BEIJING NORMAL UNIVERSITY

Measuring hhWW Coupling at the Future Lepton Collider

刘言东

Based on Phys. Rev. D 109, 073005 (2024)

In collaboration with Qing-Hong Cao, Kun Cheng and Xiao-Rui Wang

Fuzhou, December 15, 2024

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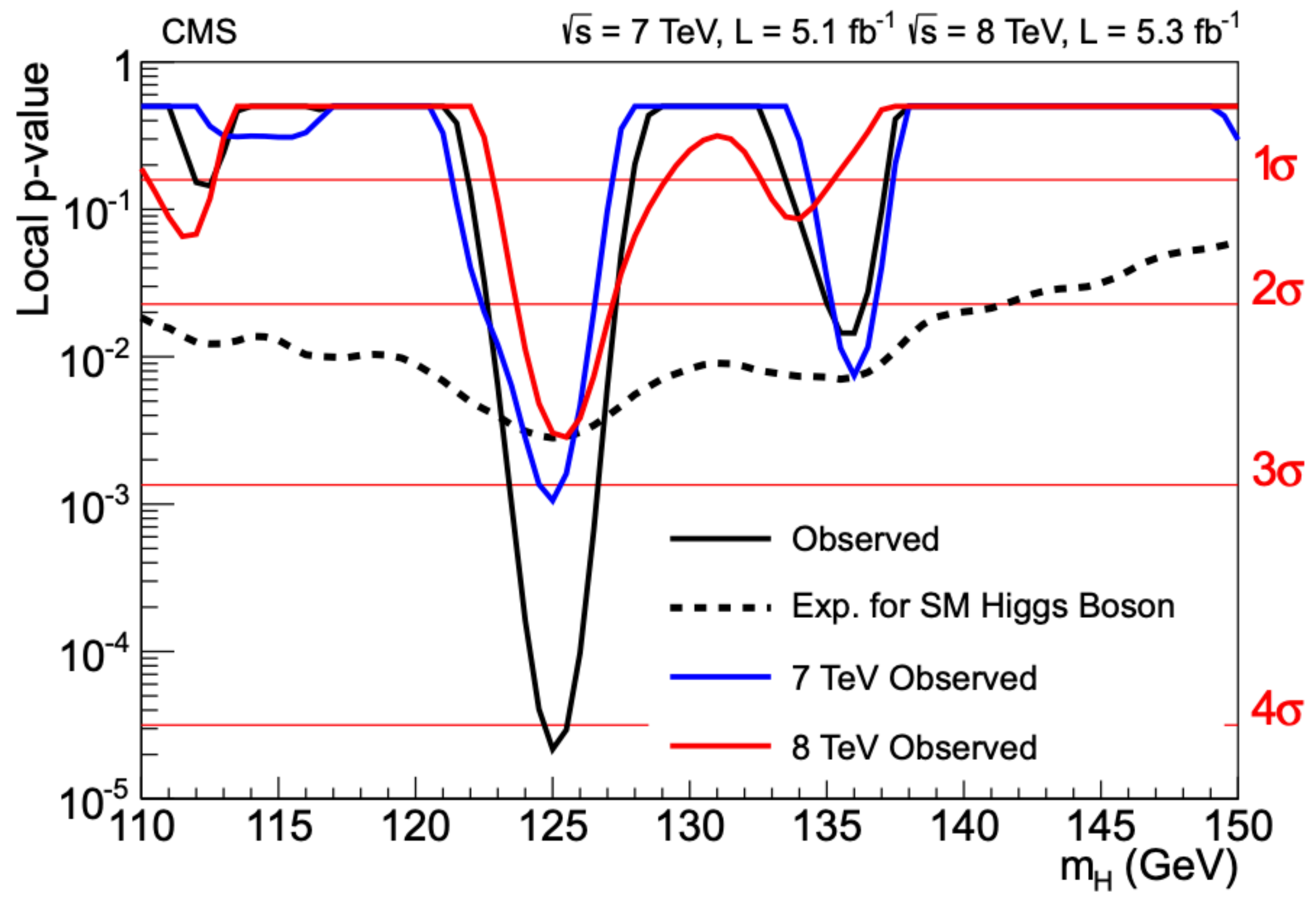
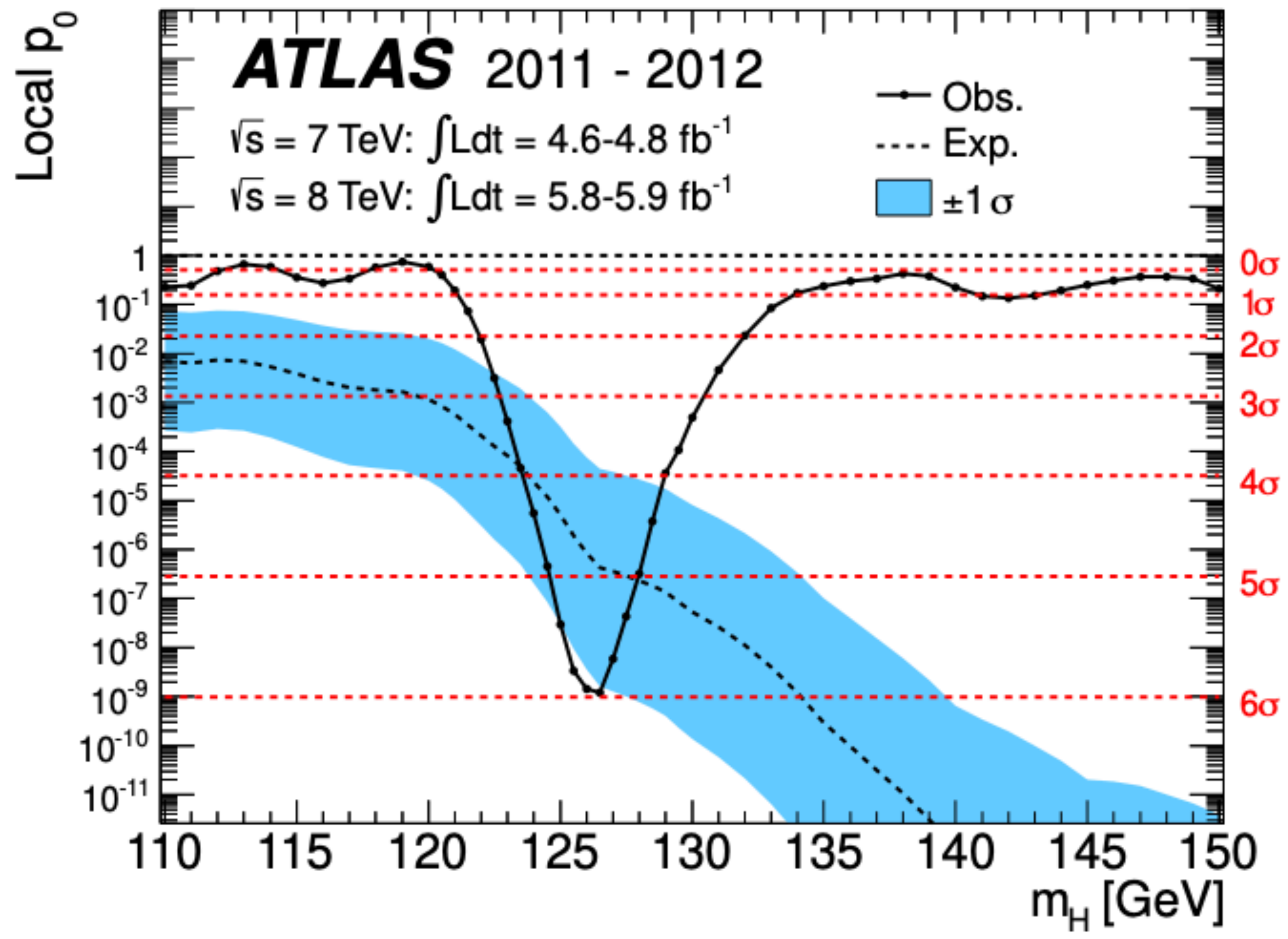
Higgs boson discovery at the LHC





Flow Chart of the Higgs Boson Couplings Measurement

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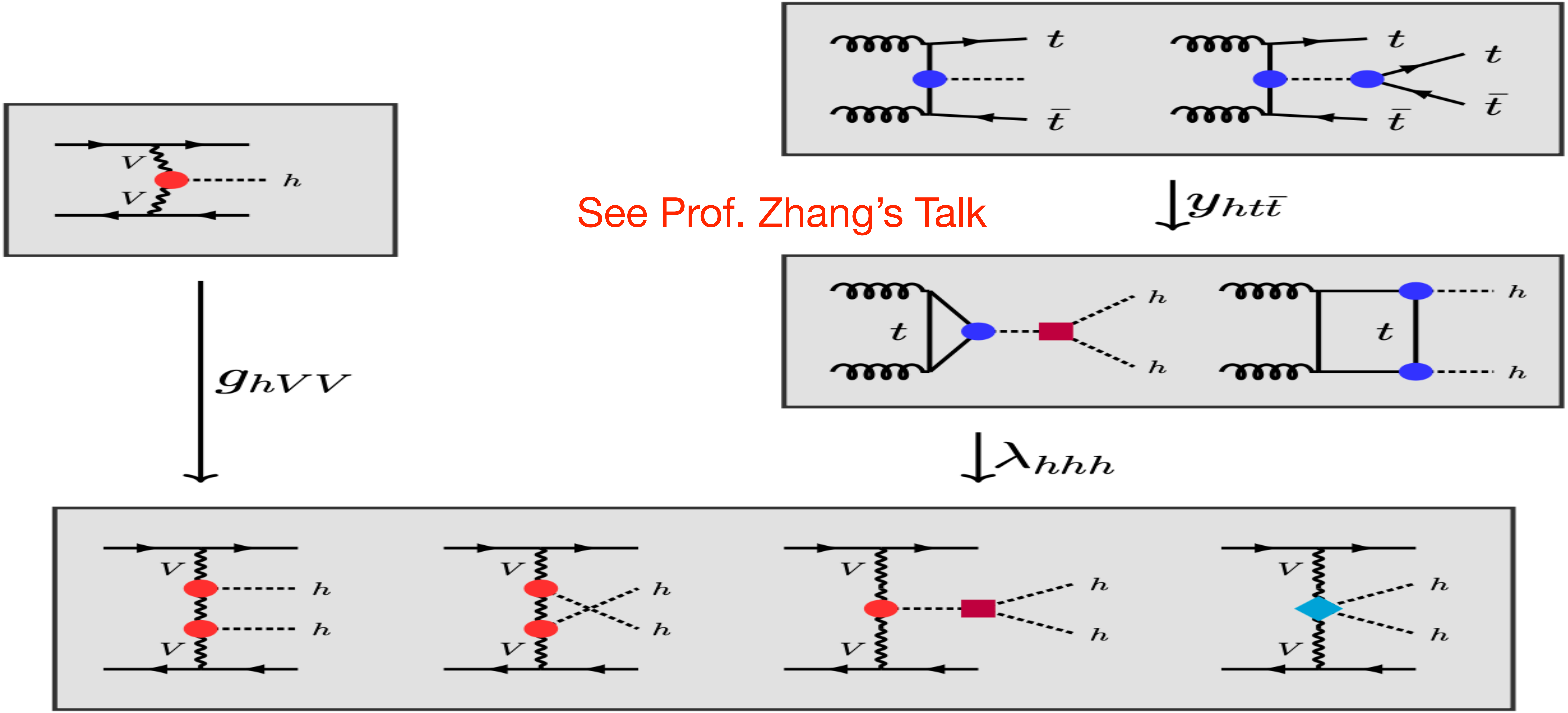

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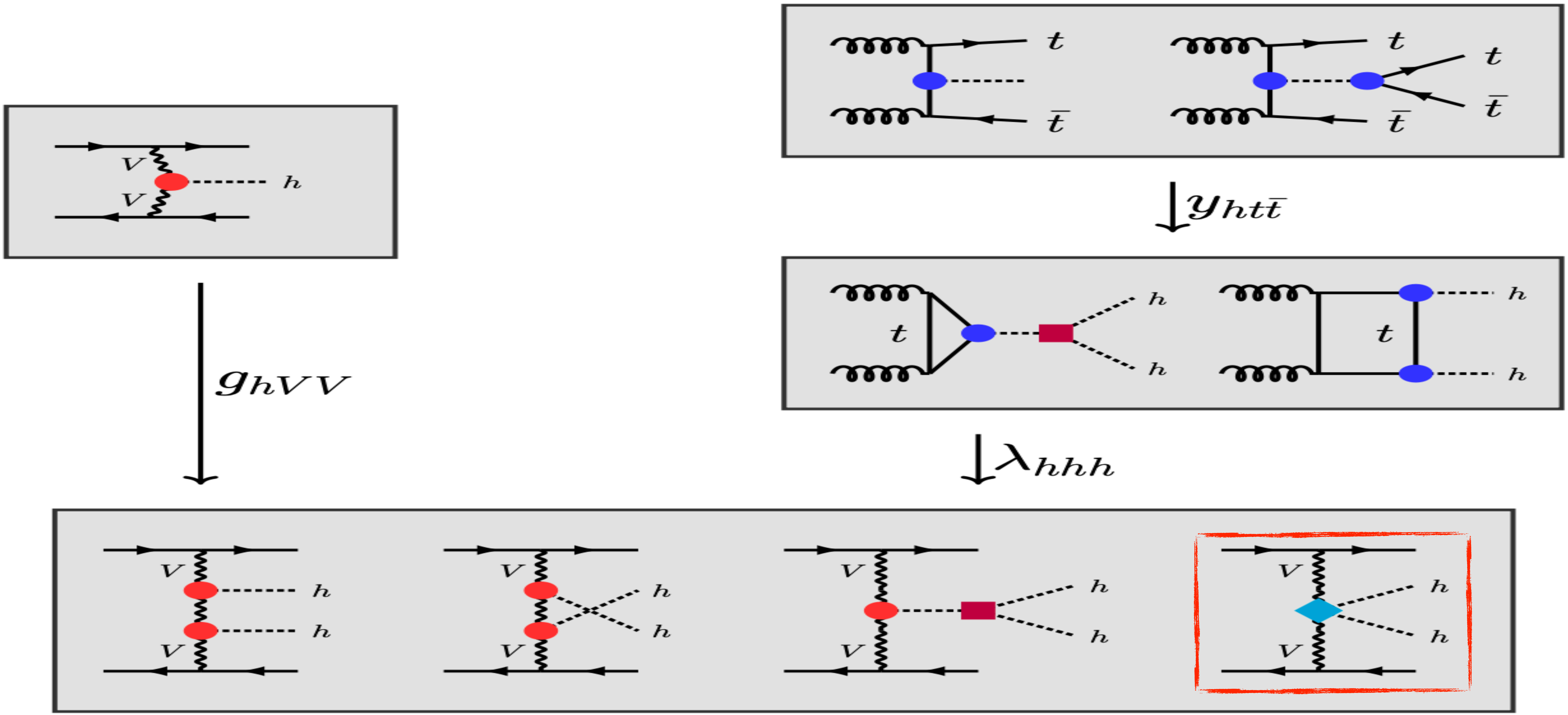
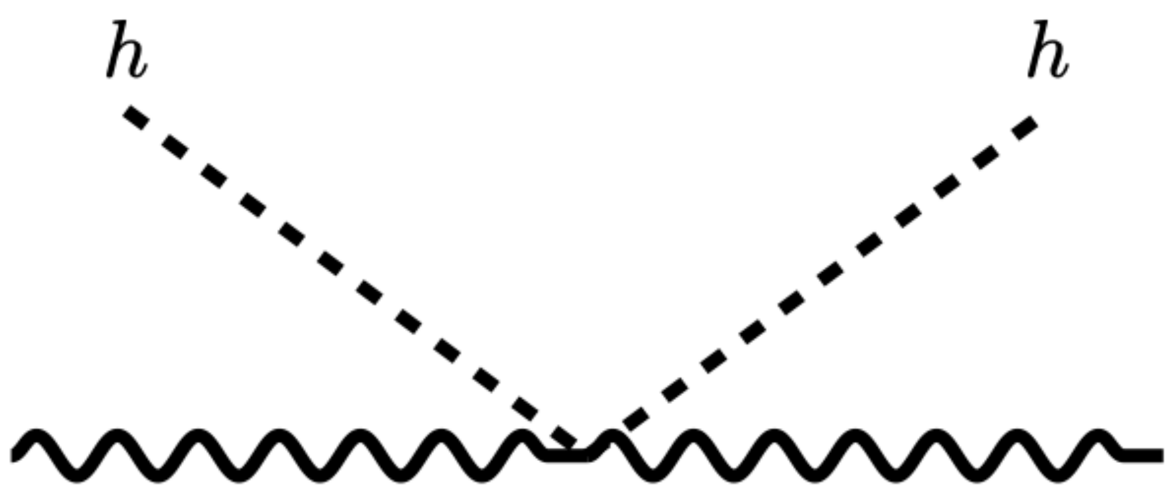
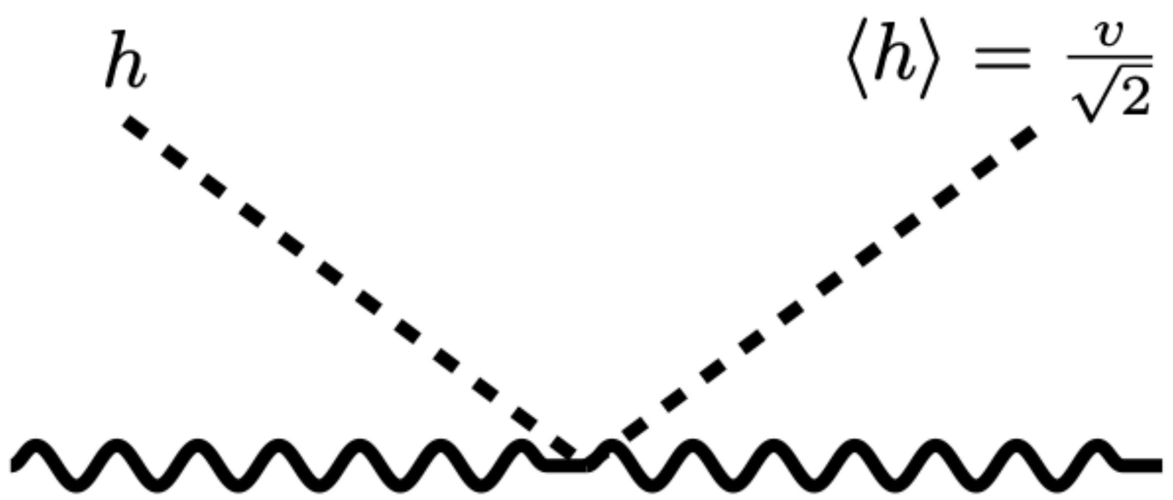


hhVV coupling in the SM and NP models

- Comparison of hhVV and hVV couplings in the Standard Model



$g_{hhVV}/g_{hhVV}^{SM} = \kappa_{hhVV}$



$g_{hVV}/g_{hVV}^{SM} = \kappa_{hVV}$

- Comparison of hhVV and hVV couplings in New Physics models

✦ Extensions of the Higgs boson sector: Triplet Higgs boson model

✦ Extensions of the gauge group: 3-3-1 model

✦ Composite Higgs boson scenarios: $\kappa_{hVV} = \sqrt{1 - v^2/f^2}, \kappa_{hhVV} = 1 - 2v^2/f^2$

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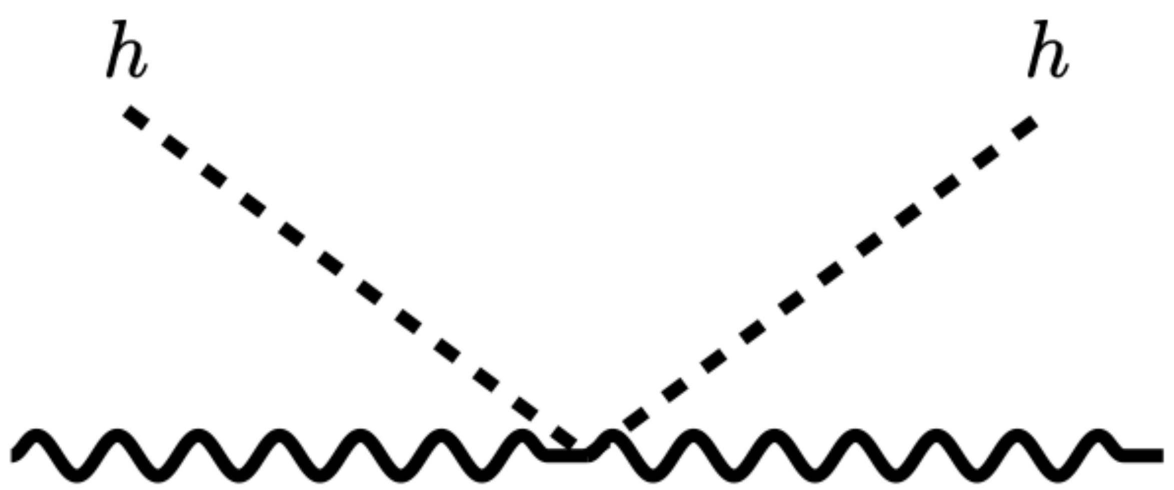

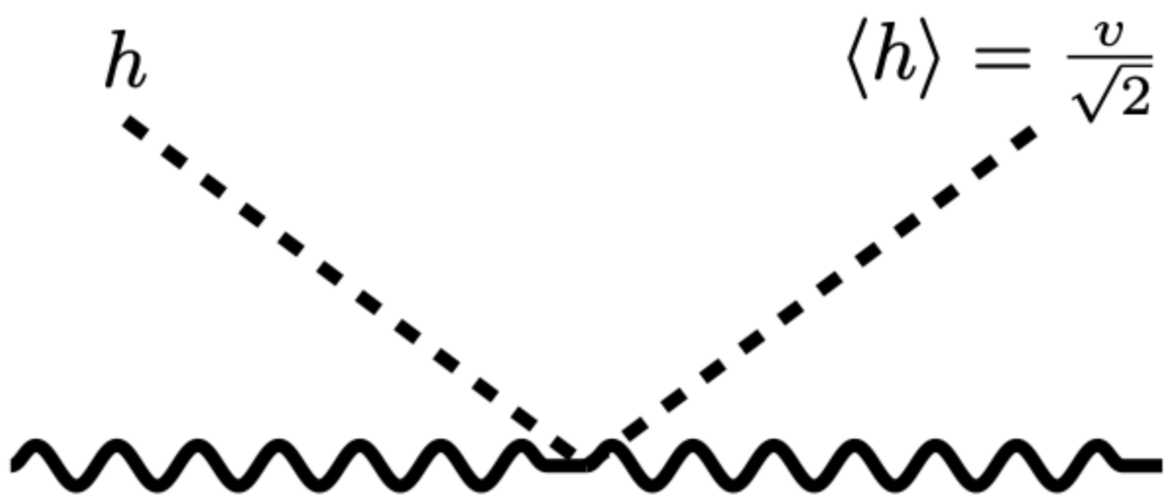

$g_{hhVV}/g_{hhVV}^{SM} = \kappa_{hhVV}$ $g_{hVV}/g_{hVV}^{SM} = \kappa_{hVV}$

Precision measurement of the SM electroweak breaking mechanism

Searching for the NP beyond the SM

- Com

✦ Extensions of the Higgs boson sector: Triplet Higgs boson model

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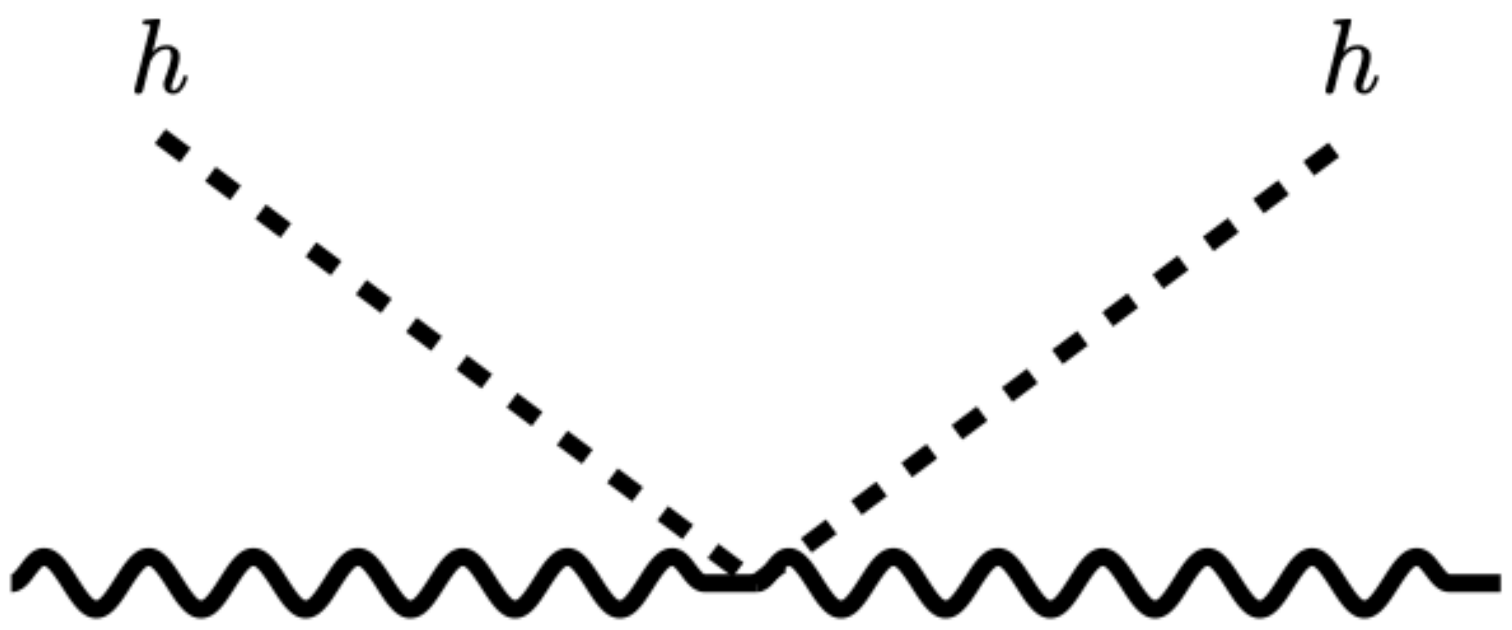
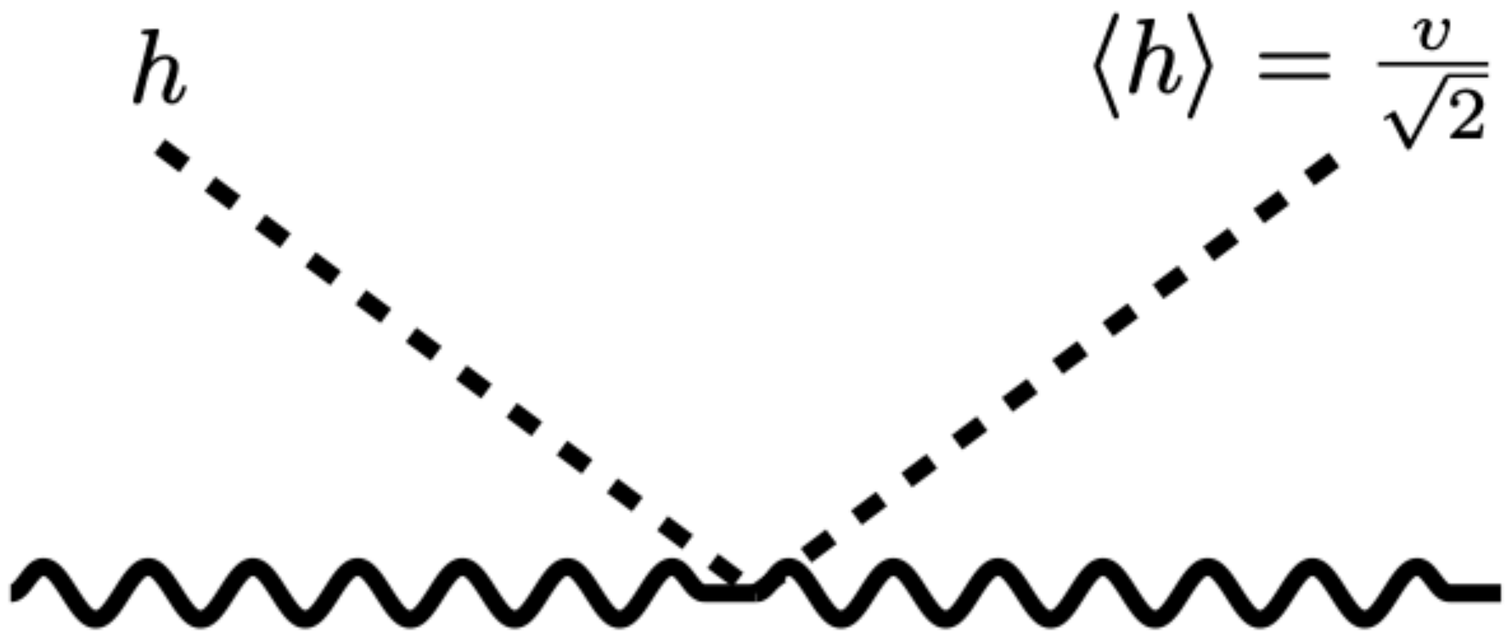
hhVV Coupling at the LHC

- κ_{hhVV} lies in the range [0, 2.1]; κ_{hVV} lies in the range [0.97, 1.13]; Phys. Rev. D 101, 012002 (2020), Phys. Rev. D 108 (2023) 052003

- The coupling κ_{hhVV} can be measured with a precision of 40 % at the HL-LHC using GNNs; JHEP2022,172, (2022)



$$g_{hhVV}/g_{hhVV}^{SM} = \kappa_{hhVV}$$



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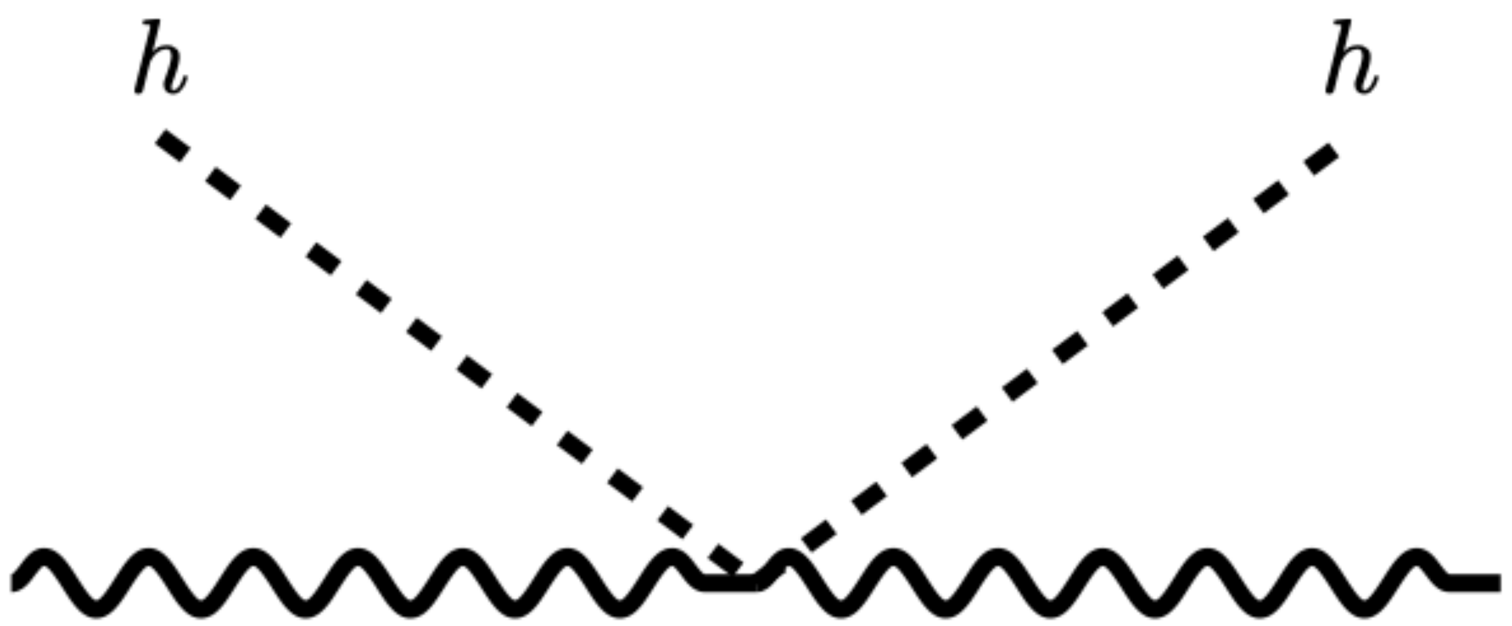

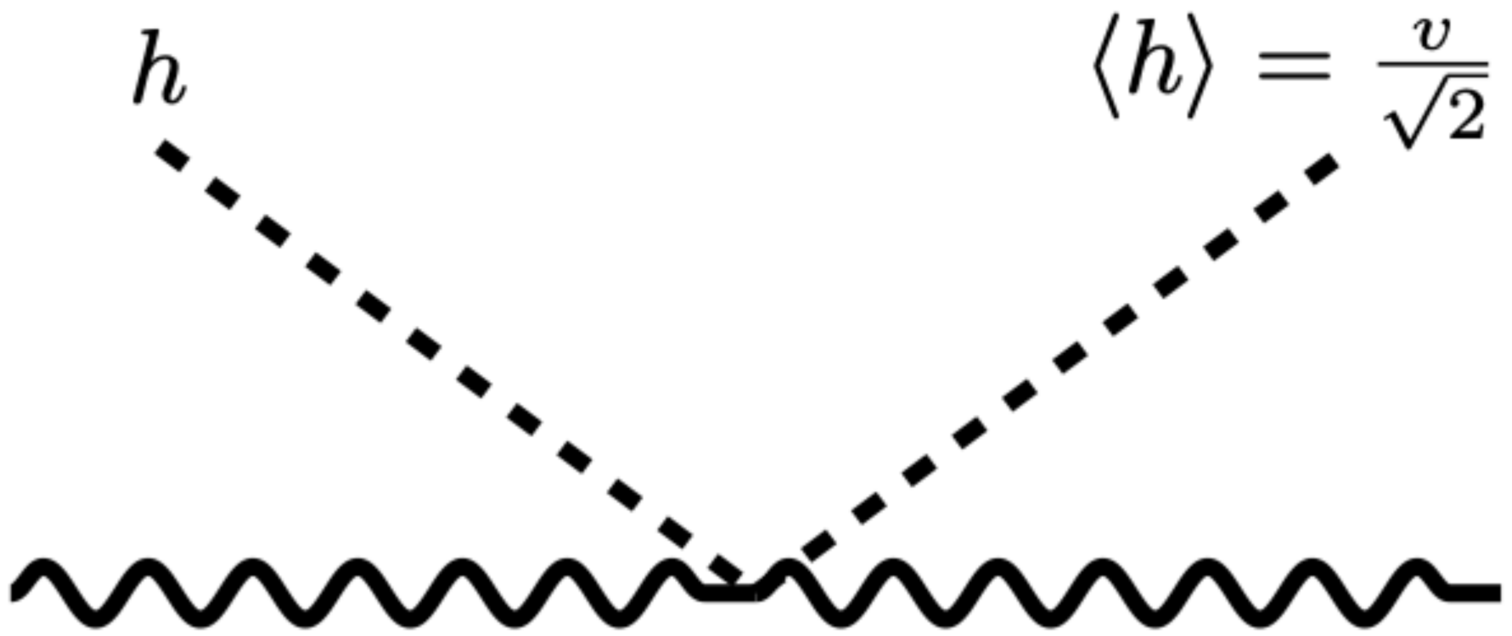

Why?

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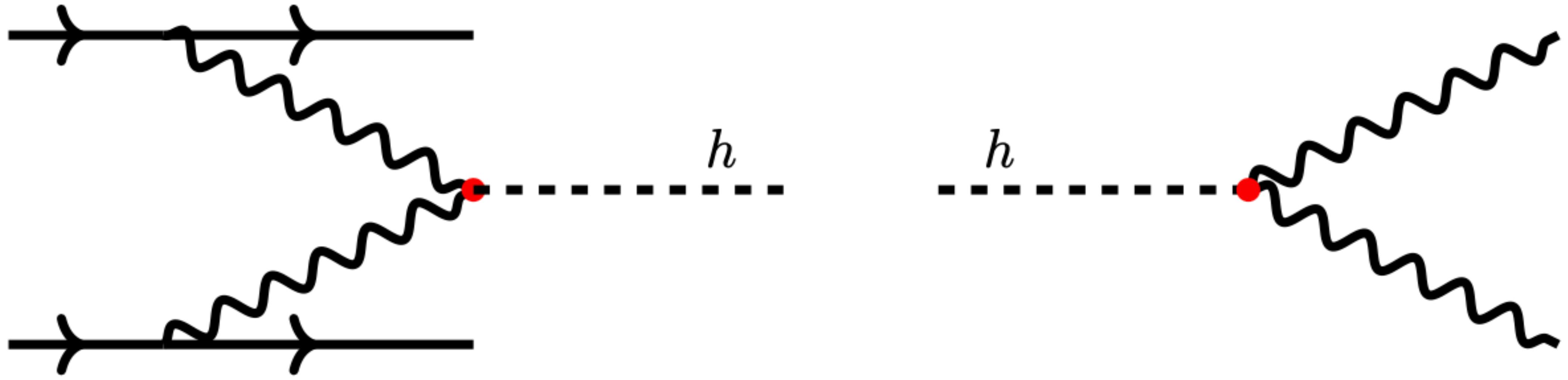
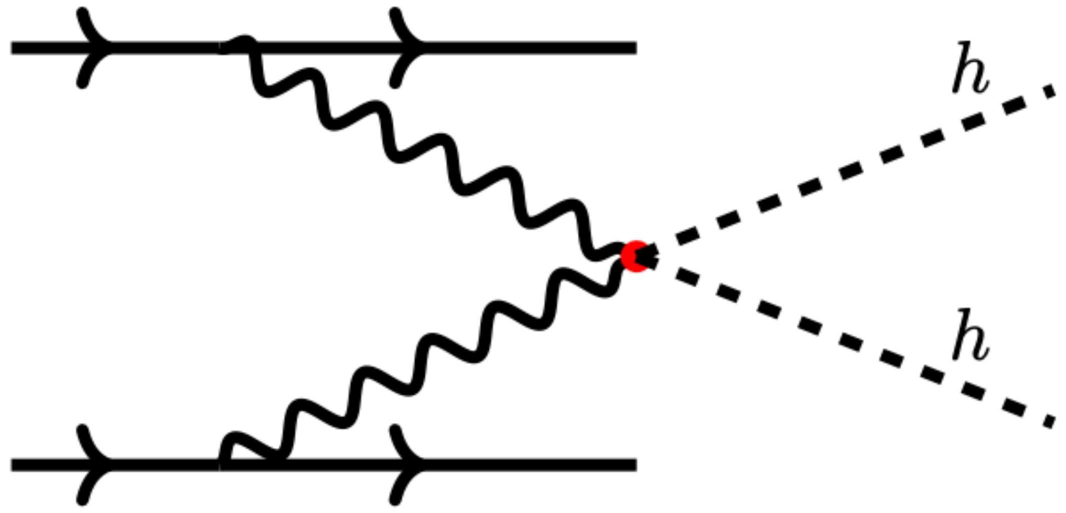
Comparison of hhVV and hVV Couplings at the LHC

- κ_{hVV} can be measured through single Higgs boson production and decay processes



- κ_{hhVV} can only be measured through di-Higgs boson production



$\sigma(pp \to jjh) \sim 3$ pb and $\sigma(pp \to jjhh) \sim 1.5$ fp at the 13 TeV LHC

- Gluon fusion dominates di-Higgs boson production at the LHC

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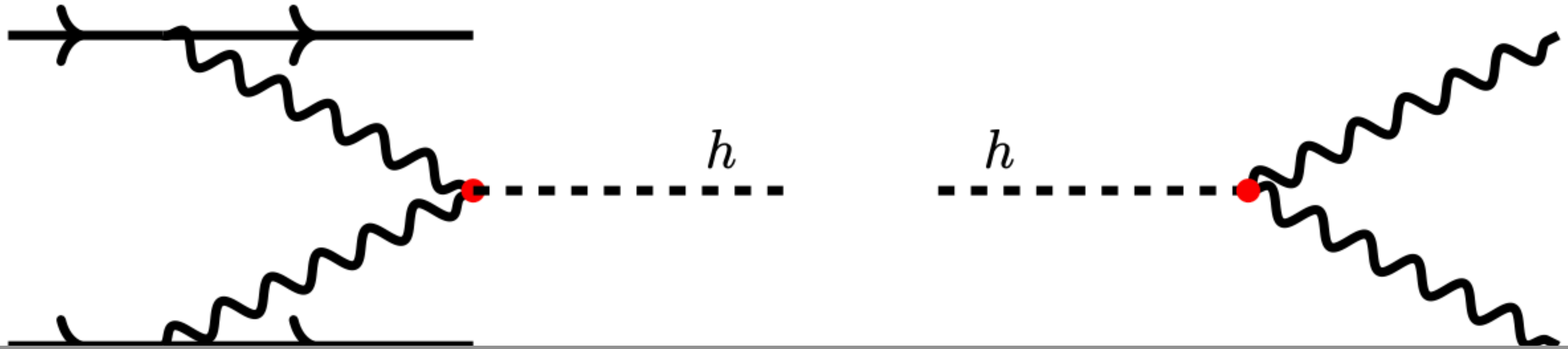
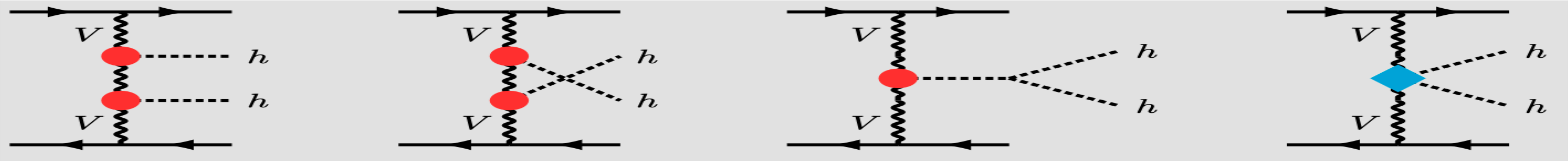


precision measurement requires a more clearer and higher energy collider

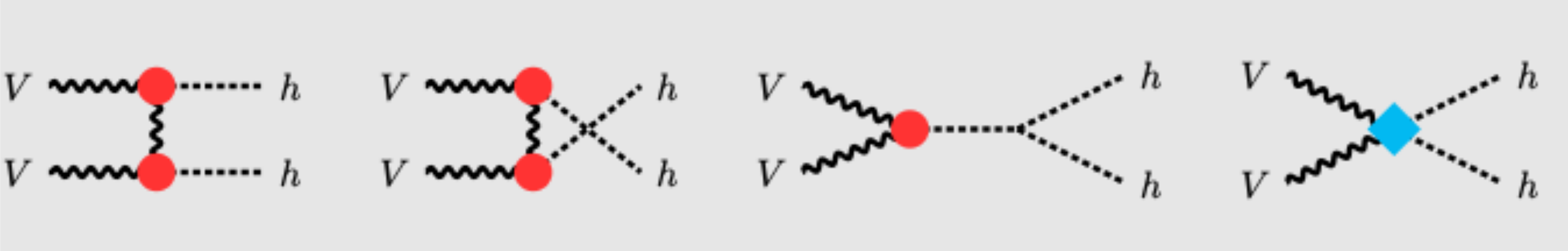
$\sigma(pp \to jjh) \sim 3$ pb and $\sigma(pp \to jjhh) \sim 1.5$ fp at the 13 TeV LHC

- Gluon fusion dominates di-Higgs boson production

Di-Higgs boson production at the lepton collider



Nucl. Phys. B 249, 42 (1985), J. High Energ. Phys. 2020, 80 (2020), JHEP 2022, 114 (2022)



- The subprocess $VV \to hh$ amplitude is sensitive to the κ_{hhWW} and κ_{hWW} couplings

$$M^{\mu\nu} = \left[\frac{3m_h^2 g_{hWW}}{(\hat{s} - m_h^2)v} + 2g_{hhWW} + \left(\frac{g_{hWW}^2}{\hat{t} - m_W^2} + \frac{g_{hWW}^2}{\hat{u} - m_W^2} \right) \right] g^{\mu\nu} - \frac{g_{hWW}^2}{m_W^2} \left[\frac{(q_1 - k_1)^\mu (q_1 - k_1)^\nu}{\hat{t} - m_W^2} + \frac{(q_1 - k_2)^\mu (q_1 - k_2)^\nu}{\hat{u} - m_W^2} \right]$$

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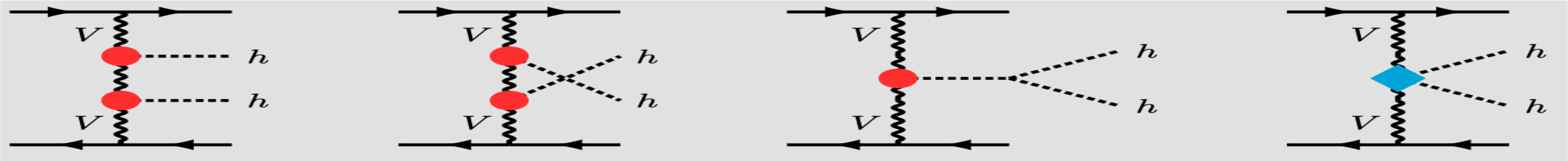
Di-Higgs boson production at the lepton colliders



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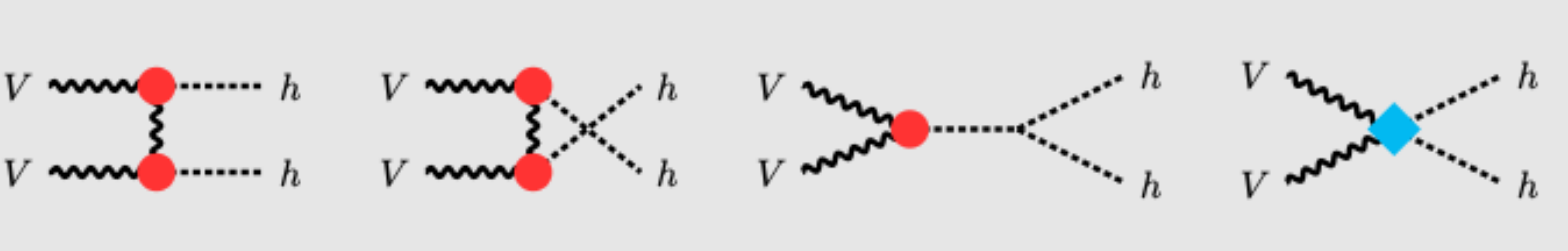

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$$M_{LL} = \frac{\hat{s}}{v^2}\left(\kappa_{hhWW} - \kappa_{hWW}^2\right) + \mathcal{O}(\hat{s}^0)$$

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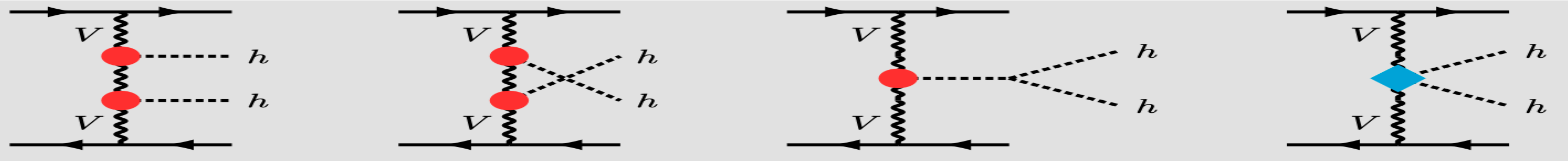

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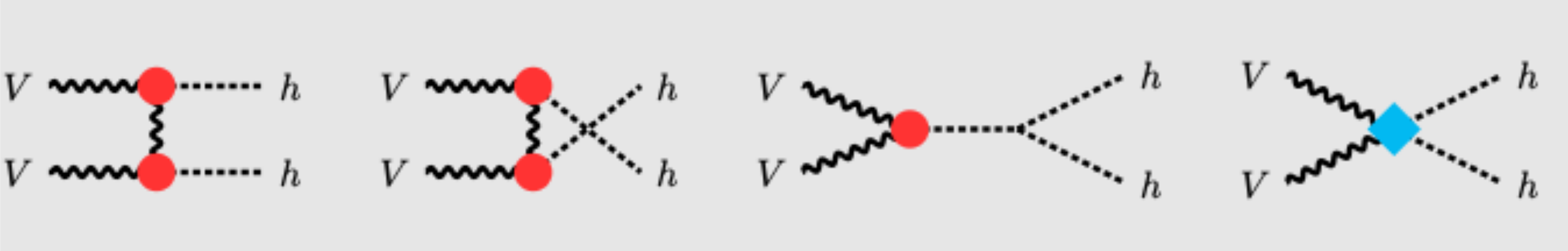
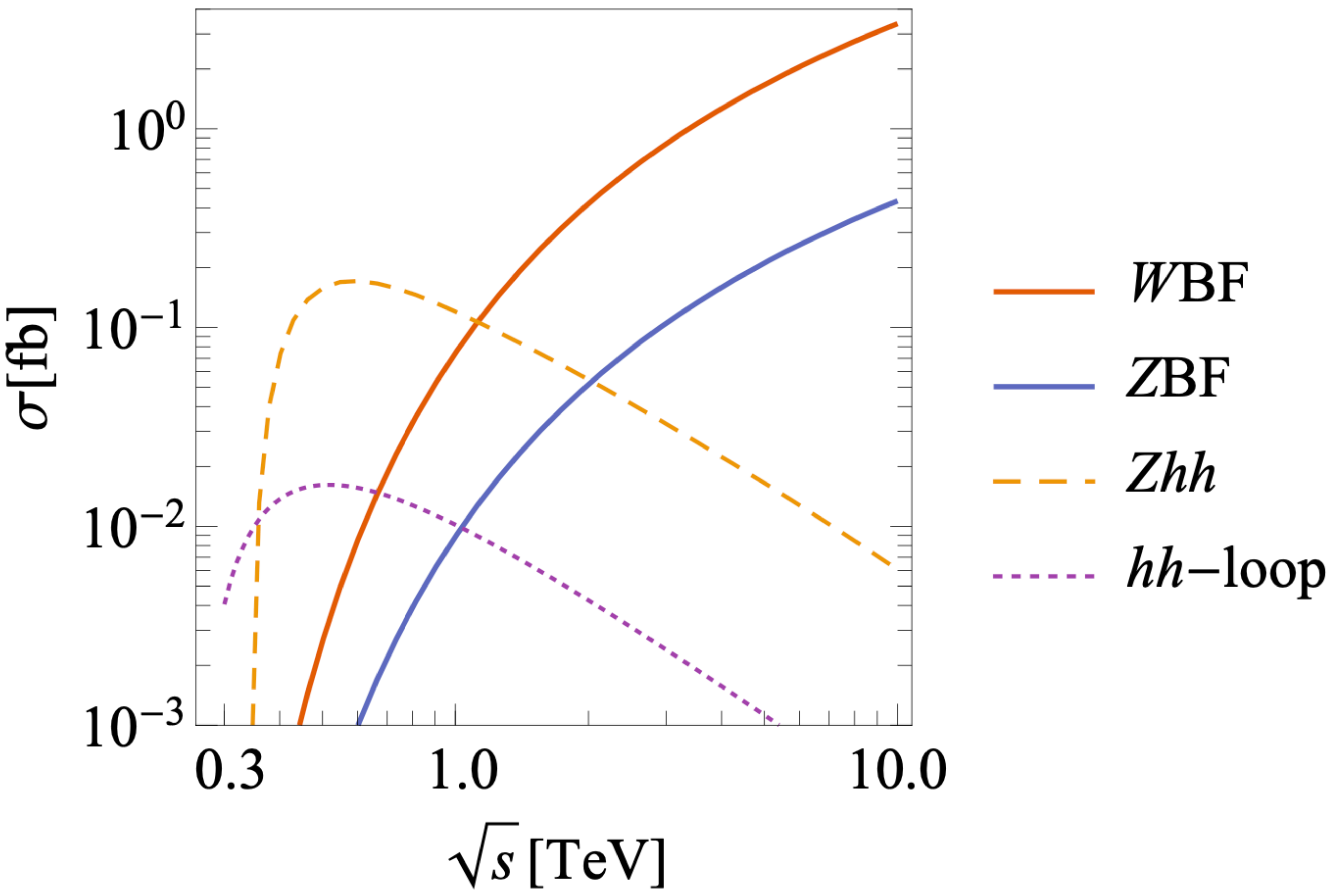


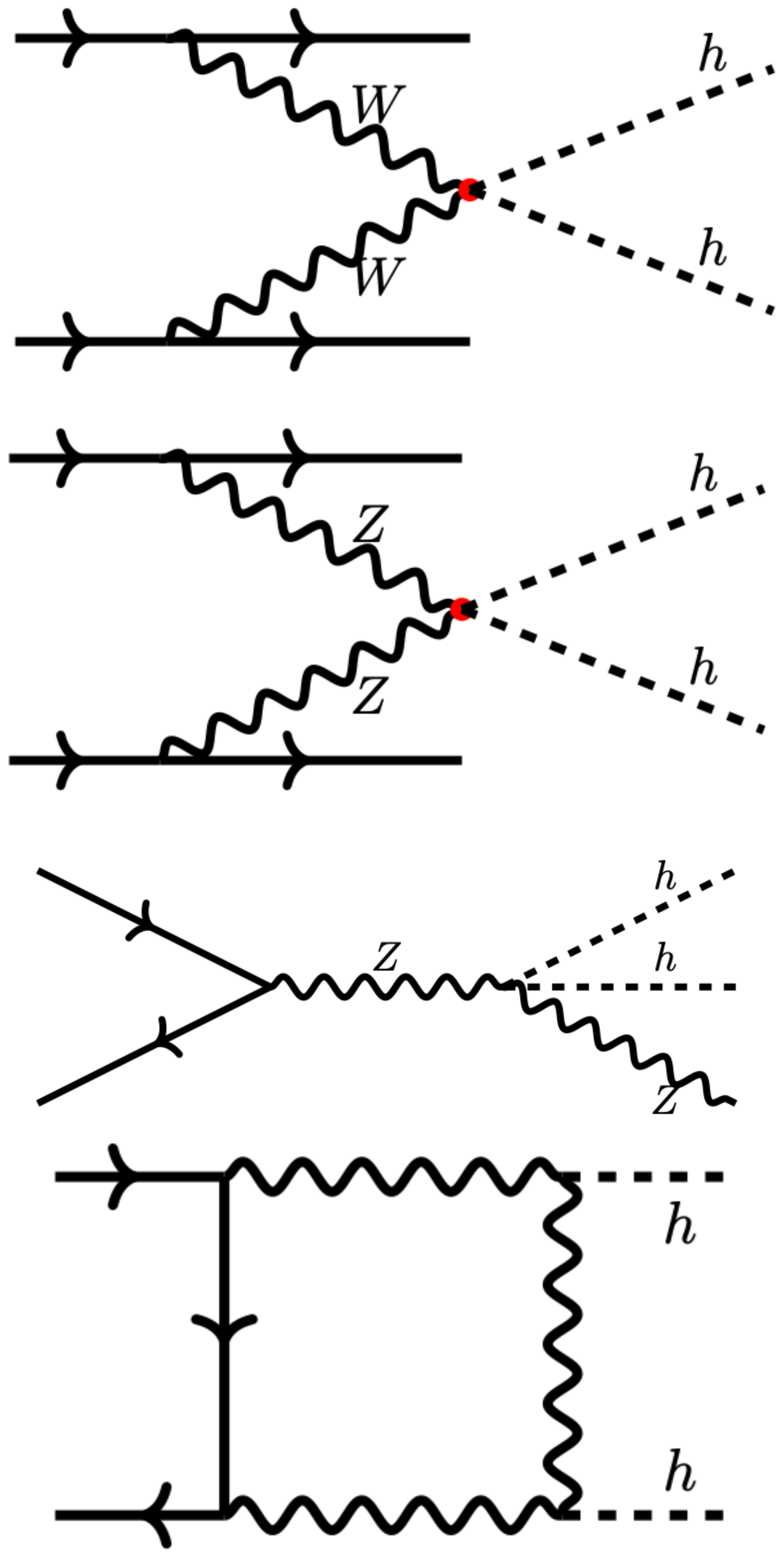
- The subprocess $VV \to hh$ amplitude is sensitive to the κ_{hhWW} and κ_{hWW} couplings

$$M_{LL} = \frac{\hat{s}}{v^2}\left(\kappa_{hhWW} - \kappa_{hWW}^2\right) + \mathcal{O}(\hat{s}^0)$$

- The coupling κ_{hWW} can be measured with a precision of 4% in single Higgs boson production; arXiv:2207.03862

Di-Higgs Boson Production at Lepton Colliders





$\log s/m_V^2$

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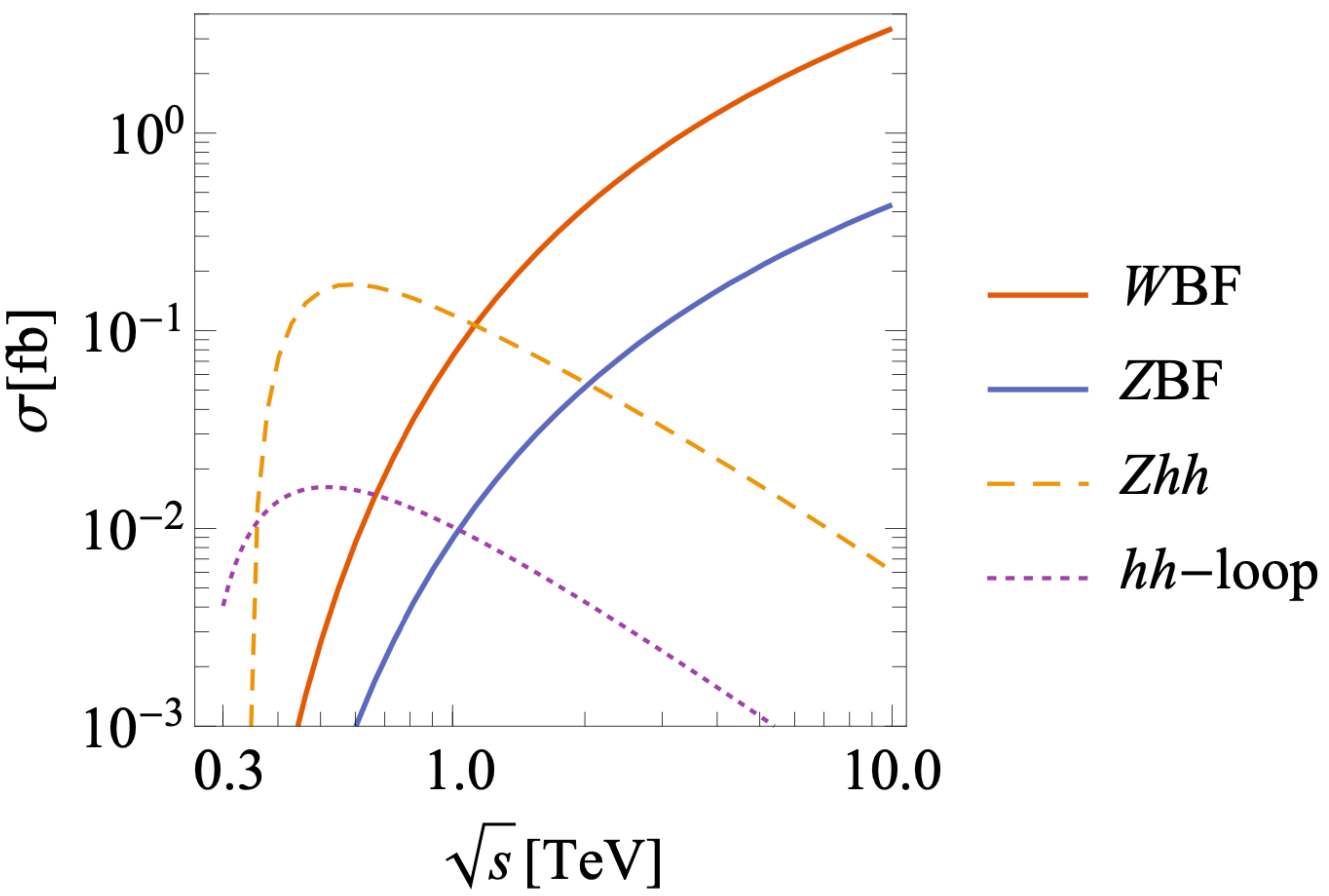
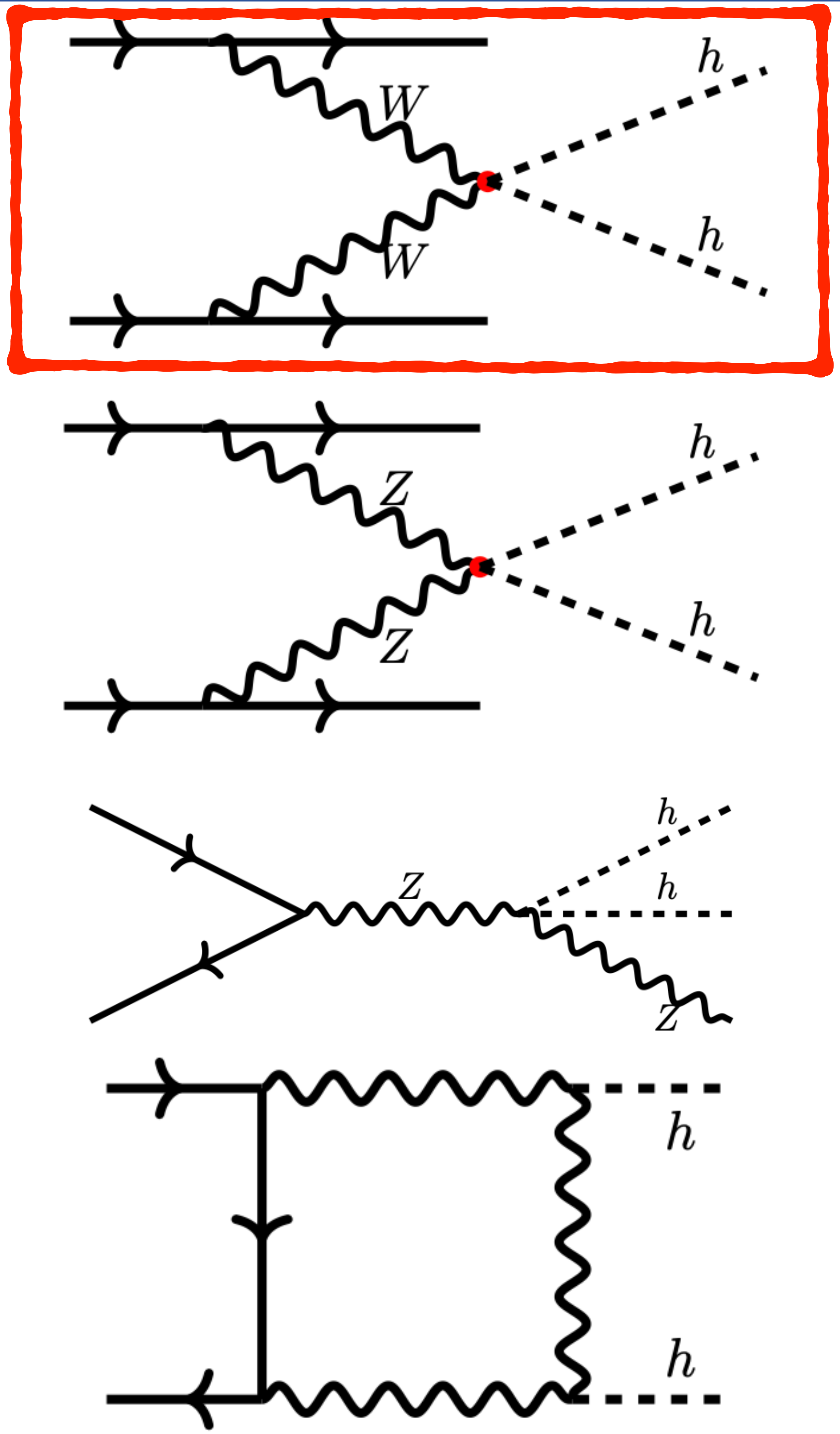
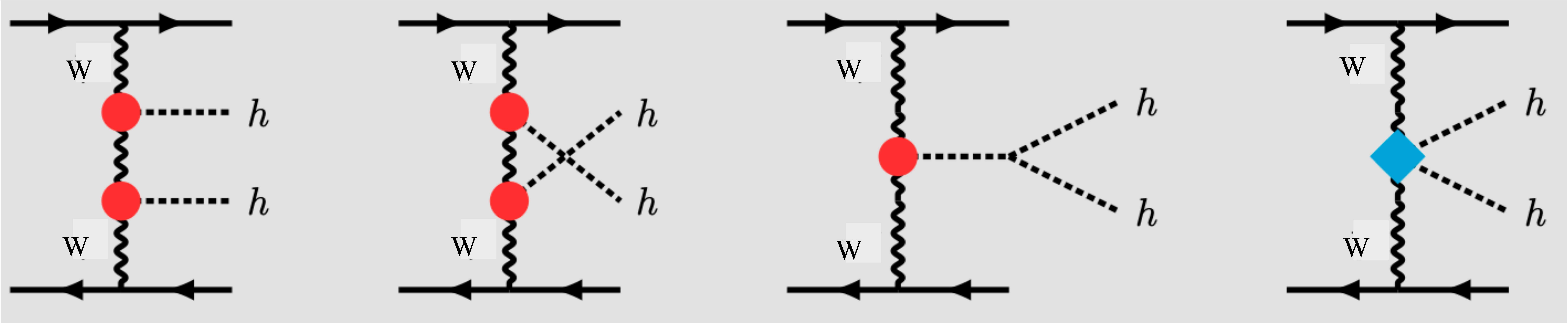
Di-Higgs Boson Production at Lepton Colliders





Di-Higgs Boson Production Rate at a 10 TeV Muon Collider



$$\sigma^{hh} = 177.2\kappa_{hhww}^2 + 206.1\kappa_{hww}^4 + 0.88\kappa_{hww}^2$$
$$-378.1\kappa_{hhww}\kappa_{hww}^2 - 12.11\kappa_{hww}^3 + 9.08\kappa_{hhww}\kappa_{hww}$$

Collider Simulation at a 10 TeV Muon Collider

- Signal $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu h(\to b\bar{b})h(\to b\bar{b}) \Rightarrow$ 4b-Jets $+ \not{E}$

- Backgrounds:

✦ $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu h(\to b\bar{b})Z(\to b\bar{b})$ $\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu Z(\to b\bar{b})Z(\to b\bar{b})$

✦ $\mu^\pm\gamma \to h(\to b\bar{b})W^\pm(\to jj)\nu_\mu(\bar{\nu}_\mu)$ $\mu^\pm\gamma \to Z(\to b\bar{b})W^\pm(\to jj)\nu_\mu(\bar{\nu}_\mu)$

✦ $\mu^+\mu^- \to Z(\to b\bar{b})Z(\to b\bar{b})$ $\mu^+\mu^- \to Z(\to b\bar{b})h(\to b\bar{b})$

$$p_{b\to b} = 0.9, \quad p_{c\to b} = 0.3, \quad p_{j\to b} = 0.05$$

Cuts Flow at the 10 TeV Muon Collider

- Pre-selection cuts:
  $n^{\ell}(p_T > 10 \text{ GeV}) = 0, \not{E} > 10\text{GeV},$
  $p_T^{jet} > 15 \text{ GeV}, \ -4.0 < \eta^{jet} < 4.0, \ \Delta R^{mn} > 0.5$

- Higgs Boson mass window:
  $100 \text{ GeV} < m_{bb} < 150 \text{ GeV}$

- Di-Higgs Boson Selection:
  $$\chi^2(m_1, m_2) \equiv \min_{i,j,k,l} \left[(m_{b_i b_j} - m_1)^2 + (m_{b_k b_l} - m_2)^2 \right],$$
  $$\chi^2(m_h, m_h) < \chi^2(m_Z, m_Z), \quad \chi^2(m_h, m_h) < \chi^2(m_h, m_Z)$$

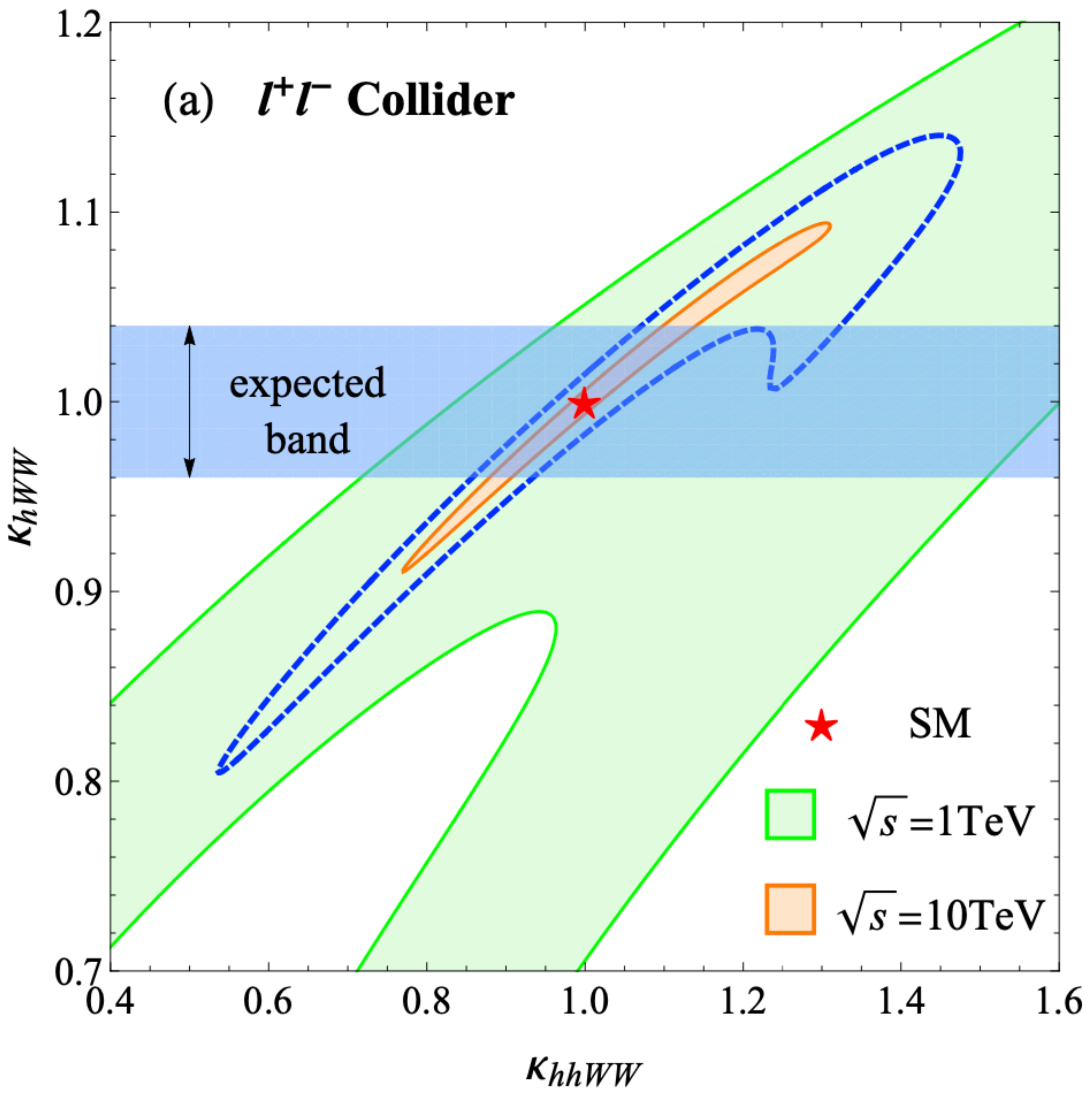
- Missing energy cut:
  $$M_{\text{recoil}} \equiv \sqrt{(p_1 + p_2 - p_{h_1} - p_{h_2})^2} \quad M_{\text{recoil}} \geq 200 \text{ GeV}$$

$\mathscr{L} = 3 \text{ ab}^{-1}$

σ [ab]	pre-cuts	m_{bb} cut	HHCUT	M_{recoil} cut
Sig.	484.4	261.5	226.5	226.3
$\nu\nu hZ$	1163.1	168.6	97.8	97.6
$\nu\nu ZZ$	1557.9	121.2	36.7	36.6
$\nu W^{\pm} h$	560.7	26.2	17.2	17.2
$\nu W^{\pm} Z$	492.3	12.3	9.3	9.3
Bkg.	-	-	-	160.7

$\kappa_{hhWW} = \kappa_{hWW} = 1$

Discovery and Exclusion Potential on κ_{hhWW}



$0.96 < \kappa_{hww} < 1.04$; arXiv:2207.03862

- 5σ discovery region
  $\kappa_{hhww} < 0.86$ or $\kappa_{hhww} > 1.32$
- 2σ exclusion region
  $\kappa_{hhww} < 0.88$ or $\kappa_{hhww} > 1.14$

谢谢！