LHC Higgs Signatures from Extended Electroweak Guage Symmetry

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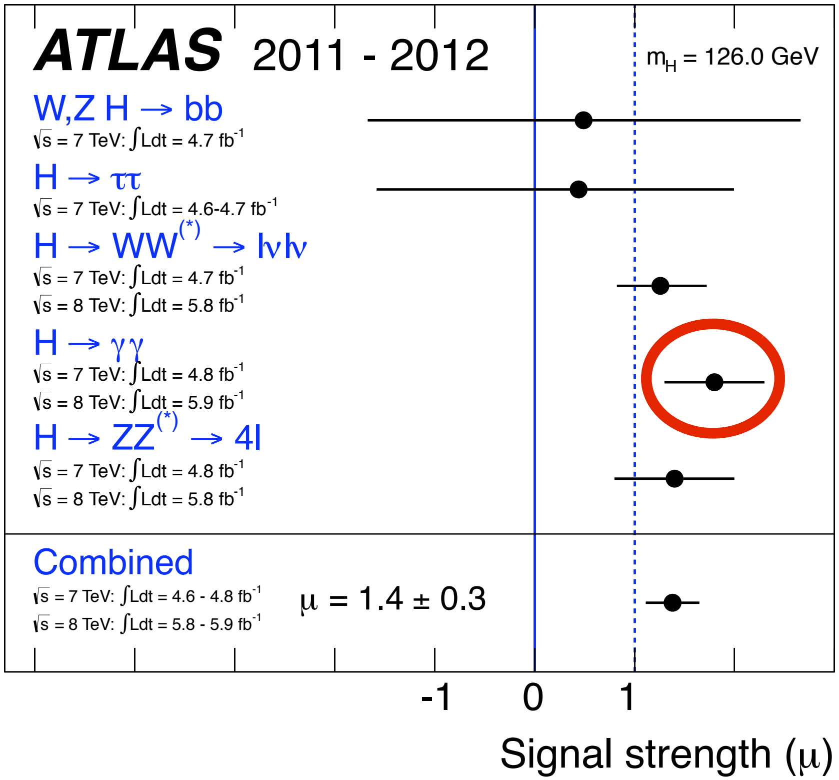
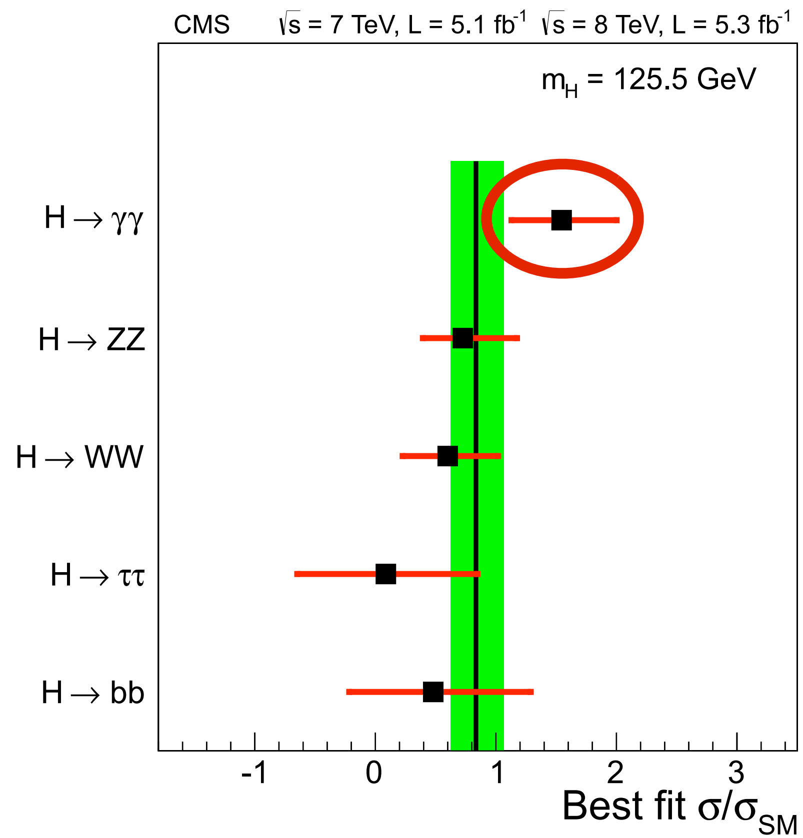
Contents

Introduction

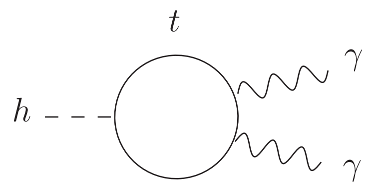
- LHC found a new particle around 125 GeV!
- 2 photon signal is larger than the SM Higgs prediction
- Are there any new physics? (or statistics...)

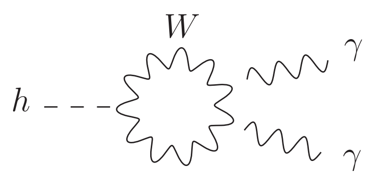




How to enhance di-photon signal?

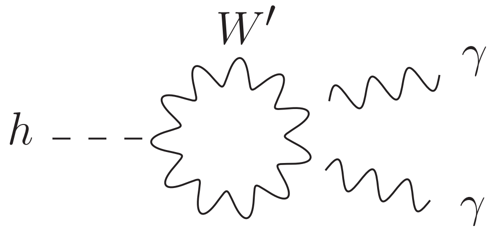
- h → γ γ is loop induced process





- new particle modify the amplitude of this process
- new particle's spin = 0, 1/2, 1........... which is better?
- naively, if new particle coupling to the higgs is the same sign as the SM case, gauge boson loop enhance the amplitude

- Does **W'** help enhancing this signal?



- ***Let us extend gauge sector and see what happen!***

Contents

Model : gauge sector

- electroweak gauge symmetry

$$SU(2)_0 \times SU(2)_1 \times U(1)_2$$

- two Higgs fields for electroweak symmetry breaking

$$H_1 = (2,2)_0 \quad \ni \left(h_1, \pi_1^1, \pi_1^2, \pi_1^3\right)$$
$$H_2 = (1,2)_{1/2} \ni \left(h_2, \pi_2^1, \pi_2^2, \pi_2^3\right)$$

- All π's are eaten by the gauge bosons
- mass eigenstates are given as linear combinations

spin 1: $W^\pm, Z, \gamma, W'^\pm, Z'$
spin 0: h, H

$$h = \cos\alpha\ h_1 - \sin\alpha\ h_2$$
$$H = \sin\alpha\ h_1 + \cos\alpha\ h_2$$

Model : fermion sector

- vector like fermions as well as chiral fermions

Fermions	$SU(2)_0$	$SU(2)_1$	$U(1)_2$	$SU(3)_c$	
Ψ_{0L}	$\mathbf{2}$	$\mathbf{1}$	$\frac{1}{6}$ $\left(-\frac{1}{2}\right)$	$\mathbf{3}$ $(\mathbf{1})$	$\leftarrow$ chiral
Ψ_{1L}	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{6}$ $\left(-\frac{1}{2}\right)$	$\mathbf{3}$ $(\mathbf{1})$	$\leftarrow$ vector like
Ψ_{1R}	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{6}$ $\left(-\frac{1}{2}\right)$	$\mathbf{3}$ $(\mathbf{1})$	
Ψ^u_{2R}	$\mathbf{1}$	$\mathbf{1}$	$\frac{2}{3}$ (0)	$\mathbf{3}$ $(\mathbf{1})$	$\leftarrow$ chiral
Ψ^d_{2R}	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{3}$ (-1)	$\mathbf{3}$ $(\mathbf{1})$	$\leftarrow$ chiral

- reasons why we introduce vector like fermions:
  1. they are mixed with chiral fermions, and relax
     - ⋆ S parameter constraint
     - ⋆ $m_{W'}$ constraint
  2. they can enhance $\sigma(gg \to h)$

Model: W'ff coupling and $m_{W'}$

- gW'ff ~ 0 is possible by tuning parameter (ideal delocalization)

$$g_{W'ff} \simeq -g_1 \left(\frac{1+r^2}{r^2} \frac{m_W^2}{m_{W'}^2} - \sin^2\theta_f \right)$$

$$r = \frac{\langle H_2 \rangle}{\langle H_1 \rangle}$$

fermion mixing angle

- Then
  - ⋆ S parameter is OK with light $m_{W'}$

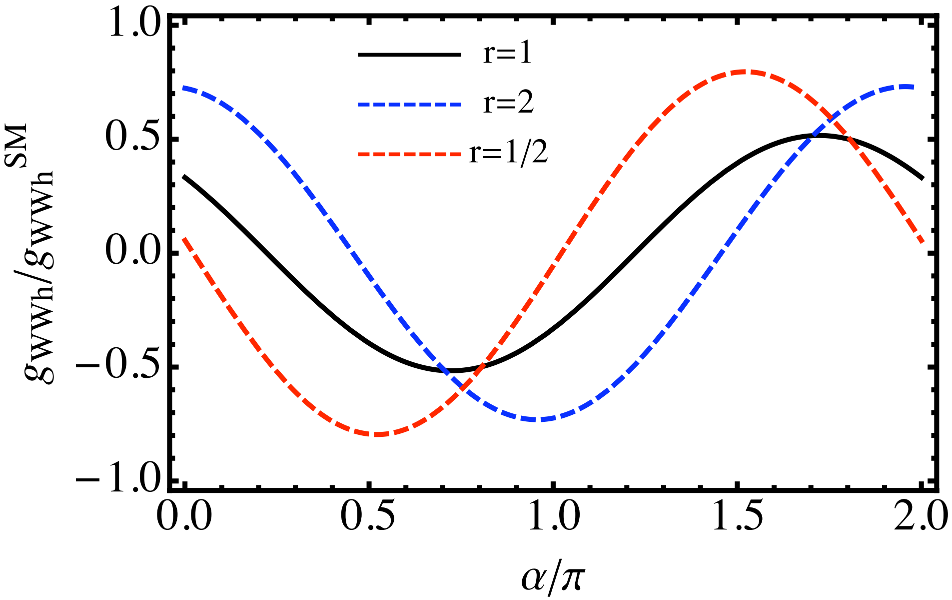
$$\alpha S \simeq -4 \sin^2\theta_W \frac{M_W}{M_{W'}} \frac{g_{W'ff}}{g_{Wff}}$$

  - ⋆ direct detection bounds through Drell-Yan process can be ignored

- Hereafter we set gW'ff = 0
  - ⋆ fermion sector depend on $m_W/m_{W'}$

Model : Higgs couplings (1)

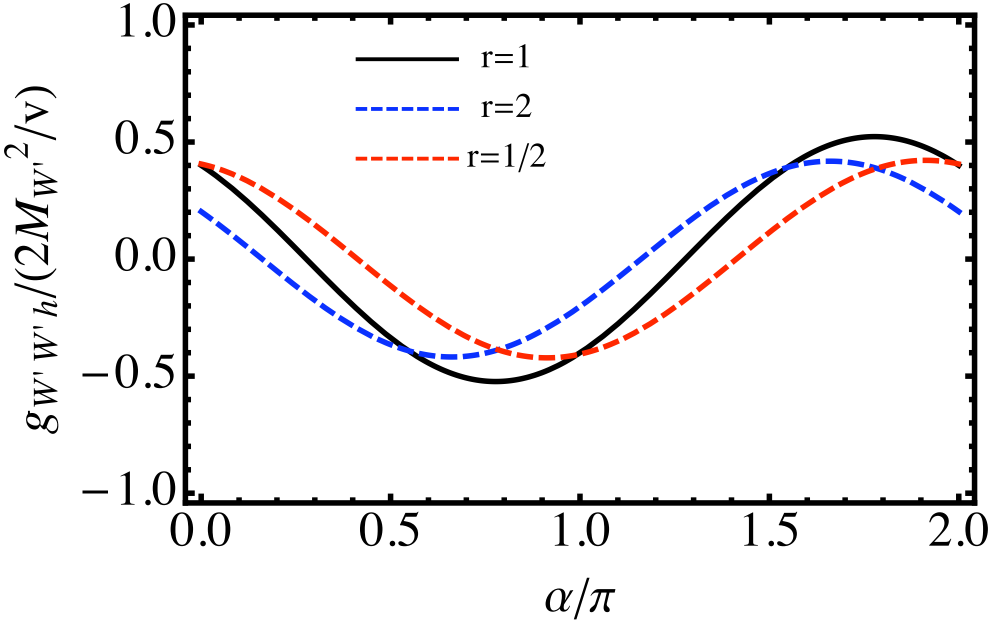
$$g_{WWh} = \frac{2m_W^2}{v}\left(\frac{r^3}{(1+r^2)^{3/2}}\cos\alpha - \frac{1}{(1+r^2)^{3/2}}\sin\alpha + \mathcal{O}\left(\frac{m_W^2}{m_{W'}^2}\right)\right) \leq g_{WWh}^{\mathrm{SM}}$$



- smaller than SM
- Br(h → γγ, WW, ZZ) highly depend on “r” and “α”

Model : Higgs couplings (2)

$$g_{W'W'h} = \frac{2m_{W'}^2}{v}\left(\frac{r}{(1+r^2)^{3/2}}\cos\alpha - \frac{r^2}{(1+r^2)^{3/2}}\sin\alpha + \mathcal{O}\left(\frac{m_W^2}{m_{W'}^2}\right)\right)$$



Model : summary of matter contens

Extra particles

$$\begin{pmatrix} u' & c' & t' \\ d' & s' & b' \end{pmatrix} \begin{pmatrix} \nu'_e & \nu'_\mu & \nu'_\tau \\ e' & \mu' & \tau' \end{pmatrix}$$

$$W' \; Z'$$

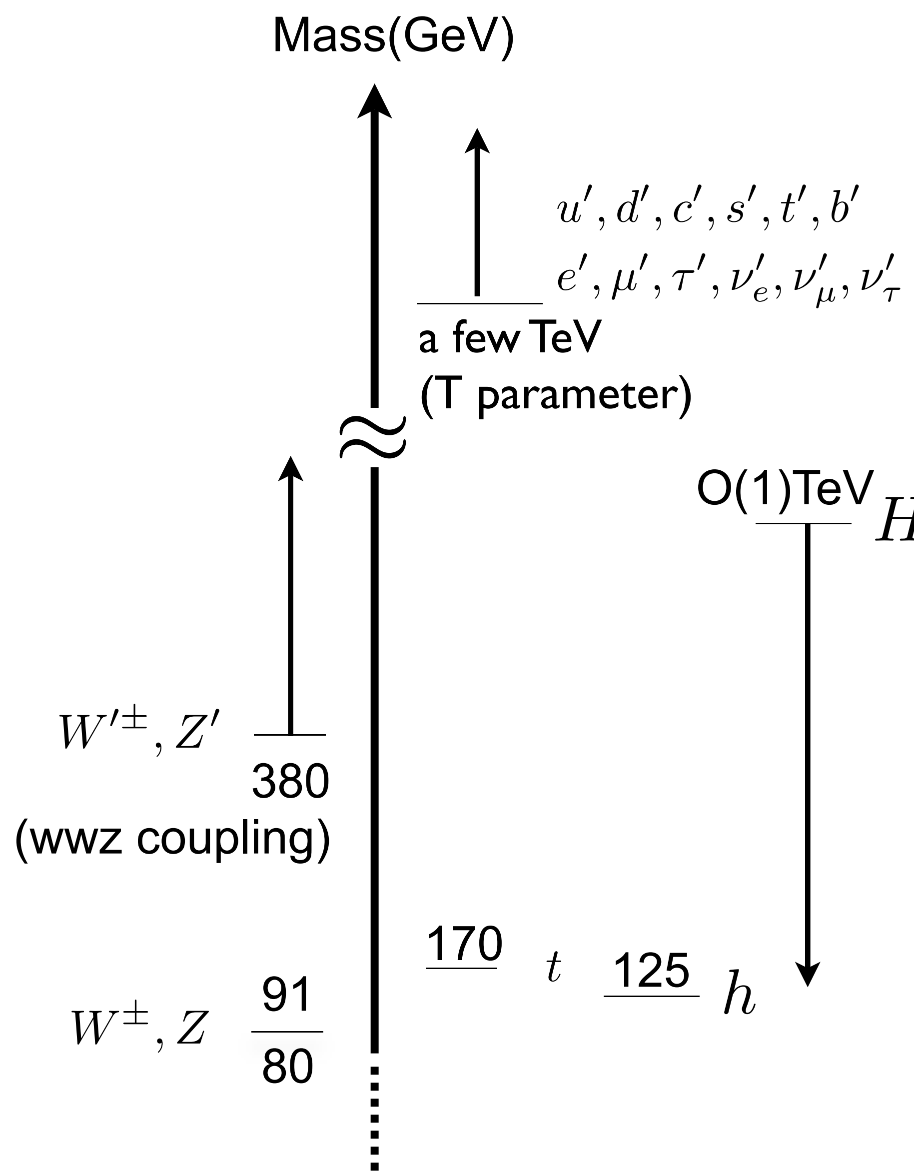
SM particles

$$\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix} \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix}$$

$$\gamma \; W \; Z \; g$$

Higgs bosons

$$h \; H$$



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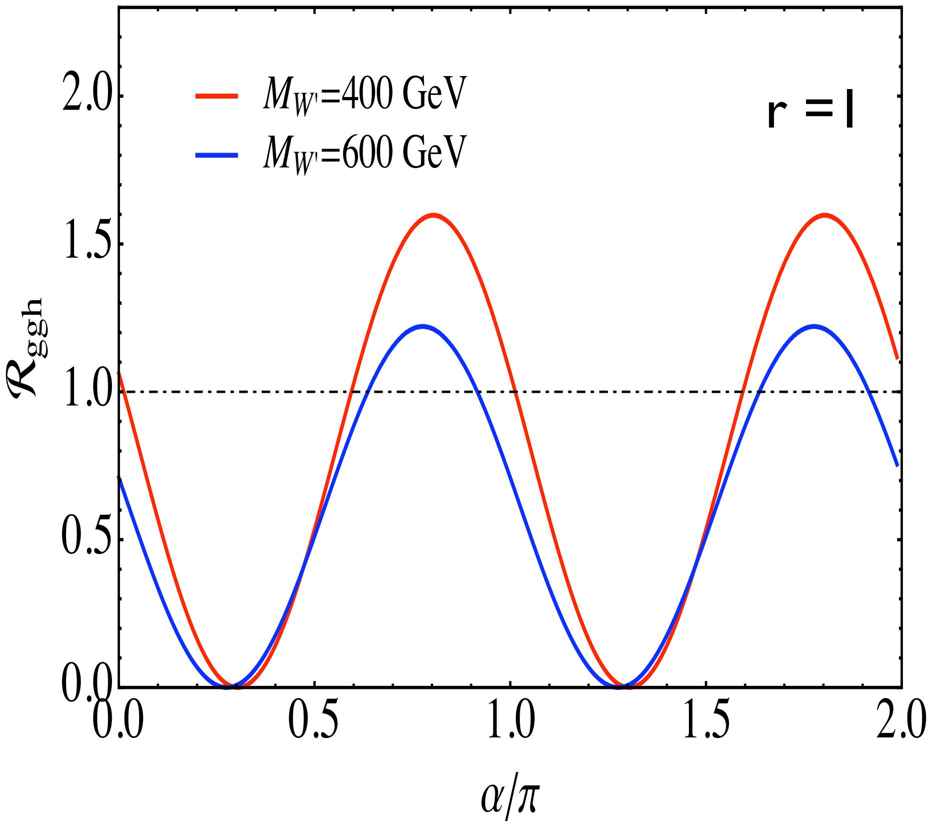
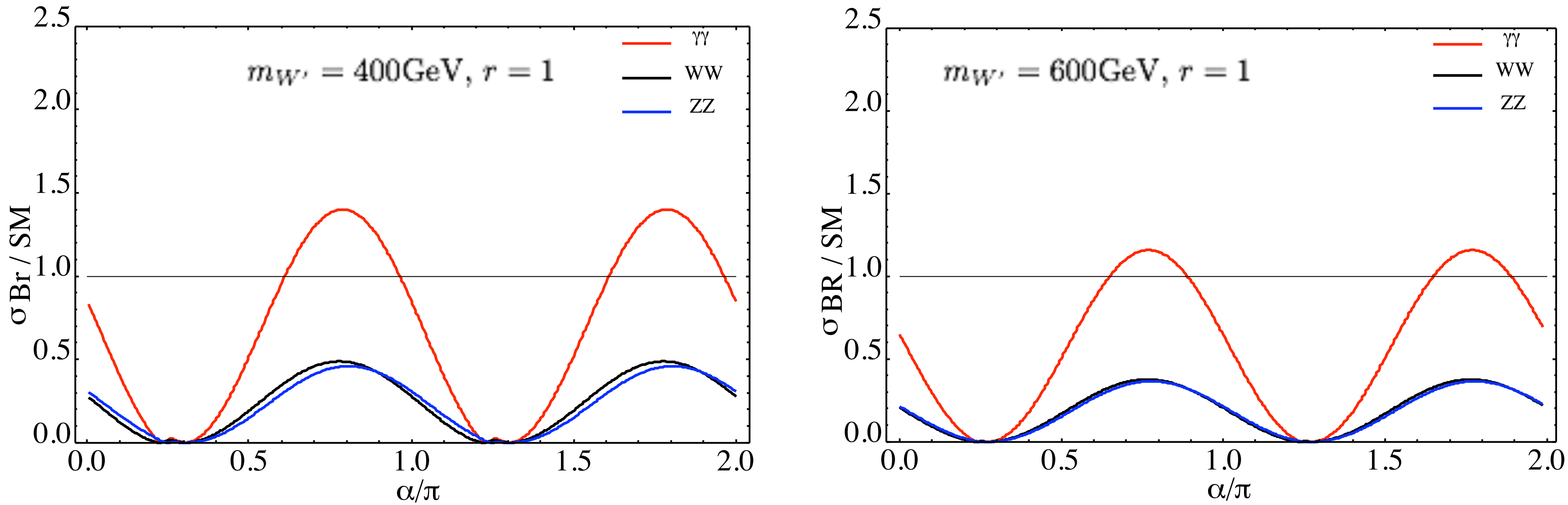
4. Summary

$\sigma(gg \to h)/\sigma(gg \to h)_{SM}$



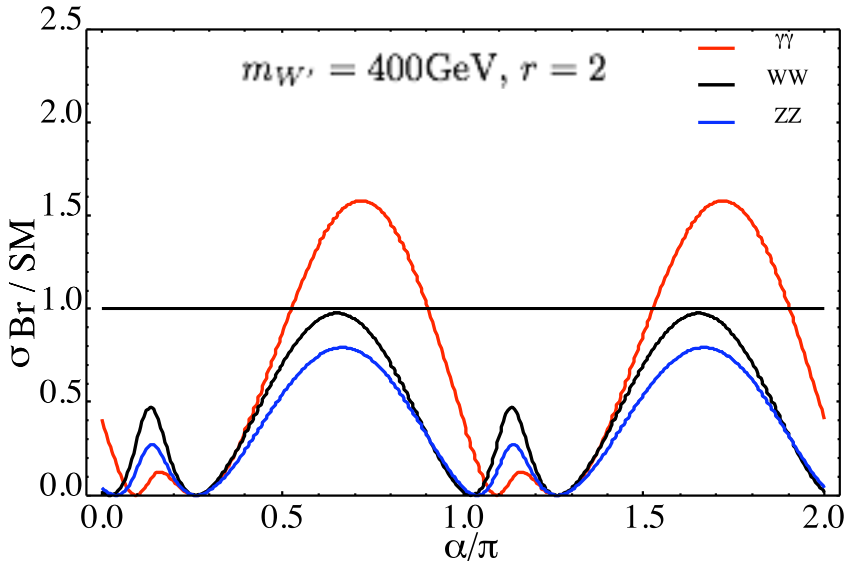
- highly depending on mixing angle, α.
- depending on $m_{W'}$.
- bigger than SM due to the heavy fermion loops.

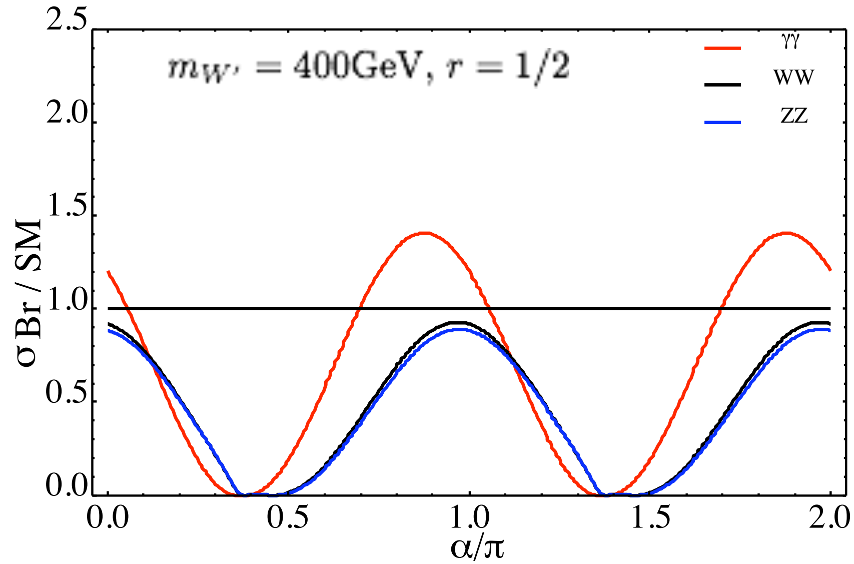
$\sigma(gg \to h)$ x BR / SM



- depending on α and $m_{W'}$
- In r = 1 case
  - ⋆ γ γ signal can be enhanced!
  - ⋆ WW and ZZ signals are suppressed

σ(gg→h) x BR / SM

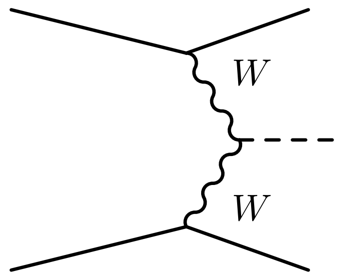


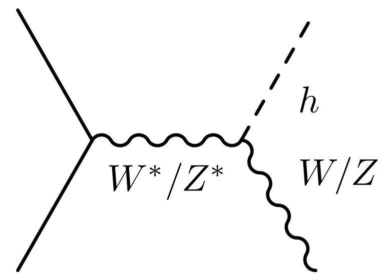


- In r ≠ 1 case
  - ⋆ γ γ signal can be enhanced!
  - ⋆ WW and ZZ signals are compareble with the SM case

σ(VBF/Wh/Zh)

- other production processes



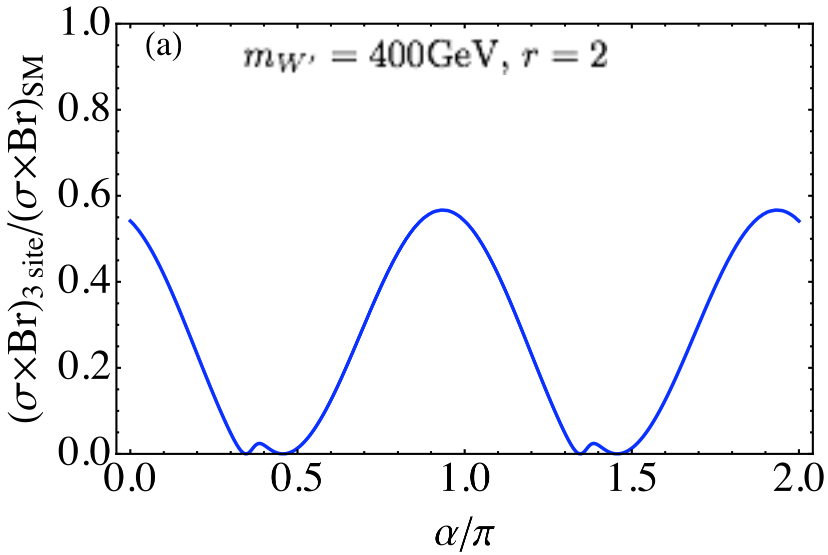


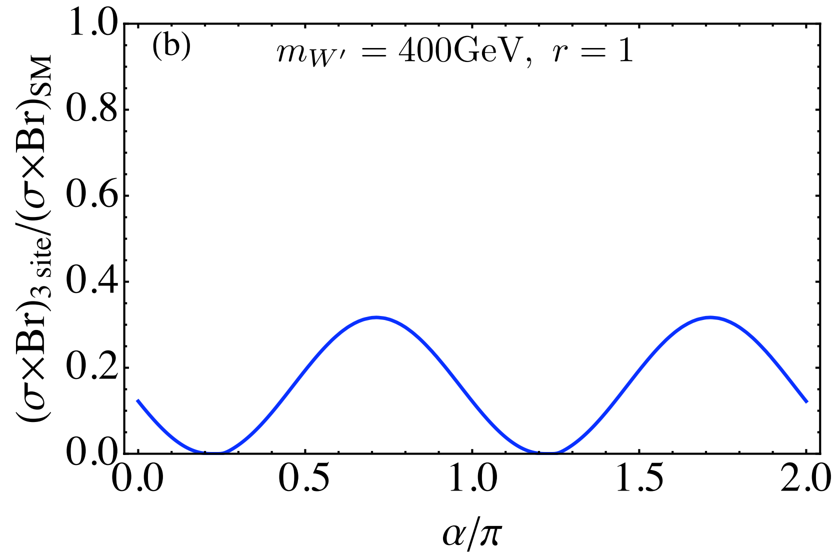
- W' does not propagate because gw'ff = 0 in our set up
- difference from the SM is gwwh coupling

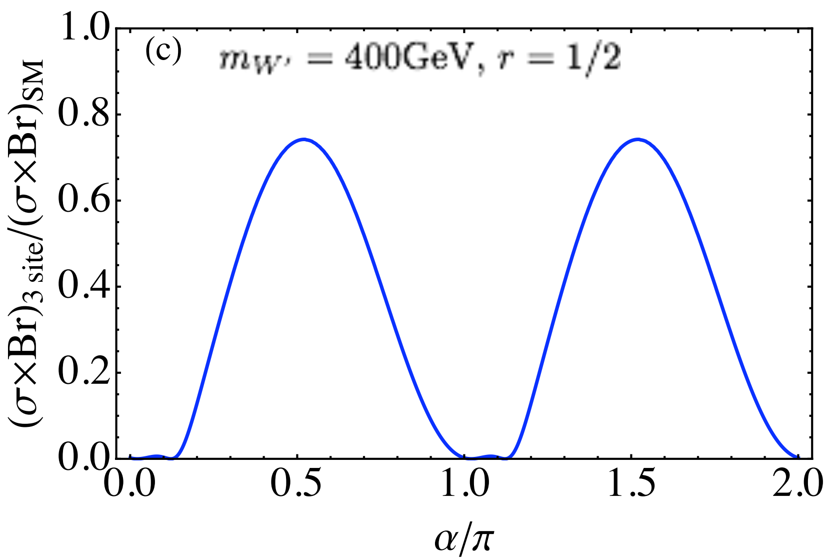
$$\frac{\sigma(pp\to hqq')}{\sigma(pp\to hqq')_{\rm SM}}=\frac{\sigma(pp\to hW)}{\sigma(pp\to hW)_{\rm SM}}=\left(\frac{g_{WWh}}{g^{\rm SM}_{WWh}}\right)^2\simeq\left(\frac{r^3}{(1+r^2)^{3/2}}\cos\alpha-\frac{1}{(1+r^2)^{3/2}}\sin\alpha\right)^2\leq 1$$

- These production xsec is always smaller than SM

σ(VBF/Wh/Zh) x BR(h→ff) / SM







- (ex) σ(VBF) Br(h→$\tau\tau^{bar}$) < SM
- suppressed
- to improve the result, for example, we need to
  - ⋆ change parameter space
  - ⋆ give up ideal delocalization
  - ⋆ change fermion sector itself
  - ⋆ ....

Contents

Summary

- LHC found a new particle around 125 GeV
- $\gamma\gamma$ signal is larger than the SM Higgs boson case
- We consider SU(2)xSU(2)xU(1) model
  - ⋆ $\sigma(gg \to h \to \gamma\gamma)/\sigma_{SM} > 1$ is possible
  - ⋆ $\sigma(gg \to h \to WW/ZZ)\ /\sigma_{SM} \leq 1$
- these are compatible with the current LHC data
- other production process is suppressed, for example
  - ⋆ $\sigma(VBF)\ Br(h \to \tau\tau^{bar}) < SM$
- These results highly depend on parameter choice and structure of fermion sector. It is worthwhile to study more general analysis in this gauge symmetry.

BACKUP SLIDES

Model : fermion mass terms

- mass terms

$$-\begin{pmatrix} \Psi^u_{0L} & \Psi^u_{1L} \end{pmatrix} \begin{pmatrix} \frac{1}{2}y_1 f_1 & 0 \\ M & \frac{1}{2}y_{2u} f_2 \end{pmatrix} \begin{pmatrix} \Psi^u_{1R} \\ \Psi^u_{2R} \end{pmatrix} - \begin{pmatrix} \Psi^d_{0L} & \Psi^d_{1L} \end{pmatrix} \begin{pmatrix} \frac{1}{2}y_1 f_1 & 0 \\ M & \frac{1}{2}y_{2d} f_2 \end{pmatrix} \begin{pmatrix} \Psi^d_{1R} \\ \Psi^d_{2R} \end{pmatrix} + (h.c.)$$

$$\langle H_1 \rangle = f_1/2, \ \langle H_2 \rangle = f_2/2$$

- mass

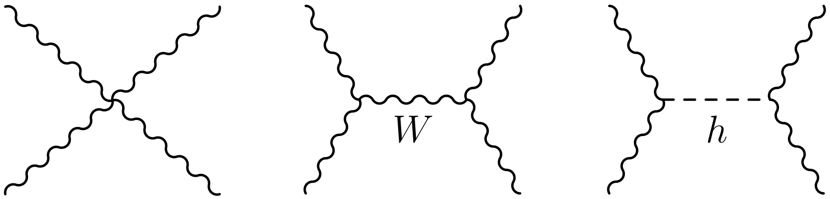
$$m_u \simeq \frac{1}{4}\frac{y_1 y_{2u} f_1 f_2}{M}$$

$$m_{u'} \simeq \sqrt{M^2 + \frac{1}{4}y_1^2 f_1^2 + \frac{1}{4}y_{2u}^2 f_2^2} \simeq M$$

- We assume M >> $y_1 f_1$, $y_2 f_2$
- y_{2x} determine the SM fermion masses
- $y_{2x} \simeq 0$ except top sector

Model : why gWWh/SM < 1 ?

- perturbative unitarity of longitudinal gauge boson scattering
  - ⋆ In the SM, Higgs cancels the E^2 behavior



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- perturbative unitarity of longitudinal gauge boson scattering
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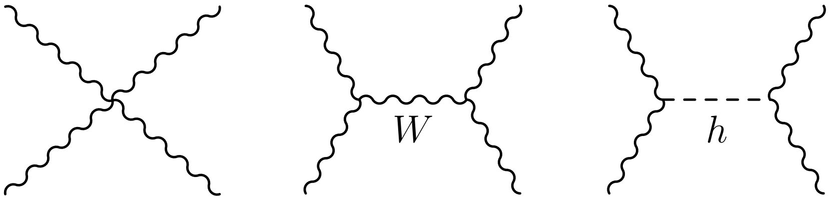
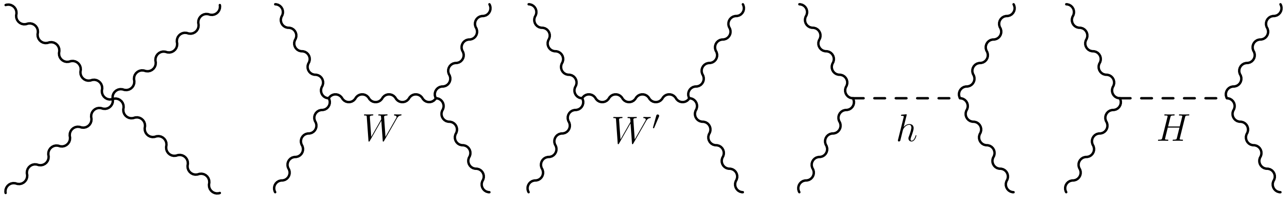


  - ⋆ In our model, W' and heavy Higgs as well as light Higgs



  - ⋆ both "spin 1" and "spin 0" particles contribute
  - ⋆ WWh coupling is smaller than the SM one

Model : perturbative unitarity (2)

- unitarity sum rules for couplings (here W stands for both W± and Z)
  - ⋆ to cancel O(E⁴) terms

$$g_{WWWW} = g_{WWW}^2 + g_{WWW'}^2$$

  - ⋆ to cancel O(E²) terms

$$4g_{WWWW}M_W^2 = 3g_{WWW}^2 M_W^2 + 3g_{WWW'}^2 M_{W'}^2 + g_{WWh}^2 + g_{WWH}^2$$

- gwww ≃ gwww^{SM} by precision measurement
- now we see the following realtion

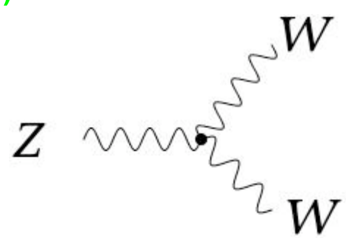
$$\left(g_{WWh}\right)^2 \leq \left(g_{WWh}^{SM}\right)^2$$

Model : lower bound on Mw’

R.S.Chivukula et.al
Phys.Rev.D74:075011 (2006)

- triple gauge boson coupling

K.Hagiwara, R.D.Peccei, D.Zeppenfeld, and K.Hikasa,
Nucl.Phys. B282,253(1987)



$$\begin{aligned}\mathcal{L} \quad = \quad & -ig^{SM}_{WWZ}\,(1+\Delta\kappa_Z)\,W^+_\mu W^-_\nu Z^{\mu\nu} \\ & -ig^{SM}_{WWZ}\,(1+\Delta g_1^Z)\,\left(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu}\right)Z^\nu\end{aligned}$$

- This model prediction

$$\Delta\kappa_Z = \Delta g_1^Z = \frac{1}{2c^2}\frac{M_W^2}{M_{W'}^2} + \mathcal{O}\left(\frac{M_W^4}{M_{W'}^4}\right)$$

$$c = \frac{M_W}{M_Z}$$

- constraint from LEP-II

$$\Delta g_1^Z < 0.028 \ (95\%\mathrm{C.L.})$$

$$\longrightarrow \quad \boxed{M_{W'} \geq 380\mathrm{GeV}}$$

Model : parameters in Higgs sector

- Higgs VEVs

$$\langle H_1 \rangle = f_1/2,\ \langle H_2 \rangle = f_2/2$$

  - ⋆ They are related to the Fermi constant

$$\sqrt{2} G_F \simeq \frac{1}{f_1^2} + \frac{1}{f_2^2} \equiv \frac{1}{v^2}$$

  - ⋆ we introduce the VEV ratio "r"

$$r = f_2/f_1$$

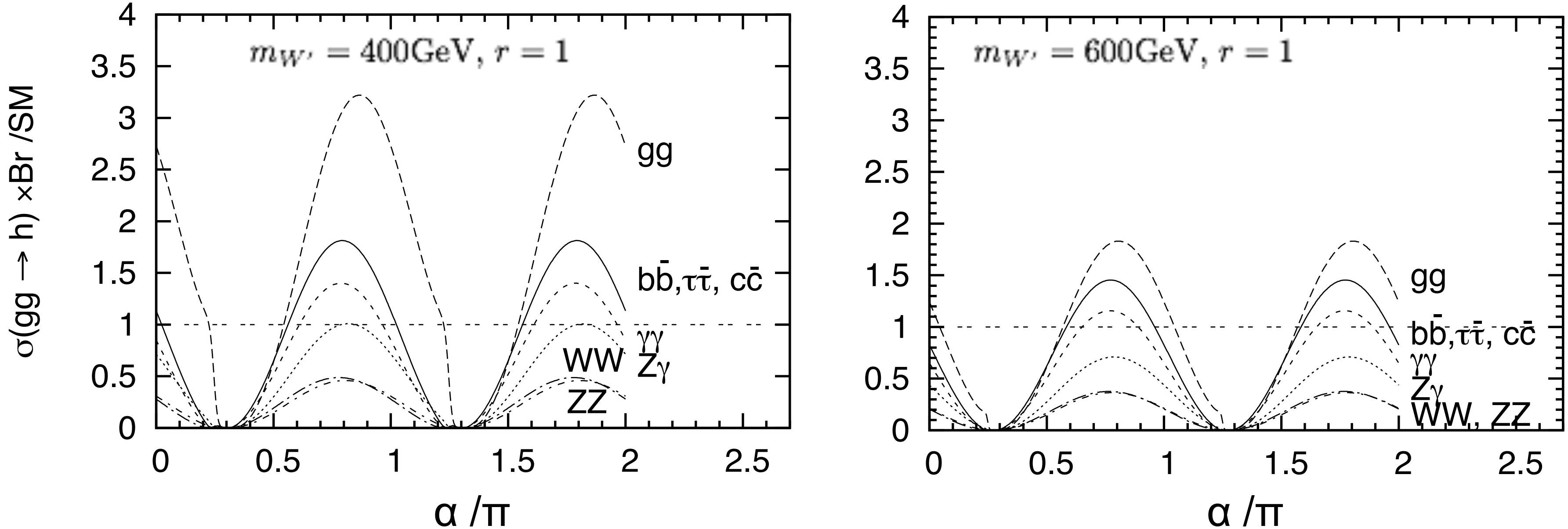
  - ⋆ we use **G_F (or v)** and **$r = f_2/f_1$** instead of f_1 and f_2

- mixing angle between two Higgses "**α**"

$$h = \cos\alpha\ h_1 - \sin\alpha\ h_2$$
$$H = \sin\alpha\ h_1 + \cos\alpha\ h_2$$

- two input parameters in Higgs sector: **α** and **r**

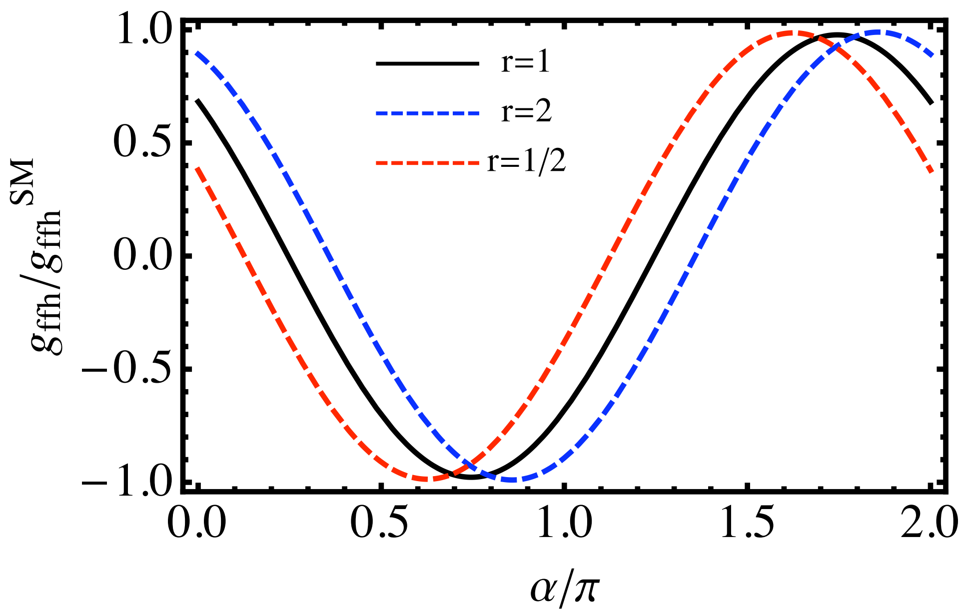
$\sigma(gg \to h)$ x BR / SM



- depending on α and $m_{W'}$
- In r =1 case
  - ⋆ γ γ signal can be enhanced!
  - ⋆ WW and ZZ signals are suppressed

Model : Higgs couplings (3)

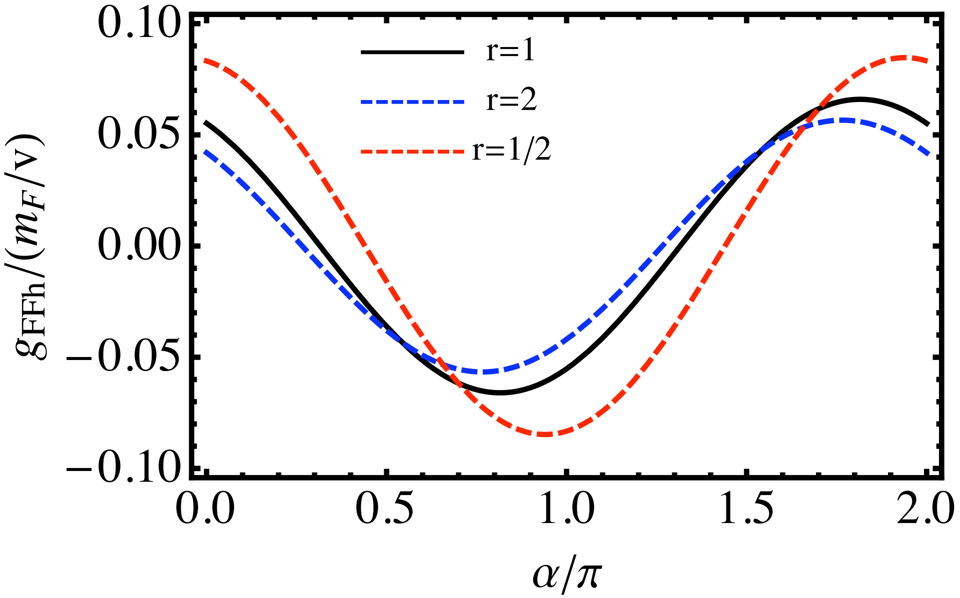
$$g_{ffh} \simeq \frac{m_f}{v}\left(\frac{r}{\sqrt{1+r^2}}\cos\alpha - \frac{1}{\sqrt{1+r^2}}\sin\alpha\right) \leq g_{ffh}^{SM}$$



- gffh is smaller than SM

Model : Higgs couplings (4)

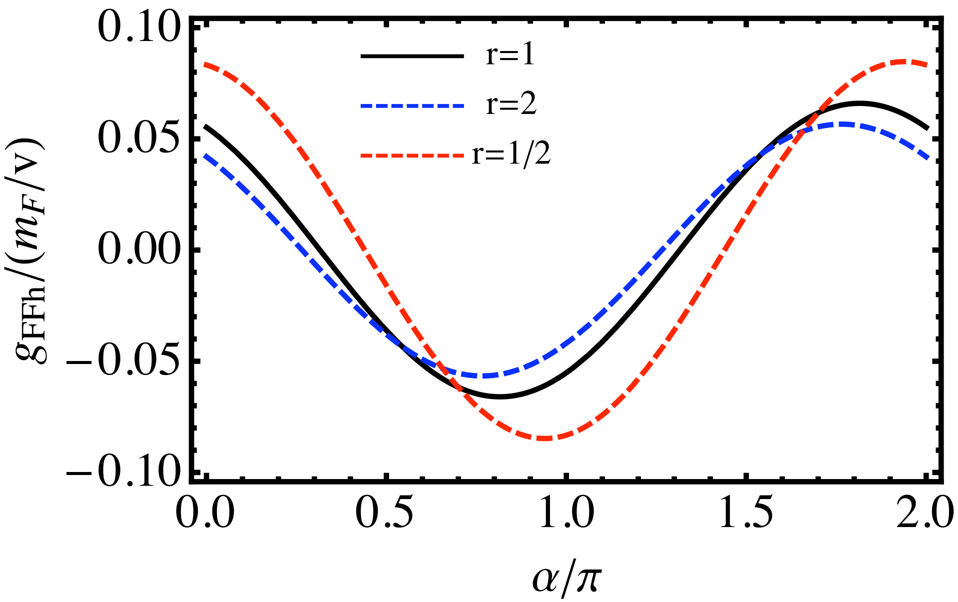
$$g_{FFh} \simeq \frac{m_F}{v} \left(\frac{\sqrt{1+r^2}}{r} \frac{m_W^2}{m_{W'}^2} \cos\alpha - \frac{m_f^2}{m_F^2} \frac{m_{W'}^2}{m_W^2} \frac{r^2}{(1+r^2)^{3/2}} \sin\alpha \right) \lesssim 0.1 \frac{m_F}{v}$$



Model : Higgs couplings (4)

$$g_{FFh} \simeq \frac{m_F}{v}\left(\frac{\sqrt{1+r^2}}{r}\frac{m_W^2}{m_{W'}^2}\cos\alpha - \frac{m_f^2}{m_F^2}\frac{m_{W'}^2}{m_W^2}\frac{r^2}{(1+r^2)^{3/2}}\sin\alpha\right) \lesssim 0.1\frac{m_F}{v}$$

suppression factors

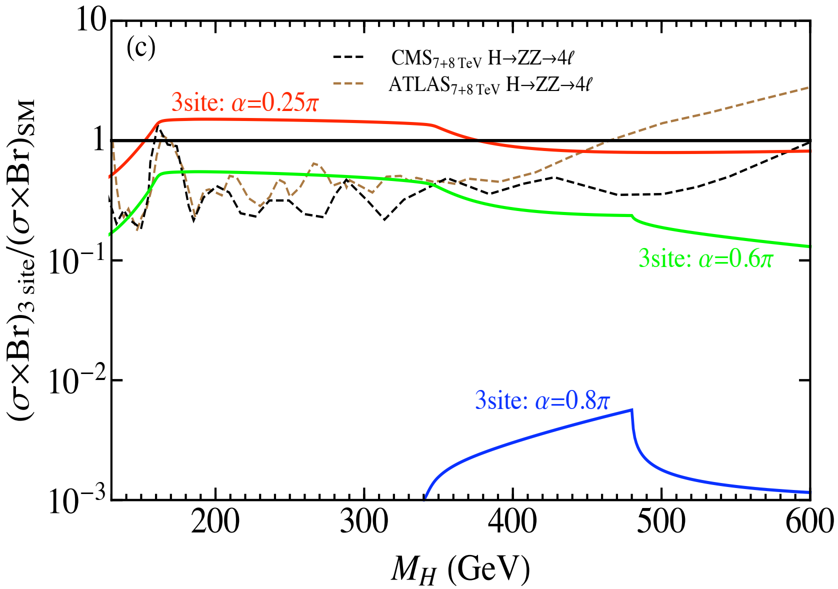


- gFFh is much suppressed, because F is almost vector like fermion

Comment on the heavy higgs

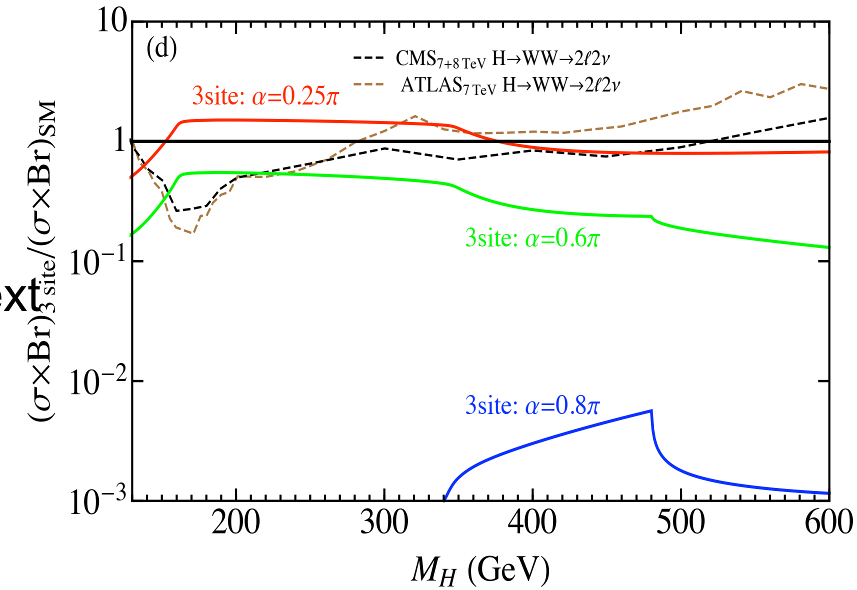
- constraint on heavy Higgs mass from LHC

H → ZZ → 4 leptons



H → WW → 2 leptons + MET

Text



- $m_{W'}$ = 400 GeV, r =1 case
- m_H < 600 GeV is allowed because $g_{WWH} < g_{WWH}^{SM}$
- very loose constraint on $\alpha = 0.8\pi$
- ($\alpha = 0.8\pi$ is prefered for $h \to \gamma\gamma$ enhancement)

Model : constraint from S parameter

- S parameter at tree level

$$\alpha S \simeq -4\sin^2\theta_W \frac{M_W}{M_{W'}} \frac{g_{W'ff}}{g_{Wff}}$$

f : SM fermion

- two ways to reduce S parameter

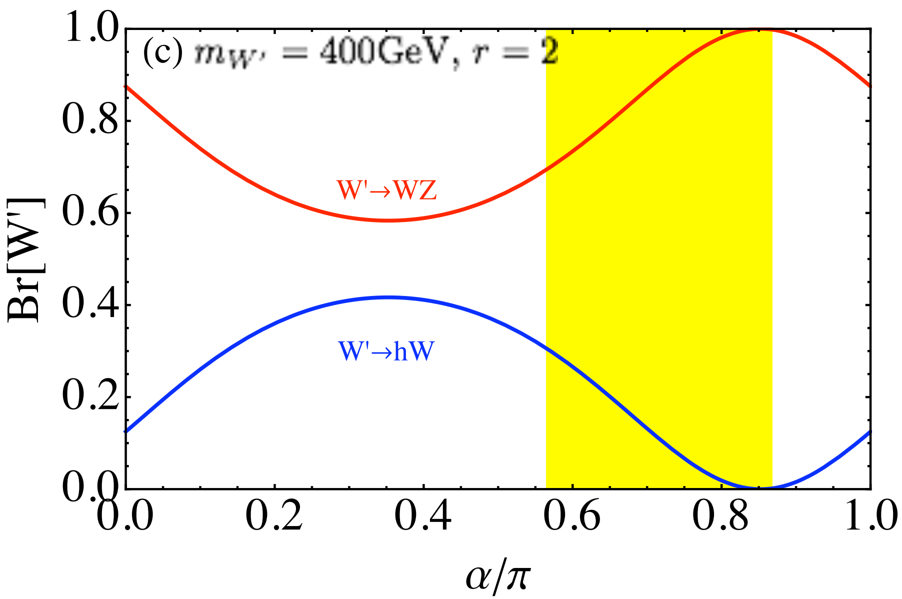
(i) Heavy W' mass

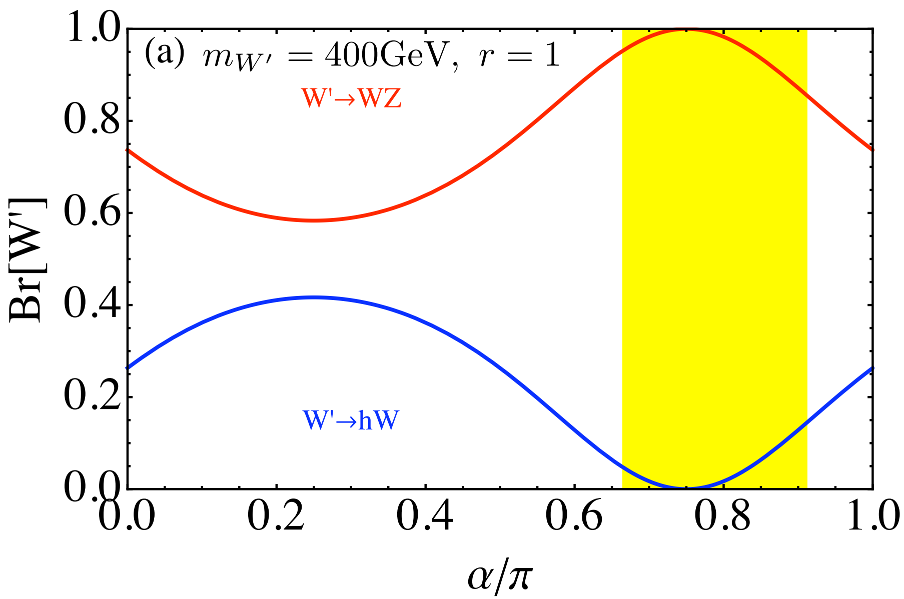
- ... but light W' seems good for changing Br(h → γ γ)
- we do not consider this case here

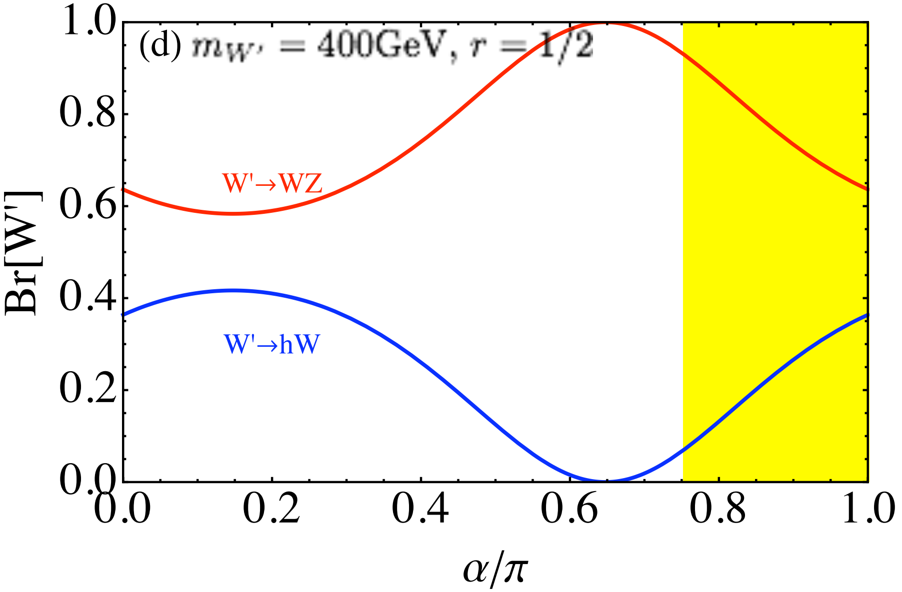
(ii) small gW'ff couplings

- gW'ff = 0 by tuning the mixing angle (ideal delocalization)
- we consider this case in this talk

W' decay mode





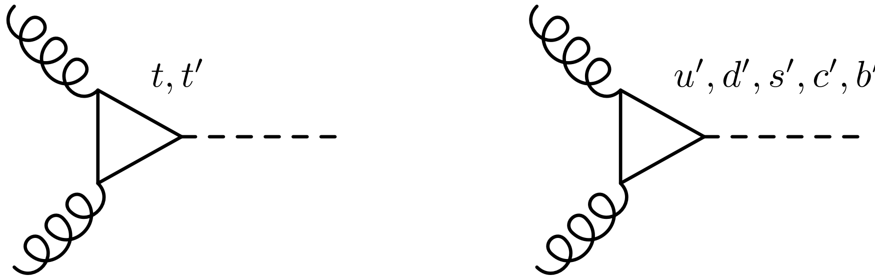


- yellow reasion is consistent with ATLAS and CMS within 1σ

- W' → WZ is dominant
- W' → hW is subdominant
- other channels are negligible

$\sigma(gg \to h)/\sigma(gg \to h)_{SM}$

- contributions from top and extra fermions



$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\rm SM}} \simeq \left| \frac{r}{\sqrt{1+r^2}} \cos\alpha - \frac{1}{\sqrt{1+r^2}} \sin\alpha + 5 \frac{m_1^2}{M^2 + m_1^2} \frac{r}{\sqrt{1+r^2}} \cos\alpha \right|^2$$

$$\simeq \left| \frac{r}{\sqrt{1+r^2}} \cos\alpha - \frac{1}{\sqrt{1+r^2}} \sin\alpha + 5 \frac{\sqrt{1+r^2}}{r} \frac{M_W^2}{M_{W'}^2} \cos\alpha \right|^2$$

- first two terms : sum of the top and heavy top contritutions
- last term : contributions from u', d', s', c', and b'.

$$m_1 = \frac{y_1 f_1}{2M}$$

- $m_1^2/(M^2 + m_1^2)$: mixing angle in fermion sector.
- assume ideal delocalization in the second line

$$g_{W'ff} \sim g_1 \frac{1+r^2}{r^2} \left(-\frac{M_W^2}{M_{W'}^2} + \frac{y_1^2 v^2}{4M^2} \right)$$

partial decay width / SM

- partial decay width (tree processes)

$$\frac{\Gamma(h \to f\bar{f})}{\Gamma(h \to f\bar{f})_{\mathrm{SM}}} = \left(\frac{g_{ffh}}{g_{ffh}^{\mathrm{SM}}}\right)^2 \simeq \left(\frac{r}{\sqrt{1+r^2}}\cos\alpha - \frac{1}{\sqrt{1+r^2}}\sin\alpha\right)^2 \leq 1$$

$$\frac{\Gamma(h \to WW)}{\Gamma(h \to WW)_{\mathrm{SM}}} = \left(\frac{g_{WWh}}{g_{WWh}^{\mathrm{SM}}}\right)^2 \simeq \left(\frac{r^3}{(1+r^2)^{3/2}}\cos\alpha - \frac{1}{(1+r^2)^{3/2}}\sin\alpha\right)^2 \leq 1$$

- Γ(h → ff) and Γ(h → WW) is smaller than the SM

partial decay width / SM

- partial decay width (loop induced processes)

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\rm SM}} \simeq \left| \frac{r}{\sqrt{1+r^2}} \cos\alpha - \frac{1}{\sqrt{1+r^2}} \sin\alpha + 5 \frac{\sqrt{1+r^2}}{r} \frac{M_W^2}{M_{W'}^2} \cos\alpha \right|^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} \simeq \left| \frac{r}{\sqrt{1+r^2}} \cos\alpha - \frac{1}{\sqrt{1+r^2}} \sin\alpha - \frac{80}{47} \frac{\sqrt{1+r^2}}{r} \frac{M_W^2}{M_{W'}^2} \cos\alpha \right|^2$$

- first two terms: t, t' (and W, W') contributions
- last terms: others

Model : Yukawa interaction

- Yukawa

$$-y_1^{ij}\overline{\Psi}^i_{0L}H_1\Psi^j_{1R} - M^{ij}\overline{\Psi}^i_{1L}\Psi^j_{1R} - \overline{\Psi}^i_{1L}H_2\begin{pmatrix} y_{2u}^{ij} & 0 \\ 0 & y_{2d}^{ij} \end{pmatrix}\begin{pmatrix} \Psi^u_{2R} \\ \Psi^d_{2R} \end{pmatrix}^j + (h.c.)$$

i and j : generation indices

- To avoid FCNC, we assume Minimal Flavor Violation

$$y_1^{ij} = y_1\delta^{ij}, \quad M^{ij} = M\delta^{ij}$$

- Flavor structure is determind by y_{2u} and y_{2d}
- y_1 is constrained by S parameter or $g_{W'ff}$ coupling

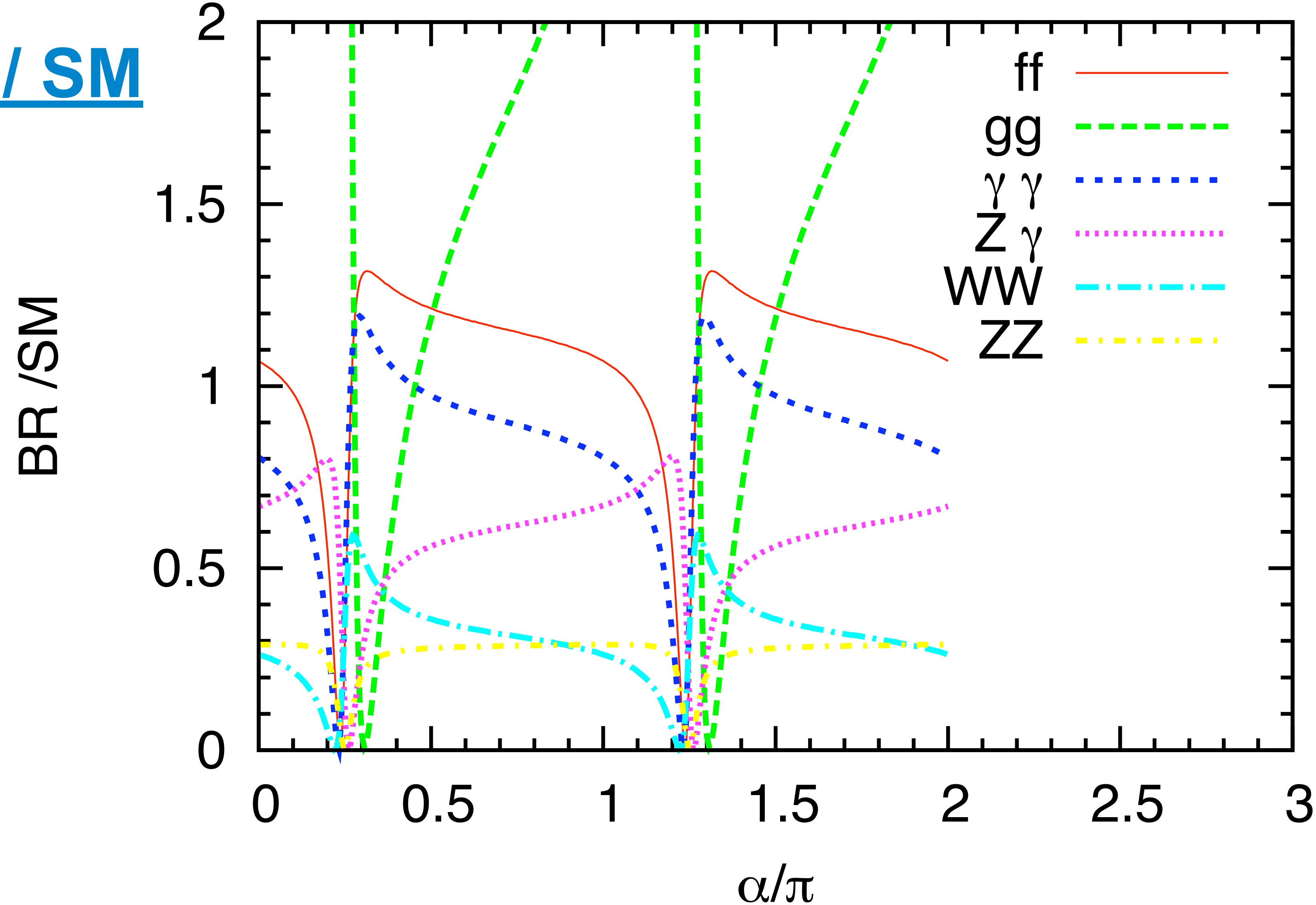
Model: W'ff coupling and $m_{W'}$

- gW'ff ~ 0 is possible by tuning parameter (ideal delocalization)

$$g_{W'ff} \sim g_1 \frac{1+r^2}{r^2} \left(-\frac{M_W^2}{M_{W'}^2} + \frac{y_1^2 v^2}{4M^2} \right)$$

- S parameter is OK with light $m_{W'}$
- A Bonus: direct detection bound is also OK
  - ⋆ we often see the lower bound on $m_{W'}$ ~ 2TeV
  - ⋆ this is derived with the following assumptions:
    - ∗ gW'ff = gWff
    - ∗ W' is produced via Drell-Yan process
  - ⋆ therefore constraint is changed if gW'ff < gWff

BR / SM



- example: m_h = 125 GeV, $m_{w'}$ = 400 GeV, M = 2500 GeV, and r = 1
- γγ can be ehnahced.