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The LHC di-photon excess at 750 GeV

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Abstract. I review the main features and some of the theoretical attempts to explain the excess around an invariant mass of 750 GeV seen in 2015 at the LHC in the di-photon channel. As this hint to new physics has now all but disappeared from the higher-luminosity 2016 data, the statistical analysis nicely illustrates why only a high level of significance can be trusted in a discovery. The various explanations that has been suggested remain interesting examples of our current understanding of physics beyond the standard model and also of the challenging task of discriminating among them.

1 Introduction

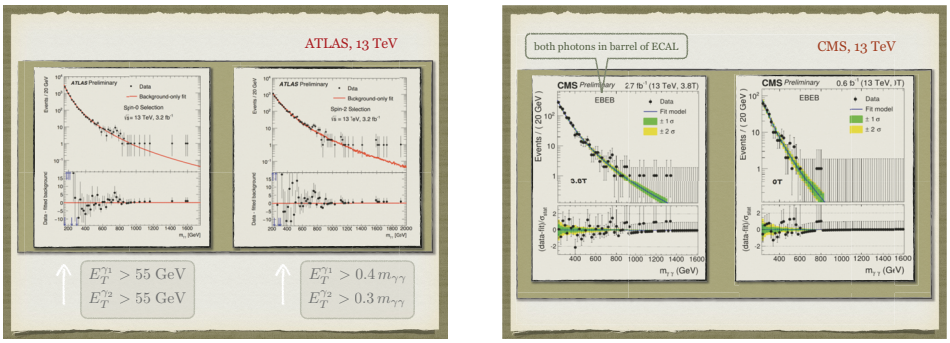

Figure 1. The data: di-photon invariant mass distribution as presented by the ATLAS (left panel) and CMS (right panel) collaborations.

The extraordinary interest aroused by the excess in the di-photon invariant mass distribution revealed by the LHC data collected in 2015 at the center-of-mass energy $\sqrt{s} = 13$ TeV [1] is easily explained by the desire of finally seeing something beyond the standard model. Never mind that this something was coming out from left field and instead of some missing transverse energy event was just what appeared to be a resonance decaying into two photons.

The analysis of the data—the fitting of the resonance shape to the di-photon invariant mass distribution and the subtraction of the continuum background—shows the many statistical subtleties

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involved and why an exceptionally high level of significance—like the one currently agreed on of 5σ—is necessary before claiming any discovery.

A review of the models put forward to explain and understand the resonance take us across most of the possible scenarios for physics beyond the standard model; these models taken together make clear both the abundance of ideas and the difficulty of discriminating among the various possibilities. This latter difficulty is a problem that was present in this instance and will be there for any, if any, future discovery.

I have included in this write up most of the talk slides as figures and some of the spoken remarks as text. As a listing of all the theoretical papers devoted to the di-photon excess would fill more than the allotted pages, I have included only those to the papers I used in this review by referring to their arXiv number in the slides where they were mentioned.

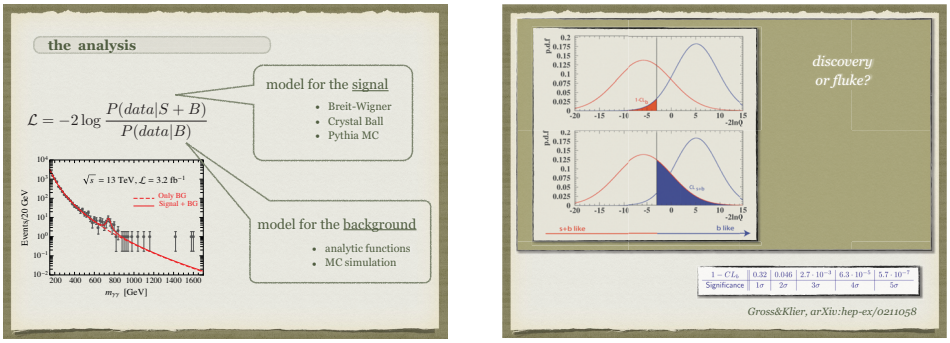


Figure 2. The fit: a likelihood function is defined by the ratio of the probabilities of the model of the signal plus the background over that of the background alone (left panel). Probability distribution functions (p.d.f.) for the hypothesis testing, confidence levels (CL_b) and the corresponding significances (right panel).

2 The facts

As many newspapers like to claim, let us try and keep the facts separated from the opinions—bearing in mind that "the fewer the facts, the stronger the opinions." [2] The facts are contained in the experimental observation of the distribution of the invariant mass of the two final photons. It is shown in Fig. 1 for, respectively, the ATLAS (left) and CMS (right) collaborations.

The plots are not homogenous. In particular the ATLAS collaboration presented two independent analyses and, accordingly, two different cuts on the photon energies. The one with looser cuts (shown on the right of the left panel of Fig. 1) was performed within the exotic group and aimed to possible spin 2 particles, the one with sharper cuts (shown on the left of the left panel of Fig. 1) was performed within the Higgs boson group in searching for spin 0 particles. The spin of the particle is here just a name holder with no physical implications. Similarly, the CMS collaboration presented two sets of data—depending of where the two photons ended up within the detector. On the right panel of Fig. 1, I have reproduce their data for the case in which both photons ended in the barrel of the electromagnetic calorimeter, as presented in two batches of, respectively, 2.7 and 0.6 inverse femto-barns of luminosity.

Having the data, we can fit them to our favorite model. The procedure followed by both collaborations is that indicated in the left panel of Fig. 2, namely of the maximization of a likelihood

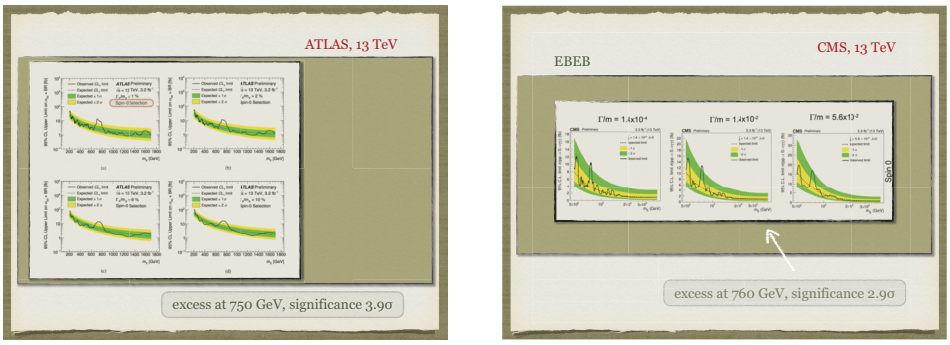


Figure 3. The significance of the bump around 750 GeV in the Brazilian flag plots: 3.9σ for ATLAS (left panel) and 2.9σ for CMS (right panel).

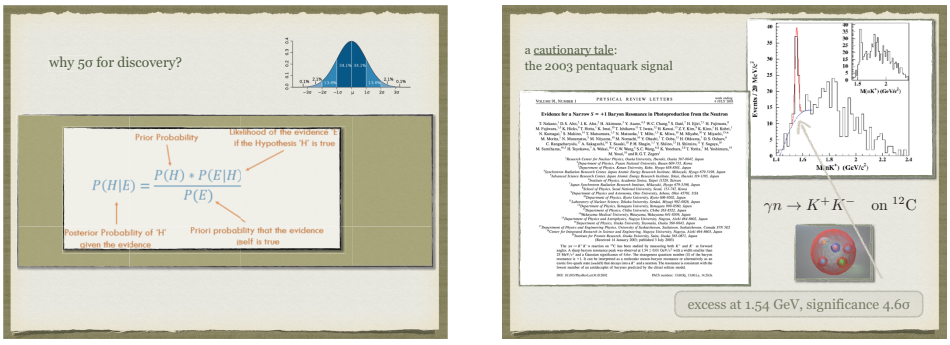


Figure 4. Bayes' theorem linking prior to posterior probabilities (left panel). The 2003 pentaquark signal: an excess at 1.45 GeV with a significance of 4.9σ (right panel).

function in which the model of the signal is included on top of the background (itself described by an appropriated model) against the case of background only. Models for the signal can vary, from the simplest Breit-Wigner resonance to a more sophisticated (read, with more parameters) Crystal Ball model or even a full Monte Carlo simulation. The final significance does not depend critically from this choice. The model for the background can either be an analytical function or, again, a Monte Carlo simulation.

The result of this procedure is shown in Fig. 3 where the significance is counted in terms of sigmas (the so-called Brazilian flag plots made popular by the Higgs boson search). A significance of 3.9σ is found by ATLAS and one of 2.9σ by CMS. This means that the probability for the data to mimic the signal is, respectively, of about 1 out of 15800 and 1 out of 370!

A number of considerations come into play before being carried away by the enthusiasm. The discussion is usually framed in terms of hypothesis testing, like in right panel of Fig. 2 where the probability distribution functions for the competing hypotheses are compared. How strong a significance we need before claiming a discovery? In every day life a significance of 3σ is clearly good enough for all common tasks. After all, the probability of a statistical fluke in this case is only of about 1 out of 370. Nevertheless, there exist examples of very unlikely fluctuations: one of them being the

2003 pentaquark signal, a cautionary tale of a signal with a significance of 4.9σ that has melted away like a snowball in the sun after more data were collected (see right panel of Fig. 4).

The significance shown above is local in the sense that it does not take into in account the entire range of the possible parameters. We were not looking at that particular value of the invariant mass and we would have been equally happy if the excess had shown up at a different value. This is what has been called the look-elsewhere effect. It is an effect that seems difficult to quantify, at least to me, because of the ambiguous definition of what should be considered elsewhere. It is the invariant mass range in the di-photon channel or all searches on all channels performed at that time at the LHC? In any case, the local significance should be tuned down by some factor and it has been by the experimental collaborations.

On the other hand: the probability we estimated by the likelihood procedure is that of the data given the model while what we really care for is the probability of the the model given the data, the posterior probability. Bayes' theorem links these two probabilities (see left panel of Fig. 4), if we know the prior probabilities for the data and the model—that we do not. Again, some factor reducing the final significance is floating around.

These and other considerations behove us to constrain the significance in high-energy physics to higher values than in ordinary life. In particular, the threshold for discovery has been put to 5σ, that is a value for which the probability of a statistical fluke is only about 1 out of 1.7 millions, and just high enough to prevent turning the significance of the 2003 pentaquark excess into a discovery.

3 The opinions

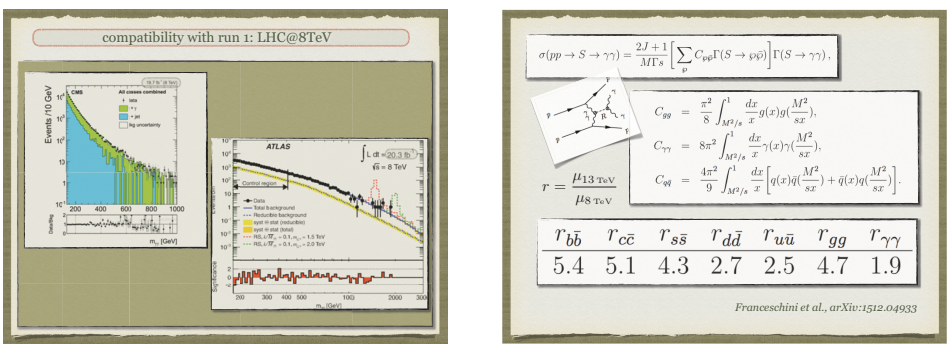


Figure 5. The data at 8 TeV (left panel) and parton distribution functions and the compatibility of the data at 13 and 8 TeV in terms of a rescaling function r (right panel).

Assume, if you will, that we do have a resonance. Let us then come to the opinions—and "that willing suspension of disbelief for the moment, which constitutes poetic faith" [3]—and to the models that have been suggested to make room for the 750 GeV resonance as seen in the 2015 LHC data.

A first problem all models have to face is that no significative excess was found in the previously collected data in the same channel at the LHC with center-of-mass energy of $\sqrt{s} = 8$ TeV. These data are shown in the left panel of Fig. 5.

In order to accommodate this lack of evidence, the rescaling of the cross section in going to the new center-of-mass energy must be taken into account. As it can be seen in the right panel of Fig. 5 different production mechanisms scale by different amounts and, depending on the model you have

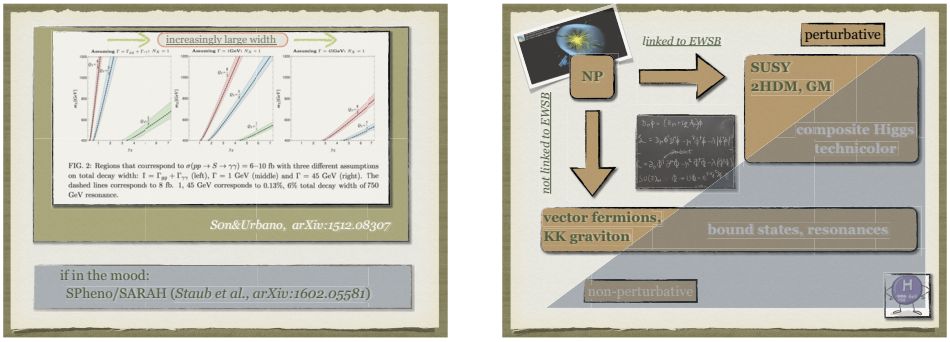


Figure 6. The running of the wilson coefficients (left panel) and classifying the new physics (NP) models: perturbative vs. non-perturbative and linked to electro-weak symmetry breaking (EWSB) vs. unrelated physics (right panel).

in mind, the compatibility between the two sets of data may or may not be an issue. At face value, models in which the production of the resonance is dominated by gluon fusion can have at 13 TeV a much larger cross section than at 8 TeV and are therefore favored.

There are many ways of explaining a resonance with the features of that glimpsed in the di-photon channel at the LHC and we need some sort of classification. Perhaps the simplest one is according to whether the model behind the resonance can be treated by perturbative methods or not; perturbative physics leads to lagrangians with known additional degrees of freedom and calculable amplitudes. Another useful criteria is whether it takes part or not in the breaking of the electro-weak symmetry: if it does not take part, there are less constraints and its signatures are going to be more elusive.

The right panel of Fig. 6 tries to summarize in a single slide these various possibilities naming some of the proposed models.

The discussion can be framed in terms of effective actions. We know that the putative resonance must couple to the photons and the gluons and therefore the effective action must contains the terms shown in Fig. 7. Different terms describe different possible parity and spin symmetries of the resonance: scalar, pseudo-scalar or tensor (spin 2). The case of spin 1 is excluded by the Landau-Yang theorem [4].

Non-perturbative models can be based on such effective actions where the couplings are tuned to a value determined by the experimental fit. Such couplings and the form of the lagrangian are then embedded within the framework of some model of strongly interacting dynamics of some constituents. By construction these models can easily fit the data but remain vague about the ultraviolet completion and the computation details.

If you want to interpret these effective actions in terms of a perturbative lagrangian, you must face the problem that the relatively large cross section implied by the data requires rather large couplings of whatever particles are present in the loop (left panel of Fig. 8) or the presence of many of them. Large couplings can easily run to even larger values thus driving the theory to a non-perturbative regime (see left panel of Fig. 6). Moreover, as explained in the right panel of Fig. 8, the masses of these particles must be large enough to prevent the opening of the threshold above which they can be produce on shell—since they have not been seen.

That said, the possible mechanisms to produce the resonance are many, the main ones shown in the left panel of Fig. 9: from the loop of higher-mass states to the cascade decay of an heavier resonance

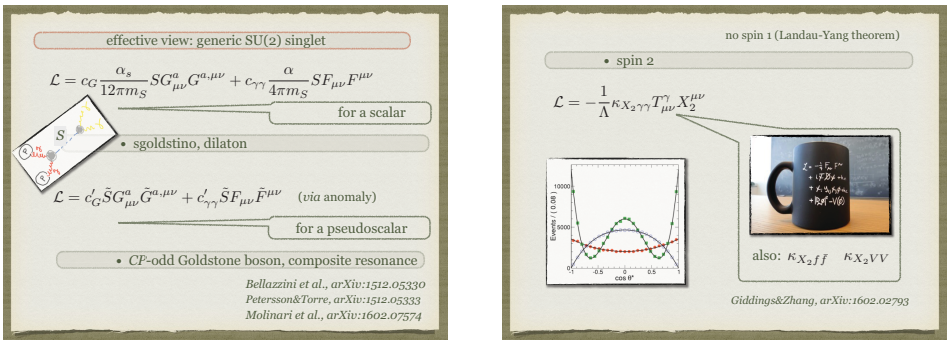
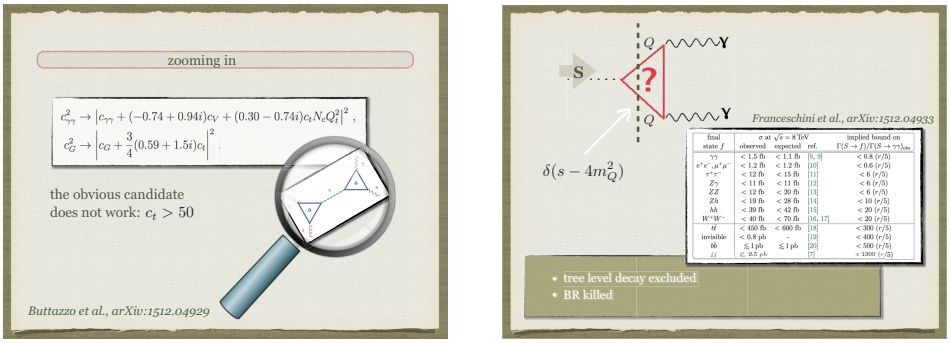


Figure 7. Effective lagrangians for scalar and pseudo-scalar (left panel) and spin 2 (right panel) resonance. The spin 2 case, implies, if the resonance is a heavy graviton, a similar coupling to all others particles.



final state f	σ at $\sqrt{s} = 8$ TeV observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\rm th}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[8, 9]	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[10]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[11]	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 11 fb	[12]	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	[13]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[14]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[15]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[16, 17]	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	[18]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[19]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[20]	$< 500\ (r/5)$
$j\,j$	$\lesssim 0.5$ pb	-	[7]	$< 1300\ (r/5)$

Figure 8. Zooming into the interaction vertex: size of the running coefficients (left panel) and constraints on the masses of the possible constituents in the loop (right panel) from the threshold for their production.

(that would help in explaining the negative result at 8 TeV) to the case in which both or one of the photons seen are actually a collimated pair of photons.

Remaining with the case of a loop of new states providing the effective coupling of the (neutral) resonance to photons and gluons, various models have been explored: from 2 Higgs doublet and Georgi-Machacek models (left panel of Fig. 10) to the always favored supersymmetric model in some of its manifold instances (right panel of Fig. 10). All these examples are linked to the breaking of the electro-weak symmetry and their parameters constrained by precision measurements.

While it is possible to fit the data with the above models, it is true that the fit can happen only in particular corners of the parameter space. For this reason, the most popular class of models has been the one where new (vector-like) fermions are simply added and their couplings and charges tuned to the required cross section (see right panel of Fig. 9). A drawback of this class of models is their *ad hoc* nature and independence of the physics of symmetry breaking at the electroweak scale.

Among the non-perturbative explanations, the resonance as a bound state of some standard, or non-standard constituents has also been advocated. Some of these are listed on the left panel of Fig. 11.

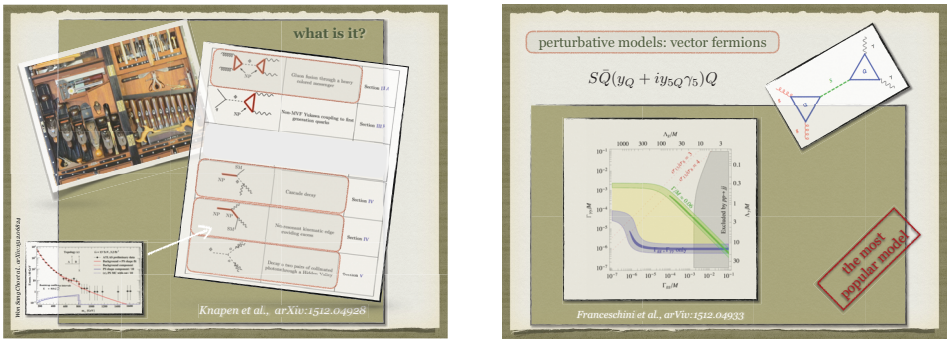


Figure 9. Possible mechanisms (left panel) and the most popular model (right panel).

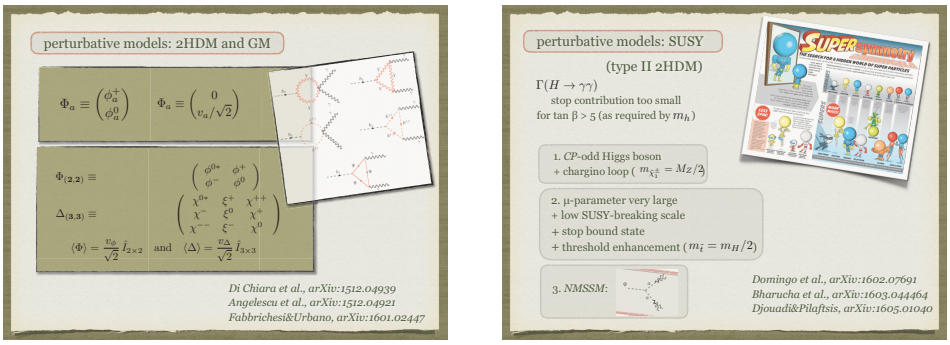


Figure 10. Other perturbative models: 2 Higgs doublets, Georgi-Machacek (left panel) and supersymmetry (SUSY) (right panel).

Finally, the possible role played by the interference between the resonance and the continuum in shaping the signal has been analysed (see right panel of Fig. 11).

4 Conclusions

To the the simple question; "What is it?" (or perhaps better: "What could it have been?"), we must answer that it can be (it could have been) almost anything (see left panel of Fig. 12). Such a resonance, with such a large cross section, was unexpected and it could be fitted only with some tugging among the known perturbative models of physics beyond the standard model. Its, by now, infamous "discovery" has offered us the chance of measuring the many models concocted over the years against a concrete example, made us more aware of the many subtleties (statistical and not) to be faced by going from the data to our favorite lagrangian, and to the importance of many analyses (see right panel of Fig. 12) in addition to the simple fit of the invariant mass distribution—the place where bumps are first seen—which are necessary to claim and understand any new discovery.

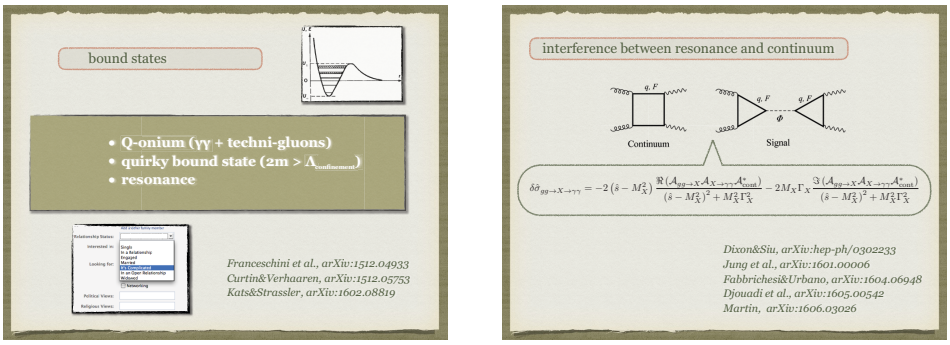


Figure 11. Non-perturbative bound states (left panel) and the interference between resonance and continuum (right panel).

Figure 12. A kind of summary (left panel) and the need-to-know data after a discovery (right panel).

References

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