Atmospheric neutrino spectrum reconstruction with JUNO

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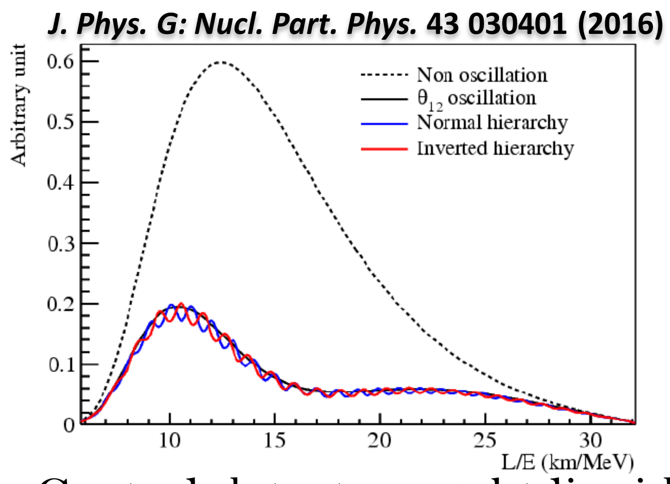
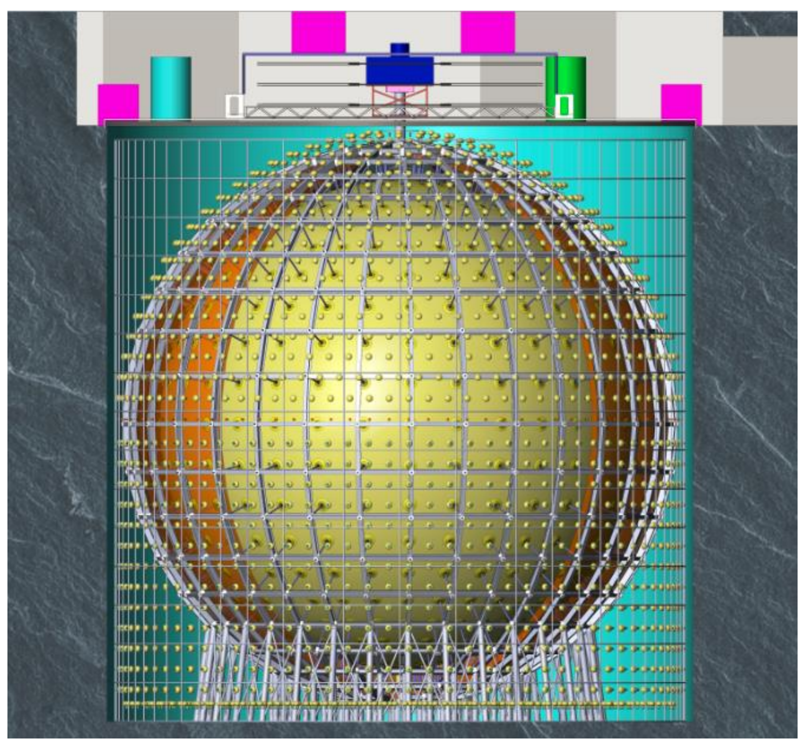
JUNO is a 20 kton multi-purpose underground **neutrino detector**, currently under construction in China, whose primary goal is the **identification of the neutrino Mass Hierarchy**.
Large fiducial volume and excellent energy resolution allow also the study of sources like **atmospheric neutrinos.**

1. JUNO detector

JUNO main goal: determine **neutrino Mass Hierarchy (MH)**

Different oscillation pattern in reactor $\bar{\nu}_e$ spectrum, depending on the hierarchy

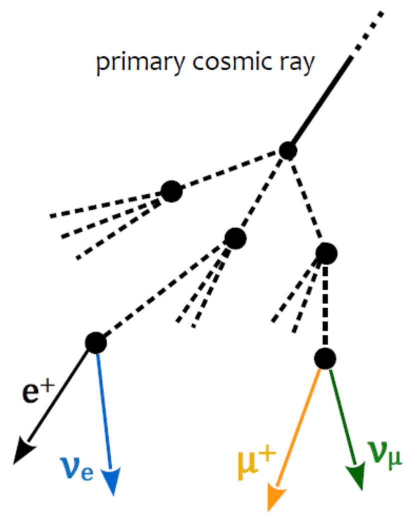


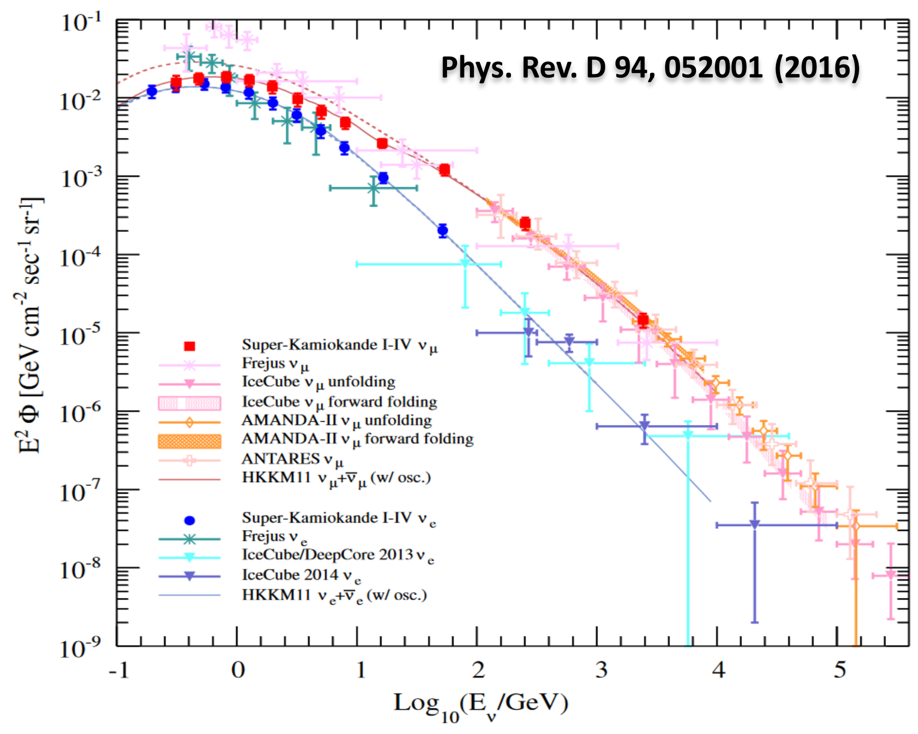


- Central detector: 20 kt liquid scintillator
  35,4 m diameter sphere
- Double photosensors system
  18.000 x 20" PMTs
  25.000 x 3" PMTs
- Outer water pool
  Cherenkov veto, 2.400 x 20" PMTs
- Top Tracker
  plastic scintillator stripes

2. Atmospheric neutrinos

- Produced in an air shower, initiated by a primary cosmic ray which hits the atmosphere.
- Almost entirely composed of **νe and νμ** (both ν and $\bar{\nu}$).





Main sources:

- **νμ** : π and K decays
- **νe** : subsequent μ decays

νμ/νe ~ 2, decreases as the μ energy gets larger.

Flux from $\pi \to \mu \to \nu$: $\frac{dN_\nu}{dE_\nu}$

$$\simeq \frac{N_0(E_\nu)}{1-Z_{NN}}\left\{\frac{A_{\pi\nu}}{1+B_{\pi\nu}cos\theta E_\nu/\epsilon_\pi} + 0{,}635\frac{A_{K\nu}}{1+B_{K\nu}cos\theta E_\nu/\epsilon_K}\right\}$$

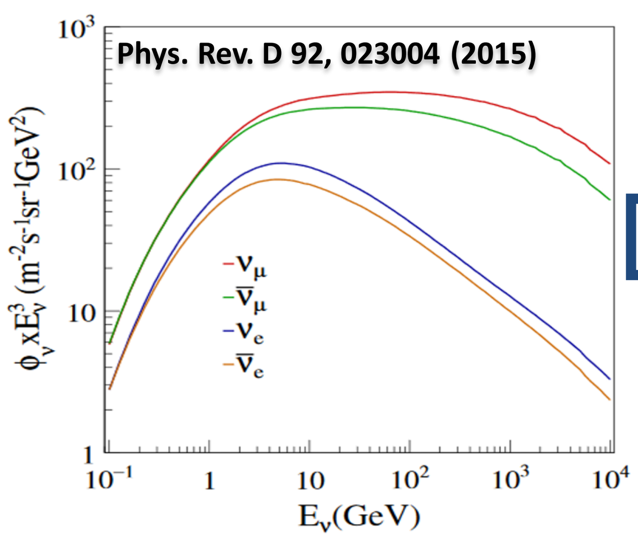
T. Gaisser, *Cosmic Rays and Particle Physics* (1990)

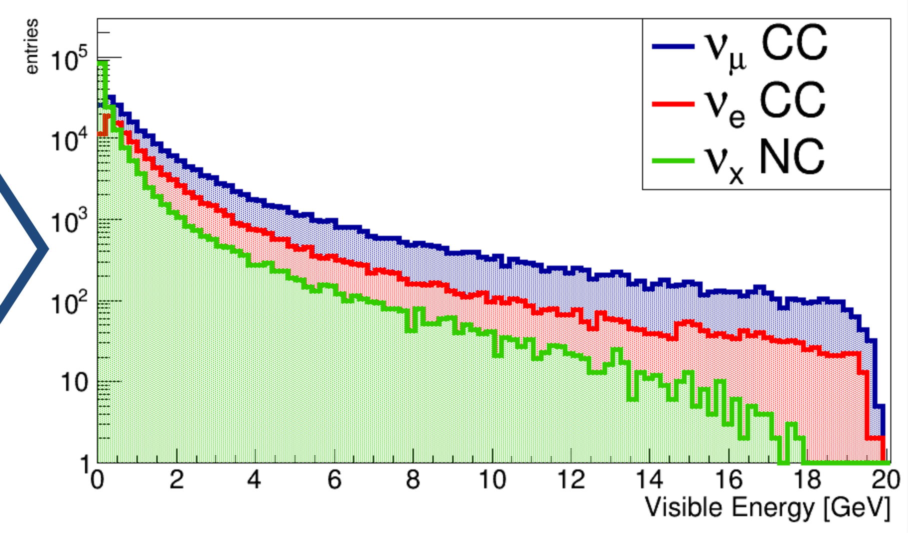
3. MC simulation

The study is based on simulated Monte Carlo events, processed in 2 main steps:

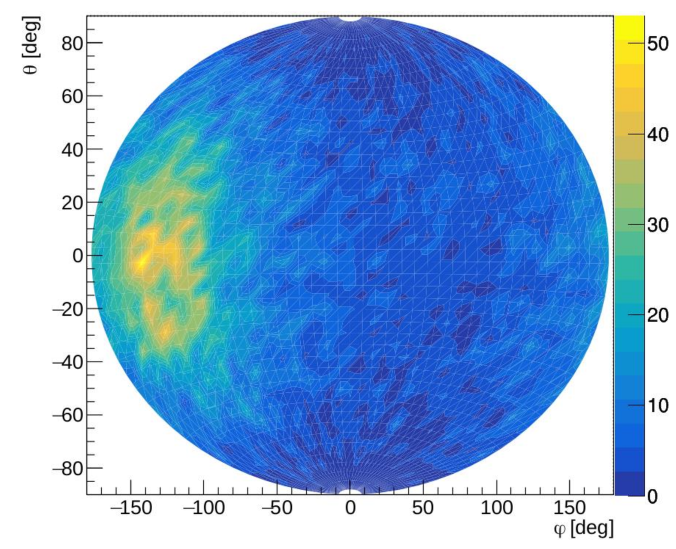
Step 1:
Neutrino interaction generation in the detector:

- **Max ν energy**: 20 GeV
- **Total events**: 500k νe + νμ (and antineutrinos).
- **Software**: *GENIE Neutrino Monte Carlo Generator*
  Nucl.Instrum.Meth.A614 87-104 (2014)





Step 2:
Propagation of secondary particles by a GEANT4 – based simulation inside JUNO
J. Phys.: Conf. Ser. 664 072053 (2015)



Hit map of a ν event on the 3" PMT system

4. νe - νμ discrimination

According to the ν interaction, there are 3 classes of events:

- **νμ CC interaction**: $\nu_\mu + {}^{12}C\ /\ p \to \mu + X$, event elongated in time because of μ ability to travel long distances and its late decay;
- **νe CC interaction**: $\nu_e + {}^{12}C\ /\ p \to e + X$, point-like event because of the short *e* track;
- **NC interaction**: $\nu_x + {}^{12}C\ /\ p \to \nu_x + X$, geometry of event depends on the particles produced.

A **time residual – based variable** tres is defined for each hit on the 3" PMT system (small time resolution): $t^i_{res} = t^i_{hit} - \left(\frac{R^i_V \cdot n}{c}\right)$, where:

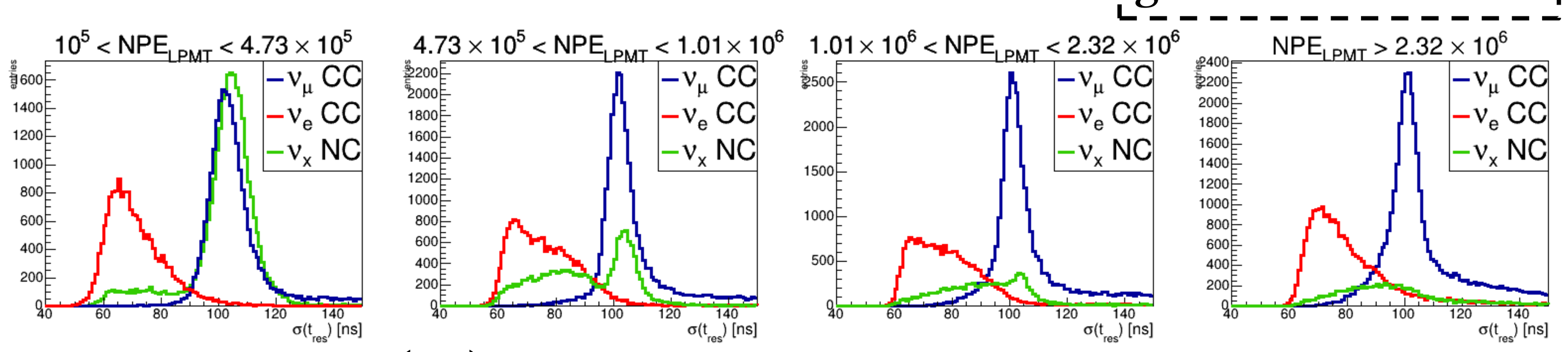
- t^i_{hit} = arrival time on the i-th PMT;
- c/n = speed of light inside the scintillator;
- R^i_V = distance of the i-th PMT from the vertex V of the event.

Preliminar fiducial cuts:

- **Rvertex < 16 m + NPE** (μ veto) **< 60** (see box 6).

V = Vtrue + **σ (1 m) gaussian smear**
t = ttrue + **σ (4 ns) gaussian smear**

The tres RMS (**σ(tres)**) is strongly flavor – dependent:



Distribution of the **σ**(tres) within 4 bins of number of photo-electrons (NPE) with equal statistics.

Cuts for **νe**	Cuts for **νμ**
σ(tres) < 75 ns + log(NPElpmt) > 5.0	σ(tres) > 95 ns + log(NPElpmt) > 5.7
EFF: ~30% **CONT**: ~10%	**EFF** : ~30% **CONT**: ~10%

5. Cosmic μ rejection

- Cosmic μ can mimic the signal topology;
- expected to produce an high amount of light both in the water cherenkov μ veto (WV) and in the central detector (CD).

→ Apply selection to μ events not tagged by veto system: NPE < 60 in WV and NPElpmt > 100K in CD.

- **Tested on 1000 cosmic μ in JUNO with full sim, 0 passed the selection.**

Estimation from toy model for rejection power: $< \mathbf{1.15 \cdot 10^{-6}}$ **@ 90% CL**

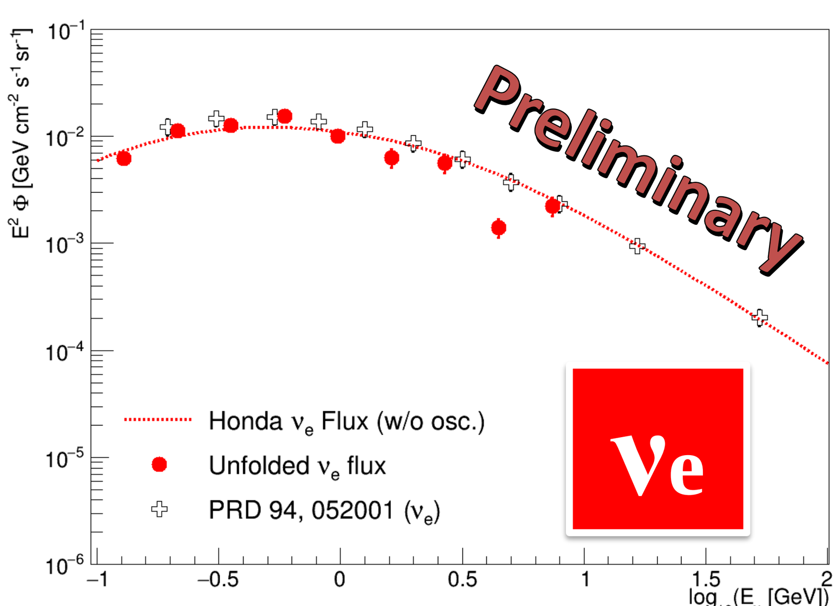
6. Spectrum reconstruction

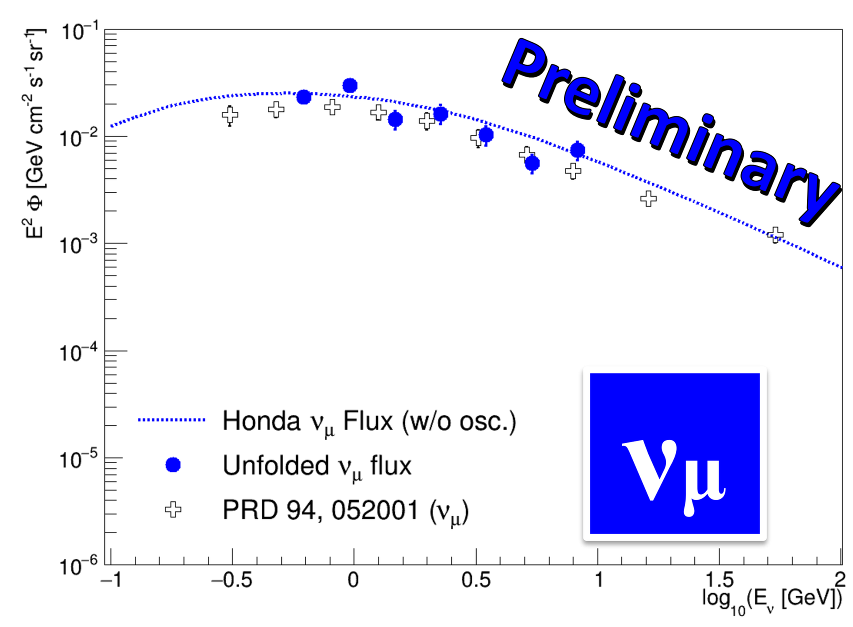
Probabilistic unfolding algorithm (based on the Bayes theorem)

Unfolded spectrum | Detector observable

$$\boxed{P(E)^{\nu\alpha}} = P(E|NPE_{LPMT})^{\nu\alpha} \cdot \boxed{P(NPE_{LPMT})^{\nu\alpha}}$$

The algorithm has been tested on an independent 10k ν sample





Work in progress:

- **Study of residual contamination;**
- **evaluation of systematic effects;**
- **spectrum distorsion introduced by flavor oscillations.**

The 27th International Workshop on Weak Interactions and Neutrinos
Bari, June 3rd - 8th, 2019