# Unitarity and the Higgs bosons

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# The Higgs era

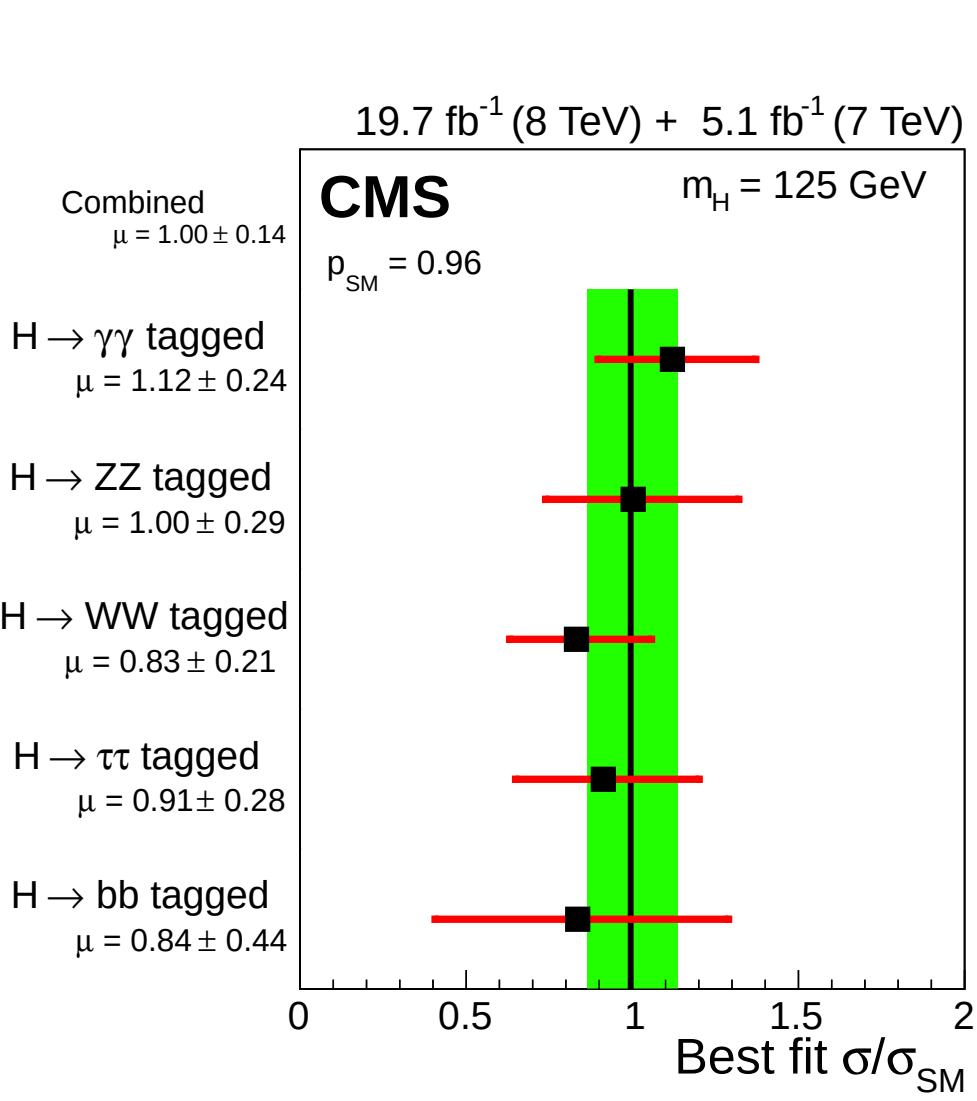
## Physicists Find Elusive Particle Seen as Key to Universe

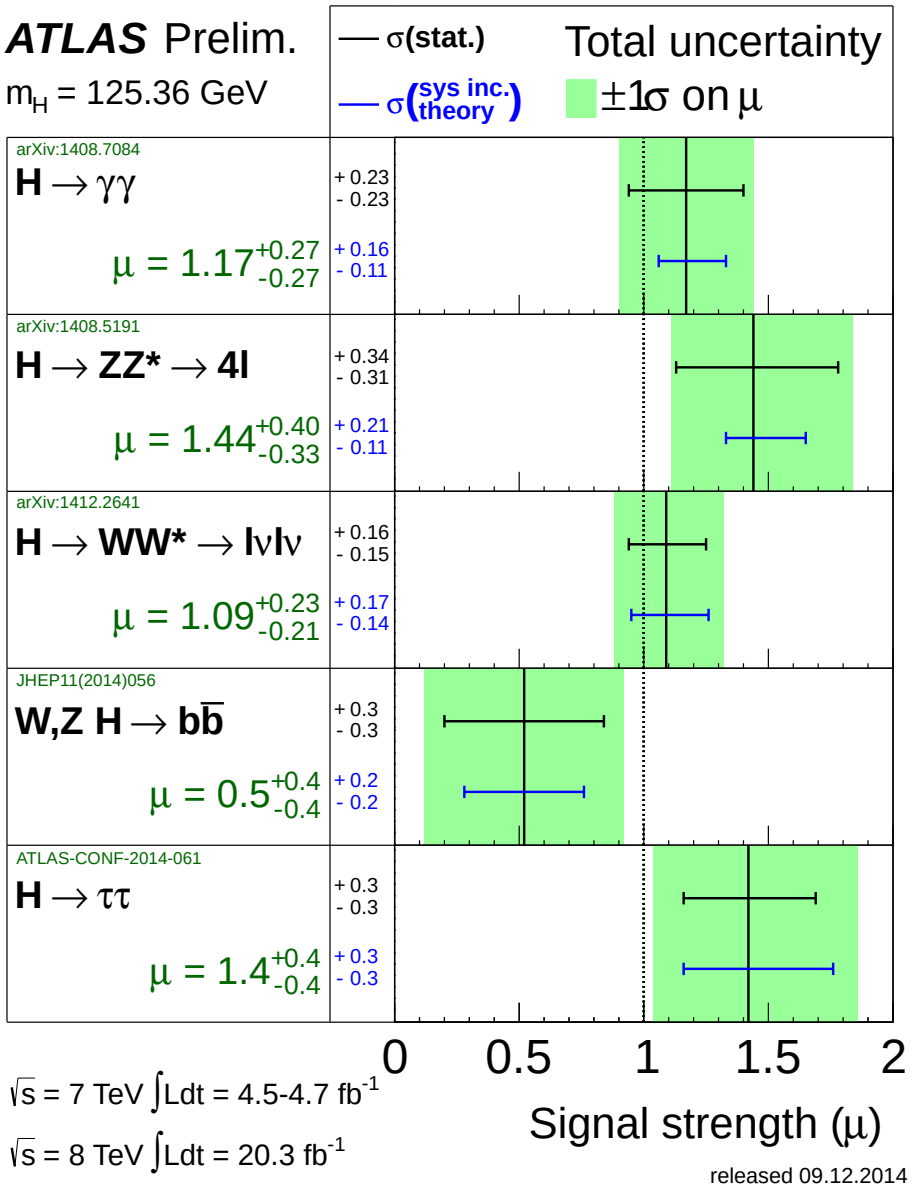
Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE
Published: July 4, 2012 | 122 Comments

# SM Higgs-like boson



Is it possible to have additional Higgs-like particles?

# Higgs-like particle

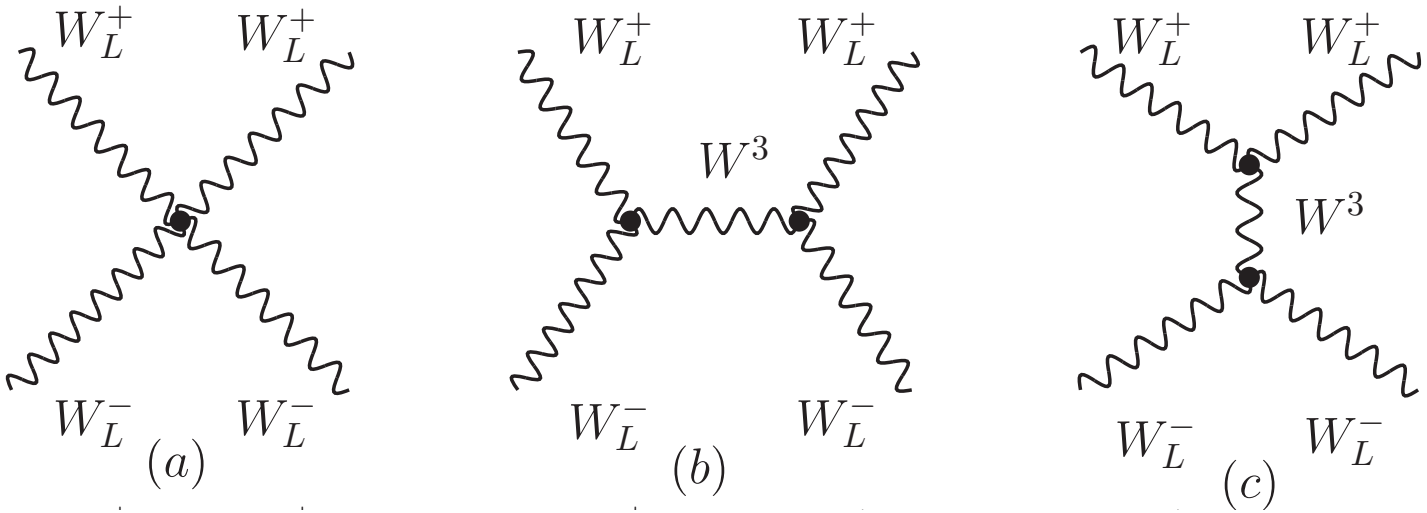
- Working definition:
  - It's a scalar particle.
  - It can have a different mass from the observed 126 GeV one.
  - It couples to a pair of electroweak vector bosons (and fermions).
  - It can be neutral or charged.

# Higgs-like particle

- Working definition:
  - It's a scalar particle.
  - It can have a different mass from the observed 126 GeV one.
  - It couples to a pair of electroweak vector bosons (and fermions).
  - It can be neutral or charged.
- If such a particle exists, what are the constraints on its properties?
  - Unitarity provides model-independent constraints on possible Higgs-like particle.
  - Unitarity: *the probability cannot be greater than 1*

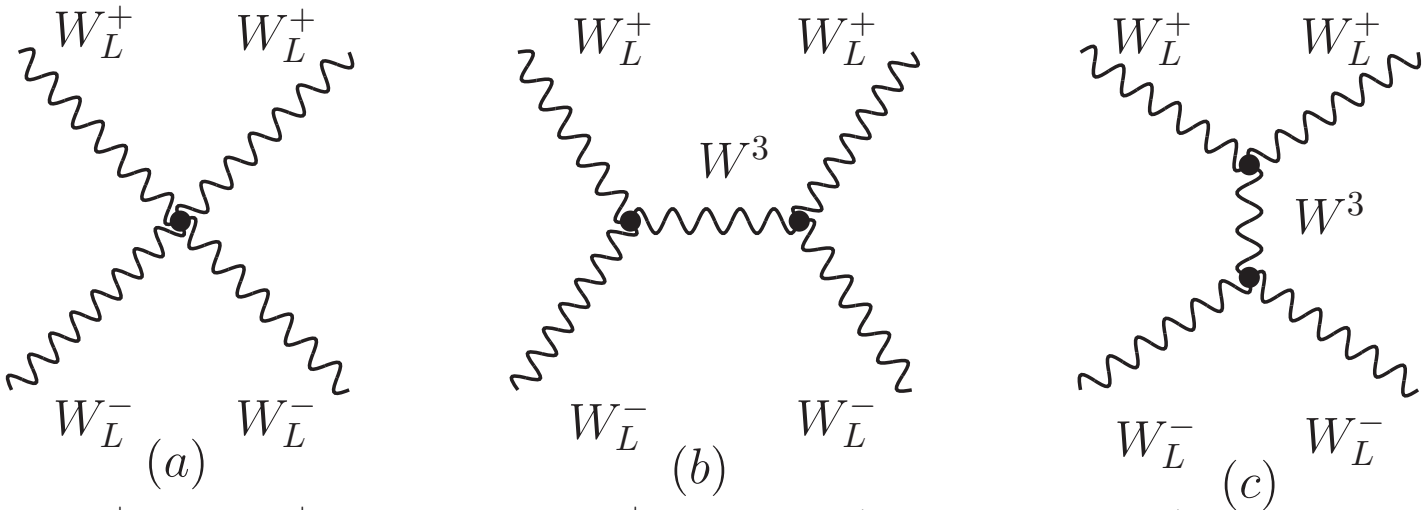
# Constraint from Unitarity: Higgs Sum Rules

# $WW$ scattering



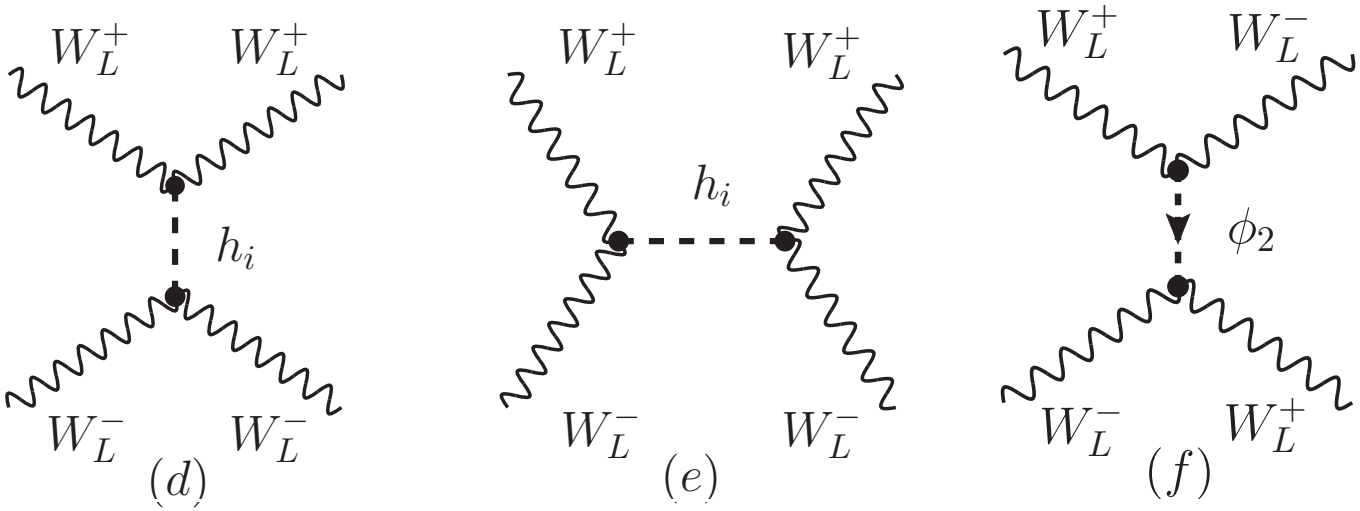

- For a massive vector, the longitudinal polarization mode grows with energy.
  - Each amplitude grows as $s^2$.
  - The sum of the three amplitudes $\sim s$.

# $WW$ scattering



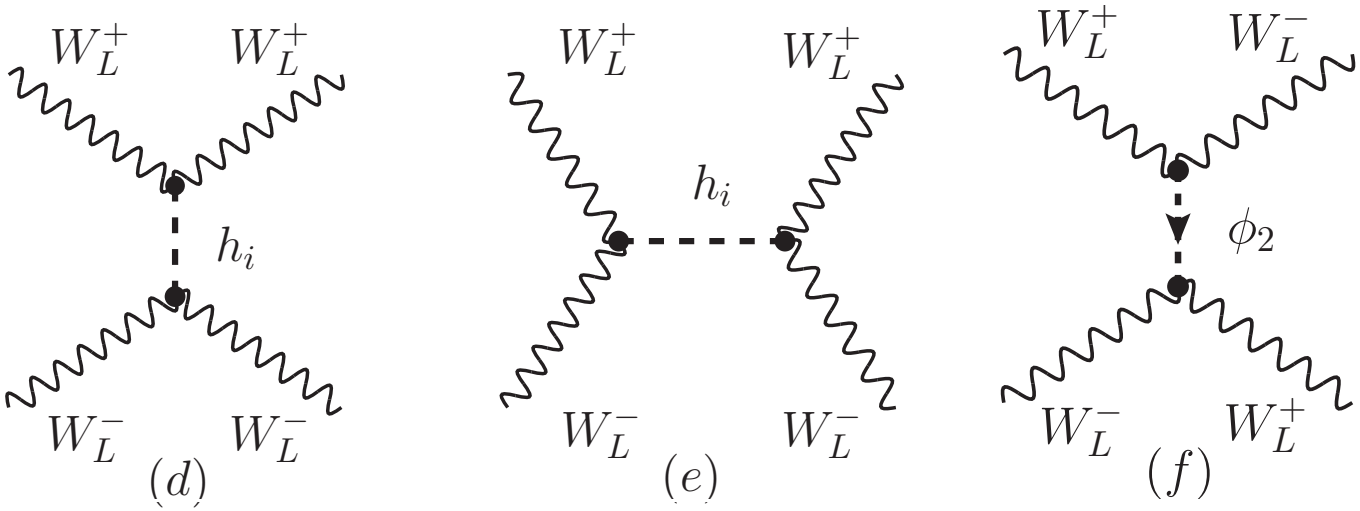

- For a massive vector, the longitudinal polarization mode grows with energy.
  - Each amplitude grows as $s^2$.
  - The sum of the three amplitudes $\sim s$.
  - Leads to a violation of unitarity at high energy!

# Restoring unitarity




- Parametrized couplings:
  - Neutral Higgses: $a$
  - Doubly charged Higgses: $b$

# Restoring unitarity




- Parametrized couplings:
  - Neutral Higgses: $a$
  - Doubly charged Higgses: $b$
- Unitarity requires

$$\sum_i a_i^2 - 4\sum_r b_r^2 = 1.$$

# (Non-trivial) Sum rules

- More sum rules
  - $WW \to ZZ$ gives sum rule involving a singly charged Higgses coupling to $W$ and $Z$, $f_i$.
  - $WW \to t\bar{t}$ gives sum rule involving the Yukawa coupling, $c_{t_i}$.

$$(W^+W^- \to W^+W^-) \quad \sum_i a_i^2 - 4\sum_r b_r^2 = 1$$

$$(W^+W^- \to ZZ) \quad \sum_i a_i^2 - \cos^2\theta_w \sum_r f_r^2 = 1$$

$$(W^+W^- \to f\bar{f}) \quad \sum_i a_i c_{t_i} = 1$$

# Implication of the sum rules, I

- From the $WW \to WW$ and $ZZ \to WW$,

$$\sum b_i^2 \sim \sum f_r^2$$

  - If there is no doubly charged Higgs, there will no singly charged Higgs coupling to $WZ$.
  - Ex: Multi-Higgs-doublet models.

# Implication of the sum rules, //

- From the $WW \to t\bar{t}$,

$$\sum a_i c_{t_i} = 1$$

- If it is saturated by a single Higgs with SM-like coupling, then either:
  - Other Higgs couplings must vanishe.
  - There are canceling contribution (requires at least two more Higgs particle)

# Getting more out of unitarity contraints

- The s-independent part of the amplitude cannot be arbitrary large.
- Unitarity of partial wave amplitude implies bounds on Higgs masses

$$\sum_i (a_i M_i^0)^2 + 2\sum_r (b_r M_r^{++})^2 \leq \frac{2\pi\sqrt{2}}{G_F}$$

$$\sum_i a_i d_i (M_i^0)^2 + 2\sum_r f_r^2 (M_r^+)^2 \leq \frac{4\pi\sqrt{2}}{\cos^2\theta_W G_F}$$

# Backup Slides

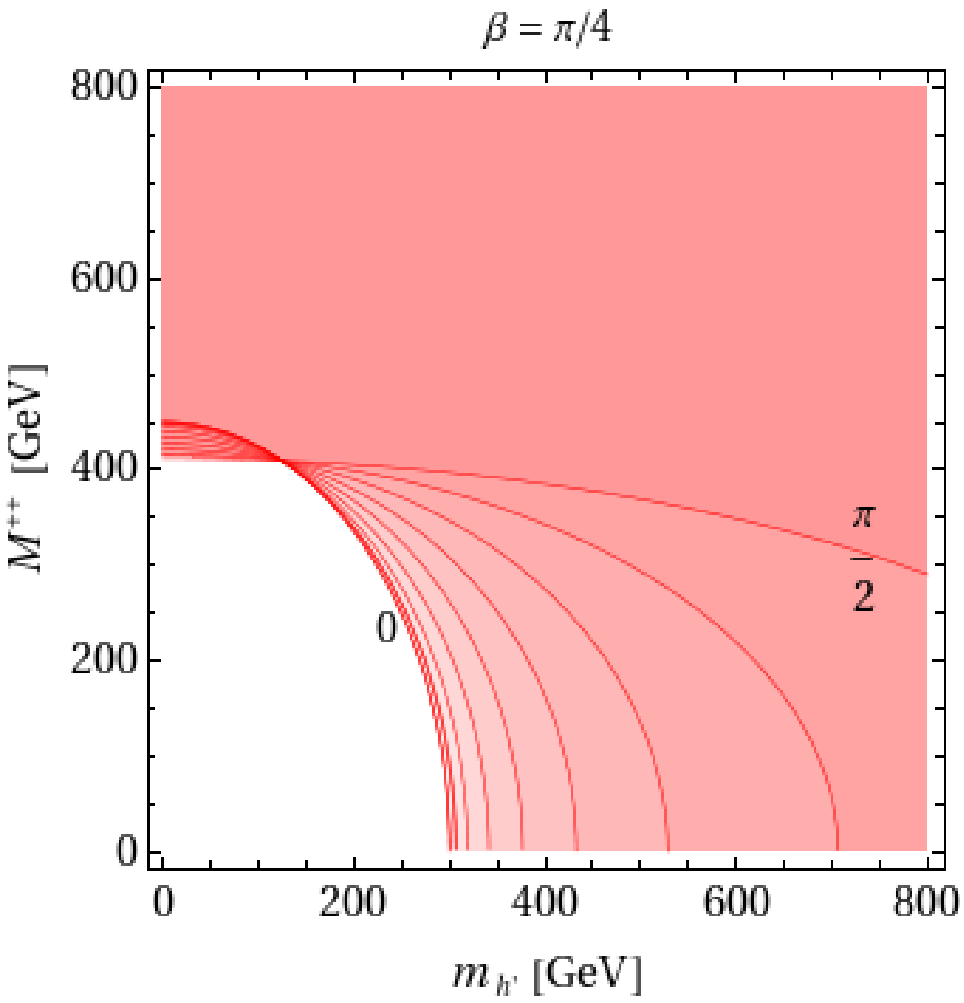
# Example: The Doublet-Septet model

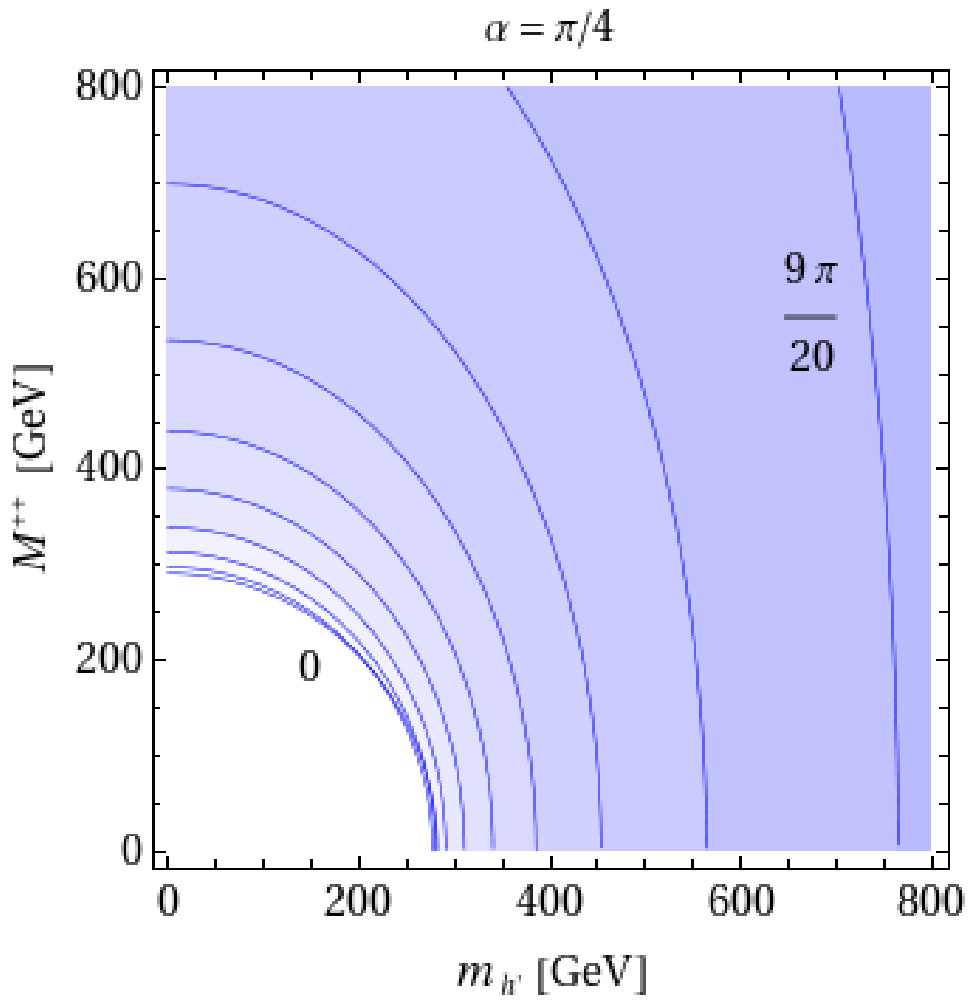
- In this model, we augment the SM with an electroweak septet with hyper-charge 2.
- It automatically preserves $\rho = 1$.
- Spectrum: 1 doubly charged Higgs, 2 singly charged Higgess, 2 CP-even neutral Higgses (and 1 CP-odd neutral Higgs.)
- The parameters $a_i$, $b_i$ and $f_i$ are given in terms of the mixing angles $\alpha$, $\beta$ and $\gamma$.

  $\alpha$: mixing angle of the two physical neutral Higges.
  $\beta$: the mixing of the two vevs.
  $\gamma$: mixing of the two physical singly charged Higges.

# Bounds from *WW*

$h' = s_\alpha \phi_2^0 + c_\alpha \phi_7^0$, $\tan\beta = v_2/(4v_7)$



# Bounds from $ZZ$

$h' = s_\alpha \phi_2^0 + c_\alpha \phi_7^0$, $\tan\beta = v_2/(4v_7)$