New Physics Beyond the Standard Model

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Spectrum

SM int.	gauge boson, spin-1	Super-partner, spin-1/2
$SU(3)_C$	g^a, $a = 1, 2, ..., 8$	gluino: $\tilde{g}^a$
$SU(2)_L$	$W_{1,2,3}$	wino: $\tilde{W}_{1,2,3}$
$U(1)_Y$	B_μ	bino: $\tilde{B}$

squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times 3$ 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	$(\widetilde{\nu} \ \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H^+_u \ \ H^0_u)$	$(\widetilde{H}^+_u \ \ \widetilde{H}^0_u)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H^0_d \ \ H^-_d)$	$(\widetilde{H}^0_d \ \ \widetilde{H}^-_d)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Minimal Supersymmetric Standard Model (MSSM)

gaugino: $\tilde{g}, \tilde{W}_{1,2,3}, \tilde{B}$

neutralino: $\tilde{B}, \tilde{W}_3, \tilde{H}^0_u, \tilde{H}^0_d$

$\tilde{N}_i$

chargino: $\tilde{W}^\pm, \tilde{H}^+_u, \tilde{H}^-_d$

$\tilde{C}_i$

SUSY: interactions

Interactions.

More details: for example, S. Martin "Supersymmmetry Primer"

- Superpartners have the same gauge quantum numbers as their SM counter parts.
  - Similar gauge interactions.

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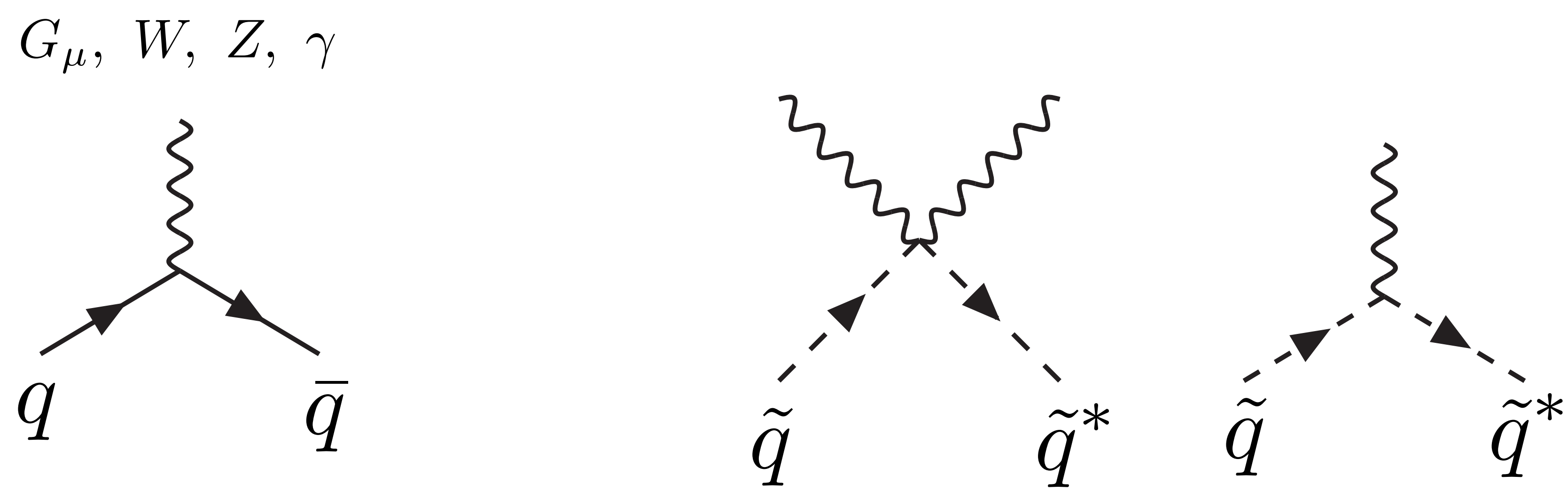

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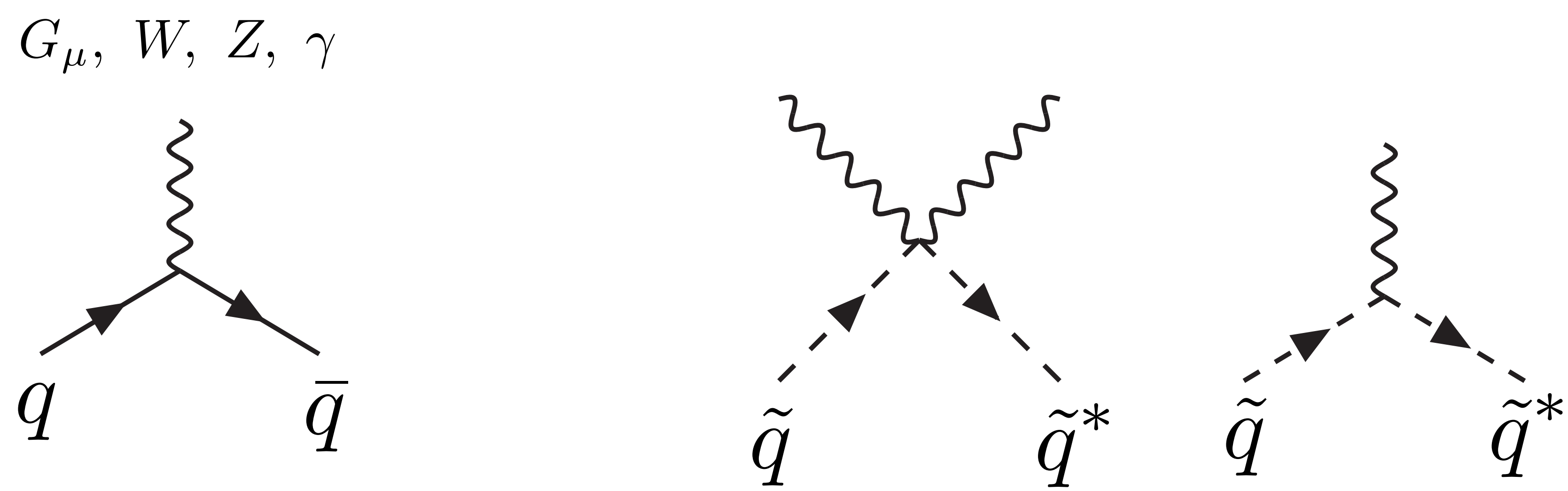
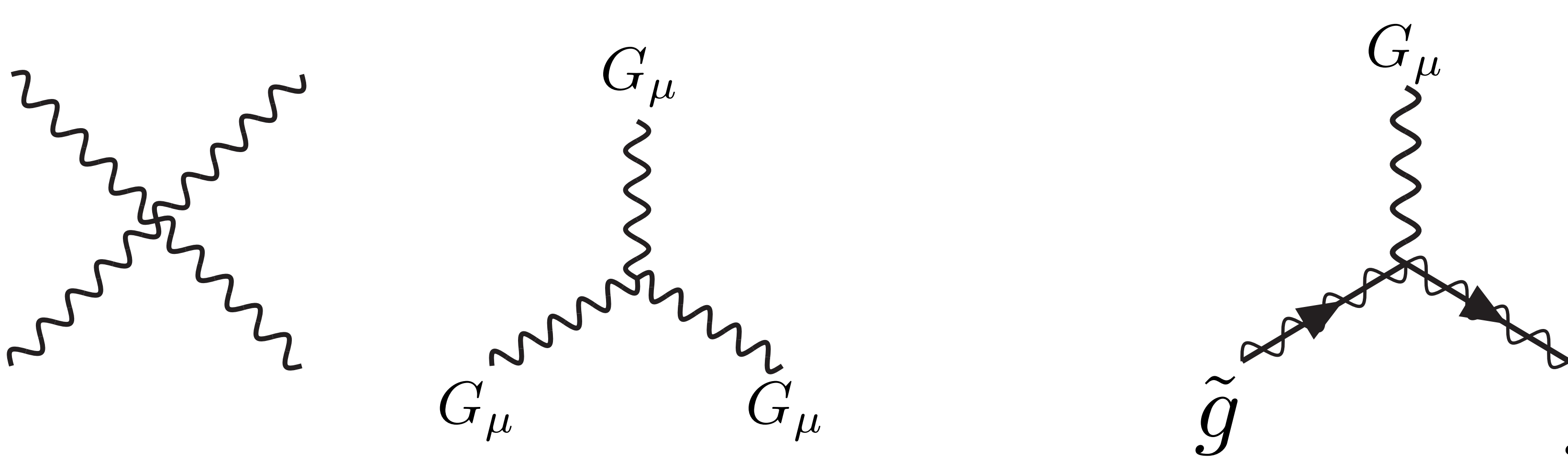


non-Abelian



Interactions.

- SUSY$\Rightarrow$ additional couplings
  - strength fixed by corresponding gauge couplings.

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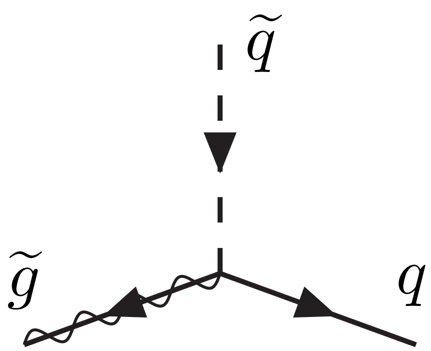
SU(3)$_{color}$



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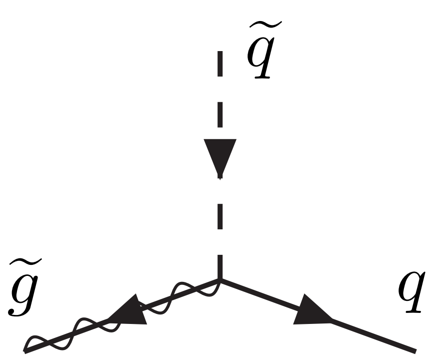
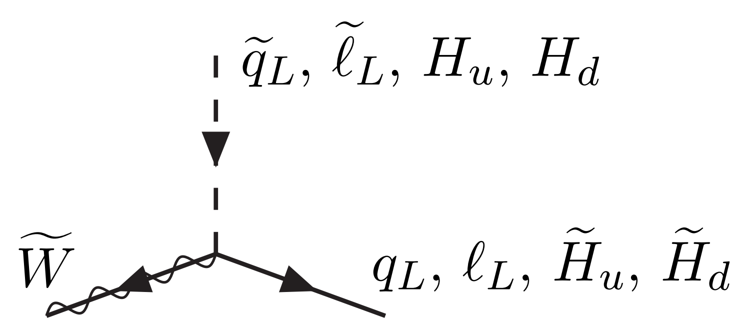


SU(2)$_L$



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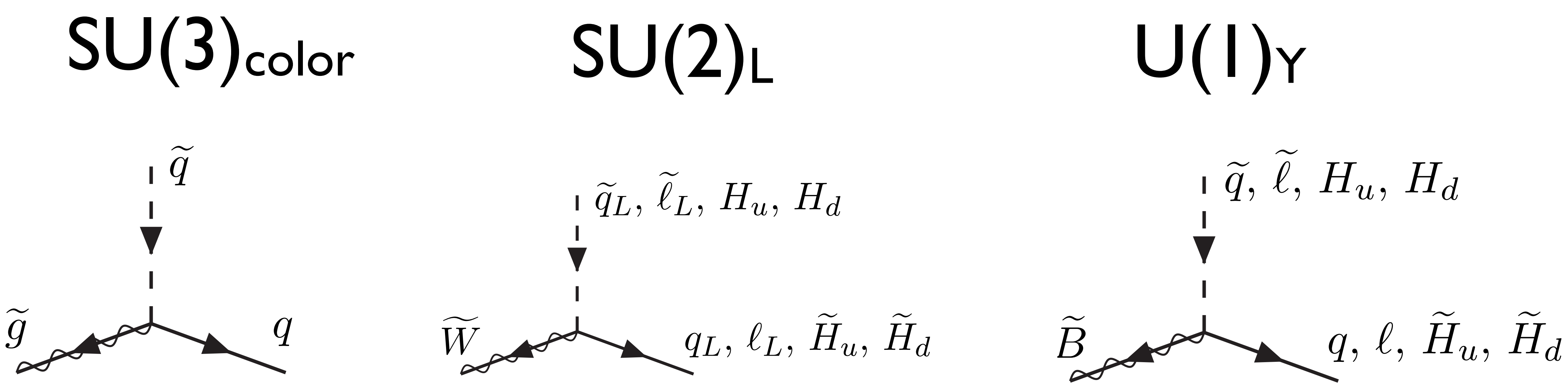

Interactions.

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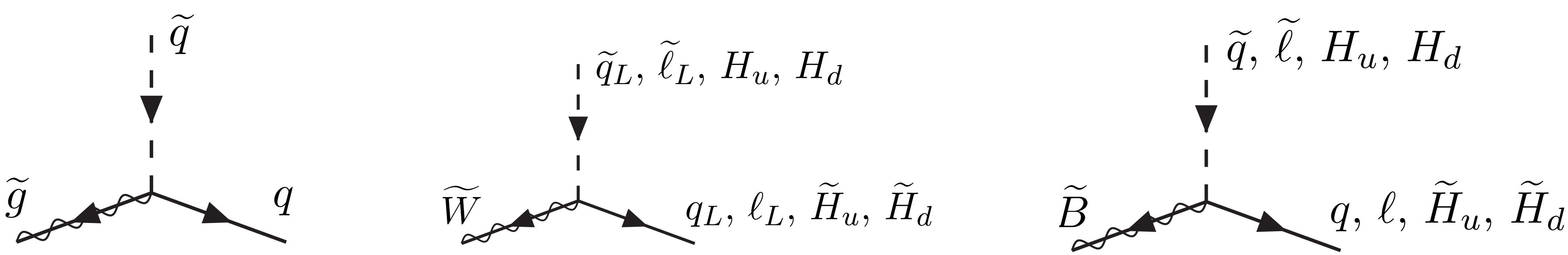
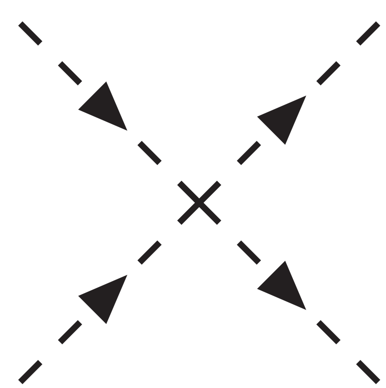
SU(3)$_{color}$ SU(2)$_L$ U(1)$_Y$

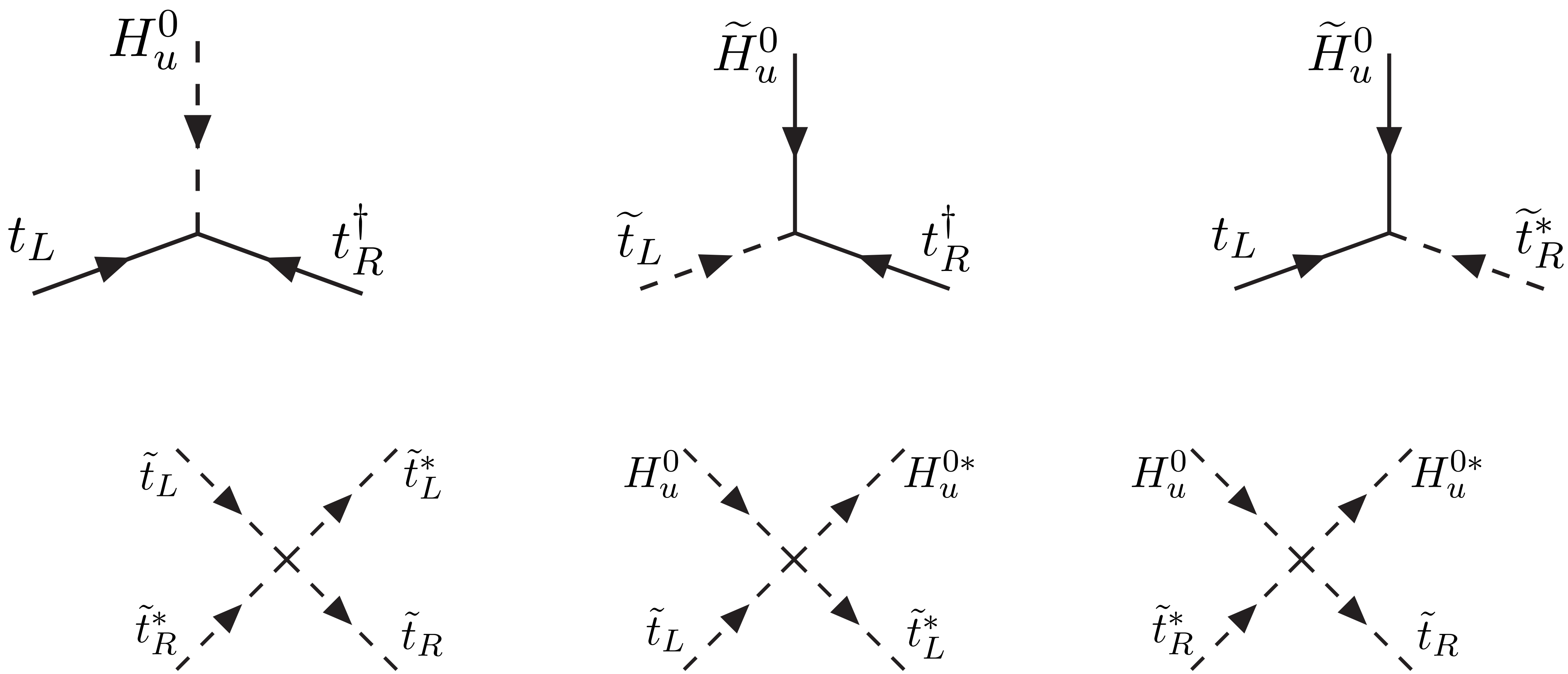


D-term: $\propto$ **g^2**



Interactions.

- SM fermions (such as the top quark) receive masses by coupling to the Higgs boson.
  - Yukawa couplings ⇒ SUSY counter parts.



Superpartners.

- We have not seen any of the superpartner yet.
  - They must be heavier than the SM particles.
- Therefore, SUSY must be a broken symmetry.
- Are we back to the beginning?
  - No.
  - SUSY can be broken in a controlled way so that the theory stays natural, soft SUSY breaking.

Superpartner mass and naturalness

- m_h^2 (physical) = $m_0^2 + c\ \Lambda^2$, c some O(0.01) number.

- New physics needed at $\Lambda \approx$ 100s GeV - TeV
  - This should be the superpartner mass for a natural theory.

- At higher energies, the theory is approximately supersymmetric. Therefore, scalar mass would be be sensitive to what happens at higher energy scales.
  - m_h^2 (physical) = $m_0^2 + c\ m(\text{superpartner})^2$

The masses of the superpartners

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

The masses of the superpartners

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$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + {\rm c.c.})\,.$$

Gaugino masses

The masses of the superpartners

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& -\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 \\
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\end{aligned}
$$

trilinear,
similar to Yukawa

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sfermion masses

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General parameterization

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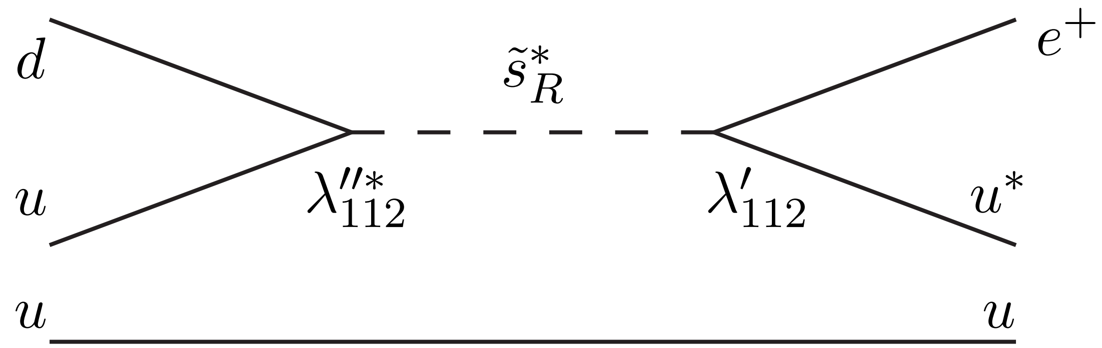
- $>$ 100 parameters.
  - Too many? Have to include all of them in the most general theory.
  - Most of them, flavor mixing, CP phases, are strongly constrained to vanish.
  - A theory of SUSY breaking typically contain much less ($<$ 10-ish) parameters.

More couplings?

- Gauge invariance and SUSY allows for more couplings. For example



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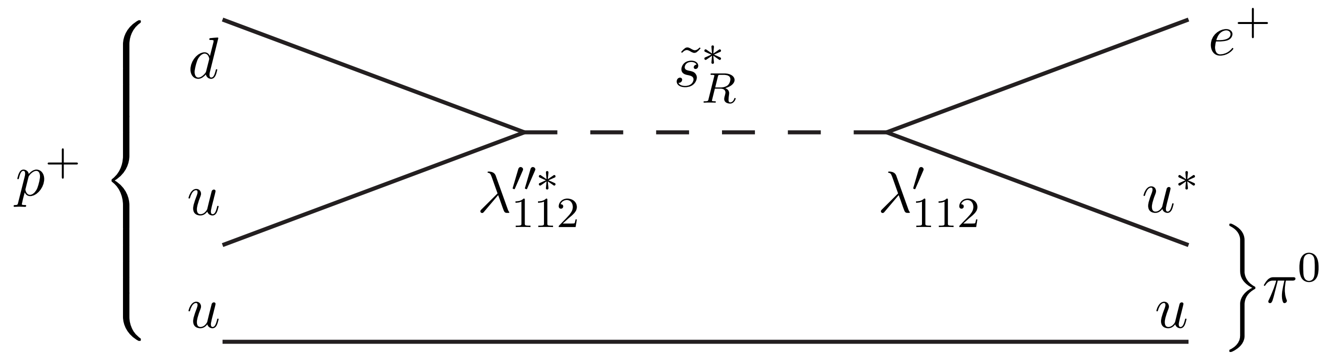

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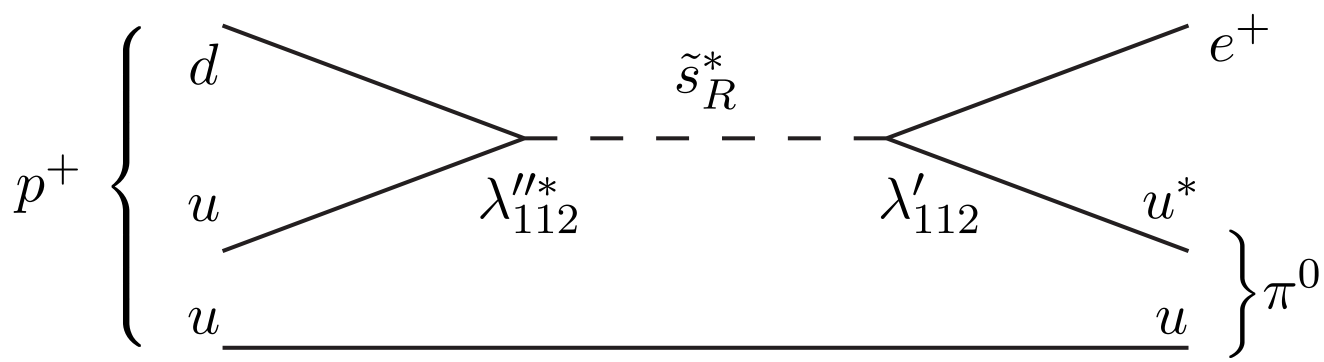

Proton decay: $$\Gamma_{p\to e^+\pi^0} \sim m^5_{\rm proton} \sum_{i=2,3} |\lambda'^{11i}\lambda''^{11i}|^2/m^4_{\tilde{d}_i}$$

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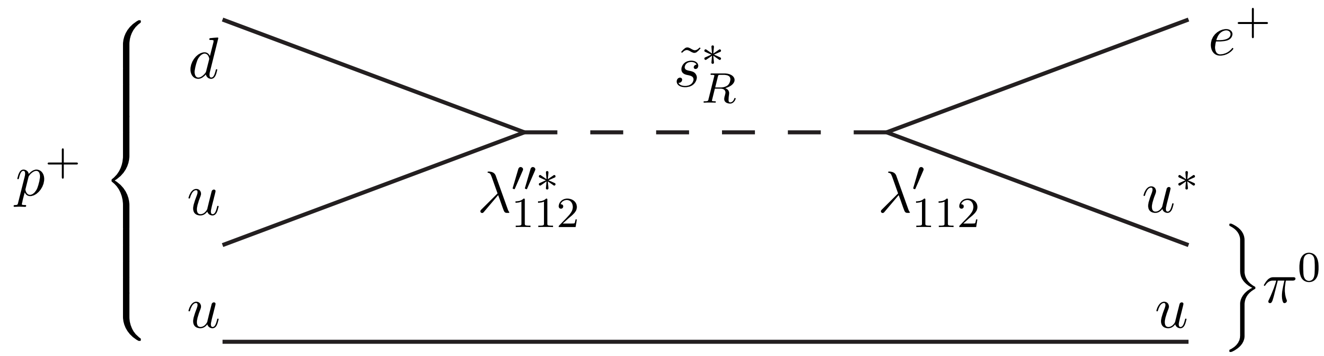


Proton decay: $\Gamma_{p\to e^+\pi^0} \sim m^5_{\rm proton} \sum_{i=2,3} |\lambda'^{11i}\lambda''^{11i}|^2/m^4_{\tilde{d}_i}$

These couplings must be extremely tiny!

A symmetry:

- Vanishing couplings usually come from a symmetry principle.

- Could impose B (B_{quark} = 1/3) or L (L_{lepton} = 1) symmetry. Slightly uncomfortable
  - Not exact symmetries in the SM.

- An interesting choice: R-parity

$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$$

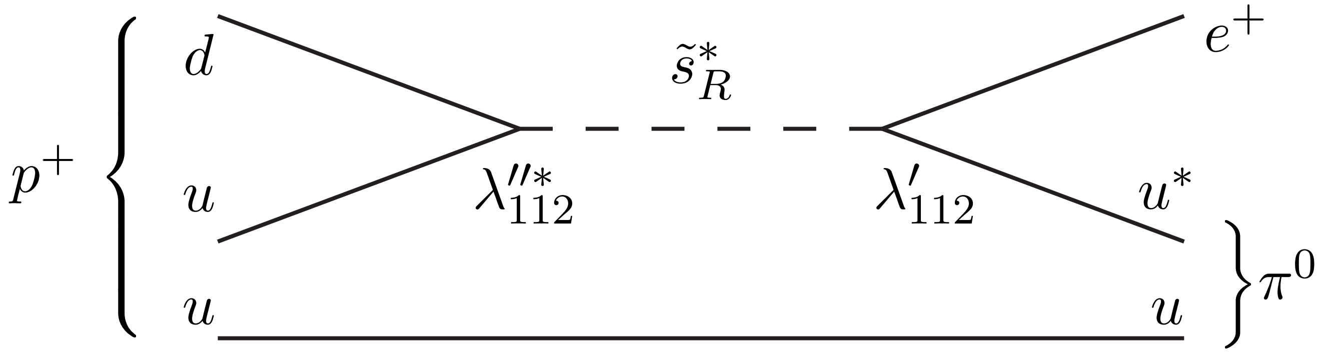
R-parity

$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$$

	spin		spin
gluon, g	1	gluino: $\tilde{g}$	1/2
$W^{\pm}, Z$	1	gaugino: $\tilde{W}^{\pm}, \tilde{Z}$	1/2
quark: q	1/2	squark: $\tilde{q}$	0
...		...	
SM		(super)partner	

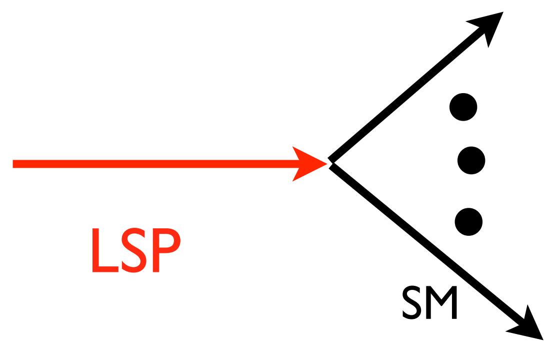
– All superpartners are odd under R-parity.

R-parity



forbidden!

Lightest SuperPartner (LSP) is stable



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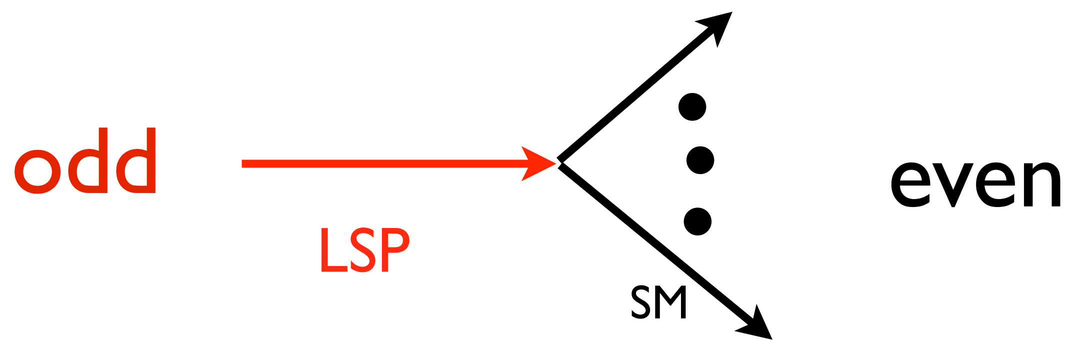

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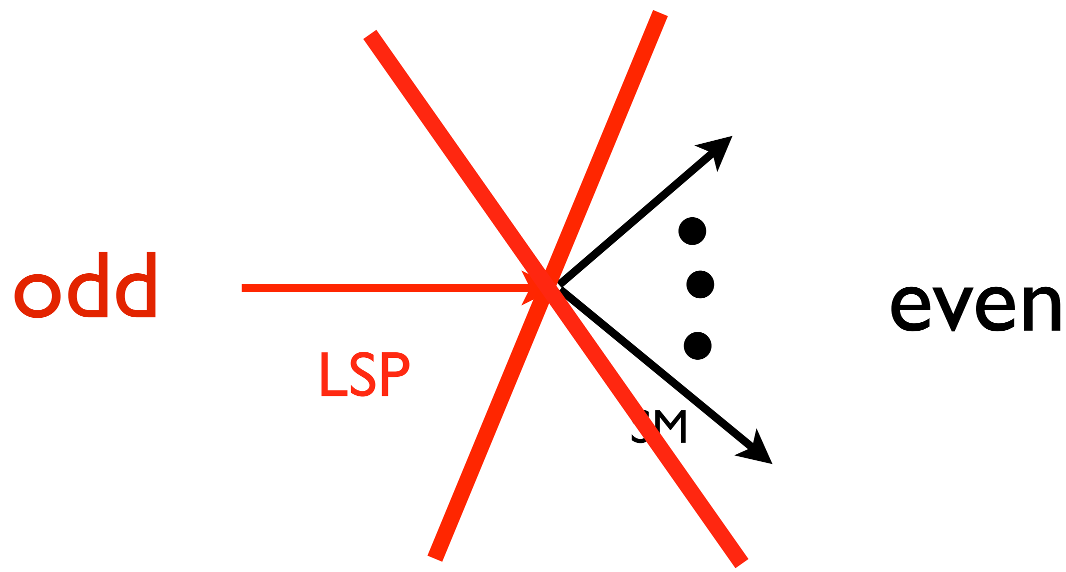

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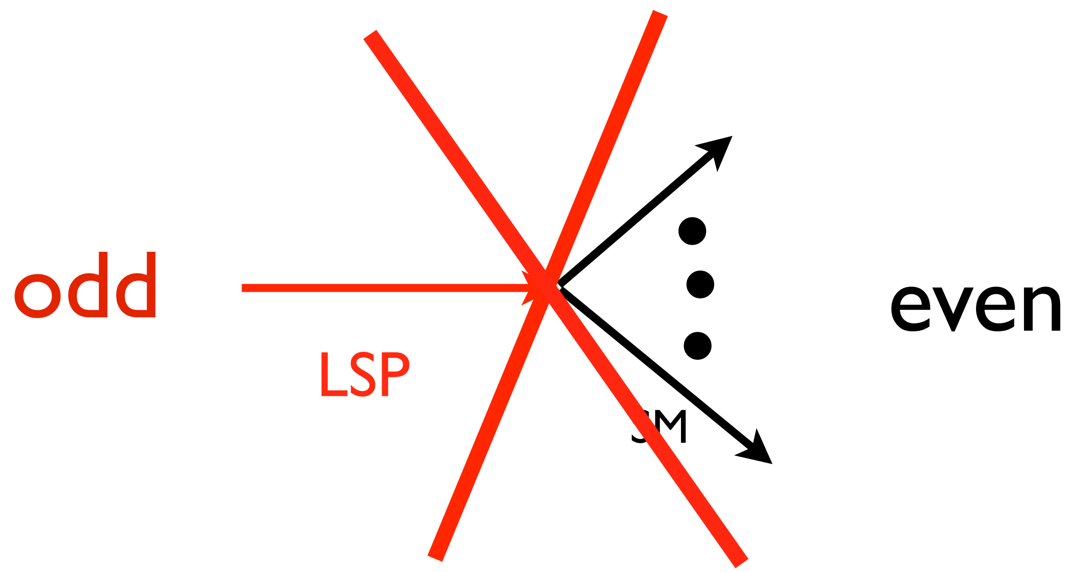
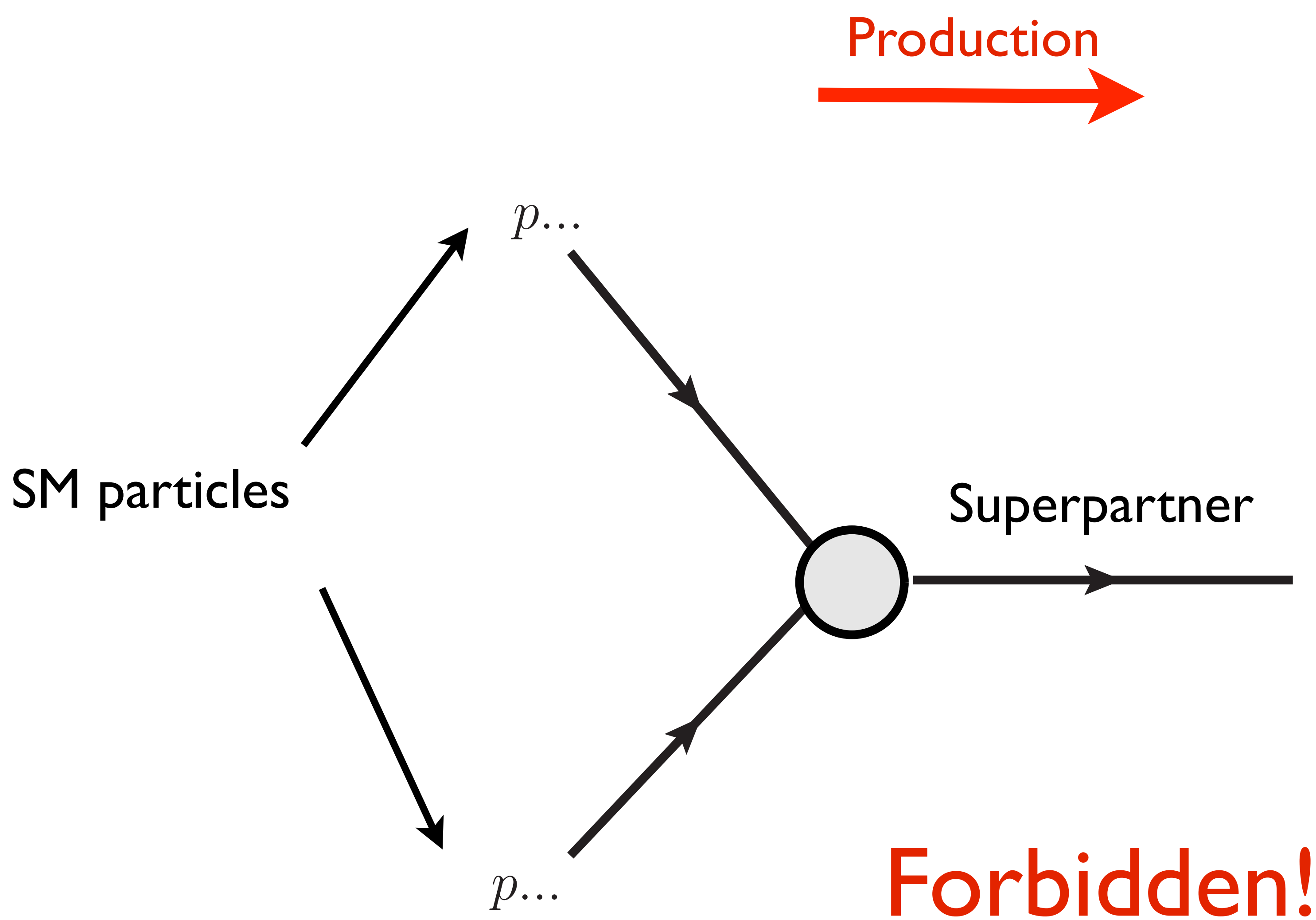


- Neutral LSP a natural candidate for WIMP dark matter.
  - $O(\Lambda_{EW})$
  - Weakly coupled.
  - Can have Similar states in other new physics scenario. With SUSY, a consequence of forbidding proton decay.

SUSY at colliders

- Superpartners must be pair produced!



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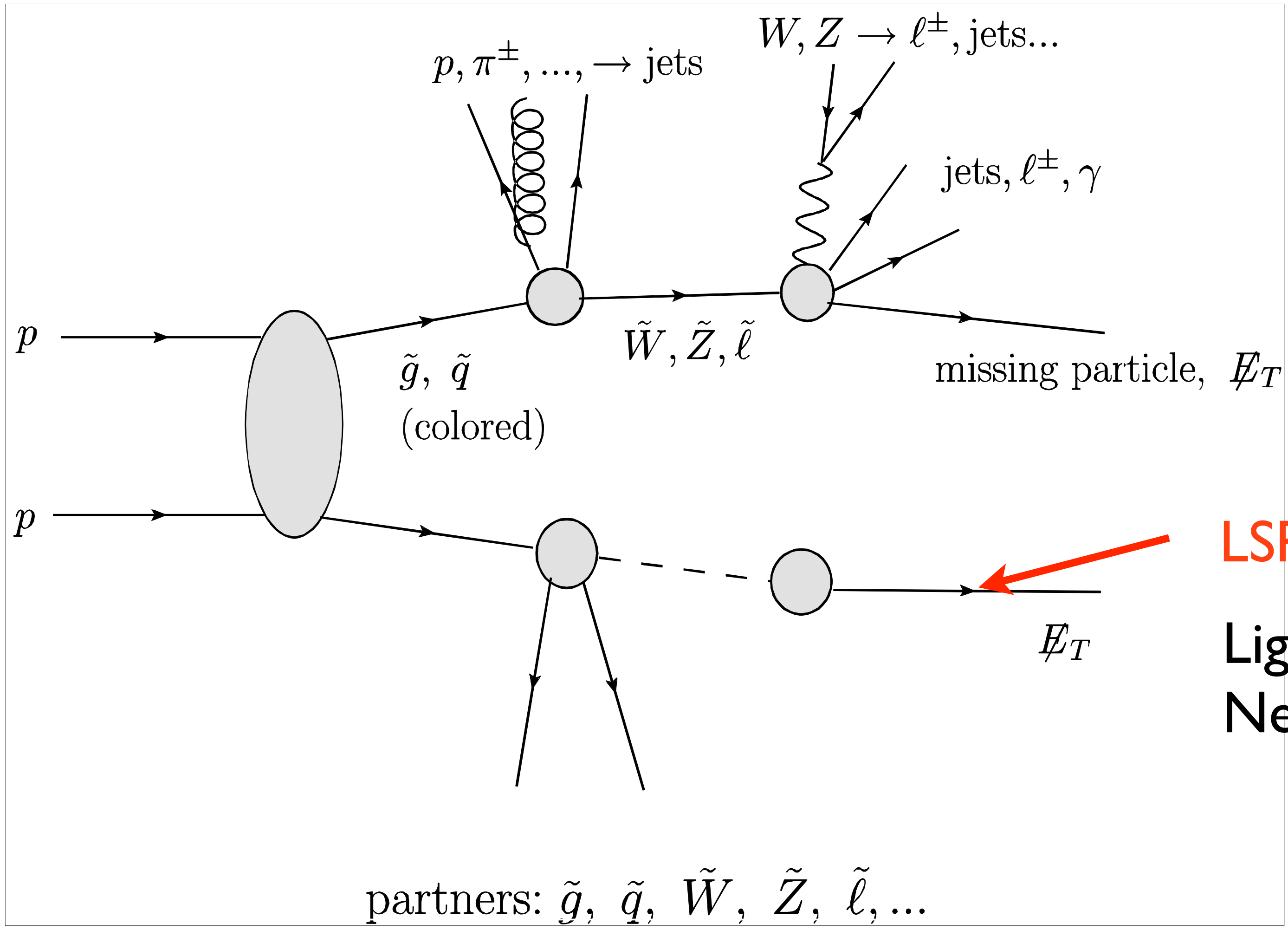
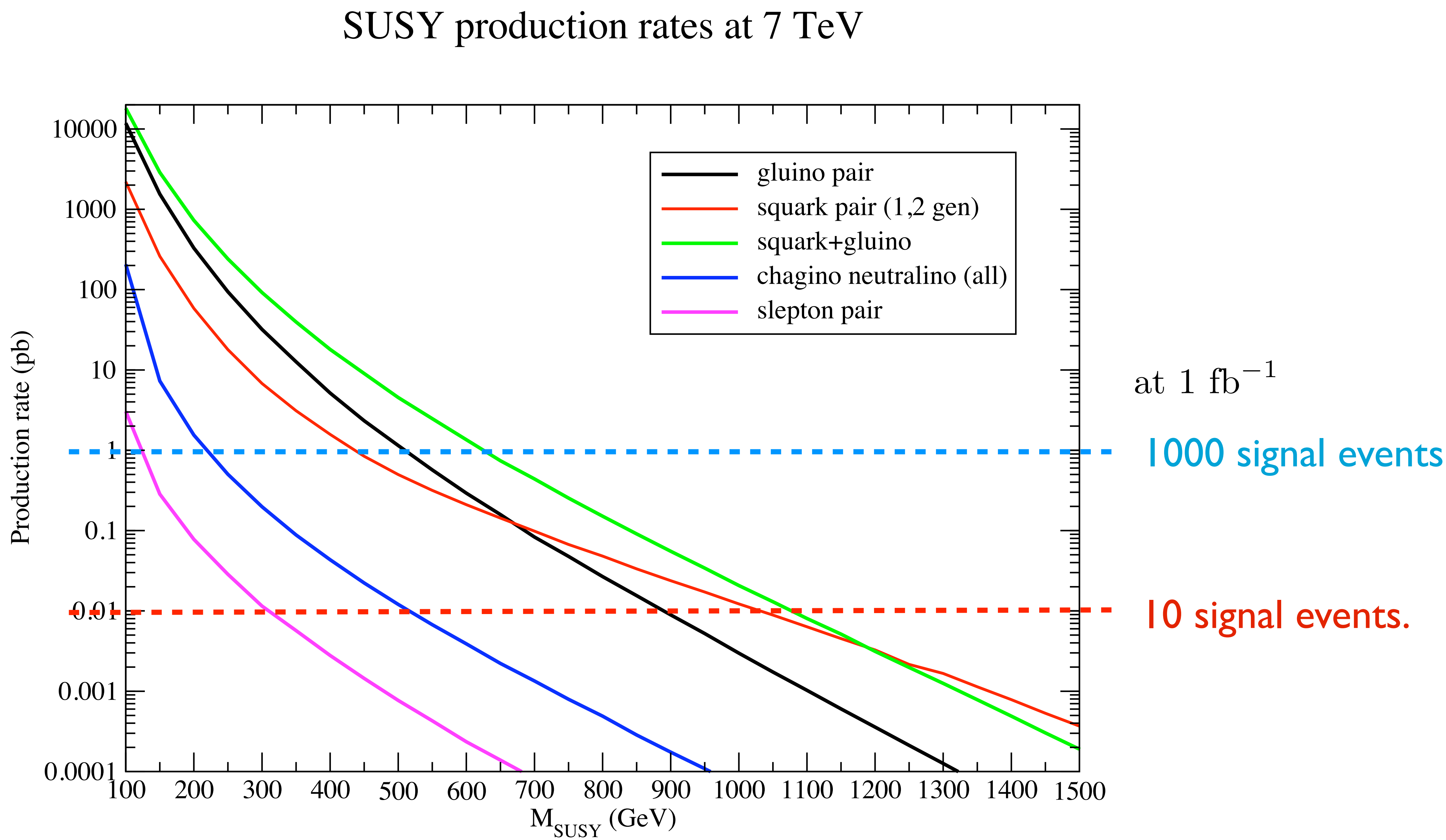


- long decay chain.
- jets, leptons, missing E_T ....
- Nice signal, good discovery potential.

Production.

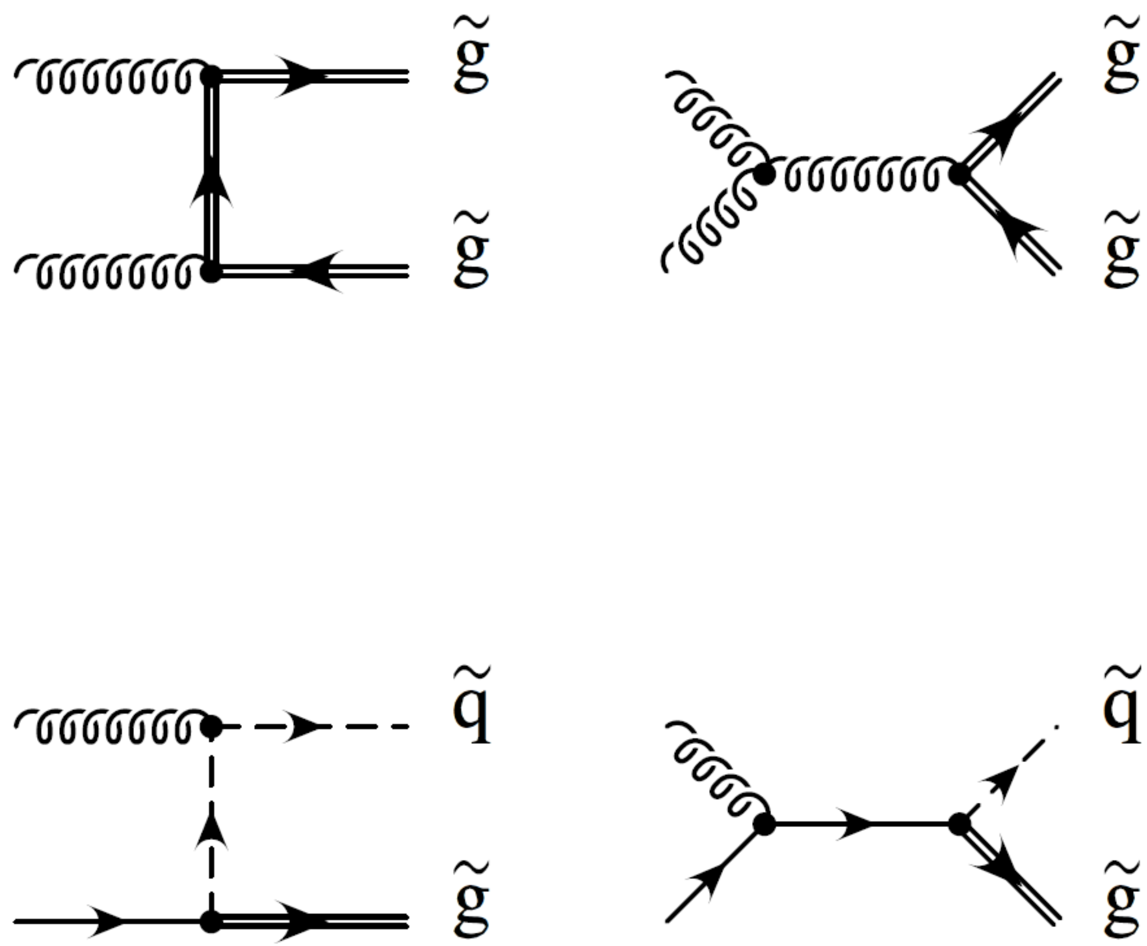


Dominated by the production of colored states.

Similar pattern for other scenarios. Overall rates scaled by spin factors.

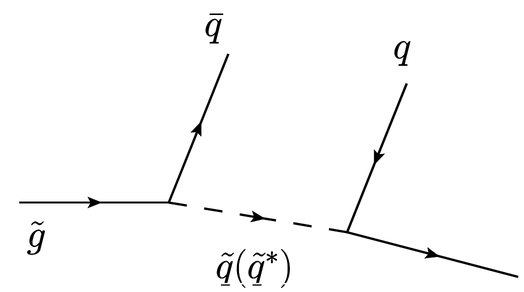
Examples of production: colored

- Squark and gluino production.

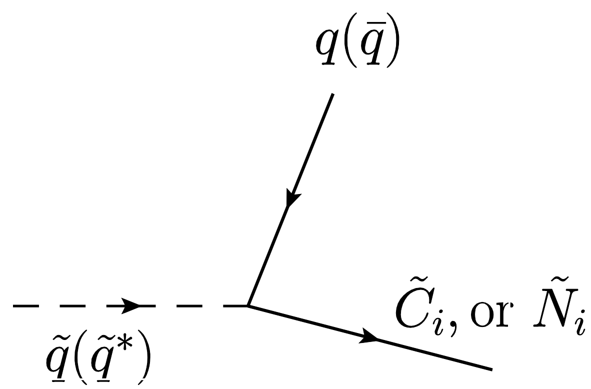


Decay of squark and gluino

- Gluino always decays into squark (on or off-shell).
  - Glunino -> squark + Jets

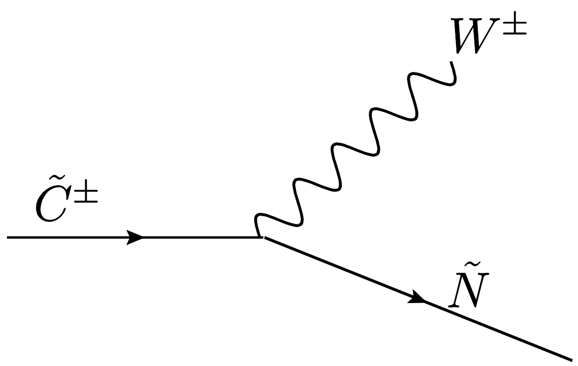


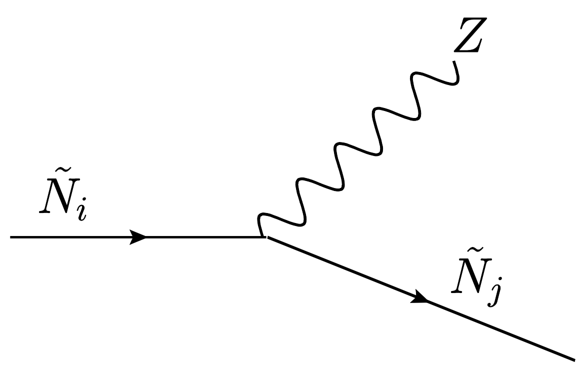
- Squark decay.
  - Jet +
    - To gluino, then go through off-shell squark.
    - To chargino or neutralino.



Next steps

- To W or Z (maybe Higgs.)

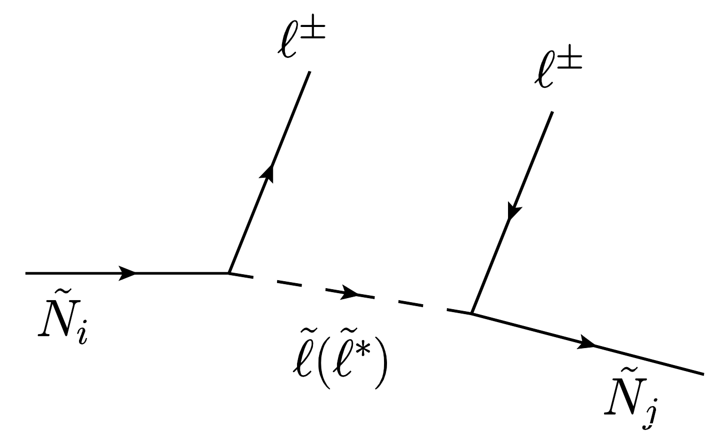


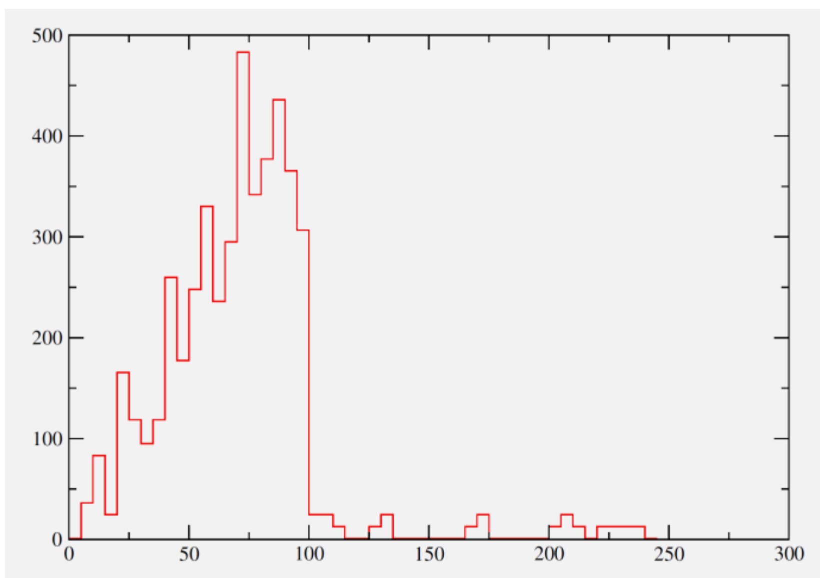


- Lepton (suppressed by W/Z-> lepton BR.)
  - 1 or 2 leptons.
- Jets (softer, constrained by W and Z mass).

More leptons if we are lucky

- A lot of leptons. No branching ratio suppression.
- On shell slepton, very distinctive feature.
  - Edge in di-lepton invariant mass.





$$m_{\tilde{\ell}} < M_{\tilde{N}_2} \quad \longrightarrow \tilde{N}_2 \to \tilde{N}_1 + [\tilde{\ell}] \to \tilde{N}_1 + \ell^+ + \ell^-$$

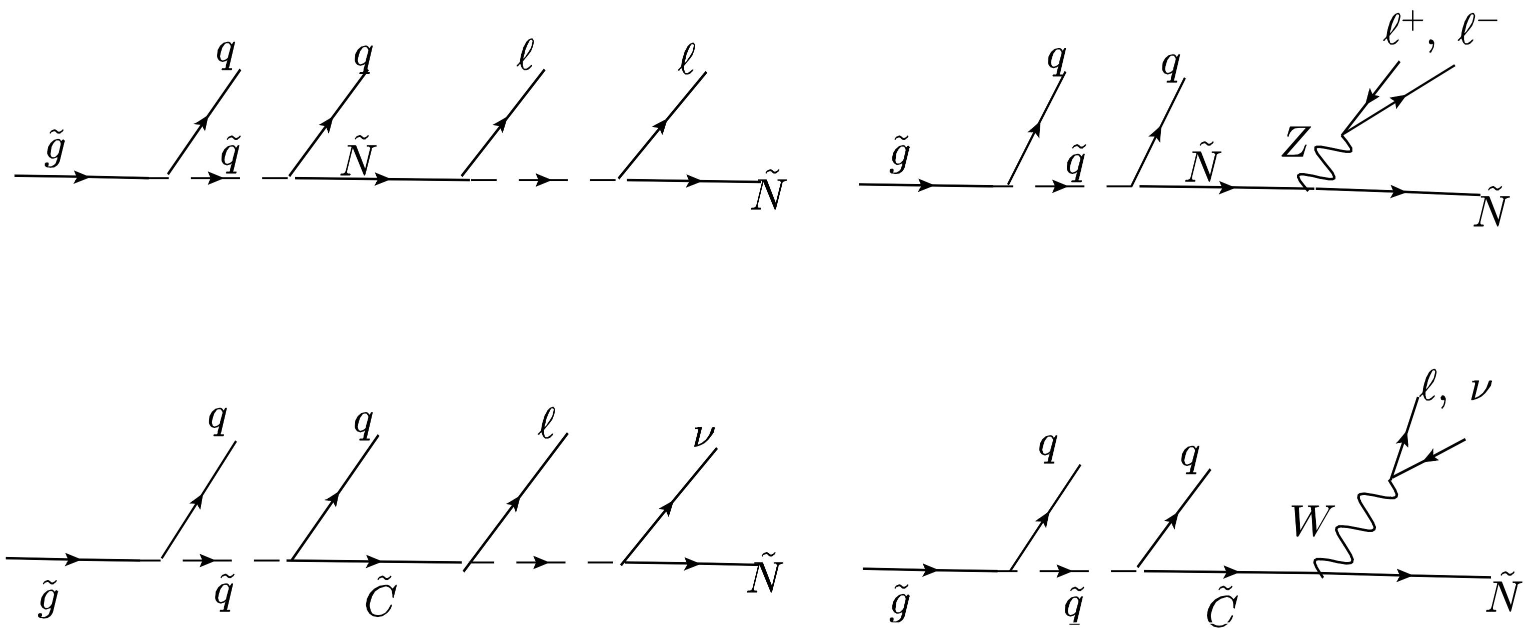
$$M_{\ell\ell}^{\mathrm{max}} = M_{\tilde{N}_2} \sqrt{1 - \frac{m_{\tilde{\ell}}^2}{M_{\tilde{N}_2}^2}} \sqrt{1 - \frac{M_{\tilde{N}_1}^2}{m_{\tilde{\ell}}^2}}$$

- More complicated edges useful, but need high statistics.

See several papers by: Miller, Osland.

Long decay chains

- Putting the pieces together.
- Many channels, many final states.



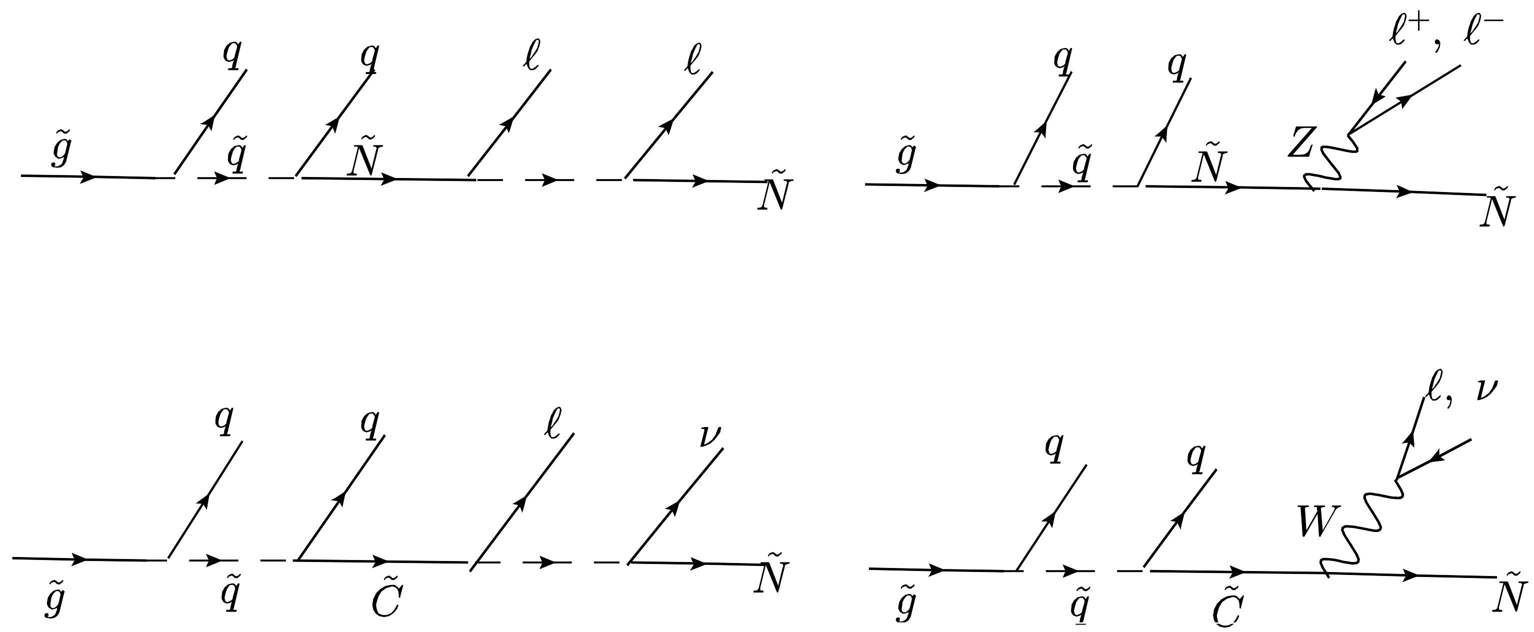
2-lepton chain

1-lepton chain

$$
\begin{aligned}
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2 \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2 [\tilde{N}_i] \rightarrow q_1 q_2 [Z] \tilde{N}_0 \rightarrow q_1 q_2 q_3 q_4 \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2 [\tilde{C}_i] \rightarrow q_1 q_2 [W] \tilde{N}_0 \rightarrow q_1 q_2 q_3 q_4 \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2 [\tilde{N}_i] \rightarrow q_1 q_2 [Z] \tilde{N}_0 \rightarrow q_1 q_2 \ell^+ \ell^- \tilde{N}_0 \\
\tilde{g} &\rightarrow q_1[\tilde{q}] \rightarrow q_1 q_2 [\tilde{N}_i] \rightarrow q_1 q_2 q_3 q_4 (\ell^+ \ell^-) \tilde{N}_0
\end{aligned}
$$

Long decay chains

- Putting the pieces together.
- Many channels, many final states.



2-lepton chain

1-lepton chain

$$\tilde{g} \;\rightarrow\; q_1[\tilde{q}] \rightarrow q_1 q_2 \tilde{N}_0$$
$$\tilde{g} \;\rightarrow\; q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{N}_i] \rightarrow q_1 q_2[Z]\tilde{N}_0 \rightarrow q_1 q_2 q_3 q_4 \tilde{N}_0$$
$$\tilde{g} \;\rightarrow\; q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{C}_i] \rightarrow q_1 q_2[W]\tilde{N}_0 \rightarrow q_1 q_2 q_3 q_4 \tilde{N}_0$$
$$\tilde{g} \;\rightarrow\; q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{N}_i] \rightarrow q_1 q_2[Z]\tilde{N}_0 \rightarrow q_1 q_2 \ell^+ \ell^- \tilde{N}_0$$
$$\tilde{g} \;\rightarrow\; q_1[\tilde{q}] \rightarrow q_1 q_2[\tilde{N}_i] \rightarrow q_1 q_2 q_3 q_4 (\ell^+ \ell^-) \tilde{N}_0$$

Exercise: draw diagrams for tri-lepton, same sign di-lepton

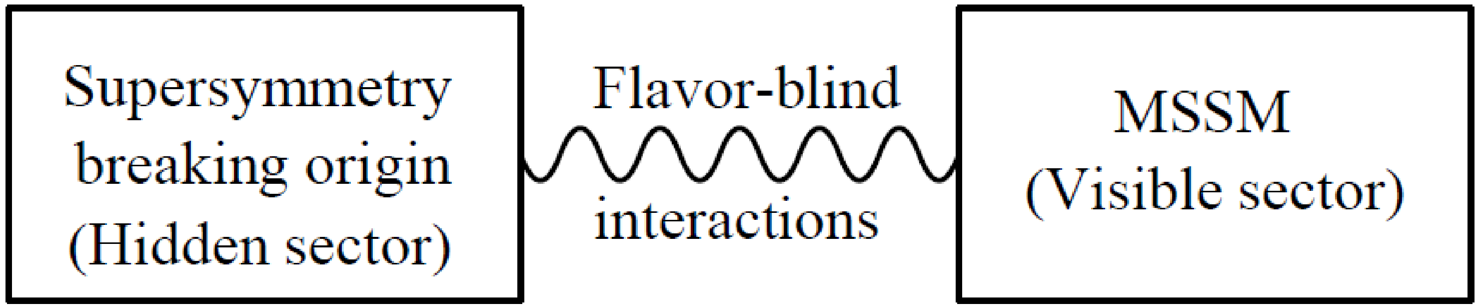
Classification of SUSY signal

- Inclusive counts.

$n_j \times$ jet	b-jet non-b-jet
$+$	
$n_\ell \times$ lepton	ℓ all flavor and charge combo: e.g. $2\ell \rightarrow 21$ comb.
$+$	
$n_\gamma \times \gamma$	

Supersymmetry: Models

SUSY breaking and mediation



- Simplest setup does not work.
  - Renormalizable coupling and at tree level
  - Sum rules like: $m^2_{\tilde{e}_1} + m^2_{\tilde{e}_2} = 2m^2_e$, not acceptable!
- Non-renormalizable coupling: gravity, moduli mediation
- Loop: gauge mediation...

High scale mediation

- SUSY broken at very high energy scale
- Mediated to MSSM through higher dimensional operator suppressed by some high mass scale.
- Low energy SUSY breaking masses obtained after taking into account (significant) renormalization effects
  - Renormalization group (RG) evolution.
- Gravity mediation, moduli mediation, ...

High scale mediation

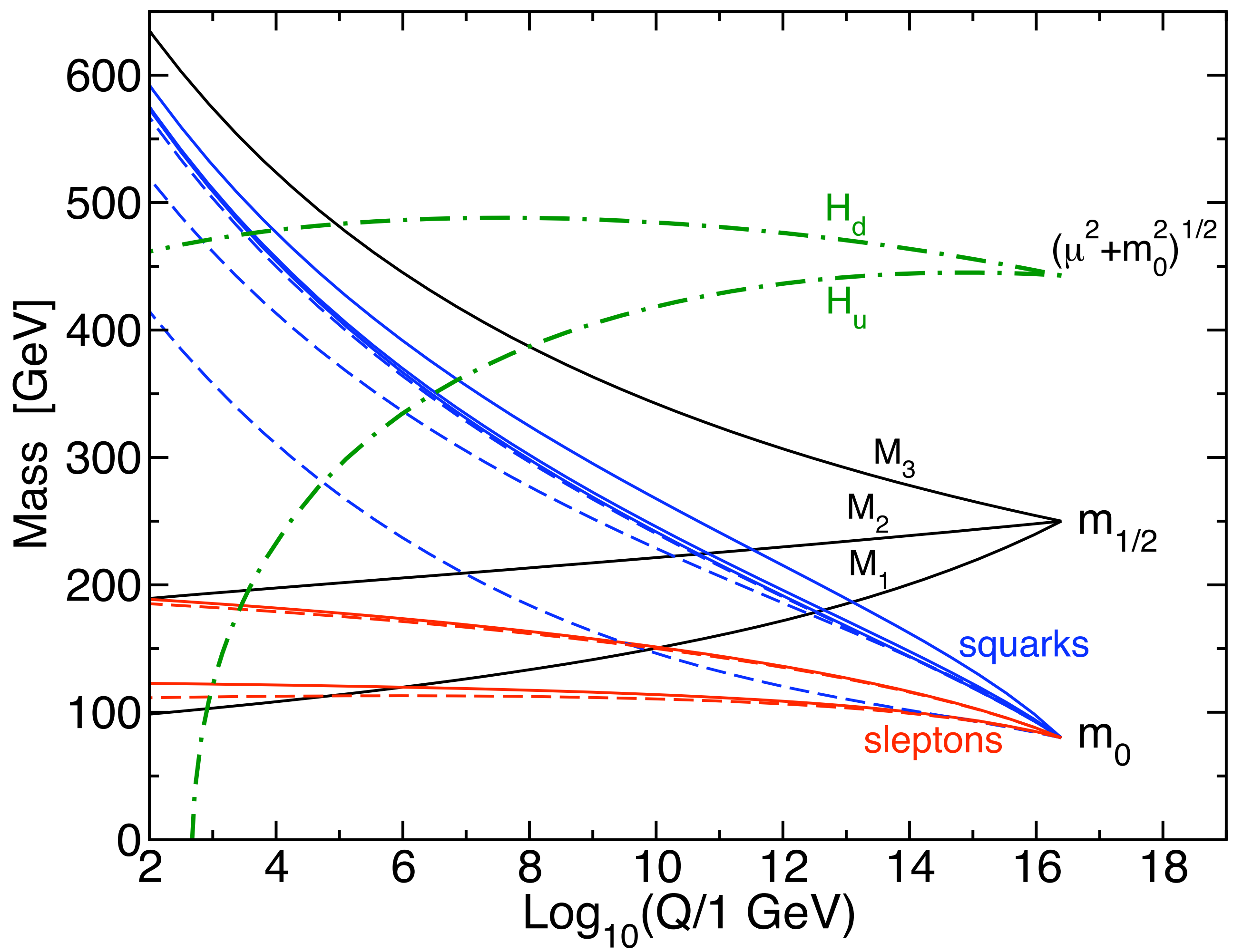
- Gravity mediation: non-renormalizable, suppressed by M_{Pl} by def.
  - SUSY breaking scale: Λ_S about 10^{11} GeV
  - $$m_{\tilde{q}} \sim m_{\tilde{\ell}} \sim M_{\text{gaugino}} \simeq \frac{\Lambda_S^2}{M_{\text{Pl}}} \sim 100(s)\ \text{GeV} - \ \text{TeV}$$
    - Follows from dimensional analysis.
    - Vanishes as $\Lambda_S \Rightarrow 0$, suppressed by M_{Pl}^{-1}.
  - Need Rernomalization Group Evolution to low energy to obtain physical masses.
  - Gravitino (spin 3/2 superpartner of the graviton)

$$m_{3/2} \sim \frac{\Lambda_S^2}{M_{\text{Pl}}}$$

gravitinoVery weakly coupled, ∝ M_{Pl}^{-1}

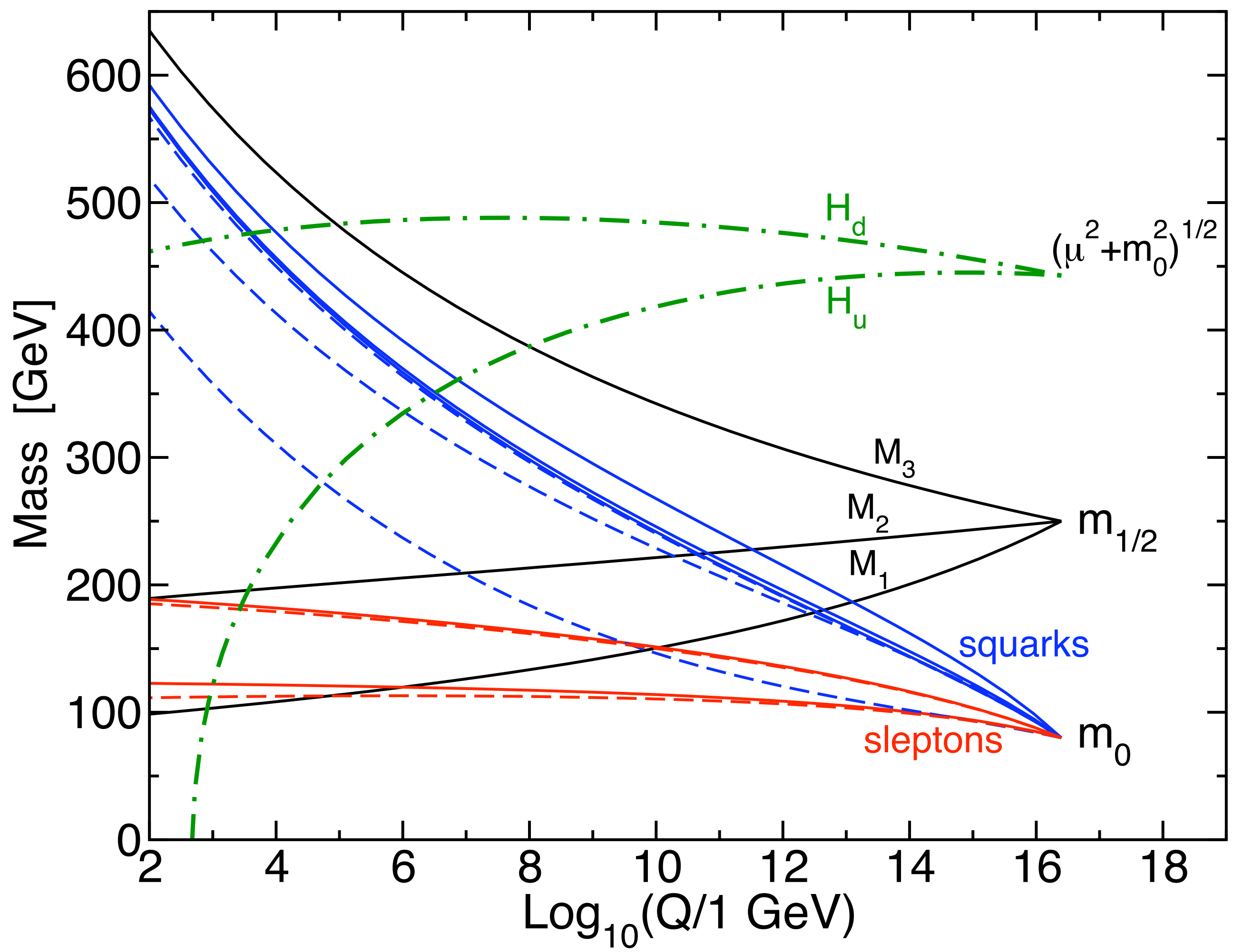
Not affecting collider signals

RG evolution



- RGE evolution down ⇒ physical masses we measure.
- Colored particles "run"s more.
  - Large, O(several), corrections.

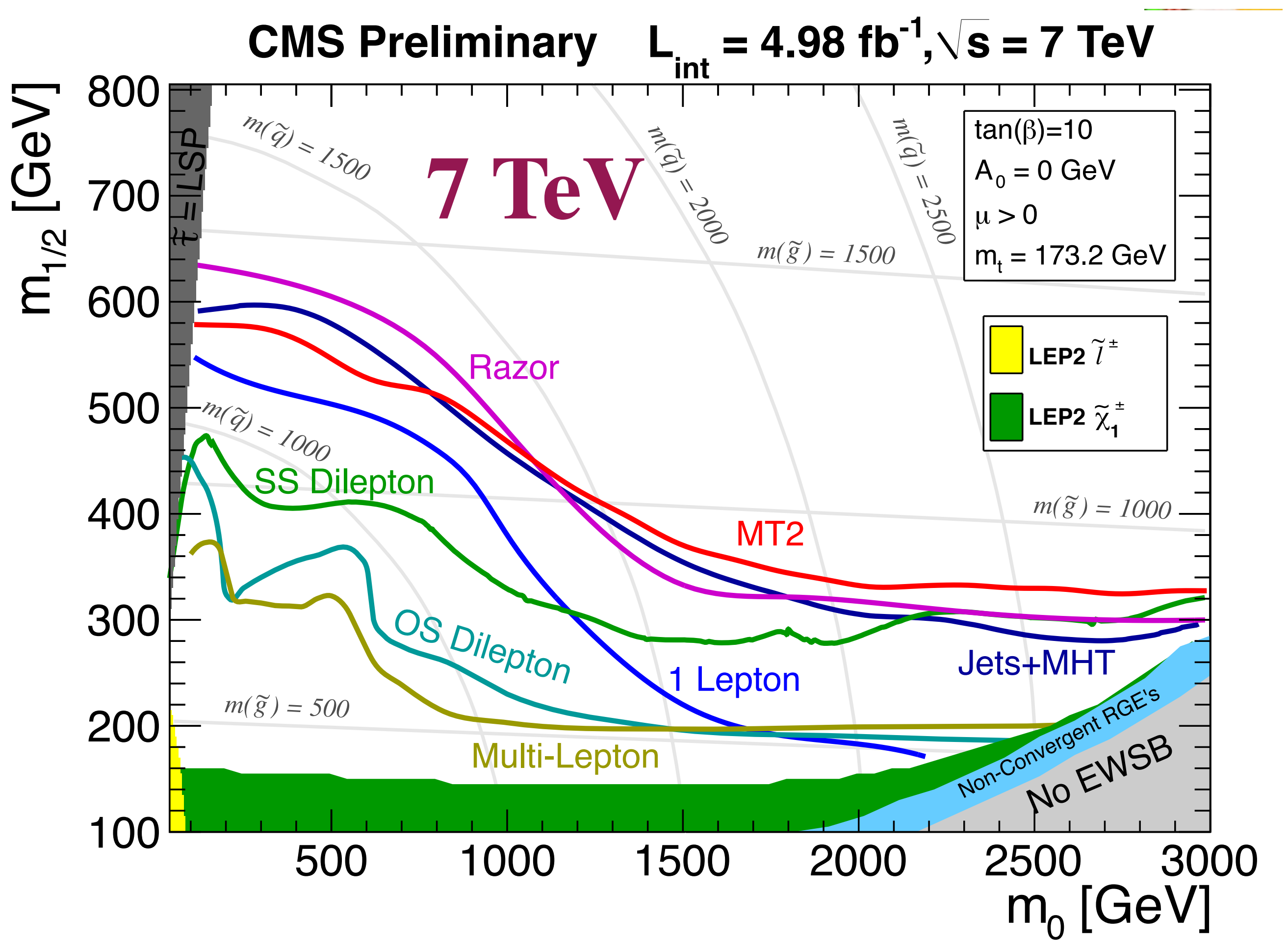
RG evolution



- Parameterizes full spectrum with 2 mass parameters, $m_{1/2}$ (common gaugino mass) and m_0 (common scalar mass).

- mSUGRA.

mSUGRA



- Useful, simple parameterization. Good for understanding basic features of SUSY signal.
  - Good for classroom demo.

- But I will bet this is not the model.

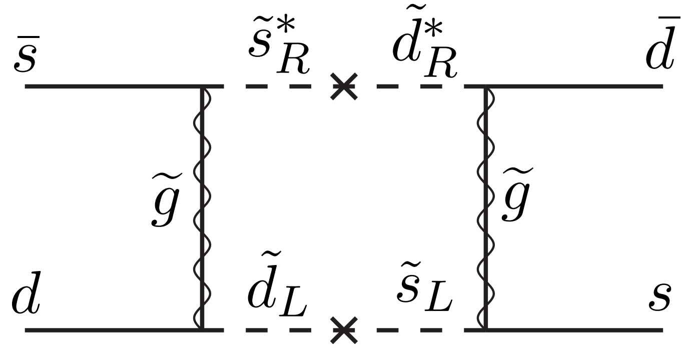
Pros and Cons

- Gravity exists, + SUSY $\Rightarrow$ supergravity. Necessary coupling to mediated SUSY breaking is always there.

- However, gravity does not know flavor (equivalence principle)
  - $-\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger$
  - soft mass m^2s are 3x3 matrices in flavor space

- Gravity mediation will generate off-diagonal term with the same size as the diagonal term.
  - Large flavor violation.

A serious problem (SUSY flovar).

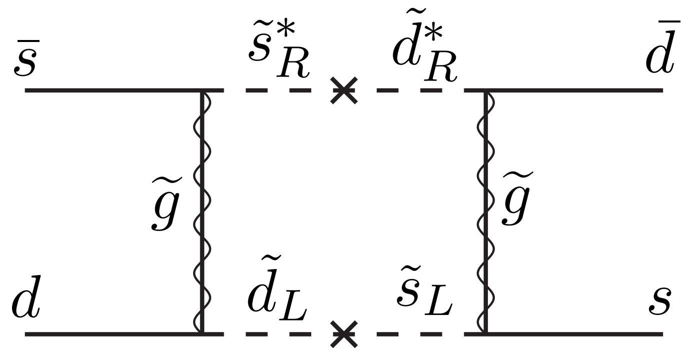


Kaon mixing

$$\frac{|\mathrm{Re}[m^2_{\tilde{s}^*_R \tilde{d}_R} m^2_{\tilde{s}^*_L \tilde{d}_L}]|^{1/2}}{m^2_{\tilde{q}}} < \left(\frac{m_{\tilde{q}}}{1000\ \mathrm{GeV}}\right) \times \begin{cases} 0.0016 & \text{for } m_{\tilde{g}} = 0.5 m_{\tilde{q}}, \\ 0.0020 & \text{for } m_{\tilde{g}} = m_{\tilde{q}}, \\ 0.0026 & \text{for } m_{\tilde{g}} = 2 m_{\tilde{q}}. \end{cases}$$

- Too heavy to be a natural theory.
- For viable gravity mediation, addition flavor symmetry (alignment) is necessary.

A serious problem (SUSY flovar).



Kaon mixing

$$\frac{|\mathrm{Re}[m^2_{\tilde{s}^*_R \tilde{d}_R} m^2_{\tilde{s}^*_L \tilde{d}_L}]|^{1/2}}{m^2_{\tilde{q}}} < \left(\frac{m_{\tilde{q}}}{1000\ \mathrm{GeV}}\right) \times \begin{cases} 0.0016 & \text{for } m_{\tilde{g}} = 0.5 m_{\tilde{q}}, \\ 0.0020 & \text{for } m_{\tilde{g}} = m_{\tilde{q}}, \\ 0.0026 & \text{for } m_{\tilde{g}} = 2 m_{\tilde{q}}. \end{cases}$$

~1 for gravity mediation

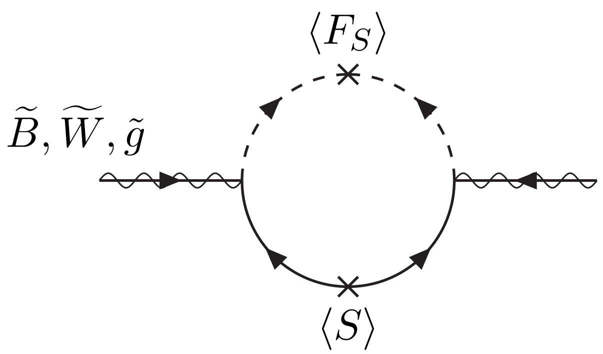
$$m_{\tilde{q}} > 100s\ \mathrm{TeV!}$$

- Too heavy to be a natural theory.
- For viable gravity mediation, addition flavor symmetry (alignment) is necessary.

Low scale mediation.

- In comparison with gravity mediation
  - Lower SUSY breaking scale.
  - Stronger coupling.
- Main attraction: new interaction may know about flavor.
- Best known example: gauge mediation.

Gauge mediation (loop induced)

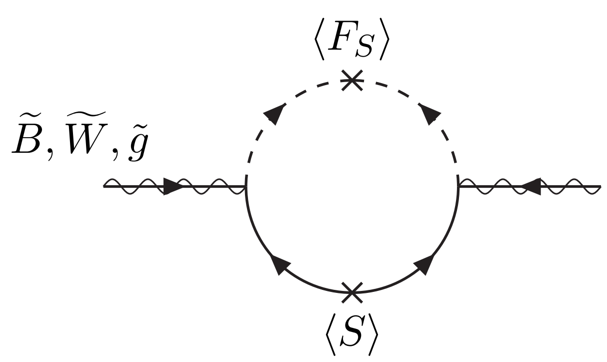


$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle}$$

S: messengers which feels SUSY breaking, with SM gauge couplings.

$F_S \approx (\Lambda_S$ = SUSY breaking scale$)^2$ ⇒ SUSY breaking order parameter.

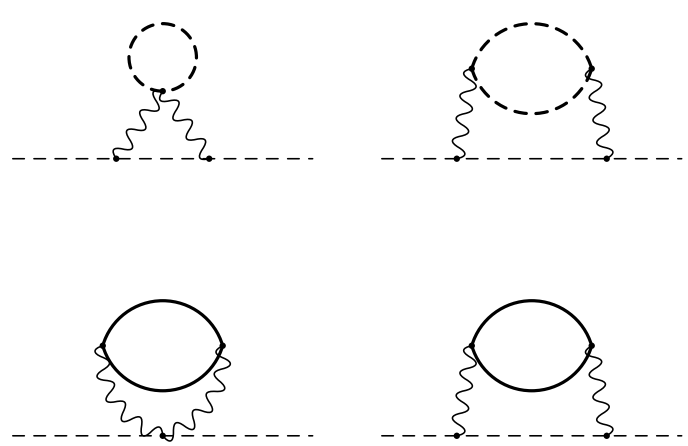
Gauge mediation (loop induced)



$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle}$$

S: messengers which feels SUSY breaking, with SM gauge couplings.

$F_S \approx (\Lambda_S$ = SUSY breaking scale$)^2 \Rightarrow$ SUSY breaking order parameter.



+ ....

$$m^2_{\text{scalar}} = \left(\frac{\alpha}{4\pi}\right)^2 M_S^2$$

Gauge mediation

$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle} \qquad m^2_{\rm scalar} = \left(\frac{\alpha}{4\pi}\right)^2 M_S^2$$

- $M_a \sim m_{scalar}$
- $M_S \sim$ 10 TeV $\Rightarrow M_a \sim m_{scalar} \sim$ TeV.
- Gravity mediation (also there), but subdominant if $F_S \approx (\Lambda_S)^2 \ll (10^{11}\ \mathrm{GeV})^2$.
- Gauge couplings, just like QED, can be flavor diagonal!!

Gravitino LSP

- Gravitino does not have gauge interactions. Its' mass is still determined by gauge mediation. Gravition is the LSP.

$$m_{3/2} \sim \frac{F_S}{M_{\rm Pl}} \ll M_{\rm gaugino,\ squark...}$$

- MSSM "LSP", such as a neutralino would be NLSP.

- NLSP decaying into gravitino
  - Could be long lived on collider time scale.

$$\Gamma(\widetilde{N}_1 \to \gamma \widetilde{G}) \; = \; 2 \times 10^{-3} \, \kappa_{1\gamma} \left(\frac{m_{\widetilde{N}_1}}{100 \text{ GeV}} \right)^5 \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}} \right)^{-4} \text{ eV}$$

$$d = 9.9 \times 10^{-3} \, \frac{1}{\kappa_{1\gamma}} \, (E^2/m^2_{\widetilde{N}_1} - 1)^{1/2} \left(\frac{m_{\widetilde{N}_1}}{100 \text{ GeV}} \right)^{-5} \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}} \right)^{4} \text{ cm}$$

Comments

- Typically assumed bino NLSP, with decay bino⇒photon+gravitino. But, this is not necessary.

  Any superpartner could be NLSP.

  General gauge mediation: Meade, Seiberg, Shih

- No flavor problem!

- Can be low scale, decoupled from unknown high scale physics (string compactification, etc.).

Comments

- Have to assume a more special structure.
  - Messenger sector feels SUSY breaking, also have SM gauge couplings.
  - Gauge coupling unification now needs to be arranged.
- Light Gravitino can not account for dark matter.
  - Other cosmological problems: light moduli...
- μ, B_μ problem.
- Having trouble with giving 125 GeV Higgs mass
  - Need additional structure.

Trying to be smart

- Many mediation mechanisms:
  - Anormaly mediation.
  - Gaugino mediation.
  - Mirage, R-symmetric, μ-driven, U(1)′, ...
- Many challenge: flavor (CP) problem, naturalness, experimental constraints.
- None of them is perfect. Some are getting quite complicated.
- Do we need to be smart? Are we lucky? Experiment will tell.