Jonathan Feng – Lecture 2 Questions

Questions marked in green were answered during the Q&A session. No attempt was made to correct grammar/spelling issues. Where a slide number was given it is shown.

Q1 (slide 26, lecture 1): In slide 26 of your talk you mentioned about dark photon as one of the possible ways of having a vector portal. My question is , is this the only gauge invariant way to have a vector portal ? I ask because in most of the literature on simplified DM models, this issue about gauge invariance is not emphasized. Another question is that the fermion loop which gets integrated out to give the mixed kinetic term must come from a field which talks to the photon in SM. Then should it not also couple to Z boson (due to gauge invariance) and give a mixing of the dark photon and Z ?

The first part was answered in the Q&A session: yes, the U(1) vector portal is special. There no gauge-invariant, renormalizable coupling of, say, an SU(2) dark gauge boson to the SM. Regarding the 2nd question, in detail, you are certainly right: the dark photon mixes with the hypercharge gauge boson, and so it has mixings with both the photon and the Z boson. Typically the mixing with the Z boson is suppressed by something like (m_A/m_Z)^4, and so this is really small for m_A ~ 100 MeV, but for heavier m_A, it can be significant.

Q2 (slide 32): Is there any difference between sterile neutrinos and HNLs?

Not really: dark fermions, sterile neutrinos, and HNLs are all names for the same gauge-singlet fields.. But typically sterile neutrinos are thought to be light, say, eV or keV, whereas HNLs are the name usually given to MeV to GeV mass range.

Q3: Is dark photon the only gauge invariant way in which we can have what we call usually the vector portal models in simplified DM model literature ? I ask because generally the gauge invariance issue with the simplified models is not emphasized in literature.

See the answers to the last questions in the Q&A for lecture 1.

Q4 (slide 34): What's the reason the electron g-2 excludes stuff from the parameter space?

Just as the dark photon can contribute to g-2 of the muon, it can contribute to g-2 of the electron through the exact same Feynman diagram, with mu -> e. If this contribution to g-2 of the electron is too big, it is excluded.

Q5 (slide 36): Why would we only get this 17 MeV particle at particular opening angles?

The opening angle can actually range from some minimal angle to 180 degrees (back-to-back). But it turns out that the distribution is highly peaked at the minimal opening angle. This can be understood very geometrically -- it turns out to be the same reason that there is a lot more area of the earth between 10 north and 10 south latitude than there is between 70 north and the north pole. See 2006.01151 for a detailed discussion.

Q6 (question related to HW problem): The mixing matrix between photon and dark photon is not orthogonal, and would result in a non-zero Jacobian. Will this affect the computations? Because we usually consider orthogonal/unitary transformations.

Yes, the transformation is not orthogonal or unitary, which is not something we encounter typically. But it is required to keep the kinetic terms canonically normalized, and once they are, all our typical calculations, for example, Feynman diagram calculations, can be done as usual.

Q7 (slide 36): Are there arguments against self-interacting dark matter (and in favor of CDM)? Why is the latter the one people usually talk about?

There are no strong data-driven reasons to prefer CDM. The main reason is that in many of the old classic physics models of DM, the DM turns out to be effectively collisionless, and also aesthetic: if the DM self-interaction could be anything, why should it be in the cm^2/g range, when there is a huge range above that is excluded, and an huge range below where it is effectively collisionless. The rise of dark sectors, though, has made the collisionful DM matter much more "generic" though.

Q8 (slide 36): Even if the interactions are completely mediated by the dark sector (as with the dark photon), how do we know that, say, the dark photon won't interact with SM particles?

One can see this by doing the homework: the required redefinition of the fields is such that the physical dark photon is just a rescaled version of the U(1) dark gauge boson, and so it never pick sup a coupling to SM particles.

Q9 (slide 36): How does self-interaction of Dark Matter cause the cusp to disappear ?

Heuristically, one can understand it as follows: when the DM density gets too big and it has large self-interactions, DM particles are effectively knocked out of the region of high density, which smooths out the cusps and makes the halo profiles cored.

Q10 (slide 38): Does this mean that we have to find another dark sector explanation for Muon g-2 that doesn't involved dark photons?

Yes, dark photons are excluded as an explanation, but other light vector gauge bosons can work, including the protophobic gauge boson, and L_mu-L-tau gauge bosons.

Q11 (slide 38): What causes the wiggles in the thermal target band?

The wiggles are caused when new annihilation channels open up or by resonances. For example, when mX is less than the muon mass, the X's can only annihilate to electrons, but when mX > m_muon, that is, when m_A' = 1.5 mX > 150 MeV, the muon channel opens, and so one sees a downward wiggle there.

Q12 (slide 38): Are the ATOMKI anomalies then not able to be explained by a dark photon (since the part of the parameter space where they interact with the red band has already been ruled out)?

Yes, the ATOMKI anomalies can't be explained by a dark photon, but they can be explained by a protophobic gauge boson, which doesn't couple to protons, and is also not produced much in pion decays, thus avoiding many of the bounds.

Q13 (slide 42): Can you please explain again that why there are spikes in the constraint plot? You said they are bump hunt scenarios, but for CMS/ATLAS also there are bump hunt analysis but we never get such spikes. Therefore, didn't understand why we are getting them at low energy experiments

I'm not sure what CMS/ATLAS analyses you are referring to, but probably it is simply a function of detector energy and angular resolution.

Q14 (slide 47): Can you explain the shapes of parameter space covered by these experiments? Different experiments have similar shapes, suggesting that they are not due to detector design but physics driven?

This seems to be the same question as Q15. There are cusps and dips caused by resonances. For example, at a resonance where the dark Higgs boson mixes with a SM particle, there is a resonant enhancement of the decay. To keep the decay length the same, then, at these resonance points, the coupling sin^2 theta must drop to compensate the kinematic enhancement, leading to a drop in the (mass, coupling) plane.

Q15 (slide 47): Why do so many of the proposed experiments have that cusp in sensitivity at around 1 GeV?

This is from mixing with the known SM resonances. These lead to enhanced decays, and so to compensate to keep the decay length constant, the coupling has to drop.

Q16 (slide 50): why are higher neutrinos preferentially produced in the forward direction?

Most neutrinos come from charged pion decay. Charged pions are produced most typically with transverse momentum p_T ~ a few 100 MeV. So if you want to have a very high energy charged pion (and high energy neutrino), you need to find ones that have very large longitudinal momentum p_L, and since p_T is constrained to be a few 100 MeV, this means they are produced in the far forward direction.

Q17 (slide 51): Why are there two FASER lines in each of the plots (filled in below and w/ error bars above)

The histograms at the bottom of these plots show the energy distribution of the detected neutrino scattering events. So they are event numbers. The points with error bars above show the resulting constraints one can set on the neutrino interaction cross section. So when the histogram has a maximum, the statistics are high, and the error bars are small. For more information about these plots, see https://arxiv.org/pdf/2001.03073.pdf.

Q18 (slide 51): Can faser also help to look for BSM in neutrinos like sterile neutrinos?

Yes, FASER can look for oscillations into sterile neutrinos, but the mass range it is most sensitive to is ~ 40 eV, which is not indicated by anything else so far. LSND and other anomalies indicate 1 eV, and sterile neutrino dark matter is keV, and there is a 3.5 keV line. But, of course, we know very little about sterile neutrinos, and so 40 eV is possible, and FASERnu would see something if this is the case. See 1908.02310, section VII.C.