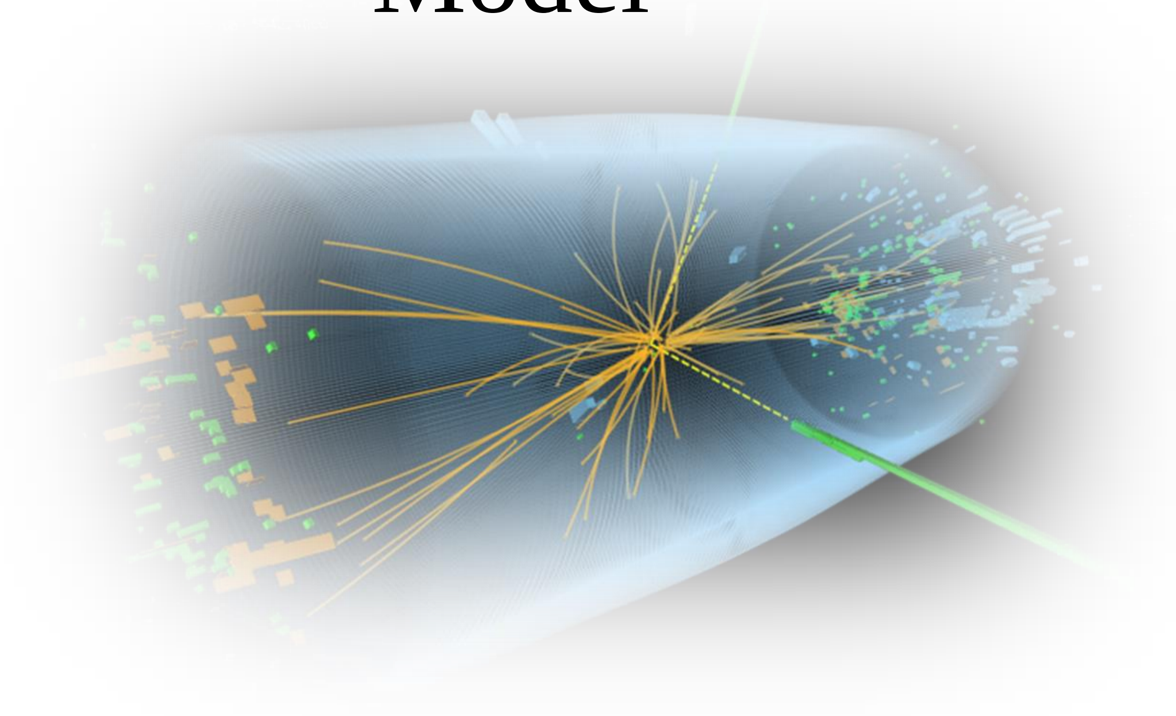
Higgs Phenomenology in Gauge Extensions of the Standard Model



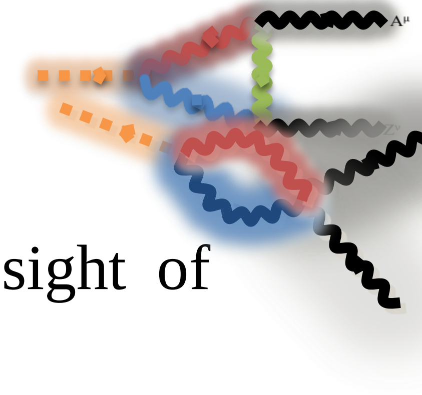
Bithika Jain

5th May , 2014

Work done with **Don Bunk, Jay Hubisz**

Phys Rev D 89 035014 (2014) [arXiv:1309.7988]

Motivation

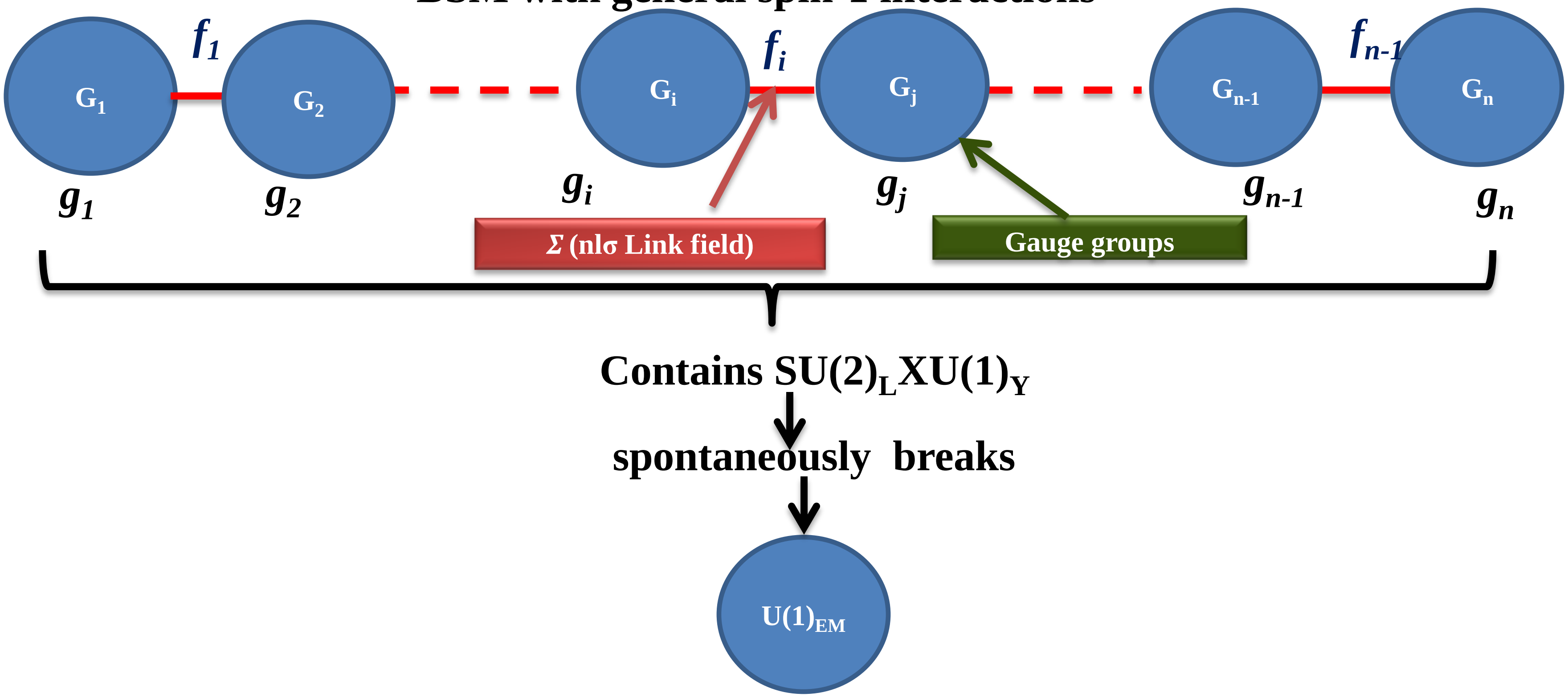


- **Lonely Higgs Problem**:- Higgs discovered but no sight of New physics.
- **Higgs Phenomenology of great interest** ; especially for the upcoming LHC run.
- Complete characterization of Higgs production and decay needed.
- Gauge extensions important since gauge contribution (e.g. W-loop) is the **dominant contribution to H →Zγ and γγ decays**
- Spin one states appear in Extra-dimensional models (KK modes), Little Higgs models (same spin partners), Strongly interacting EWSB (composite d.o.f.), Spin 1 superpartners to fermions* in SUSY.
- **A model independent study for spin-1 states is useful**

*Cai, Cheng and Terning (2008)

General Model

BSM with general spin-1 interactions



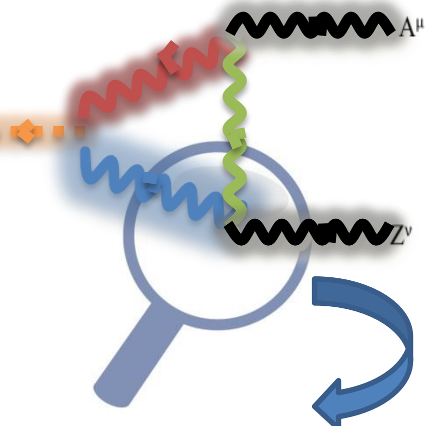
Kinetic term with gauge invariant field strengths: $\mathcal{L}_{\mathbf{kin}} = -\frac{\mathbf{1}}{\mathbf{4}} \sum_{\mathbf{l}} \mathbf{Tr}[\mathbf{V}^{\mathbf{l}}_{\mu\nu} \mathbf{V}^{\mu\nu}_{\mathbf{l}}]$

Mass terms for spin-1 fields comes from: $\mathcal{L}_{\mathrm{mass}} = \sum_{\mathbf{l}} \frac{\mathbf{f}_{\mathbf{l}}^{\mathbf{2}}}{\mathbf{4}} \mathbf{Tr} |\mathbf{D}^{\mu}_{\mathbf{l}} \boldsymbol{\Sigma}_{\mathbf{l}}|^{\mathbf{2}}.$

For **additional contributions to Higgs physics**, add a D=6 non-renormalizable 'wave-function' mixing operator $\mathcal{L}_{\mathrm{WF}} = \epsilon_{\mathbf{ij}} \mathbf{Tr}[\mathbf{V}^{\mathbf{i}}_{\mu\nu} \boldsymbol{\Sigma}_{\mathbf{ij}} \mathbf{V}^{\mathbf{j}\mu\nu} \boldsymbol{\Sigma}^{\dagger}_{\mathbf{ij}}]$

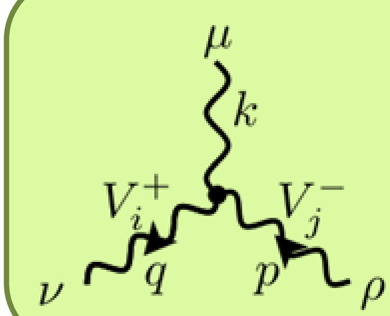
Feynman rules for general vector interactions

Post diagonalization of the quadratic part of the Lagrangian & rewriting the gauge kinetic terms in mass basis we get :



$$
\begin{aligned}
\mathcal{L}_3 = -\mathbf{i}\sum_{\mathbf{X},\mathbf{Y}} & \mathbf{g}_\gamma^{\mathbf{X},\mathbf{Y}} \mathbf{X}_\mu^+ \mathbf{Y}_\nu^- \mathbf{A}^{\mu\nu} + \mathbf{g}_\mathbf{Z}^{\mathbf{X},\mathbf{Y}} \mathbf{X}_\mu^+ \mathbf{Y}_\mu^- \mathbf{Z}^{\mu\nu} \\
& + \mathbf{G}_\mathbf{Z}^{\mathbf{X},\mathbf{Y}} \left(\mathbf{X}_{\mu\nu}^+ \mathbf{Y}^{-\mu} - \mathbf{X}_{\mu\nu}^- \mathbf{Y}^{+\mu}\right) \mathbf{Z}^\nu \\
& + \mathbf{e}\left(\mathbf{X}^{+\mu\nu}\mathbf{X}_\nu^- - \mathbf{X}^{-\mu\nu}\mathbf{X}_\nu^+\right)\mathbf{A}_\mu
\end{aligned}
$$

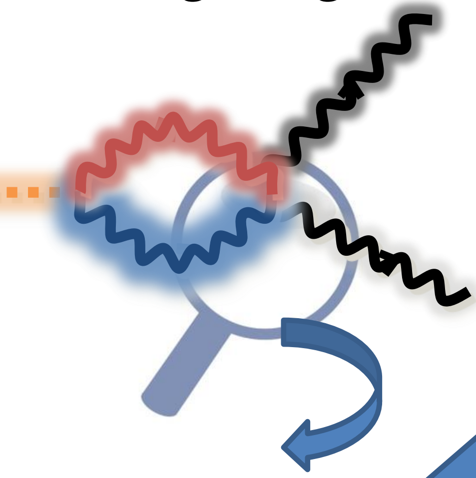
3 pt gauge interaction



$$
\begin{aligned}
-i\,[\,& g_{ij}^0 \left(k_\rho \eta_{\mu\nu} - k_\nu \eta_{\mu\rho}\right) + \\
& g_{ij}^+ \left(q_\mu \eta_{\nu\rho} - q_\rho \eta_{\mu\rho}\right) + \\
& g_{ij}^- \left(p_\nu \eta_{\mu\rho} - p_\mu \eta_{\nu\sigma}\right)]
\end{aligned}
$$

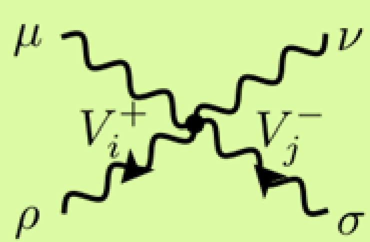
$g^0 = g^+ = g^- = 1$ (SM)

To make the contributions from 3 pt interactions gauge invariant, we need to include the 4-pt interactions which are present in fishing diagrams



$$\mathcal{L}_4 = -\sum_{X,Y} A_\mu Z_\nu X^+_\rho Y^-_\sigma \left(2a^{XY}_{\gamma Z}\, g^{\mu\nu} g^{\rho\sigma} - b^{XY}_{\gamma Z}\, g^{\mu\rho} g^{\nu\sigma} - c^{XY}_{\gamma Z}\, g^{\mu\sigma} g^{\rho\nu}\right)$$
$$-\sum_{X} e^2 A_\mu A_\nu X^+_\rho X^-_\sigma \left(2 g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\rho\nu}\right)$$

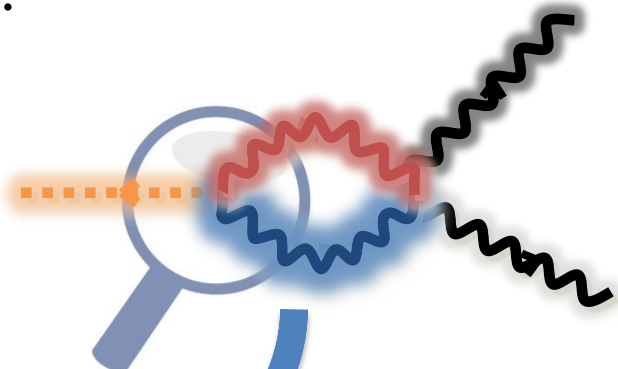
4 pt gauge interaction



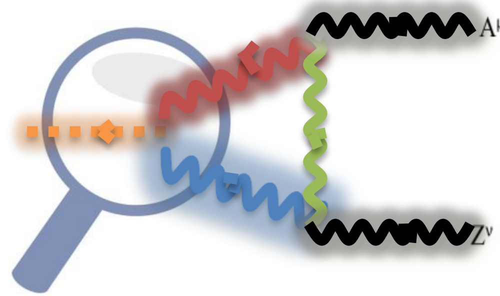
$$-i\left[2\lambda^{(1)}_{ij}\eta_{\mu\nu}\eta_{\rho\sigma} - \lambda^{(2)}_{ij}\eta_{\mu\rho}\eta_{\nu\sigma} - \lambda^{(3)}_{ij}\eta_{\mu\sigma}\eta_{\nu\rho}\right]$$

$\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = 1$ (SM)

We add “h” as CP even singlet under EM, in a delocalized way.



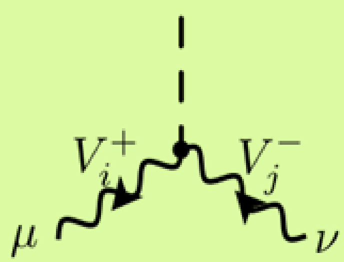
And



$f_l \to f_l\left(1 + \frac{a_l h}{f_l}\right)$ in $\mathcal{L}_{mass}$ yields

$$\mathcal{L}_{\mathrm{h-V}} = \sum_l 2a_l\left(\frac{h}{f_l}\right)\frac{f_l^2}{4} Tr\left|D_l^\mu \Sigma_l\right|^2.$$

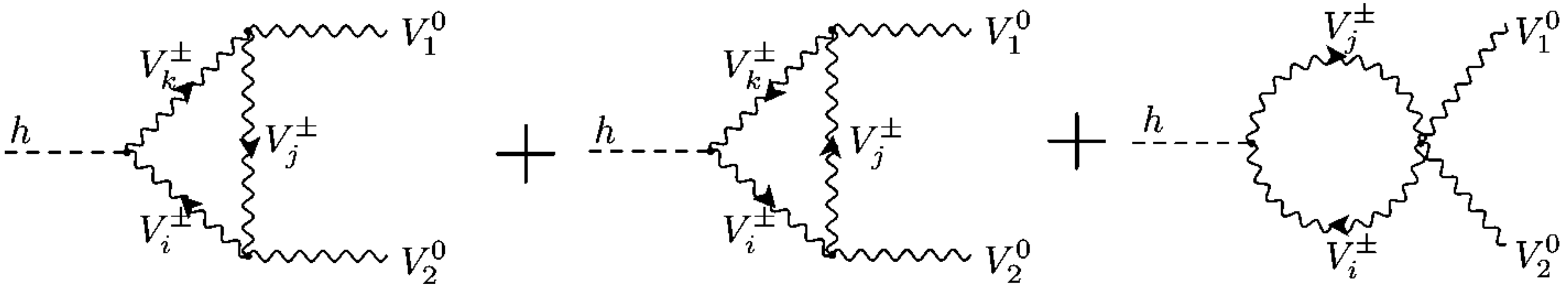
Higgs interaction



$i\kappa_{ij}\eta_{\mu\nu}$

Off diagonal term possible!

Loop level contributions to H →Z γ and H → γ γ



Triangle diagrams

$$\mathcal{M}^{\mu\nu}_{V_0^1 V_0^2} = \sum_{ijk\alpha\beta} [\kappa_h]_{ki} [\mathcal{A}^{\mu\nu}(M_i^2, M_j^2, M_k^2)]^{\alpha\beta} [g_{V_0^1}]^{\alpha}_{ji} [g_{V_0^2}]^{\beta}_{kj}$$

$$\mathcal{M}^{\times\mu\nu}_{V_0^1 V_0^2} = \sum_{ijk\alpha\beta} [\kappa_h]_{ik} [\mathcal{A}^{\times\mu\nu}(M_i^2, M_j^2, M_k^2)]^{\alpha\beta} [g_{V_0^1}]^{\alpha}_{ij} [g_{V_0^2}]^{\beta}_{jk}$$

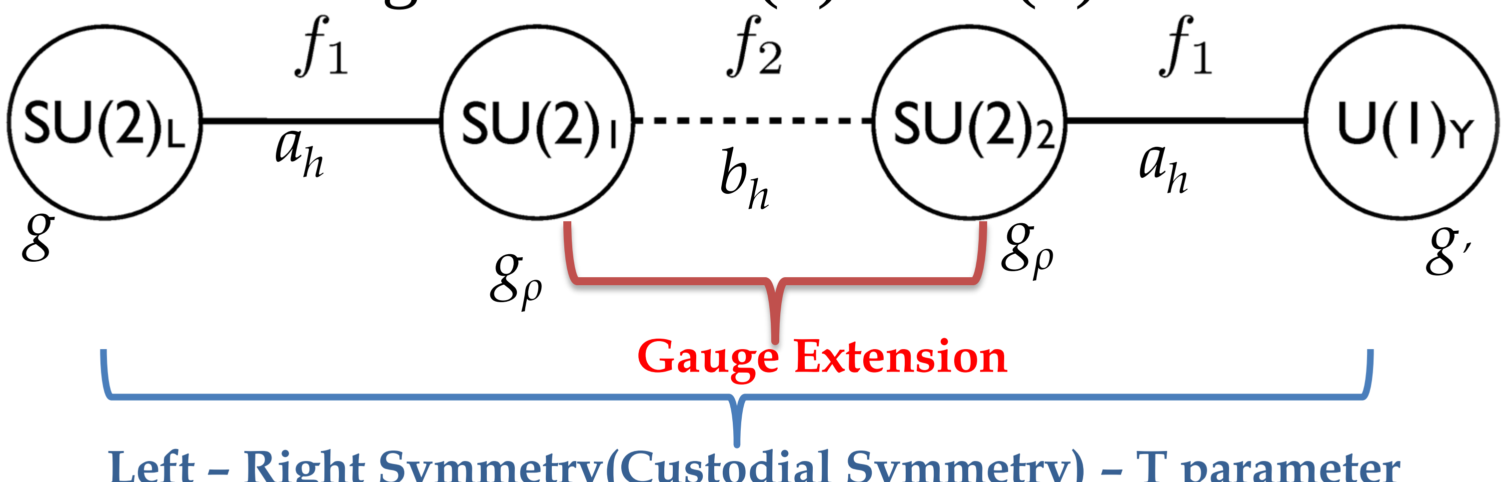
$$\mathcal{M}^{\propto\mu\nu}_{V_0^1 V_0^2} = \sum_{ij\alpha} [\kappa_h]_{ji} [\mathcal{A}^{\propto\mu\nu}(M_i^2, M_j^2)]^{\alpha} [\lambda_{V_0^1 V_0^2}]^{\alpha}_{ij},$$

Fishing diagrams

higgs coupling | Amplitude | gauge self interactions

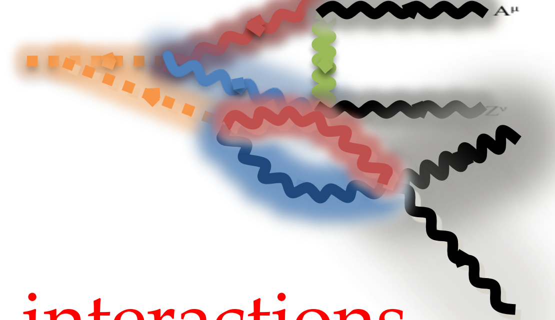
Four site deconstructed model with wave function mixing

- A template model which exhibits the most generic gauge structure that we are trying to study.
- “Moose” diagram for $SU(2)^3$ X U(1) model.

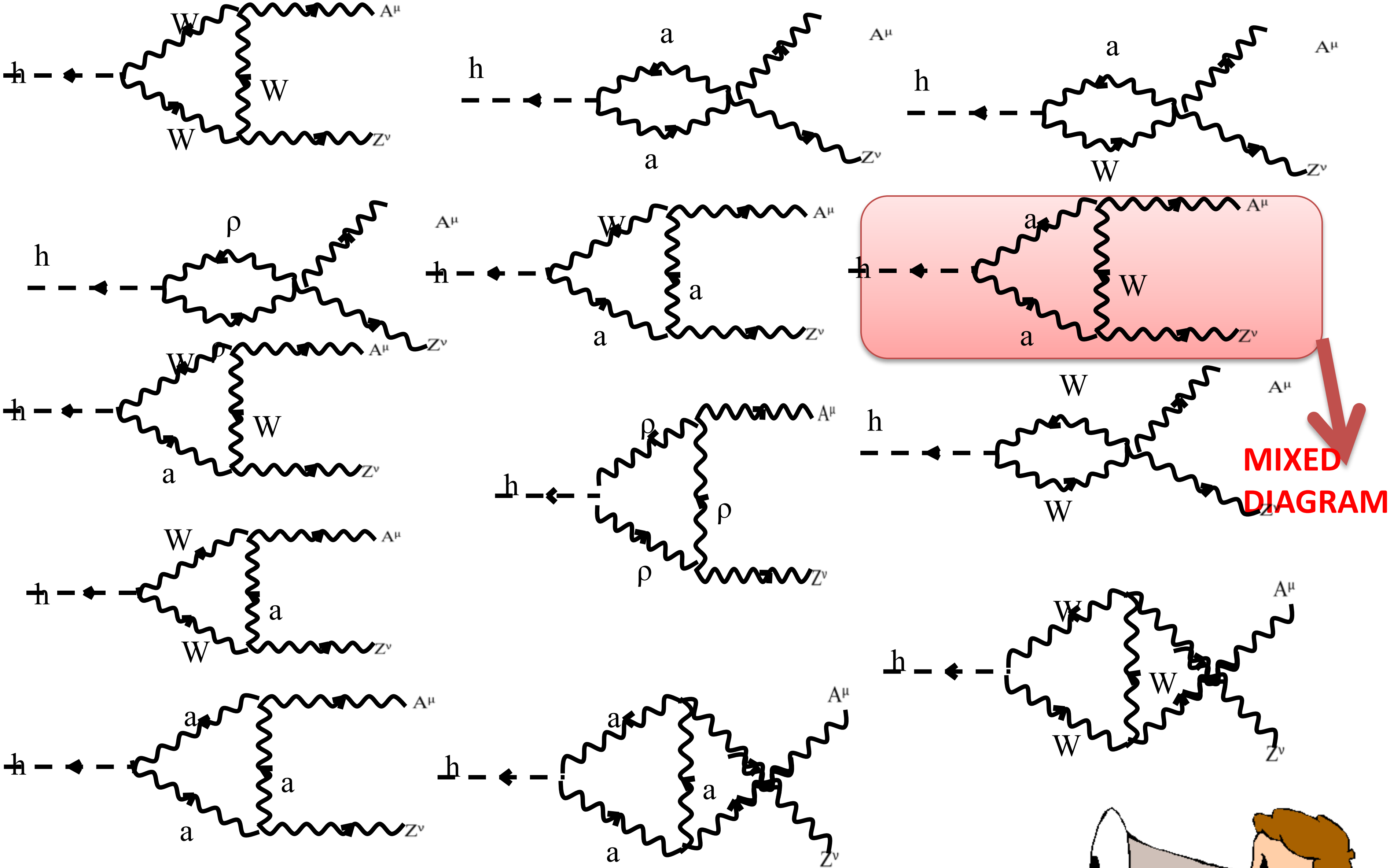


- We add $\mathcal{L}_{WF} = -\frac{1}{2}\epsilon\,\mathrm{Tr}\left[X_{(1)\mu\nu}\Sigma_{12}X_{(2)}^{\mu\nu}\Sigma_{12}^{\dagger}\right]$ which reduces tree level S parameter contributions.#

Chivukula and Simmons (2008)



- We extract relevant gauge and higgs interactions to calculate the loop induced effects to $H \to Z\gamma$ and $H \to \gamma\gamma$.
- As the couplings to gauge bosons are not diagonal here, we get a lot of mixed diagrams.
- But, the skeleton amplitudes we have calculated for the "general model" allow us to plug in the Higgs and gauge interactions.
- Without it one would have to calculate…



And a few more .....

Summary

- In 2 years the, "discovery of a scalar particle compatible with a SM Higgs Boson" has made a phase transition into "precision measurements".

- We have considered the effects of spin 1 electroweak-TeV scale resonances on the Higgs phenomenology.

- We have shown the effects of such fields on the $H \to Z\gamma$ and $H \to \gamma\gamma$ decay rates .

- A very general framework for calculations of spin-1 contributions has been constructed, with application to arbitrary gauge extensions of the SM made possible via Mathematica files that have been made available online$

- We hope that the tools provided by us would be a valuable resource as we look for new physics in future runs of LHC.

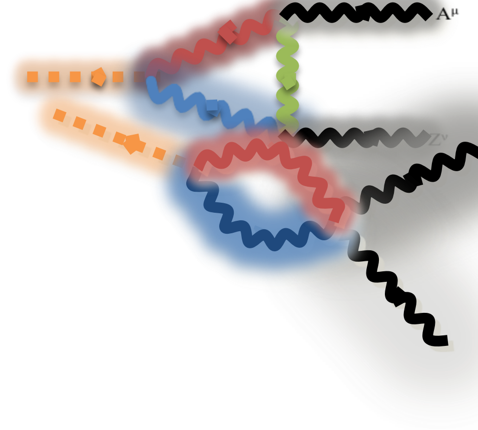
$http://www.phy.syr.edu/~jhubisz/HIGGSDECAYS/

Questions?

Thank You!


Backup

Limits on Zγ and γγ couplings



- Both $H \to \gamma\gamma$ *and* $H \to Z\gamma$ have small BR ; BR($H \to gg$) ≈ $6X10^{-2}$
- At m_H= 125 GeV

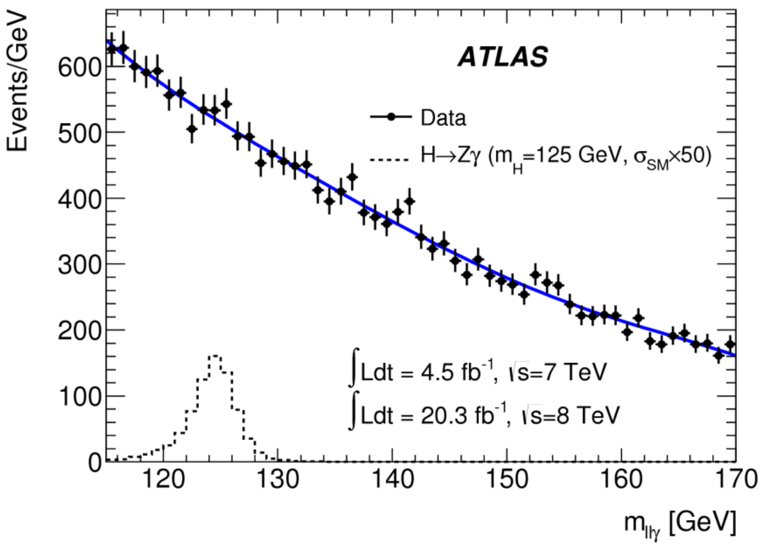
$$BR(H \to \gamma\gamma) = 2.3 \times 10^{-3}$$
$$BR(H \to Z\gamma) = 1.6 \times 10^{-3}$$

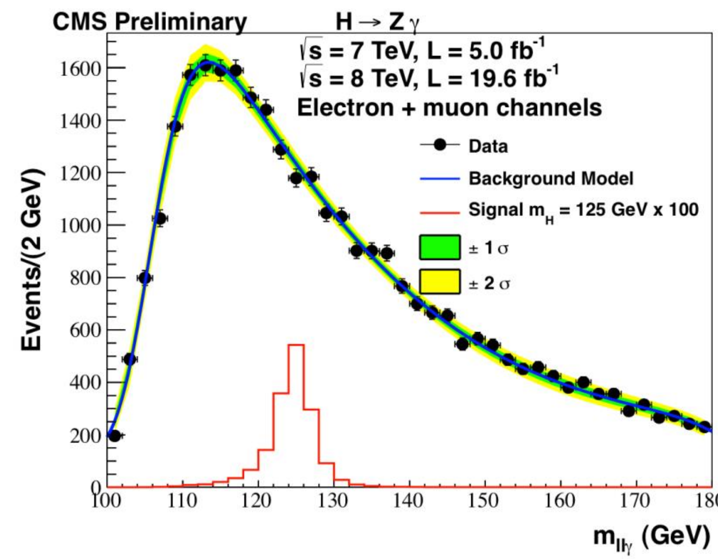
- Limits on $\kappa_{\gamma\gamma}$ κ_g, $\kappa_{Z\gamma}$ are set keeping all other tree-level couplings to be as SM.
- $\kappa_{\gamma\gamma}$, $\kappa_g \sim 1$, but $\kappa_{Z\gamma}$ has high uncertainties
- **Interesting for BSM scenarios**.

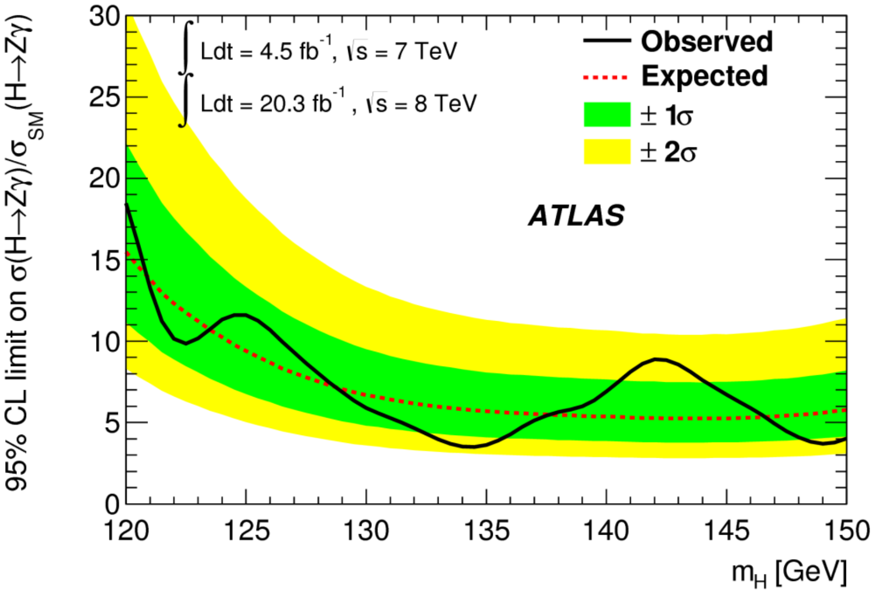
Results for H to Zγ

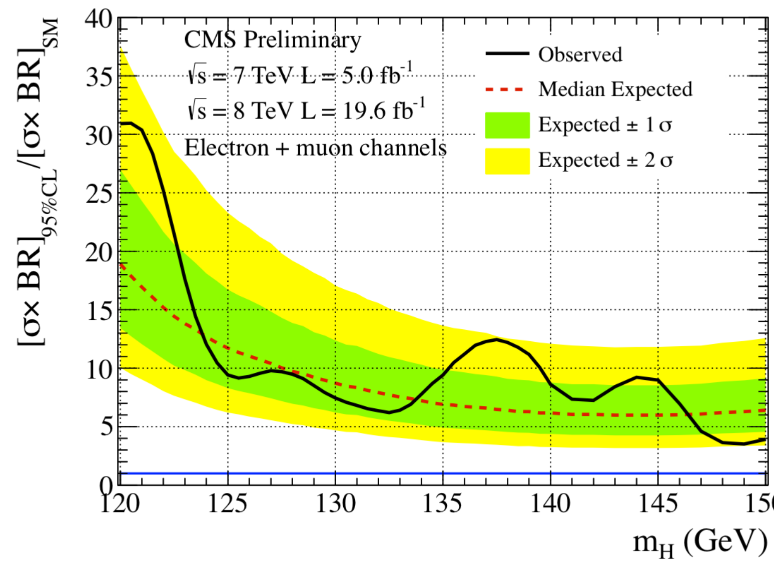
ATLAS

CMS

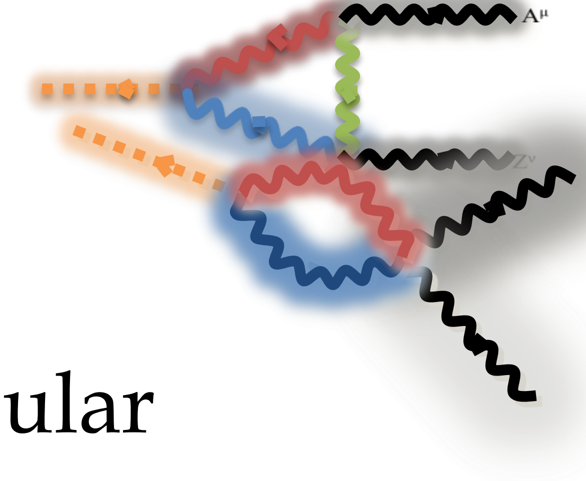








Higgs Decays



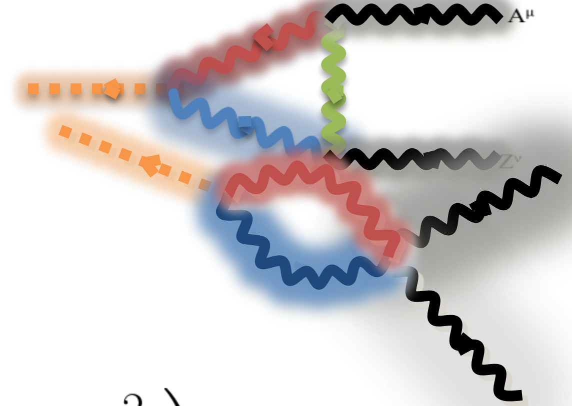
- Spin 1 resonances are of particular interest:
  - Decay width for h→γ γ:

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 g^2}{1024\pi^3}\frac{m_h^3}{m_W^2}\left|\sum_i N_{ci}\, e_i^2\, F_i\right|^2$$

For $m_{loop} \gg m_h$

$$\mathbf{F_1 \to 7\,, F_{1/2} \to -\frac{4}{3}\,, F_0 \to -\frac{1}{3}}$$

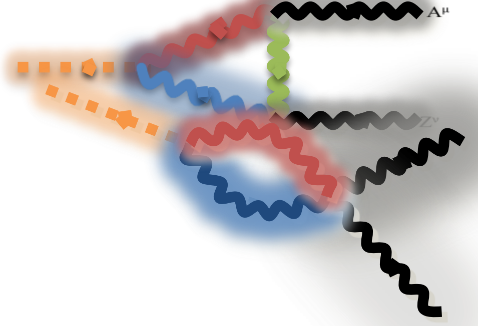
Higgs Decays



$$\Gamma(h \to Z\gamma) = \frac{\alpha^2 g^2}{512\pi^2 m_W^2} |\mathcal{A}_{\mathcal{F}} + \mathcal{A}_{\mathcal{W}}|^2 m_h^3 \left(1 - \frac{m_Z^2}{m_h^2}\right)$$

- For SM couplings spin one dominates spin half:

$$\boldsymbol{A_W \to -8, A_F \to 0.6}$$



- Gauge boson couplings are “anomalous”!
- Non-trivial Lorentz structure.

- Quartic interactions
  - With photon: constrained by gauge invariance to be

$$\boxed{e^2 = e_0^2\left(1 - \frac{2e_0^2(1+\epsilon)}{g_\rho^2} + \mathcal{O}(e_0^4/g_\rho^4)\right)}$$

  - With $Z\gamma$ there is “flavor” changing

- Cubic interactions:
  - Non-trivial couplings with photon
  - Interactions with Z are algebraically more complicated!

γW^+W^-	g_0	$e\left(1+\epsilon c_f^4\left(\frac{g}{g_\rho}\right)^2\right)$
	g_+	e
	g_-	e
$\gamma W^+\rho_A^-$	g_0	$e\epsilon c_f^2\sqrt{\frac{2}{1-\epsilon}}\left(\frac{g}{g_\rho}\right)$
$\gamma\rho_V^+\rho_V^-$	g_0	e
	g_+	e
	g_-	e
$\gamma\rho_V^+\rho_A^-$	g_0	$e\epsilon c_f^2\,(1+\epsilon)\sqrt{\frac{1+\epsilon}{1-\epsilon}}\frac{1}{2\left(\epsilon c_f^2+\frac{1}{2}(1+\epsilon)s_f^2\right)}\left(\frac{g}{g_\rho}\right)^2$
$\gamma\rho_A^+\rho_A^-$	g_0	$e\left(\frac{1+\epsilon}{1-\epsilon}-\epsilon c_f^4\left(\frac{g}{g_\rho}\right)^2\right)$
	g_+	e
	g_-	e

- We add a CP even U(1) singlet ``h” in a delocalized way, taking

$$f_l \to f_l\left(1 + \frac{a_l h}{f_l}\right)\ in\ L_{\Sigma-kin}$$ and

- Imposing L-R symmetry:

$$\mathcal{L}_{higgs} = h\left\{\underbrace{a_h\frac{f_1}{4}\mathrm{Tr}\left[\left|D_\mu\Sigma_{L1}\right|^2\right] + b_h\frac{f_2}{4}\mathrm{Tr}\left[\left|D_\mu\Sigma_{12}\right|^2\right] + a_h\frac{f_1}{4}\mathrm{Tr}\left[\left|D_\mu\Sigma_{2Y}\right|^2\right]}_{\text{Left – Right Symmetry(Custodial Symmetry)}}\right\}$$

Higgs interactions

hW^+W^-	$i\frac{2M_W^2}{v}\left(a_h\frac{s_f^3}{\sqrt{2}} + b_h c_f^3\right)$
$h\rho_V^+\rho_V^-$	$i\frac{\sqrt{2}M_\rho^2}{v}a_h s_f$
$h\rho_A^+\rho_A^-$	$i\frac{\sqrt{2}M_A^2}{v}s_f c_f\left(a_h c_f + \sqrt{2}b_h s_f\right)$
$hW^+\rho_A^-$	$i\frac{2M_W M_A}{v}s_f c_f\left(a_h\frac{s_f}{\sqrt{2}} - b_h c_f\right)$

$$c_f = \frac{f_1}{\sqrt{f_1^2 + 2f_2^2}} \qquad s_f = \frac{\sqrt{2}f_2}{\sqrt{f_1^2 + 2f_2^2}}$$

Loop level contributions to H →Z γ and H → γ γ

- Amplitudes are proportional to transverse tensor structure
- In lowest order in g/g$_\rho$ and in low energy limit ($m_{loop} \gg m_h$)

$$e^2\left(g^{\alpha_1\alpha_2}p_{\gamma^1}\cdot p_{\gamma^2} - p_{\gamma^1}^{\alpha_1}p_{\gamma^2}^{\alpha_2}\right)\mathcal{M}_{\gamma\gamma}$$

$$eg\cos\theta_w\left(g^{\alpha_1\alpha_2}p_Z\cdot p_\gamma - p_Z^{\alpha_1}p_\gamma^{\alpha_2}\right)\mathcal{M}_{Z\gamma}$$

- Where, $\mathcal{M}_{\gamma\gamma(Z\gamma)} \sim \epsilon(a_h f_2 - b_h f_1)\log\frac{\Lambda}{m_a}$ +finite term

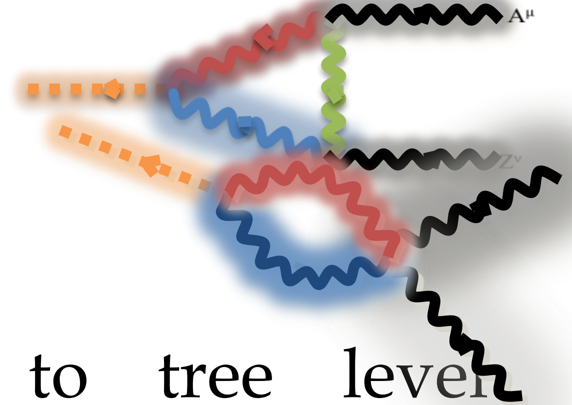
Divergent piece

- When WF mixing is turned off

$$\mathcal{M}_{\gamma\gamma} = \frac{7}{8\pi^2 f_1 f_2}(2a_h f_2 + b_h f_1)$$

$$\mathcal{M}_{Z\gamma} = \frac{7}{16\pi^2 f_1 f_2}\left[(2a_h f_2 + b_h f_1)\left(1-\tan^2\theta_w\right) + \left(a_h f_2 s_f^2 + b_h f_1 c_f^2\right)\left(1+\tan^2\theta_w\right)\right]$$

Tree level contribution to $H \rightarrow Z\gamma$ and $H \rightarrow \gamma\gamma$



- Strong coupling effects can lead to tree level contributions to $hZ\gamma$ and $h\gamma\gamma$.
- Such terms act as counter terms to the divergences in the loop amplitudes
- The tree level L-R symmetric Lagrangian before spontaneous breaking in EFT formalism is

$$\frac{c}{4\Lambda} h \left[(\rho_1^{\mu\nu\ a})^2 + (\rho_2^{\mu\nu\ a})^2 \right] + \frac{c_\epsilon}{2\Lambda} h \mathrm{Tr} \left[\rho_{1\ \mu\nu} \Sigma_{12} \rho_2^{\mu\nu} \Sigma_{12}^\dagger \right]$$

- In mass basis later this reduces to

$$\frac{(c + c_\epsilon)}{2\Lambda} \frac{eg\cos\theta_w}{g_\rho^2} \left(1 - \tan^2\theta_w\right) hZ_{\mu\nu}A^{\mu\nu} + \frac{(c + c_\epsilon)}{2\Lambda} \frac{e^2}{g_\rho^2} hA_{\mu\nu}A^{\mu\nu}$$

Electroweak Parameters†

• Left right symmetry in the model ensures that "tree- level" contribution to T parameter is zero.

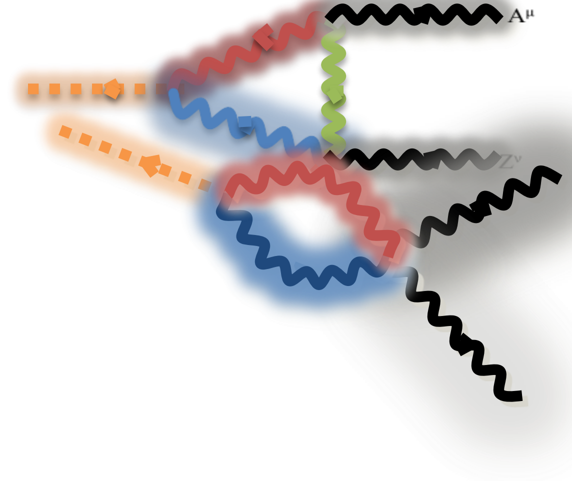
• S parameter is non-zero. And can be evaluated after integrating out the heavy resonances viz. axial and ρ vector.

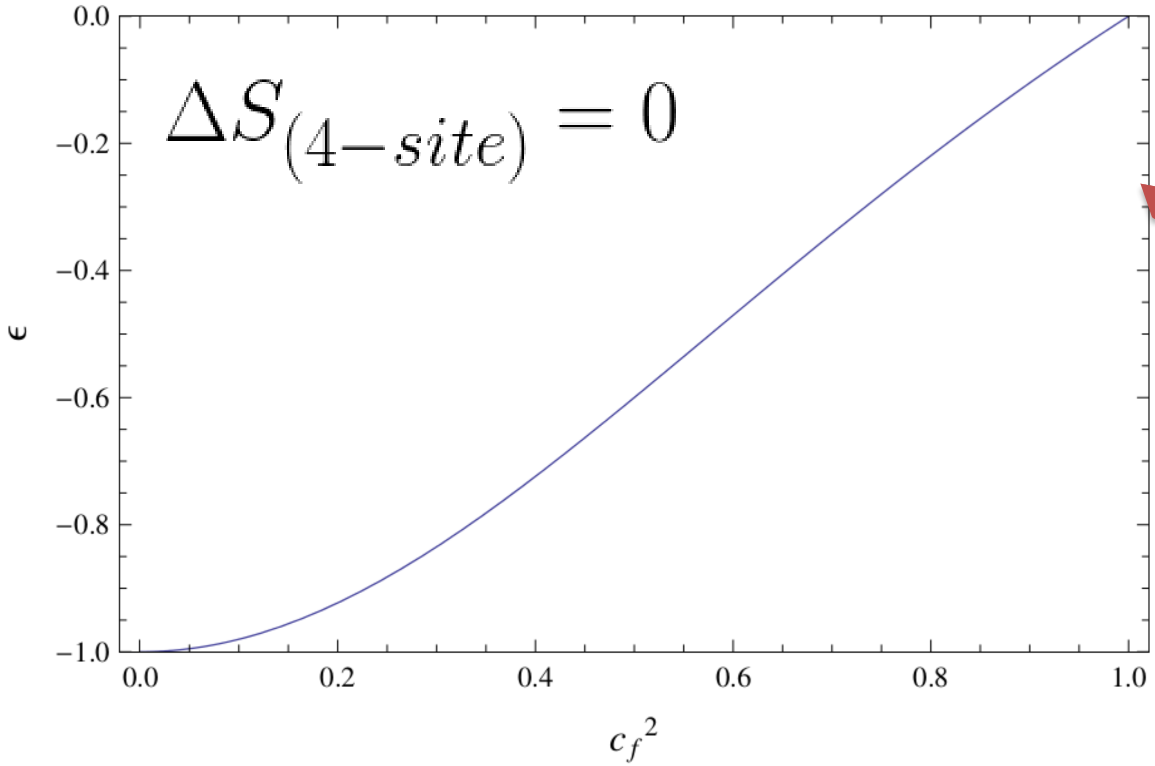
$$\Delta S \approx \frac{2\sin^2\theta_w}{\alpha}\frac{g^2}{g_\rho^2}(1+\epsilon)\left(1 - c_f^4\frac{1-\epsilon}{1+\epsilon}\right)$$
$$\approx \frac{4\sin^2\theta_w}{\alpha s_f^2}\frac{M_W^2}{M_\rho^2}\left(1 - c_f^2\frac{M_\rho^2}{M_A^2}\right).$$

• S vanishes when $\varepsilon \to -\frac{2(f_2^4 + f_1^2 f_2^2)}{f_1^4 + 2 f_1^2 f_2^2 + 2 f_2^4}$

† Phys. Rev. Lett. 65 (1990) 964

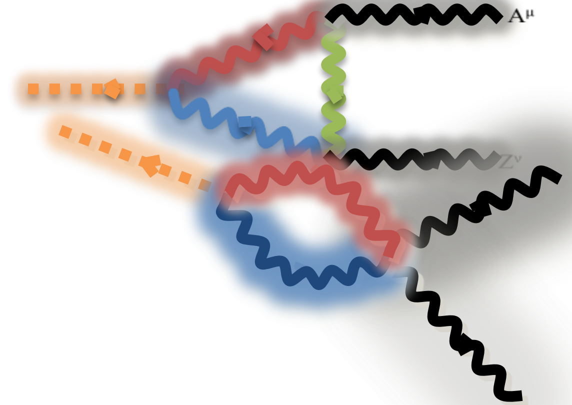
Results





Large $c_f \implies f_1 \to \infty$
vector and axial vector decouple

Mass spectrum



- The spin-1 masses are

$$m^2_{Z^{ph}} \simeq \frac{f_1^2 f_2^2 \left(g_L^2 + g_y^2\right)}{4\left(f_1^2 + 2f_2^2\right)} \qquad m^2_{W^{ph}} \simeq \frac{f_1^2 f_2^2 g_L^2}{4\left(f_1^2 + 2f_2^2\right)}$$

$$m_\rho^2 \simeq \frac{g_\rho^2 f_1^2}{4}\,, m_a^2 \simeq \frac{g_\rho^2(f_1^2 + 2f_2^2)}{4}.$$

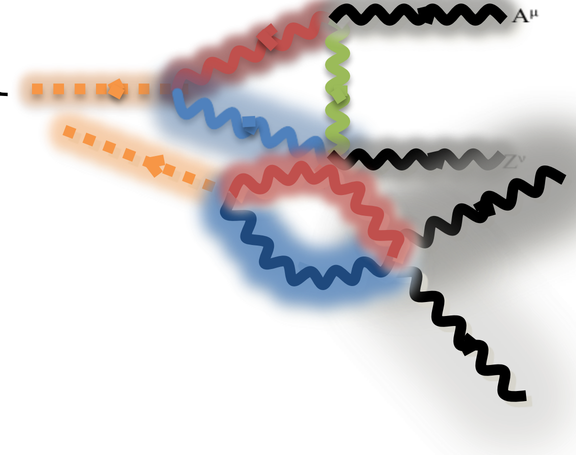
- So naively, axial vectors are heavier than rho vector

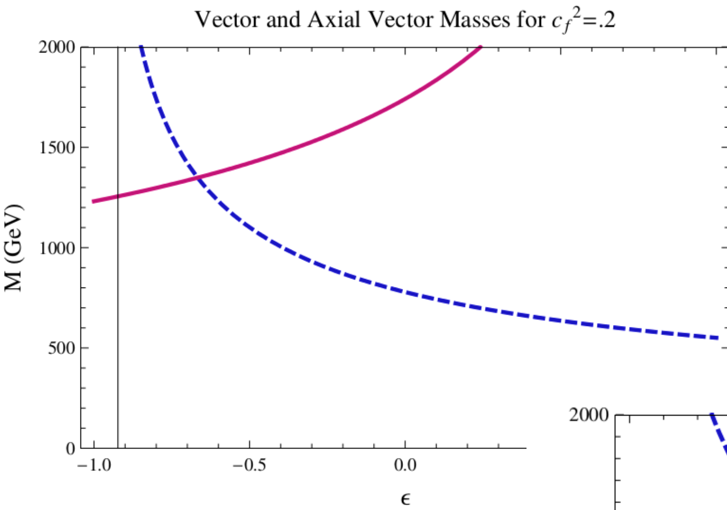
- But with the wavefunction mixing modifies them

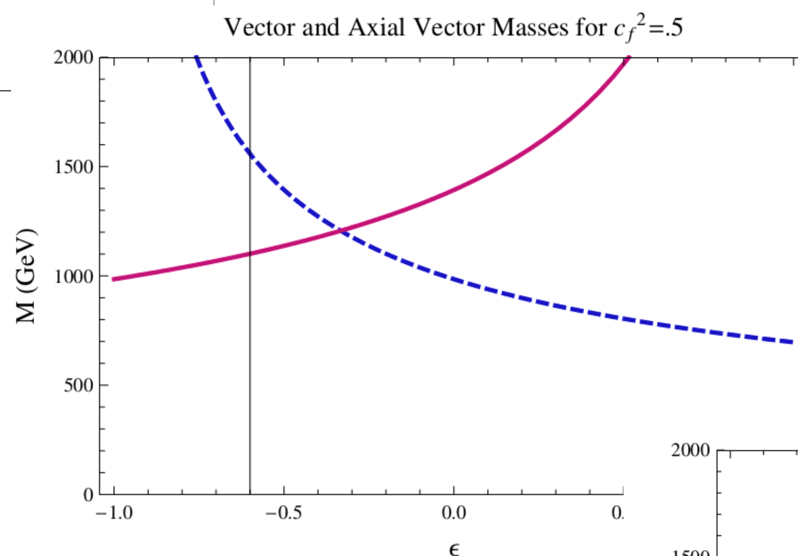
$$m^2_{a^\pm} \simeq \frac{\left(f_1^2 + 2f_2^2\right) g^2}{4(1-\epsilon)} + \frac{f_1^4 g_L^2}{8\left(f_1^2 + 2f_2^2\right)} \qquad m^2_{\rho^\pm} \simeq \frac{f_1^2 g^2}{4(\epsilon+1)} + \frac{1}{8} f_1^2 g_L^2$$

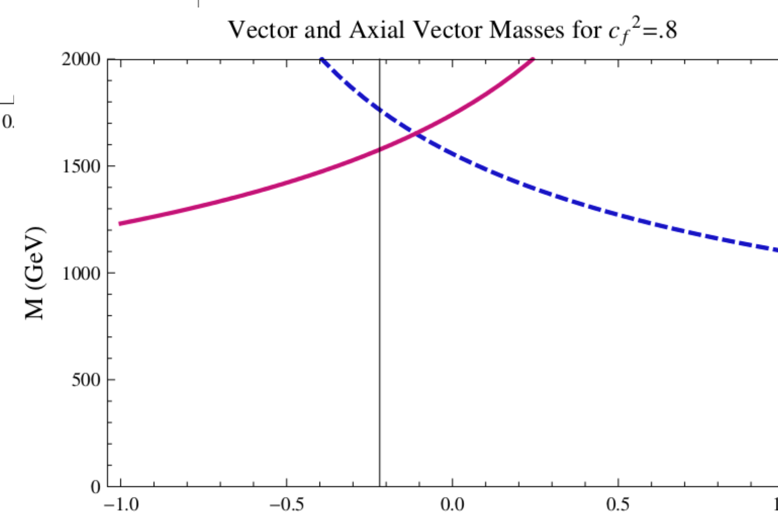
- For O(1) negative values of ε, normal hierarchy between vector Axial vectors is inverted, and S=0

Inverted spectrum









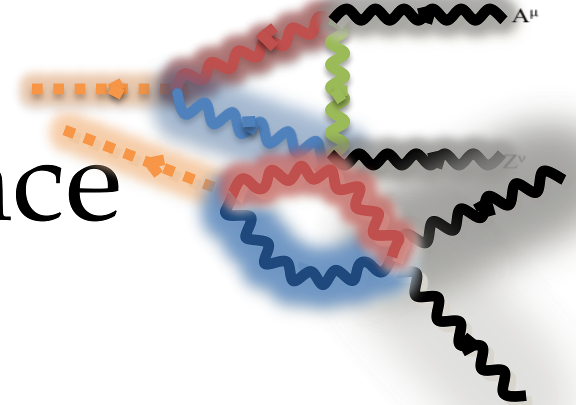
$g_\rho = 4$

M_A

M_ρ

$S = 0$

Choosing a parameter space

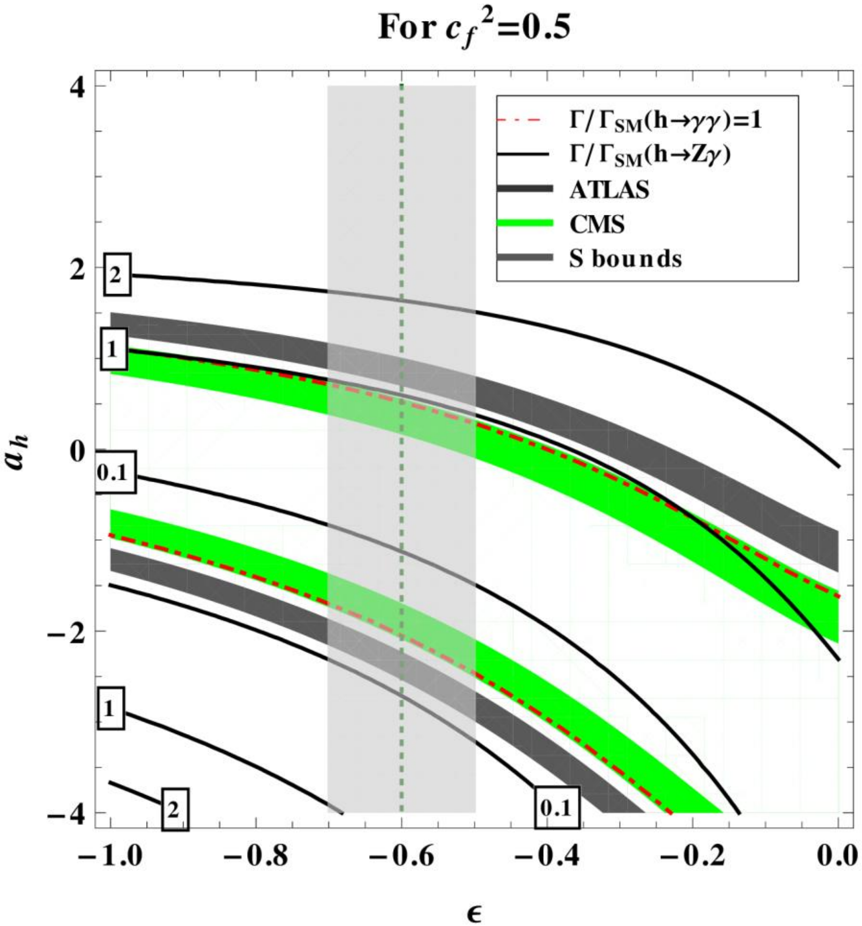


We fix the physical values such that

- $v = \dfrac{f_1 f_2}{\sqrt{f_1^2 + 2f_2^2}}$, with $v \equiv 246\ GeV.$ → fix f_1 or f_2
- $M_W \approx \dfrac{g_L v}{2} = 80.4\ \text{GeV}$
- $e^2 \approx e_0^2 \left(1 - \dfrac{2e_0^2\,(1+\epsilon)}{g_\rho^2}\right)$ where $e_0 \approx \dfrac{g_L g_Y}{\sqrt{g_Y^2 + g_L^2}}$
- $\dfrac{g_{hVV}}{g_{hVV}^{\text{SM}}} = a_h \dfrac{s_f^3}{\sqrt{2}} + b_h c_f^3 \approx 1$ → eliminate b_h and vary a_h

Decay rates

- This figure displays the ratio of the higgs partial widths to the hZγ and hγγ final states in relation to the expectation in the SM.
- The figures represent the scenario where direct contributions from higher dimensional operators are neglected.
- Loop diagrams from the vector and axial vector states are taken into account.



Decay rates(with higher dimensional operators)