Neutrino Group

João Pedro Athayde Marcondes de André

IPHC, Strasbourg

03 December 2021

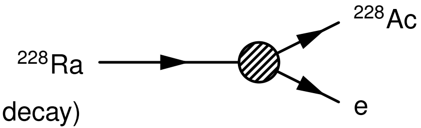
Outlook

- Intro on Neutrinos!
  - Feel free to let me know if you've already seen this stuff on lectures so I skip. . .
- Neutrinos @ IPHC

The birth of the neutrino: measuring the β spectra

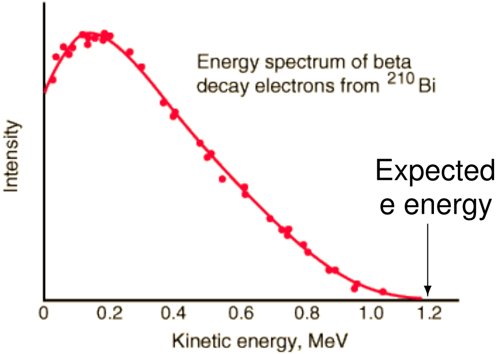
1896 Becquerel discovery of radiation

- β decay: e emission



- e observed should have known energy (2-body decay)

1914 Chadwick observed continuous electron spectra from β-decay



The birth of the neutrino: A letter from W. Pauli (1930)

W. Pauli, Phys. Today **31N9** (1978) 27.

Original – Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Grupe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetsen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsats" (1) der Statistik und den Energiesats zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

The birth of the neutrino: A letter from W. Pauli (1930)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the “wrong” statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a **desperate remedy** to save the “exchange theorem” of statistics and the law of conservation of energy. Namely, the possibility that **there could exist in the nuclei electrically neutral particles**, that I wish to call **neutrons**, which have **spin 1/2** and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that **in beta decay a neutron is emitted in addition to the electron** such that the sum of the energies of the neutron and the electron is constant. . . **I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist.** But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: “Oh, It’s well better not to think about this at all, like new taxes”. From now on, every solution to the issue must be discussed. Thus, dear radioactive people, **look and judge.**

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

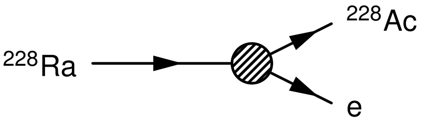
Your humble servant,

W. Pauli

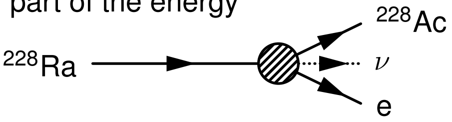
[translation to english: `http://www.pp.rhul.ac.uk/~ptd/TEACHING/PH2510/pauli-letter.html`]

The birth of the neutrino: quick (theoretical) acceptance

1896 Becquerel's β decay: e emission



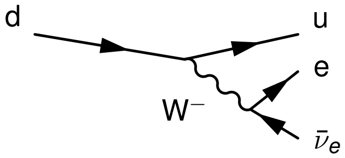
1930 Pauli's β decay: invisible ν emitted carries away part of the energy



1934 Fermi incorporated the ν in the electroweak theory

- Pauli's "neutron" renamed as neutrino due to discovery of "atomic" neutron (1932)

- Current "Standard Model" view of β decay:



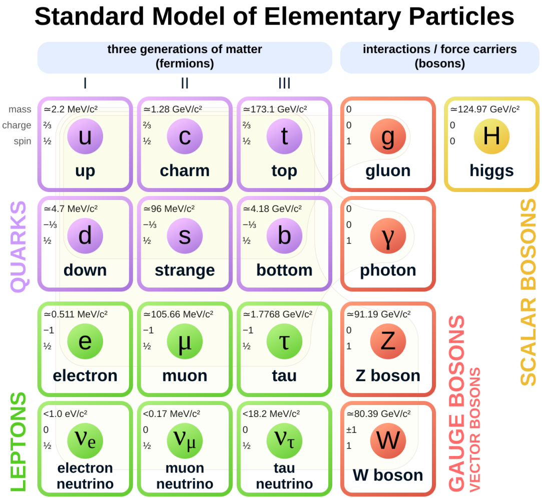
The Standard Model and Neutrinos

ν properties:

- charge = 0
- spin = 1/2
- only interact weakly
  - in SM: ν_L, but no ν_R
- mass = 0 in SM
  - From ν oscillations, $m_\nu > 0$
    - ★ Discovered in 1998–2002
    - ★ Nobel Prize 2015
  - $m_\nu \ll m_{u,d,e}$
- 3 families:

flavor: ν_e, ν_μ, ν_τ

mass: ν_1, ν_2, ν_3



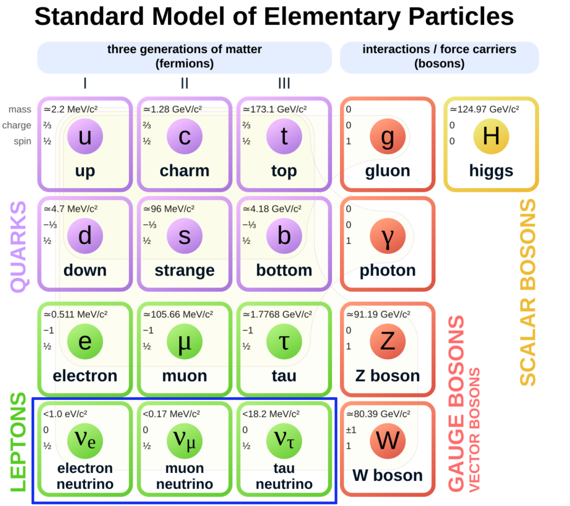
The Standard Model and Neutrinos

ν properties:

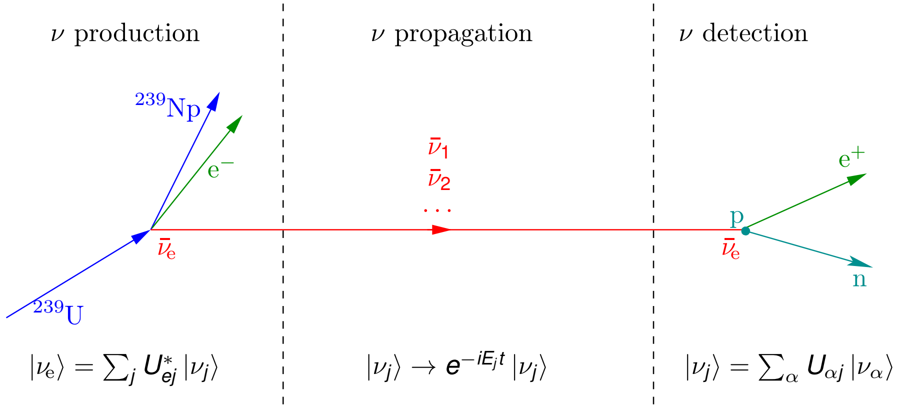
- charge = 0
- spin = 1/2
- only interact weakly
  - in SM: ν_L, but no ν_R
- mass = 0 in SM
  - From ν oscillations, $m_\nu > 0$
    - ★ Discovered in 1998–2002
    - ★ Nobel Prize 2015
  - $m_\nu \ll m_{u,d,e}$
- 3 families:

flavor: ν_e, ν_μ, ν_τ

mass: ν_1, ν_2, ν_3



Neutrino Oscillation (in vacuum) – overview



$$P(\nu_e \to \nu_e, t) = ||\langle \nu_e | \nu_e, t\rangle||^2$$

- For oscillations to happen $\{|\nu_\alpha\rangle\}$ and $\{|\nu_j\rangle\}$ different $\Rightarrow$ ν has non zero mass

Neutrino Oscillations – simplest case

2 flavor case, vacuum

- 2 ν interaction flavours (ν_e and ν_μ)
- mass eigenstates $\{|\nu_j\rangle\} = \{|\nu_1\rangle, |\nu_2\rangle\} \neq \{|\nu_\alpha\rangle\} = \{|\nu_e\rangle, |\nu_\mu\rangle\}$ flavour eigenstates
- mixing matrix U: $|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$ with $UU^\dagger = \mathbb{1}$ (ie, U rotation matrix)

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- Propagate through space time as plane waves in mass state:

$$|\nu_e, t\rangle = \sum_j U^*_{ej} e^{-iE_j t} |\nu_j\rangle = \cos\theta e^{-iE_1 t} |\nu_1\rangle + \sin\theta e^{-iE_2 t} |\nu_2\rangle$$

- $P(\nu_e \to \nu_e, t) = ||\langle\nu_e|\nu_e, t\rangle||^2 = 1 - \sin^2(2\theta)\sin^2[(E_2 - E_1)t/2]$
- Given m_i small: $E_i = \sqrt{m_i^2 + p^2} \approx p + \frac{1}{2}\frac{m_i^2}{p}$ and $t \approx L$, therefore $(E_2 - E_1)t \approx \frac{1}{2}\frac{m_2^2 - m_1^2}{p} L \approx \frac{\Delta m^2 L}{2E}$

$\Rightarrow$ $P(\nu_e \to \nu_e, L) = 1 - \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{4E}\right)$

Neutrino Oscillations

3 flavor case, vacuum

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j,k} U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k} e^{-i\Delta m^2_{jk} \frac{L}{2p}}, \qquad \Delta m^2_{jk} = m^2_j - m^2_k$$

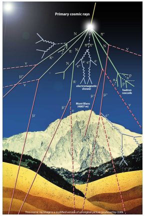
- 3 known ν interaction flavours : ν_e, ν_μ and ν_τ $\Rightarrow$ matrix U is 3×3

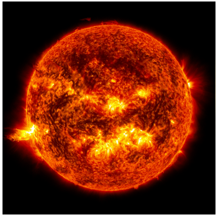
$$U = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{“atmospheric sector”}} \times \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}^{\text{“reactor sector”}} \times \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{“solar sector”}}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

- θ_{23}, θ_{13}, θ_{12}: ν mixing angles
- δ_{CP}: leptonic CP violation phase
- Δm^2_{32}, Δm^2_{21}: ν mass splitting
  - Note: $\Delta m^2_{31} = m^2_3 - m^2_1 = \Delta m^2_{32} + \Delta m^2_{21}$

Studying Neutrino Oscillations: Neutrino Sources



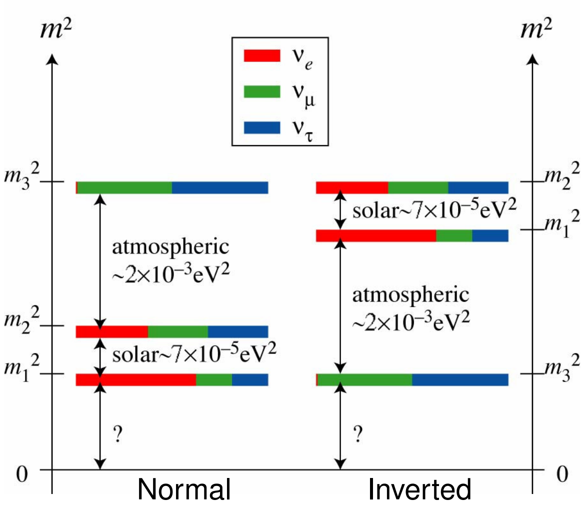


- Sun & atmosphere: two main natural sources
- Reactors
  - Good: Reactors exist independently of ν research (ie, we're not paying the bill!)
  - Good: can control L (within a certain range. . .)
  - Bad: We cannot control it's 'burning' power
  - Good/Bad: $\bar{\nu}_e$ energy spectra fixed, and hard to predict. Adding detectors $\rightarrow$ expensive
- Accelerator ν
  - Good: Control L, E and if ν_μ or $\bar{\nu}_\mu$ produced (for a traditional beam)
  - Bad: "Expensive" ν
  - Good and Bad: extra detectors useful to understand ϕ emmitted, but also expensive

Open questions in neutrino physics...

- Absolute Scale of Neutrino Masses
- Neutrino Mass Ordering
  $\Rightarrow$ JUNO
- $P(\nu_\alpha \rightarrow \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$
  - Tied to Universe Matter/AntiMatter asymmetrie?

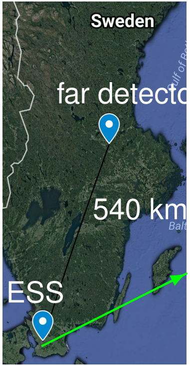
  $\Rightarrow$ ESSνSB
- Mixing Matrix U is Unitary?
  $\Rightarrow$ both via precision measurements
- Are there Sterile ν?
- ν Majorana or Dirac Particle
  $\Rightarrow$ JUNO phase 2 (maybe)

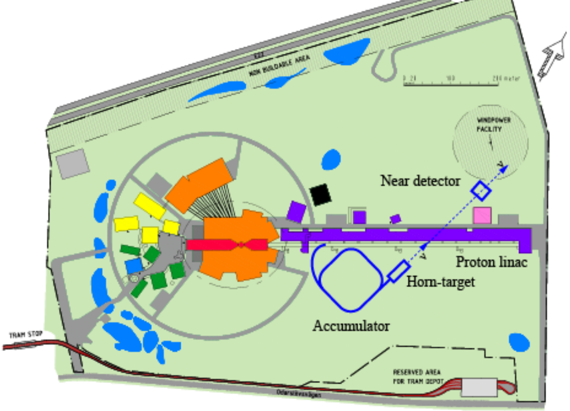


Neutrinos @ IPHC

NMO ⟶ : reactor + . . .

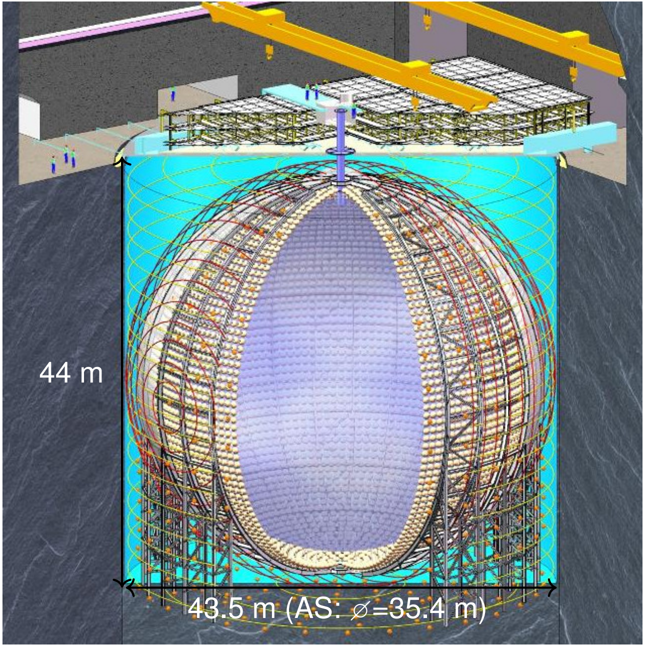
CP-violation ⟶ : accelerator + . . .





- Located in Sweden
- Upgrade ESS facility to produce ν beam
- Initial design step finishing
- Next phase of project in preparation
- Timeline: data taking for 2036 (or later)

- $\mathcal{O}$(1 Mton) far detector
- Main goal: measure CP violation
- Optimally placed for CPV at 2^{nd} oscillation maxima
- IPHC responsible for “horn” design

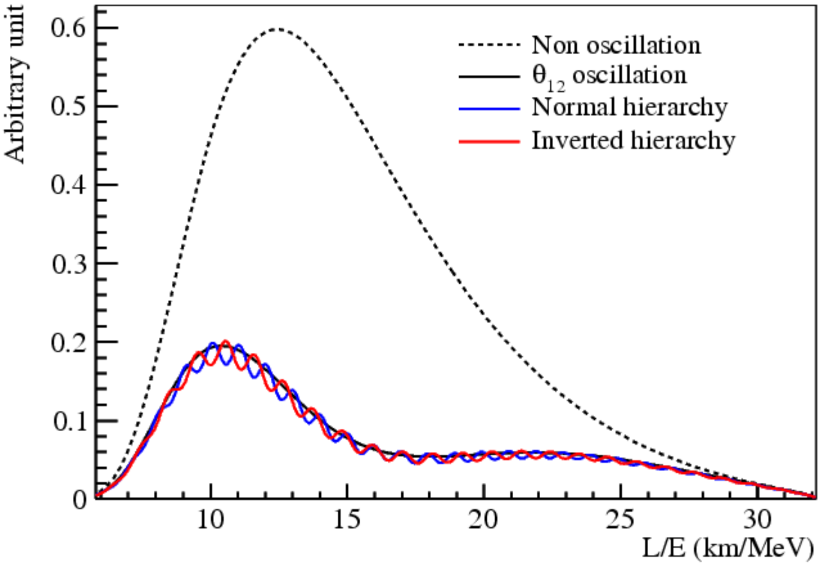


- Located in China
- 20 kton ν target mass
- built to detect $\bar{\nu}_e$ from nuclear reactors
  - Can only measure $\bar{\nu}_e$ survival: $\bar{\nu}_e \to \bar{\nu}_e$
- excellent energy resolution
- observe fast oscillations
  - first time to observe Δm^2_{32} and Δm^2_{21} together
- main goal: NMO
- Start data taking: 2022
  - construction on-going

JUNO site

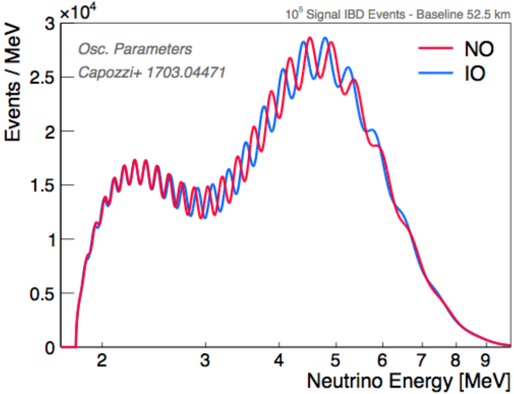
Guang Zhou
Huizhou NPP
Shen Zhen
Lufeng NPP
Jiangmen
Daya Bay NPP
Kaiping
Hong Kong
JUNO
53 km
53 km
Taishan NPP
Yangjiang NPP

Neutrino Oscillations in JUNO



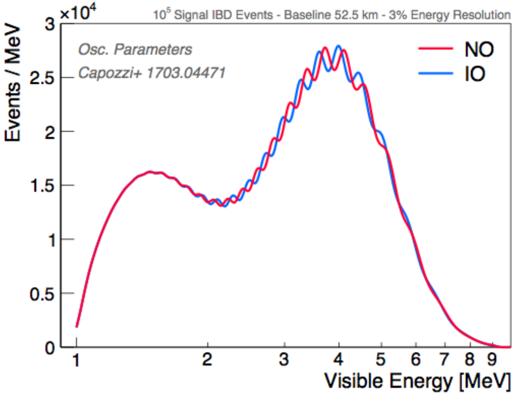
Neutrino Oscillations in JUNO: what we really will measure

$\bar{\nu}_e$ oscillated spectrum



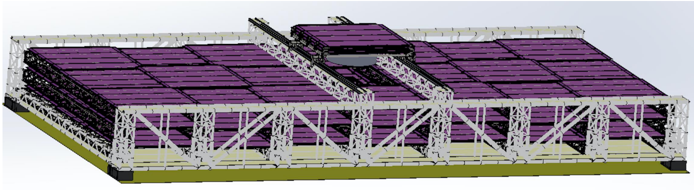
- Ideal case
- Exposure: 20 kt · 6 years

+ energy resolution

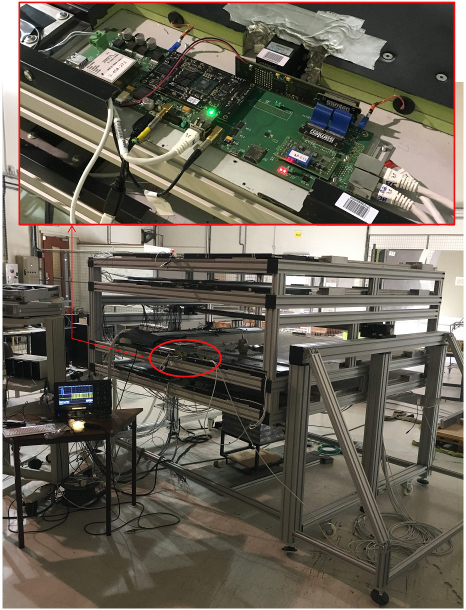


- E_{vis} from e^+ used rather than E_ν
- Assuming $3\%/\sqrt{E[\text{MeV}]}$ energy resolution

JUNO @ IPHC



- Top Tracker modules originally built at IPHC
  - TT part of JUNO veto strategy
    - Track atm. μ crossing JUNO: reject associated background
  - IPHC group leading TT efforts
  - Developping new electronics cards for TT
- Prototype detector @IPHC
  - Let me know if you want a tour!
- Thesis not restricted to TT



JUNO schedule & M2 Internships & Ph.D. thesis

- JUNO schedule:
  - Civil construction finished this year
  - Starting now to install JUNO detector
  - TT expected to be installed end of 2022 until 2023
  - Thesis to start just (assuming no delays) before TT installation
- Student project/TIPP:
  - study sensitivity to neutrino mass ordering with JUNO
- M2 internship (2022):
  - development of reconstruction in TT and TT prototype
    - test Hough method in full TT
    - could be extended to trying other methods also
- Ph.D. thesis (2022 – 2025):
  - Initial data taking on JUNO; work on TT + analysis geared towards ν oscillation
- Also feel free to talk to our current Ph.D. students (Bat 22, room 227):
  - Luis Felipe PIÑERES RICO – 4th year: finishing May 2022
  - Deshan SANDANAYAKE – 1st year