Baryon number violation in supersymmetry: neutron-antineutron oscillations as a probe beyond the LHC

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Baryon and lepton number violation

- BN, LN "accidental" SM symmetries at perturbative level
  - $BNV,\ LNV$ in SM non-perturbatively (eg instantons)
  - B-L is conserved, not $B,\ L$ separately.
- $BNV,\ LNV$ needed for baryogenesis and leptogenesis
- BNV, LNV generic features of SM extensions (eg SUSY, GUTs..)

- Need to explore the possible selection rules:

$$\Delta B \neq 0\ ,\ \Delta L = 0,\ \Delta\left[B-L\right] \neq 0$$

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.....

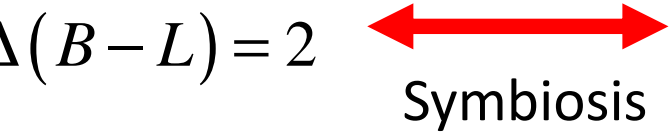
Complementary B,L-violation observables

$\Delta B = \Delta L = 1,$

$\Delta(B-L) = 0$

$\Delta B = 2, \Delta L = 0,$

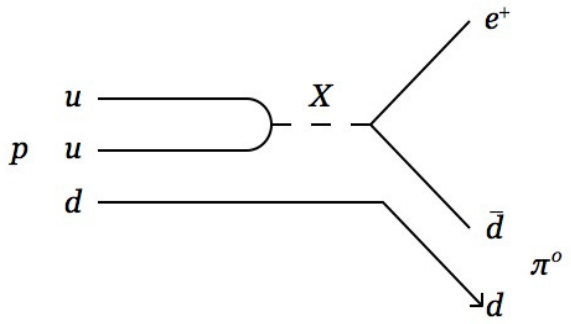
$\Delta(B-L) = 2$



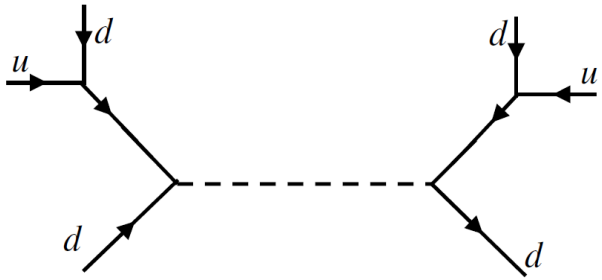
Symbiosis

$\Delta B = 0, \Delta L = 2,$

$\Delta(B-L) = 2$



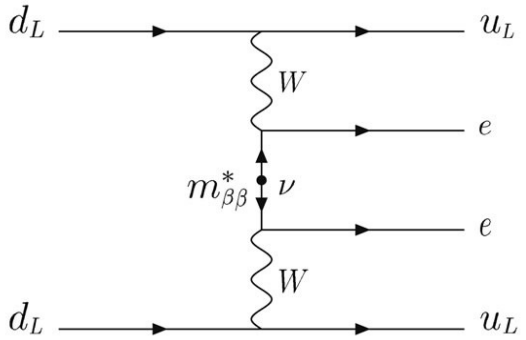
Nucleon decay



$n \to \overline{n}$, NN decay.

Stable proton.

Few pure BNV searches



$0\nu\beta\beta$

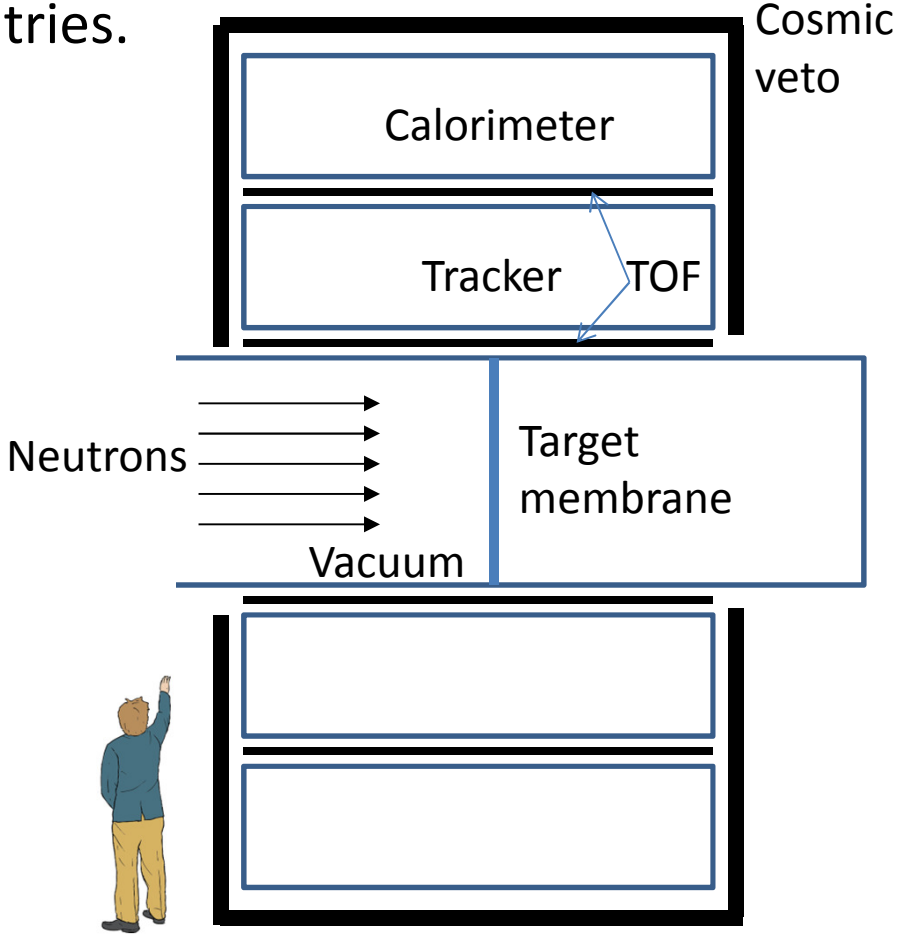
Quantify constraints in RPV-SUSY for $\Delta B = 2$ searches, LHC and flavour measurements.

A search for $n \to \bar{n}$ at the European Spallation Source

nnbar@ESS Collaboration ´: Interim spokesperson G. Broojimans

Expression of Interest submitted to ESS.

Signatories from 26 institutes , 8 countries.



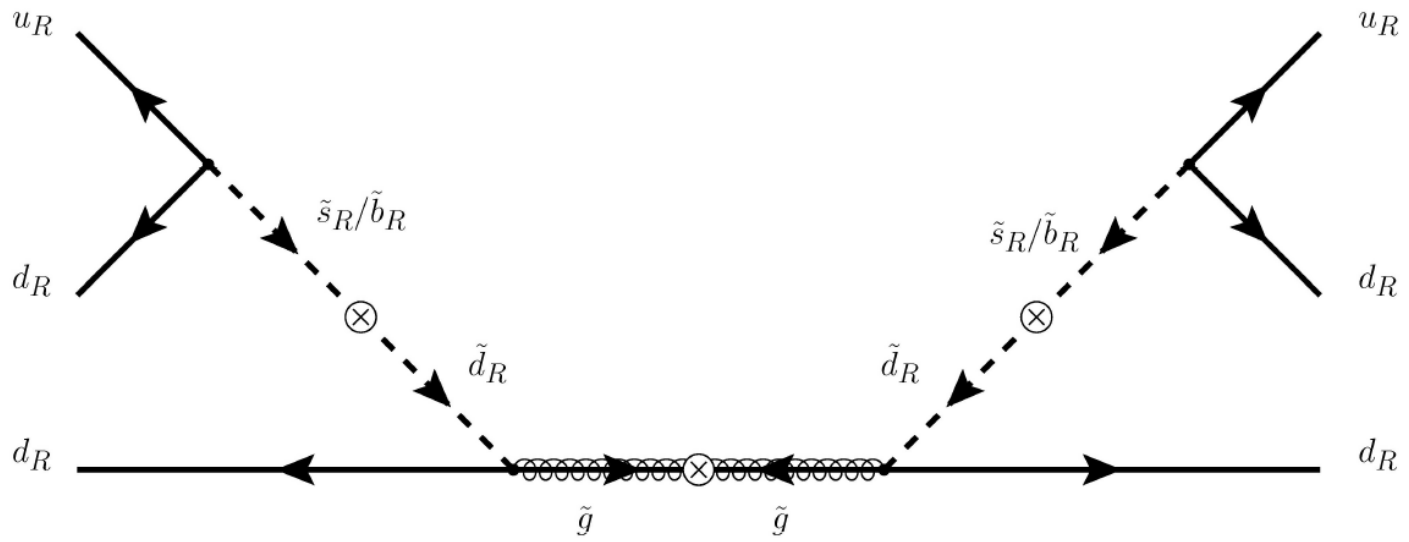
First search for free neutron oscillation since 1991

Sensitivity increase $\times 10^3$ for $P(n \to \bar{n})$

BNV in RPV-SUSY scenarios

$$W_{RPV} = \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k \;\; ; \;\; \lambda''_{ijk} = -\lambda''_{ikj} \;\; \Rightarrow \lambda''_{111} = 0$$

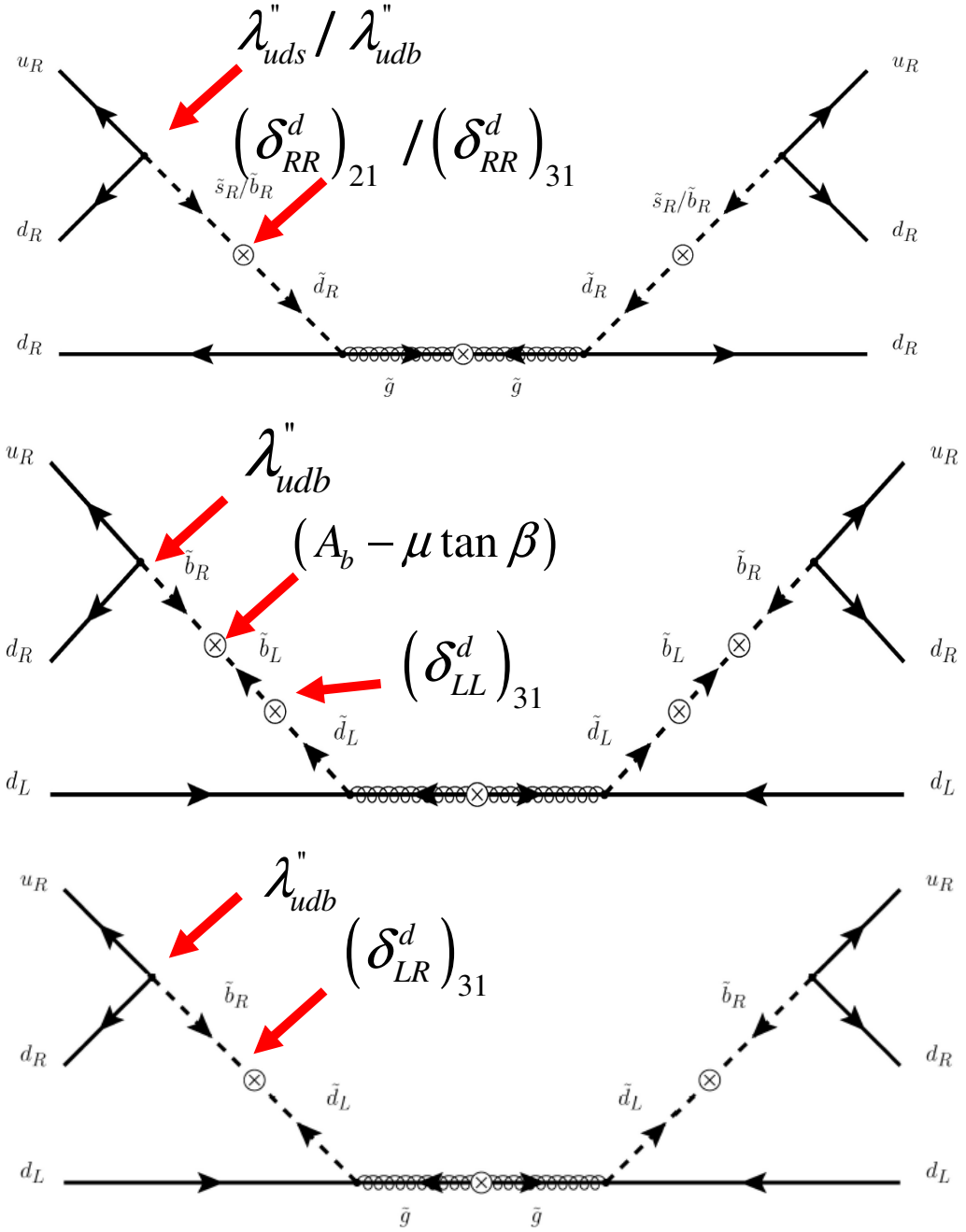
1st gen. quarks $\Leftrightarrow$ 2nd/3rd gen. squarks $\left(\lambda''_{112}, \lambda''_{113}\right)$.



Simplified models:

Parameters: sparticle masses, Yukawa coupling and mixing terms.

Scenarios – strong



Zwirner

Z_1 : $\lambda''_{uds}, (\delta^d_{RR})_{21}$

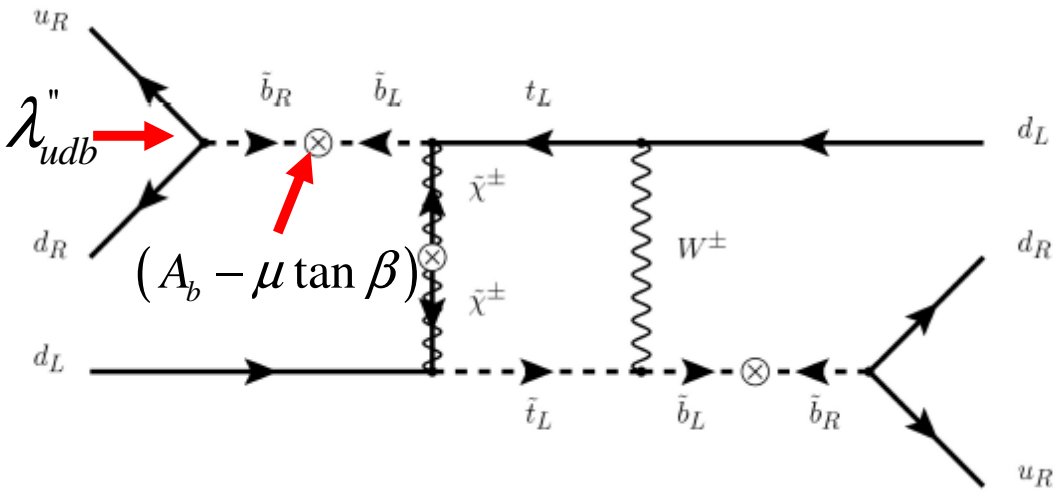
Z_2 : $\lambda''_{udb}, (\delta^d_{RR})_{31}$

Barbieri and Masiero

BM_1 : $\lambda''_{udb}, (\delta^d_{LL})_{31}, (A_b - \mu \tan\beta)$

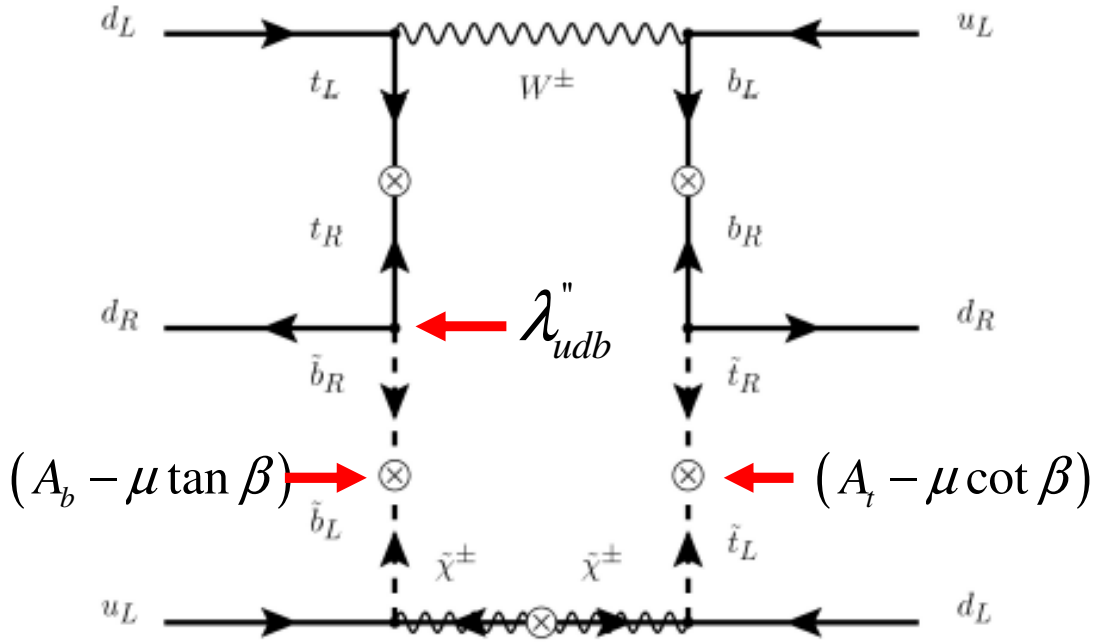
BM_2 $\lambda''_{udb}, (\delta^d_{LR})_{31}$

Scenarios – electroweak



Goity and Sher :

$\lambda''_{udb}, (A_b - \mu \tan\beta)$



Chang and Keung :

$\lambda''_{tdb}, (A_b - \mu \tan\beta),$

$(A_t - \mu \cot\beta)$

Operators and lifetime

Six quark operators $\mathcal{O}_i$ of dimension-9 :

$$(u_R d_R d_R)^2 \equiv \epsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R d^c_{R\dot{\gamma}}\ \epsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R d^{\dot{\gamma}f}_R$$

$$(u_R d_R d_L)^2 \equiv \epsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R d^{\gamma c}_L\ \epsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R d^f_{L\gamma}$$

$n \to \bar{n}, NN \to \pi\pi$

$$(u_L d_L d_R)^2 \equiv \epsilon_{abc} u^{\alpha a}_L d^b_{L\alpha} d^c_{R\dot{\gamma}}\ \epsilon_{def} u^{\beta d}_L d^e_{L\beta} d^{\dot{\gamma}f}_R$$

$$(u_R d_R s_R)^2 \equiv \epsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R s^c_{R\dot{\gamma}}\ \epsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R s^{\dot{\gamma}f}_R .$$

$NN \to KK$

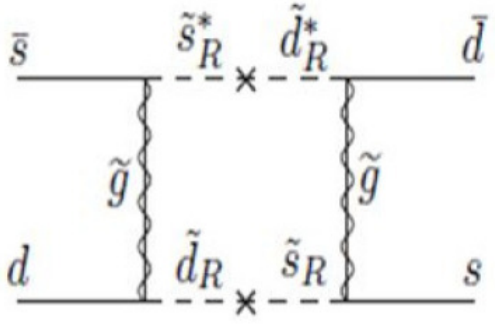
Eg $n \to \bar{n}$, Zwirner:

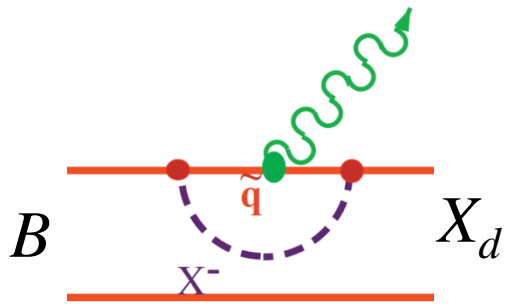
$$\tau = \left(2.5\times10^{8}\ \text{s}\right) \times \frac{\left(250\ \text{MeV}\right)^6}{\left\langle \bar{n}\left|\left(u_R d_R d_R\right)^2\right|n\right\rangle} \times \frac{m_{\tilde{g}}}{1.2\ \text{TeV}} \left(\frac{\bar{m}_D}{500\ \text{GeV}}\right)^4 \left(\frac{10^{-6}}{\lambda''_{uk}}\right)^2$$

Experimental constraints

Flavour/mixing

Observable	Parameter
Kaon mixing	$(\delta^d_{RR})_{21}$
B-mixing	$(\delta^d_{RR})_{31}$
$b \to d + \gamma$	$\mu \tan\beta, (\delta^d_{RR})_{31}$

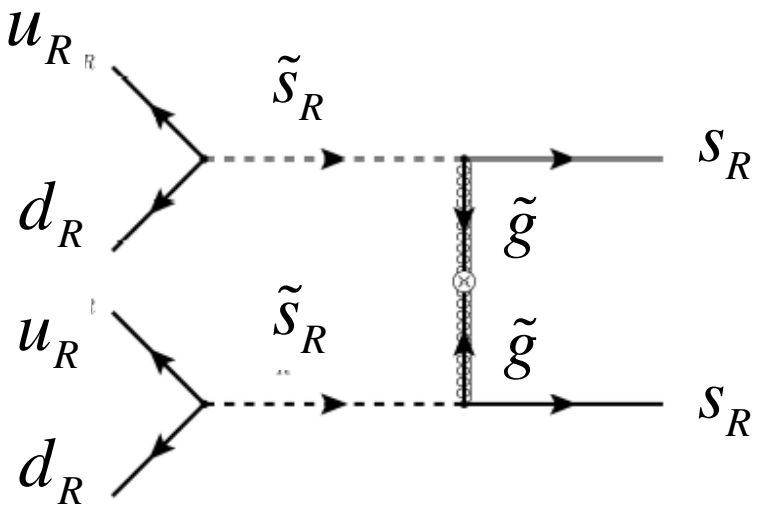




Low energy BNV

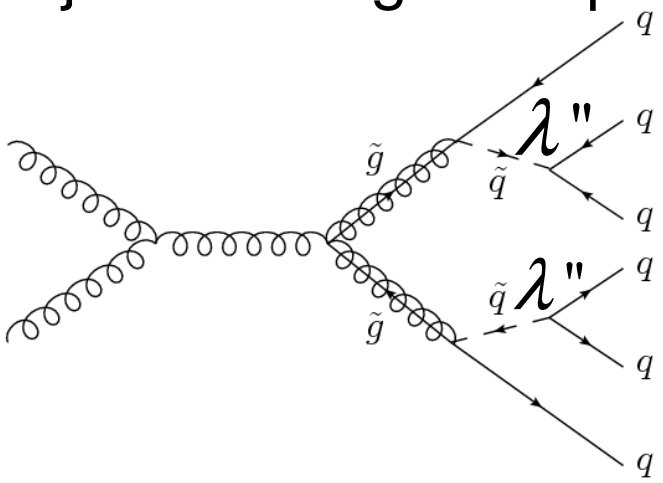
Observable	Parameter
$n \to \bar{n}$	$\lambda''_{112}, \lambda''_{113}$
$NN \to$ mesons	

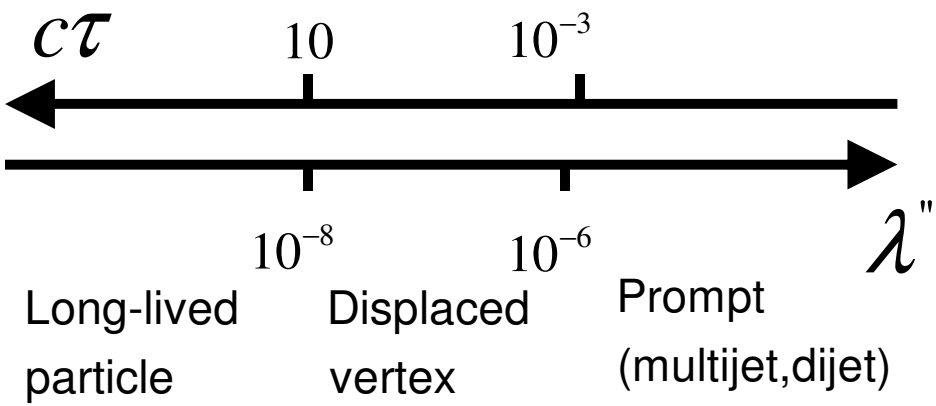
Limits from Super-K



Experimental constraints - LHC

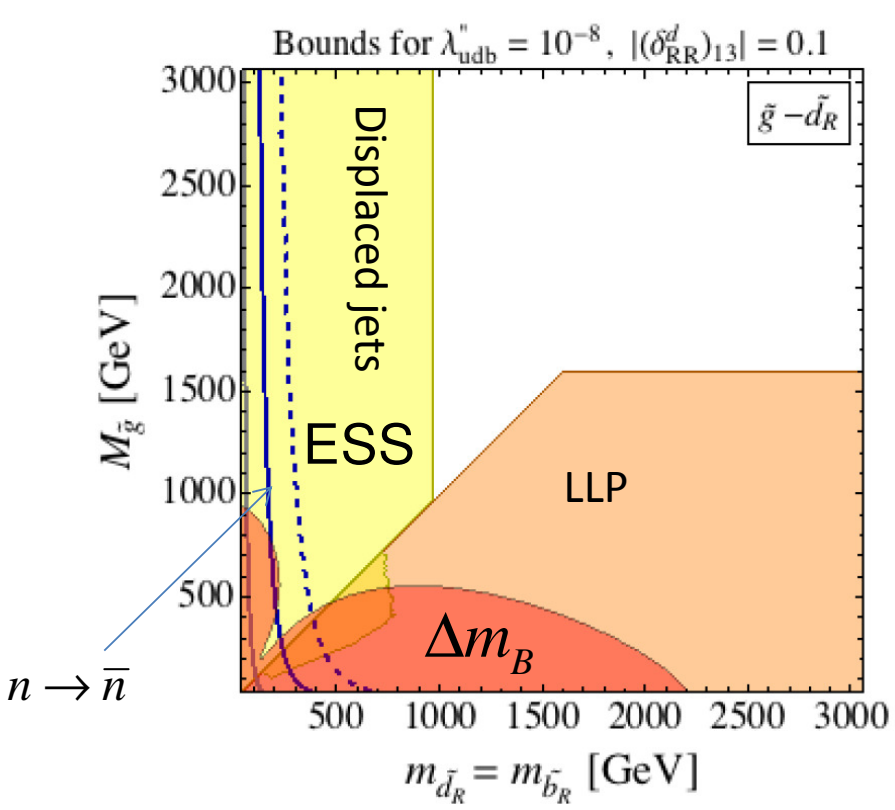
Multijet and long-lived particle signatures

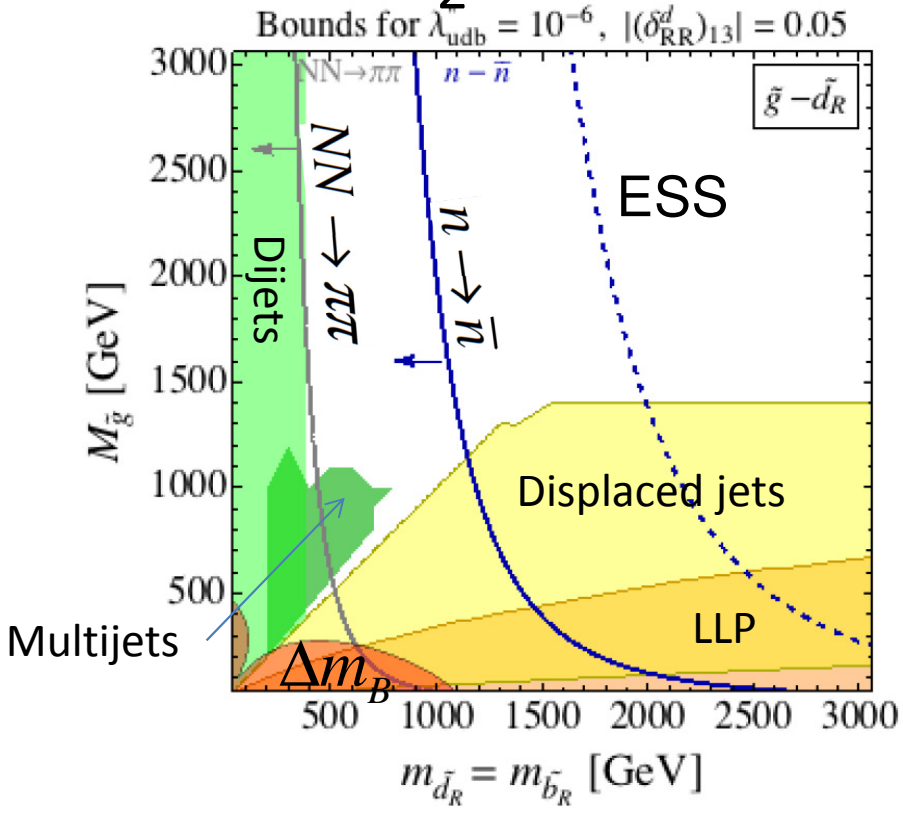




Observable	Parameter
ATLAS Multijets (Arxiv:1602.04821 hep-ex) recast with Madgraph+Pythia+Delphes	$\lambda''_{112}, \lambda''_{113}$
CMS Dijets Arxiv:1412.7706	
ATLAS/CMS Displaced vertex+ long-lived particle recast (arxiv:1503.05923, 1505.00784 hep-ph, CMS-PAS-EXO-15-010)	

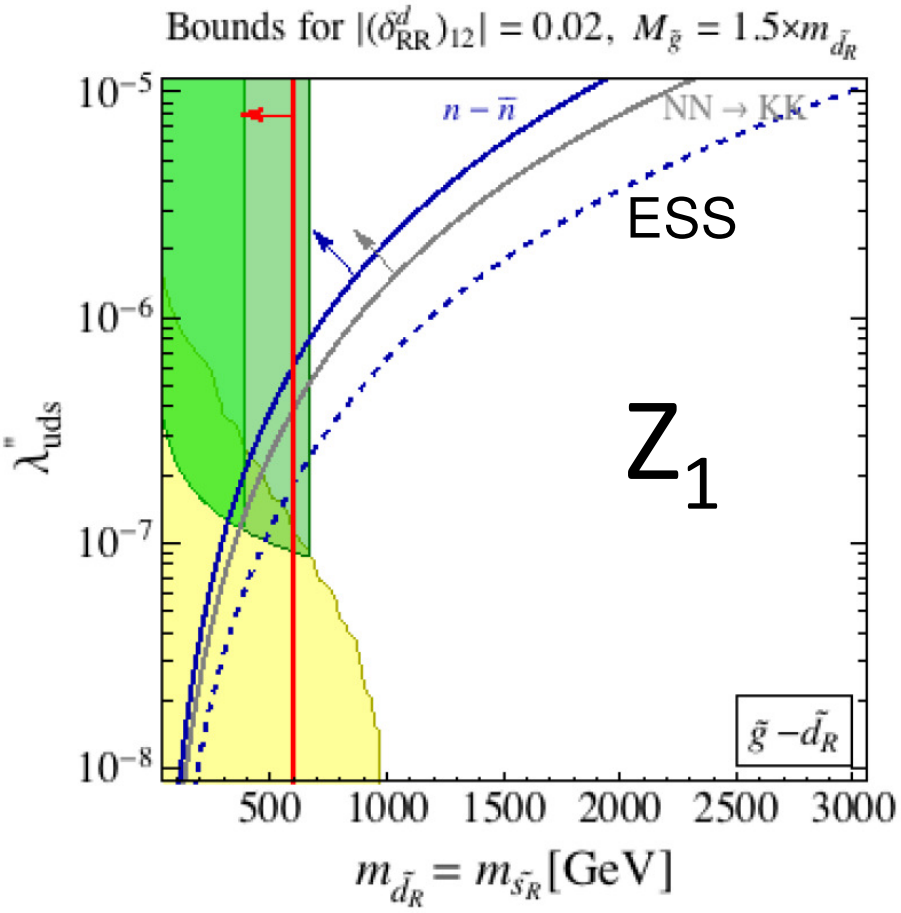
Model exclusion – Z_2

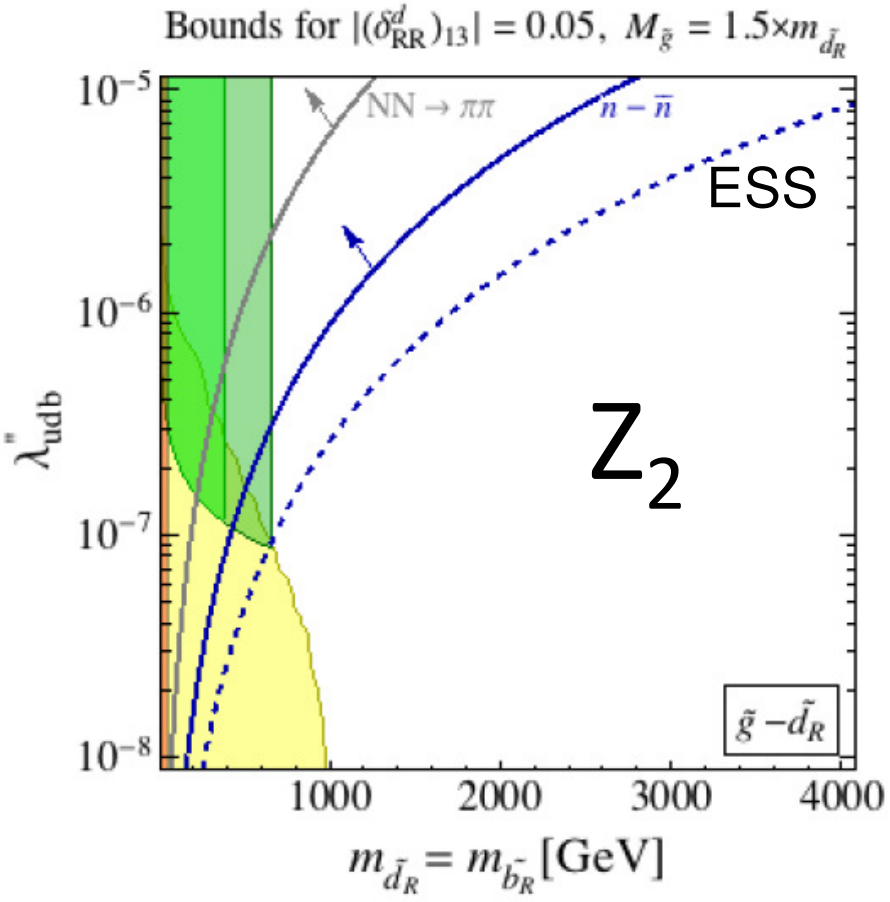




LHC dominant at low λ'' and within its kinematic reach.

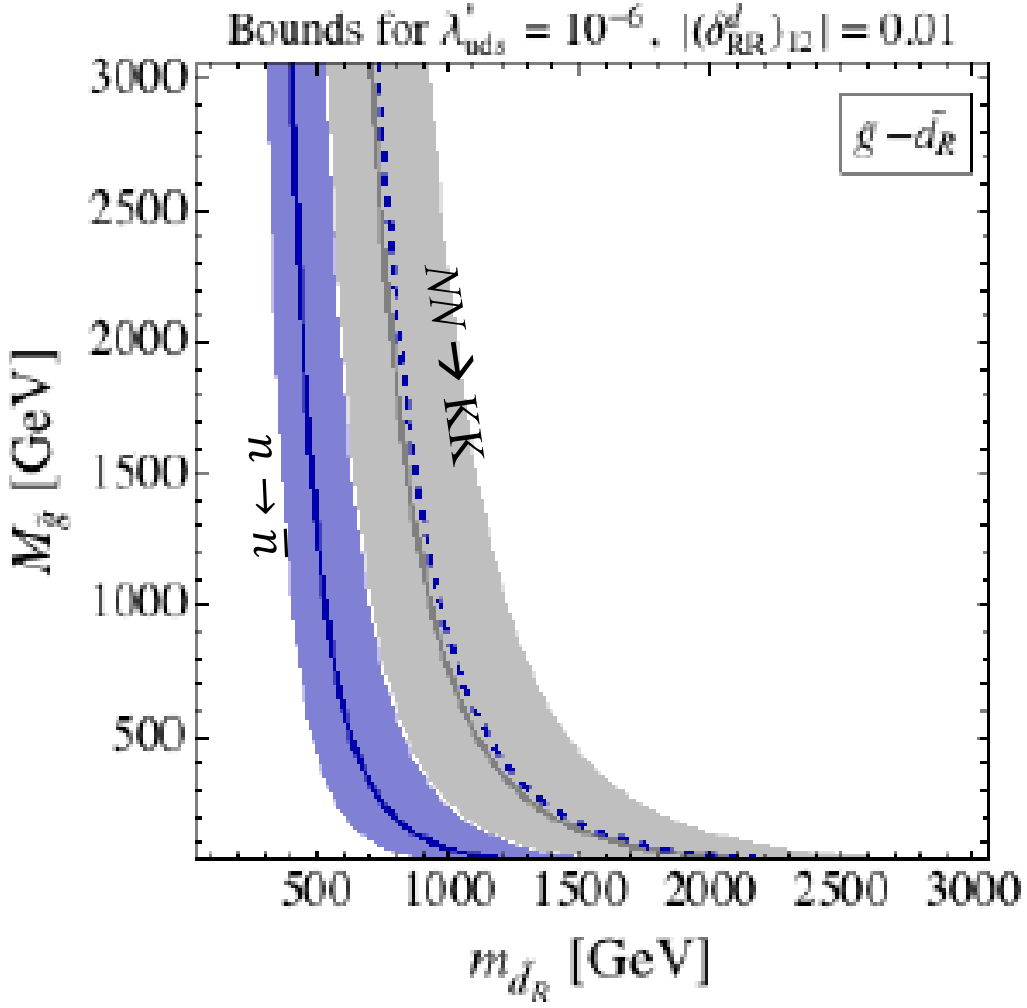
Model exclusion – Z_1, Z_2



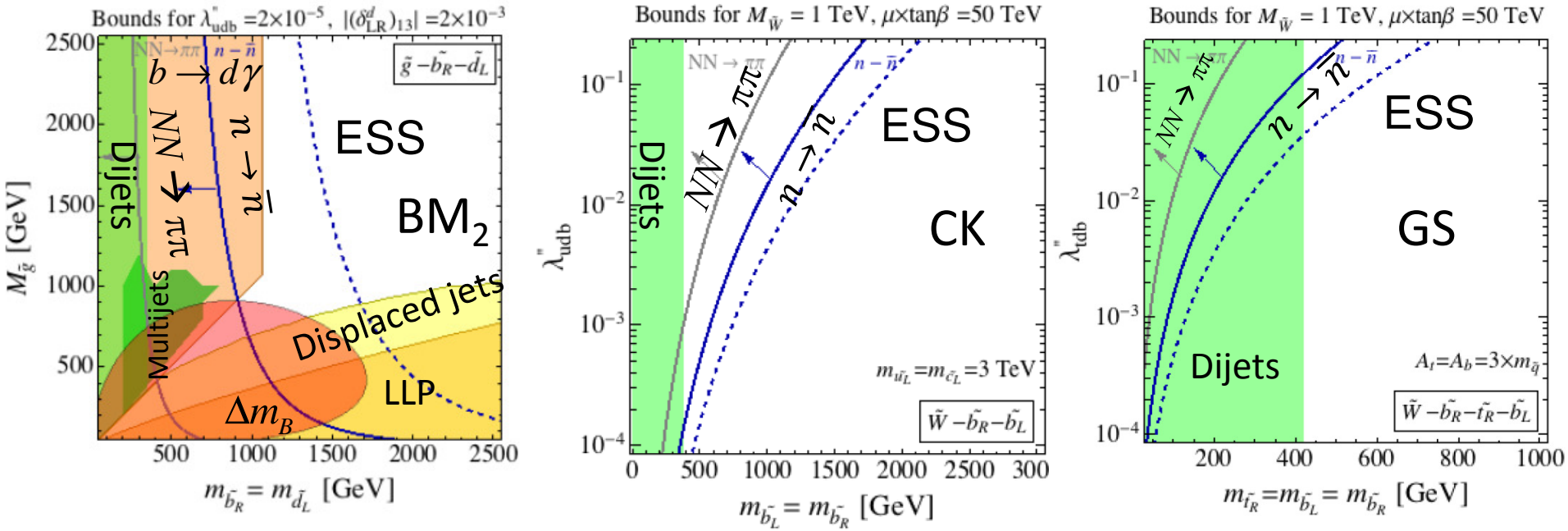


Dedicated BNV searches give sensitivity beyond the LHC.

Uncertainties from hadronic matrix elements



Model exclusion: BM_2 ,CK, GS



Consistent picture:

Dedicated BNV expts. sensitive to higher mass scales than LHC and flavour experiments.

Dependent on the coupling and mixing values.

Searches are complementary.

Summary

- BNV-only searches are an important part of program to test symmetries, search for BSM physics and understand baryogenesis.
- Complementary program of direct searches and precision flavour measurements.
- RPV SUSY provides a framework to study limits.
- Limits achieved for a number of scenarios.
- A future dedicated $n \rightarrow \overline{n}$ search can further extend sensitivity.

Operator analysis

Six quark operators $\mathcal{O}_i$ of dimension-9 :

$$(u_R d_R d_R)^2 \equiv \epsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R d^c_{R\dot{\gamma}}\ \epsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R d^{\dot{\gamma}f}_R$$

$$(u_R d_R d_L)^2 \equiv \epsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R d^{\gamma c}_L\ \epsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R d^f_{L\gamma}$$

$$(u_L d_L d_R)^2 \equiv \epsilon_{abc} u^{\alpha a}_L d^b_{L\alpha} d^c_{R\dot{\gamma}}\ \epsilon_{def} u^{\beta d}_L d^e_{L\beta} d^{\dot{\gamma}f}_R$$

$$(u_R d_R s_R)^2 \equiv \epsilon_{abc} u^a_{R\dot{\alpha}} d^{\dot{\alpha}b}_R s^c_{R\dot{\gamma}}\ \epsilon_{def} u^d_{R\dot{\beta}} d^{\dot{\beta}e}_R s^{\dot{\gamma}f}_R .$$

$n \to \bar{n}, NN \to \pi\pi$

$NN \to KK$

Eg $n \to \bar{n}$: $\left\langle \bar{n} \left| \mathcal{H}_{eff} \right| n \right\rangle = \frac{1}{M_X^5} \sum_i \kappa_i \left\langle \bar{n} \left| \mathcal{O}_i \right| n \right\rangle$

Short distance (RPV SUSY): κ_i

Long distance Hadronic ME: $\left\langle \bar{n} \left| \mathcal{O}_i \right| n \right\rangle \sim \Lambda^6_{QCD}$

Oscillation time $\tau = \frac{1}{\left\langle \bar{n} \left| \mathcal{H}_{eff} \right| n \right\rangle} \sim \frac{M_X^5}{\kappa \Lambda^6_{QCD}}$