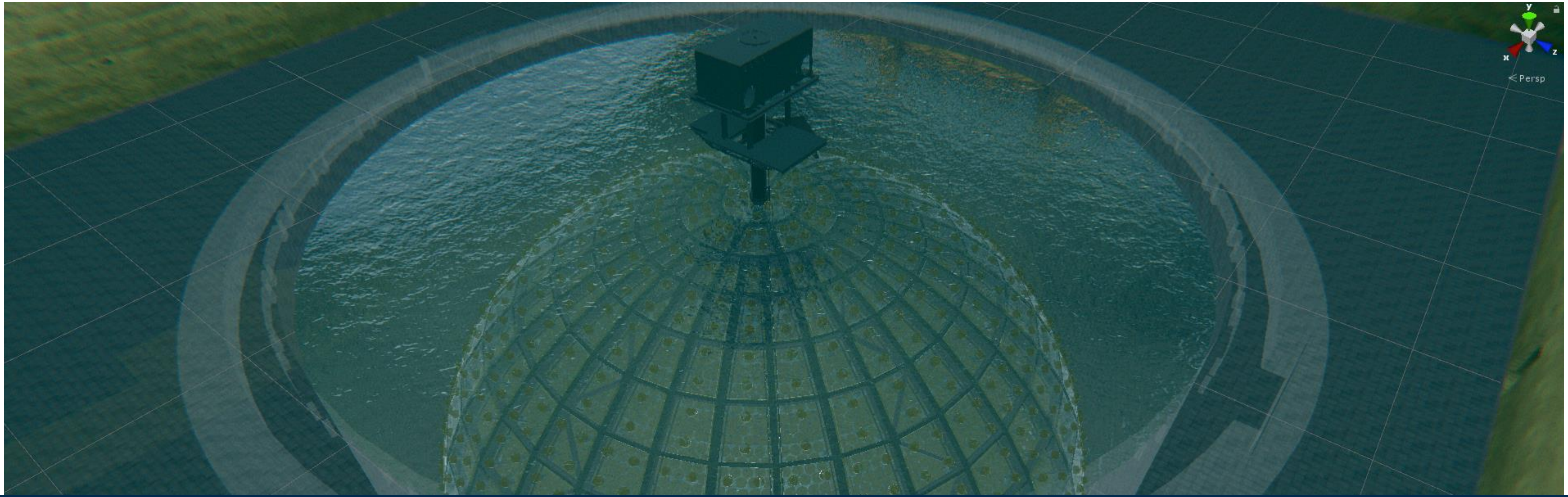


ATMOSPHERIC NEUTRINO PHYSICS WITH JUNO

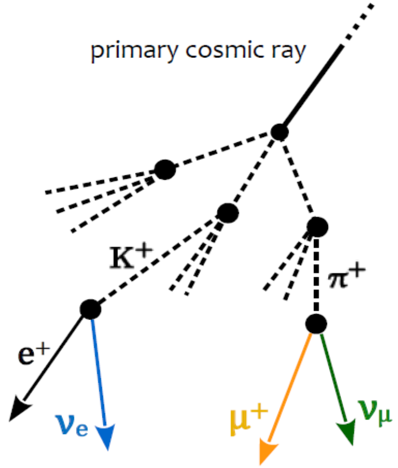
Giulio Settanta, on behalf of the JUNO Collaboration

Institut für Kernphysik, Forschungszentrum Jülich, Germany

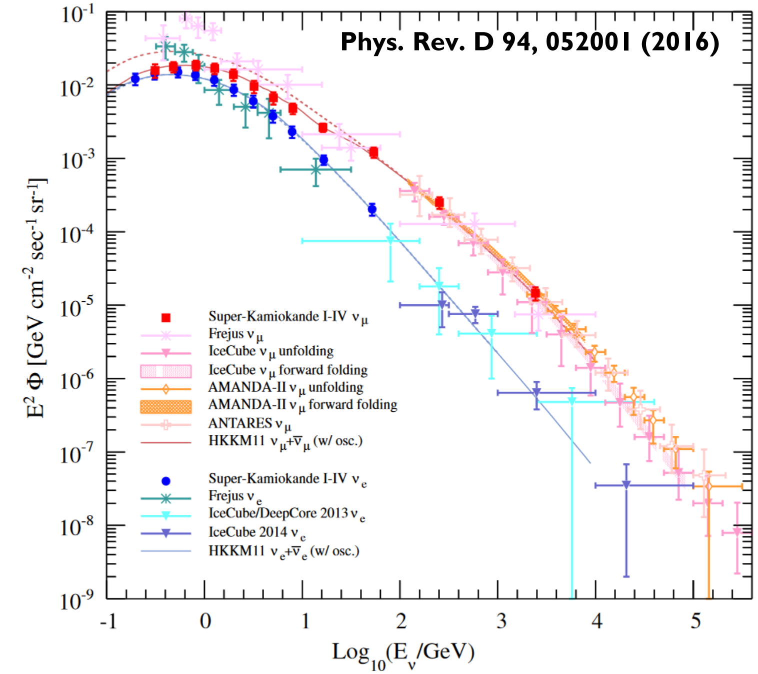
NeuTel 2021 Workshop - Neutrino Masses and Mixings - 22.02.2021

ATMOSPHERIC NEUTRINOS

- Atmospheric ν flux is detected at Earth as the result of Cosmic Rays interaction in the atmosphere and secondary hadrons decays
- "Conventional" flux from π and K dominates the spectrum
- Different branching ratios imply different flux normalizations



- Present measurements come mainly from Cherenkov detectors

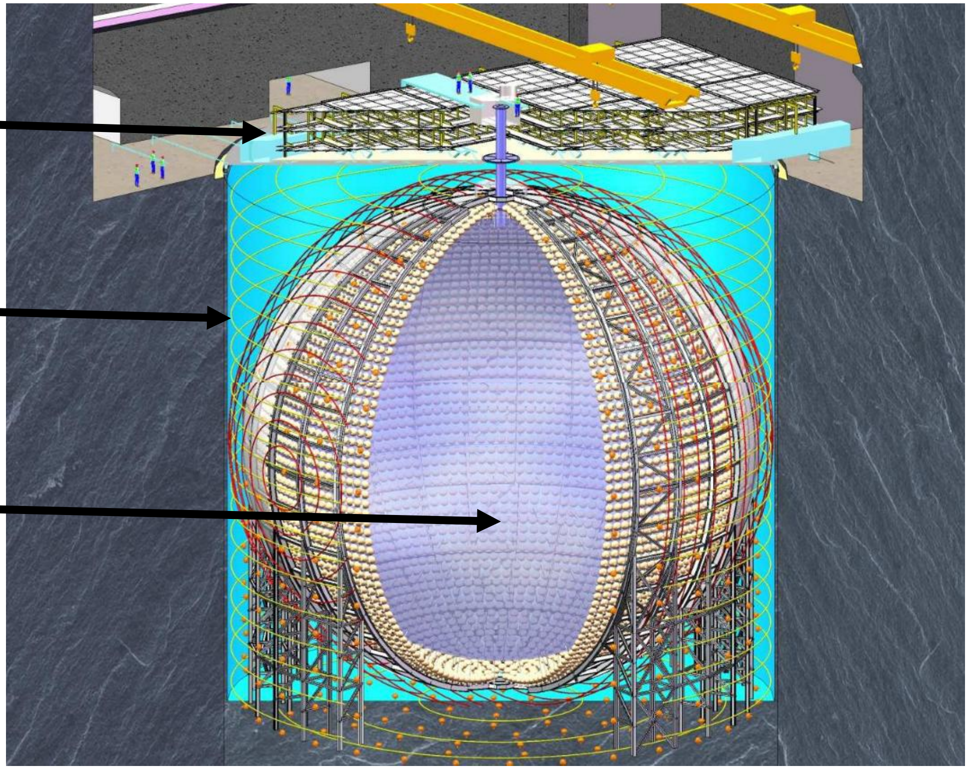


- **Next – generation liquid scintillators can contribute as well**
  - Large size and fine energy resolution
  - Reduced ability to reconstruct single – particles. But:
  - Low detection threshold
  - → <u>Great potential in exploring the low energy range</u>
  - Crucial input for theoretical models

- Which impact can a future LS – based detector like JUNO have?

JUNO DETECTOR

- Top Tracker
  - Plastic scintillator strips
  - Atm. μ median angular resolution ~ 0.2°
- Outer Water Pool (WP)
  - Cherenkov μ veto, 2400 20” PMTs
  - > 99.5% μ detection efficiency
- Central 20 kt liquid scintillator
  - ~ 36 m diameter acrylic sphere
  - 17600 20” PMTs
  - 25600 3” PMTs
- High photo – coverage (> 75%), photon yield (10k / MeV) and photon detection efficiency (> 28%)
- Main goal: neutrino mass hierarchy determination
- Construction complete in 2022
- Suitable for many other measurements, like atmospheric neutrinos!

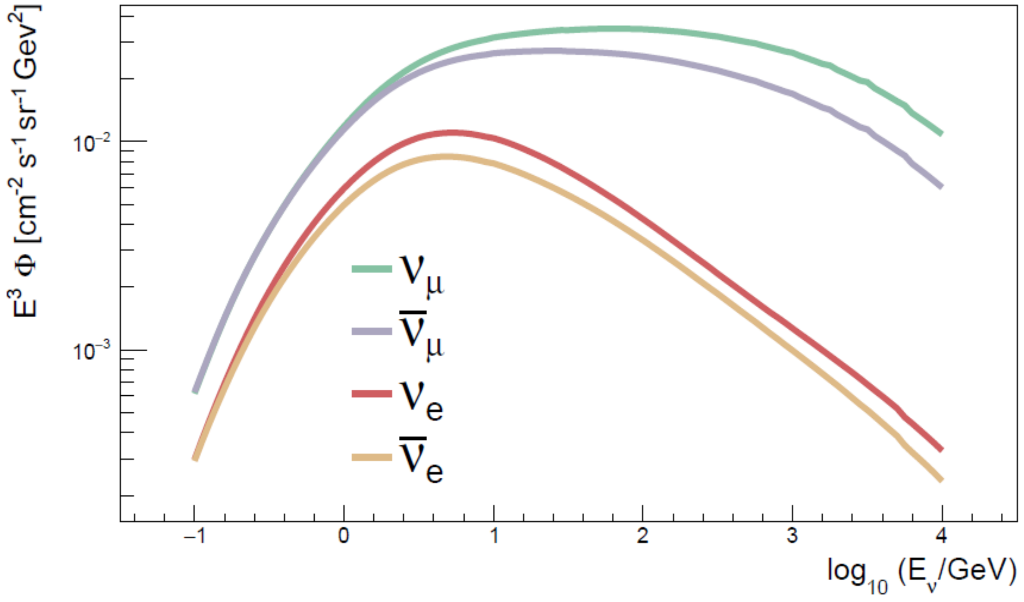


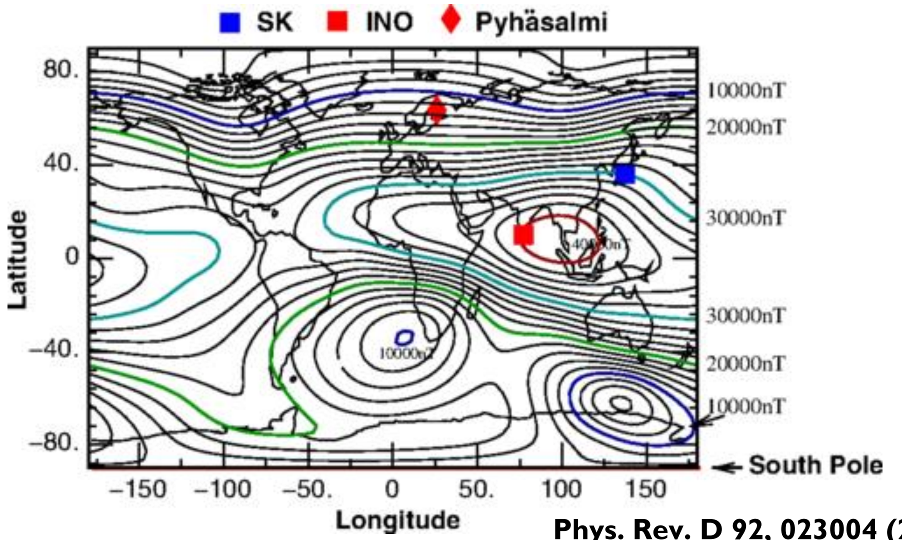
For more details:
- H. Steiger - JUNO Detector Design & Status
- Donglian Xu – JUNO plenary talk

MC SIMULATION

- The starting point is the initial flux assumption
- In this work, the HKKM14 model was used, at the JUNO location
  - ν energy, flavor, direction, ...
  - 3D MC model
  - Rigidity cutoff included
  - Total uncertainty < 10 % between 1 and 10 GeV

- JUNO can play a major role in measuring the flux in the sub – GeV energy region!





Phys. Rev. D 92, 023004 (2015)

MC SIMULATION

- The simulation is divided into 2 main steps:

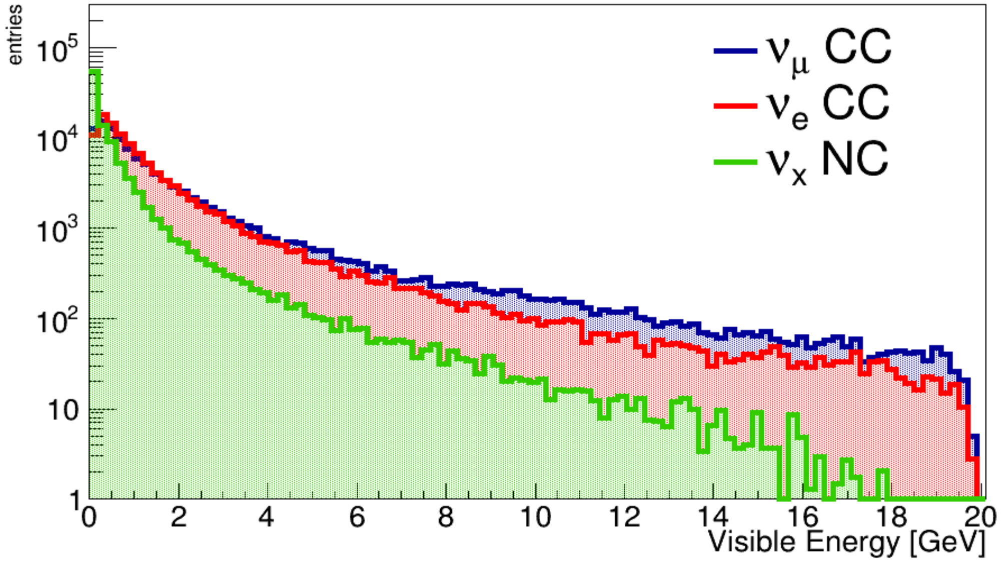
Step 1:

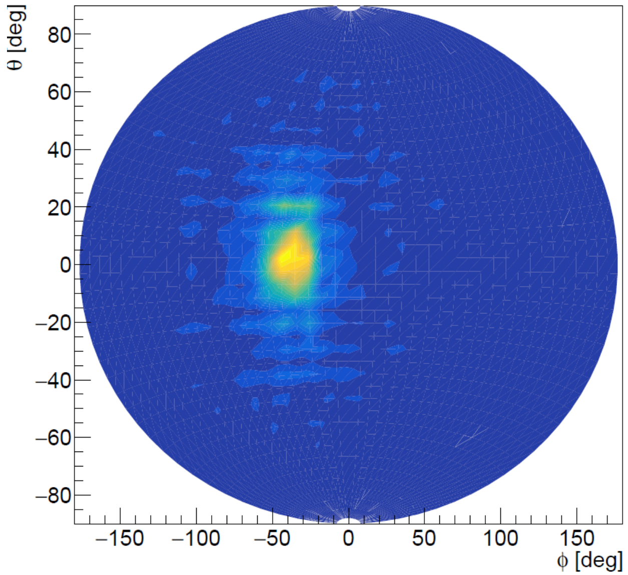
- Neutrino interaction generation inside the detector:
  - **Max energy:** 20 GeV
  - **Statistics:** ~ 400 y $\nu_e + \nu_\mu$ (and antineutrinos)
  - **Flux model:** HKKM14
  - **Software:** GENIE Neutrino Monte Carlo Generator

Step 2:

- Propagation of secondary particles
  - GEANT4 – based simulation
  - Interaction with photo – cathode included
  - *J. Phys.: Conf. Ser. 664 072053 (2015)*

- Oscillation effects included (vacuum + matter)





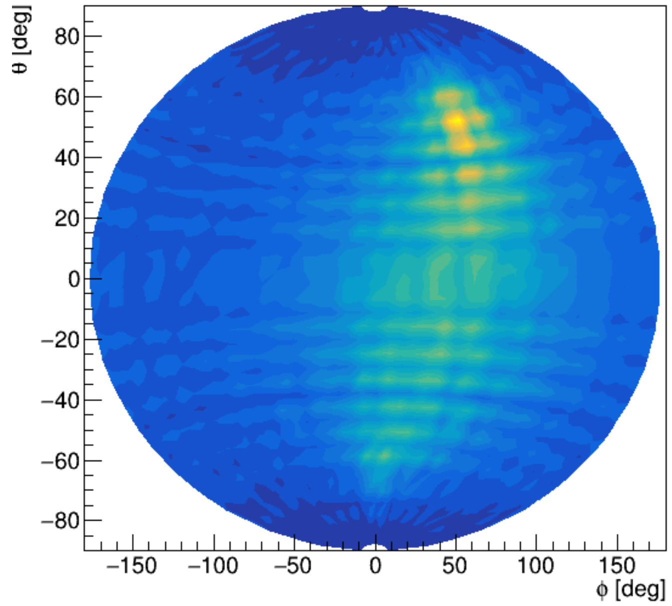
Hitmap on 3″ PMT system of a ν_e CC event, with initial energy of 900 MeV

Sample selections and flavor identification

ATMOSPHERIC μ REJECTION

- Atm. μ can contaminate the atm. ν sample
- Several orders of magnitude difference between atm. ν and atm. μ rates
  - Atm. μ rate in the CD: 3 – 4 Hz
  - Atm. μ are able to mimic the atm. ν topology
- Full MC simulation of atm. μ to evaluate the impact on the analysis
- Dark noise can be a relevant issue in WP PMTs, so it has been included
  - Single PMT – dark noise rate: several tenths of kHz

  Haiqiong Zhang et al 2020, J. Phys.: Conf. Ser.1468 012197



Hitmap on 3″ PMT system of a μ event, with 9 GeV deposited energy

- Key point for atm. μ rejection: they produce an high amount of light both in the WP and in the Central Detector (CD)

Atm. ν → much light in CD and no light in WP
Atm. μ → much light in CD and much light in WP

Selection cuts:

NHITS in WP < 50 + NPELPMT in CD > 10^5

atm. μ survival fraction @ 90% CL:

$$\varepsilon_\mu < 2.3 \times 10^{-5}$$

FIDUCIAL CUTS

- Targets:
  - Exploit calorimetric features of JUNO select Fully – Contained (FC) events
  - Select well – reconstructed events
  - Remove atm. μ events

Selection / Eff.	ν_e	ν_μ
$R_{VERTEX} < 16$ m	74%	74%
$N_{HIT}^{WP} < 50$	92%	85%
Total	68%	63%

- R_{VERTEX} ≡ vertex – center distance
  - $\rho_{RECO}(x', y', z') = \rho_{TRUE}(x, y, z) \oplus f_{GAUS}(\sigma = 1\ m)$ to reproduce uncertainty

- After fiducial cuts, the sample is composed at 97% of FC events (non – FC are almost all ν_μ)

FLAVOR IDENTIFICATION

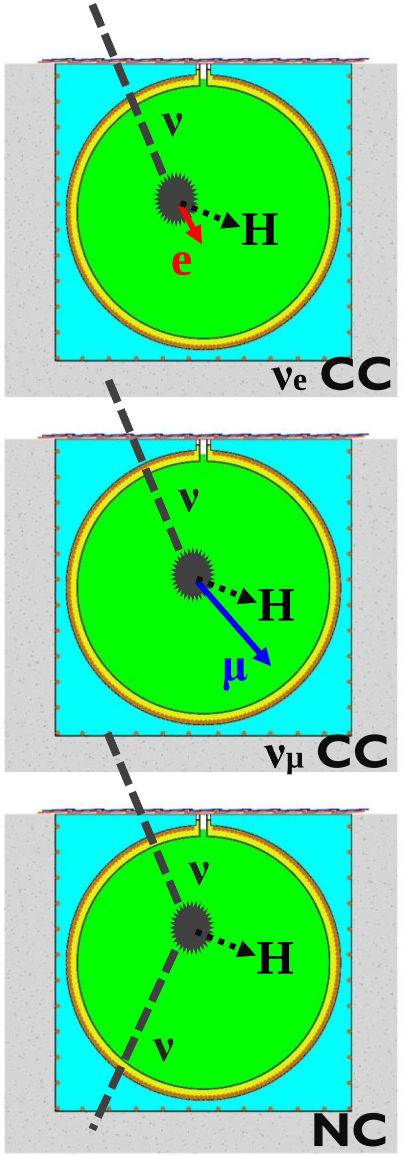
- The original neutrino flavor is inferred by timing information
- Event classification:
  - **ν_μ CC interaction**: ν_μ + ^{12}C / p → μ + H, event elongated in time because of μ ability to travel long distances and its late decay;
  - **ν_e CC interaction**: ν_e + ^{12}C / p → e + H , point-like event because of the short e track;
  - **NC interaction**: ν_x + ^{12}C / p → ν_x + H , 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).

$$t^i_{res} = t^i_{hit} - \left(\frac{R^i_V \cdot n}{c}\right)$$

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

  - σ = 1.6 ns gaussian smearing on the true vertex to simulate TTS
- Take the RMS of the profile → **σ(tres)**

EPJ Web Conf. 209 01011 (2019)



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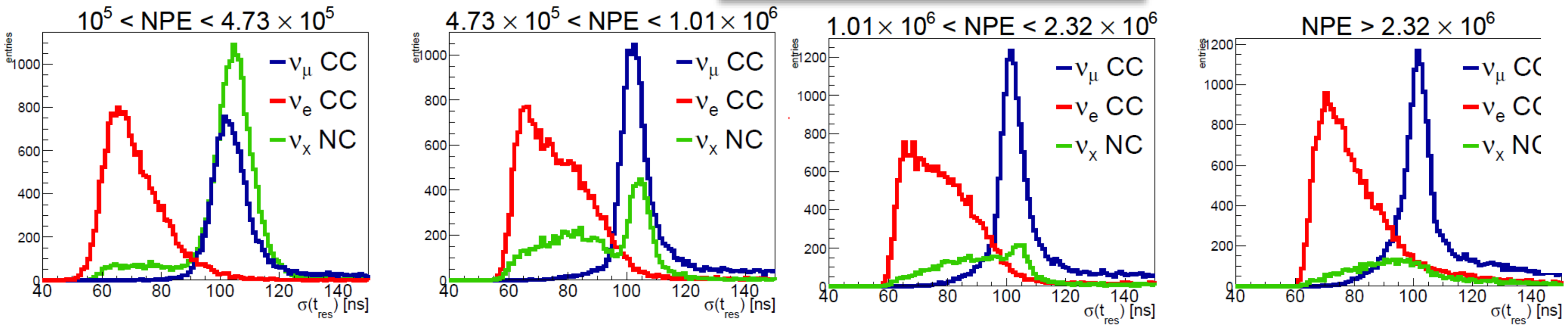

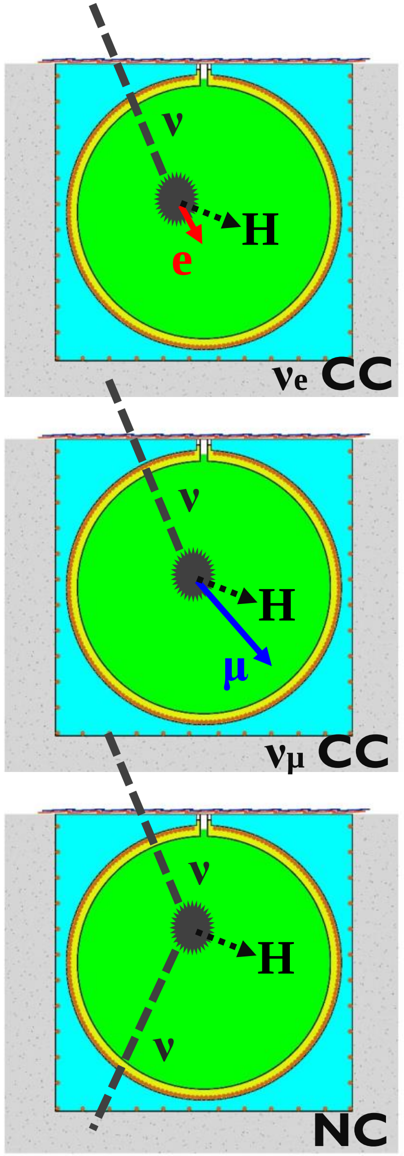

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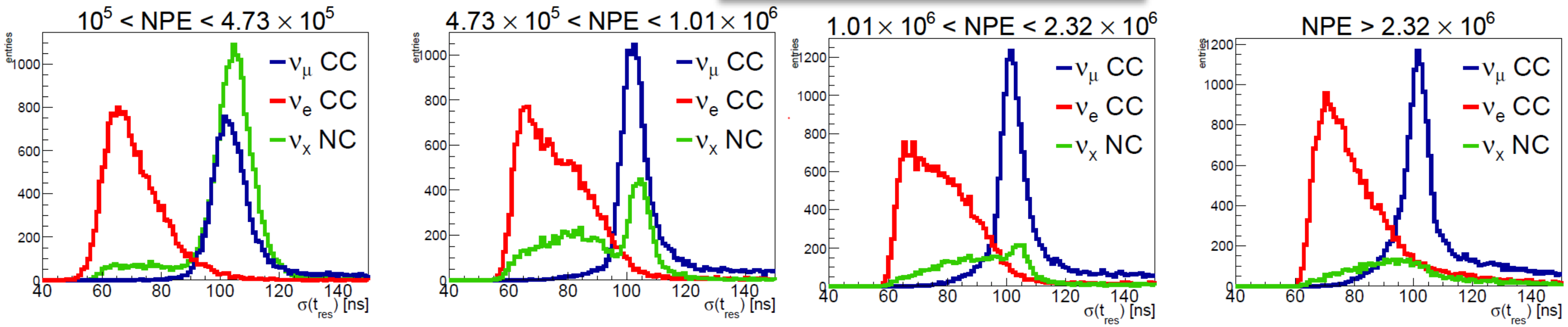
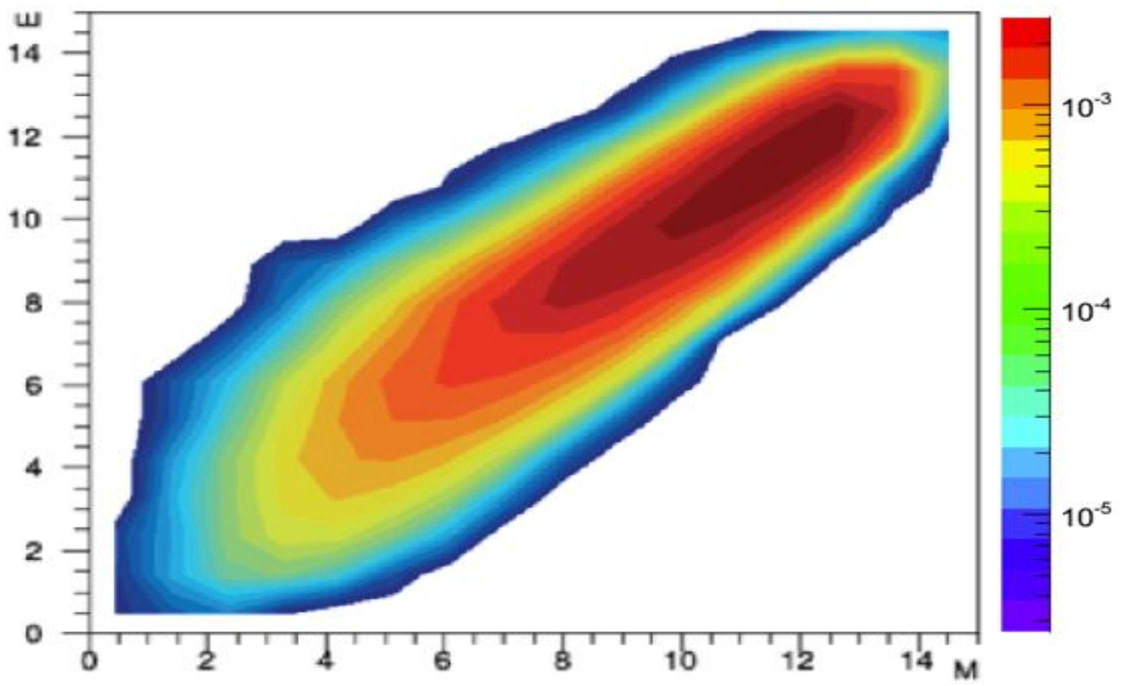
EPJ Web Conf. 209 01011 (2019)

Cut for **νe**: σ(tres) < 75 ns
5.0 < log(NPELPMT) < 7.2
EFF: ~26% **CONT**: ~5%

Cut for **νμ** : σ(tres) > 95 ns
5.7 < log(NPELPMT) < 7.2
EFF : ~35% **CONT**: ~20%

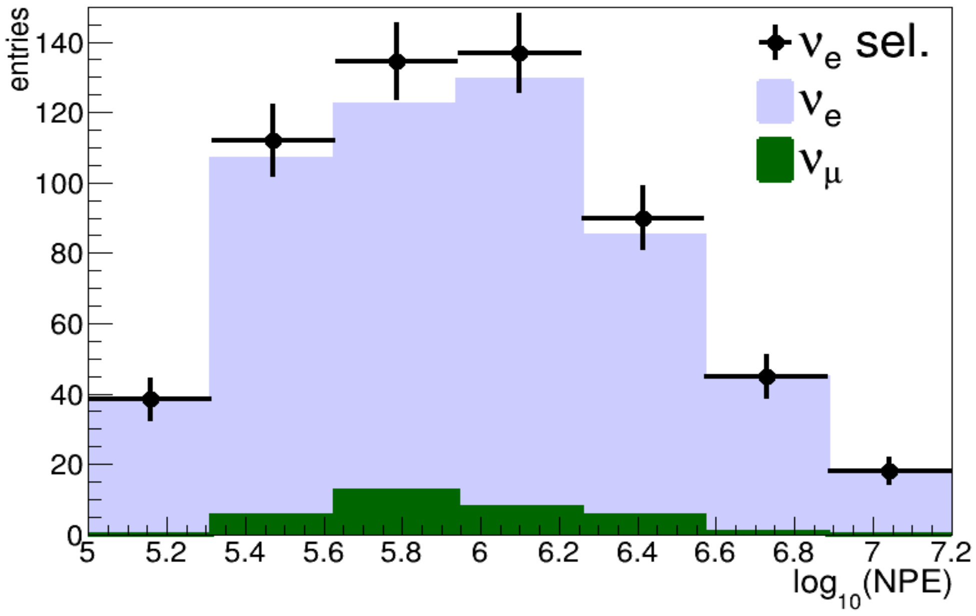


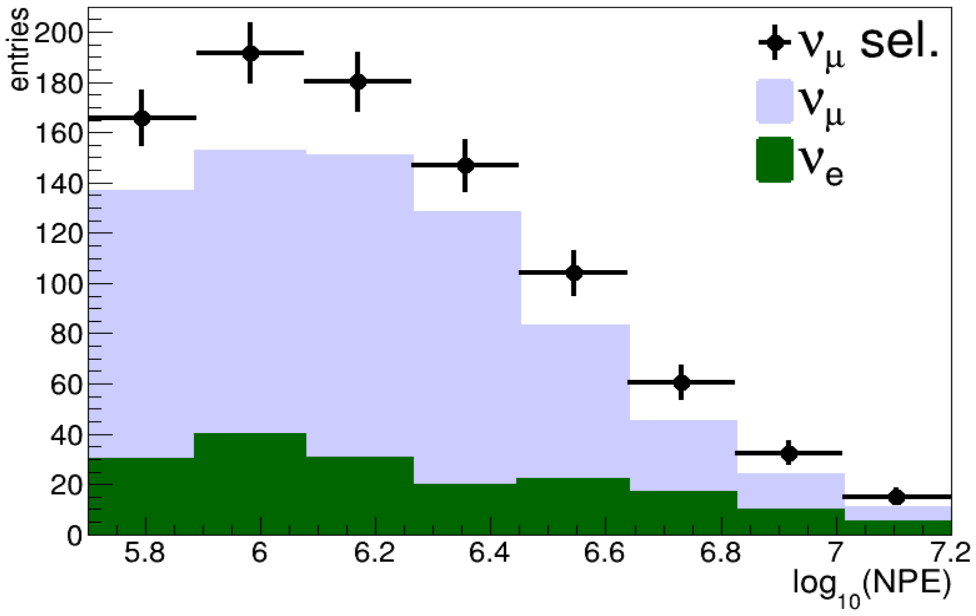


Spectrum reconstruction

SPECTRUM UNFOLDING

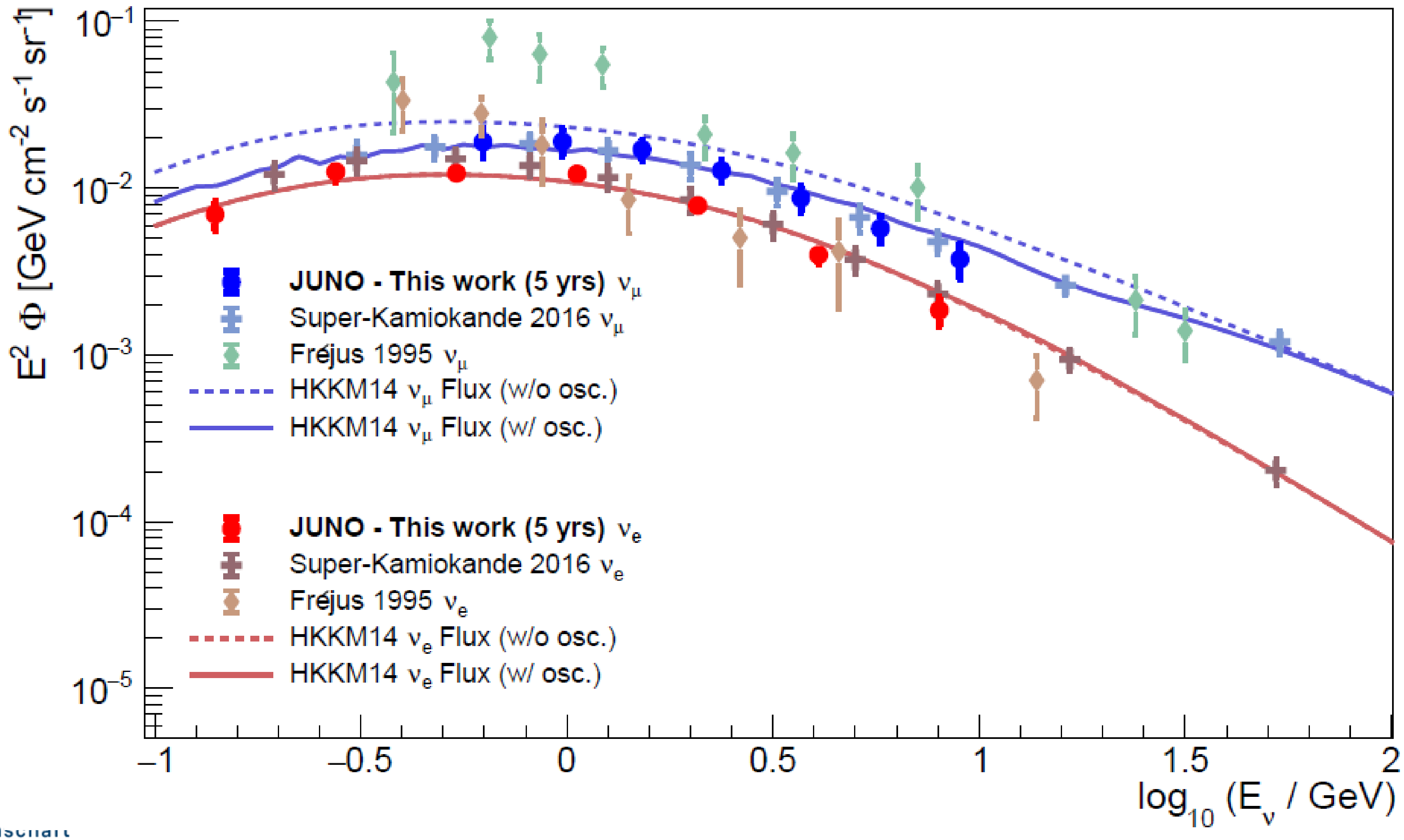
- Probabilistic method to extract the energy spectrum from detector observables
  - Based on Iterative Bayesian Unfolding
    - G. D'Agostini, Nucl.Instrum.Meth.A 362 (1995) 487-498
    - G. D'Agostini, arXiv:1010.0632
- **~5 yrs of detector livetime MC events have been generated as real data**
  - Observable distribution, after all selections:





$\nu e + \nu\mu$ SPECTRA

$$\underbrace{P(E)^{\nu_\alpha}}_{\text{Unfolded spectrum}} = P(E|NPE)^{\nu_\alpha} \cdot \underbrace{P(NPE)^{\nu_\alpha}}_{\text{Detector observable}} \qquad \alpha = e,\mu$$



SUMMARY AND CONCLUSIONS

JUNO has potential to measure the atmospheric neutrino energy spectrum

- Advantages: low energy threshold and fine energy resolution
- Sub – GeV to multi – GeV energy range
- First measurement with a LS – based detector
- Pushing measurements in multi – MeV region, interesting for rare event searches

- Time information allows a good discrimination power between ν_e and ν_μ flavor
- Energy spectrum can be measured within a 25% uncertainty in 5 yrs of detector livetime: **systematics dominated**
- Flux entirely available from beginning of data taking!

- Paper in preparation for peer-reviewed journal
  - Internal review almost complete

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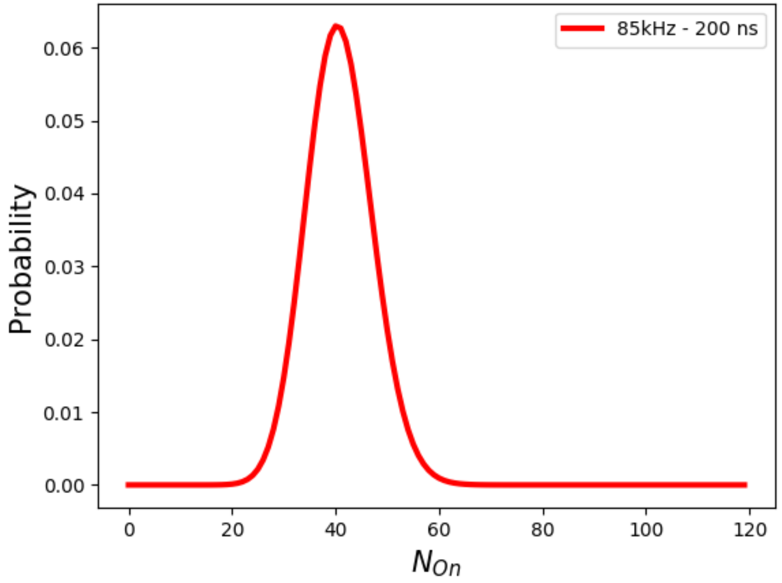
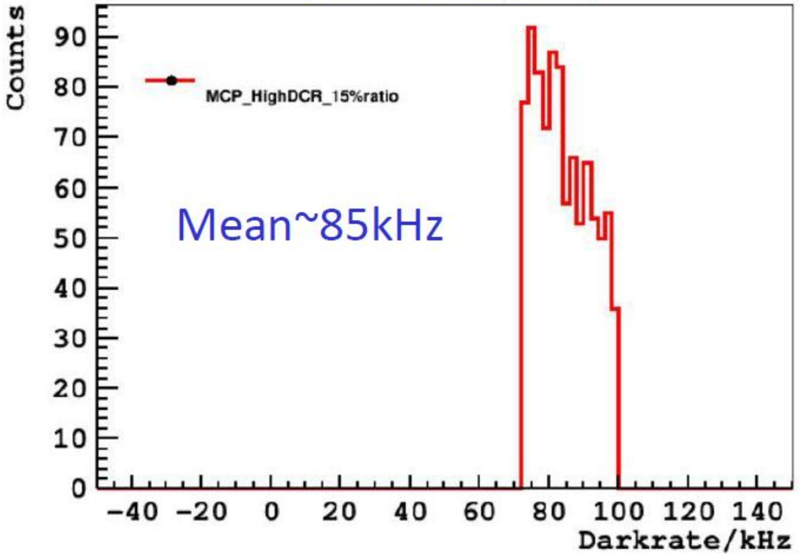
Backup slides

DARK CURRENT RATE (DCR) IMPACT

- DCR has been added to the simulation
  - Value of WP LPMTs DCR from 15% highest noise PMTs
  - μ momentum distribution from calculations within the collaboration
  - 200ns time window, targeted for cosmic μ
  - PDF of DCR:

$$P(m) = C_N^m (f\tau)^m (1 - f\tau)^{N-m}$$

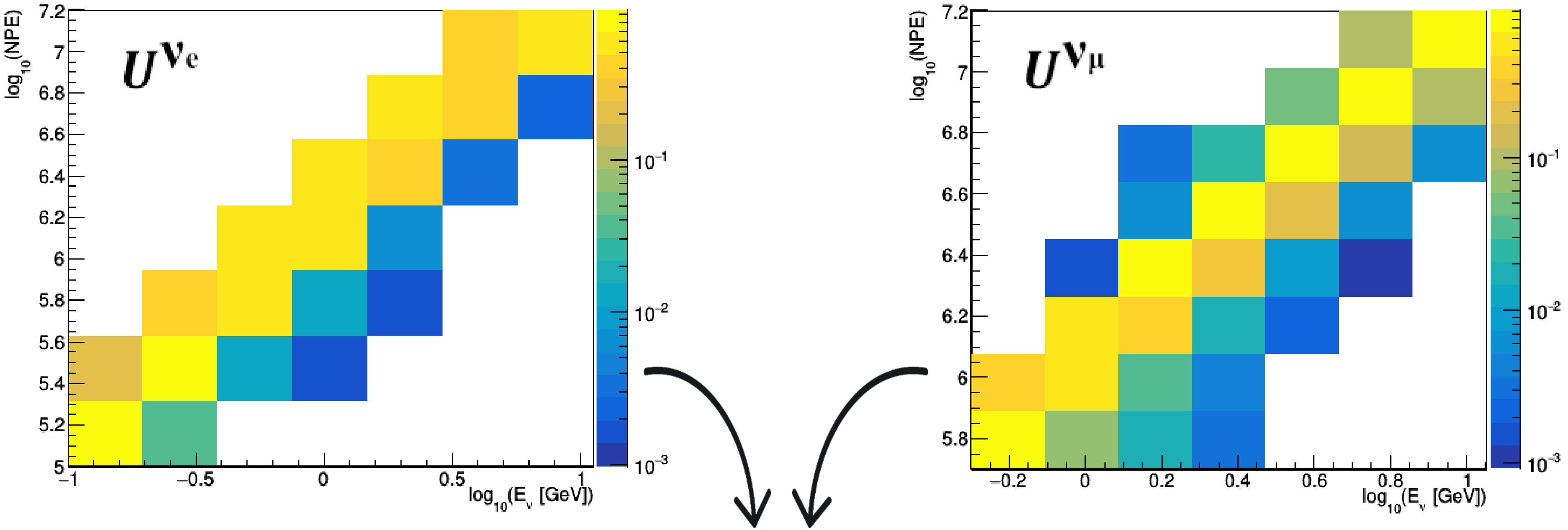




m = fired NPMTs
N = 2400
f = 85 kHz
τ = 200 ns

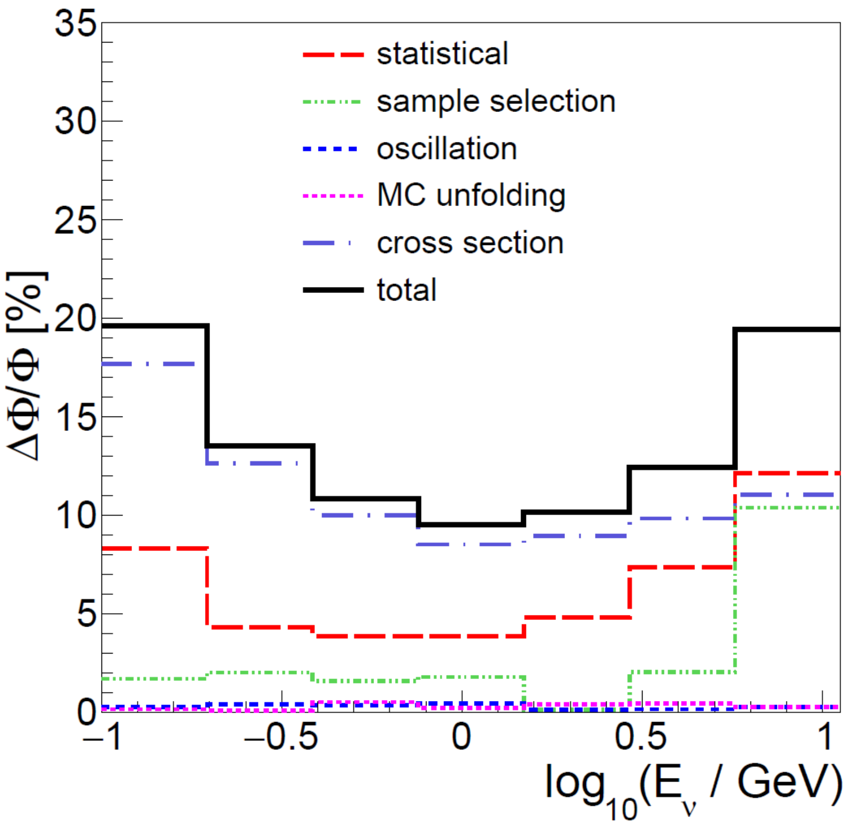
SPECTRUM UNFOLDING

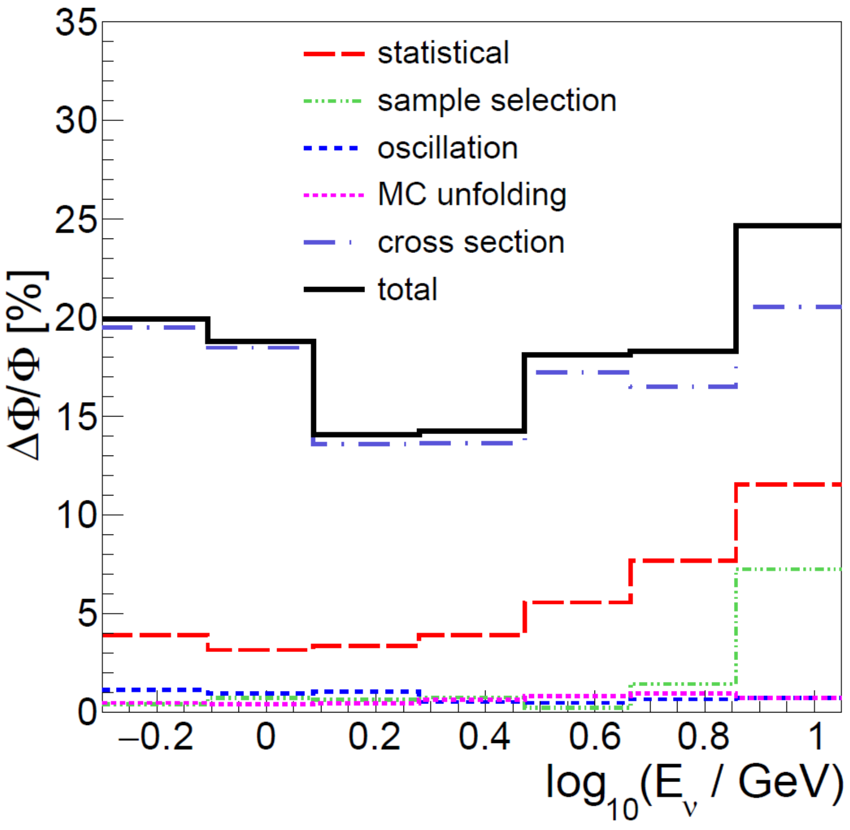
- The unfolding matrix can be interpreted as a conditional probability
- It links the effect (the observable) to the cause (the energy spectrum)



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

SYSTEMATICS BALANCE

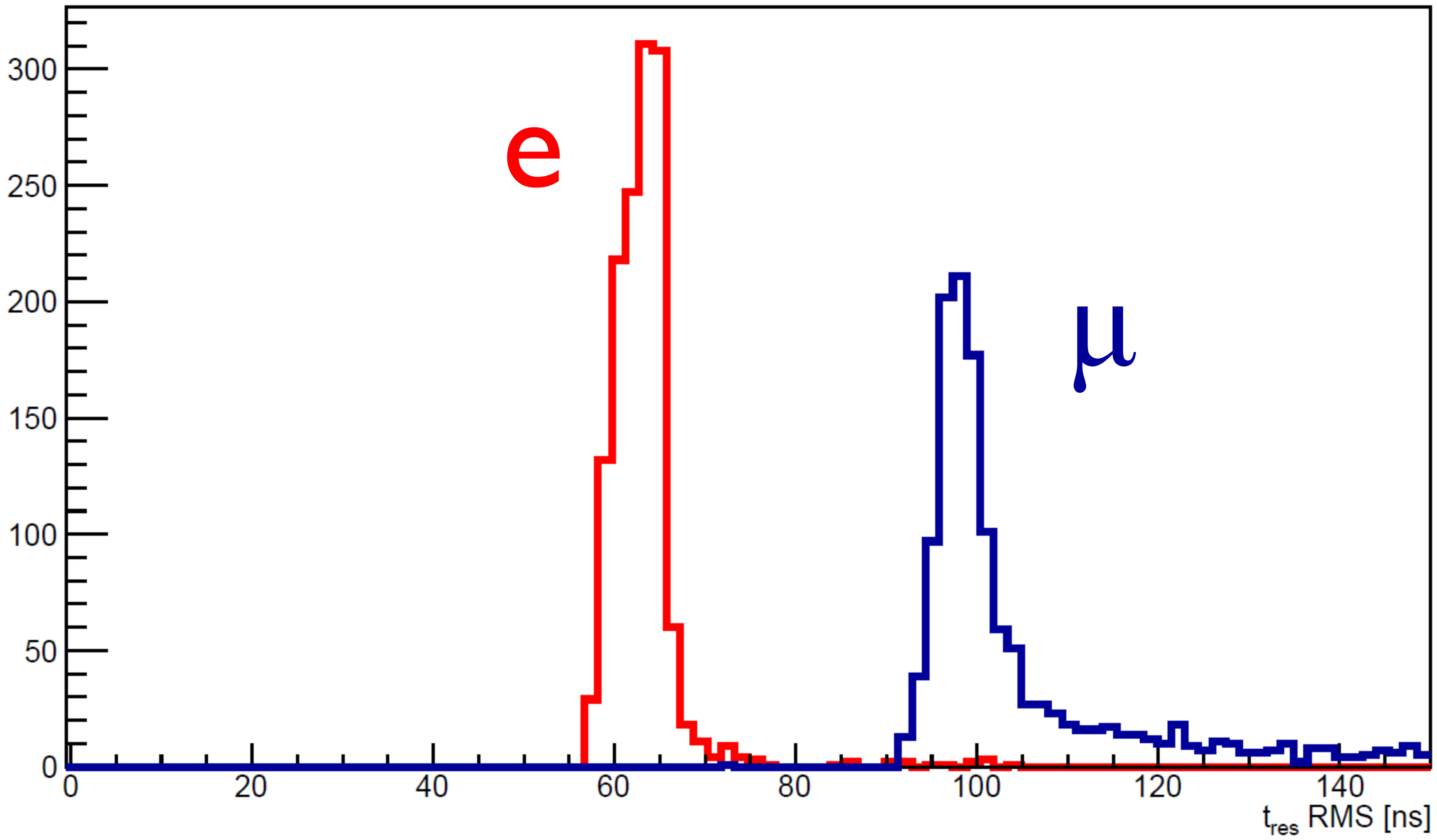




- Total uncertainty between 10 – 25%
- Dominant contribution from cross – section

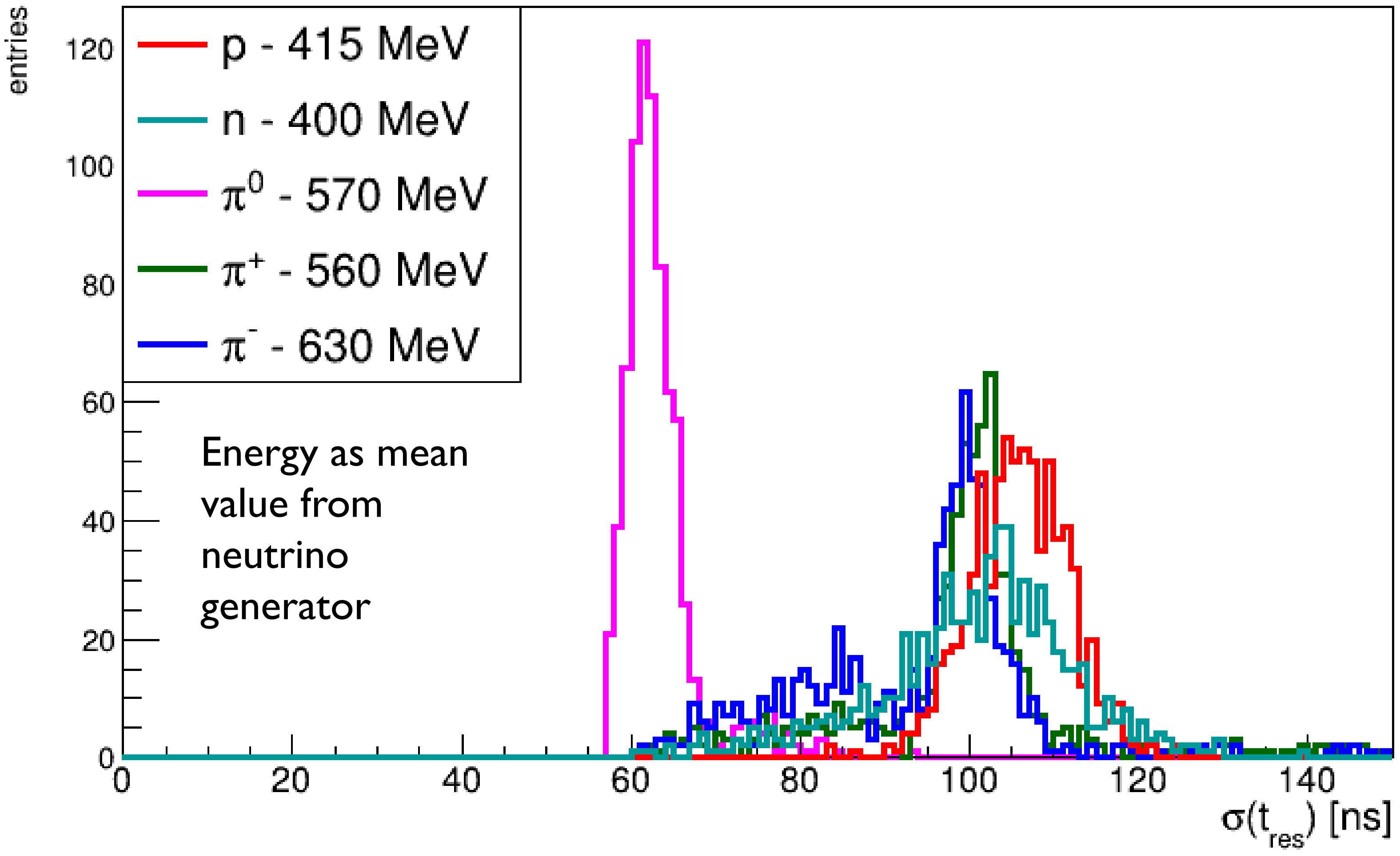
σ(t_{res}) FEATURES

- Distribution of σ(t_{res}) for pure leptons at 1 GeV



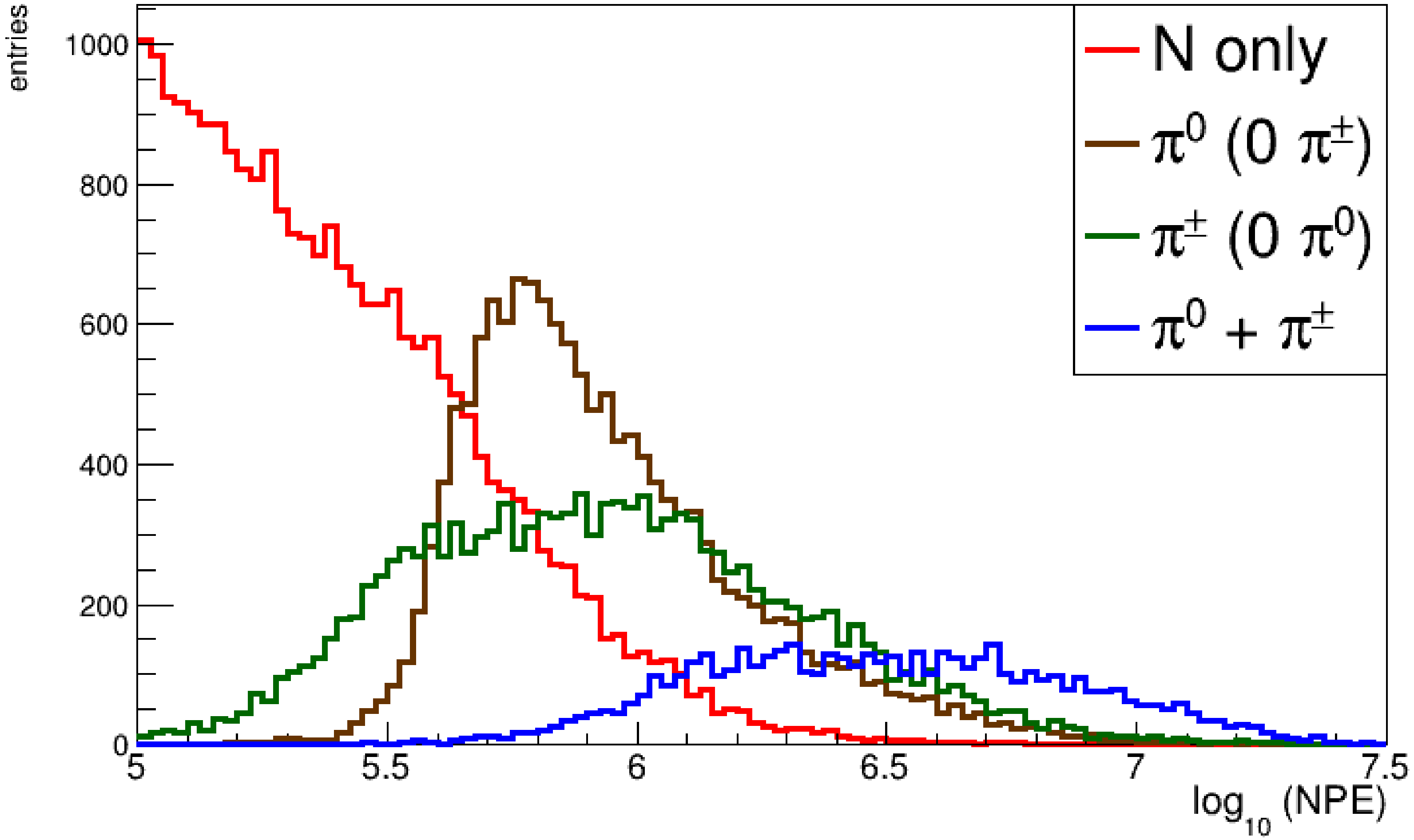
σ(tres) FEATURES

- Distribution of σ(tres) for pure hadrons



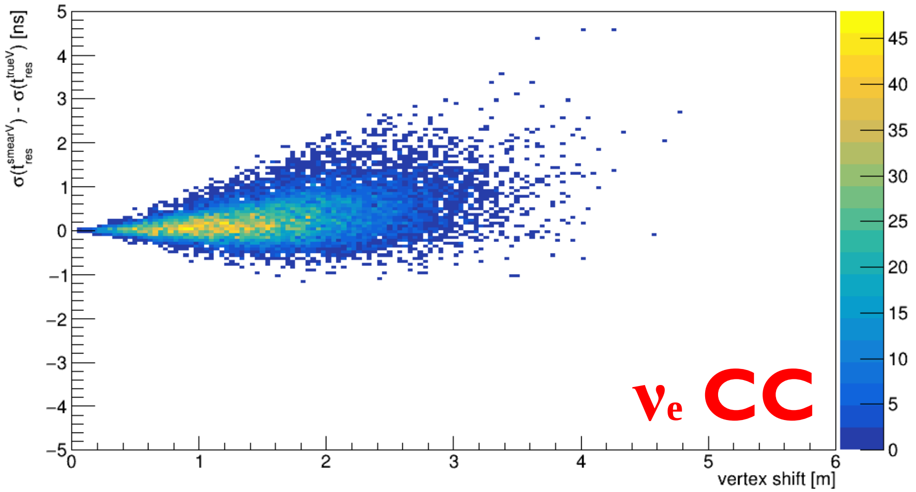
σ(tres) FEATURES

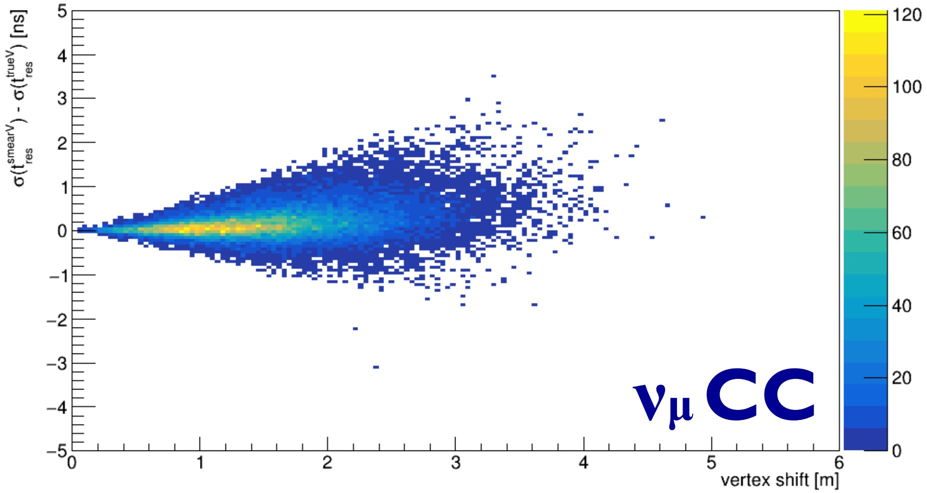
- NPE distribution for different sub – classes of NC events



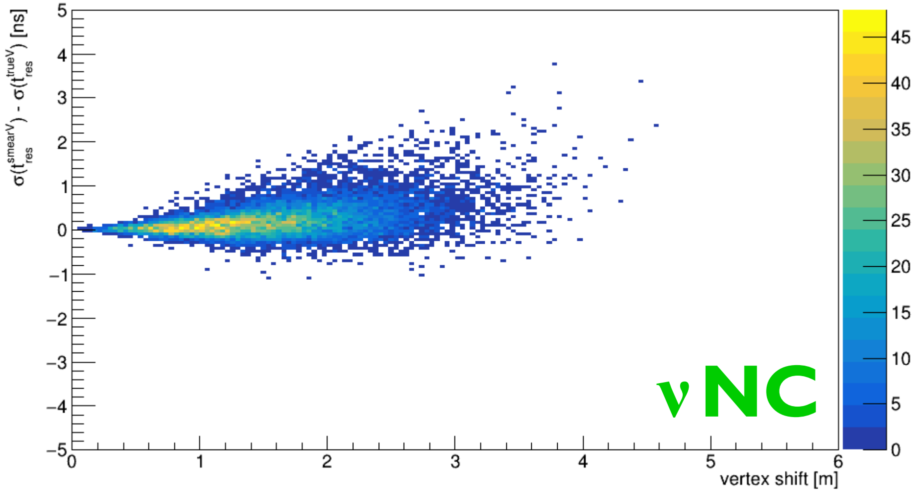
FLAVOR IDENTIFICATION

- σ(tres) spread VS vertex shift





- The spread remains within few ns

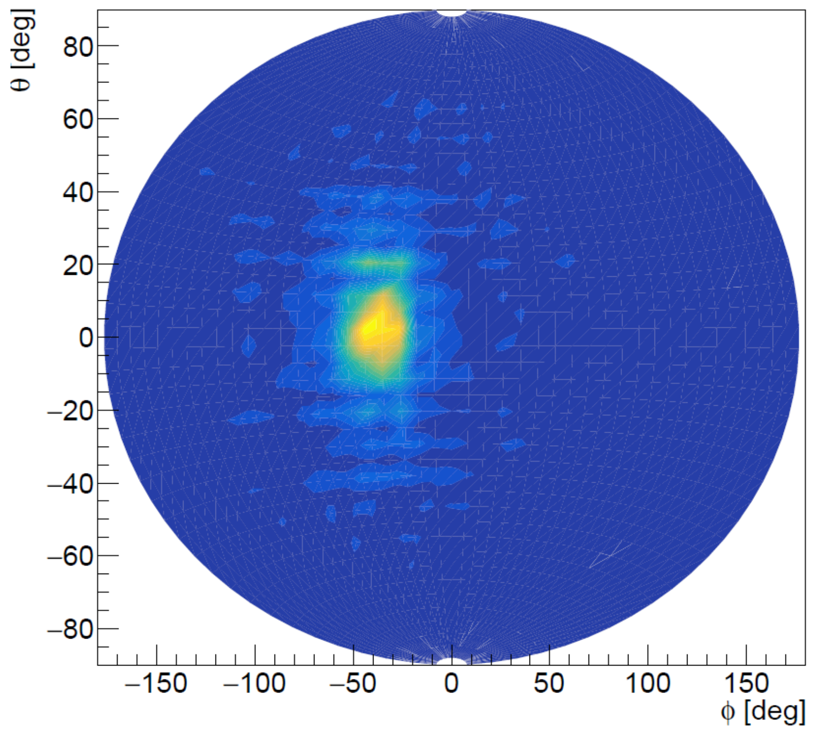


THE SNiPER FRAMEWORK

- Software for Non-collider Physics ExpeRiments

- Based on GEANT4
  - Built on C++, Python employed for user interface

- JUNO Detector Simulation includes:
  - electro-magnetic interaction
  - decay
  - hadron elastic and inelastic interactions
  - scintillation (including re-emission)
  - Cherenkov emission
  - optical absorption
  - photon – photocathode interaction (QE)



- Final result is a map of hits on the detector, in terms of charge and time

LINEARITY OF ENERGY RESPONSE

- Edge effects due to energy deposit into the acrylic, total reflections of photons…