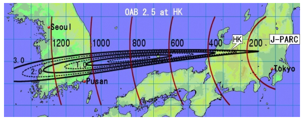
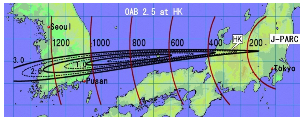
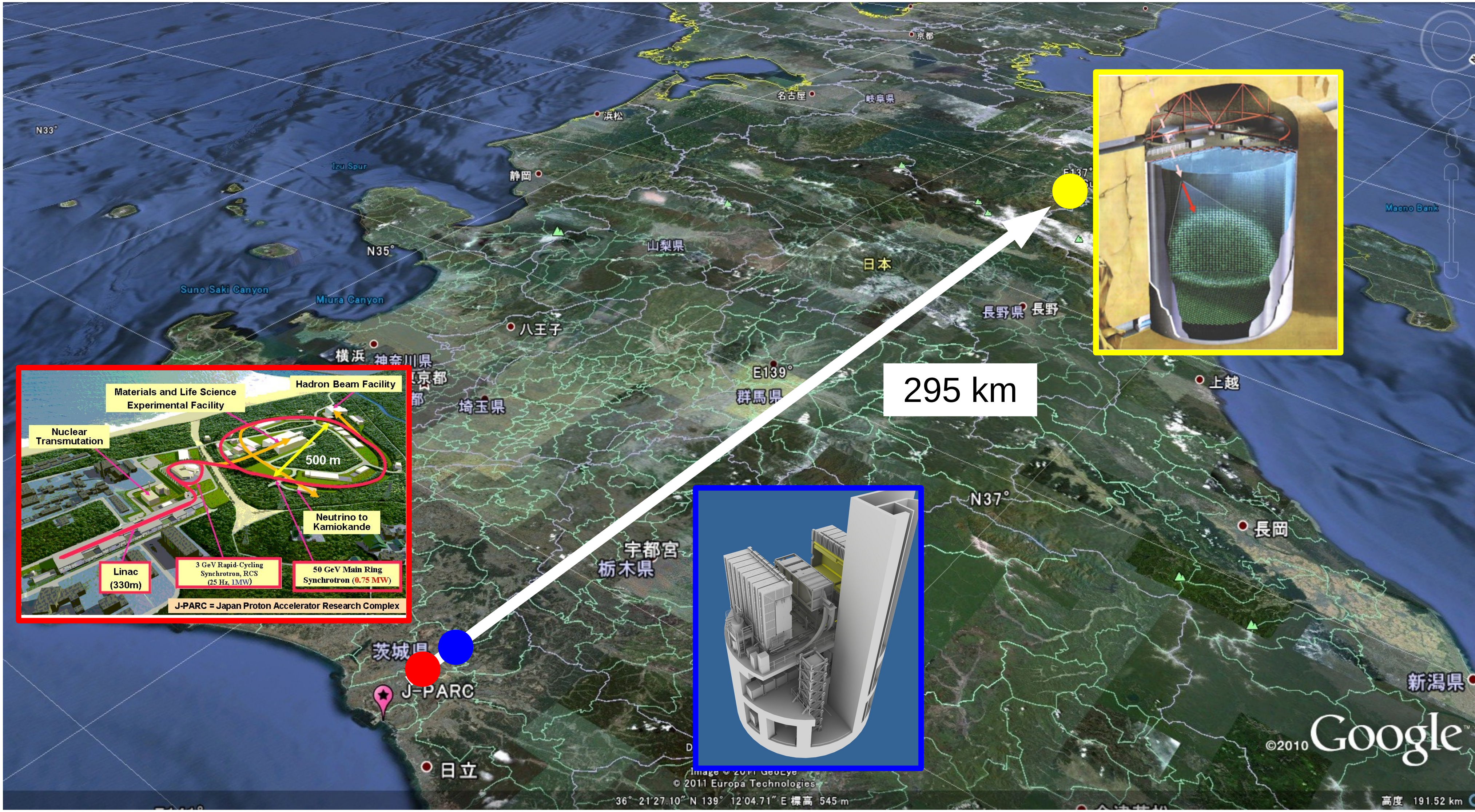


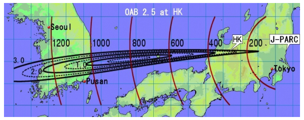
Systematic uncertainties in long baseline experiments



Tokai to Kamioka (T2K) experiment



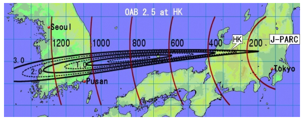
- Near detectors used to predict unoscillated neutrino rate at far detector
- Fit far data to prediction to measure oscillation parameters



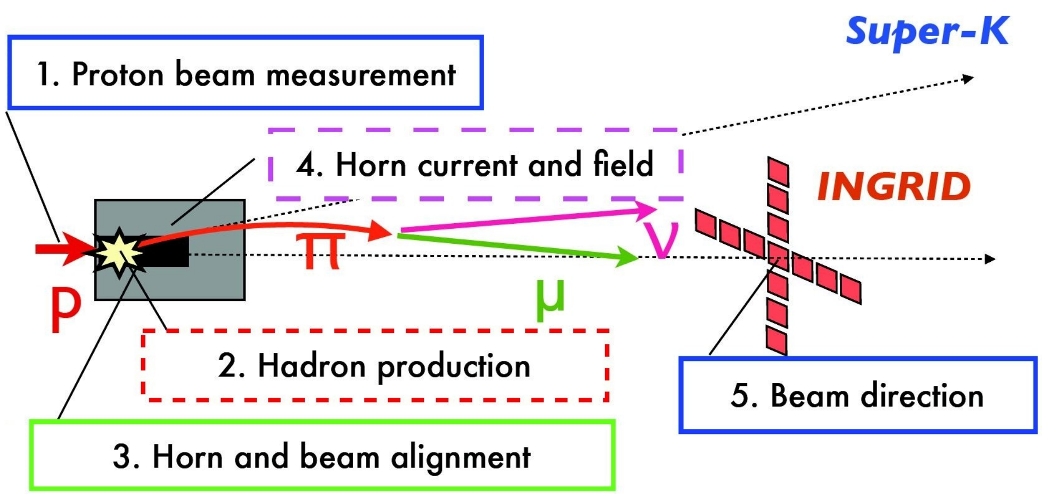
Measuring neutrino oscillations

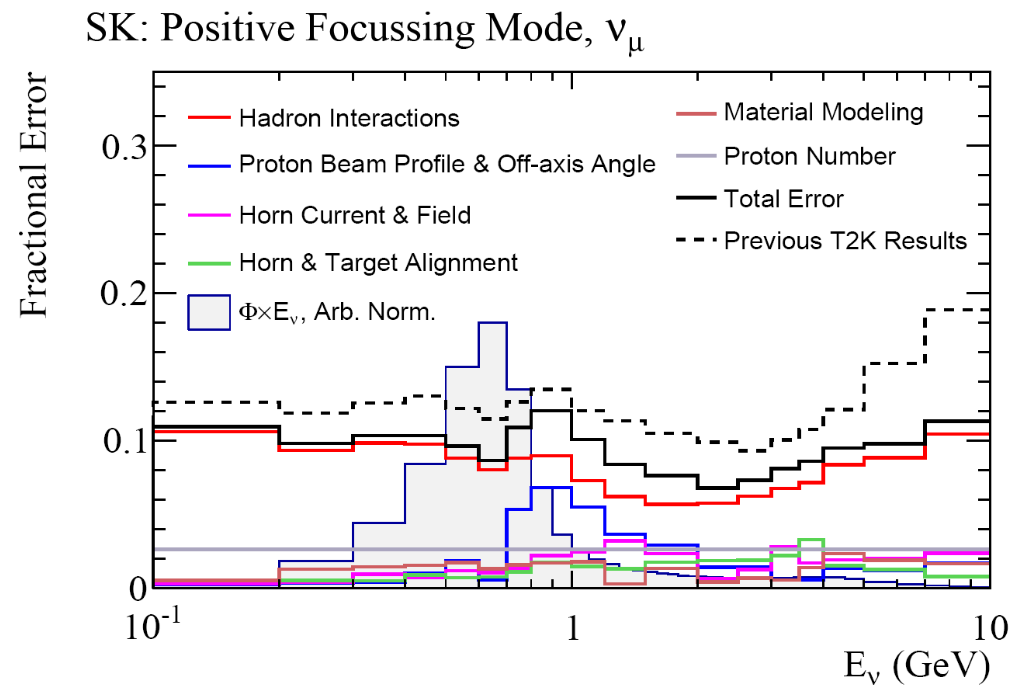
- Detectors measure interaction rate:
  - Near detector (ND280)
    - $\Phi_{ND}(E_\nu,\nu_i) * \sigma_i^{C/O}(E_\nu,\nu_i) * \varepsilon_{ND}(E_\nu)$
  - Far detector
    - $\Phi_{FD}(E_\nu,\nu_i) * \sigma_j^{O}(E_\nu,\nu_i) * \varepsilon_{FD}(E_\nu) * P[\nu_i \rightarrow \nu_j](E_\nu,\nu_i)$
- Systematic on each term

- If near and far detectors are identical, and see same flux
  - Near detector directly measures product of flux and cross-section
  - Compare to SK data to get oscillation parameters
- This is not the case:
  - Different fluxes – energy dependence and flavour both change
  - Different nuclear target
  - Different detection efficiencies

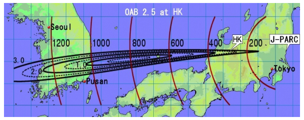


Flux uncertainties



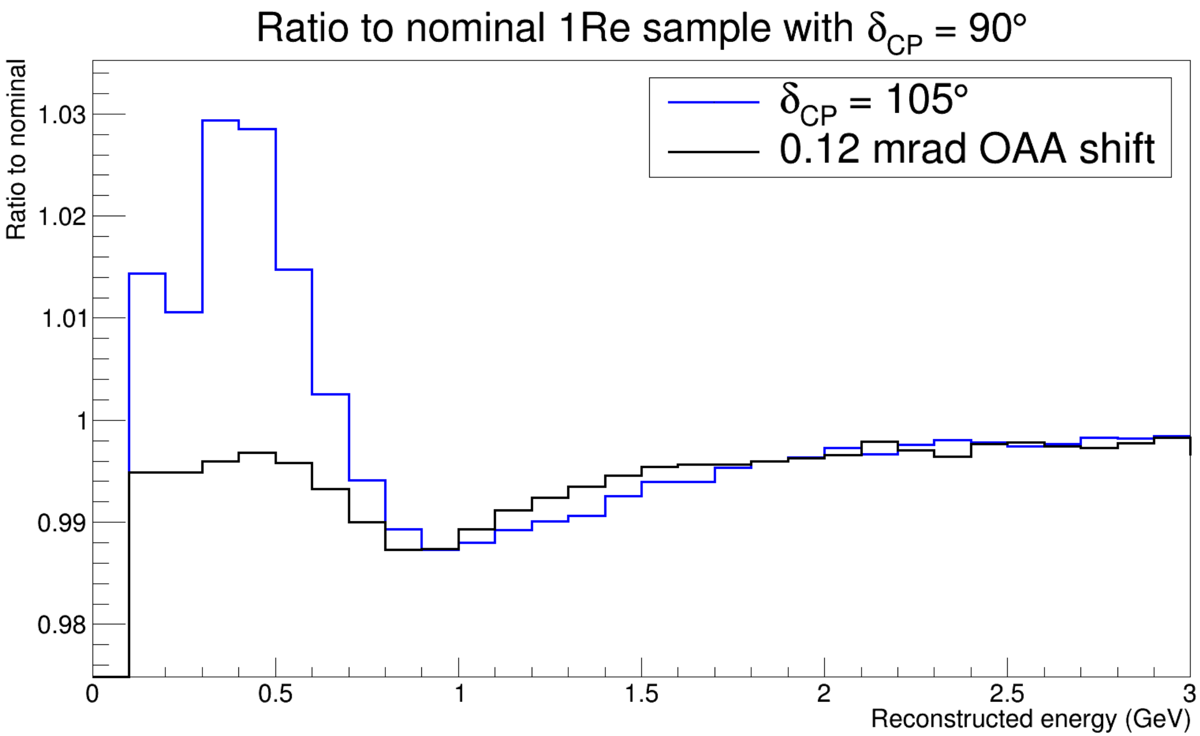


- Flux simulation tuned to data from hadron production experiments, beam line monitors, beam direction monitor (INGRID) etc.
- Gives tuned prediction and uncertainty
- Currently ~8% at beam energy peak
- Improvements expected from T2K replica target measurements
  - Near detector fit → Reducing flux uncertainty allows better constraint on cross-section model uncertainties

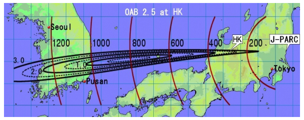


Flux systematics at T2HKK

- Off-axis angle uncertainty currently ~0.12 mrad for T2K
  - Shifts flux normalisation and shape
  - Distorts HK 1Re event spectrum in similar way to 15° change in value of δCP

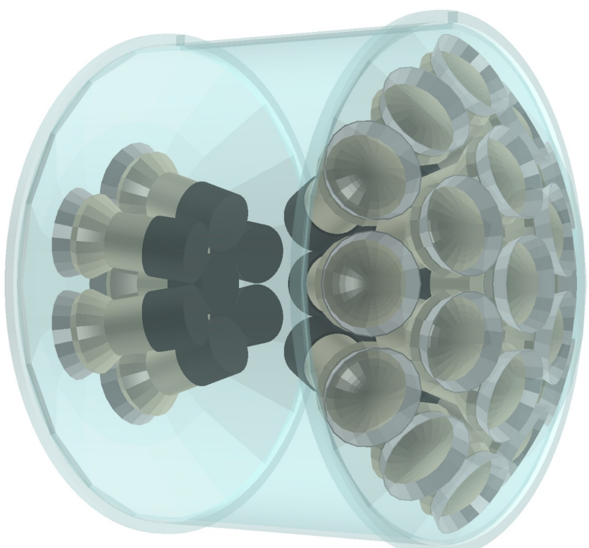


- Need to ensure we can constrain both shape and normalisation with near detector information

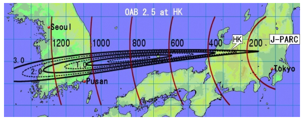


NuPRISM

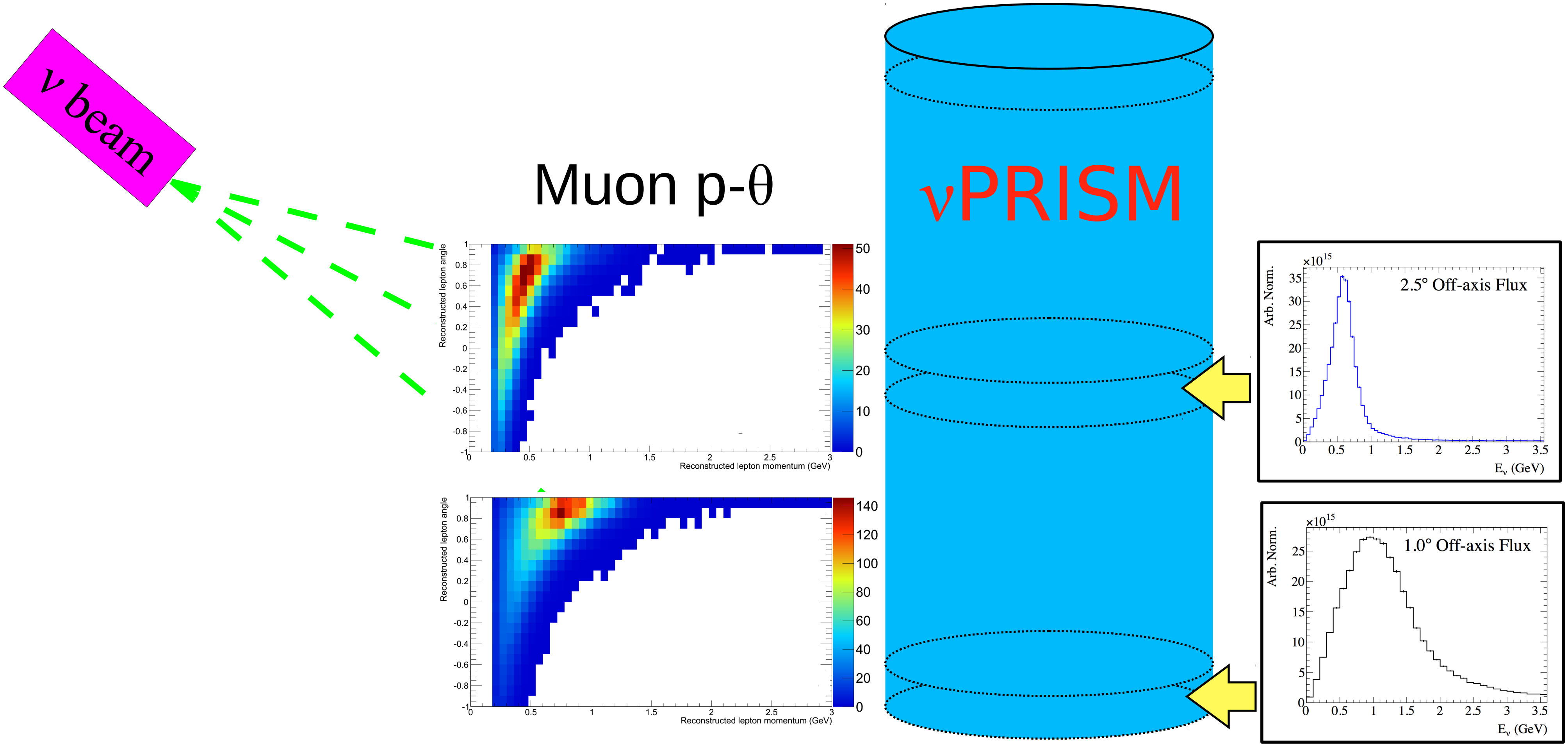
- Water Cherenkov detector spanning 1° – 4° from the neutrino beam axis
  - 52.5m tall, 1km from neutrino production target
- Instrumented movable cylinder:
  - Inner Detector (ID): 8m diameter, 10m tall
  - Outer Detector (OD): 10m diameter, 14m tall



- Multi-PMT modules instrument ID and OD
- Investigating scintillator veto planes around detector



NuPRISM fluxes

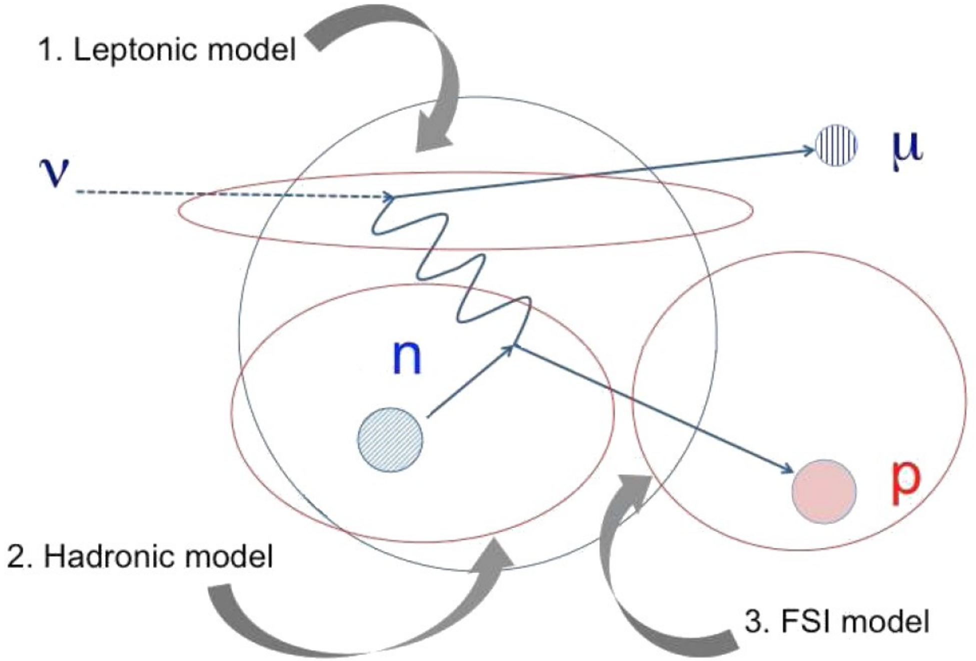


- Can measure both 2.5 and 1.3 degree fluxes with same detector
  - Correlate uncertainties
- Constrain uncertainties on both (and reduce directional uncertainty)

Nuclear models

- Example of nuclear model uncertainty – 2p2h interactions

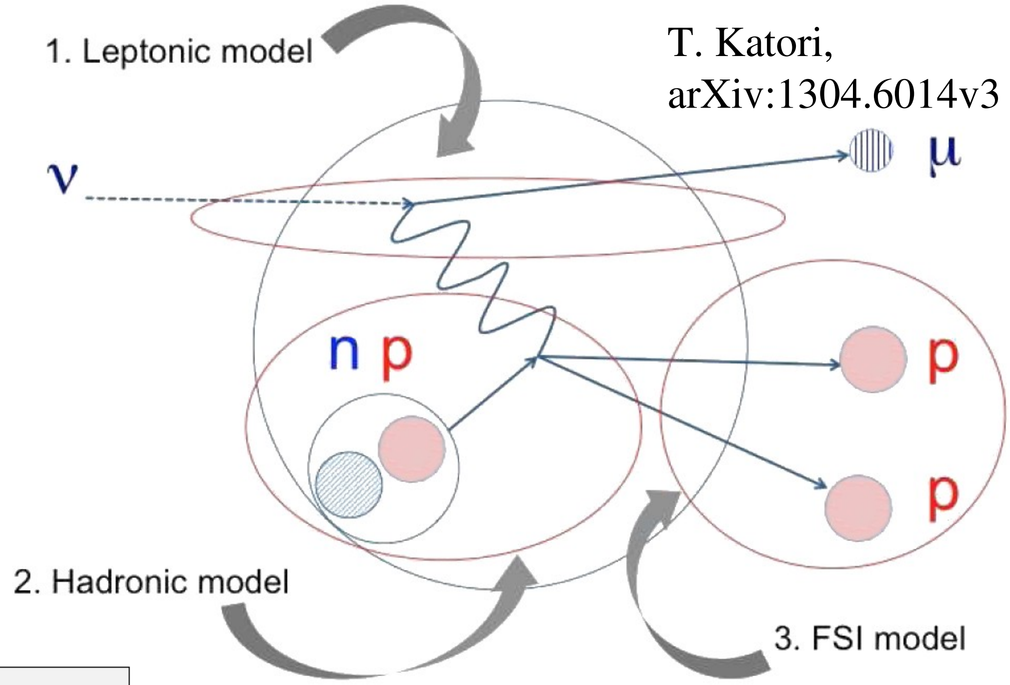
- CCQE process is main signal at far detector
  - 2-body interaction
  - Lepton kinematics give neutrino energy

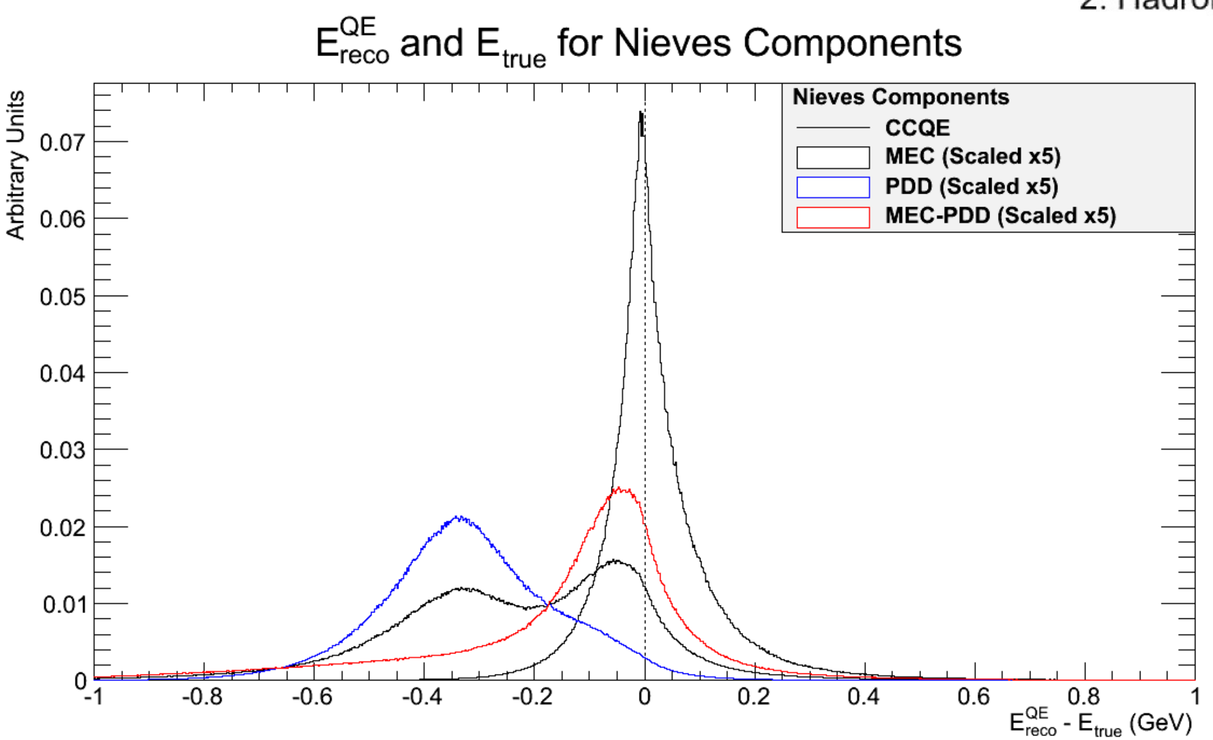


Nuclear models

- Example of nuclear model uncertainty – 2p2h interactions

- CCQE process is main signal at far detector
- Also have '2p-2h' interactions:
  - Mimic CCQE signal
  - Lepton kinematics do not give neutrino energy
  - Depends on nuclear model

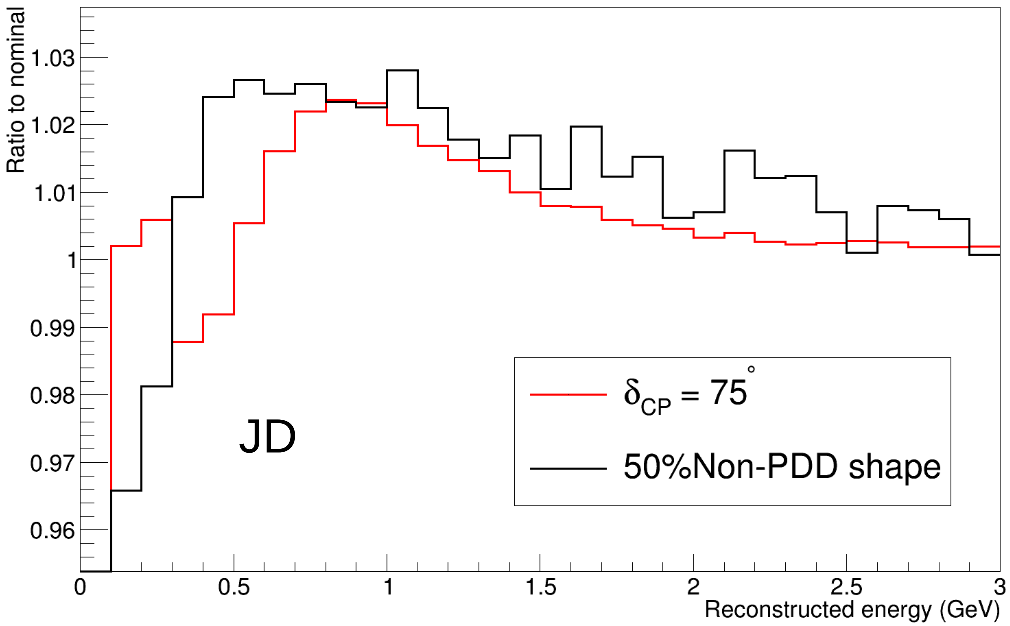




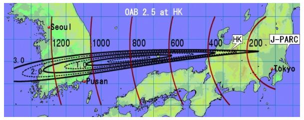
- Bias in reconstructed energy
  - CCQE peaked at 0
  - Two extreme examples of 2p-2h models
    - All PDD (blue)
    - No PDD (red)

2p2h shape at T2HK

- PDD and Non-PDD are two extremes of the 2p2h shape variation
  - Rough re-weighting to give 50% uncertainty on shape



- 2p2h shape uncertainties have similar effect to variations of δCP around 90°
  - Limits precision on measurement



2p2h shape at T2HKK

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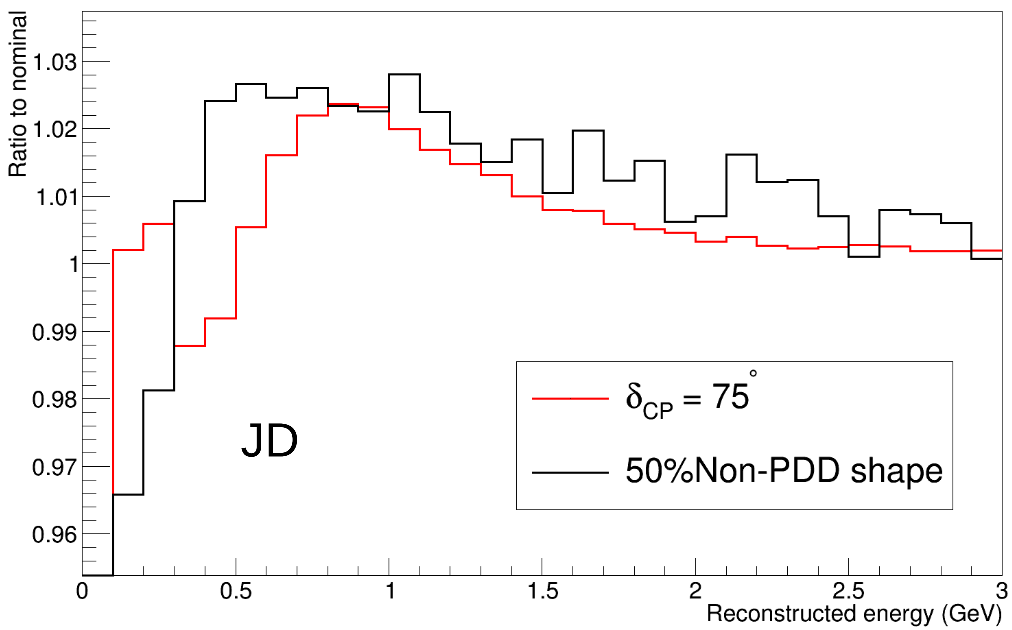
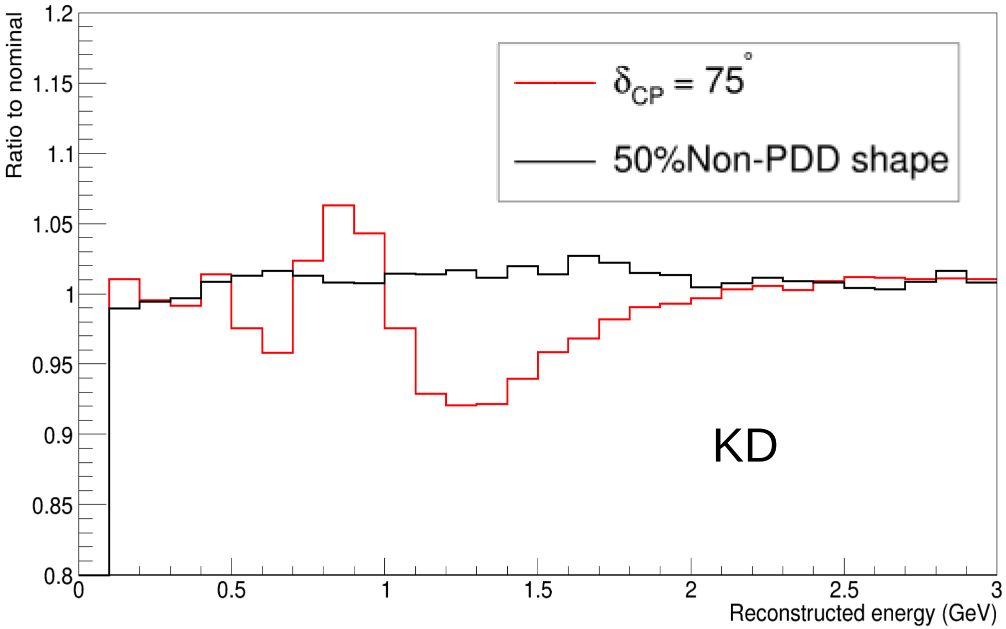
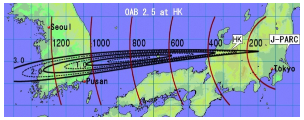




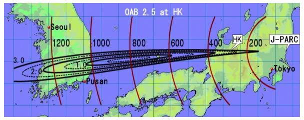
- 2p2h shape uncertainties have similar effect to variations of δCP around 90°
  - Limits precision on measurement
- At Korean detector (KD, right), variations in δCP have different shape and larger effect (y-axis changes) than at HK
  - Expect to be less affected by 2p2h shape uncertainty



NuPRISM and KD

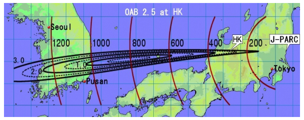
- KD more able to separate systematic effects from dCP shifts
- But, low statistics + many systematics - this separation may be difficult
  - Should incorporate these studies into VALOR KD analysis
  - New T2K cross-section model contains lots of additional freedom – will help give more accurate uncertainty in dCP measurement

- NuPRISM breaks degeneracy of flux and cross-section
  - Measure cross-sections vs neutrino energy
  - Match HK and KD oscillated fluxes – check consistency
  - Pions production and FSI/SI
    - Uncertainty in pion production models will affect KD more than JD
    - Could mimic dCP
    - NuPRISM can measure 1Pi production in water Cherenkov
      - Naturally takes FSI + SI into account

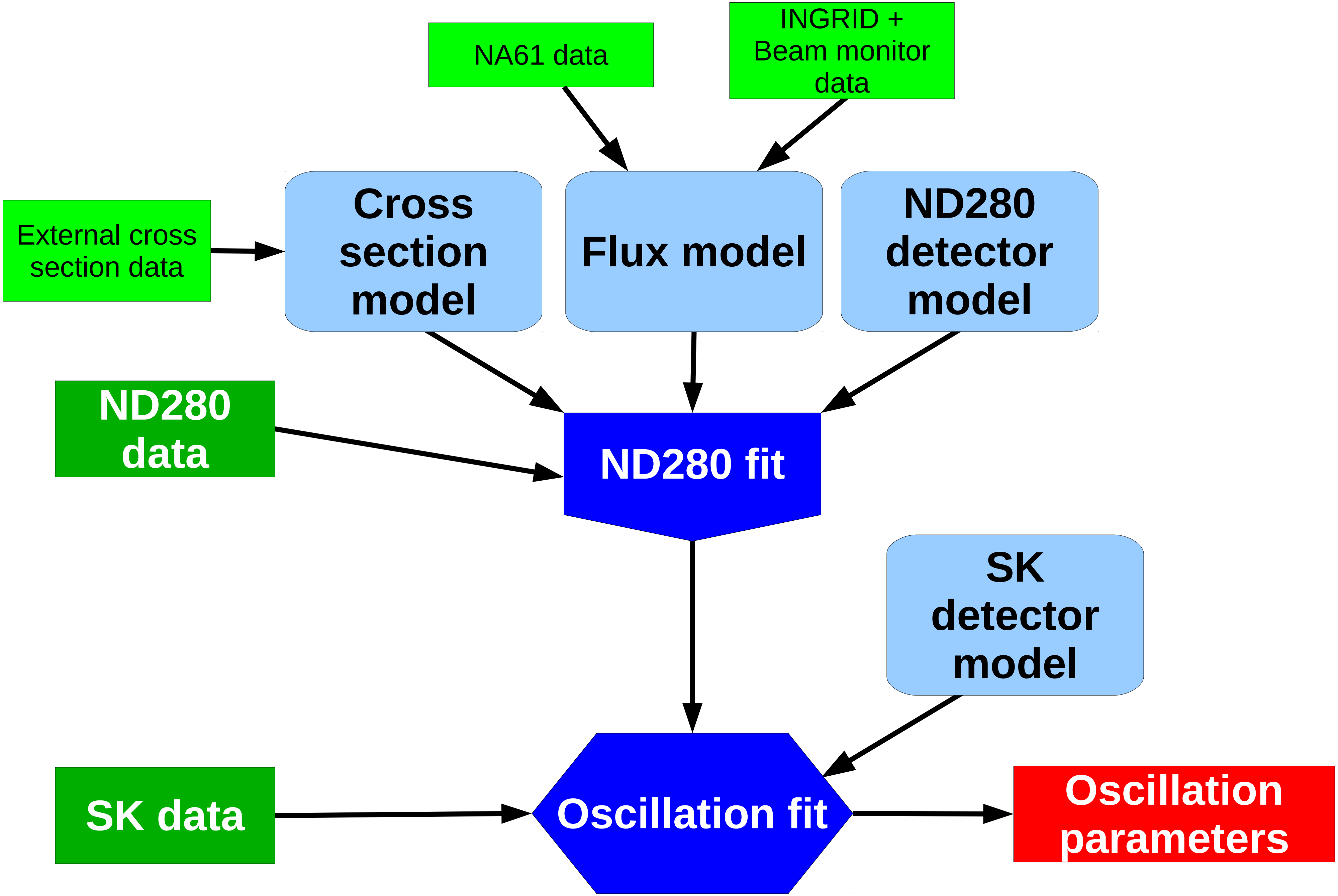


Backup slides

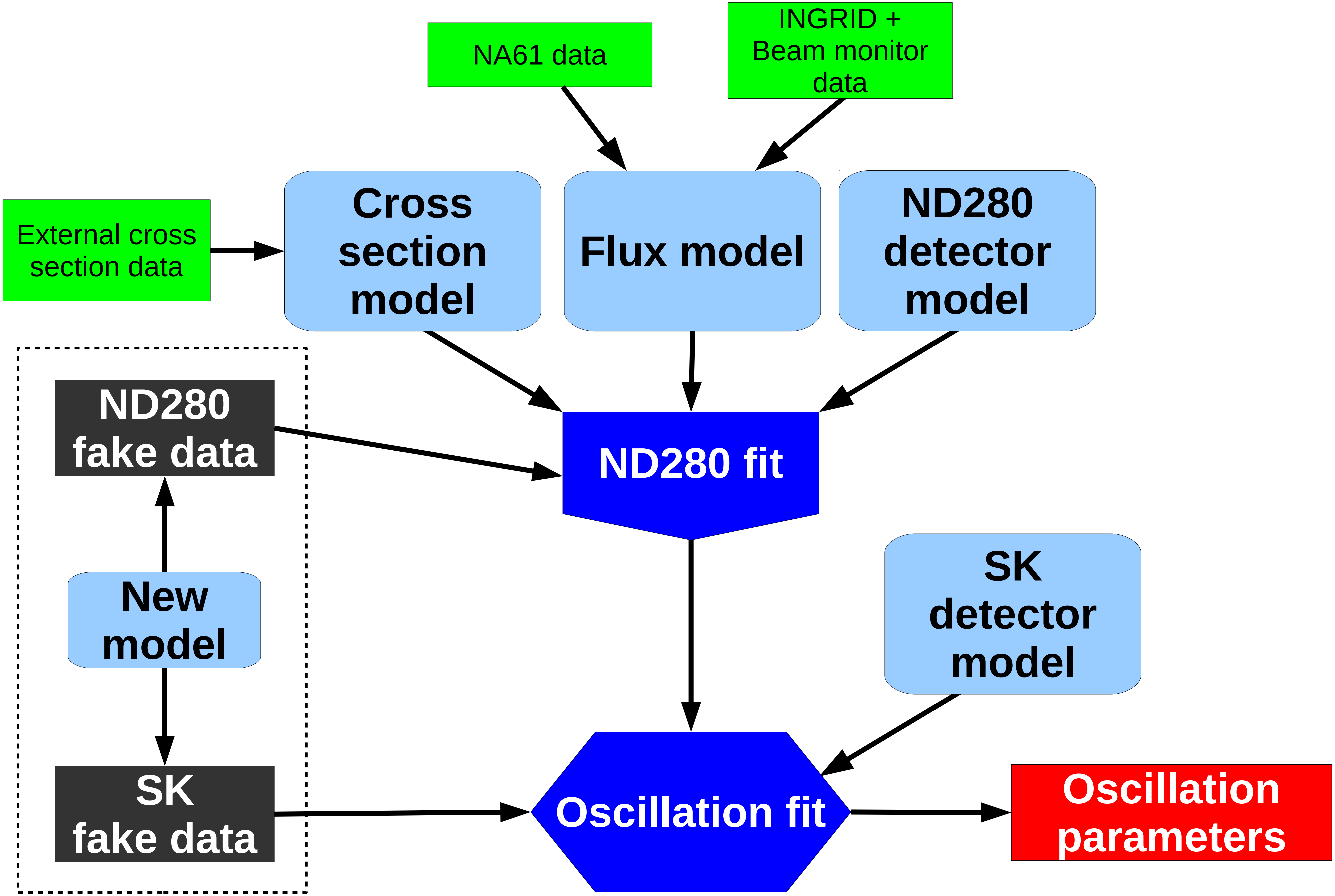
- Slides explaining fake data study procedure and example results with Martini 2p2h model

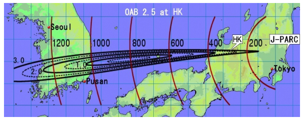


T2K oscillation analysis



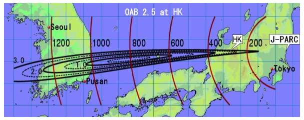
T2K fake data analysis





Procedure at T2K

- Generate fake data at SK and off-axis near detector (ND280)
  - Apply event selections to nominal MC to create event samples
  - Weight events in sample by ratio of old cross-section model to the new model, as a function of some set of variables
    - Assumes selection efficiency does not change when cross-section model changes
- Fit fake data at ND280 (known as the BANFF fit) with nominal MC and nominal cross-section parametrisation
- Extrapolate to SK to make new far detector prediction with new parameter central values and constraints
- Perform oscillation fit to SK fake data using extrapolated prediction
- Compare results to nominal oscillation fit

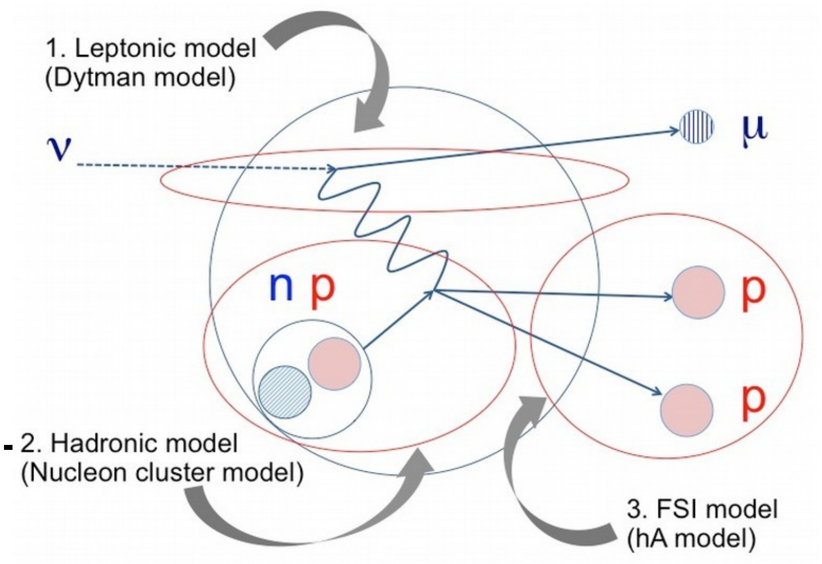


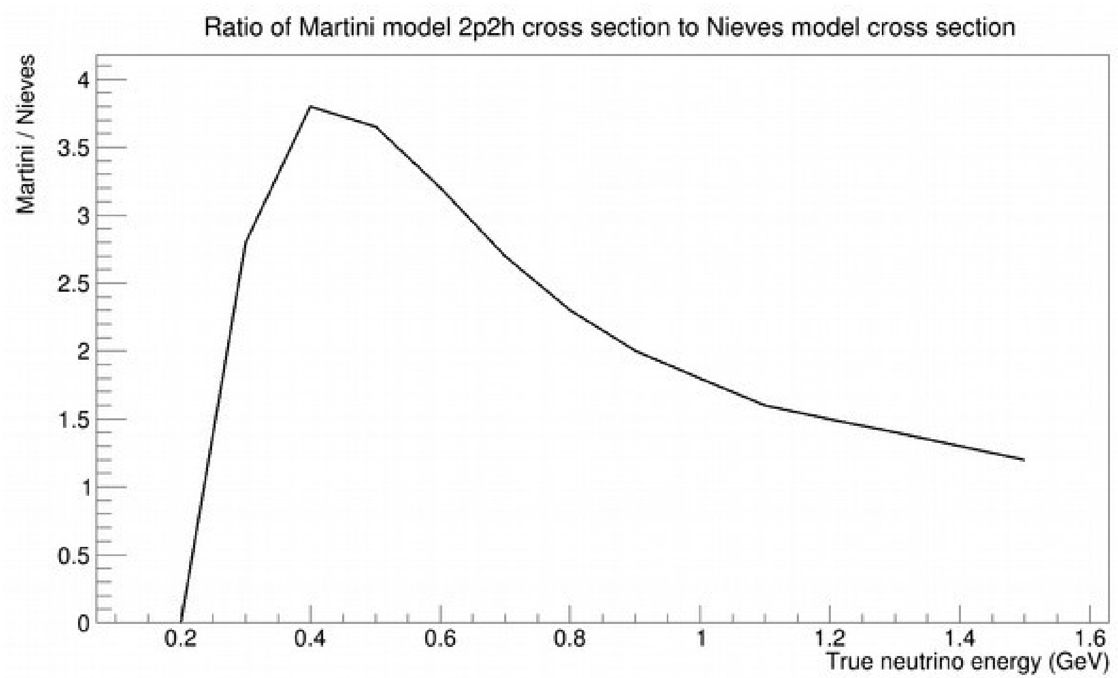
T2K status

- Fake data studies in T2K technical note 285 completed and passed collaboration review
- Have since updated studies with full fits to expected T2K-II POT
  - Currently working on including SK CC1Pi samples and increased fiducial volume at SK
  - Will publish final studies in stand-alone paper this winter
  - Starting to work on fake data studies for HK and T2HKK
- Ran fits to five fake data sets
  - Spectral function (SF) vs relativistic Fermi gas (RFG) nuclear model
  - 2p2h shape study datasets:
    - PDD-like (like pion-less delta decay process)
    - Non-PDD-like (everything else)
  - Differences between Nieves and NEUT CCQE (1p1h) models
  - Martini vs Nieves 2p2h

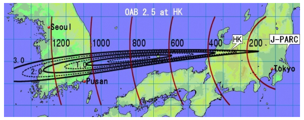
Martini 2p2h study

- Neutrino interaction generators now include 2p2h interactions (right)
  - CCQE-like in most detectors
  - Hard to measure or constrain experimentally
  - Make up 10-20% of the T2K CCQE-like event sample



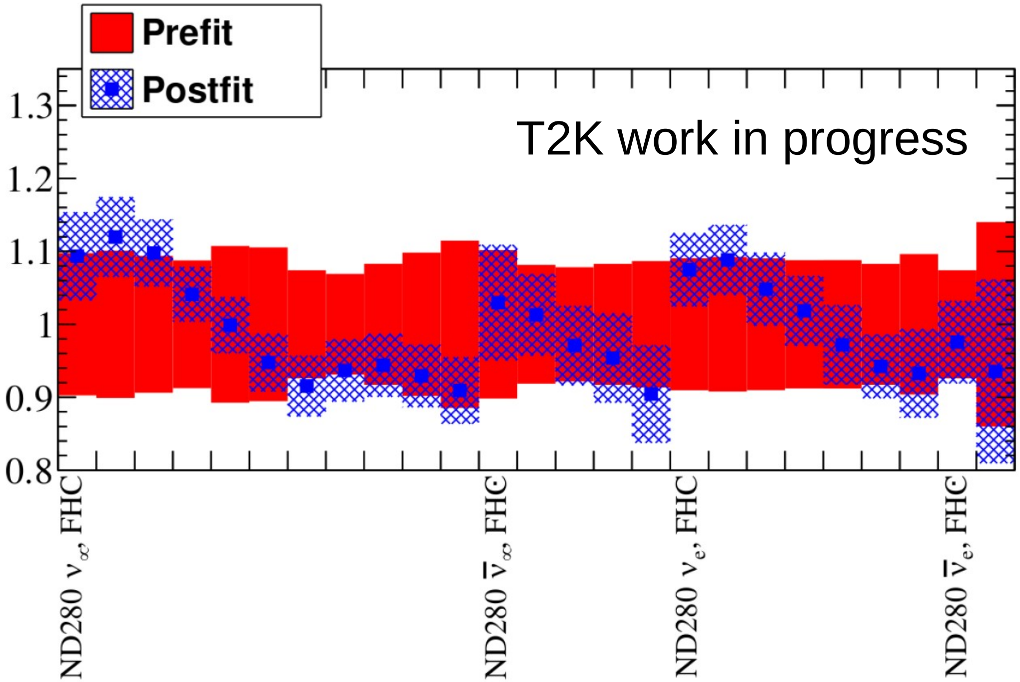


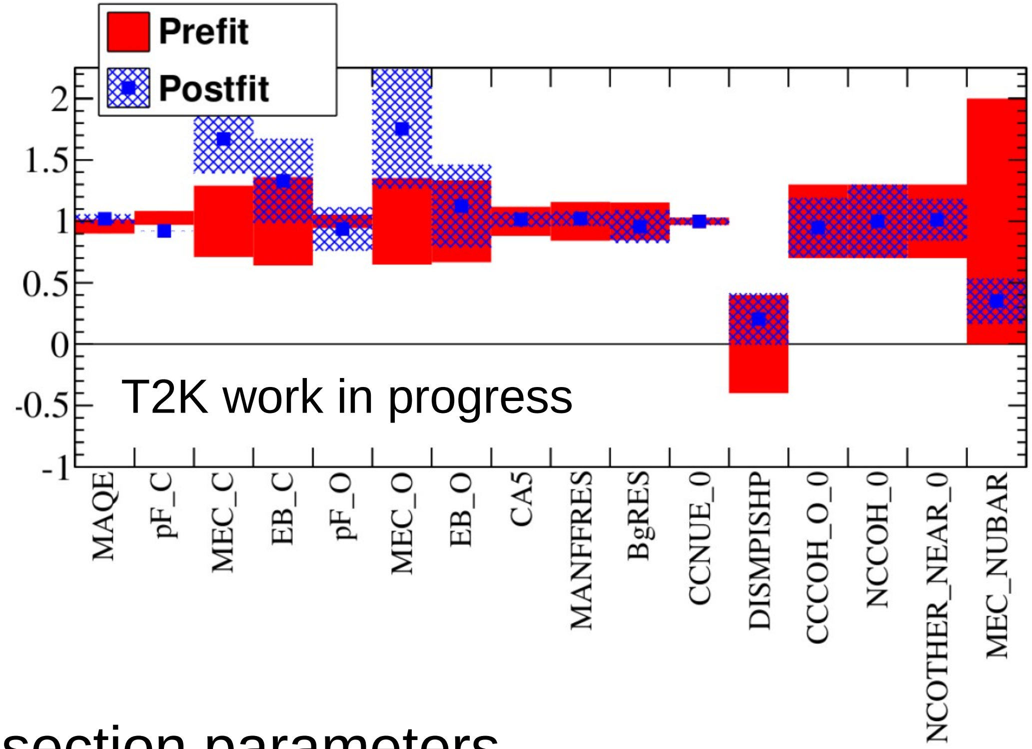
- Many models, have most information about Nieves and Martini models
- Nieves' model included in NEUT
- To study Martini model, weight 2p2h events by Martini-Nieves cross-section ratio as function of neutrino energy (left)



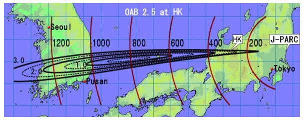
Martini fake data ND280 fit

- Fit results shown below:



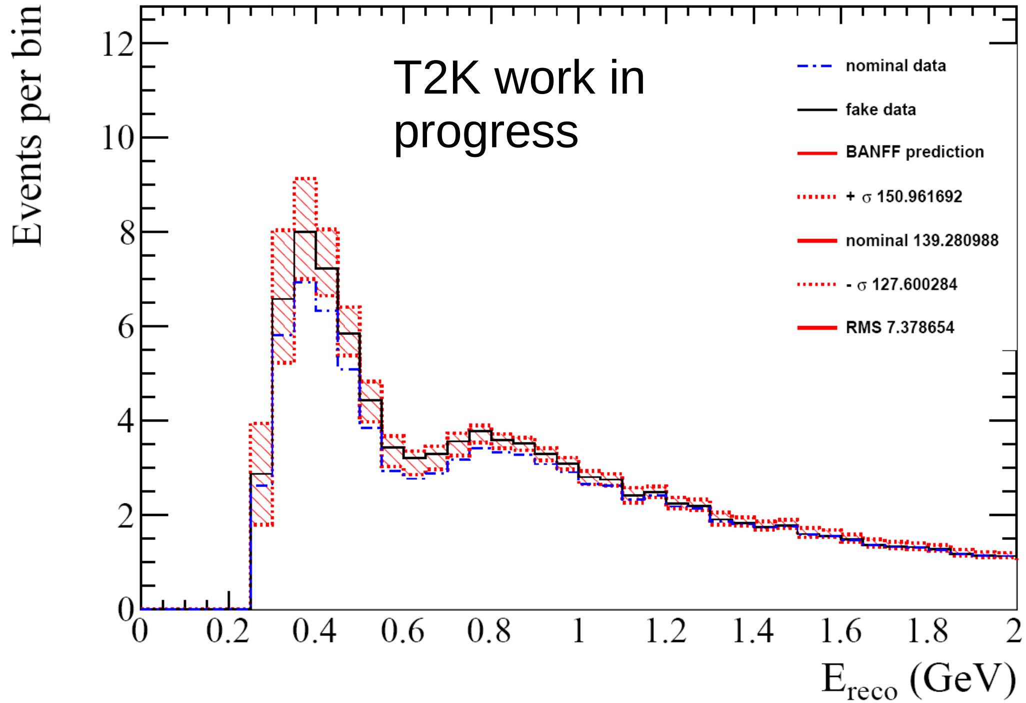


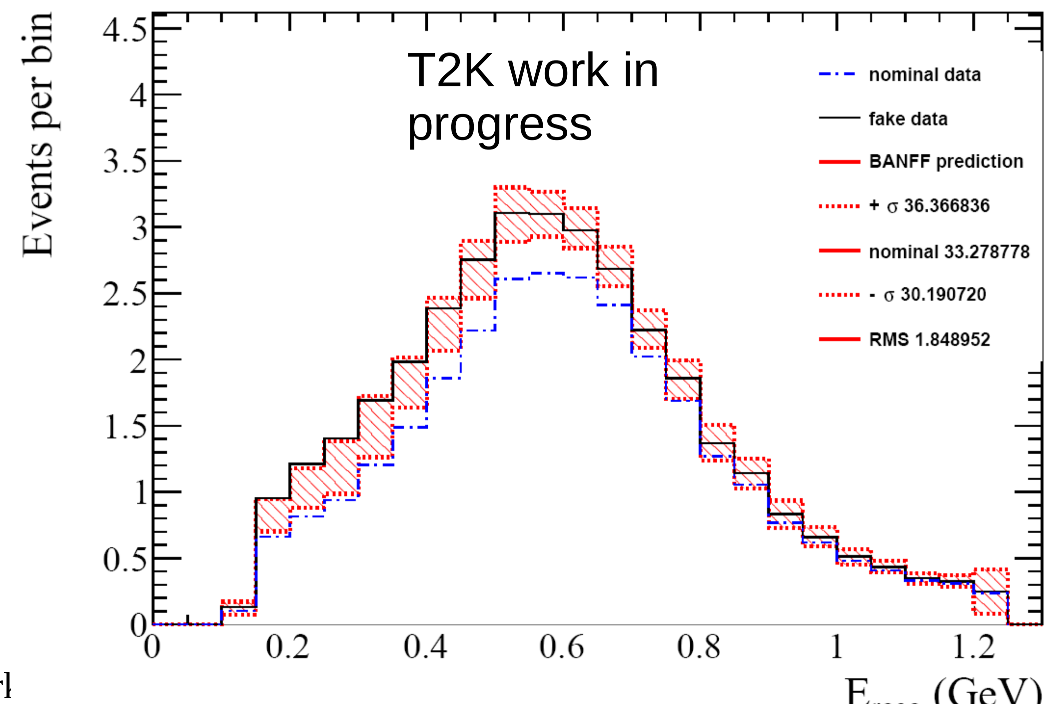
- See large change in flux and cross-section parameters
  - Martini 2p2h cross-section ~2 times the nominal NEUT value – MEC_C and MEC_O pulled up
  - Martini fake data created by weighting as a function of neutrino energy – see effect in flux
  - Anti-neutrino 2p2h cross-section less affected – MEC_NUBAR pulled down



SK spectra

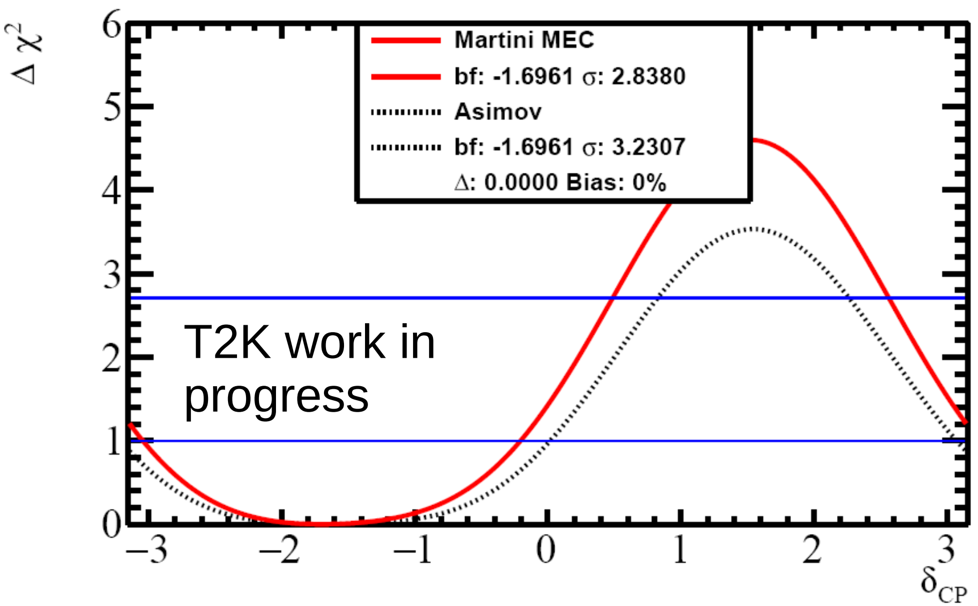
- Plot shows SK NuMu (top) and NuE (bottom) samples for Martini 2p2h fake data
  - Blue = nominal MC
  - Black = fake data
  - Red = extrapolated prediction from ND280 fit
- Prediction matches SK fake data within 1 sigma
- ND280 extrapolation under-predicts fake data
  - Around oscillation dip for NuMu
  - In low reconstructed energy region for NuE

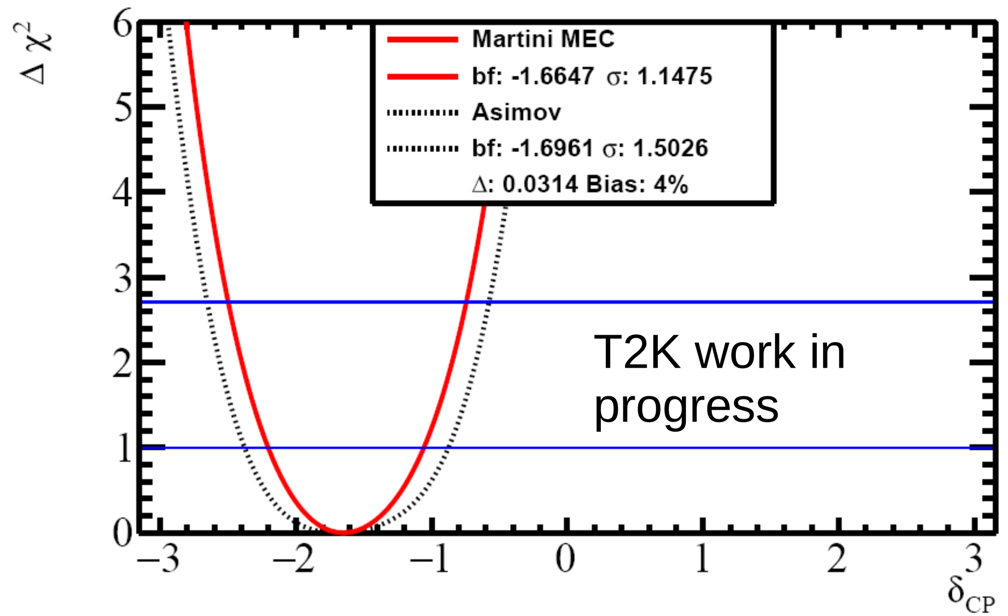




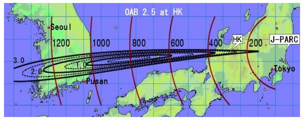
Martini fake data SK fit

- Likelihood contour shown below for delta CP
  - Black dashed = nominal, red = fake data fit
  - Left = current statistics, right = T2K-II statistics
  - Maximal disappearance and CP violation





- If Martini is correct model, using the Nieves 2p2h model artificially tightens constraints we get on delta CP
  - '1 sigma' error goes from 0.75 → 0.57



Why T2HKK?

- Different neutrino energy spectra help break degeneracies between oscillations and cross-section models
  - Higher neutrino energies at HKK
  - 2nd oscillation maximum (probably) dominated by effect of dCP rather than model changes
- Shape information at HK will be more powerful for dCP measurements compared to T2K
  - Many new shape uncertainties entering T2K oscillation analysis, could increase bias when fitting near detector data
  - HKK (probably) less affected by these
- Role of near and intermediate detectors depends on which systematics/uncertainties are dominating oscillation analysis
  - Detector upgrades need to be informed by oscillation studies