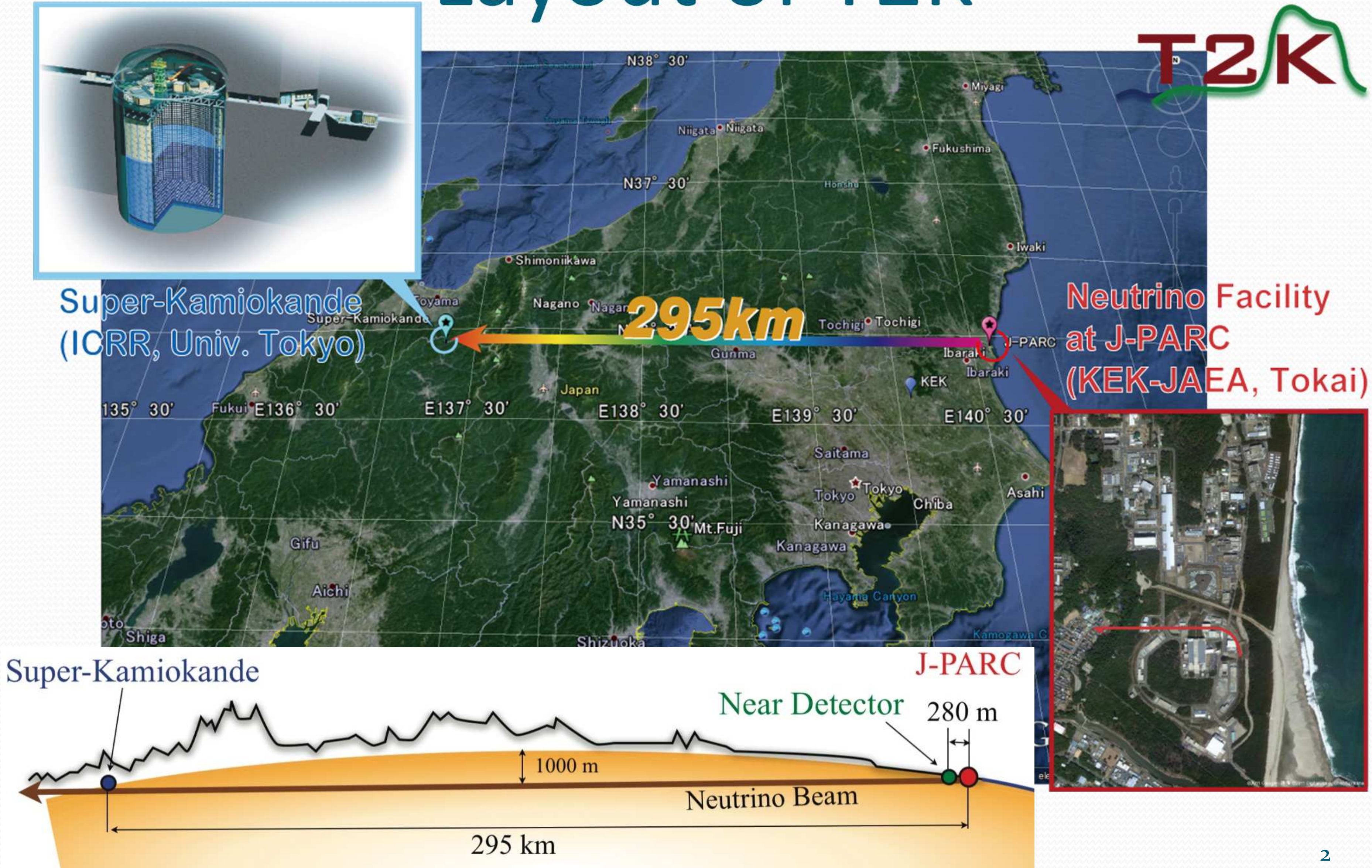
Energy measurement for the T2K oscillation analysis

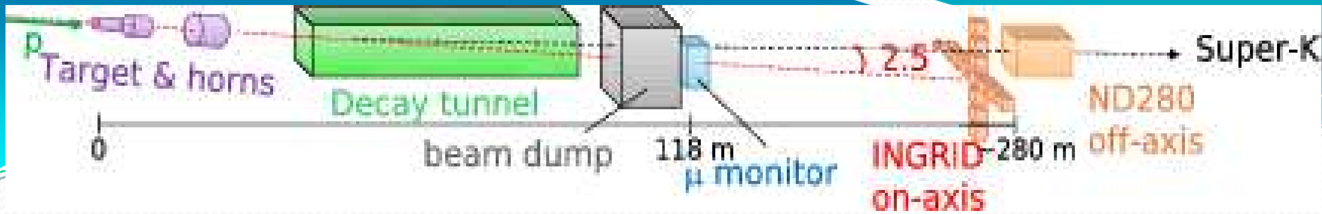
Susan Cartwright for the T2K Collaboration

- Introduction to T2K
- Energy measurement in Super-Kamiokande
  - Performance
  - Calibration and Systematics
- Near detector constraints

For oscillation <u>results</u> see
C. Bronner's talk this morning

Layout of T2K





T2K Experiment

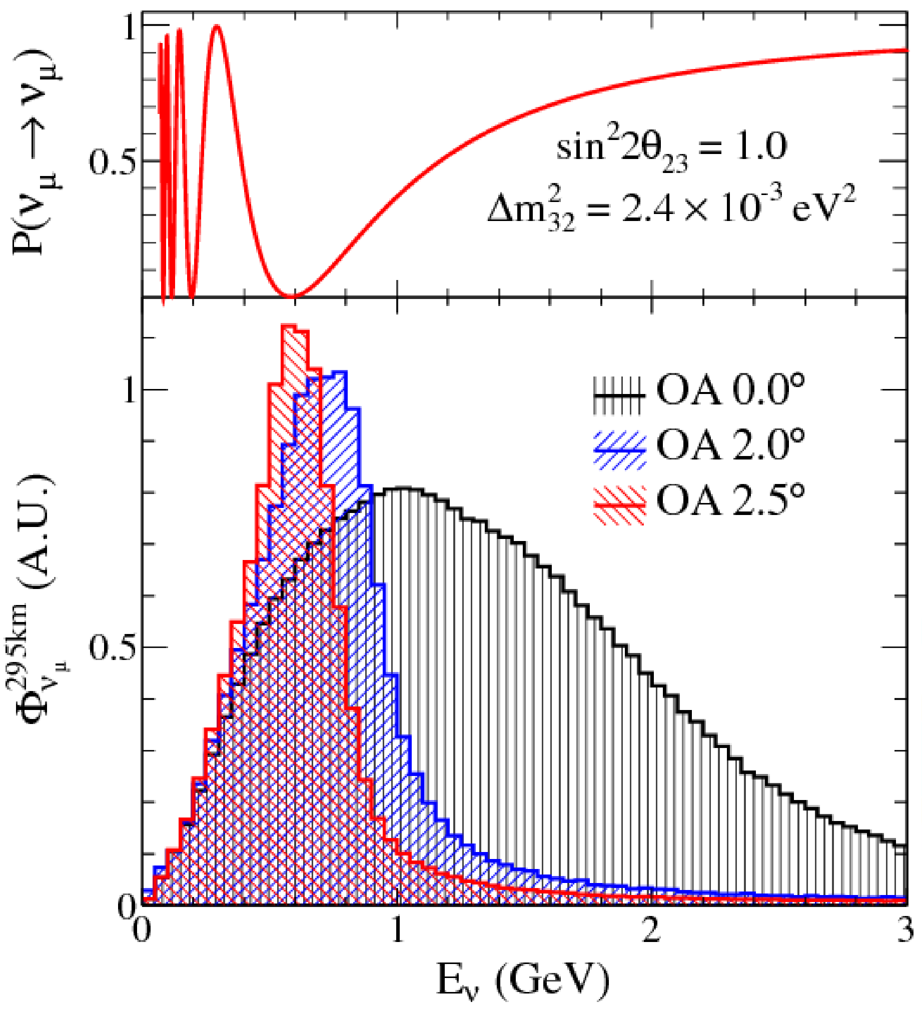
Near detector suite

- Muon monitor (MUMON) behind beam dump
  - monitors beam direction and stability
- On-axis detector (INGRID)
  - monitors beam profile and neutrino interaction rate
  - also measures some cross-sections
- Off-axis detector (ND280)
  - monitors unoscillated off-axis beam
  - measures intrinsic ν_e
  - measures ν cross-sections

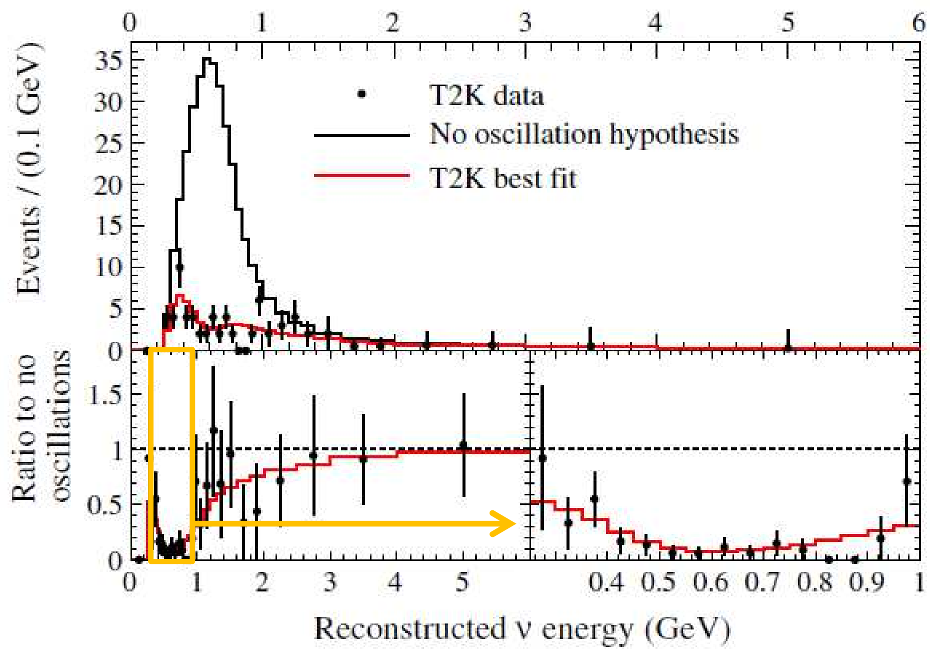
Far detector

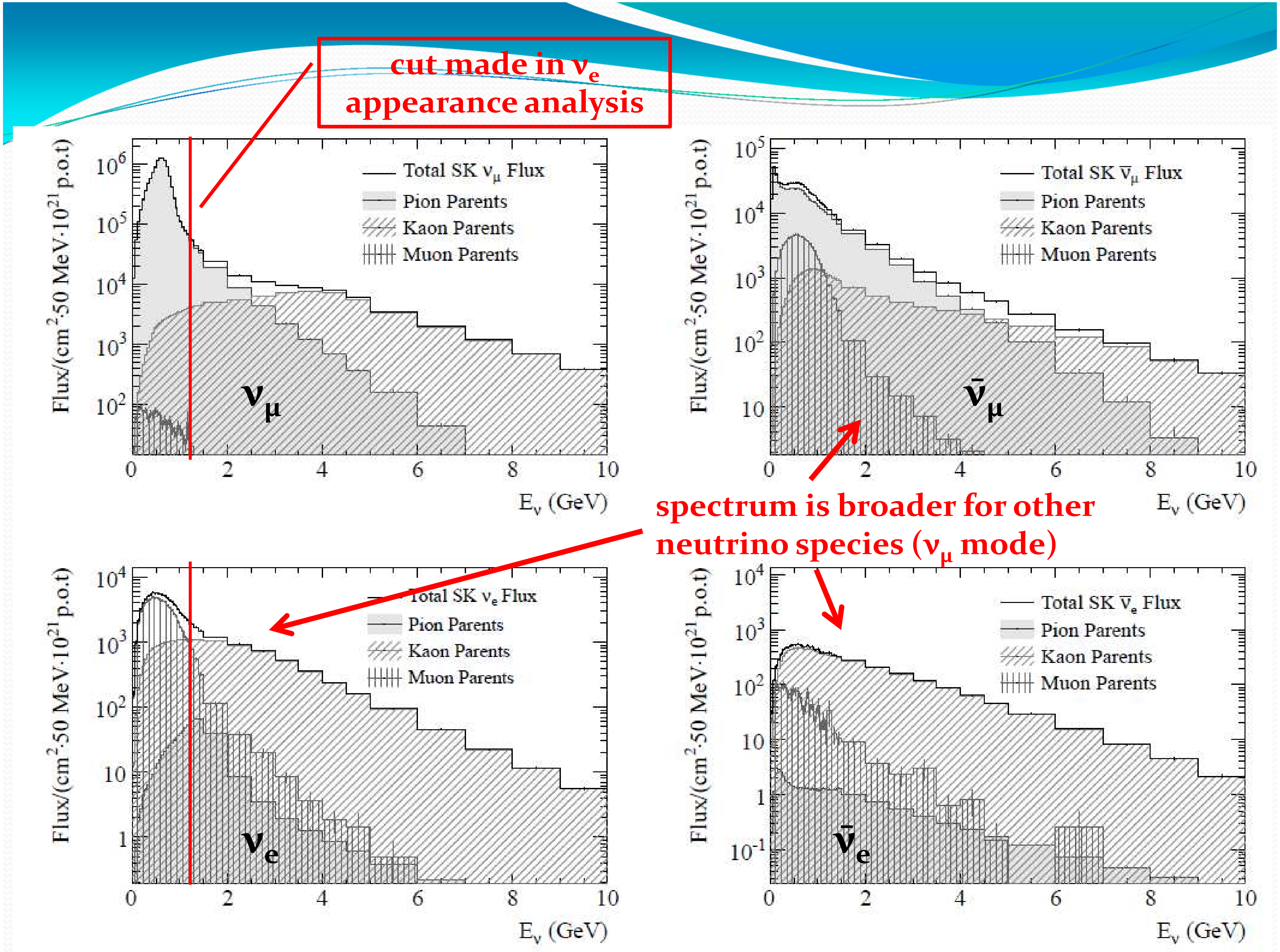
- Super-Kamiokande
  - 50 kton water Cherenkov
  - 39.3 m Ø × 41.4 m high
  - 11,129 20" PMTs in inner detector
  - outer detector (1885 8" PMTs) acts as cosmic muon veto
- Operation as T2K far detector in parallel with non-accelerator ν physics
  - atmospheric and solar ν
  - supernova ν watch
  - also proton decay

T2K beam spectrum



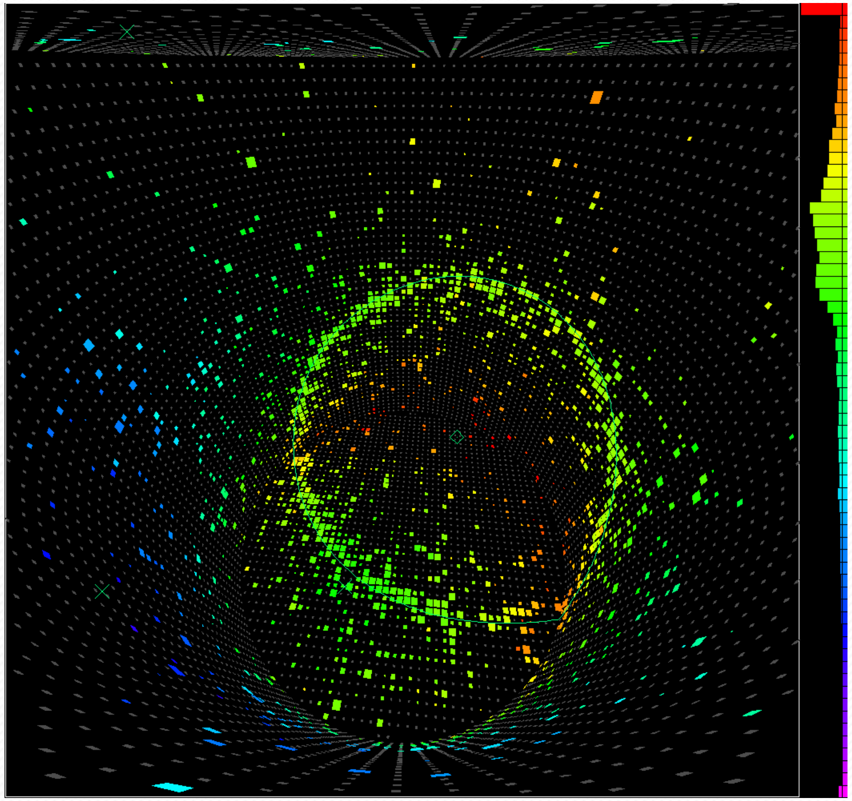
- 2.5° off-axis orientation gives narrow-band beam tuned to oscillation peak




cut made in ν_e appearance analysis
spectrum is broader for other neutrino species (ν_μ mode)
Total SK ν_μ Flux
Total SK $\bar{\nu}_\mu$ Flux
Total SK ν_e Flux
Total SK $\bar{\nu}_e$ Flux
Pion Parents
Kaon Parents
Muon Parents
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
Flux/(cm^2·50 MeV·10^{21} p.o.t)
E_ν (GeV)

Energy reconstruction in SK

- Input data
  - Charge and timing information for each PMT
  - Known detector properties
    - PMT response, photon attenuation in water, etc.
- Output data
  - Vertex position
  - Particle ID (e/μ/π)
  - Particle momentum



Energy reconstruction in SK

Standard method

Vertex
- Find event vertex from timing information

Rings
- Use Hough transform to find rings, assuming 42° cone

PID
- Use Gaussian PDF for PMT charge based on expected shape
- Readjust angle if needed

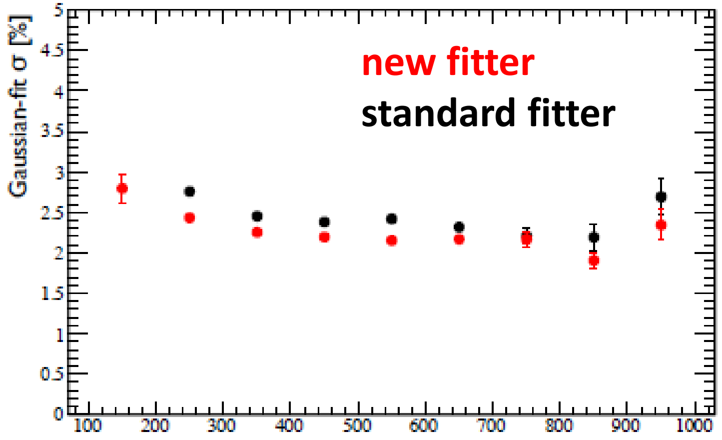
Fit *p*
- Sum all charge in 70° cone
- Adjust based on particle ID

sequential, multi-step method

New method

- Single step maximum likelihood
- $\mathcal{L}(\mathbf{x}) = \prod_i^{\text{unhit}} P(i \text{ unhit}|\mathbf{x}) \times \prod_i^{\text{hit}} P(i \text{ hit}|\mathbf{x}) f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x})$
- Vector **x** contains
  - vertex position (x,y,z,t)
  - track momentum p
  - track direction (θ,φ)
- Charge pdf f_q factorised into
  - predicted charge (# of photons)
  - PMT response

Fitter performance: muons

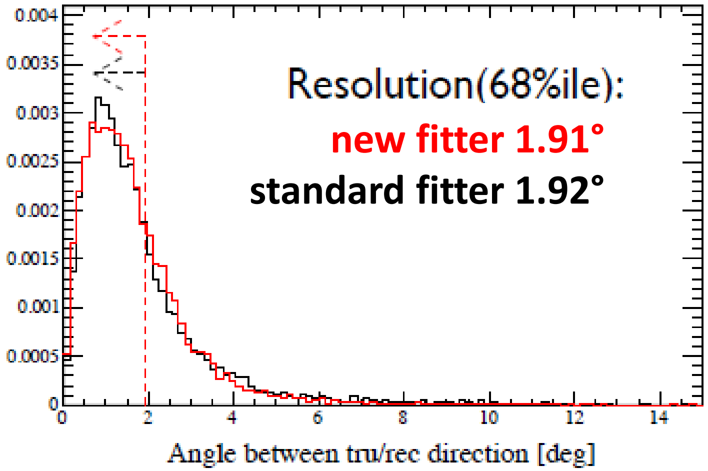


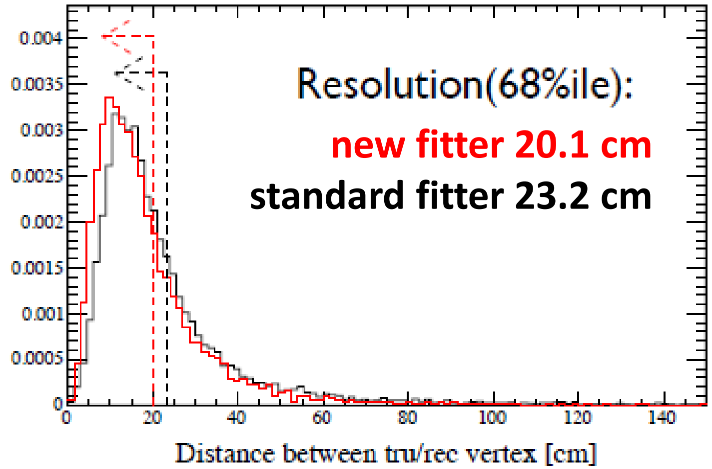
Momentum resolution

*Sample information:
T2K ν_μ CCQE, fully contained,
true fiducial volume, one-ring events

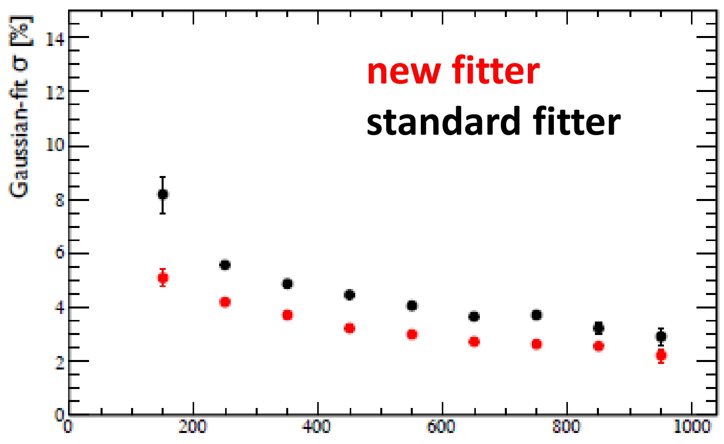
New fitter has slightly better momentum and vertex resolution

**Nuclear de-excitation γ's, decay electrons are present in this sample





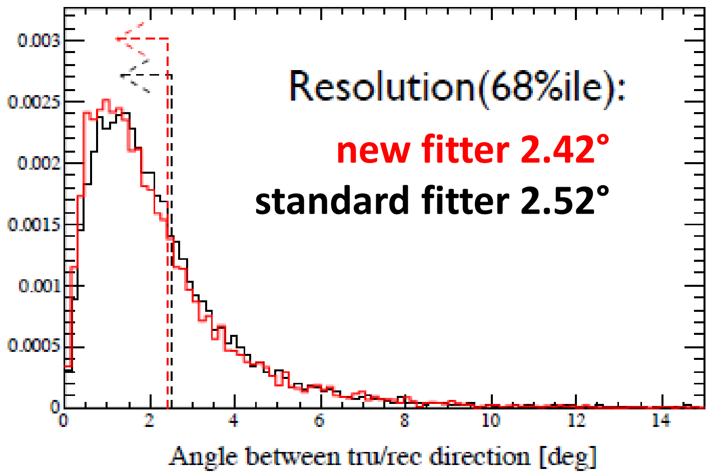
Fitter performance: electrons

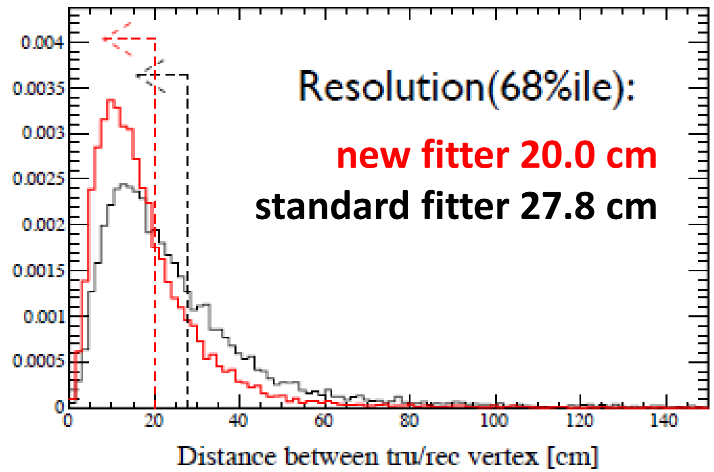


Momentum resolution

*Sample information:
T2K ν_e CCQE, fully contained,
true fiducial volume, one-ring events

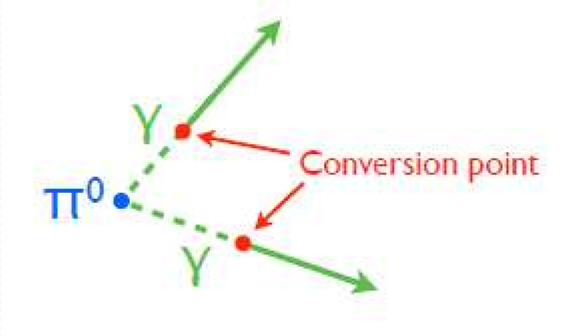
More significant resolution improvement for electrons





New fitter performance: π^0

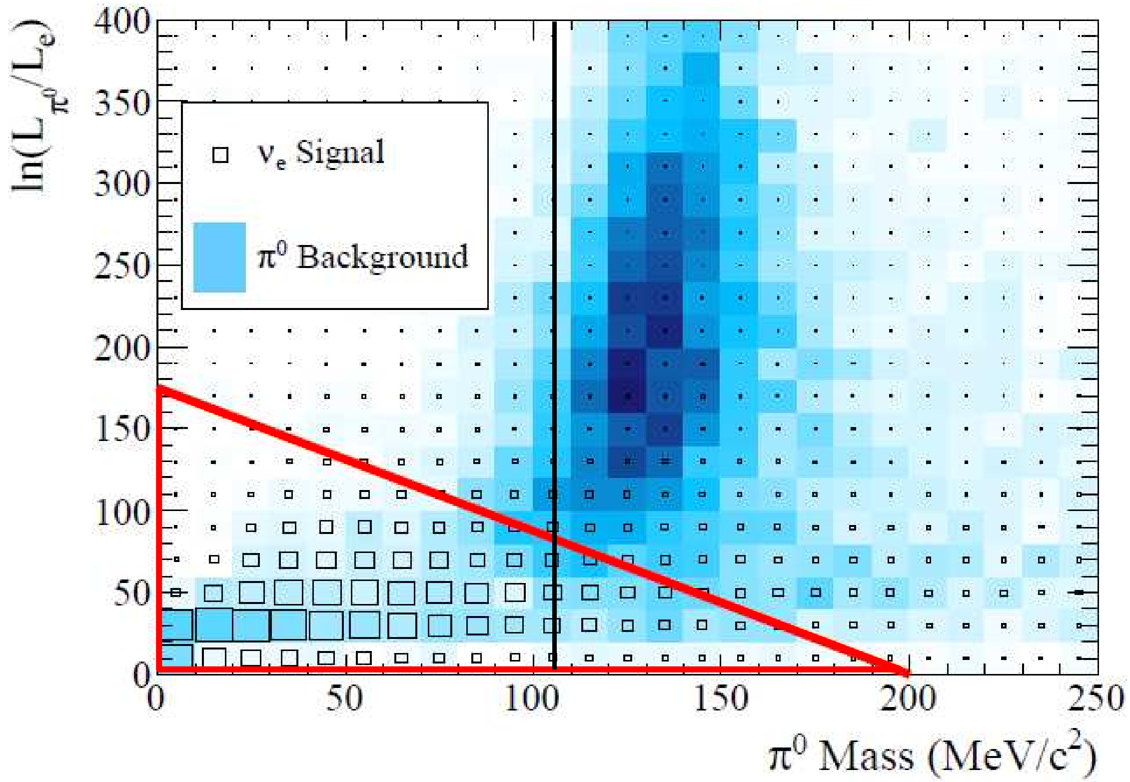
- Key issue in ν_e appearance measurement is effective rejection of NCπ^0 background
  - π^0 with one missed γ misidentified as electron
- New fitter has dedicated π^0 fit with 12 parameters
  - (x,y,z,t); (p_1,p_2); $(\theta_1,\varphi_1,\theta_2,\varphi_2)$; (c_1,c_2)
    - c = conversion length: distance from decay point to track start



  - methodology
    - add 50 MeV e to single-electron fit and scan for best direction
    - refit, floating p_1 and p_2
    - use result as input to full 12-parameter fit

π^0 rejection

- Cut on likelihood ratio and π^o mass
  - signal region inside triangle
  - cf. previous cut on π^o mass only (black line)



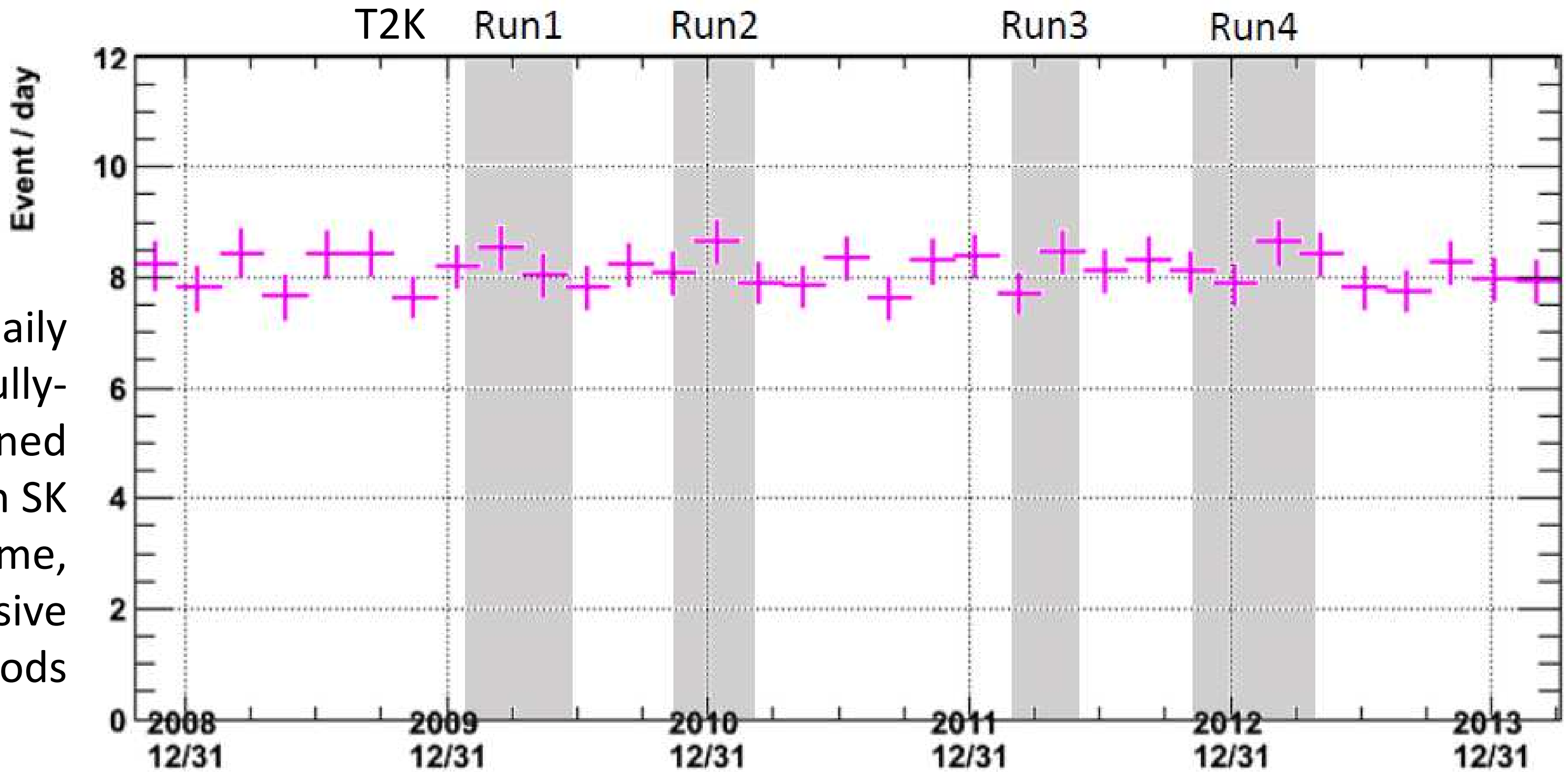
- Reduces remaining π^o background by 75% with no loss of signal efficiency
  - this produces significant reduction in systematic error since π^o production cross-section has large uncertainty

SK Calibration and monitoring

- PMT gain and timing
  - stable light source permanently deployed inside SK tank
    - nitrogen-driven dye laser with diffuser ball to produce isotropic light source
    - 398 nm, 0.2 ns pulse width
- Absolute gain
  - radioactive source calibration
    - 9 MeV γ from $^{58}Ni(n,\gamma)^{59}Ni$; neutrons from ^{252}Cf source
    - produces single photo-electron signals (average 0.004 pe/PMT)
- Light absorption and scattering in water
  - collimated laser light injected vertically downwards from top of tank (λ = 337, 375, 405, 445, 473 nm)

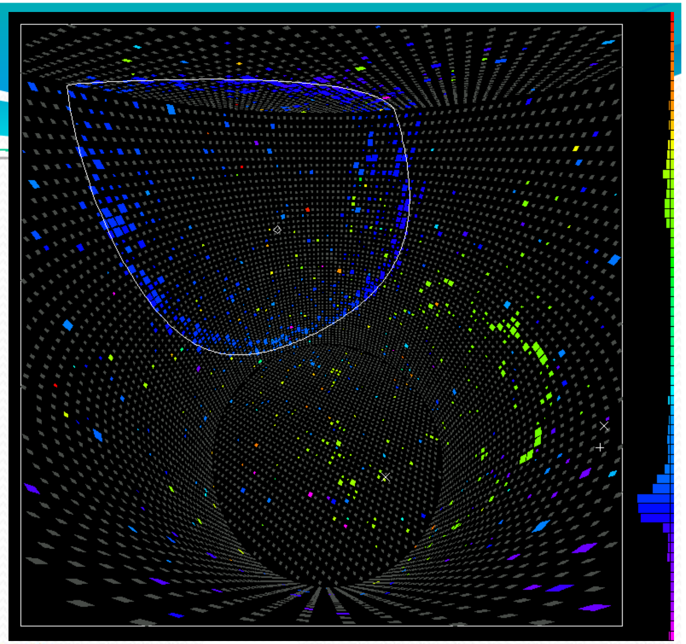
Detector stability

- Monitored with atmospheric ν data



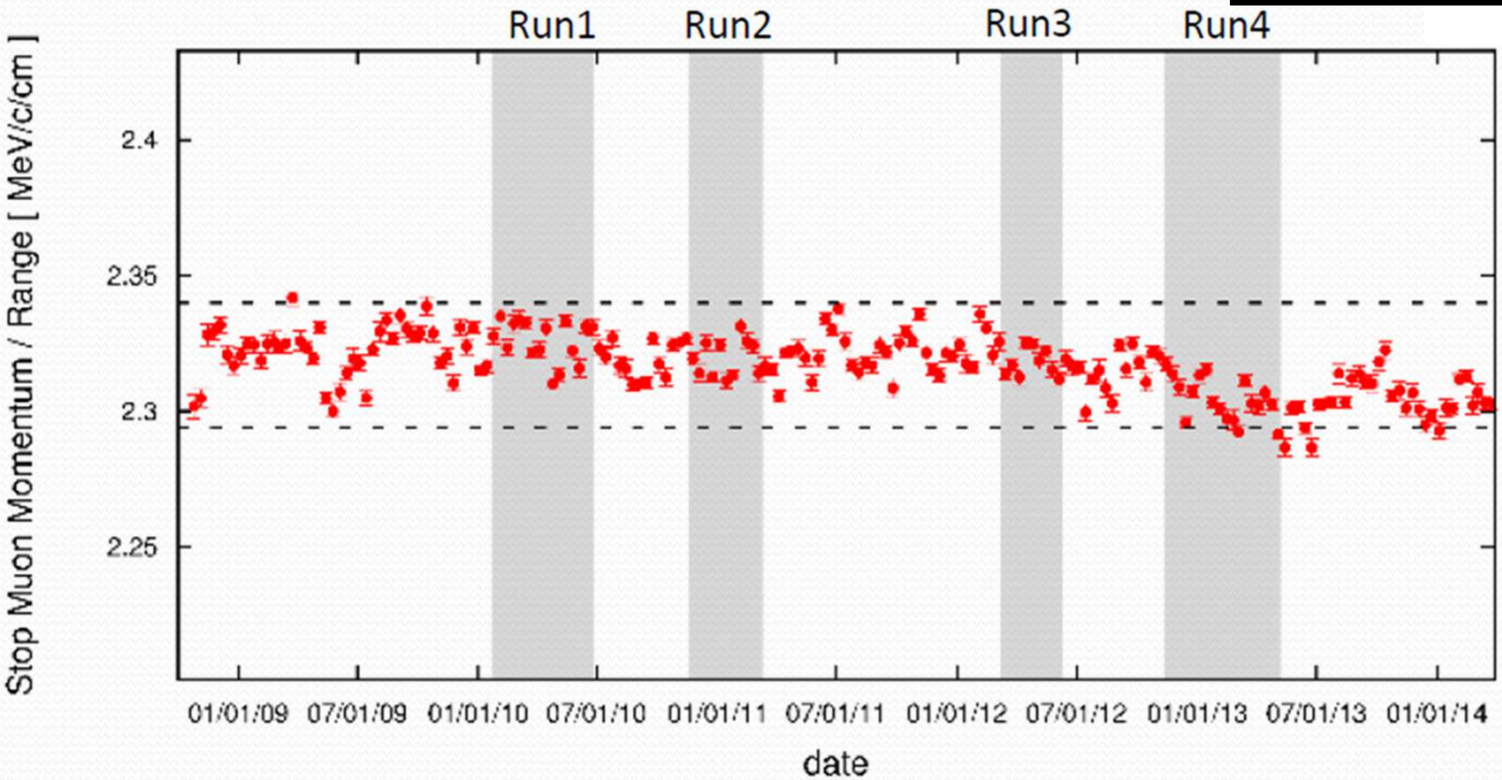
Average daily number of fully-contained events in SK fiducial volume, over successive 2-month periods

Energy scale



Monitored with stopping muons:

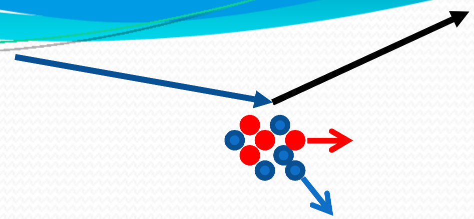
- range of muon
- energy of decay electron



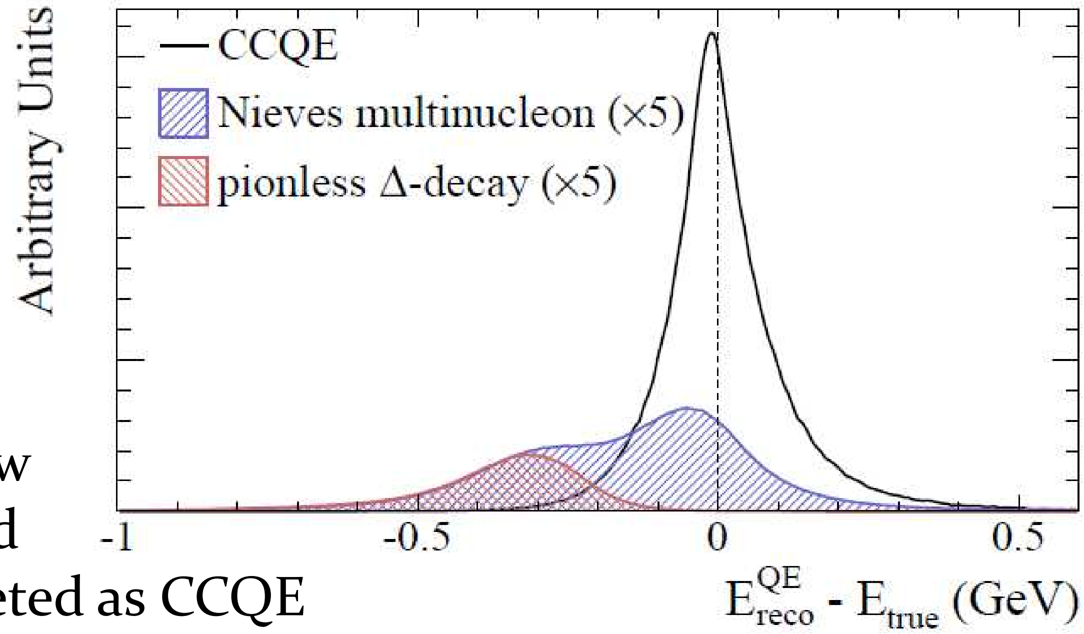
recon. π^0 mass also considered

energy scale ±2.4% (ν_μ dis.)

Final-state interactions



- Multinucleon interactions
  - affect kinematics of outgoing lepton
    - any nucleon exiting nucleus will be below Cherenkov threshold hence event interpreted as CCQE

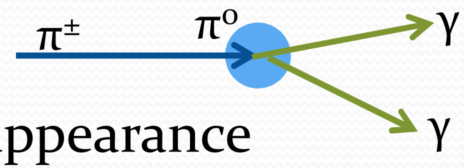


  - NEUT representation of this (pionless Δ decay) compared with Nieves model
    - biases in oscillation parameters <1%

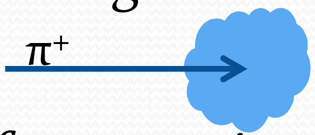
for discussion of cross-section modelling see C. Wilkinson's talk

Pion secondary interactions

- Secondary interactions of $\pi^{\pm}$ in SK detector volume can affect event classification and hence ν energy estimate
  - charge exchange scattering to π^{0}



    - potential source of background for ν_e appearance
  - absorption of π^{+}



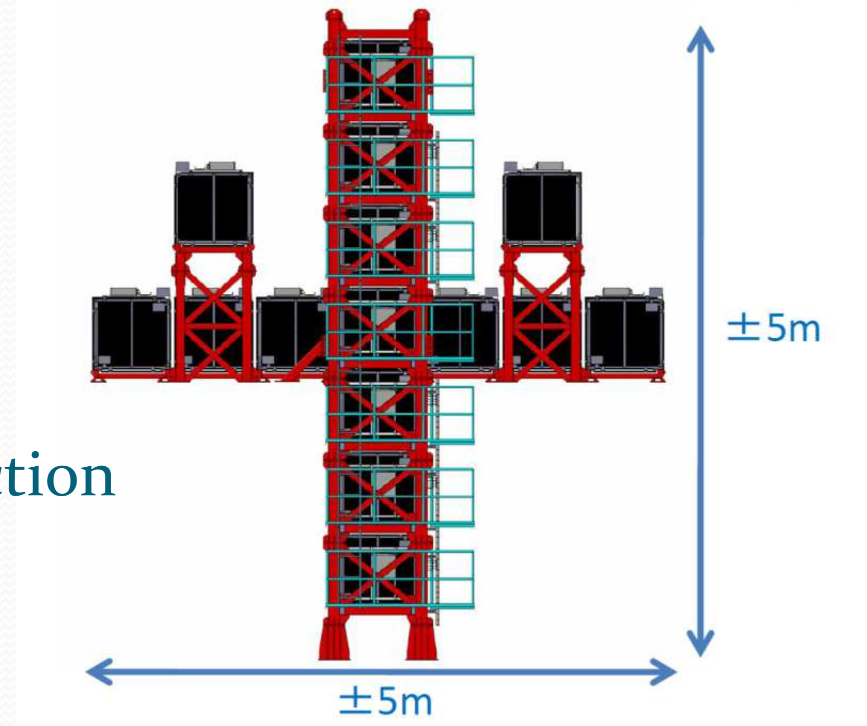
    - misidentification of event, mismeasurement of total energy
  - elastic and quasi-elastic scattering

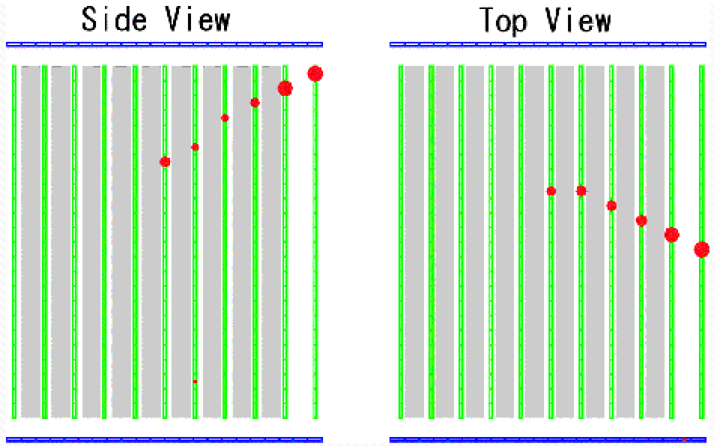
    - additional rings, blurred rings, mismeasured energy/direction
- Investigated by adjusting parameters in NEUT pion cascade model
  - effect ~ 1%

FSI+SI
±3.0%
(ν_μ dis.)

Near detectors I

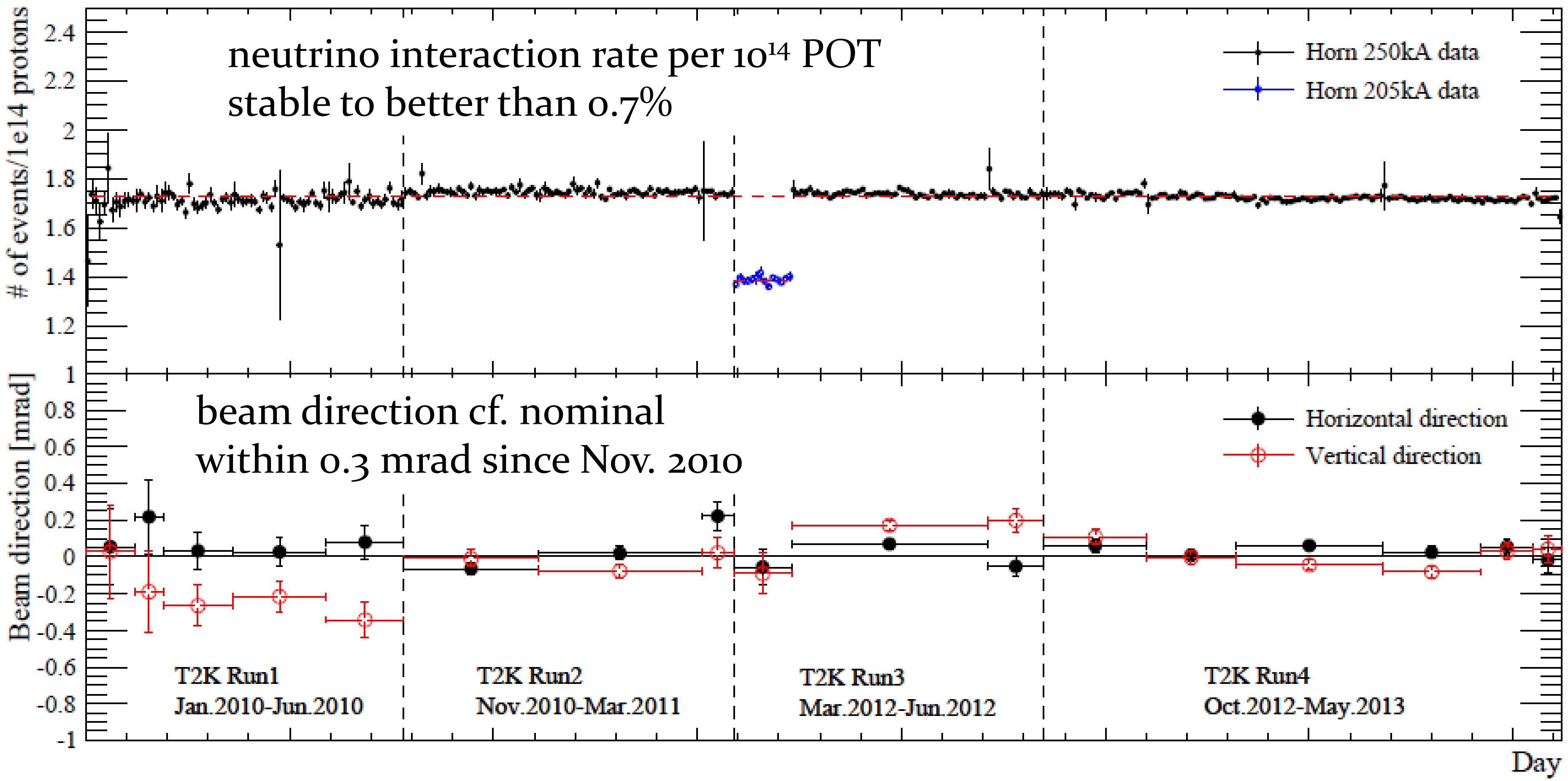
- On-axis detector (INGRID)
  - monitors beam profile and direction
  - 1 mrad change in beam direction results in 2-3% change in neutrino energy scale
    - therefore important to check stability
  - also monitors rate of ν interactions per number of protons on target (POT)





See K. Suzuki's talk this morning

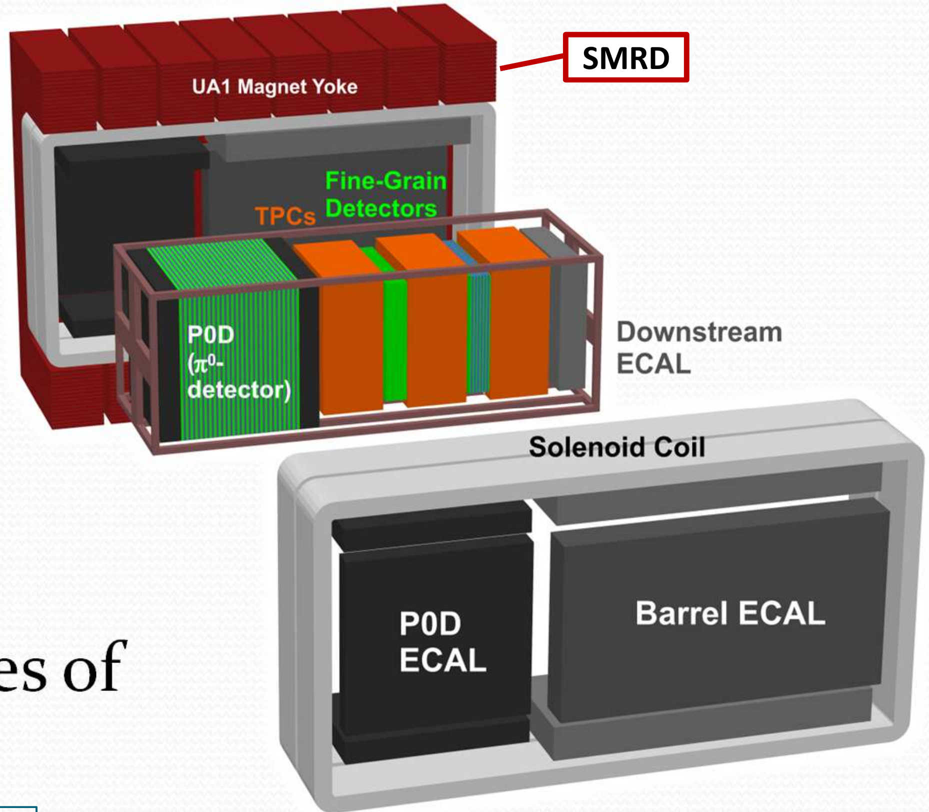
Beam stability (INGRID)



Near detectors II

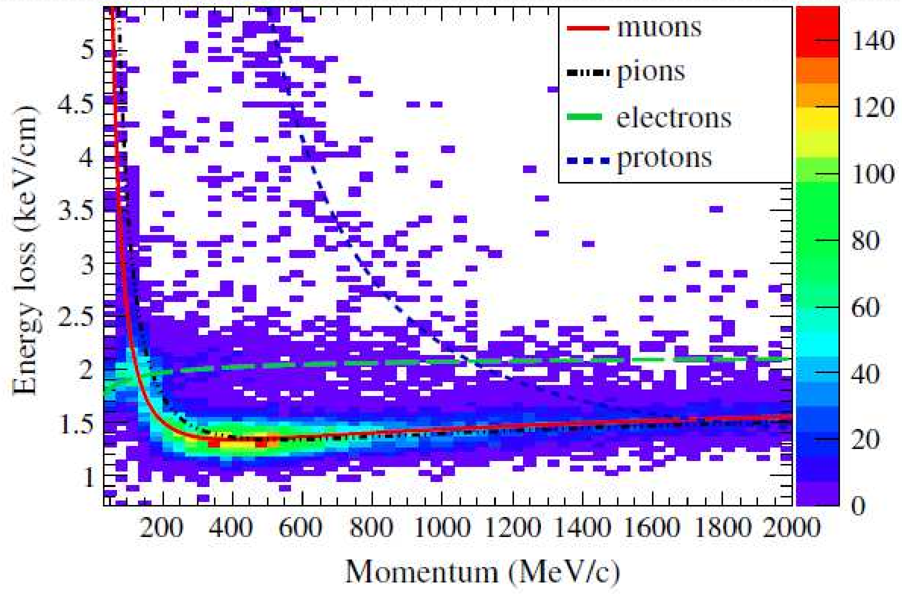
- Off-axis detector (ND280)
  - calorimetry and tracking (TPCs/FGDs)
- Intrinsic ν_e content
  - recent measurement: 1.01±0.10 × expectation
- Unoscillated ν_μCC
- Cross-sections for processes of interest, e.g. NCπ^0

See R. Castillo's talk this morning



Tracker analyses in ND280

- Interaction in FGDs
  - track momenta measured in TPC(s)
  - TPC PID by d*E*/d*x*
- ECal used for PID and energy measurement

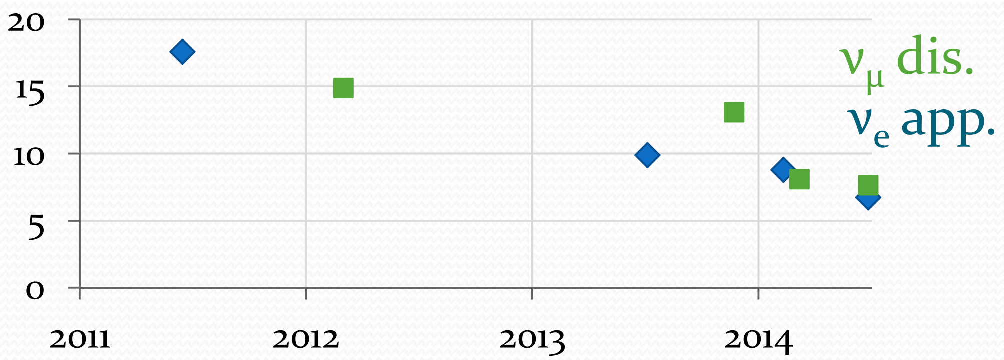


  - ECal is a lead/plastic scintillator sampling calorimeter
    - EM energy derived from maximum likelihood fit to total, RMS and skewness of deposited energy (resolution 10% at 1 GeV)
    - PID also uses cluster shape, charge distribution and ratio of deposited charge in 1st and last quarter of track

Systematic error budget for oscillation analyses (2014)

- Steady improvement in systematic errors since 2011
  - better constraints from near detector
  - better inputs from external data
  - more sophisticated cross-section models
  - more sophisticated analyses

Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SK+FSI	5.00%	3.66%
SK	4.03%	2.72%
FSI+SI(+PN)	2.98%	2.44%
Flux and correlated cross sections (prefit)	21.75%	26.04%
(postfit)	2.74%	3.15%
Independent cross sections	5.00%	4.69%
Total (prefit)	23.45%	26.80%
(postfit)	7.65%	6.75%



Summary

- T2K benefits from a well-understood far detector with mature calibration, reconstruction & analysis tools
  - However, performance is still being improved, most recently by development of new reconstruction method giving superior π^0 rejection for oscillation analyses
- Near detector inputs are crucial in reducing oscillation systematics by constraining unoscillated flux and cross-section models
- Better understanding of all aspects is steadily reducing systematic error budget

see also talk by C. Wilkinson!

Backup slides

Predicted charge distribution

Cherenkov emission profile

Decay electron momentum

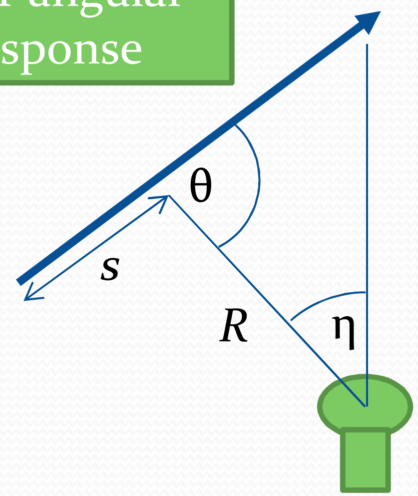
Water transparency

Predicted charge

PMT solid angle | attenuation | PMT angular response

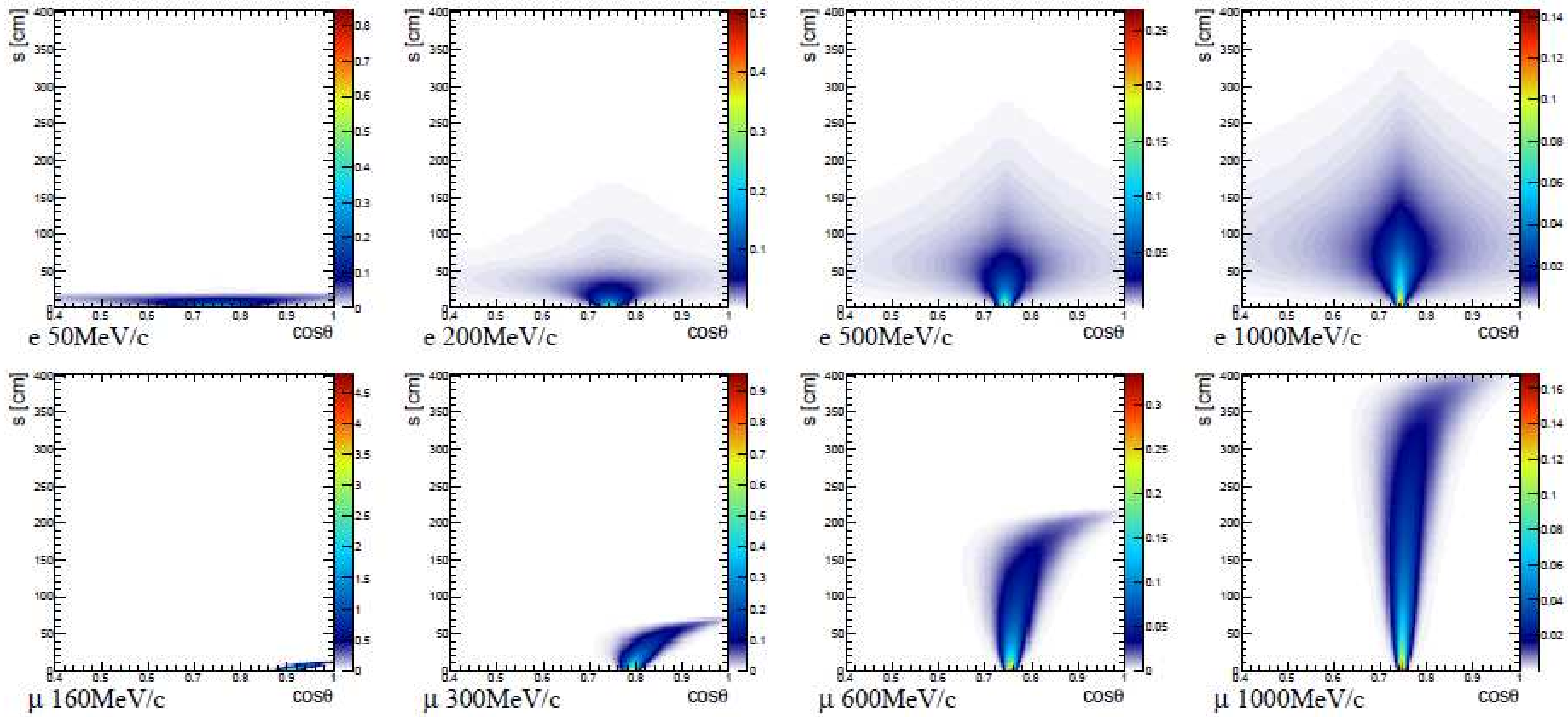
- $\mu^{\text{dir}} = \Phi(p)\int g(s, \cos\theta)\Omega(R)T(R)\epsilon(\eta)\mathrm{d}s$

light yield | emission profile



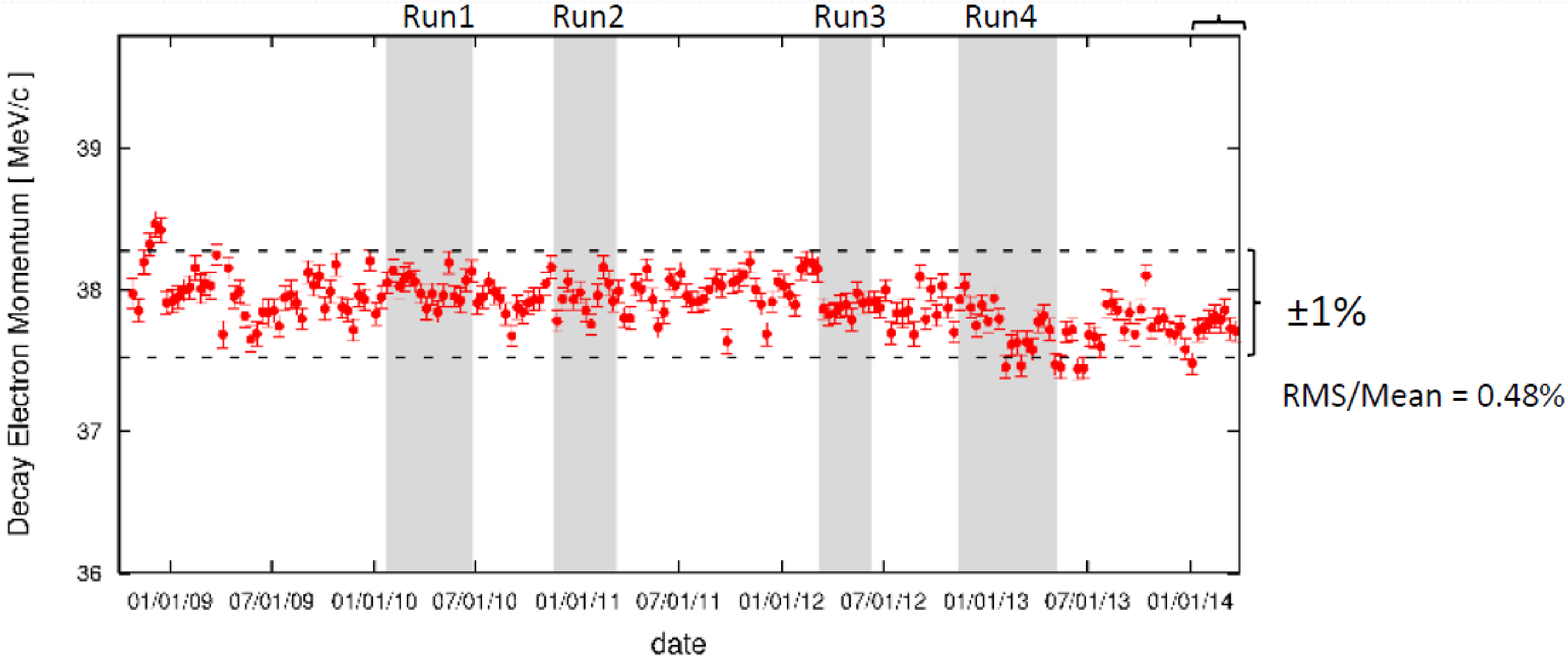
  - direct light only (scattered light handled separately)
  - Cherenkov light yield and profile depend on particle type
    - fiTQun PID comes from likelihood ratio based on this
  - Ω, *T* and ε are detector/geometry properties
    - independent of particle hypothesis

Cherenkov emission profile *g*



Detector stability

Momentum of decay electron from stopping muon events



Water transparency

Attenuation length