HIGGS DECAYS TO FOUR LEPTONS TO $\mathcal{O}(1/\Lambda^4)$ IN SMEFT

Based on arXiv:2602.12326 [Flores-Hernández, Martin]

Mario Arturo Flores Hernández (mfloresh@nd.edu)

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SMEFT

Wilson Coefficient getting imprint of UV physics

Higher dimension operators of mass dimension d

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{d>4,i} \frac{C_i^{(d)}}{\Lambda^{(d-4)}} \mathscr{O}_i^{(d)}$$

BSM physics UV scale

SMEFT

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- Bottom-up perspective:
  - No assumed UV completion
  - All operators must be included,
  - C_i treated as free parameters

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- B, L, CP conservation.

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- In the SMEFT framework

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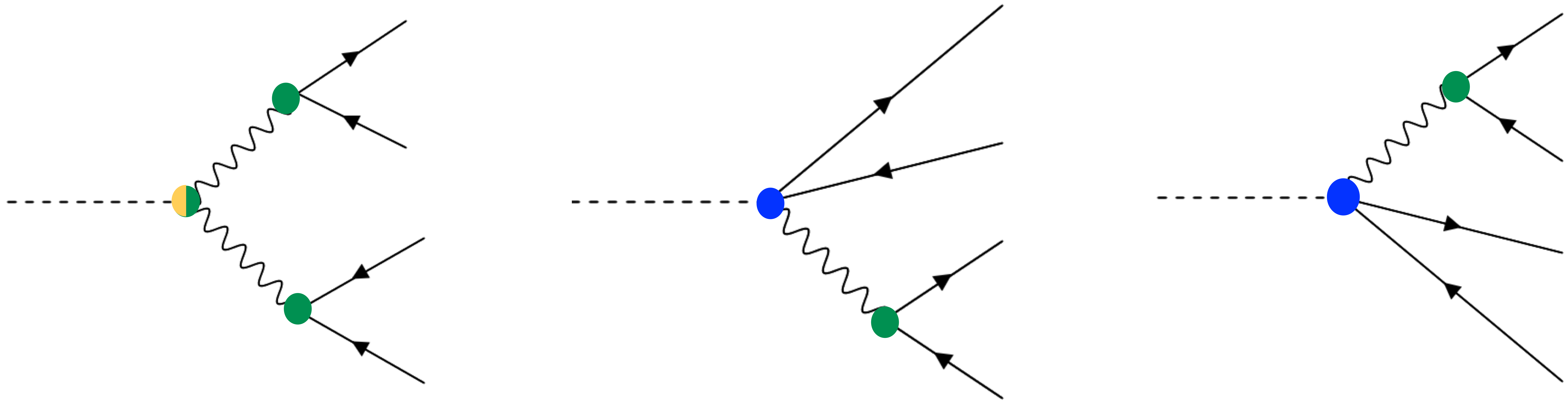
- $h \to ZZ^* \to \ell'\bar{\ell}'\ell\bar{\ell}$ and $h \to WW^* \to \ell\bar{\nu}_\ell\nu_\ell\bar{\ell}$ are known with high accuracy, making it a good place to look for SMEFT effects.

SMEFT IN $h \to 4\ell$



1. Modifies SM vertices:
2. Non-SM vertices:
3. Modify parameters $\leftrightarrow$ exp. inputs

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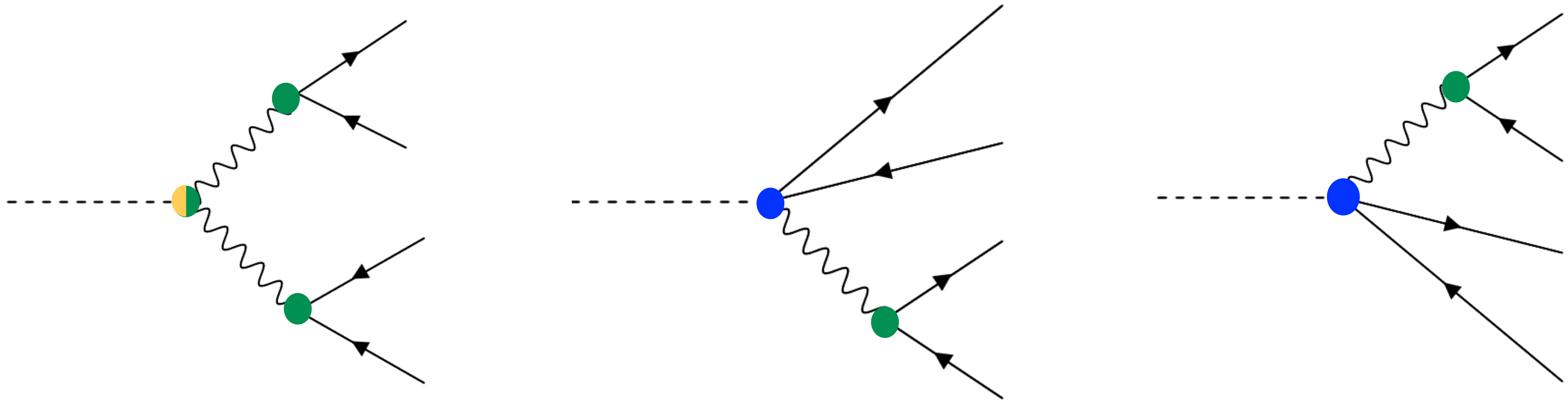

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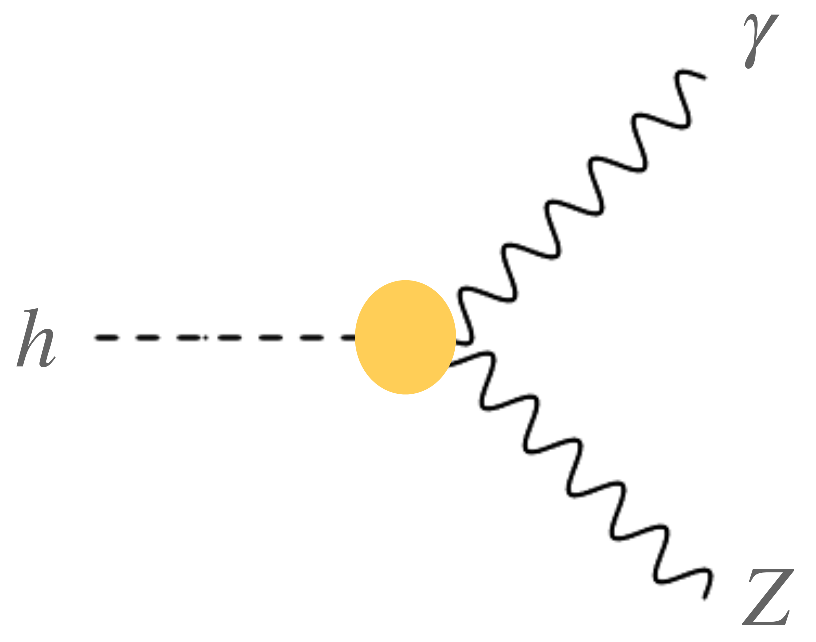

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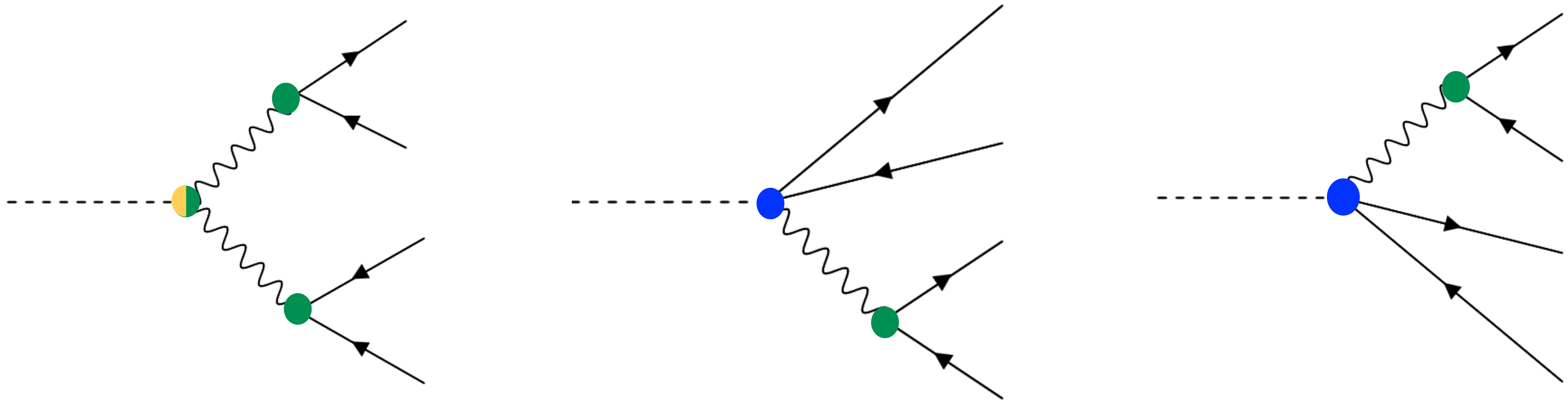

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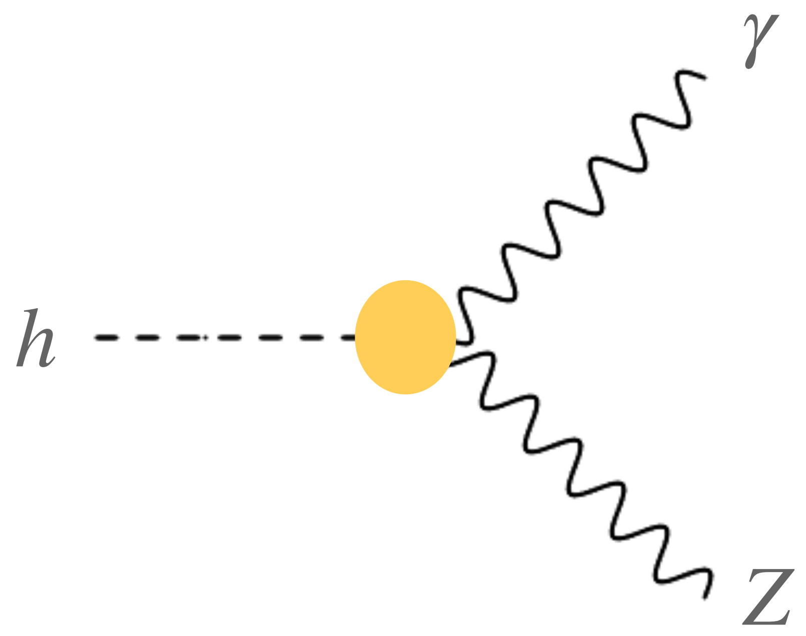

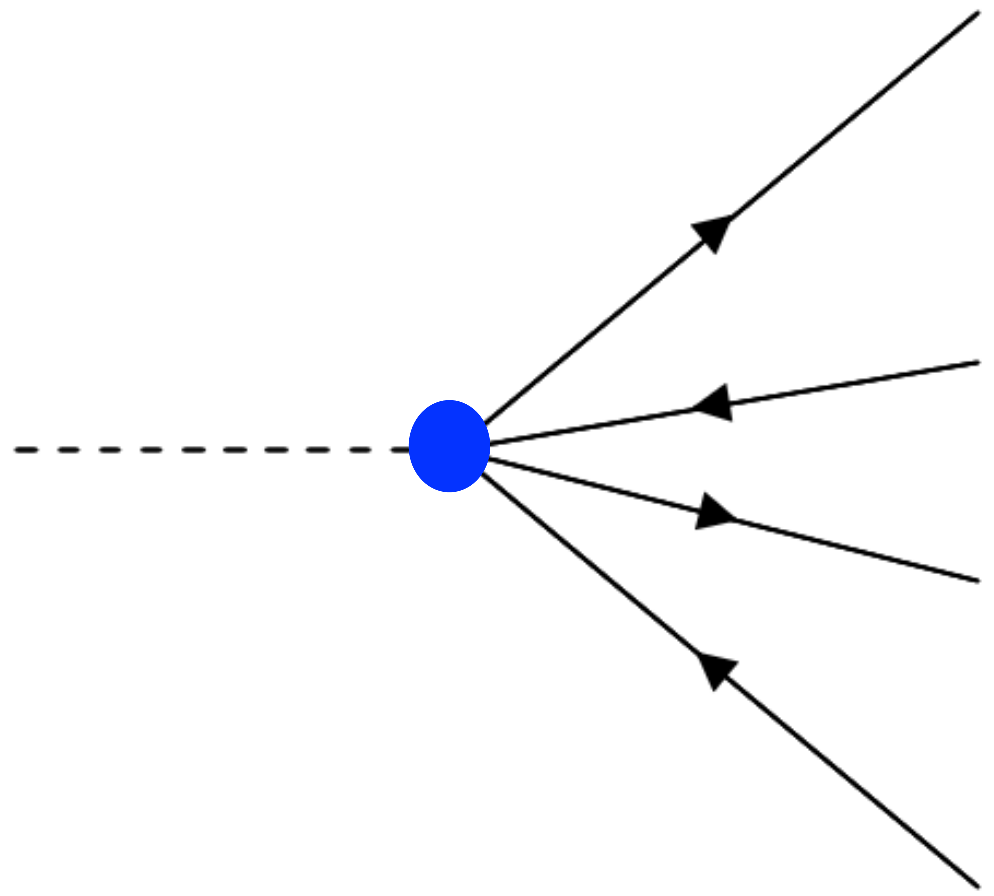

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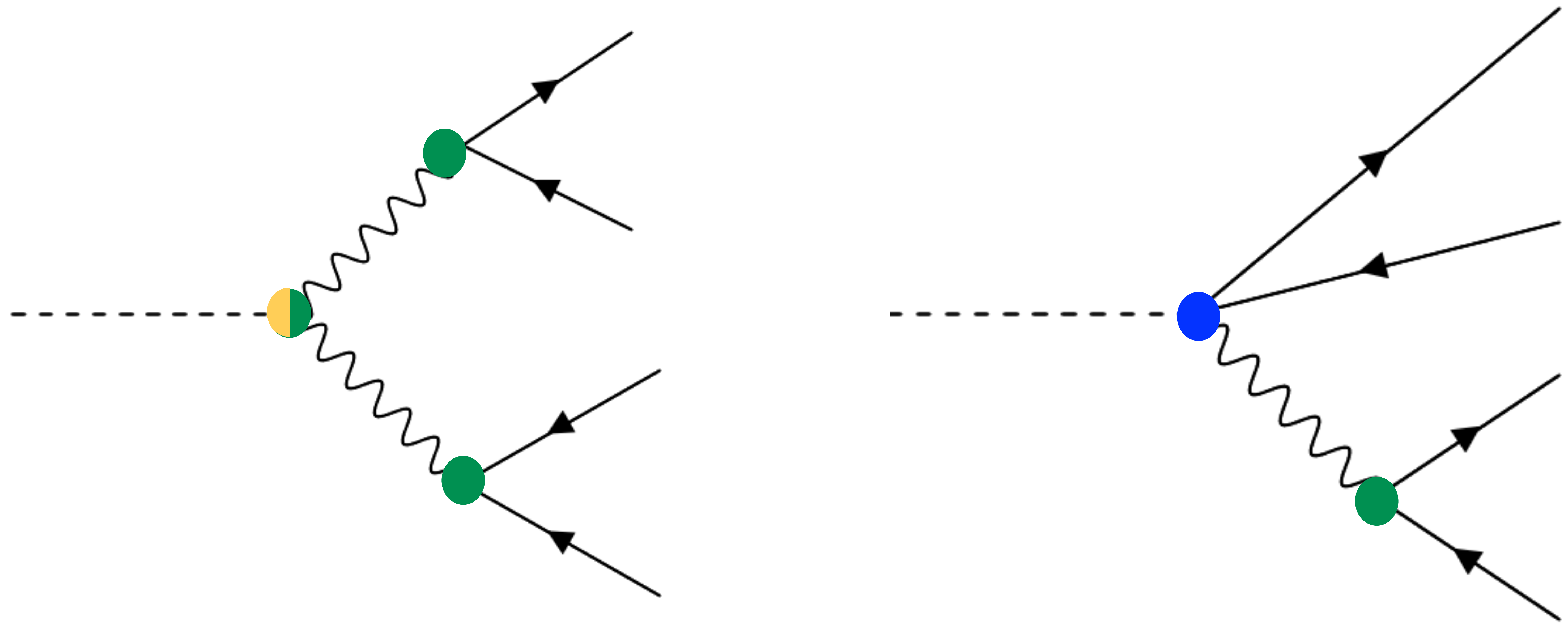

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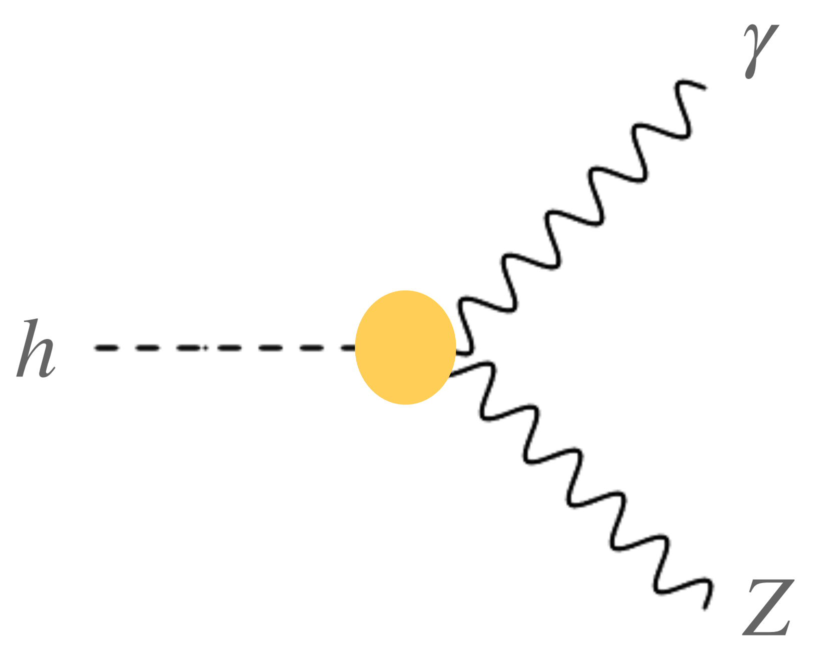

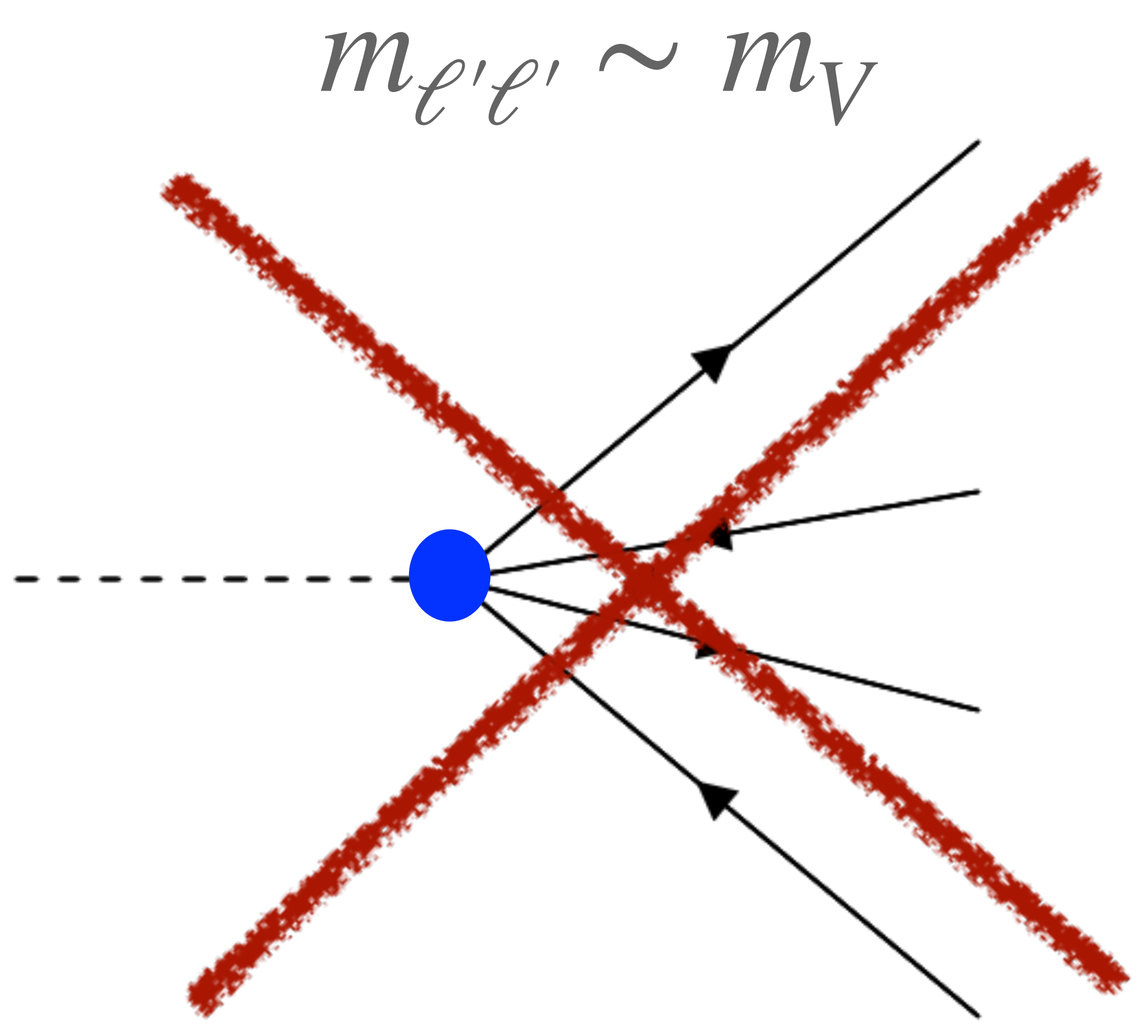

ANGULAR DISTRIBUTION

[1310.2574 Buchalla, Catà, D'Ambrosio]
[1406.1361 Beneke, Boito, Wang]

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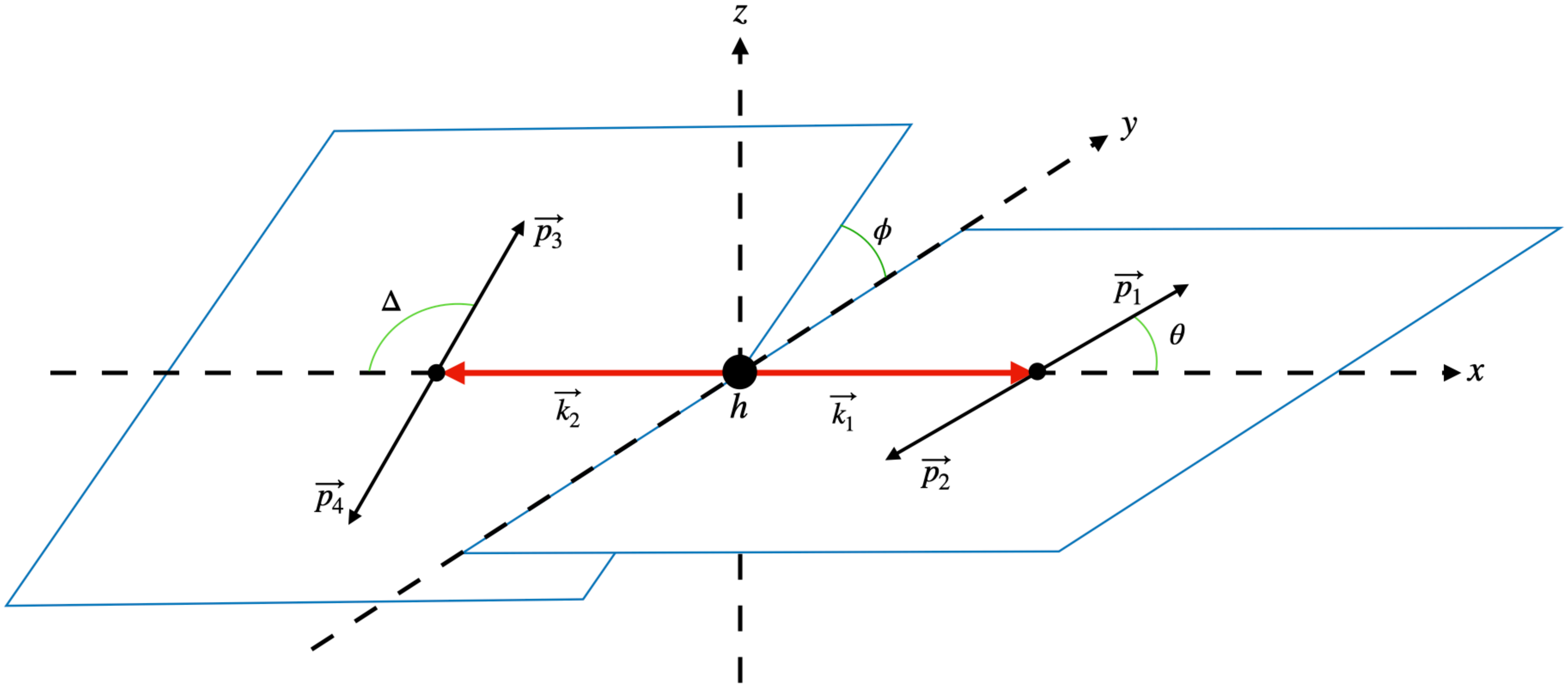
Specify a frame and define variables:

- $s = \dfrac{k_1^2}{m_h^2}$
- $r = \dfrac{k_2^2}{m_h^2}$
- Three angles (θ, Δ, ϕ)



Momenta labeled as $\ell(p_1)\overline{\ell}(p_2)\ell'(p_3)\overline{\ell'}(p_4)$

ANGULAR DISTRIBUTION IN THE SM

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Differential decay rate in the narrow-width approximation:

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In the SM

$$\begin{aligned}|\mathscr{A}(h \to \ell\bar{\ell}(Z \to \ell'\bar{\ell}'))_{SM}|^2 = {} & J^Z_{SM,1} + J^Z_{SM,2}\cos^2\theta\cos^2\Delta \\ & + J^Z_{SM,3}\cos^2\theta + J^Z_{SM,4}\cos^2\Delta + J^Z_{SM,5}\cos\theta\cos\Delta \\ & + (J^Z_{SM,6}\sin\theta\sin\Delta + J^Z_{SM,7}\sin(2\theta)\sin(2\Delta))\cos\phi \\ & + J^Z_{SM,8}\sin^2\theta\sin^2\Delta\cos(2\phi)\end{aligned}$$

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$f_i(\theta, \Delta, \phi)$

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$$J^Z_{SM,i} = J^Z_{SM,i}(s,r)$$

$$f_i(\theta,\Delta,\phi)$$

$h \to \ell\bar{\ell}\ell'\bar{\ell}'$ IN SMEFT

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|\mathscr{A}(h \to \ell\bar{\ell}(Z \to \ell'\bar{\ell}'))|^2 = & J_1^Z + J_2^Z \cos^2\theta \cos^2\Delta \\
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\end{aligned}
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J^Z_{SM,i}(s,r) \to J^Z_i(s,r,\{C_i\}) = J^Z_{SM,i}(s,r) + \frac{1}{\Lambda^2} J^Z_{dim6,i}(s,r,\{C^6_j\}) + \frac{1}{\Lambda^4} J^Z_{dim8,i}(s,r,\{C^6_j, C^8_i\})
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\begin{aligned}
|\mathscr{A}(h \to \ell\bar{\nu}_l\ell\nu_{\ell}\bar{\ell})|^2 = & J_1^W + J_2^W \cos^2\theta\cos^2\Delta \\
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Present without SMEFT.
Get SMEFT contributions

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Get SMEFT contributions

SMEFT generated

ANGULAR DISTRIBUTION

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$$Q^{(8)}_{L^2H^2D^3,4} = i(\bar{L}_p \gamma^\mu \tau^I \overleftrightarrow{D}^\nu L_p)\left[(D_\mu H)^\dagger \tau^I (D_\nu H) + (D_\nu H)^\dagger \tau^I (D_\mu H)\right]$$

$$Q^{(8)}_{L^2WH^2D,5} = \epsilon_{IJK}(\bar{L}_p \gamma^\nu \tau^I L_p) D^\mu (H^\dagger \tau^J H) W^K_{\mu\nu}$$

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Purely $\mathcal{O}(1/\Lambda^4)$ **effect**

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OBSERVABLES FOR $h \to \ell\bar{\ell}\ell'\bar{\ell}'$

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- This channel is fully reconstructible, so higgs rest frame and angles can be reconstructed.
- SMEFT enters in the J-Functions

$$J_i^Z(s,r,\{C_i\}) = J_{SM,i}^Z(s,r) + \frac{1}{\Lambda^2}J_{dim6,i}^Z(s,r,\{C_j^6\}) + \frac{1}{\Lambda^4}J_{dim8,i}^Z(s,r,\{C_j^6,C_i^8\})$$

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How to extract J functions? ⟶ **Angular Asymmetries**

[1310.2574 Buchalla, Catà, D'Ambrosio]
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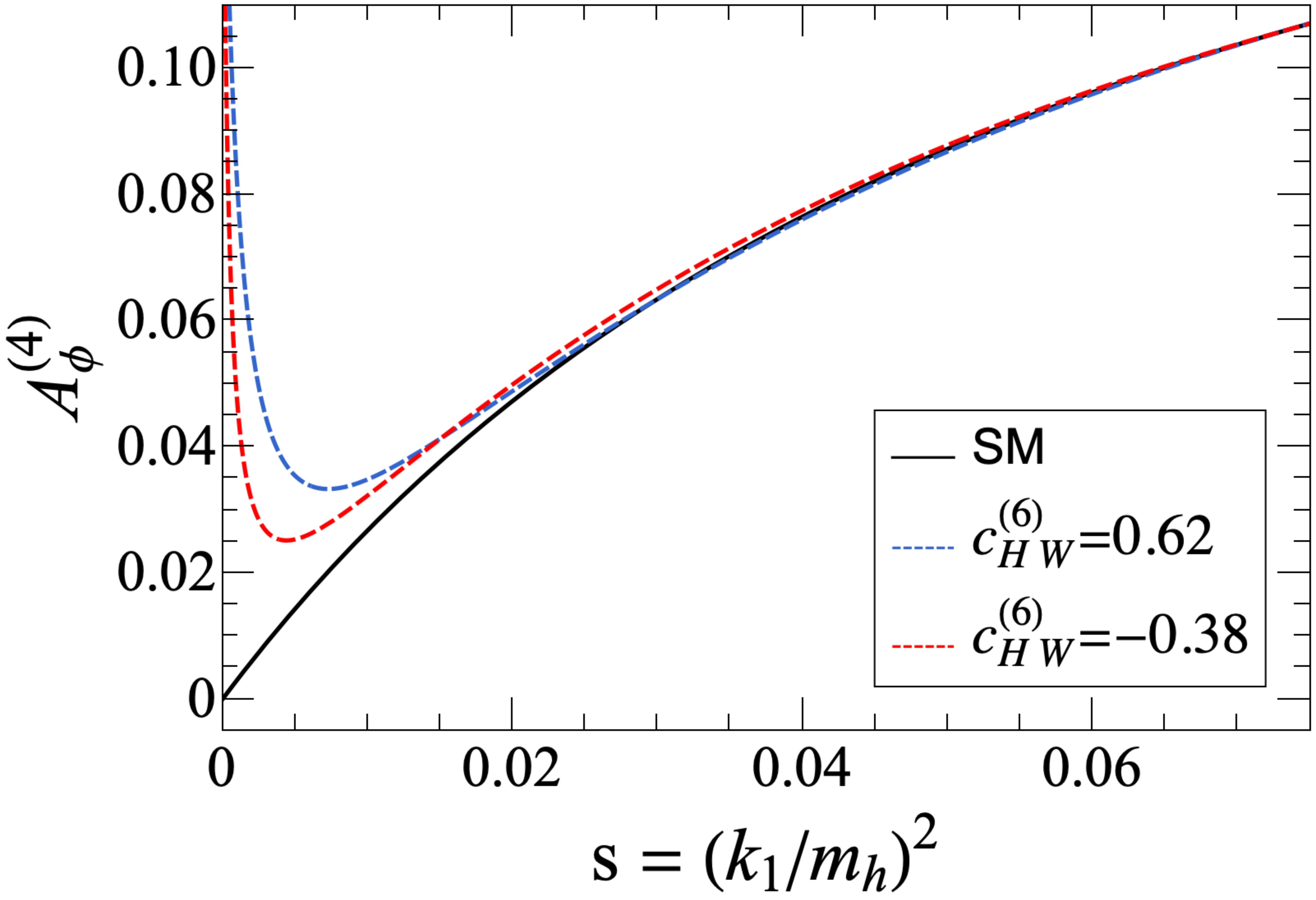
$$A_\phi^{(4)} = \left(\frac{d\Gamma}{ds}\right)^{-1} \int_0^{2\pi} \mathrm{sgn}(\cos(2\phi)) \frac{d\Gamma}{ds d\phi} d\phi \propto J_Z^8$$

EXAMPLE

$$Q_{HW}^{(6)} = (H^\dagger H) W^I_{\mu\nu} W^{I,\mu\nu}$$



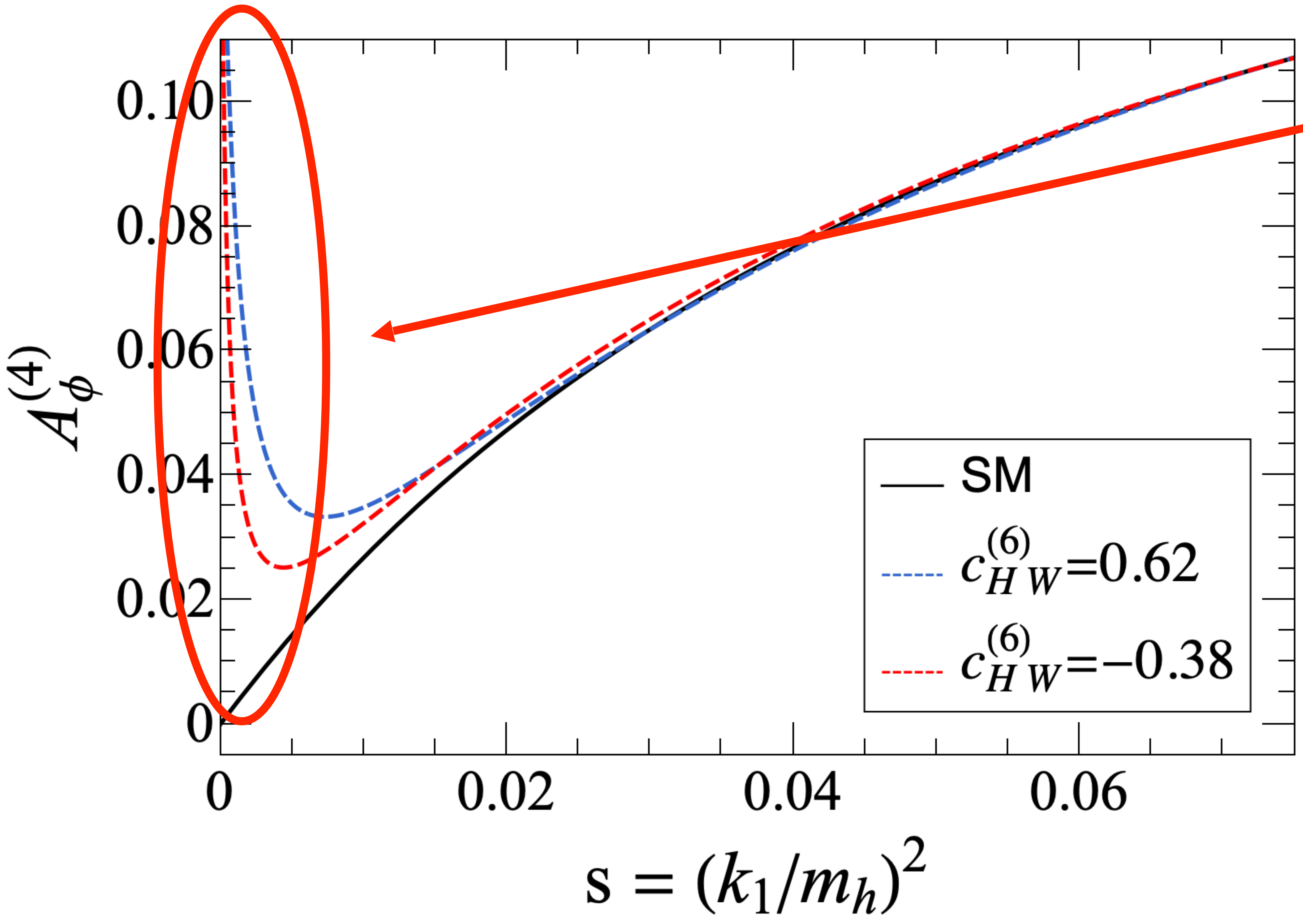
$$c_{HW}^{(6)} \equiv C_{HW}^{(6)}/\Lambda^2 \qquad \Lambda = 1\text{Tev}$$

[2012.02779 Ellis, Madigan, Mimasu, Sanz, You]

EXAMPLE

$Q_{HW}^{(6)} = (H^\dagger H) W_{\mu\nu}^I W^{I,\mu\nu}$ ← Contributes to $h\gamma Z$

$s \sim 0$



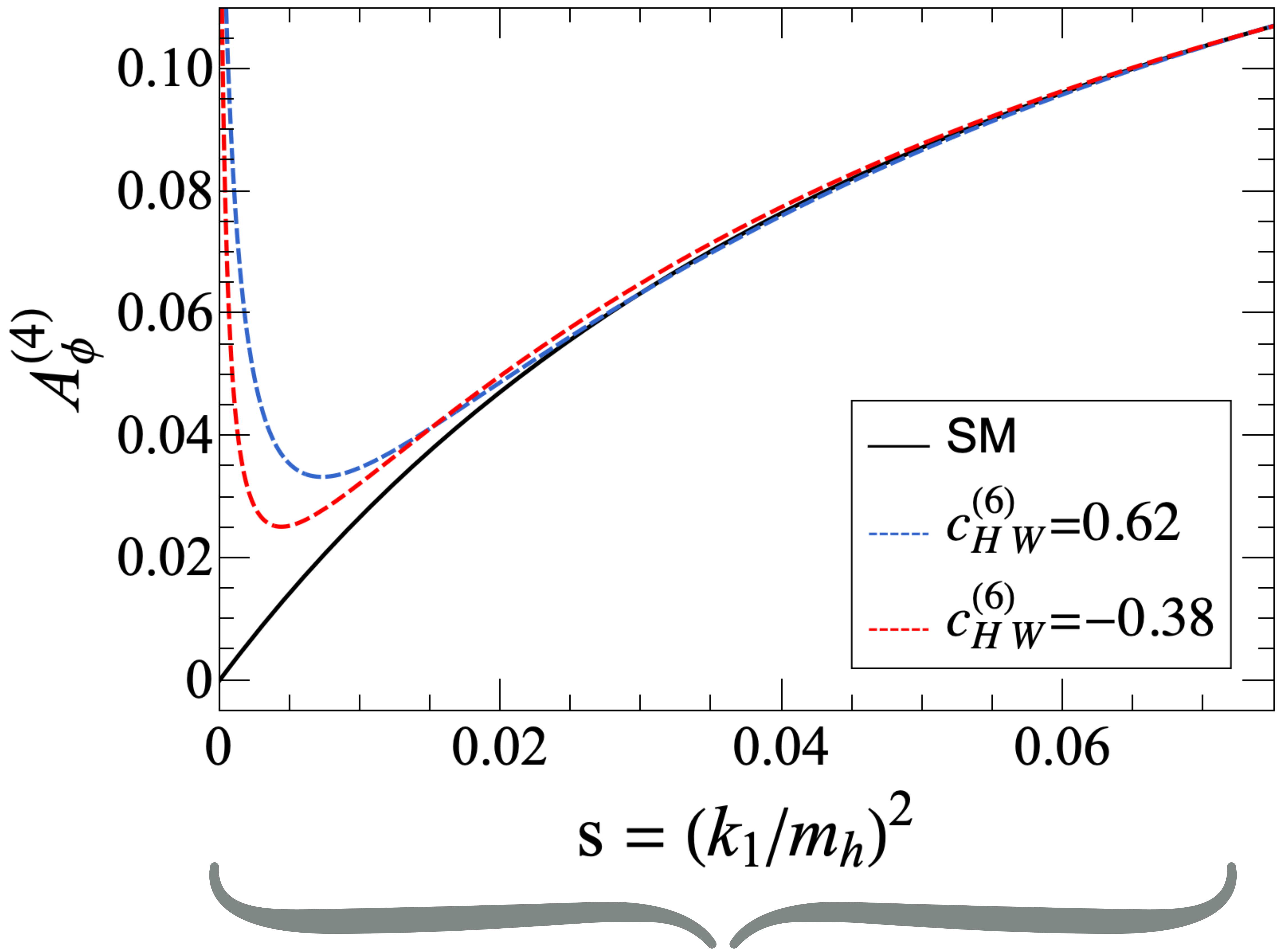
Photon pole enhancement

$\frac{1}{k_1^2} \sim \frac{1}{s}$, purely $\mathcal{O}(1/\Lambda^4)$

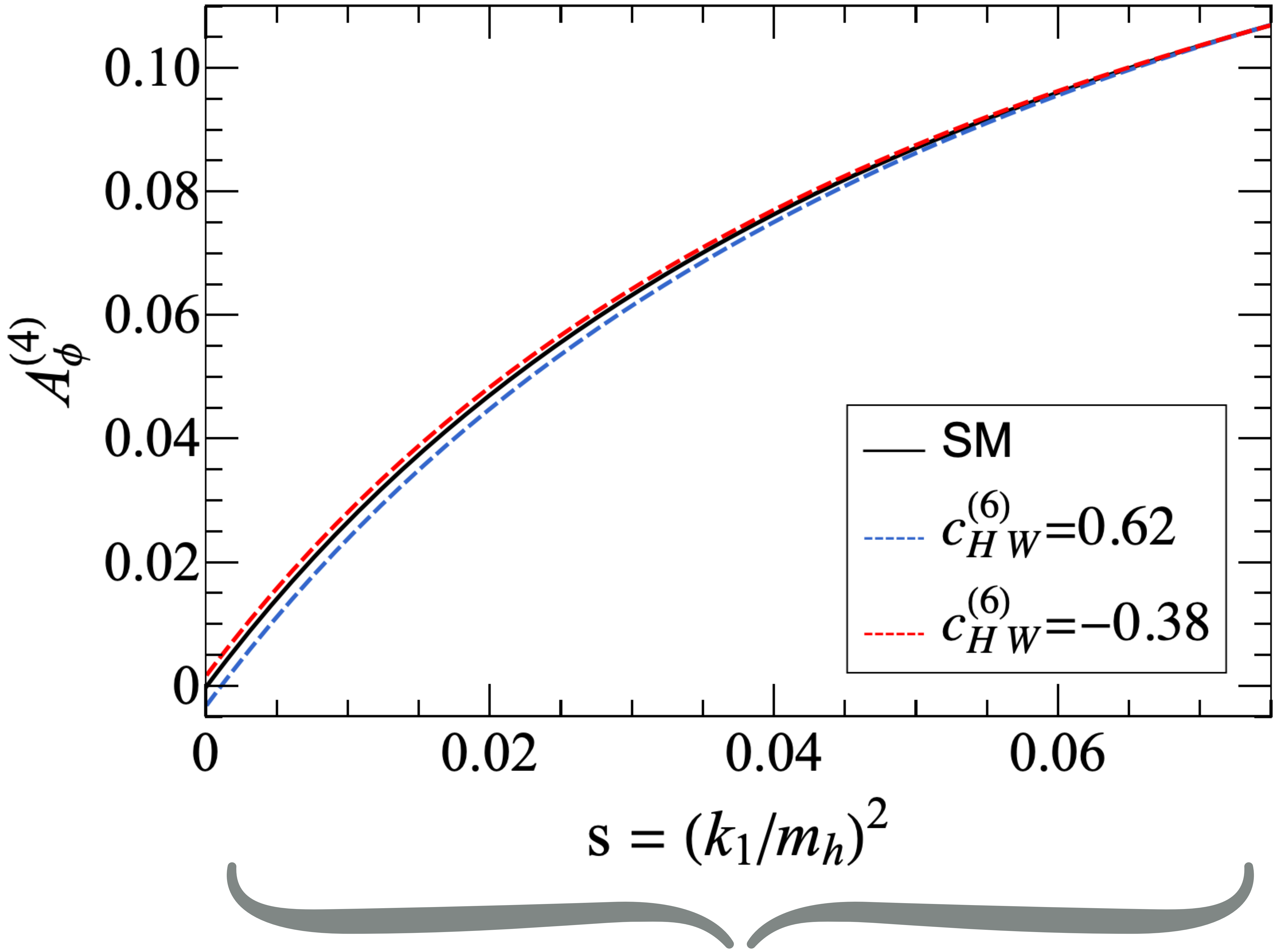
EXAMPLE

$Q_{HW}^{(6)} = (H^\dagger H) W^I_{\mu\nu} W^{I,\mu\nu}$

[1406.1361 Beneke, Boito, Wang]



$$A_\phi^{(4)} = A_{\phi,SM}^{(4)} + \frac{1}{\Lambda^2} A_{\phi,dim6}^{(4)} + \frac{1}{\Lambda^4} A_{\phi,dim8}^{(4)}$$



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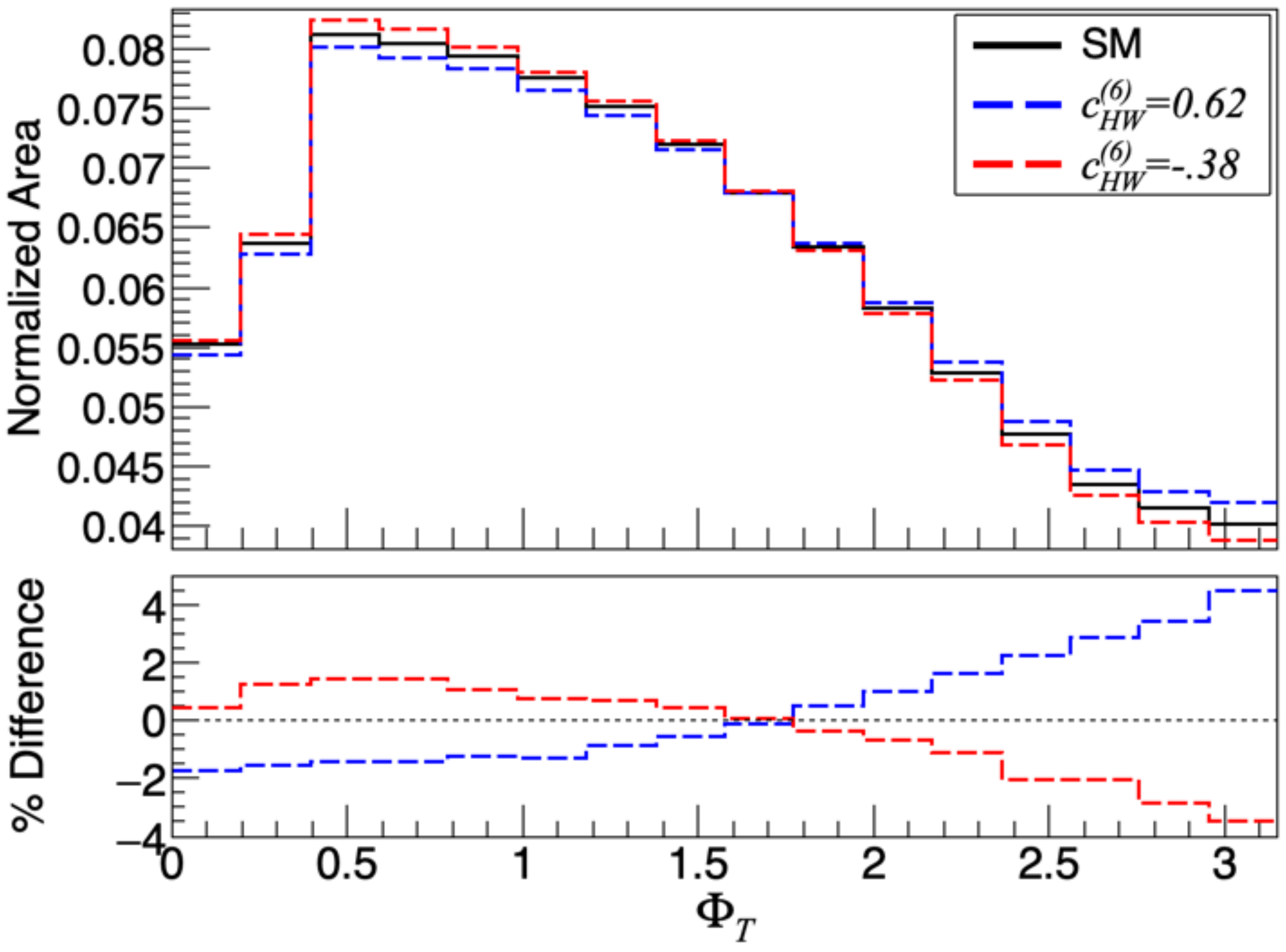
Kinematic Cuts
$p_T^{lead} > 22$ GeV
$p_T^{sublead} > 15$ GeV
$p_T^{miss} > 20$ GeV
$p_T^{\ell\ell'} > 30$ GeV
$55 \text{ GeV} > m_{\ell\ell'} > 10$ GeV
$\Delta\phi_{\ell\ell', E_T^{miss}} > \pi/2$
$\Phi_T < 1.8$

DISTRIBUTION EXAMPLE

$$Q_{HW}^{(6)} = (H^\dagger H) W^I_{\mu\nu} W^{I,\mu\nu}$$

[2012.02779 Ellis, Madigan, Mimasu, Sanz, You]



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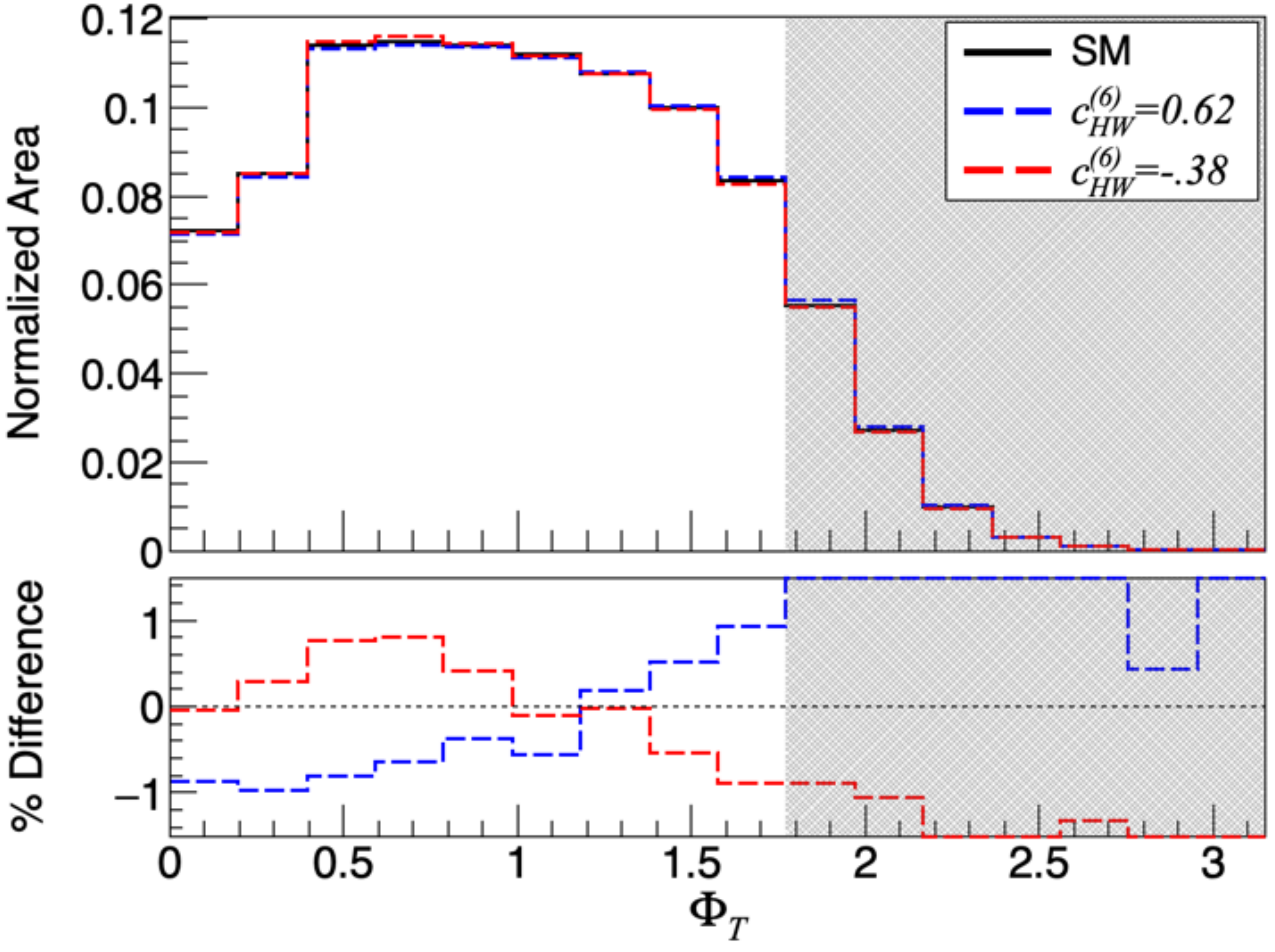

What about $Q^{(8)}_{l^2H^2D^3,4}$, $Q^{(8)}_{l^2WH^2D,5}$ and $Q^{(6)}_{eW}$ contributing to a non-SM-like distribution?

TAKEAWAYS

- Studies beyond $\mathcal{O}(1/\Lambda^4)$ can help us uncover novel kinematics of BSM physics
- Four charged lepton case :
  - No novel angular distribution.
  - $|A_6|^2$ contributions are relevant.
  - Dimension 8 operators' contributions are small.
- Two Charged lepton case:
  - Novel kinematics generated at $\mathcal{O}(1/\Lambda^4)$.
  - Non-reconstructibility obscures the novel kinematics.
  - Cuts further obscure SMEFT effects.
  - Can be relevan for future collider where Higgs momenta can be reconstructed

BACKUP

GEOSMEFT

- GeoSMEFT rearranges a subset of SMEFT operators in terms of field-space dependent quantities.

$$\mathscr{L}_{\text{geoSMEFT}} \supset h_{IJ}(\phi)(D_\mu\phi)^I(D^\mu\phi)^J + g_{AB}(\phi)\mathscr{W}^A_{\mu\nu}\mathscr{W}^{B,\mu\nu} + k^A_{IJ}(\phi)(D_\mu\phi)^I(D^\mu\phi)^J\mathscr{W}^{\mu\nu}_A$$
$$+L^{\psi,pr}_{J,A}(\phi)(D_\mu\phi)(\bar{\psi}_p\gamma^\mu\tau^A\psi_r) + (d^{e,pr}_A(\phi)\bar{l}_p\sigma^{\mu\nu}e_r\mathscr{W}^{\mu\nu}_A + h.c.)\,.$$

- Can use it to obtain 3-point vertices to all orders in the SMEFT expansion.

$$= ic^{(1)}_{hZA}2(k_1^\nu k_2^\mu - k_1\cdot k_2 g^{\mu\nu}) + ic^{(3)}_{hZA}(p\cdot k_1 g^{\mu\nu} - p^\mu k_1^\nu)$$

$$c^{(3)}_{hZA} = -\sqrt{h}^{44}\,\overline{g}_Z\overline{e}\,\overline{v}_T\left(\left\langle k^3_{34}\right\rangle\frac{1}{g_2} - \left\langle k^4_{34}\right\rangle\frac{1}{g_1}\right)$$

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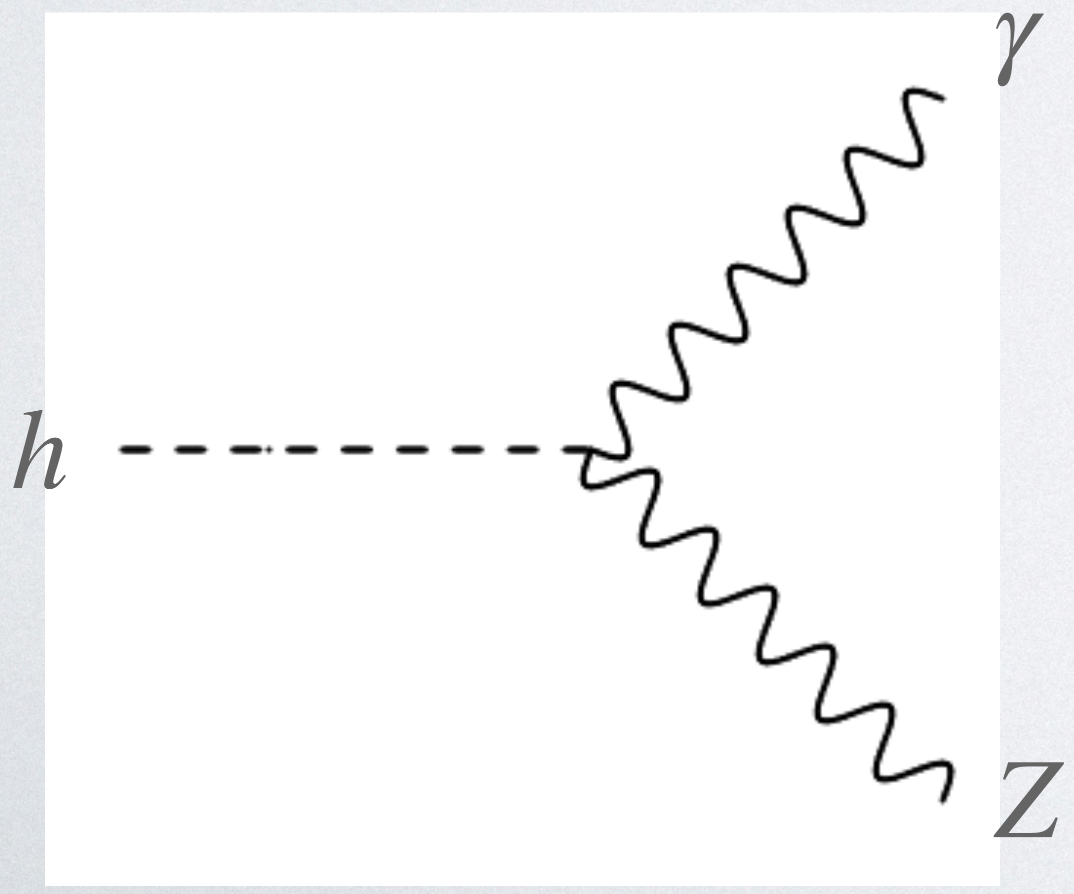

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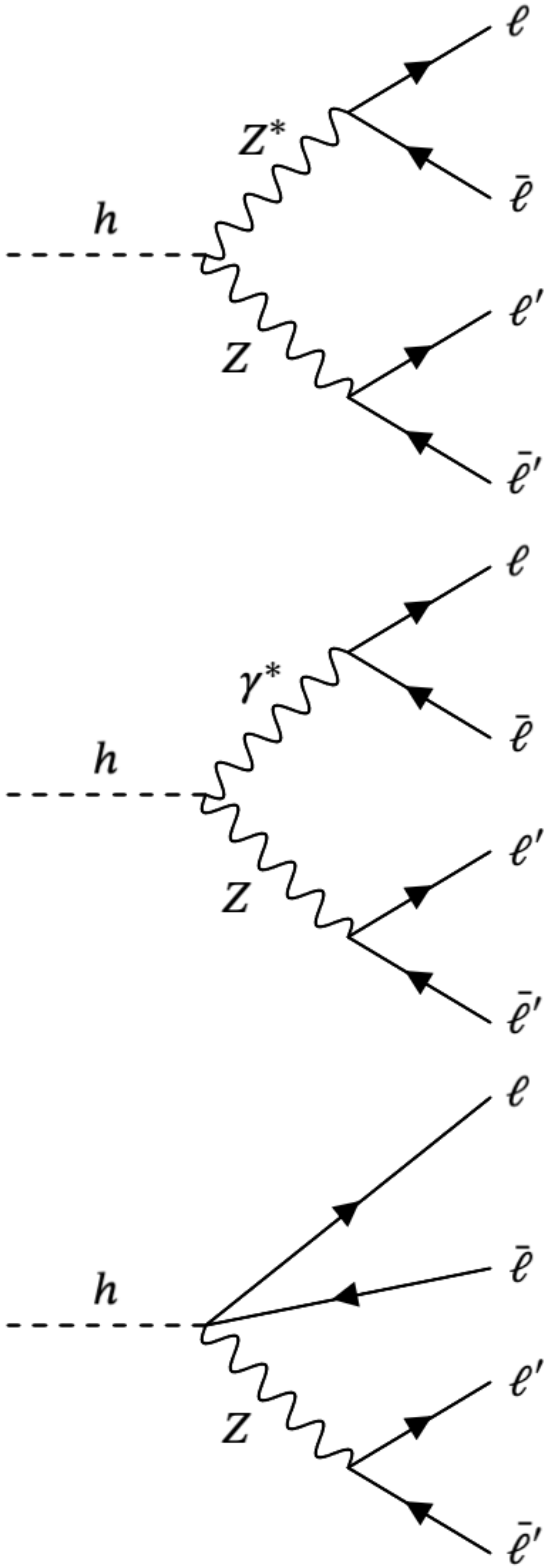
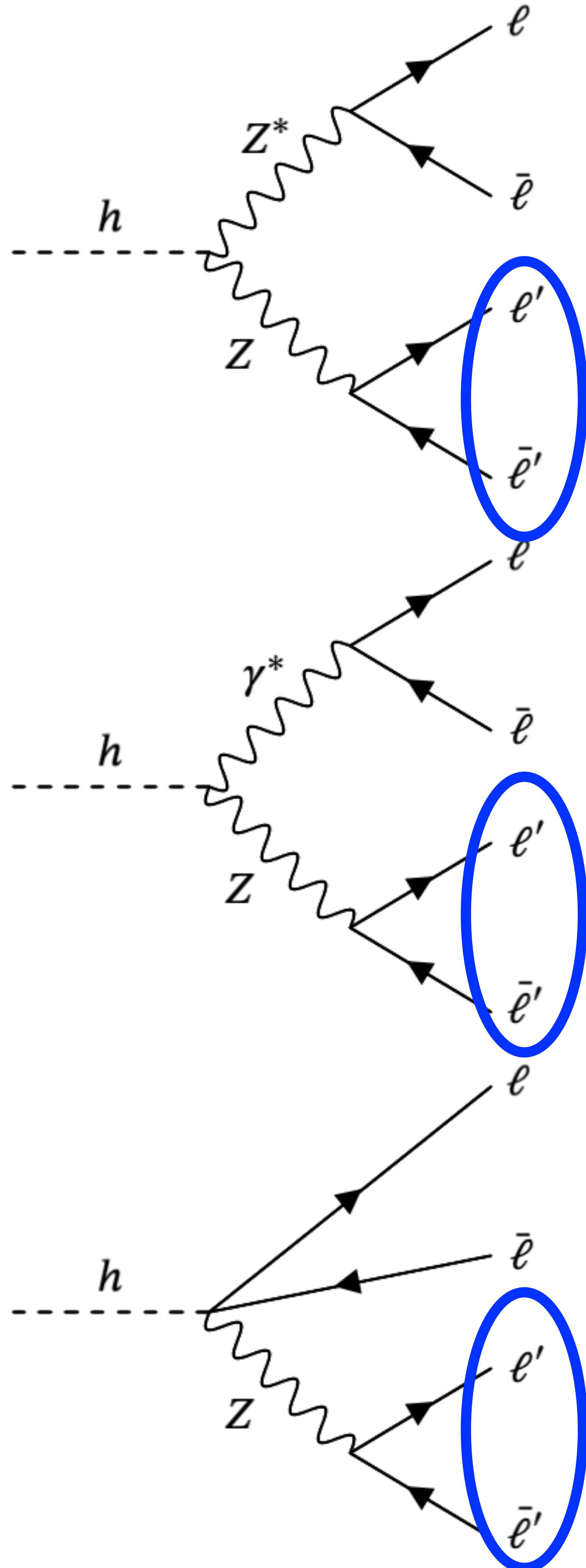


MAIN FEATURES

- Fully reconstructible, may require $m_{\ell'\ell'} \sim m_Z \rightarrow$ Narrow width approximation



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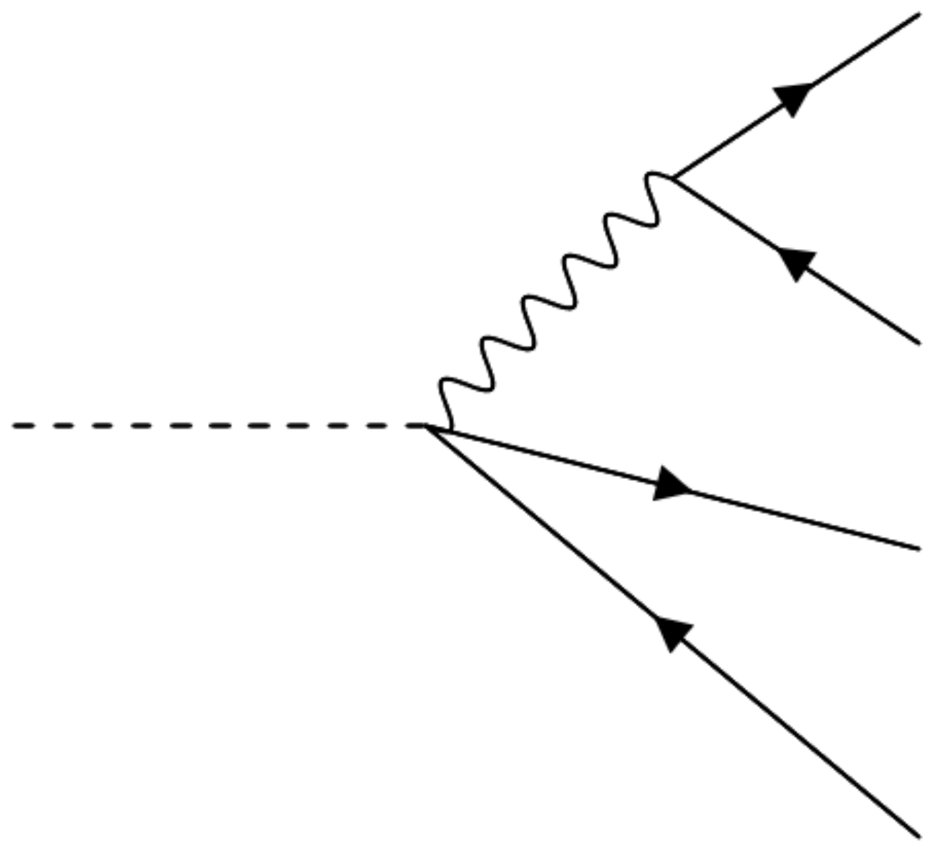
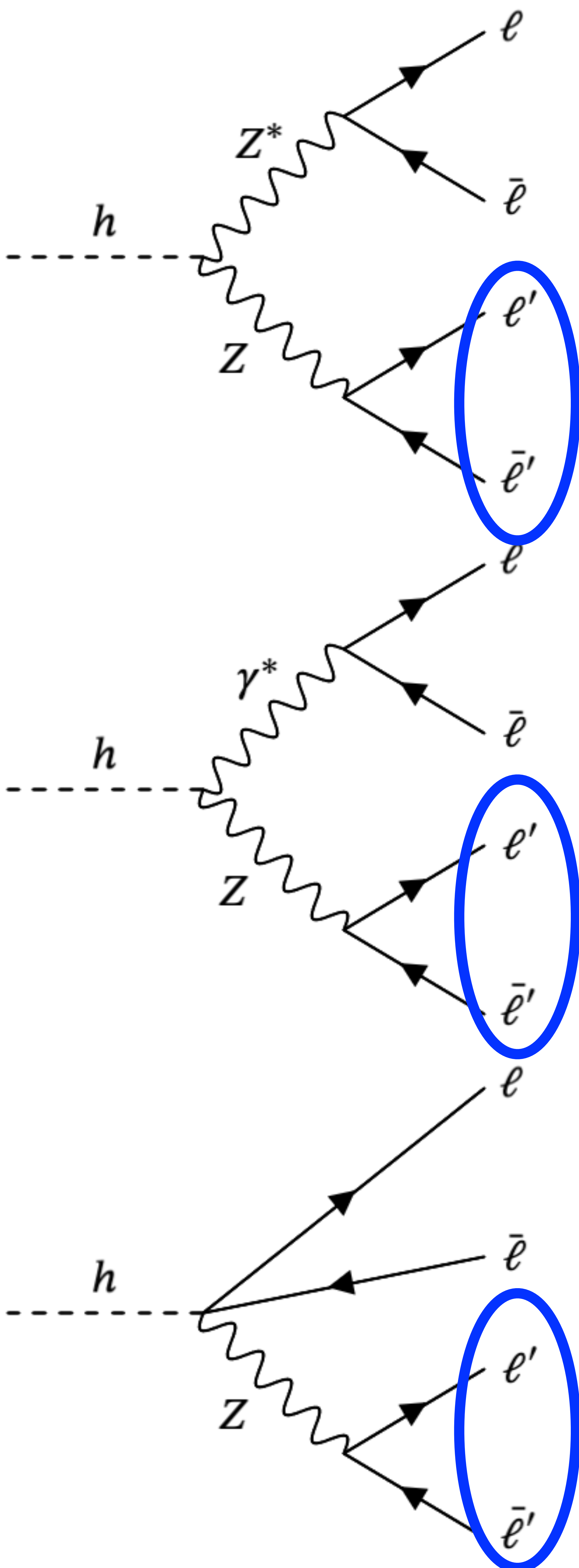


Can be neglected



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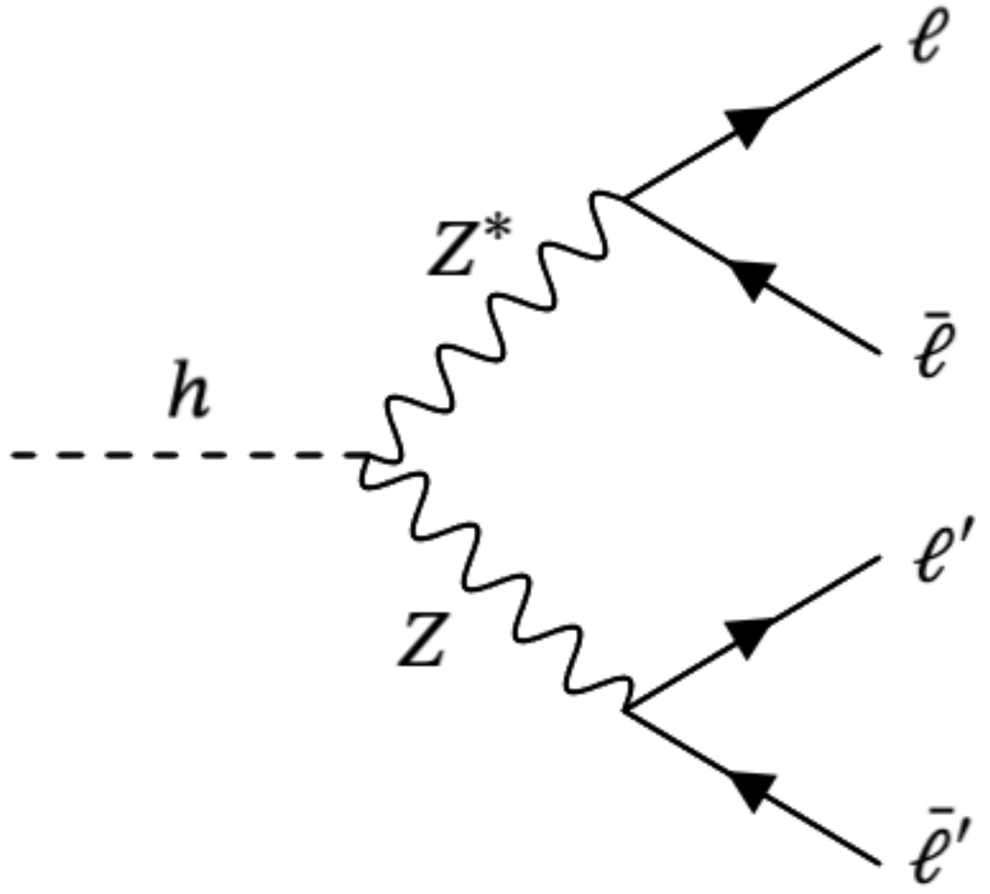

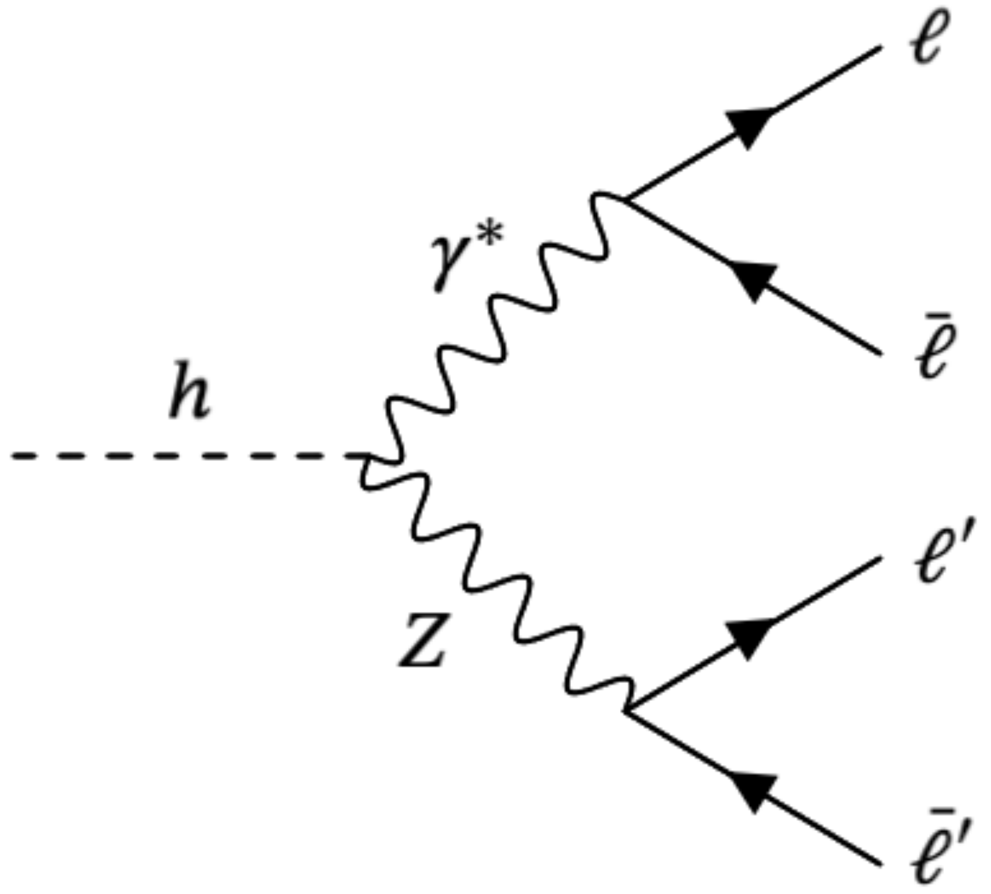

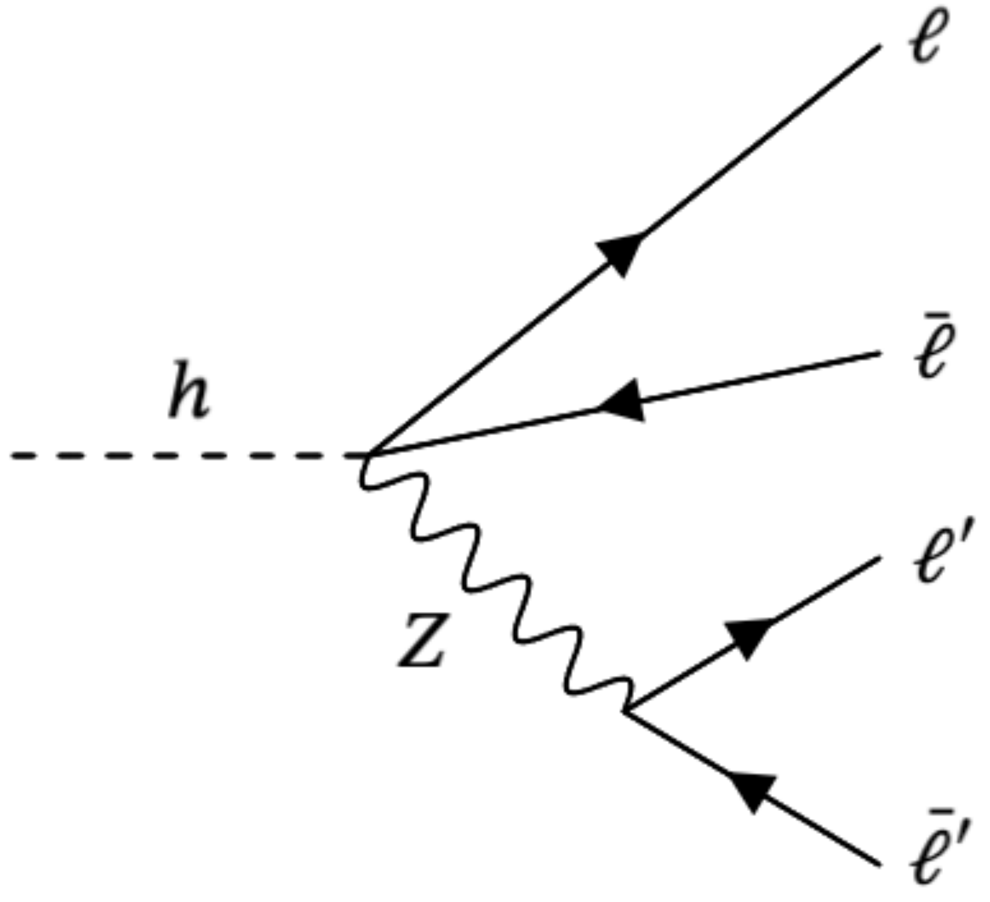

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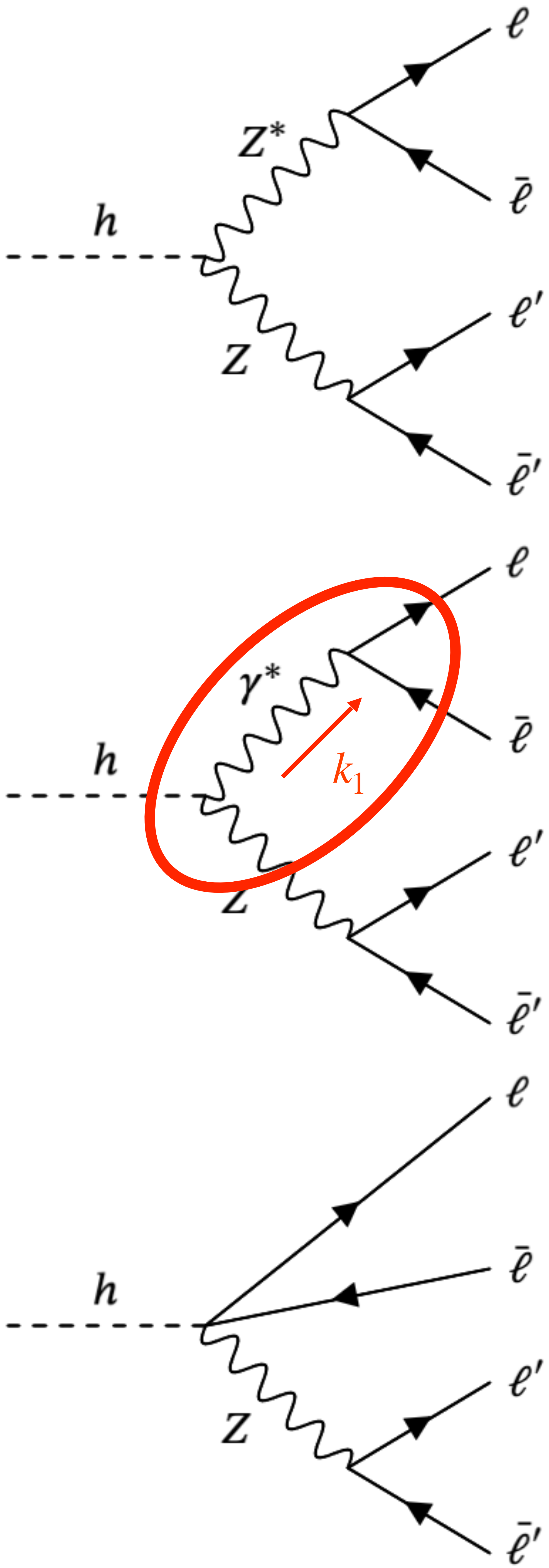

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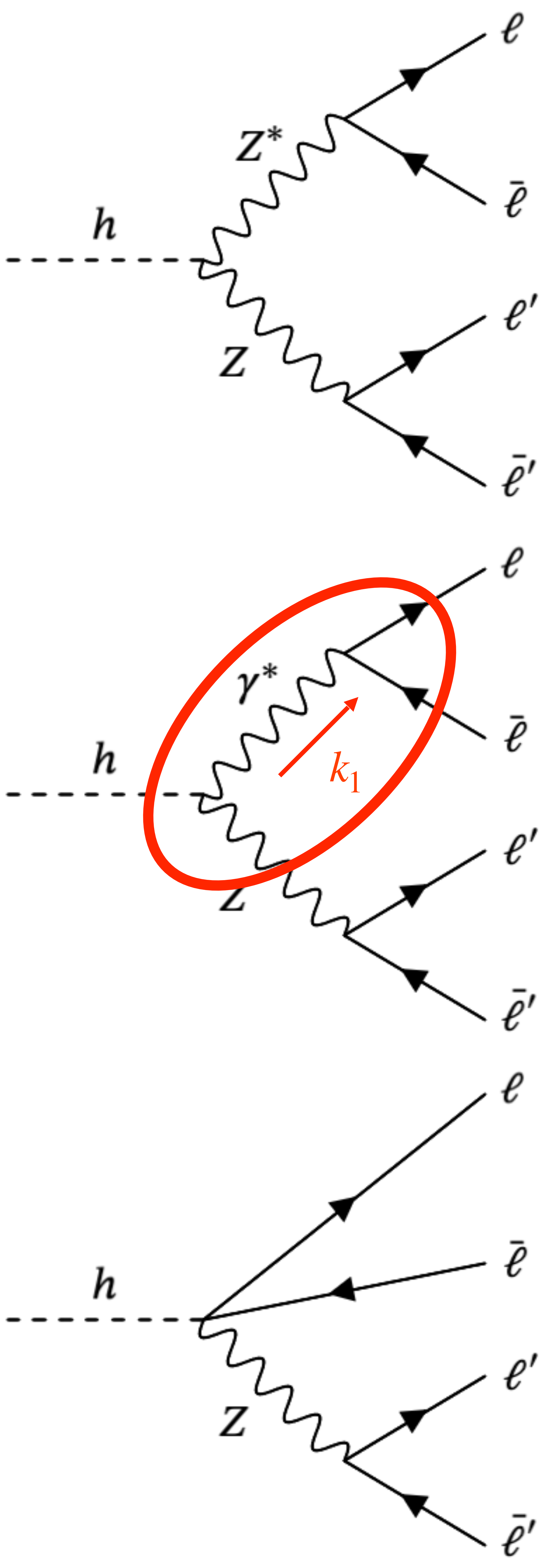
$$Q_{eW}^{(6)} = (\bar{l}\sigma_{\mu\nu}\tau^I e)HW^{I,\mu\nu} \supset e_L\sigma_{\mu\nu}e_R\partial^\mu Z^\nu$$

won't interfer

ı SM

a

contributes to $\mathcal{O}(1/\Lambda^4)$ as a $|A_6|^2$ term



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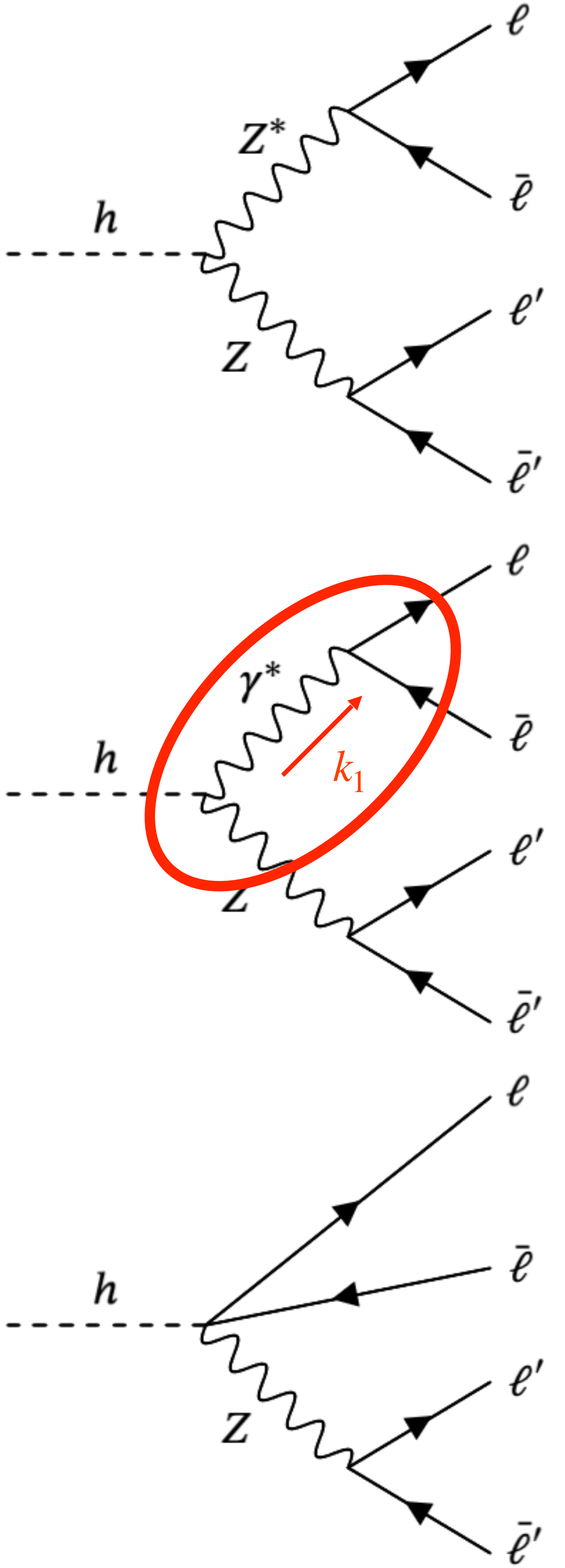
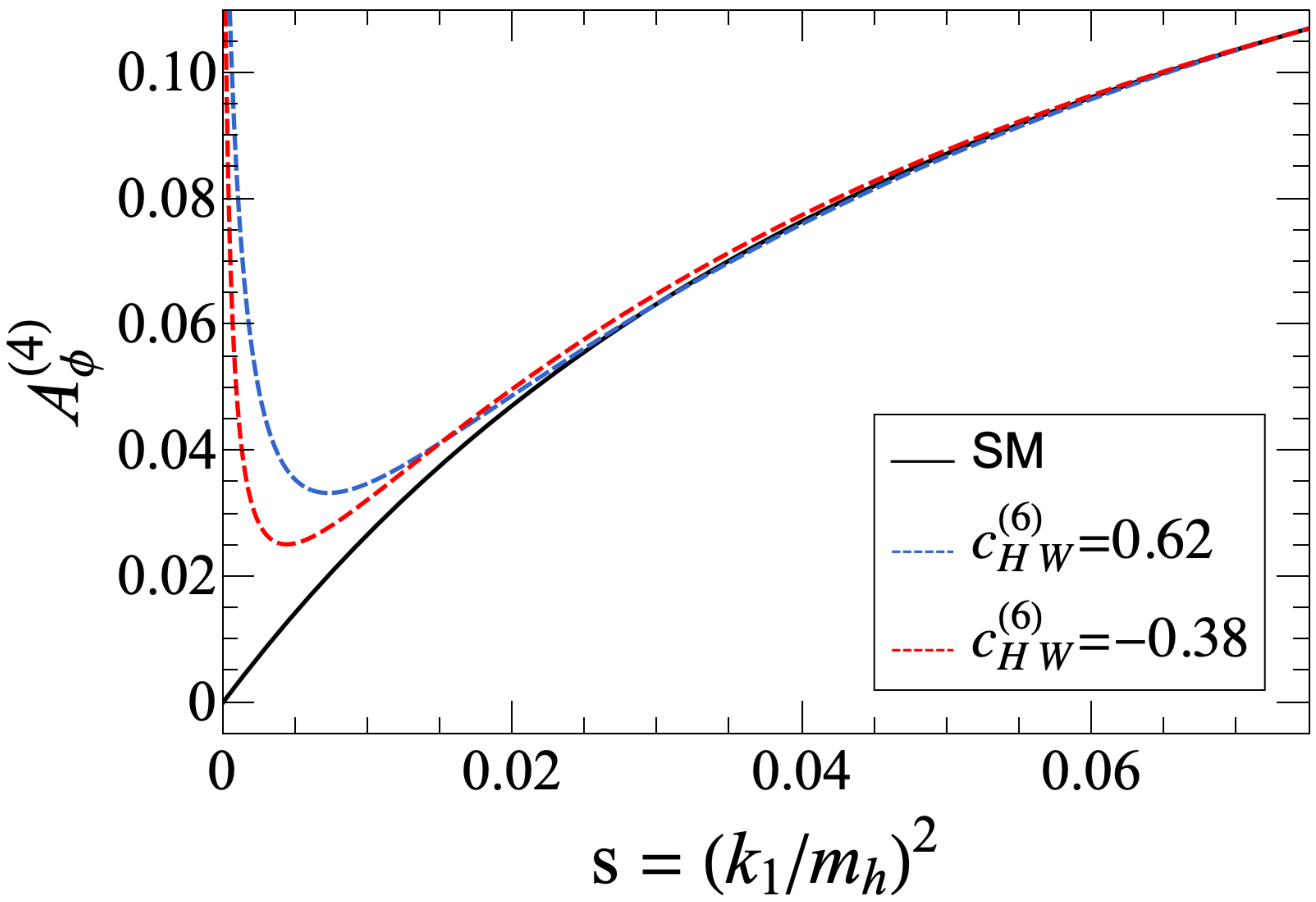
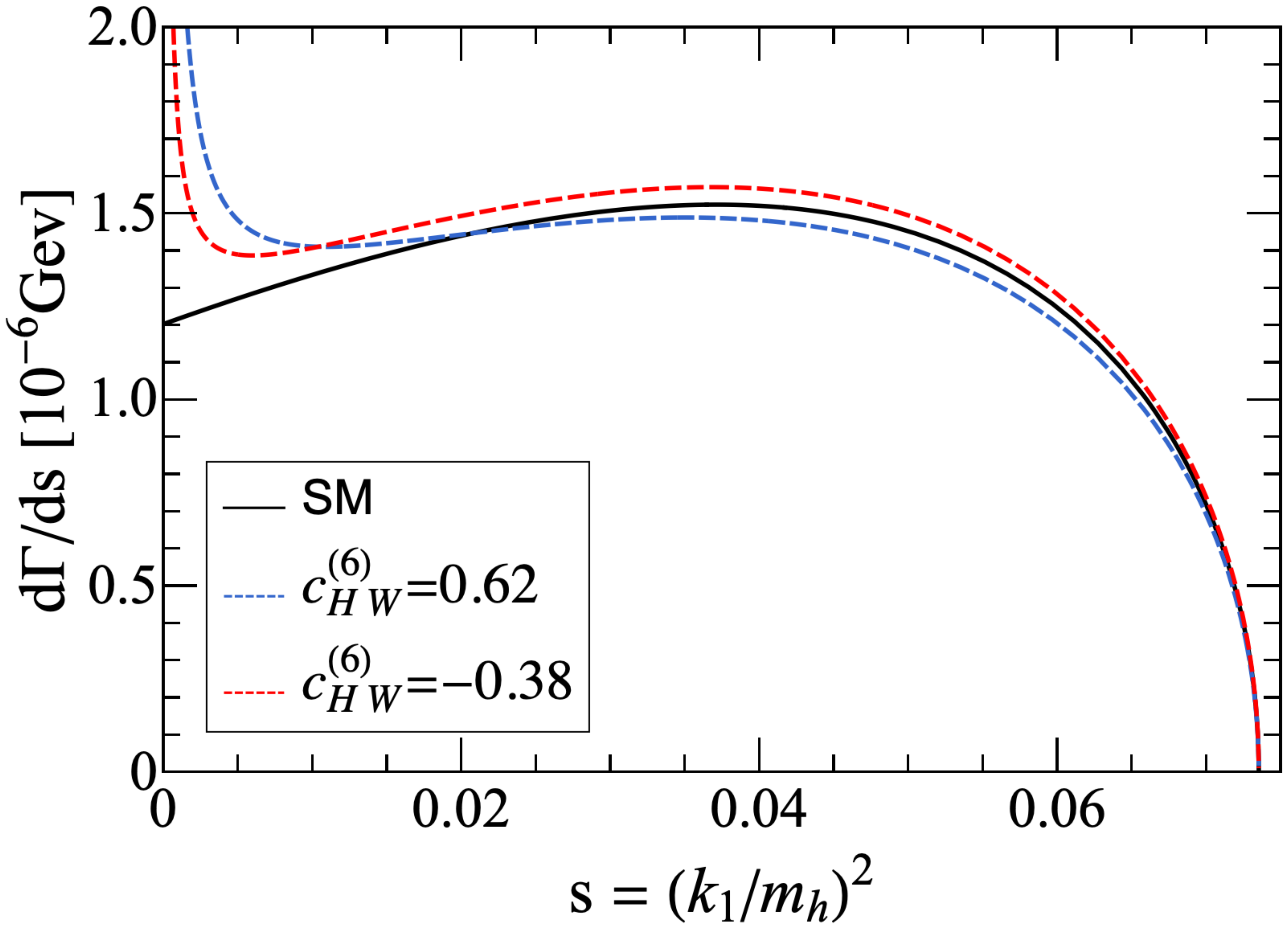
- Energy Scale of the process $E = m_h$



EXAMPLE

$Q_{HW}^{(6)} = (H^\dagger H) W_{\mu\nu}^I W^{I,\mu\nu}$ ← Contributes to hZZ and generates $hZ\gamma$





$c_{HW}^{(6)} \equiv C_{HW}^{(6)}/\Lambda^2$ $\quad \Lambda = 1$Tev

[2012.02779 Ellis, Madigan, Mimasu, Sanz, You]

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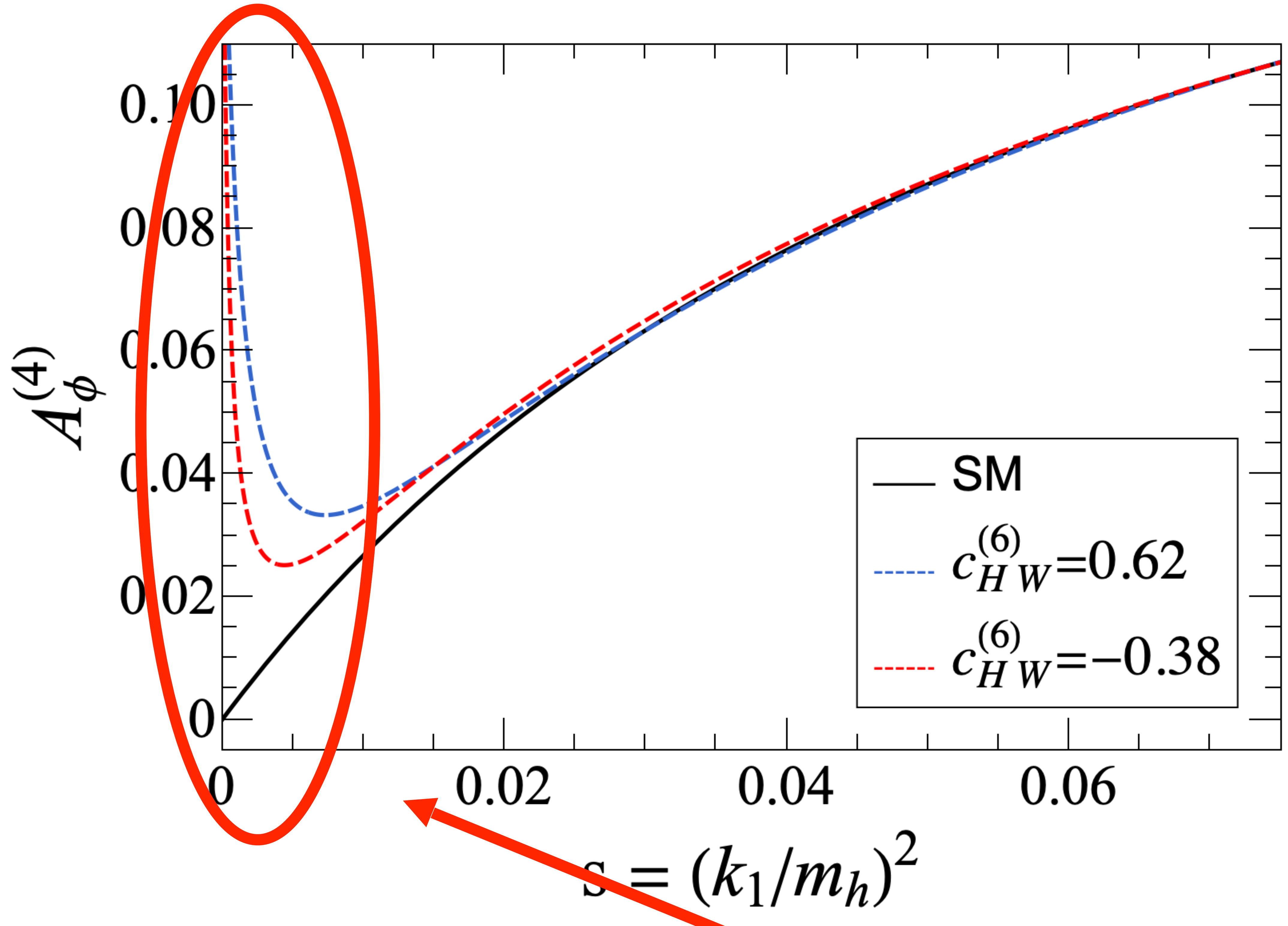

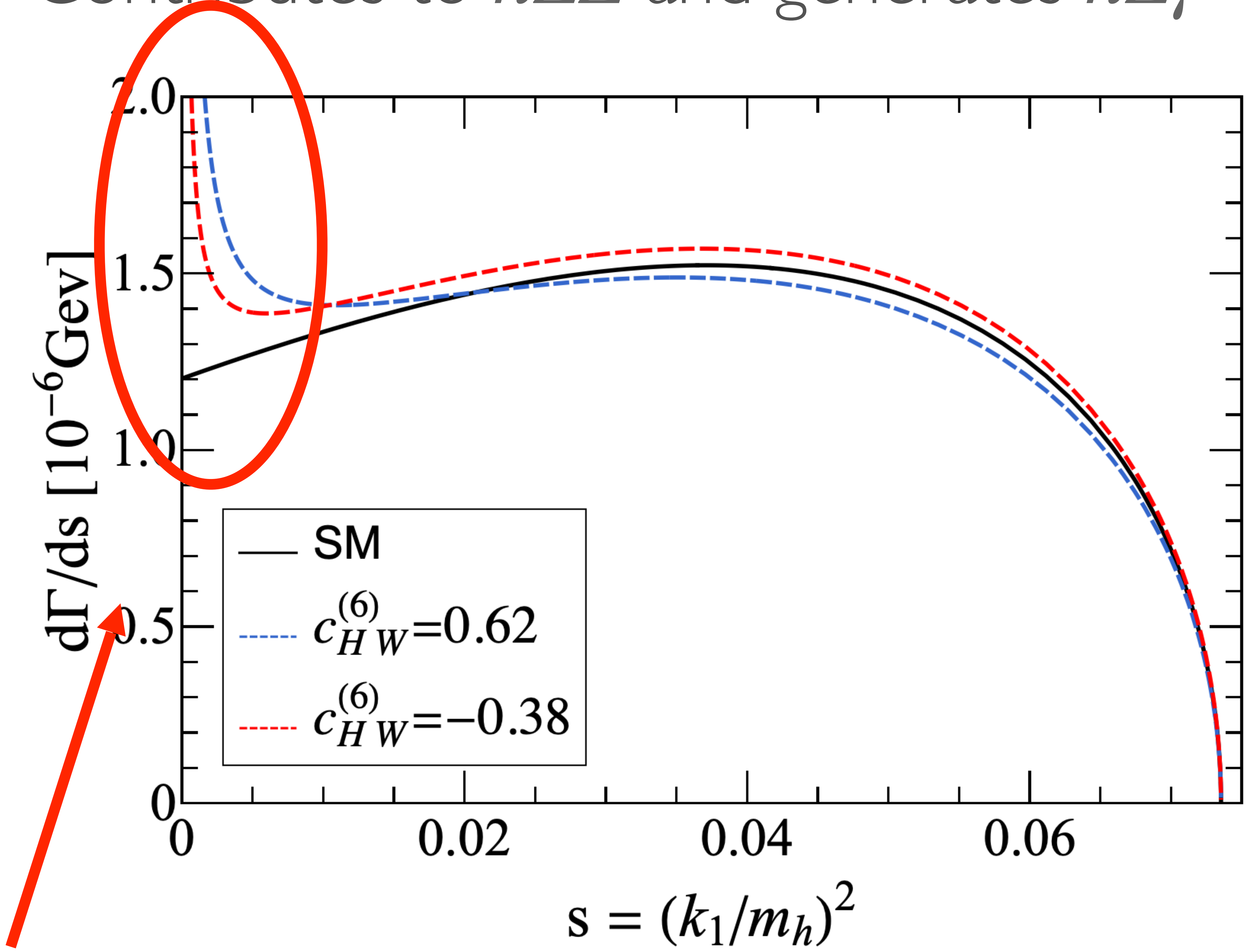

$s \sim 0$

Photon pole enhancement $\dfrac{1}{k_1^2} \sim \dfrac{1}{s}$, purely $\mathcal{O}(1/\Lambda^4)$

PHOTON POLE ENHANCEMENT

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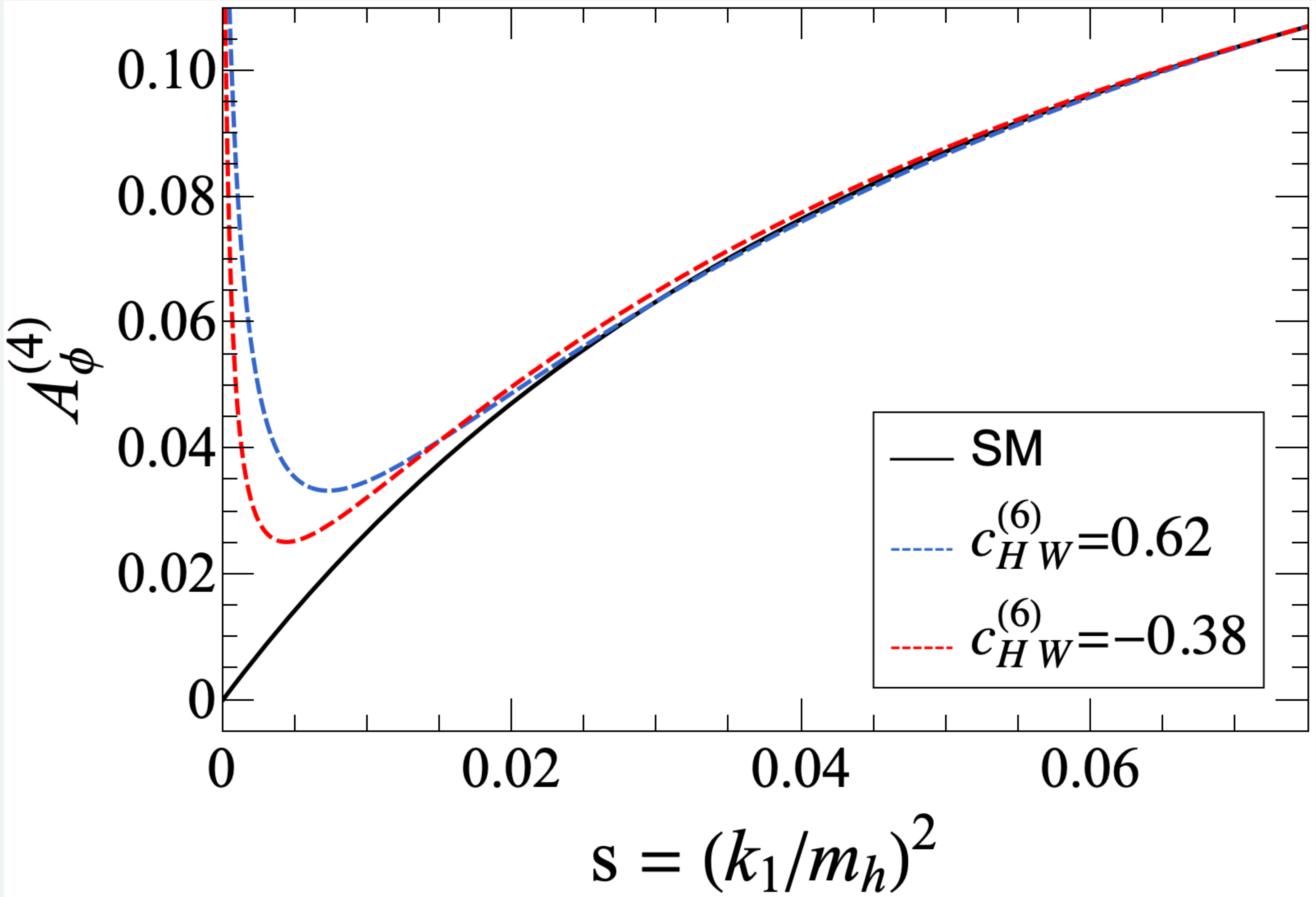
How to understand this? Look at the amplitude



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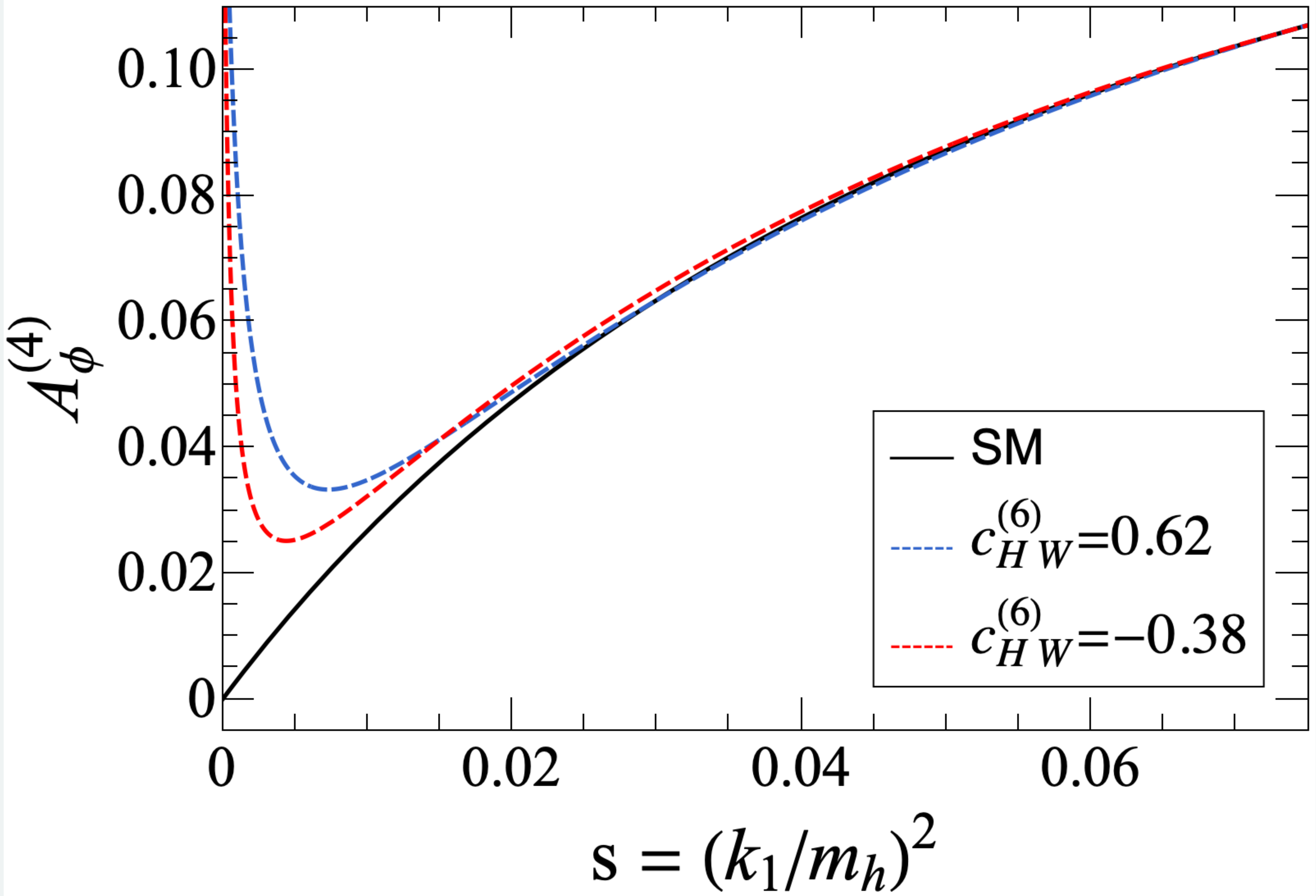

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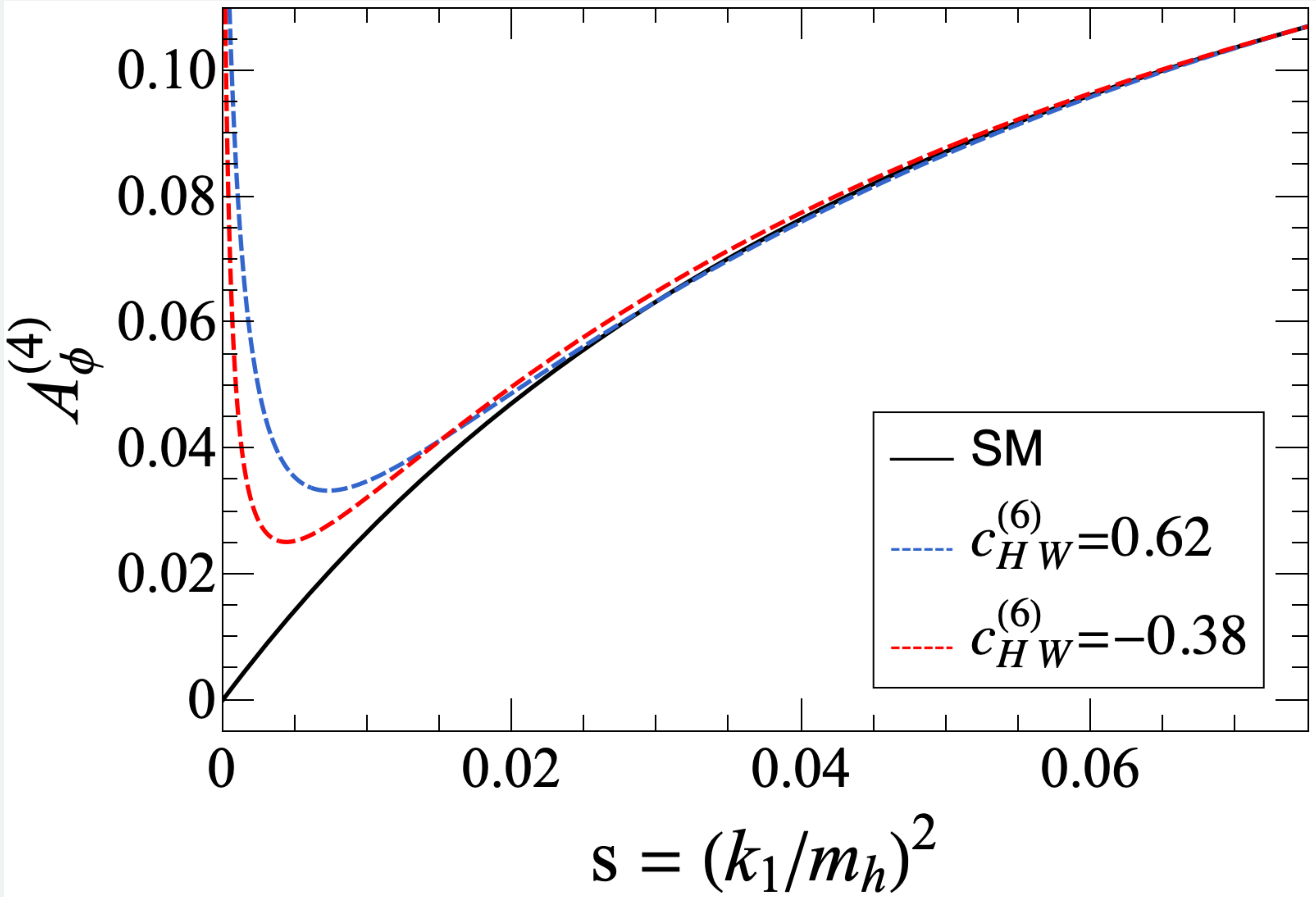

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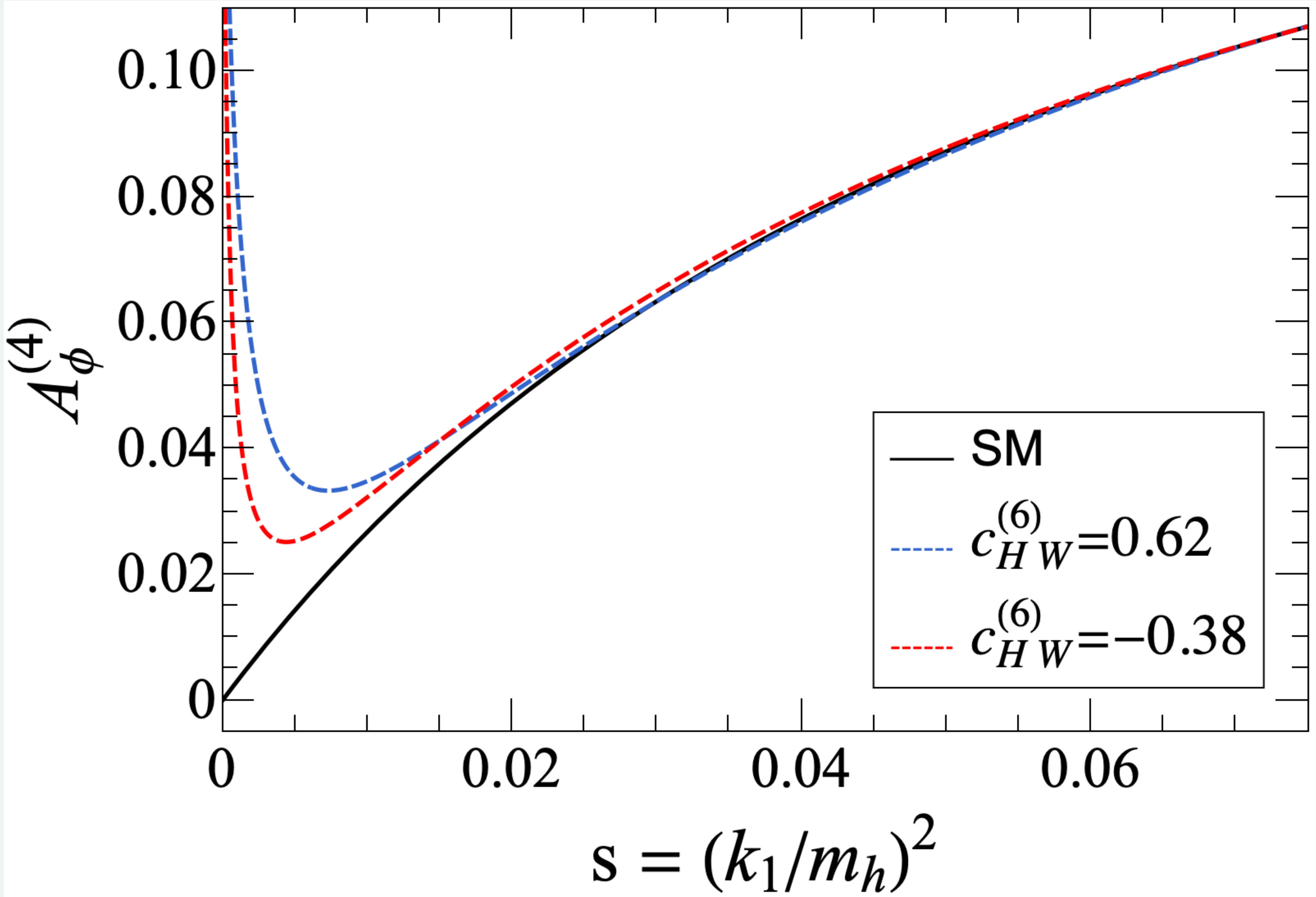

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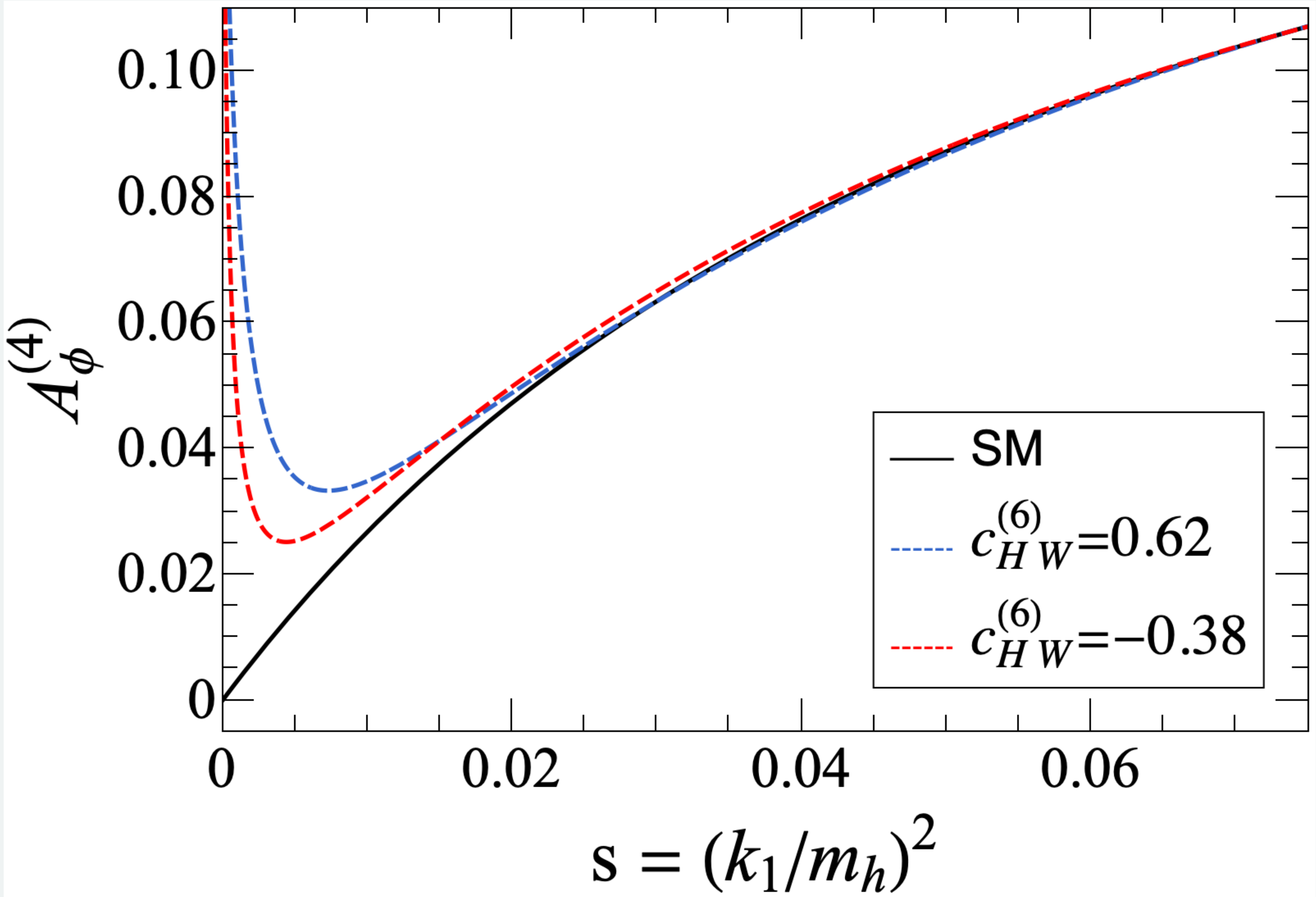

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Propagator dependance cancels

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1

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  3. 4-point contact terms are suppressed due to lack of propagator.

FOUR CHARGED LEPTON OBSERVABLES

$$\frac{d\Gamma}{ds} = \frac{\lambda}{(2\pi)^5 2^{10}\sqrt{r}\Gamma_Z}\frac{8\pi}{9}(9J_1^Z + J_2^Z + 3J_3^Z + 3J_4^Z)$$

$$\mathscr{A}_\phi^{(1)} = \left(\frac{d\Gamma}{ds}\right)^{-1}\int_0^{2\pi}\text{sgn}(\sin\phi)\frac{d\Gamma}{dsd\phi}d\phi = 0$$

$$\mathscr{A}_\phi^{(2)} = \left(\frac{d\Gamma}{ds}\right)^{-1}\int_0^{2\pi}\text{sgn}(\sin(2\phi))\frac{d\Gamma}{dsd\phi}d\phi = 0$$

$$\mathscr{A}_\phi^{(3)} = \left(\frac{d\Gamma}{ds}\right)^{-1}\int_0^{2\pi}\text{sgn}(\cos\phi)\frac{d\Gamma}{dsd\phi}d\phi = \frac{9\pi}{8}\frac{J_6^Z}{9J_1^Z + J_2^Z + 3J_3^Z + 3J_4^Z}$$

$$\mathscr{A}_\phi^{(4)} = \left(\frac{d\Gamma}{ds}\right)^{-1}\int_0^{2\pi}\text{sgn}(\cos(2\phi))\frac{d\Gamma}{dsd\phi}d\phi = \frac{8}{\pi}\frac{J_8^Z}{9J_1^Z + J_2^Z + 3J_3^Z + 3J_4^Z}$$

$$\mathscr{A}_{\theta,\Delta} = \left(\frac{d\Gamma}{ds}\right)^{-1} \int_{-1}^{1} \mathsf{sgn}(\cos\theta)\left(\int_{-1}^{1} \mathsf{sgn}(\cos\Delta)\frac{d\Gamma}{ds d\cos\Delta d\cos\Delta} d\cos\Delta\right) d\cos\theta$$

$$= \frac{9}{4}\frac{J_5^Z}{9J_1^Z + J_2^Z + 3J_3^Z + 3J_4^Z}$$

$$\mathscr{A}_{\theta}^{(2)} = \left(\frac{d\Gamma}{ds}\right)^{-1} \int_{-1}^{1} \mathsf{sgn}(\cos 2\theta)\frac{d\Gamma}{ds d\cos\theta} d\cos\theta$$

$$= 1 - \sqrt{2} + \frac{J_2^Z + 3J_3^Z}{\sqrt{2}(9J_1^Z + J_2^Z + 3J_3^Z + 3J_4^Z)}$$

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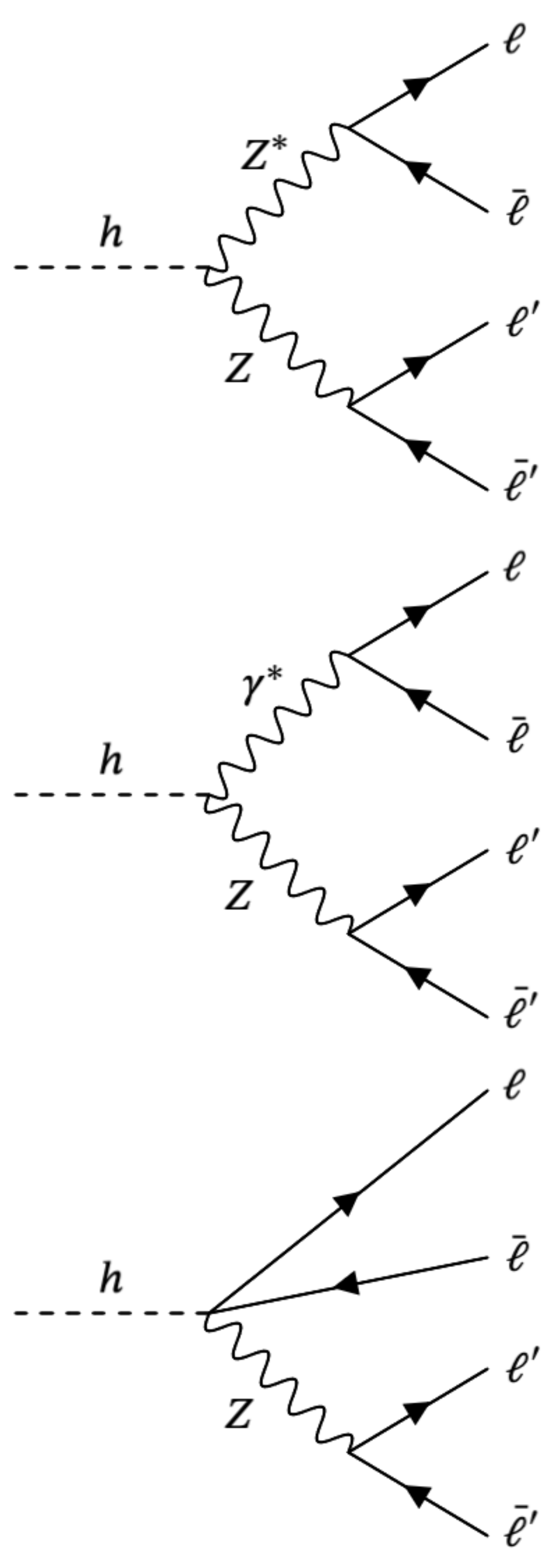
EXAMPLE J FUNCTION

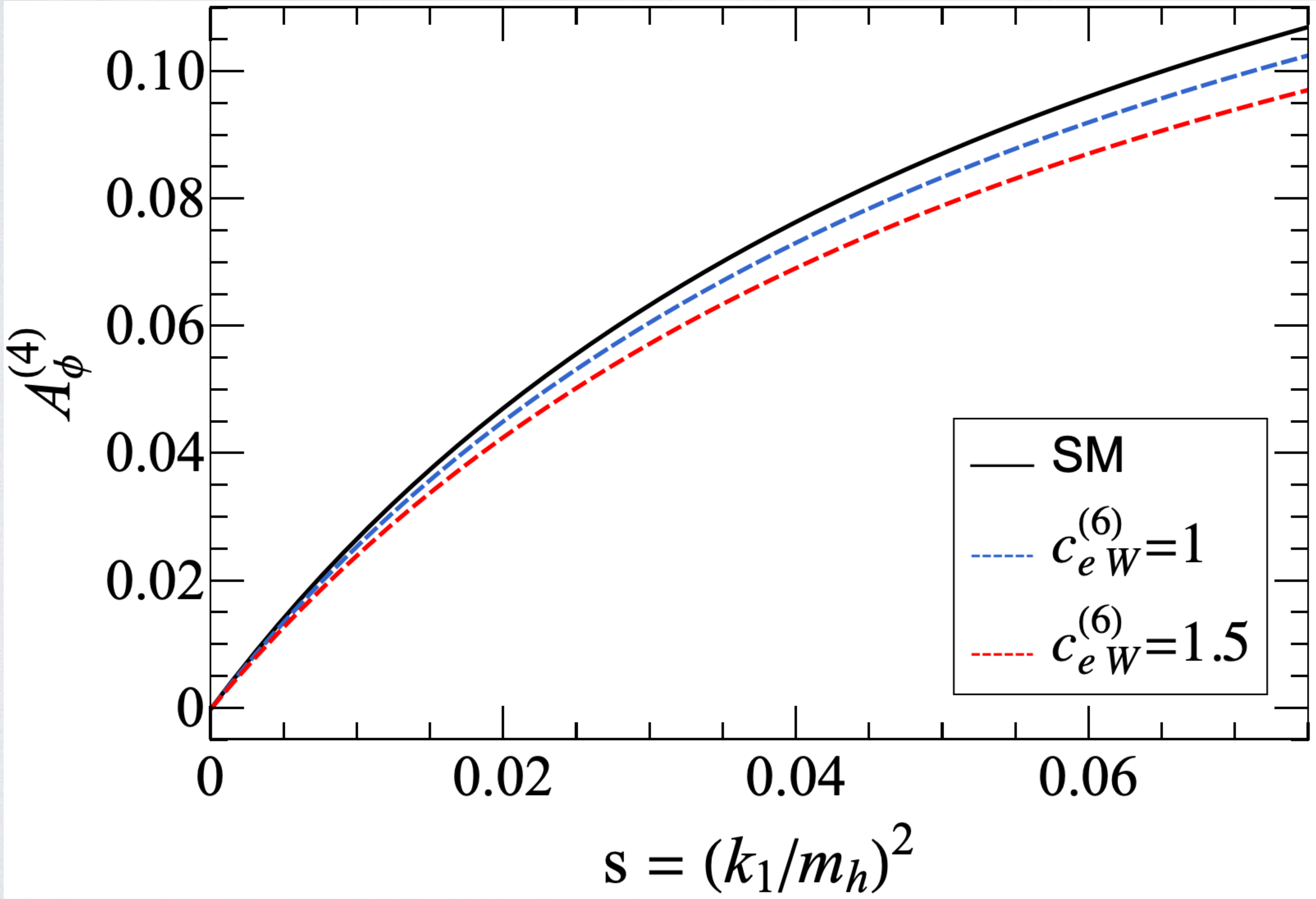
$$
\begin{aligned}
J_5^Z = \; & -\frac{8 r s G_A^2 G_v^2 \left(m_H^2 c^{(1)}_{hZZ} \left(2\kappa c^{(2)}_{hZZ} + c^{(3)}_{hZZ} \right) - \kappa^2 m_H^4 \left(c^{(2)}_{hZZ} \right)^2 - \left(c^{(1)}_{hZZ} \right)^2 \right)}{(r-s)^2} \\
& - \frac{4 r s m_H^2 G_A G_V}{r-s} \left(2 c^{(1)}_{hZZ} K_1 + m_H^2 \left((\kappa + 2r) c^{(1)}_{hZZ} K_2 - 2\kappa c^{(2)}_{hZZ} K_1 \right) \right) \\
& + 2 r m_H^4 G_A G_V H_A \left(s H_V + 2\kappa \bar{e} c^{(1)}_{hZA} \right) \\
& - \frac{4 r \bar{e} m_H^2 G_A^2 G_V}{r-s} \left(2\kappa c^{(1)}_{hZA} c^{(1)}_{hZZ} + (\kappa + 2s) c^{(2)}_{hZA} c^{(1)}_{hZZ} - 2\kappa^2 m_H^2 c^{(1)}_{hZA} c^{(2)}_{hZZ} \right)
\end{aligned}
$$

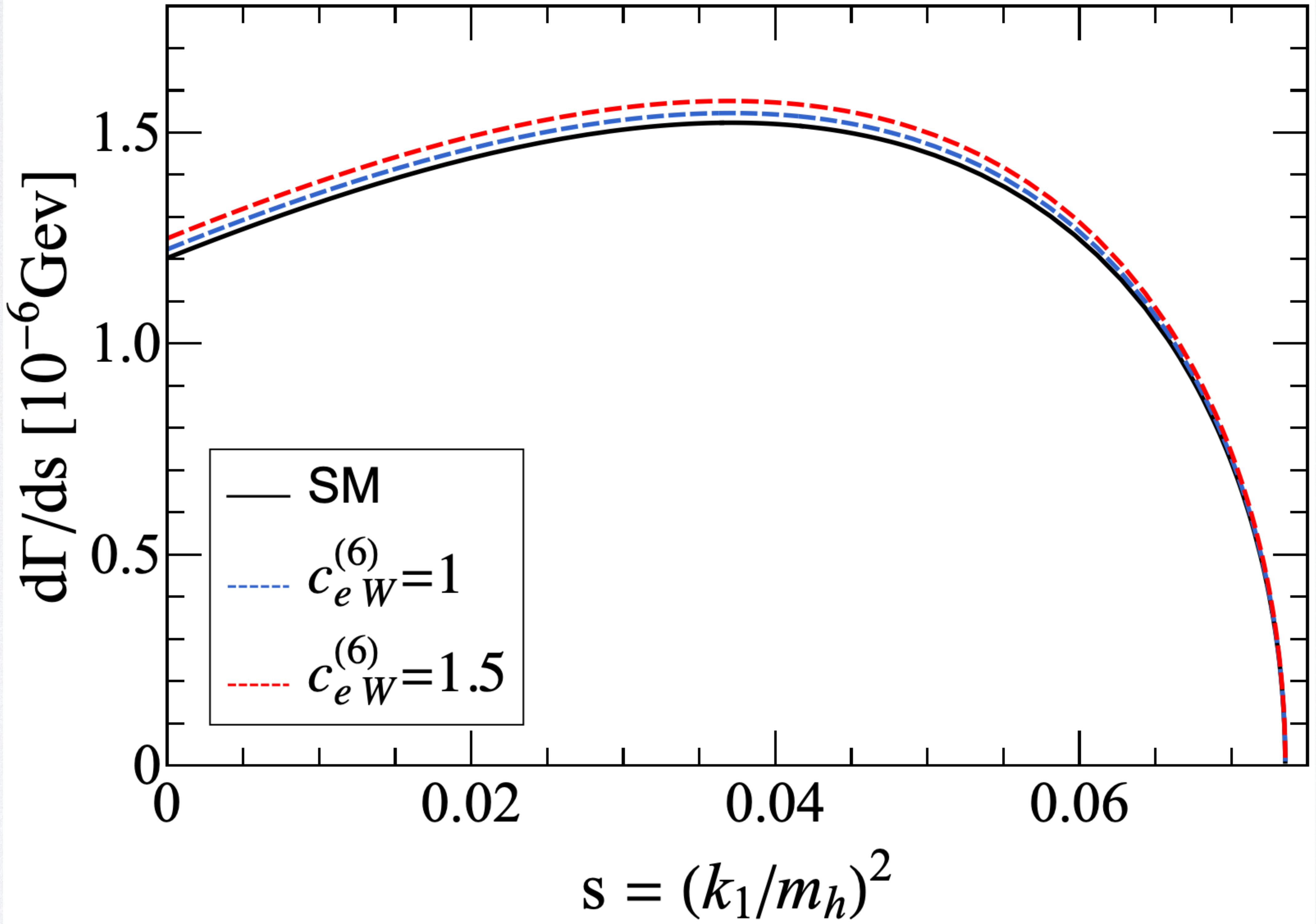


DIMENSION 6 CONTRIBUTIONS

$$Q_{eW}^{(6)} = (\bar{l}\sigma_{\mu\nu}\sigma^I e)HW^{I,\mu\nu}$$

- Induces couplings of left-handed and right-handed leptons
- Highly constrained by EDM and MDM
- Assume $c_{eW}^{(6)} \sim \mathcal{O}(1)$





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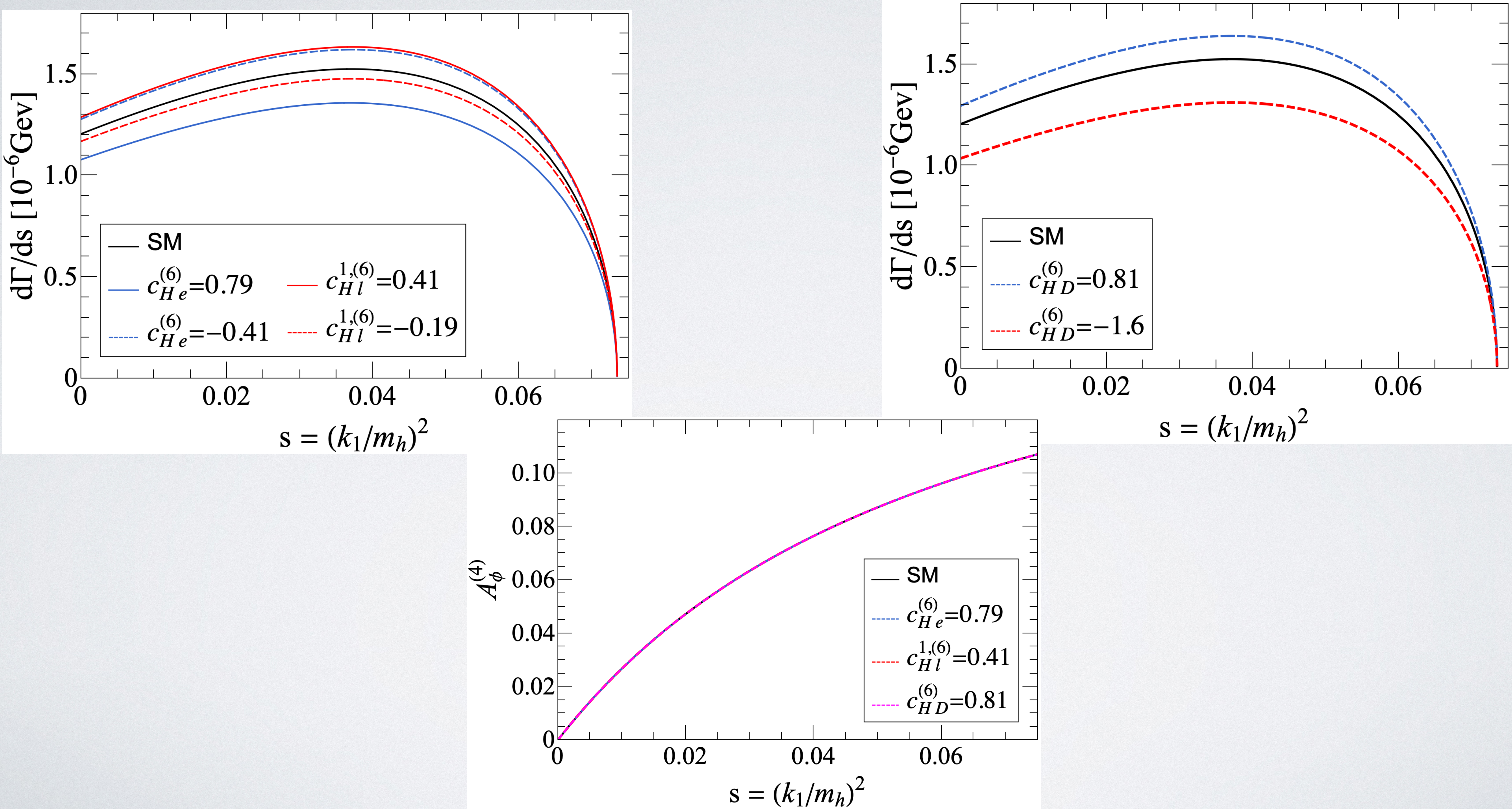

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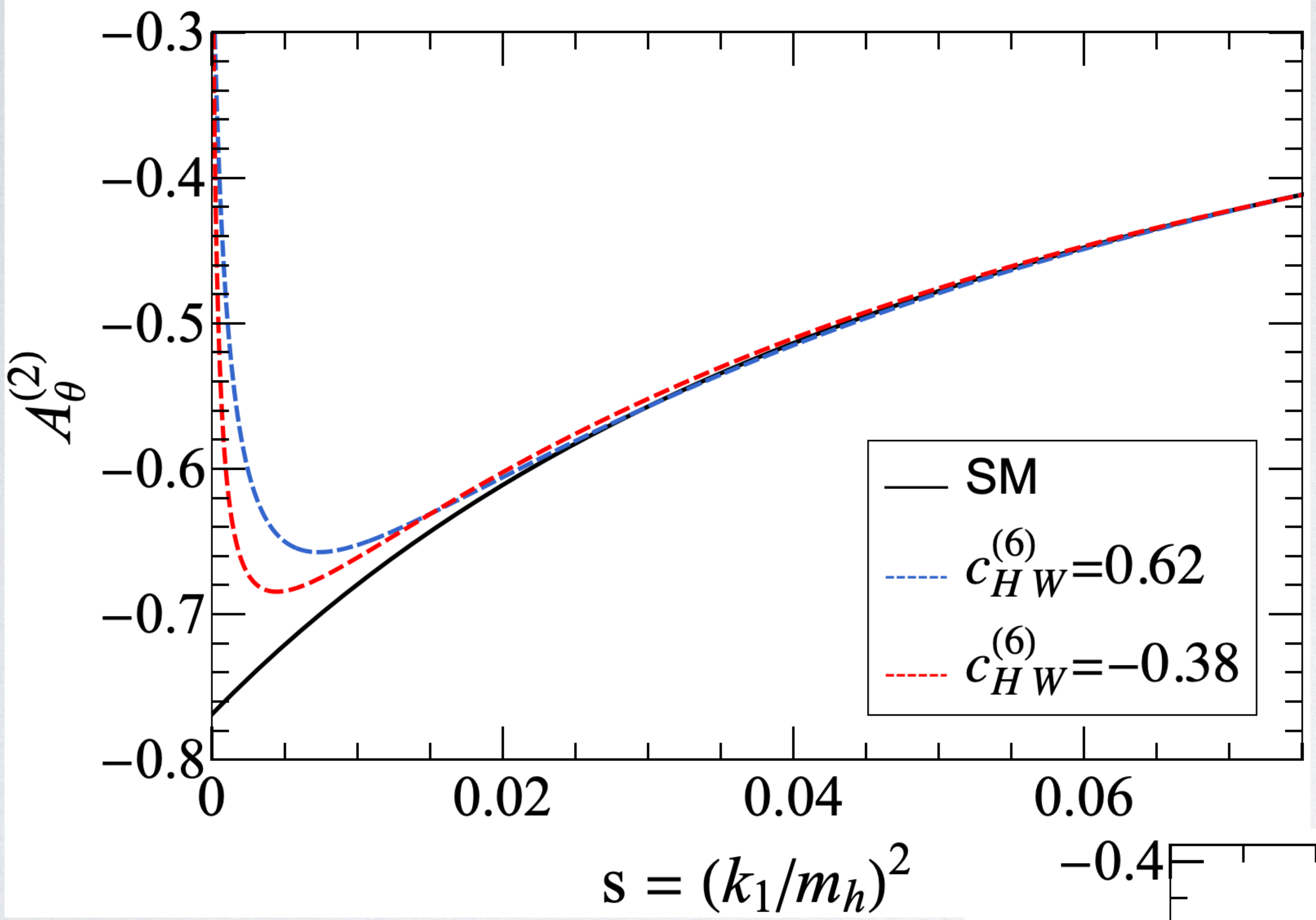
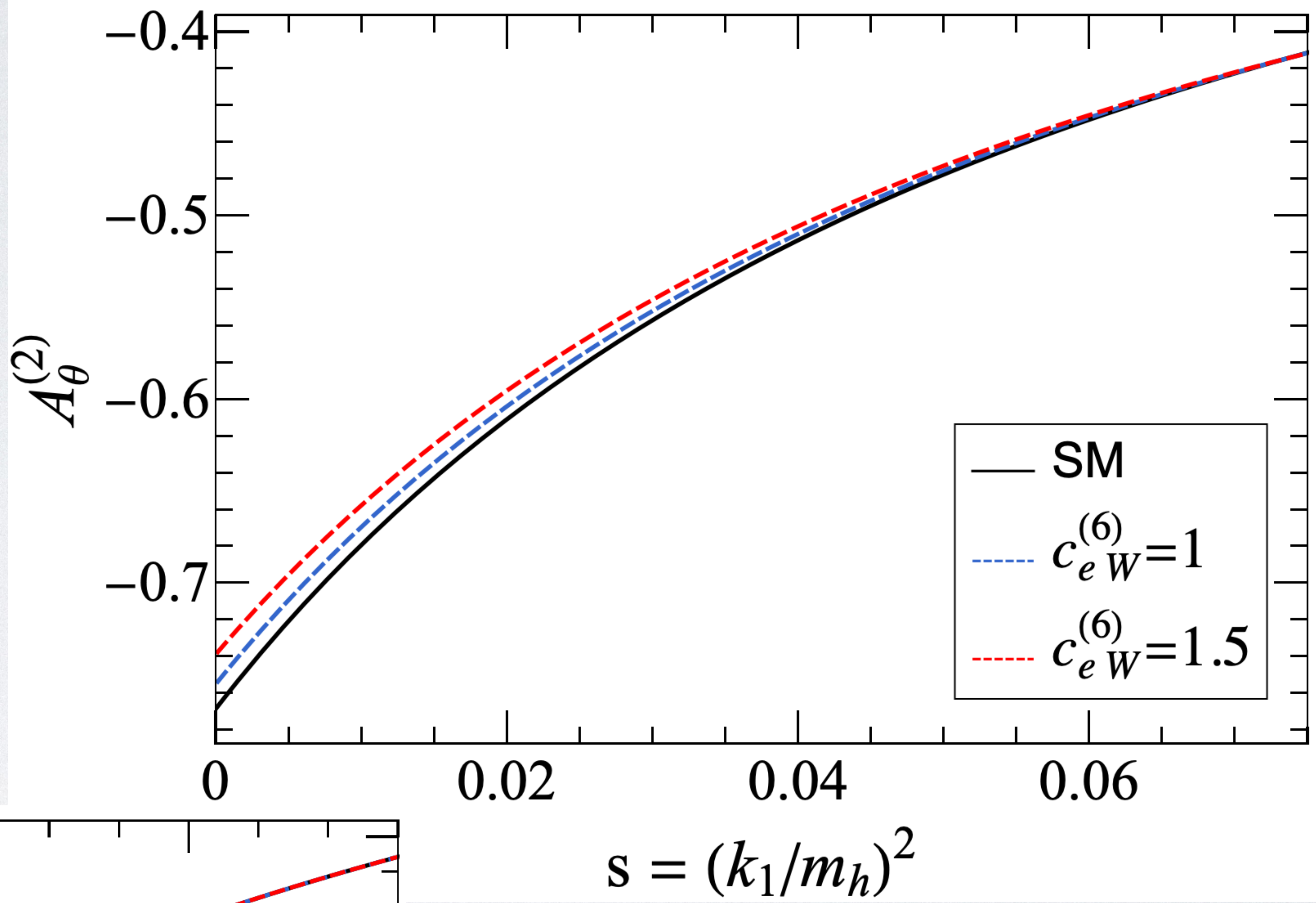
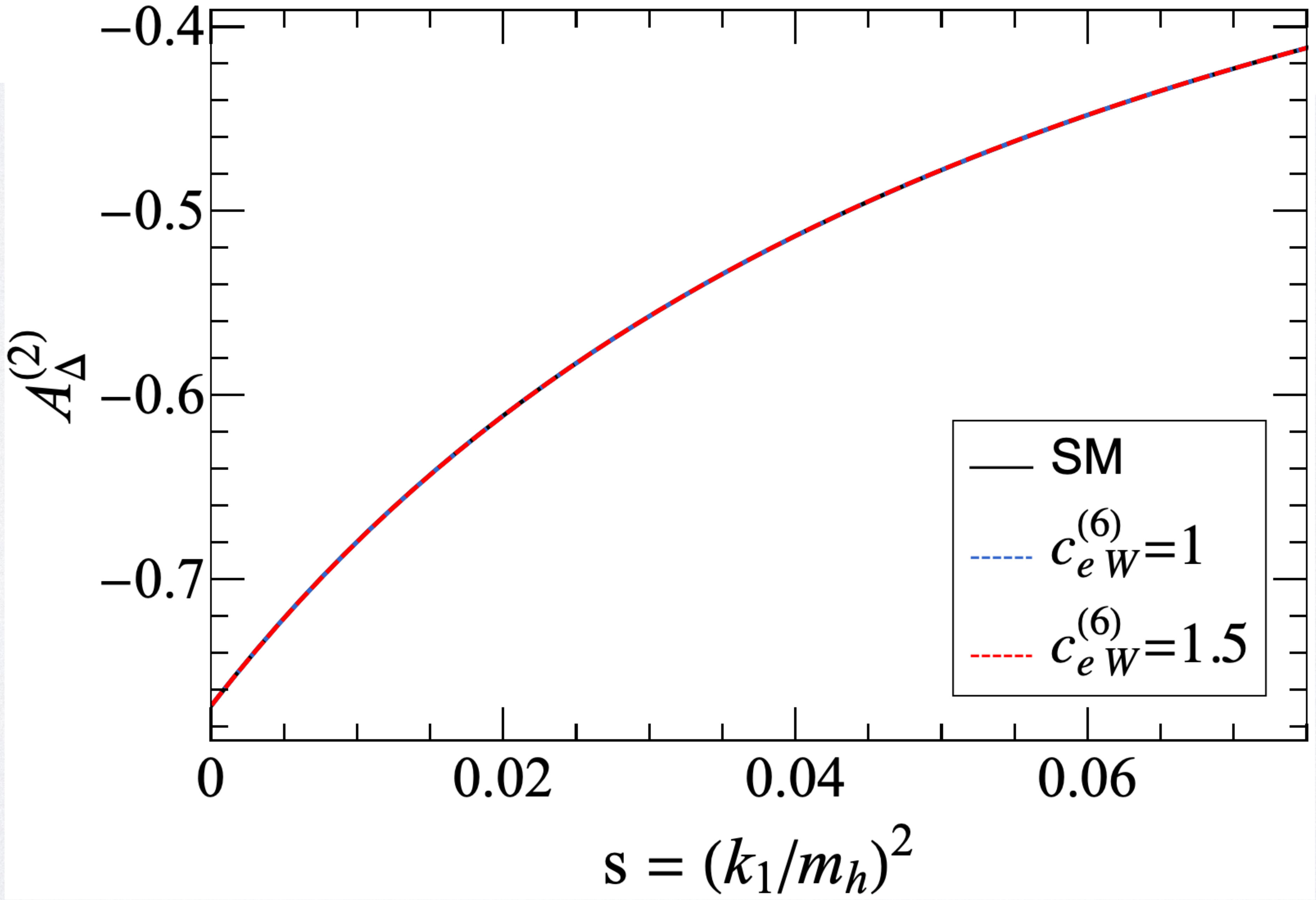
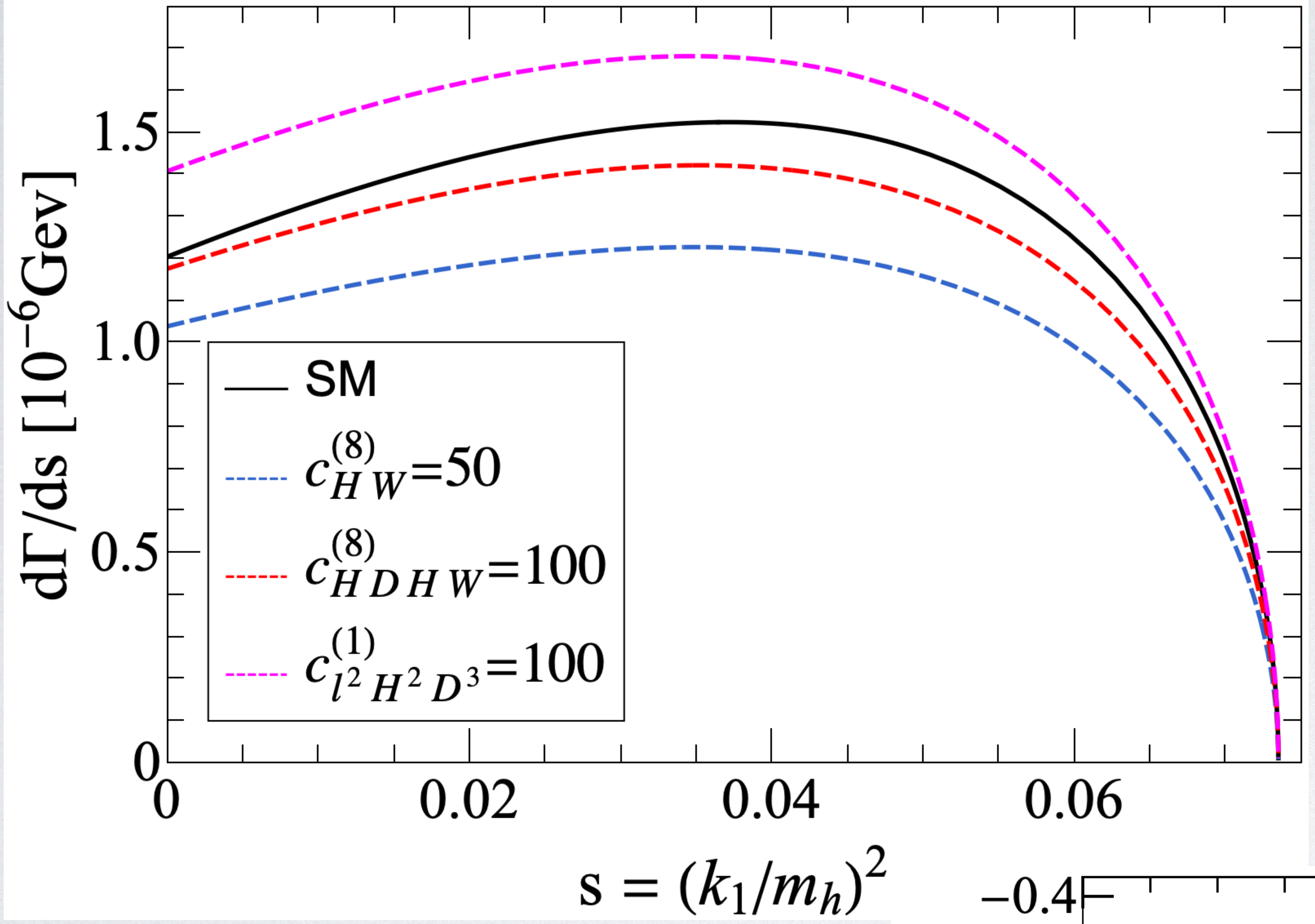
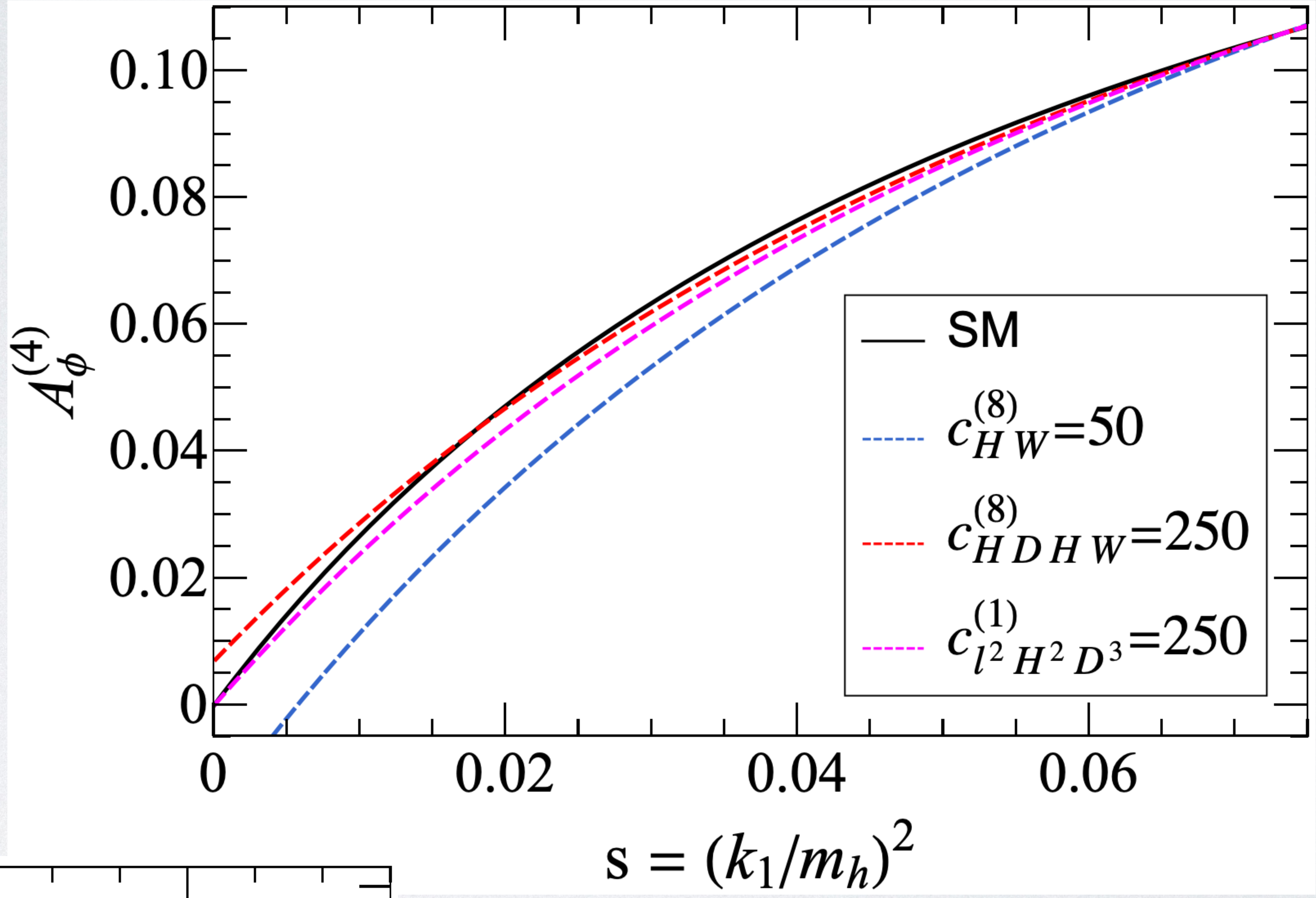


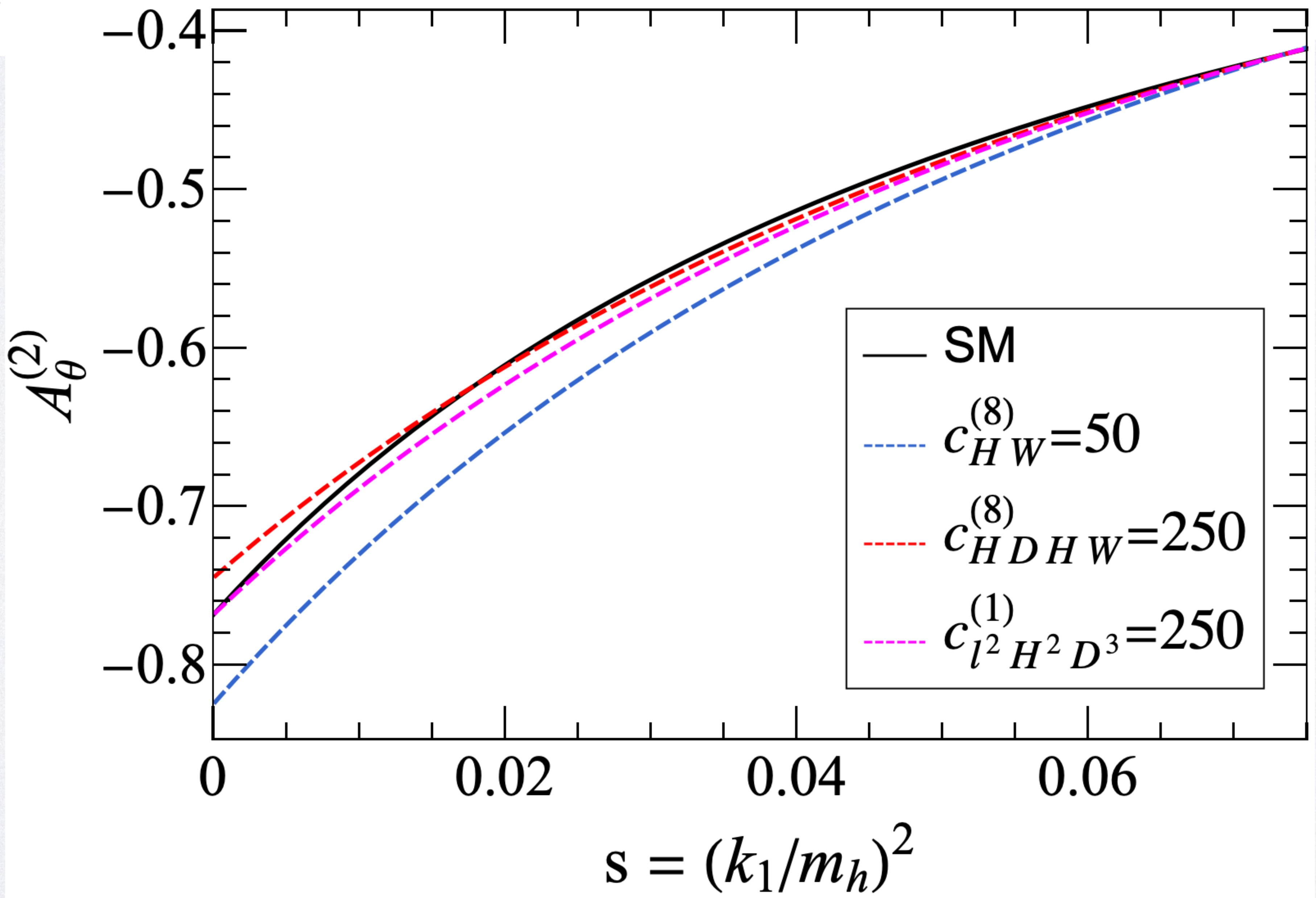




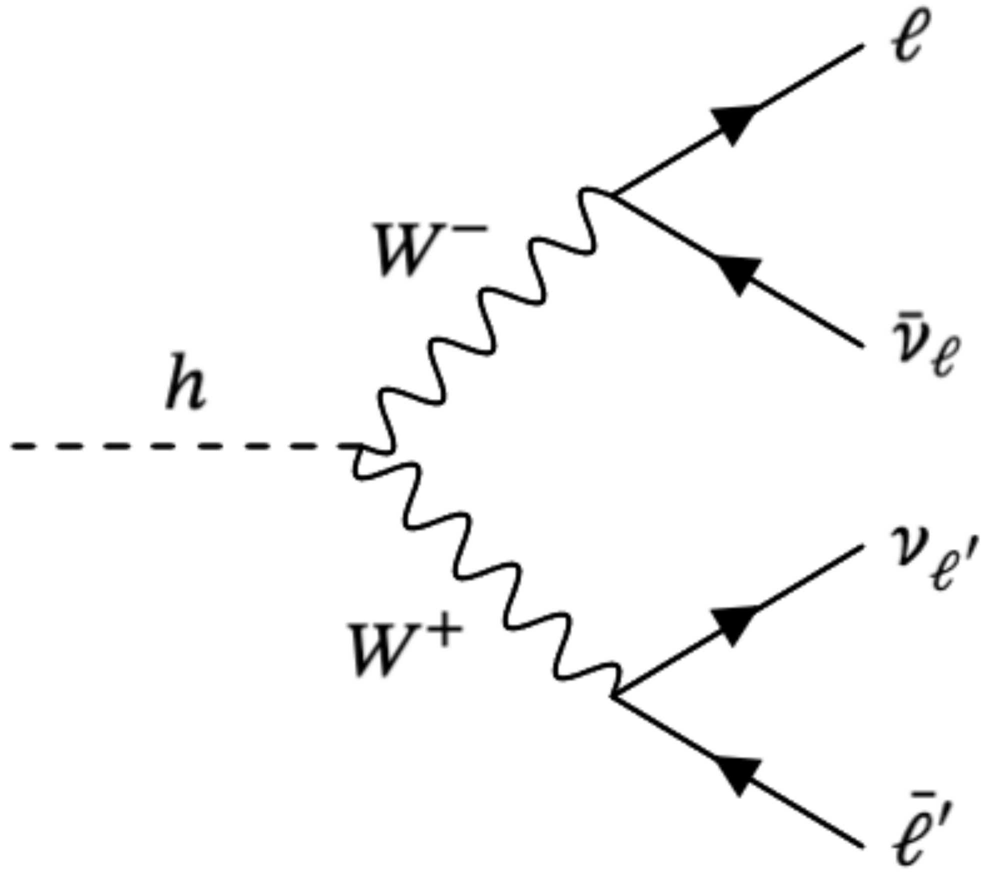
DIMENSION 8 CONTRIBUTIONS

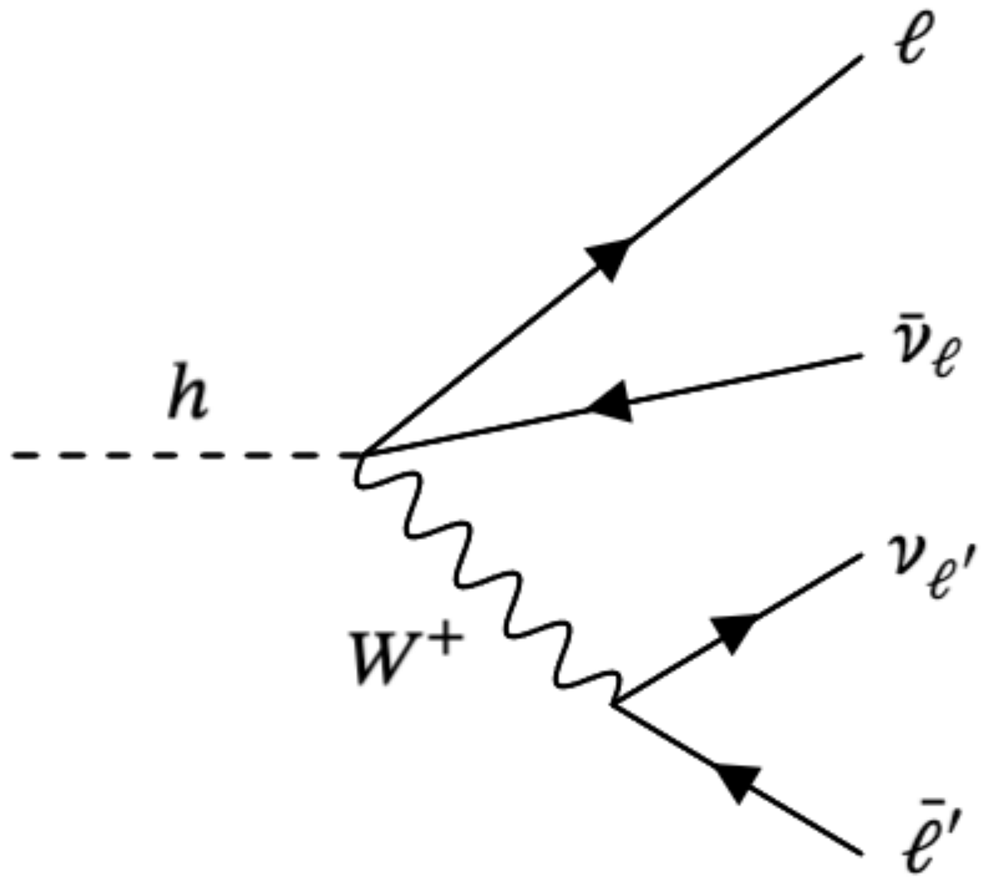


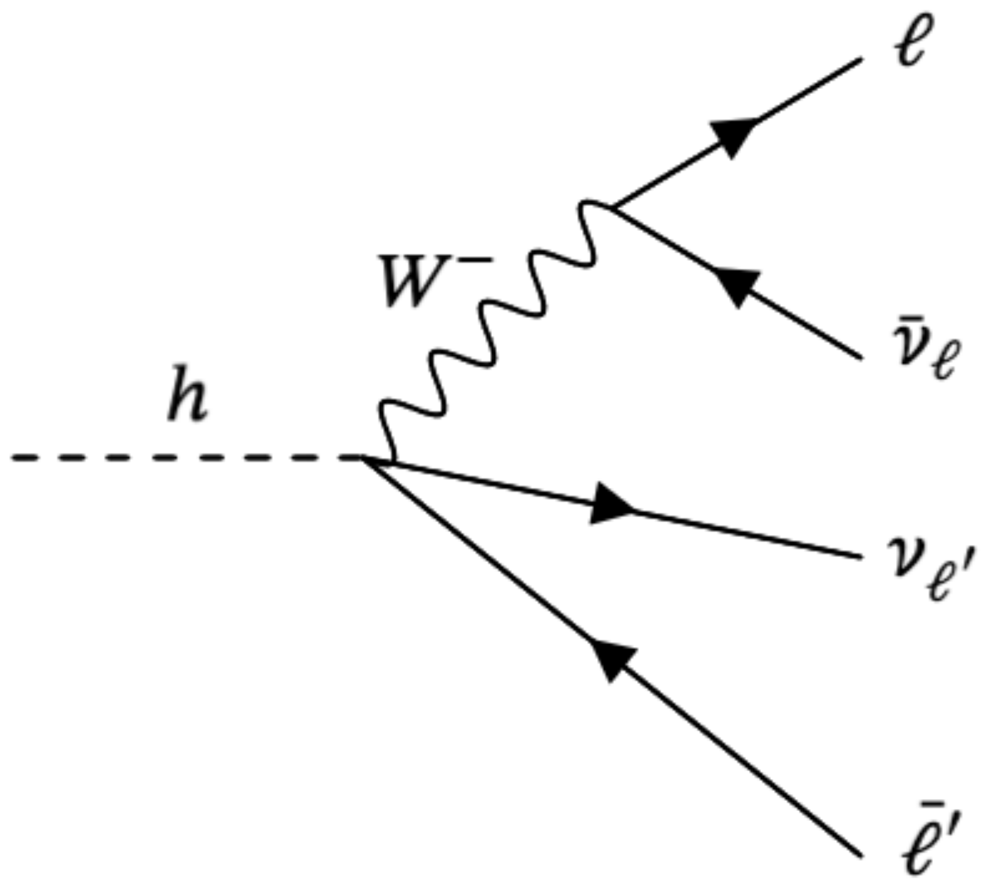




DIFFERENCES







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  - ✴ Can't neglect diagram with $m_{\nu'\ell'} \sim m_W$.
  - ✴ Can't use narrow width approximation.
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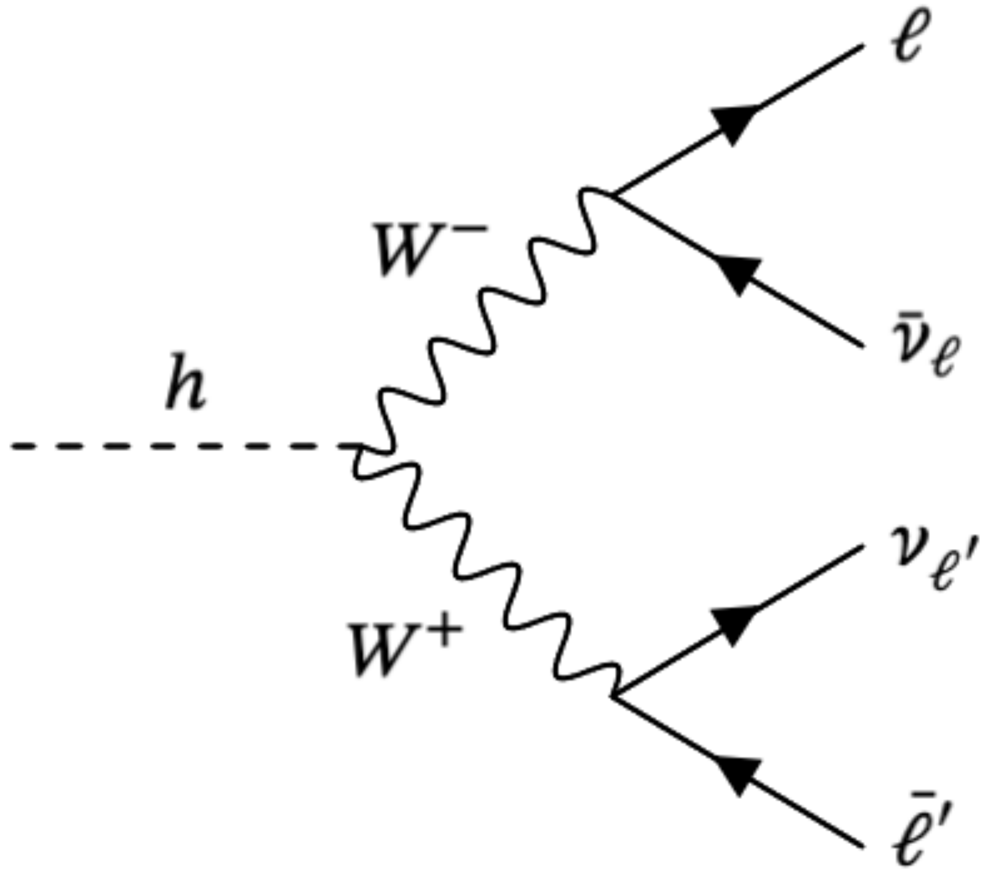

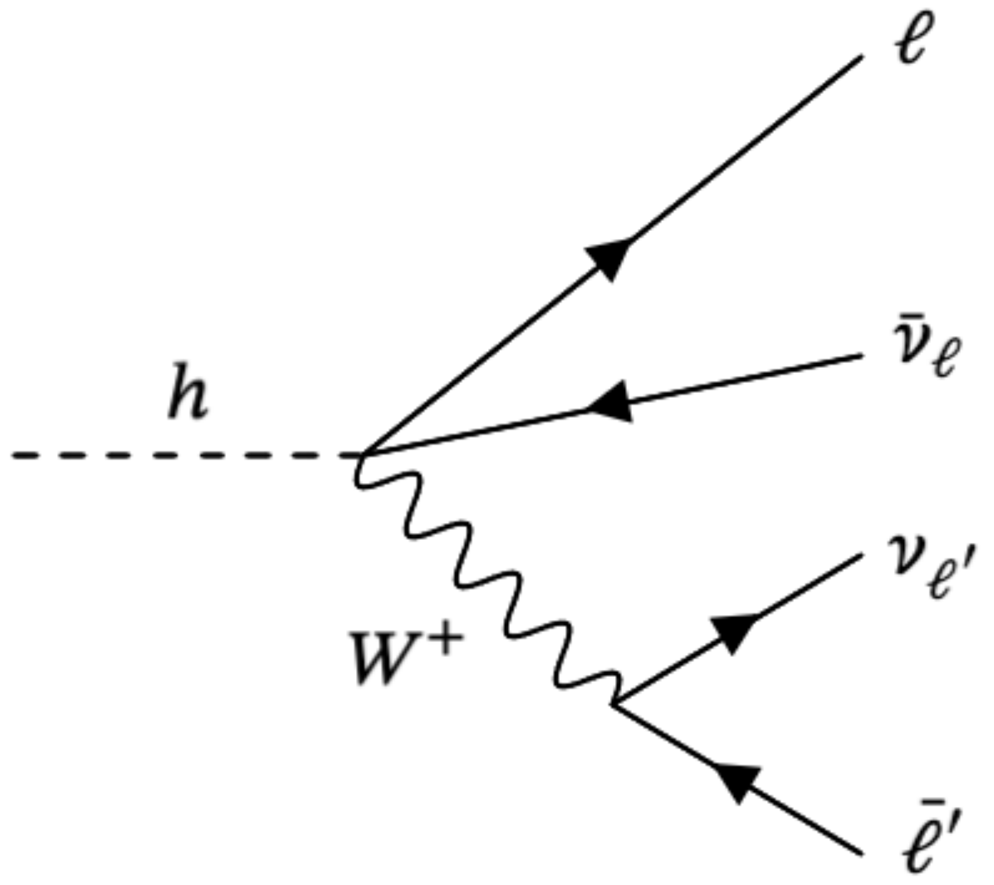

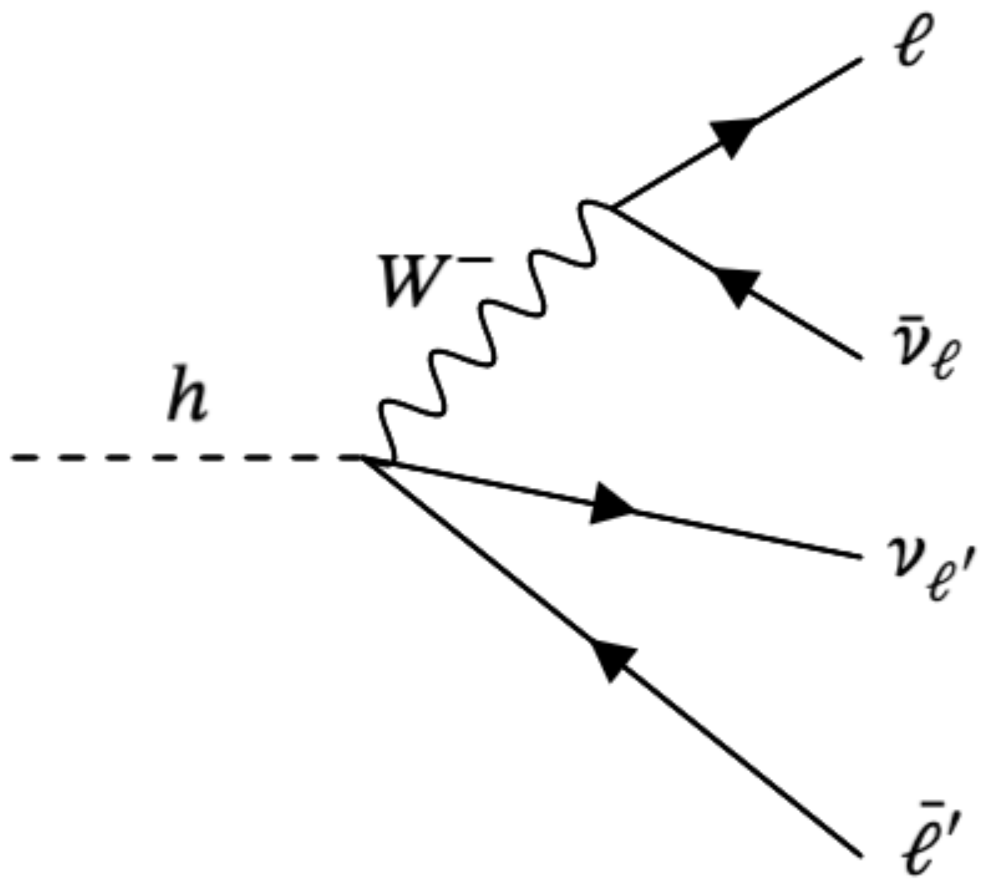

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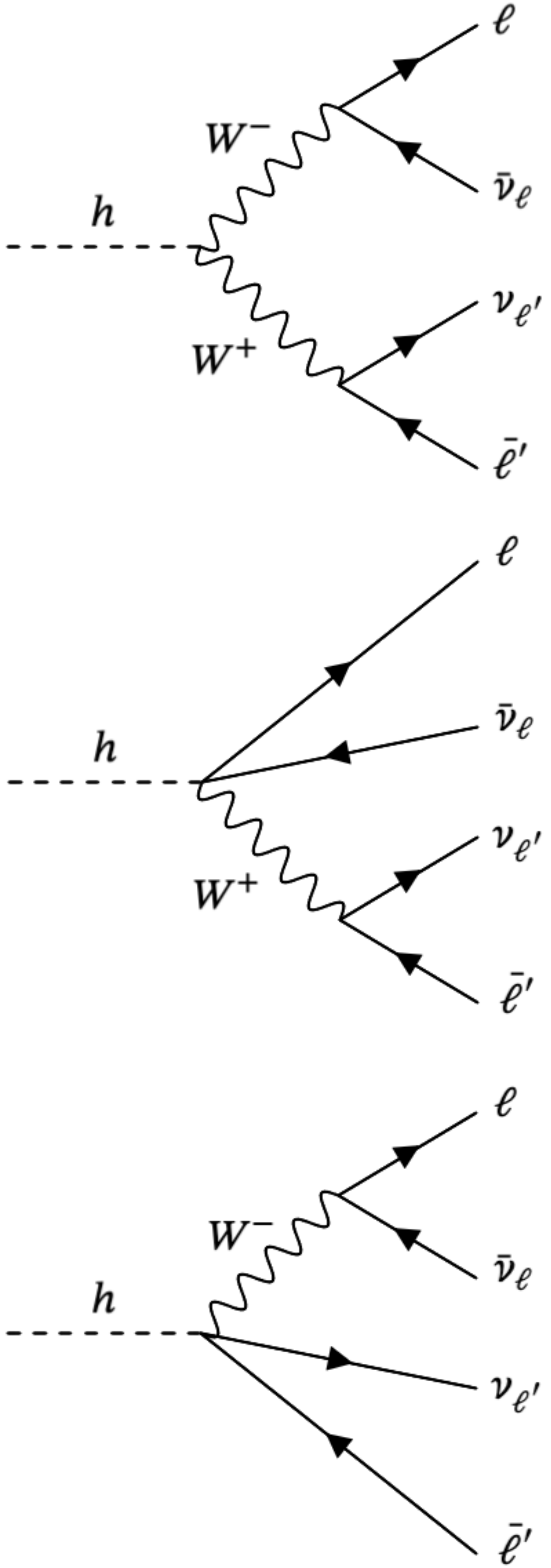

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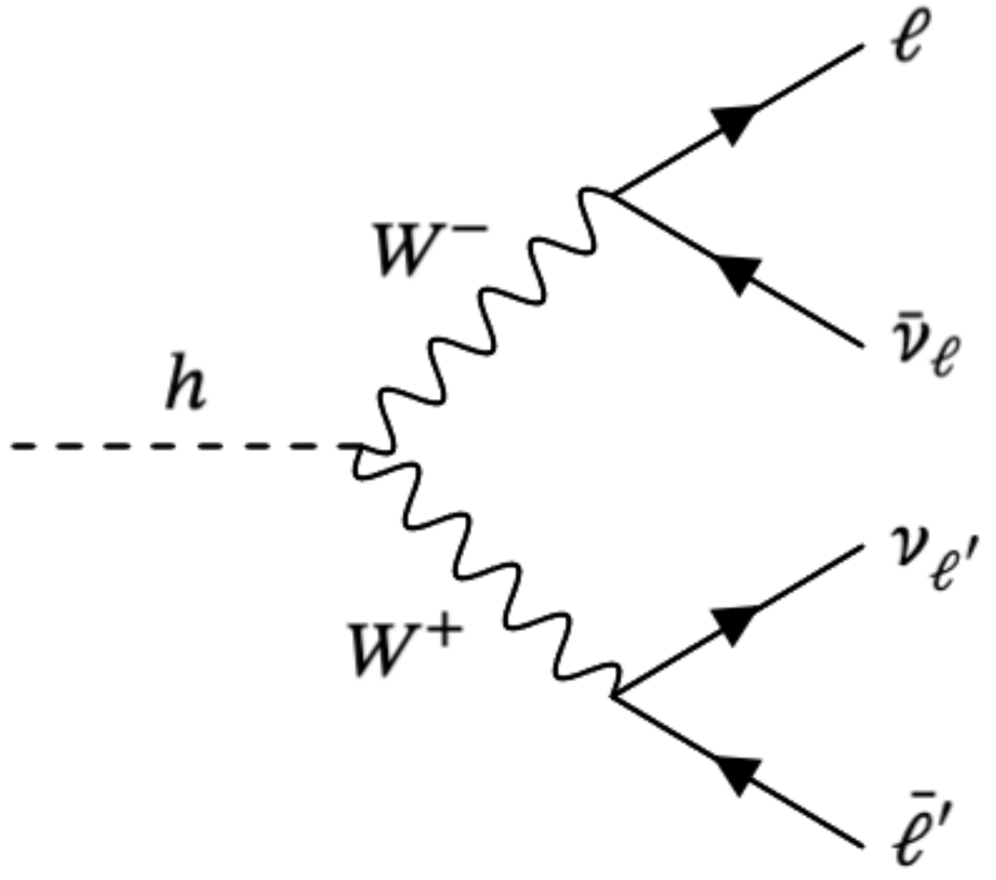
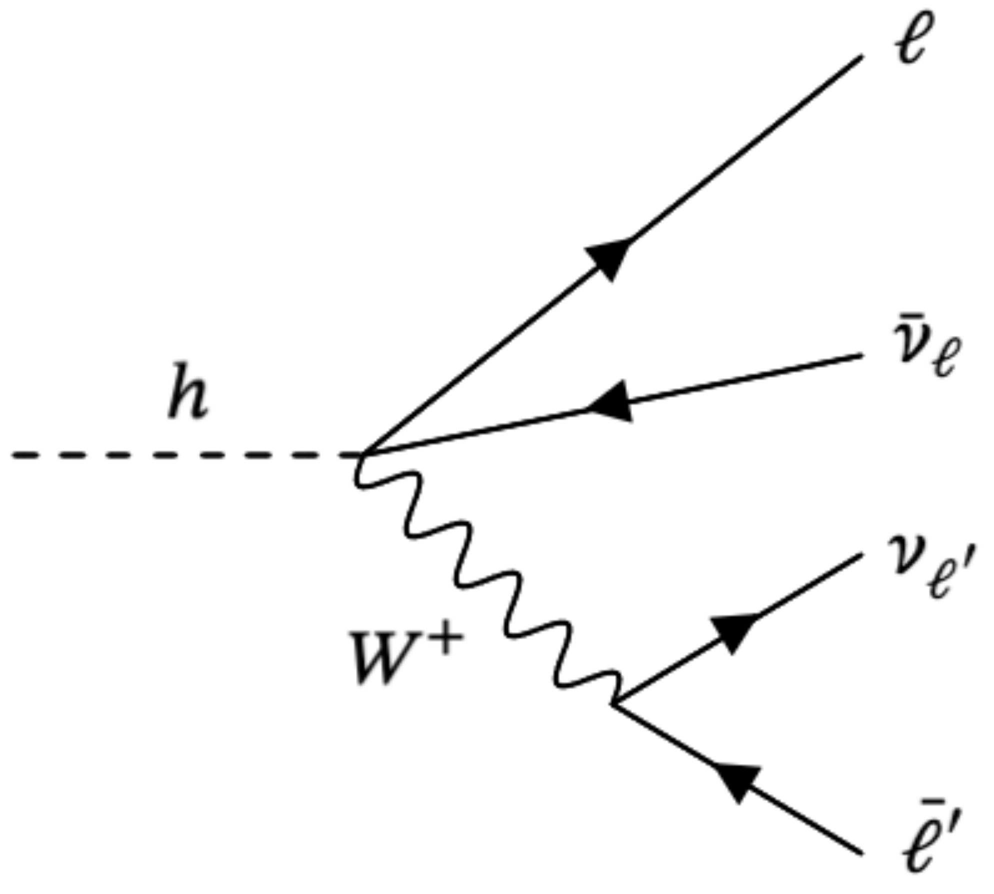
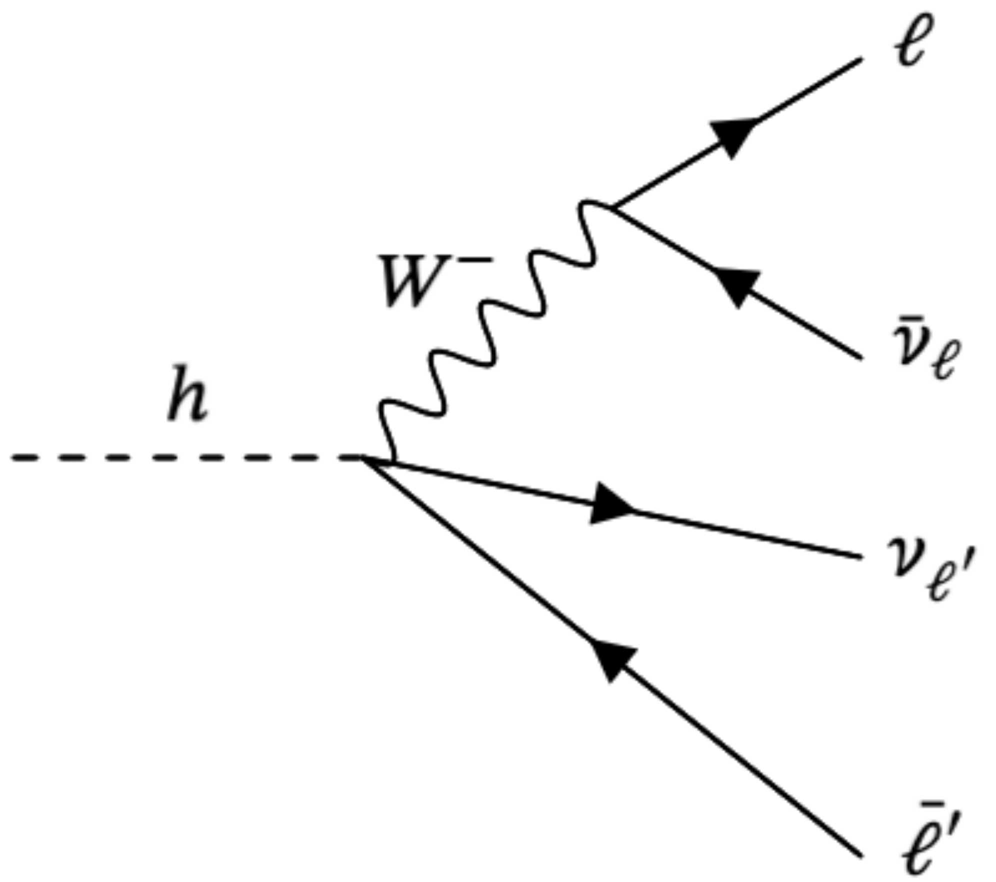
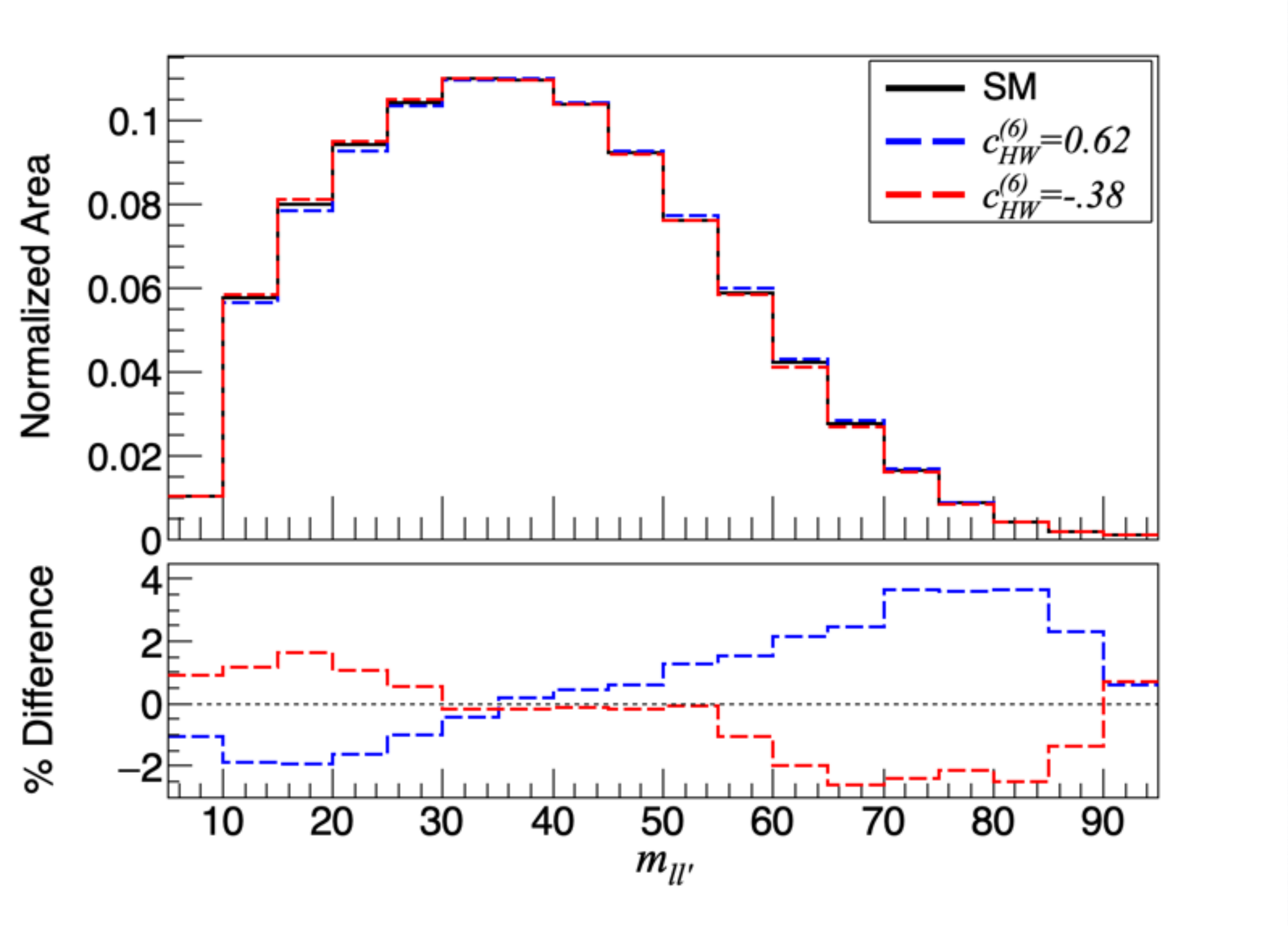
- Fewer helicity configurations since $W^{\pm}$ only couples tc left-handed neutrinos.



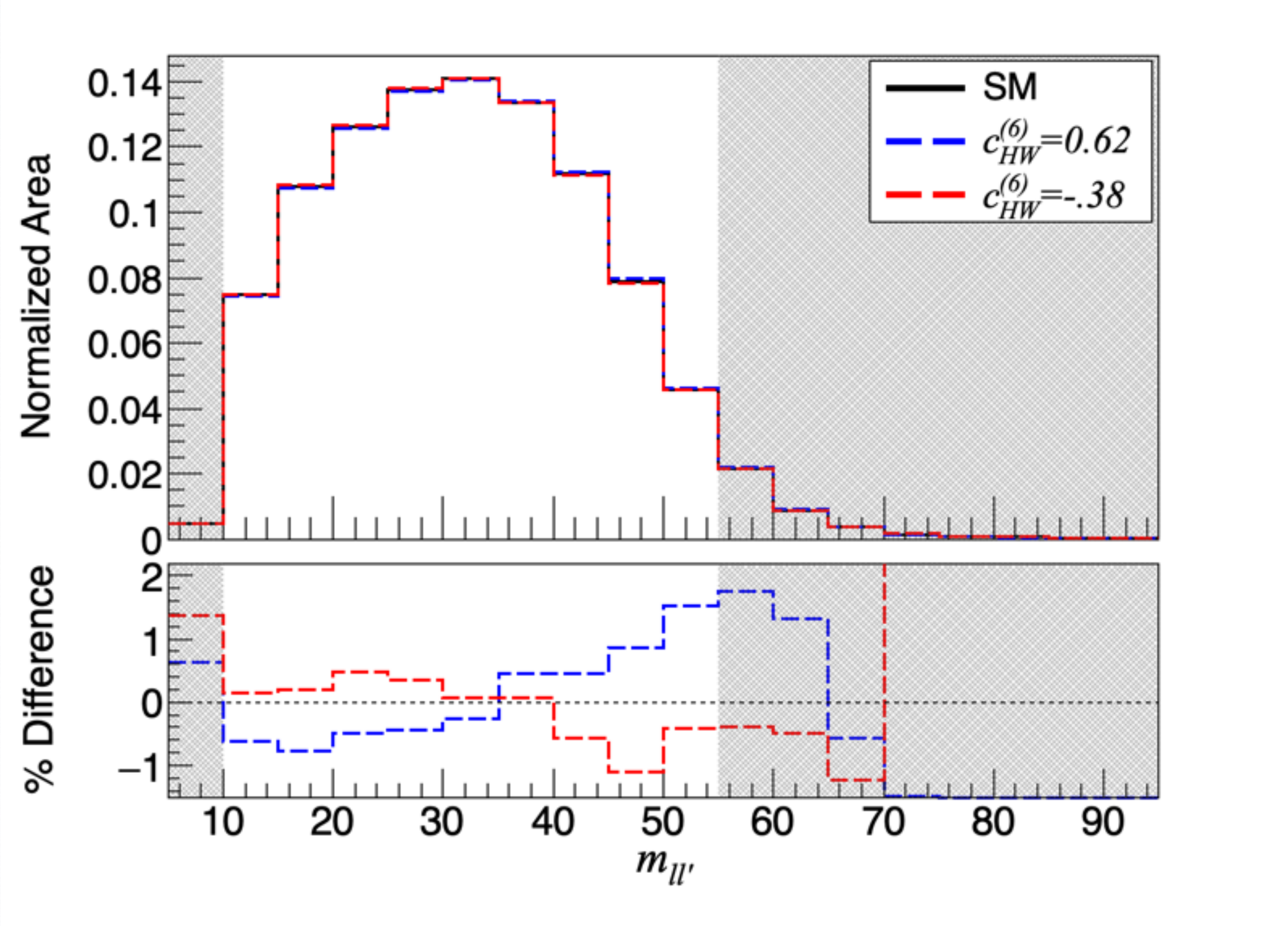




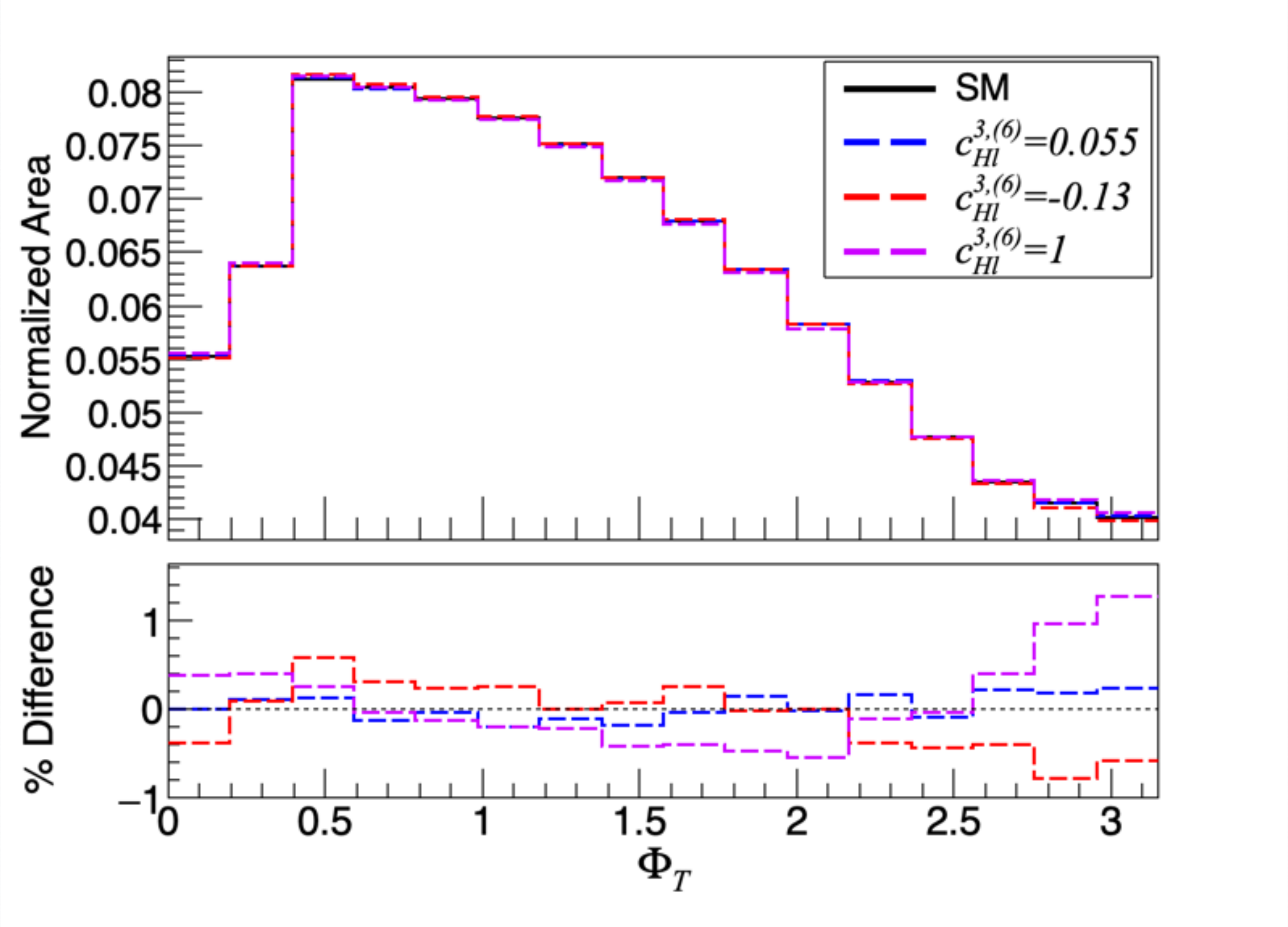
DISTRIBUTIONS DIMENSION 6

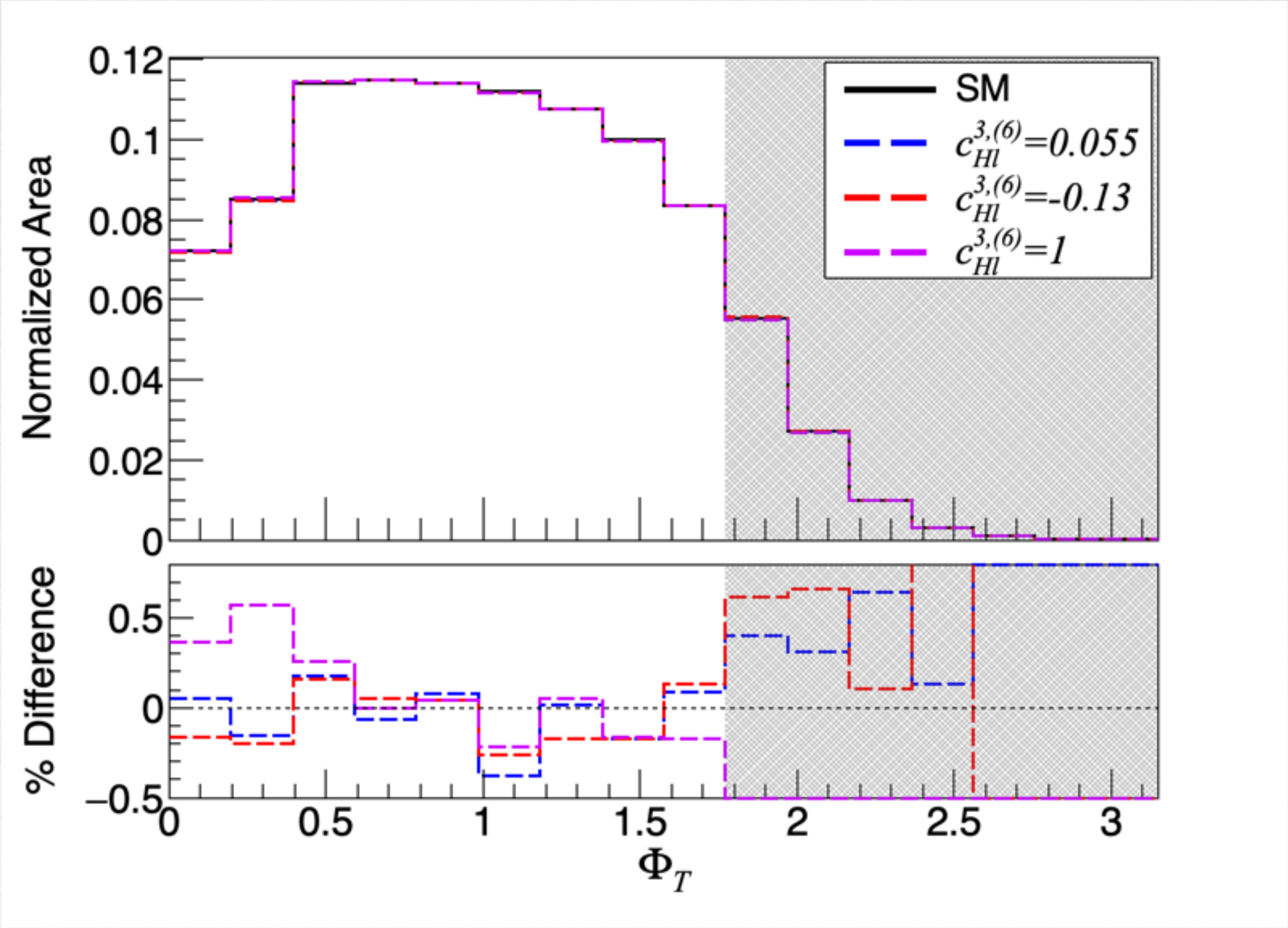


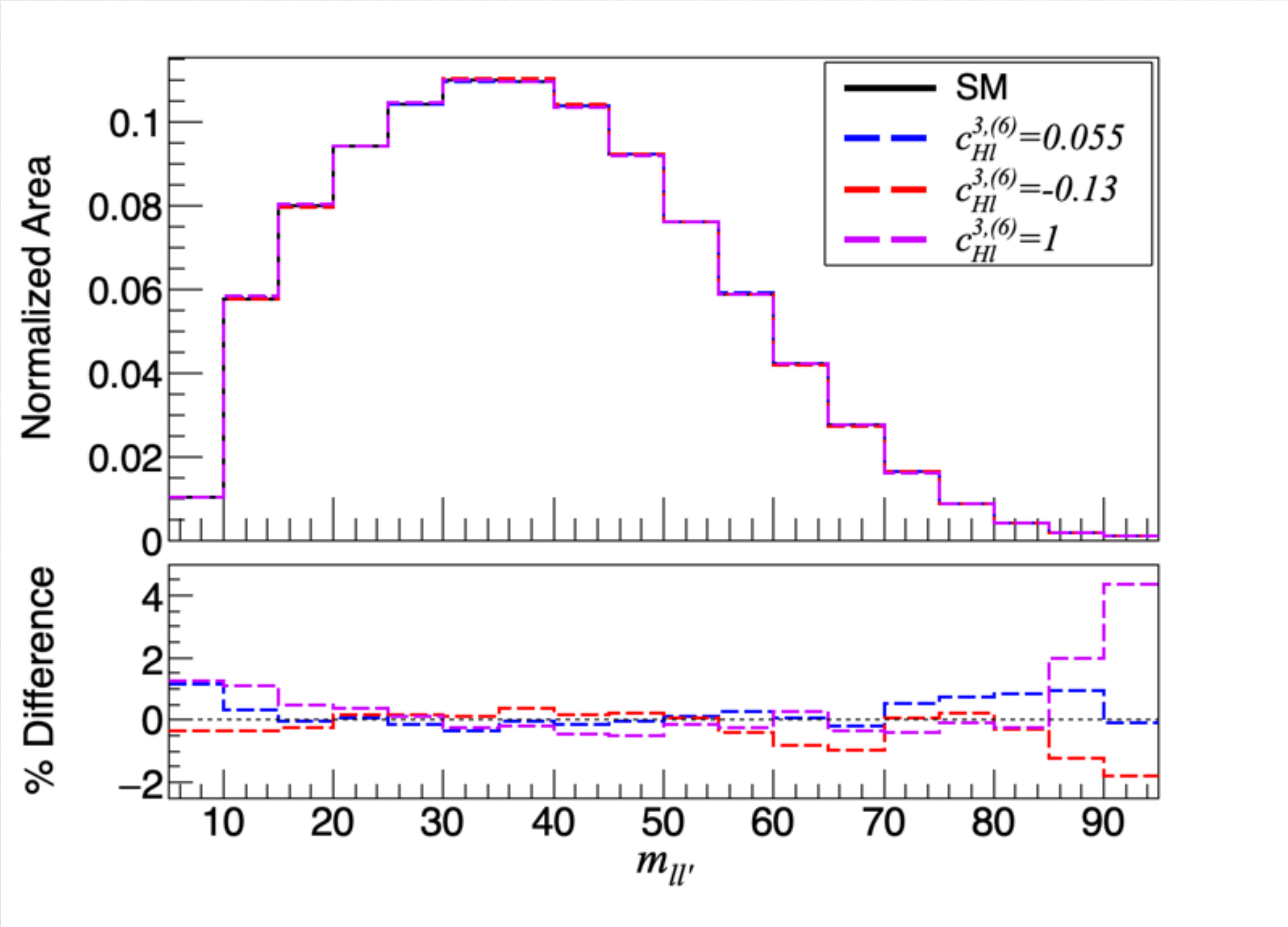
cuts

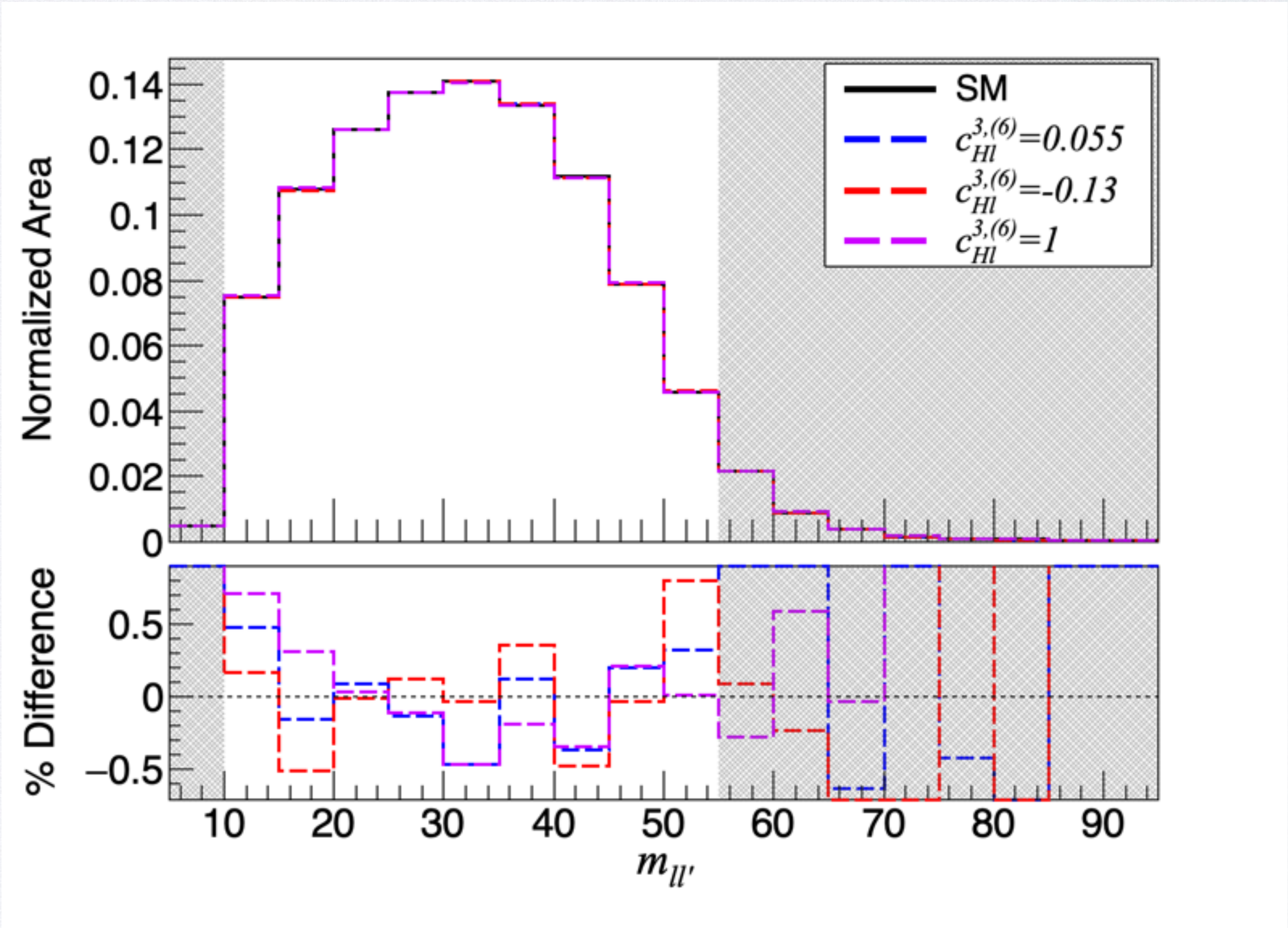


DISTRIBUTIONS DIPOLE









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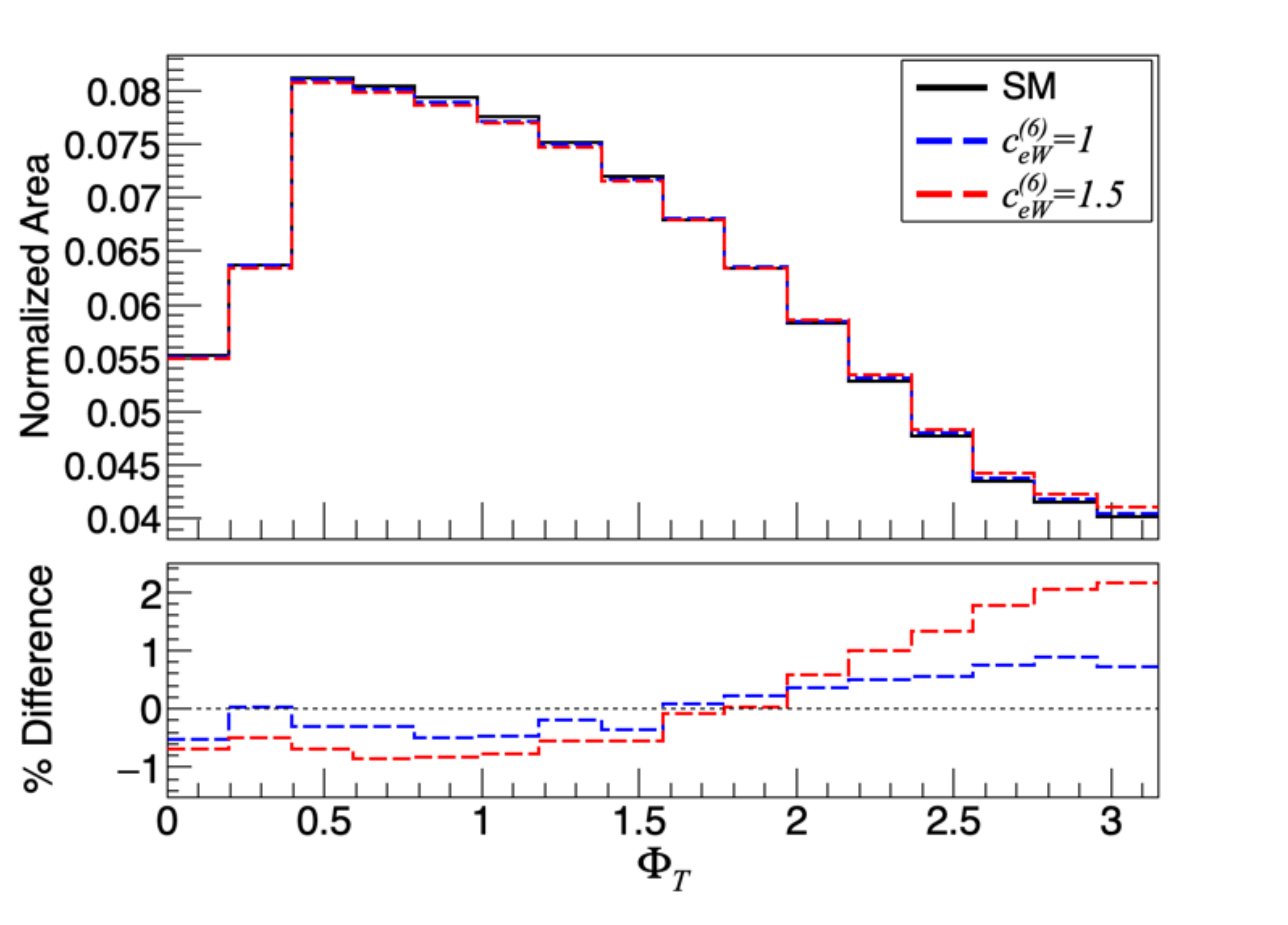
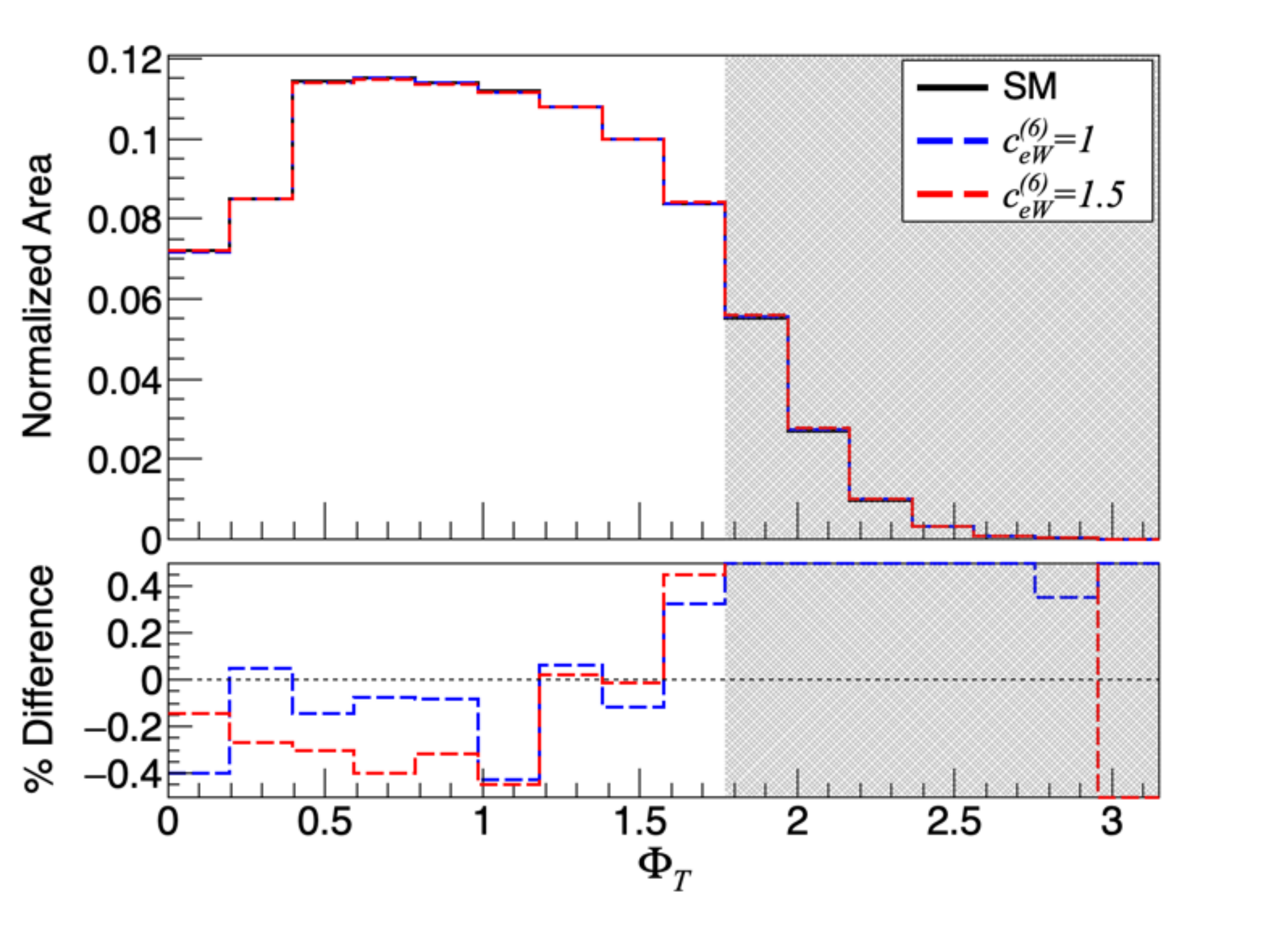
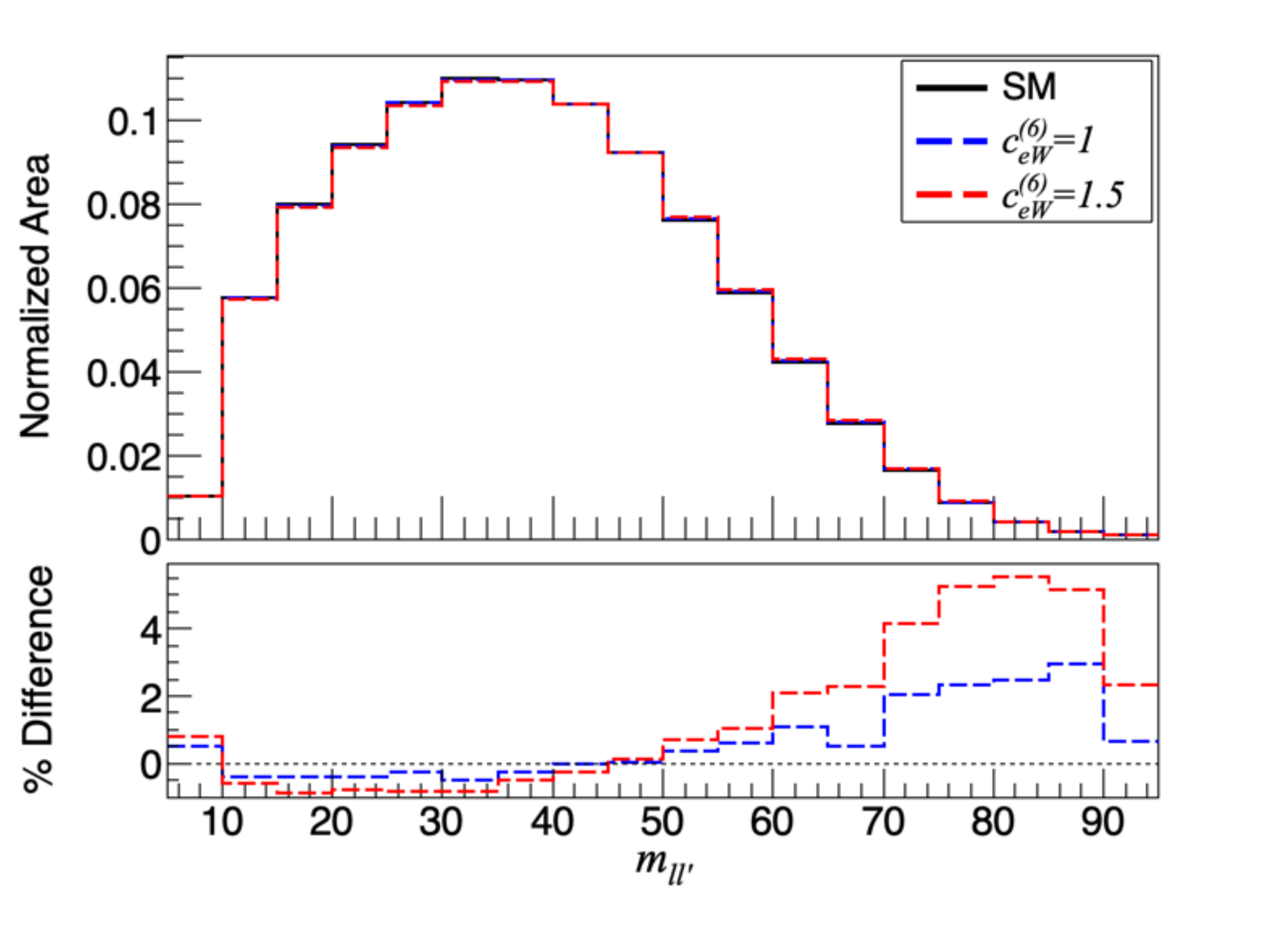
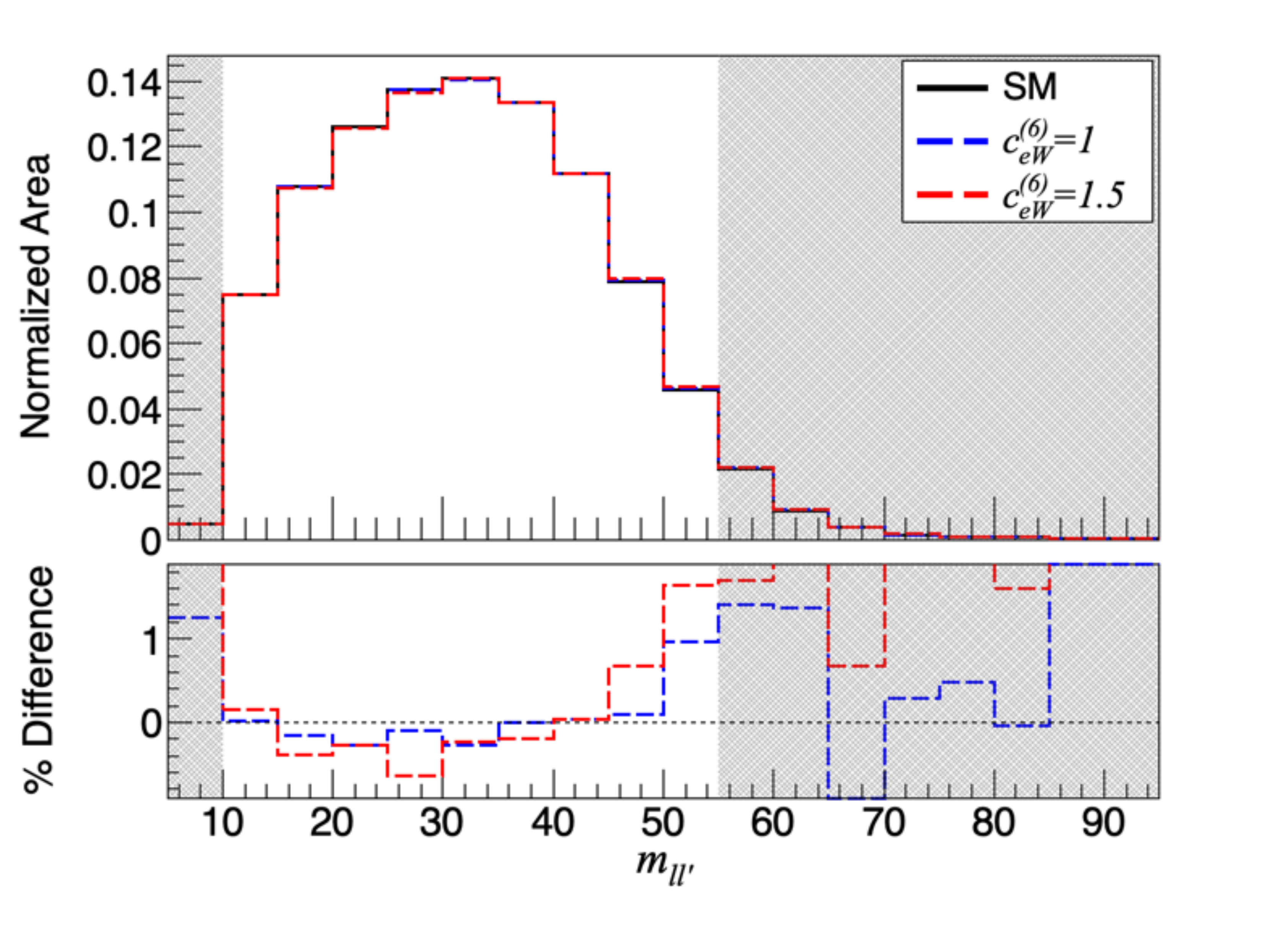
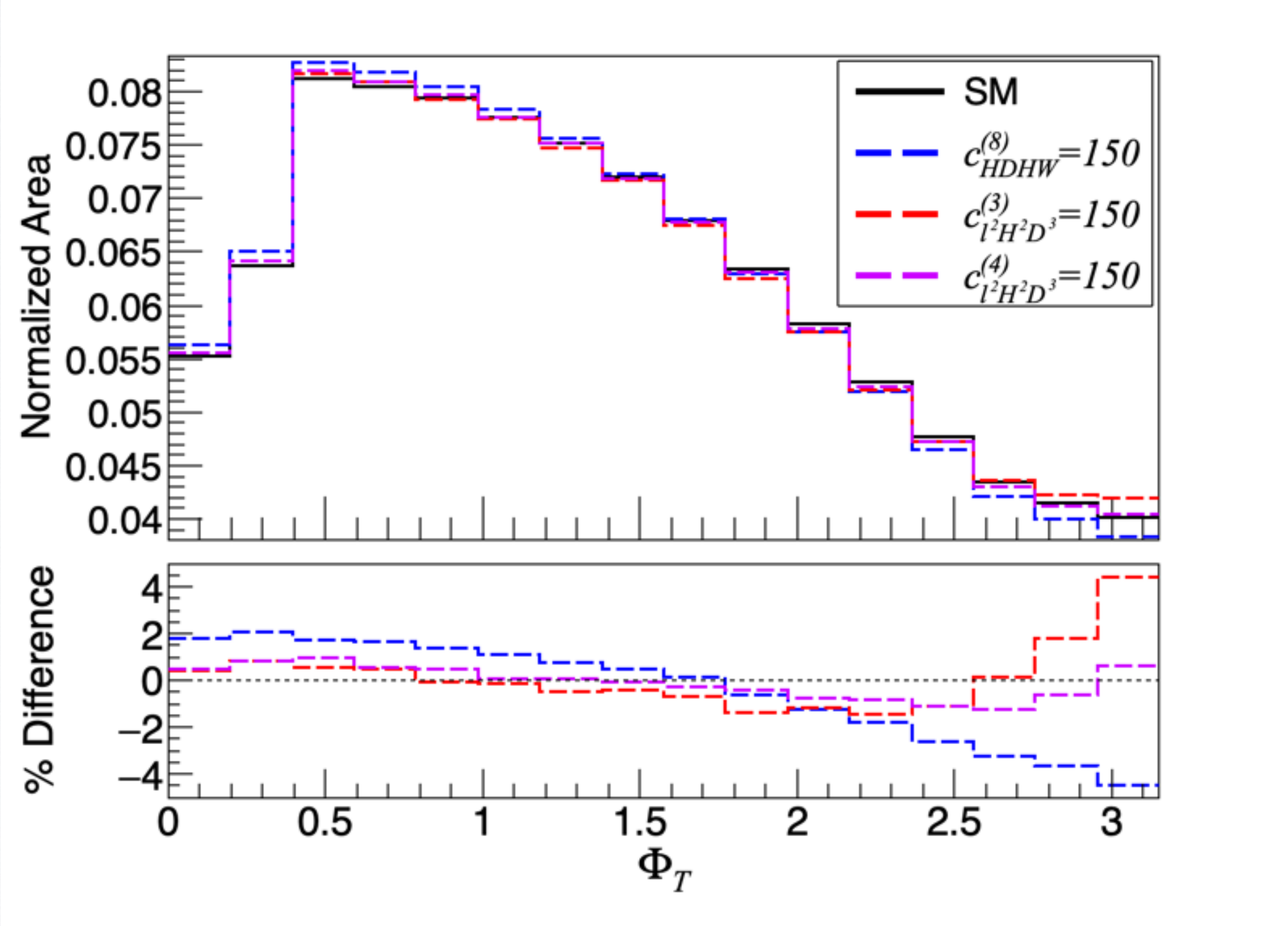


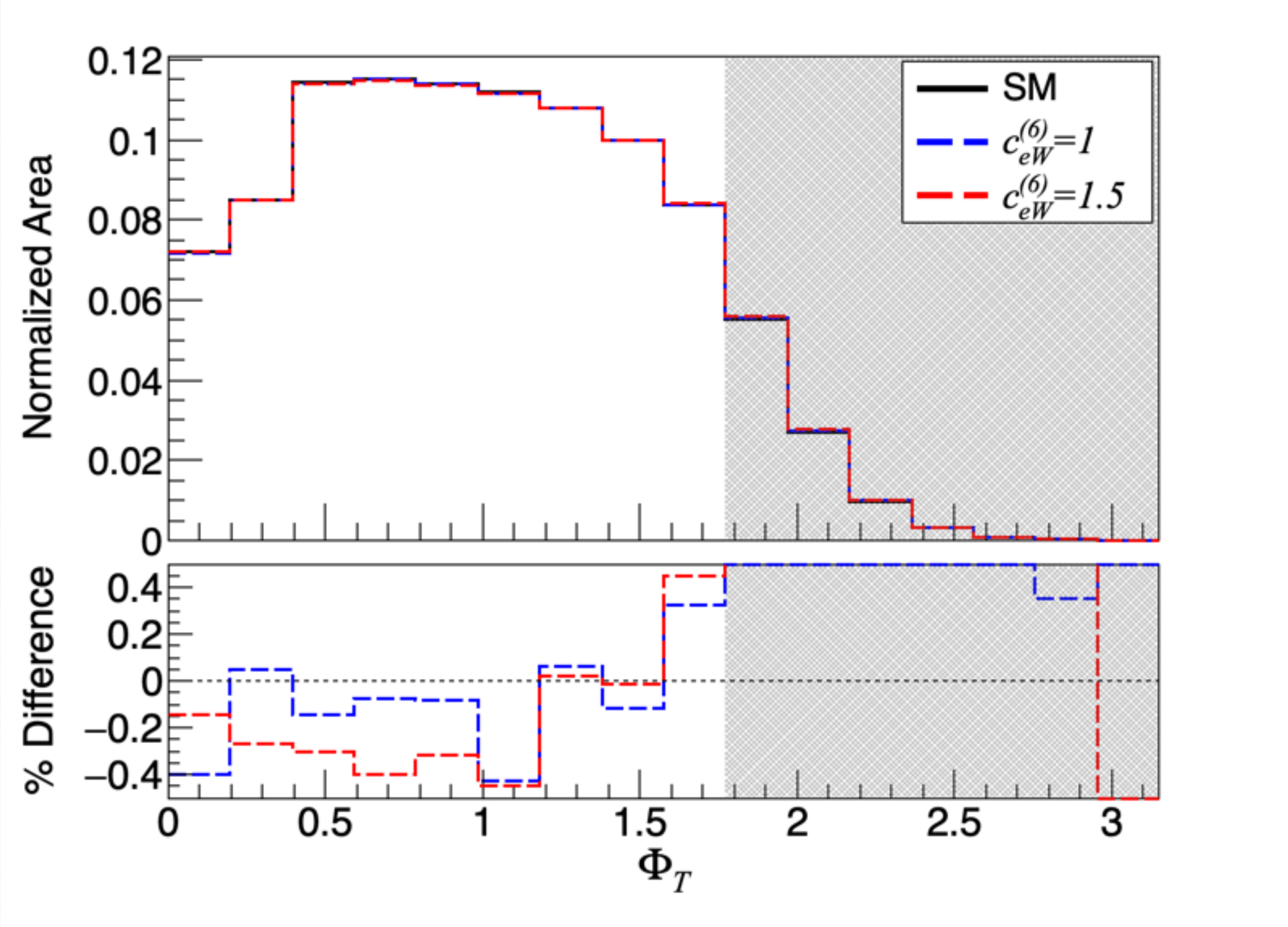


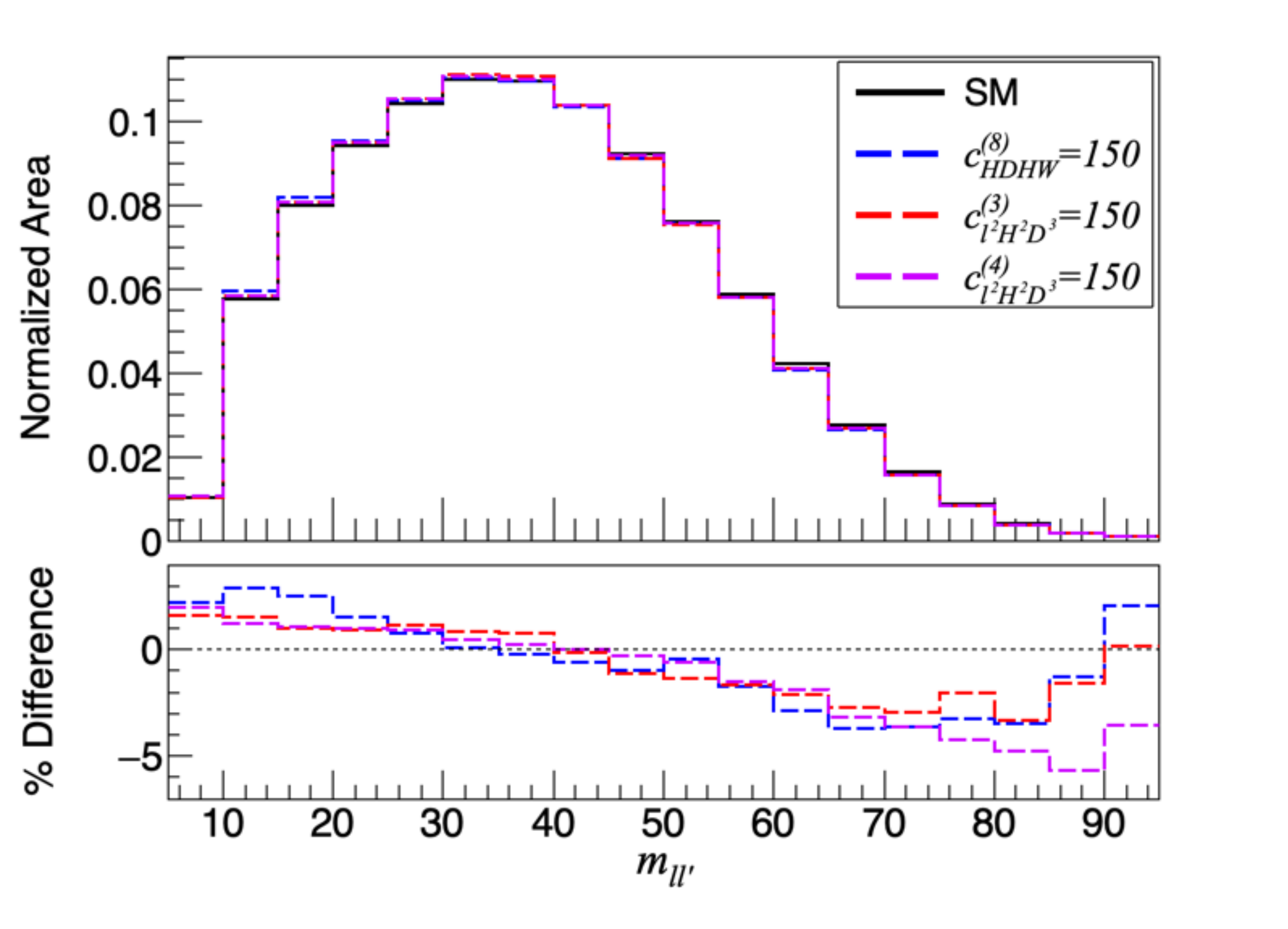


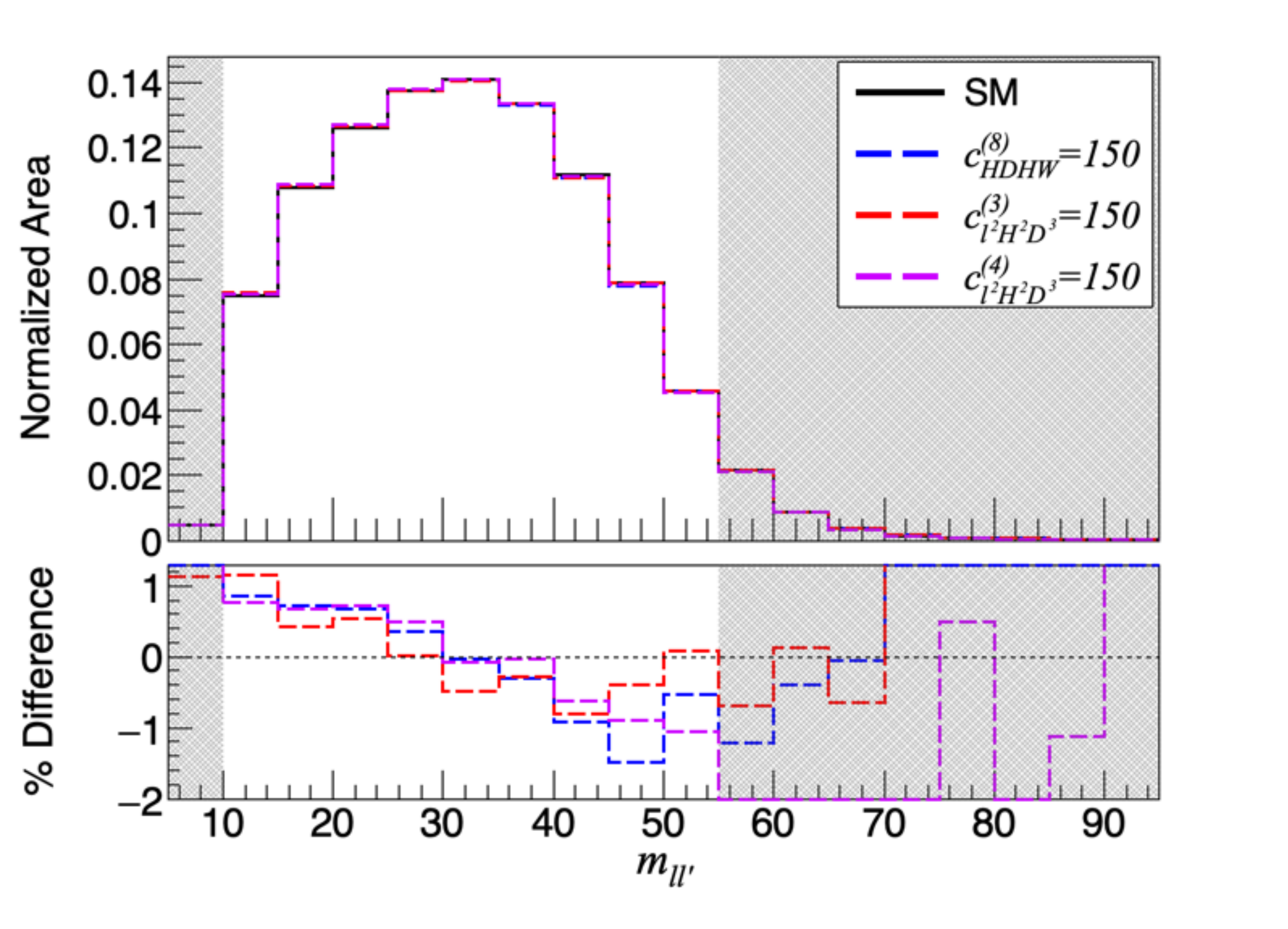


DIMENSION 8 DISTRIBUTIONS









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$$= \frac{3J^W_{21}}{9J^W_1 + J^W_2 + 3\left(J^W_3 + J^W_4\right)}$$

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Could extract $\mathcal{O}(1/\Lambda^4)$ SMEFT effects in Future collider

SUMMARY OF $h \to \ell \bar{\nu}_\ell \nu_\ell \bar{\ell}$ RESULTS

- SMEFT effects are smaller in $m_{\ell\ell'}$ distribution
- For operators generating non-SM like distribution:
  - ✴ These are purely $\mathcal{O}(1/\Lambda^4)$ effects.
  - ✴ Available observables obscure the novel kinematics.
- For operators generating SM like distribution:
  - ✴ $Q_{HW}^{(6)}$ shows the largest deviation within existing bounds.
  - ✴ Dimension 8 Operators' contributions are small for similar reasons as in $h \to \ell' \overline{\ell'} \ell \overline{\ell}$.
- Cuts assume SM like interations (Φ_T, $m_{\ell\ell'}$), further obscuring SMEFT effects (SM like or non-SM-like).

[9608317 Dittmar, Dreiner]