Soft R-Parity Violation

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arXiv : 1304.7004

LANL , Sep 26, 2013

The SUSY dilemma

The old belief :

SUSY solves the naturalness problm in a simple way

NATURAL & SIMPLE

The SUSY dilemma

Now...

Experimental result forces us to choose either

NATURAL OR SIMPLE

The SUSY dilemma

Now...

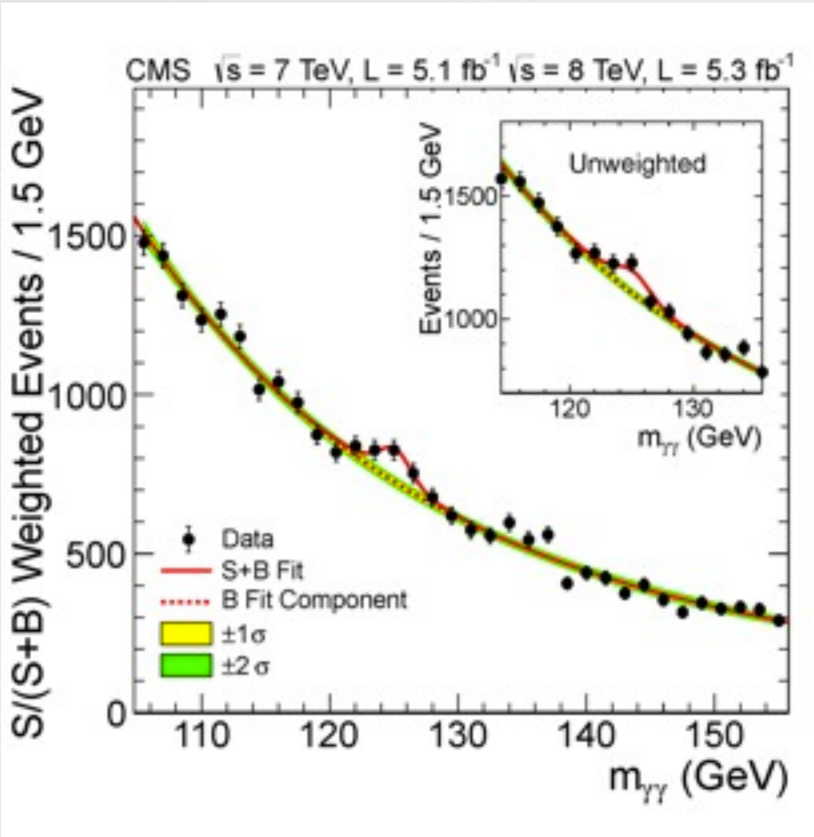
Experimental result forces us to choose either

NATURAL OR SIMPLE

focus on natural SUSY in this talk

The challenge on natural SUSY

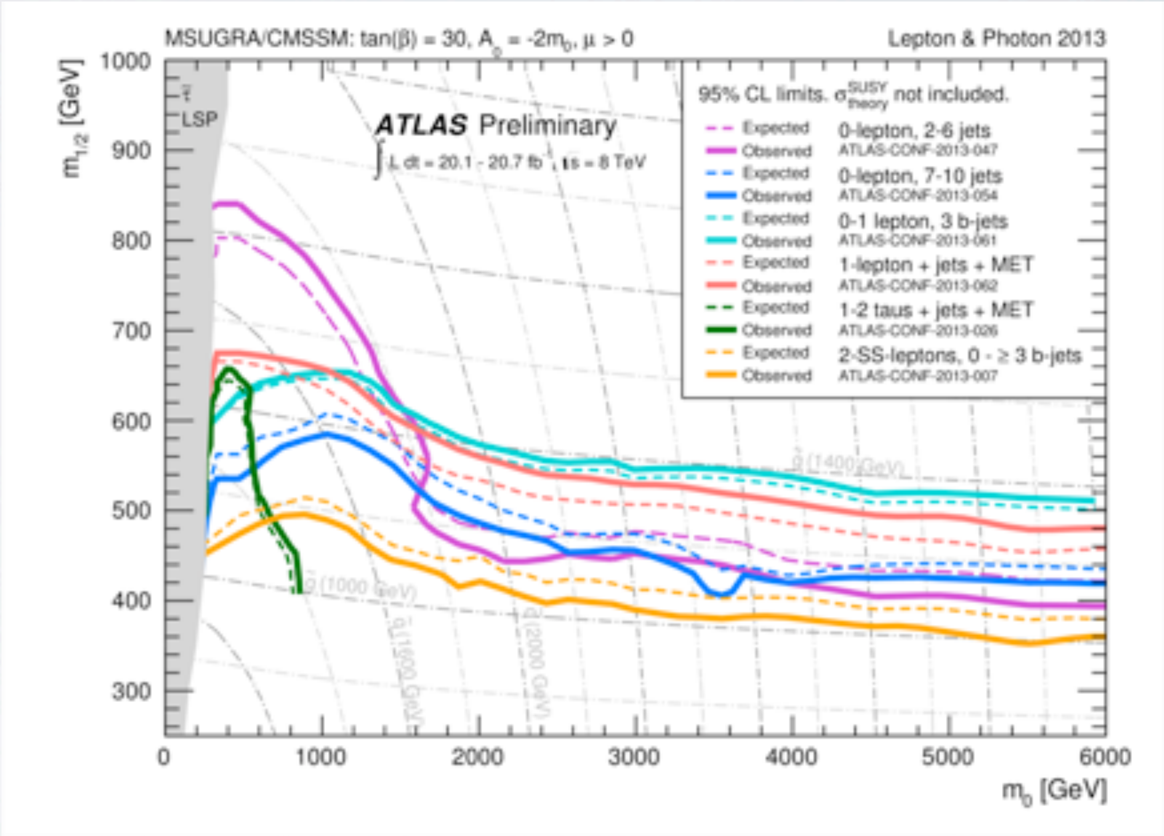
126 GeV Higgs



$$V \supset \frac{g^2}{8}(|H_u^0|^2 - |H_d^0|^2)^2$$

$$\Rightarrow m_h \simeq m_Z$$

bounds on the $\tilde{t}$ & $\tilde{g}$ masses



from missing energy searches

The challenge on natural SUSY

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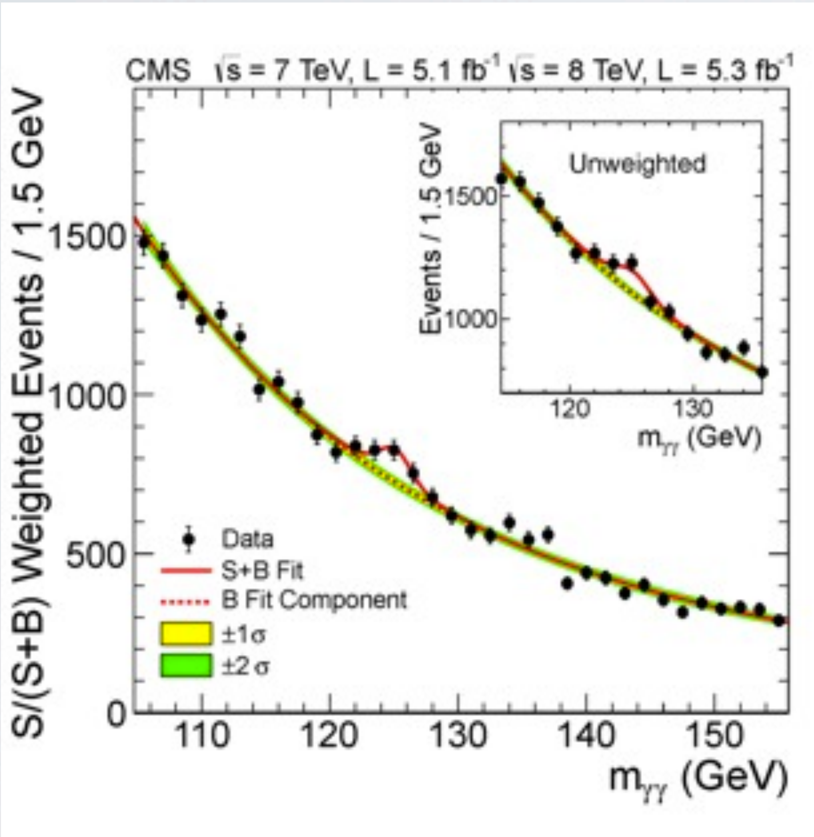

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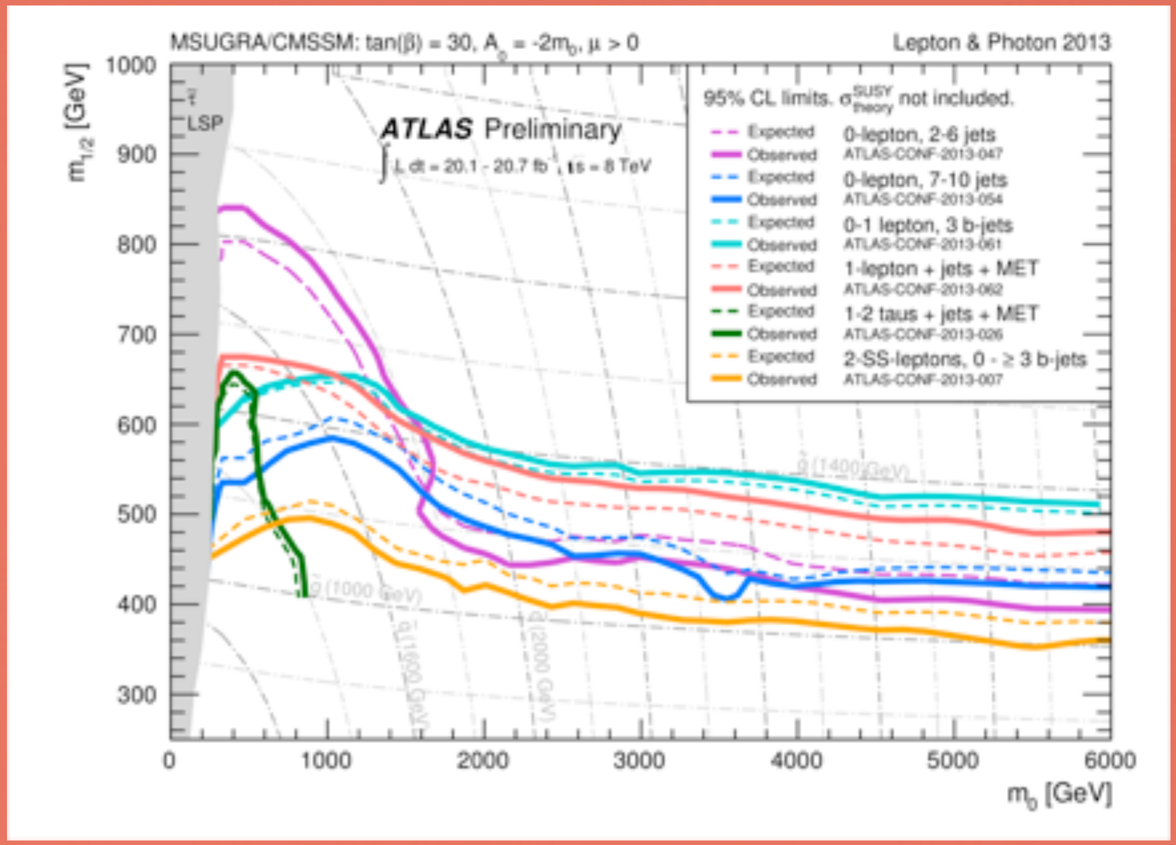
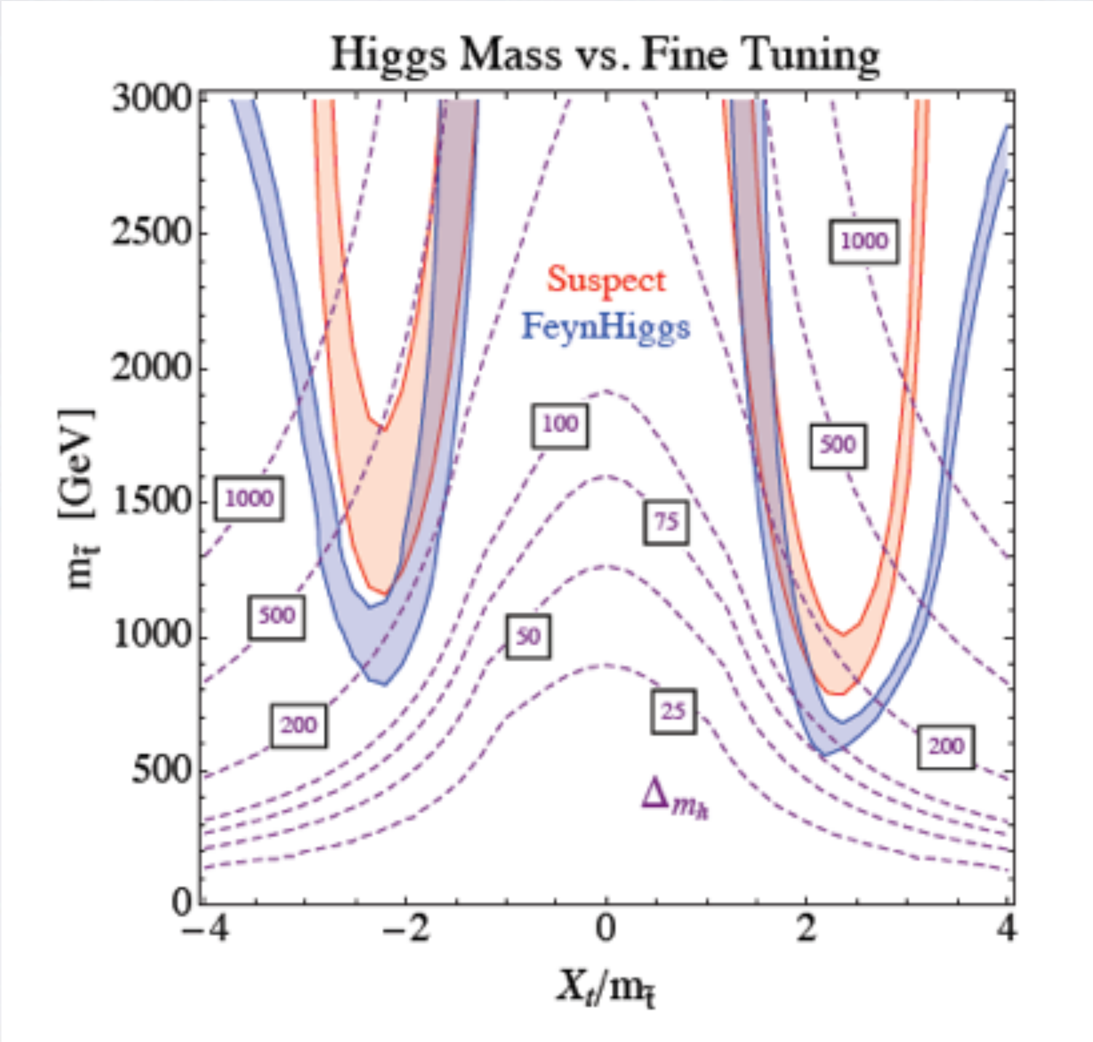


Try to relax bounds from direct searches

The challenge on natural SUSY

The amount of tuning



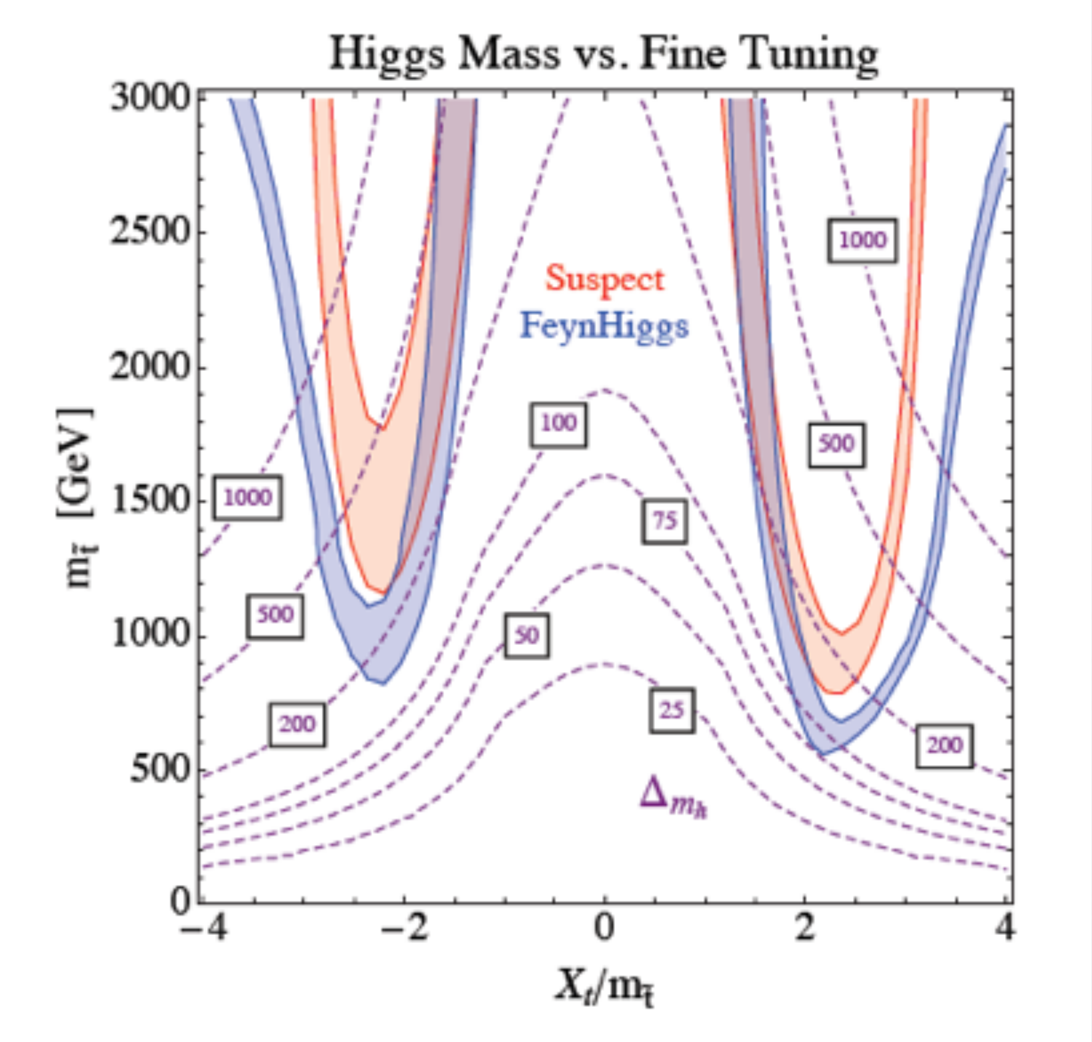
Hall, Pinner and Ruderman
(1112.2703)

Tuning from the stop & gluino

Two ways to relax the tuning :

change the radiative correction

change the collider constraint



Tuning from the stop & gluino

Two ways to relax the tuning :

change the radiative correction

Example: Supersoft SUSY

$$\delta m_{H_u}^2 = -\frac{3\,y_t^2}{8\pi^2} m_{\tilde{t}}^2 \log \frac{m_{\tilde{g}}^2}{m_{\tilde{t}}^2}$$

change the collider constraint

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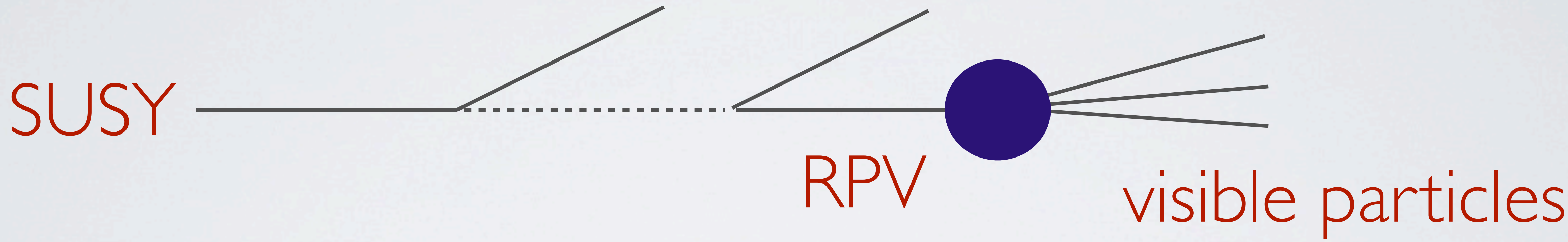
change the collider constraint

Example:

- compressed spectrum
- more cascade decays
- **R-parity violation**

R-parity violation (RPV)

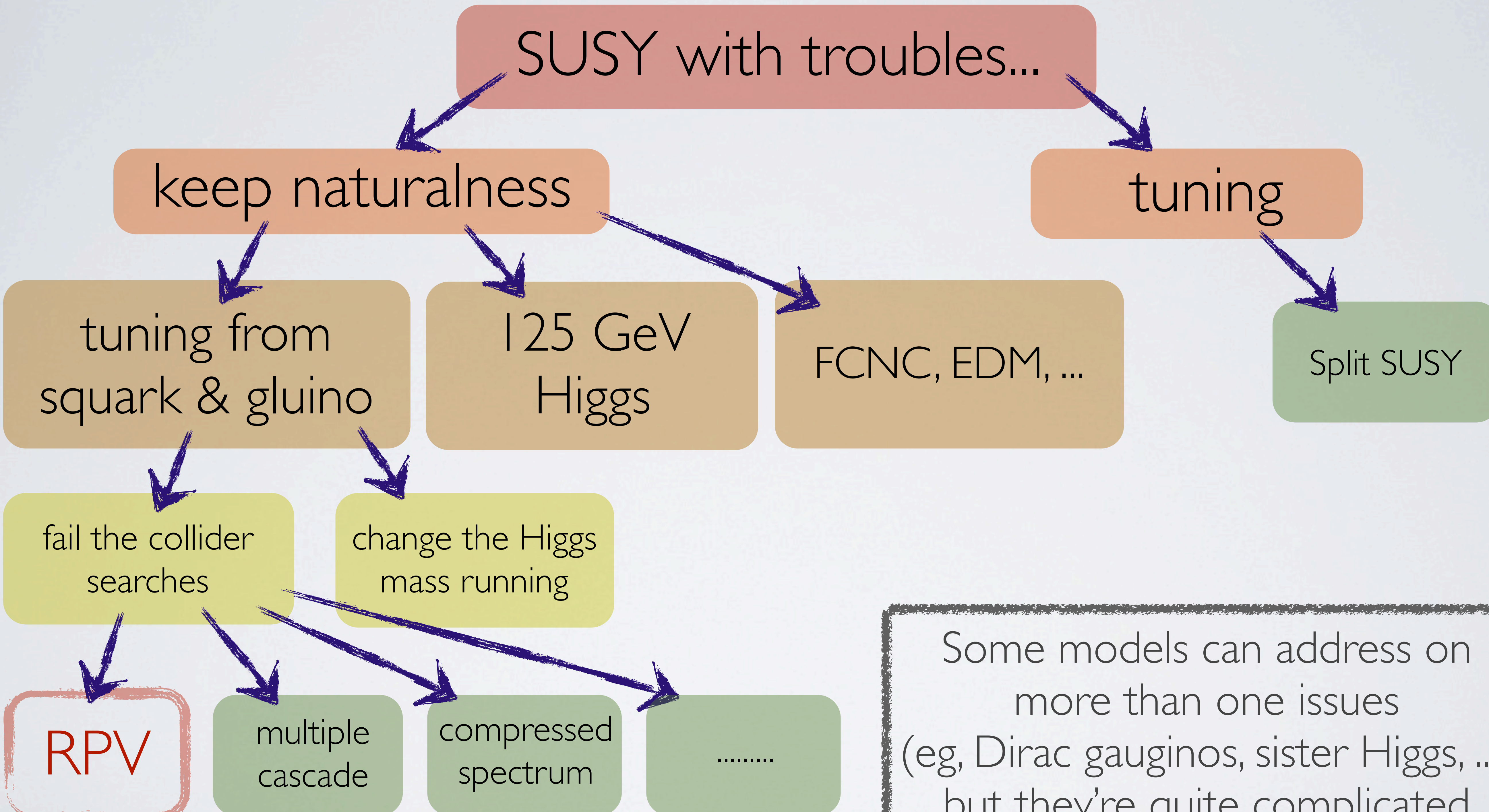
The LSP decay fails the MET searches



However, there are stringent flavor constraints!

proton decay , neutron/anti-neutron oscillations ,
di-nucleon decay , FCNC

RPV in the natural forest



Some models can address on more than one issues (eg, Dirac gauginos, sister Higgs, ...) but they're quite complicated

RPV in the natural forest

SUSY with troubles...

keep naturalness

tuning

tuning from squark & gluino

125 GeV Higgs

FCNC, EDM, ...

Split SUSY

fail the collider searches

RPV

mul... casc...

To solve the whole naturalness issue,

We better keep the RPV model simple!

- simple structure
- easy to be embedded into a larger framework

Models of RPV

The RPV couplings

supersymmetric terms

$$W_{RPV} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} Q_i L_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \mu_{L_i} L_i H_u$$

soft breaking terms

$$\mathcal{L}_{\not{SUSY}} \supset \frac{\mathcal{A}_{ijk}}{2} \widetilde{L}_i \widetilde{L}_j \widetilde{\bar{E}}_k + \mathcal{A}'_{ijk} \widetilde{Q}_i \widetilde{L}_j \widetilde{\bar{D}}_k + \underline{\frac{\mathcal{A}''_{ijk}}{2} \widetilde{\bar{U}}_i \widetilde{\bar{D}}_j \widetilde{\bar{D}}_k} + \mathcal{B}_i \widetilde{L}_i H_u + h.c.$$

It's easier to have an RPV model that only violates B-number

Leptonic RPV

$$W_{RPV} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} Q_i L_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \mu_{L_i} L_i H_u$$

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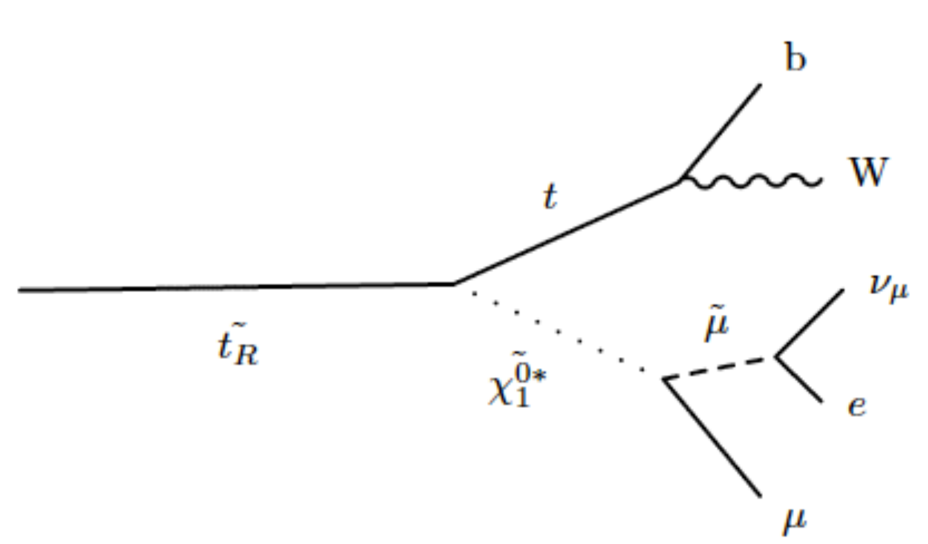
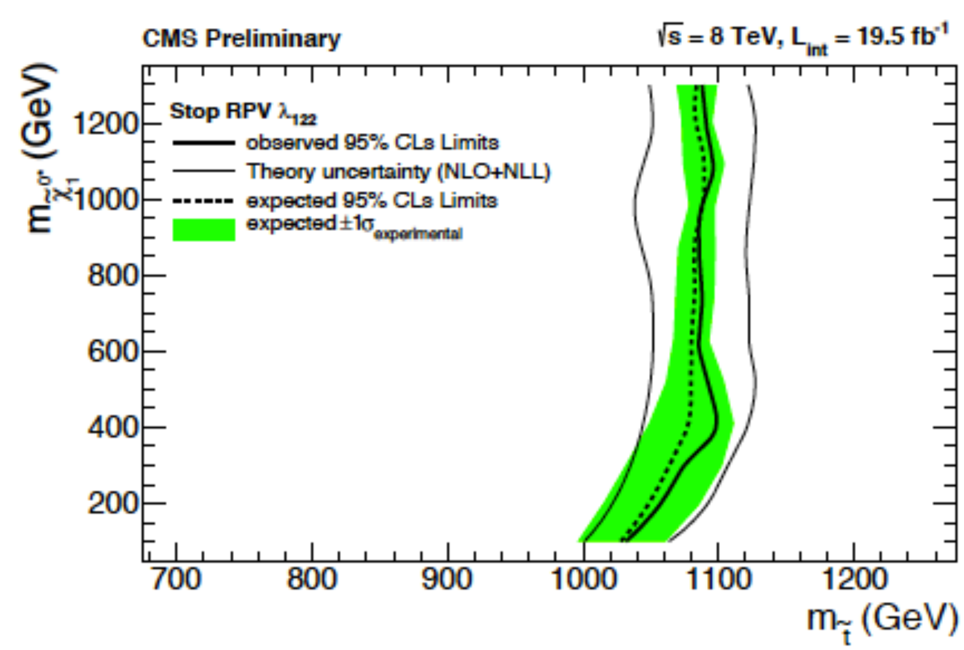
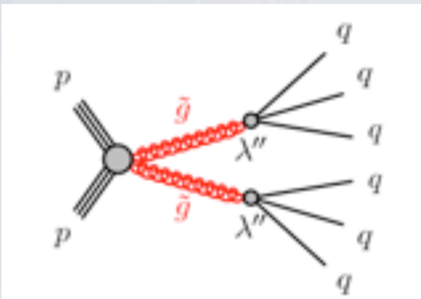




leptonic RPV is more constrained

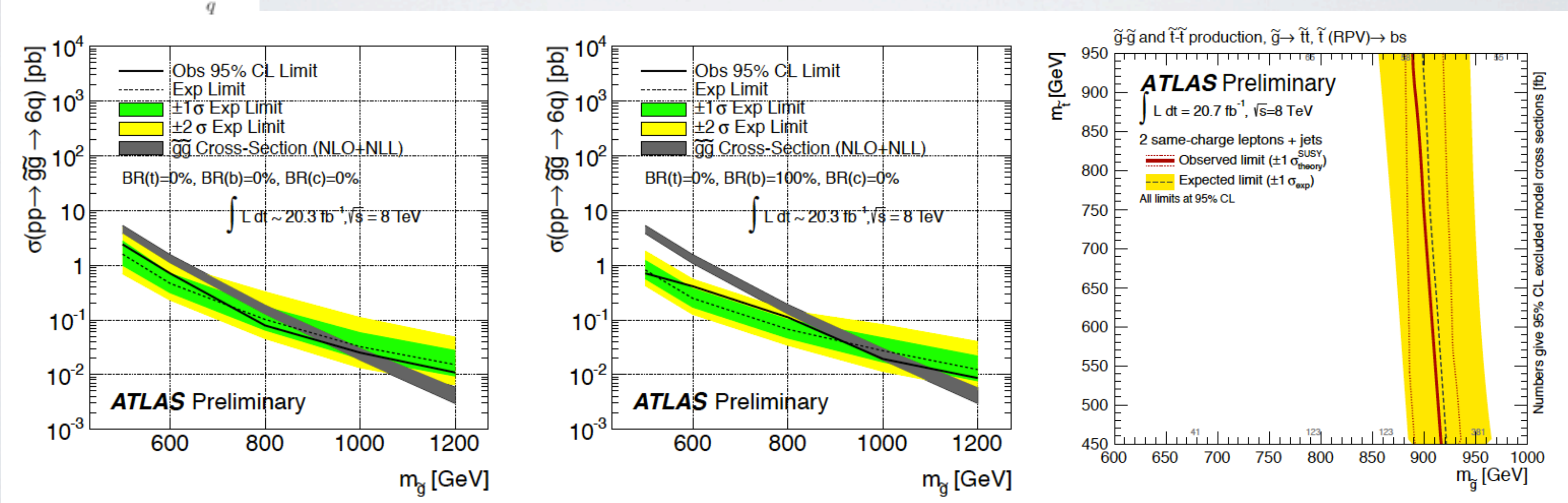
RPV through the baryon portal

$$W \supset \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \qquad \mathcal{L} \supset \mathcal{A}''_{ijk} \tilde{\bar{U}}_i \tilde{\bar{D}}_j \tilde{\bar{D}}_k$$



6-jet search

SSDL + b-jet



$$m_{\tilde{g}} > 900\,\mathrm{GeV}$$

Upper & lower bounds for $\lambda''_{u_i d_j d_k}$

With no L-number violation, we need $\lambda''_{u_i d_j d_k} \leq 10^{-7}$ to satisfy flavor constraints (the statement depends on flavor structure)

Also, we need $\lambda''_{u_i d_j d_k} \geq 10^{-7}$ for the squark decay to be prompt

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$$\lambda''_{u_i d_j d_k} \sim 10^{-7}$$

The rough size of baryonic RPV couplings

Models with UDD

Example:

Minimal Flavor Violation

Nikolidakis and Smith (0710.3129)
Csaki, Grossman and Heidenreich (1302.2146)

constrains all flavor violating processes with the appropriate Yukawa couplings, which also determine the size and scope of allowed RPV interactions.

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$	$\mathbb{Z}_2^R$
(QQQ)	1	$\square\square\square$	1/2	1	0	−
$(QQ)Q$	8	$\square$	1/2	1	0	−
$(Y_u\bar{u})(Y_u\bar{u})(Y_d\bar{d})$	$8 \oplus 1$	1	−1	−1	0	−
$(Y_u\bar{u})(Y_d\bar{d})(Y_d\bar{d})$	$8 \oplus 1$	1	0	−1	0	−
$\det \bar{u}$	1	1	−2	−1	0	−
$\det \bar{d}$	1	1	1	−1	0	−
$QY_u\bar{u}$	$8 \oplus 1$	$\square$	−1/2	0	0	+
$QY_d\bar{d}$	$8 \oplus 1$	$\square$	1/2	0	0	+
$LY_e\bar{e}$	1	$\square$	1/2	0	0	+
H_u	1	$\square$	1/2	0	0	+
H_d	1	$\square$	−1/2	0	0	+

$$W \supset Y_{u_i} Y_{d_j} Y_{d_k} \bar{U}_i \bar{D}_j \bar{D}_k$$

The UV-completion can be challenging

Krnjaic and Stolarski (1212.4860)
Csaki and Heidenreich (1302.0004)

General requirements

To obtain a small but non-zero $\lambda''_{udd} \sim 10^{-7}$, we need

- a symmetry that forbids the RPV couplings
- breaking of the symmetry
- some mediation that suppresses the λ''_{udd}

There are many other things we want beside naturalness:

SUSY breaking, dark matter, Higgs mass, ...

Are we going to include different models for each of them?

Soft RPV

Question:

given a SUSY breaking model, what's the easiest way to embed a baryonic RPV in it?

Soft RPV model

Generate RPV couplings through the SUSY breaking soft terms

Motivations

embed RPV into a SUSY breaking setup,

make the model more economic

another example: dynamical RPV by C. Csaki, E. Kuflik and T. Volansky (1309.5957)

A SoftRPV model needs...

- a symmetry G that forbids the supersymmetric RPV couplings
- G-breaking by SUSY breaking soft terms in a hidden sector
- mediation of the G-breaking effect to visible sector

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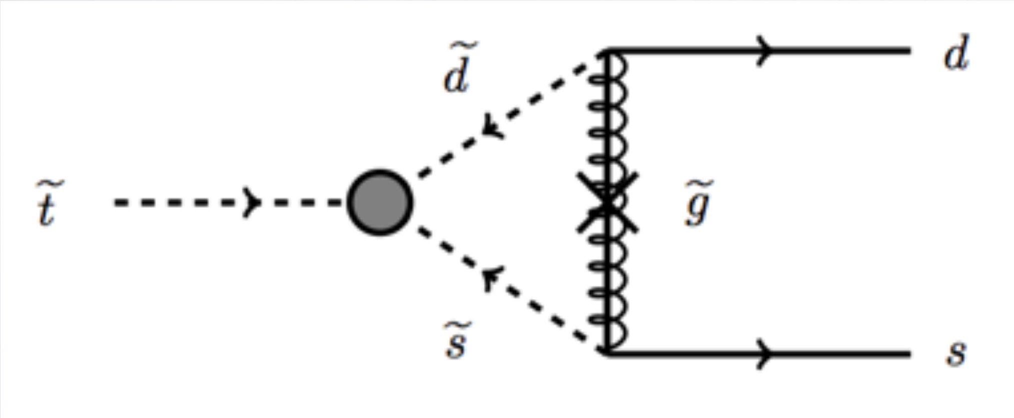
$$\mathcal{A}_{u_i d_j d_k} \tilde{\bar{U}}_i \tilde{\bar{D}}_j \tilde{\bar{D}}_k$$



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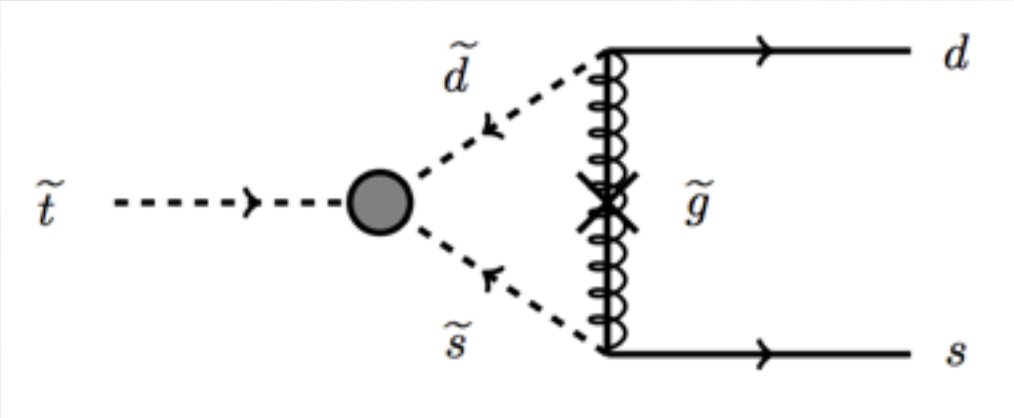

Naively, $\mathcal{A}_{u_i d_j d_k} \simeq \mathcal{A}_{soft}$

but $\lambda''_{udd} \simeq \frac{g_s^2}{16\,\pi^2} \frac{\mathcal{A}_{soft}}{m_{\tilde{g}}} \simeq 10^{-2}$

forbidden by L- or B-violating constraints

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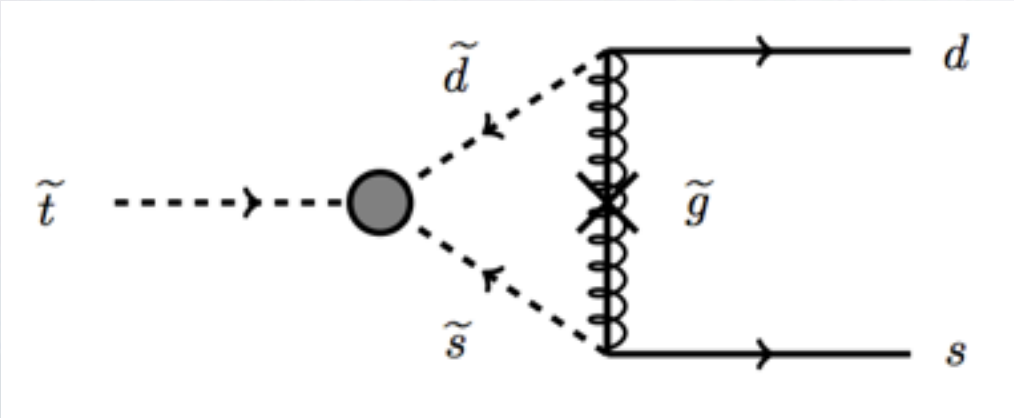

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A Gauge-Mediation Example

In this example

embed RPV in a GM setup

use R-symmetry to forbid the supersymmetric RPV terms

gravitino serves as a good dark matter candidate

no extra mass scales or small couplings need to be put in by hand

$$\lambda''_{udd} \sim \frac{g_s^2}{16\,\pi^2}\frac{m_{soft}}{\sqrt{F}}$$

To forbid the supersymmetric RPV

use the R-symmetry to forbid the RPV couplings

assign

$$R[Q,\, \bar{U},\, \bar{D}] = 1, \quad R[L] = 4/3, \quad R[\bar{E}] = 2/3, \quad R[H_u,\, H_d] = 0$$

$$W_{RPV} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} Q_i L_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \mu_{L_i} L_i H_u$$

the fractional R-charges are used to
forbid the generation of lepton-related operators

Breaking & mediation

Gauge mediation model

~~SUSY~~

R-symmetry

$X \ \Sigma \ \bar{\Sigma}$

soft R-breaking sector

$\bar{U} \quad \bar{D}$

$Q \ L \ \bar{E} \ H_u \ H_d$

visible sector

No RPV couplings

Breaking & mediation

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Breaking & mediation

Gauge mediation model

~~SUSY~~

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soft R-breaking sector

~~R-symmetry~~

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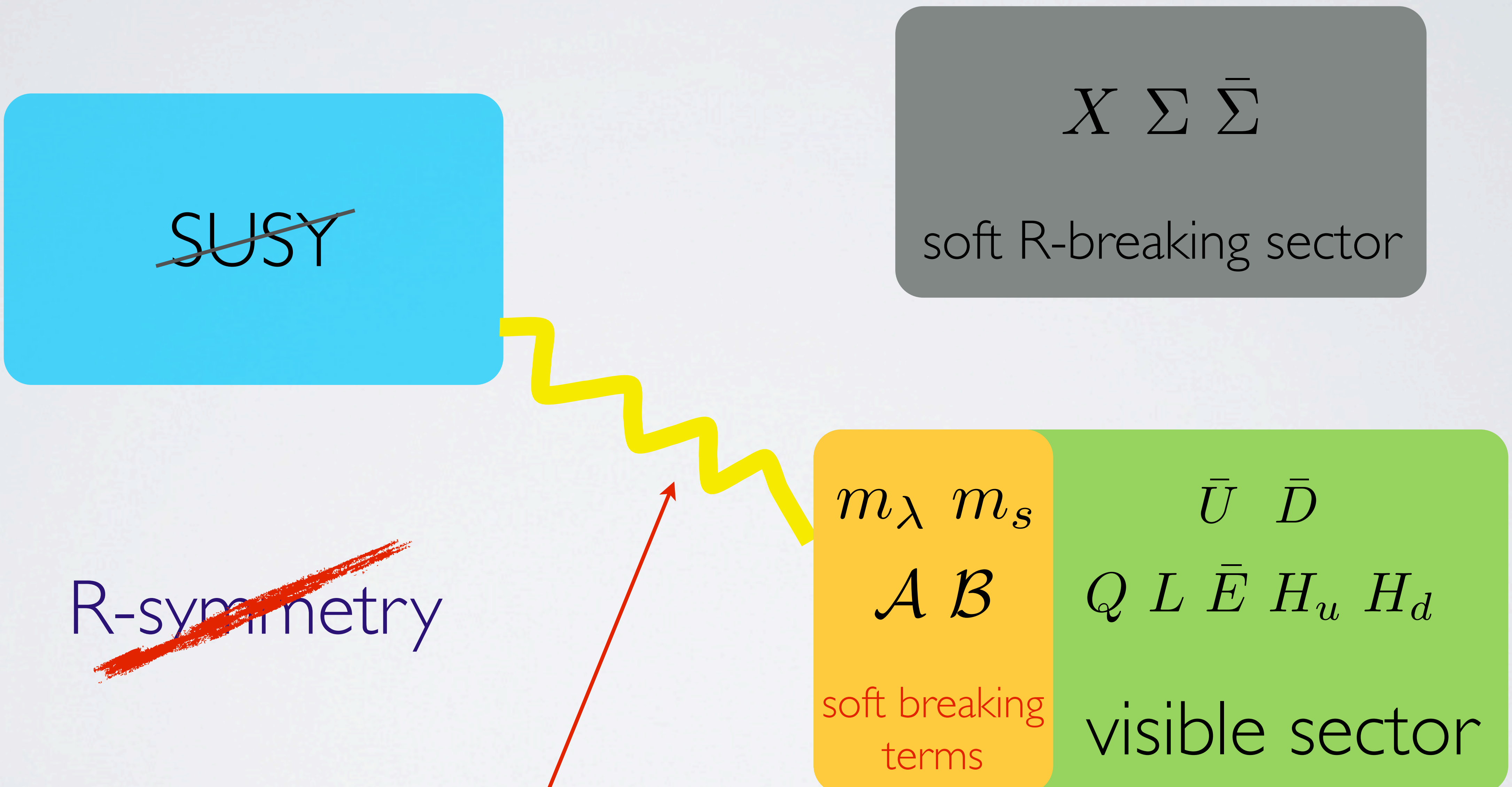
visible sector

No RPV couplings

Breaking & mediation

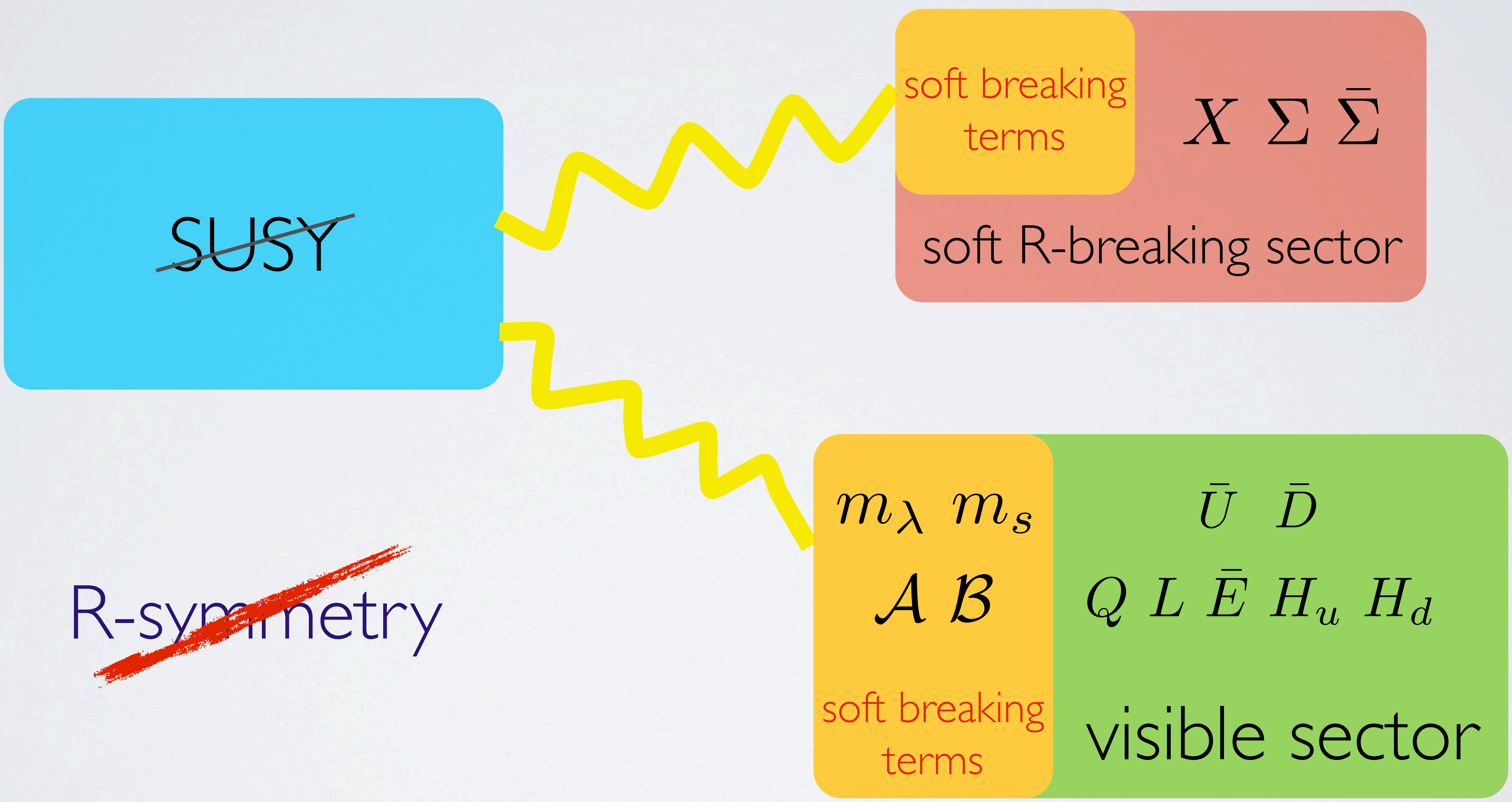
Gauge mediation model



No B- or L-violation, still no RPV couplings

Breaking & mediation

Soft RPV



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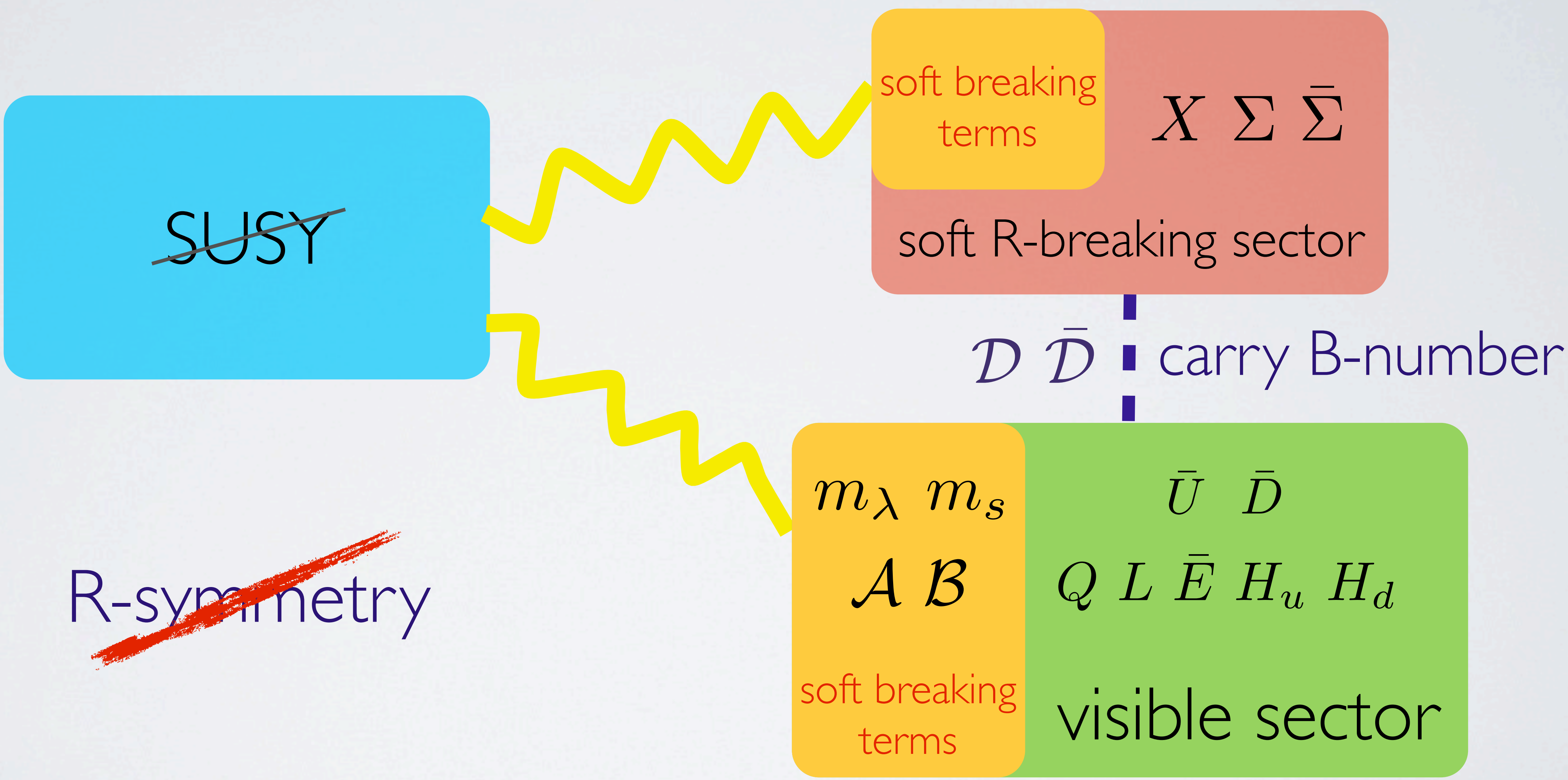

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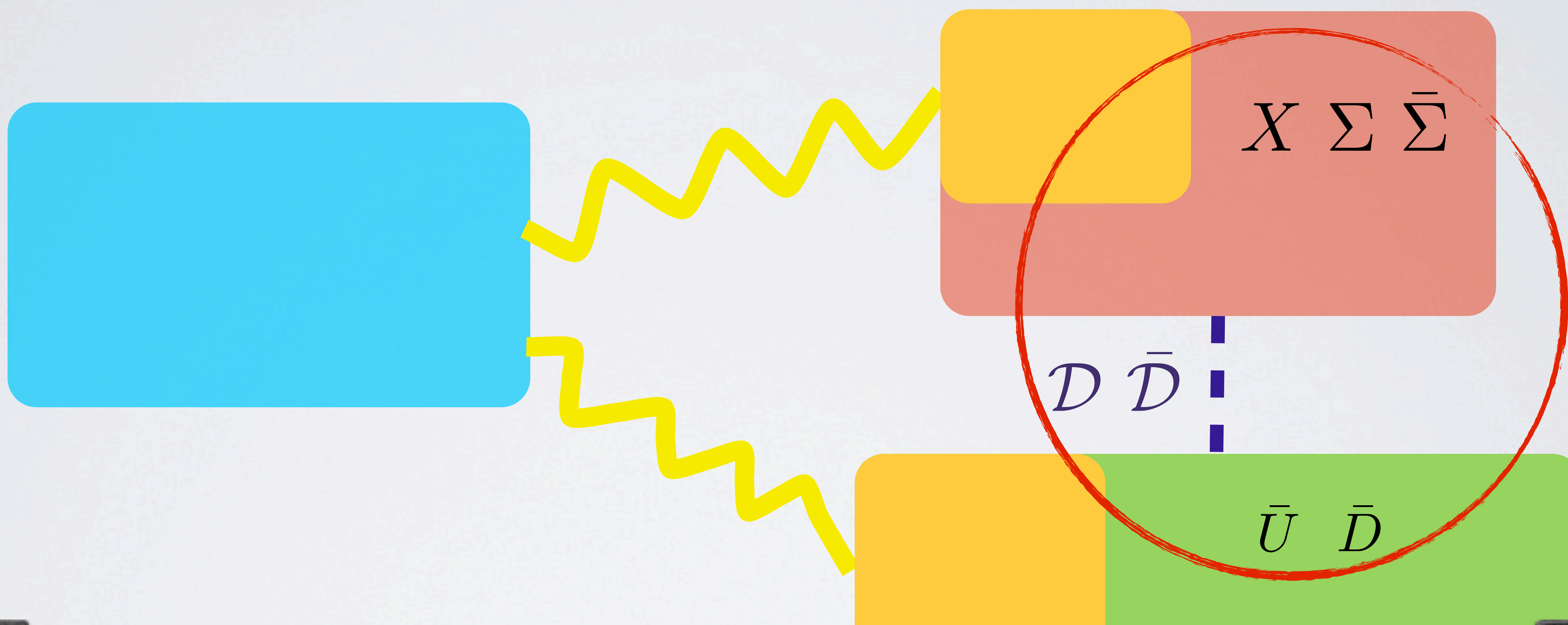


the potential $W \supset \bar{U}\bar{D}\bar{\mathcal{D}} + X\mathcal{D}\bar{D} + X\Sigma\bar{\Sigma} + M_{\mathcal{D}}\bar{\mathcal{D}}\mathcal{D}$
mediates the B-violation (induced by the R-symm breaking) to the visible sector

The UDD A-term

	$SU(3)_c$	$U(1)_Y$	$U(1)_H$	R
$\bar{U}$	$\bar{3}$	$-2/3$	0	1
$\bar{D}$	$\bar{3}$	$1/3$	0	1
$\bar{\mathscr{D}}$	$\bar{3}$	$1/3$	0	0
$\mathscr{D}$	3	$-1/3$	0	2
X	1	0	0	-1
Σ	1	0	1	$3/2$
$\bar{\Sigma}$	1	0	-1	$3/2$

$$W \supset \bar{U}\bar{D}\bar{\mathcal{D}} + X\mathcal{D}\bar{D} + X\Sigma\bar{\Sigma} + M_{\mathcal{D}}\bar{\mathcal{D}}\mathcal{D}$$

integrating out the heavy mediator

$$W \supset \frac{\bar{U}\bar{D}\bar{D}}{M_{\mathcal{D}}} X + X\Sigma\bar{\Sigma}$$

$\langle X \rangle = 0$, the RPV coupling only comes from the A-term

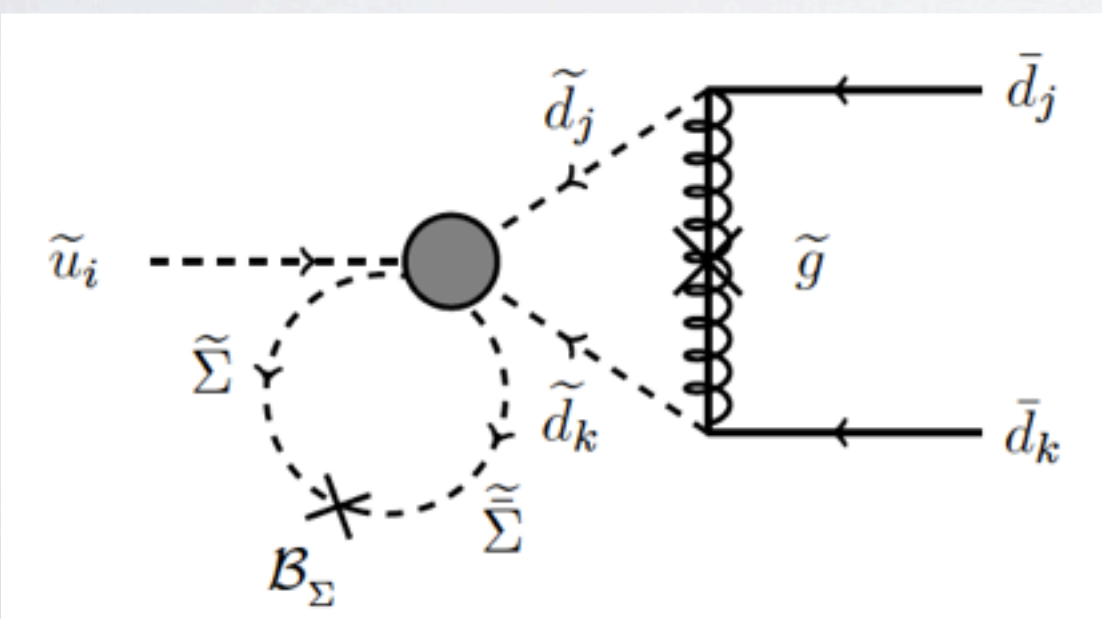
$$\mathcal{L}_{RPV} = \frac{\tilde{\bar{U}}\tilde{\bar{D}}\tilde{\bar{D}}}{M_{\mathcal{D}}}(\tilde{\Sigma}\tilde{\bar{\Sigma}})^*$$

The UDD A-term

$$\mathcal{L}_{RPV} = \kappa_{i[j}\kappa^{'}_{k]}\epsilon^{abc}\,\frac{\tilde{\bar{U}}^i_a\,\tilde{\bar{D}}^j_b\,\tilde{\bar{D}}^k_c}{M_{\mathcal{D}}}(\tilde{\Sigma}\tilde{\bar{\Sigma}})^*$$

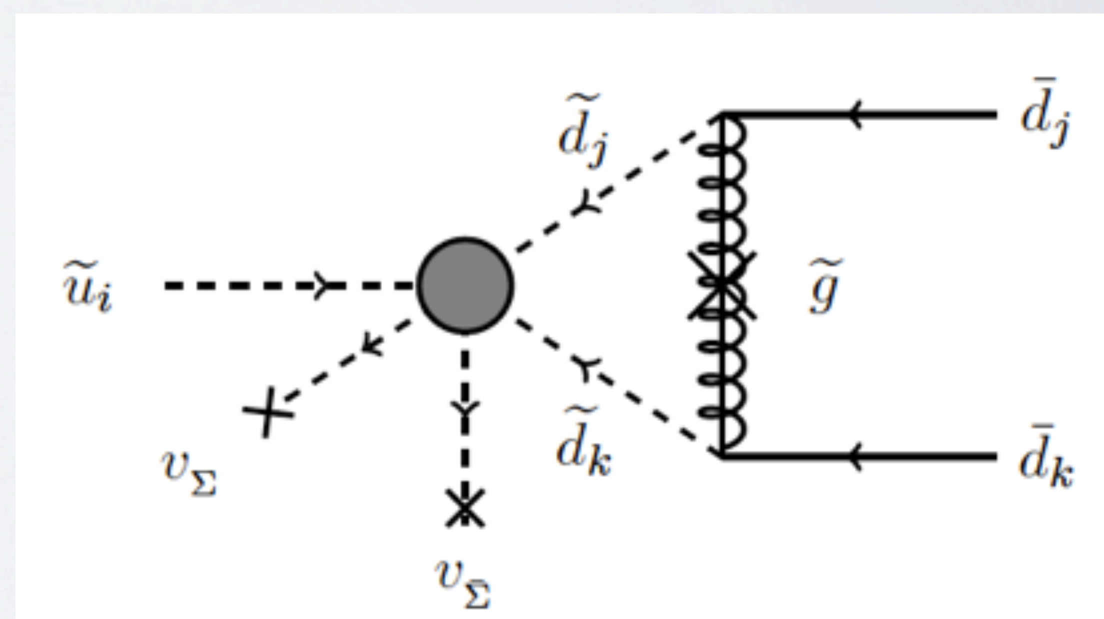
R-breaking B-term

$$\mathcal{L} \subset \mathcal{B}_{\Sigma}\,\tilde{\Sigma}\tilde{\bar{\Sigma}}$$



Radiatively induced VEV

$$\langle\tilde{\Sigma}\tilde{\bar{\Sigma}}\rangle \simeq m^2_{soft}$$

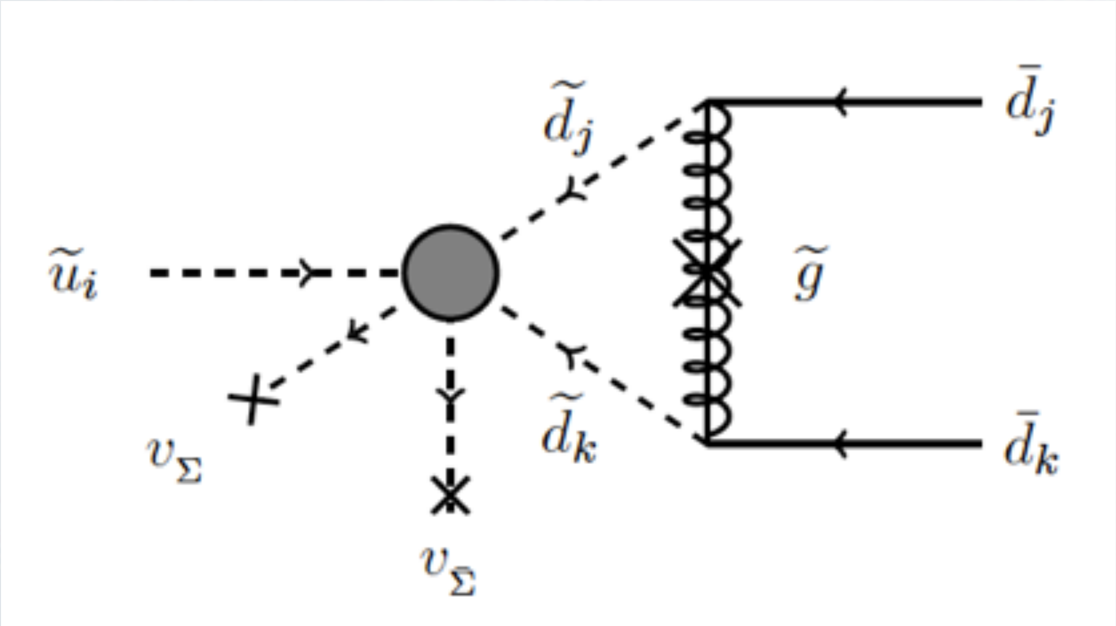


The $\langle\Sigma\rangle$ model

$$\mathcal{L}_{RPV} = \frac{\bar{\tilde{U}}\bar{\tilde{D}}\bar{\tilde{D}}}{M_{\mathcal{D}}}(\tilde{\Sigma}\bar{\tilde{\Sigma}})^* + \boxed{V(\tilde{\Sigma},\bar{\tilde{\Sigma}})}$$

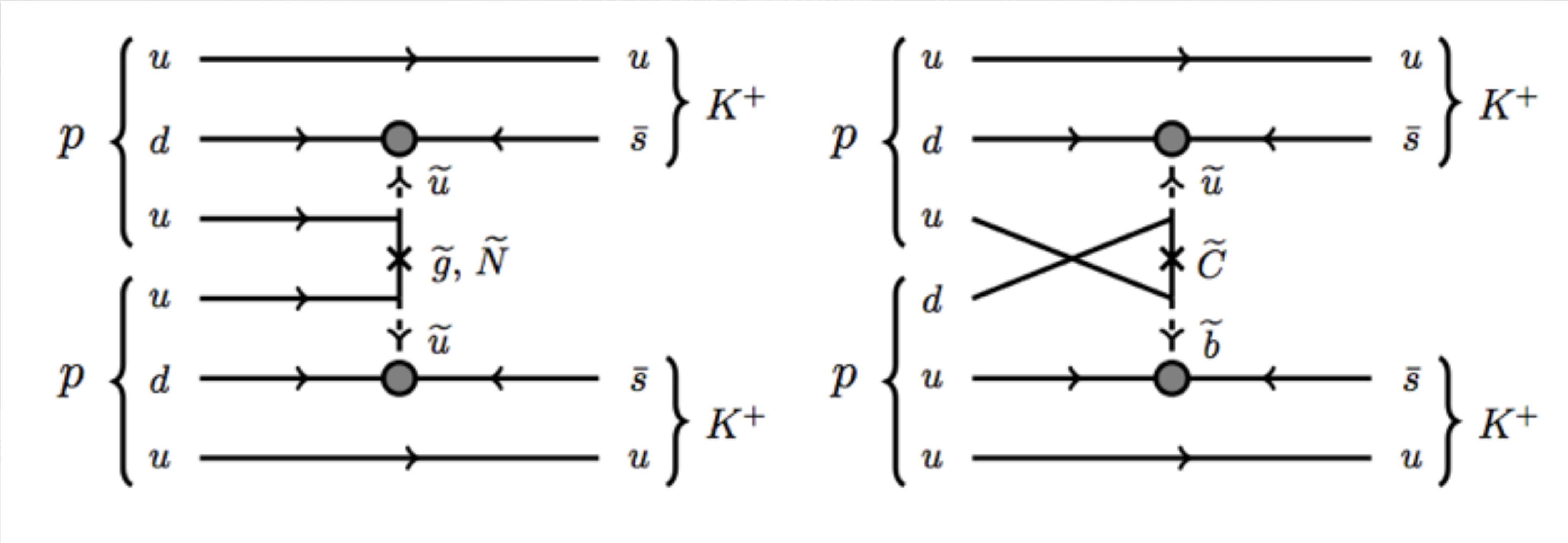
when Σ gets a tachyonic mass (assume the same mass for simplicity)

$$V(\tilde{\Sigma},\bar{\tilde{\Sigma}}) = -m_{\Sigma}^2(|\tilde{\Sigma}|^2 + |\bar{\tilde{\Sigma}}|^2) + \frac{g_H^2}{2}\left(|\tilde{\Sigma}| - |\bar{\tilde{\Sigma}}|^2\right)^2 + \eta^2\left(|\tilde{\Sigma}\bar{\tilde{\Sigma}}|^2 + |\tilde{X}\tilde{\Sigma}|^2 + |\tilde{X}\bar{\tilde{\Sigma}}|^2\right)$$



$$\lambda'' \simeq \frac{\alpha_s}{8\,\pi}\frac{v_\Sigma^2}{M_{\mathcal{D}}\,M_{\tilde{g}}}$$

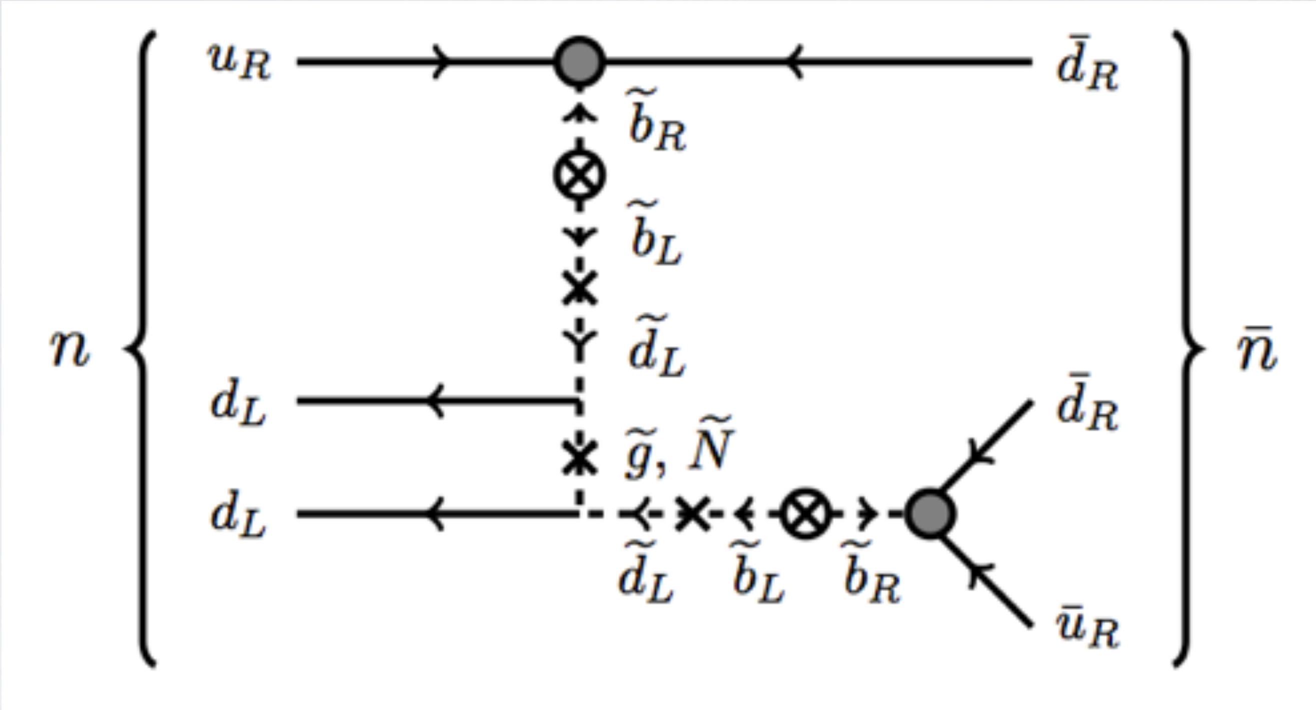
Di-nucleon decay



$$\Gamma_{pp\to KK} \sim \rho_N \frac{128\,\pi\,\alpha_s^2\,\Lambda^{10}}{m_p^2\,m_{\tilde{u}}^8\,M_{\tilde{g}}^2}\,(\lambda''_{uds})^2$$

$$\lambda''_{uds} \lesssim 2.5\times 10^{-7} \left(\frac{150\,\mathrm{MeV}}{\Lambda}\right)^{5/2} \left(\frac{M_{\tilde{g}}}{800\,\mathrm{GeV}}\right)^{1/2} \left(\frac{m_{\tilde{u}}}{500\,\mathrm{GeV}}\right)^{2}$$

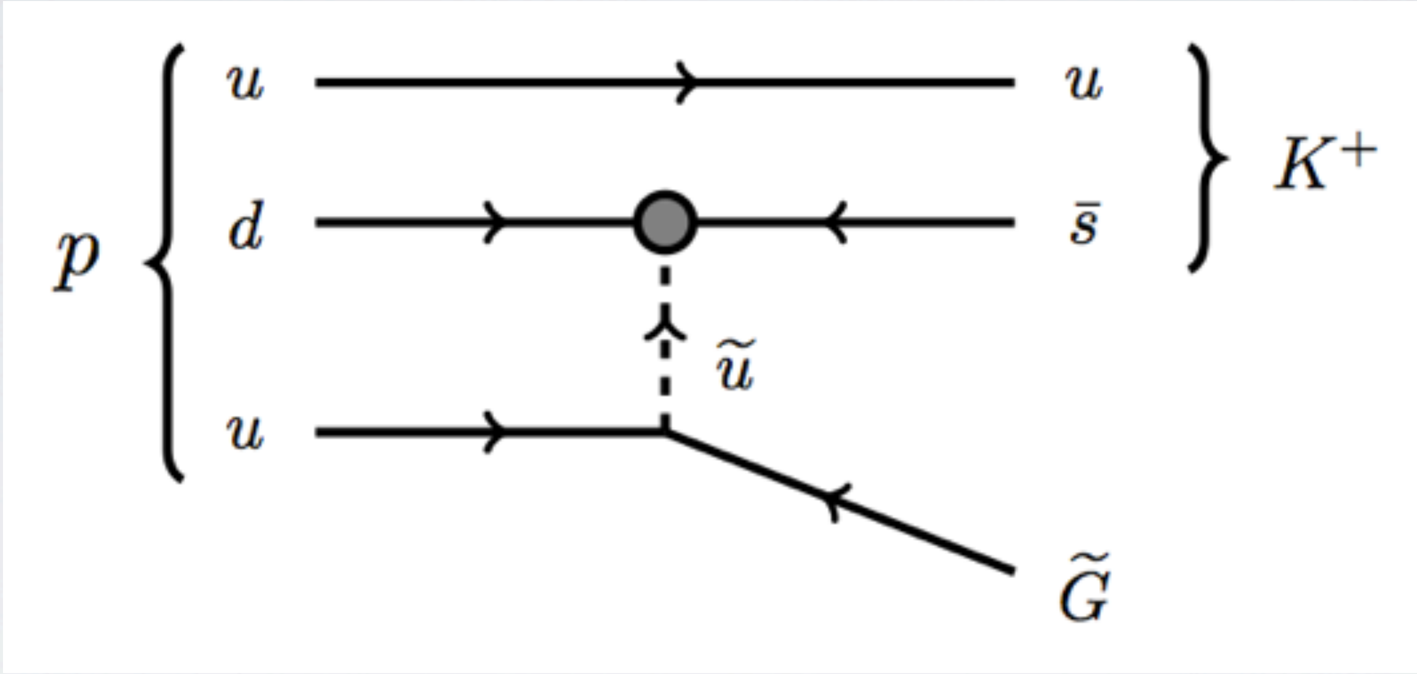
Neutron/anti-neutron oscillation



$$\mathcal{M}_{n-\bar{n}} \sim g_s^2 \epsilon^2 \lambda^6 \Lambda \left(\frac{\Lambda}{m_{\tilde{q}}}\right)^4 \left(\frac{\Lambda}{M_{\tilde{g}}}\right) (\lambda''_{udb})^2$$

$$\lambda''_{udb} \lesssim 1.7 \times 10^{-6} \epsilon^{-2} \left(\frac{m_{\tilde{q}}}{500\,\mathrm{GeV}}\right)^4 \left(\frac{250\,\mathrm{MeV}}{\Lambda}\right)^6 \left(\frac{M_{\tilde{g}}}{800\,\mathrm{GeV}}\right)$$

Proton decay

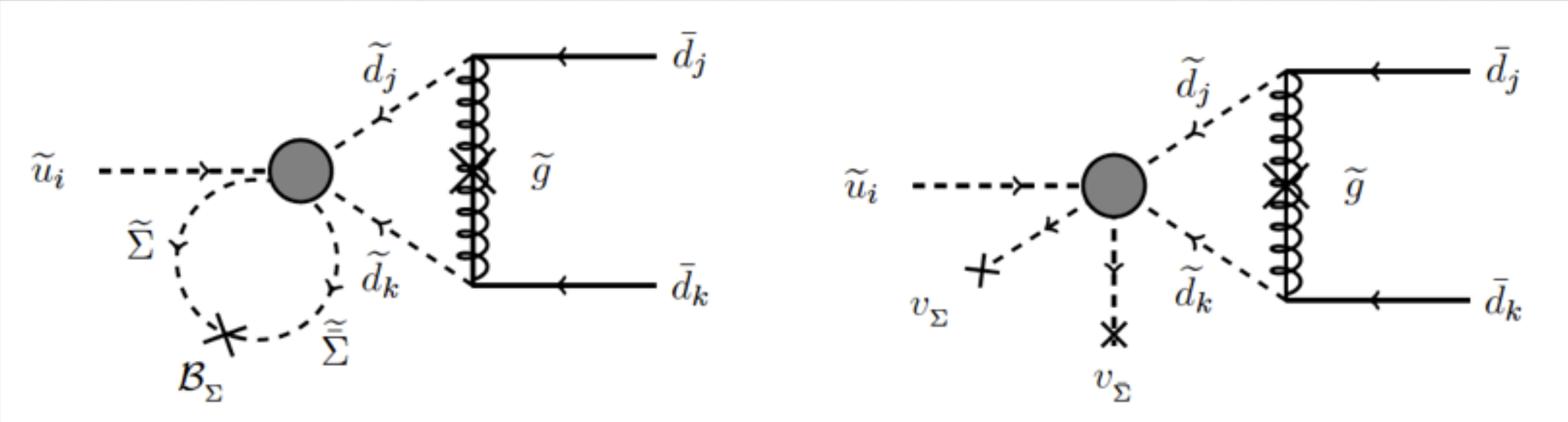


$$\Gamma_{p\to K^+\widetilde{G}} \sim \frac{m_p}{8\,\pi}\left(\frac{\Lambda}{m_{\widetilde{u}}}\right)^4\left(\frac{\Lambda^2}{\sqrt{3}\,m_{3/2}\,M_{pl}}\right)^2(\lambda''_{uds})^2$$

$$m_{3/2} \geq 4.7\,\text{MeV}\left(\frac{\Lambda}{250\,\text{MeV}}\right)^4\left(\frac{500\,\text{GeV}}{m_{\widetilde{u}}}\right)^2\left(\frac{\lambda''_{uds}}{10^{-7}}\right)$$

$$\sqrt{F} \gtrsim 3.2 \times 10^5\,\text{TeV}$$

The stop decay length



$$\Gamma_{\tilde{t}\to\bar{q}\bar{q}} = \frac{m_{\tilde{t}}}{8\,\pi}\,\sin^2\theta_{\tilde{t}}\,|\lambda''_{tqq}|^2$$

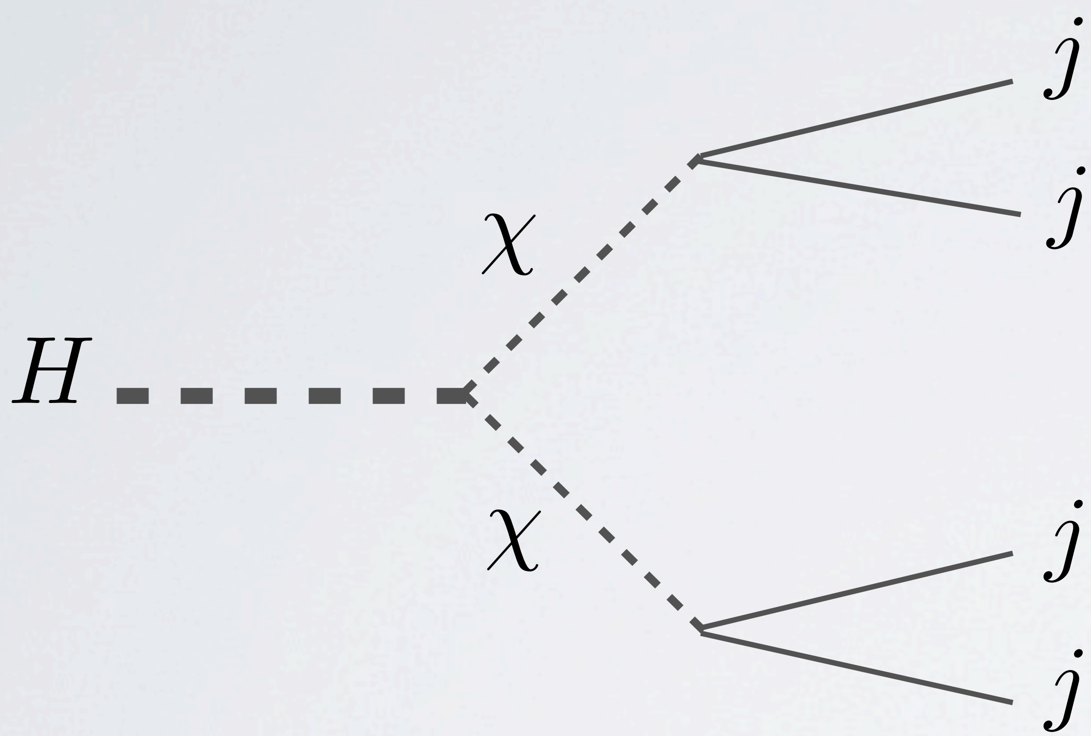
displaced jets are hard to see

$$\lambda''_{tds} > (0.26 - 1.8)\times 10^{-7}\left(\frac{300\,\mathrm{GeV}}{m_{\tilde{t}}}\right)^{1/2}$$

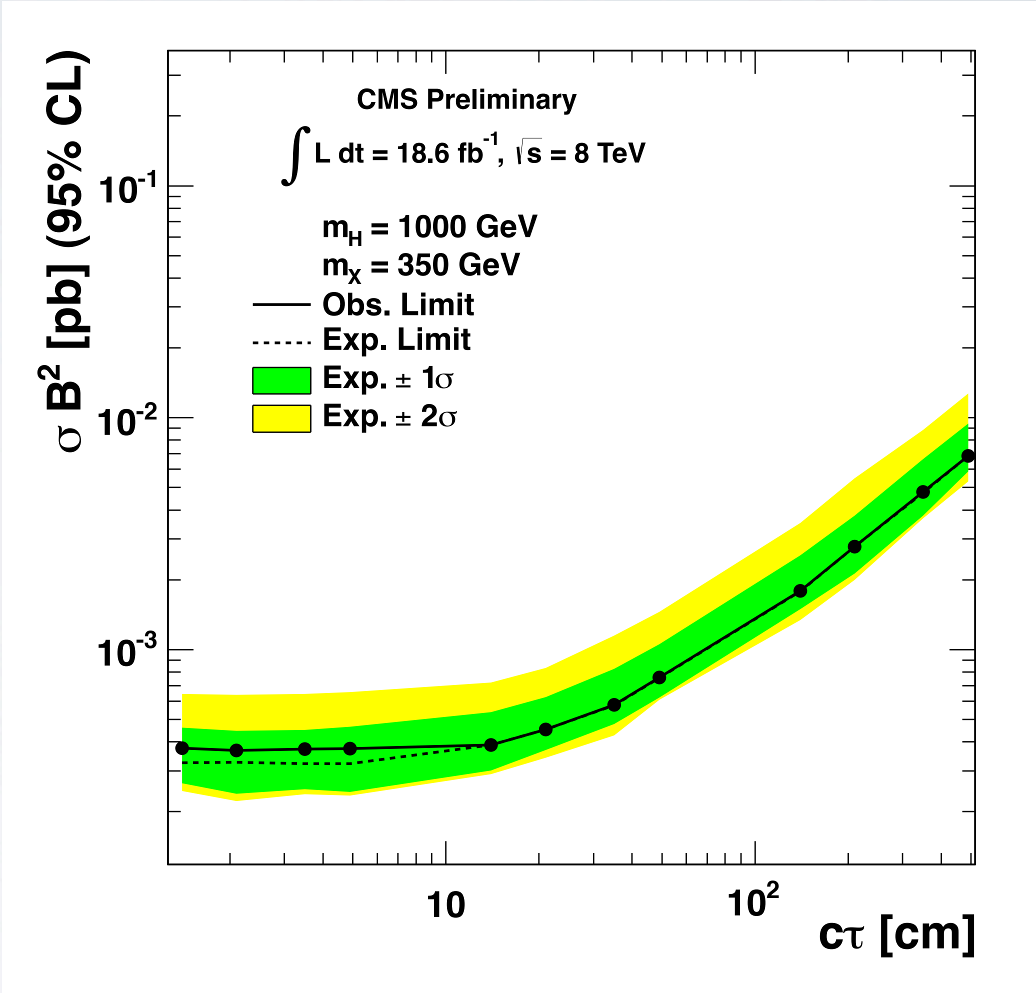
bound for $\ell_{\tilde{t}} \leq 10\,cm$

bound for $\ell_{\tilde{t}} \leq 2\,mm$

Constraint on the displaced decay



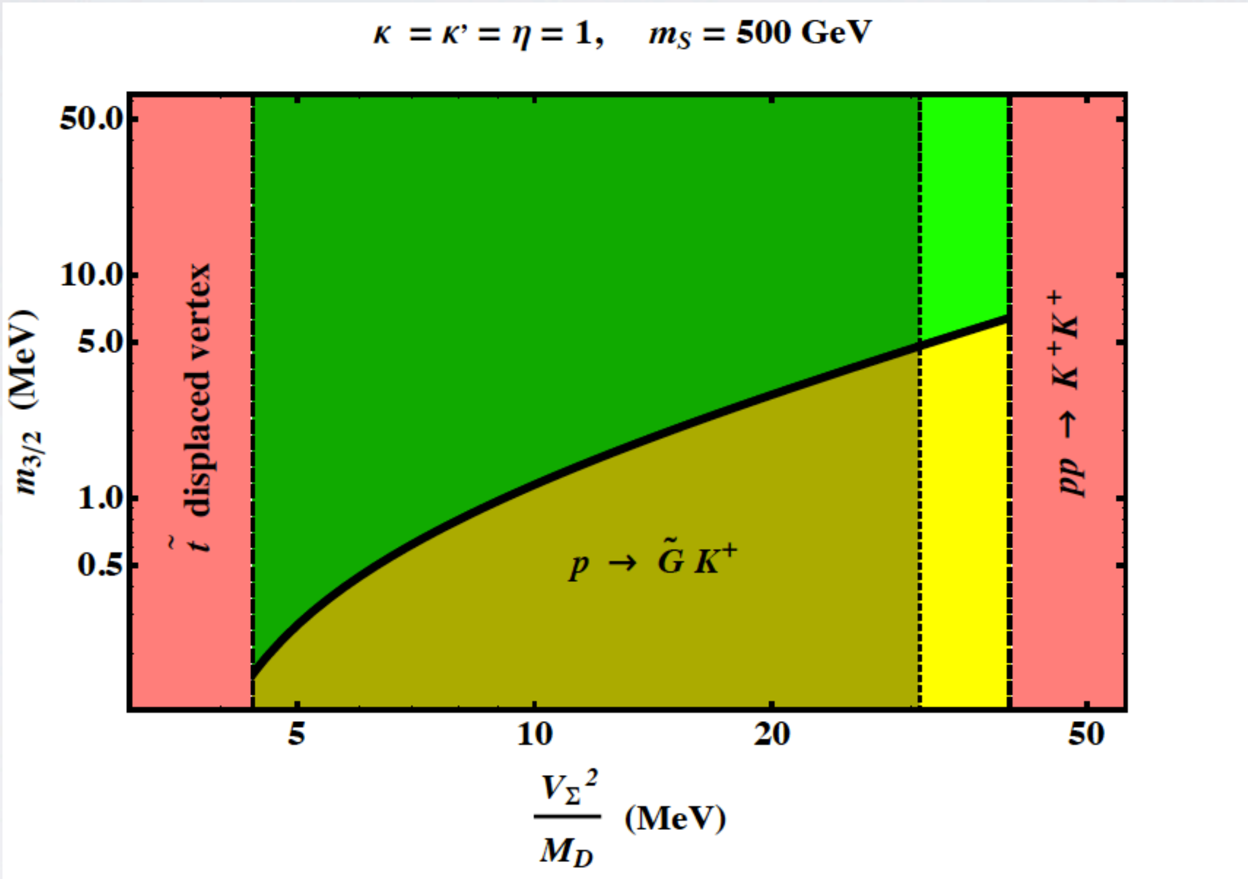
CMS PAS EXO-12-038



the bound is significant now

Parameter space

For a generic flavor structure



For $\sqrt{B_\Sigma} \simeq v_\Sigma \simeq TeV$, the RPV mediator mass

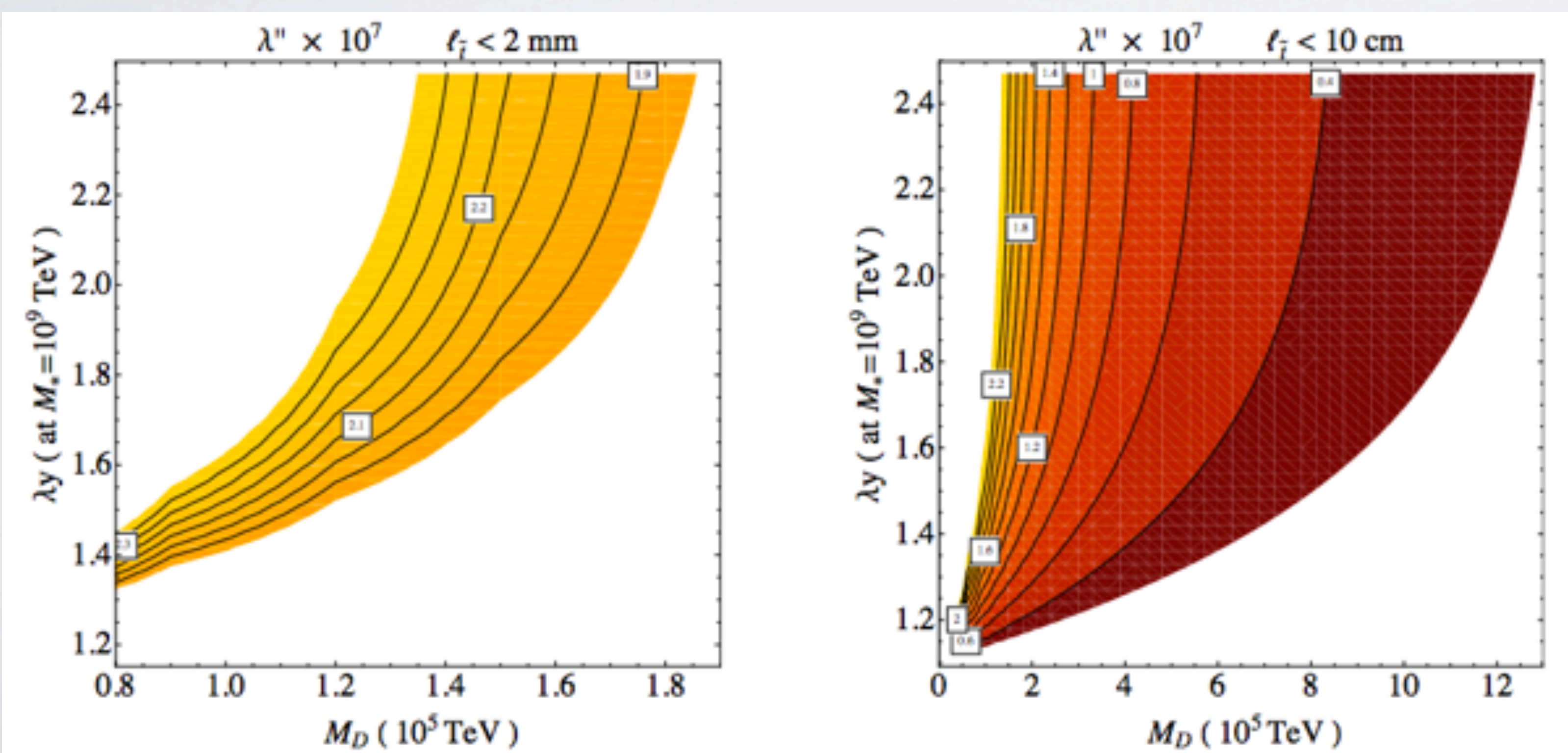
$M_{\mathcal{D}} \simeq 10^{4-5}$ TeV $\qquad M_{\mathcal{D}} \sim \sqrt{F}$

Mediator mass in the $\langle\tilde{\Sigma}\rangle$ model

to obtain $\langle\tilde{\Sigma}\rangle$, we can generate the tachyonic mass $-m_{\Sigma}^2$ through the RG running with the help of extra matter couplings. for example,

$$W \supset \eta\,\Sigma\,X\,\bar{\Sigma} + \lambda_Y \Sigma Y^2 + \lambda_{\bar{Y}} \bar{\Sigma}\bar{Y}^2$$

The size of $\langle\tilde{\Sigma}\rangle$ + experimental bounds set the upper/lower bounds on the mediator mass



here we assume

$$\sqrt{F} = 4 \times 10^5\ \mathrm{TeV}$$

from these plot

$$M_{\mathcal{D}} \sim \sqrt{F}$$

is allowed!

Dark Matter

Gravitino Dark Matter

In models with baryonic RPV, the LSP can be stable if it's lighter than hadrons

- the $\mathcal{O}(10)$ MeV scale gravitino can be a thermally produced DM
- no additional non-thermal productions due to the RPV decay

$$\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{T_R}{10^5\,\mathrm{GeV}}\right)\left(\frac{m_{3/2}}{20\,\mathrm{MeV}}\right)^{-1}\left(\frac{M_{\tilde{g}}}{800\,\mathrm{GeV}}\right)^2$$

M.Boltz, A. Brandenburg and W. Buchmuller (2000)

To conclude...

To conclude

It's nice to think about the RPV

"softly"

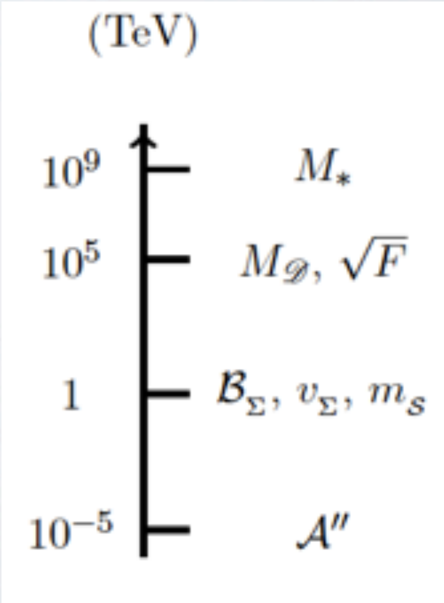
In the example we show here

no additional symmetry required to forbid RPV (use R-symmetry)

no extra mass scales or small couplings put in by hand

gives a dark matter candidate

based on the gauge mediation setup



BACKUP

Experimental Constraints

upper bound on $\lambda^{''}$ (want the process to happen slower)

di-nucleon decay $\tau_{pp\to KK} \geq 1.7 \times 10^{32} yrs$

neutron/anti-neutron oscillation $\tau_{n-\bar{n}} \geq 2.44 \times 10^{8} sec$

lower bound on $\lambda^{''}$ (want the stop to decay faster)

stop decay length $\ell_{\tilde{t}} \leq 2\, mm$ (prompt) $\ell_{\tilde{t}} \leq 10\, cm$ (displaced)

lower bound on the ~~SUSY~~ scale (a smaller gravitino coupling)

proton decay into gravitino $\tau_{p\to K^{+}\nu} \geq 2.3 \times 10^{33} yrs$