

# COLLIDER SEARCHES FOR SCALAR SINGLETs ACROSS LIFETIMES

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מכון ויצמן למדע

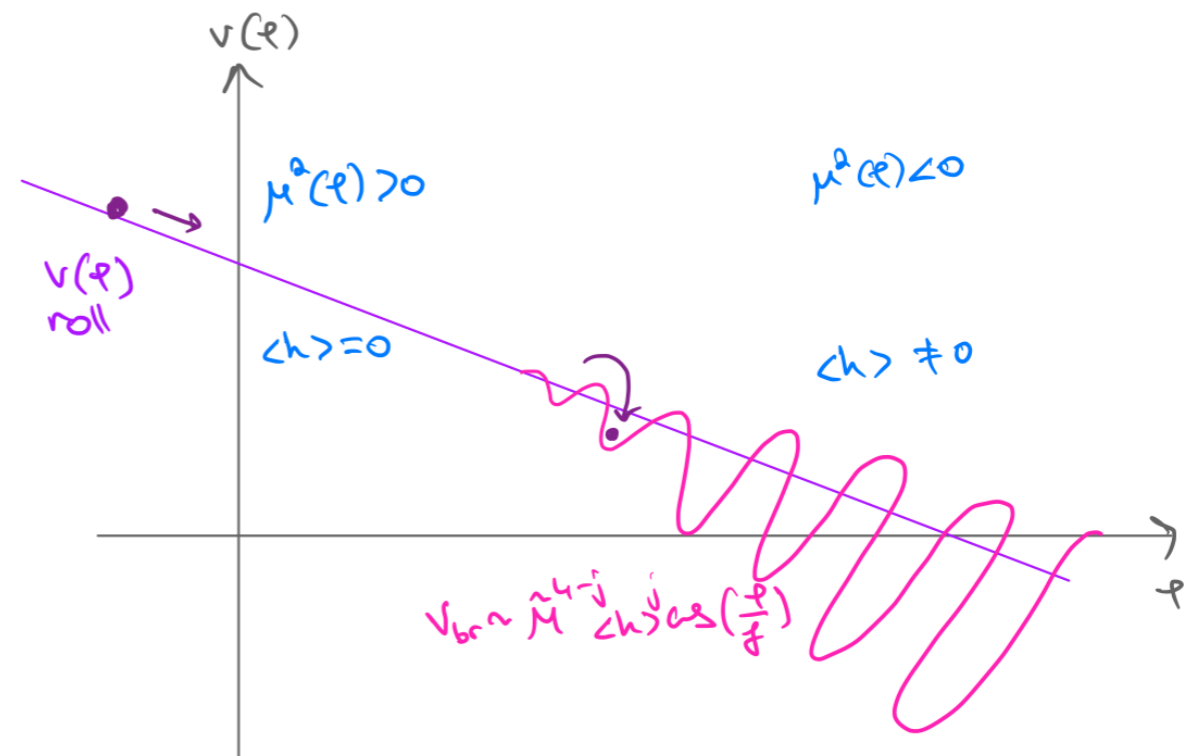
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# SCALAR SINGLET EXTENSION

- SM+ real singlet

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

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



# SINGLET-HIGGS INTERACTIONS

## ➤ Minimal renormalizable extension

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

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

## ➤ 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

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



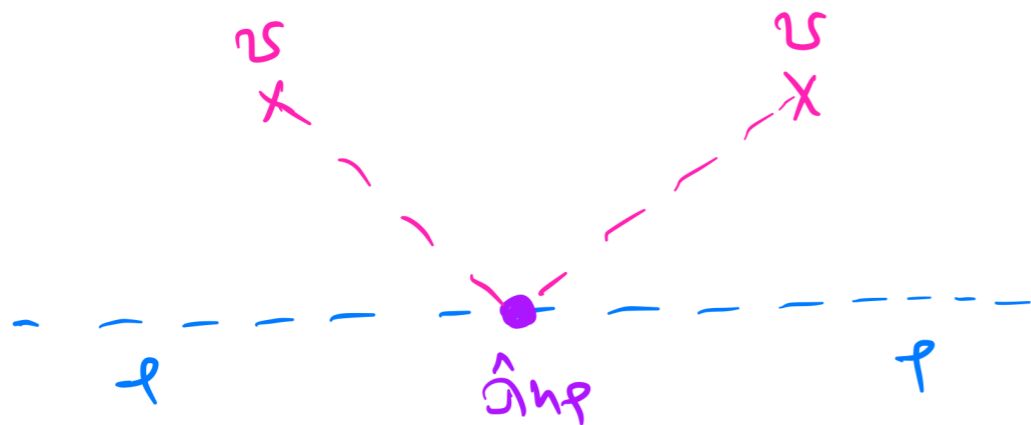
Exotic decay channel for the Higgs (if  $m_h \geq 2m_\phi$ )

# NATURAL SCALAR SINGLET EXTENSION

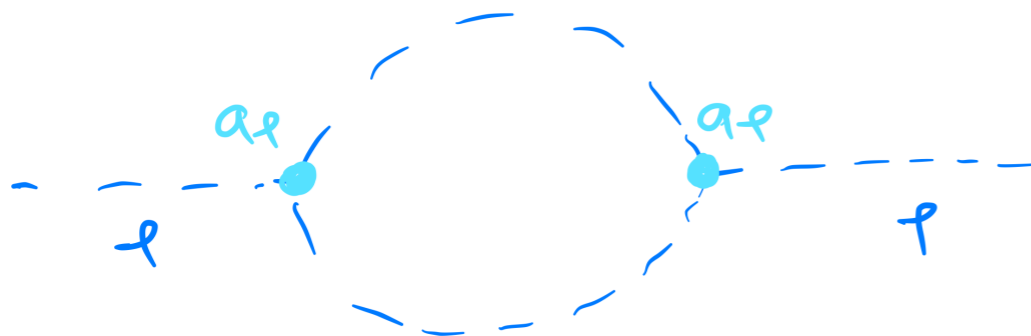
- Additive corrections to the scalar's mass set the minimal mass (no tuning)



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



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



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

# NATURAL SCALAR SINGLET EXTENSION

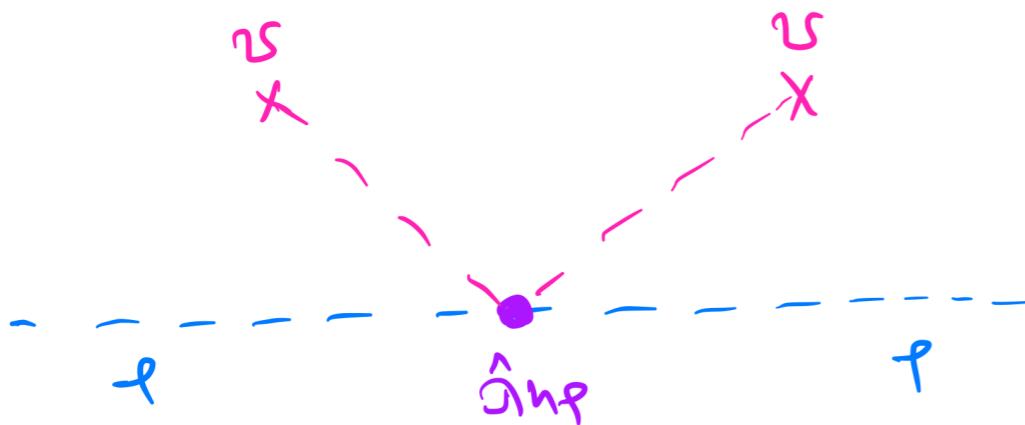
- Additive corrections to the scalar's mass set the minimal mass (no tuning)



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

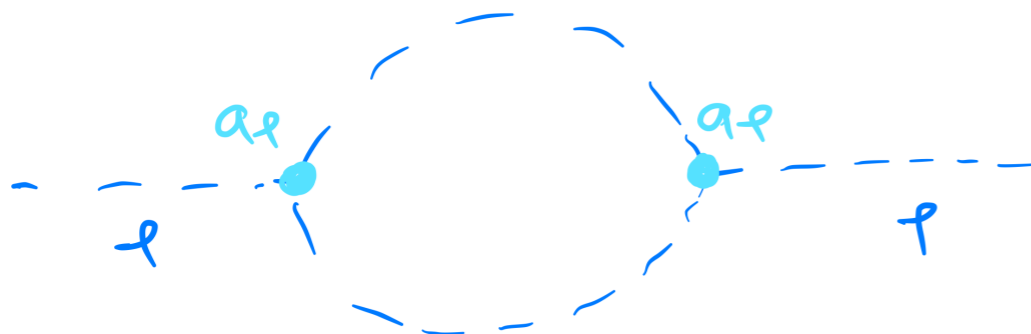
*Relaxion - can be relaxed due to dynamics*

$$\sin \theta \lesssim \left( \frac{m_\phi}{m_h} \right)^{2/3}$$



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

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

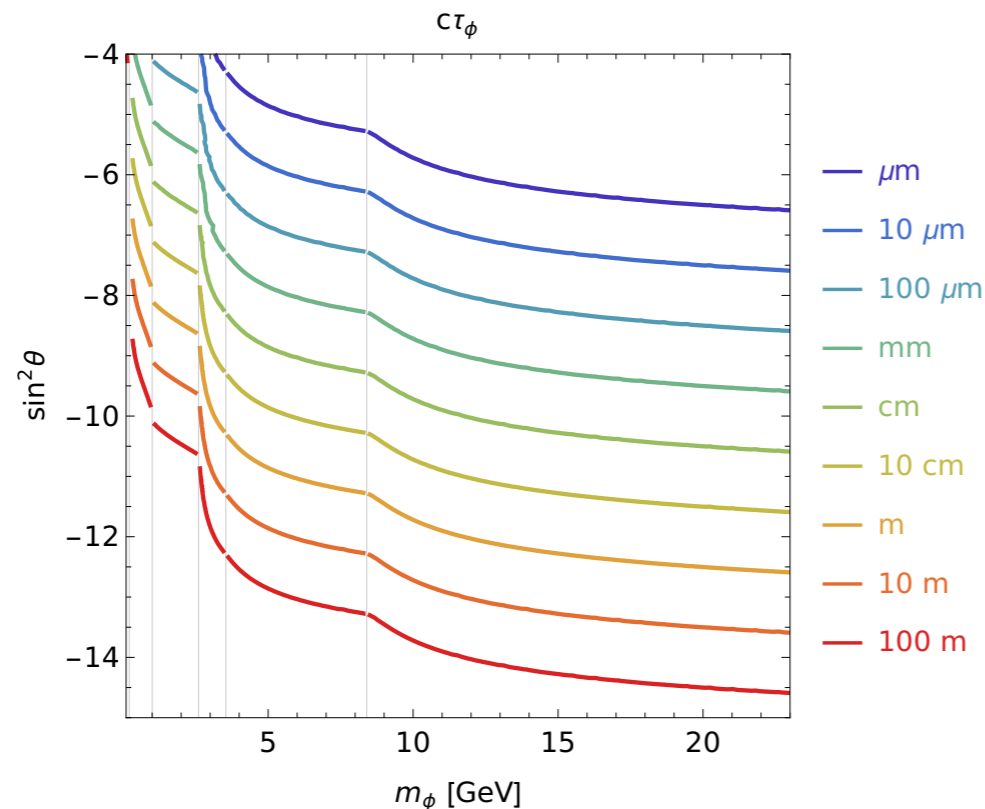


$$a_\phi \lesssim 4\pi m_\phi$$

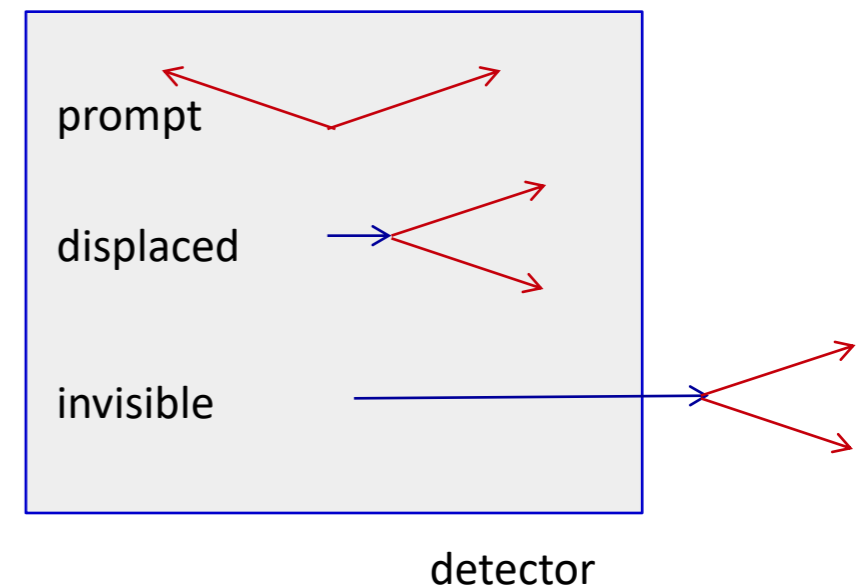
*Relaxion - no triple coupling*

# COLLIDER SEARCHES ACROSS LIFETIMES

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



Decays of  $\Phi$ :



- Goal: study these searches at all lifetimes
  - Obtain constraints in terms of model parameters  $m_\phi$ ,  $\sin \theta$ ,  $\lambda_{h\phi}$
  - Compare search strategies - prompt, displaced/delayed, invisible
  - Estimate potential to probe natural parameter space

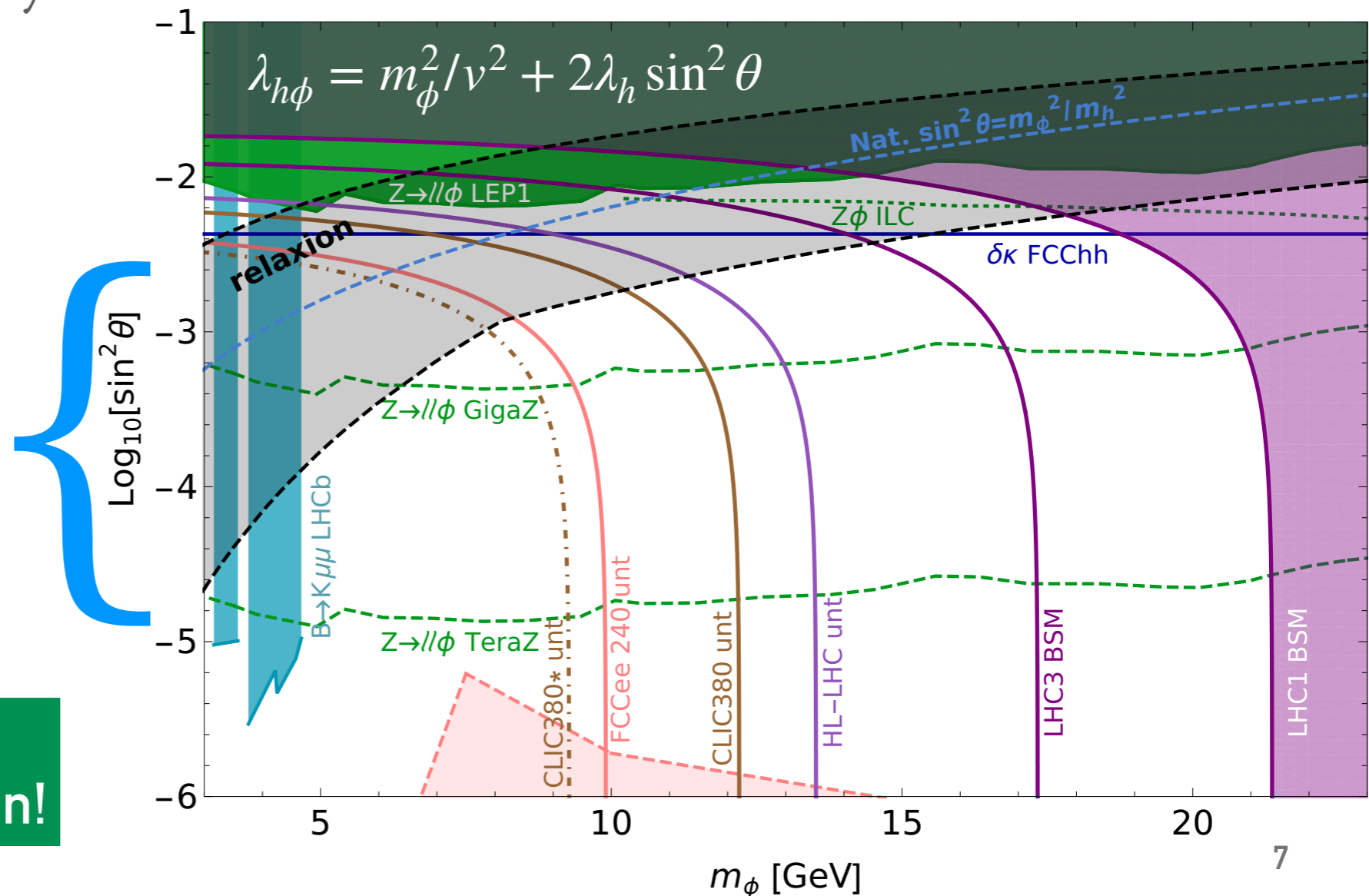
# PROMPT - DIRECT AND UNTAGGED

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

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

- Direct - Rare Z decays

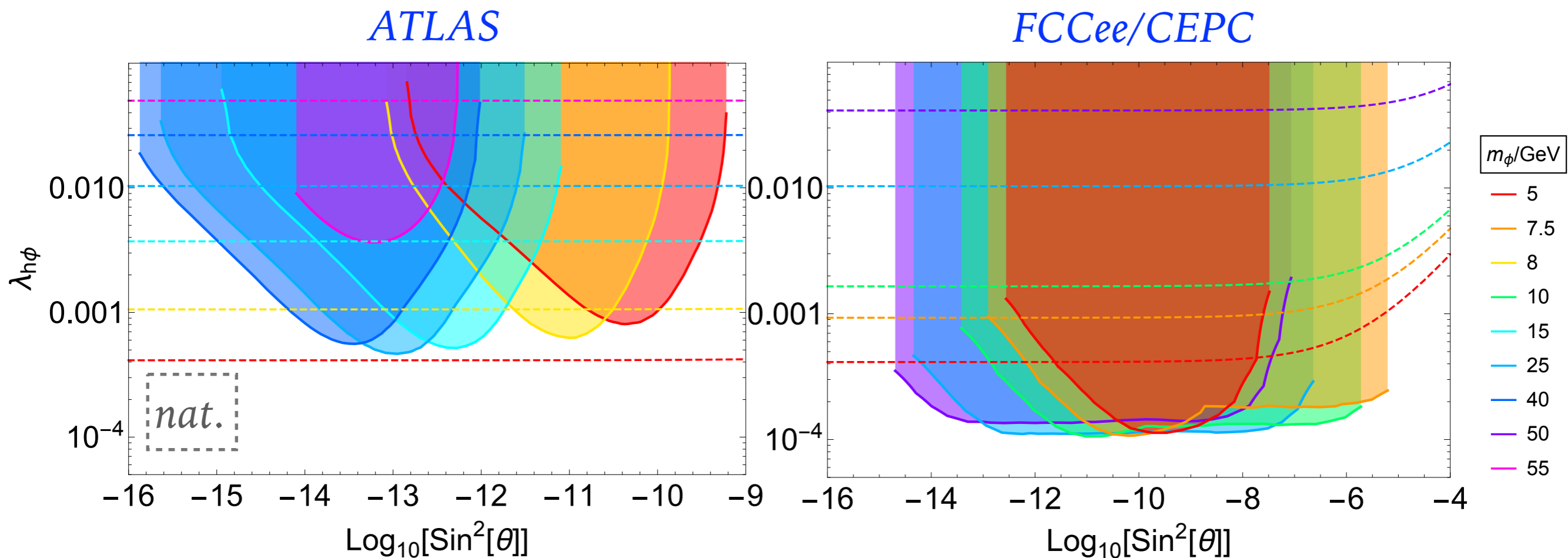
Natural  
relaxion can  
only live  
here



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.

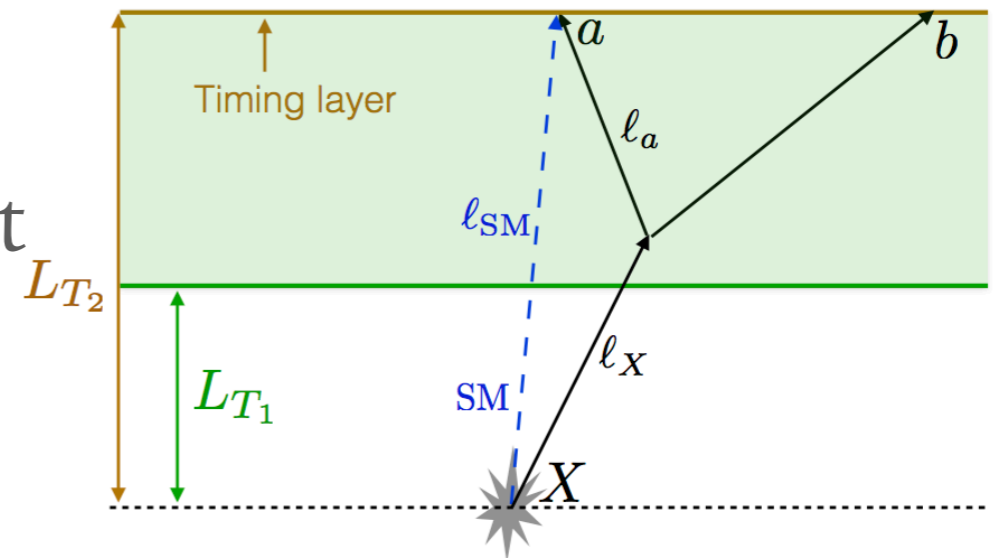




# DELAYED

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

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

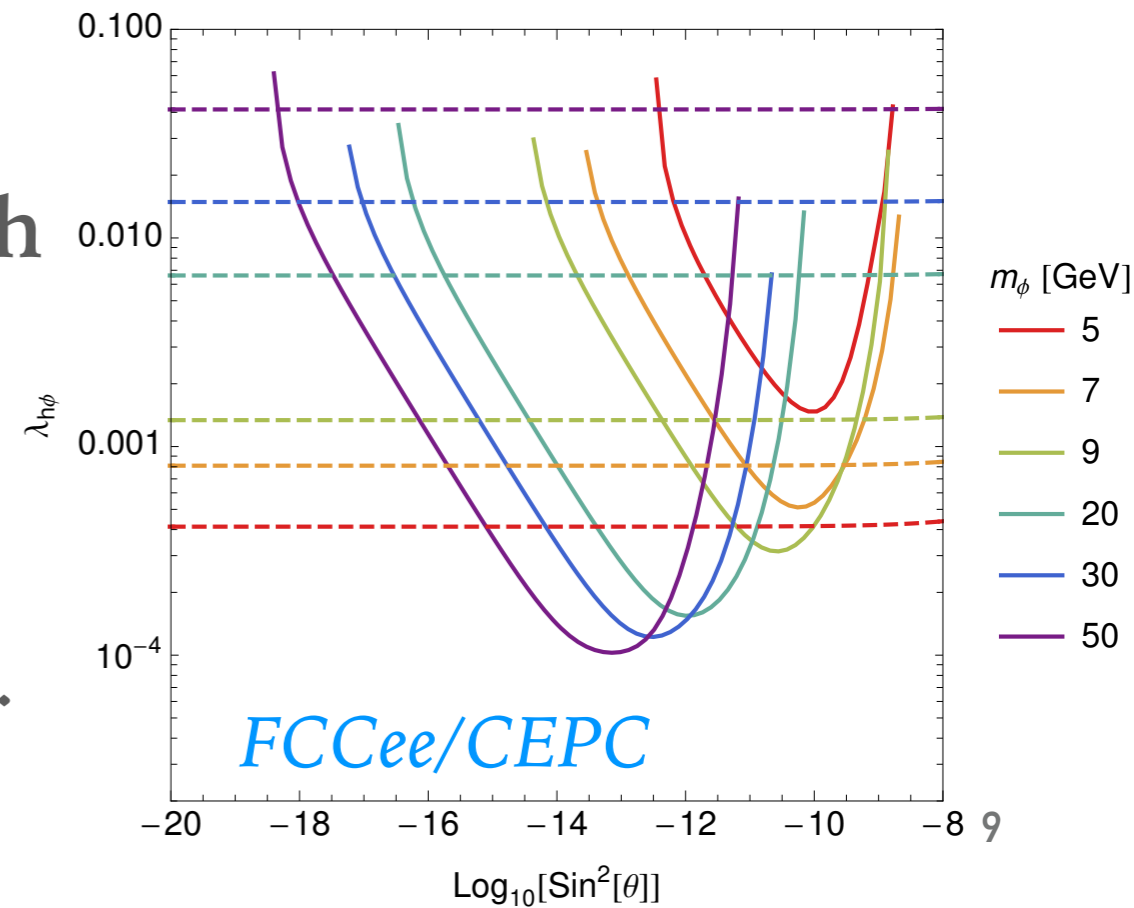


- Take advantage of the **MIP timing detector (MTD)** for the HL-LHC

- **Selections are geometrical** in terms of the scalar decay length for each event kinematics.

- Extend to all masses and lifetimes.

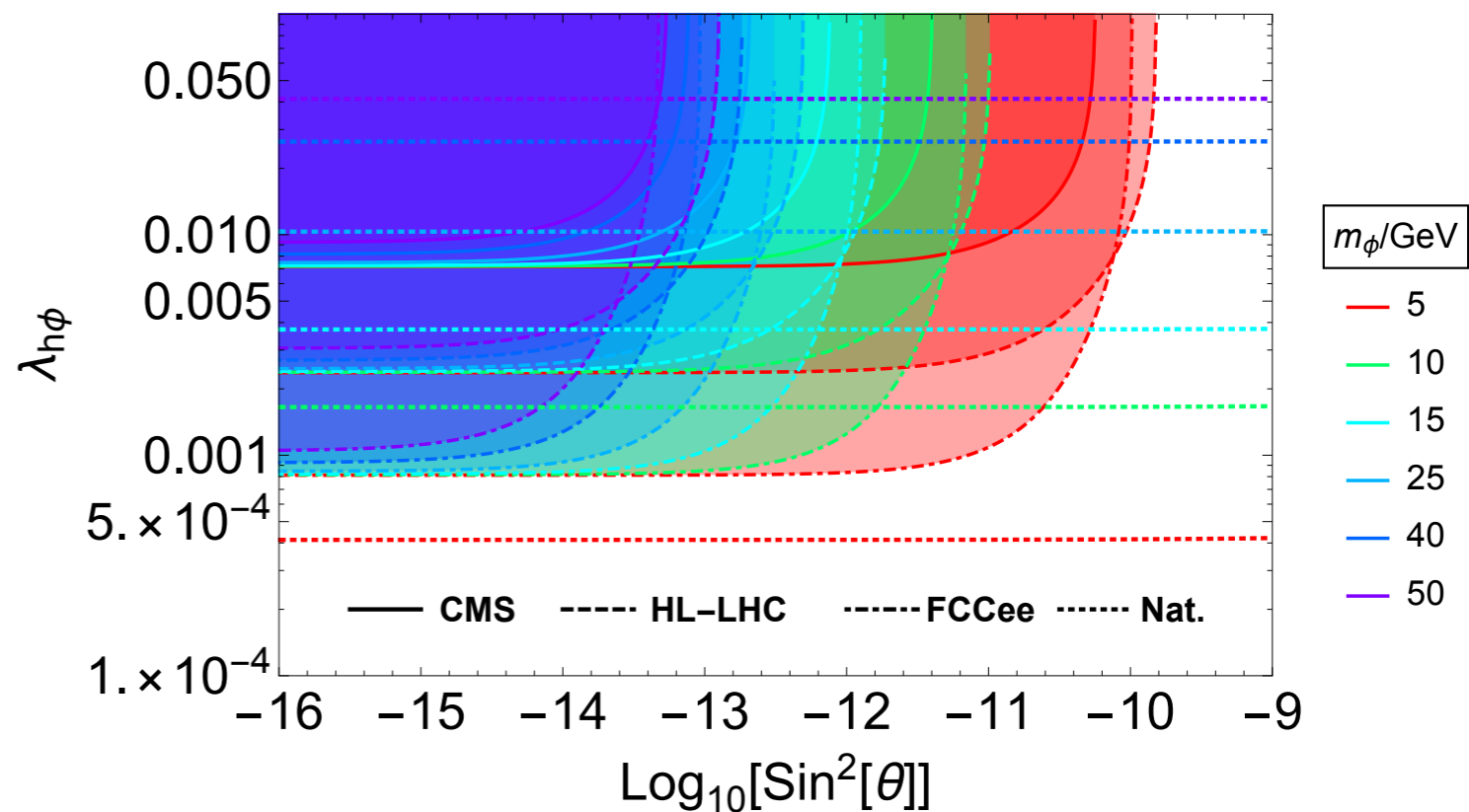
- Consider an MTD for FCCee/CEPC.



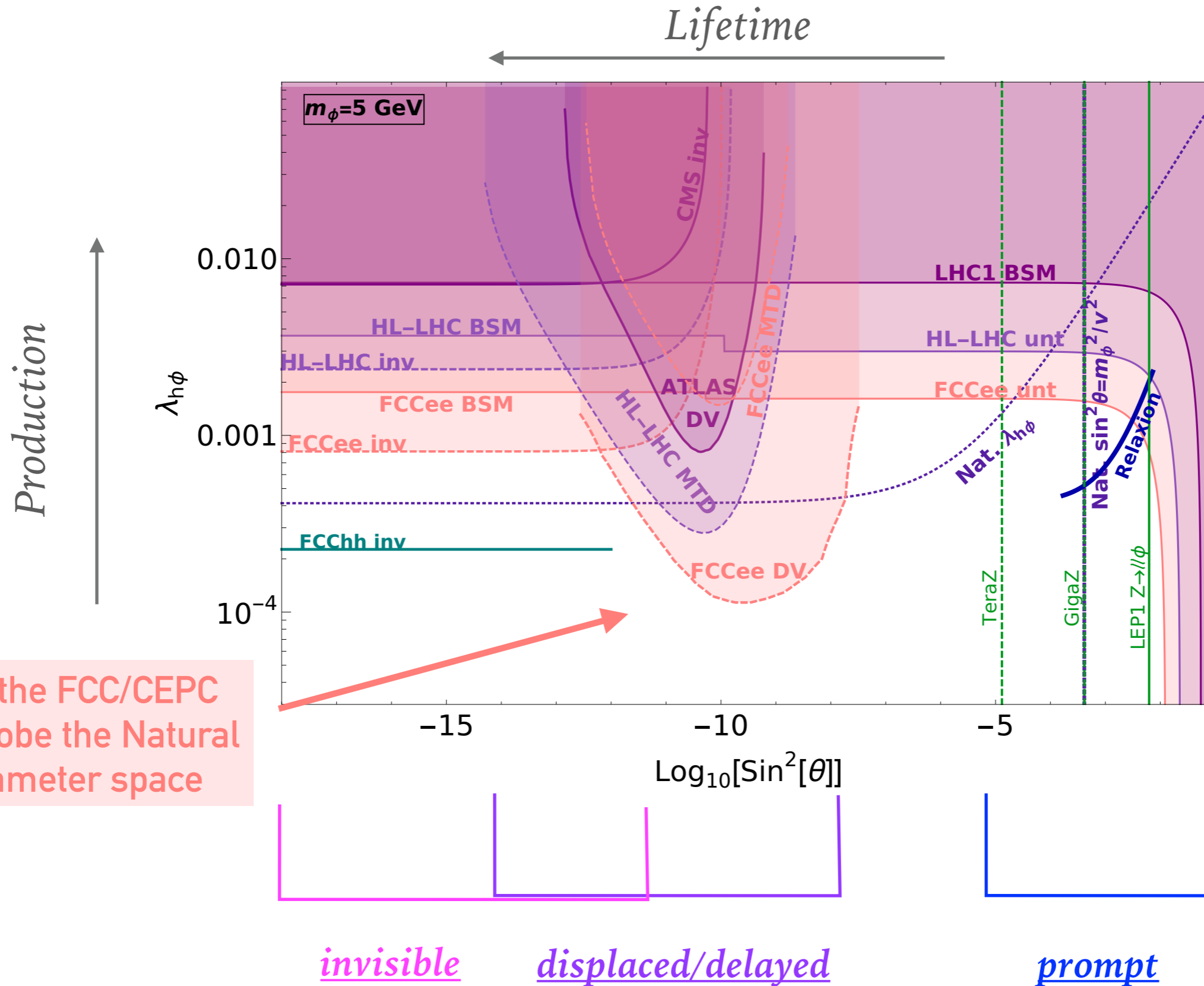
# INVISIBLE

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

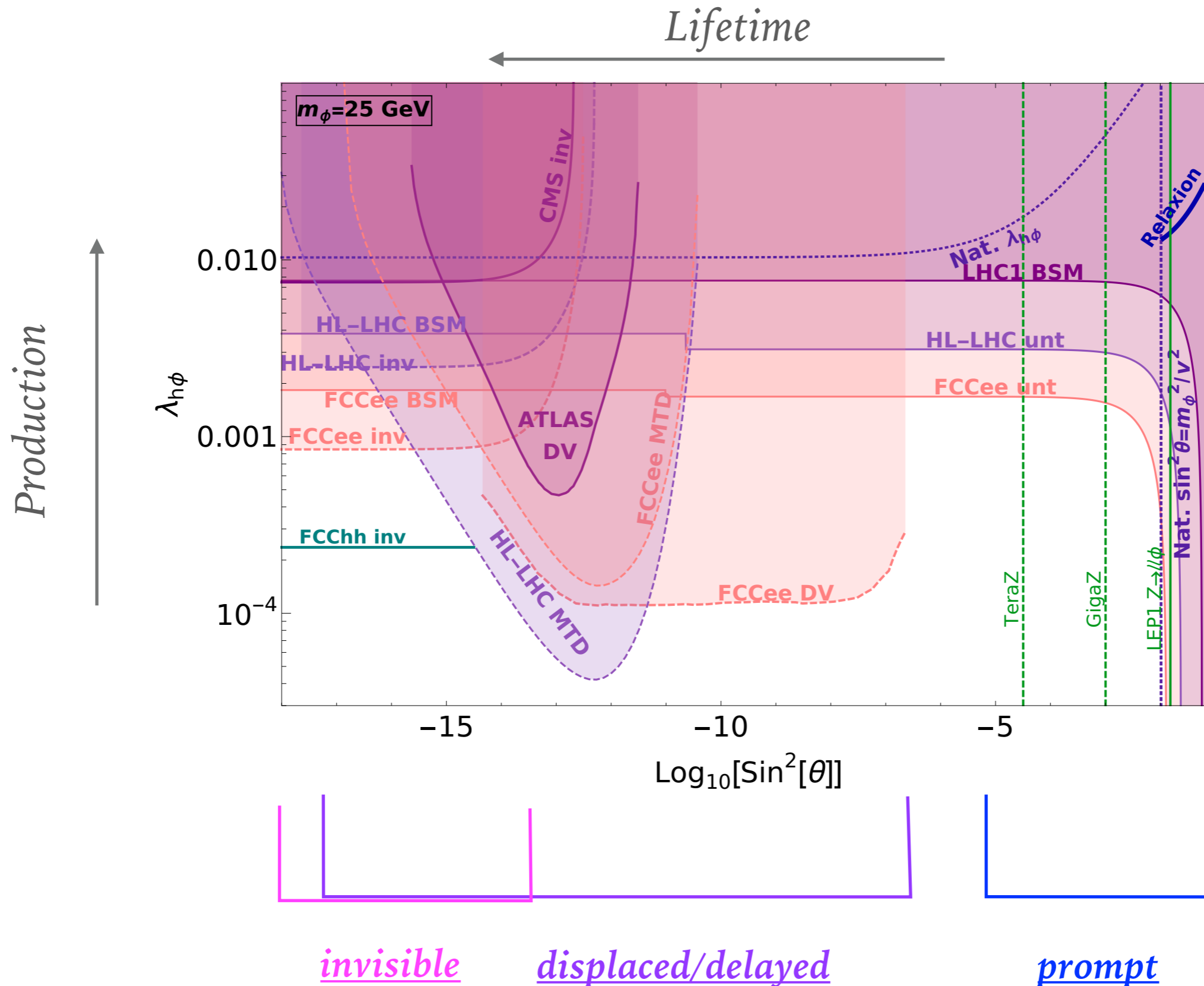
$$r = \frac{1}{N} \sum_{i=1}^N \exp \left( -\frac{m_\phi}{c\tau_\phi} \left( \frac{L_{i_1}}{p_{i_1}} + \frac{L_{i_2}}{p_{i_2}} \right) \right)$$



# OVERVIEW: 5 GEV SINGLET



# OVERVIEW: 25 GEV SINGLET



# CONCLUSIONS

- Scalar singlets are motivated SM extensions (H-portal, relaxion)
- Collider phenomenology is controlled by  $m_\phi$ ,  $\sin\theta$ ,  $\lambda_{h\phi}$
- Lifetime-dependent searches complementarity

- Prompt

h untagged/BSM, rare Z decays

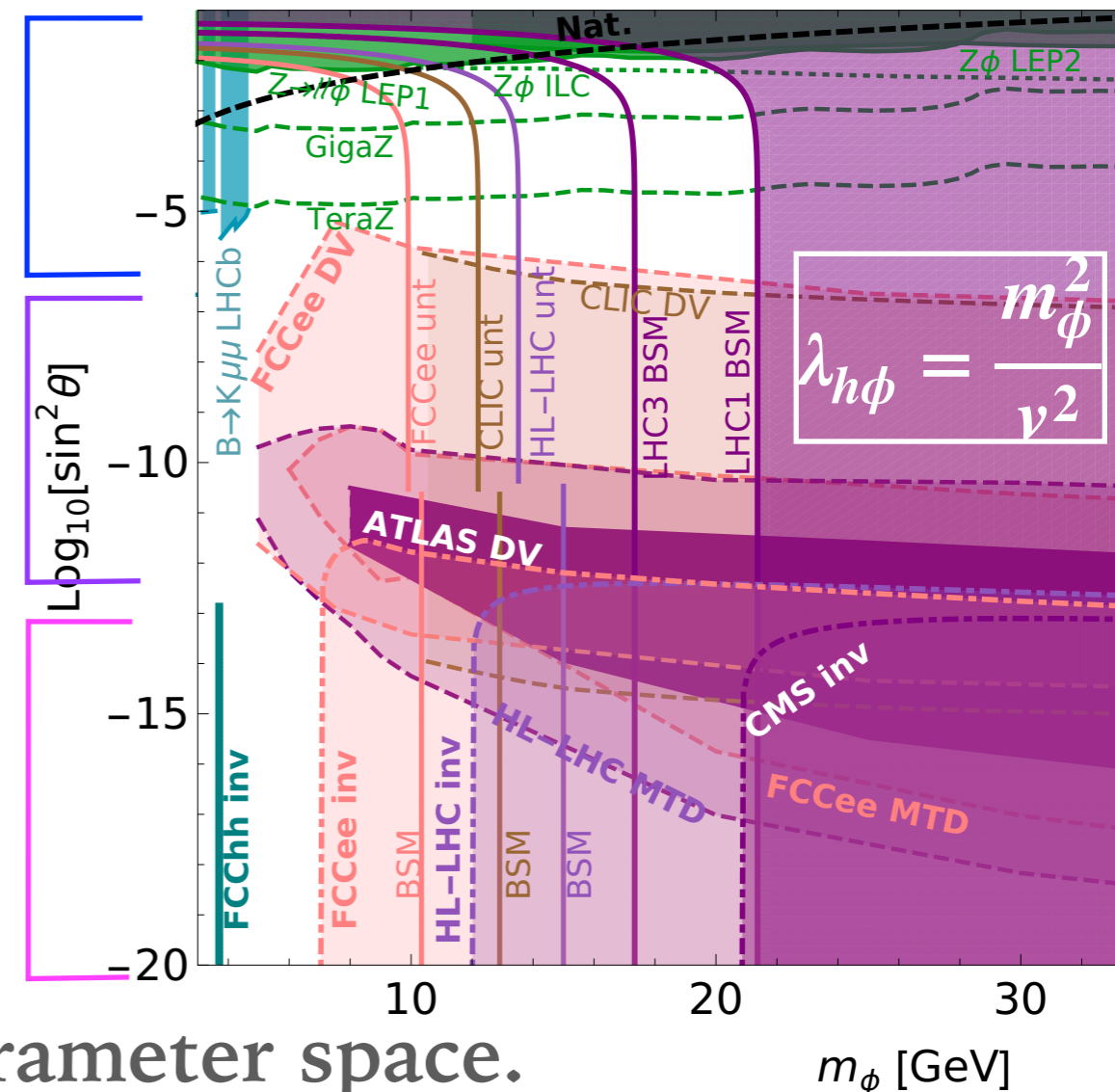
- Displaced/delayed

scalar decays in a displaced vertex

- Invisible

scalar decays outside the detector

- Current & future searches can cover the majority of the natural parameter space.



**THANK YOU!**

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# BACKUP SLIDES

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# SCALAR SINGLET EXTENSION

- Minimal renormalizable extension - (no  $Z_2$ )

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

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

- Relaxion

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

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



# INDIRECT – HIGGS COUPLING MODIFIERS

- The scalar modifies the Higgs' branchings to SM particles

- Mixing - universal modifier of all Higgs couplings

$$\Gamma_{h \rightarrow f_{SM}} = \kappa^2 \Gamma_{h \rightarrow f_{SM}}^{SM}, \quad \kappa = \cos \theta_{h\phi}$$

- Additional Higgs decay channels:

$$\Gamma_h^{NP} = \Gamma_h^{inv} + \Gamma_h^{unt}$$

- Invisible - missing energy

- Untagged - visible decay products that are not included in any specific search.

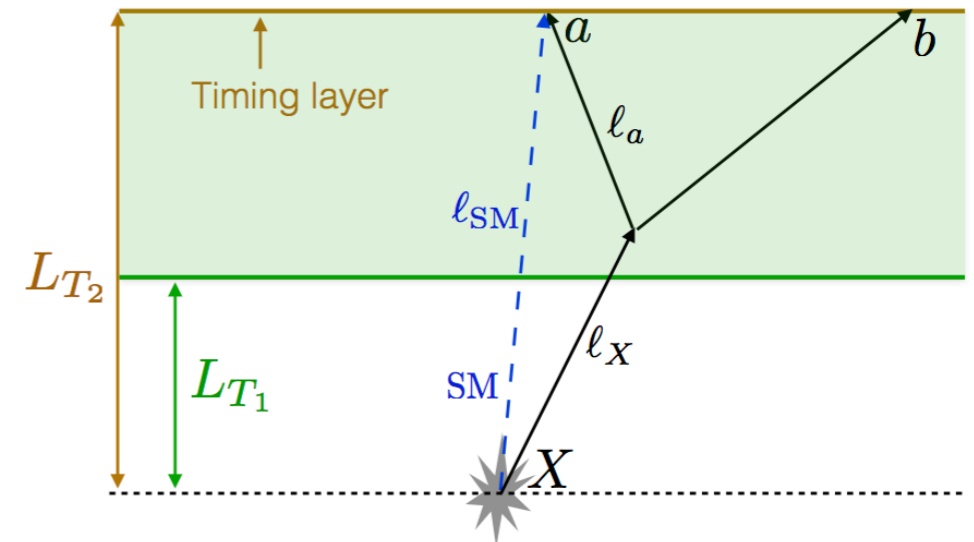
- Constraints given by fits of the signal strength

$$\mu_{if} = \frac{\sigma_{i \rightarrow h} BR_{h \rightarrow f}}{\sigma_{i \rightarrow h}^{SM} BR_{h \rightarrow f}^{SM}} = \kappa^2 \frac{\kappa^2 \Gamma_{h \rightarrow f}^{SM}}{\kappa^2 \Gamma_h^{SM} + \Gamma_h^{NP}} \approx \kappa^2 BR_{h \rightarrow f}^{SM} \left( 1 - BR_h^{NP} \right)$$

# IDENTIFYING DISPLACED DECAYS – TIMING

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

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



Jia Liu et al., [1805.05957].

- **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

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

# OVERVIEW: 50 GEV SINGLET

