Exotic Higgs Decays at a Muon Collider

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Prepared from arXiv:2604.06326v2

Motivation

Why exotic Higgs decays?

- The Higgs can act as a portal to light BSM particles.
- Exotic Higgs decays appear in scenarios related to: naturalness, dark matter, and electroweak phase transition.
- Comprehensive study and review: D. Curtin et al., Exotic decays of the 125 GeV Higgs boson, Phys. Rev. D 90 (2014) 075004 [1312.4992], M. Cepeda, S. Gori, V.M. Outschoorn and J. Shelton, Exotic Higgs Decays, 2111.12751.

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

Motivation

Can a future muon collider improve the sensitivity to exotic Higgs decays?

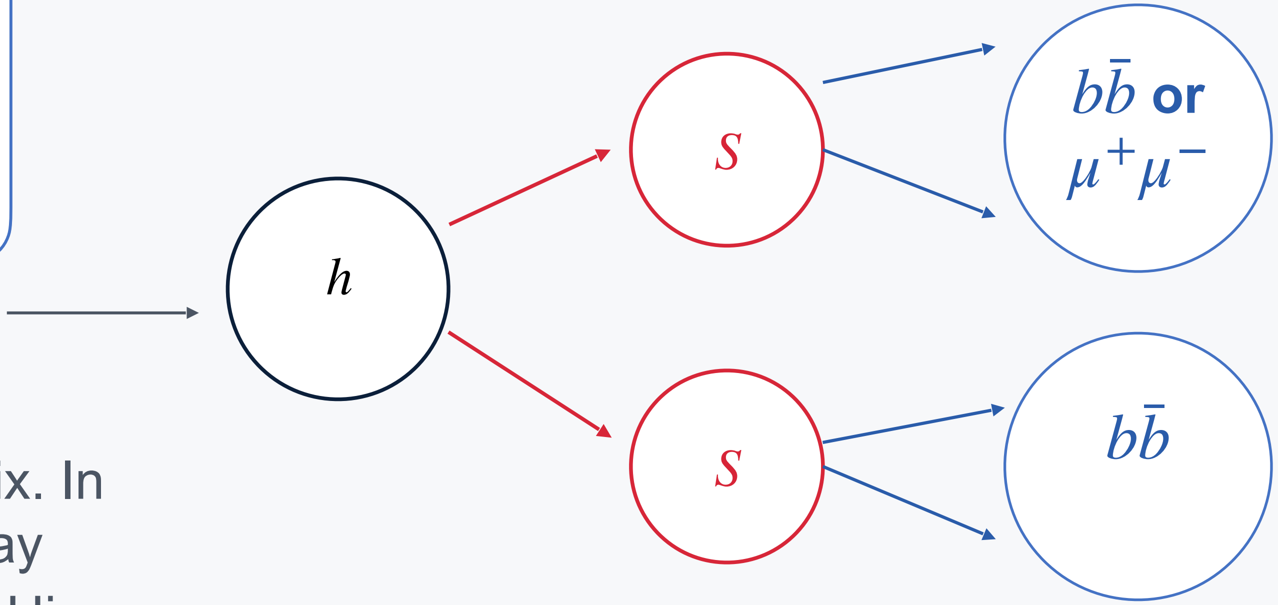
Muon collider advantages:

- cleaner than hadron colliders
- suppressed synchrotron radiation and reach higher centre of mass energy, compared to electron collid
- large vector boson fusion (VBF) Higgs production at high energy
- potentially better sensitivities to hadronic final states

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

Model : SM + real singlet scalar S

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



After electroweak symmetry breaking, h and S mix. In the small-mixing limit, the SM-like Higgs can decay exotically to the singlets S. The singlets S inherit Higgs-like couplings to SM particles. Therefore, the branching fractions of S follow those of a SM Higgs boson with mass m_S.

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

Production and final states

VBF production dominates at high-energy muon colliders

Muon collider benchmarks

3 TeV, 1 ab^{-1}
10 TeV, 10 ab^{-1}

Dominant Higgs production:
$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu h$ via W-boson fusion

σ ≈ 1 pb at $\sqrt{s} = 10$ TeV

Two analysis channels

$h \to SS \to 4b$

largest Higgs-portal rate
challenging jet combinatorics

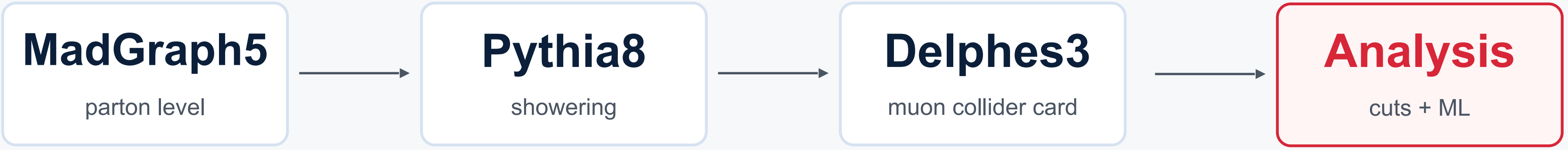
$h \to SS \to 2b2\mu$

clean dimuon resonance
smaller Higgs-portal rate

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

Simulation and object reconstruction

From partons to detector-level analysis



Generator-level cuts:

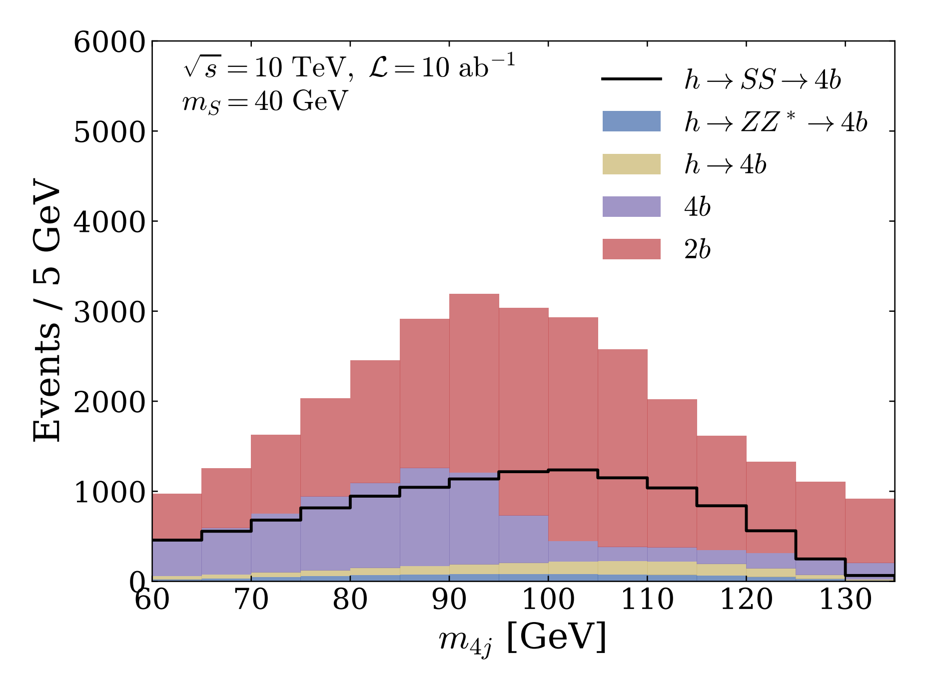
- b quarks: p_T > 15 GeV, $|\eta|$ < 2.5, ΔR_{bb} > 0.25
- muons: p_T > 0.5 GeV, $|\eta|$ < 8, $\Delta R_{\mu\mu}$ > 0.1

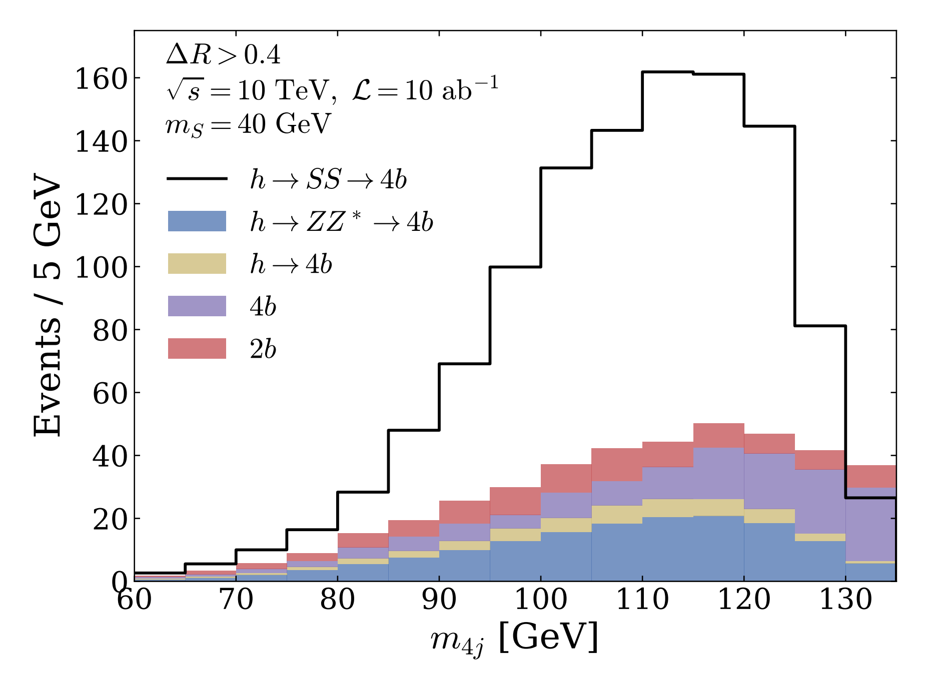
Detector-level choices

- muons selected with $|\eta_\mu|$ < 2.5
- b-tagging working point: 70% flat efficiency
- b-flavor matching cone: ΔR < 0.3

Preselection: resolve objects first

ΔR cuts suppress collinear radiation and wrong b-tagging





Preselection cuts

p_T^{jets} > 20 GeV; p_T^{μ}> 5 GeV

ΔR_{jj} > 0.4, and for $2b2\mu$ also $\Delta R_{\mu\mu}$, $\Delta R_{\mu j}$ > 0.4

Higgs window: m_{4b} or $m_{2b2\mu} \in$ [100, 150] GeV

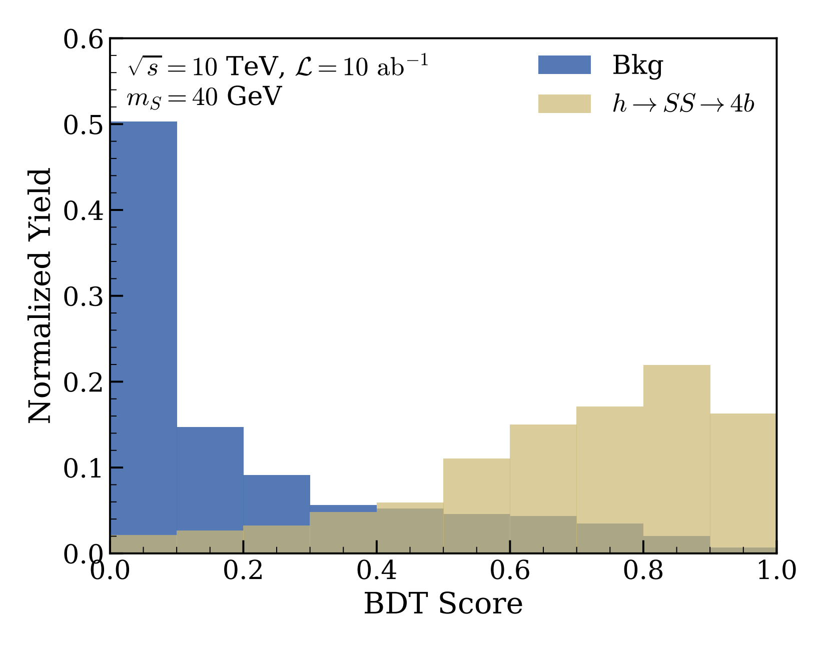
Key effect in 4b

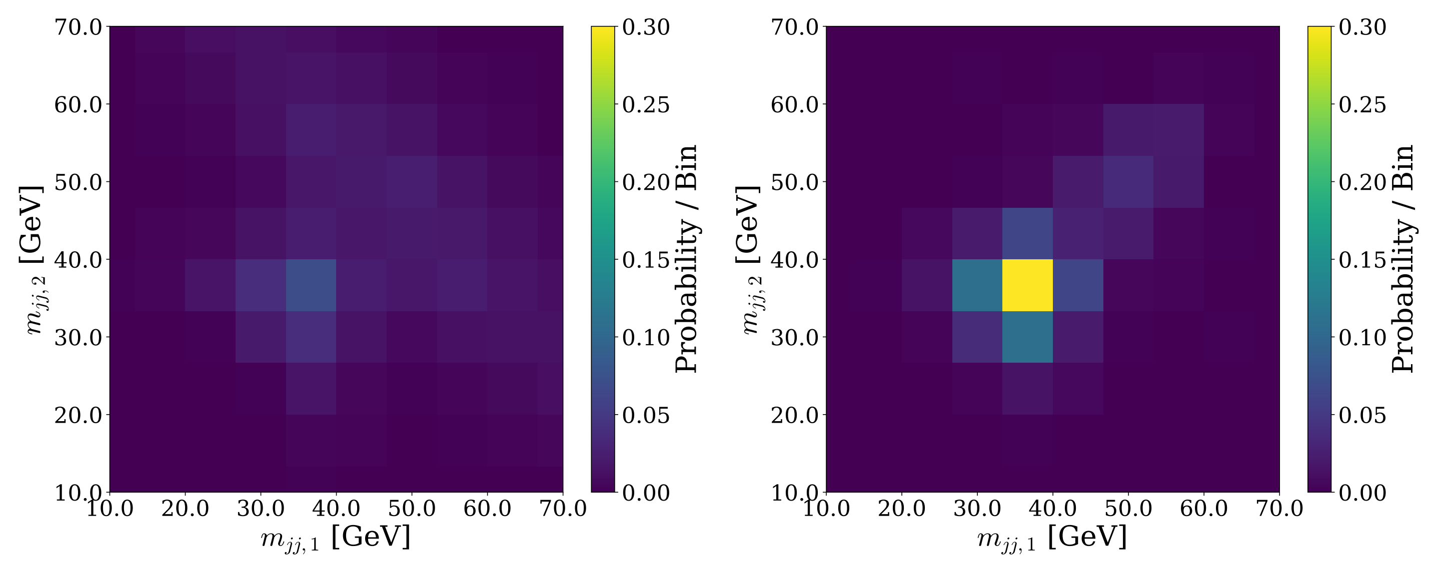
After ΔR_{jj} > 0.4, the m_{4j} peak moves closer to the Higgs mass, and reducible backgrounds drop significantly.

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

Machine learning selection

BDT learns resonance structure and jet pairing





Method

XGBoost boosted decision tree (BDT), 5 parallel models; select the threshold that maximizes $S/\sqrt{B}$ for each m_S benchmark.

What the BDT uses

$4b$: the minimum mass difference to the m_S benchmark $|m_{jj} - m_S|$.

$2b2\mu$: invariant mass of jet pairs m_{jj}

After ML, the two reconstructed S candidates concentrate near mS = 40 GeV

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

$4b$ channel after ML

m_S = 40 GeV, $\sqrt{s} = 10$ TeV, $\mathscr{L} = 10$ ab^{-1}

Process	σ [pb]	Preselection	ML selection	$4b$-tagging	Yield
Signal					
$h \to SS \to 4b$	$0.84 \times$ BR	1.0×10^{-2}	7.0×10^{-3}	1.9×10^{-3}	$1.3 \times 10^4 \times$ BR
Background					
$h \to ZZ^* \to 4b$	5.0×10^{-4}	2.3×10^{-2}	6.6×10^{-3}	1.4×10^{-3}	7.0
$h \to 4b$	1.0×10^{-3}	2.9×10^{-3}	1.3×10^{-3}	2.9×10^{-4}	2.9
$2b$	2.0×10^{-2}	8.4×10^{-4}	2.7×10^{-4}	$\leq 3.8 \times 10^{-6}$	≤ 0.76
$4b$	8.7×10^{-3}	1.1×10^{-3}	2.5×10^{-4}	1.7×10^{-5}	1.5

Why this works: small final background + sizable $4b$ branching fraction

Signal yield after all cuts:

$1.3 \times 10^4 \times$ **BR**($h \to SS \to 4b$)

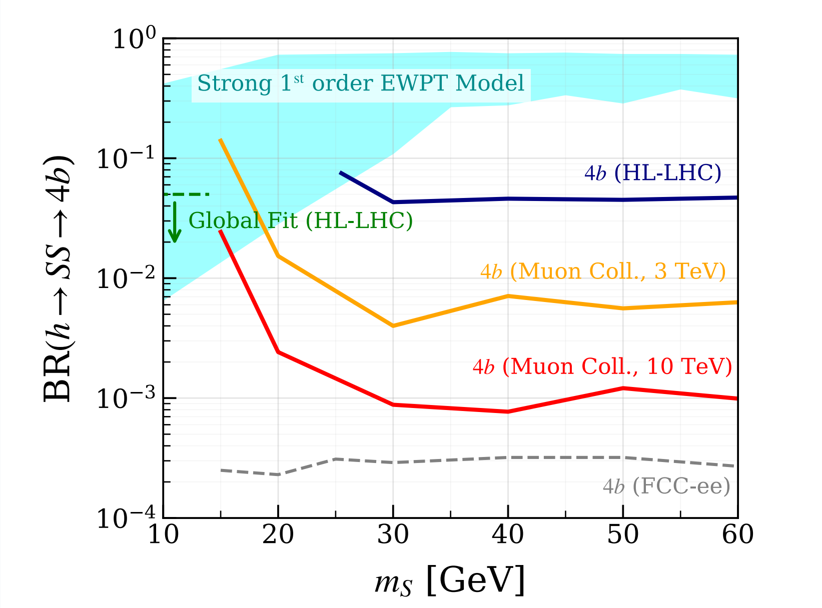
Total background: $\mathcal{O}(10)$ events

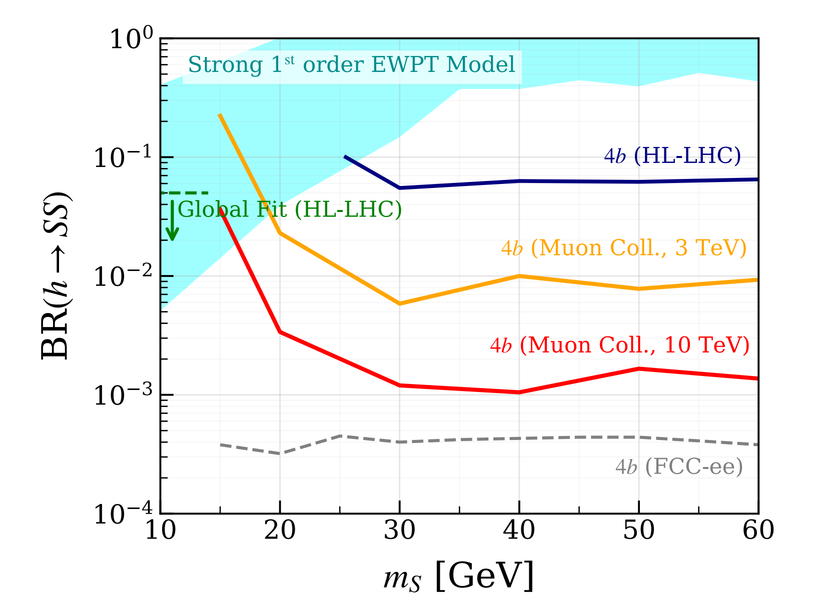
ML + $4b$-tagging leaves the irreducible $h \to ZZ^* \to 4b$ background as the largest component.

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

Main result: $4b$ sensitivity

Best channel for the Higgs-portal benchmark





Projected 95% CL reach

$\sqrt{s}$ = 10 TeV, $\mathscr{L}$ = 10 ab^{-1}:

BR($h \to SS$) ~ 10^{-3} for $m_S \gtrsim$ 20 GeV

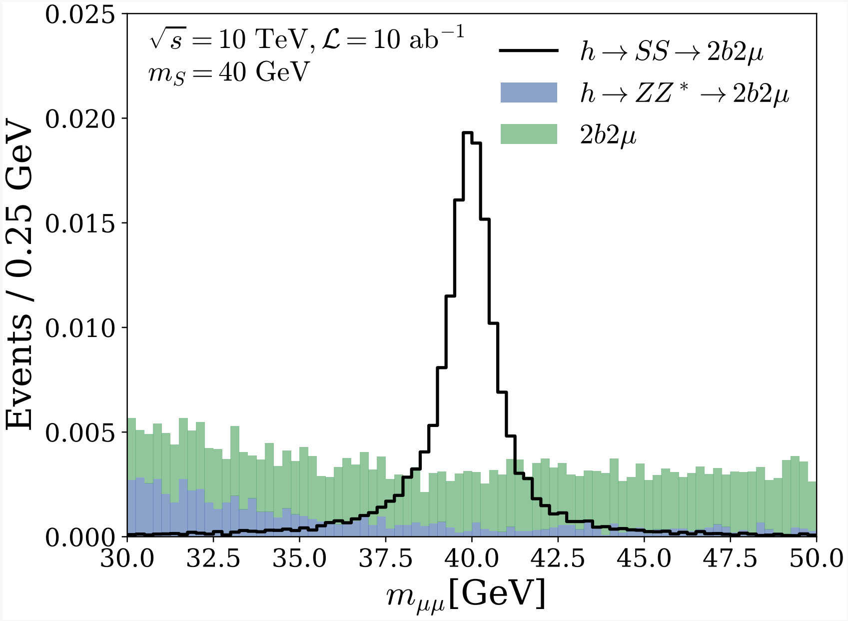
$\sqrt{s}$ = 3 TeV, $\mathscr{L}$ = 1 ab^{-1}:

BR($h \to SS$) ~ 10^{-2} for $m_S \gtrsim$ 20 GeV

Low-m_S sensitivity weakens because the jets become more collimated, making it difficult to get four resolved b-jets.

$2b2\mu$ channel: clean resonance

Use $m_{\mu\mu}$ only after ML to avoid classifier domination



Process	σ [pb]	Preselection	ML selection	$2b$-tagging	$m_{\mu\mu}$	Yield
Signal						
$h \to SS \to 2b2\mu$	$0.84\times$Br	8.0×10^{-2}	7.8×10^{-2}	3.8×10^{-2}	3.7×10^{-2}	$3.1 \times 10^{5}\times$Br
Background						
$h \to 2b2\mu$	4.4×10^{-4}	2.4×10^{-2}	4.2×10^{-3}	1.4×10^{-3}	2.2×10^{-4}	0.96
$2b2\mu$	1.2×10^{-3}	3.0×10^{-3}	9.8×10^{-4}	3.9×10^{-4}	1.0×10^{-4}	1.2

Why $2b2\mu$ helps

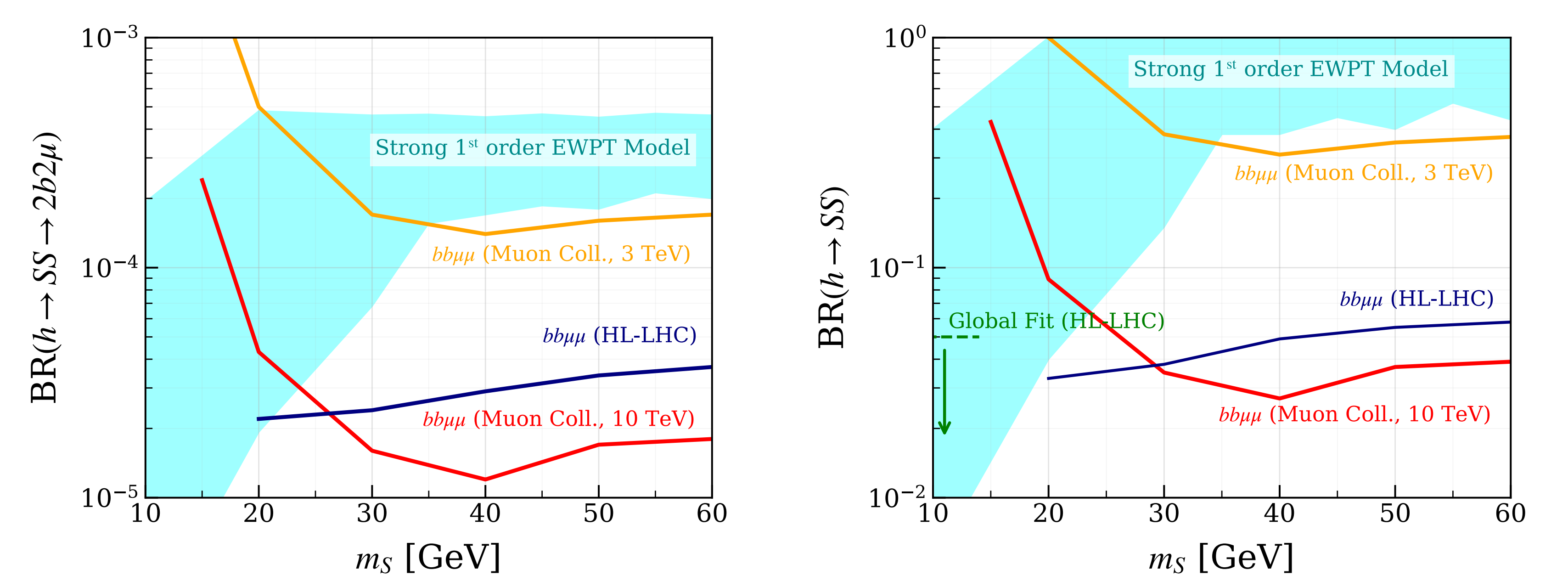
narrow dimuon resonance
small final background
strong model-independent reach

But in the Higgs-portal model, $S \to \mu\mu$ is rare, so this channel becomes rate-limited.

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

$2b2\mu$ sensitivity

Clean experimentally, but model-dependent rate is small



Model-independent final state

For $\sqrt{s}$ = 10 TeV case can probe **BR($h \to SS \to 2b2\mu$) ~ 10^{-5}**

Higgs-portal model

BR($S \to \mu\mu$) is small, so the inferred BR($h \to SS$) reach is much weaker than $4b$.

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2

Conclusions

1. A future muon collider can probe exotic Higgs decays with fully hadronic and semi-leptonic final states.

2. For $h \to SS$ in a Higgs-portal model, the $4b$ channel is the leading discovery mode.

3. **At $\sqrt{s} = 10$ TeV with $\mathscr{L} = 10$ ab^{-1}, $4b$ reaches BR($h \to SS$) ~ 10^{-3} for $m_S \gtrsim 20$ GeV.**

4. $2b2\mu$ gives a clean dimuon resonance and reaches BR($h \to SS \to 2b2\mu$) ~ 10^{-5} model-independently.

Thank you — questions?

Source: Fan, Li, Liu, Wang, Zhou, arXiv:2604.06326v2