Antonio Dobado & Felipe J. Llanes Estrada
Departamento de Física Teórica I
Universidad Complutense de Madrid

Electroweak resonances in Higgs-EFT

Long term collaboration with Rafael L. Delgado

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

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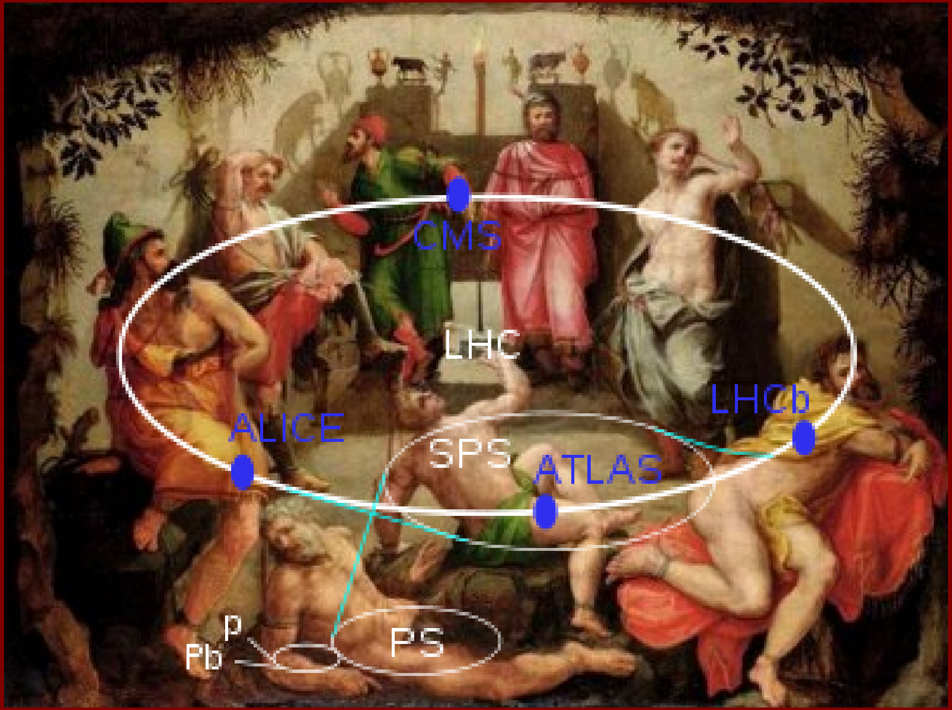
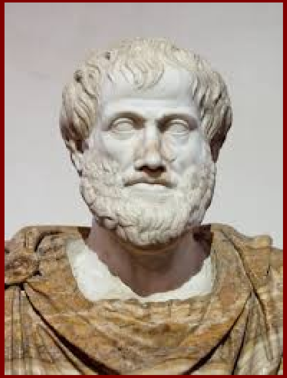
While waiting for "well motivated BSM physics"

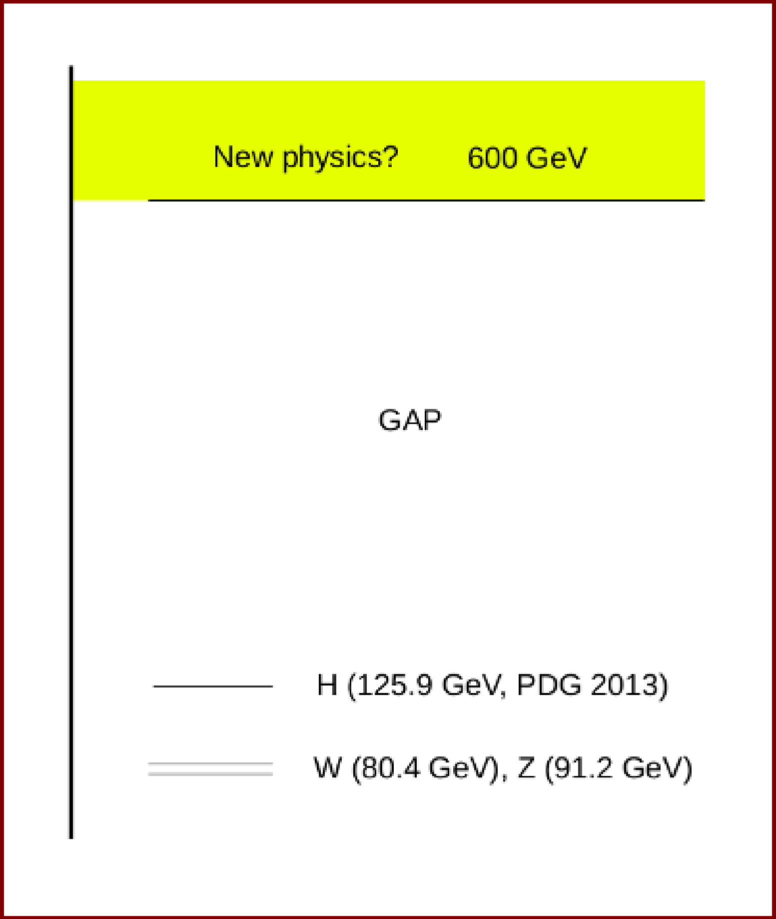




Try
Effective Field Theory
for the particles
that we do see

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

Energy desert or Gap in the spectrum



Option #1: LHC will find nothing
Enjoy the canals...

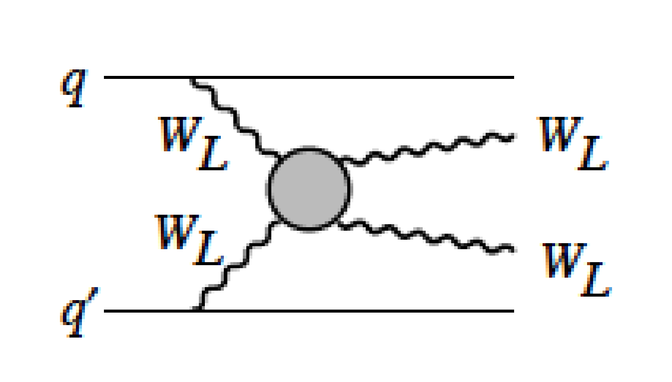
#2: New physics, weakly coupled

Keep turning stones

#3: New physics at higher E,
Perhaps out of LHC reach

a) W_L, Z_L, h Goldstone bosons?
b) How to make statements about that new physics scale

Gap → Strongly Interacting EWSBS



Longitudinal gauge boson scattering is the key

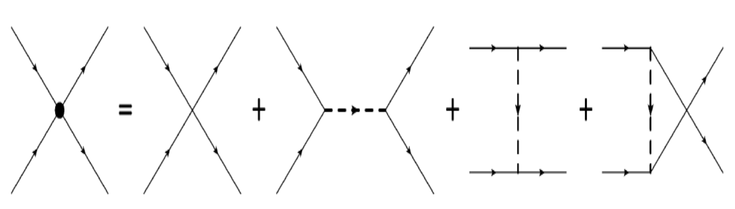
Physical spectrum well below new physics:

3 WBGB ω^a + one light scalar h HEFT

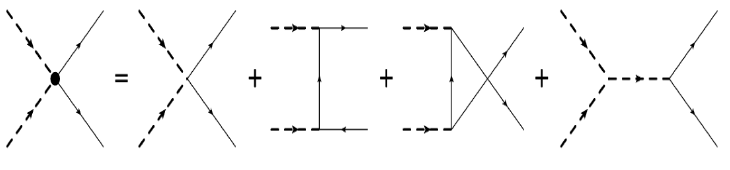
$M_h^2 \sim M_W^2 \sim M_Z^2 \sim M_t^2 \sim (100\ \mathrm{GeV})^2 \ll (500\text{-}700\ \mathrm{GeV})^2$

LO amplitudes: EWSBS ωω, hh

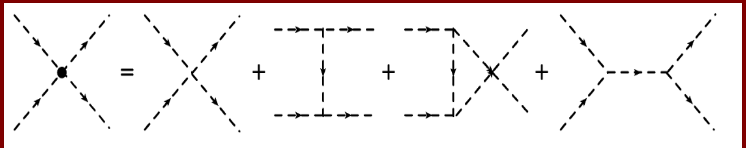
$$M_h^2 \ll s < 4\pi v \simeq 3\,\mathrm{TeV}.$$



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



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



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

Generalize Weinberg low-energy theorems for pion scattering

Automation of HEFT computations in perturbation theory

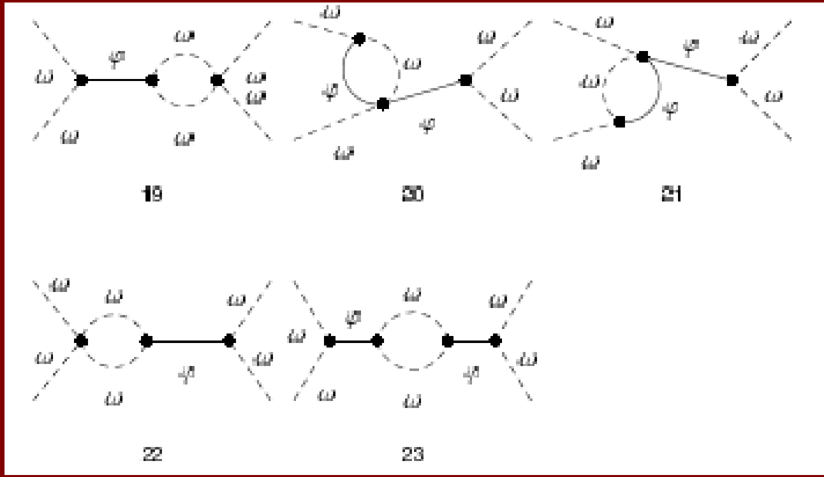
Lagrangian → FeynRules (vertices)
→ FeynArts (diagrams)
→ FormCalc (NLO scattering amplitudes)

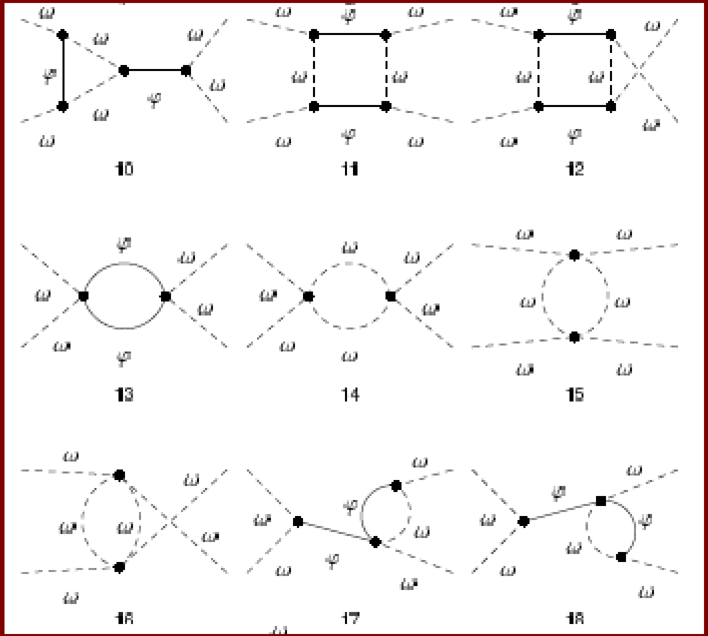
All programmed by our grad student Rafael Delgado

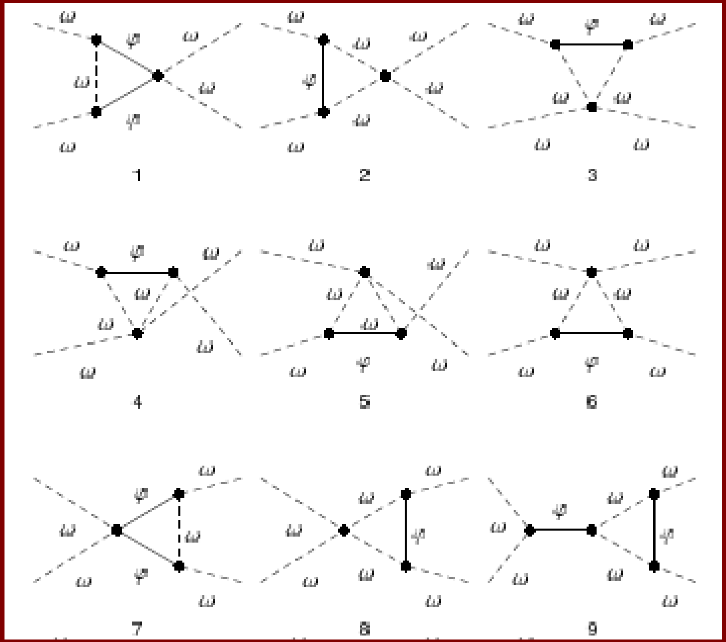
Fortran: Numerically Evaluate the amplitudes and unitarize

One-loop Feynman diagrams for

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

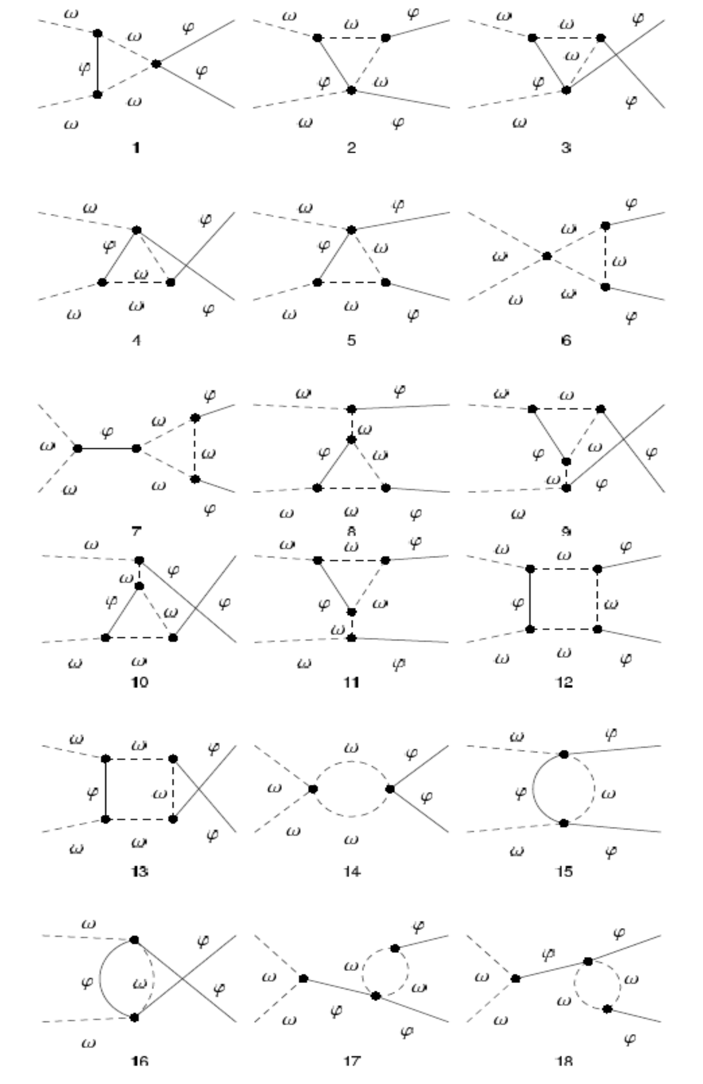


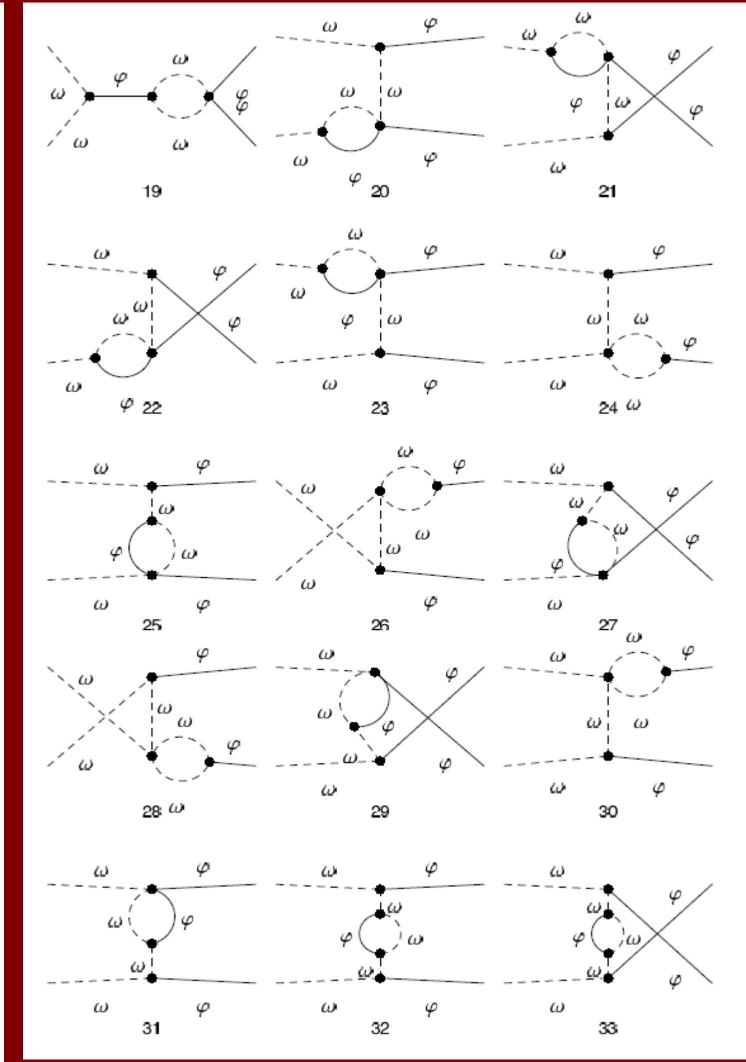




One-loop Feynman diagrams for

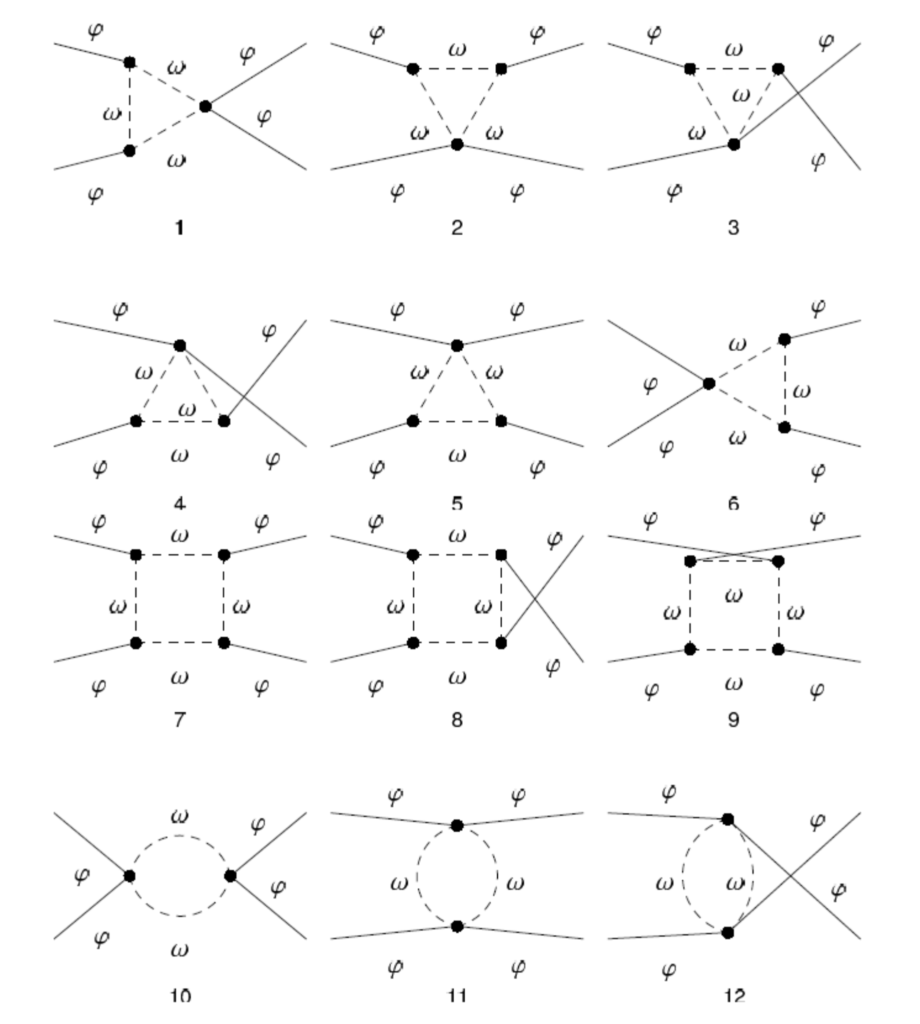
$$\omega_a \omega_b \to hh$$





One-loop Feynman diagrams for

$$hh \to hh$$



Resulting NLO 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 NLO 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 $\omega\,\omega \longrightarrow h\,h$

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

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

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

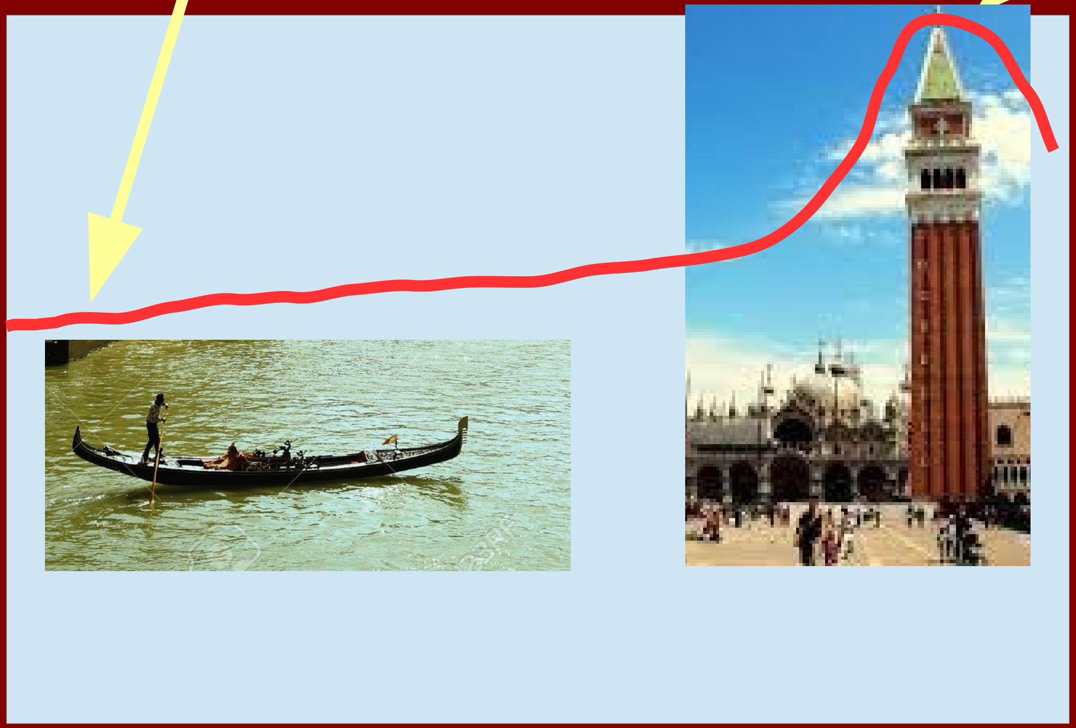
EFT parameters evtly.
measured here @LHC

Resonances at
much higher E

How to
extrapolate?

EFT parameters evtly. measured here @LHC

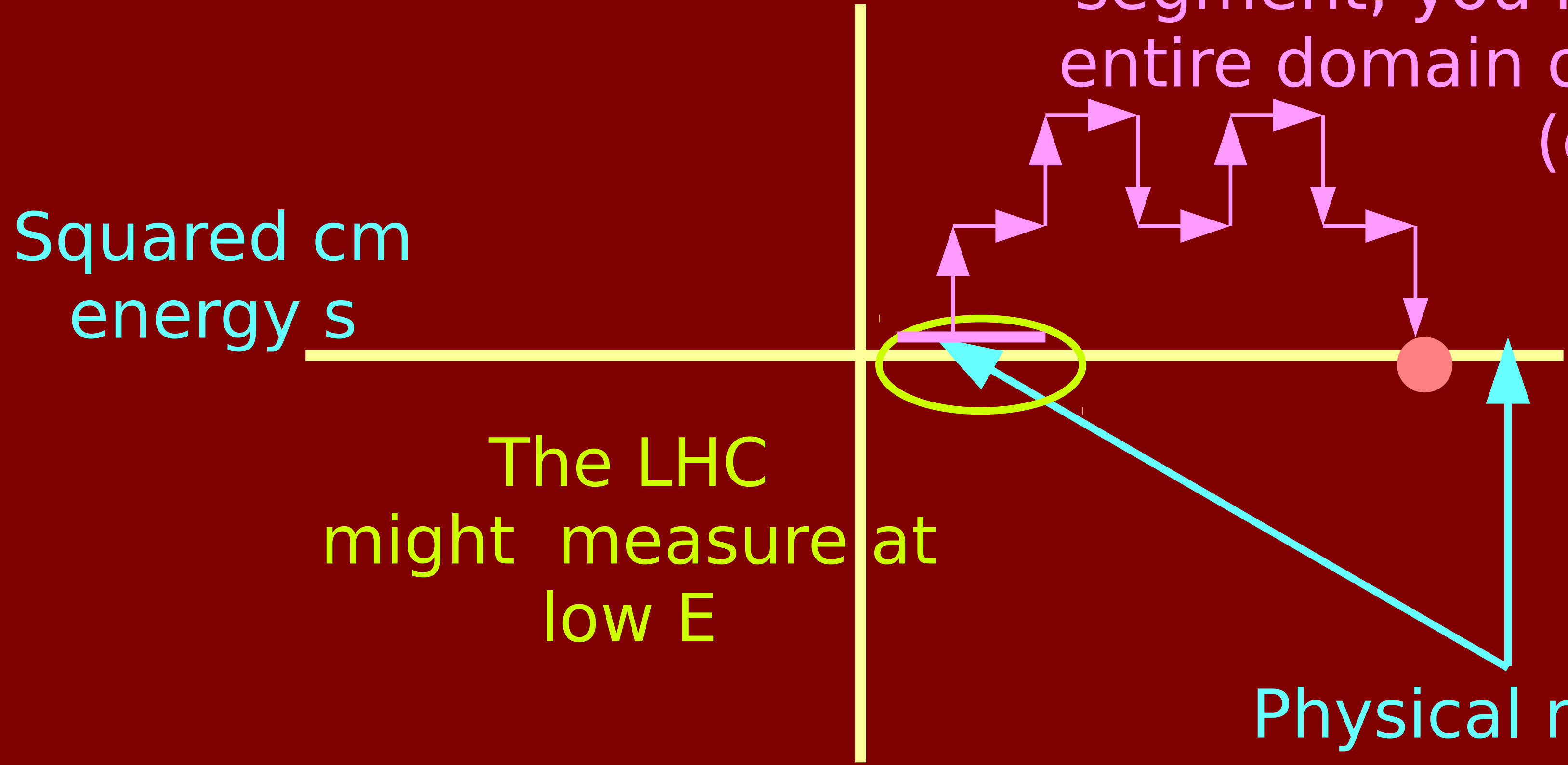
Resonances at much higher E



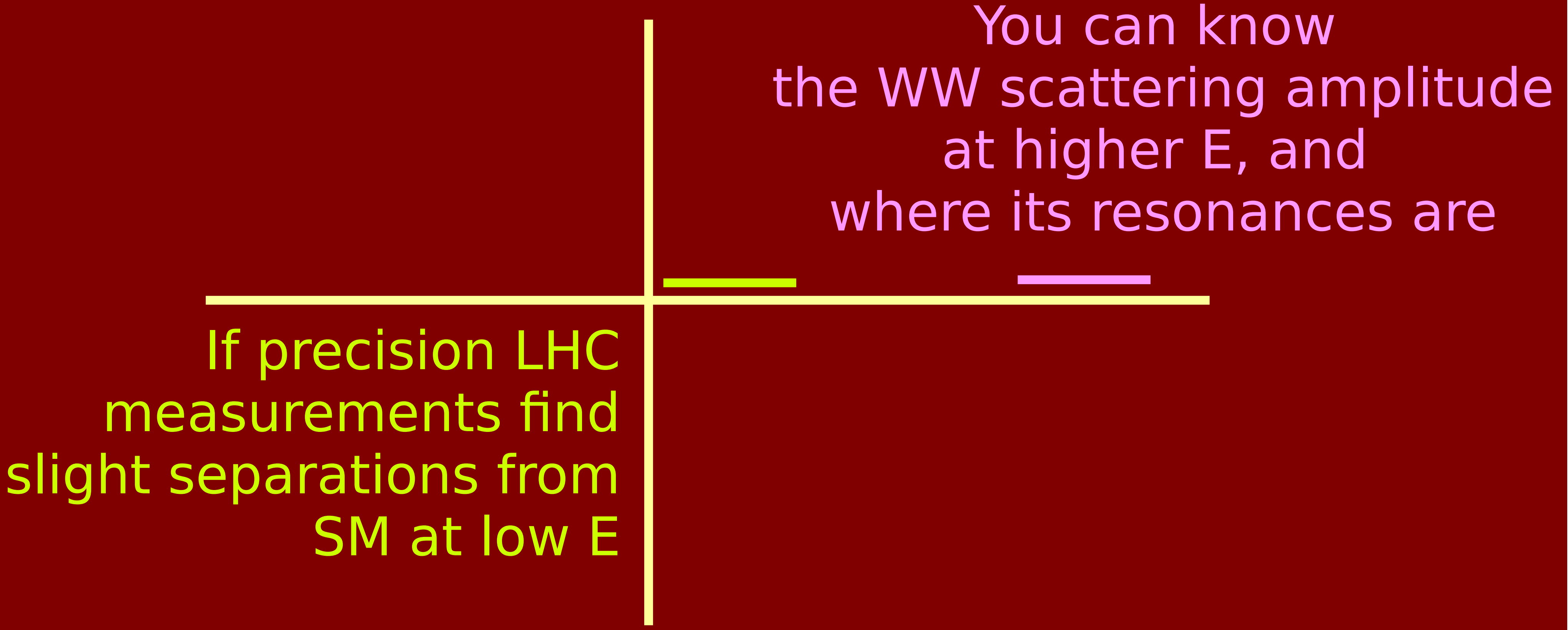
How to extrapolate?

Complex analysis magic

But if you know an analytic function on a segment, you know it in its entire domain of analyticity (e.g. Cauchy-Riemann)

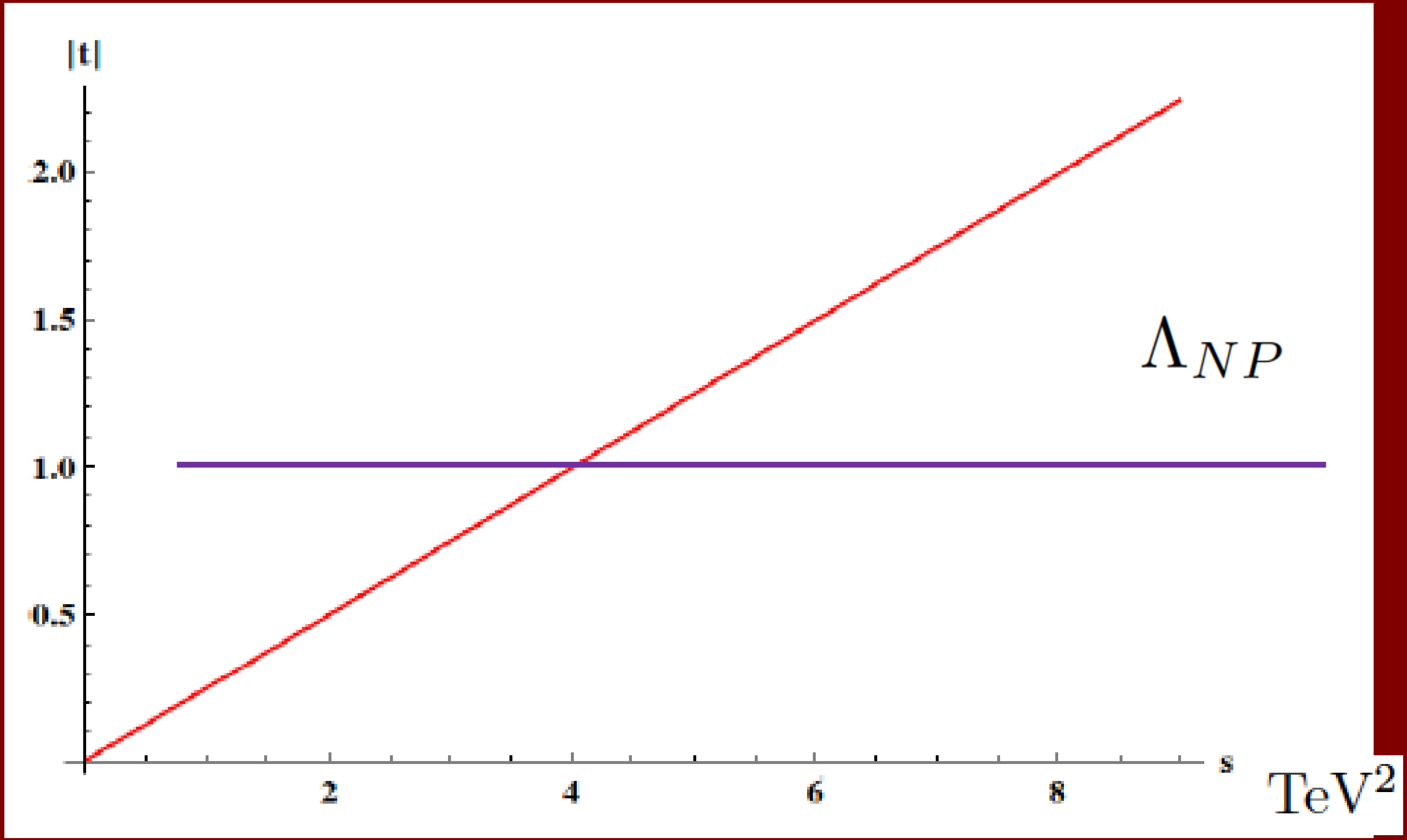


Complex analysis magic



In practice: Cauchy-Riemann unstable,
use Dispersion Relations

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



Problem of perturbation theory

Blaming it to the Lagrangian is wrong logic

Unitarity is simplest for partial waves

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

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

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

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

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

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

LO partial waves

$$A_0^0 = \frac{1}{16\pi v^2}(1-a^2)s$$

$$A_1^1 = \frac{1}{96\pi v^2}(1-a^2)s$$

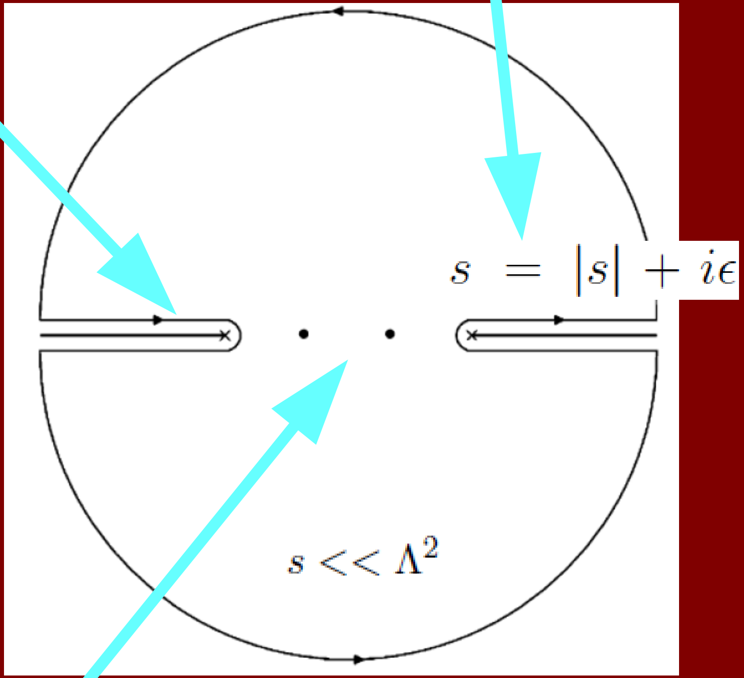
$$A_2^0 = -\frac{1}{32\pi v^2}(1-a^2)s$$

$$M^0 = \frac{\sqrt{3}}{32\pi v^2}(a^2-b)s$$

Phys.Rev. D91 (2015) 075017

Left cut: use the EFT

Right cut: use exact elastic unitarity for the inverse amplitude

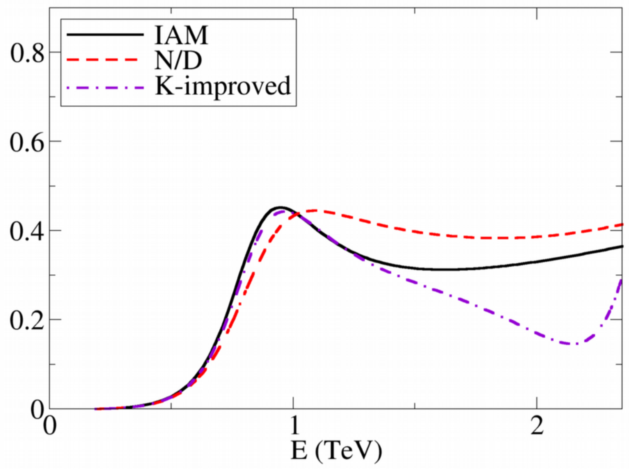


Subtractions at low s where the EFT can be used

DISPERSION RELATION for complex s

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

We have published three major unitarization methods



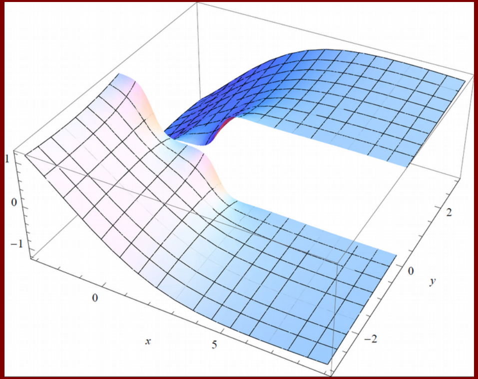
$a^2 = 1 \neq b = 2$

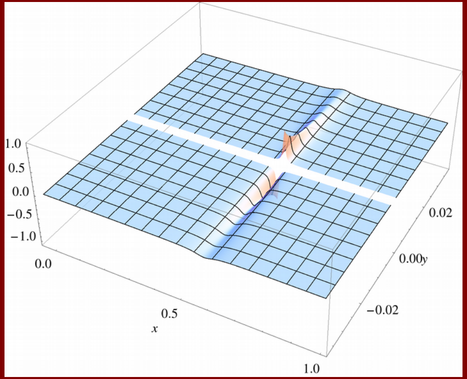
IJ	00	02	11	20	22
Method	Any	N/D, IK	IAM	Any	N/D, IK

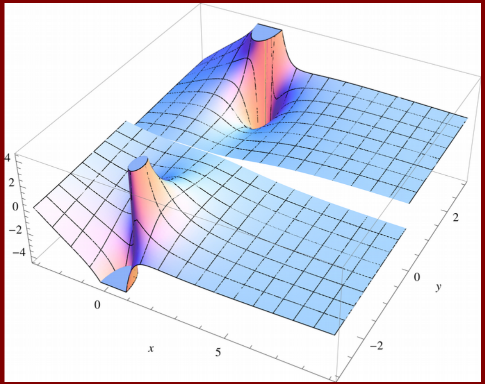
Generally:

Resonating amplitudes (s-channel) → quantitative agreement
Potential-dominated amplitudes (left cut) → qualitative

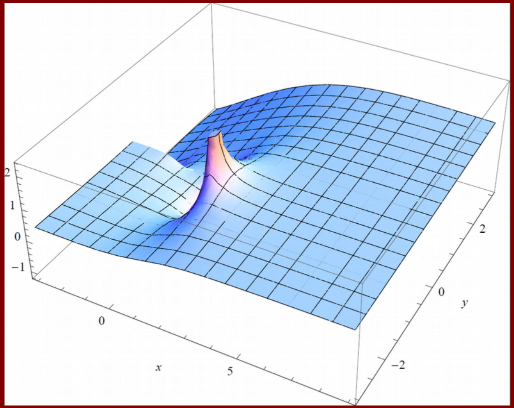
Poles in the s-complex plane are now possible (1) WW

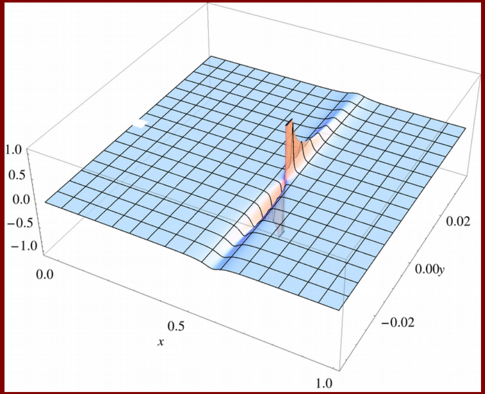


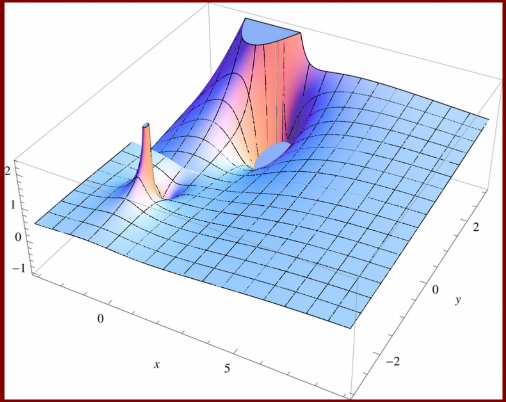




Im A:
1st and 2nd Riemann sheets



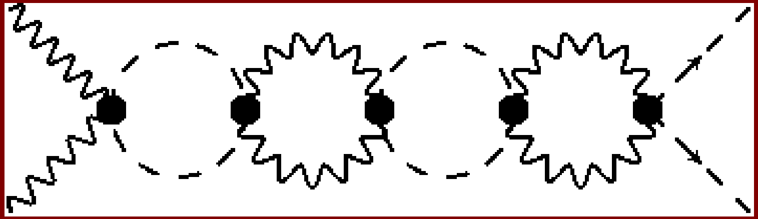




$a = 0.9$
$b = 1$
$a_4 = 0.005$
$a_5 = -a_4$

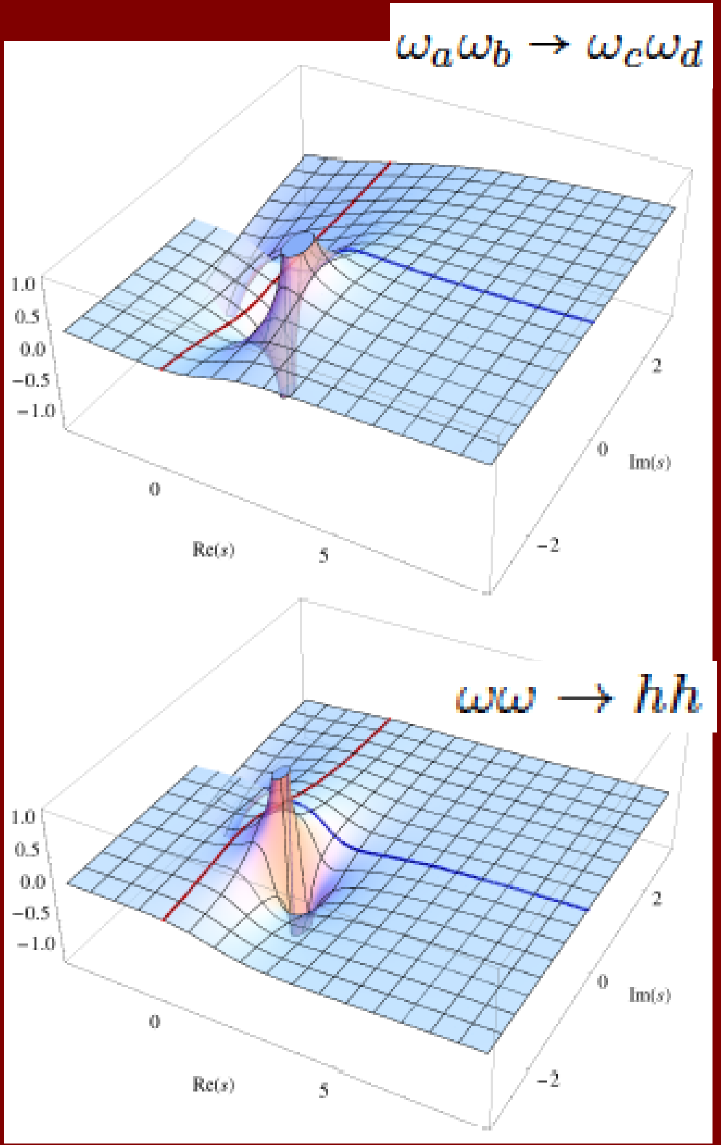
I=J=0 *I=J=1* *I=2,*

(2) hh *(I=0)*
A coupled channel resonance



$a = 1, b = 2$

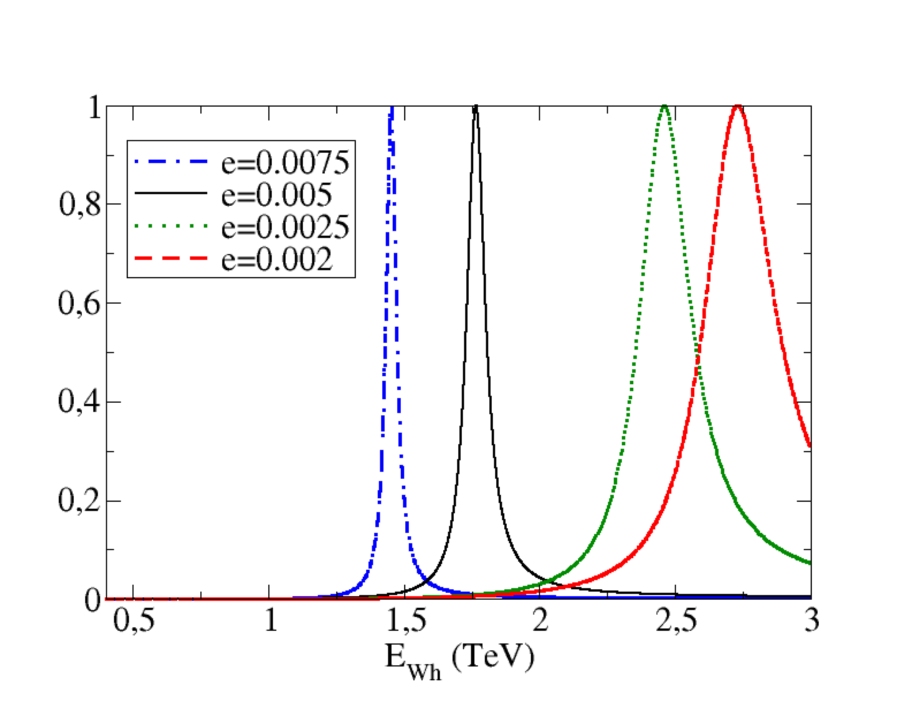
Phys.Rev.Lett. 114 (2015) no.22, 221803



“Pinball resonance”

$b \in (-1, 3)$

(3) Wh (preliminary)



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

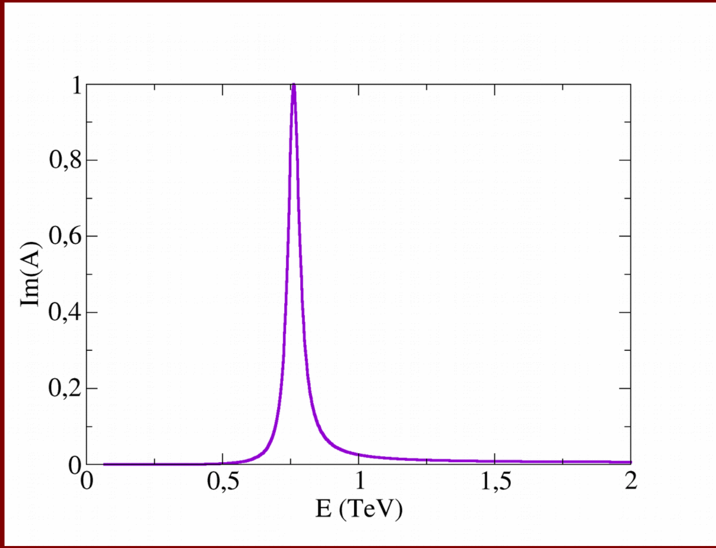
*) resonances can appear in clean $\gamma\gamma$ final state

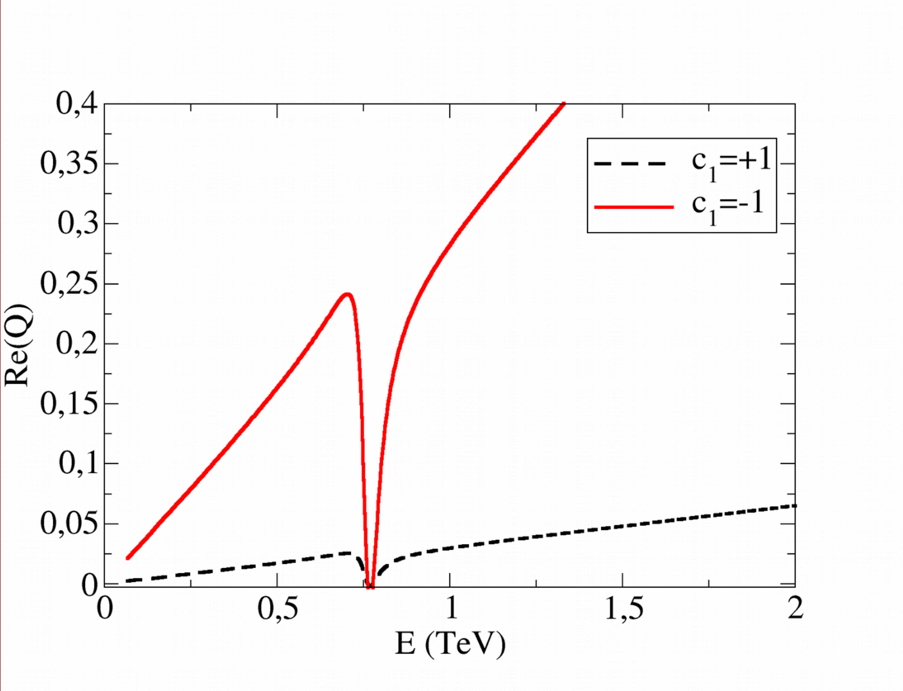
*) EM production not negligible,
charged-particle colliders are photon colliders

?

(5) LO + NLO top-antitop production

1607.01158

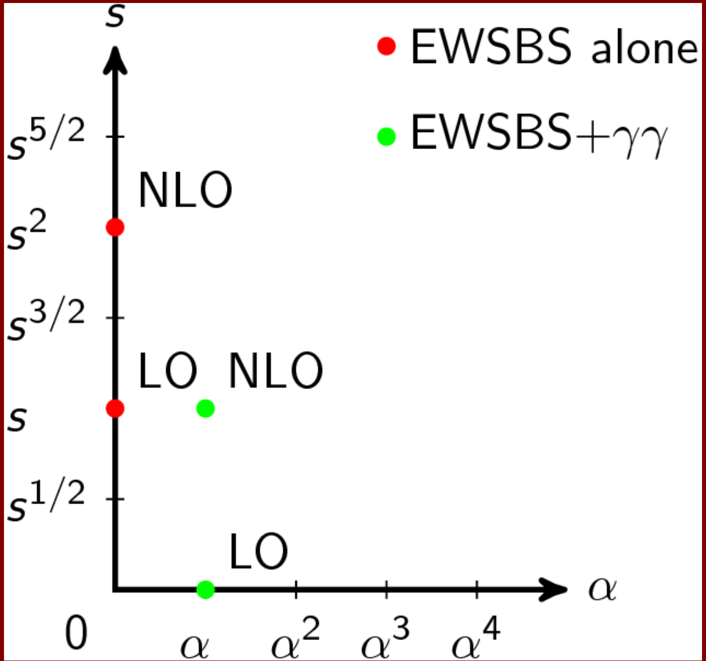


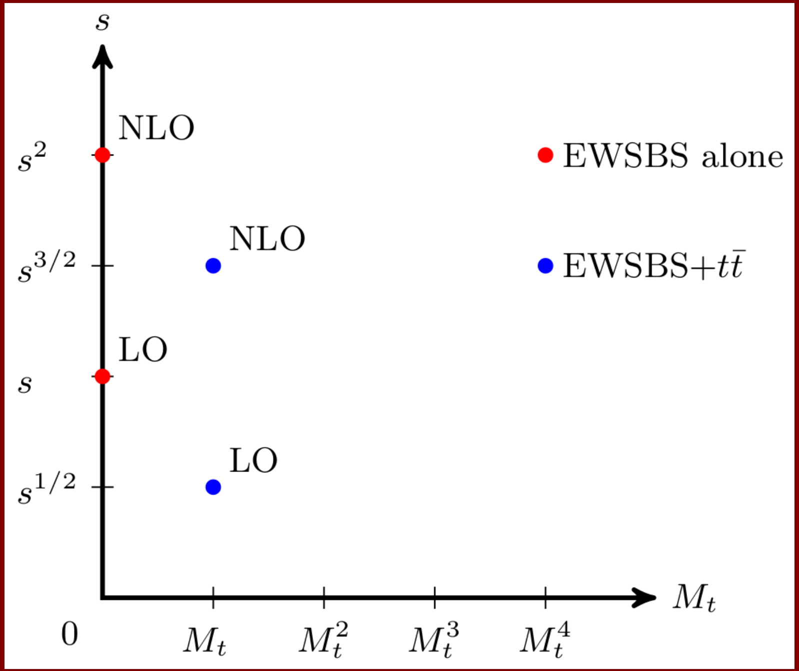


$\omega\omega \rightarrow \omega\omega$

$\omega\omega \rightarrow t\bar{t}$

Counting for EWSBS + $\gamma\gamma$ or $t\bar{t}$





Predictive power of EFT+dispersion Relation?

Can it predict new physics coupled to EWSBS? NO

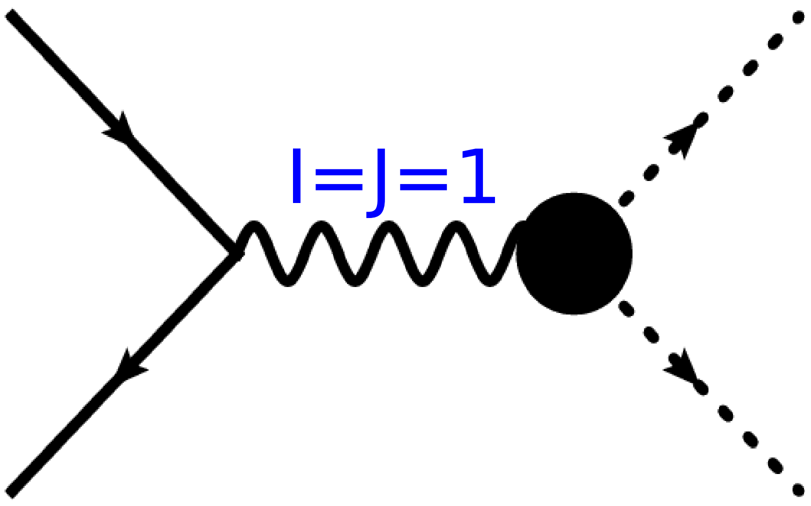
What it can do:

*) If the LHC precision program measures EFT couplings ≠ SM → can evtly. predict resonances

*) 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.

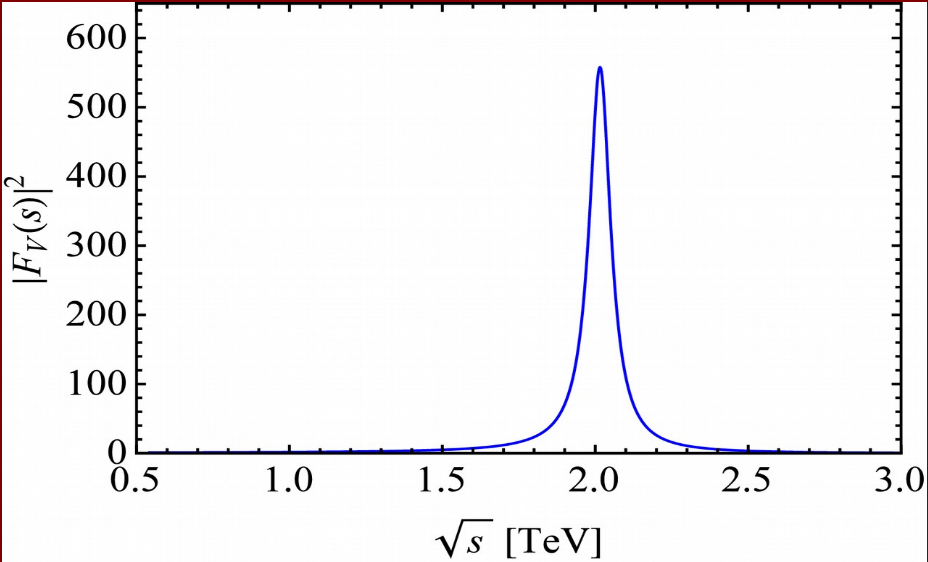
Production at the LHC and $e^- e^+$ colliders



Tree-level ρ-like resonance

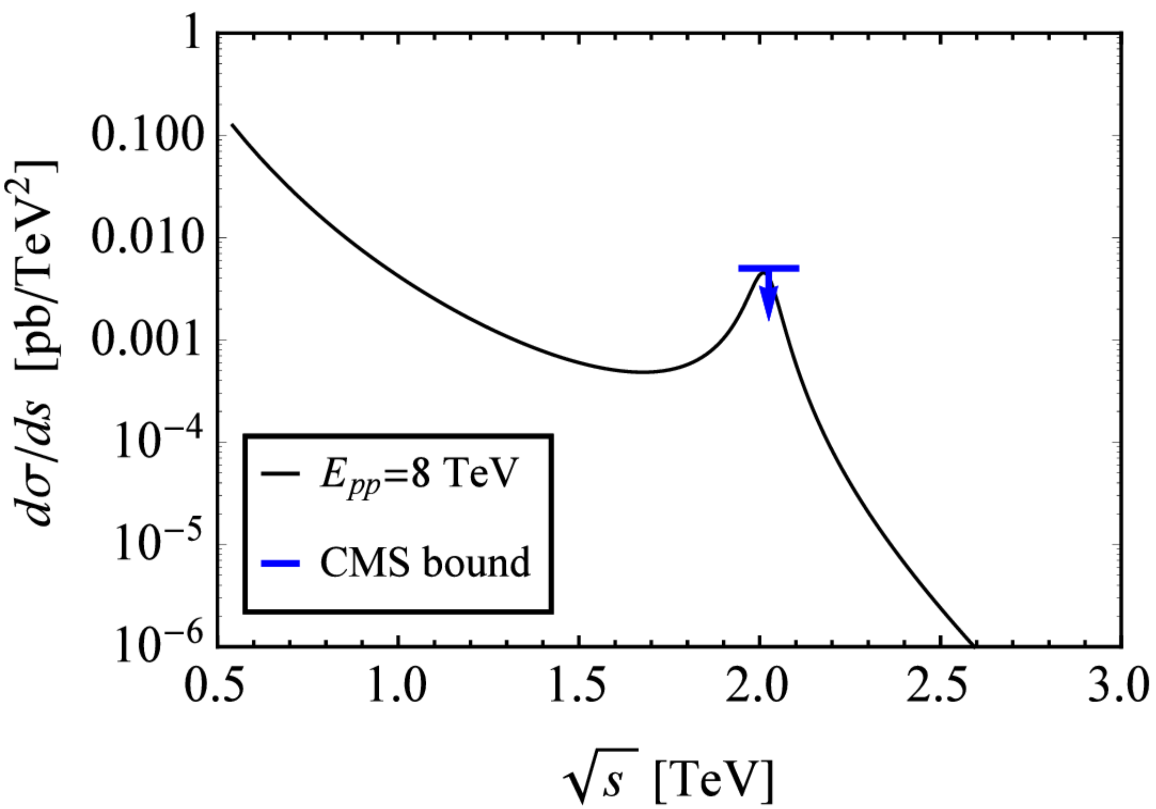
From transverse boson with IAM Form factor (Watson's final state theorem)

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



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

Let's discuss this at the poster session

Conclusions:

EW gap: 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 $\gamma\gamma$, $t\bar{t}$ 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

Antonio Dobado & Felipe J. Llanes Estrada
Departamento de Física Teórica I
Universidad Complutense de Madrid

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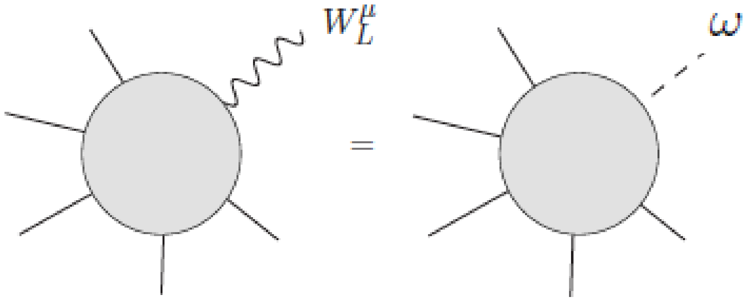
Spare Slides

LHC window to EWSBS:
W_L W_L scattering at high energy

Equivalence Theorem: use Goldstone instead of gauge bosons



$$\times \left(1 + O\left(\frac{M_W^2}{E_W^2}\right)\right)$$

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

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: $a = b = c = c_i = d_i = 1$ $\quad a_i = 0$

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

*Minimal Dilaton Model (also disfavored by run I) $h = \varphi$

New scale $f \neq v$ $\quad a^2 = b = \frac{v^2}{\hat{f}^2}$

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

(Halyo, Goldberber, Grinstein, Skiba)

*Minimal Composite Higgs Model $f \neq v$

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

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

NLO-Lagrangian (extended Apelquist-Longhitano to include the *h*)

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

$$\mathcal{P}_1(h) = g g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$
$$\mathcal{P}_2(h) = i g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$
$$\mathcal{P}_3(h) = i g \mathrm{Tr}(W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$$
$$\mathcal{P}_4(h) = i g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$
$$\mathcal{P}_5(h) = i g \mathrm{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$$

$$\mathcal{P}_6(h) = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$$
$$\mathcal{P}_7(h) = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_7(h)$$
$$\boxed{\mathcal{P}_8(h) = g^2 (\mathrm{Tr}(\mathbf{T} W^{\mu\nu}))^2 \mathcal{F}_8(h)}$$
$$\mathcal{P}_9(h) = i g \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_9(h)$$
$$\mathcal{P}_{10}(h) = g \epsilon^{\mu\nu\rho\lambda} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{10}(h)$$
$$\mathcal{P}_{11}(h) = \mathrm{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12}(h) = \mathrm{Tr}(\mathbf{T} \mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T} \mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{12}(h)$$

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

$$\mathcal{P}_{24}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{24}(h).$$

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

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

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

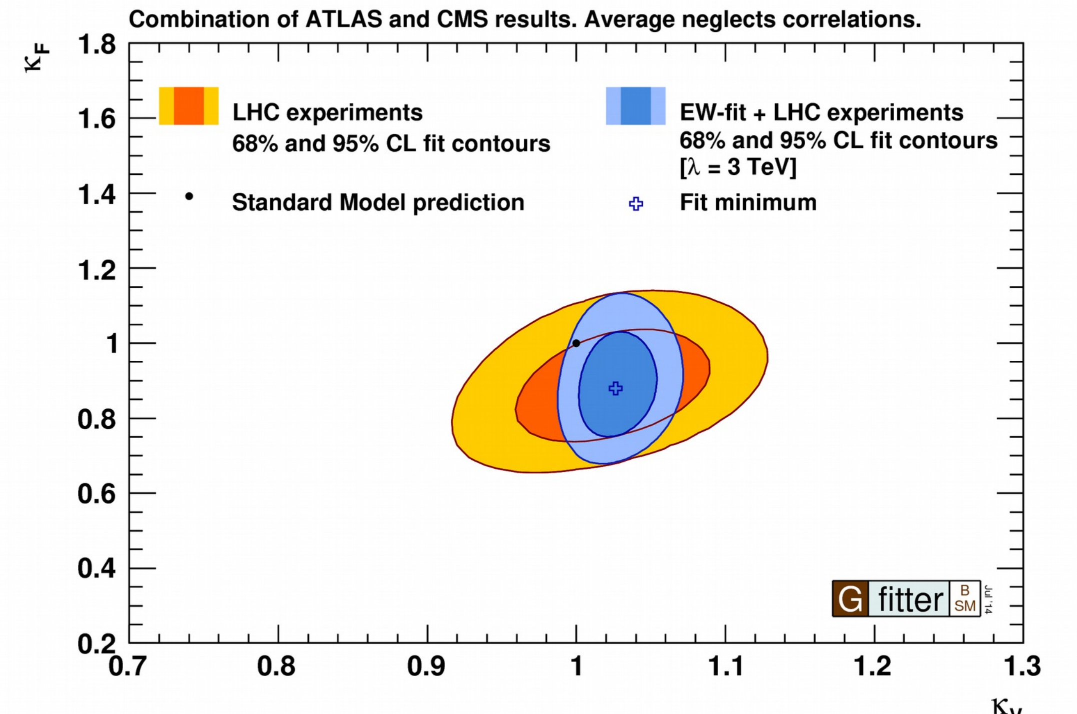
$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

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

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

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

One loop LO and NLO are the same order

Consistently use the NLO ECLh with LO one-loop corrections!

NLO Effective Lagrangian

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

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

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

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

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

Dependence on the unitarization method

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

Wrapping up $V_L V_L$ scattering:

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

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

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

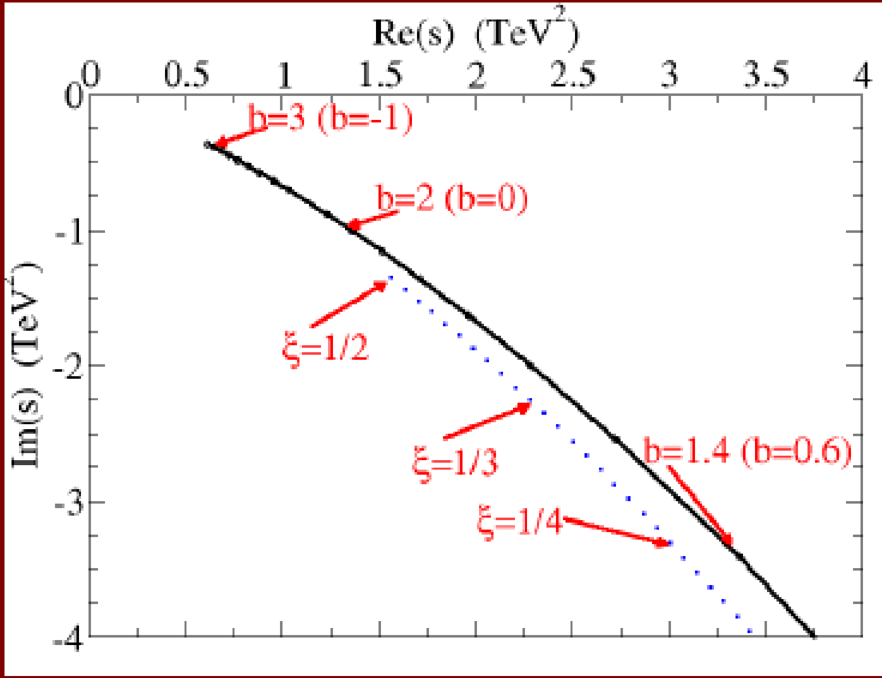
$a^2 = b$ $a^2 = 1$ → Weak, elastic (SM)

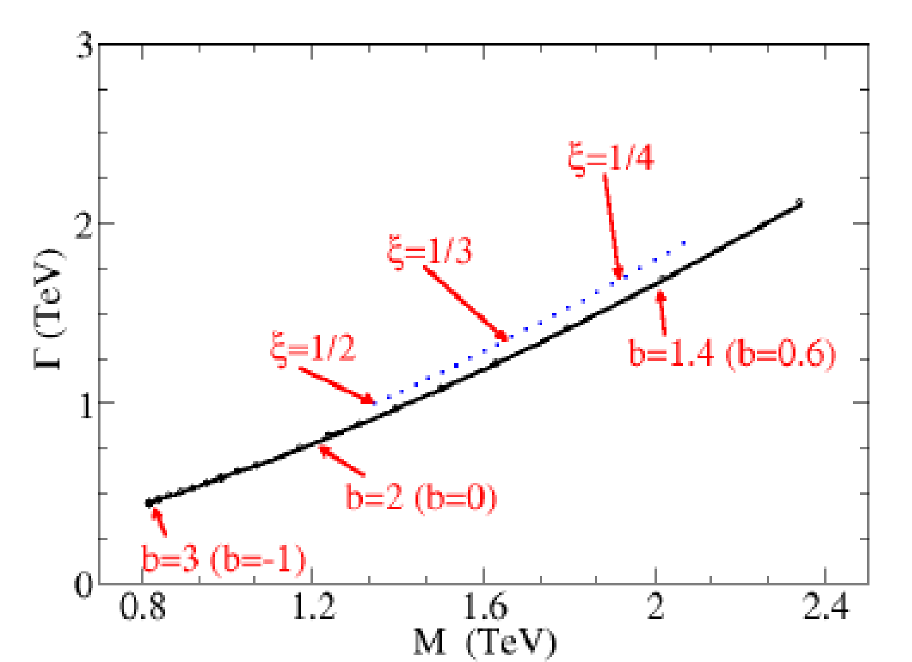
2014 95% CL

Our result

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

Position of pinball resonance in complex plane $\sqrt{s_0} = M - i\Gamma/2$





$$b \in (-1, 3)$$

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

First bound on this EFT parameter known to us

Minimum truth in SM: 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;
ω^a parametrize coset

(think of π^a and η wrt isospin in hadron physics)

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

Less symmetry; more independent higher dim. eff. operators

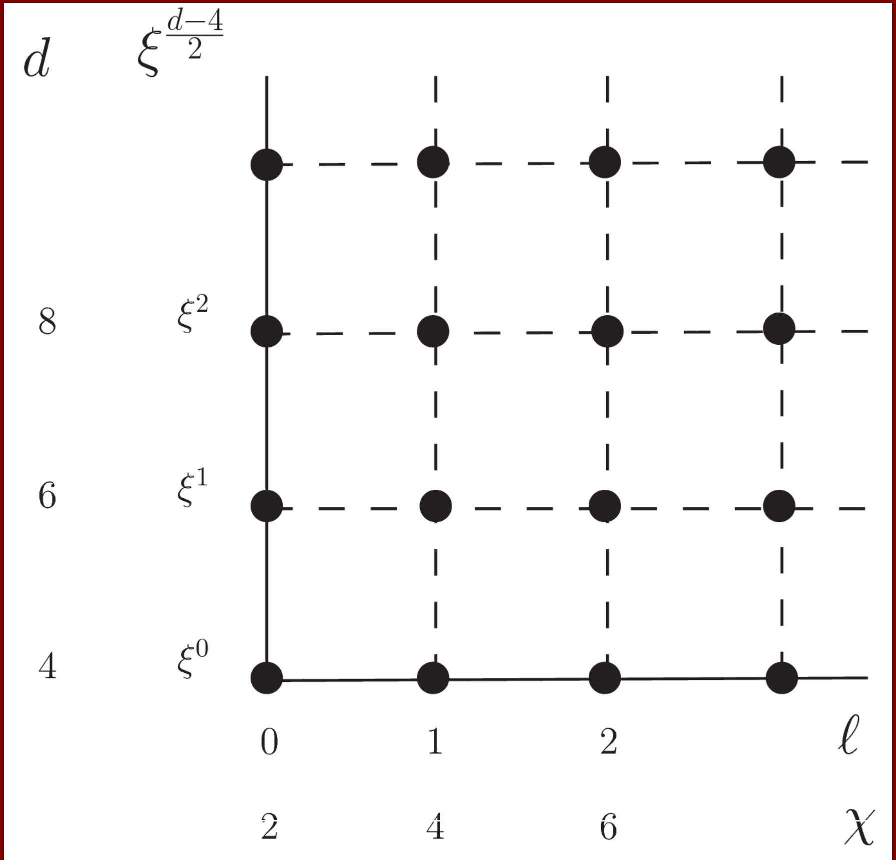
Derivative expansion → strongly interacting

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 boson number

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)

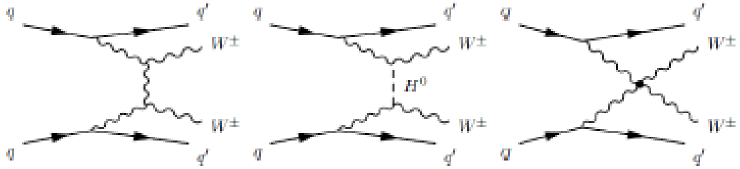
Resonance → Integrate out → LEC → IAM → Predict resonance

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

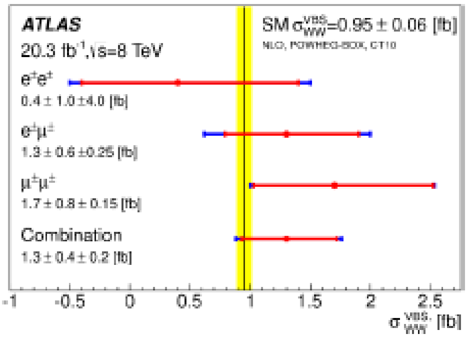
WW Scattering @ LHC

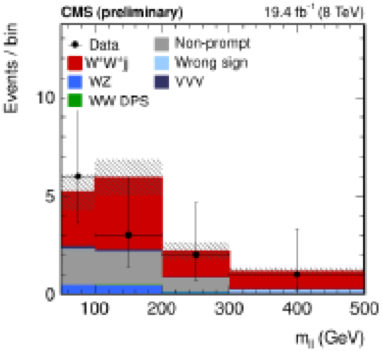
Berryhill

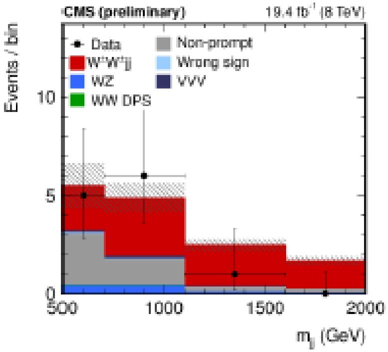
First evidence of $W^{\pm}W^{\pm}$ scattering (3.6 σ)

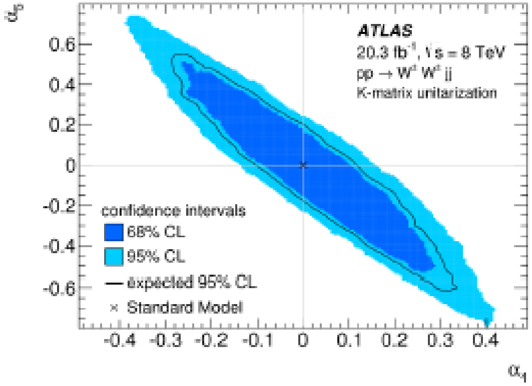


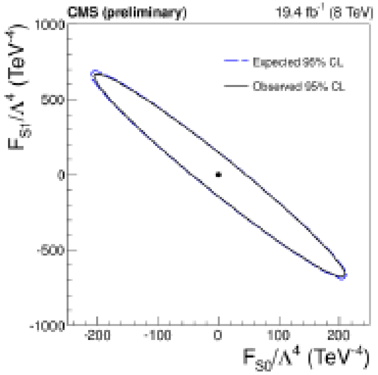
ATLAS, arxiv:1405.6241





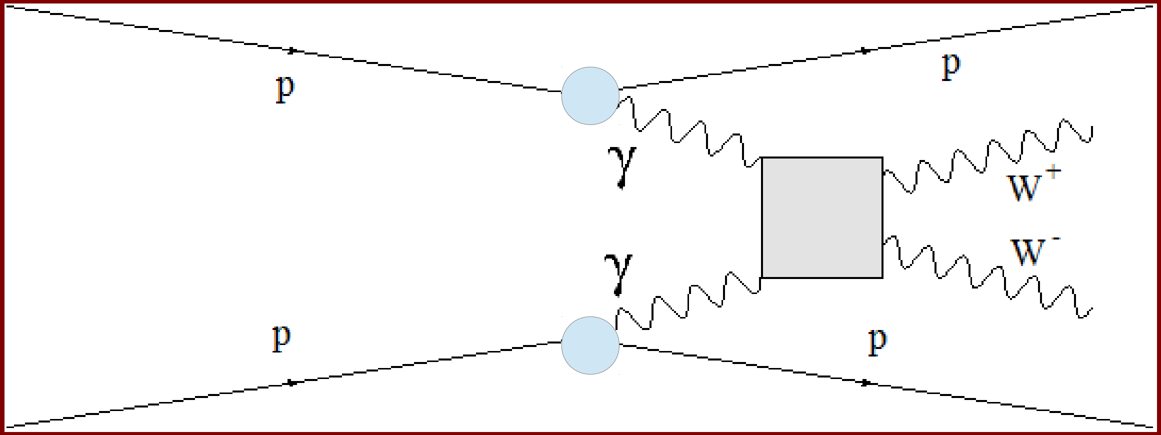




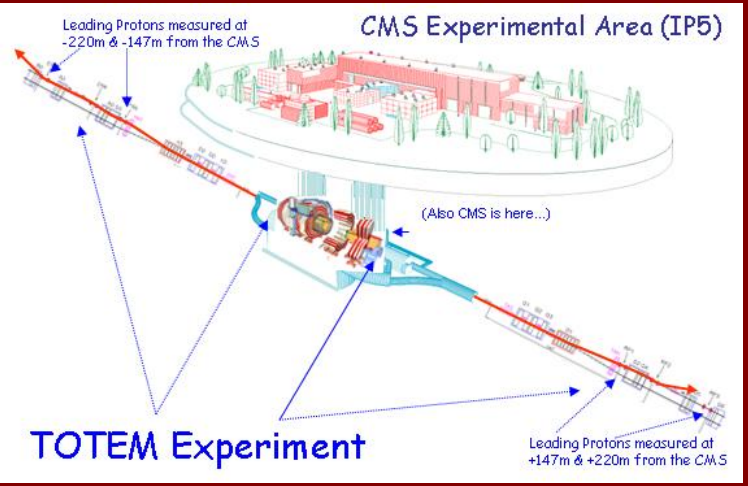


CMS-PAS-SMP-13-015

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.

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

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

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

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

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

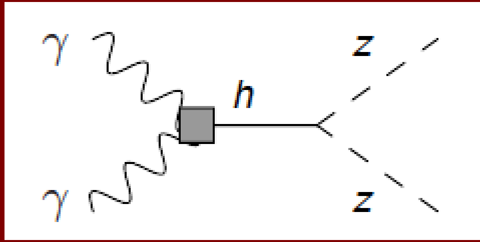
$$\mathcal{M}_{\mathrm{NLO}} = \mathcal{M}_{\mathcal{O}(e^2p^2)}^{1-\mathrm{loop}} + \mathcal{M}_{\mathcal{O}(e^2p^2)}^{\mathrm{tree}}$$

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

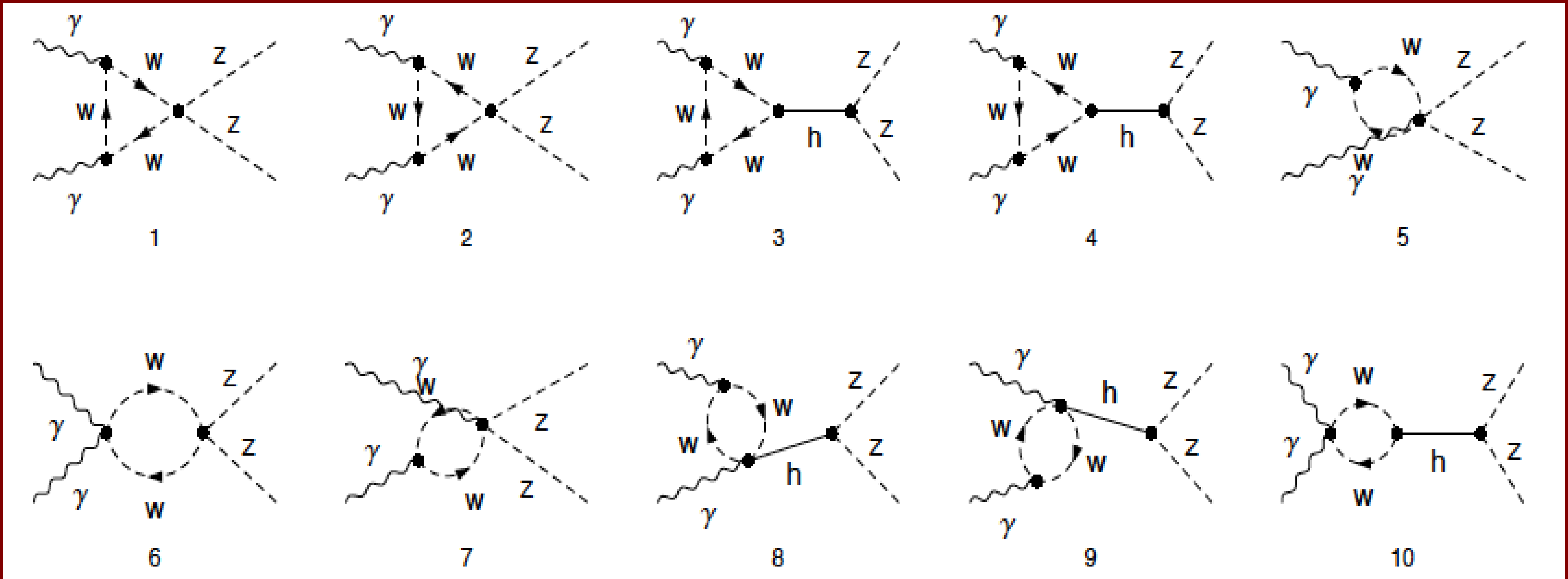
$$B = B_{\mathrm{LO}} + B_{\mathrm{NLO}}$$

$$\gamma\gamma \to zz$$

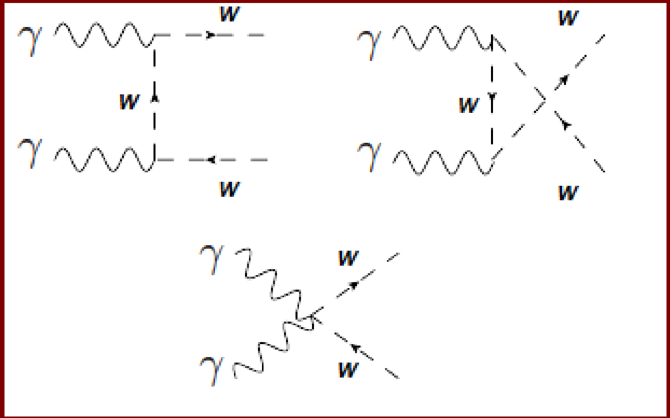
$$\mathcal{M}(\gamma\gamma \to zz)_{\mathrm{LO}} = 0$$

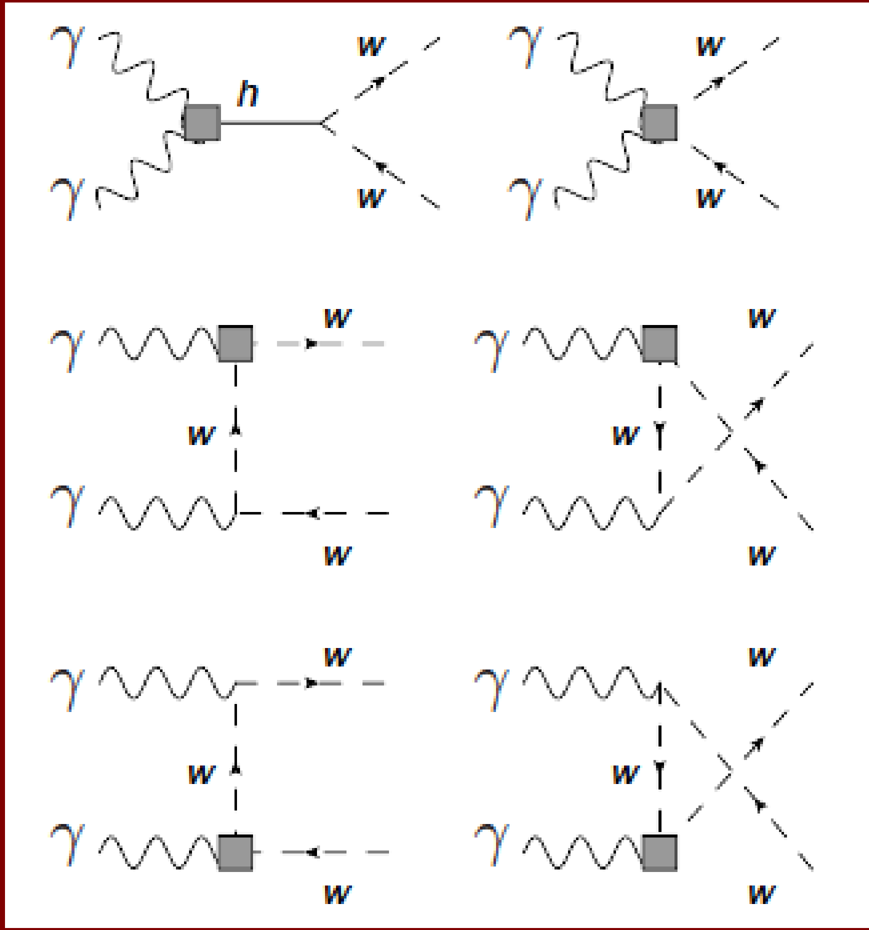


$$\begin{aligned} A(\gamma\gamma \to zz)_{\mathrm{NLO}} &= \frac{2ac^r_\gamma}{v^2} + \frac{(a^2-1)}{4\pi^2 v^2} \\ B(\gamma\gamma \to zz)_{\mathrm{NLO}} &= 0, \end{aligned}$$

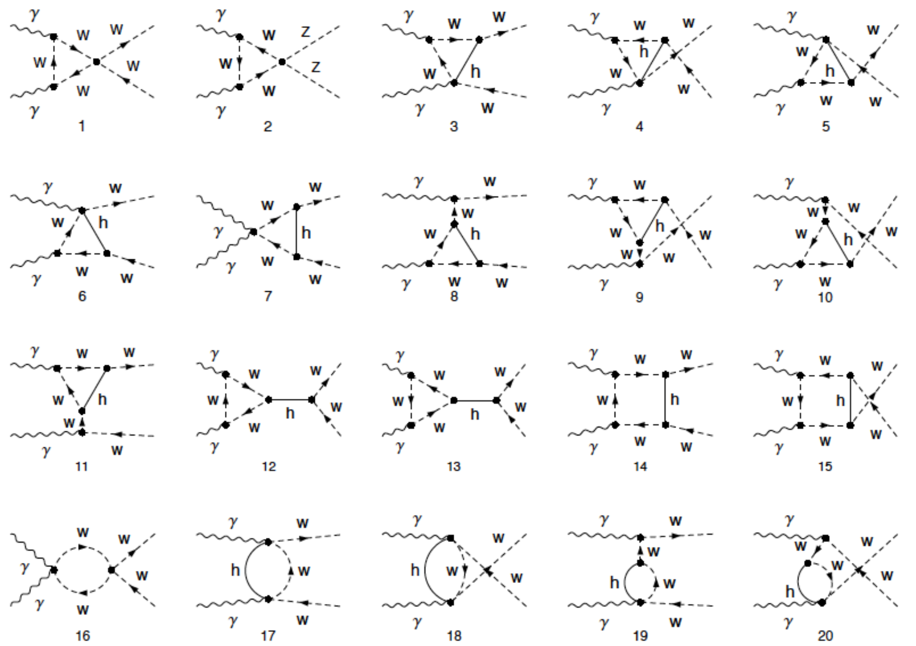


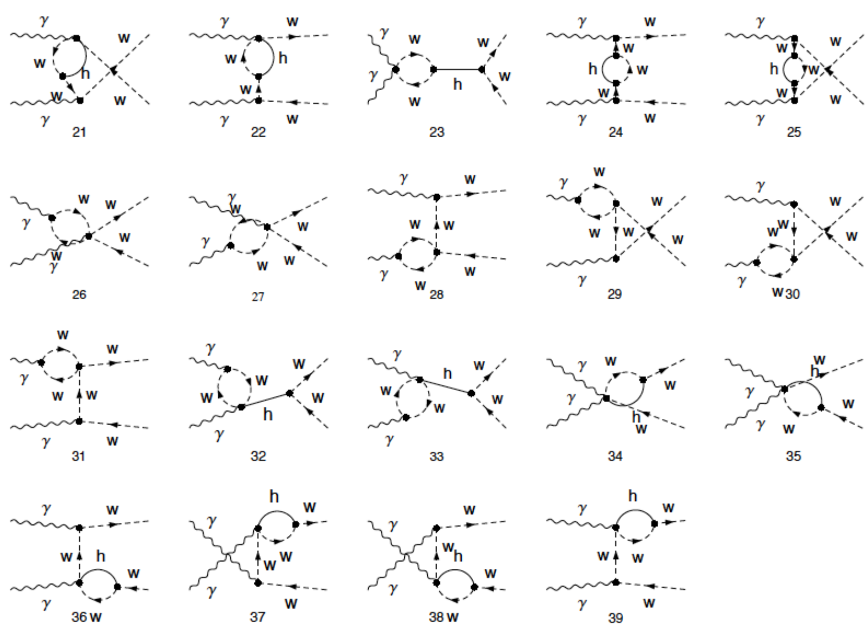
$$\gamma\gamma \to w^+ w^-$$





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





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

$$A(\gamma\gamma \to w^+w^-)_{\mathrm{NLO}} = \frac{8(a_1^r - a_2^r + a_3^r)}{v^2} + \frac{2ac_\gamma^r}{v^2} + \frac{(a^2-1)}{8\pi^2 v^2}$$

$$B(\gamma\gamma \to w^+w^-)_{\mathrm{NLO}} = 0.$$

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

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

Top-antitop production

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

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

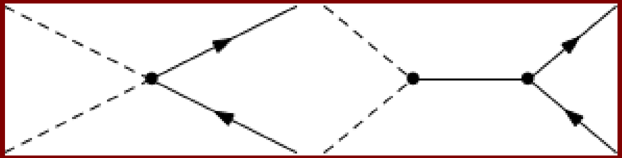
(We maintain Yukawa structure bc of B-factories success)

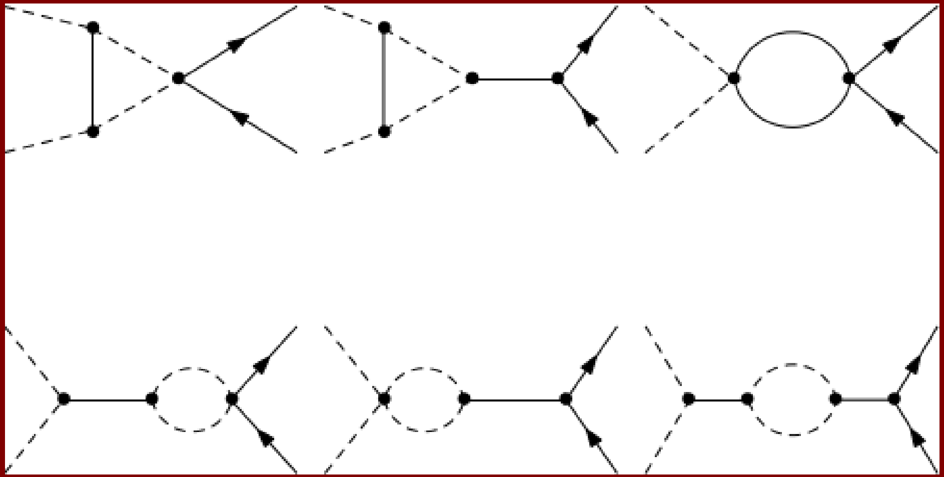
$$\begin{aligned}\mathcal{L}_4 = {} & \frac{4a_4}{v^4}\partial_\mu \omega^i \partial_\nu \omega^i \partial^\mu \omega^j \partial^\nu \omega^j + \frac{4a_5}{v^4}\partial_\mu \omega^i \partial^\mu \omega^i \partial_\nu \omega^j \partial^\nu \omega^j \\ & + \frac{2d}{v^4}\partial_\mu h \partial^\mu h \partial_\nu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

1607.01158, EPJC

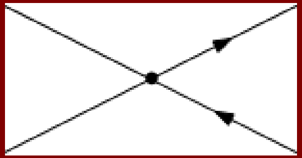
LO + NLO top-antitop production

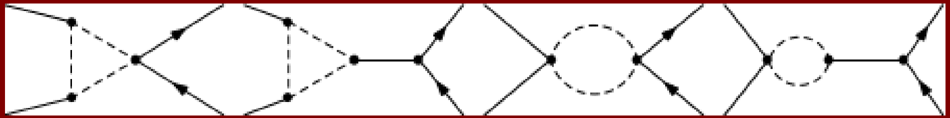
1607.01158





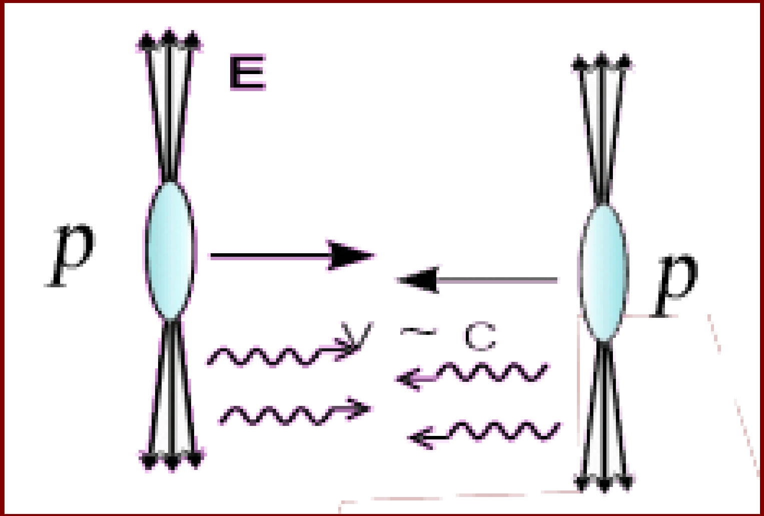
$\omega\omega \to t\bar{t}$



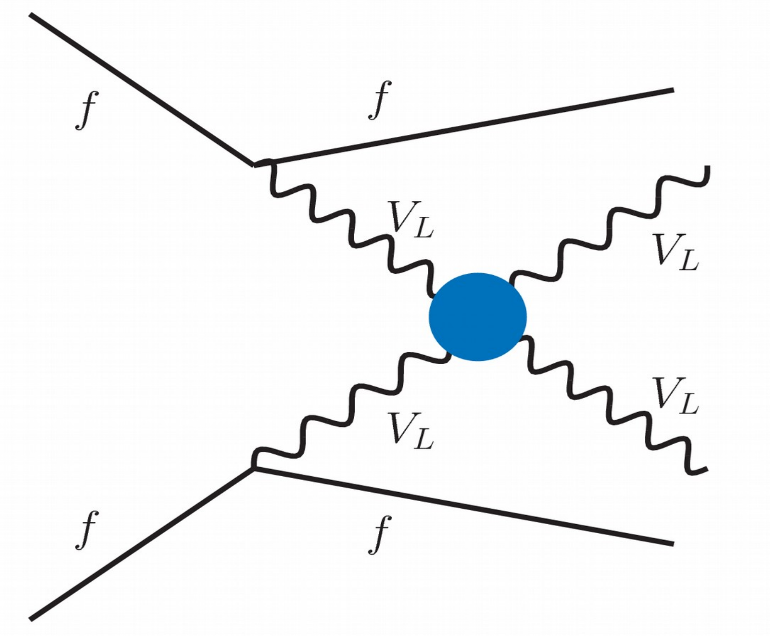


$hh \to t\bar{t}$

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)

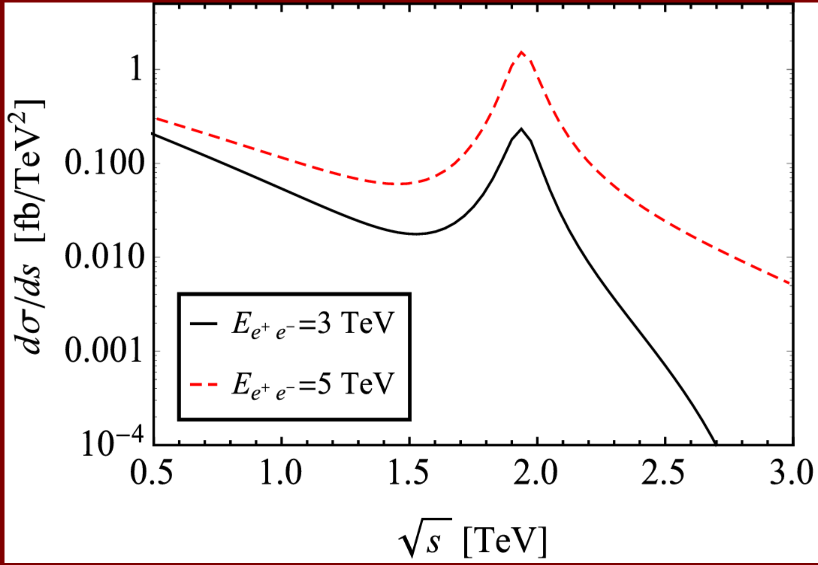
Here, I=2 (can yield signals in all of WW, ZZ and WZ)

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

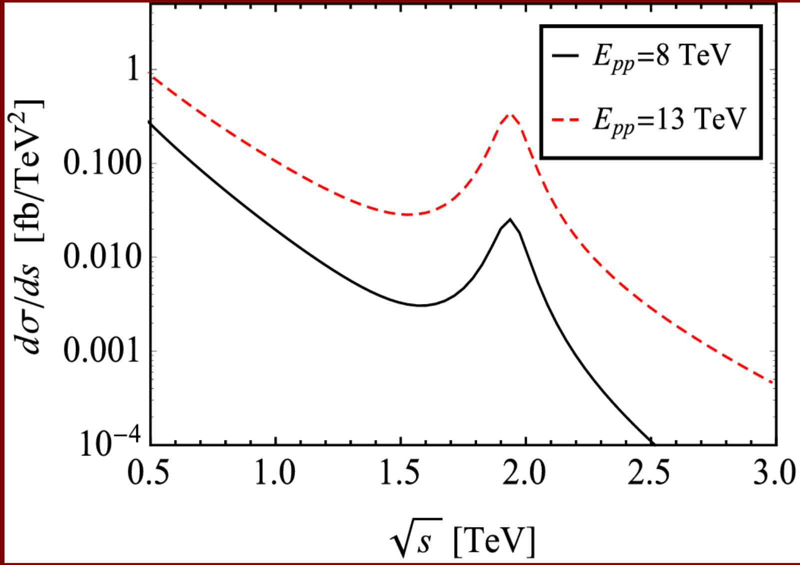
$$F_{W_L}(x) = g_W \frac{1-x}{x}, \qquad F_{Z_L}(x) = g_Z \frac{1-x}{x},$$

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

e$^-$e$^+$



p p

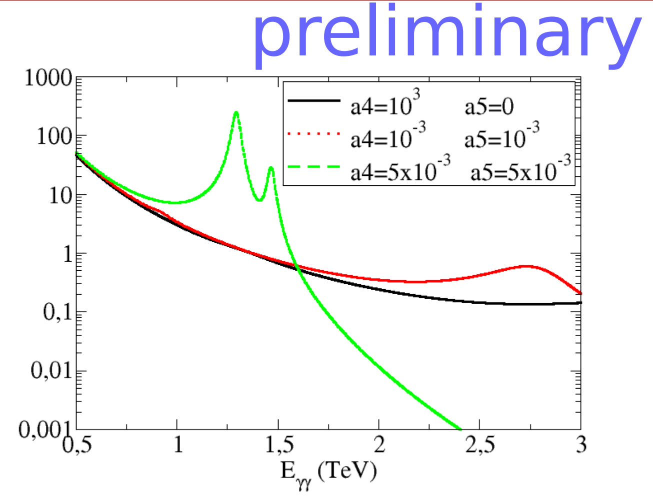


Electromagnetic production of EWSBS

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

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

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

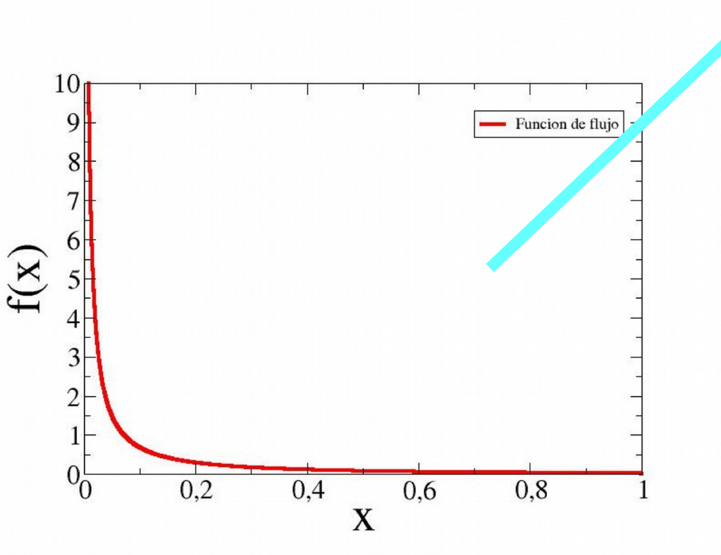


Here in the γγ → ωω cross section

Electromagnetic production of EWSBS

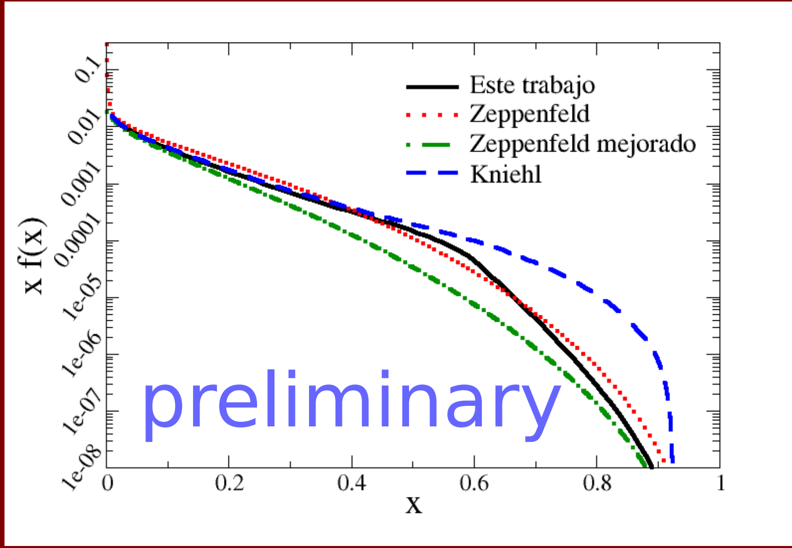
pp (or ee) → γγ +pp (or ee) → ωω +pp (or ee)

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



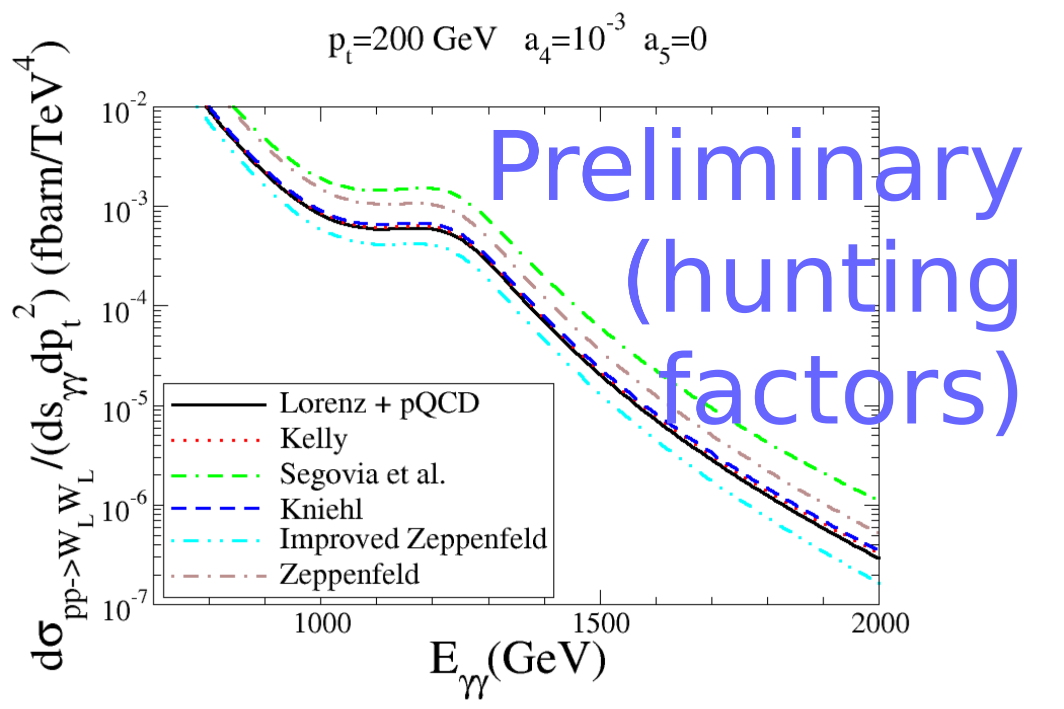
e → γ e

p → γ p
(elastic)



Electromagnetic production of EWSBS

pp (or ee) → $\gamma\gamma$ +pp (or ee) → $\omega\omega$ +pp (or ee)



Preliminary (hunting factors)

Here in pp → $\gamma\gamma$ → $\omega\omega$
Elastic contribution
(protons scatter intact)