Strongly interacting $W_L W_L$, $Z_L Z_L$ and *hh* from unitarized chiral lagrangians

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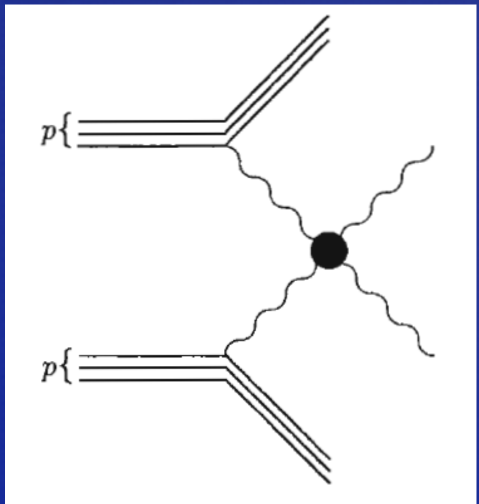
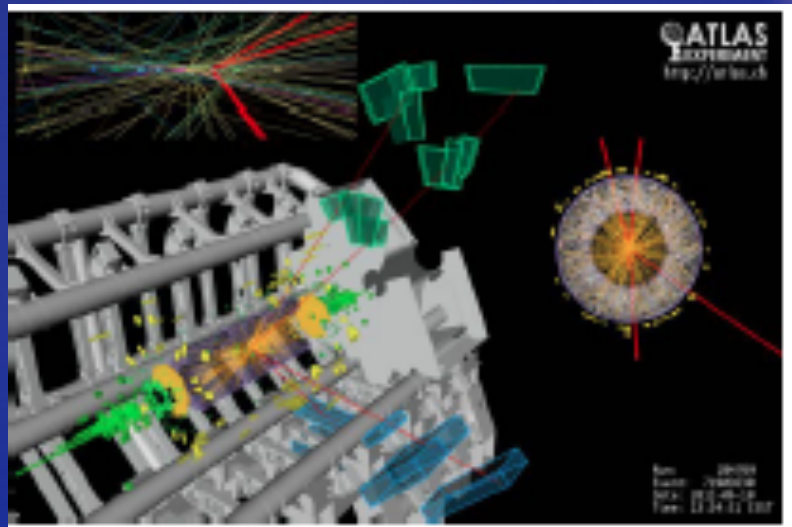




Physics Challenges in the face of LHC-14
September 25th 2014

Work done in collaboration with R. Delgado, M.J. Herrero, F. Llanes-Estrada and J.J. Sanz-Cillero

Outline

I. Experimental results (properties of the new boson)

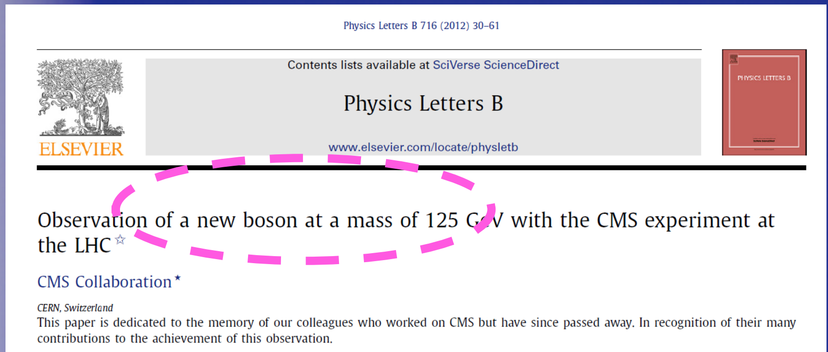
II. The case for a Strongly Interacting EWSBS

III. One-loop computations and the IAM method

IV. Conclusions

I. Experimental results (new-boson properties)

What do we really know about the new neutral boson, discovered by ATLAS and CMS and confirmed by CDF and D0?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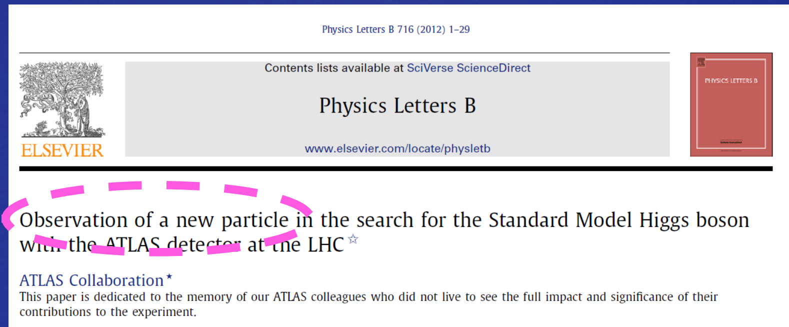
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *
CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.


Physics Letters B 716 (2012) 1–29
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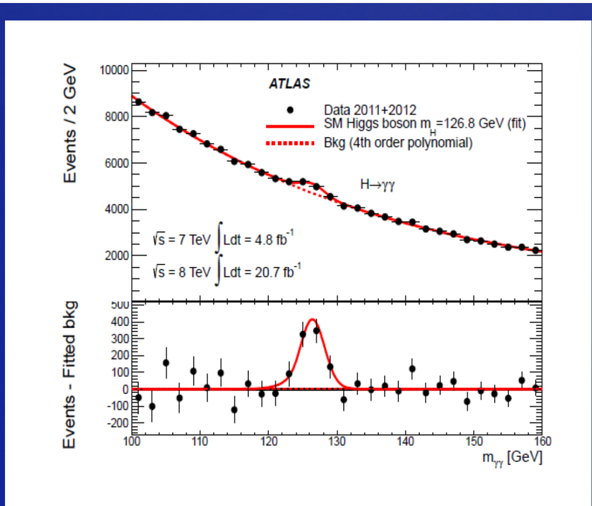
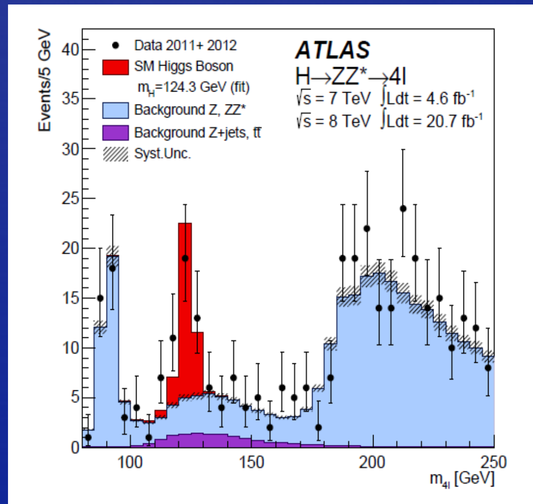
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

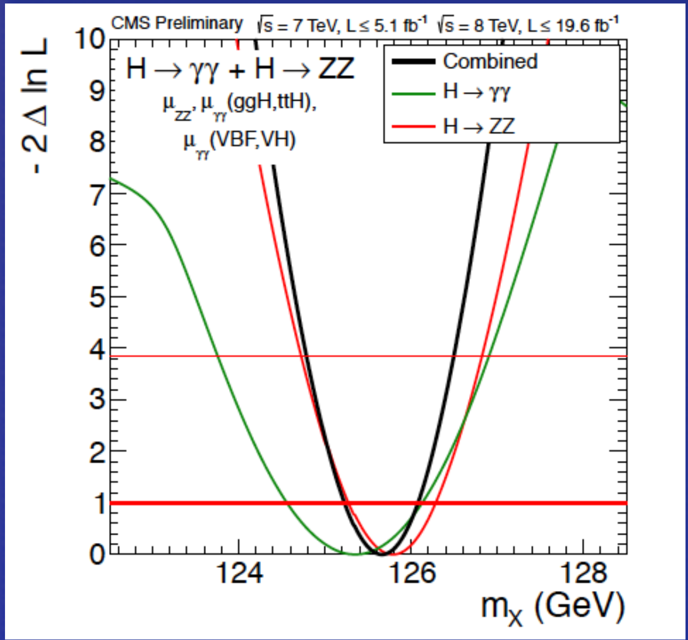
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

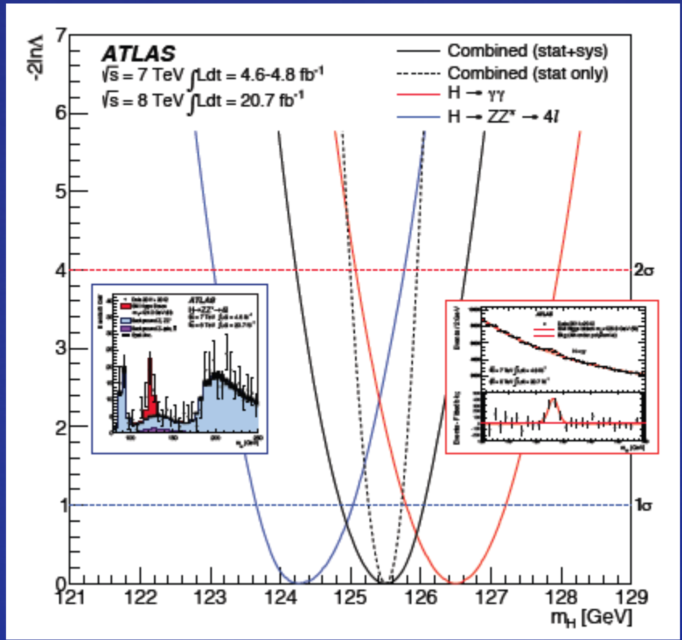




First seen in diphoton events and then confirmed in ZZ → 4 lepton events

Mass:





$$m_X = 125.7 \pm 0.3\,(\text{stat.}) \pm 0.3\,(\text{syst.})\ \text{GeV}$$

ATLAS: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

Width: $\Gamma_h < 17.4$ MeV

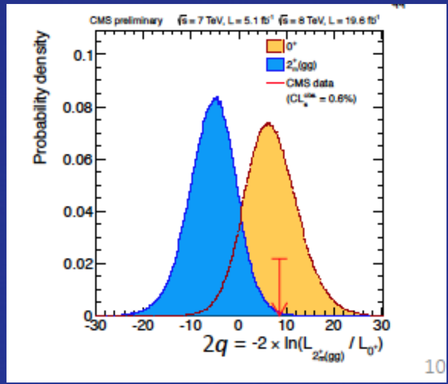
4.2 times MSM value!

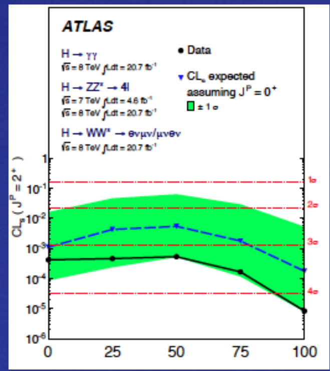
(CMS preliminar)

Spin:

On-shell X(J=1) $\not\to$ γγ by Landau-Yang theorem

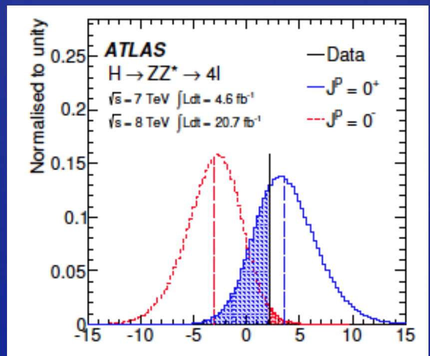
Angular distributions of the decay products are sensible to the resonance spin:

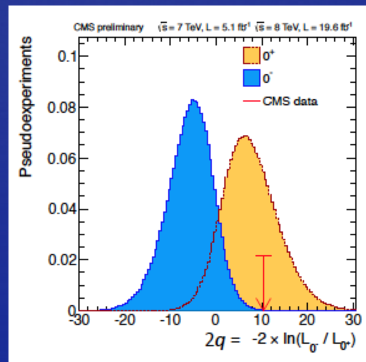




Both ATLAS and CMS exclude a J=2 resonance to 99.4% confidence level and are compatible with a J=0 resonance.

Parity:





ATLAS and CMS exclude a pseudo scalar $J^P=0^-$ versus 0^+ (scalar) at the 97.8% and 99.8% CL respectively. CMS and D0 support this results. Alternatives to $J^P=0^+$ versus 0^+ all together are excluded to the 95% CL.

Thus we have ONE new SCALAR resonance at *125.5 GeV: h(125)*

Observed decays at ATLAS, CMS and Tevatron

Signal Strengths

$$\mu \equiv \sigma \cdot \mathrm{Br}/(\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}})$$

Decay Mode	ATLAS	CMS	Tevatron
$H \to bb$	$0.2^{+0.7}_{-0.6}$	1.15 ± 0.62	$1.59^{+0.69}_{-0.72}$
$H \to \tau\tau$	$0.7^{+0.7}_{-0.6}$	1.10 ± 0.41	$1.68^{+2.28}_{-1.68}$
$H \to \gamma\gamma$	$1.55^{+0.33}_{-0.28}$	0.77 ± 0.27	$5.97^{+3.39}_{-3.12}$
$H \to WW^*$	$0.99^{+0.31}_{-0.28}$	0.68 ± 0.20	$0.94^{+0.85}_{-0.83}$
$H \to ZZ^*$	$1.43^{+0.40}_{-0.35}$	0.92 ± 0.28	
Combined	1.23 ± 0.18	0.80 ± 0.14	$1.44^{+0.59}_{-0.56}$

Couplings

Primary bosonic

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

Primary fermionic

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2 \qquad \frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

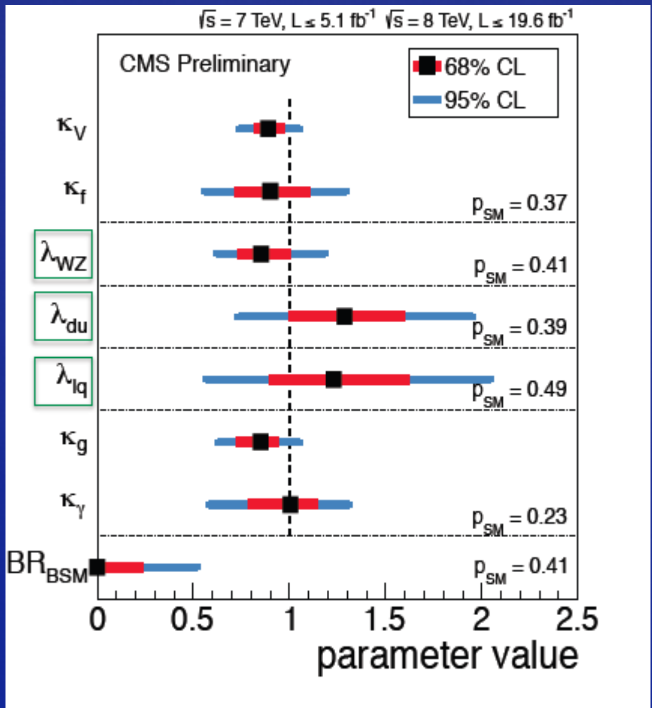
$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

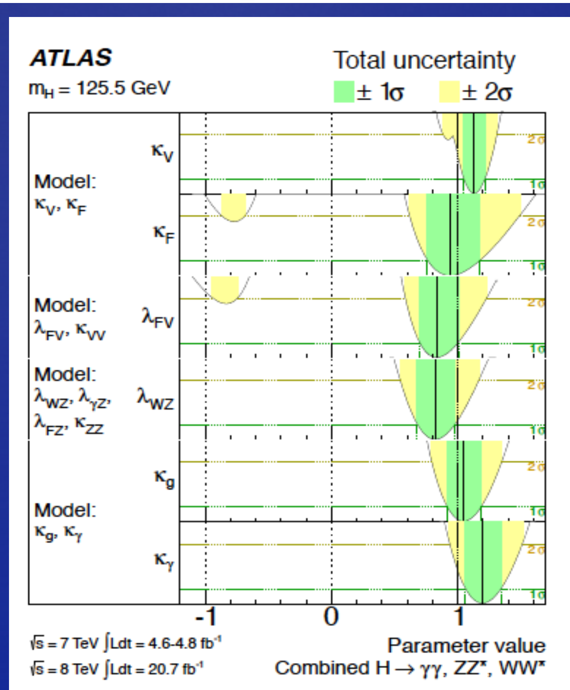
Secundary bosonic

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

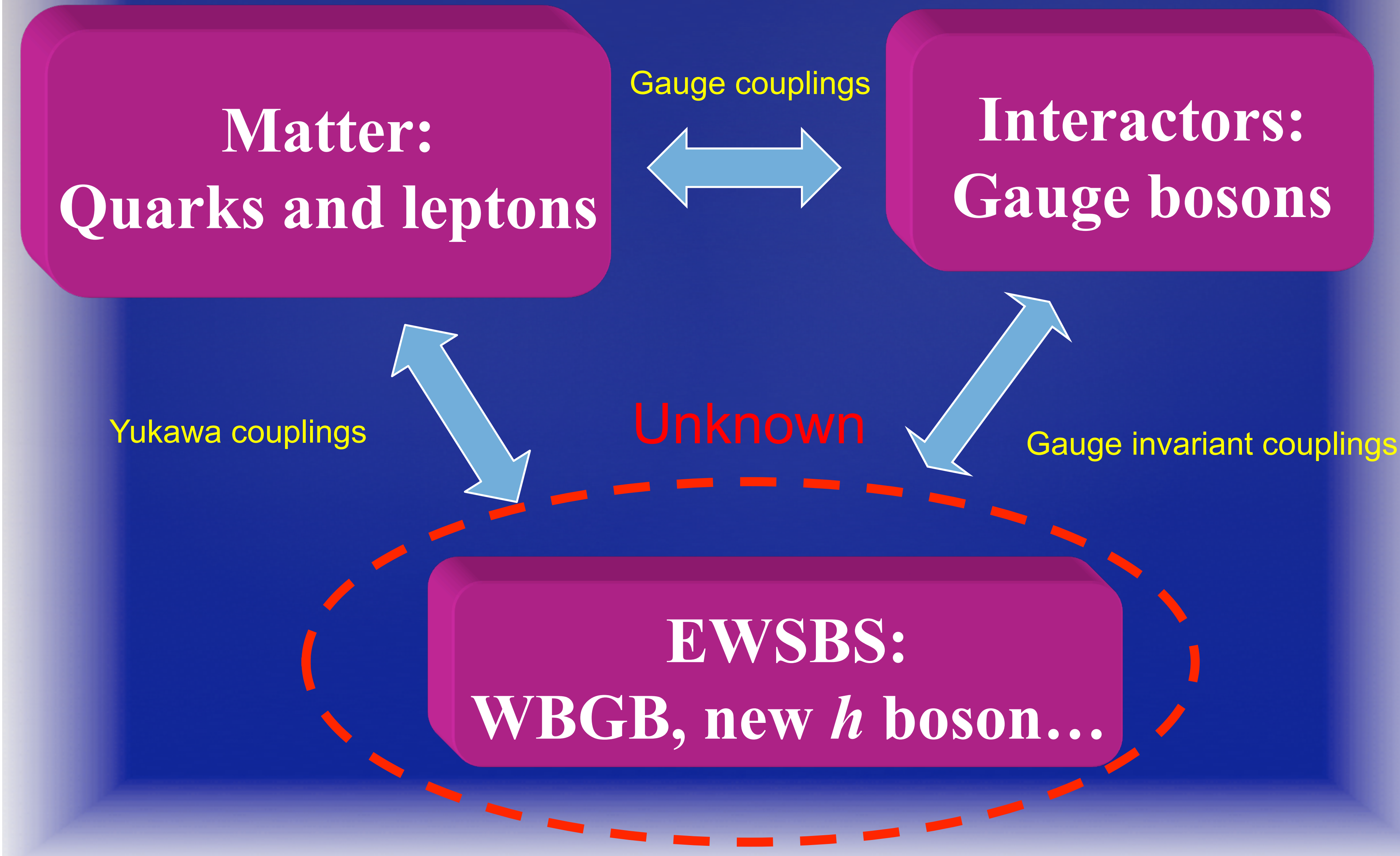
$$\kappa^2_{\gamma\gamma} = (1.6\,\kappa^2_W + 0.07\,\kappa^2_t - 0.67\,\kappa_W\kappa_t)$$

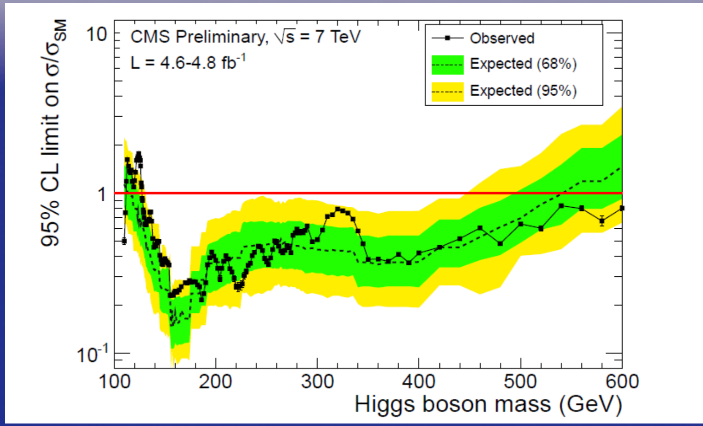


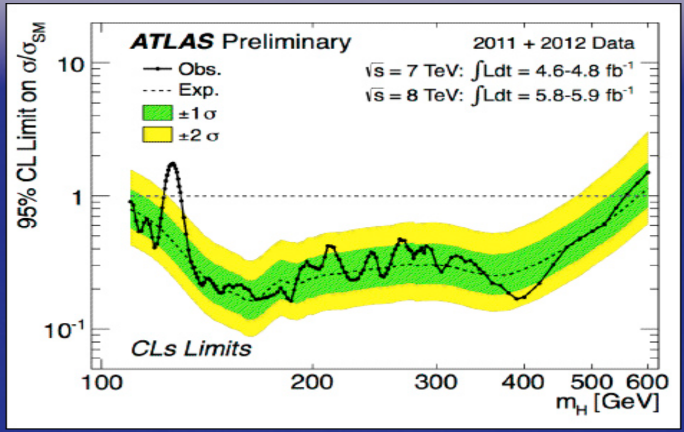


- ATLAS: κ_g =(1.04 ± 0.14) at 68% CL - κ_γ = (1.20 ± 0.15) at 68% CL
- CMS: κ_g [0.63,1.05] at 95% CL - κ_γ [0.59,1.30] at 95% CL

The Standard Model Structure

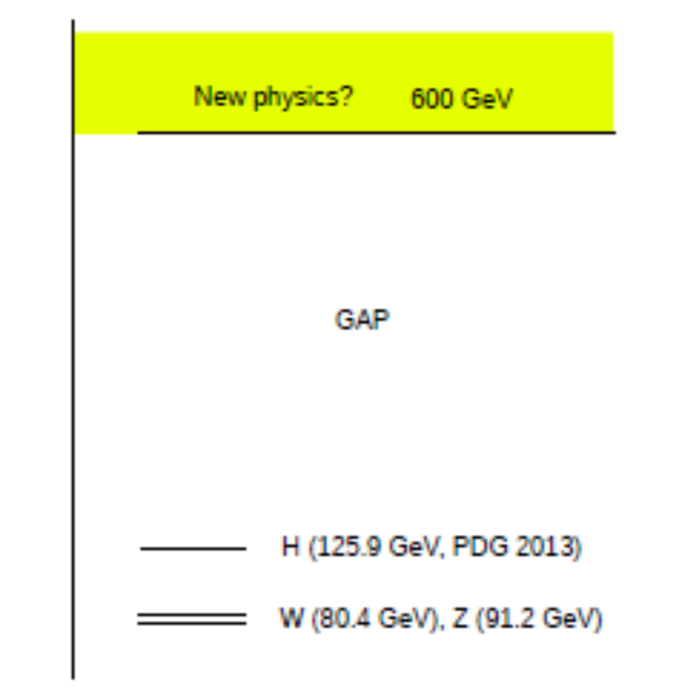






Thus we have ONE and only ONE new SCALAR resonance at 125.5 GeV

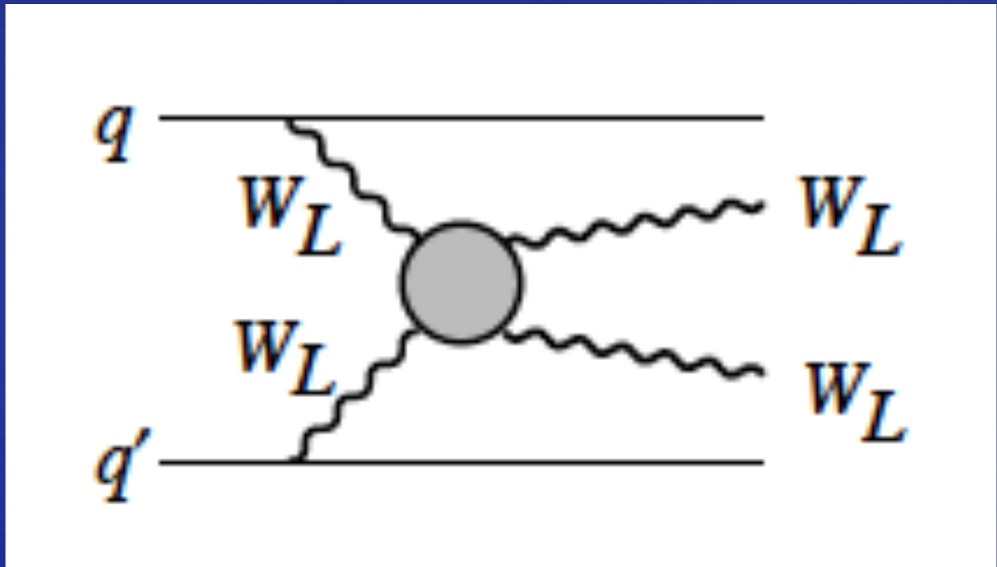
Nothing new up to 600 GeV ⇒ BIG GAP from 125 GeV to 600 GeV



The first conclusions after looking at the experimental data is that the new scalar resonance is compatible with the SM Higgs, hence the name of Higgs-like resonance.

However, in there is a lot of room for other possibilities, in particular a strongly interacting scenario for the EWSBS (compositeness, low modes as Goldstone bosons).

II. The case for a Strongly Interacting EWSBS



For describing the physics of the SBS of the SM beyond the MSM at low energies we have to include the 3 WBGB w^a + one Higgs-like light scalar h. There are at least two possibilities:

Linear representation:

The w^a and the h fits in a left $SU(2)$ doublet

The Higgs always appear in the combination: $(h + v)$

Higher symmetry

Typical situation when h is a fundamental field

ET based in a cutoff expansion: $O(d)/L^{d-4}$ (d=operator dimension, $d=4,6,8\ldots$)

Non-linear representation:

h is a $SU(2)$ singlet and w^a are coordinates on a $SU(2)\ X\ SU(2)/SU(2)=SU(2)=S^3$ coset

Lesser symmetry and more independent higher dimension effective operators

Derivative expansion

ECLh with $F(h)$ insertions

Appropriate for composite models of the SBS (h as a GB)

Strongly interacting and consistent with the presence of the GAP

A program for the study a Strongly Interacting Scenario for the SBS at the LHC

The only modes at low energies (< 600 GeV) are the WBGB and the Higgs-like particle (most probably composite GB of some highier spontaneously broken symmetry with *dim(G/H)=4*)

Built an appropriate low-energy Effective Lagrangian (ECLh with a Higgs-like particle).

Apply the Equivalence Theorem (go to high energies to decople gauge bosons)

Compute the relevant scattering amplitudes at tree level and at the one-loop level (orders s and s^2) ($\gamma\gamma \rightarrow VV$, $VV \rightarrow VV$, $VV \rightarrow hh$, $hh \rightarrow hh$…)

Unitarize the amplitudes by using dispersion relations to extrapolate to higher energies (generate resonances dynamically)

Study the properties of the emerging resonances in terms of the low-energy couplings (make predictions for other processes)

Compare with next years LHC results when possible with more realistic computations (not using the ET or the Equivalent-W approximation, include other radiative corrections, the top quark, QCD corrections… to make the results realistic for comparison with data (MC))

The main ingredients of our phenomenological Lagrangian are Gauge Bosons, Quarks, Leptons and concerning the EWSBS:

I) Scalar degrees of freedom: 3 WBGB w^a + one Higgs-like light scalar h and nothing else because of the above mentioned BIG GAP.

II) Custodial Symmetry: in the limit $g=g'=\lambda_{YK}=0$ the EWSBS suffers a spontaneous breaking from some global group G to $H_C=SU(2)_{L+R}$.

This is the case of the MSM but more generally it is supported by the Electroweak Precision Data:

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

MSM at the tree level

$$T = 0.05 \pm 0.12$$

and also by the LHC data:

$$\kappa_W \simeq \kappa_Z \simeq \kappa_V$$

LO Lagrangian

Therefore, our effective lagrangian for the EWSBS at low-energy is a gauged NLSM based in the coset:

$$SU(2)_L \times SU(2)_R / SU(2)_C = SU(2) \simeq S^3$$

$$\mathcal{L}_0 = \frac{v^2}{4}\mathcal{F}(h)(D_\mu U)^\dagger D^\mu U + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + ..$$

(Gauged) NLSM

U = WBGB Fields (GB or pions)

$$D_\mu U = \partial_\mu U + W_\mu U - UY_\mu$$

$SU(2)_L \times U(1)_Y$ Covariant derivatives

$$V(h) = \sum_{n=0}^{\infty} V_n h^n \equiv V_0 + \frac{1}{2}M_h^2 h^2 + d_3 \frac{M_h^2}{2v} h^3 + d_4 \frac{M_h^2}{8v^2} h^4 + \ldots$$

Potential

Interesting particular cases:

The Minimal Standar Model: $a = b = c = c_i = d_i = 1$ $\quad f = v$ $\quad a_i = 0$

Linear, renormalizable, unitary, predictor and weakly interacting

No Higgs Model

$f = v$ $\quad a = b = c = 0$ → Old ECL

Minimal Dilaton Model $\quad h = \varphi$ $\quad f \neq v$ $\quad$ New scale f

$$V(\varphi) = \frac{M_\varphi^2}{4f^2}(\varphi + f)^2 \left[\log\left(1 + \frac{\varphi}{f}\right) - \frac{1}{4}\right]$$

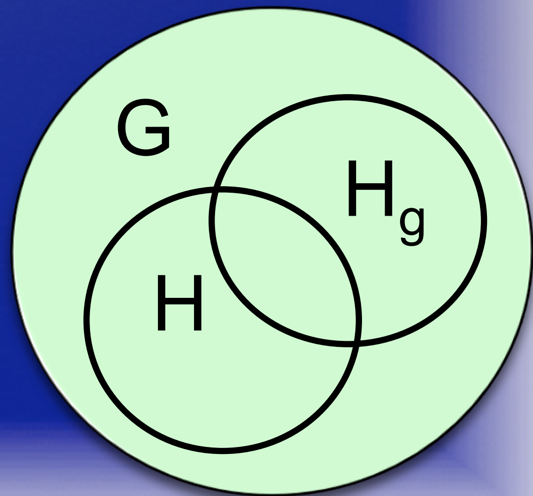
$$a^2 = b = \frac{v^2}{\hat{f}^2}$$

Halyo, Goldberber, Grinstein, Skiba

Minimal Composite Higgs Model

$SO(5)/SO(4)$ →

MCHM4	MCHM5
$a = \sqrt{1-\xi}$	$a = \sqrt{1-\xi}$
$b = 1 - 2\xi$	$b = 1 - 2\xi$
$c = \sqrt{1-\xi}$	$c = \frac{1-2\xi}{\sqrt{1-\xi}}$
$d_3 = \sqrt{1-\xi}$	$d_3 = \frac{1-2\xi}{\sqrt{1-\xi}}$

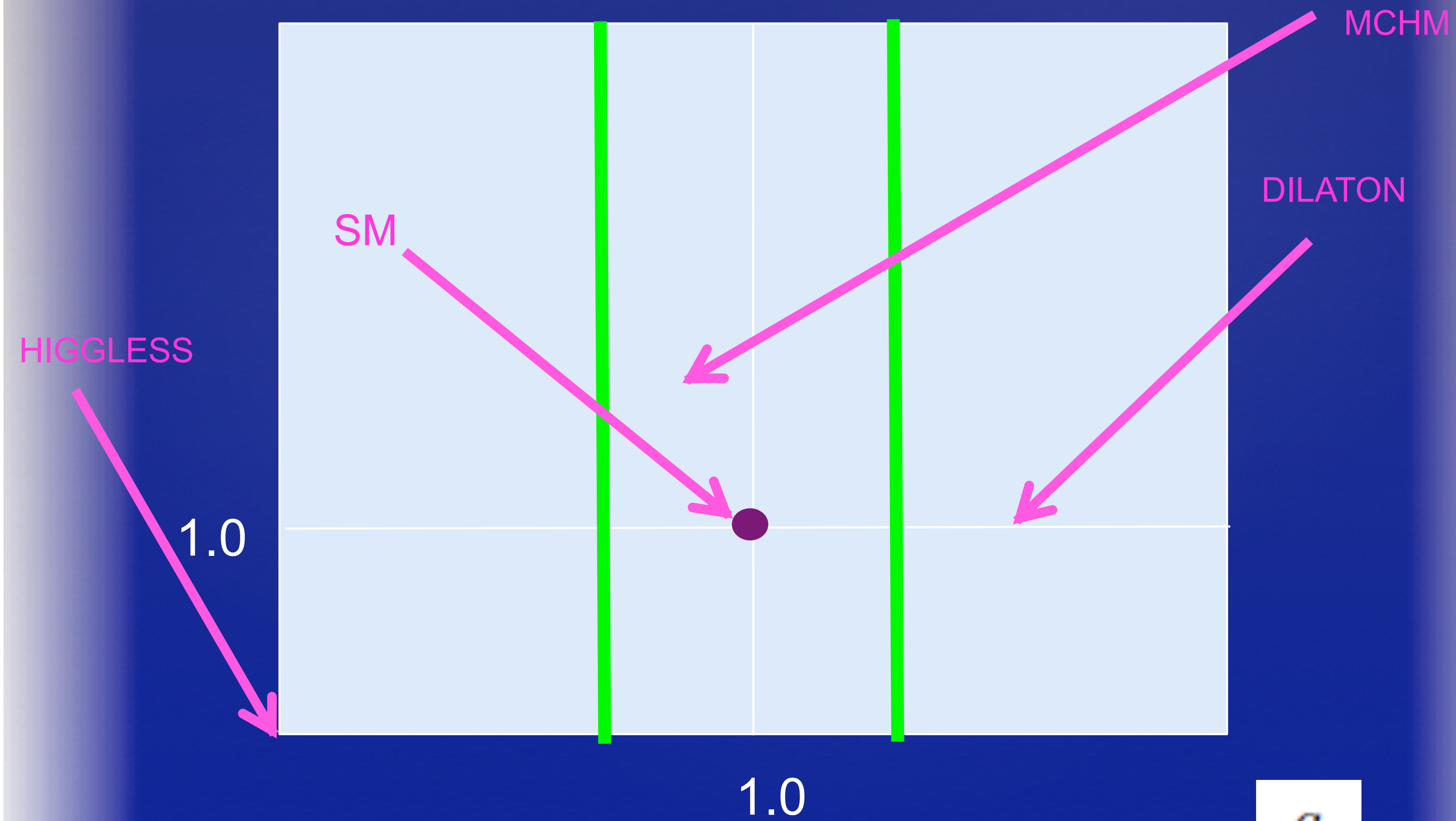


$f \neq v$ $\quad \xi = v^2/f^2$ $\quad \sin\theta = \sqrt{\xi}$

Kaplan, Georgi

Agashe, Contino, Pomarol, Da Rold

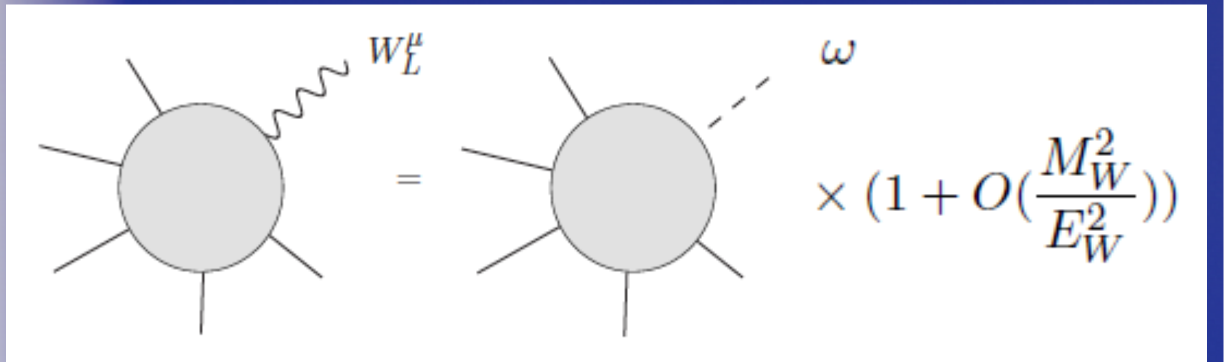
$$\beta = b/\xi = b\frac{v^2}{f^2}$$



a

The EWSBS dynamics could be studied at the LHC through the High Energy Longitudinal Electroweak Boson Scattering

The Equivalence Theorem (for R gauges)



$$T(\omega^a \omega^b \to \omega^c \omega^d) = T(W_L^a W_L^b \to W_L^c W_L^d) + O(\frac{M_W}{\sqrt{s}})$$

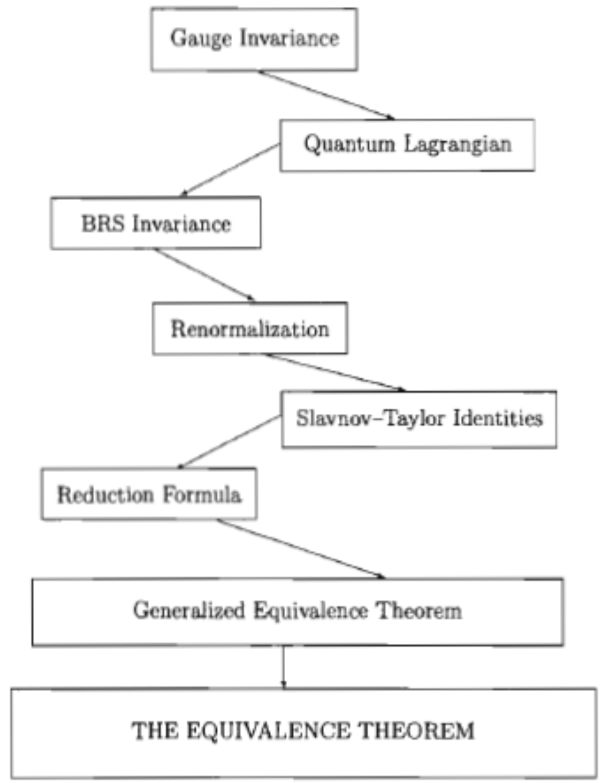
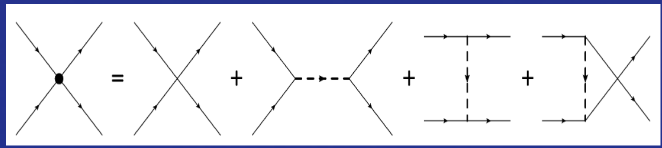


Fig. 7.3. The proof of the equivalence theorem

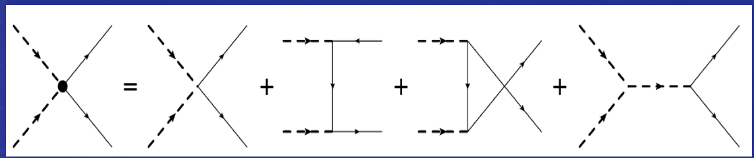
At high energies the LCGB could become strongly interacting and the TC decouple from the LC which become Goldstone Bosons

LO amplitudes:

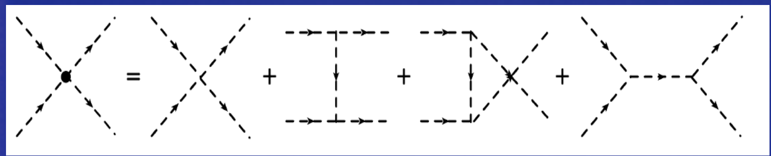
$M_h = 0$ $\quad$ $M_h^2 \ll s < 4\pi v \simeq 3\,\mathrm{TeV}.$



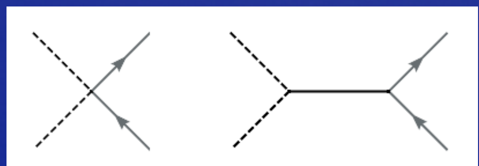
$$T(\omega^+\omega^- \to \omega^+\omega^-) = \frac{s+t}{v^2}(1-a^2)$$



$$T(\omega^a\omega^b \to hh) = \frac{s}{v^2}(a^2-b)\delta_{ab}$$



$$T(hh \to hh) = 0$$



$$T(\omega^a\omega^b \to t_L\bar{t}_R) = \frac{M_t}{v^2}(1-ac)\sqrt{s-4M_t^2}\delta_{ab}$$

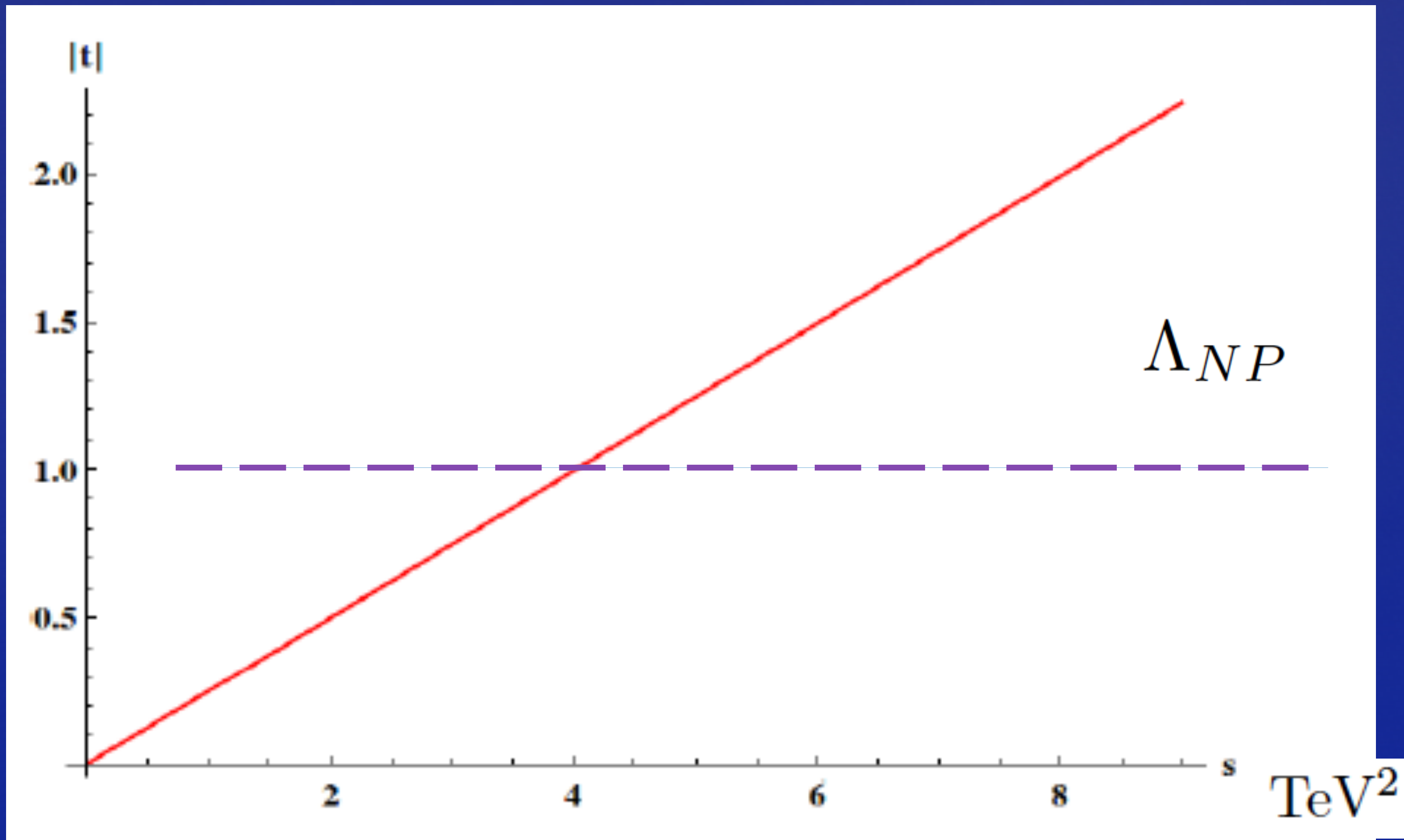
Those are the generalization of the Weinberg low-energy theorems for pion scattering
The amplitudes generically grow with the energy and then they violate unitarity at some new physics scale:

The only exception occurs for *a = b= c =1* which is the case of the MSM

Contino, Grojean, Moretti, Piccinini, Ratazzi

$$\Lambda_{NP}$$

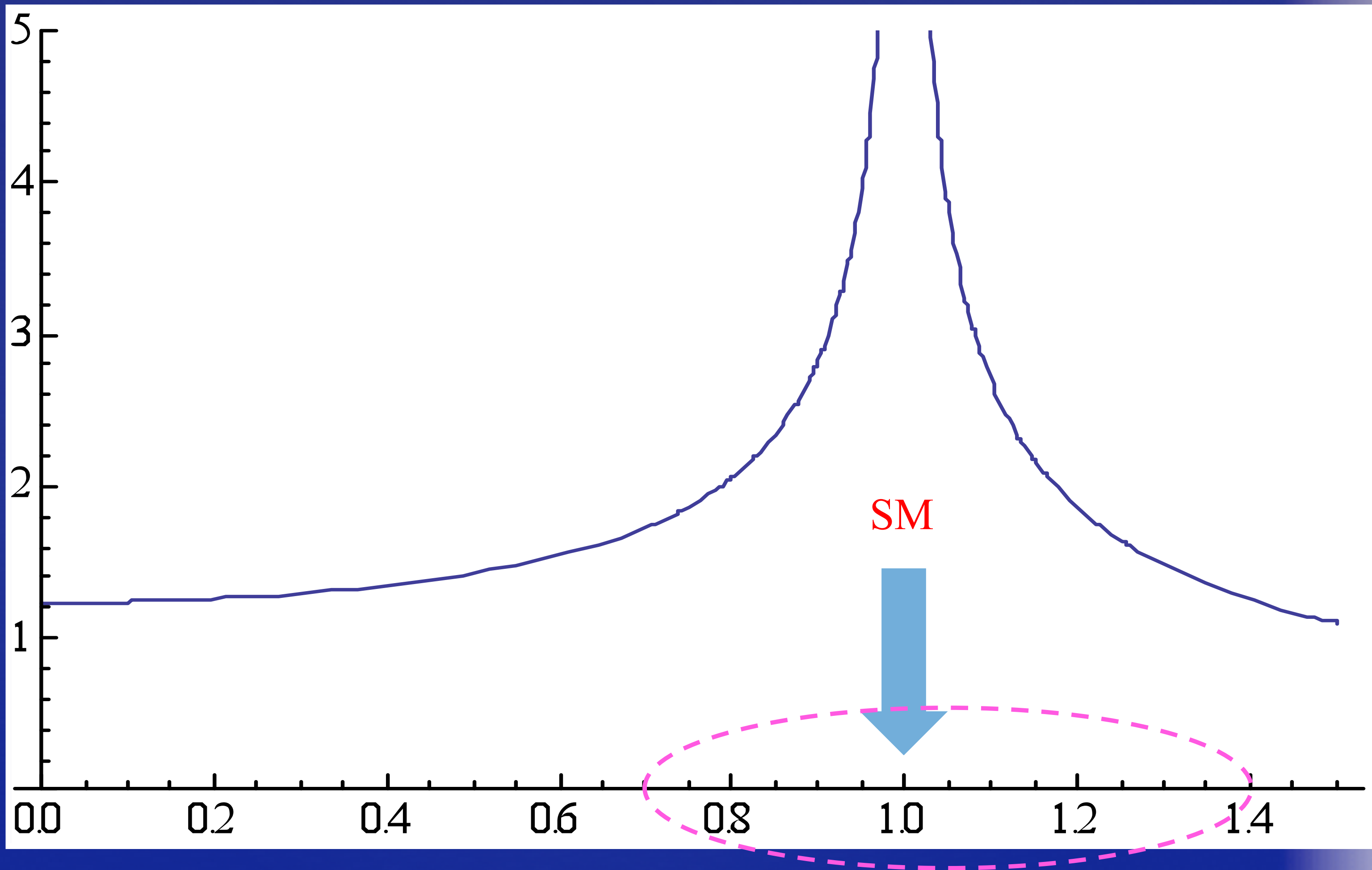
All of these amplitudes violate badly unitarity at some point



New physics scale:

Λ_{NP}

TeV



$$a \simeq \kappa_W \simeq \kappa_Z \simeq \kappa_V$$

LO ECLh (2 derivatives)

$$\mathcal{L}_2 = -\frac{1}{2g^2}\mathrm{Tr}(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}) - \frac{1}{2g'^2}\mathrm{Tr}(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}) + \frac{v^2}{4}\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right]\mathrm{Tr}(D^\mu U^\dagger D_\mu U) + \frac{1}{2}\partial^\mu h\,\partial_\mu h + \dots$$

NLO ECLh (4 derivatives)

Apelquist-Longhitano

$$a_1\mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger\hat{W}^{\mu\nu}) + ia_2\mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger[V^\mu,V^\nu]) - ia_3\mathrm{Tr}(\hat{W}_{\mu\nu}[V^\mu,V^\nu]) + a_4\left[\mathrm{Tr}(V_\mu V_\nu)\right]\left[\mathrm{Tr}(V^\mu V^\nu)\right] + a_5\left[\mathrm{Tr}(V_\mu V^\mu)\right]\left[\mathrm{Tr}(V_\nu V^\nu)\right] + \dots,$$

Additional terms including h and its derivatives (4 operators more)

One loop LO and NLO are the same order

It is not consistent to use the NLO ECLh without LO one-loop corrections!

NLO-Lagrangian

(extended Apelquist-Longhitano to include the h)

$$\mathscr{L}^h_{\chi=4} = -\frac{g_s^2}{4} G^a_{\mu\nu} G^{\mu\nu}_a \mathcal{F}_G(h) - \frac{g^2}{4} W^a_{\mu\nu} W^{\mu\nu}_a \mathcal{F}_W(h) - \frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h) + + \xi \sum_{i=1}^{5} c_i \mathcal{P}_i(h) + \xi^2 \sum_{i=6}^{20} c_i \mathcal{P}_i(h) + \xi^3 \sum_{i=21}^{23} c_i \mathcal{P}_i(h) + \xi^4 c_{24} \mathcal{P}_{24}(h)\,,$$

$$\begin{aligned}
\mathcal{P}_1(h) &= g\,g'\,B_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\,W^{\mu\nu}\right) \mathcal{F}_1(h)\\
\mathcal{P}_2(h) &= i\,g'\,B_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\,[\mathbf{V}^\mu, \mathbf{V}^\nu]\right) \mathcal{F}_2(h)\\
\mathcal{P}_3(h) &= i\,g\,\mathrm{Tr}\left(W_{\mu\nu}\,[\mathbf{V}^\mu, \mathbf{V}^\nu]\right) \mathcal{F}_3(h)\\
\mathcal{P}_4(h) &= i\,g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\,\partial^\nu \mathcal{F}_4(h)\\
\mathcal{P}_5(h) &= i\,g\,\mathrm{Tr}(W_{\mu\nu} \mathbf{V}^\mu)\,\partial^\nu \mathcal{F}_5(h)\\
\mathcal{P}_6(h) &= \left(\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right)\right)^2 \mathcal{F}_6(h)\\
\mathcal{P}_7(h) &= \left(\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}_\nu\right)\right)^2 \mathcal{F}_7(h)\\
\mathcal{P}_8(h) &= g^2 \left(\mathrm{Tr}\left(\mathbf{T}\,W^{\mu\nu}\right)\right)^2 \mathcal{F}_8(h)\\
\mathcal{P}_9(h) &= i\,g\,\mathrm{Tr}\left(\mathbf{T}\,W_{\mu\nu}\right) \mathrm{Tr}\left(\mathbf{T}\,[\mathbf{V}^\mu, \mathbf{V}^\nu]\right) \mathcal{F}_9(h)\\
\mathcal{P}_{10}(h) &= g\,\epsilon^{\mu\nu\rho\lambda} \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{V}_\nu\,W_{\rho\lambda}\right) \mathcal{F}_{10}(h)\\
\mathcal{P}_{11}(h) &= \mathrm{Tr}\left((\mathcal{D}_\mu \mathbf{V}^\mu)^2\right) \mathcal{F}_{11}(h)\\
\mathcal{P}_{12}(h) &= \mathrm{Tr}(\mathbf{T}\,\mathcal{D}_\mu \mathbf{V}^\mu)\,\mathrm{Tr}(\mathbf{T}\,\mathcal{D}_\nu \mathbf{V}^\nu)\,\mathcal{F}_{12}(h)
\end{aligned}$$

$$\begin{aligned}
\mathcal{P}_{13}(h) &= \mathrm{Tr}([\mathbf{T}\,, \mathbf{V}_\nu]\,\mathcal{D}_\mu \mathbf{V}^\mu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\,\mathcal{F}_{13}(h)\\
\mathcal{P}_{14}(h) &= i\,g\,\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\,\partial^\nu \mathcal{F}_{14}(h)\\
\mathcal{P}_{15}(h) &= \mathrm{Tr}(\mathbf{T}\,[\mathbf{V}_\mu, \mathbf{V}_\nu])\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\,\partial^\nu \mathcal{F}_{15}(h)\\
\mathcal{P}_{16}(h) &= \mathrm{Tr}(\mathbf{V}_\nu\,\mathcal{D}_\mu \mathbf{V}^\mu)\,\partial^\nu \mathcal{F}_{16}(h)\\
\mathcal{P}_{17}(h) &= \mathrm{Tr}(\mathbf{T}\,\mathcal{D}_\mu \mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\,\partial^\nu \mathcal{F}_{17}(h)\\
\mathcal{P}_{18}(h) &= \mathrm{Tr}\left(\mathbf{V}_\mu\,\mathbf{V}^\mu\right)\,\partial_\nu \partial^\nu \mathcal{F}_{18}(h)\\
\mathcal{P}_{19}(h) &= \mathrm{Tr}\left(\mathbf{V}_\mu\,\mathbf{V}_\nu\right)\,\partial^\mu \mathcal{F}_{19}(h) \partial^\nu \mathcal{F}'_{19}(h)\\
\mathcal{P}_{20}(h) &= \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right)\,\partial^\mu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)\\
\mathcal{P}_{21}(h) &= \mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right) \left(\mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right)\right)^2 \mathcal{F}_{21}(h)\\
\mathcal{P}_{22}(h) &= \mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}_\nu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^\nu\right) \mathcal{F}_{22}(h)\\
\mathcal{P}_{23}(h) &= \left(\mathrm{Tr}\left(\mathbf{T}\,\mathbf{V}_\mu\right)\right)^2 \partial_\nu \partial^\nu \mathcal{F}_{23}(h)\\
\mathcal{P}_{24}(h) &= \left(\mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right) \mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\nu\right)\right)^2 \mathcal{F}_{24}(h)\,.
\end{aligned}$$

Alonso, Gavela, Merlo, Rigolin and Yepes

The low-energy Effective Lagrangian for $W_L W_L$, $Z_L Z_L$ and hh one-loop scattering

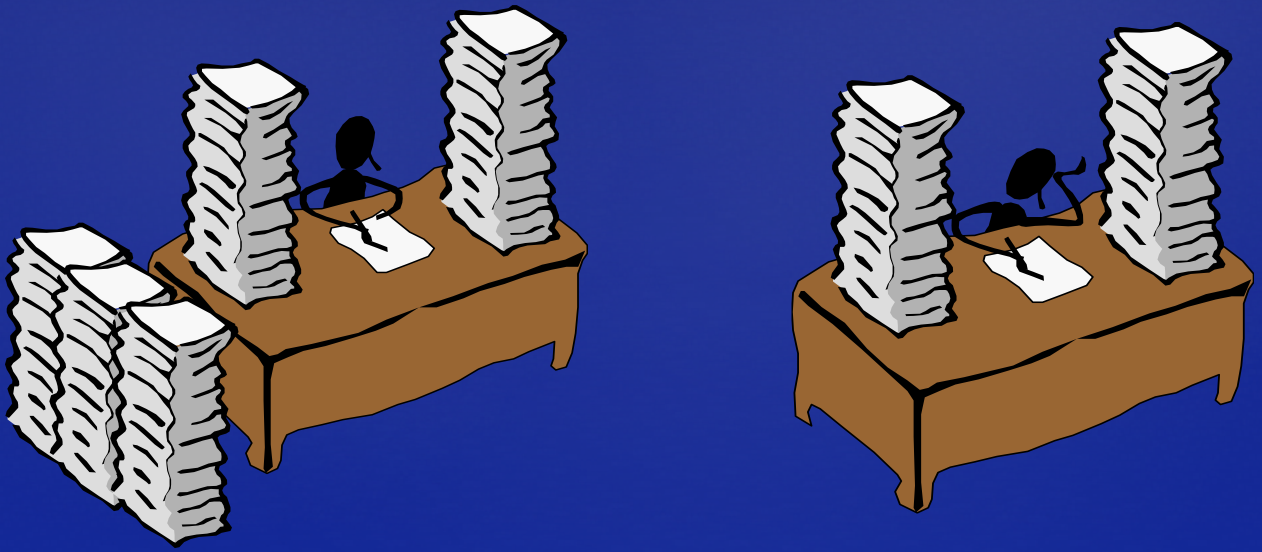
$$M_W^2, M_Z^2, M_h^2 << s << \Lambda^2$$

$$g = g' = H_{YK} = 0$$

$$\mathcal{L} = \frac{1}{2}\left(1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2\right)\partial_\mu\omega^a\partial^\mu\omega^b\left(\delta_{ab} + \frac{\omega^a\omega^b}{v^2}\right) + \frac{1}{2}\partial_\mu h\partial^\mu h$$
$$+ \frac{4a_4}{v^4}\partial_\mu\omega^a\partial_\nu\omega^a\partial^\mu\omega^b\partial^\nu\omega^b + \frac{4a_5}{v^4}\partial_\mu\omega^a\partial^\mu\omega^a\partial_\nu\omega^b\partial^\nu\omega^b + \frac{\gamma}{f^4}(\partial_\mu h\partial^\mu h)^2$$
$$+ \frac{2\delta}{v^2 f^2}\partial_\mu h\partial^\mu h\partial_\nu\omega^a\partial^\nu\omega^a + \frac{2\eta}{v^2 f^2}\partial_\mu h\partial^\nu h\partial^\mu\omega^a\partial_\nu\omega^a.$$

$$U(x) = \sqrt{1 - \frac{\omega^2}{v^2}} + i\frac{\tilde{\omega}}{v}$$

III. One-loop computation and the IAM method



Electroweak Chiral Perturbation Theory with a light Higgs-like boson up to one-loop for :

VV → VV, VV → hh, hh → hh, γγ → VV…   (V=W, Z)

Equivalence Theorem

Landau Gauge (massless WBGB and no ghosts at this level)

No fermions and g=g'=0 (custodial isospin)

Dimensional regularization

MS scheme for the NLO derivative couplings bellow
(no other renormalization is needed for vanishing *h* mass)

$$\mathcal{L}_4 = a_4(trV_\mu V_\nu)^2 + a_5(trV_\mu V^\mu)^2 \qquad V_\mu = D_\mu U U^\dagger$$

$$+\frac{\gamma}{v^4}(\partial_\mu h \partial^\mu h)^2 + \frac{\delta}{v^2}(\partial_\mu h \partial^\mu h) tr(D_\nu U)^\dagger D^\nu U + \frac{\eta}{v^2}(\partial_\mu h \partial^\nu h) tr(D^\mu U)^\dagger D_\nu U + \ldots$$

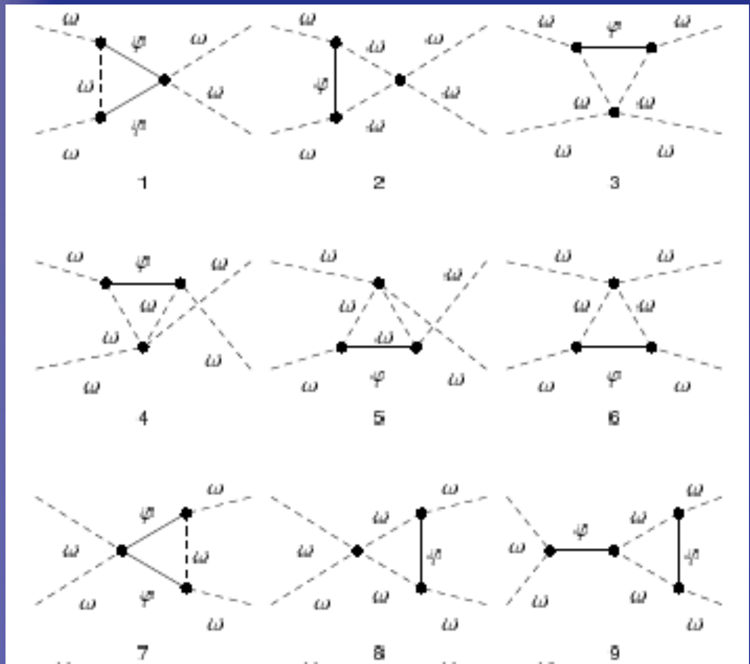
$$+\, a_1 \mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger \hat{W}^{\mu\nu}) + i a_2 \mathrm{Tr}(U\hat{B}_{\mu\nu}U^\dagger[V^\mu, V^\nu]) - i a_3 \mathrm{Tr}(\hat{W}_{\mu\nu}[V^\mu, V^\nu]) - \frac{c_\gamma}{2}\frac{h}{v}e^2 A_{\mu\nu}A^{\mu\nu}$$

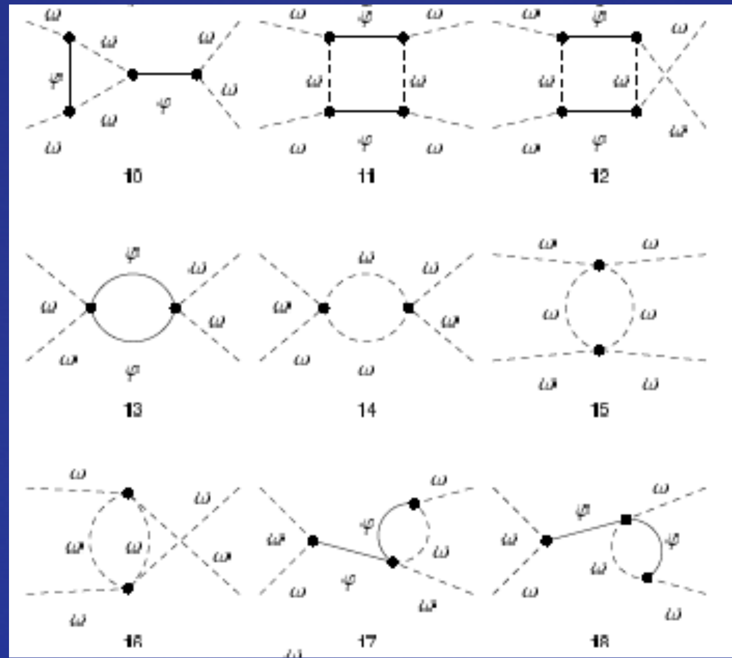
FeynRules: Generates Feynman rules from the Lagrangian. as an output produces the input for FeynArts.

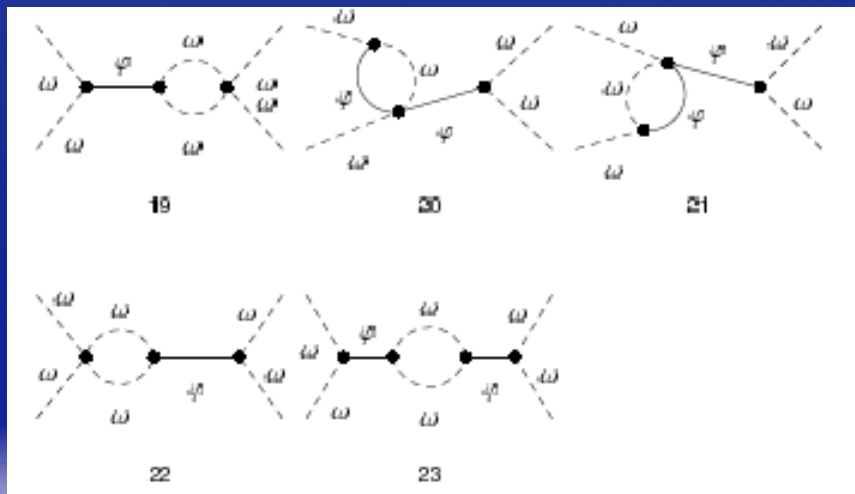
FeynArts: Obtains the Feynman diagrams to some given order. Introduces ”symbolically” the vertices generated by FeynRules.

FormCalc: Simplifies the output by FeynArts and generates an analytical output (and also a FORTRAN output for MC)

One-loop Feynman diagrams for $\omega_a \omega_b \to \omega_c \omega_d$







Electroweak Chiral Perturbation Theory with a light Higgs-like scalar up to one-loop

$\omega\ \omega \Longrightarrow \omega\ \omega$ (elastic scattering)

$$\omega_a\omega_b \to \omega_c\omega_d$$

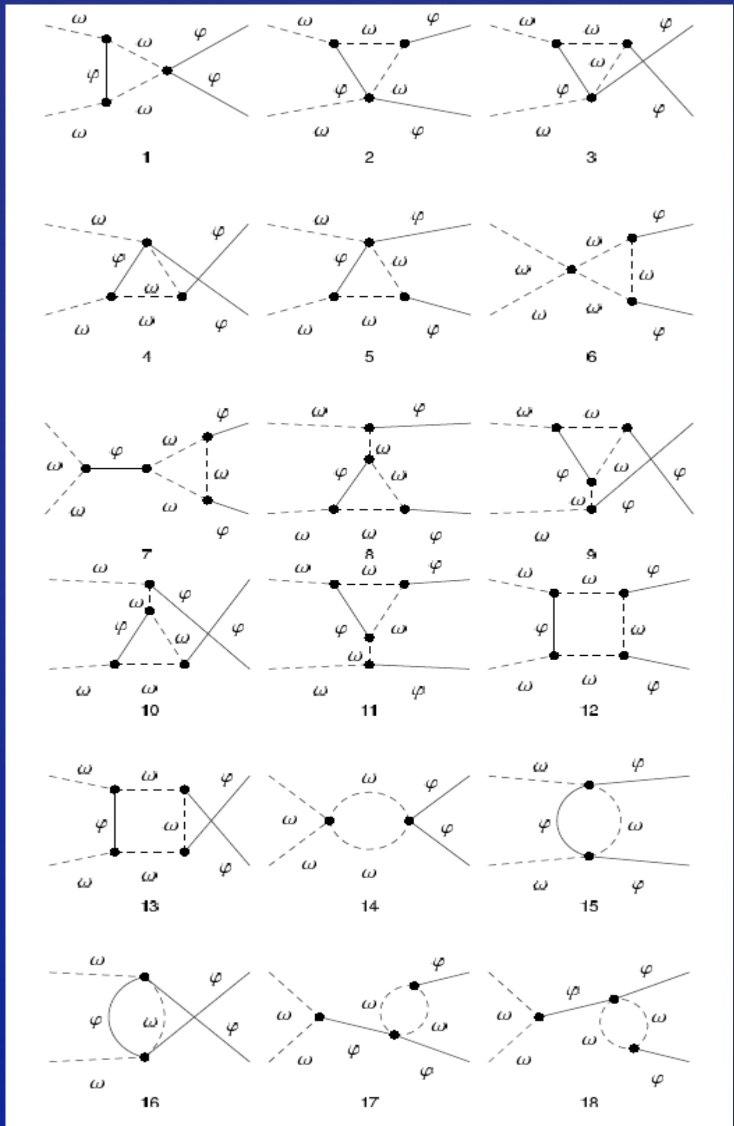
$$T_{abcd} = A(s,t,u)\delta_{ab}\delta_{cd} + B(s,t,u)\delta_{ac}\delta_{bd} + C(s.t.u)\delta_{ad}\delta_{bc}$$

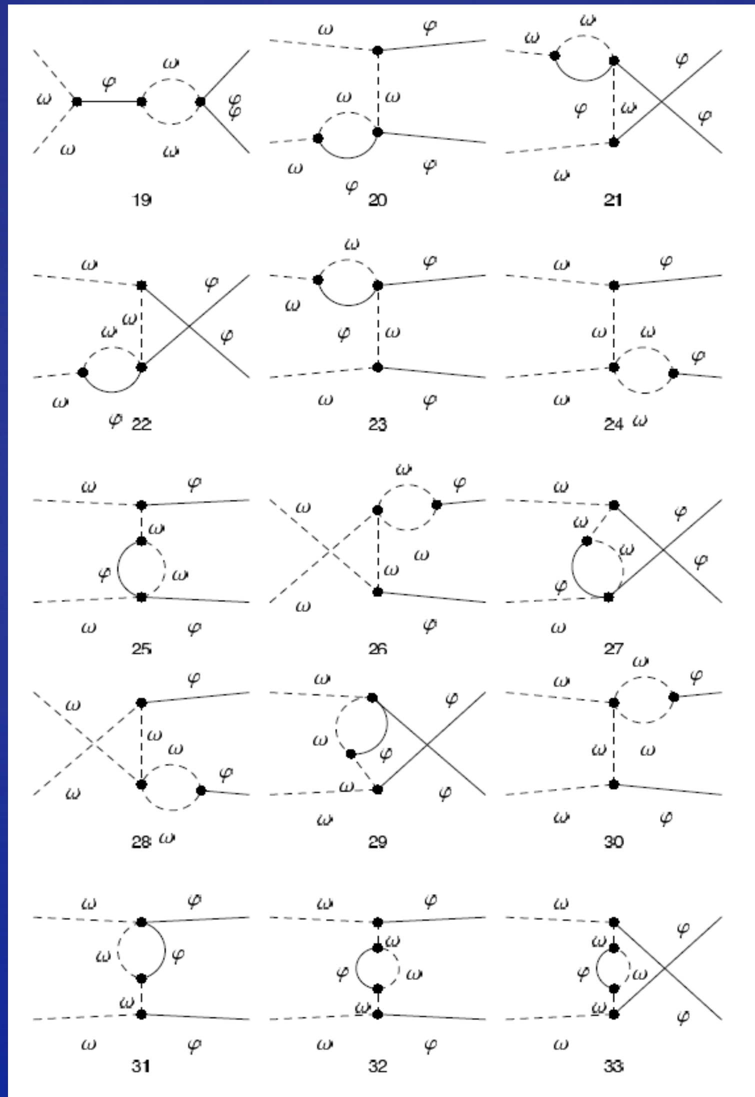
$$\begin{aligned}
A(s,t,u) = & \frac{s}{v^2}(1-a^2) + \frac{4}{v^4}[2a_5^r(\mu)s^2 + a_4^r(\mu)(t^2+u^2)] \\
& + \frac{1}{16\pi^2 v^4}\left(\frac{1}{9}(14a^4 - 10a^2 - 18a^2 b + 9b^2 + 5)s^2 + \frac{13}{18}(a^2-1)^2(t^2+u^2)\right. \\
& - \frac{1}{2}(2a^4 - 2a^2 - 2a^2 b + b^2 + 1)s^2 \log\frac{-s}{\mu^2} \\
& + \frac{1}{12}(1-a^2)^2(s^2 - 3t^2 - u^2)\log\frac{-t}{\mu^2} \\
& \left. + \frac{1}{12}(1-a^2)^2(s^2 - t^2 - 3u^2)\log\frac{-u}{\mu^2}\right) .
\end{aligned}$$

$$\begin{aligned}
a_4^r(\mu) &= a_4^r(\mu_0) - \frac{1}{192\pi^2}(1-a^2)^2 \log\frac{\mu^2}{\mu_0^2} \\
a_5^r(\mu) &= a_5^r(\mu_0) - \frac{1}{768\pi^2}(2 + 5a^4 - 4a^2 - 6a^2 b + 3b^2)\log\frac{\mu^2}{\mu_0^2}
\end{aligned}$$

Espriu, Yencho, Mescia

One-loop Feynman diagrams for $\omega_a\omega_b \to hh$





Electroweak Chiral Perturbation Theory with a light Higgs-boson up to one-loop

$$\omega\ \omega \Longrightarrow h\ h$$

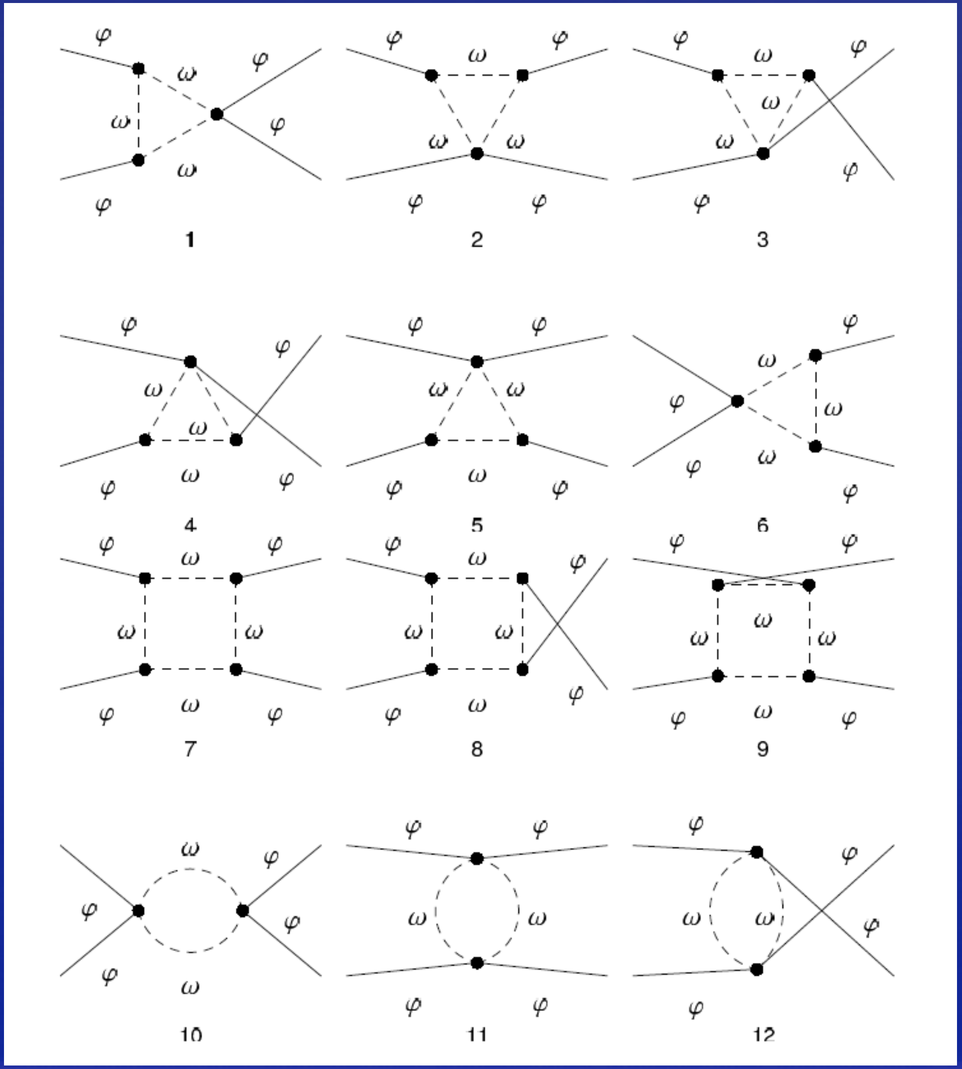
$$\omega_a \omega_b \to hh$$

$$\mathcal{M}_{ab}(s,t,u) = M(s,t,u)\delta_{ab}$$

$$\begin{aligned}
M(s,t,u) = &\ \frac{a^2-b}{v^2}s + \frac{2\delta^r(\mu)}{v^4}s^2 + \frac{\eta^r(\mu)}{v^4}(t^2+u^2) \\
&+ \frac{(a^2-b)}{576\pi^2 v^4}\left\{\left[72 - 88a^2 + 16b + 36(a^2-1)\log\frac{-s}{\mu^2}\right.\right. \\
&+ \left.3(a^2-b)\left(\log\frac{-t}{\mu^2} + \log\frac{-u}{\mu^2}\right)\right]s^2 \\
&+ (a^2-b)\left(26 - 9\log\frac{-t}{\mu^2} - 3\log\frac{-u}{\mu^2}\right)t^2 \\
&+ \left.(a^2-b)\left(26 - 9\log\frac{-u}{\mu^2} - 3\log\frac{-t}{\mu^2}\right)u^2\right\}
\end{aligned}$$

$$\begin{aligned}
\delta^r(\mu) &= \delta^r(\mu_0) + \frac{1}{192\pi^2}(a^2-b)(7a^2-b-6)\log\frac{\mu^2}{\mu_0^2} \\
\eta^r(\mu) &= \eta(\mu_0) - \frac{1}{48\pi^2}(a^2-b)^2\log\frac{\mu^2}{\mu_0^2}\ .
\end{aligned}$$

One-loop Feynman diagrams for $hh \to hh$



Electroweak Chiral Perturbation Theory (with a light Higgs-like scalar) up to one-loop

$h\ h \longrightarrow h\ h$

$hh \to hh$

$$T(s,t,u) = \frac{2\gamma^r(\mu)}{v^4}(s^2+t^2+u^2) + \frac{3(a^2-b)^2}{32\pi^2 v^4}\left[2(s^2+t^2+u^2) - s^2\log\frac{-s}{\mu^2} - t^2\log\frac{-t}{\mu^2} - u^2\log\frac{-u}{\mu^2}\right]$$

$$\gamma^r(\mu) = \gamma^r(\mu_0) - \frac{3}{64\pi^2}(a^2-b)^2\log\frac{\mu^2}{\mu_0^2}$$

Unitarity and partial waves:

$\omega\,\omega \longrightarrow \omega\,\omega$

$$A_{IJ}(s) = A^{(0)}_{IJ}(s) + A^{(1)}_{IJ}(s) + \ldots,$$

$$A_0(s,t,u) = 3A(s,t,u) + A(t,s,u) + A(u,t,s)$$
$$A_1(s,t,u) = A(t,s,u) - A(u,t,s)$$
$$A_2(s,t,u) = A(t,s,u) + A(u,t,s)\ .$$

$$A^{(0)}_{IJ}(s) = K s$$
$$A^{(1)}_{IJ}(s) = s^2\left(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2}\right)$$

$$A_{IJ}(s) = \frac{1}{64\,\pi}\int_{-1}^{1} d(\cos\theta)\, P_J(\cos\theta)\, A_I(s,t,u)$$

$I = 0$

$\omega\,\omega \longrightarrow h\,h$

$h\,h \longrightarrow h\,h$

$$M_J(s) = K's + s^2\left(B'(\mu) + D'\log\frac{s}{\mu^2} + E'\log\frac{-s}{\mu^2}\right)\ldots$$
$$T_J(s) = K''s + s^2\left(B''(\mu) + D''\log\frac{s}{\mu^2} + E''\log\frac{-s}{\mu^2}\right)\ldots$$

$$F(s) = \begin{pmatrix} F_{00} & 0 & 0 & 0 & 0 \\ 0 & F_{02} & 0 & 0 & 0 \\ 0 & 0 & F_{11} & 0 & 0 \\ 0 & 0 & 0 & F_{20} & 0 \\ 0 & 0 & 0 & 0 & \ldots \end{pmatrix}$$

$$F_{00}(s) = \begin{pmatrix} A_{00}(s) & M_0(s) \\ M_0(s) & T_0(s) \end{pmatrix}$$

$$F_{02}(s) = \begin{pmatrix} A_{02}(s) & M_2(s) \\ M_2(s) & T_2(s) \end{pmatrix}$$

$$ImF(s) = F(s)F^{\dagger}(s)$$

$I = 0$ $$F_{IJ} = F^{(0)}_{IJ} + F^{(1)}_{IJ} + \ldots$$

$$ImF^{(1)}_{IJ} = F^{(0)}_{IJ}F^{(0)}_{IJ} \Longrightarrow$$

$$\mathrm{Im}\,A^{(1)}_{0J} = |A^{(0)}_{0J}|^2 + |M^{(0)}_J|^2$$
$$\mathrm{Im}\,M^{(1)}_J = A^{(0)}_{0J}M^{(0)}_J + M^{(0)}_J T^{(0)}_J$$
$$\mathrm{Im}\,T^{(1)}_J = |M^{(0)}_J|^2 + |T^{(0)}_J|^2.$$

$I \neq 0$ $$F_{IJ}(s) = A_{IJ}(s)$$

$$\mathrm{Im}\,A^{(1)}_{IJ} = |A^{(0)}_{IJ}|^2 \quad I \neq 0$$

In any case unitarity applies $\;|\,A_{IJ}\,|^2 \leq 1\;$ necessary but not sufficient:

$IJ = 00$

$$
\begin{aligned}
K_{00} &= \frac{1}{16\pi v^2}(1-a^2) \\
B_{00}(\mu) &= \frac{1}{9216\pi^3 v^4}[101(1-a^2)^2 + 68(a^2-b)^2 + 768(7a_4(\mu)+11a_5(\mu))\pi^2] \\
D_{00} &= -\frac{1}{4608\pi^3 v^4}[7(1-a^2)^2 + 3(a^2-b)^2] \\
E_{00} &= -\frac{1}{64\pi^3 v^4}[4(1-a^2)^2 + 3(a^2-b)^2]\ .
\end{aligned}
$$

$\omega_a\omega_b \to \omega_c\omega_d$

$$
\begin{aligned}
K'_0 &= \frac{\sqrt{3}}{32\pi v^2}(a^2-b) \\
B'_0(\mu) &= \frac{\sqrt{3}}{16\pi v^4}\left(\delta(\mu) + \frac{\eta(\mu)}{3}\right) + \frac{\sqrt{3}}{18432\pi^3 v^4}(a^2-b)[72(1-a^2)+(a^2-b)] \\
D'_0 &= -\frac{\sqrt{3}(a^2-b)^2}{9216\pi^3 v^4} \\
E'_0 &= -\frac{\sqrt{3}(a^2-b)(1-a^2)}{512\pi^3 v^4}
\end{aligned}
$$

$\omega\omega \to hh$

$$
\begin{aligned}
K'_2 &= 0 \\
B'_2(\mu) &= \frac{\eta(\mu)}{160\sqrt{3}\pi v^4} + \frac{83(a^2-b)^2}{307200\sqrt{3}\pi^3 v^4} \\
D'_2 &= -\frac{(a^2-b)^2}{7680\sqrt{3}\pi^3 v^4} \\
E'_2 &= 0\ .
\end{aligned}
$$

$hh \to hh$

The Inverse Amplitude Method

A.D. , Herrero, Truong, Pelaez…

$$A(s) = A^{NLO}(s) + O(s^3)$$

$$I \neq 0$$

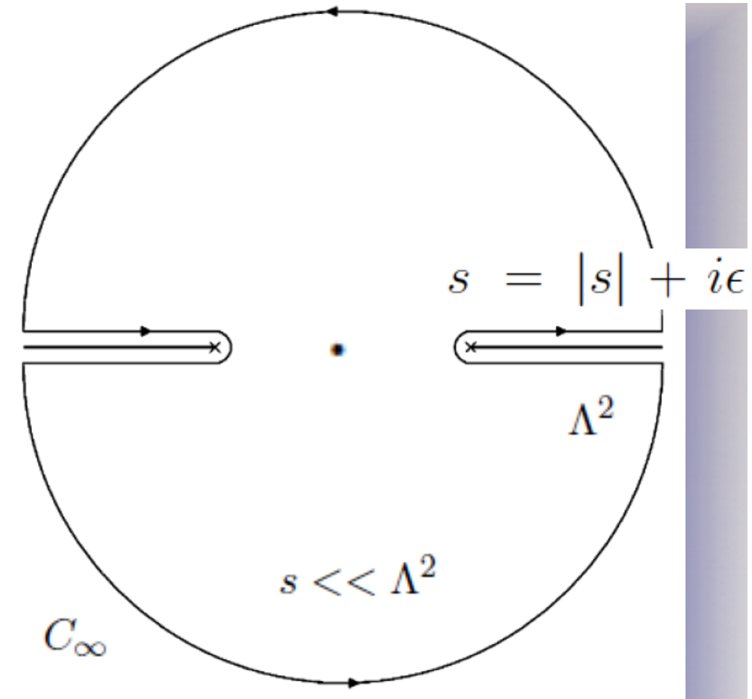
$$A^{NLO}(s) = A^{(0)}(s) + A^{(1)}(s)$$

$$A^{(0)}(s) = Ks$$
$$A^{(1)}(s) = s^2\left(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2}\right)$$

$$\mathrm{Im}\,A^{(1)} = (A^{(0)})^2$$

$$K^2 = -E\pi$$

$$B(\mu) = B(\mu_0) + (D+E)\log\frac{\mu^2}{\mu_0^2}$$



$$f(s) = \frac{A^{NLO}(s) - A^{(0)}(s)}{s^2}$$

$$f(s) = \frac{1}{\pi}\int_0^{\Lambda^2}\frac{ds'\,\mathrm{Im}\,f(s')}{s'-s-i\epsilon} + \frac{1}{\pi}\int_{-\Lambda^2}^{0}\frac{ds'\,\mathrm{Im}\,f(s')}{s'-s-i\epsilon} + \frac{1}{2\pi i}\int_{C_\infty}\frac{ds'\,f(s')}{s'-s}$$

$$A^{NLO}(s) = Ks + \frac{s^2}{\pi}\int_0^{\Lambda^2}\frac{ds'\,\mathrm{Im}\,A^{NLO}(s')}{s'^2(s'-s-i\epsilon)} + \frac{s^2}{\pi}\int_{-\Lambda^2}^{0}\frac{ds'\,\mathrm{Im}\,A^{NLO}(s')}{s'^2(s'-s-i\epsilon)} + \frac{s^2}{2\pi i}\int_{C_\infty}\frac{ds'\,A^{NLO}(s')}{s'^2(s'-s)}.$$

$$A^{NLO}(s) = Ks + s^2(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2})$$

Inverse Amplitude

$$g(s)=\frac{(A^{(0)}(s))^2}{A(s)}$$

$$g(s)=Ks+\frac{s^2}{\pi}\int_0^{\Lambda^2}\frac{ds'\,\mathrm{Im}\,g(s')}{s'^2(s'-s-i\epsilon)}+\frac{s^2}{\pi}\int_{-\Lambda^2}^{0}\frac{ds'\,\mathrm{Im}\,g(s')}{s'^2(s'-s-i\epsilon)}+\frac{s^2}{2\pi i}\int_{C_\infty}\frac{ds'\,g(s')}{s'^2(s'-s)}$$

RC $\mathrm{Im}\,G = -K^2 s^2$

LC $\mathrm{Im}\,G \simeq -\,\mathrm{Im}\,A^{(1)}$

$$g(s)\simeq Ks-Ds^2\log\frac{s}{\Lambda^2}-Es^2\log\frac{-s}{\Lambda^2}+\frac{s^2}{2\pi i}\int_{C_\infty}\frac{ds'\,g(s')}{s'^2(s'-s)}$$

$$A_{IJ}^{IAM}(s)=\frac{(A_{IJ}^{(0)}(s))^2}{A_{IJ}^{(0)}(s)-A_{IJ}^{(1)}(s)}$$

$$\mathrm{Im}\,A_{IJ}^{IAM}=A_{IJ}^{IAM}(A_{IJ}^{IAM})^*$$

$$A^{IAM}(s)=A^{NLO}(s)+O(s)$$

The IAM method produces:

Unitary amplitudes with the same low energy limit as the NLO, the proper analytical structure which can have poles in the second Riemann sheet reproducing new resonances. Extension to coupled channels for massless particles:

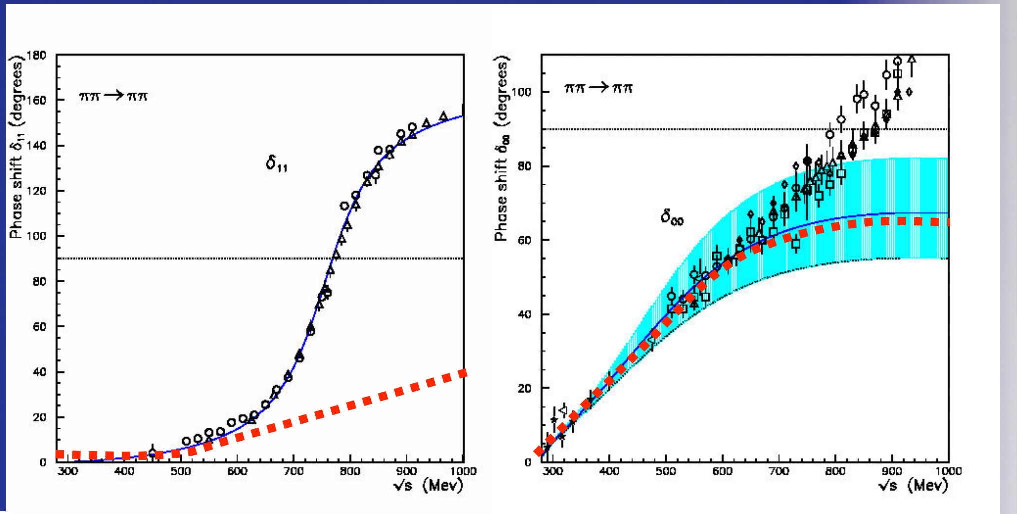
$$F_{IJ}^{IAM}=F_{IJ}^{(0)}(F_{IJ}^{(0)}-F_{IJ}^{(1)})^{-1}F_{IJ}^{(0)}$$

$$\mathrm{Im}\,F_{IJ}^{IAM}=F_{IJ}^{IAM}(F_{IJ}^{IAM})^\dagger$$

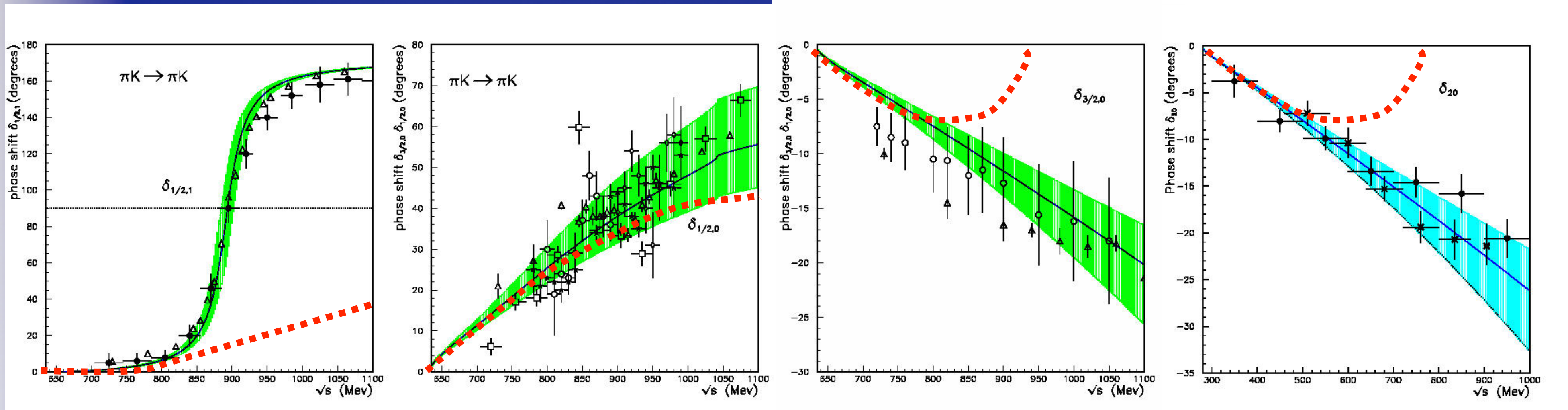
The Inverse Amplitude Method in ChPT

Chiral Perturbation Theory plus Dispersion Relations

Simultaneous description of ππ→ππ and πK→πK up to 800-1000 MeV including resonances



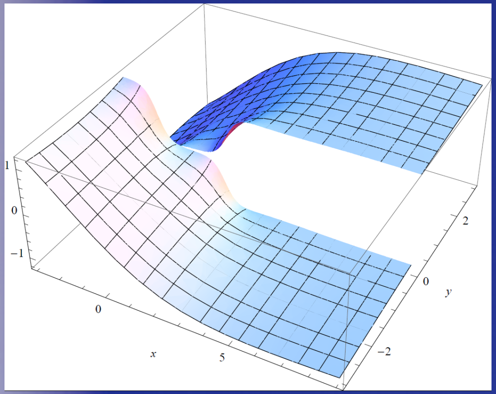
Lowest order ChPT (Weinberg Theorems) and even one-loop computations are only valid at very low energies

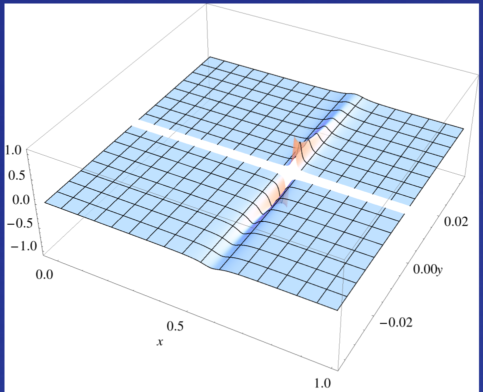


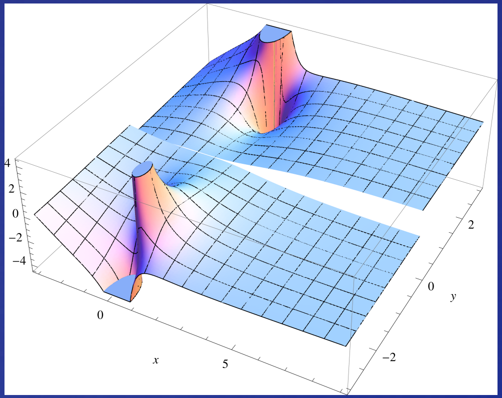
A.D., Pelaez

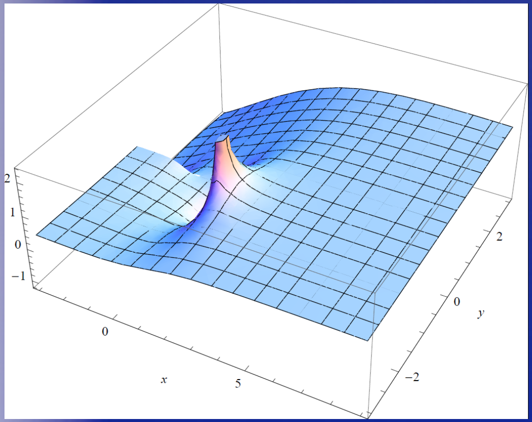
$a = 0.9, \quad b = 1, \; \mathbf{a_4} = 0.005$ $\qquad\qquad$ $\mathbf{a_4} = -0.005$

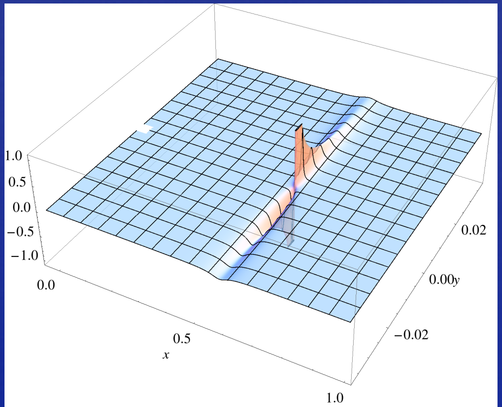
I=J=0 $\qquad$ I=J=1 $\qquad$ I=2, J=0

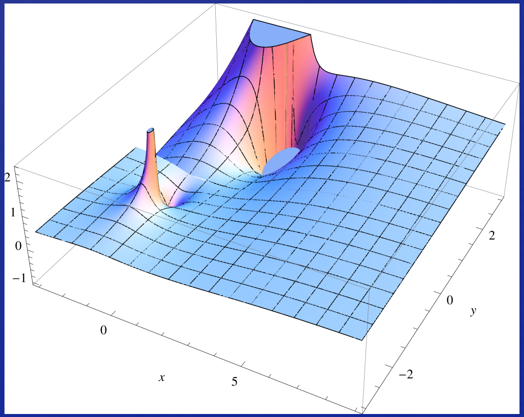






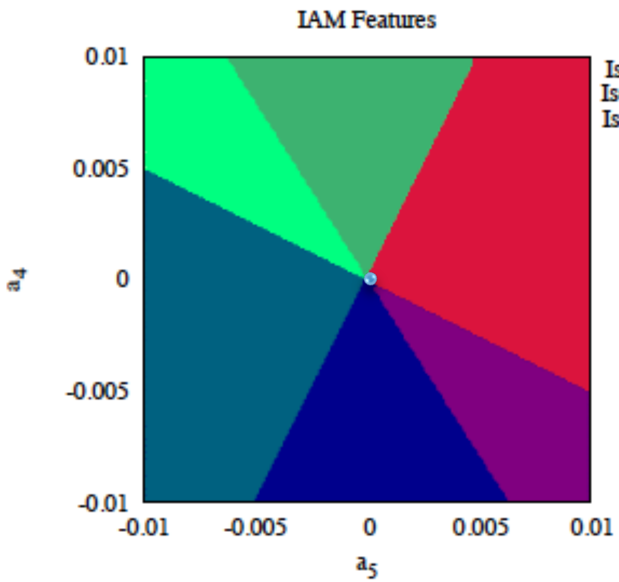


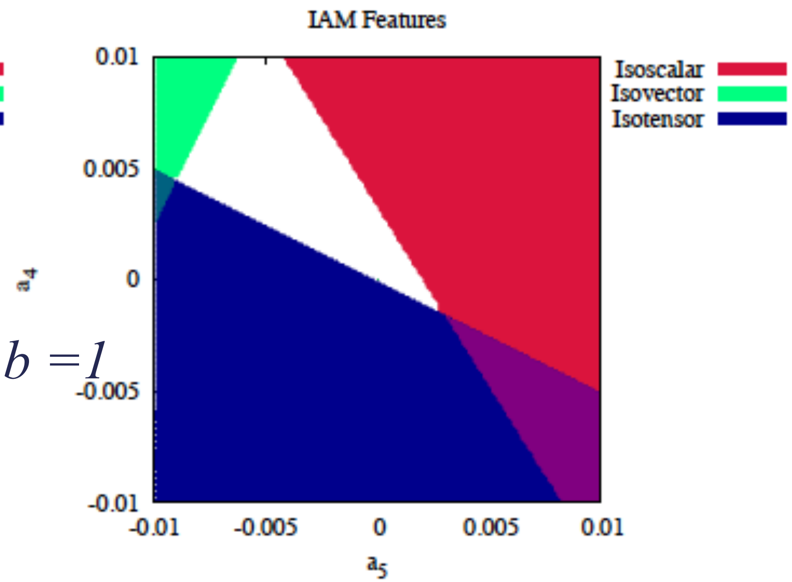




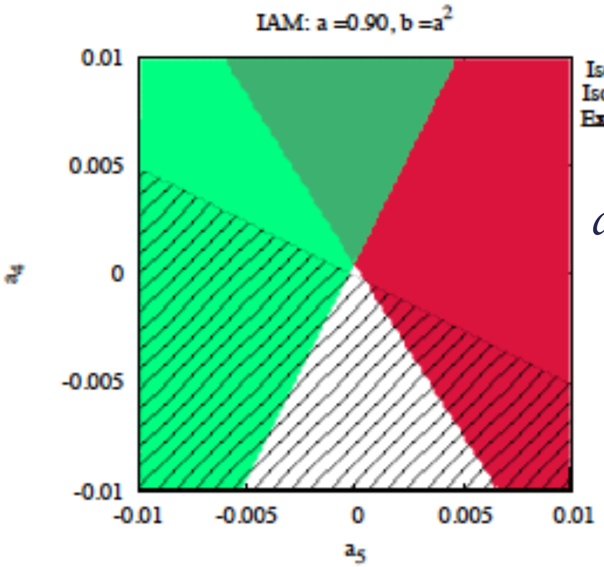
Im A: 1º and 2º Riemann Sheet

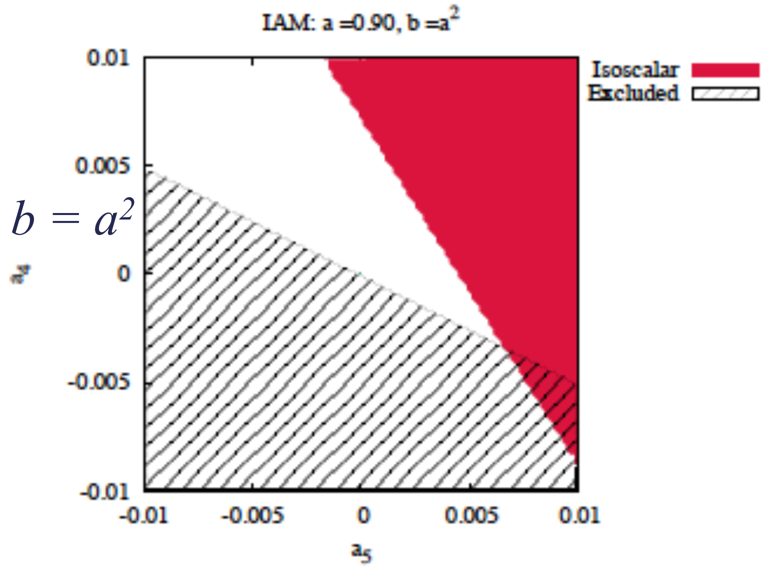
Resonant spectrum





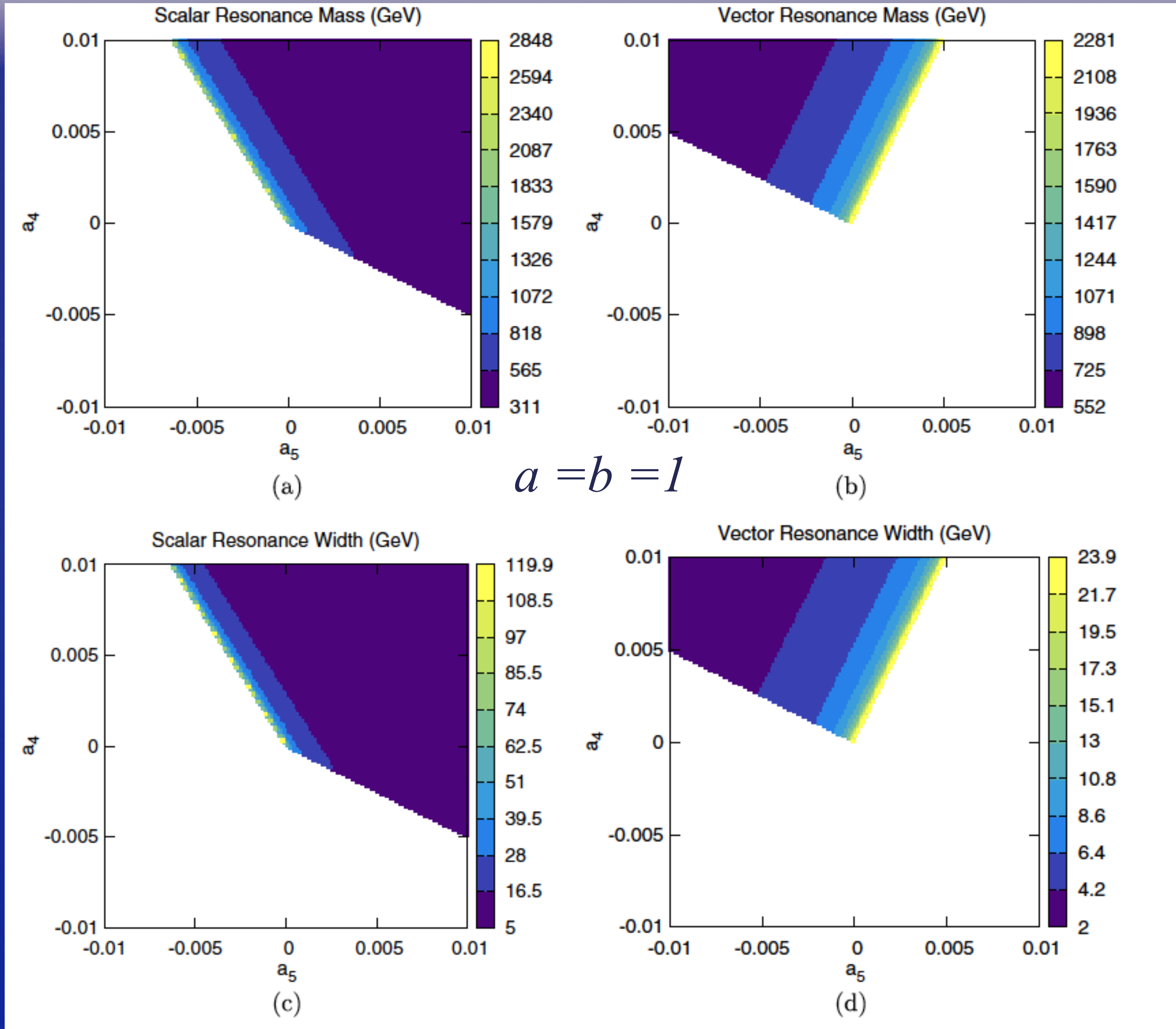
$a = b = 1$





$a = 0.9;\ b = a^2$

Espriu, Yencho, Mescia


Scalar Resonance Mass (GeV)
2848
2594
2340
2087
1833
1579
1326
1072
818
565
311
Vector Resonance Mass (GeV)
2281
2108
1936
1763
1590
1417
1244
1071
898
725
552
Scalar Resonance Width (GeV)
119.9
108.5
97
85.5
74
62.5
51
39.5
28
16.5
5
Vector Resonance Width (GeV)
23.9
21.7
19.5
17.3
15.1
13
10.8
8.6
6.4
4.2
2
a4
a5
0.01
0.005
0
-0.005
-0.01
(a)
(b)
(c)
(d)

$a = b = 1$

A coupled channel resonance *(I=J=0)*

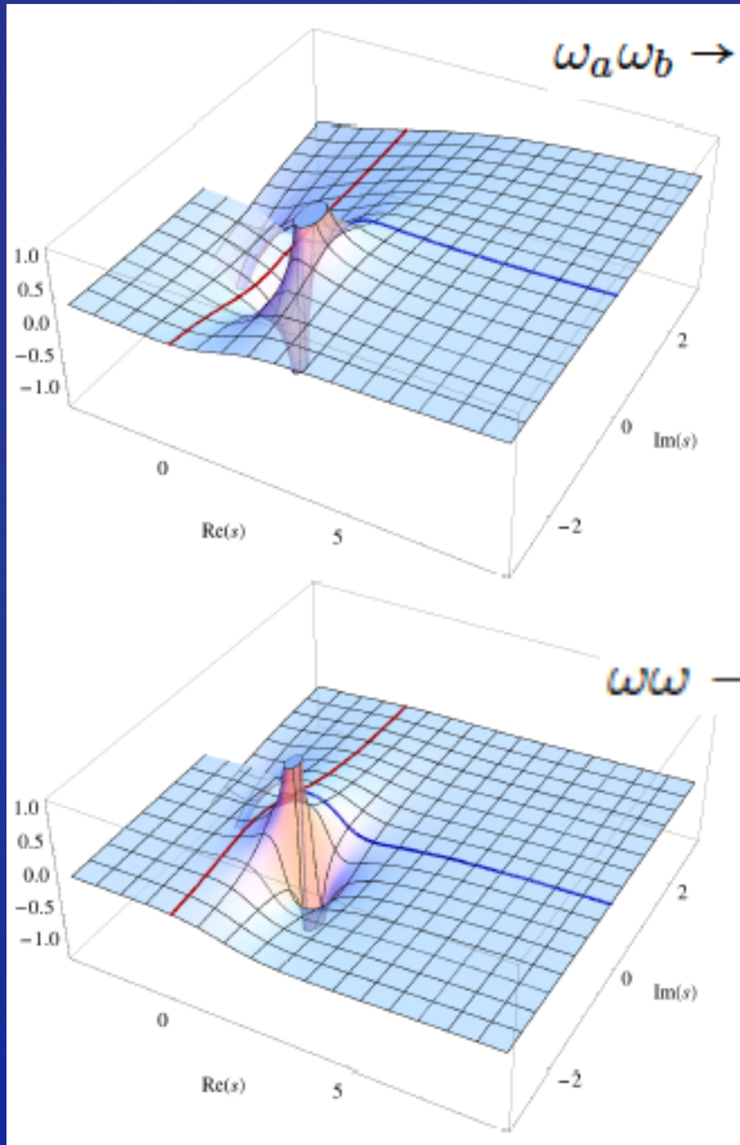
$$\begin{aligned} A_0(\omega\omega\to\omega\omega) &= \frac{s}{16\pi v^2}(1-a^2) \\ T_0(hh\to hh) &= 0 \\ M_0(\omega\omega\to hh) &= \frac{\sqrt{3}s}{32\pi v^2}(a^2-b) \end{aligned}$$

$a = 1.$

$$A_1(\omega\omega\to\omega\omega) = \frac{s^2(1-b)^2}{256\pi^3 v^4}\times$$
$$\left(\frac{17}{9}-\frac{1}{6}\log\left(\frac{s}{\mu^2}\right)-\frac{3}{4}\log\left(\frac{-s}{\mu^2}\right)\right)$$
$$T_1(hh\to hh) = \frac{s^2(1-b)^2}{32\pi^3 v^4}\times$$
$$\left(\frac{1}{3}-\frac{1}{16}\log\left(\frac{s}{\mu^2}\right)-\frac{3}{32}\log\left(\frac{-s}{\mu^2}\right)\right)$$
$$M_1(\omega\omega\to hh) = \frac{\sqrt{3}(1-b)s}{32\pi v^2}+$$
$$\frac{\sqrt{3}s^2(1-b)^2}{9216\pi^3 v^4}\left(\frac{1}{2}-\log\left(\frac{s}{\mu^2}\right)\right).$$

$$F^{IAM} = \frac{M_0^2}{(M_0-M_1)^2-A_1T_1}\begin{pmatrix} A_1 & M_0-M_1 \\ M_0-M_1 & T_1 \end{pmatrix}$$

$\omega_a\omega_b \to \omega_c\omega_d$



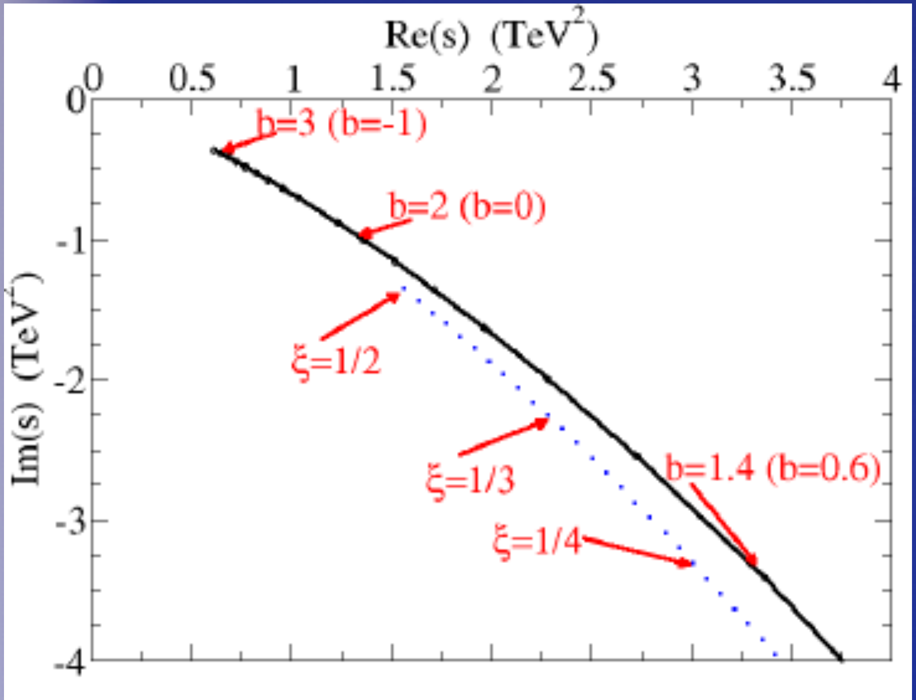
$\omega\omega \to hh$

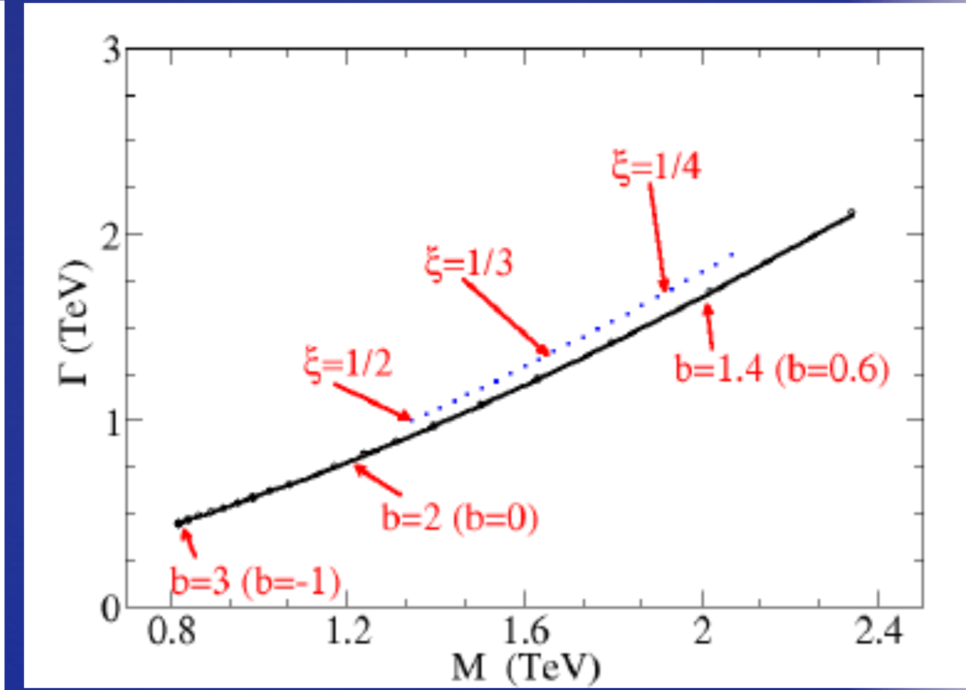
$a = 1, b = 2$

New resonance parameters

$\sqrt{s_0} = M - i\Gamma/2$

$a = \sqrt{1-\xi}$ and $b = 1 - 2\xi$ $\quad \xi = v^2/f^2$





Example:

$SO(5)/SO(4)$

$b \in (-1, 3)$

Main results for $V_L V_L$ scattering:

$a^2 = b$ $\quad$ $a^2 \neq 1$ $\Rightarrow$ Strong elastic $W_L W_L$ scattering

$a^2 \neq b$ $\quad$ $a^2 = 1$ $\Rightarrow$ Strong $W_L W_L$ scattering through resonant coupling to the *HH* channel

$a^2 \neq b$ $\quad$ $a^2 \neq 1$ $\Rightarrow$ Strong $W_L W_L$ scattering and strong coupling to the *HH* channel

$a^2 = b$ $\quad$ $a^2 = 1$ $\Rightarrow$ Weak elastic $W_L W_L$ scattering

(MSM)

CMS: 95% CL $\quad$ $a \simeq \kappa_V \in [0.7, 1.3]$

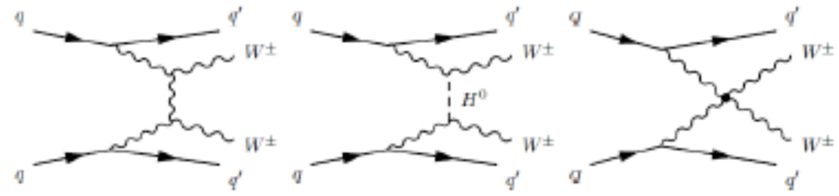
ATLAS: 95% CL $\quad$ $a \simeq \kappa_V \in [0.8, 1.4]$

$b \in (-1, 3)$

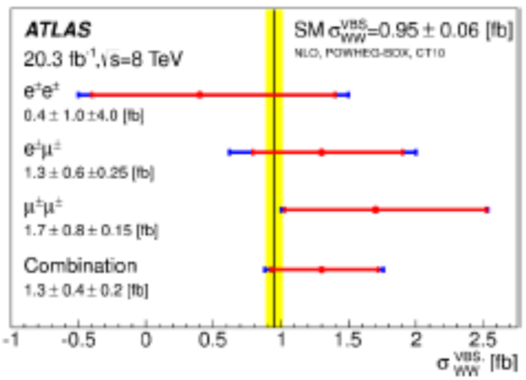
W W Scattering @ LHC

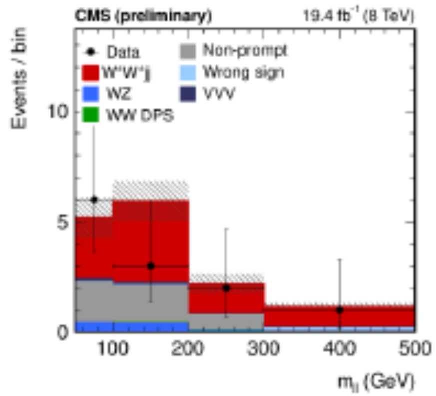
Berryhill

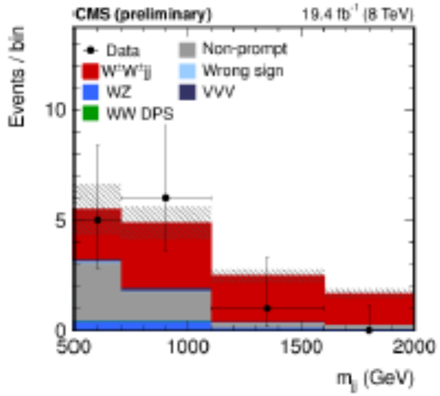
First evidence of $W^\pm W^\pm$ scattering (3.6 σ)

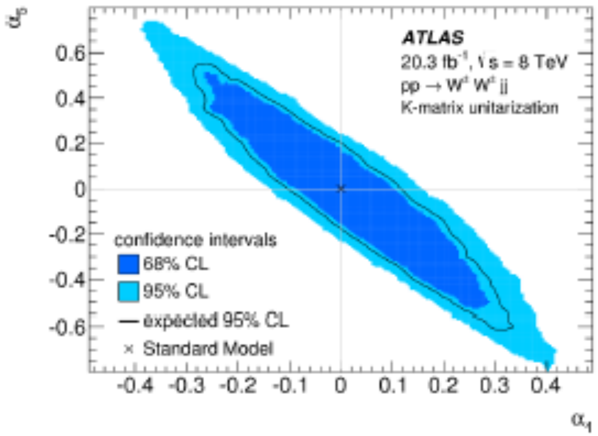


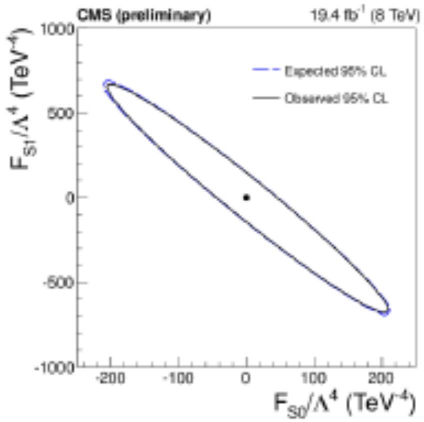
ATLAS, arxiv:1405.6241











CMS-PAS-SMP-13-015

IV. Conclusions:

The new boson discovered recently at CERN has the same quantum numbers and a behavior compatible with the MSM Higgs.

However assuming only custodial symmetry, the existence of the Higgs-like light boson and the huge gap, makes it possible to write a non-linear effective ECLh, containing the MSM as a particular case.

By using this Lagrangian at the one-loop level, complemented with dispersion relations and the ET, it possible to study the scattering of the longitudinal components of the EWGB related with the underlying unknown EWSBS dynamics in terms of a small number of parameters.

In the parameter space the $Z_L Z_L$, $W_L W_L$ scattering is generically strongly interacting and give rise to new resonant states in many cases and also to other processes which are suppressed in the MSM as $\gamma\gamma \rightarrow Z_L Z_L$, $W_L W_L$.

Thus strongly interacting $W_L W_L$ scattering would be a signal of new physics BSM. Much more work is needed for making realistic predictions

Wait for the LHC 2015 run to know!

$\gamma\gamma \to Z_L Z_L\,,\; W_L W_L$ at the one-loop level

Interesting for new physics research since they don't recieve any contribution from the Higgs at the tree level. In particular the neutral channel vanishes in the MSM.

$$\mathcal{M} = ie^2(\epsilon_1^\mu \epsilon_2^\nu T^{(1)}_{\mu\nu})A(s,t,u) + ie^2(\epsilon_1^\mu \epsilon_2^\nu T^{(2)}_{\mu\nu})B(s,t,u)$$

$$\begin{aligned}(\epsilon_1^\mu \epsilon_2^\nu T^{(1)}_{\mu\nu}) &= \frac{s}{2}(\epsilon_1\epsilon_2) - (\epsilon_1 k_2)(\epsilon_2 k_1),\\ (\epsilon_1^\mu \epsilon_2^\nu T^{(2)}_{\mu\nu}) &= 2s(\epsilon_1\Delta)(\epsilon_2\Delta) - (t-u)^2(\epsilon_1\epsilon_2) - 2(t-u)[(\epsilon_1\Delta)(\epsilon_2 k_1) - (\epsilon_1 k_2)(\epsilon_2\Delta)]\end{aligned}$$

$$\mathcal{M} = \mathcal{M}_{\rm LO} + \mathcal{M}_{\rm NLO},$$

$$\Delta^\mu \equiv p_1^\mu - p_2^\mu$$

$$-\frac{c_\gamma}{2}\frac{h}{v}e^2 A_{\mu\nu}A^{\mu\nu}$$

$$\mathcal{M}_{\rm NLO} = \mathcal{M}^{\rm 1-loop}_{\mathcal{O}(e^2p^2)} + \mathcal{M}^{\rm tree}_{\mathcal{O}(e^2p^2)}$$

$$A = A_{\rm LO} + A_{\rm NLO},$$

$$B = B_{\rm LO} + B_{\rm NLO}$$

The effect of the coset parametrization (SU(2)=S^3)

$$U(x) \;=\; \exp i\frac{\tilde{\pi}}{v}$$

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}$$

$$\begin{aligned}
\mathcal{L}_2(\pi, h, \gamma) \;=\;& \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\mathcal{F}(h)(2\partial_\mu \pi^+ \partial^\mu \pi^- + \partial_\mu \pi^0 \partial^\mu \pi^0) \\
+\;& \frac{\mathcal{F}(h)}{6v^2}[(\partial_\mu \pi^+ \pi^- + \pi^+ \partial_\mu \pi^- + \pi^0 \partial_\mu \pi^0)^2 - \pi^2(2\partial_\mu \pi^+ \partial^\mu \pi^- + \partial_\mu \pi^0 \partial^\mu \pi^0)] \\
+\;& ie\mathcal{F}(h)\left\{ A^\mu \left[(\partial_\mu \pi^+ \pi^- \left(1 - \frac{\pi^2}{3v^2}\right) - \frac{\pi^+ \pi^-}{6v^2}\partial_\mu \pi^2 \right] + h.c. \right\} \\
+\;& e^2 \mathcal{F}(h) A_\mu A^\mu \pi^+ \pi^- \left(1 - \frac{\pi^2}{3v^2}\right)
\end{aligned}$$

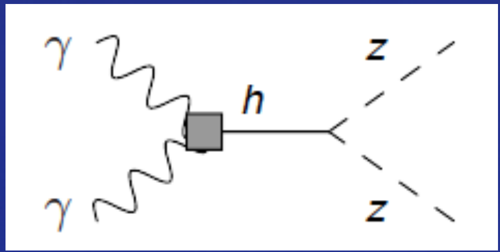
$$U(x) \;=\; \sqrt{1 - \frac{\omega^2}{v^2}} + i\frac{\tilde{\omega}}{v}$$

$$\begin{aligned}
\mathcal{L}_2(\omega, h, \gamma) \;=\;& \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\mathcal{F}(h)(2\partial_\mu \omega^+ \partial^\mu \omega^- + \partial_\mu \omega^0 \partial^\mu \omega^0) \\
+\;& \frac{\mathcal{F}(h)}{2v^2}(\partial_\mu \omega^+ \omega^- + \omega^+ \partial_\mu \omega^- + \omega^0 \partial_\mu \omega^0)^2 \\
+\;& ie\mathcal{F}(h)A^\mu(\partial_\mu \omega^+ \omega^- - \omega^+ \partial_\mu \omega^-) + e^2 \mathcal{F}(h) A_\mu A^\mu \omega^+ \omega^-
\end{aligned}$$

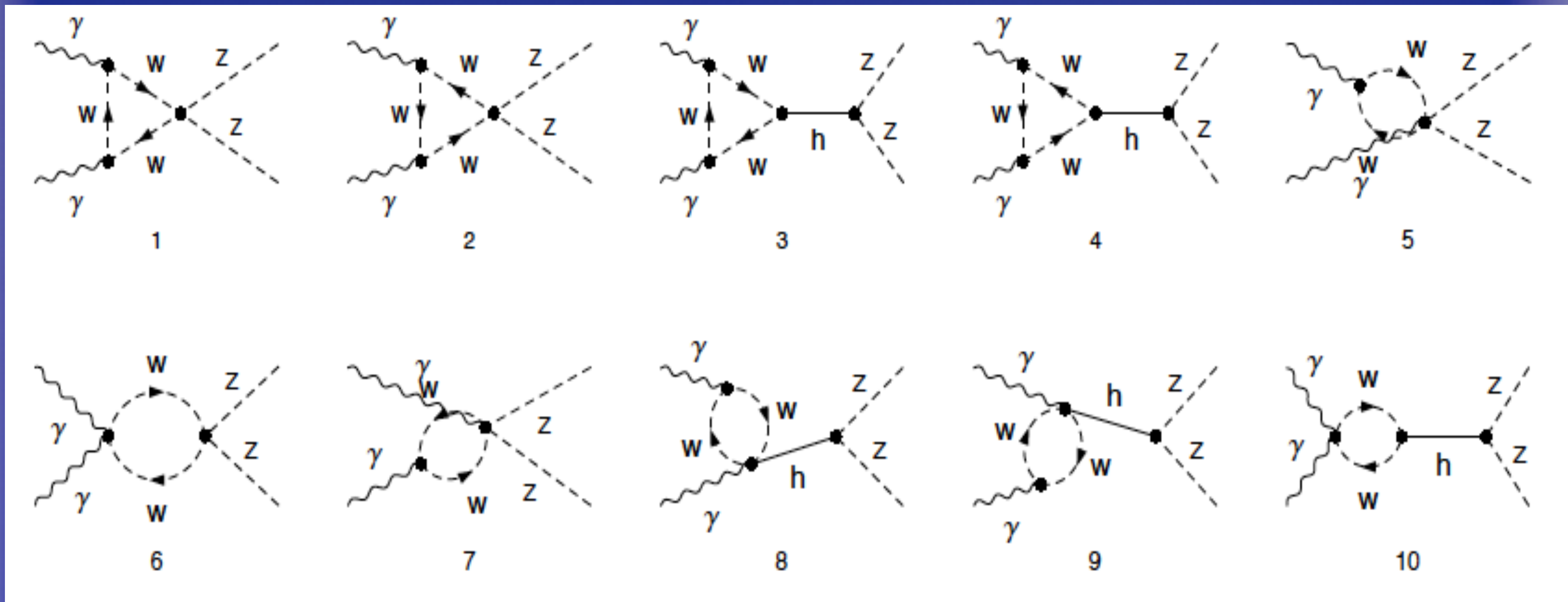
The Lagrangian, the Feynman rules and diagrams
are the different but the S matrix elements are the same

$$\gamma\gamma \rightarrow zz$$

$$\mathcal{M}(\gamma\gamma \rightarrow zz)_{\mathrm{LO}} = 0$$

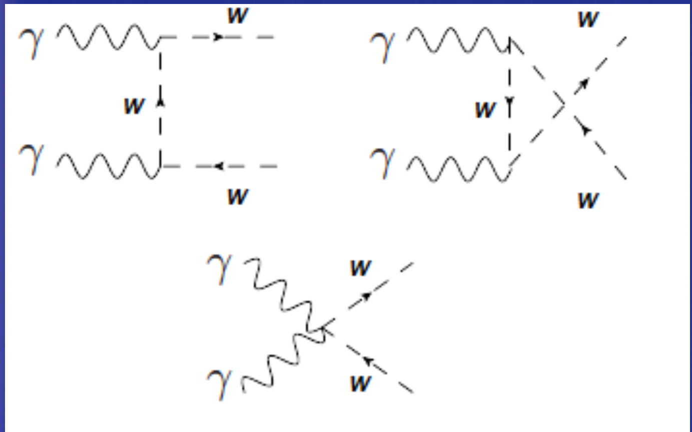


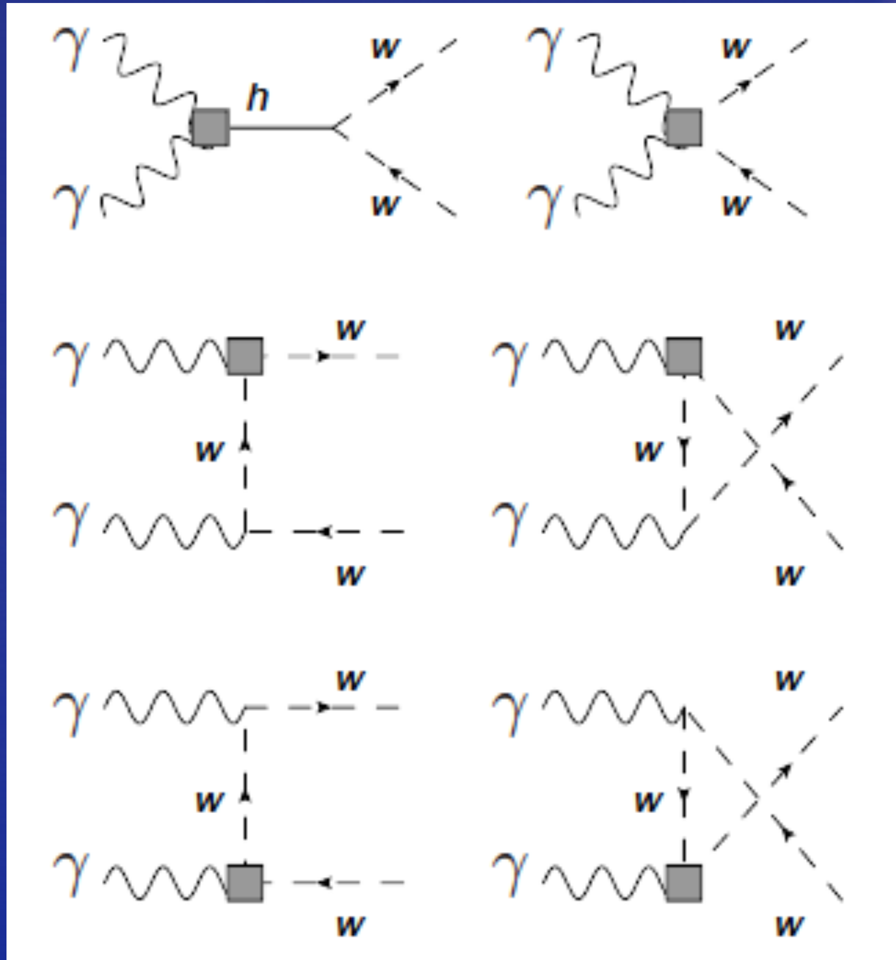
$$A(\gamma\gamma \rightarrow zz)_{\mathrm{NLO}} = \frac{2ac_\gamma^r}{v^2} + \frac{(a^2-1)}{4\pi^2 v^2}$$
$$B(\gamma\gamma \rightarrow zz)_{\mathrm{NLO}} = 0,$$



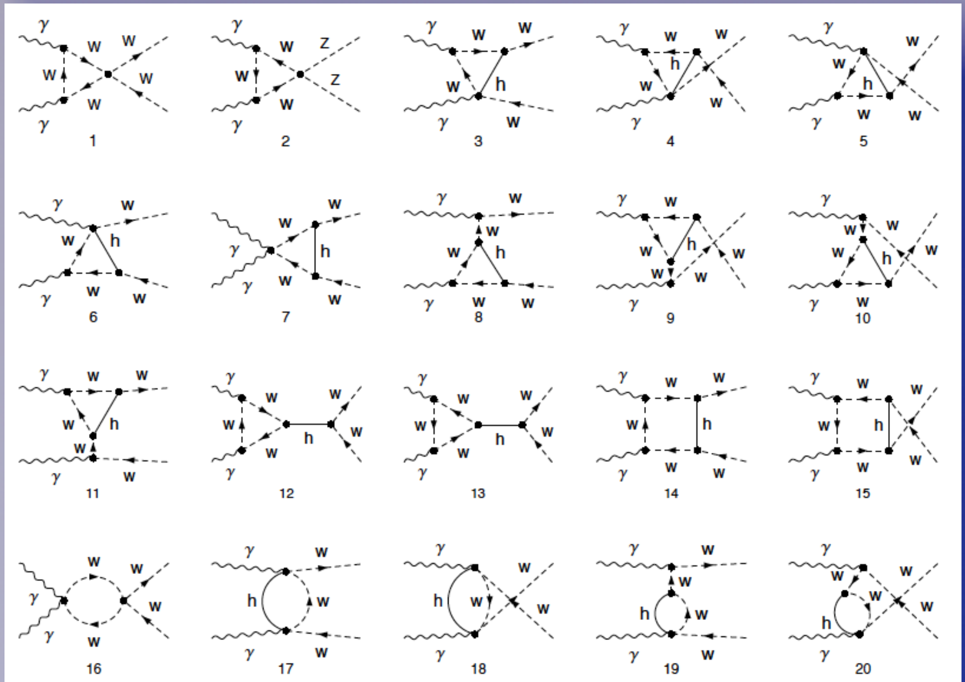
$$c_\gamma^r = c_\gamma$$

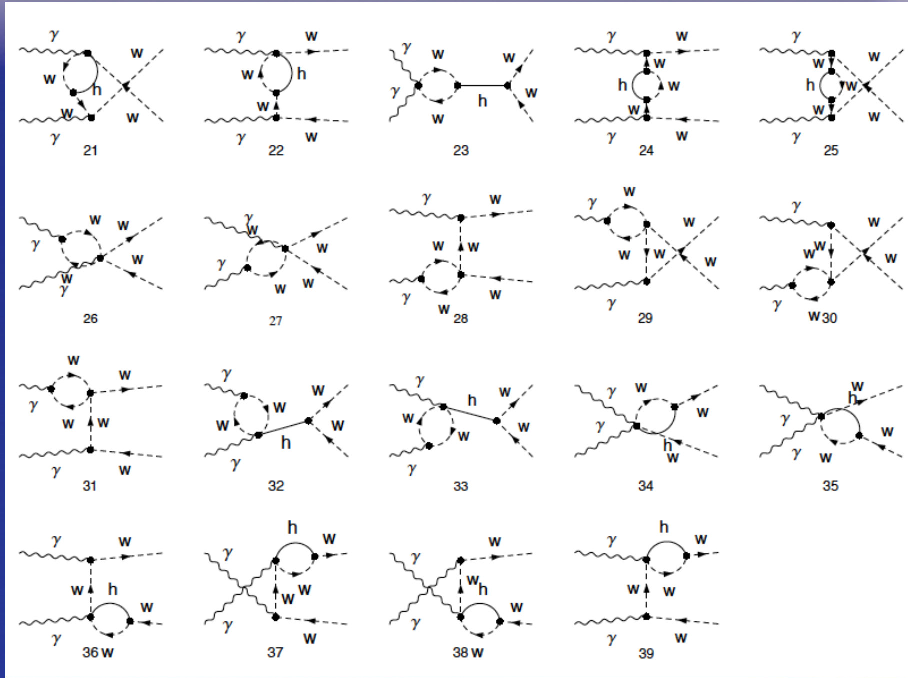
$$\gamma\gamma \to w^+ w^-$$





$$A(\gamma\gamma \to w^+ w^-)_{\rm LO} = 2sB(\gamma\gamma \to w^+ w^-)_{\rm LO} = -\frac{1}{t} - \frac{1}{u},$$





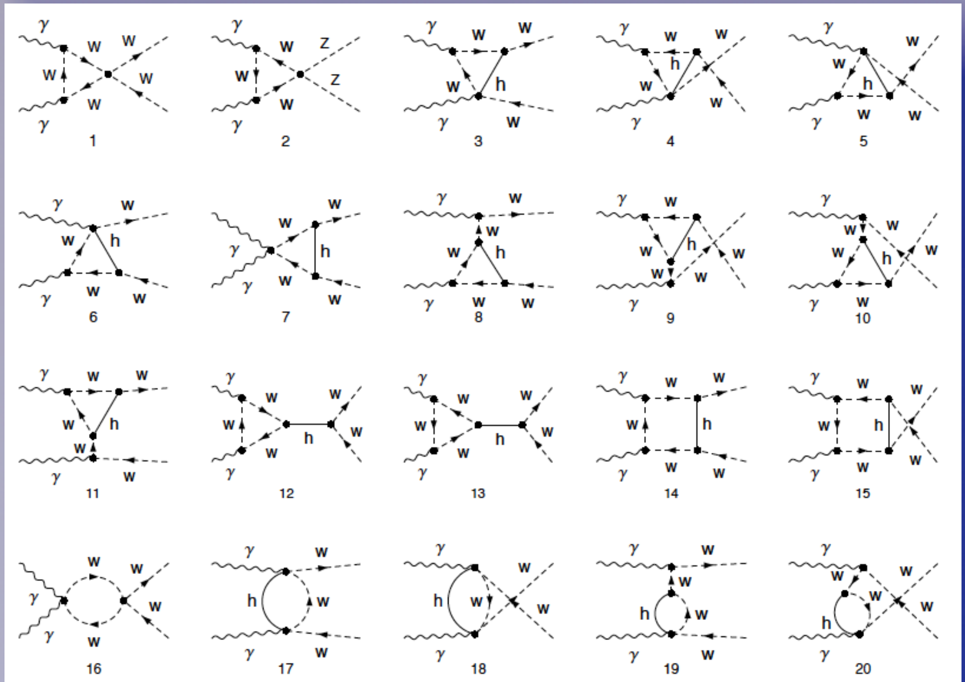
$$A(\gamma\gamma \to w^+w^-)_{\rm LO} = 2sB(\gamma\gamma \to w^+w^-)_{\rm LO} = -\frac{1}{t} - \frac{1}{u};$$

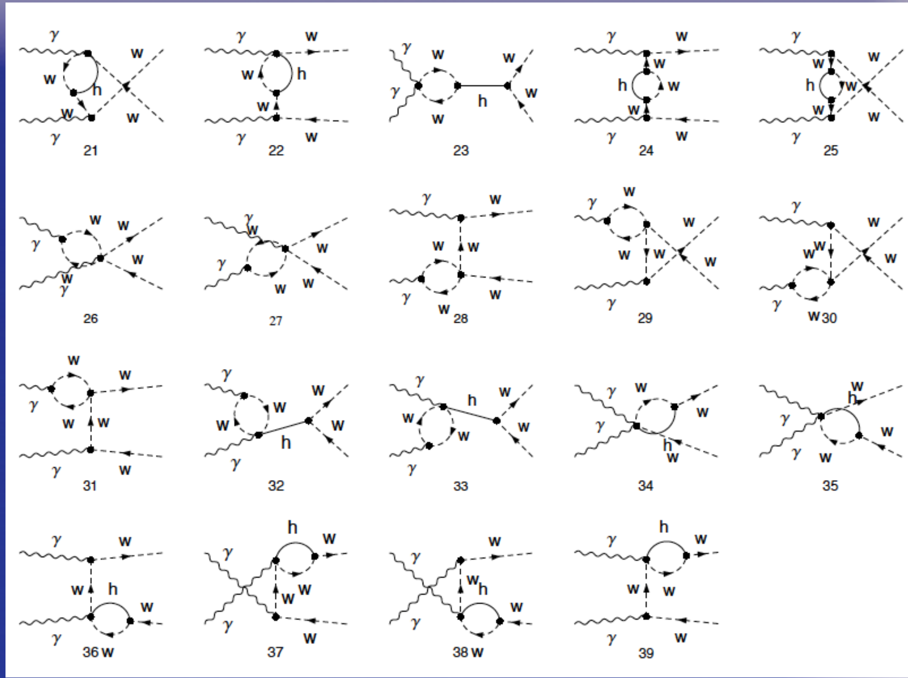
$$\begin{aligned} A(\gamma\gamma \to w^+w^-)_{\rm NLO} &= \frac{8(a_1^r - a_2^r + a_3^r)}{v^2} + \frac{2ac_\gamma^r}{v^2} + \frac{(a^2-1)}{8\pi^2 v^2} \\ B(\gamma\gamma \to w^+w^-)_{\rm NLO} &= 0. \end{aligned}$$

$$(a_1^r - a_2^r + a_3^r) = (a_1 - a_2 + a_3)$$

$$c_\gamma^r = c_\gamma$$

Finite one-loop result in both cases!





$$A(\gamma\gamma \to w^+w^-)_{\rm LO} = 2sB(\gamma\gamma \to w^+w^-)_{\rm LO} = -\frac{1}{t} - \frac{1}{u};$$

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$$(a_1^r - a_2^r + a_3^r) = (a_1 - a_2 + a_3)$$

$$c_\gamma^r = c_\gamma.$$

Finite one-loop result in both cases!

ECLh coupling renormalization

Observables	Relevant combinations of parameters from $\mathcal{L}_2$	Relevant combinations of parameters from $\mathcal{L}_4$
$\mathcal{M}(\gamma\gamma \to zz)$	a	c_γ^r
$\mathcal{M}(\gamma\gamma \to w^+w^-)$	a	$(a_1^r - a_2^r + a_3^r)$, c_γ^r
$\Gamma(h \to \gamma\gamma)$	a	c_γ^r
S–parameter	a	a_1^r
$\mathcal{F}_{\gamma^* ww}$	a	$(a_2^r - a_3^r)$
$\mathcal{F}_{\gamma^* \gamma h}$	–	c_γ^r

	ECLh	**ECL** (Higgsless)
$\Gamma_{a_1 - a_2 + a_3}$	0	0
Γ_{c_γ}	0	-
Γ_{a_1}	$-\frac{1}{6}(1-a^2)$	$-\frac{1}{6}$
$\Gamma_{a_2 - a_3}$	$-\frac{1}{6}(1-a^2)$	$-\frac{1}{6}$
Γ_{a_4}	$\frac{1}{6}(1-a^2)^2$	$\frac{1}{6}$
Γ_{a_5}	$\frac{1}{8}(b-a^2)^2 + \frac{1}{12}(1-a^2)^2$	$\frac{1}{12}$

The Minimal Standard Model EWSBS

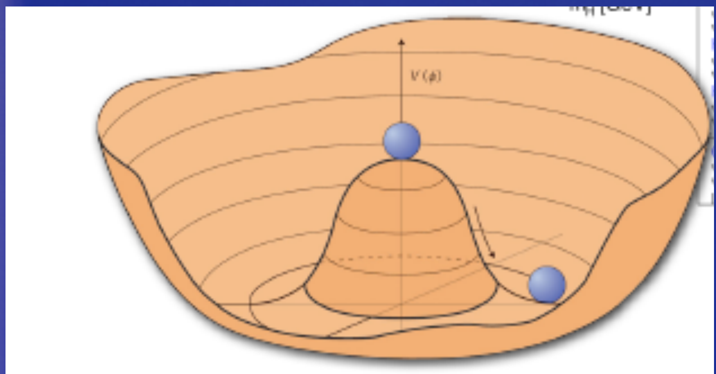
$$\mathcal{L}_{SBS} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) + \mathcal{L}_{YK}$$

$$\phi^T = (\phi^+, \phi^0)$$

$$D_\mu \phi = \left(\partial_\mu + i\frac{g'}{2} B_\mu - ig\frac{\tau^a}{2} W_\mu^a \right) \phi$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\chi \end{pmatrix}$$

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



$$M_W = \frac{gv}{2}$$

$$M_Z = \frac{M_W}{\cos\theta_W}$$

$$v \simeq 250\,\mathrm{GeV},$$

$$M_H^2 = 2\lambda v^2$$

- We introduce an *ad hoc* potential to induce the Higgs mechanism.
- We have 4 new degrees of freedom: 3 WBGB and one massive scalar (THE HIGGS BOSON).
- Fermion masses are produced by the Yukawa couplings in a gauge invariant way.
- The theory is unitary and renormalizable.
- The dynamics producing the EWSB is gauge invariant but it is not a gauge interaction
- Light Higgs means weak interactions in the SBS

- The Higgs always appear in the combination $h+v$.

Production and decay of the MSM Higgs boson at the LHC