Atmospheric neutrino spectrum reconstruction with JUNO

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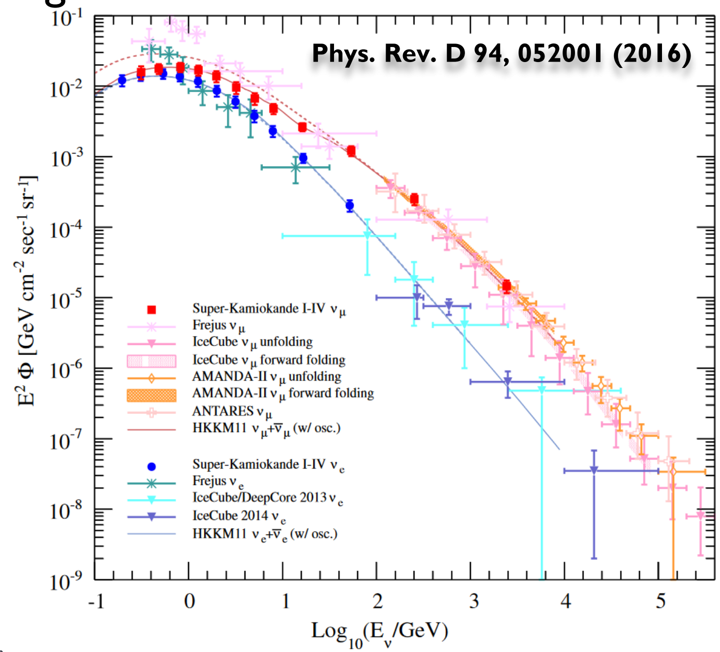
On behalf of the JUNO collaboration

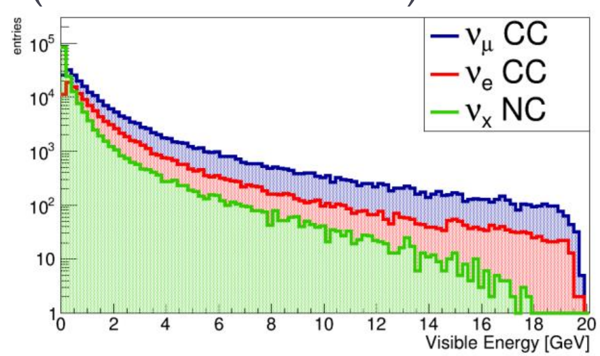
Outline

- Atmospheric neutrinos
- The JUNO detector
- Flavor identification
- $\nu_e + \nu_\mu$ spectra
- Uncertainties evaluation
- Summary and conclusions

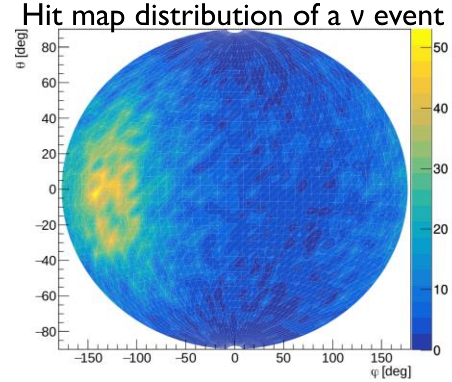
Atmospheric neutrinos

- Spectrum has been explored over a wide energy range
  - Some miscrepancies survive at low energy
- ν_e and ν_μ have different flux normalization
  - Different branching ratios of light mesons
  - ν_e from μ decay-in-flight are less abundant as the μ energy gets larger
- Present measurements come from Cherenkov detectors
  - Which performances with a LS – based one?
- MC simulation
  - HKKM14 flux model + GENIE (neutrino interactions) + GEANT4 (particle tracking)



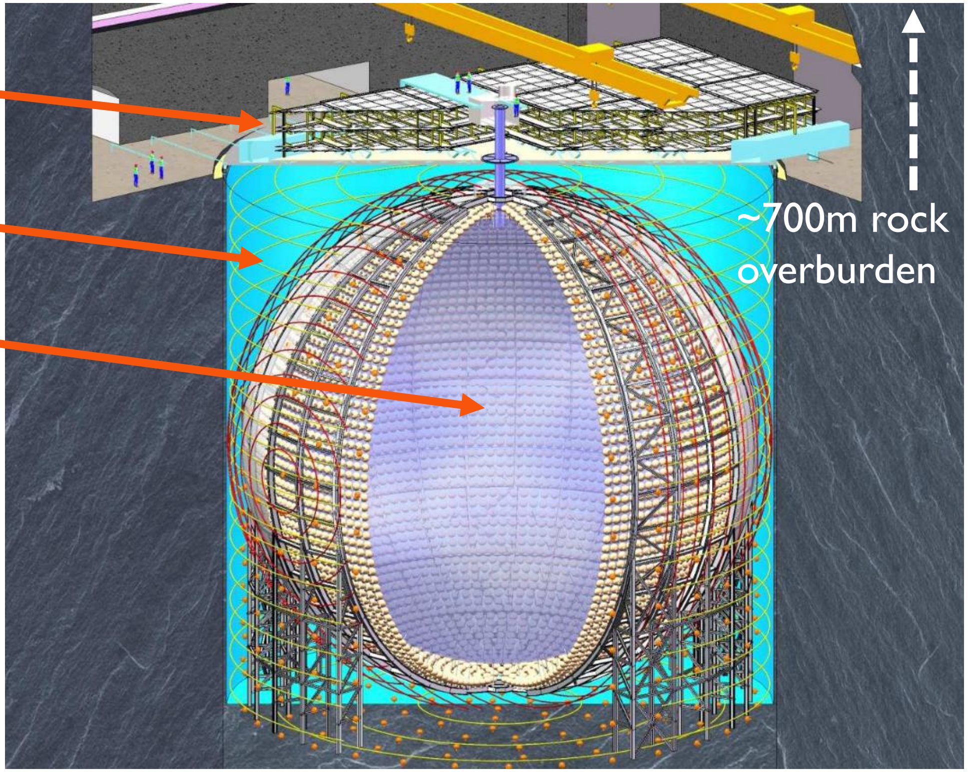


Hit map distribution of a ν event



The JUNO detector

- Top Tracker
  - Plastic scintillator stripes
- Outer water pool
  - Cherenkov μ veto, 2.400 x 20” PMTs
- Central 20 kt liquid scintillator
  - ~36 m diameter sphere
- Double photosensors system
  - 18.000 x 20” PMTs
  - 25.000 x 3” PMTs
- High photo-coverage (>75%), photon yield (10k ph/MeV) and energy resolution (< 3% @ 1 MeV)

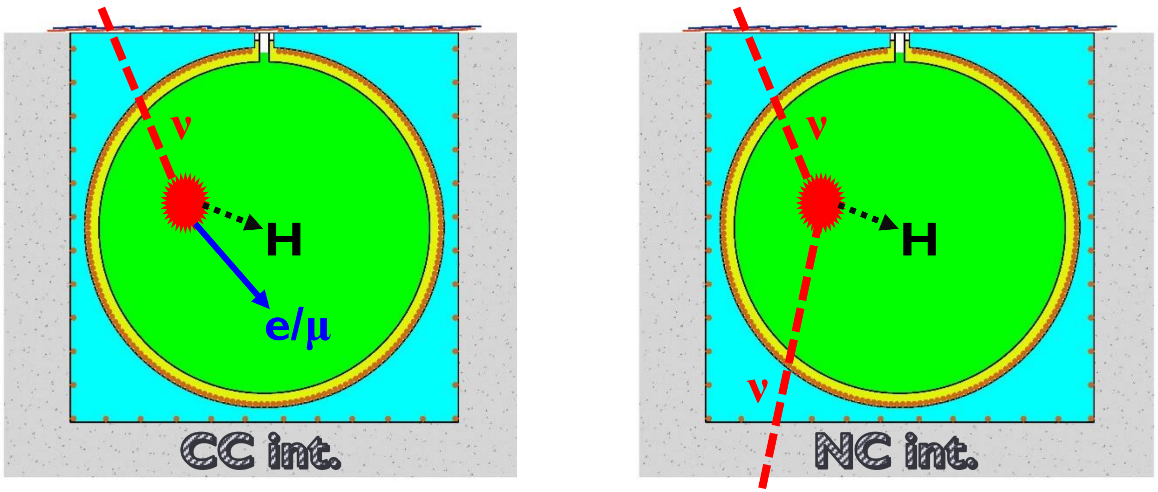


Data – taking to start in 2021

- Main goal: neutrino mass hierarchy determination through inverse beta-decays (IBD) of $\bar{\nu}_e$ with protons of the scintillator

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:
  - **νμ 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;
  - **νe 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.

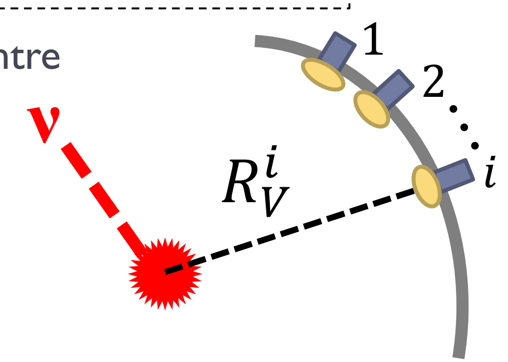


Flavor identification

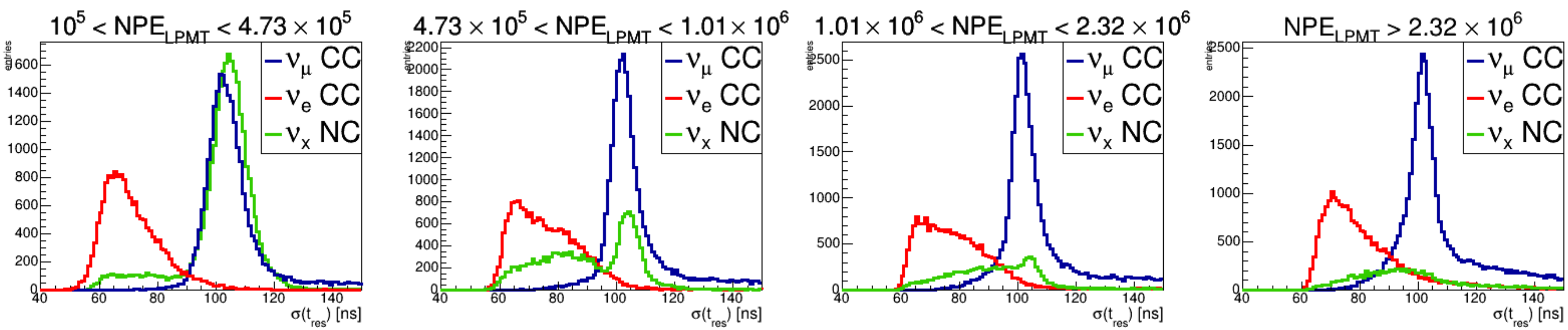
https://doi.org/10.1051/epjconf/201920901011

- A **time residual – based variable** tres is defined for each hit on the 3” PMT system (small time resolution): → $t^i_{res} = t^i_{hit} - \left(\frac{R^i_V \cdot n}{c}\right)$
  - **σ** = 1m gaussian smearing on the true vertex position to reproduce the experimental uncertainty conservatively
  - The new vertex is required to be within 16 m from the detector centre
  - **σ** = 4 ns gaussian smearing on the true vertex to simulate TTS
- Take the RMS of the profile → σ(tres)

t^i_{hit} : arrival time of the hit on the i-th PMT
R^i_V: vertex – i-th PMT distance



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

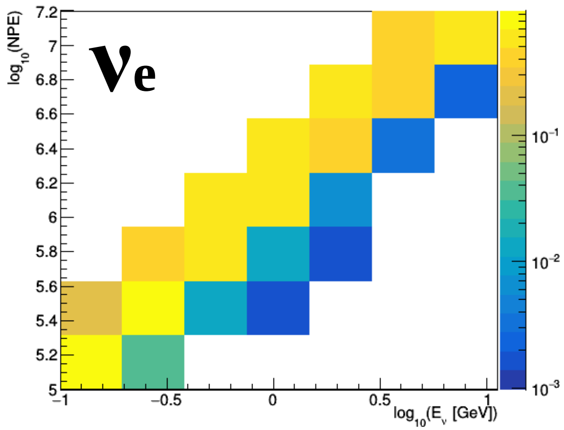


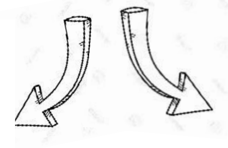
$\nu_e + \nu_\mu$ spectra

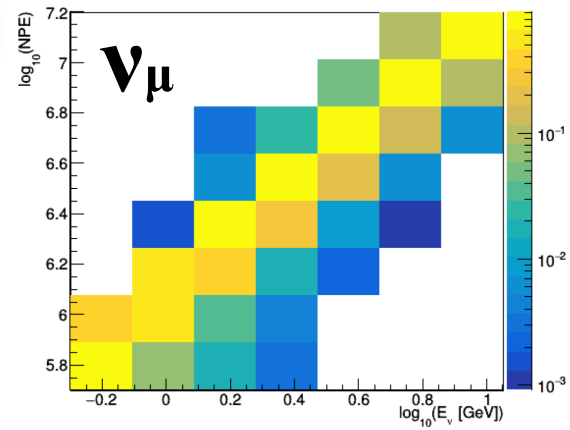
- Probabilistic unfolding algorithm to extract the spectrum (based on the Bayes theorem)

$$P(E)^{\nu_\alpha} = P(E|NPE_{LPMT})^{\nu_\alpha} \cdot P(NPE_{LPMT})^{\nu_\alpha} \qquad \alpha = e,\mu$$

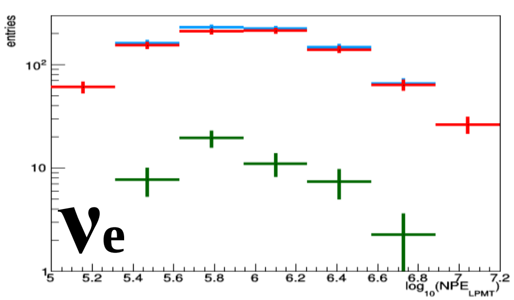
Unfolded spectrum **Detector observable**



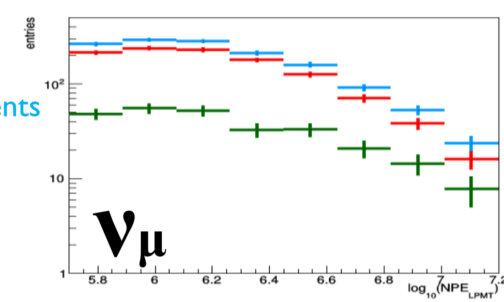




- <u>**10k ν events (~8 yrs) have been generated as real data**</u>



Blue: selected events
Red: selected sgn events
Green: res bkg



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Unfolded spectrum — **Detector observable**

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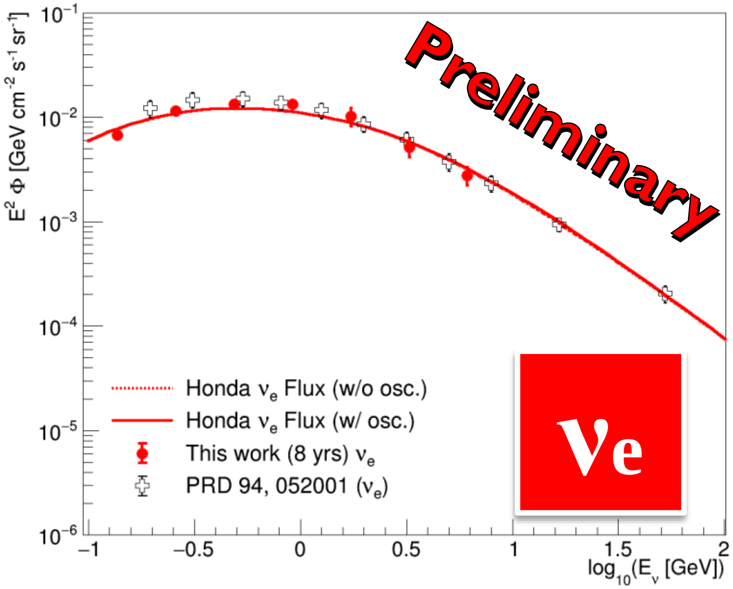
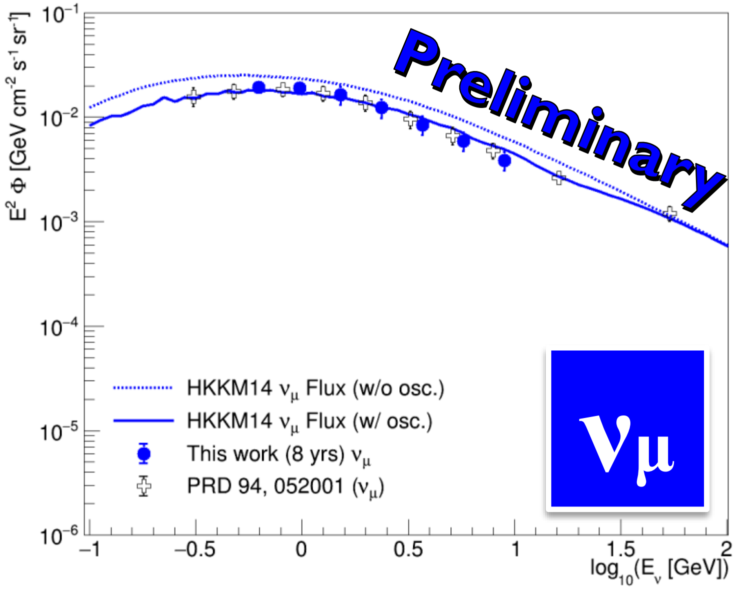
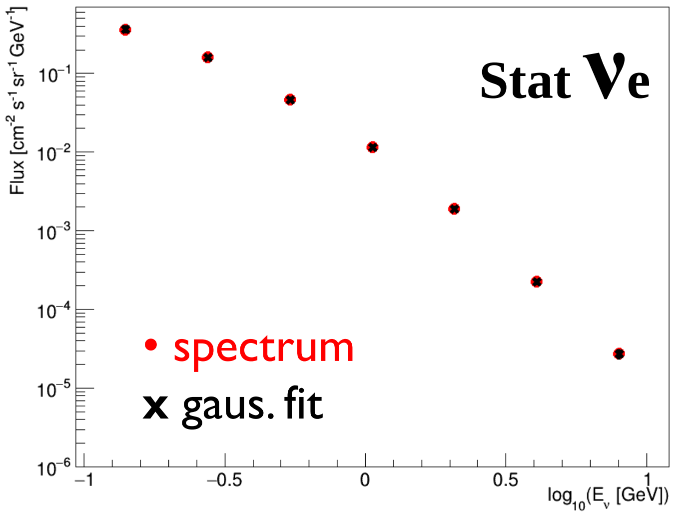
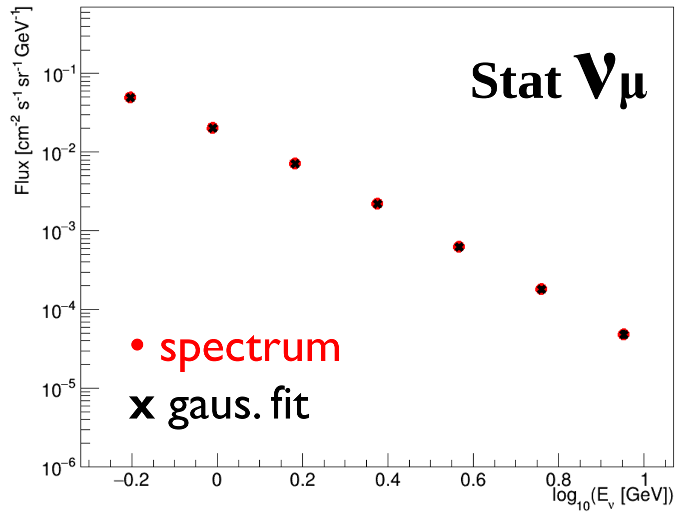




Uncertainties evaluation

- Statistical error is between 2 – 10 %
  - 1000 toys, varying the input NPE distribution





- Comprehensive evaluation of systematics is still ongoing
  - Main contribution from cross section uncertainties
  - Preliminary estimations: total contribution around 25 %

Summary and conclusions

- JUNO has potential to measure the atmospheric neutrino energy spectrum
  - Advantages: large fiducial volume and energy resolution
- Time information allows a good discrimination power between ν_e and ν_μ flavor
- Energy spectrum can be measured with a ~25 % uncertainty within 8 yrs detector livetime
- Correct understanding of systematics is crucial to estimate the final detector sensitivity

Backup slides

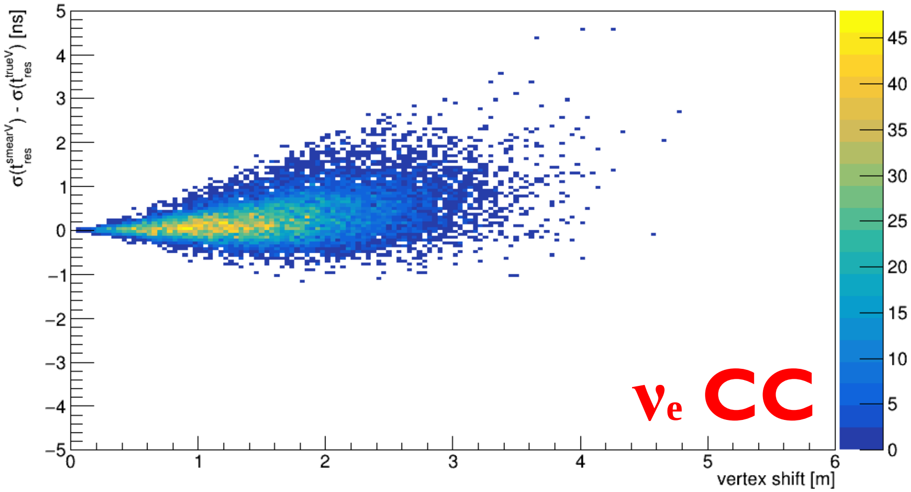
Cosmic μ rejection

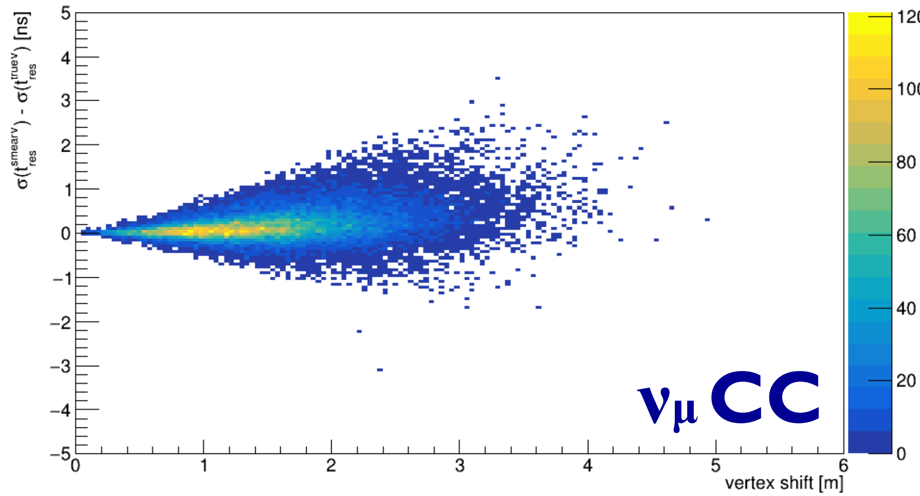
- Cosmic Muons can contaminate the atmospheric neutrino sample
- Several order of magnitudes of difference bewtween atm. ν and cosm. μ rates
  - Cosm. μ can mimic the atm. ν topology
- Given the high CPU time needed to perform a full simulation of a cosm. μ, a toy MC model has been built
- The (2D) model implements a simplified JUNO geometry and simulates the physical processes for light production and detection
  - Stochastic fluctuations included
- The toy model reproduces the expected veto performances (simple majority 98%)

- Cosm. μ are expected to produce an high amount of light both in the water cherenkov veto (WV) and in the central detector (CD)
  - Require NPE < 60 in WV and NPE_{LPMT} > 100K in CD
- Toy MC gives a rejection power < $1.15 \cdot 10^{-6}$ @ 90% CL

Flavor identification

- σ(tres) spread VS the vertex shift





- The spread remains within a few ns