LPT HIGHLIGHTS, 2014-2015

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OPENING A WINDOW ON NEW PHYSICS WITH RARE B-DECAYS

The flavorful world of quarks

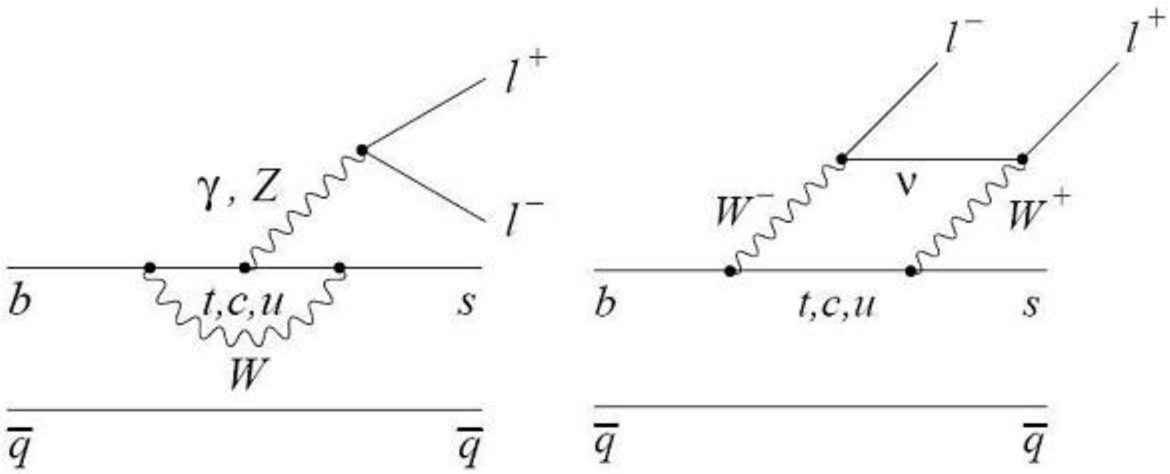
Our view of physics at its smallest accessible scales is embedded in the so-called Standard Model, which summarises the behaviour of matter under 3 fundamental interactions -- electromagnetic, strong and weak. Everyday life matter is based on up (u) and down (d) quarks bound by the strong interaction into protons and neutrons. But 4 other types (or flavours) of quarks have been observed and studied in high-energy experiments. These flavours, called s,c,b and t. are very similar to the u and d quarks, as far as their interactions are concerned, but they are much heavier. Each of these flavours decays quickly into a lighter quark (of different flavour) under the effect of the weak interaction, in a cascade that ends once one reaches an up or down quark.

Among these weak processes changing the flavour of quarks, one category has been recently under intense scrutiny, bearing the name of "Flavour-Changing Neutral Currents" (FCNC). Theses processes change the overall quark flavour content from the initial to the final state, but without changing the total electrical charge. This happens for instance when a B_d meson (made from an antiquark b and a quark d bound by the strong interaction) gets transformed into a \bar{B}_d meson (a quark b and an antiquark d bound in a similar way). This transition increases by 2 units the number of b quarks (an anti-quark counts as (-1) quark here) and decreases by 2 units the number of d quarks, without changing the charge -- as both b and d quark have the same electric charge -1/3|e|, opposite to that of their antiquarks.

The LHCb experiment, one of the four major experiments in activity at the LHC, dedicated to the study of the b-quark

In the Standard Model, such FCNC transitions are severely suppressed : they can occur only via so-called "loop" diagrams. These diagrams arise from the interplay of quantum mechanics and relativity, as they involve intermediate states consisting of several particles whose masses are a priori arbitrary : they can be of lower mass than the initial state... but they can also be heavier ! Indeed, the only constraint is that the final, observed, state is lighter than the initial one. These processes exhibit therefore a quantum sensitivity to higher energy scales via the intermediate states that they can go through.

As these FCNC are severely suppressed in the Standard Model, additional particles could contribute significantly to these processes, even if these new particles are so heavy that they could not be produced directly at the LHC. In the past, these transitions have been used to assume the existence and constrain the properties of yet unknown particles: it was the case for the charm and top quarks prior to their discovery. One may hope that history will repeat itself, and that physics beyond the Standard Model could reveal itself via such decays.



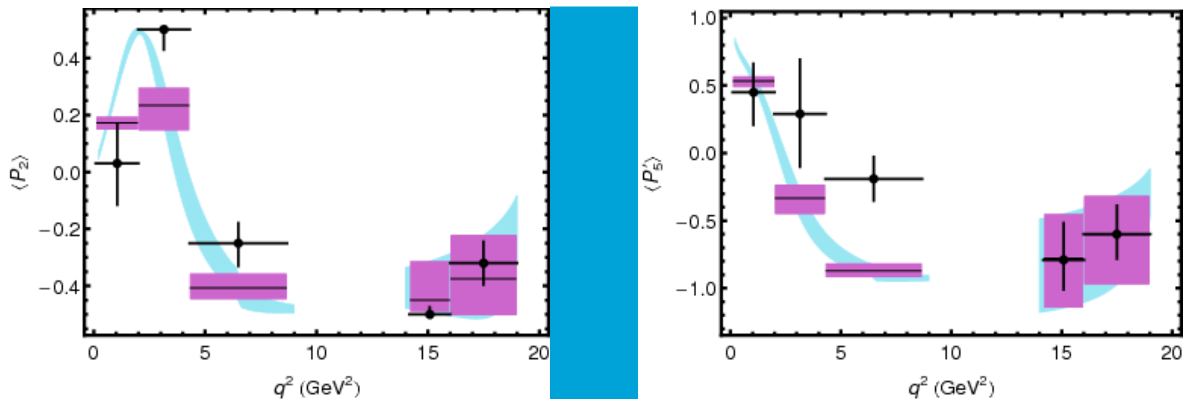
Two diagrams contributing to the rare decay B->K* mu mu. The underlying quark transition b-> s mu mu is ``dressed'', as quarks are bound into mesons (the incoming B meson corresponding to a b-quark and an antiquark q-bar, whereas the outgoing K^* is made of a s-quark and the same antiquark q-bar). Already in the Standard Model, the intermediate states involve particles (weak interaction gauge boson W, quark top) that are heavier than the incoming and outgoing states. New particles involved in extensions of the Standard Model might also appear in these intermediate states.

A rare scent of New Physics

These features explain why one of the four experiments on the LHC collider, the LHCb experiment, was particularly designed to observe FCNC decays of the b-quark, with a particular interest for b -> s mu mu. This quark-level transition can be observed through ``radiative transitions'' between bound states of quarks, for instance the meson transition B -> K* mu mu, the K* meson decaying into K pi through the strong interaction. This four-body decay has a complicated but rich kinematics, allowing one to define many parameters, or angular coefficients, describing the geomettical distribution of the decay products in probabalistic terms.

If measuring these parameters is an experimental challenge met by the LHCb experiment [1], the theoretical computation is also difficult. If the weak-interaction part can be computed quite easily and potential high-energy new physics contributions can be parametrised in a general way, there are also contributions from the strong interaction binding the b- and s-quarks into the observed B and K* mesons. Those contributions are encoded into seven so-called ``form factors'' parametrising our ignorance of strong-interaction dynamics. In some specific kinematic regimes, where the K* meson carries either a very limited recoil energy or almost the whole available energy, it is however possible to related these form factors and to build interesting observables out of the angular coefficients. Indeed, these observables exhibit a limited sensitivity to the strong-interaction contributions and they are particularly well designed to single out the electroweak part as well as potential new physics contributions.

Researchers from LPT together with theory colleagues from Universitat Autonoma de Barcelona (Catalunya) have built such observables in the case where the K* exhibits a large-recoil energy, predicting their values in the Standard Model showing the potential of these observables to determine hints of new physics [2]. In 2013, the LHCb experiment announced a significant deviation from these SM predictions for some (combinations of) B->K* mu mu angular observables. These results combined with data on other radiative processes were given a consistent interpretation by the same team of theorists as a shift compared to the Standard Model expectations for the short-distance part of radiative transitions [3]. These findings were confirmed by other groups of theorists performing global analyses of radiative decays [4], and LHCb has announced recently other deviations in related radiative decays such as B->K mu mu [5] and confirmed the results for B->K* mu mu [6].



Two observables based on the angular distribution of B->K* mu mu, as a function of the mu-mu invariant mass q^2. The blue curve corresponds to the Standard Model prediction, the purple box to the same predictions integrated over the corresponding q^2 range, and the crosses are the LHCb measurements. In both cases, there is a significant disagreement between measurements and Standard Model predictions.

Even though these results are intriguing, they are still under intense discussion, in particular concerning two issues. First, what is the exact role of resonances that may occur as intermediate states before decaying into a mu+ mu- pair ? The question is whether they can generate contributions that mimic or dilute the contributions from New Physics. Second, are there theories beyond the Standard Model able to reproduce the pattern of shifts observed in b->s mu mu transitions ? For the moment, an additional Z' boson seems the most likely candidate to explain the latter [7]. Its direct production and its effect on low-energy observables are currently studied both experimentally and theoretically. These topics are currently generating a lot of scientific activity around these rare decays and the new physics that they could hint at.

[1] « Implications of LHCb measurements and future prospects », LHCb Collaboration, arXiv:1208.3355 [hep-ex], Eur.Phys.J. C73 (2013) 2373.

[2] « Implications from clean observables for the binned analysis of B -> K* $\mu^+ \mu^-$ at large recoil », S. Descotes-Genon, J. Matias, M. Ramon, J. Virto. arXiv:1207.2753 [hep-ph], JHEP 1301 (2013) 048; « Optimizing the basis of B -> K* $e^+ e^-$ observables in the full kinematic range », S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, arXiv:1303.5794 [hep-ph], JHEP 1305 (2013) 137.

[3] « Measurement of Form-Factor-Independent Observables in the Decay B^0 -> K^{*0} $\mu^+ \mu^-$ », LHCb Collaboration, Phys. Rev. Lett. 111, 191801 (2013) [arXiv:1308.1707 [hep-ex]]; « Understanding the B -> K* $\mu^+ \mu^-$ Anomaly», S. Descotes-Genon, J. Matias, J. Virto. arXiv:1307.5683 [hep-ph], Phys.Rev. D88 (2013) 7, 074002.

[4] « New physics in B -> K* μ μ » , W. Altmannshofer and D. M. Straub. arXiv:1308.1501 [hep-ph], Eur.Phys.J. C73 (2013) 2646; « Comprehensive Bayesian analysis of rare (semi)leptonic and radiative B decays », F. Beaujean, Ch. Bobeth, D. van Dyk. arXiv:1310.2478 [hep-ph]. Eur.Phys.J. C74 (2014) 2897.

[5] « Differential branching fractions and isospin asymmetries of B -> K* $\mu^+ \mu^-$ decays », LHCb Collaboration (R. Aaij et al.). arXiv:1403.8044 [hep-ex], JHEP 1406 (2014) 133.

[6] "Angular analysis of the B^0 -> K^{*0} $\mu^+ \mu^-$ decay," LHCb Collaboration [LHCb Collaboration],LHCb-CONF-2015-002, CERN-LHCb-CONF-2015-002.

[7] « 331 models facing new b -> s $\mu^+ \mu^-$ data », A. J. Buras, F. De Fazio, J. Girrbach, arXiv:1311.6729 [hep-ph], JHEP 1402 (2014) 112; « An explicit Z'-boson explanation of the B -> K* $\mu^+ \mu^-$ anomaly », R. Gauld, F. Goertz, U. Haisch. arXiv:1310.1082 [hep-ph]. JHEP 1401 (2014) 069.

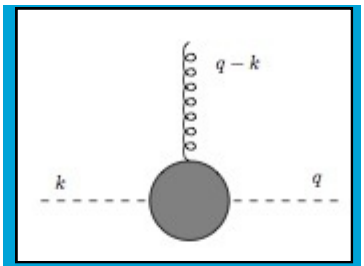
PLAYING DICE TO COMPUTE THE FORCE AMONG QUARKS

Quantify the Higgs boson production and stabilize the Universe

The Nobel prize in physics 2013 was awarded to François Englert and Peter Higgs in recognition of their prediction that a Goldstone boson was at the origin of masses of other fundamental particles, through the spontaneous breaking of electroweak symmetry. It was an appealing explanation of the short range behaviour of the weak interaction. 50 years after that theoretical work was performed, an experimental confirmation took place at LHC [1], [2], thanks to a huge effort by the world-wide community of particle physicists, both theorists and experimentalists, as well as engineer and technical staff. Probing new physics effects is nowadays a research topic of key importance in high energy physics. The direct search consists in detecting new particles, typically at the electroweak scale, but low energy processes are also quite attractive because they offer a complementary set of constraints, either on new couplings or on properties of new particles in quantum fluctuations. Higgs boson physics and the determination of its couplings to other particles is also a living activity; as the main production channel is gluon-gluon fusion, the uncertainty on the strong coupling constant, one of the parameters of the Standard Model, propagates to Higgs boson branching fractions. It has also be stressed that, in a scenario without any new physics up to the Planck scale, the electroweak vacuum might be metastable, with a decay time through quantum tunnelling smaller than the age of the Universe if the Higgs mass was smaller, or stable up to the Planck scale if the strong coupling constant (measuring the strength of one of the four fundamental interaction in the Universe, see the figure 1) was 3σ above its central value [3]. A lot of determinations of α_s have been proposed in the literature, one of the most elegant one is based on numerical simulations.

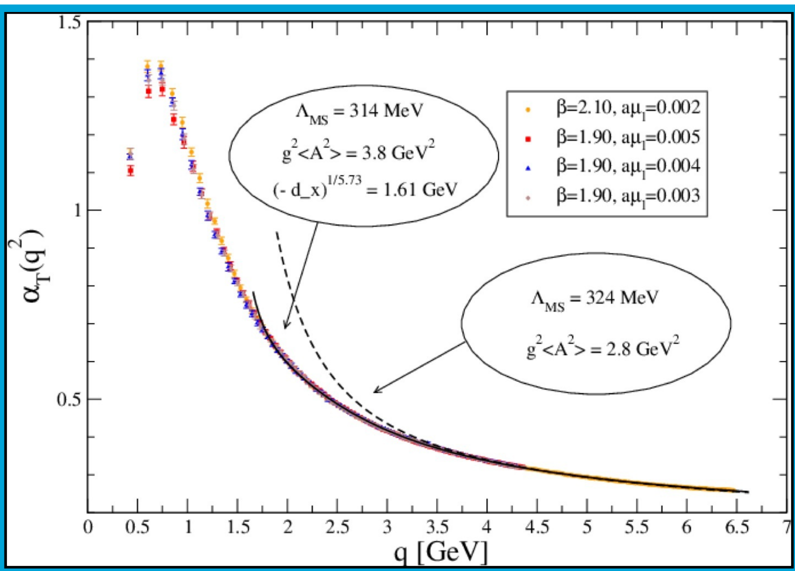
An ab-initio measurement of the strong coupling constant

The most important property of the strong interaction is the confinement of quarks and gluons in hadrons. It means that one does not observe directly the fundamental particles in experiments, but rather bound states of them. The running strong coupling constant increases at large distance, making unreliable any perturbative computations at low energy scale. A numerical approach has been followed since 40 years and it is based on first principles of quantum field theories that one applies to Quantum Chromodynamics (QCD): lattice QCD. One calculates in a finite



The strong coupling constant is extracted by computing numerically the ghost-ghost-gluon 3-pt correlator.

volume of discretized Euclidean space time correlation functions by a Monte Carlo sampling over quark and gluon fields, whose the measure is given by the Boltzmann weight of the Euclidean QCD action. Our lattice set-up includes the vacuum polarization effects of the *u*, *d*, *s* quarks and, for the first time, of the *c* quark [4]. After a gauge fixing in the Landau gauge, we have estimated the so-called "ghost-ghost-gluon" vertex in a particular kinematical configuration of in-going and out-going momenta of the fields, which sets the scale of the renormalized α_s in the Taylor scheme. We let vary that scale and perform a fit of the curve that we obtain, using the Operator Product Expansion (OPE) formalism. Taking care of power corrections and removing the lattice spacing cut-off effects, we can apply the running up to the scale M_Z, commonly used by phenomenologists. We can also run down to the scale m_τ in order to compare with computations through $\tau \rightarrow$ hadrons decay.

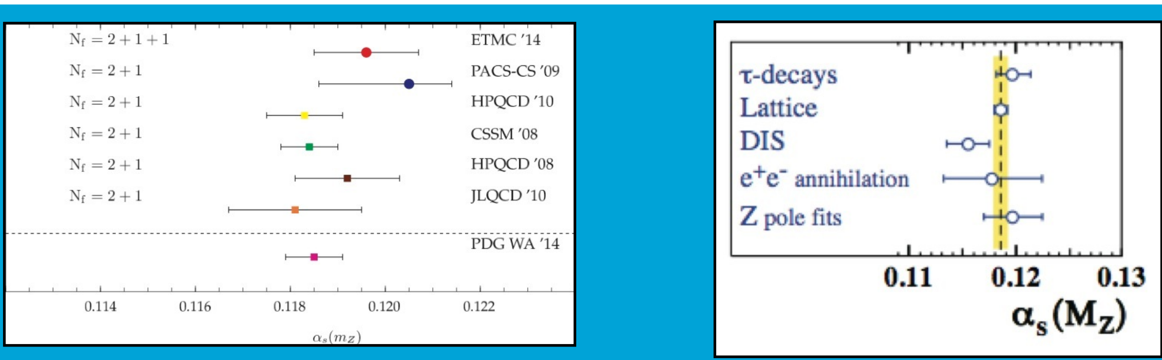


Renormalized alpha_s(Q) in the so-called Taylor renormalization scheme at the scale after a removal of lattice spacing artifacts; the solid (dashed) curves are fitted to the perturbative running up to the first (second) power correction in the OPE formalism. Raw data correspond to numerical simulations with different sea quark masses and lattice spacings.

Some other determinations of α_s

Comparing deep inelastic scattering data with QCD predictions is a common approach to access to $\alpha_s(Q)$, where Q is the 4-momentum exchanged between the target and the probe. Analyses of event shapes and jet physics in $e^+ e^-$ collisions have also been performed since long, though with a large systematics coming from the delicate modelling in Monte Carlo simulations of the fragmentation of hadrons in jets. τ decay provides a further source of data used by phenomenologists to compute the strong coupling constant in the OPE framework. The lattice QCD community has proposed different strategies as well: measure Wilson loops of short distance or moments of charmonium 2-pt correlation functions and compare to perturbation theory, study the hadronic vacuum polarization tensor by OPE, integrate numerically the β function of a finite-volume renormalization scheme at discrete points until reaching the perturbative regime or extract the strong coupling constant from a 3-gluon correlation function.

An exhaustive review of those computations is available in Chapter 3 of [5]. The numerical simulation estimates are much more precise than all the other ones and it will be probably tough to reduce much below the % level the error. It seems legitimate to us to take the spread over lattice values delta α_s^{latt} = +/- 0.002 as the theoretical uncertainty $\Delta\ \alpha_s^{th}$ on the Higgs boson production from gluon-gluon fusion.



Collection of lattice results and Particle Data Group average of $\alpha_S(M_Z)$ and partial averages on performed by PDG within each approach, including deep inelastic scattering, collisions and τ decay.

[1] « Observation of a new particle in the search of the Standard Model Higgs boson with the ATLAS detector at the LHC » by the ATLAS Collaboration, Phys. Lett. B 716, 1 (2012): http://arxiv.org/abs/1207.7214

[2] « Observation of a new boson at a mass of 125 GeV » by the CMS Collaboration, Phys. Lett. B 716, 30 (2012); http://arxiv.org/abs/1207.7235

[3] « Vacuum Stability and the Higgs boson » by J. Espinosa: http://arxiv.org/abs/1311.1970

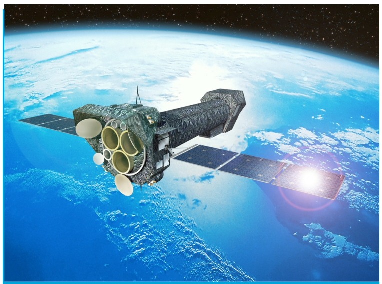
[4] « High statistics determination of the strong coupling constant in Taylor scheme and its OPE Wilson coefficient from lattice QCD with a dynamical charm » by B. Blossier, Ph. Boucaud, M. Brinet, F. De Soto, V. Morénas, O. Pène, K. Petrov, J. Rodriguez-Quintero, Phys. Rev. D 89, 014507 (2014); http://arxiv.org/abs/1310.3763

[5] « On the first principles determination of the Standard Model parameters in the quark sector » by B. Blossier : http://arxiv.org/abs/1405.0005

OBSERVATION OF A LIGHT DARK MATTER SIGNAL?

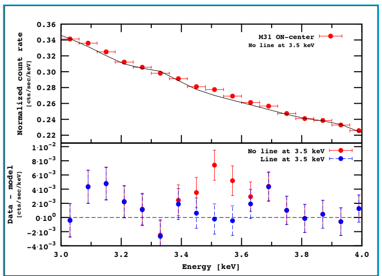
The fact: observation

In February 2014, the authors of [1] and [2] analyzed data of the European satellite XMM-Newton. These studies were based on the X-rays observation of the spectrum emitted by clusters of galaxies like Perseus or nearby dwarf galaxies as Andromeda (M31). These clusters are some of the more massive objects in the Universe and contain thousands of galaxies of the Milky Way type. Perseus is at a distance of 240 millions light years and is immersed in a giant cloud of gaz of millions degrees, emitting radiation of the order of keV[1] (kilo-electronVolt) corresponding to X-rays frequencies. This range of frequencies is precisely the one observed by satellites like Chandra (NASA) or XMM-Newton (ESA), both launched in 1999.



The satellite XMM Newton (X-ray Multi-Mirror) was launched by the European Space Agency in 1999. It gives a cartography of the sky between 0.1 and 12 keV.

The results of these analyses surprised the astrophysics and nuclear community. Indeed, the spectrum has some unexplained features, an excess under the form of a « peak » (at more than 99.9% of confidence level) for photons of energy around 3.5 keV (see figure on the right). This signal corresponds to a flux of one photon per meter square and per second. Several articles then appeared trying to find a coherent explanation to this phenomena. Until now, not a single astrophysical source can justify such an excess of photons at this energy.



Photon spectrum (number of photons as function of their energy in keV) emitted by Andromeda galaxy (M31) in the X-rays frequencies, and observed by XMM-Newton [2]. In the lower plot, the blue dots correspond to the values predicted by astrophysical model without dark matter component, the red ones are the values observed by XMM-Newton. We clearly see an excess of red points around 3.5 keV.

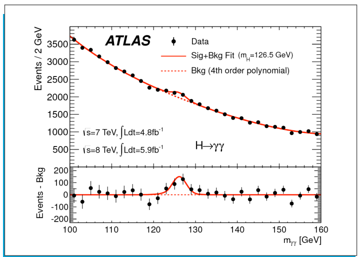
The interpretation: a dark matter candidate?

The galaxies and clusters of galaxies are very well studied objects in astrophysics, and more precisely in the field of astroparticle. Indeed, these massive objects are considered as being the main place to look for the dark matter in the Universe. The visible light that we observe, emitted by stars or interstellar gaz, represents only 10% of such structures. The dark

[1] The electronvolt is a typical unit of mass and energy in particle physics. One electronvolt corresponds to the energy acquired by an electron accelerated under a potential of one volt. A proton travelling at 300 km/s (typical velocity in our galaxies) possess a 1 keV kinetic energy.

matter (that we call χ of mass M_χ) interacts only very weakly with gaz or compact objects like stars or pulsars. Its detection is by observing indirect processes through its auto-annihilation where two particles collide, or its decay if it is unstable. The main effect of such interactions is the emission of photons with an energy of the order of the dark matter mass (energy conservation). Moreover, if the annihilation occurs directly without intermediate state, the energy $E\gamma$ of the photon is monochromatic and thus has a well defined energy $E\gamma = M_\chi$. This produce a spectrum with a peak, of the same nature than the one observed by XMM-Newton.

Recently, researchers from the LPT Orsay and Ecole Polytechnique proposed a scenario [3] where a relatively light dark matter could be the source of such a signal. During their trajectories in the cluster of galaxies, there exists a non-null probability that two particles of dark matter collide (see the frame below). In this case, as a results, two mono-energetic photons of opposite directions are produced: one travelling toward our solar system and the satellite, whereas the other one escaped from the cluster. The researchers computed the probability for such an event to occur corresponding to the signal observed (a « cross section » σv). They obtained[2] $\sigma v = 10^{-37}\ cm^2\ s^{-1}$. They then showed that this interaction rate is quite natural in the framework of motivated theoretical buildings where the dark matter interacts via the exchange of a second Higgs boson (ϕ) much lighter than the one discovered at the LHC in July 2012 (h) : $M_\phi = 1$ MeV (M_h=125 000 MeV). Moreover, this second Higgs boson is also predicted in order to explain large scale structures formation, solar anomalies, or the shape of the dark matter profiles near galactic centers. The decay of this intermediate boson in two photons : $\chi\ \chi \to \phi \to \gamma\ \gamma$ is by chance the same process which gave the opportunity to discover the standard Higgs boson at CERN through its decay $h \to \gamma\ \gamma$, generating a similar peak in the spectrum of LHC detectors (see figure on the right).



Photon spectrum of the Higgs boson discovery in 2012 at CERN. Notice the similarities with the spectrum observed by XMM-Newton (figure in the preceding page) justifying naturally the presence of a second lighter Higgs boson.

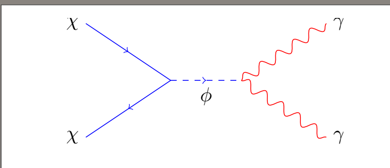
Alternatives

The signal has not yet any pure astrophysical explanation. On the other hand, other candidates have been proposed by Japanese [4] and American [5] team. In the first case, the authors proposed an unstable dark matter candidate, coupling very weakly to the neutrino, a standard model particle almost massless. If the coupling is sufficiently weak, the dark matter can have a lifetime of the order of 10^{28} seconds, much more than the age of the Universe, but decaying slowly into photon and neutrino (see frame). The other possibility developed in [5], is the presence of an excited state of the dark matter, as it exists in nuclear physics. During the process of desexcitation, there would be emission of a mono-energetic photon of 3.5 keV, the one observed by XMM-Newton.

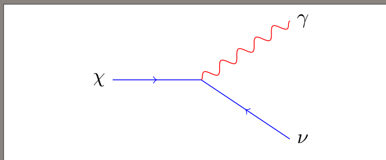
[2] This corresponds to a collision every 10^{28} seconds, largely compensated by the huge number of dark matter particles in the clusters of galaxies.

It is also interesting to notice that all the candidates proposed belong to a family of dark matter called « warm dark matter », by opposition to « cold dark matter » or « hot dark matter ». Indeed, keV particles are relatively light[3] and their ratio kinetic energy / mass is quite high. They are thus « warm ». This characteristic can explain the small number of satellite galaxies around the Milky Way, because the kinetic energy of the dark matter would forbid the formation of too large structures; this is the « free-streaming » mechanism: a too hot dark matter candidate would inferred the formation of our own galaxy, whereas a too cold dark matter would have allowed the creation of hundreds of galaxies around us that have not been observed[4]. In any case, this signal open a new way of research and gives interest to light dark matter models which will be very promising in the next few years.

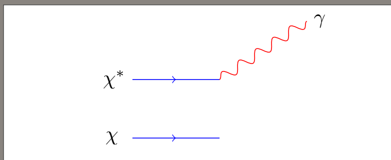
Annihilating, decaying or exciting dark matter?



Annihilation [3]



Désintégration [4]



Désexcitation [5]

Following the discovery of the anormal signal emitted by clusters of galaxies, several dark matter scenarios has been proposed by the authors of [4,5,6]. The dark matter χ could annihilate in the clusters of galaxies after several collisions. They would produce a light Higgs boson ϕ which would decay into two photons γ (left). Another possibility is that the dark matter is not completely stable but possesses a lifetime longer than the age of the Universe, giving us an illusion of stability. Its decay into photon γ and neutrino ν would be the source of the signal observed by XMM-Newton (middle). A third possibility would be that the dark matter exist under two states: one stable, χ and the other excited χ*, as it exists in the radioactive element families on earth (right). The photon emitted during the desexcitation of the dark matter would be the one precisely observed by the satellite.

[1] « Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters » by E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall; http://arxiv.org/abs/1402.2301

[2] « An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster » by A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse; http://arxiv.org/abs/1402.4119

[3] « Generating X-ray lines from annihilating dark matter » by E. Dudas, L. Heurtier and Y. Mambrini

[4] « 7 keV sterile neutrino dark matter from split flavor mechanism » by H. Ishida, K.S. Jeong, F. Takahashi; http://arxiv.org/abs/arXiv:1402.5837

[5] « An X-Ray Line from eXciting Dark Matter » by D. P. Finkbeiner and N. Weiner; http://arxiv.org/abs/1402.6671

[3] Compared to the Higgs boson, 100 000 times heavier.

[4] The Milky Way is surrounded by only 20 nearby galaxies.

PRECISION CONSTRAINTS ON NEW PHYSICS

Current status

The current theory of fundamental interactions is called the Standard Model. It specifies the list of elementary particles, all of which have been observed in experiment. However, we strongly suspect that this list is not complete, and that there are more elementary particles to be found in nature. The main goal of the Large Hadron Collider (LHC) constructed at CERN in Geneva is precisely to find new particles from beyond the Standard Model. The strategy is to smash together very energetic protons and then look for traces of new particles created out of the collision's energy. This is the most direct and robust method, but it may not be the best one. Indeed, further progress along this road will not be easy. The LHC is already a colossal enterprise, with a 27 km long tunnel and more than 1000 superconducting magnets to accelerate protons. This allows us to search for new particles with masses up to several teraelectronvolts (TeV)[5]. Further increasing the collision energy will require an even longer tunnel and/or even more powerful magnets. This will eventually happen, but the process may be painstakingly slow.

Fortunately, there is another way that may be taken in parallel. It is referred to, very broadly, as precision measurements. The point is that the Standard Model allows us to make very precise calculations of physical quantities. How precise? One impressive example is the magnetic moment of the muon, predicted with the precision of 12 digits and experimentally measured with a similar accuracy. This example is exceptional, but there are literally thousands of observables that can be precisely predicted and accurately measured. These calculations depend on the masses and couplings of the Standard Model particles, even the relatively heavy ones. The reason is that, in a quantum theory, all particles are spontaneously created (and very quickly annihilated) from a vacuum, as a consequence of the Heisenberg uncertainty principle. That virtual presence affects the properties of matter in a observable and measurable way. New particles from beyond the Standard Model must obey the same rules. Even if we cannot produces them directly in a collider (because they are too massive), they should still be popping up from the vacuum and affect our precision observables. Thus, by accurately measuring processes involving the familiar Standard Model particles, we may actually discover new particles and new interactions!

[5] In particle physics mass or energy are typically expressed using electronvolts (eV) in a unit system where c =1. Then, 1 TeV=10^{12} eV = 1.8 10^{24} kg. For comparison, the mass of the top quark (the heaviest particle of the Standard Model) is 0.173 TeV.

This is not just a wishful thinking. We have many example from the past where the presence of heavy particles had been indirectly inferred from precision observables well before they could be directly produced in colliders. The most recent example of this kind is the Higgs boson. Its discovery in 2012 at CERN was a huge event and a reason for celebration, but it was hardly a surprise. That's because the existence of the Higgs boson affects in an observable way various electroweak precision observables, such as the ratio of the W boson and the Z boson masses. That ratio is not a free parameter in the Standard Model: it can be currently predicted up to 4 digits as a function of the Higgs boson mass. From measurements of the W and Z boson masses and other electroweak precision observables we had known, before the LHC started operation, that the Higgs boson mass m_h should be in the range 0.039 TeV < m_h < 0.155 TeV at 95% confidence level [1]. We also knew from direct searches performed in the 90s in the LEP collider at CERN that mh > 0.1144 TeV [2]. That didn't leave much room for the Higgs to hide. And indeed, the mass of the Higgs boson measured by the LHC experimental collaborations turns out to be m_h = (0.12509 +/- 0.00024) TeV [3], in good agreement with the indirect determination from electroweak precision observables.

Going beyond

Can we pull another trick like that again? We already know all particles of the Standard Model and their masses. This way, we can predict any electroweak precision observable without free parameters (up to an uncertainty regarding the Standard Model parameters, which is currently dominated by the fact that the precision of the top quark mass measurement is « only » 0.5%. Therefore, if we find deviations of these observables from the Standard Model predictions, we will be able to infer the presence of new particles from beyond the Standard Model. Recently A. Falkowski has been working on this issue with collaborators from EPFL Lausanne in Switzerland [4] and from Weizmann Institute in Israel [5]. New heavy particles could effectively lead to new interactions between the SM particles that are not present in the SM. This could be, for example, interactions between 2 Higgs fields H and 2 fermion fields f (in the literature denoted as $\mathbf{O_{Hf}}$ where f can be electrons e, up quarks u, etc.) that change the coupling strength of the Z boson to leptons and quarks. Or it could be a new interaction between 4 Higgs fields ($\mathbf{O_T}$) that changes the ratio of the Z and W boson masses; or else a new interaction between 2 Higgs fields and 2 vector fields ($\mathbf{O_{WB}}$) that leads to a mixing between the Z boson and the photon. Signatures of these interactions have been searched for in electroweak precision observables, with negative results so far. Therefore, currently, we can only constrain new physics. In other words, given a set of assumptions, we can conclude that the new particles must be heavier than a certain mass scale.

One way to represent these constraints is to give the lower limits on the mass scale suppressing the interactions $\mathbf{O_{WB}}$, $\mathbf{O_T}$ and $\mathbf{O_{Hf}}$. The results are illustrated in the figure below. Interpretation of these results is model-dependent but, roughly speaking, the lower limit on can be interpreted as a lower limit on the mass of new particles interacting with the SM fields with a typical coupling strength. One should appreciate the fact that electroweak precision observables indirectly probe new physics at the scale of order 10 TeV, well beyond the direct reach of the LHC! In Refs. [4, 5]

we performed a comprehensive analysis of these constraints. In particular, for the first time, we studied the case where all possible effective interactions summarized in $\mathbf{O_{WB}}$, $\mathbf{O_T}$ and $\mathbf{O_{Hf}}$ can be present simultaneously.

Apart from the electroweak observables, there are many more precision observables that can indirectly probe new physics well beyond the energy scale accessible at the LHC. These include flavor and CP violating transitions, anomalous magnetic and electric moments of the electron and other particles, parity violation in atomic transitions, etc. Given the challenges involved in constructing new high-energy colliders, the importance of precision experiments will only increase. This will also promote synergy between particle physics and other domains of physics, such as atomic physics, laser physics, condensed matter physics, nuclear physics, etc. It is perfectly possible that, in the coming years, one of the precision experiments will conclusively measure a deviation from the Standard Model predictions.

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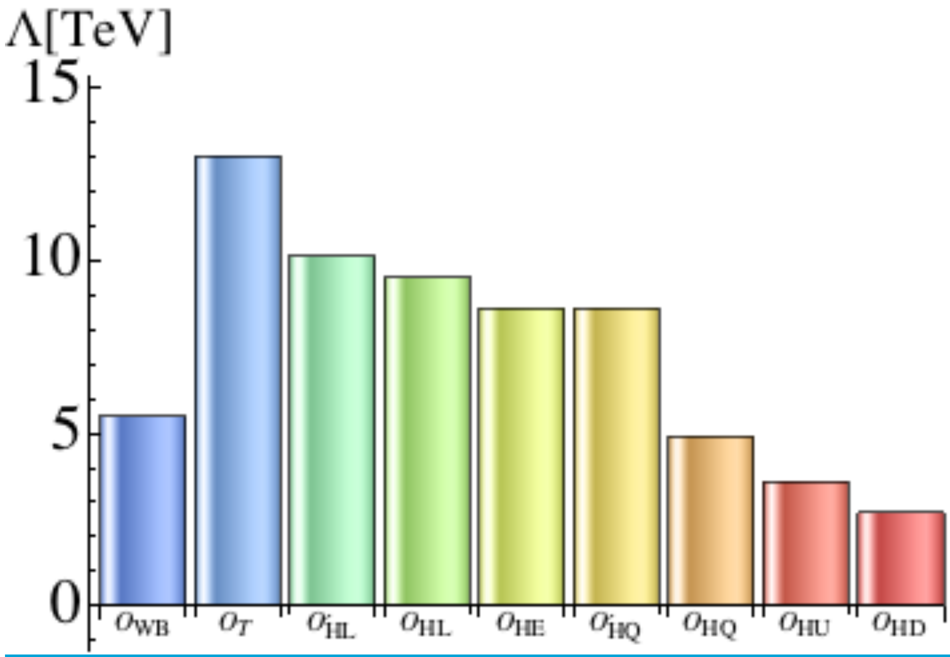

Lower limits on the scale suppressing various effective interactions that could be induced at low energies by new heavy particles. These limits assume that only one of these interactions is present at a time. See Ref. [5] for a precise definition of these interactions and limits in a more general situation when all these interactions are present simultaneously.

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