

B+L violation at colliders and new physics

Carlos Tamarit, Technische Universität München

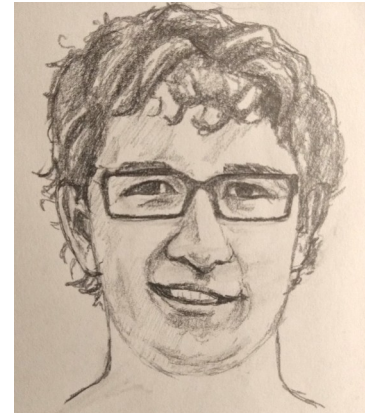
JHEP 1804 (2018) 076

In collaboration with...

David Cerdeño
IPPP Durham



Peter Reimitz
Heidelberg



Kazuki Sakurai
Warsaw



The aim:

Show that the **rates of B+L -violating processes** at high-energy colliders can be **enhanced** by several orders of magnitude 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 of SU(2) with Dynkin index T_k

$$\text{Tr}_k T^a T^b = T_k \delta^{ab}$$

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

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

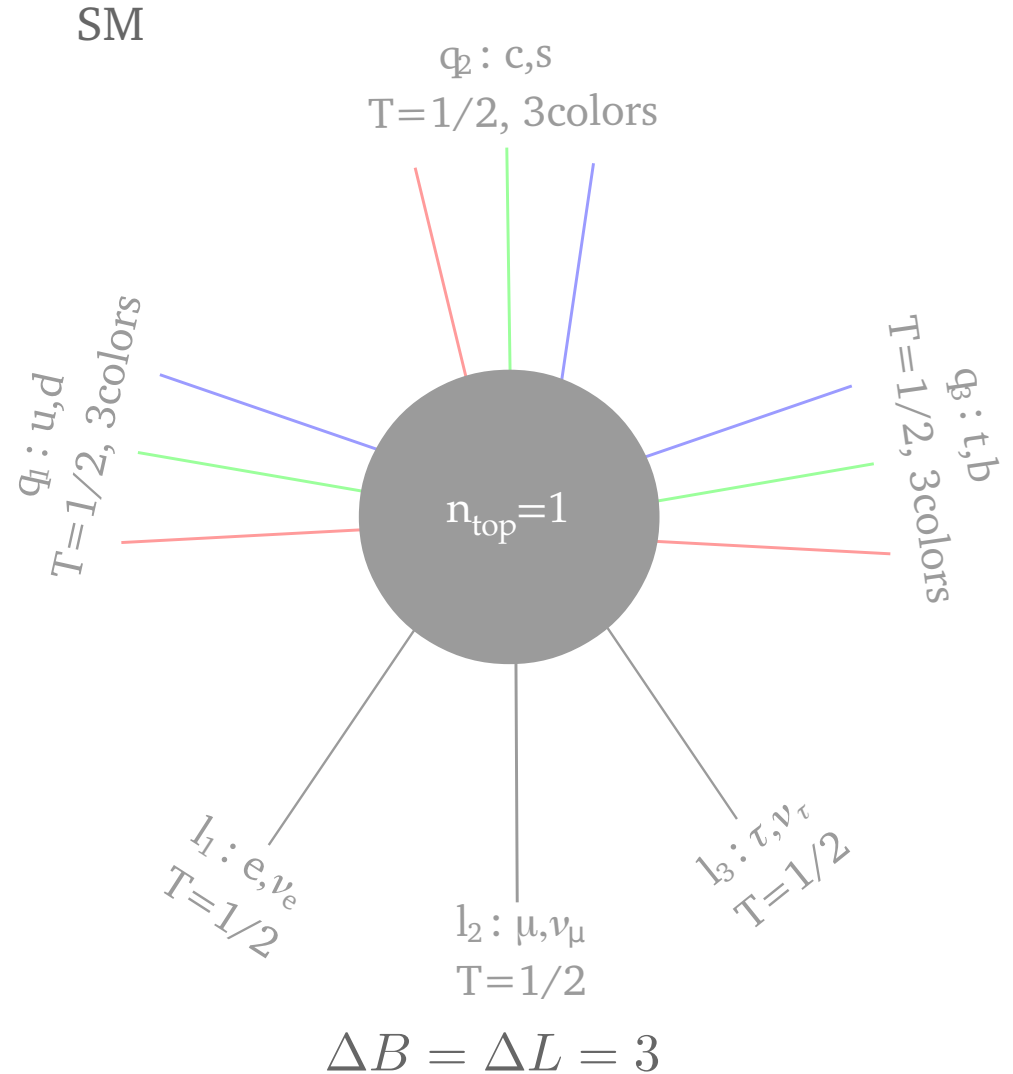
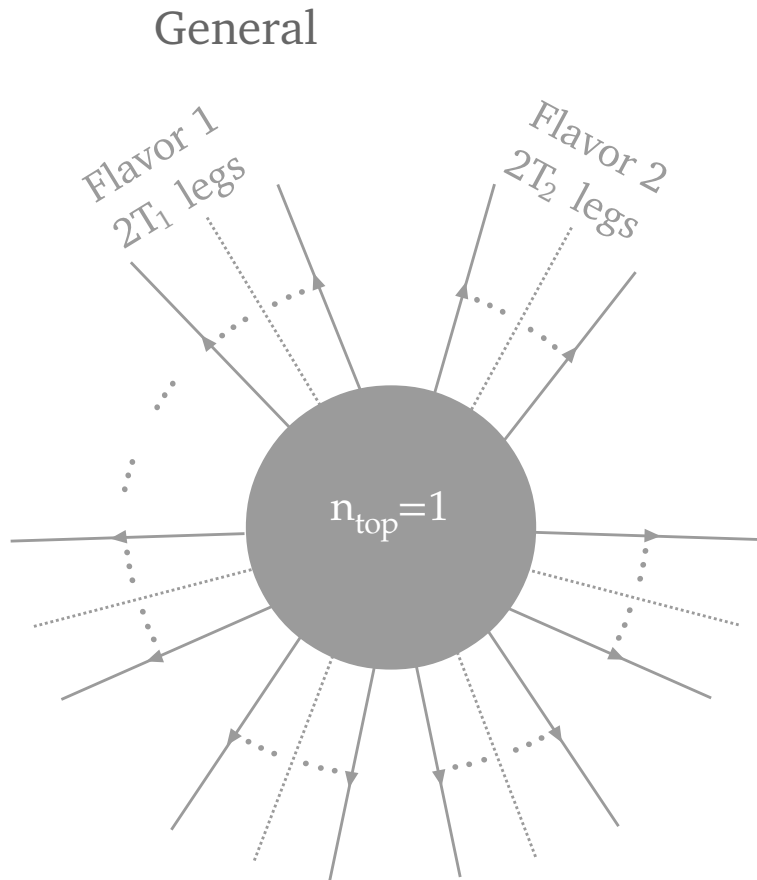
Quantum effects imply a violation of the conservation of the associated Noether charge

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

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

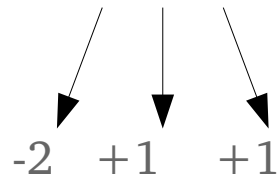


12 fermion B+L violating SM vertex! Party in the detector?

SU(2) anomalies for massive fermions

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

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



Classical symmetry is restored when treating m as charged field.

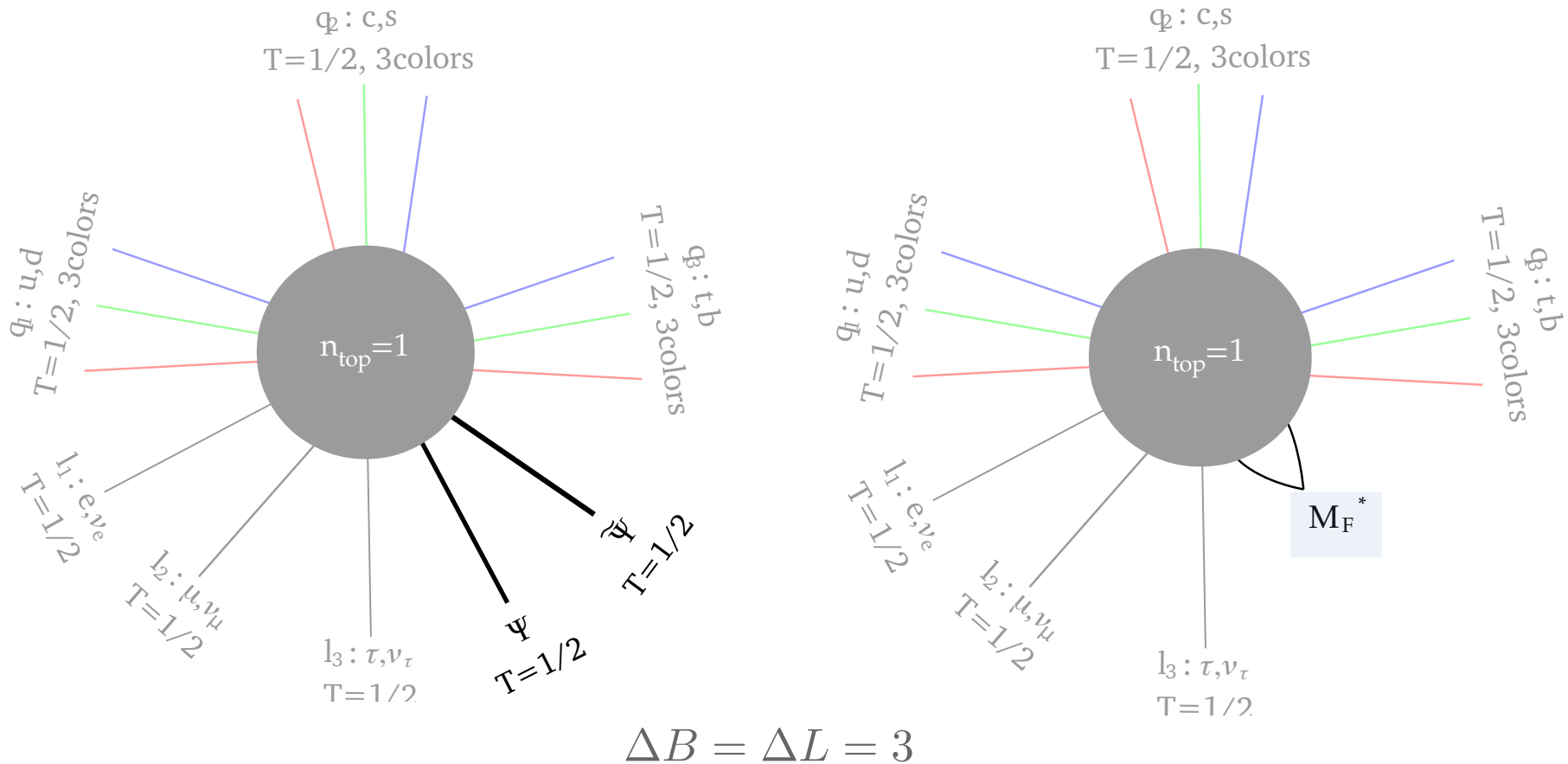
The symmetry is violated as before by the anomaly, but charge can be carried by mass insertions. Can trade legs of fermions $\psi_k \psi_l$ for insertion of m_{kl}^* !

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)

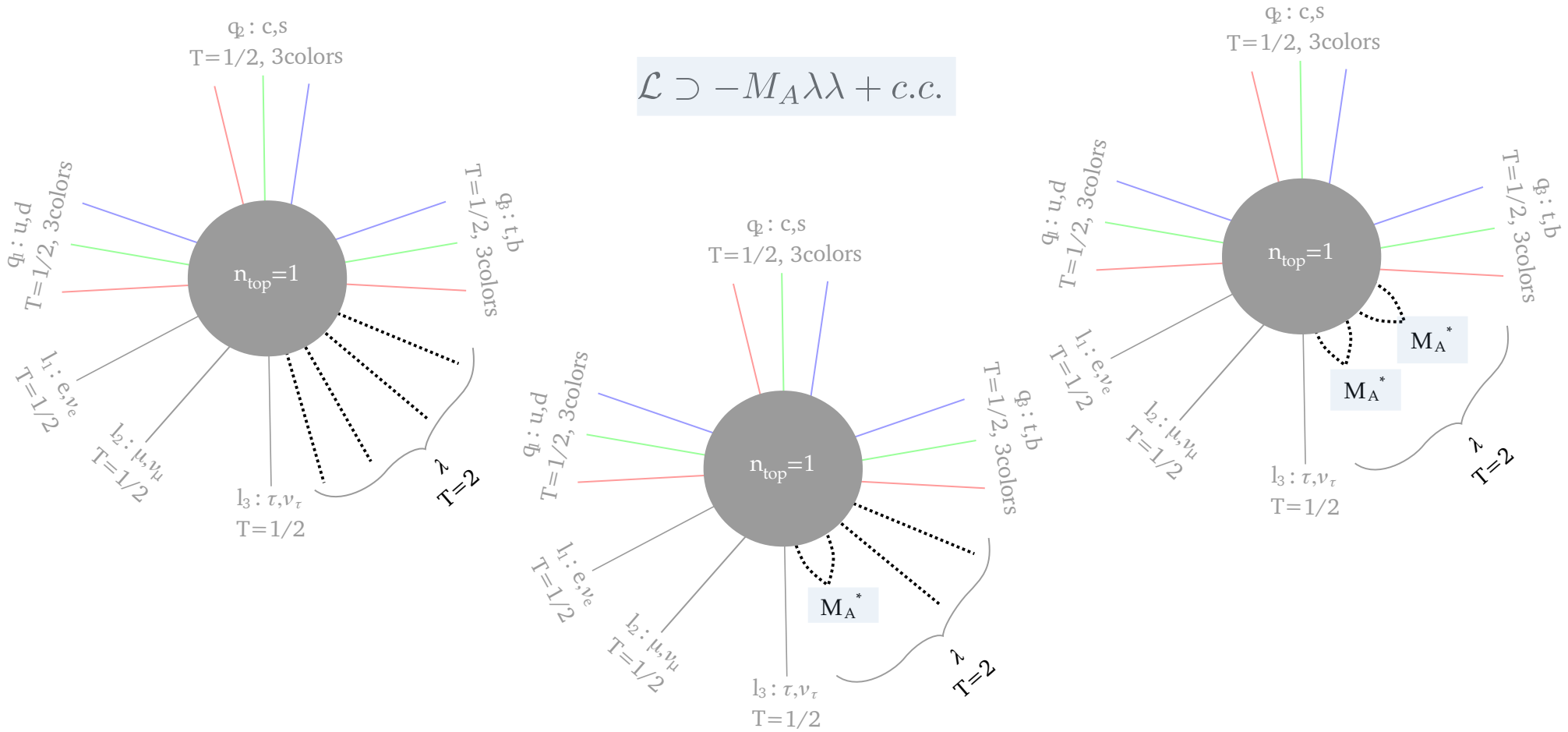
$$\mathcal{L} \supset -M\tilde{\Psi}\Psi + c.c.$$



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 ($T_{\text{adj}}=2$)

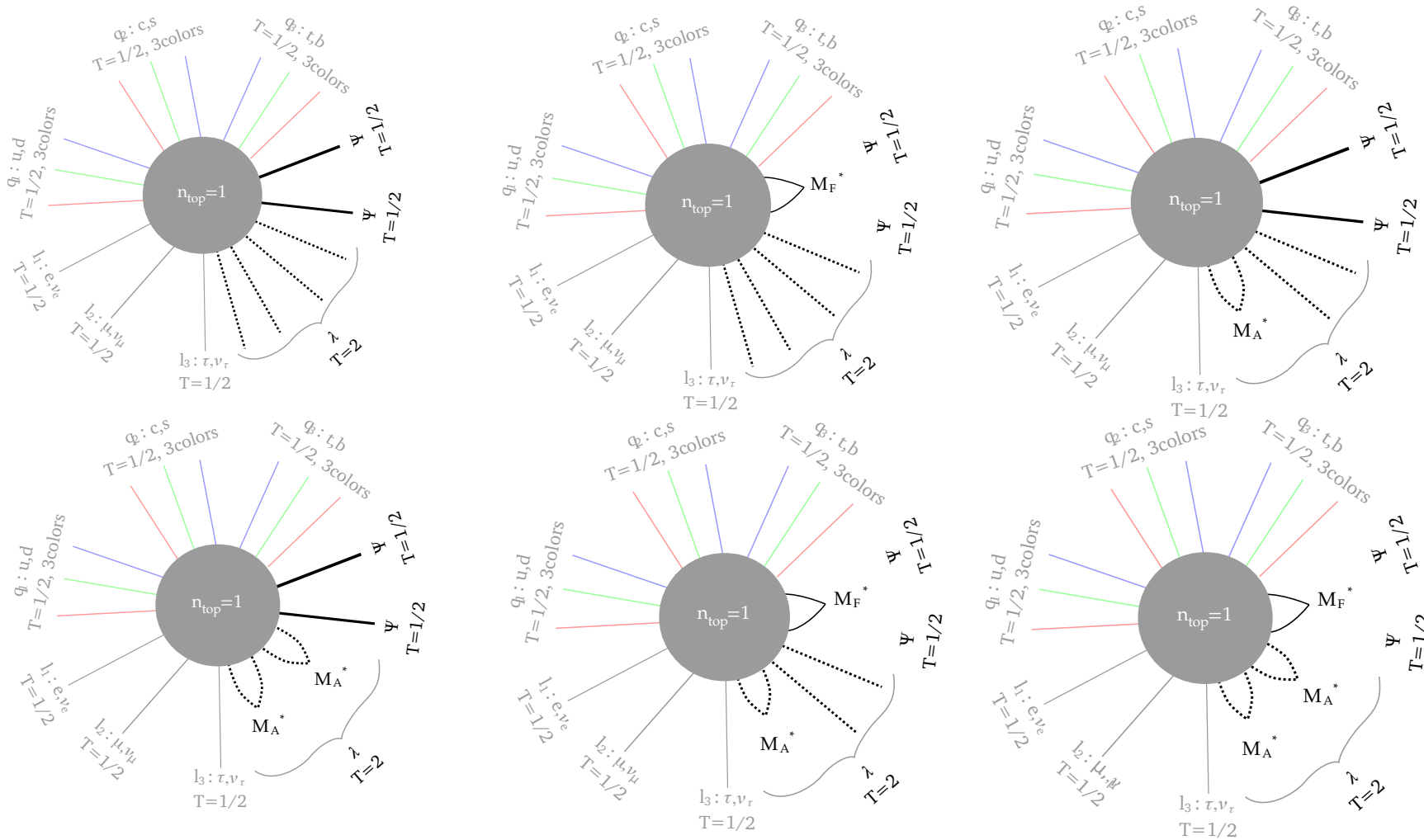


Up to 16 fermions!

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

Anomalous vertices with massive fermions

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



Up to 18 fermions!

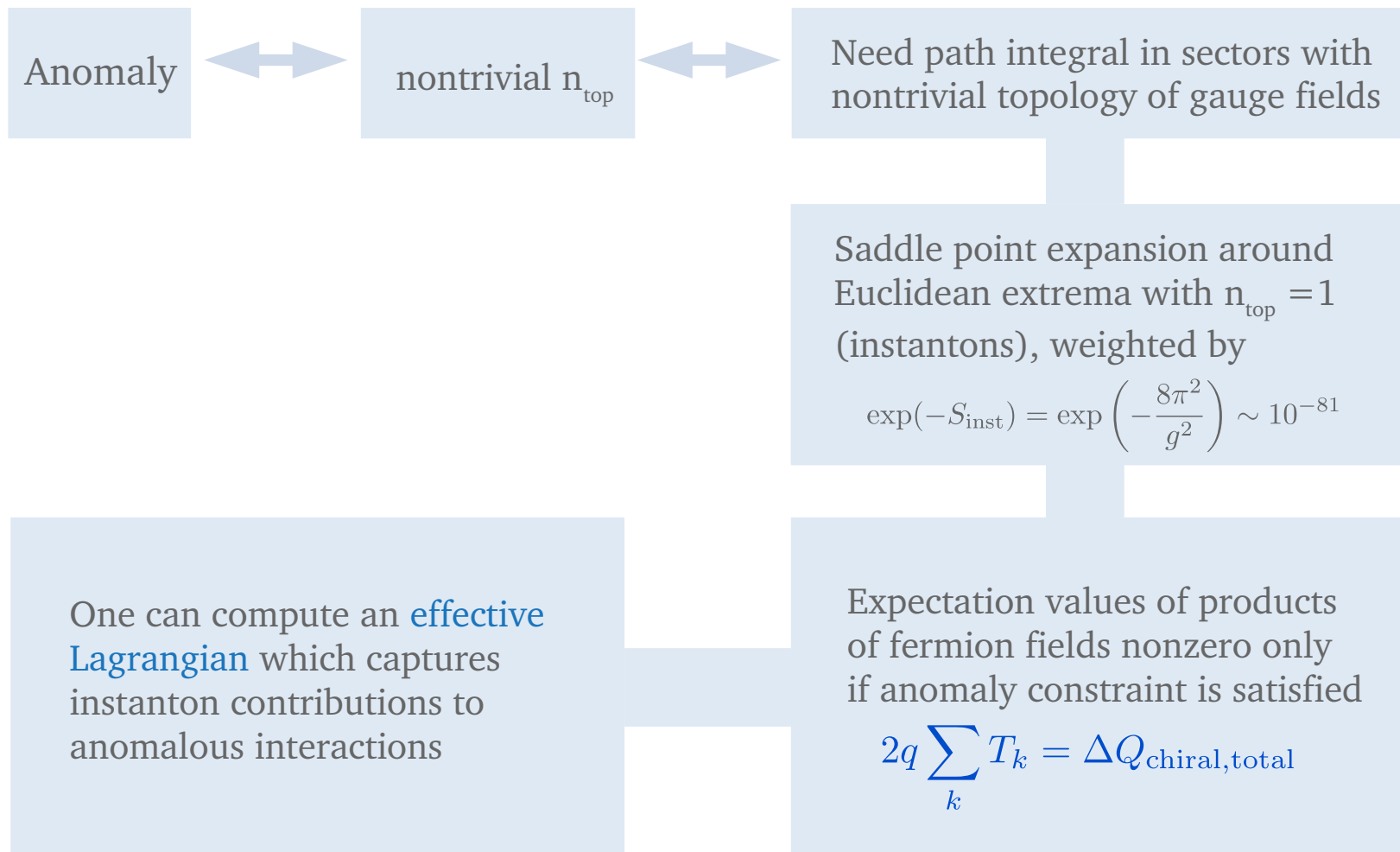
$$\Delta B = \Delta L = 3$$

Which $B+L$ -violating processes dominate?
SM-like or exotic?

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.



How is the anomaly recovered?

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

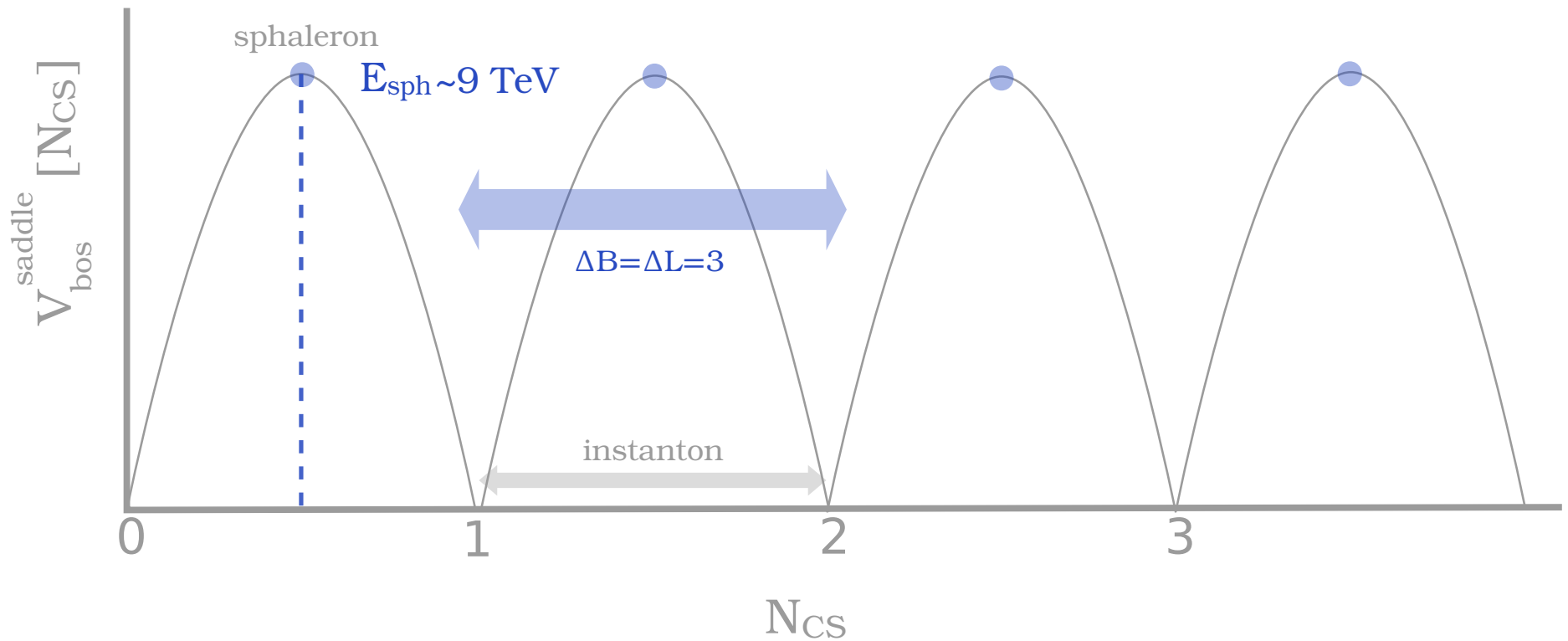


$$\prod_{(kl)} (m_{kl}^*)^{T_k + T_l} \qquad (m_{kl}^*)^{-1}$$

In the massless case need $\sum T_k$ fermion propagators \rightarrow vertices with $2 \sum T_k$ fermions!

$$\Delta Q_{\text{chiral, total}} = 2q \sum_k T_k$$

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]

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

Unsuppressed for energies $\sim E_{\text{sph}}$ (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 $E > E_{\text{sph}}$

The epic quest for the Holy Grail

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

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

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] $F \gtrsim 0$

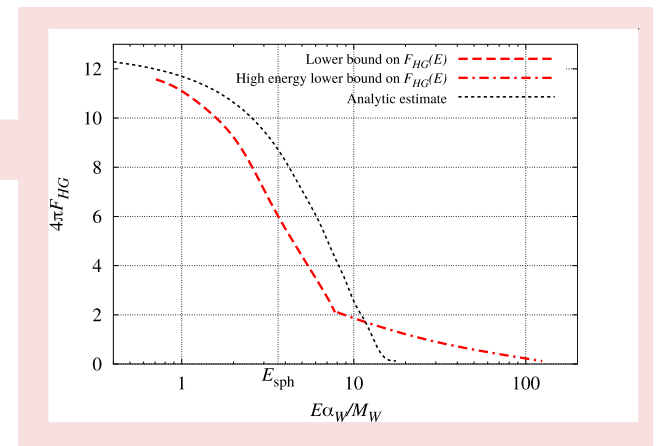
Dispersion relations [Zakharov, Porrati, Khoze & Ringwald]

Coherent state approach [Rubakov & Tinyakov, Bezrukov et al]

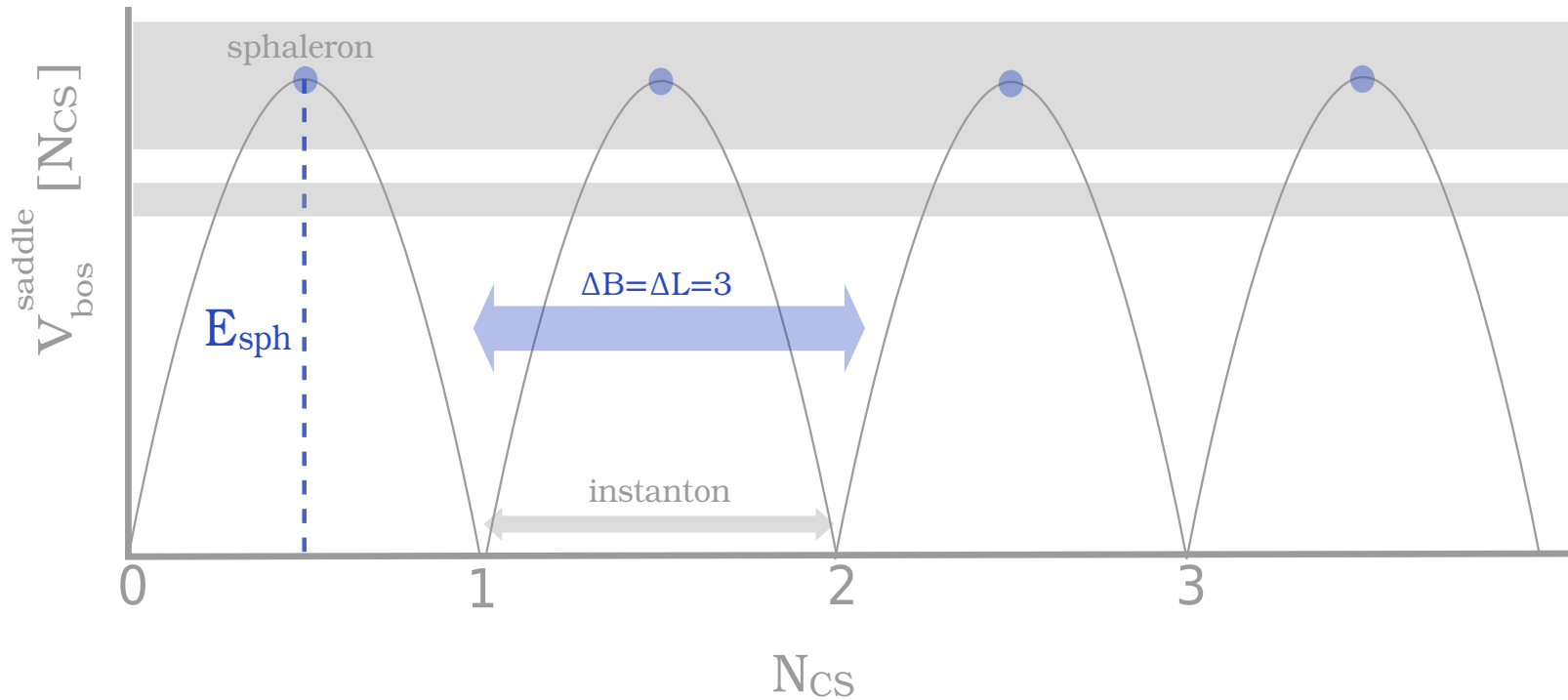
$$\sigma_{B+L}^{2 \rightarrow \text{any}} = E(s, \delta, M) \frac{0.15}{m_W^2} \left(\frac{2\pi}{\alpha_W} \right)^{7/2} \left(\frac{\sqrt{\hat{s}}}{E_0} \right)^{\frac{74}{9}} e^{-\frac{4\pi}{\alpha_W} F[(\sqrt{\hat{s}} - \delta M)/E_0]}$$

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

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 $\sim O(b)$ (Just a 10 order of magnitude 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 by computing ratios of rates

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

For heavy exotic fermions decoupling should work: 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 effects (and have some fun with nontrivial consistency checks for the SU(2) θ angle).

Instanton-induced, simplified effective Lagrangian

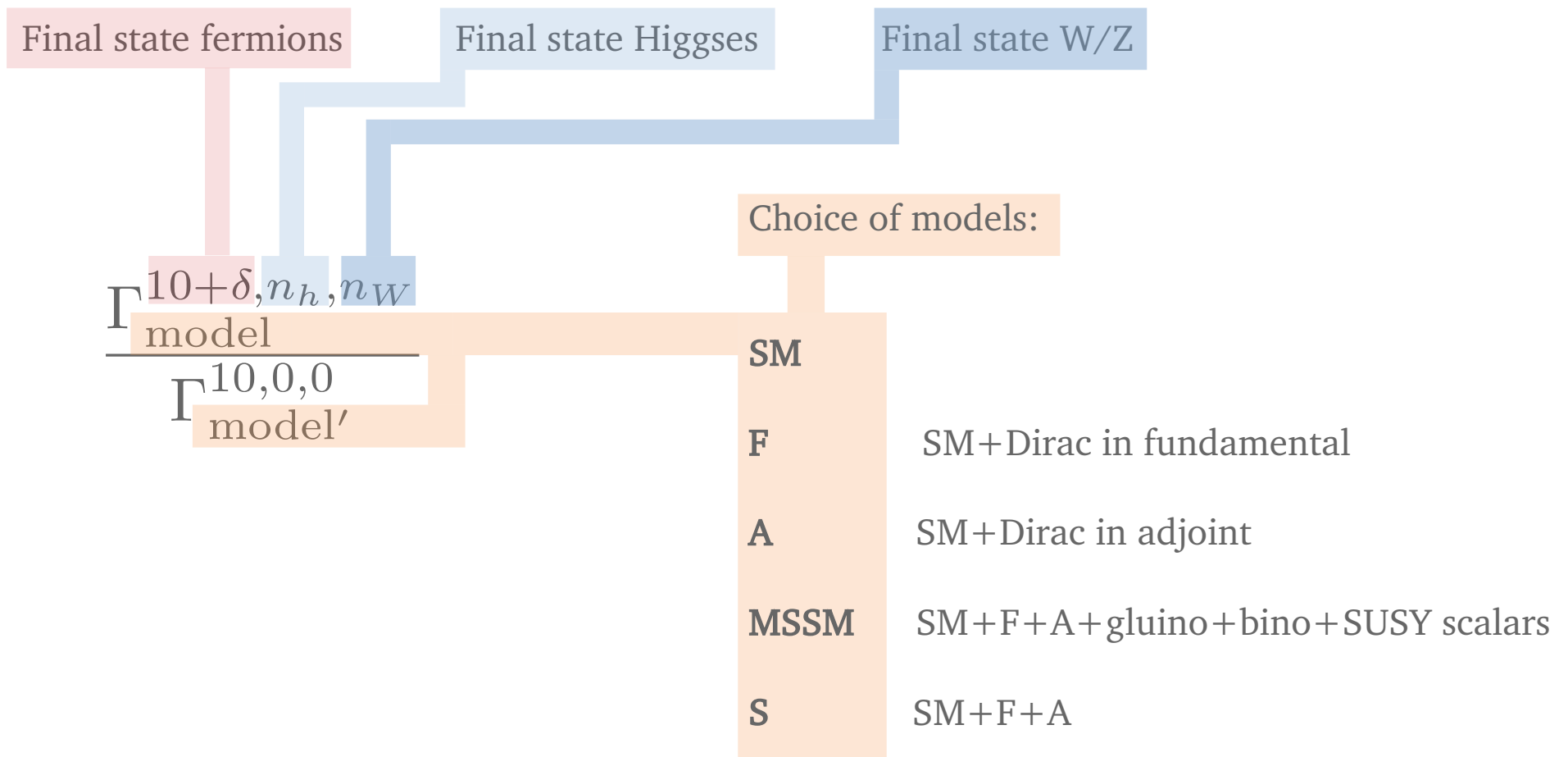
The diagram illustrates the structure of the instanton-induced effective Lagrangian, with components color-coded and labeled:

- Vacuum-to-vacuum amplitude** (grey box): $\Delta L \supset \sum_{n_W, n_h} \int \frac{d\rho}{\rho^5} \tilde{C}_I(\rho)$
- H emission** (blue box): $(-\sqrt{2}\pi^2 \rho^2 v h)^{n_h}$
- W/Z emission** (blue box): $\left(-\frac{4\pi^2 \rho^2}{g} \eta_{\alpha\mu\nu} \partial_\nu W_\mu^a \right)^{n_W}$
- Dirac Fermions** (orange box): $\times \prod_{[k,l]} \left\{ (\rho |M_{kl}|)^{N_{kl}^0 b_{kl}} \sum_{j=0}^{N_{kl}^0} (\mathcal{F}_{kl})^j (\psi_k \psi_l)^j (\rho M_{kl}^*)^{N_{kl}^0 - j} \right\}$
- Majorana Fermions** (red box): $\times \prod_m \left\{ (\rho |M_{mm}|)^{1/2 N_{mm}^0 b_{mm}} \sum_{i=0}^{1/2 N_{mm}^0} (\mathcal{F}_{mm})^i (\psi_m \psi_m)^i (\rho M_{mm}^*)^{1/2 N_{mm}^0 - i} \right\},$
- Decoupling corrections** (red box): $b_{mn} = \begin{cases} 0, & \rho |M_{mn}| < 1, \\ -1/3, & \rho |M_{mn}| \gtrsim 1. \end{cases}$
- Fermion zero-mode form factors** (red box): $(\mathcal{F}_{kl})^j$ and $(\mathcal{F}_{mm})^i$
- Mass insertions breaking chiral sym** (red box): $(\psi_k \psi_l)^j$ and $(\psi_m \psi_m)^i$

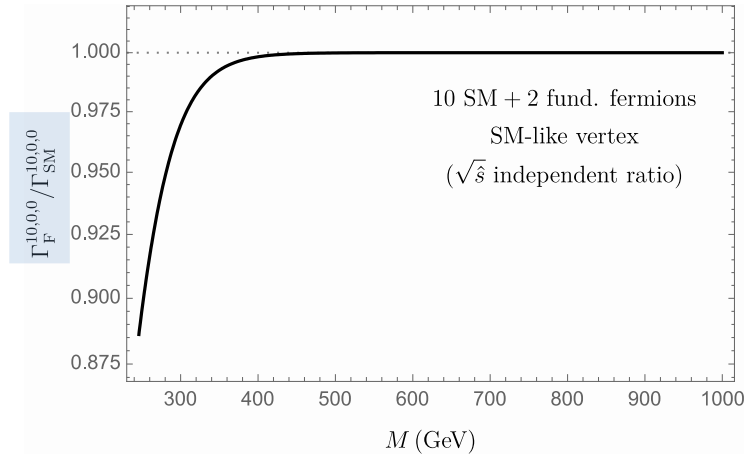
SM fermions count as massless Dirac fermions. Lagrangian satisfies anomaly selection rules

Ratios of rates

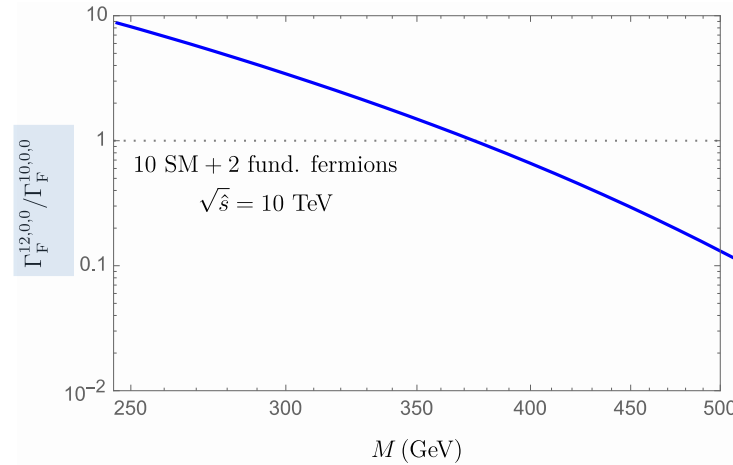
Assume 2 quark initial state: 10 fermions in final state in SM-like processes



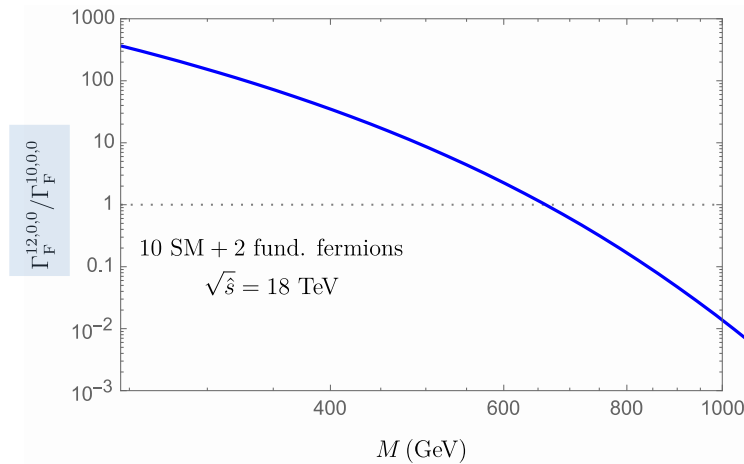
Results: enhancement from BSM fermions in F



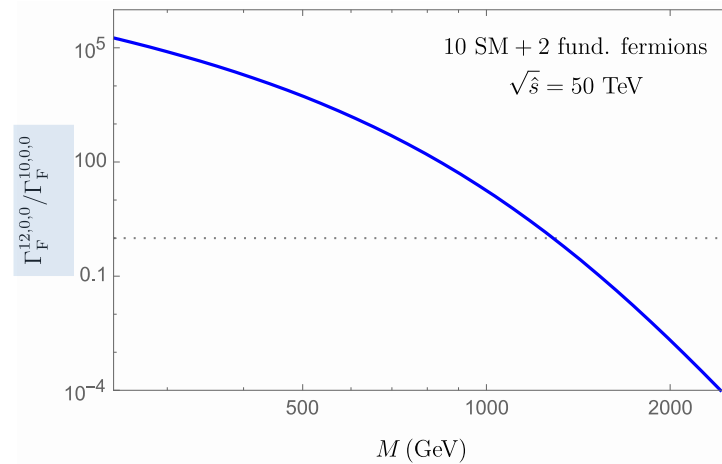
(a) SM-like/SM vertex



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

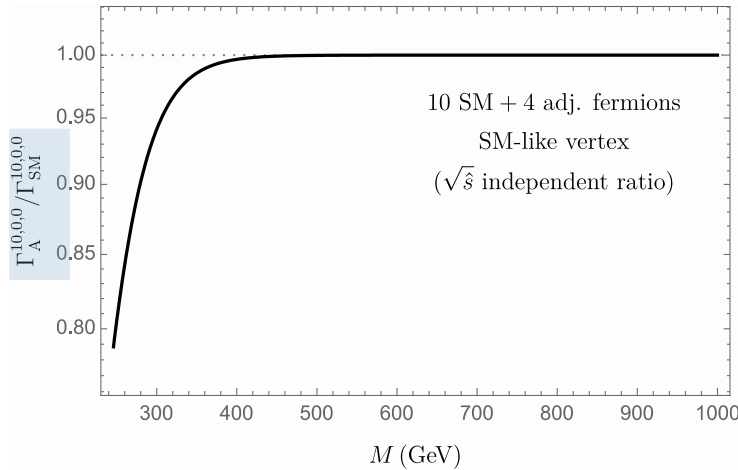


(c) qq collision energy $\sqrt{\hat{s}} = 18 \text{ TeV}$

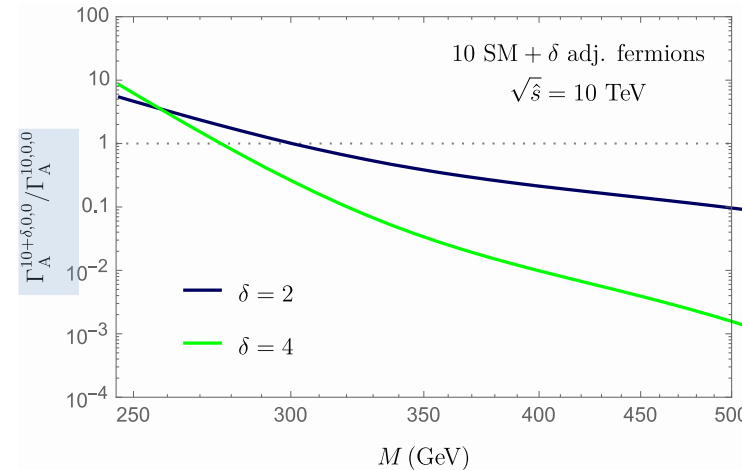


(d) qq collision energy $\sqrt{\hat{s}} = 50 \text{ TeV}$

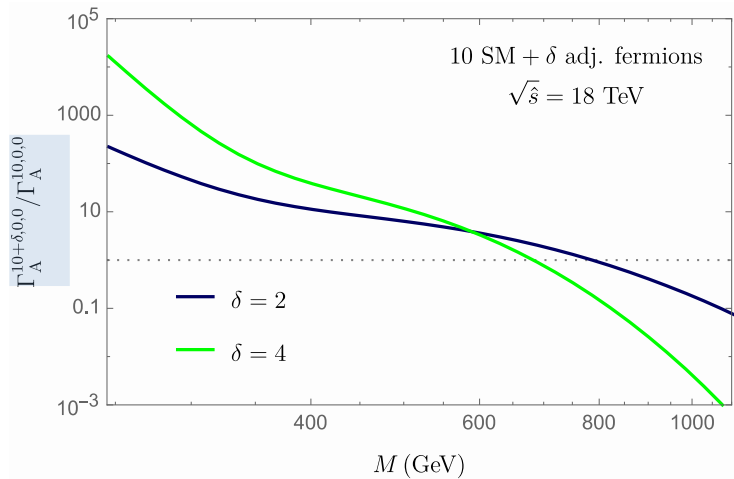
Results: enhancement from BSM fermions in A



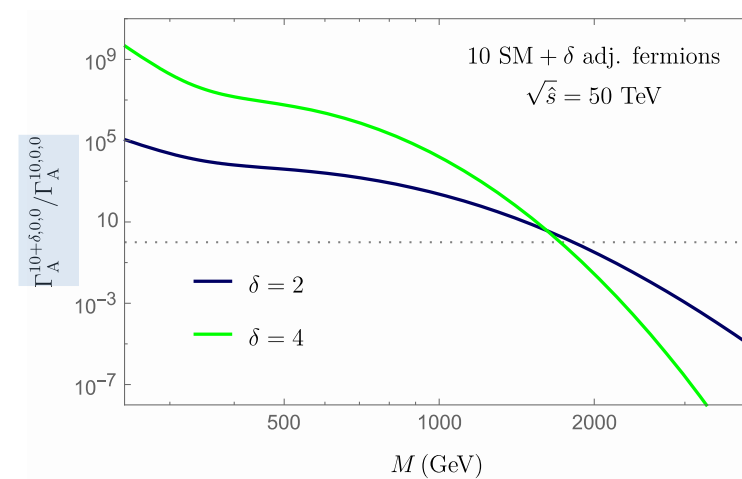
(a) SM-like/SM vertex



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

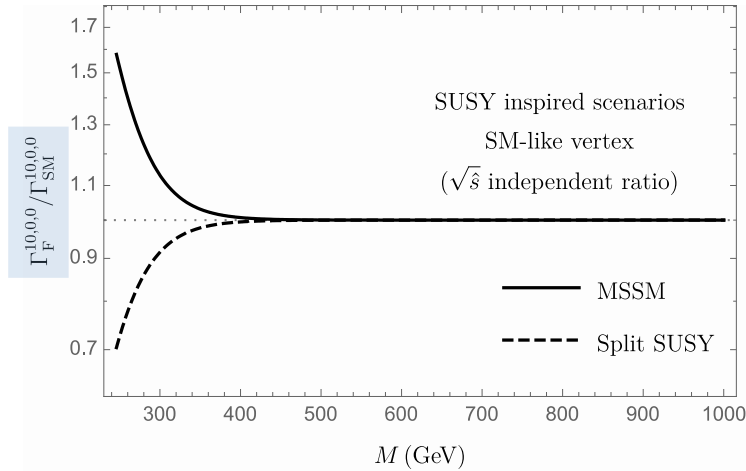


(c) qq collision energy $\sqrt{\hat{s}} = 18$ TeV

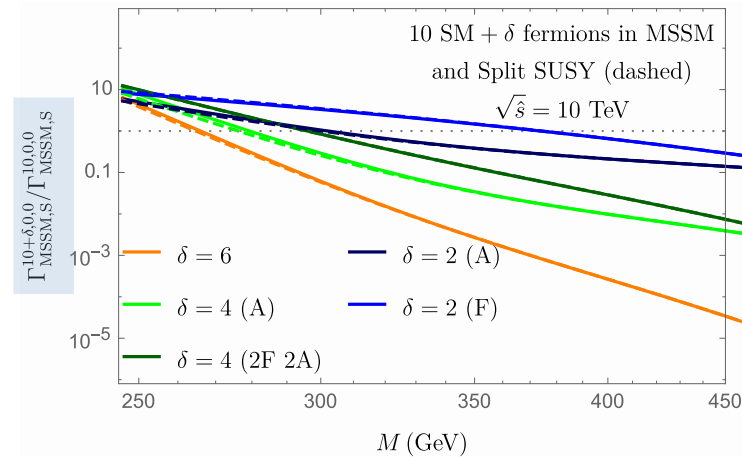


(d) qq collision energy $\sqrt{\hat{s}} = 50$ TeV

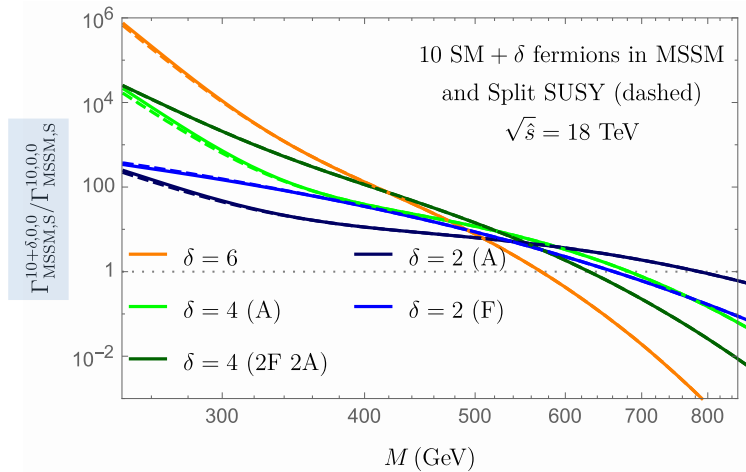
Results: enhancement from BSM fermions in MSSM/S



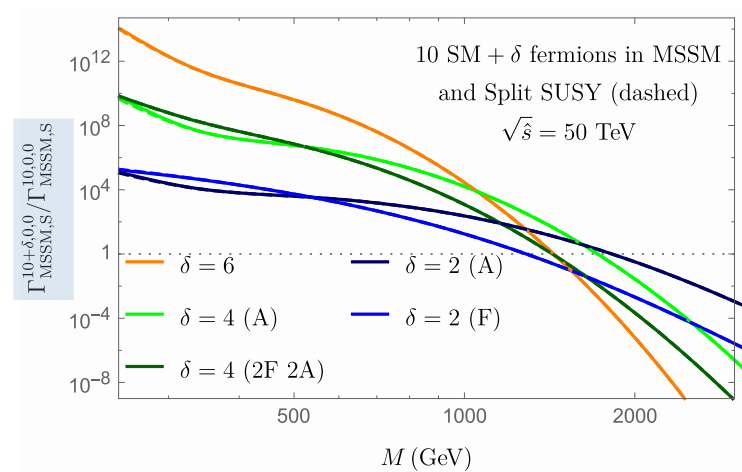
(a) SM-like/SM vertex



(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 emission 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

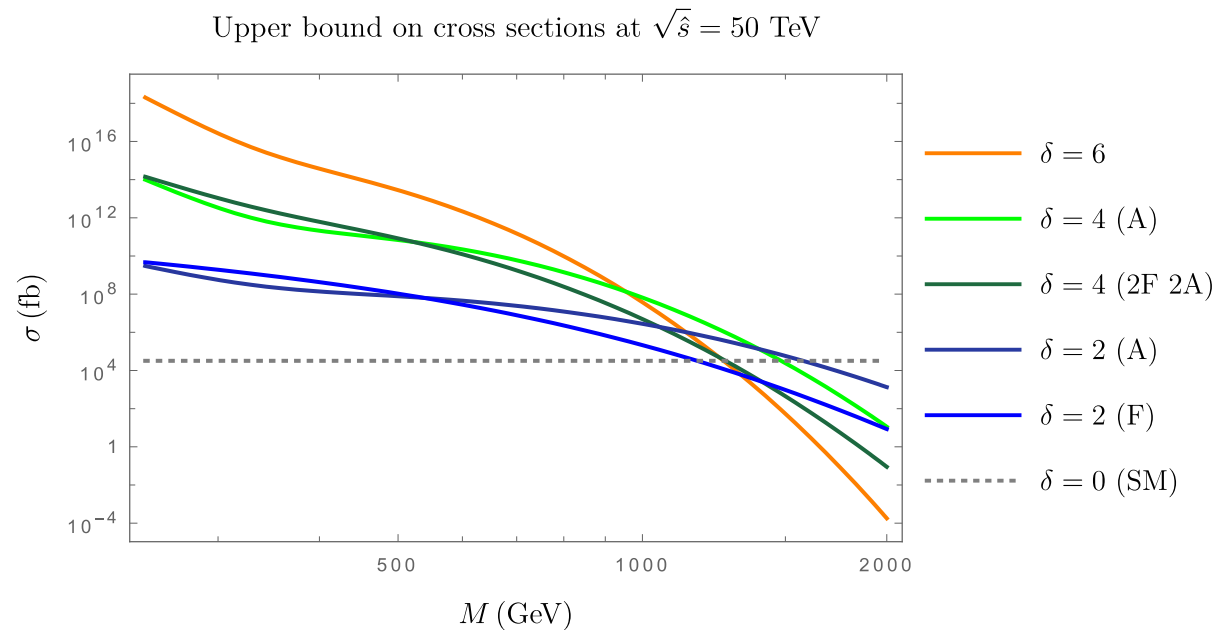
$$\sigma_{B+L}^{2 \rightarrow \text{any}} = 0.15 \frac{E(s, \delta, M)}{m_W^2} \left(\frac{2\pi}{\alpha_W} \right)^{7/2} \left(\frac{\sqrt{\hat{s}}}{E_0} \right) e^{-\frac{4\pi}{\alpha_W} F[(\sqrt{\hat{s}} - \delta M)/E_0]}$$

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 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

However, (long) extrapolation of direct estimates of F_{HG} up to 20 TeV, rather than lower bound, [Bezrukov et al] still give unobservable results

SM	$\sigma \lesssim 2.5$ fb
F@1TeV	$\sigma \lesssim 289$ fb
A@1TeV	$\sigma \lesssim 2.4 \times 10^6$ fb
S@1TeV	$\sigma \lesssim 5.7 \times 10^7$ 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 magnitude above the SM rate!

This enhancement was estimated from ratios of rates, and is thus expected to be 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