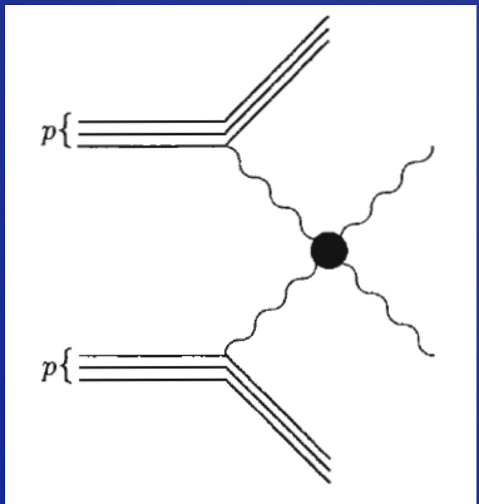
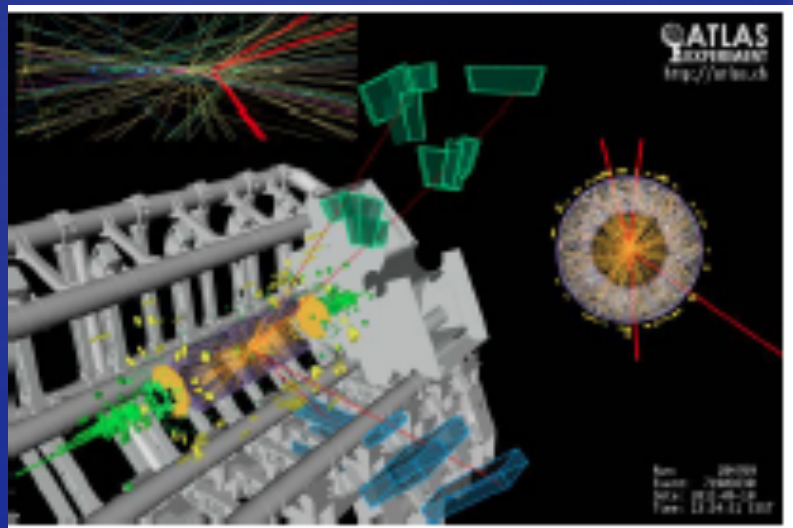
Strongly interacting $W_L W_L$, $Z_L Z_L$ and *hh* at high energies

Antonio Dobado

Universidad Complutense de Madrid





CERN-TH, June 2014

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

ABSTRACT

In this talk we review the main ATLAS and CMS results leading to the recent finding of a 125-GeV light Higgs-like boson. In the context of the Minimal Standard Model (MSM) this implies a $W_L W_L$ system weakly interacting. However this is an exceptional feature not generally true if new physics exists beyond the mass gap found at the LHC up to 600 GeV. By using an extension of the Electroweak Chiral Lagrangian, including one light boson (ECLh), it is possible to study the $W_L W_L$, $Z_L Z_L$ and *hh* scattering at high energies relevant for the future LHC data. In this talk we show the results of our computations at the one-loop level by using the Equivalence Theorem. Then we Introduce the Inverse Amplitude (IAM) method in this context to unitarize the partial waves. For most of the parameter space, the scattering is strongly interacting (with the MSM being a remarkable exception) and the IAM method produces poles in the second Riemann sheet of the amplitude in many cases that have a natural interpretation as dynamical resonances. Therefore, the finding of the Higgs boson could be more a signal for new strongly interacting physics (composite Higgs) rather than a confirmation of the SM.

Outline

I. Introduction

II. Experimental results (properties of the new boson)

III. The Higgs in the Minimal Standard Model

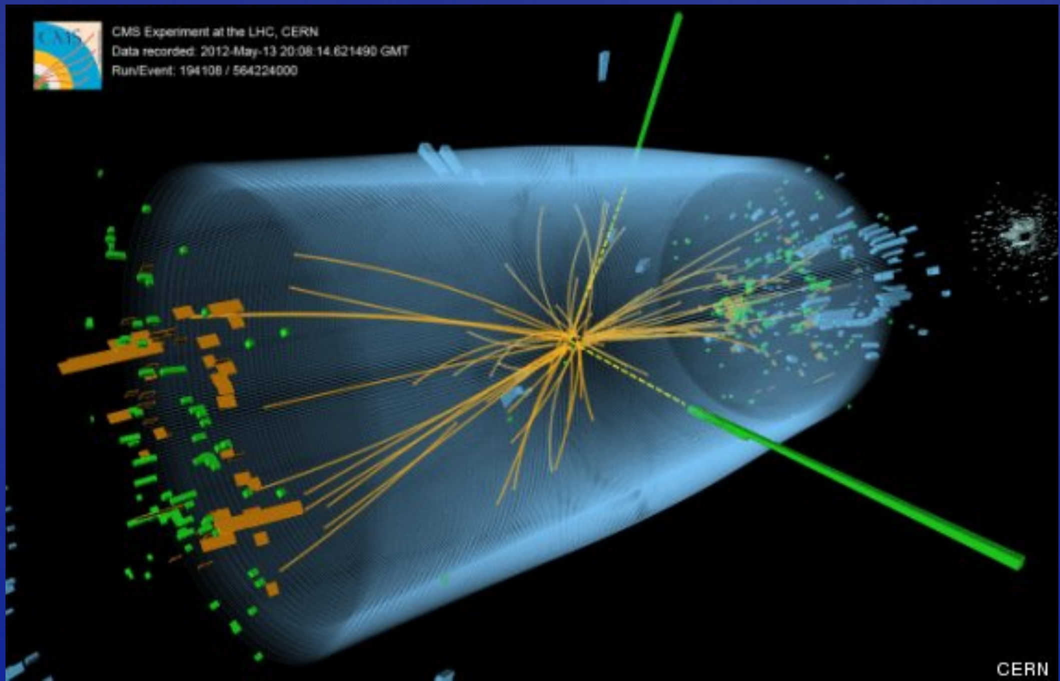
IV. The Higss-like boson behavior

V. The case for a Strongly Interacting SBS

VI. One-loop computations and the IAM method

VII. Conclusions

I. Introduction



First publications claiming the new-boson discovery by ATLAS and CMS at 2012

Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

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ELSEVIER

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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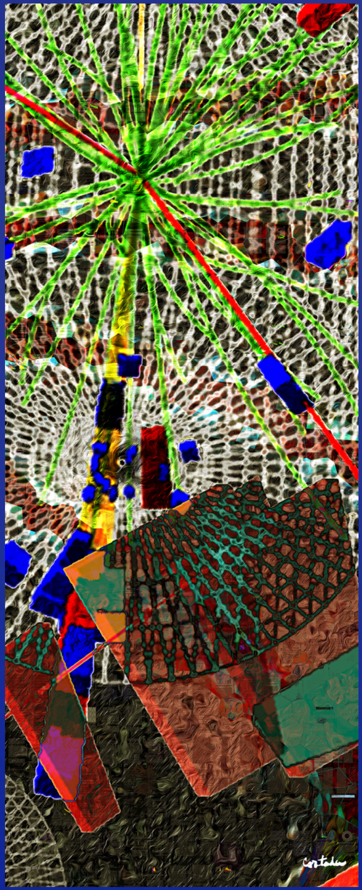
ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

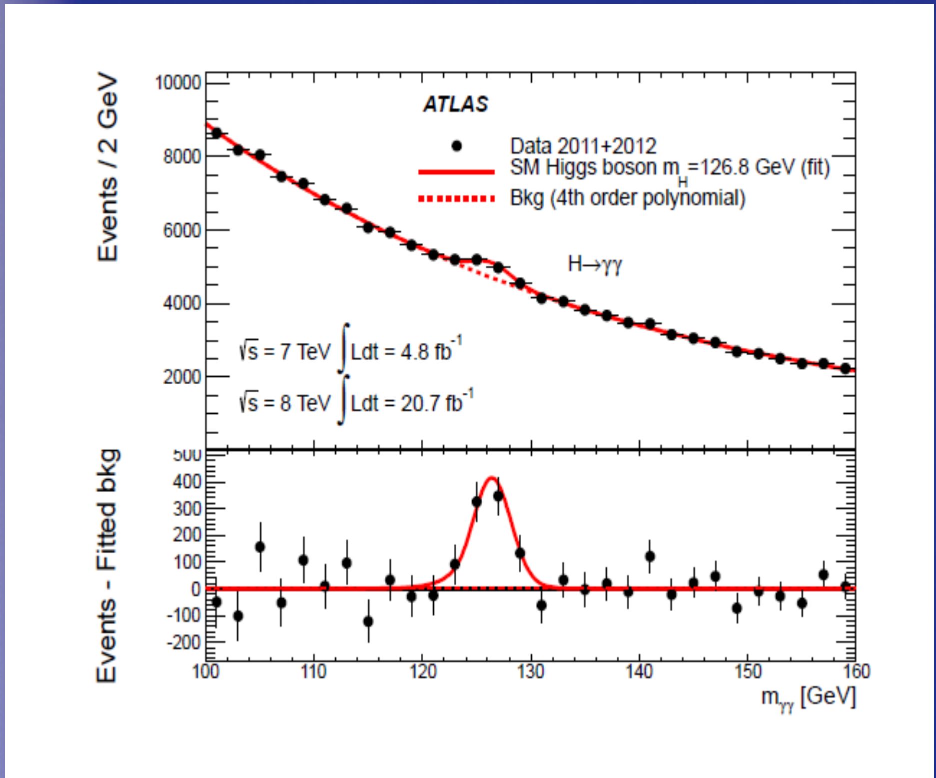
ATLAS Collaboration *

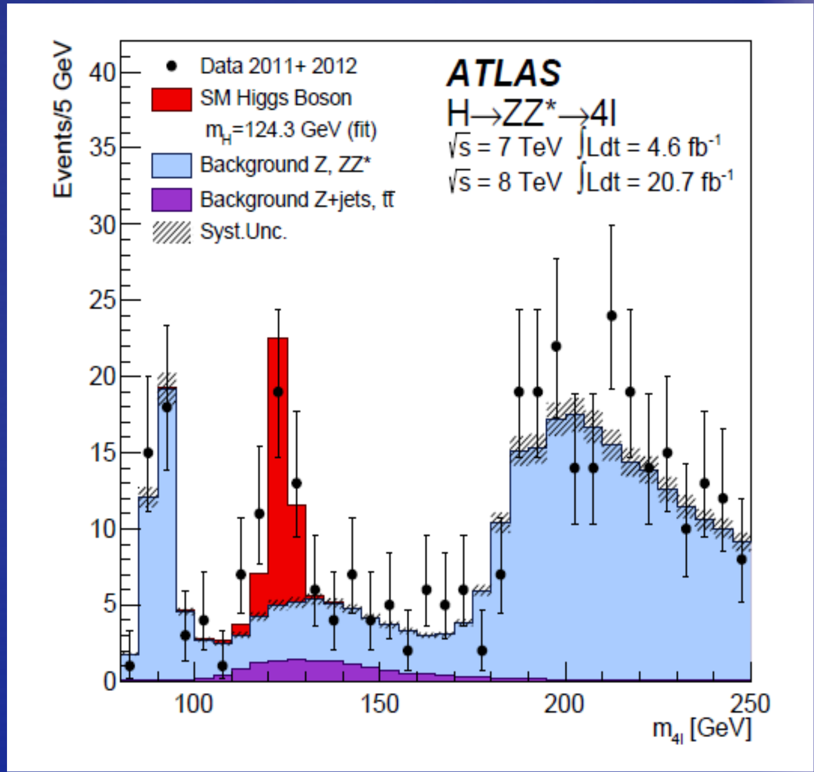
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

I. Experimental results
(new-boson properties)



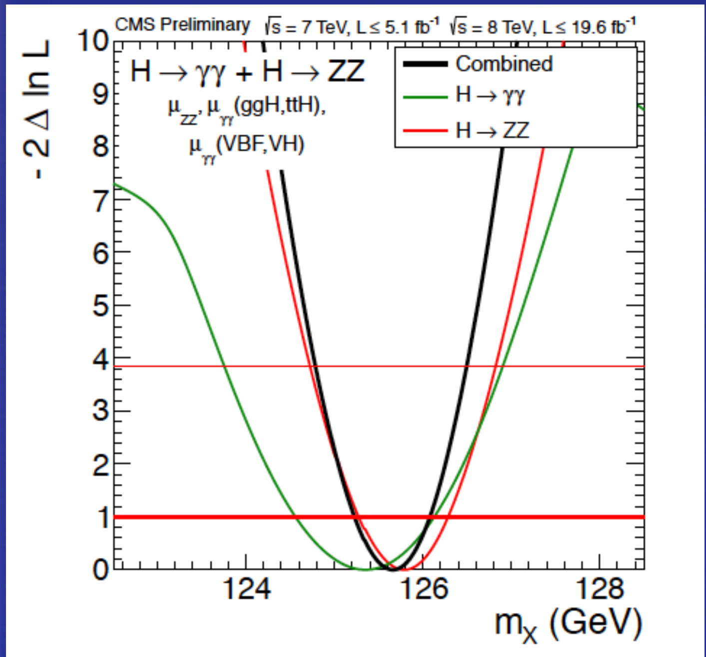
What do we really know about the new neutral boson, discovered by ATLAS and CMS and confirmed by CDF and D0?

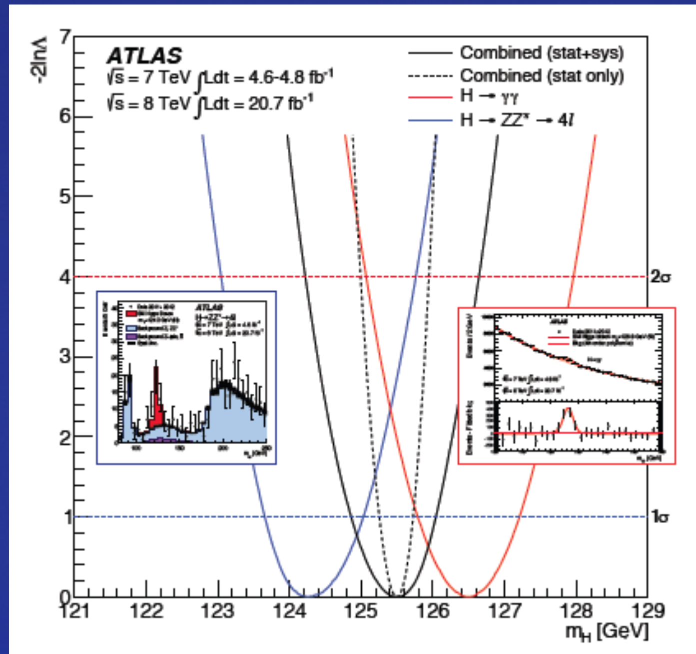




First seen in diphoton events and then confirmed in $ZZ \rightarrow 4$ lepton events

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

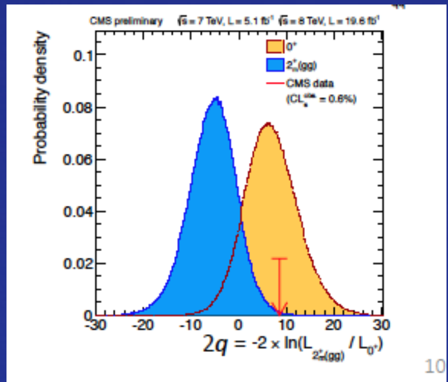
Width: $\Gamma_h < 17.4$ MeV 4.2 times MSM value!

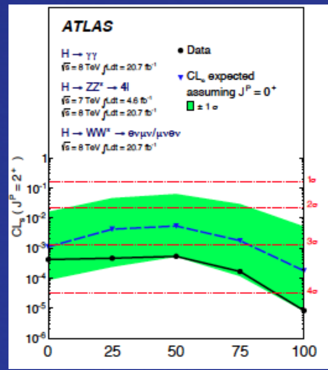
(CMS preliminar)

Spin:

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

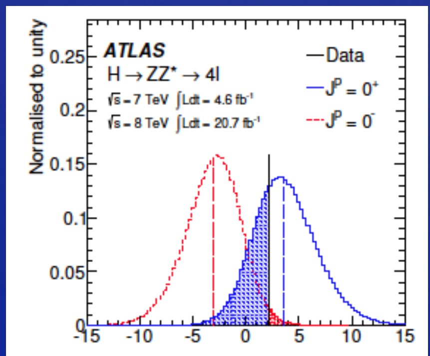
Angular distributions of the decay products are sensible to the resonance spin:

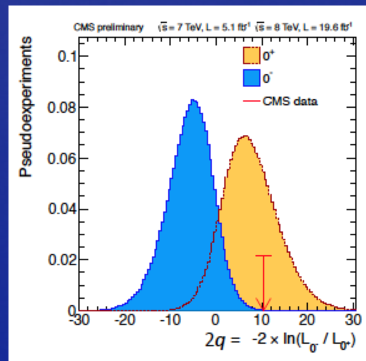




Both ATLAS and CMS exclude a J=2 resonance to 99.4% confidence level and are compatible with a J=0 resonance.

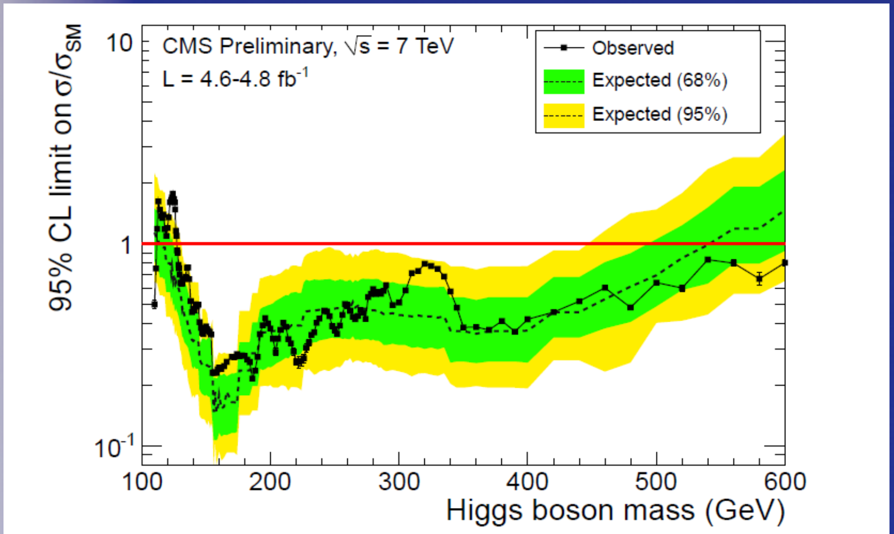
Parity:

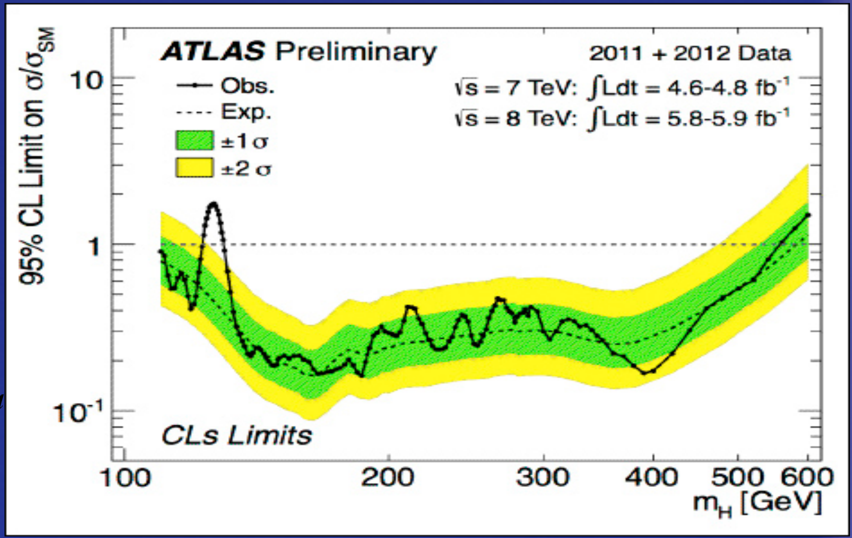




ATLAS and CMS exclude a pseudo scalar $J^P=0^-$ versus 0^+ (scalar) at the 97.8% and 99.8% CL respectively. CMS and D0 support this results. Alternatives to $J^P=0^+$ versus 0^+ all together are excluded to the 95% CL.

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





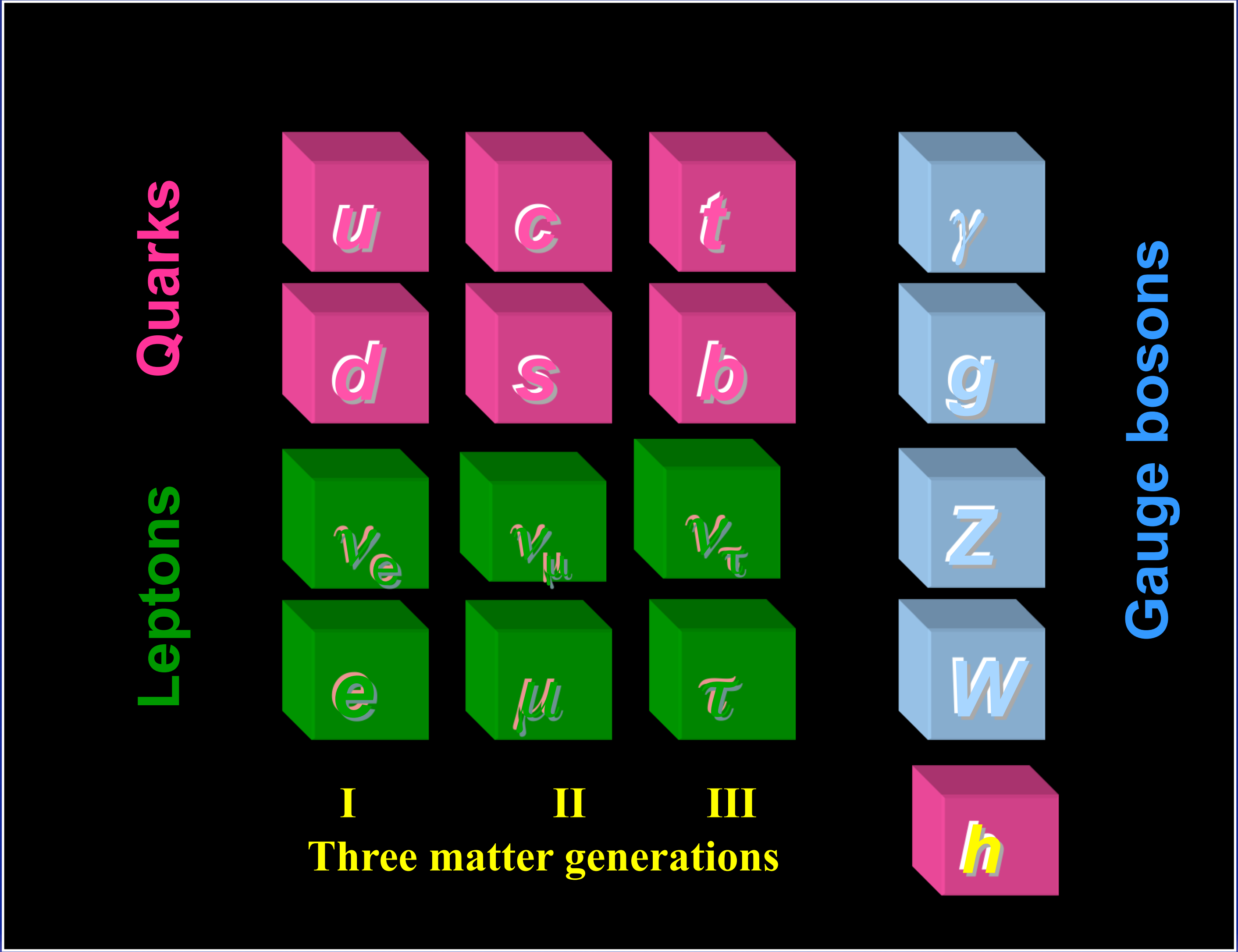
Nothing new up to 600 GeV → BIG GAP from 125 GeV to 600 GeV

Thus we have ONE and only ONE new SCALAR resonance at 125.5 GeV: → h(125)

So what is this new resonance?

To answer this question we have to start from the well stablished paradigm in particle physics, namely:

III. The Higgs in the Minimal Standard Model



$$SU(N_c) \times SU(2)_L \times U(1)_Y$$

Gauge Theory of Strong and Electroweak Interactions

$$\mathcal{L}_{YM} = \frac{1}{2g_s^2}\mathrm{tr}G_{\mu\nu}G^{\mu\nu} + \frac{1}{2g^2}\mathrm{tr}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{L}_m = i\bar{\mathcal{Q}}\,\not{D}_{\mathcal{Q}}\mathcal{Q} + i\bar{\mathcal{L}}\,\not{D}_{\mathcal{L}}\mathcal{L}\,.$$

$$A_\mu = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2+g'^2}}$$

$$Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2+g'^2}}$$

$$\not{D}^{\mathcal{Q}} = \gamma^\mu D_\mu^{\mathcal{Q}} = \gamma^\mu\left[\partial_\mu + G_\mu + W_\mu P_L + ig'(Y_L^{\mathcal{Q}}P_L + Y_R^{\mathcal{Q}}P_R)B_\mu\right]$$
$$\not{D}^{\mathcal{L}} = \gamma^\mu D_\mu^{\mathcal{L}} = \gamma^\mu\left[\partial_\mu + W_\mu P_L + ig'(Y_L^{\mathcal{L}}P_L + Y_R^{\mathcal{L}}P_R)B_\mu\right]\;,$$

$$e = \frac{gg'}{\sqrt{g^2+g'^2}}$$

Quarks and leptons belong to different (chiral) representations

$$\mathcal{Q} = \begin{pmatrix}\mathcal{U}\\ \mathcal{D}\end{pmatrix} \quad \mathcal{L} = \begin{pmatrix}\mathcal{N}\\ \mathcal{E}\end{pmatrix}$$

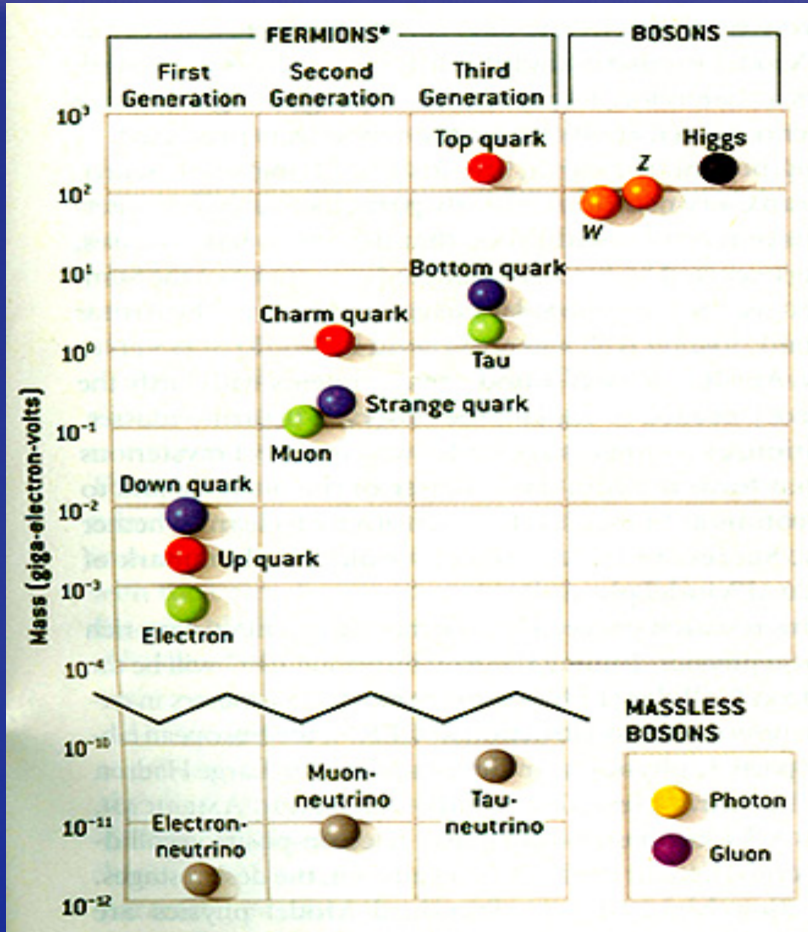
Cancelation of gauge and gravitational anomalies through an almost unique hypercharge asignement

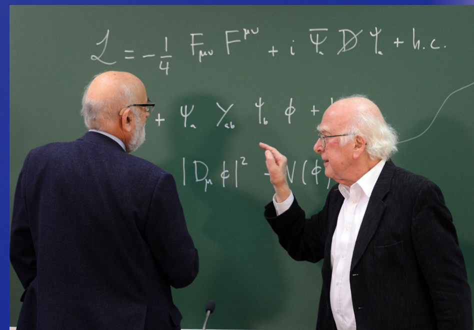
	$\mathcal{U}_R$	$\mathcal{U}_L$	$\mathcal{D}_R$	$\mathcal{D}_L$	$\mathcal{N}_L$	$\mathcal{E}_R$	$\mathcal{E}_L$
$\mathcal{Y}$	2/3	1/6	−1/3	1/6	−1/2	−1	−1/2
T_3	0	1/2	0	−1/2	1/2	0	−1/2
Q	2/3	2/3	−1/3	−1/3	0	−1	−1

$$\mathcal{U} = (u^\alpha, c^\alpha, t^\alpha)$$
$$\mathcal{D} = (d^\alpha, s^\alpha, b^\alpha)$$

$$\mathcal{N} = (\nu_e, \nu_\mu, \nu_\tau)$$
$$\mathcal{E} = (e^-, \mu^-, \tau^-)$$

But what about masses?





Gauge boson masses break gauge invariance

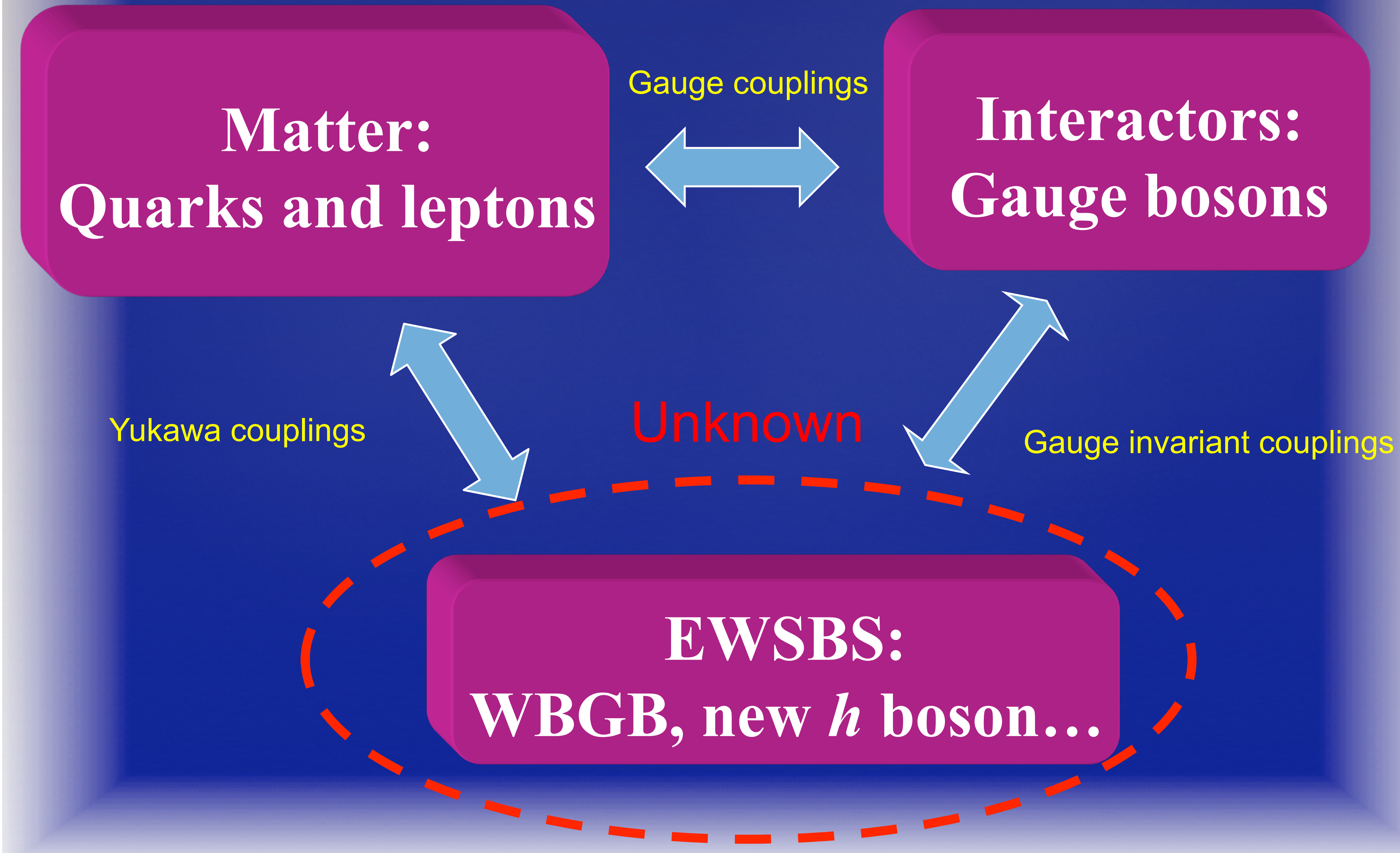
$$M_W^2 W_\mu^a W^{\mu a}$$

Dirac fermion masses break chiral gauge invariance

$$-m\bar{\Psi}\Psi = -m(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L)$$

Higgs
(Englert and Brout)
Mechanism

The Standard Model Structure



The Minimal Standard Model EWSBS

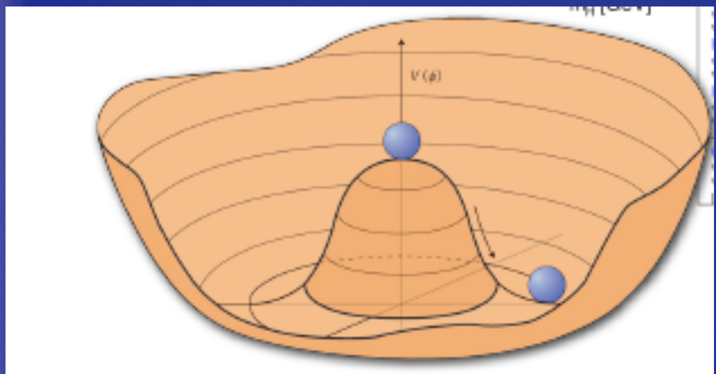
$$\mathcal{L}_{SBS} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) + \mathcal{L}_{YK}$$

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

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

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

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



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

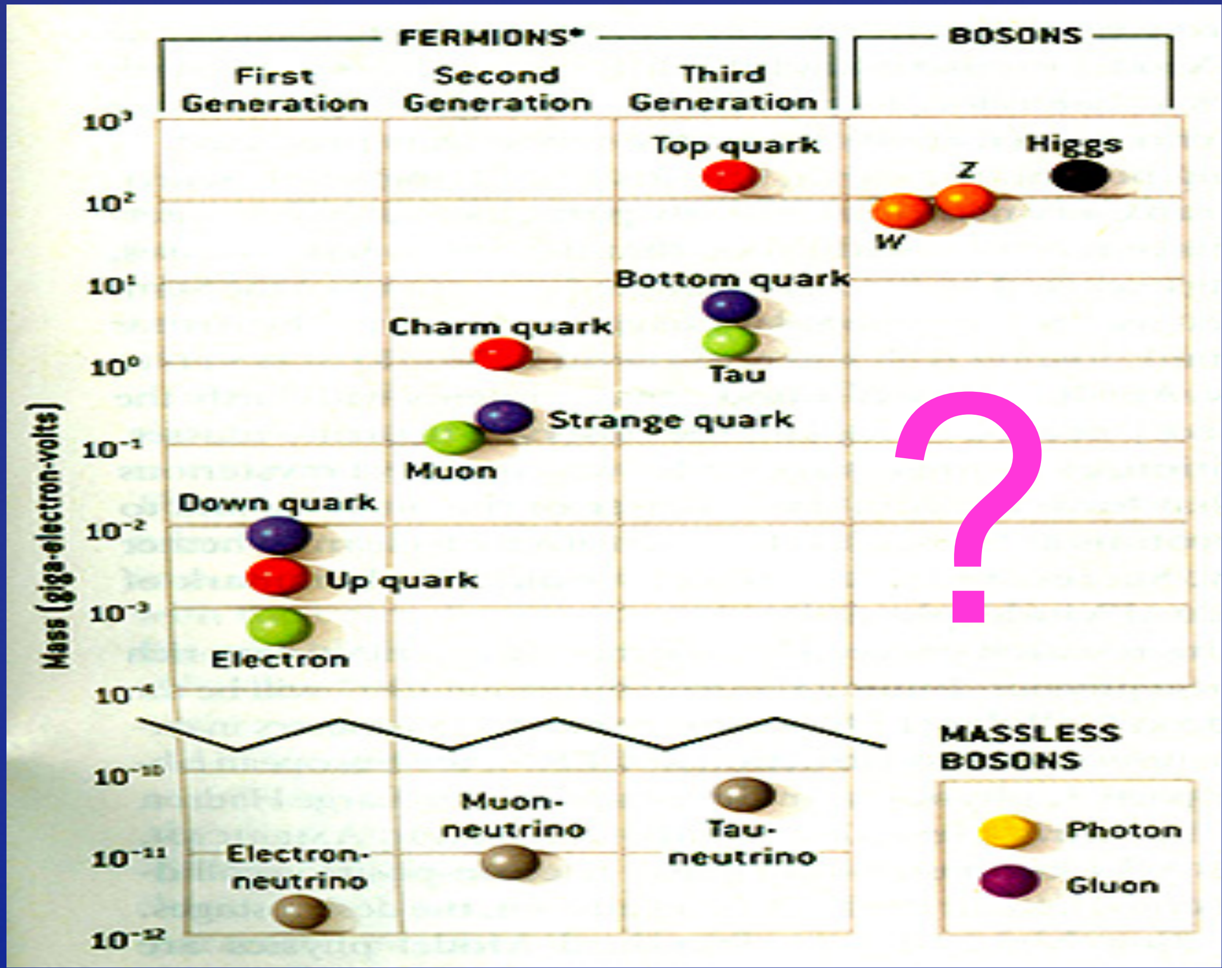
$$M_Z = \frac{M_W}{\cos\theta_W}$$

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

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

- 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 $h+v$.



The Standard Model can incorporate the gauge boson and femion masses but it cannot explain their values

Problems of the Minimal Standard Model

- Origin and nature of the Electroweak Symmetry Breaking

- Light scalars are unnatural because of the big radiative corrections to their masses and the issue of vacuum (meta) stability.

- Origin and values of its many parameters (masses, elements of the CKM and PMNS* matrices, couplings...)

- The strong CP problem

- Why **is** $\boldsymbol{v} \ll \boldsymbol{M_P}$?

- Dark matter and dark energy?

- What about gravity?

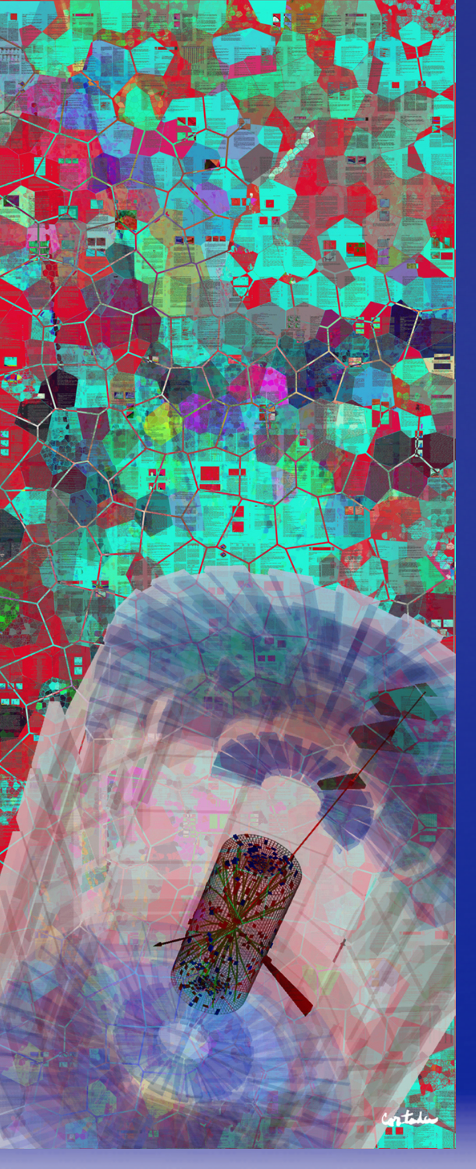
* Pontecorvo–Maki–Nakagawa–Sakata

So is the new Higgs like particle the MSM Higgs boson?

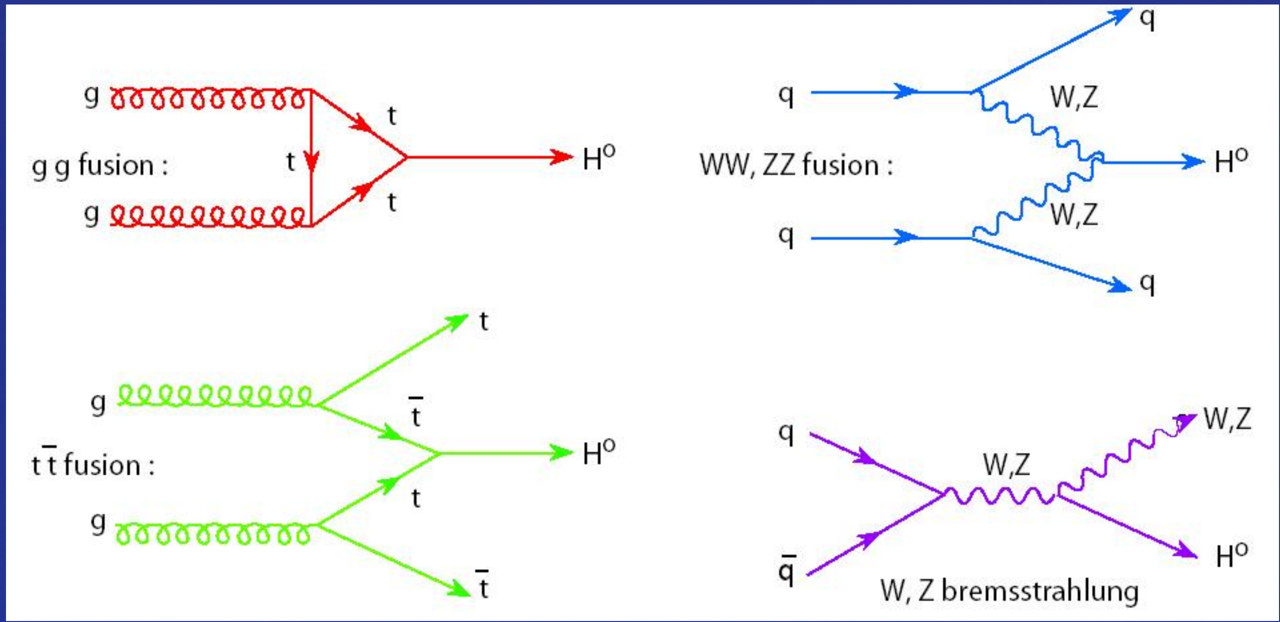
Is it elementary or composite?

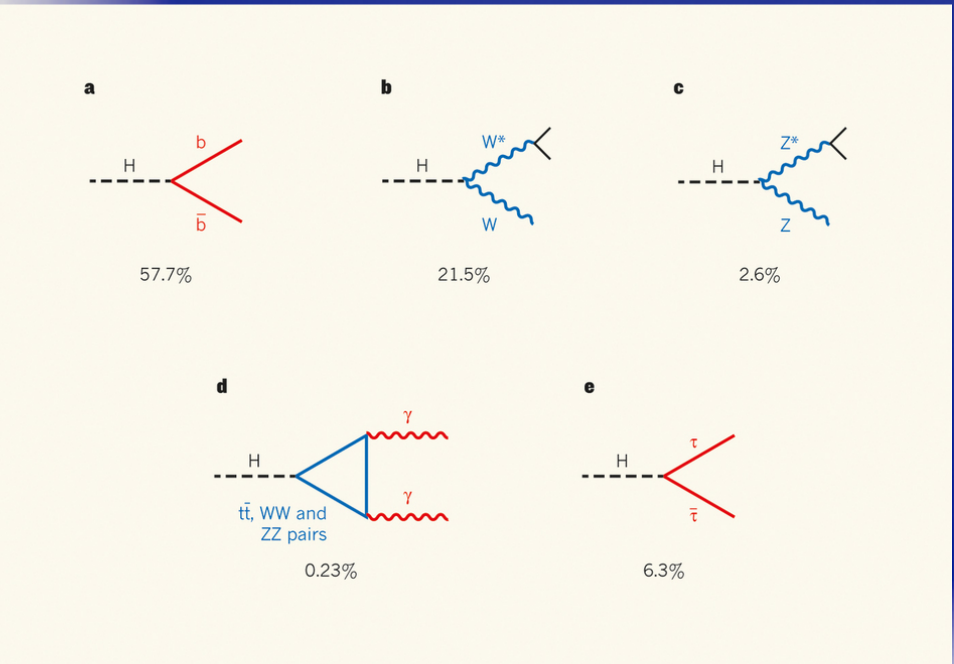
To answer this question we have to look carefuly at the new boson interactions which are well defined in MSM if it were the Higg boson.

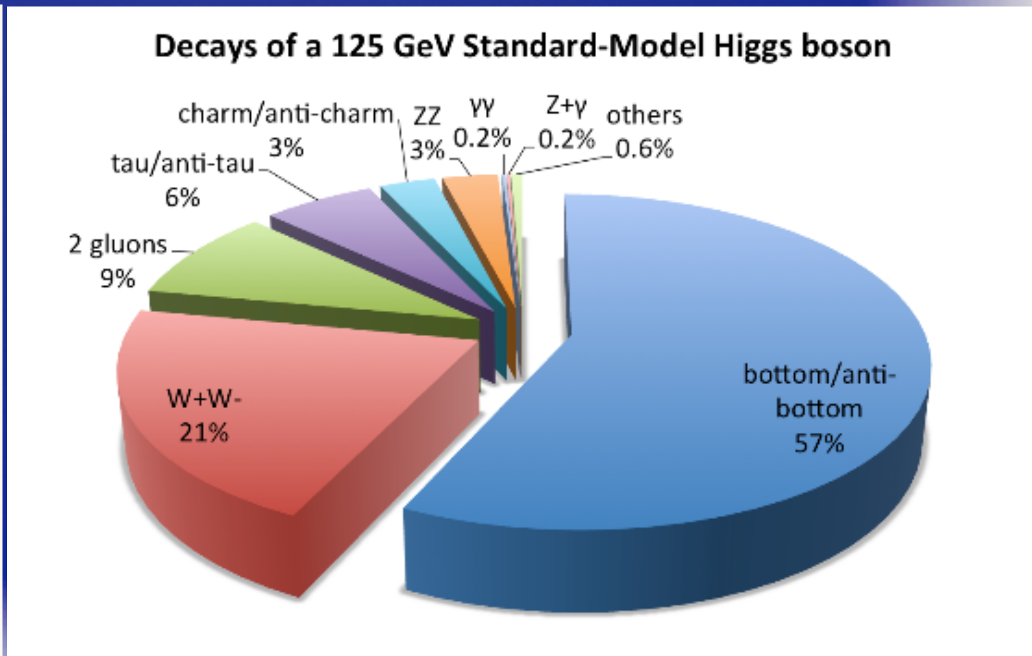
IV. The h(125) behavior



Production and decay of the MSM Higgs boson at the LHC





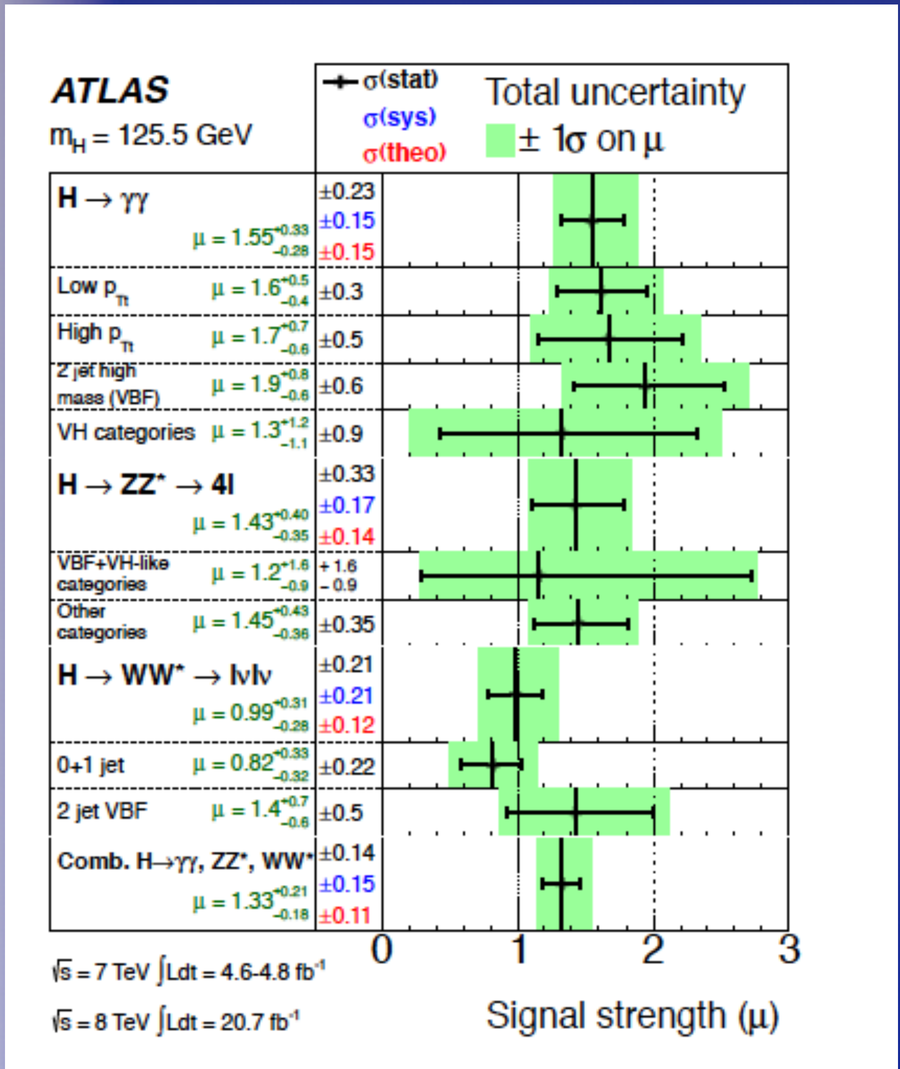


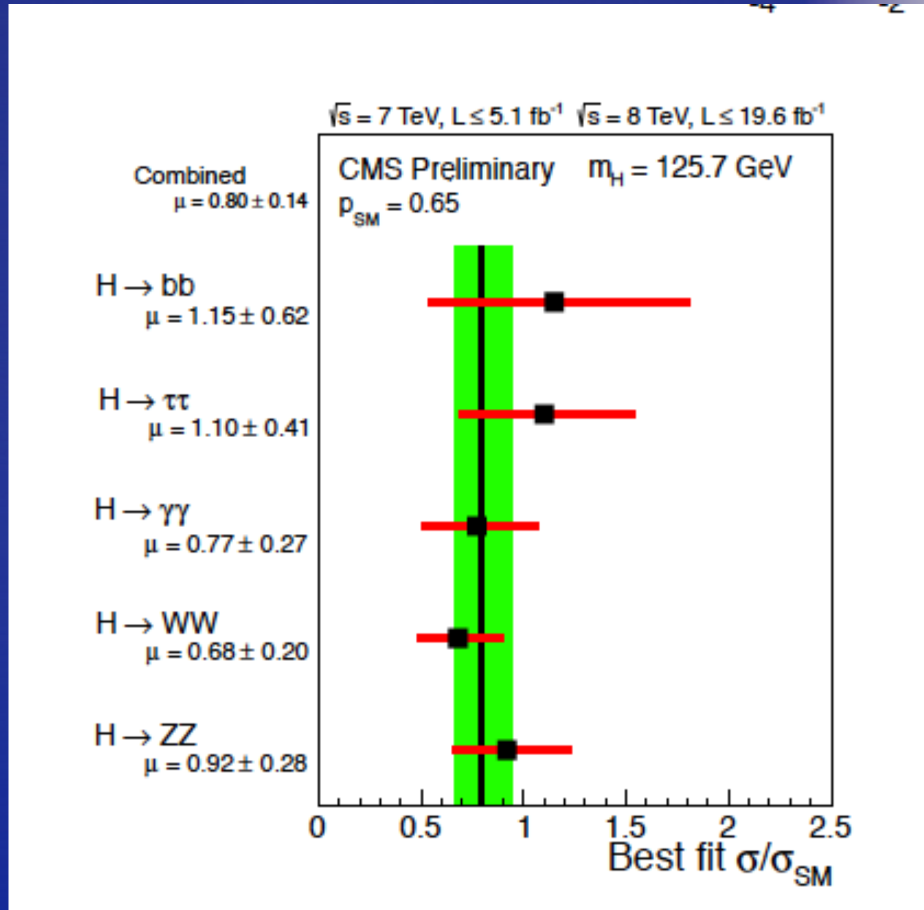
Observed decays at ATLAS, CMS and Tevatron

Signal Strengths

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

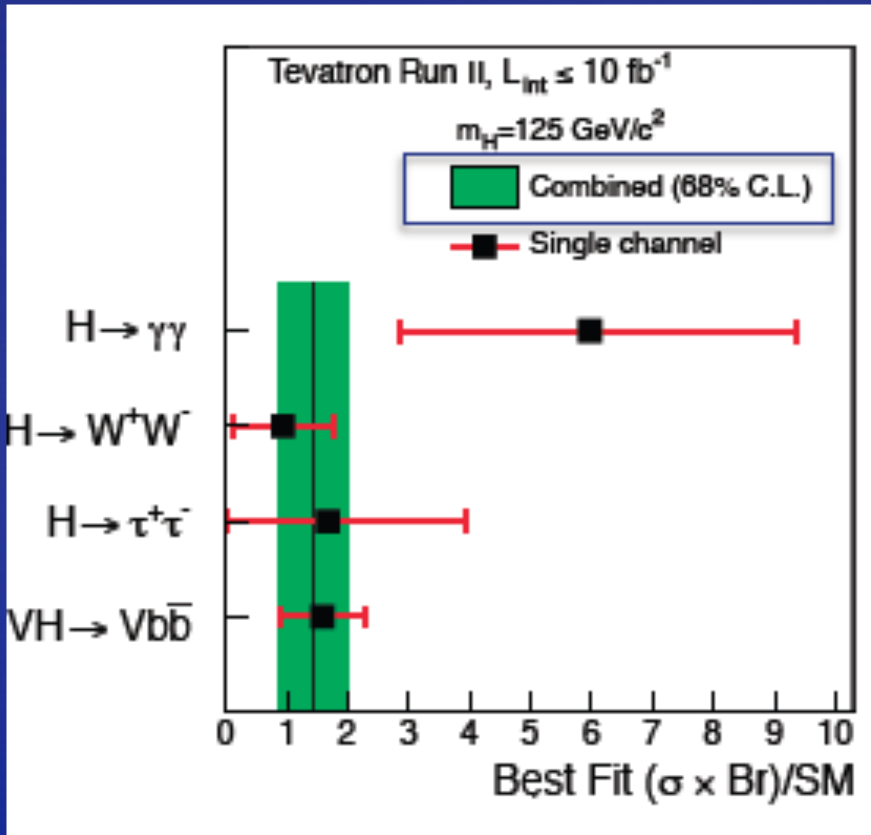
Decay Mode	ATLAS	CMS	Tevatron
$H \to bb$	$0.2^{+0.7}_{-0.6}$	1.15 ± 0.62	$1.59^{+0.69}_{-0.72}$
$H \to \tau\tau$	$0.7^{+0.7}_{-0.6}$	1.10 ± 0.41	$1.68^{+2.28}_{-1.68}$
$H \to \gamma\gamma$	$1.55^{+0.33}_{-0.28}$	0.77 ± 0.27	$5.97^{+3.39}_{-3.12}$
$H \to WW^*$	$0.99^{+0.31}_{-0.28}$	0.68 ± 0.20	$0.94^{+0.85}_{-0.83}$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





$\mu = (1.33 \pm 0.20)$

$\mu = (0.80 \pm 0.14)$


Tevatron Run II, $L_{int} \leq 10\ fb^{-1}$
m_H=125 GeV/c^2
Combined (68% C.L.)
Single channel
$H \to \gamma\gamma$
$H \to W^+W^-$
$H \to \tau^+\tau^-$
$VH \to Vb\bar{b}$
0 1 2 3 4 5 6 7 8 9 10
Best Fit $(\sigma \times Br)$/SM

$\mu = (1.44 \pm 0.60)$

Couplings

Primary bosonic

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

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

Primary fermionic

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

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

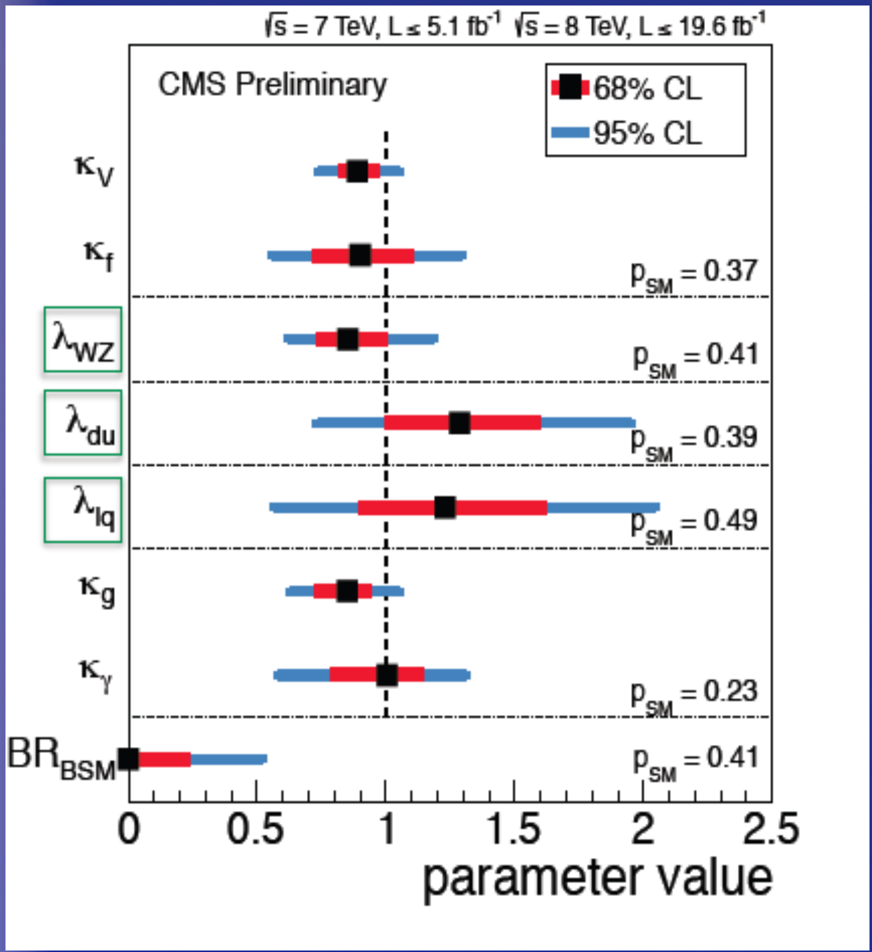
Secundary bosonic

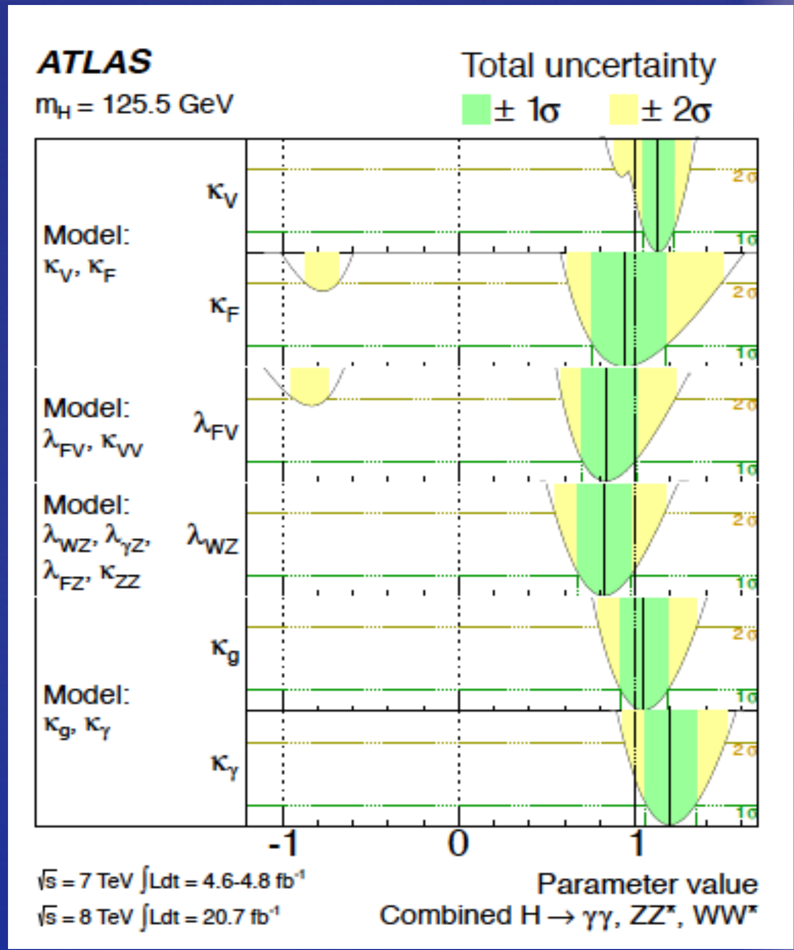
$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

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

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

Destructive interference





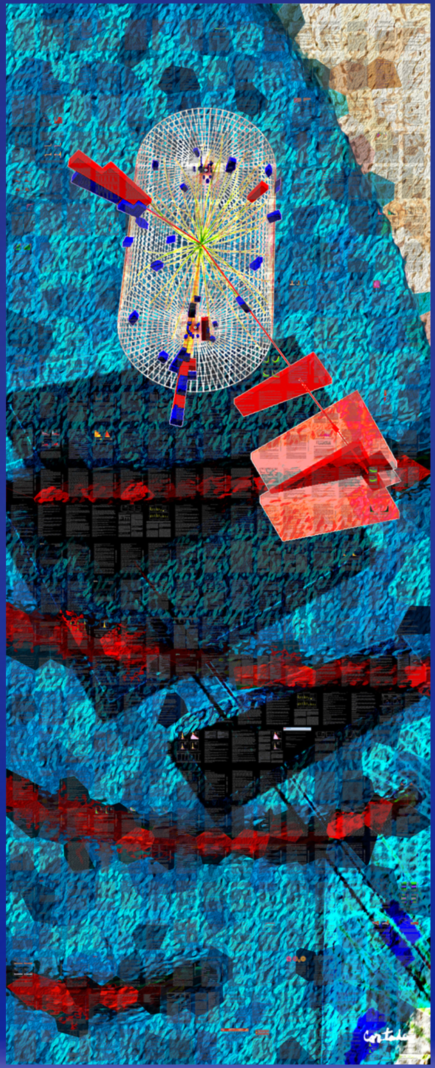
– ATLAS: κ_g =(1.04 ± 0.14) at 68% CL - κ_γ = (1.20 ± 0.15) at 68% CL

– CMS: κ_g [0.63,1.05] at 95% CL - κ_γ [0.59,1.30] at 95% CL

The 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).

V. The case for a Strongly Interacting SBS



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

a) Linear representation:

- The ω^a and the *h* fit 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: $O(d)/\Lambda^{d-4}$ (*d*=operator dimension, *d=4,6,8…*)

b) Non-linear representation:

- *h* is a *SU(2)* singlet and ω^a are coordinates on a $SU(2)XSU(2)/SU(2)=SU(2)=S^3$ coset
- Lesser symmetry and more independent higher dimension effective operators
- Derivative expansion
-
- ECLh with $\mathcal{F}(h)$ 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

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 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 (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 ω^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 $\quad U$ = WBGB Fields

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

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

$$\mathcal{L}_{YK} = -v\bar{\mathcal{Q}}_L H_{\mathcal{Q}} U \mathcal{G}_{\mathcal{Q}}(h) \mathcal{Q}_R + h.c.$$

$$\mathcal{G}_{\mathcal{Q}}(h) = \begin{pmatrix} \mathcal{G}_{\mathcal{U}}(h) & 0 \\ 0 & \mathcal{G}_{\mathcal{D}}(h) \end{pmatrix}$$

$$\mathcal{Q}^T = (\mathcal{U}, \mathcal{D})$$

$$\mathcal{U}^T = (u, c, t)$$

$$\mathcal{D}^T = (d, s, b)$$

$$\mathcal{G}_{\mathcal{U}}(h) = \mathcal{G}_{\mathcal{D}}(h) = \mathcal{G}(h) = 1 + c\frac{h}{v} + c_2\left(\frac{h}{v}\right)^2 + \ldots$$

$$H_{\mathcal{Q}} = \begin{pmatrix} H_{\mathcal{U}} & 0 \\ 0 & H_{\mathcal{D}} \end{pmatrix}$$

$$\mathcal{M}_{\mathcal{U},\mathcal{D}} = v H_{\mathcal{U},\mathcal{D}}$$

NLO-Lagrangian

(extended Apelquist-Longhitano)

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

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

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

Alonso, Gavela, Merlo, Rigolin and Yepes

LO ECLh (2 derivatives)

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

NLO ECLh (4 derivatives)

Apelquist-Longhitano

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

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!

Interesting particular cases:

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

Linear, renormalizable, unitary, predictor and weakly interacting

No Higgs Model

$f=v$ $a=b=c=0$ ⇒ Old ECL

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

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

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

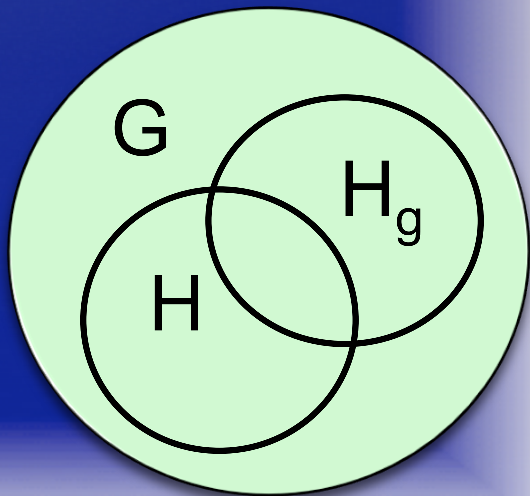
Halyo, Goldberber, Grinstein, Skiba

Minimal Composite Higgs Model

$SO(5)/SO(4)$ ⇒

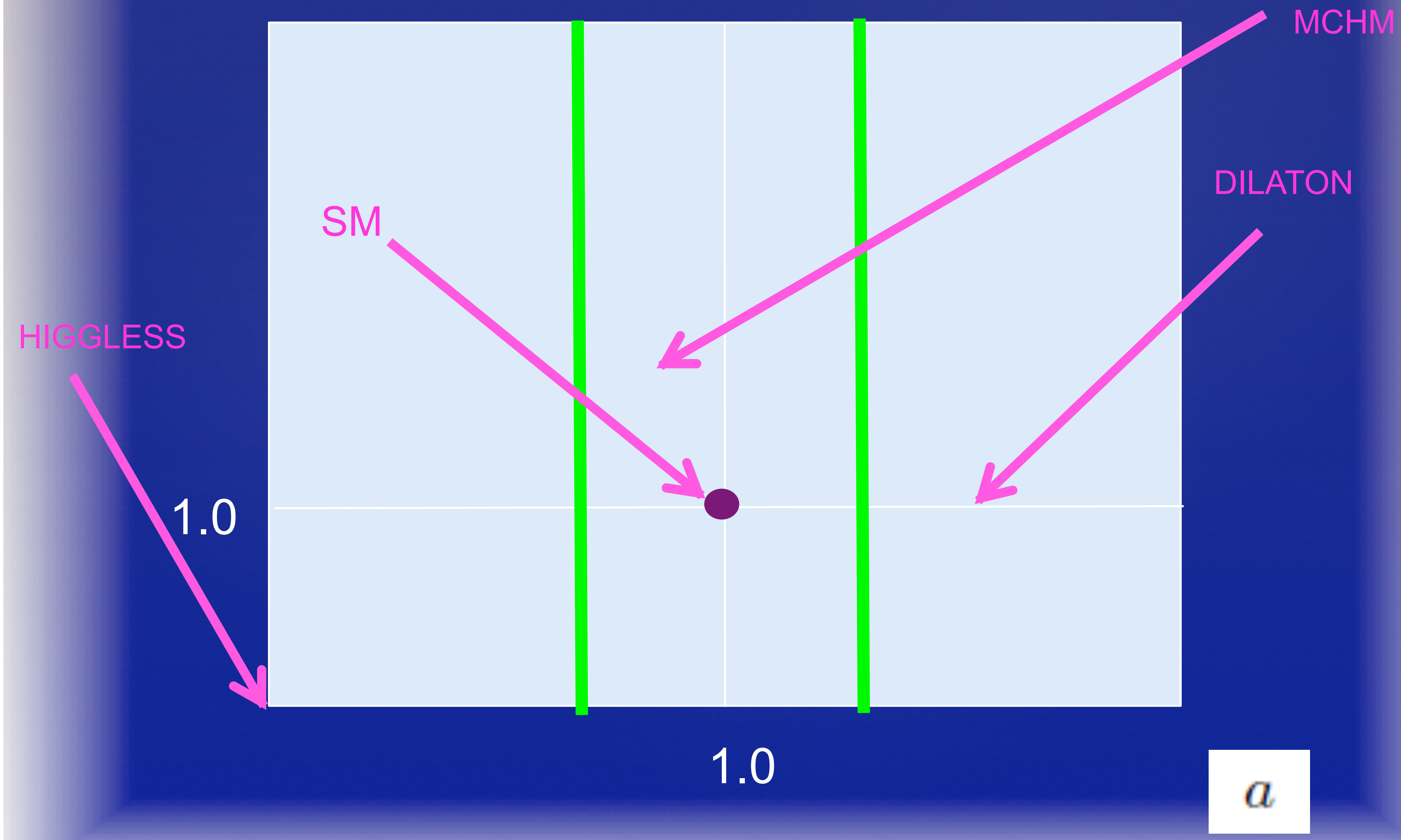
MCHM4	MCHM5
$a=\sqrt{1-\xi}$	$a=\sqrt{1-\xi}$
$b=1-2\xi$	$b=1-2\xi$
$c=\sqrt{1-\xi}$	$c=\frac{1-2\xi}{\sqrt{1-\xi}}$
$d_3=\sqrt{1-\xi}$	$d_3=\frac{1-2\xi}{\sqrt{1-\xi}}$

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



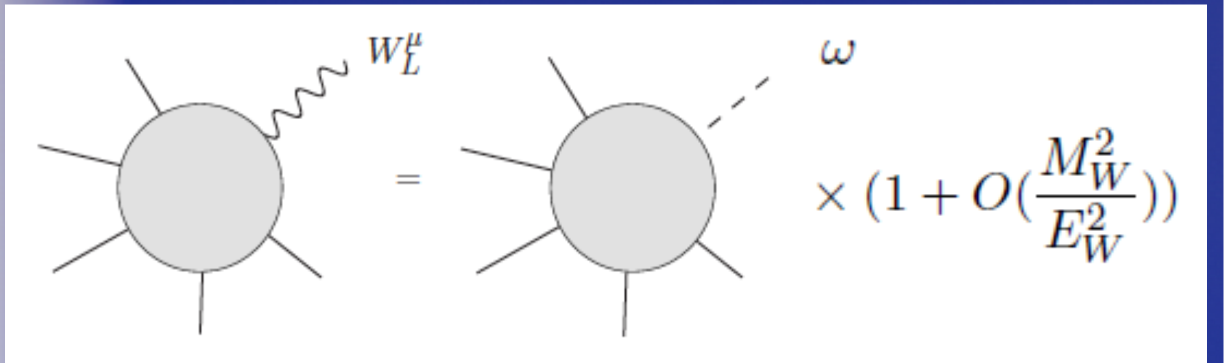
Kaplan, Georgi
Agashe, Contino, Pomarol, Da Rold

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



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

The Equivalence Theorem (for R gauges)



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

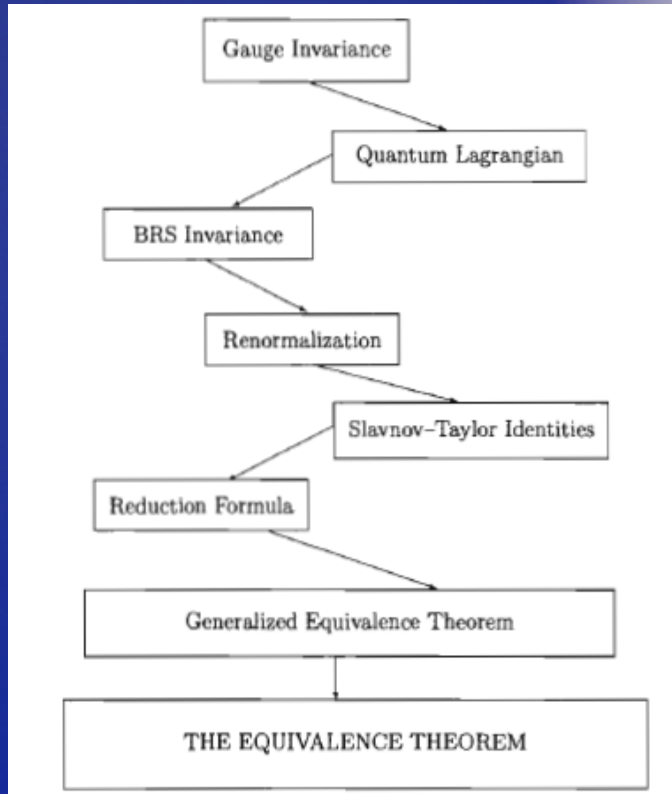


Fig. 7.3. The proof of the equivalence theorem

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

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

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

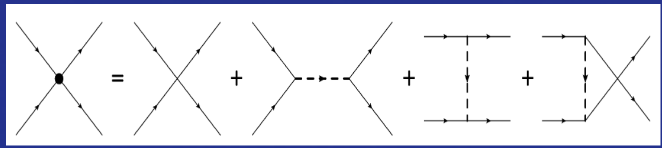
$$g = g' = H_{YK} = 0$$

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

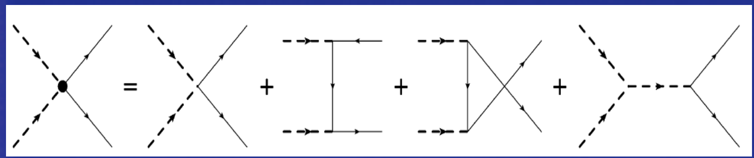
$$U(x) \;=\; \sqrt{1 - \frac{\omega^2}{v^2}} + i\frac{\tilde{\omega}}{v}$$

LO amplitudes:

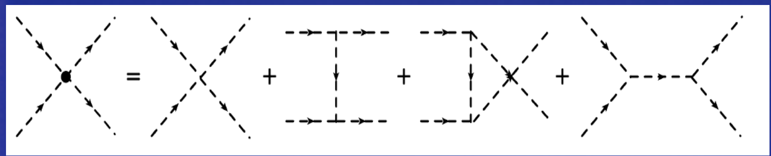
$M_h = 0$ $\quad$ $M_h^2 \ll s < 4\pi v \simeq 3\,\mathrm{TeV}.$



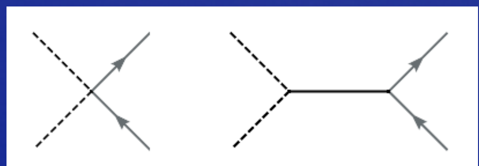
$$T(\omega^+\omega^- \to \omega^+\omega^-) = \frac{s+t}{v^2}(1-a^2)$$



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



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



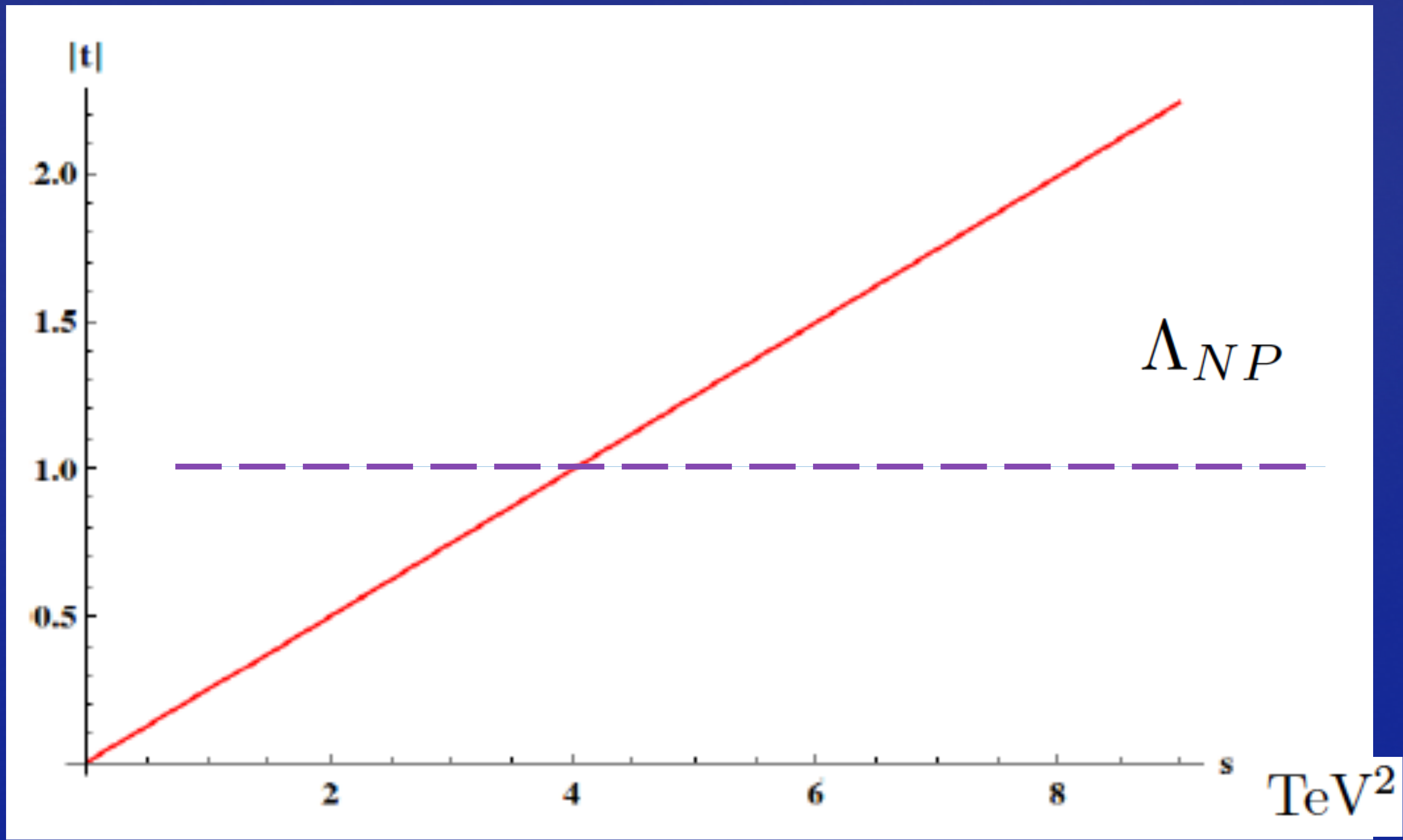
$$T(\omega^a\omega^b \to t_L\bar{t}_R) = \frac{M_t}{v^2}(1-ac)\sqrt{s-4M_t^2}\,\delta_{ab}$$

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

$$\Lambda_{NP}$$

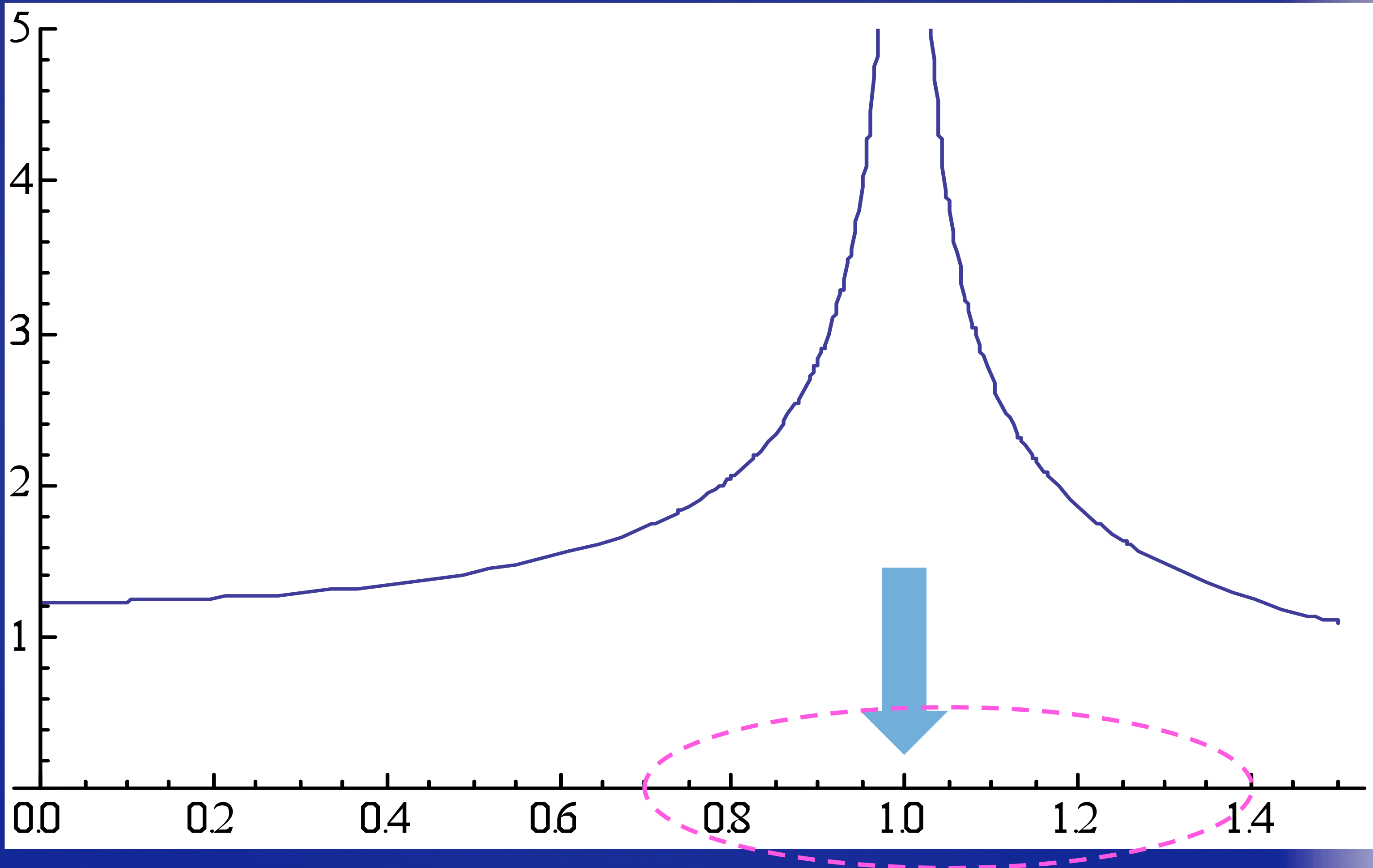
All of these amplitudes violate badly unitarity at some point



New physics scale:

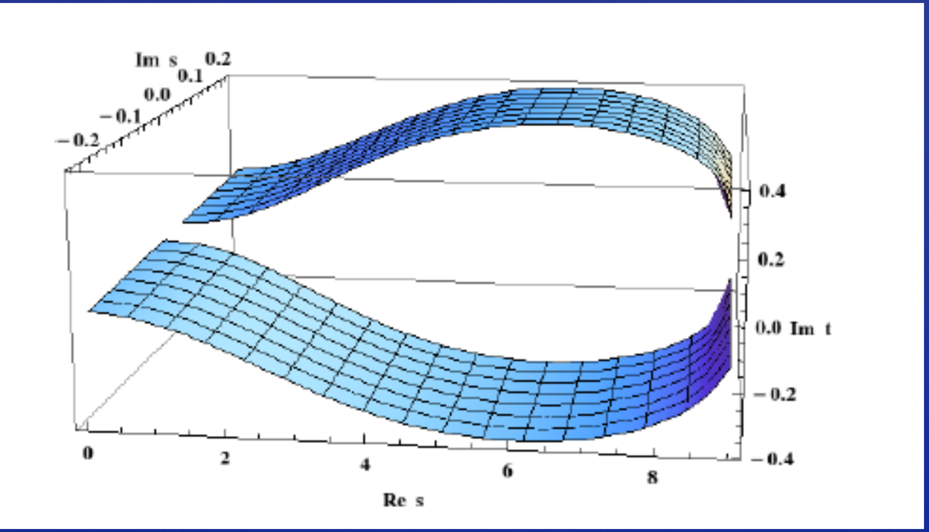
Λ_{NP}

TeV



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

VI. 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
- $\overline{\text{MS}}$ scheme for the NLO derivatives couplings bellow

(no other renormalization is needed for vanishing *h* mass)

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

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

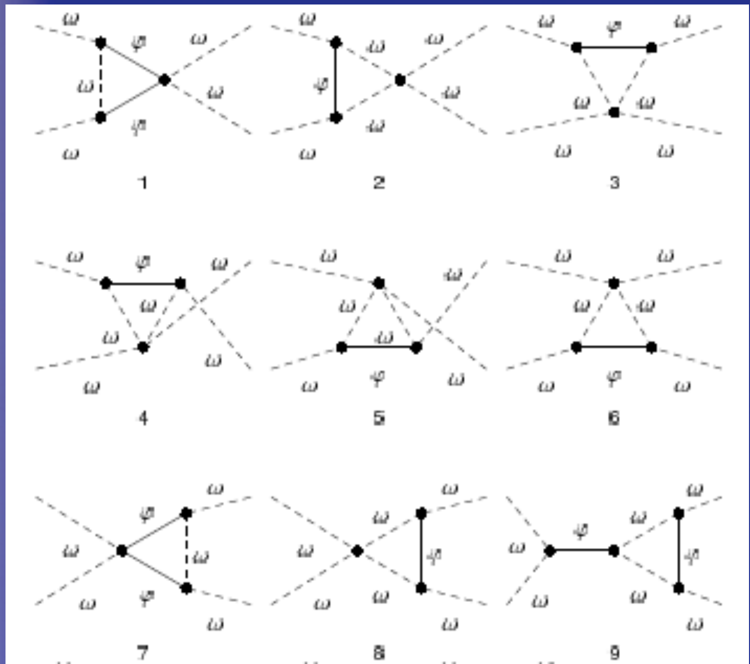
$$+ \; a_1 \mathrm{Tr}(U \hat{B}_{\mu\nu} U^\dagger \hat{W}^{\mu\nu}) + i a_2 \mathrm{Tr}(U \hat{B}_{\mu\nu} U^\dagger [V^\mu, V^\nu]) - i a_3 \mathrm{Tr}(\hat{W}_{\mu\nu}[V^\mu, V^\nu]) - \frac{c_\gamma}{2}\frac{h}{v} e^2 A_{\mu\nu} A^{\mu\nu}$$

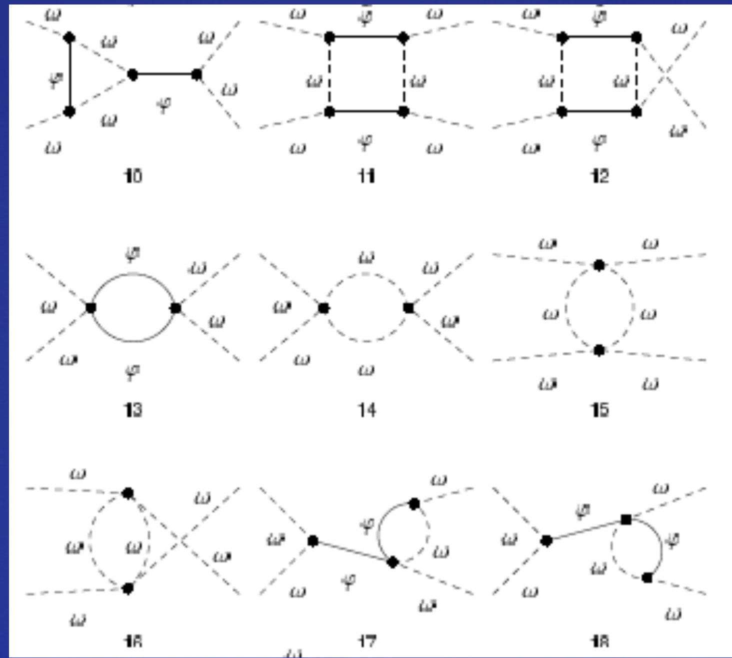
FeynRules: Generates Feynman rules from the Lagrangian. as an output produces the input for FeynArts.

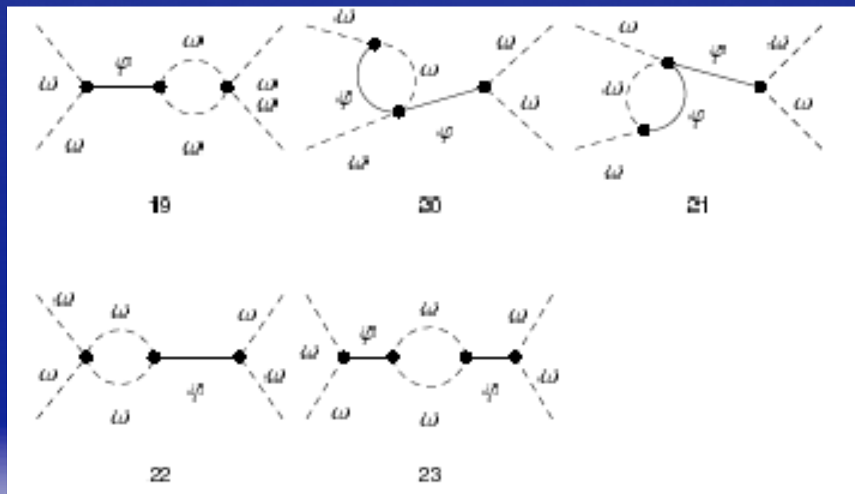
FeynArts: Obtains the Feynman diagrams to some given order. Introduces ”symbolically” the vertices generated by FeynRules.

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)

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

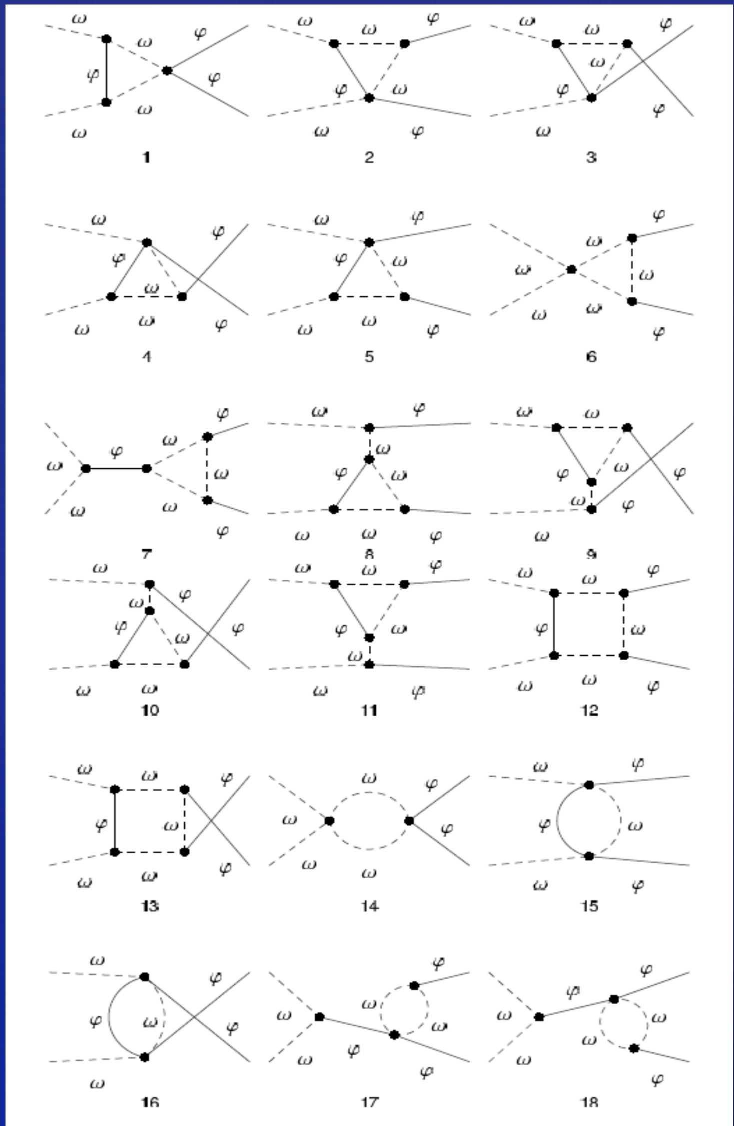
$$T_{abcd} = A(s,t,u)\delta_{ab}\delta_{cd} + B(s,t,u)\delta_{ac}\delta_{bd} + C(s.t.u)\delta_{ad}\delta_{bc}$$

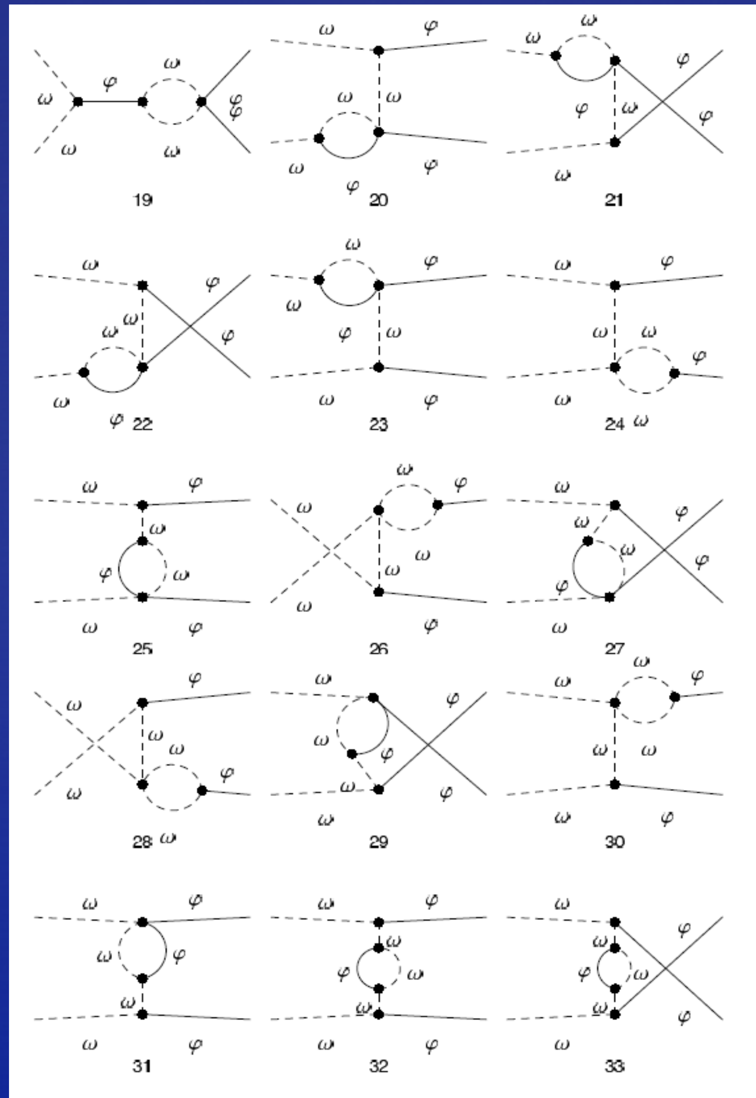
$$\begin{aligned}
A(s,t,u) = & \frac{s}{v^2}(1-a^2) + \frac{4}{v^4}[2a_5^r(\mu)s^2 + a_4^r(\mu)(t^2+u^2)] \\
& + \frac{1}{16\pi^2 v^4}\left(\frac{1}{9}(14a^4 - 10a^2 - 18a^2b + 9b^2 + 5)s^2 + \frac{13}{18}(a^2-1)^2(t^2+u^2)\right. \\
& - \frac{1}{2}(2a^4 - 2a^2 - 2a^2b + b^2 + 1)s^2 \log\frac{-s}{\mu^2}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

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

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

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

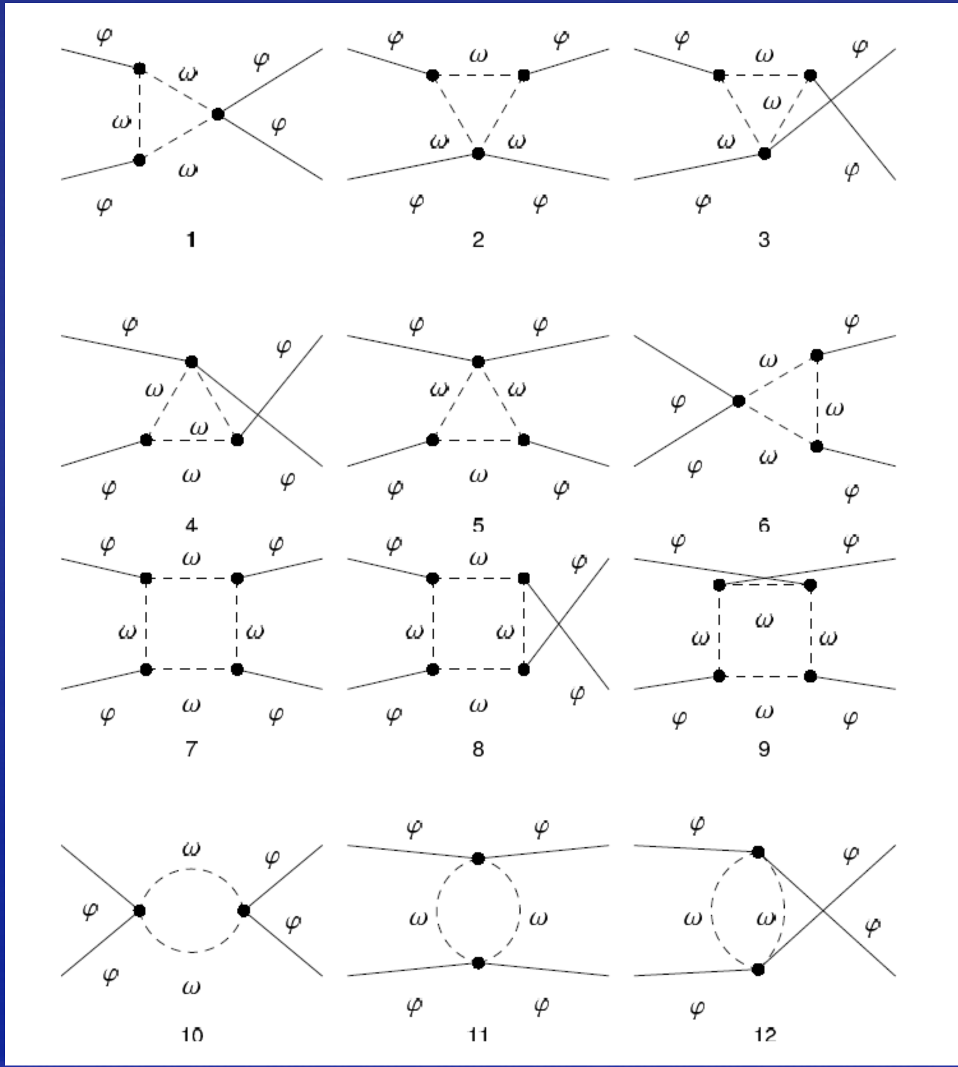
$$\omega_a \omega_b \to hh$$

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

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

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

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



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

h h ⟹ *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:

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

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

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

$$\begin{aligned} A_0(s,t,u) &= 3A(s,t,u) + A(t,s,u) + A(u,t,s) \\ A_1(s,t,u) &= A(t,s,u) - A(u,t,s) \\ A_2(s,t,u) &= A(t,s,u) + A(u,t,s)\ . \end{aligned}$$

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

$I = 0$

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

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

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

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

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

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

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

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

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

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

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

$IJ = 00$

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

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

$$\begin{aligned}
K_0' &= \frac{\sqrt{3}}{32\pi v^2}(a^2-b) \\
B_0'(\mu) &= \frac{\sqrt{3}}{16\pi v^4}\left(\delta(\mu)+\frac{\eta(\mu)}{3}\right) + \frac{\sqrt{3}}{18432\pi^3 v^4}(a^2-b)[72(1-a^2)+(a^2-b)] \\
D_0' &= -\frac{\sqrt{3}(a^2-b)^2}{9216\pi^3 v^4} \\
E_0' &= -\frac{\sqrt{3}(a^2-b)(1-a^2)}{512\pi^3 v^4}
\end{aligned}$$

$\omega\omega \to hh$

$$\begin{aligned}
K_2' &= 0 \\
B_2'(\mu) &= \frac{\eta(\mu)}{160\sqrt{3}\pi v^4} + \frac{83(a^2-b)^2}{307200\sqrt{3}\pi^3 v^4} \\
D_2' &= -\frac{(a^2-b)^2}{7680\sqrt{3}\pi^3 v^4} \\
E_2' &= 0 \,.
\end{aligned}$$

$hh \to hh$

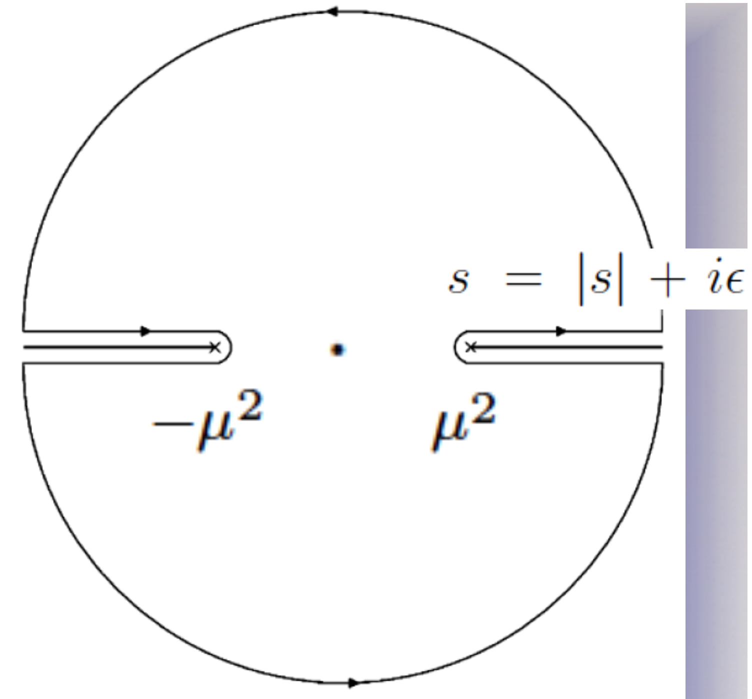
The Inverse Amplitude Method

A.D. , Herrero, Truong, Pelaez…

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

$$I \neq 0$$

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



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

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

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

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

$$A^{NLO}(s) = b_1 s + b_2 s^2 + \frac{s^3}{\pi}\int_{\mu^2}^{\infty}\frac{ds' \operatorname{Im} A^{NLO}(s')}{s'^3(s'-s-i\epsilon)} + \frac{s^3}{\pi}\int_{-\infty}^{-\mu^2}\frac{ds' \operatorname{Im} A^{NLO}(s')}{s'^3(s'-s-i\epsilon)}$$

$$A^{NLO}(s) = b_1 s + b_2 s^2 + Ds^2\log\frac{s}{\mu^2} + Es^2\log\frac{-s}{\mu^2}$$

$$b_1 = K$$

$$b_2 = B(\mu^2)$$

$$G(s) = (A^{(0)}(s))^2/A(s)$$

Inverse Amplitude

$$G(s) = g_1 s + g_2 s^2 + \frac{s^3}{\pi}\int_0^\infty \frac{ds' ImG(s')}{s'^3(s'-s-i\epsilon)} + \frac{s^3}{\pi}\int_{-\infty}^0 \frac{ds' ImG(s')}{s'^3(s'-s-i\epsilon)}$$

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

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

$$G(s) \simeq A^{(0)}(s) - A^{(1)}(s) \Rightarrow \boxed{A_{IJ}^{IAM}(s) = \frac{(A_{IJ}^{(0)}(s))^2}{A_{IJ}^{(0)}(s) - A_{IJ}^{(1)}(s)}}$$

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

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

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.

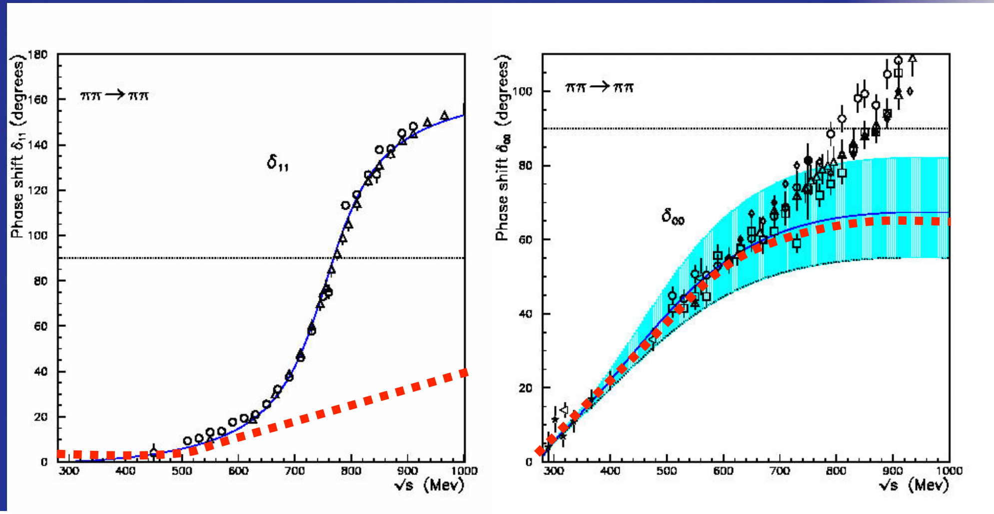
$$F_{IJ}^{IAM} = F_{IJ}^{(0)}(F_{IJ}^{(0)} - F_{IJ}^{(1)})^{-1}F_{IJ}^{(0)}$$

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

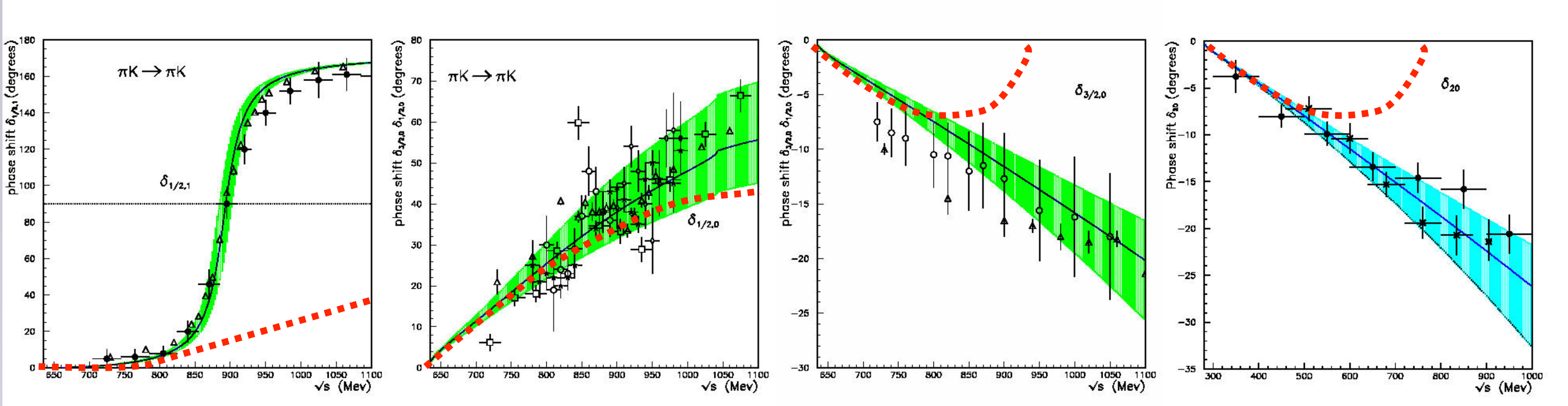
The Inverse Amplitude Method in ChPT

Chiral Perturbation Theory plus Dispersion Relations

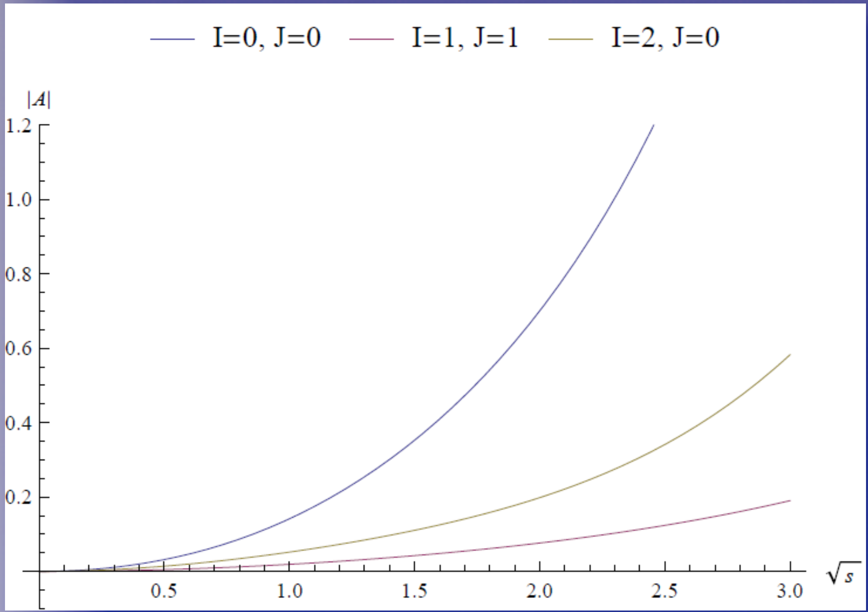
Simultaneous description of ππ→ππ and πK→πK up to 800-1000 MeV including resonances

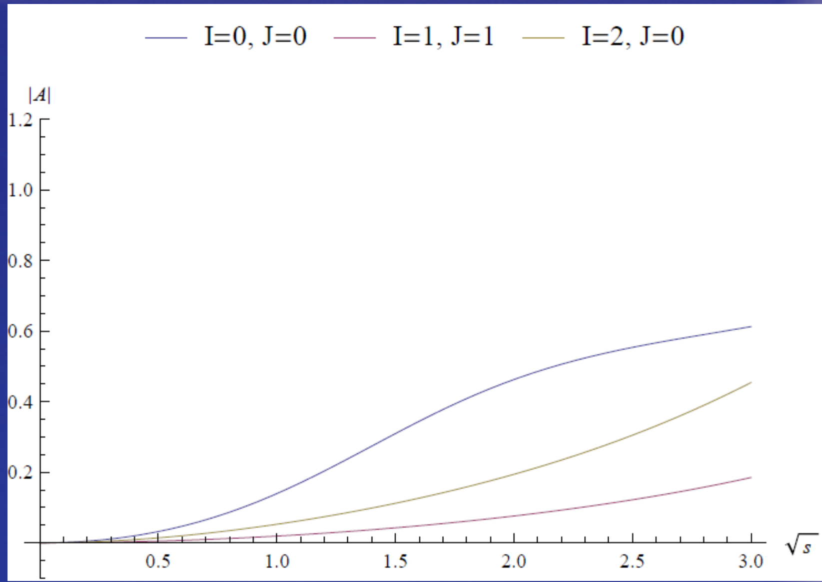


Lowest order ChPT (WeinbergTheorems) and even one-loop computations are only valid at very low energies

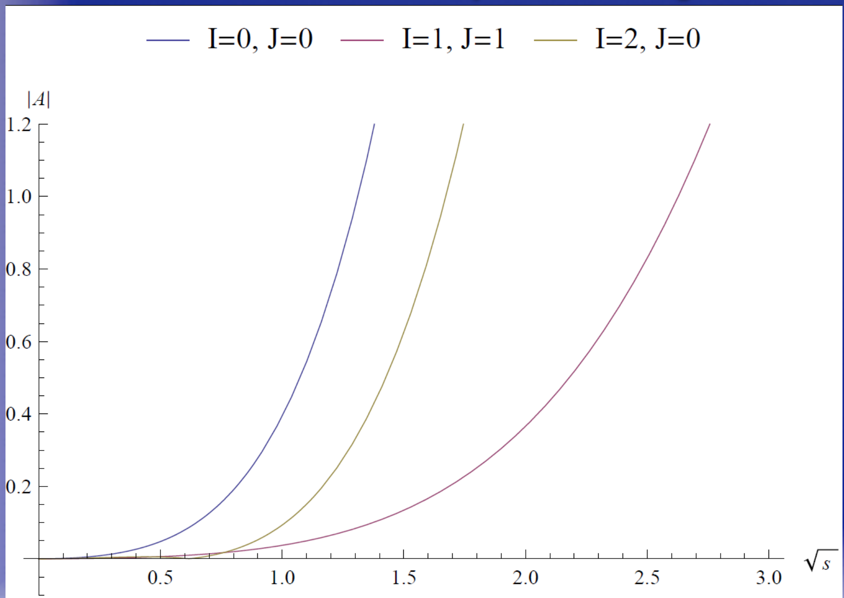


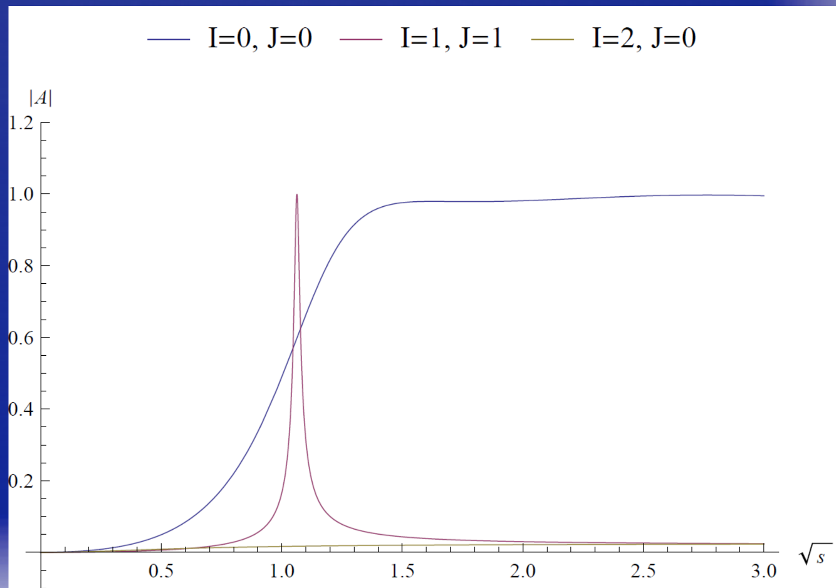
$a = 0.8$, $b = 1$, $a_4 = 0$, $a_5 = 0$, $WW \to WW$;



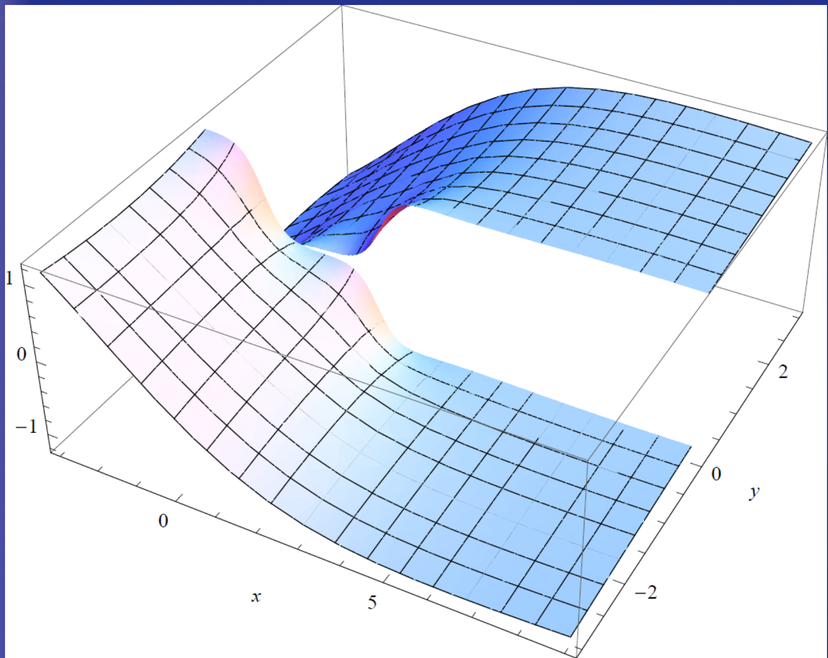


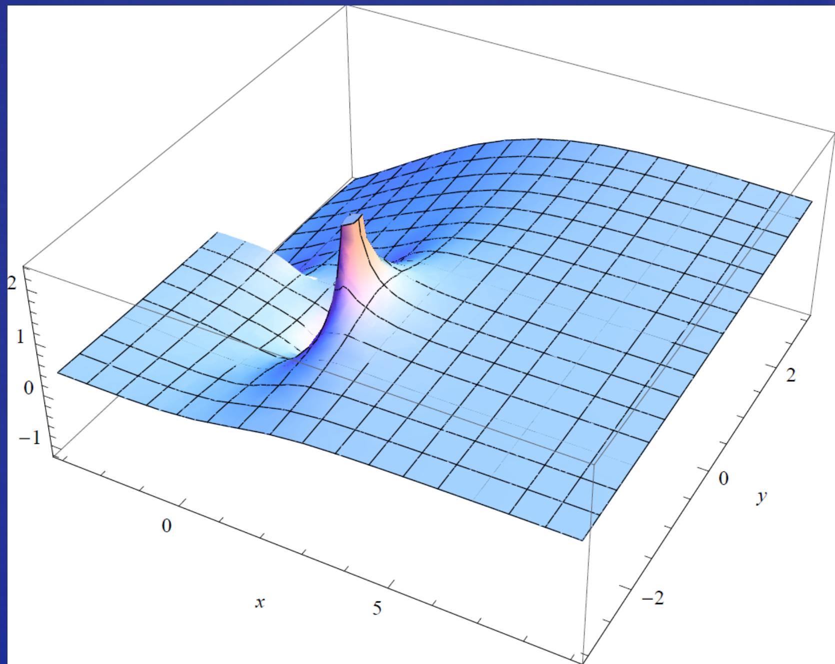
$a = 0.8$, $b = 1$, , $a_4 = 0$, $a_5 = 0.005$ $WW \to WW$





$a = 0.9, \quad b = 1, \; \mathbf{a_4} = 0.005 \;\; I=J=0$

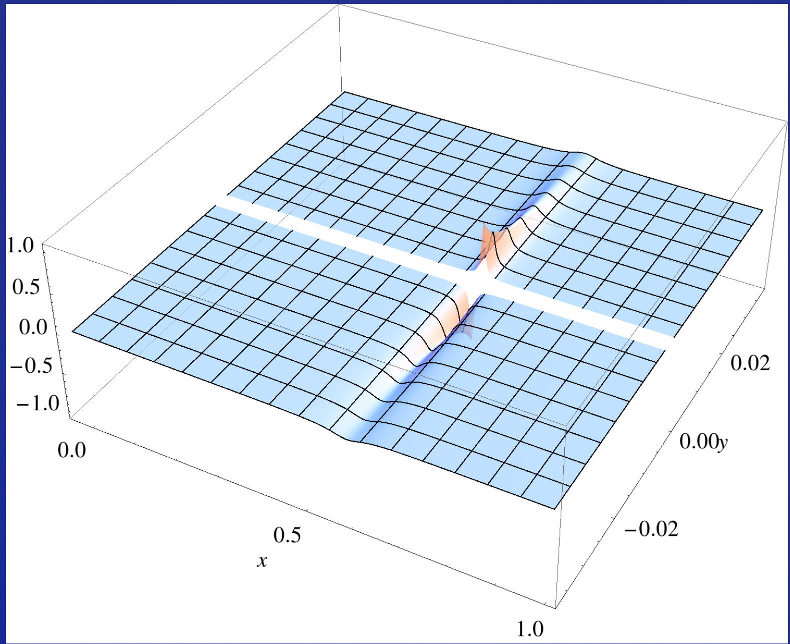




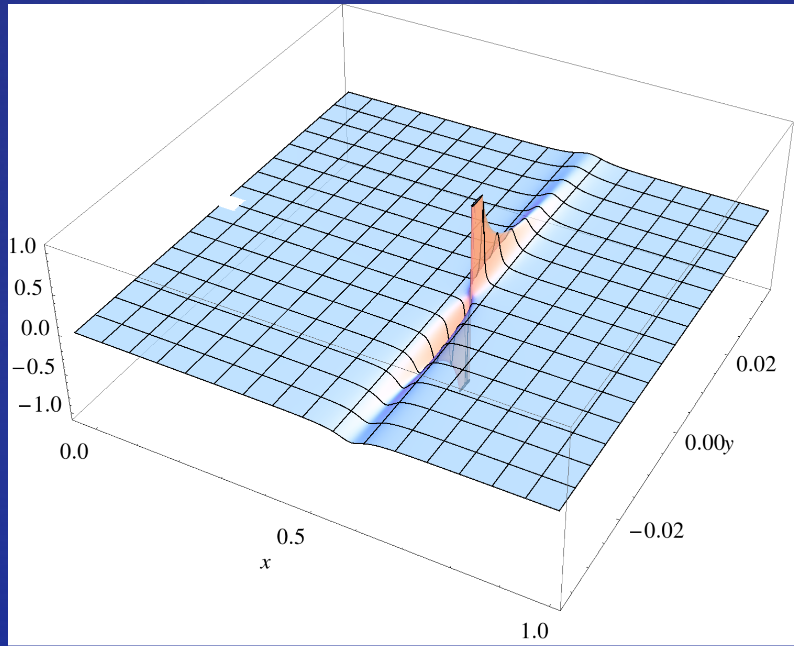
Im A: 1º Riemann Sheet

Im A: 2º Riemann Sheet

$a = 0.9, \quad b = 1, \mathbf{a_4} = 0.005 \quad I=J=1$

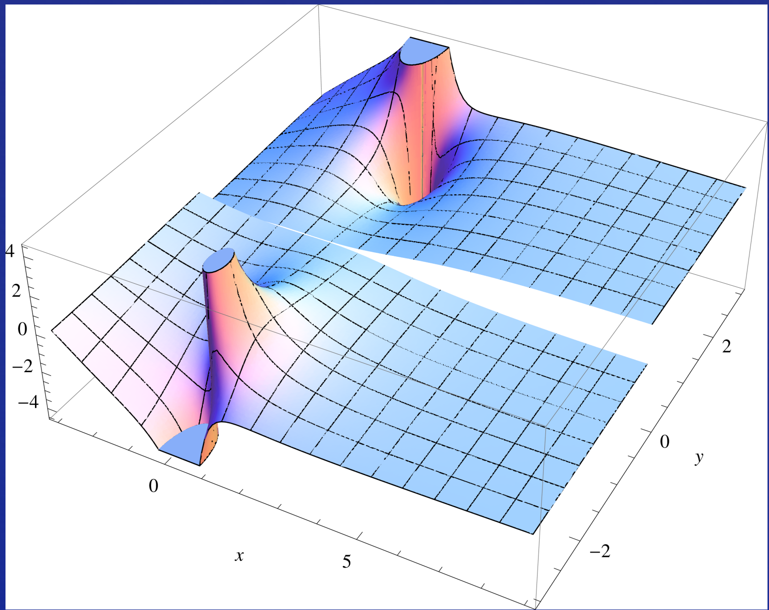


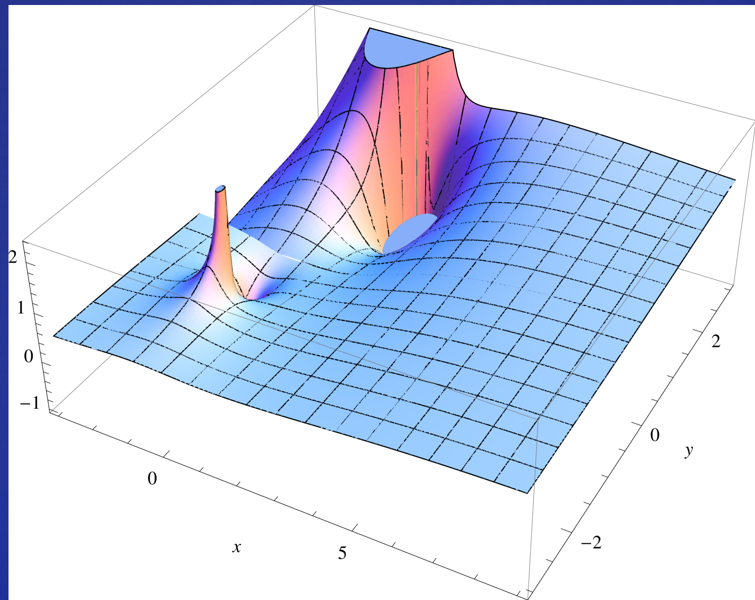
Im A: 1º Riemann Sheet



Im A: 2º Riemann Sheet

$a = 0.9, \quad b = 1, \mathbf{a_4} = -0.005, I=2, J=0$

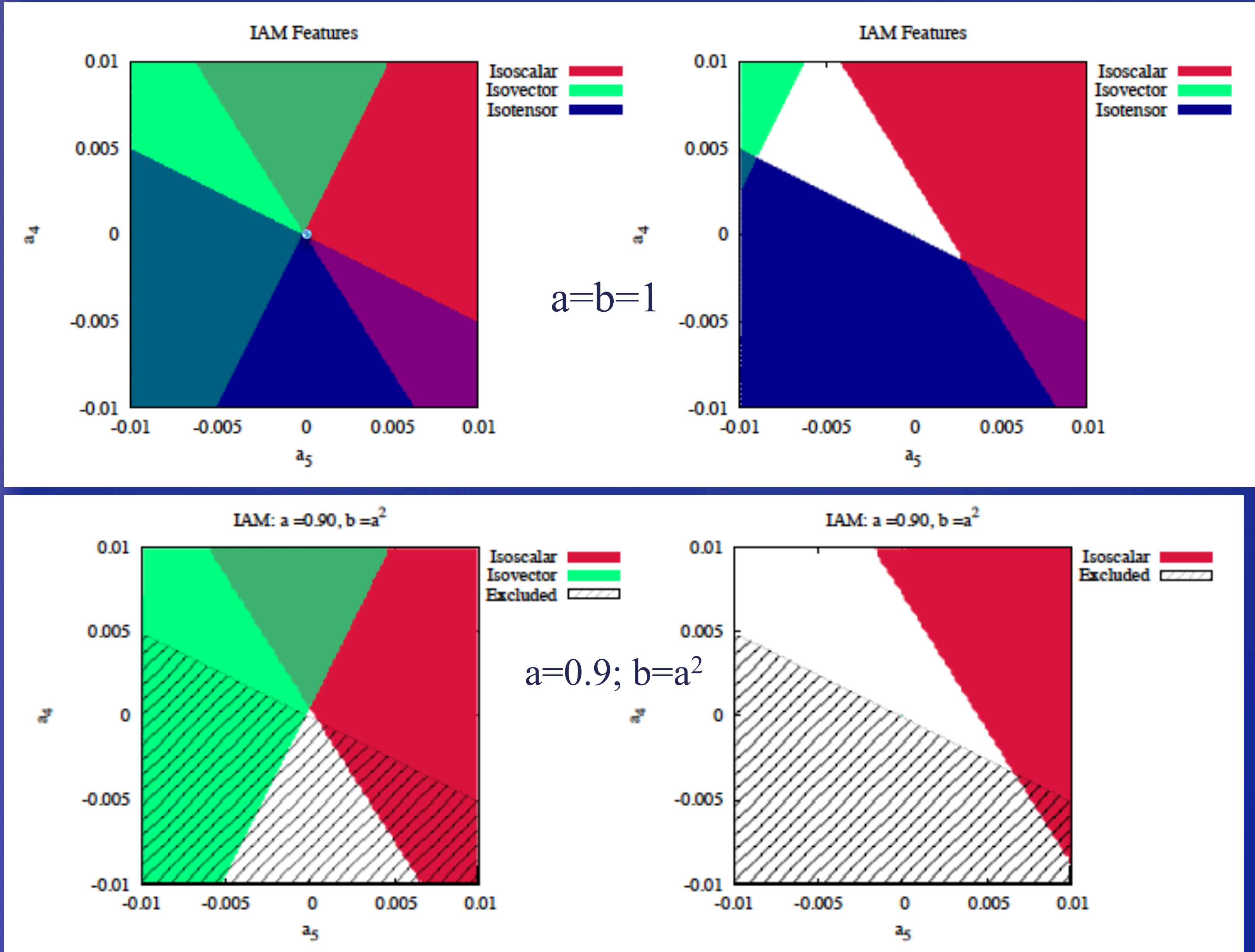




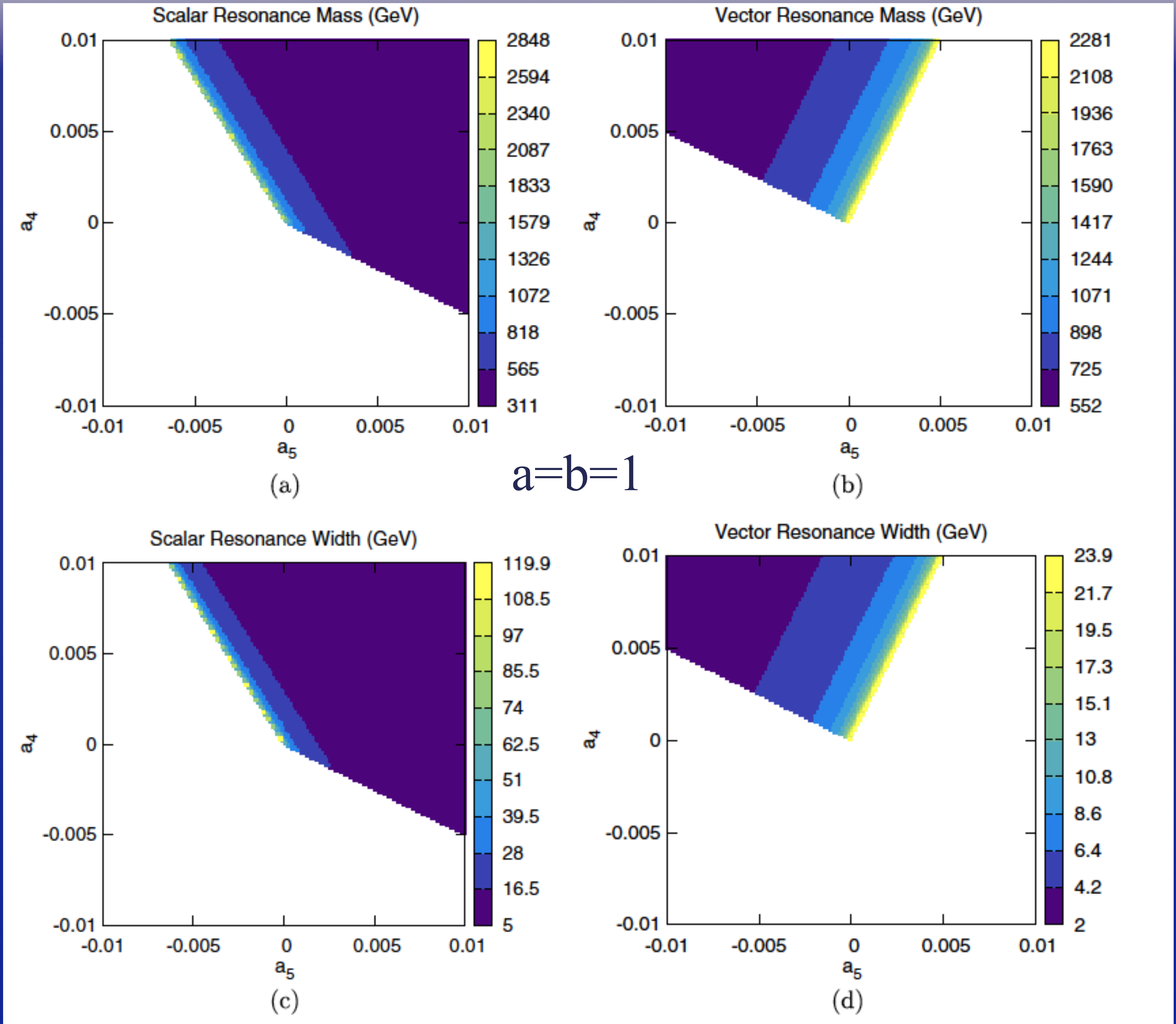
Im A: 1º Riemann Sheet

Im A: 2º Riemann Sheet

Resonant spectrum



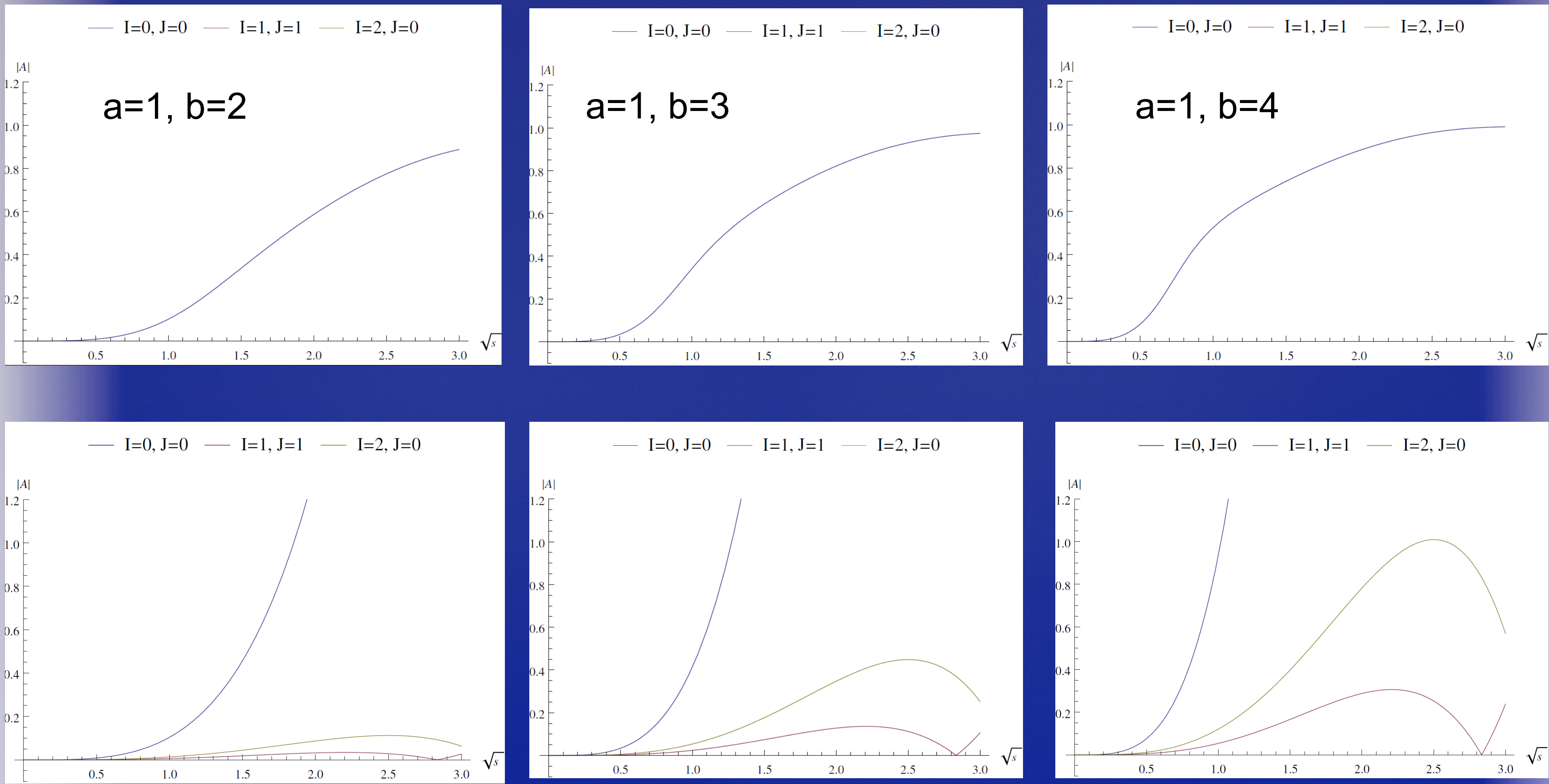
Espriu, Yencho, Mescia



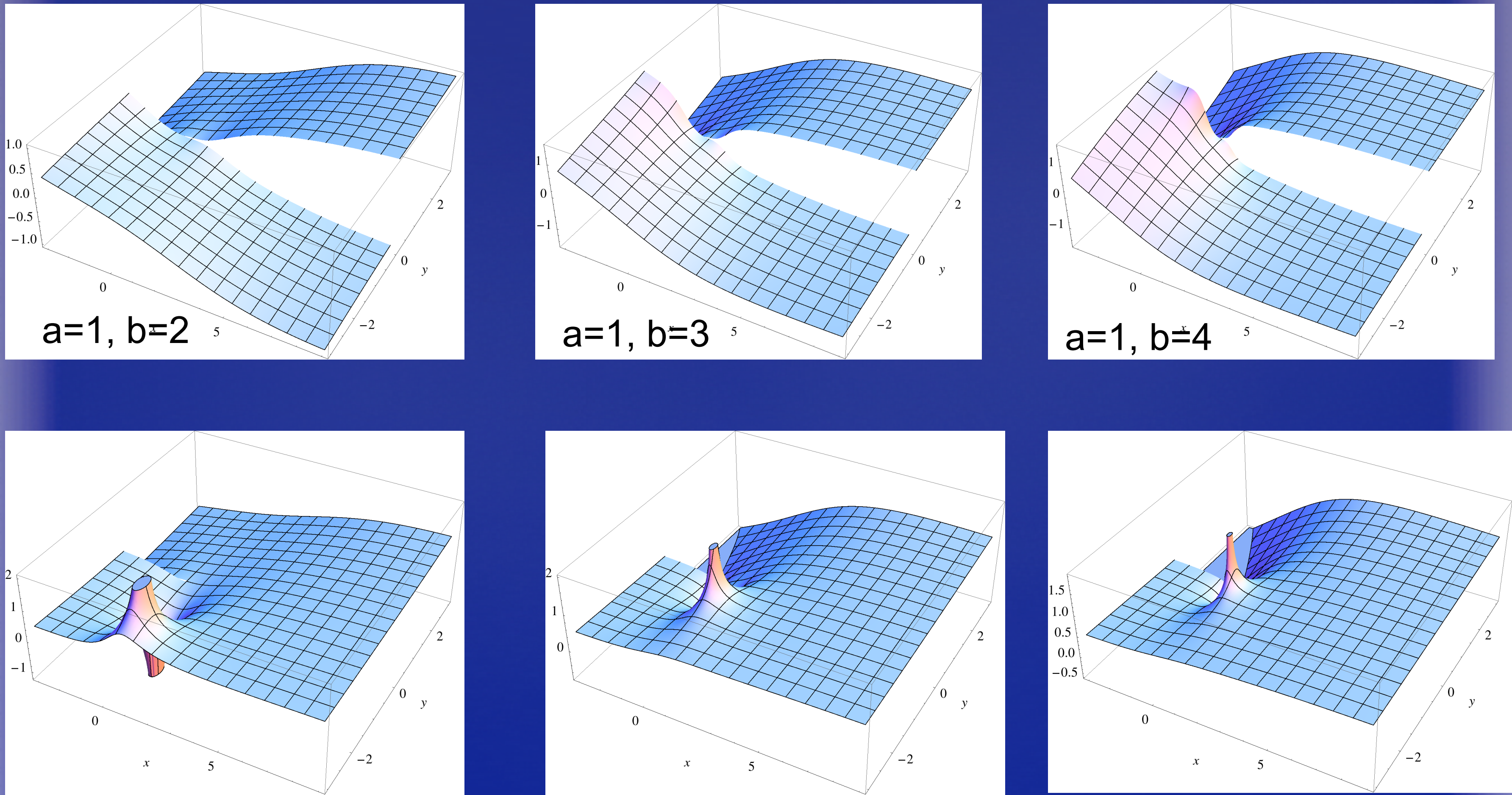
a=b=1

Espriu, Yencho, Mescia

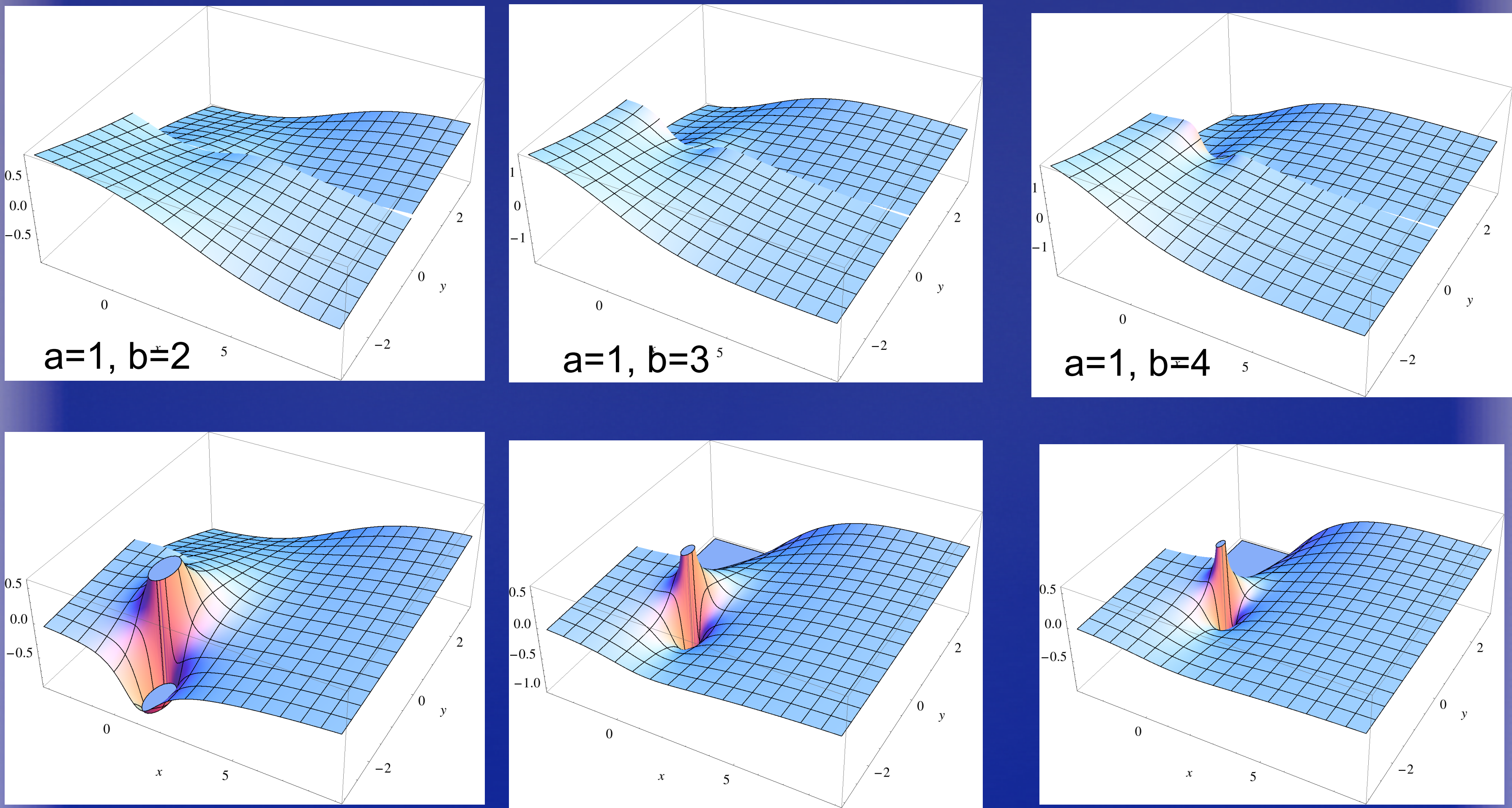
$WW \rightarrow WW \quad (a_4 = a_5 = 0)$



$WW \rightarrow WW \quad (a_4 = a_5 = 0)$



$WW \rightarrow hh \quad (a_4 = a_5 = 0)$



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 $\quad a \simeq \kappa_V \in [0.8, 1.4]$

$b = ?$

$\gamma\gamma \to Z_L Z_L$, $W_L W_L$ 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.

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

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

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

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

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

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

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

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

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

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

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

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

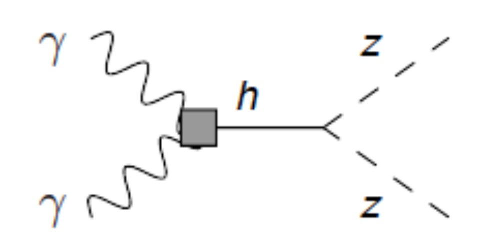
$$U(x) = \sqrt{1 - \frac{\omega^2}{v^2}} + i\frac{\tilde{\omega}}{v}$$

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

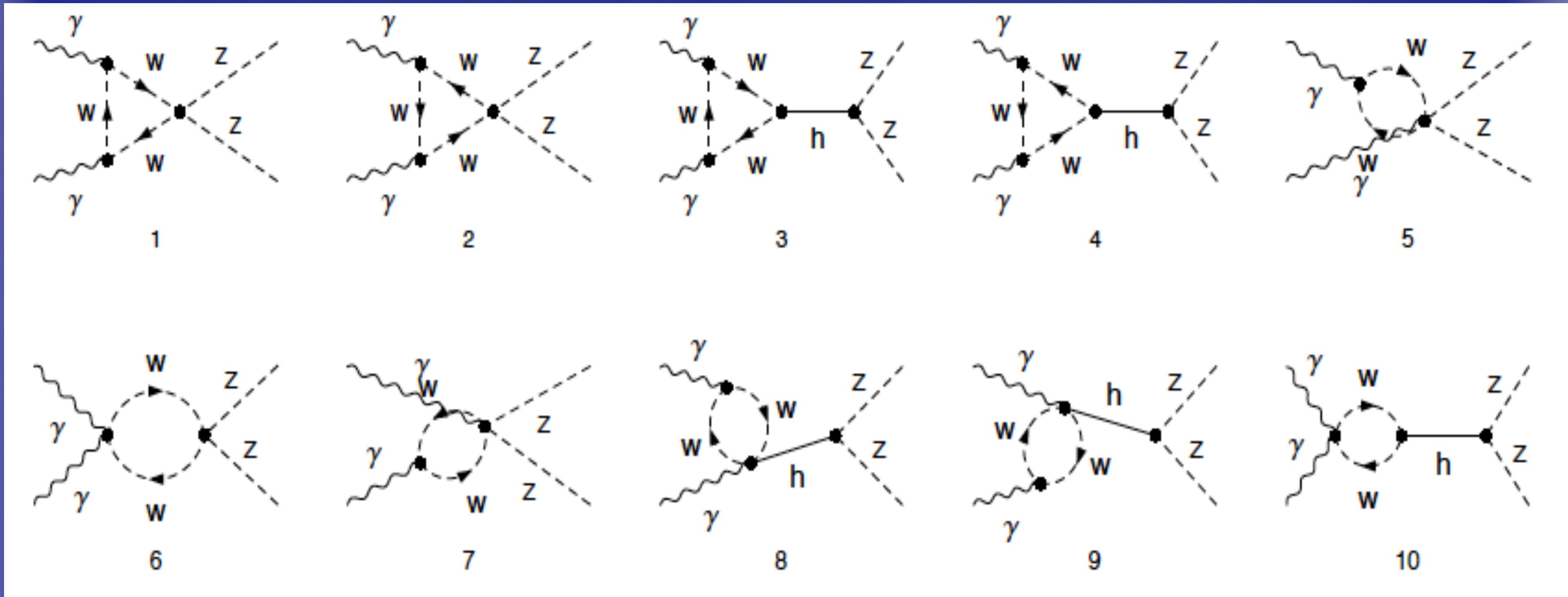
The Lagrangian, the Feynman rules and diagrams are the different but the S matrix elements are the same

$$\gamma\gamma \to zz$$

$$\mathcal{M}(\gamma\gamma \to zz)_{\rm LO} = 0$$

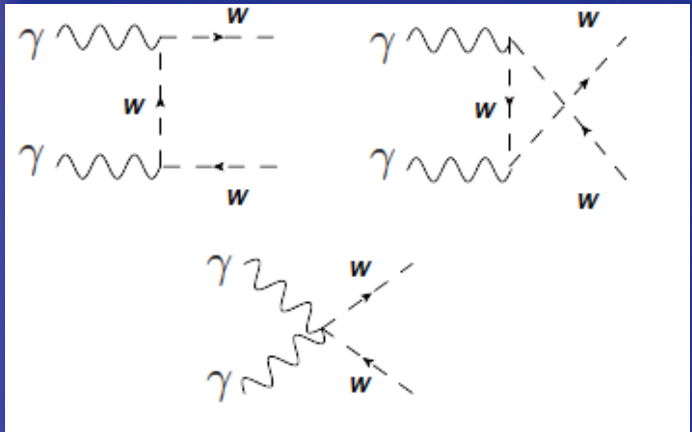


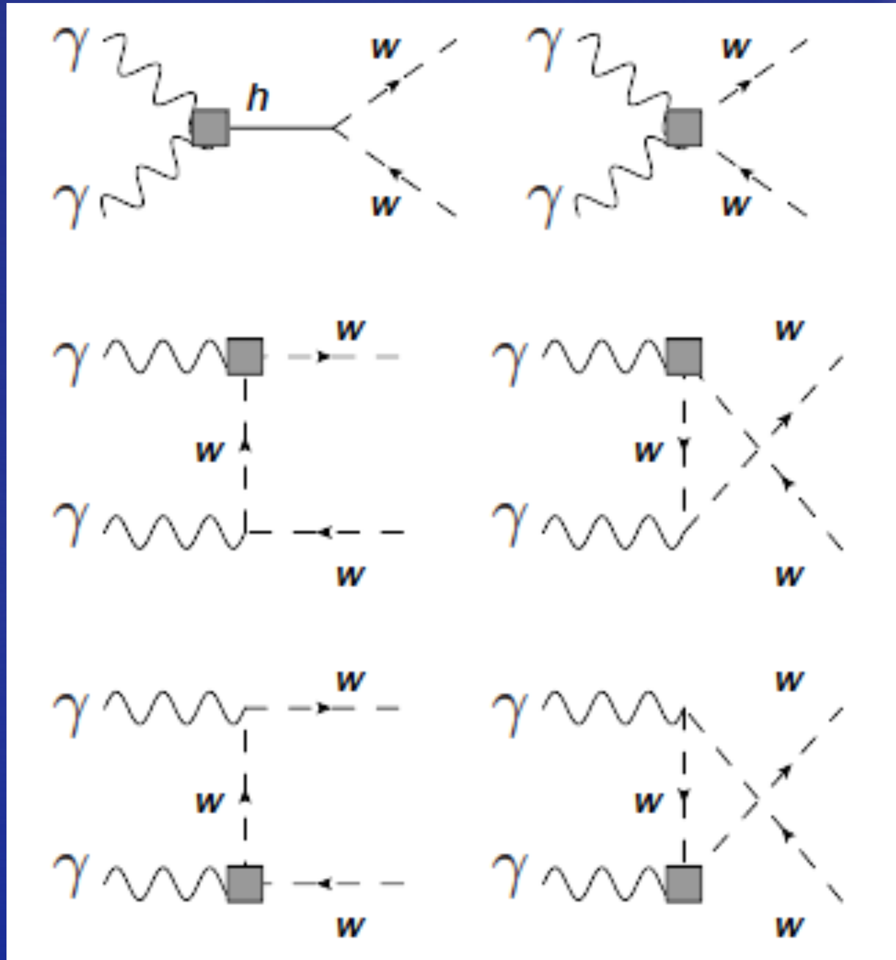
$$A(\gamma\gamma \to zz)_{\rm NLO} = \frac{2ac_\gamma^r}{v^2} + \frac{(a^2-1)}{4\pi^2 v^2}$$
$$B(\gamma\gamma \to zz)_{\rm NLO} = 0,$$



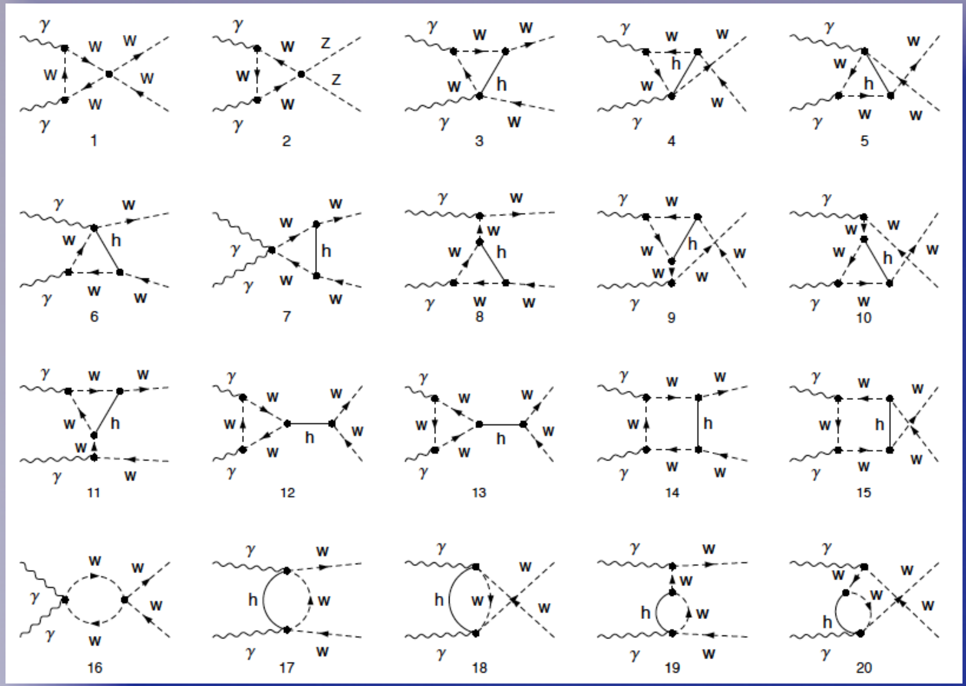
$$c_\gamma^r = c_\gamma$$

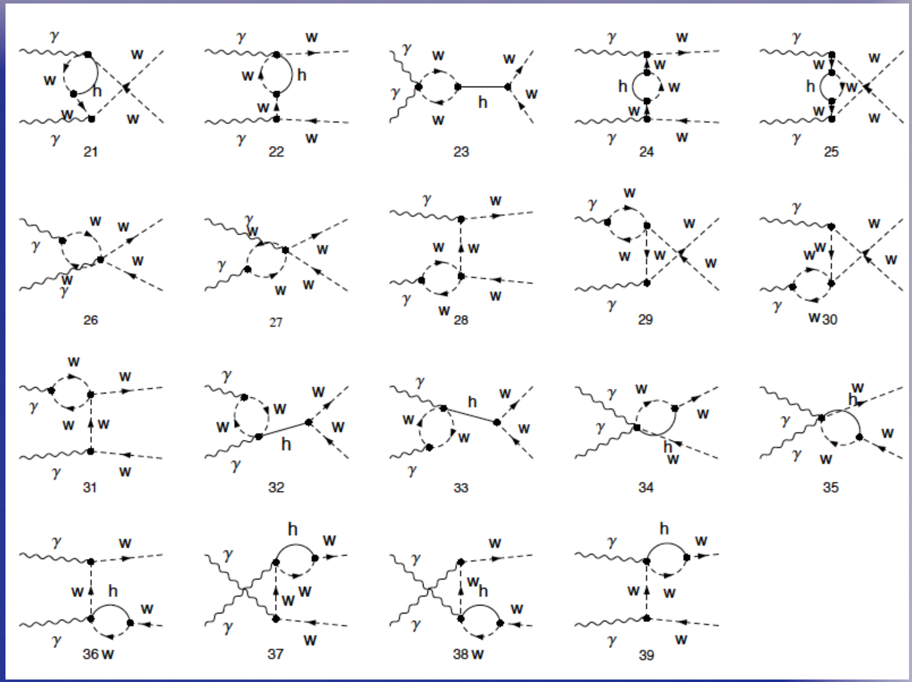
$\gamma\gamma \to w^+w^-$





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



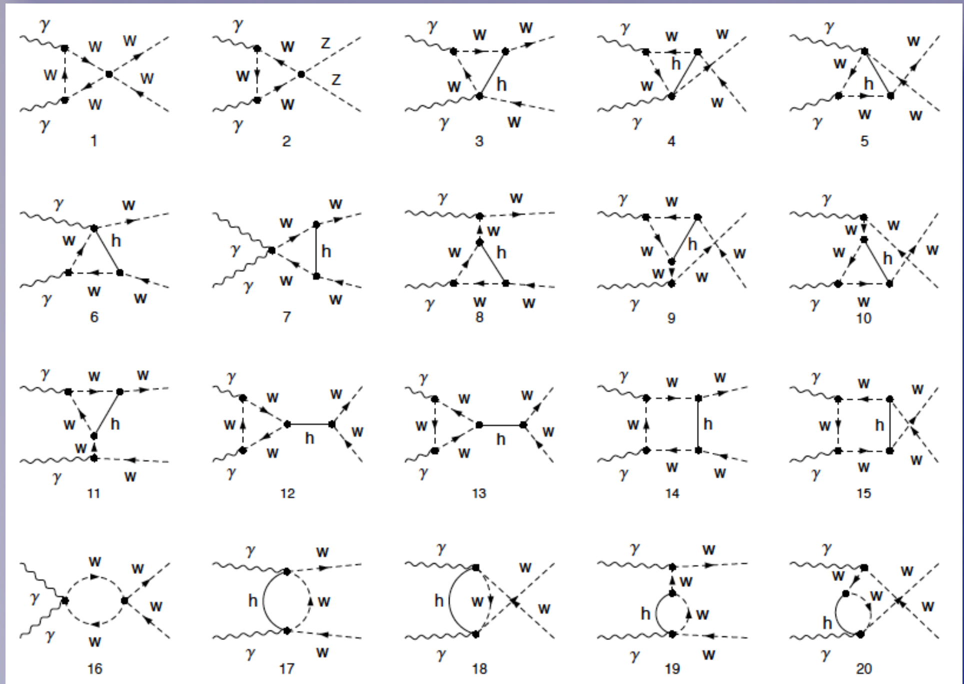


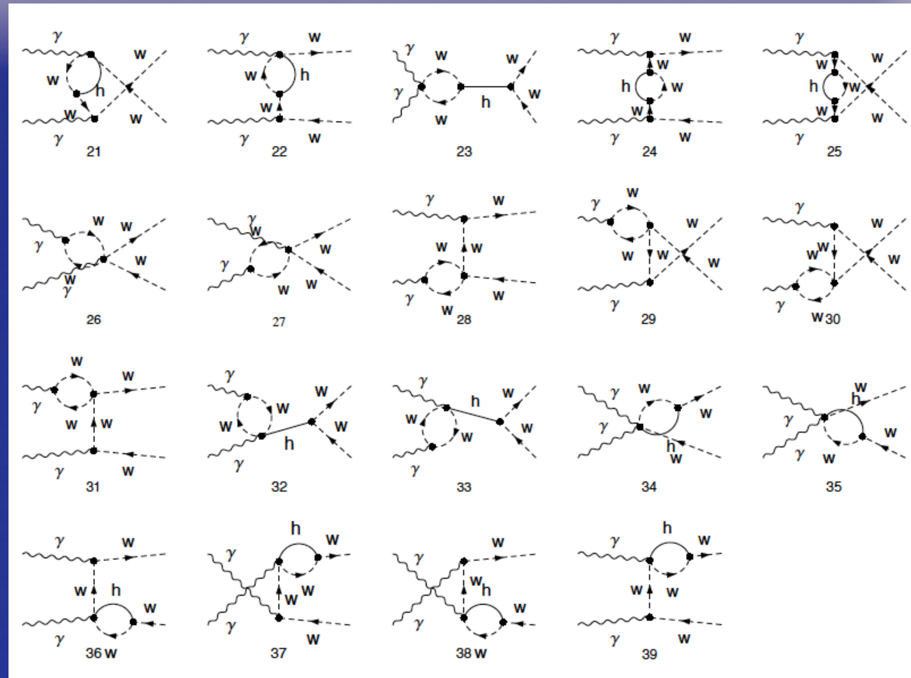
$$A(\gamma\gamma \to w^+w^-)_{\rm LO} = 2sB(\gamma\gamma \to w^+w^-)_{\rm LO} = -\frac{1}{t} - \frac{1}{u}$$

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

$$(a_1^r - a_2^r + a_3^r) = (a_1 - a_2 + a_3) \qquad c_\gamma^r = c_\gamma$$

Finite one-loop result in both cases!





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

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

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

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

Finite one-loop result in both cases!

ECLh coupling renormalization

Observables	Relevant combinations of parameters from $\mathcal{L}_2$	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}	$\frac{1}{8}(b-a^2)^2 + \frac{1}{12}(1-a^2)^2$	$\frac{1}{12}$

VII. 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 next LHC run to know!