Dark Higgs as Probe for Dark Matter

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Dark Matter

- While the Standard Model (SM) has been highly successful, it still fails to account for several key experimental observations. Among these unresolved questions is the existence of Dark Matter (DM), a form of matter that does not interact through electromagnetic or strong forces. Evidence supporting Dark Matter includes:
  - **Galactic rotation curves**: The rotational speeds at the outskirts of spiral galaxies cannot be attributed to visible matter alone.
  - **Gravitational lensing**: The bending of light around massive objects implies more mass than is visible.
  - **Galaxy cluster dynamics**: The radial velocities of galaxies and X-ray emissions from hot gas within clusters also indicate unseen mass.
  - **Cosmic Microwave Background (CMB) anisotropies**: Measurements suggest that Dark Matter constitutes approximately 85% of the total matter in the Universe.
- The absence of a Dark Matter candidate within the Standard Model is one of the primary drivers for exploring physics beyond the Standard Model (BSM).

Beyond Standard Model

- Several Beyond the Standard Model (BSM) theories offer candidates for dark matter or new particles, including:
  - **Two-Higgs Doublet Models**
  - **Little Higgs Models**
  - **Next-to-Minimal Supersymmetric Standard Model (NMSSM)**
  - **Hidden Valleys Models**
- In particular, Hidden Valley models propose a "hidden" or "dark" sector, comprising light particles that interact weakly with the Standard Model (SM) through a heavy mediator. This dark sector provides potential solutions for dark matter. The heavy mediator serves as a bridge between the SM and the hidden sector. In these models, a new scalar particle, which couples to the Higgs boson, could be long-lived.
- The model used in this study is the **Hidden Abelian Higgs Model**.

motivation for the FCC-ee

Based on :

- The luminosity for the Zh stage is L = 5 ab^{-1}.
- The estimated production of the collider at the different stages are
  - 5×10^{12} Z bosons at 91 GeV,
  - 10^{8} W boson pairs at 160 GeV,
  - 10^{6} Higgs bosons at 240 GeV and
  - 10^{6} $t\bar{t}$ pairs at 350 GeV.
- The high statistics increase the precision.
- Constraining the parameters could reveal deviations from the SM predictions, which in turn hints at new physics at higher energies than those currently reachable

Hidden Abelian Higgs Model

- A very simple extension of the standard model
- Adding a "dark" U(1) gauge group that is broken by a dark higgs vev.
- The "dark vector" ZD can then kinetically mix with the U(1)B gauge boson,
- The "**dark higgs**" S (or **hS**) can mix with the SM doublet higgs via the higgs portal |H|2|S|2 operator.
- This can induce a variety of higgs decays like:
  - h → Z ZD (if kinetic mixing dominates)
  - h → ZD ZD (if higgs mixing dominates)
  - **h → S S (if higgs mixing dominates)**
- This model has been studied in the literature, see e.g. Wells et al.

Lagrangian of The Model

- The lagrangian is

$$\mathcal{L}_{SM} \ni \underbrace{\frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_s S^4}_{\text{scalar potential}} - \underbrace{\frac{1}{2}\kappa S^2|H|^2}_{\text{portal term}} + \underbrace{\mu^2|H|^2 - \lambda|H|^4}_{\text{Higgs potential}},$$

$$\begin{aligned}\mathcal{L}_\Phi \;\; = \;\; & |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + \mu_{\Phi_H}^2 |\Phi_H|^2 + \mu_{\Phi_{SM}}^2 |\Phi_{SM}|^2 \\ & - \lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \kappa|\Phi_{SM}|^2|\Phi_H|^2,\end{aligned}$$

- The partial decay width of the Higgs boson to the new scalars is given by

$$\Gamma(h \to ss) \approx \frac{\kappa^2 v_h^2}{32\pi m_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}},$$

- The decay of the scalar is determined by its partial decay width which is given at leading order by

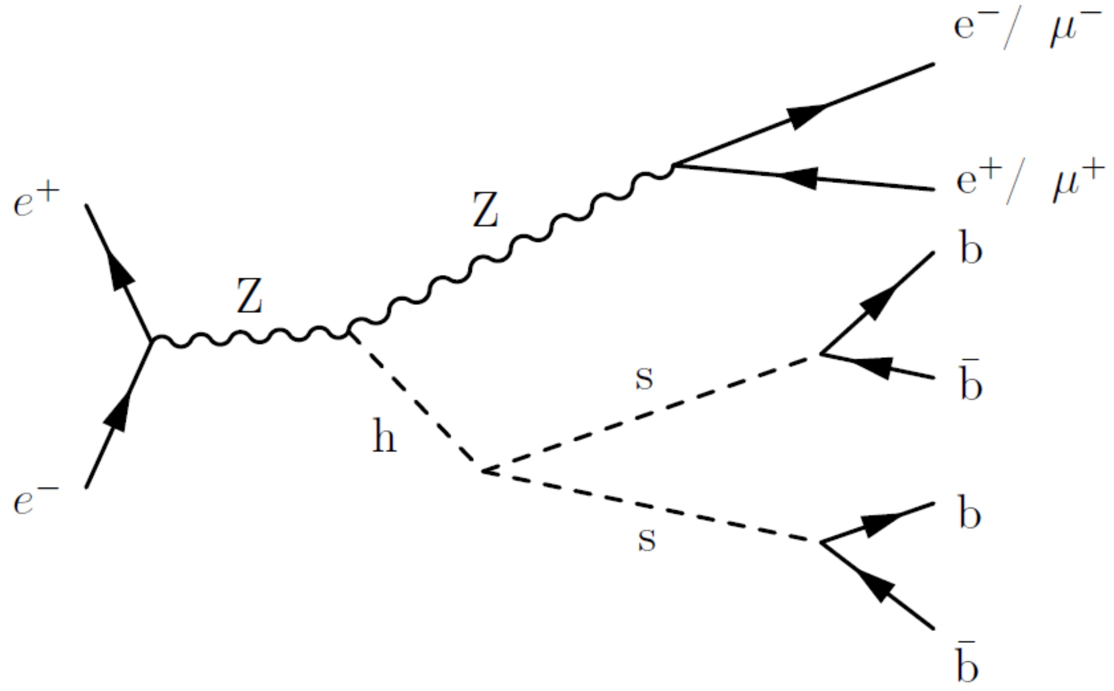
$$\Gamma(s \to f\bar{f}) \approx \sin^2\theta \frac{N_c}{8\pi}\frac{m_s m_f^2}{v_h^2}\left(1 - \frac{4m_f^2}{m_s^2}\right)^{3/2},$$

Process of Dark Higgs from Higgs decays

- The complete production process:

  $e^+ e^- \rightarrow Z\,h$ with $Z \rightarrow e^+ e^-$ or $\mu^+ \mu^-$ and $h \rightarrow hs\,hs \rightarrow b\bar{b}$

- The Feynman diagram:



Setting the parameters of the process:

- the Hidden Abelian Higgs Model deals with SM, dark photon, and dark higgs.
- mass of the dark photon, m_{ZD}:
- the kinetic mixing coupling constant of the dark photon, ϵ,:
- the mass of the scalar, m_s: 20 GeV
- the coupling constant between the scalar and the Higgs boson, κ:
- The total decay width of the scalar for a $b\bar{b}$ final state can be calculated as

$$\Gamma_s = \sin^2\theta \frac{3}{0.9 \times 8\pi} \frac{m_s m_b^2}{v_h^2} \left(1 - \frac{4m_b^2}{m_s^2}\right)^{3/2}$$

Setting of Parameters

- Branching ratio is $BR(h \to ss) \propto 10^{-4}$.
- Branching ratio $BR(s \to b\bar{b}) = 0.9$,
- b quark mass is $m_b = 4.2$ GeV,
- Higgs vev vh = 246 GeV
- Number of colors $N_c = 3$.
- All signal samples are generated with 10,000 events,
- The total events generated is 360,000 events
- The mixing angles are $\sin\theta = 10^{-5}$, 10^{-6} or 10^{-7} for each mass,
- Decay lengths of order 1 mm to 10 m.
- The scalar- Higgs coupling constant κ is set to $\kappa = 0.001$ for all events,
- This is lower than current constraints from searches at LHC.
- the center-of-mass energy, $\sqrt{s} = 240$ GeV

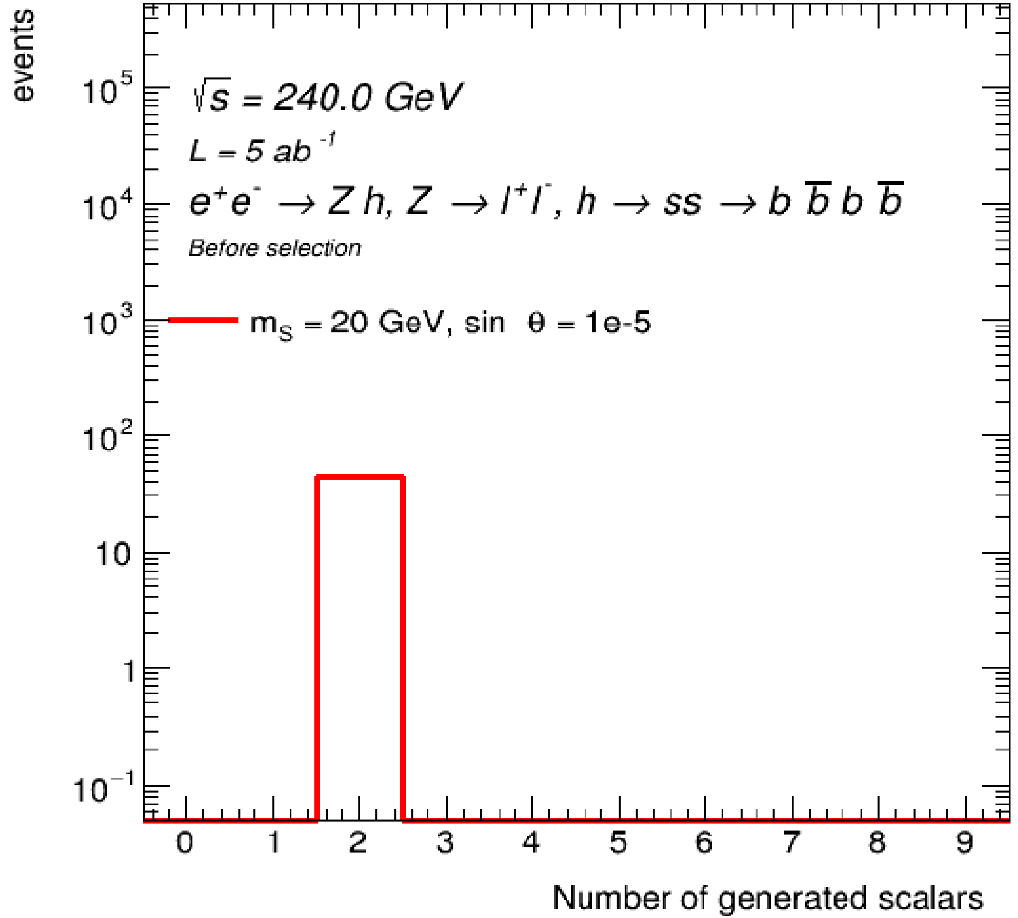
The generating value for simulation parameters:

- Considered generated values for
  - the scalar mass m_s
  - mixing angle $\sin\theta$,
  - scalar width Γ_s

Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Width of Scalar Γ_s [GeV]
20	1×10^{-5}	5.779×10^{-14}
20	1×10^{-6}	5.779×10^{-16}
20	1×10^{-7}	5.779×10^{-18}

The result of mass and number of scalars

- The number of generated scalars in each event for the signal sample ms = 20 GeV, $\sin\theta = 10^{-5}$



Scalar Mass

- mass of the scalars for signal samples

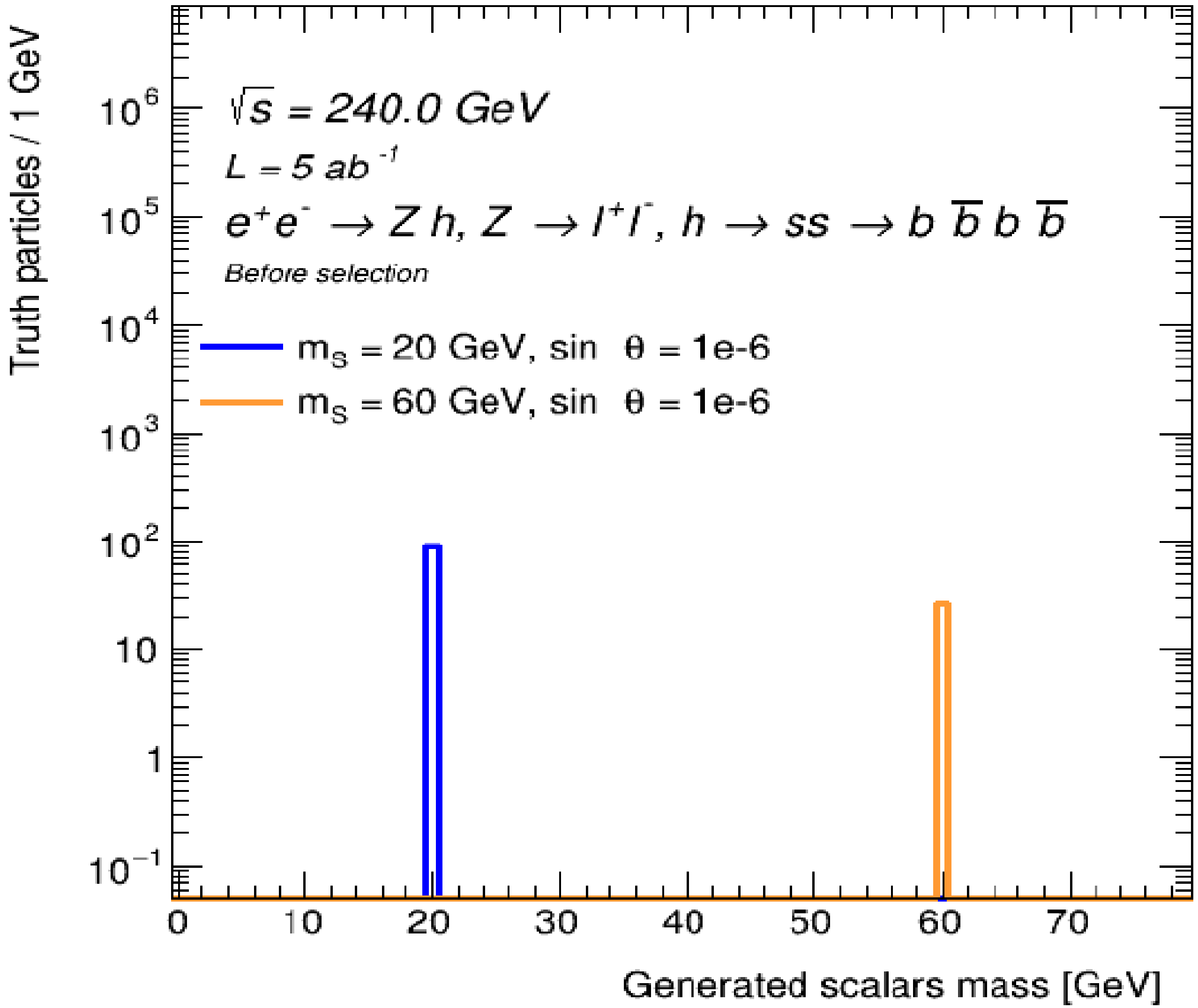
with $\sin\theta = 10^{-6}$

and masses

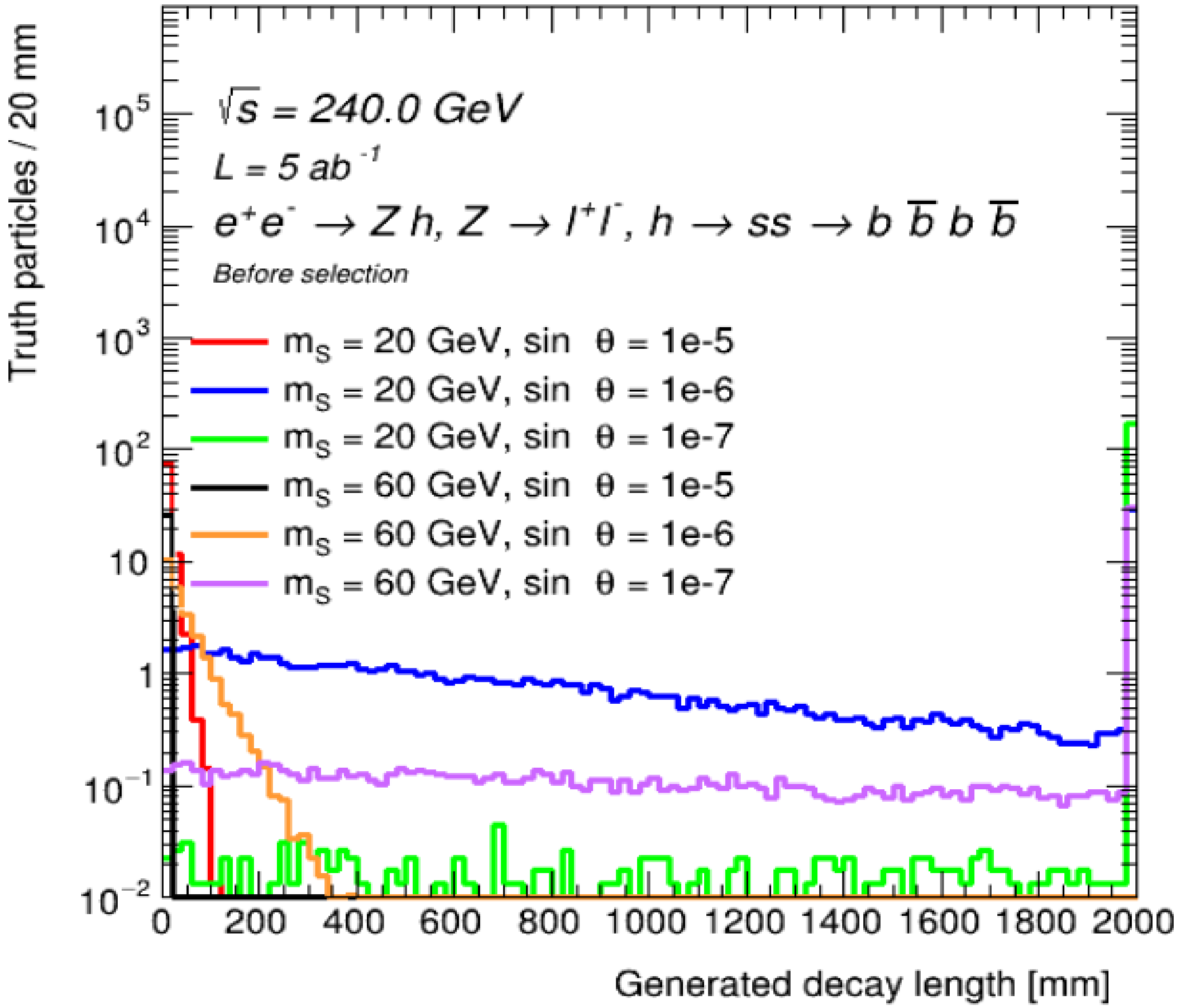
m_s = 20 GeV

and

m_s = 60 GeV:



Generated decay lengths



Lifetime of Dark Higgs

- Time distributions with

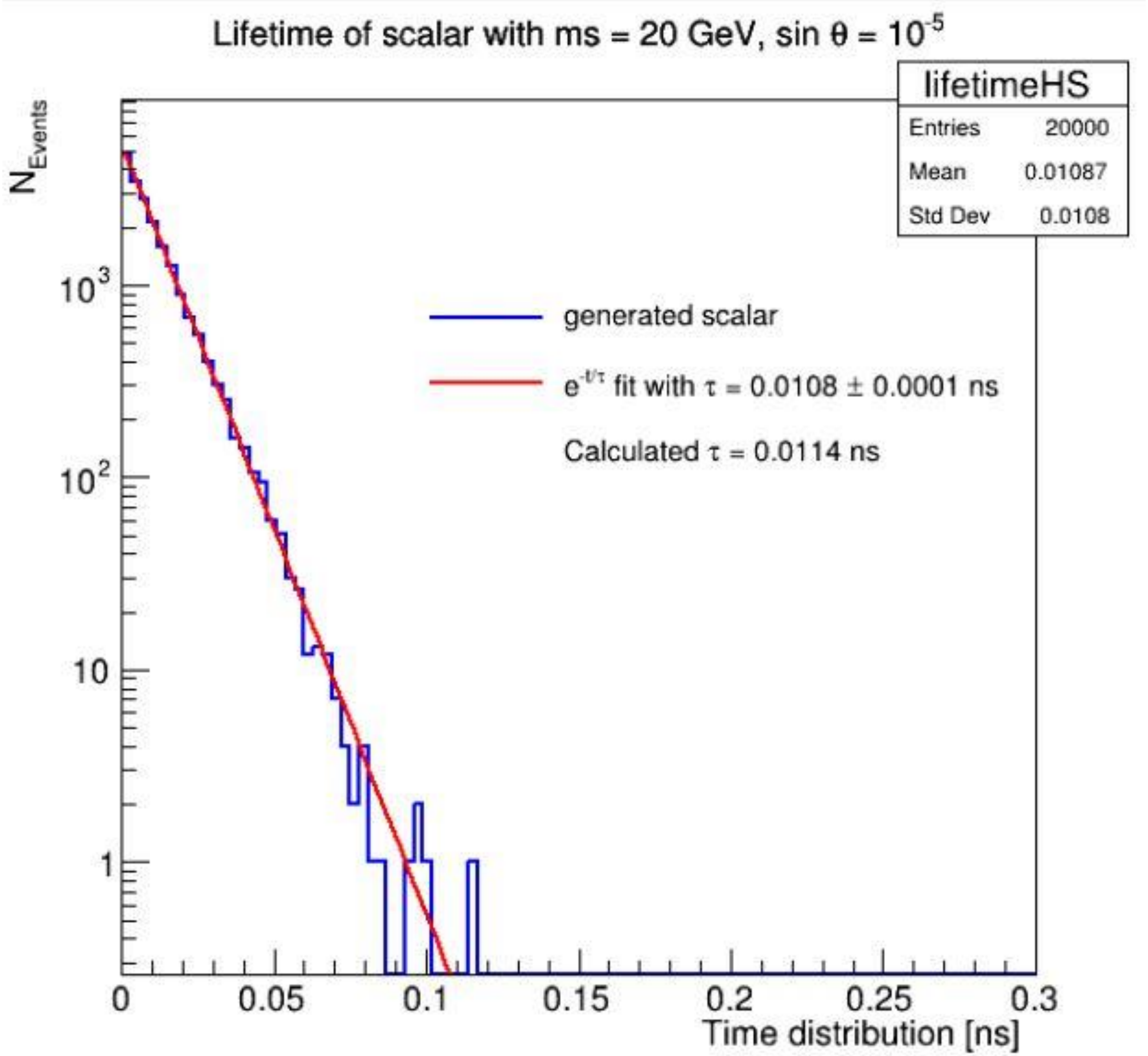
exponential fit

for each mixing angle

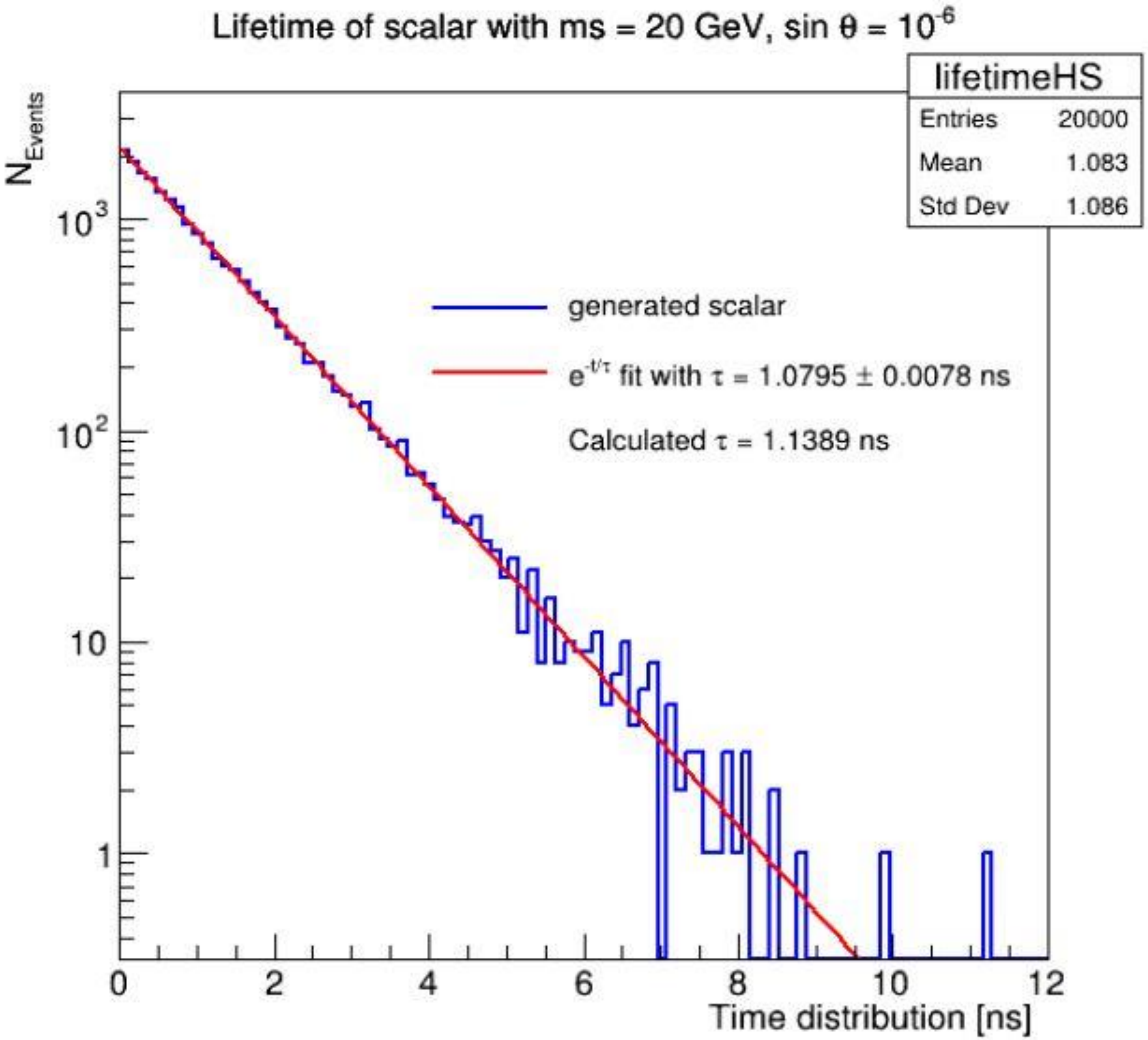
sin θ =

- 10^{-5},
- 10^{-6},
- 10^{-7},

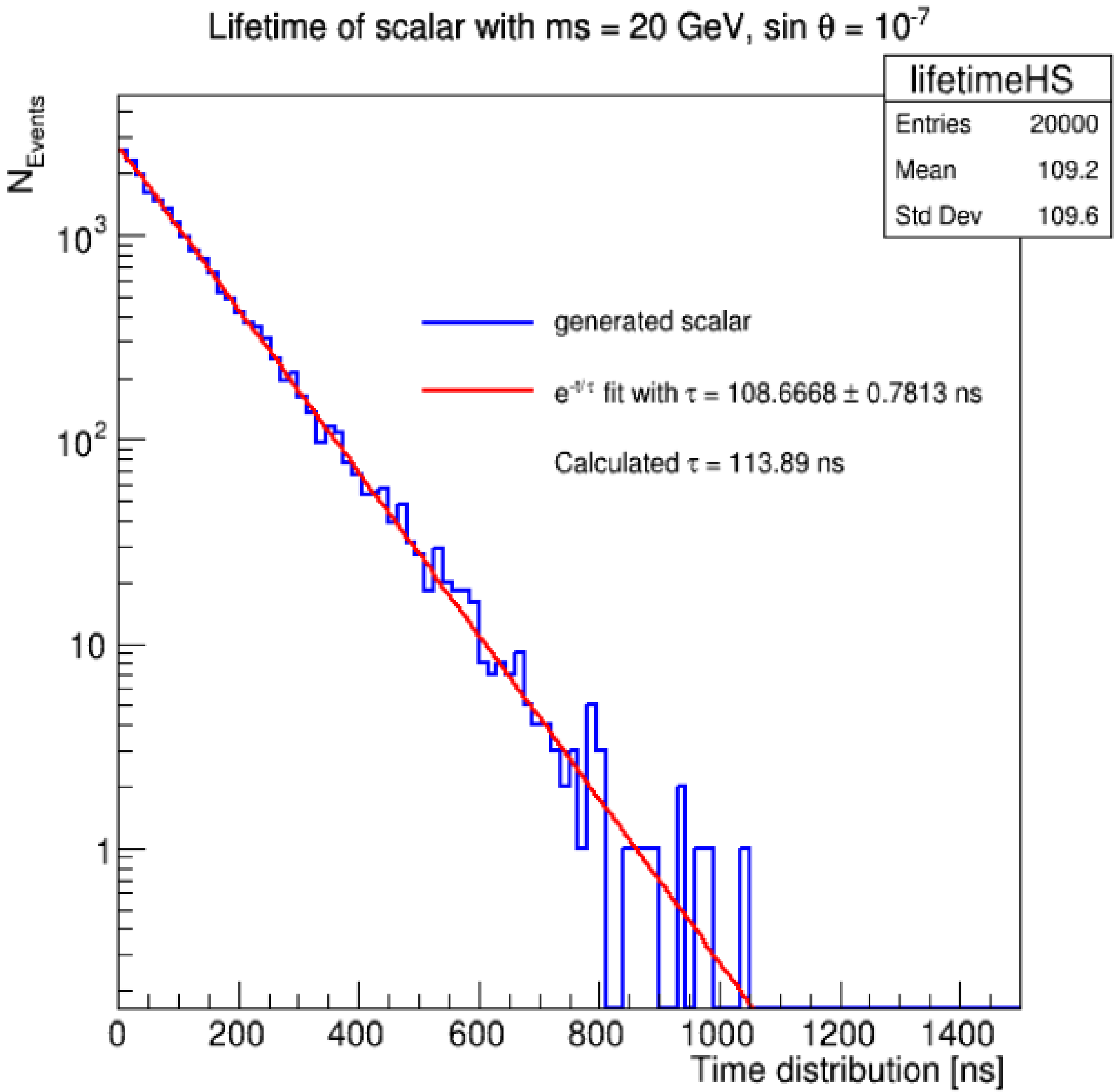
with m_s = 20 GeV



- For $\theta = 10^{-6}$



- For $\theta = 10^{-7}$



"Thank You"

for your listening