J-PARC E61 EXPERIMENT

REDUCING CROSS-SECTION UNCERTAINTIES IN NEUTRINO OSCILLATION EXPERIMENTS

APS DIVISION OF PARTICLES AND FIELDS MEETING

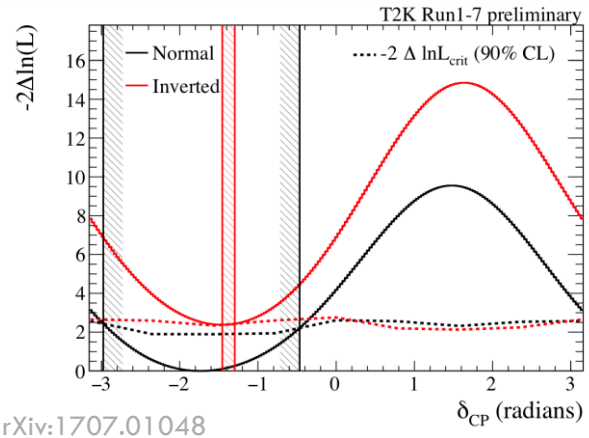
FERMILAB, AUGUST 3RD, 2017

Stony Brook University

Cristóvão Vilela

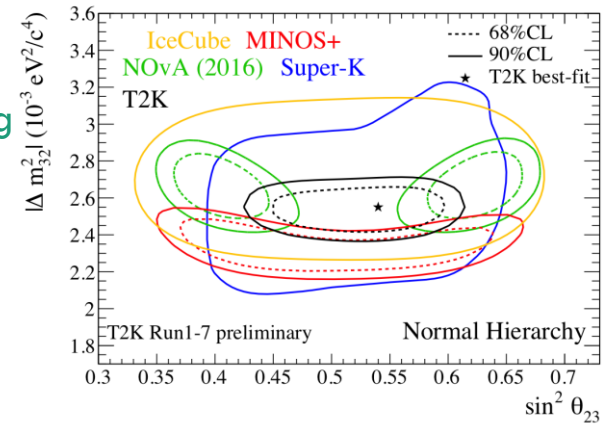
THE TOKAI-TO-KAMIOKA (T2K) EXPERIMENT

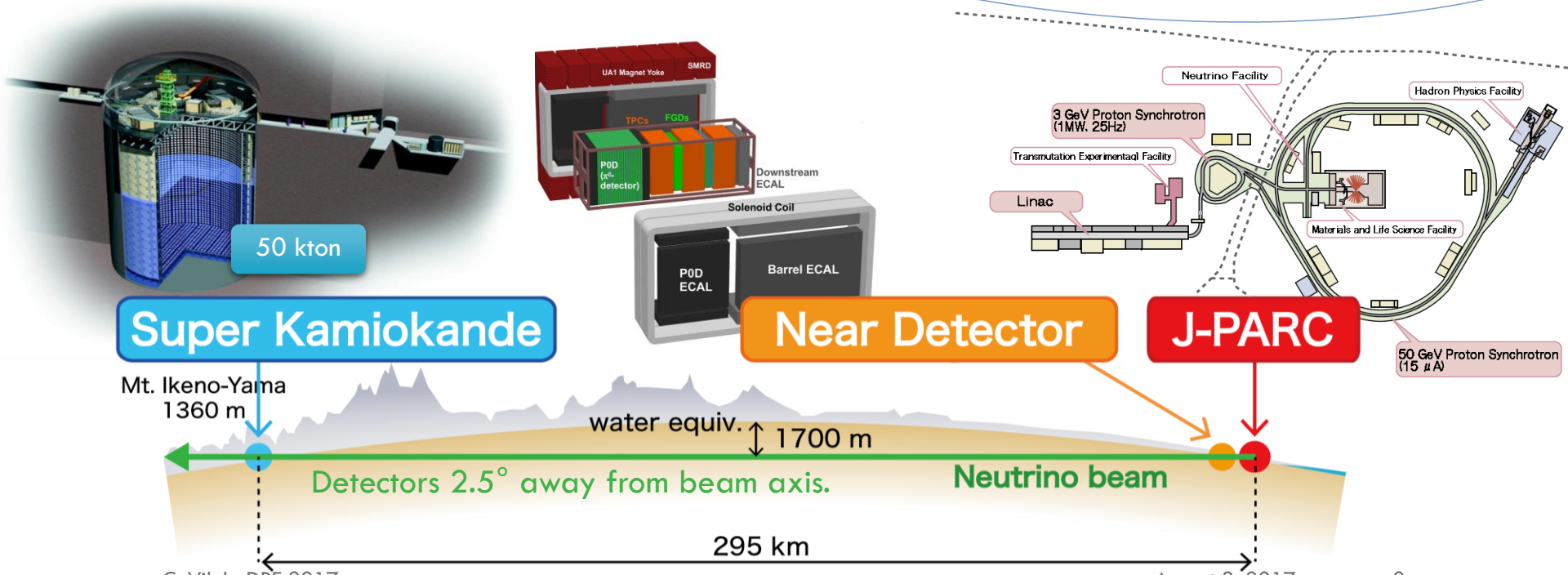
Exclusion of CP conservation in lepton sector at 90% CL.



T2K Collaboration, arXiv:1707.01048

World-leading measurements of $\sin^2\theta_{23}$ and Δm^2_{23}.





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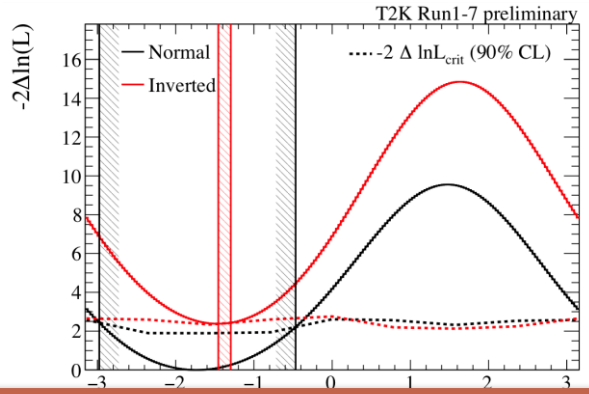

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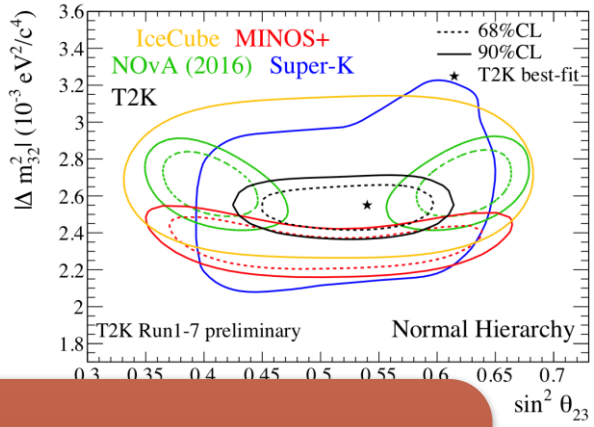
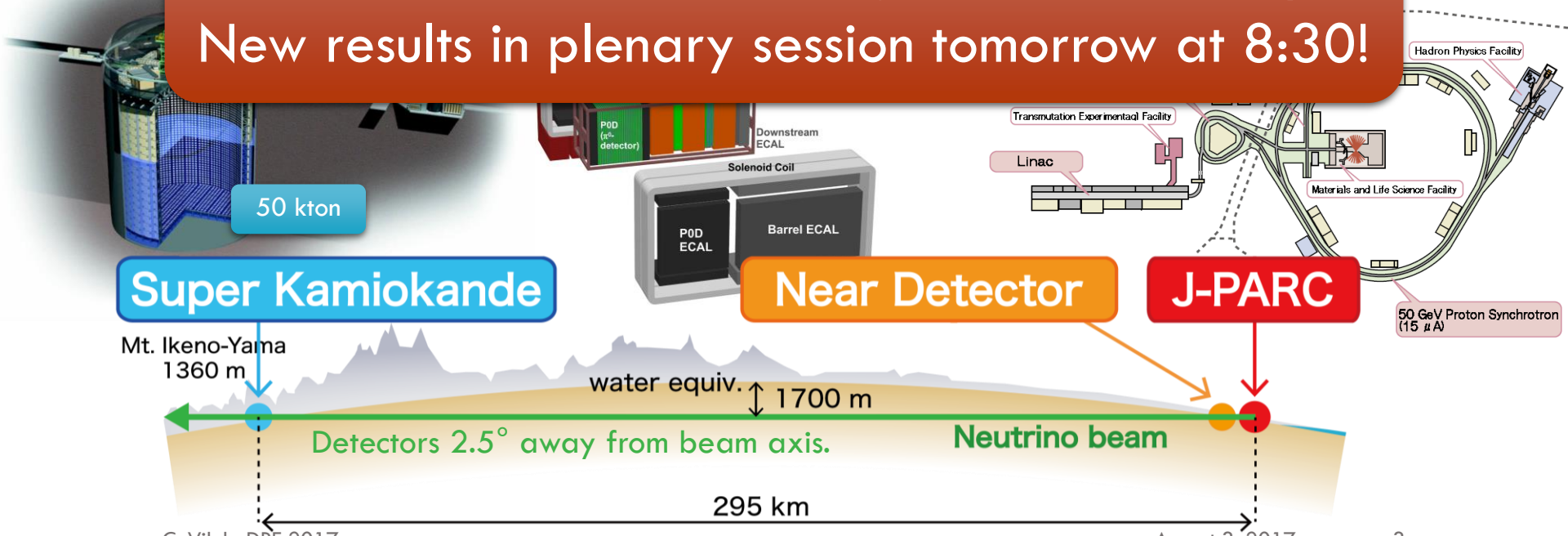


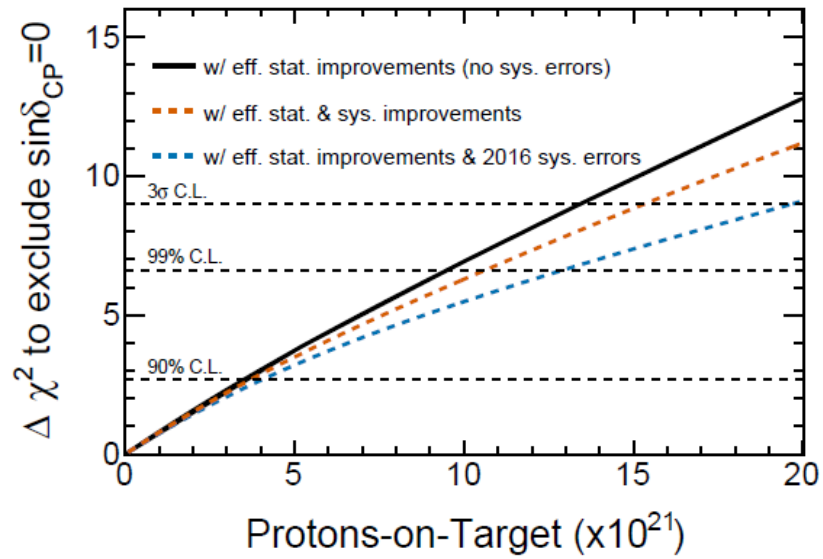
T2K Colla

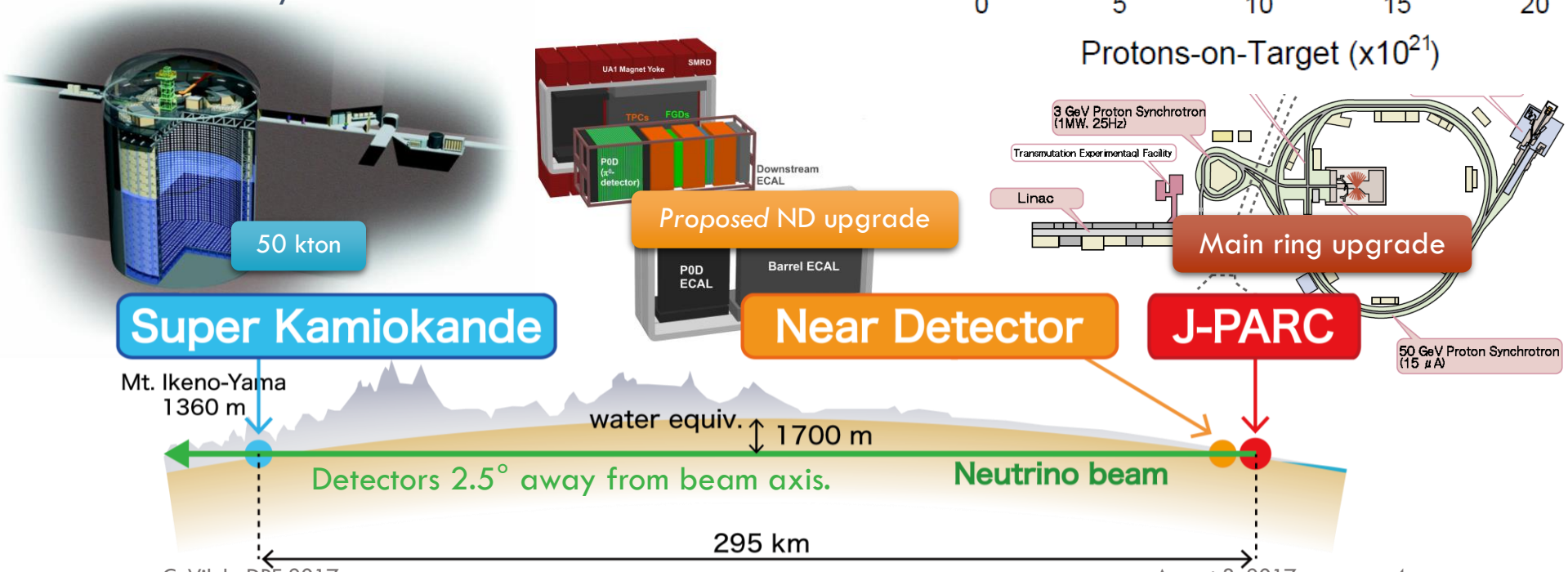
More detail in X. Li's talk given last Monday.
New results in plenary session tomorrow at 8:30!



PROPOSED EXTENDED RUN OF T2K (T2K-II)

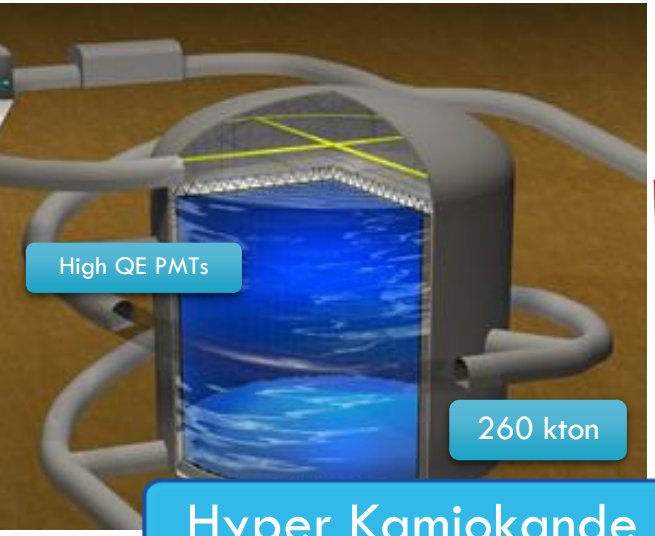
- *Proposal* to extend T2K run from 7.8×10^{21} to 20×10^{21} POT. K. Abe et al, arXiv:1609.04111
- Benefit from:
  - Accelerator upgrade to 800 kW (and then 1.3 MW).
  - *Proposed* near detector upgrade.
  - *Proposed* intermediate water Cherenkov detector: **E61**
- 3σ sensitivity to maximal CP violation

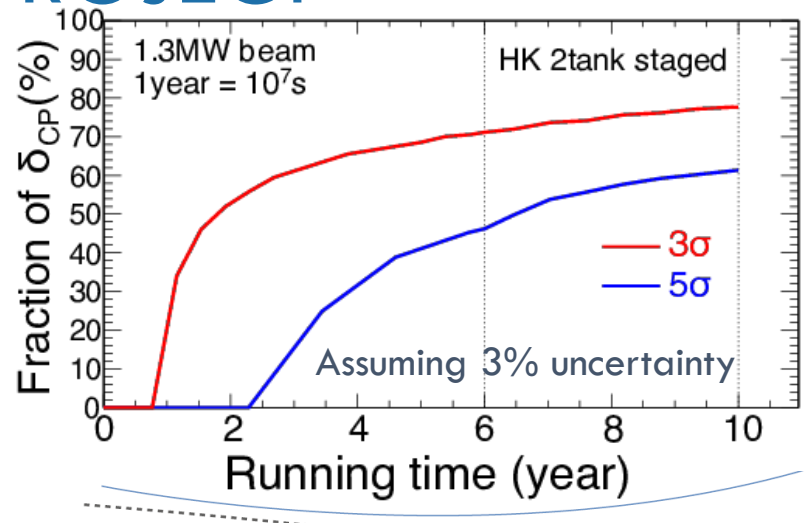


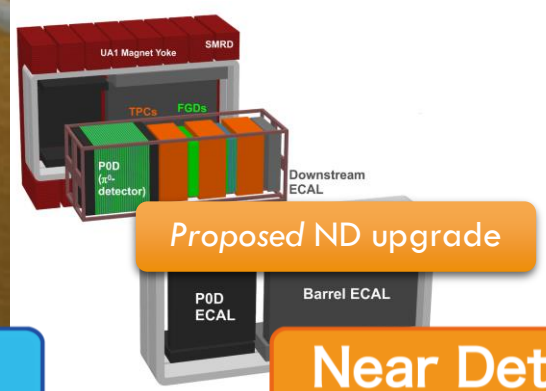


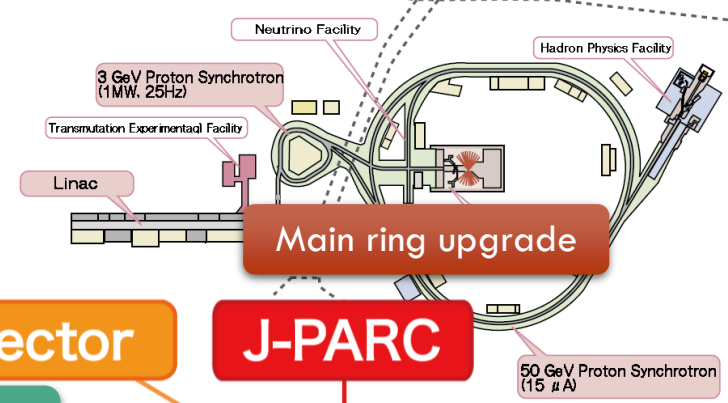
HYPER KAMIOKANDE PROJECT

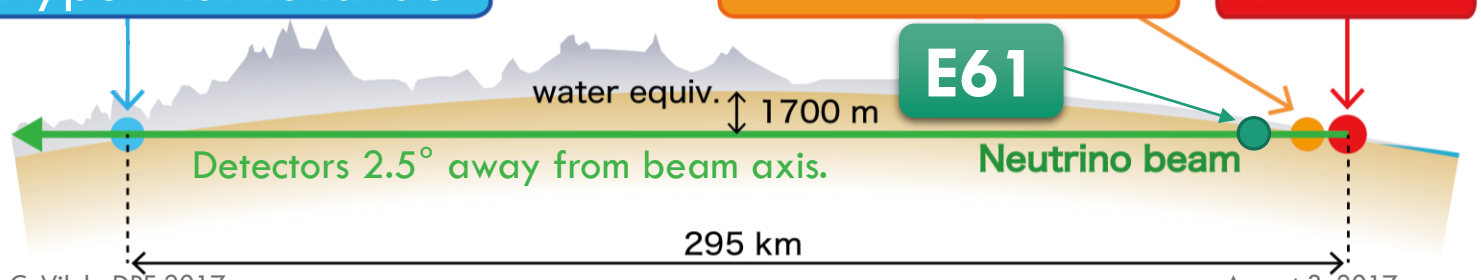
- Next-generation water Cherenkov detector with extensive Physics program
- 5σ sensitivity for a wide range of δ_{CP} values
  - Requires strong constraints on systematic uncertainties
- Intermediate water Cherenkov detector: **E61**





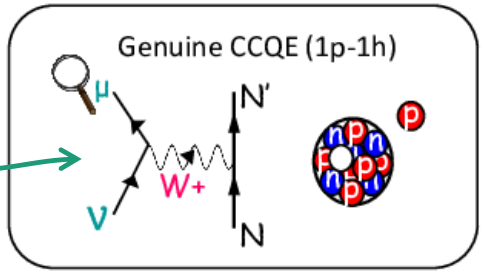


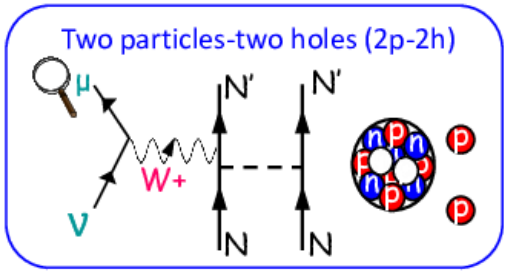




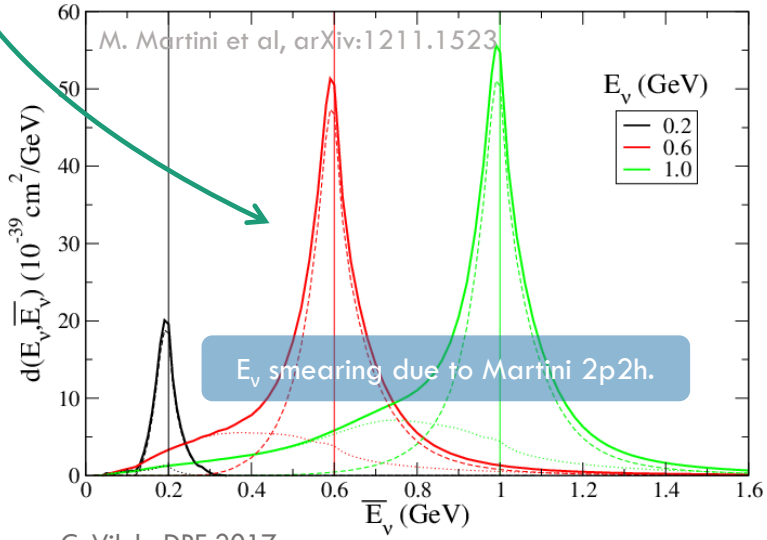
MEASURING NEUTRINO ENERGY

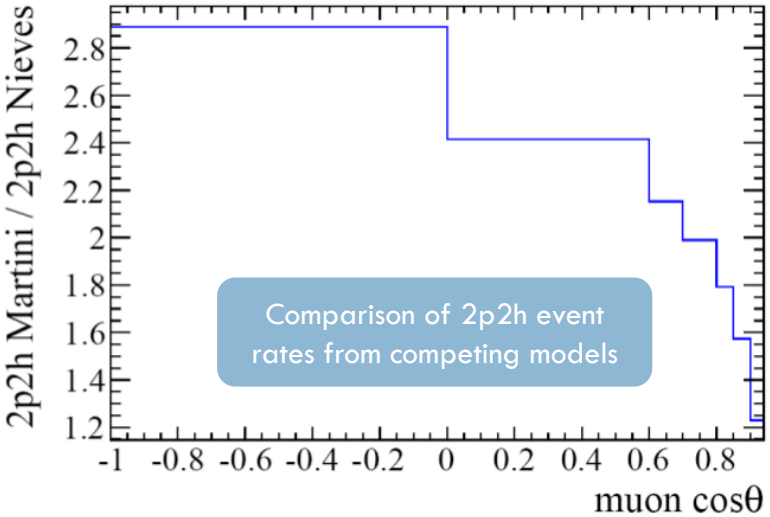
- Model assumptions play important role in inferring neutrino energy from detected neutrino-nucleus interaction products.
- In Super-K charged lepton kinematics are measured and CCQE dynamics are assumed.
  - Multi-nucleon contributions to CCQE cross-section can bias E_ν significantly.
  - Large uncertainties from final state and secondary interaction models.
- Calorimetric measurements suffer from similar model dependence.
  - For example, through uncertainties in the multiplicity of (undetected) neutrons.





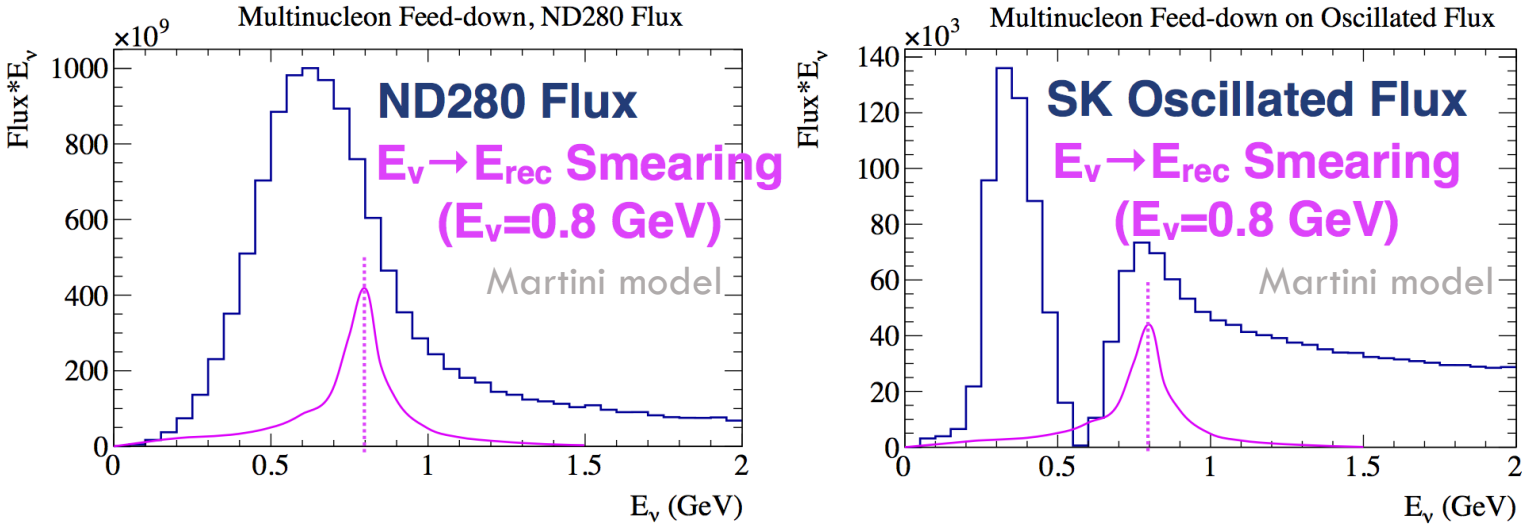
T. Katori, M. Martini, arXiv:1611.07770





NEAR DETECTOR CONSTRAINTS

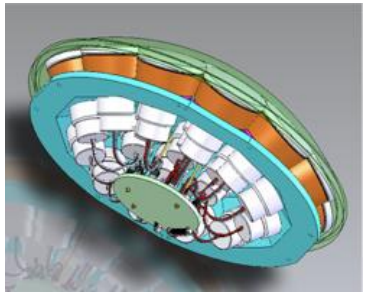
- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!

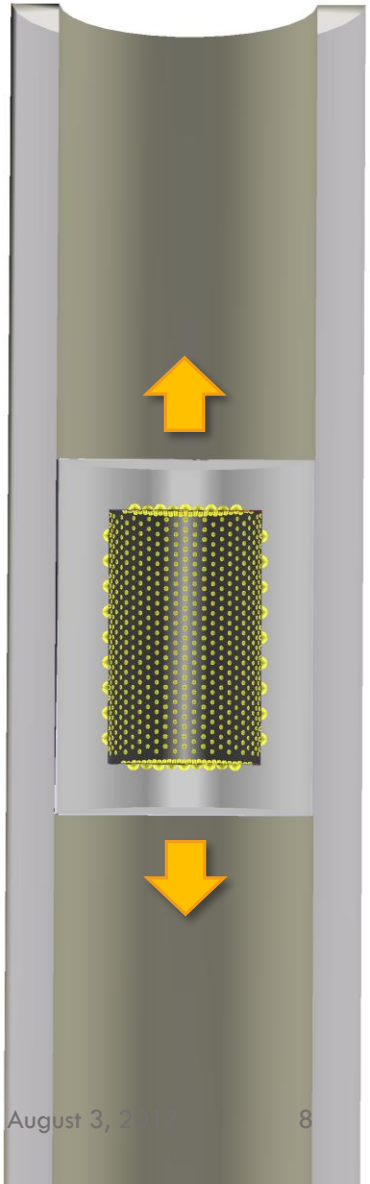


- This presents an additional difficulty in constraining neutrino interaction models.
- We only ever measure a combination of flux and cross-section.
- Multi-nucleon effects can smear reconstructed neutrino energy into oscillation **dip** at far detector, biasing the measurement.
  - But this is obscured by the flux **peak** at the near detector!

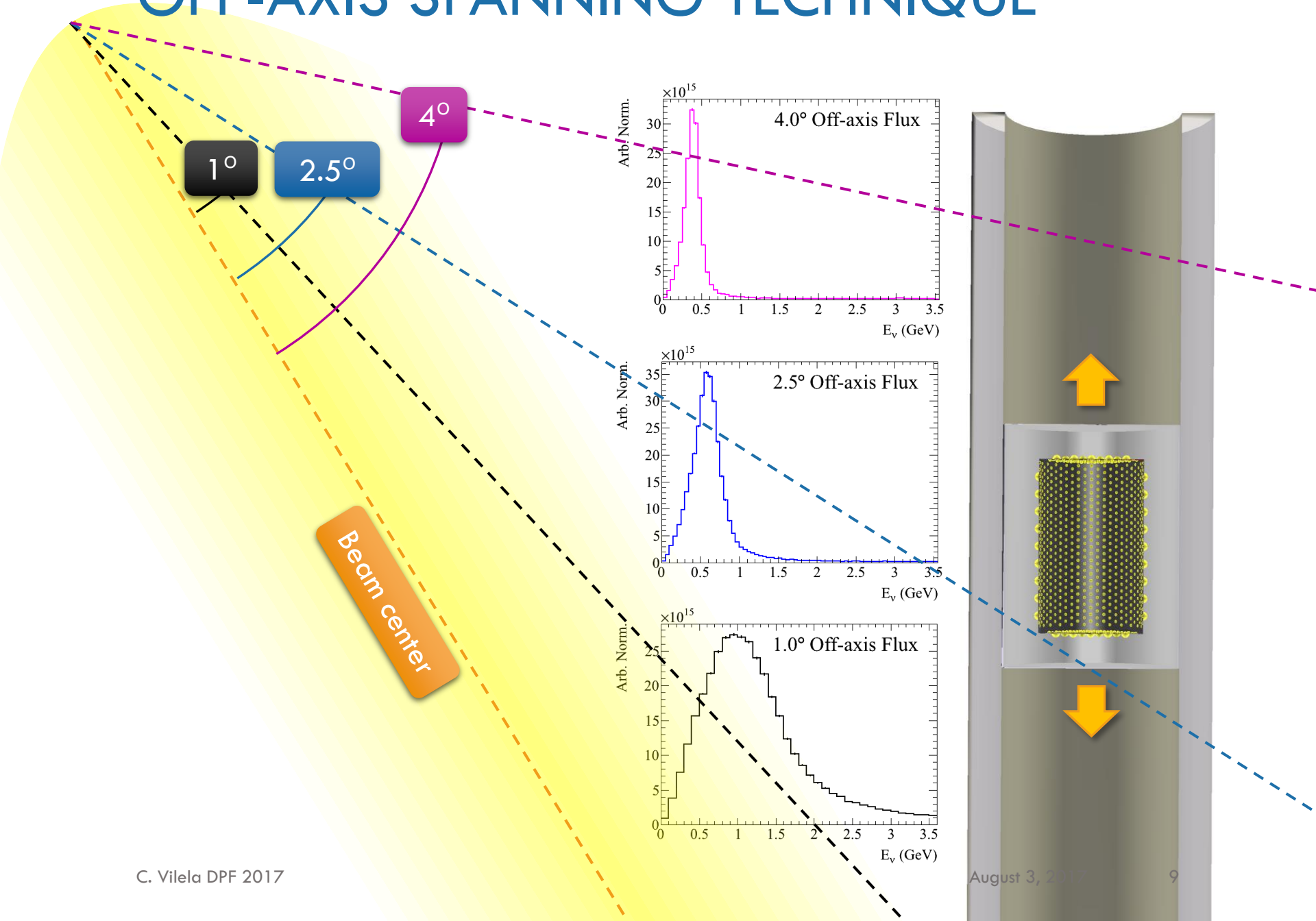
THE E61 EXPERIMENT

- An intermediate water Cherenkov detector on the J-PARC beam path.
  - Measures unoscillated flux with the same nuclear target and experimental technique as the far detector.
- Instrumented portion of the detector is moveable within a deep pit.
  - Sample neutrino interactions from a wide range of off-axis angles.
- Optically separated inner and outer detector volumes.
  - Inner detector 6 – 10 m tall and 8 m diameter.
  - Outer detector 10 – 14 m tall and 10 m diameter.
- Populated with multi-PMT modules.
  - Modules contain 3" PMTs facing both inner and outer detector volumes.
  - Use of reflectors to increase effective photocathode coverage.
  - Integrated electronics.
- Option to load water with Gadolinium.
  - Precise measurements of neutron emission in neutrino interactions and capture rates.





OFF-AXIS SPANNING TECHNIQUE

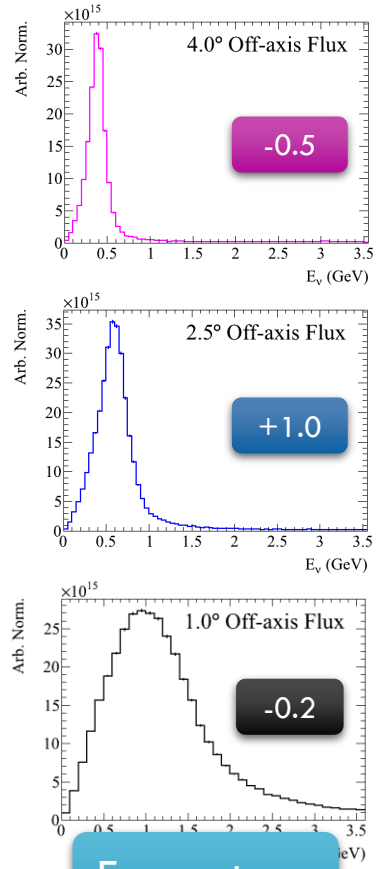


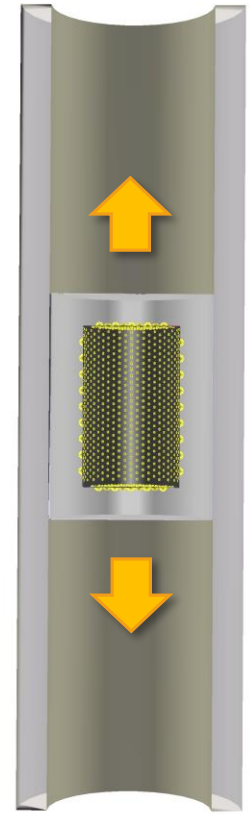
COMBINATIONS OF OFF-AXIS SAMPLES

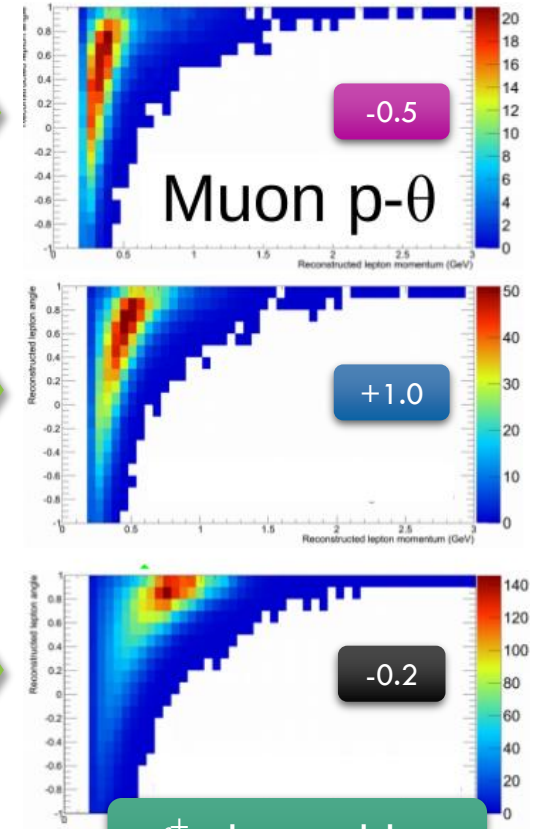
- Make use of the off-axis angle dependence of ν flux:

1. Bin data in off-axis angle.
2. Take combinations of different off-axis angle bins.
3. Get distribution of observables for a known E_ν spectrum.

Coefficients determined by the desired E_ν spectrum.

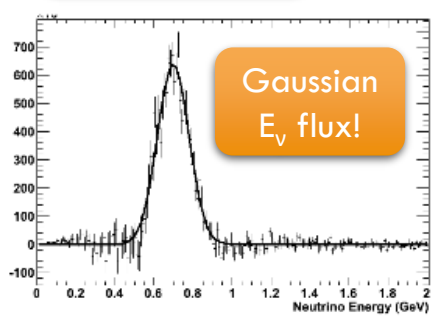






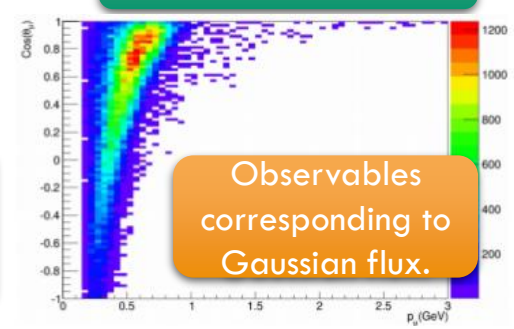
E_ν spectrum

$\ell^\pm$ observables



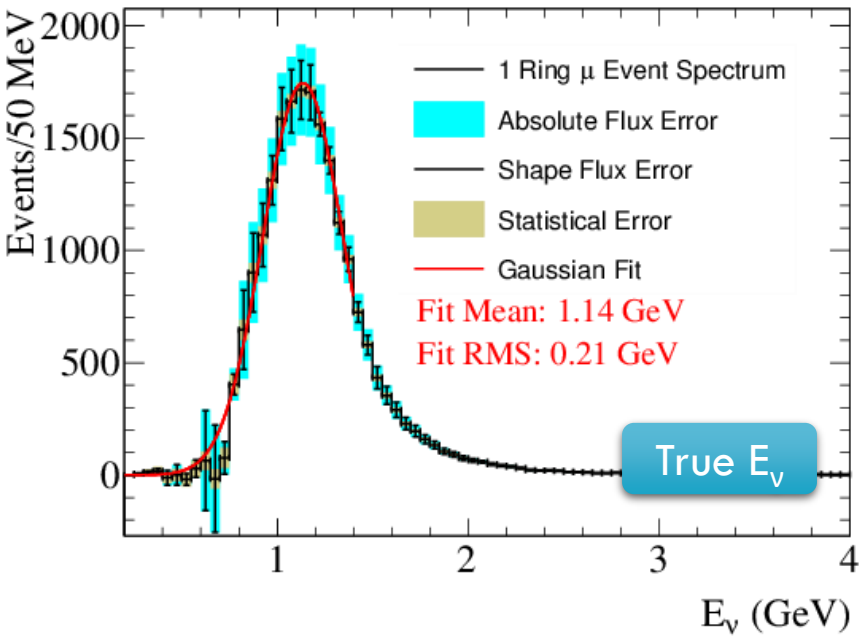
Take linear combinations of 60 off-axis angle bins.

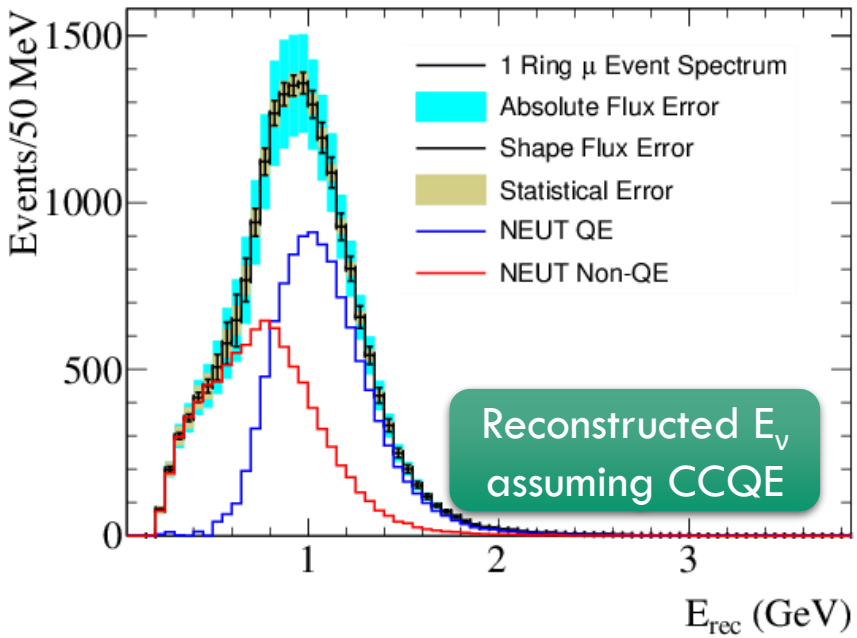
Apply same coefficients to distributions of observables.



PSEUDO-MONOCHROMATIC BEAMS

- Single muon candidate events after off-axis coefficients are applied to give monochromatic flux centered at 1.2 GeV.

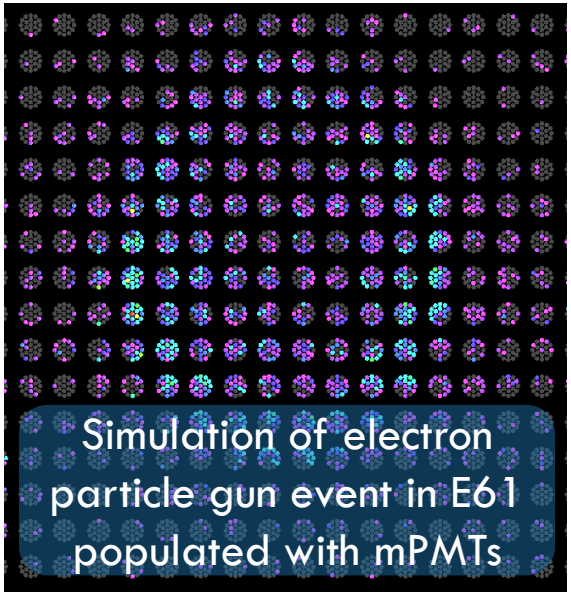




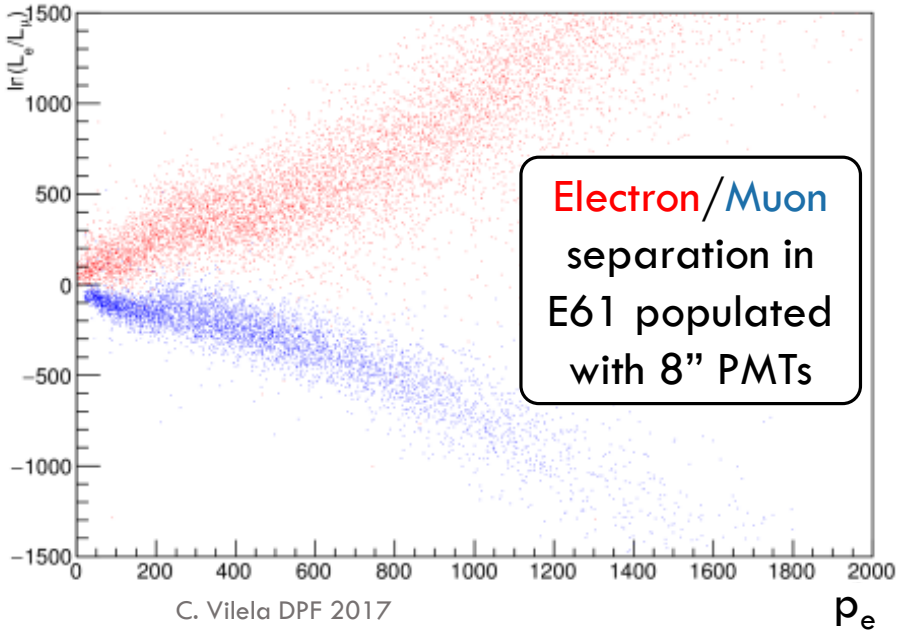
- Measure cross-sections as a function of true neutrino energy.
- Q^2 and ω available – detailed neutrino measurements *a la* electron scattering.
- Powerful probe of interaction models, such as departures from CCQE due to multinucleon effects.

E61 SIMULATION AND RECONSTRUCTION

- Complete simulation and reconstruction chain has been developed for E61.
  - In use for physics and detector optimization studies
- The Geant4-based WCSim package is used for simulation.
  - Highly configurable water Cherenkov detector geometries, several PMT models available.
  - Recently implemented multi-PMT modules.



Simulation of electron particle gun event in E61 populated with mPMTs

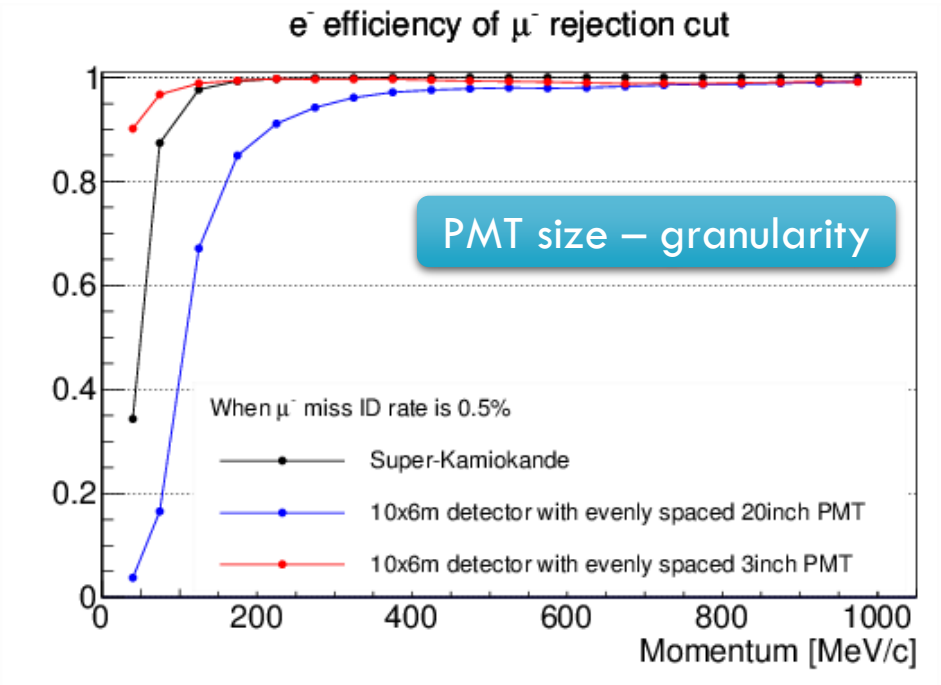


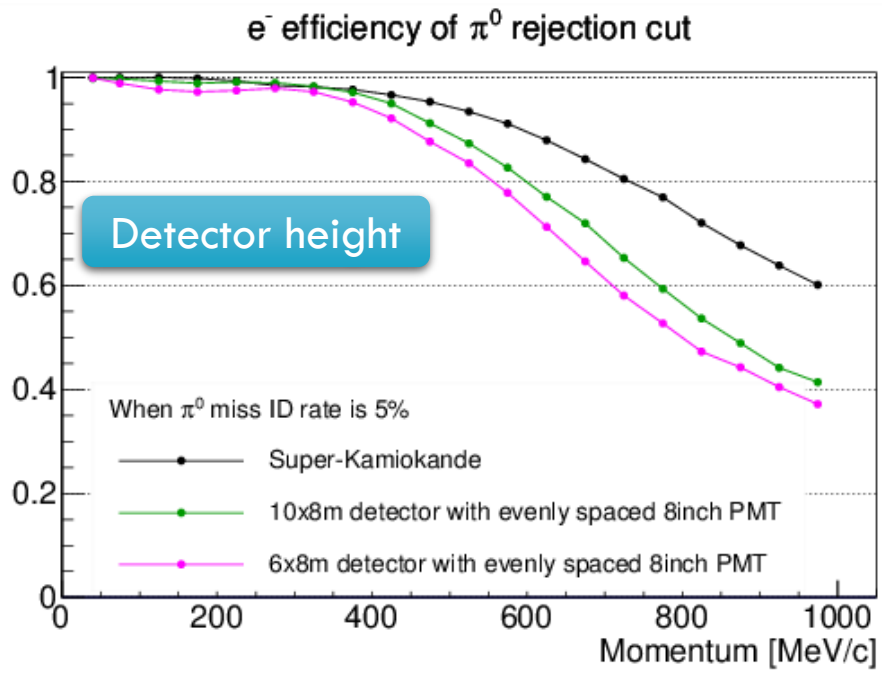
- Reconstruction with fiTQun.
  - Maximum likelihood estimation of track parameters using all the information in an event.
    - Hit/unhit, time and charge.
  - Developed and deployed at Super-K, now also running on WCSim output.

Same software chain as Hyper-K

E61 DETECTOR OPTIMIZATION STUDIES

- Complete simulation and reconstruction chain using WCSim and fiTQun is being actively used in detector optimization studies.

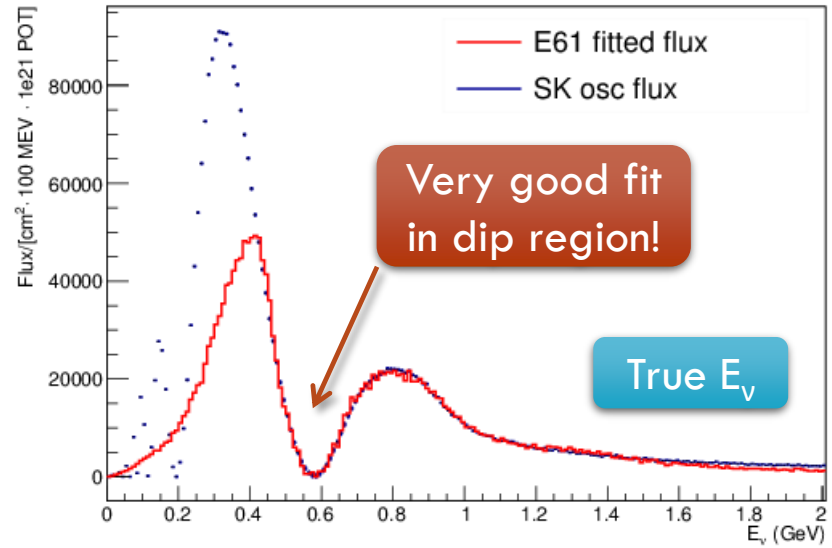


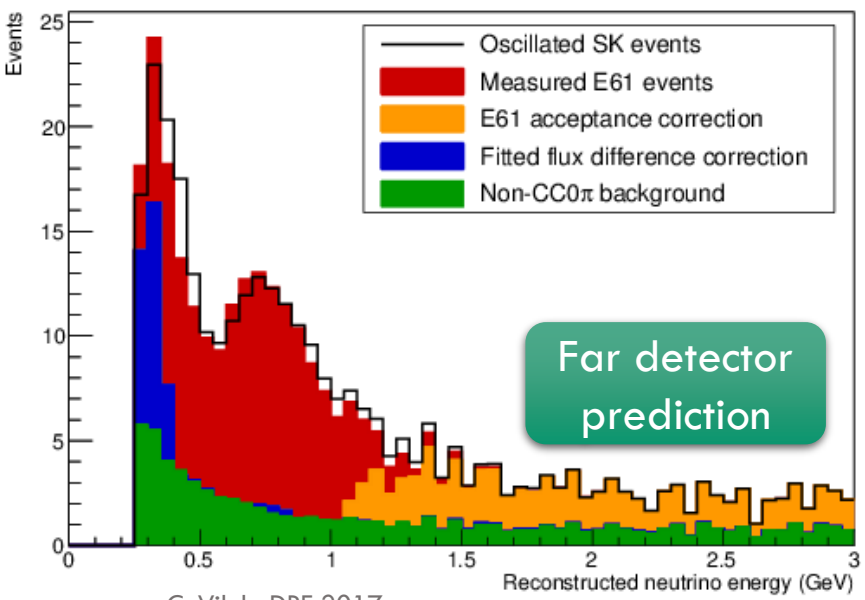


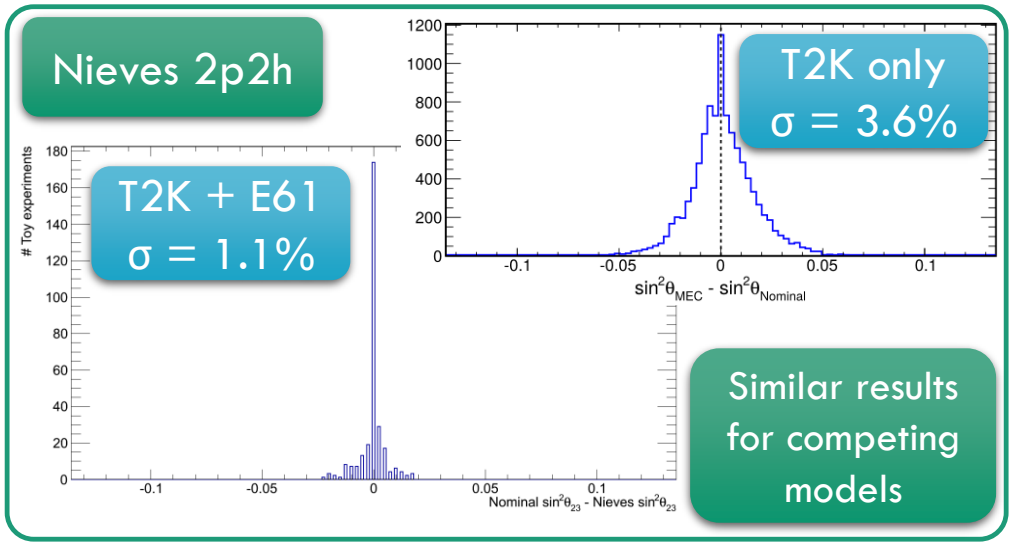
- Study major detector parameters such as overall dimensions, photosensor size and density, mPMT module configuration.
- Parameters are optimized as a function of detector performance:
  - Electron / muon separation; electron / π^0 separation, detection efficiencies, …

ν_μ DISAPPEARANCE WITH E61

- Take linear combinations of off-axis binned to reproduce the far detector oscillated neutrino flux.
- Use the corresponding observables to make a prediction for the far detector data with little model dependence.
- Background, flux and acceptance corrections necessary for SK prediction.

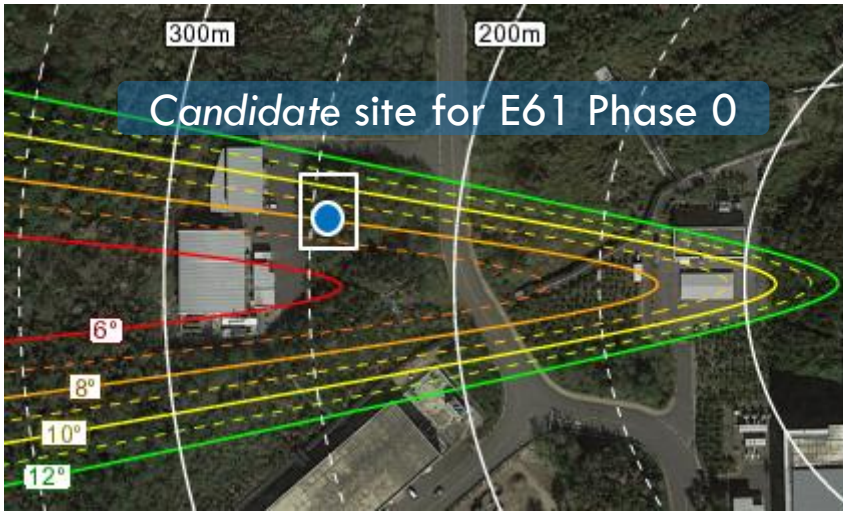


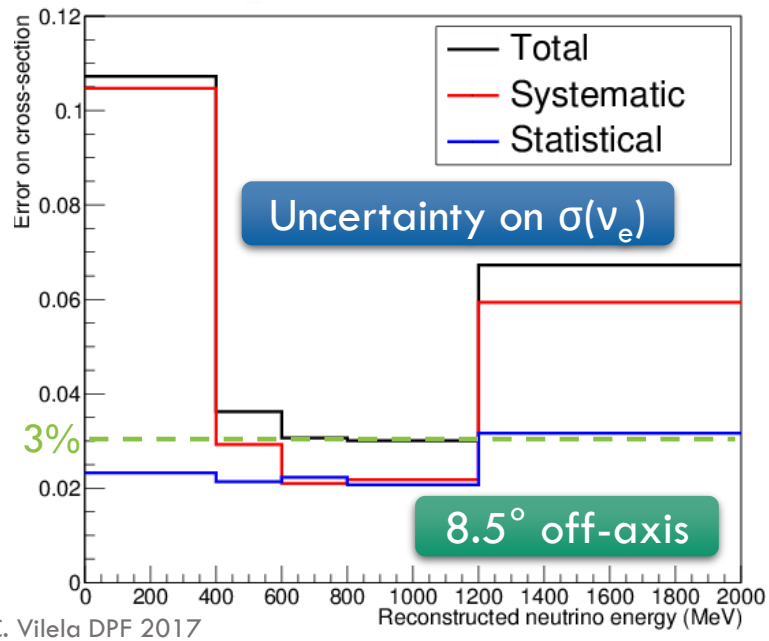


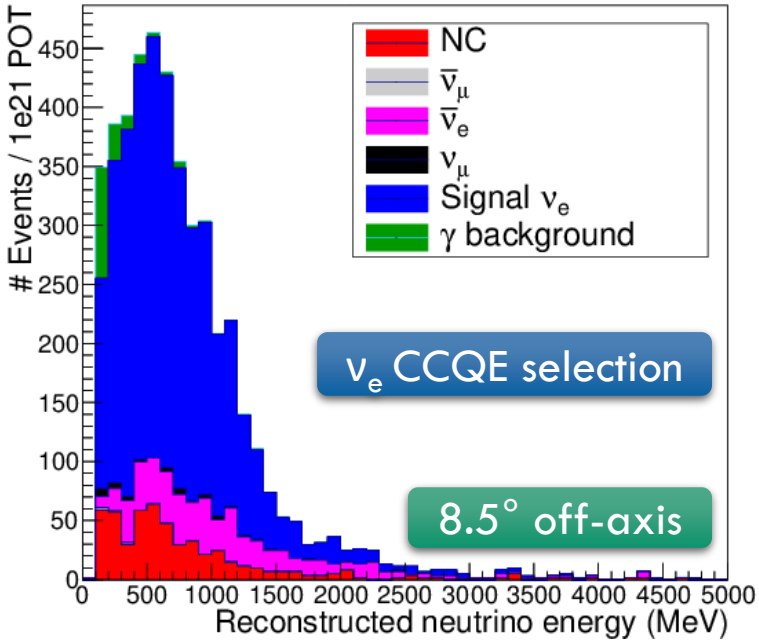


A STAGED APPROACH – E61 PHASE 0

- In an initial phase, the E61 detector will be built and installed on the surface at the J-PARC site.
- Running in this mode will allow for:
  - Detector performance and calibration requirements to be demonstrated;
  - A precise measurement of the ν_e cross-section on water.
    - $\sigma(\nu_e)/\sigma(\nu_\mu)$ is a large, theory-driven contribution to the uncertainty on T2K δ_{CP} measurement.

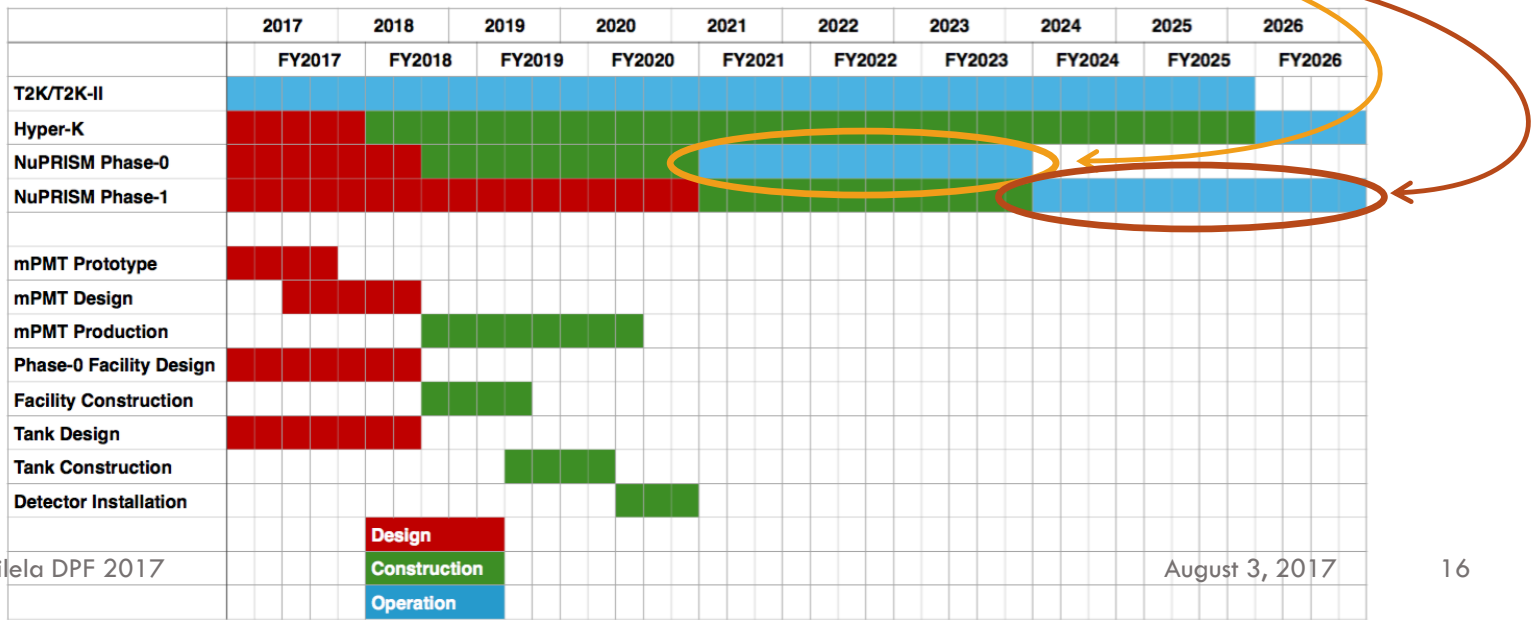






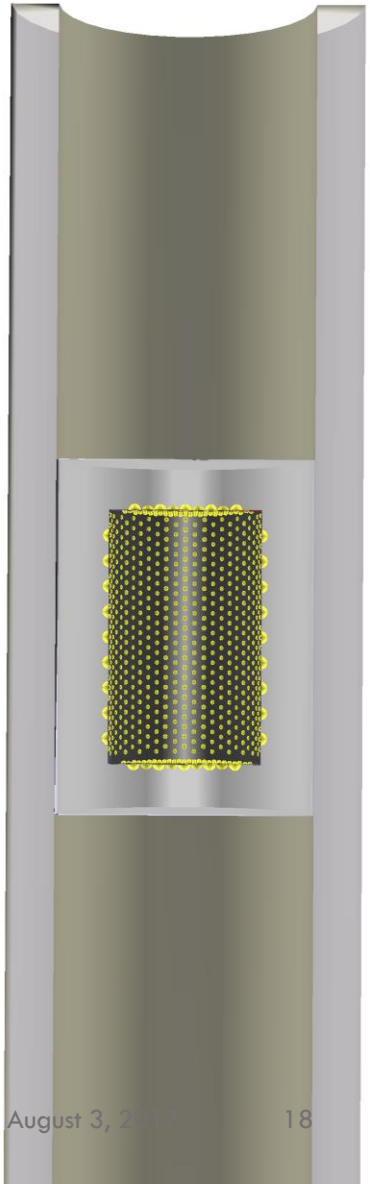
STATUS AND PROSPECTS

- Project received J-PARC Stage 1 approval in July 2016.
- NuPRISM and TITUS efforts merged into single collaboration: E61.
- Technical Design Report under development aiming for final J-PARC approval in 2018.
- Aim to take beam data:
  - For 2 years in Phase 0
  - For 2 to 3 years in Phase 1 concurrently with T2K-II



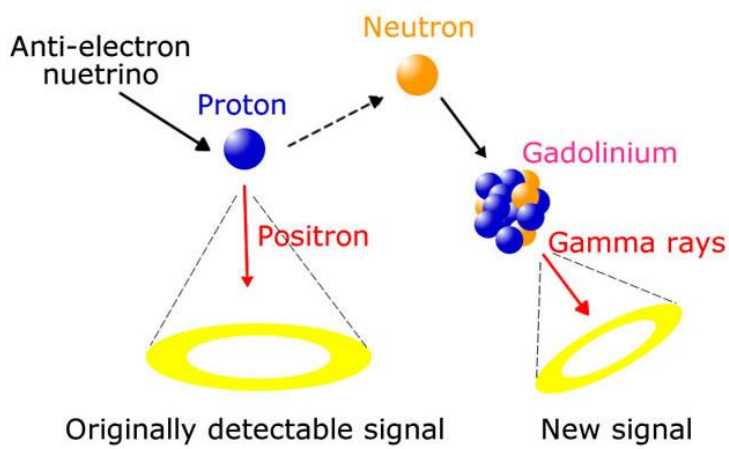
THANK YOU!

SUPPLEMENTARY

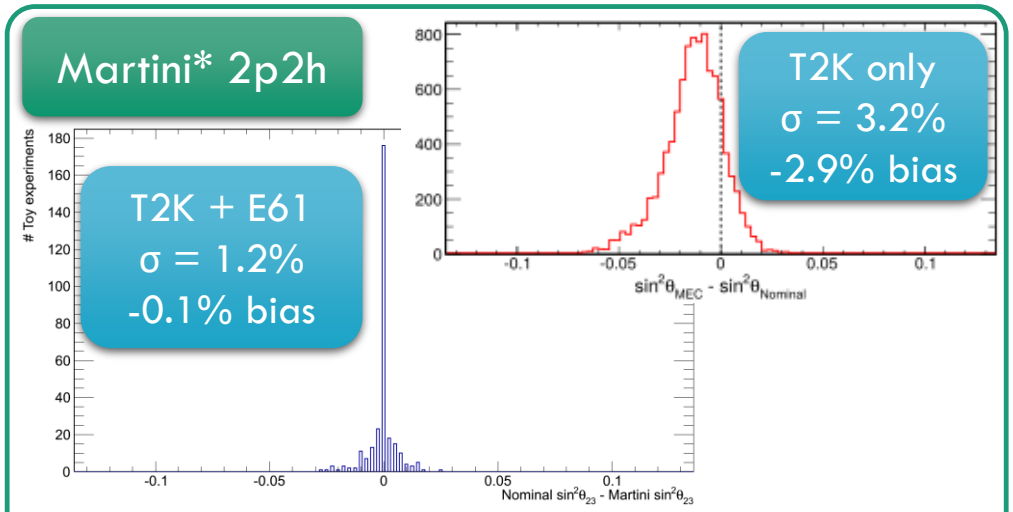


GADOLINIUM LOADING

- Program to load Super-K water with Gadolinium is now well established.
  - Required tank liner refurbishment work planned for 2018.
- Neutron tagging with Gd might be useful in separating ν/anti-ν interactions, reducing wrong-sign backgrounds.
  - Expect more neutrons in anti-ν interactions.
  - However, large uncertainties on neutron multiplicity – unclear picture from both theory and experiment.
- Option to load E61 water with Gd provides an opportunity to measure neutron emission and capture on Gd as a function of E_ν.



E61 ν_μ DISAPPEARANCE MODEL INDEPENDENCE



* "Hacked" model, with Nieves final states.