GAUGING THE WAY TO MEV

DANIEL STOLARSKI

GORDAN KRNJAIC, DS, arXiv:1212.4860

THE STANDARD

SM describes all short distance phenomena down to d ~ 10^{-18} cm.

$$
\begin{aligned}
\mathcal{L}_{\rm SM} = & -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} && \text{Gauge bosons} \\
& + i\bar{\psi}_i \not{D} \psi_i && \text{Fermions} \\
& + \psi_i \mathbf{y}_{ij} \psi_j \phi + \text{ h.c.} && \text{Yukawa couplings} \\
& + |D_\mu \phi|^2 - V(\phi) && \text{Higgs}
\end{aligned}
$$

SM QUARK SECTOR

$$\mathcal{L}_{\text{quark}} = i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i$$
$$+ q_i \mathbf{y}^u_{ij} \psi_j u + q_i \mathbf{y}^d_{ij} d_j \phi + \text{ h.c.}$$

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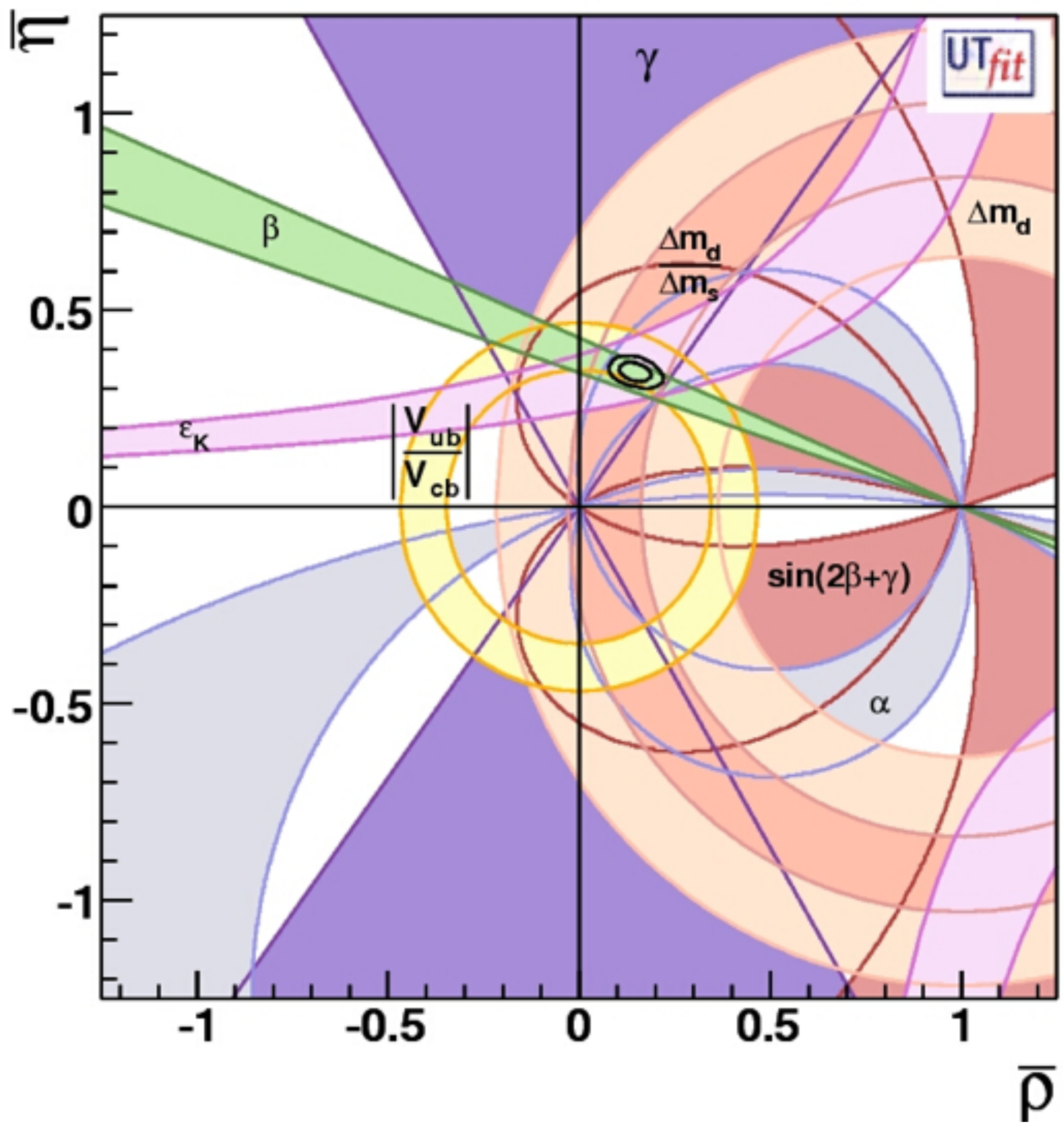
Without Yukawa couplings, SM possesses a large global flavor symmetry: $U(3)_Q \times U(3)_U \times U(3)_D$

With Yukawa couplings, flavor structure still very predicative, supressed FCNC's, small CP violation, lepton and baryon number conservation, etc.

SM FLAVOR

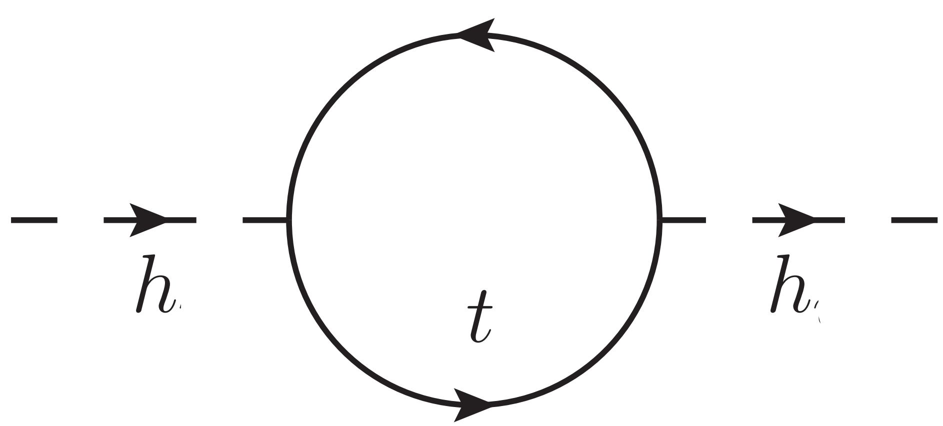


SM flavor structure very delicate

SM HIGGS SECTOR

$$\mathcal{L}_{\text{Higgs}} = |D_\mu \phi|^2 - m^2 \phi^\dagger \phi - \frac{\lambda}{4}(\phi^\dagger \phi)^2$$

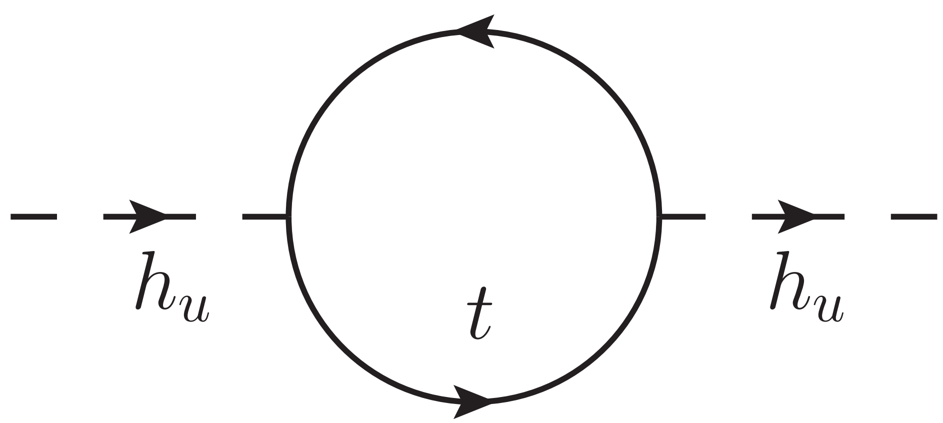
Higgs potential has only dimensionful parameter in SM

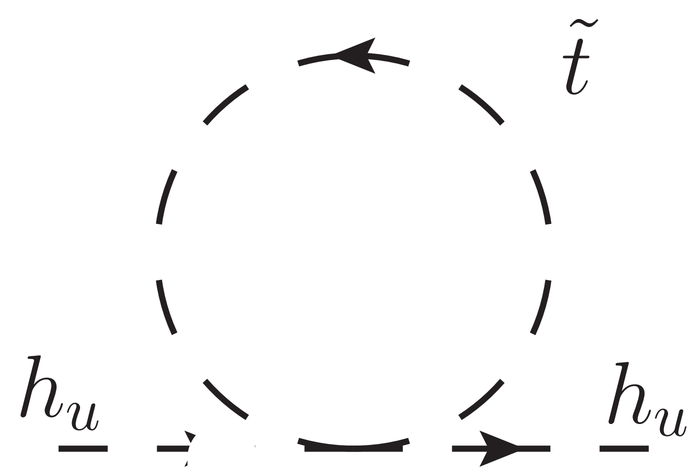


Quantum corrections make the mass parameter unstable: the hierarchy problem.

SUPERSYMMETRY

Introduce "superpartner" of different spin to cancel quadratic divergences

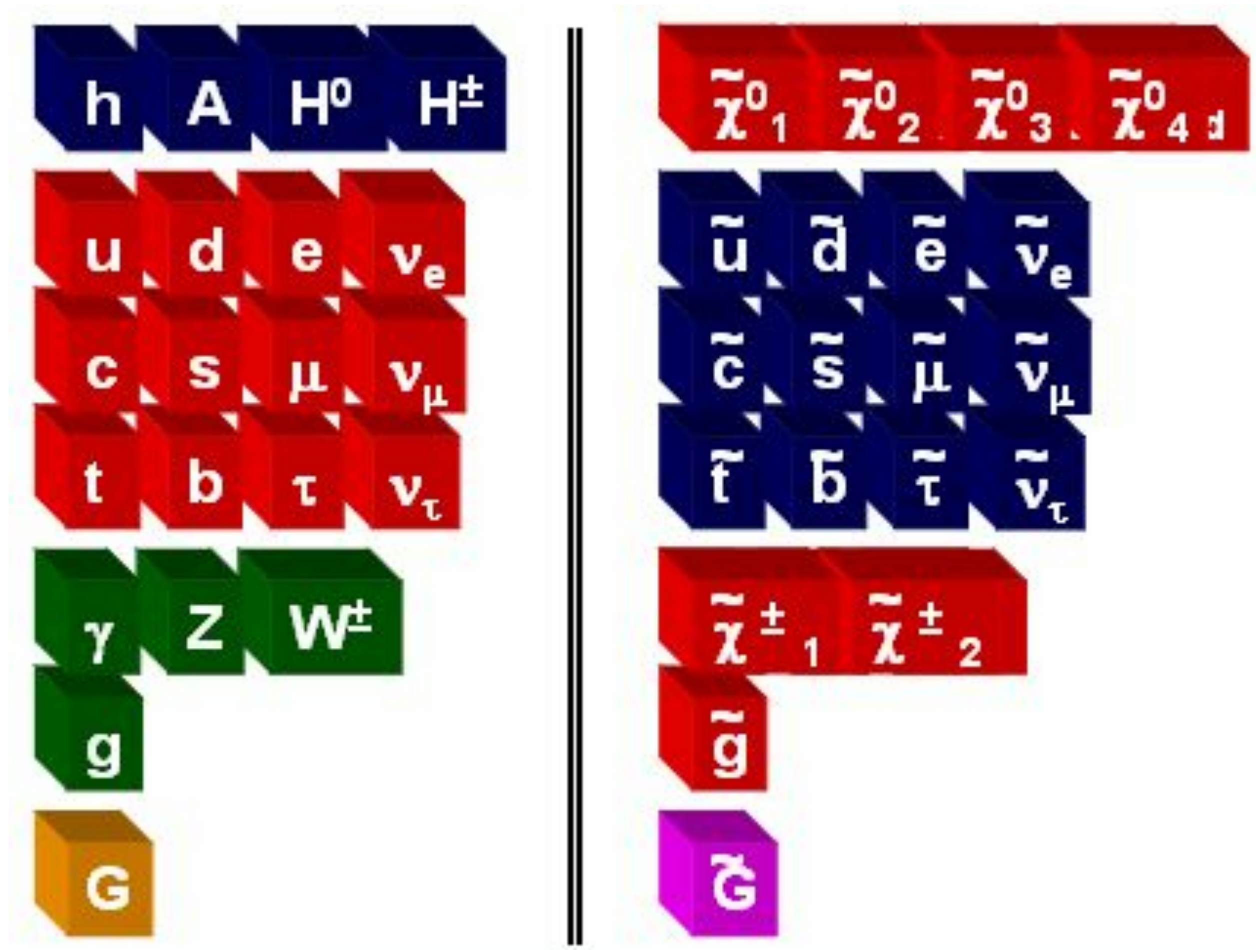




Quantum corrections only log sensitive to cutoff

SUSY IS GREAT!

- Rich and interesting collider phenomenology
- Elegant extension of spacetime symmetries
- Grand unification works better than SM
- Well motivated R-parity automatically gives dark matter candidate

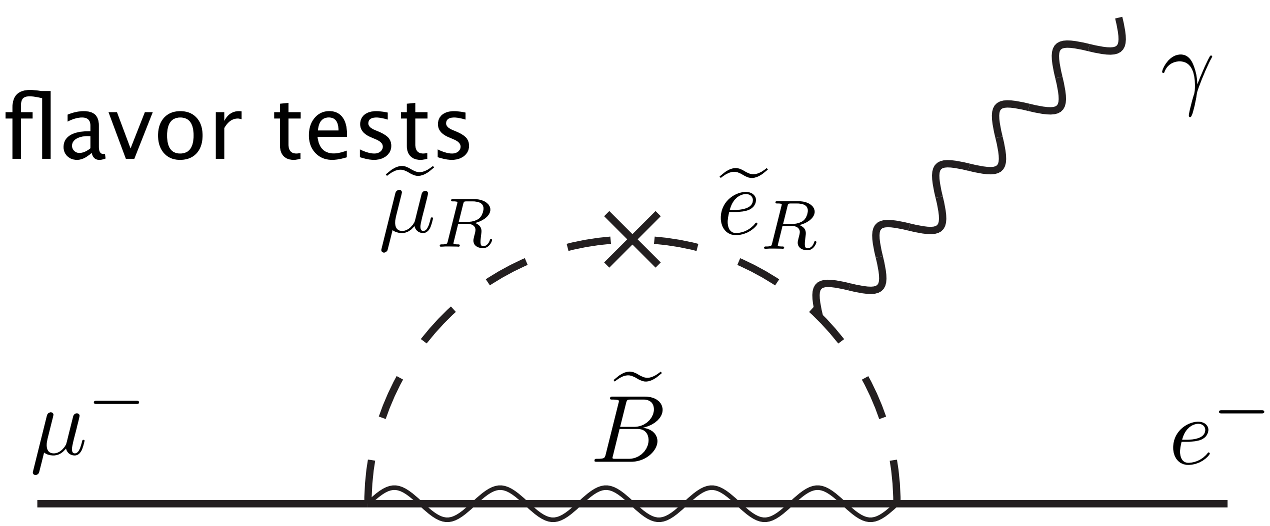


SUSY FLAVOR

SUSY must be broken, many new flavor violating

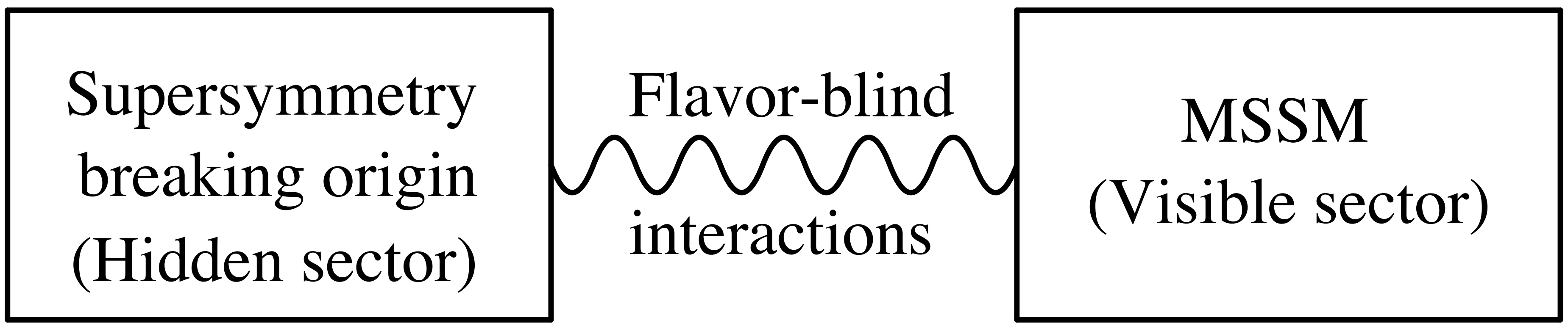
$$\begin{pmatrix} \tilde{q}_1 & \tilde{q}_2 & \tilde{q}_3 \end{pmatrix}^\dagger \times \begin{pmatrix} \# & \# & \# \\ \# & \# & \# \\ \# & \# & \# \end{pmatrix} \times \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$$

Generic TeV scale values of mass matrix are badly ruled out
by low energy flavor tests



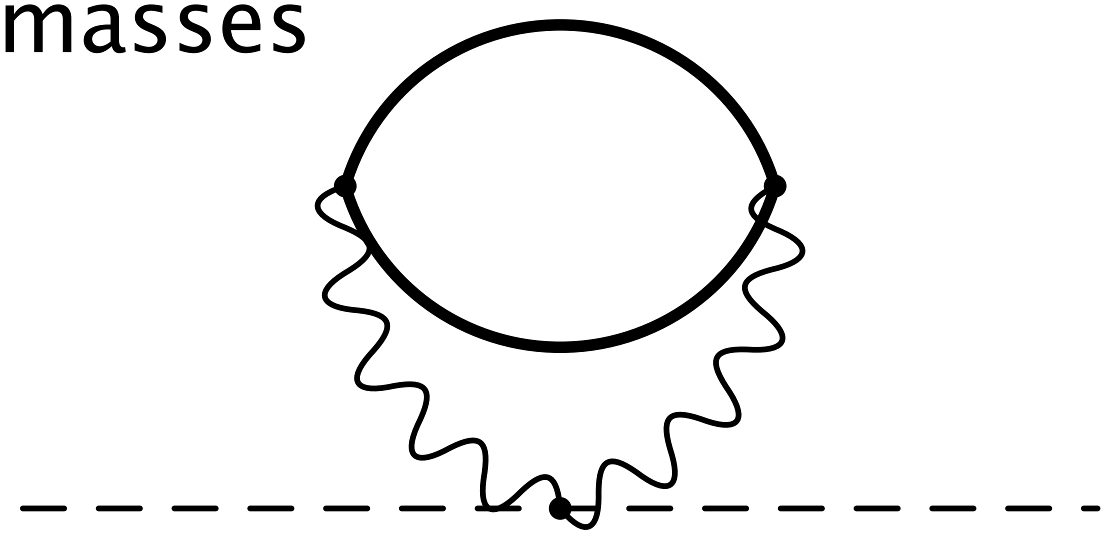
FLAVOR BLIND

Assume mediation of SUSY breaking is flavor blind



Martin, Supersymmetry Primer, arXiv:9709356 [hep-ph].

Alternatively, a framework like gauge mediation predicts flavor blind soft masses



MINIMAL FLAVOR

Promote SU(3) flavor group to full symmetry

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$+1/6$
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Y_u	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0
Y_d	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	0

Ansatz that all flavor violation proportional to Y_u and Y_d

Chivukula and Georgi, 1987. Hall and Randall, 1990. Ciuchini et. al. 1998. Buras et. al. 2001. D'Ambrosio et. al. 2002. Cirigliano et. al. 2005.

MFV SUSY

Soft SUSY parameters now fixed up to flavor universal dimensionful coefficients

$$m^2_{\mathrm{soft}}\tilde{u}_i^\dagger \left(1\!\!1 + Y_u^\dagger Y_u + ...\right)_{ij} \tilde{u}_j$$

$$A_{\mathrm{soft}}(Y_u + ...)_{ij}\tilde{q}_i\tilde{u}_j h_u$$

Flavor universality up to corrections that are largest for 3rd generation

Flavor bounds are much more easily satisfied

FLAVORFUL SUSY

Soft SUSY parameters parametrically the same size as Yukawa's, matrices not aligned

Nomura, Papucci, DS, 2007. Nomura, DS 2008.

$$\mathbf{a}_{ij} \sim A_{\rm soft}\, Y_{ij} \qquad\qquad \mathbf{a} \not\propto Y$$

Low energy constraints can still be easily satisfied, phenomenology often quite be different

Much easier to build models which satisfy this property

Nomura, Papucci, DS 2008.

SUSY PRE 2010

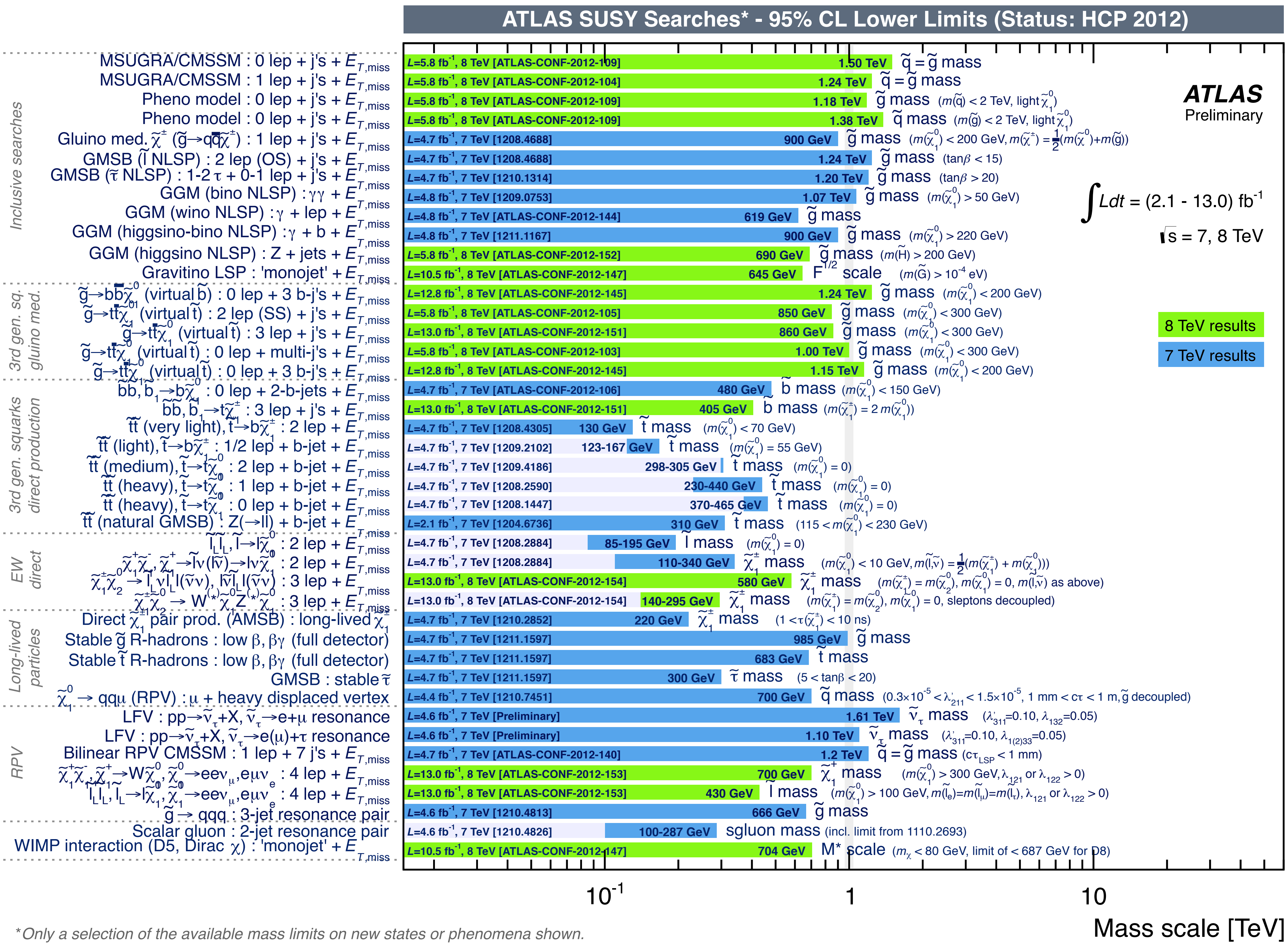
- Elegant solution to the hierarchy problem with many nice features

- Makes a big mess of flavor in simplest incarnation

- Many solutions including gauge mediation, MFV, flavorful SUSY

- In 2010, we were very hopeful that the LHC would turn on find huge excesses in missing energy events

LHC ASSAULT



Wednesday, February 6, 13

LHC ASSAULT

Supersymmetry may not be dead but these latest results have certainly put it in the HOSPITAL.

– Prof. Chris Parkes, quoted by the BBC

R-PARITY

Additional allowed operators usually forbidden by R-parity

$$W_{\rm RPV} = \frac{1}{2}\lambda^{ijk} L_i L_j e_k + \lambda'^{ijk} L_i Q_j d_k + \mu'^i L_i H_u + \frac{1}{2}\lambda''^{ijk} u_i d_j d_k$$

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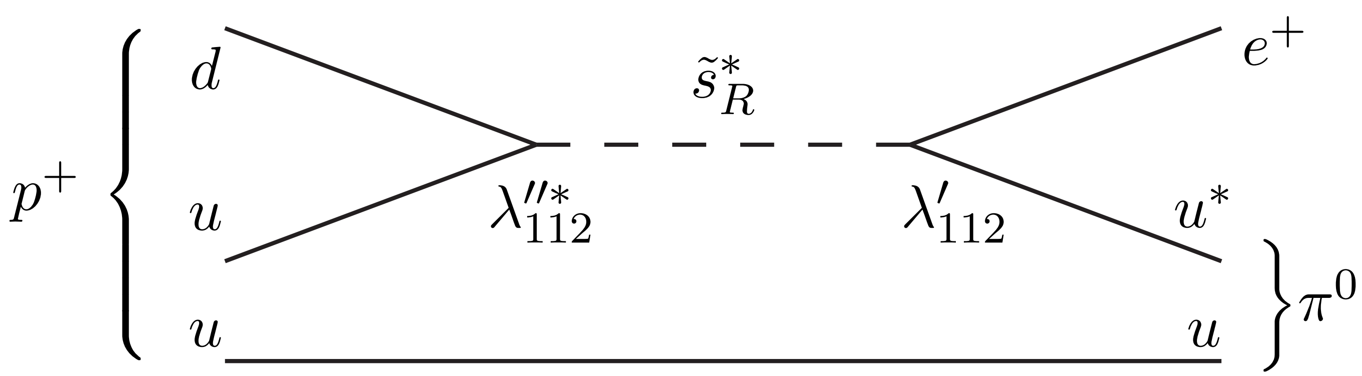
Can decay the proton and make a (bigger) mess of flavor



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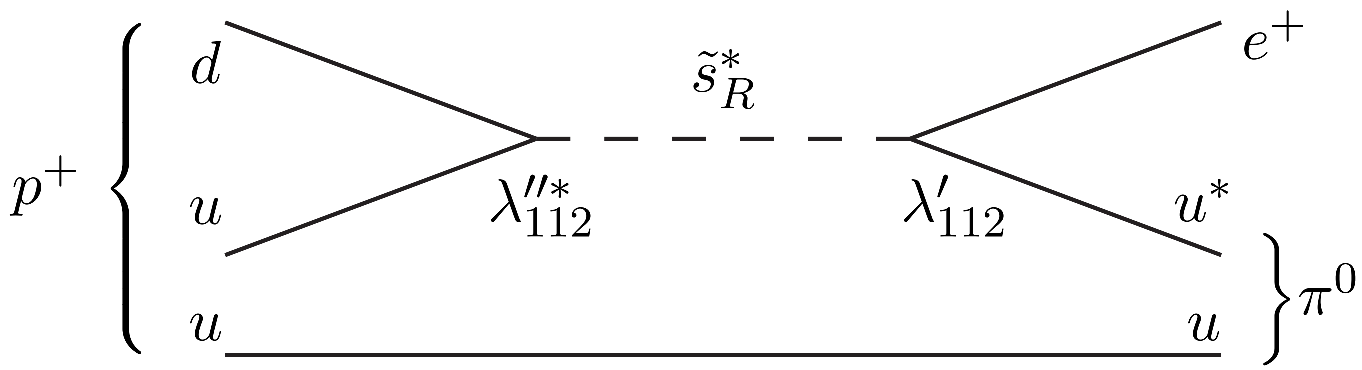

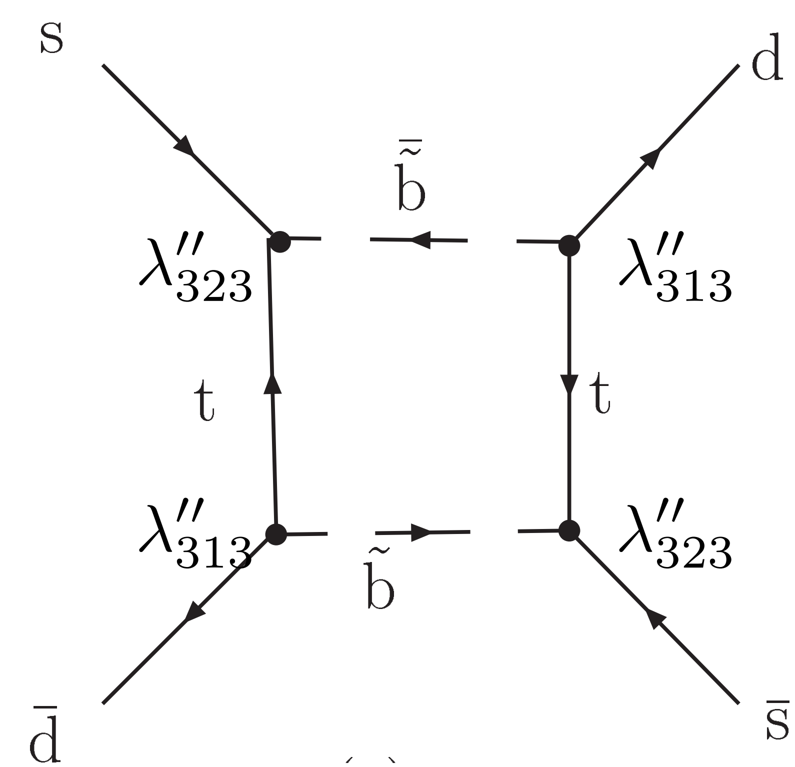

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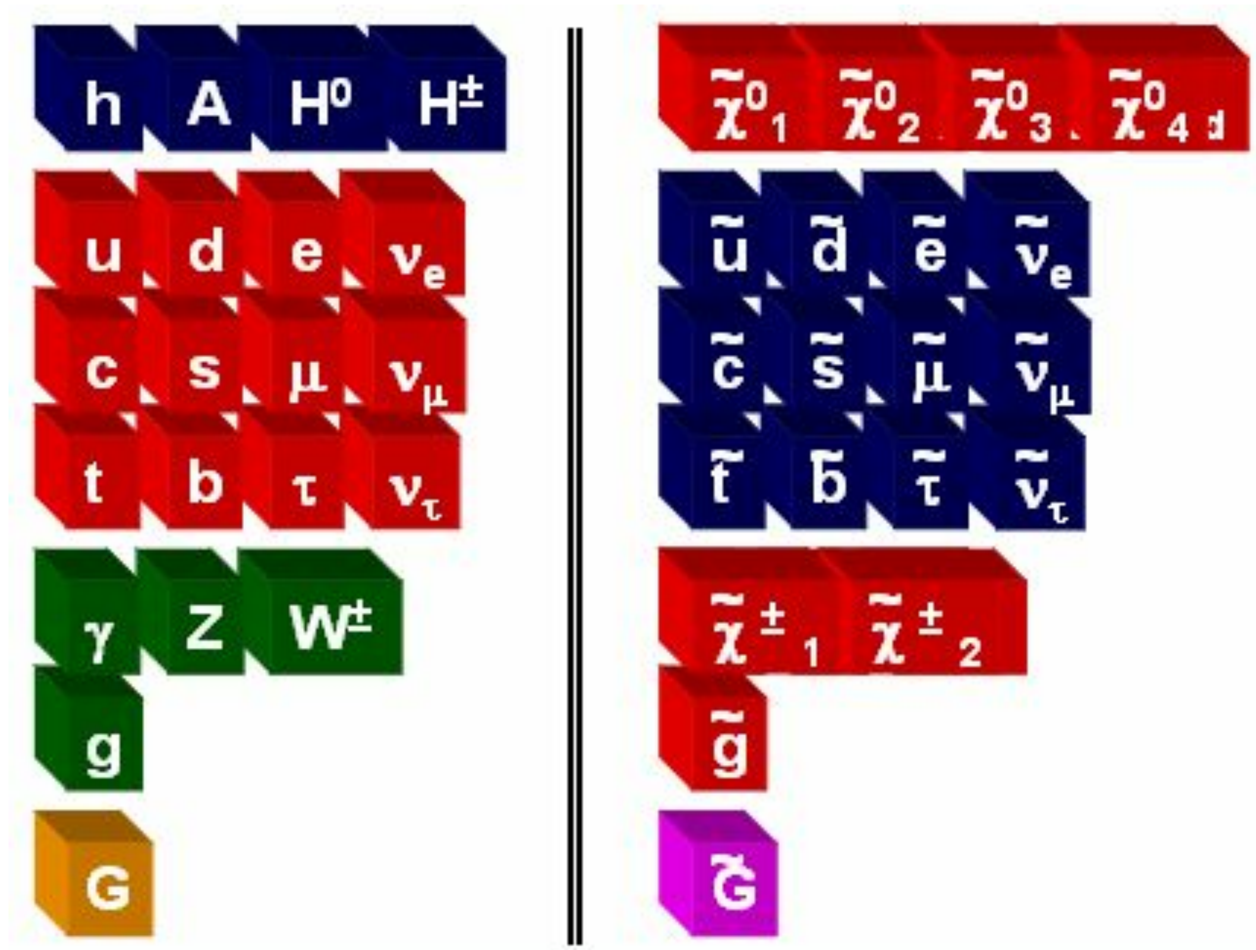

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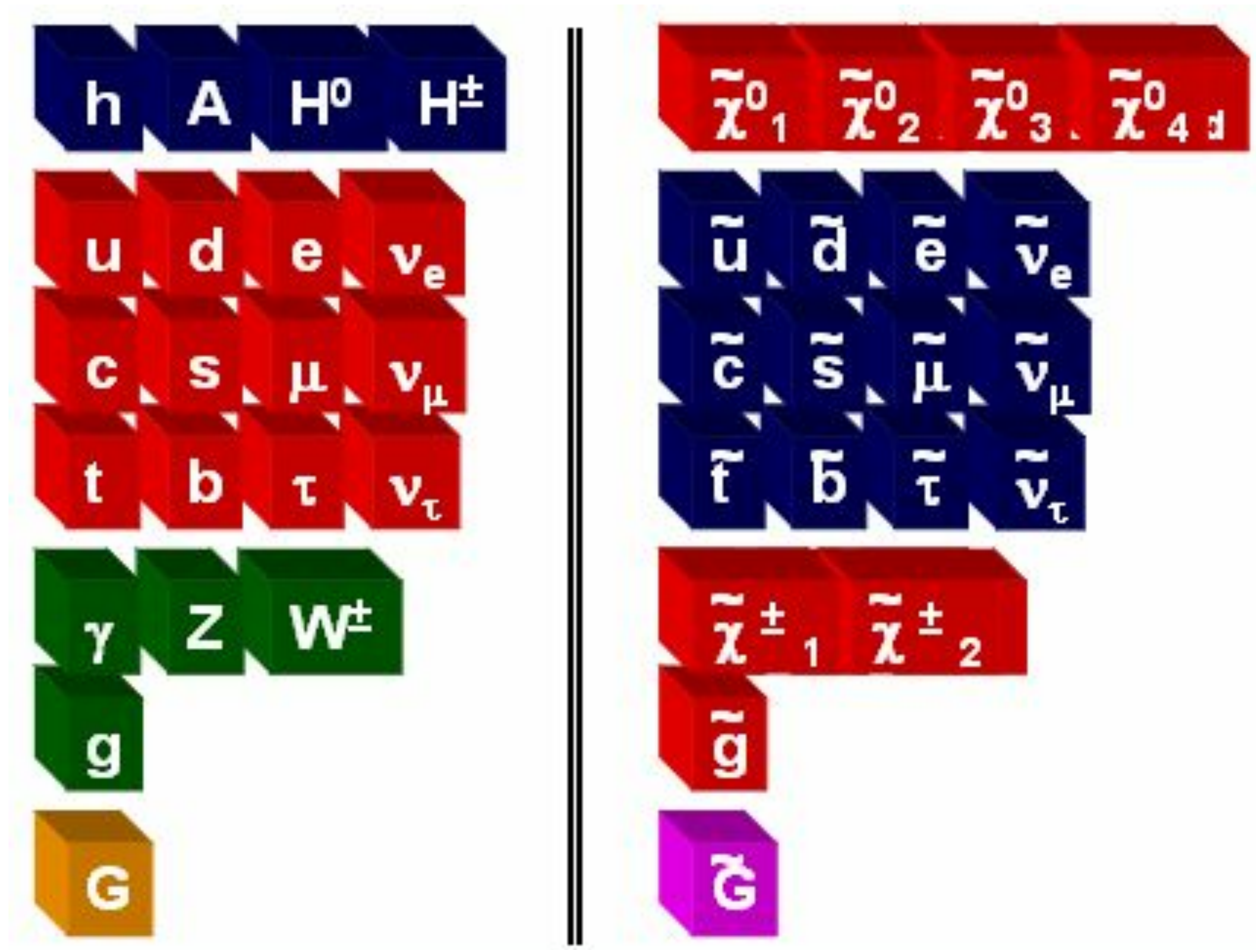

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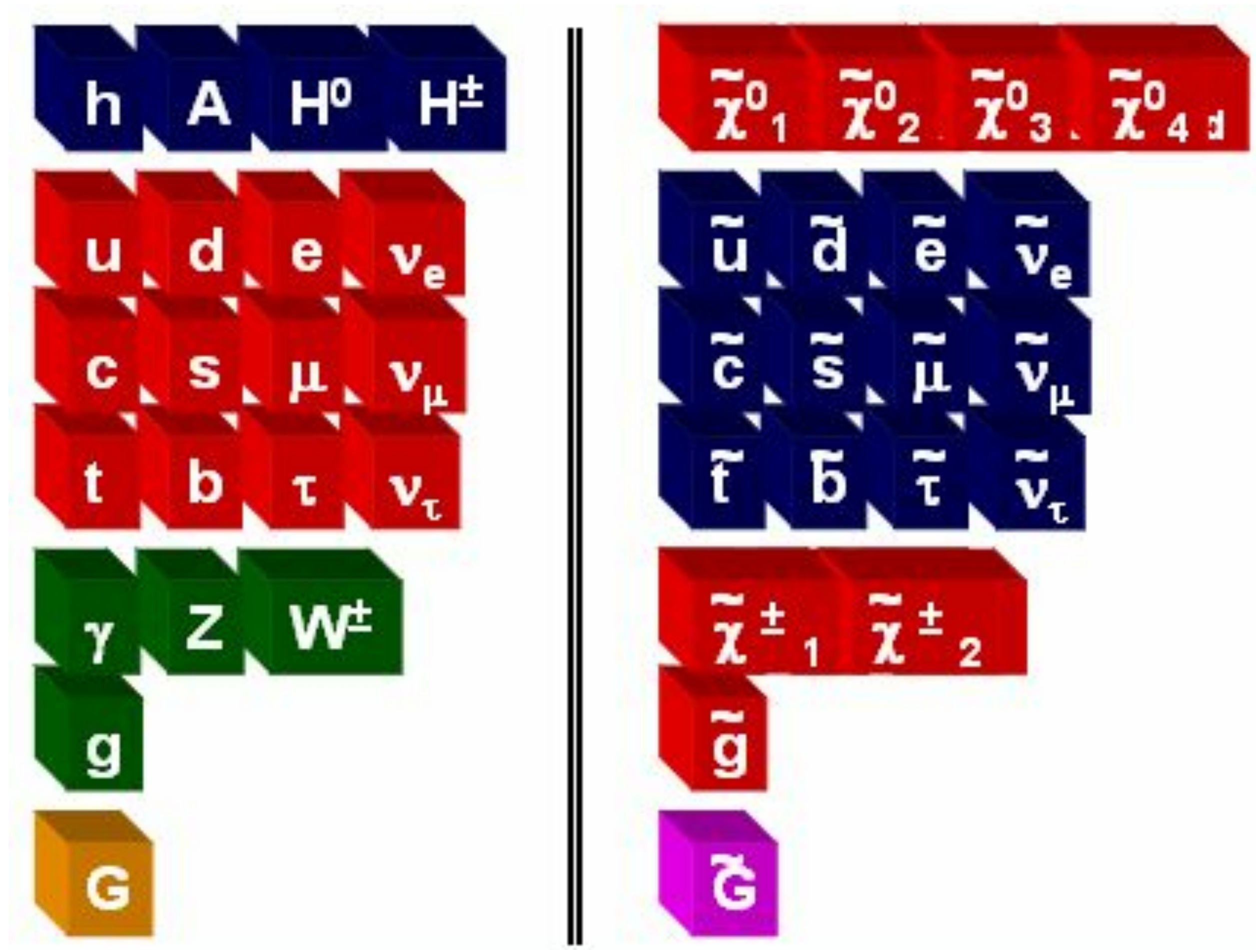

MFV RPV

Imposing MFV on the RPV sector dramatically reduces the allowed parameter space and ameliorates the flavor problem.

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$$\lambda''_{\alpha'\beta'\gamma'} = \epsilon^{\alpha\beta\gamma}(Y^u_{\alpha\alpha'})(Y^d_{\beta\beta'})(Y^d_{\gamma\gamma'})$$

RNV OPERATOR

$$W_{\mathrm{MFV}} = \frac{1}{2}\lambda''^{\alpha\beta\gamma} u_\alpha d_\beta d_\gamma$$

$$\lambda''_{\alpha'\beta'\gamma'} = \epsilon^{\alpha\beta\gamma}(Y^u_{\alpha\alpha'})(Y^d_{\beta\beta'})(Y^d_{\gamma\gamma'})$$

$$\lambda'' \simeq \begin{array}{c|ccc} & s\,b & b\,d & d\,s \\ \hline u & 5\times10^{-7} & 6\times10^{-9} & 3\times10^{-12} \\ c & 4\times10^{-5} & 1.2\times10^{-5} & 1.2\times10^{-8} \\ t & 2\times10^{-4} & 6\times10^{-5} & 4\times10^{-5} \end{array} \times \left(\frac{\tan\beta}{50}\right)^2$$

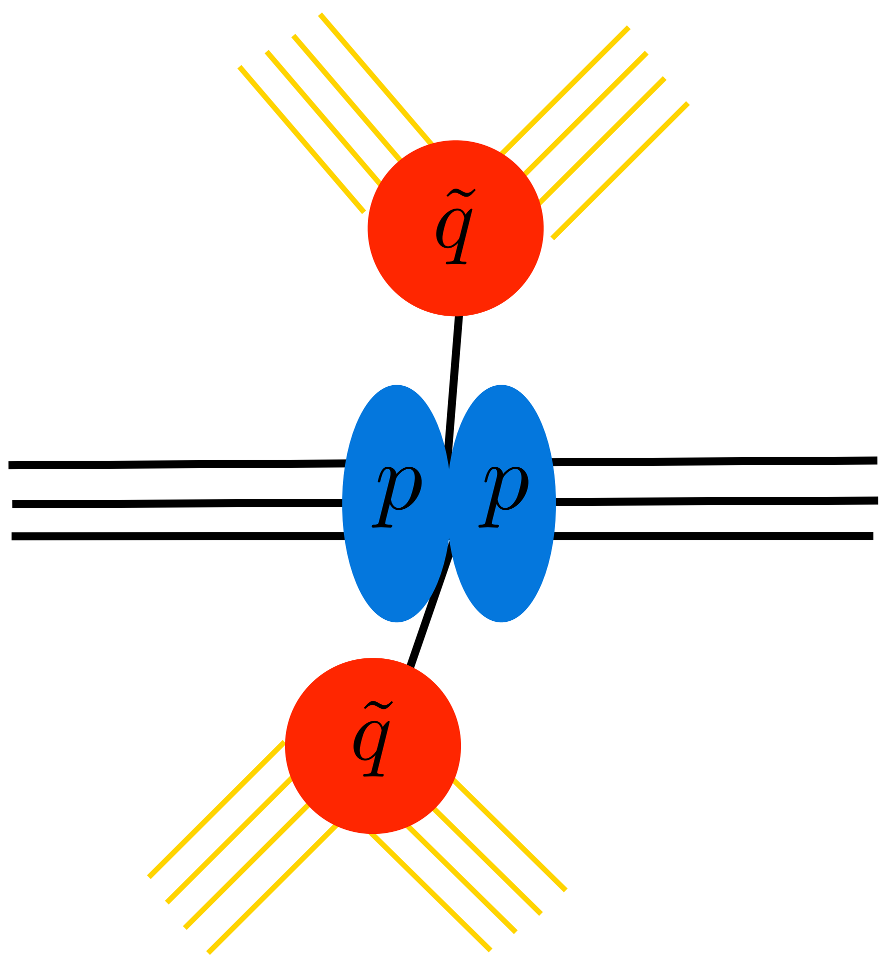
- R-parity is an approximate symmetry

- Lepton number is an exact symmetry (up to neutrino

SOME

LHC pheno depends strongly on who is the LSP

Csaki, Grossman, Heidenreich, 2012.



<u>Squark LSP Case:</u>

- Squark pair production lead to pairs of di-jets
- Gluino pair production gives pairs of tri-jets

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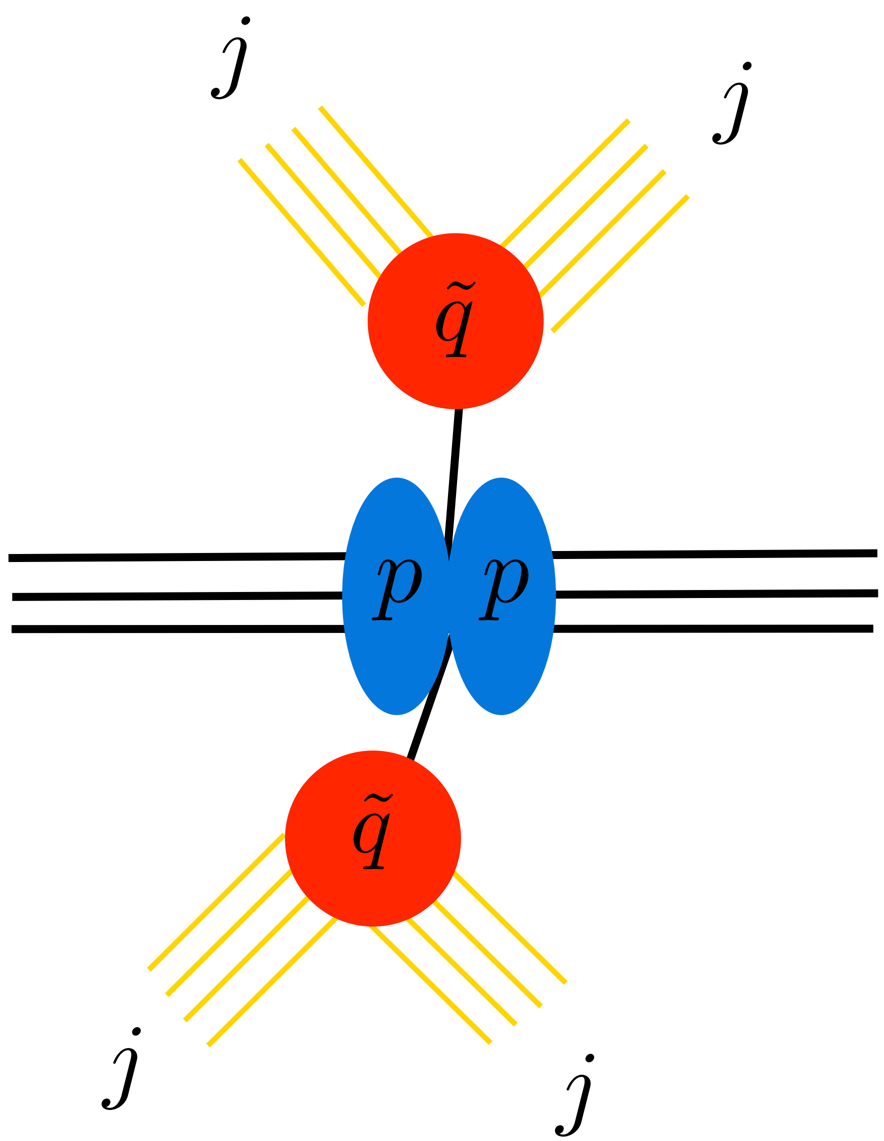

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MAXIMAL GAUGE

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MAXIMAL GAUGE

- Gauge full non-abelian SM flavor group
  Grinstein, Redi, Villadoro, 2010.
- Add minimal matter content to cancel anomalies
- ψ_u and $\bar{u}$ are vectorlike under all gauge symmetries
- In addition to MSSM matter, theory contains exotics, and flavor gauge fields
- Previous LR-SUSY version: Mohapatra, 2012.

YUKAWA COUPLINGS

$$W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} \; + \; (u \to d)$$

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O(1) flavor universal couplings

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Can’t write down usual Yukawa coupling

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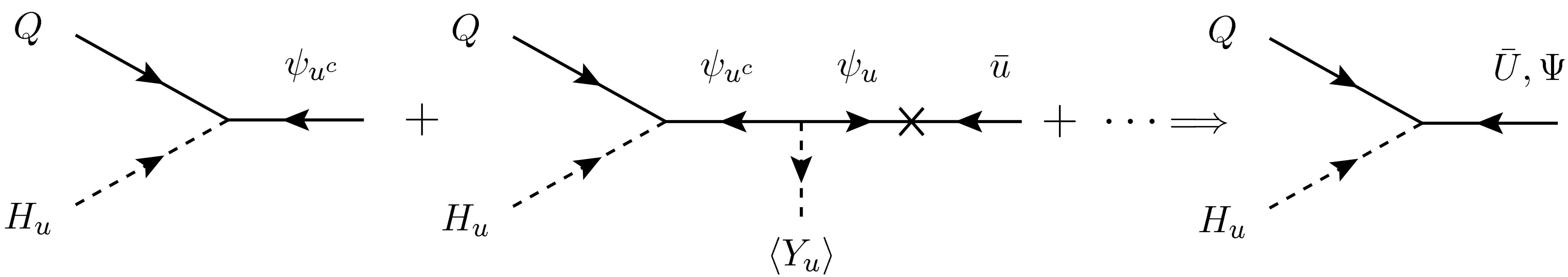

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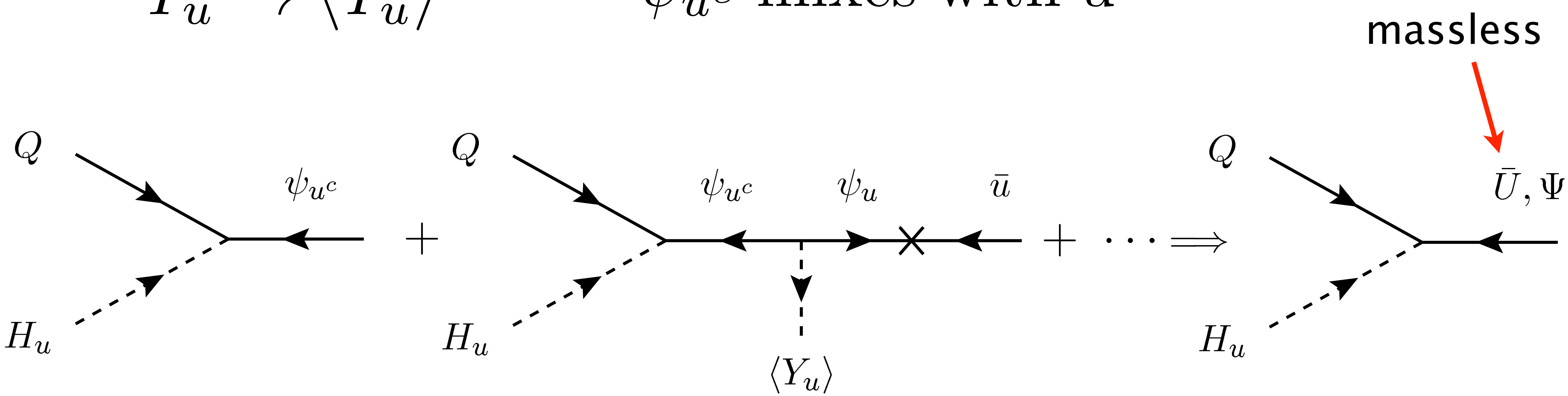

YUKAWA COUPLINGS

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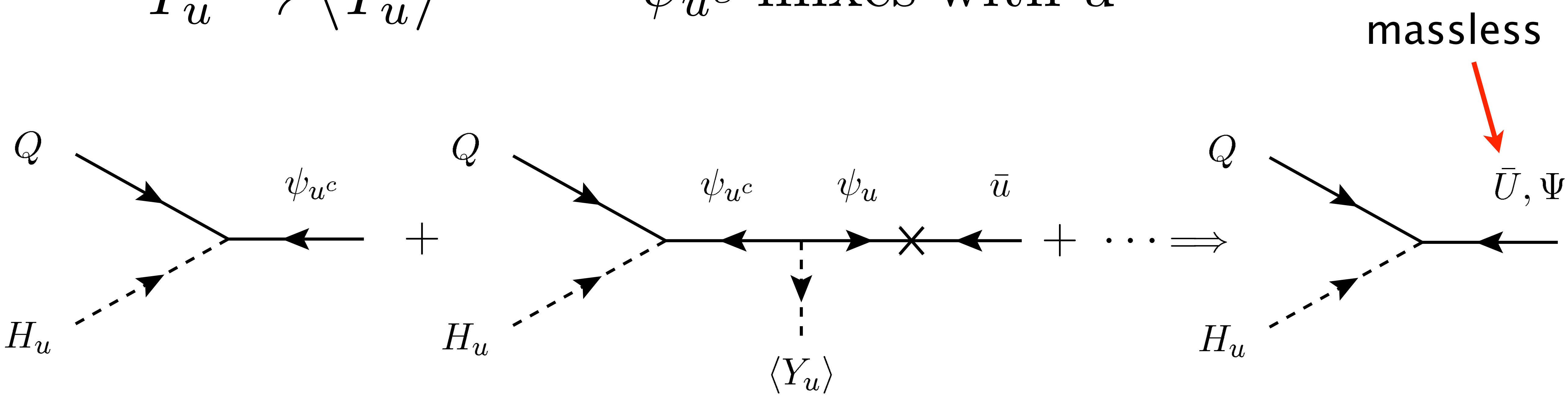
$$Y_u \to \langle Y_u \rangle \qquad\qquad \psi_{u^c} \text{ mixes with } \bar{\text{u}}$$



$$H_u Q^\alpha (\psi_{u^c})_\alpha \to H_u Q^\alpha (\mathcal{V}^u_{\alpha\beta'} \bar{U}^{\beta'}) \equiv (\mathcal{Y}_u)_{\alpha\beta'} H_u Q^\alpha \bar{U}^{\beta'}$$

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$$W = \lambda_u H_u Q \psi_{u^c} + \lambda'_u Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} \; + \; (u \to d)$$

$$\underline{\text{Consider } \langle Y_u \rangle \gg M_u}$$

$$\text{Massless state} : \bar{U} \simeq \bar{u} - \frac{M_u}{\langle Y_u \rangle} \psi_{u^c}$$

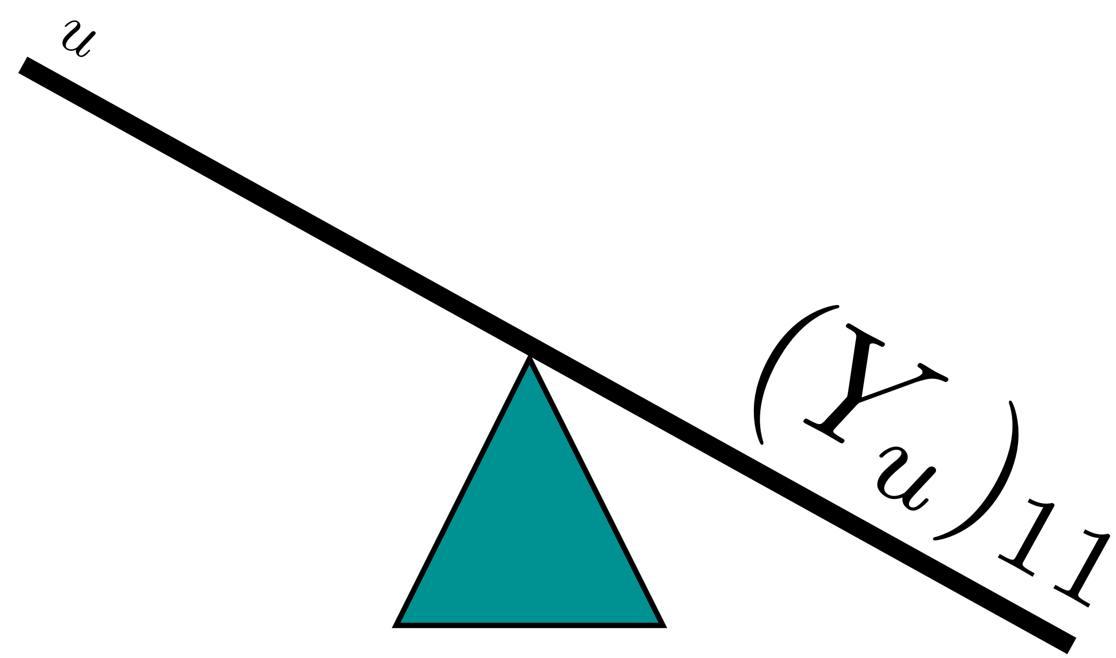
$$\text{Yukawa coupling} : \mathcal{Y}_u \simeq \lambda_u \frac{M_u}{\langle Y_u \rangle}$$

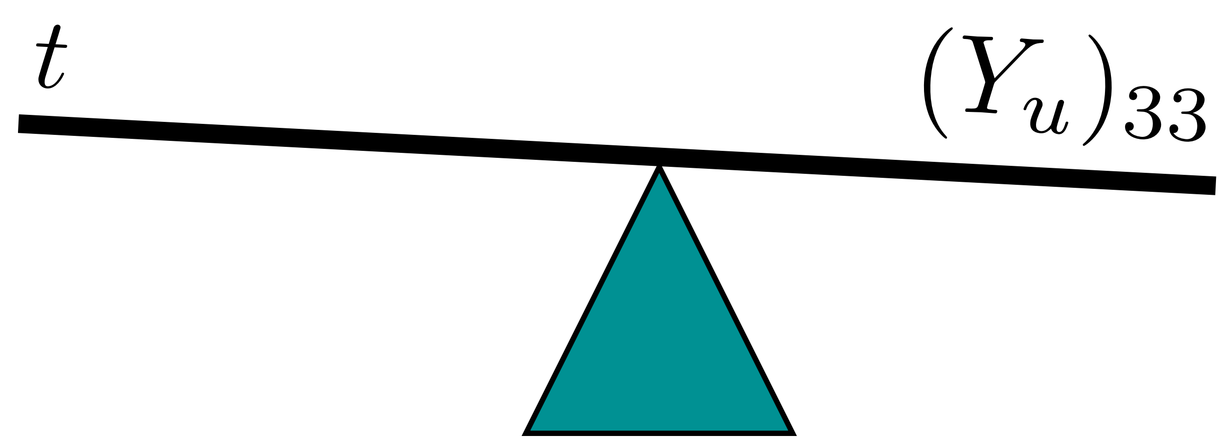
$$\text{Mass of exotic} \simeq \langle Y_u \rangle$$

INVERTED

- Seesaw mechanism for quarks

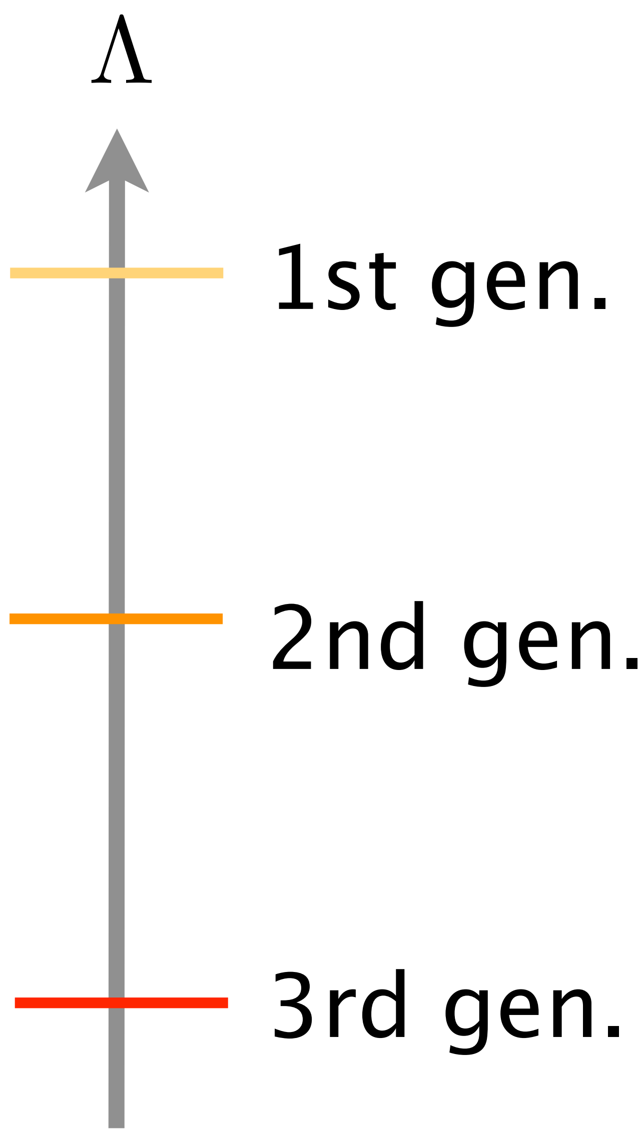
- Exotics and flavor gauge multiplets have opposite hierarchy of SM

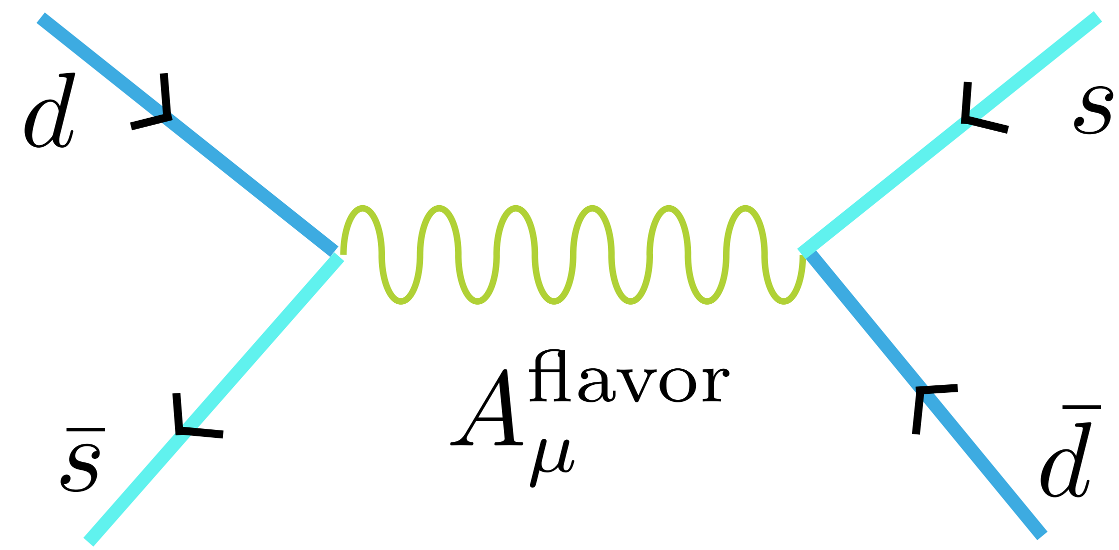




FEATURES OF

Spectrum of flavor gauge bosons and exotics





- FCNC's among 1st and 2nd gen. suppressed
- 3rd gen exotics and gauge bosons potentially accessible at LHC

R- PARITY

$$W_{\mathrm{RPV}} = \bar{u}\bar{d}\bar{d}$$

R-PARITY

$$W_{\mathrm{RPV}} = \bar{u}\bar{d}\bar{d}$$

$\mathbf{3}$ of $SU(3)_U$

R PARITY

$$W_{\text{RPV}} = \bar{u}\bar{d}\bar{d}$$

$\mathbf{3}$ of $SU(3)_D$

$\mathbf{3}$ of $SU(3)_U$

R PARITY

$$W_{\text{RPV}} = \cancel{\bar{u}\bar{d}\bar{d}}$$

$\mathbf{3}$ of $SU(3)_D$

$\mathbf{3}$ of $SU(3)_U$

R-PARITY

$$W_{\mathrm{RPV}} = \cancel{\bar{u}\bar{d}\bar{d}}$$

$$W_{\mathrm{RPV}} = \psi_{u^c}\psi_{d^c}\psi_{d^c}$$

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Only allowed operator that breaks R-parity

$\mathbf{3}$ of $SU(3)_Q$

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R-PARITY

$$W_{\text{RPV}} = \cancel{\bar{u}\bar{d}\bar{d}}$$

$$W_{\text{RPV}} = \psi_{u^c}\psi_{d^c}\psi_{d^c}$$ Only allowed operator that breaks R-parity

$Y \to \langle Y \rangle$: transform to mass basis

$$W \to \epsilon^{abc}\epsilon^{\alpha\beta\gamma}(\mathcal{Y}^u_{\alpha\alpha'}\bar{U}^{\alpha'}_a)(\mathcal{Y}^d_{\beta\beta'}\bar{D}^{\beta'}_b)(\mathcal{Y}^d_{\gamma\gamma'}\bar{D}^{\gamma'}_c)$$

R-PARITY

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Color indices

Flavor indices

R- PARITY

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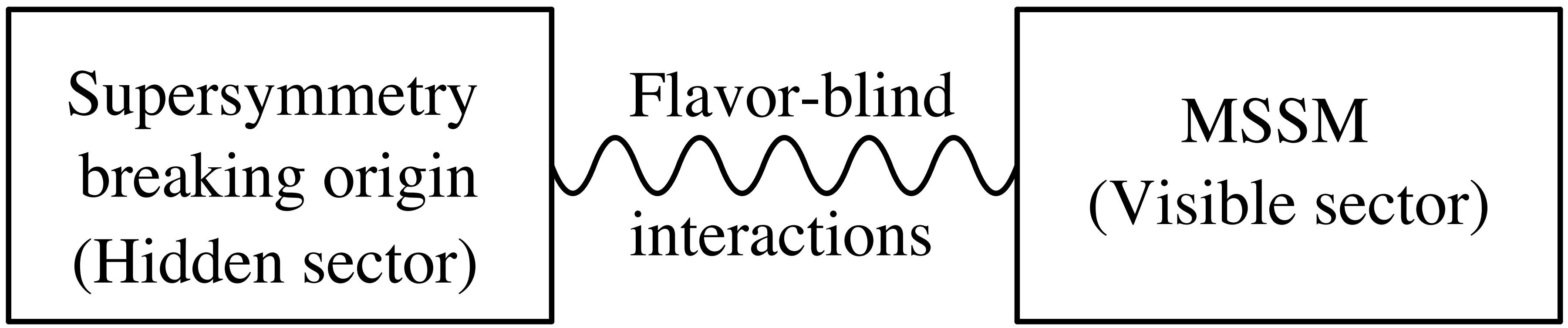
Color indices

Flavor indices

Exactly the MFV form!

SUSY BREAKING



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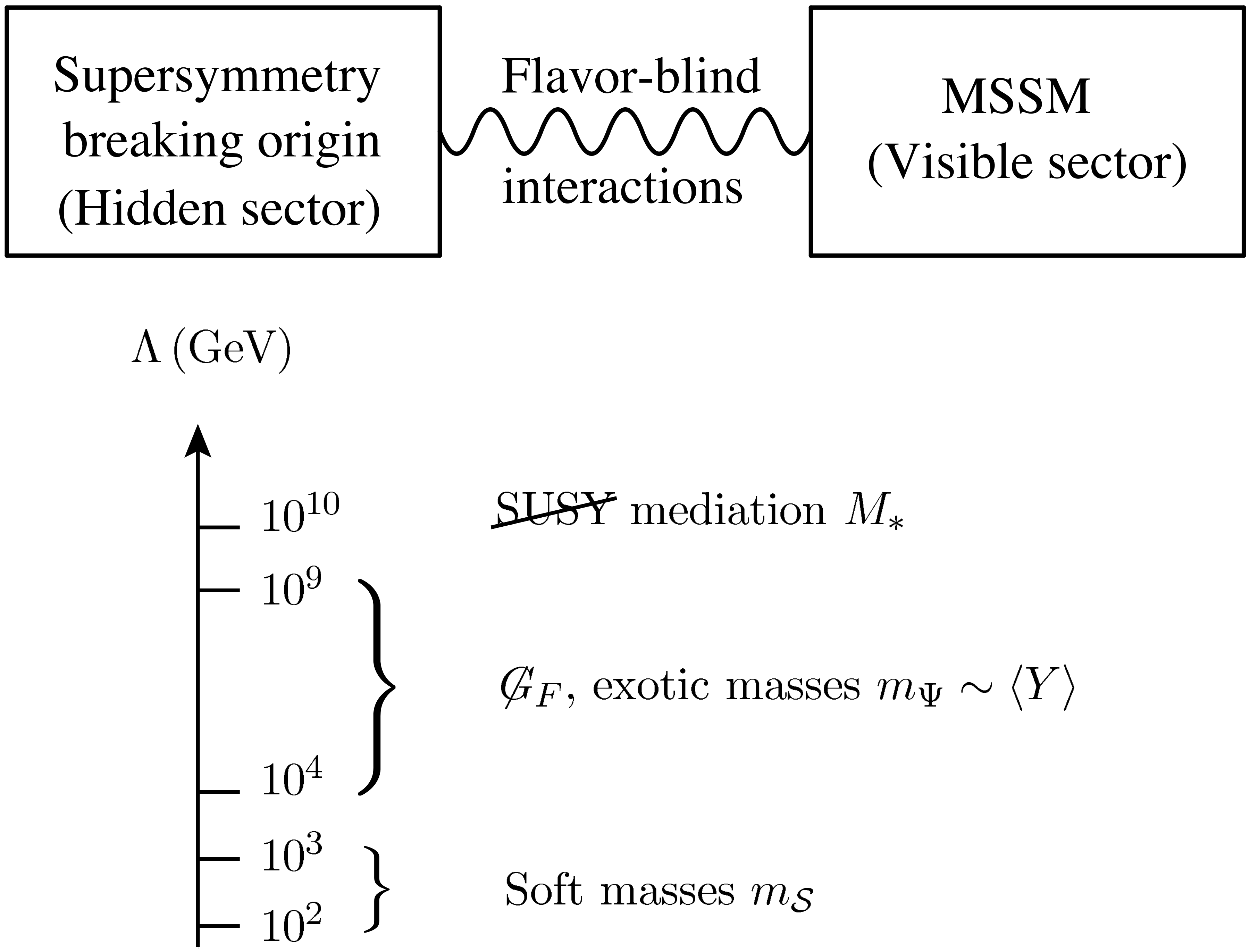

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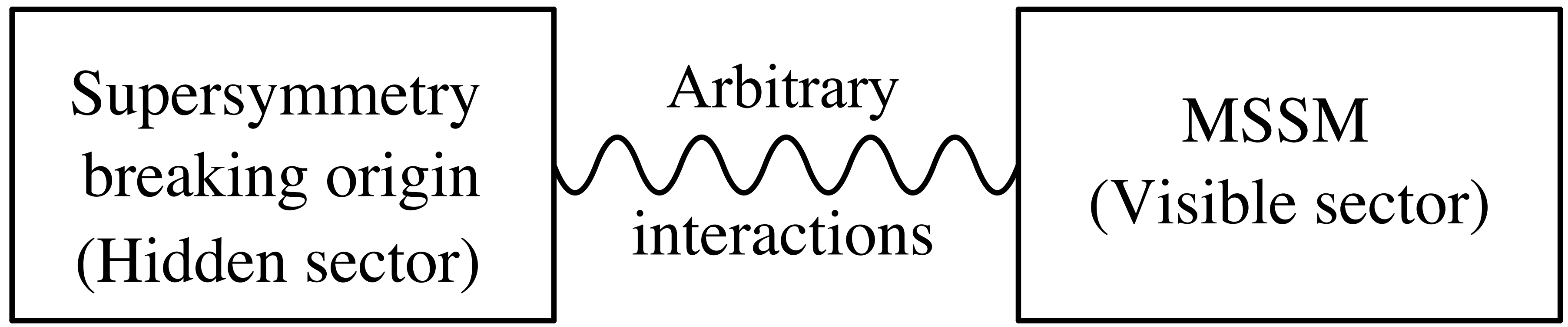

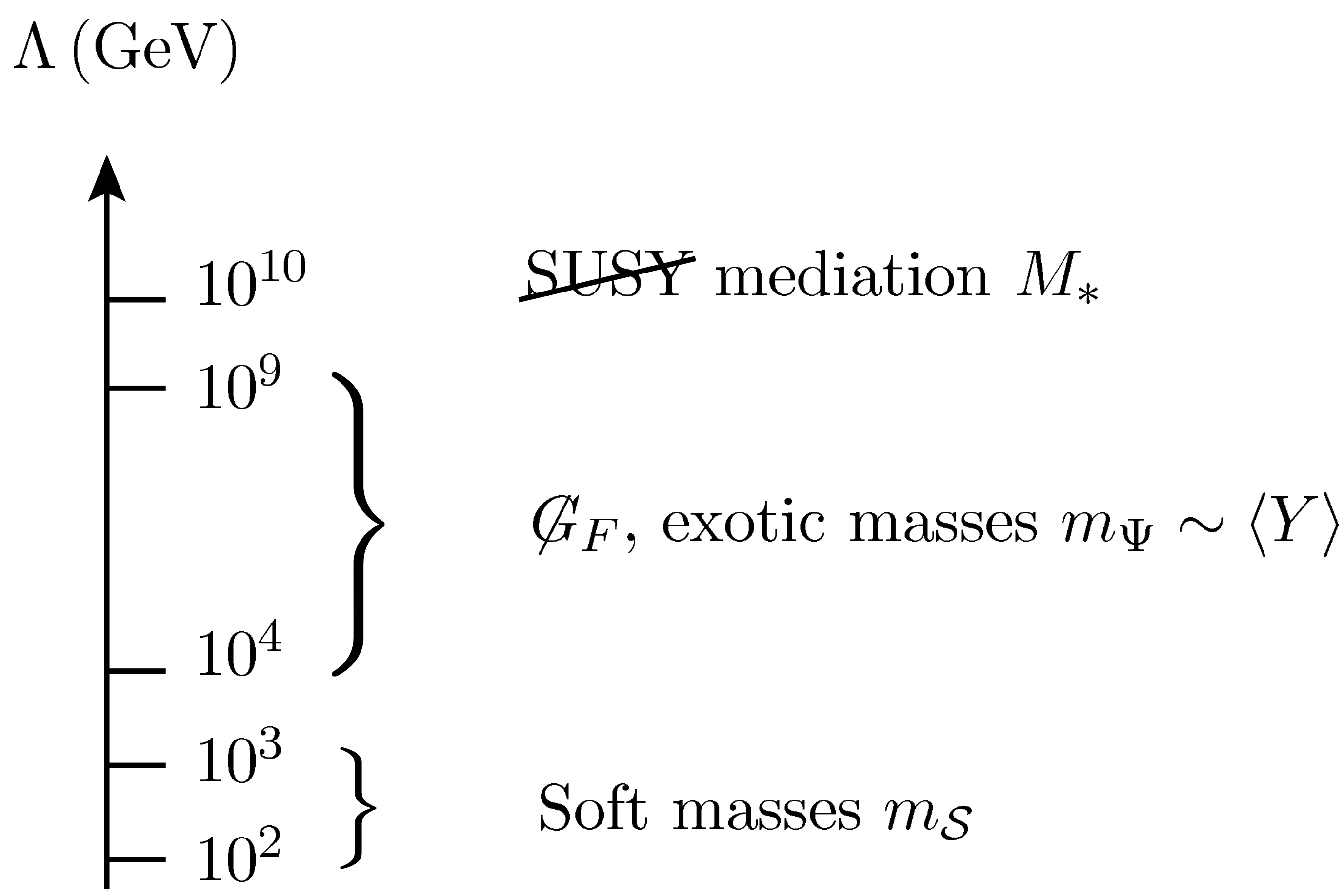

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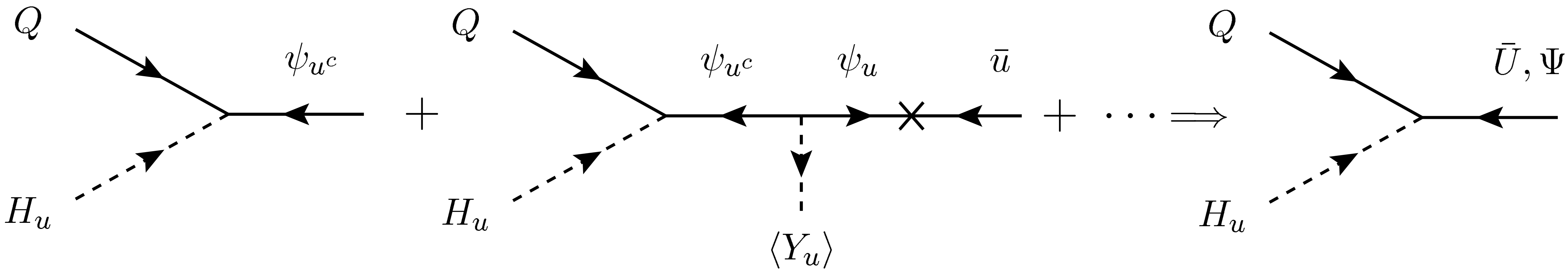

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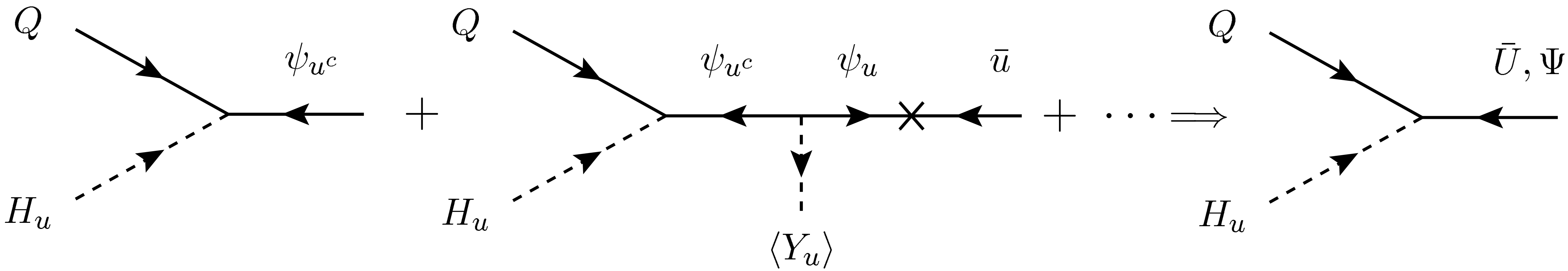

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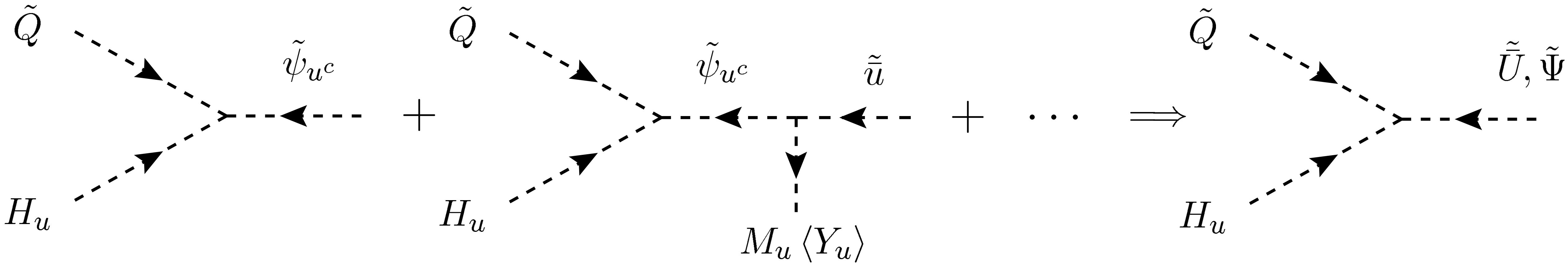

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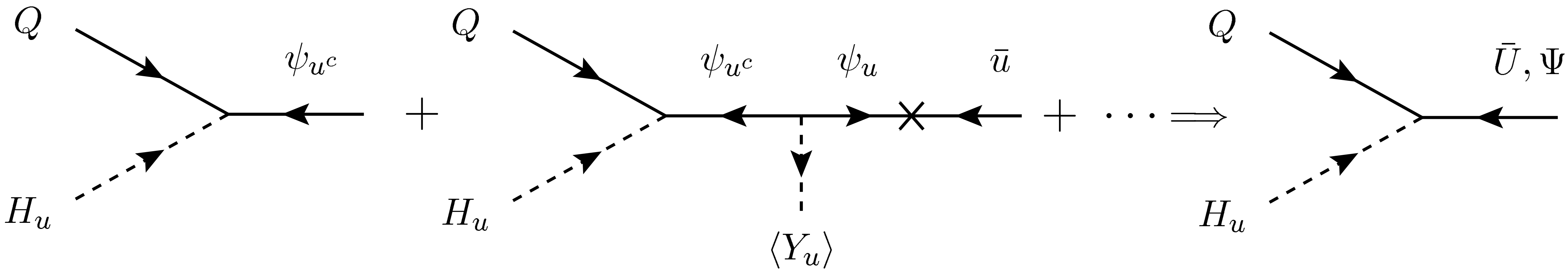

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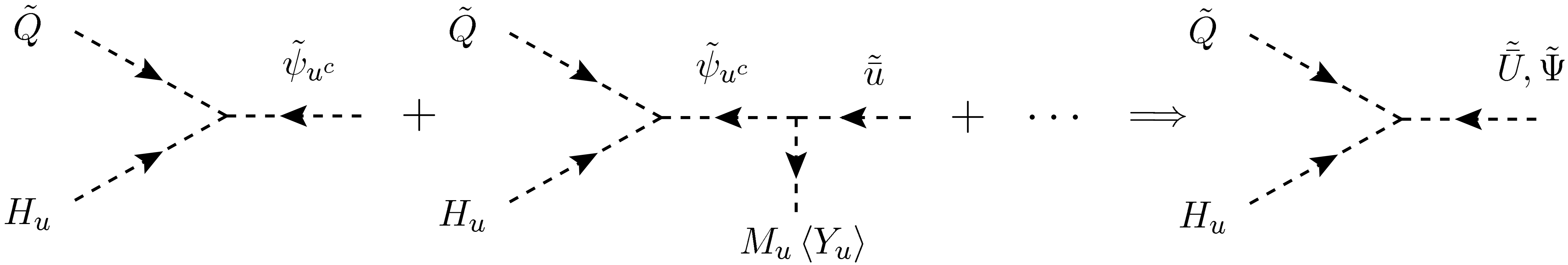

$$A\, H_u \widetilde{Q}(\widetilde{\psi}_{u^c}) \to A\, H_u \widetilde{Q}(\mathcal{V}^u \widetilde{\bar{U}}) \simeq A\, (\mathcal{Y}_u) H_u \widetilde{Q} \widetilde{\bar{U}}$$

DEVIATIONS

Need $\mathcal{V}_{\text{fermion}} = \mathcal{V}_{\text{scalar}}$ up to small corrections.

Equivalent to $m_s^2 = M_f^\dagger M_f$, so SUSY breaking is small

Deviation goes like $\frac{m^2_{\text{soft}}}{\langle Y \rangle^2}$

Inverted hierarchy comes to the rescue again!

FLAVON

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$
Y_u	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$
Y_d	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$
Y_u^c	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$
Y_d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\overline{\mathbf{3}}$

$$W_Y = \lambda_{Y_u} Y_u Y_u Y_u + \lambda_{Y_u^c} Y_u^c Y_u^c Y_u^c + \mu_{Y_u} Y_u Y_u^c + (u \to d)$$

FLAVON

$$W_Y = \lambda_{Y_u} Y_u Y_u Y_u + \lambda_{Y_u^c} Y_u^c Y_u^c Y_u^c + \mu_{Y_u} Y_u Y_u^c + (u \to d)$$

All these parameters must because they induce additional SUSY breaking

$$-F_Y^* = \lambda_Y YY + \mu_Y Y^c$$

$$|D_Q|^2 = \frac{g_Q^2}{2}\Big| Y_u^* T_Q^a Y_u - Y_u^c T_Q^a Y_u^{c*} + \widetilde{Q}^* T_Q^a \widetilde{Q} - \widetilde{\psi}_{u^c} T_Q^a \widetilde{\psi}_{u^c}^* + (u \to d)\Big|^2$$

SOFT PARAMETERS

$$A\left[\mathcal{Y}+\mathcal{O}\left(\mathcal{Y}\lambda_Y\right)+\mathcal{O}\left(\mathcal{Y}\frac{\mu_Y}{\langle Y\rangle}\right)+\mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^2}{\langle Y\rangle^2}\right)\right]H_u\widetilde{Q}\widetilde{\bar{U}}$$

SOFT PARAMETERS

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Exactly MFV

SOFT PARAMETERS

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Exactly MFV

Flavorful SUSY

SOFT PARAMETERS

$$A\left[\mathcal{Y}+\mathcal{O}\left(\mathcal{Y}\lambda_Y\right)+\mathcal{O}\left(\mathcal{Y}\frac{\mu_Y}{\langle Y\rangle}\right)+\mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^2}{\langle Y\rangle^2}\right)\right]H_u\widetilde{Q}\widetilde{\bar{U}}$$

$$m_{\mathcal{S}}^2\left\{1\!\!1+\frac{v^2}{m_{\mathcal{S}}^2}\mathcal{Y}^\dagger\mathcal{Y}+\mathcal{Y}\left[\mathcal{O}\left(\mathcal{Y}\lambda_Y\right)+\mathcal{O}\left(\mathcal{Y}\frac{\mu_Y}{\langle Y\rangle}\right)+\mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^2}{\langle Y\rangle^2}\right)\right]\right.$$

$$\left.+g_F^2\left[\mathcal{O}(1)+\mathcal{O}\left(\frac{\lambda_Y^4}{\lambda_S^4}\frac{\langle Y\rangle^2}{m_{\mathcal{S}}^2}\right)\right]\right\}$$

SOFT PARAMETERS

$$A\left[\mathcal{Y}+\mathcal{O}\left(\mathcal{Y}\lambda_Y\right)+\mathcal{O}\left(\mathcal{Y}\frac{\mu_Y}{\langle Y\rangle}\right)+\mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^2}{\langle Y\rangle^2}\right)\right]H_u\widetilde{Q}\widetilde{\bar{U}}$$

Flavor universal

$$m_{\mathcal{S}}^2\left\{\mathbb{1}+\frac{v^2}{m_{\mathcal{S}}^2}\mathcal{Y}^\dagger\mathcal{Y}+\mathcal{Y}\left[\mathcal{O}\left(\mathcal{Y}\lambda_Y\right)+\mathcal{O}\left(\mathcal{Y}\frac{\mu_Y}{\langle Y\rangle}\right)+\mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^2}{\langle Y\rangle^2}\right)\right]\right.$$
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Exactly MFV

SOFT PARAMETERS

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Flavor universal

Flavorful SUSY

$$m_{\mathcal{S}}^2\left\{\mathbb{1}+\frac{v^2}{m_{\mathcal{S}}^2}\mathcal{Y}^\dagger\mathcal{Y}+\mathcal{Y}\left[\mathcal{O}\left(\mathcal{Y}\lambda_Y\right)+\mathcal{O}\left(\mathcal{Y}\frac{\mu_Y}{\langle Y\rangle}\right)+\mathcal{O}\left(\mathcal{Y}\frac{m_{\mathcal{S}}^2}{\langle Y\rangle^2}\right)\right]\right.$$
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Exactly MFV

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Flavor universal

Flavorful SUSY

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$$\left.+g_F^2\left[\mathcal{O}(1)+\mathcal{O}\left(\frac{\lambda_Y^4}{\lambda_{\mathcal{S}}^4}\frac{\langle Y\rangle^2}{m_{\mathcal{S}}^2}\right)\right]\right\}$$

Exactly MFV

Flavor anarchy

AWAY FROM MFV

<u>Exact MFV</u>

- $\langle Y \rangle \ll M_*$
- $\mu_Y \ll \langle Y \rangle$
- $\lambda_Y \ll 1$
- $g_F \ll 1$
- $m_{\mathcal{S}}, v \ll \langle Y \rangle$

AWAY FROM MFV

Exact MFV

- $\langle Y \rangle \ll M_*$
- $\mu_Y \ll \langle Y \rangle$
- $\lambda_Y \ll 1$
- $g_F \ll 1$
- $m_{\mathcal{S}}, v \ll \langle Y \rangle$

Not a corner of parameter space, but a tool for computation

CONSTRAINTS

Many of the constrained processes in this model are studied in the literature.

Nomura, DS, 2008. Grinstein, Redi, Villadoro, 2010. Csaki Grossman, Heidenreich, 2011. Buras et. al. 2012.

Direct constraints:

- RPV gluino search
- Search for Z', W'
- Search for top partners

Indirect constraints:

- $K - \bar{K}$ mixing
- Neutron EDM
- $n - \bar{n}$ oscillations
- Proton decay
- $Z \to b\bar{b}$
- V_{tb}

PARAMETER

Λ

$M_* \gtrsim 10^{10}$ GeV

$\langle Y \rangle_{11} \gtrsim 10^{7}$ GeV

$\langle Y \rangle_{33} \gtrsim 10^{4}$ GeV

$m_{\tilde{g}} \gtrsim 700$ GeV

$m_{\tilde{q}} \gtrsim \text{few} \times 100$ GeV

$g_F \lesssim 0.03$

$$\frac{\mu_Y}{\langle Y \rangle_{11}} \lesssim 10^{-3}$$

$\lambda_Y \lesssim 10^{-4}$

LEPTONS

	$SU(3)_L$	$SU(3)_E$	$SU(3)_N$	$U(1)_Y$
L	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
$\bar{e}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$+1$
$\bar{N}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	0
ψ_{e^c}	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$+1$
ψ_N	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	0
ψ_e	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	-1
ψ_ν	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	0
Y_ν	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	0
Y_ν^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	0
Y_e	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	0
Y_e^c	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	0

PURE DIRAC

$$W_L = \lambda_e H_d L \psi_{e^c} + \lambda'_e Y_e \psi_e \psi_{e^c} + M_e \psi_e \bar{e}$$
$$+ (d \to u,\, e \to \nu,\, \bar{e} \to \bar{N})$$

$$\mathcal{Y}_\nu \sim \lambda_\nu M_\nu / \lambda'_\nu \langle Y_\nu \rangle$$

Marjoana mass for $\bar{N}$ forbidden by $SU(3)_N$

Natural realization of pure Dirac neutrinos, still reminiscent of traditional seesaw scenario

CONCLUSIONS

- SUSY can solve the hierarchy problem, makes a mess of flavor
- Natural SUSY is in trouble, even lepton violating RPV
- MFV RPV allowed, can be natural, interesting pheno
- Lots of interest in baryon number RPV since our paper:
  Bhattacherjee, Evans, Ibe, Matsumoto, Yanagida, 2013. Franceschini, Mohapatra, 2013. Csaki, Heidenreich, 2013.

CONCLUSIONS

- Maximal gauge flavor allows model of approximate MFV
- MFV limit allows computation, all bounds can be satisfied
- 3rd generation structure could be accessible at LHC
- Could give a window into SM flavor puzzle

THANK YOU

SM GAUGE

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
ψ_{u^c}	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
ψ_{d^c}	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$+1/3$
ψ_u	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$+2/3$
ψ_d	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$

Additional matter charged under SM group, not in complete SU(5) multiplets

Hypercharge hits landau pole as low as 10^{14} GeV

$SU(3)^6$ gauge symmetry not compatible with naive SU(5) unification

FLAVON VEV

Can generate vev for Y and Y^c with a singlet S

$$W = \lambda_S \, S \left(Y Y^c - w^2 \right)$$

Single Y field not enough to break all gauge symmetries and generate SM Yukawa's

Extend to M copies of Y and Y^c and add N singlets S

$$W = \lambda_{S_i} \, S^i \left(C_{ijk} Y^j (Y^c)^k - w_i^2 \right)$$

Replace Y_u with $\sum_i Y_u^i$ in superpotential