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Comparing mesons and $W_L W_L$ TeV-resonances*

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Abstract. Tantalizing LHC hints suggest that resonances of the Electroweak Symmetry Breaking Sector might exist at the TeV scale. We recall a few key meson-meson resonances in the GeV region that could have high-energy analogues which we compare, as well as the corresponding unitarized effective theories describing them. While detailed dynamics may be different, the constraints of unitarity, causality and global-symmetry breaking, incorporated in the Inverse Amplitude Method, allow to carry some intuition over to the largely unmeasured higher energy domain. If the 2 TeV ATLAS excess advances one such new resonance, this could indicate an anomalous $q\bar{q}W$ coupling.

1 Non-linear EFT for $W_L W_L$ and hh

The Electroweak Symmetry Breaking Sector of the Standard Model (SM) has a low-energy spectrum composed of the longitudinal $W_L^{\pm}$, Z_L and the Higgs-like h bosons. Various dynamical relations suggest that the longitudinal gauge bosons are a triplet under the custodial $SU(2)_c$, and h is a singlet. This is analogous to hadron physics where pions fall in a triplet and the η meson is a singlet. The global symmetry breaking pattern, $SU(2) \times SU(2) \to SU(2)_c$ is shared between the two fields.

The resulting effective Lagrangian, employing Goldstone bosons $\omega^a \sim W_L,\ Z_L$ as per the Equivalence Theorem (valid for energies sufficiently larger than M_W, M_Z), in the non-linear representation, is [1–3],

$$\begin{aligned}\mathcal{L} = &\frac{1}{2}\left[1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2\right]\partial_\mu\omega^i\partial^\mu\omega^j\left(\delta_{ij} + \frac{\omega^i\omega^j}{v^2}\right) + \frac{1}{2}\partial_\mu h\partial^\mu h \\ &+ \frac{4a_4}{v^4}\partial_\mu\omega^i\partial_\nu\omega^i\partial^\mu\omega^j\partial^\nu\omega^j + \frac{4a_5}{v^4}\partial_\mu\omega^i\partial^\mu\omega^i\partial_\nu\omega^j\partial^\nu\omega^j + \frac{g}{v^4}(\partial_\mu h\partial^\mu h)^2 \\ &+ \frac{2d}{v^4}\partial_\mu h\partial^\mu h\partial_\nu\omega^i\partial^\nu\omega^i + \frac{2e}{v^4}\partial_\mu h\partial^\nu h\partial^\mu\omega^i\partial_\nu\omega^i \qquad (1)\end{aligned}$$

This Lagrangian is adequate to explore the energy region 1-3 TeV $\gg$ 100 GeV, and contains seven parameters. Their status is given in [1] and basically amounts to

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$a \in (0.88, 1.3)$ (1 in the SM), $b \in (-1, 3)$ (1 in the SM) and the other, NLO parameters (vanishing in the SM) largely unconstrained. This is a reasonably manageable Lagrangian for LHC exploration of electroweak symmetry breaking in the TeV region, before diving into the space of the fully fledged effective theory [3].

Partial wave scattering amplitudes in perturbation theory $A_I^J(s) = A_{IJ}^{(LO)}(s) + A_{IJ}^{(NLO)}(s)\dots$ for $\omega\omega$ and hh, have been reported to NLO in [4]. For example, the LO amplitudes of $I = 0$, 1 and 2, and the $\omega\omega \to hh$ channel-coupling one are

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

and we see how any small separation of the parameters from the SM value $a^2 = b = 1$ leads to energy growth, and eventually to strong interactions. To NLO, the amplitudes closely resemble those of chiral perturbation theory

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

with a left cut carried by the $Ds^2\log s$ term, a right cut in the $Es^2\log(-s)$ term, and the $Ks + Bs^2$ tree-level polynomial. B, D and E can be found in [4] and satisfy perturbative renormalizability (in the chiral sense).

2 Resonances

The perturbative amplitudes in Eq. (2) do not make sense for large s (TeV-region) where they violate unitarity $\mathrm{Im}A_{IJ} = |A_{IJ}|^2$, relation satisfied only order by order in perturbation theory, namely $\mathrm{Im}A_{IJ}^{(NLO)} = |A_{IJ}^{(LO)}|^2$.

In hadron physics, the solution is to construct new amplitudes that satisfy unitarity exactly and reproduce the effective theory at low energy (see the lectures [5]) via dispersive analysis. This combination of dispersion relations with effective theory exploits all model-independent information in the two-body experimental data, and is known in both the electroweak symmetry breaking sector and the QCD sector of the Standard Model [7]. A salient example is the NLO Inverse Amplitude Method,

$$A_{IJ} = \frac{\left(A_{IJ}^{(LO)}\right)^2}{A_{IJ}^{(LO)} - A_{IJ}^{(NLO)}} \tag{3}$$

a simple formula that can be rigorously generalized to two channels of massless particles by upgrading the various A to matrices. The denominator of Eq. (3) allows for scattering resonances (poles in the 2nd Riemann sheet).

In meson physics, the most salient elastic resonance of the $\pi\pi$ system is the isovector $\rho(770)$ meson, that dominates low-energy dipion production in most experiments; for example, its prominence in COMPASS data [6] is visible in the

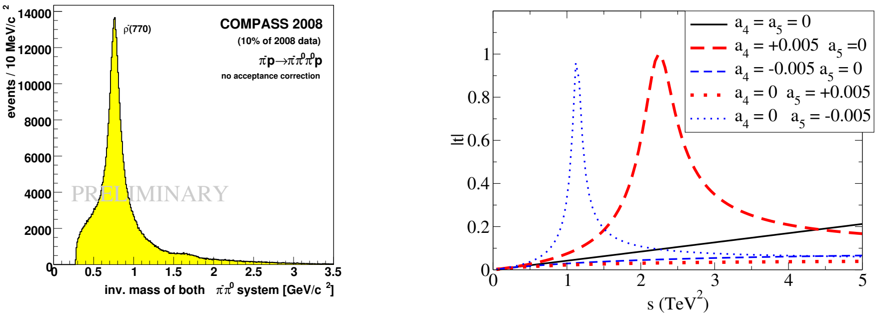

Fig. 1. Left: the physical ρ in the COMPASS $\pi\pi$ spectrum. (Reprinted from [6]. Copyright 2008, AIP Publishing LLC). Right: a possible equivalent *WW*, *WZ* state for various a_4, a_5.

left plot of figure 1. Independently of particular technicolor models, values of a_4 and a_5 at the 10^{-4}-10^{-3} level produce a ρ-like meson of the electroweak sector in the TeV region. The right panel of figure 1 demonstrates this.

The central attraction of the nuclear potential suggested the introduction of a scalar σ meson in the $\pi\pi$ spectrum whose existence was long disputed but that is now well established [8]. In addition to detailed dispersive analysis, it gives strength to the low-energy $\pi\pi$ spectrum if the ρ channel is filtered out by cautious quantum number choice, such as $J/\psi \to \omega\pi\pi$ that forces the pion subsystem to have positive charge conjugation because the other two mesons both have $C = (-1)$. An analysis of BES data by D. Bugg is shown in the left plot of fig. 2. The right plot shows the equivalent resonance in $\omega\omega \sim W_L W_L$, that appears for

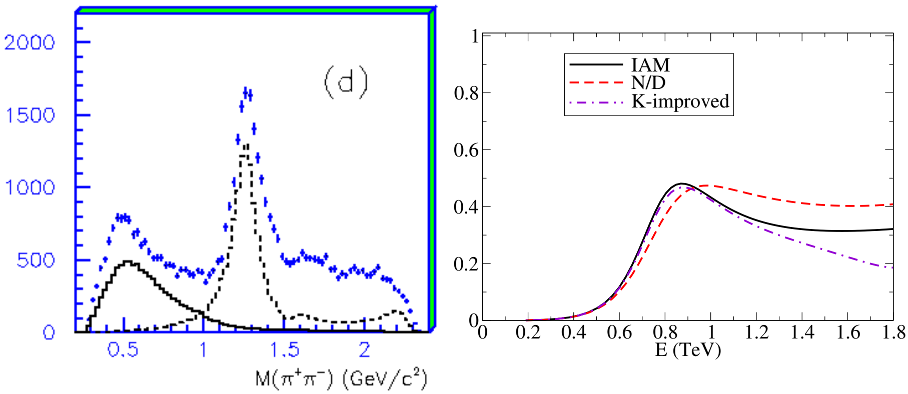

Fig. 2. Left: $\pi\pi$ spectrum with positive charge conjugation clearly showing an enhancement at low invariant mass, related to the $f_0(500)$ (or σ) meson; (Reprinted from [9] with permission. Copyright 2008, AIP Publishing LLC). Right: $IJ = 00$ $\omega\omega$ scattering in the IAM and other unitarization methods producing an equivalent electroweak resonance.

$a \neq 1$ and/or $b \neq a^2$ (if the resonance is induced by b alone it is a pure coupled channel one [4], that also has analogues in hadron physics, though less straightforward ones).

The same BES data also reveals another salient meson resonance, the $f_2(1270)$. Partial waves with $J = 2$ cannot be treated with the NLO IAM, as $A_0^{2\ \mathrm{LO}} = 0$ but a similar structure has been obtained with the N/D or K-matrix unitarization methods, and we show it in figure 3.

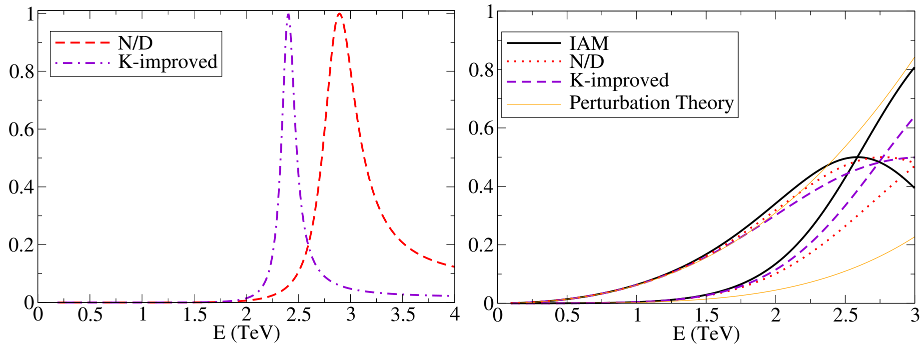

Fig. 3. Left: generating an $IJ = 02$ resonance in the electroweak sector is possible with adequate values of a_4, a_5. Right: positive values of $a^2 - 1$ also generate an isotensor $I = 2$ resonance, though this is more disputed [2]. In hadron physics the isotensor wave is repulsive, and thus, not resonant.

3 ATLAS excess in two-jet events

Renewed interest in TeV-scale resonances is due to a possible excess in ATLAS data [10] plotted in figure 4 together with comparable, older CMS data [11] that does not show such an enhancement. The excess is seen in two-jet events tagged as vector boson pairs by invariant mass reconstruction (82 and 91 GeV respectively). The experimental error makes the identification loose, so that the three-channels cross-feed and we should not take seriously the excess to be seen in all three yet. Because WZ is a charged channel, an $I = 0$ resonance cannot decay there. Likewise ZZ cannot come from an $I = 1$ resonance because the corresponding Clebsch-Gordan coefficient $\langle 1010|10 \rangle$ vanishes. A combination of both $I = 0, 1$ could explain all three signals simultaneously (as would also an isotensor $I = 2$ resonance).

A relevant relation imported from hadron physics that the IAM naturally incorporates restricts the width of a vector boson. This one-channel KSFR relation [12] links the mass and width of the vector resonance with the low-energy constants v and a in a quite striking manner,

$$\Gamma^{\mathrm{IAM}} = \frac{M^3_{\mathrm{IAM}}}{96\pi v^2}(1 - a^2)\ . \tag{4}$$

For $M \sim 2$ TeV and $\Gamma \sim 0.2$ TeV (see fig. 4), we get $a \sim 0.73$ which is in tension with the ATLAS-deduced bound $a|_{2\sigma} > 0.88$ at 4-5σ level; Eq. (4) predicts that a 2 TeV $J = 1$ resonance, with current low-energy constants, needs to have $\Gamma < 50$ GeV, a fact confirmed by more detailed calculations [1,2]. However scalar resonances tend to be substantially broader.

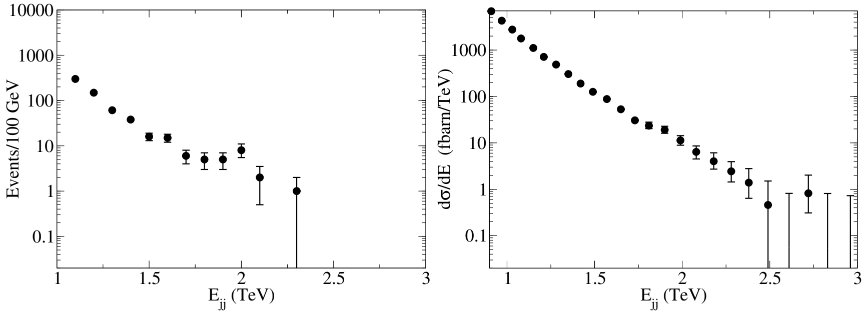

Fig. 4. Left: replot of the ATLAS data [10] for $WZ \rightarrow 2$ jet, with a slight excess at 2 TeV (also visible in the other isospin combinations WW and ZZ, not shown). The jet analysis is under intense scrutiny [15]. Right: equivalent CMS data [11] with vector-boson originating jets. No excess is visible at 2 TeV (though perhaps some near 1.8-1.9 TeV).

The cross section for the reaction $pp \rightarrow W^+Z{+}X$ for a given WZ Mandelstam s, and with the E^2 total energy in the proton-proton cm frame, can be written [13] in standard LO QCD factorization as

$$\frac{d\sigma}{ds} = \int_0^1 dx_u \int_0^1 dx_{\bar{d}} \delta(s - x_u x_{\bar{d}} E^2_{tot} f(x_u) f(x_{\bar{d}}) \hat{\sigma}(u\bar{d} \rightarrow \omega^+ z) \ . \tag{5}$$

The parton-level cross section $\hat{\sigma}$ is calculated, with the help of the factorization theorem, from the effective Lagrangian in Eq. (1) above. Following [13], we would

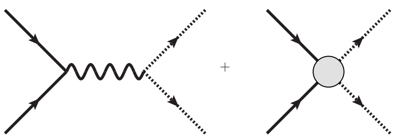

Fig. 5. Production of a pair of Goldstone bosons by $u\bar{d}$ annihilation through a W-meson and anomalous BSM vertex enhancing it.

expect an amplitude (from the left diagram of figure 5) given by $\mathcal{M} = \bar{u}\gamma^\mu_L v(-ig/\sqrt{8})^2(i/q^2)(k_1 - k_2)_\mu$ in perturbation theory. Further, dispersive analysis reveals the need of a vector form factor in the presence of strong final state rescattering, to guarantee Watson's final state theorem; the phase of the production amplitude must be equal to that of the elastic $\omega\omega$ scattering amplitude. If the later is represented by the Inverse Amplitude Method, the form factor in the $W\omega\omega$ vertex is $F_V(s) = \left[1 - \frac{A^{(1)}_{11}(s)}{A^{(0)}_{11}(s)}\right]^{-1}$. The resulting cross section [13] was found to be slightly below the CMS bound, and perhaps insufficient to explain the possible ATLAS excess. With current precision this statement should not be taken to earnestly, but it is nonetheless not too soon to ask ourselves what would happen in the presence of additional non-SM fermion couplings.

Thus, an original contribution of this note is to add to Eq. (1) a term [1]

$$\mathcal{L}_{\text{fermion anomalous}} = \frac{\delta_1}{v^2} \bar{\psi}_L \omega \not\partial \omega \psi_L \tag{6}$$

(for a derivation see, e.g. [14]). The parton level cross-section is then

$$\left[\frac{d\hat{\sigma}}{d\Omega}\right]_{\text{cm}} = \frac{1}{64\pi^2 s} \frac{g^4}{32} \sin^2\theta \left(1 + \frac{\delta_1 s}{v^2}\right)^2 |F_V(s)|^2 , \tag{7}$$

and if $\delta_1 \neq 0$ additional production strength appears in the TeV region. The sign of this δ_1 might be determined from the line shape due to interference with the background [16].

4 Conclusion

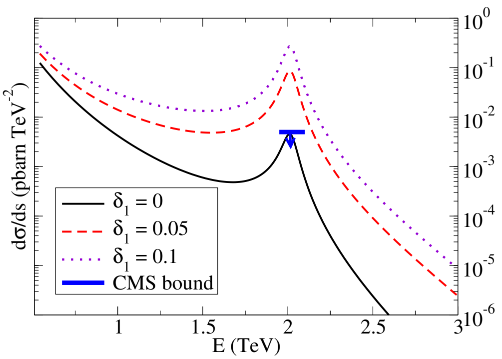

Fig. 6. Tree-level W production of $\omega\omega$ [13] with final-state resonance; non-zero parameters are a=0.9, b= a^2, $a_4 = 7\times10^{-4}$ (at $\mu = 3$ TeV). Also shown is a CMS cross-section upper bound (see fig. 4). This can be exceeded with the δ_1 coupling of Eq. (6).

The 13 TeV LHC run II entails larger cross sections and allows addressing the typical σ, ρ-like $\omega\omega$ resonances, at the edge of the run I sensitivity limit as shown in fig. 6. The large rate at which such a resonance would have to be produced to explain the ATLAS excess (at the 10fbarn level [17]) is a bit puzzling, though it can be incorporated theoretically with the δ_1 parameter. Hopefully this ATLAS excess will soon be refuted or confirmed. In any case, the combination of effective theory and unitarity that the IAM encodes is a powerful tool to describe data up to $E = 3$ TeV in the electroweak sector if new, strongly interacting phenomena

[1] This is only one of the possible additional operators. There is a second one with R fields, and several custodially breaking others. The gauge-invariant version of Eq. (6) actually modifies the fermion-gauge coupling by a factor $(1+\delta_1)$: this cannot be excluded because it would be the quantity that is actually well measured in β decay. The triple gauge boson vertex would then need not coincide with this coupling. However the latter is much less precisely known and there is room for deviations at the 5-10% level.

appear, with only few independent parameters. The content of new, Beyond the Standard Model theories, can then be matched onto those parameters for quick tests of their phenomenological viability.

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Resonance states and branching ratios from a time-dependent perspective.

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The spectrum of a given Hermitian quantum mechanical system can be generally separated into a discrete part containing the bound states and a continuous part of scattering states above the threshold. These states are solutions to the time-independent Schrödinger equation (TISE) with the corresponding boundary conditions. The discrete nature of the bound spectrum enables the characterization of the stable part of the studied system along with its physical properties based on its energy levels. The continuum can be used to characterize the system by probing it through scattering experiments. In this context instead of discrete energy levels the discussion is usually shifted to resonances in the scattering profile of the studied system. These appear as sharp features in the energy profile of the interaction.

Wavepacket dynamics in the continuum of meta-stable open quantum systems reveals that in the interaction region the evolution resembles that of bound states. There is, however, one difference where a bound system preserves probability in a meta-stable one when we observe decay in time. When the decay from the interaction region tends to follow an exponential form then the energy content of the localized part of the wavepacket assumes a constant value. This value is complex where the real part represents the energy of a resonance of the system and the imaginary part is related to the width of this resonance. The dynamics outside the interaction region exhibit a spatial exponential increase which drops off at the edge of the escaping wavefront. The velocity of the escaping part of the wavepacket has the momentum corresponding to the average energy inside. Similar dynamics is observed when scattering a wavepacket off a potential at a resonant energy. Initially the arriving wavepacket populates a resonant bound-like state inside the interaction region and consequently the formed meta-stable state decays.

The time-dependent dynamics observed in meta-stable systems demonstrates the properties of both stationary bound and scattering states. This type of dynamics usually occurs due to either the shape of the potential of interaction where the variation can lead to confinement of finite time or due the coupling of a bound state in an closed channel with the continuum of an open channel. The first type of states is often termed shape-type resonance whereas the second type is usually called Feshbach-type resonances. The above discussion suggests that the essence of the dynamics can be captured by solving a time independent equation with appropriate boundary conditions. Such boundary conditions allow only outgoing flux. Solving the TISE with outgoing boundary conditions leads to solutions with complex momentum. This makes the energies of these states complex just as the portrayed dynamics and it also displays the asymptotic divergence which was observed.

In order to be able to calculate the energies of the resonance states one needs to be able to fix the asymptotic divergence. This can be achieved in various ways which all lead to a non-Hermitian Hamiltonian. Some of the techniques used are: (1) scaling of the coordinate by a complex factor (complex scaling); (2) addition of a complex absorbing potential at the asymptotes far from the interaction region; (3) Feshabch projection formalism which separates between the spaces of localized and scattering states; (4) Siegert pseudo states which satisfy the required boundary condition on a given surface but lead to a quadratic eiegnvalue problem.

The use of Non-Hermitian Hamiltonians readily yields the information regarding the lifetime of a given meta-stable state in addition to its energy. On the other hand, it leads to some complications due the non-Hermiticity. First of all, the resonance states are not orthogonal with respect to the conventional scalar Dirac product. Instead one needs to find and additional set of states which are orthogonal to them. These are the eigenstates of the Hermitian conjugate Hamiltonian which physically are their time-reversed counterparts. The two bi-orthogonal states form together the resolution of the identity. Another aspect is the loss of the probabilistic interpretation due to the non-Hermitiicty. This can be amended by redefining the inner product based on the bi-orthogonal set of states. By doing so the probabilistic interpretation is retained along with the non-unitary evolution resulting from the decay of the system. This allows to describe very complicated dynamics in the continuum based on dynamics of several resonance states alone.

In decaying few-body systems there are often several channels open to decay. In such case the decay rate of the resonance contains contributions due to the flux in each of the open channels. When considering the above mentioned outgoing boundary conditions one finds that the momentum of the outgoing flux in each channel depends on the resonance energy and the threshold energy of the given channel. When following the wavepacket dynamics in such systems one observes that at every channel the wavepacket leaks at the velocity given by the momentum in that channel. Consequently all the information regarding the partial widths to the different channels and their branching ratios can be extracted from the stationary resonance wavefunction. All that is needed in order to evaluate the branching ratios is the complex amplitude of the resonance wavefunction at the asymptotes and the momentum at every given channel which is obtained from the difference between the resonance energy and the channel's threshold energy.

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Analitična zgradba neperturbativnih kvarkovih propagatorjev in mezonskih procesov

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Raziskujemo analitično zgradbo nekaterih nastavkov za kvarkove propagatorje v neperturbativnem področju kromodinamike. Če izberemo fizikalno motivirano parametrizacijo masne funkcije $M(p^2)$ oblečenih kvarkov, odvisne od gibalne količine in z določeno analitično zgradbo, je skrajno težavno napovedati in obvladati analitično zgradbo ustreznega neperturbativnega kvarkovega propagatorja. Tudi problem Wickove rotacije, ki povezuje izražavo v prostoru Minkowskega in Evklida, je skrajno težaven v neperturbativnem območju. Izpeljemo obliko propagatorja, ki omogoča Wickovo rotacijo in dopušča enakovredne račune v prostoru Minkowskega in Evklida. Kljub preprostosti nudi ta model dober kvalitativen in semikvantitativen opis nekaterih procesov z psevdoskalarnimi mezoni.

Primerjava med mezoni in resonancami $W_L W_L$ pri energijah več TeV

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Mikavni signali z Velikega hadronskega trkalnika (LHC) namigujejo, da morda obstajajo v področju zloma elektro-šibke simetrije resonance v območju več TeV. Spomnimo na nekaj ključnih resonanc mezon-mezon v območju GeV, ki bi utegnile imeti analogne resonance pri visokih energijah in nam služijo za primerjavo, hkrati z odgovarjujočo unitarizirano efektivno teorijo. Čeprav je podrobna dinamika lahko različna, pa zahteve po unitarnosti, kavzalnosti in globalnem zlomu simetrije (z uporabo metode inverzne amplitude) dovoljujejo prenos intuicije v večinoma neizmerjeno območje visokih energij. Če bo povečano število dogodkov na ATLASU okrog 2 TeV podprlo tako novo resonanco, to lahko pomeni anomalno sklopitev $q\bar{q}W$.

Resonance v konstituentnem kvarkovem modelu.

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Na kratko poročamo o današnjem opisu barionskih resonanc v realističnem modelu s konstituentnimi kvarki, v katerem običajno obravnavamo resonance kot