New Higgs Signatures for LHC

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LHC Meeting – 7th Workshop on TeV Physics, Beijing, Nov. 12-14, 2012

1. **Why Higgs Boson ?**
   - Spin-0 Higgs vs Unitarity in SM
2. **Joint Mechanism of Unitarity and LHC Signals**
   - Unitarity via Both Spin-0 and Spin-1 Bosons
   - LHC Signatures of Higgs h^0 and H^0
3. **Why is 4th Family Special? and LHC Signals**
   - Why not 4G with 1-Higgs-doublet (SM4)?
   - 4G with 2-Higgs-doublet and LHC Signals
4. **Summary**

Recollection

— My collaboration with Prof. Kuang started since 24 years ago when I was a student. I have continued collaborations with him since my graduation, and so far we published 23 papers together, many of which are highly cited.
I am glad to be Prof. Kuang's most productive collaborator.

—Below is our newest paper published on Prof. Kuang's birthday on Nov.9 (Beijing time):

PHYSICAL REVIEW D **86,** 095011 (2012)

Discovering new gauge bosons of electroweak symmetry breaking at LHC-8

Chun Du,[1] Hong-Jian He,[1,2] Yu-Ping Kuang,[1] Bin Zhang,[1] Neil D. Christensen,[3]
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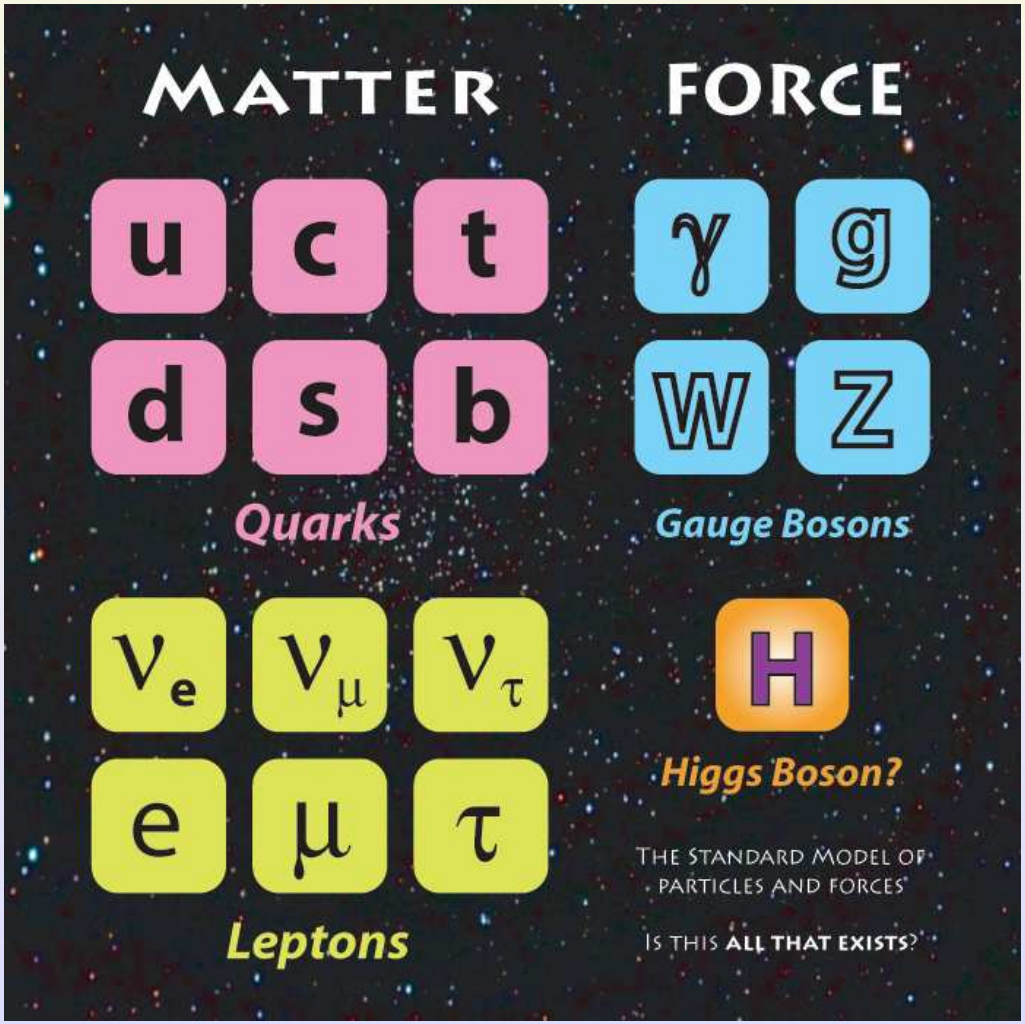
(Received 27 June 2012; published 8 November 2012)

Gift: One of my most favorable Symbolism Paintings

- Is this flower you imagined & expected ? or Something New ?!

- Happy 80th birthday to Prof. Yu-Ping Kuang !

Real Big Puzzles in the SM ?



Real Big Puzzles in the SM ?

(1) **Origin of Particle Masses ?**

Why Spin-0 Higgs Boson in SM ?

Role of Spin-1 New Gauge Boson ?

(2) **Why Only 3 Families ?**

Why Not 4th Family ? Why is it Special ?

(3) **Why Parity Violation? How to restore it ?**

(4) **Why Dark Matter ? & Common Origin with Matter ?**

- **All may be connected to Electroweak Symmetry Breaking !**
- **They may all have impacts on LHC !**

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Real Big Puzzles in the SM ?

- All the 4 Questions above already arise at Tree-Level !
- They are Real Physical Questions, instead of technical one.

No.1: Why is Higgs Boson crucial in SM ?

- Ensure Perturbative Renormalizability of the SM
- Ensure Perturbative Unitarity of the SM
- Mass Generation for W/Z and Fermions
- In fact, Cornwall-Levin-Tiktopoulos (1974) showed that in 4d only Renormalizable gauge theories with spontaneous symmetry breaking (such as SM) can have perturbative tree-level Unitarity.

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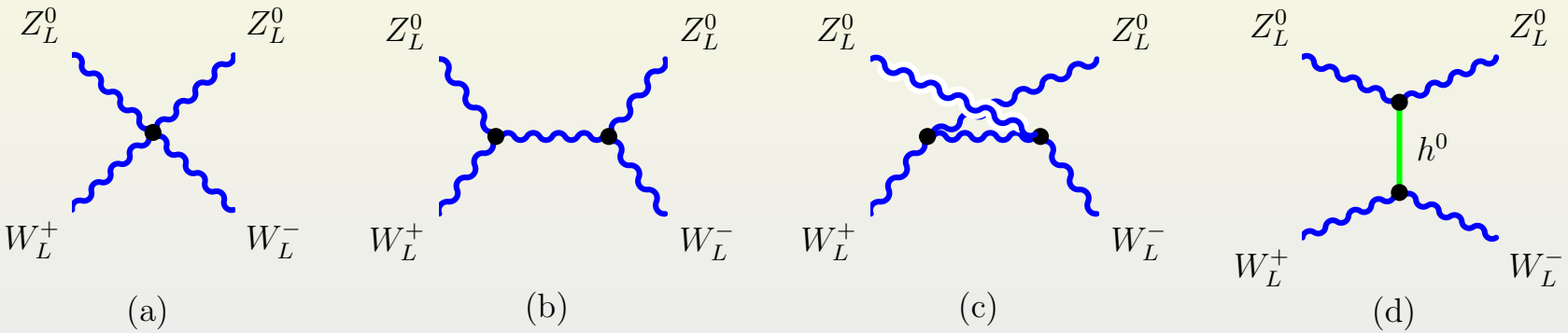
Unitarity of WW Scattering in SM

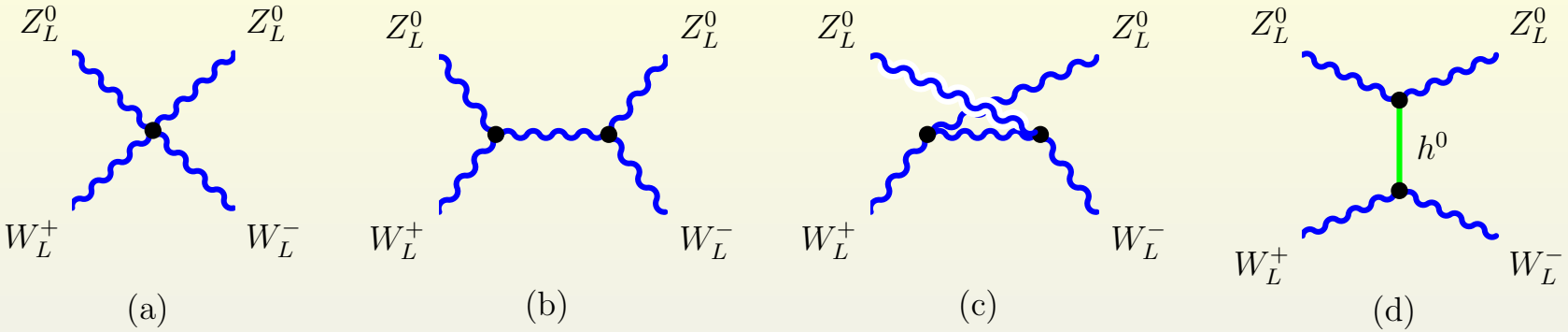


- **At high energies $E \gg M_W$, Longitudinal Polarization of W (Z) boson is proportional to its 4-momentum,**

$$\epsilon_L^\mu \propto k^\mu / M_W$$

- **Hence, each diagram has the form:**

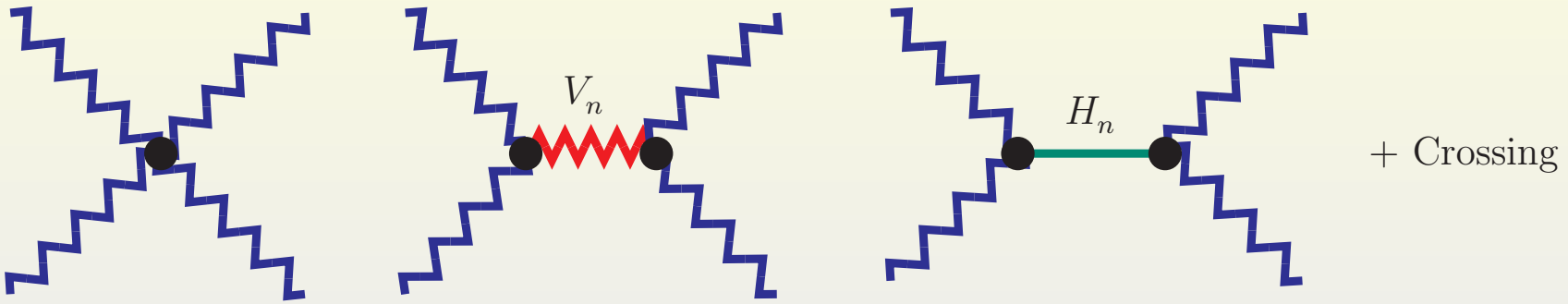
$$\mathcal{T} = A \cdot E_{cm}^4 + B \cdot E_{cm}^2 + \mathcal{O}(E_{cm}^0)$$



$$\mathcal{T} = A \cdot E_{\rm cm}^4 + B \cdot E_{\rm cm}^2 + \mathcal{O}(E_{\rm cm}^0)$$

- **In conventional 4d SM, perturbative Unitarity requires $\mathcal{O}(E_{\rm cm}^4)$ and $\mathcal{O}(E_{\rm cm}^2)$ terms to exactly cancel.**
- **$\mathcal{O}(E_{\rm cm}^4)$ cancelation is ensured by YM gauge structure.**
- **$\mathcal{O}(E_{\rm cm}^2)$ cancelation is ensured by Higgs boson of SM !**
- **But, "Higgs Boson" is not the only way or only story to realize perturbative Unitarity !**

Joint Mechanism for E^2 Cancellation



- $V_0^L V_0^L \to V_0^L V_0^L$ **Scattering ($V_0 = W, Z$):**

General Sum Rule for E^2 Cancellation,

with exchanges of any numbers of V_n and H_n :

$$G_{VVVV} - \frac{3}{4} G_{VVV}^2 = \sum_n \frac{3}{4} \frac{M_{V_n}^2}{m_V^2} G_{VVV_n}^2 + \sum_n \frac{G_{VVH_n}^2}{4 m_V^2}$$

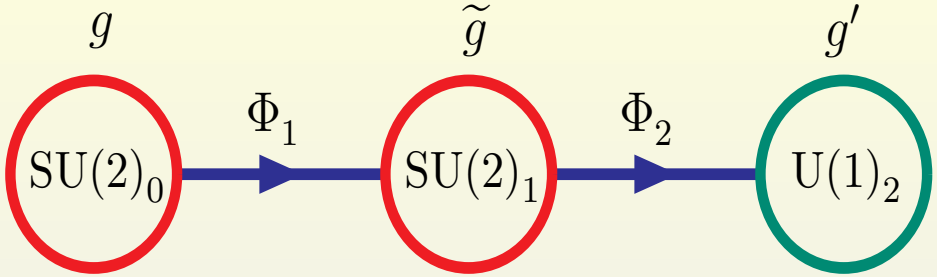
Abe, Chen, He, arXiv:1207.4103

An Explicit Realization: the 221 Model

- **Assign fermions & Higgs under** $\mathrm{S}U(2) \otimes \mathrm{S}U(2) \otimes \mathrm{U}(1)$

Fermions	$\mathrm{S}U(2)_0$	$\mathrm{S}U(2)_1$	$\mathrm{U}(1)_2$
Ψ_{0L}	**2**	**1**	$\frac{1}{6}\ \left(-\frac{1}{2}\right)$
Ψ_{1L}	**1**	**2**	$\frac{1}{6}\ \left(-\frac{1}{2}\right)$
Ψ_{1R}	**1**	**2**	$\frac{1}{6}\ \left(-\frac{1}{2}\right)$
Ψ^u_{2R}	**1**	**1**	$\frac{2}{3}\ (0)$
Ψ^d_{2R}	**1**	**1**	$-\frac{1}{3}\ (-1)$
Φ_1	**2**	**2**	0
Φ_2	**1**	**2**	$\frac{1}{2}$

- **Our 221 construction has VEV ratio:** $f_2/f_1 = O(1)$



- **UV Completed 3-Site Model (221 Model):**

$$\begin{aligned} \mathrm{SU}(2)_0 \otimes \mathrm{SU}(2)_1 &\xrightarrow{\langle\Phi_1\rangle\neq 0} \mathrm{SU}(2)_V \\ \mathrm{SU}(2)_1 \otimes \mathrm{U}(1)_2 &\xrightarrow{\langle\Phi_2\rangle\neq 0} \mathrm{U}(1)_V \end{aligned}$$

- **The UV Completed Lagrangian,**

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}\sum_{a=1}^{3} W_{0\mu\nu}^{a} W_{0}^{a\mu\nu} - \frac{1}{4}\sum_{a=1}^{3} W_{1\mu\nu}^{a} W_{1}^{a\mu\nu} - \frac{1}{4} B_{2\mu\nu} B_{2}^{\mu\nu} \\ & + \sum_{j=1,2} \mathrm{tr}\left[(D_\mu \Phi_j)^\dagger (D^\mu \Phi_j)\right] - V(\Phi_1, \Phi_2) \end{aligned}$$

- **The two Higgs doublets** $(j = 1, 2)$,

$$\Phi_j = \frac{1}{2}\left(f_j + h_j + i\tau^a \pi_j^a\right)$$

- **General 221 Higgs Potential:**

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

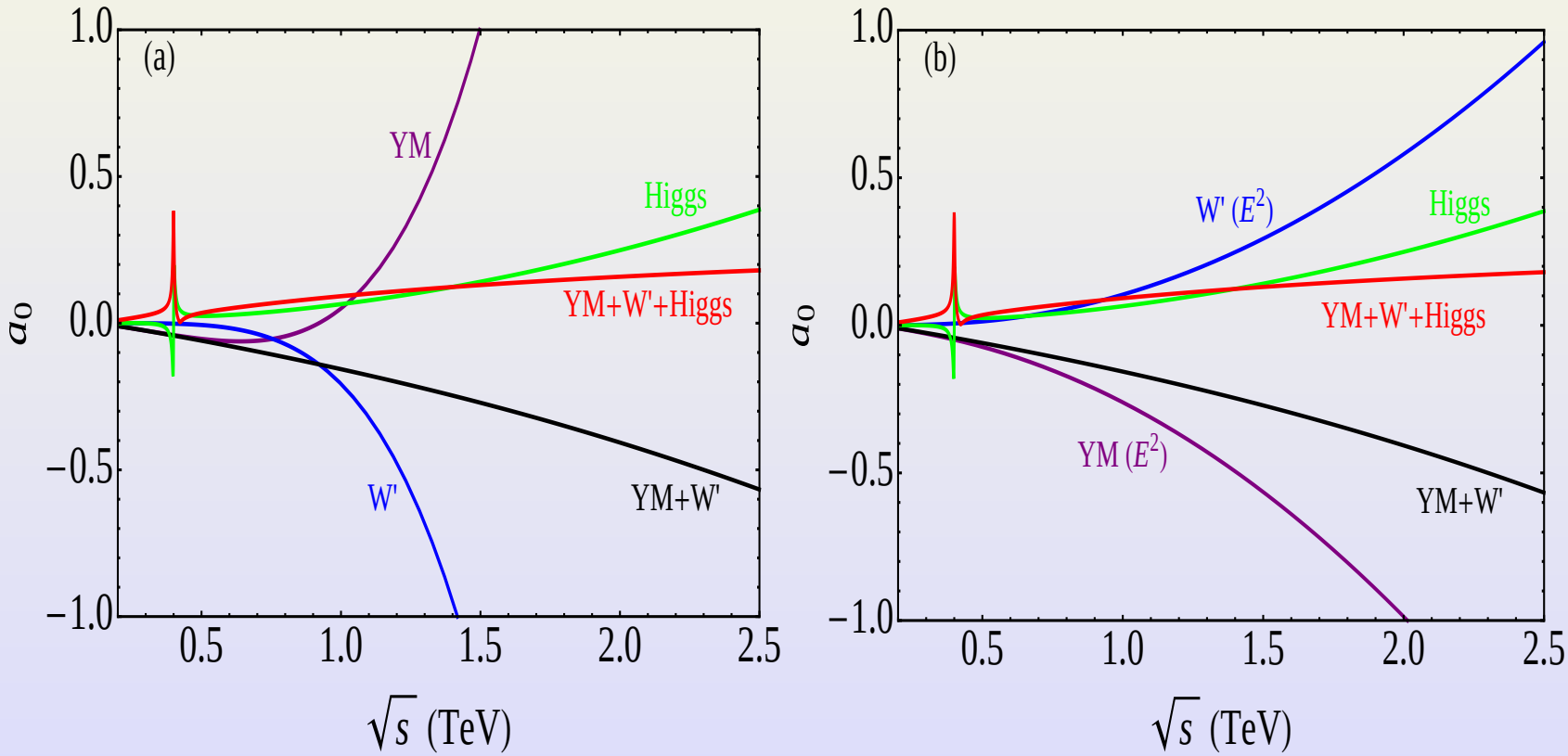
- V **has 5 free parameters (3 couplings and 2 VEVs), where** $f_1^{-2} + f_2^{-2} = v^{-2}$.

- **So, imposing** $M_h = 125\mathrm{GeV}$ **and** $f_2/f_1 = O(1)$**, we have only 2 input parameters — heavier Higgs mass and Higgs mixing angle:** (M_H, α) .

Abe, Chen, He, arXiv:1207.4103

Joint Mechanism for Unitarity

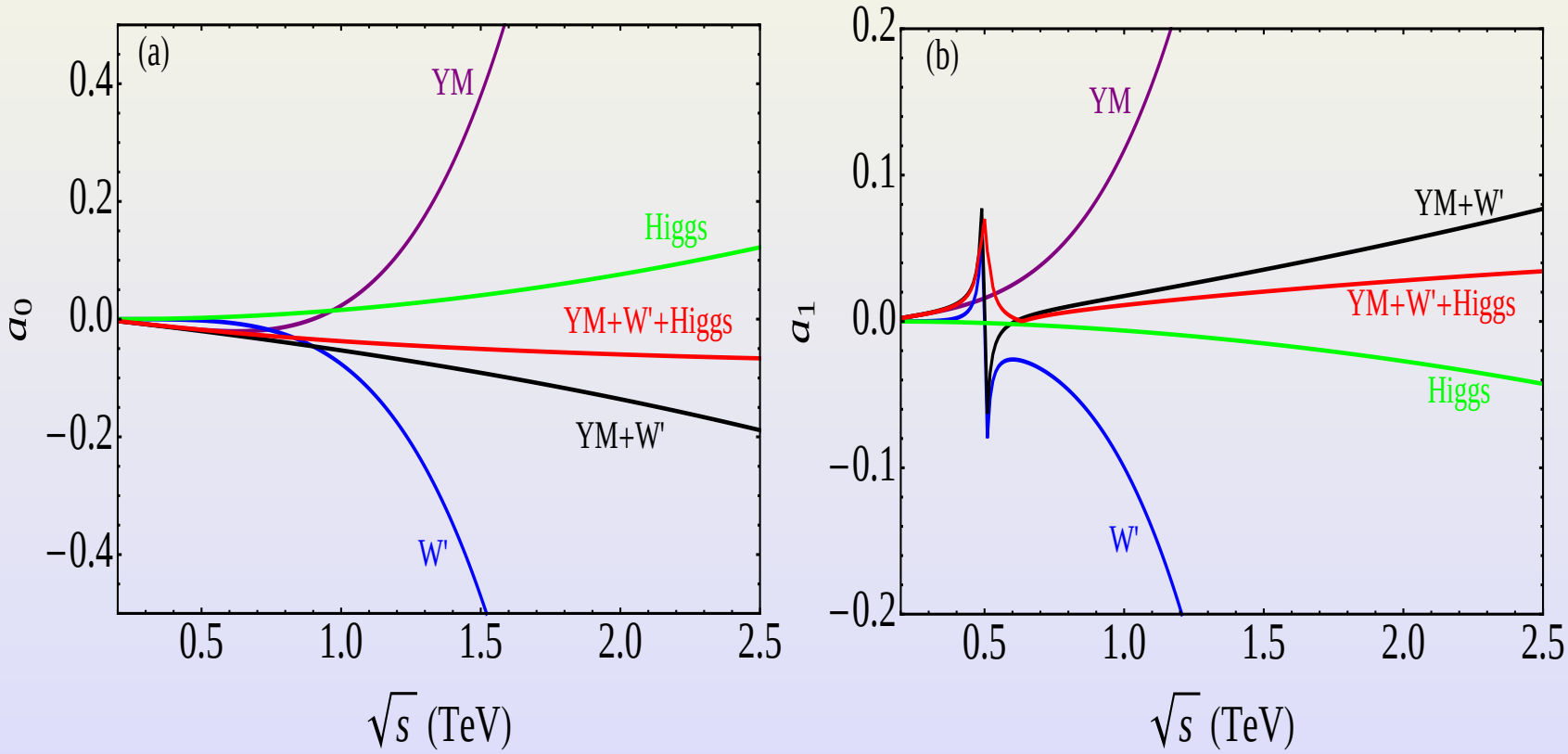
- E^4 and E^2 Cancellations: Roles of W'/Z' and Higgs
- s-Wave Unitarity of $W_L W_L \to Z_L Z_L$ Scattering



Abe, Chen, He, arXiv:1207.4103

Joint Mechanism for Unitarity

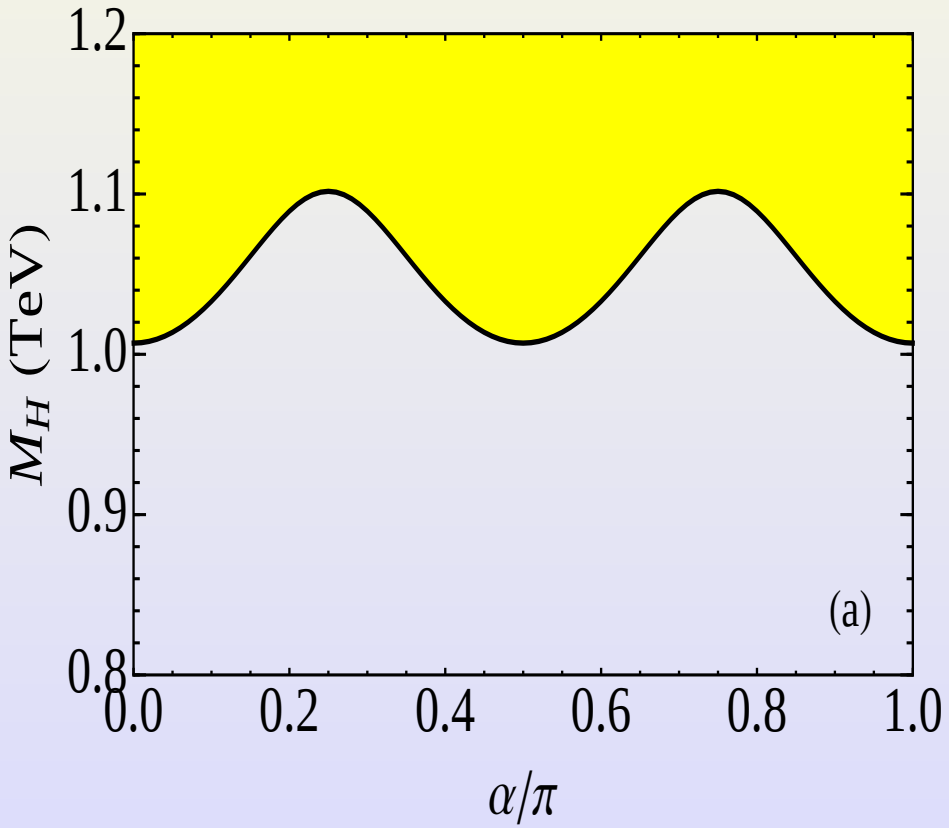
- E^4 and E^2 Cancellations: Roles of W'/Z' and Higgs
- s-Wave & p-Wave Unitarity of $W_L Z_L \to W_L Z_L$ Scattering



Abe, Chen, He, arXiv:1207.4103

Unitarity Bound on Heavier Higgs Boson H^0

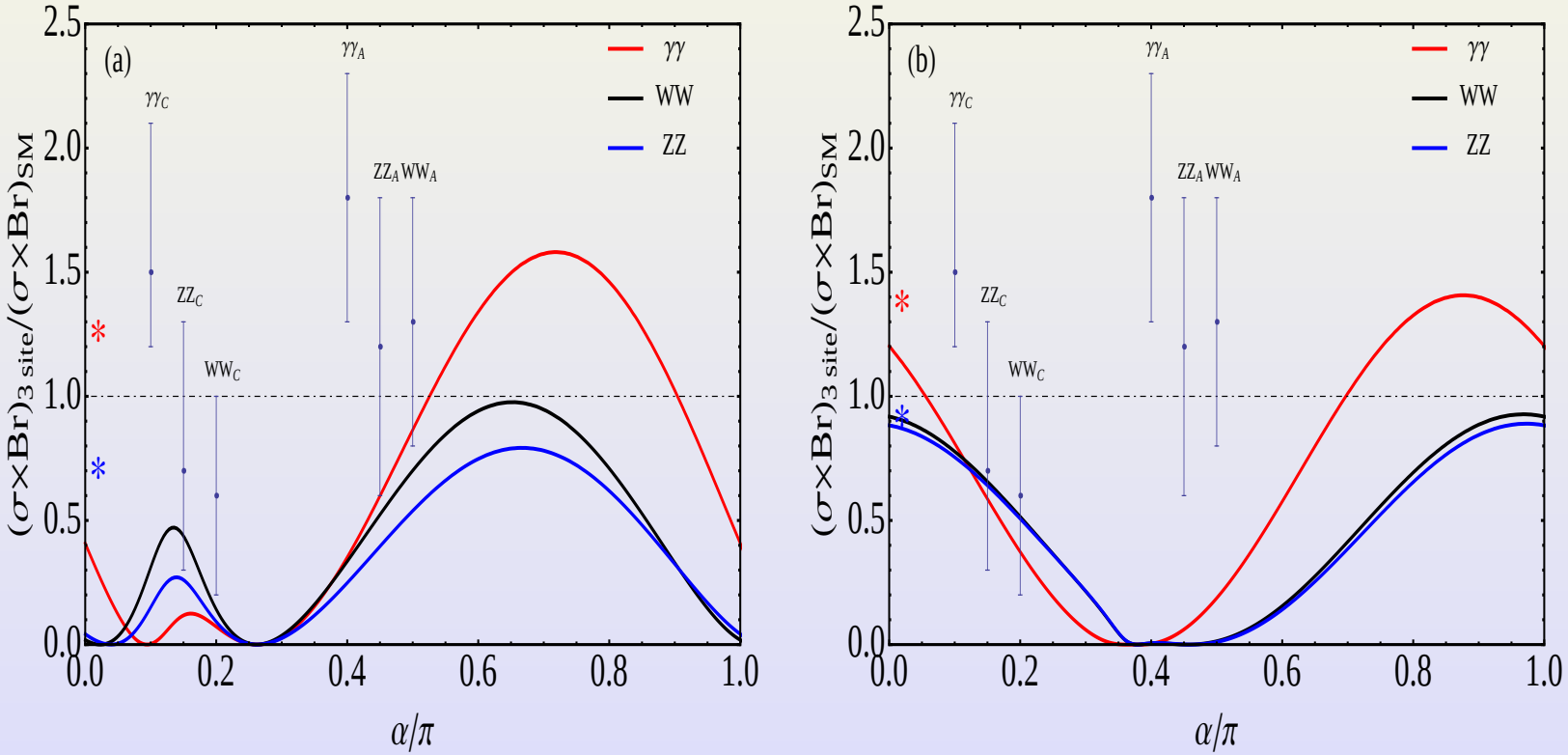
- **Identify lighter Higgs h^0:** $M_h = 125\,\mathrm{GeV}$
- **Derive unitarity bound on H^0 mass:** $M_H \leqslant 1.0 - 1.1\,\mathrm{TeV}$



arXiv:1207.4103

LHC Signal Rates of $gg \to h^0 \to \gamma\gamma, WW^*, ZZ^*$

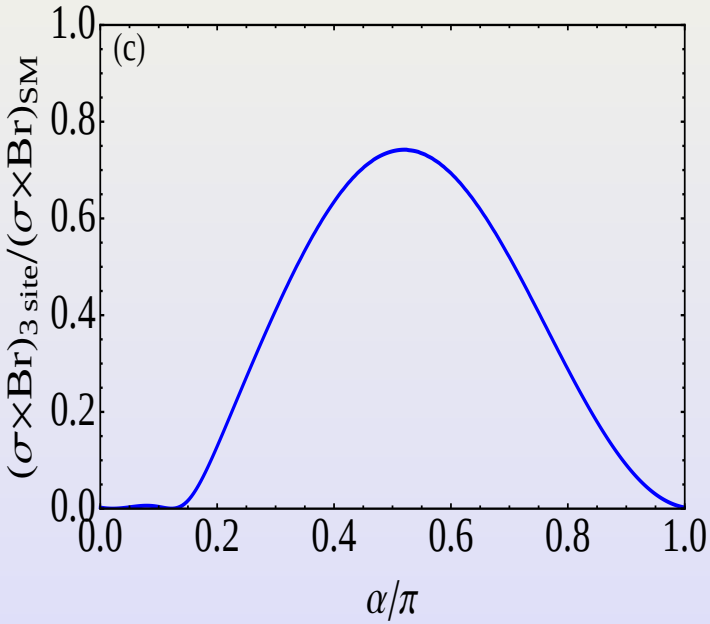
- **Inputs:** $M_h = 125\,\mathrm{GeV}$, $(M_{W'}, M_F) = (0.4,\ 2.5)\mathrm{TeV}$
- $f_2/f_1 = \frac{1}{2}$ **in plot-(a) and** $f_2/f_1 = 2$ **in plot-(b).**

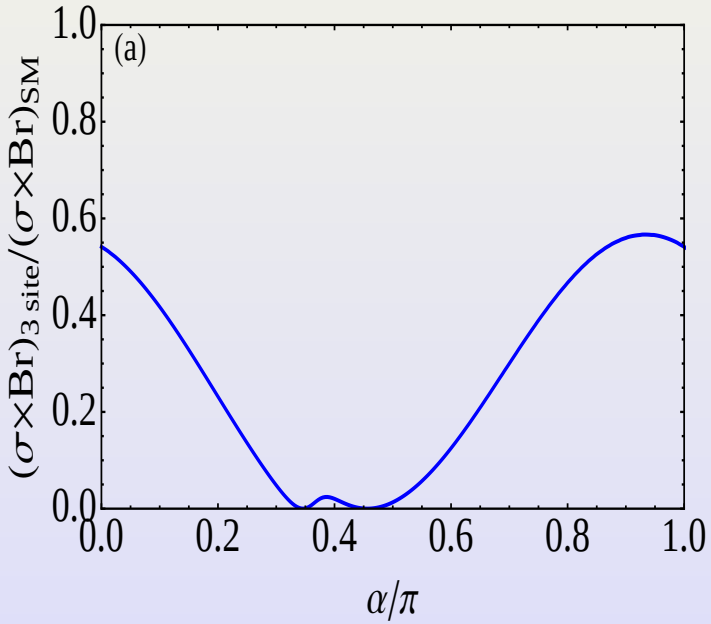


Abe, Chen, He, arXiv:1207.4103

Associate Production & Vector Boson Fusion

- **Inputs:** $M_h = 125\mathrm{GeV}$, $M_F = 2.5\mathrm{TeV}$, $M_{W'} = 400\mathrm{GeV}$
- $f_2/f_1 = (\frac{1}{2}, 2)$ **in left and right plots, respectively.**

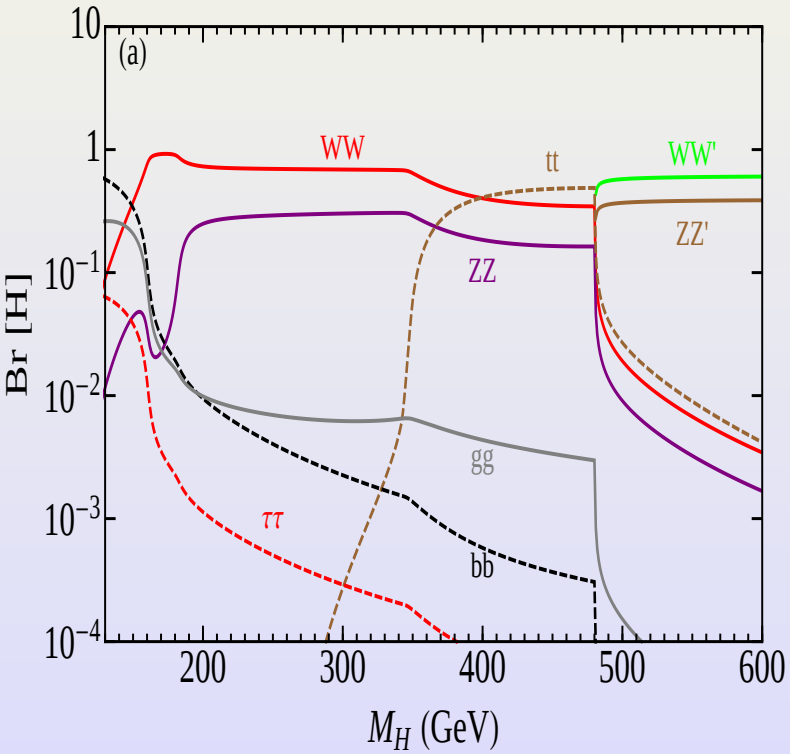


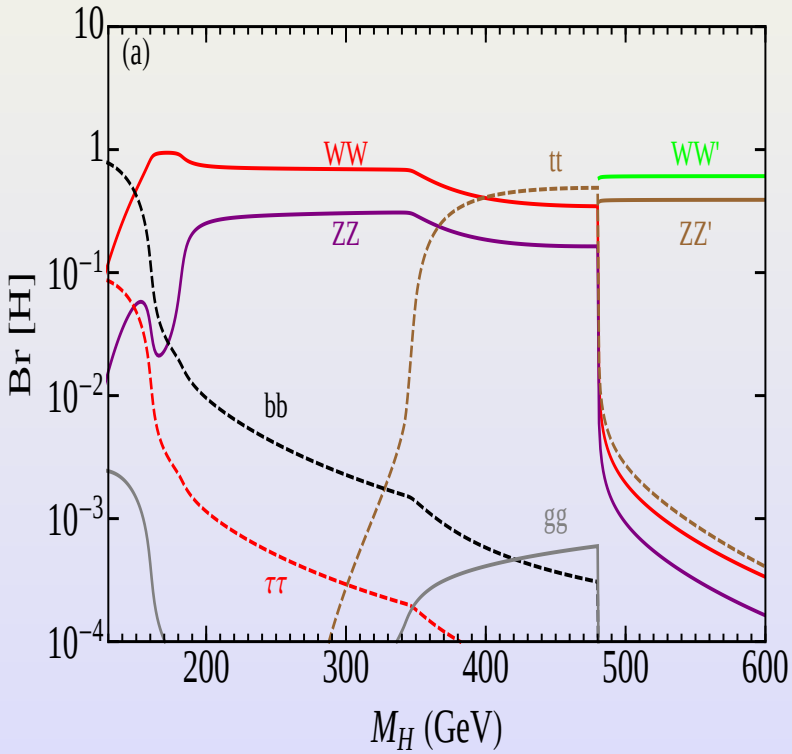


arXiv:1207.4103

New Physics Discriminator: H^0

- **Inputs:** $f_1 = f_2$, $M_{W'} = 400\,\mathrm{GeV}$, $M_F = 2.5\,\mathrm{TeV}$
- **Higgs mixing** $\alpha = 0.6\pi$ **in plot-(a) and** $\alpha = 0.8\pi$ **in plot-(b)**
- **New channel:** $H^0 \to WW', ZZ' \to Z^0 W^+ W^- \to 3\ell + jj + \not{E}_T$

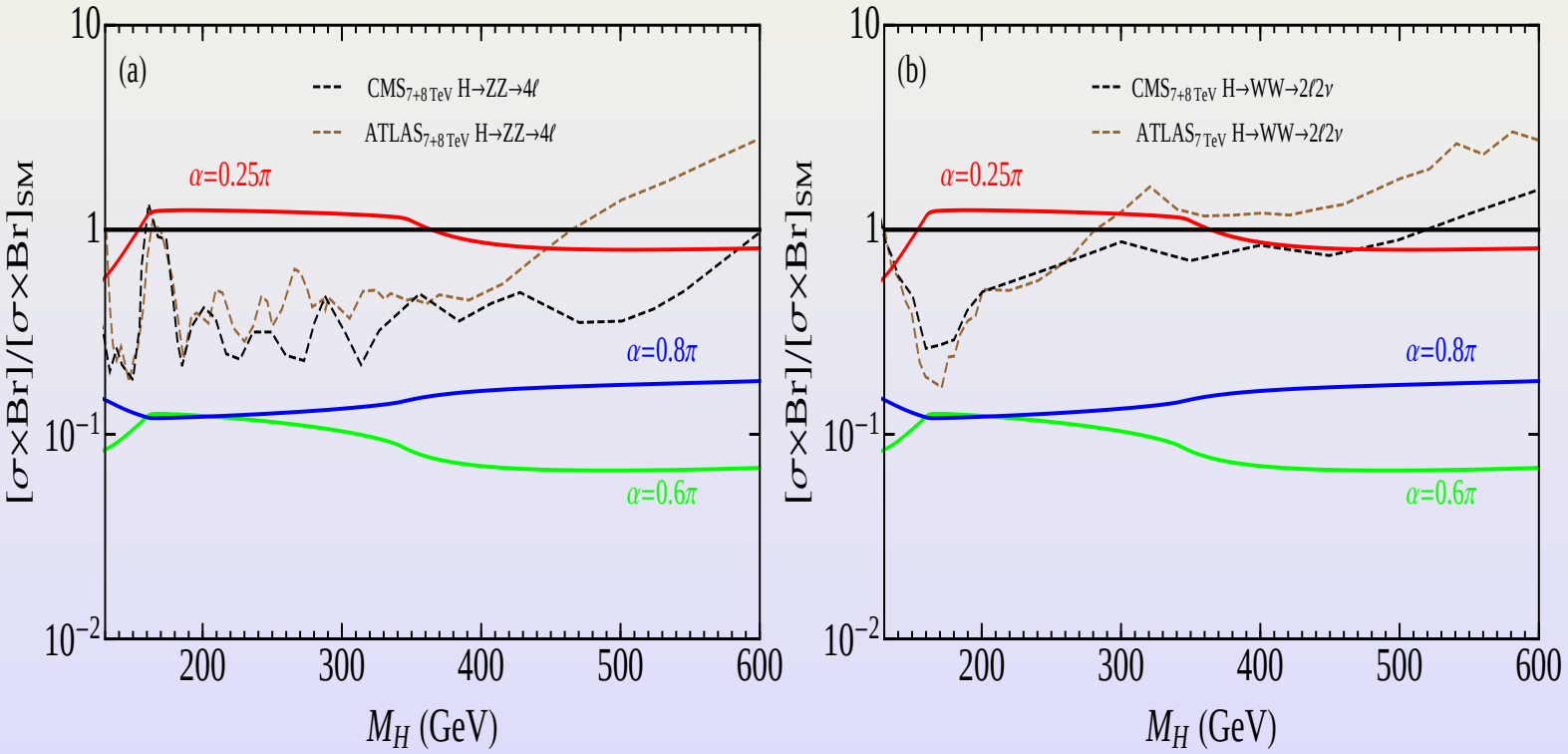




arXiv:1207.4103

LHC Signals of H^0 and Constraints

- **Inputs:** $f_1/f_2 = 2$, $M_{W'} = 600\,GeV$, $M_F = 2.5$ **TeV**
- **Higgs mixing** $gg \to ZZ \to 4\ell$ **in plot-(a) and** $gg \to WW \to 2\ell 2\nu$ **in plot-(b)**



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LHC Signals of H^0 and Constraints

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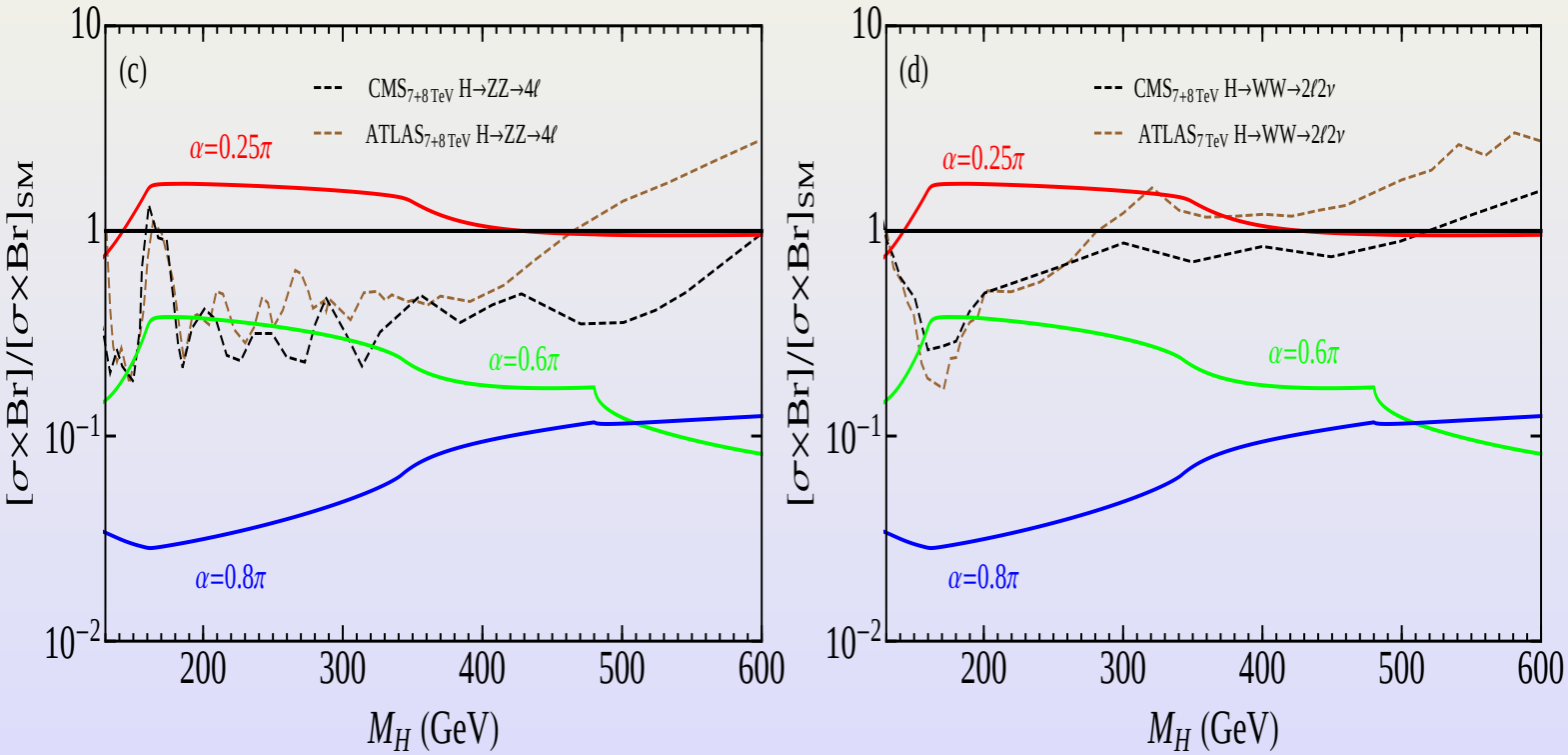

arXiv:1207.4103

No.2: Why only 3 Families? Is 4th Family Special?

- **SM does not explain why only 3 families.**
- **4th Family is a simplest New Phys Extension of SM.**
- Then, Why is 4th Family Special ?
- 4th Family Quarks are significantly heavier than top, and have larger Yukawa coupling of $O(2-3)$ with Higgs boson !
- As a result, Higgs production in gg Fusion and Higgs radiative decays in $\gamma\gamma$ channel are significantly changed.

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Indirect and Direct Constraints

- **EW precision bounds are OK.** (*He, Polonsky, Su, hep-ph/0102144*)
  For update, Erler et al, arXiv:1205.5580; Gfitter, arXiv:1107.0975

- **95%CL LHC search limits:**

  $M_{t'} \gtrsim 404\mathrm{GeV}$, $M_{b'} \gtrsim 480\mathrm{GeV}$, (*ATLAS*)

  $M_{t'} \gtrsim 557\mathrm{GeV}$, $M_{b'} \gtrsim 611\mathrm{GeV}$, (*CMS*)

- **Limit on 4G charged lepton (*LEP*-2):** $M_{\ell_4} \gtrsim 100.8\mathrm{GeV}$

- **Limits 4G neutrino ν_4:** $M_{\nu_4} \gtrsim M_Z/2$, **but,**

  Stable ν_4: $M_{\nu_4} \gtrsim 39.5\mathrm{GeV}$

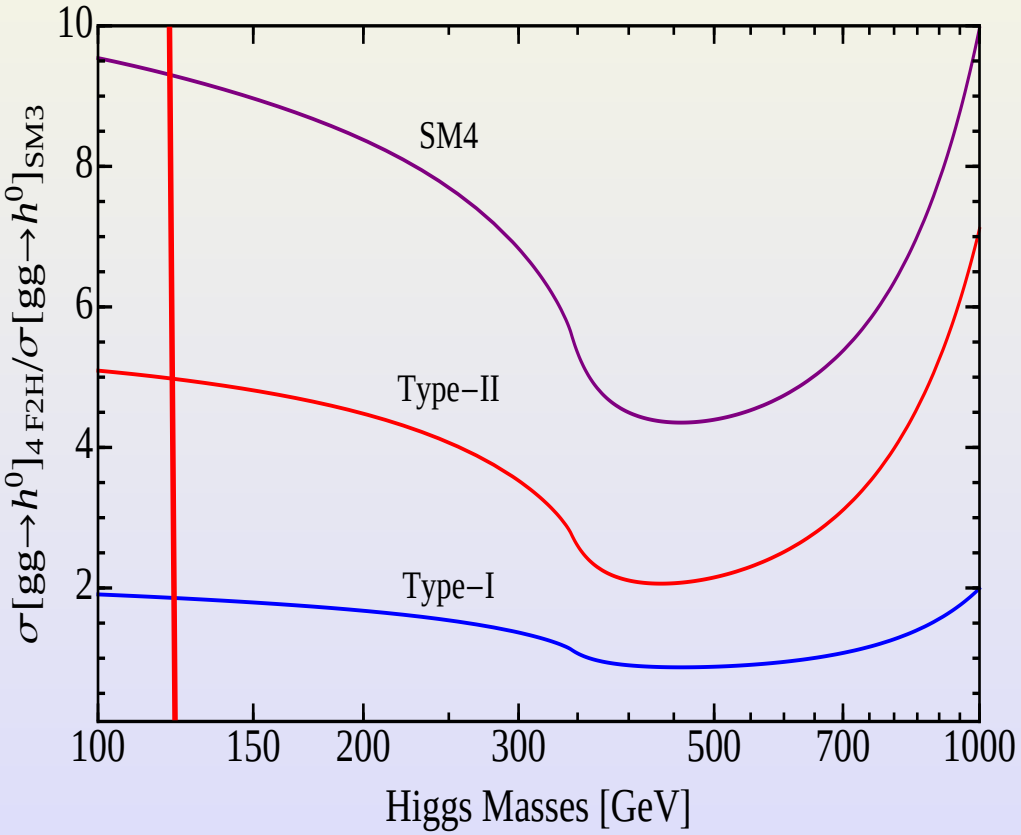
  Unstable ν_4 ($\nu_{4L} \to \ell^{\pm} W^{\mp}$): $M_{\nu_4} \gtrsim 90.3\mathrm{GeV}$

- **4G-parity (*Lee & Soni, arXiv:1206.6110*): 4G fermions can be much lighter and 4th Neutrino ν_4 is a natural L4P. $\Rightarrow$ Much relax lower mass-bound from direct searches.**

LHC Higgs Production with 4th Family

- **Comparison of 4G Higgs Productions via $gg \to h^0$:**

One-Higgs-doublet vs Two-Higgs-doublets (type-I and type-II)

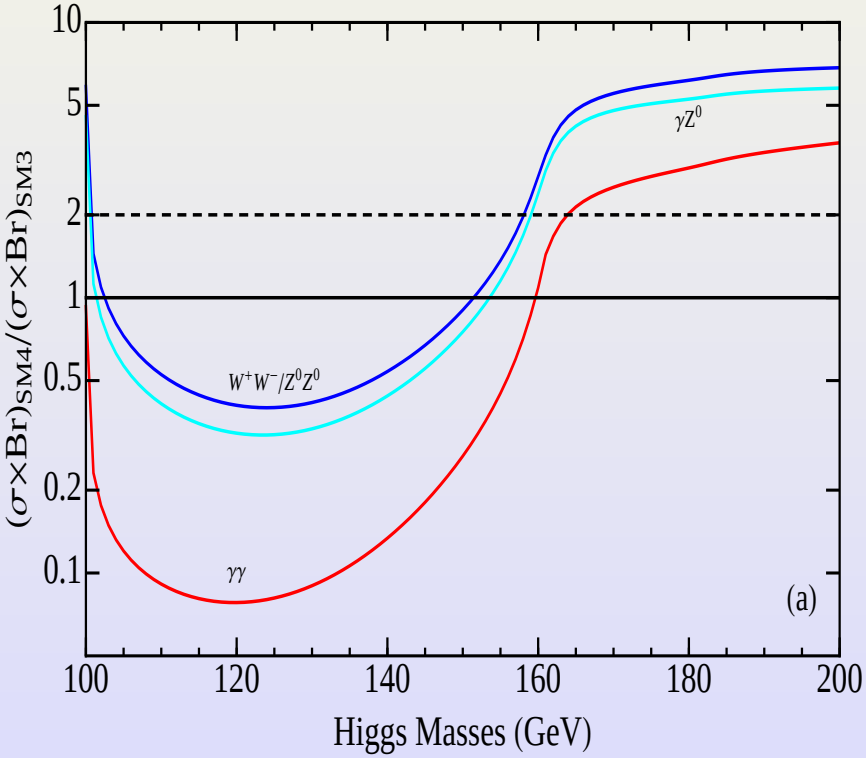


Chen and He, arXiv:1202.3072

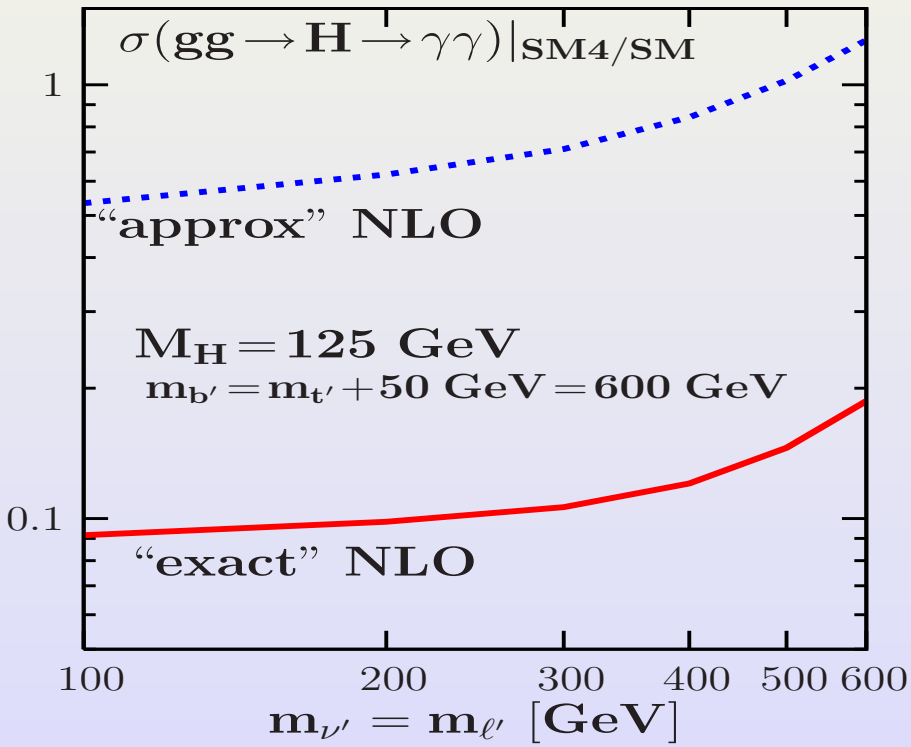
Higgs Signals: 4G with 1-Higgs-doublet

- SM4 with (i) invisible decays $h \to \nu_4 \nu_4$, or, (ii) exact NLO EW corrections, cannot explain signal-excess at $125 GeV$.

Keung et al, Cetin et al, Chen & He

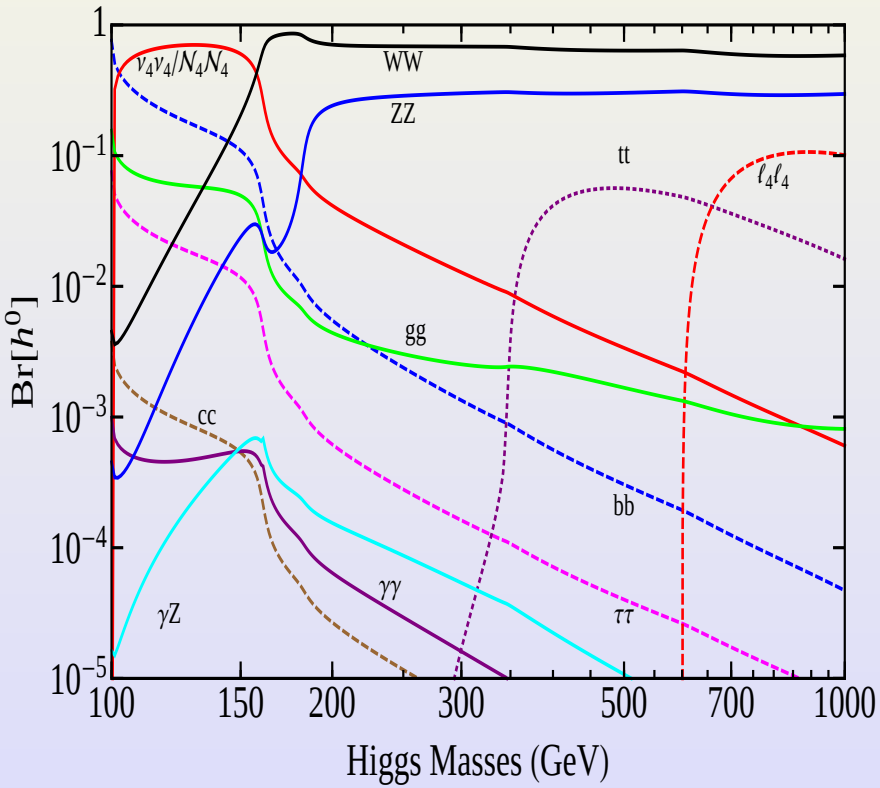


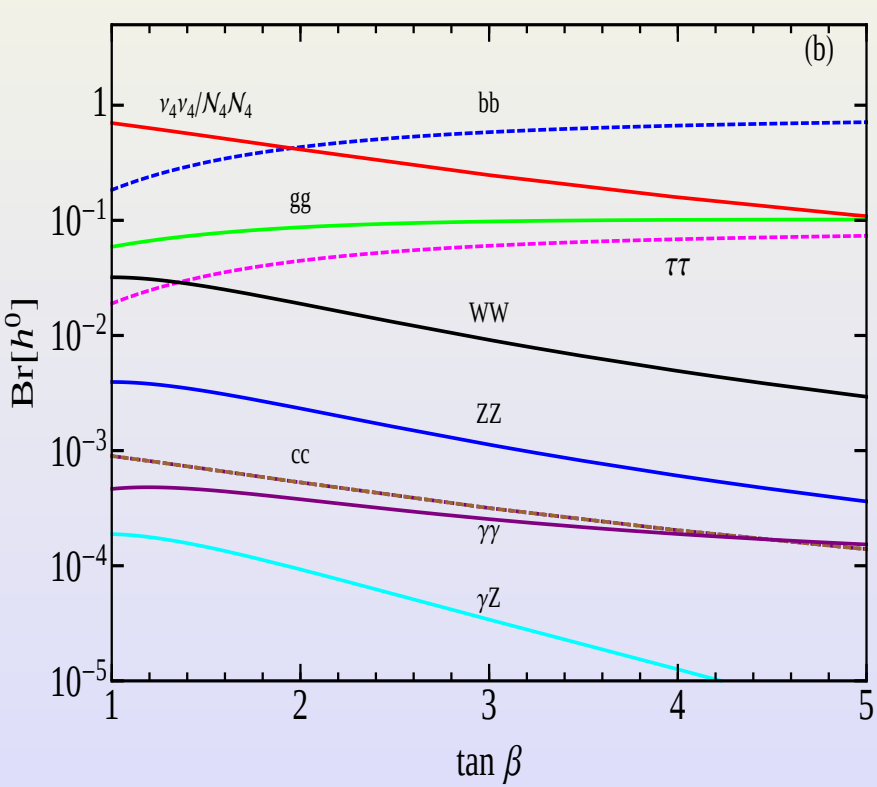
Djouadj & Lenz



Higss Signals: 4G with 2-Higgs-doublets

- **Decay branching fractions of CP-even Higgs h^0, where invisible decays $h \to \nu_4\nu_4$ dominate in the mass-range $M_h = 100 - 160 GeV$ and $\tan\beta < 2$.**

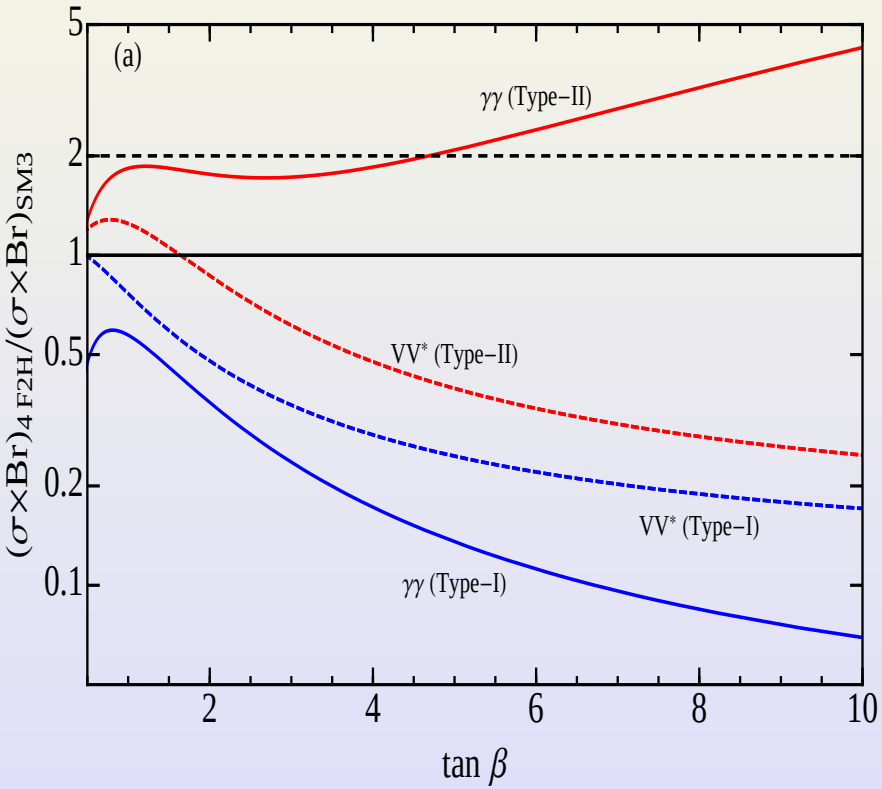


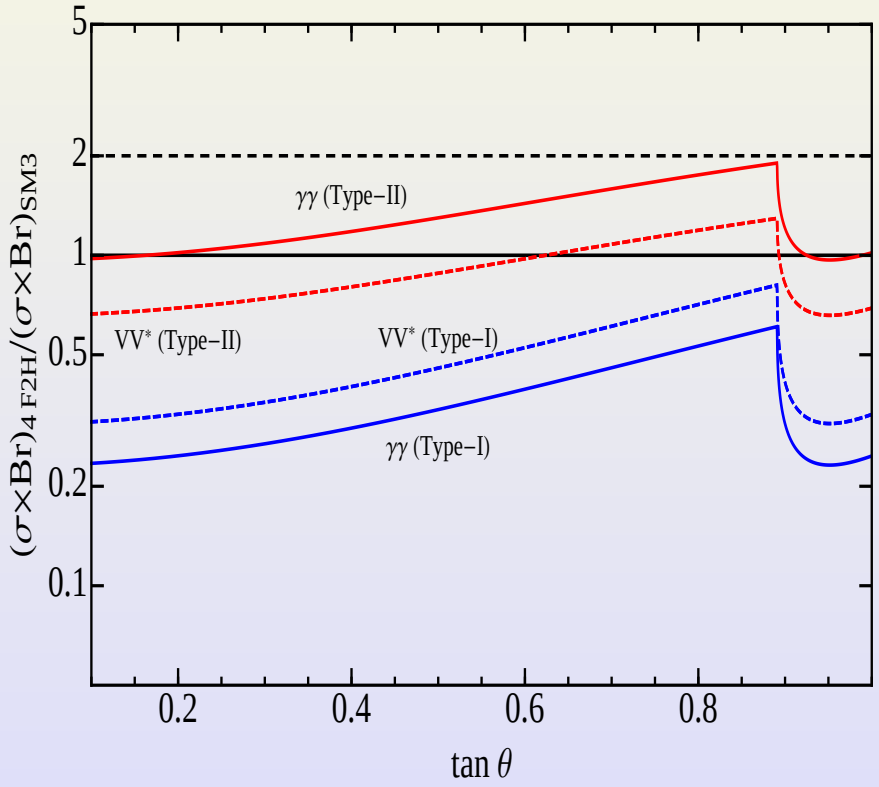


Chen and He, arXiv:1202.3072

Higss Signals: 4G with 2-Higgs-doublets

- **4th Family with 2-Higgs-doublets and invisible decays $h \to \nu_4 \nu_4$ nicely explains signal-excess at $126 GeV$.**





Chen and He, JHEP.04(2012)062, arXiv:1202.3072

Summary: Real Puzzles in the SM vs New Physics

(1) Origin of Particle Masses ?

Spin-0 Higgs Boson is crucial for mass generation. But,

Spin-1 New Gauge Boson can join Spin-0 for Unitarization Mechanism — Testable at LHC !

(2) Why Only 3 Families ?

4th Family has larger masses, comparable to top.

4G with 2-Higgs-Doublets is viable.

$\Rightarrow$ New Higgs Phys for LHC !

(3)* Why Parity Violation? How to restore it ? $\Rightarrow$ *arXiv*:1110.6893

$\Rightarrow$ Mirror Universe & Spontaneous P Violation.

$\Rightarrow$ Common Origin of Matter and Mirror Dark Matter.

★ They are connected to EWSB and Testable at LHC !

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Summary: Real Puzzles in the SM vs New Physics

(1) Origin of Particle Masses ?

Spin-0 Higgs Boson is crucial for mass generation. But,

Spin-1 New Gauge Boson can join Spin-0 for Unitarization Mechanism — Testable at LHC !

(2) Why Only 3 Families ?

4th Family has larger masses, comparable to top.
4G with 2-Higgs-Doublets is viable.
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$(3)^*$ Why Parity Violation? How to restore it ? $\Rightarrow$*arXiv*:1110.6893
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Summary: Symbolism Art vs New Physics

- Is this flower you imagined & expected ? or Something New ?!

- Is this Higgs Boson you imagined & expected ? or Else ??!!