The Higgs in The Extended Electroweak Gauge Symmetries

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The old story of perturbative unitarity

The model description of the $SU(2)_0 \times SU(2)_1 \times U(1)_2$

The unitarity constraints in the 221-model

Experimental constraints to the model

Conclusion

The perturbative unitarity

- Example-1: $\nu\bar{\nu} \to W^+W^-$, $\mathcal{T}_t^e \sim G_F s$. High energy E^2 behavior canceled by $\mathcal{T}_u^{E^+}$ or $\mathcal{T}_s^Z$.
- Example-2: vector boson scatterings in the SM, e.g. $W^+W^- \to W^+W^-$.

$$\mathcal{T} \xrightarrow{s \gg M_W^2} \sqrt{2}G_F\left[s + t - \frac{s^2}{s - M_h^2} - \frac{t^2}{t - M_h^2}\right]$$

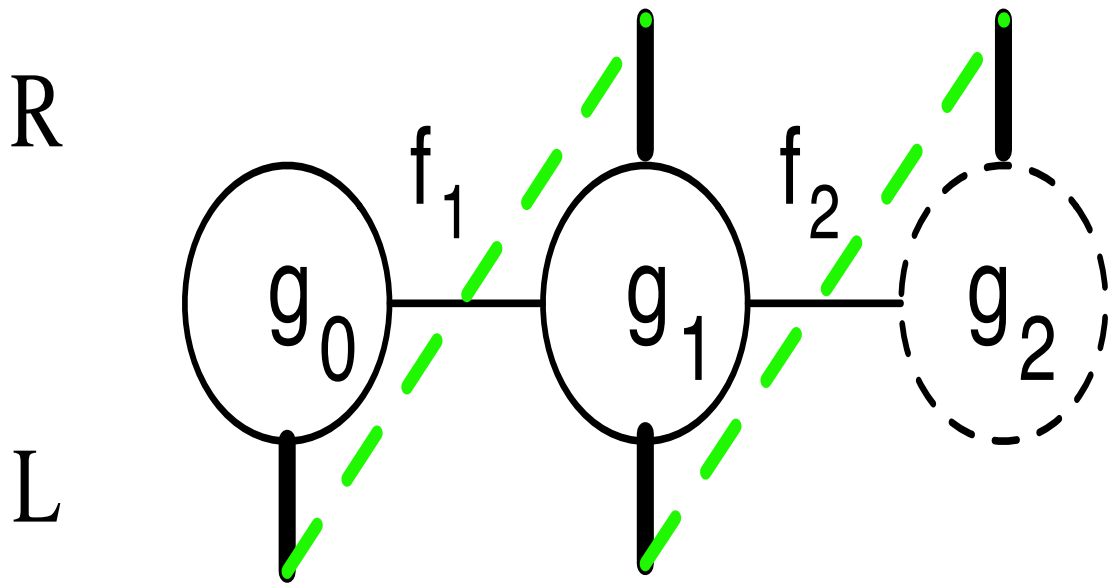
The corresponding s-wave amplitude:

$$a_0 \xrightarrow{s \gg M_W^2} -\frac{M_h^2}{8\pi v^2} : \quad M_h \lesssim 870 \ \mathrm{GeV}$$

- Can vector boson scatterings in LHC tell us something more?

The Moose diagram

- Solid circles: $\mathrm{SU}(2)'$s, dashed circles: $\mathrm{U}(1)$. Vertical bars: left/right-handed fermions. Green dashed lines: Yukawa couplings (see below).



Higgs fields

- Introduce two Higgs multiplets $\Phi_1 \in (2\,,2\,,0)$ and $\Phi_2 \in (1\,,2\,,\frac{1}{2})$ for the spontaneous symmetry breaking:

$$\begin{aligned} \mathrm{SU}(2)_0 \times \mathrm{SU}(2)_1 &\xrightarrow{\langle\Phi_1\rangle = f_1} \mathrm{SU}(2)_\mathrm{V} \\ \mathrm{SU}(2)_1 \times \mathrm{U}(1)_2 &\xrightarrow{\langle\Phi_2\rangle = f_2} \mathrm{U}(1)_\mathrm{V} \end{aligned}$$

with $1/f_1^2 + 1/f_2^2 = \sqrt{2}G_F$ and $r \equiv f_2/f_1 \sim \mathcal{O}(1)$.

- The Higgs Yukawa couplings and fermion mass-terms:

$$-\mathcal{L}_Y = \sum_{i,j} \left[y_{1ij} \bar{\Psi}^i_{0L} \Phi_1 \Psi^j_{1R} + y_{2ij} \bar{\Psi}^i_{1L} \Phi_2 \Psi^j_{2R} + \bar{\Psi}^i_{1L} M_{ij} \Psi^j_{1R} + h.c. \right]$$

Higgs fields [cont.]

- The generic Higgs potential:

$$
\begin{aligned}
V(\Phi_1\,,\Phi_2) \quad = \quad & \frac{1}{2}\lambda_1\Big[\,\mathrm{Tr}(\Phi_1^\dagger\Phi_1)-\frac{f_1^2}{2}\Big]^2+\frac{1}{2}\lambda_2\Big[\,\mathrm{Tr}(\Phi_2^\dagger\Phi_2)-\frac{f_2^2}{2}\Big]^2 \\
& +\lambda_{12}\Big[\,\mathrm{Tr}(\Phi_1^\dagger\Phi_1)-\frac{f_1^2}{2}\Big]\Big[\,\mathrm{Tr}(\Phi_2^\dagger\Phi_2)-\frac{f_2^2}{2}\Big]\,,
\end{aligned}
$$

- One is left with $(h_1\,,h_2)\to(h\,,H)$ after the symmetry breaking. The scalar self-couplings $(\lambda_1\,,\lambda_2\,,\lambda_{12})$:

$$
\begin{aligned}
\lambda_1 \quad &= \quad \frac{1}{f_1^2}(c_\alpha^2 M_h^2+s_\alpha^2 M_H^2)\,, \\
\lambda_2 \quad &= \quad \frac{1}{f_2^2}(s_\alpha^2 M_h^2+c_\alpha^2 M_H^2)\,, \\
\lambda_{12} \quad &= \quad \frac{c_\alpha s_\alpha}{f_1 f_2}\Big(M_H^2-M_h^2\Big)\,.
\end{aligned}
$$

Gauge fields

- The gauge fields of $\mathrm{SU}(2)_0 \times \mathrm{SU}(2)_1 \times \mathrm{U}(1)_2$: (V_0^a, V_1^a, B).
- The mass eigenstates of gauge fields: (W, Z, A) and (W', Z'):

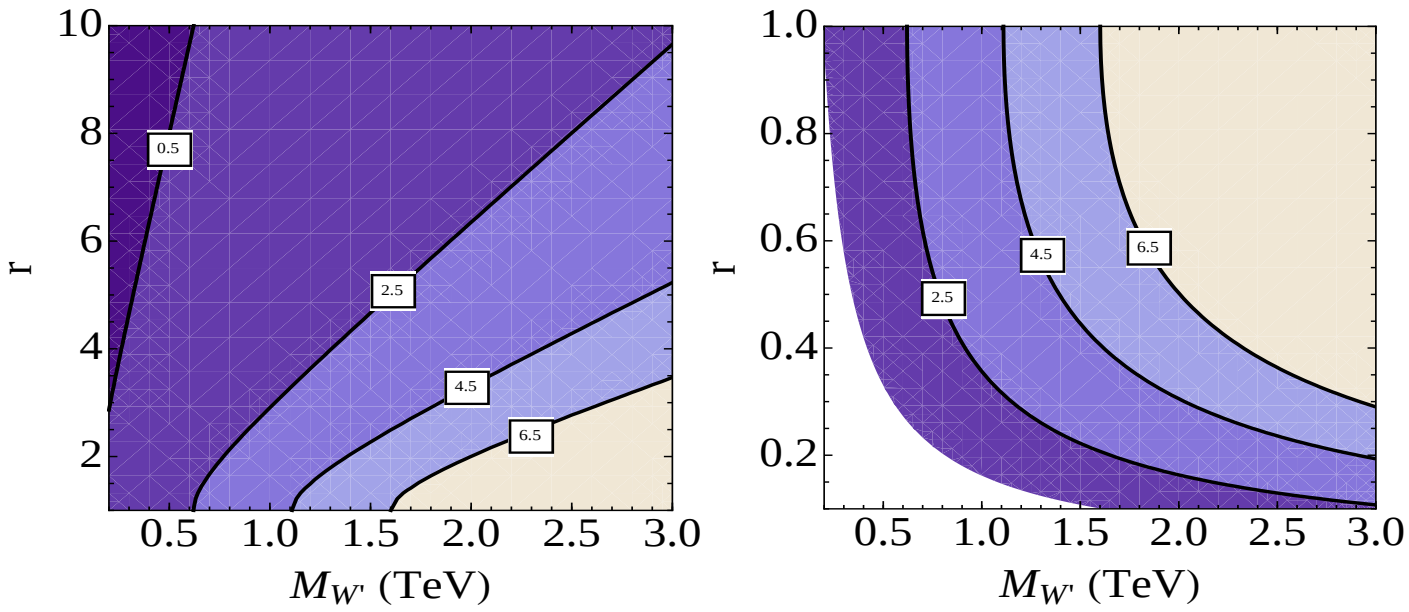
$$\begin{pmatrix} V_0^{\pm} \\ V_1^{\pm} \end{pmatrix} = \begin{pmatrix} v_W^0 & -v_W^1 \\ v_W^1 & v_W^0 \end{pmatrix} \cdot \begin{pmatrix} W^{\pm} \\ W'^{\pm} \end{pmatrix}$$

$$\begin{pmatrix} V_0^3 \\ V_1^3 \\ B \end{pmatrix} = \begin{pmatrix} v_W^0 & -v_W^1 & 0 \\ v_W^1 & v_W^0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} Z \\ Z' \\ A \end{pmatrix}$$

- Ideal delocalization: to minimize the corrections to the EW precision parameters, and V' couplings to SM fermions are vanishing.

Gauge couplings

- Gauge couplings: $g_1 \gg (g_0\,, g_2) \simeq (g\,, g')$:



with:

$$(M_{V'}^2 - M_V^2)^2 \quad \geq \quad \frac{4}{r^2} M_V^2 M_{V'}^2$$

Gauge couplings [cont.]

- The quartic gauge couplings $G^{(4)}_{mnkl}$: (G_{VVVV} , $G_{VVVV'}$, $G_{VVV'V'}$, $G_{VV'V'V'}$, $G_{V'V'V'V'}$).
- The cubic gauge couplings $G^{(3)}_{mnj}$: (G_{VVV} , $G_{VVV'}$, $G_{VV'V'}$, $G_{V'V'V'}$).
- The Higgs gauge couplings $G_{h_j mn}$: (G_{hVV} , $G_{hVV'}$, $G_{hV'V'}$, G_{HVV} , $G_{HVV'}$, $G_{HV'V'}$).
- The sum rule for the SM:

$$\mathcal{O}(s^2) \quad : \quad G_{VVVV} = G^2_{VVV}$$

$$\mathcal{O}(s) \quad : \quad G_{VVVV} - \frac{3}{4} G^2_{VVV} = \frac{G^2_{hVV}}{4M^2_V}$$

Tree-level unitarity: single-channel scatterings

- The general structure of the scattering amplitude for the $\mathcal{V}^a_m \mathcal{V}^b_n \to \mathcal{V}^c_k \mathcal{V}^d_l$, with $\mathcal{V} = (V\,, V')$:

$$\mathcal{T} \quad = \quad \mathcal{T}^c + \mathcal{T}^{\mathcal{V}} + \mathcal{T}^{h_j}$$

- The $(s\,, t\,, u)$-channel decomposition of the amplitudes:

$$\begin{aligned} \mathcal{T} \quad &= \quad \delta^{ab}\delta^{cd}(\mathcal{T}^c_{t+u} + \mathcal{T}^{\mathcal{V}}_{t+u} + \mathcal{T}^{h_j}_s) \\ &+ \quad \delta^{ac}\delta^{bd}(\mathcal{T}^c_{s-u} + \mathcal{T}^{\mathcal{V}}_{s-u} + \mathcal{T}^{h_j}_t) \\ &+ \quad \delta^{ad}\delta^{bc}(-\mathcal{T}^c_{s+t} - \mathcal{T}^{\mathcal{V}}_{s+t} + \mathcal{T}^{h_j}_u) \end{aligned}$$

Specific example: $WW \to ZZ$

- Contributions from the contact term, V/V'-exchanging, and the Higgs exchanging:

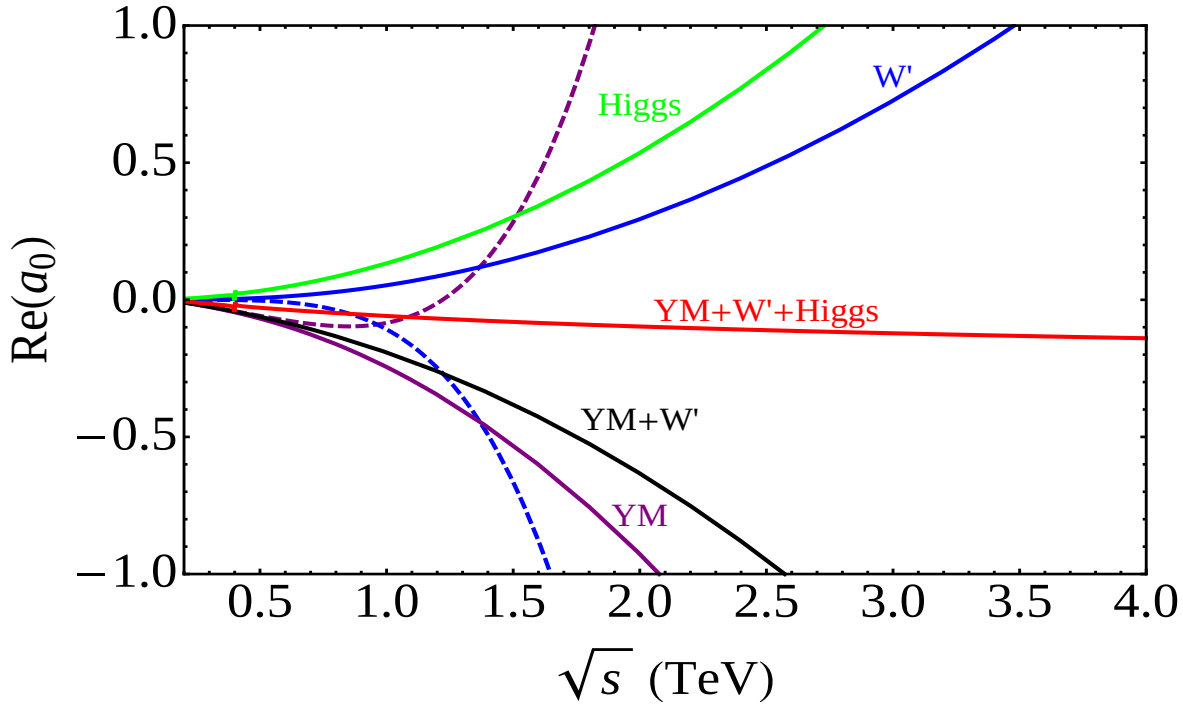
$$
\begin{aligned}
\mathcal{T}_s^c &= \frac{G_{VVVV}}{8M_V^4}(3-c_\theta^2)s^2 - \frac{G_{VVVV}}{M_V^2}s + \mathcal{O}(s^0) \\
\mathcal{T}_{t+u}^{V+V'} &= -\frac{G_{VVV}^2 + G_{VVV'}^2}{8M_V^4}(3-c_\theta^2)s^2 \\
&+ \frac{3}{4M_V^2 M_{V'}^2}\left(\frac{G_{VVV}^2}{M_{V'}^2} + \frac{G_{VVV'}^2}{M_V^2}\right)s + \mathcal{O}(s^0) \\
\mathcal{T}_s^{h+H} &= \frac{G_{hVV}^2 + G_{HVV}^2}{4M_V^4}s + \mathcal{O}(s^0)
\end{aligned}
$$

- The corresponding sum rules:

$$
\begin{aligned}
\mathcal{O}(s^2) &: \quad G_{VVVV} = G_{VVV}^2 + G_{VVV'}^2 \\
\mathcal{O}(s) &: \quad M_V^2 G_{VVVV} - \frac{3}{4}\sum_{\mathcal{V}=V,V'} \hat{M}_{\mathcal{V}}^2 G_{VV\mathcal{V}}^2 = \frac{1}{4}\sum_{h_j} G_{h_j VV}^2
\end{aligned}
$$

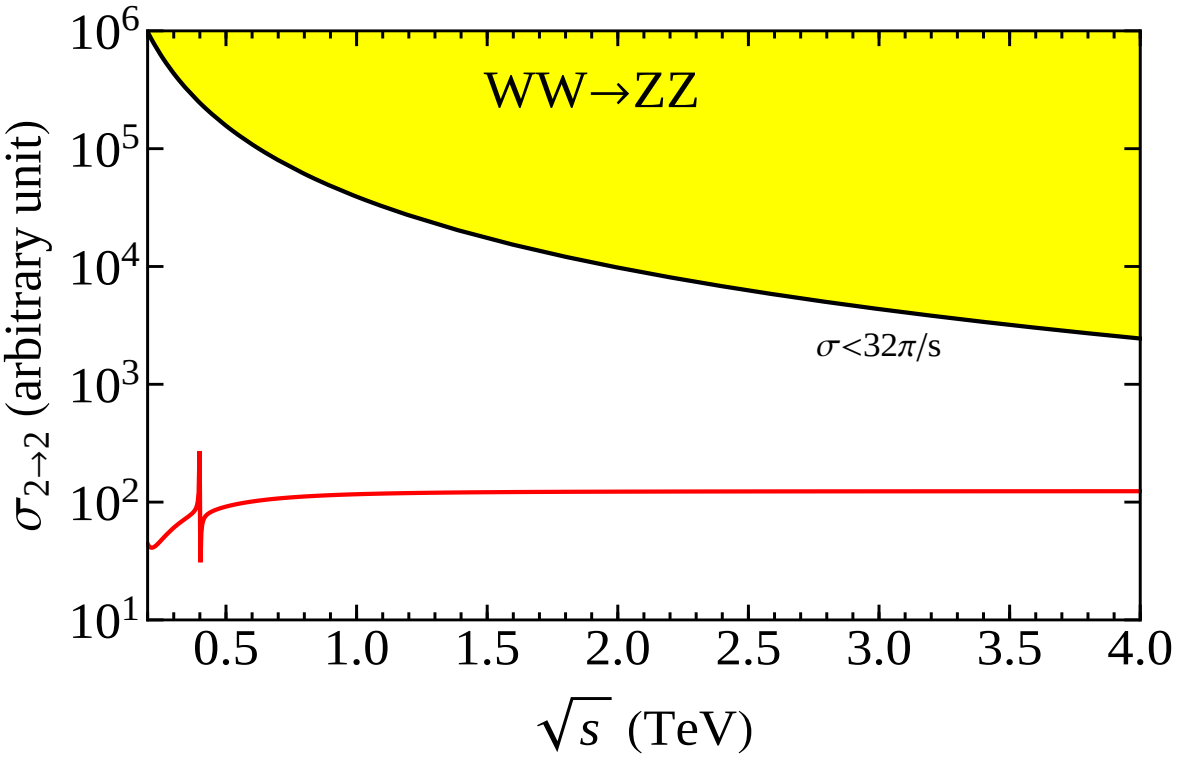
Specific example: $WW \to ZZ$ [cont.]

- The anatomy of the s-wave amplitude a_0:



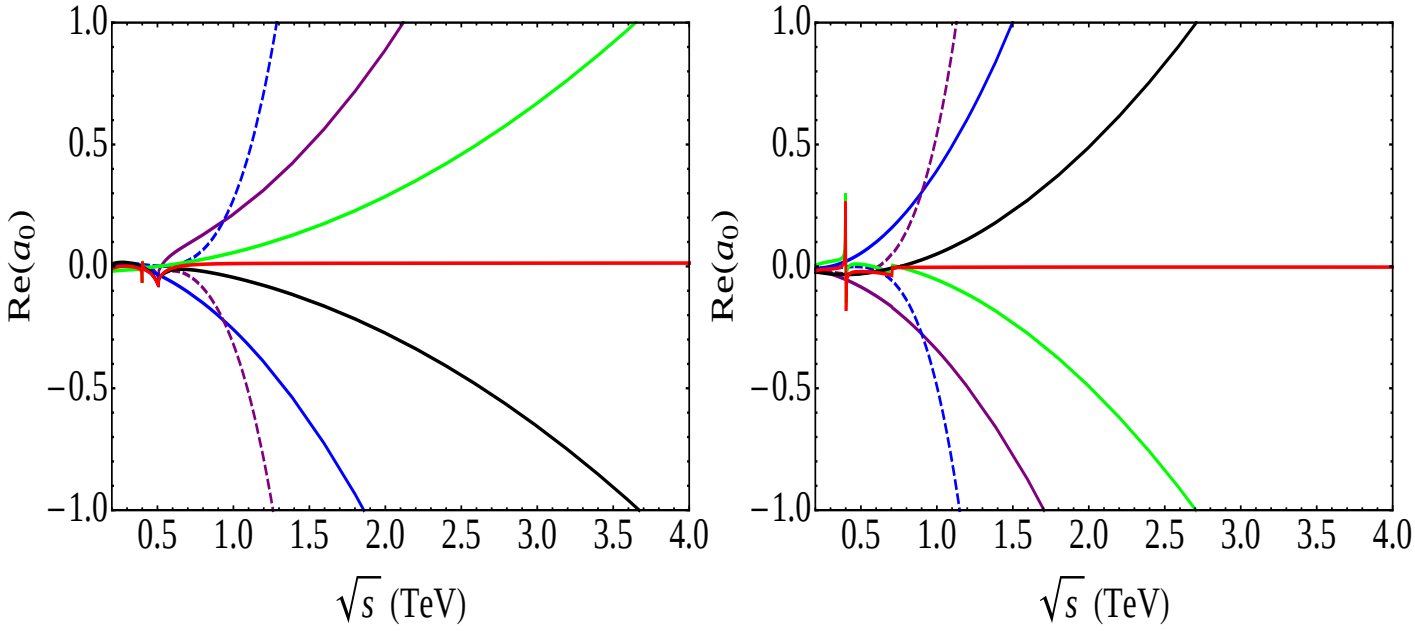
Specific example: $WW \to ZZ$ [cont.]

- The cross section of $WW \to ZZ$ Vs. the c.m. energy $\sqrt{s}$:



Inelastic scatterings

- The inelastic scatterings are also unitarized by Higgs: $WW \to ZZ'$ (left) and $WW \to Z'Z'$ (right).



Tree-level unitarity: coupled-channel analysis

- The charge-neutral states for the coupled-channel scattering amplitudes:

$$|W_L^+ W_L^-\rangle\,,\quad |\frac{1}{\sqrt{2}}Z_L Z_L\rangle\,,\quad |\frac{1}{\sqrt{2}}hh\rangle\,,\quad |Z_L h\rangle$$

with

$$a_0 \quad \propto \quad \frac{M_h^2}{v^2}\begin{pmatrix} 1 & \frac{\sqrt{2}}{4} & \frac{\sqrt{2}}{4} & 0 \\ \frac{\sqrt{2}}{4} & \frac{3}{4} & \frac{1}{4} & 0 \\ \frac{\sqrt{2}}{4} & \frac{1}{4} & \frac{3}{4} & 0 \\ 0 & 0 & 0 & \frac{1}{2} \end{pmatrix}$$

- Lee-Quigg-Thacker: requiring $|a_0^{\max}| \leq 1/2$.

Tree-level unitarity: coupled-channel analysis [cont.]

- Extending to the coupled-channel scattering amplitudes for all scalars in the 221-model:

$$
\begin{aligned}
|\mathcal{A}_{11}\rangle \quad &: \quad |\pi_1^+\pi_1^-\rangle \;\; \frac{1}{\sqrt{2}}|\pi_1^3\pi_1^3\rangle \;\; \frac{1}{\sqrt{2}}|h_1 h_1\rangle\,, \\
|\mathcal{A}_{22}\rangle \quad &: \quad |\pi_2^+\pi_2^-\rangle \;\; \frac{1}{\sqrt{2}}|\pi_2^3\pi_2^3\rangle \;\; \frac{1}{\sqrt{2}}|h_2 h_2\rangle\,, \\
|\mathcal{A}_{12}\rangle \quad &: \quad |\pi_1^+\pi_2^-\rangle \;\; |\pi_1^-\pi_2^+\rangle \;\; |\pi_1^3\pi_2^3\rangle \;\; |h_1 h_2\rangle \;\; |\pi_1^3 h_2\rangle \;\; |h_1\pi_2^3\rangle\,, \\
|\mathcal{B}_{\pi h}\rangle \quad &: \quad |\pi_1^3 h_1\rangle \;\; |\pi_2^3 h_2\rangle\,.
\end{aligned}
$$

- The full 14×14 $\mathcal{T}$-matrix for the scattering amplitude is block-diagonalized as:

$$
\begin{pmatrix} \langle\mathcal{A}_{11}|\mathcal{T}|\mathcal{A}_{11}\rangle & \langle\mathcal{A}_{11}|\mathcal{T}|\mathcal{A}_{22}\rangle \\ \langle\mathcal{A}_{22}|\mathcal{T}|\mathcal{A}_{11}\rangle & \langle\mathcal{A}_{22}|\mathcal{T}|\mathcal{A}_{22}\rangle \end{pmatrix}_{6\times 6}\,,
$$

$$
(\langle\mathcal{A}_{12}|\mathcal{T}|\mathcal{A}_{12}\rangle)_{6\times 6}\,, \quad (\langle\mathcal{B}_{\pi h}|\mathcal{T}|\mathcal{B}_{\pi h}\rangle)_{2\times 2}\,.
$$

Tree-level unitarity: coupled-channel analysis [cont.]

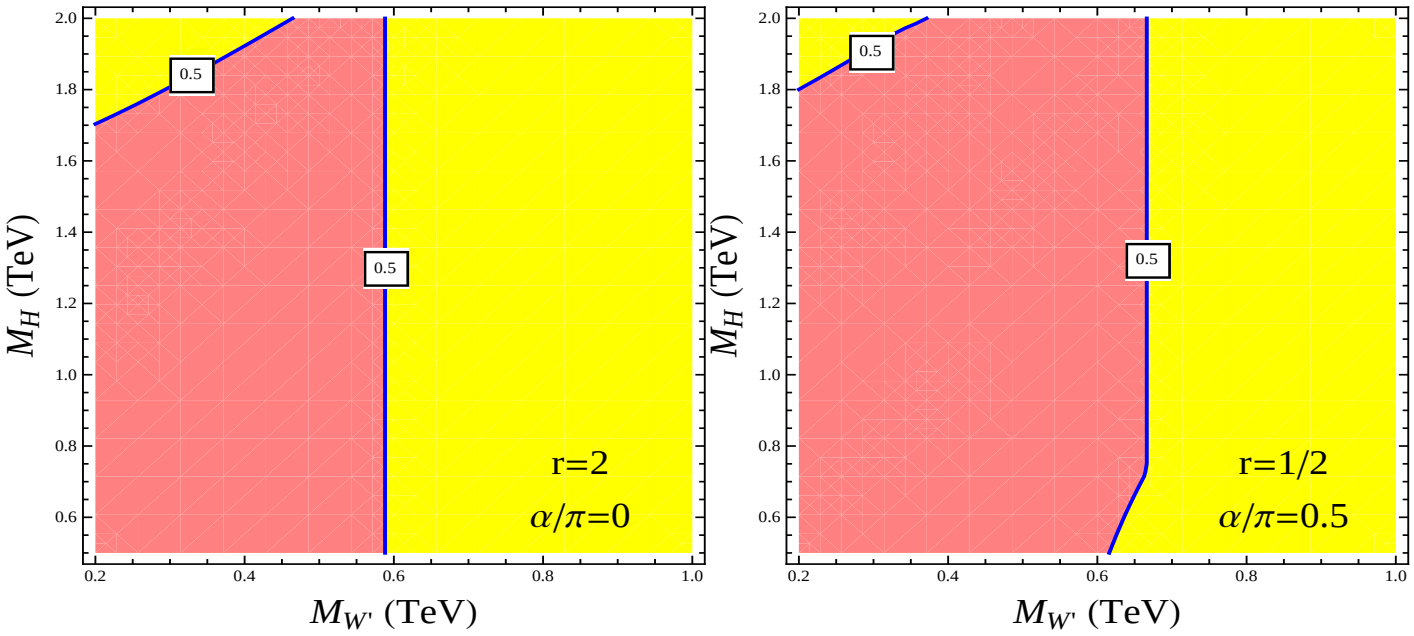
- The $\mathcal{T}$-matrix receives contributions from the scalar contact terms from the Higgs potential, plus the $\mathcal{V}$-exchanging contributions:

$$\begin{aligned} \mathcal{T} &= \mathcal{T}[\text{contact}] + \mathcal{T}[\text{gauge}] \\ \text{elements} &: \sim \lambda_1 - (g_0^2 + g_1^2)\,, \;\; \lambda_2 - (g_0^2 + g_1^2) \ldots \end{aligned}$$

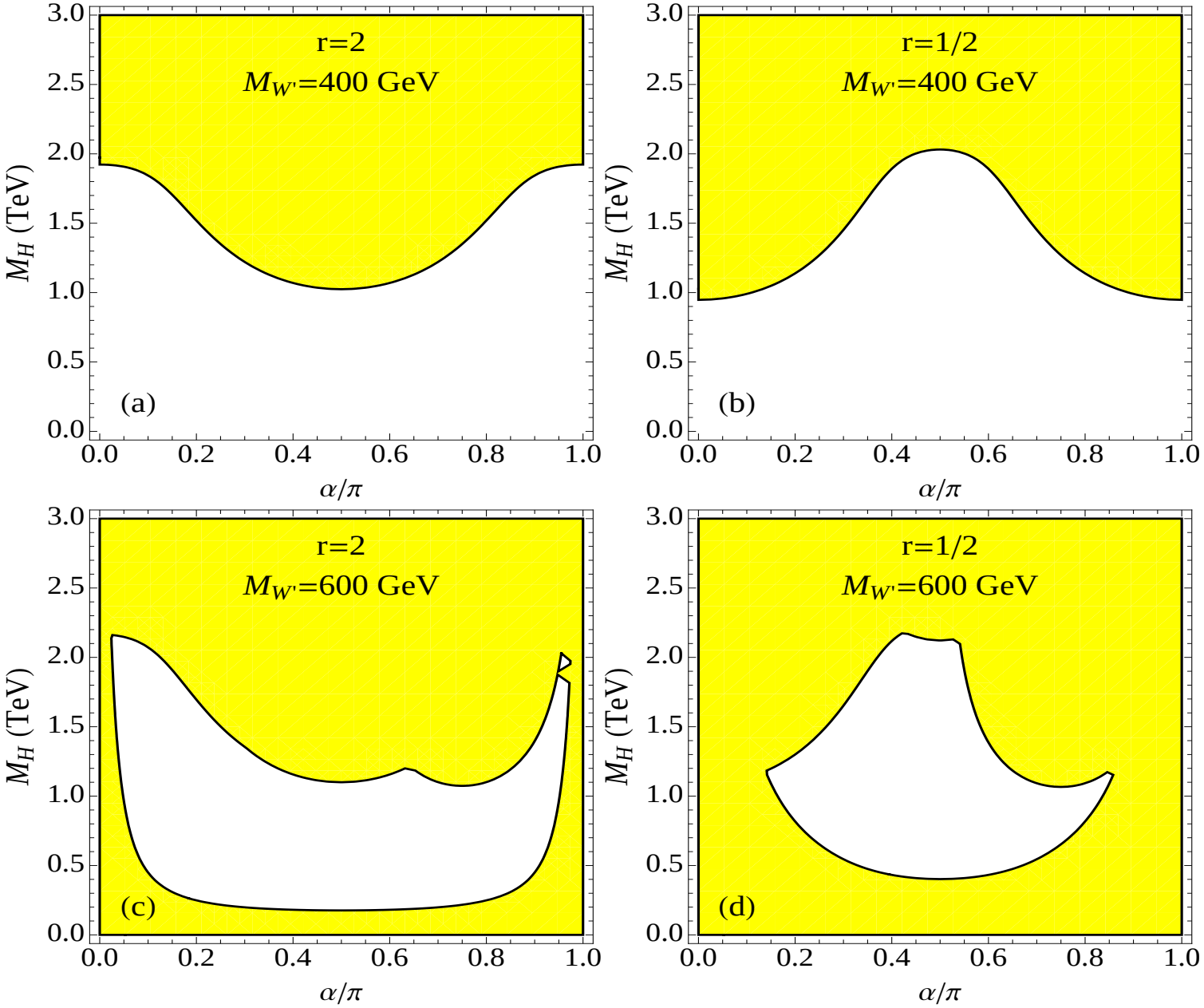
- Inputs: $(M_h\,, M_W\,, M_H\,, \alpha\,, M_{W'})$.
- The unitarity requirement leads to the mass bounds of $(M_{W'}\,, M_H)$.

Tree-level unitarity: coupled-channel analysis [cont.]

- The unitarity bounds to the $(M_{W'}, M_H)$ through the coupled-channel scattering amplitudes:

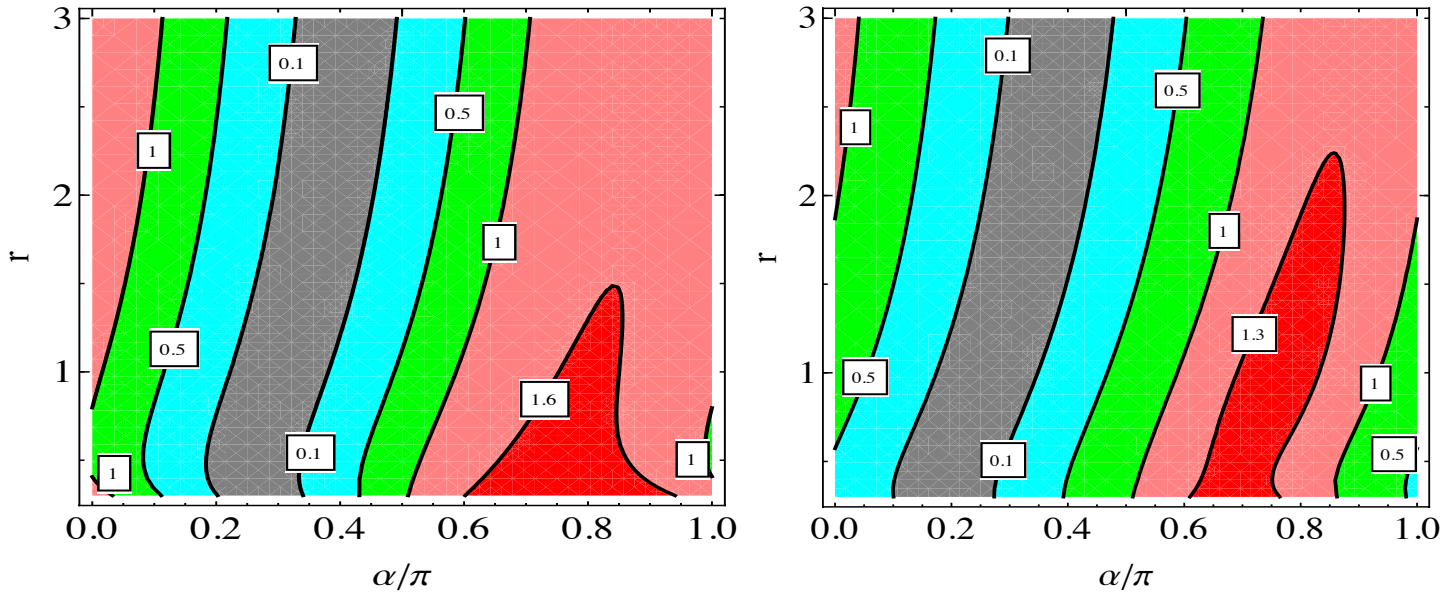


The unitarity bounds to M_H Vs. α



The productions/decays of 125 GeV Higgs

- Assume the light Higgs with mass $M_h = 125\ \mathrm{GeV}$.
- The ggF production ratio $\mathcal{R}_{ggh}$:



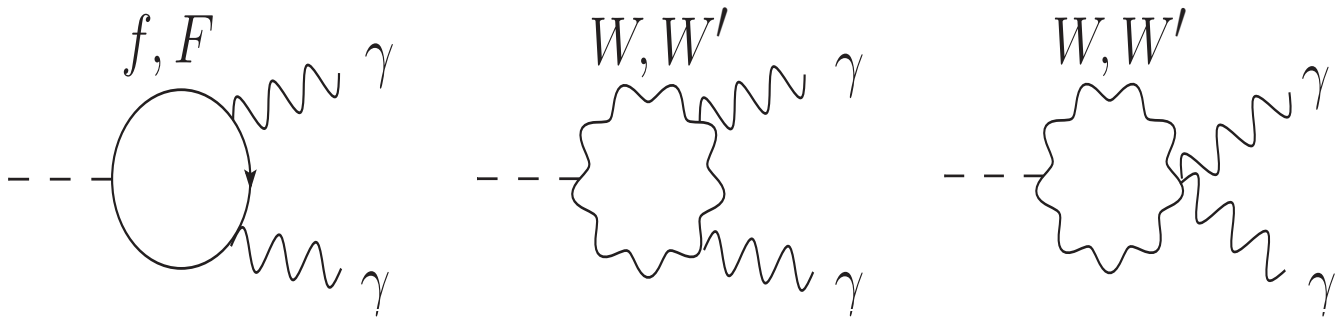
for $M_{W'} = 400\ \mathrm{GeV}$ (left) and $M_{W'} = 600\ \mathrm{GeV}$ (right) respectively.

The productions/decays of 125 GeV Higgs [cont.]

- The tree-level decay modes with modified G_{hff} and G_{hVV} couplings:

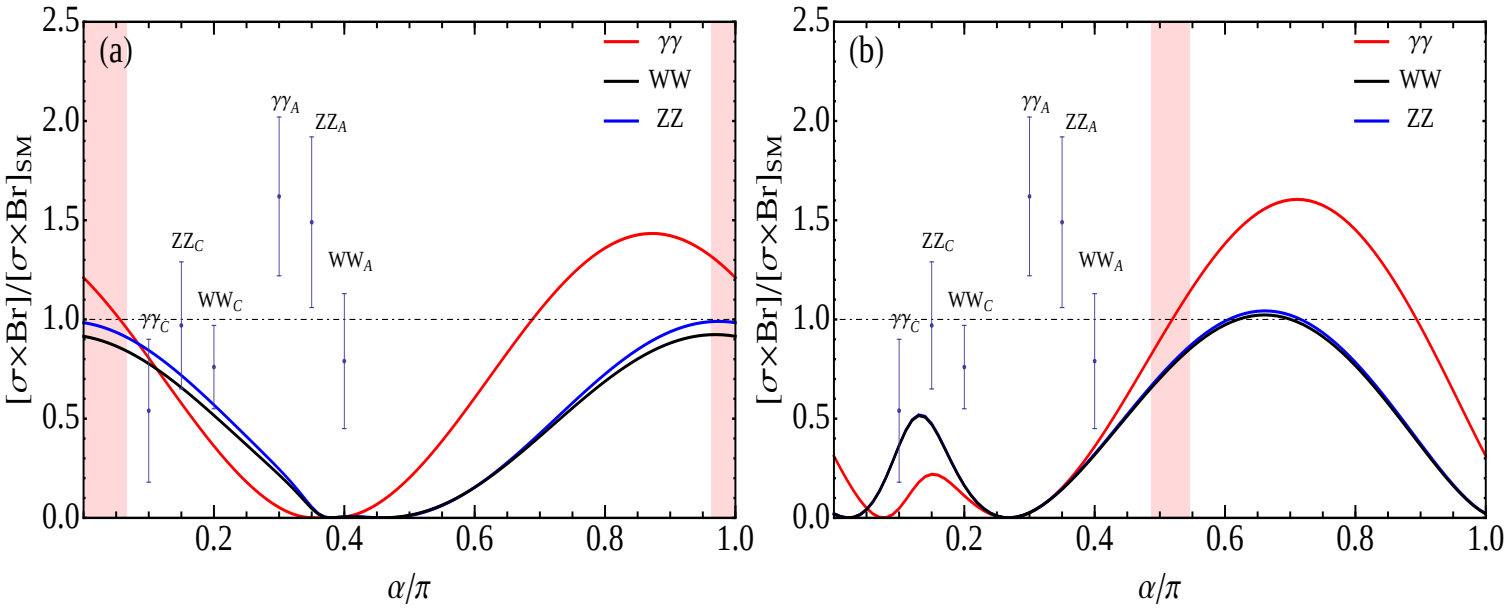
$$G_{hff} = \frac{m_f}{v}\xi_{hff} \quad \xi_{hff} \approx \frac{rc_\alpha - s_\alpha}{(1+r^2)^{1/2}} + \mathcal{O}(x^2)$$

- The loop-induced decay modes with new contributions together with modified couplings:



The signal strengths of the 125 GeV Higgs

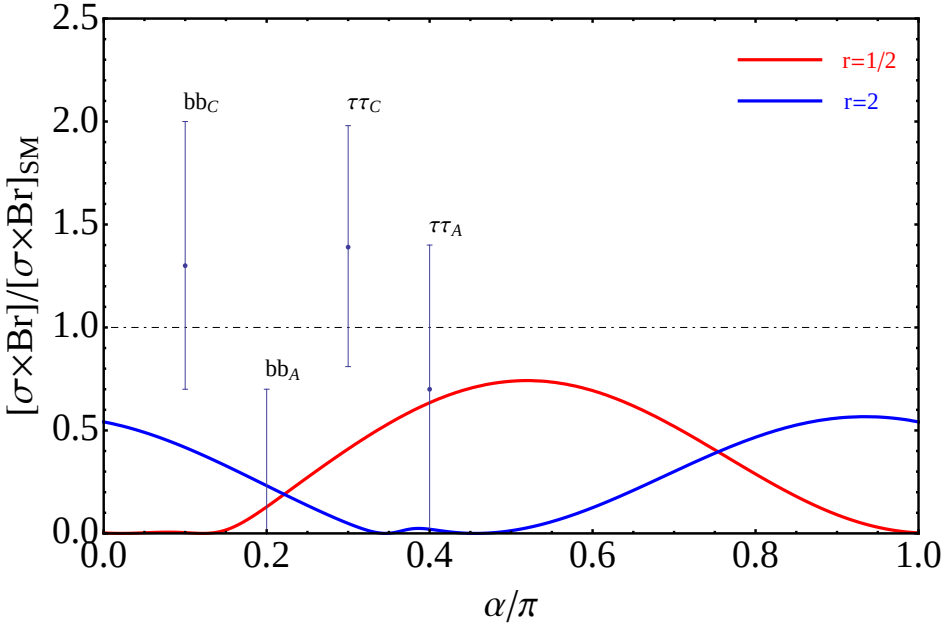
- The signal ratios of the most sensitive channels: $(\gamma\gamma\,, ZZ^* \to 4\ell\,, WW^* \to 2\ell 2\nu)$



left: $r = f_2/f_1 = 2$, right: $r = f_2/f_1 = 1/2$.

The signal strengths of the 125 GeV Higgs [cont.]

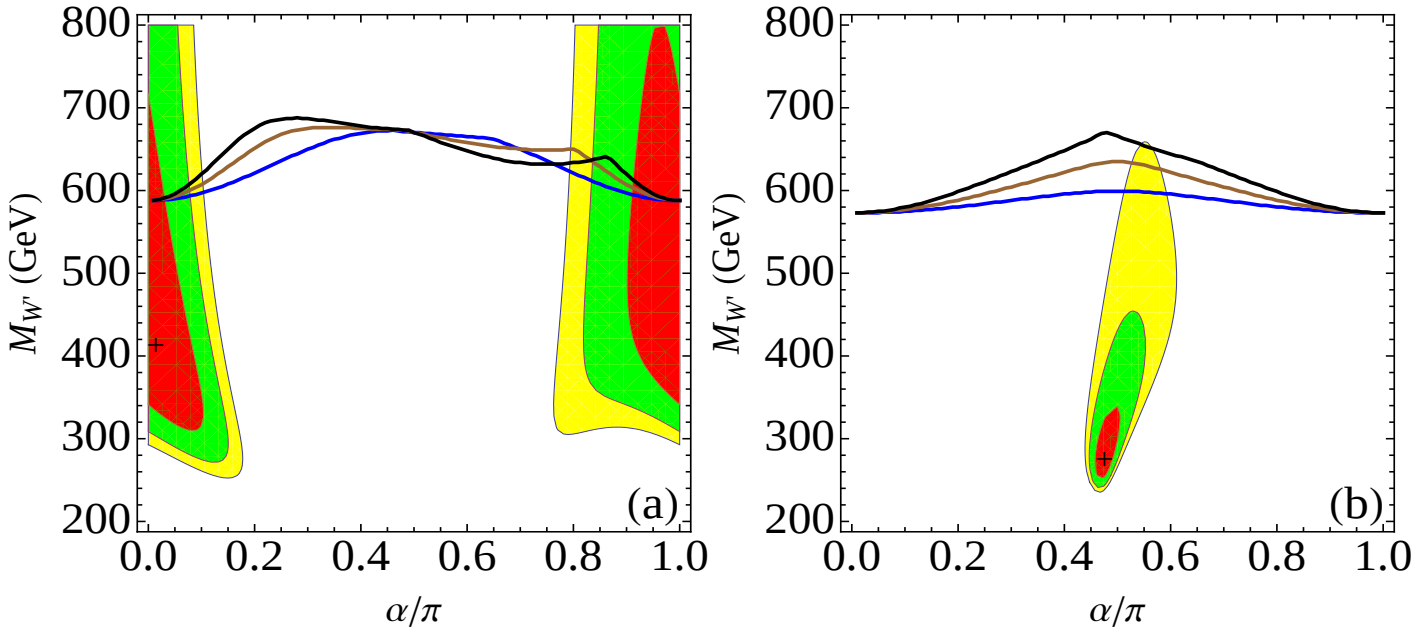
- The signal ratios of the fermionic decay modes: $(bb\,,\tau^+\tau^-)$



The $\bar{b}b$ via the *VH* associated production channel, and $\tau^+\tau^-$ via the VBF channel.

The combined χ^2 fit

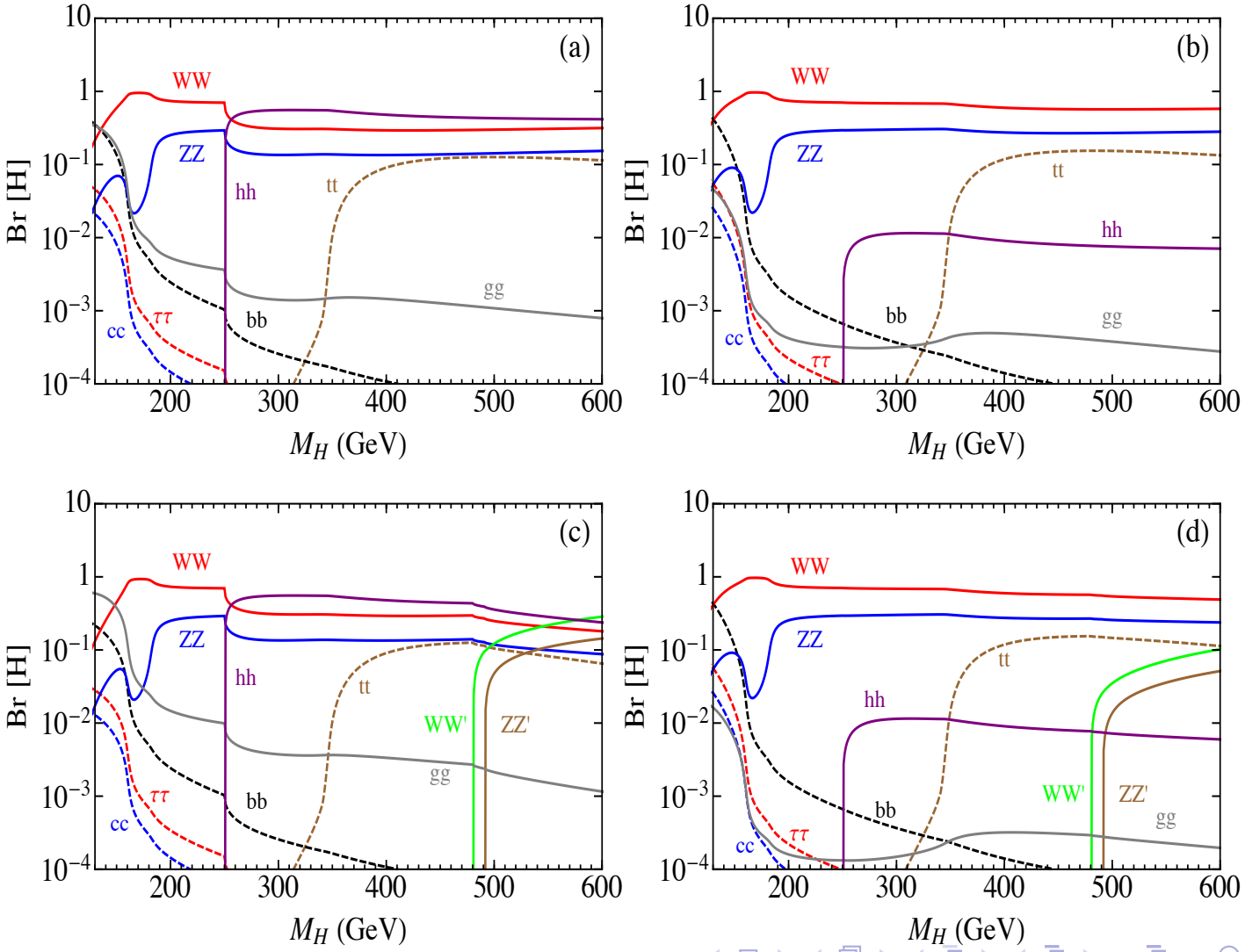
- Combining the ATLAS and CMS experimental data for all five channels:



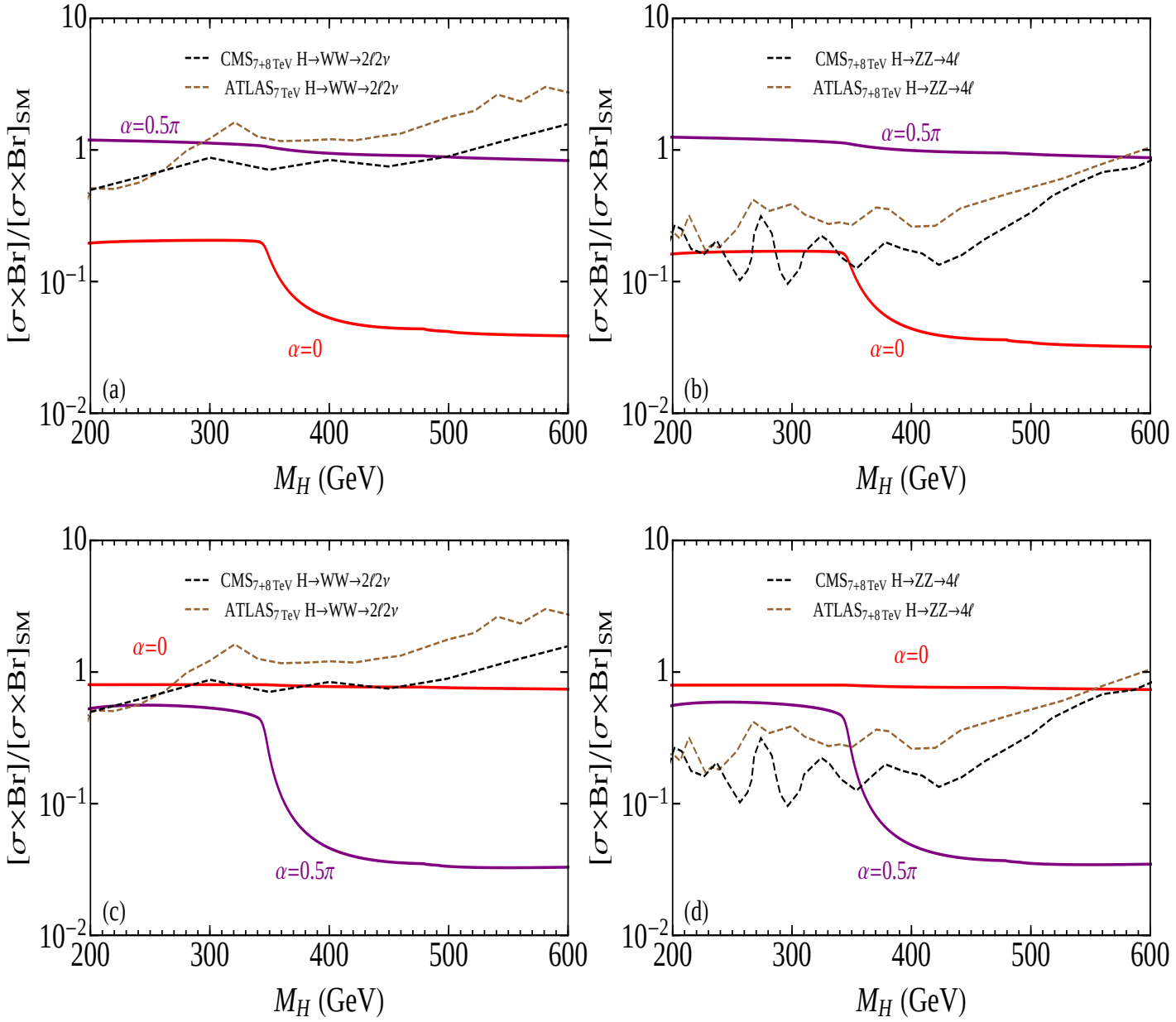
The 68% (red), 95% (green), and 99% (yellow) confidence regions for the $(\alpha\,, M_{W'})$ parameter space displayed. The unitarity upper bounds of $M_{W'}$ Vs. α with $M_H = 400\ \mathrm{GeV}$ (blue), $M_H = 600\ \mathrm{GeV}$ (brown) and $M_H = 800\ \mathrm{GeV}$ (black) are also shown.

Decay modes of H

- The usual SM final states: $H \to (WW\,, ZZ\,, \bar{t}t\,, \bar{b}b\,, \tau^+\tau^-\,, gg)$
- The possible exotic decay modes: $H \to hh$ and $H \to VV'$ (for $M_H > M_V + M_{V'}$).



The direct experimental limit on H: $r = 2$ (upper) and $r = 1/2$ (lower)



Conclusion

- The E^2 cancellation for the vector boson scatterings: by spin-0 Higgs fields and spin-1 vector bosons.
- The VBF process can probe the new heavy states in the model.
- The coupled-channel unitarity analysis: upper bounds to $(M_{W'}, M_H)$.
- The χ^2 fit is performed for the model parameters via the light 125 GeV Higgs boson.
- Experimental bounds to the model: χ^2 fit for the light Higgs signals, and exclusion limits to the heavy Higgs boson. Exotic searching modes are possible for the heavy Higgs.