Prolog: situation of PANDA-FAIR funding (U. Wiedner)

- $>$ 70 scientists wrote to German government stating that the findings of the ad-hoc committee, giving PANDA "low discovery potential", hence lowest priority of all FAIR experiments is wrong and unjustified. THANK YOU ALL!
- A thorough investigation (unfinished and preliminary) suggests cost savings by cutting $\bar{p}$s and PANDA $<<$ than thought.
- Letters from PANDA quoting the international "peers" and explaining again the incomprehension of the PANDA collaboration with the review by underlying the uniqueness of the physics program sent to the supervisory body of GSI (meeting in ∼1week), the FAIR scientific council and the FAIR council members (meeting in ∼2 weeks).
- Other member states suggest unreadiness to decide on FAIR's future in the end of June meeting.
- Conclusion: international support helps and can change things

Should we draft a support statement?

Dear Dr. Schütte, dear members of the FAIR council:
the scientists of the Spanish Excellence Network in Hadron Physics, comprising six nodes at the universities of Barcelona, Granada, Madrid, Murcia, Salamanca and Valencia, as well as the Consejo Superior de Investigaciones Científicas, hereby state that

- The antiproton program at FAIR and in particular the PANDA experiment are of great intrinsic interest from the theoretical, experimental and technical points of view.
- That there are many unique contributions not achievable elsewhere that this facility can make as private and open letters by many colleagues have already argued.
- And that every effort should be made to preserve its funding and secure completion of the facility as designed after a decade of work.

Great expectations at the LHC
New strong interactions and resonances?

Felipe J. Llanes-Estrada

Universidad Complutense de Madrid

June 16th, 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.

Meeting of the spanish Hadron Network
IFIC-UV

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The Higgs and beyond

Analogy with the hadron-physics formulation

A few well-known resonances

Coupled channel resonance

Will Stella and I find a resonance?

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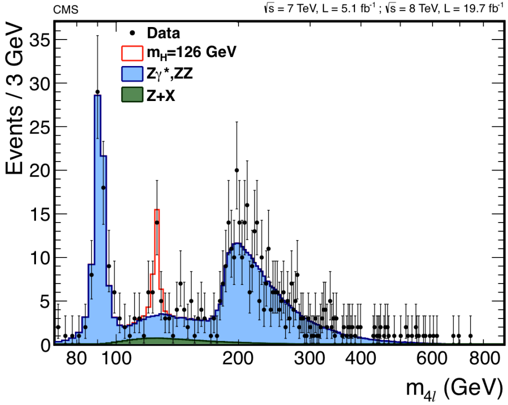

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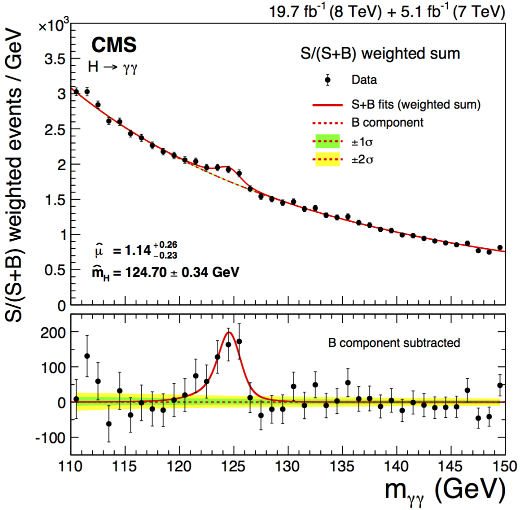

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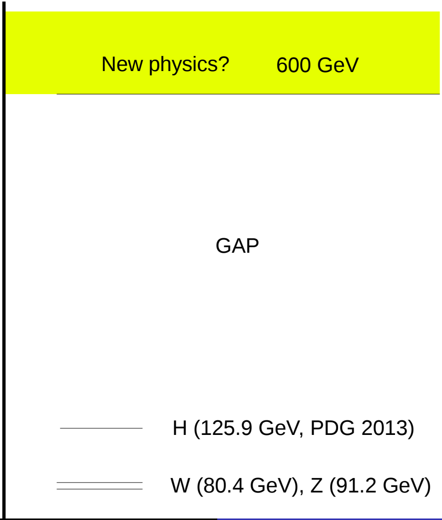
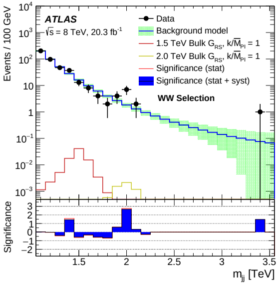


WW spectrum from ATLAS (1506.00962)



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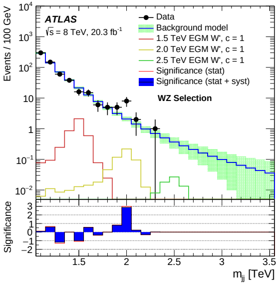
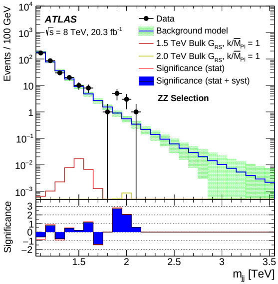
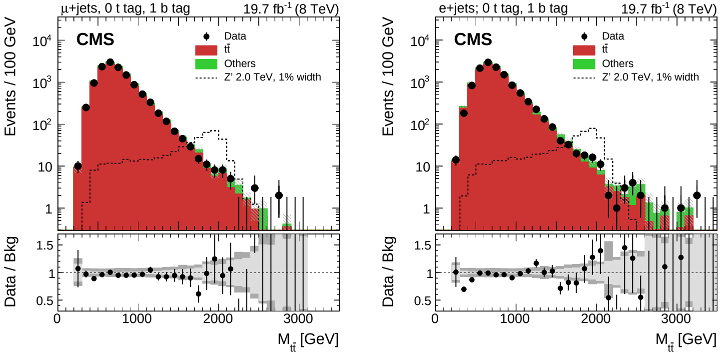


WZ



ZZ

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



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Coupled channel resonance

Particle content

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

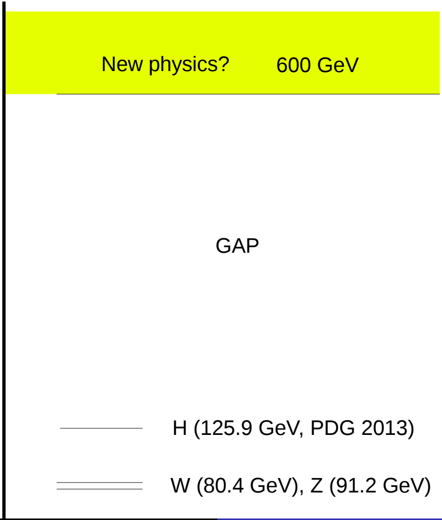
Global Symmetries

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

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

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

If additionally the Higgs is a Goldstone boson itself



Global Symmetries

- Minimum composite Higgs models:
  $SO(5) \rightarrow SO(4) \simeq SU(2) \times SU(2) \rightarrow SU(2)$
  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)

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

- Equivalence Theorem (between scattering amplitudes with π Goldstone bosons and longitudinal component of vector bosons): $A(\pi\pi) = A(W_L W_L) + O(s/m_W^2)$
- 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...

We use three unitarization methods

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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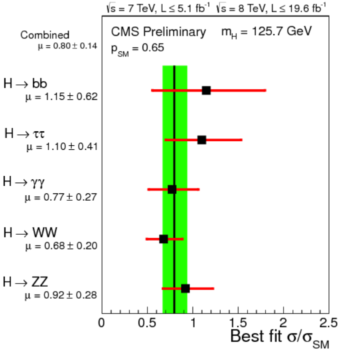
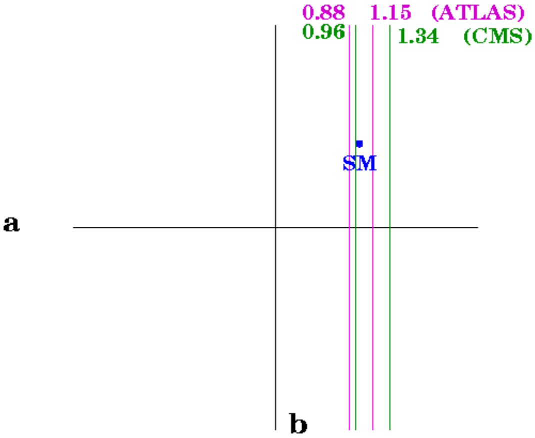
A word on the parameters



- 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

Gell-Mann's totalitarian principle

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

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

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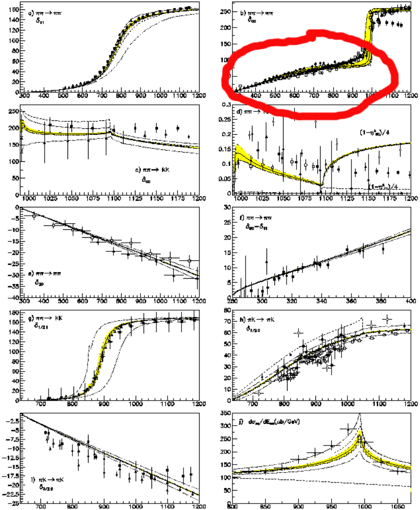
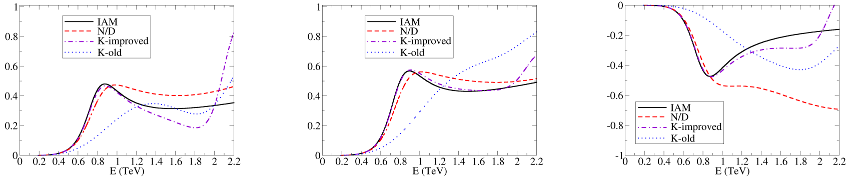
Coupled channel resonance

The scalar-isoscalar σ



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

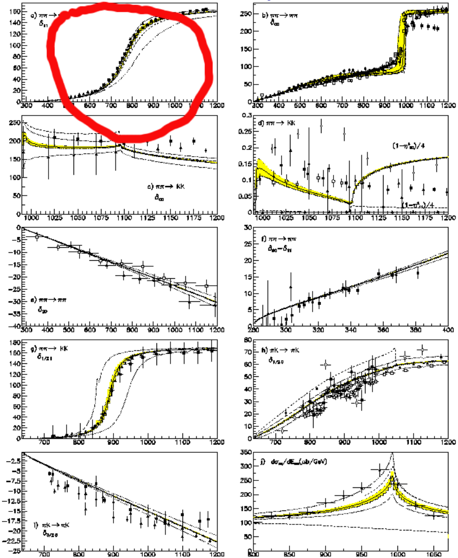
Scalar-isoscalar: independence of unitarization method



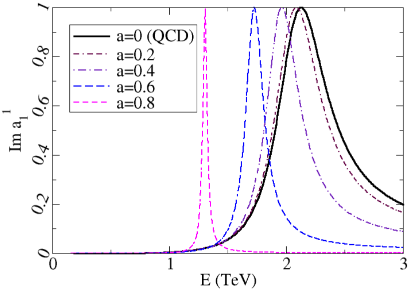
$\pi\pi \longrightarrow \pi\pi$ $\quad hh \longrightarrow hh$ $\quad \pi\pi \longrightarrow hh$

Unitarization + analyticity in complex plane $\longrightarrow$ 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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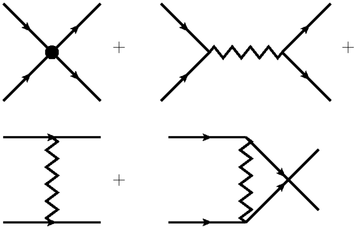
A word on Composite Higgs Models

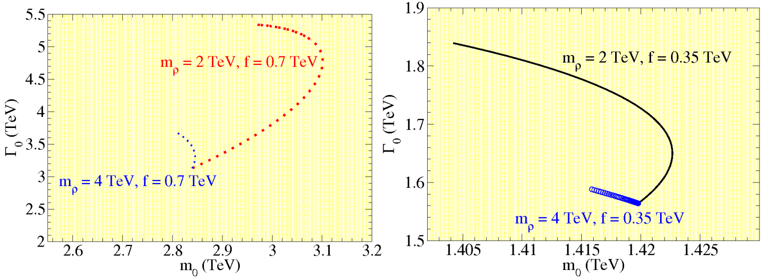
A couple of useful relations,

- 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
  $$(a^2 - b) = (1 - a^2)$$



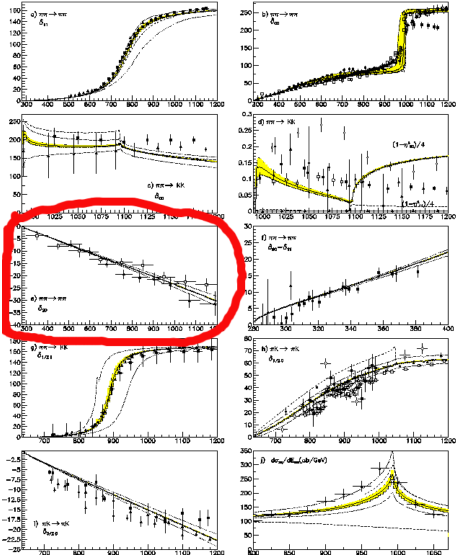
More on the ρ: a word on Composite Higgs Models

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

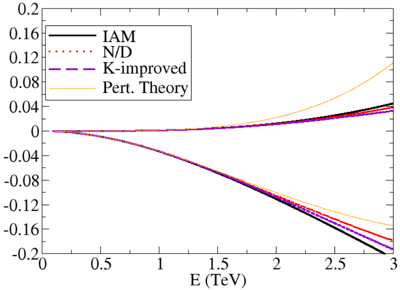


(the parameter of the curves is $g_{\rho\pi\pi}$)

Repulsive scalar-isotensor wave



Isotensor channel: repulsive for $a < 1$

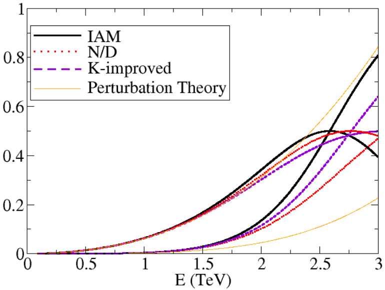


$a = 0.88$
(The LO amplitude has opposite sign as the scalar)

That's my sign of a, if you don't like it...

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

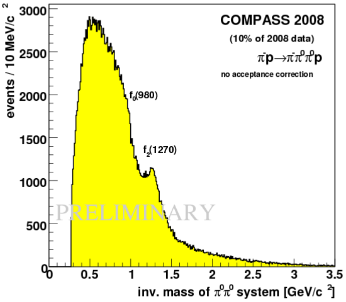
Isotensor channel: attractive for $a > 1$



$a = 1.15$

- 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



Tensor isoscalar f_2

To a large extent...

- For about 75% of the community it is a quark-antiquark meson
- For about 24% it is a meson-meson state
- But for one of us...

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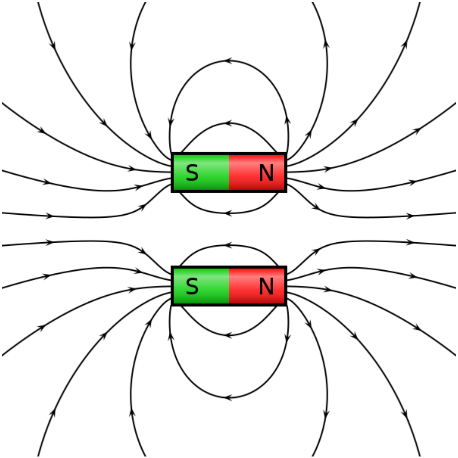
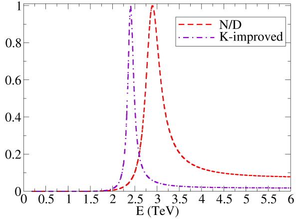
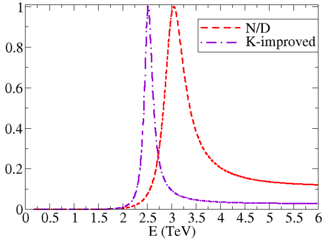
It is a magnet!

(two spin-aligned ρs)



f_2





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

Perhaps more fun,

$C_2\ O_2 \to C_2\ O_2$ weak... Van der Waals interaction

$CO\ CO \to CO\ CO$ weak... dipole-dipole interaction, but

$C_2\ O_2 \to CO\ CO$ strong! combustion!

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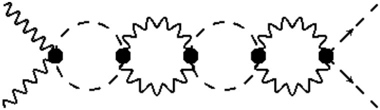

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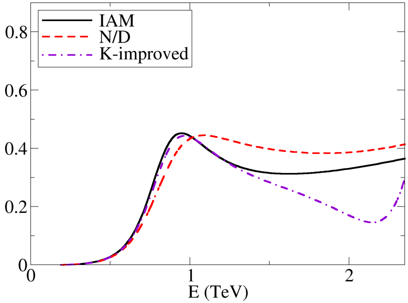
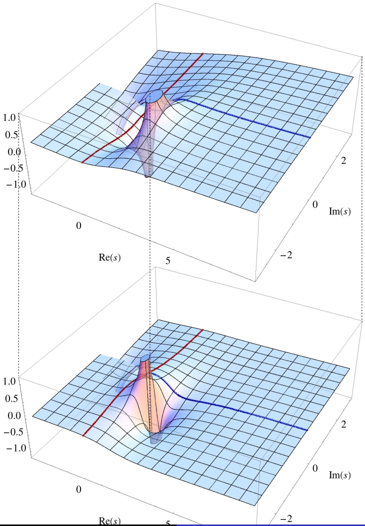


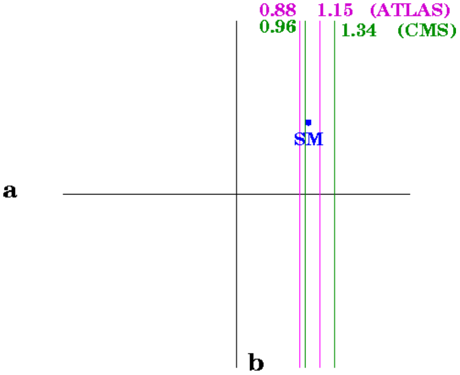
$a^2 = 1 \neq b = 2$

pole in the second Riemann sheet



Motivation: no bound on b

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



Motivation: no bound on *b*

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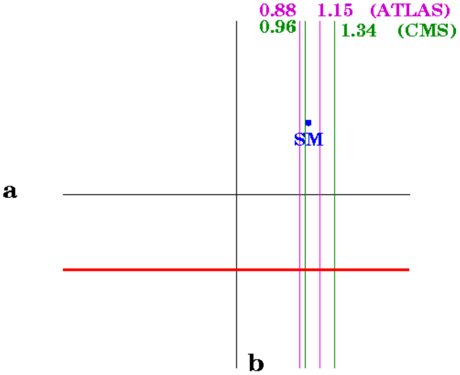

$b \in (-1, 3)$

Generic conclusions

- A generic Electroweak Symmetry Breaking Sector of the SM is strongly coupled and Hadron Physics has a lot to teach.
- 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 $\frac{\partial m_\sigma}{m_\rho} > 0$ (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, $b \in (-1, 3)$

Will Stella and I find a resonance?

Perhaps soon

Great expectations at the LHC
New strong interactions and resonances?

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Universidad Complutense de Madrid
June 16th, 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.

Meeting of the spanish Hadron Network
IFIC-UV

The three unitarization methods

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

Dependence on the renormalization scale

1-Loop divergences absorbed in NLO a_4, $a_5 \dots$ counterterms Example: A_0^0, $a = 1$, $b = 2$, NLO set to zero.