B+L violation at colliders and new physics

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The aim:

Show that the rates of B+L -violating processes at high-energy colliders can be enhanced by several orders of mangitude in the presence of BSM fermions charged under the weak group.

The novelty:

The discussion on B+L rates was until now centered on boson emission in the SM, which impacts the rate through an exponential "holy-grail" function.

We focus instead on the effect of BSM fermions in the non-exponential contributions, which can still have a large impact.

The plan:

Review of anomalous weak interactions

Instantons in an instant, and the search for the Holy Grail

Enhancement from BSM fermions

Review of anomalous weak interactions

SU(2) anomalies for massless fermions

Consider Weyl massless fermions ψ_k in representations k of the SU(2) group, with Dynkin index $T_k, \ \mathrm{Tr}_k T^a T^b = T_k \delta^{ab}$

We have classical chiral symmetries S_k associated with each flavour of Weyl spinors:

$$S_k : \quad \psi_k \to e^{i\alpha} \psi_k$$

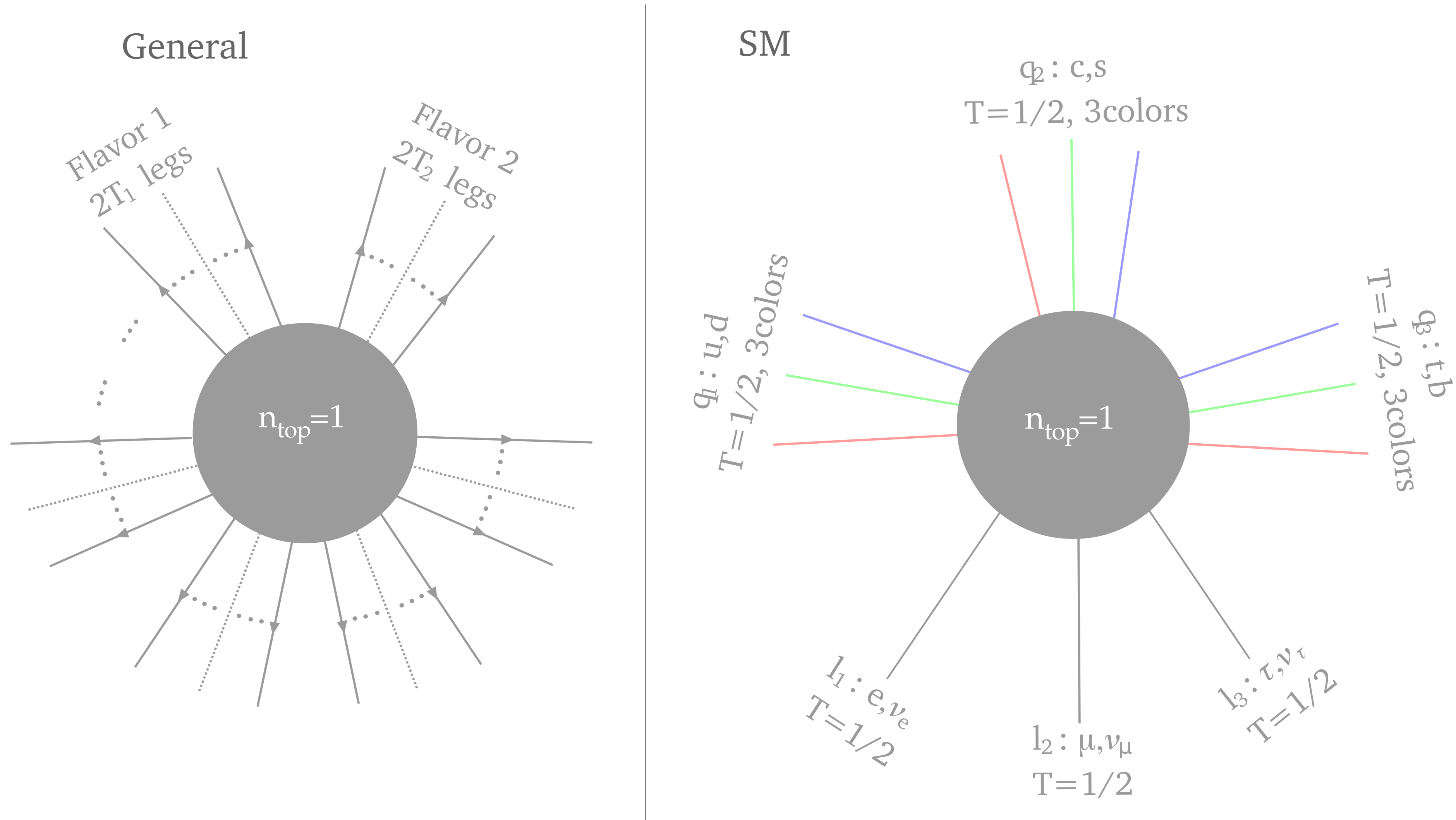
Quantum effects imply a violation of the conservation of the associated Noether charge

$$\langle Q_k(t=\infty)\rangle - \langle Q_k(t=-\infty)\rangle = \int d^4x \, \langle \partial_\mu J_k^\mu \rangle = 2 T_k n_{\mathrm{top}}$$

For every Weyl fermion in a representation k, minimal violation of chiral symmetry is by $2 \ T_k$ units !

E.g. Dirac fermion in fundamental: 2 Weyl fermions with T_k=1/2, violation by 2 units.

Anomalous interaction vertices



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

12 fermion B+L violating SM vertex! Party in the detector?

SU(2) anomalies for massive fermions

Mass terms pairing $\psi_k \quad \psi_l$ violate classical invariance under chiral transformations S_{k+l}. Still, we can get selection rules by assigning a spurious chiral charge to the mass

$$\mathcal{L} \supset m_{kl}\psi_k\psi_l + c.c.$$

-2 +1 +1

Classical symmetry is restored when treating m as charged field.

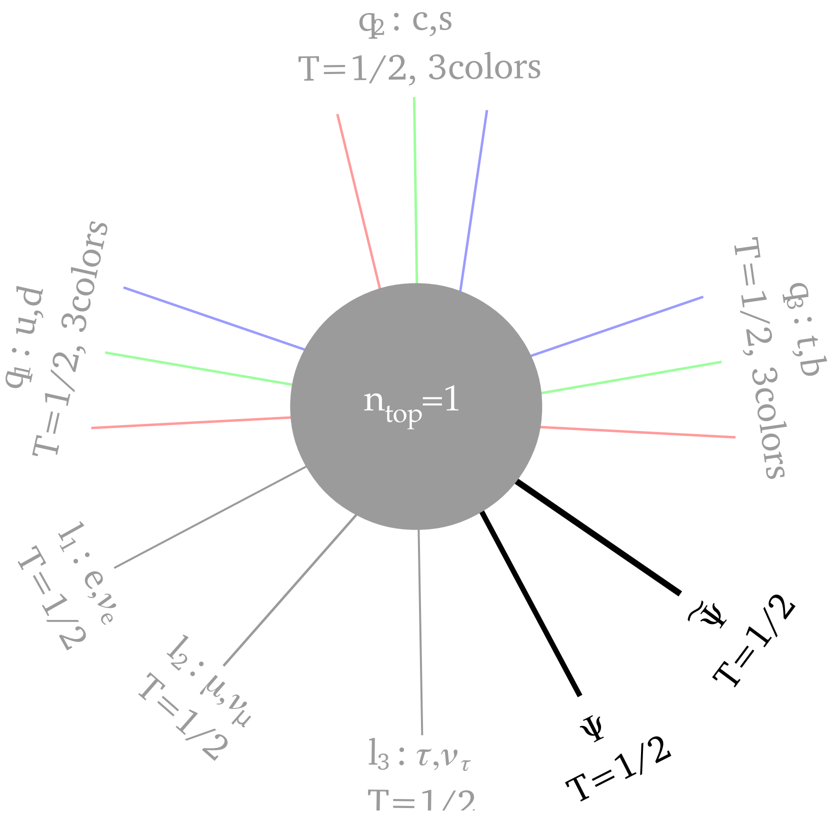
The symmetry is violated as before by the anomaly, and the anomalous interaction vertices carry same charge as before, but charge can be carried by mass insertions. Can trade legs of fermions $\psi_k \quad \psi_l$ for insertion of m^*_{kl}!

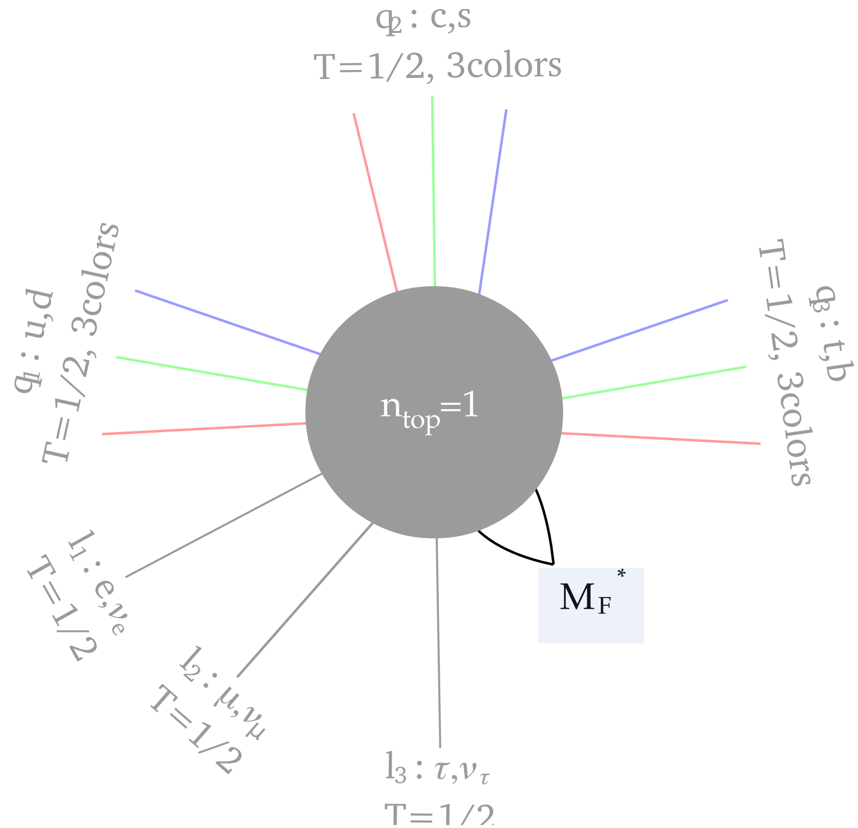
Smooth massless limits restricts us to positive powers of mass.

Anomalous vertices with massive fermions

SM+Heavy Dirac in fundamental (2 Weyl fermions coupled through mass term)

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





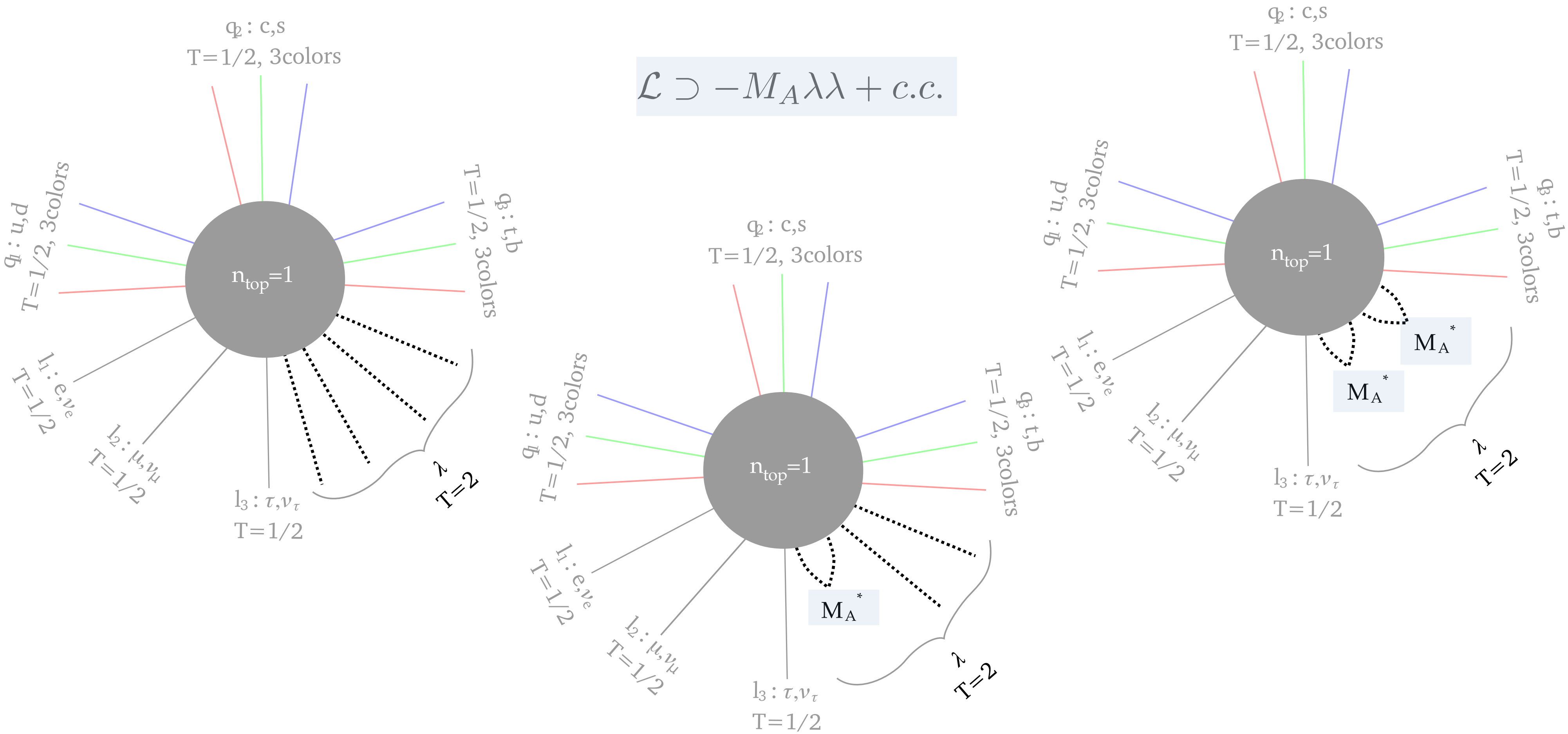
$$\Delta B = \Delta L = 3$$

Exotic and SM-like vertices! The latter should reproduce the SM result for large M (decoupling)

Anomalous vertices with massive fermions

SM+Heavy Weyl in adjoint (T_{adj}=2)

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

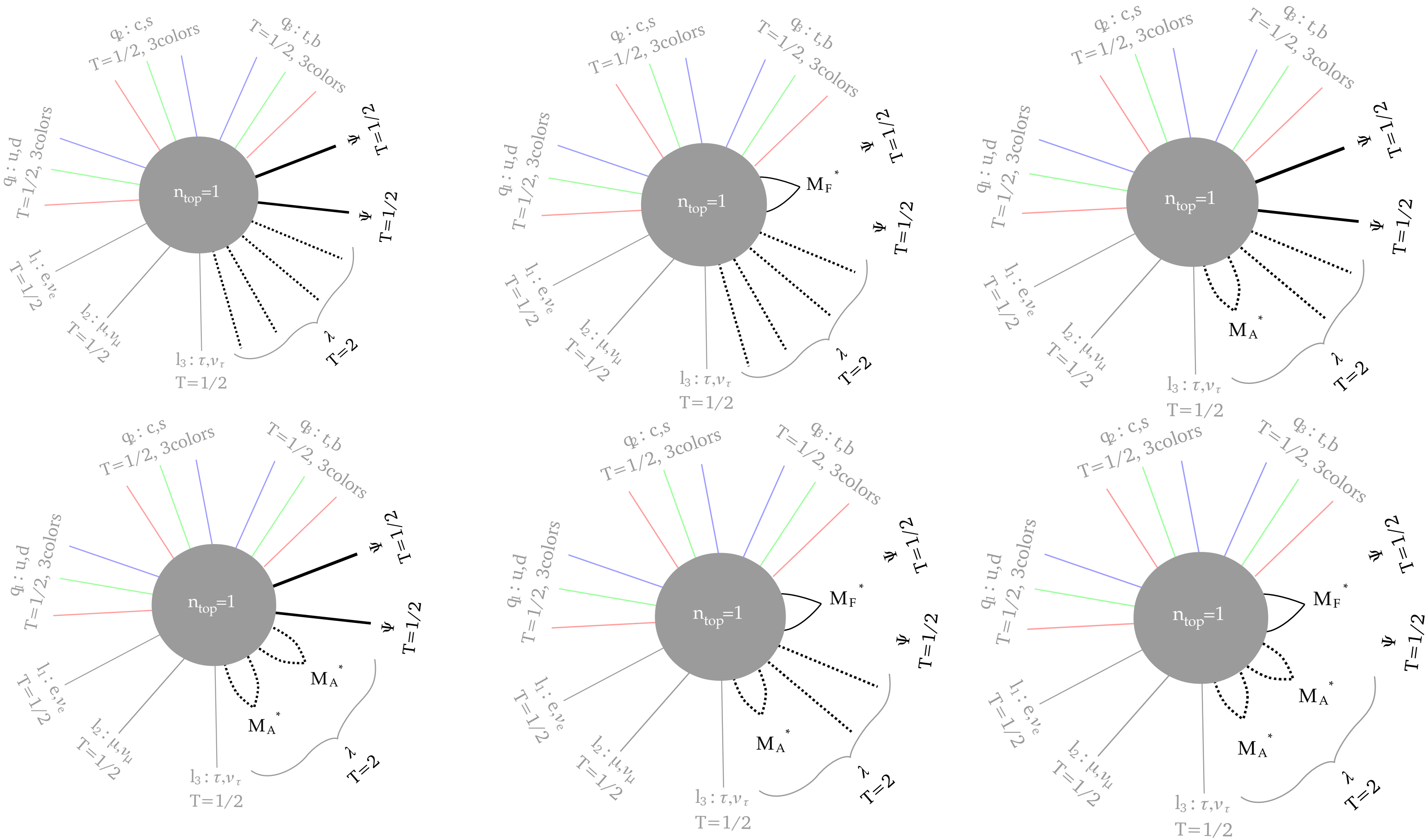


Up to 16 fermions!

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

Anomalous vertices with massive fermions

SM+Heavy Dirac in fundamental (~Higgsinos)+Heavy Weyl in adjoint (~weakino)



Up to 18 fermions!

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

Which B+L-violating processes dominate?

Instantons in an instant, and the search for the Holy Grail

Instanton calculus in one slide

Interested in effective action that reproduces anomalous effects in the expectation values of products of fermion fields.

Anomaly ⟷ nontrivial n_{top} ⟷ Need path integral in sectors with nontrivial topology of gauge fields

$$\langle \psi_{k_1} \ldots \psi_{k_N} \rangle = \int \Pi_m [d\psi]_m [d\psi^\dagger]_m \sum_{n_{\text{top}}=q} \int [dA^a_\mu]_q \exp(-S) \psi_{k_1} \ldots \psi_{k_N}$$

- Perform saddle point expansion on each sector $n_{top}=q$ around extremal of S: q-instanton, encoding tunneling between topological vacua.
- 1-instanton dominates anomalous contributions: $\exp(-S_{\text{inst}}) = \exp\left(-\frac{8\pi^2}{g^2} n_{\text{top}}\right)$
- Group Weyl fermions $\psi_k,\ \psi_l$ into Dirac Ψ_{kl}

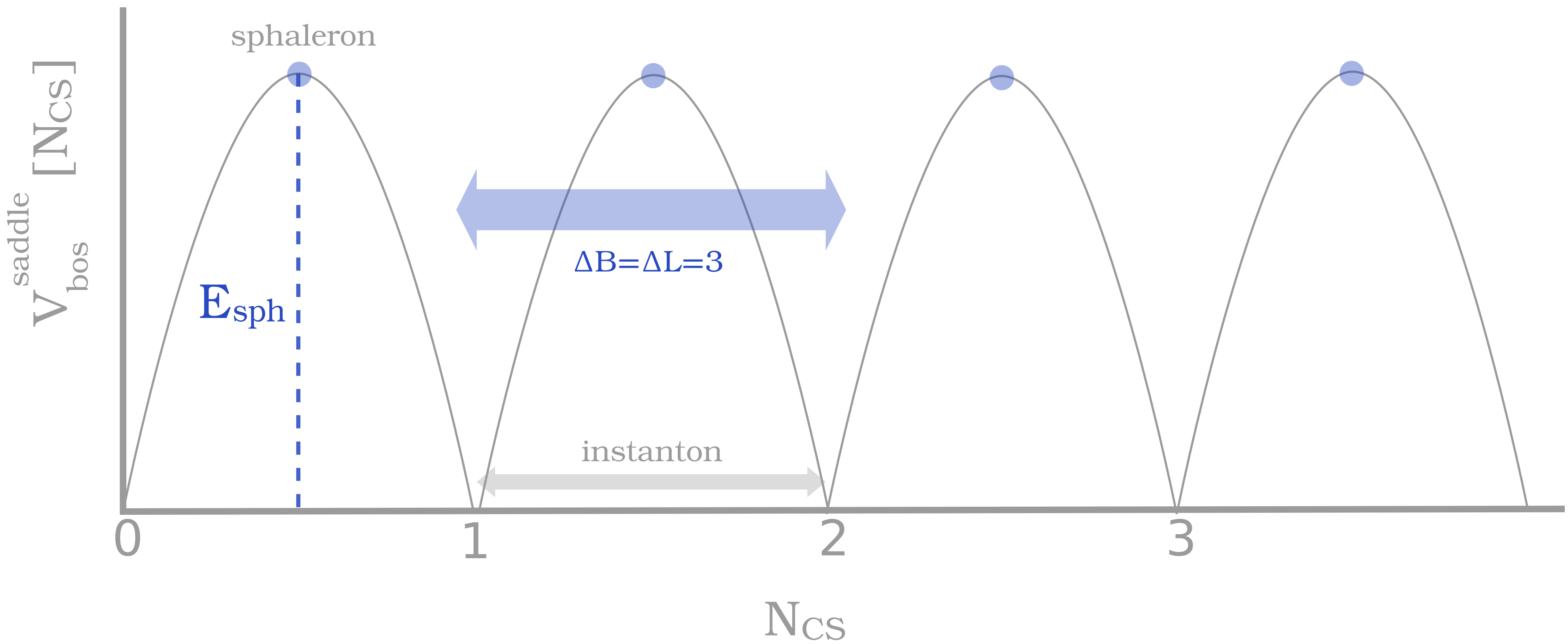
$$\langle \Pi \overline{\Psi}_{kl} \Psi_{kl} \rangle \propto \det\left(\frac{\delta^2 S}{\delta \overline{\Psi} \delta \Psi}\right) \Pi(\text{Fermion prop. in instanton bg.})$$

$\Pi(m^*_{kl})^{T_k+T_l}$ $\qquad$ $(m^*_{kl})^{-1}$

No negative powers of masses for # of fermions up to $2q \sum_k T_k = \Delta Q_{\text{chiral,total}}$

Anomaly equation recovered!

The vacuum picture



Baryons produced in transitions between topological vacua.

… Too much baryon violation?

One can dress the fermion amplitudes with as many gauge bosons as allowed by energy.

First instanton estimates yield exponential corrections to rate when summing over gauge boson emission! [Ringwald, O. Espinosa]

$$\sigma^{2\to\text{any}}_{B+L,\text{leading}} = f(\hat{s})e^{-\frac{4\pi}{\alpha_W}F[\sqrt{\hat{s}}/E_0]} \;, \quad F\left[\frac{\sqrt{\hat{s}}}{E_0}\right] = 1 - \frac{9}{8}\left(\frac{\sqrt{\hat{s}}}{E_0}\right)^{4/3} \;, \; E_0 = \frac{6\pi m_W}{\alpha_W} \sim E_{\text{sph}}$$

Unsuppressed for energies $\sim E_{sph}$ (barrier between topological vacua)

… or too little baryon violation?

The above is in conflict with unitarity arguments/dispersion relations!

Instanton loop corrections yield higher powers of (E/E_0) within the exponent: instanton perturbation theory breaks down at region of interest $E>E_{sph}$

The epic quest for the Holy Grail

Higher order instanton corrections are known to still exponentiate [Arnold & Mattis, Khlebnikov & Rubakov & Tinyakov, Mueller, Khoze & Ringwald]

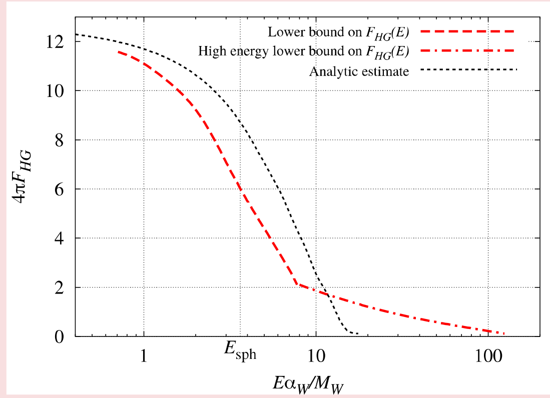
$$\sigma_{B+L}^{2\to\mathrm{any}} = f(\hat{s}) e^{-\frac{4\pi}{\alpha_W} F[\sqrt{\hat{s}}/E_0]}$$

Holy Grail function, not calculable with instanton perturbation theory for $E > E_0$.

Exponentiation points towards alternative semiclassical expansion of the full dressed amplitude.
Alternative evaluations:

Unitarity [Zakharov, Maggiore & Shifman, Veneziano] $F \gtrsim 0$
Dispersion relations [Zakharov, Porrati, Khoze & Ringwald]
Coherent state approach [Rubakov &Tinyakov, Bezrukov et al]

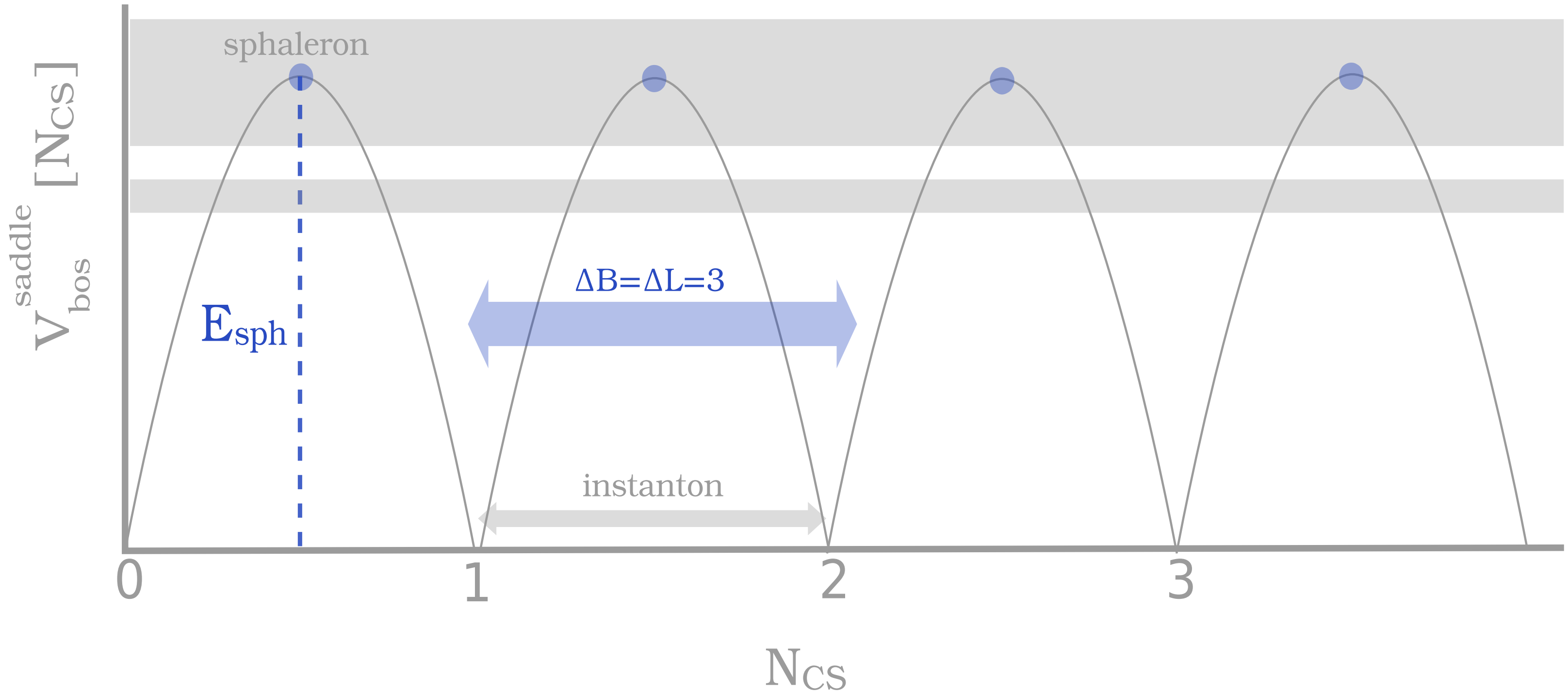
$$\sigma_{B+L}^{2\to\mathrm{any}} = \frac{1}{m_W^2} \left(\frac{2\pi}{\alpha_W}\right)^{7/2} e^{-\frac{4\pi}{\alpha_W} F[\sqrt{\hat{s}}/E_0]}$$



SM cross section < 5fb at $\sqrt{\hat{s}} = 50$ TeV

Lower bound on F [Bezrukov et al]

A new band structure in town?



Does one have an effective 1D dynamics in the N_{cs} direction of field space? Then one has a band structure and tunneling may be unsuppressed [Tye & Wong, Funakubo et al]

SM cross section unsuppressed ~O(b) (Just a 15 order of mangnitude difference at 50 TeV)

Enhancement from BSM fermions

Let’s be ratio-nal

Anomalies restricts number of fermions ⟶ no corrections to holy grail from fermions

We factor out the effect of holy grail function in boson emission by computing ratios of rates, with or without exotic fermions

Fewer fermionic legs imply better behaved instanton corrections for fermion lines: can use ordinary instanton techniques.

Let’s be a bit fancier and implement decoupling

Since we are interested in exotic massive fermions, we need to ensure that our estimates are compatible with decoupling: SM-like vertices should yield SM rate for heavy exotic fermions.

We can do this by correcting the vacuum-to-vacuum transition for large instantons to account for threshold effets (and have some fun with nontrivial consitency checks for the SU(2) θ angle).

Instanton-induced, simplified effective Lagrangian

Vacuum-to-vacuum amplitude | H emission | W/Z emission

$$\Delta L \supset \sum_{n_W, n_h} \int \frac{d\rho}{\rho^5} \tilde{C}_I(\rho) \left(-\sqrt{2}\pi^2 \rho^2 v h\right)^{n_h} \left(-\frac{4\pi^2\rho^2}{g} \eta_{a\mu\nu} \partial_\nu W^a_\mu\right)^{n_W}$$

$$\times \prod_{[k,l]} \left\{ (\rho |M_{kl}|)^{N^0_{kl} b_{kl}} \sum_{j=0}^{N^0_{kl}} (\mathcal{F}_{kl})^j \, (\psi_k \psi_l)^j (\rho M^*_{kl})^{N^0_{kl}-j} \right\}$$

$$\times \prod_{m} \left\{ (\rho |M_{mm}|)^{1/2 N^0_{mm} b_{mm}} \sum_{i=0}^{1/2 N^0_{mm}} (\mathcal{F}_{mm})^i \, (\psi_m \psi_m)^i (\rho M^*_{mm})^{1/2 N^0_{mm}-i} \right\},$$

Dirac Fermions

$$b_{mn} = \begin{cases} 0, & \rho |M_{mn}| < 1, \\ -1/3, & \rho |M_{mn}| \gtrsim 1. \end{cases}$$

Majorana Fermions

Decoupling corrections | Fermion zero-mode form factors | Mass insertions breaking chiral sym

SM fermions count as massless Dirac fermions. Lagrangian satisfies anomaly selection rules

Ratios of rates

Assume 2 quark initial state: 10 fermions in final state in SM-like processes

Final state fermions

Final state Higgses

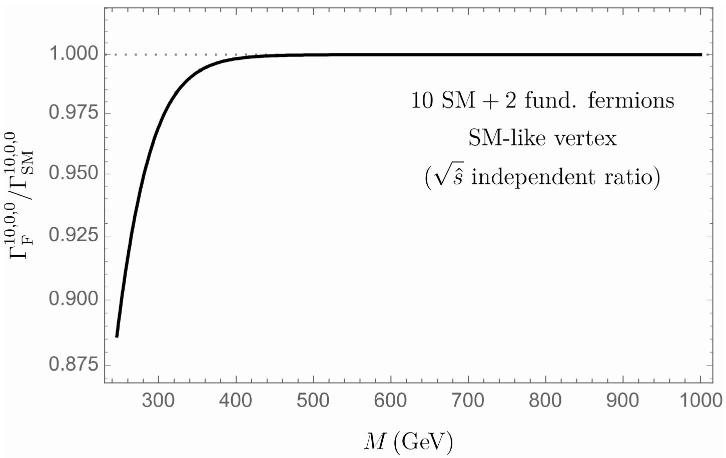
Final state W/Z

$$\frac{\Gamma^{10+\delta, n_h, n_W}_{\text{model}}}{\Gamma^{10,0,0}_{\text{model}'}}$$

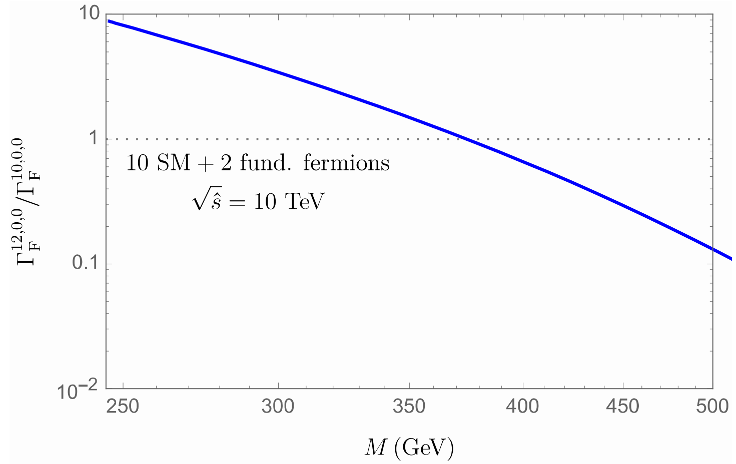
Choice of models:

SM	
F	SM+Dirac in fundamental
A	SM+Dirac in adjoint
MSSM	SM+F+A+gluino+bino+SUSY scalars
S	SM+F+A

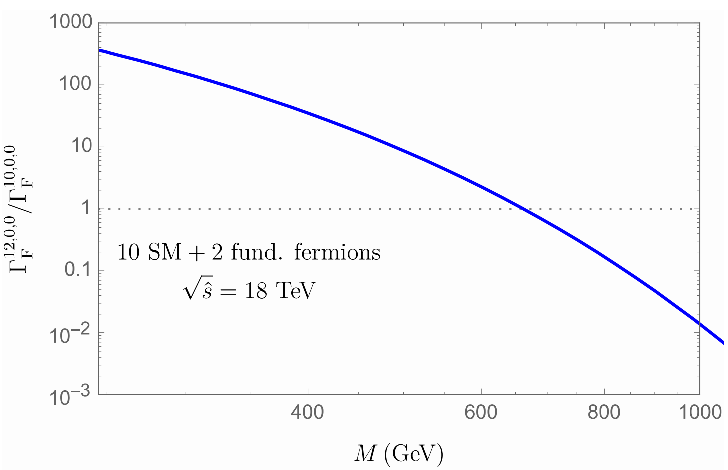
Results: enhancement from BSM fermions in F



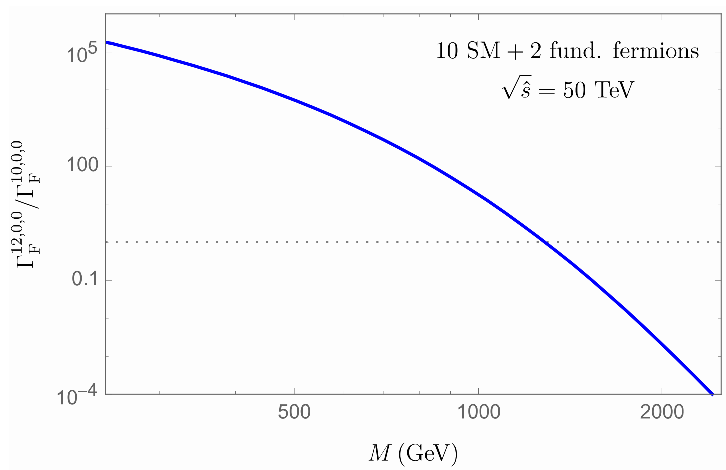
(a) SM-like/SM vertex



(b) qq collision energy $\sqrt{\hat{s}} = 10$ TeV

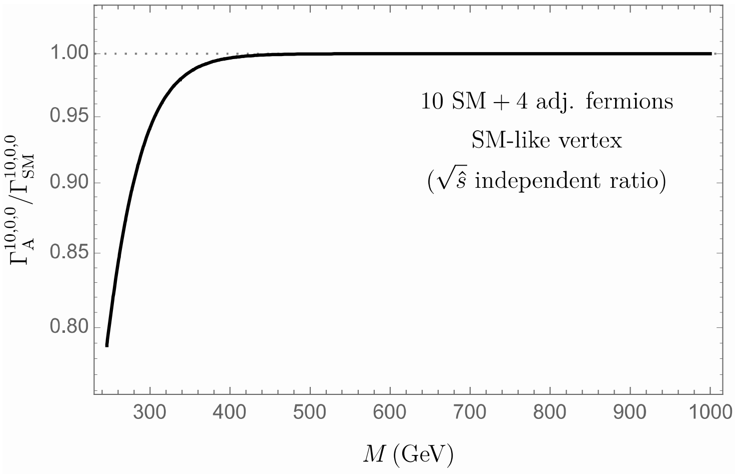


(c) qq collision energy $\sqrt{\hat{s}} = 18$ TeV



(d) qq collision energy $\sqrt{\hat{s}} = 50$ TeV

Results: enhancement from BSM fermions in A



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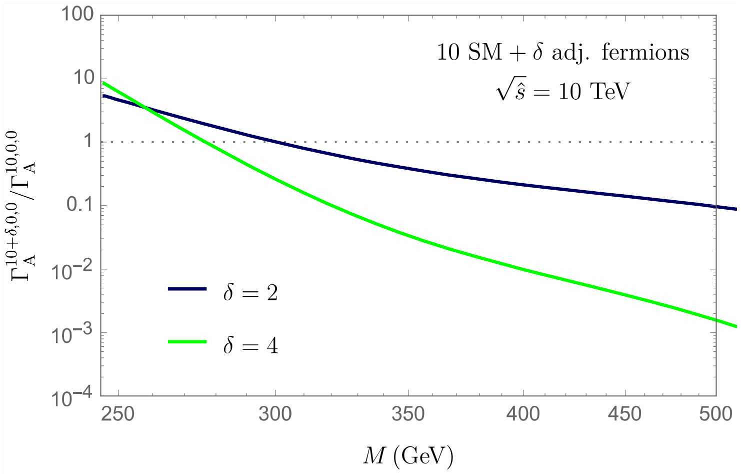
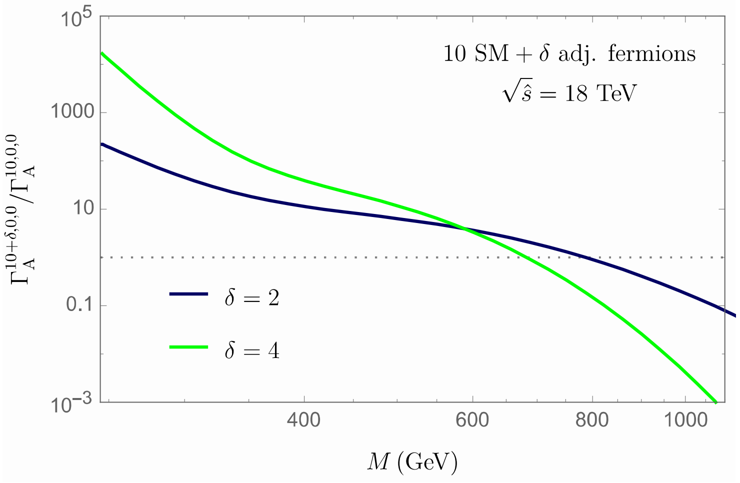
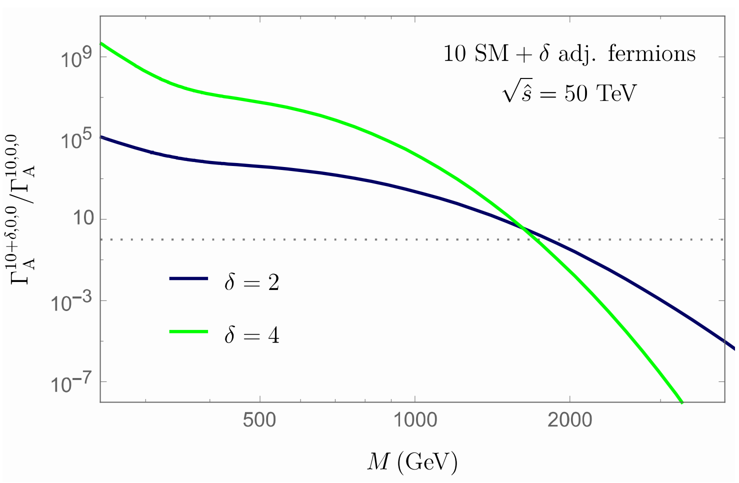


(b) qq collision energy $\sqrt{\hat{s}} = 10$ TeV

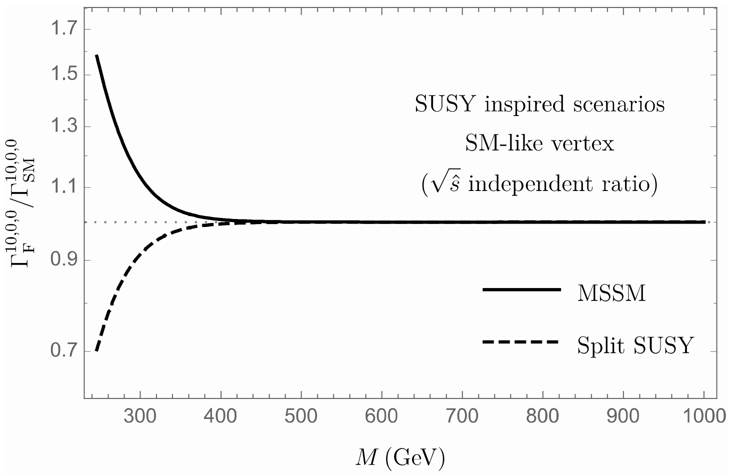


(c) qq collision energy $\sqrt{\hat{s}} = 18$ TeV

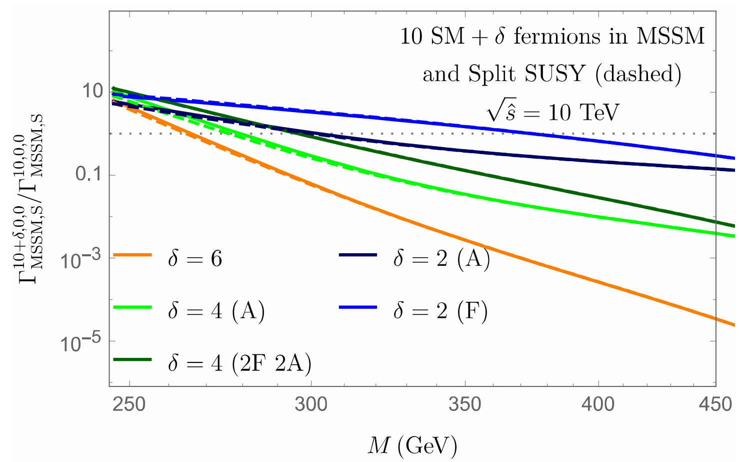


(d) qq collision energy $\sqrt{\hat{s}} = 50$ TeV

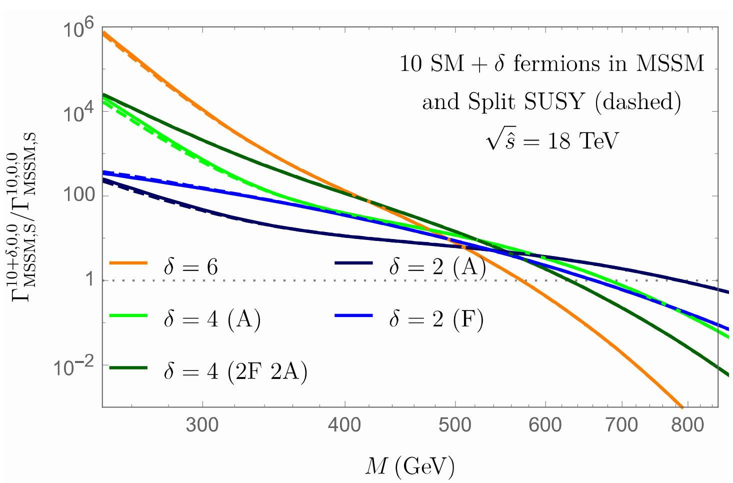
Results: enhancement from BSM fermions in MSSM/S



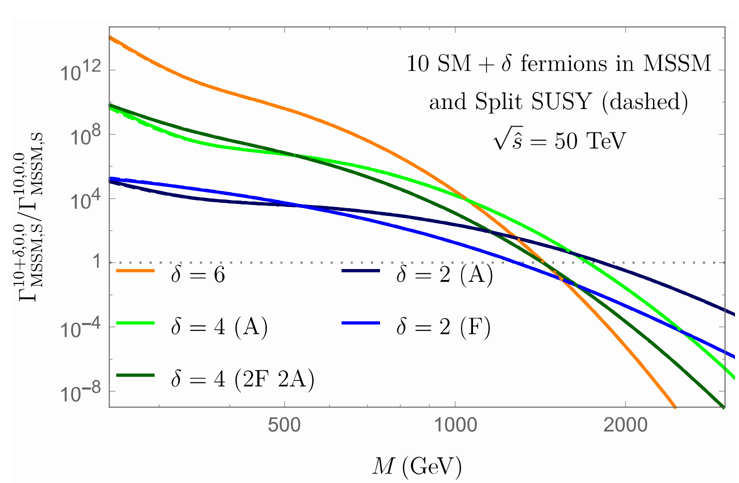
(a) SM-like/SM vertex



(b) qq collision energy $\sqrt{\hat{s}} = 10$ TeV



(c) qq collision energy $\sqrt{\hat{s}} = 18$ TeV



(d) qq collision energy $\sqrt{\hat{s}} = 50$ TeV

Ansatz for total cross-sections with boson emission

Although our instanton calculations including boson emision can only capture the first term in the badly convergent (E/E_0) expansion of the holy grail function, we can still check how the result changes when including BSM fermions.

Results seem compatible with simple Ansatz

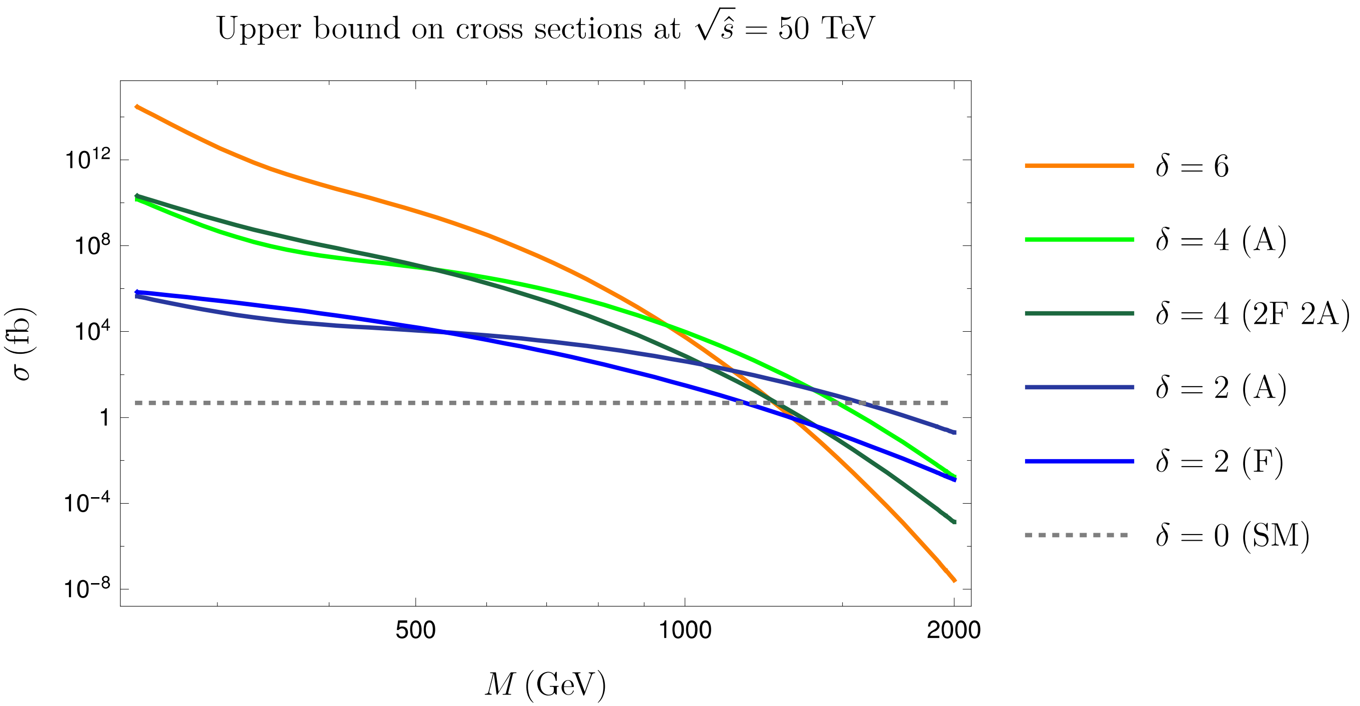
$$\sigma_{B+L}^{2\to\text{any}} = \frac{E(s,\delta,M)}{m_W^2}\left(\frac{2\pi}{\alpha_W}\right)^{7/2} e^{-\frac{4\pi}{\alpha_W}F[(\sqrt{\hat{s}}-\delta M)/E_0]}$$

Enhancement factor, depending on BSM fermions in vertex (δ) and their mass M.

Holy Grail function evaluated at max. energy available for gauge boson production

Upper bounds on partonic cross sections

Using: lower bound on Holy Grail function from [Bezrukov et al]
SM prefactor from [Khoze & Ringwald]
Our BSM enhancement factors



Convoluting with pdfs extrapolated to 100 TeV collider

SM	$\sigma \lesssim 6 \times 10^{-5}$ fb
F@400GeV	$\sigma \lesssim 5 \times 10^{-3}$ fb
A@1TeV	$\sigma \lesssim 40$ fb
S@1TeV	$\sigma \lesssim 180$ fb

Conclusions

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 mangnitude above the SM rate!

This enhancement was estimated from ratios of rates, and is thus independent of the much discussed normalization of the SM rate

If B+L-violating interactions are ever seen at colliders, they could be tied to physics beyond the Standard Model