Soft R-Parity Violation

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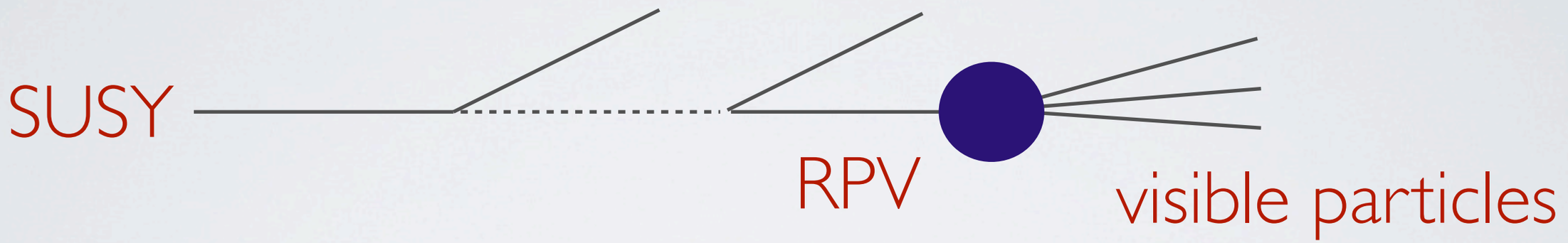
R-parity violation (RPV)

The LSP decay fails the MET searches



However, there are stringent flavor constraints!

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

Soft RPV model

Generate RPV couplings through
soft SUSY breaking terms

Motivations

embed RPV into a SUSY breaking setup,

make the model more economic

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

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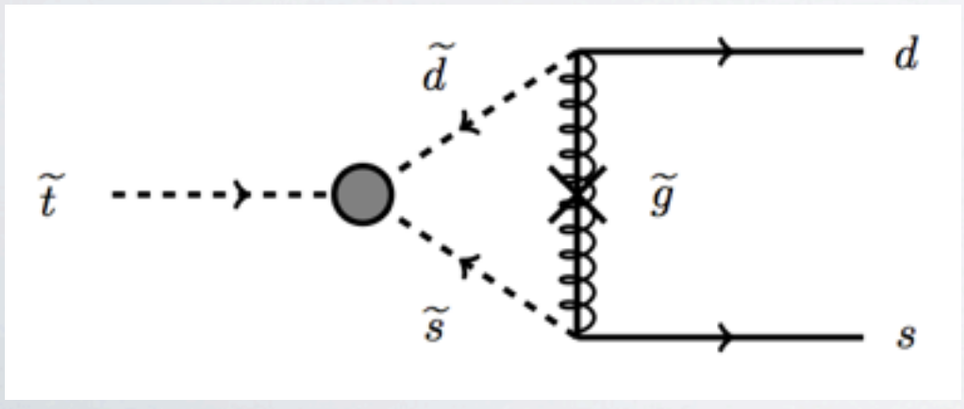
$$\mathcal{A}_{u_i d_j d_k} \tilde{\bar{U}}_i \tilde{\bar{D}}_j \tilde{\bar{D}}_k$$



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

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

which is forbidden by L- or B-violating constraints

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

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

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

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

Breaking & mediation

Gauge mediation model

SUSY

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

soft R-breaking sector

R-symmetry

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

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

visible sector

No RPV couplings

Breaking & mediation

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Gauge mediation model

SUSY

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

soft R-breaking sector

R-symmetry

$m_\lambda\ m_s$

$\mathcal{A}\ \mathcal{B}$

soft breaking terms

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

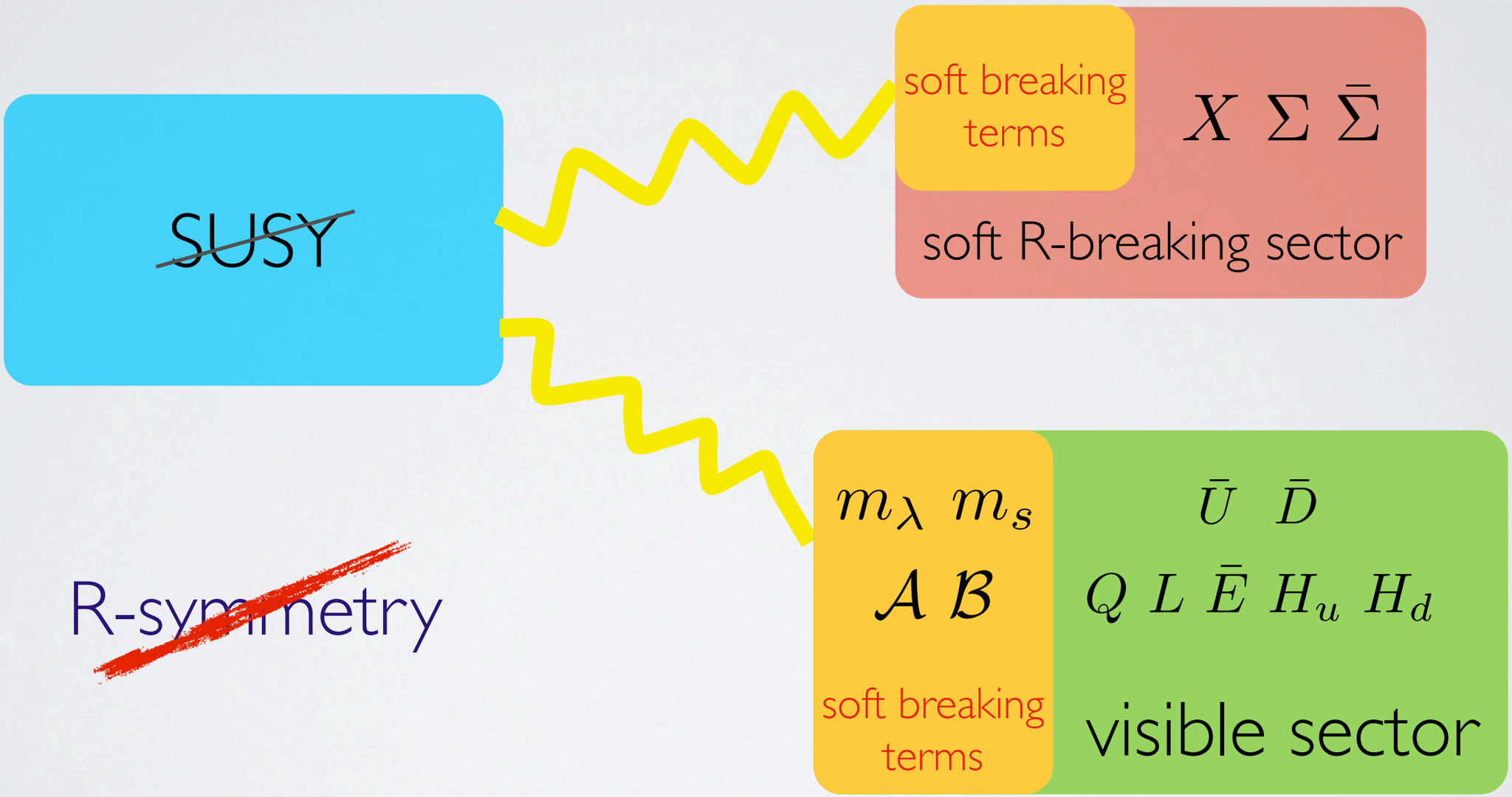
$Q\ L\ \bar{E}\ H_u\ H_d$

visible sector

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

Breaking & mediation

Soft RPV



Breaking & mediation

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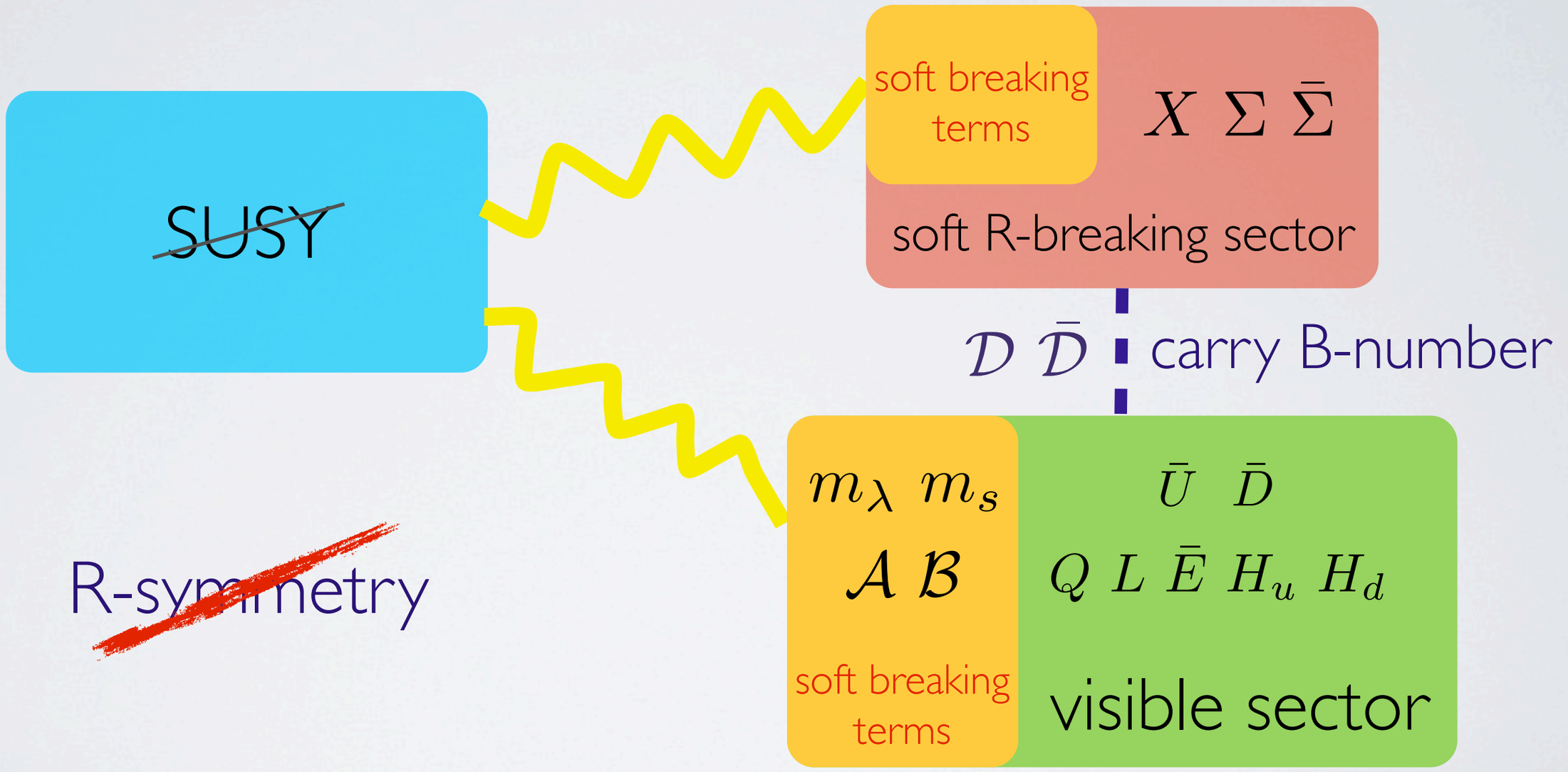

Breaking & mediation

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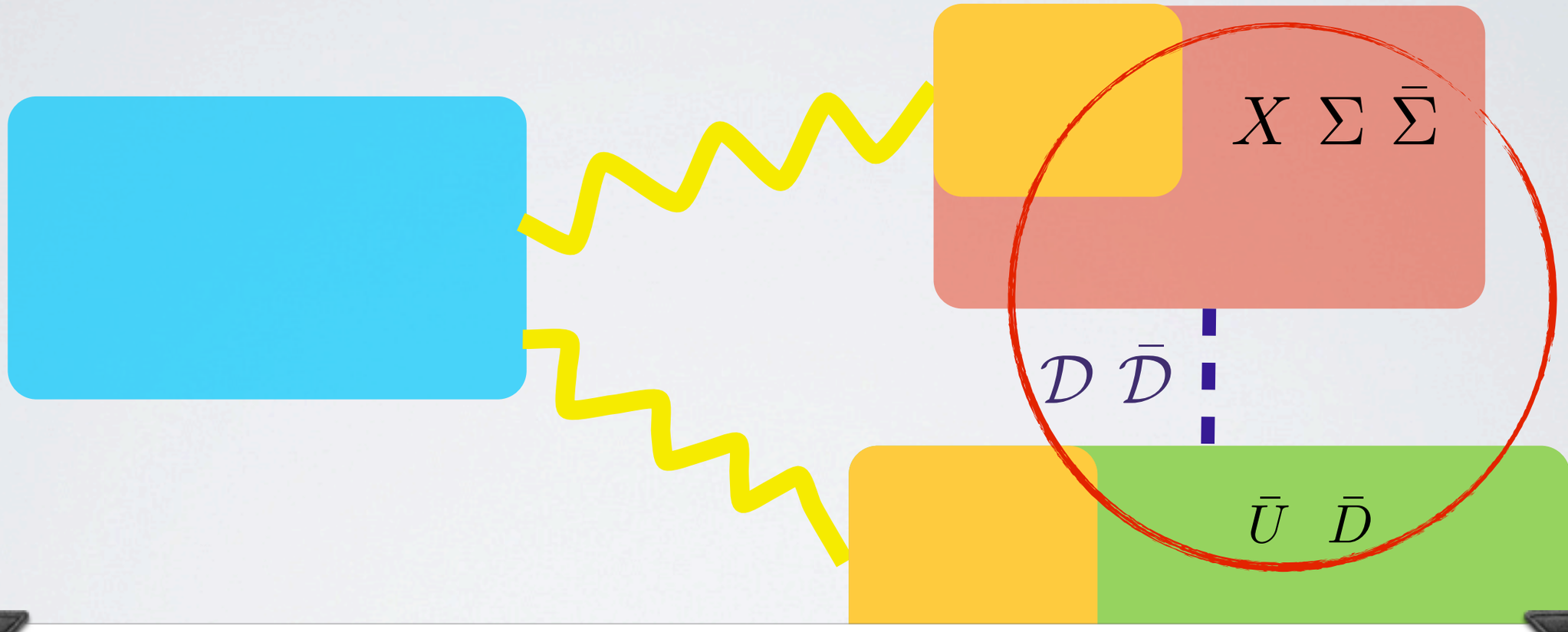


the potential $W \supset \bar{U}\bar{D}\bar{\mathcal{D}} + X\mathcal{D}\bar{D} + X\Sigma\bar{\Sigma} + M_{\mathcal{D}}\bar{\mathcal{D}}\mathcal{D}$

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
$\bar{\mathcal{D}}$	$\bar{3}$	$1/3$	0	0
$\mathcal{D}$	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

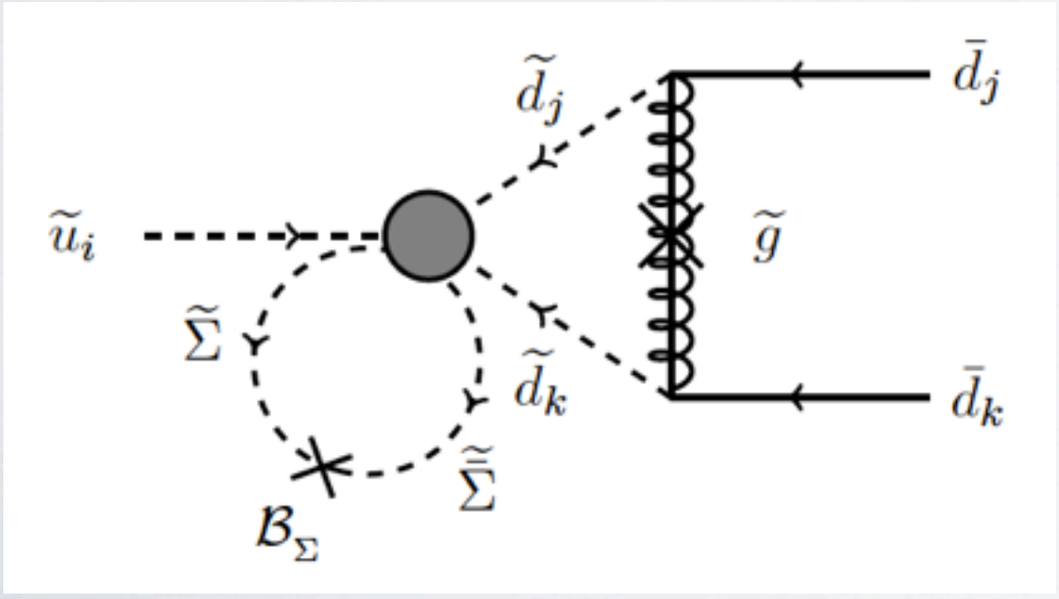
$$\mathcal{L}_{RPV} = \frac{\tilde{\bar{U}}\tilde{\bar{D}}\tilde{\bar{D}}}{M_{\mathcal{D}}} (\tilde{\Sigma}\tilde{\bar{\Sigma}})^*$$

The UDD A-term

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

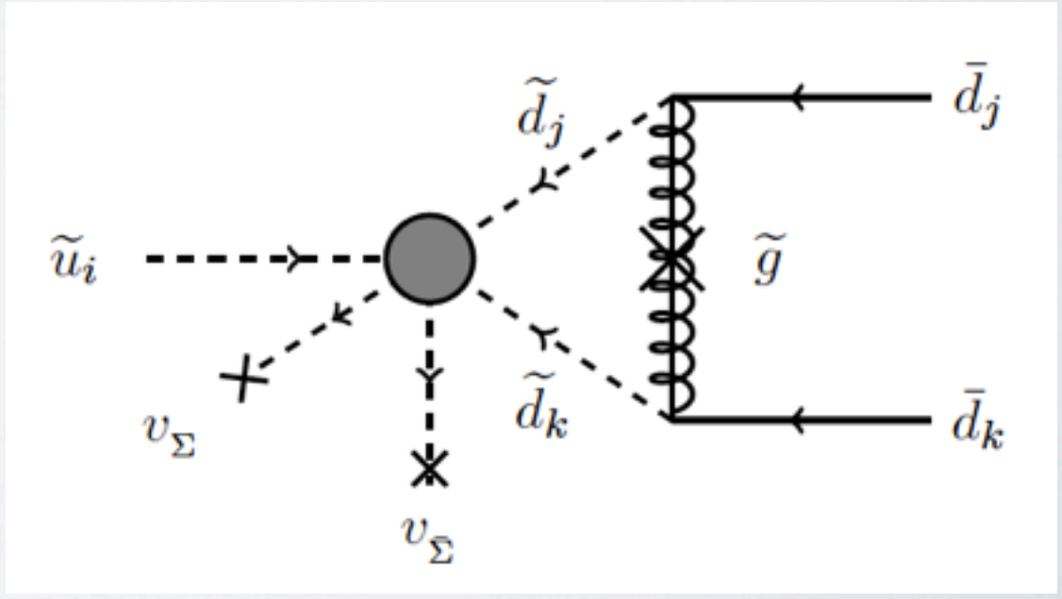
R-breaking B-term

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



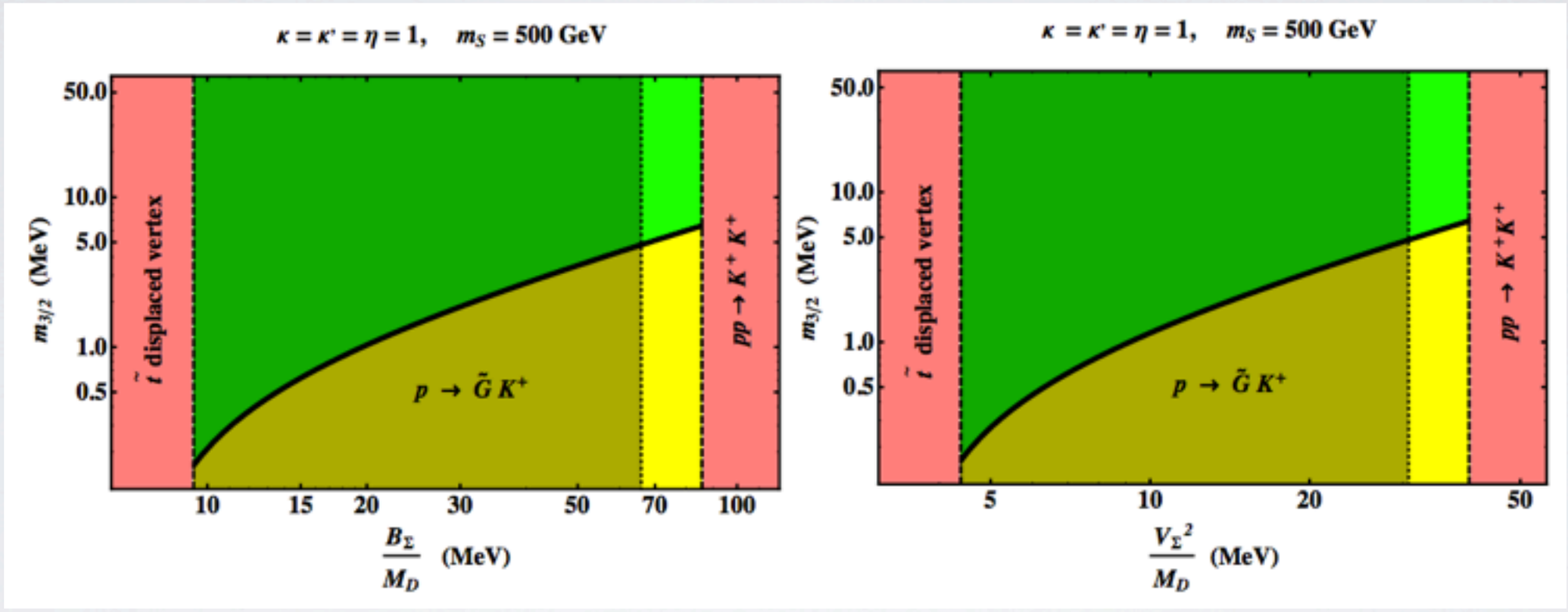
Radiatively induced VEV

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



Parameter space

For a generic flavor structure



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

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

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

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 λ'' (want the process to happen slower)

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

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

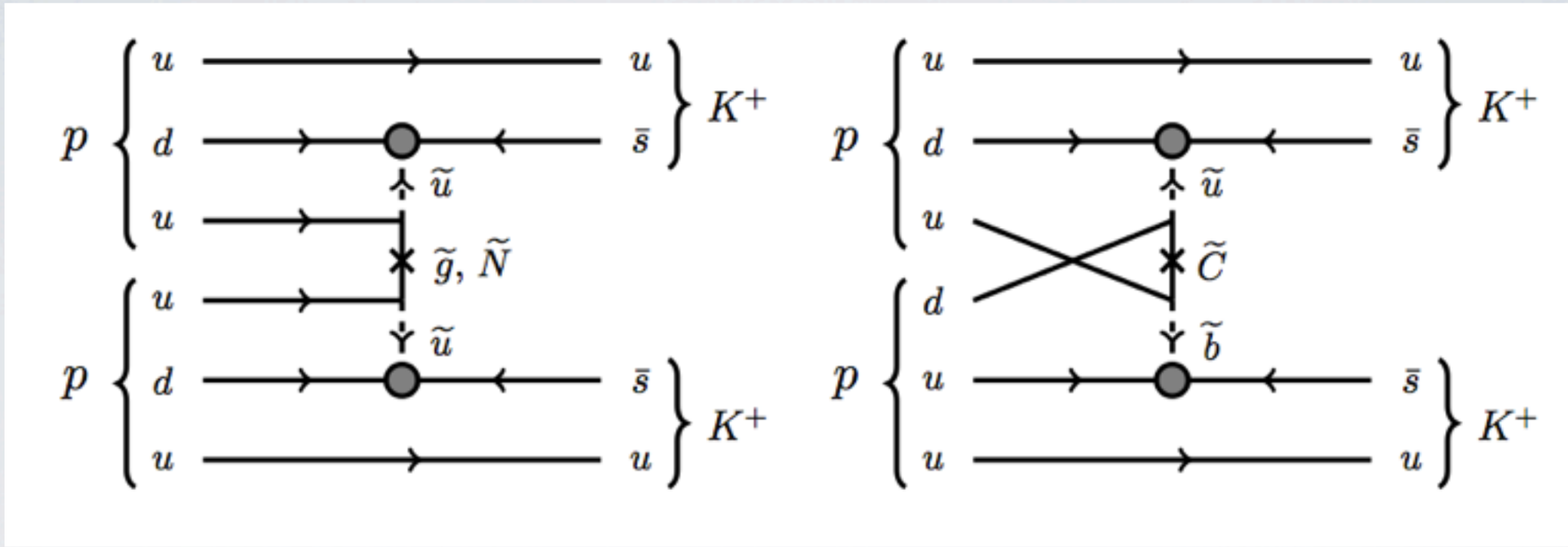
lower bound on λ'' (want the stop to decay faster)

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

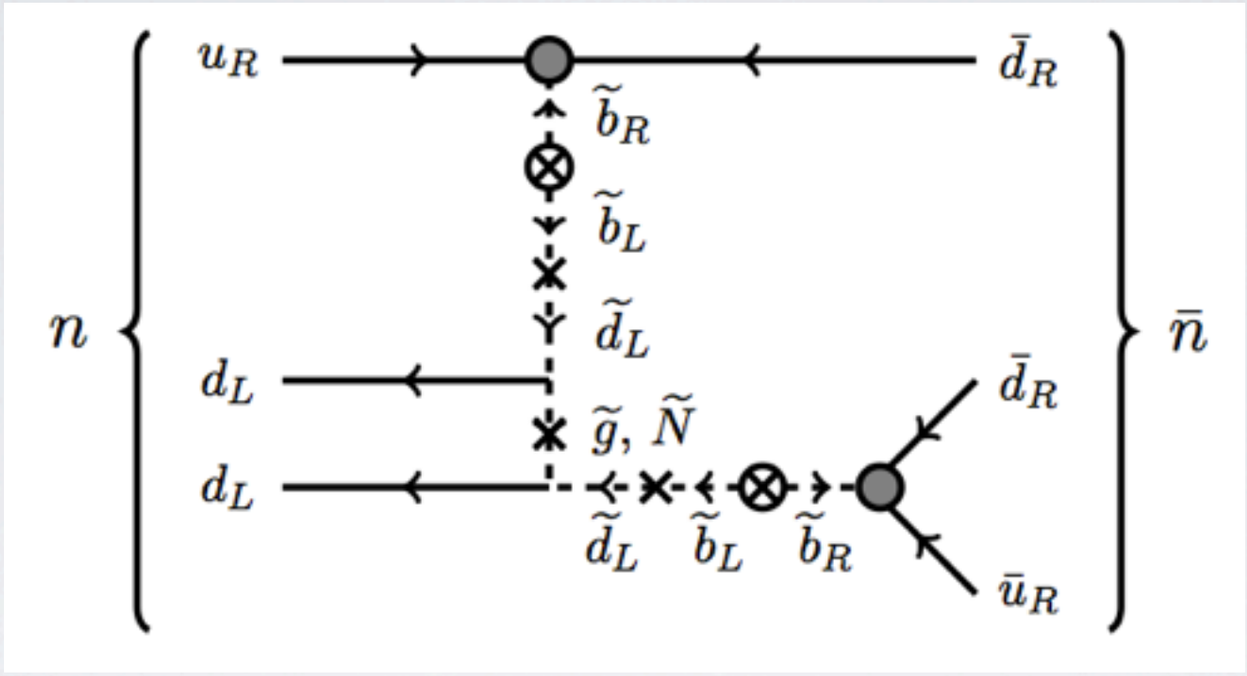
Di-nucleon decay



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

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

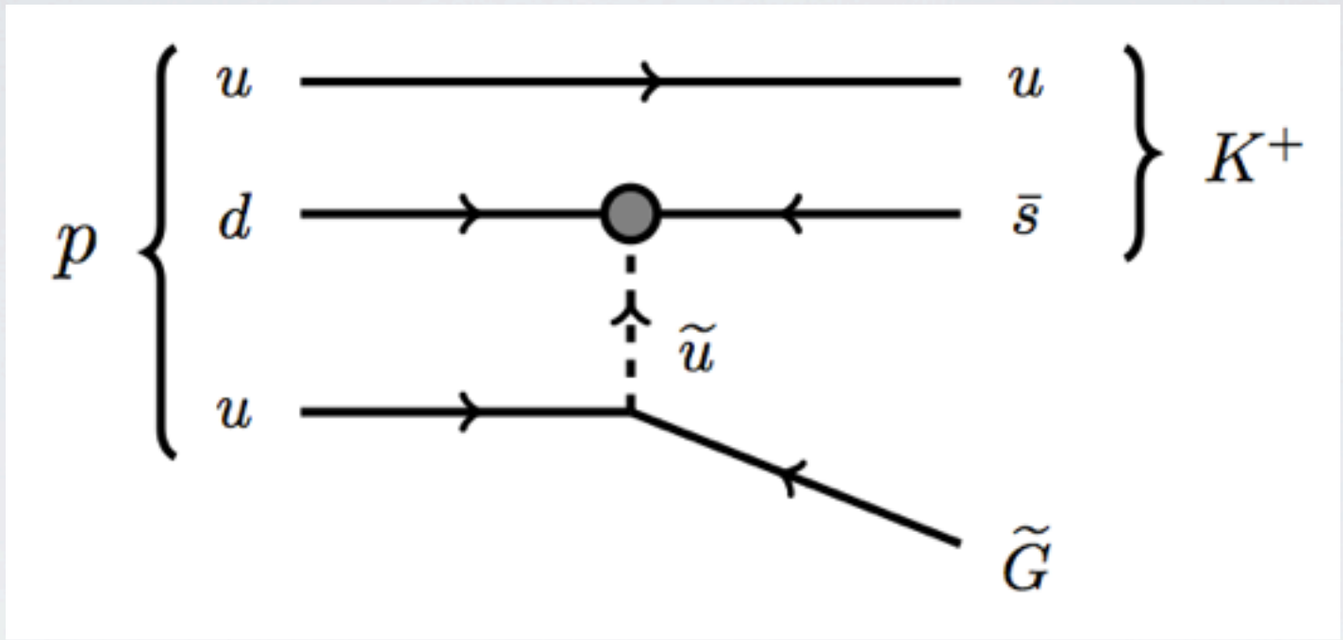
Neutron/anti-neutron oscillation



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

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

Proton decay

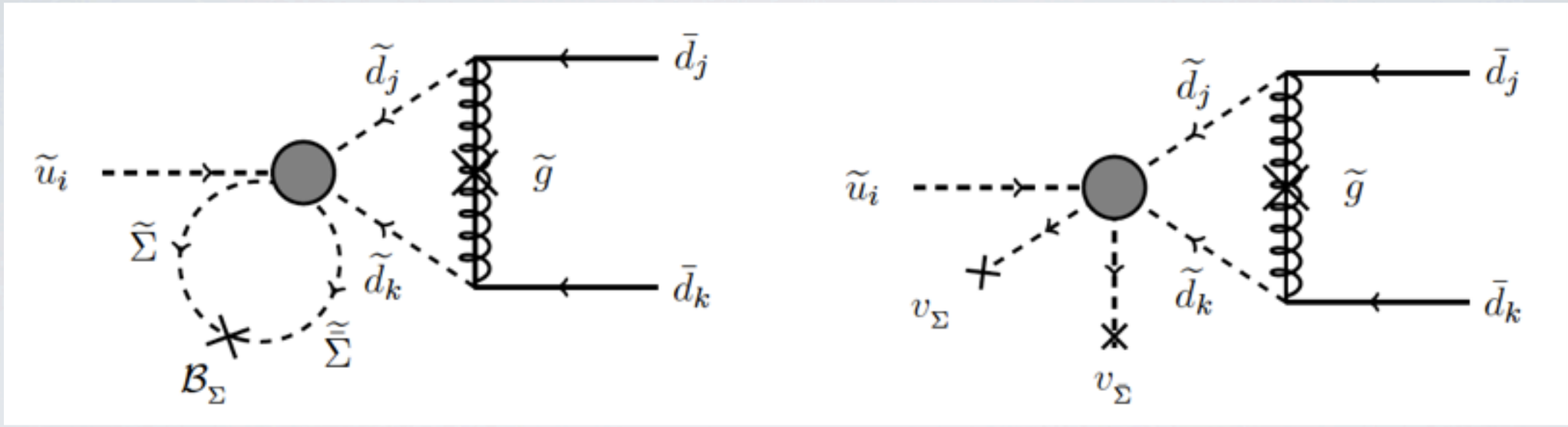


$$\Gamma_{p\to K+\tilde{G}} \sim \frac{m_p}{8\pi}\left(\frac{\Lambda}{m_{\tilde{u}}}\right)^4\left(\frac{\Lambda^2}{\sqrt{3}\,m_{3/2}\,M_{pl}}\right)^2(\lambda''_{uds})^2$$

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

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

The stop decay length



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

displaced jets are hard to see

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

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

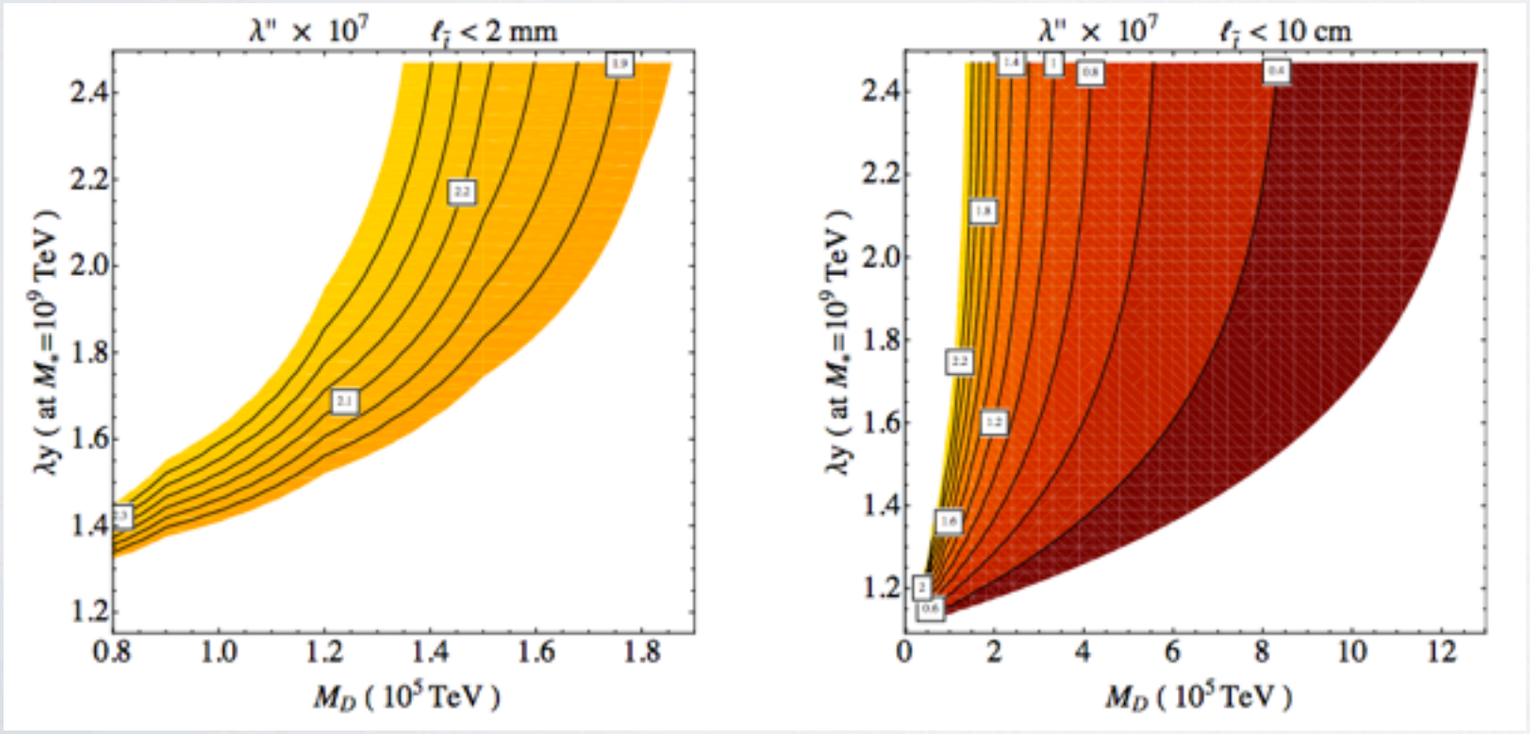
bound for $\ell_{\widetilde{t}} \leq 2\,mm$

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!