Neutrino Phenomenology

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KPS Pioneer symposium on sterile neutrinos and the JSNS2 experiment October 27, 2017 2017 KPS Fall Meeting Gyeongju, Korea

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The big questions

- Are neutrinos Majorana?
- δ_{CP}
- Mass hierarchy
- $\theta_{23} = \pi/4?$
- Resolution of LSND and the other short-baseline anomalies
- New physics (on top of neutrino mass)?

Status quo

A common framework for all the neutrino data[†] is oscillation of three active neutrinos

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5} \,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m_{31}^2 \sim 2 \cdot 10^{-3} \,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2 \cdot 10^{-3} \,\mathrm{eV}^2} \sim 0.04 \,\mathrm{eV}$$

[†] apart from short-baseline anomalies

Mixing matrices

Quarks

$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrinos

$$|U_{\nu}| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.



The Nobel Prize in Physics 2015 Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015



Photo: A. Mahmoud Takaaki Kajita Prize share: 1/2



Photo: A. Mahmoud Arthur B. McDonald Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

We always knew they are ...

The SM, likely, is an effective field theory, *i.e.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + rac{1}{\Lambda}\mathcal{L}_5 + rac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda} (LH)(LH) \to \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_{\nu} \nu \nu$$

Weinberg

Effective theories

The problem in effective theories is, that there are *a priori* unknown pre-factors for each operator

$$\mathcal{L}_{SM} + \frac{\#}{\Lambda} \mathcal{L}_5 + \frac{\#}{\Lambda^2} \mathcal{L}_6 + \dots$$

Typically, one has $\# = \mathcal{O}(1)$, but there may be reasons for this being wrong.

Therefore, we do not know the scale of new physics responsible for neutrino masses – anywhere from keV to the Planck scale is possible.

Neutrino masses are different

The crucial difference between neutrinos and other fermions is the possibility of a Majorana mass term

 $m_L \bar{\psi}_L \psi_R^C + m_R \bar{\psi}_R \psi_L^C$

on top of the usual Dirac mass term

 $m_D \bar{\psi}_L \psi_R$

Neutrino mass determination

Finding the scale Λ of neutrino mass generation rests crucially on knowing

- Dirac vs Majorana mass
- Absolute size of mass

All direct experimental techniques for mass determination rely on ν_e , which is mostly made up of m_1 and m_2 .

Mass hierarchy

Literature survey arXiv:1307.5487



Many experiments are expected to have a result at or above 3σ within a decade from now.

First hints for non-maximal θ_{23}



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CP violation

There are only very few parameters in the ν SM which can violate CP

- CKM phase measured to be $\gamma \simeq 70^\circ$
- θ of the QCD vacuum measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe...

First hints for CP violation?



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Unitarity triangles



We currently have no way to directly measure any of sides containing ν_{τ} .

What did we learn from that?

Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.



- CKM describes all flavor effects
- SM baryogenesis difficult
- New Physics at a TeV
 - does not exist or
 - has a special flavor structure

and a vast number of parameter and model space excluded.

Non-standard interactions

NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_f \epsilon^{fP}_{\alpha\beta} (\bar{\nu}_{\alpha}\gamma^{\rho}\nu_{\beta}) (\bar{f}\gamma_{\rho}Pf) ,$$

where f can be any fermion and P is the projection onto right and left-handed components. Wolfenstein, 1978

Impact on three flavors



Three flavor analysis are not safe from these effects!

PH, D. Vanegas, 2016 In this examp

In this example, CP conserving new physics fakes CP violation in oscillation!

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

$$dU = ds_{12}^2 \, dc_{13}^4 \, ds_{23}^2 \, d\delta_{CP} \, d\chi_1 \, d\chi_2$$

predicts flat distribution in δ_{CP}

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

$$\begin{pmatrix} \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

to still fit data, obviously corrections are needed – predictivity?

Sum rules



 3σ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

How low can you go?



PH, Bross, Palmer, 2014.

What can we learn from that?

 If we refute three flavor oscillation with significance, we have found new physics, but this requires great precision.

 If we confirm three flavor oscillation with great precision, we need the context of specific models to learn anything about BSM physics.

Corollary: Only if we do this **precisely** we really will learn something!

The way forward



Neutrino cross sections



PH, Mezzetto, Schwetz, 2007

Using current cross section uncertainties and a perfect near detector.

Differences between ν_e and ν_{μ} are significant below 1 GeV, see e.g. Day, McFarland, 2012

Nuclear effects – example



Ankowski et al., 2015

In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC \Rightarrow missing energy

Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people working on this...

Any result will be based on assumptions and not on controlled approximation.



Finding a sterile neutrino

All pieces of evidence have in common that they are less than 5σ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments, if not:

- N sterile neutrinos are the simplest explanation
- Tension with null results in disappearance remains

Due to their special nature as SM gauge singlets sterile neutrinos are strong candidates for being a portal to a hidden sector – significant experimental activity.

LSND and MiniBooNE





$P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}) \simeq 0.003$ JSNS2 will crucially test the original LSND result.

Summary

Neutrino oscillation is solid evidence for new physics

- Current data allows large corrections to three flavor. framework
- Precision measurements have the best potential to uncover even "newer" physics either by finding discrepancies or correlations among results.
- Persistent hints for light sterile neutrinos.
- If confirmed, likely portal to hidden sector.