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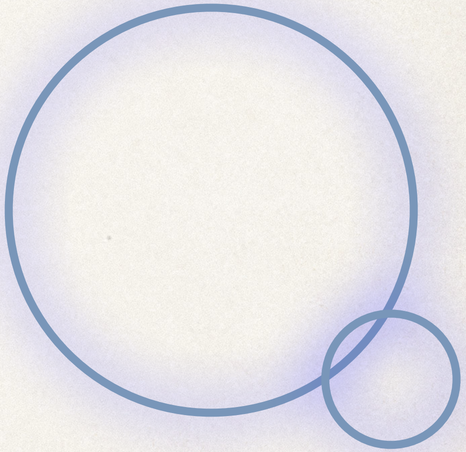
Probing High Scale Physics with Standard Model Parameters



7th FCC Workshop • Annecy, France

David Dunsky, Lawrence Hall, Keisuke Harigaya

01-30-24

arXiv:1902.07726 , 1908.02756 , 2007.12711

The Higgs Quartic

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

- 1967: $\langle H \rangle = v$ Weinberg
- 2012: m, λ ATLAS, CMS

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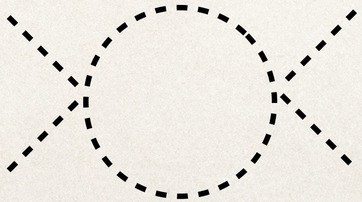
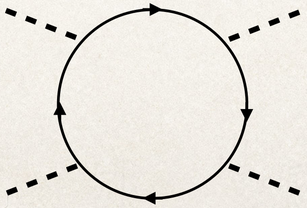
- 1967: $\langle H \rangle = v$ Weinberg
- 2012: m, λ ATLAS, CMS
- Inferred value of λ appears special:



Higgs loop

λ ↑

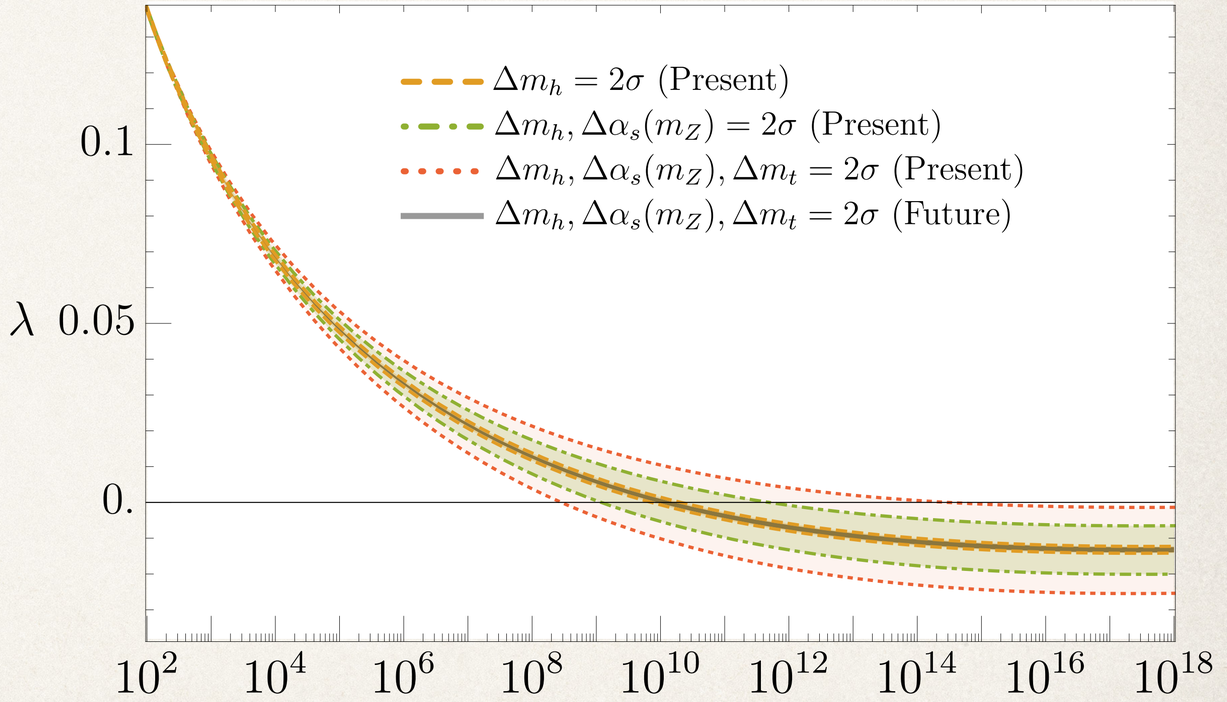


top loop

λ ↓

The Higgs Quartic

- Why is $\lambda \sim .01$ above 10^9 GeV?
- Why does λ cross 0 between $10^9 - 10^{13}$ GeV?
- Vanishing λ hint of new, high scale physics?



Buttazzo et al 2013

Vanishing of Higgs Quartic by a Z_2

- Consider a Z_2

$$SU(2) \leftrightarrow SU(2)'$$
$$\underset{(2,1)}{H} \leftrightarrow \underset{(1,2)}{H'}$$

- Most general potential

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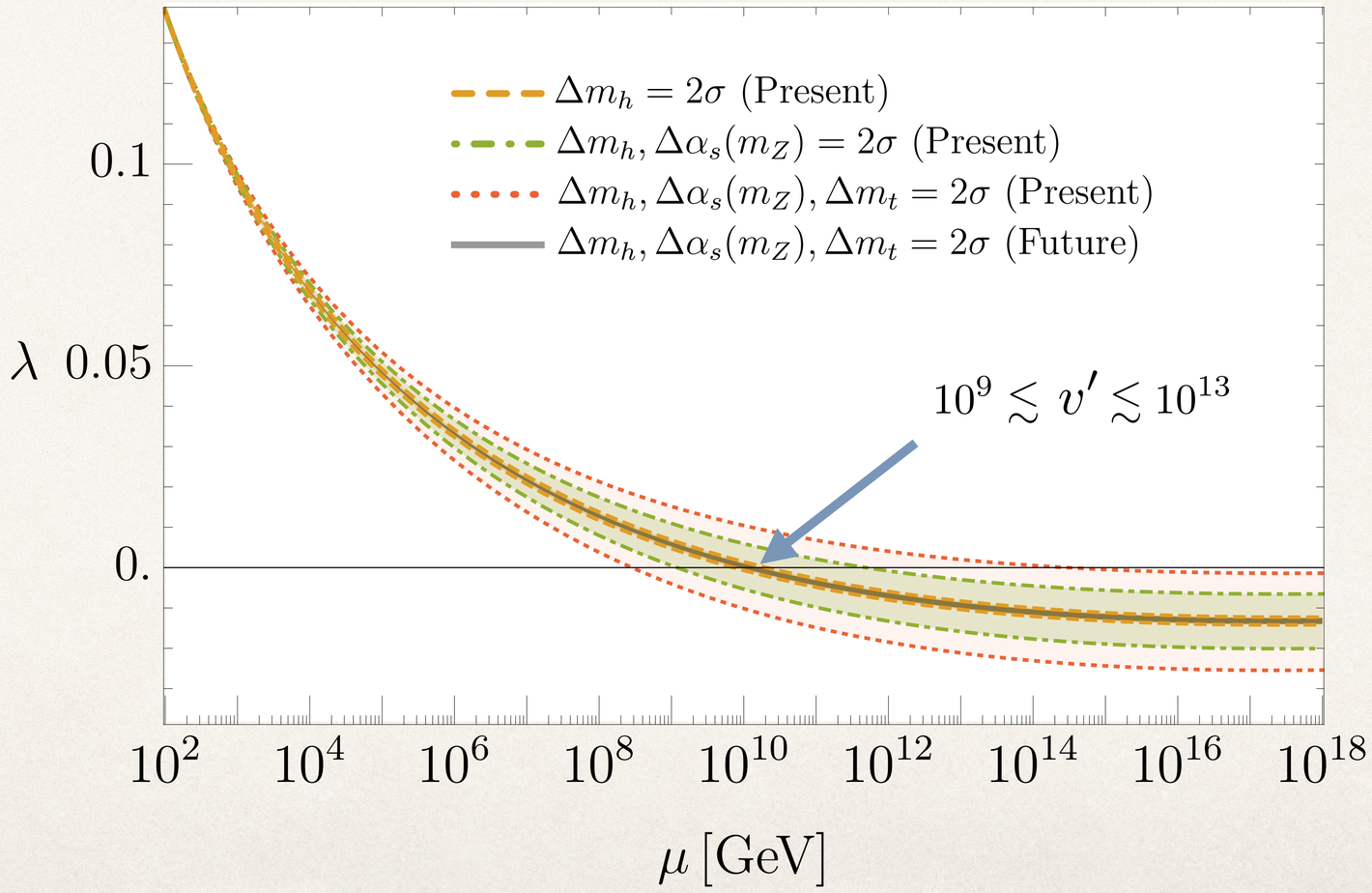
- Requiring $v \ll v'$ $\longrightarrow$ $\lambda' \ll 1$ $\longrightarrow$ $\lambda_{\text{SM}} \approx 0$

Renormalization Running of λ



Fine-Tuning

- Fine-tuning required, but same as Standard Model

$$\frac{v^2}{m^2} \times \frac{m^2}{\Lambda^2} = \frac{v^2}{\Lambda^2}$$

Tuning of λ' Tuning of v'

Importance of Precise SM Parameter Measurements

- Important to measure m_t , m_h , $\alpha_s(m_Z)$ precisely!

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- Important to measure m_t , m_h , $\alpha_s(m_Z)$ precisely!
- FCC will be fantastic at this
- In phenomenological models, the BSM physics depend only (or mostly) on v'
  - No new free parameters for most new observables!
  - FCC will provide precise predictions

Models of Higgs Parity

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    2007.12711
- Focus on first one for this talk, will mention interesting signals of others

The Mirror Electroweak Sector

- Extend Z_2 to mirror electroweak sector
- Identify Z_2 with spacetime parity

$$SU(2) \times U(1) \leftrightarrow SU(2)' \times U(1)'$$
$$\vec{x} \leftrightarrow -\vec{x}$$
$$q, \bar{u}, \bar{d}, l, \bar{e} \leftrightarrow (q', \bar{u}', \bar{d}', l', \bar{e}')^\dagger$$
$$H \leftrightarrow H'$$

- Implications?

Solves Strong CP Problem

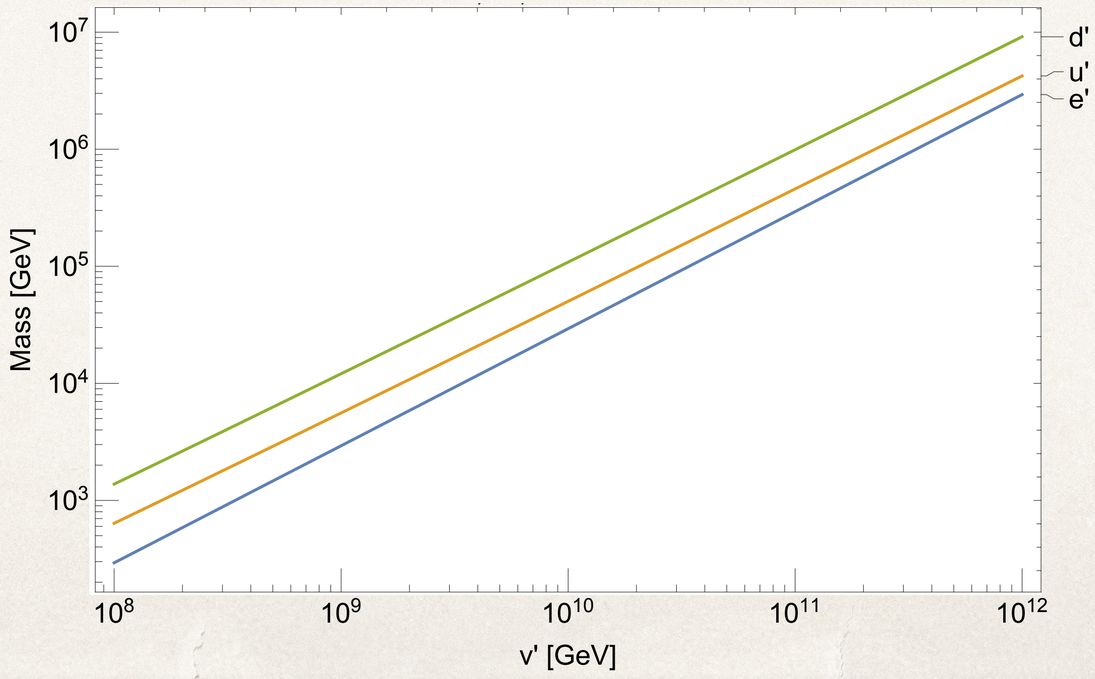
- $SU(3) \times (SU(2) \times U(1)) \times (SU(2)' \times U(1)')$ solves strong CP problem

  Babu, Chang, Senjanovic (1991)

- Parity *is* a symmetry
  - $\dfrac{\theta}{32\pi^2} G\tilde{G}$ forbidden
- No $\bar{\theta}$ contribution from Yukawa sectors
- $$\arg\det \begin{pmatrix} y_{u,d}\ v & 0 \\ 0 & y^*_{u,d}\ v' \end{pmatrix} = 0$$

Mirror Dark Matter

- Natural DM candidate lightest $U(1)'_{\mathrm{EM}}$ particle, e'
- DM mass $m_{e'} = y_{e'} v' = m_e \dfrac{v'}{v}$ (1-10^4TeV)



Signals: Neutron EDM

- Higher dimensional operators generate

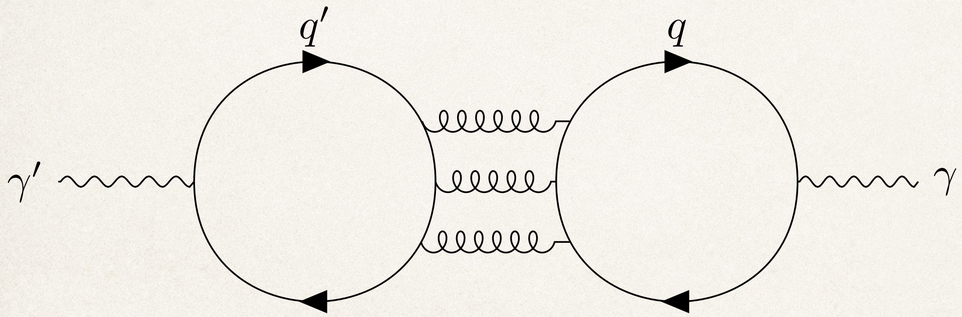
$$\mathcal{L}_6 = \frac{C}{M_{Pl}^2}\left(|H|^2 - |H'|^2\right) G\tilde{G}$$

$$\theta = 32\pi^2 C \left(\frac{v'}{M_{Pl}}\right)^2 = 5\times 10^{-11} C \left(\frac{v'}{10^{12}\ \mathrm{GeV}}\right)^2$$

- Current neutron EDM limit $\theta < 10^{-10}$ Baker, et al (2006)

Signals: Kinetic Mixing

- $\mathcal{L} \supset -\frac{\epsilon_B}{2} B^{\mu\nu} B'_{\mu\nu}$ allowed
- Generated by



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(Calculable from 4-loop QCD beta function)

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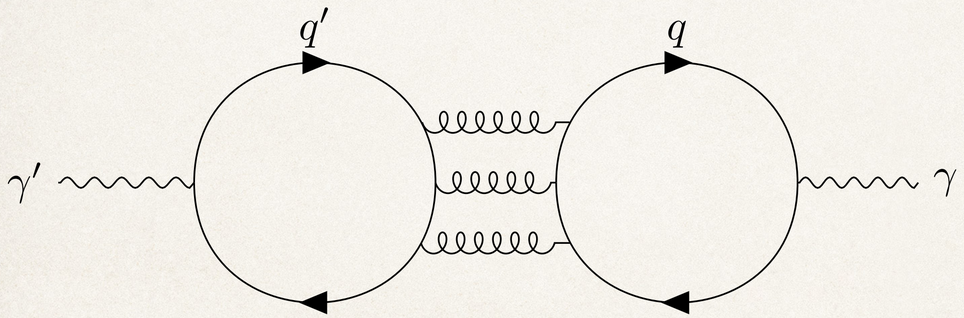

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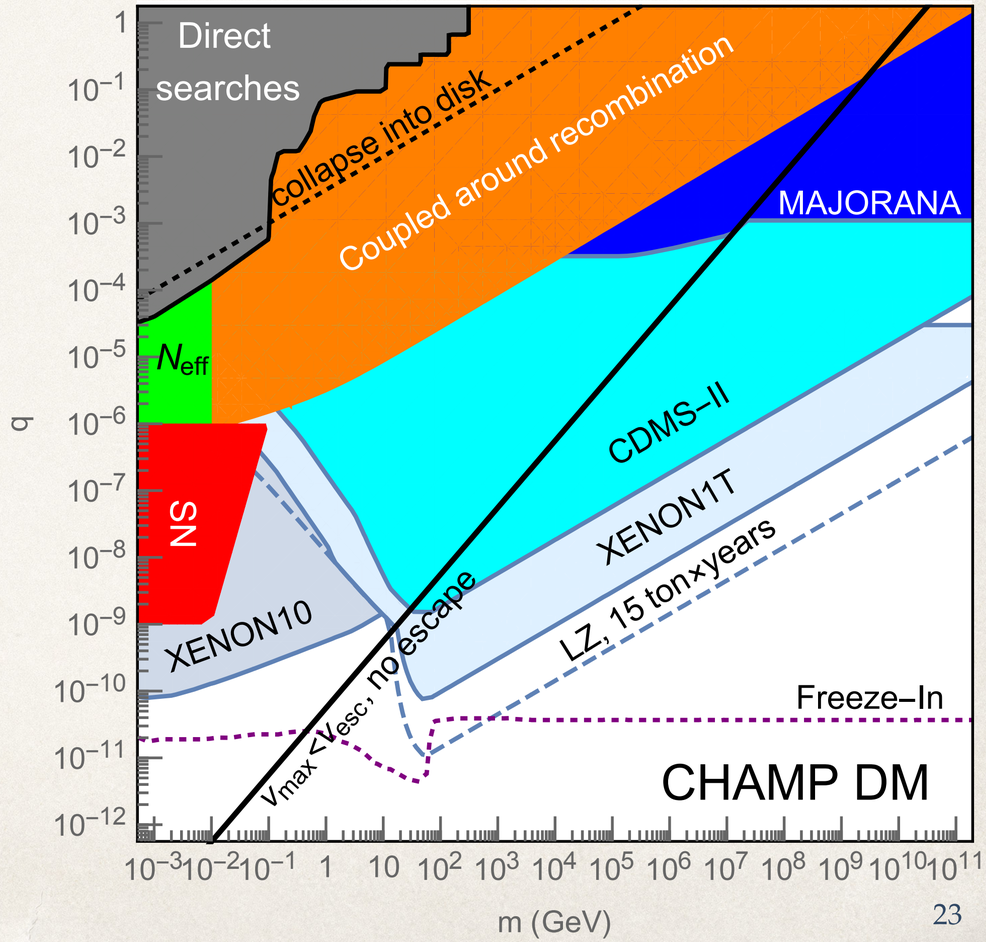
Dunsky, Hall, Harigaya (2018) arXiv:1812.11116



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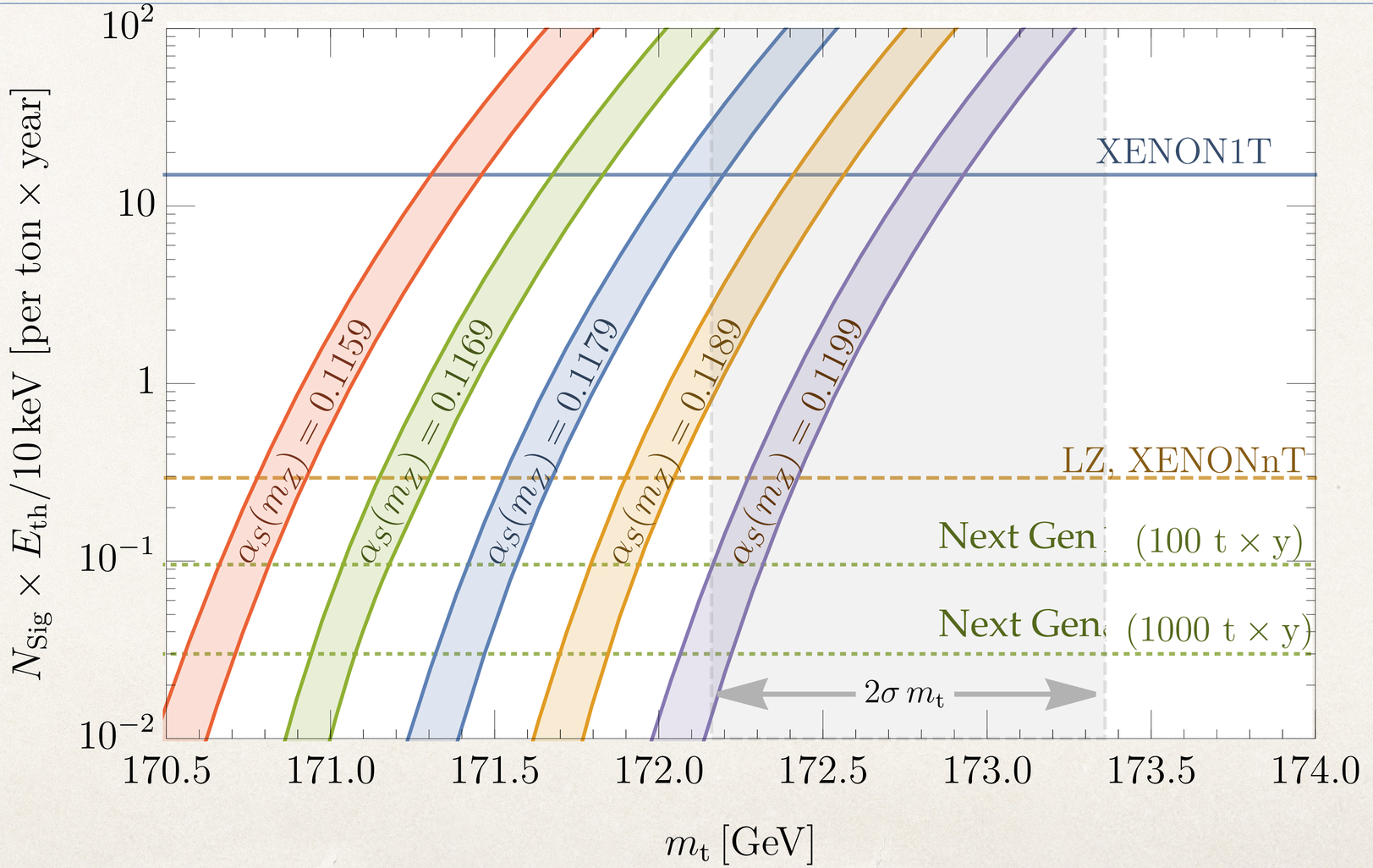
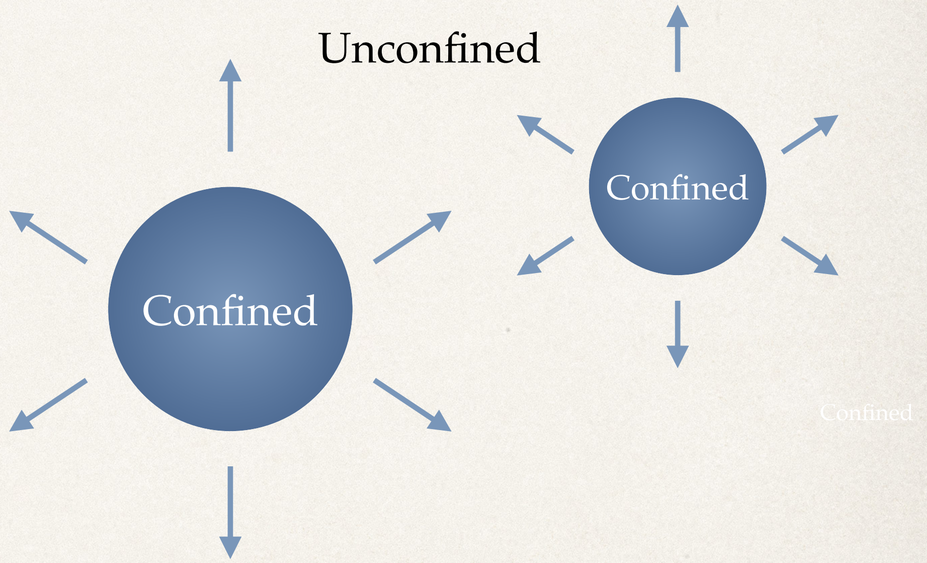


Other Higgs Parity Models: $G_{\mathrm{SM}} \times G_{\mathrm{SM}'}$

- Unlike Standard Model, mirror quark masses > $\Lambda_{\mathrm{QCD}'}$

- QCD′ phase transition is 1st order

  Yaffe & Svetitsky 1982 & 1983



- Gives rise to expanding bubbles

- Gravitational Waves from bubble collisions and interactions with plasma. Signal depends on v'

Witten 1982

Other Higgs Parity Models: $SU(2)_L \times SU(2)_R$

- Necessarily predicts right-handed neutrinos $\begin{pmatrix}\nu\\ e\end{pmatrix}_L \leftrightarrow \begin{pmatrix}N\\ e\end{pmatrix}_R$
- N SM gauge singlets. If long-lived, N_1 can be dark matter
- *Three* Weinberg operators $-\mathcal{L}_{\rm LR} \supset f_{ij}\frac{1}{\Lambda}(\ell_i\,\bar{\ell}_j)\,H_L H_R + f'_{ij}\frac{1}{\Lambda}(\ell_i\,\ell_j)\,H_L^2 + f'^{(*)}_{ij}\frac{1}{\Lambda}(\bar{\ell}_i\,\bar{\ell}_j)\,H_R^2 + \text{h.c.}$

$$\downarrow$$

$$M_N \simeq m_\nu (v_R/v)^2$$

- Interesting phenomenology. N_1 DM mass and $N_{2,3}$ leptogenesis depend on v_R

Summary

- Observed Higgs mass imply next symmetry breaking scale of nature?
- Motivated by Strong CP ⟶ Higgs Parity, no QCD'
- Motivated by DM ⟶ mirror electroweak (also Left-Right)
- Same number of parameters as SM below v'
- Future measurements of m_t , m_h , $\alpha_s(m_Z)$ by FCC will hone in on v'
- Entire parameter space will be probed/corroborated by future detectors