Overview on RPV SUSY

Saurabh Nangia (BCTP, Uni Bonn)

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Roadmap

- The RPV MSSM:
  Of Theorists' Dreams & Experimentalists' Nightmares
- Pheno 1: Taming the RPV Landscape
- Pheno 2: The Future is Bright
- Pheno 3: Let there be Light (SUSY)
- Outlook

The RPV MSSM

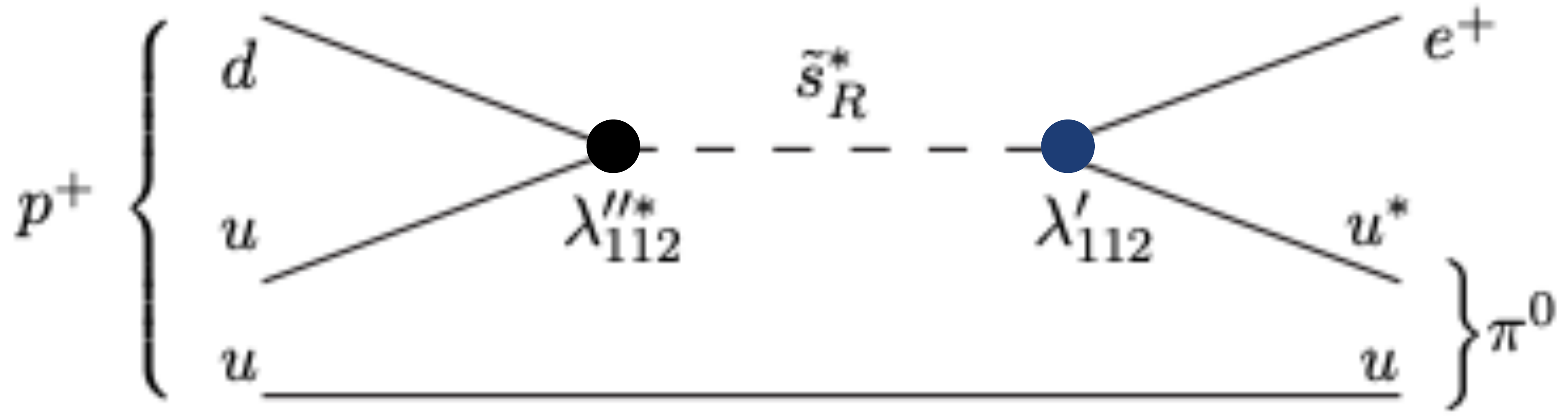
- Minimal SUSY: Poincare (+SUSY) invariance, SM gauge, MSSM content

$$W = W_{\text{MSSM}} + \lambda_{ijk}\, \mathrm{L^iL^jE^k} + \lambda'_{ijk}\, \mathrm{L^iQ^jD^k} + \kappa_i\, \mathrm{L^iH^d} \quad \text{LNV}$$
$$+\lambda''_{ijk}\, \mathrm{U^iD^jD^k} \quad \text{BNV}$$

- LNV + BNV

Proton decay

Bound ~ 10^{34} yrs



The RPV MSSM

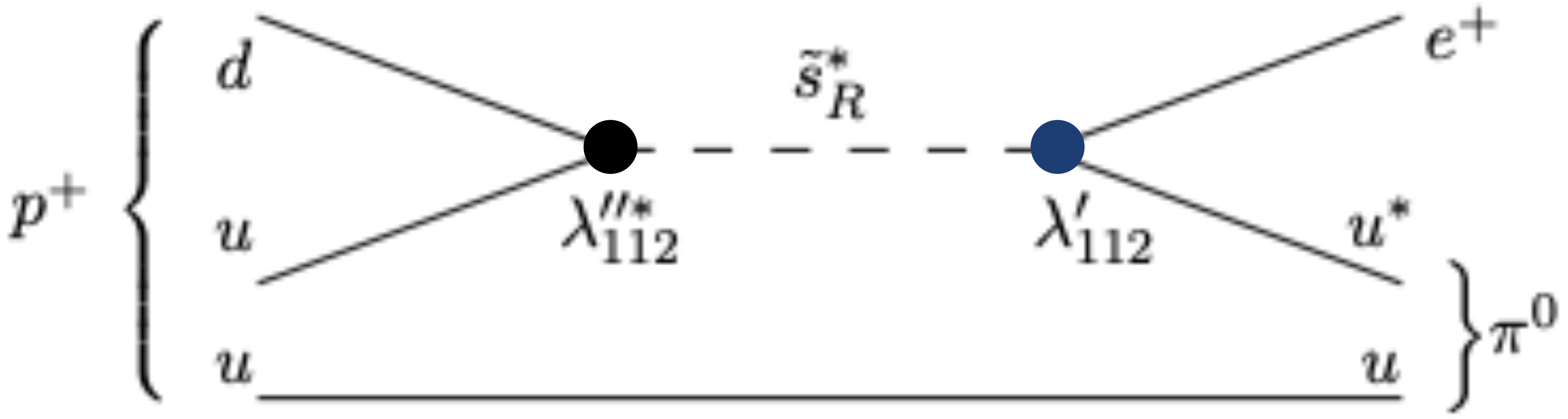
- MSSM: Impose R-parity

$$R = (-1)^{3(B-L)+2s} = \begin{cases} +1 \text{ for SM particles, higgses} \\ -1 \text{ for SUSY particles} \end{cases}$$

- $W = W_{\text{MSSM}} + W_{\text{LNV}} + W_{\text{BNV}}$ Proton stable! (@ tree-level)

The RPV MSSM

- But to protect the proton removing either ● or ● can be sufficient



- Indeed R is excessive! Baryon triality B_3 protects the proton (even better than R!)

$$W_{\text{RPV}} = W_{\text{MSSM}} + W_{\text{LNV}} + W_{\text{BNV}}$$

The RPV MSSM

Drastic changes RPV vs MSSM:

- Lightest SUSY particle (LSP) is stable -> no longer!

  (odd in R)

- LSP is neutralino -> no longer!

  (no longer DM candidate)

  LSP $\in \{\chi_1^0, \chi_1^+, \tilde{\nu}_L, \tilde{\ell}^{\pm}_{L,R}, \tilde{\tau}_1^{\pm}, \tilde{q}_{L,R}, \tilde{t}_1, \tilde{g}\}$

SUSY signature no longer MET!

- Single SUSY production possible

Colliders can have 2x reach!

The RPV MSSM:
A Theorist's Dream

RPV has many nice features; all following from minimal SUSY:

- Ingredients for baryogenesis

- Ingredients for neutrino masses

- Ingredients for LFUV, muon (g-2), leptoquarks, etc.

- Playground for many new opportunities: lepton PDFs, Long Lived Particles, etc.

The RPV MSSM:
An Experimentalist's Nightmare

- Vanilla MSSM:

  SUSY pair production —> Decay to Neutralino LSP —> MET signature

- RPV SUSY:

$$\text{sig.} = \begin{pmatrix} \tilde{q}\tilde{q} \\ \tilde{q}\tilde{g} \\ \tilde{g}\tilde{g} \\ \tilde{\ell}^+\tilde{\ell}^- \\ \tilde{\nu}\tilde{\nu} \\ \tilde{\chi}^0\tilde{\chi}^\pm \end{pmatrix}_{\text{prod}} \otimes \begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_1^\pm \\ \tilde{\nu}_i \\ \tilde{\ell}_i^\pm \\ \tilde{\tau} \\ \tilde{q} \\ \tilde{b} \\ \tilde{t} \\ \tilde{g} \end{pmatrix}_{\substack{\text{possible} \\ \text{LSP}}} \otimes \begin{pmatrix} L_1 L_2 \bar{E}_1 \\ \cdots \\ L_1 Q_1 \bar{D}_1 \\ \cdots \\ \bar{U}_3 \bar{D}_2 \bar{D}_3 \end{pmatrix}_{\substack{\text{LSP} \\ \text{decay}}}$$

45 couplings!

Pheno 1: Taming the RPV Landscape

How well can we exclude SUSY?

Vanilla MSSM	RPV MSSM
-> Missing energy searches	-> ?
-> Coloured sector upto $\mathcal{O}$(TeV)	-> ?

Have we systematically investigated RPV MSSM?

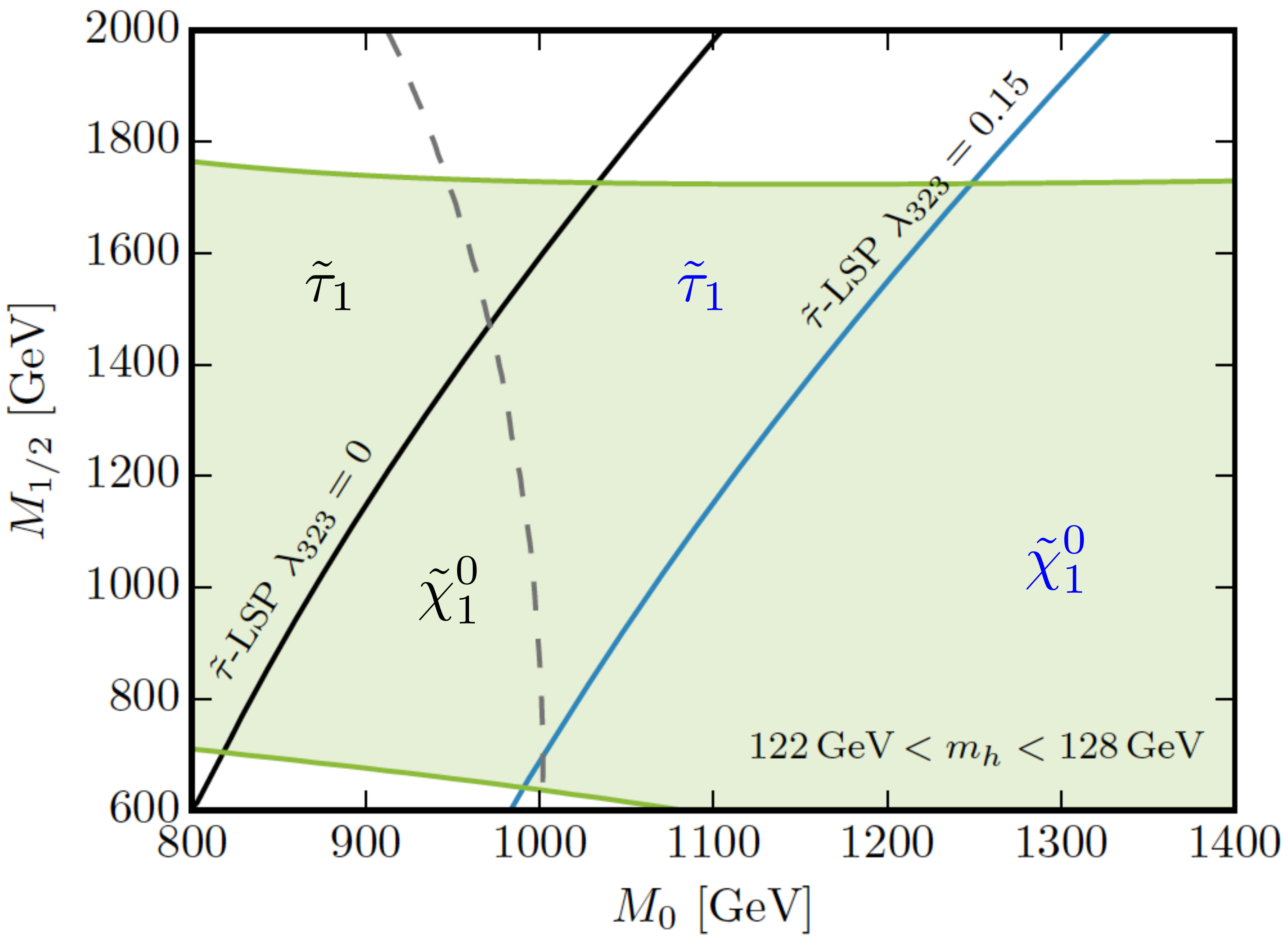
arXiv: 1706.09418 [Dreiner et al.]

Pheno 1: Taming the RPV Landscape

Assumptions:

- Work in CMSSM
  Spectrum fixed by 5 parameters
  LSPs: $\tilde{\chi}^0_1$, $\tilde{\tau}$ mainly

LSP	Required Couplings
$\tilde{\chi}^0_1$	$\Lambda_{\not R_p} \ll 1$ or large M_0
$\tilde{\tau}_1$	$\Lambda_{\not R_p} \ll 1$, small M_0 and large $M_{1/2}$
$\tilde{\tau}_1$	λ_{ij3} (dominantly $\tilde{\tau}_R$), λ'_{3jk} ($\tilde{\tau}_L$)
$\tilde{e}_R$	λ_{ij1}
$\tilde{\mu}_R$	λ_{ij2}
$\tilde{\nu}_e$	λ'_{1jk}, $\{j,k\} \neq \{1,1\}^{\ddagger}$
$\tilde{\nu}_\mu$	λ'_{2jk}
$\tilde{s}_R, \tilde{d}_R$	λ''_{212} (degenerate LSPs)
$\tilde{b}_1$	λ''_{123}, λ''_{213}, $\lambda''_{223}{}^{\ddagger}$ (dominantly $\tilde{b}_R$)
$\tilde{t}_1$	λ''_{3jk} (dominantly $\tilde{t}_R$)



$$A_0 = -3\,\text{TeV},\ \tan\beta = 30$$

Pheno 1: Taming the RPV Landscape

Main take away message:

- Can reduce RPV scenarios to set of few signatures

$$\{\text{LSP, coupling}\} = \{\tilde{q}\,, \lambda''_{312}\}$$

$\tilde{q}$ →

$\tilde{B} + j \to \tilde{H} + \nu + j \to \tilde{t} + \nu + t + j \to \nu + t + 3j$

$\tilde{g} + j \to \tilde{t} + t + j \to t + 3j$

$\tilde{g} + j \to \tilde{d} + 2j \to t + 3j$

$\tilde{B} + j \to \tilde{t} + t + j \to t + 3j$

$\tilde{B} + j \to \tilde{d} + 2j \to t + 3j$

- Used this to identify gaps: Few in $\tilde{\chi}^1_0$ case; more in $\tilde{\tau}$

- Recast existing searches to cover gaps: RPV coverage is comparable to RPC for CMSSM!

Pheno 1: Taming the RPV Landscape

LSP	LLE (I)	LL_3E (II)	LLE_3 (III)	LL_3E_3 (IV)
$\tilde{l}\,(\tilde{\nu})$	$(3l + E_T^{miss})$ / $4l$	$(2l + 1\tau + E_T^{miss})$ / $(2l + 2\tau)$	$(1l + 2\tau + E_T^{miss})$/ $(2l + 2\tau)$	$(3\tau + E_T^{miss})$/ 4τ
$\tilde{e}$	$(2l + E_T^{miss})$	$(2l + E_T^{miss})/(1l + 1\tau + E_T^{miss})$	$4l + 2\tau + E_T^{miss}$	$(4l + 2\tau + E_T^{miss})/(3l + 3\tau + E_T^{miss})$
$\tilde{\tau}\,(\tilde{\nu}_\tau)$	$(4l + 2\tau + E_T^{miss})$ / $(4l + 1\tau + E_T^{miss})$	$(3l + E_T^{miss})$/ $4l$	$(2l + 4\tau + E_T^{miss})$ / $(2l + 3\tau + E_T^{miss})$	$(2l + 2\tau)$/ $(1l + 2\tau + E_T^{miss})$
$\tilde{\tau}_R$	$4l + 2\tau + E_T^{miss}$	$(4l + 2\tau + E_T^{miss})/3l + 3\tau + E_T^{miss})$	$2l + E_T^{miss}$	$(2l + E_T^{miss})/(1l + 1\tau + E_T^{miss})$
$\tilde{g}$	$4l + 4J + E_T^{miss}$	$(4l + 4J + E_T^{miss})/(3l + 1\tau + 4J + E_T^{miss})$	$2l + 2\tau + 4J + E_T^{miss}$	$(2l + 2\tau + 4J + E_T^{miss})/(1l + 3\tau + 4J + E_T^{miss})$
$\tilde{q}/\tilde{u}/\tilde{d}$	$4l + 2j_l + E_T^{miss}$	$(4l + 2j_l + E_T^{miss})/(3l + 1\tau + 2j_l + E_T^{miss})$	$2l + 2\tau + 2j_l + E_T^{miss}$	$(2l + 2\tau + 2j_l + E_T^{miss})/(1l + 3\tau + 2j_l + E_T^{miss})$
$\tilde{t}_L(\tilde{b}_L)/\tilde{t}_R$	$(4l + 2j_3 + E_T^{miss})$	$(4l + 2j_3 + E_T^{miss})/(3l + 1\tau + 2j_3 + E_T^{miss})$	$(2l + 2\tau + 2j_3 + E_T^{miss})$	$(2l + 2\tau + 2j_3 + E_T^{miss})/(1l + 3\tau + 2j_3 + E_T^{miss})$
$\tilde{b}_R$	$(4l + 2b + E_T^{miss})$	$(4l + 2b + E_T^{miss})/(3l + 1\tau + 2b + E_T^{miss})$	$2l + 2\tau + 2b + E_T^{miss}$	$(2l + 2\tau + 2b + E_T^{miss})/(1l + 3\tau + 2b + E_T^{miss})$
$\tilde{B}/\tilde{W}/\tilde{H}$	$4l + E_T^{miss}$	$(4l + E_T^{miss})/(3l + 1\tau + E_T^{miss})$	$2l + 2\tau + E_T^{miss}$	$(2l + 2\tau + E_T^{miss})/(1l + 3\tau + E_T^{miss})$

Recently made more general

- All LSPs
- No assumptions about model

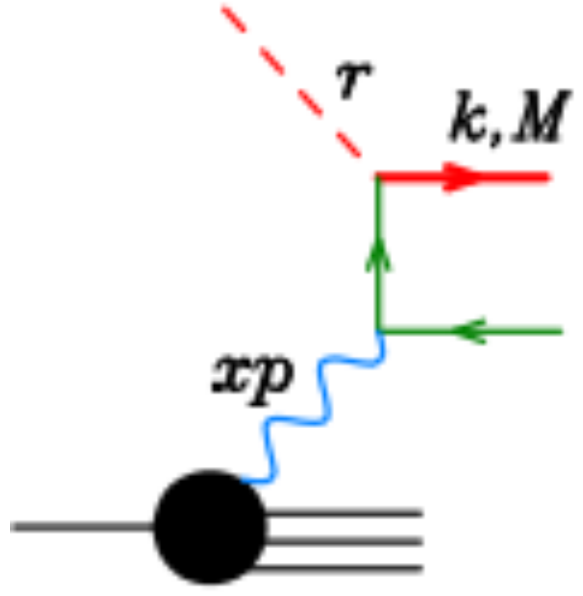
[work with H Dreiner, D Köhler, KY Sheng
in collab. with ATLAS, CMS]

- l: e/μ
- L: $e/\mu/\tau$
- j_l: light jet
- b: bottom jet
- t: top jet
- j_3: b/t
- J: j_l/j_3

1. Four leptons 1: $4L + E_T^{miss}$ (- or + 2J or +4J)
2. Four leptons 2: $4L$
3. Two leptons: $2L + E_T^{miss}$
4. Three leptons: $3L + E_T^{miss}$
5. Five leptons: $5L + E_T^{miss}$
6. Six leptons: $6L + E_T^{miss}$

Pheno 2: The Future is Bright

- Lepton PDFs in proton (suppressed but…)



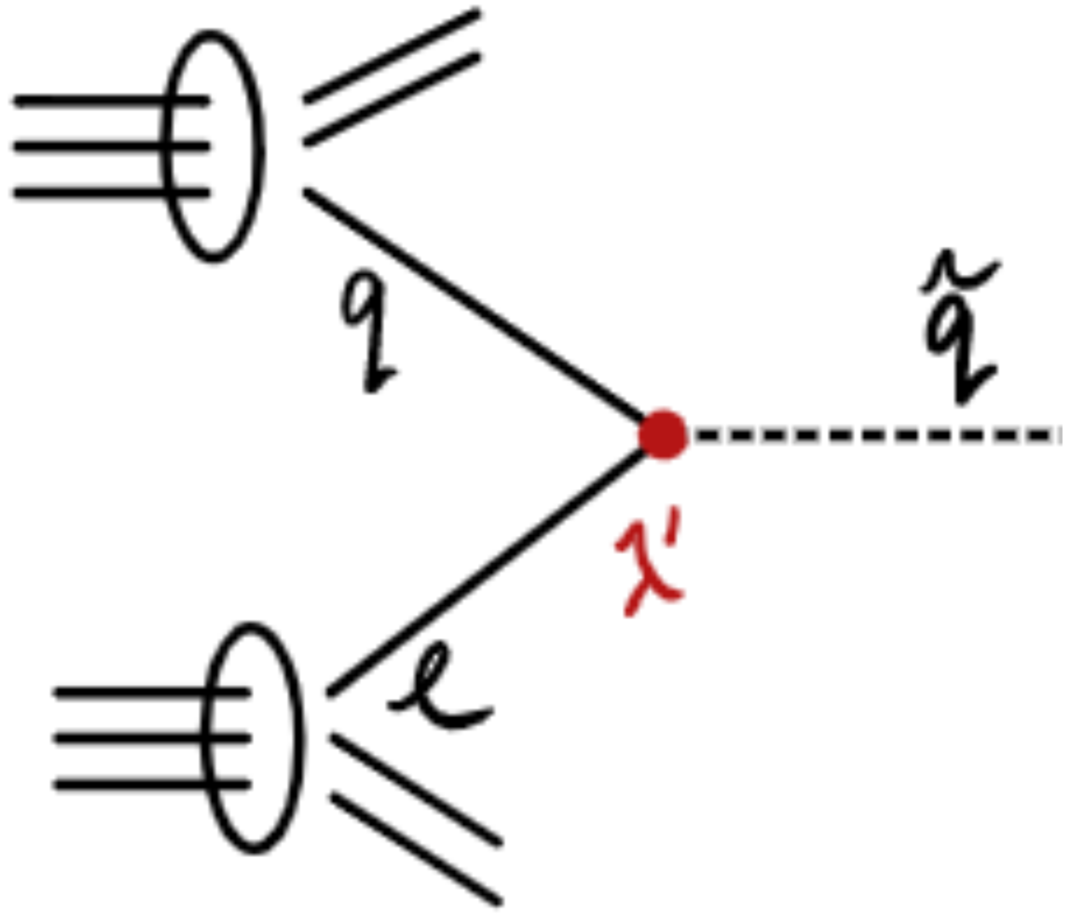
2 powers of α_{EM}

arXiv: 2005.06477 [Buonocore et al.]

- HL-LHC can overcome rare

  Currently 200 fb^-1, HL-LHC: 250 fb^-1 per yr

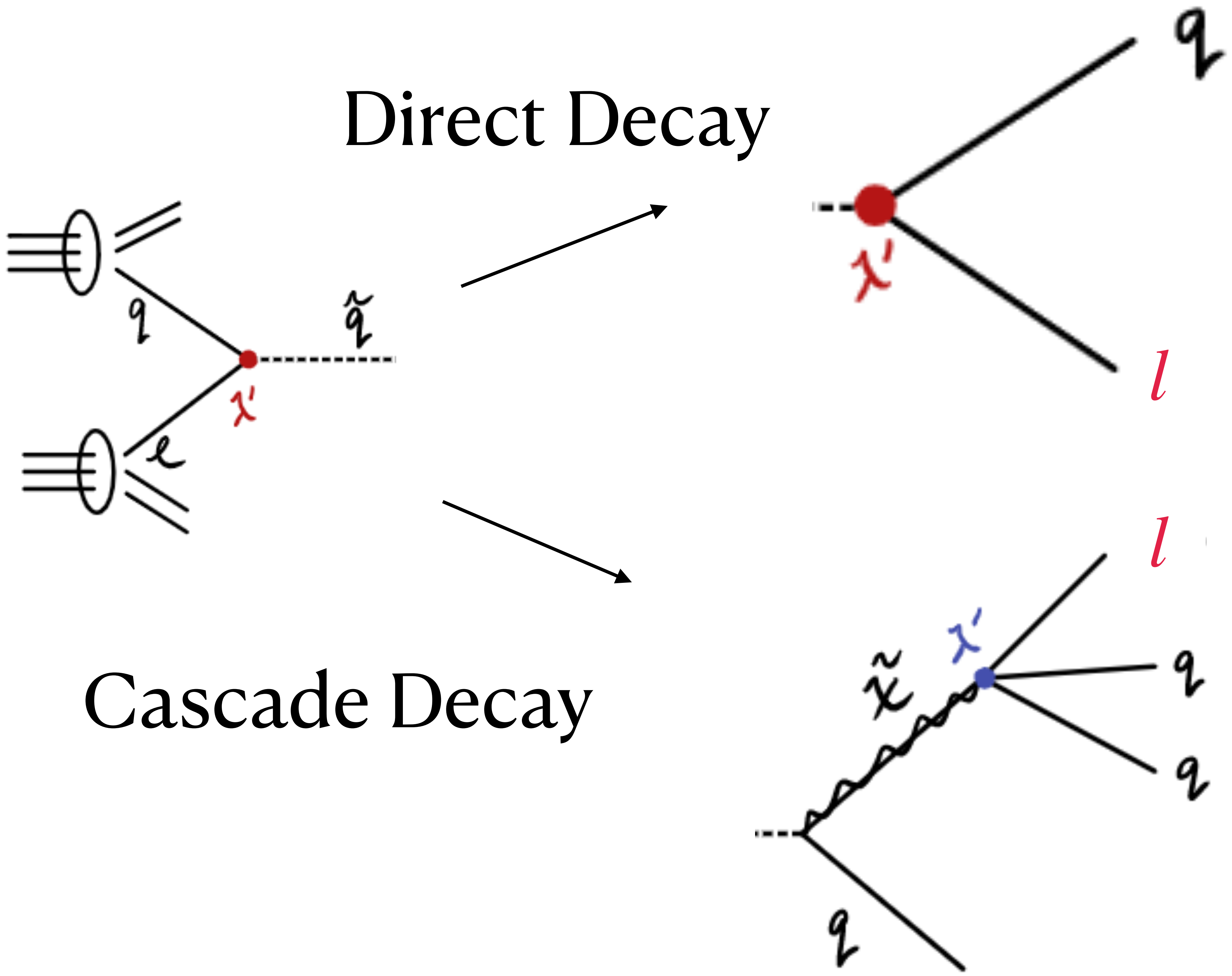
- Single production possible in RPV



2x Kinematic reach!

arXiv: 2112.12755 [work with H Dreiner, T Opferkuch, VM Lozano]

Pheno 2: The Future is Bright

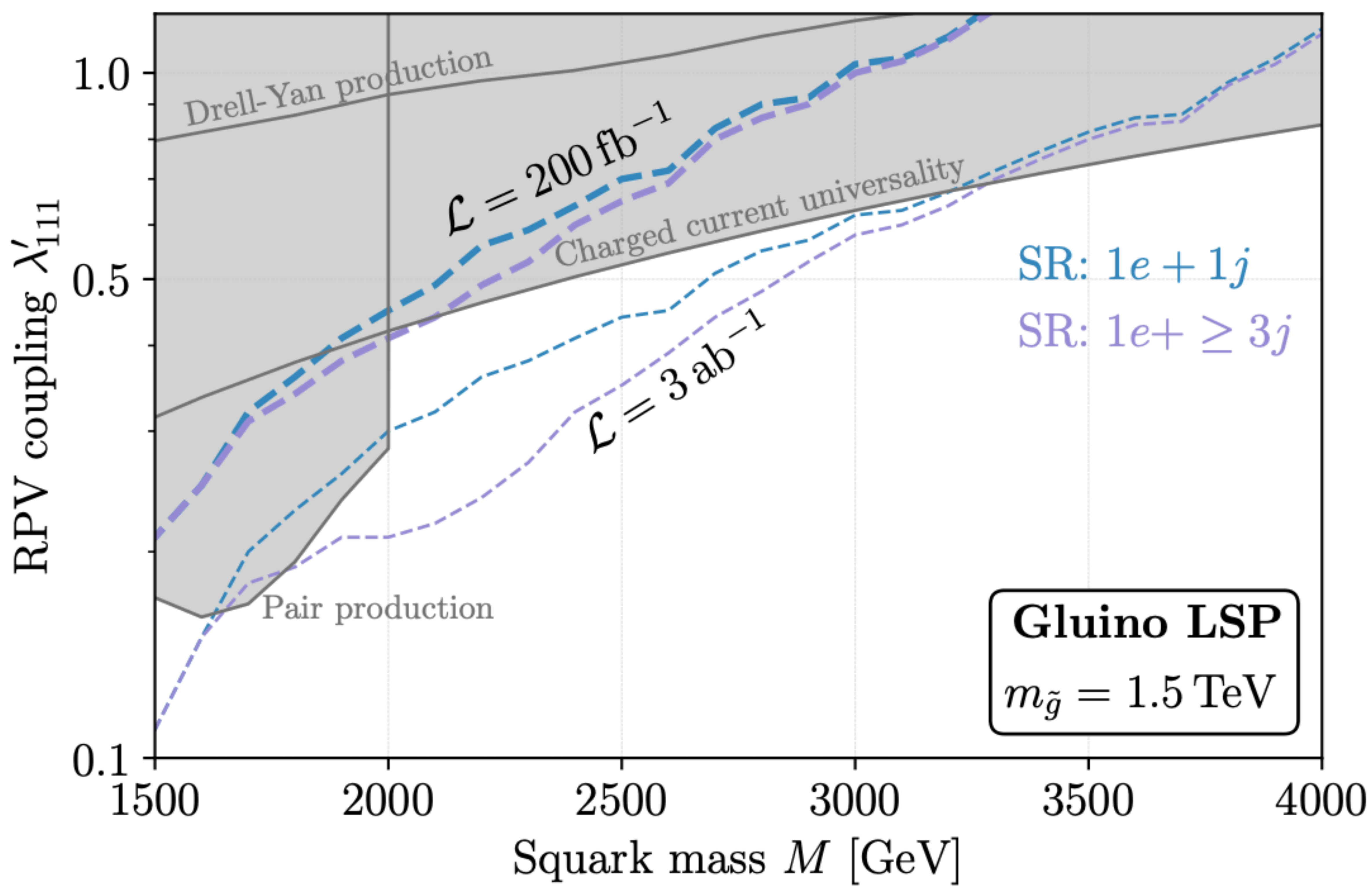


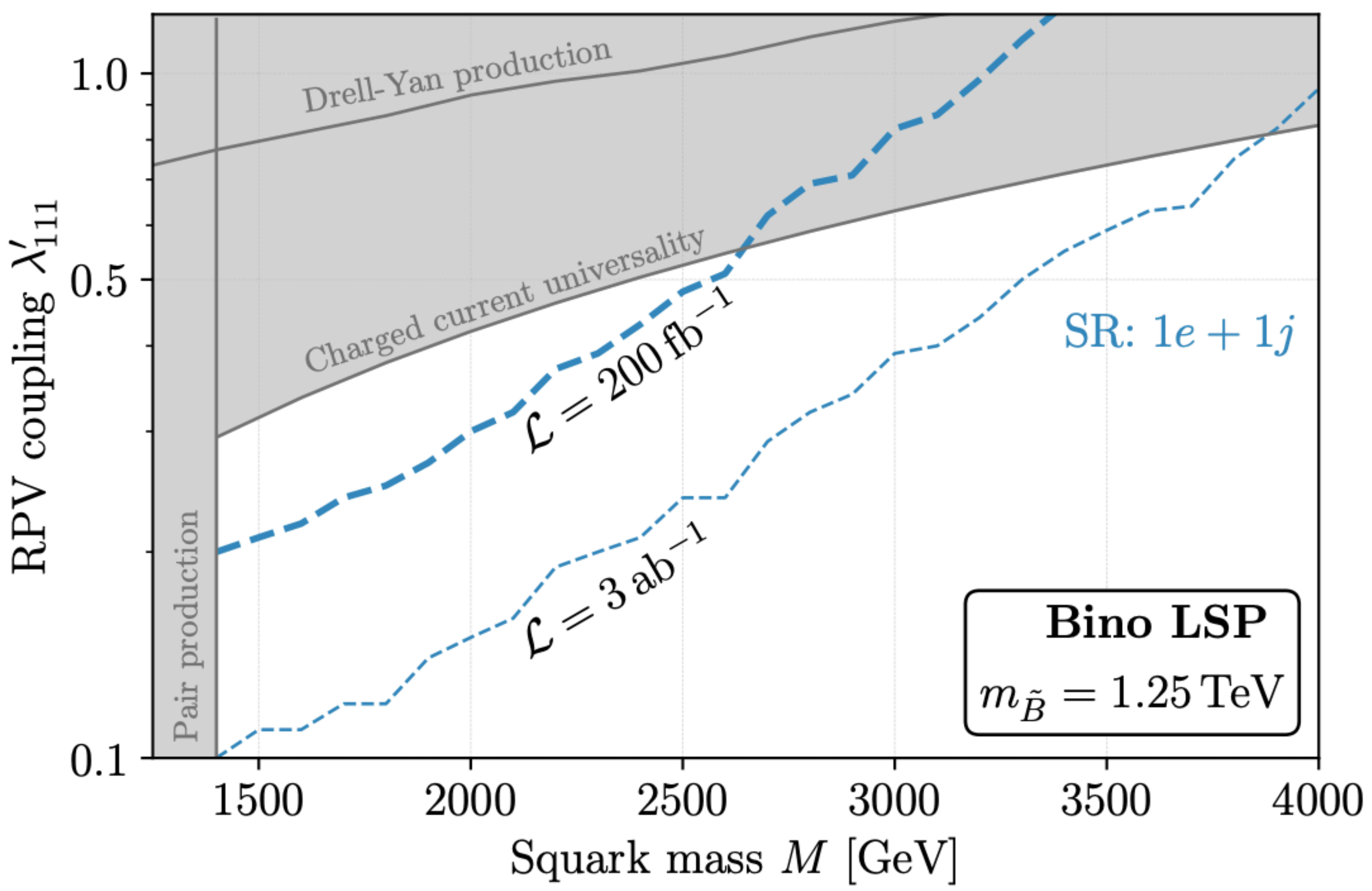
Both Single
Lepton Channels!

Very model independent!

Cascade End	Example	Signal
$\widetilde{B}$	$\tilde{d} \to \widetilde{B} + 1j$	$1\ell + 3j$
$\widetilde{W}$	$\tilde{d} \to \tilde{g} + 1j \to \tilde{q} + 2j \to \widetilde{W} + 3j$	$1\ell + 5j$
$\tilde{g}$	$\tilde{d} \to \tilde{g} + 1j$	$1\ell + 3j$
$\tilde{q}$	$\tilde{d} \to \tilde{g} + 1j \to \tilde{q} + 2j$	$1\ell + 3j$
$\tilde{d}$	–	$1\ell + 1j$
$\tilde{u}$	$\tilde{d} \to \tilde{g} + 1j \to \tilde{u} + 2j$	$1\ell + 5j$
$\tilde{l}$	$\tilde{d} \to \tilde{g} + 1j \to \tilde{q} + 2j$ $\to \widetilde{W}^0 + 3j \to \tilde{\ell} + 1\ell + 3j$	$1\ell + 5j$
$\tilde{v}$	$\tilde{d} \to \tilde{g} + 1j \to \tilde{q} + 2j$ $\to \widetilde{W}^{\pm} + 3j \to \tilde{v} + 1\ell + 3j$	$1\ell + 5j$
$\tilde{e}$	$\tilde{d} \to \widetilde{B} + 1j \to \tilde{e} + 1\ell + 1j$	$3l + 2j$

Pheno 2: The Future is Bright





Pheno 3: Let There be Light (SUSY)

- Is there still scope for light SUSY?

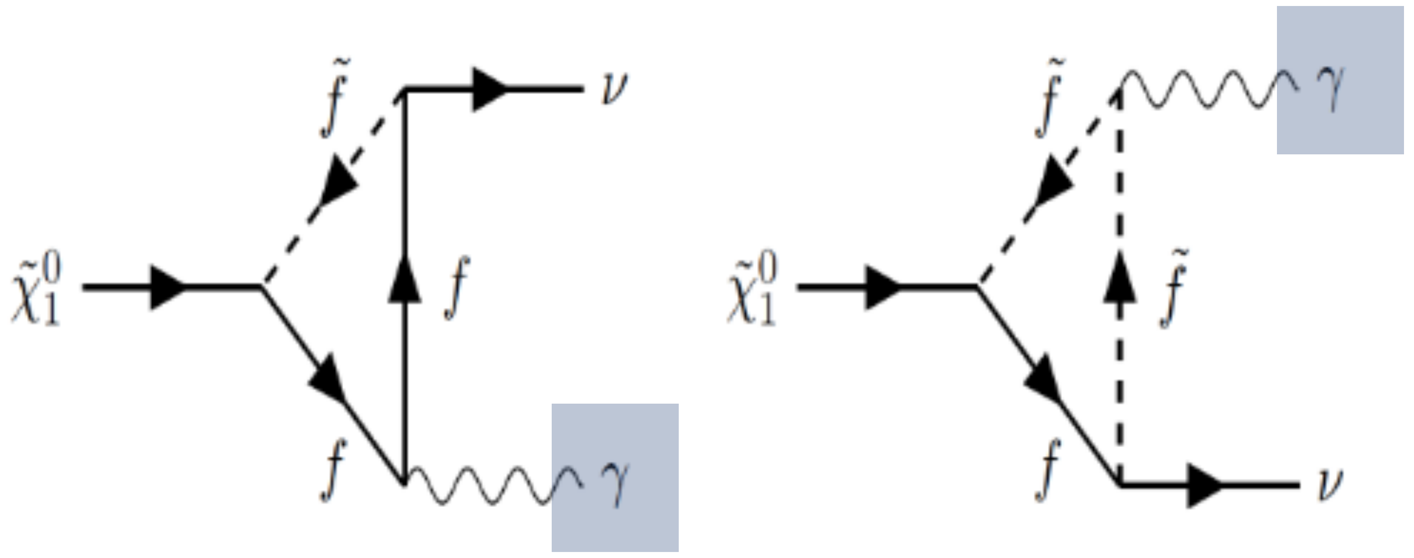
- If $\tilde{\chi}_0^1$ bino-like, no mass bounds from colliders

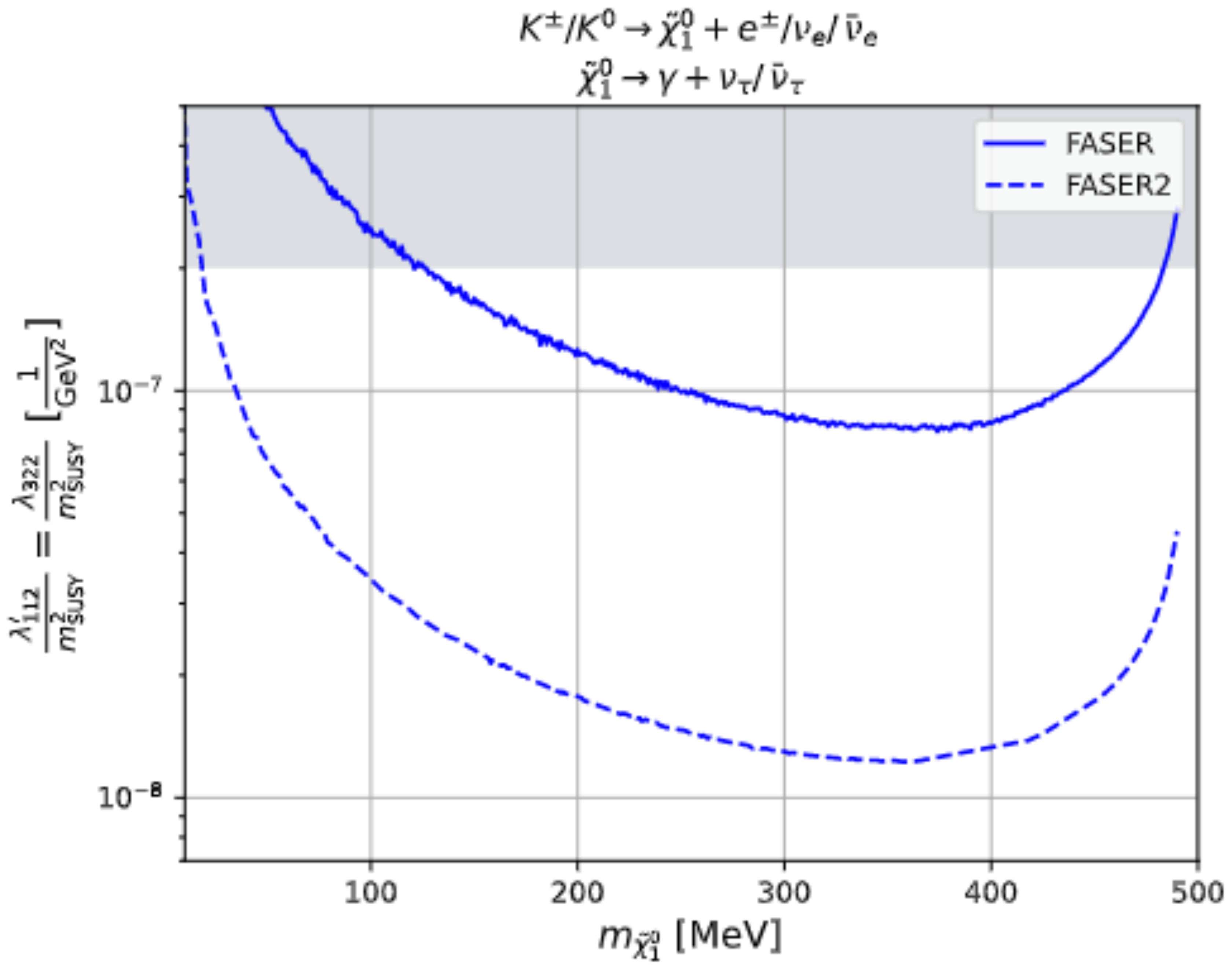
- Cosmology requires $m_{\tilde{\chi}_0^1} \gtrsim 45$ GeV if dark matter (Lee, Weinberg)

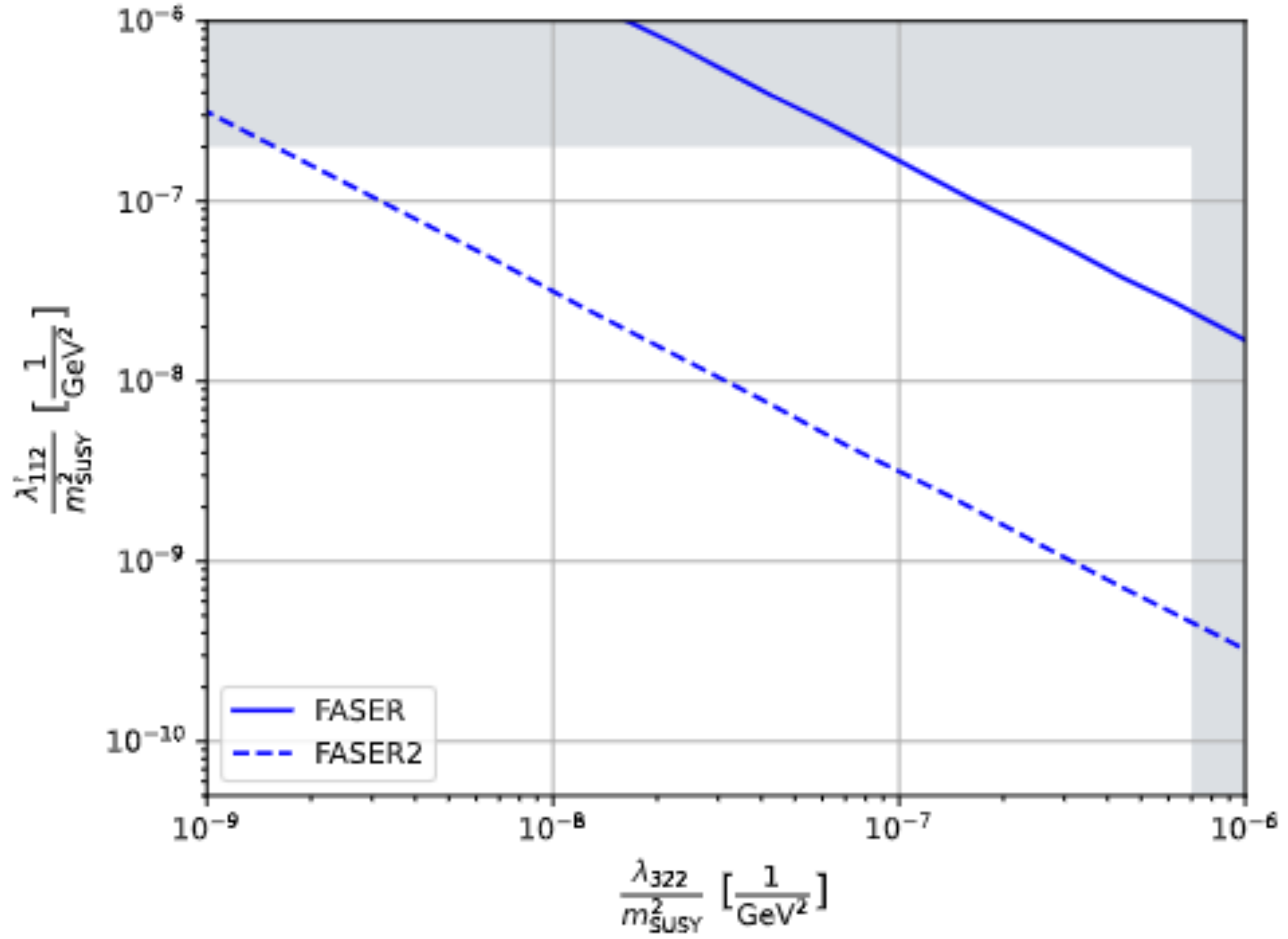
- But unstable neutralino (as in RPV) can be massless! -> This is a real gap in our searches

Pheno 3: Let There be Light (SUSY)

- Long-lived particle program at LHC: FASER, MATHUSLA, CODEX-b, ANUBIS, etc.
- Very light (sub-GeV) $\tilde{\chi}_0^1$ produced in meson decays via RPV
- Long-lived, far detector decay







Sensitive to all λ_{ijj}, λ'_{ijj}

arXiv: 2203.05090 [work with H Dreiner, D Köhler, ZS Wang]

Outlook

- RPV SUSY is just as well motivated as RPC SUSY
- Signatures are very different; many complex possibilities
- Can classify systematically in model-independent way -> towards more complete coverage
- Very recent developments: Lepton PDFs and LLPs
  RPV SUSY shows up here too
  Can implement model-independent analyses here too!

Thanks for your time!