A Roadmap to Reconstruct Higgs Potentials @ colliders

Qi-Shu Yan (UCAS, Beijing)

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Outline

- Introduction
- Higgs Potentials of a few Models
- Higgs Potentials at future colliders
- Prospects

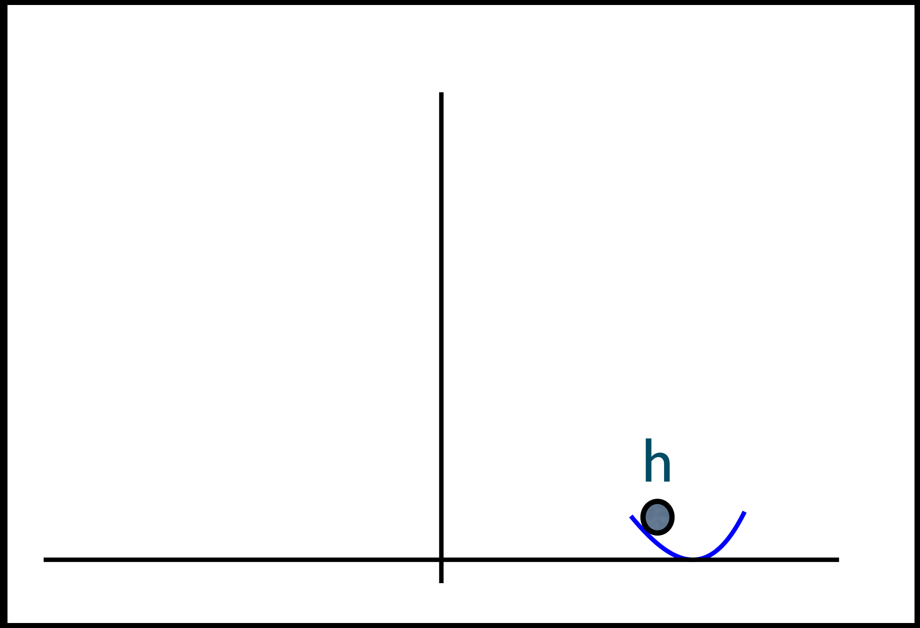
Based on:
Q.Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611
C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007, arXiv:1510.04013
X.R. Zhao, Q. Li, Z. Li, QY, in preparation

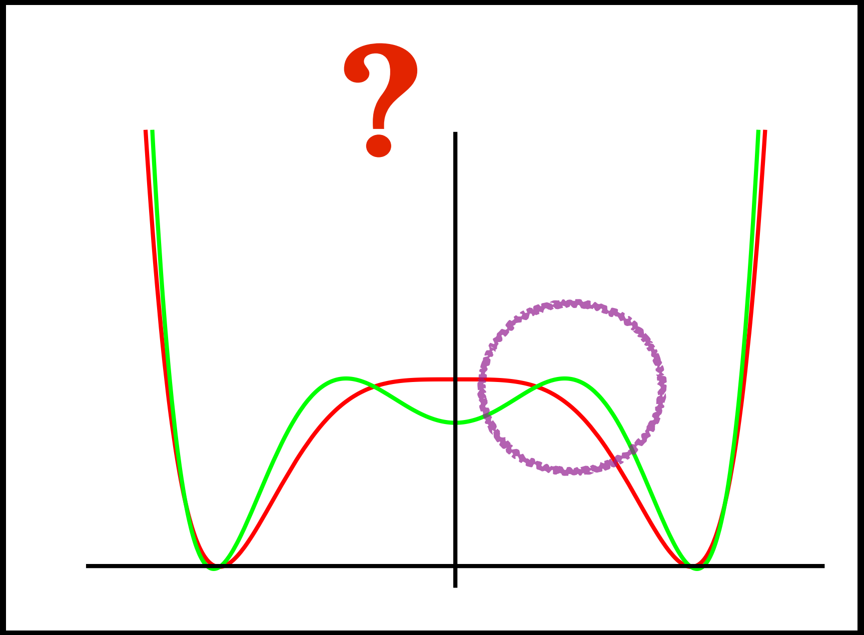
Introduction

Why Higgs Potential?

- 1) It determines the EWSB mechanisms, mass generation of Higgs bosons, Higgs self-couplings
- 2) It relate to the EW phase transition in the early universe and might leave a finger print in the primordial gravitational wave
- 3) It could relate to the EW baryogensis scenario, spontaneous CP breaking, spontaneous parity breaking
- 4) It directly connects with new physics (new particles, dark matter,)

Can it make difference?





A big question: the shape of Higgs potential is crucial for the strong first order electroweak phase transition, which is needed in the EW Baryogenesis scenarios.

CEPC Pre-CDR report
M. Trodden, Rev.Mod.Phys.71(1999)1463
D.E. Morrissey, M.J. Musolf, NJP14(2012)125003
N.Arkani-Hamed, T.Han, M.Mangano, L.T.Wang, 1511.06495

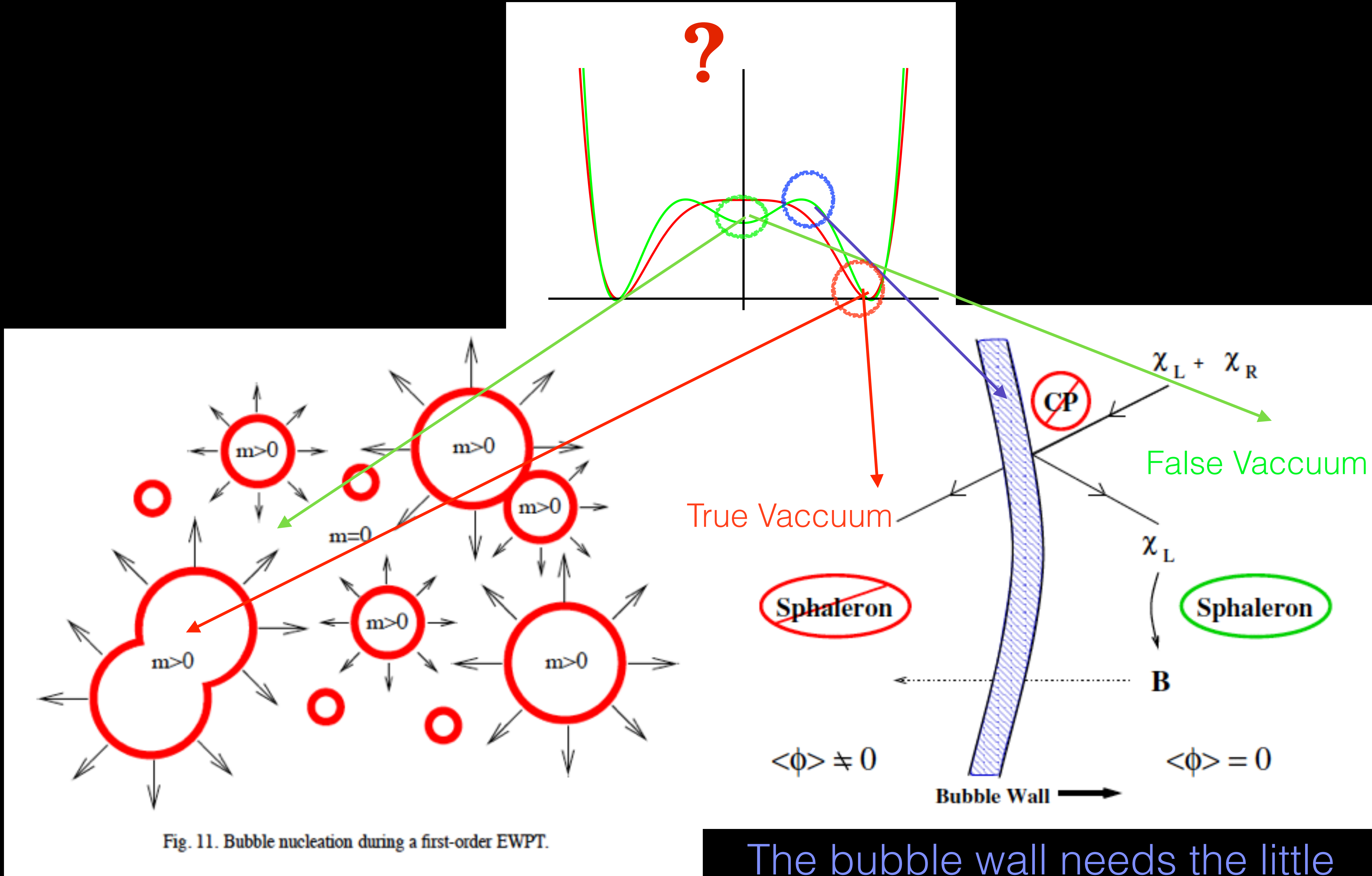


Fig. 11. Bubble nucleation during a first-order EWPT.

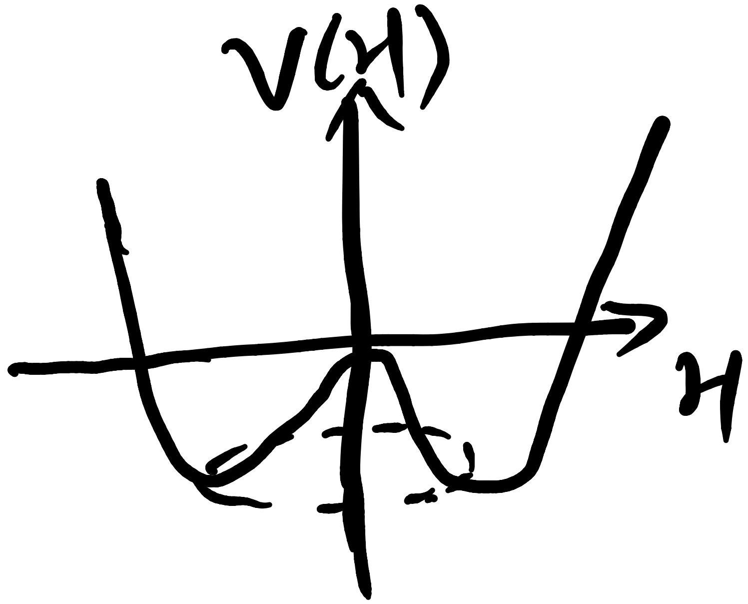
The bubble wall needs the little bump in potential shape

J.M. Cline, hep-ph/0609145
D.E. Morrissey, M.J. Musolf, NJP14(2012)125003

2. Higgs Potentials of a few models

① Higgs Potential in the SM

$$V(H) = -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$



$$\langle H \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$H = \begin{pmatrix} G^- \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{\lambda}{4} v h^3 + \frac{\lambda}{16} h^4$$

$$m_h^2 = \frac{\lambda}{4} v^2$$

*1) $$(D_\mu H)^\dagger (D^\mu H) \longrightarrow \frac{1}{2}\partial h \partial h + (v+h)^2 \left[\frac{g^2}{4} W^+ W^- + \frac{g_z^2}{8} ZZ\right]$$

*2) $$\mathcal{L}_{Yukawa} = Y_{t\bar{t}h}\,\bar{t}th + Y_{b\bar{b}h}\,\bar{b}bh + Y_{\tau\bar{\tau}h}\,\bar{\tau}\tau h + \cdots$$

Effective theories:

$$\mathcal{L}_Y^{eff} = Y_t \bar{t}(a + b i \gamma_5) t h + g_{tthh} \frac{1}{v} \bar{t} t h^2 + \cdots$$

$$\mathcal{L}_V^{eff} = d_1 v h \left[\frac{g^2}{2} W^+ W^- + \frac{g_Z^2}{4} Z \cdot Z\right] + d_2 h^2 \left[\frac{g^2}{4} W^+ W^- + \frac{g_Z^2}{8} Z \cdot Z\right]$$

$$+ \frac{h}{v}\Big(g_{hgg} G_{\mu\nu}^2 + g_{hZZ} Z_{\mu\nu}^2 + g_{h\gamma\gamma} A_{\mu\nu}^2 + \tilde{g}_{hgg} G\tilde{G}_{\mu\nu} + \tilde{g}_{hZZ} Z\tilde{Z}_{\mu\nu} + \tilde{g}_{h\gamma\gamma} A\tilde{A}_{\mu\nu}$$

$$+ g_{hWW} W_{\mu\nu} W^{\mu\nu} + \tilde{g}_{hWW} W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$+ g_{hZA} Z^{\mu\nu} A_{\mu\nu} + \tilde{g}_{hZA} Z_{\mu\nu} \tilde{A})$$

$$+ \frac{h^2}{v^2} (g_{hhGG} G_{\mu\nu}^2 + \cdots)$$

$$\mathcal{L}_{HS}^{eff} = - \lambda_3 \lambda_{SM}^3 h^3 - \lambda_4 \lambda_{SM}^4 h^4$$

$$+ \frac{c}{v} \partial h \partial h h + \frac{\lambda_5}{v} h^5 + \cdots$$

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \ ,$$

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu ,$$

$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{f} f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{f} f \ .$$

J. Baglio, A. Djouadi, J. Quevillon, 1511.07853

② Higgs potential in the Singlet + SM

$$V = V(H) + V(S) + V_x(S,H) + V_{ph}$$

$$V(H) = -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$

$$V(S) = -m_S^2 S^\dagger S + \frac{\lambda_S}{4}(S^\dagger S)^2$$

$$V_x(S,H) = \lambda_x (S^\dagger S)(H^\dagger H)$$

$$V_{ph} = 2(\mu^2 + \lambda_1 S^\dagger S + \lambda_2 H^\dagger H)\cdot \mathrm{Re}S^2$$
$$+ 2\lambda_3 \mathrm{Re}(S^4)$$

$$\mathcal{L} = M \overline{D_L} D_R + (f_j S + f_j' S^*) \overline{D_L} d_R^j + h.c.$$

$$\langle H\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad \langle S\rangle = \frac{v_s}{\sqrt{2}} e^{i\alpha}$$

$\Uparrow$

$$V_{ph} = a\cos 2\alpha + b\cos 4\alpha$$

Spontaneous CP violation!

$$H = \begin{pmatrix} G^- \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}, \quad S = [(v_R + s_R) + (v_I + s_I)]/\sqrt{2}$$

$$\mathcal{L}_2 = (h \;\; s_R \;\; s_I)\; M \begin{pmatrix} h \\ s_R \\ s_I \end{pmatrix}$$

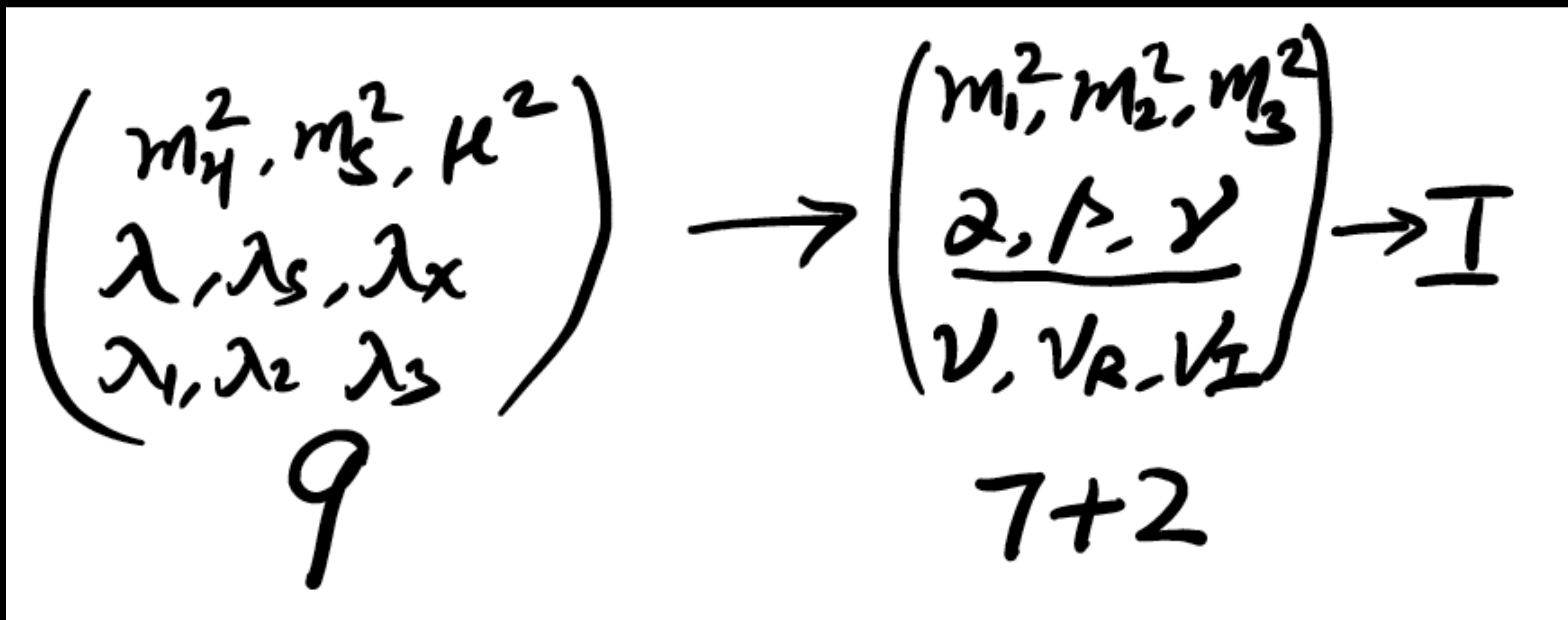
$$M = \begin{pmatrix} \frac{\lambda}{2}v^2 & (2\lambda_2+\lambda_x)vv_R & (-2\lambda_2+\lambda_x)vv_I \\ \cdot\cdot & \frac{1}{2}(8\lambda_1+8\lambda_3+\lambda_s)v_R^2 & \frac{1}{2}(-24\lambda_3+\lambda_s)v_Iv_R \\ \cdot\cdot & \cdot\cdot & \frac{1}{2}(-8\lambda_1+8\lambda_3+\lambda_s)v_I^2 \end{pmatrix}$$

Triple/quartic Higgs Coupling in the model:

$$\mathcal{L} = C_{lkj} S_l S_k S_j + C_{kljm} S_k S_l S_j S_m$$

$$C_{lkj} = \frac{T_{1l} m_l^2 T_{1k} T_{1j}}{2v} + \frac{T_{2l} m_l^2 T_{2k} T_{2j}}{2v_R} + \frac{T_{3l} m_l^2 T_{3k} T_{3j}}{2v_I}$$

$$\begin{aligned} C_{kljm} = \frac{1}{8} \sum_i \Big[& \frac{m_i^2}{v^2} T_{1i} T_{1i} T_{1k} T_{1l} T_{1j} T_{1m} + \frac{m_i^2}{v_R^2} T_{2i} T_{2i} T_{2k} T_{2l} \\ & T_{2j} T_{2m} + \frac{m_i^2}{v_I^2} T_{3i} T_{3i} T_{3k} T_{3l} T_{3j} T_{3m} + \\ & \frac{m_i^2}{v v_R} T_{1i} T_{2i} \left(T_{1k} T_{1l} T_{2j} T_{2m} + T_{1j} T_{1m} T_{2k} T_{2l} \right) + \\ & \frac{m_i^2}{v v_I} T_{1i} T_{3i} \left(T_{1k} T_{1l} T_{3j} T_{3m} + T_{1j} T_{1m} T_{3k} T_{3l} \right) + \\ & \frac{m_i^2}{v_I v_R} T_{2i} T_{3i} \left(T_{2k} T_{2l} T_{3j} T_{3m} + T_{2j} T_{2m} T_{3k} T_{3l} \right) \Big] \end{aligned}$$



A simple roadmap for this model:

1) To discover extra neutral Higgs bosons
2) To measure three mixing angles
3) 2 must be extracted from T/Q coupling measurement

③ Higgs potential of the 2HDM

$$V = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.)$$

$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2)$$

$$+ \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$

$$+ \Big[\frac{\lambda_5}{2}(H_1^\dagger H_2)(H_1^\dagger H_2) + \lambda_6 (H_1^\dagger H_2)(H_1^\dagger H_1)$$

$$+ \lambda_7 (H_1^\dagger H_2)(H_2^\dagger H_2) + h.c. \Big]$$

Higgs Basis

Triple/Quartic Couplings in 2HDM

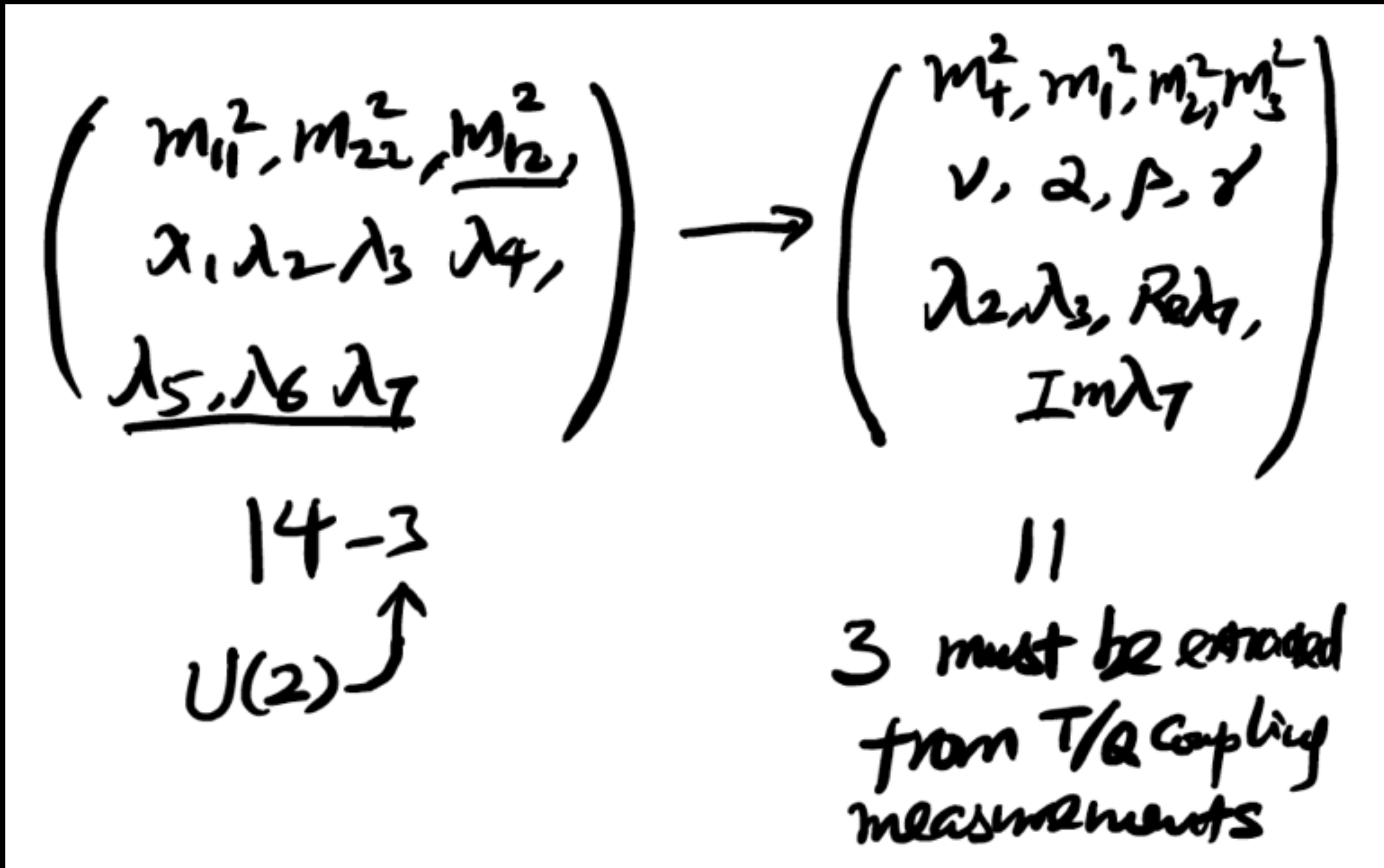
$$\mathcal{L} = v H^+ H^- C_i S_i$$
$$+ \; C_{ijk} S_i S_j S_k$$
$$+ \frac{\lambda_2}{2} H^+ H^- H^+ H^-$$
$$+ \; C_{kl} H^+ H^- S_k S_l$$
$$+ \; C_{kl,jm} S_k S_l S_j S_m$$

$$C_j = T_{1j}\lambda_3 + T_{2j}\mathrm{Re}\lambda_7 - T_{3j}\mathrm{Im}\lambda_7$$

$$C_{jkl} = \frac{v}{2} C_j (\delta_{kl} - T_{1k}T_{1l}) + \frac{1}{v}\left(m_+^2 - \frac{m_j}{2}\right) T_{1j}T_{1k}T_{1l} + \frac{1}{v}(m_k^2 - m_+^2) T_{1j}\delta_{kl}$$

$$C_{kl} = \frac{\lambda_2}{2}\delta_{kl} - \frac{\lambda_2+\lambda_3}{2} T_{1k}T_{1l} + C_l T_{1k}$$

$$C_{kl,jm} = \frac{m_i^2 T_{1i}T_{1i}}{8v^2} T_{1k}T_{1l}T_{1j}T_{1m} + \left[\frac{\lambda_2}{8}(\delta_{kl} - T_{1k}T_{1l}) - \frac{\lambda_3}{4} T_{1k}T_{1l} + \frac{C_k}{2} T_{1l} + \frac{m_j^2 - m_+^2}{2v^2} T_{1k}T_{1l}\right] \cdot (\delta_{jm} - T_{1j}T_{1m})$$



A simple roadmap for 2HDM:

1) To discover 3 extra neutral HB, 2 charged HB
2) To measure three mixing angles
3) 3 must be extracted from T/Q couplings

④ n-Higgs Doublet model:

$$\mathcal{L} = m_{ii}^2 \phi_i^\dagger \phi_i + [m_{ij}^2 \phi_i^\dagger \phi_j + h.c.]$$
$$+ a_{ij} (\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j)$$
$$+ b_{ij} (\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i)$$
$$+ [C^1_{ijk} \phi_i^\dagger \phi_j \phi_k^\dagger \phi_k + C^2_{ij} \phi_i^\dagger \phi_j \phi_i^\dagger \phi_j$$
$$+ d_{ijkl} \phi_i^\dagger \phi_j \phi_k^\dagger \phi_l + h.c.]$$

$$\frac{n^4}{2} + \frac{3n^2}{2} - 2n + 1$$

No. of CP phases: $\frac{1}{4}n^2(n^2-1)-(n-1)$

No. of charged Higgs bosons:

$n-1$, T matrix $\in SO(n-1)$

No. of Neutral Higgs bosons:

$2n-1$, T matrix $\in SO(2n-1)$

No. of parameters must be probed via triple/quartic couplings:

$$N_{t/q} = \frac{n^4}{2} - n^2 - \frac{n}{2} + 1$$

$n=3$, $N_{t/q} = 31$

$n=4$, $N_{t/q} = 111$

⑤ Higgs potential of the left-right model

$$V = V(\Delta_L, \Delta_R) + V(\phi_1, \phi_2) + V(\Delta, \phi)$$

$$V(\Delta_L, \Delta_R) = -\mu^2 \, \mathrm{Tr}(\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R)$$
$$+ \rho_1 \left[\mathrm{Tr}(\Delta_L^\dagger \Delta_L)^2 + \mathrm{Tr}(\Delta_R^\dagger \Delta_R)^2 \right]$$
$$+ \rho_2 \left[\mathrm{Tr}(\Delta_L^\dagger \Delta_L \Delta_L^\dagger \Delta_L) + \mathrm{Tr}(\Delta_R^\dagger \Delta_R \Delta_R^\dagger \Delta_R) \right]$$
$$+ \rho_3 \left[\mathrm{Tr}(\Delta_L^\dagger \Delta_L) \mathrm{Tr}(\Delta_R^\dagger \Delta_R) \right]$$
$$+ \rho_4 \left[\mathrm{Tr}(\Delta_L^\dagger \Delta_L) \mathrm{Tr}(\Delta_L \Delta_L) + \mathrm{Tr}(\Delta_R^\dagger \Delta_R) \mathrm{Tr}(\Delta_R \Delta_R) \right]$$

$$\Delta_{L,R} = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}_{L,R}$$

5 free parameters

$$V(\phi_1,\phi_2) = -\mu_{ij}^2 \,\mathrm{Tr}(\phi_i^\dagger \phi_j)$$
$$+\lambda_{ijkl}\,\mathrm{Tr}(\phi_i^\dagger \phi_j)\,\mathrm{Tr}(\phi_k^\dagger \phi_l)$$
$$+\lambda'_{ijkl}\,\mathrm{Tr}(\phi_i^\dagger \phi_j \phi_k^\dagger \phi_l)$$

(T4)

$$\phi_1 = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} \qquad \phi_2 = \tau_2 \phi_1^* \tau_2$$

$$V(\Delta,\phi) = \alpha_{ij}\,\mathrm{Tr}(\phi_i^\dagger \phi_j)\,\mathrm{Tr}(\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R)$$
$$+\beta_{ij}\,\mathrm{Tr}(\phi_i^\dagger \phi_j \Delta_L^\dagger \Delta_L + \phi_i \phi_j^\dagger \Delta_R^\dagger \Delta_R)$$
$$+(\gamma_{ij}\,\mathrm{Tr}(\Delta_L^\dagger \phi_i \Delta_R \phi_j^\dagger) + h.c.)$$

(T2)

$$\langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}$$

$$\langle \phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} e^{i\alpha}$$

$$v_L = \left(\frac{\gamma_{12}}{2(\rho_1 + \rho_2) - \rho_3} \right) \frac{\kappa^2}{v_R}$$

Rich Higgs plano:

2: $\delta_1^{++}\ \delta_2^{++} \longleftarrow \delta_L^{++}, \delta_R^{++}$

2: $\dfrac{(\delta_1^{+}\ \delta_2^{+})}{(G_1^{+}\ G_2^{+})} \longleftarrow \delta_L^{+}, \delta_R^{+}, \phi_1^{+}, \phi_2^{+}$

6: $\delta_1^{0} \cdots \delta_6^{0} \longleftarrow \delta_L^{0}, \delta_R^{0}, \phi_1^{0}, \phi_2^{0}$

(G_1^{0}, G_2^{0})

No. of physics parameters

$(2+1) + (2+1) + (6 + \frac{6\times 5}{2}) = 27$

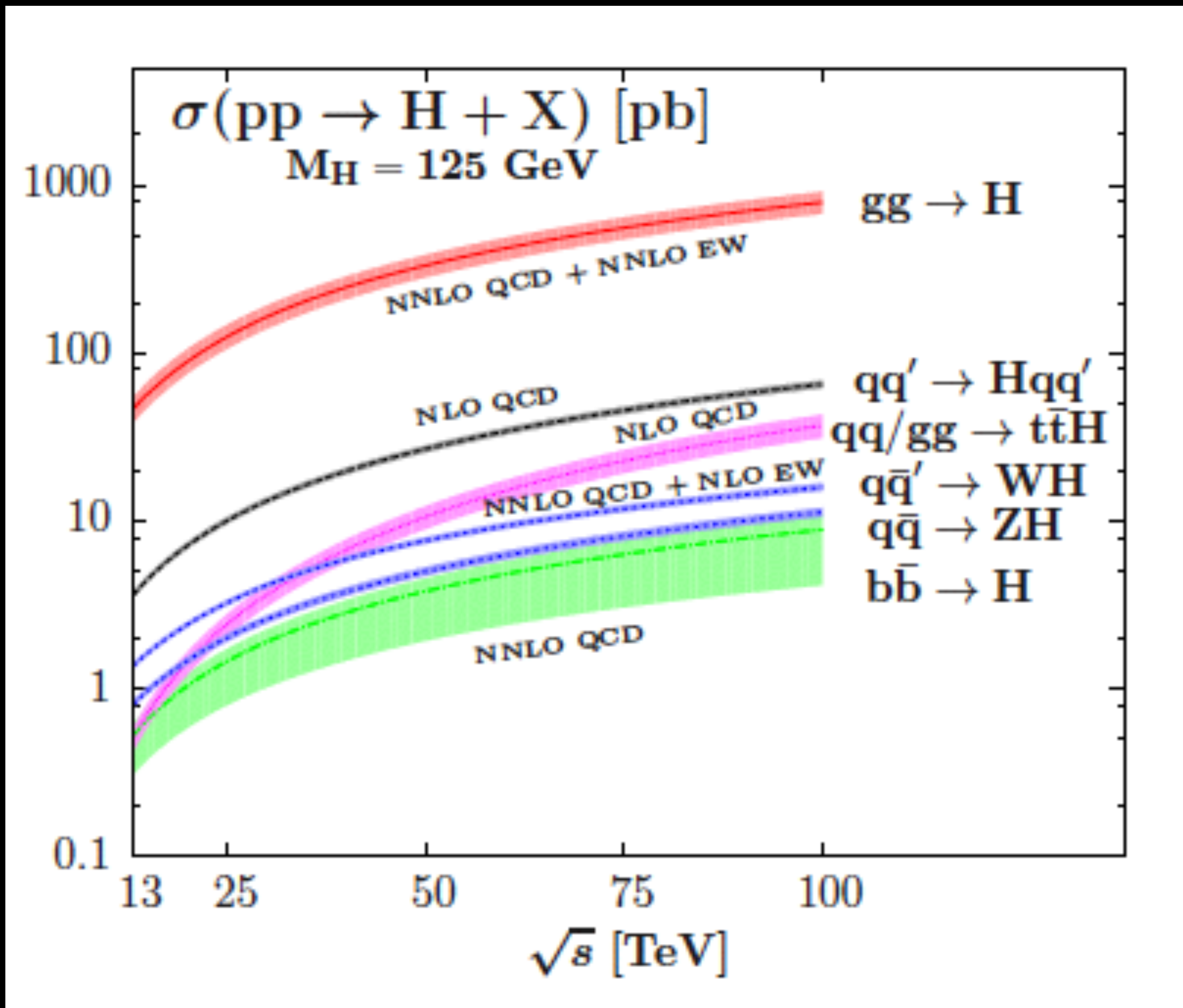
No. of independent parameters in T/Q Couplings

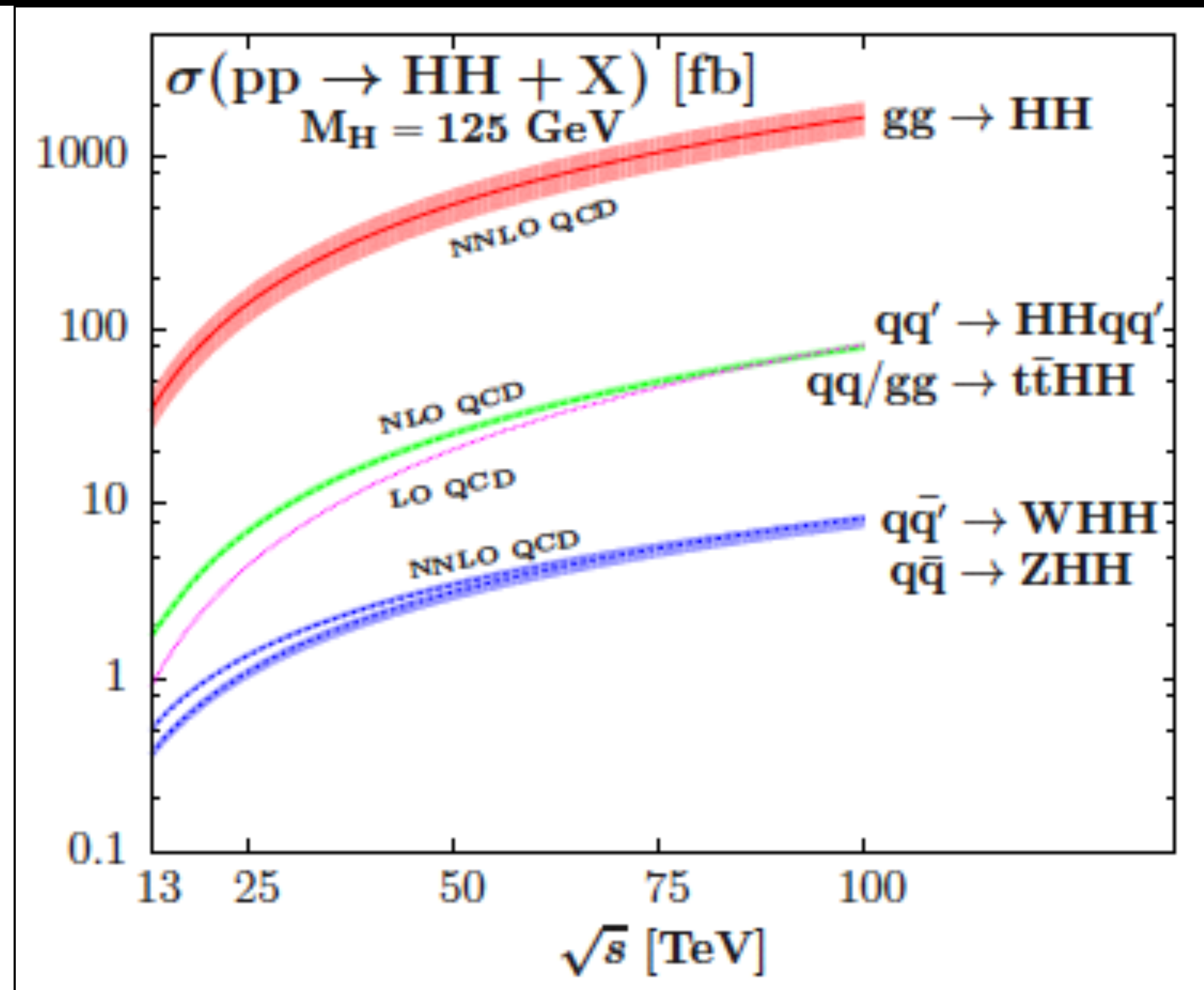
$31 - 27 = 4$

(a naive count)

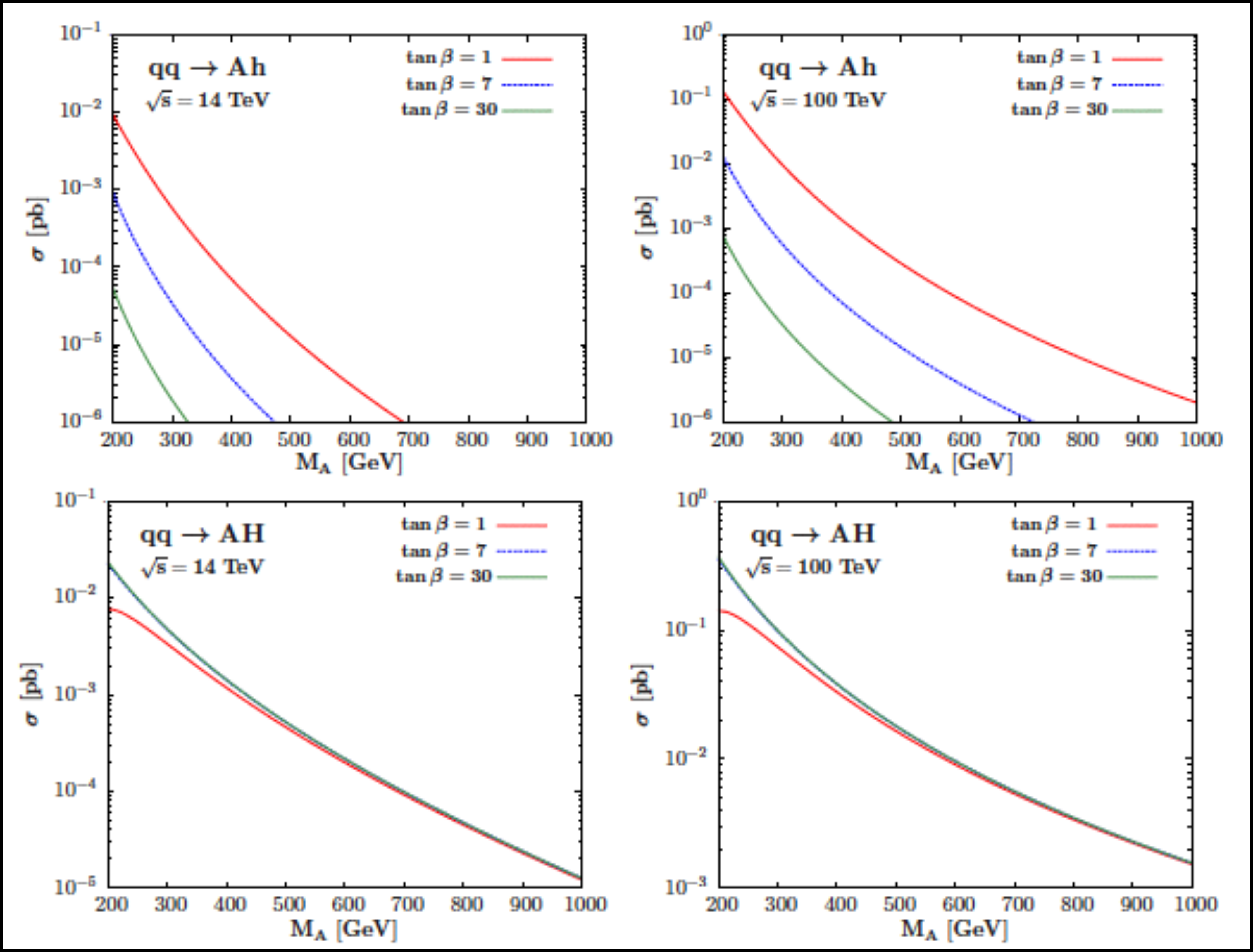
3. Higgs Potentials@Colliders

- The production and decay of new Higgs bosons
- The determinations of mixing angles
- The measurement of T/Q Couplings
- Global fit to the Higgs potential



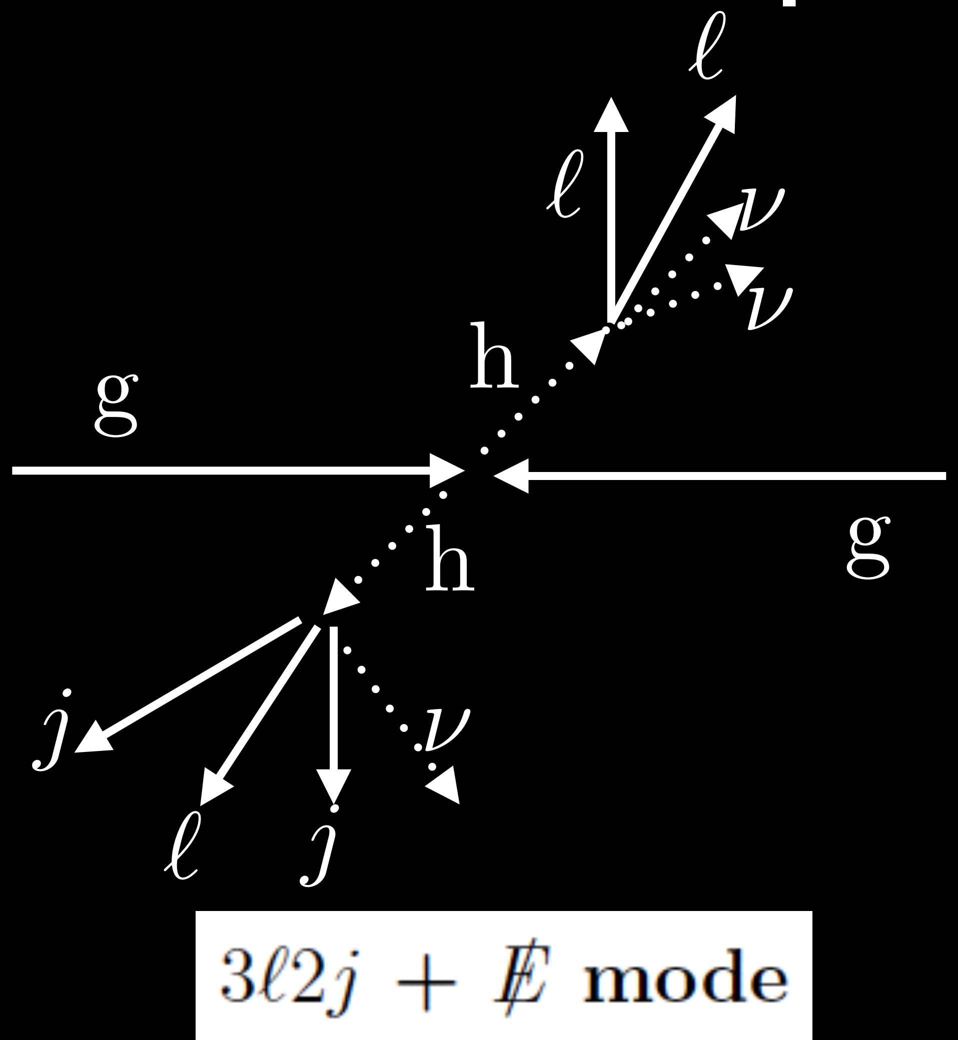


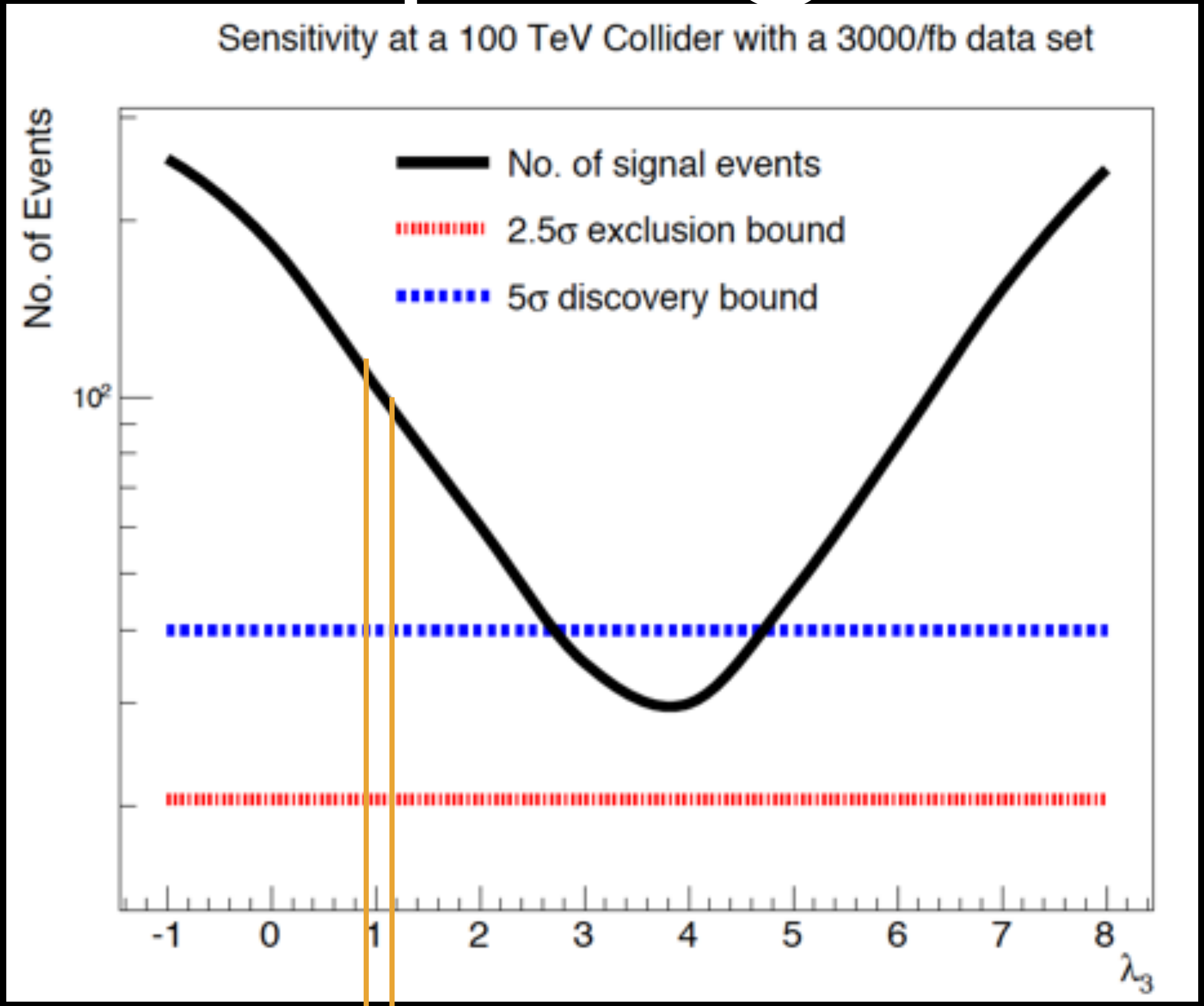
J. Baglio, A. Djouadi, J. Quevillon, 1511.07853



J. Baglio, A. Djouadi, J. Quevillon, 1511.07853

Triple Coupling



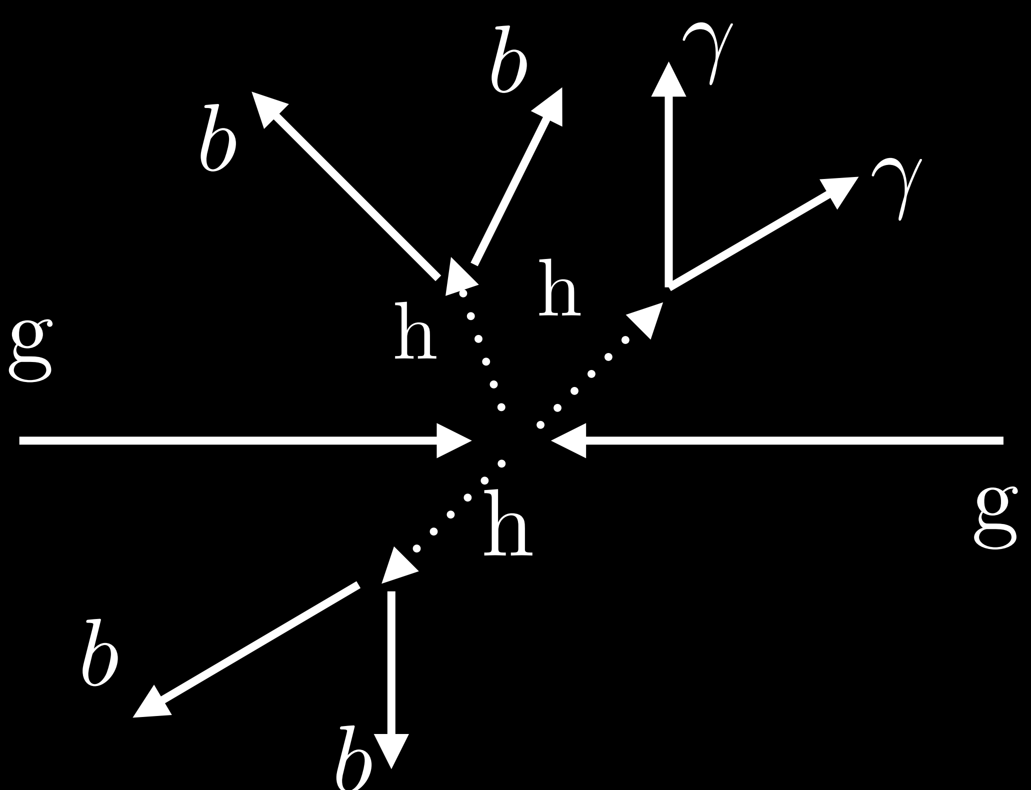


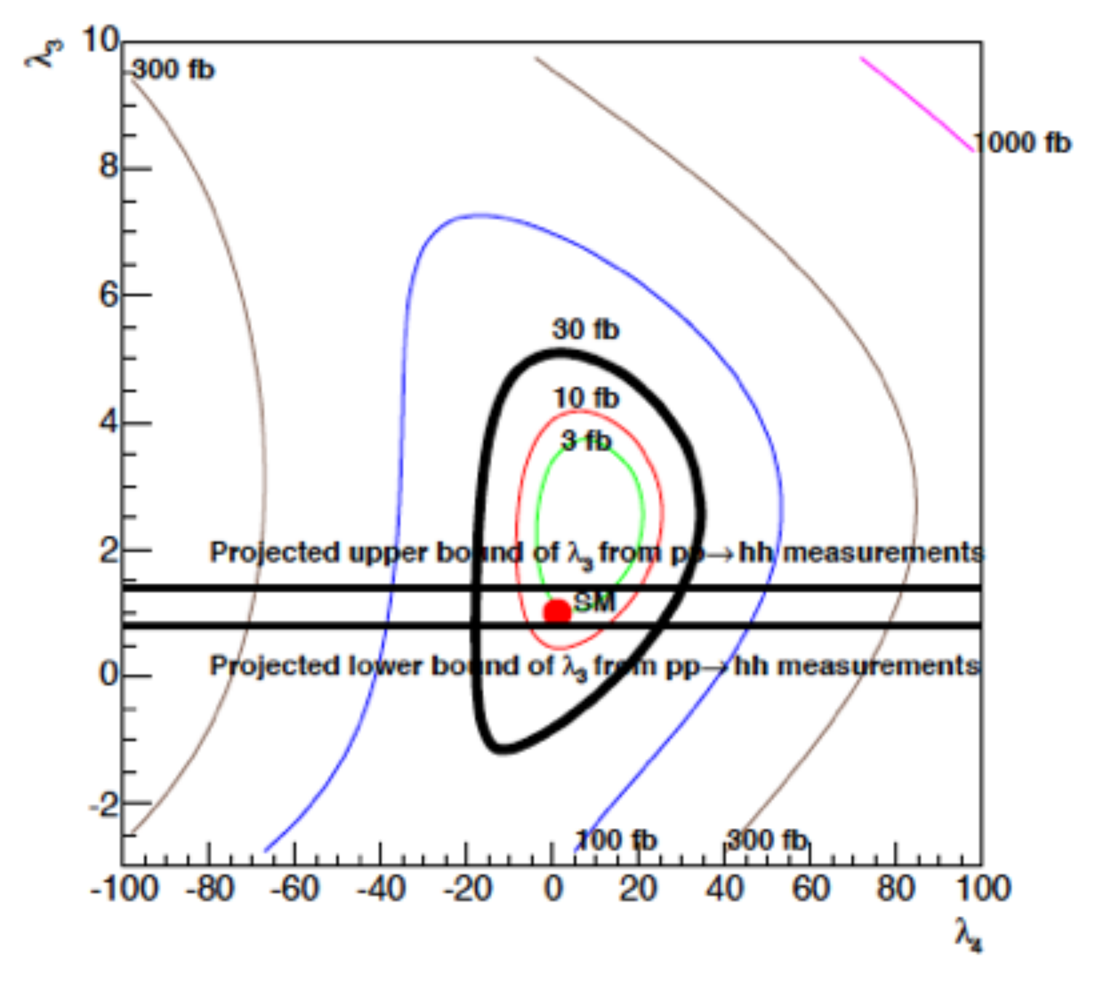
To overcome the b mistag and photo mistag issues, $gg \to hh \to WW^*WW^* \to 3\ell + 2j + MET$ is proposed.

By using this mode, SPPC can determine λ_3 to the window [0.9,1.2]

Q. Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611

Quartic Coupling





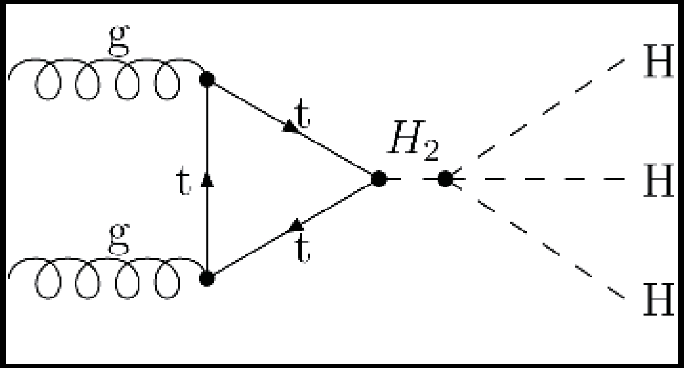
(b)The feasibility of λ_3 and λ_4

A 100 TeV collider can set a loose bound to λ_4
via $gg \to hhh \to 4b2\gamma$ mode.
Better modes are under searching.

C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

Heavy Higgs in single+SM

	B1	B2	B3
m_{H_2} (GeV)	460	500	490
θ	0.354	0.354	0.354
a_2	3.29	3.48	3.43
b_3 (GeV)	-706	-612	-637
b_4	8.38	8.38	8.38

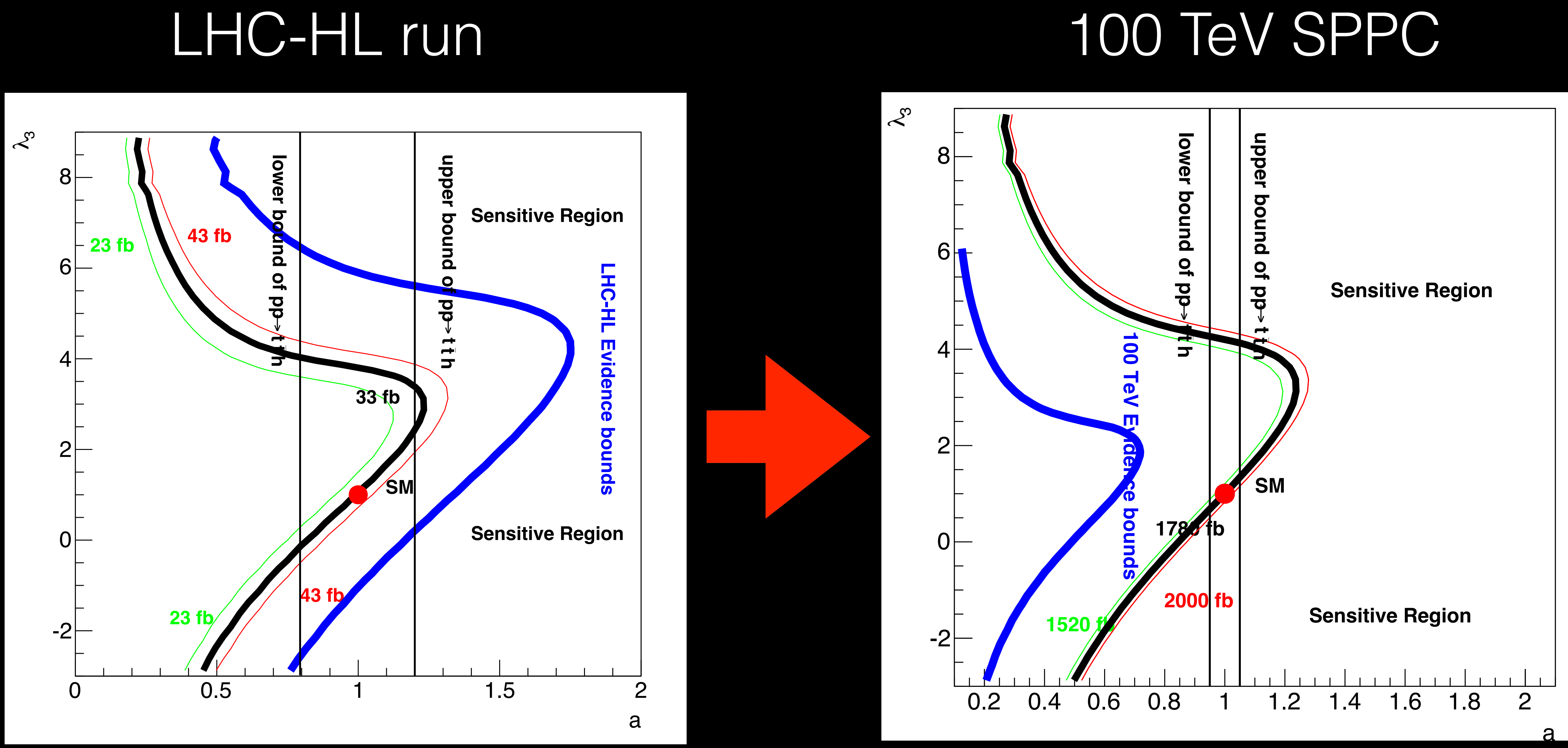


Production rate is enhanced!

	B1	B2	B3
$\Gamma_{tot}(H_2)$ (GeV)	5.6	7.5	7.0
$BR(H_2 \to W^+W^-)$	0.57	0.56	0.57
$BR(H_2 \to ZZ)$	0.27	0.27	0.27
$BR(H_2 \to t\bar{t})$	0.15	0.16	0.16
$BR(H_2 \to b\bar{b})$	3.4×10^{-4}	2.8×10^{-4}	2.9×10^{-4}
$BR(H_2 \to HH)$	5.3×10^{-7}	8.8×10^{-7}	1.5×10^{-7}
$BR(H_2 \to HHH)$	1.0×10^{-3}	1.4×10^{-3}	1.3×10^{-3}
$\sigma(gg \to H_2)$ @ 14 TeV (fb)	3.2×10^2	2.3×10^2	2.5×10^2
$\sigma(gg \to HHH)$ @ 14 TeV (fb)	0.70	0.69	0.71
$\sigma(gg \to H_2)$ @ 100 TeV (fb)	1.4×10^4	1.1×10^4	1.2×10^4
$\sigma(gg \to HHH)$ @ 100 TeV (fb)	37	38	39

C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

Interplay between tth and hh

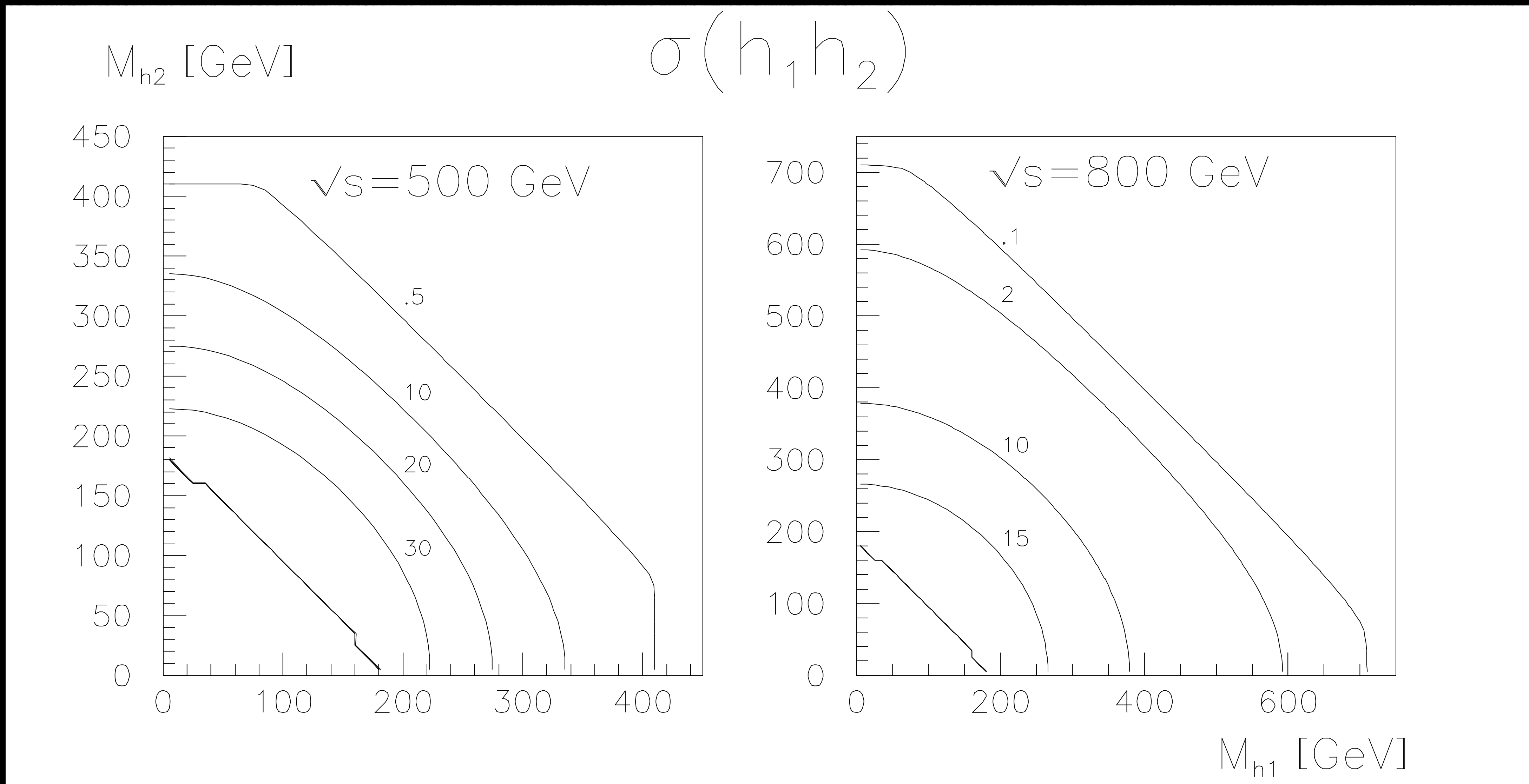


$$\Delta\mathcal{L} = Y_t\,(a\,\bar{t}t + i\,b\,\bar{t}\gamma_5 t)\,h + \lambda_3\,\lambda_{SM}\,v\,h\,h\,h + \cdots$$

J.F. Gunion, B. Grzadkowski, X.G. He, PRL77(1996)5172

Q. Li, Z. Li, QY, X.R. Zhao, in preparation

$e^+e^- \to h_i \, h_j$



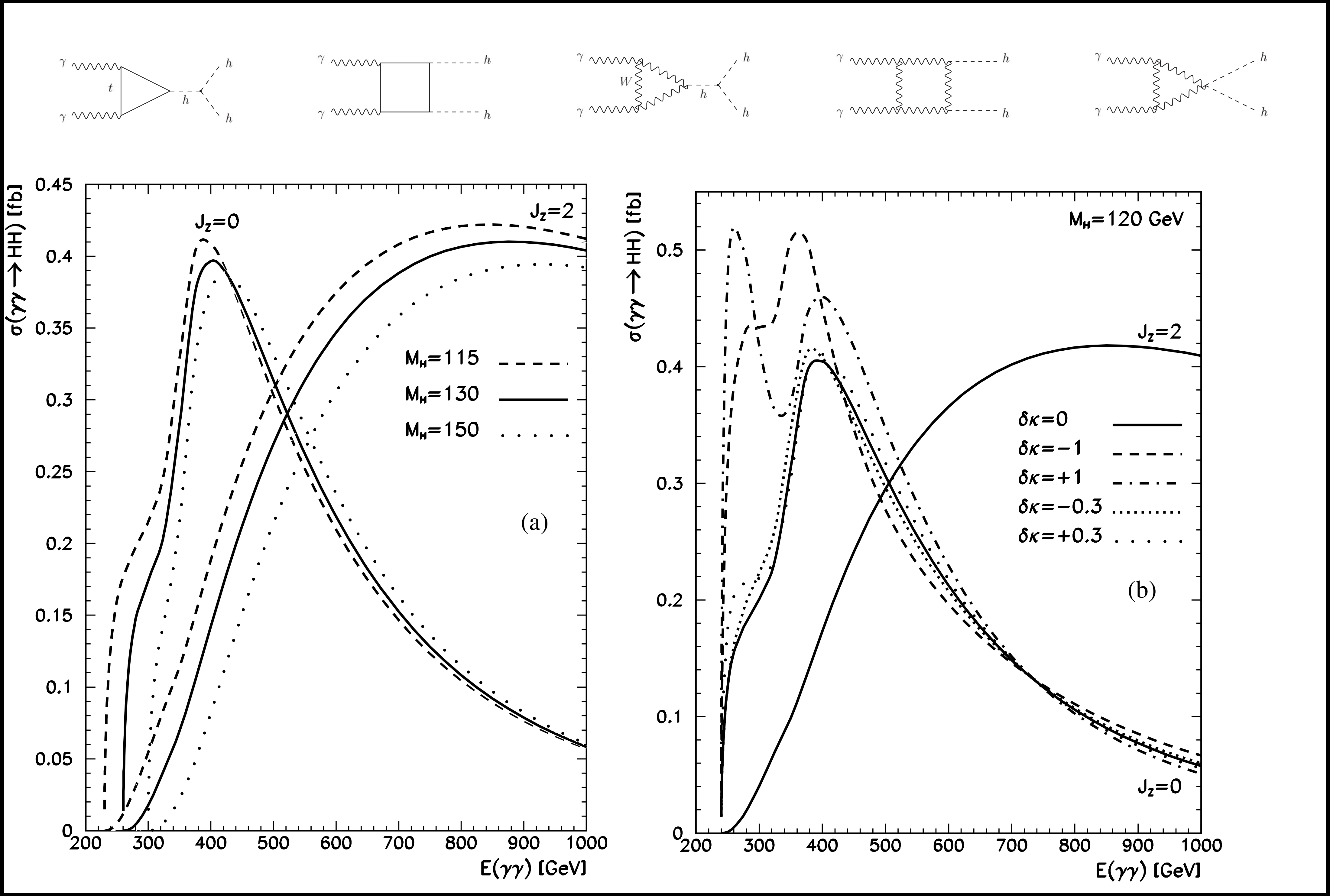
$$\frac{g_z}{2} Z_\mu \; \varepsilon_{ijk} T_{ki} \, S_j \partial^\mu S_k$$

$$J_1 = -v^2 \, \mathrm{Im}(\lambda_6^* \lambda_5^2)$$
$$= (m_1^2 - m_2^2)(m_2^2 - m_3^2)(m_3^2 - m_1^2) \, T_{11} T_{12} T_{13}$$

A. Mendez, A. Pomarol, PLB272(1991)313

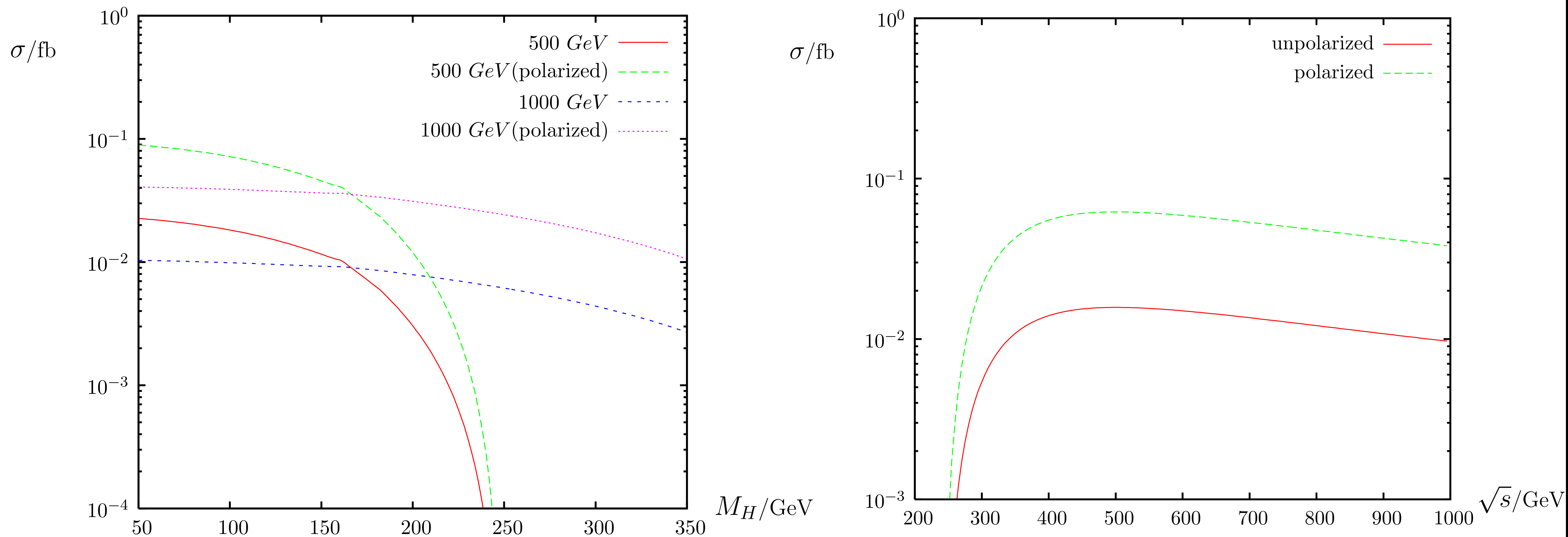
B.Grzadkowski, G.F. Gunion, J. Kalinowski, PLB480(2000)287

$\gamma\gamma \to hh$



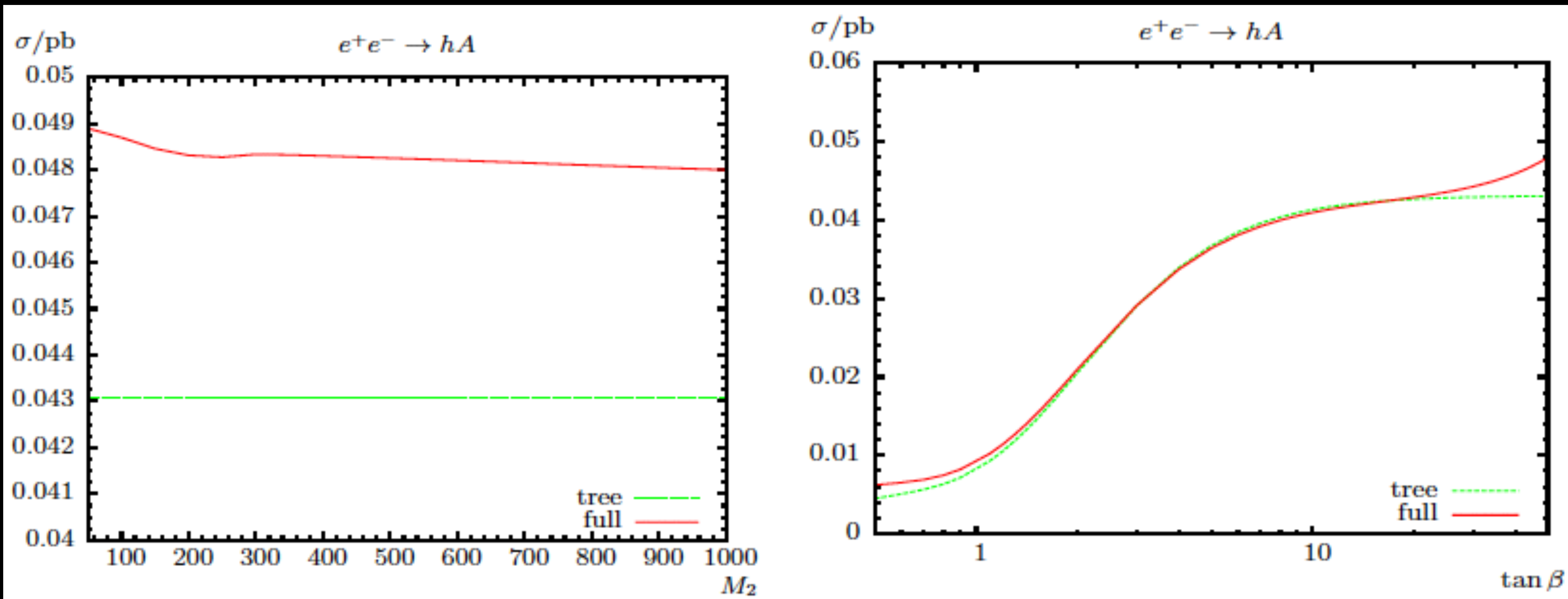
R. Belusevic, G. Jikia, PRD70(2004)073017

$e^+e^- \to hh$



J.J.Lopez-Villarejo and J.A.M. Vermaseren, PLB675,356

S. Heinemeyer and C. Schappacher, 1511.06002



S. Heinemeyer and C. Schappacher, 1511.06002

Higgs Decay :

	Order	Scale uncertainty	Ref.	Comment
$b\bar{b}, c\bar{c}$	N^4LO, QCD	0.1%	0511063	massless
$\tau\bar{\tau}$	NLO, EW	1~2%	Z. Phys. C53, 507	
gg	N^3LO, QCD	3%	0604194	Large m_t
$\gamma\gamma$	N^2LO QCD + NLO EW	<1%	1212.6233	
$Z\gamma$	NLO QCD	<5%	PLB262, 350	
$WW/ZZ \to 4f$	NLO QCD NLO EW	~0.5%	0708.4123	interference included

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Higgs Production @HC

	Order	scale uncertainty	ref.
gF	N^3LO QCD	4%	1603.08000
VBF	N^2LO QCD	2%	1003.4451
HV	NNLO	2%	0307206
ttH	NLO	10~15%	0211352

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Prospects

- High Precision predictions for Higgs Physics
- Discovery new Higgs Bosons
- Multi-Higgs boson Final States, Discovery and Precision measurement
- CP phases determination of Higgs potentials
- Higgs portal and dark matter