PASCOS 2023

Conserved Currents and the Power of Enhancement

Tyler Smith

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Conserved Currents and the Power of Enhancement: Unveiling New Bounds*

Tyler B. Smith† and Tim M.P. Tait‡

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Coming Soon!

Outline

Motivation for $U(1)_{B-L}$

Gauging $U(1)_{B-L}$

Previous Work

Our Model

New Constraints

Motivations for $U(1)_{B-L}$

Other than being the only conserved global symmetry in the standard model it can also help explain other BSM physics:

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Portal to DM

G. Choi et al., arXiv: 2008.12180

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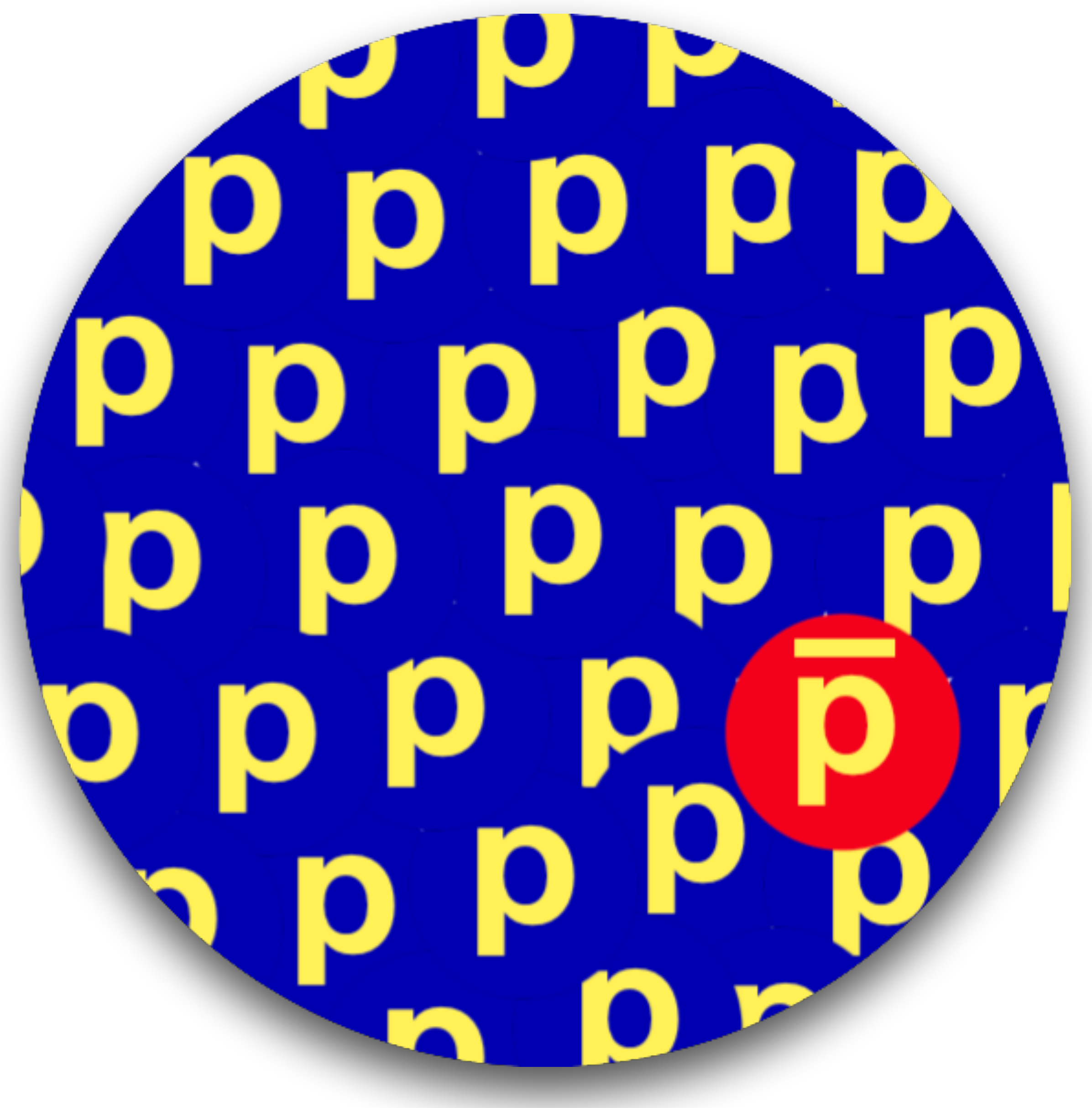
Baryon Asymmetry



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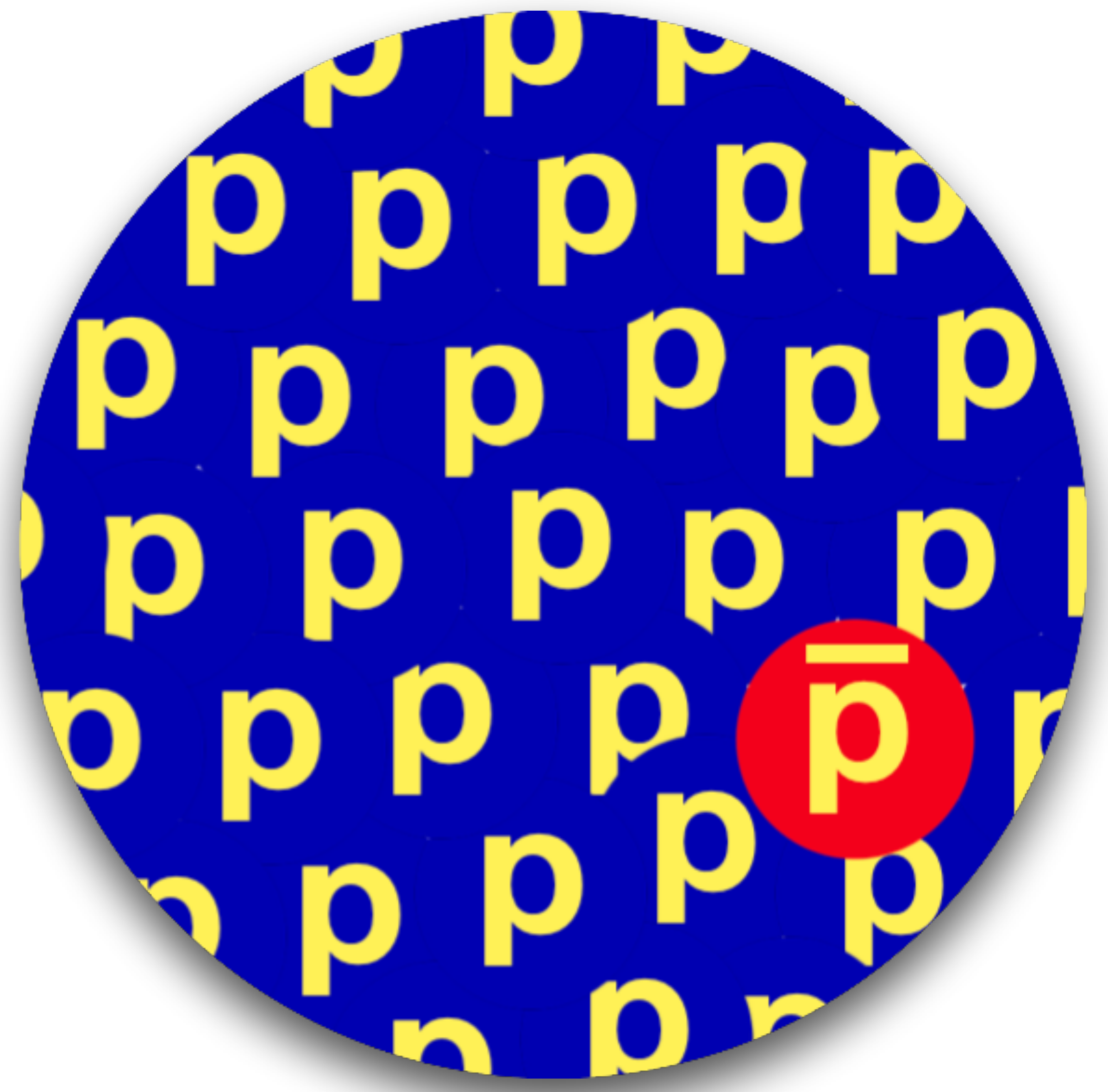

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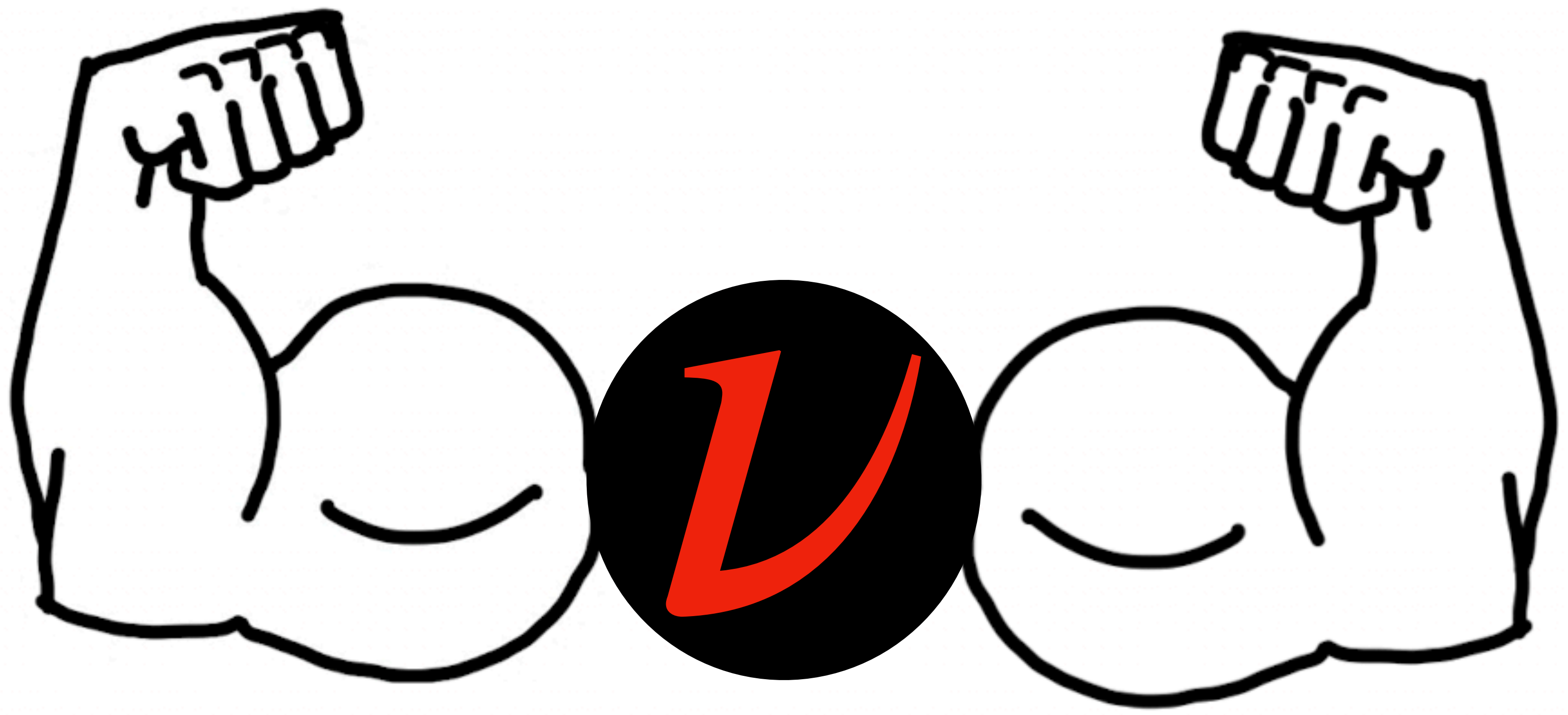
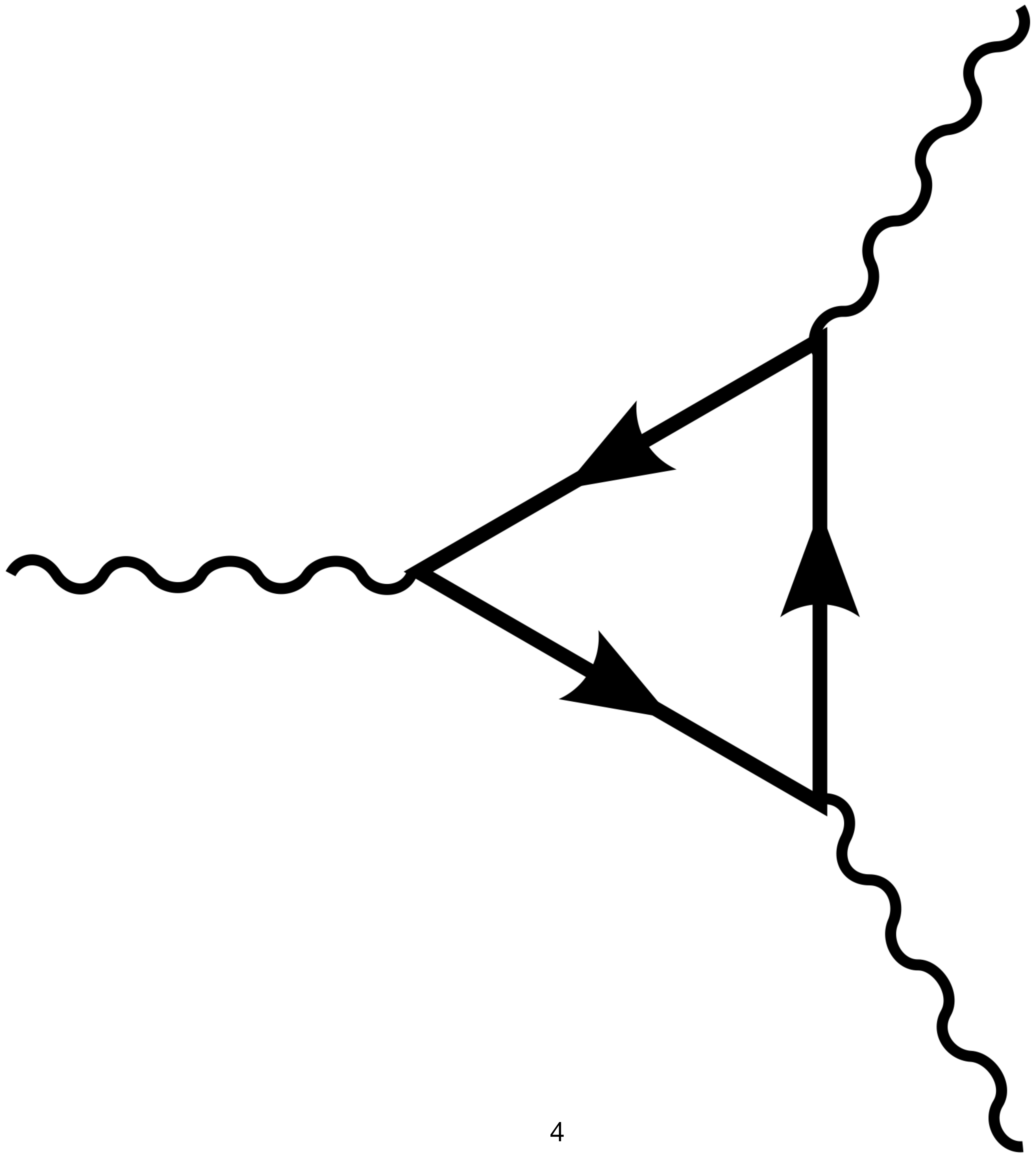
Massive neutrinos



Gauging U(1)B-L

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$$



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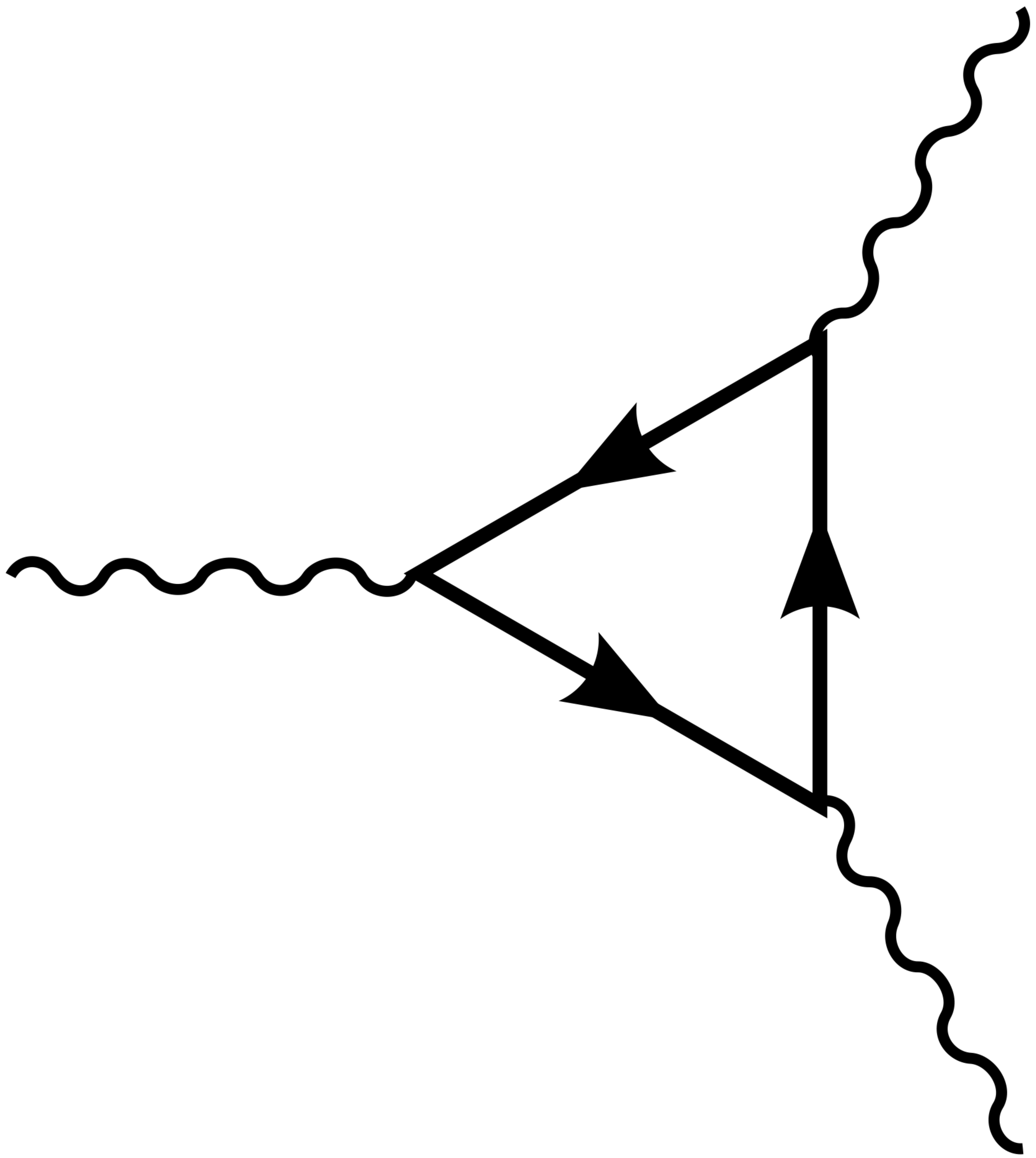
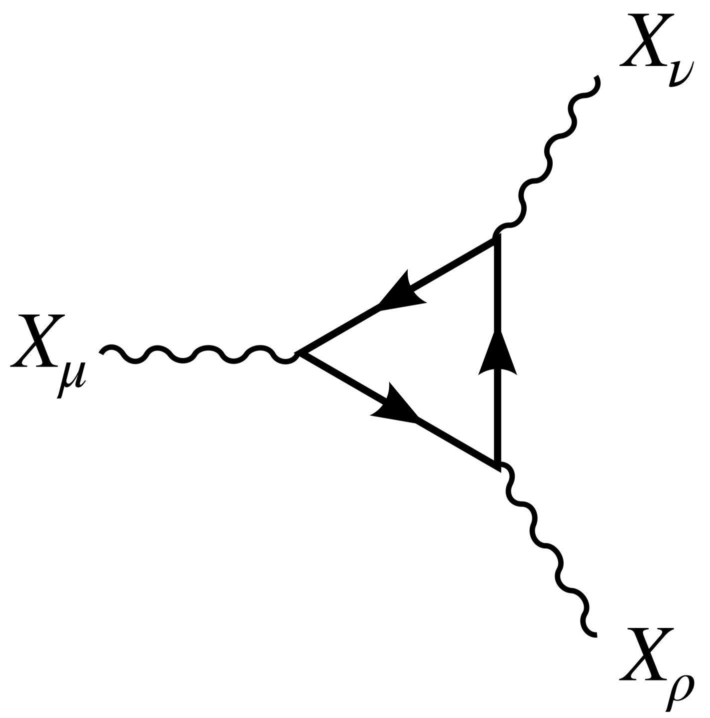


Anomaly free with the standard model

...but not with itself



$U(1)^3_{B-L}$ $\quad\quad$ $\partial_\mu \mathscr{M}^\mu \neq 0$

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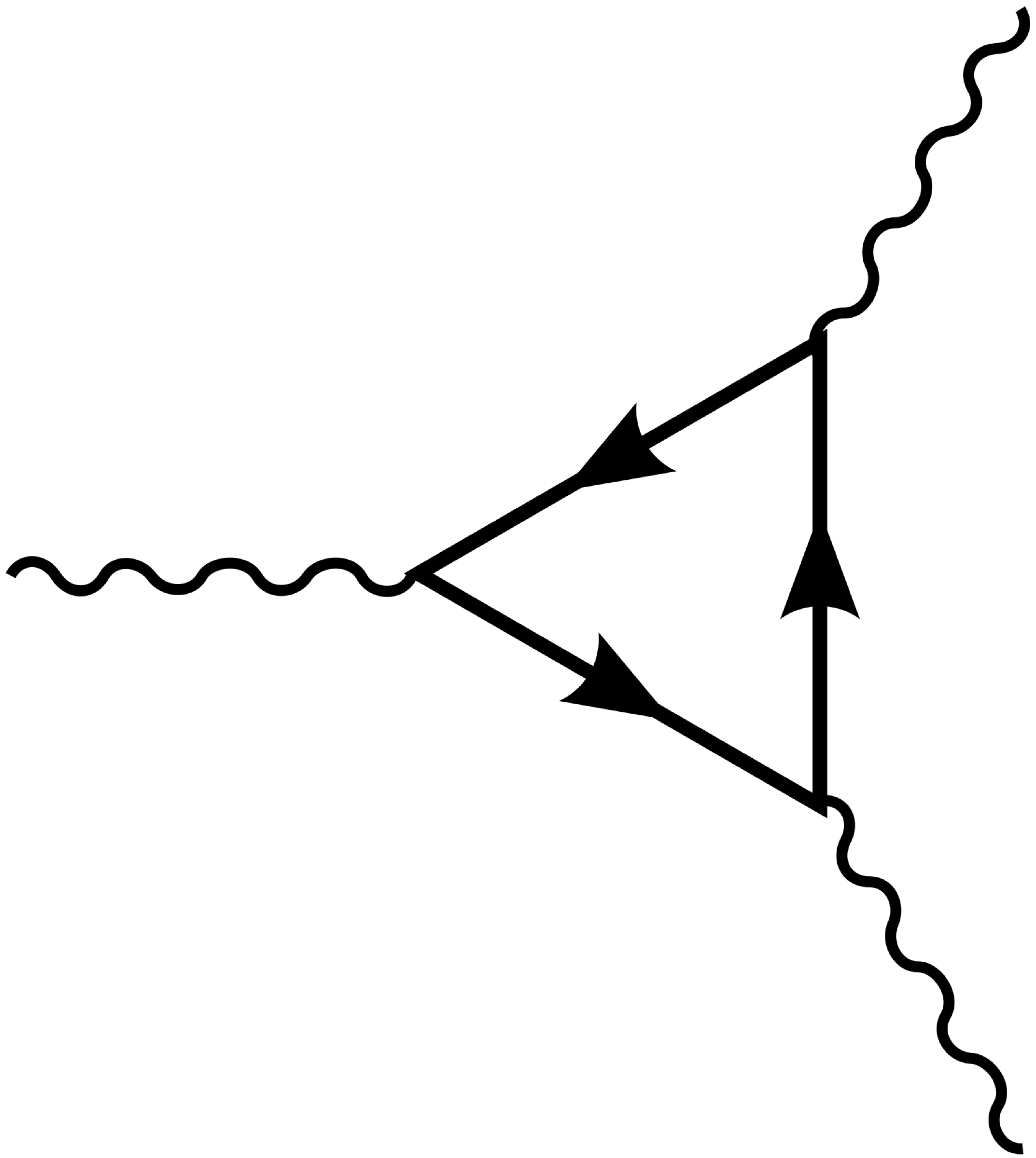

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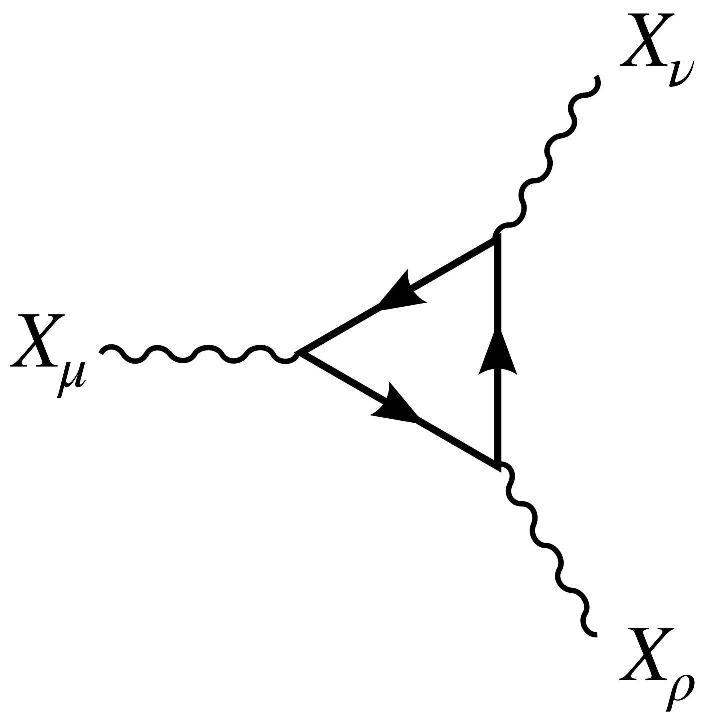

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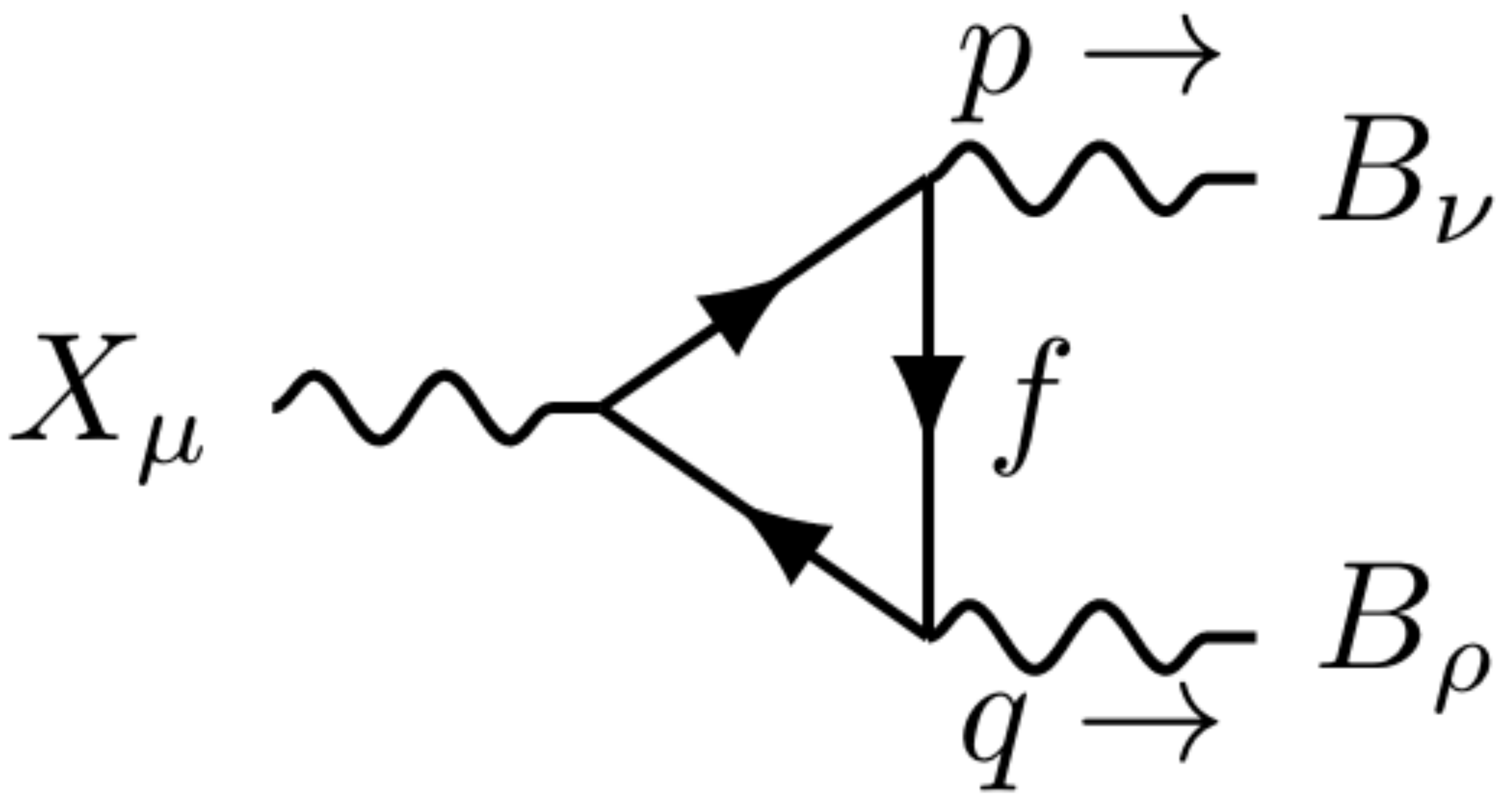
Anomaly-free

Helps generate **Dirac** neutrino masses

$$\mathcal{M}^{\mu\nu\rho} \equiv \sum_{f, f_{\rm SM}}$$ 

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Dror et al. 2017, arXiv:1707.01503

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$$\partial^\mu J^X_\mu = \frac{\mathcal{A}_{XBB}}{16\pi^2}\left(g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu} - g^2 W^a_{\mu\nu}(\tilde{W}^a)^{\mu\nu}\right)$$

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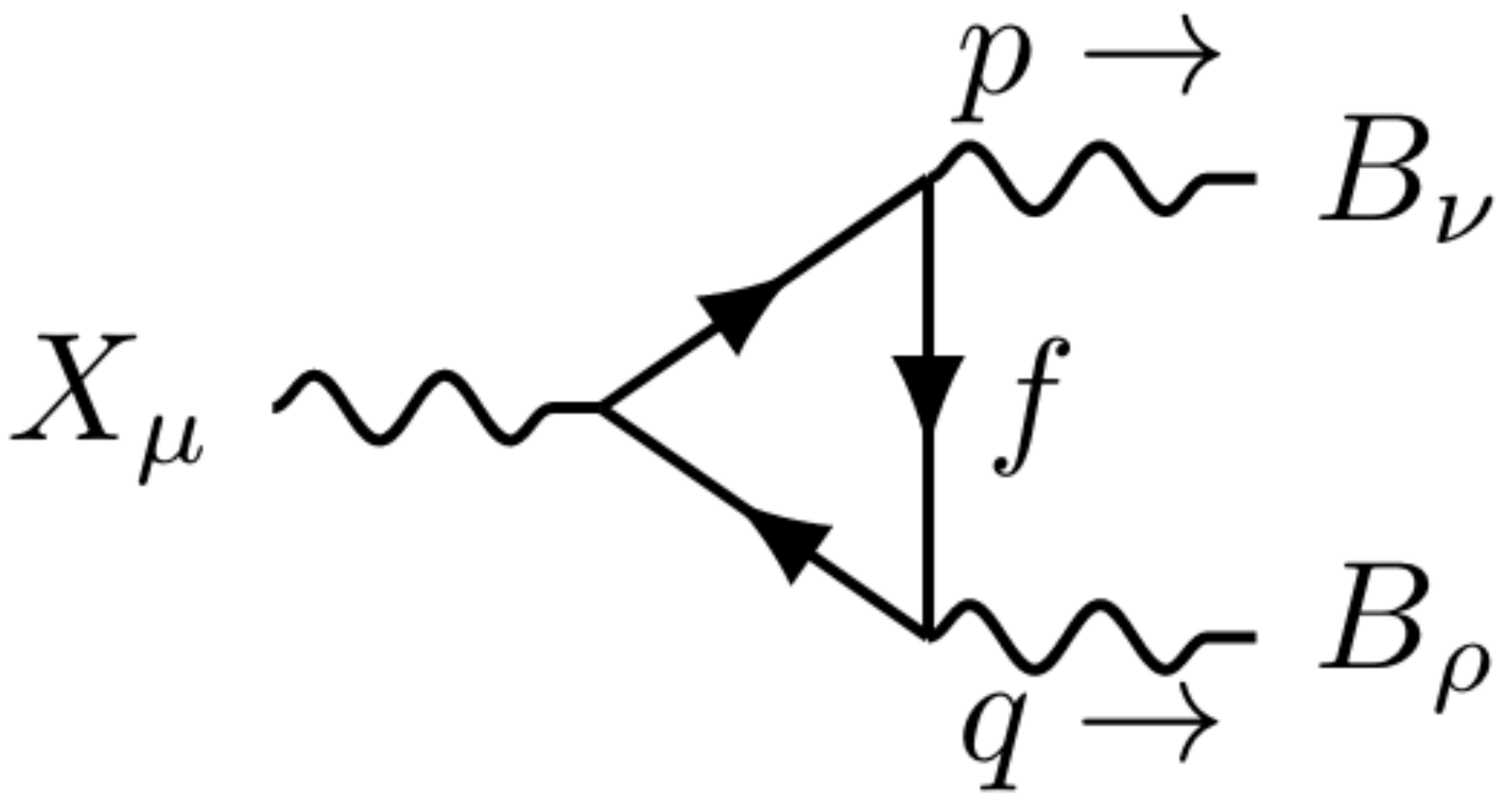

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Couple X axially to the new fermions to induce a mass term

$$-(p+q)_\mu \mathcal{M}^{\mu\nu\rho} = \frac{1}{2\pi^2}\epsilon^{\nu\rho\lambda\sigma} p_\lambda q_\sigma g_X g'^2 \times \sum_f 2m_f^2 I_{00}(m_f, p, q) X_{A,f} Y_f^2,$$

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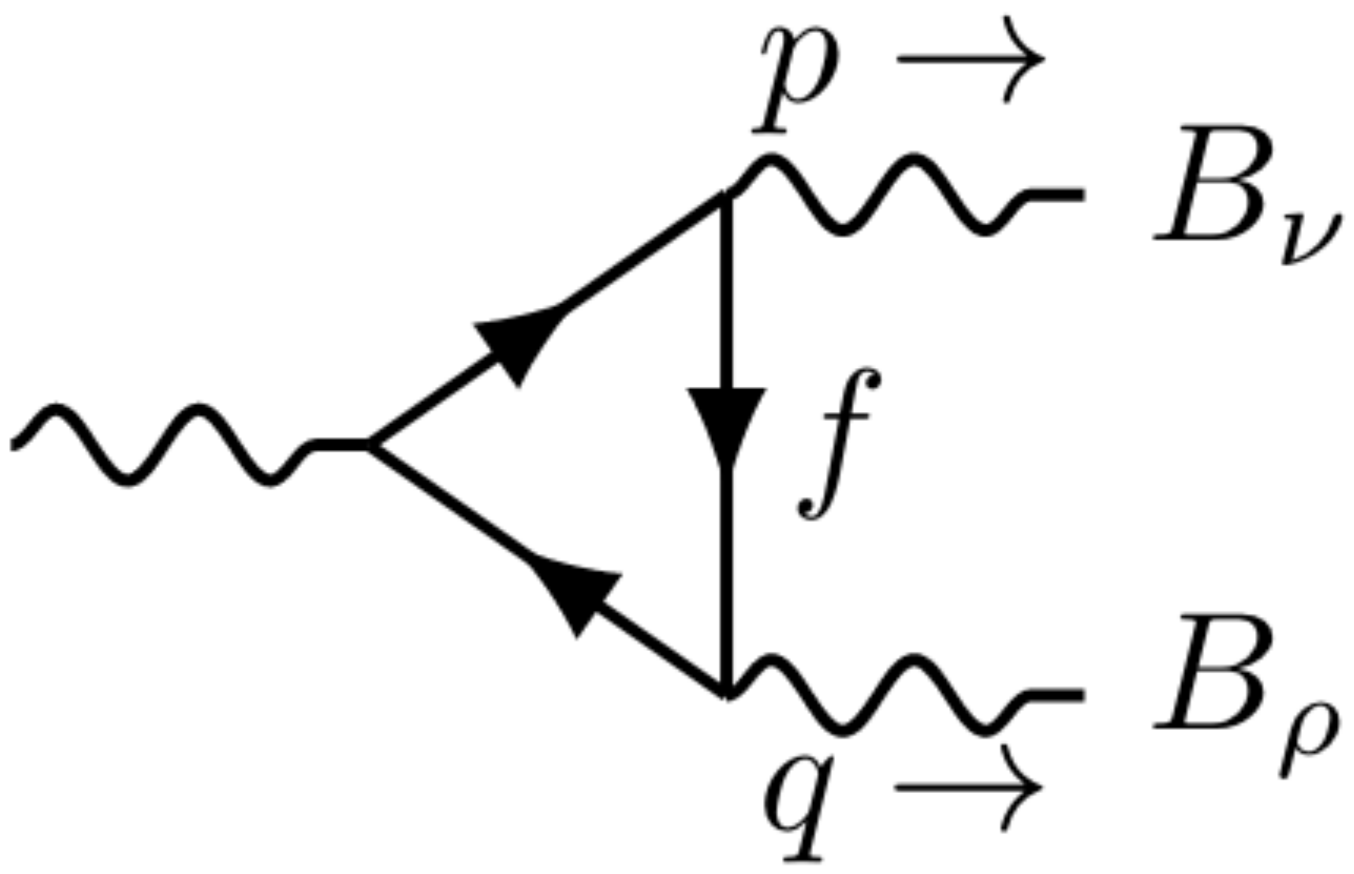

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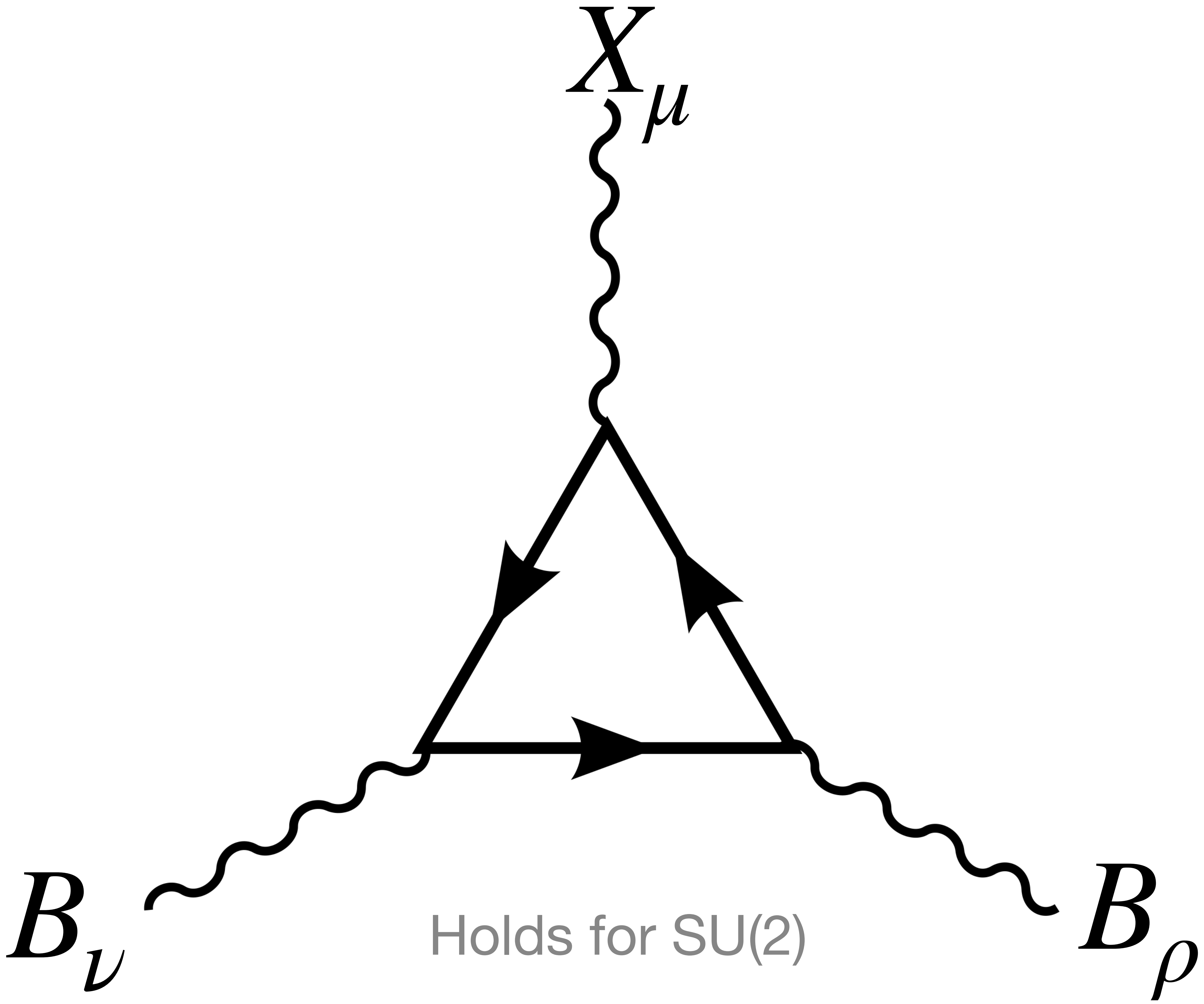
Use this amplitude to search for rare Z decays and FCNC meson decays.



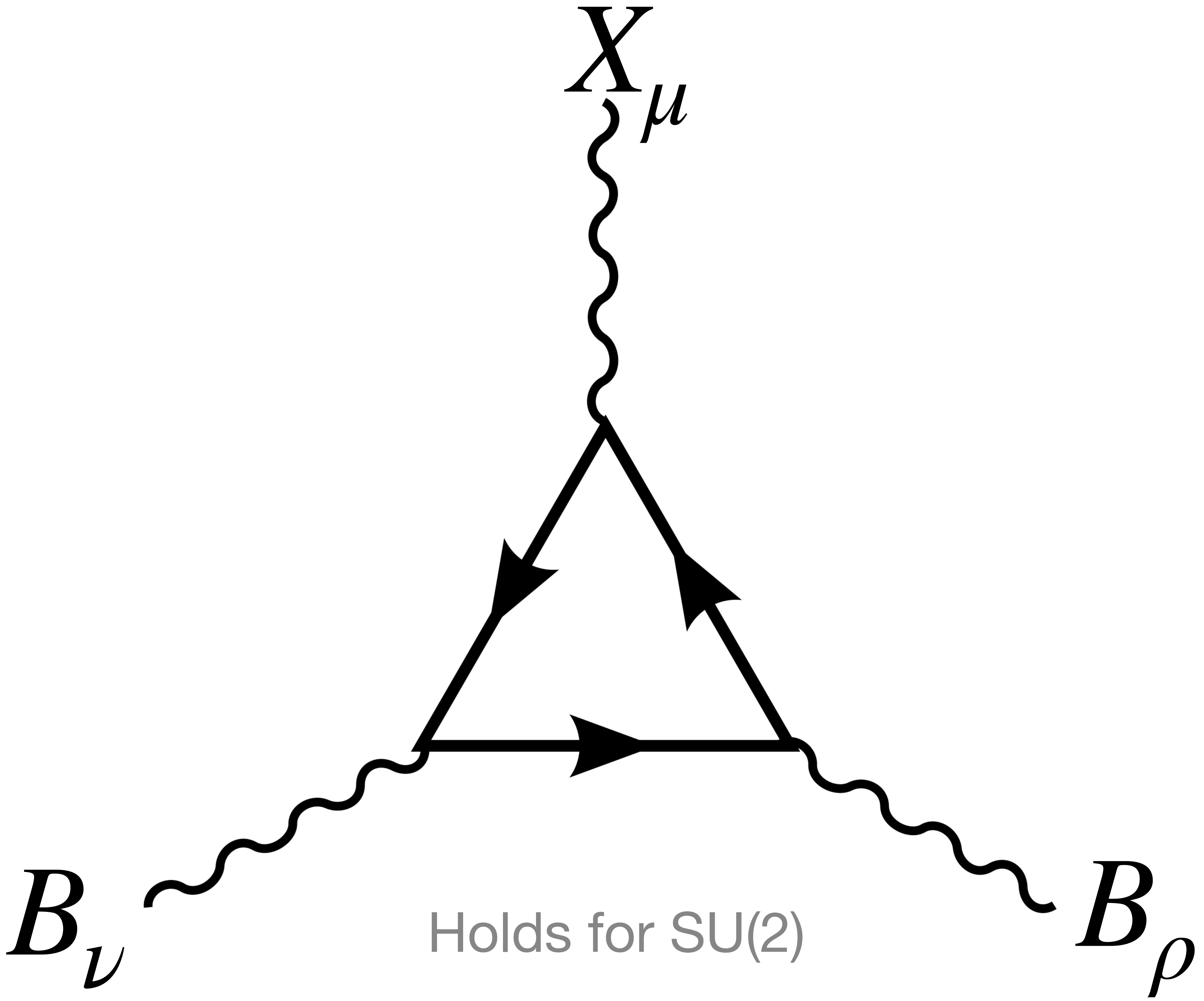
Holds for SU(2)

What's new then:
We couple to the conserved current $U(1)_{B-L}$, where for these amplitudes we do not need to include new fermions to cancel the anomaly. Rather, we use SM fermions to obtain a non-zero amplitude to do phenomenology with.

$$I_{00} = \int_0^1 dx \int_0^{1-x} \frac{dz}{m_f^2 - z(1-z)p^2 - x(1-x)q^2 - 2xz(p\cdot q)}$$

$$(p+q)_\mu \mathcal{M}^{\mu\nu\rho}_{XBB} = \sum_f \frac{g_X g_V g_A}{\pi^2}(B-L)\epsilon^{\alpha\beta\nu\rho} q_\alpha p_\beta (1 - 2m_f^2 I_{00})$$

For conserved currents one may expect these divergences to go to zero, and thus there is nothing to gain, but we will show that this is not true if we are careful about the energy regime we choose to work in.



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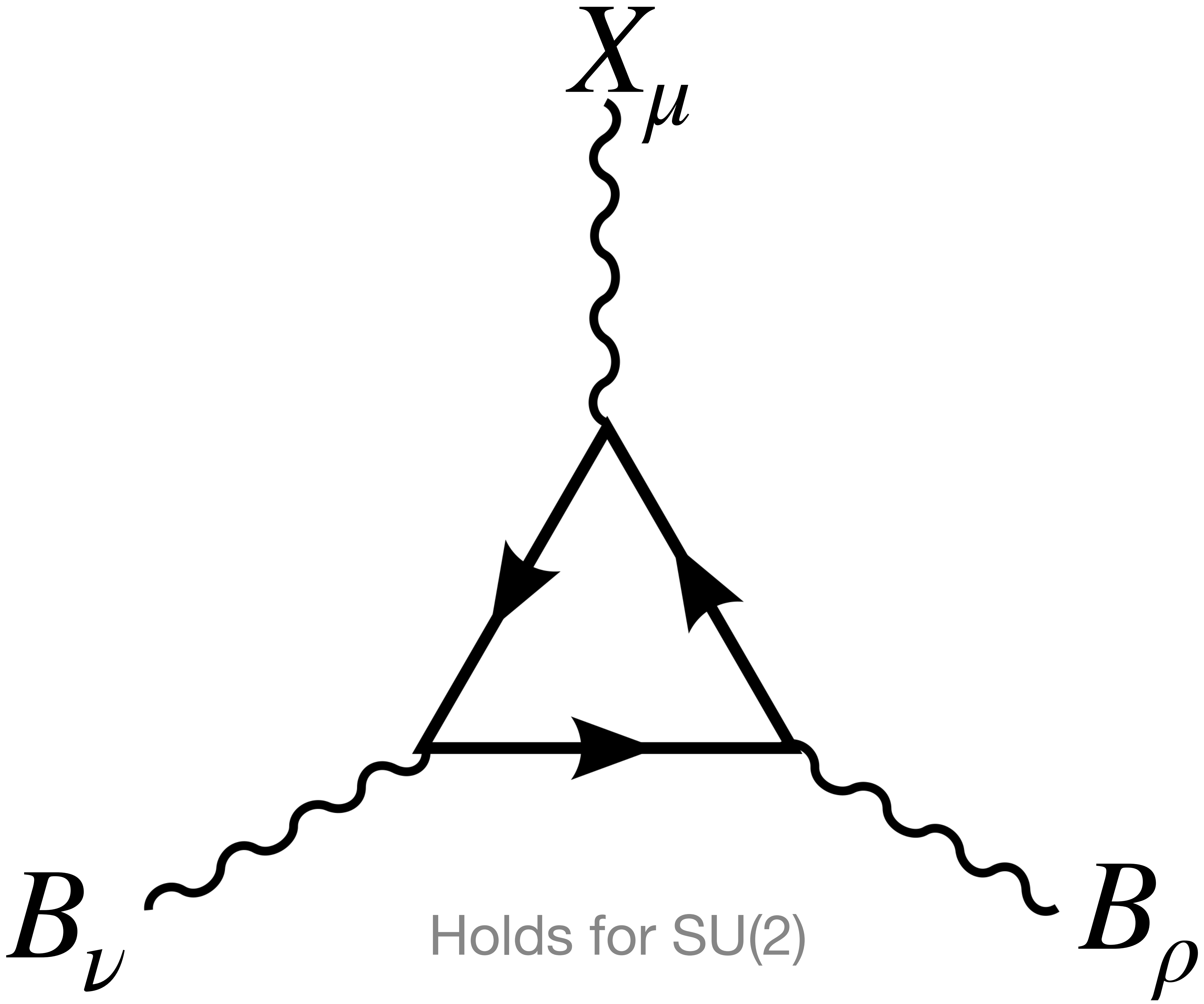

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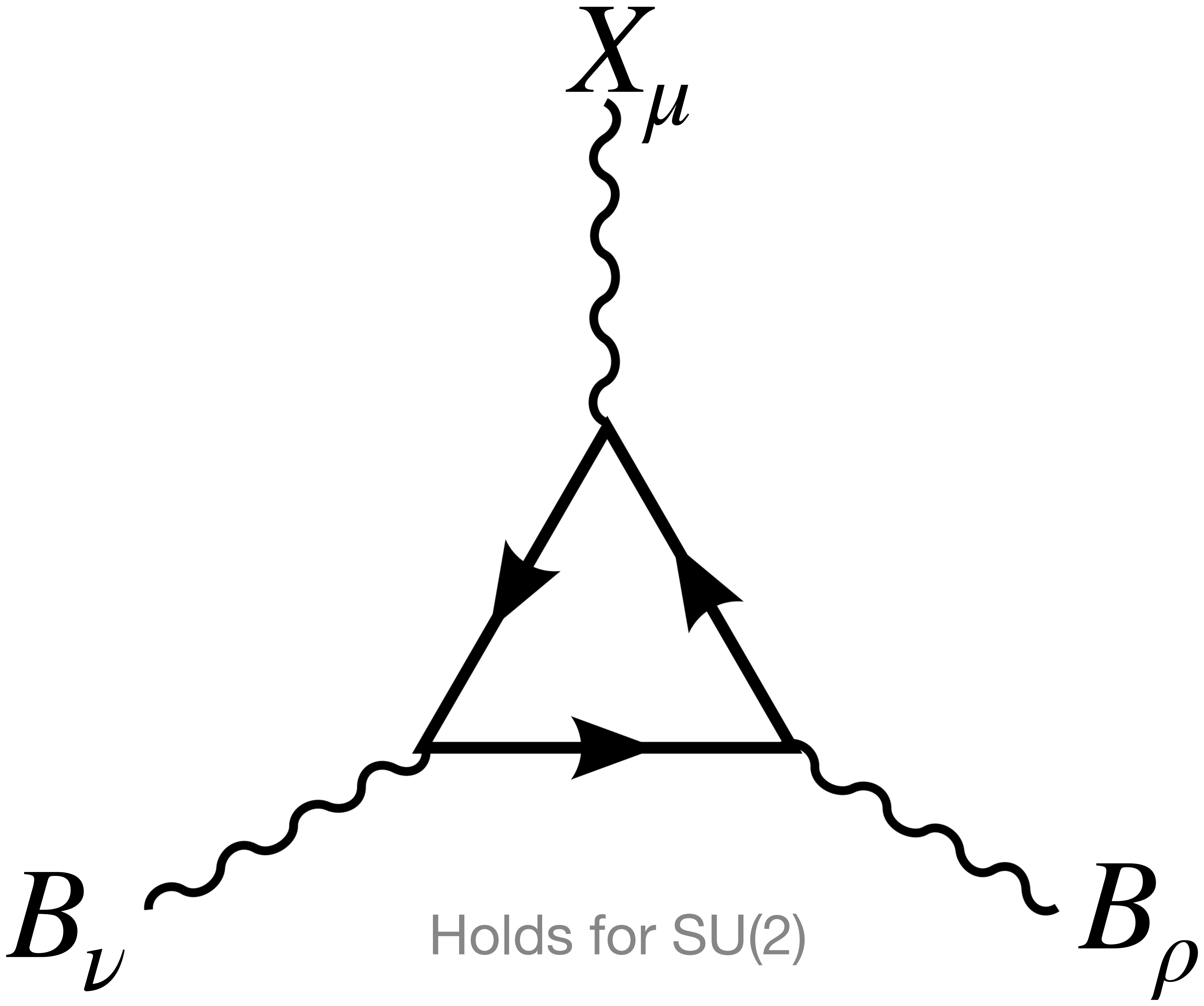
$= 1$ for $p^2, q^2 \ll m_f^2$ — Fermions decouple

$= 0$ for $p^2, q^2 \gg m_f^2$ — Massless limit



Holds for SU(2)

When summing over all the standard model fermions we obtain 0 contribution, but...

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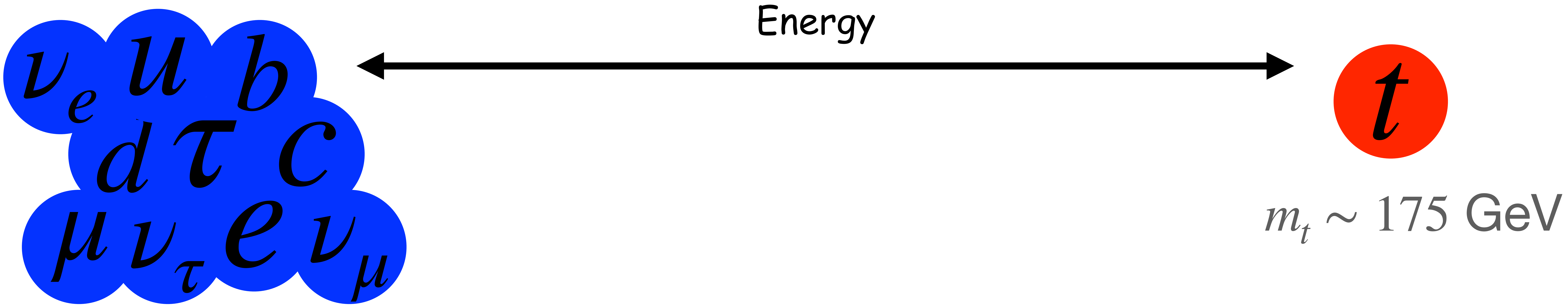

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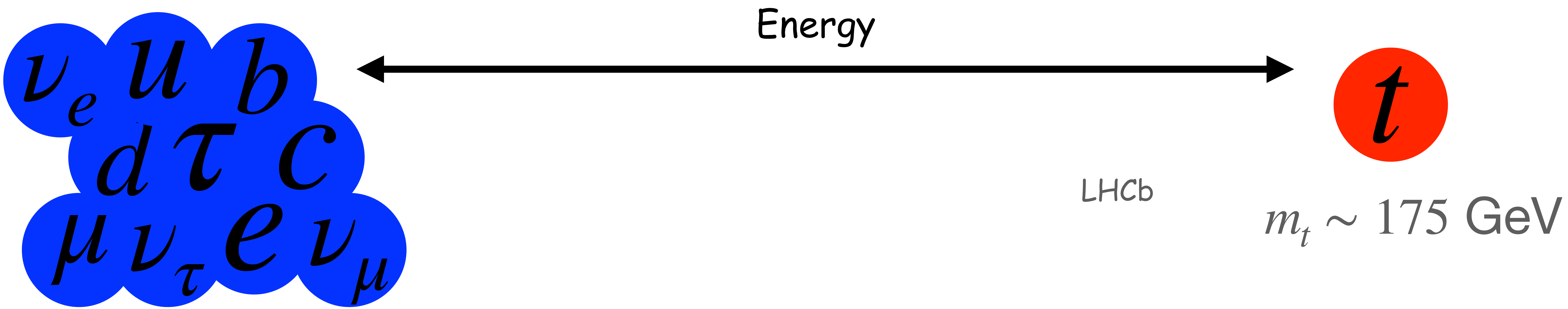
The massless piece will go to zero
The massive piece will have all fermions but the top quark contribution go to zero

Thus, there will be a leftover non-zero amplitude which we use to search for the B-L vector boson.



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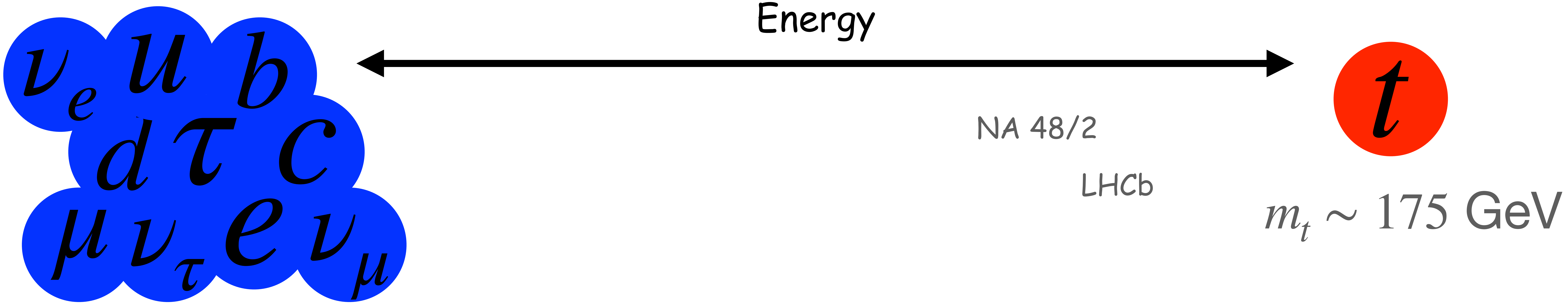

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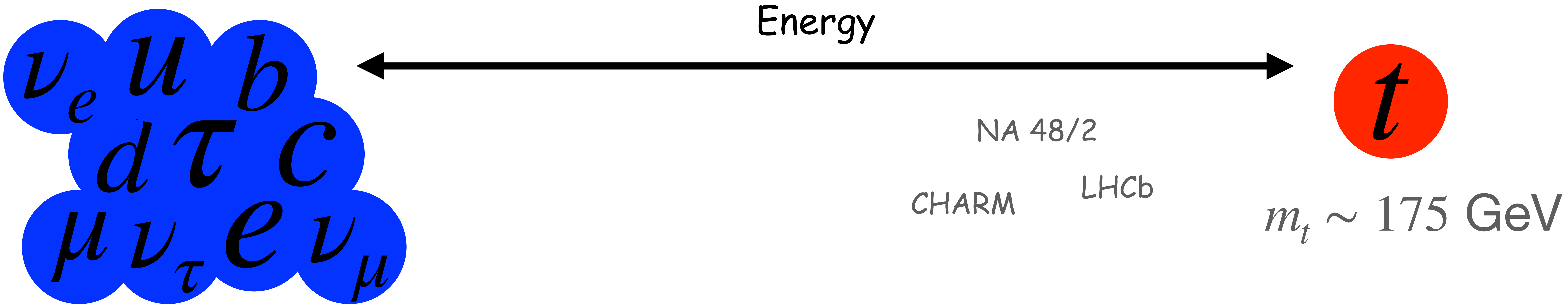

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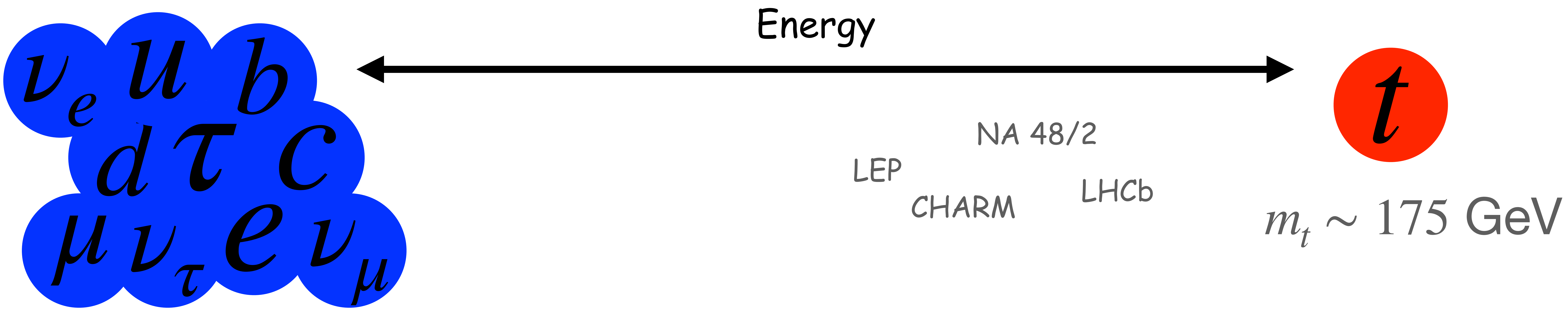

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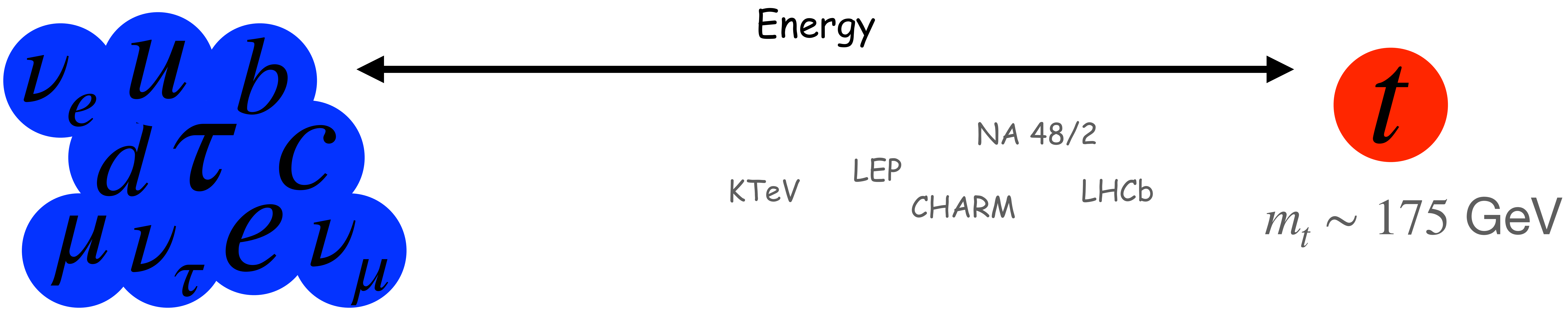

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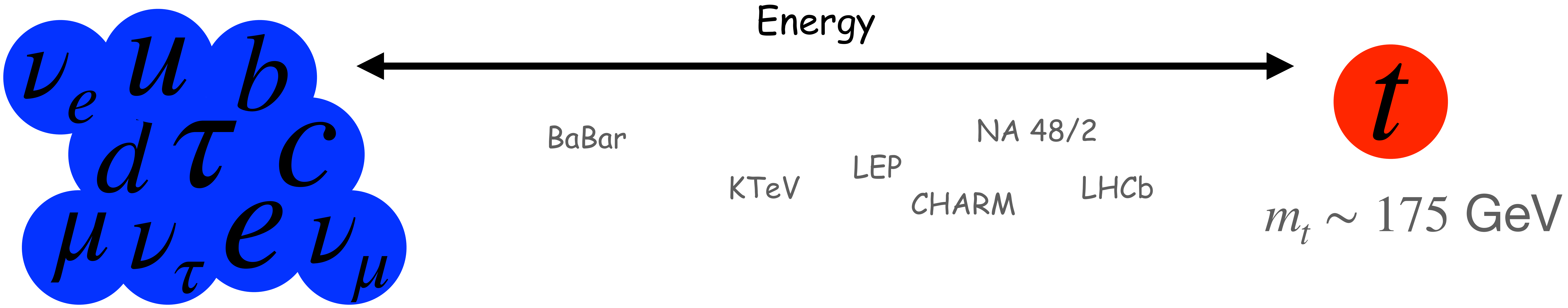

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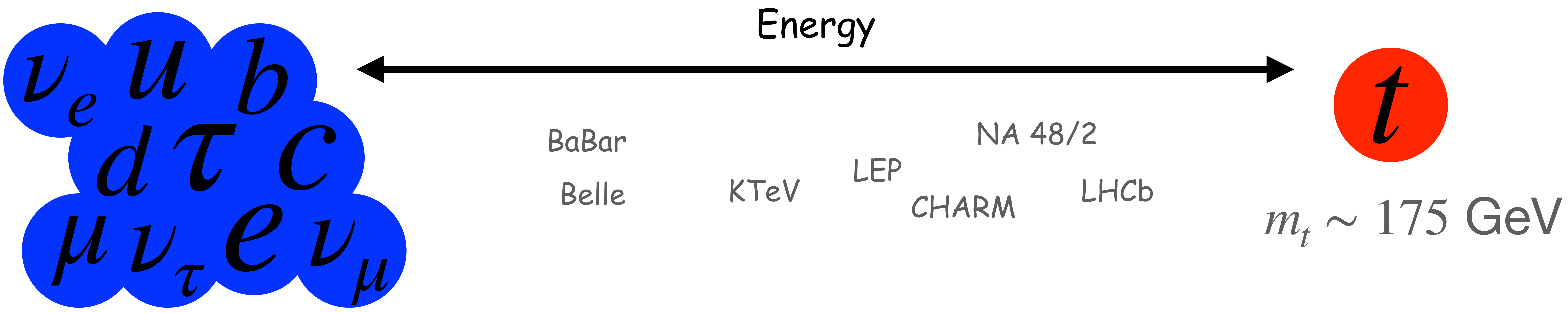

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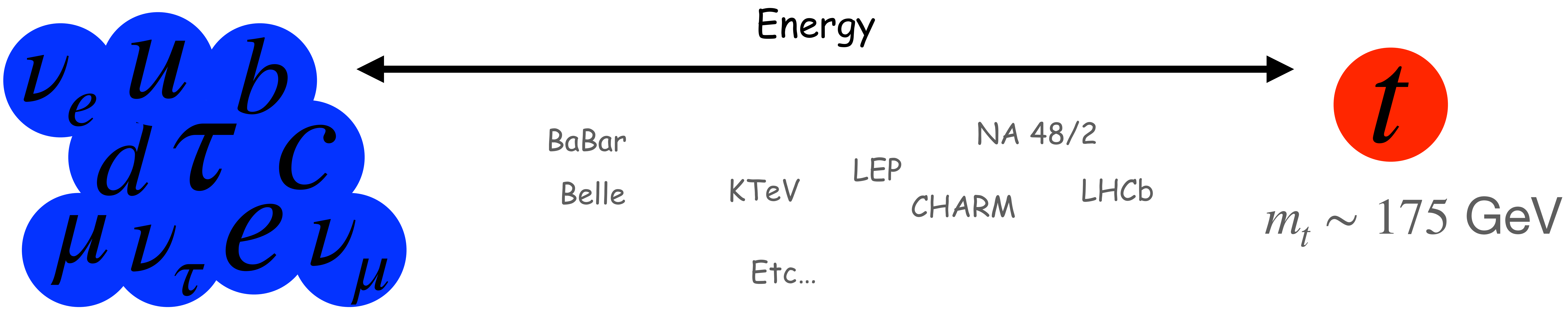

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Slight Detour

Goldstone Boson Equivalence Theorem

At high energies the interaction of a longitudinally polarized massive gauge boson is equivalent to the interaction of the corresponding Goldstone boson that it ate.

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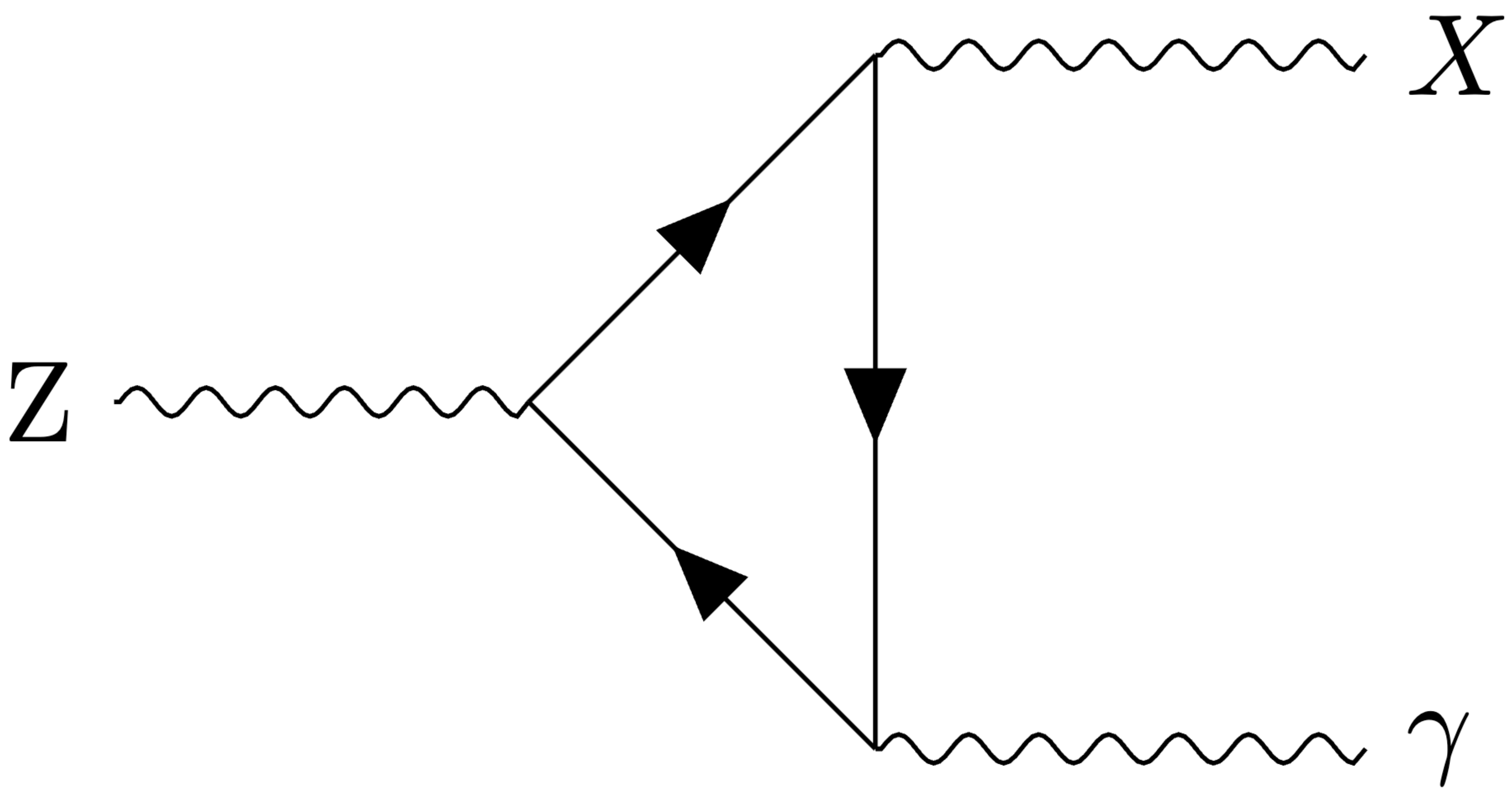
$$g_X X_\mu \to \frac{1}{f_X}\partial_\mu \varphi$$

Rare Z Decays



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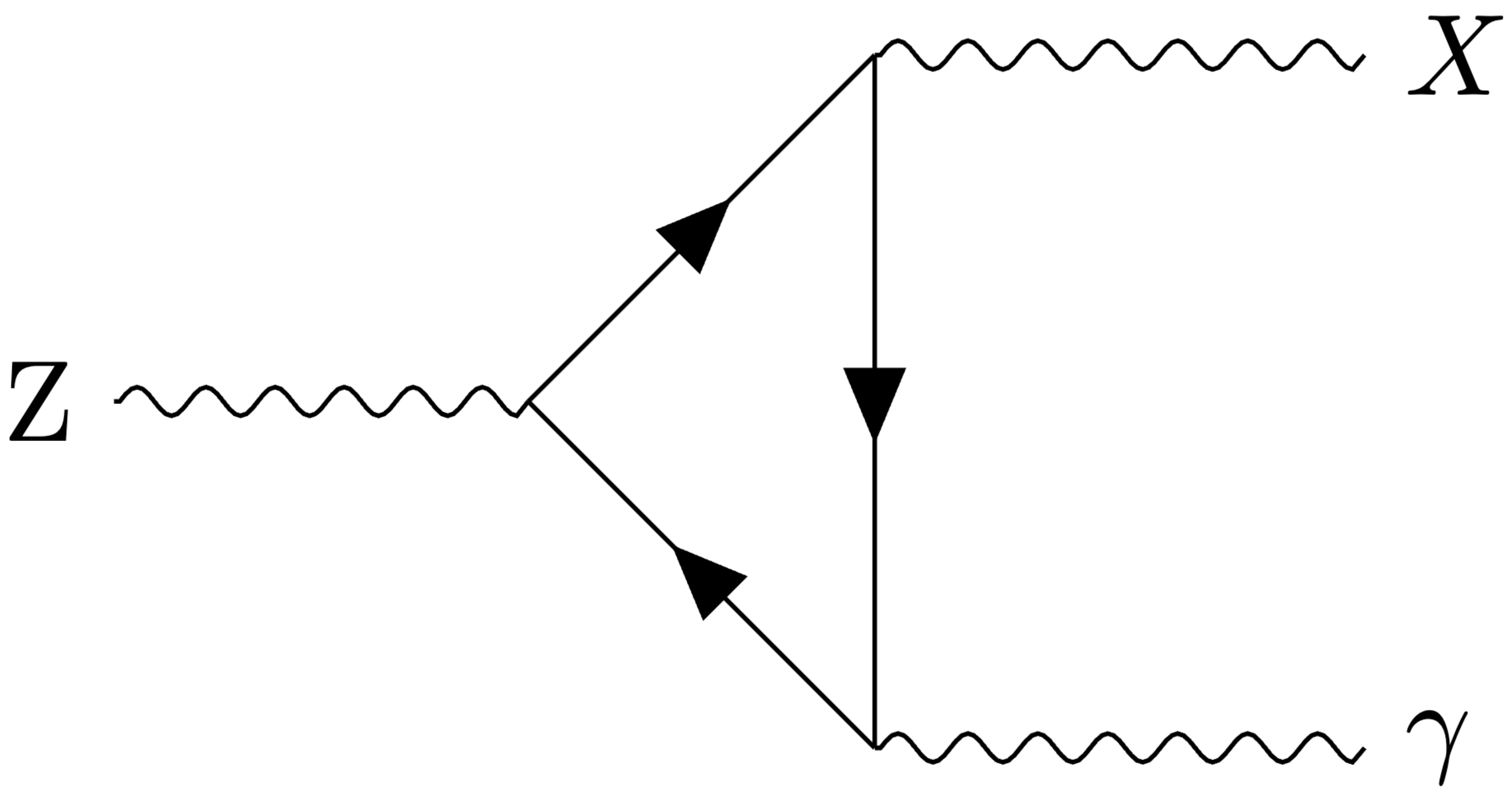

$$\mathrm{BR}(Z \to X\gamma) \approx 4 \times 10^{-10} \left[1 - \left(\frac{m_X}{m_Z}\right)^2\right]^3 \left(\frac{\mathrm{TeV}}{m_X/g_X}\right)^2$$

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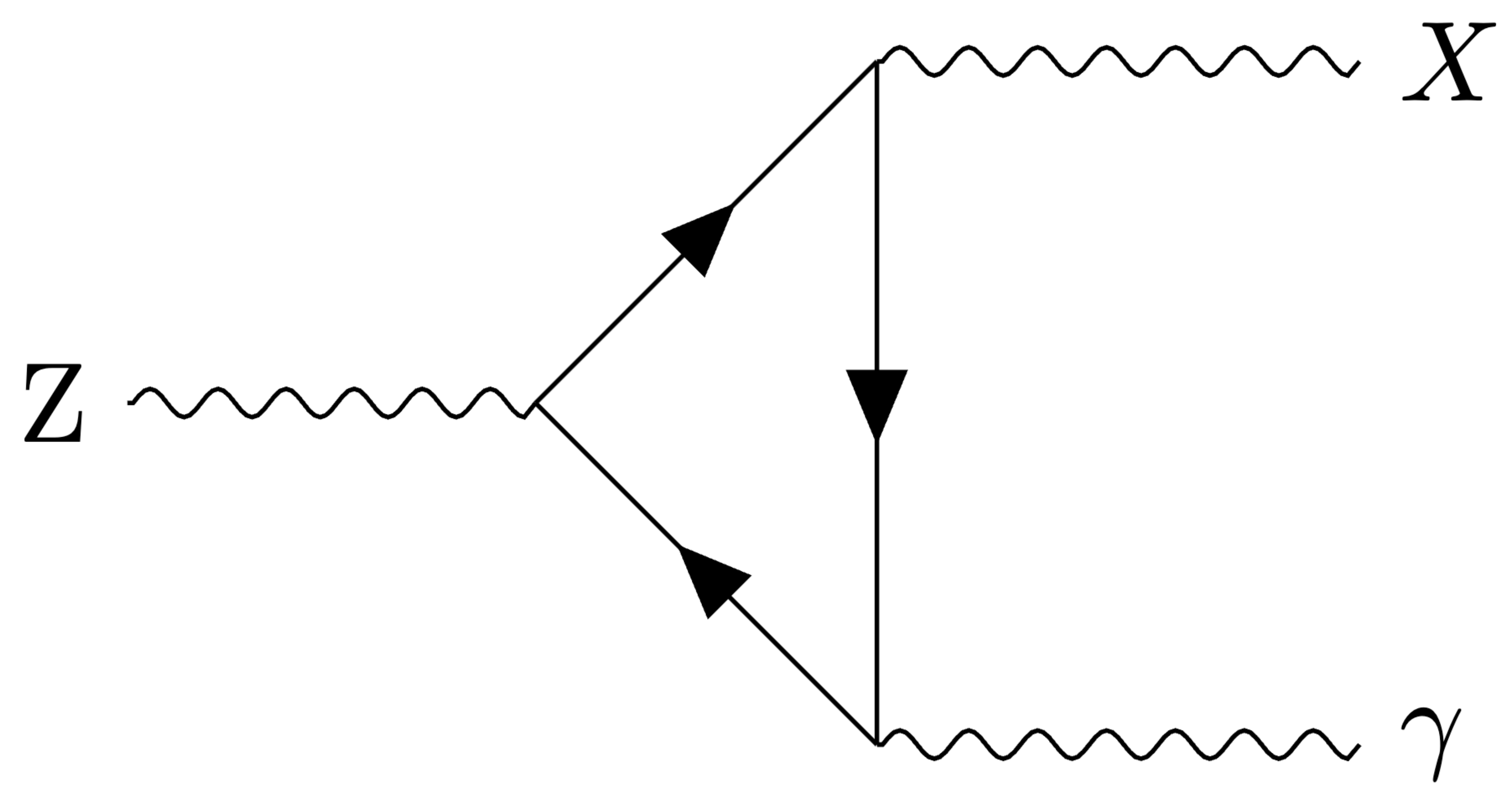

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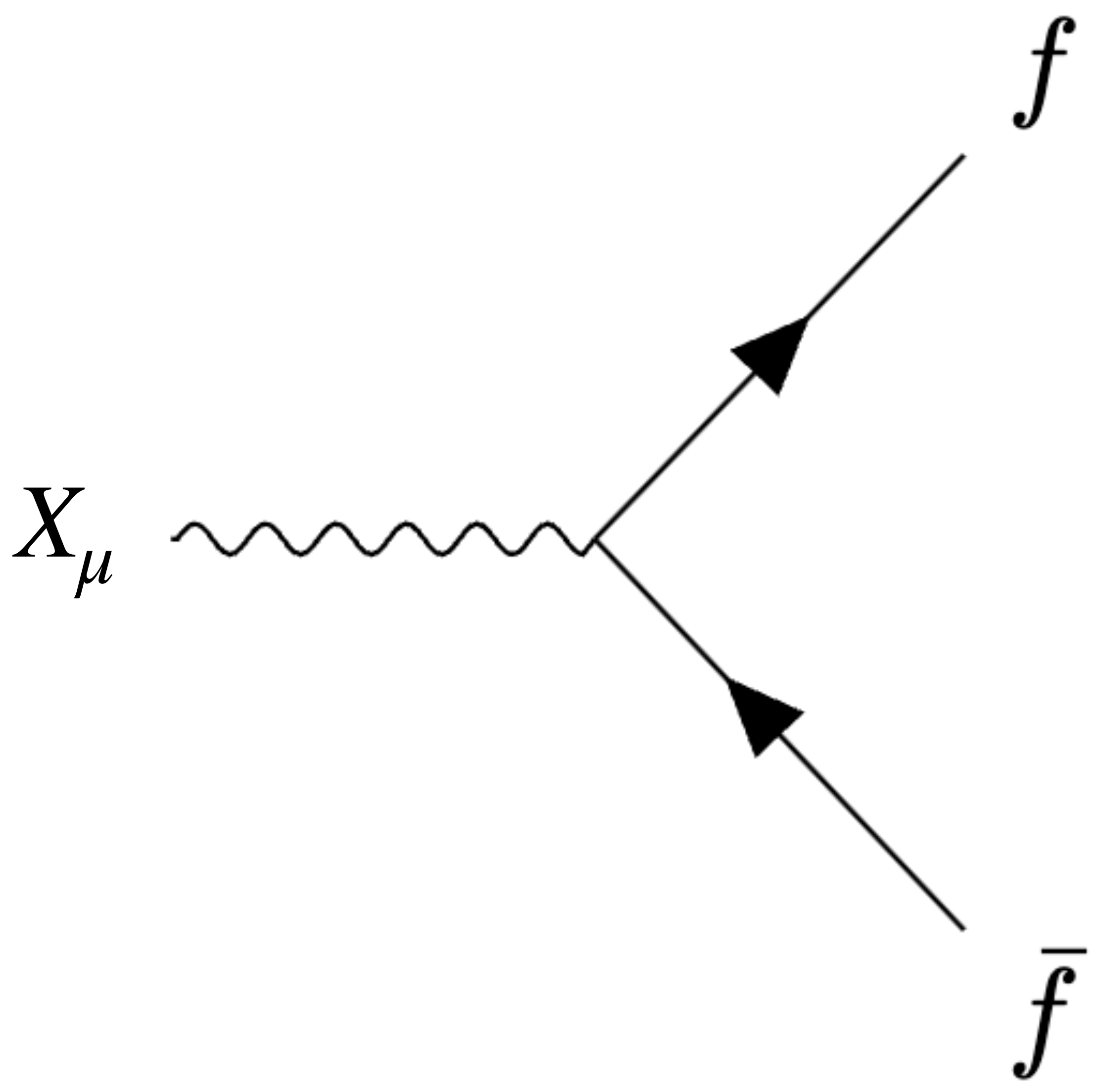
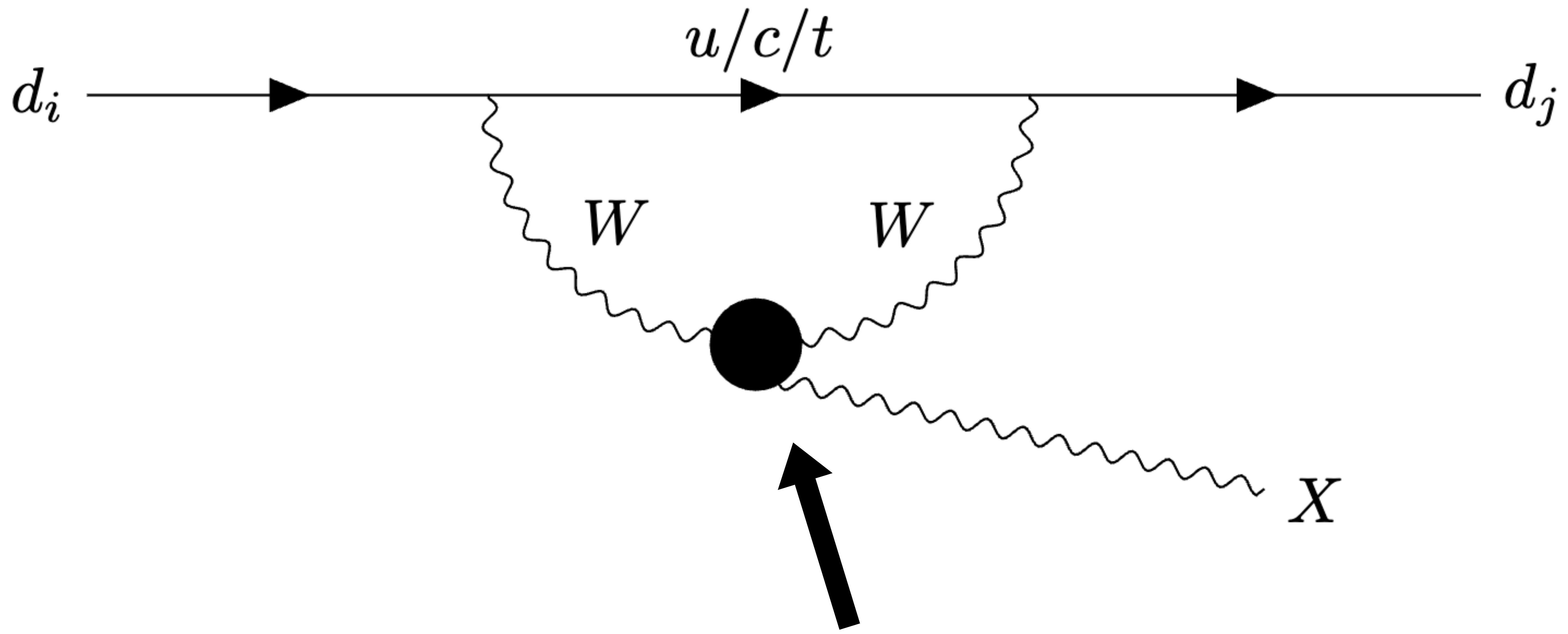


We then can use experimental data from the LEP detectors that search for visible decays to electrons and muons as well as invisible decays

Flavor Changing Neutral Currents



We plug in our effective vertex and obtain the effective Lagrangian for this process:

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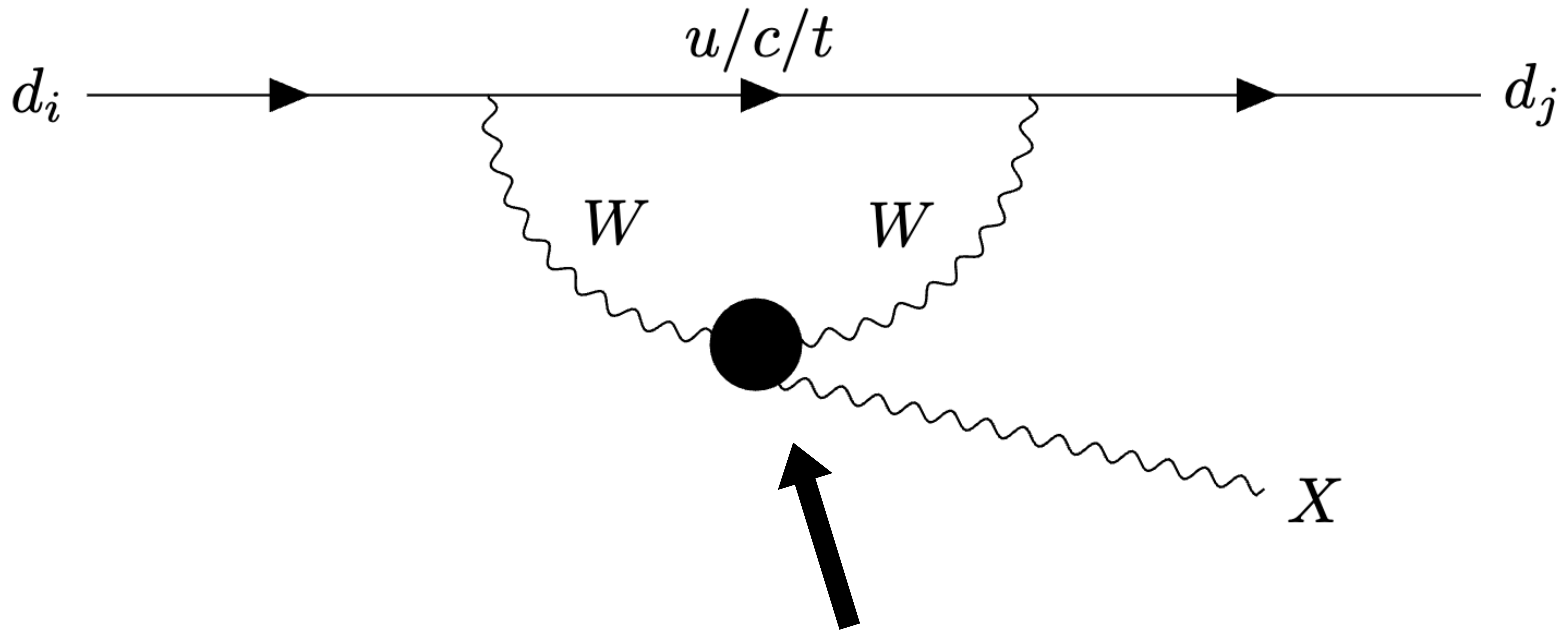

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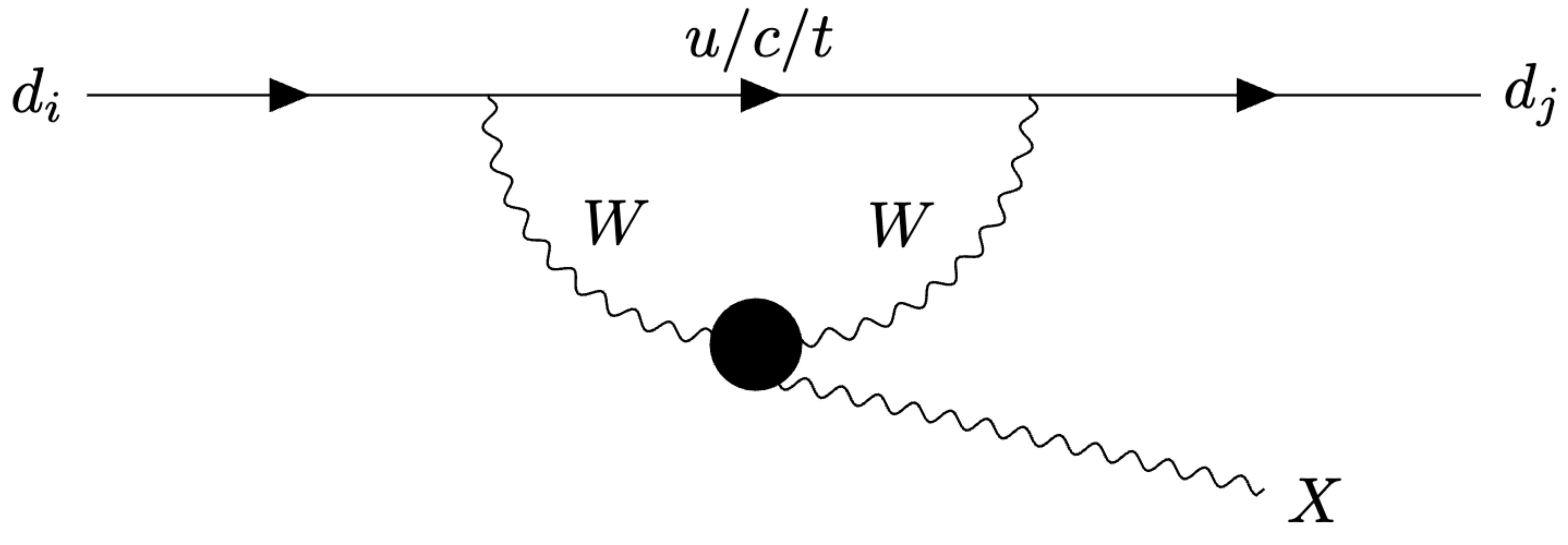
$$\mathscr{L} = g_{Xd_id_j} X_\mu \bar{d}_j \gamma^\mu P_L d_i + h.c.$$

We can then calculate B to K and K to pi decays.
First, to translate this to an amplitude for meson decays we need to calculate the necessary form factors…

Flavor Changing Neutral Currents



The form factors are given in

P. Ball, R. Zwicky arXiv:hep-ph/0406232

P. Ball, R. Zwicky arXiv:hep-ph/0412079

$$B \to K$$

$$\langle P(p)|V_\mu^P|B(p_B)\rangle = \left\{(p + p_B)_\mu - \frac{m_B^2 - m_P^2}{q^2} q_\mu\right\} f_+^P(q^2) + \left\{\frac{m_B^2 - m_P^2}{q^2} q_\mu\right\} f_0^P(q^2),$$

$$B \to K^*$$

$$\begin{aligned} c_V \langle V(p)|\bar{q}\gamma_\mu(1-\gamma_5)b|B(p_B)\rangle &= -ie_\mu^*(m_B + m_V)A_1(q^2) \\ &+ i(p_B + p)_\mu(e^* q)\frac{A_2(q^2)}{m_B + m_V} \\ &+ iq_\mu(e^* q)\frac{2m_V}{q^2}[A_3(q^2) - A_0(q^2)] \\ &+ \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu} p_B^\rho p^\sigma \frac{2V(q^2)}{m_B + m_V}, \end{aligned}$$

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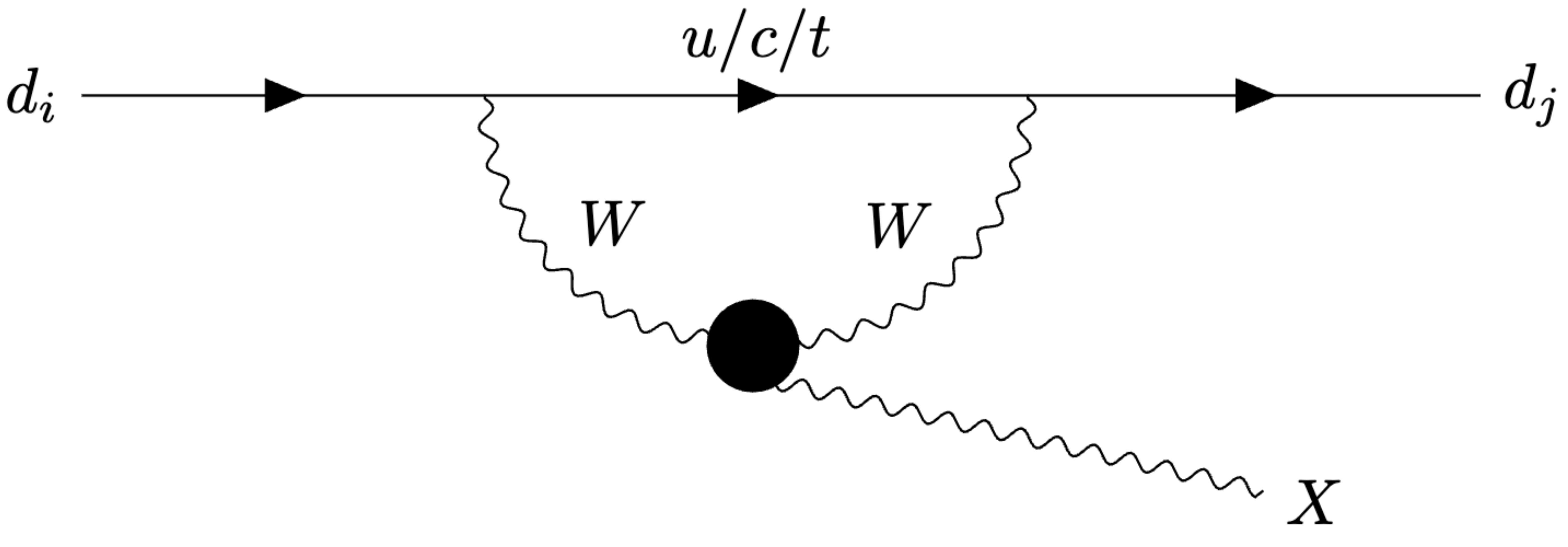

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$$f_+ \sim 0.3$$

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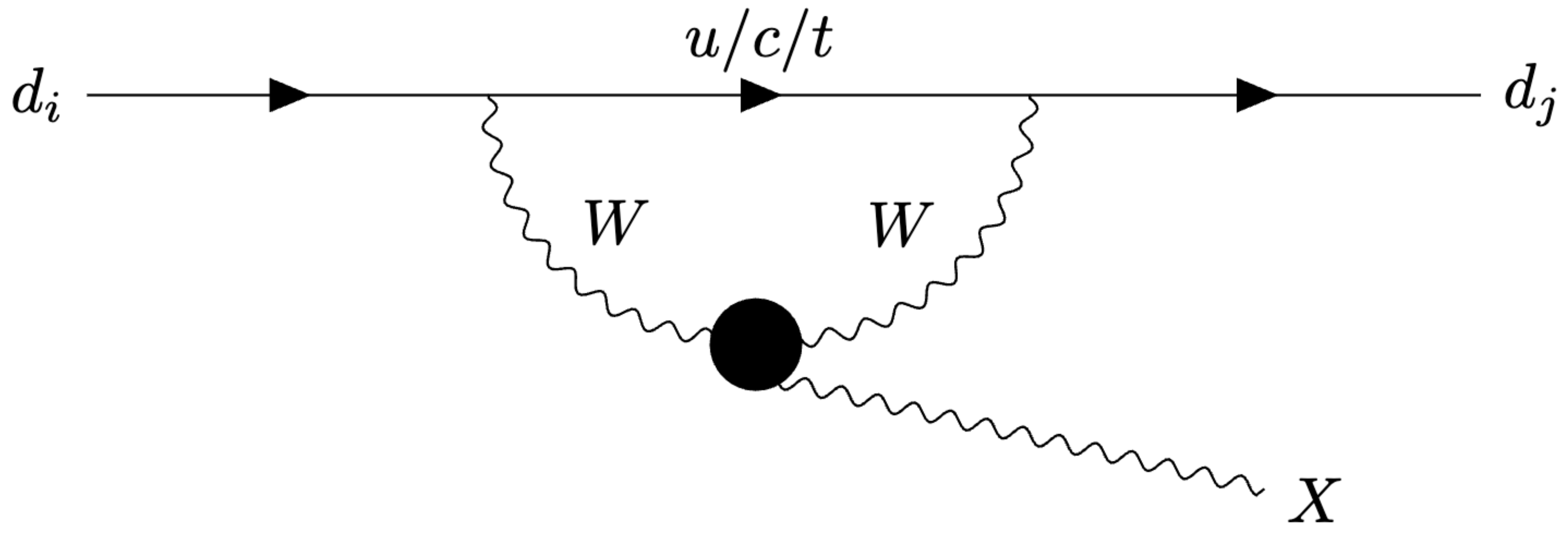
$$\begin{aligned} c_V\langle V(p)|\bar{q}\gamma_\mu(1-\gamma_5)b|B(p_B)\rangle &= -ie_\mu^*(m_B + m_V)A_1(q^2) \\ &+ i(p_B + p)_\mu(e^*q)\frac{A_2(q^2)}{m_B + m_V} \\ &+ iq_\mu(e^*q)\frac{2m_V}{q^2}[A_3(q^2) - A_0(q^2)] \\ &+ \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p_B^\rho p^\sigma \frac{2V(q^2)}{m_B + m_V}, \end{aligned}$$

Flavor Changing Neutral Currents



The form factors are given in

P. Ball, R. Zwicky arXiv:hep-ph/0406232

P. Ball, R. Zwicky arXiv:hep-ph/0412079

$B \to K$

$$\langle P(p)|V_\mu^P|B(p_B)\rangle = \left\{(p+p_B)_\mu - \frac{m_B^2 - m_P^2}{q^2} q_\mu\right\} f_+^P(q^2) + \left\{\frac{m_B^2 - m_P^2}{q^2} q_\mu\right\} f_0^P(q^2),$$

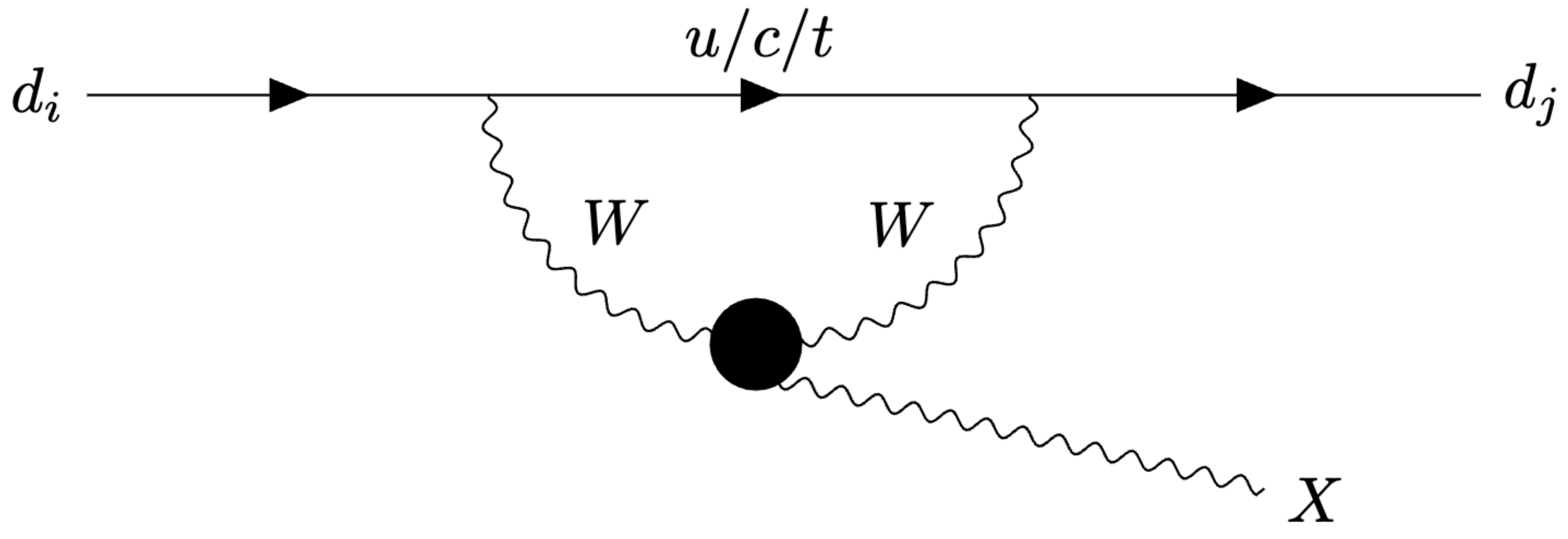
$f_+ \sim 0.3$

$B \to K^*$

$$\begin{aligned} c_V\langle V(p)|\bar{q}\gamma_\mu(1-\gamma_5)b|B(p_B)\rangle &= -ie^*_\mu(m_B+m_V)A_1(q^2) \\ &+ i(p_B+p)_\mu(e^*q)\frac{A_2(q^2)}{m_B+m_V} \\ &+ iq_\mu(e^*q)\frac{2m_V}{q^2}[A_3(q^2)-A_0(q^2)] \\ &+ \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p_B^\rho p^\sigma\frac{2V(q^2)}{m_B+m_V}, \end{aligned}$$

$A_0 = 0.374$

Flavor Changing Neutral Currents



We then have for our decay widths:

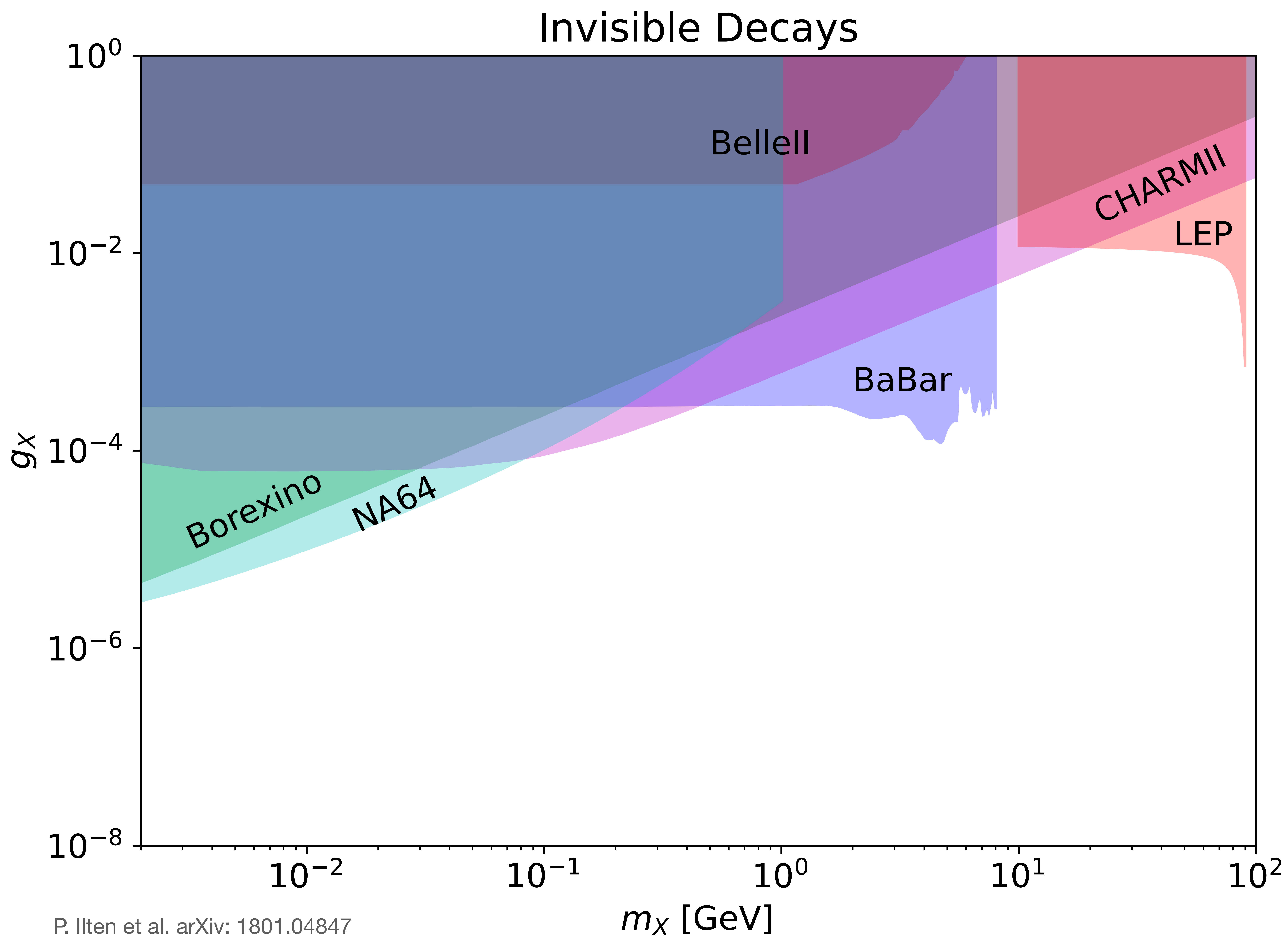
$$\Gamma(B \to KX) \simeq \frac{m_B^3}{64\pi m_X^2} |g_{bsX}|^2 \left(1 - \frac{m_K^2}{m_B^2}\right)^2 |f_K(m_X^2)|^2 \frac{2Q}{m_B}$$

$$\Gamma(B \to K^* X) \simeq \frac{m_B^3}{64\pi m_X^2} |g_{bsX}|^2 |f_{K^*}(m_X^2)|^2 \left(\frac{2Q}{m_B}\right)^3$$

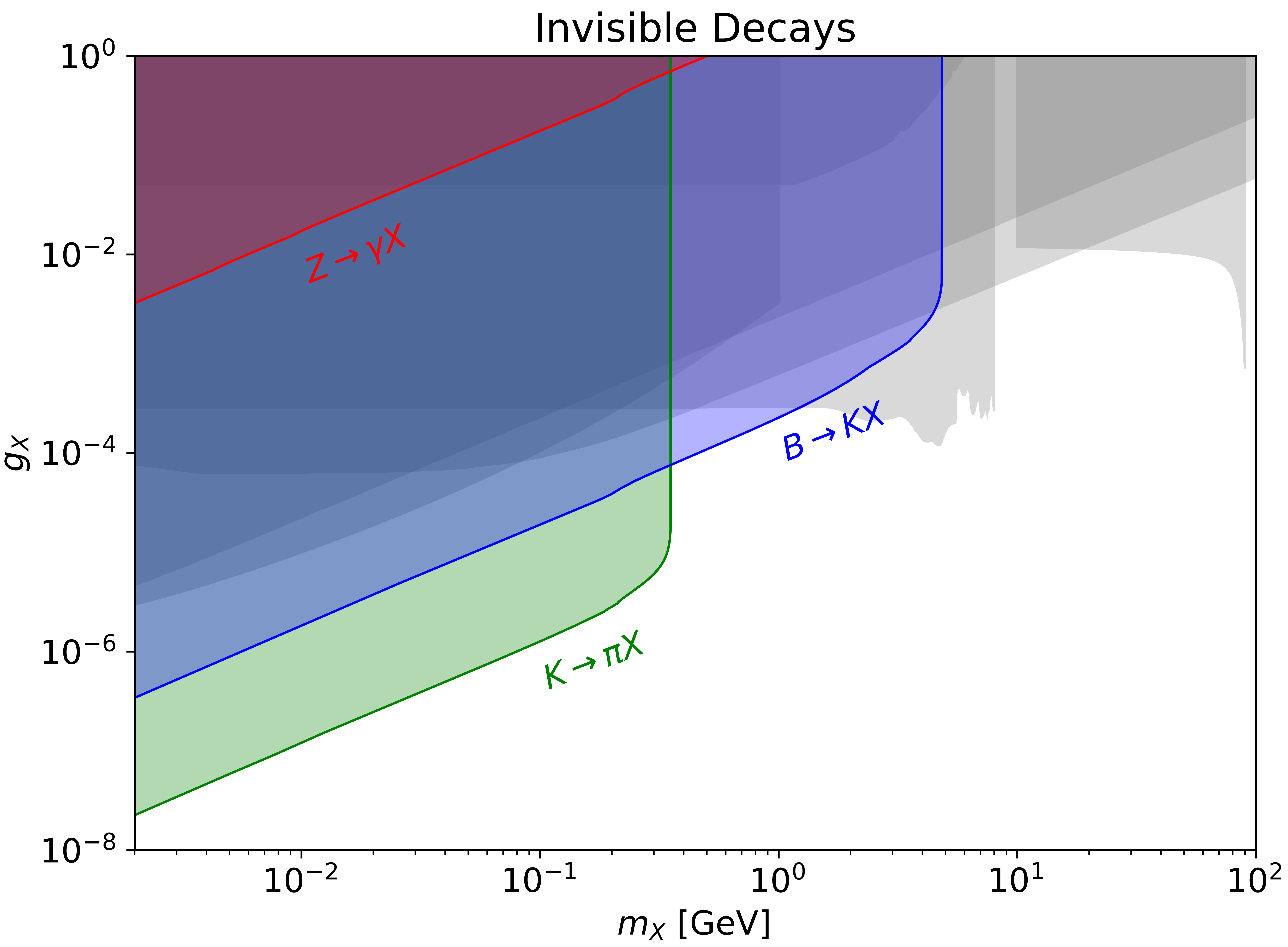
$$\Gamma(K^\pm \to \pi^\pm X) \simeq \frac{m_{K^\pm}^3}{64\pi m_X^2} \left(1 - \frac{m_{\pi^\pm}^2}{m_{K^\pm}^2}\right)^2 |g_{sdX}|^2 \frac{2Q}{m_{K^\pm}}$$

$$\Gamma(K_L \to \pi^0 X) \simeq \frac{m_{K_L}^3}{64\pi m_X^2} \left(1 - \frac{m_{\pi^0}^2}{m_{K_L}^2}\right)^2 \mathrm{Im}(g_{sdX})^2 \frac{2Q}{m_{K_L}}$$

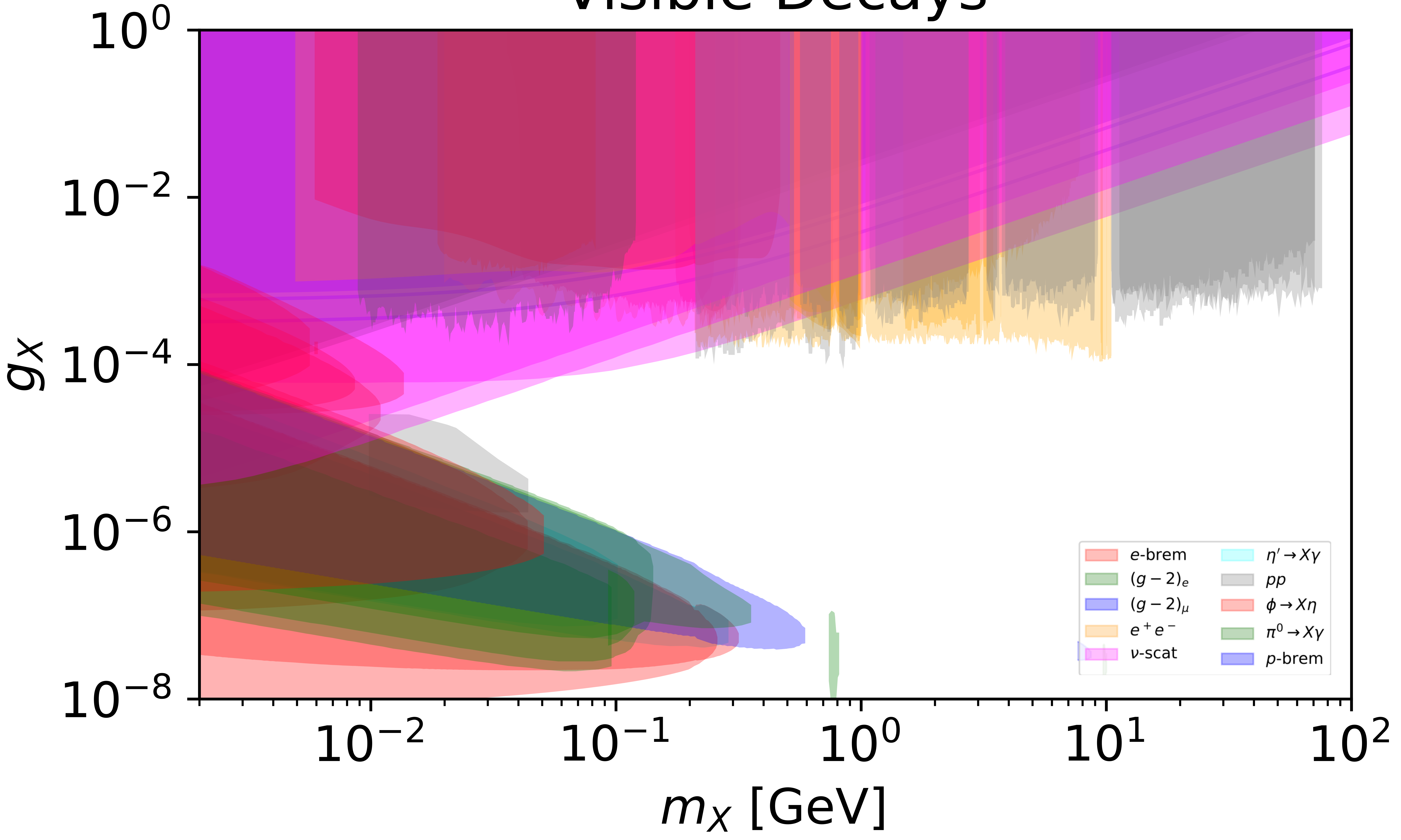
Constraints



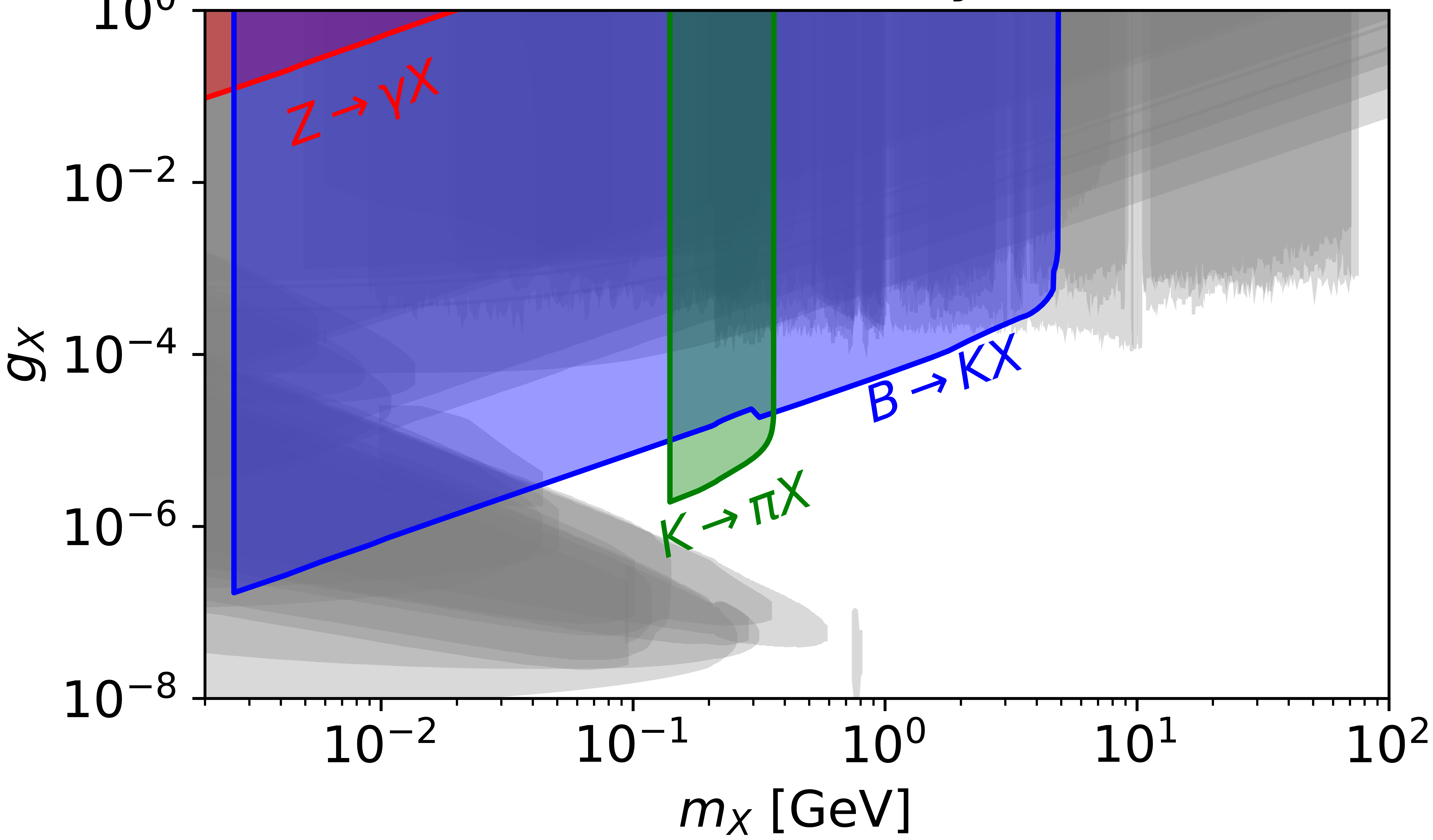
P. Ilten et al. arXiv: 1801.04847


Invisible Decays
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
g_X
$Z \to \gamma X$
$B \to KX$
$K \to \pi X$
10^{-2}
10^{-1}
10^0
10^1
10^2
m_X [GeV]

Visible Decays



Visible Decays



Summary

$U(1)_{B-L}$ is an interesting theory to study

Within particular energy regimes we can obtain non-zero anomalous amplitudes that lead to enhanced processes

These processes can then lead to leading bounds in some regions of parameter space

Note: This phenomena is more general than $U(1)_{B-L}$ and can be applied to say $U(1)_{L_\mu - L_\tau}$

Thank you!