Investigating the Invisible Higgs Coupling at a Muon Collider

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Introduction

- Investigating the invisible Higgs coupling at a MuC with a dedicated forward muon detector
- Clean experimental environment of MuC enables high sensitivity, especially when combined with ML techniques
- After observing a signal, it is crucial to verify whether the Higgs truly mediates the process
- ML-based hypothesis test provides strong discrimination between the signal and alternative models

The signal model

$$\mathscr{L}_{\text{int.}} \supset -\frac{1}{\Lambda}|H|^2\bar{\chi}\chi$$

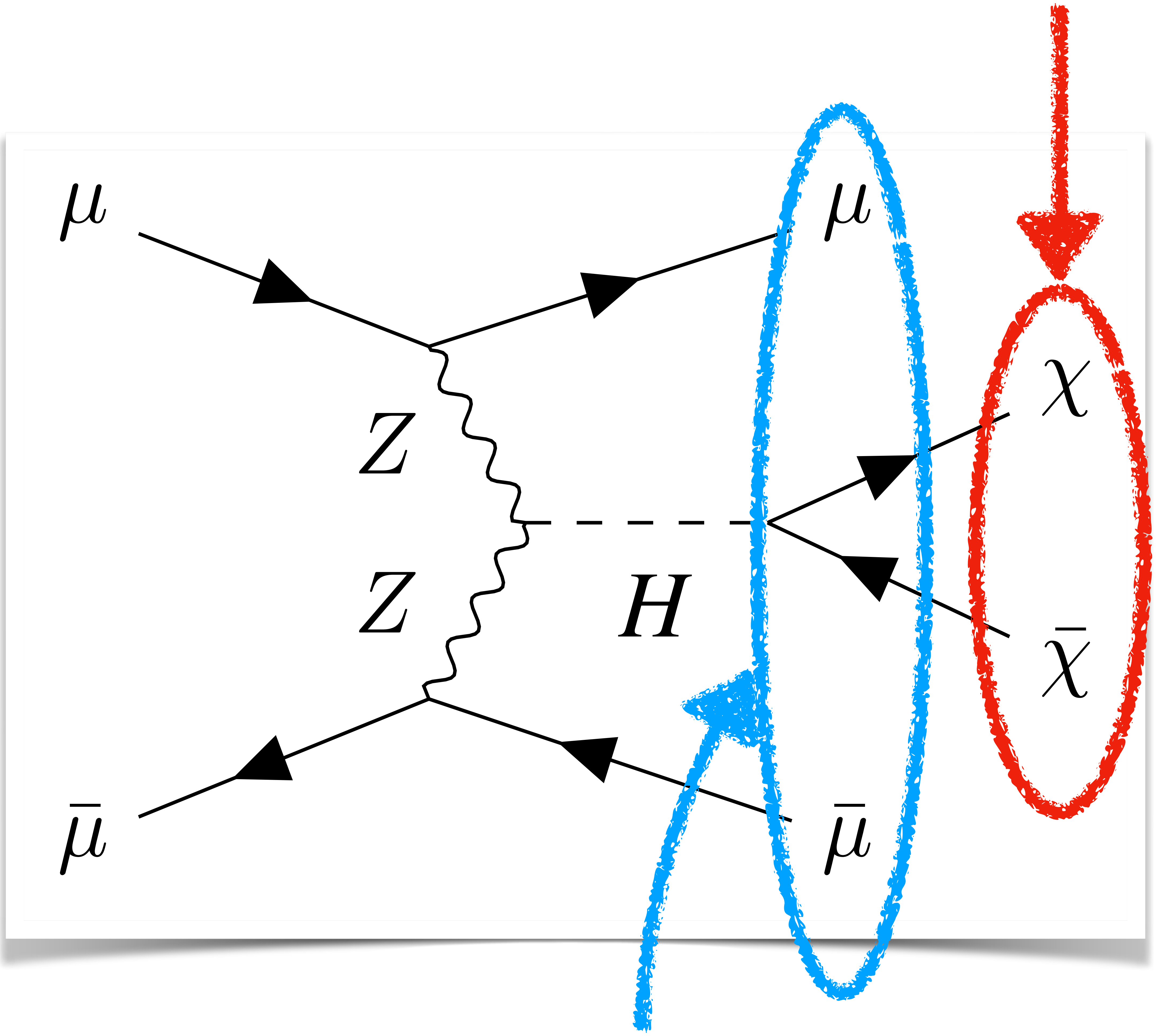
χ : Heavy dirac fermion

$$\mu\bar{\mu} \rightarrow \mu\bar{\mu}\chi\bar{\chi}$$

At high energy, $Z_L Z_L \rightarrow \chi\bar{\chi}$ is dominant

$\sqrt{s} \gg M_\chi > m_H, m_Z$ $\longrightarrow$ $\sigma \propto \frac{1}{\Lambda^2}\log^2\left(\frac{s}{4M_\chi^2}\right)$

BSM particle pair; we cannot see, missing energy



Forwad muon pair; we can see

Discovery potential

Benchmark experiment scenario & detector setting

- $\sqrt{s} = 10$ TeV
- $\mathscr{L} = 10\ \text{ab}^{-1}$
- $|\eta_{\text{main}}| < 2.44$
- $2.44 < |\eta_{\text{forwad}}| < 6.0$;

  Only muons and antimuons are detected in this region
- $\delta E_{\text{forward}} = 10\,\%$;

  Only uncertainties in the forward detector region

Discovery potential

Background consideration & baseline cut

Two types of backgrounds

1. $\mu\bar{\mu} \to \bar{\mu}\mu$ + **Neutrinos**

2. $\mu\bar{\mu} \to \bar{\mu}\mu$ + **Visible particles escaping the main detector; Undetected by forward muon detector**

$\mu\bar{\mu} \to \mu\bar{\mu}\nu\bar{\nu}$

$\mu\bar{\mu} \to \tau\bar{\tau}, \quad \tau \to \mu\nu\nu$

$\mu\bar{\mu} \to W^-W^+\nu\bar{\nu}, \quad W \to \mu\nu$

$\mu\bar{\mu} \to \mu\bar{\mu}\gamma$

$\mu\bar{\mu} \to \mu\bar{\mu}f\bar{f}, \quad f \in \{l, q\}$

$\mu\bar{\mu} \to \mu\bar{\mu}W^-W^+, \quad W \to l\nu$ or $q\bar{q}$

- $6.0 > |\eta_{\mu(\bar{\mu})}|$
- $\eta_\mu > 0 > \eta_{\bar{\mu}}$
- $\Delta R_{\mu\bar{\mu}} > 0.4$
- $E_{\text{min}} > 500$ GeV

$\leftarrow$ Select VBF

- $p_T^{\mu\bar{\mu}} > 50$ GeV

Suppress elastic scattering $\mu\bar{\mu} \to \mu\bar{\mu}$

$$\Delta R_{\mu\bar{\mu}} = \sqrt{\Delta\phi_{\mu\bar{\mu}}^2 + \Delta\eta_{\mu\bar{\mu}}^2}$$

$$\Delta\phi_{\mu\bar{\mu}} = \phi_\mu - \phi_{\bar{\mu}}$$

$$\Delta\eta_{\mu\bar{\mu}} = \eta_\mu - \eta_{\bar{\mu}}$$

$$E_{\text{min.}} = \min(E_\mu, E_{\bar{\mu}})$$

$$p_T^{\mu\bar{\mu}} = p_T^\mu + p_T^{\bar{\mu}}$$

Discovery potential

Neural network

- Clean environment of a muon collider enables a well-reconstructed final state
  $\rightarrow$ Conventional kinematic variables are sufficient as input features:

$$\log\left(\frac{p_T^{\mu(\bar{\mu})}}{20\ \text{GeV}}\right),\quad \log\left(\frac{p_T^{\mu\bar{\mu}}}{50\ \text{GeV}}\right),\quad \frac{\eta_{\mu(\bar{\mu})}}{6},\quad \frac{\Delta\eta_{\mu\bar{\mu}}}{12},\quad \frac{|\Delta\phi_{\mu\bar{\mu}}|}{\pi},\quad \frac{E_{\min}}{\sqrt{s}/2},\quad \frac{M_{\mu\bar{\mu}}}{\sqrt{s}},\quad \frac{M^2_{\chi\bar{\chi}}}{s}$$

- We train NNs for each M_χ and obtain optimal sensitivity limit

$$M_{\mu\bar{\mu}} = \sqrt{(p^\mu + p^{\bar{\mu}})^2}$$

$$M^2_{\chi\bar{\chi}} = (p_i - p^\mu - p^{\bar{\mu}})^2$$

$$p_i = (\sqrt{s}, \vec{0})$$


$M_\chi = 200$ GeV
NN
$H \to \chi\bar{\chi}$ ($M_\chi = 200$GeV)
$\mu\bar{\mu}\nu\bar{\nu}$
$\mu\bar{\mu}\gamma$
$\mu\bar{\mu}f\bar{f}$
$\mu\bar{\mu}W^-W^+$
$W^-W^+\nu\bar{\nu}$
$\tau\bar{\tau}$
Normalized events
$\log(\frac{p_T^{\mu}}{20\,\mathrm{GeV}})$
$\log(\frac{p_T^{\bar{\mu}}}{20\,\mathrm{GeV}})$
$H \to \chi\bar{\chi}$ ($M_\chi = 200$GeV)
Total Background

$M_\chi = 200$ GeV

NN

$M_\chi = 200$ GeV

NN →

$M_\chi = 200$ GeV

NN

$H\to\chi\bar{\chi}$ ($M_\chi = 200$GeV)
$\mu\bar{\mu}\nu\bar{\nu}$
$\mu\bar{\mu}\gamma$
$\mu\bar{\mu}f\bar{f}$
$\mu\bar{\mu}W^-W^+$
$W^-W^+\nu\bar{\nu}$
$\tau\bar{\tau}$
Normalized events
$\frac{|\Delta\phi_{\mu\bar{\mu}}|}{\pi}$
$\frac{\Delta\phi_{\mu\bar{\mu}}}{\pi}$
$H\to\chi\bar{\chi}$ ($M_\chi = 200$GeV)
Total Background
$\frac{E_{min}}{\sqrt{s}/2}$

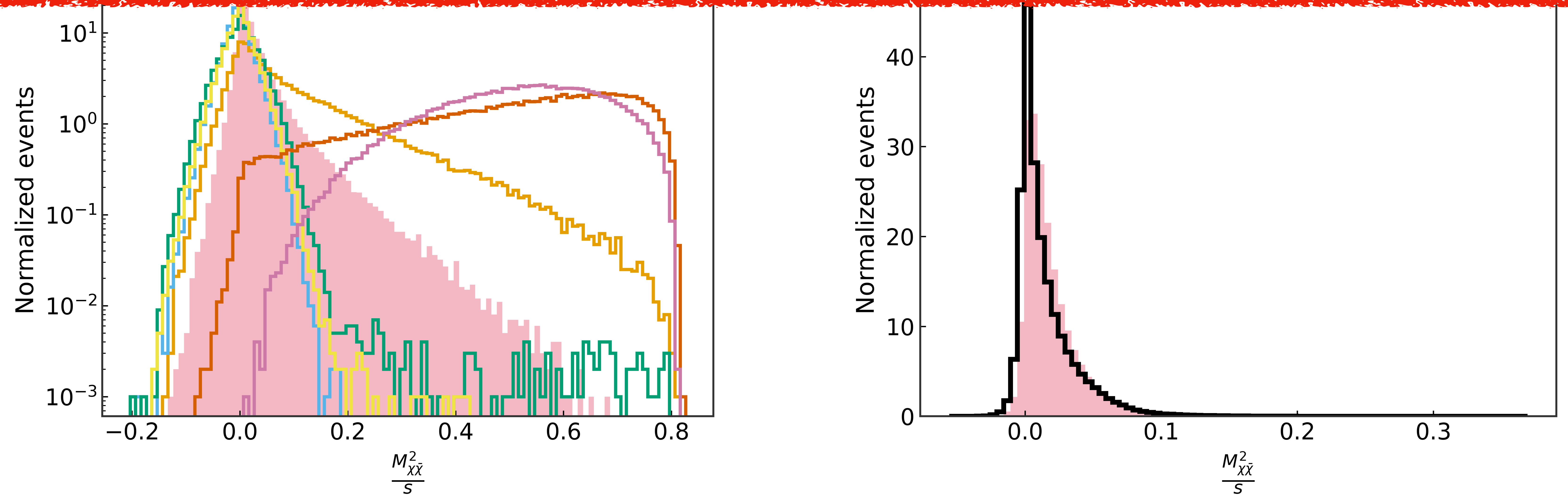
$M_\chi = 200$ GeV

NN →

$M_\chi = 200$ GeV

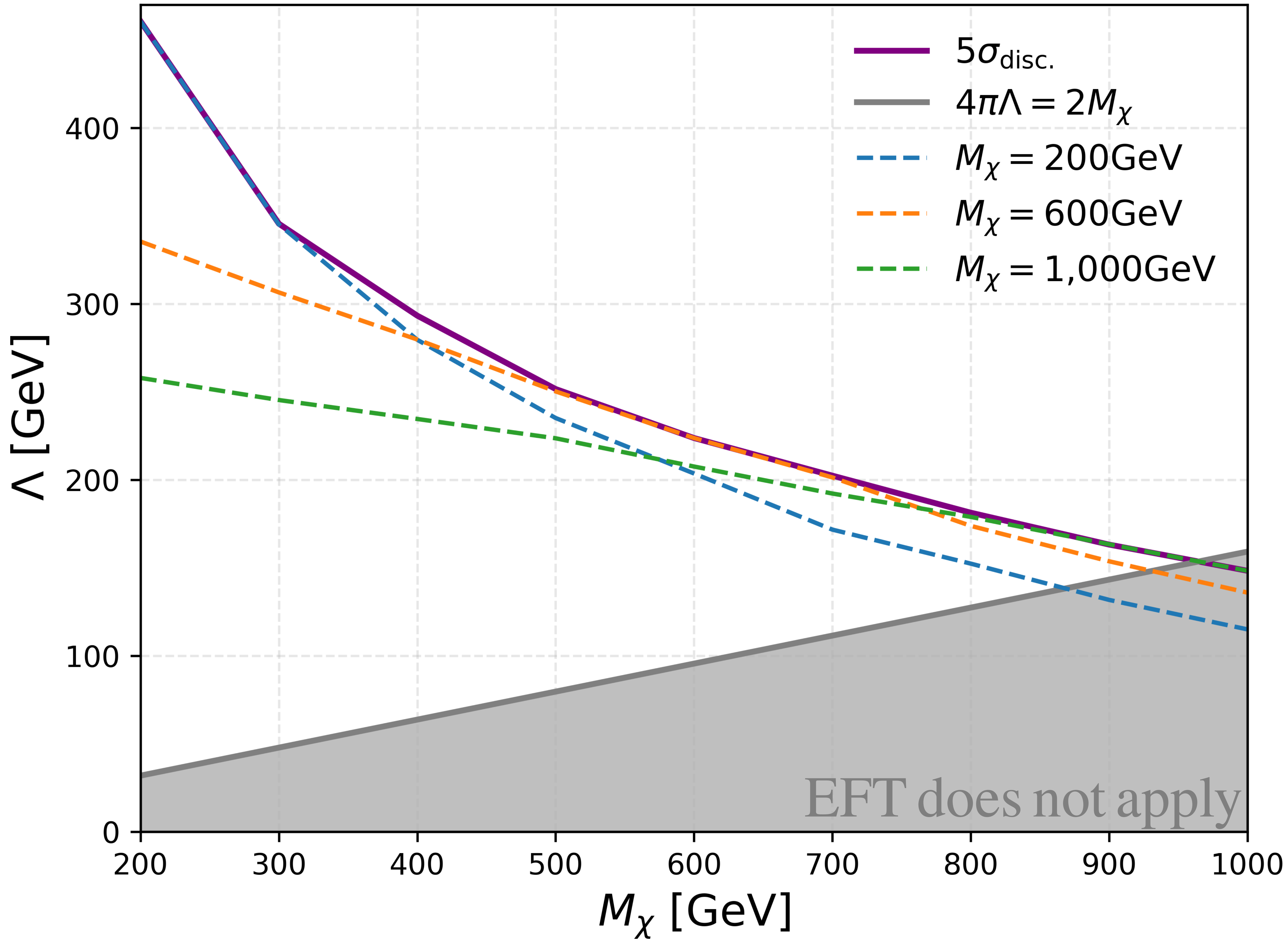
NN →

NN shapes the background to resemble the signal



Discovery potential

Results



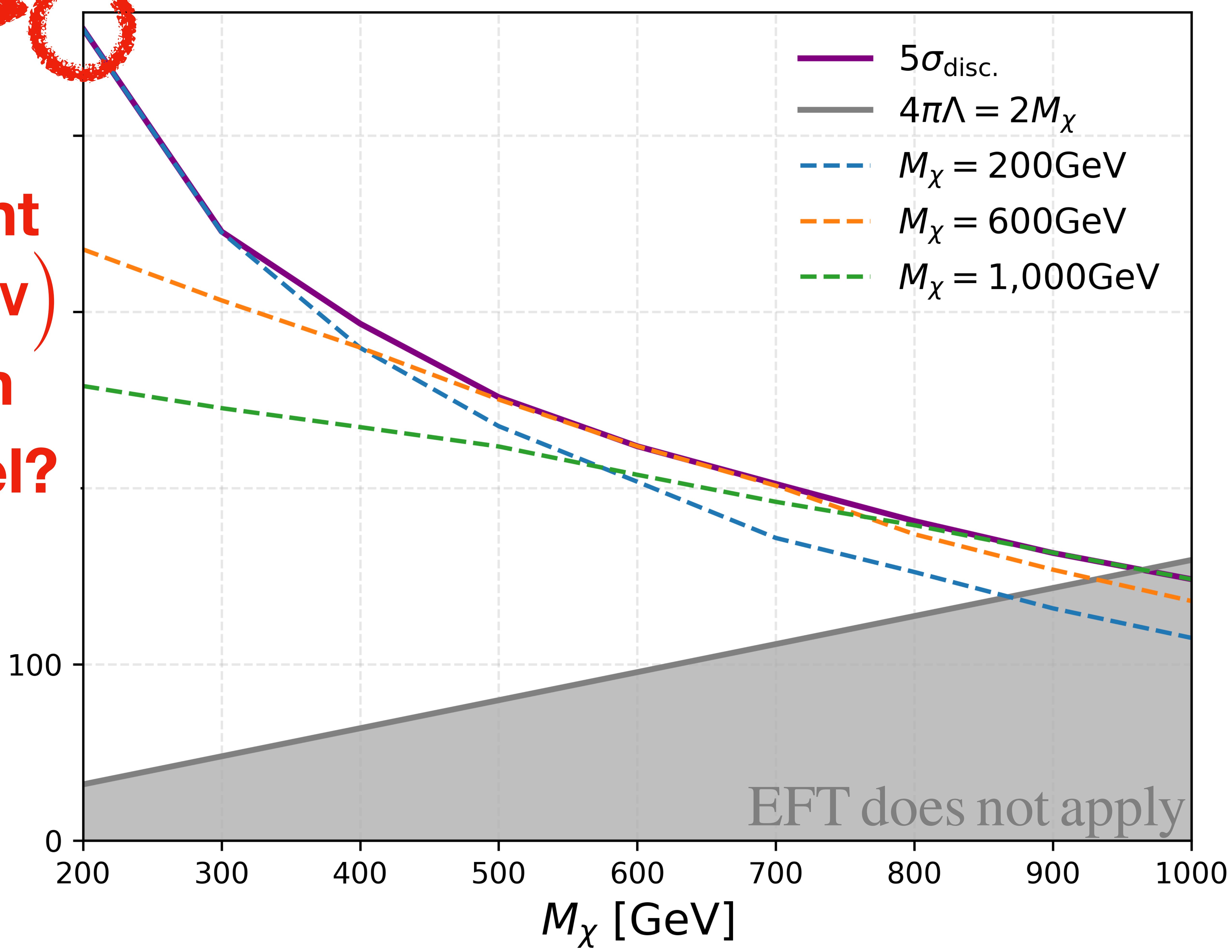
5σ discovery

Discovery potential

Results

Assuming a signal is confirmed at this point $\left(M_\chi = 200 \text{ GeV}, \Lambda = 460 \text{ GeV}\right)$

Is the signal truly from the H-mediated model?



5σ **discovery**

Mediator discrimination

Alternative models

$m_S = m_A = m_H$

- We introduce new BSM scalar S and pseudoscalar A , which give a similar signature. These fields are not involved in the EWSB.

$$\begin{cases} \mathscr{L}_S = \frac{1}{\Lambda_S} S Z^{\mu\nu} Z_{\mu\nu} + g_S S \bar{\chi} \chi \\ \mathscr{L}_A = \frac{1}{\Lambda_A} A \tilde{Z}^{\mu\nu} Z_{\mu\nu} + g_A A \bar{\chi} \left(i\gamma^5 \right) \chi \end{cases}$$

- Different coupling structures induce distinct Z boson polarization contributions:

$Z_{\pm} Z_{\pm} \rightarrow S/A \rightarrow \chi\bar{\chi}$ **is dominant at high energy**

- Helicity formalism reveals this difference as a characteristic angular correlation, $\Delta\phi_{\mu\bar{\mu}}$.

Mediator discrimination

Helicity formalism

$$\frac{d\sigma}{d\Delta\phi_{\mu\bar{\mu}}} = C_0 + C_1\cos(\Delta\phi_{\mu\bar{\mu}}) + C_2\cos(2\Delta\phi_{\mu\bar{\mu}}) + S_1\sin(\Delta\phi_{\mu\bar{\mu}}) + S_2\sin(2\Delta\phi_{\mu\bar{\mu}})$$

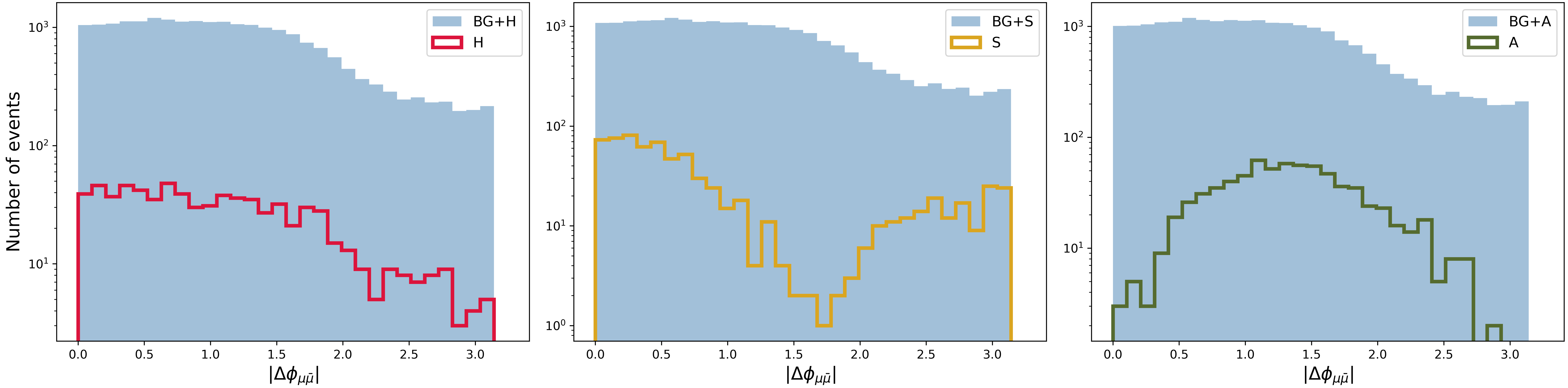
Surviving only with both CP-conserving and CP-violating terms

- $\frac{d\sigma_H}{d\Delta\phi_{\mu\bar{\mu}}} \approx C_0^H$
- $\frac{d\sigma_S}{d\Delta\phi_{\mu\bar{\mu}}} \approx C_0^S + C_2^S\cos(2\Delta\phi_{\mu\bar{\mu}})$
- $\frac{d\sigma_A}{d\Delta\phi_{\mu\bar{\mu}}} \approx C_0^A - C_2^A\cos(2\Delta\phi_{\mu\bar{\mu}})$

Mediator discrimination

Helicity formalism

$M_\chi = 200$ GeV **After NN selection**



The background covers the signal

→ Distribution alone is insufficient for discrimination

→ A hypothesis test is necessary

Mediator discrimination

Hypothesis test

- Neyman-Pearson lemma:
  Likelihood ratio test is universally most powerful

- Test statistic Λ as log-likelihood ratio:

$$\Lambda = \log \frac{\mathscr{L}(\mathbb{H}_1)}{\mathscr{L}(\mathbb{H}_0)} \overset{\text{IID}}{=} \log \frac{\Pi_i P(\vec{x}_i \,|\, \mathbb{H}_1)}{\Pi_i P(\vec{x}_i \,|\, \mathbb{H}_0)} = \sum_i \log \frac{P(\vec{x}_i \,|\, \mathbb{H}_1)}{P(\vec{x}_i \,|\, \mathbb{H}_0)}$$

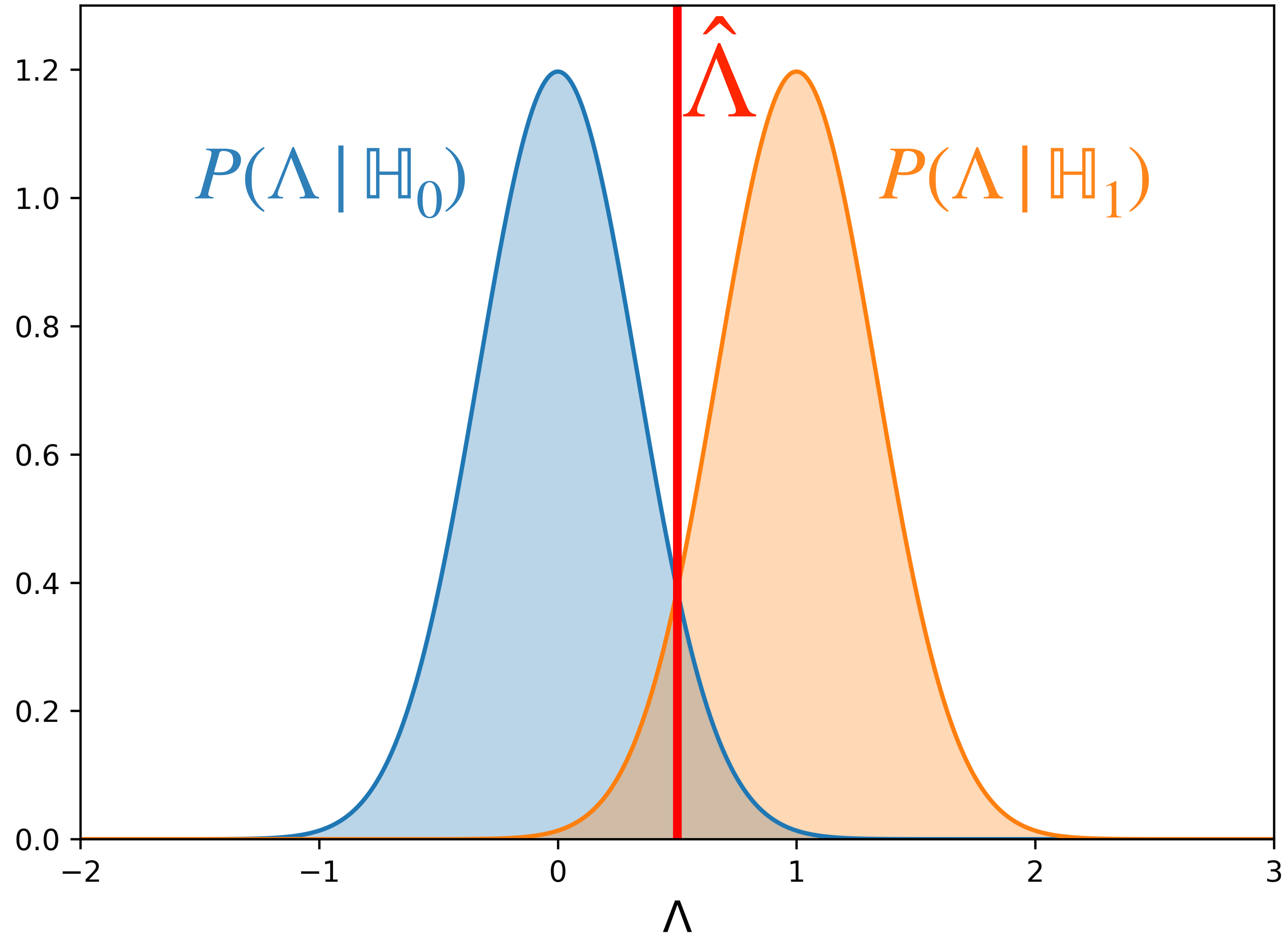
- Performing pseudoexperiments to obtain Λ distribution.

- Tail probability $\mathscr{P}$ in a symmetric way:

$$\mathscr{P} = P(\Lambda > \hat{\Lambda} \,|\, \mathbb{H}_0) = P(\Lambda < \hat{\Lambda} \,|\, \mathbb{H}_1)$$

- Separation power Z:

$$\mathscr{P} = \int_{\tilde{Z}}^{\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)dx \rightarrow Z = 2\tilde{Z} \; [\sigma]$$



Mediator discrimination

Hypothesis test

- To extract $[P(\vec{x}_i \,|\, \mathbb{H}_1)/P(\vec{x}_i \,|\, \mathbb{H}_0)]$, we construct an NN to classify events under two hypotheses, $\mathbb{H}_0$ and $\mathbb{H}_1$.

- Optimally trained NN with Cross-entropy loss function satisfies

$$\frac{f(\vec{x}_i)}{1 - f(\vec{x}_i)} = \frac{P(\vec{x}_i \,|\, \mathbb{H}_1)}{P(\vec{x}_i \,|\, \mathbb{H}_0)}$$

- Test statistic becomes

$$\Lambda = \sum_i \log\left(\frac{f(\vec{x}_i)}{1 - f(\vec{x}_i)}\right)$$

Mediator discrimination

Hypothesis test

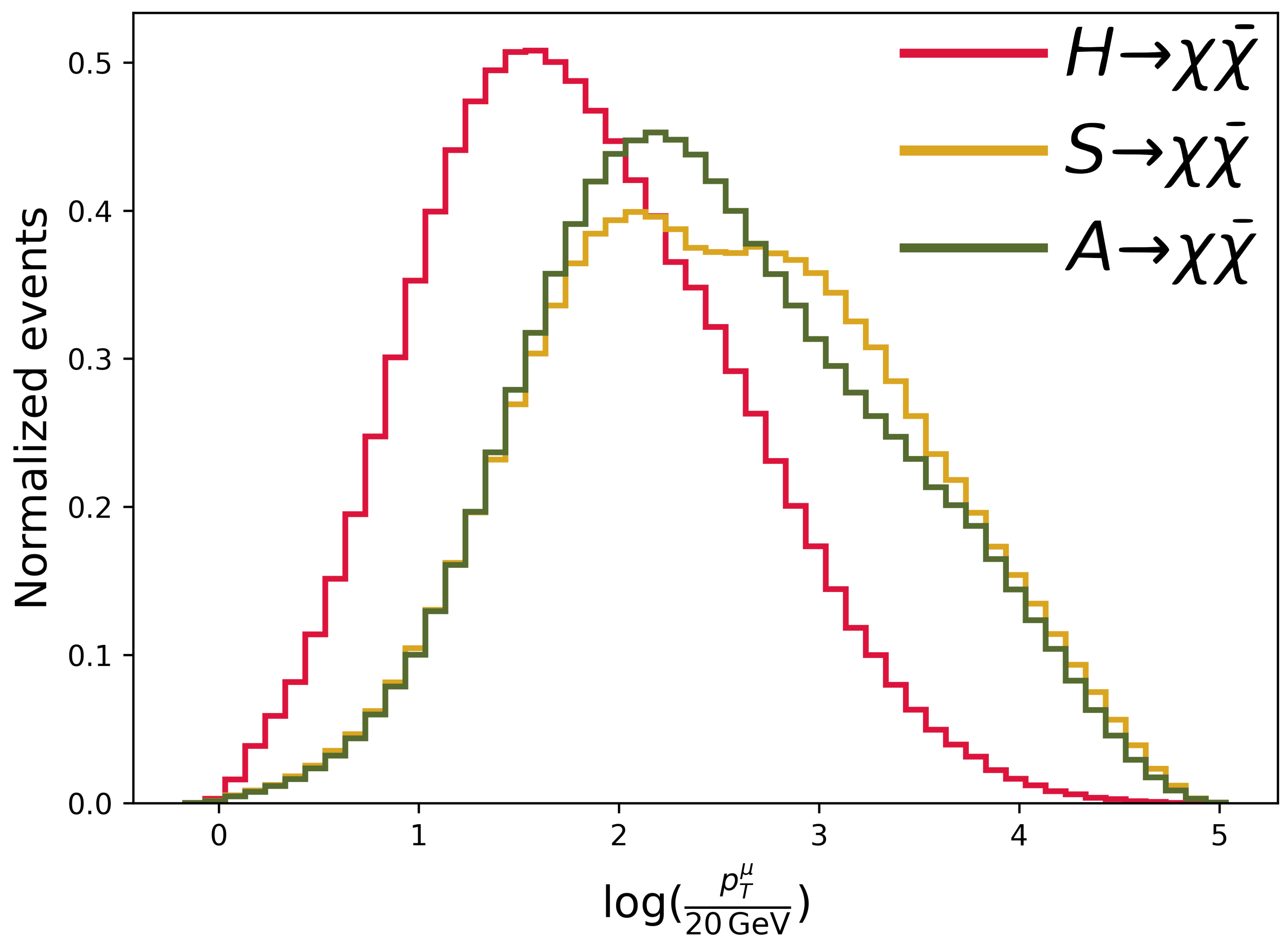
- The absence of interference between signal models and backgrounds allows NN training without background events.
- Five input features encoding properties of the ZZX coupling:

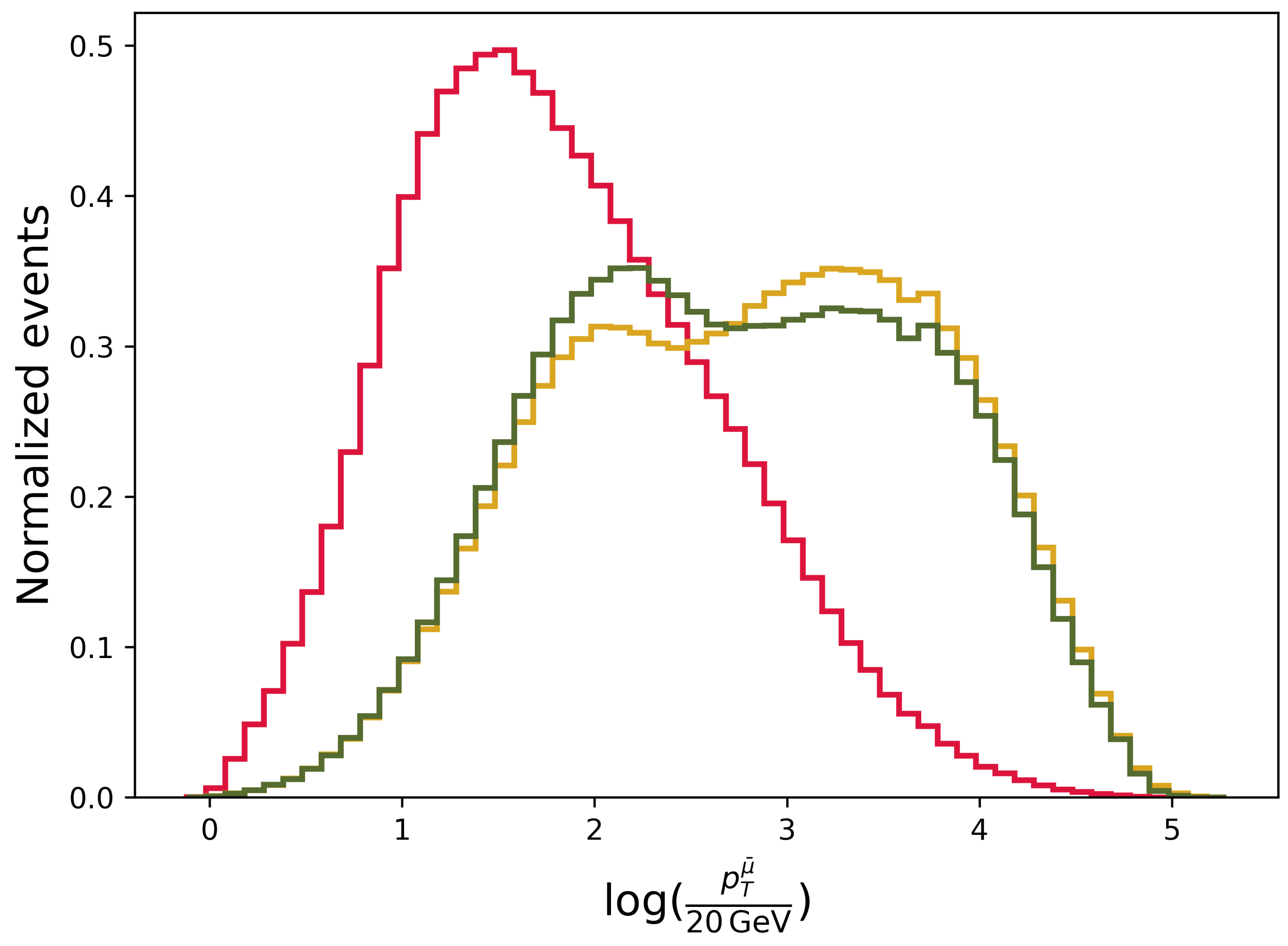
$$\log\left(\frac{p_T^{\mu(\bar{\mu})}}{20\ \text{GeV}}\right), \quad \log\left(\frac{p_T^{\mu\bar{\mu}}}{50\ \text{GeV}}\right), \quad \frac{\Delta\eta_{\mu\bar{\mu}}}{12}, \quad \frac{|\Delta\phi_{\mu\bar{\mu}}|}{\pi}$$

Mediator discrimination

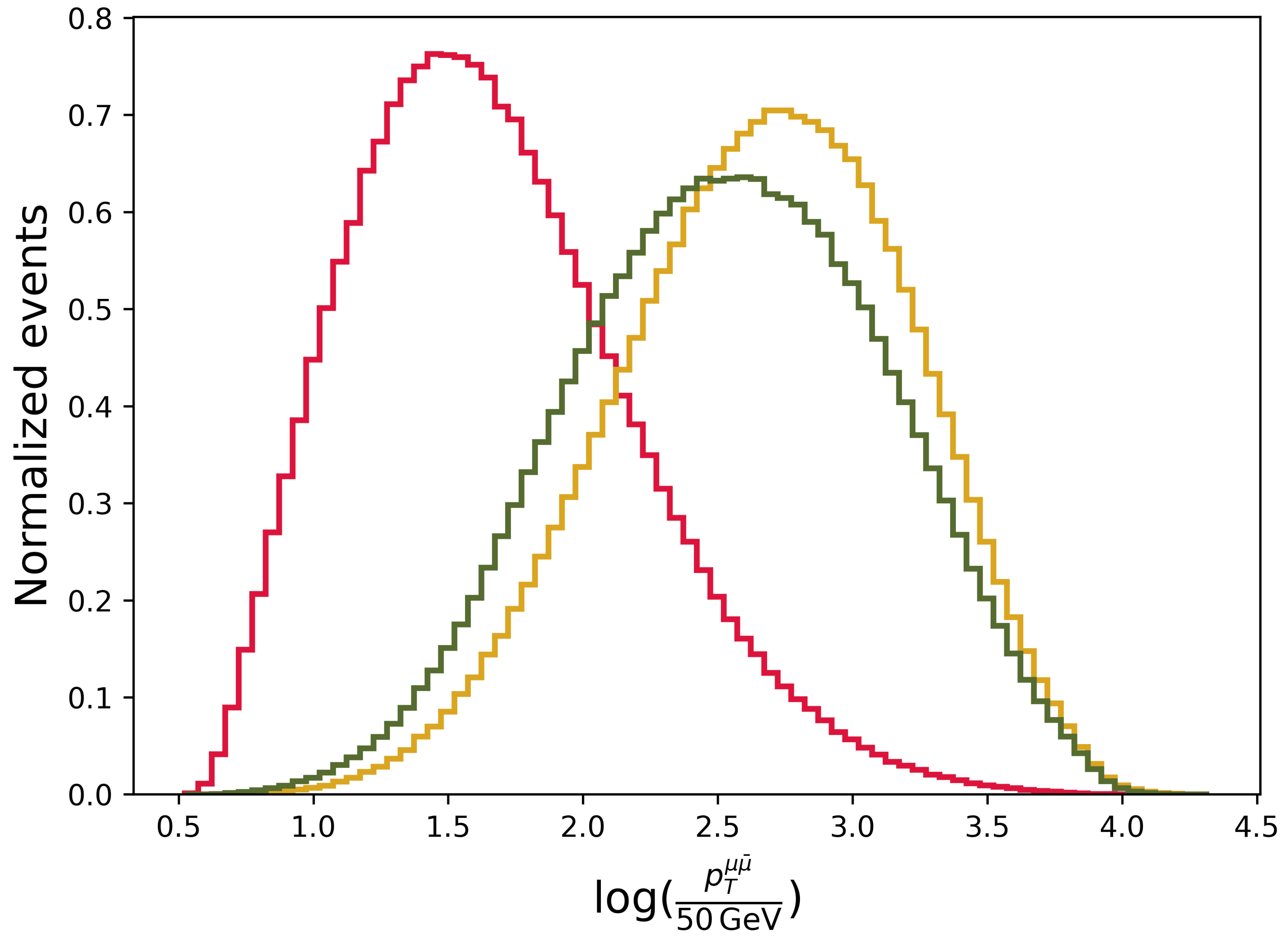
$M_\chi = 200$ GeV

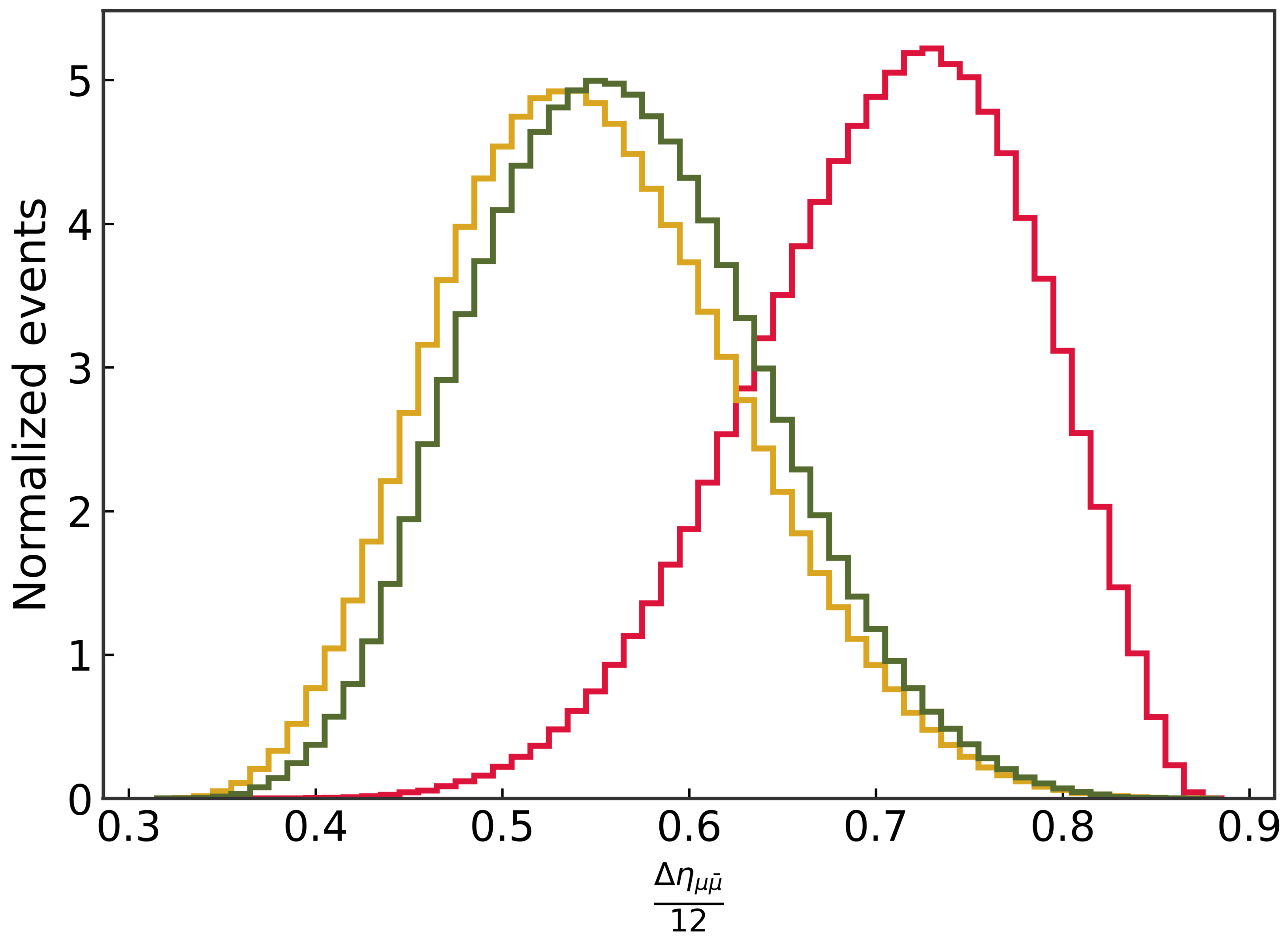
Hypothesis test

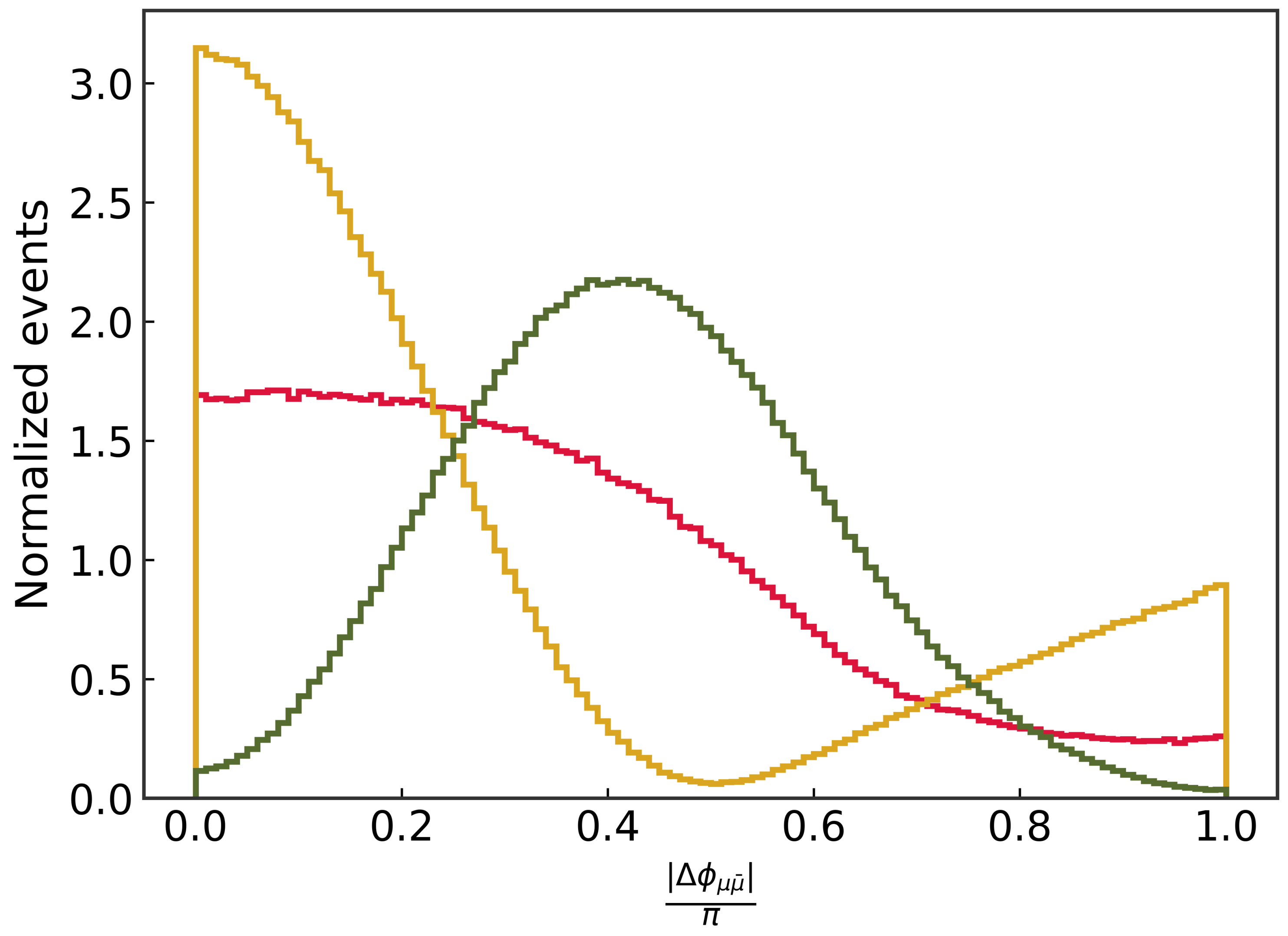




After NN selection, alternative models (S, A) show distributions distinct from the H-mediated signal, unlike the background



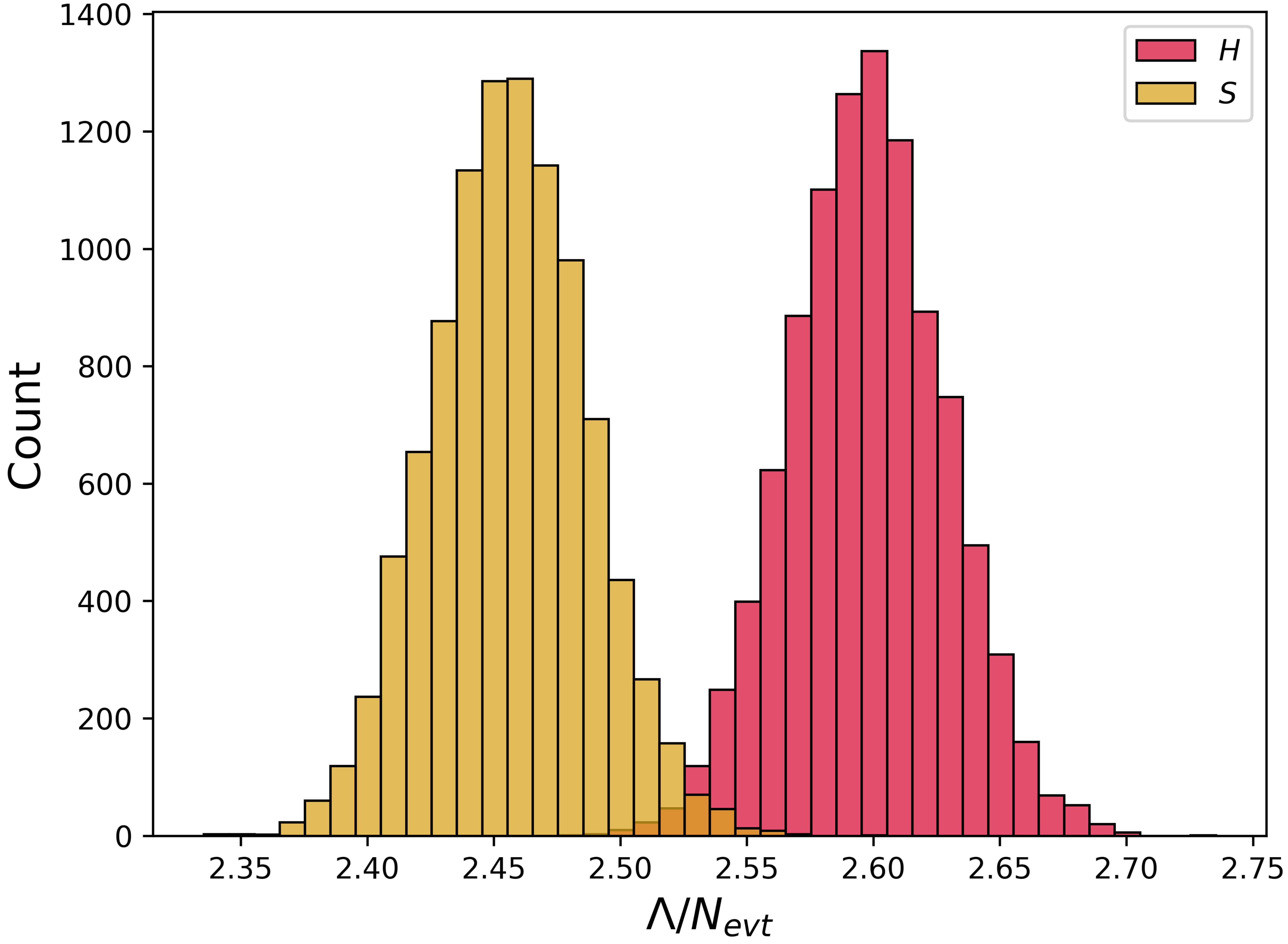




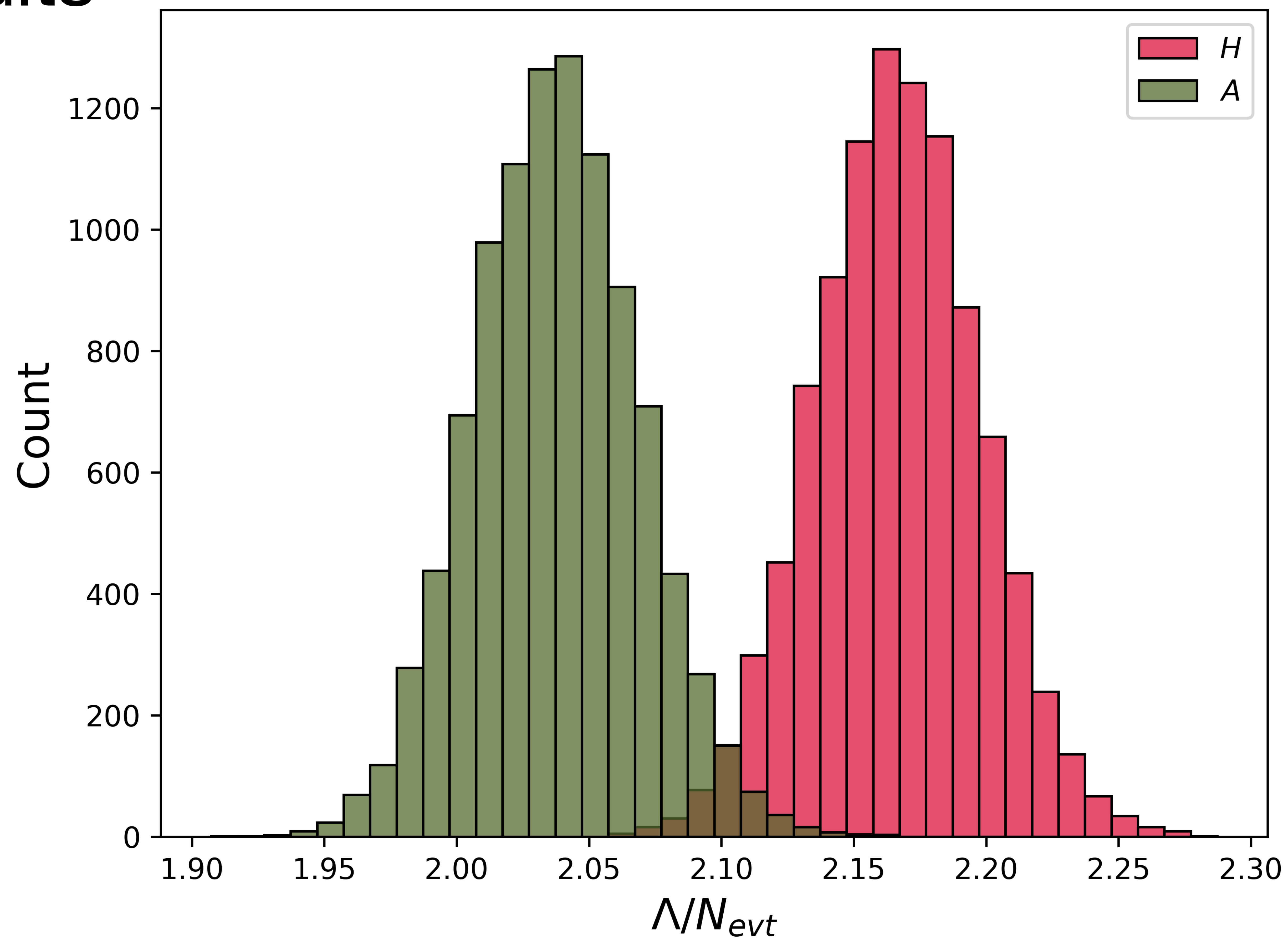
Mediator discrimination

M_χ = 200 GeV

Results



$\hat{\Lambda}$: 2.53
$\mathscr{P}$: 0.012
Z: 4.51σ



$\hat{\Lambda}$: 2.13
$\mathscr{P}$: 0.017
Z: 4.26σ

Conclusion

- High-energy MuC with a forward muon detector is an ideal place to search for new Higgs couplings.
- Clean environment of a muon collider allows high sensitivity with a relatively simple neural network.
- ML-based hypothesis test is an effective procedure for verifying whether an observed signal truly originates from the Higgs mediation.

Thank you