Atmospheric neutrinos in JUNO

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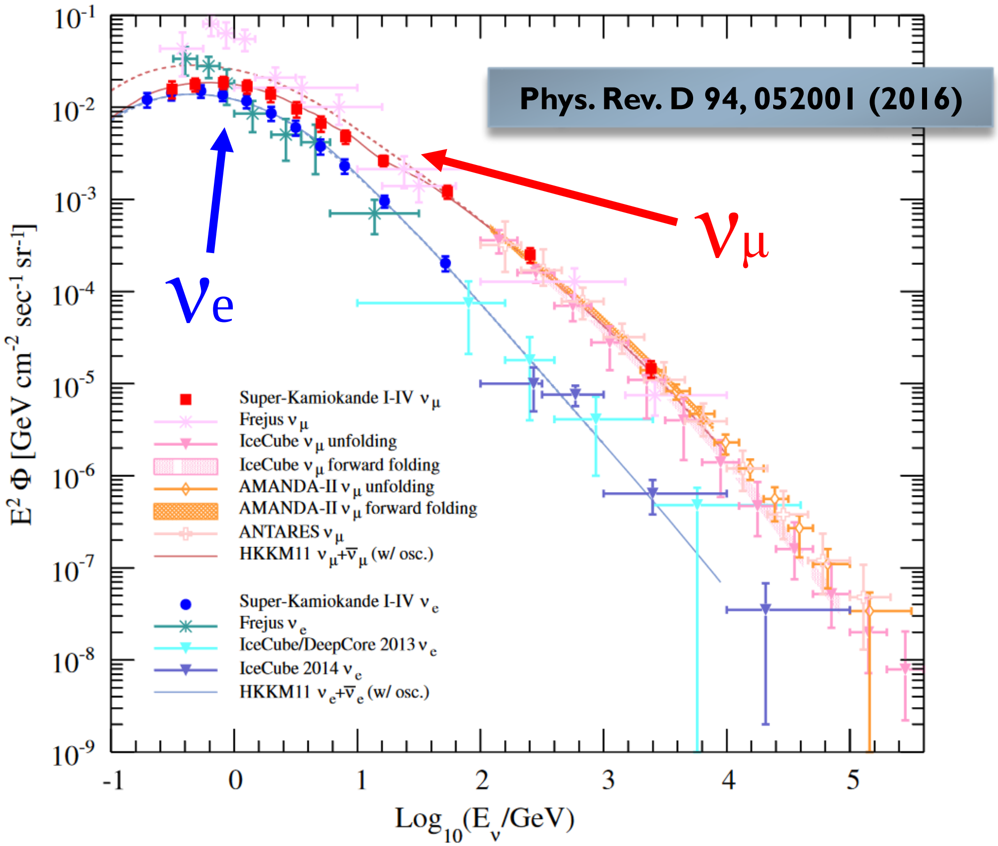
JUNO – Italia meeting, Ferrara, 09.05.2019

Motivations summary

- First measurement of atm. νs with a LS detector
  - Which performances?

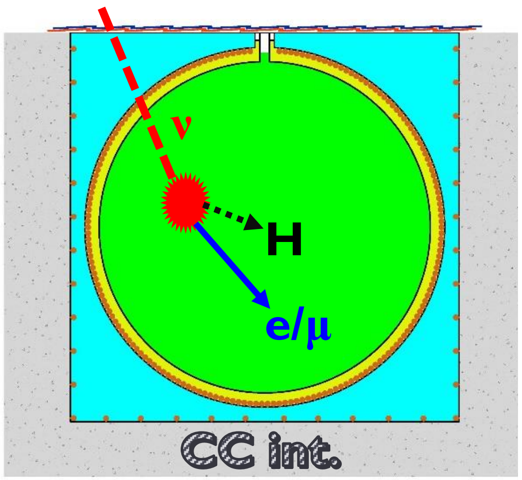
- Open questions:
  - Spectrum in (100-1000) MeV
  - Geomagnetic effect
  - Seasonal variations
  - Sun modulation

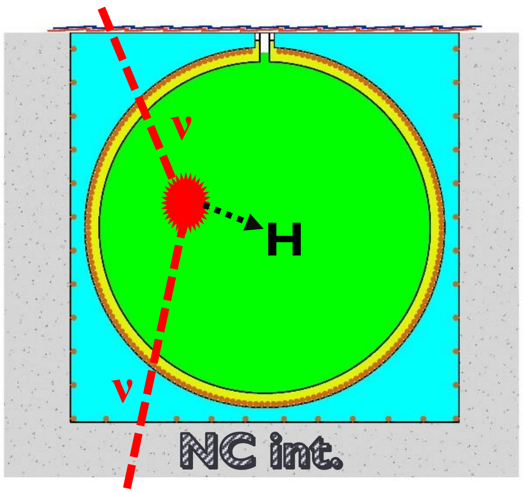
- Two main steps:
  - Flavor identification
  - Spectrum unfolding



Flavor identification

- In the atm. ν energy range, the dominant target are the nuclei of the scintillator → CCQE, RES, DIS
- νs can undergo a charged – current (CC) interaction, or a neutral – current (NC) interaction:
  - **ν_μ CC interaction**: $\nu_\mu + {}^{12}C\ /\ p \rightarrow \mu + X$, event elongated in time because of μ ability to travel long distances and its late decay;
  - **ν_e CC interaction**: $\nu_e + {}^{12}C\ /\ p \rightarrow e + X$, point-like event because of the short e track;
  - **NC interaction**: $\nu_x + {}^{12}C\ /\ p \rightarrow \nu_x + X$, geometry of event depends on the particles produced.

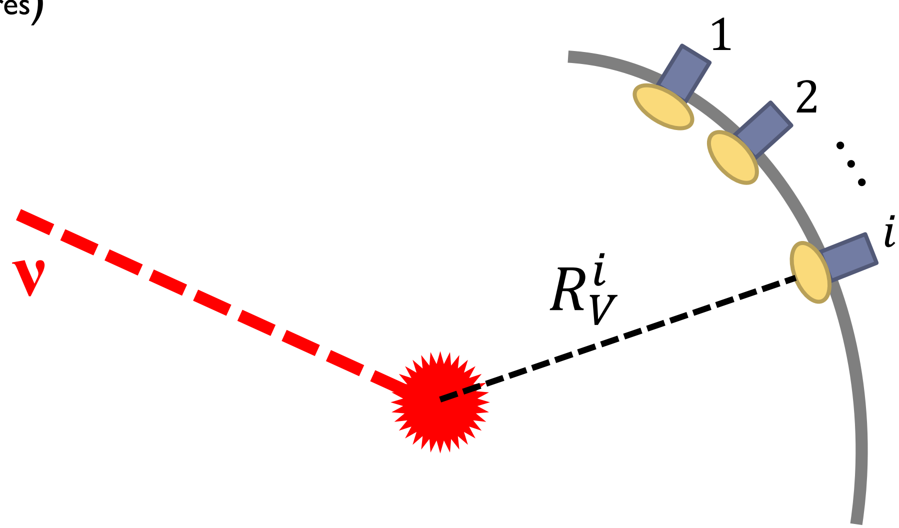




Flavor identification

- Discrimination is based on the time profile of the event
- A time residual profile is built, with respect of the event vertex, assuming all the hits come from the same point → $t_{res}^{i} = t_{hit}^{i} - \left(\frac{c}{n \cdot R_V^i}\right)$
  - SPMTs hit time only is considered (small TTS)
    - true hits + artificial σ = 4 ns Gaussian smearing to reproduce TTS conservatively
  - true V + artificial σ = 1 m Gaussian smearing to reproduce resolution uncertainty
- Take the RMS of the profile → $\sigma(t_{res})$

t_{hit}^{i} : arrival time of the hit on the i-th PMT
R_V^i: vertex – i-th PMT distance

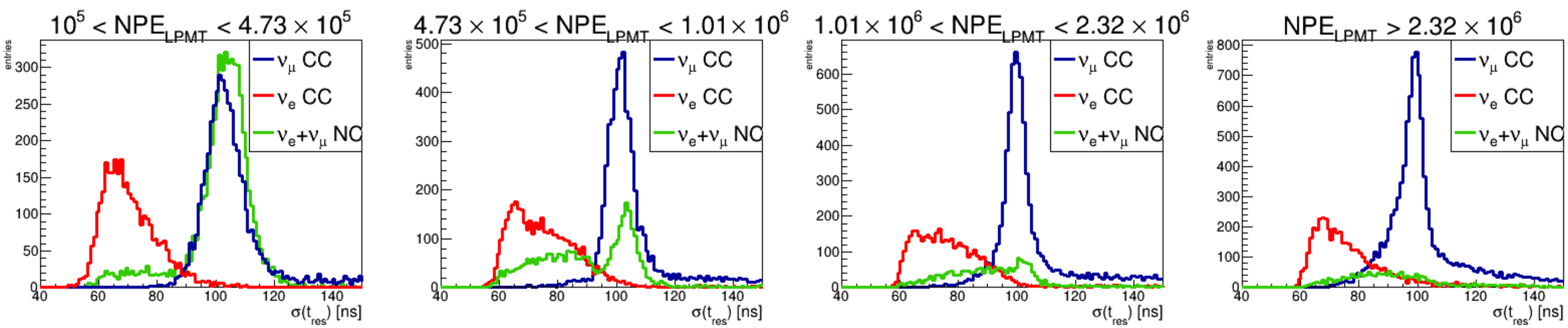


Simulation details

- Generator: GENIE V2.12.10
- Input flux: HKKM (Honda) flux for JUNO location
  - http://www.icrr.u-tokyo.ac.jp/~mhonda/nflx2014/index.html
- Target: JUNO LS
  - offline/Detector/Geometry/share/CdGeom.gdml
- Cross sections: from GENIE tables
  - hepforge.org/archive/genie/data/2.12.0/DefaultPlusMECwithNC/gxsplFNALsmall.xml
- GENIE events are then processed with JUNO software (J18v1r1-Pre1)
- 100k $\nu_e + \nu_\mu$ events, in the 0-20 GeV energy range
- Unless specified, all plots include a fiducial volume R_{smear}**v** < 16m cut

Selection criteria: recap

- The separation method has been described in previous Coll. Meetings:
  - **JUNO-doc-3624**
  - **JUNO-doc-4170**
- The algorithm is based of the $\sigma(t_{res})$ variable:

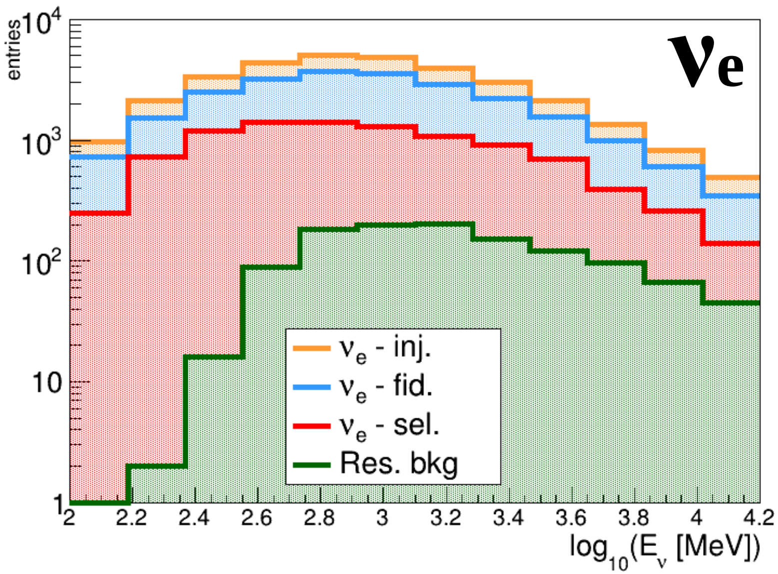


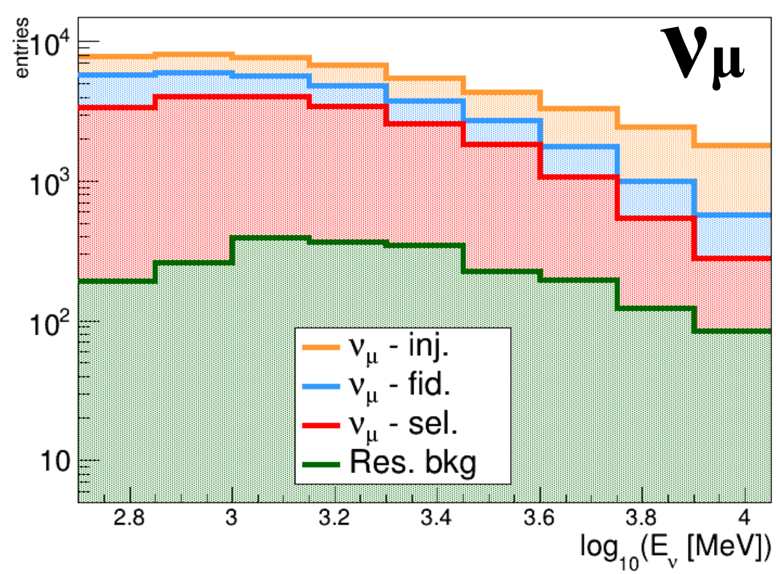
- The NC component is treated statistically, as it is composed both of ν_e and ν_μ
- The cuts on $\sigma(t_{res})$ are coupled to different cuts on NPE for ν_e and ν_μ
- The cut values and the performances, for ν_e and ν_μ are:

Cuts for ν_e	Cuts for ν_μ
Cuts for **ν_e**: $\sigma(t_{res}) < 75$ ns + $\log(NPE_{LPMT}) > 5.0$	Cuts for **ν_μ** : $\sigma(t_{res}) > 95$ ns + $\log(NPE_{LPMT}) > 5.7$
EFF: ~30% **CONT**: < 10%	**EFF** : ~30% **CONT**: < 10%

Selection efficiency

- Here is reported the selection efficiencies as a function of the neutrino energy:





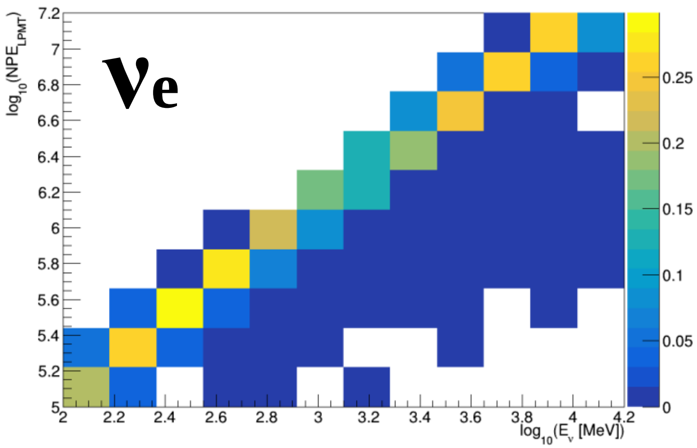
- The cut flow is:
  - Injected ν flux
  - Fiducial volume cut = **RVERTEX < 16 m**
  - NPELPMT cut + σ(tres)
    - **νe :** NPELPMT $> 10^5$
    - **νμ :** NPELPMT $> 5\ x10^5$

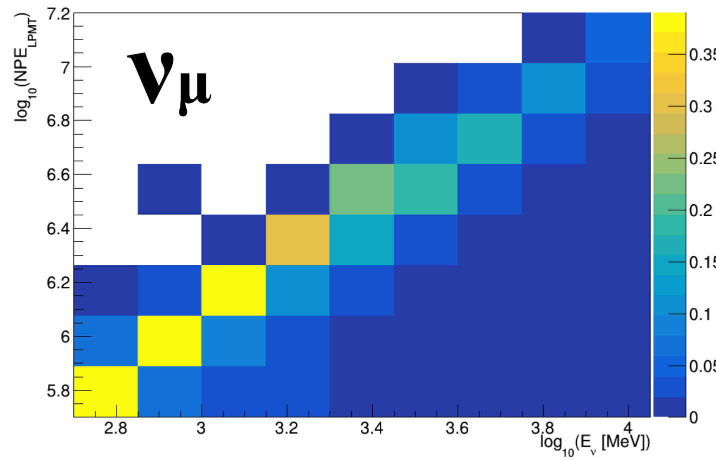
Spectrum unfolding

- The unfolding procedure has been described in **JUNO-doc-4170**
  - The relationship between the M observables and the N unfolded spectrum:

$$M_j = \sum_i L_{ji} N_i$$

where *L* is the detector response matrix *(Likelihood)*:



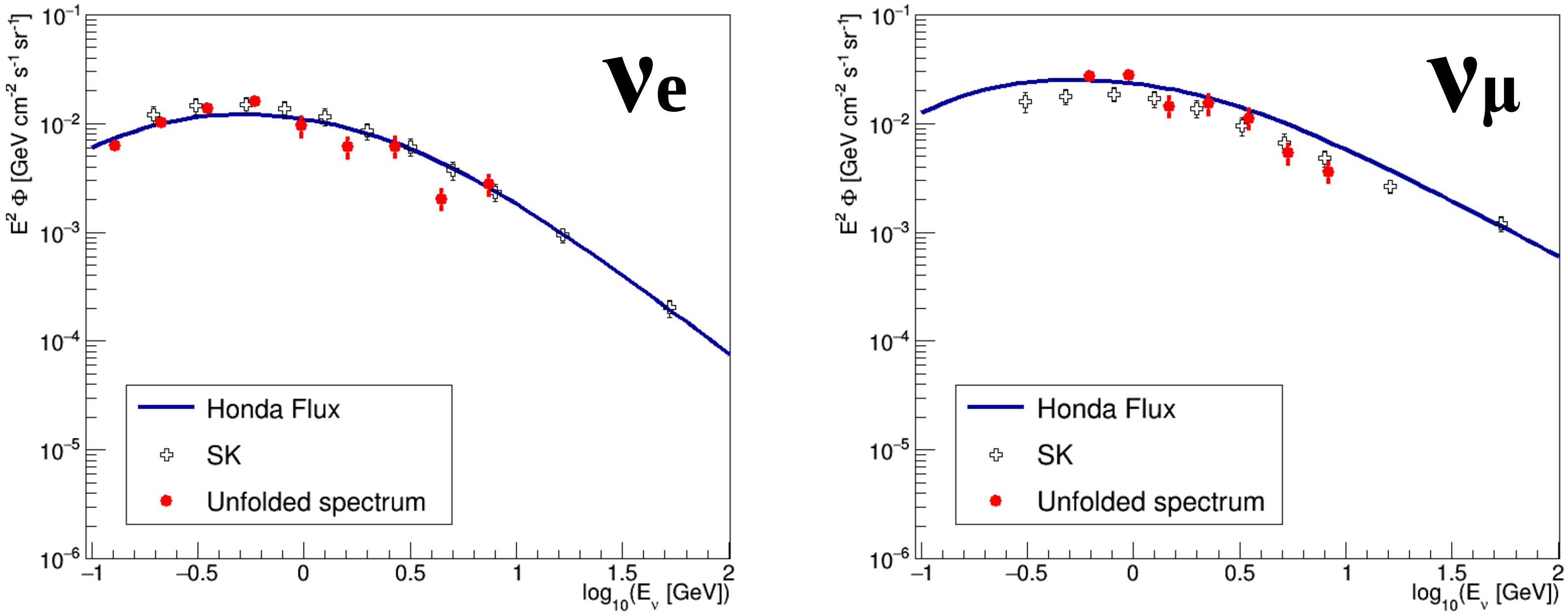


- The inverse relationship allows to infer the neutrino energy spectrum from the detector observable distribution
  - *U* is built by means of the Bayes Theorem

$$\boldsymbol{N_i = \sum_j U_{ij} M_j}$$

Spectrum unfolding

- We used an independent 10k neutrino sample to test the method

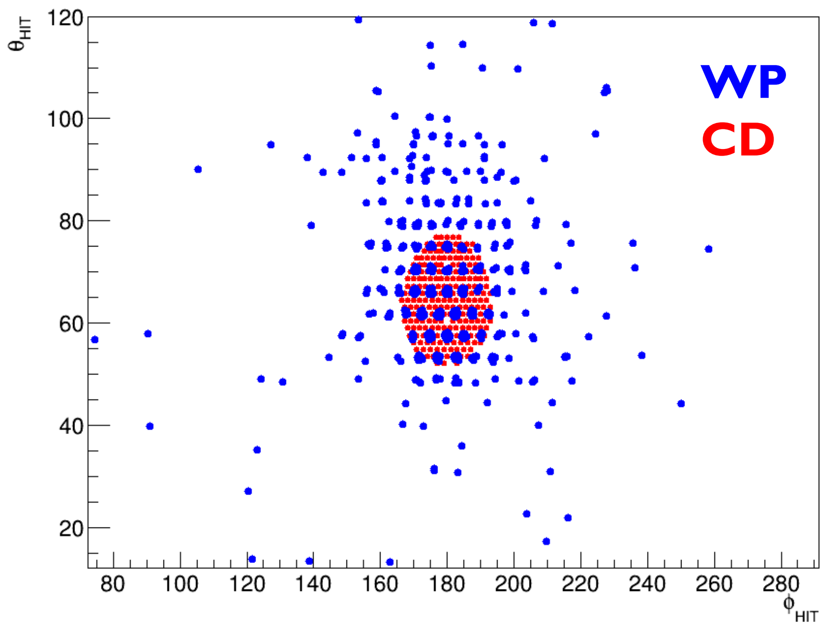


- Uncertainties in the unfolded spectrum include both the contribution from the probabilities and from statistics; the contribution from the model and from cuts is still under evaluation
- A dedicated study of the edge bins, as requested by the Bayesian unfolding, is undergoing
- The treatment of the residual contamination is still under study

Cosmic Muon background

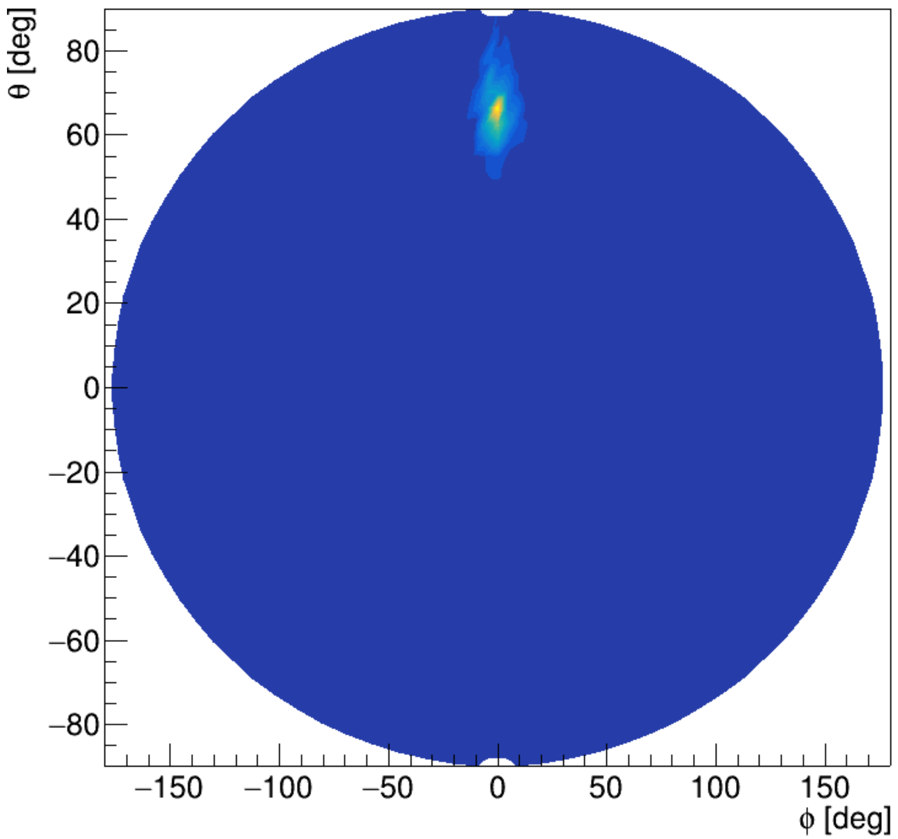
- Cosmic muons: strategy is based on water veto, but flux is much higher
- High energy through – going muons are easy to tag
- Low energy muons stopping inside the CD are more challenging

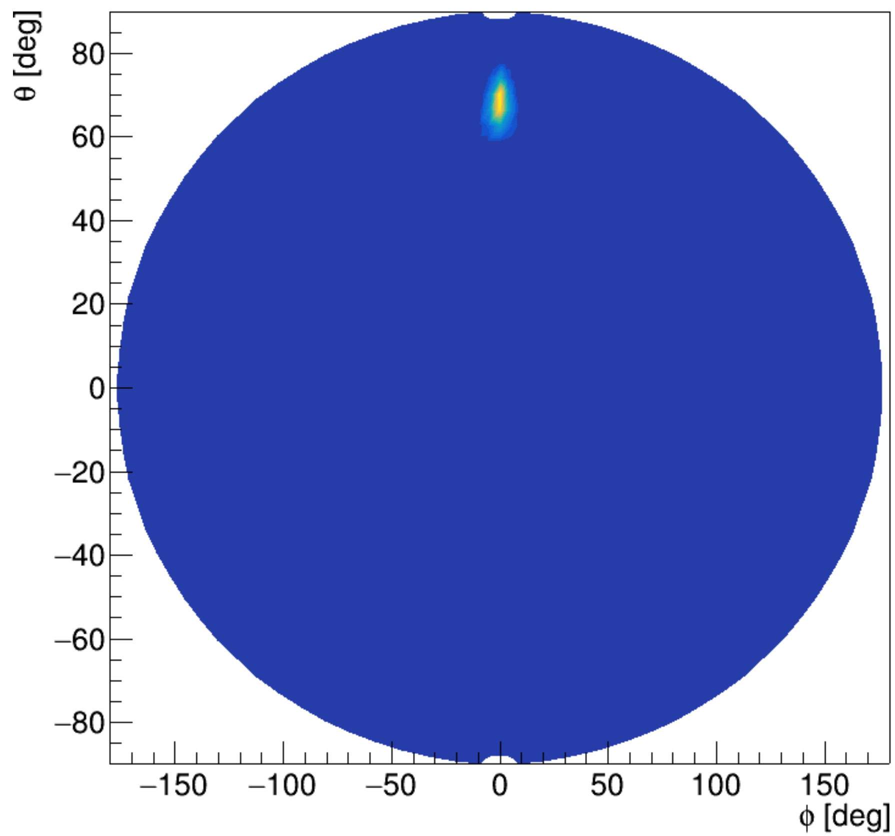
- Approach: find correlation between WP and CD PMTs
  - Hits are clustered around muon entry point



Cosmic Muon background

- Water pool and central detector (first 50 ns) images





Work in progress

- The analysis on the atm. neutrino energy spectrum is on finalization
- Good discrimination power between ν_e and ν_μ flavor
- JUNO has the potential to measure the spectrum in the same energy region of SK

Further steps:

- Refine the evaluation of the uncertainties
  - new MC production to reduce prob. contribution
- Finalize the cosmic muons rejection algorithm
- Include oscillation effects

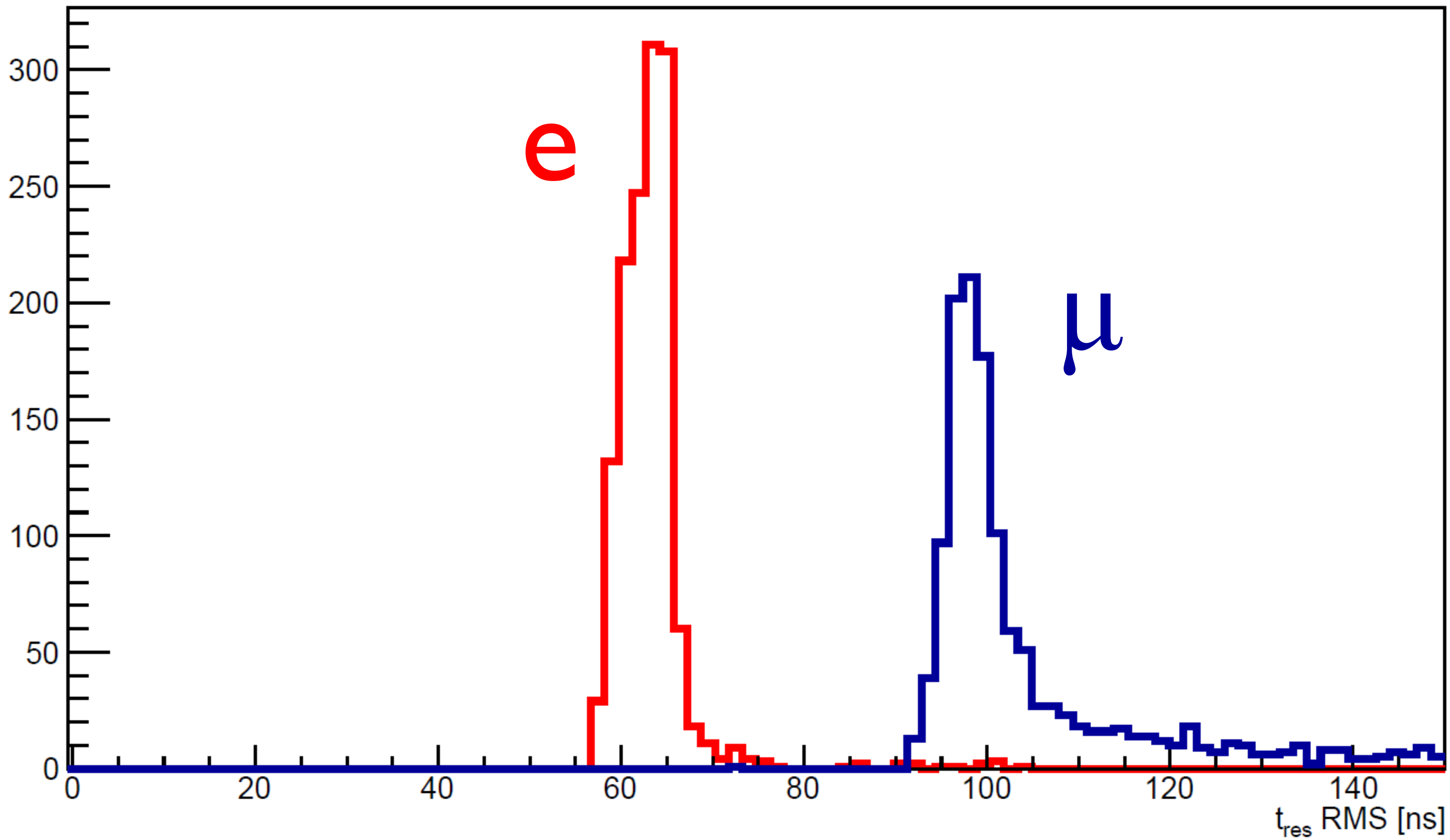
- Temporal benchmark: JUNO coll. meeting in July

Thank you for your attention!

Extra slides

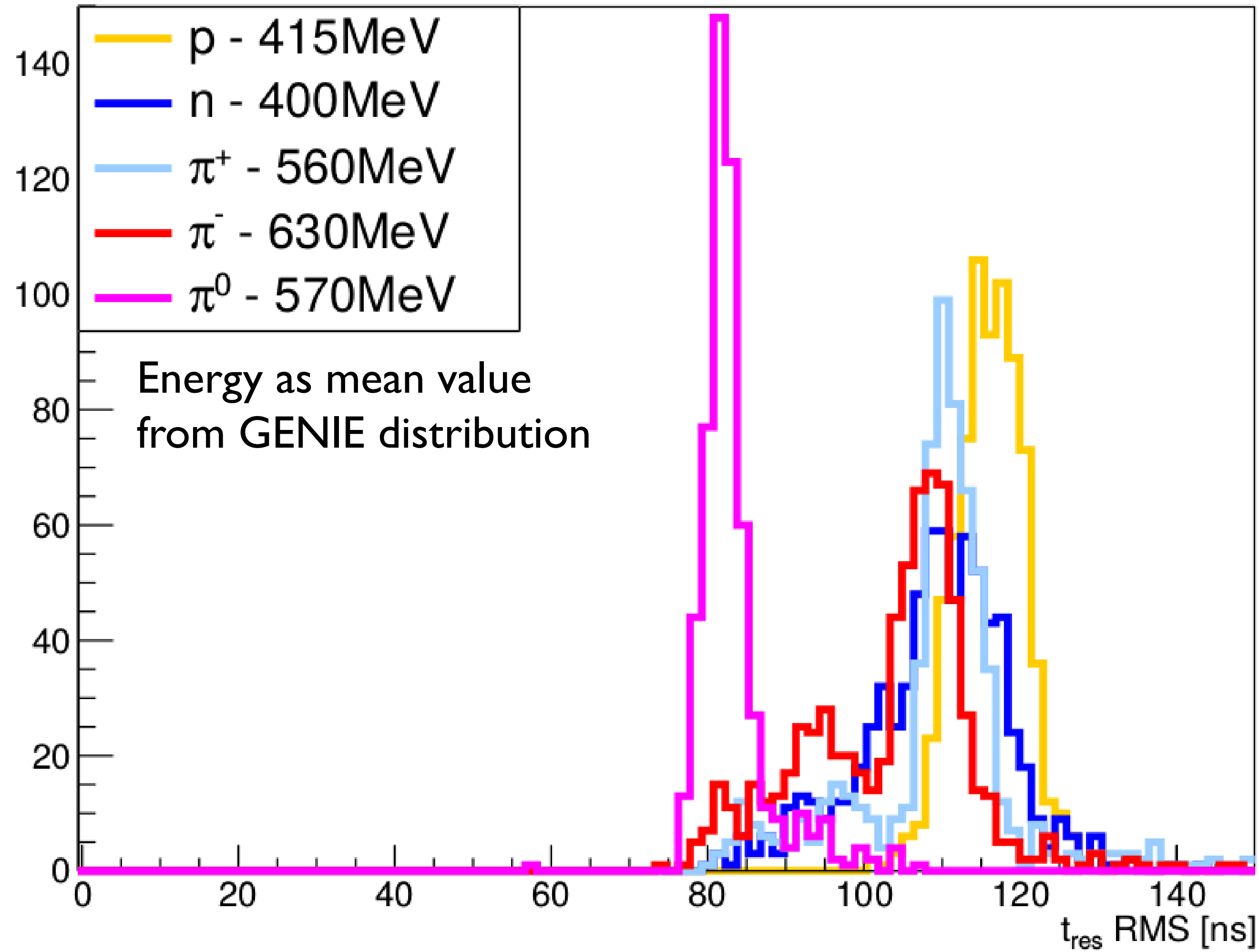
Pure leptons

- Distribution of σ(tres) for pure leptons at 1 GeV



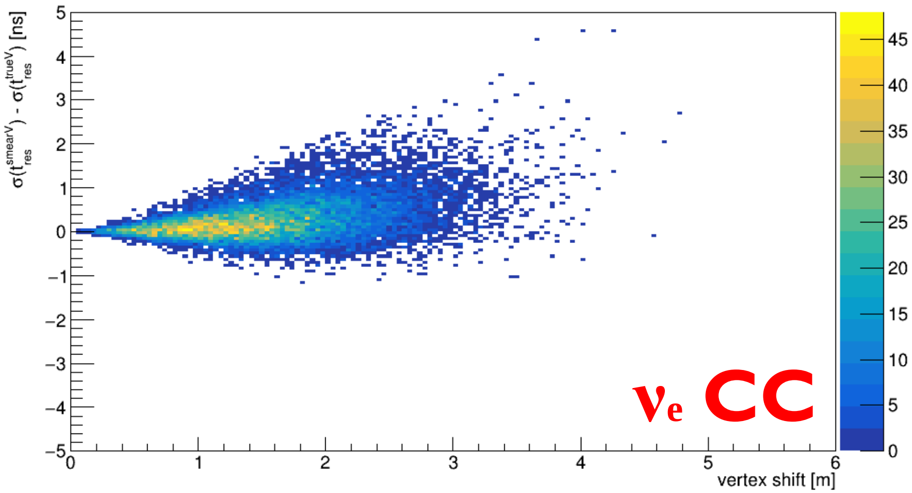
Hadrons simulation

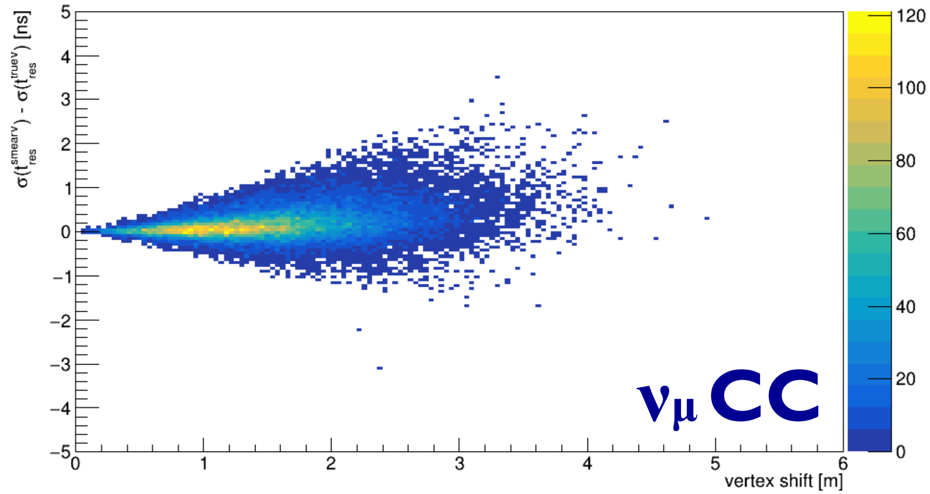
- Distribution of σ(tres) for hadrons, to understand their effect in ν interactions



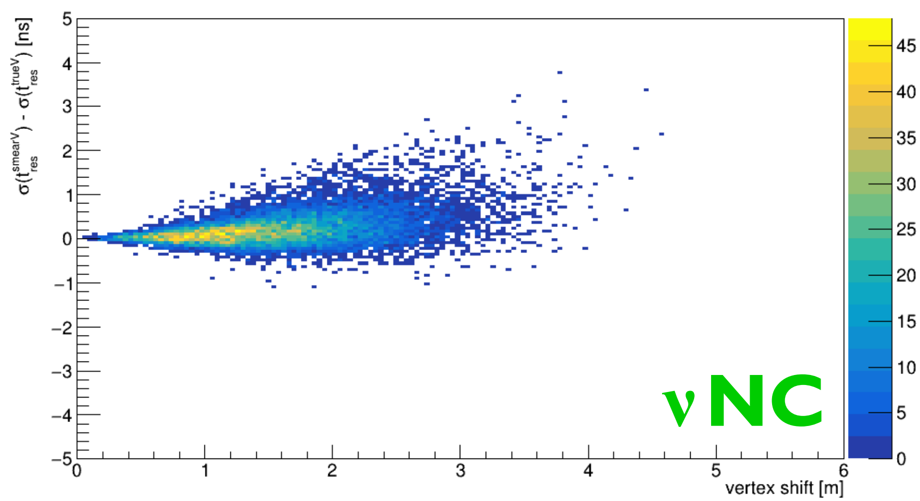
Flavor identification

- σ(tres) spread VS the vertex shift



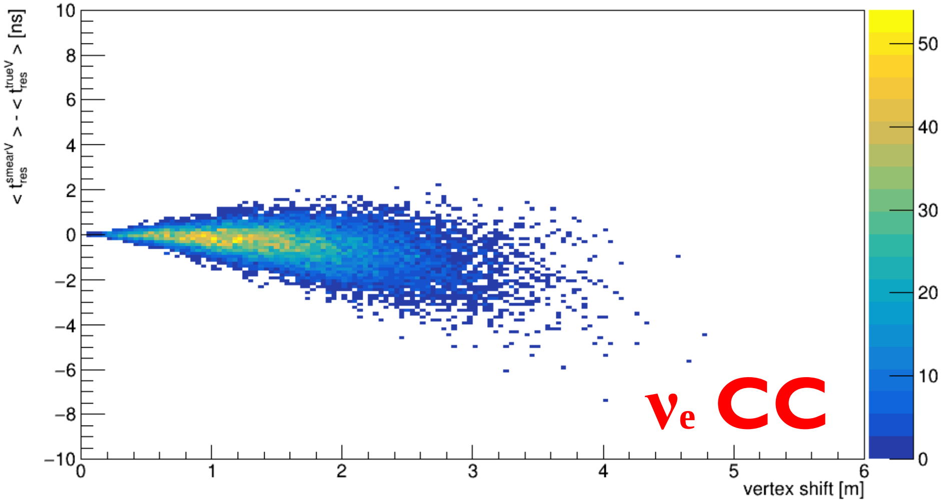


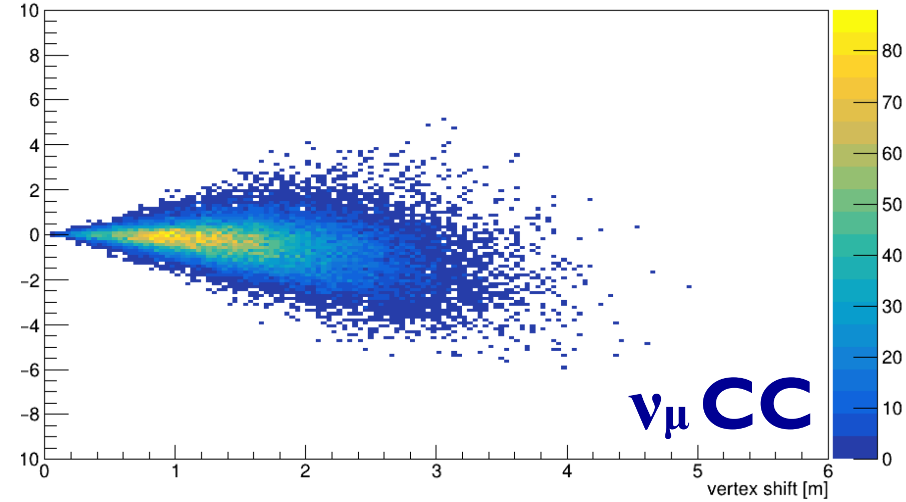
- The spread remains within a few ns



Flavor identification

- <(tres)> spread VS the vertex shift





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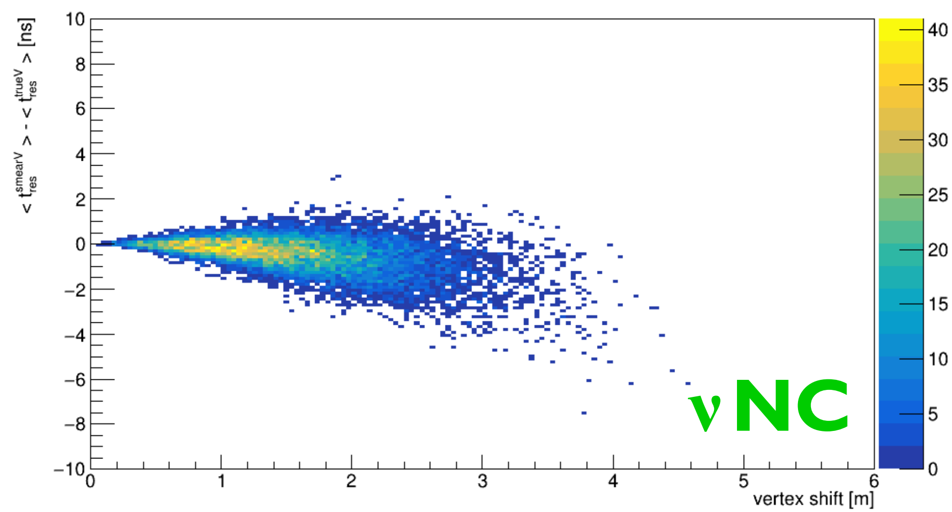
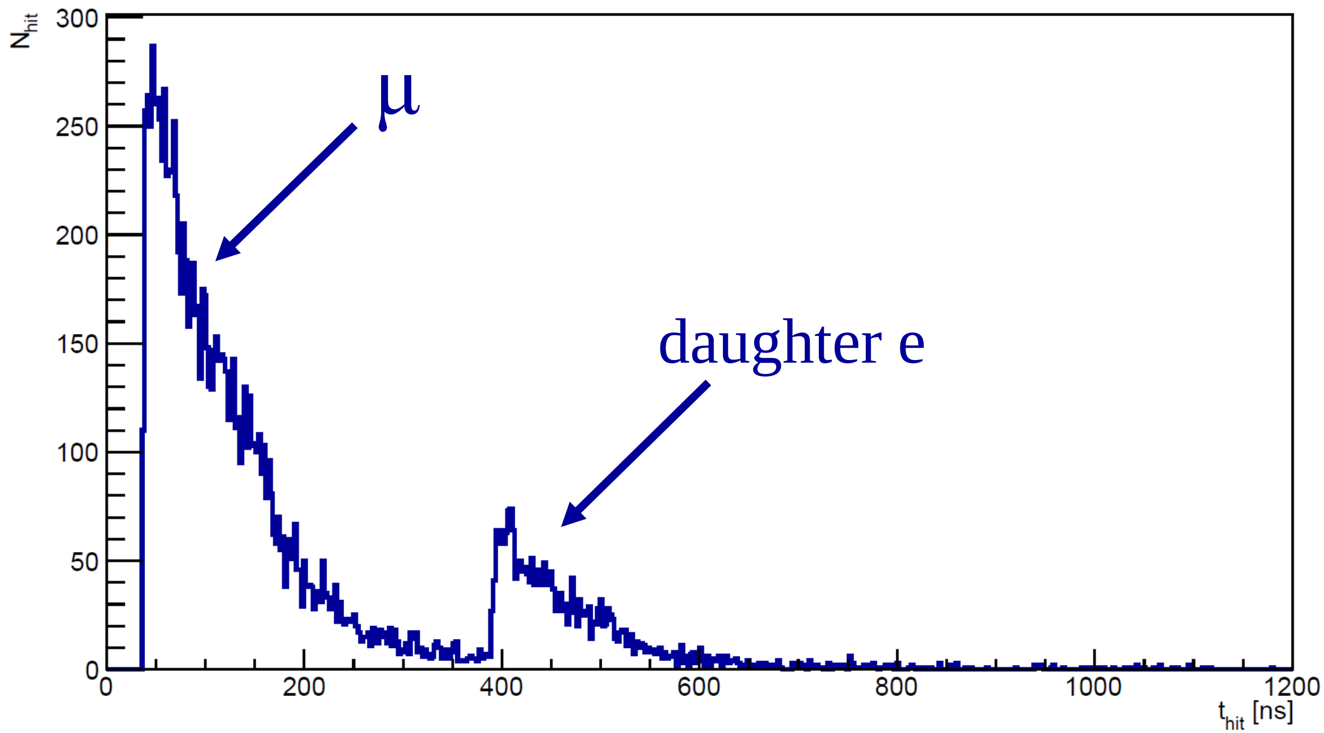


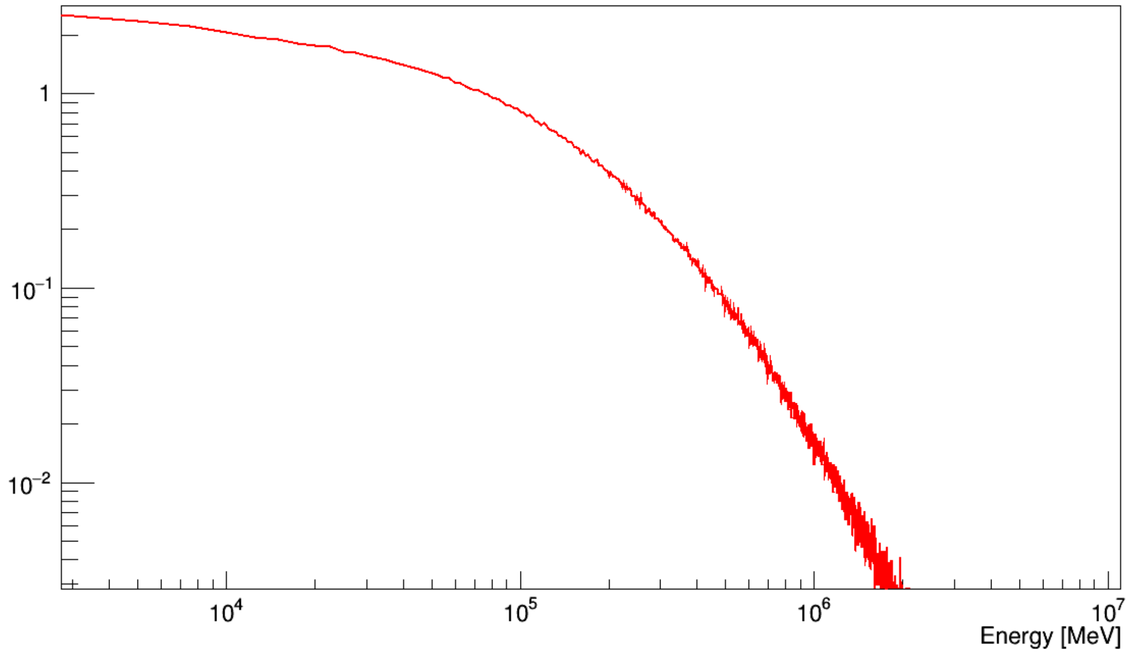
Flavor identification at low E

- Separation appears very good even when e/μ ranges are similar
- Idea: the major role in the light distribution difference is played by the Michel electron
  - Late light emission after the μ decay



Background

- Main source: cosmic muons, not tagged by veto system
- Even an high tagging efficiency have to be convolved with the much higher rate of μ:
  - $R_{\text{atmo}\,\mu}/R_{\text{atmo}\,\nu} \cong 10^6$



- Sampling of the spectrum to evaluate the background inside JUNO, in terms of PE → energy and inclination