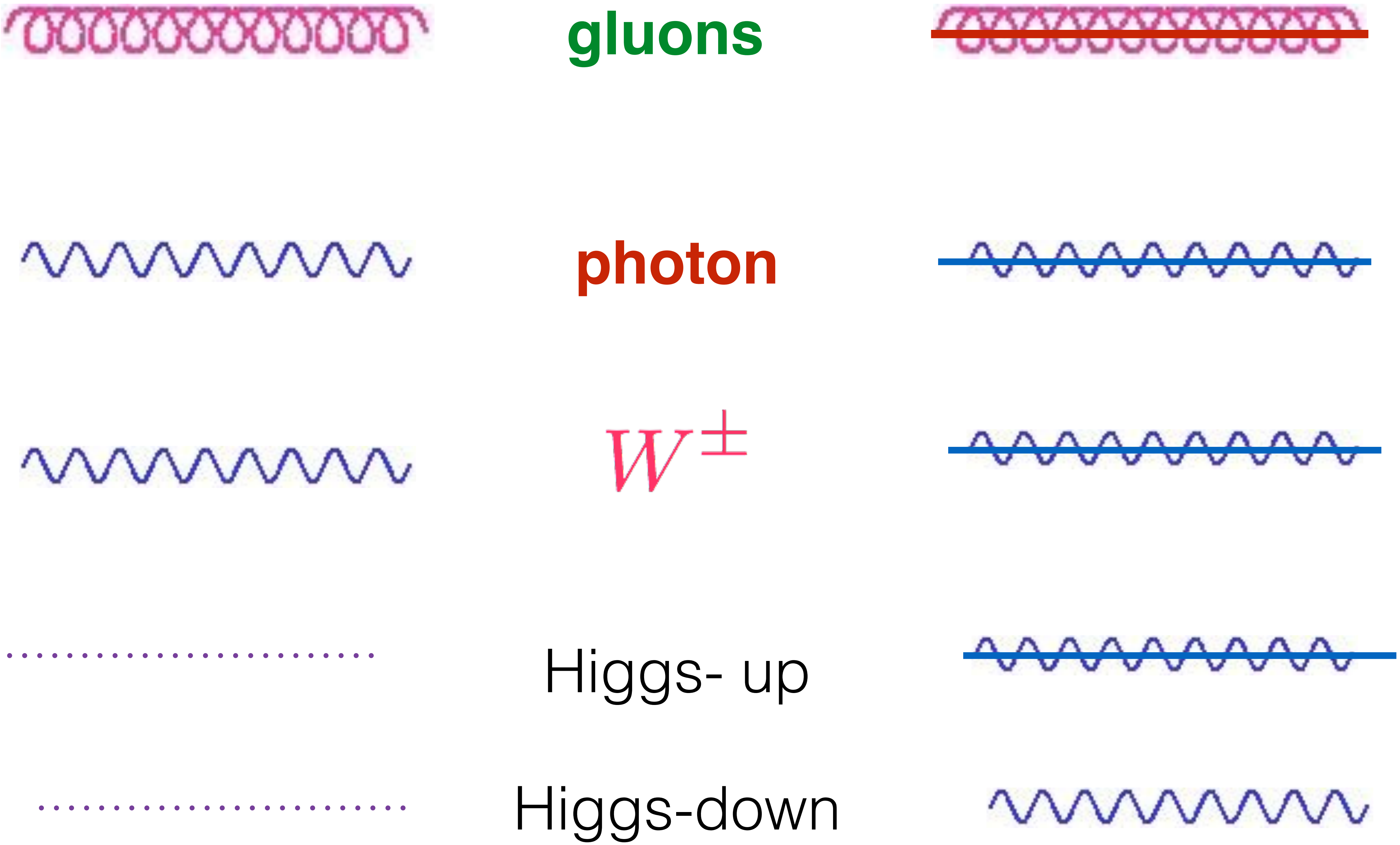
every matterfield with chiral multiplet

$$W \Longrightarrow (W, \tilde{W})$$

every vector field with vector multiplet



Supersymmetric Standard Model -1



gluons

photon

$W^{\pm}$

Higgs- up

Higgs-down

Supersymmetric Standard Model Spectrum -2

S. Vempati, SERC Lecture Notes, arXiv:1201.0334

Three functions of superfields

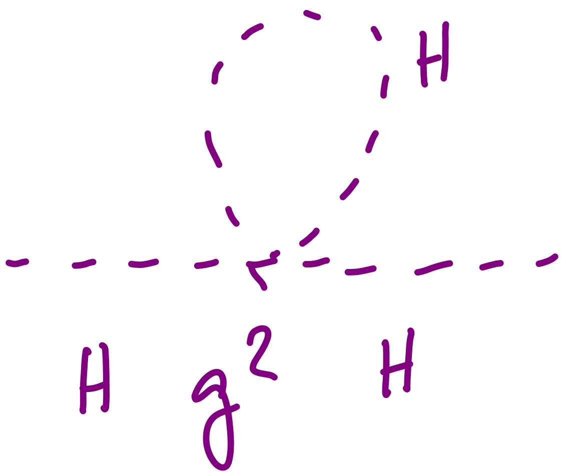
$\mathcal{L}_{\text{Kinetic; gauge}} \supset \int d^4\theta\, K = \Phi^\dagger e^{gV} \Phi$ real fn of chiral and vector multiplets

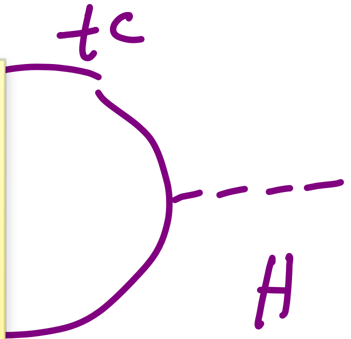
$\mathcal{L}_{\text{Yukawa}} \supset \int d^2\theta\, W = \Phi_i \Phi_j \Phi_k$ analytic fn of chiral multiplets

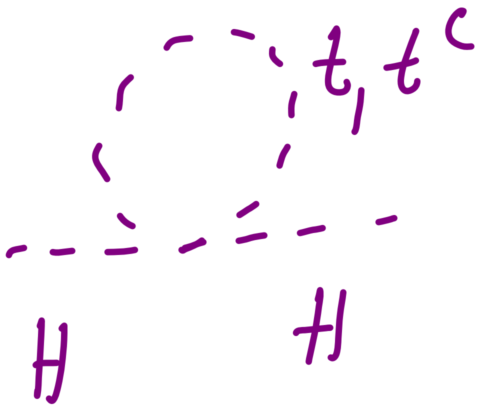
two Higgs doublets required to cancel anomalies

How SUSY works

susy qed as an example.







quantic coupling replaced by gauge coupling

If $m_t \approx m_{\tilde{t}}$ quadratic divergences cancel from both the diagrams

MSSM SUPERPOTENTIAL

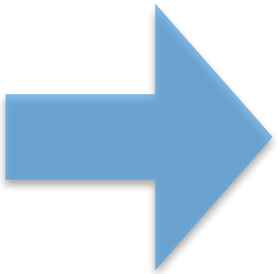
$$W = W_0 + W_1$$

$$W_0 = h_u Q u^c H_u + h_d Q d^c H_d + h_e L e^c H_d + \mu H_u H_d$$

$$W_1 = \lambda L L e^c + \lambda' L Q d^c + \lambda'' u^c d^c d^c + \epsilon L H_u$$

Baryon and Lepton Number Violating !

Imposing R-parity



$$W_1 = 0$$

LSP stable

Dark Matter Candidate

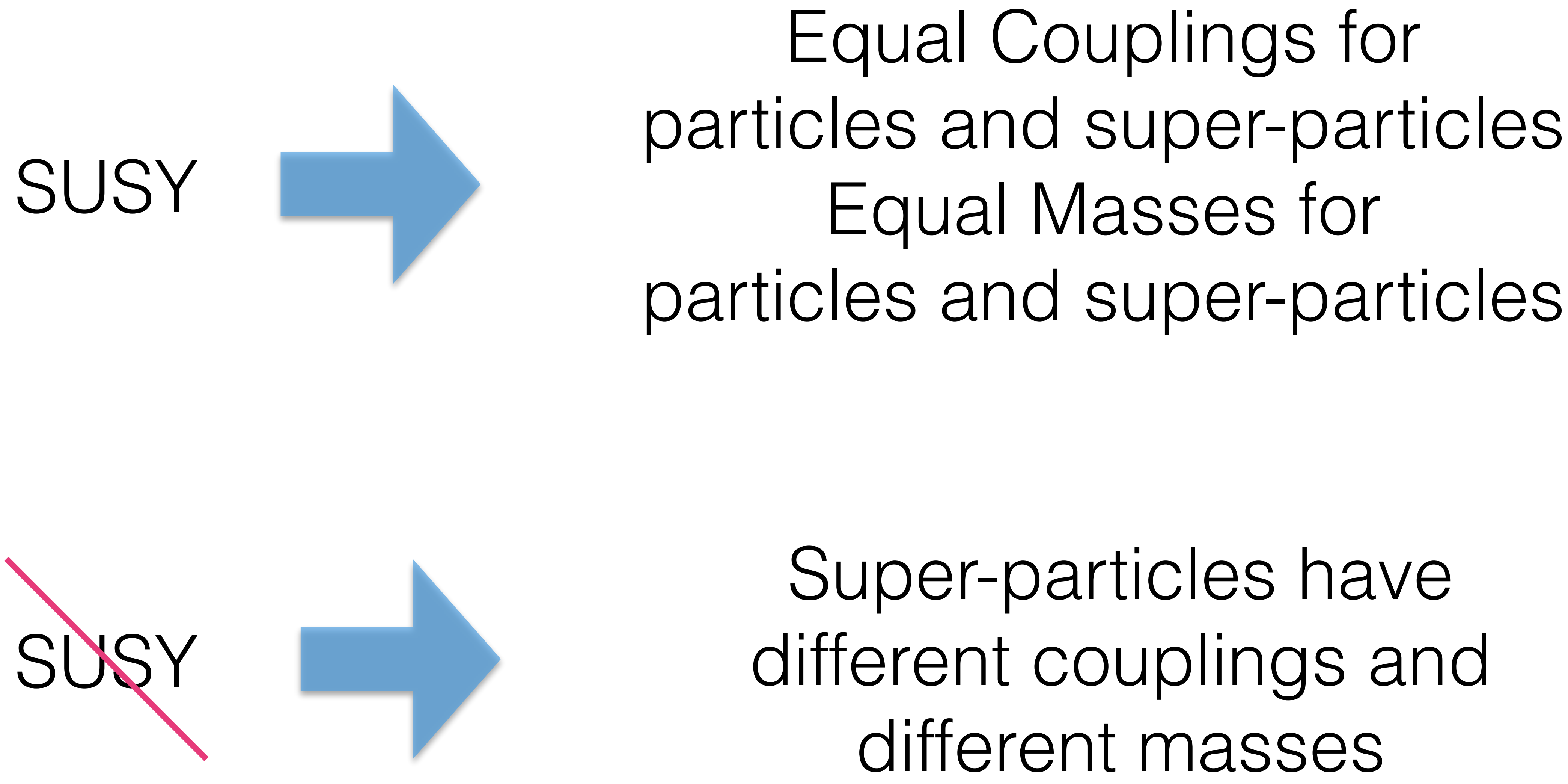
$$R_p = (-1)^{(3B+L+2S)}$$

Supersymmetry breaking

E. Witten, Nucl. Phys B. 188(1981)513;
B. 202 (1982)253,
M. Luty, hep-ph/0509029
Y.Shirman, hep-ph/0907.0039
E. Dudas ,Pramana, 72,(2009) 131

soft susy breaking

Spontaneous Supersymmetry breaking leads to soft supersymmetry breaking terms.



SUSY

Equal Couplings for particles and super-particles
Equal Masses for particles and super-particles

~~SUSY~~

Super-particles have different couplings and different masses

soft susy breaking

Giradello -Grisaru
Dimpolous-Georgi

gaugino masses $M_1 \tilde{B}\tilde{B}, M_2 \tilde{W}_I \tilde{W}_I, M_3 \tilde{G}_A \tilde{G}_A,$

scalar mass terms $m^2_{Q_{ij}} \tilde{Q}^\dagger_i \tilde{Q}_j, m^2_{u_{ij}} \tilde{u^c}^\star{}_i \tilde{u^c}{}_j, m^2_{d_{ij}} \tilde{d^c}^\star{}_i \tilde{d^c}{}_j, m^2_{L_{ij}} \tilde{L}^\dagger_i \tilde{L}_j, m^2_{e_{ij}} \tilde{e^c}^\star{}_i \tilde{e^c}{}_j, m^2_{H_1} H^\dagger_1 H_1, m^2_{H_2} H^\dagger_2 H_2.$

trilinear couplings $A^u_{ij} \tilde{Q}_i \tilde{u}^c_j H_2, A^d_{ij} \tilde{Q}_i \tilde{d}^c_j H_1, A^e_{ij} \tilde{L}_i \tilde{e}^c_j H_1$

bilinear couplings $B H_1 H_2$

A total of about 105 parameters

SUSY FEYNMAN Rules: some examples .

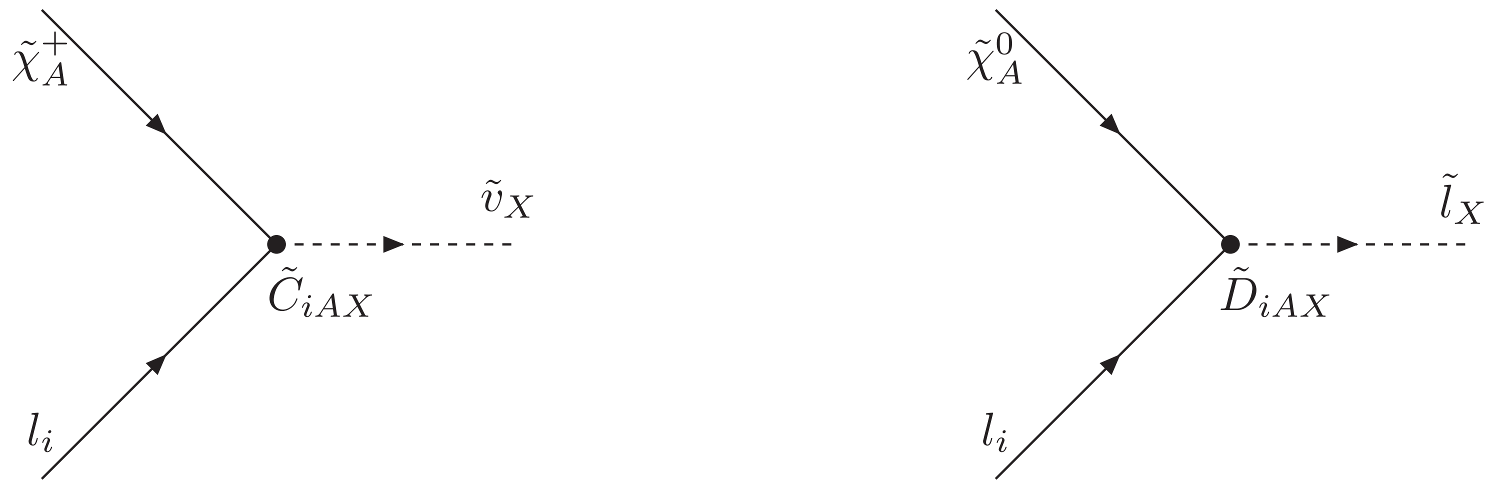


FIG. 3: lepton-slepton-chargino and lepton-slepton-neutralino vertices.

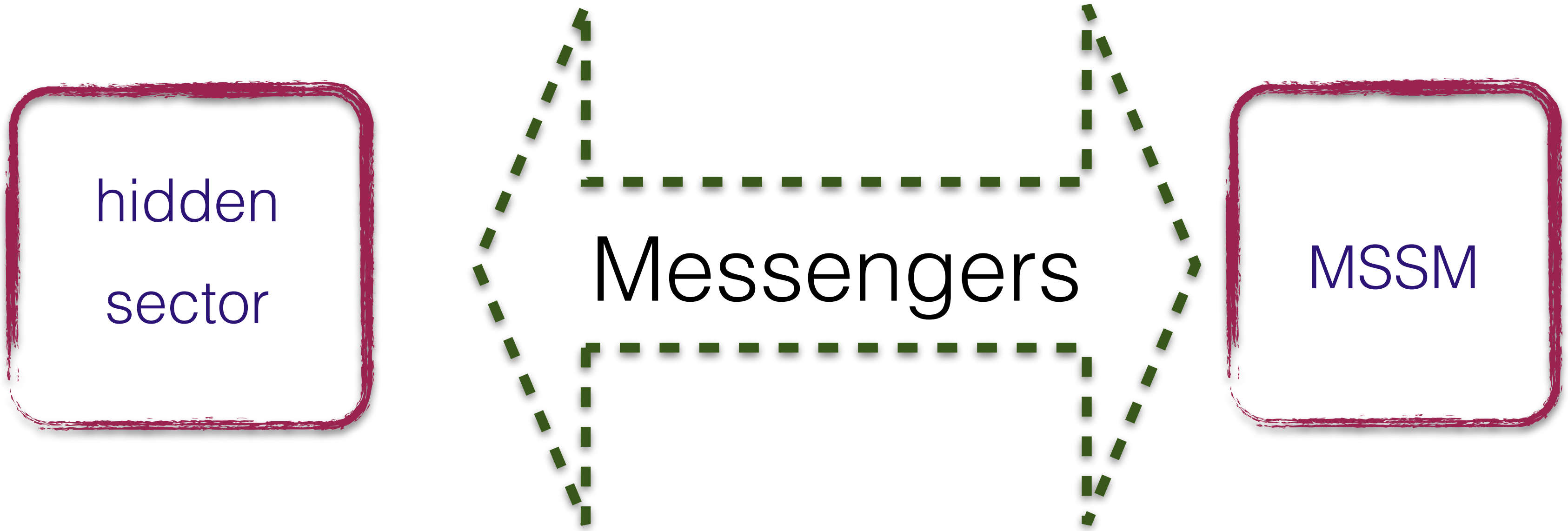
BUT, SUSY cannot be broken spontaneously in any of the MSSM multiplets including Higgs

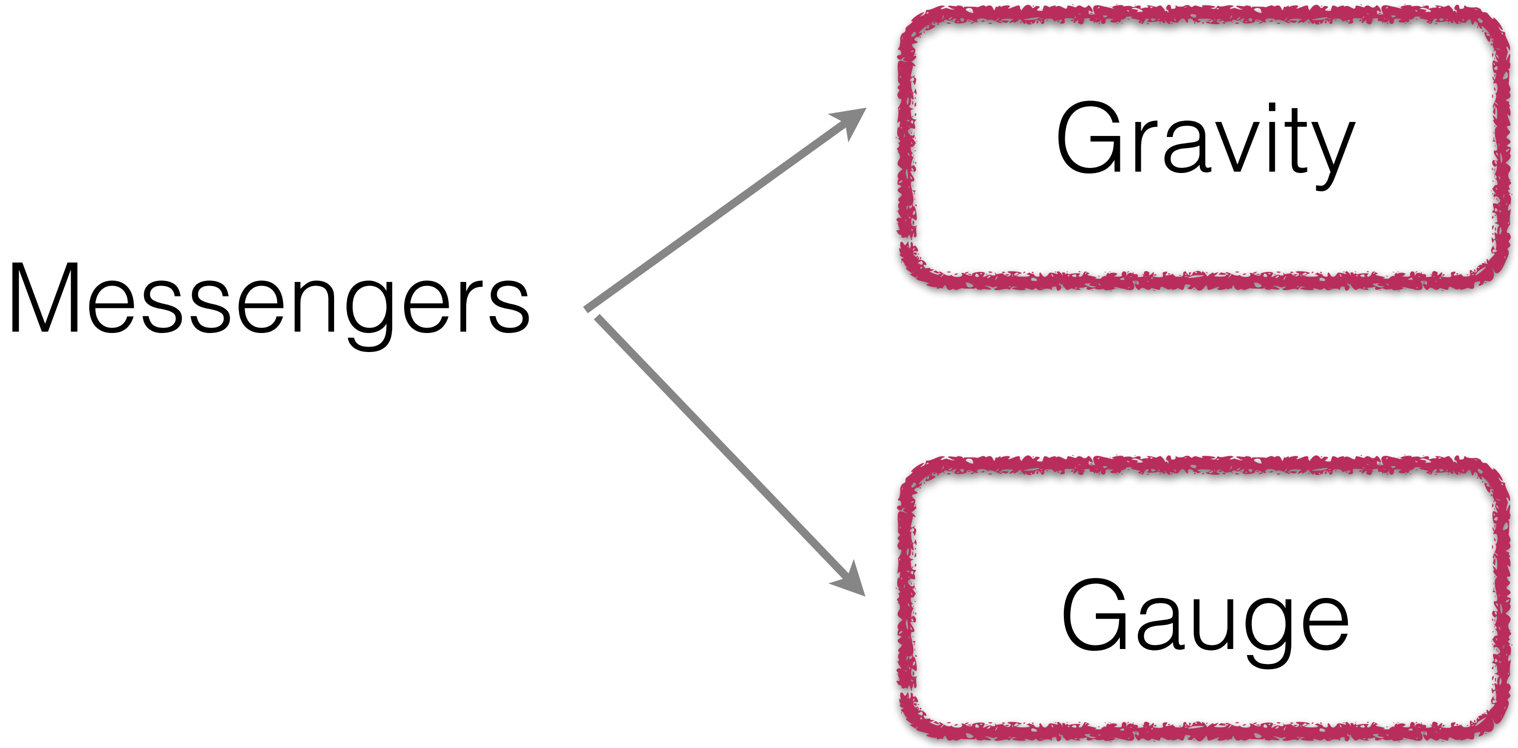
Constraints from Phenomenology

HIDDEN SECTOR IDEAS

Consider a set of fields neutral (uncharged) under the Standard Model Gauge Group

Break supersymmetry spontaneously in that sector and propagate the breaking to the MSSM sector





Hidden and Visible sector fields need not be at the same space time points

(non-traditional models)

Some traditional Models

minimal Supergravity

$$K = X_i^\dagger X_i + \Phi_i^\dagger \Phi_i + \cdots\cdots$$

$$W = W_{hidden} + W_{MSSM}$$

$$V = e^{G}\left(G_i G^i - 3\right)$$

$$G = K + \ln |W|^2$$

$$G_i = \frac{\partial G}{\partial \Phi_i}$$

* As long as Kahler potential is in Canonical form:

$$m_{\tilde{f}}^2 = m_0^2$$

$$M_i = M_{1/2}$$

$$A_{ijk} = A_0$$

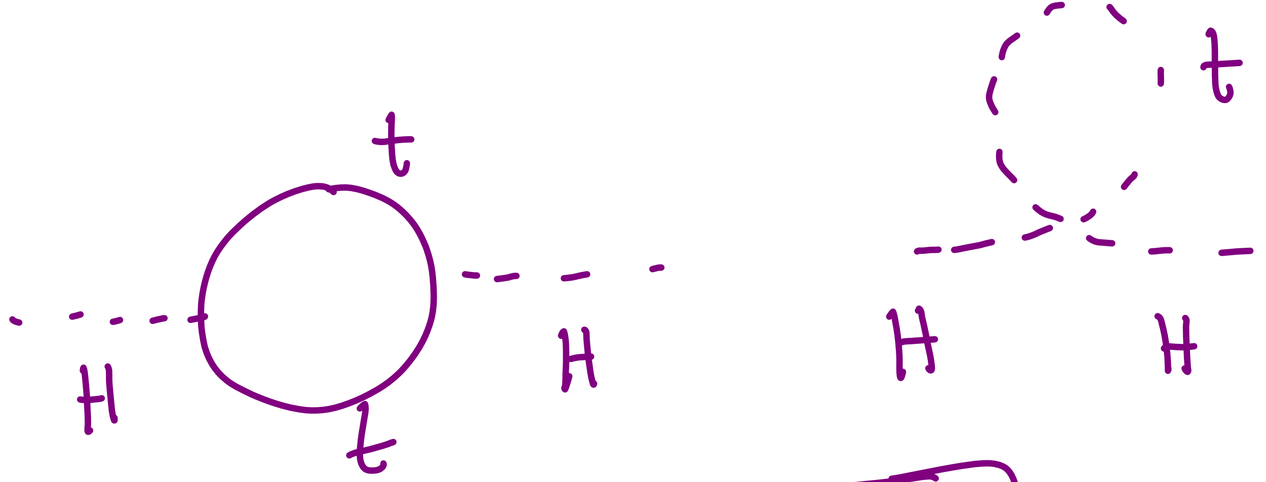
$$B_{ij} = B$$

A small set of parameters describing the entire supersymmetric spectrum at weak scale

Renormalisable theory after integrating out the gravity Multiplet ($M_{Pl} \to \infty$; $m_{3/2}$ fixed)

Dynamical understanding of Electroweak Symmetry Breaking

$m^2_{H_u, H_d} > 0$ $\quad q^2 \simeq m^2_{pl}$ or m^2_{GUT}



RGE

$$\mu \frac{d m^2_{H_u}}{d\mu} \propto h_t^2 m^2_{\hat{q}}$$

$\boxed{m^2_{H_u} < 0}$ @ weak scale

Ibanez, Lopez, Barbieri, Hall, Ross etc.

Gauge Mediation

* Introduce a bunch of Matter superfields which are charged under gauge interactions but couple to the hidden sector.

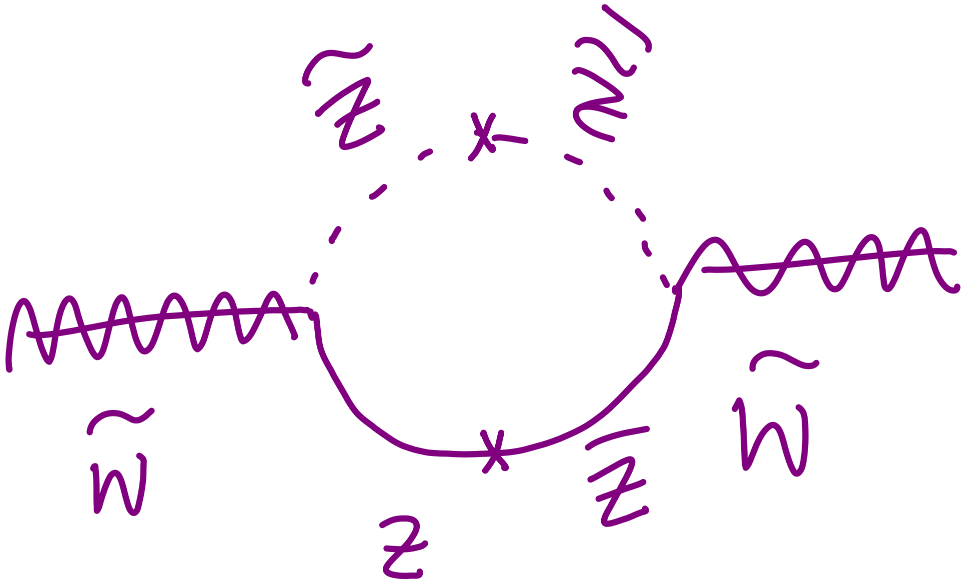
* $W \supset \lambda X Z \bar{Z}$

Hidden Sector

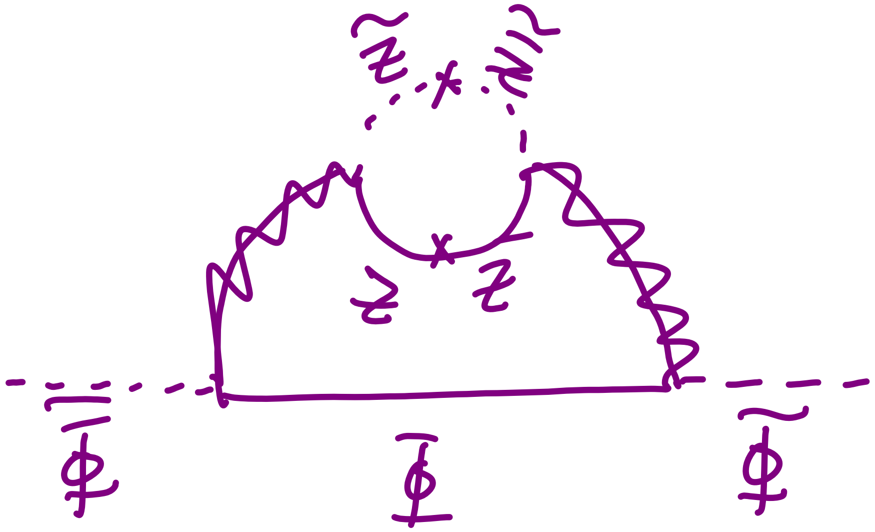
Messenger sector

Giudice and Rattazzi, Phys. Reports Review

SUSY broken spontaneously by X

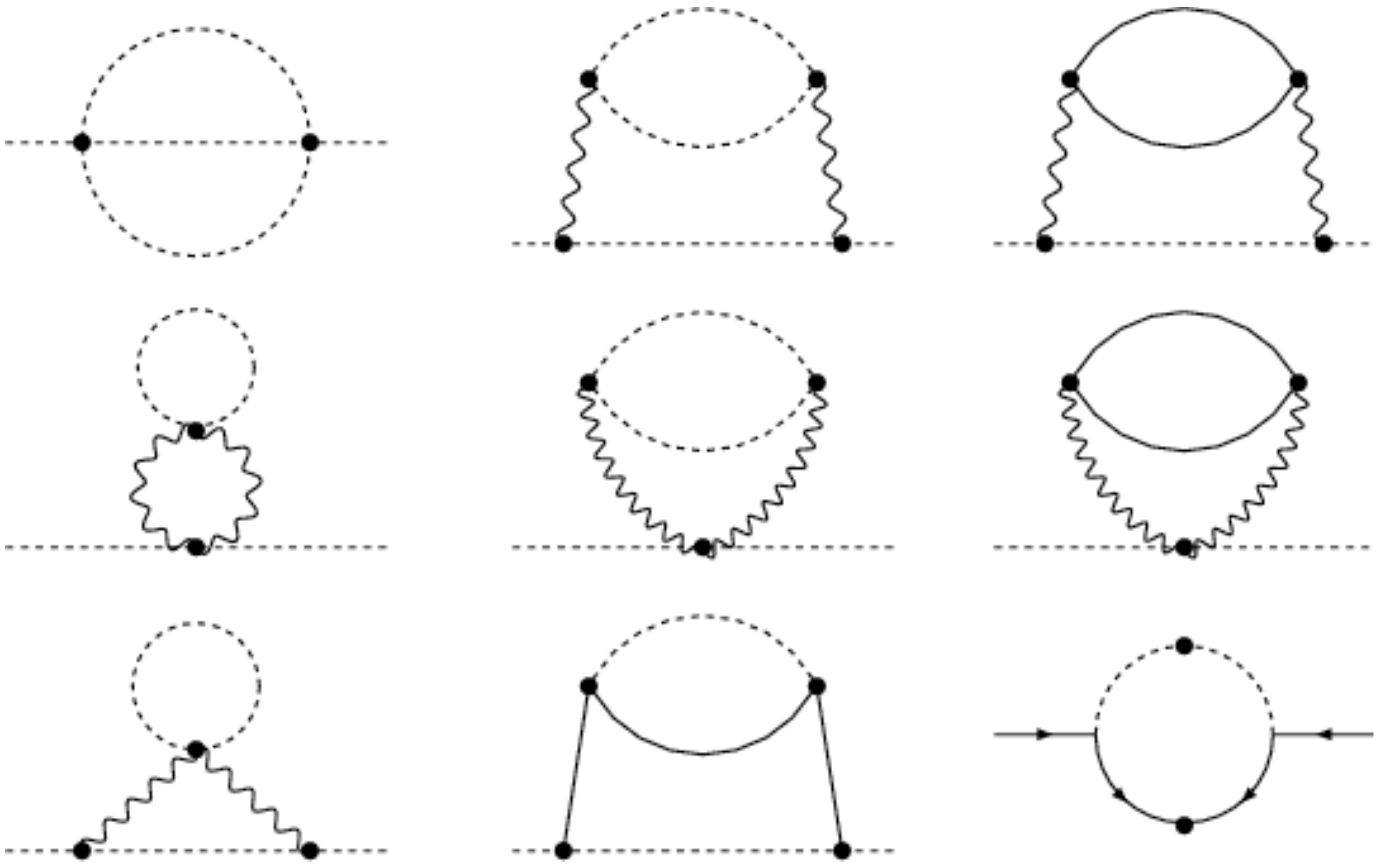


Soft masses in MSSM through loops



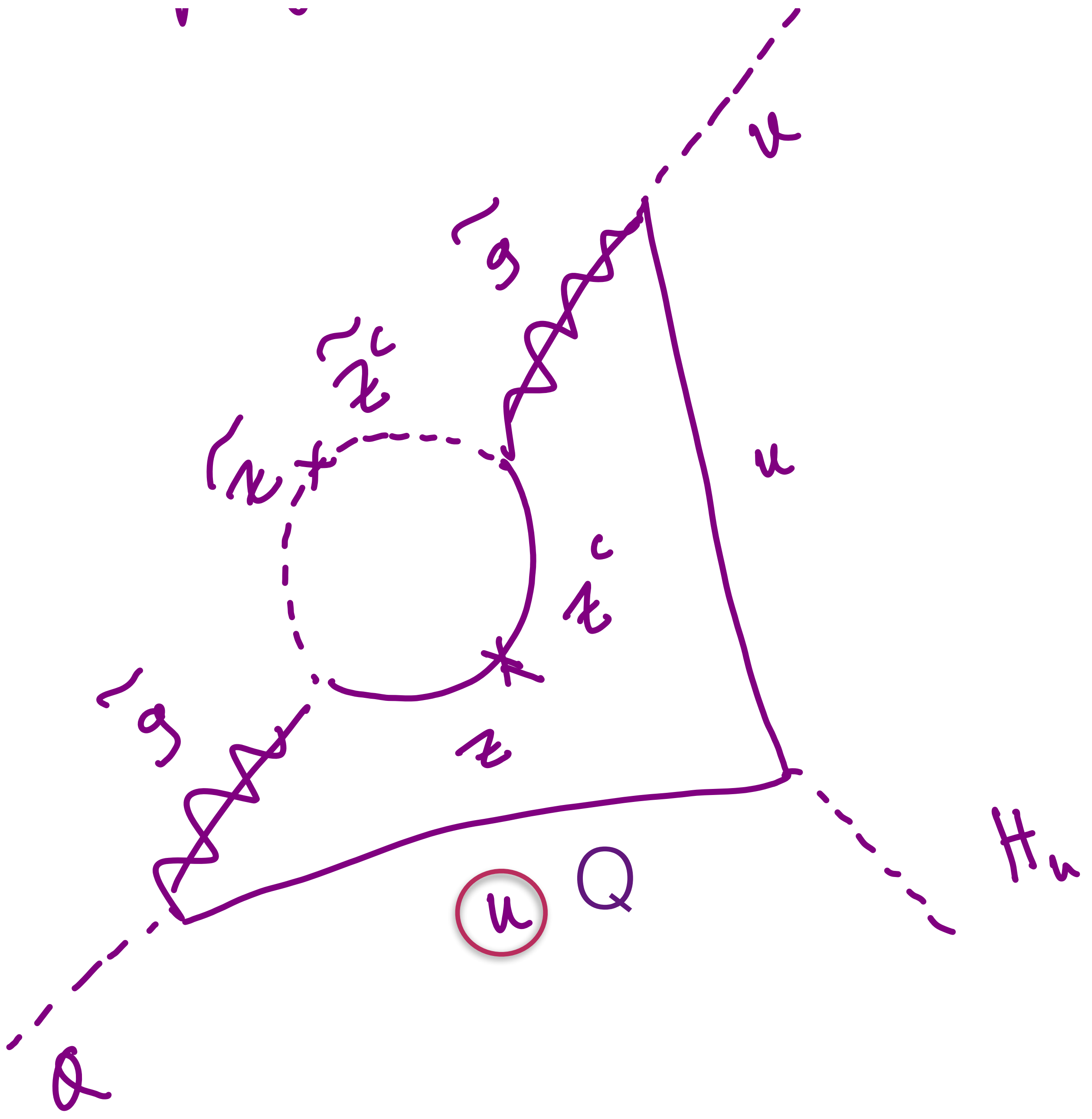
+ - - bunch of two loop diagrams

Two loop diagrams contributing to soft masses



Trilinear Couplings

dimensional-full couplings



additional coupling suppression

A-terms are essentially zero !!!

Non-Traditional Models

- Supergravity models without Singlets (roughly, Mediation through supergravity loops) : Anomaly Mediation Models and their variants **Luty, Shirman Reviews**
- Extra Dimensional Models : Gaugino Mediation Models, Randall-Sundrum Models, Strongly coupled models **Luty, Shirman Reviews, Nomura et.al, Terning Text book + lecture notes, Nelson-Strassler etc.**
- String Inspired Models : Moduli Mediation, KKLT, Hybrid Mediation models,

  Choi et.al , Nilles et.al
- F-Theory Inspired Models (more gauge Mediation)

  Maharana and Palti, 1212.0555,
  Heckman, 1001.4084

Other advantages of SUSY

- Its calculable and thus in principle, predictable.
- Dark Matter candidate if R-parity is conserved.
- Gauge coupling unification (GUTs with neutrino masses and mixing)
- Lightest Higgs boson can be SM -like in regions of parameter space.