# COLLIDER SEARCHES FOR SCALAR SINGLETS ACROSS LIFETIMES

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# CURRENT INTERESTS

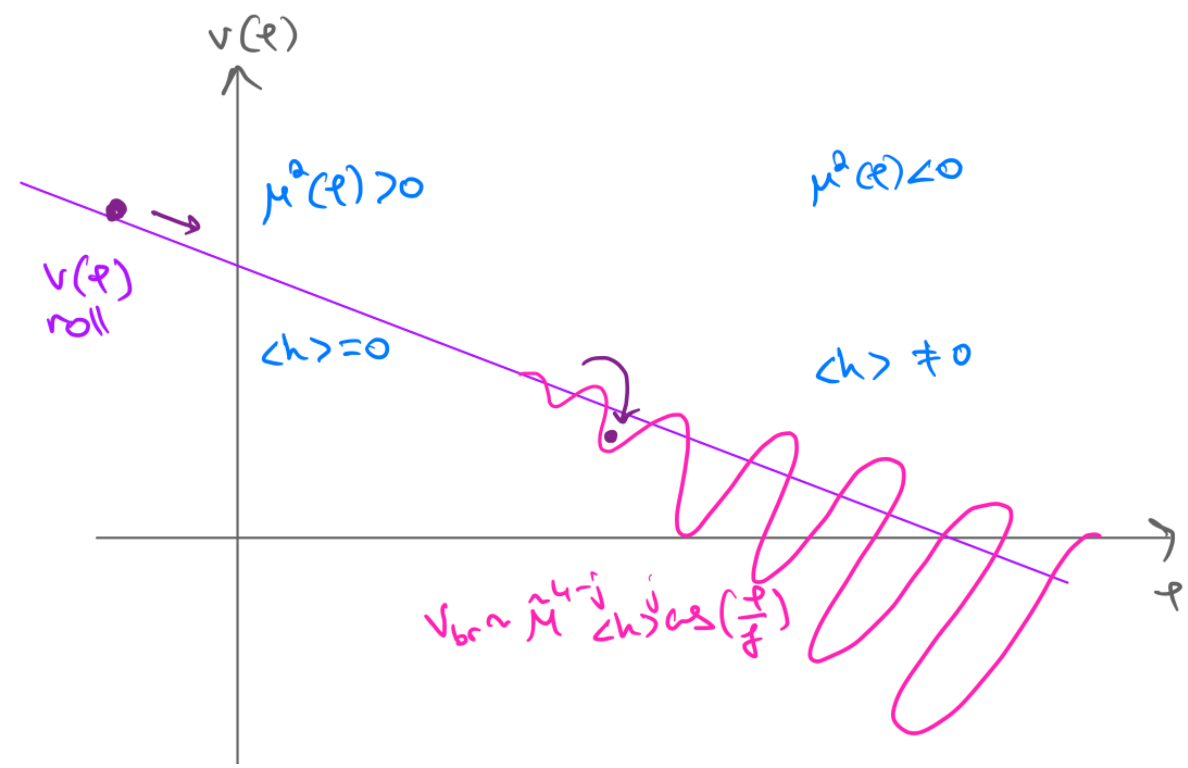
- Ultralight DM precision tests with table top experiments
- CP-violation effects in photon self-interactions
  - LUXE
  - Cavities
- Long-lived particles at colliders

# SCALAR SINGLET EXTENSION

- **SM+ real singlet**

$$V_s(\Phi, H) = V(\Phi) + \mu^2(\Phi)H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

- **Higgs Portal** - mediator to a dark sector.
- Can be a **dark matter** candidate.
- **Relaxion** - dynamically set the Higgs VEV




W. Graham at el, 1504.07551

# SINGLET-HIGGS INTERACTIONS

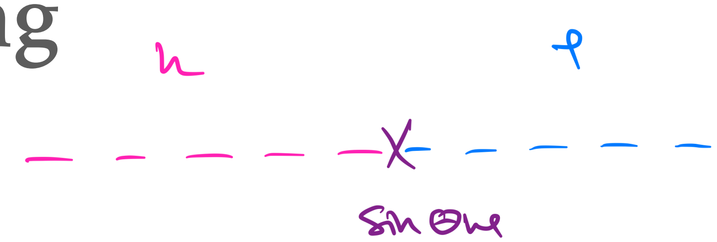
- **Minimal renormalizable extension**

$$V_s(\Phi, H) = V(\Phi) + \mu^2(\Phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

$$t\Phi + \frac{1}{2} m_0^2 \Phi^2 + \frac{a_\phi}{3}\Phi^3 + \frac{\lambda_\phi}{4}\Phi^4 \qquad -\mu_0^2 H^\dagger H + 2a_{h\phi}\Phi H^\dagger H + \hat{\lambda}_{h\phi}\Phi^2 H^\dagger H$$

- Phenomenologically relevant parameters
  - **Higgs - Singlet mixing**

$$\sin\theta \approx \frac{a_{h\phi}}{v\lambda_h}$$




The scalar inherits the Higgs coupling to the SM, suppressed by $\sin\theta$

  - **Higgs - Singlet pair vertex**

$$c_{h\phi\phi} \approx \sin^2\theta v\lambda_h + \underbrace{\hat{\lambda}_{h\phi} v + a_\phi \sin\theta}_{\lambda_{h\phi}}$$

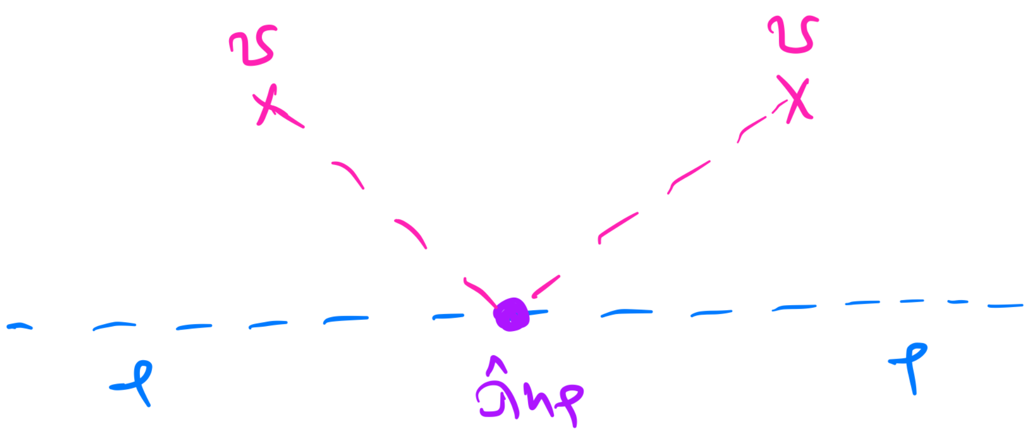

Exotic decay channel for the Higgs (if $m_h \geq 2m_\phi$ )

B. Heinemann and Y. Nir [1905.00382]

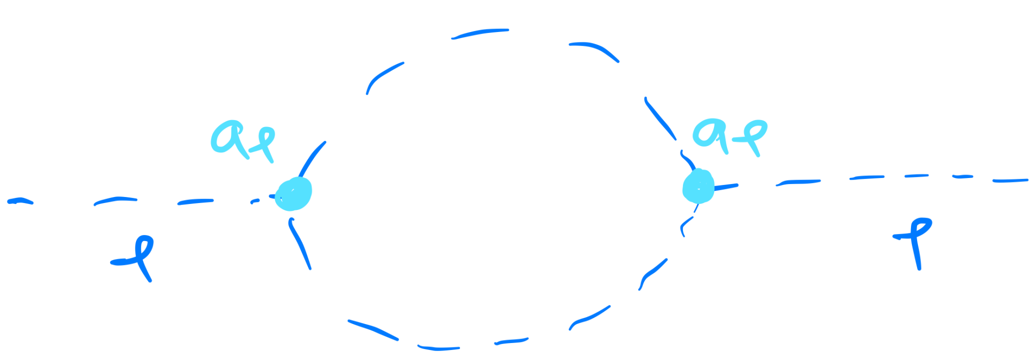
# NATURAL SCALAR SINGLET EXTENSION

➤ Additive corrections to the scalar's mass set the minimal mass (no tuning)

$$\sin\theta \lesssim \frac{m_\phi}{m_h}$$



$$\hat{\lambda}_{h\phi} \lesssim \frac{m_\phi^2}{v^2}$$



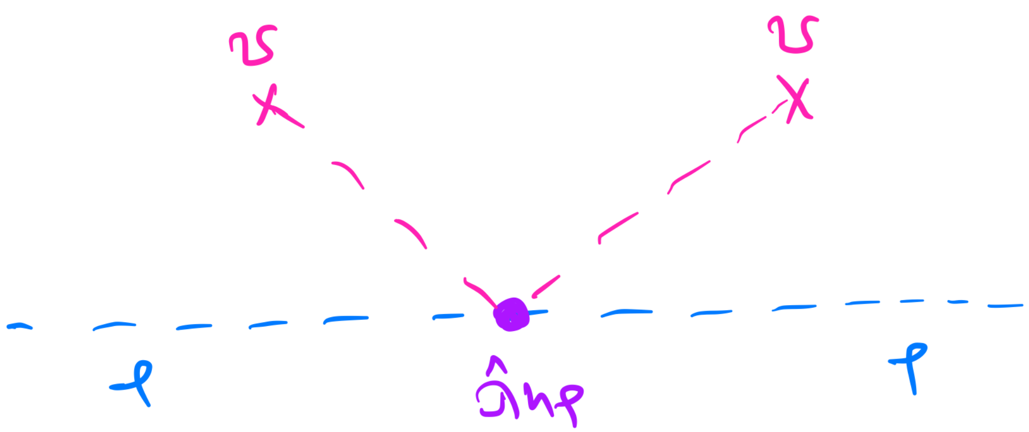
$$a_\phi \lesssim 4\pi m_\phi$$

# NATURAL SCALAR SINGLET EXTENSION

- Additive corrections to the scalar's mass set the minimal mass (no tuning)

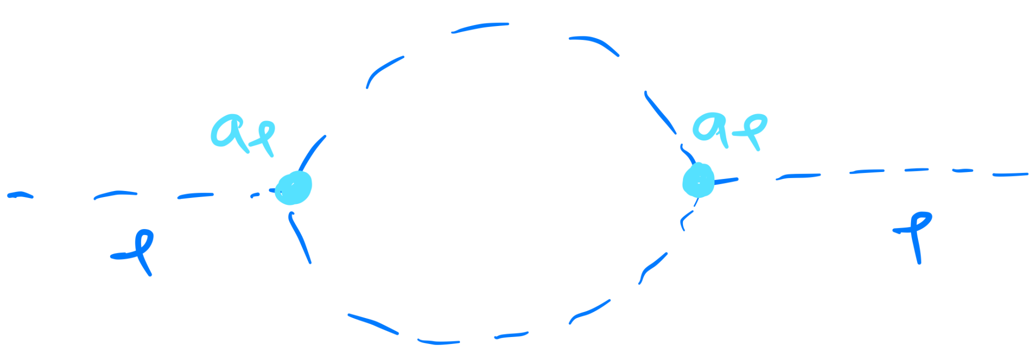
$$\sin\theta \lesssim \frac{m_\phi}{m_h}$$

*Relaxion - can be violated due to dynamics (Abhishek's talk)*



$$\hat{\lambda}_{h\phi} \lesssim \frac{m_\phi^2}{v^2}$$

*Relaxion - is not a free parameter, automatically saturated*

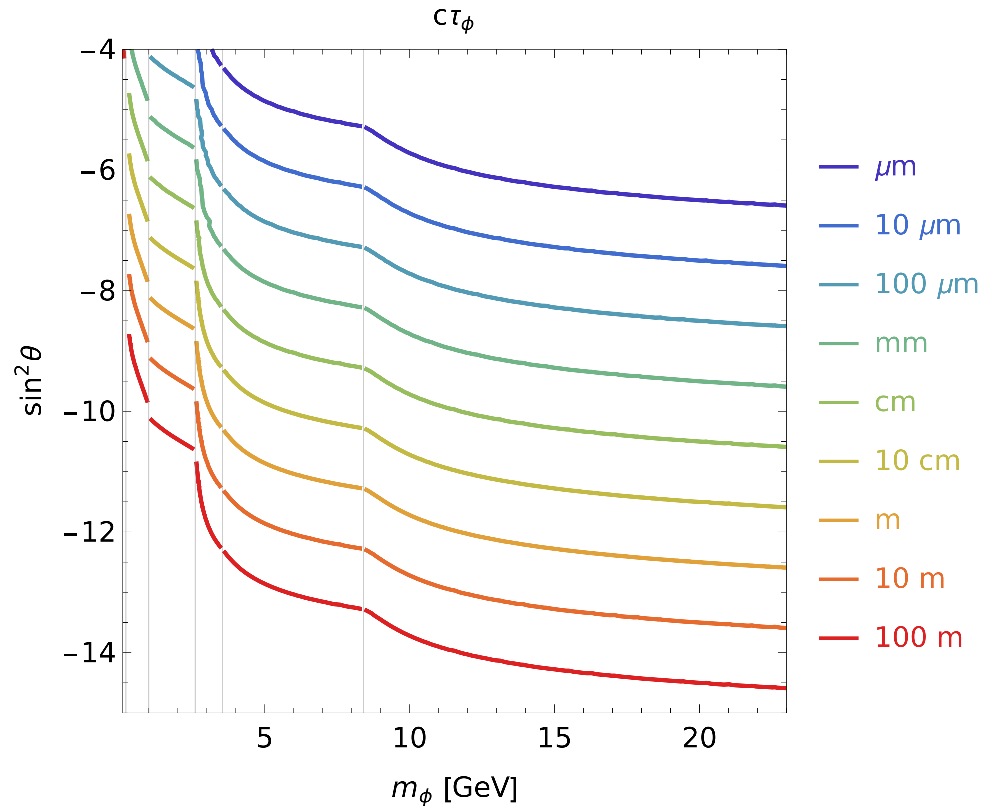


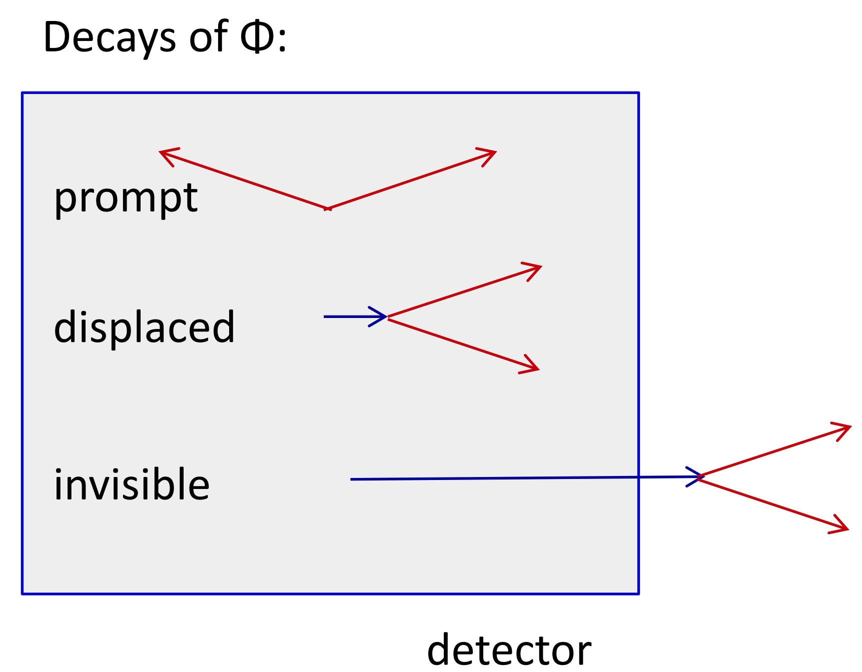
$$a_\phi \lesssim 4\pi m_\phi$$

*Relaxion - no triple coupling*

# COLLIDER SEARCHES ACROSS LIFETIMES

- **Wide range of scalar lifetimes - controlled by mass and mixing**




- **Goal: study these searches at all lifetimes**
  - Obtain constraints in terms of model parameters
  - Compare different search strategies - complementarity
  - Estimate potential to probe Natural parameter space

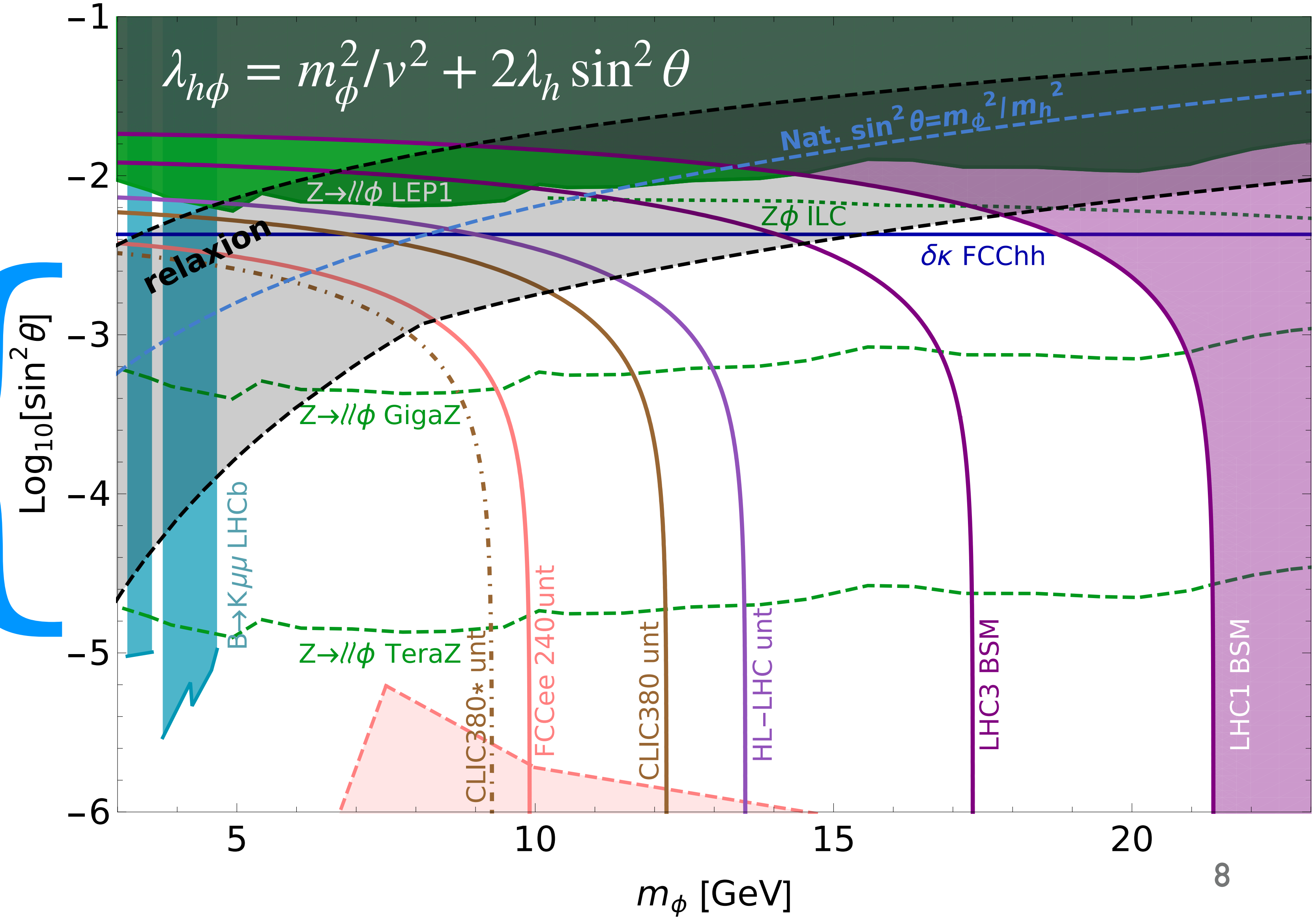
# PROMPT - DIRECT AND UNTAGGED

- Indirect - Depletion of Higgs decays to SM particles (untagged)

$$\mu_{if} = \frac{\sigma_{i\to h}}{\sigma_{i\to h}^{SM}} \frac{BR_{h\to f}}{BR_{h\to f}^{SM}} = \approx \cos^2\theta \, BR_{h\to f}^{SM}\left(1 - BR_h^{NP}\right)$$

- Direct - Rare Z decays

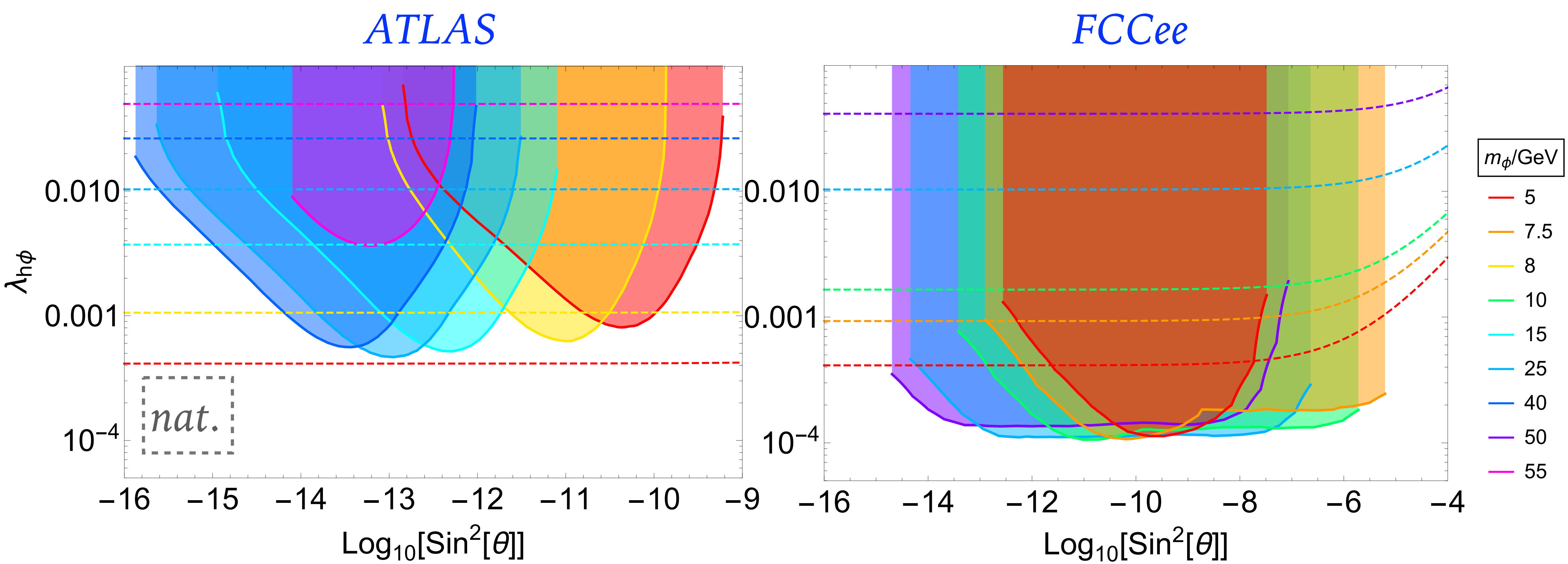
Natural relaxion can only live




TeraZ will be able to exclude the heavy relaxion!

# DISPLACED

- Direct searches for Higgs decays into **displaced jets**.
- Longer lifetime - **production almost mixing independent**.
- Reinterpret results for displaced Higgs vertices in terms of model parameters.



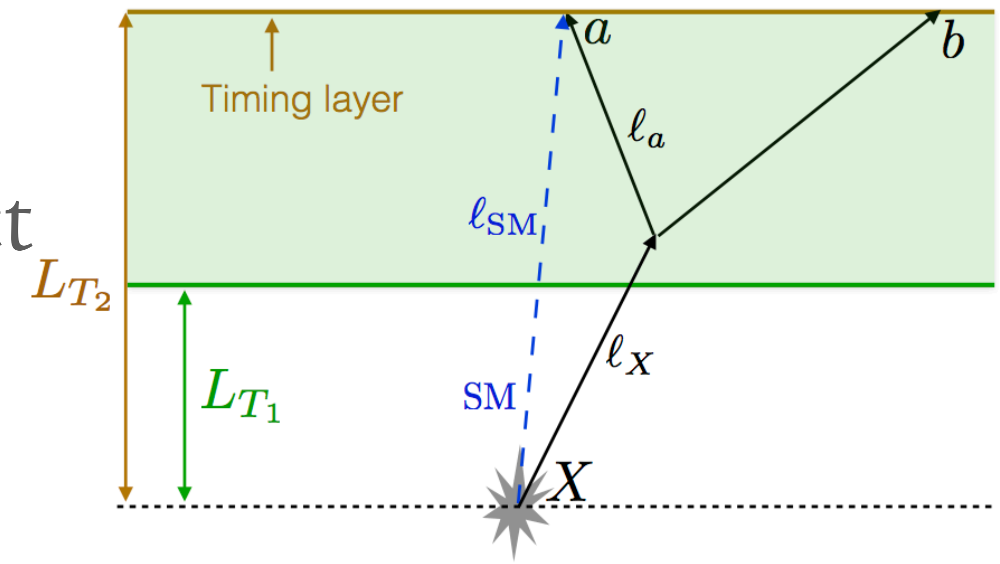

ATLAS, [1811.07370, 1902.03094, 1911.12575]

S. Alipour-Fard et al, [1812.05588]

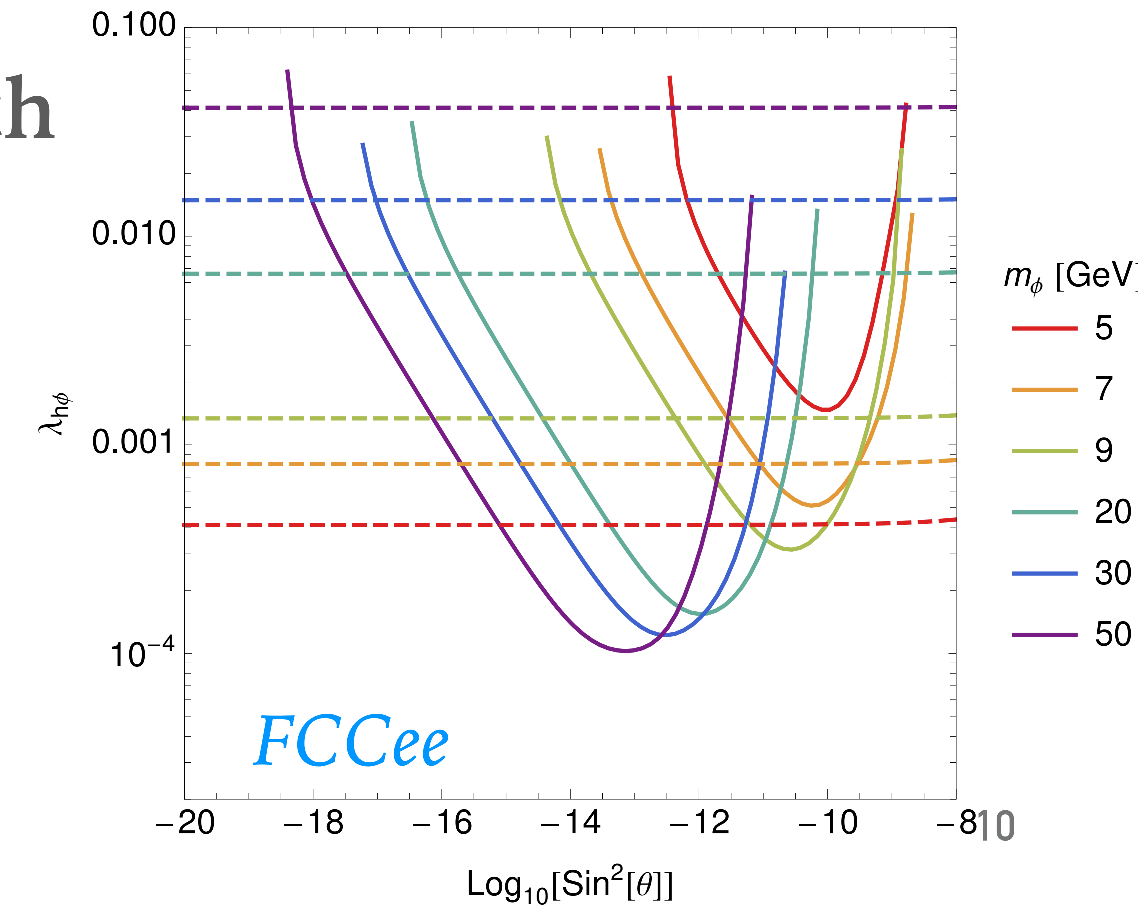
# DELAYED

- Identify long-lived particles by the **time delay** of the decay product

$$\Delta t \cdot c = \frac{l_x}{\beta_x} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}}$$




- Take advantage of the MIP timing detector for the HL-LHC
- **Selections are geometrical in terms of the scalar decay length** for each event kinematics.
- Extend to all masses and lifetimes.
- Consider an MTD for the FCCee.

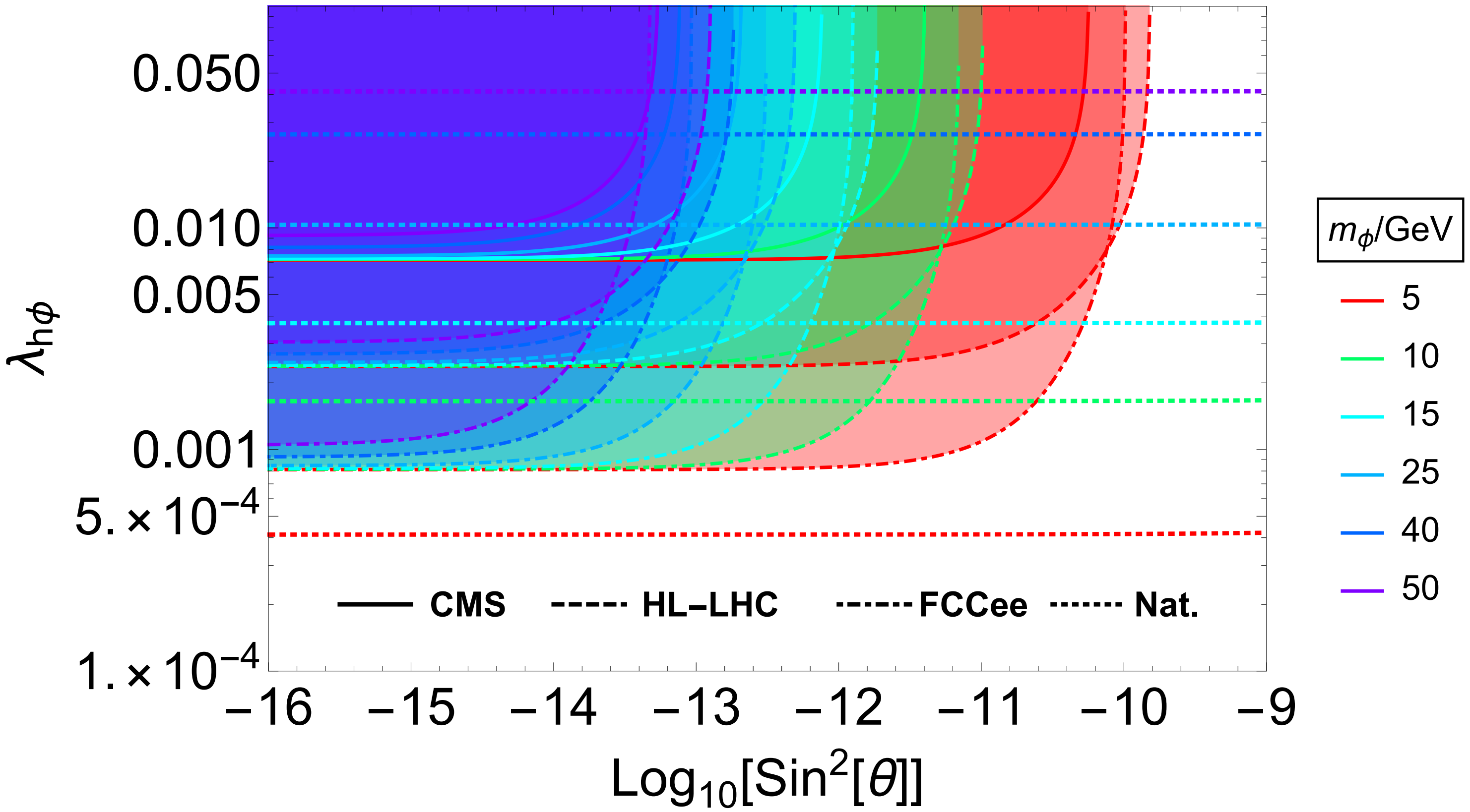



Jia Liu et al., [1805.05957].

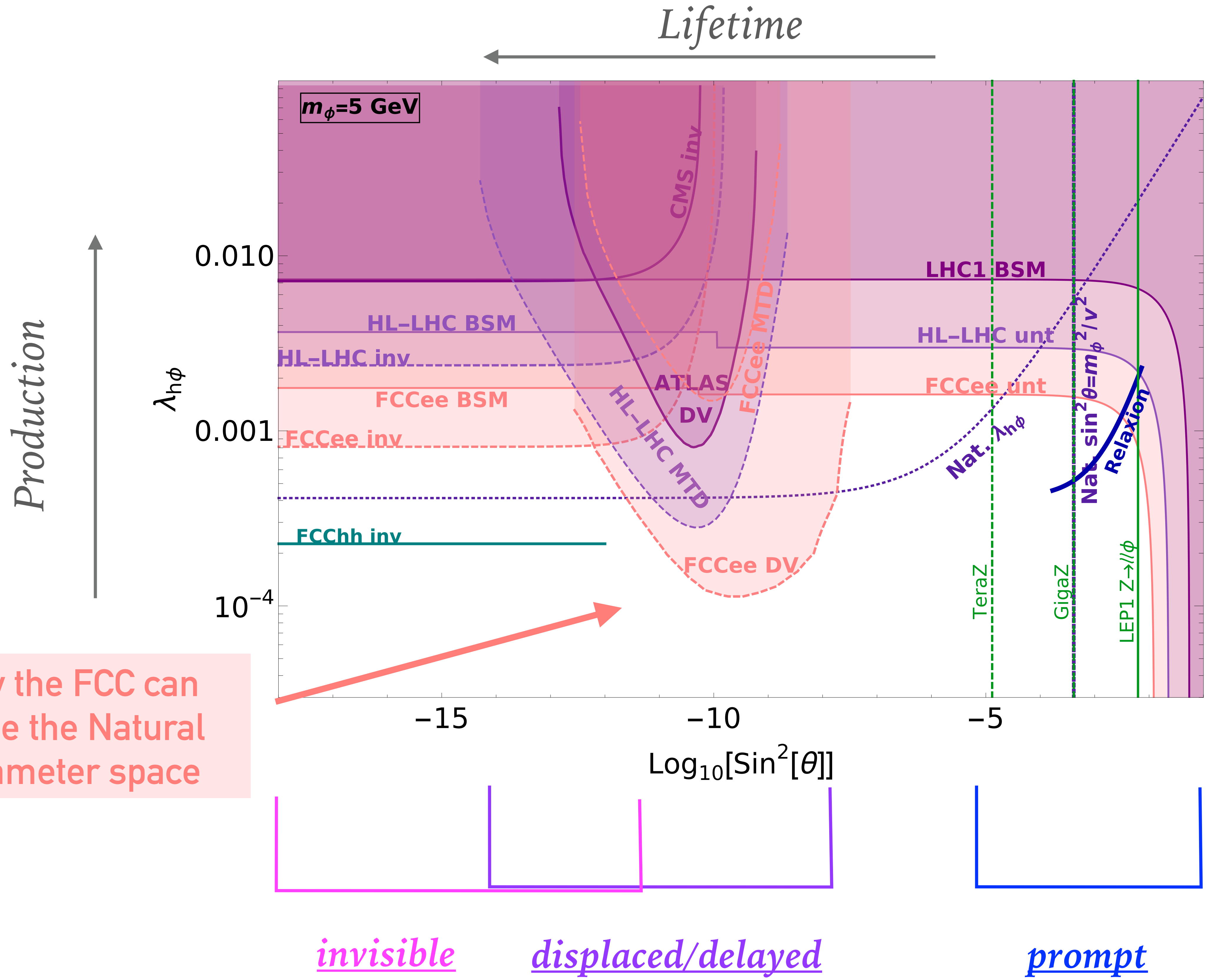
# INVISIBLE

- ➤ Direct searches for Higgs decays into missing ET.
- ➤ Account for the fraction r of scalars decaying outside the detector

$$r = \frac{1}{N}\sum_{i=1}^{N} \exp\left(-\frac{m_\phi}{c\tau_\phi}\left(\frac{L_{i_1}}{p_{i_1}} + \frac{L_{i_2}}{p_{i_2}}\right)\right)$$

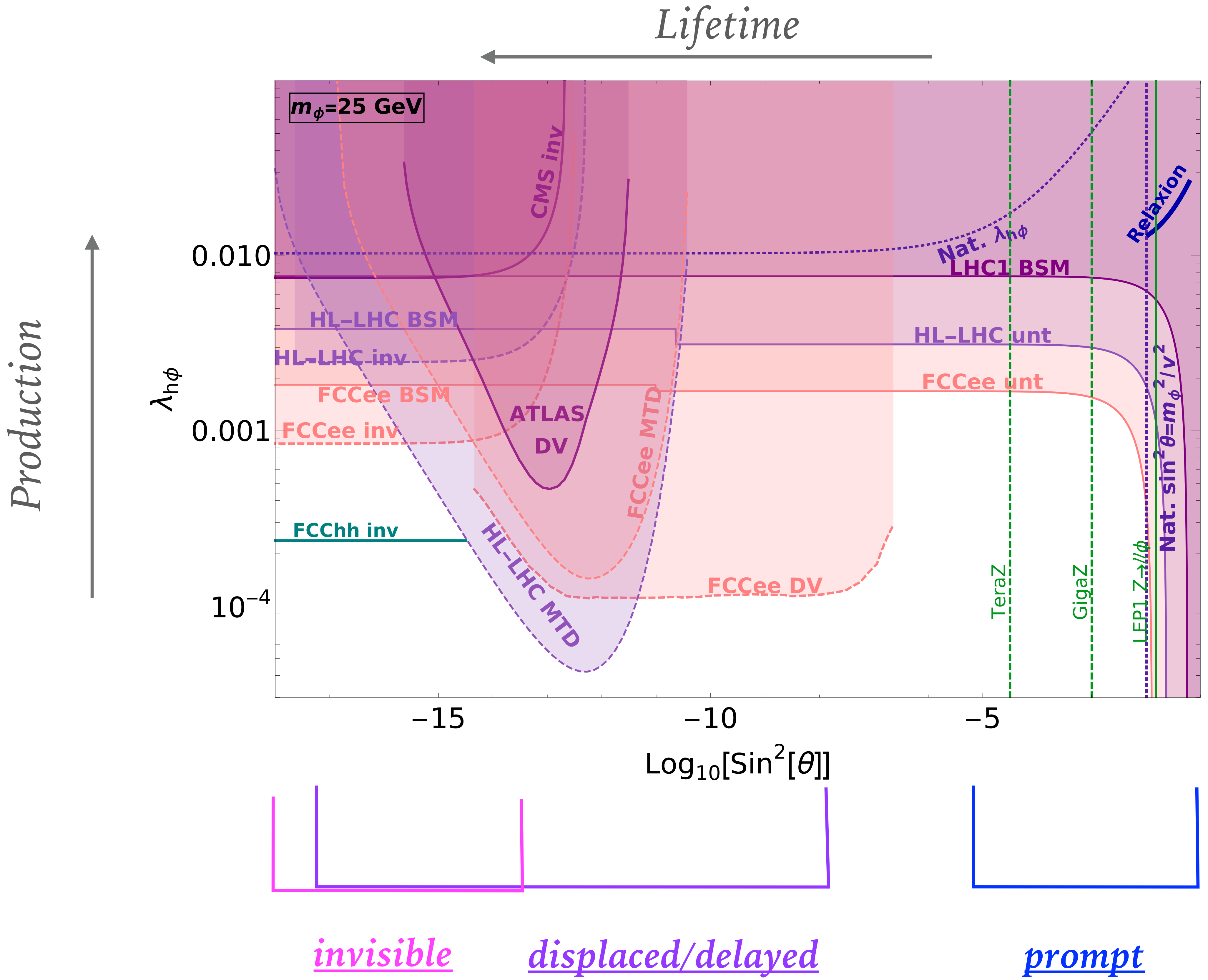


# OVERVIEW: 5 GEV SINGLET




Only the FCC can probe the Natural parameter space

# OVERVIEW: 25 GEV SINGLET



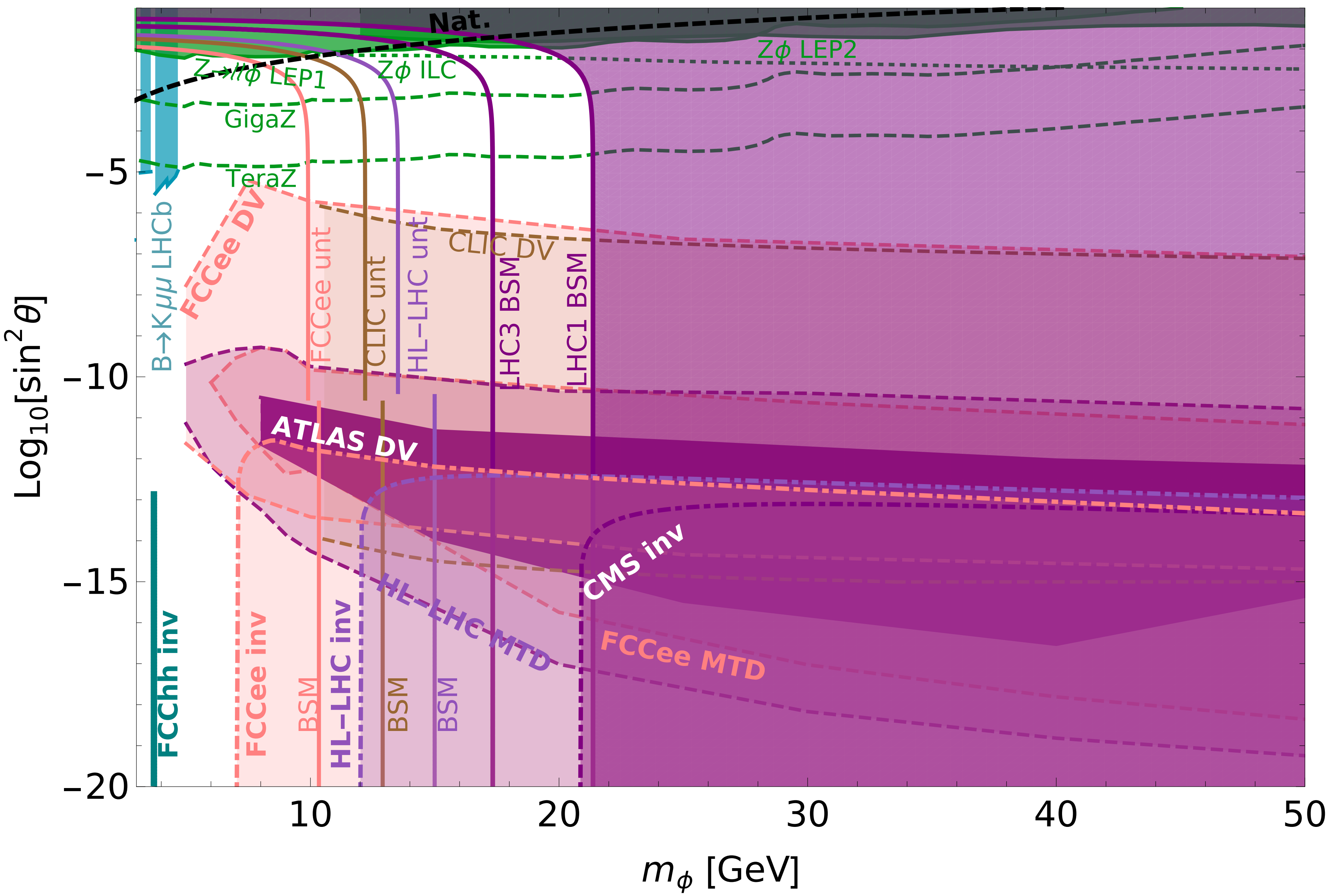
# OVERVIEW: NATURAL SINGLET

➤ Set $\lambda_{h\phi} = m_\phi^2/v^2 = \hat{\lambda}_{h\phi}^{nat.}$

***prompt***
*h untagged/BSM*
*Rare Z decays*

***displaced/delayed***
*scalar decays in*
*a displaced vertex*
*in the detector*

***invisible***
*scalar decays*
*outside the detector*



# THANK YOU!

# BACKUP SLIDES

# SCALAR SINGLET EXTENSION

- **Minimal renormalizable extension** - (no $Z_2$)

$$V_s(\Phi, H) = V(\Phi) + \mu^2(\Phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

$$t\Phi + \frac{1}{2} m_0^2 \Phi^2 + \frac{a_\phi}{3}\Phi^3 + \frac{\lambda_\phi}{4}\Phi^4 \qquad -\mu_0^2 H^\dagger H + 2a_{h\phi}\Phi H^\dagger H + \hat{\lambda}_{h\phi}\Phi^2 H^\dagger H$$

- **Relaxion**

$$V_s(\Phi, H) = V(\Phi) + \mu^2(\Phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

$$rg\Lambda^3\Phi \qquad -\Lambda^2 H^\dagger H + g\Lambda\Phi H^\dagger H - \tilde{M}^2 \cos\left(\frac{\Phi}{f}\right) H^\dagger H$$

# INDIRECT – HIGGS COUPLING MODIFIERS

- **The scalar modifies the Higgs' branchings to SM particles**
  - Mixing - universal modifier of all Higgs couplings

$$\Gamma_{h\to f_{SM}} = \kappa^2 \Gamma^{SM}_{h\to f_{SM}}, \qquad \kappa = \cos\theta_{h\phi}$$

  - Additional Higgs decay channels:

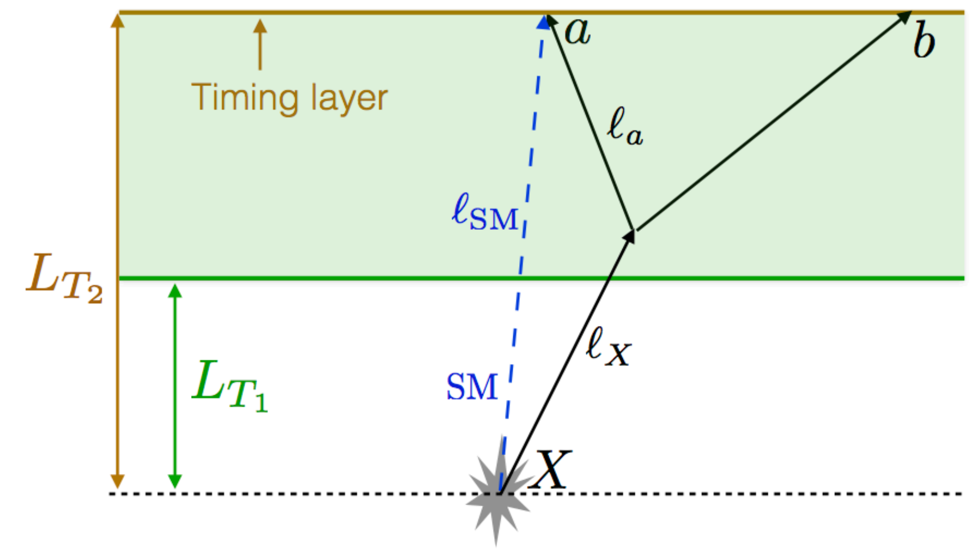
$$\Gamma^{NP}_h = \Gamma^{inv}_h + \Gamma^{unt}_h$$

    - **Invisible** - missing energy
    - **Untagged** - visible decay products that are not included in any specific search.

- Constraints given by fits of the signal strength

$$\mu_{if} = \frac{\sigma_{i\to h}}{\sigma^{SM}_{i\to h}} \frac{BR_{h\to f}}{BR^{SM}_{h\to f}} = \kappa^2 \frac{\kappa^2 \Gamma^{SM}_{h\to f}}{\kappa^2 \Gamma^{SM}_h + \Gamma^{NP}_h} \approx \kappa^2 BR^{SM}_{h\to f}\left(1 - BR^{NP}_h\right)$$

# IDENTIFYING DISPLACED DECAYS - TIMING



Jia Liu et al., [1805.05957].

- Identify a secondary vertex by time delay with respect to a prompt light particle (ISR, prompt decay, etc.)

$$\Delta t \cdot c = \frac{l_x}{\beta_x} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}},$$

- **Main selections**: time delay+ scalar decays between L1 and L2+decay product reaches the timing layer - **all geometrical in terms of lab-frame scalar decay length.**
- Efficiency calculation can be reduced to -
  - MC generation of event kinematics for each scalar mass (e.g. MadGraph).
  - Analytically calculating the allowed range for $l_\phi$ for each event kinematics.
  - Calculating the event weight for each proper lifetime

$$w = \exp\left(-l_\phi^{min}/c\tau\gamma_\phi\beta_\phi\right) - \exp\left(-l_\phi^{max}/c\tau\gamma_\phi\beta_\phi\right)$$