Baryon Number Violation at Colliders

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Outline

- Role of colliders
  - Precision frontier
  - High energy frontier
- Collider/non-collider complementarity for $n \to \bar{n}$ and dinucleon decay

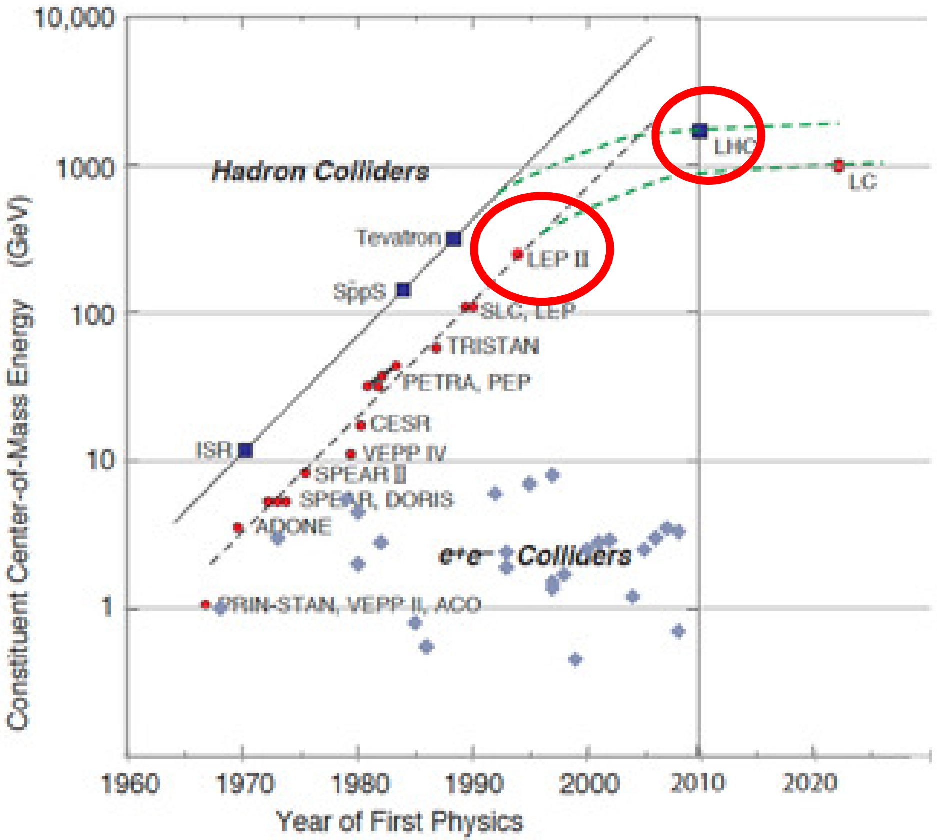
What role can colliders play ?

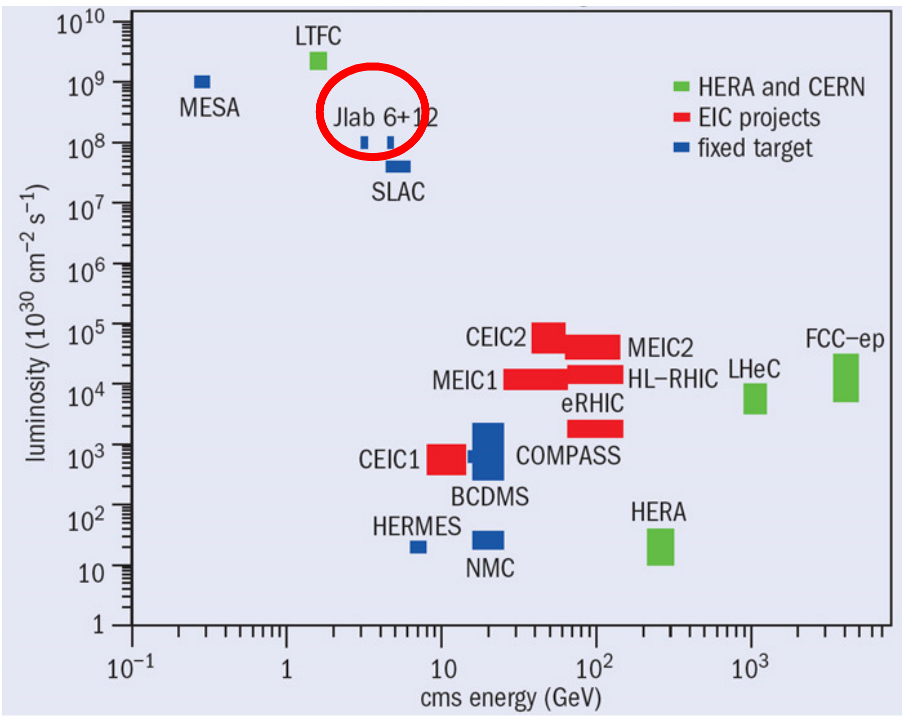
Important to probe different selection rules of $\Delta B, \Delta L$, $\Delta(B-L)$

- Precision frontier
  - Searches for forbidden decays
  - No QCD uncertainties
  - $\Delta B, \Delta L \neq 0$, $\Delta(B-L) = 0$

- High energy frontier
  - LHC
  - Direct production of BNV-inducing particles/phenomena
  - $\Delta B, \Delta L \neq 0$, $\Delta(B-L) = 0, \Delta(B-L) \neq 0$
  - $\Delta B \neq 0$, $\Delta L = 0$, $\Delta(B-L) \neq 0$

Colliders in one slide





Hadron-hadron, e^+ - e^- , lepton-hadron / γ-hadron

The Precision Frontier

Searches for forbidden decays

BARYON NUMBER

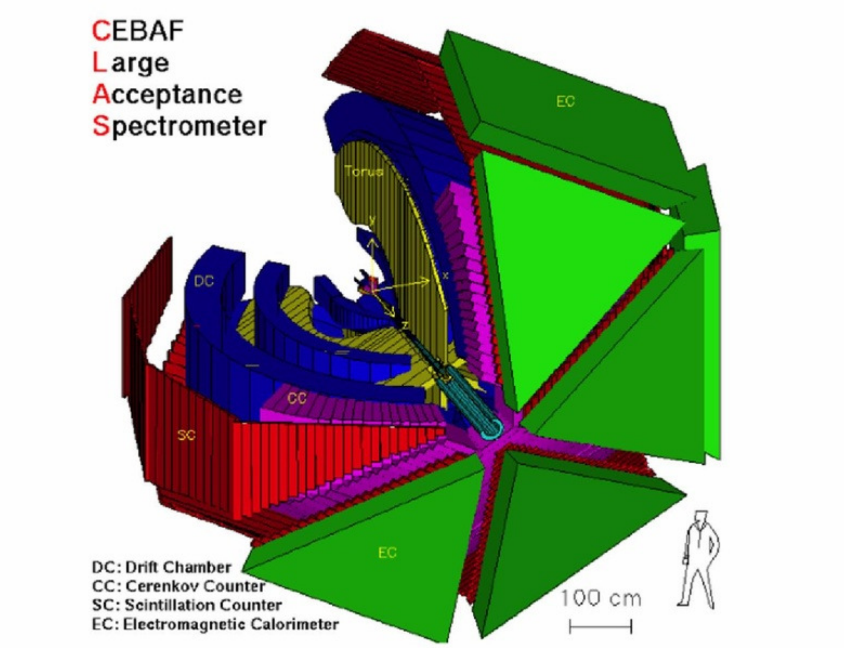
$\Gamma(Z \to pe)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{total}$		$<4.4 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{total}$		$<3.3 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{total}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{total}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{total}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{total}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{total}$		$<2.7 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{total}$		$<7.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \overline{\Lambda}\pi^-)/\Gamma_{total}$		$<1.4 \times 10^{-7}$, CL = 90%
$\Gamma(D^0 \to pe^-)/\Gamma_{total}$	[r]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{total}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0 e^+)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0 e^+)/\Gamma_{total}$		$<8 \times 10^{-8}$, CL = 90%
$\Gamma(B^0 \to \Lambda_c^+\mu^-)/\Gamma_{total}$		$<1.4 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to \Lambda_c^+ e^-)/\Gamma_{total}$		$<4 \times 10^{-6}$, CL = 90%
p mean life	[t]	$>2.1 \times 10^{29}$ years, CL = 90%
$\tau(N \to e^+\pi)$		> 2000 (n), > 8200 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+\pi)$		> 1000 (n), > 6600 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to e^+K)$		> 17 (n), > 1000 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+K)$		> 26 (n), > 1600 (p) $\times 10^{30}$ years, CL = 90%
limit on $n\overline{n}$ oscillations (free n)		$>0.86 \times 10^8$ s, CL = 90%
limit on $n\overline{n}$ oscillations (bound n)	[u]	$>1.3 \times 10^8$ s, CL = 90%
$\Gamma(\Lambda \to \pi^+e^-)/\Gamma_{total}$		$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^+\mu^-)/\Gamma_{total}$		$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^-e^+)/\Gamma_{total}$		$<4 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^-\mu^+)/\Gamma_{total}$		$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to K^+e^-)/\Gamma_{total}$		$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^+\mu^-)/\Gamma_{total}$		$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-e^+)/\Gamma_{total}$		$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-\mu^+)/\Gamma_{total}$		$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K_S^0\nu)/\Gamma_{total}$		$<2 \times 10^{-5}$, CL = 90%
$\Gamma(\Lambda \to \overline{p}\pi^+)/\Gamma_{total}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2e^+)/\Gamma_{total}$		$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2\mu^+)/\Gamma_{total}$		$<9.4 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}e^+\mu^+)/\Gamma_{total}$		$<1.6 \times 10^{-5}$, CL = 90%

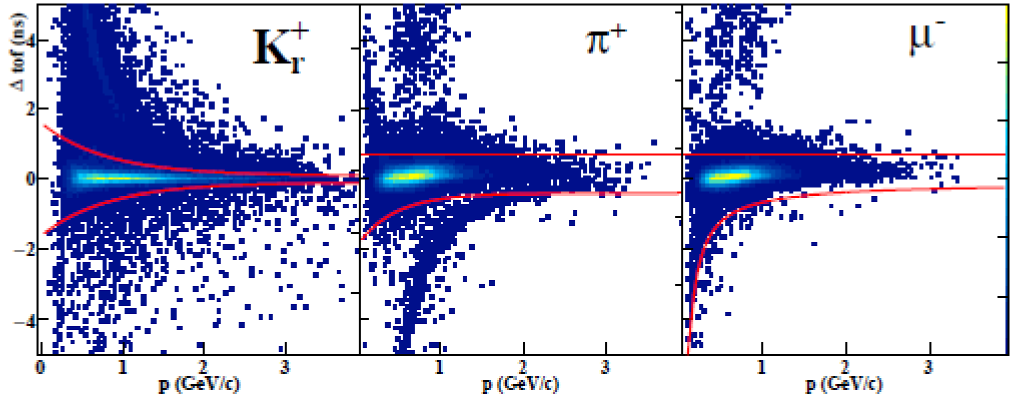
$\Gamma(\Xi^0 \to \Sigma^- e^+\nu_e)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^0 \to \Sigma^- \mu^+\nu_\mu)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%

Systematic exploration of possible observables.

Typically: $\Delta B, \Delta L \neq 0\ ,\ \Delta(B-L) = 0$

Forbidden λ-decays



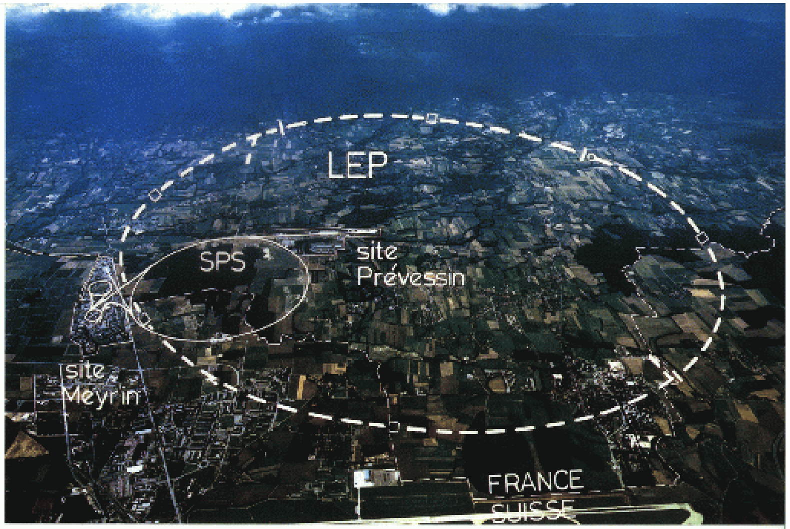


CLAS experiment at the Jefferson Laboratory

Reaction	w_1	w_2	ϵ (%)	$N_{\rm eb}$	$N_{\rm obs}$	$N_{\rm UL}$	$\mathcal{B}_{\rm UL}$
$\Lambda \to K^+e^-$	2.50×10^{-4}	0.01625	4.13	0	1	4.36	2×10^{-6}
$\Lambda \to K^+\mu^-$	3.25×10^{-4}	0.0125	4.42	0	2	5.91	3×10^{-6}
$\Lambda \to K^-e^+$	1.80×10^{-3}	0.01375	4.63	0	1	4.36	2×10^{-6}
$\Lambda \to K^-\mu^+$	3.00×10^{-4}	0.0300	4.40	0	2	5.91	3×10^{-6}
$\Lambda \to \pi^+e^-$	2.75×10^{-4}	0.00900	7.02	0	0	2.44	6×10^{-7}
$\Lambda \to \pi^+\mu^-$	3.25×10^{-4}	0.00900	7.91	0	0	2.44	6×10^{-7}
$\Lambda \to \pi^-e^+$	4.75×10^{-4}	0.0125	8.65	0.75	0	1.94	4×10^{-7}
$\Lambda \to \pi^-\mu^+$	3.50×10^{-4}	0.00900	7.92	0.25	0	2.44	6×10^{-7}
$\Lambda \to \bar{p}\pi^+$	5.00×10^{-4}	0.0425	4.98	0	0	2.44	9×10^{-7}
$\Lambda \to K^0_S\nu$	0.01875	0.0600	2.23	239.25	-3.88	14.1	2×10^{-5}

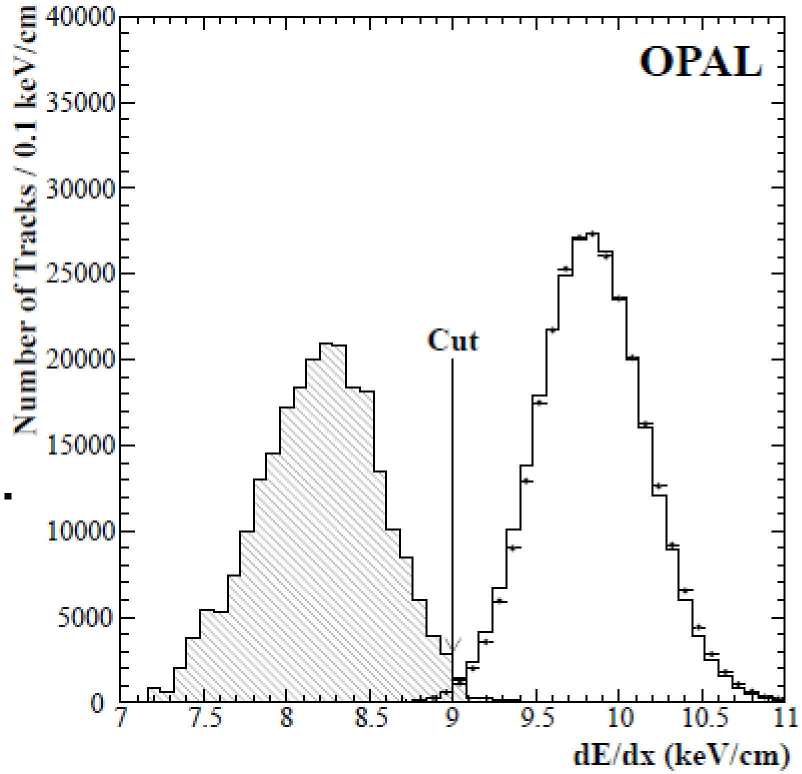
Wide range of channels
Arxiv: 1507.03859 (hep-ex)

BNV-violating Z^0-decays



LEP1 $E_{cm} = M_{Z^0}$

$$e^+ + e^- \to Z^0 \to pe^-, p\mu$$



Particle identification technique for p, lepton discrimination.

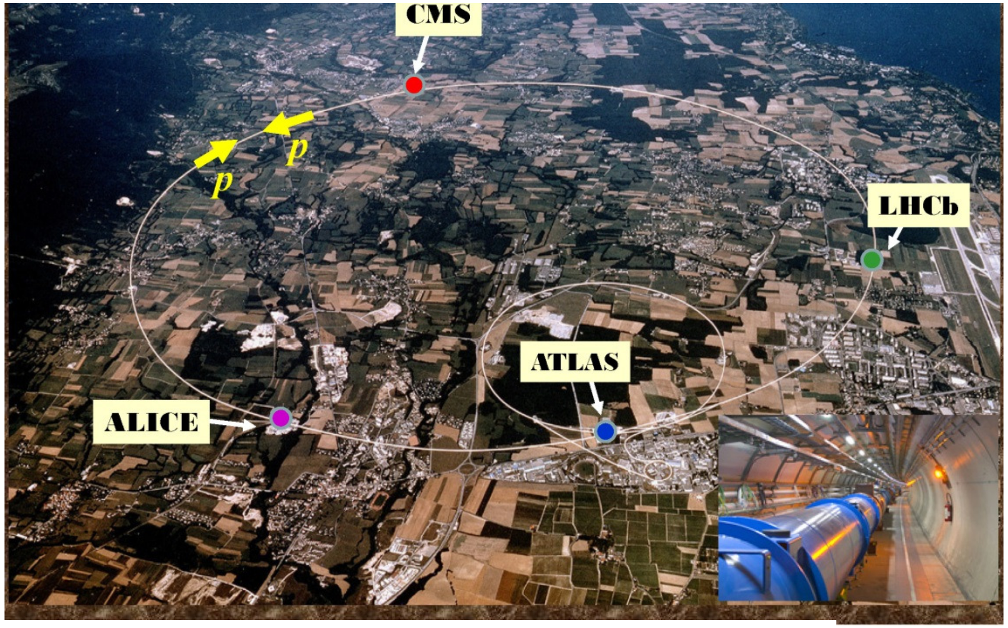
Decay mode	$\Gamma(Z^0 \to pX)$ (keV) - limit
$Z^0 \to pe$	4.6
$Z^0 \to p\mu$	4.4

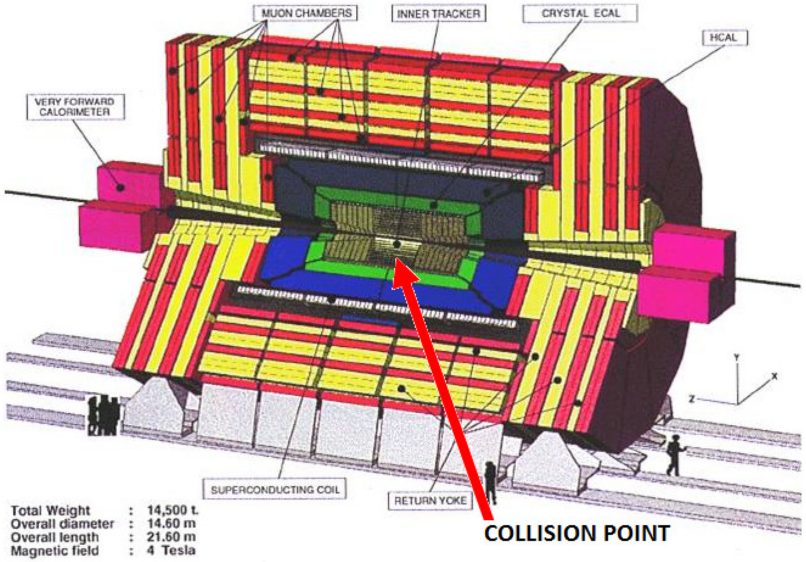
Large Hadron Collider

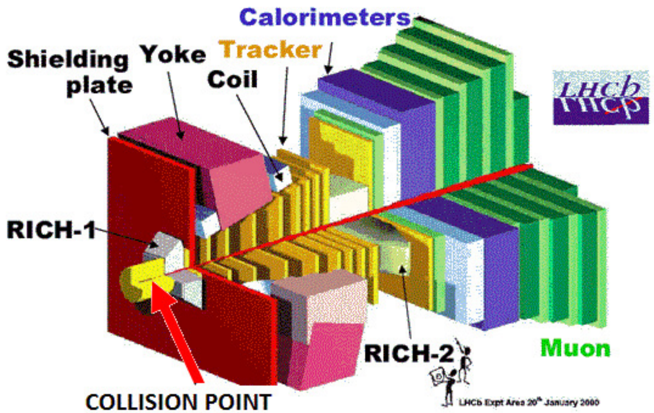
$\sqrt{s} = 7, 8, 13$ TeV

Expect $\sim 10^3$ fb^{-1}

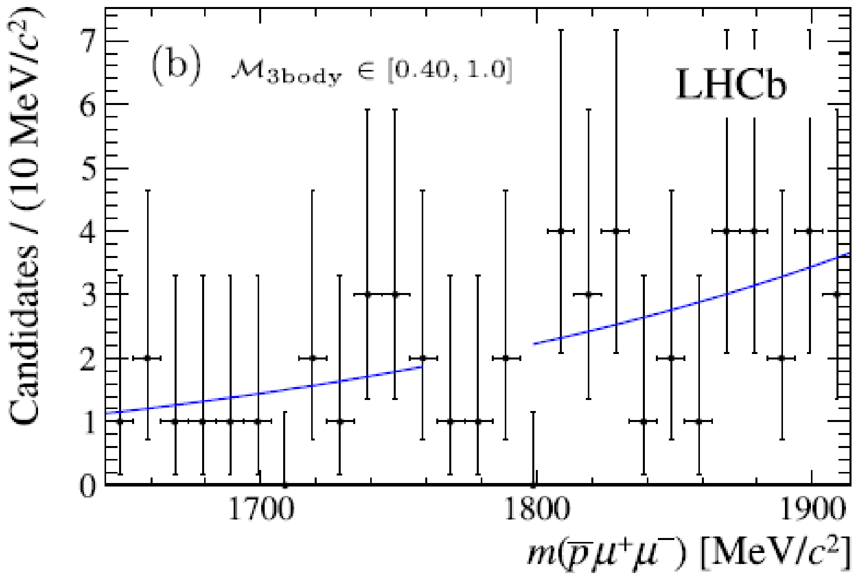
Multi-purpose and dedicated experiments.

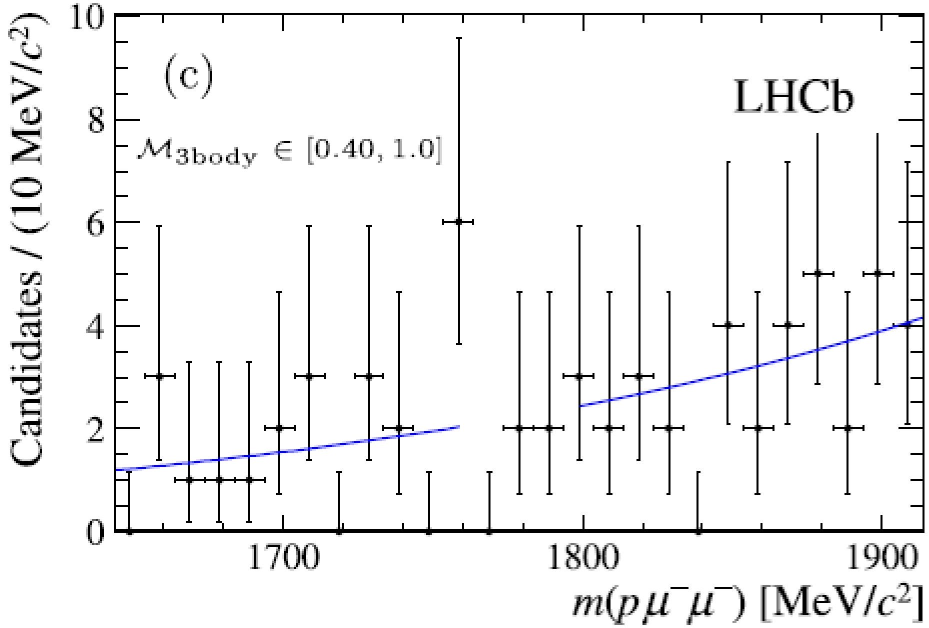






Search for $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ at LHCb

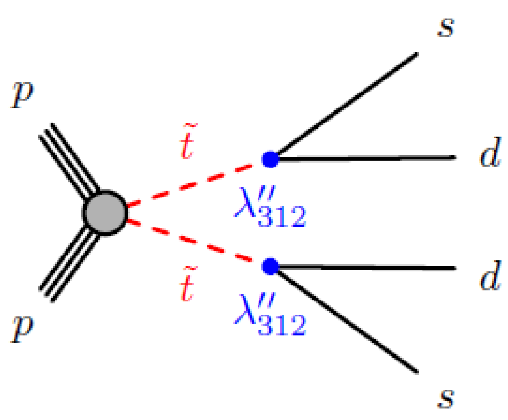


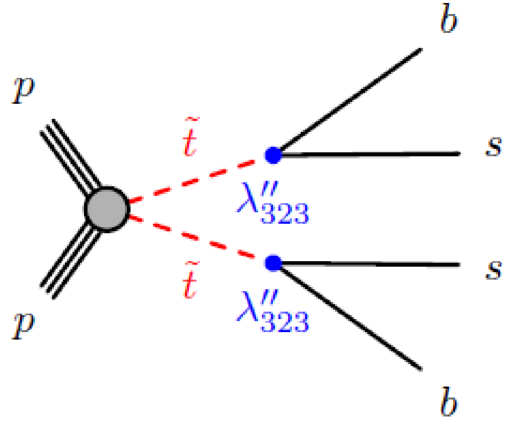


Decay mode	BR limit
$\tau^- \to \bar{p}\mu^+\mu^-$	3.3×10^{-7}
$\tau^- \to p\mu^-\mu^-$	4.4×10^{-7}

The High Energy Frontier

BNV with SUSY

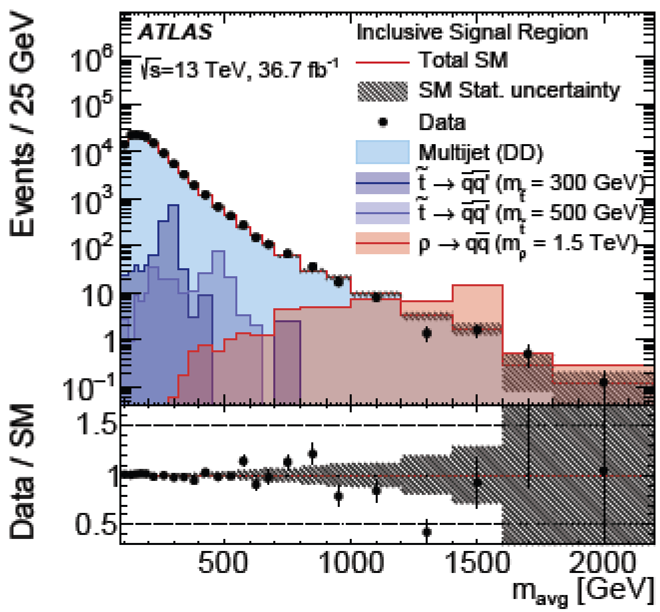


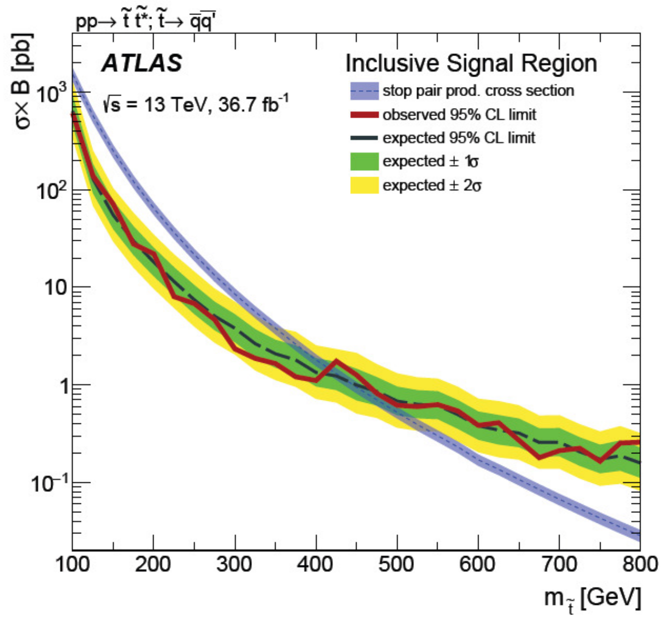


$\Delta B, \Delta L \neq 0\ , \Delta(B-L) \neq 0$

Searches for multijets and heavy flavour states.

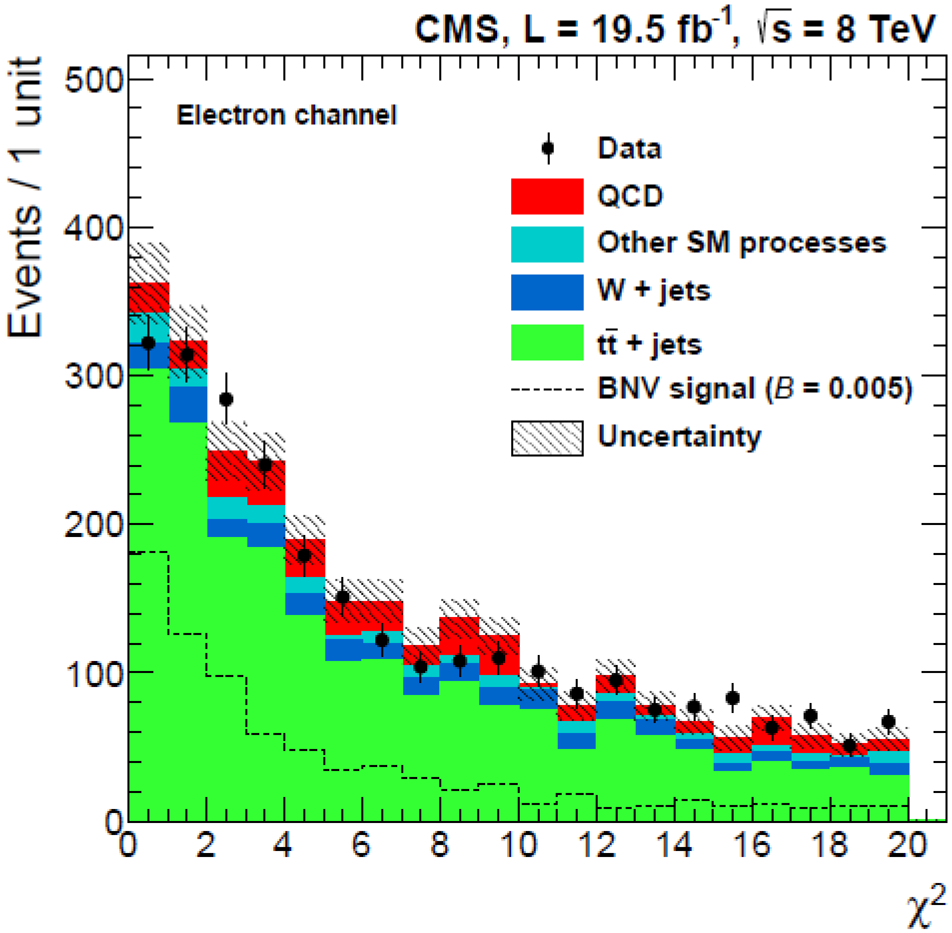
Often made within RPV-SUSY.





BNV via top decays

$$t \rightarrow \overline{b}\overline{c}e^{+}, t \rightarrow \overline{b}\overline{u}e^{+} \qquad \Delta B, \Delta L \neq 0, \ \ \Delta(B-L) = 0$$



CMS: Arxiv: 1310.1618 (hep-ex)

Channel	95% CL	Expected	68% CL exp. range
Muon	0.0016	0.0029	[0.0017, 0.0046]
Electron	0.0017	0.0030	[0.0017, 0.0047]
Combined	0.0015	0.0028	[0.0016, 0.0046]

Limits on BNV branching ratios.

BNV in the Standard Model

Bosonic sector of EW theory

Infinite no. of vacua

Vacua distinguished by fermion energy levels.

Instantons and sphalerons

Fluctuation of background W field

$\Rightarrow$ Vacuum minima change.

Energy level raises above (or falls below)

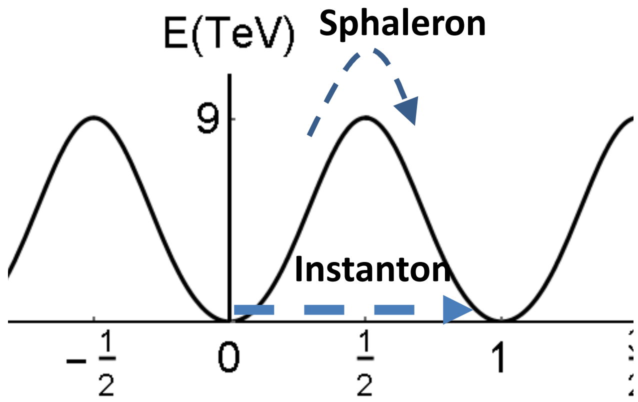
the surface of the Dirac sea.

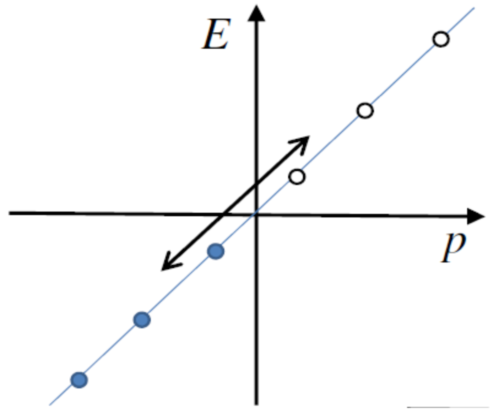
$\Rightarrow$ No. leptons and quarks changes

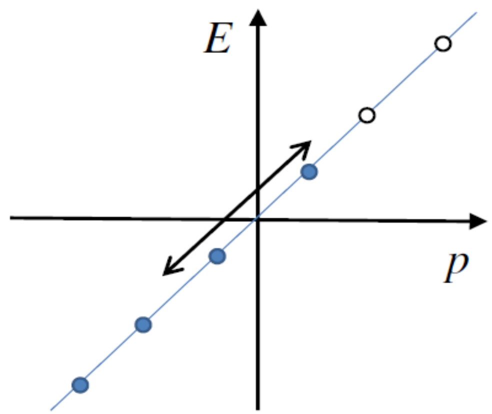
$\Rightarrow \Delta(B+L) \neq 0, \Delta L = \Delta B \neq 0, \ \Delta(B-L)=0,$

Non-perturbative and exponentially suppressed.

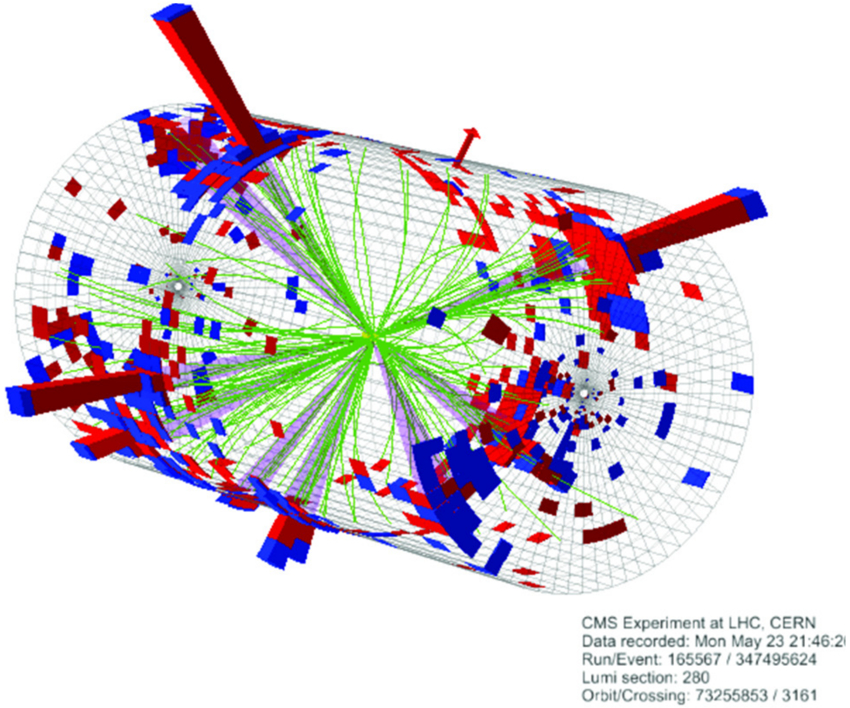
Nothing for a collider ?

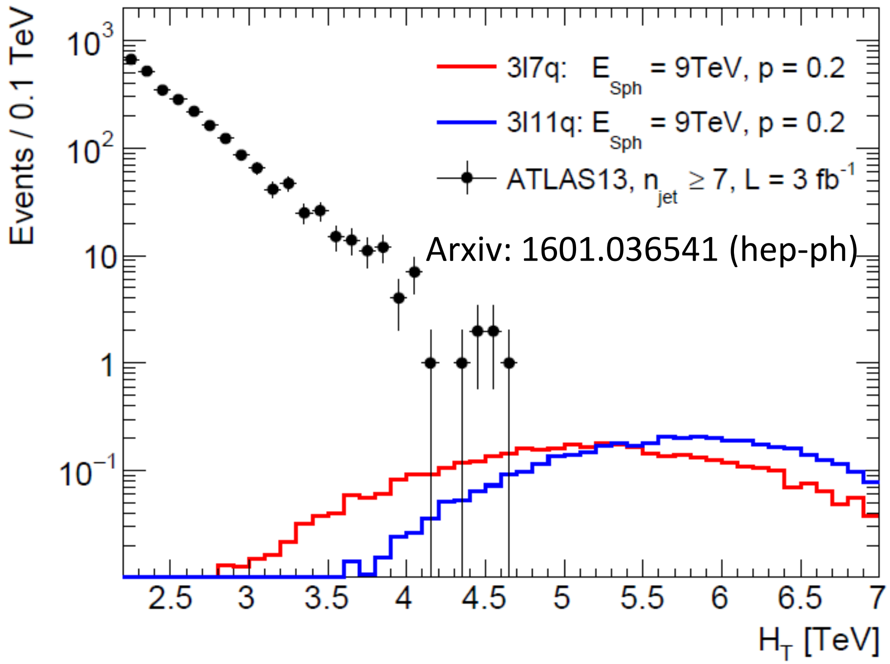






Sphalerons at the LHC





Fireball – multijet signature as for microscopic black holes.
Recast interpretation made for ATLAS BH search
Under study for the Future Circular Collider

Collider/non-collider complementarity for $n \rightarrow \bar{n}$ and dinucleon decays

arXiv:1602.04821

BNV in RPV-SUSY

General (R-parity violating) SUSY :

$$W_{RPV} = W_{MSSM} + \lambda_{ijk} LLE^c \quad + \lambda'_{ijk} LQD^c \quad + \lambda''_{ijk} U^c D^c D^c$$

LNV LNV BNV

No theoretical reason to conserve R-parity: $P_R = (-1)^{3B+L+2S}$

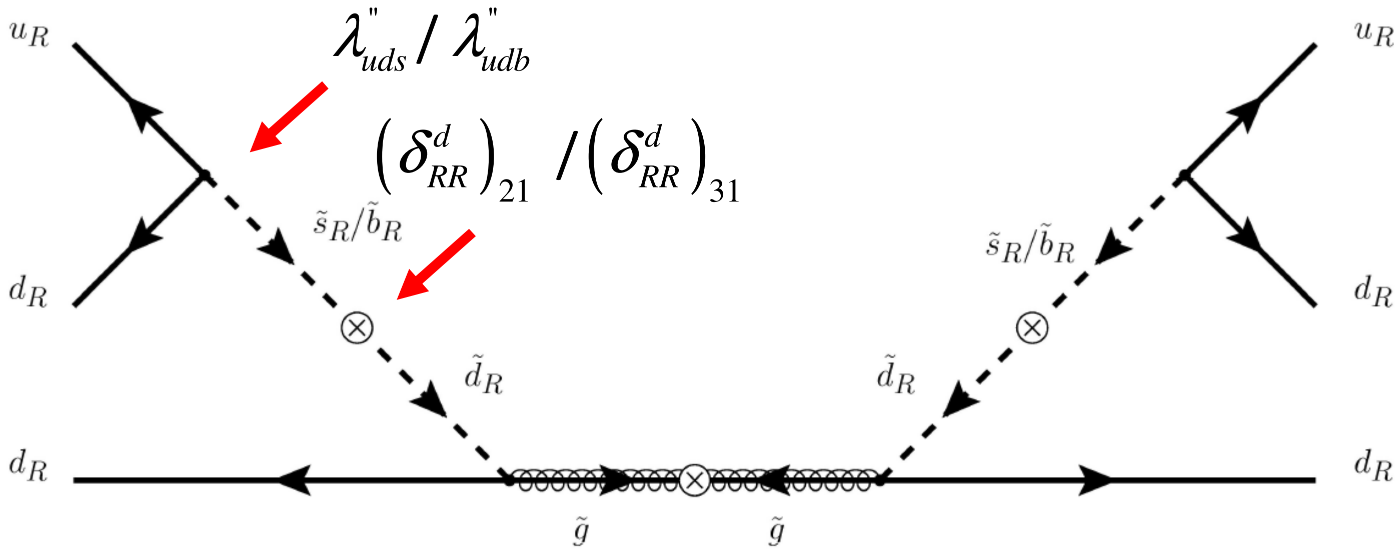
$$W_{RPV} = \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \quad ; \quad \lambda''_{ijk} = -\lambda''_{ikj} \quad \Rightarrow \lambda''_{111} = 0$$

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

Simplified models - strong and electroweak.

Parameters: sparticle masses, Yukawa coupling and mixing terms.

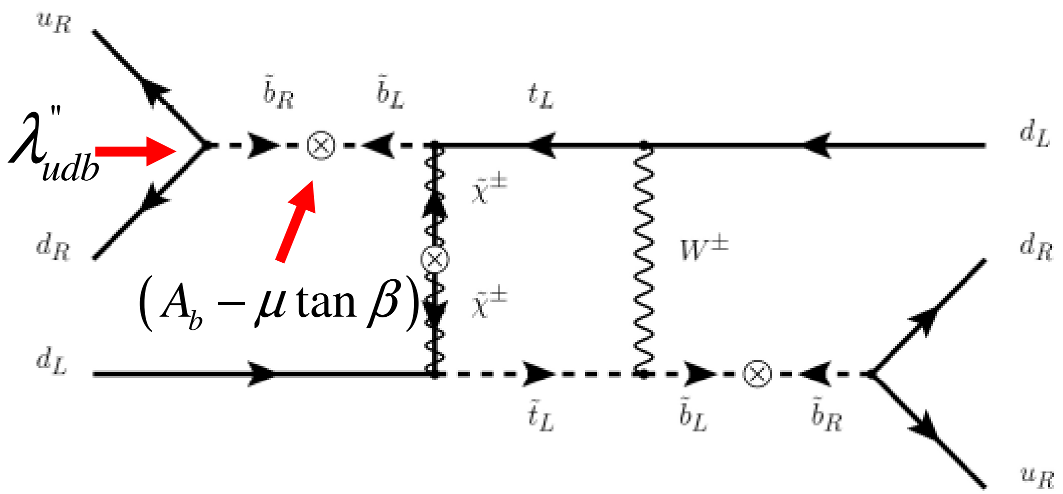
RPV-SUSY scenarios for $n \to \bar{n}$



Zwirner:

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

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



Goity and Sher :

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

Total of 6 scenarios considered.

Operator analysis

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

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

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

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

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

(first three operators) $n \to \bar{n},\ NN \to \pi\pi$

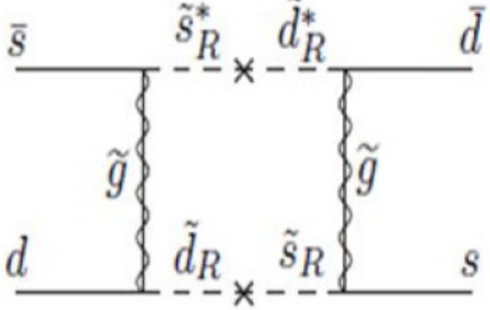
(last operator) $NN \to KK$

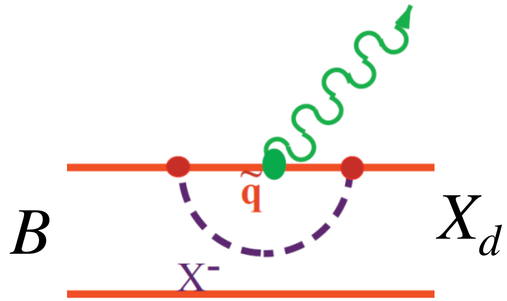
Eg Zwirner: $\tau = \left(2.5\times 10^8 \text{ s}\right) \times \dfrac{(250 \text{ MeV})^6}{\langle \bar{n} | (u_R d_R d_R)^2 | n \rangle} \times \dfrac{m_{\tilde{g}}}{1.2 \text{ TeV}} \left(\dfrac{\bar{m}_D}{500 \text{ GeV}} \right)^4 \left(\dfrac{10^{-6}}{\lambda''_{uk}} \right)^2$

Experimental constraints

Flavour/mixing

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

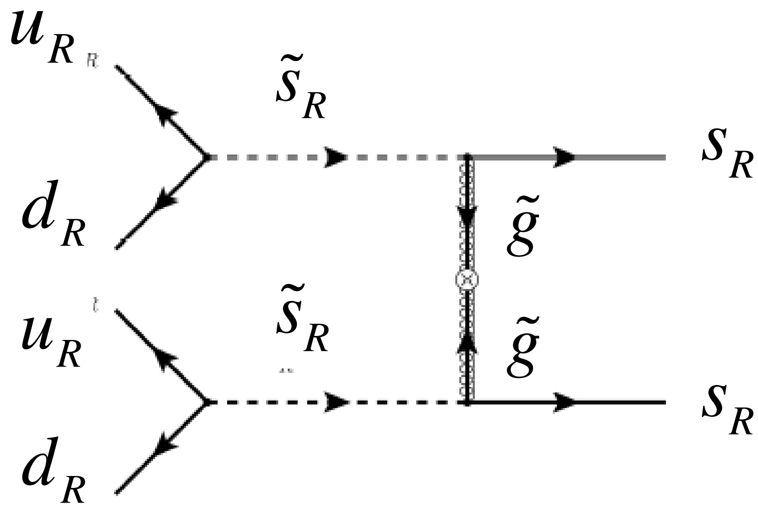




Low energy BNV

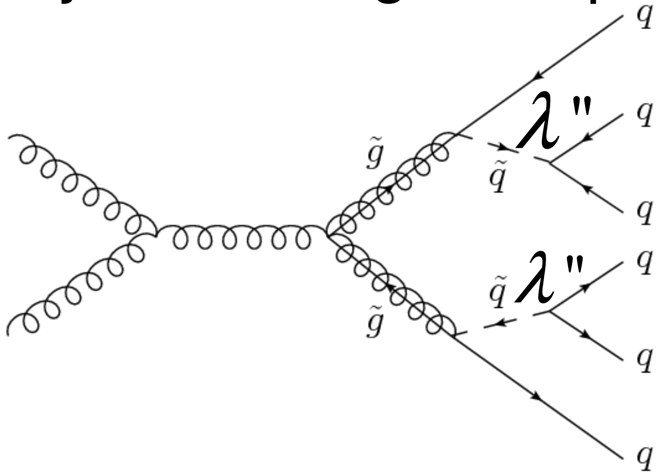
Observable	Parameter
$n \to \bar{n}$	$\lambda''_{112}, \lambda''_{113}$
$NN \to$ mesons	

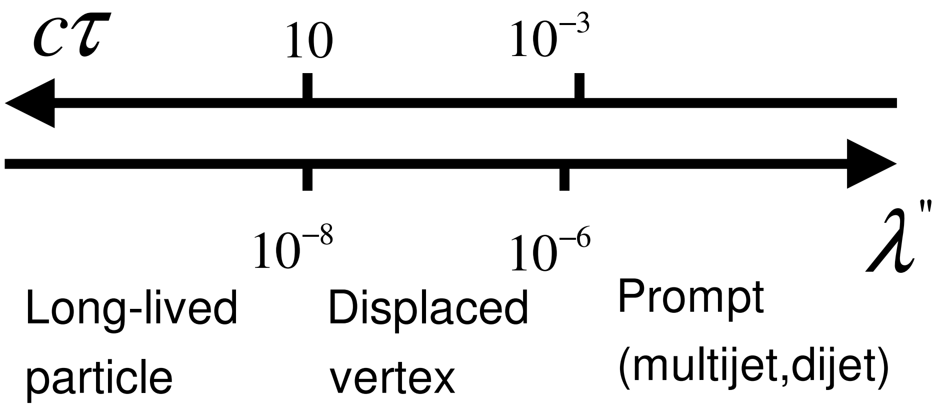
Limits from Super-K



LHC constraints

Multijet and long-lived particle signatures

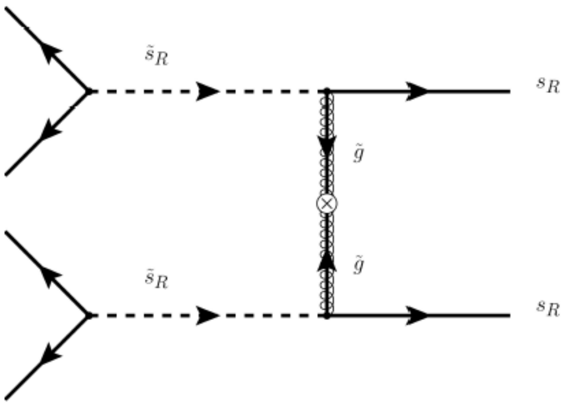




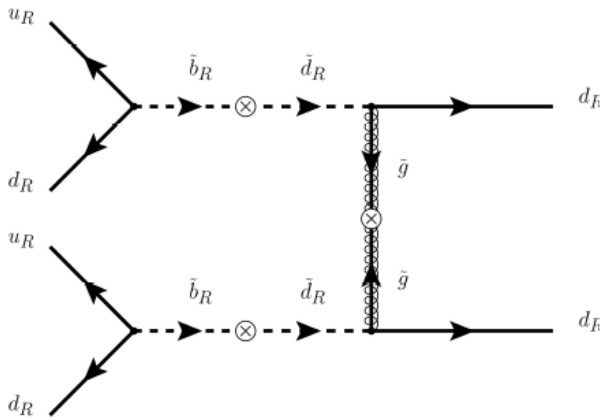
Observable	Parameter
ATLAS Multijets (Arxiv:1602.04821 hep-ex) recast with Madgraph+Pythia+Delphes	$\lambda''_{112}, \lambda''_{113}$
CMS Dijets Arxiv:1412.7706	
ATLAS/CMS Displaced vertex+ long-lived particle recast (arxiv:1503.05923, 1505.00784 hep-ph, CMS-PAS-EXO-15-010)	

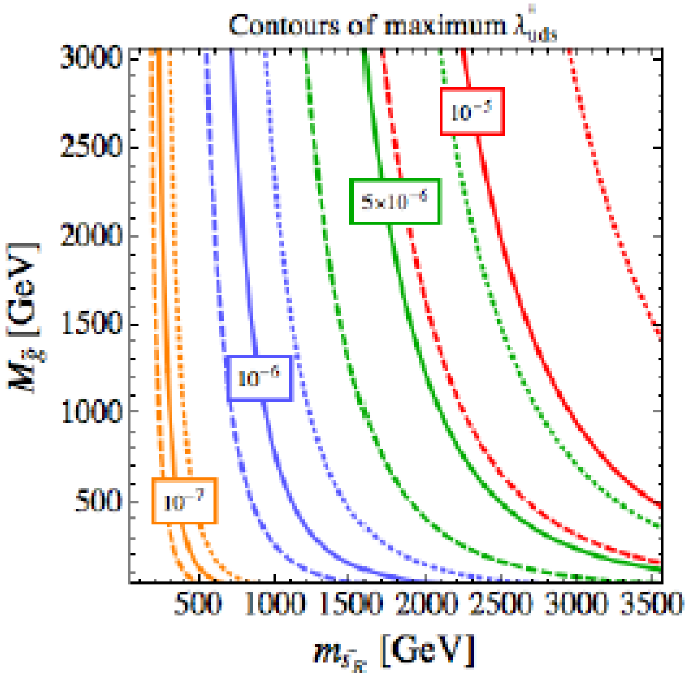
Dinucleon decays

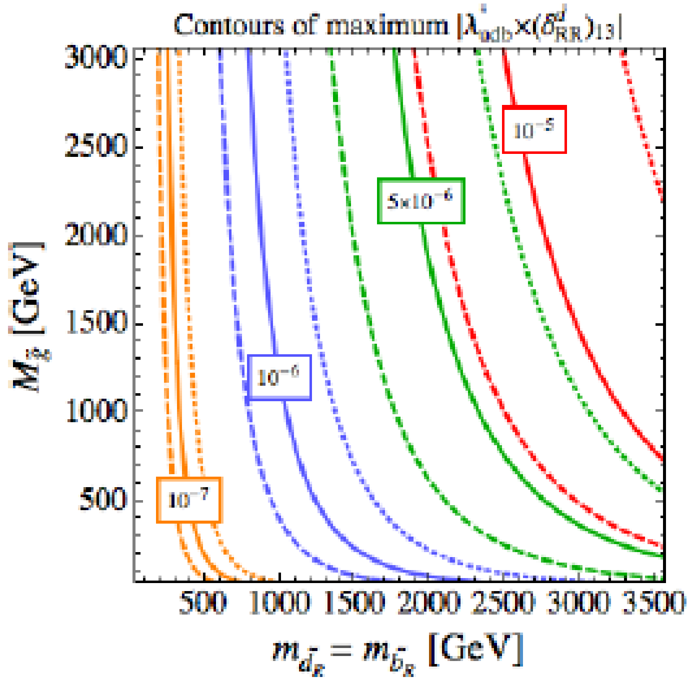
$NN \to KK$



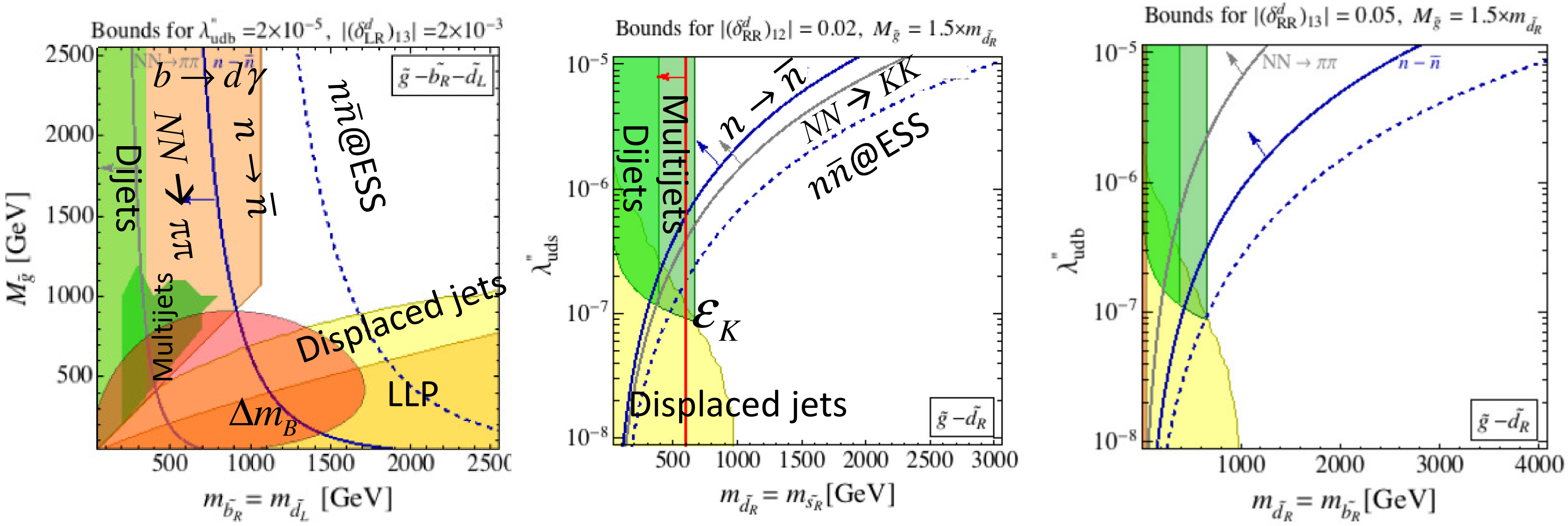
$NN \to \pi\pi$







Model exclusion: BM_2 ,CK, GS



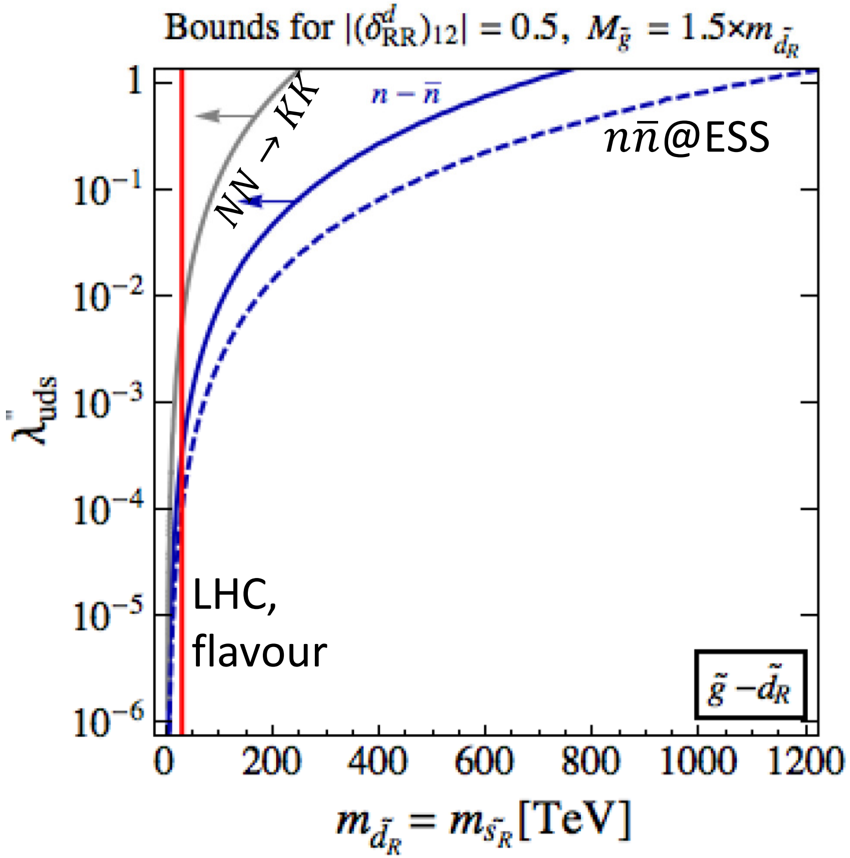
Consistent picture:

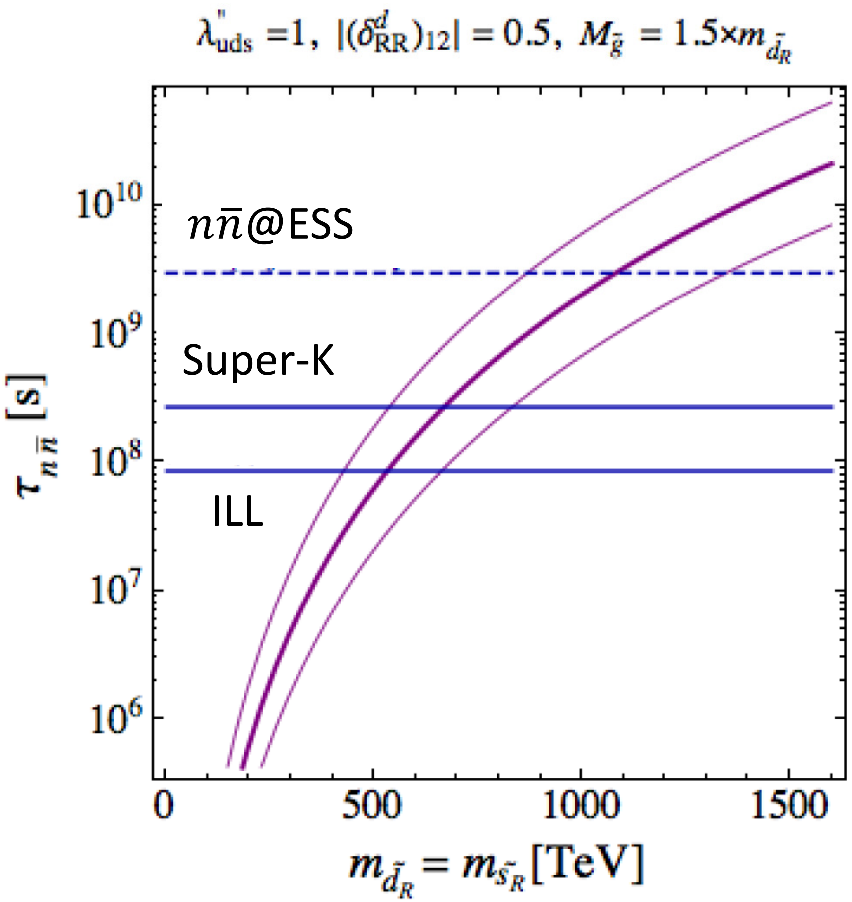
Dedicated BNV expts. sensitive to higher mass scales than LHC and flavour experiments.

Dependent on the coupling and mixing values.

Searches are complementary.

Beyond the TeV scale





Model: Zwirner - strong

Constraints vanish for >> TeV masses

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

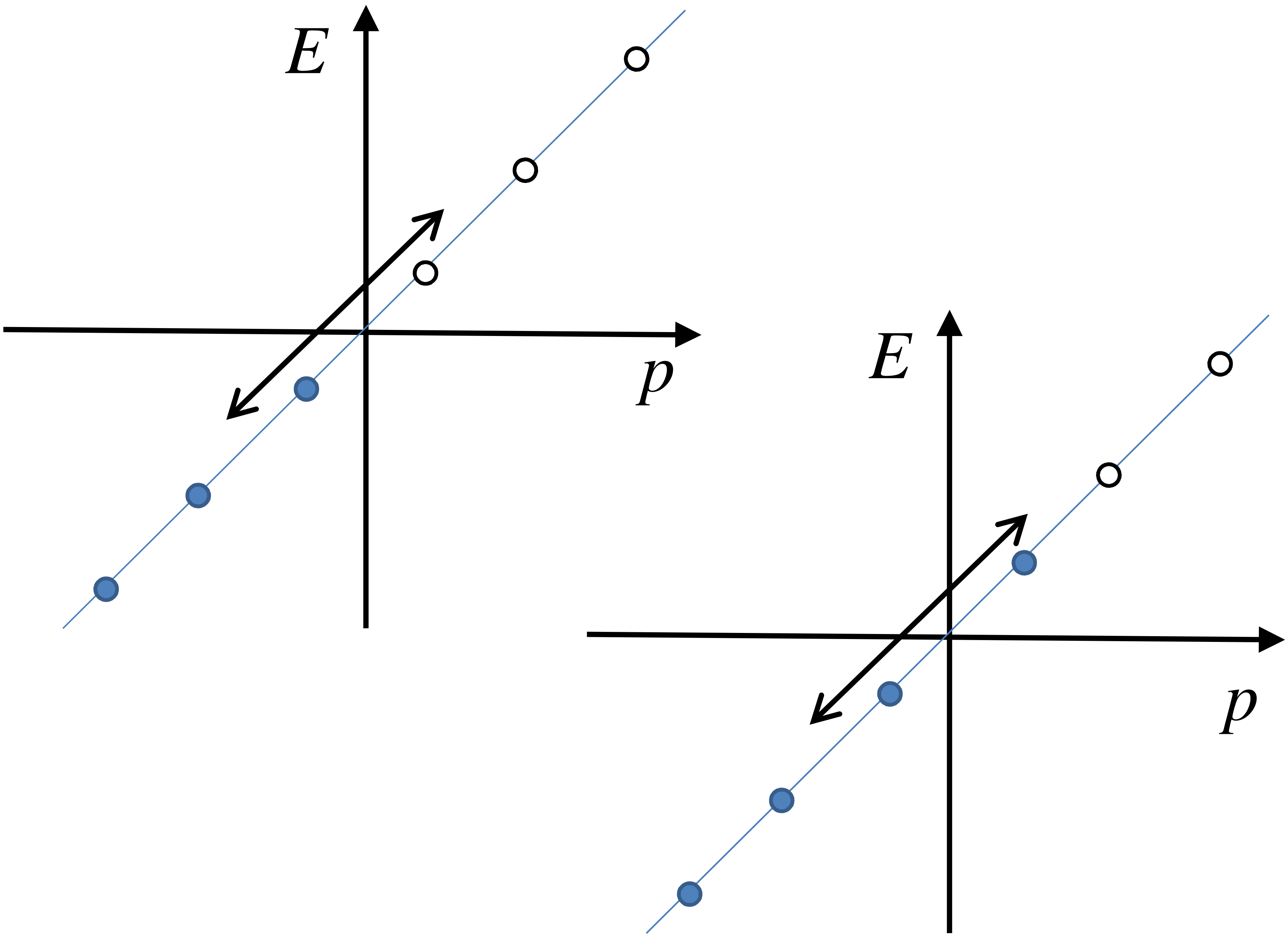
: pushes into the PeV scale

Possible topic for discussion

- Each limit/search is vital information on nature works.
- Tables of limits = stamp collecting.
- Can a connection be made between them in a given theoretical framework
  - Identify useful missing channels and most promising channels
  - LHC about to go into a long shutdown with headline analyses done
    - Ideal chance to promote a comprehensive sweep over possible forbidden decays
  - Older experiments (eg at LEP) have open data access.
    - A search is not glamorous but a discovery would be.

Summary

- Colliders search for BNV via the intensity and high energy frontiers
- Span a range of selection rules of $\Delta B, \Delta L, \Delta(B-L)$
- Complementarity with non-colliders
- Collective interpretation
  - Possible/realistic ?
  - Adds value ?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