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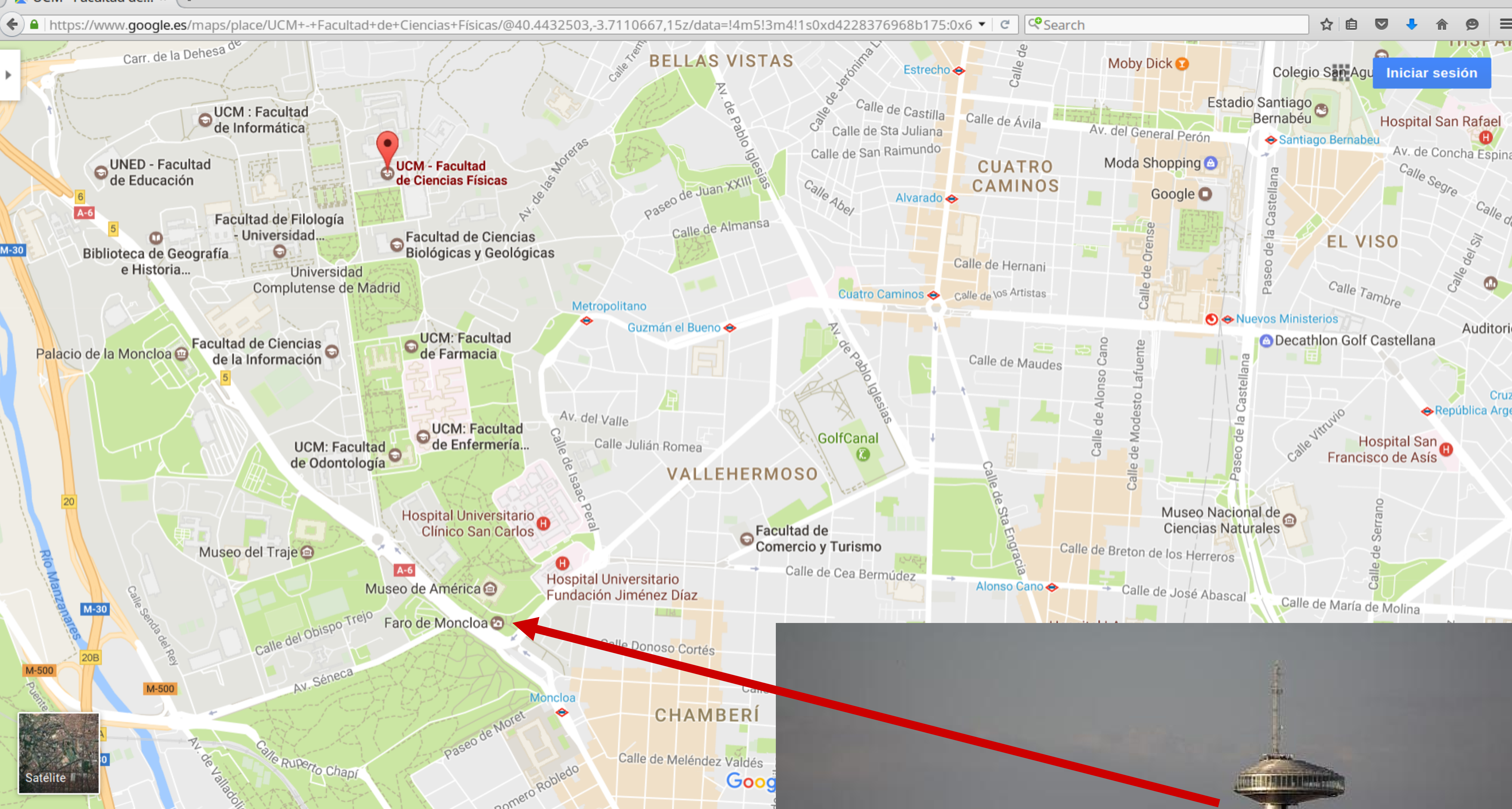
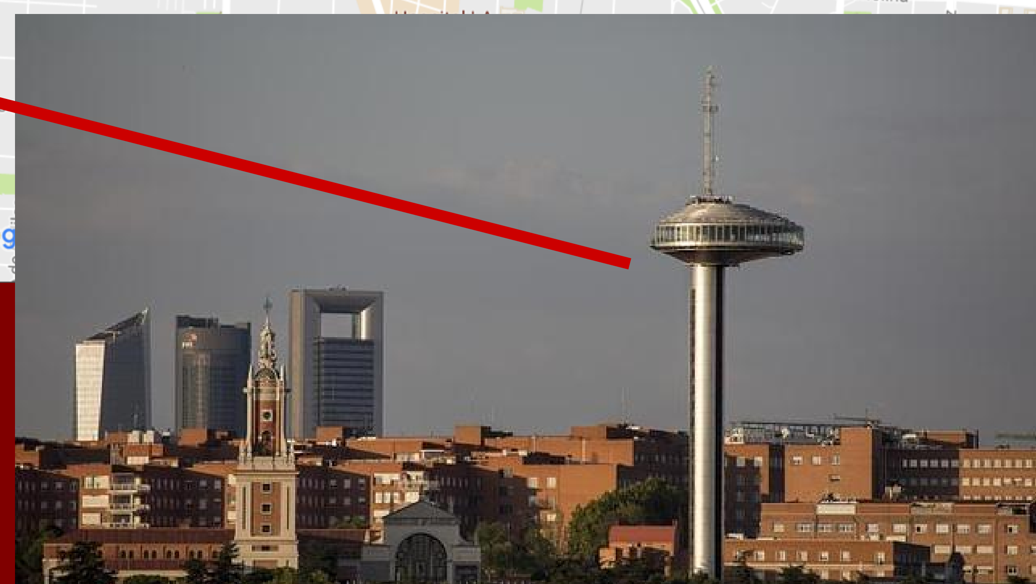
Resonances of the Electroweak Symmetry Breaking Sector in unitarized Higgs-EFT

Universidad Autónoma-CSIC,
Instituto de Física Teórica,
May 8th 2017

Long term collaboration with Antonio Dobado, Rafael L. Delgado
Andrés Castillo, and students Iván León Merino, Miguel Espada

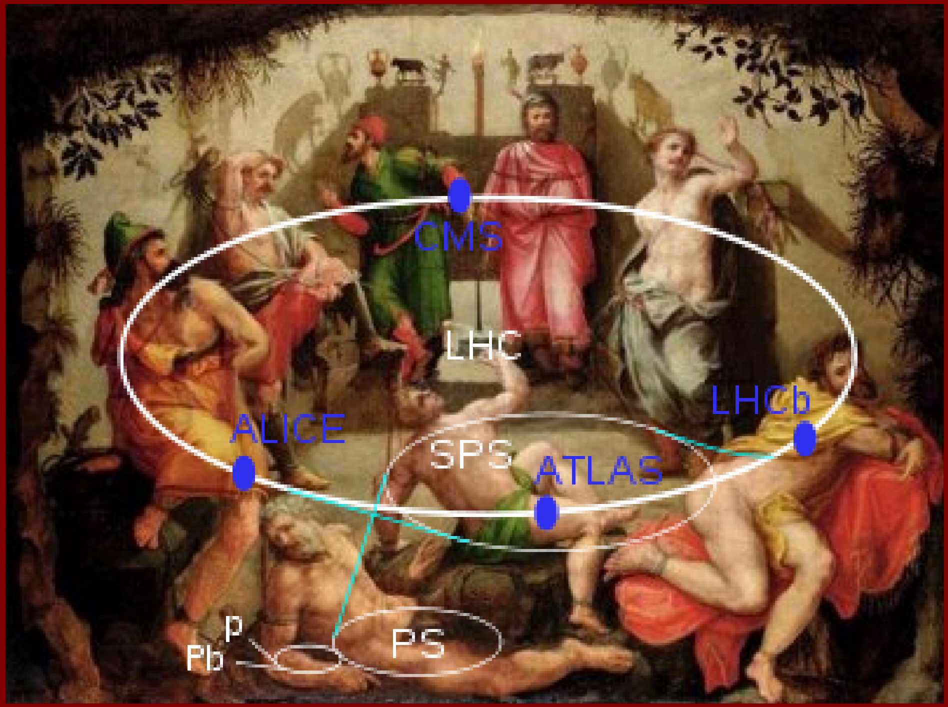


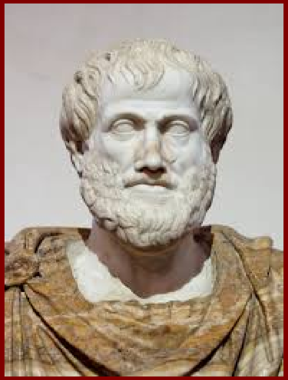


Visit us sometime

Beyond-SM physics at the LHC
(as of May 2017)

While waiting for
“well motivated BSM physics”

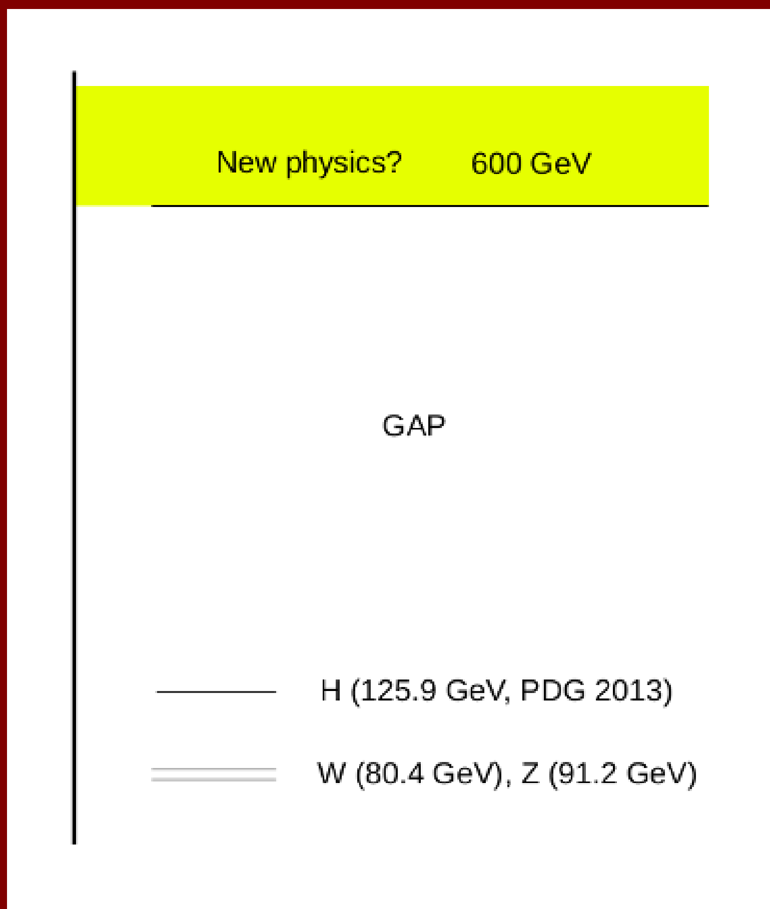




Try
Effective Field Theory
for the particles
that we do see

ArXiv:1610.07922 contains an *aperçu*
(CERN Yellow Report #4 of the Higgs Cross Section Working Group)

Energy desert or Gap in the spectrum?



Nothing?

Enjoy the campus...

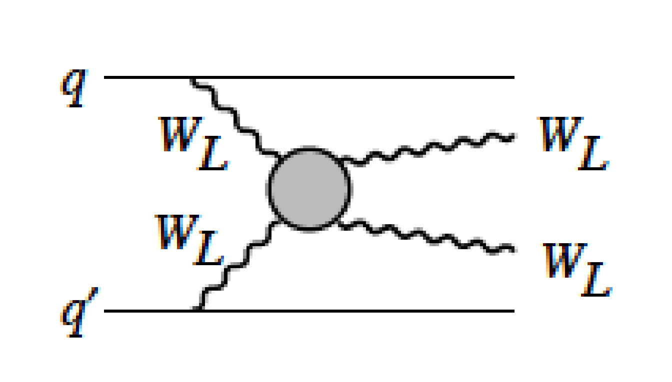
Small cross section

Keep turning stones

New physics at higher E

Goldstone bosons?

Gap → Strongly Interacting EWSBS



Longitudinal gauge boson scattering is the key

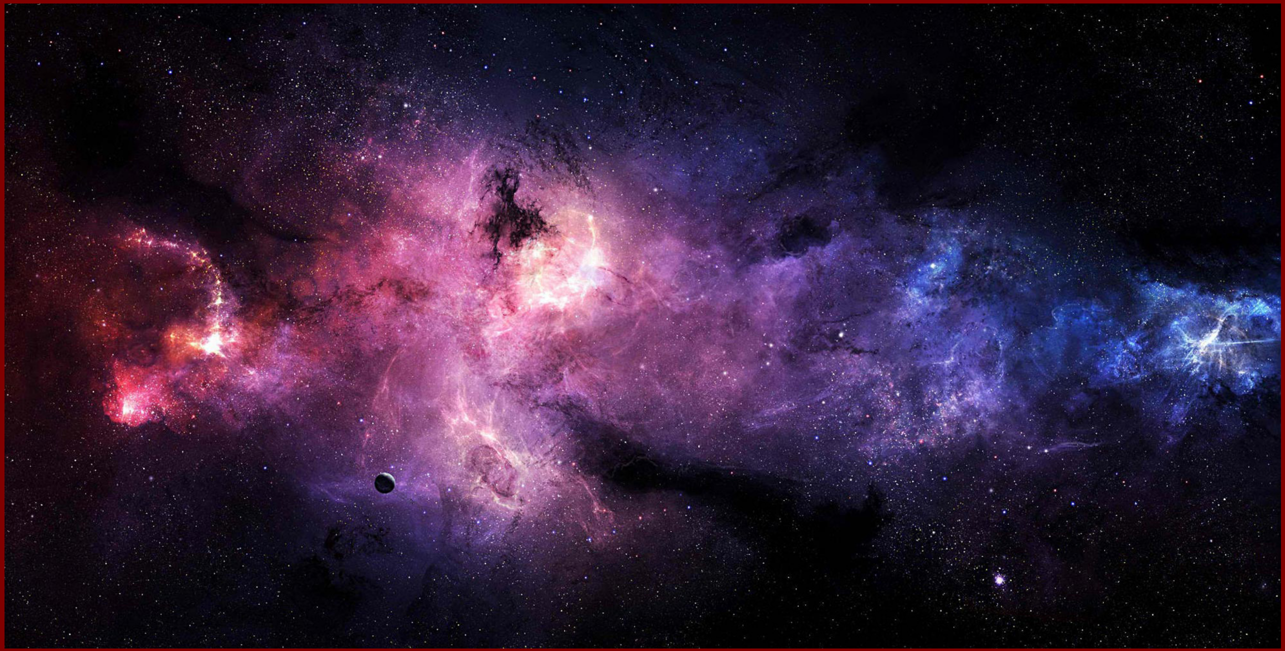
Physical spectrum well below new physics:

3 WBGB $\omega^a \sim W_L^a$ + one light scalar h

$M_h^2 \sim M_W^2 \sim M_Z^2 \sim M_t^2 \sim (100\ \text{GeV})^2 \ll (500\text{-}700\ \text{GeV})^2$

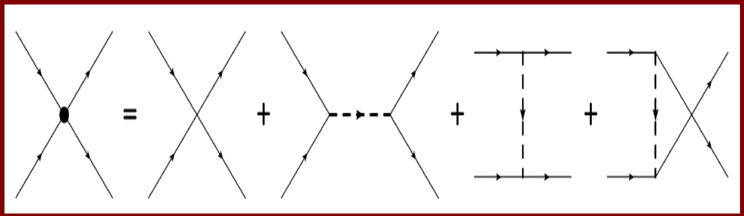
But among the 39 papers of CMS to Moriond 2017
https://cms.cern/news/cms-new-results-Moriond-2017
You cannot find “longitudinal” nor “W_L”

This is the background image of the current CMS webpage

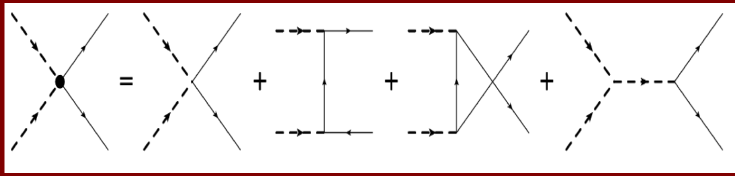


LO amplitudes: EWSBS ωω, hh

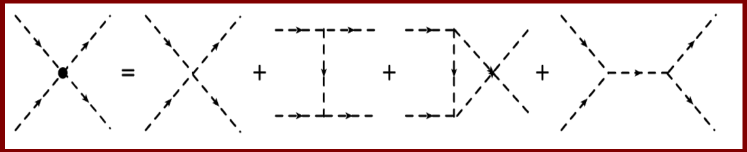
$M_h^2 \ll s < 4\pi v \simeq 3\,\mathrm{TeV}.$



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



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



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

Generalize Weinberg low-energy theorems for pion scattering

Contino, Grojean, Moretti, Piccinini, Ratazzi

Automation of HEFT computations in perturbation theory

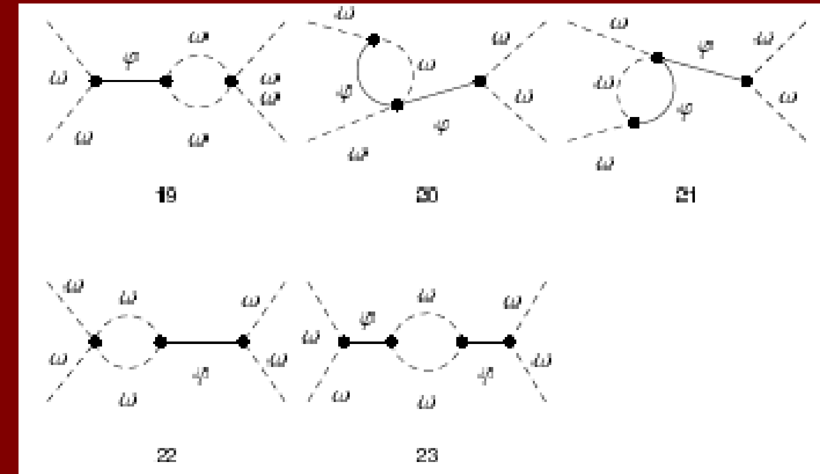
Lagrangian → FeynRules (vertices)
→ FeynArts (diagrams)
→ FormCalc (NLO scattering amplitudes)

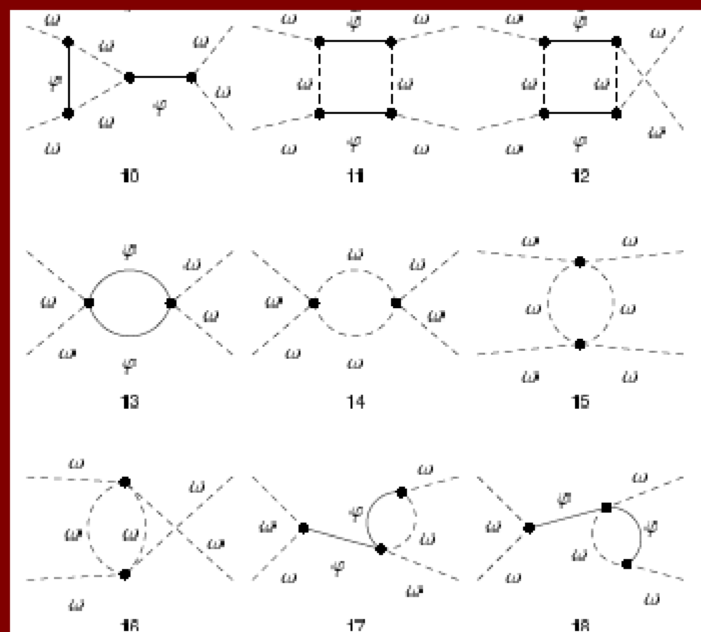
All programmed by
our recent grad student Rafael Delgado

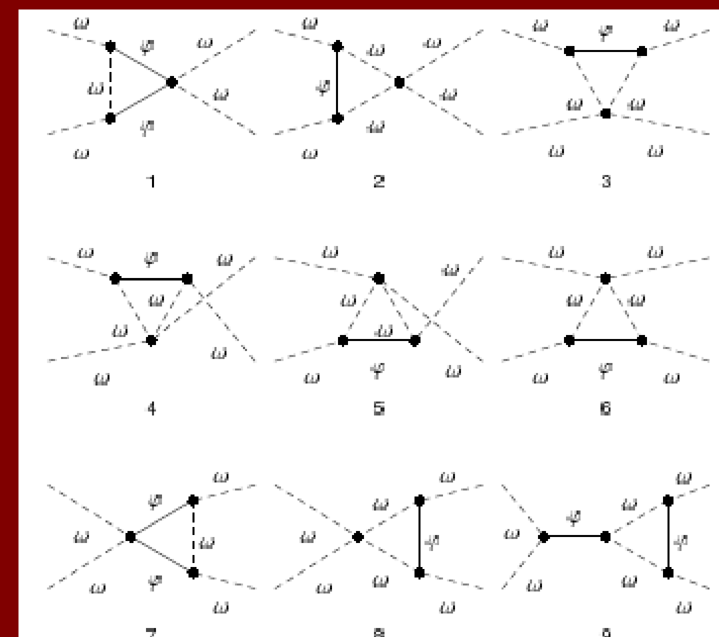
Fortran: Numerically Evaluate the amplitudes and unitarize

One-loop Feynman diagrams for

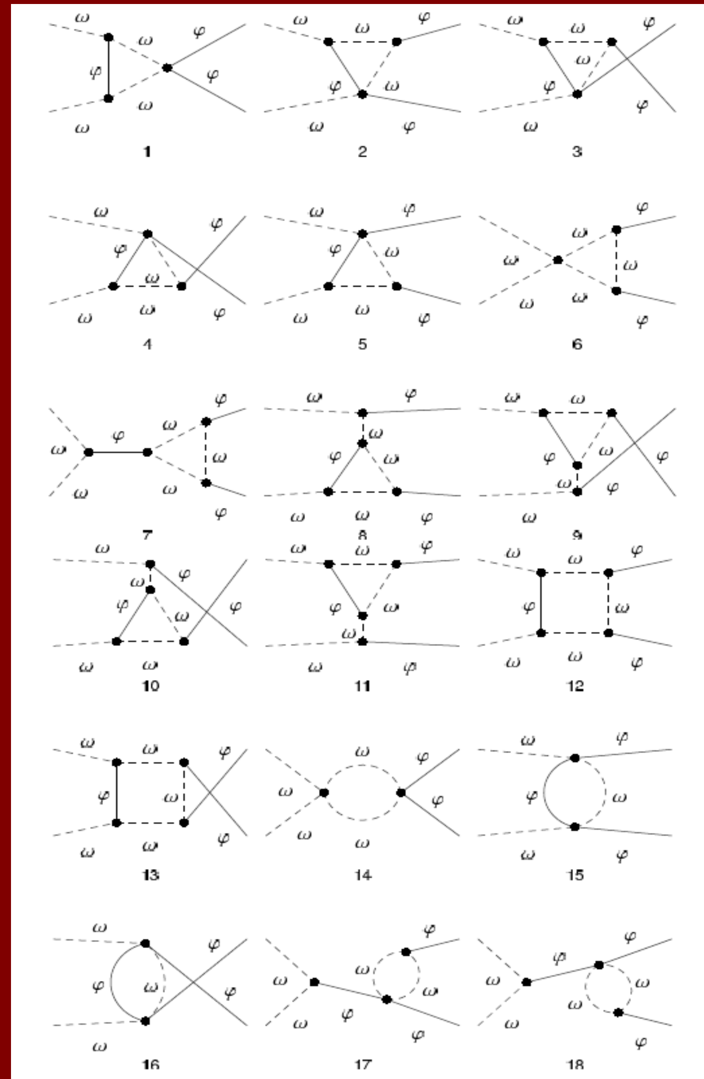
$$\omega_a \omega_b \to \omega_c \omega_d$$

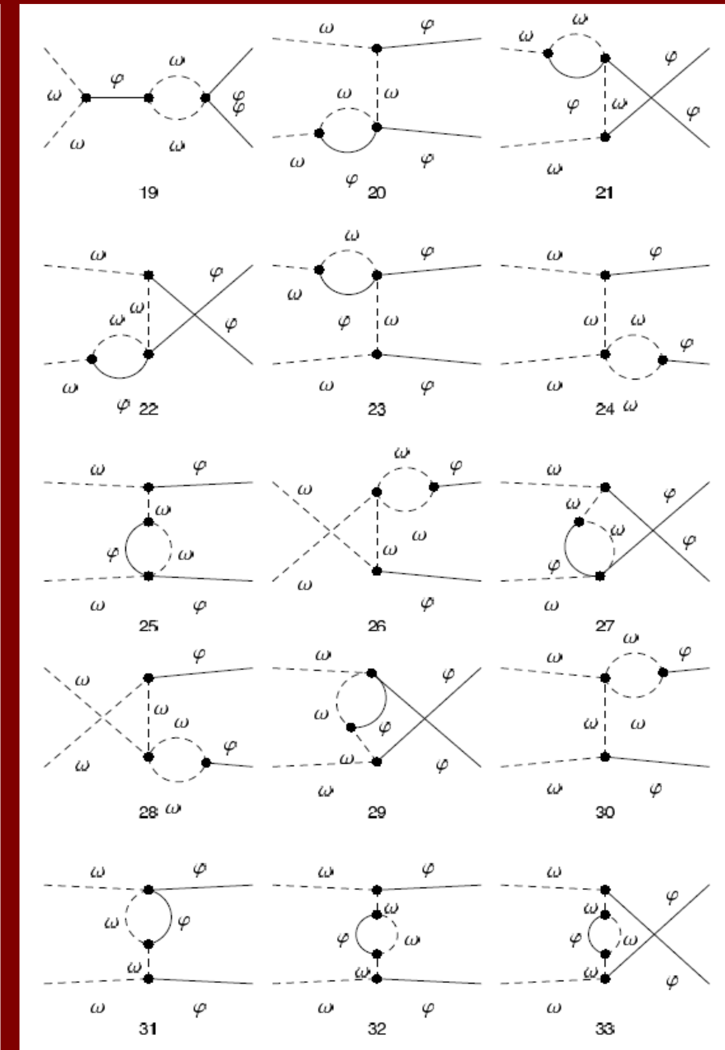






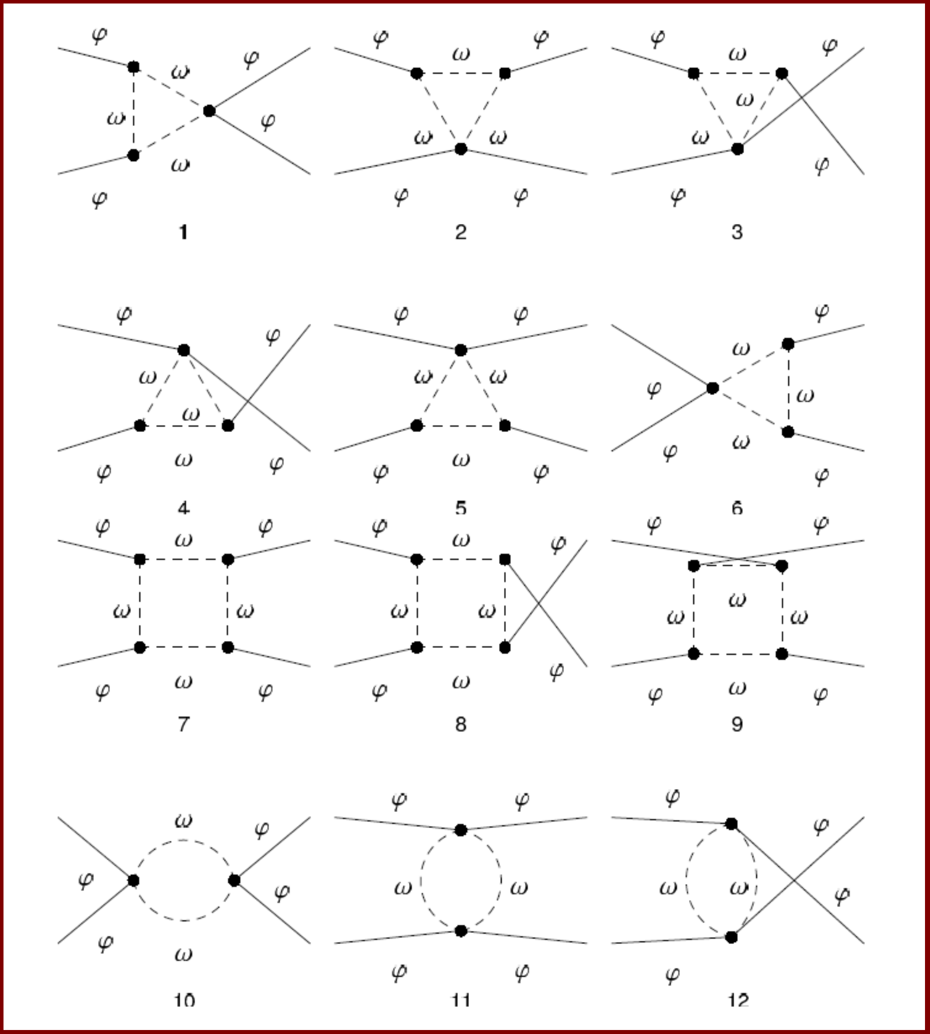
One-loop Feynman diagrams for $\omega_a \omega_b \to hh$





One-loop Feynman diagrams for

$hh \to hh$



Resulting one-loop amplitudes

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

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

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

Resulting one-loop amplitudes

$\omega\ \omega \longrightarrow \omega\ \omega$ (elastic scattering)

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

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

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

Espriu, Yencho, Mescia

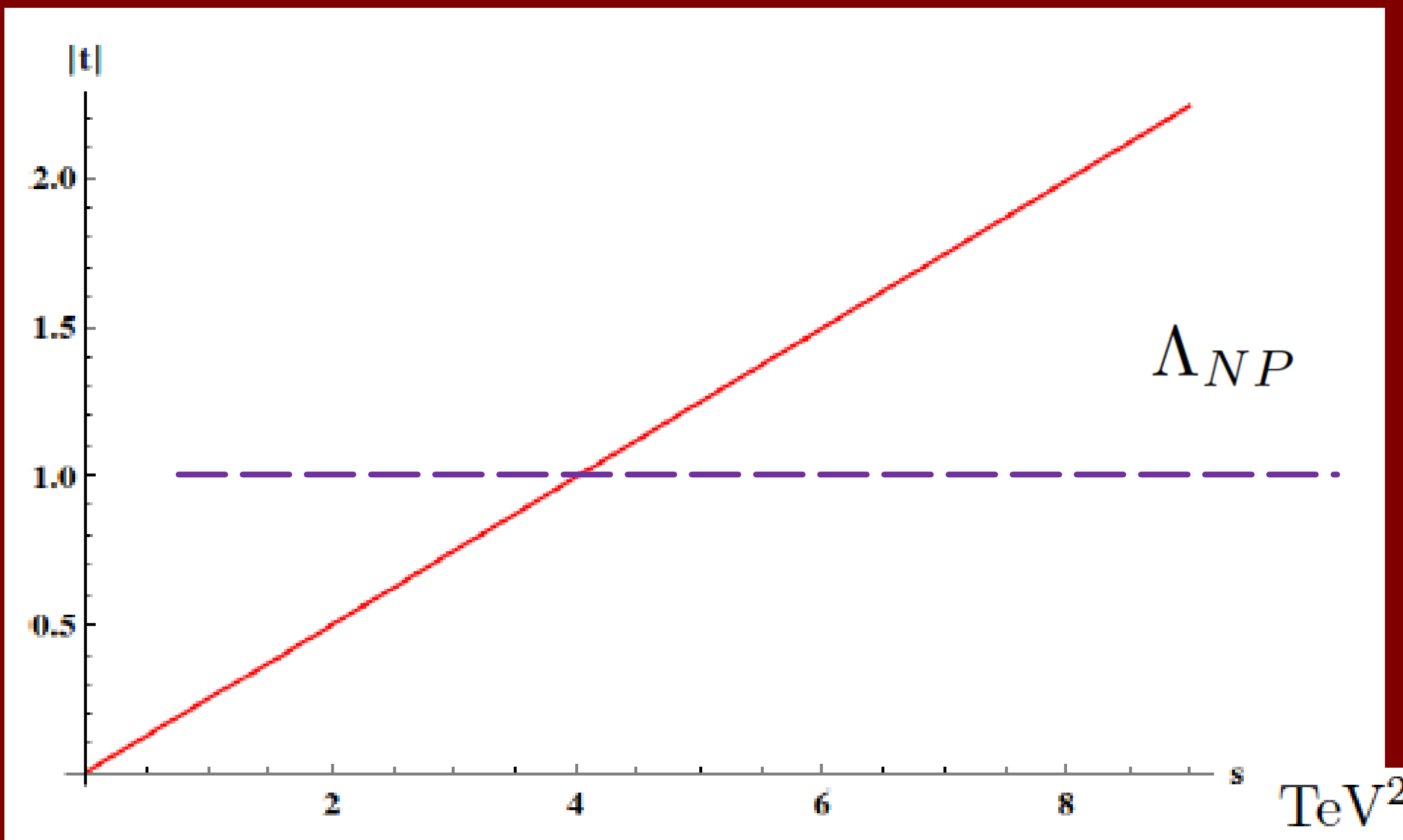
Resulting one-loop amplitudes $\omega\,\omega \longrightarrow h\,h$

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

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

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

BSM Amplitudes in EFT grow with energy and eventually **violate unitarity bound** at some new physics scale:



Problem of perturbation theory

Blaming it to the Lagrangian is wrong logic

Unitarity is simplest for partial waves

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

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

$$\mathrm{Im}\, A_{IJ} = |A_{IJ}|^2 \longrightarrow |\, A_{IJ}\, |^2 \leq 1$$

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

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

(Perturbation theory satisfies it to one order less than calculated)

Unitarity
is a consequence of
probabilities adding to one

Slight violations… long term you lose

LO partial waves

$$
\begin{aligned}
A_0^0 &= \frac{1}{16\pi v^2}(1-a^2)s \\
A_1^1 &= \frac{1}{96\pi v^2}(1-a^2)s \\
A_2^0 &= -\frac{1}{32\pi v^2}(1-a^2)s \\
M^0 &= \frac{\sqrt{3}}{32\pi v^2}(a^2-b)s
\end{aligned}
$$

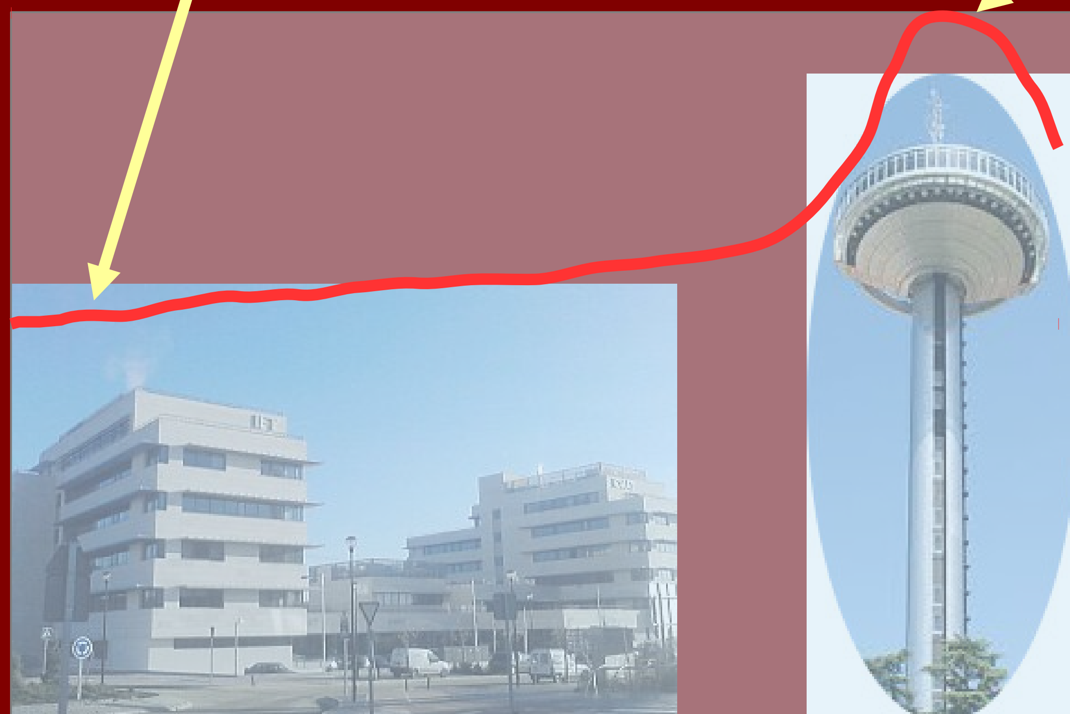
Phys.Rev. D91 (2015) 075017

EFT parameters evtly. measured here @LHC

Resonances at much higher E

EFT parameters evtly. measured here @LHC

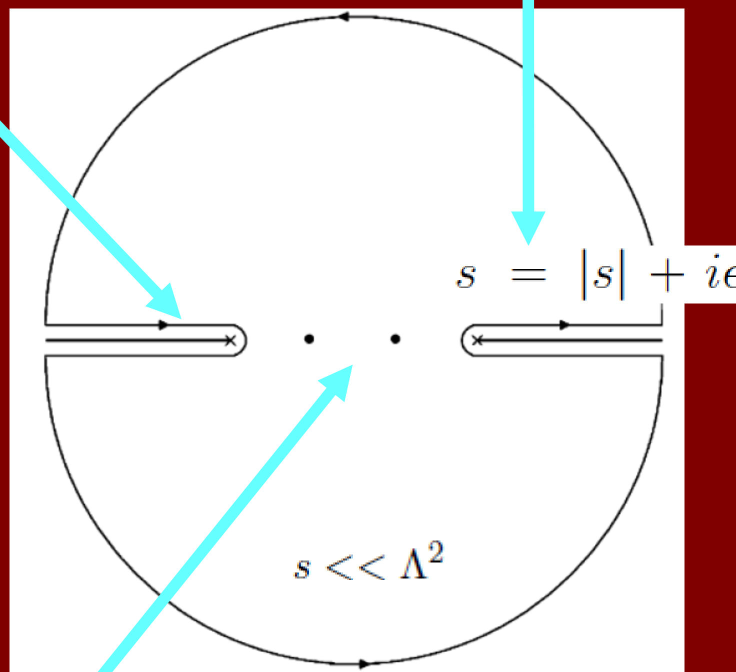
Resonances at much higher E



Can discuss resonances without new parameters

Left cut: use the EFT

Right cut: use exact elastic unitarity for the inverse amplitude

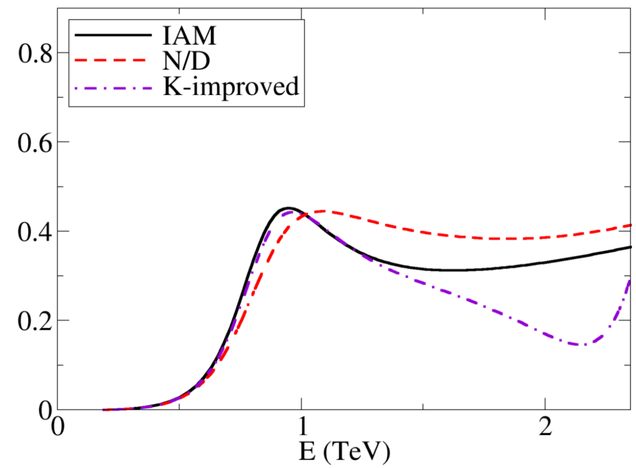


<u>DISPERSION RELATION for complex s</u>

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

Subtractions at low s where the EFT can be used

We have published three major unitarization methods



$a^2 = 1 \neq b = 2$

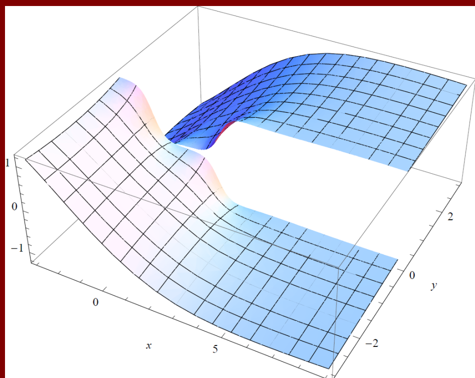
IJ	00	02	11	20	22
Method	Any	N/D, IK	IAM	Any	N/D, IK

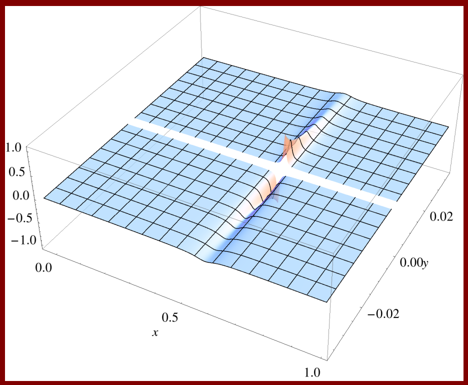
Generally:

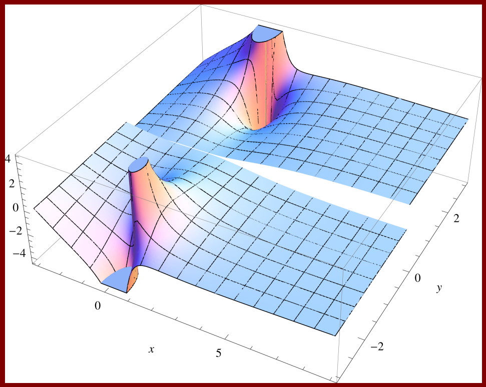
Resonating amplitudes (s-channel) → quantitative agreement

Potential-dominated amplitudes (left cut) → qualitative

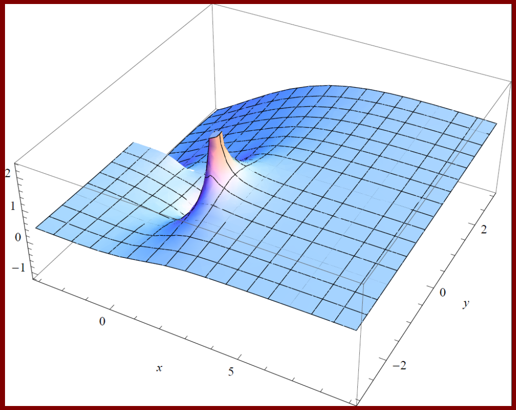
Poles in the s-complex plane are now possible

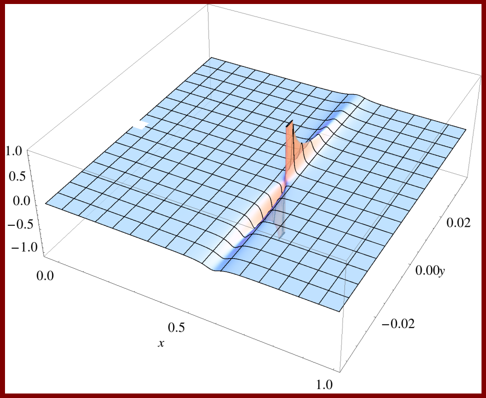


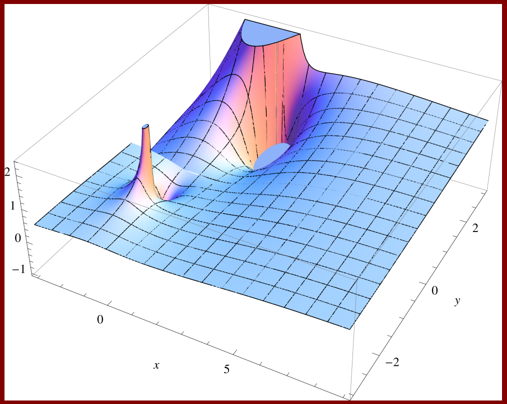




Im A:
1^{st} and 2^{nd} Riemann sheets



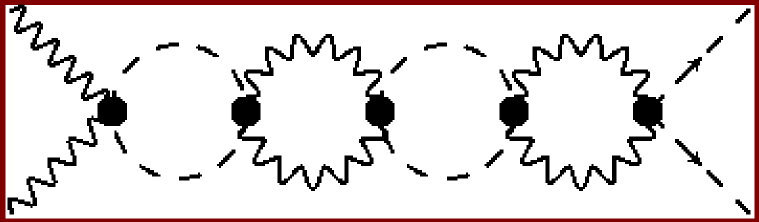




$a = 0.9$
$b = 1$
$a_4 = 0.005$
$a_5 = -a_4$

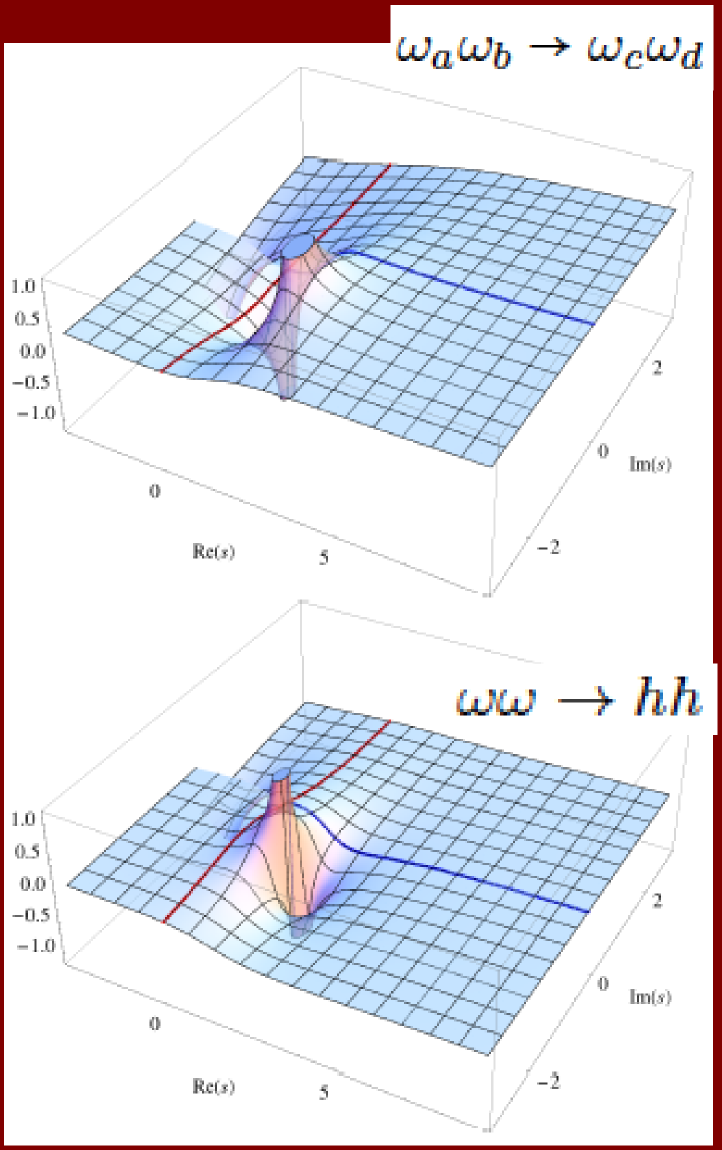
I=J=0 | *I=J=1* | *I=2, J=0*

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



$a = 1, b = 2$

Phys.Rev.Lett. 114 (2015) no.22, 221803



"Pinball resonance"

$b \in (-1, 3)$

Predictive power of EFT+dispersion Relation?

Can it predict new physics coupled to EWSBS? NO

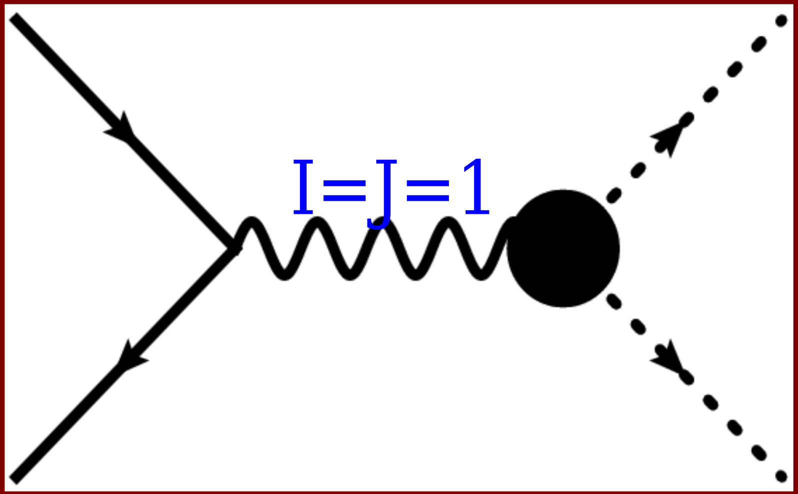
What it can do:

*) If the LHC precision program measures EFT couplings ≠ SM → can evtly. predict resonances (no new parameters)

*) Resonance @ LHC → describe line shape and constrain M, Γ, LECs.

*) It can then predict the line shape of production amplitudes in weakly coupled channels (Watson's f.s.t.) from the same underlying complex plane pole.

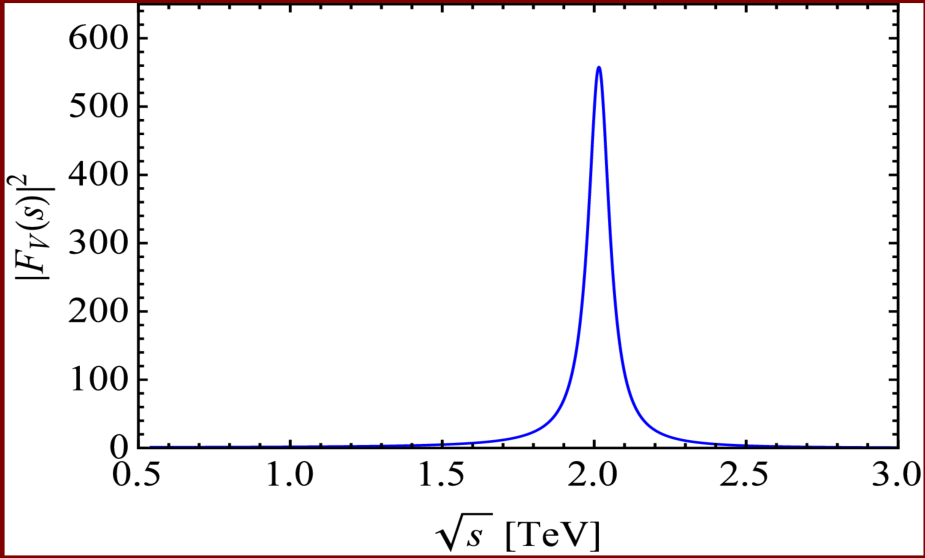
Production at the LHC and $e^- e^+$ colliders



Tree-level ρ-like resonance

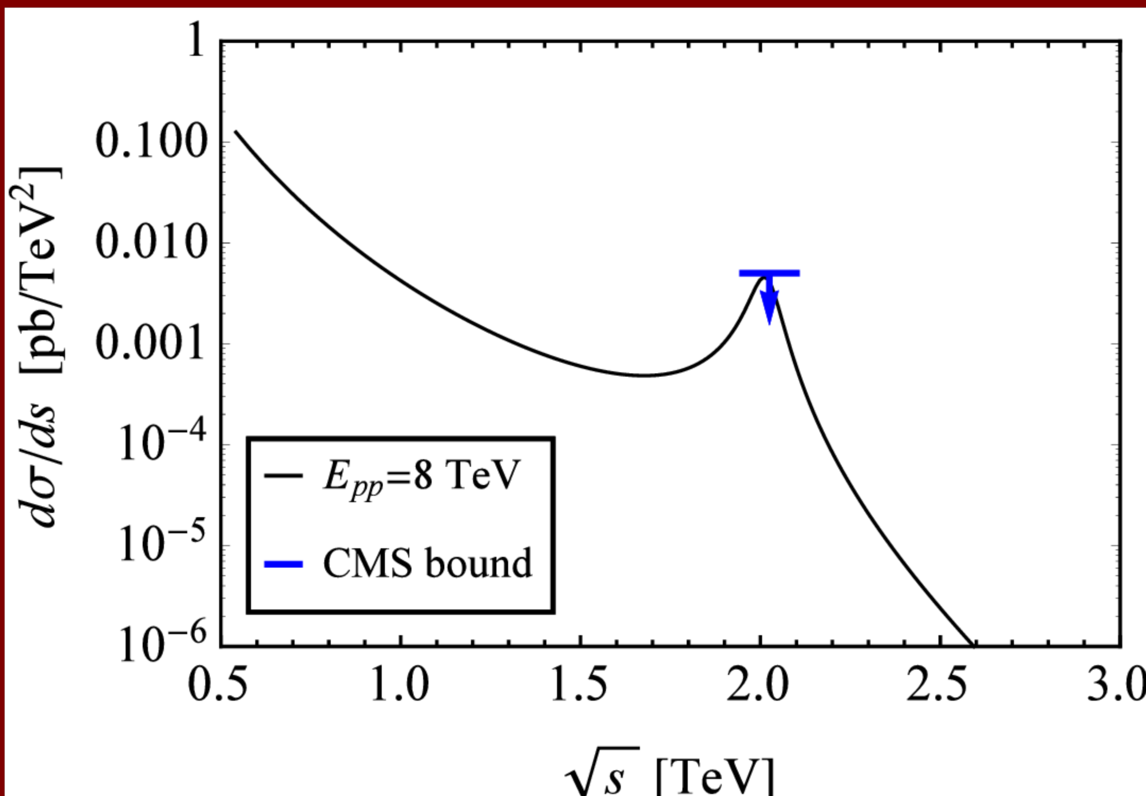
From transverse boson with
IAM Form factor
(Watson's final state theorem)

$$F_V(s) = F_{11}(s) = \left[1 - \frac{A_{11}^{(1)}(s)}{A_{11}^{(0)}(s)}\right]^{-1} .$$



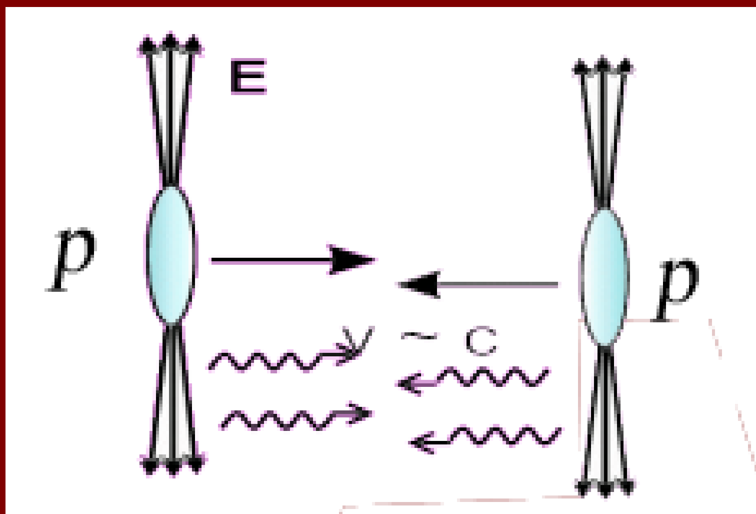
Commun.Theor.Phys. 64
(2015) 701-709

$$\frac{d\hat{\sigma}(u\bar{d} \to w^+ z)}{d\Omega_{\rm CM}} = \frac{1}{64\pi^2 s}\left(\frac{1}{4}\right)\left(\frac{g^4}{8}\right) \mid F_V(s)\mid^2 \sin^2\theta \, .$$

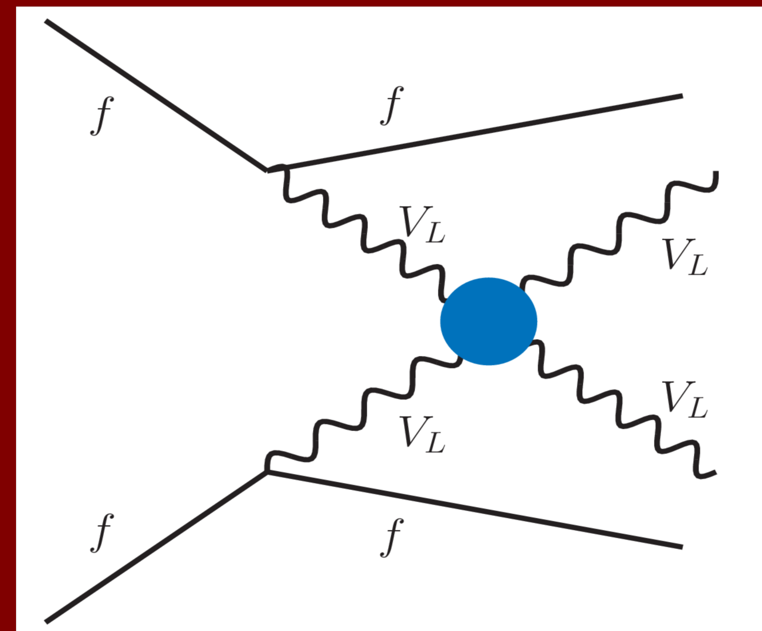


Typical TeV-scale
cross sections
are smaller
than current data allows

Quantum numbers other than J=I=1; need to emit >1 boson



EM field near fast charge ~ transverse wave



Weizsäcker-Williams or “equivalent boson approx.” for collinear W emission (Very crude: would have worked better at the SSC)

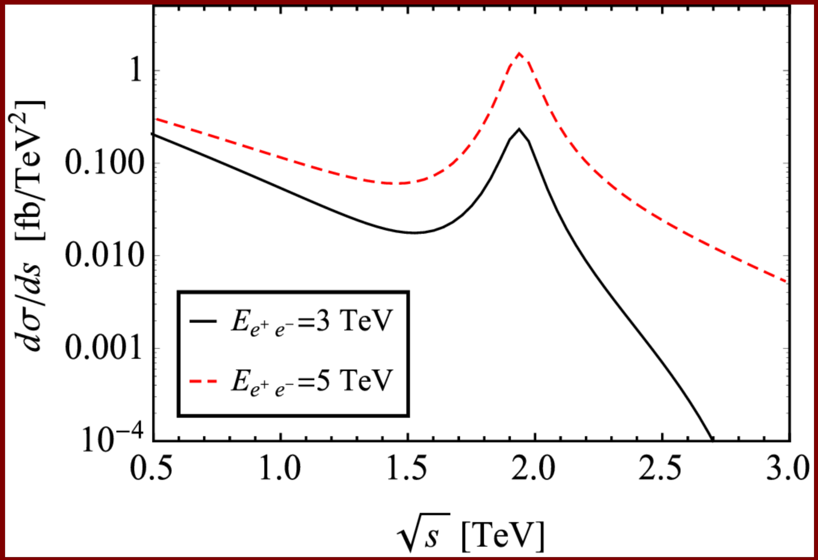
Here, I=2 (can yield signals in all of WW, ZZ and WZ)

$$\frac{d\sigma}{ds} = \int_0^1 dx_+ \int_0^1 dx_- \,\hat{\sigma}(s)\,\delta(s - x_+ x_- E_{\rm tot}^2)\;[F_1(x_+)F_2(x_-) + F_2(x_-)F_1(x_+)]$$

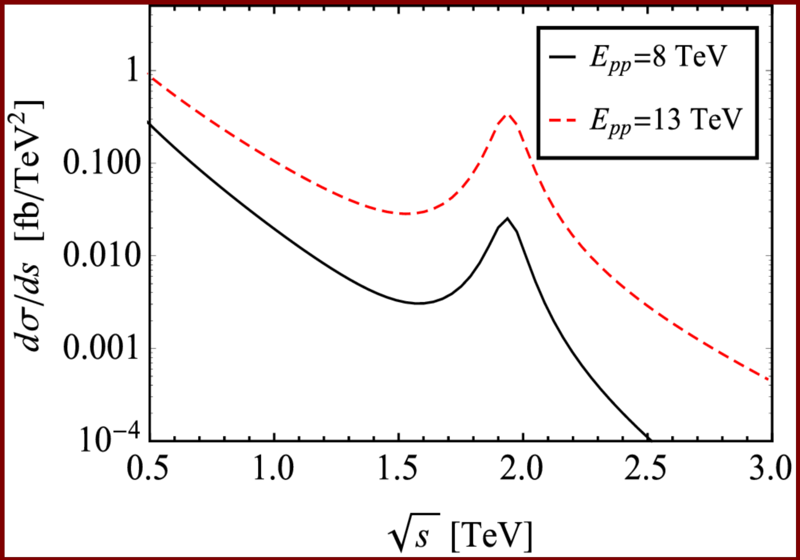
$$F_{W_L}(x) = g_W \frac{1-x}{x}, \qquad F_{Z_L}(x) = g_Z \frac{1-x}{x},$$

$$F^p_{W_L}(x) \equiv \int_x^1 \frac{dy}{y} \sum_i f_i(y) \times F^{q_i}_{W_L}\left(\frac{x}{y}\right)$$

$e^- e^+$



p p



$\gamma\gamma \longleftrightarrow Z_L Z_L\,, W_L W_L\,, hh$ at one-loop

*) resonances can appear in clean $\gamma\gamma$ final state

*) EM production not negligible,
charged-particle colliders are photon colliders

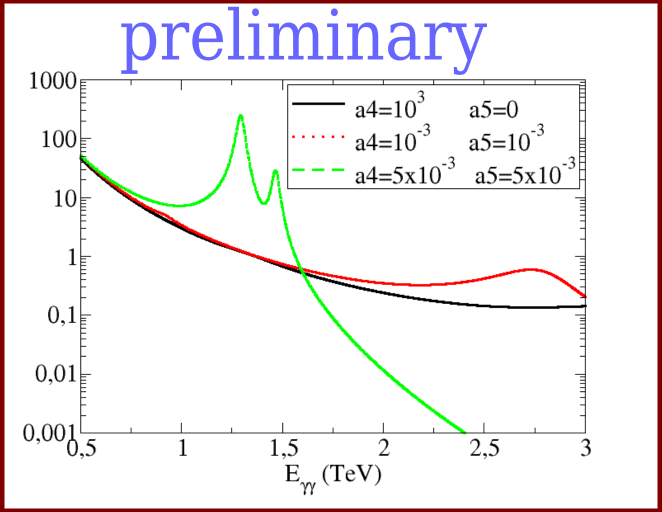
?

Electromagnetic production of EWSBS

pp (or ee) → γγ +pp (or ee) → ωω +pp (or ee)

$$\frac{d\sigma_{\gamma\gamma\to\omega\omega}}{d\Omega} = \frac{1}{64\pi^2 s_{\gamma\gamma}}\frac{1}{4}\sum_j |M_J|^2 =$$

$$= \frac{16\pi}{s_{\gamma\gamma}}\sum_{I\epsilon\{0,2\}}\left[\left[\tilde{P_{I0}}Y_{0,0}(\Omega)\right]^2 + \left[\tilde{P_{I2}}Y_{2,2}(\Omega)\right]^2 + \left[\tilde{P_{I2}}Y_{2,-2}(\Omega)\right]^2\right] =$$

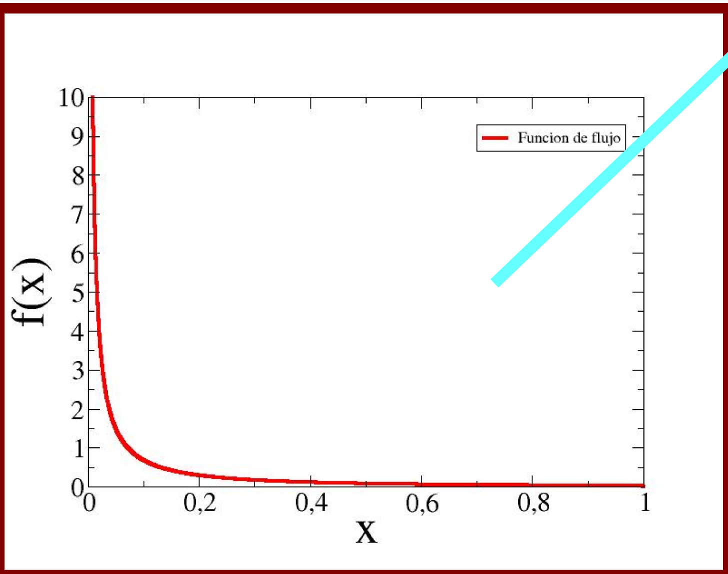


Here in the γγ → ωω cross section

Electromagnetic production of EWSBS

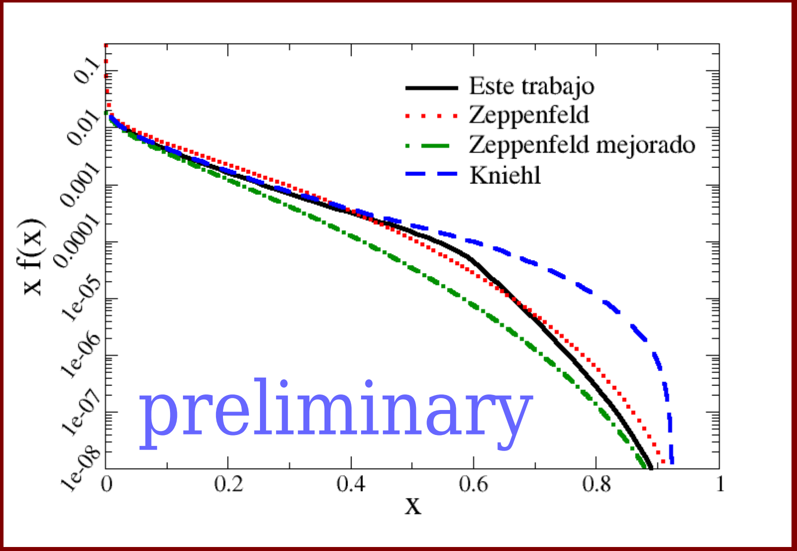
pp (or ee) → γγ +pp (or ee) → ωω +pp (or ee)

$$\frac{d\sigma}{ds\,dp_T^2}\left(s_{\gamma\gamma},\theta\right)=\frac{1}{s_{\gamma\gamma}}\int_{x_{min}}^{x_{max}} dx_1\,\frac{f\left(x_1\right)}{x_1} f\left(\frac{s_{\gamma\gamma}}{s_{ee}x}\right)\frac{d\sigma_{\gamma\gamma\to\omega\omega}\left(s_{\gamma\gamma},\theta\right)}{dp_T^2}$$



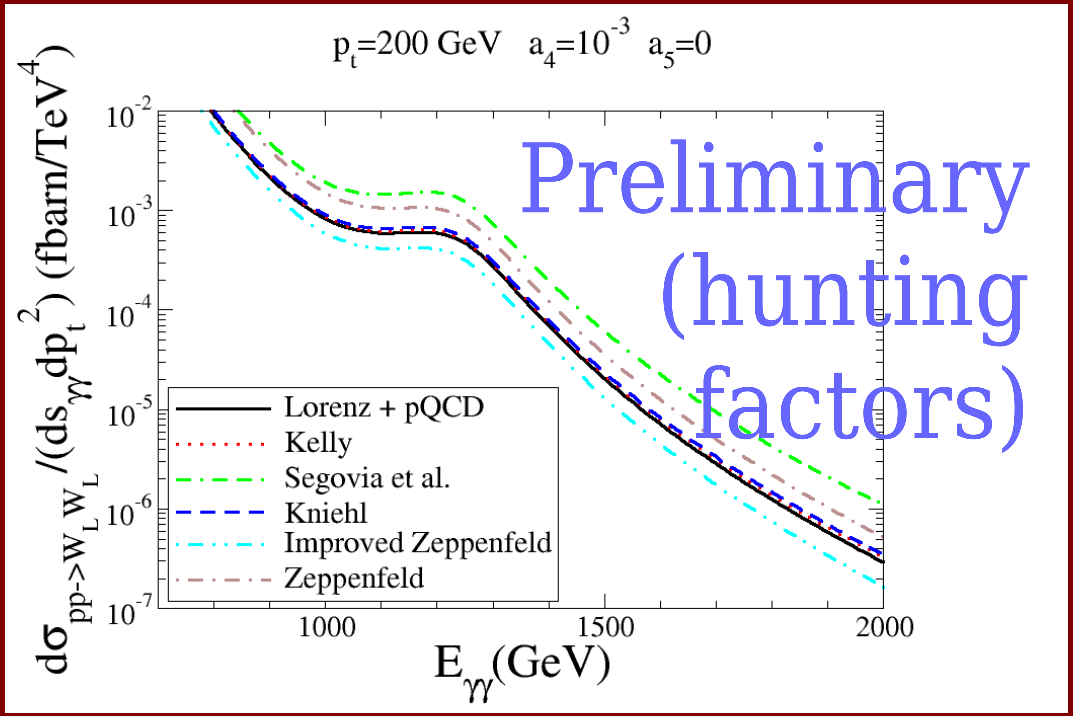
e → γ e

p → γ p
(elastic)



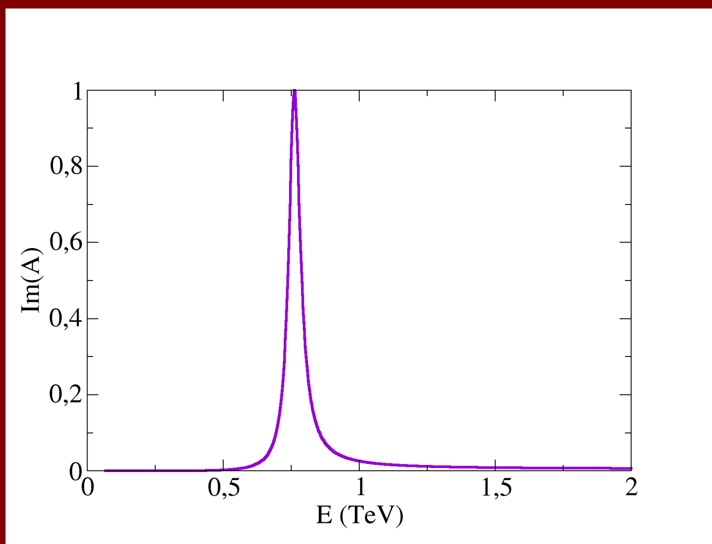
Electromagnetic production of EWSBS

pp (or ee) → γγ +pp (or ee) → ωω +pp (or ee)

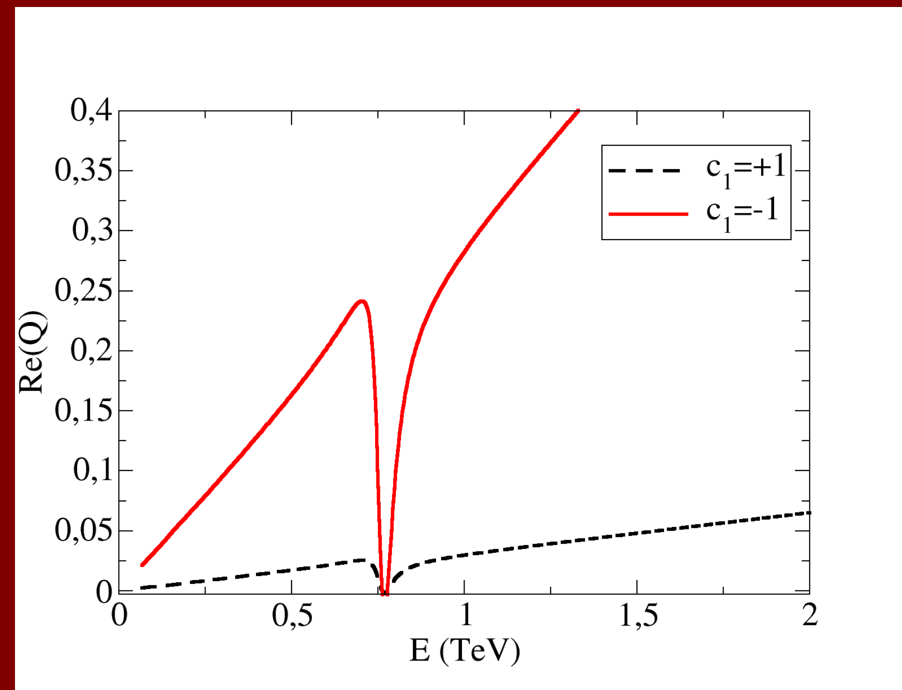


Here in pp → γγ → ωω
Elastic contribution
(protons scatter intact)

LO + NLO top-antitop production 1607.01158



$\omega\omega \to \omega\omega$



$\omega\omega \to tt$

Conclusions:

EWgap: scattering of “Low-Energy” particles W_L, Z_L, h described by

non-linear HEFT at 1-loop + dispersion relations, Equivalence Theorem

Generically strongly interacting → resonances

Coupling to $\gamma\gamma$, tt available

More work needed for realistic predictions; but with cross sections at hand
it appears that the LHC could not yet have found
strong resonances of the EWSBS above 1 TeV.

Theory reach: up to $4\pi v \sim 3$ TeV or, if new physics with “low-E” scale f, $4\pi f$

We can in principle provide differential cross sections
to swipe EFT parameter space with resonance-search data

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Resonances of the Electroweak Symmetry Breaking Sector in unitarized Higgs-EFT

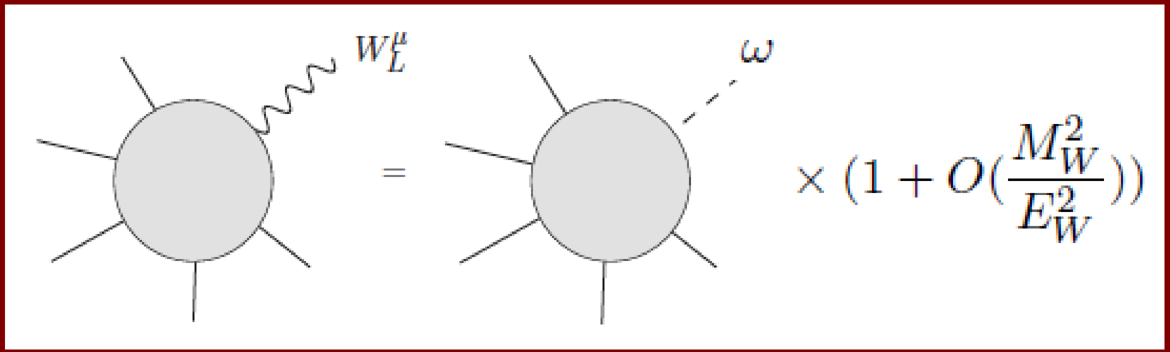
Universidad Autónoma-CSIC,
Instituto de Física Teórica,
May 8th 2017

Long term collaboration with Antonio Dobado, Rafael L. Delgado
Andrés Castillo, and students Iván León Merino, Miguel Espada

Spare Slides

LHC window to EWSBS:
W_L W_L scattering at high energy

Equivalence Theorem: use Goldstone instead of gauge bosons



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

LO Effective Lagrangian

Therefore, HEFT for the EWSBS at low-energy may be taken as a

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

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

(Gauged) NLSM   U = WBGB Fields (GB or pions)

"Small" effects at the 500 GeV scale:

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

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

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

Interesting particular cases:

*Minimal Standard Model: $a = b = c = c_i = d_i = 1$ $a_i = 0$

*No-Higgs Model (ruled ou $a = b = c = 0$

*Minimal Dilaton Model $h = \varphi$ New scale $f \neq v$ $a^2 = b = \frac{v^2}{\hat{f}^2}$
(also disfavored by run I)

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

(Halyo, Goldberber, Grinstein, Skiba)

*Minimal Composite Higgs Mod $f \neq v$

$SO(5)/SO(4)$ $\xi = v^2/f^2$

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

Kaplan, Georgi
Agashe, Contino, Pomarol, Da Rold

NLO-Lagrangian

(extended Apelquist-Longhitano to include the h)

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

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

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

Alonso, Gavela, Merlo, Rigolin and Yepes

Restricting anomalous couplings

Primary bosonic

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

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

Primary fermionic

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

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

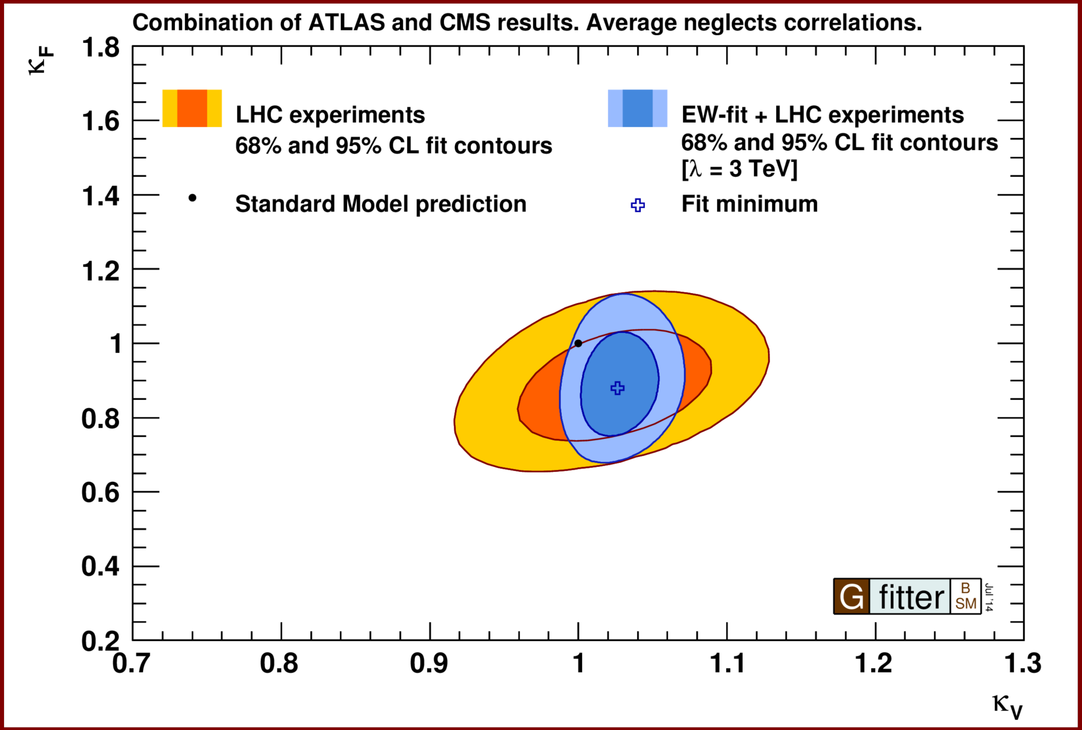
$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

Secondary bosonic

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

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

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



LO ECLh (2 derivatives)

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

NLO ECLh (4 derivatives)

Apelquist-Longhitano

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

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 Effective Lagrangian

for $W_L W_L$, $Z_L Z_L$ and hh one-loop scattering

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

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

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

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

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

Unitarity is simplest for partial waves:

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

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

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

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

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

$I = 0$

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

$h\ h \longrightarrow h\ h$

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

$$F_{00}(s) = \begin{pmatrix} A_{00}(s) & M_0(s) \\ M_0(s) & T_0(s) \end{pmatrix} \qquad F_{02}(s) = \begin{pmatrix} A_{02}(s) & M_2(s) \\ M_2(s) & T_2(s) \end{pmatrix}$$

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

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

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

$$|\ A_{IJ}\ |^2 \leq 1$$

Constants to reconstruct partial waves with I=J=0

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

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

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

$\omega\omega \to hh$

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

$hh \to hh$

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The Inverse Amplitude Method

Dobado. Herrero, Truong, Pelaez…

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

$$I \neq 0$$

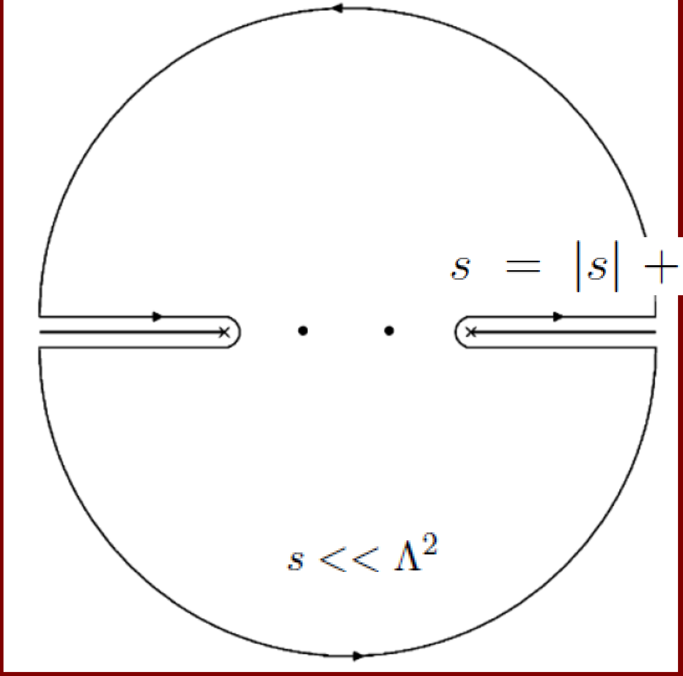
$$A^{NLO}(s) = A^{(0)}(s) + A^{(1)}(s)$$

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

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

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

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



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

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

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

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

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

Inverse Amplitude

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

RC $\quad \mathrm{Im}\,G\;=\;-K^2s^2$ $\quad$ LC $\quad \mathrm{Im}\,G\simeq-\,\mathrm{Im}\,A^{(1)}$

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

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

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

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

The IAM method produces:

Unitary amplitudes equal to NLO EFT at low energy; the proper analytical structure which can have poles in the second Riemann sheet reproducing new resonances. Extension to coupled channels for massless particles:

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

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

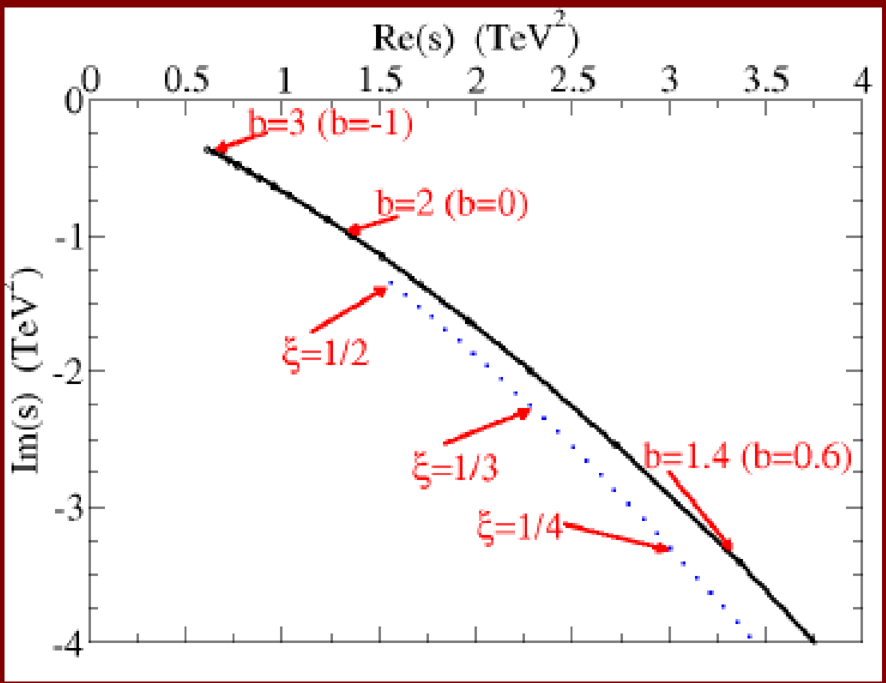
Dependence on the unitarization method

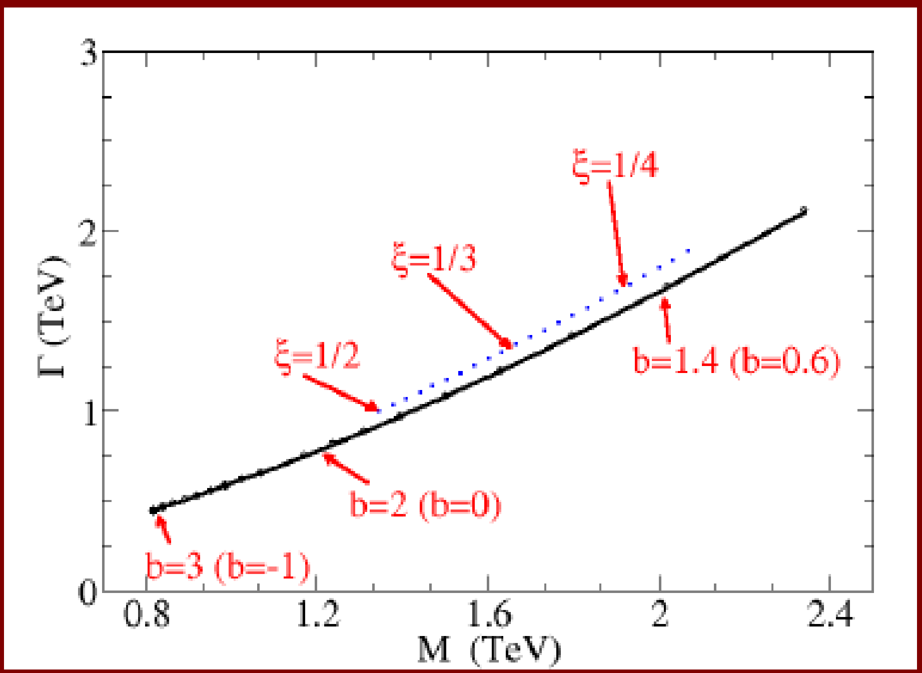
$$
\begin{aligned}
A^{\mathrm{IAM}}(s) &= \frac{[A^{(0)}(s)]^2}{A^{(0)}(s) - A^{(1)}(s)} \\
&= \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} - \left(\frac{A_L(s)}{A^{(0)}(s)}\right)^2 + g(s)A_L(s)} \\
A^{\mathrm{N/D}}(s) &= \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + \frac{1}{2}g(s)A_L(-s)} \\
A^{\mathrm{IK}}(s) &= \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + g(s)A_L(s)}.
\end{aligned}
$$

The formulae differ only if A_L (left cut contribution) is large

Position of pinball resonance in complex plane

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





$SO(5)/SO(4)$

$b \in (-1, 3)$

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

First bound on this EFT parameter known to us

Wrapping up $V_L V_L$ scattering:

$a^2 = b$ $a^2 \neq 1$ $\longrightarrow$ Strong, elastic

$a^2 \neq b$ $a^2 = 1$ $\longrightarrow$ Strong, resonating through hh

$a^2 \neq b$ $a^2 \neq 1$ $\longrightarrow$ Both elastic, resonating are strong

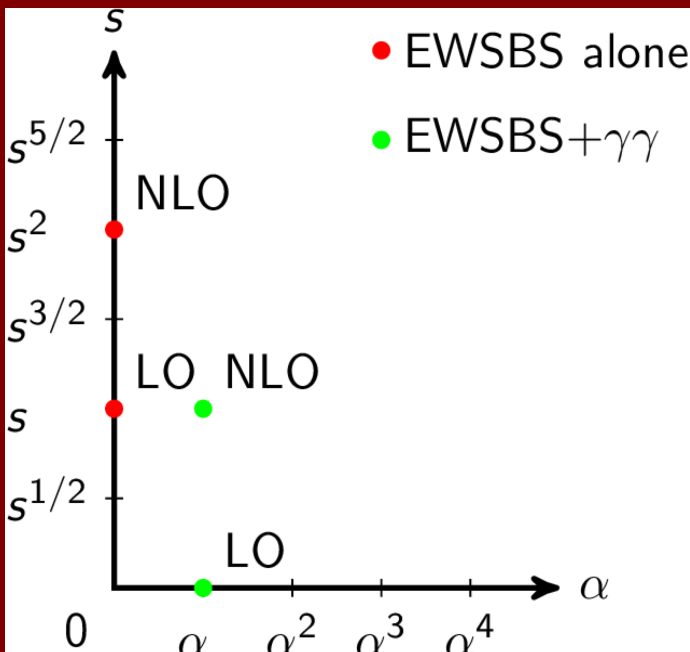
$a^2 = b$ $a^2 = 1$ $\longrightarrow$ Weak, elastic (SM)

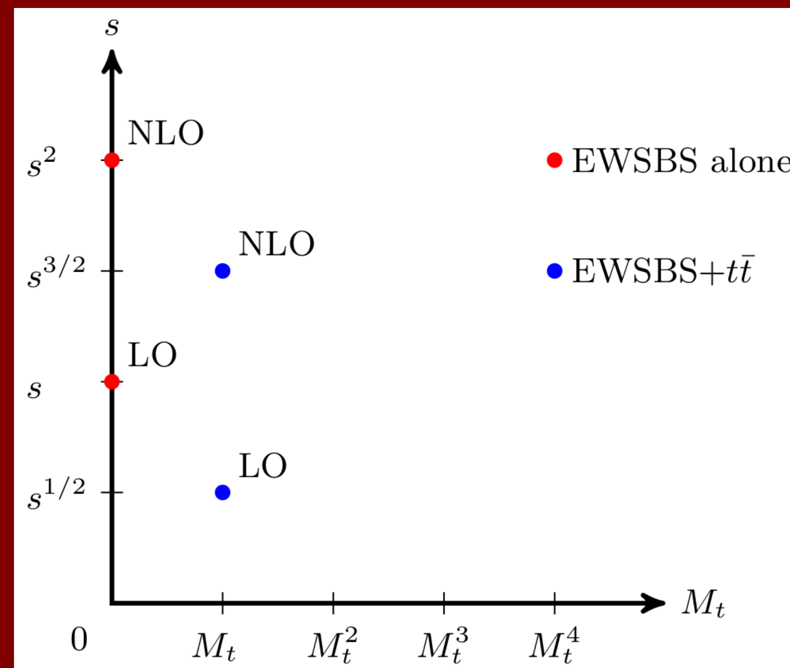
2014 95% CL

Our result

CMS $a \simeq \kappa_V \in [0.7, 1.3]$ *ATLAS* $a \simeq \kappa_V \in [0.8, 1.4]$ $b \in (-1, 3)$

Counting for EWSBS + γγ or tt





Minimum truth in it: global SU(2) X SU(2) → SU(2)

SMEFT (linear representation)

ω^a and h form a left SU(2) doublet

Always the combination (h + v)

Higher symmetry

Typical situation when h is a fundamental field

EFT based in counting dimensions: $O(d)/\Lambda^{d-4}$
(d=4,6,8…)

Philosophy: the SM is basically true, extend it

Minimum truth in it: global SU(2) X SU(2) → SU(2)

HEFT (nonlinear representation)

h is a custodial SU(2) singlet; (think of π^a and η wrt isospin in hadron physics)

ω^a parametrize coset

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

Less symmetry; more independent higher dim. eff. operators

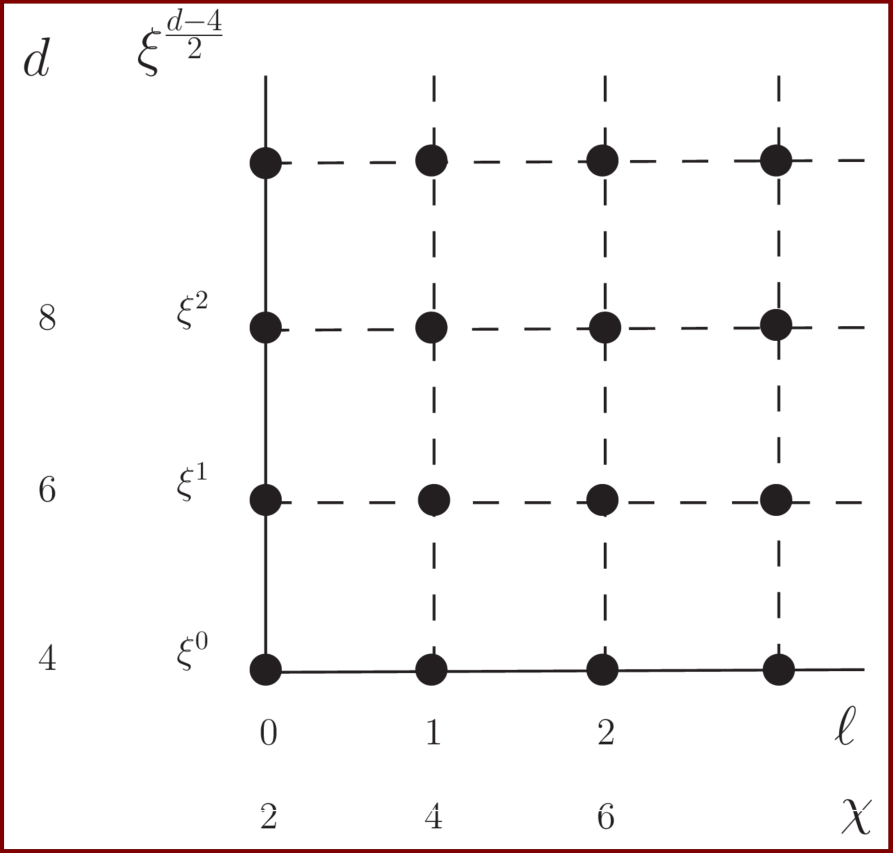
Derivative expansion → strongly interacting

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

Philosophy: agnostic respect to SM

Differences in counting

SMEFT: count canonical dimensions indep. Of how many loops to yield operator



Buchalla, Catà... e.g. 1512.07140v1

HEFT: count loops (chiral dimension) indep. of number of bosons

High-mass particles contribution to LECs

Typically a_i = (number) x $C^2 / M^2 \sim \Gamma / M^2$

(see tables in A.Pich et al. 1609.06659)

An interesting exercise (1509.01585)

Resonance → Integrate out → LEC → IAM → Predict resonance

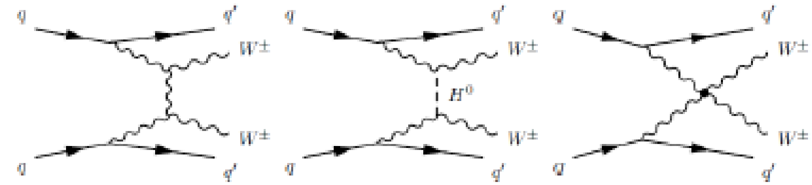
(mass, J,P ok; Γ somewhat overestimated)

W W Scattering @ LHC

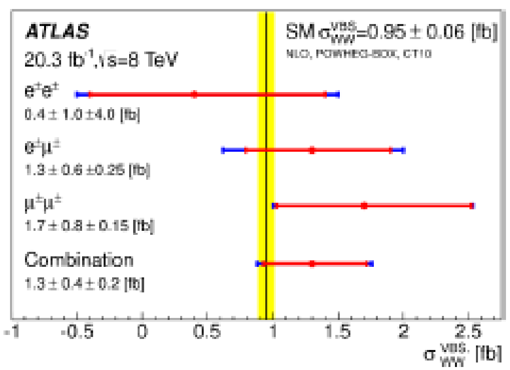
Berryhill

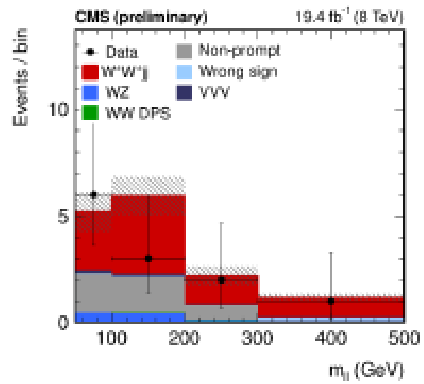
First evidence of $W^\pm W^\pm$ scattering

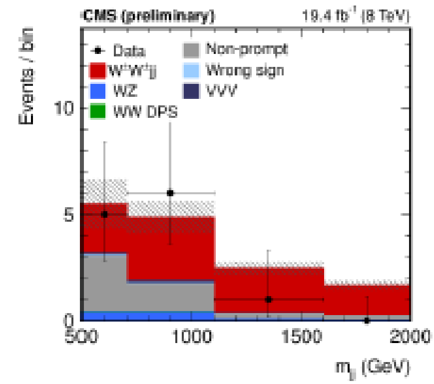
(3.6 σ)

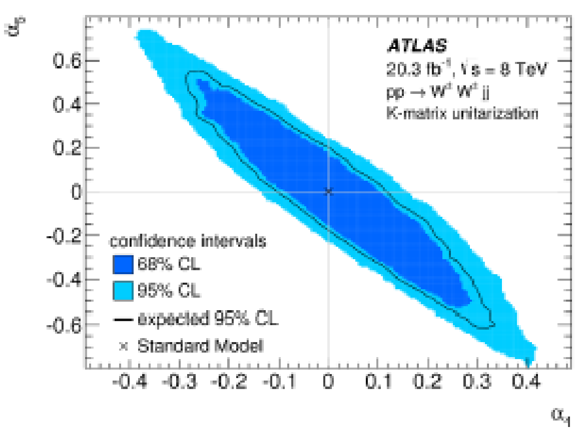


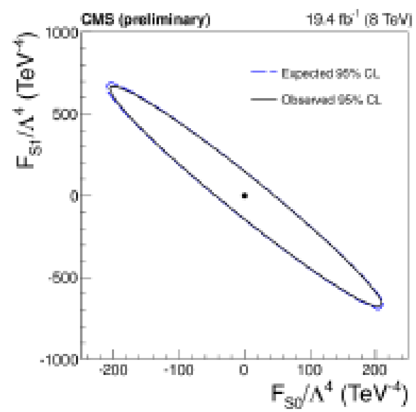
ATLAS, arxiv:1405.6241





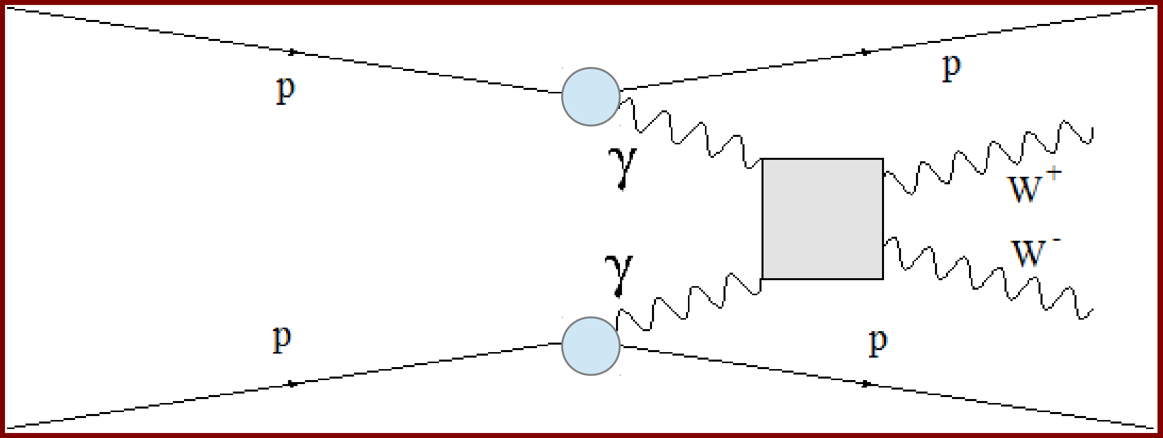




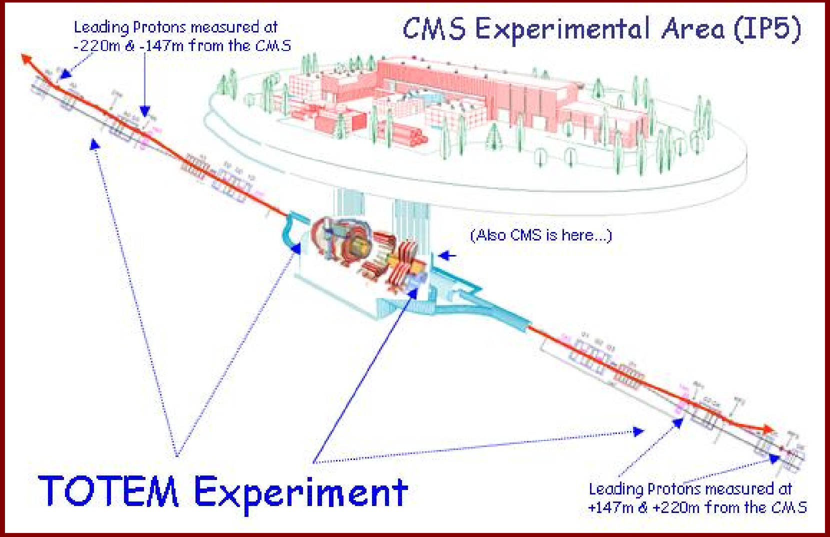


CMS-PAS-SMP-13-015

EM production of EWSBS at the LHC



Photon flows



$\gamma\gamma \longleftrightarrow Z_L Z_L$, $W_L W_L$, hh at one-loop

Interesting for new physics: no Higgs contribution at tree level;
In particular the neutral channel vanishes in the MSM JHEP 1407 (2014) 149.

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

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

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

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

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

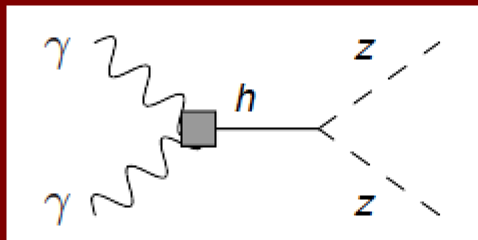
$$\mathcal{M}_{\mathrm{NLO}} = \mathcal{M}^{1-\mathrm{loop}}_{\mathcal{O}(e^2p^2)} + \mathcal{M}^{\mathrm{tree}}_{\mathcal{O}(e^2p^2)}$$

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

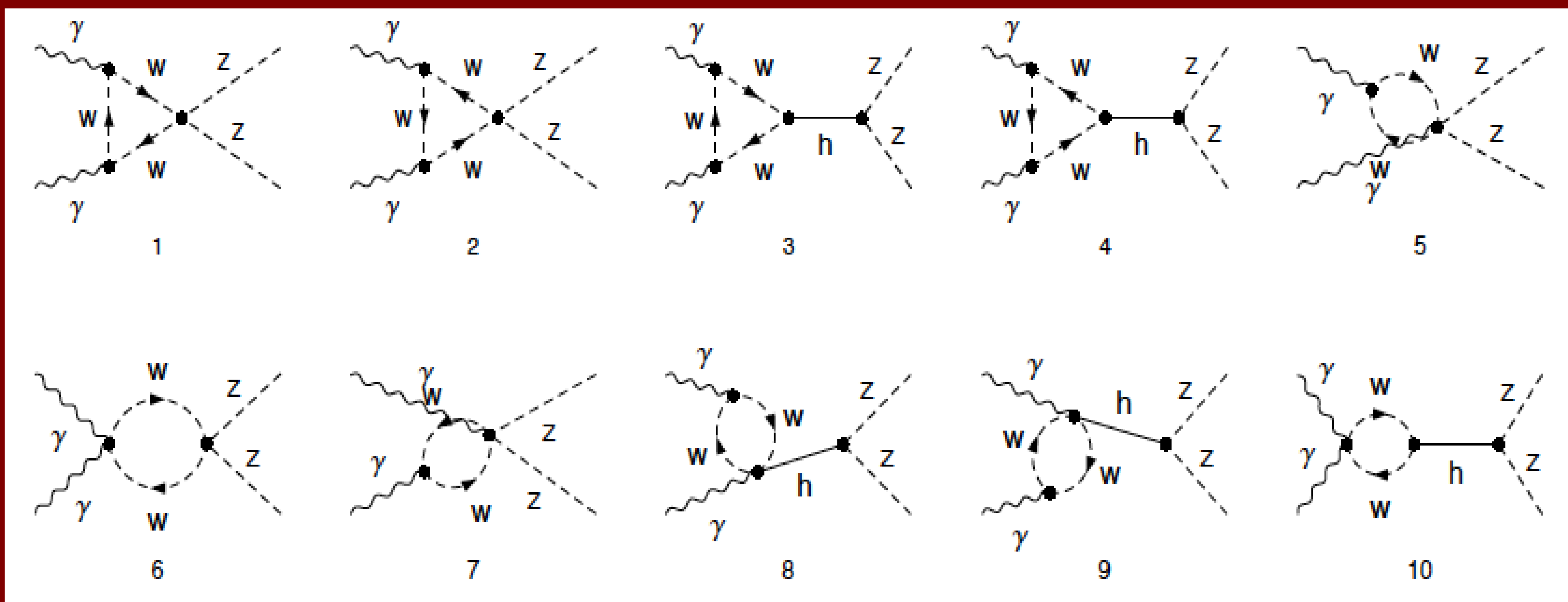
$$B = B_{\mathrm{LO}} + B_{\mathrm{NLO}}$$

$$\gamma\gamma \to zz$$

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

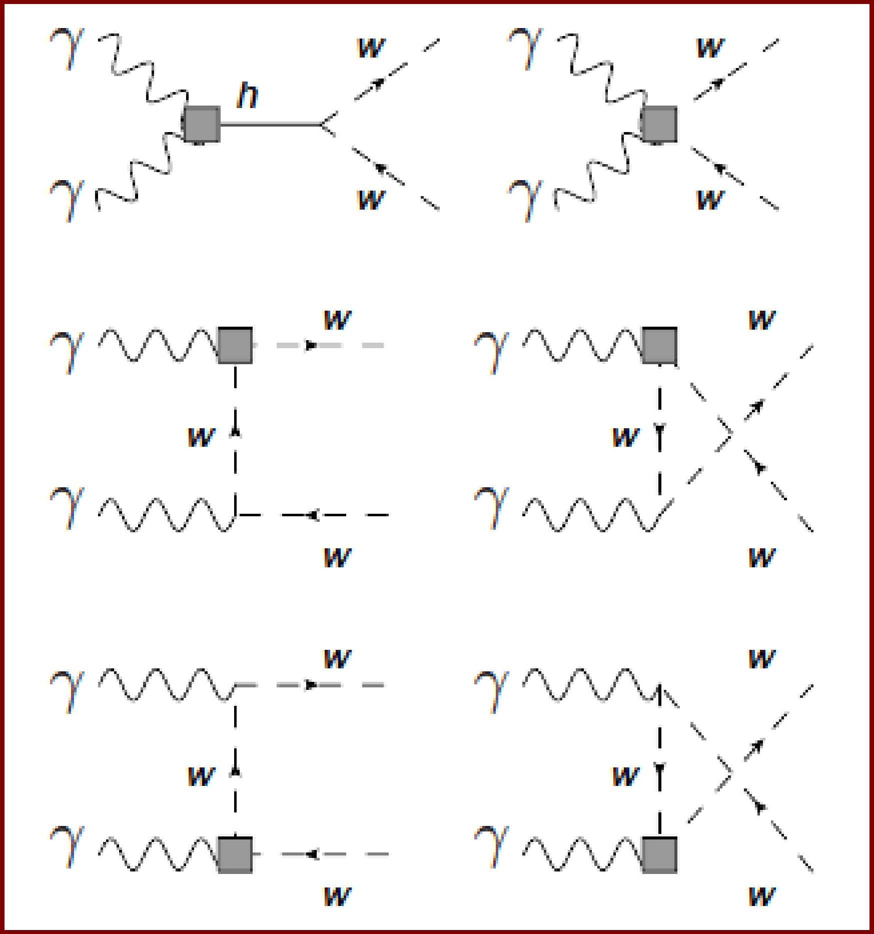


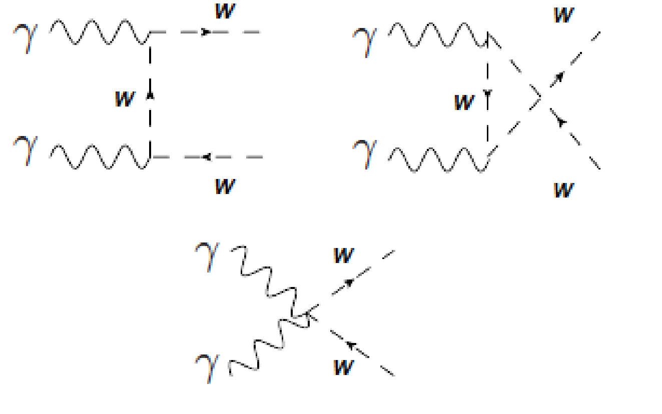
$$A(\gamma\gamma \to zz)_{\rm NLO} = \frac{2ac_\gamma^r}{v^2} + \frac{(a^2-1)}{4\pi^2 v^2}$$
$$B(\gamma\gamma \to zz)_{\rm NLO} = 0,$$



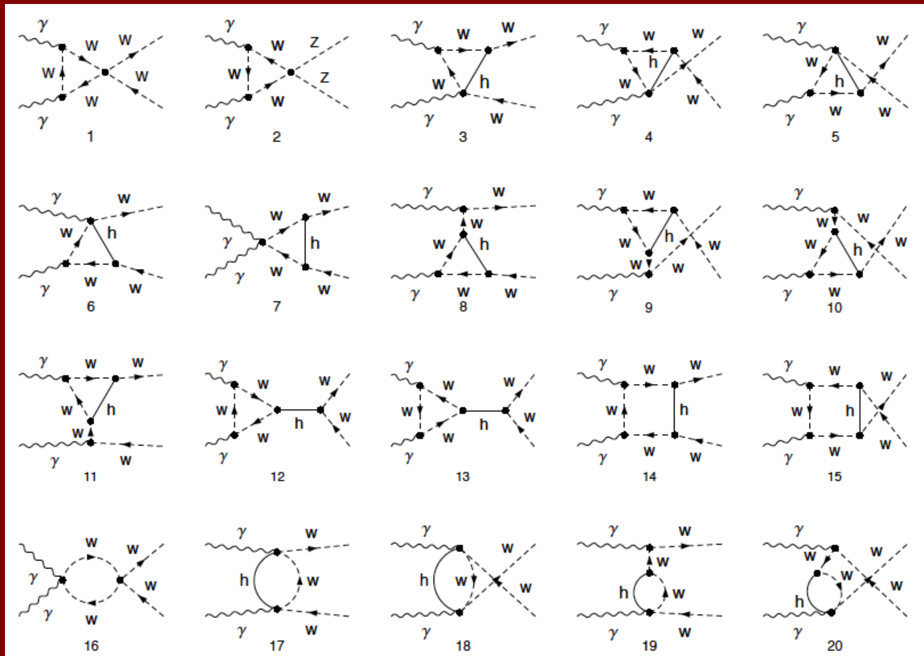
$$c_\gamma^r = c_\gamma$$

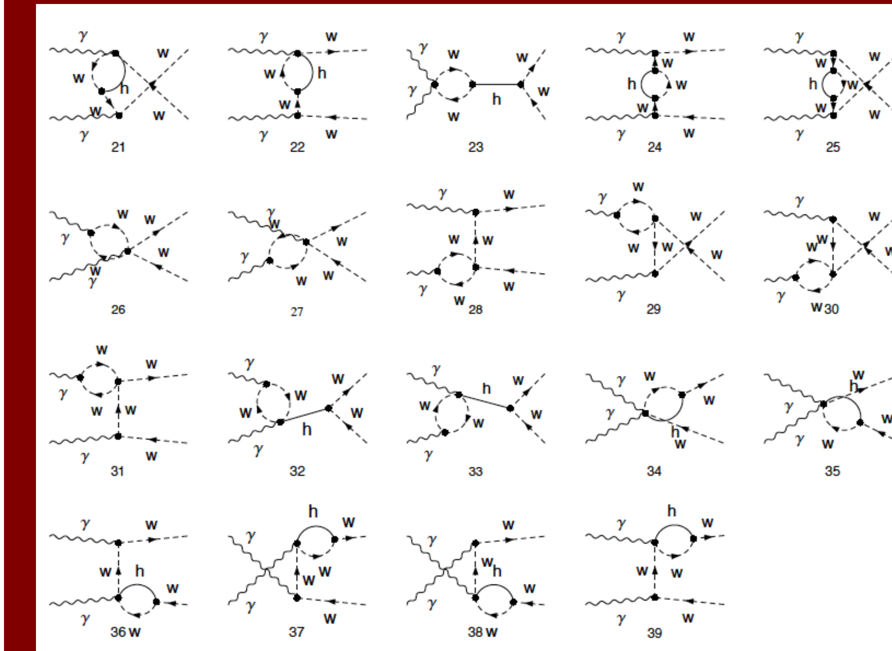
$$\gamma\gamma \to w^+ w^-$$





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





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

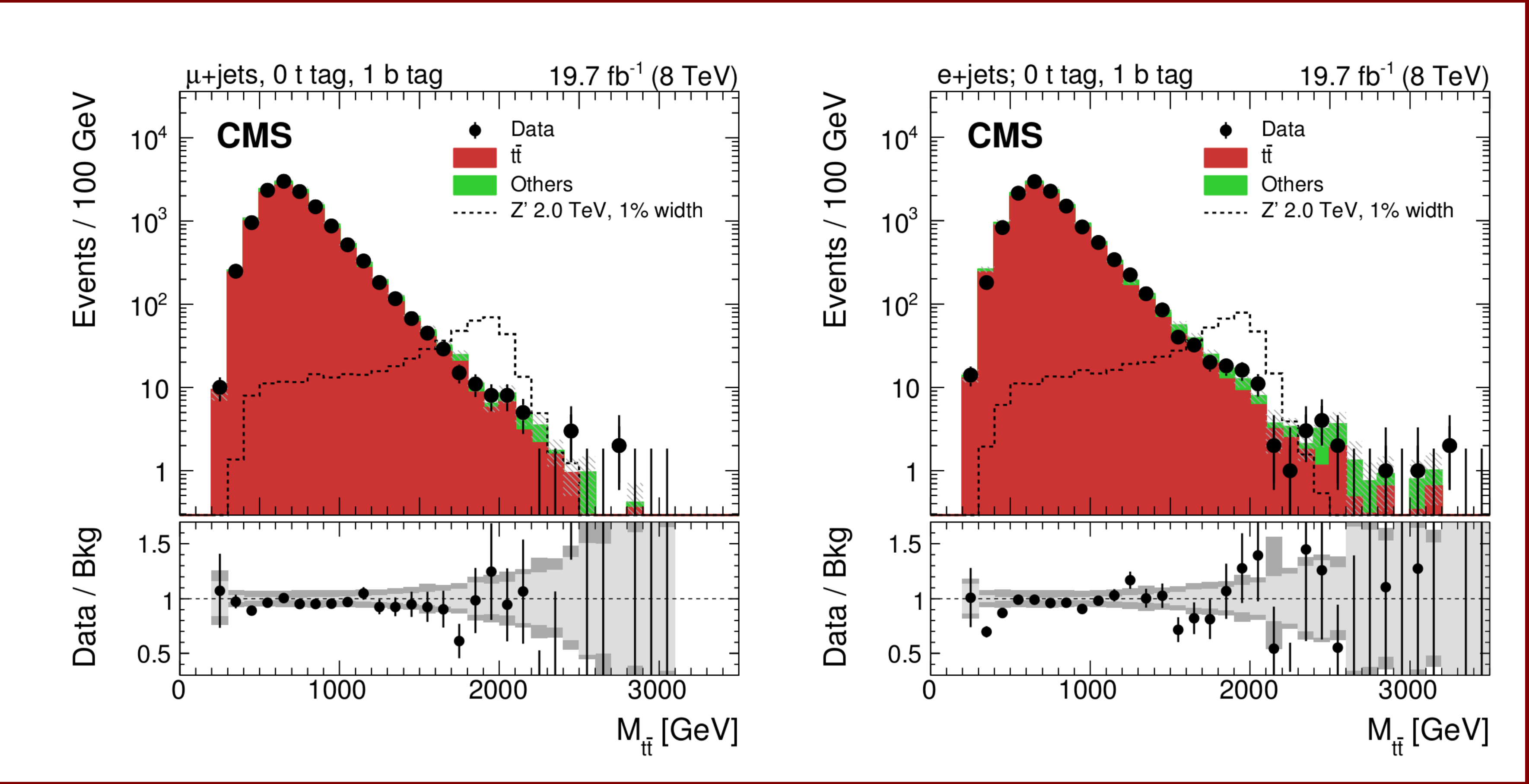
$$\begin{aligned} A(\gamma\gamma \to w^+w^-)_{\rm NLO} &= \frac{8(a_1^r - a_2^r + a_3^r)}{v^2} + \frac{2ac_\gamma^r}{v^2} + \frac{(a^2-1)}{8\pi^2 v^2} \\ B(\gamma\gamma \to w^+w^-)_{\rm NLO} &= 0. \end{aligned}$$

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

Finite one-loop result ! No renormalization needed

Now unitarized too: Eur.Phys.J. C77 (2017) 205

Top-antitop



μ+jets, 0 t tag, 1 b tag
19.7 fb-1 (8 TeV)
CMS
Data
tt̄
Others
Z' 2.0 TeV, 1% width
Events / 100 GeV
Data / Bkg
M_tt̄ [GeV]
e+jets; 0 t tag, 1 b tag
19.7 fb-1 (8 TeV)
CMS
Data
tt̄
Others
Z' 2.0 TeV, 1% width
Events / 100 GeV
Data / Bkg
M_tt̄ [GeV]

Top-antitop production

* Because the top has the largest fermion mass,
its coupling to the EWSBS is largest among fermions

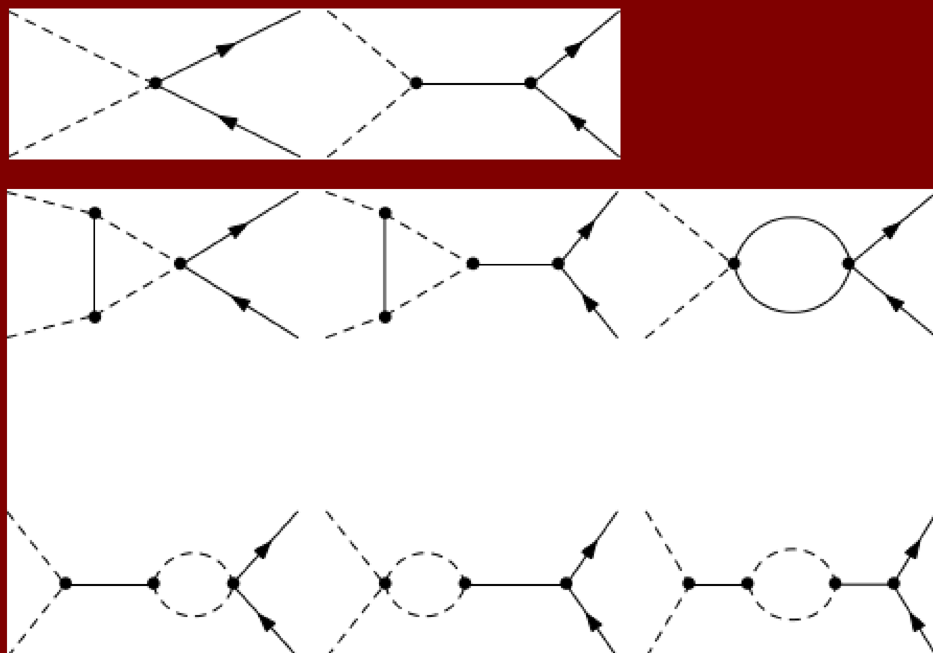
$$\mathcal{L} = \frac{1}{2}\partial_\mu h \partial^\mu h - \left(1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2}\right)\left\{\left(1 - \frac{\omega^2}{2v^2}\right)M_t t\bar{t} + \frac{i\sqrt{2}\omega^0}{v}M_t\bar{t}\gamma^5 t - i\sqrt{2}\frac{\omega^+}{v}M_t\bar{t}_R b_L + i\sqrt{2}\frac{\omega^-}{v}M_t\bar{b}_L t_R\right\}$$
$$+ \frac{1}{2}\left(1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2\right)\partial_\mu\omega^i\partial^\mu\omega_j\left(\delta_{ij} + \frac{\omega_i\omega_j}{v^2}\right).$$

(We maintain Yukawa structure
bc of B-factories success)

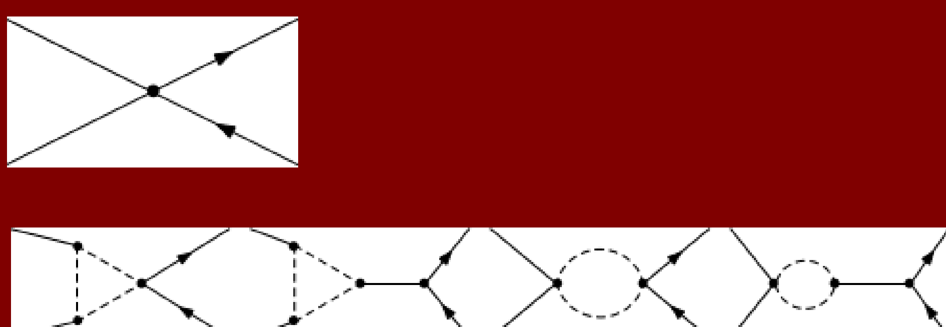
$$\begin{aligned}\mathcal{L}_4 = {} & \frac{4a_4}{v^4}\partial_\mu\omega^i\partial_\nu\omega^i\partial^\mu\omega^j\partial^\nu\omega^j + \frac{4a_5}{v^4}\partial_\mu\omega^i\partial^\mu\omega^i\partial_\nu\omega^j\partial^\nu\omega^j \\ & + \frac{2d}{v^4}\partial_\mu h\partial^\mu h\partial_\nu\omega^i\partial^\nu\omega^i + \frac{2e}{v^4}\partial_\mu h\partial^\nu h\partial^\mu\omega^i\partial_\nu\omega^i \\ & + \frac{g}{v^4}\left(\partial_\mu h\partial^\mu h\right)^2 \\ & + g_t\frac{M_t}{v^4}(\partial_\mu\omega^i\partial^\mu\omega^j)t\bar{t} + g_t'\frac{M_t}{v^4}(\partial_\mu h\partial^\mu h)t\bar{t}. \qquad (16)\end{aligned}$$

1607.01158

LO + NLO top-antitop production 1607.01158



$\omega\omega \to tt$



$hh \to tt$