Bounds on Gauge Bosons Coupled to Non-conserved Currents

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Light gauge bosons

- Well-motivated: can function as dark matter or mediators to dark sectors, have cosmological applications

- Scenarios with coupling to non-conserved currents are interesting:

  e.g., Preskill '91, Fayet '06, Barger et al. '11, Karshenboim et al.'14 Dror et al. '17 ...

    - due to anomaly, e.g., $U(1)_B$
    - due to fermion mass, e.g., $U(1)_{L_\mu - L_\tau}$

Toy effective Lagrangian

- Consider chiral couplings of A_X to a single Dirac fermion:

$$\mathcal{L} = -\frac{1}{4}F_X^2 + i\bar{\nu}\left(\partial\!\!\!/ - ig_X A\!\!\!/_X P_L\right)\nu - m_\nu\bar{\nu}\nu + \frac{1}{2}m_X^2 A_X^2$$

- An EFT with the radial mode of the scalar field responsible for m_X integrated out → Stueckelberg limit

- Primary questions:
  - High energy behavior of the above EFT?
  - Parameter space of an EFT with SM+a light $U(1)_{L_\mu - L_\tau}$ boson?

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High Energy Behavior

Toy effective Lagrangian after a chiral rotation

$$\mathcal{L} = -\frac{1}{4}F_X^2 + i\bar{\nu}\left(\not{\partial} - ig_X \not{A}_X P_L\right)\nu - m_\nu \bar{\nu}\nu + \frac{1}{2}m_X^2 A_X^2$$

- We consider scattering at $E \gg m_X$ involving longitudinal polarization $A_X^L \rightarrow$ Goldstone boson equivalence theorem.

- To isolate Goldstone coupling do a chiral transformation: $\nu_L \rightarrow \exp(ig_X\phi/m_X)\nu_L$, mass term not gauge invariant*:

$$V = m_\nu \bar{\nu} e^{ig_X P_L \phi/m_X}\nu = \sum_n \bar{\nu}\frac{m_\nu}{n!}\left(\frac{ig_X P_L \phi}{m_X}\right)^n \nu$$

*for Dirac mass, assume right-handed ν to be uncharged

Bounding the growth in amplitudes

$$V = m_\nu \bar{\nu} e^{i g_X P_L \phi / m_X} \nu = \sum_n \bar{\nu} \frac{m_\nu}{n!} \left(\frac{i g_X P_L \phi}{m_X} \right)^n \nu$$

- Higher-dimensional interactions → expect growth of amplitudes and the theory to break down at high-scale

- Study scattering amplitudes to estimate precisely:

$$S = \mathbf{1} + iT \qquad \langle P', \alpha' \mid T \mid P, \alpha \rangle = (2\pi)^4 \delta^4(P - P') \hat{\mathbf{M}}_{\alpha\alpha'}$$

- Primary requirement: $|\hat{\mathbf{M}}_{\alpha\alpha'}| \leq 1$ for all states α and α' at tree level

e.g., Chang, Luty '19

$\nu + n\phi \to \nu + n\phi$ scattering

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$$|\hat{\mathbf{M}}(\nu + n\,\phi \to \nu + n\,\phi)| = \frac{g_X m_\nu}{2m_X(n+1)!n!(n-1)!}\left(\frac{g_X E}{4\pi m_X}\right)^{2n-1}$$

- Naively grows for increasing n, but for large enough n the $1/n!$ factorial suppression from final states dominates:

$$n_{\text{opt}} \approx (g_X E/4\pi m_X)^{2/3}$$

controlled expansion in n

- Demanding $|\hat{\mathbf{M}}_{\text{opt}}| < 1$

$$E = \Lambda \approx \frac{4\pi m_X}{\sqrt{27}g_X}\log^{3/2}\left(\frac{m_X}{g_X m_\nu}\right)$$

same parametric was obtained first using $\nu\nu \to n\phi$ by Craig et al.,'19

Strong Constraints on SM+$U(1)_{L_\mu - L_\tau}$ Boson EFT

Including flavor

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- $U(1)_{L_\mu - L_\tau}$ model with Dirac* ν mass, assuming right handed ν's are uncharged: $\mathscr{L}^D_{\nu\,\text{mass}} = \nu^c M_d U^\dagger P \nu_F + \text{h.c.}$:

$$\sum_{n,j} \frac{1}{n!} \left(\frac{i g_X \phi}{m_X} \right)^n \nu^c_j M_{d,j} \left(U^\dagger_{j\mu} \nu_\mu + (-1)^n U^\dagger_{j\tau} \nu_\tau \right)$$

$$P = \text{diag}\left(1, e^{+i g_X \phi / m_X}, e^{-i g_X \phi / m_X}\right)$$

- 3-flavor results follow from 1-flavor result via the replacement,

PMNS matrix

$$m^2_\nu \to \sum_{j=1}^{3} \left(|U_{\mu j}|^2 + |U_{\tau j}|^2 \right) m^2_j$$

*constraints for Majorana mass approximately obtained by $g_X \to 2 g_X$

W width

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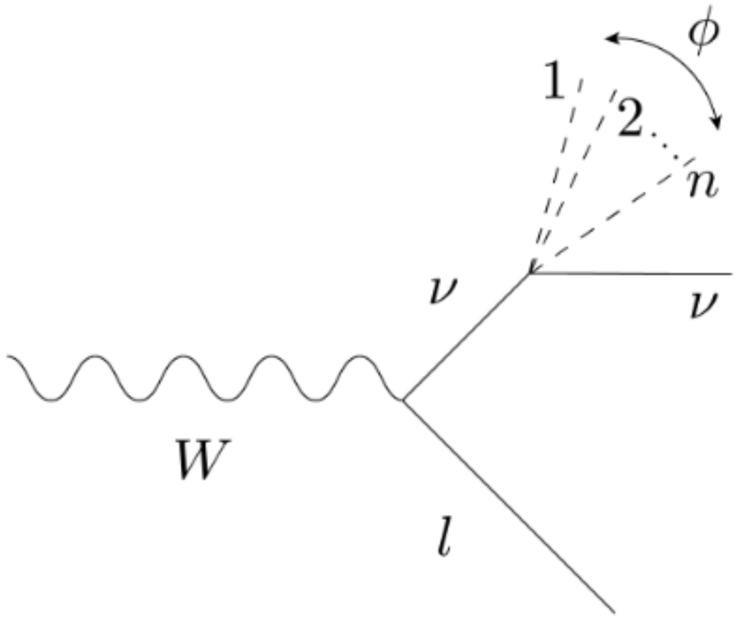
- Emission of many longitudinal gauge modes,

$$\Gamma(W \to l + \nu + n\phi) = \frac{g_2^2 M_W^{2n-1} \kappa_n^2}{(4\pi)^{2n}} \frac{1}{16\pi (n!)^2 (n+2)!(n-1)}$$



$$\Gamma_{\text{BSM}} \equiv \sum_{n>1} \Gamma(W \to l + \nu + n\phi) = \frac{1}{16\pi \times 96} \frac{g_2^2 m_\nu^2}{M_W} \left(\frac{M_W g_X}{4\pi m_X}\right)^4 {}_2F_4\left(\{1,1\}, \{2,3,3,5\}, \left(\frac{M_W g_X}{4\pi m_X}\right)^2\right)$$

- Requiring $\Gamma_{\text{BSM}} < \Gamma_W$ gives

$\frac{1}{x^{20/3}} e^{3x^{2/3}}$ with $x = \frac{M_W g_X}{4\pi m_X}$

$$m_X / g_X > 54 \text{ MeV}$$

Can we do better?

Mono-lepton+MET search

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- A process like $pp \to W^\star \to l\nu$ involves,

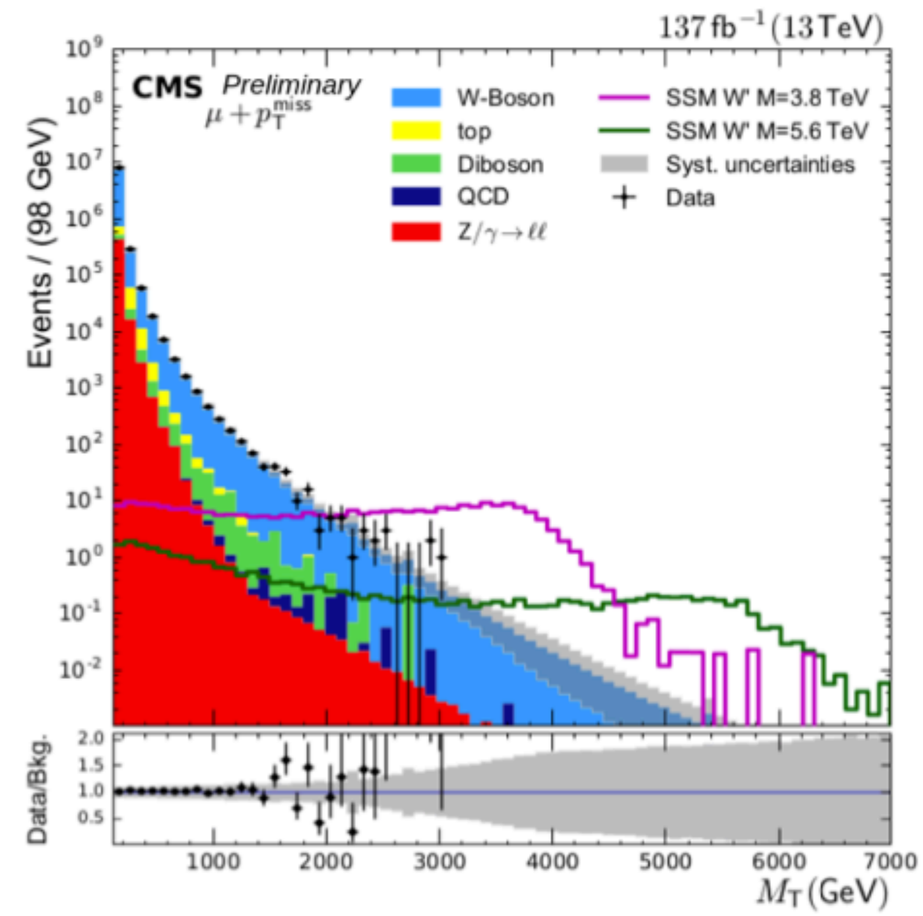
$$\frac{i}{s - M_W^2 + \Sigma(s)}; \qquad \mathrm{Im}(\Sigma(s)) = M_W \Gamma_W(s)$$

- $\mathcal{O}(1)$ modification when $M_W \Gamma_W(s) \sim s$ $\to$ suppression of rates, but no excess up to $\sqrt{s} \geq M_T \simeq 2$ TeV.

- Constraint: $\sqrt{2s} \gtrsim M_W \Gamma_W(s)$ at 2 TeV

$$m_X / g_X > 1.3 \text{ GeV}$$

CMS-PAS-EXO-19-017



Constraints

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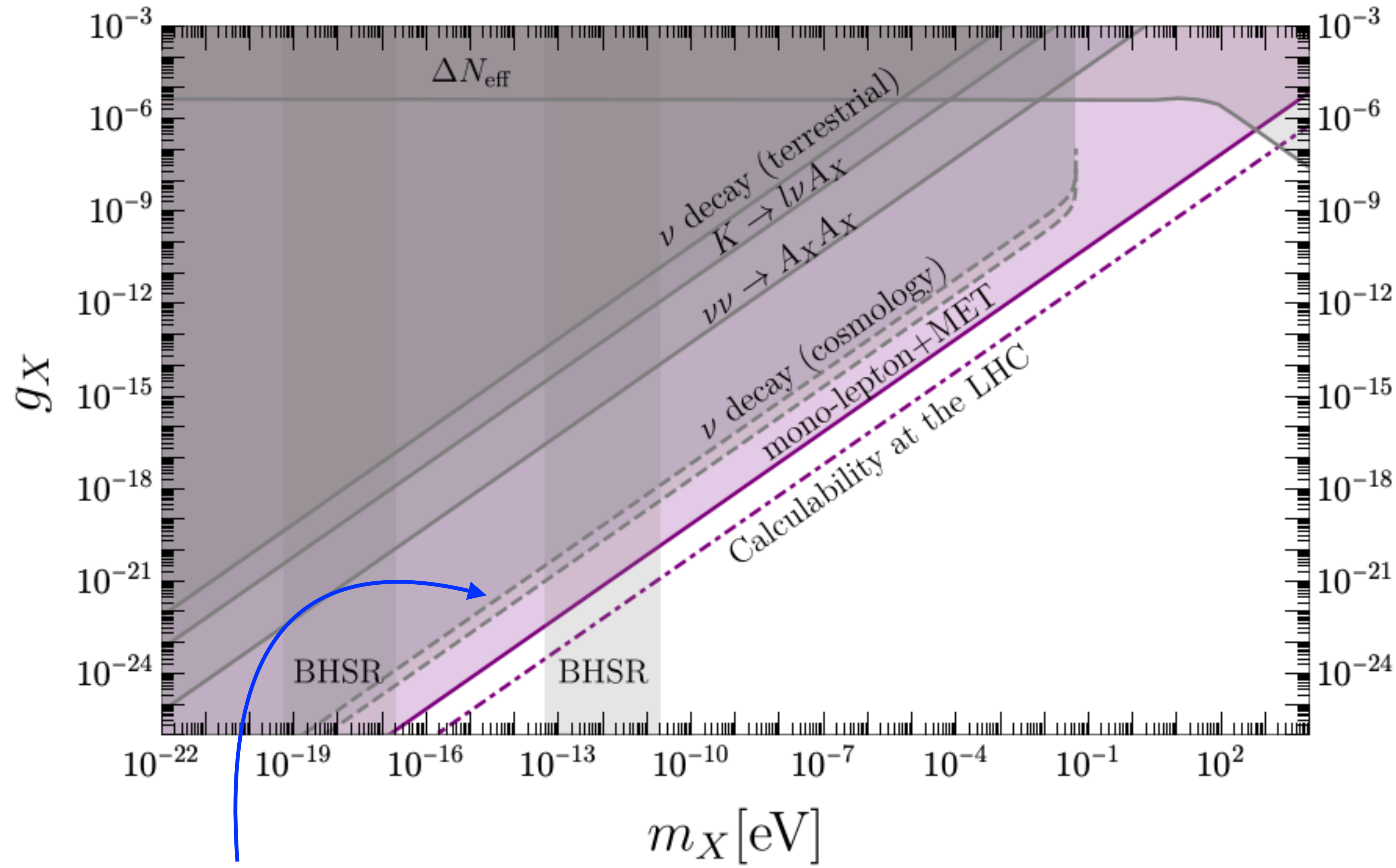


model dependent

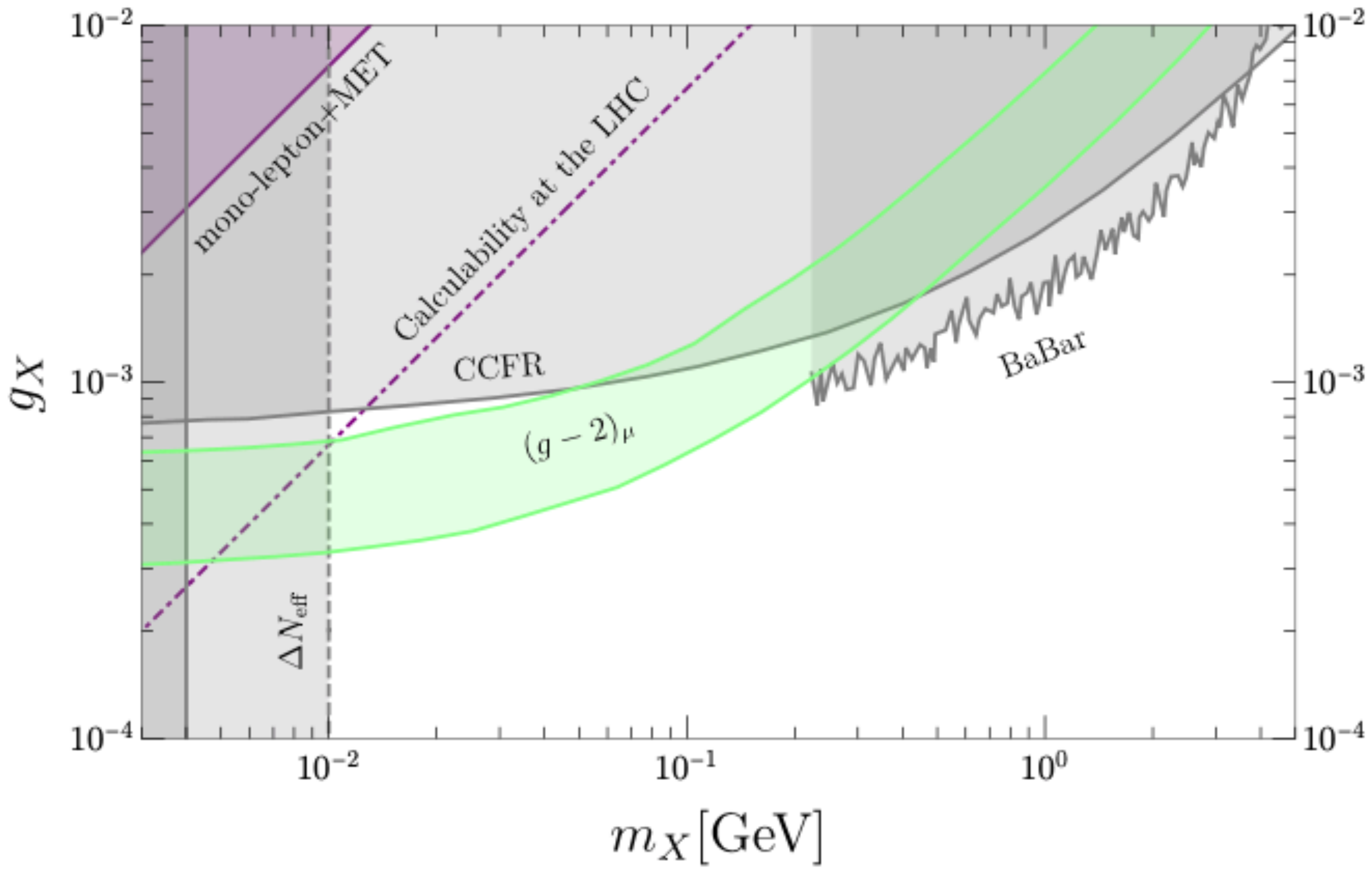
*<u>Compatibility at the LHC</u> from requiring perturbativity at 8 TeV

Conclusions

- Growth of amplitudes in SM+light gauge boson EFT for non-conservation due to mass term.
- Implies a perturbative unitarity bound before which the radial mode must come in.
- Generally applicable: benchmark model $U(1)_{L_\mu - L_\tau}$.
- Mono-lepton+MET LHC search best constraint for most masses below keV.

Thanks for your attention!

High mass constraints



Normalization

- For $\nu + n\phi \to \nu + n\phi$ scattering,

$$| P, n, \alpha\rangle = C_n \int d^4 x e^{-iPx} \phi^{(-)}(x)^n \nu_\alpha^{(-)}(x) \mid 0\rangle$$

$$\langle P', n', \dot{\alpha} \mid P, n, \alpha\rangle = (2\pi)^4 \delta^4(P - P')\delta_{nn'} \frac{\not{P}^{\alpha\dot{\alpha}}}{E}$$

$$\frac{1}{|C_n|^2} = \frac{1}{2(n+1)(n-1)!}\left(\frac{E}{4\pi}\right)^{2n-1}$$

- The full amplitude:

$$\langle P', n, \alpha \mid (-i) \int d^4 x \bar{\nu}(x) \frac{m_\nu}{(2n)!}\left(\frac{i g_X P_L \phi(x)}{m_X}\right)^{2n} \nu(x) \mid P, n, \alpha\rangle = (2\pi)^4 \delta^4(P - P') i\hat{\mathbf{M}}(\nu + n\phi \to \nu + n\phi)$$

UV completion

- How to obtain a separation between m_X/g_X and Λ?

$$V = \frac{y\Phi^q}{\Lambda'^q} H L \nu^c \qquad m_\nu = \frac{y\, v\, f^q}{\Lambda'^q}$$

$$m_\Phi \sim f; \; m_X \sim g_X f/q$$

- Higgs does come in below Λ

$$\Lambda \approx \frac{4\pi m_X}{\sqrt{27} g_X} \log^{3/2}\left(\frac{m_X}{g_X m_\nu}\right) > m_\Phi$$

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