BSM physics with neutron oscillations

D. Milstead

Stockholms Universitet

1. An experimentalist perspective
2. A theory perspective
3. A new experiment

An experimentalist's perspective

Hypothesis: baryon number is weakly violated. How do we look for it ?

Need processes in which only BNV takes place.

Single nucleon decay searches, eg, $p \rightarrow \pi^0 + e^+$?

$\Rightarrow \; |\Delta B| = 1 \; , \; |\Delta L| = 1$!

Decays without leptons, eg, $p \rightarrow \pi + \pi$, impossible due to angular momentum conservation.

$|\Delta B| \neq 0 \; , \; \Delta L = 0$ observables restricted by Nature.

$n \rightarrow \bar{n}, n'$ and dinucleon decay searches sensitive to BNV-only.

Free $n \rightarrow \bar{n}, n'$ searches $\Rightarrow$ cleanest experimental and theoretical approach.

Searches for BNV

Decay mode	Partial mean life ($\times 10^{30}$ yrs)
$N \to e^+ \pi$	> 2000 (n), > 8200 (p)
$N \to \mu^+ \pi$	> 1000 (n), > 6600 (p)
$N \to \nu \pi$	> 1100 (n), > 390 (p)
$p \to e^+ \eta$	> 4200
$p \to \mu^+ \eta$	> 1300
$n \to \nu \eta$	> 158
$N \to e^+ \rho$	> 217 (n), > 710 (p)
$N \to \mu^+ \rho$	> 228 (n), > 160 (p)
$N \to \nu \rho$	> 19 (n), > 162 (p)
$p \to e^+ \omega$	> 320
$p \to \mu^+ \omega$	> 780
$n \to \nu \omega$	> 108
$N \to e^+ K$	> 17 (n), > 1000 (p)
$N \to \mu^+ K$	> 26 (n), > 1600 (p)
$N \to \nu K$	> 86 (n), > 5900 (p)
$n \to \nu K^0_S$	> 260
$p \to e^+ K^*(892)^0$	> 84
$N \to \nu K^*(892)$	> 78 (n), > 51 (p)
$p \to e^+ \pi^+ \pi^-$	> 82
$p \to e^+ \pi^0 \pi^0$	> 147
$n \to e^+ \pi^- \pi^0$	> 52
$p \to \mu^+ \pi^+ \pi^-$	> 133
$p \to \mu^+ \pi^0 \pi^0$	> 101
$n \to \mu^+ \pi^- \pi^0$	> 74
$n \to e^+ K^0 \pi^-$	> 18
$n \to e^- \pi^+$	> 65
$n \to \mu^- \pi^+$	> 49
$n \to e^- \rho^+$	> 62
$n \to \mu^- \rho^+$	> 7
$n \to e^- K^+$	> 32
$n \to \mu^- K^+$	> 57
$p \to e^- \pi^+ \pi^+$	> 30
$n \to e^- \pi^+ \pi^0$	> 29
$p \to \mu^- \pi^+ \pi^+$	> 17
$n \to \mu^- \pi^+ \pi^0$	> 34
$p \to e^- \pi^+ K^+$	> 75
$p \to \mu^- \pi^+ K^+$	> 245

(RPP)

Decay mode	Partial mean life ($\times 10^{30}$ yrs)
$p \to e^+ \gamma$	> 670
$p \to \mu^+ \gamma$	> 478
$n \to \nu \gamma$	> 28
$p \to e^+ \gamma\gamma$	> 100
$n \to \nu \gamma\gamma$	> 219
$p \to e^+ e^+ e^-$	> 793
$p \to e^+ \mu^+ \mu^-$	> 359
$p \to e^+ \nu \nu$	> 170
$n \to e^+ e^- \nu$	> 257
$n \to \mu^+ e^- \nu$	> 83
$n \to \mu^+ \mu^- \nu$	> 79
$p \to \mu^+ e^+ e^-$	> 529
$p \to \mu^+ \mu^+ \mu^-$	> 675
$p \to \mu^+ \nu \nu$	> 220
$p \to e^- \mu^+ \mu^+$	> 6
$n \to 3\nu$	> 0.0005
$N \to e^+$ anything	> 0.6 (n, p)
$N \to \mu^+$ anything	> 12 (n, p)
$N \to e^+ \pi^0$ anything	> 0.6 (n, p)
$pp \to \pi^+ \pi^+$	> 0.7
$pn \to \pi^+ \pi^0$	> 2
$nn \to \pi^+ \pi^-$	> 0.7
$nn \to \pi^0 \pi^0$	> 3.4
$pp \to K^+ K^+$	> 170
$pp \to e^+ e^+$	> 5.8
$pp \to e^+ \mu^+$	> 3.6
$pp \to \mu^+ \mu^+$	> 1.7
$pn \to e^+ \overline{\nu}$	> 2.8
$pn \to \mu^+ \overline{\nu}$	> 1.6
$pn \to \tau^+ \overline{\nu}_\tau$	> 1.0
$nn \to \nu_e \overline{\nu}_e$	> 1.4
$nn \to \nu_\mu \overline{\nu}_\mu$	> 1.4

$\Delta B \neq 0, \Delta L \neq 0$

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

Few searches for BNV only.

$n \to \bar{n} \;\Rightarrow$ nuclear instability.

Highly suppressed due to non-degeneracy of $n, \bar{n}$

$\tau_{n\to\bar{n}}$: 2.5 $\times 10^8$ s

(Super-K, model-dependent)

Last search with free neutrons (ILL) $\tau_{n\to\bar{n}} > 0.8\times10^8$ s

New search proposed for European Spallation Source.

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:

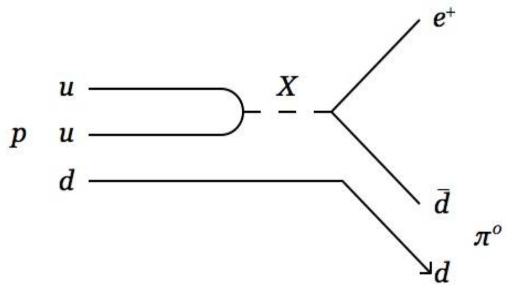
$$\Delta B \neq 0 \;,\; \Delta L = 0,\; \Delta\left[B - L\right] \neq 0$$

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

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

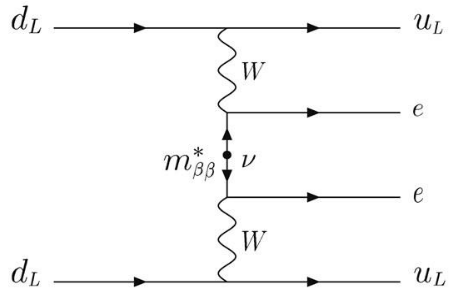
.....

Complementary B,L-violation observables



$$p \to e^{+} + \pi^{0}$$

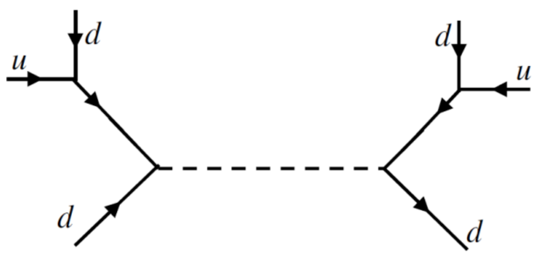
$$\Delta B = 1, \Delta L = 1$$



$$0\nu\beta\beta$$

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

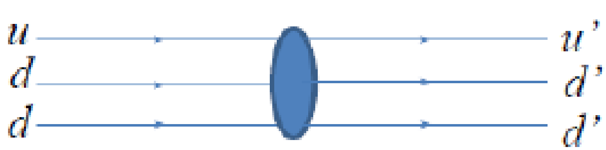
Symbiosis



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

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

Neutron oscillation



$n \to n'$ (mirror).

$$\Delta B = 1, \Delta L = 0$$

Neutron-antineutron oscillations

- R-parity violating supersymmetry, minimal flavour violation SUSY
- Unification models: $M \sim 10^{15}$ GeV
- Left-right symmetric models ($n\bar{n}$ and $0\nu 2\beta$)
- Extra dimensions models
- Post-sphaleron baryogenesis
- Bottom-up EFT - baryogenesis (C. Grojean, B. Shakya, J. Wells, Z. Zhang (**arxiv: 1806.00011 -hep-ph)**

High precision $n \rightarrow \bar{n}$ search

$\Rightarrow$ Scan over wide range of phase space for generic BNV

+

$\Rightarrow$ model constaints.

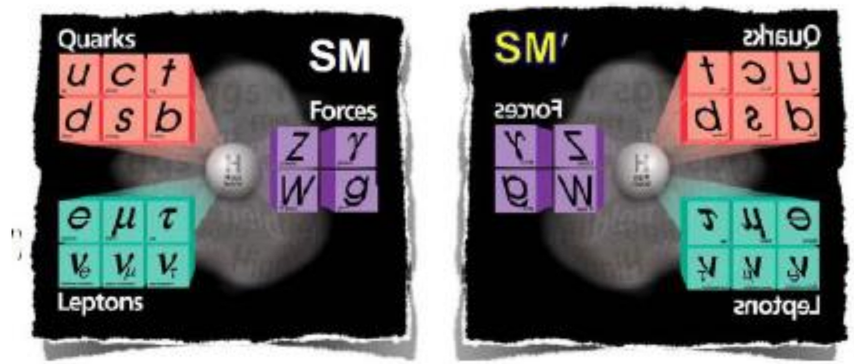
Mirror neutrons

Hidden/mirror sector

Restores parity symmetry

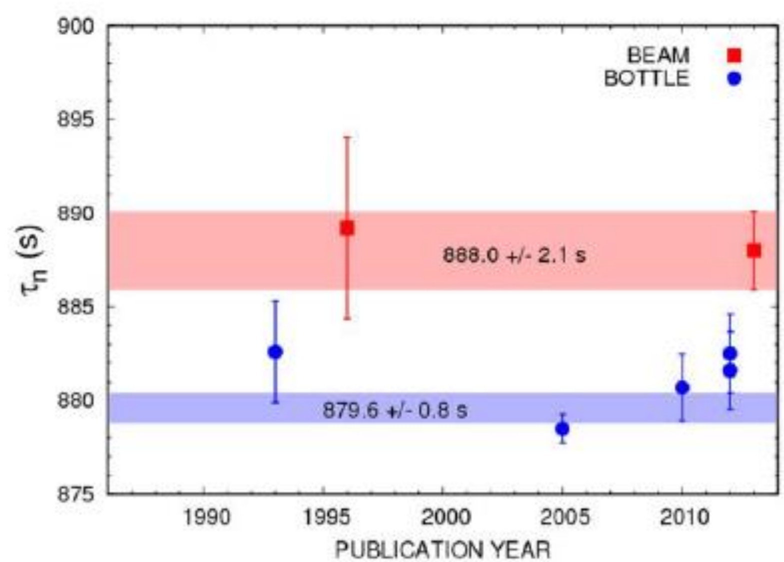
Mixing for $Q = 0$ particles, eg $n \rightarrow n'$

Mirror matter: dark matter candidates



Explain neutron lifetime discrepancy

in bottle and beam experiments.



Operator analysis

Six quark operators 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 $n \to \bar{n}$: $\langle \bar{n} | \mathrm{H}_{eff} | n \rangle = \frac{1}{M_X^5} \sum_i \kappa_i \langle \bar{n} | \mathrm{O}_i | n \rangle$

Short distance (RPV SUSY): κ_i

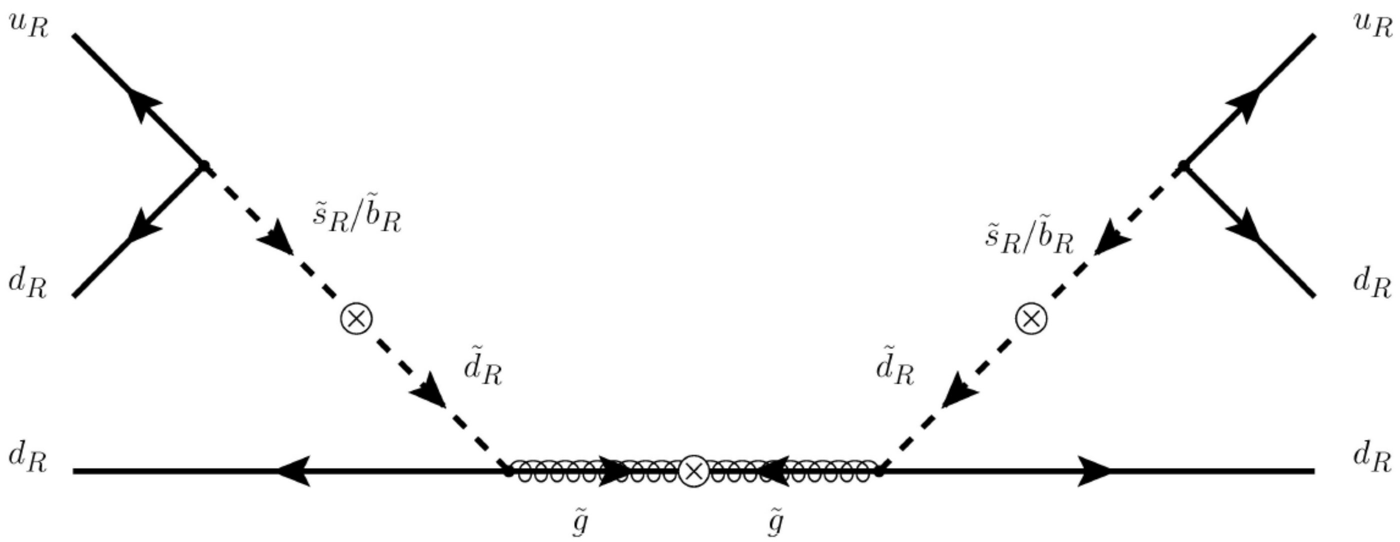
Long distance Hadronic ME: $\langle \bar{n} | \mathrm{O}_i | n \rangle : \Lambda_{QCD}^6$

Oscillation time $\tau = \frac{1}{\langle \bar{n} | \mathrm{H}_{eff} | n \rangle} : \frac{M_X^5}{\kappa \Lambda_{QCD}^6}$

BNV in RPV-SUSY scenarios

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

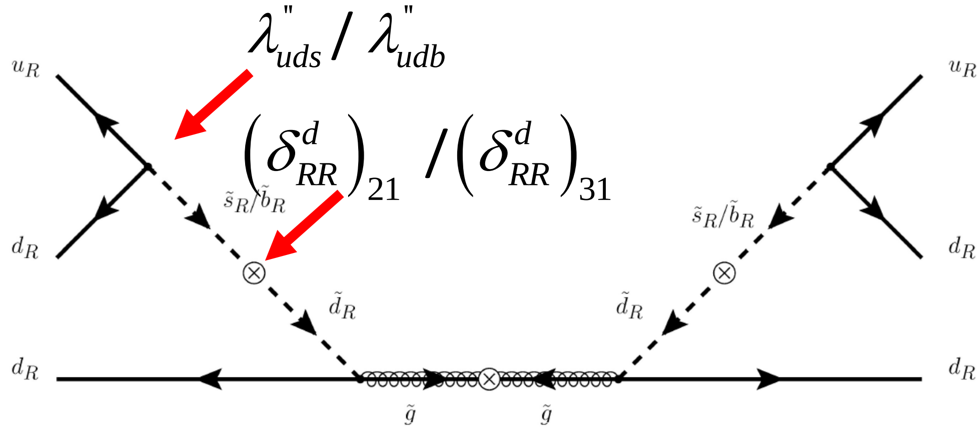
1st gen. quarks $\Leftrightarrow$ 2nd/3rd gen. squarks $\left(\lambda^{''}_{112}, \lambda^{''}_{113}\right)$.



Simplified models: sparticle masses, Yukawa coupling and mixing terms.

JHEP 1605 (2016) 144 (arXiv:1602.04821)
L. Calibbi, G. Ferretti, D. Milstead, C. Petersson, R. Pöttgen

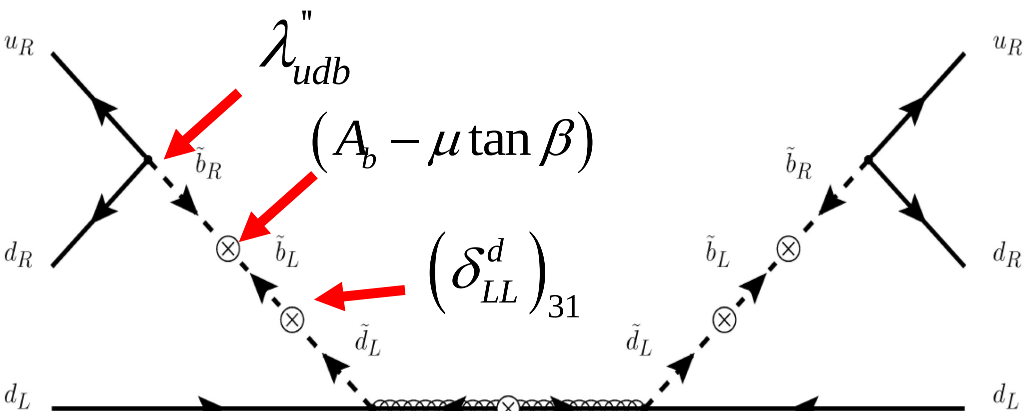
Scenarios – strong



Zwirner

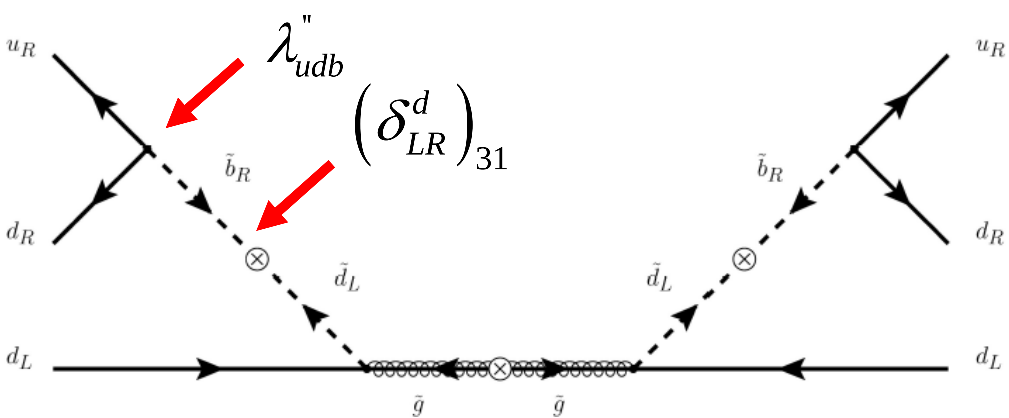
$Z_1: \quad \lambda''_{uds}, \left(\delta^d_{RR}\right)_{21}$

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



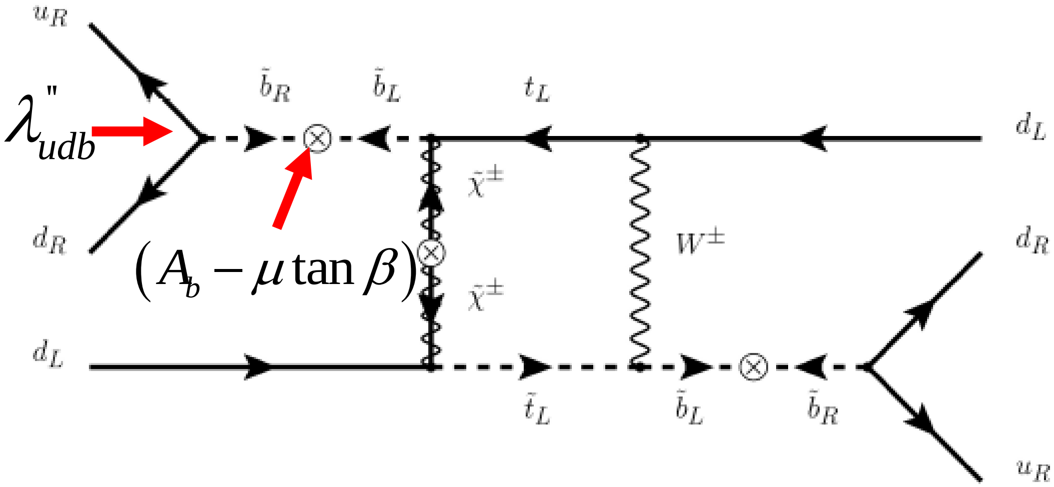
Barbieri and Masiero

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



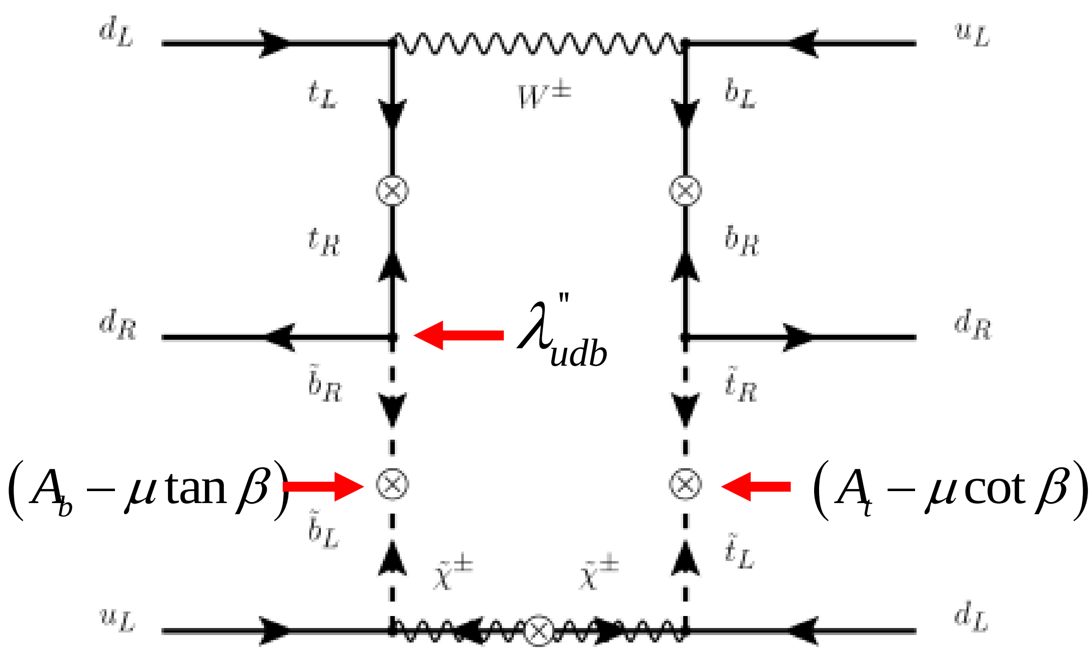
$BM_2 \quad \lambda''_{udb}, \left(\delta^d_{LR}\right)_{31}$

Scenarios – electroweak



Goity and Sher :

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



Chang and Keung :

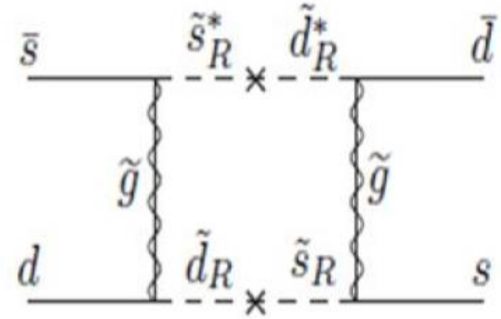
$\lambda''_{tdb}, (A_b - \mu \tan\beta),$

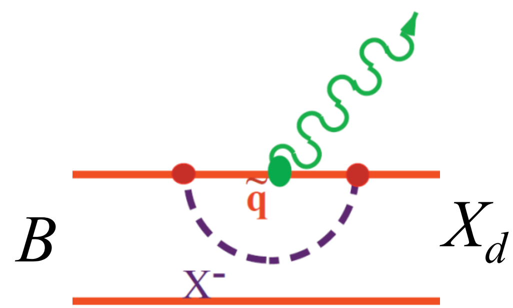
$(A_t - \mu \cot\beta)$

Experimental constraints

Flavour/mixing

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

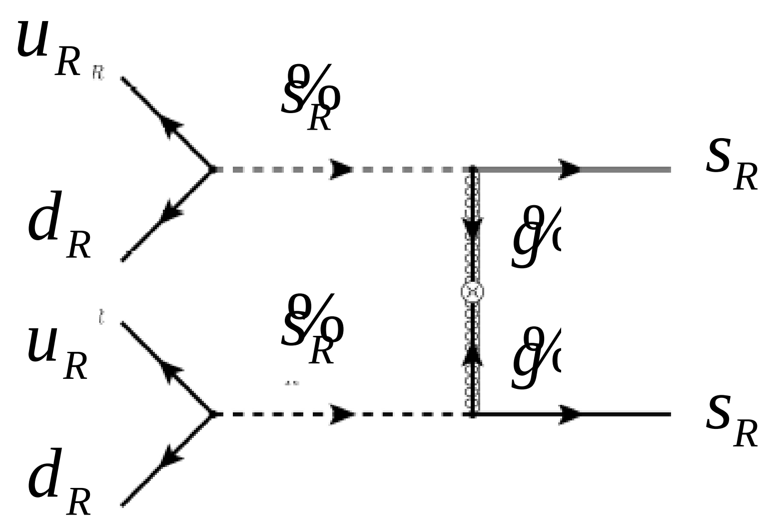




Low energy BNV

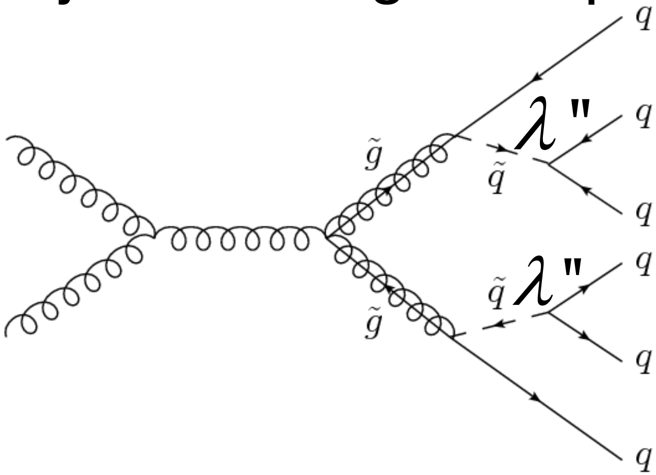
Observable	Parameter
$n \to \bar{n}$	$\lambda''_{112}, \lambda''_{113}$
$NN \to$ mesons	

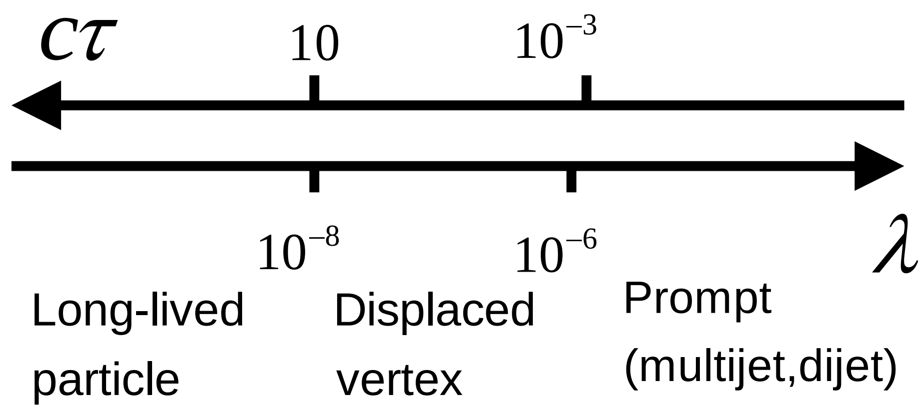
Limits from Super-K



Experimental constraints - LHC

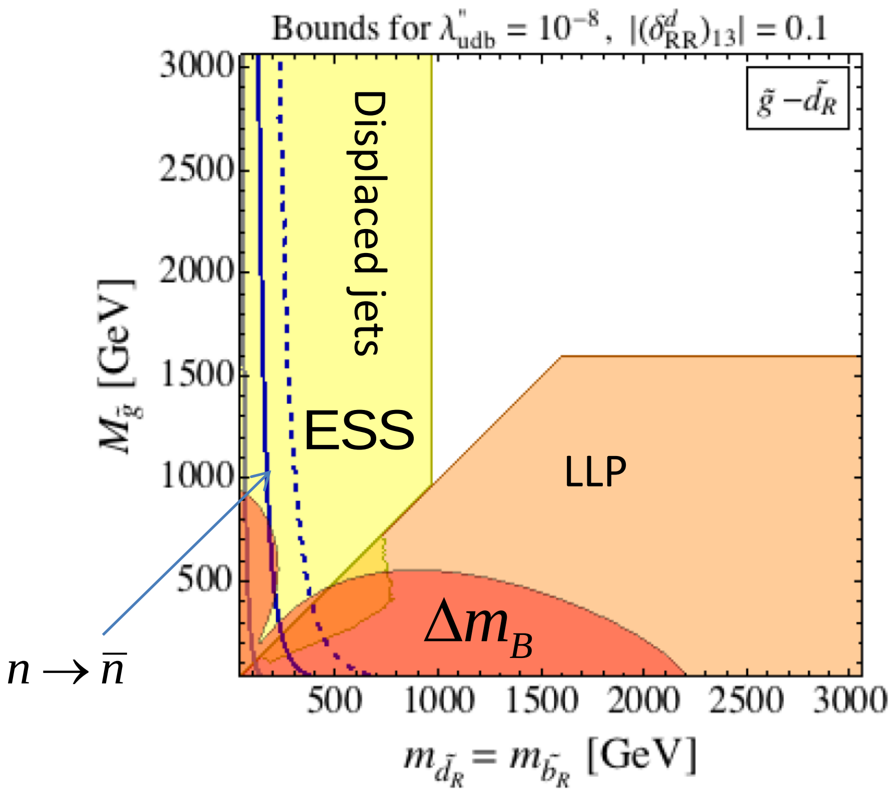
Multijet and long-lived particle signatures

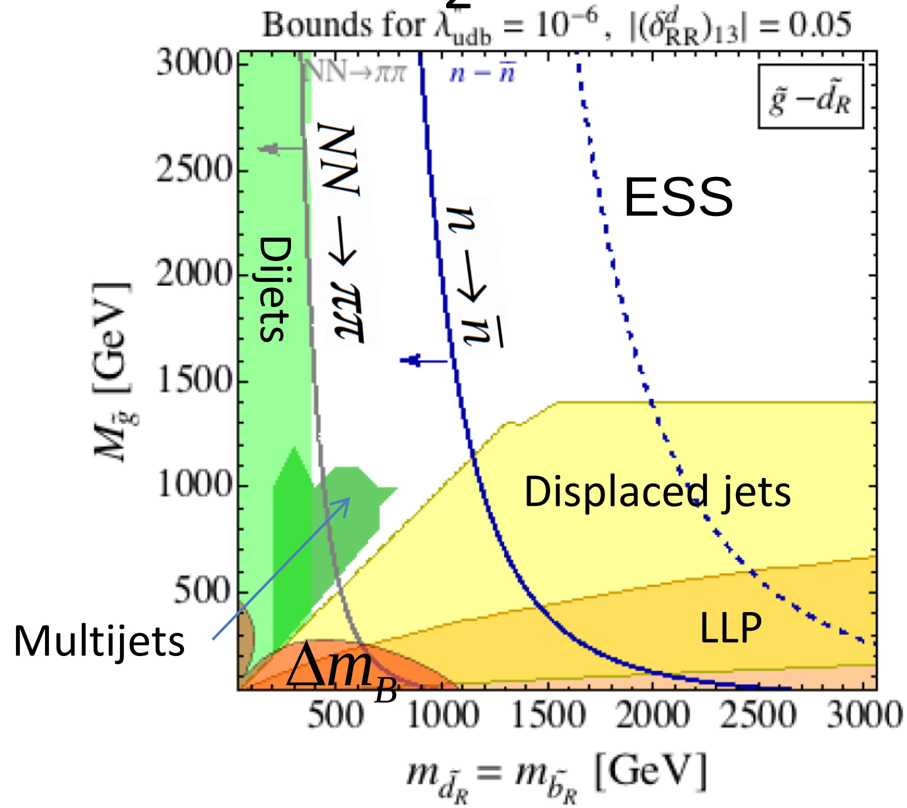




Observable	Parameter
ATLAS Multijets (Arxiv:1602.04821 hep-ex) recast with Madgraph+Pythia+Delphes	$\lambda''_{112}, \lambda''_{113}$
CMS Dijets Arxiv:1412.7706	
ATLAS/CMS Displaced vertex+ long-lived particle recast (arxiv:1503.05923, 1505.00784 hep-ph, CMS-PAS-EXO-15-010)	

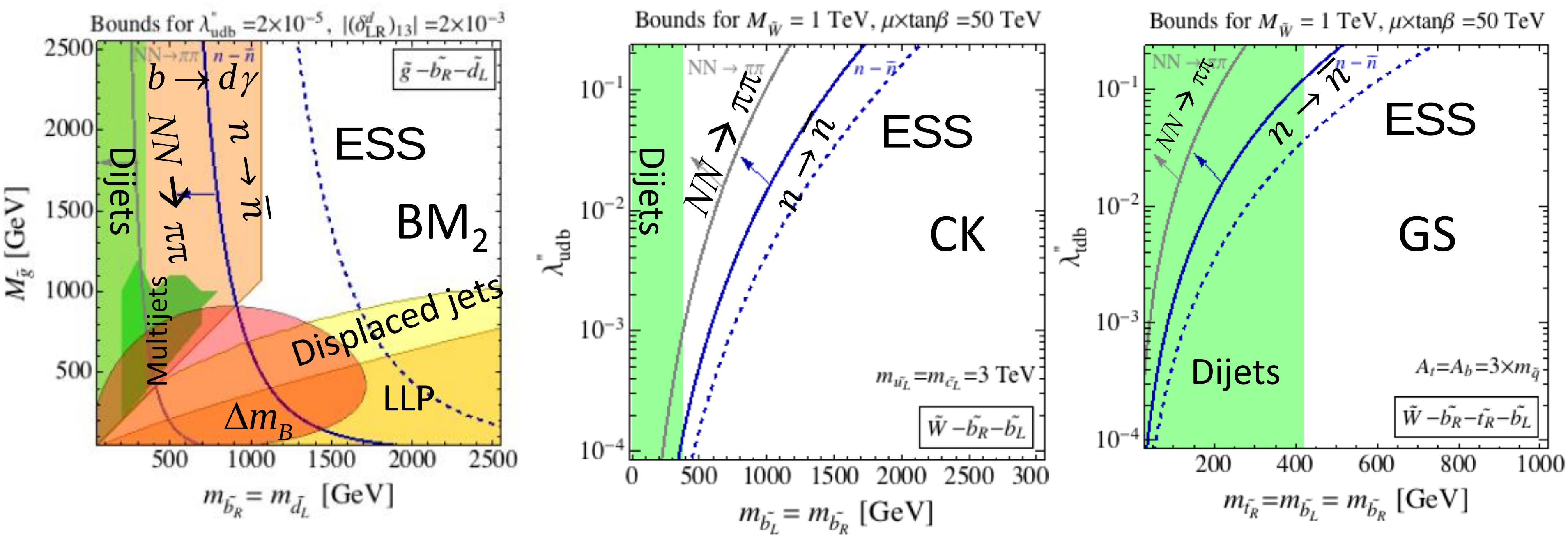
Model exclusion – Z_2





LHC is the dominant player at ~ TeV

Model exclusion: BM_2 ,CK, GS



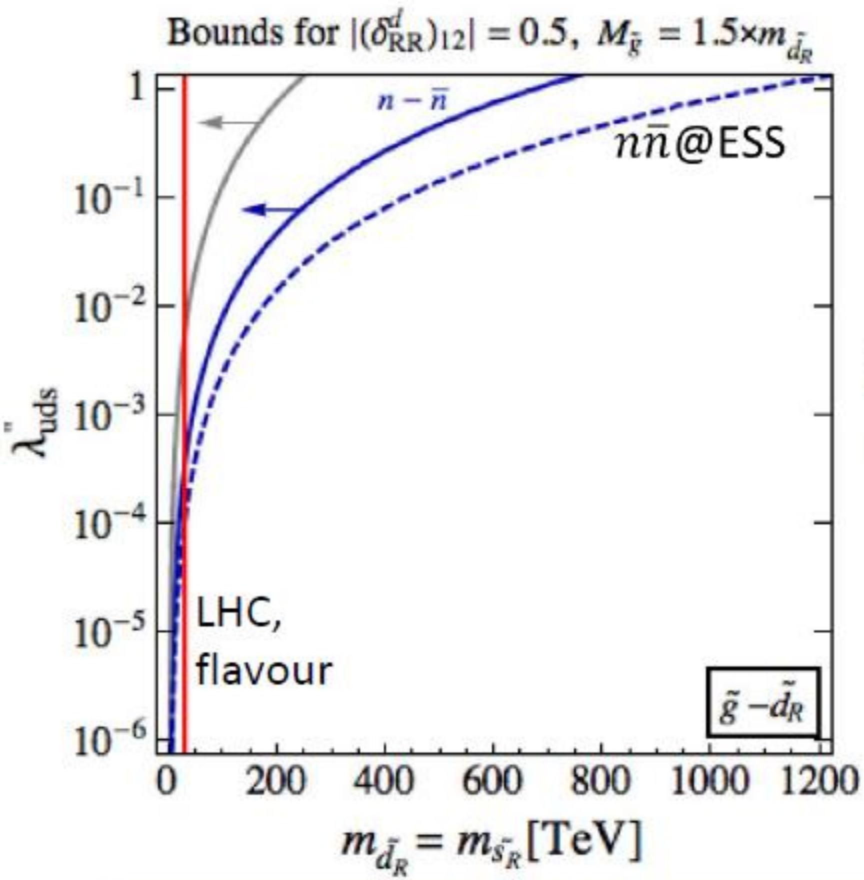
Consistent picture:

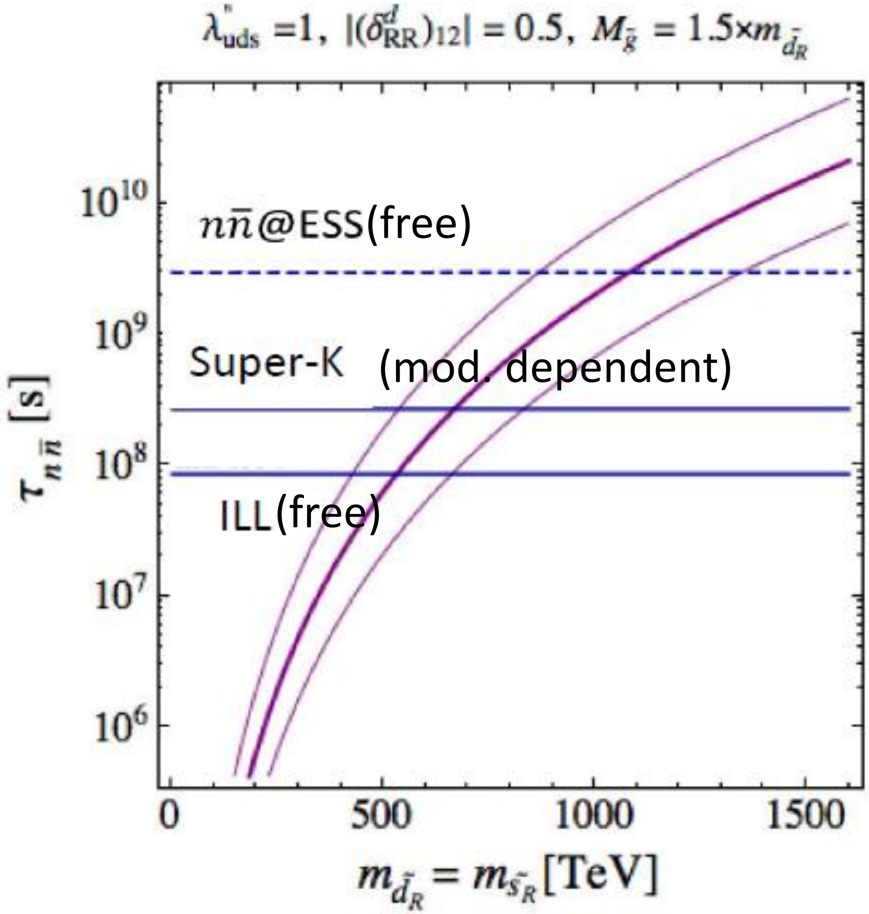
Dedicated BNV expts. sensitive to higher mass scales than LHC and flavour experiments.

Dependent on the coupling and mixing values.

Searches are complementary.

Beyond the TeV scale





Constraints vanish for >> TeV masses

nnbar@ESS: extends mass range by up to ~400 TeV cf Super-K

: pushes into the PeV scale

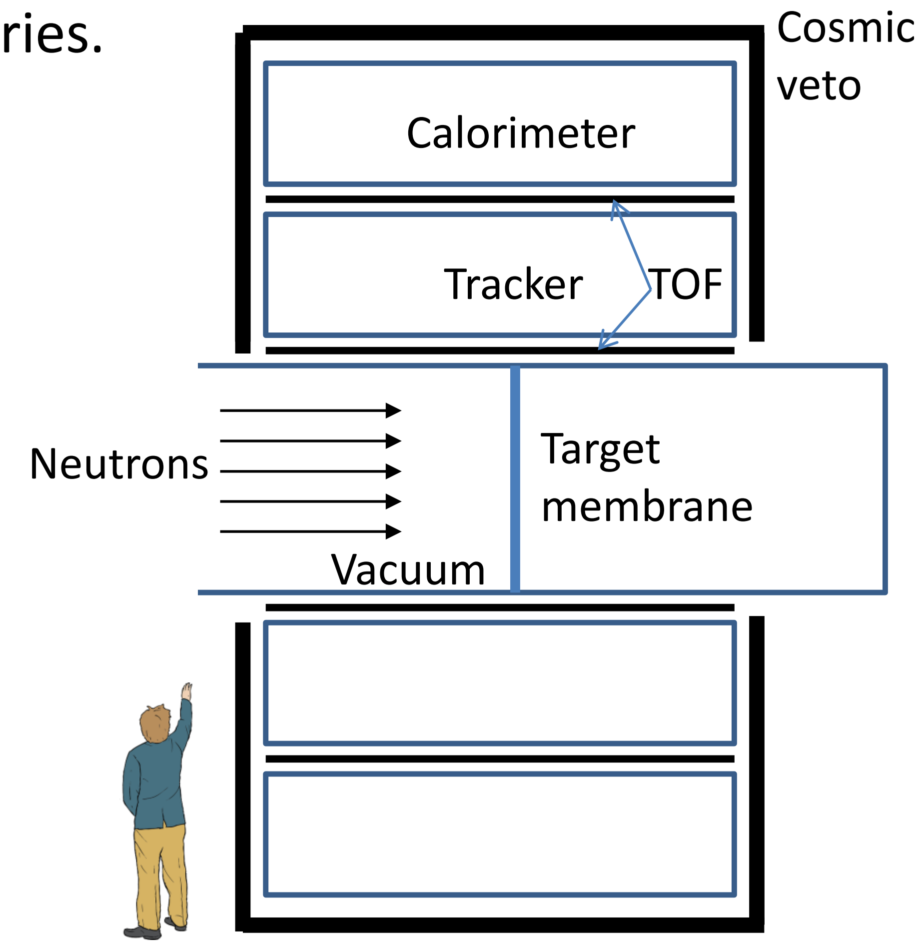
: Reach beyond the LHC

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

nnbar@ESS Collaboration: Co-Spokespersons G. Broojimans, D. Milstead

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 $P(n \to \bar{n})$

The proposed program

Stage 1

HIBEAM - high intensity baryon extraction and measurement

Early to late 2020s

- Match or improve sensitivity to $P(n \rightarrow \bar{n})$ wrt previous search at ILL
- Search for mirror neutrons (regeneration)
- R&D for full experiment (*NNBAR*)

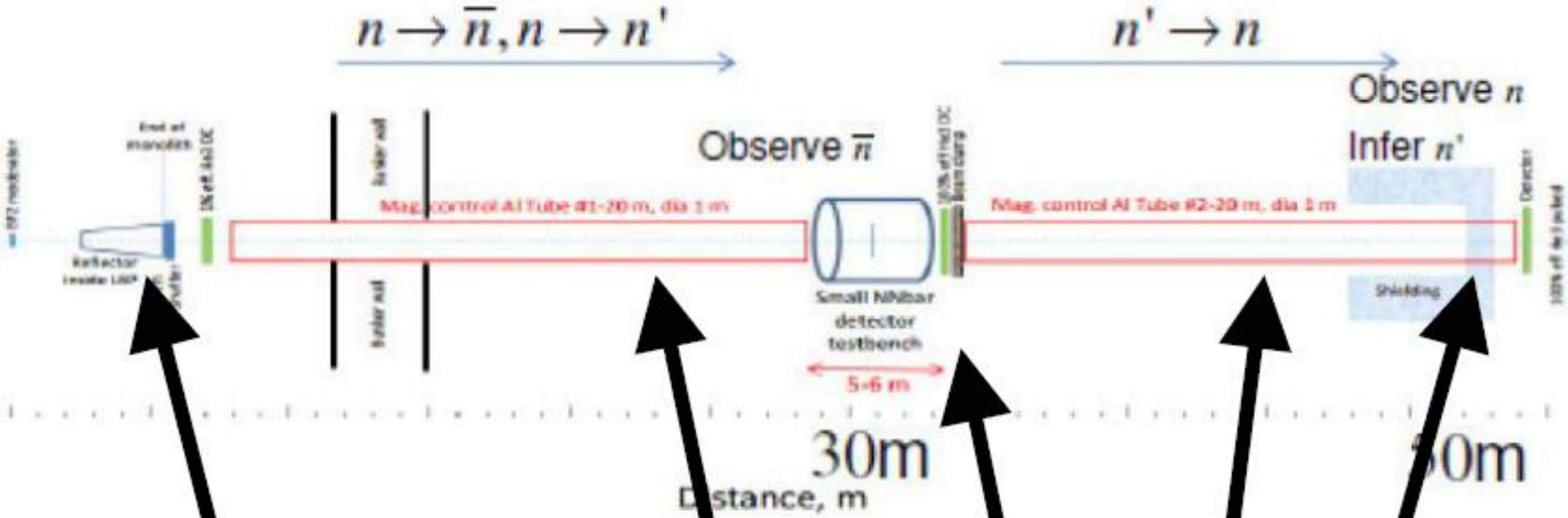
Stage 2

NNBAR experiment

Late 2020's + 5 years

- Improve sensitivity to $P(n \rightarrow \bar{n})$ by $\sim 10^3$
- Further mirror neutron searches

HIBEAM and nnbar



1. Neutron focusing
2. Passage through shielded tube
3. If $n \to \bar{n} \to$ annihilation of $\bar{n}$ in C target

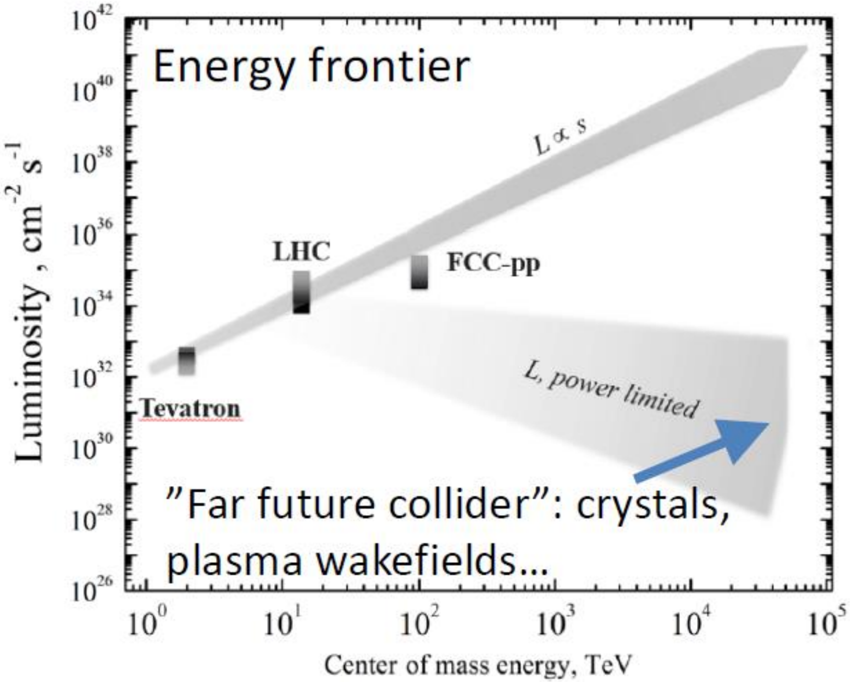
4. If $n \to n' \to$ passage through absorber
5. $n' \to n \to$ measure n in neutron counter

Nnbar experiment – extend to ~300m

Summary

- BNV-only searches are an important part of program to test symmetries, search for BSM physics and understand baryogenesis.
- If Nature chose BNV-only She hid it but we know how to look.
- RPV SUSY provides a framework to study sensitivity.
- A future dedicated $n \to \overline{n}, n'$ search can massively extend sensitivity.

We live in interesting times

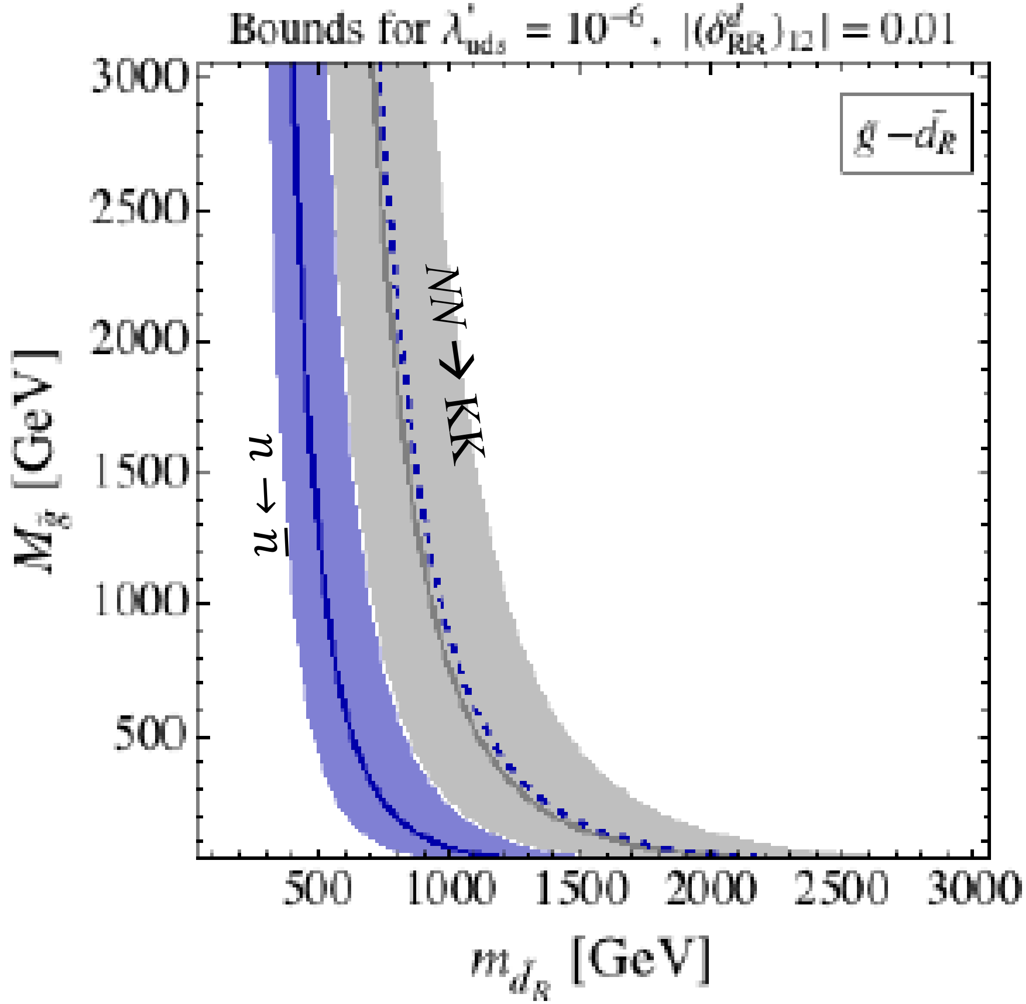


Future discoveries or walking a few km in a desert ?

For the first time in 50 years, going to higher collision energies no longer offers a clear path to discoveries or fundamental insights.

Need a complementary set of collider +non-collider experiments with unique physics potentials and reach of energy scale.

Uncertainties from hadronic matrix elements



Operators and lifetime

Six quark operators O_i of dimension-9 :

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

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

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

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

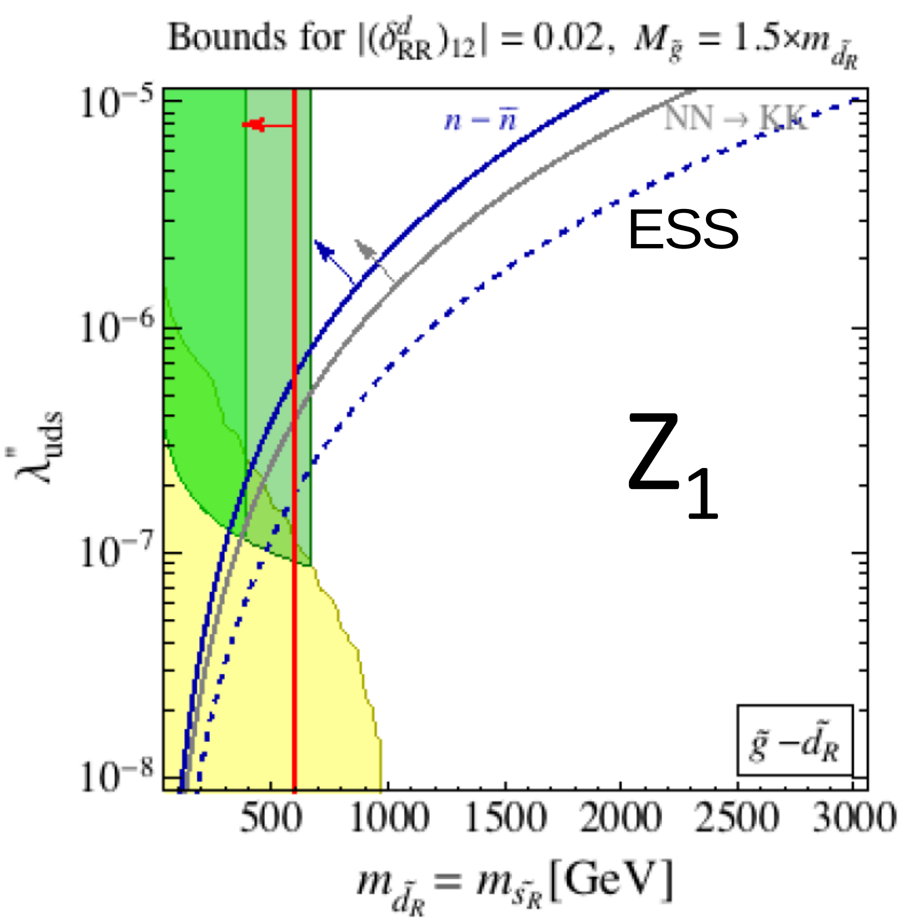
First three operators: $n \to \bar{n},\ NN \to \pi\pi$

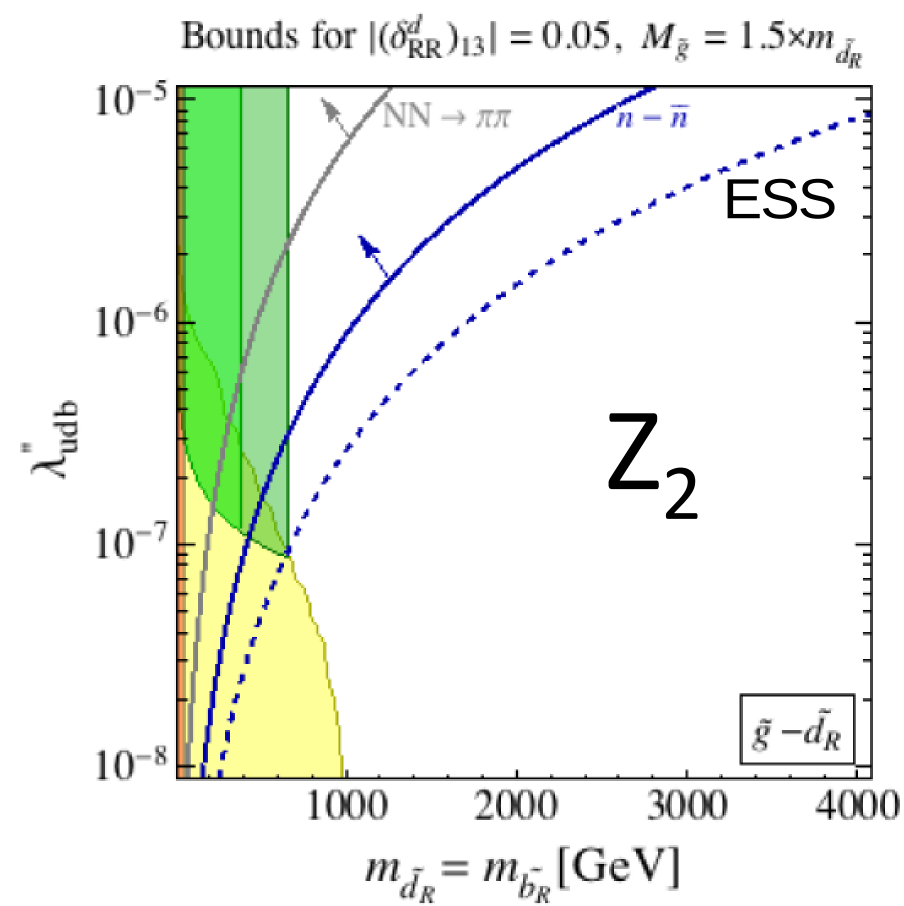
Last two operators: $NN \to KK$

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

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

Model exclusion – Z_1, Z_2





Dedicated BNV searches give sensitivity beyond the LHC.