$B + L$ violation at colliders and new physics

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May 31, 2018

based on JHEP 1804 (2018) 076 (arxiv:1801.03492) with
D.G. Cerdeño, C. Tamarit, K. Sakurai

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$B + L$ violation+Dark Matter $\rightarrow$ at Colliders?

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BEYOND STANDARD MODEL

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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Baryon Number Violating Processes

In the Standard Model:

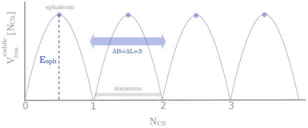
- accidental baryon and lepton symmetries
- has been confirmed by all experiments so far
- broken by quantum anomalies $\rightarrow$ Instanton Theory

Impact on physics of the early Universe:

- important in electroweak baryogenesis
- play a crucial role for baryogenesis through leptogenesis

DM can take part in sphaleron processes! (seen later)

$B + L$ violation from $SU(2)$ Anomalies



- global anomaly for $U(1)$ baryon and lepton charges:

$$\int \partial_\mu J^\mu_{B+L} = 6n_{\rm top} = 6\Delta N_{\rm CS}$$

- chiral anomaly on a quantum level

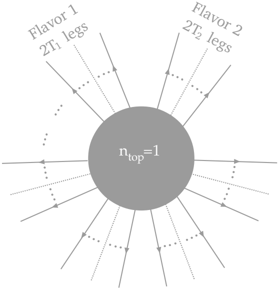
$$\Delta Q_{\rm chiral} = \int \partial_\mu J^\mu_{\rm chiral} = n_{\rm top} \sum_k 2T_k$$

with the topological charge $n_{\rm top} = \frac{g^2}{16\pi^2} \int {\rm Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) = 1, 2, \ldots$ and representation k with Dynkin index T_k.

General Case:

- electric neutrality
- neutral under $SU(3)_C$
- number of left-handed fermions determined by chiral anomaly
- "mixture" of particles determined by violation of additional global charges

General



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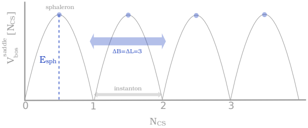

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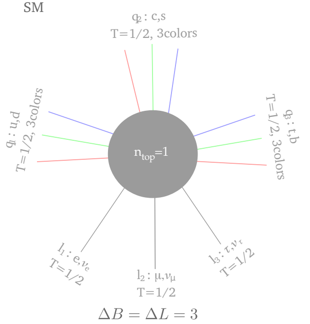
SM Case:

- $B+L$ violation by 6 (for $n_{\rm top} = 1$)
- **12 left-handed Weyl-fermions** in fundamental representation $T_k = 1/2$
- SM vertex:

$$\mathcal{O}_{\rm SM} = \prod_{i=1,2,3} (q_L q_L q_L l_L)_i$$



$B+L$ violation from $SU(2)$ Anomalies

- global anomaly for $U(1)$ baryon and lepton charges:

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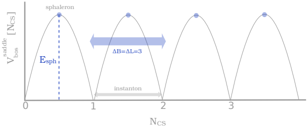

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How can BSM influence the vertices?

- $\Delta(B+L) = 6$ plus additional charge violation?
- **12 left-handed Weyl-fermions** in fundamental representation $T(r) = 1/2$ plus more $SU(2)$ fermions?

Possible BSM extensions:

- additional fermion number violation strongly constrained
- But additional $SU(2)$ fermions in certain representation k with T_k can extend the vertices!

Anomalous vertices with massive fermions

Mass terms for Weyl fermions $\psi_{k,l}$:

$$\mathcal{L} \supset \underbrace{m_{kl}}_{-2} \underbrace{\psi_k}_{+1} \underbrace{\psi_l}_{+1} + c.c.$$

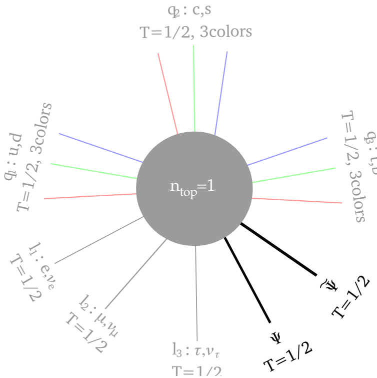
Classical symmetry restored by treating m as charged field.

- symmetry violated as before by anomaly
- anomalous interaction vertices carry same charge as before
- spurious charge can be carried by mass insertions m^*_{kl}

Taking into Account more SU(2) particles

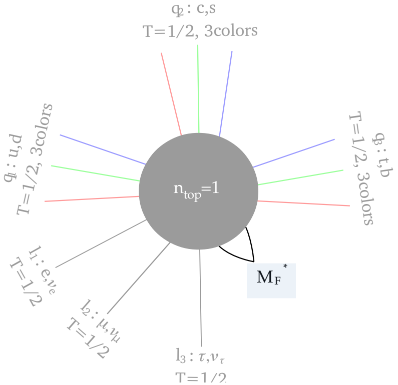
SM + Heavy Dirac in fundamental:

$$\mathcal{L} \supset -M\tilde{\Psi}\Psi + c.c.$$



BSM vertex

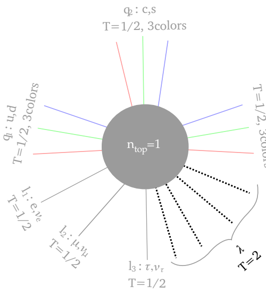
$$\Delta B = \Delta L = 3$$



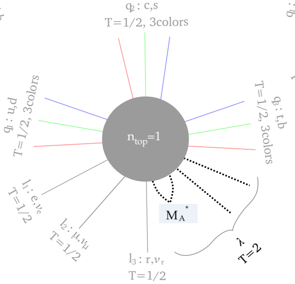
SM vertex!

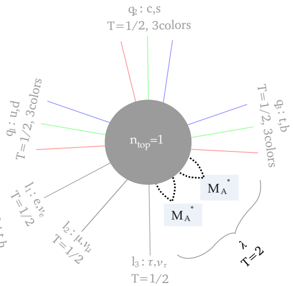
Taking into Account more SU(2) particles

SM + Heavy Weyl in adjoint:



$\mathcal{L} \supset -M_A \lambda\lambda + c.c.$

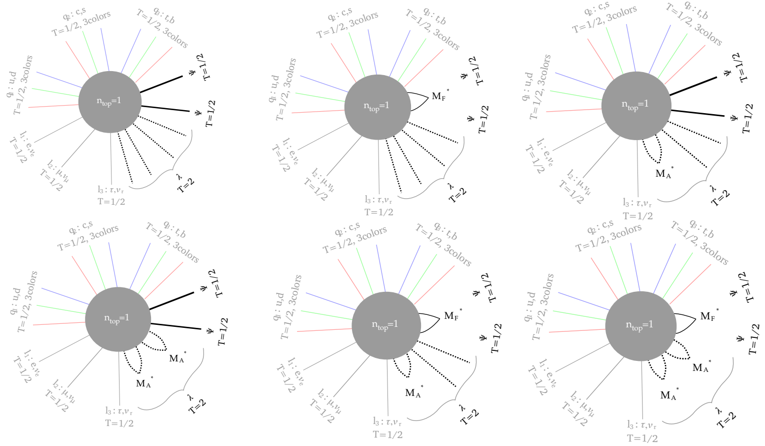




Up to 16 fermions!

$$\Delta B = \Delta L = 3$$

SM + Heavy Dirac in fundamental + Heavy Weyl in adjoint:

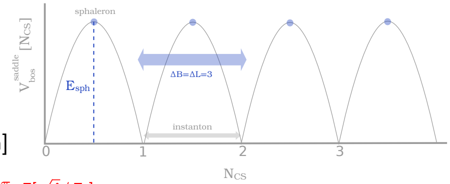


Up to 18 fermions!

$$\Delta B = \Delta L = 3$$

Can we observe such processes at colliders?

Dressing fermion amplitudes with gauge bosons:
First instanton estimates yield exponential corrections to rate when summing over gauge boson emission [Ringwald, O.Espinosa]



$$\sigma_{B+L,\text{leading}}^{2\to\text{any}} = f(\hat{s})e^{-\frac{4\pi}{\alpha_W}F[\sqrt{\hat{s}}/E_0]},$$

$$F\left[\frac{\sqrt{\hat{s}}}{E_0}\right] = 1 - \frac{9}{8}\left(\frac{\sqrt{\hat{s}}}{E_0}\right)^{4/3}, \quad E_0 = \frac{6\pi m_W}{\alpha_W} \gtrsim E_{\text{sph}}$$

$\Rightarrow$ unsuppressed above E_{sph}, but in conflict with unitarity arguments
Instanton loop corrections:

$$F\left[\frac{\sqrt{\hat{s}}}{E_0}\right] = 1 - \frac{9}{8}\left(\frac{\sqrt{\hat{s}}}{E_0}\right)^{4/3} + \frac{9}{16}\left(\frac{\sqrt{\hat{s}}}{E_0}\right)^{2} + \ldots$$

breaks down above $\sqrt{\hat{s}} > E_0 \ldots$

Can we observe such processes at colliders?

Further progress [Arnold& Mattis, Khlebnikov & Rubakov &Tinyakov, Mueller, Khoze & Ringwald]

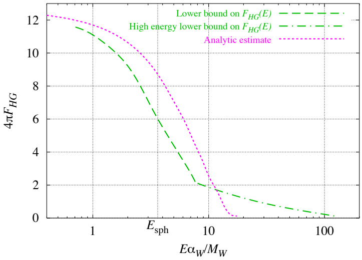
- cross-section looks like

$$\sigma_{B+L,\mathrm{leading}}^{2\to\mathrm{any}} = f(\hat{s}) e^{-\frac{4\pi}{\alpha_W} F[\sqrt{\hat{s}}/E_0]}$$

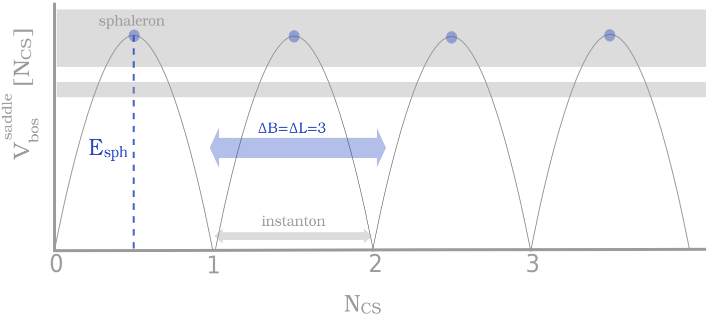
- with:
  1. Unitarity bound $F \gtrsim 0$ [Zakharov, Maggiore & Shifman, Veneziano]
  2. Dispersion relation [Zakharov, Porrati, Khoze & Ringwald]

$$f(\hat{s}) = \frac{1}{m_W^2} \left(\frac{2\pi}{\alpha_W} \right)^{7/2}$$

  3. lower bound on F [Rubakov &Tinyakov, Bezrukov et al]



Can we observe such processes at colliders?



Problem solved?
Take N_{CS} as kinetic variable and get 1D dynamics in the N_{CS} direction
$\Rightarrow$ one has a band structure and tunneling may be unsuppressed for $\sqrt{\hat{s}} \geq E_{\mathrm{sph}}$
[Tye & Wong, Funakubo et al]

$\Rightarrow$ arises attention: `BaryoGEN` [1805.02786], CMS study [1805.06013]

How to Add More Particles

Calculate effective couplings with ordinary instanton techniques:

$$\langle \psi_{k_1} ... \psi_{k_N} \rangle = \int \prod_m [\mathrm{d}\psi]_m [\mathrm{d}\psi^\dagger]_m \sum_{n_{\mathrm{top}}=q} \int [\mathrm{d}A^a_\mu]_q \exp(-S) \psi_{k_1} ... \psi_{k_N}$$

- Saddle point expansion around extremal of S
- 1-instanton dominates: $\exp(-S_{\mathrm{inst}}) = exp\left(-\frac{4\pi}{\alpha_W} n_{\mathrm{top}}\right)$
- Group Weyl fermions ψ_k, ψ_l into Dirac Ψ_{kl}

$$\langle \bar{\Psi}_{kl} \Psi_{kl} \rangle \propto \det \left(\frac{\delta^2 S}{\delta \bar{\Psi} \delta \Psi} \right) \prod (\text{Fermion prop. in instanton bg.})$$

- Ensure compatibility with decoupling: Get SM-like vertices for heavy exotic fermions

We consider ratios of rates

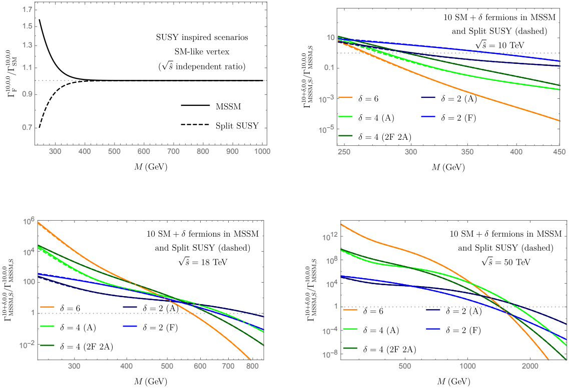
$$E(\sqrt{\hat{s}}, \delta, M) = \frac{\Gamma^{10+\delta, n_h, n_W}_{\mathrm{model}}}{\Gamma^{10,0,0}_{\mathrm{model}'}} \sim \frac{\mathrm{BSM}}{\mathrm{SM-like}}$$

fermions have no impact on $F[\sqrt{\hat{s}}] \to$ cancels in ratio

Candidates

BSM:
The "obvious" choice for models with additional $SU(2)$ fermions is SUSY

- MSSM: **SM+ fundamental fermions (Higgsino) + adjoint fermions (Wino)** + gluino+ bino+ SUSY scalars
- Split SUSY: **SM+ fundamental fermions + adjoint fermions**



Sphaleron rate is significantly enhanced compared to the SM if the underlying theory has relatively light BSM fermions charged under $SU(2)$!

Candidates

Dark Matter:
several DM candidates in various $SU(2)$ representations
$\Rightarrow$ focus on doublet and triplet with Spin 1/2

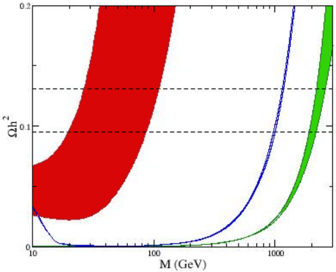
Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\,dt$ =100/fb	σ_{SI} in 10^{-45} cm^2
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

[Cirelli, Fornengo, Strumia]

Sweet spot to obtain the DM relic density:

1. Higgsino (doublet) with $m_\chi \sim 1$ TeV
2. Wino (triplet) $m_\chi \sim 2$ TeV
   +Sommerfeld effect
   $\Rightarrow m_\chi \sim 2.7 - 3$ TeV [hep-ph/0610249]

Bino, Higgsino, Wino



[Arkani-Hamed, Delgado, Giudice]

Cross Sections at Colliders

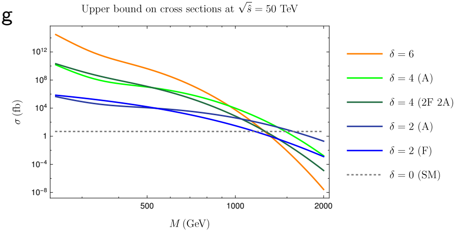
By comparing our results with former instanton calculations, we see that our results seem to be compatible with simple Ansatz

$$\sigma_{B+L,\mathrm{leading}}^{2\to\mathrm{any}} = \frac{E(\sqrt{\hat{s}}, \delta, M)}{m_W^2} \left(\frac{2\pi}{\alpha_W}\right)^{7/2} e^{-\frac{4\pi}{\alpha_W} F[(\sqrt{\hat{s}} - \delta M)/E_0]}$$

for partonic cross sections.

Upper bounds for cross sections obtained by using

1. lower bound on Holy Grail function from [Bezrukov et al]
2. SM prefactor from [Khoze, Ringwald]
3. our BSM enhancement factors



Cross Sections at Colliders

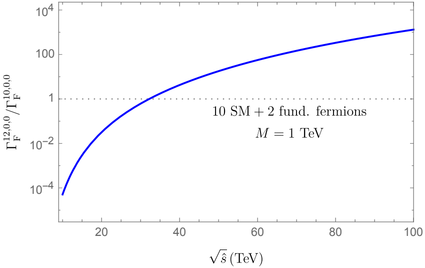
Convoluting with pdfs extrapolated to
100 TeV collider (with $\mathcal{L} = 30\ \mathrm{ab}^{-1}$) yields

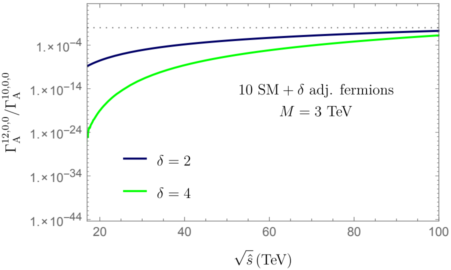
SM:
$\sigma \lesssim 6 \times 10^{-5}$ fb $\rightarrow N \lesssim 1.8$ events

Higgsino DM with $m_\chi = 1$ TeV
$\sigma \lesssim 4.9 \times 10^{-3}$ fb $\rightarrow N \lesssim 150$ events

Wino DM with $m_\chi = 3$ TeV
$\sigma \lesssim 4 \times 10^{-10}$ fb $\rightarrow N \lesssim 1.2 \times 10^{-5}$ events

If DM is 1 TeV Higgsino,
and taking the lower bound of the Holy Grail function, sphalerons should be observable at 100 TeV
$\Rightarrow$ Holy Grail functions can be tested at 100 TeV





Summary & Outlook

- $SU(2)$ anomalies predict new $B + L$-violating interaction vertices in the presence of BSM fermions charged under the gauge group
- Rates of new processes can be orders of magnitude above the SM rate!
- ratios of rates are independent of overall unknown cross section
- DM might make sphalerons observable and/or test Holy Grail functions
- If $B + L$ violating interactions are ever seen at colliders, they could be tied to BSM physics