di-Higgs day

Di-Higgs bosons in the SM

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Konkuk University, 2019.6.27

References

PHYSICAL REVIEW D **87,** 014007 (2013)

Unravelling an extended quark sector through multiple Higgs production?

S. Dawson, E. Furlan, and I. Lewis

Higgs boson pair production in new physics models at hadron, lepton, and photon colliders

Eri Asakawa,[1,*] Daisuke Harada,[2,3,†] Shinya Kanemura,[4,‡]
Yasuhiro Okada,[2,3,§] and Koji Tsumura[5,¶]

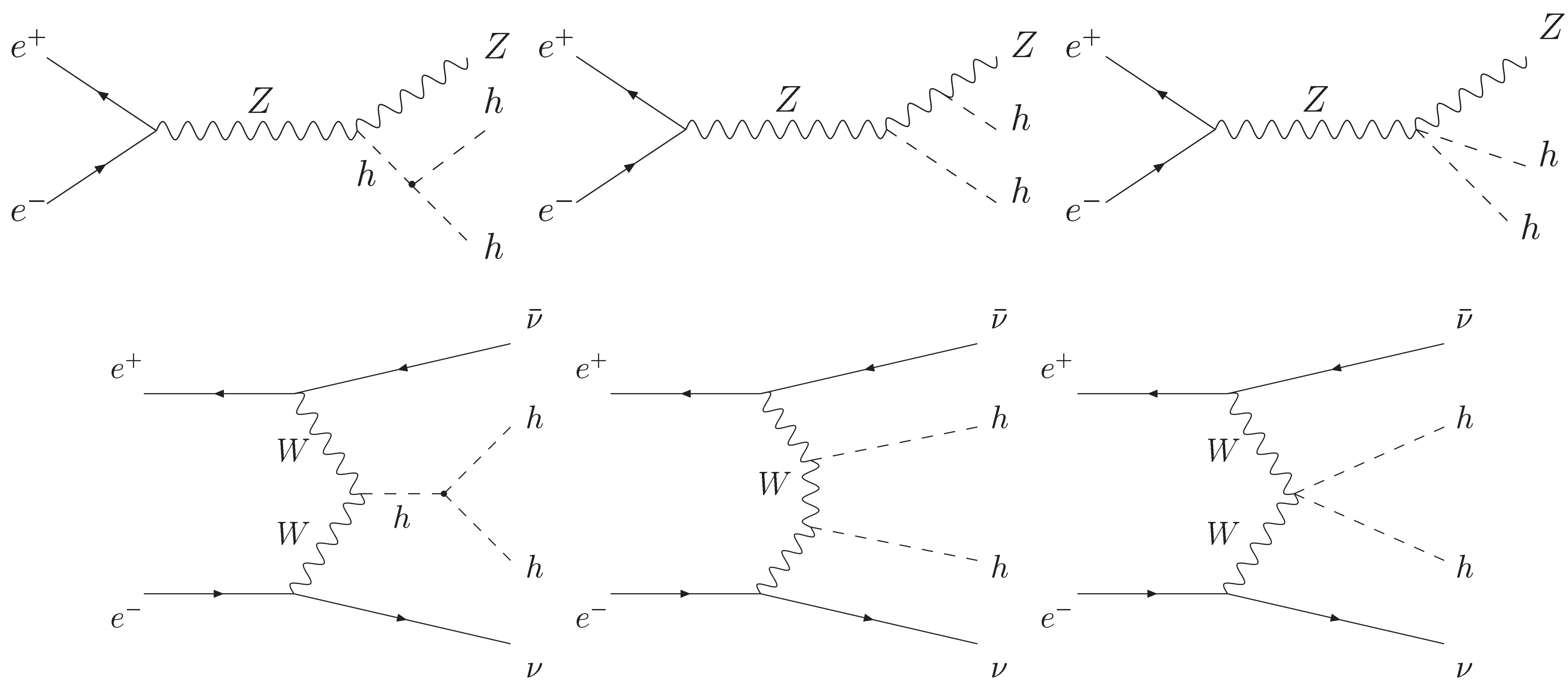
Higgs triple coupling

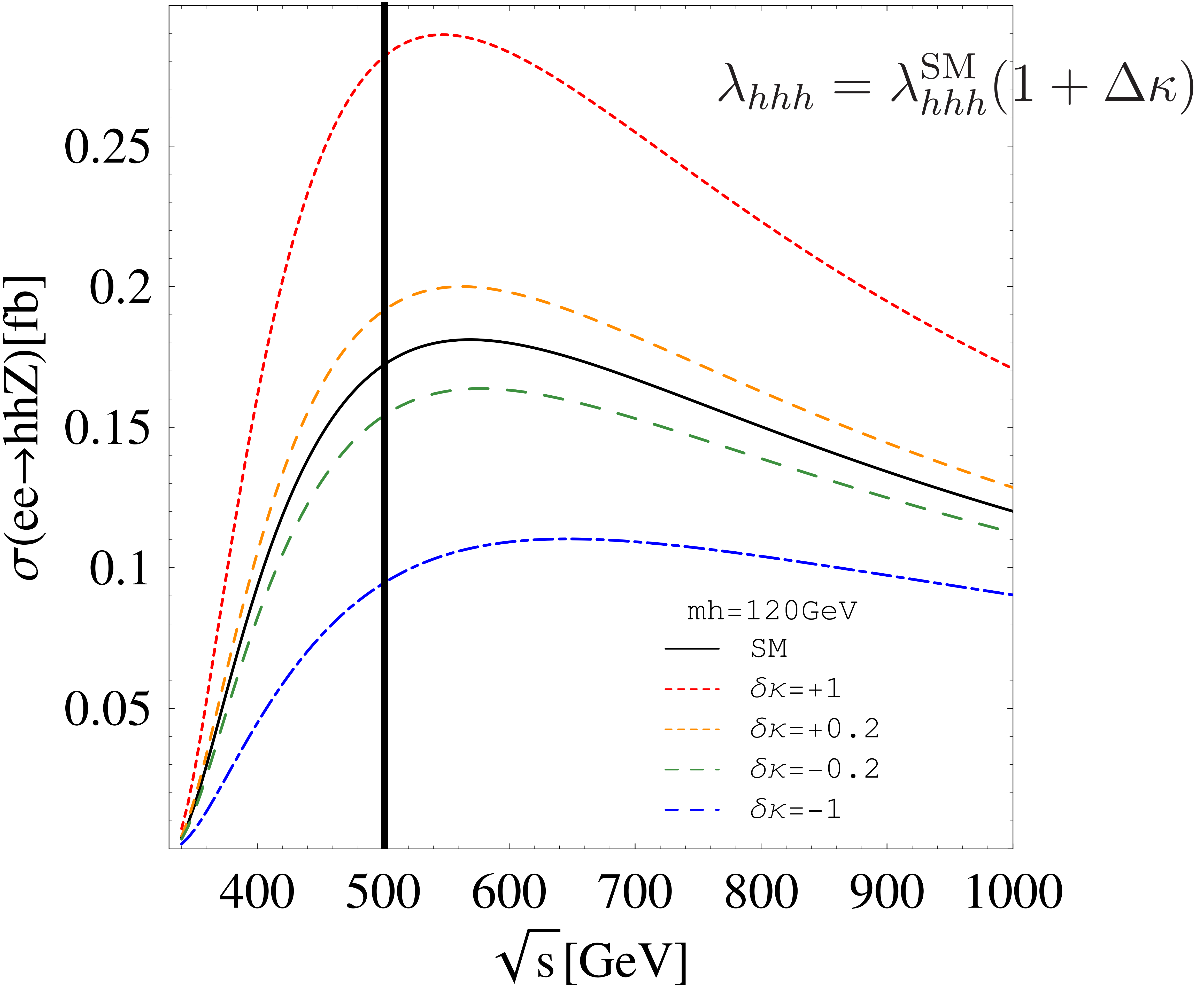
$$\lambda_{hhh}^{\text{SM}} = -3m_h^2/v \text{ at the tree level}$$

At the one-loop order, the effective hhh vertex function

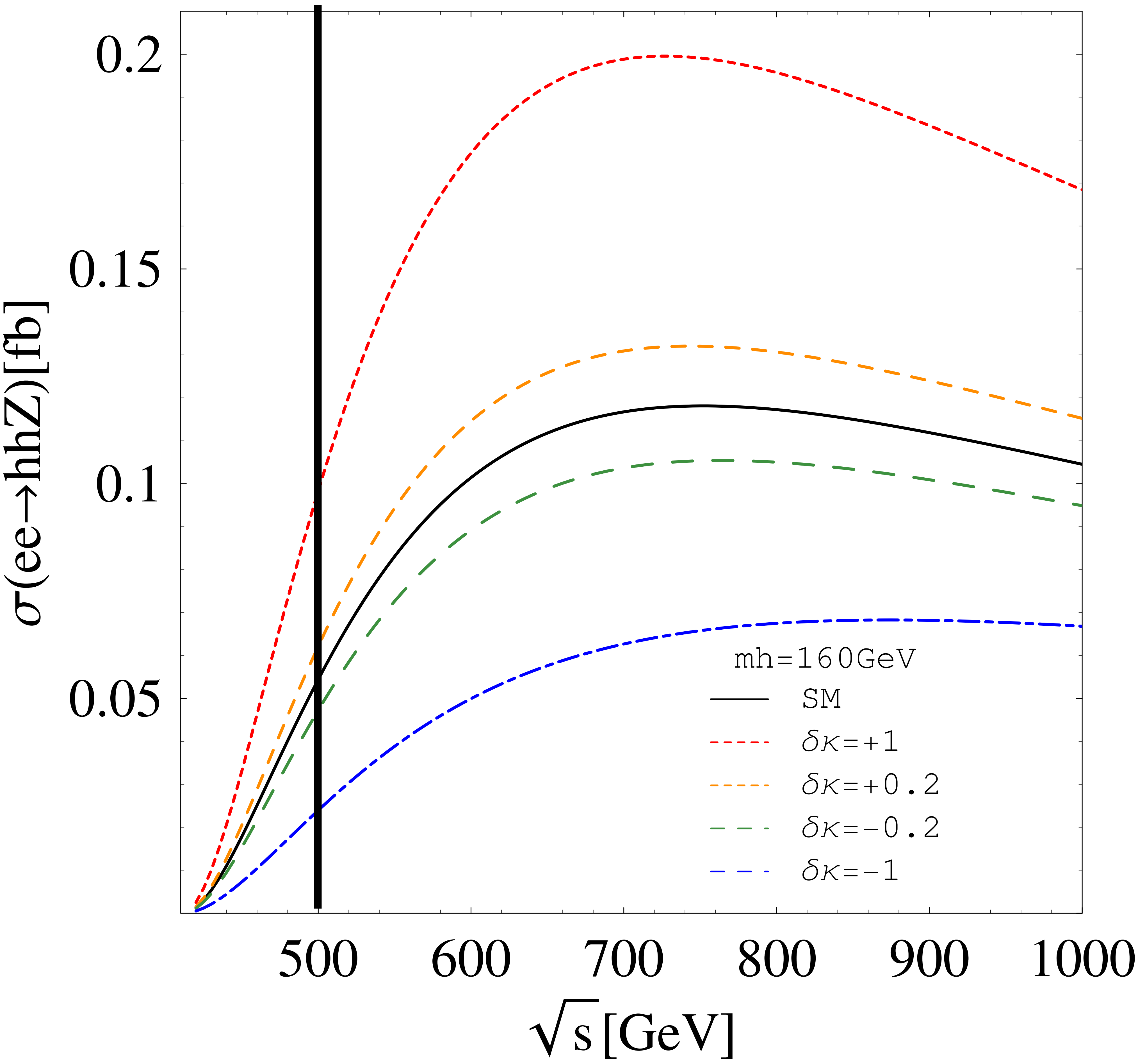
$$\Gamma_{hhh}^{\text{SM}}(\hat{s}, m_h^2, m_h^2) \simeq -\frac{3m_h^2}{v}\left\{1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\left[1 + \mathcal{O}\left(\frac{m_h^2}{m_t^2}, \frac{\hat{s}}{m_t^2}\right)\right]\right\}$$

The double Higgs boson production at the e+e− collider



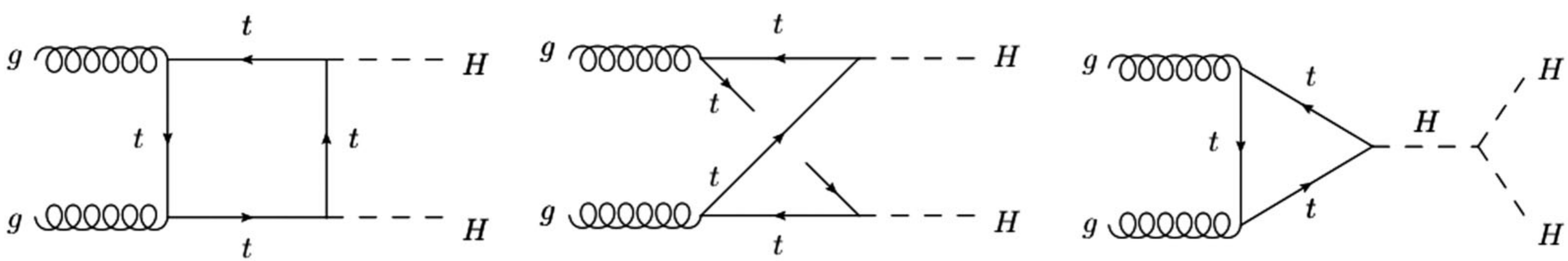


$\lambda_{hhh} = \lambda_{hhh}^{\rm SM}(1+\Delta\kappa)$
0.25
0.2
0.15
0.1
0.05
σ(ee→hhZ)[fb]
400
500
600
700
800
900
1000
$\sqrt{s}$[GeV]
mh=120GeV
SM
δκ=+1
δκ=+0.2
δκ=-0.2
δκ=-1



0.2
0.15
0.1
0.05
σ(ee→hhZ)[fb]
500
600
700
800
900
1000
√s [GeV]
mh=160GeV
SM
δκ=+1
δκ=+0.2
δκ=-0.2
δκ=-1

The double Higgs boson production at the LHC



The amplitude for $g^{a,\mu}(p_1)g^{b,\nu}(p_2) \longrightarrow H(p_3)H(p_4)$

$$A^{\mu\nu}_{ab} = \frac{\alpha_s}{8\pi v^2}\delta_{ab}[P_1^{\mu\nu}(p_1, p_2)F_1(s, t, u, m_t^2) + P_2^{\mu\nu}(p_1, p_2, p_3)F_2(s, t, u, m_t^2)],$$

$$P_1^{\mu\nu}(p_1, p_2) = g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{p_1 \cdot p_2},$$

Projection op. for spin-0

$$P_2^{\mu\nu}(p_1, p_2, p_3) = g^{\mu\nu} + \frac{2}{s p_T^2}(m_H^2 p_1^\nu p_2^\mu - 2p_1.p_3 p_2^\mu p_3^\nu - 2p_2.p_3 p_1^\nu p_3^\mu + s p_3^\mu p_3^\nu);$$

Projection op. for spin-2

partonic cross section

$$\frac{d\hat{\sigma}(gg \rightarrow HH)}{dt} = \frac{\alpha_s^2}{2^{15}\pi^3 v^4} \frac{|F_1(s,t,u,m_t^2)|^2 + |F_2(s,t,u,m_t^2)|^2}{s^2},$$

In the SM, the top quark contribution is dominant.

LET (Low energy theorem) : $m_t^2 \gg s$

Projection for spin-0

$$F_1(s,t,u,m_t^2) \equiv F_1^{\text{tri}}(s,t,u,m_t^2) + F_1^{\text{box}}(s,t,u,m_t^2),$$

$$F_1^{\text{tri}}(s,t,u,m_t^2) = \frac{4m_H^2}{s-m_H^2}s\left\{1+\frac{7}{120}\frac{s}{m_t^2}+\frac{1}{168}\frac{s^2}{m_t^4}+\mathcal{O}\left(\frac{s^3}{m_t^6}\right)\right\},$$

$$F_1^{\text{box}}(s,t,u,m_t^2) = -\frac{4}{3}s\left\{1+\frac{7}{20}\frac{m_H^2}{m_t^2}+\frac{90m_H^4-28m_H^2s+12s^2-13p_T^2s}{840m_t^4}+\mathcal{O}\left(\frac{s^3}{m_t^6}\right)\right\};$$

LET (Low energy theorem) : $m_t^2 \gg s$

Projection for spin-0

$$F_1(s,t,u,m_t^2) \equiv F_1^{\rm tri}(s,t,u,m_t^2) + F_1^{\rm box}(s,t,u,m_t^2),$$

$$F_1^{\rm tri}(s,t,u,m_t^2) = \frac{4m_H^2}{s-m_H^2}\, s\left\{1 + \frac{7}{120}\frac{s}{m_t^2} + \frac{1}{168}\frac{s^2}{m_t^4} + \mathcal{O}\left(\frac{s^3}{m_t^6}\right)\right\},$$

$$F_1^{\rm box}(s,t,u,m_t^2) = -\frac{4}{3}\, s\left\{1 + \frac{7}{20}\frac{m_H^2}{m_t^2} + \frac{90m_H^4 - 28m_H^2 s + 12s^2 - \boxed{13p_T^2 s}}{840m_t^4} + \mathcal{O}\left(\frac{s^3}{m_t^6}\right)\right\};$$

Triangle diagram (Higgs triple coupling): No angular dependence

Box diagram (Higgs triple coupling): angular dependence in mt^(-4)

$$F_1^{\rm box}(s,t,u,m_t^2) = -\frac{4}{3}s\left[\left(1+\frac{7}{20}\frac{m_H^2}{m_t^2}+\frac{540m_H^4-116m_H^2s+59s^2}{5040m_t^4}\right)d^0_{0,0}(\theta)\right.$$

$$\left.+\frac{13s^2-52m_H^2s}{5040m_t^4}d^2_{0,0}(\theta)+\mathcal{O}\left(\frac{s^3}{m_t^6}\right)\right],$$

$$F_2^{\rm box}(s,t,u,m_t^2) = -\frac{11}{45}s\frac{s-4m_H^2}{\sqrt{6}m_t^2}\left[1+\frac{62m_H^2-5s}{154m_t^2}+\mathcal{O}\left(\frac{s^2}{m_t^4}\right)\right]d^2_{2,0}(\theta).$$

Wigner d-functions, $d^j_{s_i,s_f}$

j is the total angular

s_i (s_f) is the initial (final) state spin:

$$F_2(s,t,u,m_t^2) = -\frac{11}{45}\, s\, \frac{p_T^2}{m_t^2} \left\{ 1 + \frac{62 m_H^2 - 5s}{154 m_t^2} + \mathcal{O}\left(\frac{s^2}{m_t^4}\right) \right\}.$$

Angular dependence

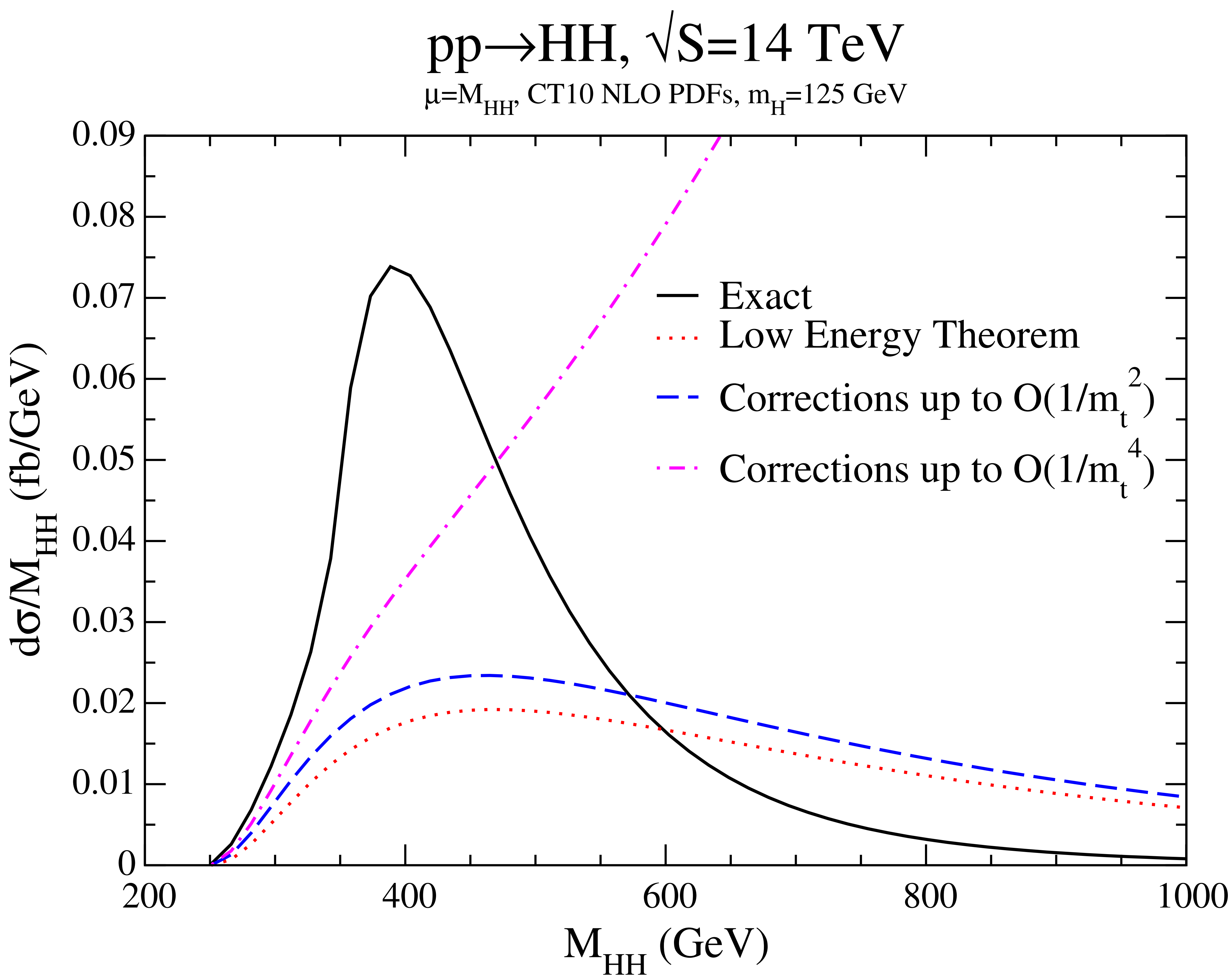
At leading order,

Box **Triangle**

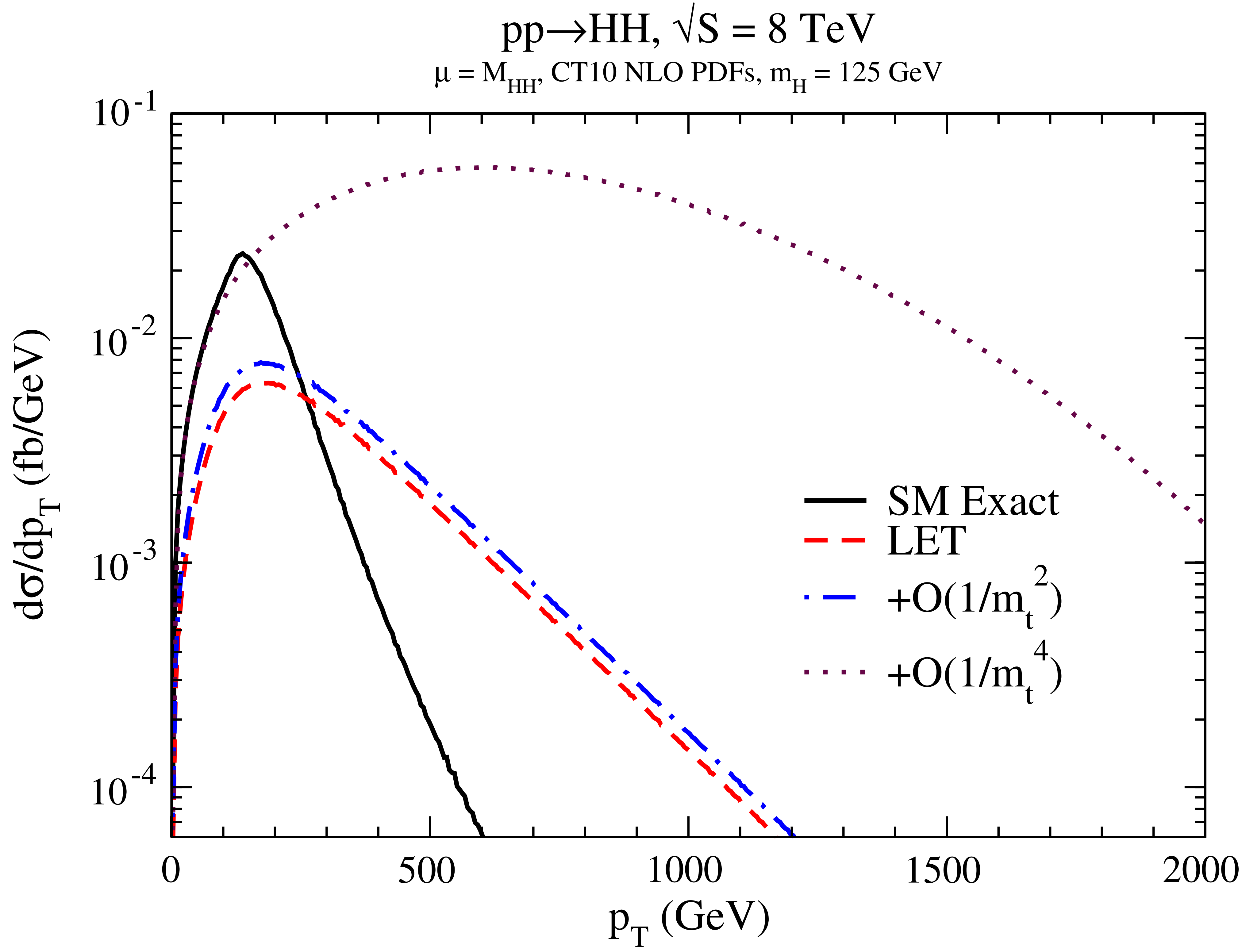
$$F_1(s,t,u,m_t^2)|_{\text{LET}} \longrightarrow \left(-\frac{4}{3} + \frac{4m_H^2}{s - m_H^2}\right) s,$$

$$F_2(s,t,u,m_t^2)|_{\text{LET}} \longrightarrow 0.$$

LET is a poor approximation for di-Higgs

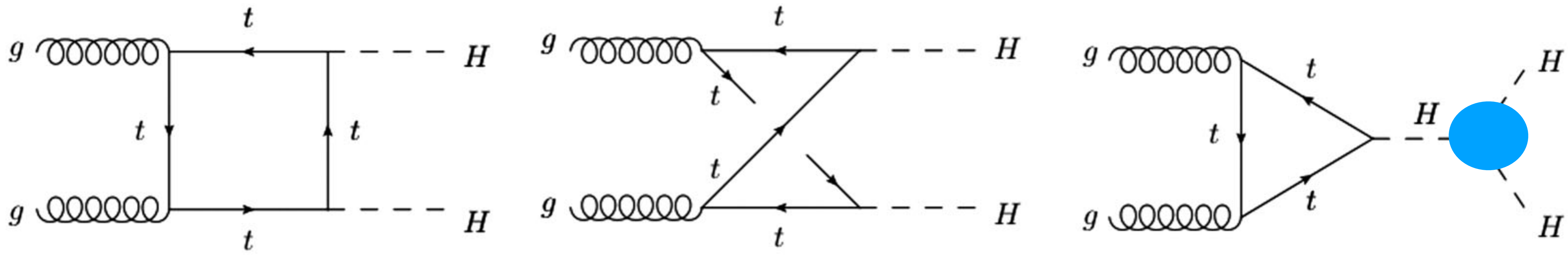


pp→HH, √S=14 TeV
μ=M_HH, CT10 NLO PDFs, m_H=125 GeV
dσ/M_HH (fb/GeV)
M_HH (GeV)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
200
400
600
800
1000
Exact
Low Energy Theorem
Corrections up to O(1/m_t^2)
Corrections up to O(1/m_t^4)

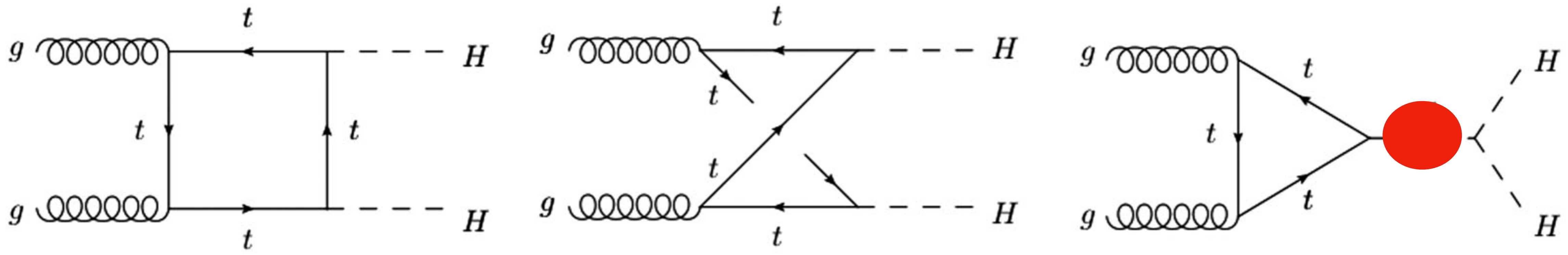


pp→HH, √S = 8 TeV
μ = M_HH, CT10 NLO PDFs, m_H = 125 GeV
10^-1
10^-2
10^-3
10^-4
dσ/dp_T (fb/GeV)
0
500
1000
1500
2000
p_T (GeV)
SM Exact
LET
+O(1/m_t^2)
+O(1/m_t^4)

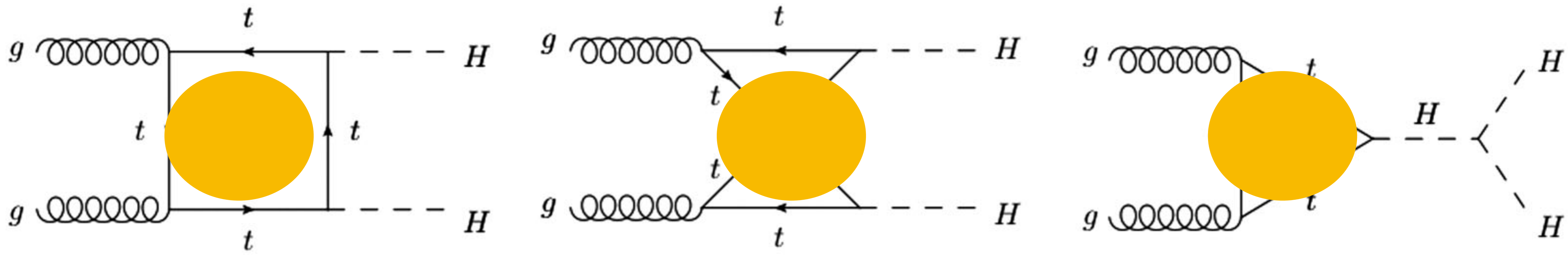
How to deviate the SM result for the gluon fusion?



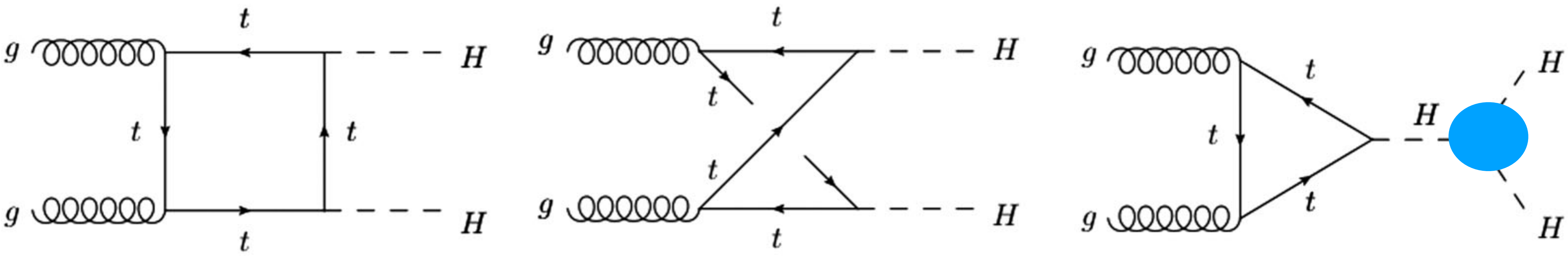
1. New λ_{hhh}
2. New Scalar
3. New colored fermions



1. New λ_{hhh}
2. New Scalar
3. New colored fermions



1. New λ_{hhh}
2. New Scalar
3. New colored fermions



2HDM

Two Higgs doublets

$$\Phi_1 \text{ and } \Phi_2$$

In order to suppress FCNC at tree level,
we impose Z2 symmetry

$$\Phi_1 \rightarrow \Phi_1 \quad \text{and} \quad \Phi_2 \rightarrow -\Phi_2$$

Higgs potential

Softly broken Z2

$$\begin{aligned} V = \quad & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \mathrm{H.c.}) \\ & + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + \mathrm{H.c.} \right] \end{aligned}$$

Alignment limit

$$H^{\mathrm{SM}} = s_{\beta-\alpha} h^0 + c_{\beta-\alpha} H^0$$

For $h^0 = h_{125}$

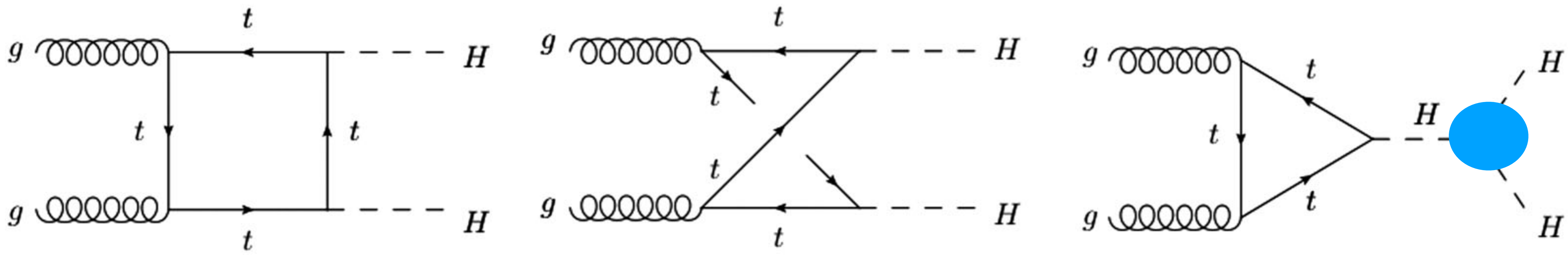
$$s_{\beta-\alpha} = 1$$

$\sin(\beta - \alpha)$: $g_{hW^+W^-}$, g_{hZZ}, g_{ZAH}, $g_{W^\pm H^\mp H}$,

$\cos(\beta - \alpha)$: $g_{HW^+W^-}$, g_{HZZ}, g_{ZAh}, $g_{W^\pm H^\mp h}$, g_{Hhh}.

ZERO!

No resonance decay into hh!

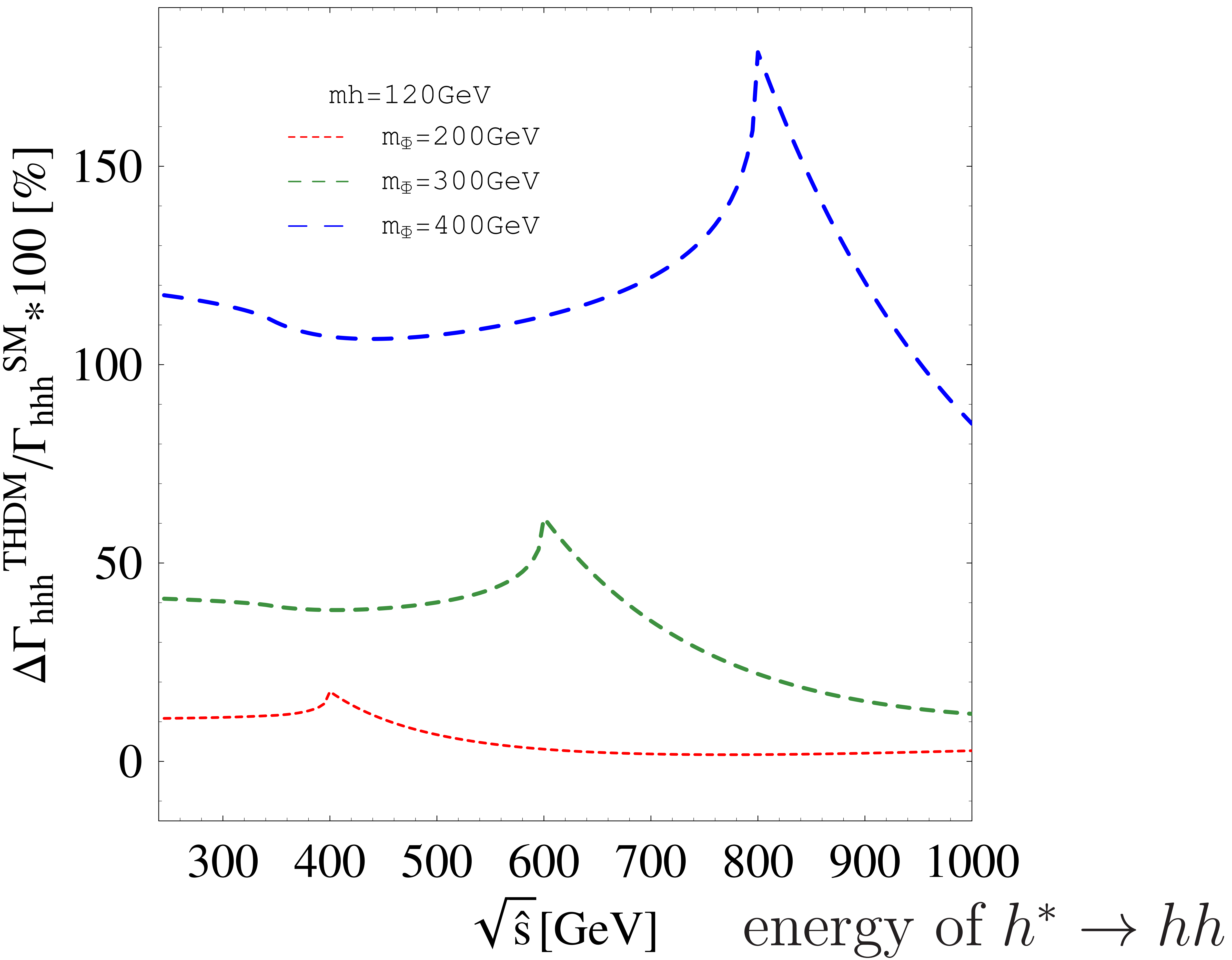


2HDM

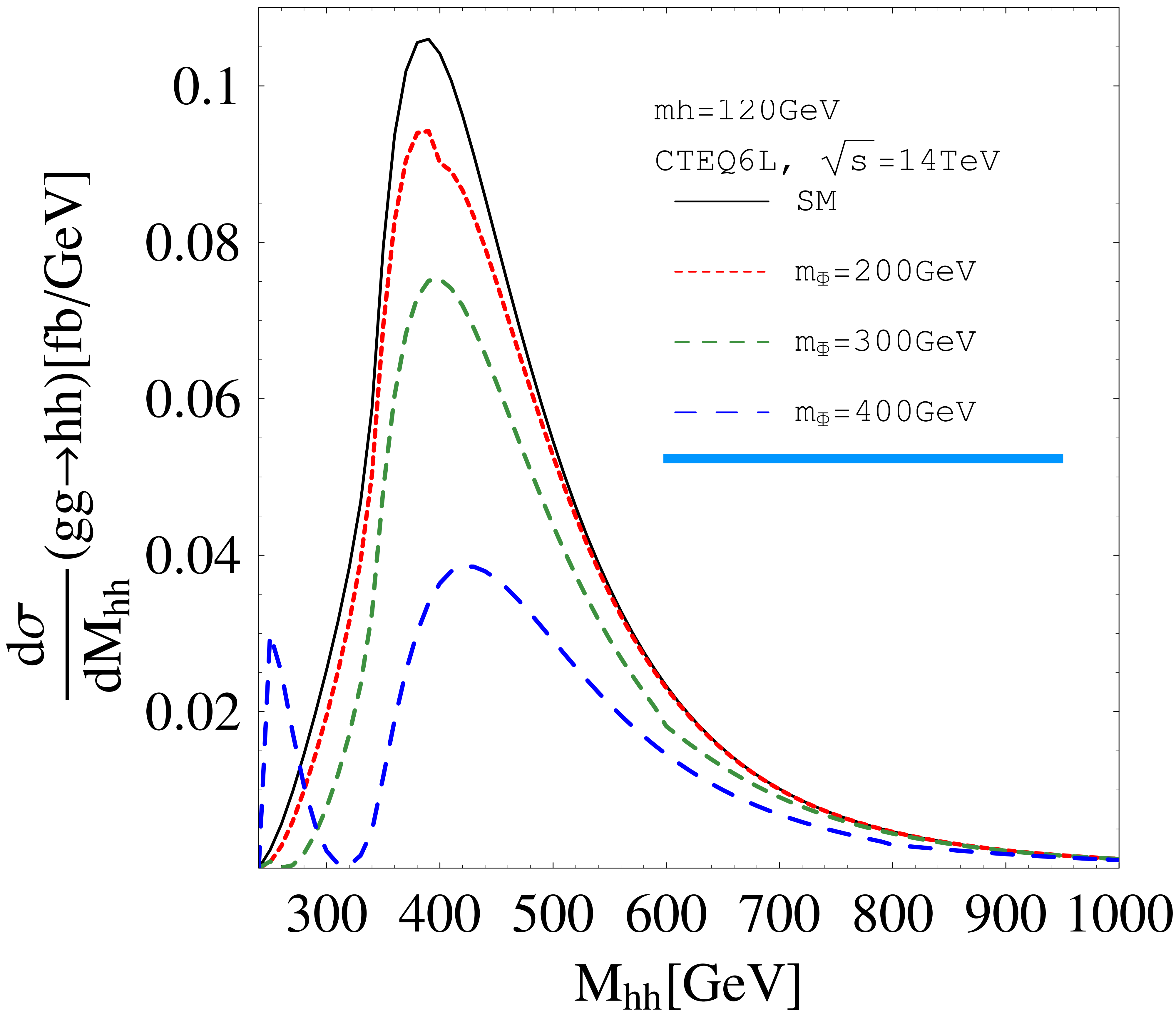
$$\frac{\Gamma^{\rm THDM}_{hhh}}{\Gamma^{\rm SM}_{hhh}} \simeq 1 + \frac{m^4_{H^\pm}}{6\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m^2_{H^\pm}}\right)^3 + \frac{m^4_H}{12\pi^2 v^2 m_h^2} \times \left(1 - \frac{M^2}{m^2_H}\right)^3 + \frac{m^4_A}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m^2_A}\right)^3,$$

Unless $M \approx m_{H^\pm} \approx m_H \approx m_A$

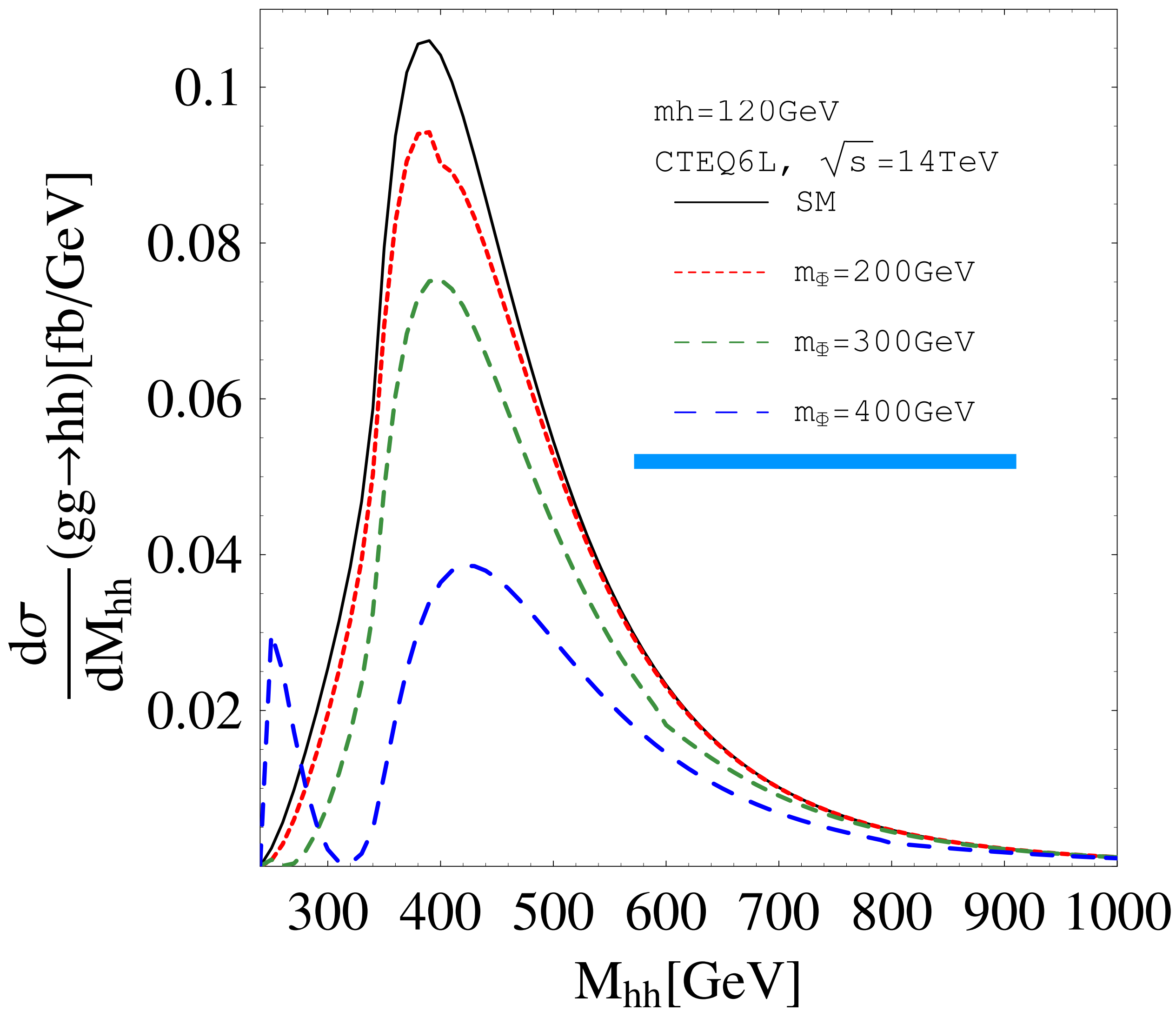
$\Delta\lambda_{hhh}$ can be large!


mh=120GeV
m_Φ=200GeV
m_Φ=300GeV
m_Φ=400GeV
ΔΓ_hhh^THDM/Γ_hhh^SM*100 [%]
150
100
50
0
300
400
500
600
700
800
900
1000
√ŝ [GeV]
energy of h* → hh

peaks around $M_{hh} \sim 400$



peaks around $M_{hh} \sim 400$



1. interference effects b/w Δ and $\Box$
2. Enhanced λ_{hhh} decreases $\sigma(gg \to hh)$.

At leading order,

λ_{hhh}

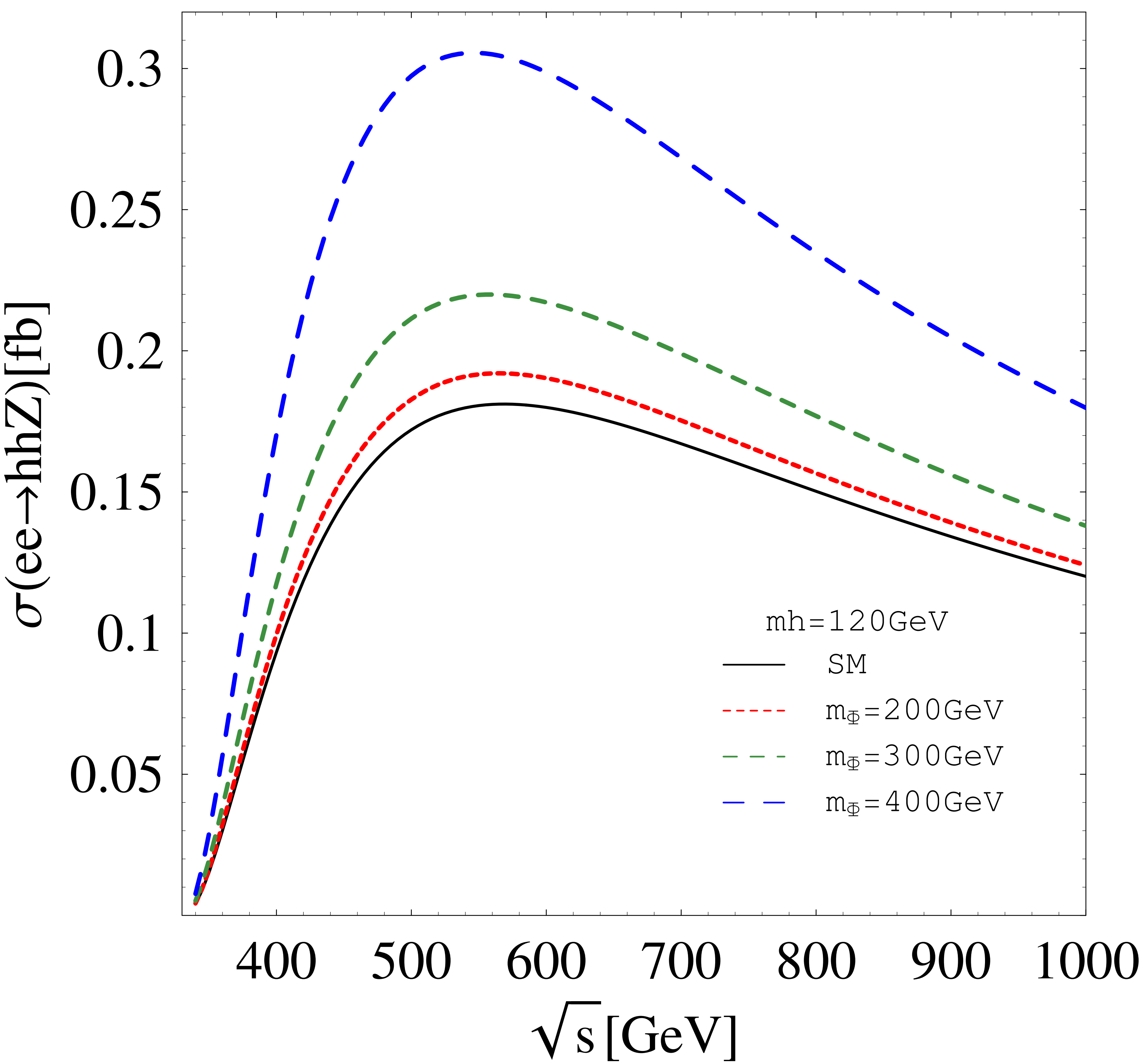
Box **Triangle**

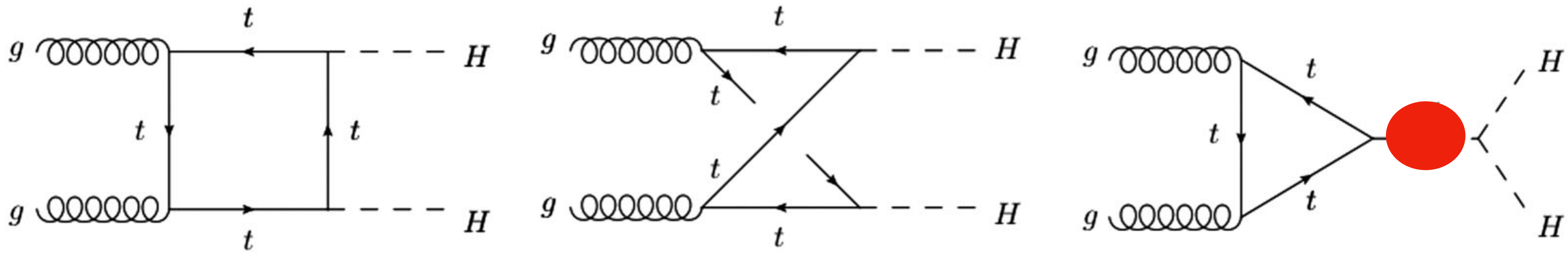
$$F_1(s,t,u,m_t^2)|_{\mathrm{LET}} \to \left(-\frac{4}{3} + \frac{4m_H^2}{s - m_H^2}\right)s,$$

$$F_2(s,t,u,m_t^2)|_{\mathrm{LET}} \to 0.$$

At $\sqrt{s} = 400\ \mathrm{GeV},\ \dfrac{m_H^2}{s - m_H^2} \sim 0.1.$

At e^+e^- collider

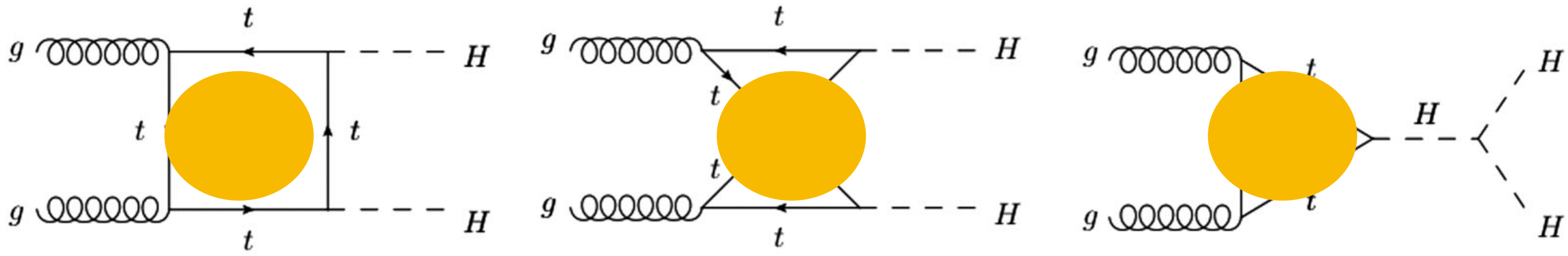




Not in the aligned 2HDM

1. New λ_{hhh}
2. New Scalar
3. New colored fermions

S.C. Park



New heavy quarks!

But we have to satisfy the single Higgs rate & EWPD

Mirror fermions

a generation of heavy mirror fermions

$$\psi_L^1 = \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{B}_L^1 \end{pmatrix}, \mathcal{T}_R^1, \mathcal{B}_R^1; \qquad \psi_R^2 = \begin{pmatrix} \mathcal{T}_R^2 \\ \mathcal{B}_R^2 \end{pmatrix}, \mathcal{T}_L^2, \mathcal{B}_L^2.$$

with charges $\frac{2}{3}$ and $-\frac{1}{3}$

The couplings of the fermion mass eigenstates to the Higgs boson

$$
\begin{aligned}
-\mathcal{L}_M^H = & \frac{c_{T_1T_1}}{2v}\bar{T}_{1L}T_{1R}H + \frac{c_{T_2T_2}}{2v}\bar{T}_{2L}T_{2R}H \\
& + \frac{c_{T_1T_2}}{2v}\bar{T}_{1L}T_{2R}H + \frac{c_{T_2T_1}}{2v}\bar{T}_{2L}T_{1R}H \\
& + \frac{c_{B_1B_1}}{2v}\bar{B}_{1L}B_{1R}H + \frac{c_{B_2B_2}}{2v}\bar{B}_{2L}B_{2R}H \\
& + \frac{c_{B_1B_2}}{2v}\bar{B}_{1L}B_{2R}H + \frac{c_{B_2B_1}}{2v}\bar{B}_{2L}B_{1R}H + \mathrm{H.c.},
\end{aligned}
$$

For single Higgs production through top quark and mirror fermion loops,

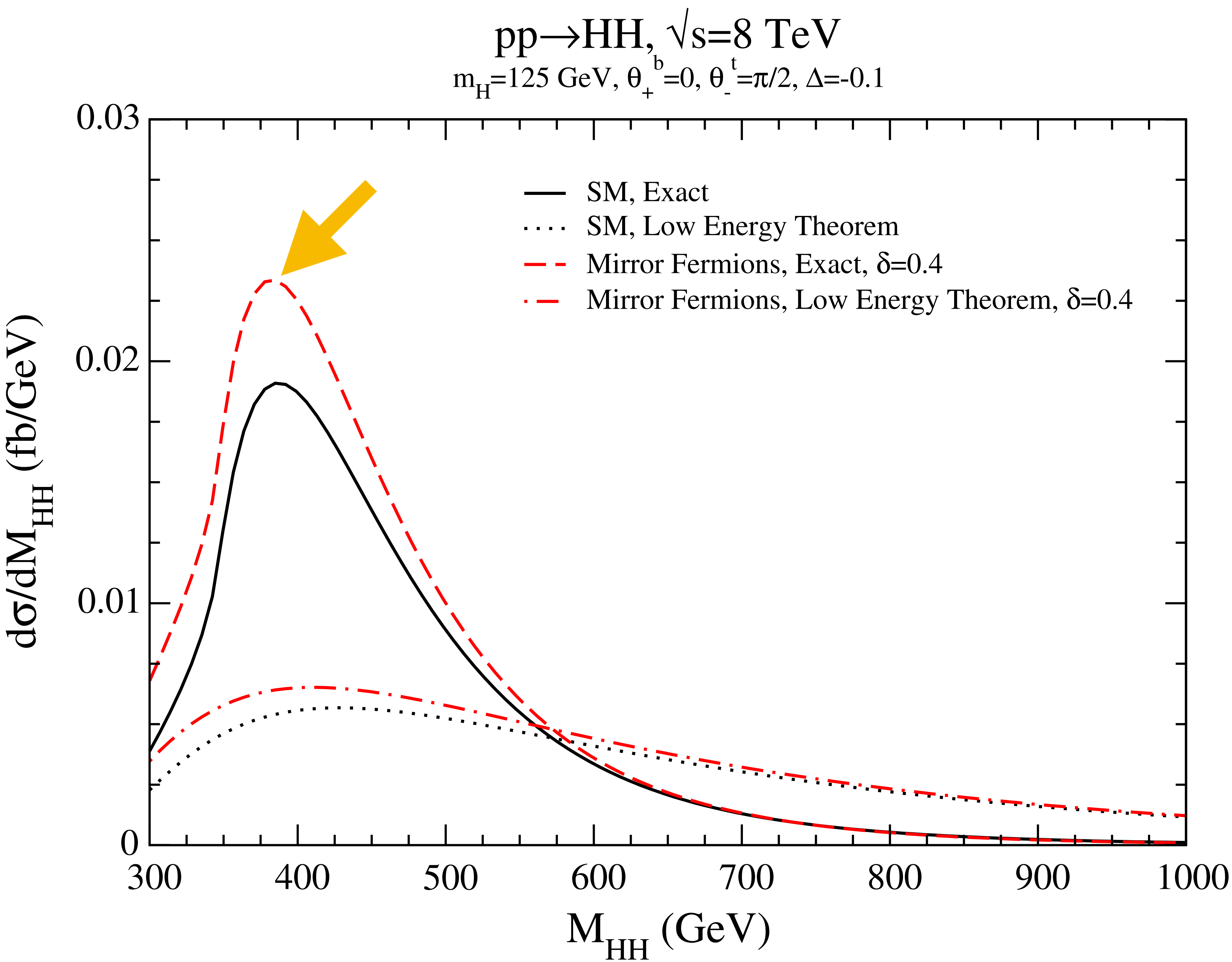
$$A_{gg\to H} = A^{\rm SM}_{gg\to H}\left(1 + \frac{c_{T_1T_1}}{2M_{T_1}} + \frac{c_{T_2T_2}}{2M_{T_2}} + \frac{c_{B_1B_1}}{2M_{B_1}} + \frac{c_{B_2B_2}}{2M_{B_2}}\right)$$

LET

For $gg \to hh$

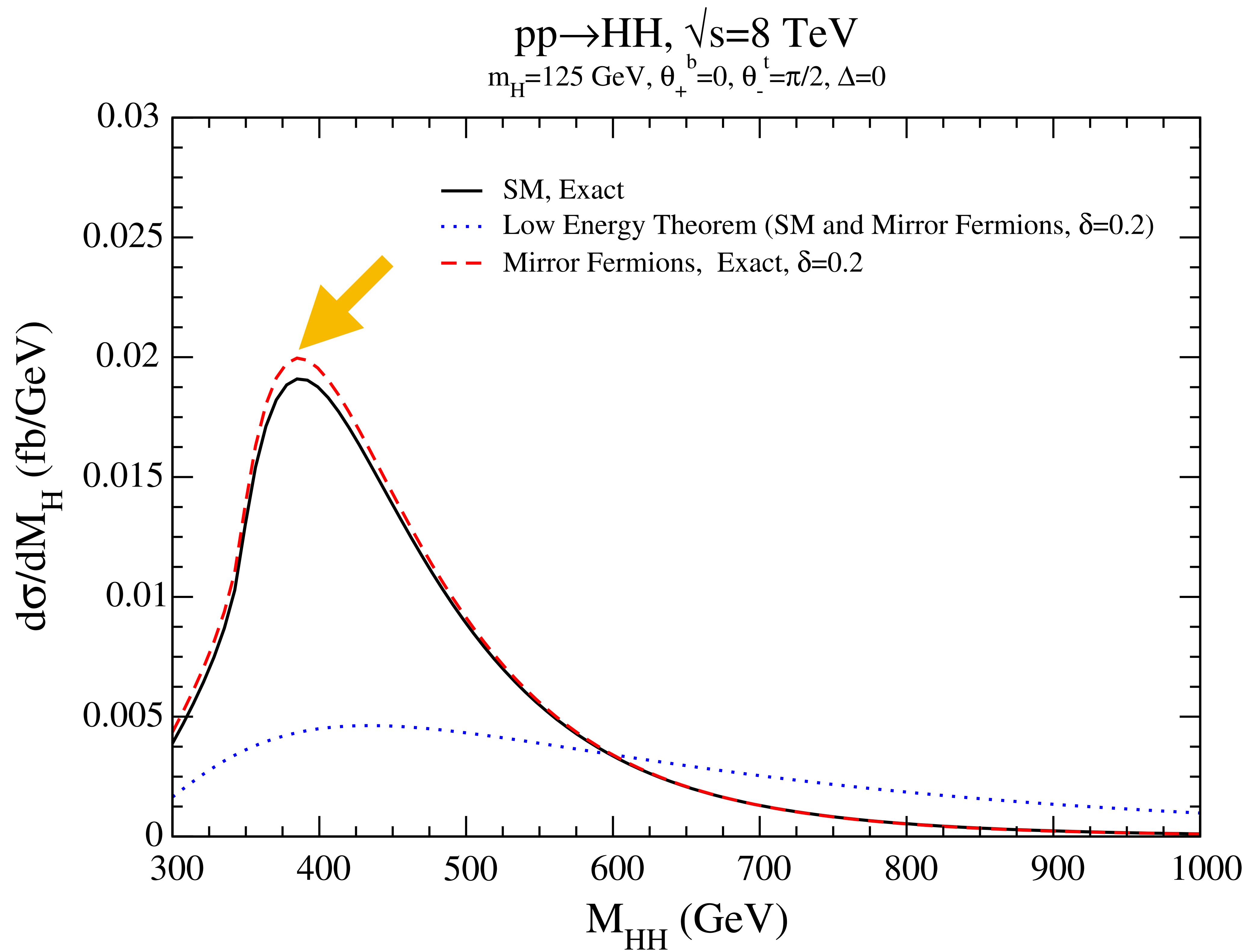
$$F_1^{\rm box} \equiv F_1^{\rm box,SM}(1 + \Delta_{\rm box});$$

$$\Delta_{\rm box} = \frac{c^2_{T_1T_1}}{4M^2_{T_1}} + \frac{c^2_{T_2T_2}}{4M^2_{T_2}} + \frac{c^2_{B_1B_1}}{4M^2_{B_1}} + \frac{c^2_{B_2B_2}}{4M^2_{B_2}} + \frac{c_{T_1T_2}c_{T_2T_1}}{2M_{T_1}M_{T_2}} + \frac{c_{B_1B_2}c_{B_2B_1}}{2M_{B_1}M_{B_2}}$$


pp→HH, √s=8 TeV
m_H=125 GeV, θ_+^b=0, θ_-^t=π/2, Δ=-0.1
SM, Exact
SM, Low Energy Theorem
Mirror Fermions, Exact, δ=0.4
Mirror Fermions, Low Energy Theorem, δ=0.4
0.03
0.02
0.01
0
300
400
500
600
700
800
900
1000
dσ/dM_HH (fb/GeV)
M_HH (GeV)

(a)

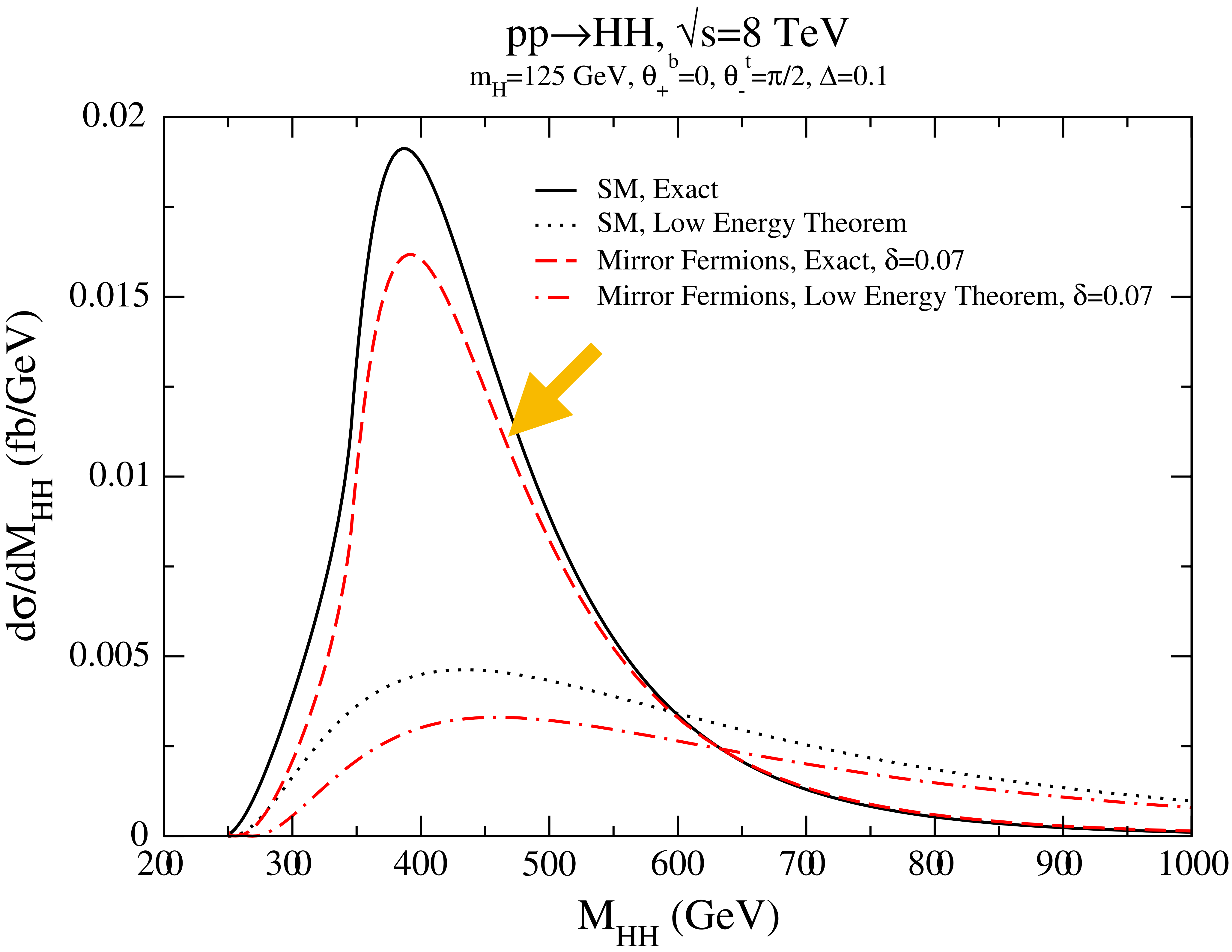
$\kappa_g = 90\%$



pp→HH, √s=8 TeV
m_H=125 GeV, θ_+^b=0, θ_-^t=π/2, Δ=0
SM, Exact
Low Energy Theorem (SM and Mirror Fermions, δ=0.2)
Mirror Fermions, Exact, δ=0.2
dσ/dM_H (fb/GeV)
M_HH (GeV)
0
0.005
0.01
0.015
0.02
0.025
0.03
300
400
500
600
700
800
900
1000

(b)

$\kappa_g = 100\%$


pp→HH, √s=8 TeV
m_H=125 GeV, θ_+^b=0, θ_-^t=π/2, Δ=0.1
SM, Exact
SM, Low Energy Theorem
Mirror Fermions, Exact, δ=0.07
Mirror Fermions, Low Energy Theorem, δ=0.07
dσ/dM_HH (fb/GeV)
M_HH (GeV)
0.02
0.015
0.01
0.005
0
200
300
400
500
600
700
800
900
1000

(c)

$\kappa_g = 110\%$

Conclusions

- Di-Higgs process is elusive.
- In the SM, the signal rate is very small.
- It is very difficult to have large NP effects.