Probing Fermionic Higgs Portal Interactions in $gg \to 4\ell$ Production

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Outline

1. Motivation - The Necessity for BSM Physics

- SM of particle physics: renormalizable QFT

  $\Rightarrow$ extremely successful (e.g. Higgs discovery at the LHC)

- However: SM has a Hierarchy Problem for NP associated to some scale Λ_{NP}

- Need for NP: Breakdown EFT of Gravity at M_{Pl} and Dark Matter (DM)

  $\Rightarrow$ interpret SM as leading terms of an EFT expansion

1. Motivation - The Necessity for BSM Physics

Hierarchy Problem (HP)	Dark Matter Puzzle
• one-loop correction to Higgs mass: $\delta m_h^2 \propto \Lambda^2$ • have to require cancellation: $m_h^2 = m_{h,0}^2 + \delta m_h^2$ natural for cut-off close to TeV scale $\Rightarrow$ NP	• observational evidence: rotation curves of spiral galaxies, grav. lensing,... • Planck measurement: $\Omega_{\rm DM}\, h^2 \simeq 0.12, \;\; h \approx 0.67$

2. The Fermionic Higgs Portal Operator $\mathcal{O}_{\psi H}$

How to address the aforementioned tensions with the SM?

We explore the Fermionic Higgs Portal Operator as a viable BSM extension:

$\mathcal{O}_{\psi H} = \bar{\psi}\psi|H|^2$ with the BSM fermion ψ being a singlet under the SM

$\Longrightarrow$ Fraternal Twin Higgs (little HP), Fermionic DM

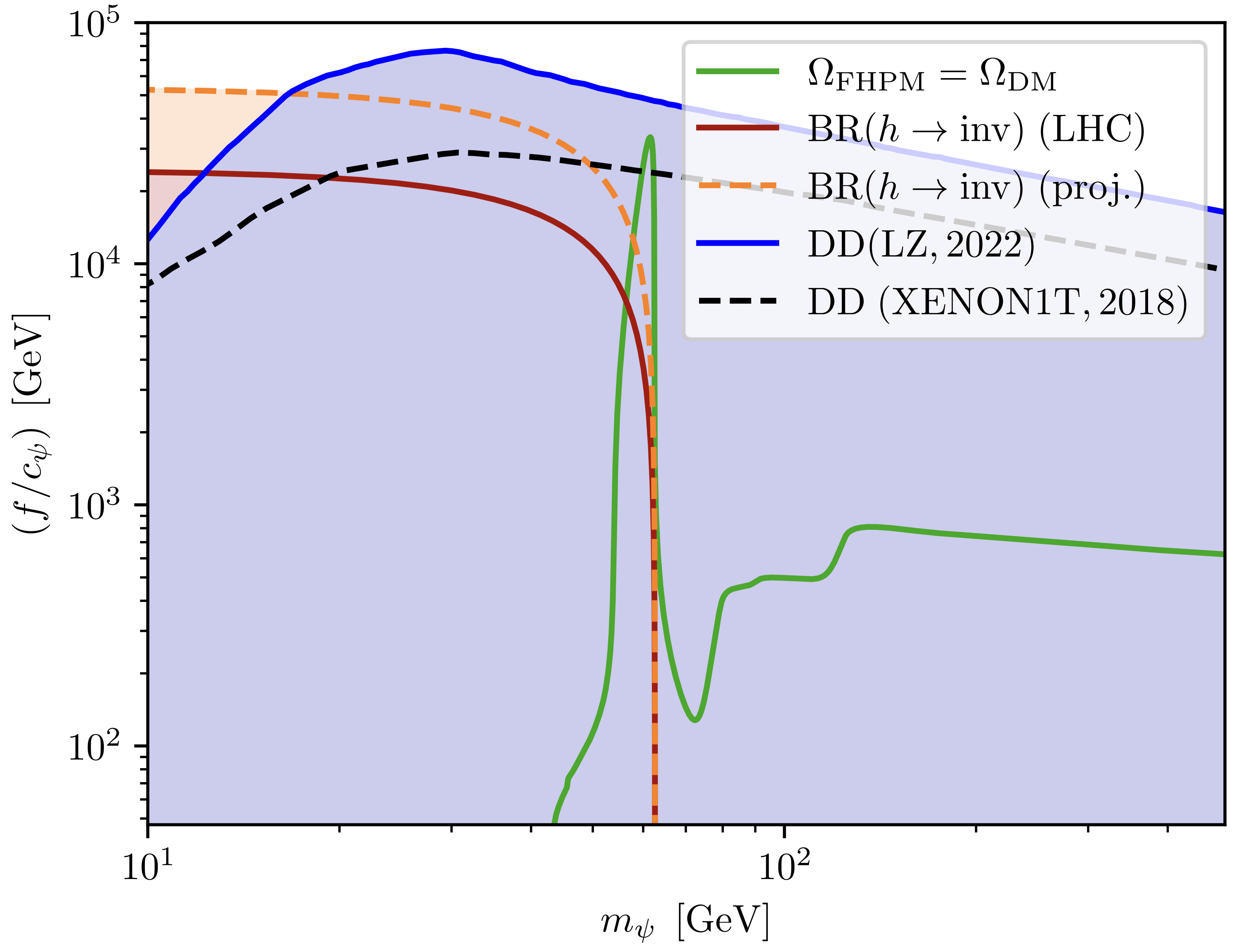
2.1 Fraternal Twin Higgs Model

- core feature: Higgs as pNGB, thus: naturally light (SSB and GB EFT)
- tackles little Hierarchy Problem: increases naturalness cut-off up to $\Lambda \sim 5 - 10\,\text{TeV}$
- introduction of top partner (SM singlet, charged under twin $SU(3)_B$)
- couples to SM Higgs via FHP: $\mathcal{L}^B_{\text{Yuk, top}} \supset \frac{\lambda_{B,t}}{2f}\,\bar{t}_B t_B |H|^2$
- cancels quadratic divergence of top loop when imposing twin parity

2.2 Dark Matter Analysis

- consider the case where ψ is a gauge singlet: $\mathcal{L}_{\text{FHPM}} = \bar{\psi}(i\partial\!\!\!/ - \mu_\psi)\psi + \frac{c_\psi}{f}\bar{\psi}\psi|H|^2$

- coupling ensures thermal equilibrium of dark sector with SM $\Rightarrow$ WIMP freeze-out



- severe Direct Detection constraints exclude minimal model completely

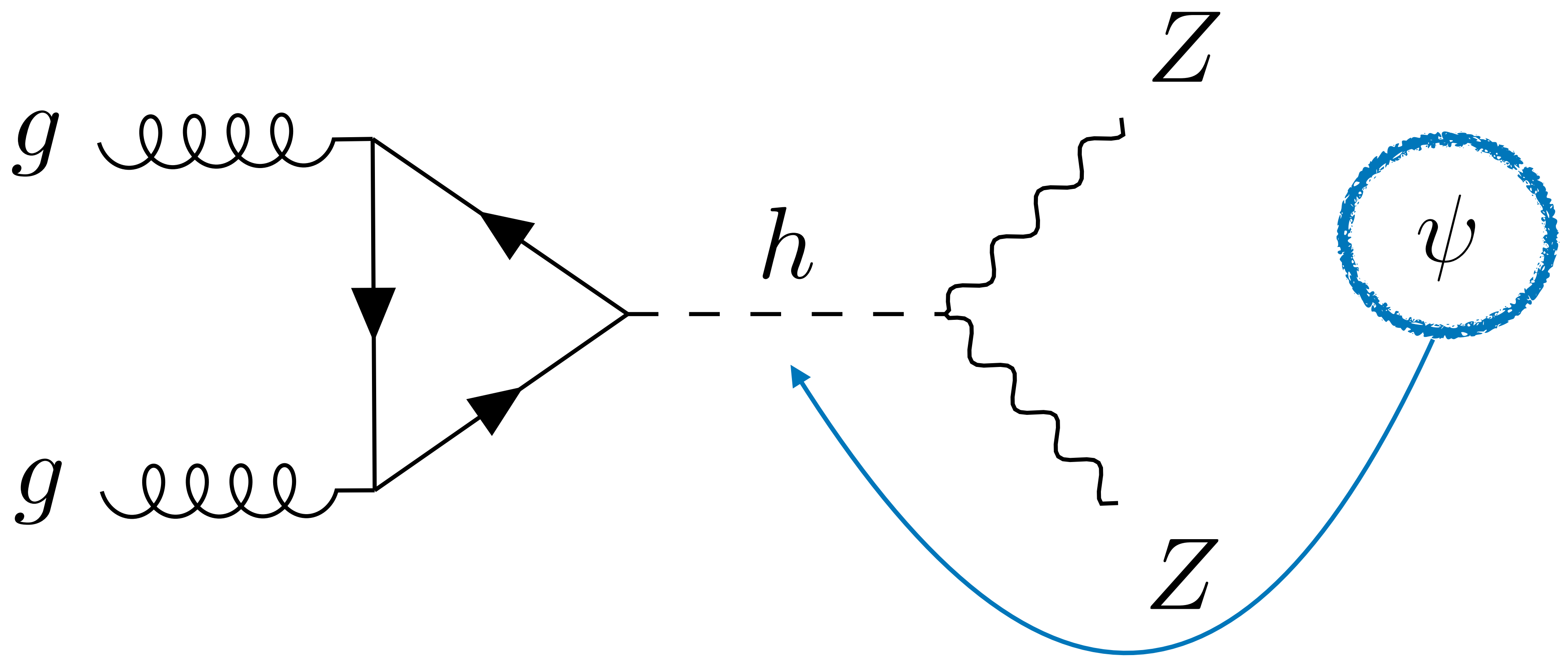
- need more complex extensions
$\Rightarrow$ gauge interactions, richer dark sector

3. Model-Independent Study of $\mathcal{O}_{\psi H}$ in $gg \to 4\ell$

Why do we investigate BSM contributions of $\mathcal{O}_{\psi H}$ in the $gg \to 4\ell$ Process?

- BSM fermion ψ not charged under QCD $\Longrightarrow$ exploit coupling to the Higgs

$\Longrightarrow$ indirect:



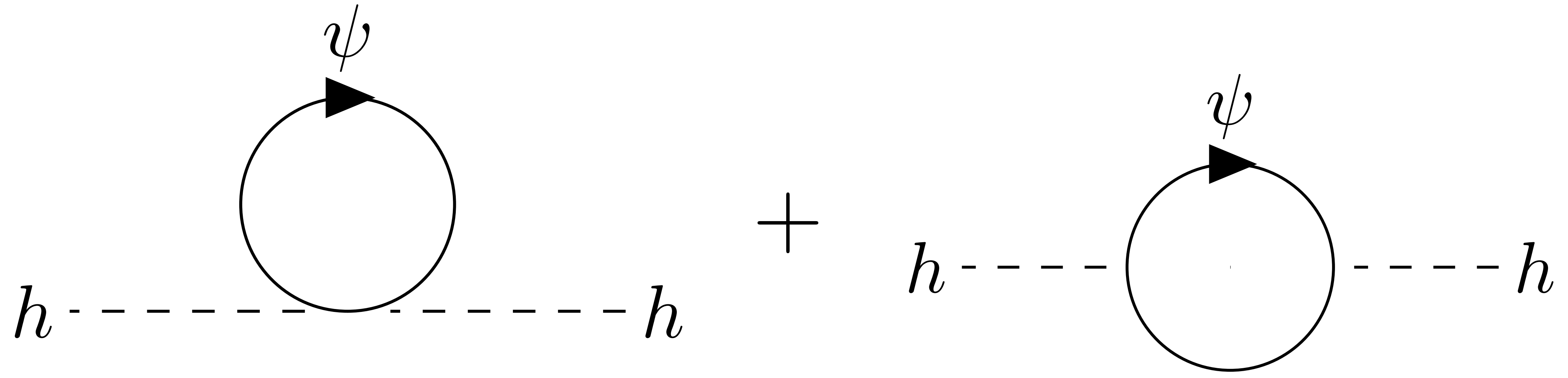
4ℓ final state takes advantage of:

- narrow background
- high lepton energy resolution

3. Model-Independent Study of $\mathcal{O}_{\psi H}$ in $gg \to 4\ell$

Computation of One-Loop Corrections to Higgs Self-Energy:

$$\mathcal{L} \supset \frac{c_\psi}{f}\,\bar{\psi}\psi|H|^2 \;\Rightarrow\; i\Sigma(\hat{s}) =$$



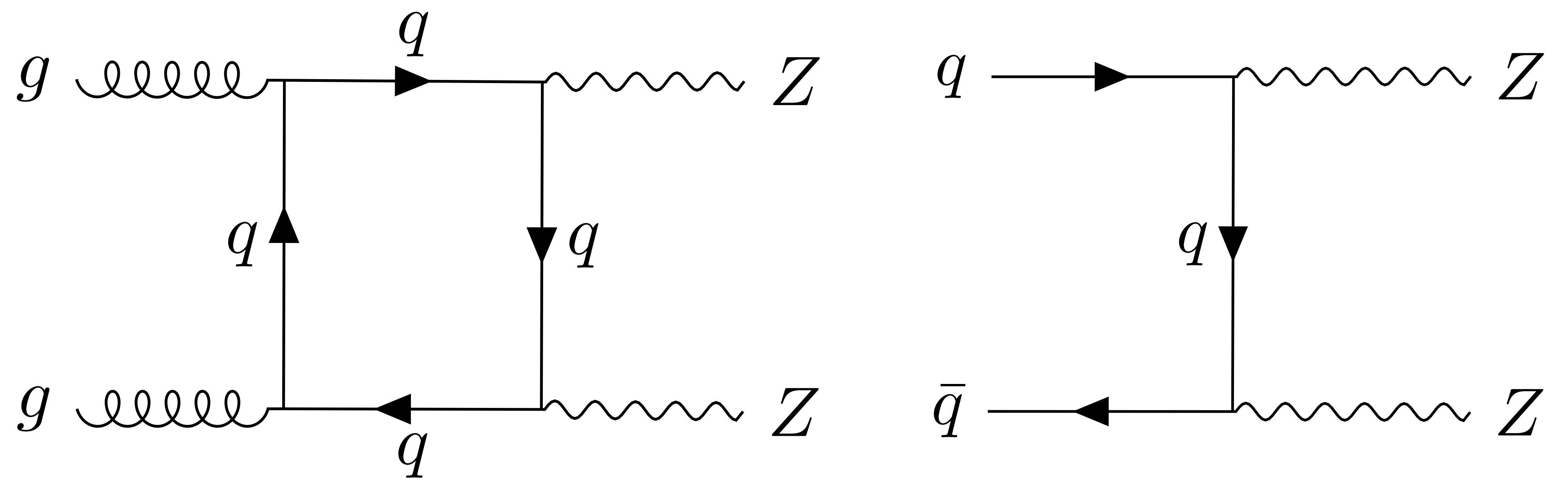
- amplitude in on-shell scheme: $\mathcal{M}^{\mathrm{FHPM}}_{gg\to h^*\to ZZ} = (1-\Delta_\psi)\,\mathcal{M}^{\mathrm{SM}}_{gg\to h^*\to ZZ}$ with

$$\Delta_\psi = \frac{N c_\psi^2 v_{\mathrm{EW}}^2}{8\pi^2 f^2}\left[\frac{\hat{s}-4m_\psi^2}{\hat{s}-m_h^2}\left(B_0(\hat{s},m_\psi^2,m_\psi^2) - B_0(m_h^2,m_\psi^2,m_\psi^2)\right) + (4m_\psi^2 - m_h^2)\frac{d}{d\hat{s}}B_0(\hat{s},m_\psi^2,m_\psi^2)\bigg|_{\hat{s}=m_h^2}\right]$$

- $\psi \in \boldsymbol{N}$ of dark $SU(N)$, typical modifications: $|\mathrm{Re}(\Delta_\psi)|, \mathrm{Im}(\Delta_\psi) \sim \mathcal{O}(3\% - 4\%)$

3. Model-Independent Study of $\mathcal{O}_{\psi H}$ in $gg \to 4\ell$

- upshot: cannot rely on very large deviations
- dominant SM background:

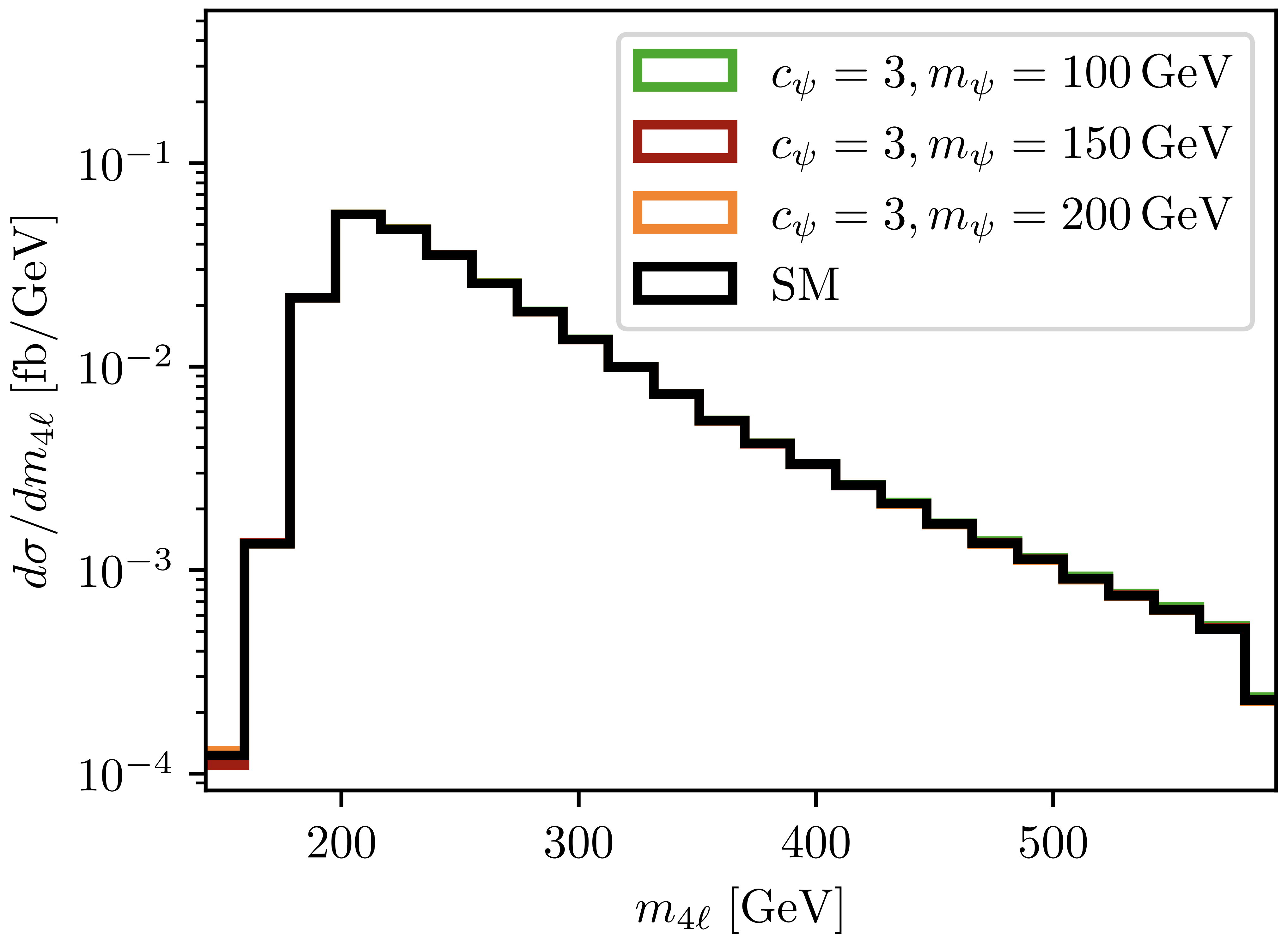


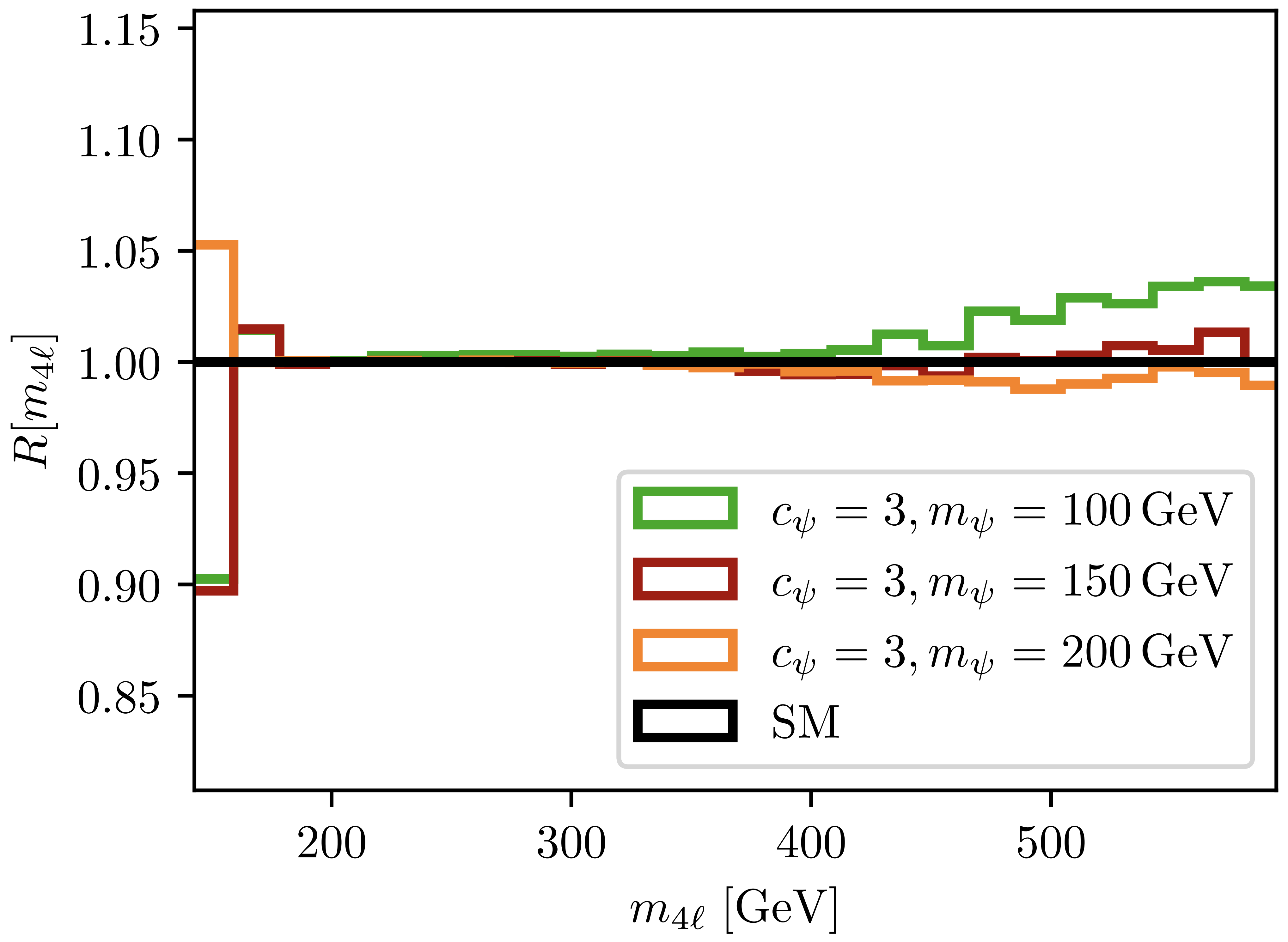
- define Matrix-element (ME) based discriminant: $D_S = \log_{10}\left(\frac{P_h}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$,

  where $P_h, P_{gg}, P_{q\bar{q}}$ are squared MEs for $gg \to h^* \to ZZ$, $gg \to ZZ$, $q\bar{q} \to ZZ$

3. Model-Independent Study of $\mathcal{O}_{\psi H}$ in $gg \to 4\ell$

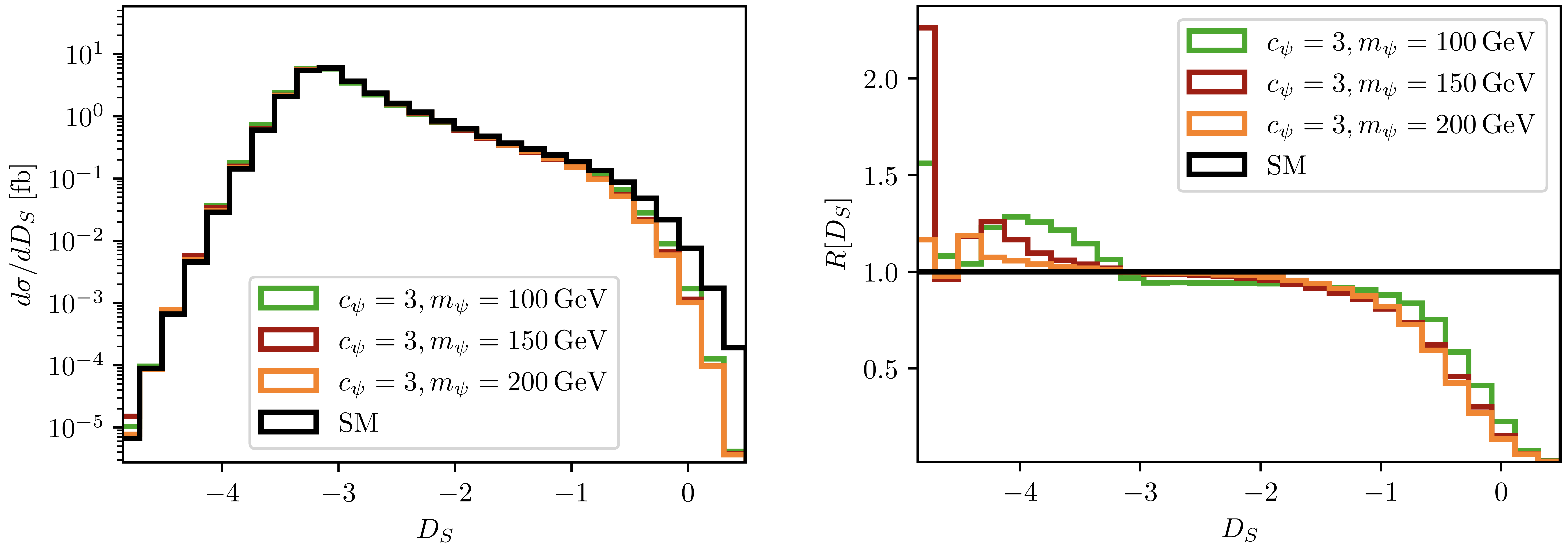
Spectra for $gg \to 4\ell$ using four-lepton invariant mass:





3. Model-Independent Study of $\mathcal{O}_{\psi H}$ in $gg \to 4\ell$

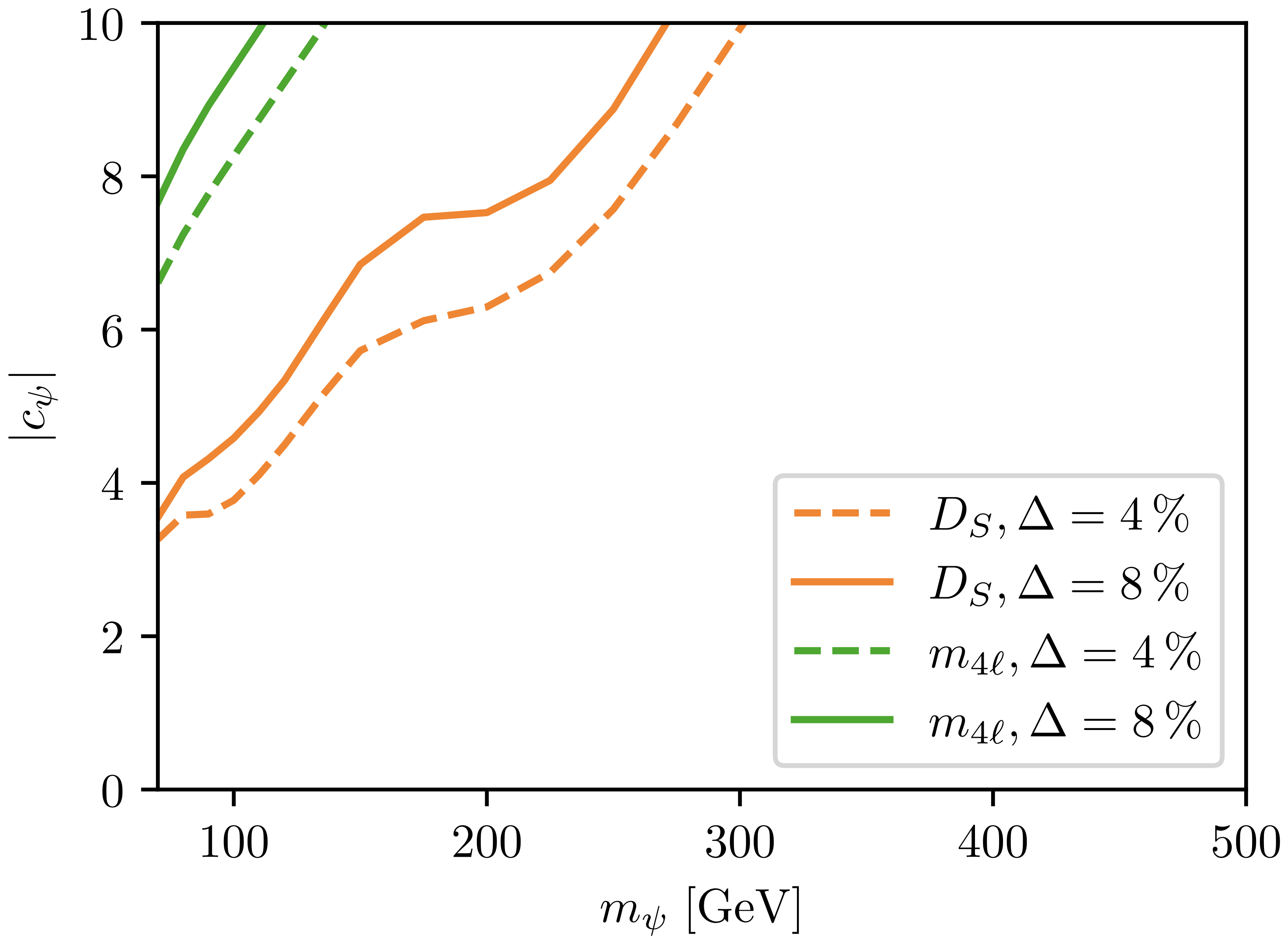
Spectra for $gg \to 4\ell$ using the ME based Discriminant:

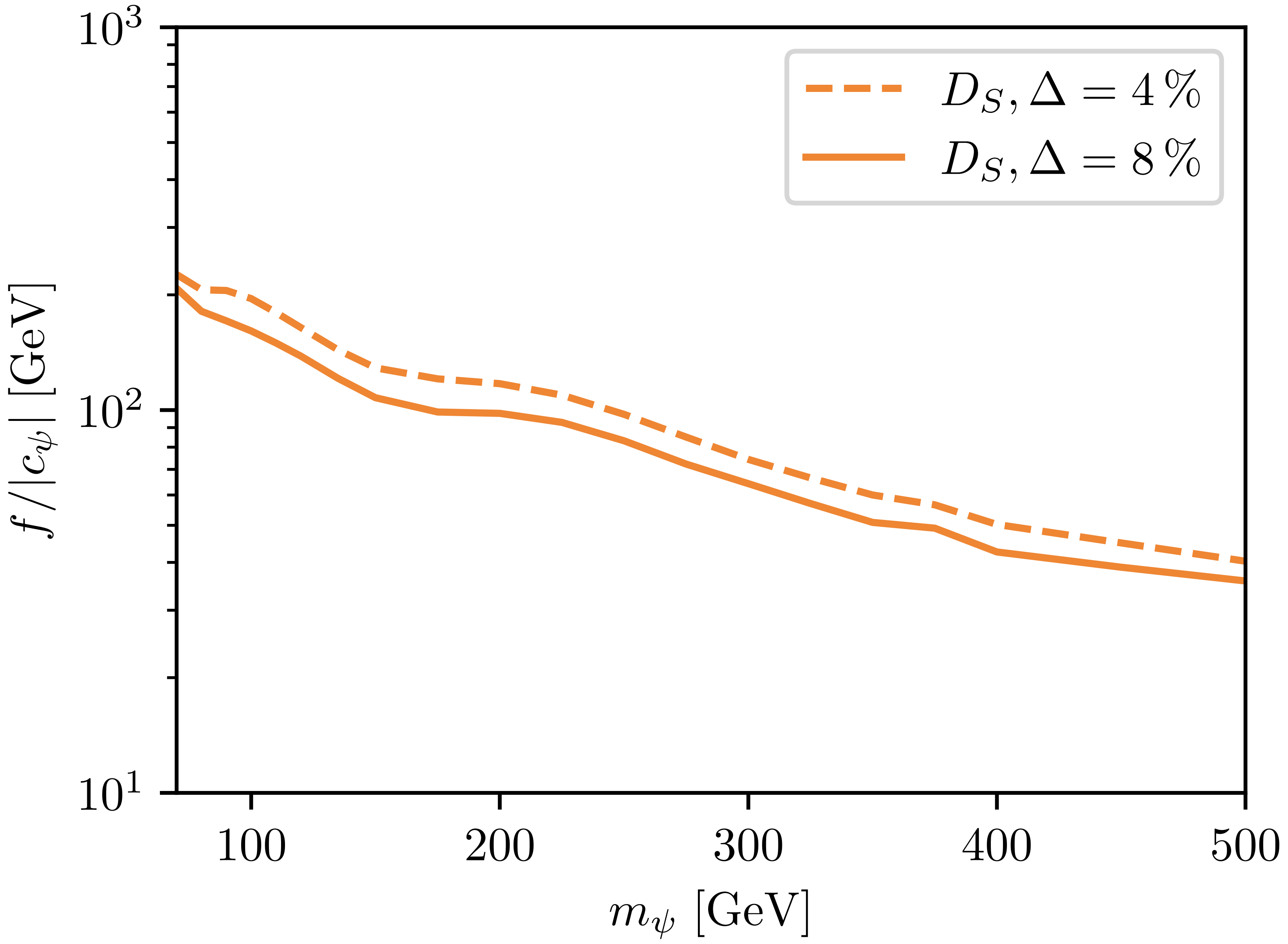


3. Model-Independent Study of $\mathcal{O}_{\psi H}$ in $gg \to 4\ell$

Bounds at the HL-LHC:

- statistical test of SM hypothesis, background uncertainty: $\sigma_{b_i} = \Delta\, b_i$

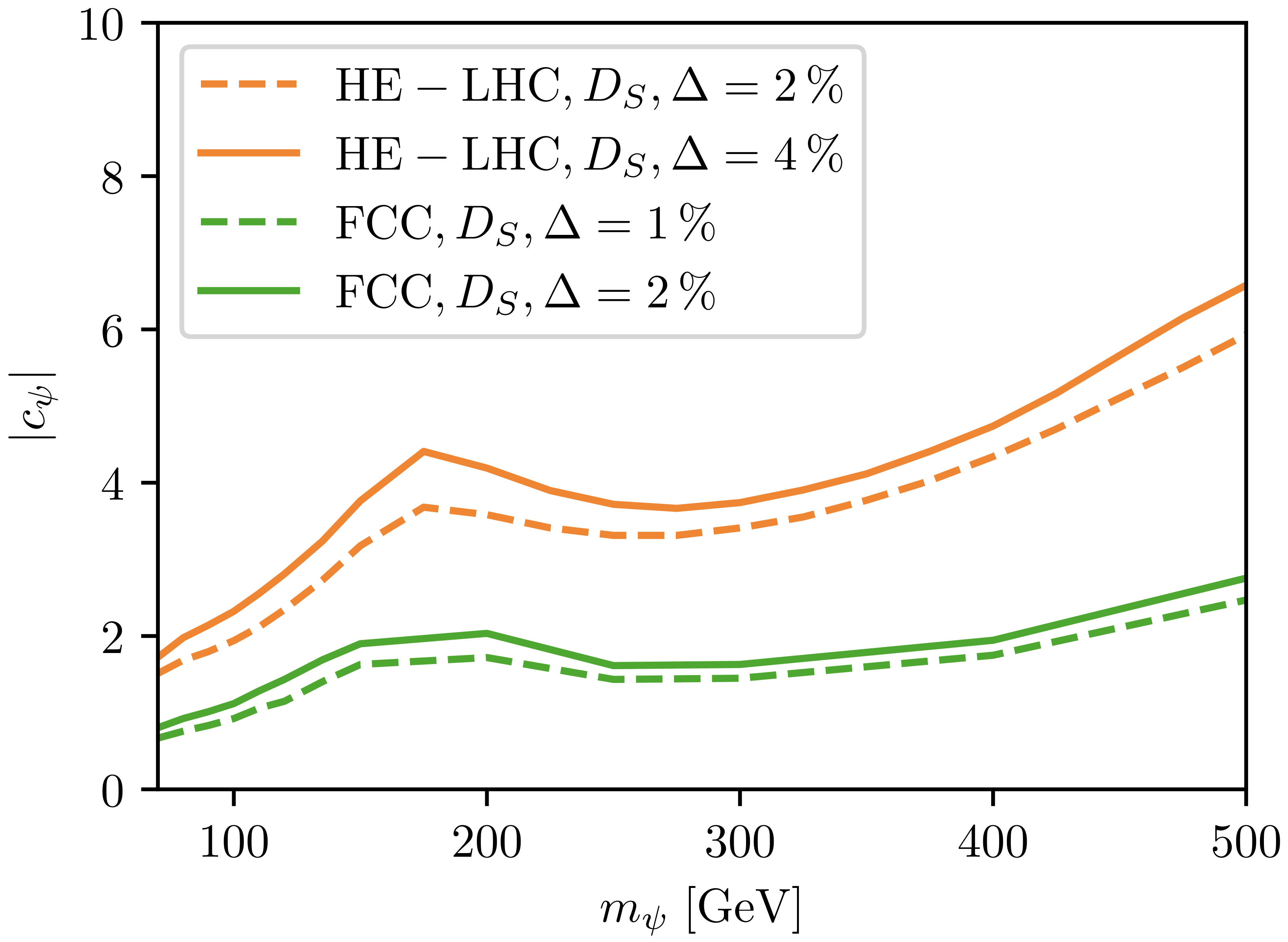


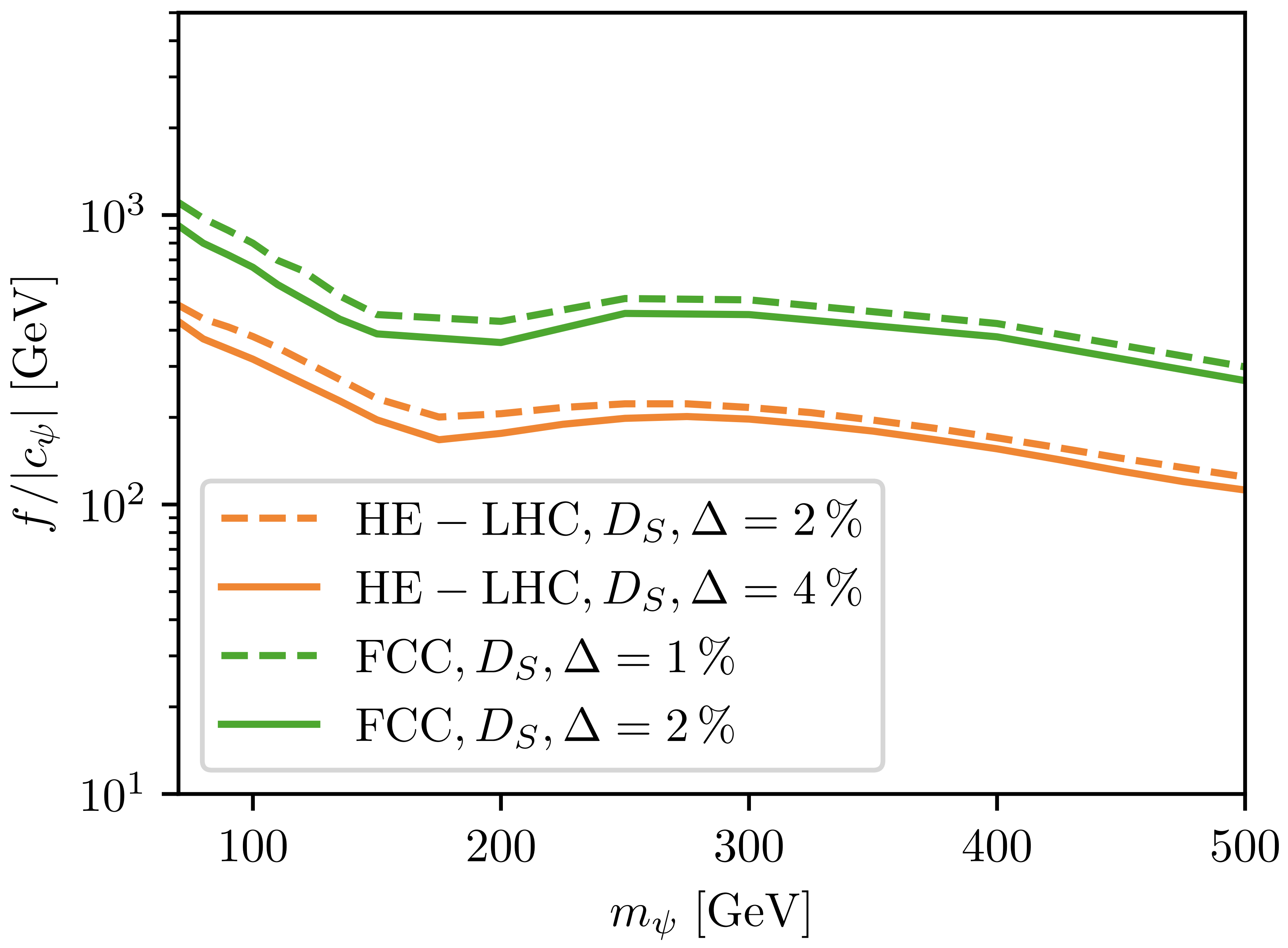


$$N = 3,\, f = 3 v_{\mathrm{EW}},\, \sqrt{s} = 14\,\mathrm{TeV},\, L = 3000\,\mathrm{fb}^{-1}$$

3. Model-Independent Study of $\mathcal{O}_{\psi H}$ in $gg \to 4\ell$

Bounds at the HE-LHC and FCC:



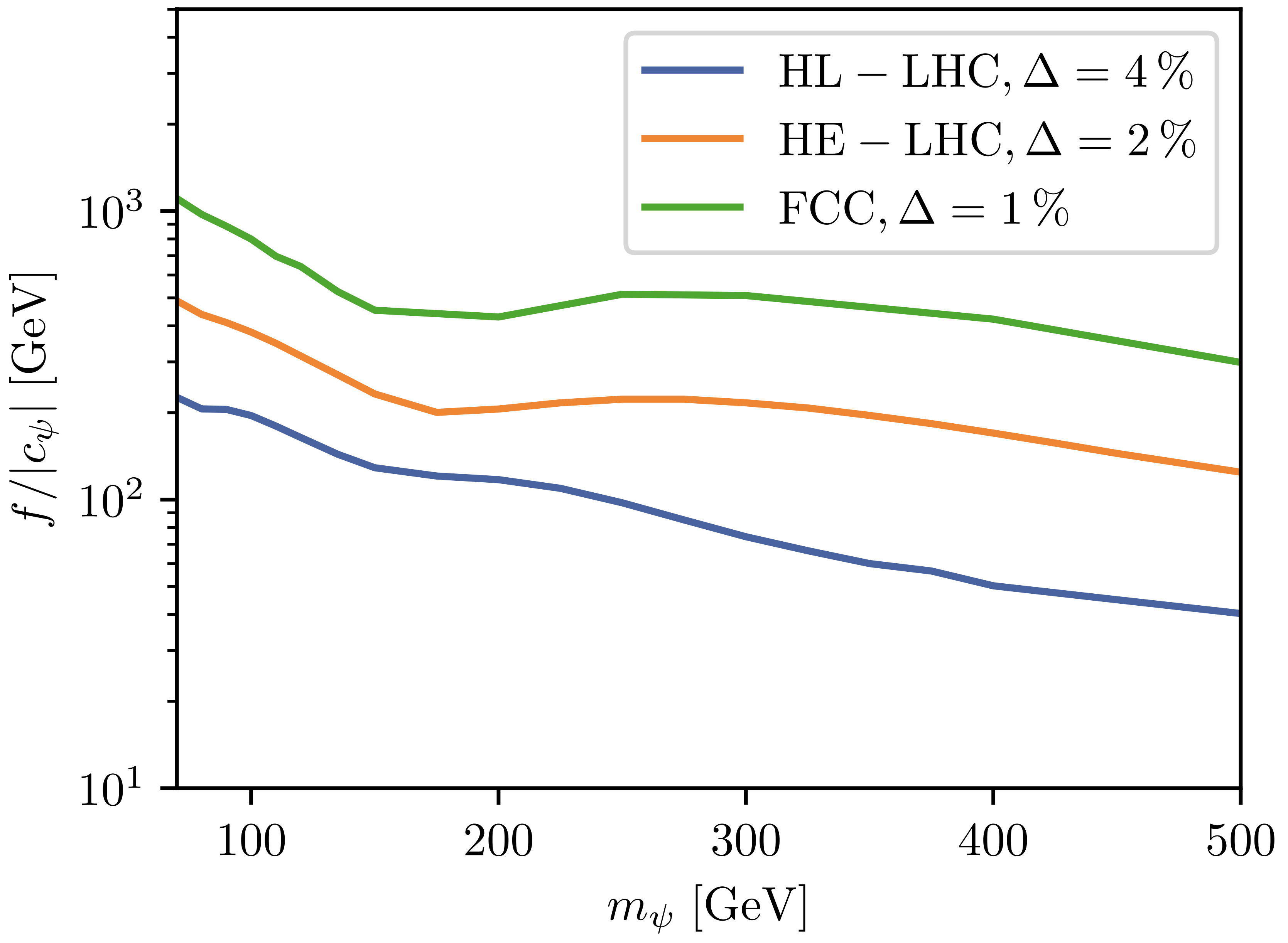


$$\mathrm{HE-LHC}: \sqrt{s} = 27\,\mathrm{TeV}, L = 15\,\mathrm{ab}^{-1}, \mathrm{FCC}: \sqrt{s} = 100\,\mathrm{TeV}, L = 30\,\mathrm{ab}^{-1}$$

4. Conclusions and Outlook

- FHP $\mathcal{O}_{\psi H} = \bar{\psi}\psi|H|^2$ is a well-motivated BSM extension (little HP, DM)

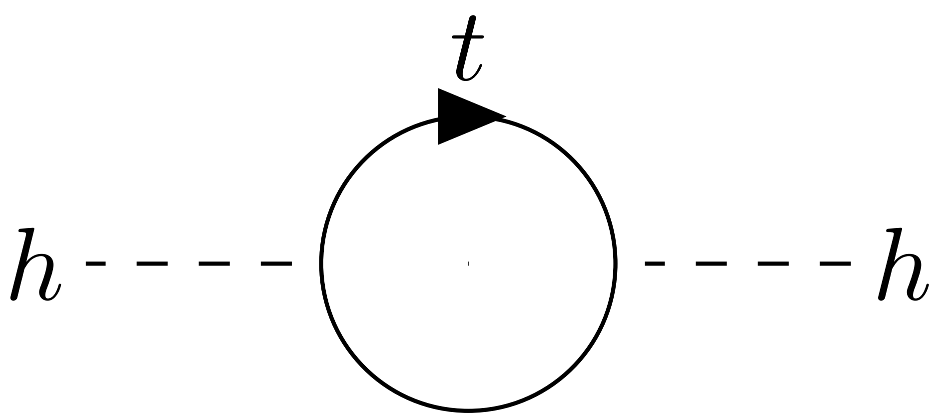
- model-independent study in four-lepton final state: contribution of BSM fermion to Higgs 2-point function



- probes scales up to 1 TeV at the FCC
- Outlook: Double-Higgs Production

Backup

Hierarchy Problem of the SM Higgs



$$+ \ldots \quad \Rightarrow \quad \delta m_h^2 = \frac{3\Lambda^2}{16\pi^2 v_{\text{EW}}^2}\left(4m_t^2 - m_h^2 - 2m_W^2 - m_Z^2\right)$$

- physical Higgs mass requires miraculous cancellation: $m_h^2 = m_{h,0}^2 + \delta m_h^2$
- fine-tuning parameter: $\Delta = \frac{\delta m_h^2}{m_h^2} \sim \begin{cases} 10^{32}, & \Lambda \sim M_{Pl} \\ 10, & \Lambda \sim 2\,\text{TeV} \end{cases} \Rightarrow$ **Expect NP close to TeV scale**
- solutions to little HP: push naturalness cut-off up to $\Lambda \sim 5 - 10\,\text{TeV}$

Fraternal Twin Higgs Model I

- core feature: Higgs as pNGB, thus naturally light
- construct GB EFT: start with complex scalar $\mathcal{H} \in \mathbf{4}$ of a global $U(4)$ $[O(8)]$
- scalar attains vev $|\langle\mathcal{H}\rangle| = f$ and induces SSB $U(4) \to U(3)$ $[O(8) \to O(7)]$: 7 GBs
- under $SU(2)_A \times SU(2)_B \subset U(4)$ subgroup: $\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{i\Theta/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$
- break global symmetry by gauging subgroup: $\mathcal{L} = |D_\mu^A H_A|^2 + |D_\mu^B H_B|^2$

Fraternal Twin Higgs Model II

- symmetry breaking $SU(2)_B \times U(1)_B \to U(1)'_B$, 3 GBs get eaten, 4 d.o.f. Higgs doublet

$$\Rightarrow \quad H_A = f \sin\left(\frac{|H|}{f}\right) \frac{H}{|H|}, \; H_B = f \cos\left(\frac{|H|}{f}\right) \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

- increase scale up to which our theory is natural by canceling top loop introducing a top partner charged under a twin $SU(3)_B$:

$$\mathcal{L}^A_{\text{Yuk, top}} = -\lambda_{A,t} \bar{Q}^a_L \tilde{H}_A t^a_R + \text{h.c.}, \; \mathcal{L}^B_{\text{Yuk, top}} = -\lambda_{B,t} \bar{Q}^b_{B_L} \tilde{H}_B t^b_{B_R} + \text{h.c.}$$

- cancellation due to FHP operator and twin parity: $\boxed{\mathcal{L}^B_{\text{Yuk, top}} \supset \frac{\lambda_{B,t}}{2f} \bar{t}_B t_B |H|^2}$

Dark Matter Analysis I

- consider the case where ψ is a gauge singlet: $\mathcal{L}_{\text{FHPM}} = \bar{\psi}(i\partial\!\!\!/ - \mu_\psi)\psi + \frac{c_\psi}{f}\bar{\psi}\psi|H|^2$

1) thermal equilibrium of dark sector with SM particles

2) annihilation regime DM DM $\longrightarrow$ SM SM

3) DM does not find partners to annihilate

$\Longrightarrow$ abundance freezes out

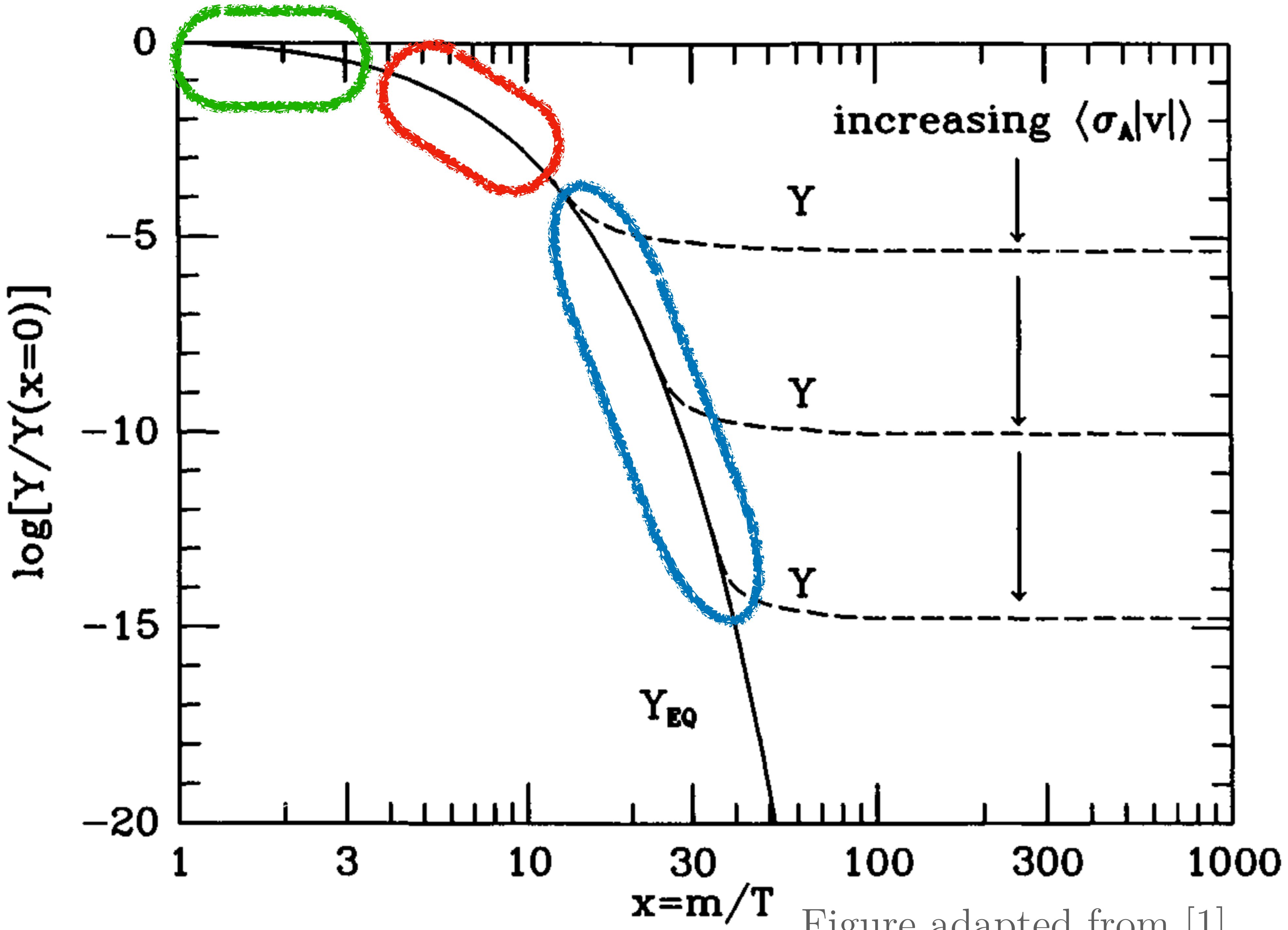


Figure adapted from [1].

Boltzmann Equation and Relic Abundance

- evolution of DM number density follows Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v_{\mathrm{rel}} \rangle \left(n_\chi^2 - n_{\chi,\,\mathrm{equ}}^2 \right)$$

- thermal average over cross section: $\langle \sigma v_{\mathrm{rel}} \rangle = \dfrac{\int d^3p_1 \int d^3p_2 \; e^{-\frac{E_1}{T}} \; e^{-\frac{E_2}{T}} \; \sigma v_{\mathrm{rel}}}{\int d^3p_1 \int d^3p_2 \, e^{-\frac{E_1}{T}} \; e^{-\frac{E_2}{T}}}$

- approximate solution: $\Omega_{\mathrm{DM}}\, h^2 \approx \dfrac{3 \times 10^{-27} \mathrm{cm}^3\, \mathrm{s}^{-1}}{\langle \sigma v_{\mathrm{rel}} \rangle (T_f)}$

Dark Matter Analysis II

Parameter Space Constraints:

1) avoid overproduction of the measured DM relic abundance $\Omega_{\mathrm{DM}}\, h^2 \simeq 0.12$

2) invisible Higgs decays: $\mathrm{BR}(h \to \bar{\psi}\psi) < 11\,\%\,(\mathrm{LHC}), 2.5\,\%\,(\mathrm{HL-LHC, proj.})$

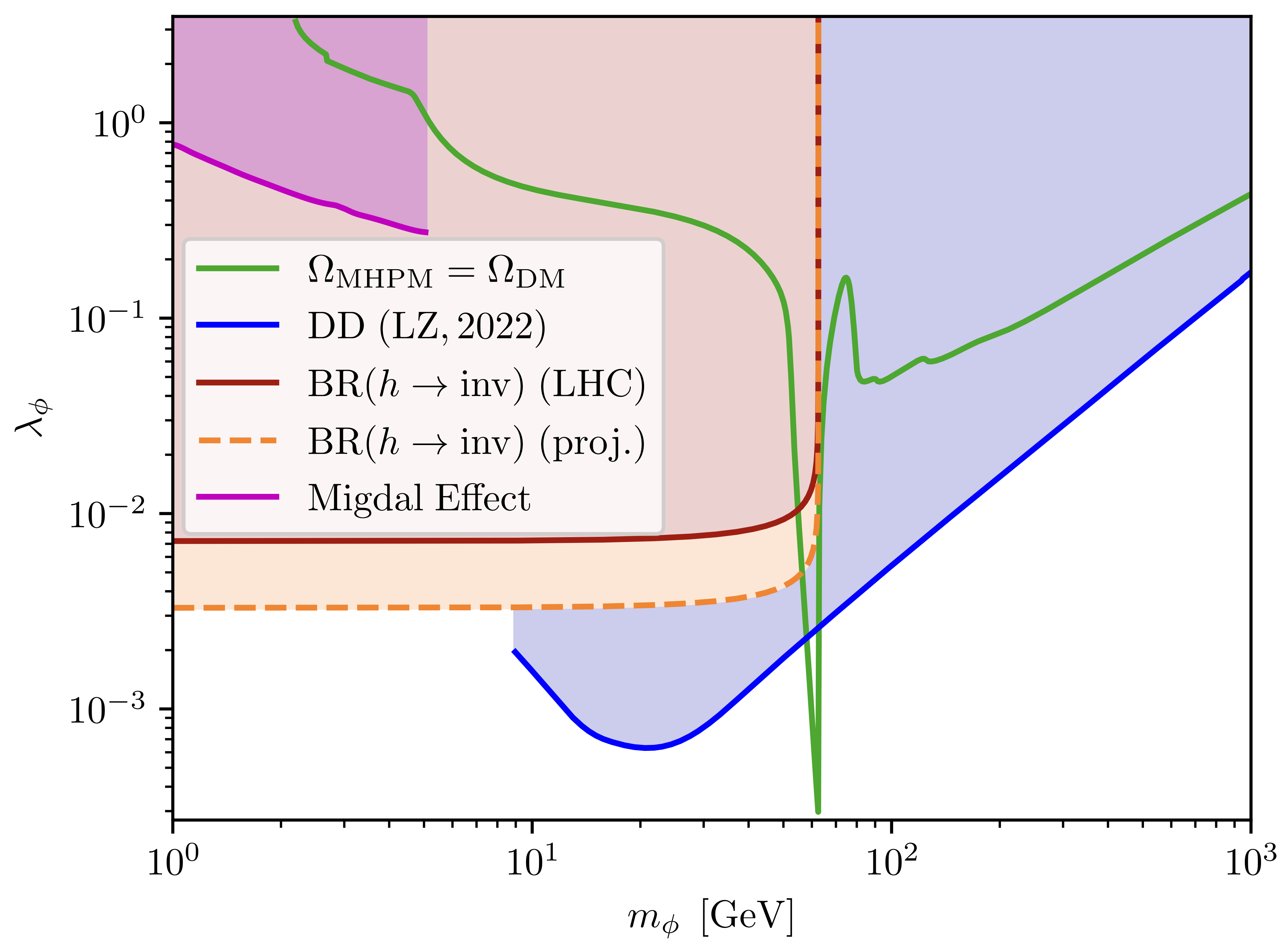
3) Direct Detection: measurement of nuclear recoil energy due to scattering of DM particle off a nucleus (XENON1T, LUX-ZEPLIN)

Direct Detection

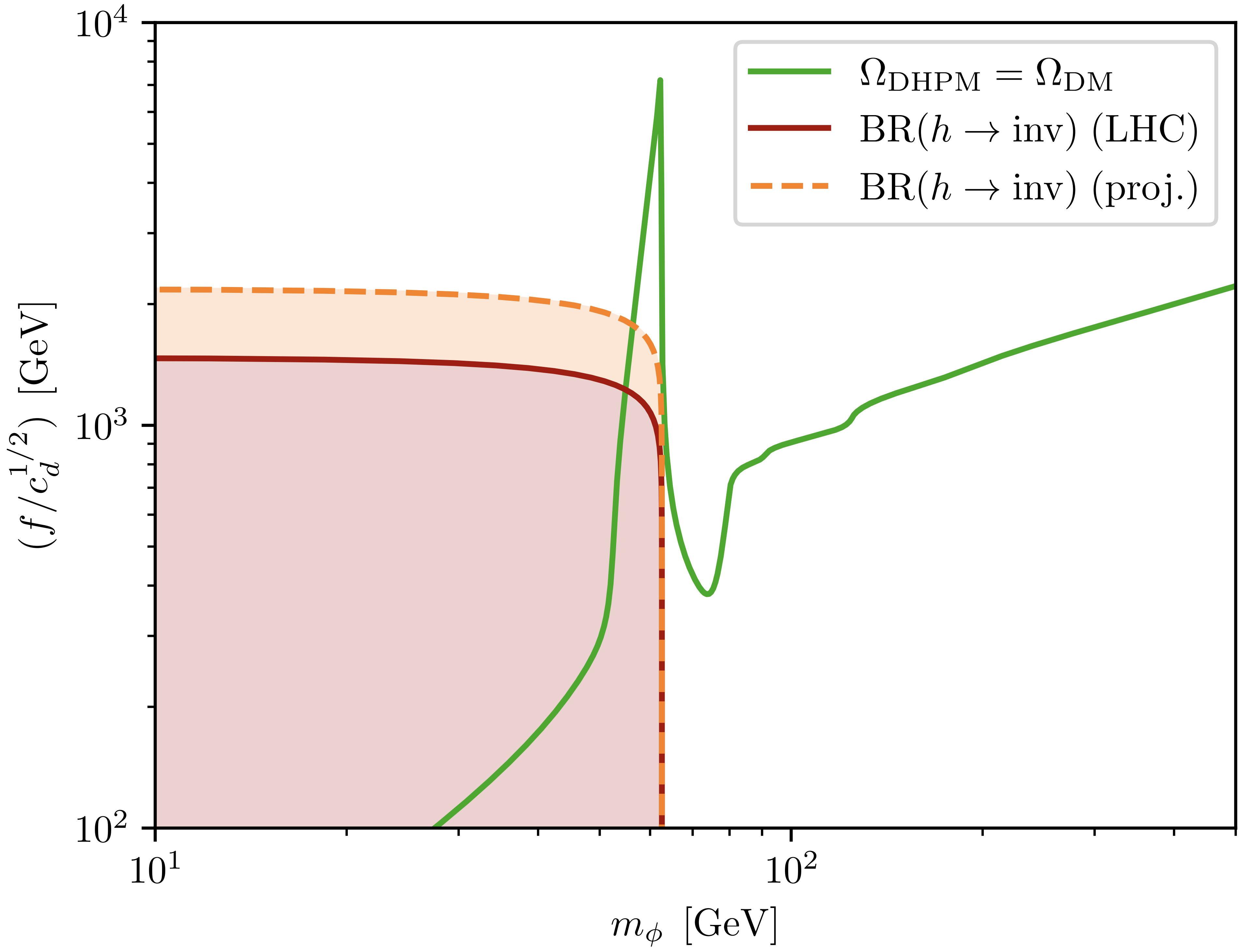
- nucleon mass operator: $m_N = \langle N | \Theta^\mu_\mu | N \rangle$
- trace of QCD energy-momentum tensor: $\Theta^\mu_\mu = \sum_{q=u,d,s} m_q \bar{q} q - \frac{9\alpha_s}{8\pi} G^a_{\mu\nu} G^{a\mu\nu}$
- non-relativistic quark densities: $\langle N | m_q \bar{q} q | N \rangle = m_N f^N_{T_q}$
- for heavy quarks: $\langle N | m_h \bar{h} h | N \rangle = \frac{2}{27} m_N f^N_{T_G}$
- effective Lagrangian: $\mathcal{L}^{\mathrm{DD}}_{\mathrm{eff}} = \sum_{q=u,d,s} 2 m_q g_{\chi q} \bar{\chi}\chi \bar{q} q + g_{\chi g} \frac{\alpha_s}{4\pi} \bar{\chi}\chi G^a_{\mu\nu} G^{a\mu\nu}$
- match to: $\mathcal{L}_N = 2 f_N \, \bar{\chi}\chi \bar{N} N$, here: $f_N = m_N \left(\sum_{q=u,d,s} f^N_{T_q} \, g_{\chi q} - \frac{1}{9} \, f_{T_G} \, g_{\chi g} \right)$

Scalar DM Models

$$\mathcal{L}_{\rm MHPM} = \partial_\mu \phi \, \partial^\mu \phi^* - \mu_\phi^2 |\phi|^2 - \lambda_\phi |\phi|^2 |H|^2$$

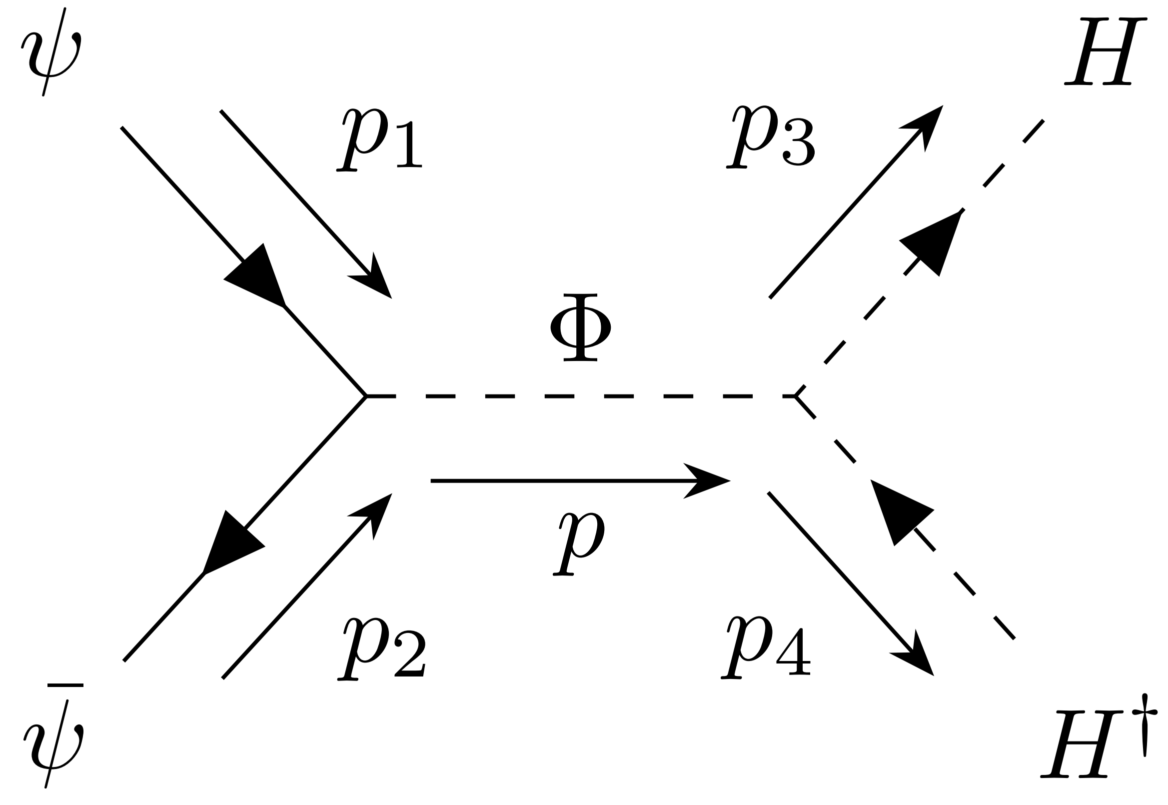


$$\mathcal{L}_{\rm DHPM} \supset \frac{c_d}{f^2} \partial_\mu |\phi|^2 \partial^\mu |H|^2$$



Toy Model for Top-Down EFT

$$\mathcal{L}_{\text{UV}} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi + \bar{\psi}(i\partial\!\!\!/ - \mu_\psi)\psi - \frac{1}{2}m_\Phi^2\Phi^2 + y_\psi\bar{\psi}\Phi\psi + \kappa\Phi|H|^2$$



match to: $\frac{c_\psi}{\Lambda}\mathcal{O}_{\psi H} = \frac{c_\psi}{\Lambda}\bar{\psi}\psi|H|^2$ $\longrightarrow$ $c_\psi = \frac{y_\psi\kappa}{m_\Phi}, \Lambda = m_\Phi$

$\Longrightarrow$ in accordance with power counting: $c_i^{(d)} \sim (\text{coupling})^{n-2}$

Collinear Factorization

$$\sigma_{\text{tot}} = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i,j} f_i(x_1, \mu)\, f_j(x_2, \mu)\, \hat{\sigma}_{ij}(x_1 x_2 s, \mu)$$

Parton distribution functions (not perturbatively accessible)

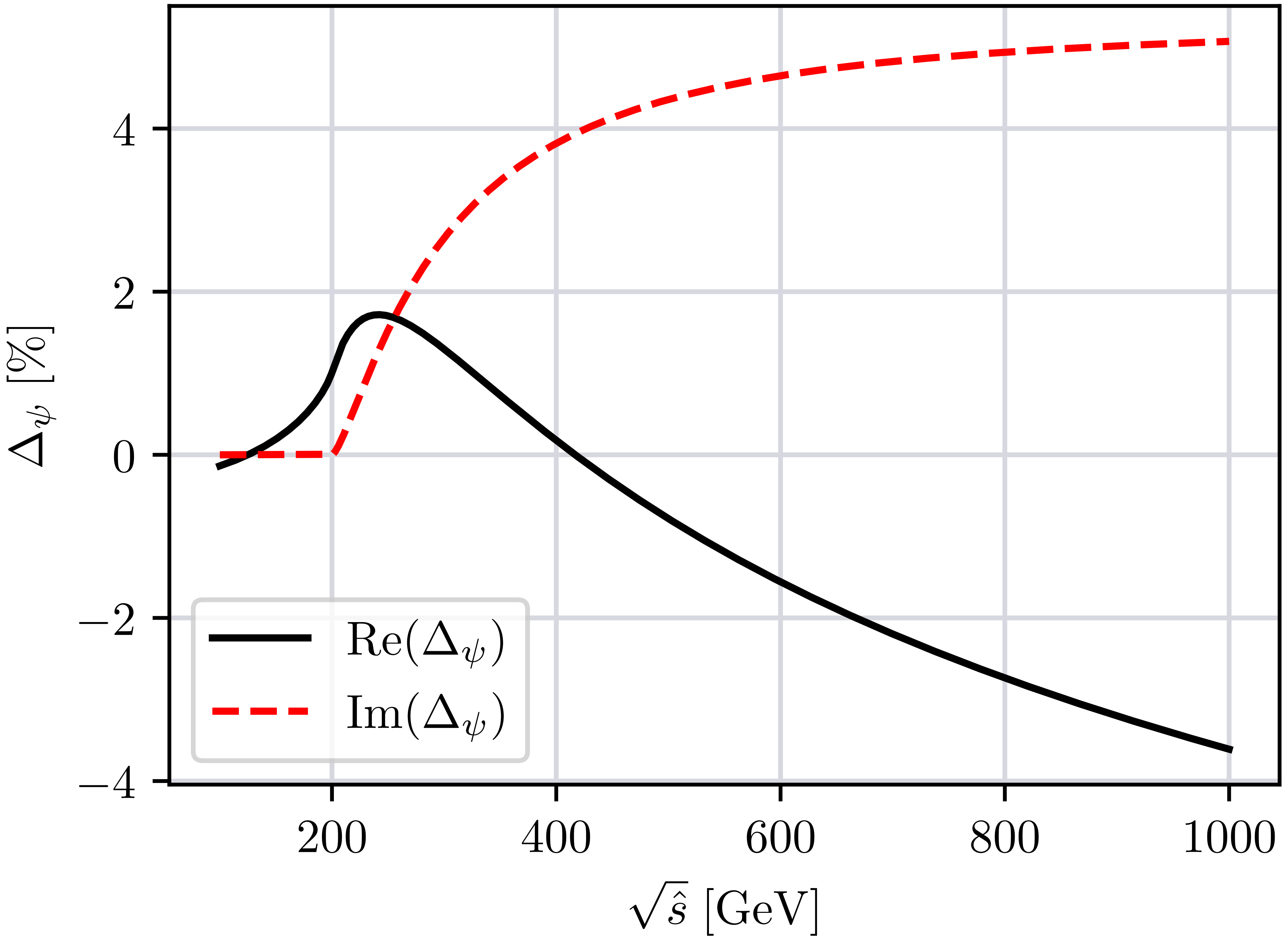
Behavior of Δ_ψ

Remarks on the result:

1) ψ in fundamental of $SU(N)$: factor of N

2) symmetric under $c_\psi \to -c_\psi$

3) no dependence on renormalization scale



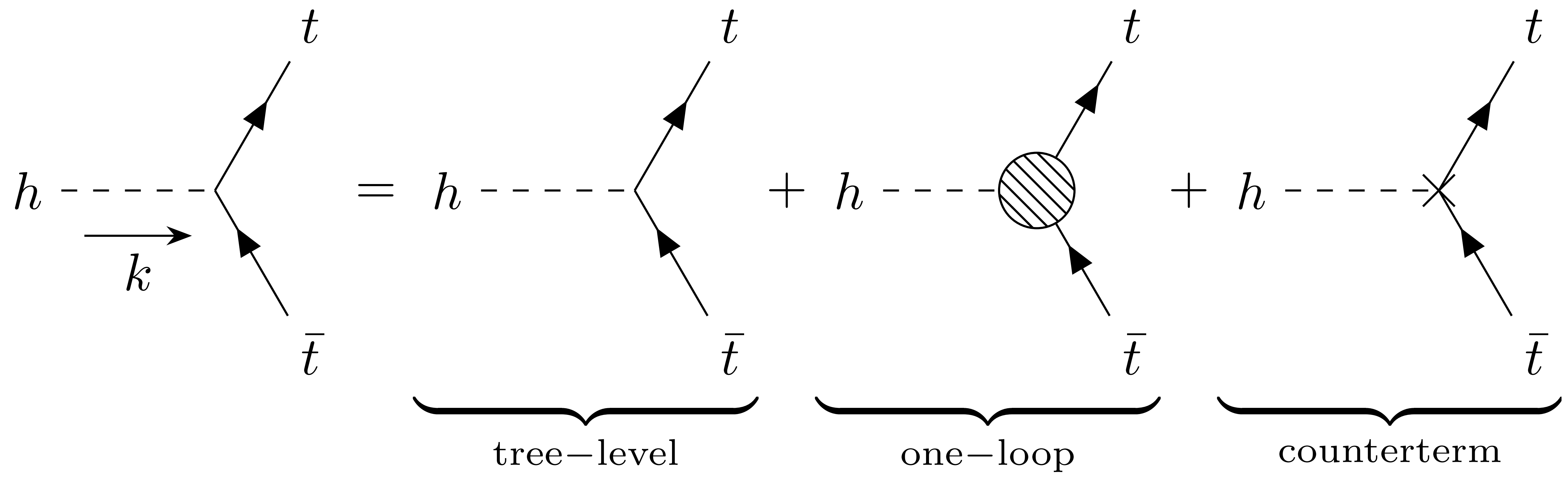
$c_\psi = 2,\, f = 3v_{\mathrm{EW}},\, m_\psi = 100\,\mathrm{GeV}$

Discussion of Higgs Vertices in the SM

- start from Lagrangian with bare fields/couplings: $\mathcal{L}_{\text{int}} = g_t^{(0)} h^{(0)} \bar{t}^{(0)} t^{(0)}$

- after introducing renorm. constants: $\mathcal{L}_{\text{int}} = g_t h \bar{t} t + \left(\delta Z_g + \frac{1}{2}\delta Z_t + \frac{1}{2}\delta Z_h \right) g_t h \bar{t} t + \mathcal{O}(\delta Z_i^2)$

- impose renorm. condition:



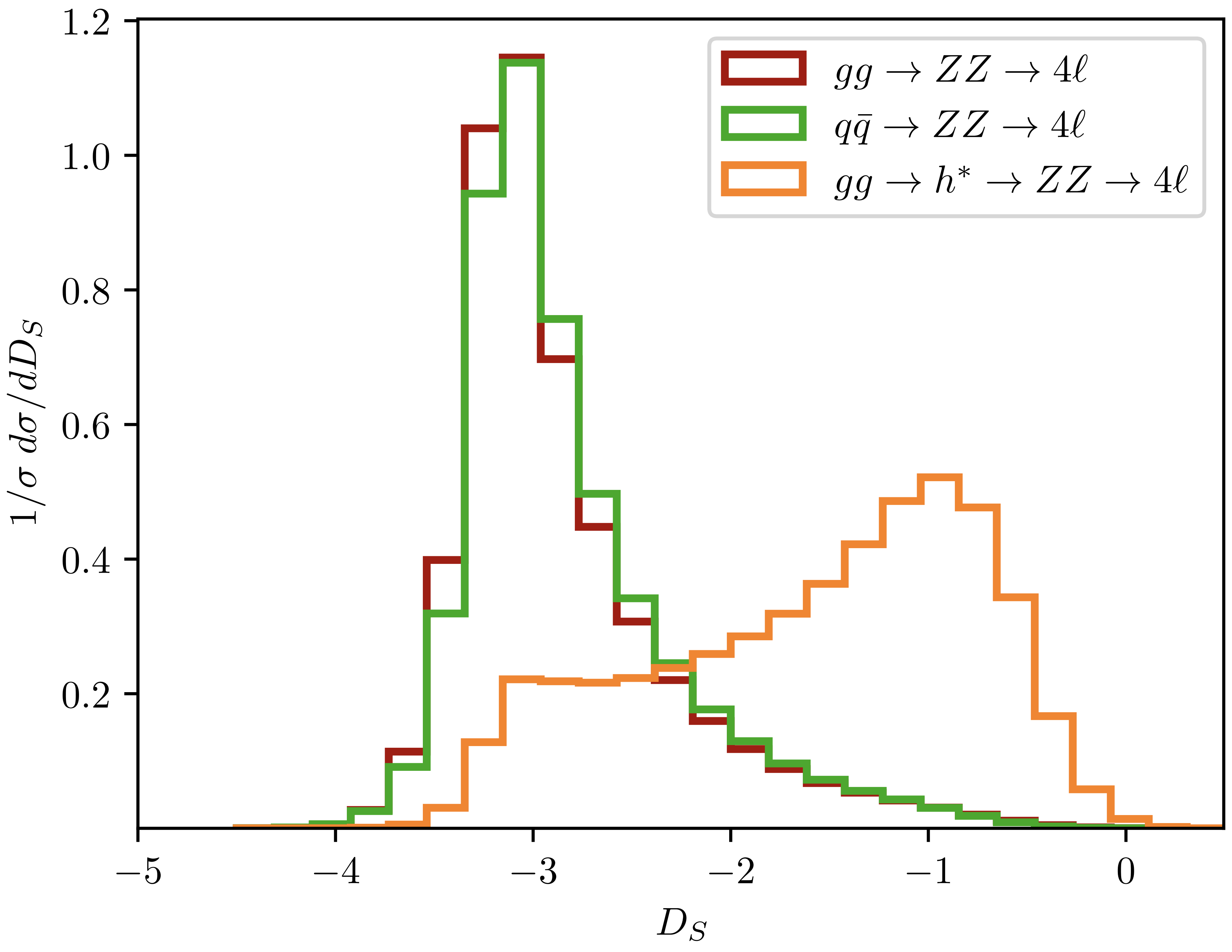
- for finiteness at $\mathcal{O}(c_\psi^2)$: condition $\delta Z_g = -\frac{1}{2}\delta Z_h$ (for all SM Higgs vertices)

Higher-Order QCD Effects

- estimate higher-order QCD effects using K-factors defined as ratio of fiducial cross section to certain order in QCD to LO QCD prediction
- numerical values: $K_{gg}^{\mathrm{NLO}} = 1.83, K_{q\bar{q}}^{\mathrm{NNLO}} = 1.55$
- QCD-improved spectra: $\left(\frac{d\sigma_{pp}}{dO}\right)_{\mathrm{improved}} = K_{gg}^{\mathrm{NLO}} \left(\frac{d\sigma_{gg}}{dO}\right)_{\mathrm{LO}} + K_{q\bar{q}}^{\mathrm{NNLO}} \left(\frac{d\sigma_{q\bar{q}}}{dO}\right)_{\mathrm{LO}}$

Illustration of Discriminating effect (SM spectra)

We use version 8.0 of MCFM and apply similar event cuts as ATLAS and CMS.



- Process of interest features a distinct peak at $D_S \simeq -1$
- sharp cut-off in SM spectra at $D_S \simeq -4$ and 0

Event Cuts

Event Cut	Description
$140\,\text{GeV} < m_{4\ell} < 600\,\text{GeV}$	four-lepton invariant mass
$\|\eta_\ell\| < 2.5$	pseudorapidity range for the leptons
$p_{T,\ell_1} > 20\,\text{GeV}$	highest lepton transverse momentum
$p_{T,\ell_2} > 15\,\text{GeV}$	second highest lepton transverse momentum
$p_{T,\ell_3} > 10\,\text{GeV}$	third highest lepton transverse momentum
$p_{T,\ell_4} > 6\,\text{GeV}$	fourth highest lepton transverse momentum
$50\,\text{GeV} < m_{12} < 106\,\text{GeV}$	invariant mass of the leading lepton pair
$50\,\text{GeV} < m_{34} < 115\,\text{GeV}$	invariant mass of the subleading lepton pair

Statistical Analysis

- use Poisson distribution to construct likelihood and profile-likelihood ratio

- Asimov Data Set: counts in bin correspond to expectation value

- Asimov Approximation for significance including background uncertainty:

$$Z_i = \sqrt{2\left((s_i + b_i)\ln\left[\frac{(s_i + b_i)(b_i + \sigma_{b_i}^2)}{b_i^2 + (s_i + b_i)\sigma_{b_i}^2}\right] - \frac{b_i^2}{\sigma_{b_i}^2}\ln\left[1 + \frac{\sigma_{b_i}^2 s_i}{b_i(b_i + \sigma_{b_i}^2)}\right]\right)}$$

- condition: $Z > \sqrt{2}\,\mathrm{erf}^{-1}(\mathrm{CL})$ with $\mathrm{CL} = 95\%$

References

[1] E.W. Kolb and M.S. Turner. The Early Universe. Vol. 69. 1990. ISBN 978-0-201-62674-2.