since 1887

Phenomenological Studies of models with a pseudo Nambu Goldstone Boson

Tetsuo Shindou
Division of Liberal-Arts, Kogakuin University

Mainly based on:
S. Kanemura, K. Kaneta, N. Machida, S. Odori, T.S, Phys. Rev. D94, 015028 (2016)

08. 07. 2019, Bled2019 Workshop, Bled

The Standard Model

The Higgs boson was discovered in 2012

&

Its properties are consistent with a SM Higgs boson

↓

The SM seems to be established

However, it's not the end of the story

We still require the NP beyond the SM

- Baryon asymmetry of the Universe?
- What's the Dark Matter?
- Origin of tiny neutrino mass?
- Charge quantization?⟵Unified theory ? (Hierarchy problem)
- Some excess might be found (muon g-2, …)
- …

Elementary or Composite?

The Higgs sector is not understood yet

- What is the origin of spin-0 scalar?
- What is the dynamics of the Higgs behind?

  Is Higgs boson elementary or composite?
- The answer to this question determines the direction to the Grand Unified Theory
  - Elementary Scalar $\longrightarrow$ SUSY? GUT over grand desert?
  - Composite State$\longrightarrow$Rich field before GUT?

Modern CHM (Higgs=pNGB) is an attractive example

Kaplan&Georgi, PLB136,183&187 etc.

Higgs boson as NGB

Higgs boson is identified with pNGB, so that it can be much lighter than the composite scale.

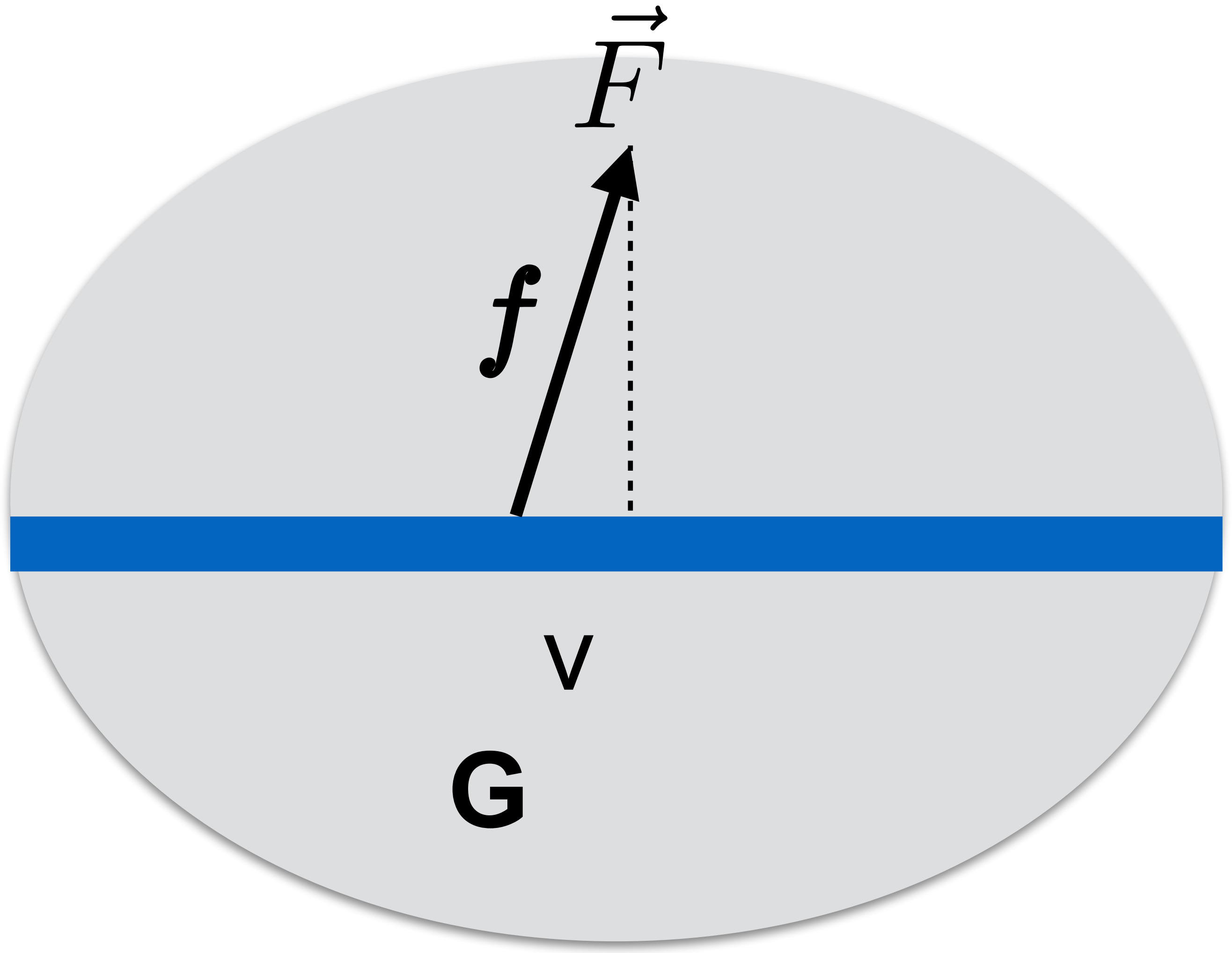
Symmetry breaking: G → H

f :symmetry breaking scale

$$\overrightarrow{\Phi}(x) = e^{i\theta^{\hat{a}}\hat{T}^{\hat{a}}}\overrightarrow{F}$$

$$\{T^A\} = \{T^a, \hat{T}^{\hat{a}}\}$$

G H broken



H $\supset \mathrm{SU(2)_L \times U(1)_Y}$

$\xi \equiv \dfrac{v^2}{f^2}$ **is an important parameter**

Construction of composite Higgs models

see e.g. Contino, arXiv:1005.4269

Identify G/H

- GSM is embedded in H
- G/H contains at least one SU(2)L doublet

vev G/H(coset) generators

$$\Sigma = \Sigma_0 \exp(-iT^{\hat{a}} h^{\hat{a}} \sqrt{2}/f)$$

$$\mathcal{L} = \frac{1}{2}(P_T)^{\mu\nu}\left[\Pi_0(q^2)\mathrm{tr}(A_\mu A_\nu) + \Pi_1(q^2)\Sigma A_\mu A_\nu \Sigma^t\right]$$

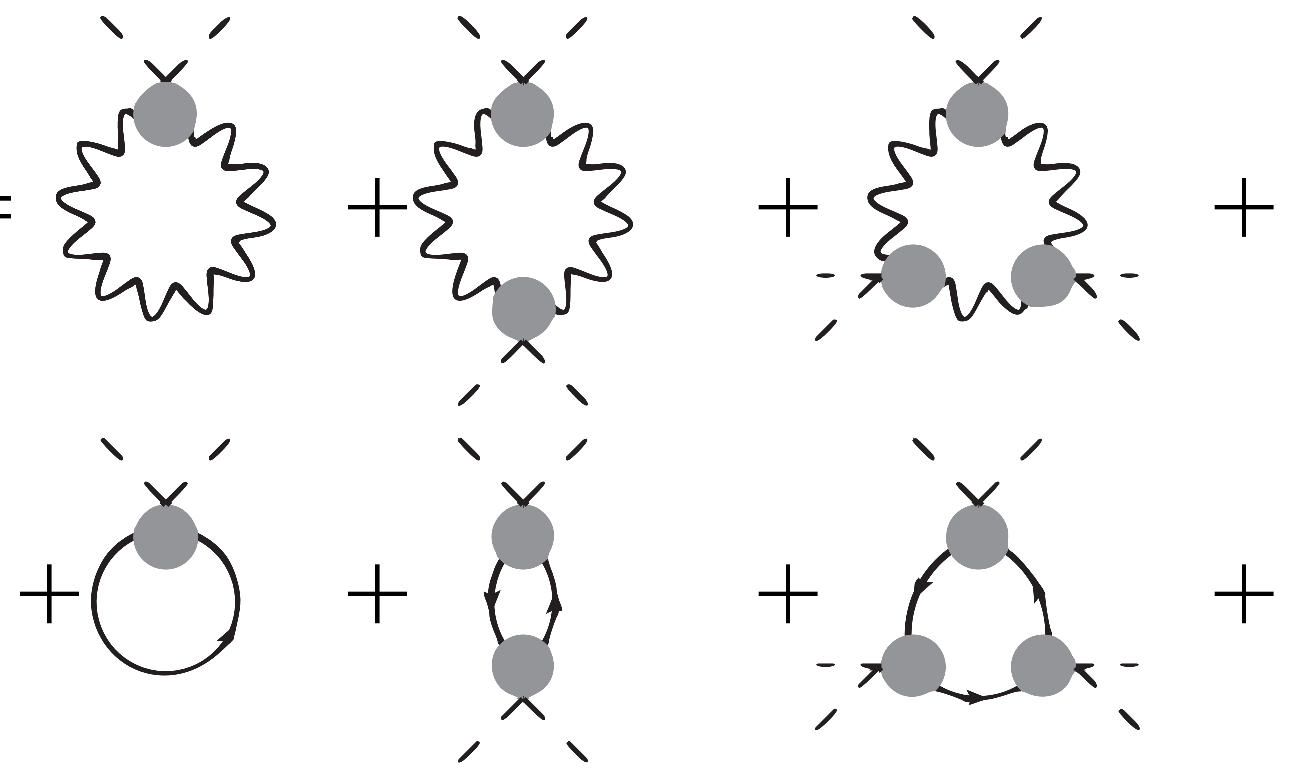
Determine Fermion Representation

The quarks&leptons are part of large multiplets

$$\mathcal{L} = \sum_{r=q,u,d} \bar{\Psi}_r \not{p}\left[\Pi_0^r(p) + \Pi_1^r(p)\Gamma^i\Sigma_i\right]\Psi_r + \sum_{r=u,d} \bar{\Psi}_q\left[M_0^r(p) + M_1^r(p)\Gamma^i\Sigma_i\right]\Psi_r$$

Compute Coleman-Weinberg potential

$V =$



G and H

Higgs boson is identified with pNGB associated with the spontaneous breaking of global symmetry $G \rightarrow H$

- G_{SM} is embedded in H (the gauge coupling breaks G)
- G/H contains at least one $SU(2)_L$ doublet NGB(4 d.o.f)

There are many possibilities of choosing G and H

	G	H	n_{NG}	see e.g.
minimal	SO(5)	SO(4)	4	Agashe et al., NPB719,165, Contino et al., PRD75,055014
DM(SM+S)	SO(6)	SO(5)	5	Grispaios et al., JHEP0904,070
2HDM	SO(6)	SO(4)xSO(2)	8	Mrazek et al., NPB853,1
	SO(9)	SO(8)	8	Beruzzo et al., JHEP1305,153
	…	…	…	…

In this talk, we focus on the MCHM: SO(5)/SO(4)

Example: MCHM4

Agashe et al., NPB719,165

- SO(5)/SO(4): 4NG Bosons (Higgs sector is SM-like)

$$\Sigma = \frac{\sin(h/f)}{f}(h^1, h^2, h^3, h^4, h\cot(h/f)), \quad h = \sqrt{h^{\hat a} h^{\hat a}}$$

$$H = \begin{pmatrix} -h^1 + ih^2 \\ h^3 + ih^4 \end{pmatrix}$$

Physical Higgs (h^3)

- Matters are part of 4-dim representation of SO(5)

$$\Psi_q = \begin{pmatrix} q_L \\ Q_L \end{pmatrix}, \quad \Psi_u = \begin{pmatrix} q_R^u \\ \begin{pmatrix} u_R \\ d'_R \end{pmatrix} \end{pmatrix}, \quad \Psi_d = \begin{pmatrix} q_R^u \\ \begin{pmatrix} u'_R \\ d_R \end{pmatrix} \end{pmatrix}$$

non-dynamical suprions (q_R^u, u'_R)

- Coleman-Weinberg potential: $V \simeq \alpha \cos\frac{h}{f} - \beta \sin^2\frac{h}{f}$

$$\alpha = 2N_C \int \frac{d^4p}{(2\pi)^4} \left(\frac{\Pi_1^u}{\Pi_0^u} - 2\frac{\Pi_1^q}{\Pi_0^q} \right), \quad \beta = \int \frac{d^4p}{(2\pi)^4} \left(2N_C \frac{|M_1^u|^2}{(-p^2)(\Pi_0^q + \Pi_1^q)(\Pi_0^u - \Pi_1^u)} - \frac{9}{8}\frac{\Pi_1}{\Pi_0} \right)$$

The Higgs coupling

hVV, hhVV

The effective Lagrangian is

$$\mathcal{L}_{\rm eff} = P^{\mu\nu}\Bigg[\frac{1}{2}\left(\frac{f^2\sin^2(h/f)}{4}\right)(B_\mu B_\nu + W^3_\mu W^3_\nu - 2W^3_\mu B_\nu) + \left(\frac{fr\sin^2(h/f)}{4}\right)W^+_\mu W^-_\nu$$

$$+\frac{p^2}{2}\left(\Pi'(0)W^a_\mu W^a_\nu + (\Pi'_0(0)+\Pi_0^{X}{}'(0))B_\mu B_\nu\right)+\cdots\Bigg], \qquad P^{\mu\nu} = \eta^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}$$

$$h = \langle h\rangle + \hat{h}$$

Deviations from the SM prediction

$$P^{\mu\nu}\frac{f^2\sin^2(h/f)}{4}W^+_\mu W^-_\nu \simeq \frac{v^2}{4}W^+_\mu W^-_\nu + \frac{v}{2}\sqrt{1-\xi}\,\hat{h}W^+_\mu W^-_\nu + \frac{1-2\xi}{4}\hat{h}^2 W^+_\mu W^-_\nu$$

$$\text{here}, v = f\sin\frac{\langle h\rangle}{f} = 246\text{GeV}\ , \qquad \xi \equiv \frac{v^2}{f^2} = \sin^2\frac{\langle h\rangle}{f}$$

- The deviations are controlled by the parameter ξ
- The hVV&hhVV couplings are determined by G/H and independent of matter sector

The Higgs coupling

Higgs potential In MCHM4

$$V \simeq \alpha \cos\frac{h}{f} - \beta \sin^2\frac{h}{f}$$

$$\left.\frac{\partial V}{\partial h}\right|_{\hat{h}=0} = -\frac{\sin(\langle h\rangle/f)}{f}\left(\alpha + \beta\cos(\langle h\rangle/f)\right) = 0$$

$$\left.\frac{\partial^2 V}{\partial h^2}\right|_{\hat{h}=0} = \frac{2\beta}{f^2}\left[1 - \frac{\alpha^2}{4\beta^2}\right] \equiv M_h^2$$

$$\left.\frac{\partial^3 V}{\partial h^3}\right|_{\hat{h}=0} = \frac{3M_h^2}{v}\sqrt{1-\xi} \equiv \lambda_{hhh}$$

Deviation from the SM prediction

Top Yukawa coupling

$$\mathcal{L} \simeq M^t \sin\frac{h}{f}\bar{t}_L t_R = M_t \bar{t}_L \bar{t}_R + \frac{M_t\sqrt{1-\xi}}{v}\hat{h}\bar{t}_L t_R - \frac{M_t \xi}{2v^2}\hat{h}^2\bar{t}_L t_R$$

Deviation from the SM prediction

New dim-5 interaction

Matter representation

There are variations of the SO(5)/SO(4) model,due to matter representations

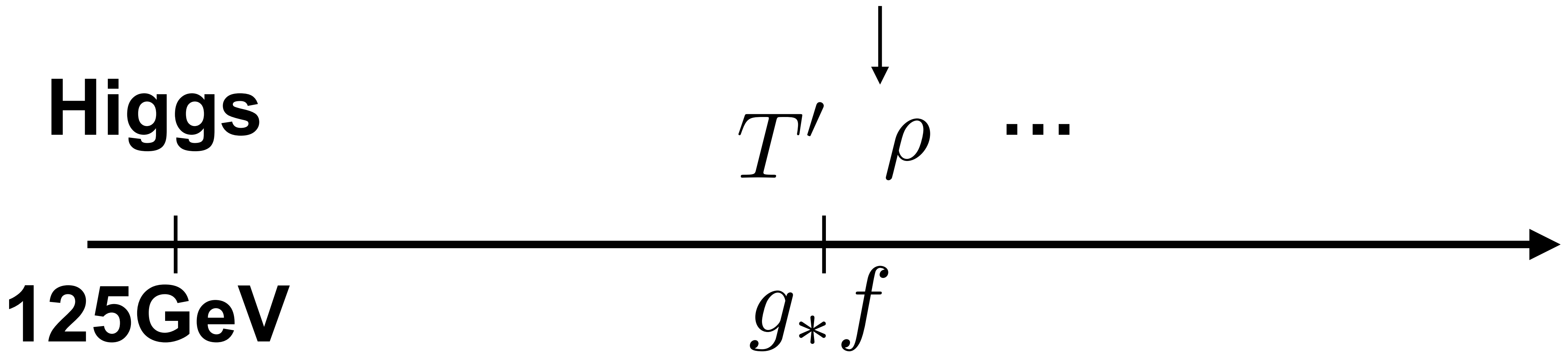
In general, $q_L, u_R, d_R, \ell_L, e_R$ can independently embedded into SO(5) multiplets such as 1-, 4-, 5-, 10-, 14-dim rep.

We consider typical examples:

MCHM4 **MCHM5** **MCHM14**

All the matter fermions are embedded into 4-, 5- or 14-rep.

For simplicity, we ignore the extra heavy particles



Lagrangian for Matter sector

MCHM$_4$

$$\mathcal{L}_{\rm eff}^{\rm matter} = \sum_{r=q,u,d} \overline{\Psi}_r^{(4)} \not{p} \left[\Pi_0^r(p) + \Pi_1^r(p)\Gamma^i\Sigma_i\right] \Psi_r^{(4)} + \sum_{r=u,d} \overline{\Psi}_q^{(4)} \left[M_0^r(p) + M_1^r(p)\Gamma^i\Sigma_i\right] \Psi_r^{(4)} ,$$

MCHM$_5$

$$\mathcal{L}_{\rm eff}^{\rm matter} = \sum_{r=t_L,t_R,b_L,b_R} \overline{\Psi}_r^{(5)} \left[\not{p}\Pi_0^r + \Sigma^\dagger \not{p}\Pi_1^r \Sigma\right] \Psi_r^{(5)}$$
$$+ \overline{\Psi}_{t_L}^{(5)} \left[M_0^t + \Sigma^\dagger M_1^t \Sigma\right] \Psi_{t_R}^{(5)} + \overline{\Psi}_{b_L}^{(5)} \left[M_0^b + \Sigma^\dagger M_1^b \Sigma\right] \Psi_{b_R}^{(5)} + \text{h.c.} \; .$$

MCHM$_{14}$

$$\mathcal{L}_{\rm eff}^{\rm matter} = \sum_{r=q_L,t_R,b_R} \left[\overline{\Psi}_r^{(14)} \not{p}\Pi_0^r \Psi_r^{(14)} + (\Sigma\overline{\Psi}_r^{(14)})\not{p}\Pi_1^r(\Psi_r^{(14)}\Sigma^\dagger) + (\Sigma\overline{\Psi}_r^{(14)}\Sigma^\dagger)\not{p}\Pi_2^r(\Sigma\Psi_r^{(14)}\Sigma^\dagger)\right]$$
$$+ \overline{\Psi}_{q_L}^{(14)} M_0^t \Psi_{t_R}^{(14)} + (\Sigma\overline{\Psi}_{q_L}^{(14)}) M_1^t (\Psi_{t_R}^{(14)}\Sigma^\dagger) + (\Sigma\overline{\Psi}_{q_L}^{(14)}\Sigma^\dagger) M_2^t (\Sigma\Psi_{t_R}^{(14)}\Sigma^\dagger)$$
$$+ \overline{\Psi}_{q_L}^{(14)} M_0^b \Psi_{b_R}^{(14)} + (\Sigma\overline{\Psi}_{q_L}^{(14)}) M_1^b (\Psi_{b_R}^{(14)}\Sigma^\dagger) + (\Sigma\overline{\Psi}_{q_L}^{(14)}\Sigma^\dagger) M_2^b (\Sigma\Psi_{b_R}^{(14)}\Sigma^\dagger) + \text{h.c.}$$

Deviation pattern in MCHMs

see e.g. Carena et al,JHEP1406 159, Kanemura, Kaneta, Machida, TS, PRD91,115016

<table>
<tr><th>Model</th><th>κ_V</th><th>κ_{hhh}</th><th>κ_t</th><th>κ_{hhVV}</th><th>c_{hhhh}</th><th>c_{hhtt}</th></tr>
<tr><td>MCHM4</td><td rowspan="3">$1-\frac{1}{2}\xi$</td><td>$1-\frac{1}{2}\xi$</td><td>$1-\frac{1}{2}\xi$</td><td rowspan="3">$1-2\xi$</td><td>$1-\frac{7}{3}\xi$</td><td>$-\xi$</td></tr>
<tr><td>MCHM5</td><td rowspan="2">$1-\frac{3}{2}\xi$</td><td>$1-\frac{3}{2}\xi$</td><td rowspan="2">$1-\frac{25}{2}\xi$</td><td>-4ξ</td></tr>
<tr><td>MCHM14</td><td>$1-\frac{9M_1^t+64M_2^t}{6M_1^t+16M_2^t}\xi$</td><td>$-\frac{4(3M_1^t+23M_2^t)}{3M_1^t+8M_2^t}\xi$</td></tr>
</table>

$$+\mathcal{O}(\xi^2)$$

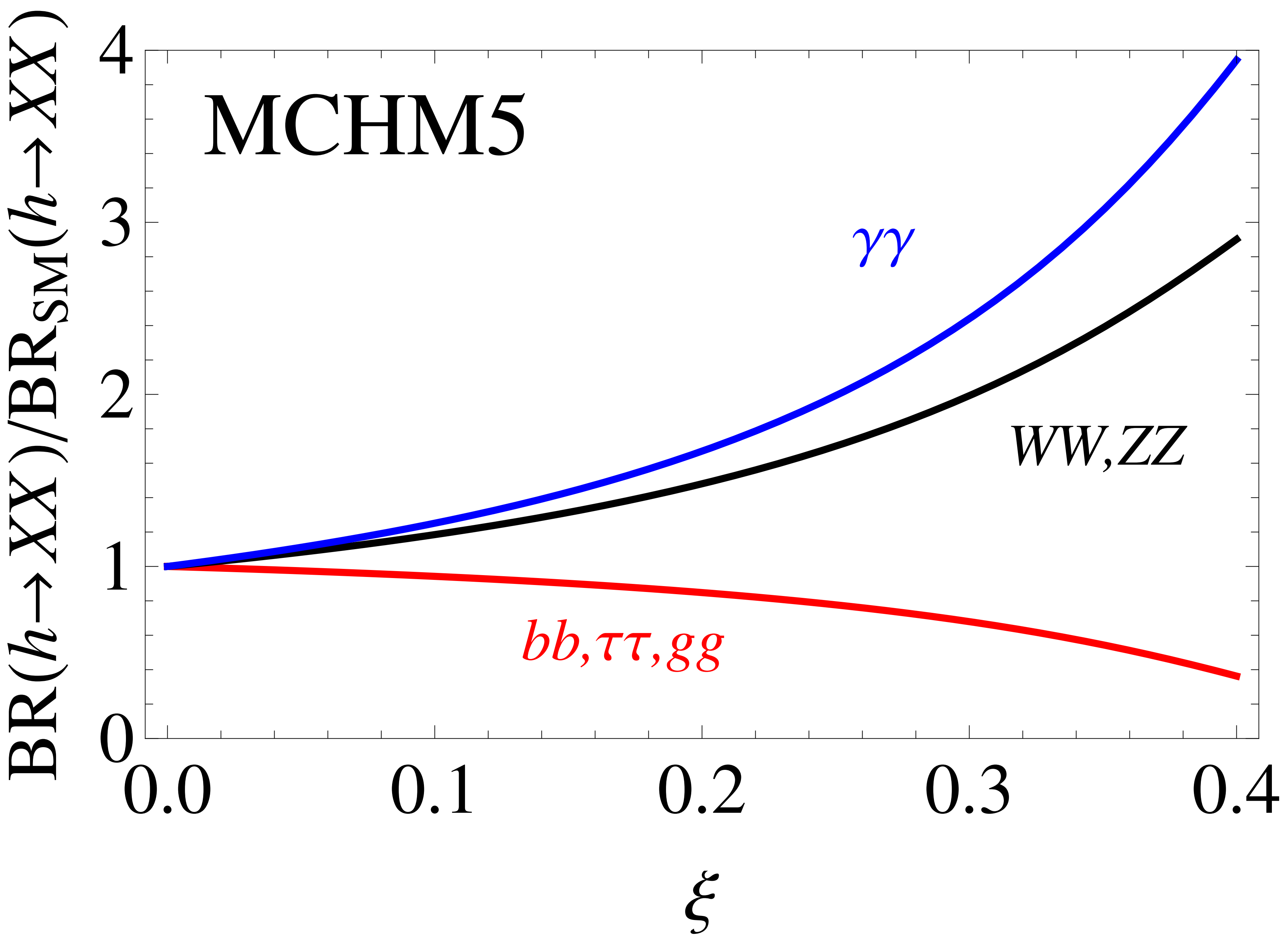
★ In MCHM4, $\kappa_V=\kappa_t(=\kappa_b)$

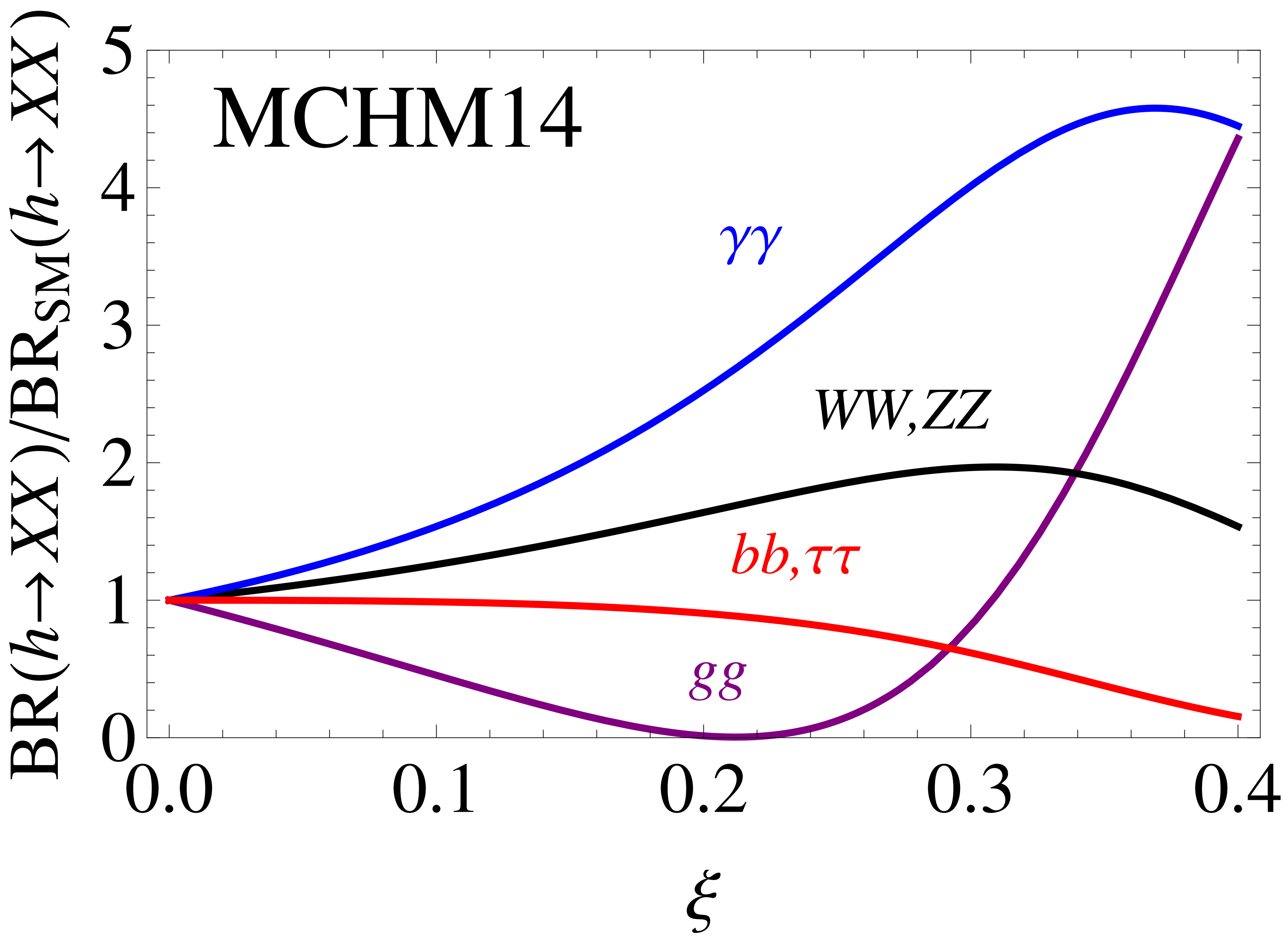
★In MCHM14, the deviation of top Yukawa coupling depend on the ratio of two form factors M_1^t/M_2^t besides the parameter ξ

In the following, we consider $M_1^t \ll M_2^t$ case for $MCHM_{14}$

Decay Branching Ratio

S.Kanemura, K. Kaneta, N.Machida, S. Odori, TS, PRD94





For MCHM4, BR_{MCHM}/BR_{SM}=1 for all the decay modes

$$\kappa_{hXX} = \sqrt{1-\xi} \longrightarrow \Gamma(h \to XX)/\Gamma_{SM}(h \to XX) = 1 - \xi$$

Mode	bb	WW	ZZ	$\gamma\gamma$
BR_{SM}	0.55	0.23	0.027	0.0024

@m_h=125GeV

Phenomenology at LHC

1. single Higgs boson production
2. double Higgs boson production
3. gg to ZH

Constraints on ξ

How strong the compositeness parameter is constrained?

☆ Electroweak Precision Test

Correction to S-parameter and $\Delta\rho$ leads to

$$\xi \lesssim 0.25$$

Agashe&Contino, NPB742, 59

☆ LHC

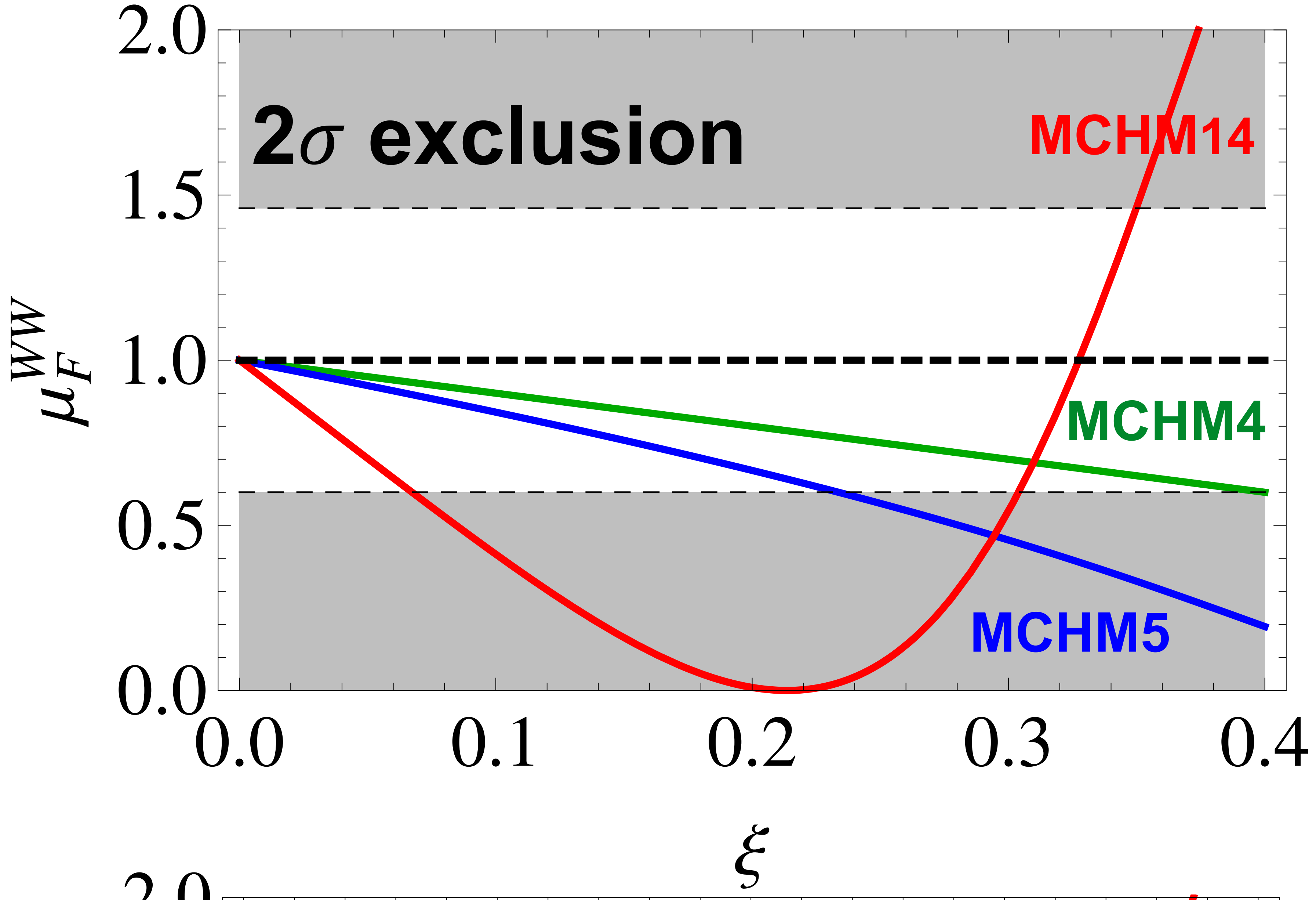
For extracting the constraint from the data,

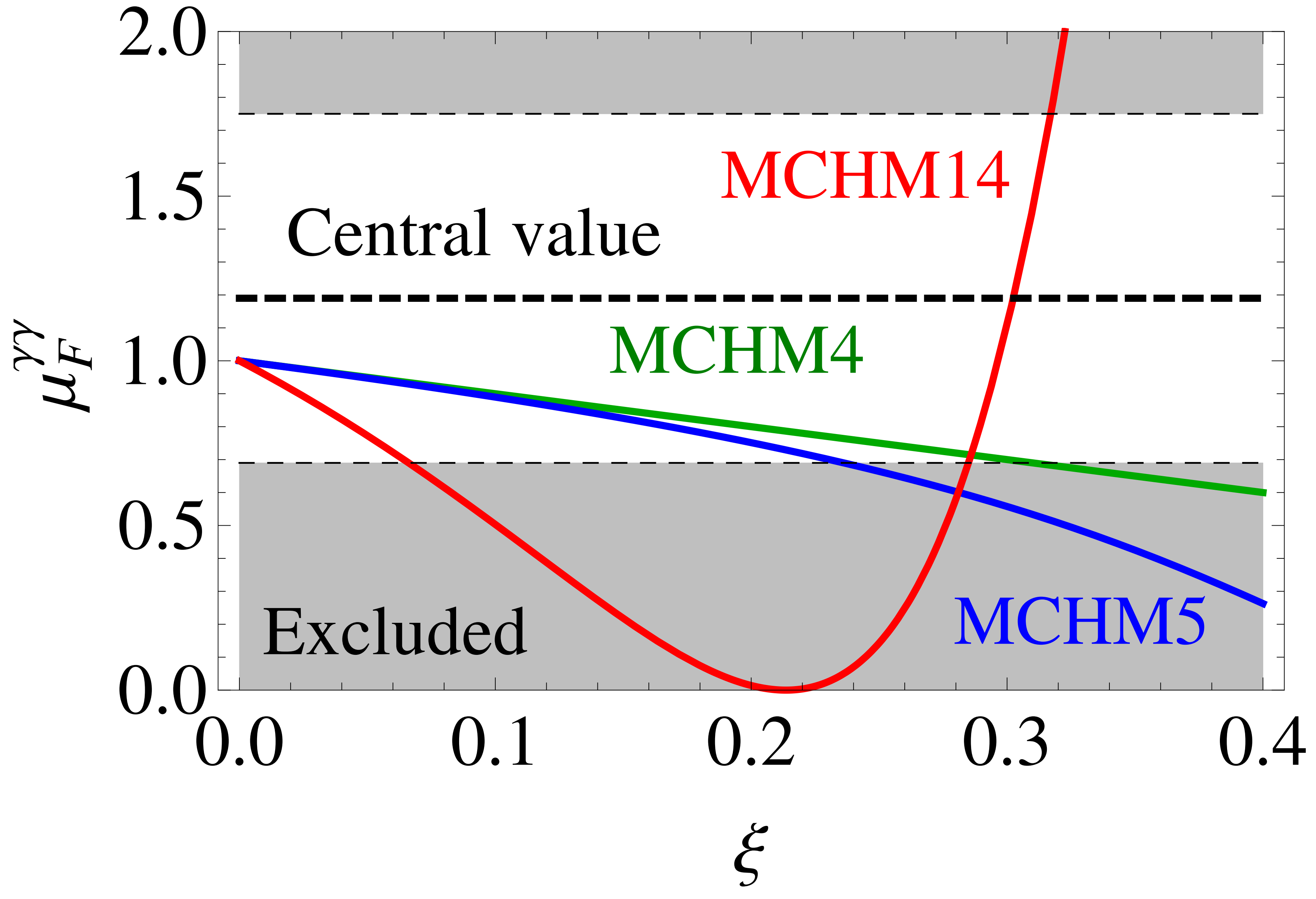
we utilize the signal strength

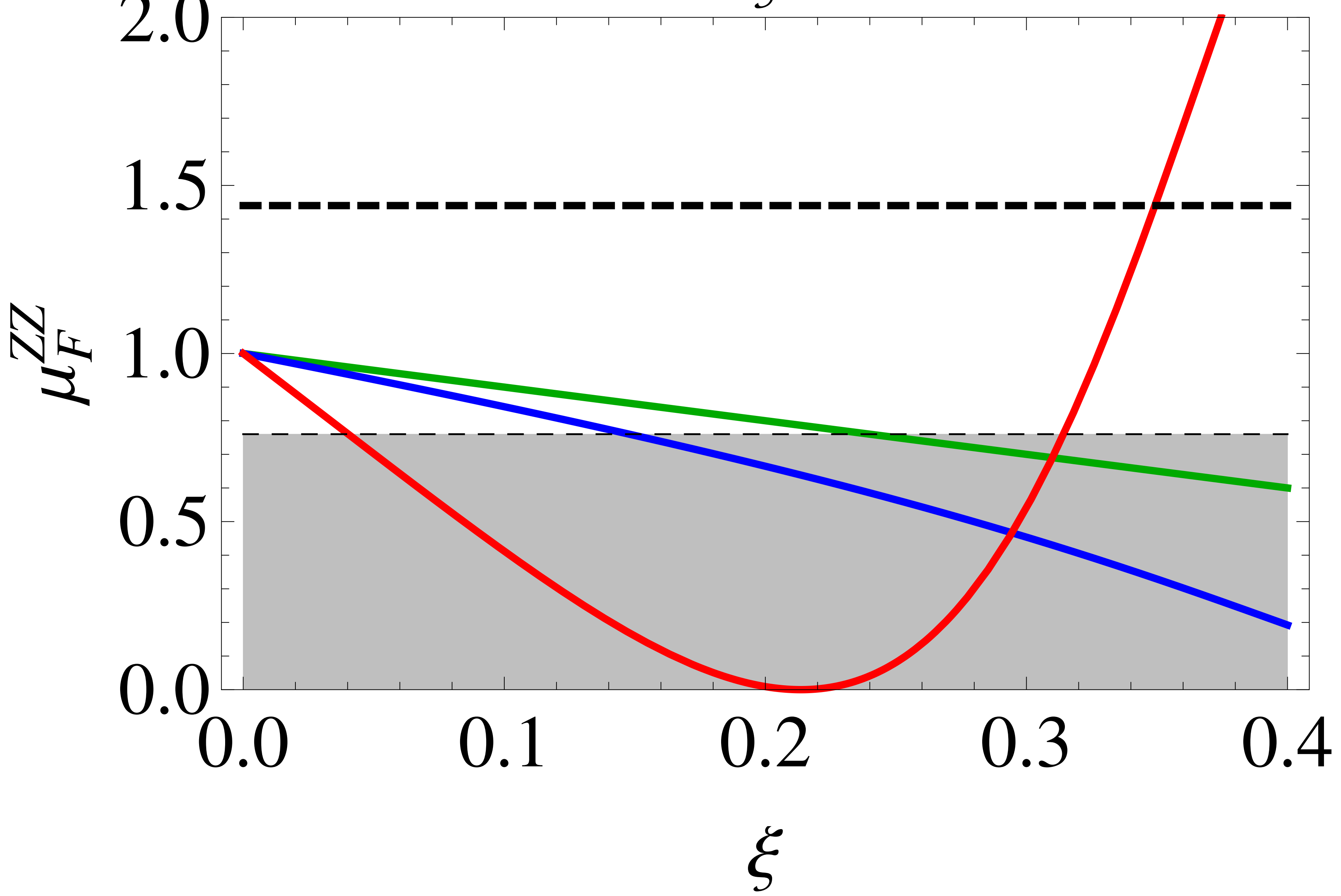
$$\mu = \frac{\sigma(\text{prod}) \cdot \text{Br}(h \to FF)}{\sigma(\text{prod})_{\text{SM}} \cdot \text{Br}(h \to FF)_{\text{SM}}}$$

Constraints from LHC Run-I

S.Kanemura, K. Kaneta, N.Machida, S. Odori, TS, PRD94







$$\mu_F^{XX} \simeq \kappa_t^2 \frac{\mathrm{BR}(h \to XX)}{\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$

	$\mu_F^{\gamma\gamma}$	μ_F^{WW}	μ_F^{ZZ}
MCHM_4	$\xi < 0.31$	$\xi < 0.40$	$\xi < 0.24$
MCHM_5	$\xi < 0.23$	$\xi < 0.23$	$\xi < 0.15$
MCHM_{14}	$\xi < 0.07$	$\xi < 0.07$	$\xi < 0.04$

Double Higgs production at LHC

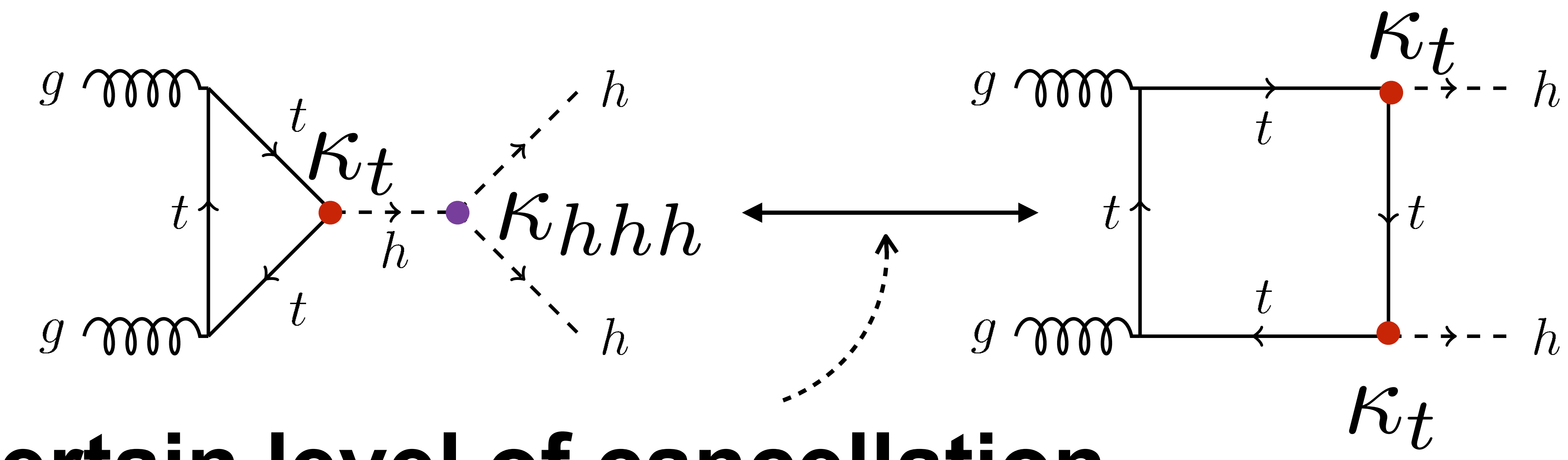
Double Higgs production provides crucial hint to explore the Higgs sector

- The dominant process is Gluon Fusion
  - It has sensitivity to the contact interaction $hh\bar{t}_L t_R$ as well as the Higgs self coupling hhh
- Vector Boson Fusion (VBF) is subdominant process
  - It provides information on the HVV and HHVV couplings

↑

single Higgs boson production

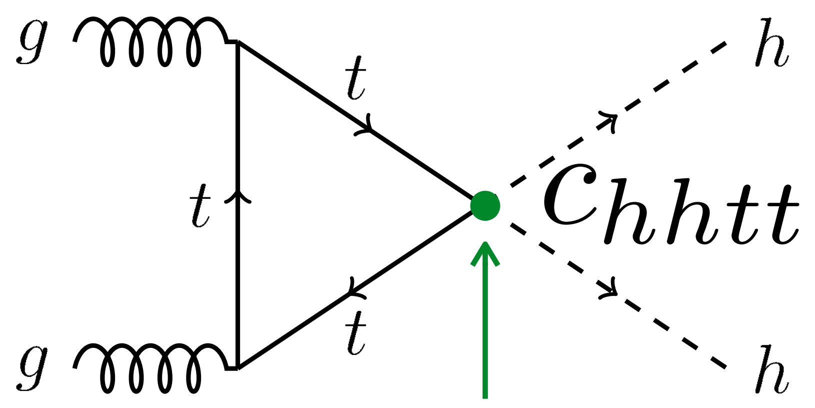
Gluon Fusion Process



Certain level of cancellation

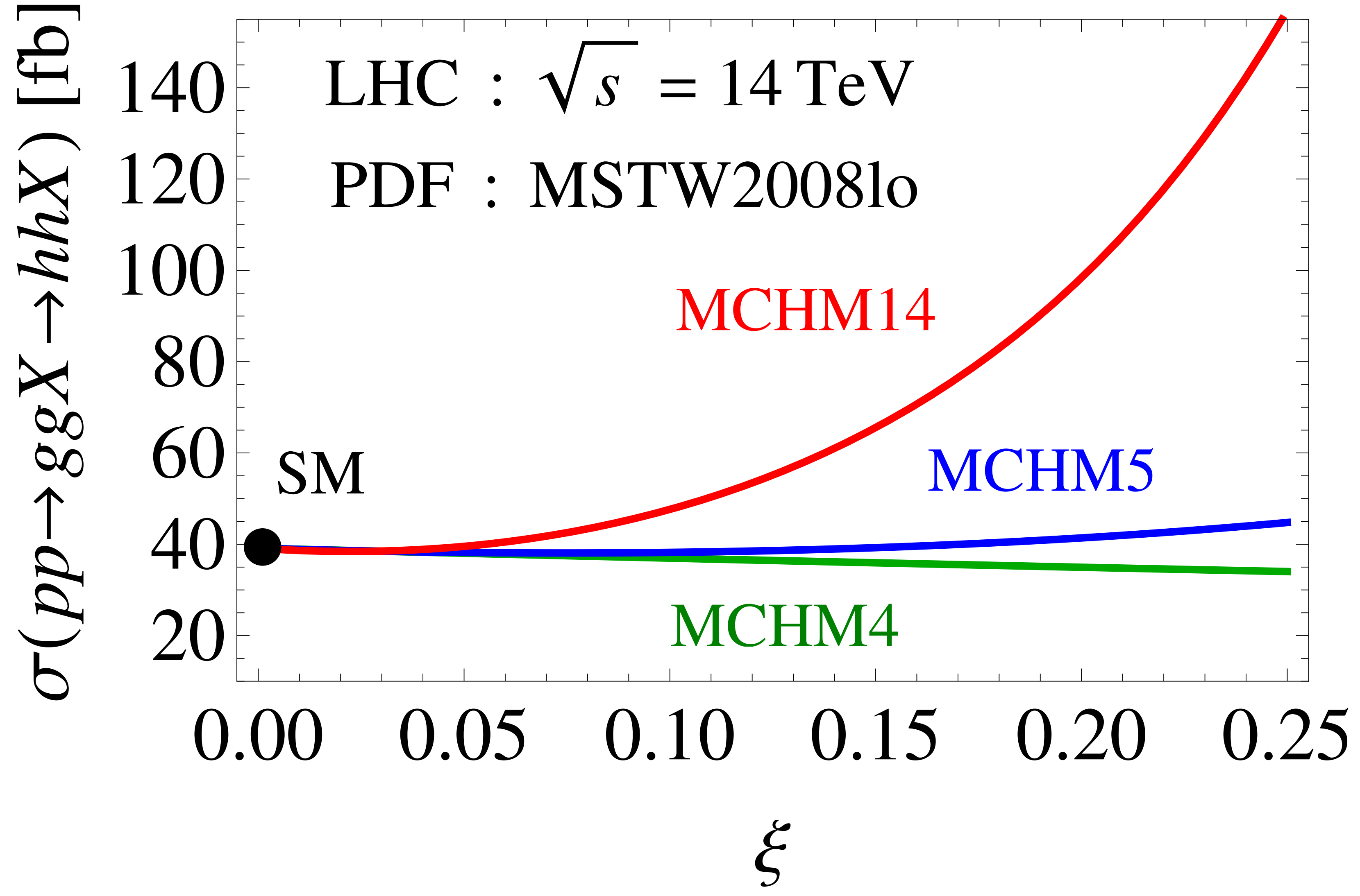
Model	κ_{hhh}	κ_t	c_{hhtt}
MCHM_4	$1-\frac{1}{2}\xi$	$1-\frac{1}{2}\xi$	$-\xi$
MCHM_5	$1-\frac{1}{2}\xi$	$1-\frac{3}{2}\xi$	-4ξ
MCHM_{14}		$1-4\xi$	$-\frac{23}{2}\xi$

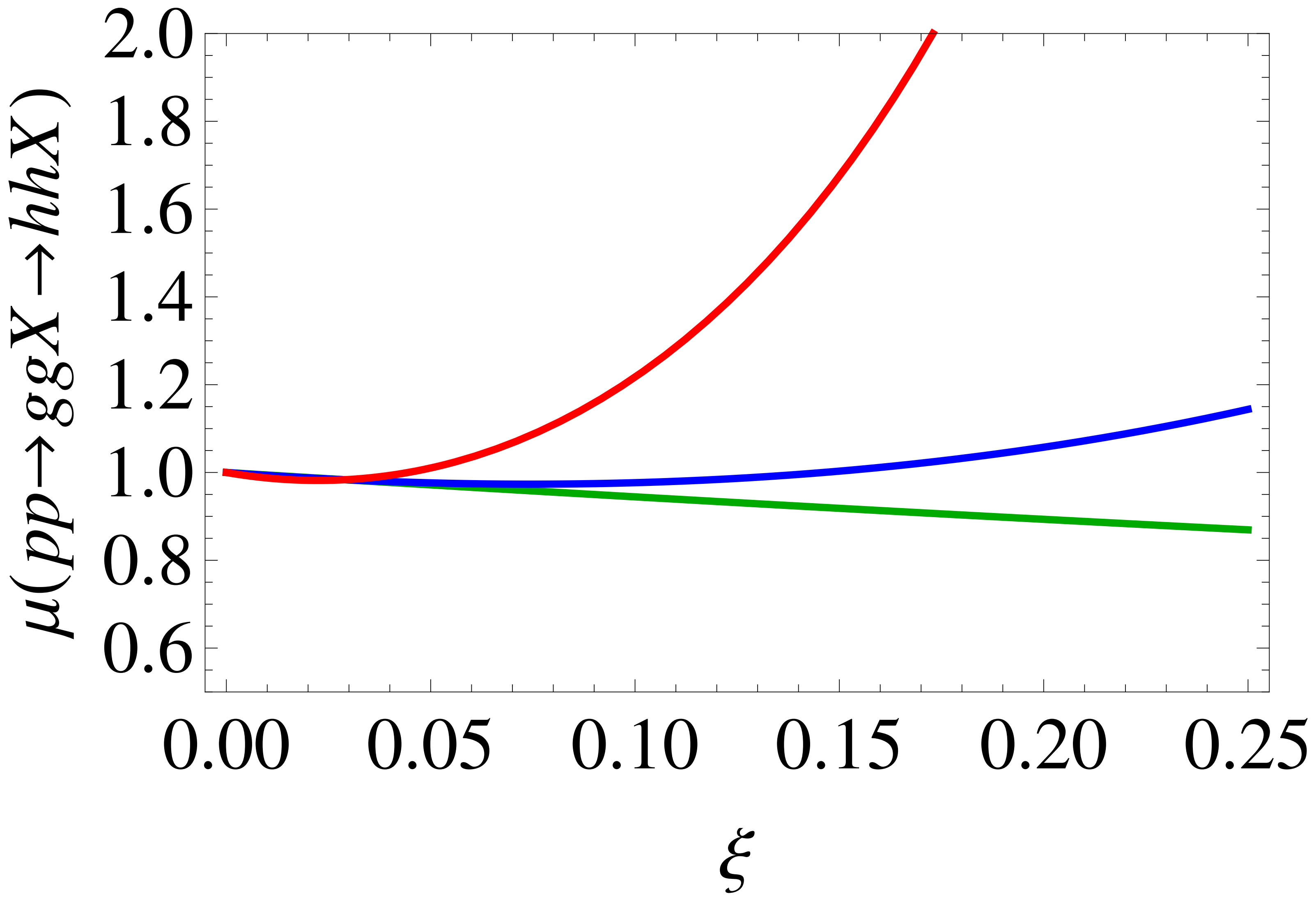
$+\mathcal{O}(\xi^2)$



New coupling in MCHMs

Enhancement





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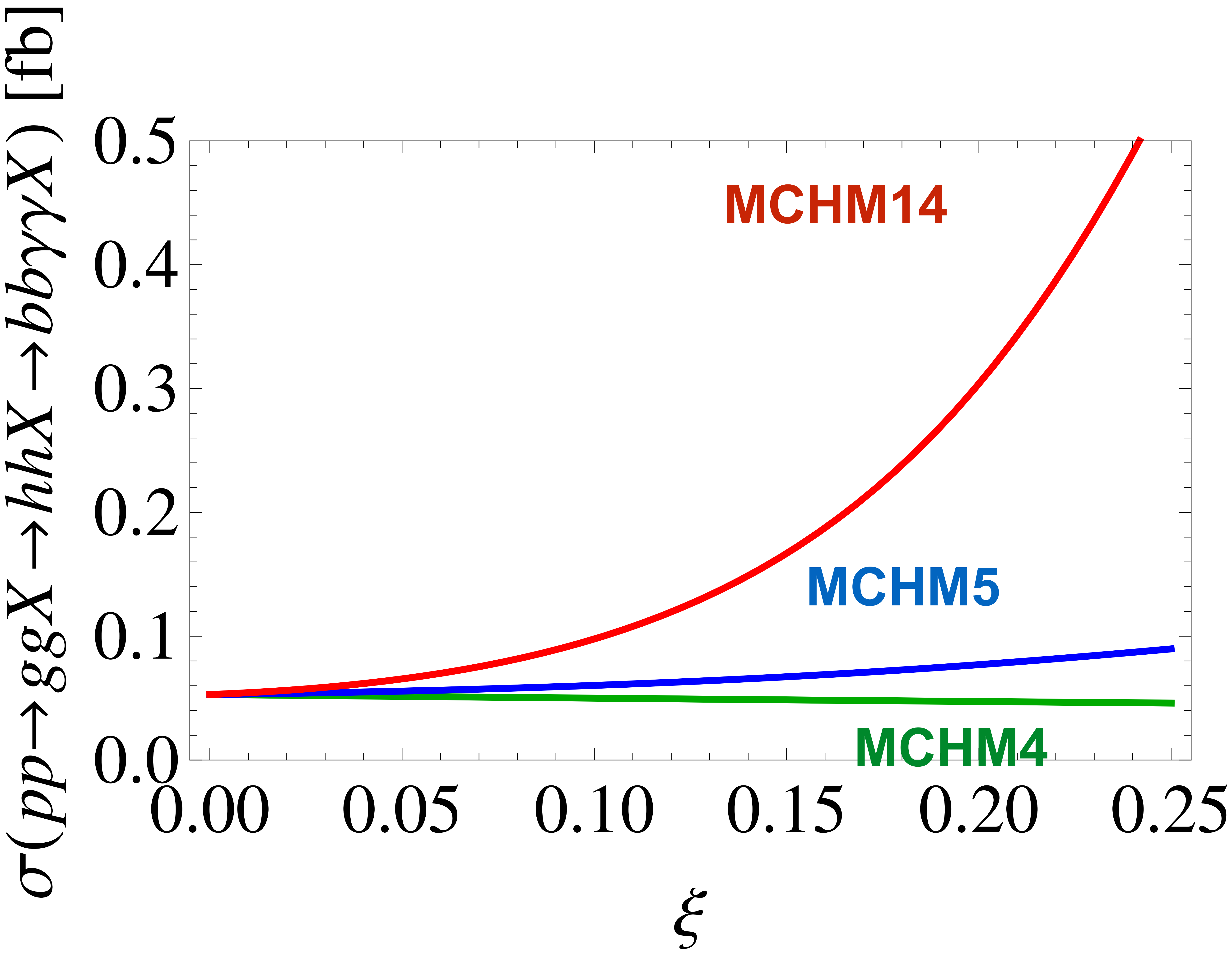
pp →hhX→γγbb

γγbb mode is the most clean mode for hh production



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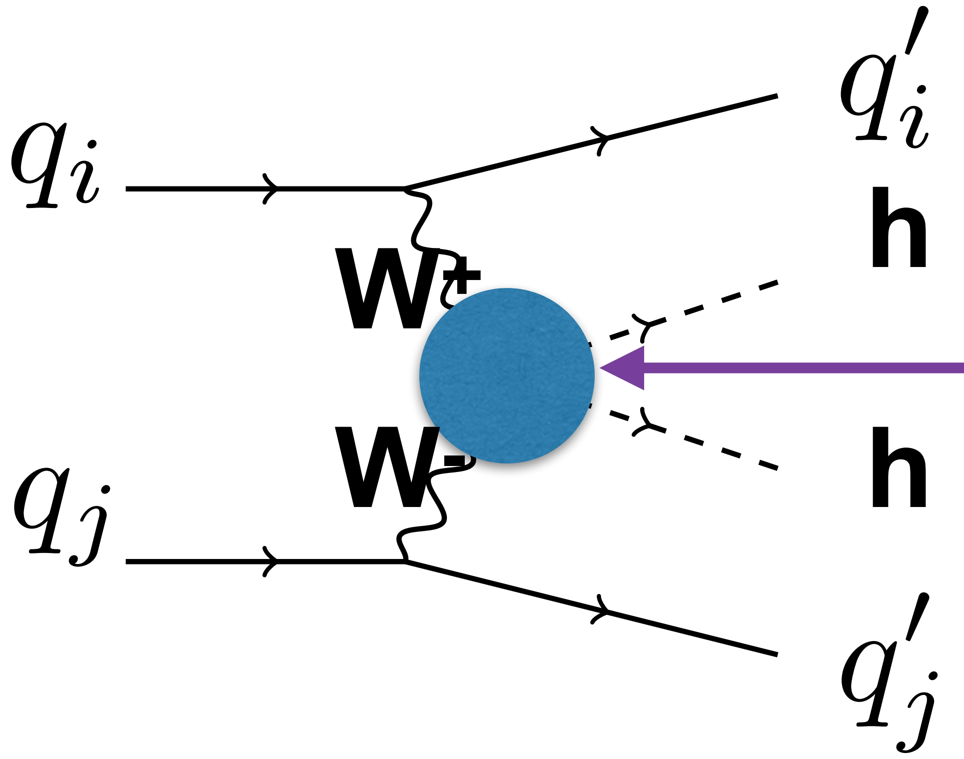
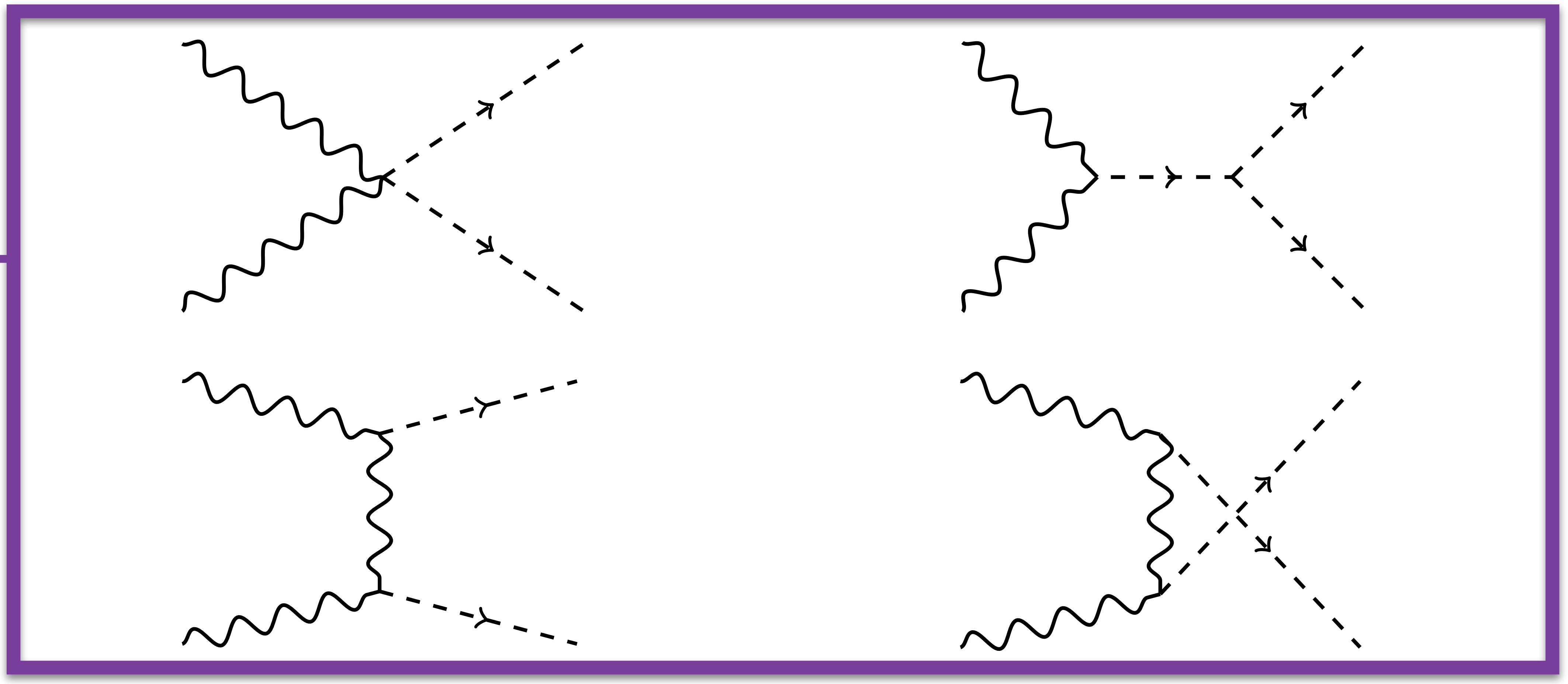
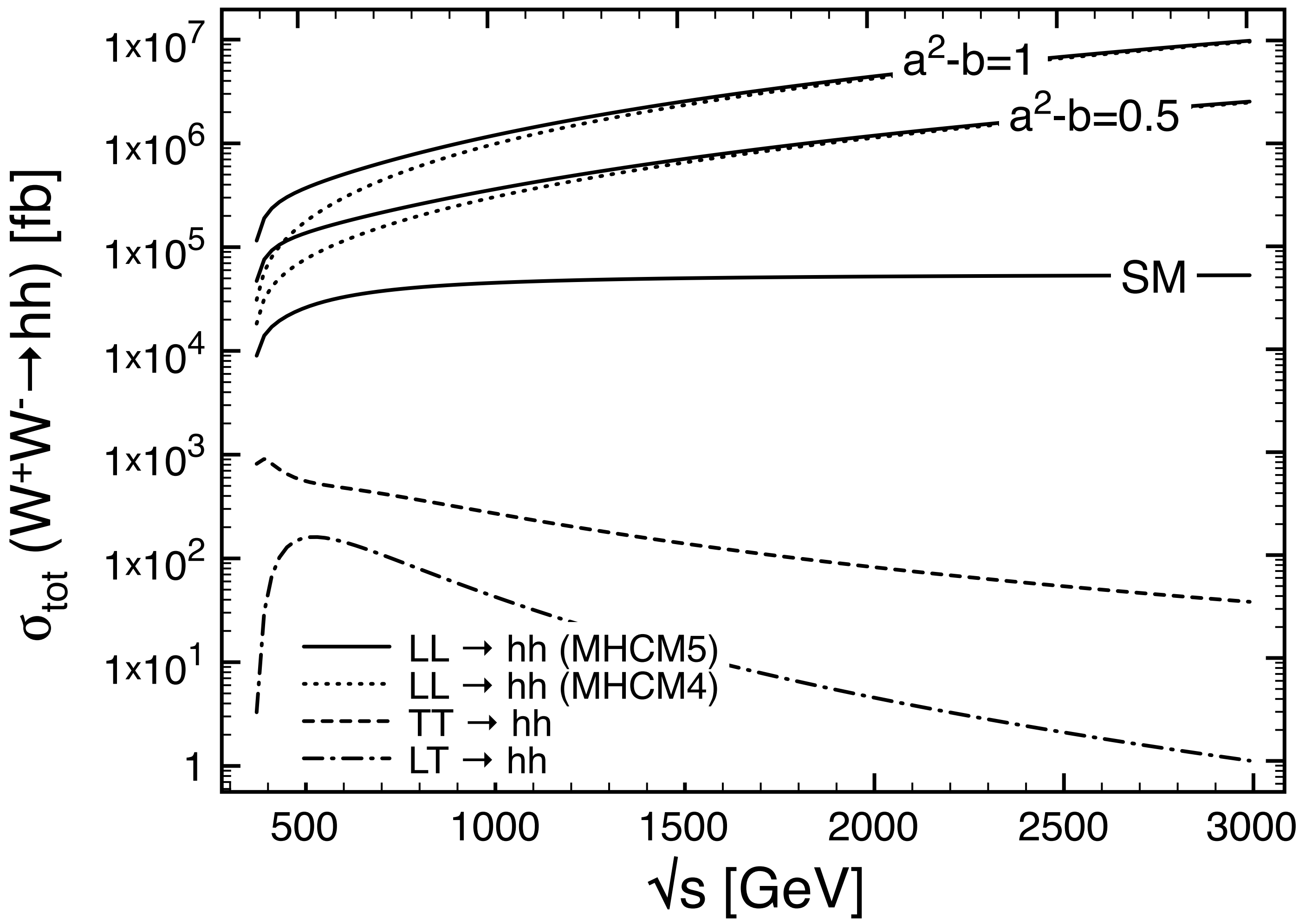
Vector Boson Fusion Process





In the SM, unitarity cancellation occurs

In the MCHMs, the unitarity cancellation is spoiled



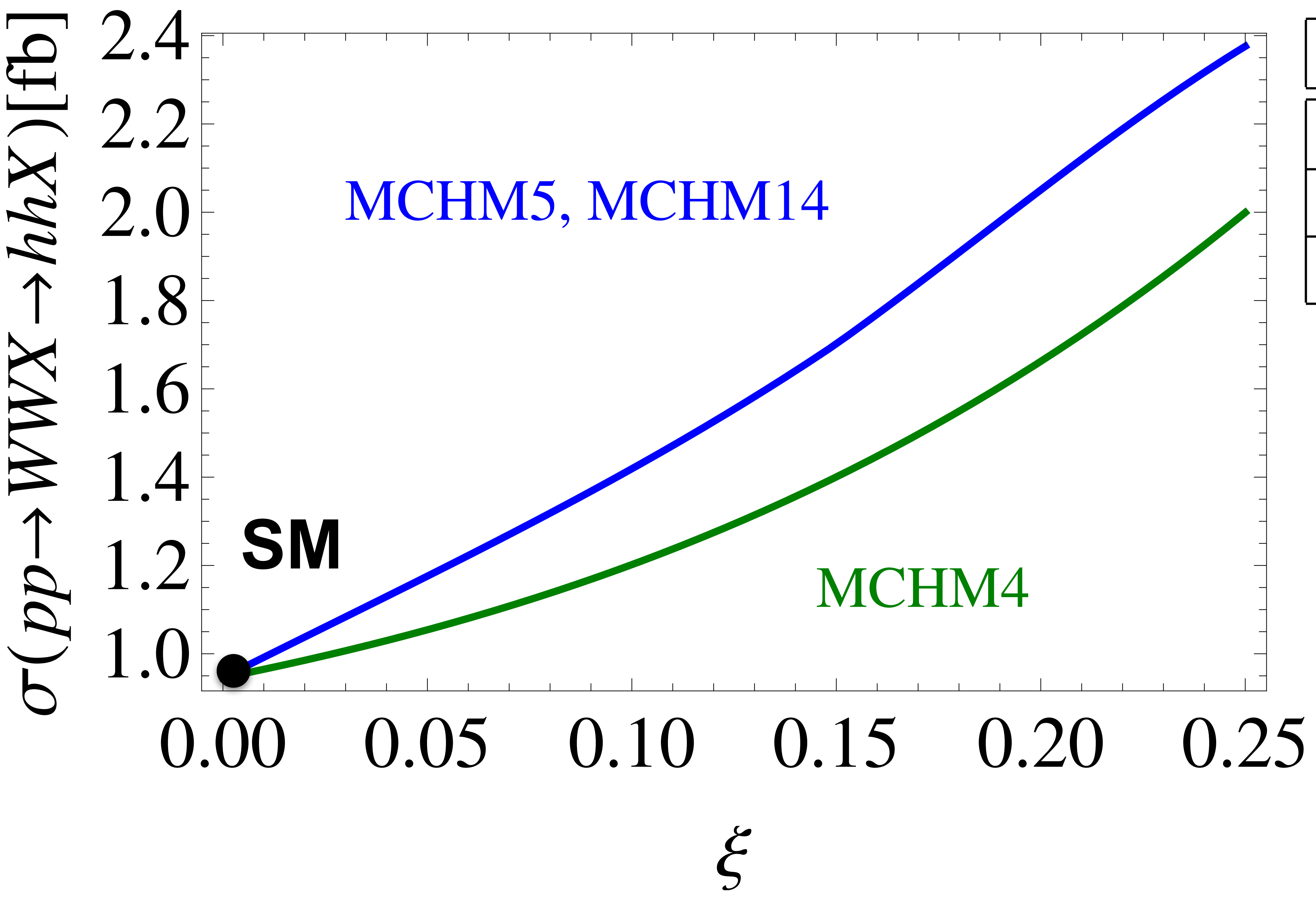
$$\mathcal{A} \simeq A_0 + \frac{g^2(c_{hhVV} - \kappa_V^2)}{4m_W^2}\hat{s}$$

The perturbative unitarity will be restored at higher energy scale M by heavy resonance contribution ("delayed unitarity")

R. Contino et al.,JHEP1005, 089

Vector Boson Fusion Process

S.Kanemura, K. Kaneta, N.Machida, S. Odori, TS, PRD94



Model	κ_V	c_{hhVV}	κ_{hhh}
MCHM_4	$1-\frac{1}{2}\xi$	$1-2\xi$	$1-\frac{1}{2}\xi$
MCHM_5			$1-\frac{3}{2}\xi$
MCHM_{14}			

$+\mathcal{O}(\xi^2)$

Delayed unitarity → **Large enhancement**

Exclusive modes

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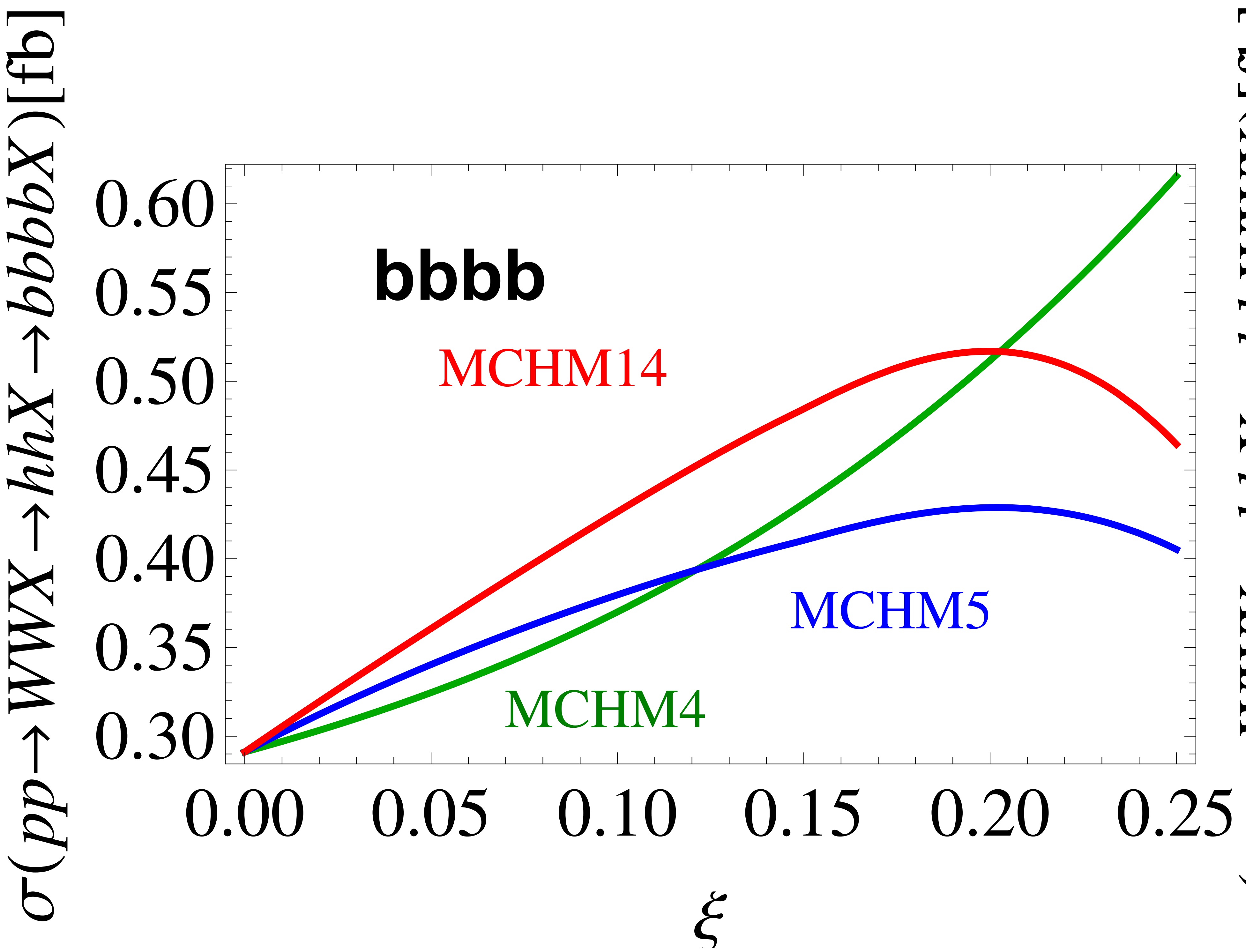
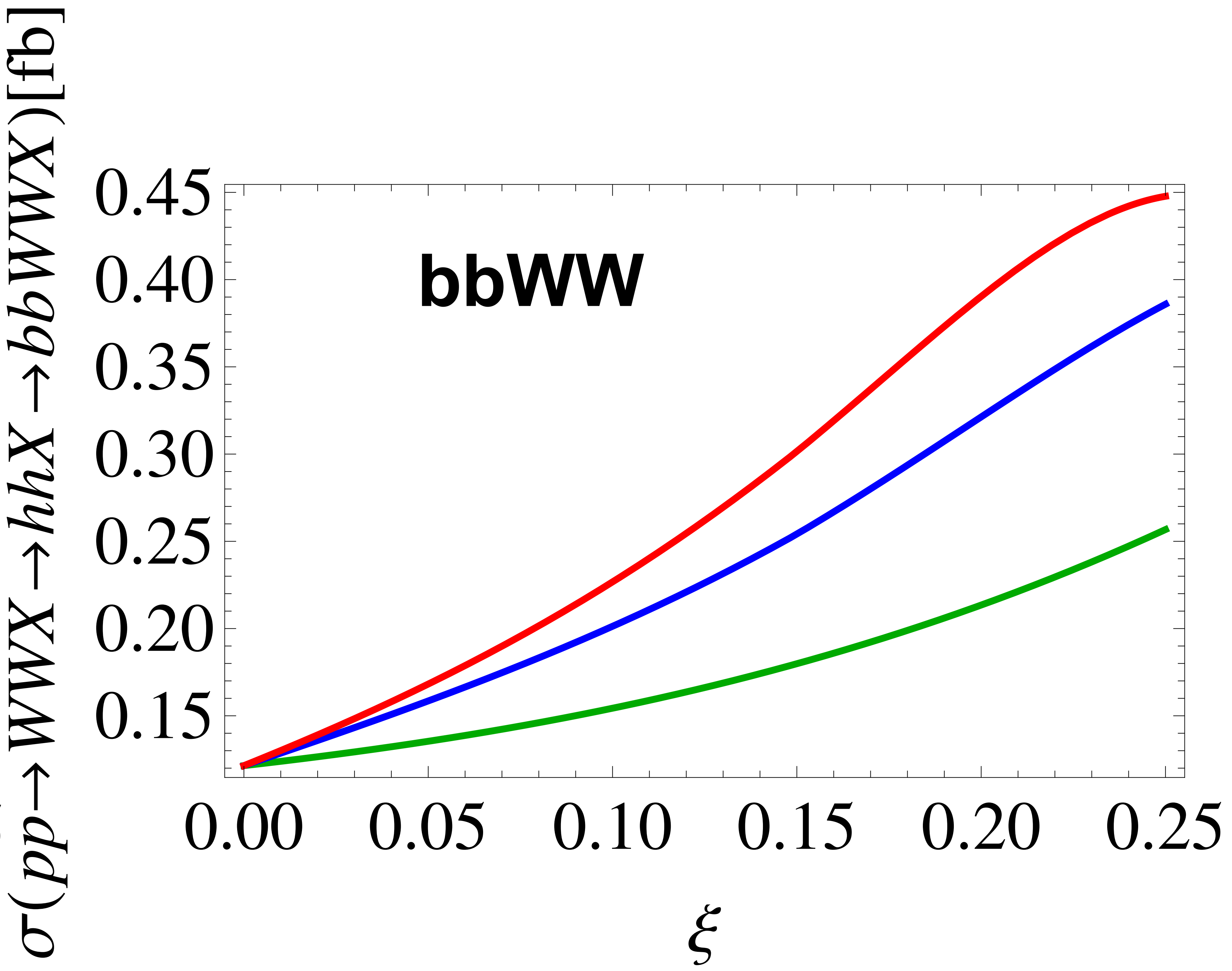


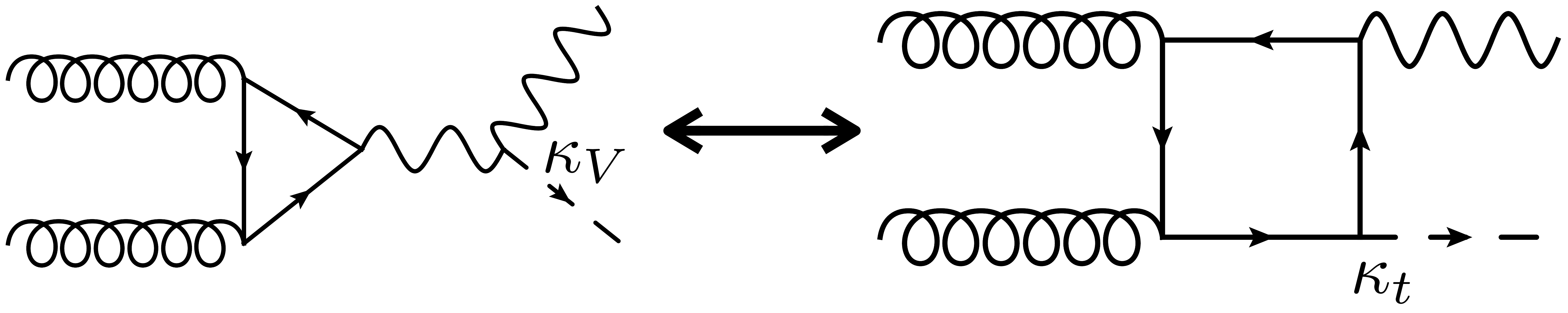


Degeneracy between MCHM5 and MCHM14 is resolved

gg to ZH

$$gg \to Zh$$

In the SM, there is a strong cancellation between diagrams



This cancellation is kept, only if relevant scale factors of couplings are universal like MCHM4

But in models with non-universal scale factors as MCHM5, we expect significant enhancement…

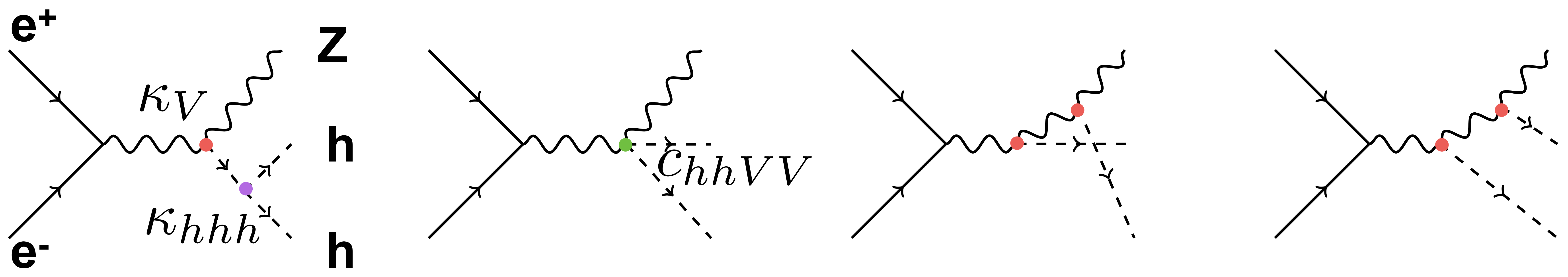
E. Accomando, D. Englert, S. Moretti, T.S. in progress

Double Higgs Production at e+e- Collider

Double Higgs production at e+e- Collider

- Double Higgs production at e+e- collider is also important process to explore the Higgs sector
- There are two processes of production
  - The double-Higgs-strahlung process
  - W-fusion process

Z Strahlung ee→Zhh



Model	κ_V	c_{hhVV}	κ_{hhh}
$MCHM_4$	$1-\frac{1}{2}\xi$	$1-2\xi$	$1-\frac{1}{2}\xi$
$MCHM_5$			$1-\frac{3}{2}\xi$
$MCHM_{14}$			

$+\mathcal{O}(\xi^2)$

The relevant couplings are suppressed

↓

The cross section is always suppressed

The production cross section

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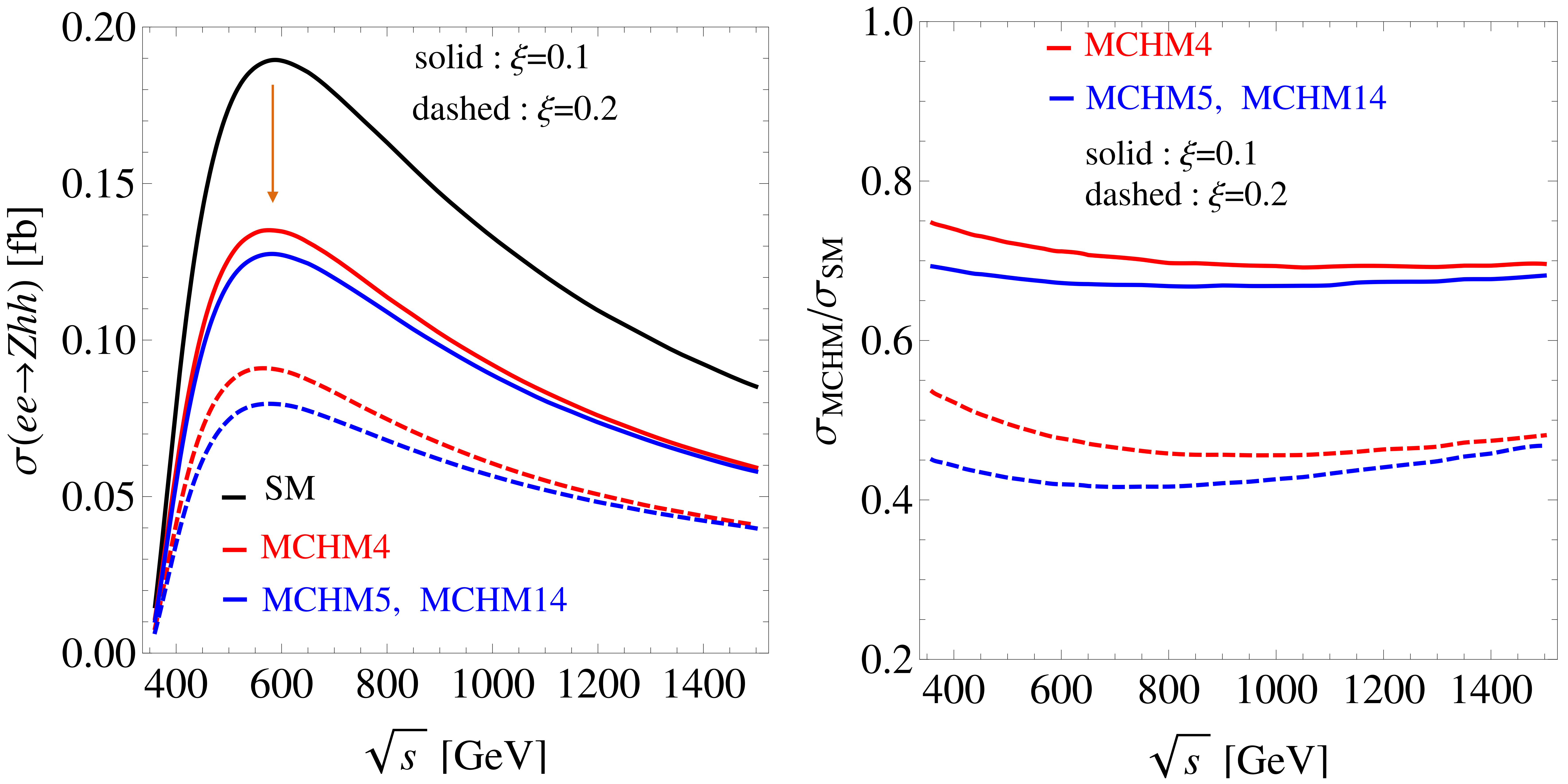


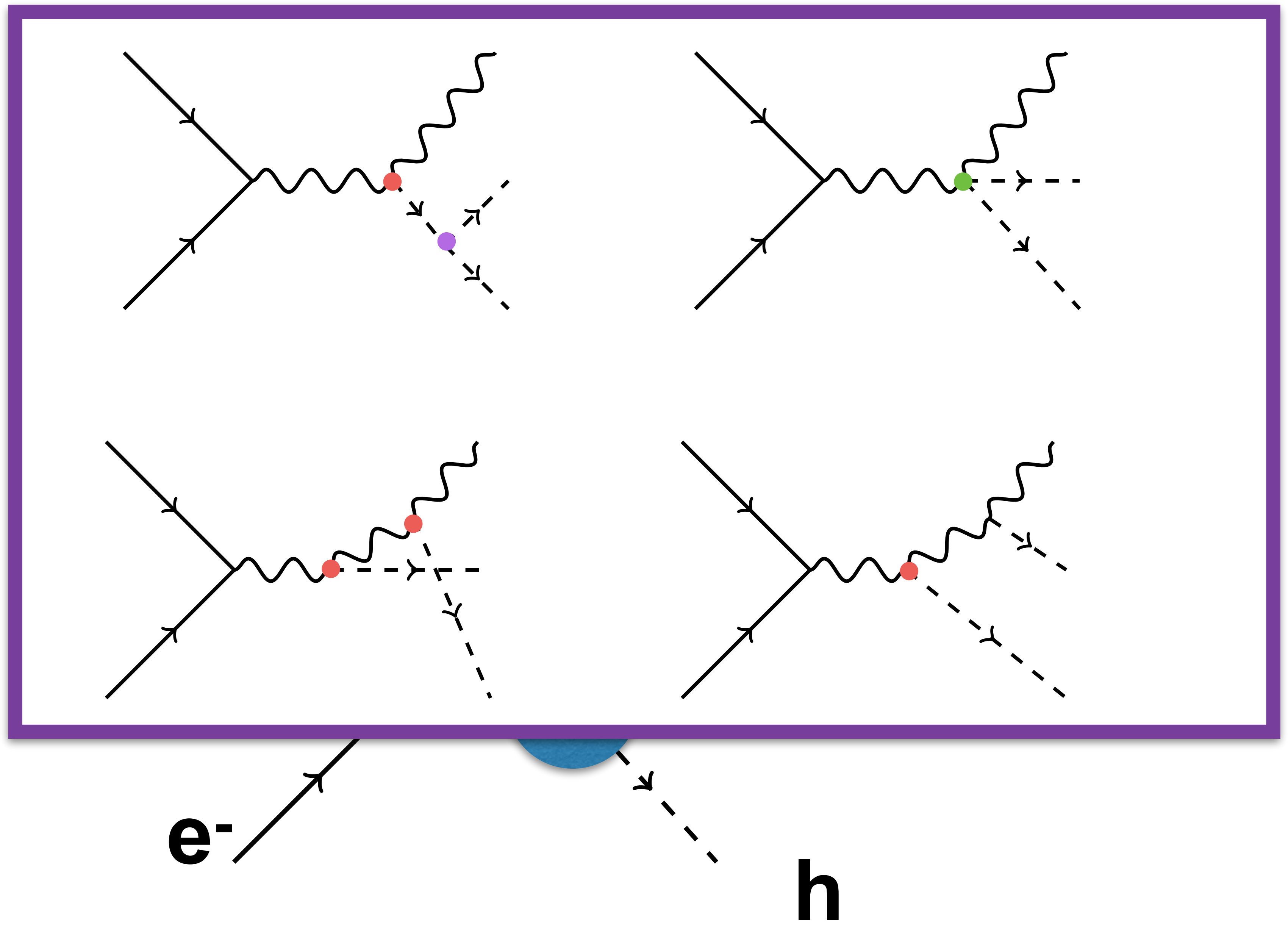
ee→hhνν

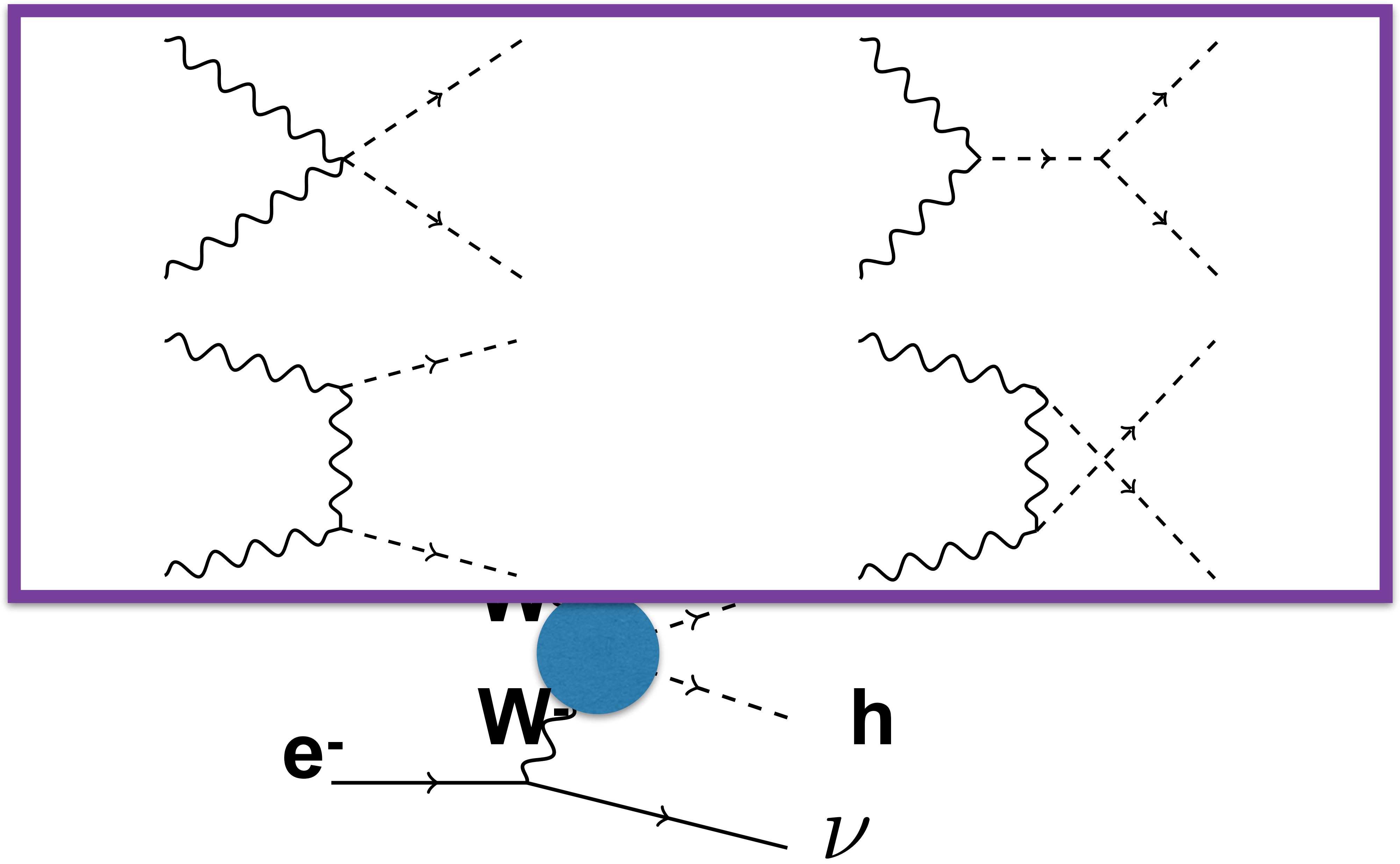
$$e^+e^- \to hh\bar{\nu}\nu$$

2 types of contributions

$$e^+e^- \to hhZ \to hh\bar{\nu}\nu$$

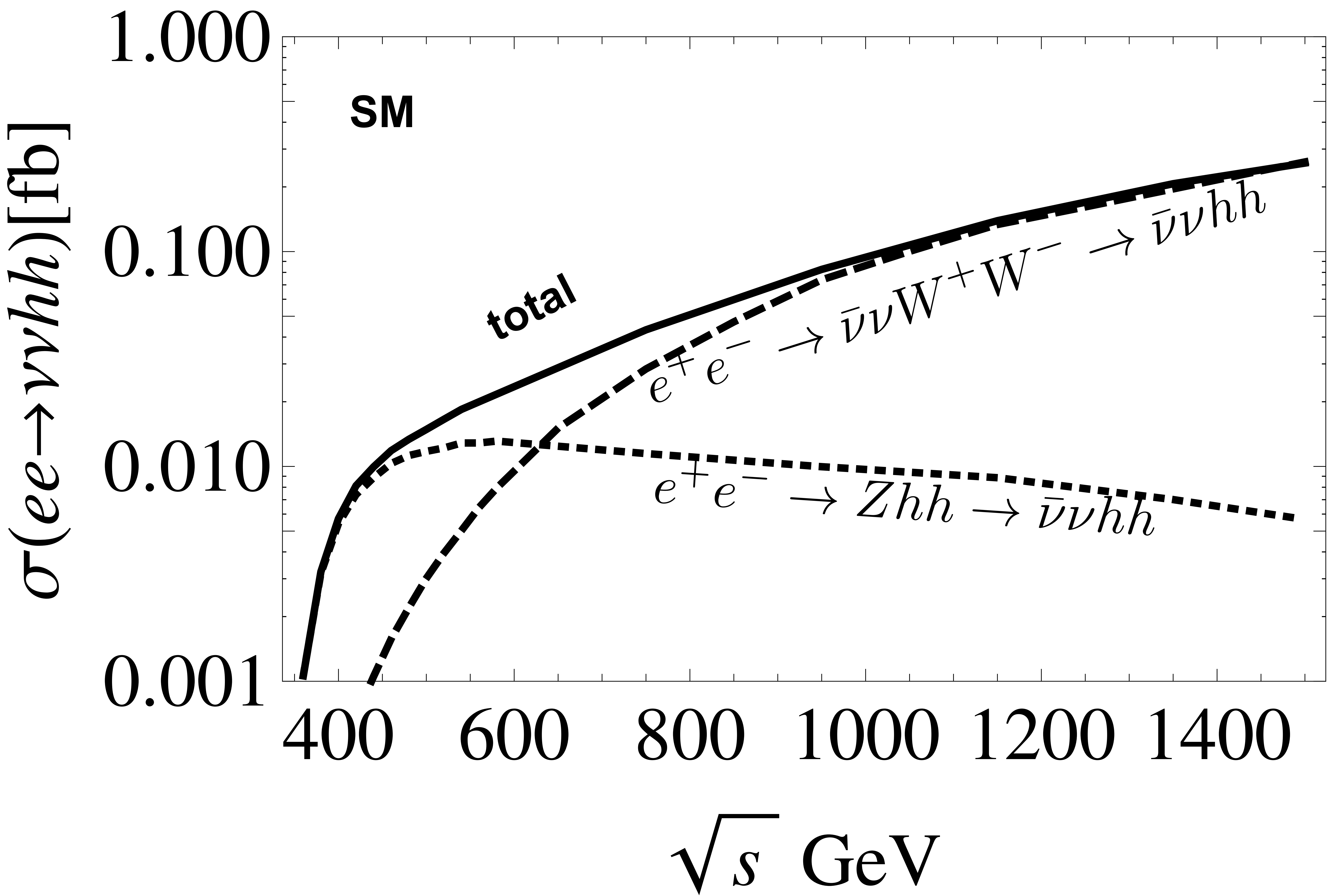
$$e^+e^- \to W^+W^-\bar{\nu}\nu \to hh\bar{\nu}\nu$$





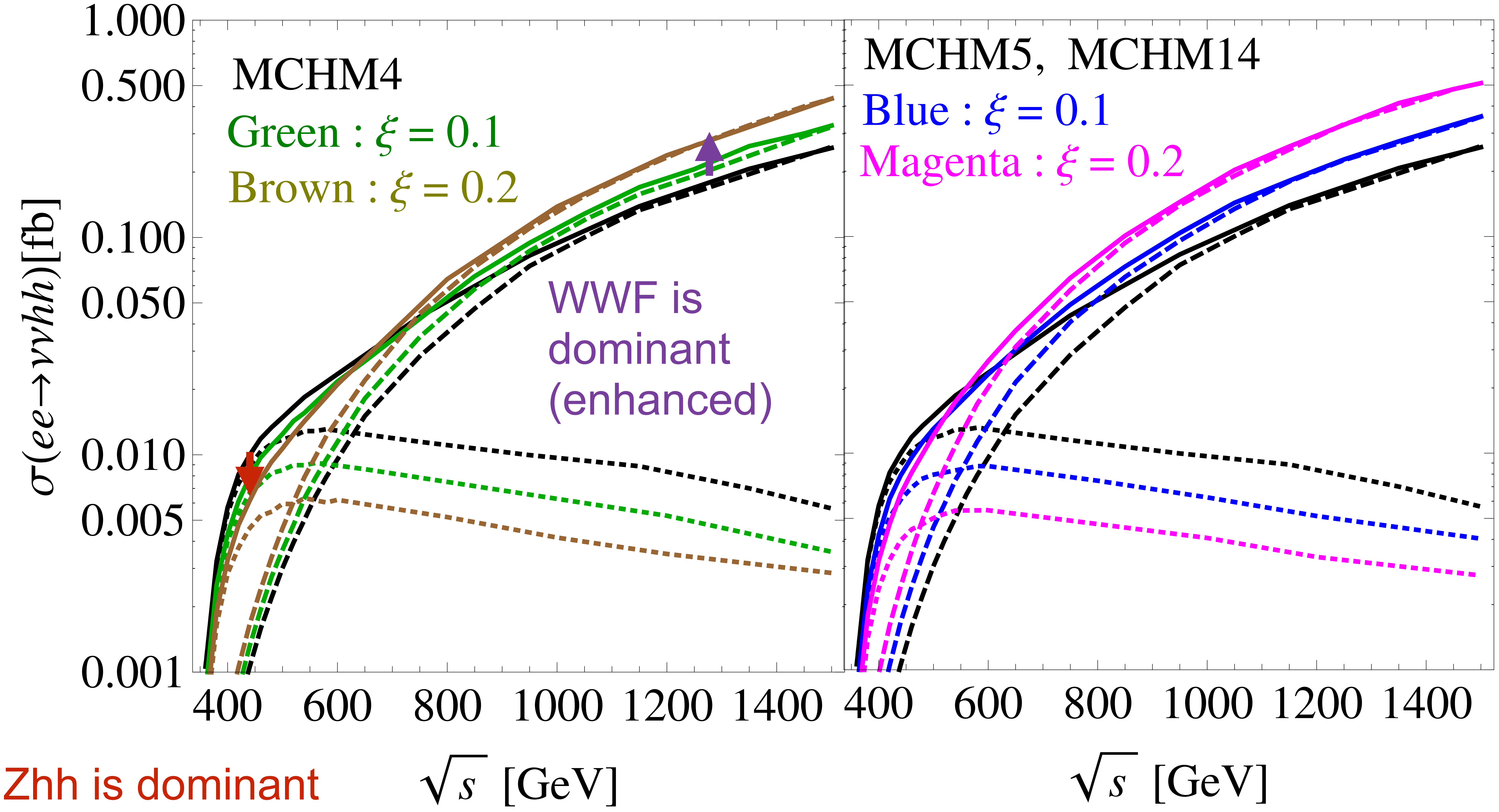
Production Cross Section

S.Kanemura, K. Kaneta, N.Machida, S. Odori, TS, PRD94



Production Cross Section

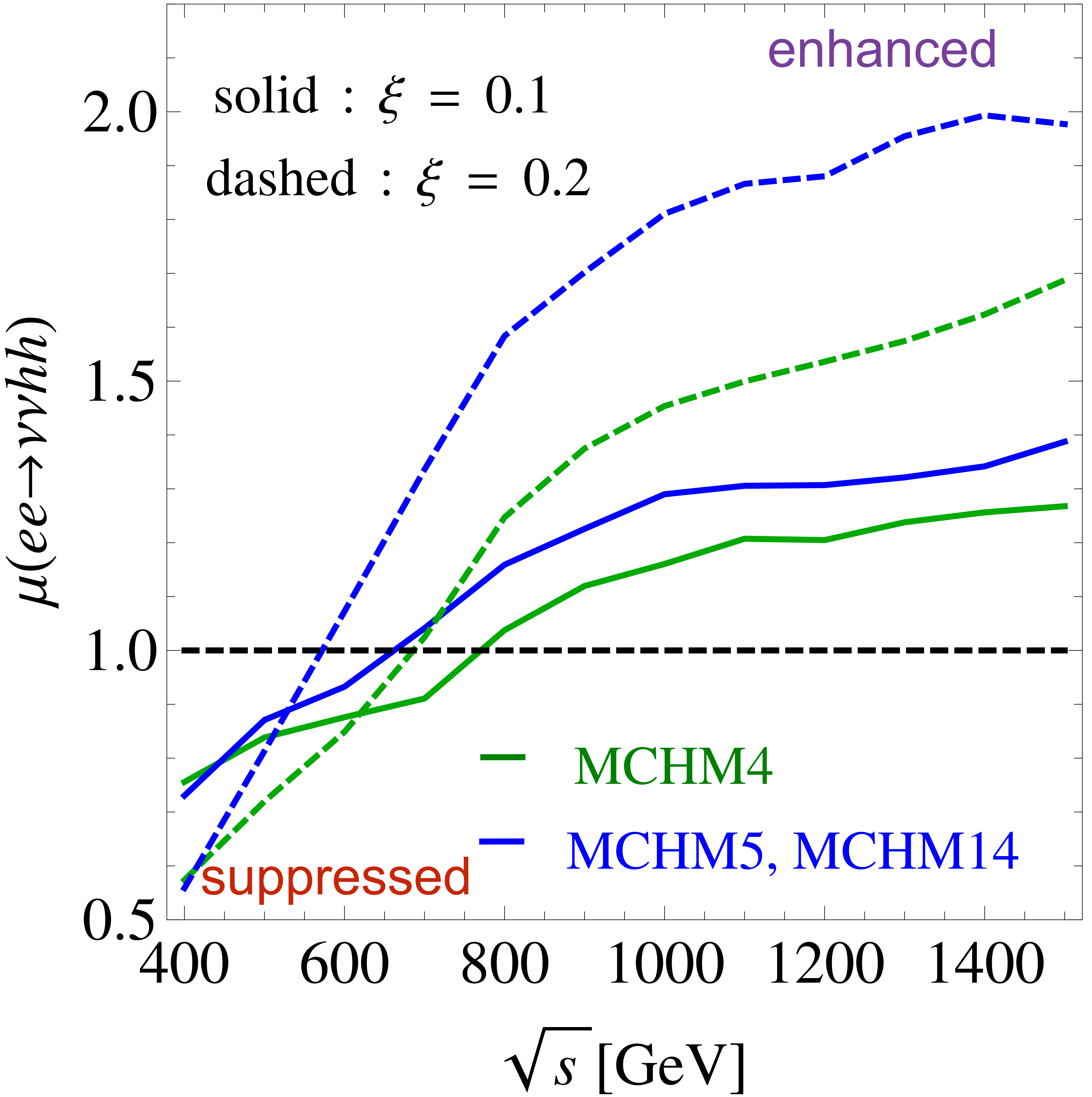
S.Kanemura, K. Kaneta, N.Machida, S. Odori, TS, PRD94



Zhh is dominant
(suppressed)

σ/σ_{SM} for energy scan

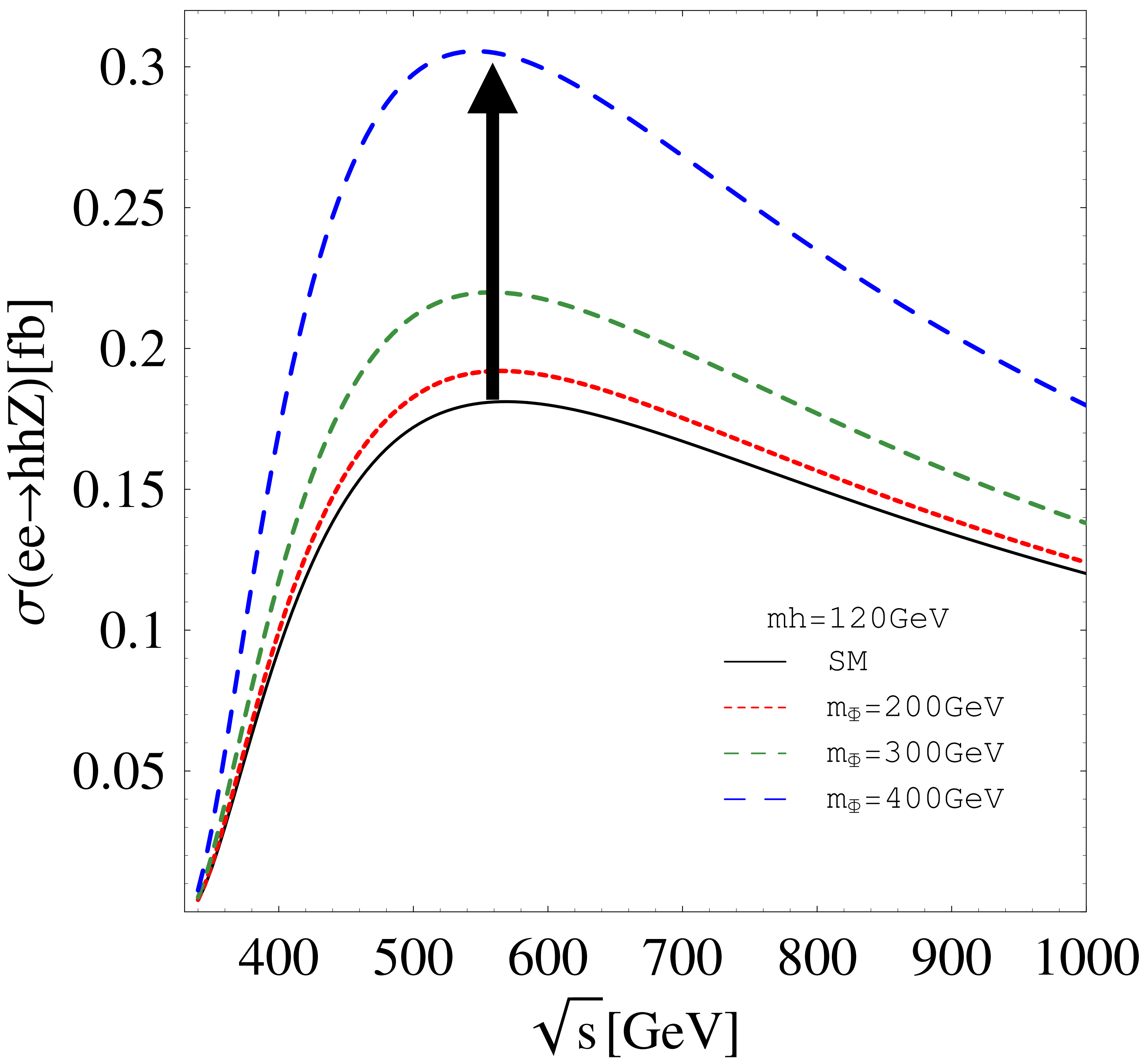
S.Kanemura, K. Kaneta, N.Machida, S. Odori, TS, PRD94

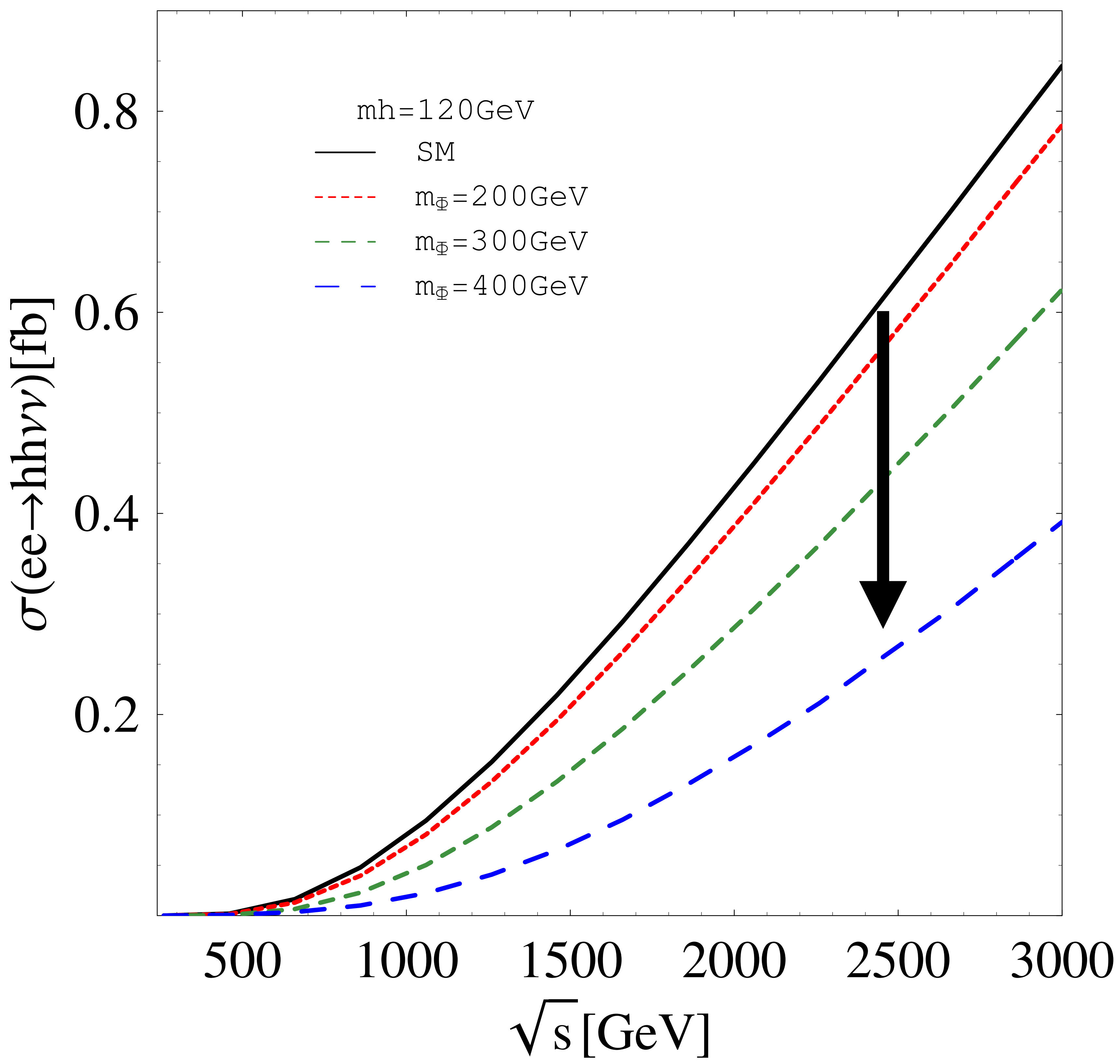


$$\mu = \frac{\sigma}{\sigma_{SM}}$$

Comparing with a 2HDM

Asakwa&Harada&Kanemura&Okada&Tsumura, PRD82,115002





MCHM case shows different behaviour from
a 2HDM with large contribution to hhh coupling

Summary

- We discuss how to probe MCHMs at collider experiments
- $gg \to Zh$ process can be useful to distinguish models
- Double Higgs production process is interesting
  - MCHM shows specific behaviour in the production cross section
  - In particular, interesting behaviour appears in the energy scan at e+e- collider

To solve problems in SM

- Framework of CHM may be able to solve hierarchy problem
- But the other problems in the SM cannot be solved in MCHMs (Neutrino mass, DM, BAU, etc)

→ Non-Minimal model

e.g. A Model by Chala, Nardini, Sobolev

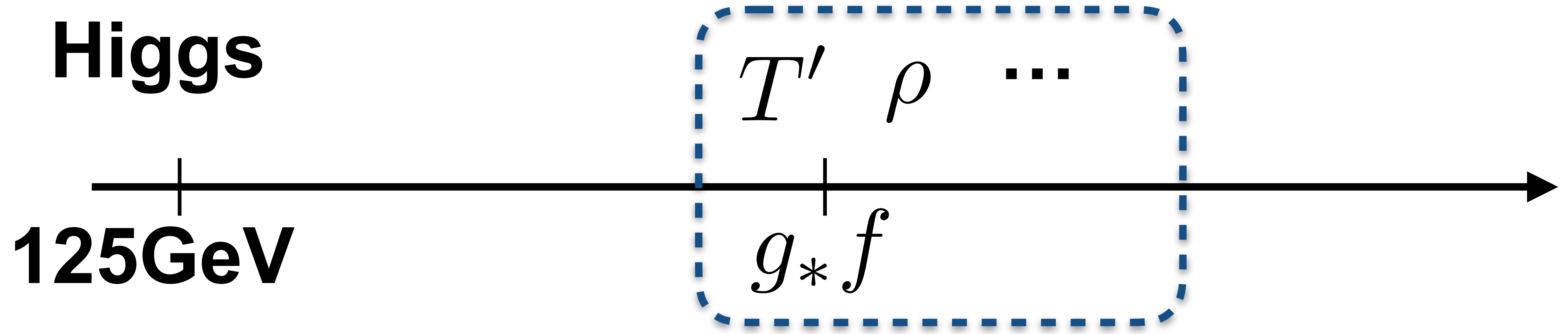
PRD94,055006

SO(7)/SO(6)→6 NGBs (1 doublet + 2 singlets)

- Two step 1st order EWPT (strong enough)
- DM candidate

Toward UV completion

In this talk, we ignore the heavy resonances



But they can significantly affect some phenomena

In order to study phenomenology with such resonances,
some UV picture should be taken into account.
(Especially, in the case of flavour phenomenology)

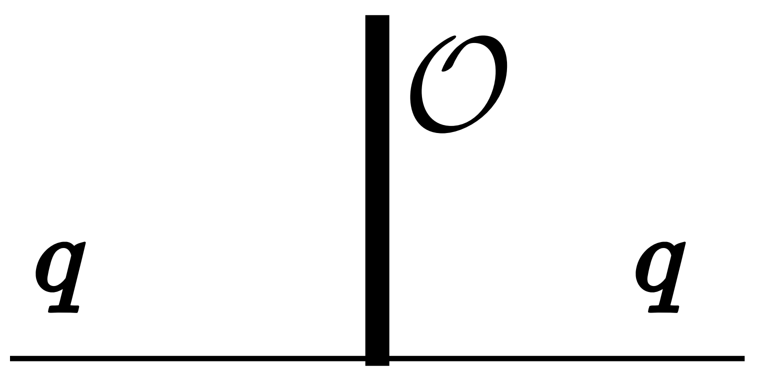
- What resonances are there?
- How is the spectrum?
- How is the flavour structure ?
- …

Fermion mass and interaction

see e.g. G. Panico, A. Wulzer 1506.01961

There are two manners

comp. sector



Bilinear type: $\mathcal{L} \supset \frac{\lambda}{\Lambda^{d-1}} \bar{q}_L \mathcal{O} t_R + \text{h.c.}$

Scalar operator of dim. d which carries Higgs quantum number

Running down to a scale μ $m_t \sim \lambda v \left(\frac{\mu}{\Lambda}\right)^{d-1}$ (d–1>0)

$$y_t = \sqrt{2}\frac{m_t}{v} \sim \lambda \left(\frac{\mu}{\Lambda}\right)^{d-1}$$

It is often difficult to provide a large top Yukawa coupling

d=1 is O.K. but it is nothing but a elementary scalar case …

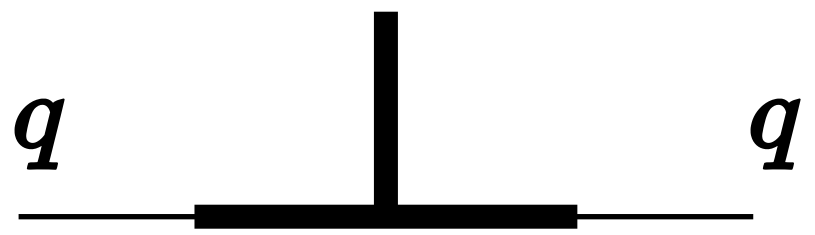
Partial Composite scenario

Kaplan, NPB365, 259

Linear type: $\mathcal{L} \supset \frac{\lambda_L}{\Lambda^{d_L - 5/2}} \bar{q}_L \mathcal{O}_L + \frac{\lambda_R}{\Lambda^{d_R - 5/2}} \bar{t}_R \mathcal{O}_R$

Fermionic operator of dim. $d_{L,R}$ which carries quark quantum number

The top mass at a scale μ $\quad m_t \sim \lambda_L \lambda_R v \left(\frac{\mu}{\Lambda}\right)^{d_L + d_R - 5}$



No direct coupling to composite sector
(only through mixing terms)

This framework is called a partial composite scenario

Toward UV completion

There are several (not many) attempts to construct a UV complete model of CHMs based on partial compositeness

SUSY	Caracciolo,Parolini,Serone(2013)
5Dim (4DCHM)	De Curtis, Redi, Tesi(2011)
TC fermion&scalar	Sannino, Strumia, Test, Vigiani (2016) Gacciapaglia, Gertov, Sannino, Thomsen (2017)
Gauge theory	Ferretti (2013),(2014), (2016)

Backup

The University was established in 1887

In the physics group: 5 faculties (incl. me)

- 2 Particle theorists
- 1 ILC experimentalist
- 2 Astrophysicists (Theorist & ALMA)

Coset: SO(7)/SO(6)

→ 6 NGBs (4 of them are identified with SM-like Higgs)

at least at the (unsuppressed) leading order. In particular, if we want κ to lead to a two-step EWPT and η to be a DM candidate without conflicting with Higgs searches (see Secs. IV and V), the following conditions must hold: (i) $\eta \to -\eta$ is an unbroken symmetry; (ii) $\mu_\kappa^2 < 0$; and (iii) the physical masses of h and κ are such that $m_h < 2m_\kappa$, which is favored by $\lambda_{h\kappa} \gtrsim \lambda_h$.

In order to realise such a situation

SM fermions are embedded to 7 and 27 of SO(7)

$$B_R = (\,0 \quad 0 \quad 0 \quad 0 \quad 0 \quad i\gamma b_R \quad b_R\,)^{\mathrm{T}}, \tag{20}$$

$$Q_L^b = \frac{1}{\sqrt{2}}(\,-it_L \quad t_L \quad ib_L \quad b_L \quad 0 \quad 0 \quad 0\,)^{\mathrm{T}}, \tag{21}$$

$$Q_L^t = \frac{1}{2}\begin{pmatrix} \mathbf{0}_{6\times 6} & & & & & & ib_L \\ & & & & & & b_L \\ & & & & & & it_L \\ & & & & & & -t_L \\ & & & & & & 0 \\ & & & & & & 0 \\ ib_L & b_L & it_L & -t_L & 0 & 0 & 0 \end{pmatrix},$$

$$Q_L^c = \frac{1}{2}\begin{pmatrix} \mathbf{0}_{5\times 5} & & & & & \zeta s_L & is_L \\ & & & & & -i\zeta s_L & s_L \\ & & & & & \zeta c_L & ic_L \\ & & & & & i\zeta c_L & -c_L \\ & & & & & 0 & 0 \\ \zeta s_L & -i\zeta s_L & \zeta c_L & i\zeta c_L & 0 & 0 & 0 \\ is_L & s_L & ic_L & -c_L & 0 & 0 & 0 \end{pmatrix}. \tag{22}$$

$$\mathcal{L}_\sigma = \mathcal{L}_{\text{kinetic}} + \frac{1}{2}\frac{(h\partial_\mu h + \eta\partial_\mu \eta + \kappa\partial_\mu \kappa)^2}{f^2 - h^2 - \eta^2 - \kappa^2}$$

$$V = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{2}\mu_\eta^2 \eta^2 + \frac{1}{2}\mu_\kappa^2 \kappa^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_\kappa \kappa^4 + \frac{1}{4}\lambda_{h\eta} h^2 \eta^2 + \frac{1}{4}\lambda_{h\kappa} h^2 \kappa^2 .$$

$$\mathcal{L}_y = -\sum_{q=t,b,c} y_q \bar{q} q h \left[1 - \frac{1}{f^2}(h^2 + \eta^2 + \kappa^2)\right]^{\frac{1}{2}} - i\frac{h}{f}\kappa[\gamma y_b \bar{b}\gamma_5 b + \zeta y_c \bar{c}\gamma_5 c],$$

$$V = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{2}\mu_\eta^2 \eta^2 + \frac{1}{2}\mu_\kappa^2 \kappa^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_\kappa \kappa^4 + \frac{1}{4}\lambda_{h\eta} h^2 \eta^2 + \frac{1}{4}\lambda_{h\kappa} h^2 \kappa^2 .$$

The quartic coupling λ_κ is generated only at the next-to-leading order, but it has been introduced since it plays an important role in the EWPT phenomenology. At any rate, it is expected to be much smaller than the other quartic couplings. The rest of the parameters are functions of the dimensionless spurion coefficients $\alpha_{q,i}$, as well as γ and ζ,

$$\mu_h^2 = -\frac{1}{2} f^2 (4\alpha_{t,1} - 7\alpha_{t,2} + \alpha_{c,2}\zeta^2), \tag{24}$$

$$\mu_\eta^2 = -2\alpha_{t,2} f^2, \tag{25}$$

$$\mu_\kappa^2 = 2 f^2 (\alpha_b \gamma^2 + \alpha_{c,2}\zeta^2 - \alpha_{t,2}), \tag{26}$$

$$\lambda_h = 4(\alpha_{t,2} - \alpha_{t,1}), \tag{27}$$

$$\lambda_{h\eta} = 4(\alpha_{t,2} - \alpha_{t,1}), \tag{28}$$

$$\lambda_{h\kappa} = 4[\alpha_{t,2} - \alpha_{t,1} + (\alpha_{c,1} - \alpha_{c,2})\zeta^2]. \tag{29}$$

Two Regimes:

Regime I: $\alpha_{c,2} = -\alpha_{c,1}$. This is the most natural scenario since the size of these two coefficients is expected to be similar, and it still allows for $\lambda_{h\kappa} \gtrsim \lambda_h$, contrary to the case $\alpha_{c,2} = \alpha_{c,1}$.

Regime II: $|\alpha_{c,2}| \ll |\alpha_{c,1}| \sim |\alpha_{t,i}/\zeta^2|$. As we will see, accounting for the DM relic density observation will completely fix the mass of η and its interactions with nuclei in this case.[4]

in *Regime I* we obtain

$$\mu_\eta^2 = \frac{1}{3} f^2 \left[\frac{7}{4}\lambda_h + \frac{1}{4}\lambda_{h\kappa} - 4\lambda_h \xi\right], \tag{30}$$

$$\lambda_{h\eta} = \lambda_h, \tag{31}$$

while in *Regime II* we get

$$\mu_\eta^2 = \frac{2}{3}\lambda_h f^2 (1 - 2\xi), \tag{32}$$

$$\lambda_{h\eta} = \lambda_h, \tag{33}$$

Annihilation processes:

$$\sigma(\eta\eta \to hh)v_0 \sim \frac{1}{m_\eta^2}\left[\lambda_h - \frac{4m_\eta^2}{f^2}\right]^2, \tag{35}$$

$$\sigma(\eta\eta \to \kappa\kappa)v_0 \sim \frac{1}{m_\eta^2}\left[\frac{4m_\eta^2}{f^2}\right]^2, \tag{36}$$

$$\sigma(\eta\eta \to t\bar{t})v_0 \sim \frac{1}{m_\eta^2}\left[\frac{m_t m_\eta}{f^2}\right]^2, \tag{37}$$

Different from SO(6)/SO(5)

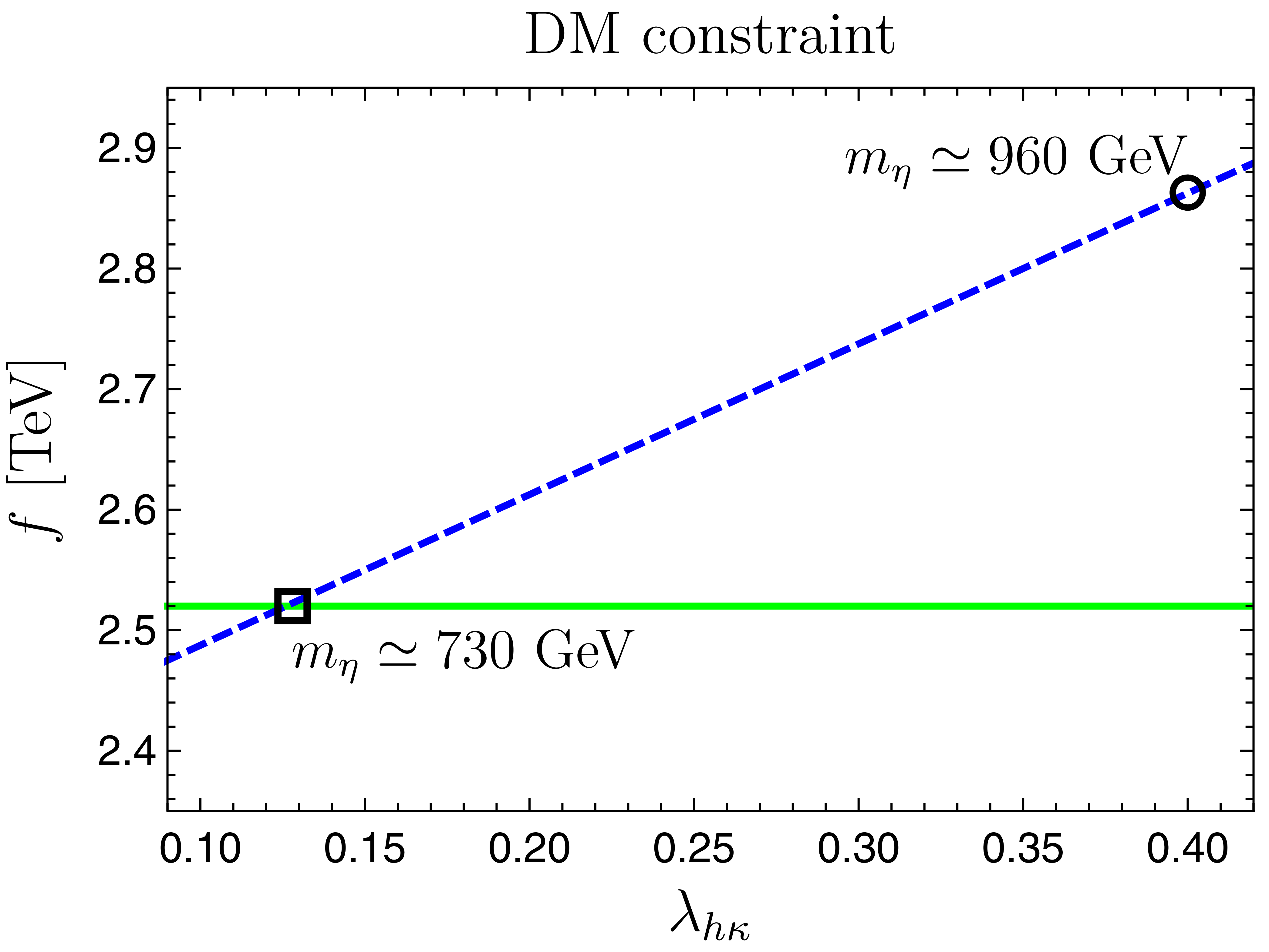


FIG. 2. Value of f leading to $\Omega_\eta = \Omega_{\rm DM}$ as a function of $\lambda_{h\kappa}$ in *Regime I* (dashed blue line) and *Regime II* (solid green line). The masses m_η corresponding to two extreme points are also depicted.

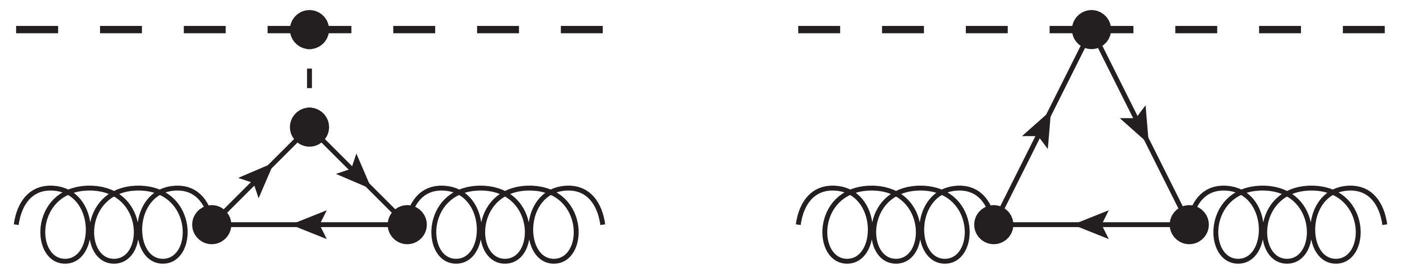


FIG. 4. Main diagrams contributing to the scattering of DM particles by nuclei.

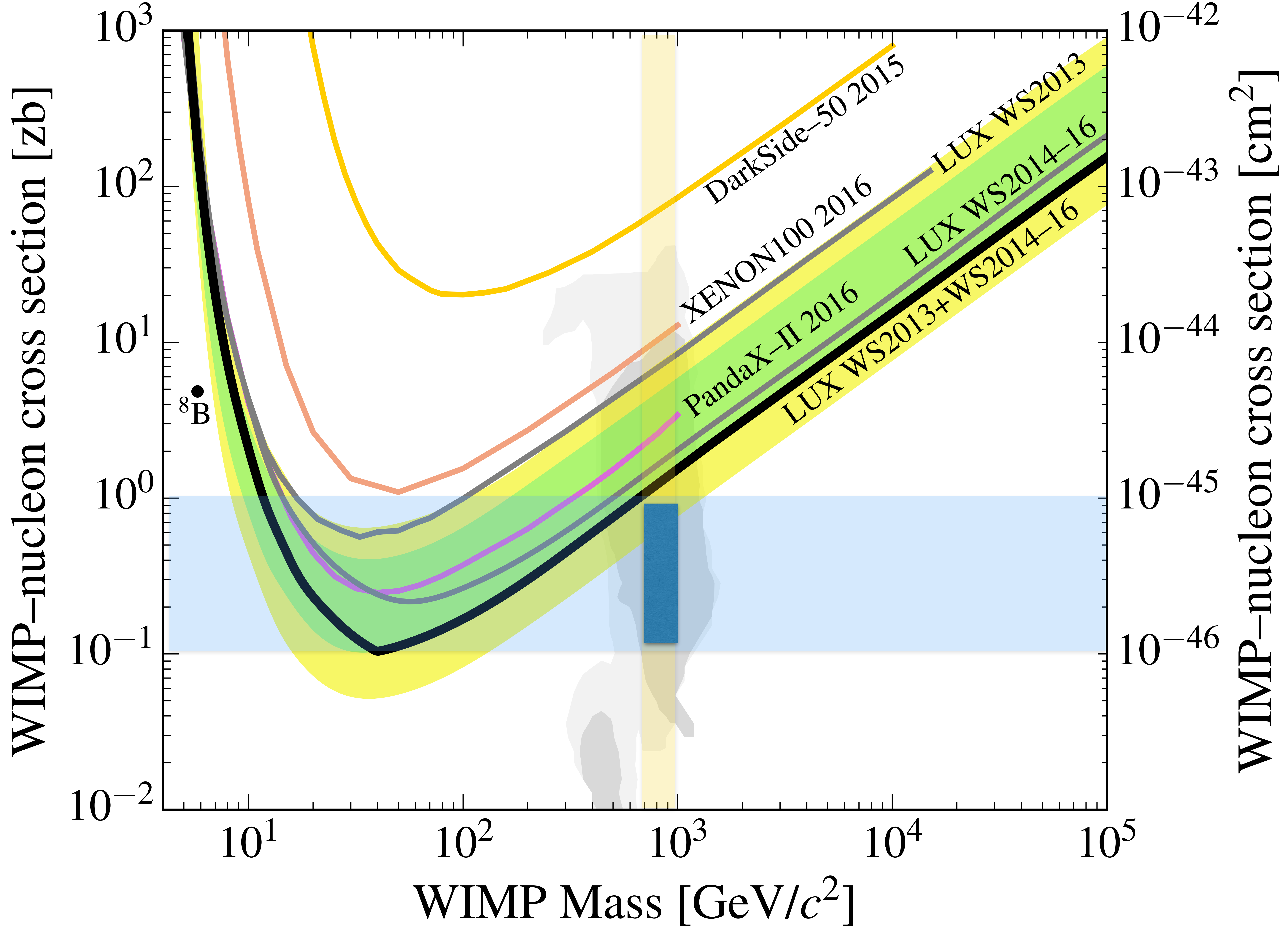
Concerning direct detection experiments, the two main diagrams contributing to the scattering between DM particles and nuclei are depicted in Fig. 4. The corresponding cross section can be parametrized as [22]

$$\sigma = \lambda_h^2 \frac{f_N^2}{4\pi} \frac{\mu_r^2 m_n^2}{m_h^4 m_\eta^2} \left[1 + \frac{m_\eta^2}{f^2}\right], \tag{56}$$

where m_n is the nucleon mass, μ_r is the reduced mass of the system (with $m_\eta \gg m_n$)

$$\mu_r = \frac{m_\eta m_n}{m_\eta + m_n} \sim m_n \sim 1 \text{ GeV}, \tag{57}$$

and $f_N \sim 0.3$ [54–56]. For the considered ranges of parameter values, Eq. (56) yields $\sigma \sim 10^{-46}$–10^{-45} cm^2, depending on the actual value of f. These values are around 1 order of magnitude below the Large Underground Xenon (LUX) experiment bound in the DM mass range 730–960 GeV [57]. However, it will definitely be reachable in the new round of data and experiments [58].[11]



WIMP–nucleon cross section [zb]
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
DarkSide–50 2015
XENON100 2016
LUX WS2013
LUX WS2014–16
PandaX–II 2016
LUX WS2013+WS2014–16
^{8}B
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^1
10^2
10^3
10^4
10^5

EWPT

Two step phase transition:

$$v_1 = (v, 0, 0)$$
$$v_2 = (0, v_\kappa, 0)$$
$$(h, \kappa, \eta)$$

$$(0,0,0) \to v_2(T'), \quad v_2(T_n) \to v_1(T_n) \quad (T' > T_n)$$

$$|v_1(T_n)|/T_n > 1$$ **: necessary for EWBG**

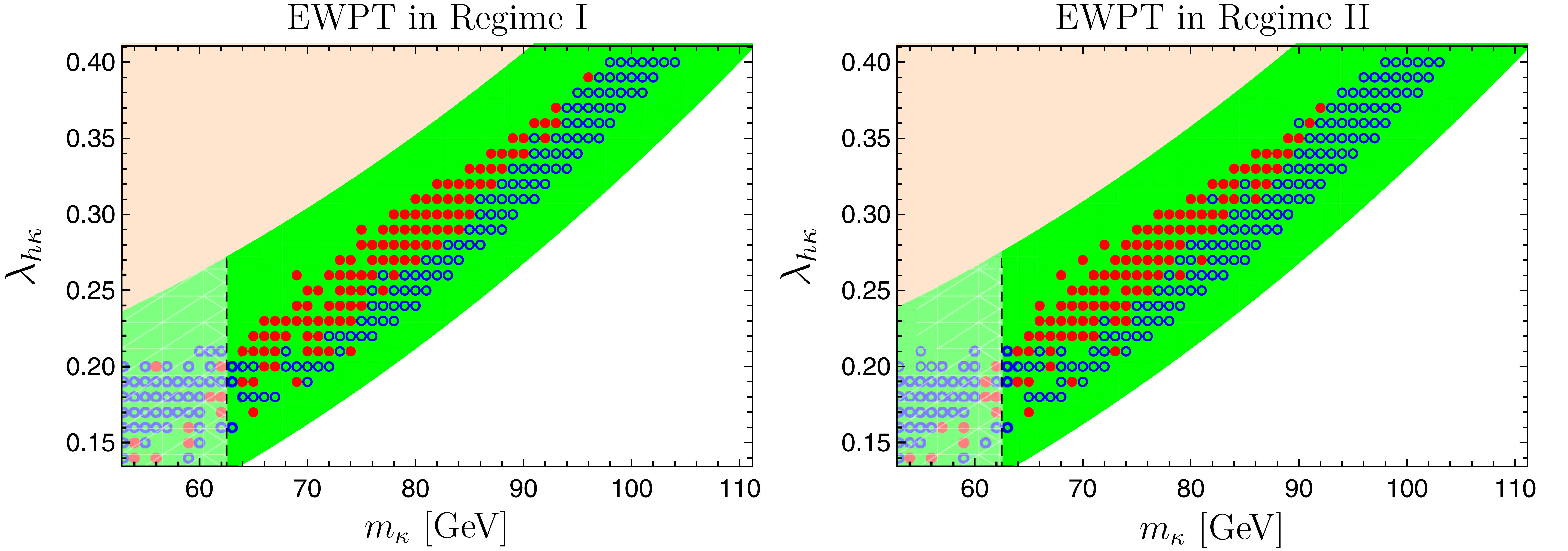


FIG. 3. Scatter plot of the parameter space exhibiting a strong EWPT in *Regime I* (left panel) and *Regime II* (right panel). The region in green indicates the points for which $V_{1L}(h, \kappa; T=0)$ has a local minimum at v_1 (the contrary in the white area) and such a minimum is deeper than the one at v_2 (the contrary in the orange area). The points on the left of the black dashed line are unfavored by the Higgs searches. The filled (empty) circles correspond to EWPTs with bubbles expanding (not expanding) at the speed of light. For some parameter points the outcome is not determined because of numerical instabilities in CosmoTransitions, as commented in footnote 9.

eLISA sensitivity

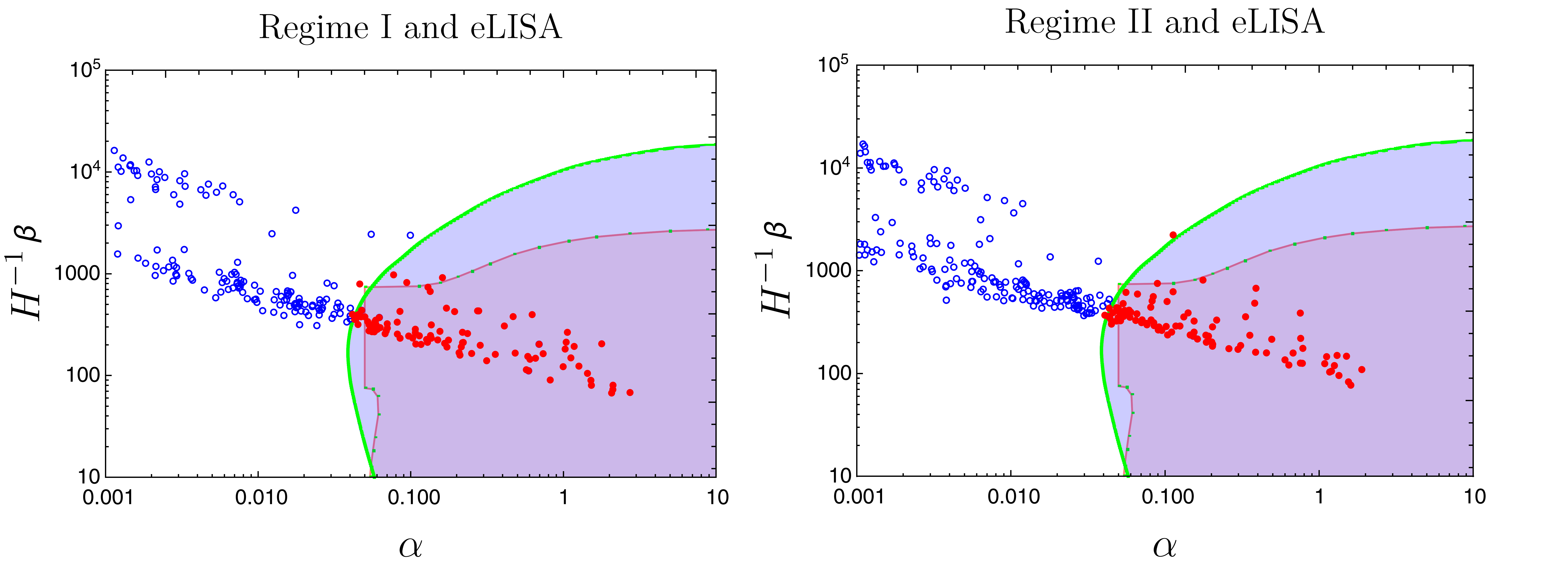


FIG. 5. The identified first-order EWPTs of *Regime I* (left panel) and *Regime II* (right panel) in the $\{\alpha, \beta/H\}$ plane. Empty blue circles and filled red circles represent the EWPTs with a nonrunaway and a runaway behavior, respectively. eLISA in the N2A5M5L6 experimental design can test the nonrunaway EWPTs in the (either purple or blue) region on the right of the green curve and the runaway EWPTs in the (purple) region on the right of the red curve.

Measurements at LHC RUN-I

ATLAS-CONF-2015-044

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
10-parameter fit of μ_F^f and μ_V^f				
$\mu_V^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$^{+0.42}_{-0.38}$	$0.69^{+0.64}_{-0.58}$	$1.37^{+0.62}_{-0.56}$
μ_V^{ZZ}	$0.48^{+1.37}_{-0.91}$	$^{+1.16}_{-0.84}$	$0.26^{+1.60}_{-0.91}$	$1.44^{+2.32}_{-2.30}$
μ_V^{WW}	$1.38^{+0.41}_{-0.37}$	$^{+0.38}_{-0.35}$	$1.56^{+0.52}_{-0.46}$	$1.08^{+0.65}_{-0.58}$
$\mu_V^{\tau\tau}$	$1.12^{+0.37}_{-0.35}$	$^{+0.38}_{-0.36}$	$1.29^{+0.58}_{-0.53}$	$0.87^{+0.49}_{-0.45}$
μ_V^{bb}	$0.65^{+0.30}_{-0.29}$	$^{+0.32}_{-0.30}$	$0.50^{+0.39}_{-0.37}$	$0.85^{+0.47}_{-0.44}$
$\mu_F^{\gamma\gamma}$	$1.19^{+0.28}_{-0.25}$	$^{+0.25}_{-0.23}$	$1.31^{+0.37}_{-0.34}$	$1.01^{+0.34}_{-0.31}$
μ_F^{ZZ}	$1.44^{+0.38}_{-0.34}$	$^{+0.29}_{-0.25}$	$1.73^{+0.51}_{-0.45}$	$0.97^{+0.54}_{-0.42}$
μ_F^{WW}	$1.00^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$1.10^{+0.29}_{-0.26}$	$0.85^{+0.28}_{-0.25}$
$\mu_F^{\tau\tau}$	$1.10^{+0.61}_{-0.58}$	$^{+0.56}_{-0.53}$	$1.72^{+1.24}_{-1.13}$	$0.91^{+0.69}_{-0.64}$
μ_F^{bb}	$1.09^{+0.93}_{-0.89}$	$^{+0.91}_{-0.86}$	$1.51^{+1.15}_{-1.08}$	$0.10^{+1.83}_{-1.86}$

μ_V^{XX} :VBF+VH μ_F^{XX} :ggF+tth

Finger printing of MCHM

Kanemura,Kaneta,Machida, TS, PRD91,115016

Q-U-D,	hVV	$hhVV$	hhh	$hhhh$	huu	hdd	$hhuu$	$hhdd$
MCHM_4	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
MCHM_5	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM_{10}	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM_{14}	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ
$\mathrm{MCHM}_{5\text{-}1\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	0	no EWSB 0	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
$\mathrm{MCHM}_{5\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
$\mathrm{MCHM}_{5\text{-}10\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
$\mathrm{MCHM}_{5\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_8	$-\xi$
$\mathrm{MCHM}_{10\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
$\mathrm{MCHM}_{10\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
$\mathrm{MCHM}_{14\text{-}1\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
$\mathrm{MCHM}_{14\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_4	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ
$\mathrm{MCHM}_{14\text{-}10\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
$\mathrm{MCHM}_{14\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ

Finger printing of MCHM

Kanemura,Kaneta,Machida, TS, PRD91,115016

$$F_3 \equiv \frac{1}{\sqrt{1-\xi}} \frac{3(1-2\xi)M_1^t + 2(4-23\xi+20\xi^2)M_2^t}{3M_1^t + 2(4-5\xi)M_2^t},$$

$$F_4 \equiv \sqrt{1-\xi}\frac{M_1^t + 2M_2^t(1-3\xi)}{M_1^t + 2M_2^t(1-\xi)},$$

$$F_5 \equiv \sqrt{1-\xi}\frac{M_1^t - M_2^t(4-15\xi)}{M_1^t - M_2(4-5\xi)},$$

$$F_6 \equiv -4\xi\frac{3M_1^t + (23-40\xi)M_2^t}{3M_1^t + 2(4-5\xi)M_2^t},$$

$$F_7 \equiv -\xi\frac{M_1^t + 2M_2^t(7-9\xi)}{M_1^t + 2M_2^t(1-\xi)},$$

$$F_8 \equiv -\xi\frac{M_1^t - M_2^t(34-45\xi)}{M_1^t - M_2(4-5\xi)}.$$

$$H_1 = 1 - \frac{3\xi}{2} - \frac{5\xi^2}{8} + \frac{1}{3m_h^2}\left(-\frac{21m_h^2}{16} + \frac{48\gamma}{v^2}\right)\xi^3,$$

$$H_2 = 1 - \frac{25\xi}{2} + \xi^2 + \frac{1}{3m_h^2}\left(3m_h^2 + \frac{288\gamma}{v^2}\right)\xi^3.$$

With 14-rep the Higgs potential has the form of

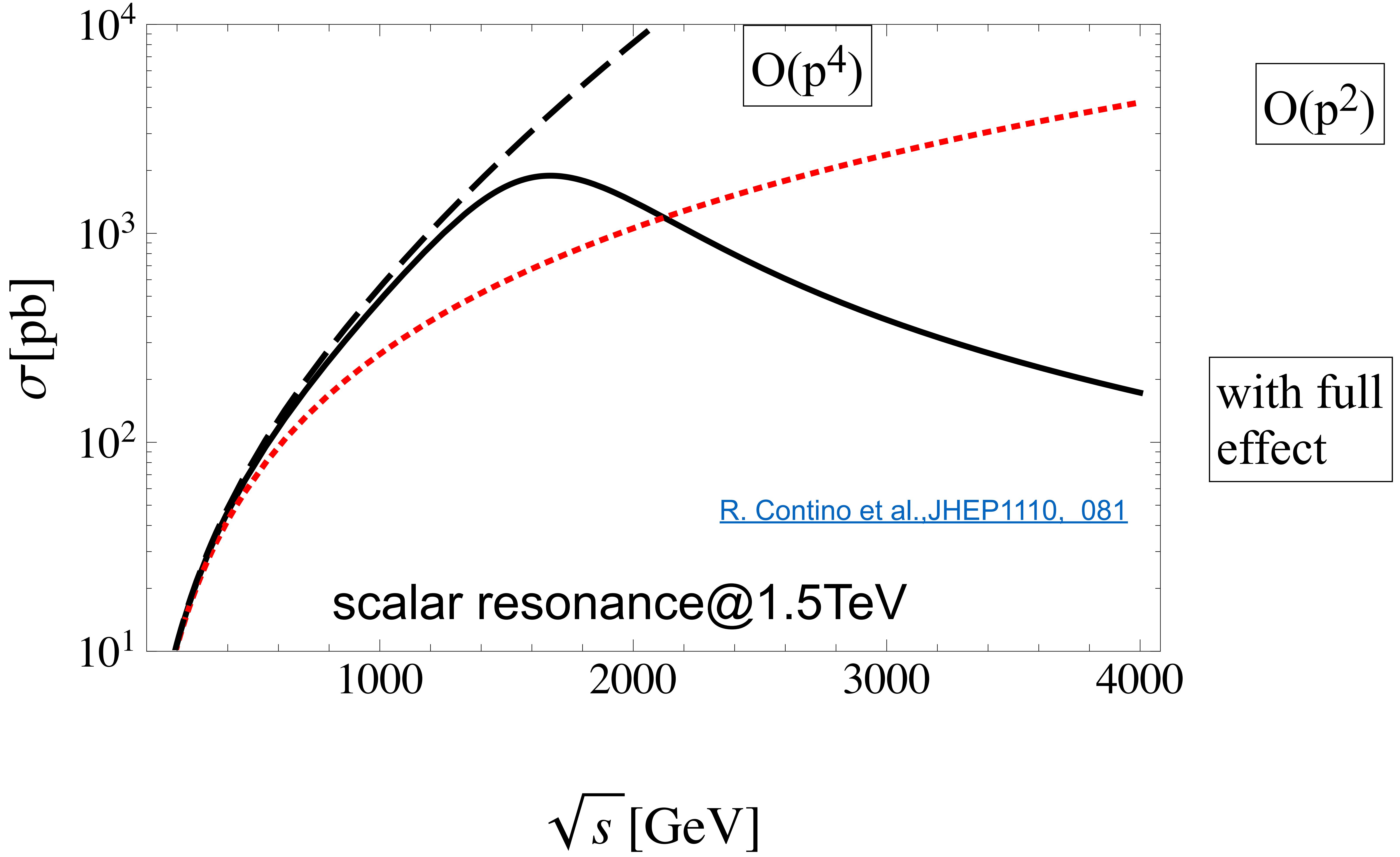
$$V \simeq \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f} + \gamma \sin^6 \frac{h}{f}$$

In the cases of (q_L,t_R)=(14,14),(14,5),(5,14), the mass terms includes

$$\begin{aligned}\mathcal{L}_{\rm matter} =& \bar{\Psi}_{q_L} M_0^t \Psi_{t_R} \\ &+ (\Sigma\bar{\Psi}_{q_L})M_1^t(\Psi_{t_R}\Sigma^\dagger) \\ &+ (\Sigma\bar{\Psi}_{q_L}\Sigma^\dagger)M_2^t(\Sigma\Psi_{t_R}\Sigma^\dagger)\end{aligned}$$

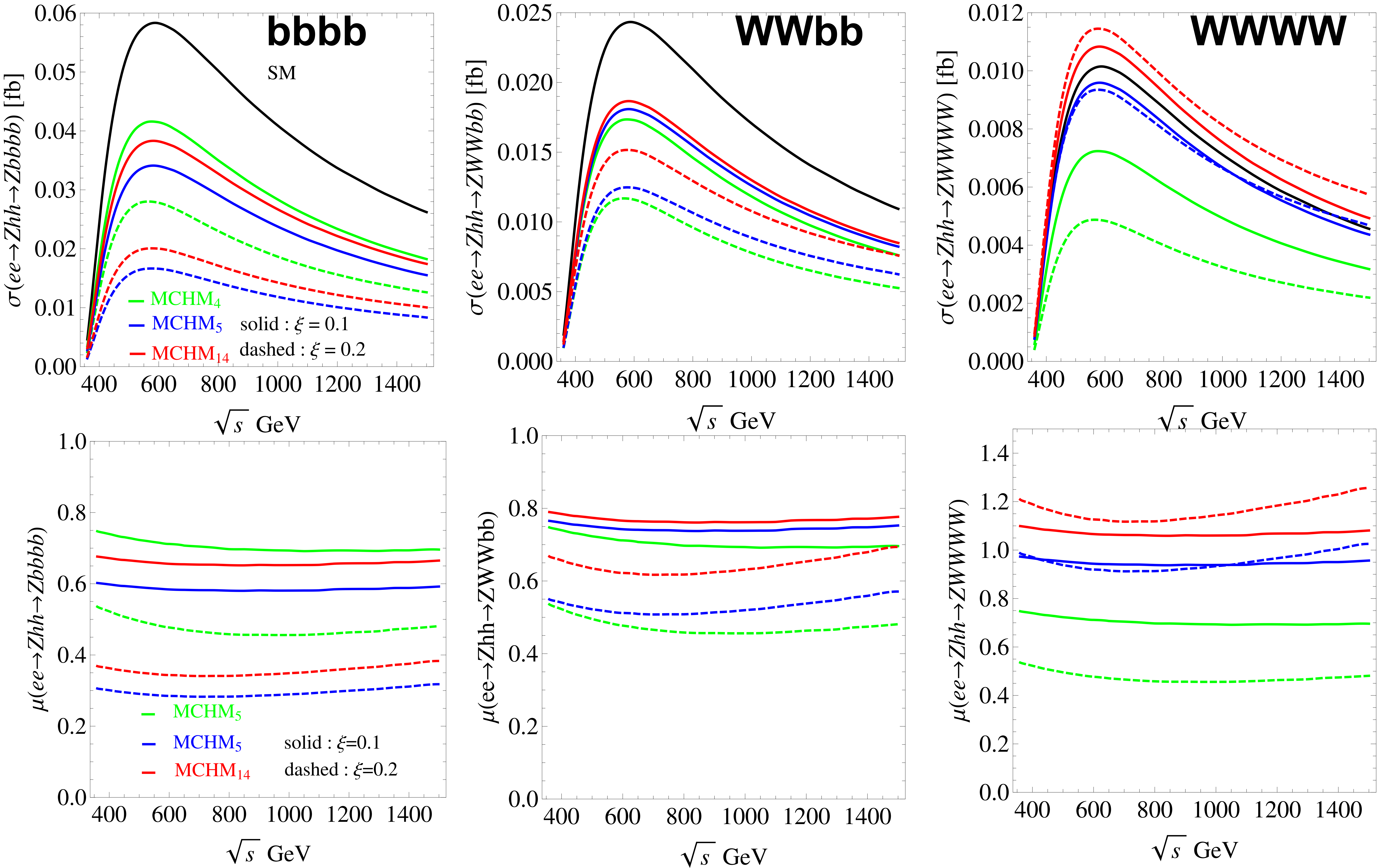
Delayed Unitarity

$W^+W^- \to hh$



Including decay of h

S.Kanemura, K. Kaneta, N.Machida, S. Odori, TS, PRD94



ee→hh$\nu\nu$

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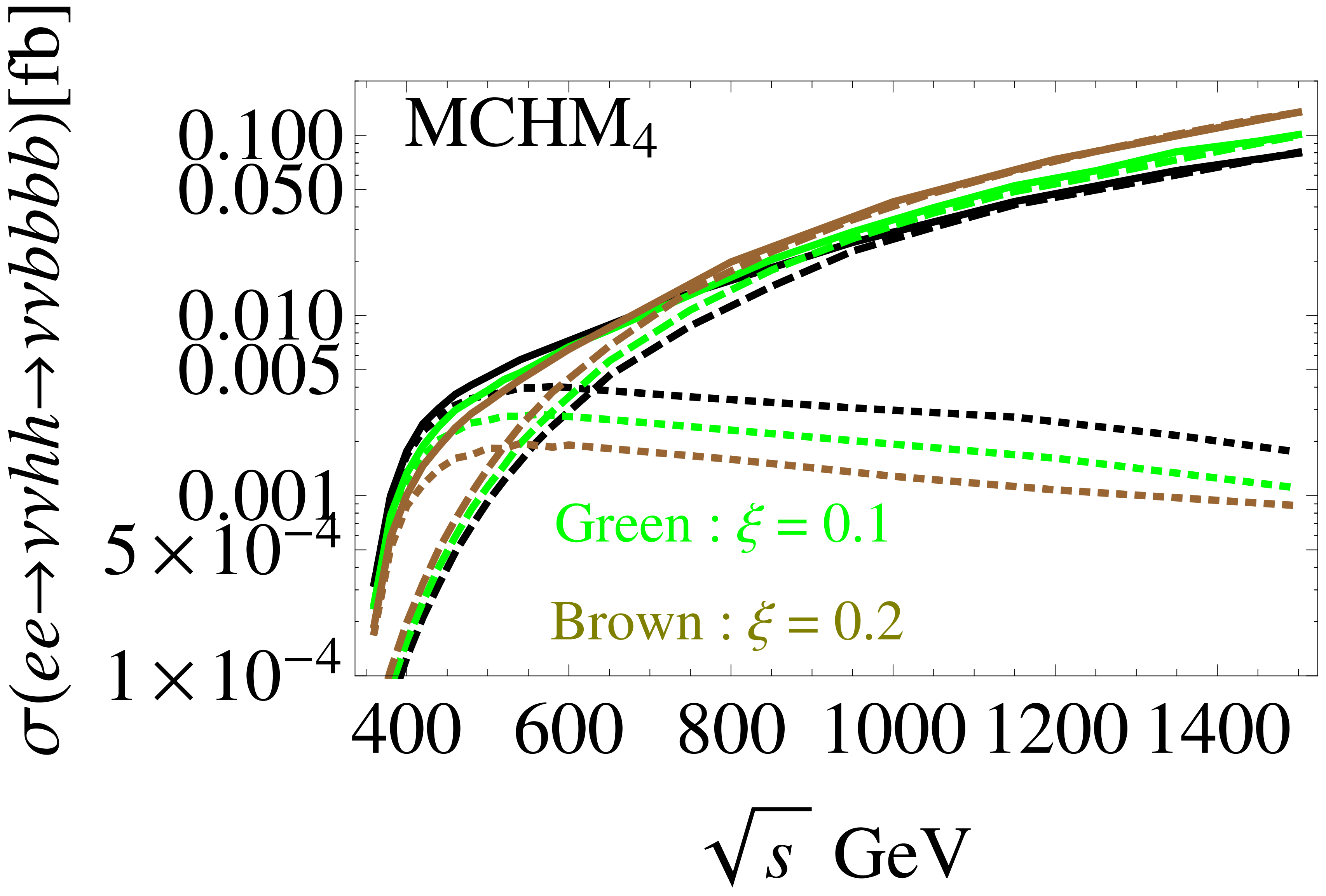

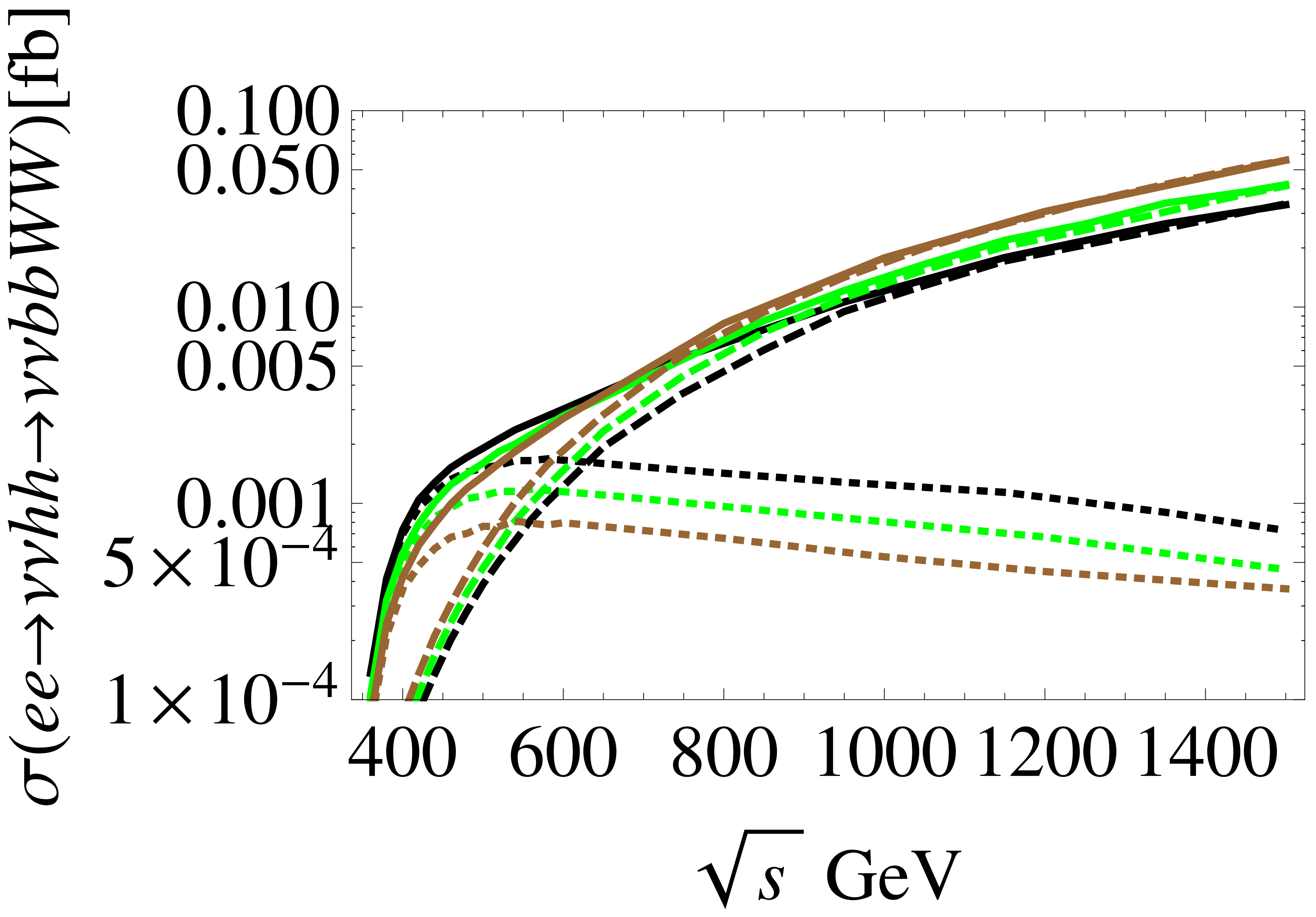

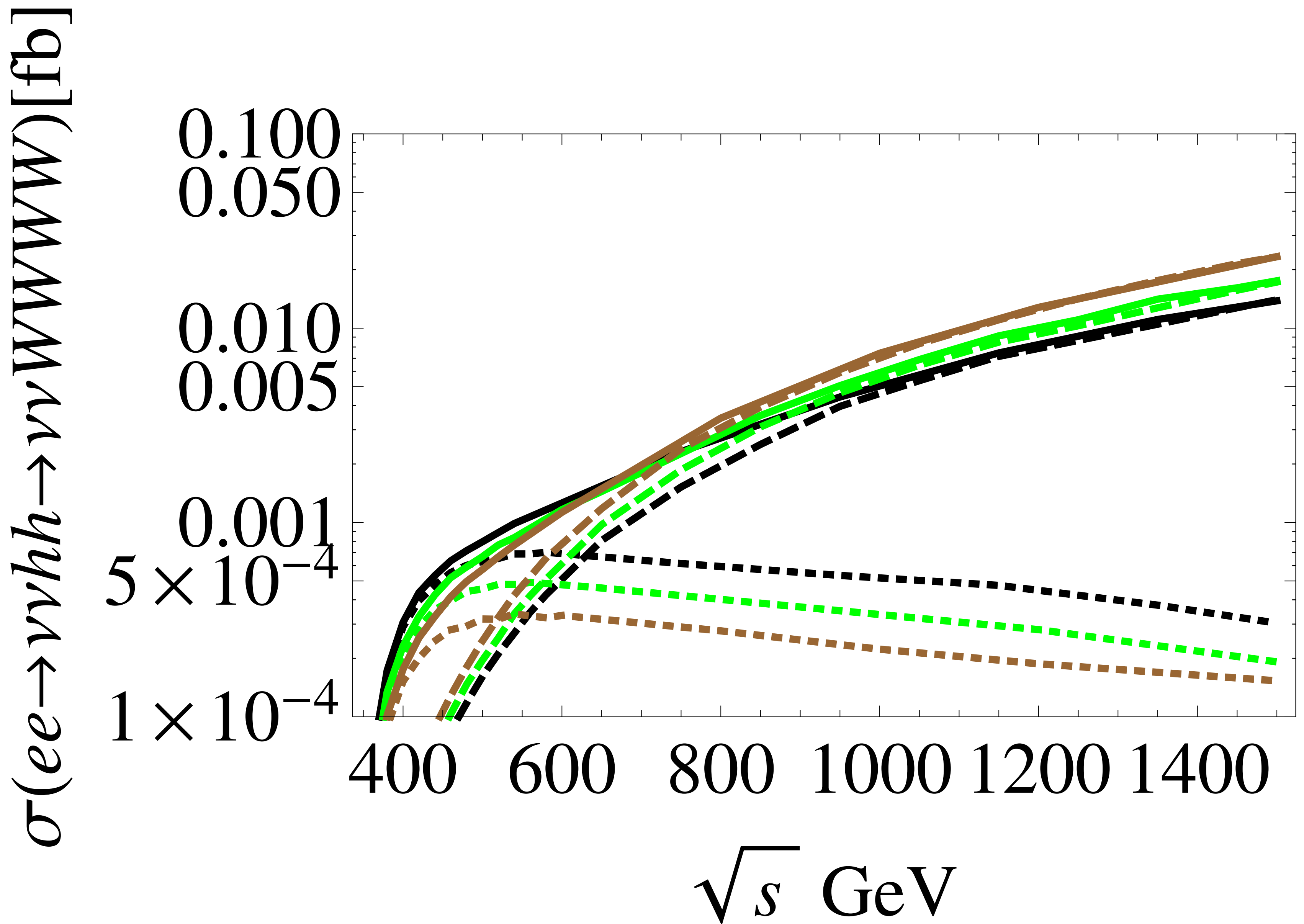

ee→hh$\nu\nu$

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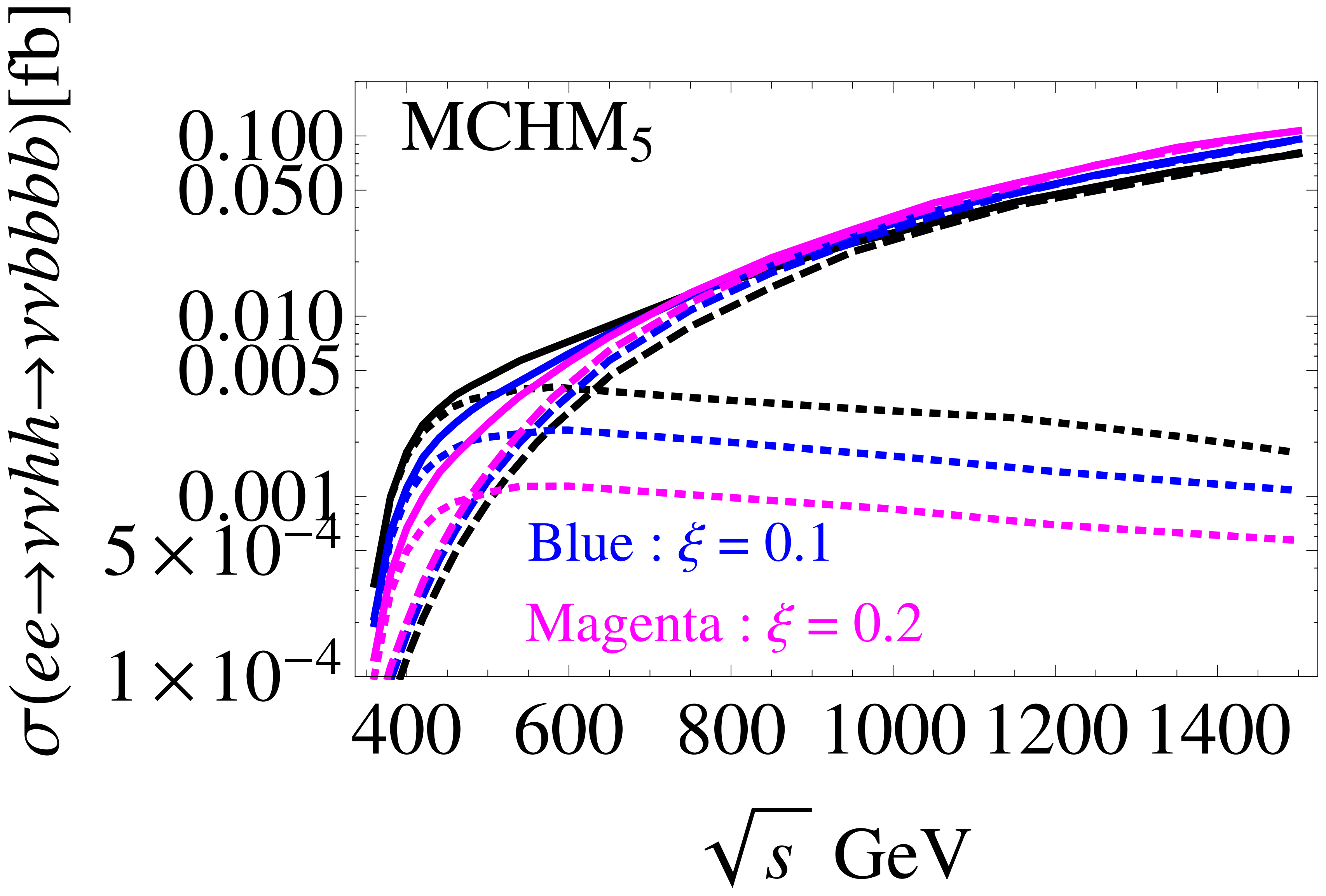

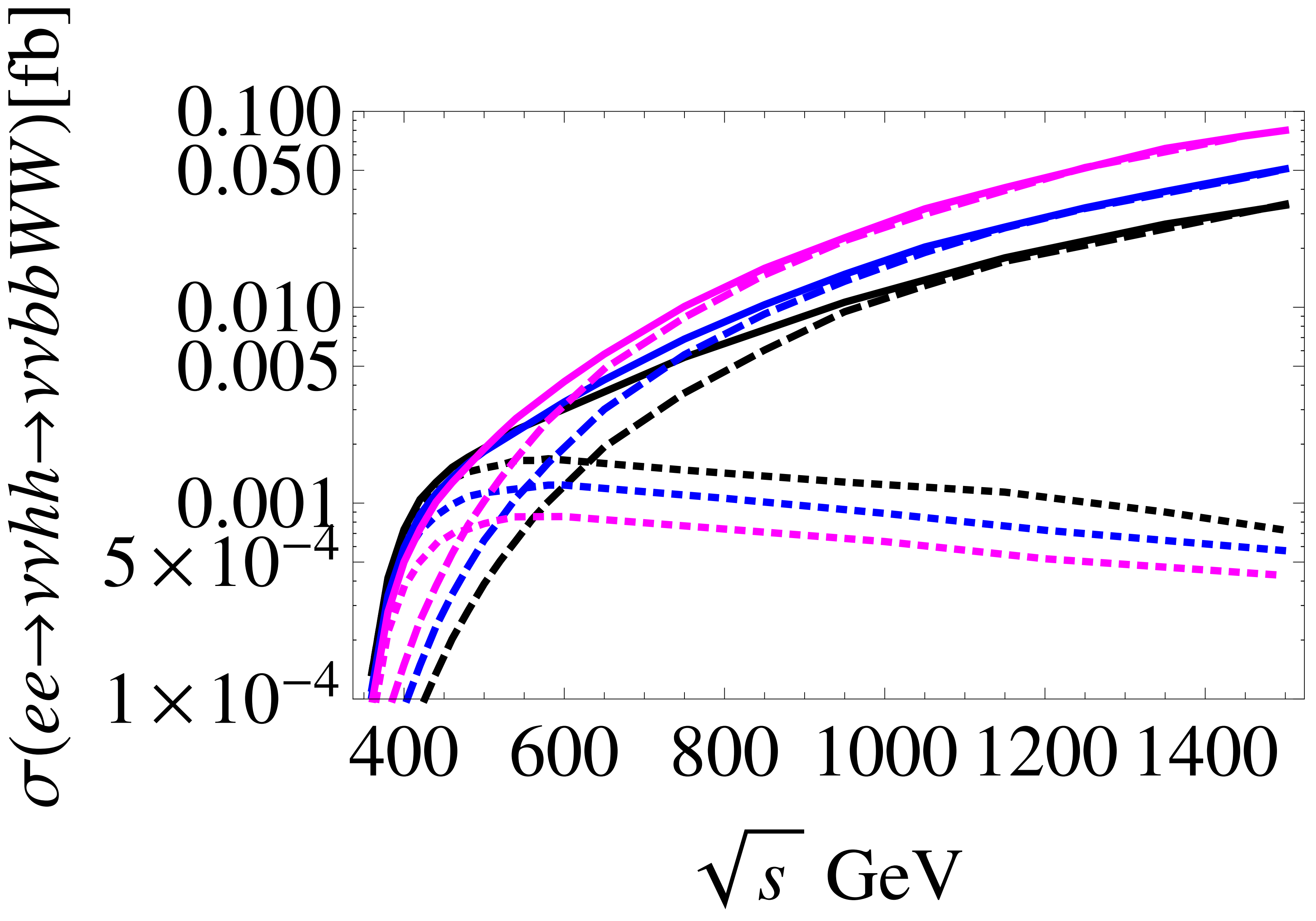

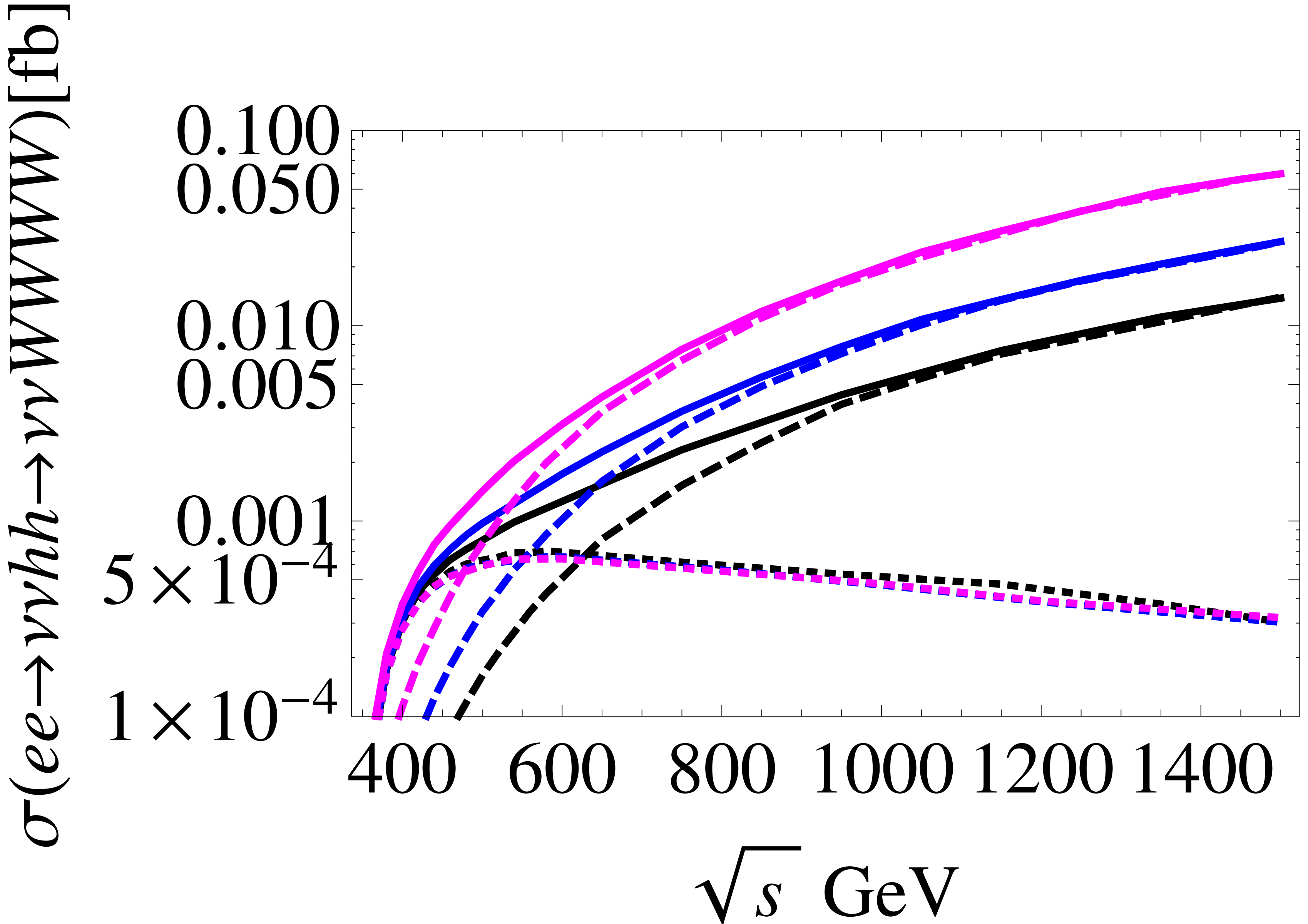

ee→hhνν

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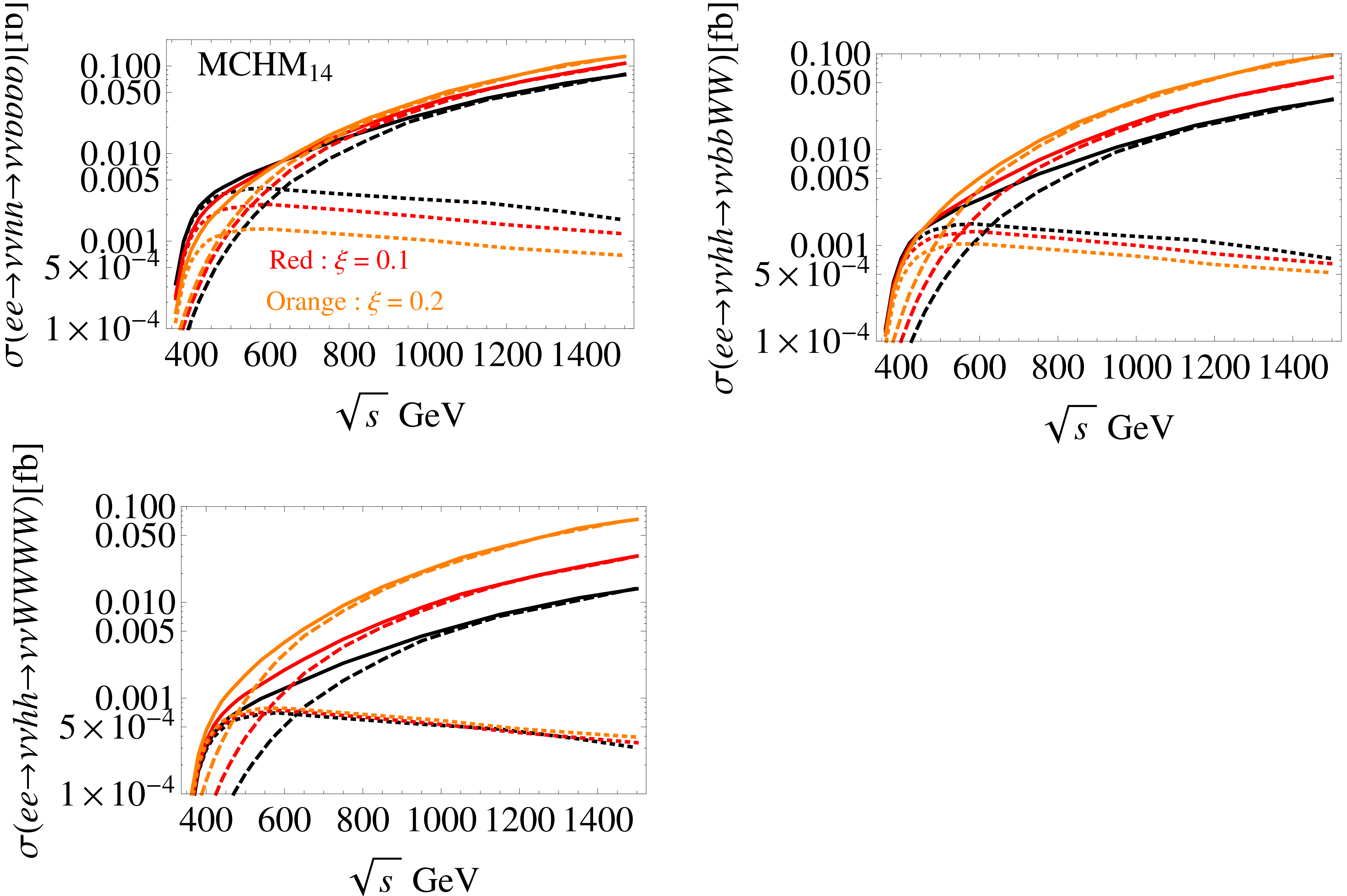

Including decay of h

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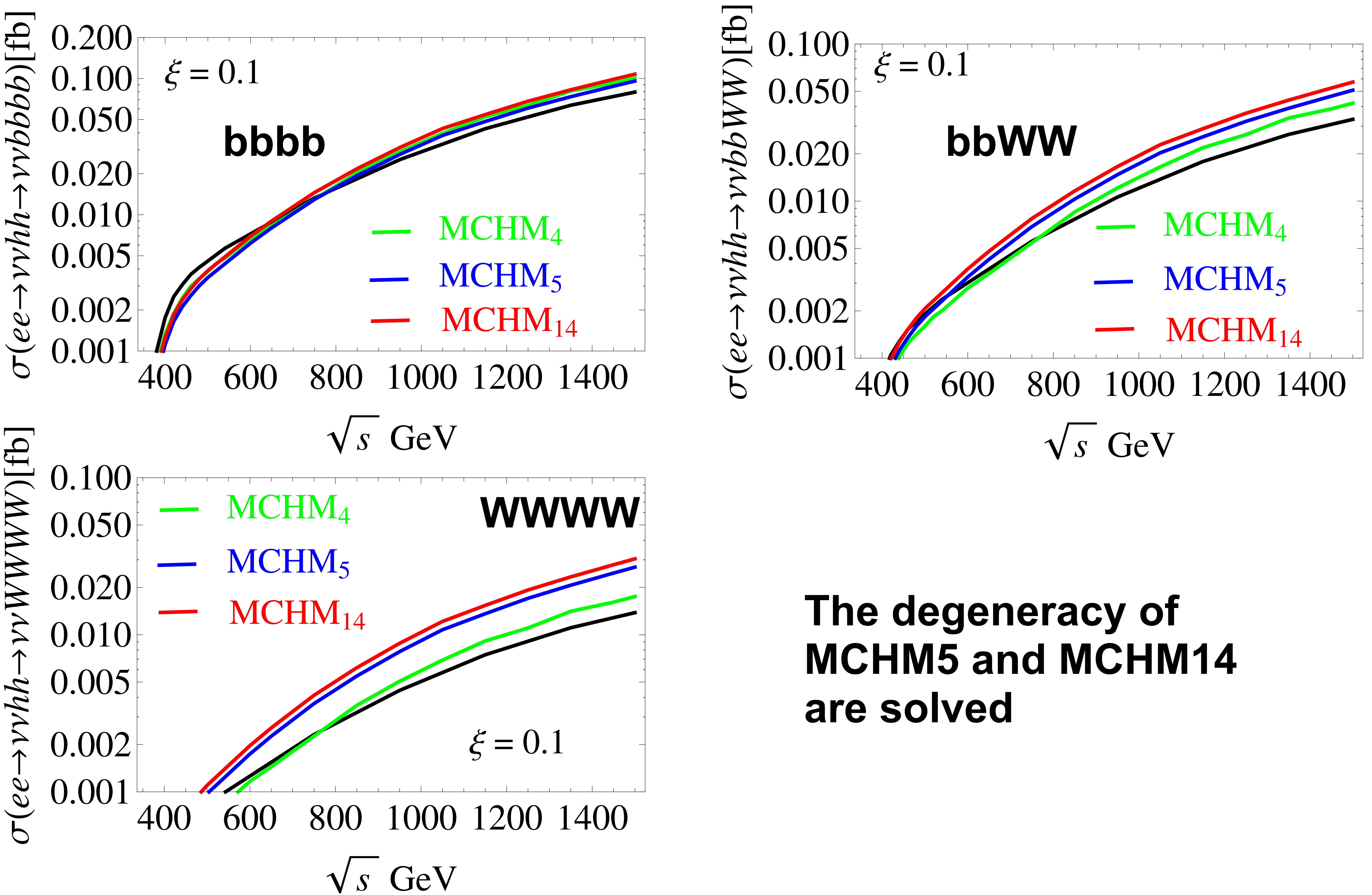

The degeneracy of MCHM5 and MCHM14 are solved

Including decay of h

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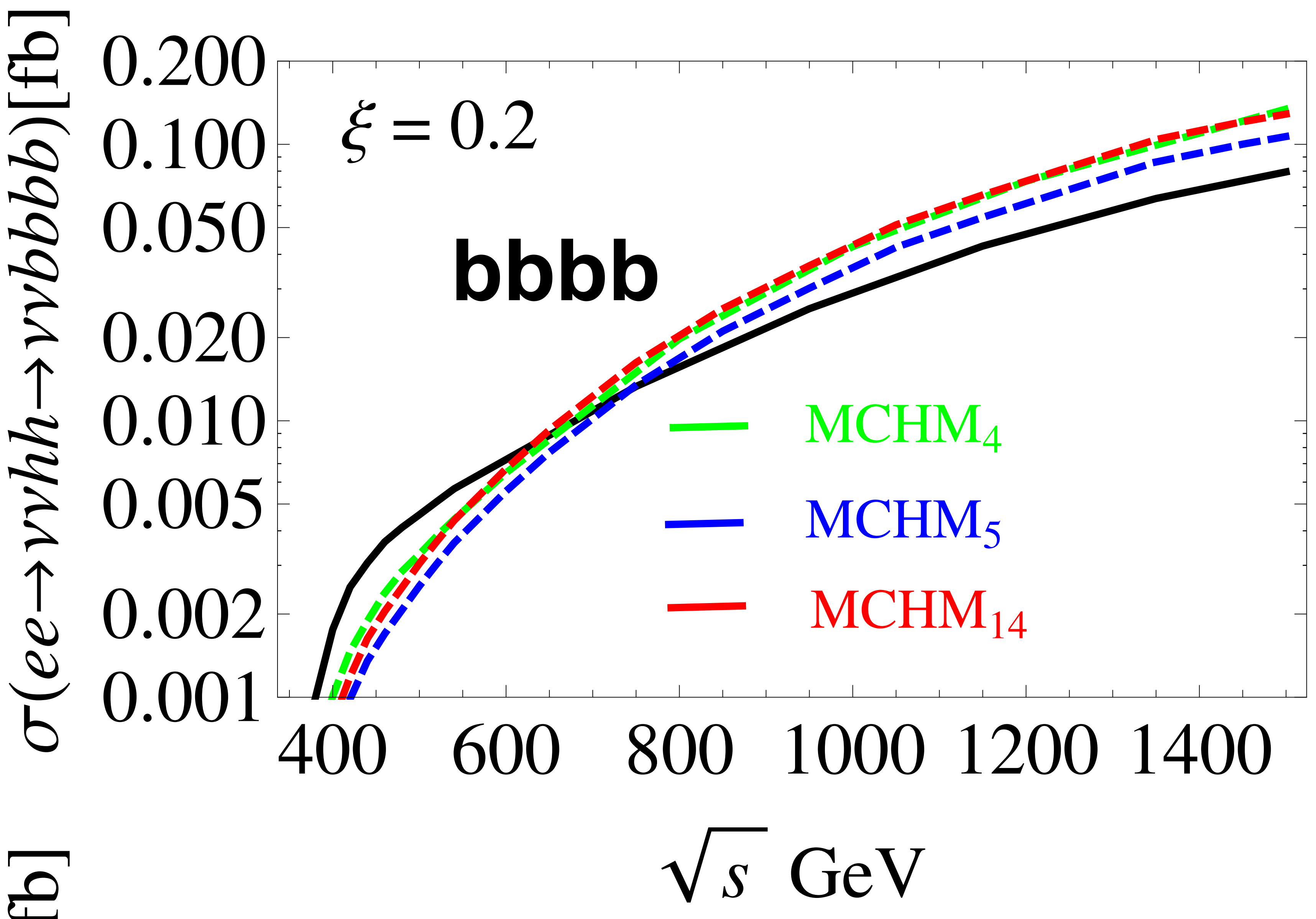

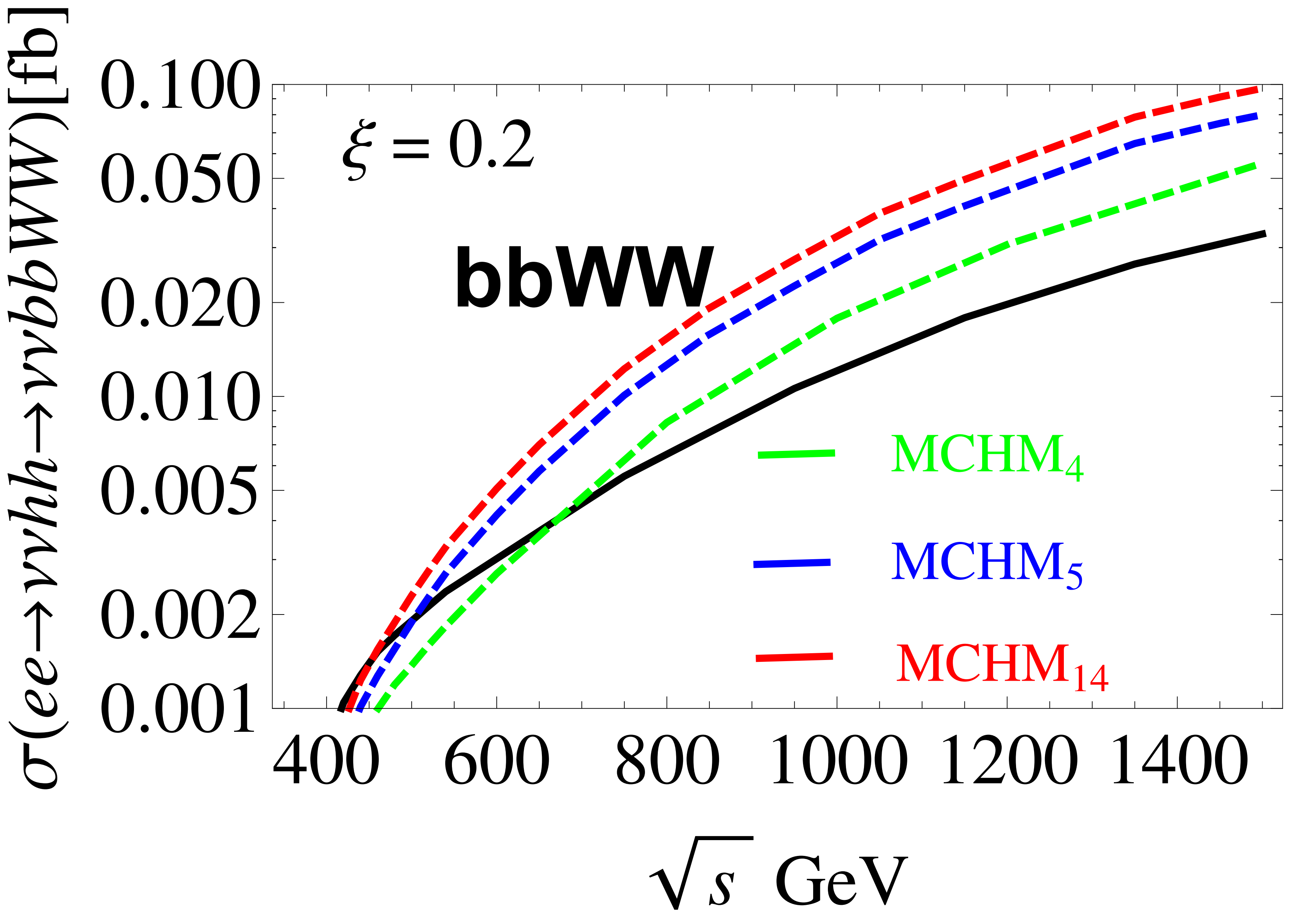

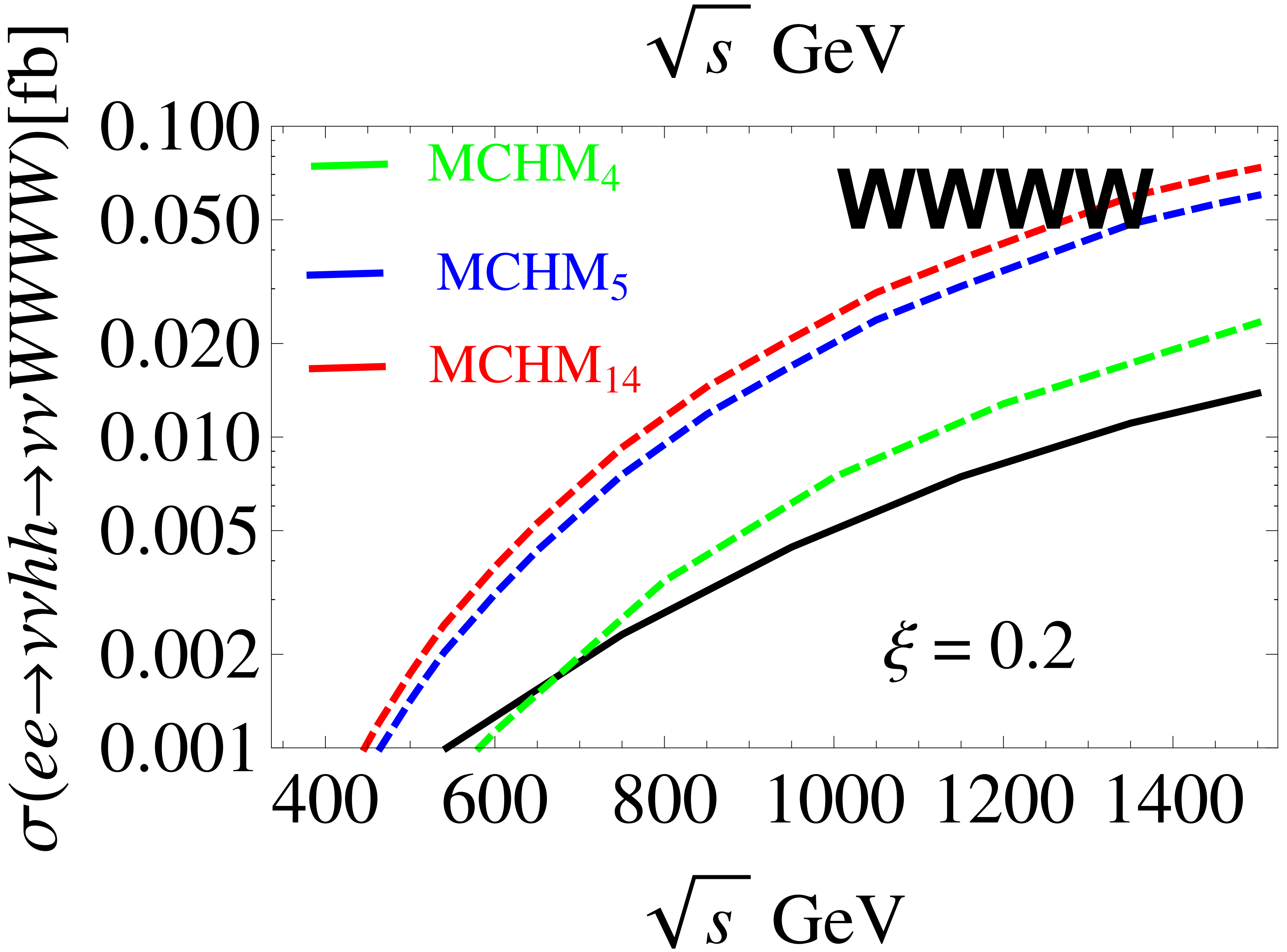

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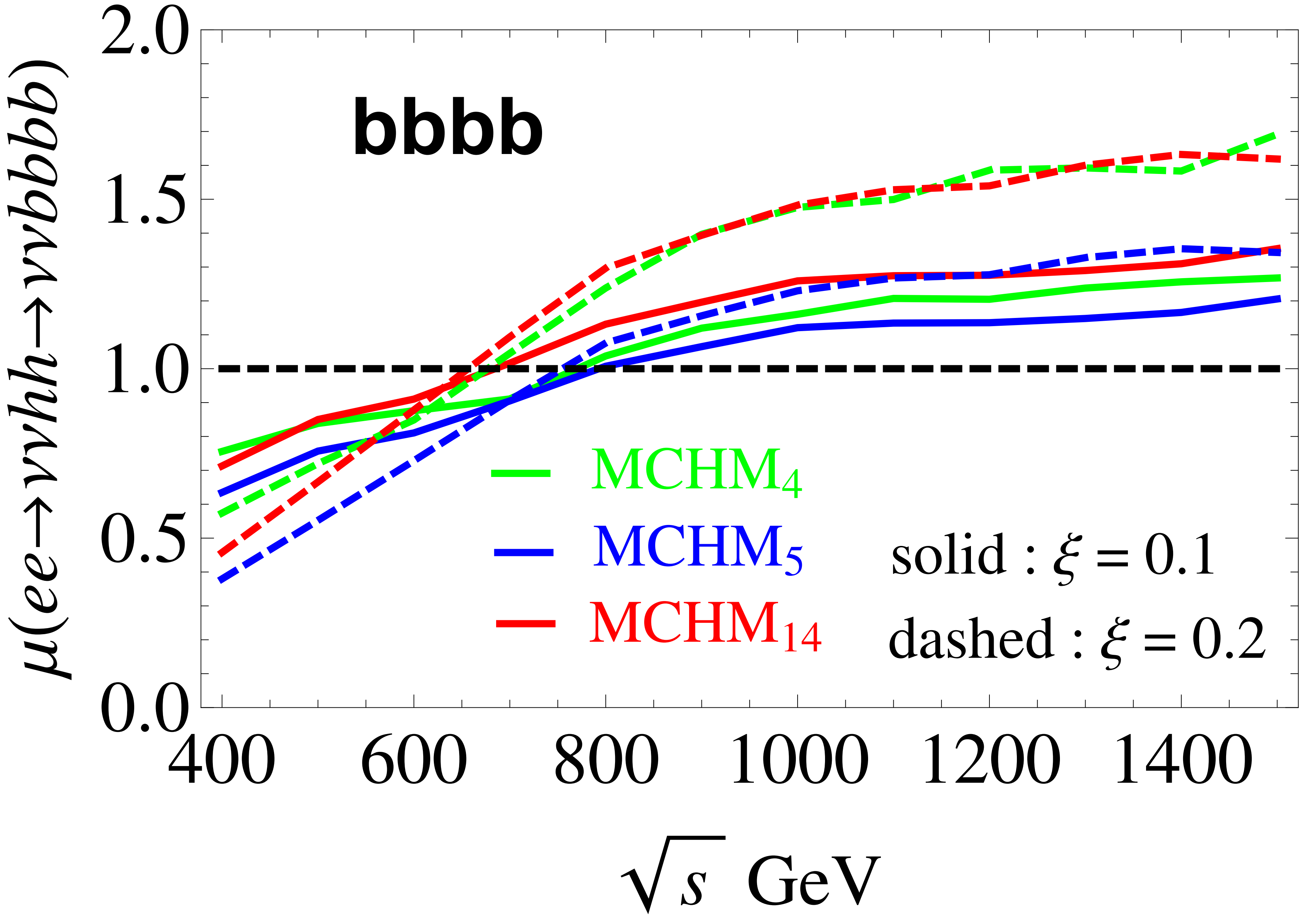

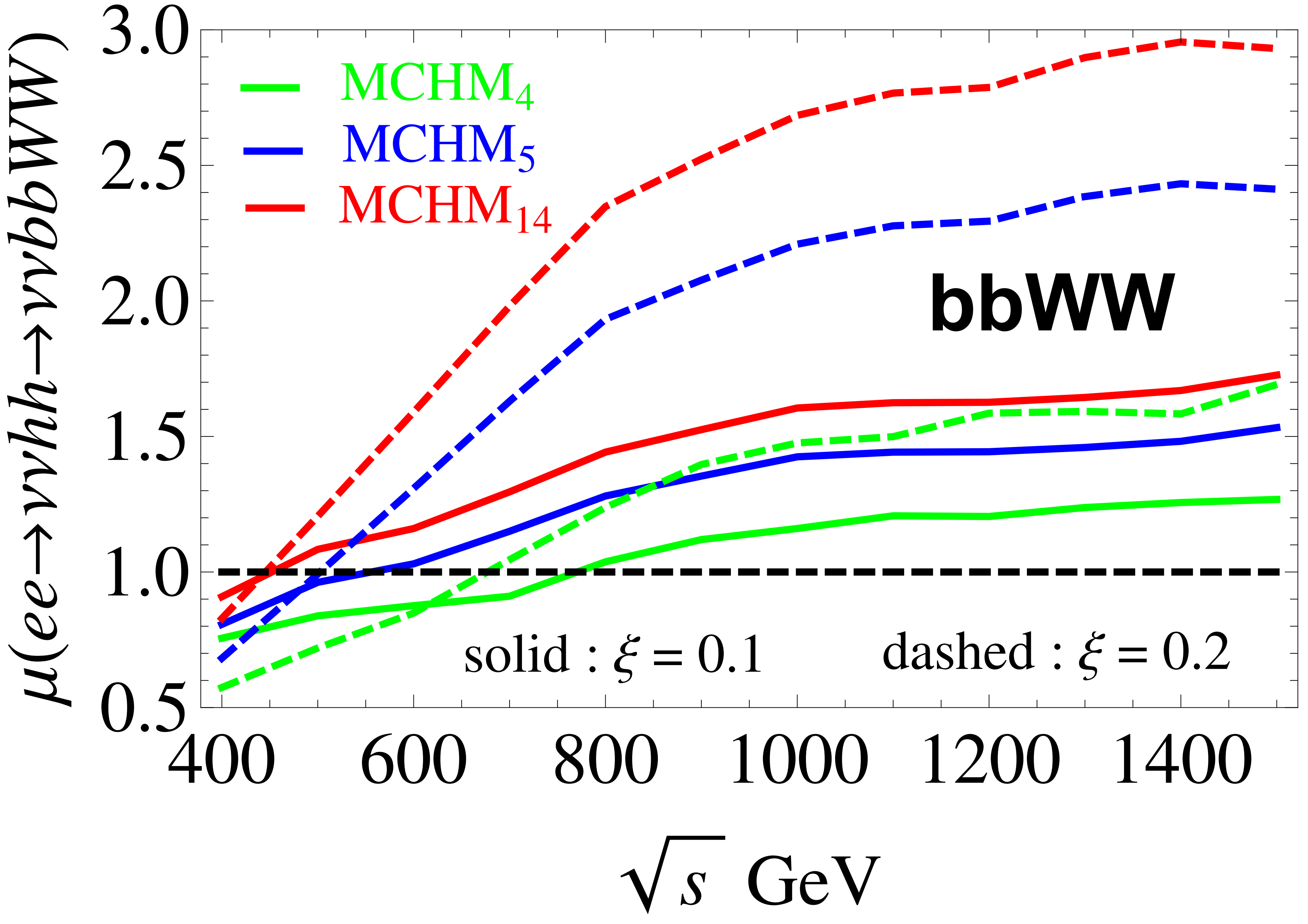

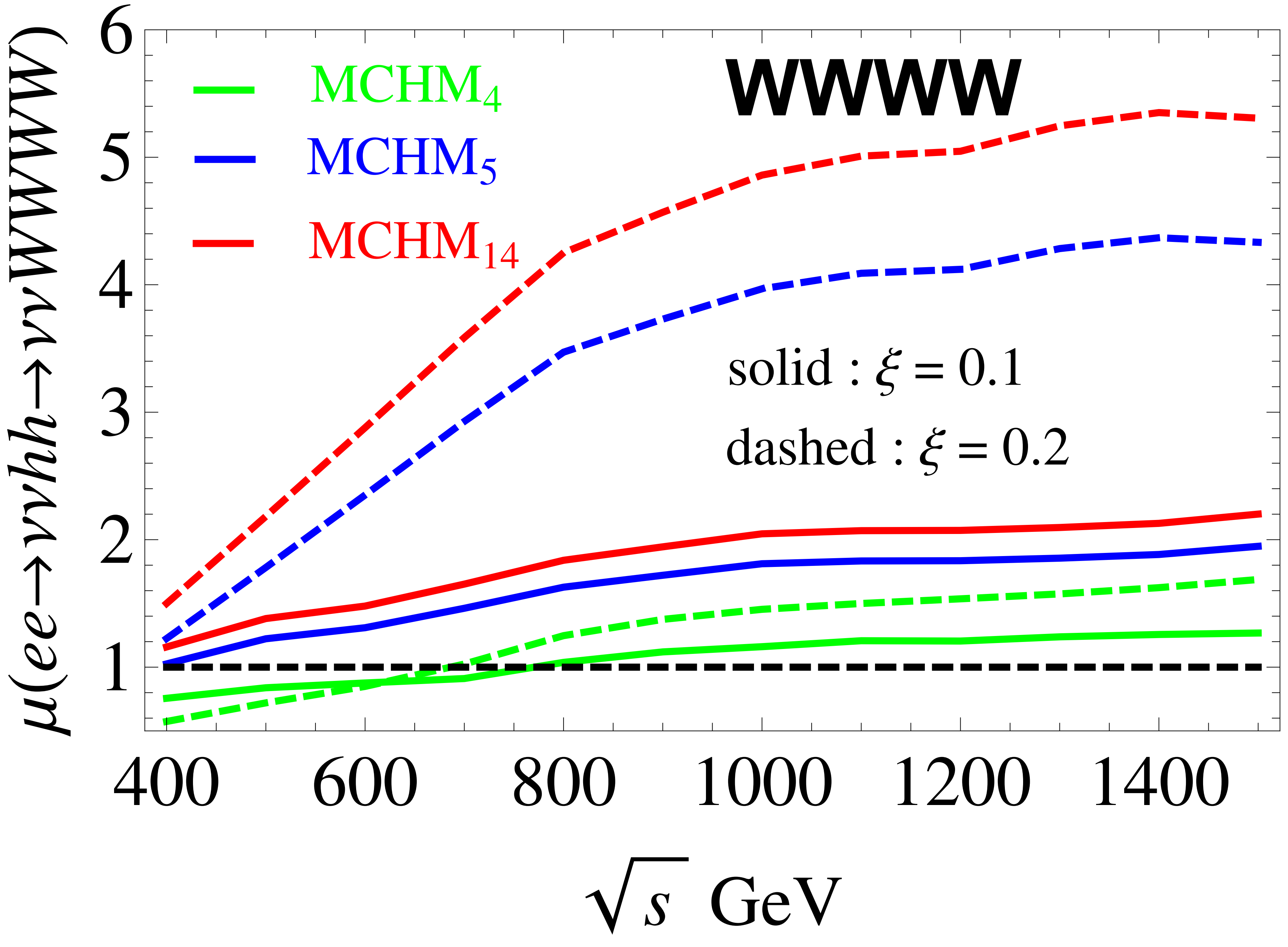

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}}$$

ILC Higgs White paper, arXiv:1310.0763

Table 6.2. Expxected accuracies $\Delta g_i/g_i$ for Higgs boson couplings for a completely model independent fit assuming theory errors of $\Delta F_i/F_i = 0.5\%$

Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.9 %	1.2 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.2 %	2.0 %
$b\bar{b}$	5.3 %	1.7 %	1.3 %	0.8 %
$\tau^+\tau^-$	5.8 %	2.4 %	1.8 %	1.0 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.1 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
$\Gamma_T(h)$	12 %	5.0 %	4.6 %	2.5 %

CHM with DM

Composite Scalar Dark Matter

Michele Frigerio[a], Alex Pomarol[b], Francesco Riva[c] and Alfredo Urbano[d]

[a] *CNRS, Laboratoire Charles Coulomb, UMR 5221, F-34095 Montpellier, FRANCE* & *Université Montpellier 2, Laboratoire Charles Coulomb, UMR 5221, F-34095 Montpellier, FRANCE*

[b] *Departament de Fisica, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, SPAIN*

[c] *IFAE, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, SPAIN*

[d] *Laboratoire de Physique Théorique de l'École Normale Supérieure, 24 rue Lhomond, F-75231 Paris, FRANCE*

arXiv:1204.2808v3 [hep-ph] 30 Jul 2012

Abstract

We show that the dark matter (DM) could be a light composite scalar η, emerging from a TeV-scale strongly-coupled sector as a pseudo Nambu-Goldstone boson (pNGB). Such state arises naturally in scenarios where the Higgs is also a composite pNGB, as in $O(6)/O(5)$ models, which are particularly predictive, since the low-energy interactions of η are determined by symmetry considerations. We identify the region of parameters where η has the required DM relic density, satisfying at the same time the constraints from Higgs searches at the LHC, as well as DM direct searches. Compositeness, in addition to justify the lightness of the scalars, can enhance the DM scattering rates and lead to an excellent discovery prospect for the near future. For a Higgs mass $m_h \simeq 125$ GeV and a pNGB characteristic scale $f \lesssim 1$ TeV, we find that the DM mass is either $m_\eta \simeq 50 - 70$ GeV, with DM annihilations driven by the Higgs resonance, or in the range $100 - 500$ GeV, where the DM derivative interaction with the Higgs becomes dominant. In the former case the invisible Higgs decay to two DM particles could weaken the LHC Higgs signal.