Probing the Electroweak Phase Transition with Long-Lived Scalars at Future Lepton Colliders

Xiang Chen[1], Xinchen Li[2], Liang Li[1], Michael J. Ramsey-Musolf[2]

[1] School of Physics and Astronomy, Shanghai Jiao Tong University

[2] Tsung-Dao Lee Institute, Shanghai Jiao Tong University

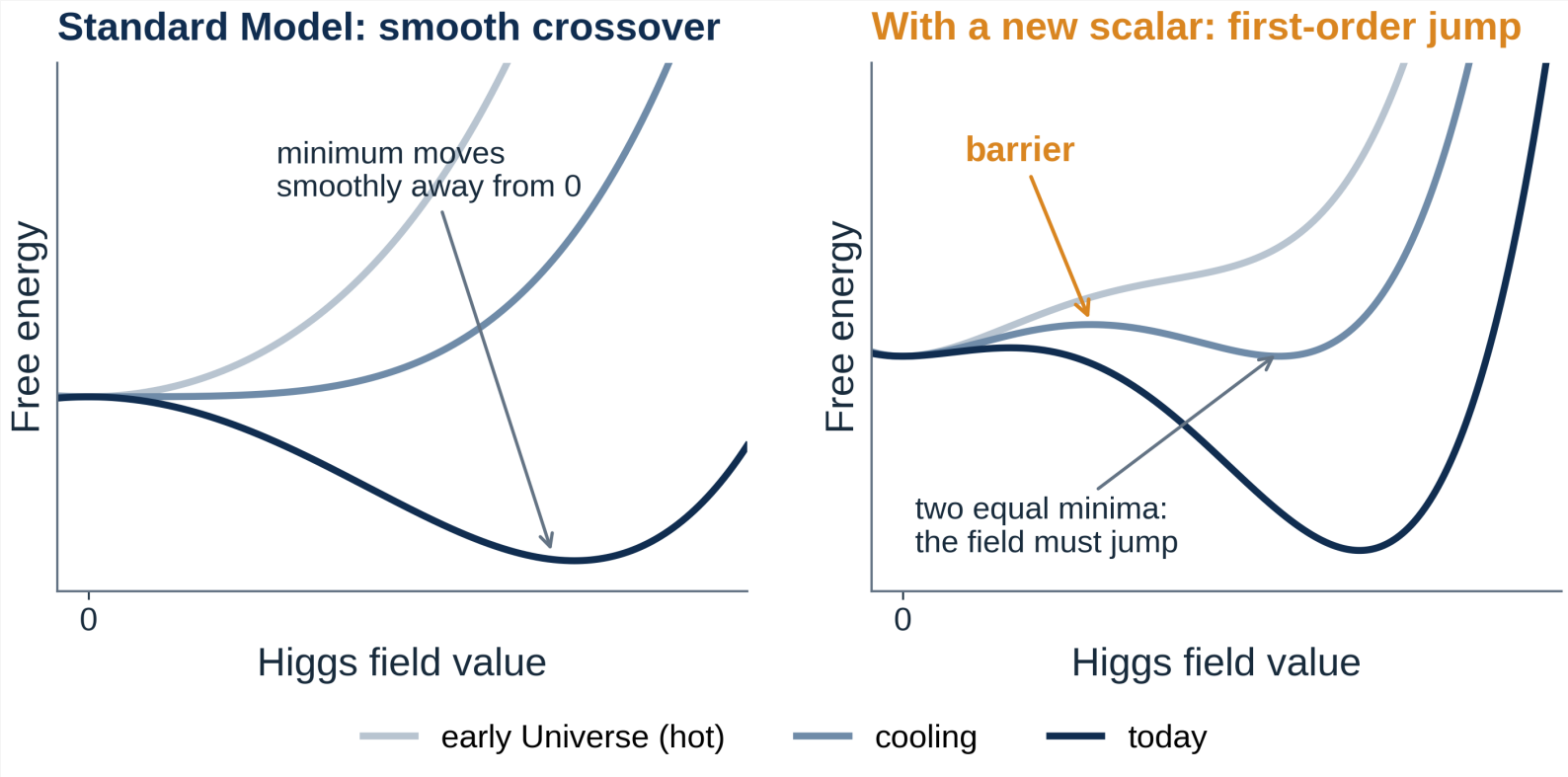
The 2026 International Workshop on the High Energy Circular Electron Positron Collider

2026/10/23

饮 水 思 源 • 爱 国 荣 校

Electroweak Phase Transition (EWPT)

- In the Standard Model, electroweak symmetry breaking proceeds through a **smooth crossover**, rather than a true phase transition.
- New physics could instead produce a strong first-order electroweak phase transition, produce gravitational waves
- A new scalar can reshape the finite-temperature Higgs potential and make the transition first order.



Electroweak Phase Transition and Long-Lived Scalars

- A **new gauge singlet S** is introduced [*Phys.Rev.D* 101 (2020) 11, 115035, *JHEP* 09 (2020) 179]
- **Coupling angle θ connects the EWPT model to the long-live particles (LLPs)**
- Strong first-order EWPT implies a non-zero BR(H → ss)
- Small mixing makes the scalar long-lived.

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \tfrac{1}{2}a_1|H|^2 S + \tfrac{1}{2}a_2|H|^2 S^2 + b_1 S + \tfrac{1}{2}b_2 S^2 + \tfrac{1}{3}b_3 S^3 + \tfrac{1}{4}b_4 S^4$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h \end{pmatrix}, \qquad S = v_s + s$$

$$h_1 = s\cos\theta + h\sin\theta$$
$$h_2 = -s\sin\theta + h\cos\theta$$

Mixing angle θ sets the lifetime

$$\Gamma_s \simeq \sin^2\theta\, \Gamma_{\mathrm{SM}}(m_s) \quad \Rightarrow \quad \tau \propto \frac{1}{\theta^2}$$

small θ → long-lived scalar

- The measurement of BR(H->ss) constrain the a2, which is the mixing parameter between SM and scalar particle

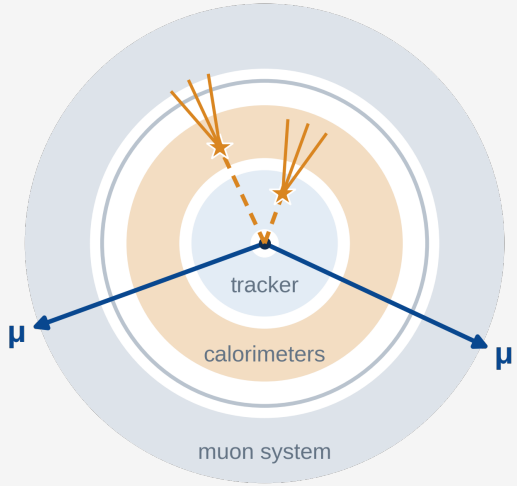
$$\Gamma(H \to ss) \simeq \frac{a_2^2 v^2}{32\pi m_H}\sqrt{1 - \frac{4m_s^2}{m_H^2}}$$

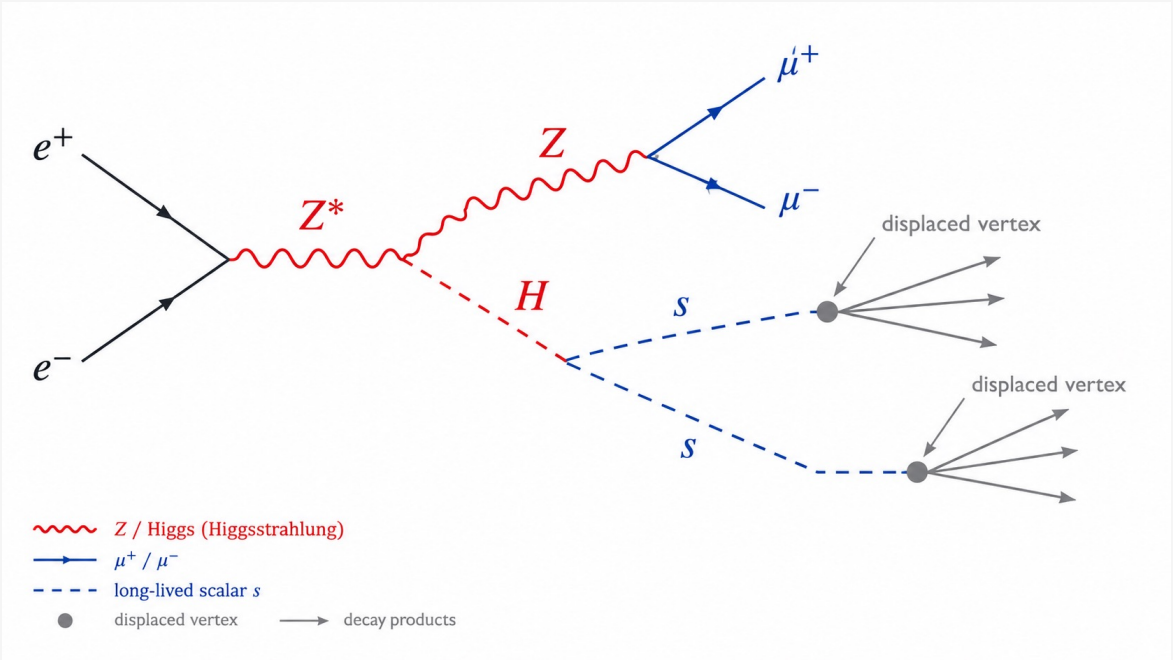
From Scalar Lifetime to Detector Acceptance

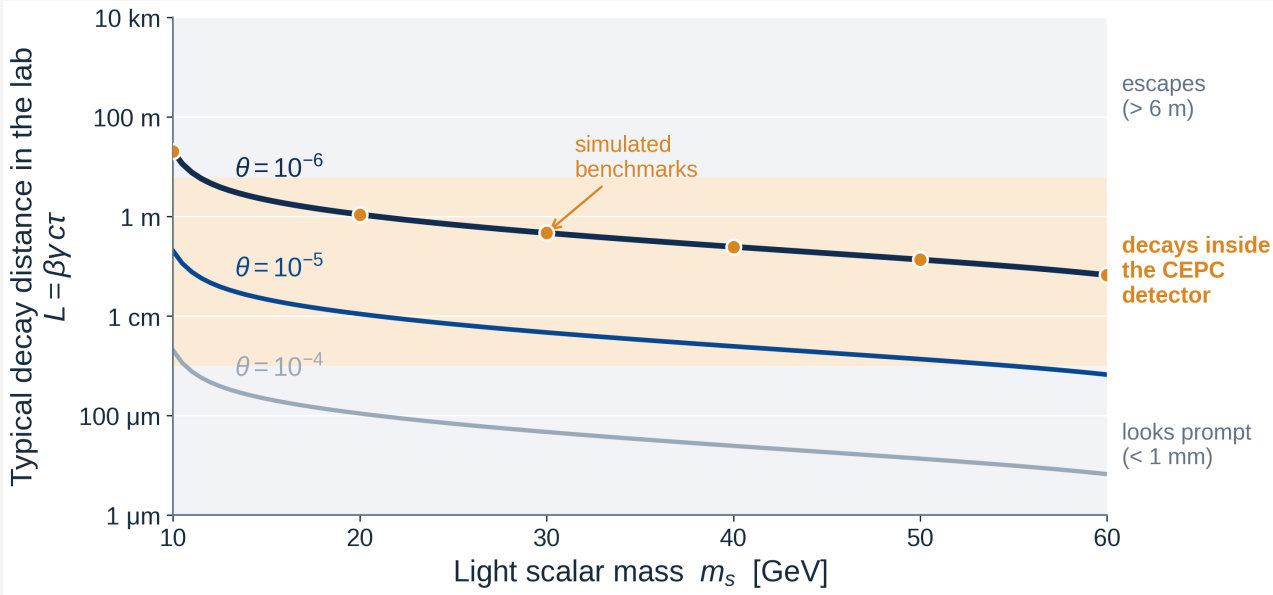
- Mixing angle gives different decay lengths at different masses.
- CEPC detector is sensitive for searching scalar S with θ in [10^{-4}-10^{-6}] region

$$\tau_s = \frac{\hbar}{\sin^2\theta\,\Gamma_{\mathrm{SM}}(m_s)}$$

$$\Gamma(s \to f\bar{f}) \sim \frac{N_c G_F m_s m_f^2}{4\sqrt{2}\pi}\left(1 - \frac{4m_f^2}{m_s^2}\right)^{3/2}$$



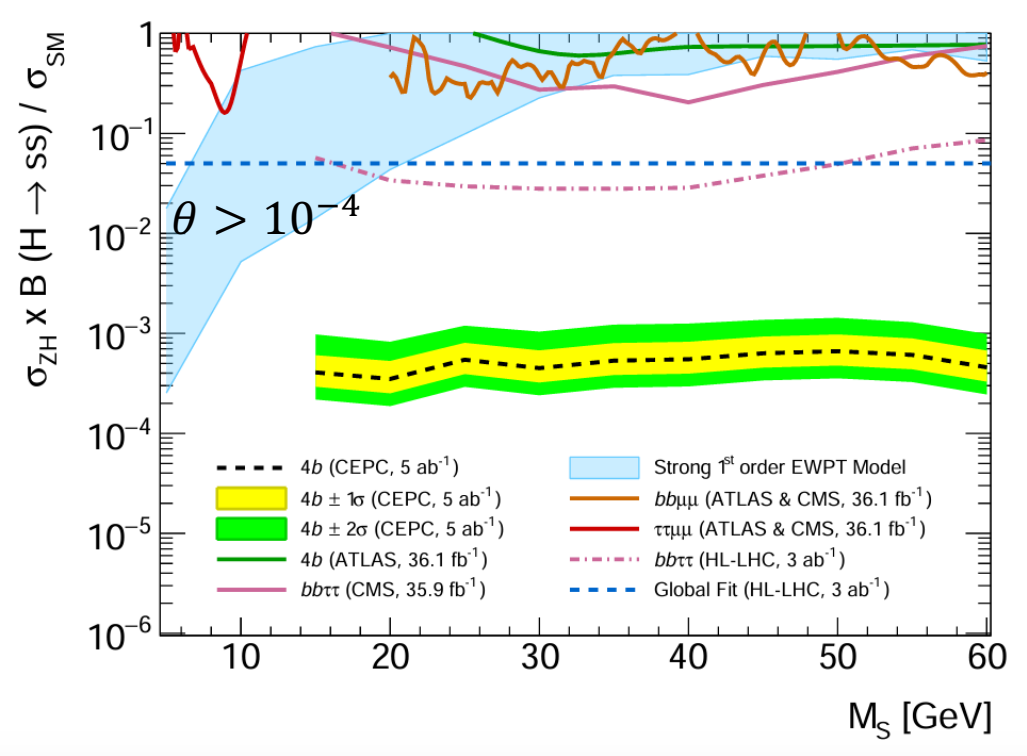




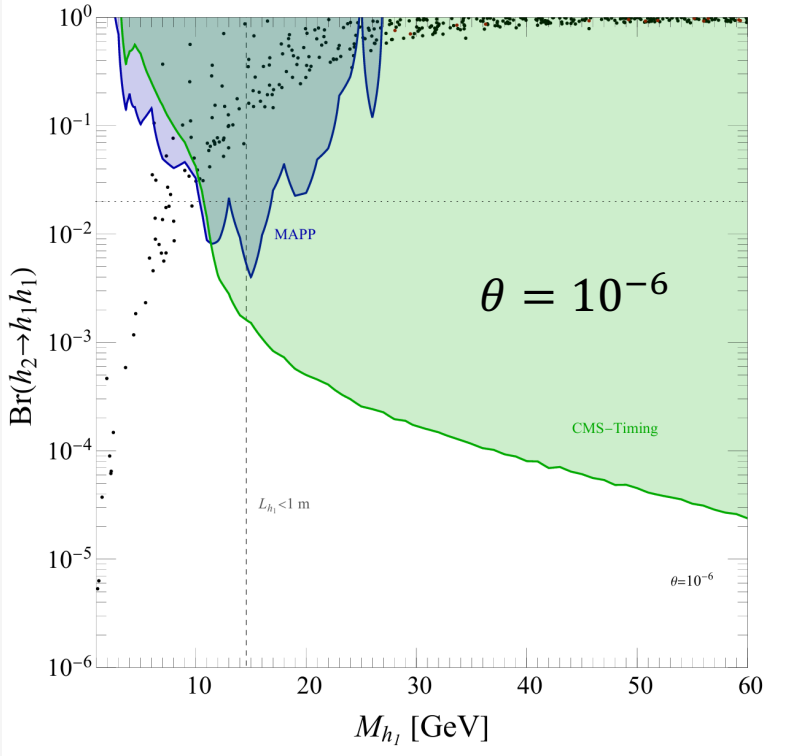
EWPT Search Status

- Prompt searches at the HL-LHC are sensitive to mixing angles down to 10^{-2}, while CPEC can extend to 10^{-4}
- For $\theta > 10^{-4}$, the light scalar becomes long-lived and poorly constrained
- For $\theta = 10^{-6}$, mostly long-lived, a large part of M_h versus Br(H->ss) phase space remains to be explored

LHEP 2023 (2023) 436



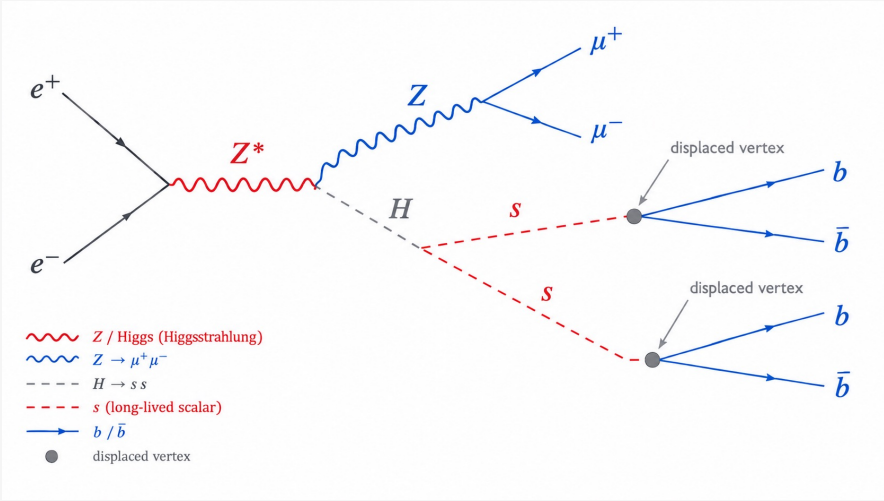
PhysRevD.105.115040 (2022)



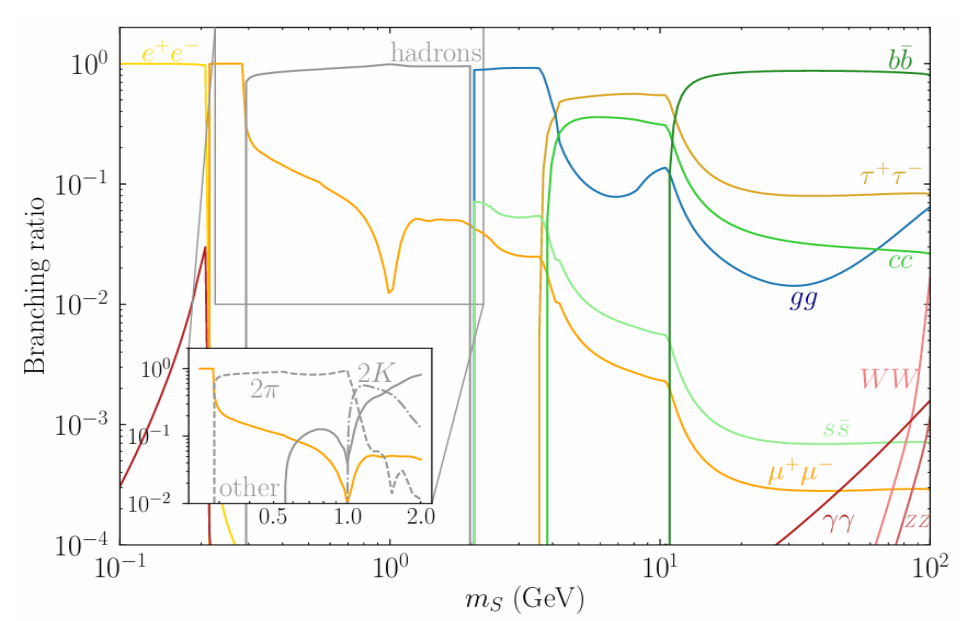
EWPT LLP Signal Detection

- Br(s->bb) reaches 80%, focusing on the h->ss->4b final state
- $\mu\mu + 4b$ channel is prioritized to make use of Z→$\mu\mu$ tagging and muon detector information
  - ee+$4b$ channel will be investigated later
- Major backgrounds:
  - m_s >10 GeV : ZH→$\mu\mu$qq and ZZ→$\mu\mu$qq
  - m_s < 10 GeV: ZH→$\mu\mu\tau\tau$ and ZZ→$\mu\mu\tau\tau$

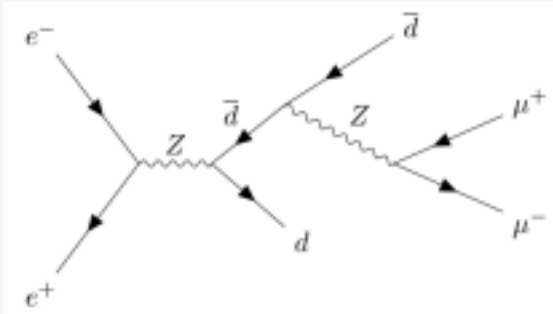
EWPT-LLP signal



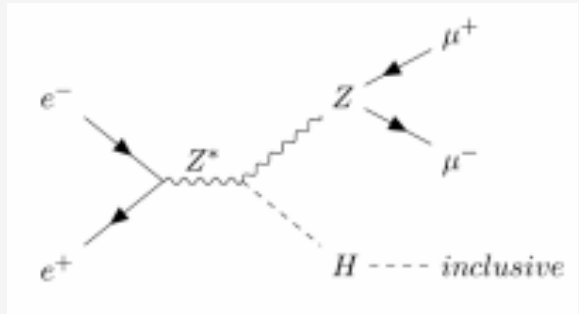
Decay branching ratio of the scalar s



ee → ZZ→$\mu\mu$qq

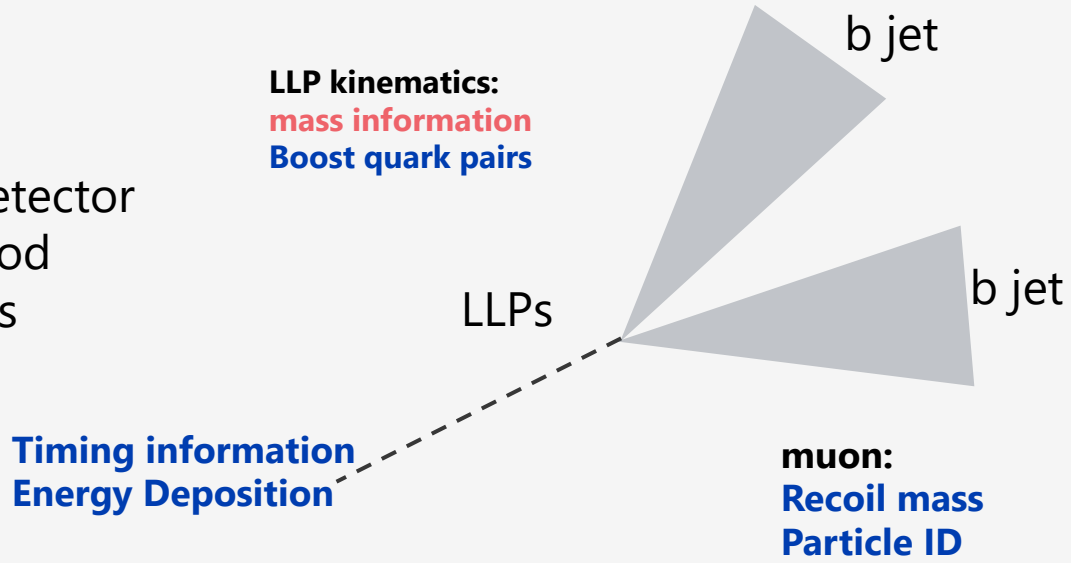


ee → ZH→$\mu\mu$bb



Analysis Strategy

- Using the **full simulation** samples with CEPC TDR detector
- Selection based method and machine learning method
- The most discriminating variable is the invariant mass
- Timing information can also help in some cases



Preprocessing
lepton ID WP selection

Selection-based method

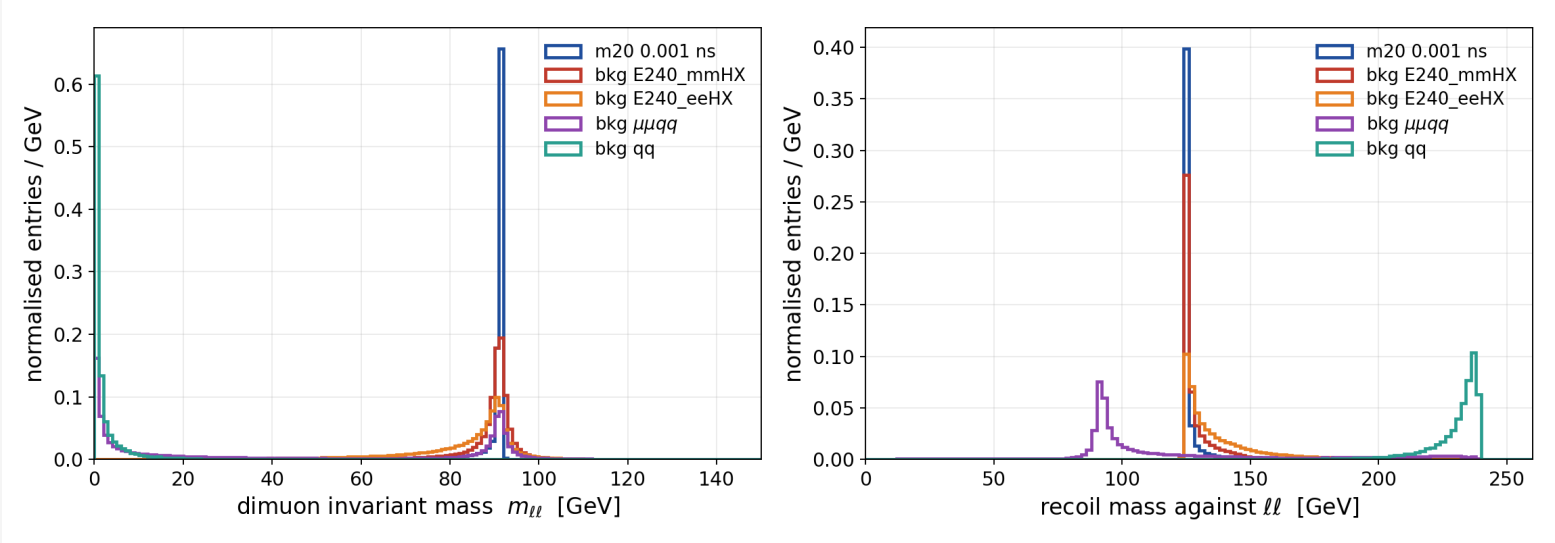
Two leptons and its invariant mass
Recoil mass(GeV): Z veto
Invariant mass(GeV): LLP signal mass selection
ΔT > 0.1 ns(0.05ns): LLP decay signal has large time difference

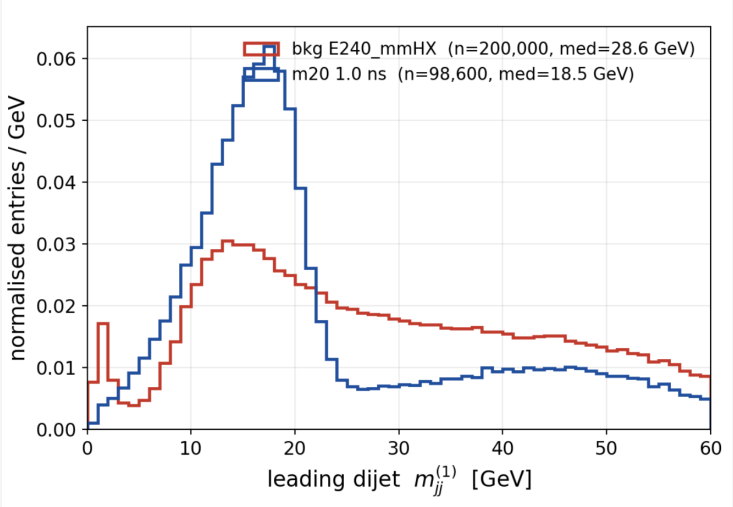
Machine learning method

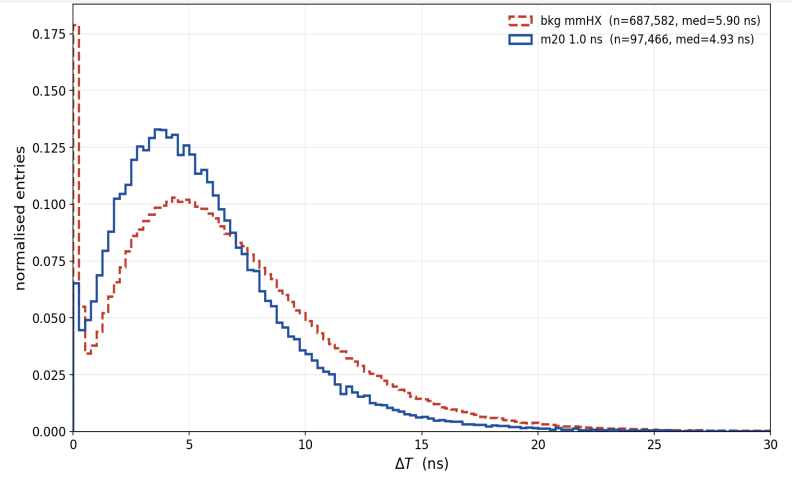
- CNN incorporates displaced-vertex information.
- XGBoost training with lepton and jet variables
- KFold optimization

Analysis Strategy: Selection-based Method

- Using CEPCSW v25.3.6 for full simulation.
- Time-of-Flight (TOF) detector with 10 ps timing resolution
- Background rejection reached 10^6, ~10^3 background yields remain (20 ab^{-1})
- Signal efficiency is ~1%, and the s/sqrt(b) is ~0.02

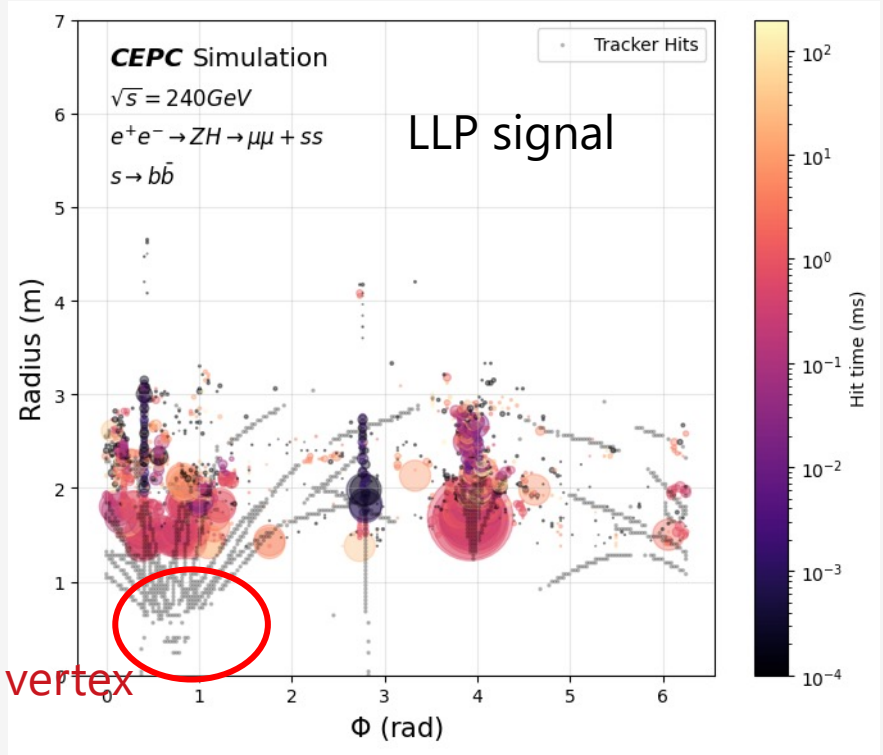




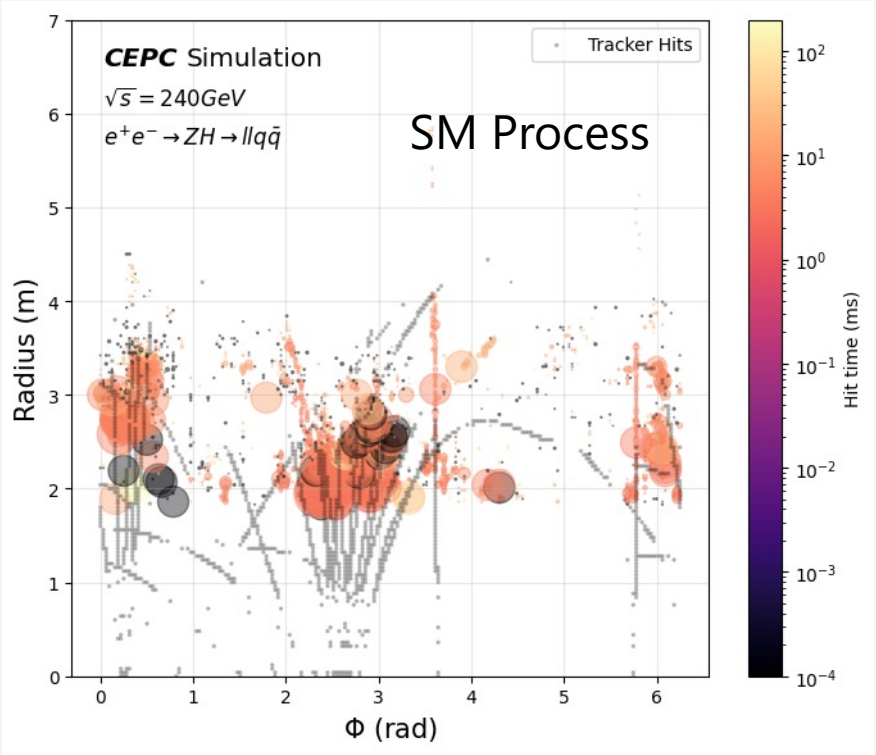


Machine Learning Method: CNN-ResNet

- Use low-level detection information without full event reconstruction
- Detector input information has been digitized and detector resolution has been considered
- Converting the detector information to 2D image
- Use ResNet18 model with the cross-entropy loss



Displaced vertex

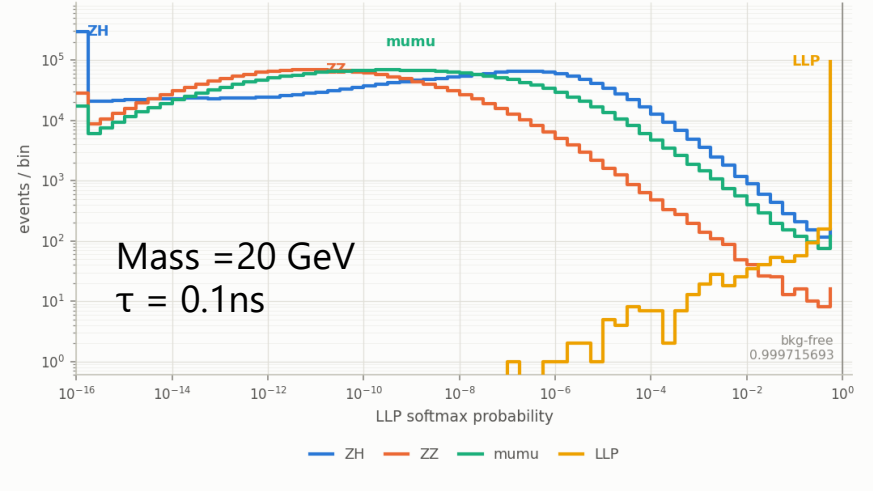


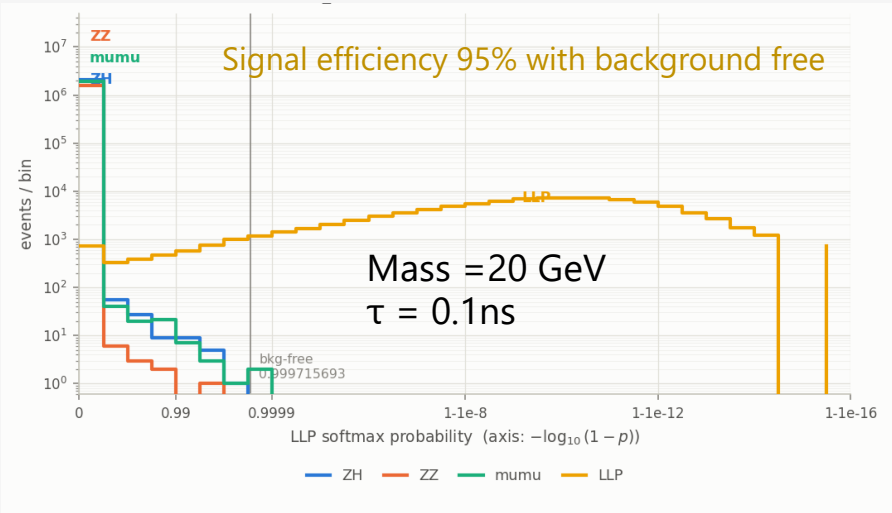
Cross Entropy Loss: $loss = -[\omega_0 * y_0 \log(x_0) + \omega_1 * y_1 \log(x_1) + \omega_2 * y_2 \log(x_2)]$

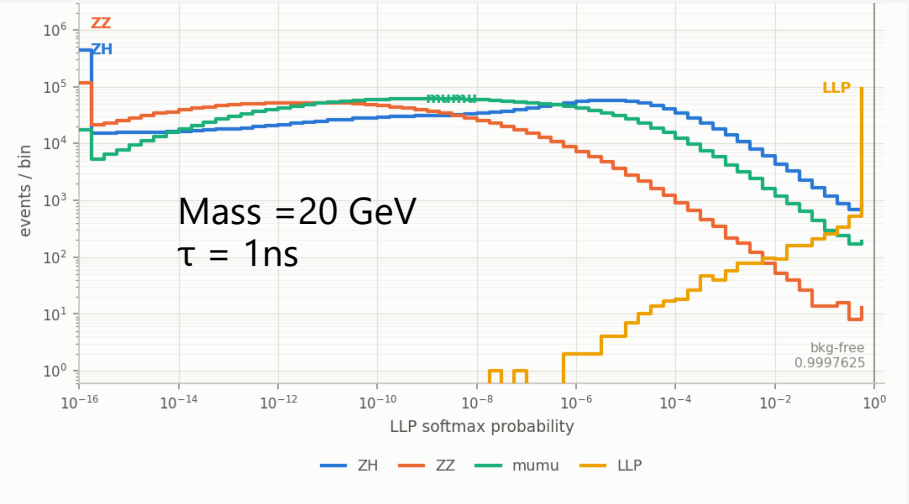
Class 0: 2-fermion bkg	Class 1: 4-fermion bkg	Class 2: LLP Signal
$\omega_0 = 0.5$	$\omega_1 = 0.25$	$\omega_2 = 0.25$

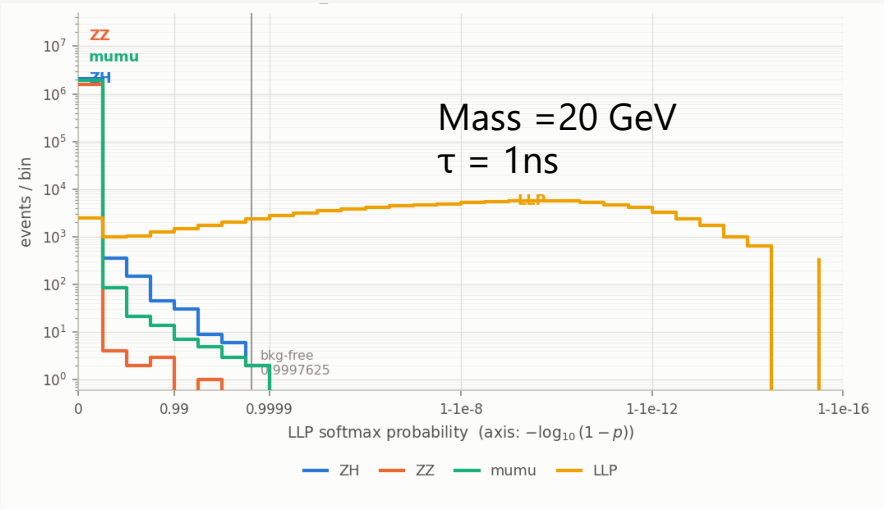
CNN Training Result

- Three class training: ZH vs $\mu\mu$qq vs EWPT LLP signal
- Training statistics: 10^7 MC events
- Good separation between signal and background with τ > 0.1ns



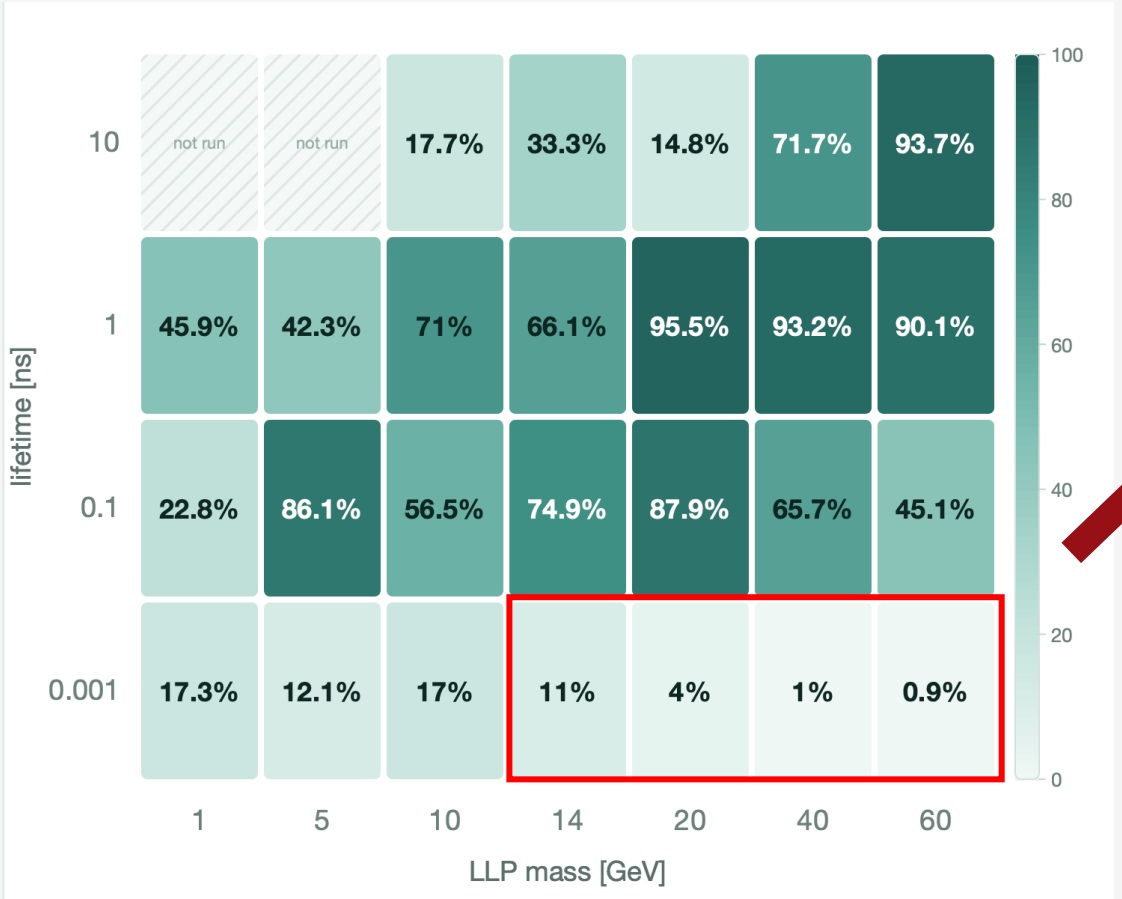




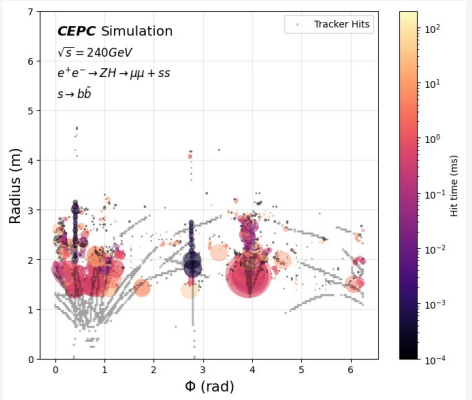


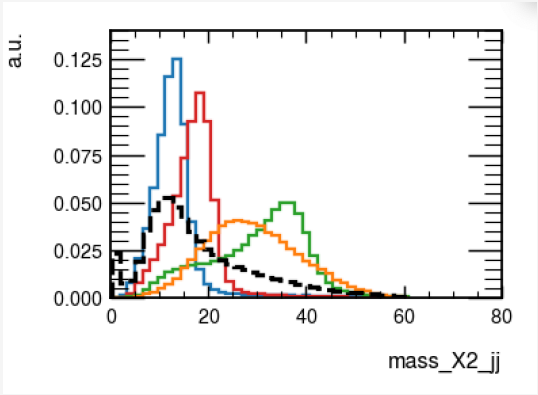
ML-based Analysis Result

- Signal efficiency > 90% at 1 ns for m_s from 20 to 60 GeV with nearly background free
- Efficiency decrease in the low mass and the higher lifetime region
- **Best efficiency at 95% with 20 GeV, 1ns**



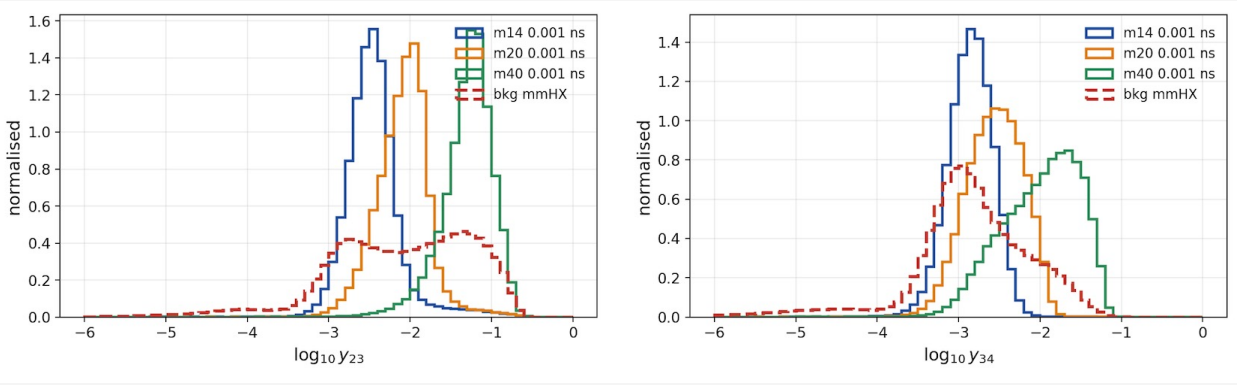
- Poor performance in short life-time with m_s >10 GeV: less discriminating displaced vertex pattern for CNN
- Can be improved when combining with jet and other variables

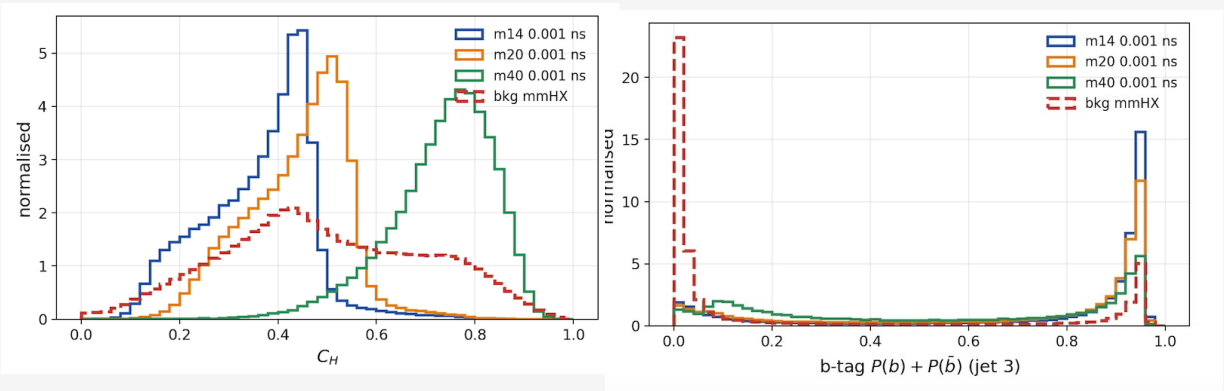




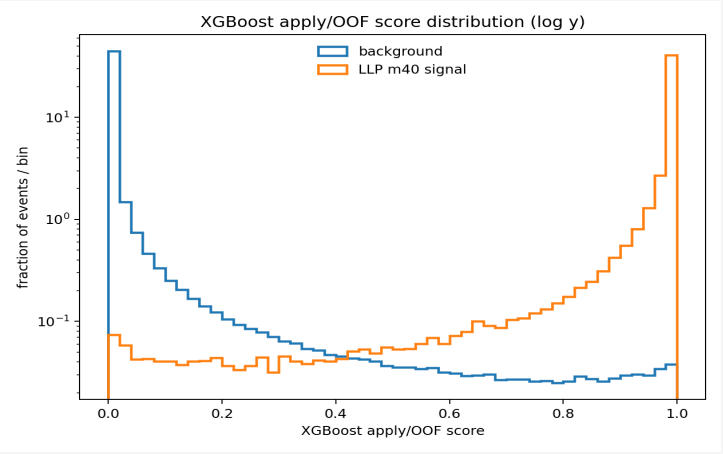
ML-based Analysis: Jet Varables

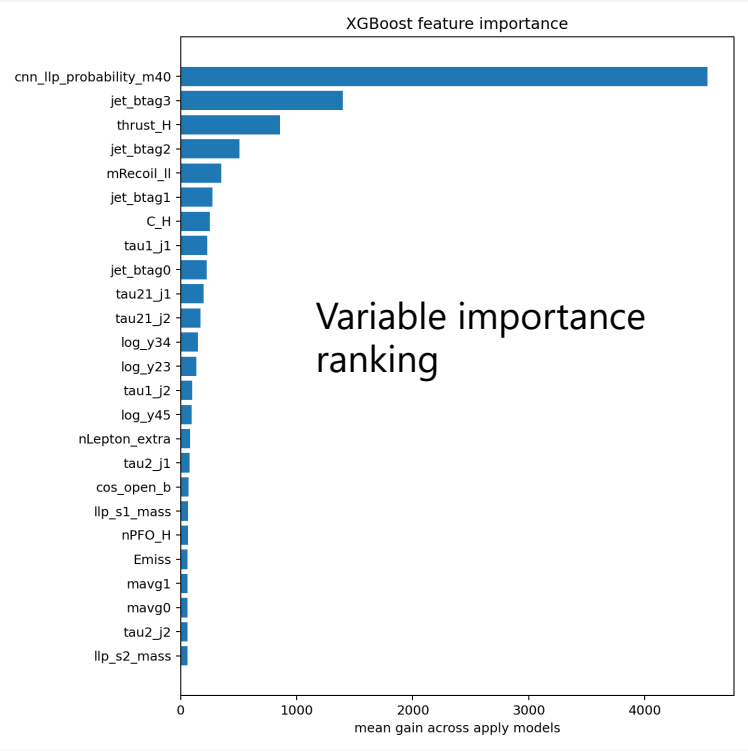
- The key challenge is to find 4 jets + lepton pairs in the final state
- Using event topological variables, such as b-tagging information, jet substructure(y34, y23), invariant mass information
- B-tagging done by the CEPCSW, using jet origin identification





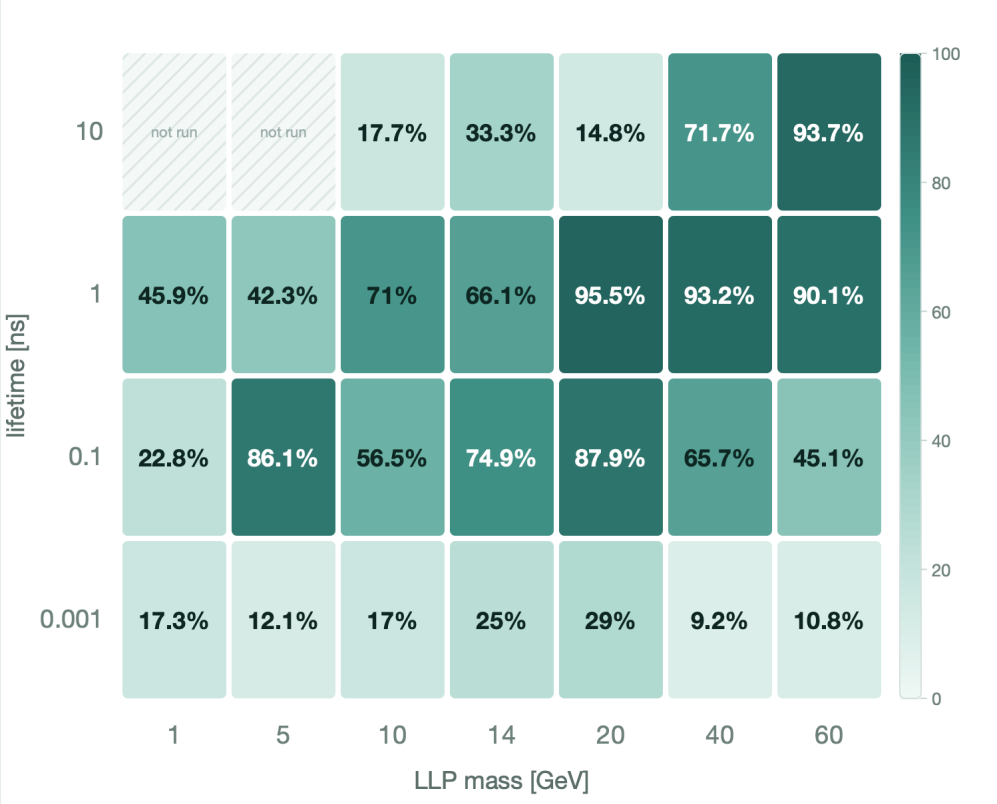
Signal efficiency improved from 4% to 25% at 20 GeV 0.001 ns

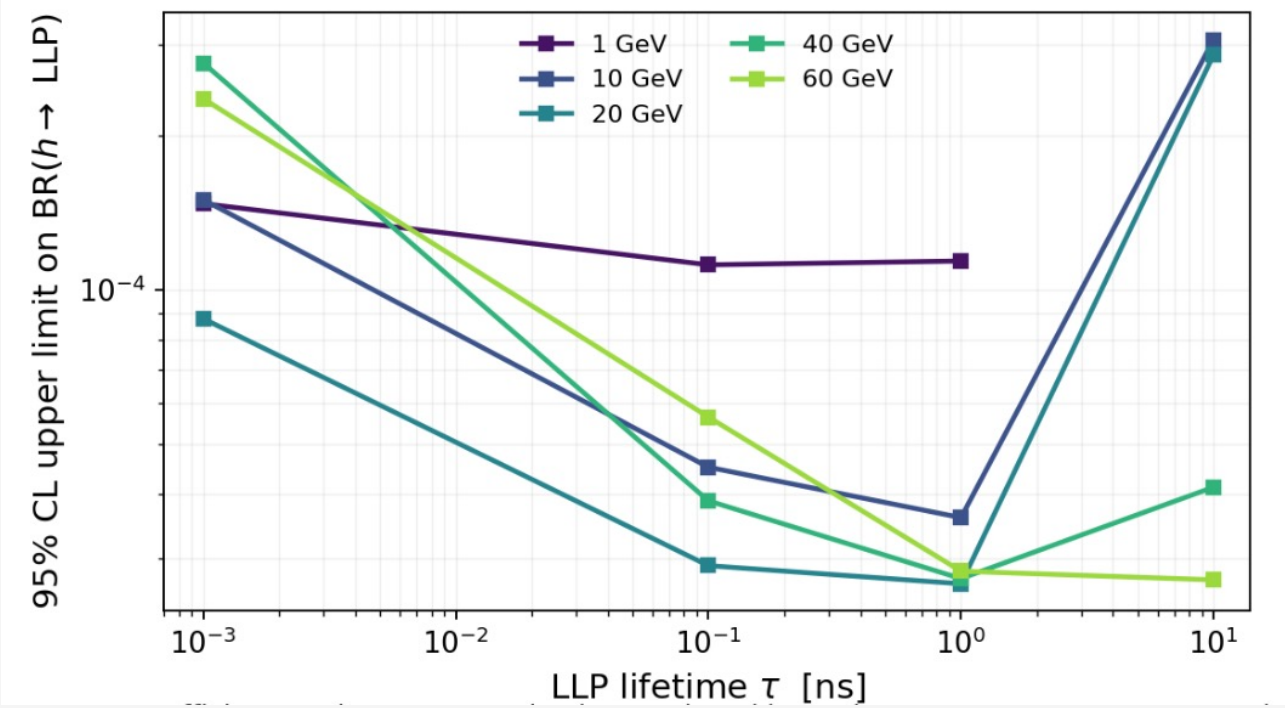




ML-Based Analysis Result

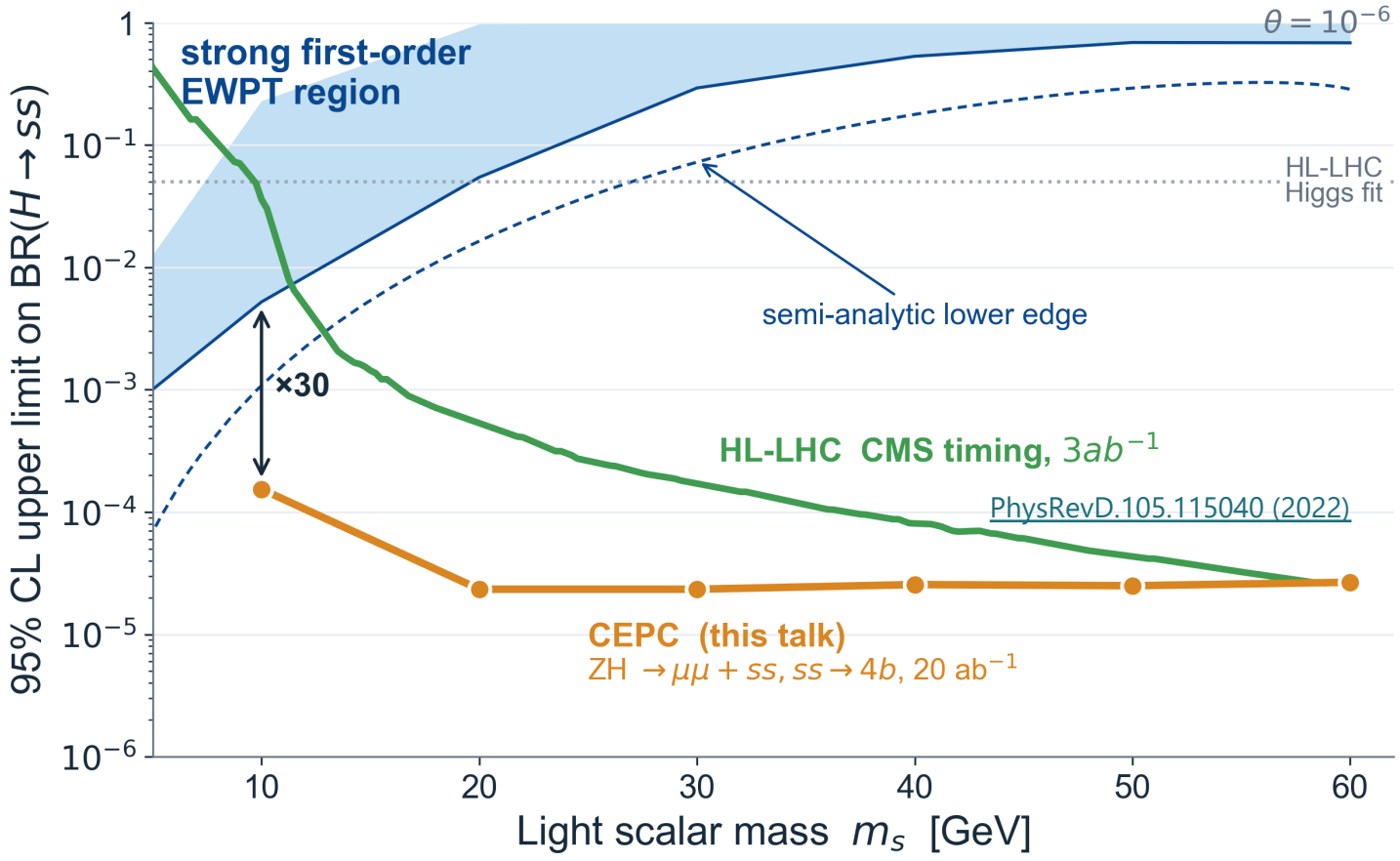
- The 0.001 ns signals efficiency has been improved 10 times with nearly background free condition, after combining CNN output and discriminating variables
- With 20 ab^{-1} luminosity, the best expected limit of BR(H → ss) reaches 10^{-5}





EWPT LLP Sensitivity

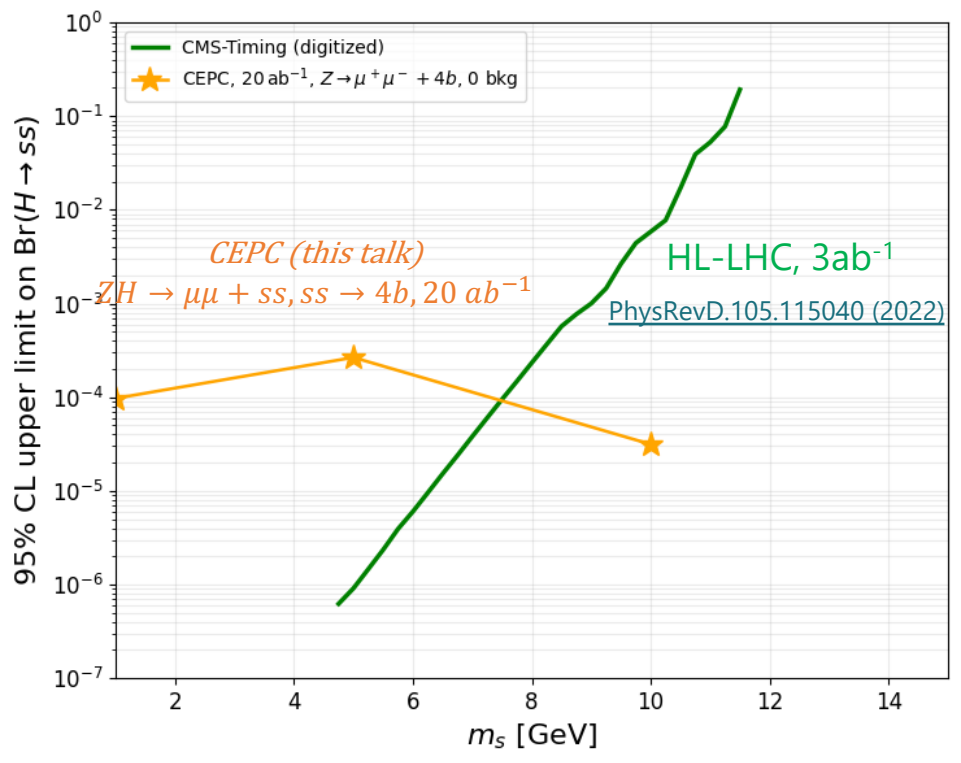
- Improvement compared to HL-LHC projection when θ =10^{-6}, τ from 0.3-10 ns
- 30 times better around 10 GeV region compared to HL-LHC projection

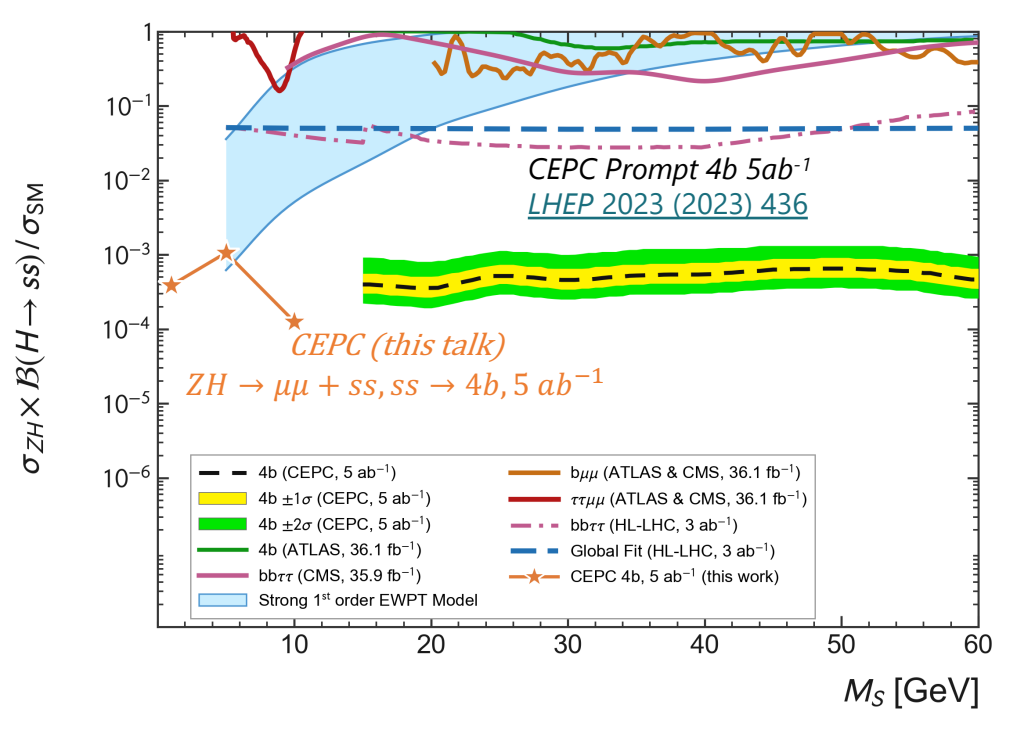


Mass	Limit @ bkg free
10 GeV	1.54*10^{-4}
20 GeV	2.34*10^{-5}
30 GeV	2.34*10^{-5}
40 GeV	2.55*10^{-5}
50 GeV	2.50*10^{-5}
60 GeV	2.67*10^{-5}

EWPT LLP Sensitivity

- Extend to previously unexplored light scalar region (m_s< 15 GeV) when θ =10^{-4} , τ from 0.003-0.1 ns
- Br(H->ss) reaches 10^{-5} at m_s =10GeV, 3 orders better than HL-LHC projection
- m_s < 10 GeV region dominated by tau and light quark final states, need dedicated tau/light quark analysis





Mass	Limit @ bkg free
1 GeV	9.7*10^{-5}
5 GeV	2.6*10^{-4}
10 GeV	3.1*10^{-5}

Summary and Outlook

- **EWPT LLPs search with deep learning at lepton collider**
  - CEPC offers a clean environment for searching for long-lived scalars in H → ss, ss → 4b
  - Preliminary covering the whole strong first-order region for 1–60 GeV, with the largest gain over HL-LHC at low mass.

- **Significant enhancement using deep learning techniques**
  - Low level detector images enable discrimination without full object reconstruction.
  - The signal efficiency using CNN method reaches 95% for m_s = 20 GeV at τ = 1 ns.
  - Adding XGBoost with event-level kinematics improves sensitivity to short lived signals by about an order of magnitude.

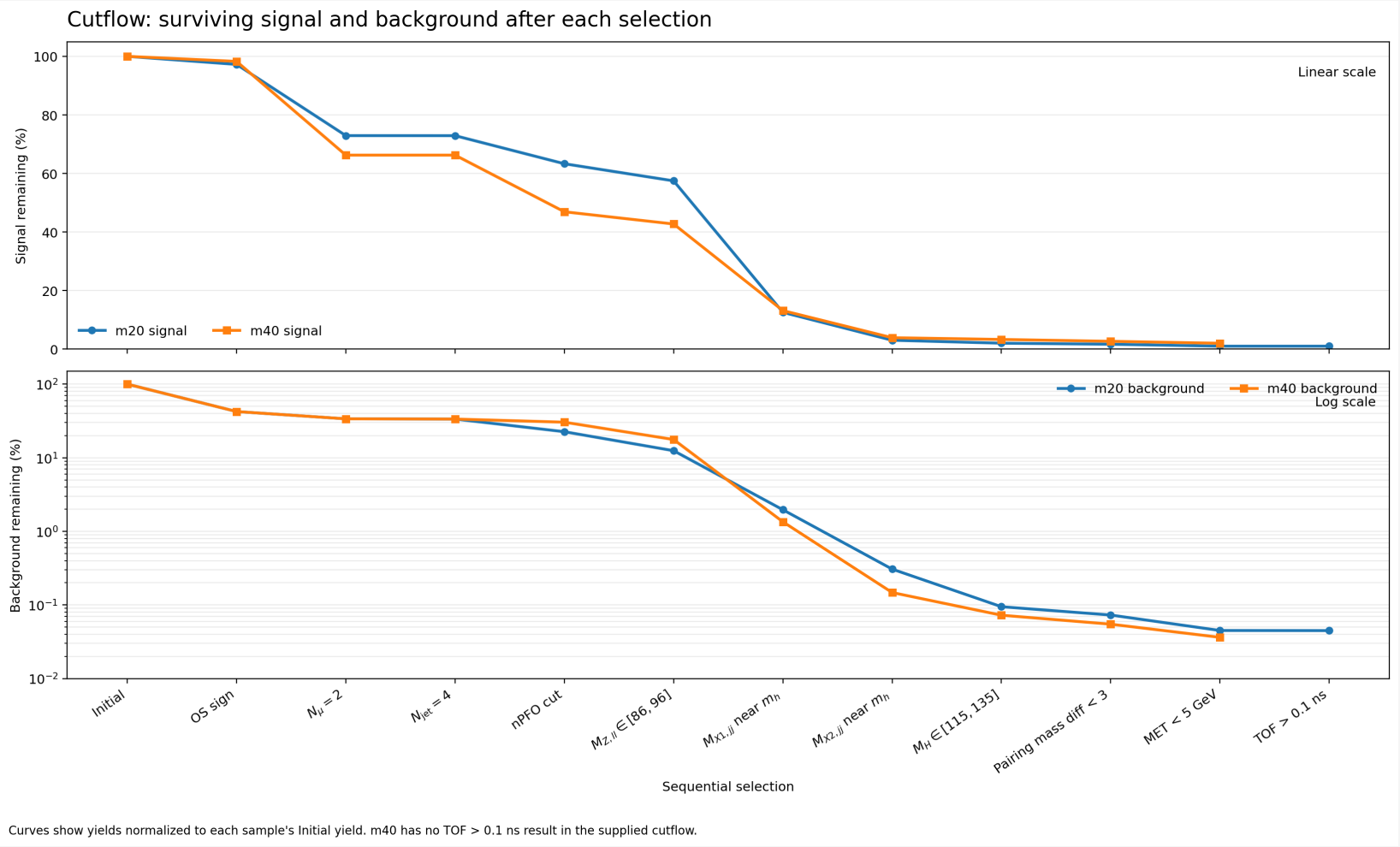
- **The BR(H → ss) sensitivity reaches the 10^{-5} level with 20 ab^{-1} in the $\mu\mu$+4b channel**
  - 30 times better sensitivity compared to HL-LHC projection around m_s=10 GeV region at $\theta = 10^{-6}$
  - Extend to low mass region (m_s < 15 GeV) at $\theta = 10^{-4}$, 3 order of magnitude improvement compared to HL-LHC projection with m_s =10 GeV

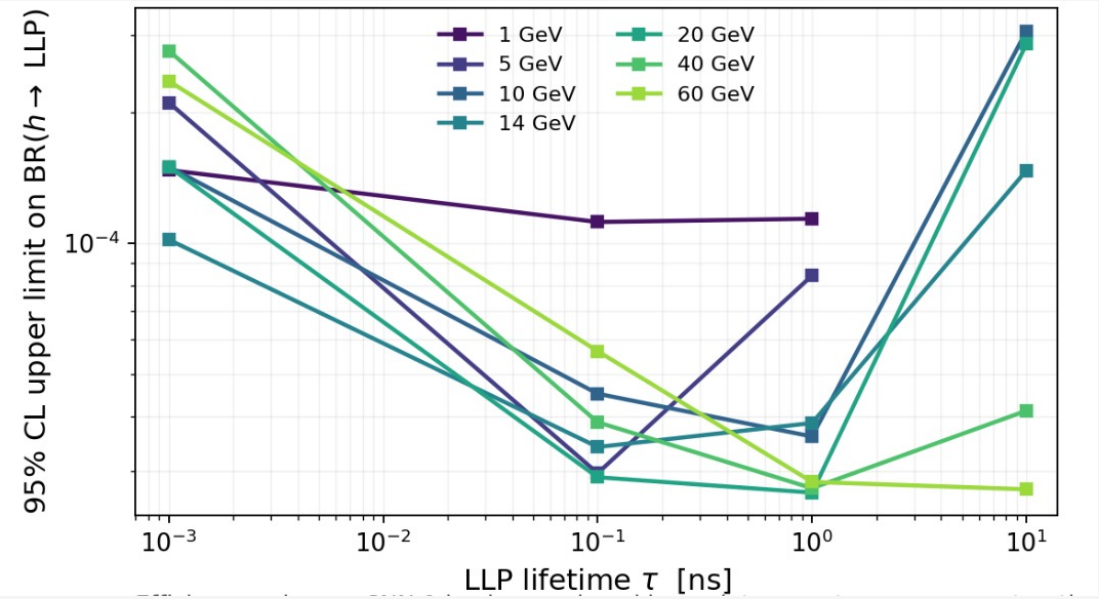
- **Outlook**:
  - Further optimize the sensitivity in the low-mass and short-lifetime regions.
  - Evaluate detector and modeling systematic uncertainties and refine the expected limits.
  - Explore ee+4b channel and tau/light quark final state

Backup

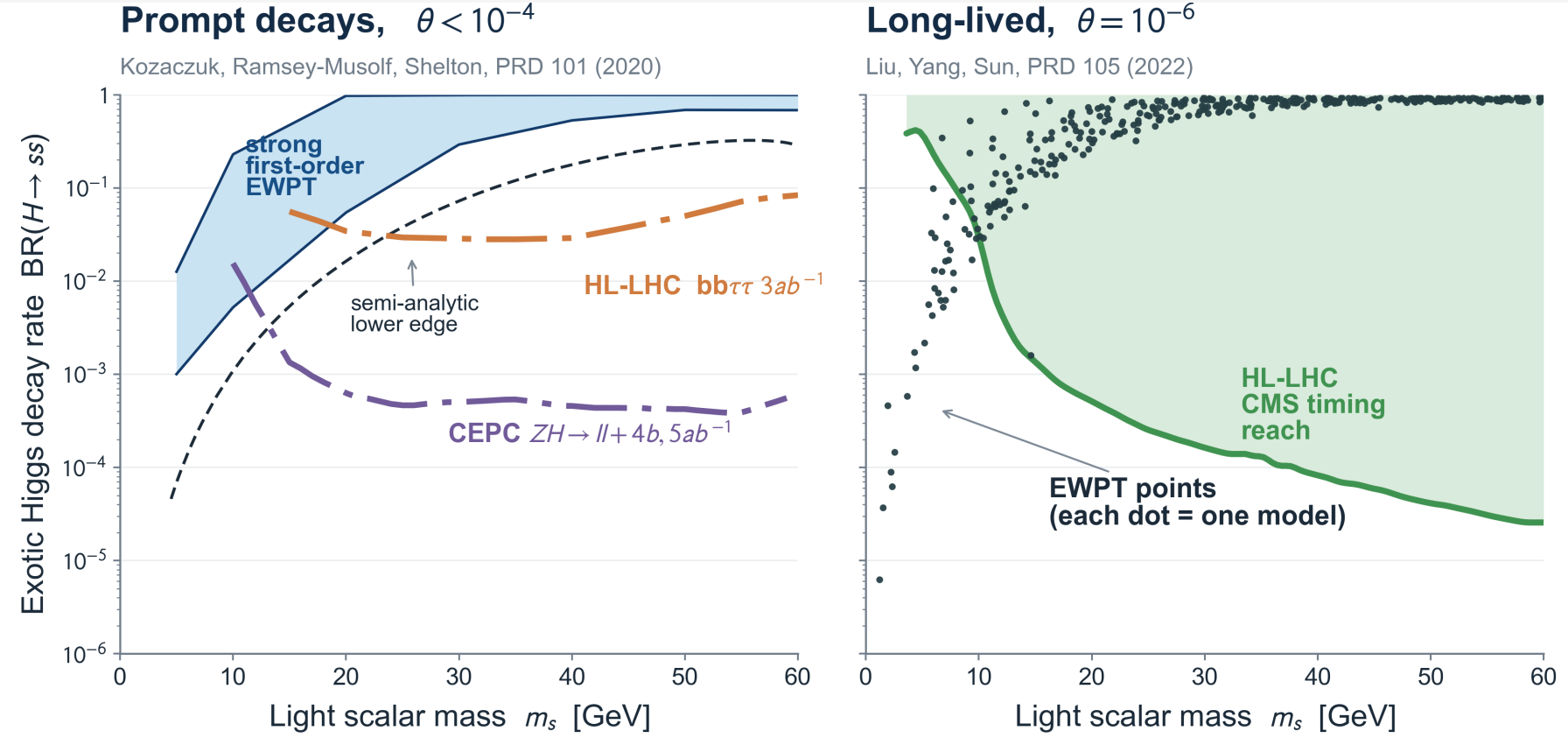
Analysis Strategy: Selection Based Selection

- Cut flow: the background rejection achieves 10^{-6}, with ~1%
- Invariant mass selection is the most powerful selection





m_s (GeV)	τ (ns), $\theta = 10^{-4}$	τ (ns), $\theta = 10^{-5}$	τ (ns), $\theta = 10^{-6}$
1	0.120	12.0	1200
5	0.0329	3.29	329
10	1.017×10^{-3}	0.1017	10.17
14	3.446×10^{-4}	0.03446	3.446
20	1.097×10^{-4}	0.01097	1.097
30	7.480×10^{-5}	0.007480	0.7480
40	5.724×10^{-5}	0.005724	0.5724
60	3.872×10^{-5}	0.003872	0.3872


Prompt decays, $\theta < 10^{-4}$
Kozaczuk, Ramsey-Musolf, Shelton, PRD 101 (2020)
strong first-order EWPT
semi-analytic lower edge
HL-LHC $bb\tau\tau$ $3ab^{-1}$
CEPC $ZH \to ll + 4b, 5ab^{-1}$
Exotic Higgs decay rate BR($H \to ss$)
Light scalar mass m_s [GeV]
Long-lived, $\theta = 10^{-6}$
Liu, Yang, Sun, PRD 105 (2022)
HL-LHC CMS timing reach
EWPT points (each dot = one model)
Light scalar mass m_s [GeV]

\(m_s\) (GeV)	0.001 ns	0.1 ns	1 ns	10 ns
1	100	99.86	48.76	6.49
5	100	99.92	71.44	24.41
10	100	100	99.78	46.8
20	100	100	99.84	59.93
40	100	100	99.95	86.18
60	100	100	100	100