INSTITUTE OF PARTICLE PHYSICS

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ν-int NEEDS OF WATER CHERENKOV DETECTORS

FunFACT!

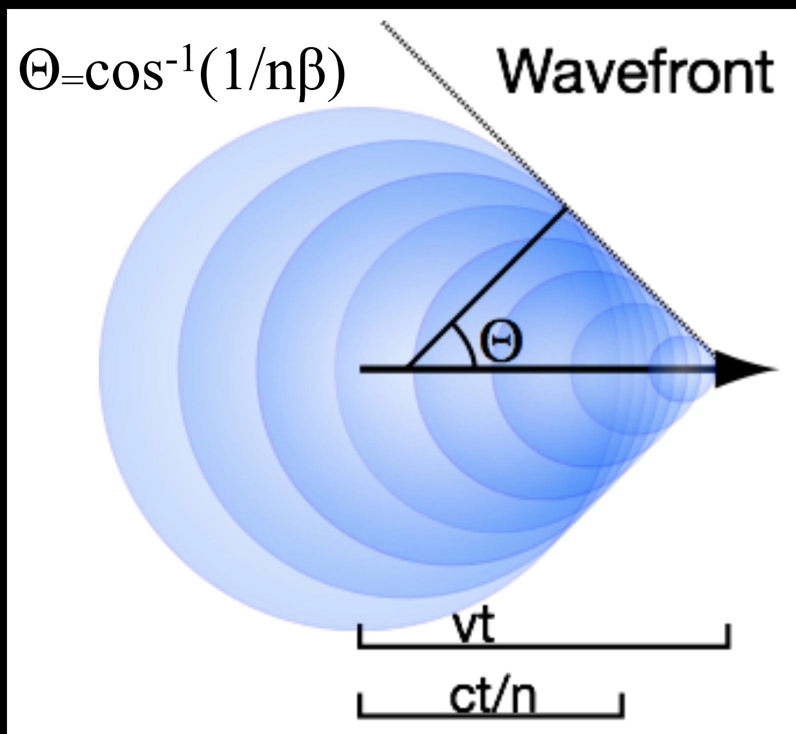
May 2015 JLAB

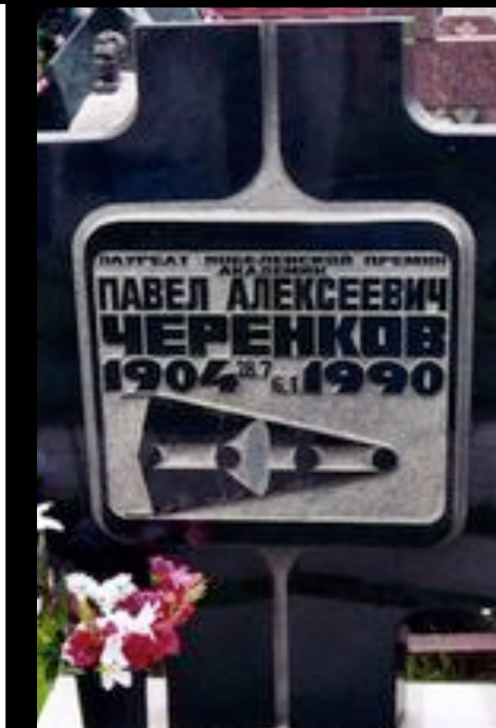
OVERVIEW

- Introduction to Water Cherenkov (WČ) technique
- "Classic" analysis with single ring/CCQE events
- Selected extensions to the technique:
    - reconstruction
    - enhancements (neutron capture, scintillator)

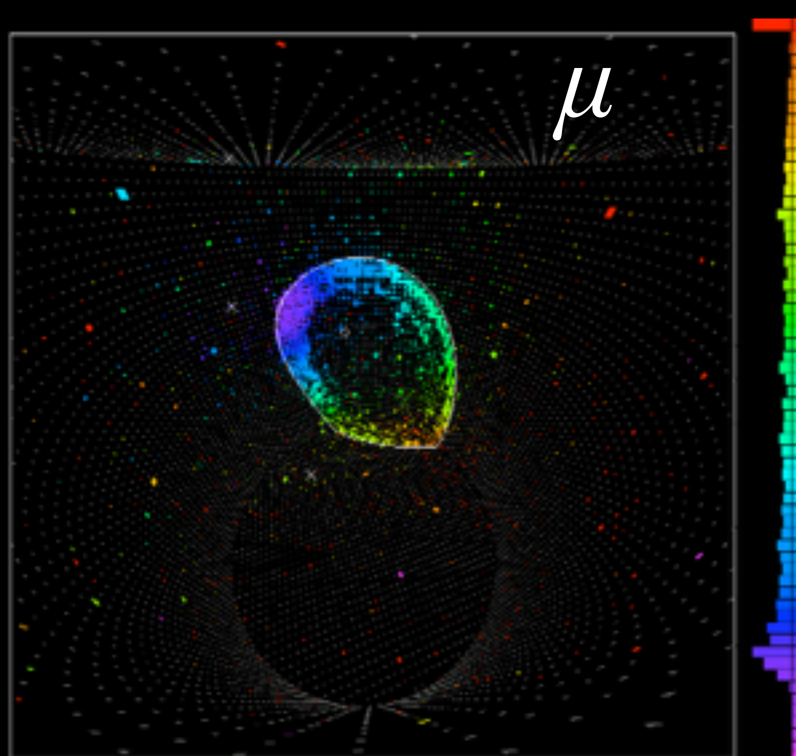
- ν-int/FSI issues, opportunities

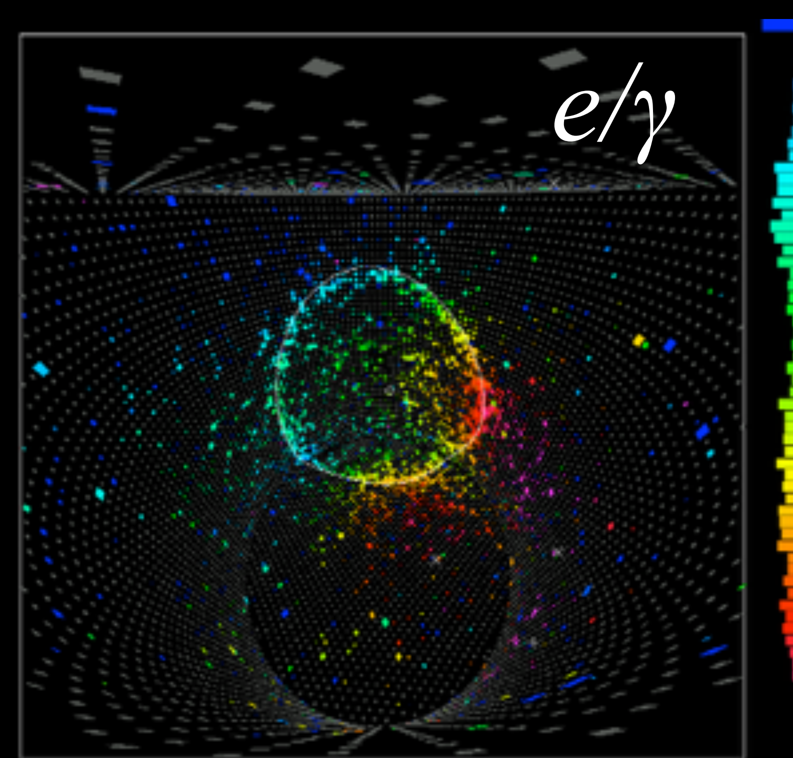
THE WATER CHERENKOV METHOD



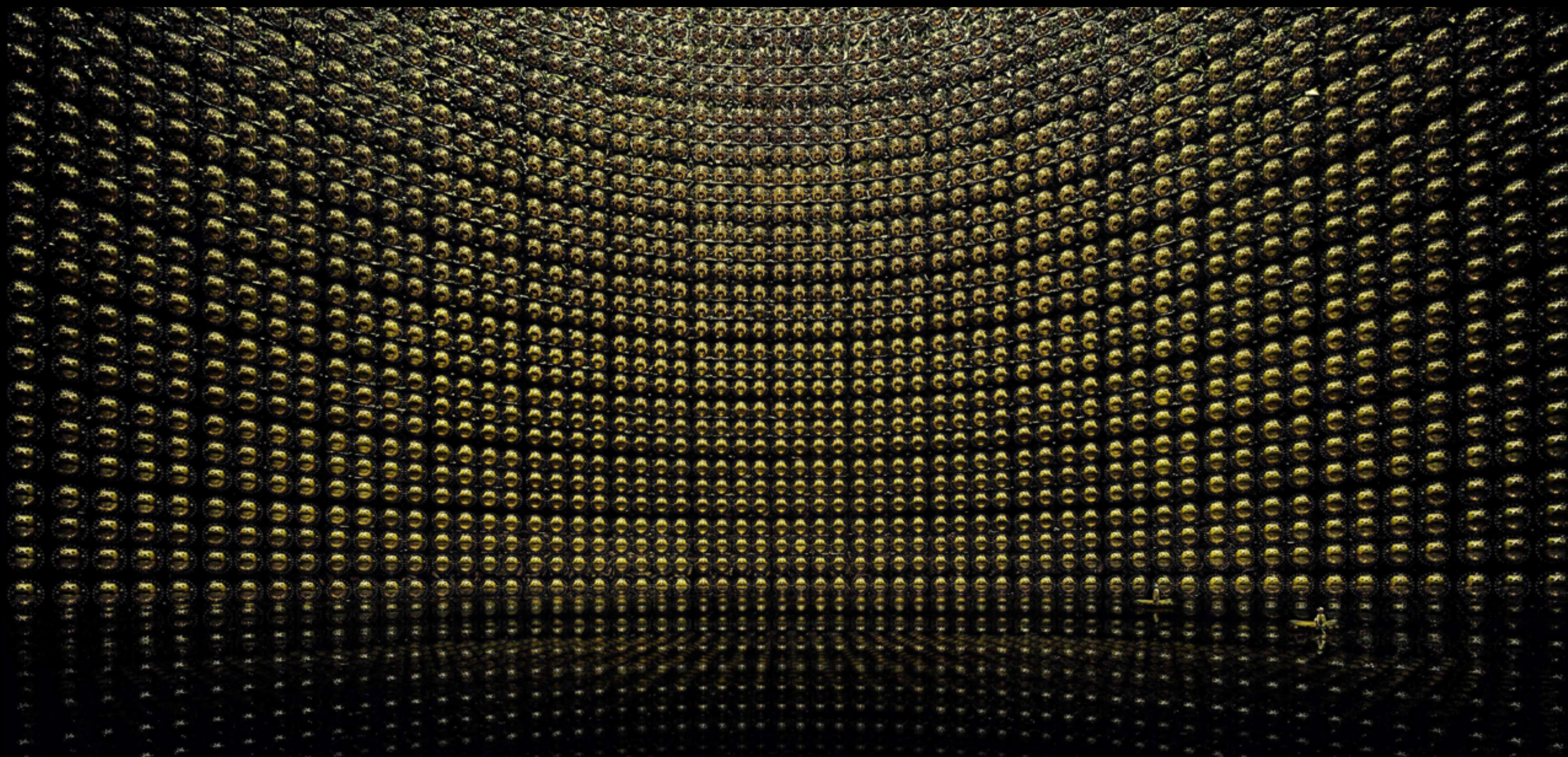


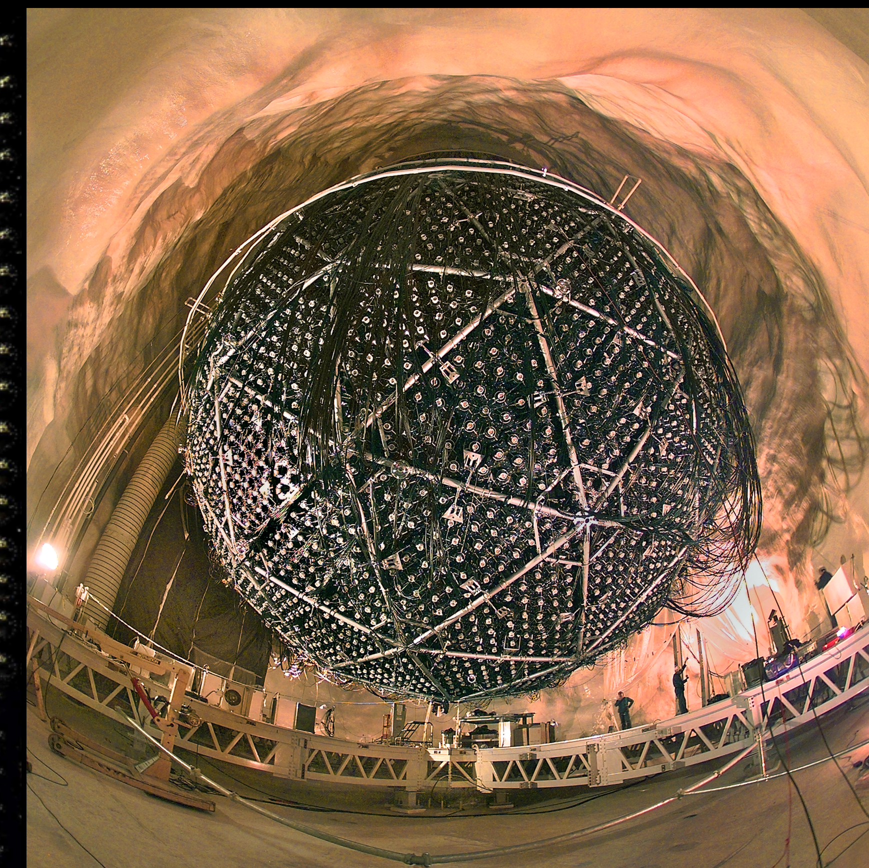
- Light emission by $\beta > c_n$ particles
- Ring provides track information
  - vertex, direction, momentum,
- Ring topology provides particle identification information

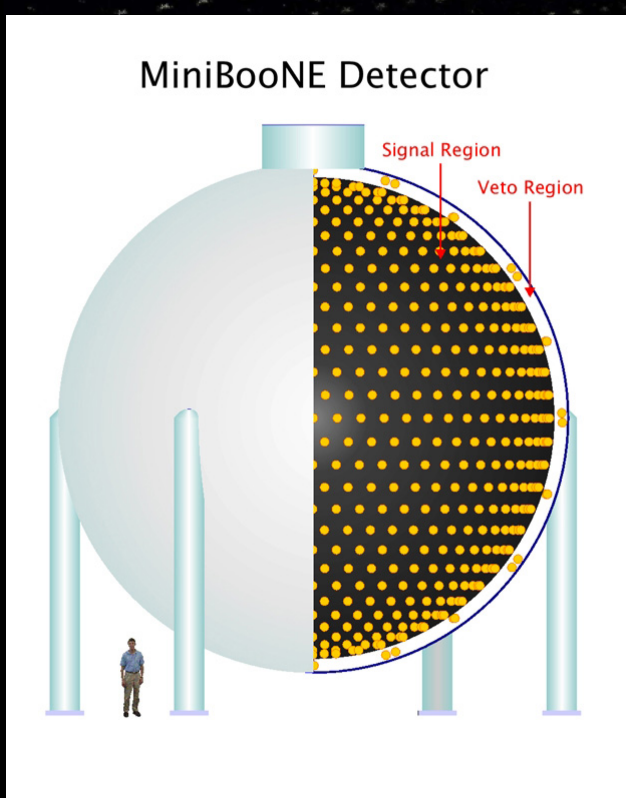


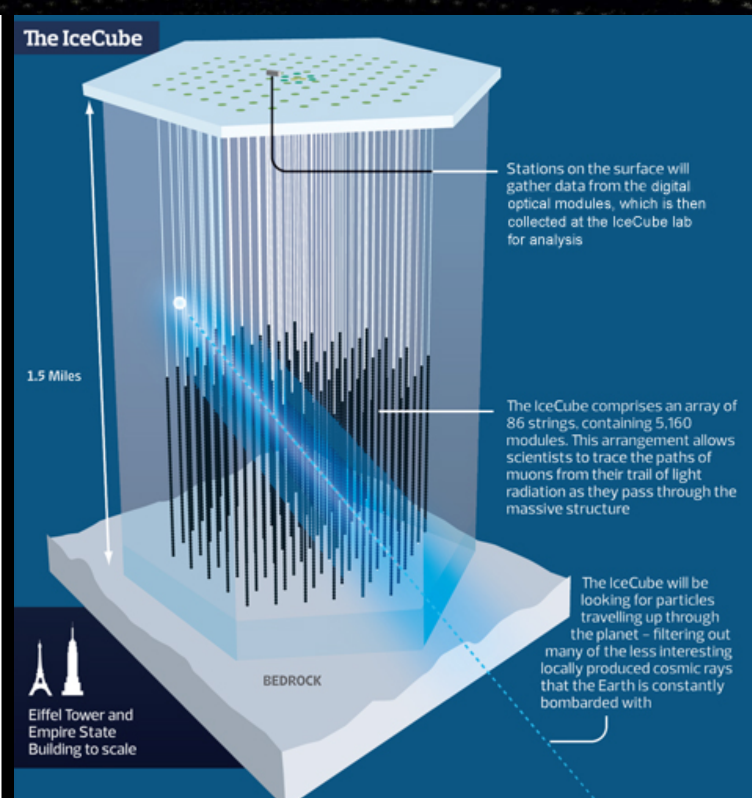


SOME EXAMPLES:



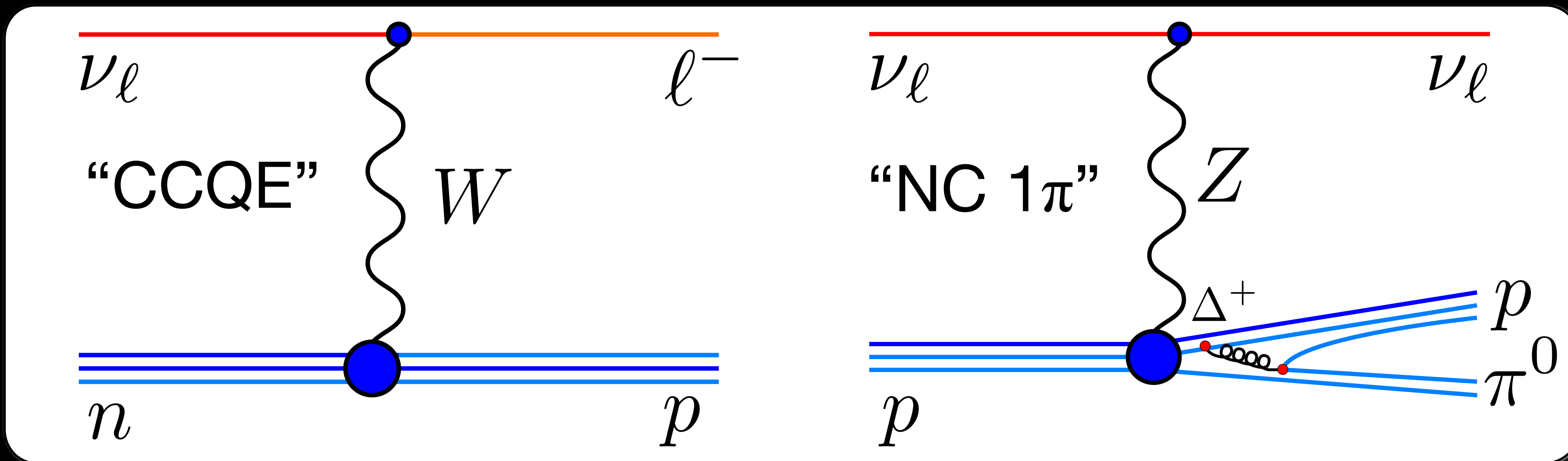






- Enormous success ~MeV, >PeV
  - resolve solar neutrino problem
  - discover neutrino oscillations
  - precision oscillation measurements
  - discover astrophysical neutrinos
  - . . . .
- Focus today on ~GeV physics

EXAMPLE: T2K



$\nu_\ell + n \to \ell^- + p$ $\quad$ $\bar{\nu}_\ell + p \to \ell^+ + n$

Signal

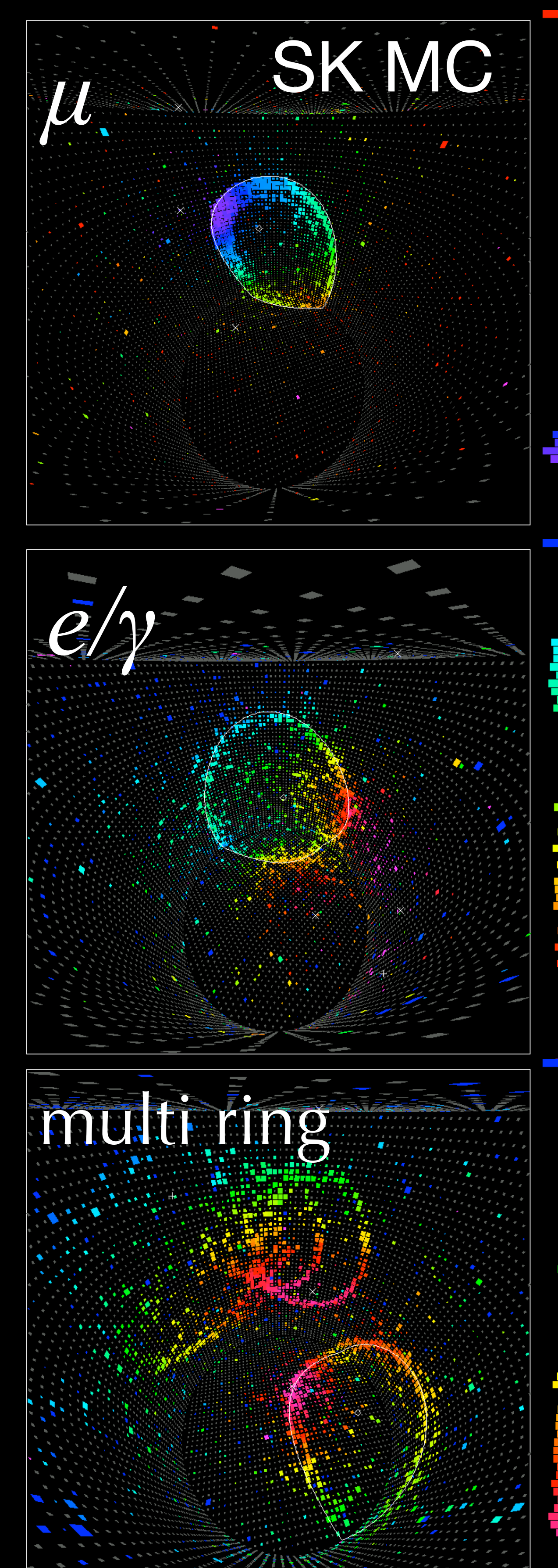
- Appears as single μ/e-like ring
- E_ν by energy/direction of ring relative to beam
  - assumes CCQE kinematics

$\nu_\ell + (n/p) \to \nu_\ell + (n/p) + \pi^0$

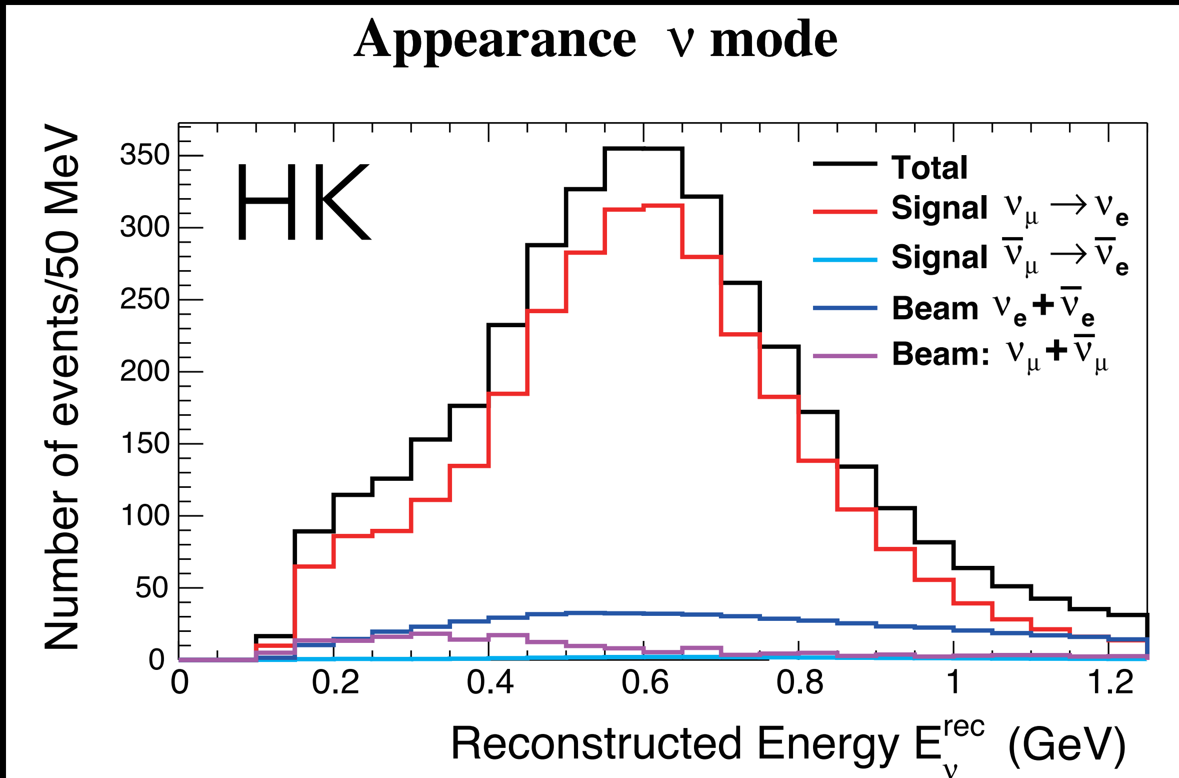
$\nu_\ell + (n/p) \to \ell^- + (n/p) + \pi$

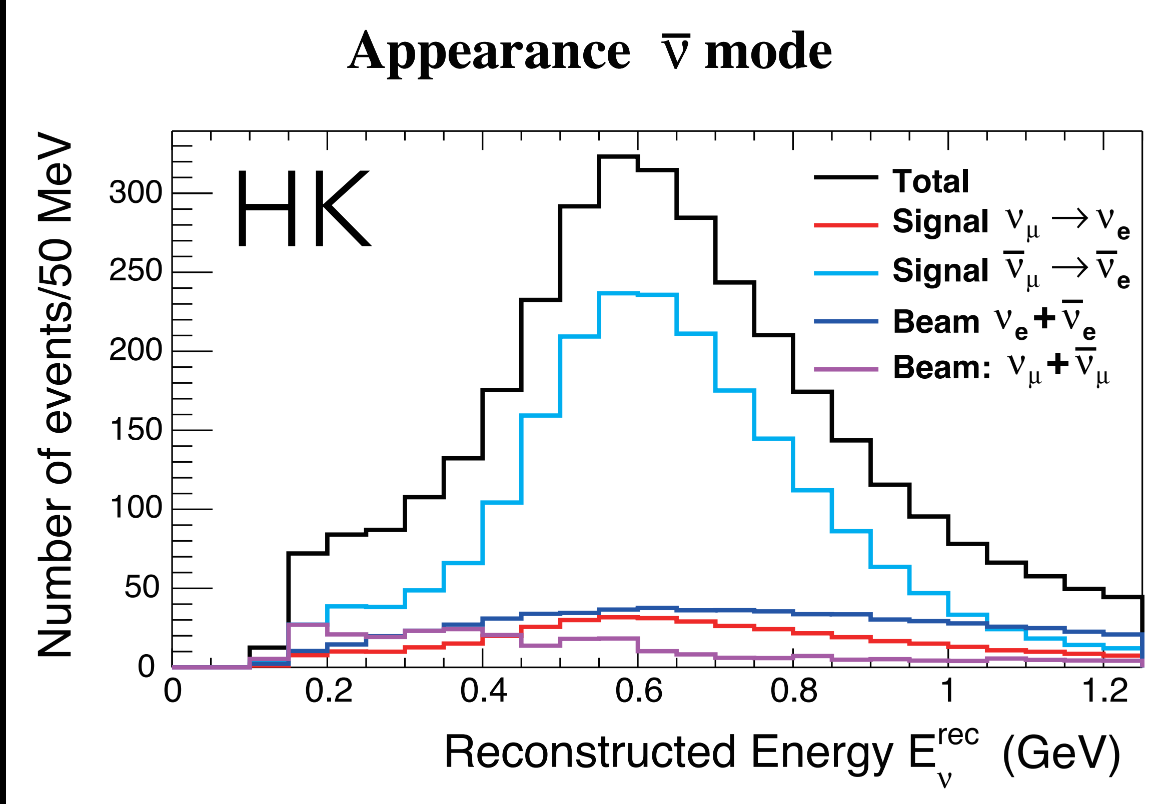
Backgrounds

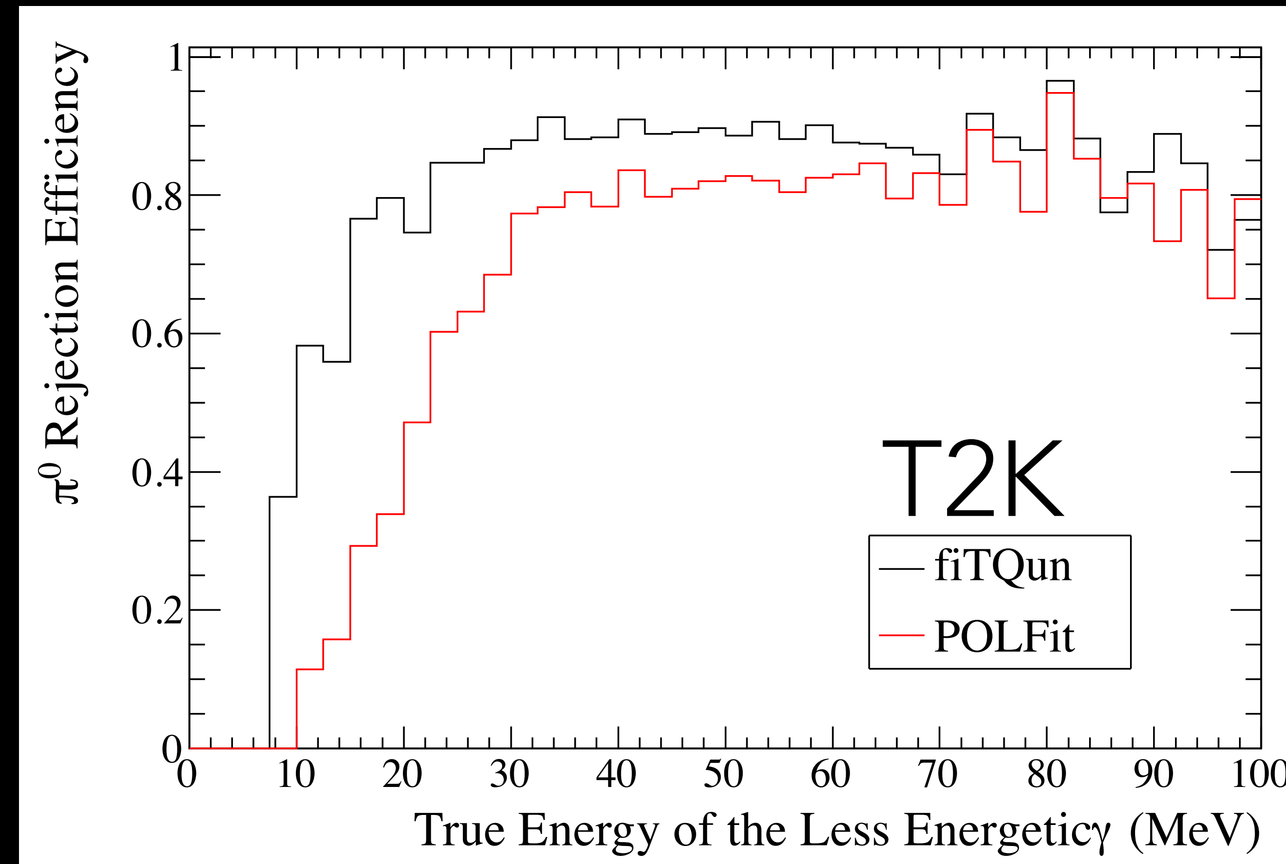
- $\pi^0 \to \gamma + \gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
- μ/π^+: ring counting, decay electron cut



PERFORMANCE:

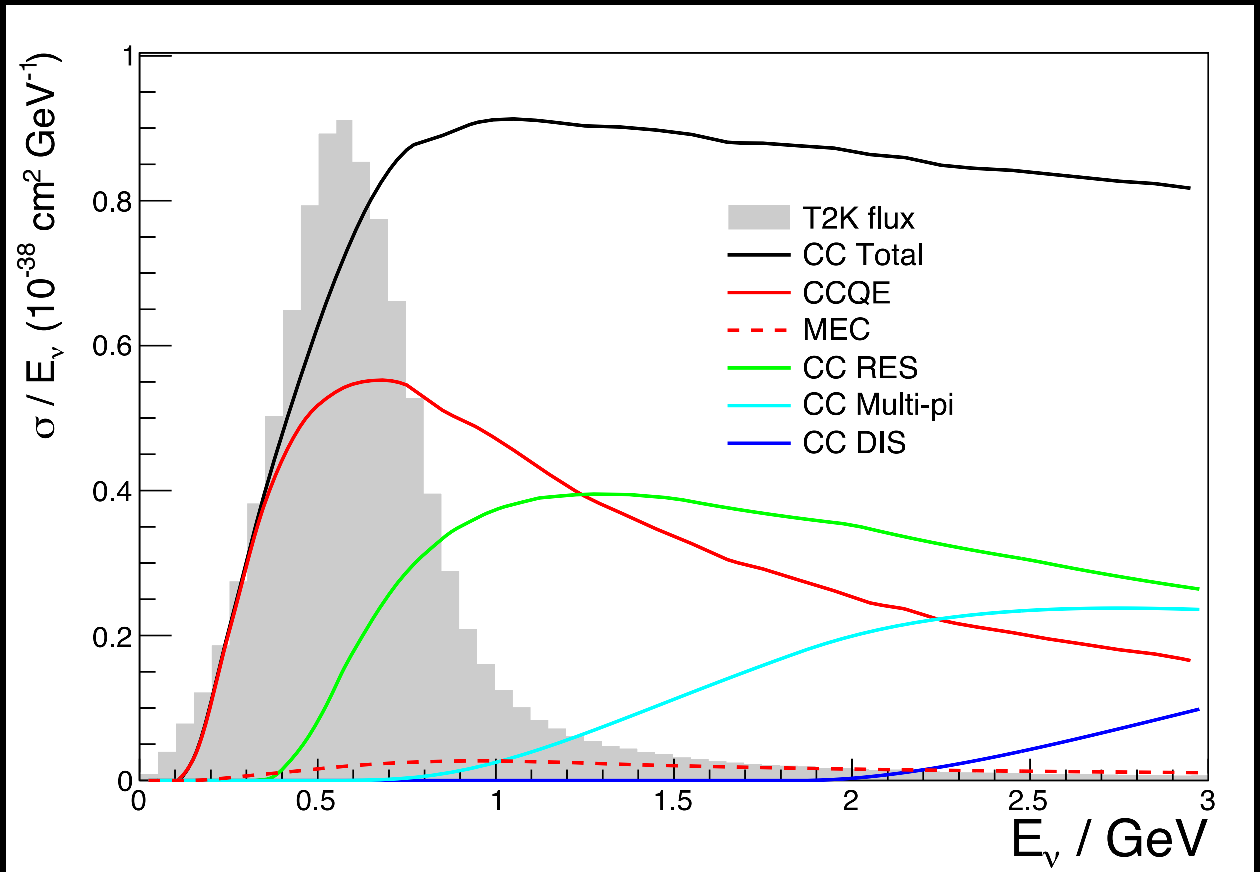






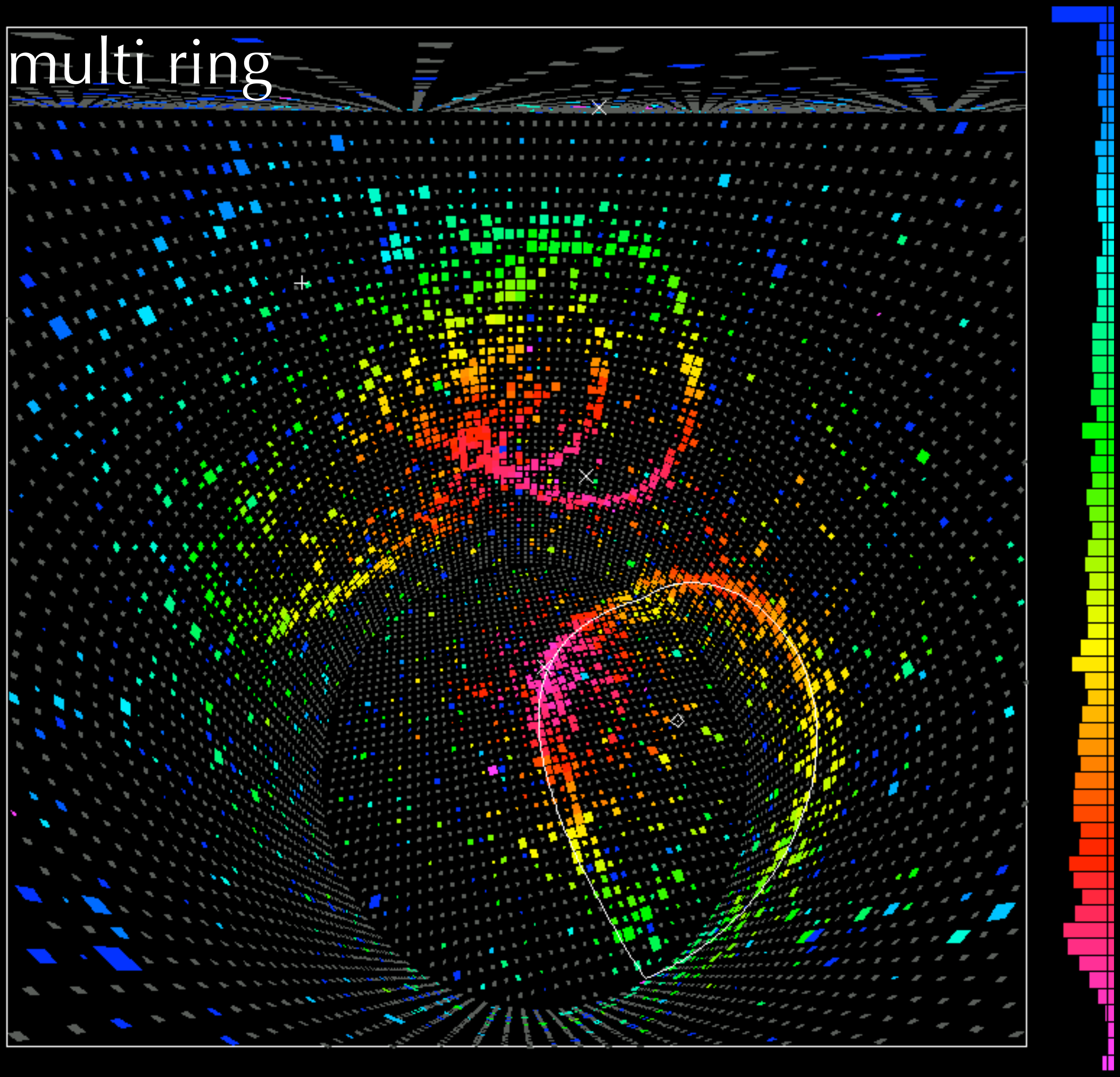
- Excellent particle identification
  - ~1% $\mu \leftrightarrow e$ misidentification
  - negligible background in ν_e selection
- Recent advances in π^0 rejection
  - achieve ~2% π^0 misidentification
- **Dominant background is intrinsically irreducible beam ν_e contribution**

OBSERVATIONS



- WČ detectors are ideally suited to ~1 GeV energy region
  - clean selection of single ring topologies
- CCQE is dominant at ~1 GeV
  - results in single ring events
- High purity and efficiency selection of CCQE events
- Detailed nuclear final state largely invisible to WČ
  - "insensitive" to details . . . . but cannot separate different channels.
  - new ideas (WbLS, neutron tagging, etc.)
- Multi-ring topologies (non-CCQE) have been a frontier for some time
  - continuous improvement over time
  - will discuss one of the many tools that have developed . . . .

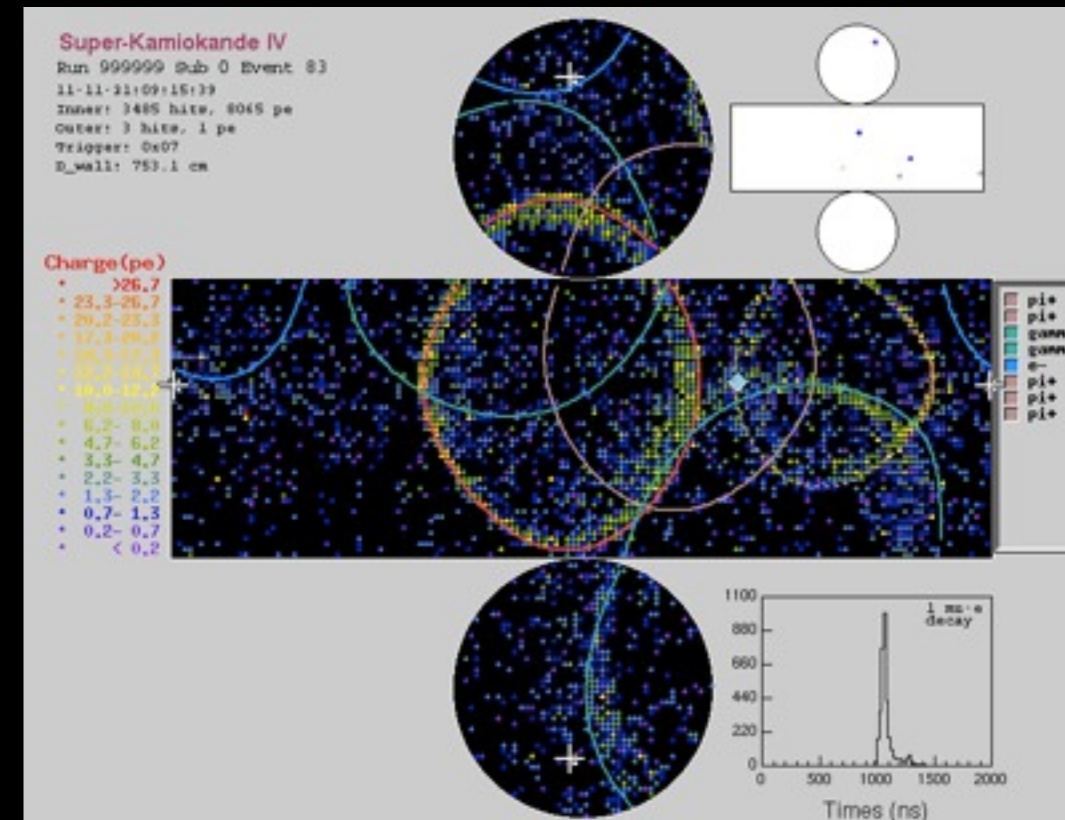
OTHER TOPOLOGIES

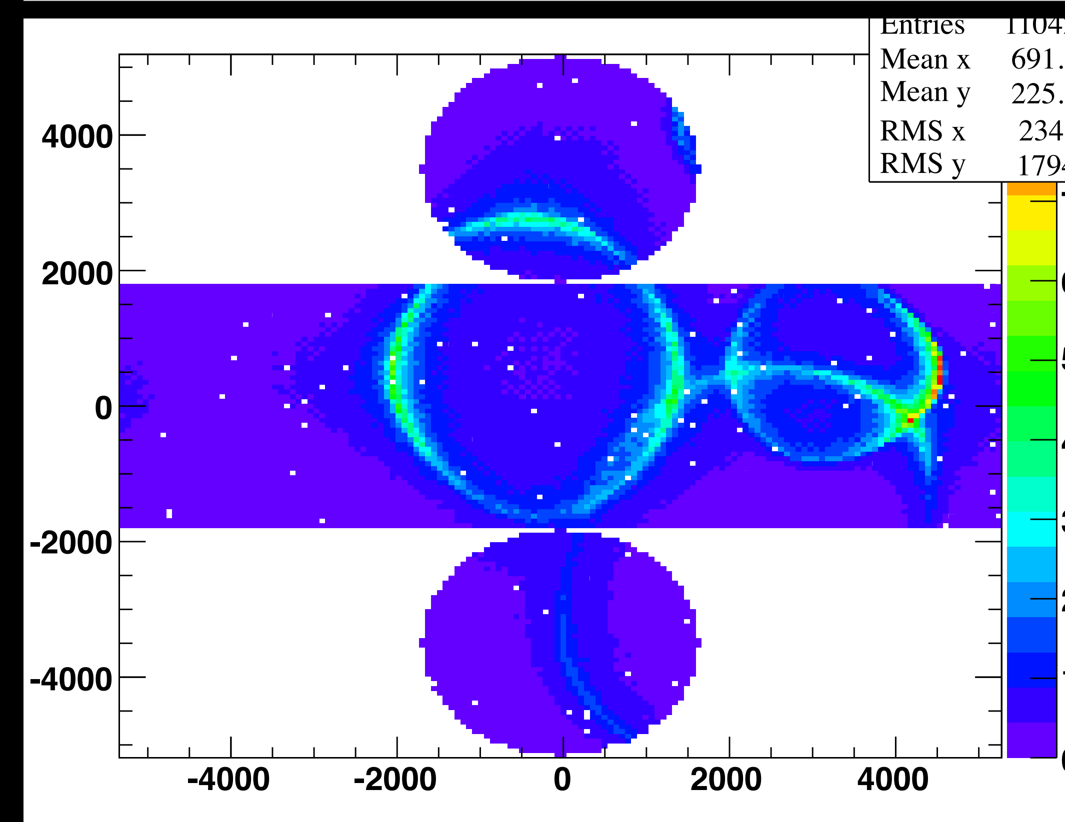


- WČ detectors have powerful multi-ring reconstruction capabilities
  - pattern recognition based on Hough transform to "count" rings.
  - particle identification on "brightest" ring
- Charged pions:
  - sometimes MIP like, sometimes "shower"-like
  - can we do more to identify these particles?

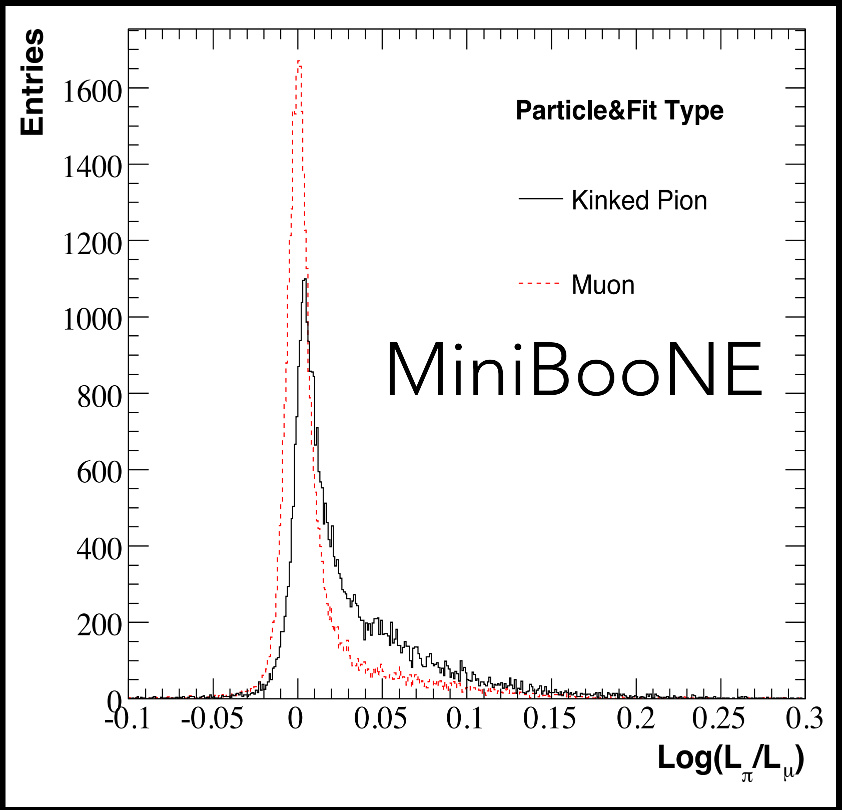
GENERALIZATION

- General framework ("fiTQun") for fitting arbitrary ring hypotheses
  - "any" number of rings
  - specific ring particle hypotheses
  - variable geometric configurations
    - e.g. photon conversion
  - Kinematic/geometric constraints
    - e.g. invariant mass

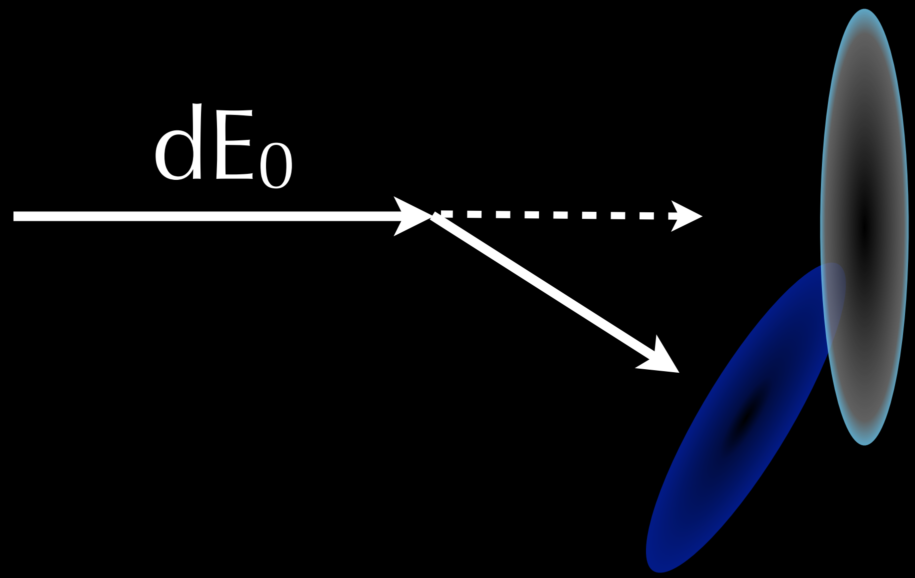




NEW: PION RECONSTRUCTION

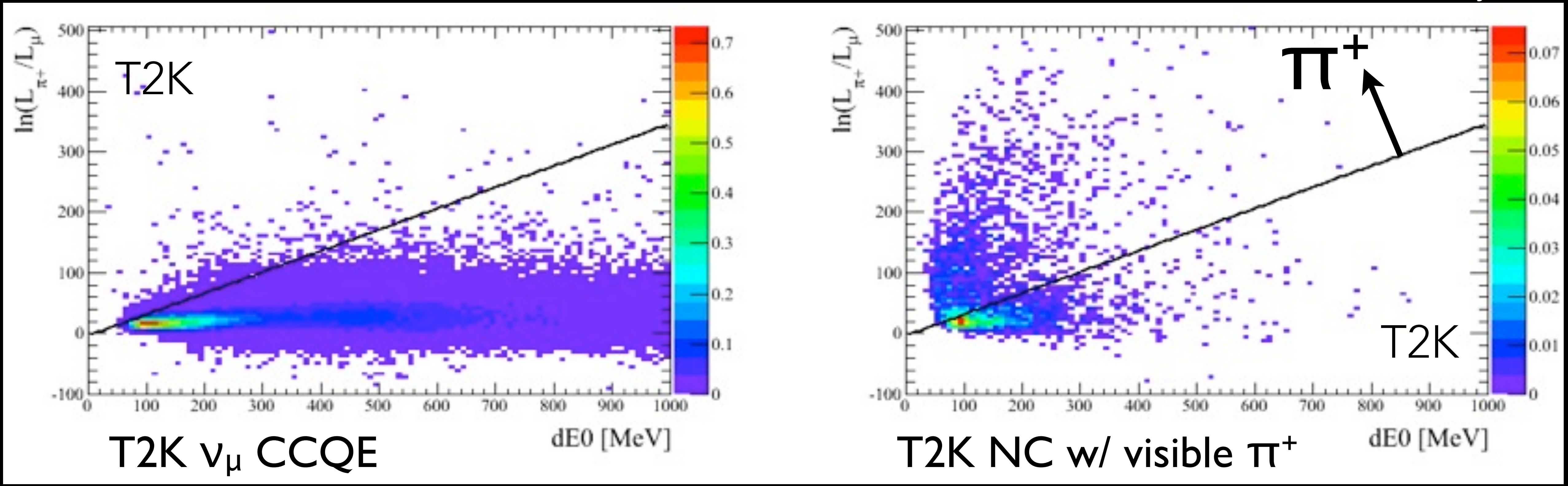


MiniBooNE: M. Wilking



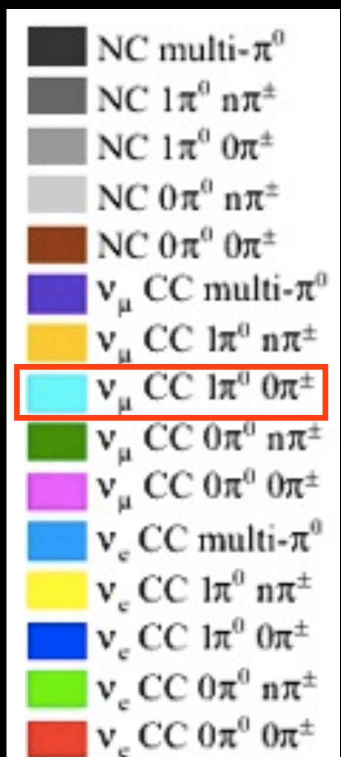
- μ/π separation by hadronic interaction
  - scatter results in up/downstream rings

T2K: S. Tobayama

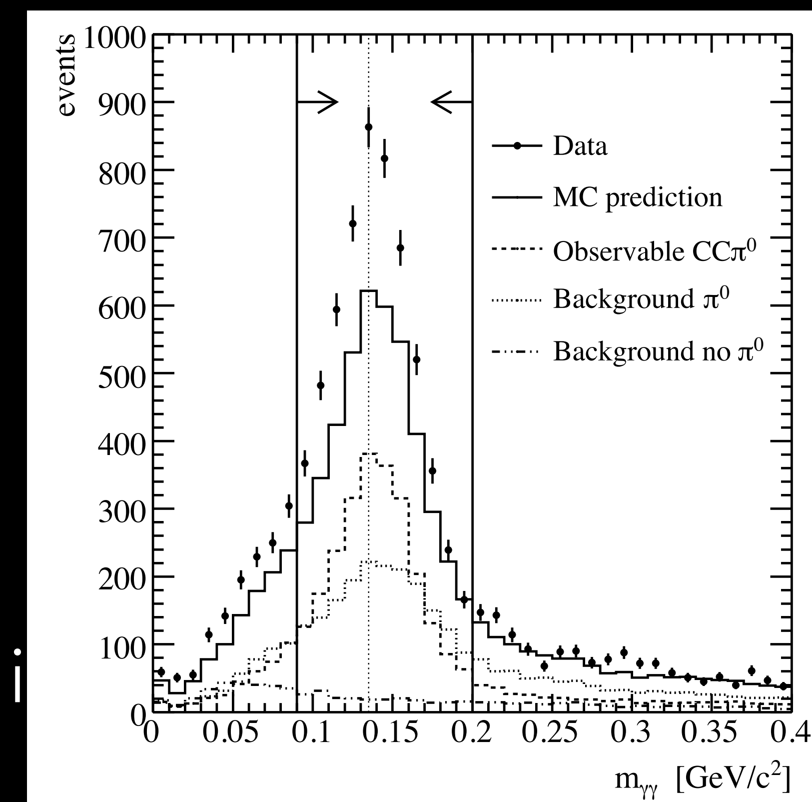


MULTI RING RECONSTRUCTION

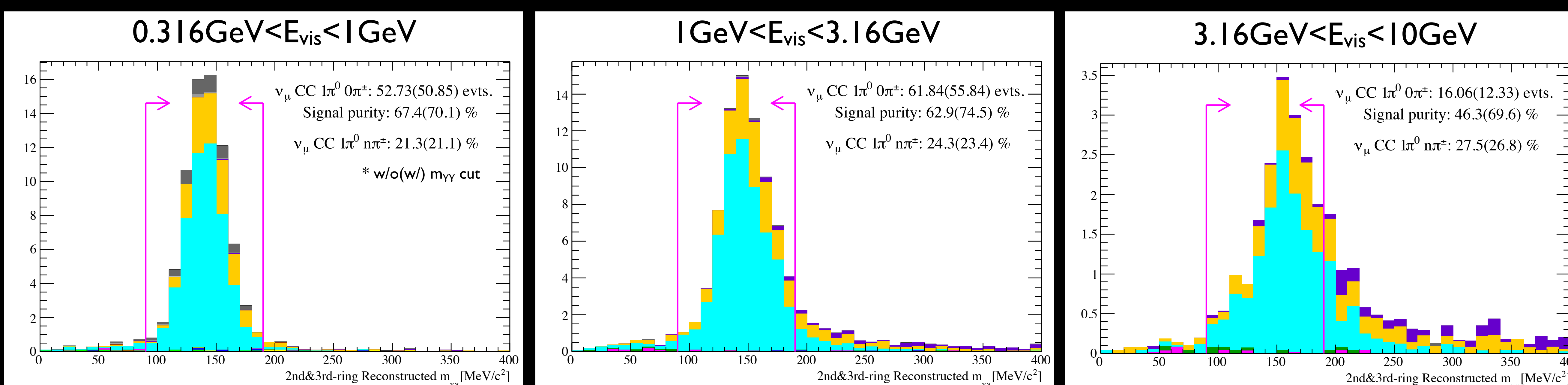
- ν_μ CC π^0 reconstruction
  - 3 ring $\mu + \gamma + \gamma$ topology
  - Pioneered on MiniBooNE in Mineral Oil
- Now applied to SK detector H_2O:
  - ~70(90)% purity for ν_μ CC π^0 (+N $\pi^\pm$) in multi-GeV region



MiniBooNE, R. H. Nelson

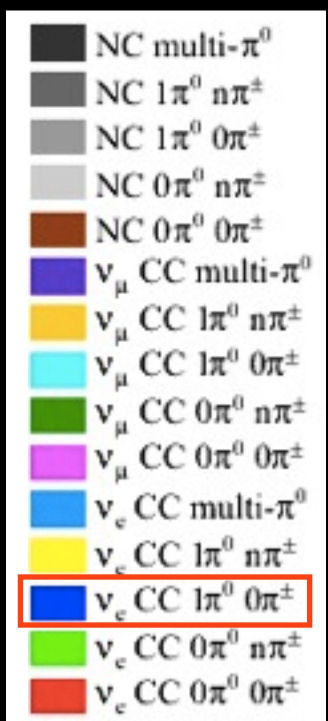


SK: S. Tobayama

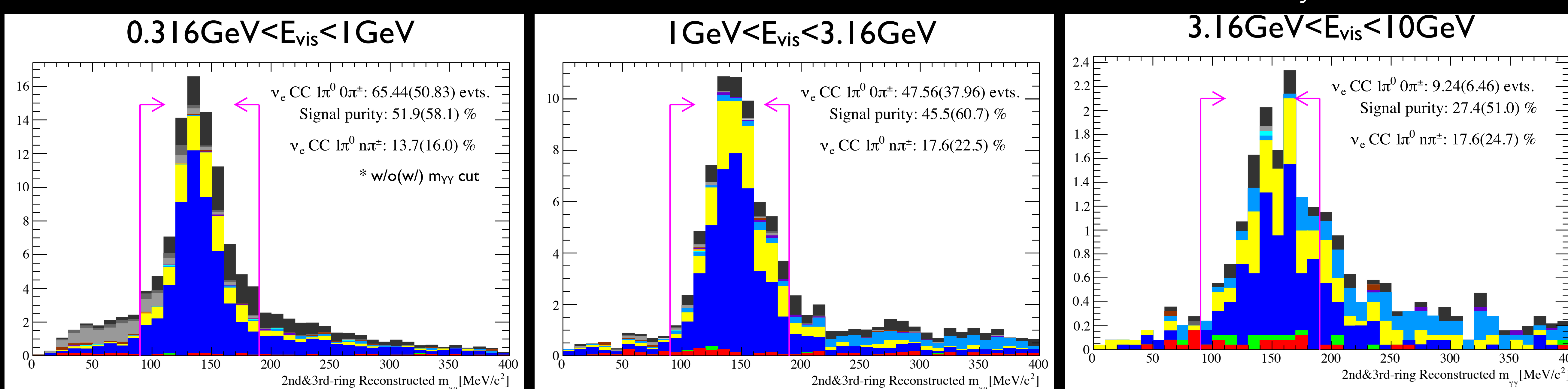


ν_e CC π^0 RECONSTRUCTION

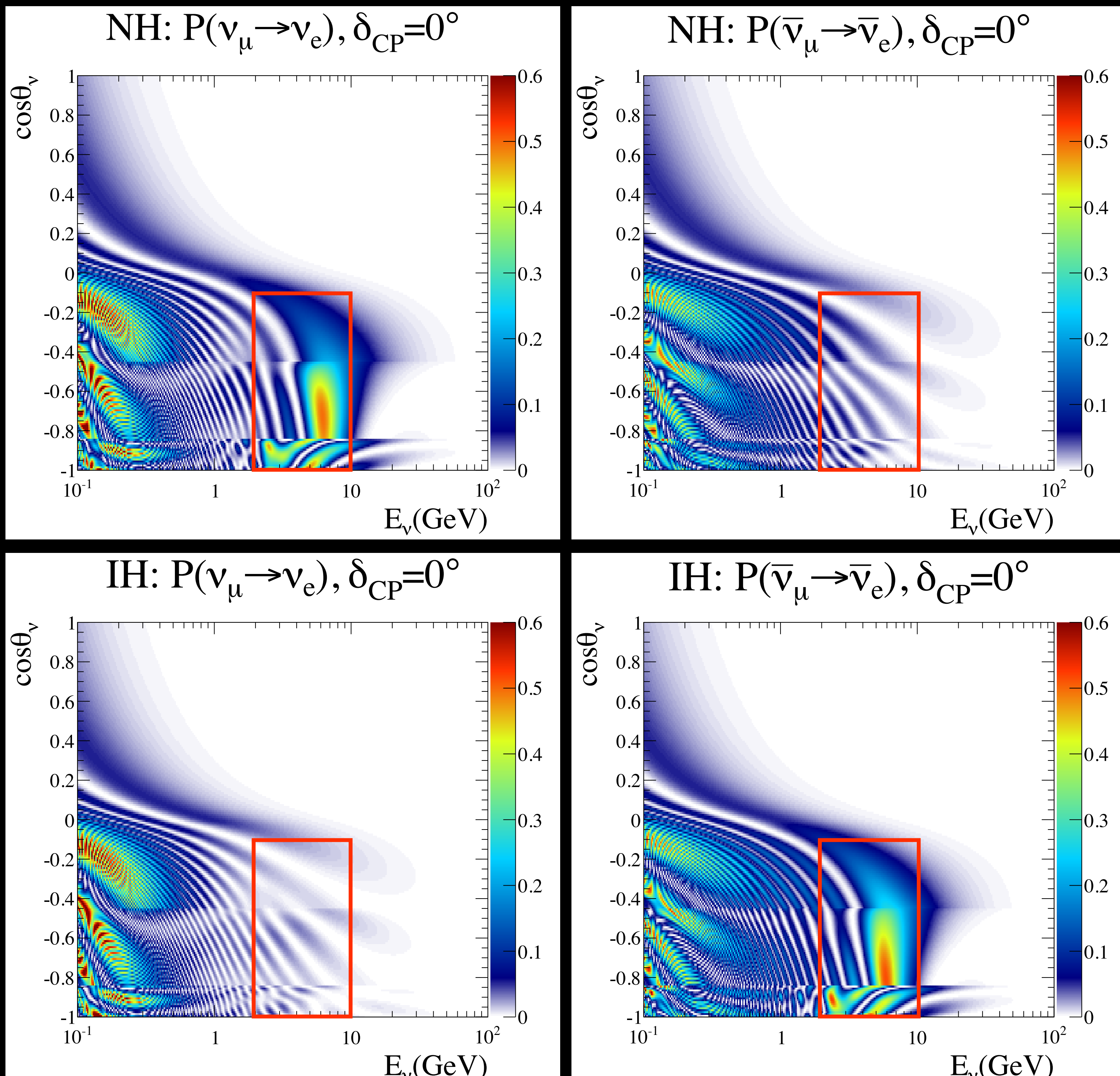
- Extension to ν_e CC π^0 reconstruction
  - 3 ring e+γ+γ topology
  - "Messier" than ν_μ channel due to electron shower
- Now developed for SK detector
  - π^0 mass peak clearly visible even at high energy.
  - ~60(75)% purity for ν_e CC π^0 (+N $\pi^\pm$) in multi-GeV region



SK: S. Tobayama



APPLICATION:

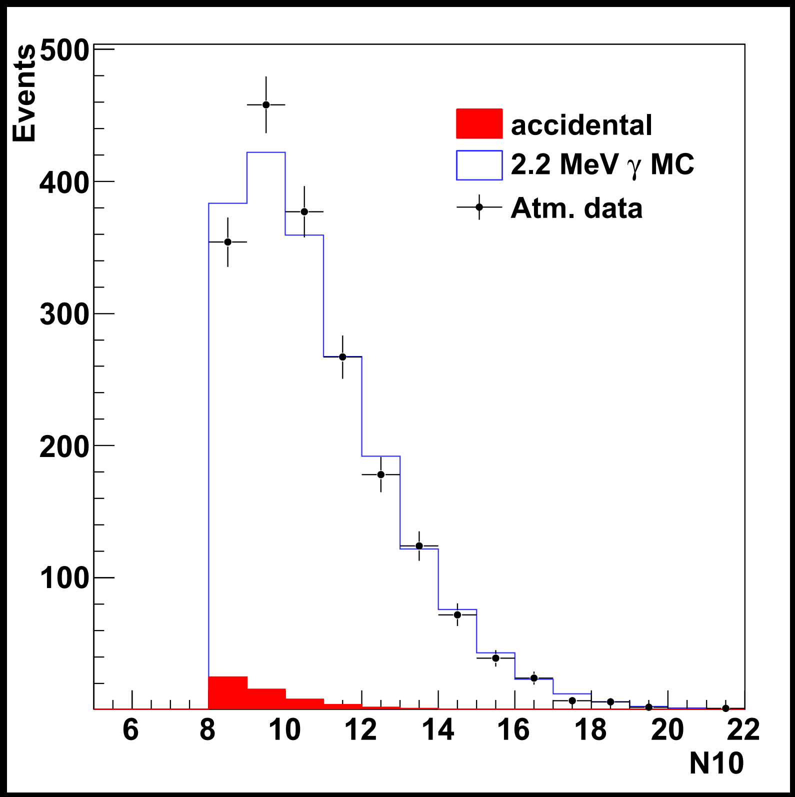


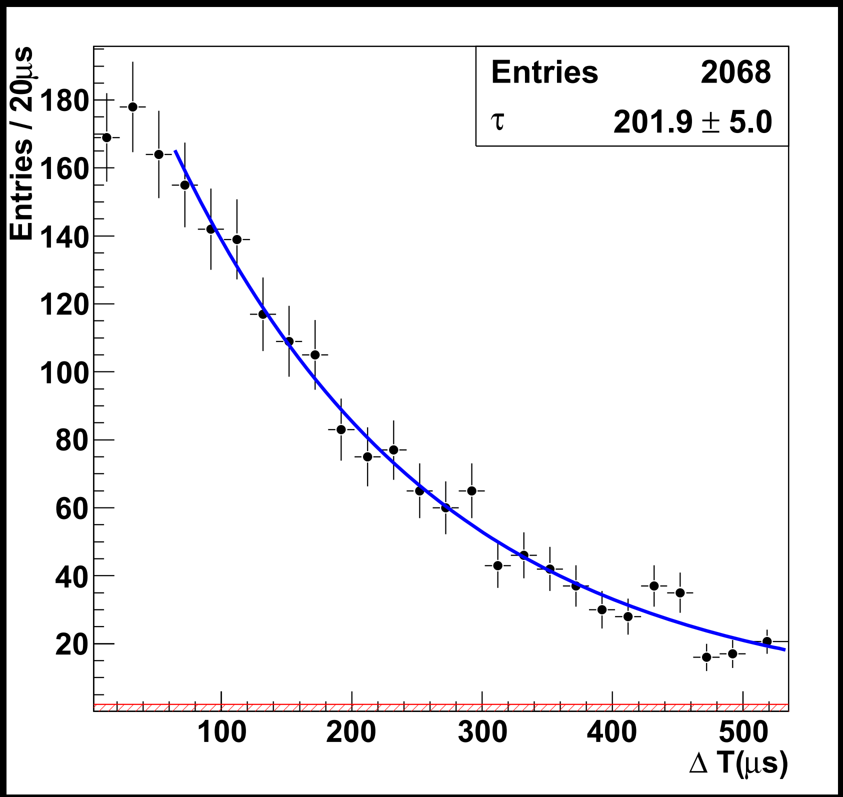
- ~Several GeV region is where matter effects (core/mantle) impact $P(\nu_\mu \rightarrow \nu_e)$ significantly
- Identifying and cleanly reconstructing ν_e events at high energy is critical

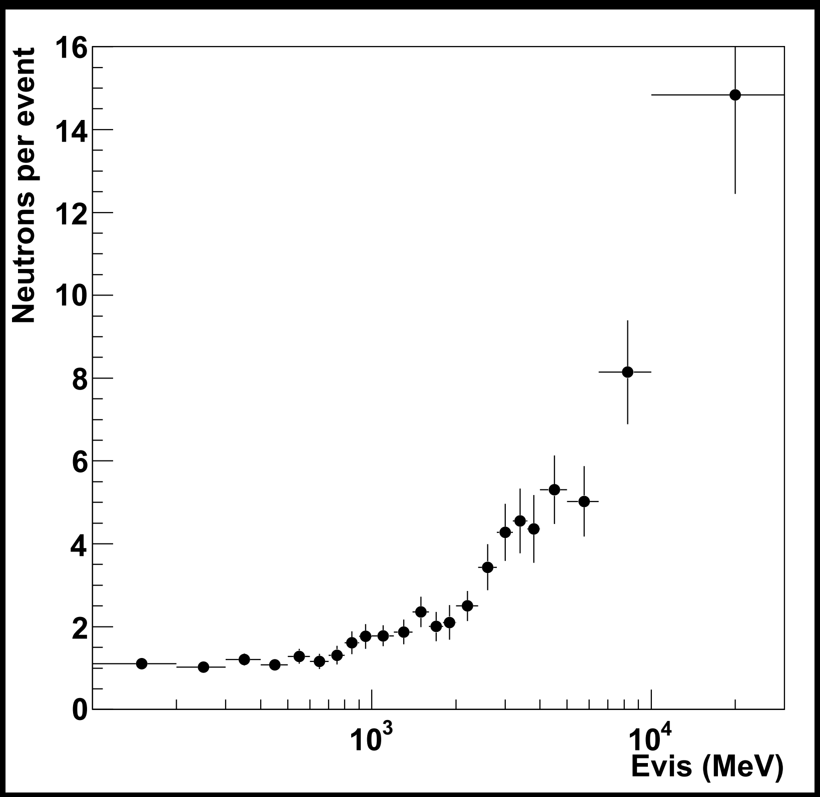
- Improved efficiency/purity → improved mass hierarchy sensitivity

NEUTRON RECONSTRUCTION

H. Zhang ICRC

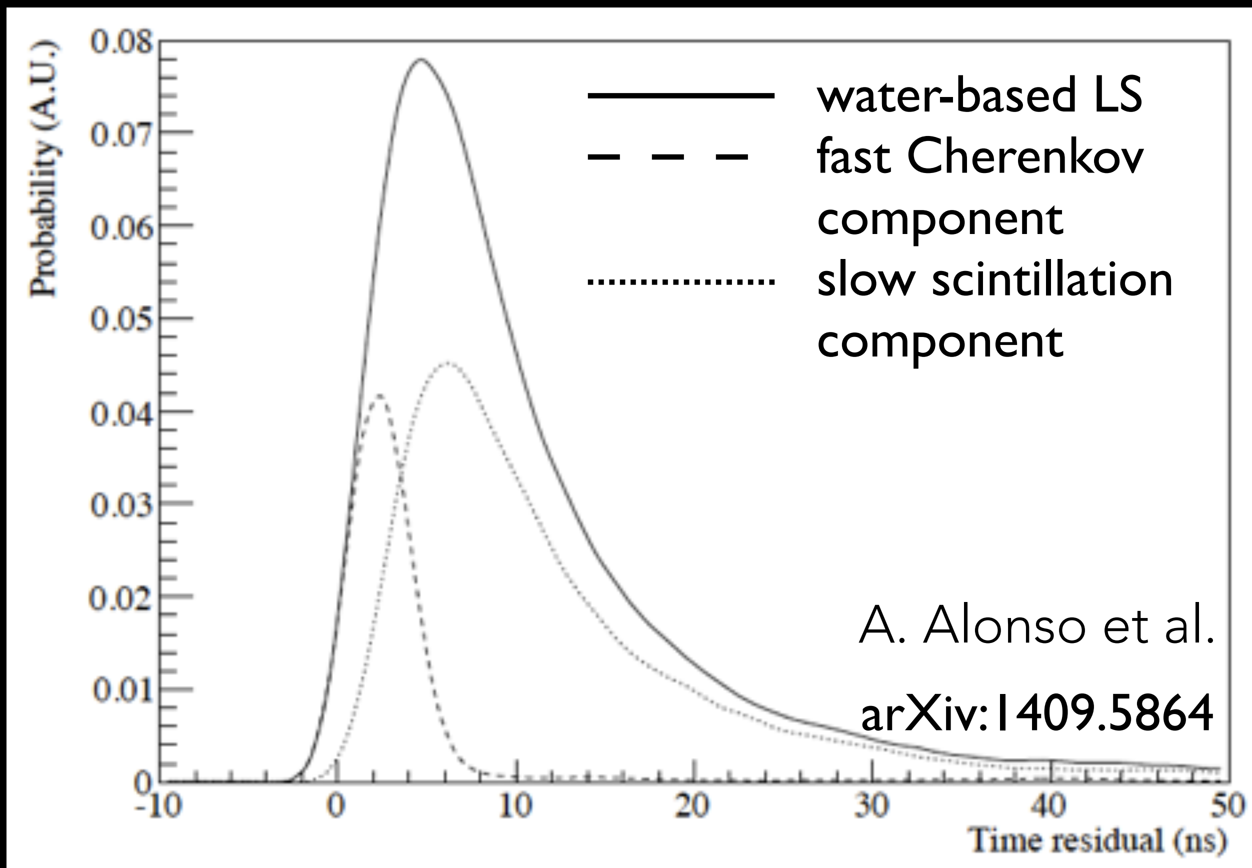






- Neutron detection via capture:n + p → d + γ (2.2 MeV) can be observed in SK
  - checked with neutron source (Am/Be)
- Applications:
  - $\bar{\nu}_l$ tagging ($\bar{\nu}_l$ + p → l^+ + n)
  - background reduction in proton decay (ANNIE)
  - enhance neutron capture signal with Gd-doping (GADZOOKS)

WATER-BASED SCINTILLATOR

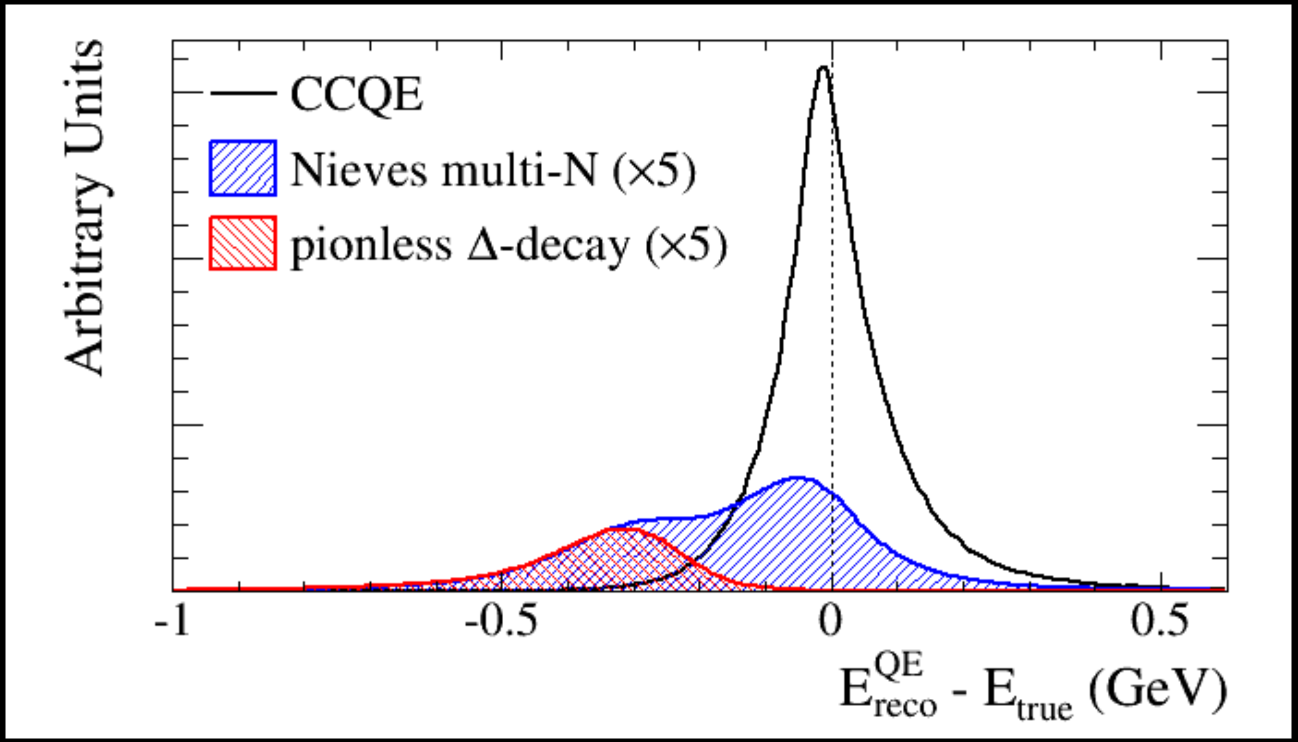


- Potential uses:
  - "calorimetric" measurement of E_ν in CCQE (measure p energy)
  - tagging sub-Č K^+ in proton decay ($p \rightarrow K^+ + \nu$)
- Many exciting possibilities!

- New development in dissolving LAB-based scintillator in water with surfactants (M. Yeh, BNL)
- Many possible applications!
- For WČ detectors:
  - Obtain signal from both Cherenkov radiation and scintillation.
  - Delayed and isotropic scintillation from sub-Č particles!
  - Utilized in some analysis at MiniBooNE (scintillation+ Č from pure mineral oil)

NOW THE FUN

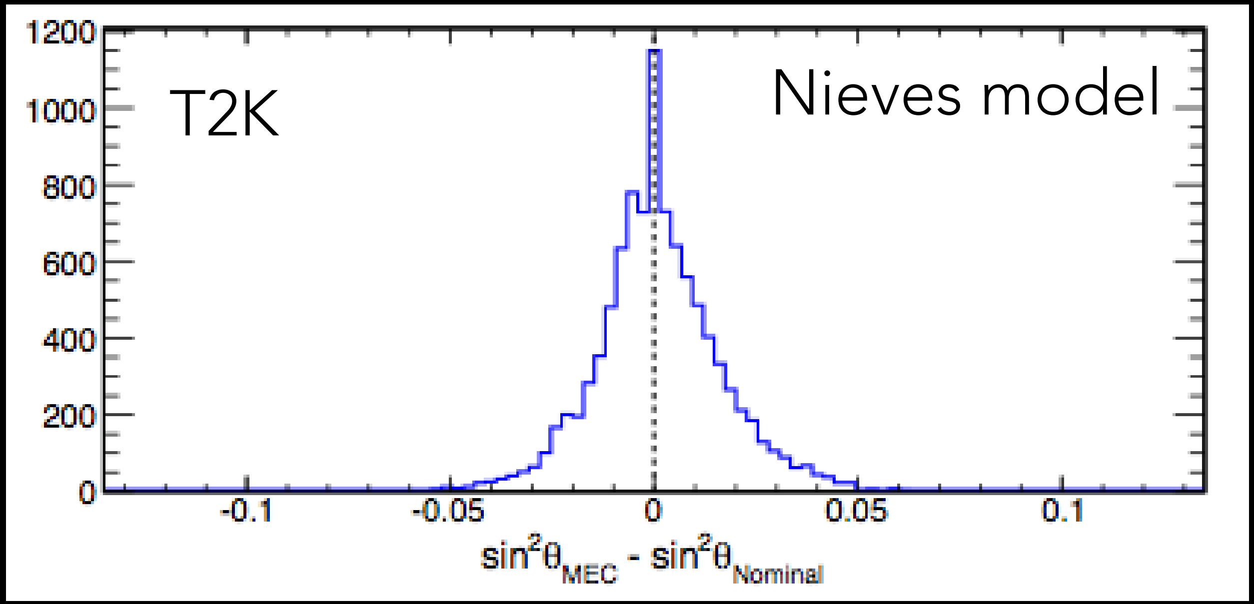
NEUTRINO ENERGY RECONSTRUCTION

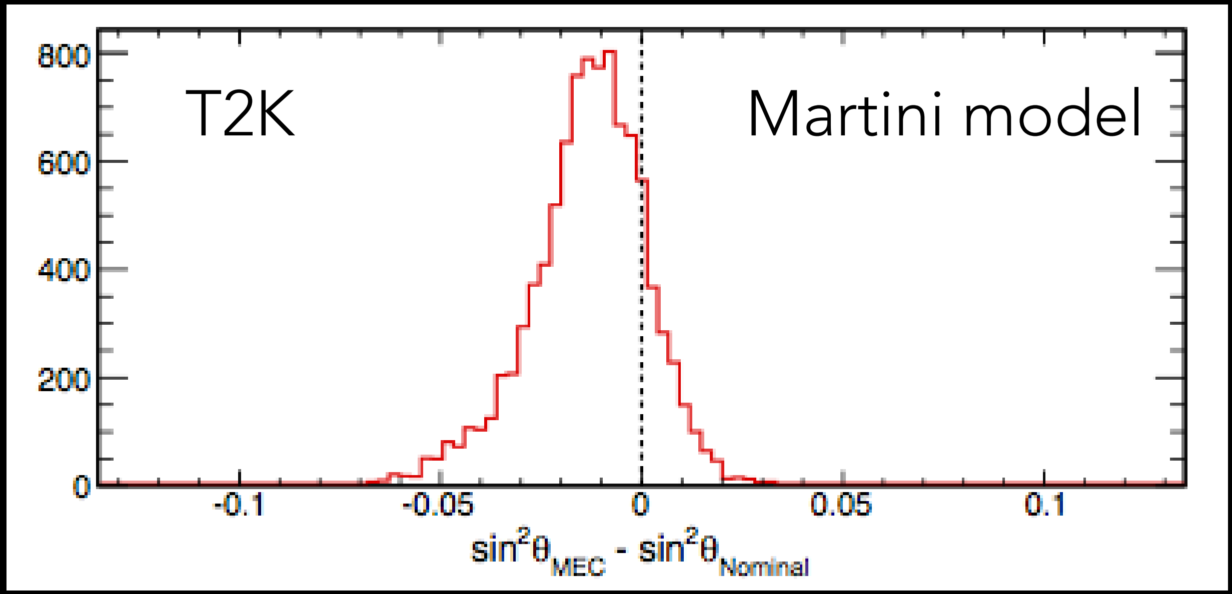


- Neutrino energy reconstruction critical for neutrino oscillations studies
- Extensive discussion in literature (e.g.):
  - A. Butkevich, PRC78 (2008) 015501
  - T. Leitner *et al.*, PRC81 (2010) 064614
  - M. Martini *et al.*, PRD87 (2013) 1, 013009
  - U. Mosel *et al.*, PRL112 (2014) 151802
  - . . . . . .

- Neutrino energy is based on kinematic assumptions
  - quasi-two body CCQE process: $\nu_l + n \rightarrow l + p$
    - Single e/μ Č ring identified, proton below threshold (invisible)
  - use outgoing lepton momentum to determine E_ν
- Other mechanisms can give rise indistinguishable topologies in WČ
  - Δ production: absorption of pion, pionless Δ de-excitation
  - multi-nucleon interactions (M. Martini, the MiniBooNE CCQE “excess”)
- FSI critical to correctly modelling this!

IMPACT ON T2K θ_{23} MEASUREMENT





- Biases arising from multinucleon effects studied
  - introducing these interactions into the MC samples
  - fit without their contribution (model mismatch)
- RMS and bias of few %.
- Does not impact current results significantly
  - results limited by statistical uncertainty
  - important source for more precise measurements.

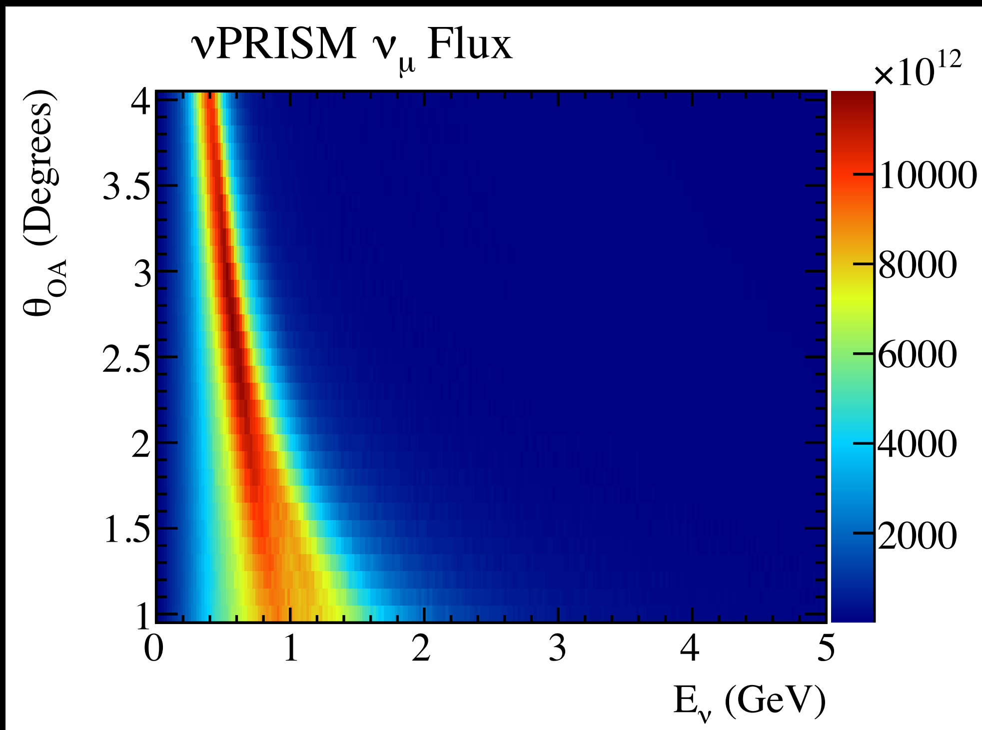
NEEDS FOR "CC0P"

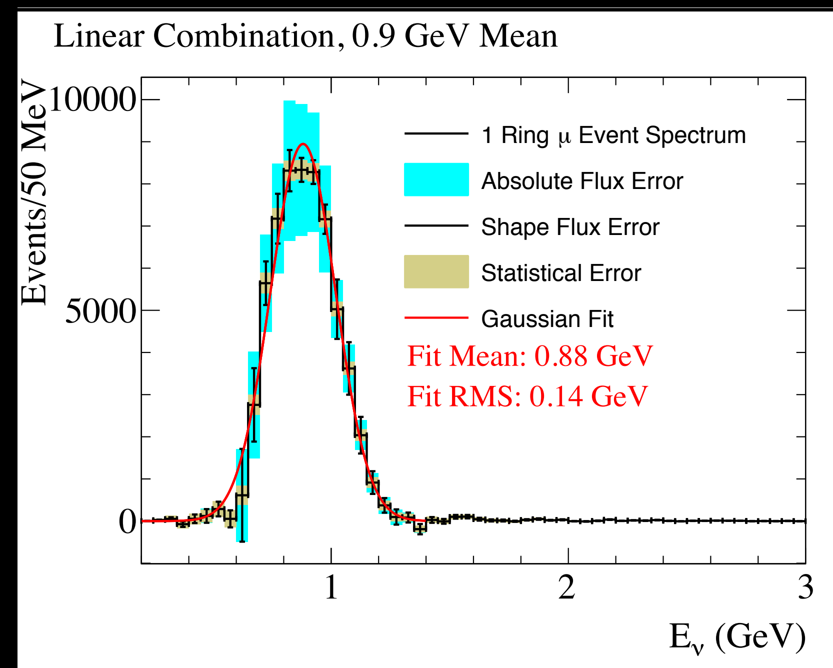
- In selecting "CCQE" WČ detectors select an effective final state:
  - e/μ + (no $\pi^{\pm}$ above Č or decay electron) + nucleons
  - we need the following relation from our model:

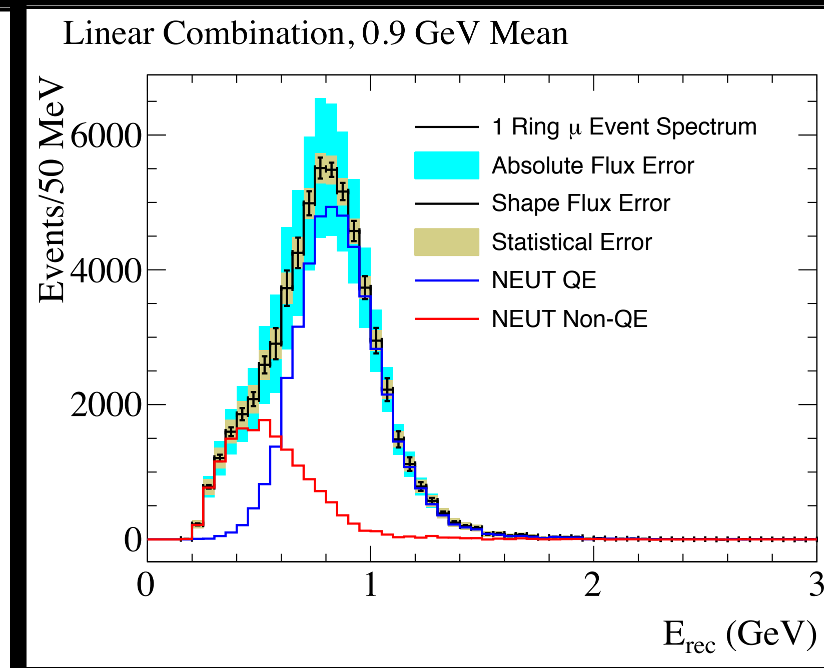
$$\frac{d^2\sigma}{dE_\ell \; d\Omega_\ell}(E_\nu)$$

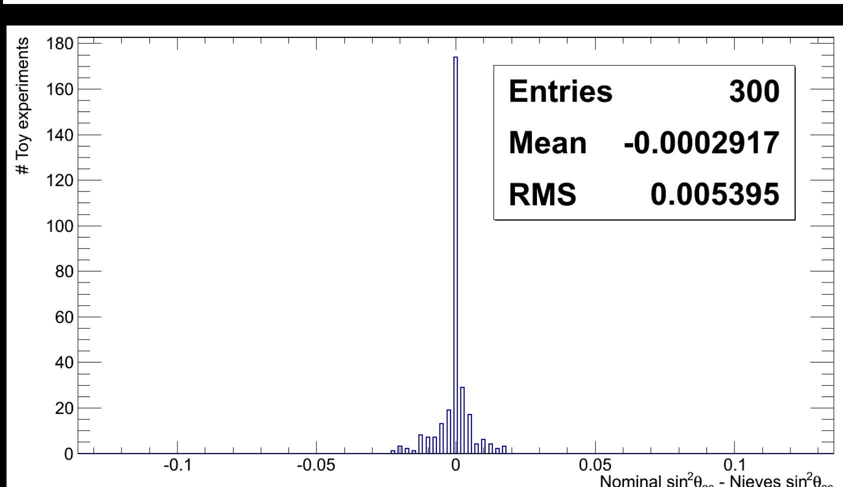
  - i.e. the outgoing lepton momentum/angular distribution for a neutrino with energy E_ν interacting to give the "CC0π" final state
- This allows us to:
  - predict the outgoing lepton spectrum given a predicted flux
  - correctly apply oscillation probabilities P($\nu_\alpha \rightarrow \nu_\beta$; E_ν)
- For me, this is the most pressing issue for the LBL program where kinematic reconstruction of this type is used (not just WČ).
  - FSI plays a critical role in determining the final state.
  - Need to confront with multi-nucleon effects (Martini, et al.)

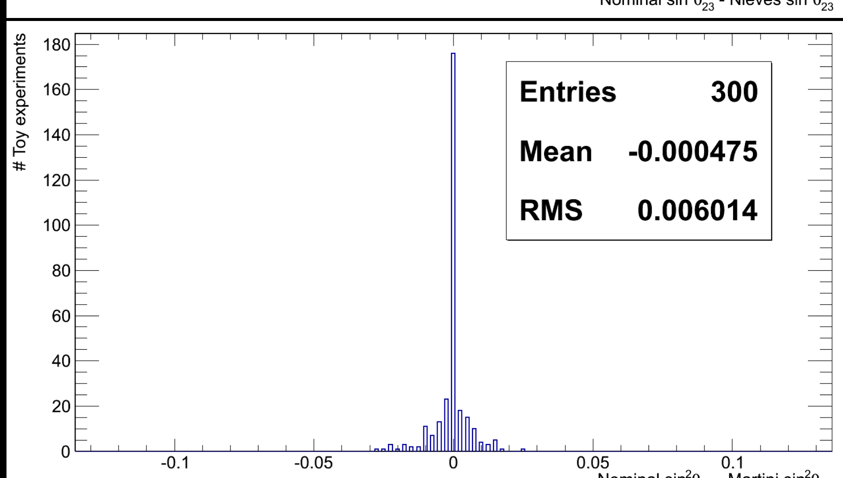
BYPASSING THE MODEL? νPRISM







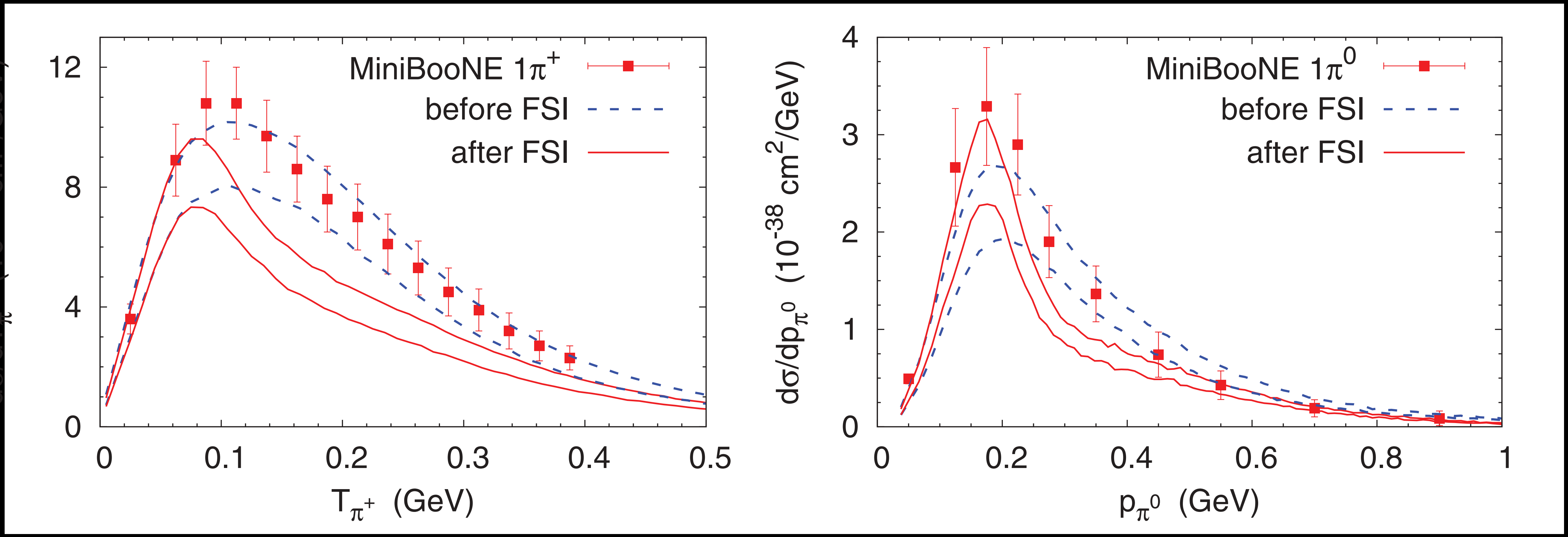




- Exploit variation of E_ν with angle to beam axis
  - "off-axis effect", requires well-known flux
- Simulate detector response (e.g. lepton kinematics) from narrow band of E_ν
- Potential to greatly reduce uncertainties from underlying mechanisms contributing to CC0π sample in WČ detectors

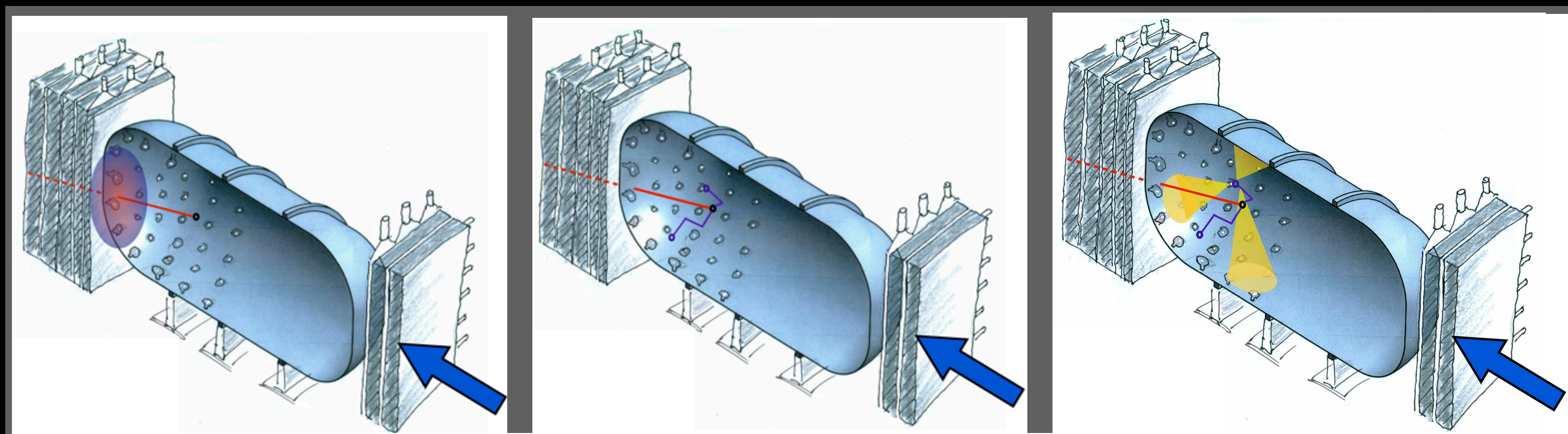
BEYOND CCQE/0π

Lalakulich and Mosel
PRC 87, 014602



- Modelling of CC1π is important in order to utilize these channels at the same level as CCQE
  - misidentified backgrounds in CC0π selection
  - Extending to using CC1π channels in T2K
  - High energy analyses e.g. SK atmospheric analysis
- FSI significantly impacts the properties of the outgoing pions
  - e.g. how many π^+ are above Č threshold and reconstructable.

NEUTRON CAPTURE

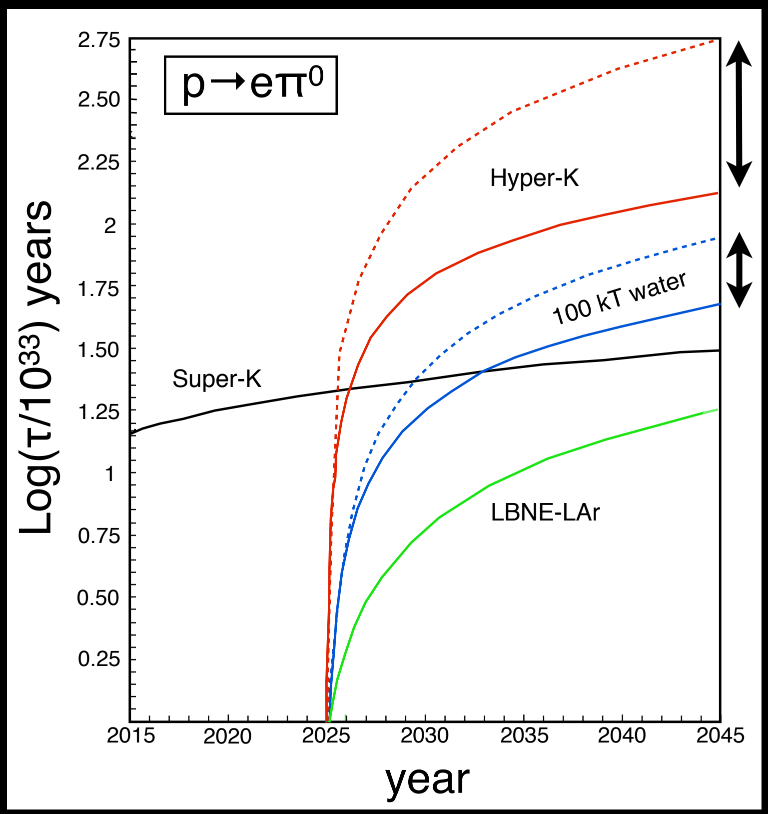


Prompt muon tracks through water volume, ranges in MRD

neutrons thermalize and stop in water

neutrons capture on Gd, flashes of light are detected

- Reduction of atmospheric neutrino backgrounds has potential to significantly improve proton decay sensitivity in WC
  - need to understand neutron emission in atmospheric neutrino interactions
- Extra neutrons expected in $\bar{\nu}$ vs ν interactions due to p→n transition
  - statistical separation of $\nu/\bar{\nu}$ interactions in WC



CONCLUSIONS:

- WČ detectors have/will continue to play a critical role in studying neutrinos
  - a program next generation of experiments is in the works (Hyper-Kamiokande, PINGU, ORKA, etc.)
- The method is particularly well matched to neutrino interactions ~1 GeV where CCQE/0π interactions are dominant
  - more ambitious goals in the study of neutrino oscillations means more demands on modelling and FSI.
  - "Energy reconstruction" issue
- Continuous improvement of the method has been underway
  - Utilize a broader sample of events beyond CCQE(0π)
  - New techniques: neutron tagging, scintillation, etc.
  - Additional frontiers for FSI . . . . . and FUN!