Snowmass 2021 — The Energy Frontier

R-Parity Violating SUSY

Strategies for the Next Era

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Lightning Review of R-Parity

- Starting from field content of the MSSM, the most general superpotential, preserving all gauge symmetries, is:

B & L Conserving

$$W_{MSSM} = \boxed{y_{u_{ij}} u_i^c Q_j H_u - y_{d_{ij}} d_i^c Q_j H_d - y_{e_{ij}} e_i^c L_j H_d + \mu H_u H_d}$$

$$+\boxed{\frac{1}{2}\lambda_{ijk} L_i L_j e_k^c + \lambda'_{ijk} L_i Q_j d_k^c + \mu'_i L_i H_u}$$

L Violating $W_{\Delta L=1}$

$$+\boxed{\frac{1}{2}\lambda''_{ijk} u_i^c d_j^c d_k^c}$$

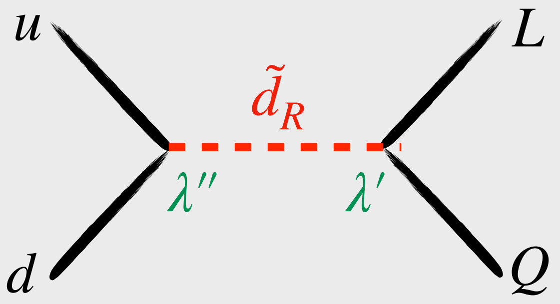
B Violating $W_{\Delta B=1}$

i, *j*, *k*: generation indices

- Unlike SM, baryon and lepton number do not appear automatically as accidental symmetries of the renormalizable theory.

Proton decay at tree level:

$$\mathscr{L} \supset \lambda' L Q \tilde{d}_R^* + \lambda'' u^c d^c \tilde{d}_R^* + \ldots$$



- Experimental data requires, $m_{\tilde{d}_R} \gtrsim$ **10^{15} GeV if** $\lambda', \lambda'' \sim O(1)$

R-Parity

- Define a new multiplicative quantum number: [Farrar & Fayet, '78]

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

R_P = +1 for SM particles (R_P even)
R_P = -1 for superpartners (R_P odd)

B & L Conserving

$$W_{MSSM} = \boxed{y_{u_{ij}} u_i^c Q_j H_u - y_{d_{ij}} d_i^c Q_j H_d - y_{e_{ij}} e_i^c L_j H_d + \mu H_u H_d}$$

$$\cancel{+\boxed{\frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j d_k^c + \mu'_i L_i H_u}}$$

L Violating

$\cancel{W_{\Delta L=1}}$

$$\cancel{+\boxed{\frac{1}{2}\lambda''_{ijk} u_i^c d_j^c d_k^c}}$$

B Violating

$\cancel{W_{\Delta B=1}}$

$$\boxed{W_{\Delta L=1} = W_{\Delta B=1} = 0}$$

R-Parity

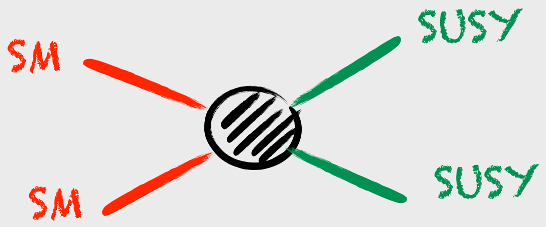
- Define a new multiplicative quantum number:

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

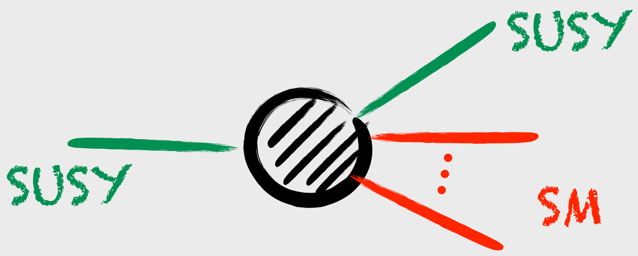
R_P = +1 for SM particles (R_P even)
R_P = -1 for superpartners (R_P odd)

Additional consequences of imposing R-Parity:

- At colliders, sparticles can only be produced in even numbers.



- Each sparticle must decay into an odd number of sparticles.

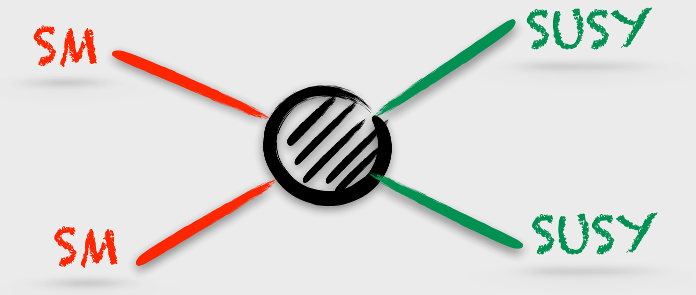


- The Lightest Supersymmetric Particle (LSP) is stable.
  - ➥ Thus LSP makes for an attractive dark matter candidate, but must be neutral!

R-Parity and SUSY Searches

- Conservation of R-Parity an essential feature of many of our SUSY search strategies:

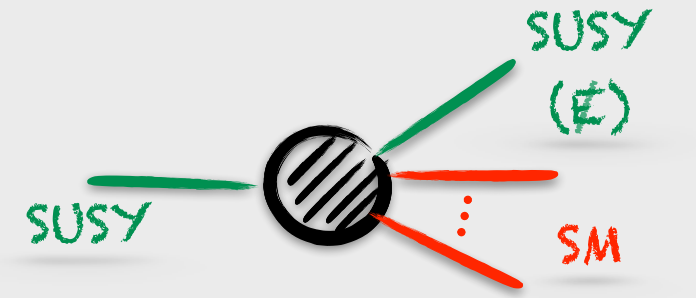
Canonical production mode



Pair production of on-shell sparticles

➥ Costs $2m_{\tilde{f}}$ to make SUSY

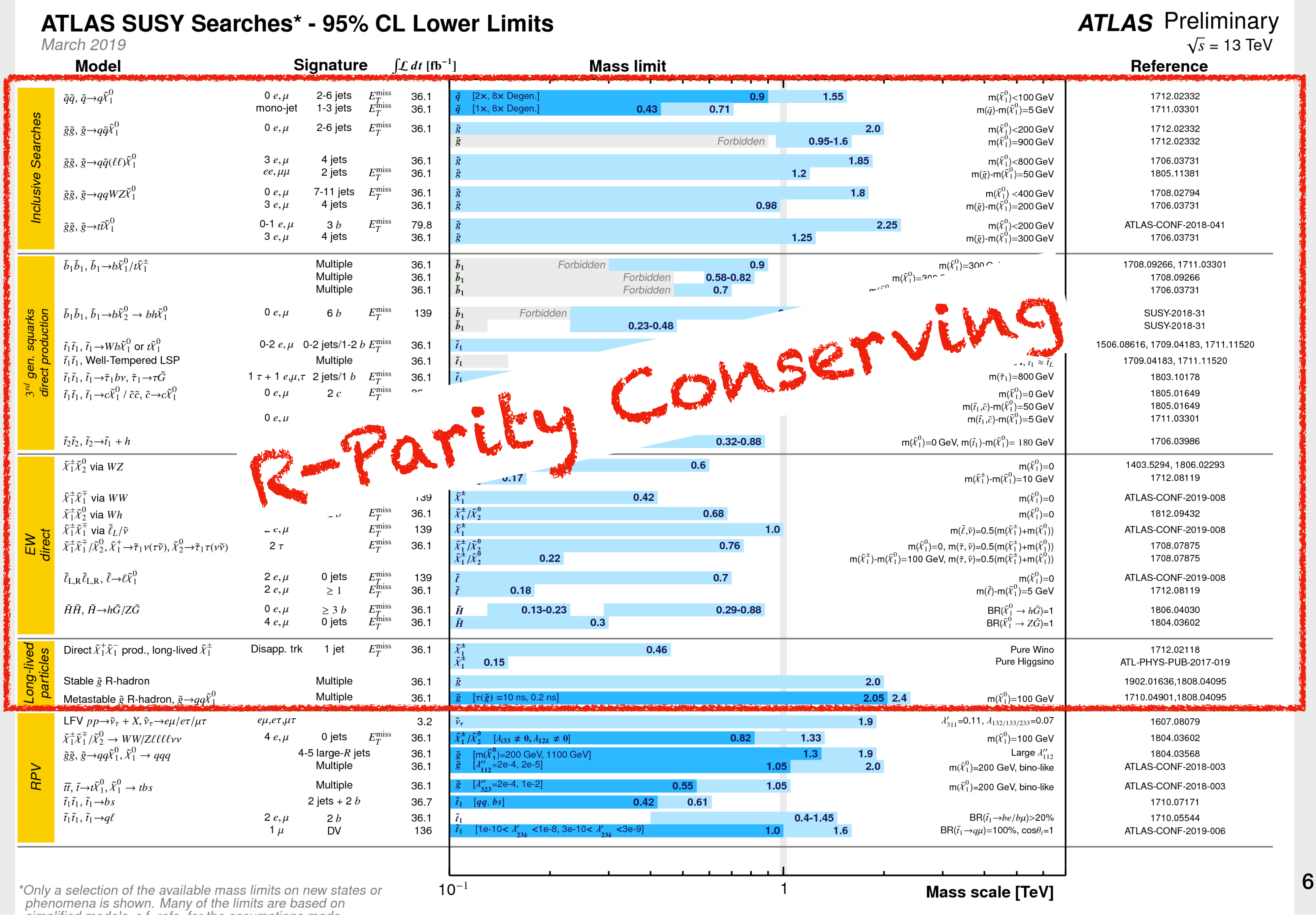
Canonical decay mode



Decay chains of sparticles always end in 1 or more LSP's

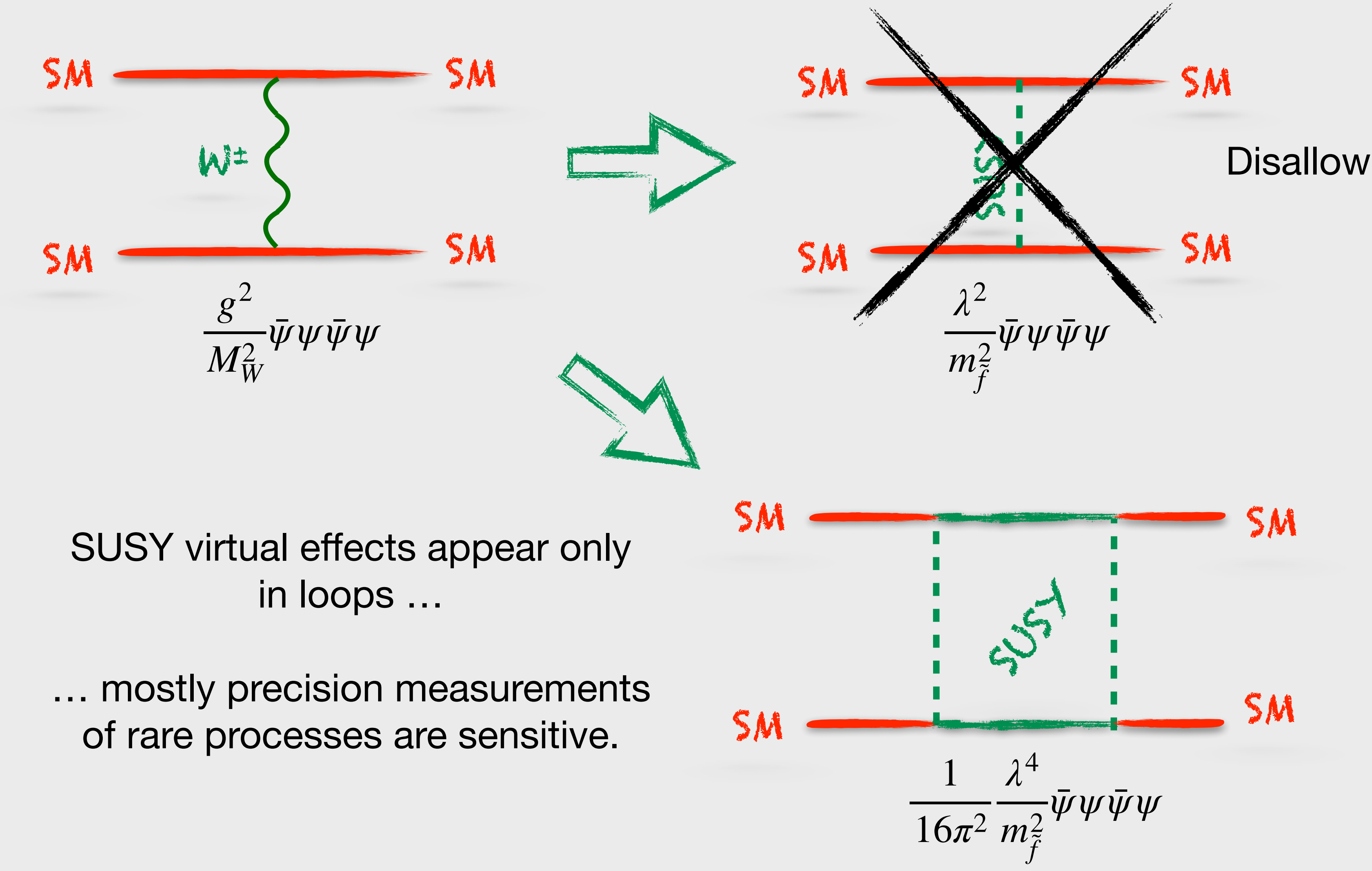
➥ Lots of missing energy!

R-Parity and SUSY Searches



R-Parity and SUSY Searches

What about finding SUSY through virtual particle exchange?



$$\frac{g^2}{M_W^2}\bar{\psi}\psi\bar{\psi}\psi$$

$$\frac{\lambda^2}{m_{\tilde{f}}^2}\bar{\psi}\psi\bar{\psi}\psi$$

Disallowed by R_P

$$\frac{1}{16\pi^2}\frac{\lambda^4}{m_{\tilde{f}}^2}\bar{\psi}\psi\bar{\psi}\psi$$

SUSY virtual effects appear only in loops …

… mostly precision measurements of rare processes are sensitive.

What if R-Parity is not conserved?

$$W_{MSSM} = W_{R_P} + W_{\not{R}_P}$$

$$W_{R_P} = y_{u_{ij}} u_i^c Q_j H_u - y_{d_{ij}} d_i^c Q_j H_d - y_{e_{ij}} e_i^c L_j H_d + \mu H_u H_d$$

$$W_{\not{R}_P} = \boxed{\frac{1}{2}\lambda_{ijk} L_i L_j e_k^c + \lambda'_{ijk} L_i Q_j d_k^c + \mu'_i L_i H_u} + \boxed{\frac{1}{2}\lambda''_{ijk} u_i^c d_j^c d_k^c}$$

$\boxed{W_{\not{R}_P} \text{ leads to fast proton decay}}$

But fast proton decay can be avoided by considering only L or B violating couplings.

$\boxed{\lambda = \lambda' = \mu' = 0}$ or $\boxed{\lambda'' = 0}$

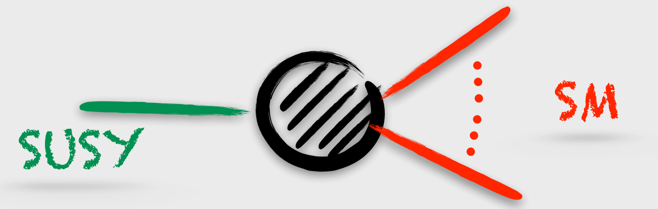
Viable RPV models assume only B- or L-violating terms are non-zero.

Still leaves many free parameters:

$$\begin{array}{ccccccccc} LLe & & LQd & & LH_u & & udd & \\ 9 & + & 27 & + & 3 & \text{or} & 9 & \text{parameters} \end{array}$$

What if R-Parity is not conserved?

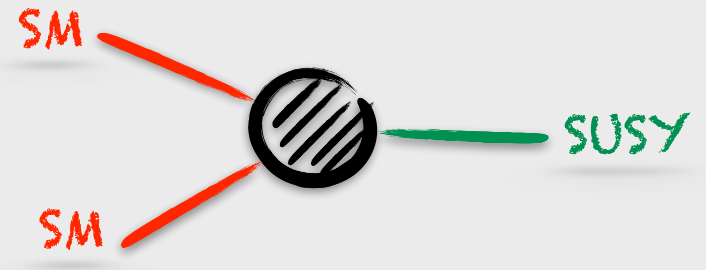
- LSP is no longer absolutely stable – will decay into 2+ SM particles.



Identities of final state SM particles depends both on:

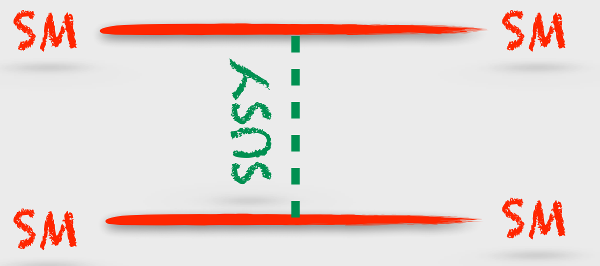
- identity of LSP
- RPV couplings of LSP

- Sparticles can be singly produced through RPV interactions.



- Production rates depend crucially on RPV couplings.
- Final states involve competition between R_P-conserving and RPV couplings.

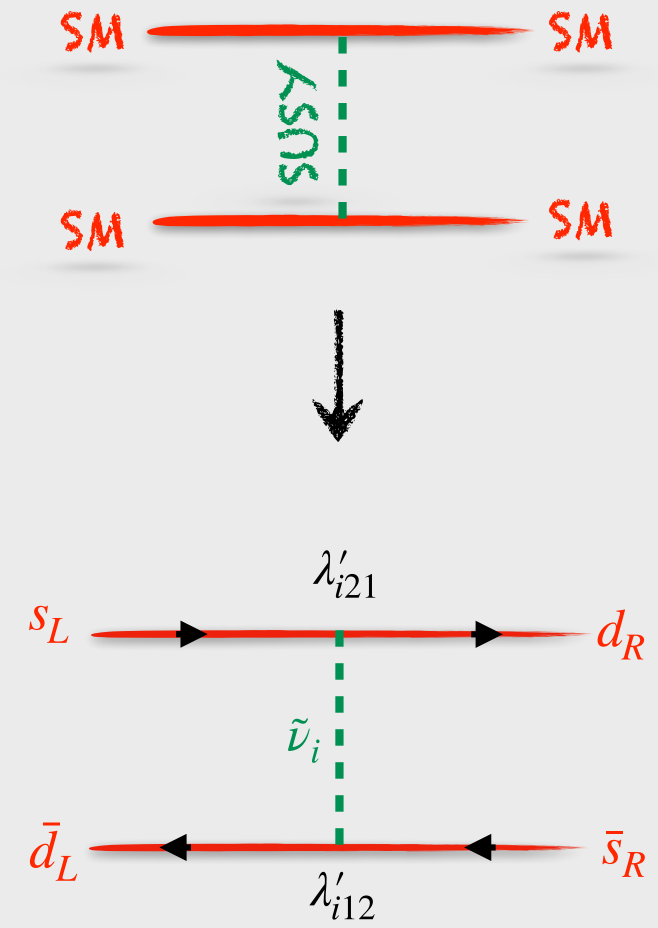
- Virtual sparticle exchange/deviations in SM observables.



- Single particle exchange possible, so much bigger effect than in R_P-conserving models!
- Sensitive to masses, but also pairs of RPV couplings.

What if R-Parity is not conserved?

- Virtual sparticle exchange/deviations in SM observables.



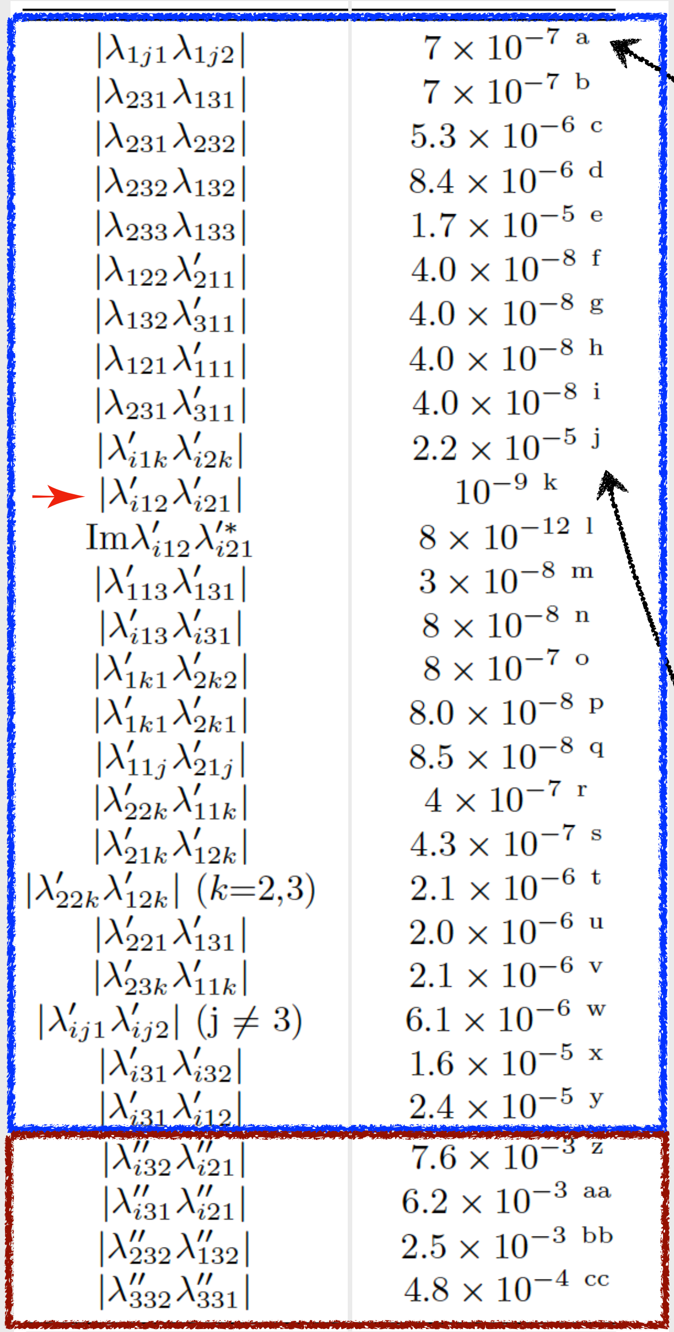
Most commonly considered in context of low-energy, high precision measurements of rare processes.

$$\Delta m_K \Longrightarrow \left|\lambda'_{i12}\,\lambda'_{i21}\right| \times \left(\frac{1\,\text{TeV}}{m_{\tilde{\nu}}}\right)^2 < 2.2\times 10^{-8}$$

[Domingo, Dreiner, Kim, Krauss, Lozano, Wang (2018)]

Generally, the most constraining of SM processes (FCNC, CPV, LFV) require more than one non-zero coupling ➛ ***constraints on pairs of couplings can be quite strong!***

What if R-Parity is not conserved?

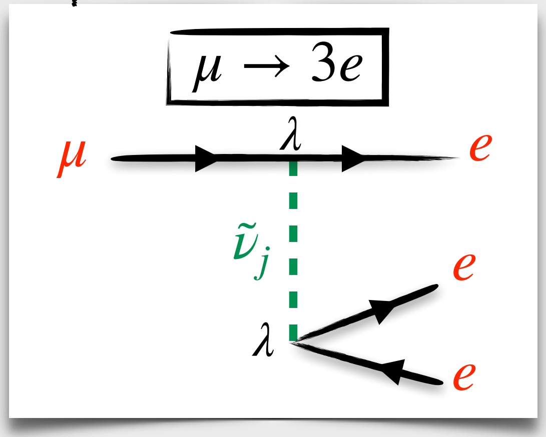


$\lvert\lambda_{1j1}\lambda_{1j2}\rvert$	7×10^{-7} [a]
$\lvert\lambda_{231}\lambda_{131}\rvert$	7×10^{-7} [b]
$\lvert\lambda_{231}\lambda_{232}\rvert$	5.3×10^{-6} [c]
$\lvert\lambda_{232}\lambda_{132}\rvert$	8.4×10^{-6} [d]
$\lvert\lambda_{233}\lambda_{133}\rvert$	1.7×10^{-5} [e]
$\lvert\lambda_{122}\lambda'_{211}\rvert$	4.0×10^{-8} [f]
$\lvert\lambda_{132}\lambda'_{311}\rvert$	4.0×10^{-8} [g]
$\lvert\lambda_{121}\lambda'_{111}\rvert$	4.0×10^{-8} [h]
$\lvert\lambda_{231}\lambda'_{311}\rvert$	4.0×10^{-8} [i]
$\lvert\lambda'_{i1k}\lambda'_{i2k}\rvert$	2.2×10^{-5} [j]
→ $\lvert\lambda'_{i12}\lambda'_{i21}\rvert$	10^{-9} [k]
$\mathrm{Im}\lambda'_{i12}\lambda'^{*}_{i21}$	8×10^{-12} [l]
$\lvert\lambda'_{113}\lambda'_{131}\rvert$	3×10^{-8} [m]
$\lvert\lambda'_{i13}\lambda'_{i31}\rvert$	8×10^{-8} [n]
$\lvert\lambda'_{1k1}\lambda'_{2k2}\rvert$	8×10^{-7} [o]
$\lvert\lambda'_{1k1}\lambda'_{2k1}\rvert$	8.0×10^{-8} [p]
$\lvert\lambda'_{11j}\lambda'_{21j}\rvert$	8.5×10^{-8} [q]
$\lvert\lambda'_{22k}\lambda'_{11k}\rvert$	4×10^{-7} [r]
$\lvert\lambda'_{21k}\lambda'_{12k}\rvert$	4.3×10^{-7} [s]
$\lvert\lambda'_{22k}\lambda'_{12k}\rvert$ $(k{=}2,3)$	2.1×10^{-6} [t]
$\lvert\lambda'_{221}\lambda'_{131}\rvert$	2.0×10^{-6} [u]
$\lvert\lambda'_{23k}\lambda'_{11k}\rvert$	2.1×10^{-6} [v]
$\lvert\lambda'_{ij1}\lambda'_{ij2}\rvert$ $(j\neq3)$	6.1×10^{-6} [w]
$\lvert\lambda'_{i31}\lambda'_{i32}\rvert$	1.6×10^{-5} [x]
$\lvert\lambda'_{i31}\lambda'_{i12}\rvert$	2.4×10^{-5} [y]
$\lvert\lambda''_{i32}\lambda''_{i21}\rvert$	7.6×10^{-3} [z]
$\lvert\lambda''_{i31}\lambda''_{i21}\rvert$	6.2×10^{-3} [aa]
$\lvert\lambda''_{232}\lambda''_{132}\rvert$	2.5×10^{-3} [bb]
$\lvert\lambda''_{332}\lambda''_{331}\rvert$	4.8×10^{-4} [cc]

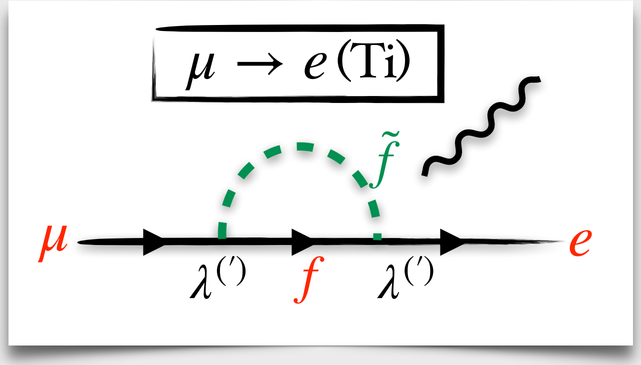
[B. C. Allanach, A. Dedes and H. K. Dreiner (1999); assumes M_{SUSY} = 100 GeV]

$\not{L} \sim O(10^{-5}) - O(10^{-9})$

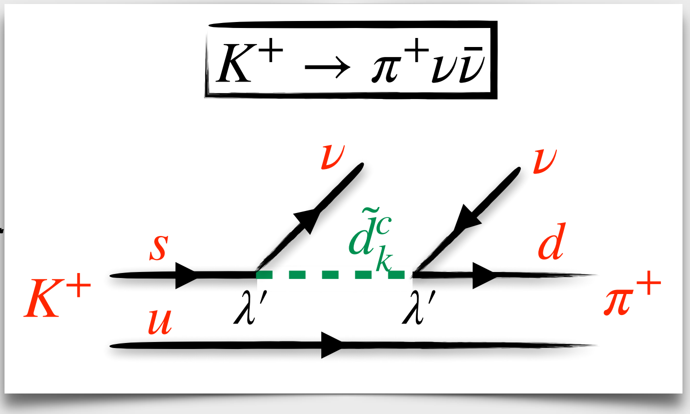
$\not{B} \sim O(10^{-3}) - O(10^{-4})$



[I. Hinchliffe & T. Kaeding (1993)]

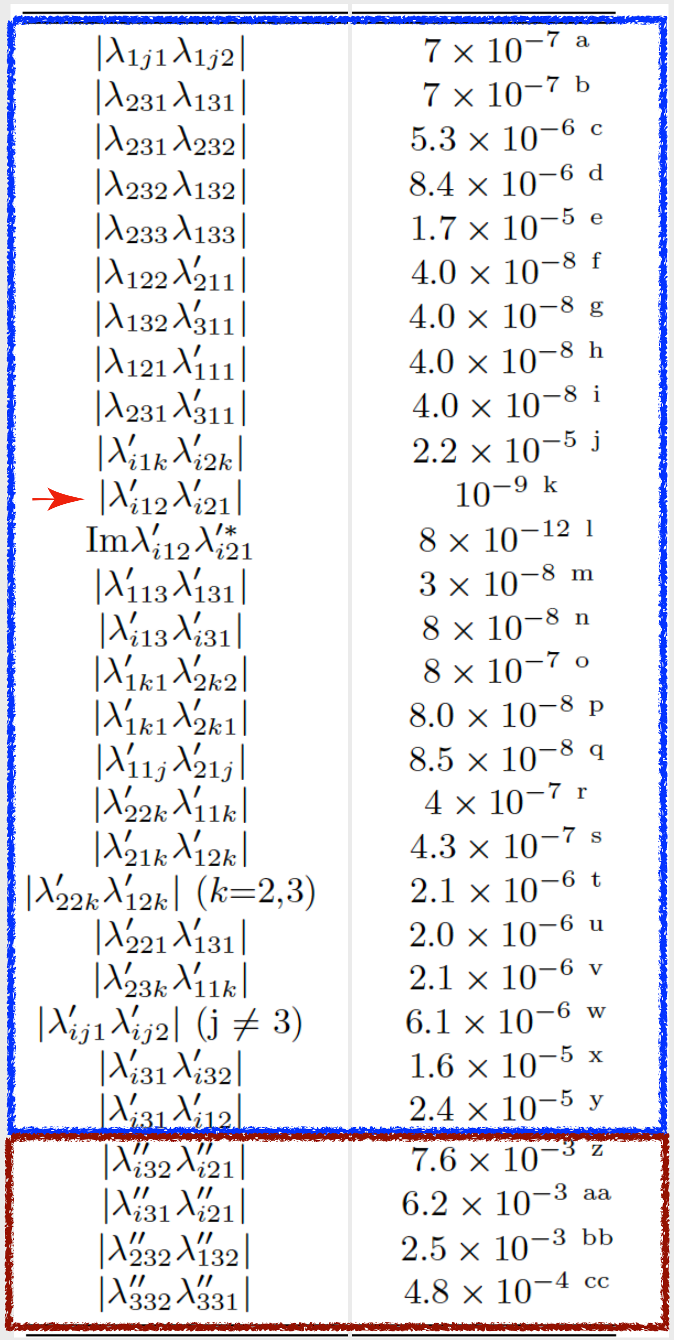


[Huitu, Maalampi, Raidal and Santamaria (1997)]



[K. Agashe and M. Graesser (1995)]

What if R-Parity is not conserved?



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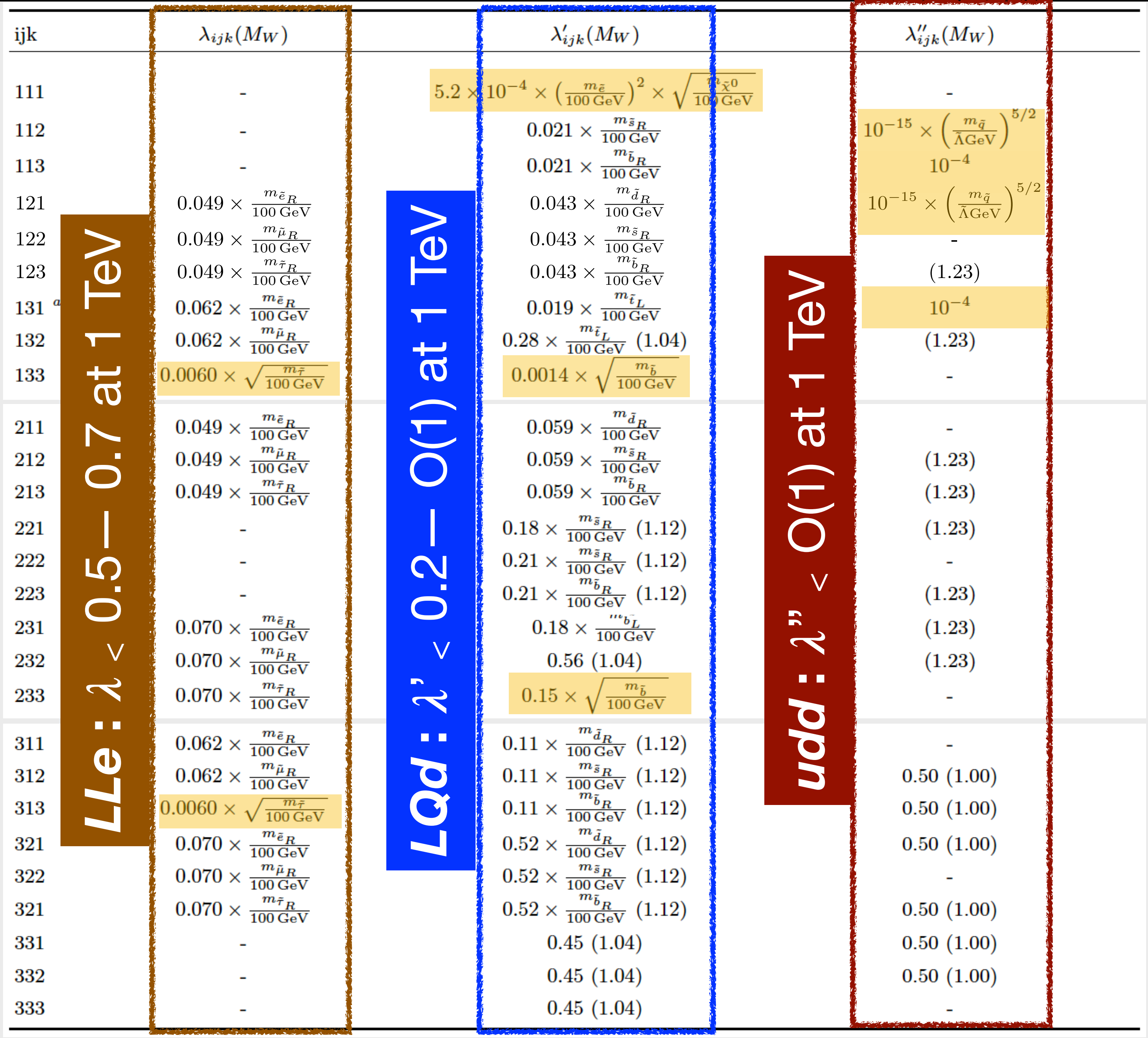
These observables are covered by the **Rare Processes and Precision Measurements Frontier.**

Opportunity for collaboration and cross-pollination of ideas with Energy Frontier.

But these constraints are always on pairs of couplings, not on individual couplings.

[B. C. Allanach, A. Dedes and H. K. Dreiner (1999); assumes M_{SUSY} = 100 GeV]

Constraints on individual couplings



ijk	$\lambda_{ijk}(M_W)$	$\lambda'_{ijk}(M_W)$	$\lambda''_{ijk}(M_W)$
111	-	$5.2 \times 10^{-4} \times \left(\frac{m_{\tilde{e}}}{100\,\mathrm{GeV}}\right)^2 \times \sqrt{\frac{m_{\tilde{\chi}^0}}{100\,\mathrm{GeV}}}$	-
112	-	$0.021 \times \frac{m_{\tilde{s}_R}}{100\,\mathrm{GeV}}$	$10^{-15} \times \left(\frac{m_{\tilde{q}}}{\tilde{\Lambda}\mathrm{GeV}}\right)^{5/2}$
113	-	$0.021 \times \frac{m_{\tilde{b}_R}}{100\,\mathrm{GeV}}$	10^{-4}
121	$0.049 \times \frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}$	$0.043 \times \frac{m_{\tilde{d}_R}}{100\,\mathrm{GeV}}$	$10^{-15} \times \left(\frac{m_{\tilde{q}}}{\tilde{\Lambda}\mathrm{GeV}}\right)^{5/2}$
122	$0.049 \times \frac{m_{\tilde{\mu}_R}}{100\,\mathrm{GeV}}$	$0.043 \times \frac{m_{\tilde{s}_R}}{100\,\mathrm{GeV}}$	-
123	$0.049 \times \frac{m_{\tilde{\tau}_R}}{100\,\mathrm{GeV}}$	$0.043 \times \frac{m_{\tilde{b}_R}}{100\,\mathrm{GeV}}$	(1.23)
131[a]	$0.062 \times \frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}$	$0.019 \times \frac{m_{\tilde{t}_L}}{100\,\mathrm{GeV}}$	10^{-4}
132	$0.062 \times \frac{m_{\tilde{\mu}_R}}{100\,\mathrm{GeV}}$	$0.28 \times \frac{m_{\tilde{t}_L}}{100\,\mathrm{GeV}}$ (1.04)	(1.23)
133	$0.0060 \times \sqrt{\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}}}$	$0.0014 \times \sqrt{\frac{m_{\tilde{b}}}{100\,\mathrm{GeV}}}$	-
211	$0.049 \times \frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}$	$0.059 \times \frac{m_{\tilde{d}_R}}{100\,\mathrm{GeV}}$	-
212	$0.049 \times \frac{m_{\tilde{\mu}_R}}{100\,\mathrm{GeV}}$	$0.059 \times \frac{m_{\tilde{s}_R}}{100\,\mathrm{GeV}}$	(1.23)
213	$0.049 \times \frac{m_{\tilde{\tau}_R}}{100\,\mathrm{GeV}}$	$0.059 \times \frac{m_{\tilde{b}_R}}{100\,\mathrm{GeV}}$	(1.23)
221	-	$0.18 \times \frac{m_{\tilde{s}_R}}{100\,\mathrm{GeV}}$ (1.12)	(1.23)
222	-	$0.21 \times \frac{m_{\tilde{s}_R}}{100\,\mathrm{GeV}}$ (1.12)	-
223	-	$0.21 \times \frac{m_{\tilde{b}_R}}{100\,\mathrm{GeV}}$ (1.12)	(1.23)
231	$0.070 \times \frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}$	$0.18 \times \frac{m_{\tilde{b}_L}}{100\,\mathrm{GeV}}$	(1.23)
232	$0.070 \times \frac{m_{\tilde{\mu}_R}}{100\,\mathrm{GeV}}$	0.56 (1.04)	(1.23)
233	$0.070 \times \frac{m_{\tilde{\tau}_R}}{100\,\mathrm{GeV}}$	$0.15 \times \sqrt{\frac{m_{\tilde{b}}}{100\,\mathrm{GeV}}}$	-
311	$0.062 \times \frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}$	$0.11 \times \frac{m_{\tilde{d}_R}}{100\,\mathrm{GeV}}$ (1.12)	-
312	$0.062 \times \frac{m_{\tilde{\mu}_R}}{100\,\mathrm{GeV}}$	$0.11 \times \frac{m_{\tilde{s}_R}}{100\,\mathrm{GeV}}$ (1.12)	0.50 (1.00)
313	$0.0060 \times \sqrt{\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}}}$	$0.11 \times \frac{m_{\tilde{b}_R}}{100\,\mathrm{GeV}}$ (1.12)	0.50 (1.00)
321	$0.070 \times \frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}$	$0.52 \times \frac{m_{\tilde{d}_R}}{100\,\mathrm{GeV}}$ (1.12)	0.50 (1.00)
322	$0.070 \times \frac{m_{\tilde{\mu}_R}}{100\,\mathrm{GeV}}$	$0.52 \times \frac{m_{\tilde{s}_R}}{100\,\mathrm{GeV}}$ (1.12)	-
321	$0.070 \times \frac{m_{\tilde{\tau}_R}}{100\,\mathrm{GeV}}$	$0.52 \times \frac{m_{\tilde{b}_R}}{100\,\mathrm{GeV}}$ (1.12)	0.50 (1.00)
331	-	0.45 (1.04)	0.50 (1.00)
332	-	0.45 (1.04)	0.50 (1.00)
333	-	0.45 (1.04)	-

LLe : λ < 0.5 — 0.7 at 1 TeV

LQd : λ' < 0.2 — O(1) at 1 TeV

udd : λ'' < O(1) at 1 TeV

Strongest bounds from neutrino masses and $0\nu\beta\beta$ and $N - \bar{N}$ oscillations

Original numbers quoted at 100 GeV

[D. Dercks, H. Dreiner, M. E. Krauss, T. Opferkuch and A. Reinert (2017)]

RPV Collider Searches

$$W_{\not{R}_P} = \frac{1}{2}\lambda_{ijk}L_iL_je^c_k + \lambda'_{ijk}L_iQ_jd^c_k + \mu'_iL_iH_u + \frac{1}{2}\lambda''_{ijk}u^c_id^c_jd^c_k$$

In discussing searches for RPV, strategies differ by operator, and often even the {*i*,*j*,*k*}-generation indices of the operator.

LQd : Squarks behave like leptoquarks with this operator.

- $L_3Q_3d_3$: Can generate $\tilde{t} \to \tau b$ and $\tilde{b} \to t\tau$, competing with RPC decays.

udd : Squarks behave as diquark resonances, but perhaps more importantly, neutralinos can decay to 3 jets.

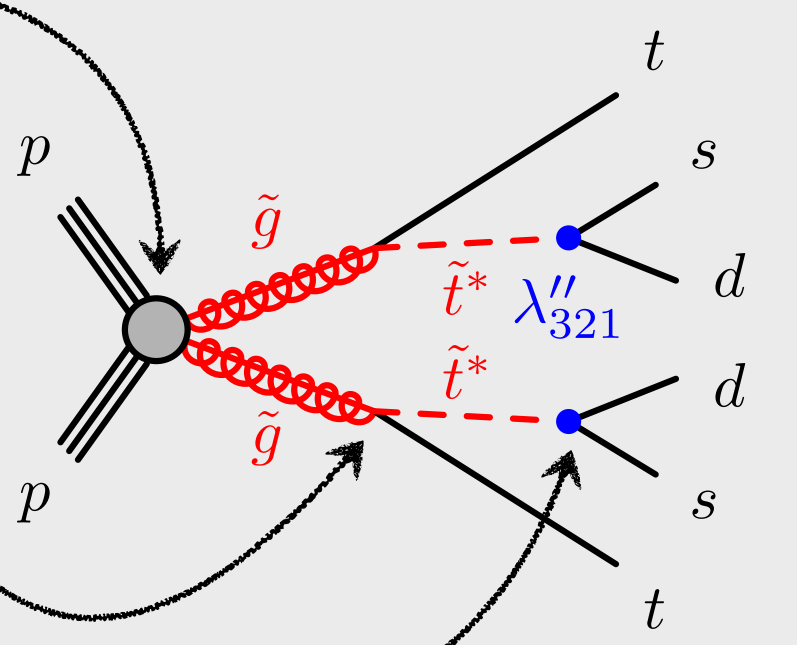
LH_u : Called *bRPV* scenario, can generate neutrino-Higgsino mixing (also sneutrino-Higgs mixing), leading to $\tilde{H} \to W\tau$, possibly correlated with $\tilde{H} \to W\mu$.

Even though UV models may generate multiple RPV operators, it is technically natural to talk about them one at a time, since operator coefficients set to zero will not be generated by loops, thanks to non-renormalization theorem.

RPV Collider Searches

Most collider searches for RPV follow a similar pattern:

- Production of SUSY in pairs begins with (R_P-conserving) strong interactions.
- Decays typically proceed by R_P-***conserving*** interactions until no longer possible (*i.e.,* decay to LSP).
- LSP decays through R_P-***violating*** interactions, either promptly (for “large couplings”) or with displaced vertex (for “small couplings” within a limited range).

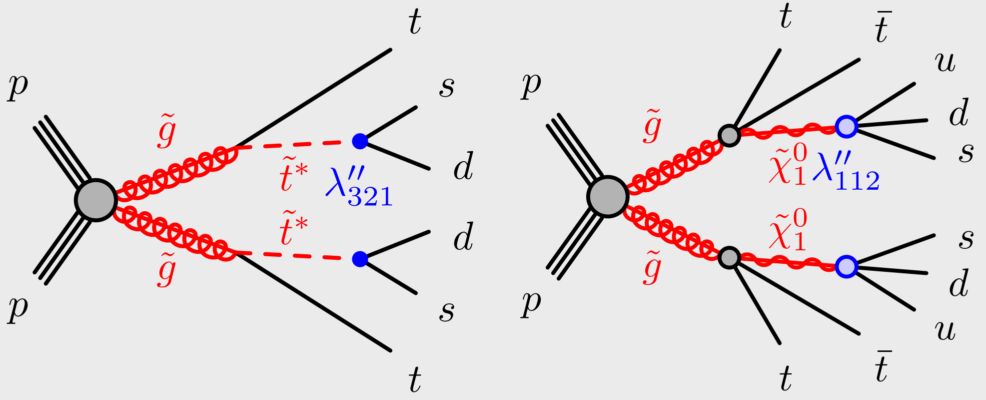


[Fig by ATLAS]

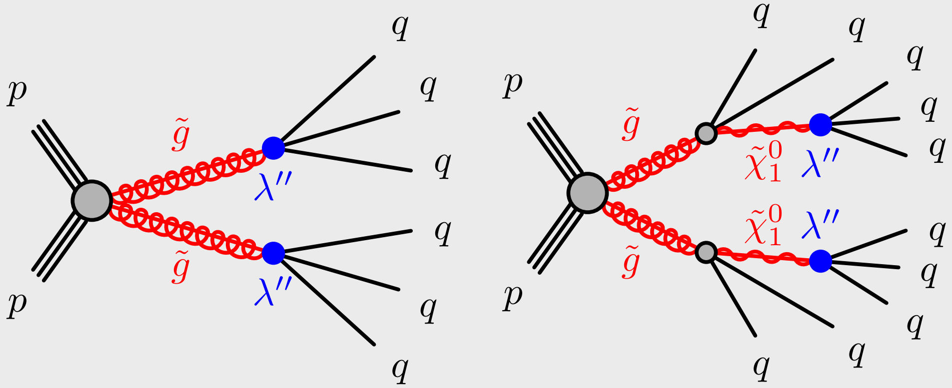
Collider Searches - RPV Decays

For **B-violating RPV** (*i.e., UDD* scenario):

- Final state dominated by jets.
- Searches strategies at hadron colliders include:
  - gluino pair production, with tops among gluino decay products (decaying to lepton(s)), and stops or neutralinos decaying to jets.



  - gluino pair production decaying directly or indirectly to *n*-jets, for large *n*



Basic strategy

1. Pair produce gluinos (or squarks) thru strong interaction.

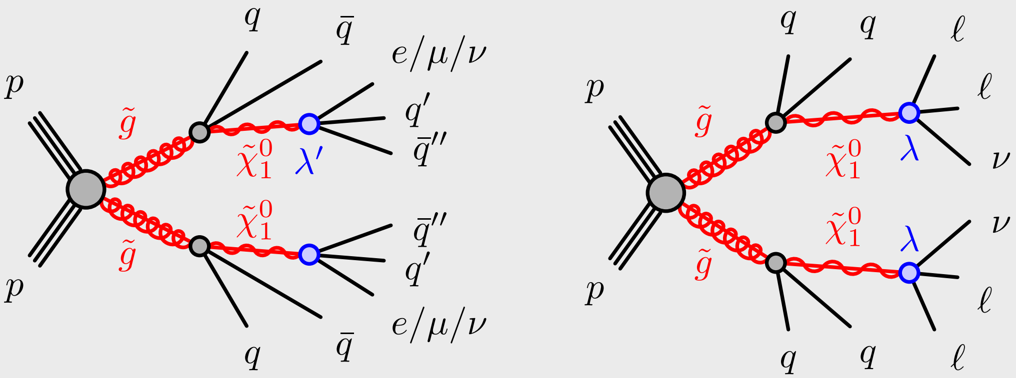
2. After gluino decays, decay final state(s) using RPV couplings into quark jets.

Role of RPV entirely in final step of the decay cascade!

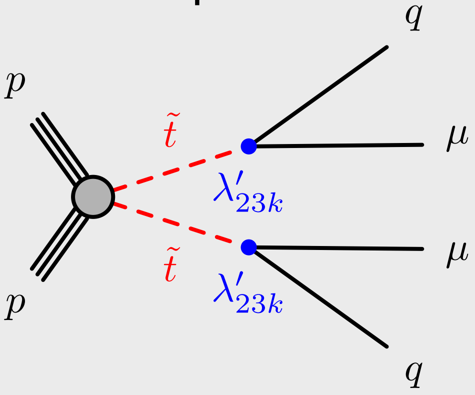
Collider Searches - RPV Decays

For **L-violating RPV** (*i.e., LQD or LLE* scenario):

- Final state has one or more leptons!
- Searches strategies at hadron colliders include:
  - gluino pair production, cascading down to LSP which has 1+ leptons among decay products



  - stop production, with stops decaying directly to quarks and leptons.



Basic strategy

1. Pair produce gluinos (or squarks) thru strong interaction.

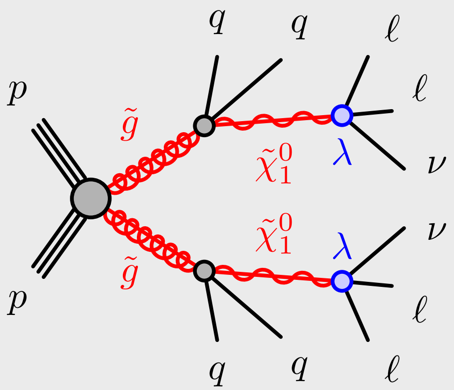
2. After gluino decays, decay final state(s) using RPV couplings into quark jets plus leptons, or leptons and missing energy.

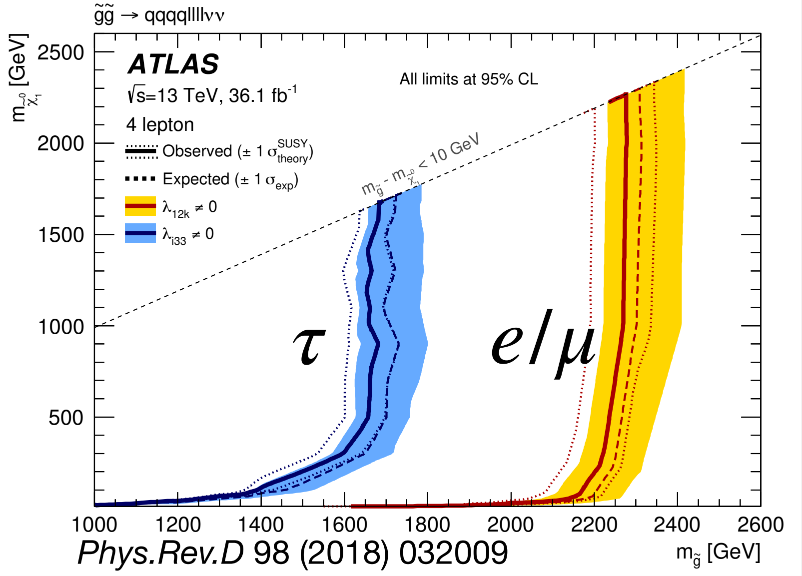
Role of RPV entirely in final step of the decay cascade!

Collider Searches - RPV Decays

Bounds on sparticles in RPV models are typically similar to those in RPC models:

***LLE* Scenario**





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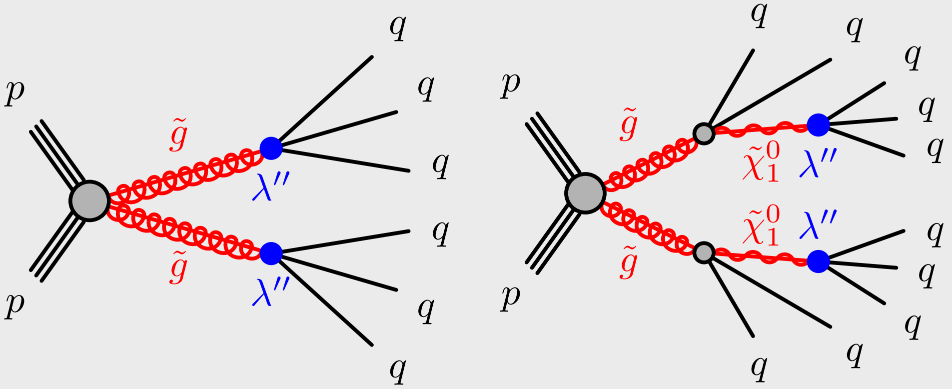
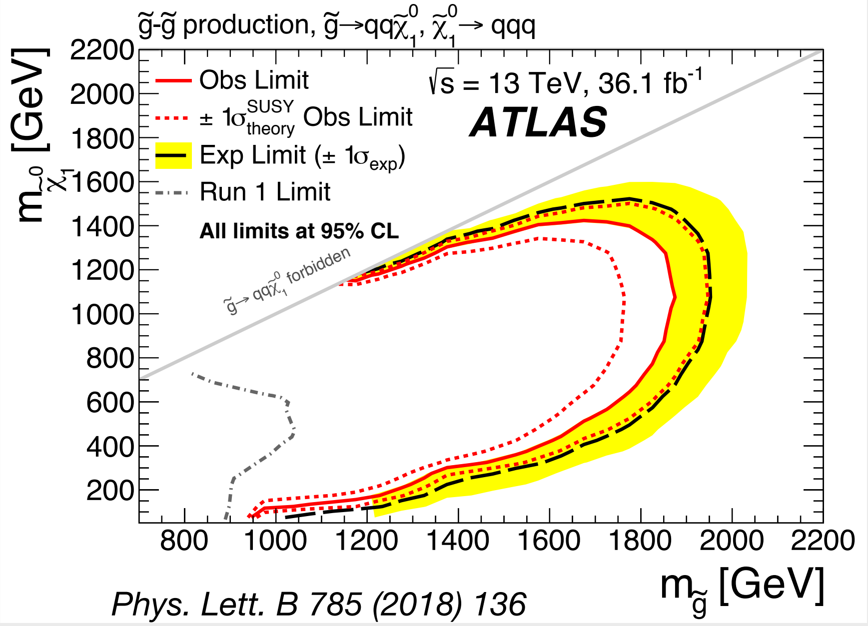
***UDD* Scenario**





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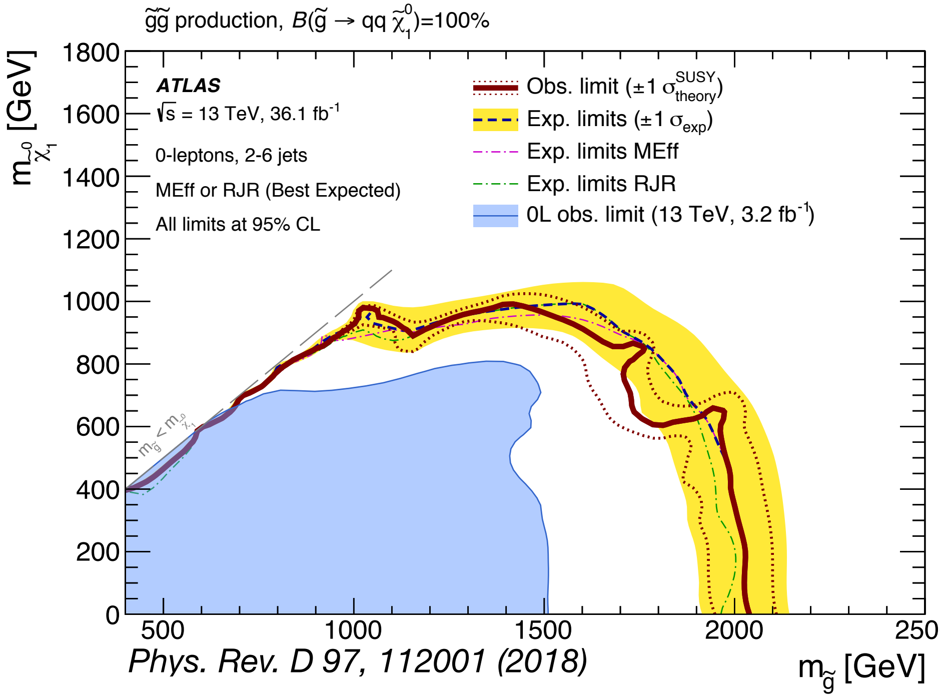
Collider Searches - RPV Decays

Bounds on sparticles in RPV models are typically similar to those in RPC models:

RPC SUSY



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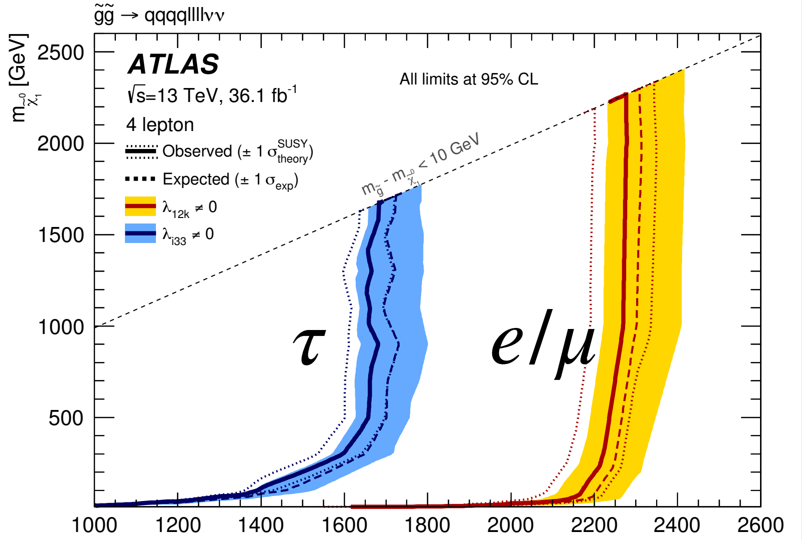

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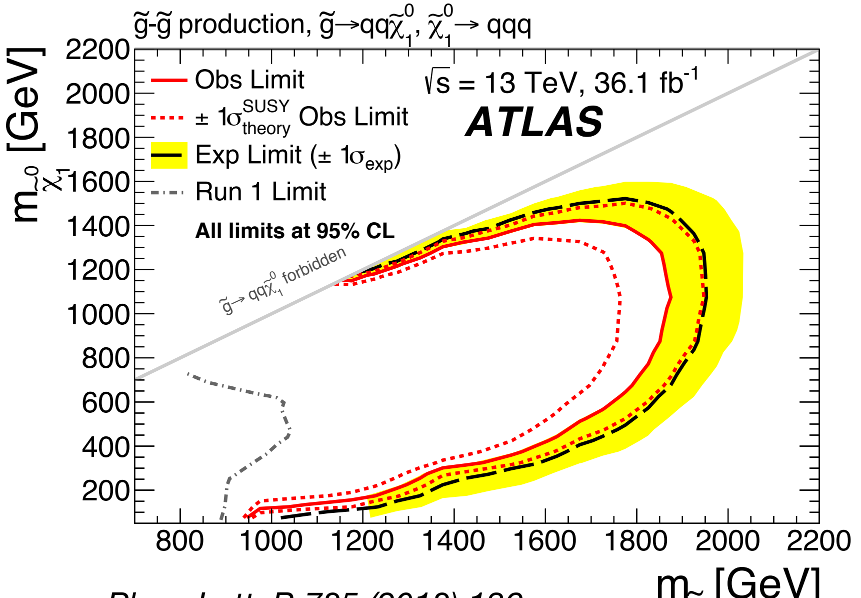

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Collider Searches - RPV Decays

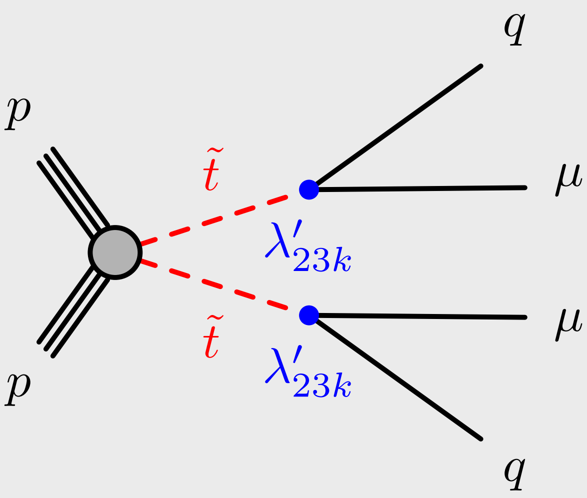
For **small RPV couplings**:

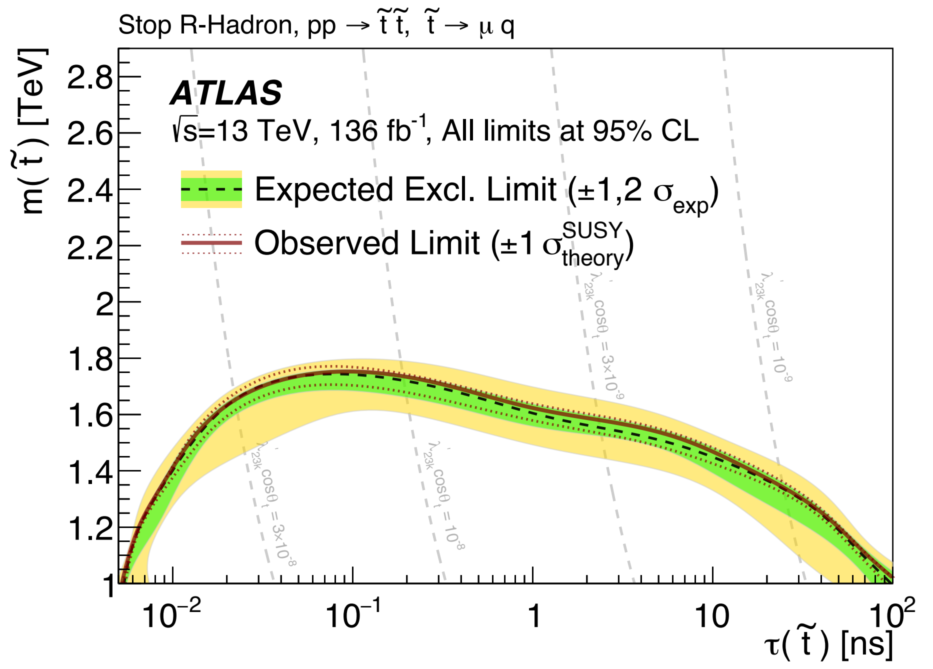
- Couplings within some range lead to displaced vertices.

Example: ATLAS searches for displaced vertices in stop LSP scenarios with LQd RPV couplings place bounds on stops approaching 1-1.8 TeV for the range:

$$10^{-9} < \lambda'_{23k} < 10^{-7}$$

corresponding to decay lengths of mm to 10’s of meters.





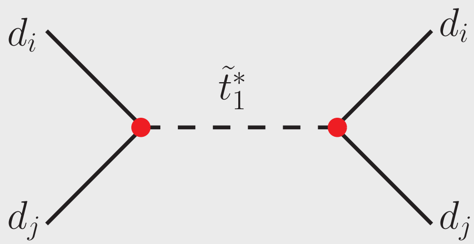
arXiv:2003.11956

Collider Searches - RPV Production

Unlike R_P-conserving SUSY, in RPV sparticles can be singly produced:

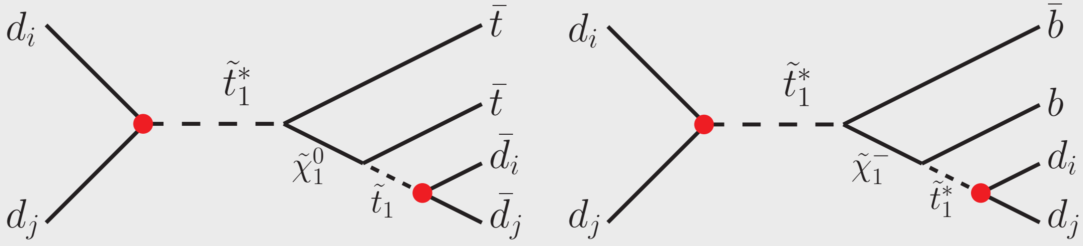
For **B-violating RPV** (*i.e., UDD* scenario):

- Squarks can be produced singly
- Will decay either through same RPV coupling back to quarks …



… or through R_P-conserving interactions in a cascade, to LSP.

- LSP then decays to quark jets.



Advantage:

- Because this is single production, limits are roughly twice as strong as typical pair production bounds!

Disadvantage:

- Because sparticle can decay through RPC *or* RPV couplings, decay chain introduced lots of model dependence.

Collider Searches - RPV Production

For **L-violating RPV** (*i.e., LQD* and *LLE* couplings):

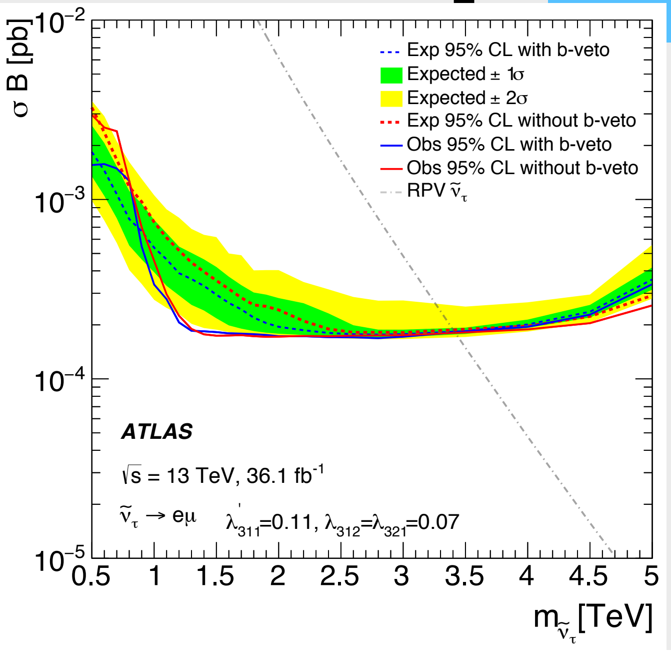
- LLE couplings only relevant for production in future lepton colliders

- LQD couplings produce sleptons at hadron colliders
  - slepton can decay promptly back to dijets
  - OR, slepton can cascade decay to LSP, and then to dijets.

Mimics the UDD scenario from previous slides

- Both LQD *and* LLE together allow for production of sleptons in any collider, and then decay to leptons, but competition between dijet final state and dilepton final state always present.

Mimics searches for Z' decaying to dileptons and dijets



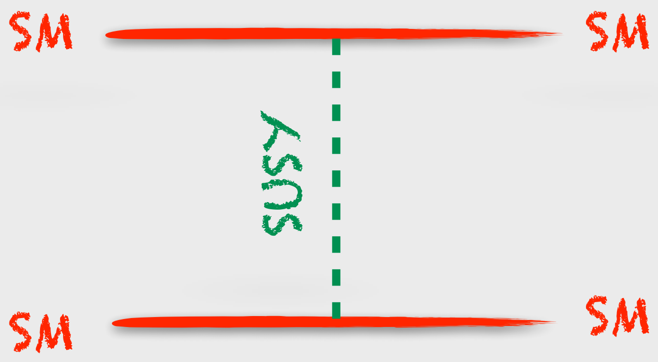
$$\lambda'_{311} = 0.11$$
$$\lambda_{312} = 0.07$$
$$\lambda_{321} = 0.07$$

These searches are highly model-dependent, with signals depending on both spectrum and couplings in a multi-dimensional parameter space!

Phys.Rev.D 98 (2018) 092008

Collider Searches - Virtual RPV

- Virtual sparticle exchange/deviations in SM processes.



Tree-level exchange of sparticles can generate observable deviations in SM processes even for sparticle masses too heavy for on-shell production. Perfect target for Energy Frontier.

In heavy mass/decoupling limit, $\mathscr{M} \propto \lambda^2/\tilde{m}^2$, for a **single coupling** λ.

Two simplest processes to consider at hadron colliders:

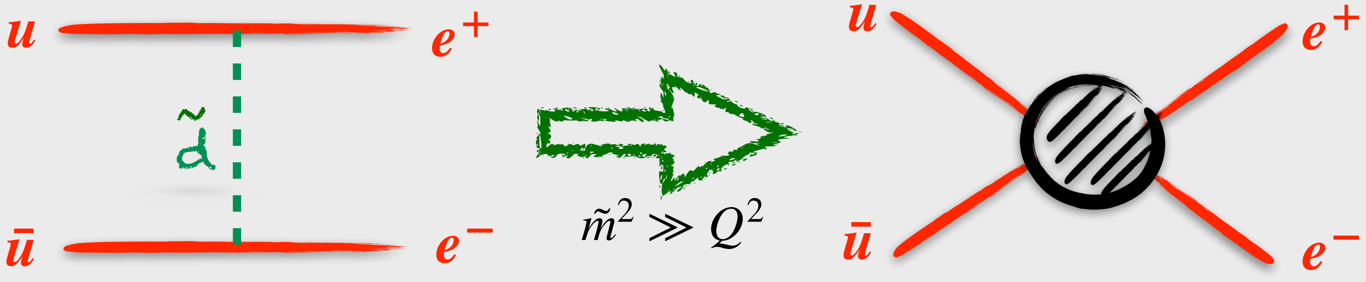
- Drell-Yan scattering thru LQd operator.
- Dijet production thru LQd or uud operators

At lepton colliders, both LLe and LQd can be probed.

Collider Searches - Virtual RPV

At large masses, this approaches the limit of an effective operator analysis:

- Consider the $\lambda'_{11k} L_1 Q_1 d^c_k$ coupling, for $m^2_{\tilde{d}_k} \gg Q^2$ for all relevant Q^2.



$$\frac{(\lambda'_{11k})^2}{m^2_{\tilde{d}_R}}(LQ)(LQ)$$

After Fierzing and comparing to LHC results:

$$m_{\tilde{d}_R} \gtrsim 17\,\mathrm{TeV}\ \ (\text{if } \lambda' = \sqrt{4\pi}) \implies m_{\tilde{d}_R} \gtrsim 4.8\,\mathrm{TeV}\ \ (\text{if } \lambda' = 1)$$

Limitations of effective operator approach:

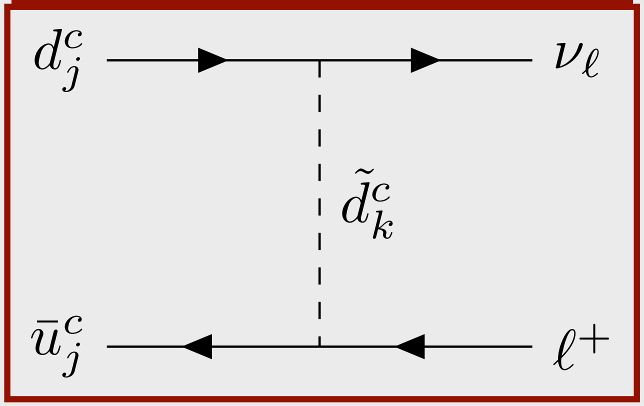
- Effective operator is not really “effective” for *O*(TeV) sparticles.
- Each RPV coupling yields multiple processes and multiple effective operators!

Collider Searches - Virtual RPV

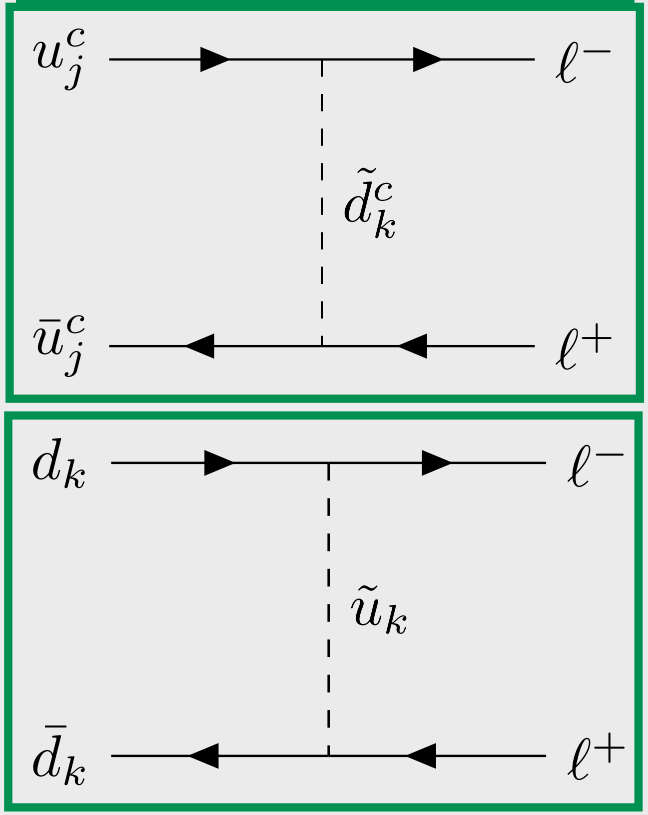
- The Lagrangian for the λ’ term:

$$\mathscr{L} = \lambda'_{ijk}\Big[\Big(\bar{d}^c_j P_L \nu_i - \bar{u}^c_j P_L \ell_i\Big)\tilde{d}^c_k + \Big(\bar{d}_k P_L \nu_i \tilde{d}_j - \bar{d}_k P_L \ell_i \tilde{u}_j\Big) + \Big(\bar{d}_k P_L d_j \tilde{\nu}_i + \bar{d}_k P_L u_j \tilde{\ell}_i\Big)\Big]$$

Monolepton



Dilepton



Good news:

Shares most of the same systematics, backgrounds, etc. with the dim-6 EFT analyses in Drell-Yan and dijet production.

An Analysis of LQd at LHC

- Previous work: In two papers we* used DY events from 36 $\text{fb}^{-1}$of data from ATLAS to obtain bounds on the 27 LQd couplings and associated squark masses from differential cross sections, similar to techniques used by ATLAS and CMS for their 4-fermion operator analyses.

** = S. Bansal, A. Delgado, CK and M. Quiros*
[Phys Rev D99, 093008 (2019), arXiv:1812.04232]
[Phys Rev D100, 093005 (2019), arXiv:1906.01063]

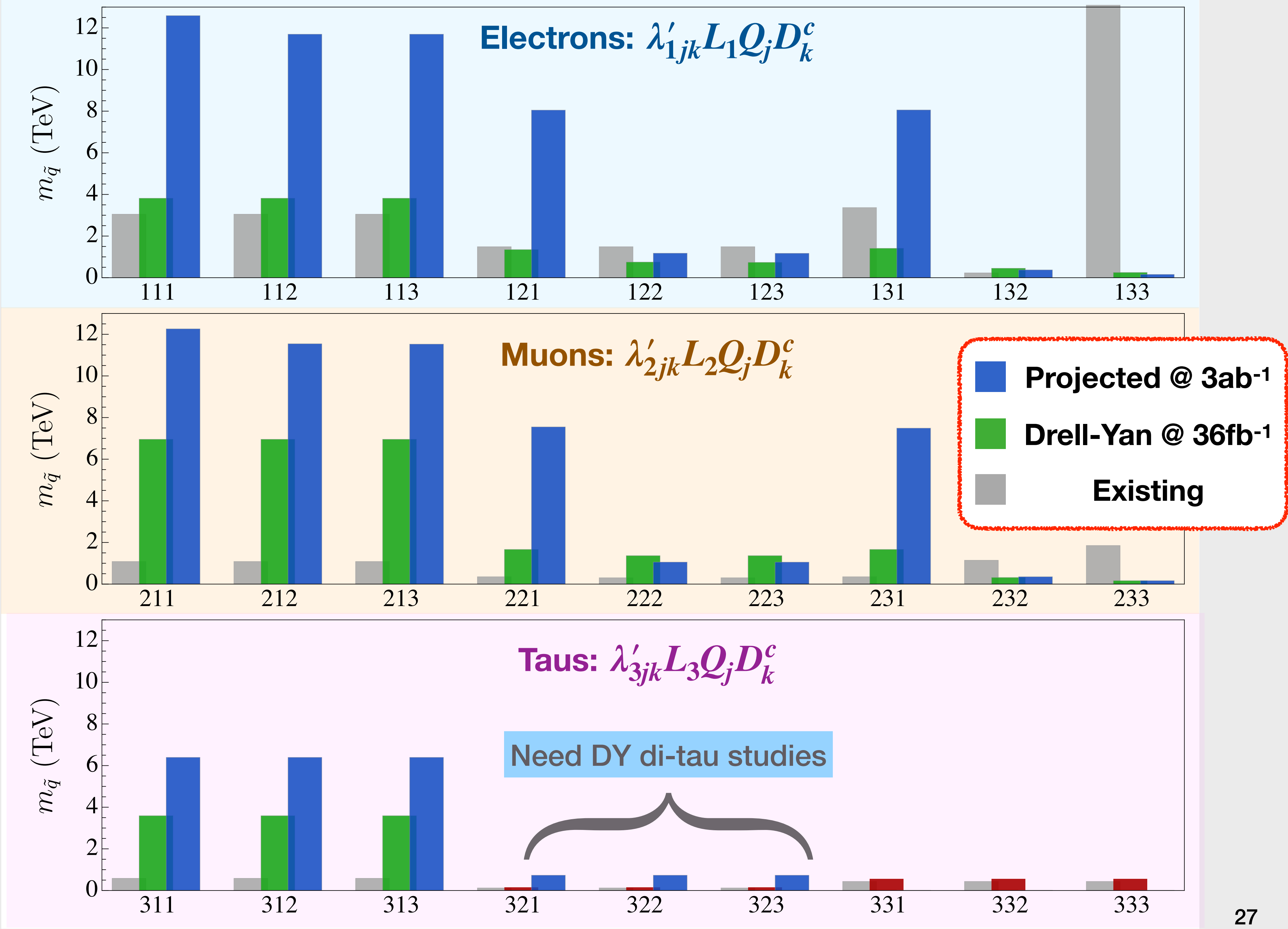
- From existing data, we found bounds on 15 of 27 couplings that are stronger than those in literature.

- Projection for HL-LHC also made, pushing some mass bounds above 10 TeV for weak-strength couplings ($\lambda = 0.64$).

- Because no on-shell sparticles are created, these searches continue to gain power rapidly with increased luminosity, not just increased energy.

Current & Future Limits

$\lambda' = 0.64$



Need DY di-tau studies

Work to be Done

- This analysis was possible thanks to ATLAS working out their systematics, efficiencies, backgrounds, etc, bin-by-bin for most of their DY data.
  - Di-tau final states at HL-LHC have not been estimated.
  - To extend to future colliders, estimates of all of these will need to be done.
  - But analysis should share most of these with EFT/four-fermion operator analyses.
- The uud dijet case is currently being studied by part of Notre Dame group (Bansal, Delgado, Kim and Martin). Based on published compositeness limits, current bounds on *uds* and *udb* interactions should be somewhere around 2-3 TeV for $\lambda''_{11k} = 0.64$.
- The LLe case for lepton colliders remains to be done.
- NLO corrections to LQd and udd operators at hadron colliders are probably significant — may boost signal rate significantly.

RPV: A Multi-Pronged Approach

Searching for RPV SUSY at the LHC benefits from a multi-prong approach:

- For RPV couplings that are extremely small $(\lesssim 10^{-8})$:
  - sparticles are pair produced thru gauge/RPC interactions,
  - cascade down to LSP, and
  - LSPs decay with displaced vertices.

  Searches already underway at ATLAS/CMS, more planned for future.

- For RPV couplings that are moderately small $(10^{-8} \lesssim \lambda^{(',")} \lesssim 0.1)$:
  - Traditional RPV signals, following above, but with prompt LSP decay to leptons or jets.

- For RPV couplings that are sizable $(\gtrsim 0.1)$:
  - Search for s-channel production, mimicking *Z'* analyses.
    - Doubles mass reach, but very model dependent!

  - Study deviations in differential cross sections, *à la* 4-fermion operator or compositeness analyses.
    - *Model-independent, probing to O(5 TeV) now, O(20 TeV) for HL-LHC.*
    - *Could potentially be go much higher (or to much smaller couplings) with next-generation colliders.*
    - *Steady improvement in reach not just with* $\sqrt{s}$ *but also* $\mathscr{L}_{\text{int}}$.