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Neutrino phenomenology: from mass and mixing studies to Standard Model precision tests with natural and artificial sources

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Abstract

Different topics of neutrino phenomenology, on which the author has been and is still working in collaboration with various members of the Milano Physics Department and INFN Section, are discussed. The attention is focused on the recent advancements in the oscillation studies and in solar neutrino physics, and on the mass hierarchy problem and the discovery potential in this field of the JUNO experiment, that will soon start the data taking in China. At last, we also discuss the study done of the possibility to perform low energy precision tests of the Standard Model by using high intensity artificial neutrino beams, like the ones of T2K and of the future american project DUNE-LBNF.

The neutrino mass and oscillation

Neutrino physics fundamental since ever for **Elementary Particles and Astrophysics** and connection between the two.

- **Neutrinos massive and oscillating:** one of the 1st indications of the **need to go beyond the Standard Model** of e.w. interactions.
- The **Milano research group on neutrino phenomenology** took part in the derivation of this result with a series of global analyses on solar neutrinos (ν) around 2002. See e.g.: P. Aliani, V. Antonelli, R. Ferrari, M.Picariello, E. Torrente-Lujan, **PRD 67** (2003) 013006 and **PRD 69** (2004)013005 (both top cited 50+).

Solar neutrinos after 2002

- **After** the annus mirabilis **2002** new results and analyses of previous data by SNO, SuperK, Borexino and KamLAND made possible the precise **determination of mass and mixing parameters and study of solar neutrino spectrum**, to test the oscillation pattern and check the **consistency of LMA** (Large Mixing Angle) MSW **solution** of the Solar Neutrino Puzzle.
- For the **status and perspectives of solar neutrino physics** see, for instance, V. Antonelli, L. Miramonti, C. Pena-Garay and A. Serenelli, **Adv. High Energy Phys. 2013** (2013) 351926 .

Open issues: solar metallicity problem and search for upturn in ν_e survival probability

- General agreement between solar neutrino fluxes and the Standard Solar Models (SSM) predictions.
- Discrepancies between the **High Z** (**Space Sci. Rev. 85** (98) 161) and the **Low Z** (**Ann. Rev. Astron. Astroph. 47** (2009) 481) **versions of the SSM**.
  The 2nd one obtained with a more refined 3D analysis, but in worst agreement with heliosismology ⇒
  Solar Metallicity Problem (see, e.g. **JHEP 1603** (2016) 132)
- From the study of the solar neutrino spectrum: test of the oscillaton pattern **searching for the predicted upturn of the ν_e survival probability** in the transition region from the high energy zone (above 3-4 MeV, where the MSW matter interaction dominates) to the lower energy (below 1-1.5 MeV) vacuum oscillation region.

SEE LATER DISCUSSION ABOUT THIS TOPIC STUDY AT JUNO

The neutrino mass hierarchy

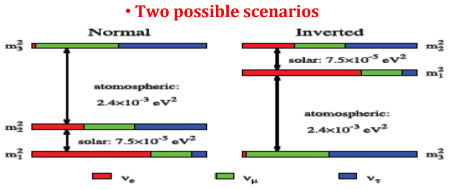
- The neutrino **absolute mass scale and its real nature** (Majorana or Dirac fermion) **still unknown but** the differences of the squared **mass eigenvalues** $\Delta m^2_{ij} = m^2_i - m^2_j$ are **known**

(e.g. **JHEP 1701**(2017)087; **PRD 95**(2017)n.9, 096014; **NPB00**(2016)1)

$\Delta m^2_{21} = (7.37 \pm 0.17) x 10^{-5} eV^2$ From solar and KamLAND

$|\Delta m^2_{31(32)}| = (2.52 \pm 0.04) x 10^{-3} eV^2$ From atmospheric and LBL

• **Two possible scenarios**



Normal Hierarchy (NH) | **Inverted Hierarchy (IH)**

NH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$, $|\Delta m^2_{31}| > |\Delta m^2_{32}|$

IH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$, $|\Delta m^2_{31}| < |\Delta m^2_{32}|$

• **Neutrino mass hierarchy is important for**
- **Discrimination** between **models** Beyond the Standard Model
- **Discovery potential** of **experiments** (0ν2β ; CP violation)

• Thanks to relatively large value of θ_{13} ($\sin^2(2\theta_{13}) \approx 0.08-0.09$)

⇓

Possible study of **oscillation probability** corrections **dependent on Mass Hierarchy (MH)** sign (proportional to $\sin^2(2\theta_{13})$) in the inverse β decay of **medium baseline reactor antineutrinos.**(Idea by Choubey Petcov e Piai, **PRD 68** (2003) 113006)

•$\bar{\nu}_e$ survival probability

$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \sin^2(2\theta_{13})\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]$$

The last term, sensitive to mass hierarchy, can be written in the form

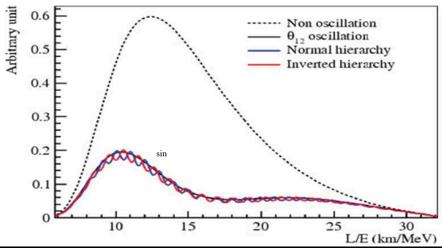
$$\frac{1}{2}\sin^2(2\theta_{13})\left[1 - \left[1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)\right]^{1/2}\cos\left(2\left|\frac{\Delta m^2_{ee}L}{4E}\right| \pm \phi\right)\right]$$

where $\Delta m^2_{ee} = \cos^2(\theta_{12})\Delta m^2_{31} + \sin^2(\theta_{12})\Delta m^2_{32}$ and sinφ and cosφ denote combinations of mass and mixing parameters of the 1-2 sector.

Sign of **φ term** depends on mass hierarchy: **+1 for NH and -1 for IH**

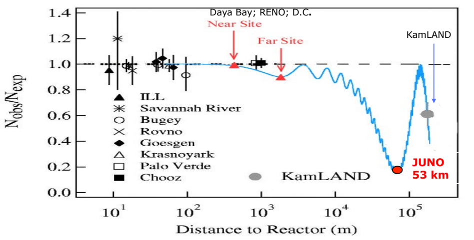
⇓

Fastly oscillating terms opposite for the two hierarchies, superimposed to the **general oscillation pattern.**



The JUNO option

JUNO (Jiangmen Underground Neutrino Observatory): **multipurpose** reactor $\bar{\nu}_e$ **experiment**, under construction near Kaiping (China) (more than 70 institution of 3 continents) . **Baseline** reactor-detector (about 53 km): **optimized in the region of maximun 1-2 oscillation**



• The **detector**, that will be operating **underground** (with about 700 m of rock overburden), is made up by **20 ktons** of **liquid scintillator** (LAB+PPO+bisMB) contained in acrylic sphere of 35.4 m of diameter, supported by a steel structure, holding 2 kinds of PMTs: Large (20") and Small (3").

• Main reaction will be the **inverse β decay. of $\bar{\nu}_e$** :

$$\bar{\nu}_e + p^+ -> n + e^+ \quad ; \ E_\nu \geq 1.8 \text{ MeV} .$$

JUNO main features

-High statistics (detector large mass and close to several reactors);
- Very good E resolution (σ(E)/√E = 3%);
-High photon yield (1200 p.e./MeV) (thanks to liquid scintillator and to PMTs);
-Reduction of cosmogenic background (rock overburden and muon veto system);
- Looking at vacuum oscillation, **it doesn't suffer** from the **uncertainties** on the **Earth density** profile **and** the ambiguity on **CP violation phase** (different from LBL experiments).

Mass hierarchy determination at JUNO

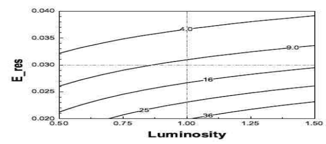
The MH sensitivity is expressed in terms of

$$\Delta\chi^2_{MH} = |\chi^2_{MIN}(NH) - \chi^2_{MIN}(IH)|$$

Mass hierarchy determination @ JUNO

See the **JUNO Yellow Book** (YB): F. An, G. An, Q. An, V. Antonelli et al, **J. Phys. G. 43** (2016) n.3, 030401

• From analysis: iso-$\Delta\chi^2$ contour lines representing $\Delta\chi^2_{MH}$ as function of E resolution and luminosity (L=1 means 6 years of data with nominal anti-ν flux and 80%efficiency)



• Possible to obtain **$\Delta\chi^2_{MH}$ at the 3-4 σ level**

Other JUNO physics goals

(**See JUNO YB or**: **V. Antonelli, L. Miramonti**, "Status and perspectives of JUNO experiment (invited talk)", **Proc.** of **Neutrino Telescopes,** Venice **2017**, in preparation)

❑ Supernova burst & diffuse **supernova neutrinos**
❑ **Geoneutrinos**; **Sterile ν** and **nucleon decay** searches
❑ **Precision** measures of **oscillation parameters** at subpercent level (thanks to statistics and E resolution)

Oscillation parameters	Present accuracy (global 1 σ)	Dominant experiment(s)	JUNO potentialities
Δm^2_{21}	2.3%	KamLAND	**0.59%**
$\Delta m^2 = \left\|m_3^2 - \frac{1}{2}(m_2^2+m_1^2)\right\|$	1.6%	MINOS, T2K	**0.44%**
$\sin^2(\theta_{12})$	4-6%	SNO	**0.67%**

❑ **Solar neutrinos at JUNO**

Advantages: Very high **statistics** (large detector mass) and energy **resolution**; **Potential problems**:
a) Underground but less than other exp. (possible **cosmogenic background); b)** Need to reduce **radioactive bckg.** at levels comparable to Borexino
• Studies of the **^{7}Be and ^{8}B contributions** to the spectrum ⇒ Possible improvement of the accuracy in **ν flux determinations**
• The solution of the **Solar Metallicity Problem** will come by a future CNO ν measurement, but a better determination of **^{7}Be and ^{8}B ν** would help to **discriminate** different **versions of Standard Solar Models**:High Z, Low Z and Low Z with modified opacity.
• **Solar ν spectrum**: check of **consistency of LMA oscillation** solution. **Search for the upturn** in the transition region (E≈3-4 MeV) between high (MSW oscillation) and low (vacuum oscillation) energies.

❑ Non Standard ν Interactions (NSI)

Search for **NSI**, that is terms **non diagonal in flavor** modifying the ν interactions with matter. NSI **predicted in models beyond SM**, like SUSY or dark matter models.
Two possible ways of searching for NSI at JUNO:
1) looking for deviations from the LMA oscillation pattern in the solar ν spectrum (upturn problem....) and
2) comparison between the values obtained for mixing parameters and the ones obtained from other future experiments (like HyperKamiokande. **Research group on this topic together with Chinese colleagues.**

Low E tests of the SM with ν beams

•High intensity frontier. Very **high intensity ν beams** available **at LBL superbeams** (like T2K) and eventually future β beams: also **tests of Standard Model at medium-low E** (≅1 GeV), zone of partial data deficit with respect to high E region, covered by colliders ⇒ test of theory stability and eventual hints of new physics.
•Low E measure of **Weinberg angle from Quasi Elastic ν-nucleon scattering** and comparison with high E value. Possible to **disentangle** the **dependence on $\sin^2\theta_W$ from** the one on the 8 **hadronic form factors** and obtain a competitive **low E** value of **$\sin^2\theta_W$ at 1% level.**
• Ideal detector LAr TPC (a few ktons; also near detector).
• Analys successfully developed for **T2K case** (see V. A., G. Battistoni, S. Forte, **NPB Proc. Suppl. 168** (2007) 192 and V. Antonelli **"Astroparticle, Part., Space phys. and Detectors for Phys. Appl., Vol. 7**, World Scientific, Oct. 2011, https://doi.org/10.1142/9789814405072_0043)
• Under investigation the possibility to extend to the case of **LNBF-DUNE** (with ICARUS and/or other LAr detector)