Unitarization and resonances in $W_L W_L$ and hh scattering

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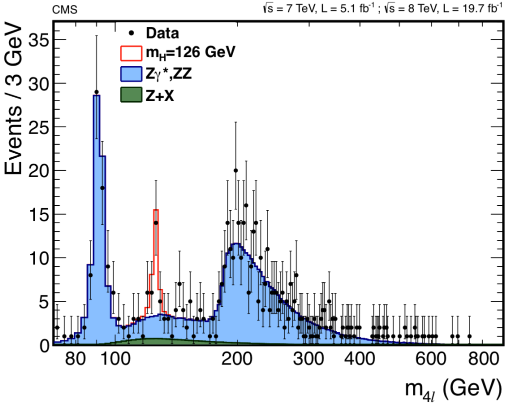
based on PRL**114** (2015) 22, 221803; PRD**91** (2015) 7, 075017; JHEP**1402** (2014) 121; JPG**41** (2014) 025002 in coll. with Antonio Dobado and Rafael L. Delgado, and on D.Barducci *et al.* PRD**91** (2015) 9, 095013.

Workshop Bled 2015: What comes beyond the Standard Model

Content

Outline

The boson and the gap

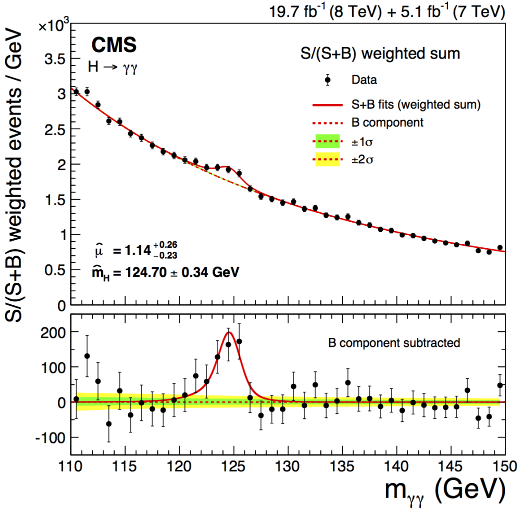


Mass now known to 2 per mille, $m_h \simeq 125$ GeV,

Very narrow... (visible $\Gamma \rightarrow$ expt. resolution)

It clearly fits the Bled 2015 criterion

The boson and the gap



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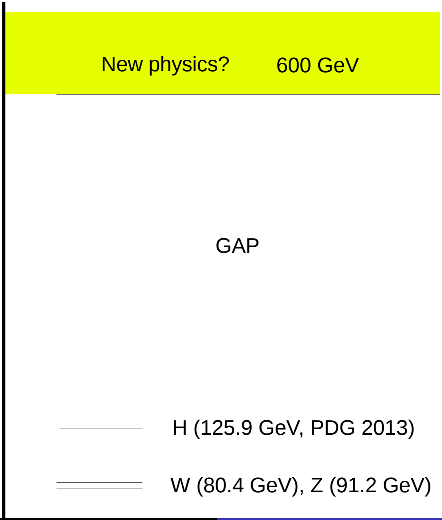
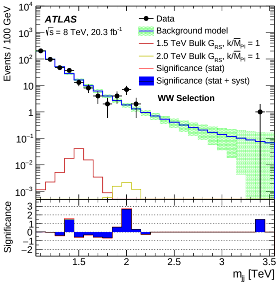


WW spectrum from ATLAS (1506.00962)



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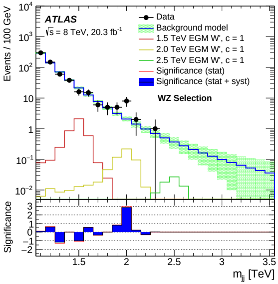
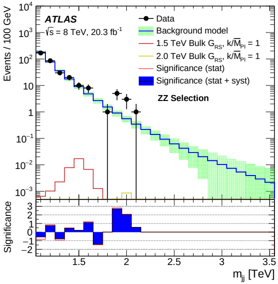
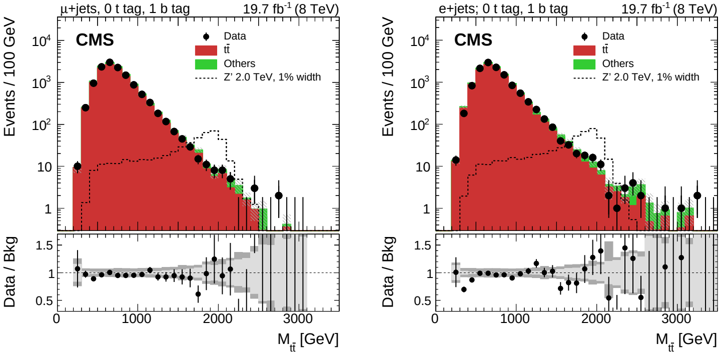


WZ



ZZ

$t\bar{t}$ spectrum from CMS (1506.0306)



Shouldn't the top be sensitive? e.g.

$y_t = \frac{\sqrt{2} m_t}{v} \sim 1$... perhaps not

The boson and the gap

- Option 1: the SM is largely right, no new particles below e.g. GUT scale
- Option 2 (a wish?): new physics at $\sim$ few TeV. Then...
- Quantum corrections $\delta M_h \propto \Lambda^2_{\rm NP}$; perhaps a symmetry argument sets them to 0?

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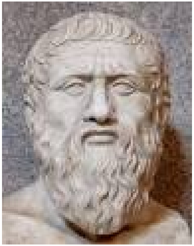
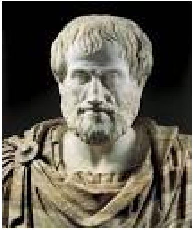
Plato or Aristotle?

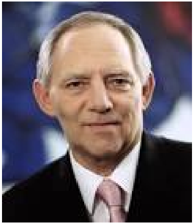


There are beautiful things we do not (yet) see that you could include in your model

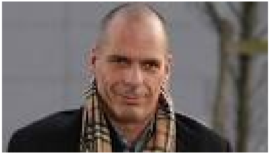


You should include only those things that are seen

Plato or Aristotle?



Greece should pay its debts in full cutting and saving as necessary



The economy will collapse and we will not be able to repay anything

Particle content

- Electroweak sector:
  3 long. vector bosons $W_L^{\pm}, Z_L$, Higgs h
- Hadron physics: 3π, $4K$, η

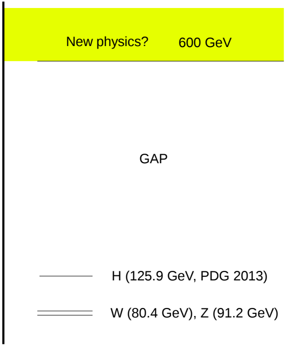
Global Symmetries

Local symmetries cannot be broken (Elizur's theorem); Electroweak symmetry breaking is about a global symmetry, just like QCD.

- Electroweak sector:
  $SU(2) \times SU(2) \rightarrow SU(2)_{\rm custodial}$
- Hadron physics:
  $SU(2)_{\rm left} \times SU(2)_{\rm right} \rightarrow SU(2)_{\rm Isospin}$

(Note I am skipping all the $U(1)'s$)

If additionally the Higgs is a Goldstone boson itself



This work: nonlinear realization of low-E Lagrangian (a bit more general than SM Higgs-weak-doublet structure)

Global Symmetries

- Minimum composite Higgs models:
  $SO(5) \to SO(4) \simeq SU(2) \times SU(2) \to SU(2)$
  Higgs doublet; $(W_L^{\pm}, Z_L, h)$
- Dilaton models (now disfavored by $h\gamma\gamma$, hgg couplings)

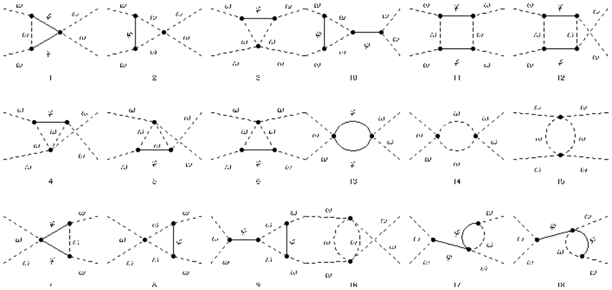
(Agashe, Contino and Pomarol, NPB**719**, 165, 2005;
Goldberger, Grinstein and Skiba, PRL 100 (2008) 111802;
Giardino *et al.* JHEP 1405 (2014) 046.)

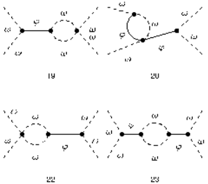
Effective Lagrangian for EWSBS (massless particles)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{D>4} \sum_{k} \frac{c_k^D}{\Lambda_{\rm NP}^{D-4}} O_k^{(D)}$$

- D=5: only Weinberg *L*-violating operator, nothing to do with *WW*
- D=6: 1149 operators that respect *L* (R. Alonso *et al.* JHEP **1404** (2014) 159.)
- Forget flavor: concentrate on *WW*
- It is most convenient to use massless Goldstone-bosons instead of massive *W's*

Here the "convenient" Goldstone version of $W_L W_L$





(Automated by Madrid grad student Rafael L. Delgado)

Effective Lagrangian for EWSBS (massless particles)

$$\mathcal{L} = \frac{1}{2}\left(1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2\right)\partial_\mu\pi^a\partial^\mu\pi^b\left(\delta_{ab} + \frac{\pi^a\pi^b}{v^2}\right) + \frac{1}{2}\partial_\mu h\partial^\mu h$$
$$+\frac{4a_4}{v^4}\partial_\mu\pi^a\partial_\nu\pi^a\partial^\mu\pi^b\partial^\nu\pi^b + \frac{4a_5}{v^4}\partial_\mu\pi^a\partial^\mu\pi^a\partial_\nu\pi^b\partial^\nu\pi^b + \frac{g}{v^4}(\partial_\mu h\partial^\mu h)^2$$
$$+\frac{2d}{v^4}\partial_\mu h\partial^\mu h\partial_\nu\pi^a\partial^\nu\pi^a + \frac{2e}{v^4}\partial_\mu h\partial^\nu h\partial^\mu\pi^a\partial_\nu\pi^a$$

- Equivalence Theorem (between scattering amplitudes with π Goldstone bosons and longitudinal component of vector bosons): $A(\pi\pi) = A(W_L W_L) + O(m_W^2/s)$
- To be used in energy region $m_W^2 \ll s \ll (4\pi v)^2$

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Amplitude structure

I, J-projected amplitudes

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

Chiral-momentum expansion

$$A_I^J(s) = A_{IJ}^{(0)}(s) + A_{IJ}^{(1)}(s) + \dots$$

$$A_{IJ}(s) = Ks + \left(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2}\right) s^2 + \dots$$

Unitarity is only satisfied perturbatively...

ChPT in terms of Goldstone bosons not really usable

- At low E, small p (ChPT converges) but $\pi \neq W_L$
- At high E, $\pi \simeq W_L$ but p high (not convergent)

Solution: employ Unitarized ChPT at the TeV scale

- Reliable at somewhat higher E ✓
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We use three unitarization methods

Some technical improvements:

- 2-subtraction derivation of IAM (for $m = 0$)
- New solution for the once-iterated N/D method, separating L and R cuts (at the expense of losing 11-channel)
- Improved K-matrix: unitary, also analytic

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

When all three can be used, good qualitative agreement.

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The Inverse Amplitude Method

$$A_{IJ} = \frac{\left(A_{IJ}^{(0)}\right)^2}{A_{IJ}^{(0)} - A_{IJ}^{(1)}}$$

- Dispersion relation for $A(s)$: exact but useless
- Dispersion relation for $A^{(0)} + A^{(1)}$: trivial
- The trick is to write one for $\frac{\left(A^{(0)}\right)^2}{A}$

(Truong; Dobado, Herrero and Truong)

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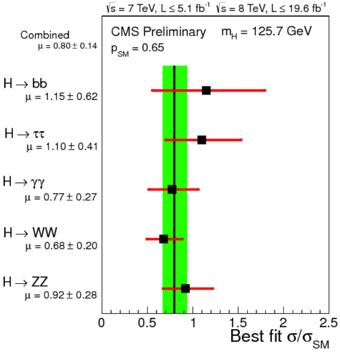
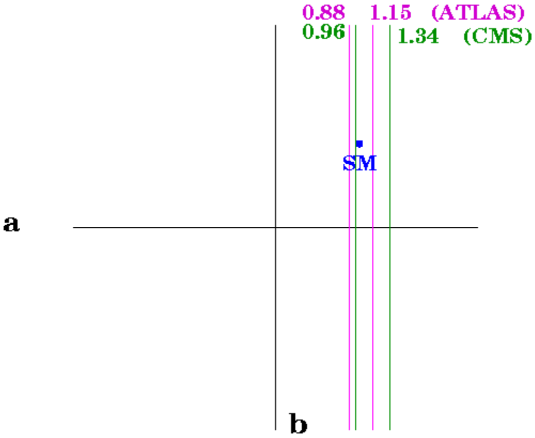
A word on the parameters



- Standard Model: $a = b = 1$
- Higgsless EW-symmetry sector: $a = b = 0$ (ruled out)
- Dilaton model: $a^2 = b = \xi^2 = v^2/f^2$ (disfavored)
- Composite Higgs model: $a = \sqrt{1-\xi}$, $b = 1 - 2\xi$ (open)

A word on the parameters



Gell-Mann's totalitarian principle

Everything not forbidden is compulsory

- The most general effective Lagrangian deviates from the Standard Model, and requires either new physics or it becomes strongly interacting (new physics!)
- The Standard Model is a fine-tuned, zero measure case (but renormalizable)

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The moment $a \neq 1$ or $b \neq a^2$, strong coupling

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

A word on the parameters

$$\mathcal{L} = \frac{1}{2}\left(1 + 2\mathbf{a}\frac{h}{v} + \mathbf{b}\left(\frac{h}{v}\right)^2\right)\partial_\mu\pi^a\partial^\mu\pi^b\left(\delta_{ab} + \frac{\pi^a\pi^b}{v^2}\right) + \frac{1}{2}\partial_\mu h\partial^\mu h$$
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a	b	a_4	a_5	g	d	e
(0.88, 1, 34)	a^2?	0?	0?	0?	0?	0?

Outline

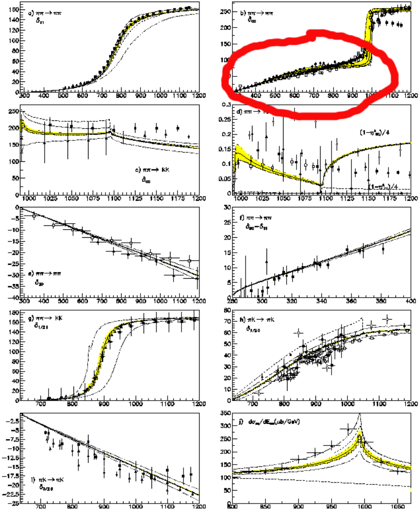
The Higgs and nothing more yet

Nonlinear Electroweak Symmetry Breaking Sector

A few well-known resonances

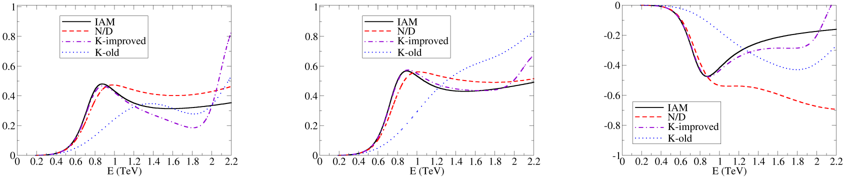
Coupled channel resonance

The scalar-isoscalar σ



Gómez Nicola and Peláez, PRD**65** (2002) 054009

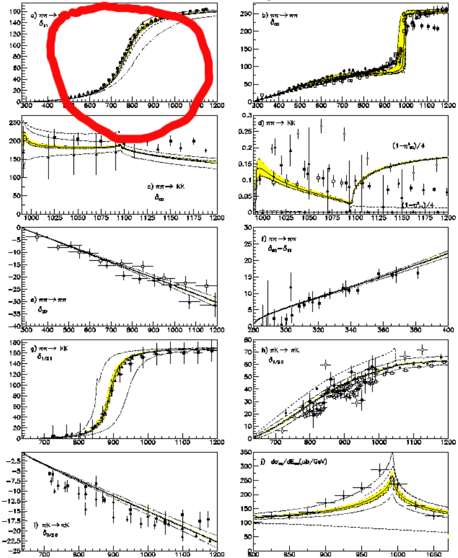
Scalar-isoscalar: independence of unitarization method



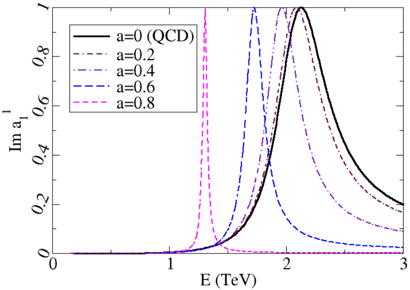
$\pi\pi \to \pi\pi$ $\quad$ $hh \to hh$ $\quad$ $\pi\pi \to hh$

Unitarization + analyticity in complex plane $\to$ scalar resonance (a=0.88, b=3, μ=3 TeV)

Vector-isovector resonance: the ρ



Vector-isovector resonance: the ρ



A word on Composite Higgs Models

Generally, both vector and axial resonances.

We worked in two versions of the model

- m_a finite: indep. variables are $f, m_\rho, \Gamma_\rho, g_{\rho\pi\pi}$.
- $m_a \longrightarrow \infty$: $g_{\rho\pi\pi} = \sqrt{2}m_\rho/f$ and there is a KSFR relation $\Gamma_{\rho\pi\pi} = \frac{m_\rho^3}{192\pi f^2}$.

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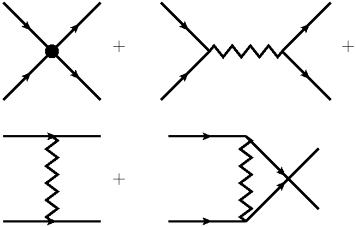
A word on Composite Higgs Models

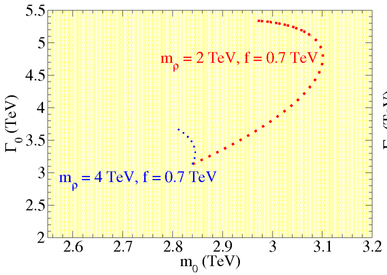
A couple of useful relations,

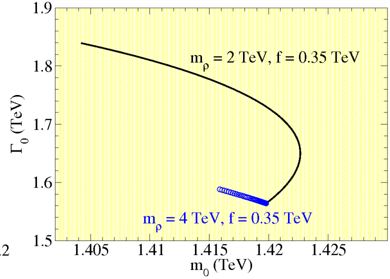
- Partial wave in the scalar channel
$$a_0^0(s) = K_1 s + K_2 \left[\left(\frac{m_\rho^2}{s} + 2 \right) \log \left(1 + \frac{s}{m_\rho^2} \right) - 1 \right]$$
- Inelastic $\pi\pi \to hh$ scattering not independent
$(a^2 - b) = (1 - a^2)$



More on the ρ: a word on Composite Higgs Models

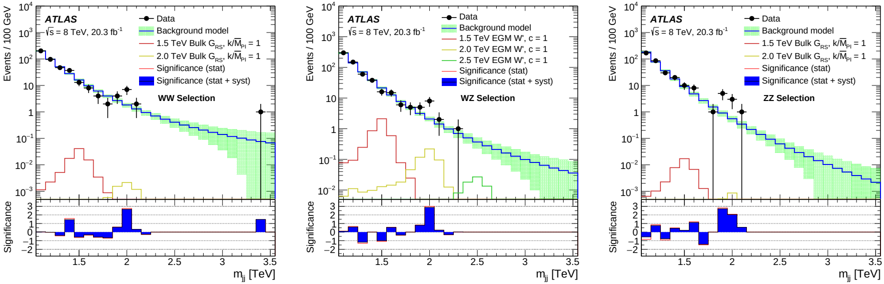
Coupling a ρ-like state to the low-energy particles improves unitarity: the σ recedes to higher mass.





(the parameter of the curves is $g_{\rho\pi\pi}$)

So, is there a vector resonance in the ATLAS data?



WW *WZ* *ZZ*

So, is there a vector resonance in the ATLAS data?

- Narrow resonance $\rightarrow$ KSFR relation in EFT
- Tree-level resonance $\rightarrow$ EFT matching
- $\Gamma^{\rm IAM} = \frac{M^3_{\rm IAM}}{96\pi v^2}(1 - \mathbf{a}^2)$
- For $M \sim 2$ TeV, $\Gamma \sim 0.2$ TeV, get $\mathbf{a} \sim 0.73$
- In tension with ATLAS' $\mathbf{a}|_{2\sigma} > 0.88$ at 4-5σ level (but careful with instrumental resolution, it could be narrower than measured)
- What with the ZZ channel...

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- $\Gamma^{\rm IAM} = \frac{M^3_{\rm IAM}}{96\pi v^2}(1 - \mathbf{a}^2)$
- For $M \sim 2$ TeV, $\Gamma \sim 0.2$ TeV, get $\mathbf{a} \sim 0.73$
- In tension with ATLAS' $\mathbf{a}|_{2\sigma} > 0.88$ at 4-5σ level (but careful with instrumental resolution, it could be narrower than measured)
- What with the ZZ channel...

Other options?

- Scalar-isoscalar: what is with WZ? misreconstruction of mass?
- Scalar-isotensor: $a = 1.05$, $a_4 = 1.25 \times 10^{-4}$
- In this case $I = 2$, W^+W^+
- For the time being, need more data

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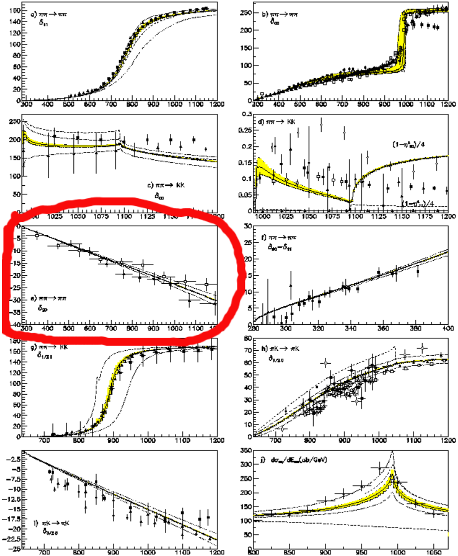
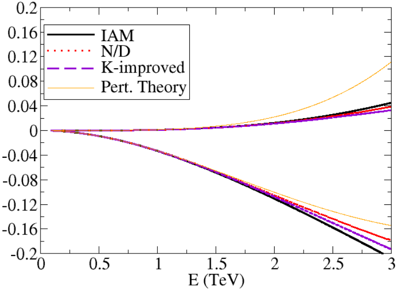
Repulsive scalar-isotensor wave



Isotensor channel: repulsive for $a^2 < 1$

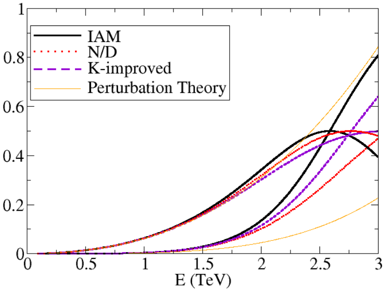


$a = 0.88$
(The LO amplitude has opposite sign as the scalar)

That's my sign of $1 - a^2$, if you don't like it...

$$A_0^0 \propto +(1 - a^2)$$
$$A_2^0 \propto -(1 - a^2)$$

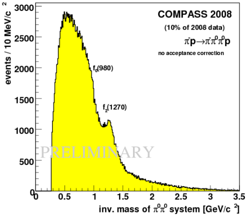
Isotensor channel: attractive for $a^2 > 1$

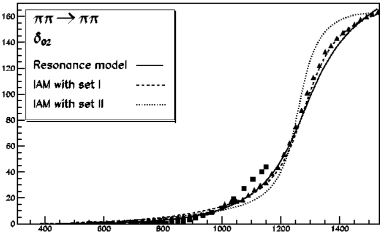


$a = 1.15$

- Hadron physics just does not work this way, but there could be a W^+W^+ "exotic" resonance... only then, no σ.
- Remember that the spin-orbit interaction has opposite sign in atomic and in nuclear physics.

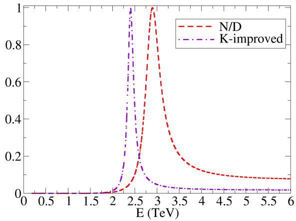
Tensor isoscalar f_2

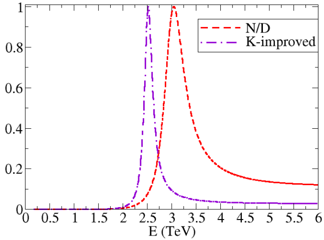




(Compass collaboration; Dobado and Peláez 2001.)

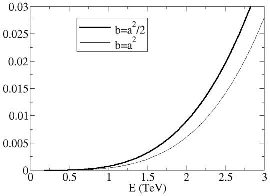
Electroweak sector: can also produce f_2





Tensor-isotensor channel

- Nothing there in hadron physics (no exotic, doubly charged tensor meson)
- Large enough a_4 can produce such a resonance
- But $M_{22} > M_{11}$ so the ρ will be found first



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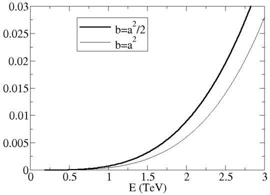

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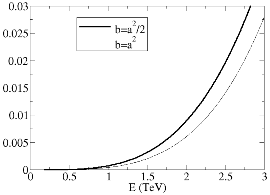

Oh NO! HE'S GOING TO SHOW THEM ALL!

- Don't worry, that's it. With NLO we have two powers of s;
  We cannot reach partial waves with $J > 2$
- Except... I can still go on with the coupled channels to hh

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Outline

Coupled channel resonance

Example in hadron physics: $\phi N \rightarrow K^* \Lambda$ by Oset and Ramos, EPJA**44** (2010) 445, Khemchandani *et al* PRD**83** (2011) 114041.

Perhaps more fun,

- $C_2\ O_2 \rightarrow C_2\ O_2$ weak... Van der Waals interaction
- $CO\ CO \rightarrow CO\ CO$ weak... dipole-dipole interaction, but
- $C_2\ O_2 \rightarrow CO\ CO$ strong! combustion!

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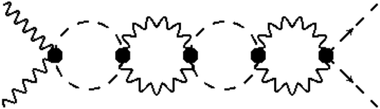
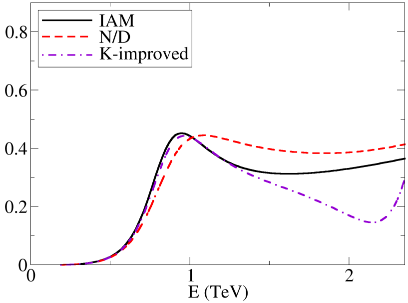
Coupled channel resonance

Here, for $I = 0$, two channels: hh and $W_L W_L$

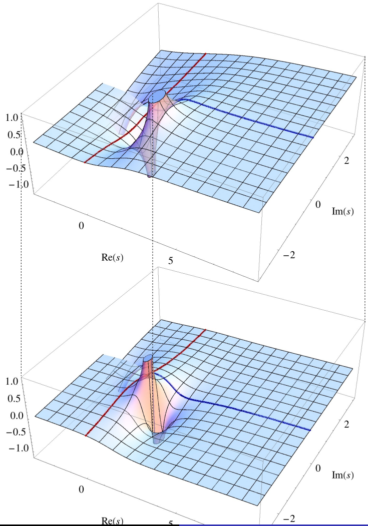


Coupled channel resonance

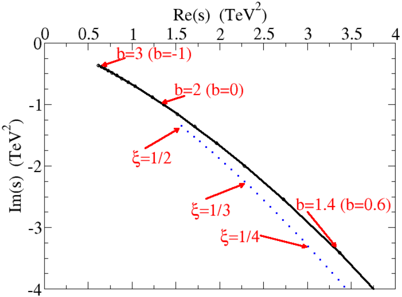


$a^2 = 1 \neq b = 2$

pole in the second Riemann sheet

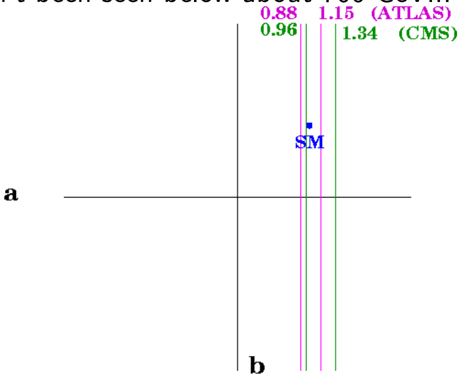


Motion of pole in the complex plane



Motivation: no bound on b

Because it hasn't been seen below about 700 GeV...



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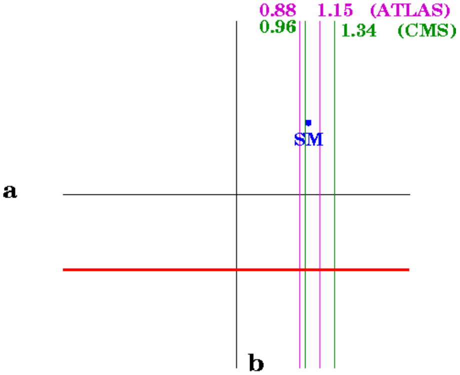
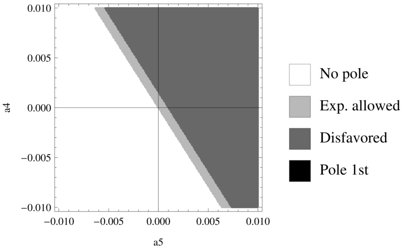
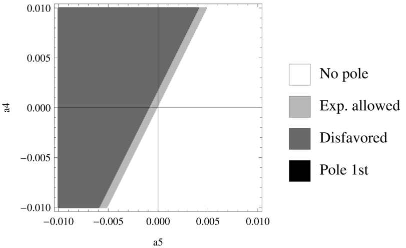


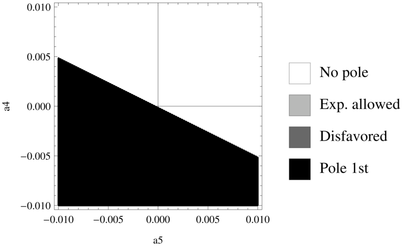
$b \in (-1, 3)$

Swipe parameter space: here a_4 and a_5





- $a = 0.90,\ b = a^2$
  PRD **91** (2015) 075017
- From left, clockwise,
  $IJ = 00,\ 11,\ 20$
- Excluding resonances
  $M_S < 700\,\mathrm{GeV},\ M_V < 1.5\,\mathrm{TeV}$



Generic conclusions

- A generic Electroweak Symmetry Breaking Sector of the SM is strongly coupled and there are hadron analogies.
- BSM scenarios with $m_\sigma \sim 1$ TeV, $m_\rho \sim 2$ TeV, and other resonances higher up, perfectly viable.
- The theory reach is $4\pi v \sim O(3)$TeV and the LHC run II can falsify it.

Specific conclusions

- Unitarization methods agree qualitatively in predicting similar resonances for same parameter set
- In CHM $\frac{\partial m_\sigma}{\partial m_\rho} < 0$ (while in generic theories, because of unitarity in A_0^0, the inequality is reversed).
- Possible coupled-channel resonance in $W_L W_L \longrightarrow hh$ proposed.
- First bound on the b parameter, $b \in (-1, 3)$

Set out to map this parameter space at the LHC

The world as understood in 1490

And perhaps we'll come to a new shore

Unitarization and resonances in $W_L W_L$ and hh scattering

Felipe J. Llanes-Estrada

Universidad Complutense de Madrid

July 12th, 2015

based on PRL**114** (2015) 22, 221803; PRD**91** (2015) 7, 075017; JHEP**1402** (2014) 121; JPG**41** (2014) 025002 in coll. with Antonio Dobado and Rafael L. Delgado, and on D.Barducci *et al.* PRD**91** (2015) 9, 095013.

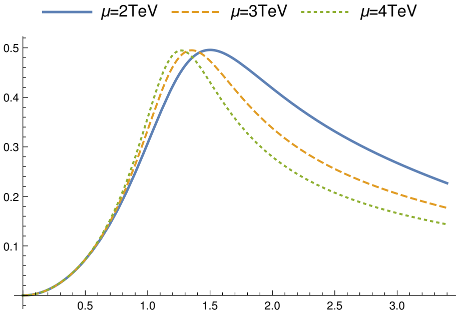
Workshop Bled 2015: What comes beyond the Standard Model

The three unitarization methods

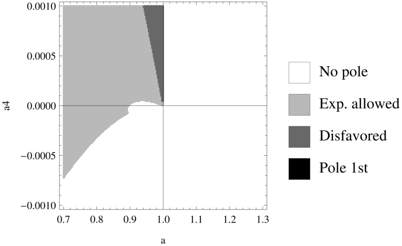
$$
\begin{aligned}
A^{\mathrm{IAM}}(s) &= \frac{[A^{(0)}(s)]^2}{A^{(0)}(s) - A^{(1)}(s)} \\
&= \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} - \left(\frac{A_L(s)}{A^{(0)}(s)}\right)^2 + g(s)A_L(s)} \\
A^{\mathrm{N/D}}(s) &= \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + \frac{1}{2}g(s)A_L(-s)}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

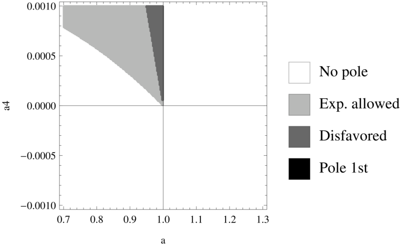
Independence on the renormalization scale

1-Loop divergences absorbed in NLO a_4, $a_5 \ldots$ counterterms ✓
But we may plot A_0^0, $a = 1$, $b = 2$, NLO set to zero for all μ.



Resonances in $W_L W_L \to W_L W_L$ due to a and a_4 parameters





- $b = a^2$
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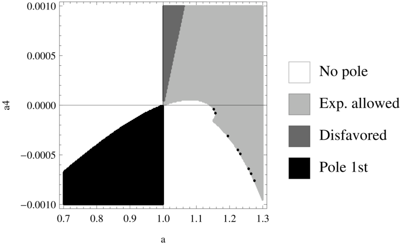
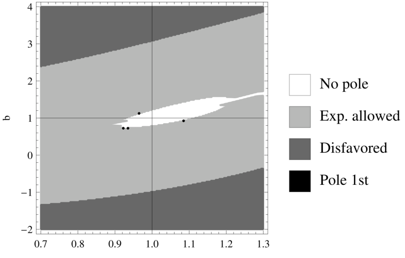
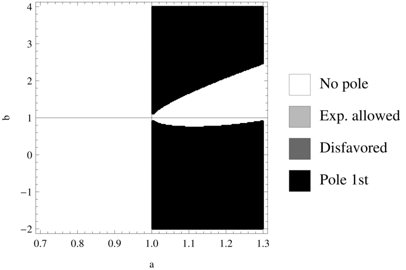
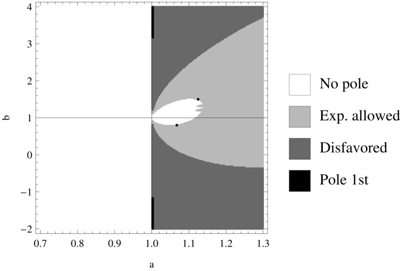


Resonances in $W_L W_L \to W_L W_L$ due to a and b parameters

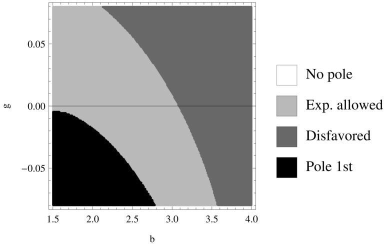


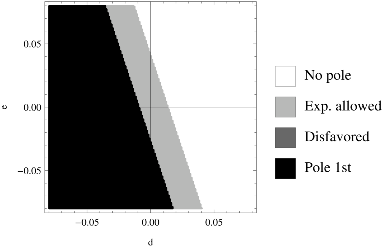


- PRL & PRD **91** (2015) 075017
- From left, clockwise, $IJ = 00,\ 11,\ 20$
- Excluding resonances $M_S < 700\,\mathrm{GeV}$, $M_V < 1.5\,\mathrm{TeV}$
- Constraint over b even without data about $W_L W_L \to hh$ and $hh \to hh$ scattering processes.



Resonances in $W_L W_L \to W_L W_L$ due to b, g, d and e parameters





Effective Theory, PRD **91** (2015) 075017, isoscalar channels ($I = J = 0$).

IAM derivation

A. Dobado and J. R. Peláez, PRD**56**, 3057 (1997)

$$A^{(0)}_{IJ} = a_0 + a_1 s$$

$$A^{(1)}_{IJ} = b_0 + b_1 s + b_2 s^2 + \frac{s^3}{\pi}\int_{(M_\alpha+M_\beta)^2}^{\infty} \frac{\mathrm{Im} A^{(1)}_{IJ}(s')ds'}{s'^3(s'-s-i\epsilon)} + LC(A^{(1)}_{IJ})$$

$$\frac{A^{(0)2}_{IJ}}{A_{IJ}} \simeq a_0 + a_1 s - b_0 - b_1 s - b_2 s^2$$

$$- \frac{s^3}{\pi}\int_{(M_\alpha+M_\beta)^2}^{\infty} \frac{\mathrm{Im} A^{(1)}_{IJ}(s')ds'}{s'^3(s'-s-i\epsilon)} - LC(A^{(1)}_{IJ}) + PC \simeq A^{(0)}_{IJ} - A^{(1)}_{IJ}$$

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$$A_{IJ} \simeq \frac{A_{IJ}^{(0)2}}{A_{IJ}^{(0)} - A_{IJ}^{(1)}} \qquad (1)$$