New (*) Neutrino Oscillation Results from T2K

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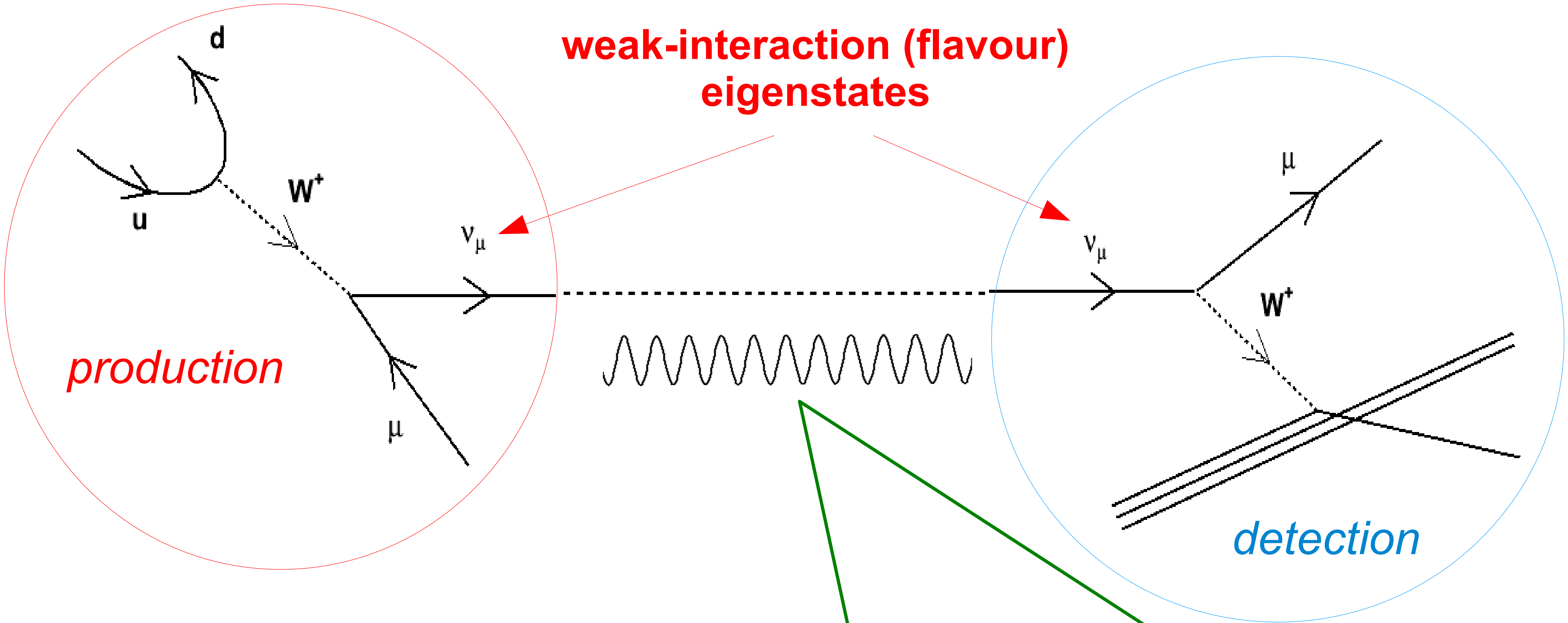
(*) Run1+2 (1.431E+20 protons on target) dataset

Science & Technology Facilities Council

Outline

- Neutrino oscillations
- The T2K experimental setup → arXiv:1106.1238v2, accepted for publication by Nucl.Instrum.Meth. A
- Measuring oscillation parameters at T2K
- Data-taking operations *(Physics Runs 1+2, January 2010 – March 2011)*
- Data reduction & Oscillation analysis strategy *(2010)*
- Electron-neutrino appearance results → Phys.Rev.Lett.107,041801(2011)
- Muon-neutrino disappearance results → Phys.Rev.Lett. *in preparation*
- Summary

Neutrino Oscillations



mass-eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

propagation described by plane waves

$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E} |\nu_i(0)\rangle$$

Neutrino oscillation ($\nu_\alpha \rightarrow \nu_\beta$) probability

Depends on:

Mixing matrix elements
(determined experimentally)

Squared neutrino mass splittings
(determined experimentally)

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Sensitivity to oscillations
by matching the L / E (baseline to energy) ratio
to a particular Δm^2

What do measure in neutrino oscillation experiments?

- With 3 neutrinos, **any 2** squared mass splittings **Δm^2**
- 3 mixing angles, **θ_{12}, θ_{23}, θ_{13}**
- 1 CP violating phase **δ**

"23" sector probed mainly by atmospheric and LBL accelerator expts

"13" sector probed mainly by SBL reactor (not δ) and LBL accelerator expts

"12" sector probed mainly by LBL reactor and solar expts

Majorana phases

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

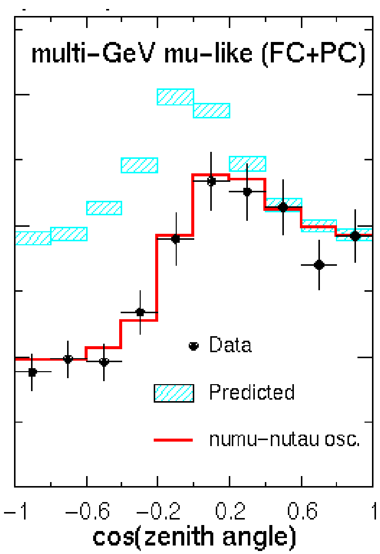
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

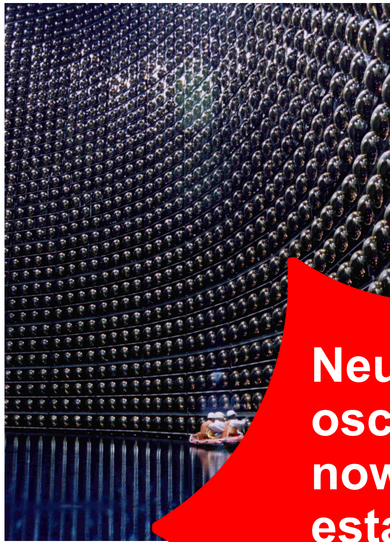
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

1997-2010

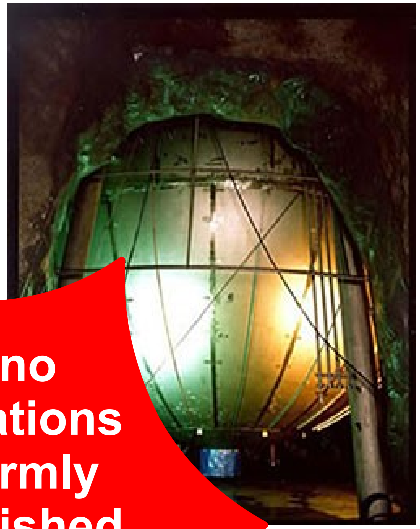
First age of neutrino-mixing exploration

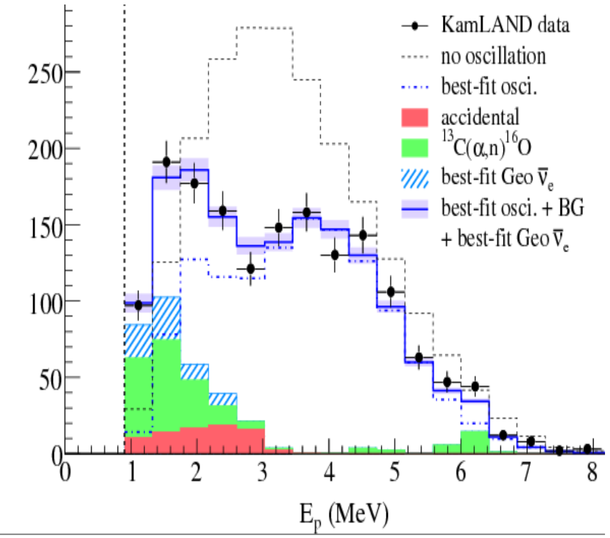
... the atmosphere *(SuperK, Soudan, ,...)*





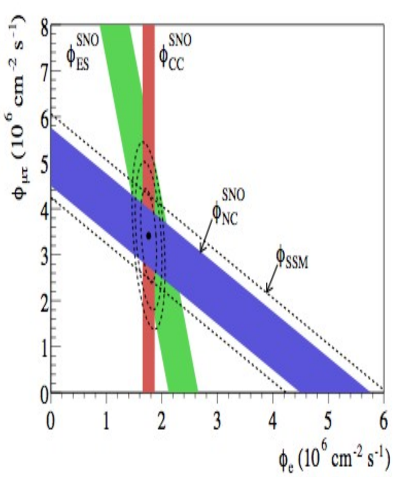
... nuclear reactors *(KamLAND,...)*

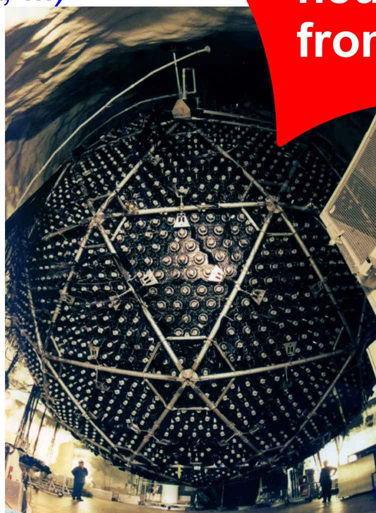




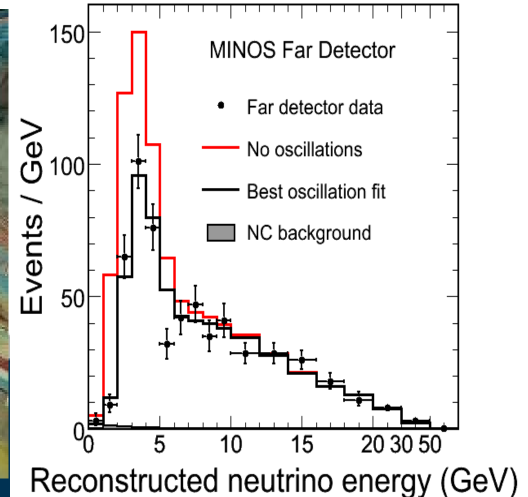
Neutrino oscillations now firmly established studying neutrinos from ...

... the Sun *(SNO, SuperK, ...)*



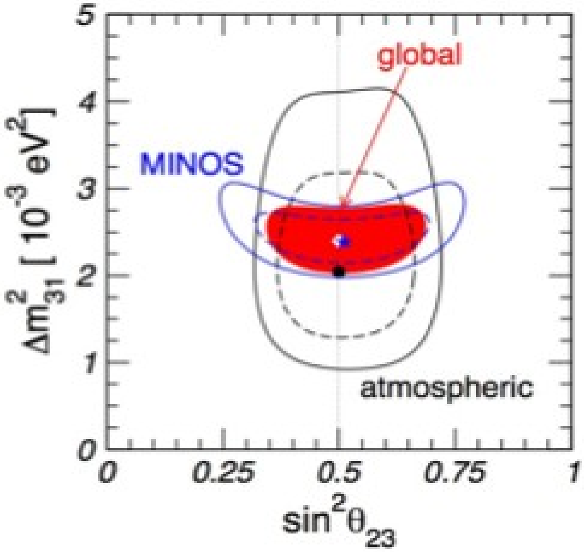


... accelerators *(K2K, MINOS,...)*

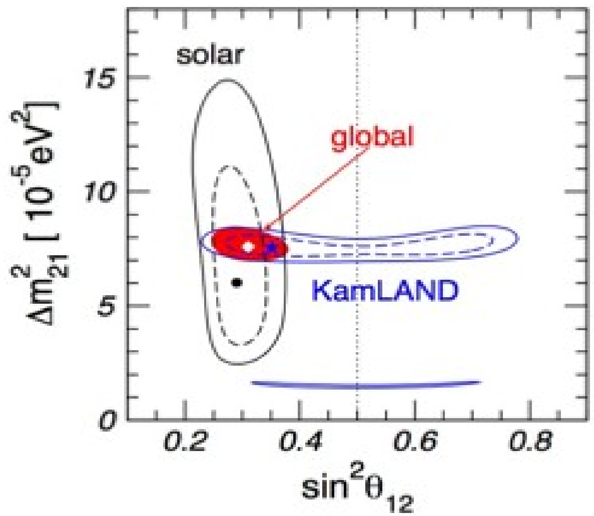


Results from the first age of neutrino-mixing exploration

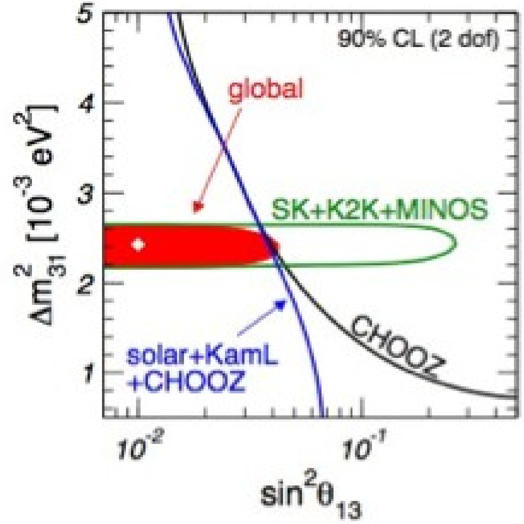
"**23**" : LBL accelerator & atmospheric



"**12**" : LBL reactor & solar



"**13**" : LBL accelerator & SBL reactor



	parameter	best fit	
(solar) →	Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.23}_{-0.18}$	~ 3%
(atmospheric) →	$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	~ 4%
	$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	~ 6%
	$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	~ 14%

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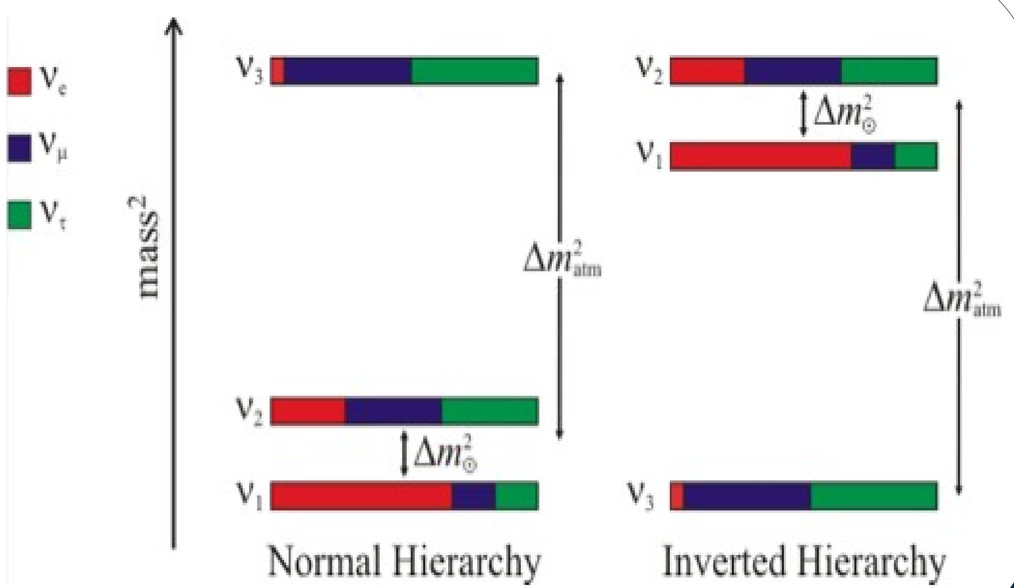
Next big questions in neutrino physics...

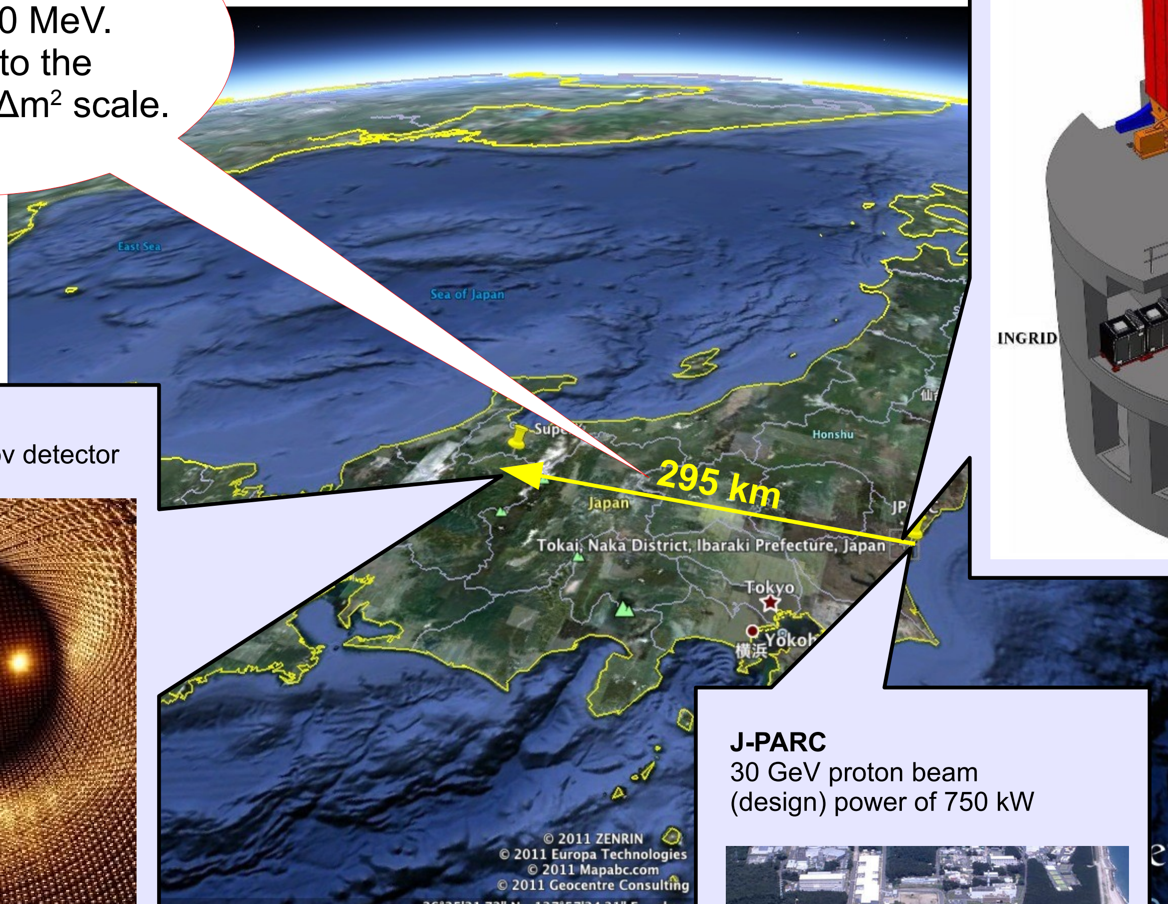
- θ_{13} non-zero?
- θ_{23} maximal?
- CP violation in the neutrino sector?
- Mass hierarchy?
- *Dirac or Majorana?*
- *Absolute mass scale?*

T2K

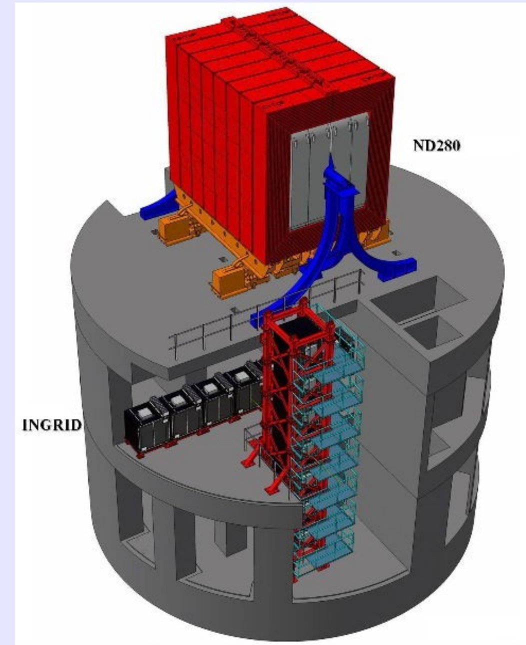


T2K Experiment Overview

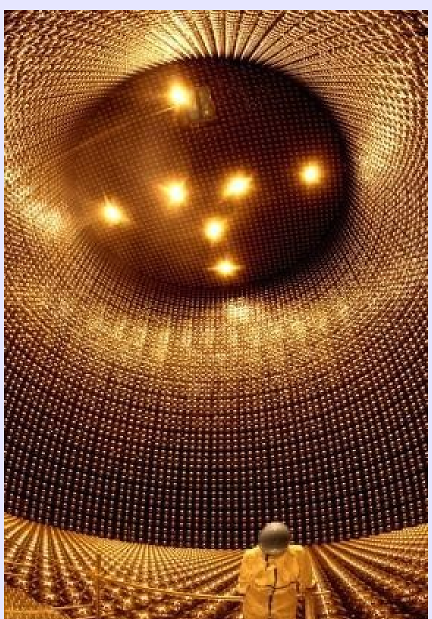
Almost pure ν_μ beam
Peak at 600 MeV.
L/E tuned to the
`atmospheric' Δm^2 scale.



280m detector suite



Super-Kamiokande
50 kton water-Cherenkov detector



J-PARC
30 GeV proton beam
(design) power of 750 kW

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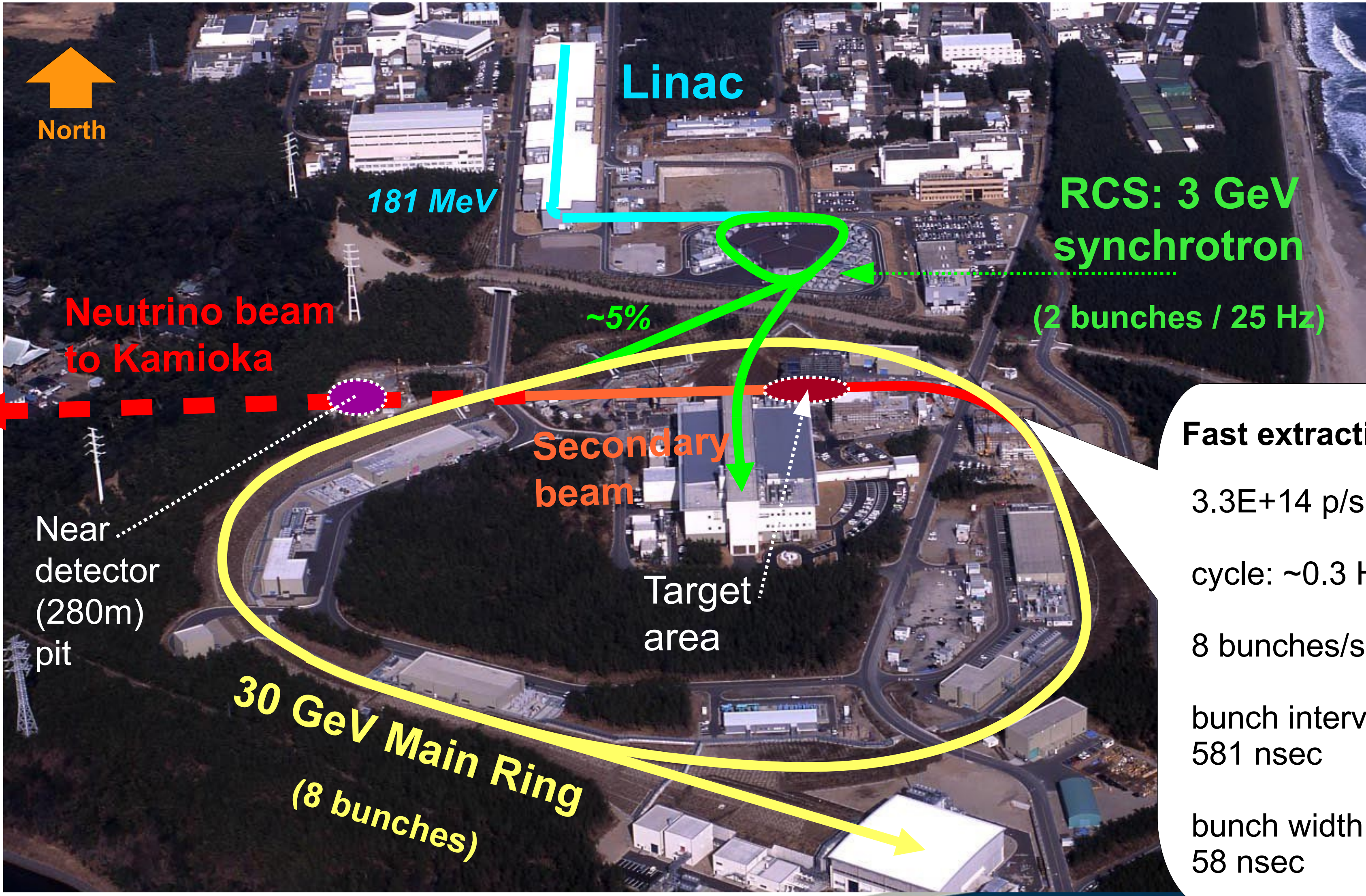
J-PARC facility (KEK / JAEA)



Fast extraction

3.3E+14 p/spill

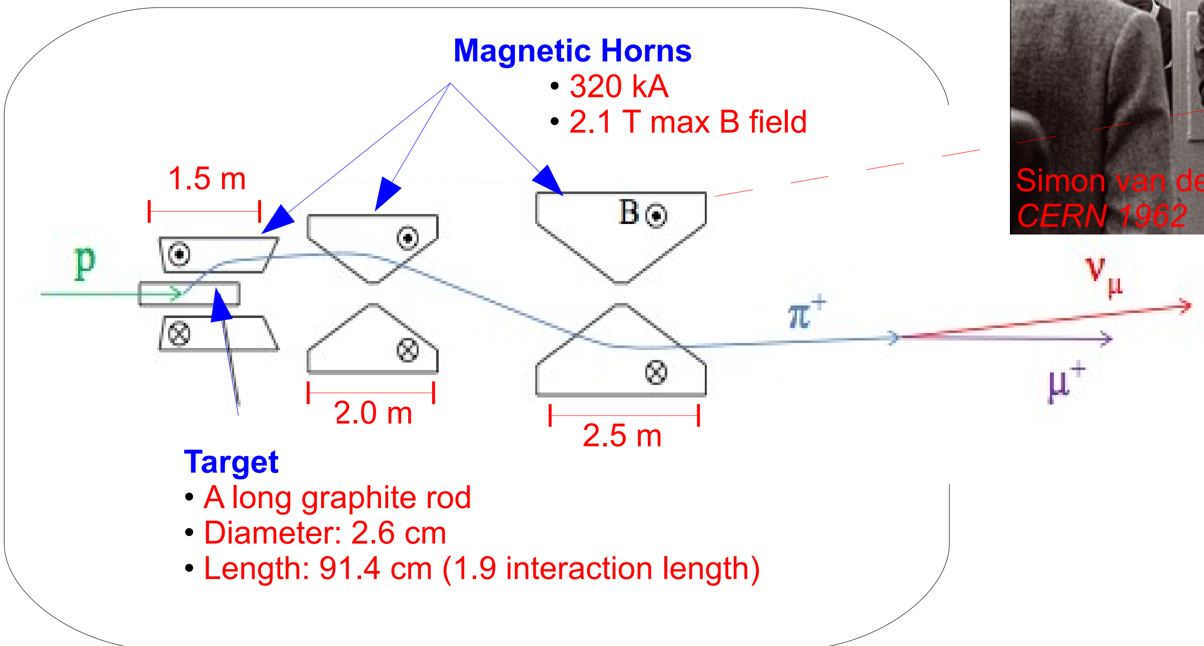
cycle: ~0.3 Hz

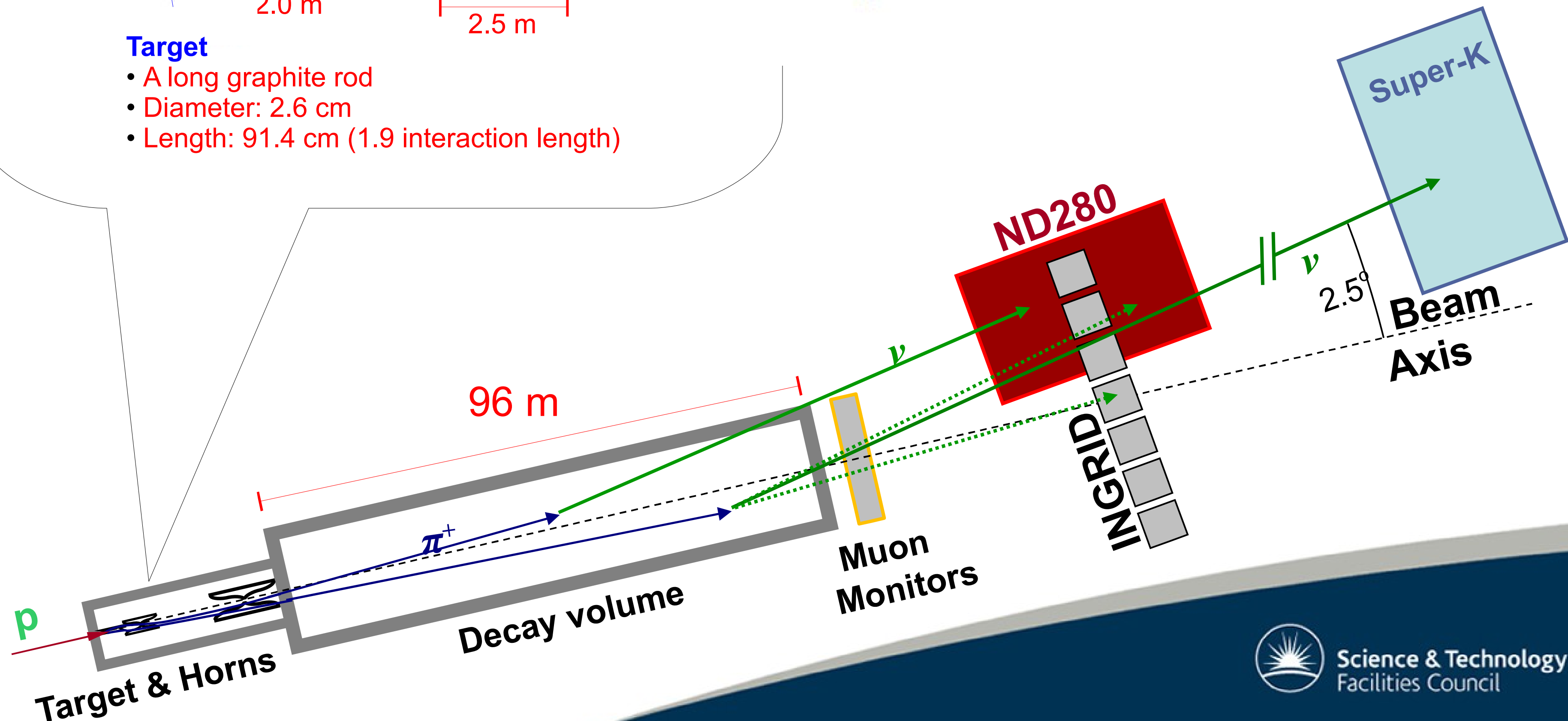
8 bunches/spill

bunch interval: 581 nsec

bunch width: 58 nsec

The neutrino beam-line

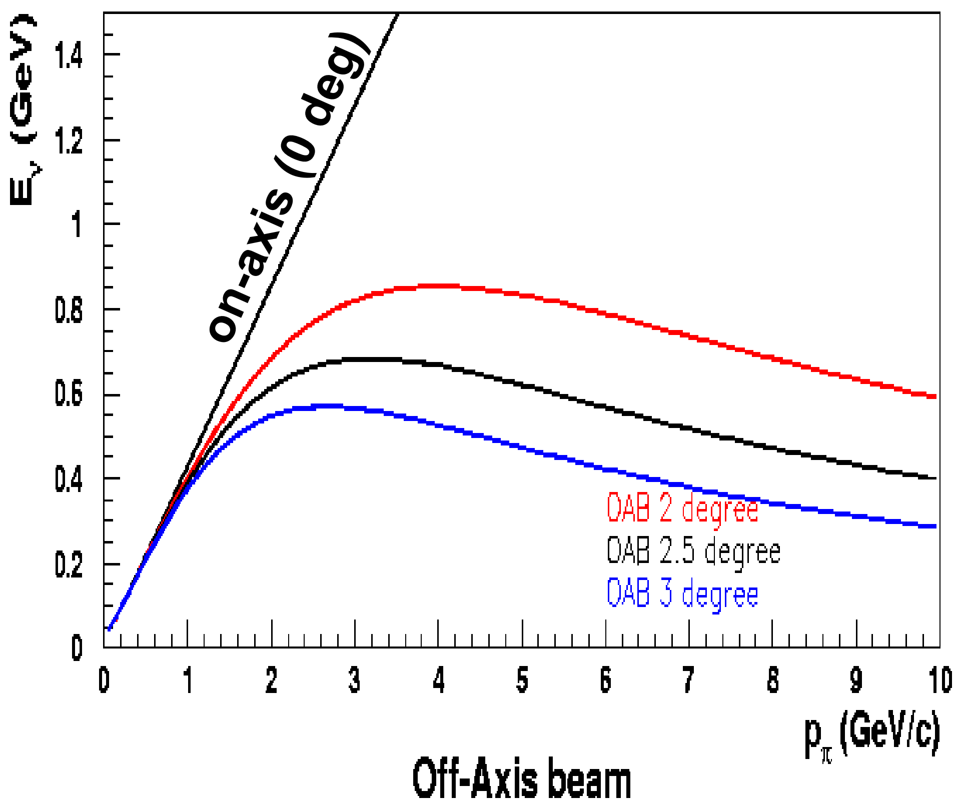


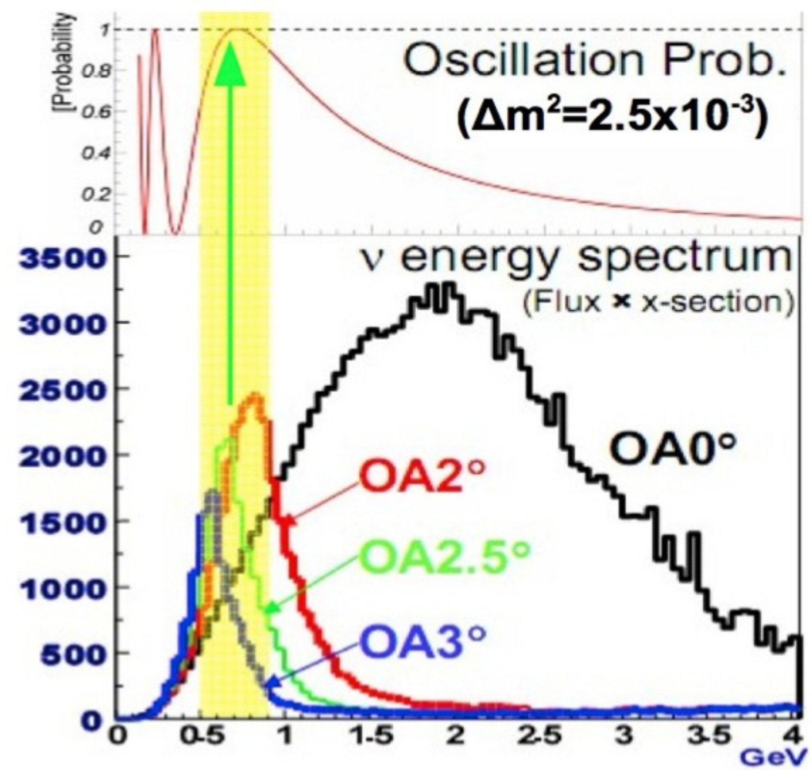


The `off-axis' trick

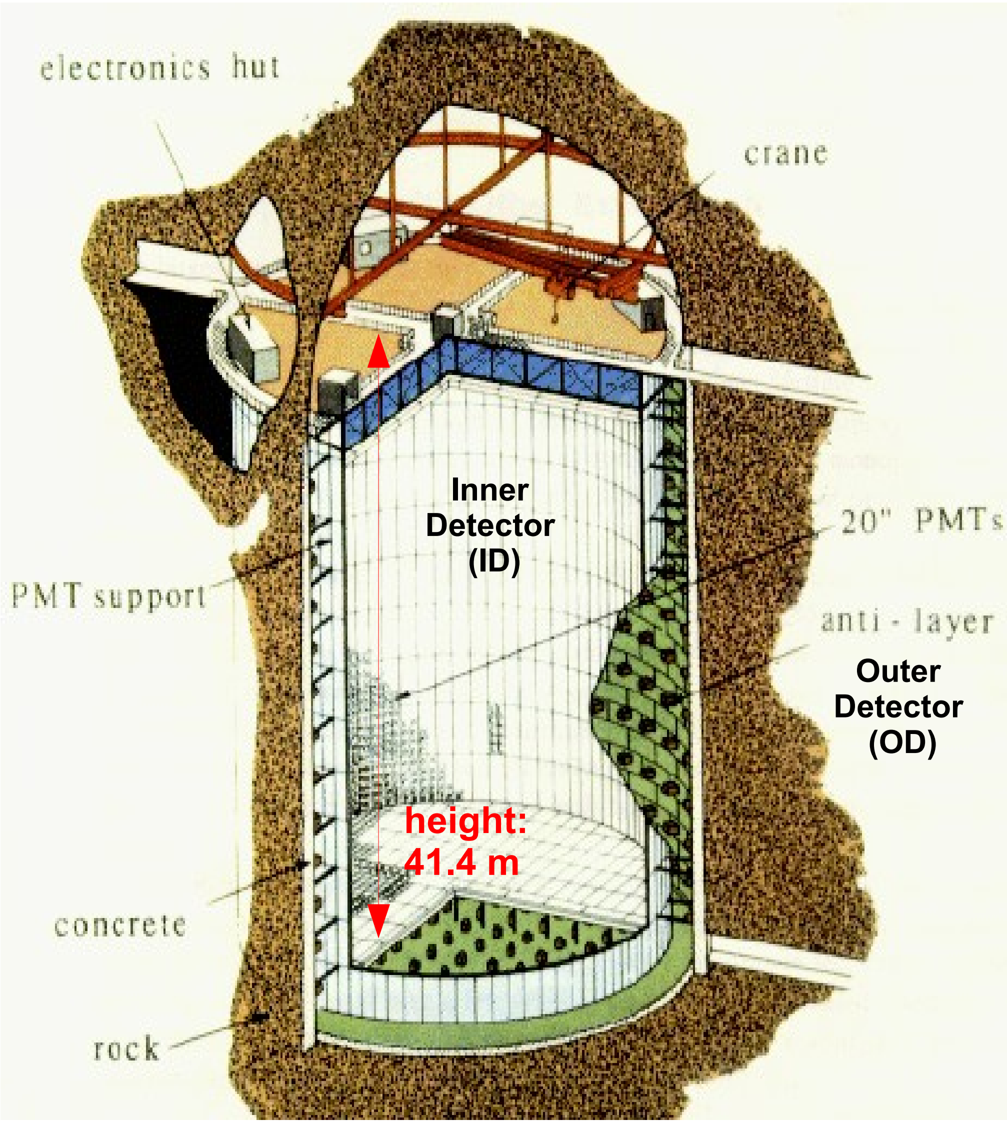
T2K is first accelerator neutrino experiment employing the `off-axis' trick.

Exploit kinematical properties of pion decay to create a narrow neutrino beam peaked at a particular energy (chosen to maximise oscillation probability at the SuperK location)





Super-K (IV)



50 kt Water Cherenkov detector
(**22.5 kt** fiducial mass)

Overburden (shielding): **2700 mwe**

Inner detector: **11,129 20" PMTs**
(40% photo-cathode coverage)

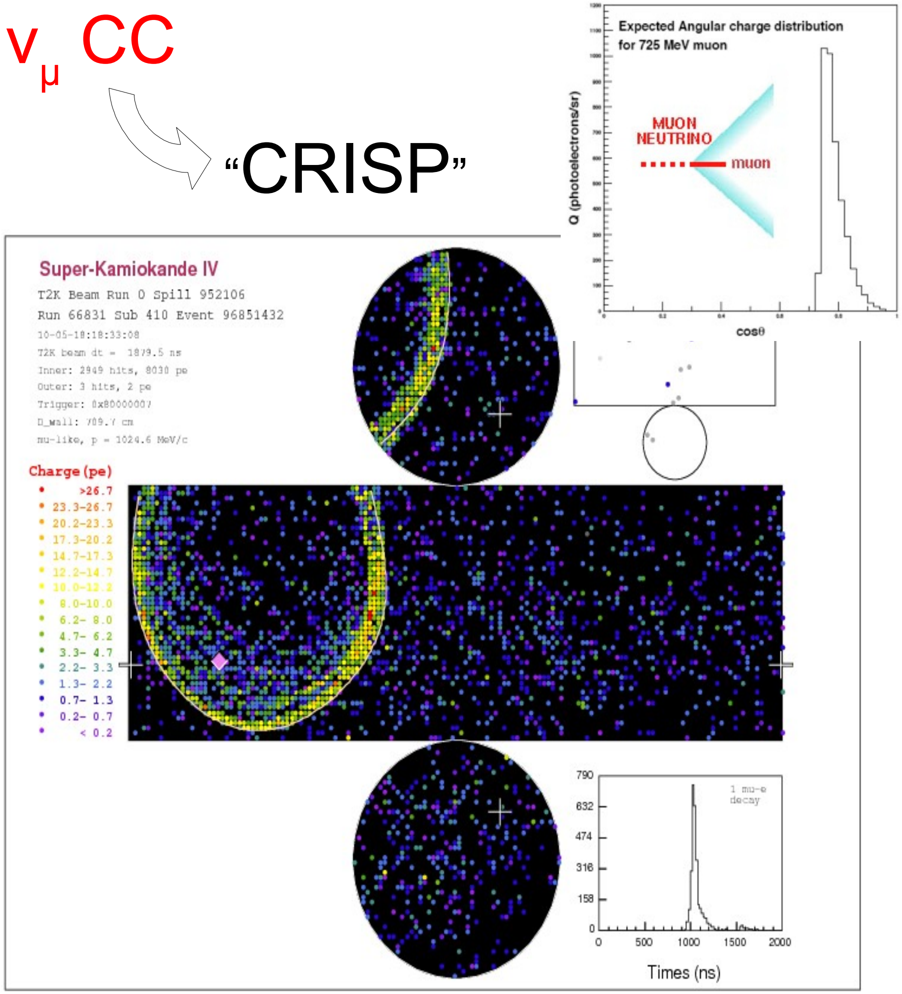
Outer detector: **1,885 8" PMTs**

DAQ: No dead-time

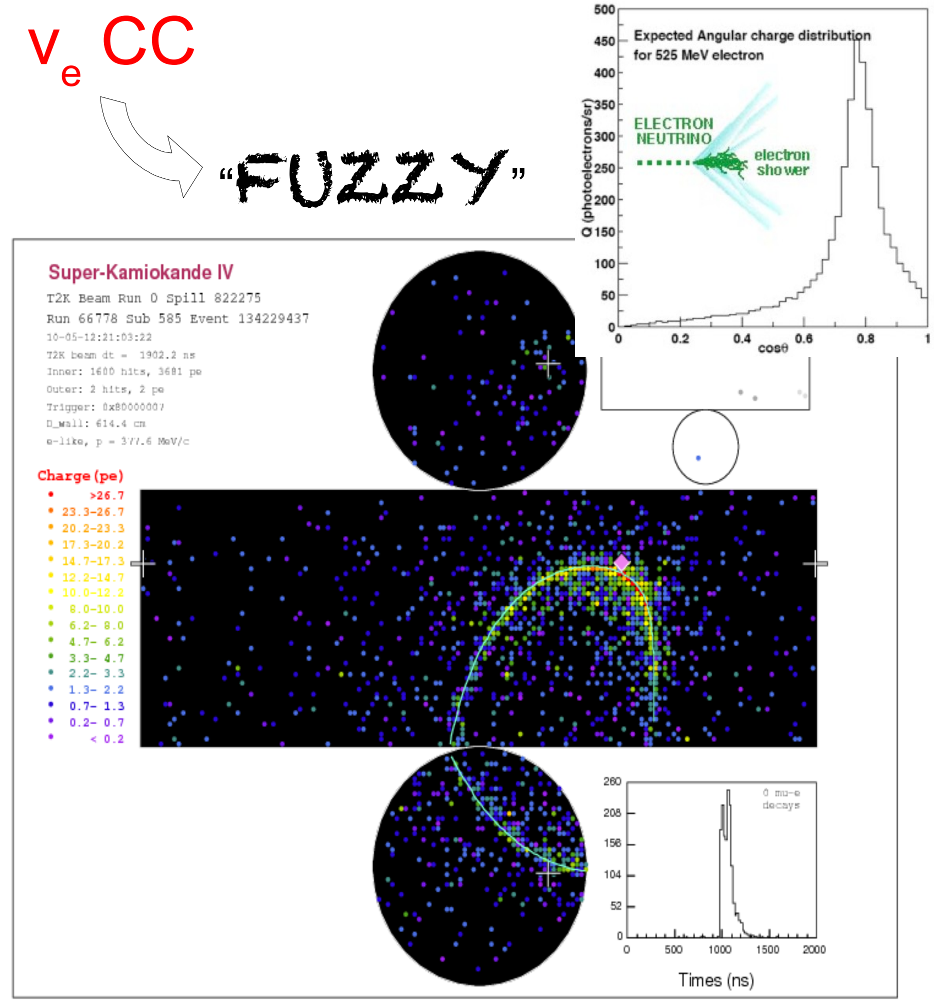
Energy threshold: ~4.5 MeV

Water Cherenkov imaging

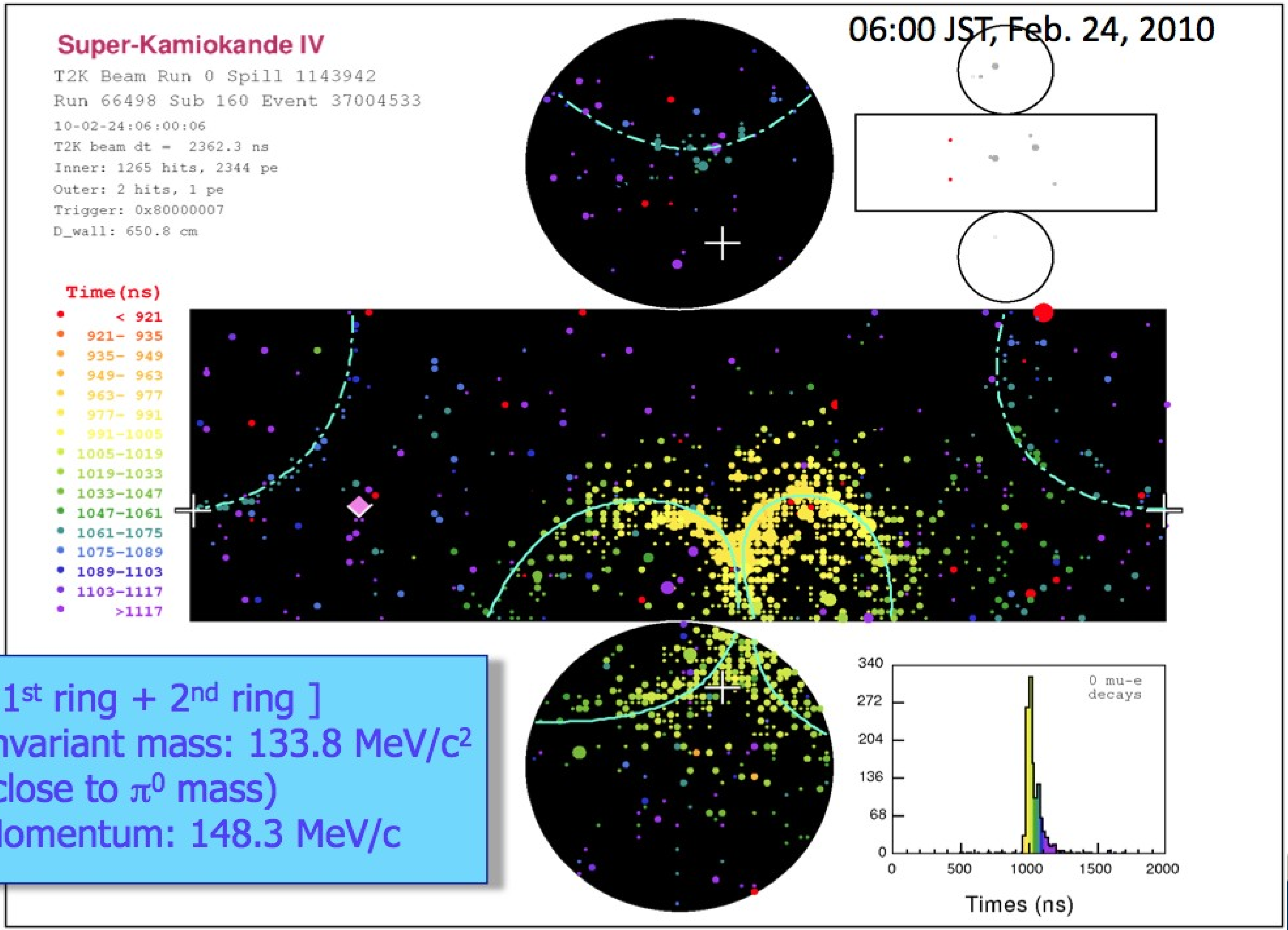
ν_μ CC → "CRISP"



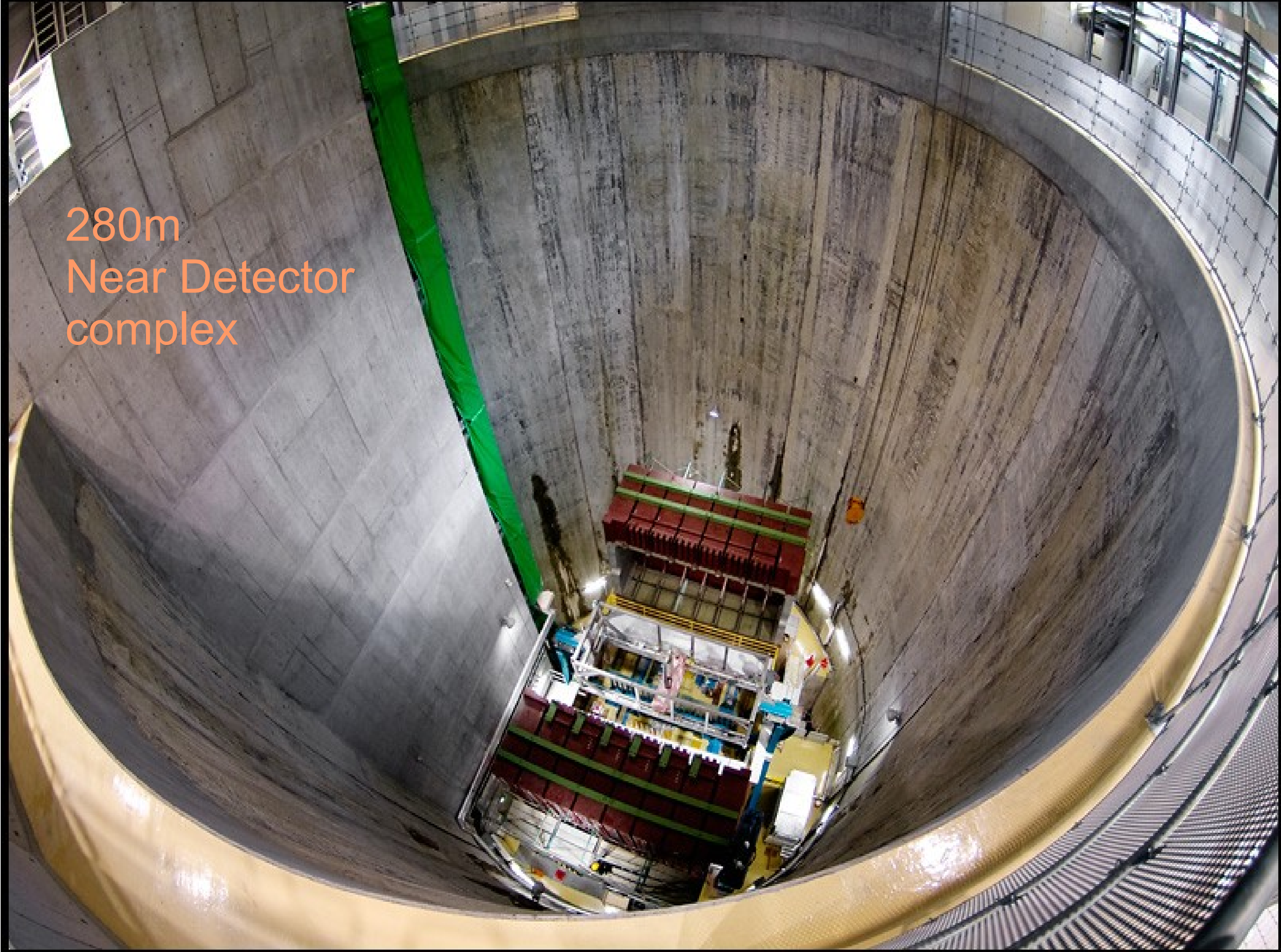
ν_e CC → "FUZZY"



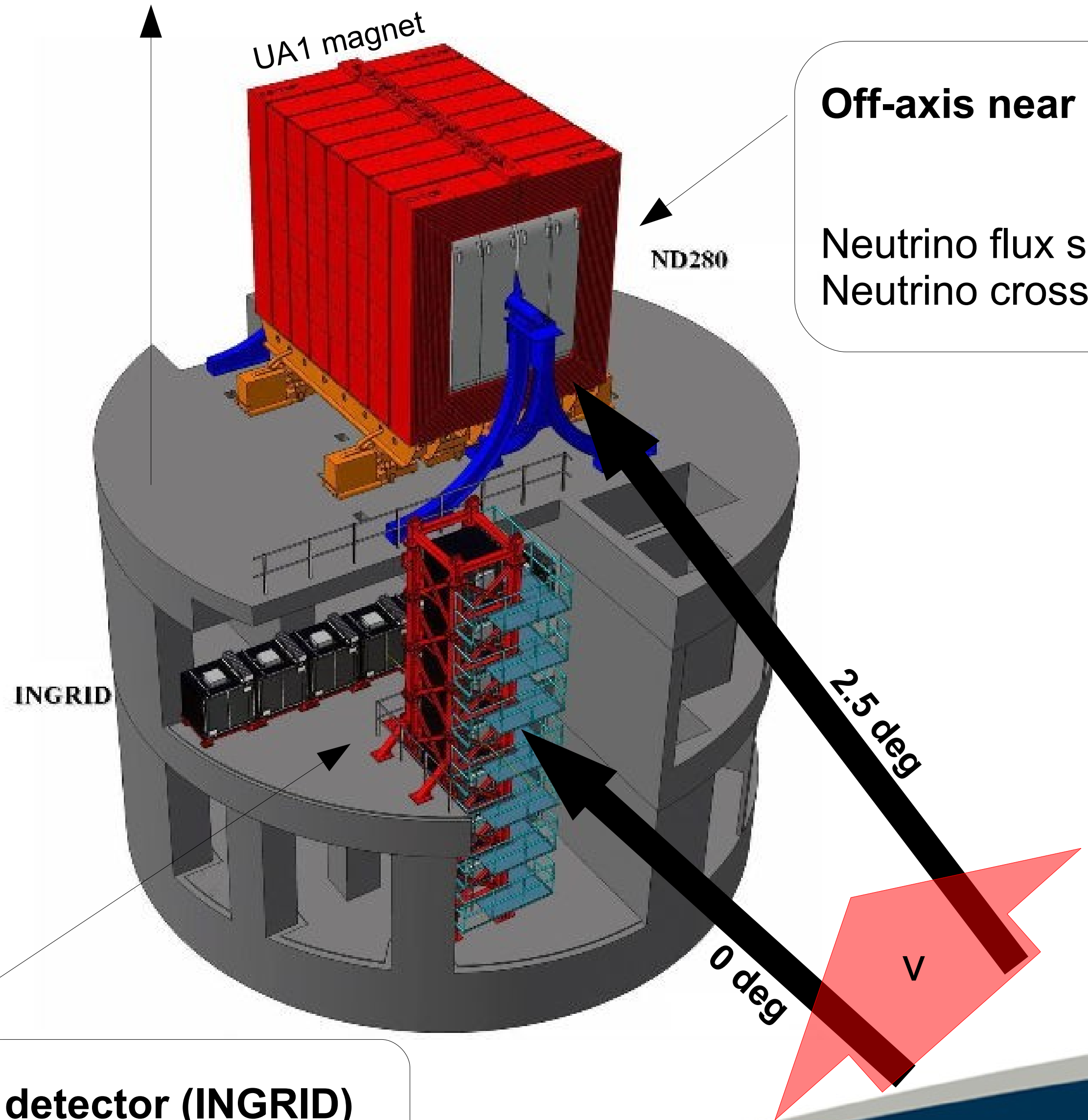
First T2K neutrino event at SuperK



[1st ring + 2nd ring]
Invariant mass: 133.8 MeV/c^2
(close to π^0 mass)
Momentum: 148.3 MeV/c


280m
Near Detector
complex

280m Near Detector complex

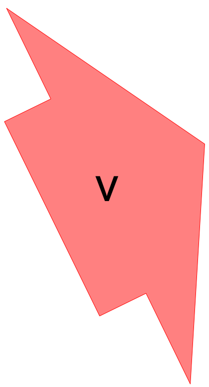


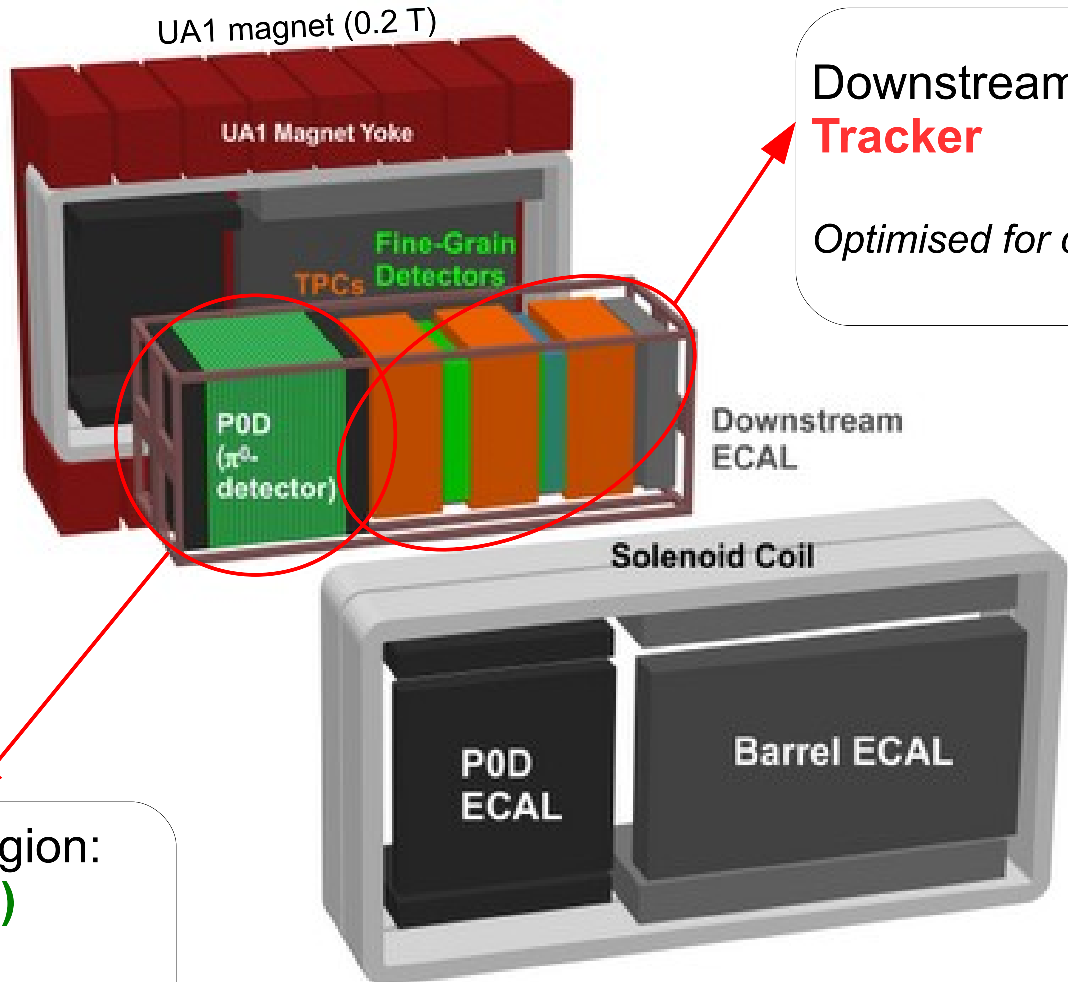
Off-axis near detector (ND280)

Neutrino flux spectrum characteristics
Neutrino cross sections

On-axis near detector (INGRID)
Monitor neutrino beam direction

Off-axis near detector (ND280)





Downstream target region:
Tracker

Optimised for charged particles

Upstream target region:
Pi0 Detector (P0D)

Optimised for pi0 measurement

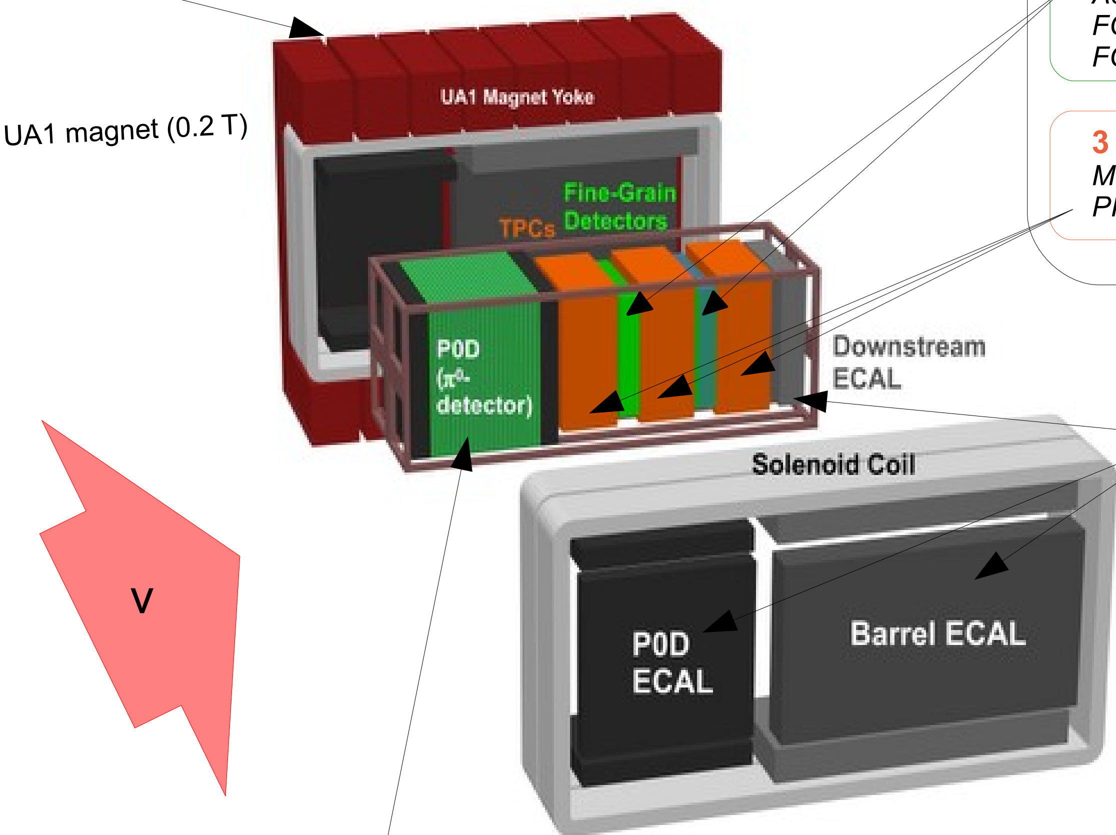
Off-axis near detector (ND280)

SMRD (Side Muon Range Detector)
Scintillator planes in magnet yoke
Veto + CR trigger + aid in momentum measurement

Tracker

2 FGDs (Fine Grained Detectors)
Active target mass
FGD1: 1.0 ton scintillator
FGD2: 0.5 ton scintillator + 0.5 ton water

3 TPCs (Time Projection Chambers)
Momentum measurement of charged particles
PID via dE/dx



P0D, Barrel and Downstream ECAL
E/M showers from inner detector

P0D (π0 detector)
Scintillator planes interleaved with lead and water layers
13 tons lead + 3 tons water
Optimised for γ detection

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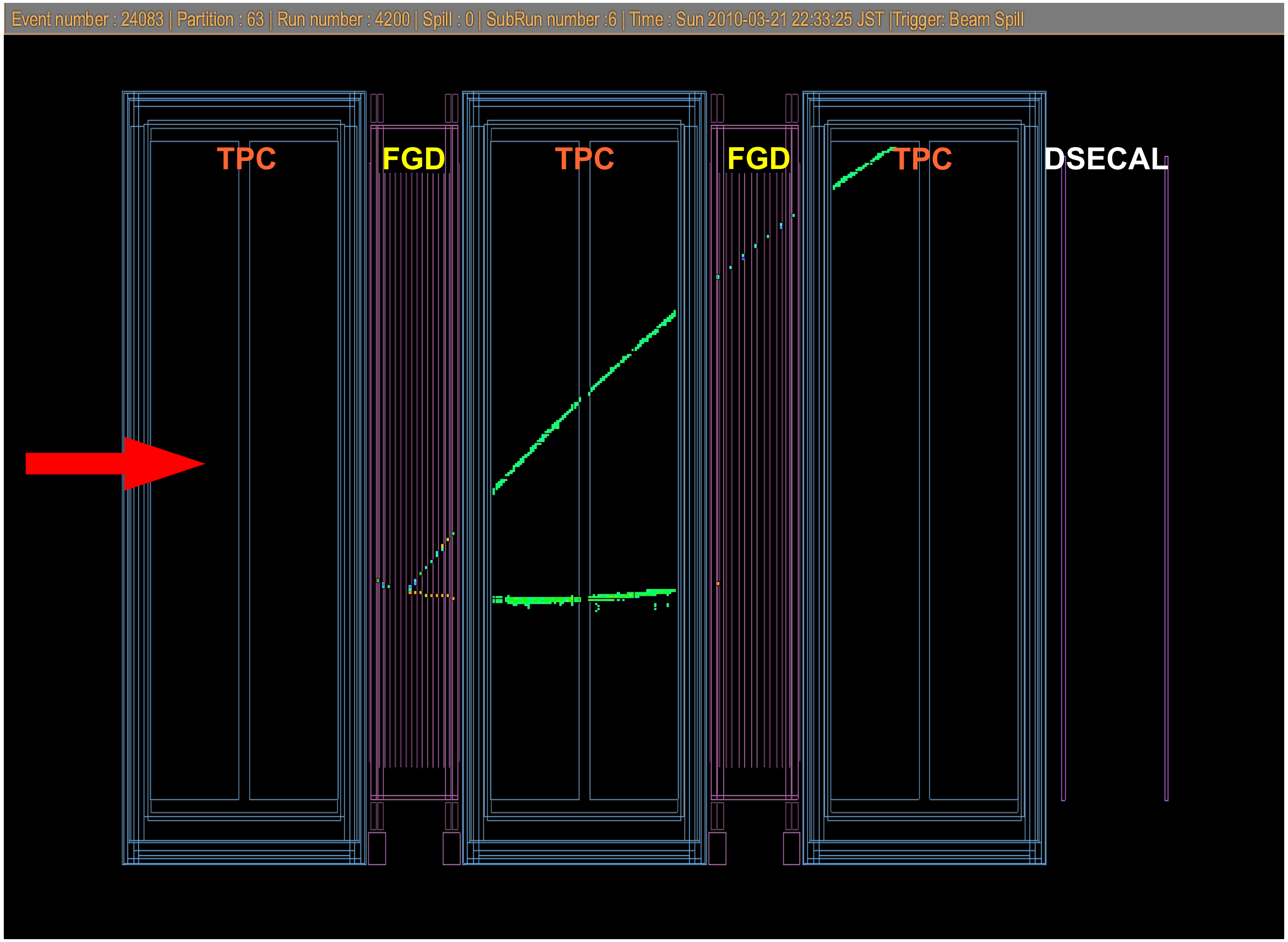
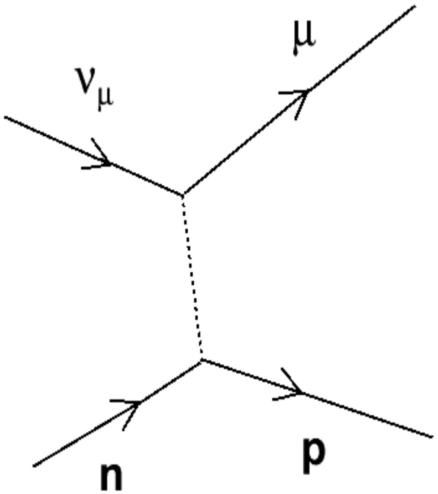
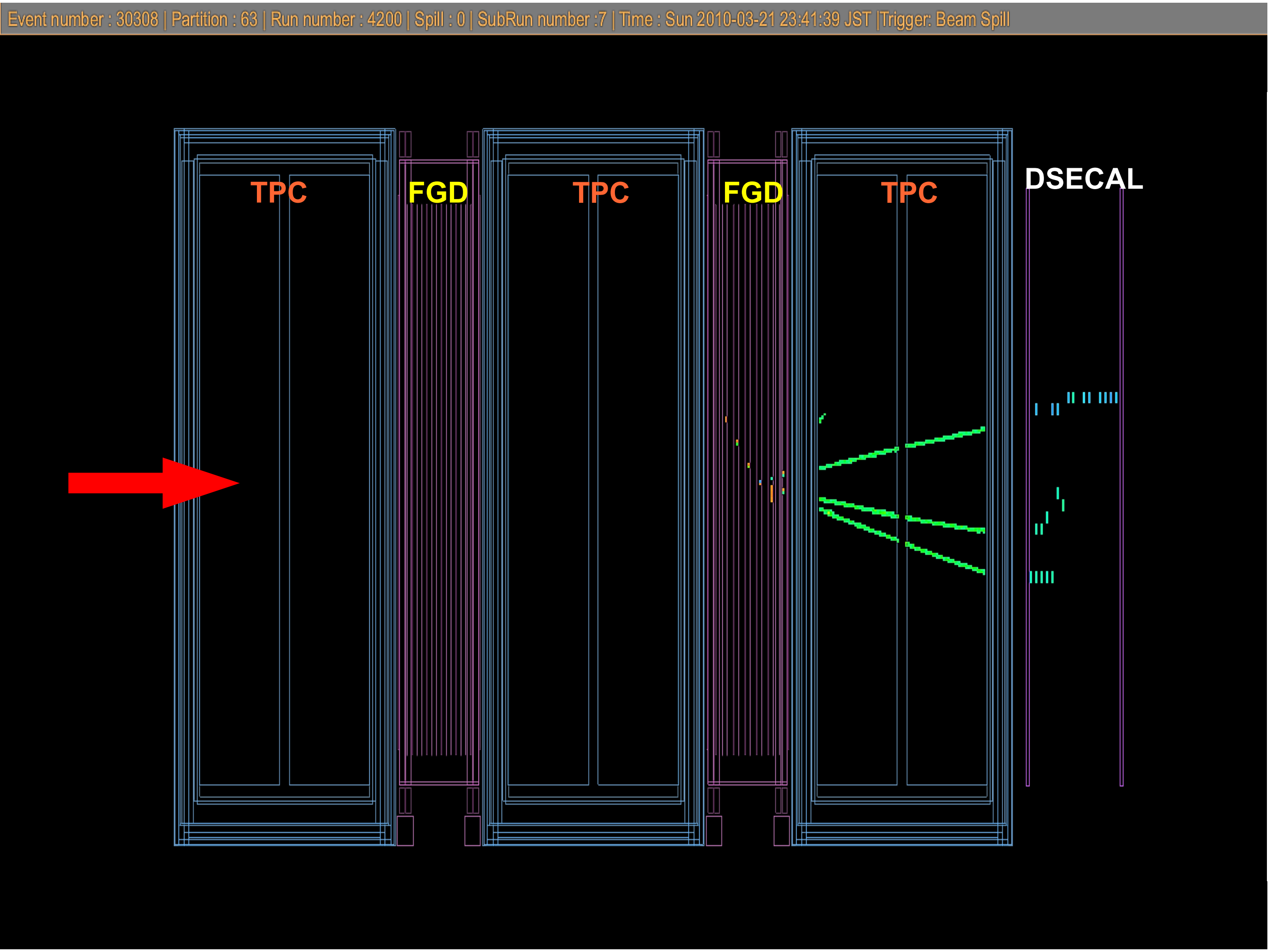
ND280 off-axis detector event (in the Tracker)

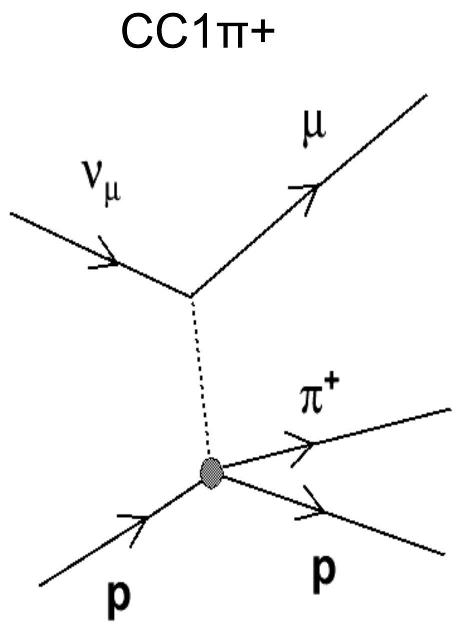


CCQE

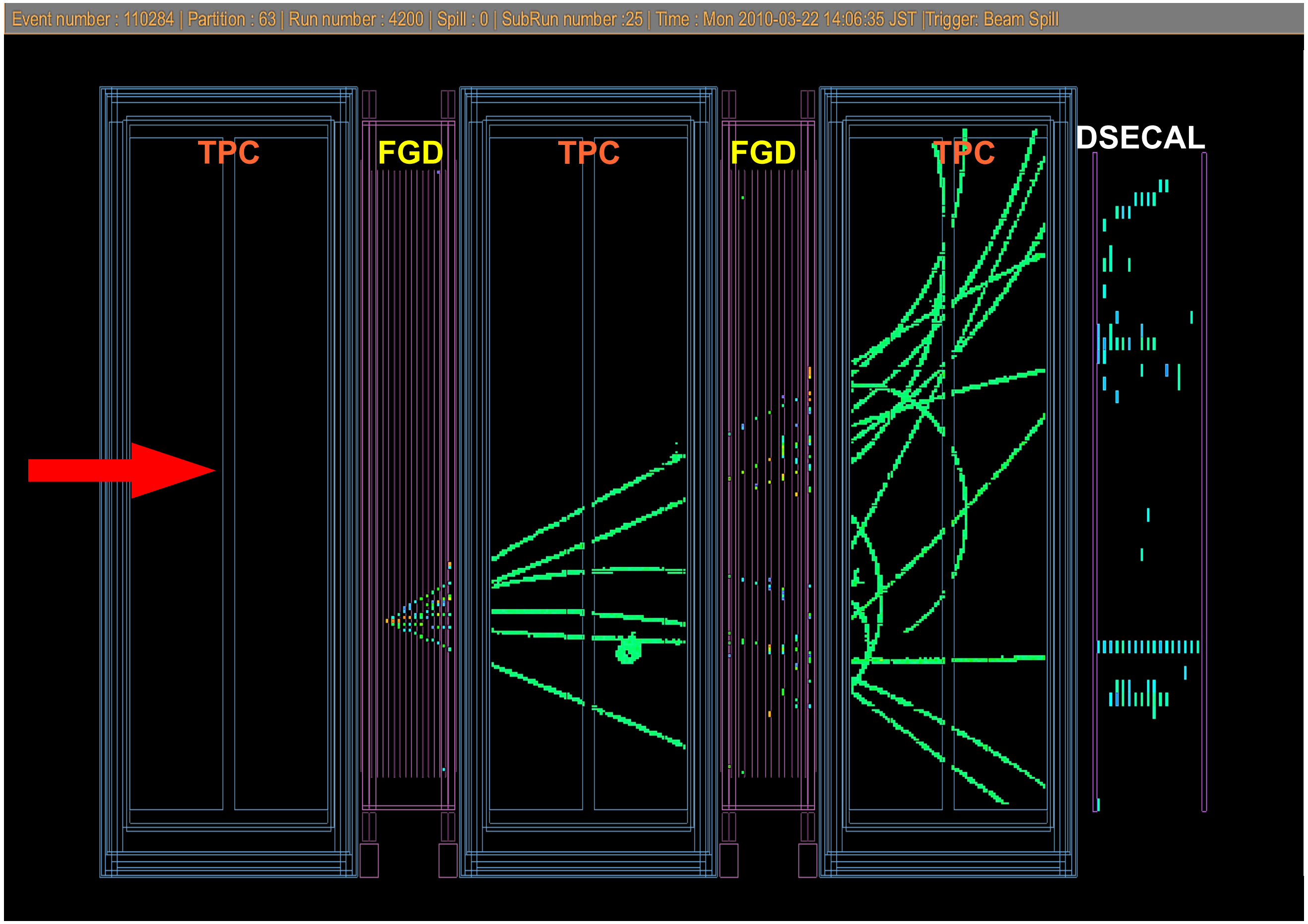


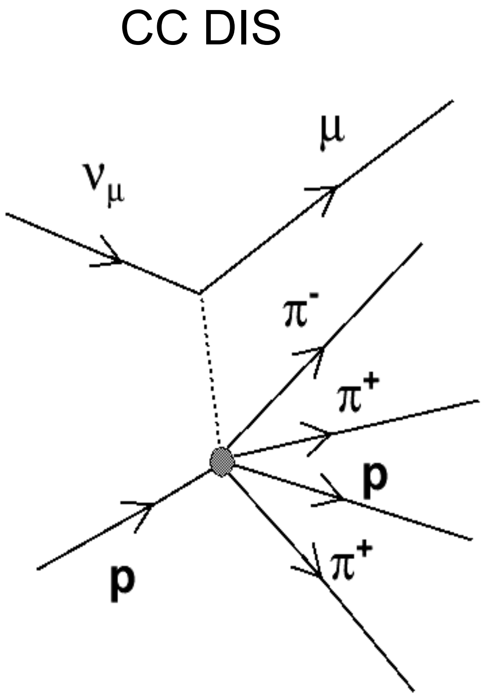
ND280 off-axis detector event (in the Tracker)



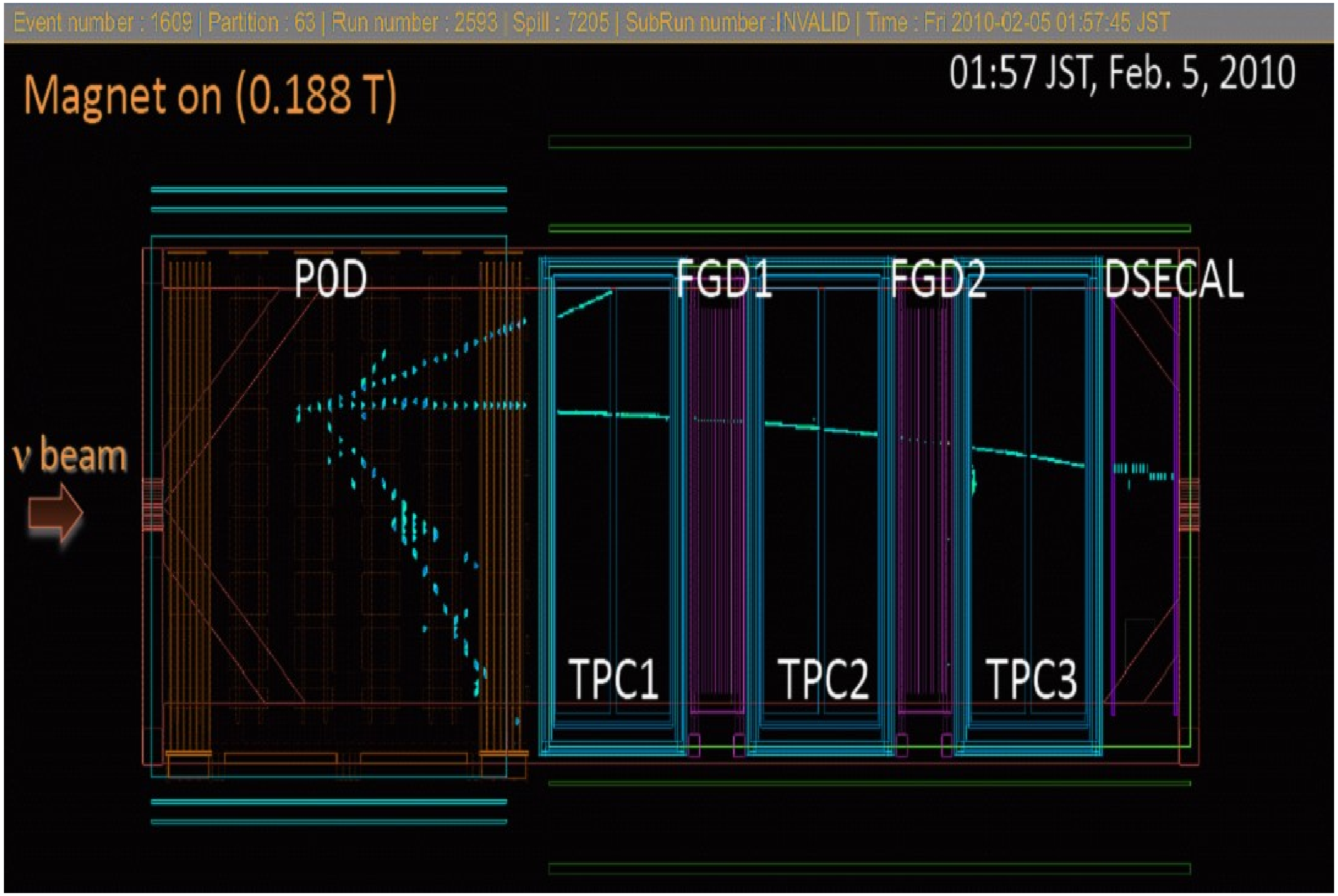


ND280 off-axis detector event (in the Tracker)

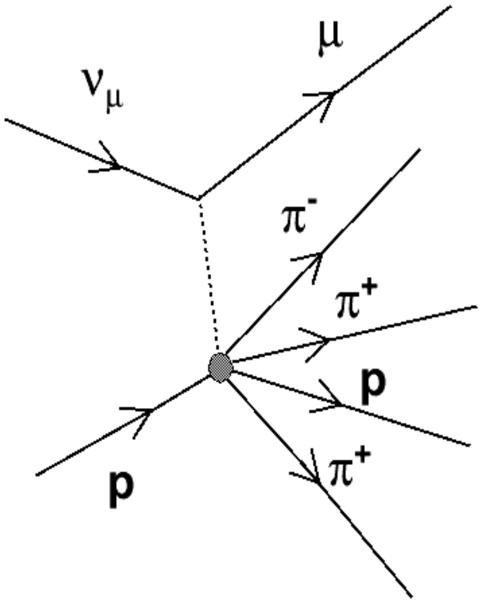




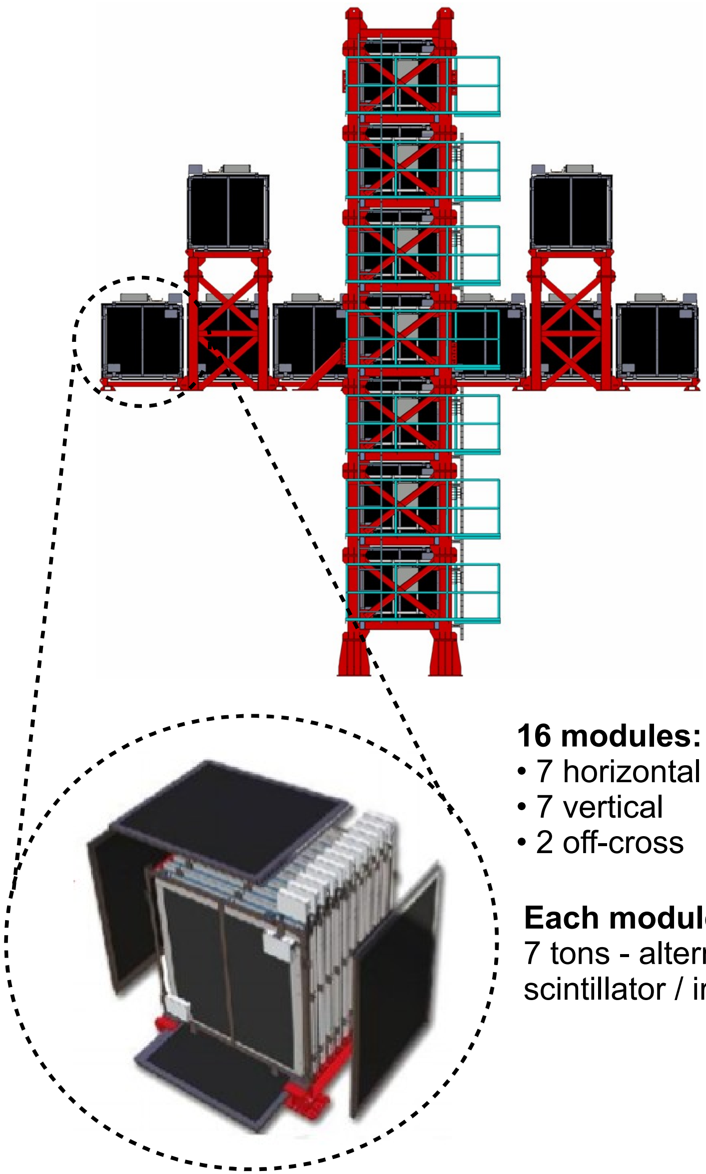
ND280 off-axis detector event (in the P0D)



CC DIS



On-axis near detector (INGRID)



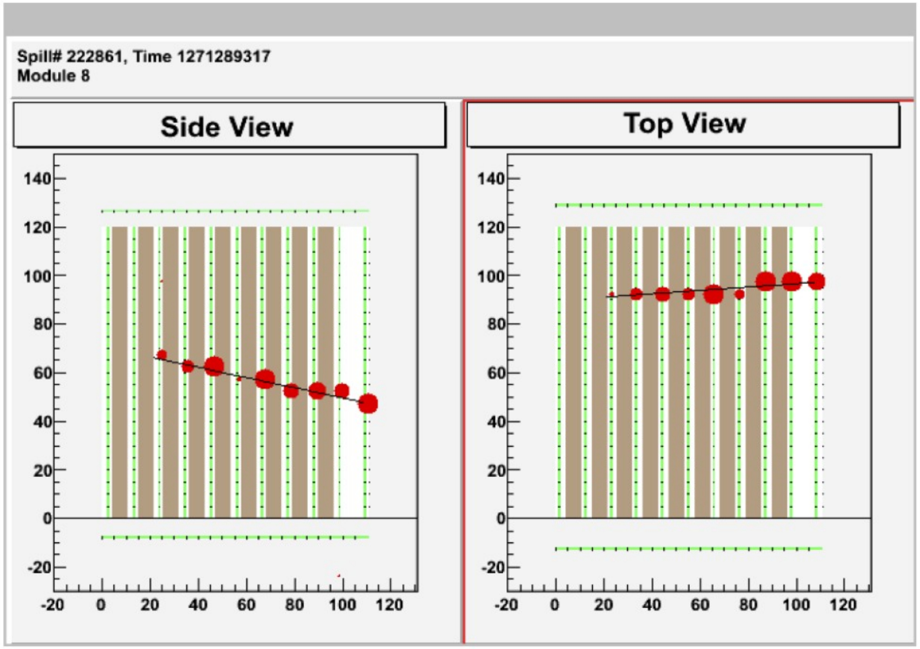
16 modules:
• 7 horizontal
• 7 vertical
• 2 off-cross

Each module:
7 tons - alternating scintillator / iron planes

• 10 m x 10 m beam coverage

• ~700 neutrino interactions day at 50 kW

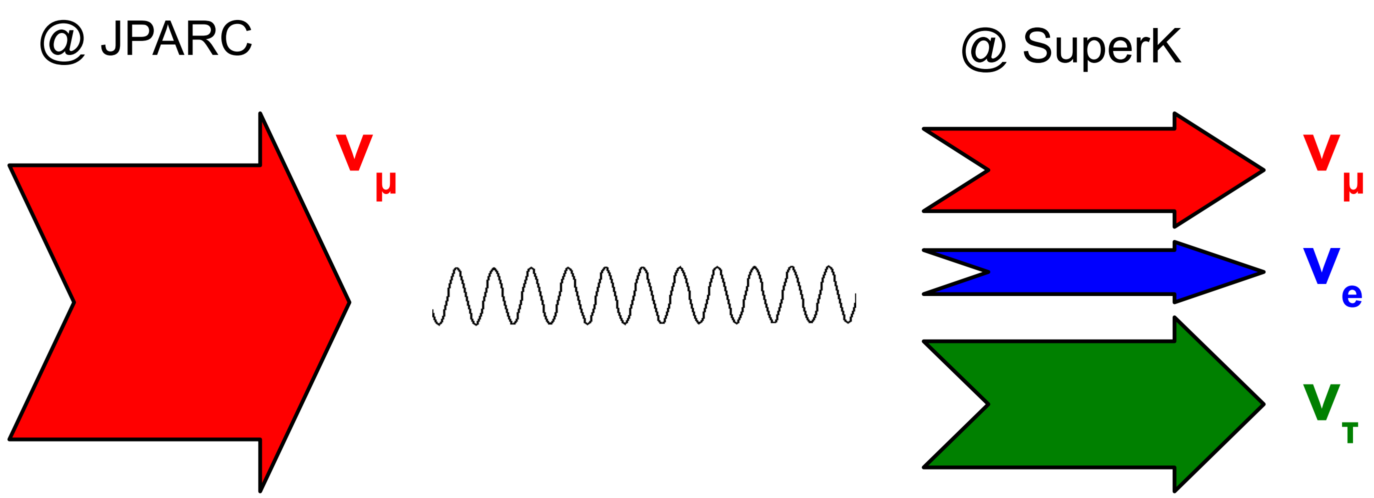
• Monitor neutrino beam direction
  • *Off-axis angle precision goal < 1 mrad*
  • *1 mrad → 2% SuperK flux change at peak energy*



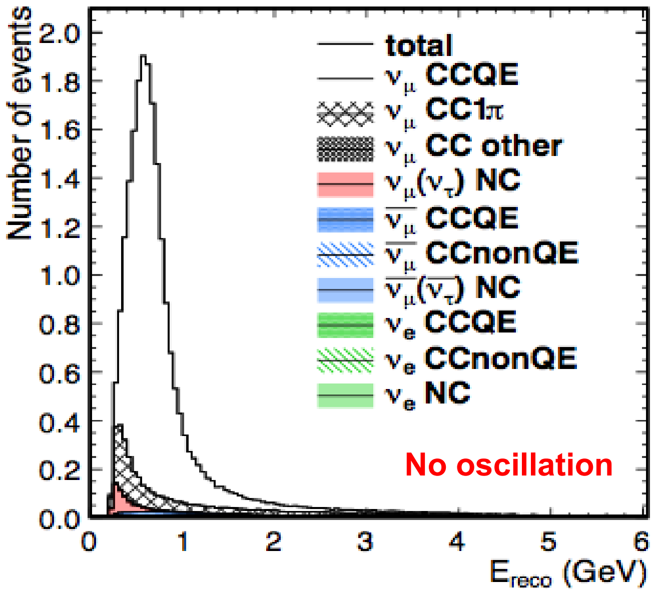
Measuring oscillation parameters at T2K

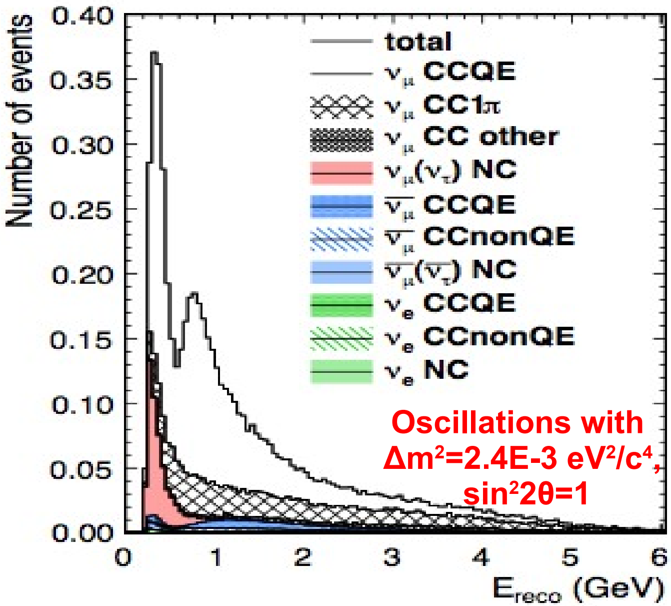
- The `(ν_μ) *disappearance*' channel

- The `(ν_e) *appearance*' channel

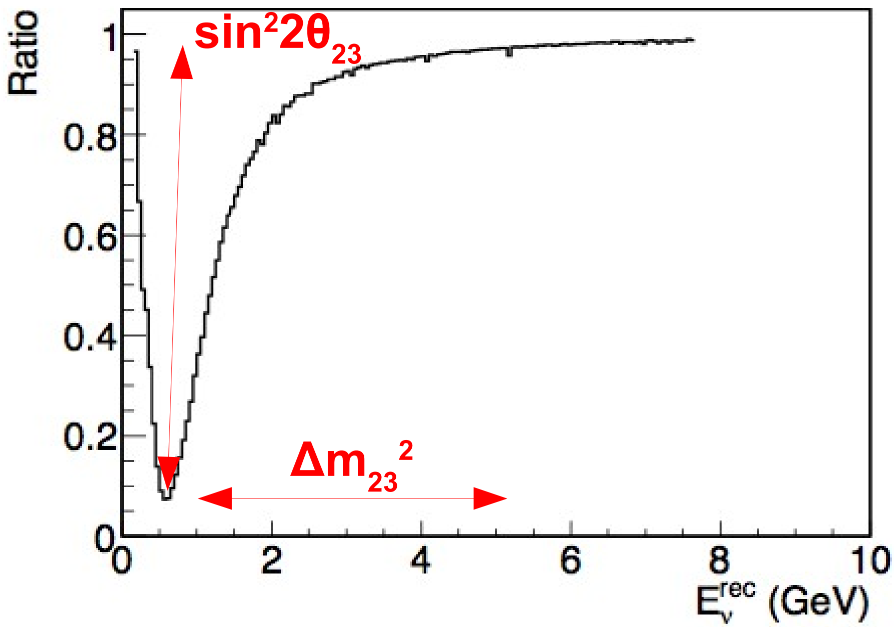


Disappearance channel: Measuring $\sin^2 2\theta_{23}$ and Δm^2_{23}





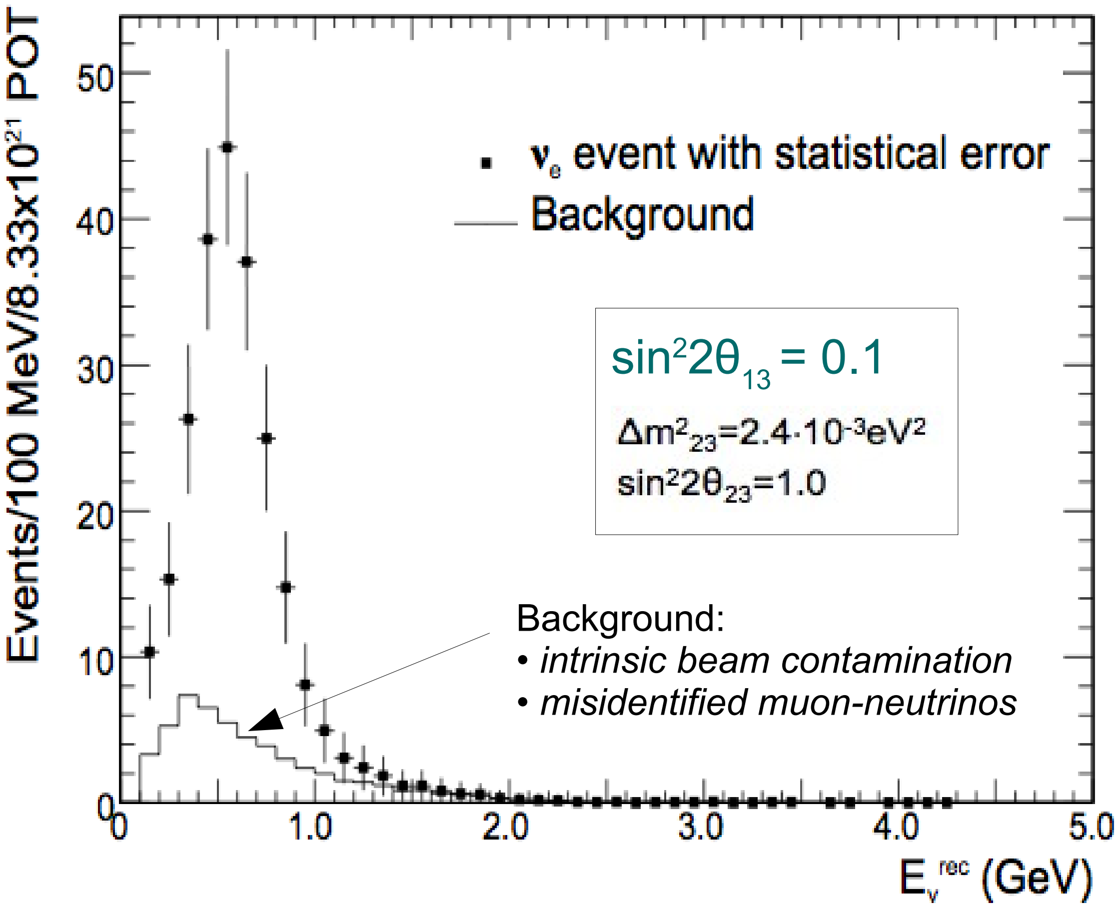
Looking for: Energy dependent depletion of muon-like events



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$

Appearance channel: Measuring $\sin^2 2\theta_{13}$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2\left(1.27\Delta m^2_{13} \frac{L}{E}\right)$$



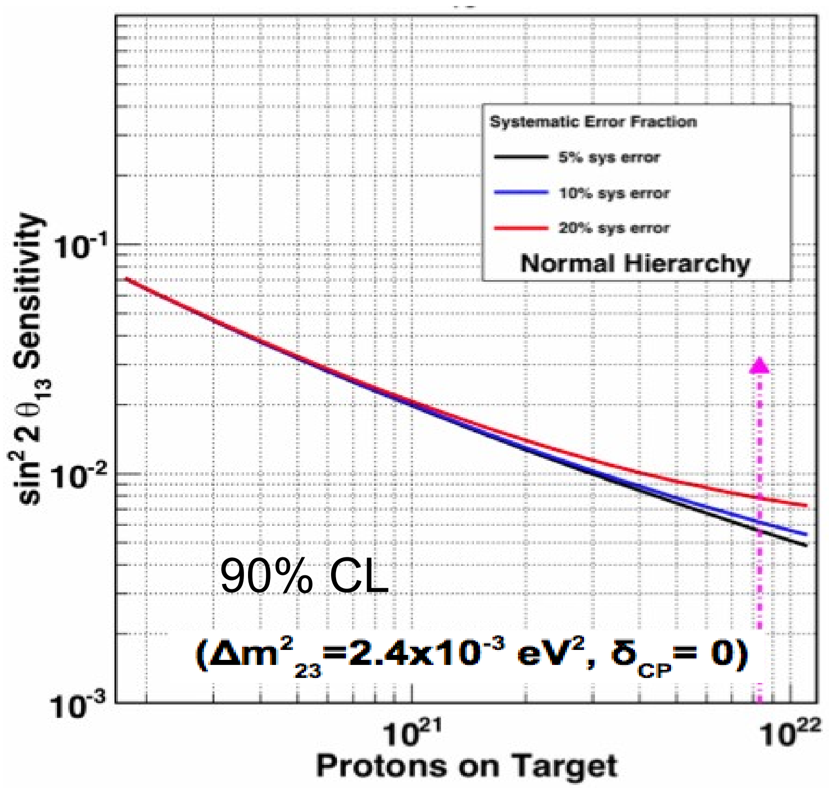
Looking for:

Energy-dependent excess of electron-like events

T2K ultimate *(5 yrs x 750 kW)* sensitivity

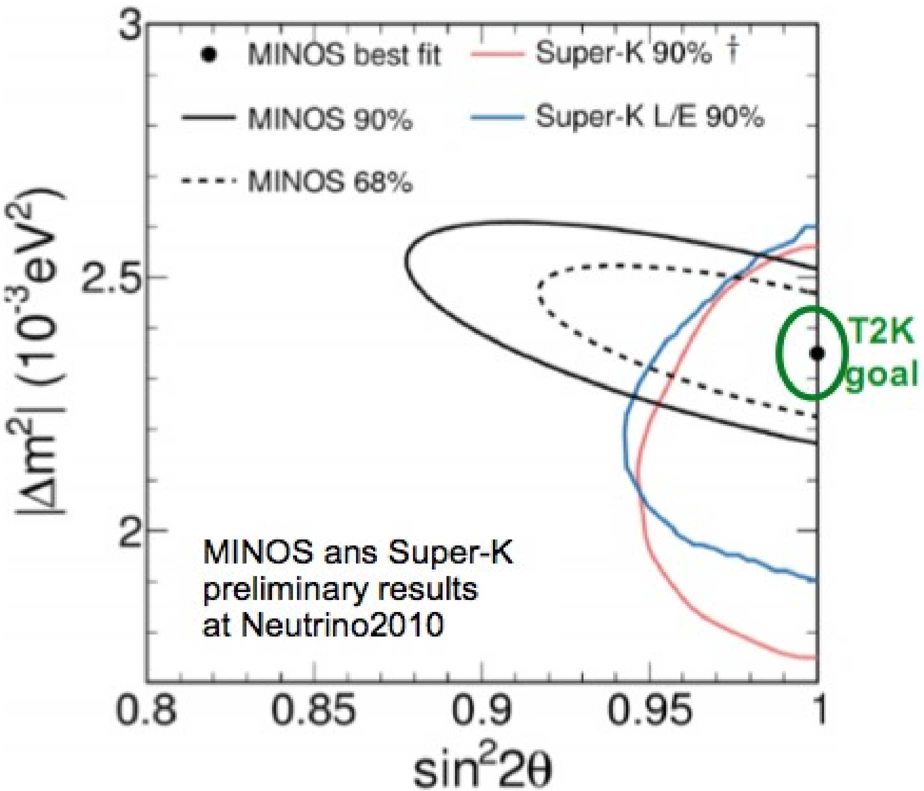
ν_e appearance:

$\sin^2 2\theta_{13} < 0.008$ (90% CL)



ν_μ disappearance:

$\delta(\sin^2 2\theta_{23})$ ~ 1E-2 (90% CL)
$\delta(\Delta m^2_{23})$ ~ 1E-4 eV^2/c^4 (90% CL)



Data-taking operations & beam stability

T2K data-taking operations

Run-1

- January 2010: *Start of Run-1*
  - February 24, 2010: *First event seen in SuperK*
- June 26, 2010: *End of Run-1*

3.23E+19 POT
on tape!

Run-2

- November 16, 2010: *Start of Run-2*
  - December 25, 2010: *Start of end-of-year shutdown*
  - January 20, 2011: *End of end-of-year shutdown*
  - March 11, 2011: ***Earthquake***

data-taking stopped

- July 1, 2011: *Scheduled end of Run-2*

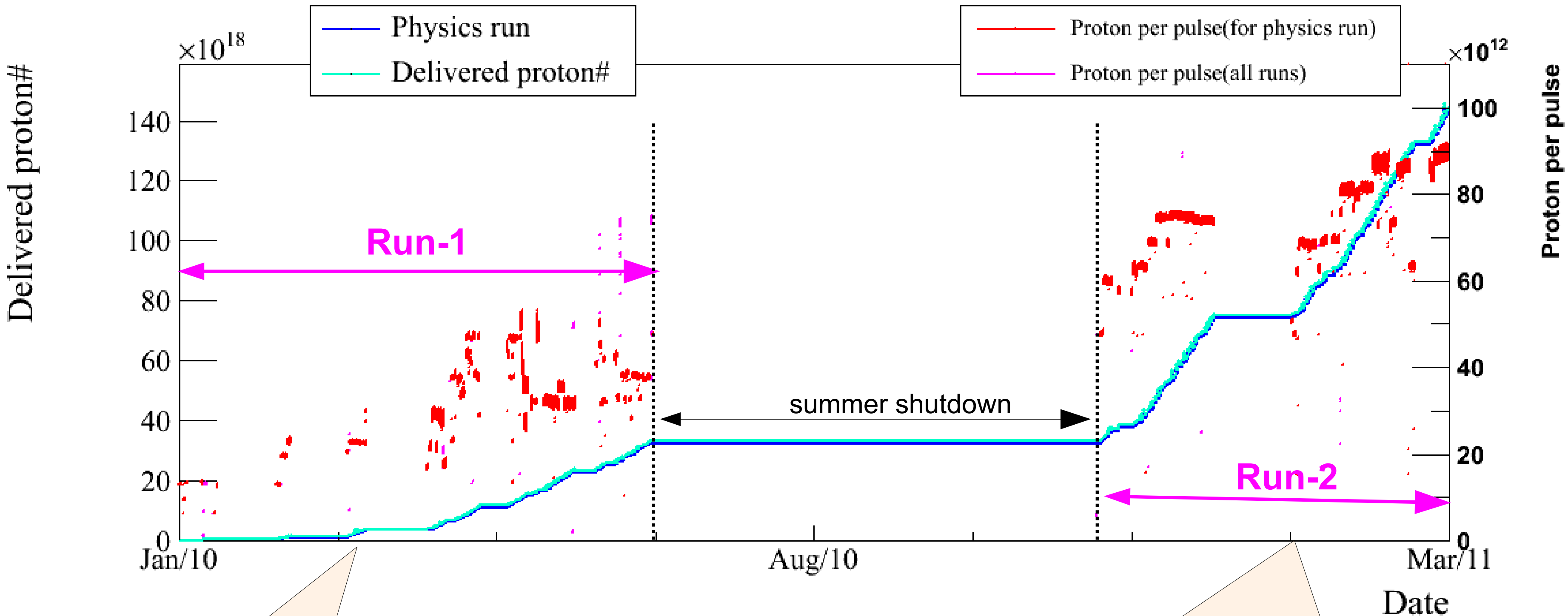
Additional
1.136E+20 POT
on tape!

Total on tape:
1.459E+20 POT

Estimated total
at end of Run-2
was ~3E+20 POT

Expect to restart data-taking operations
late in 2011 / early in 2012

Number of protons delivered by MR



Run-1 *(Jan-Jun 2010)***:**
- **6** bunches / spill **(~3E+13 PPP)**
- **3.52 sec** cycle
- **50 kW** stable operation
  - *100 kW trials*
- Integrated exposure (physics): **3.23E+19 POT**

Run-2 (Nov 16, 2010 – Mar 11, 2011)**:**
- **8** bunches / spill **(~9E+13 PPP)**
- **3.04 sec** cycle
- **135-145 kW** stable operation
- Integrated (Run1+2) exposure (physics): **1.459E+20 POT**

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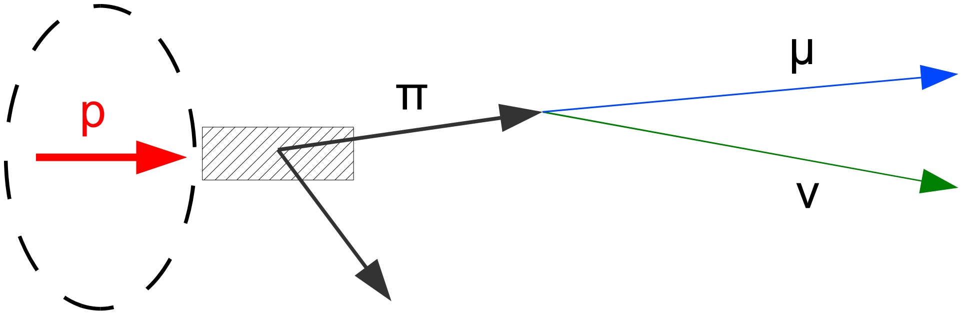
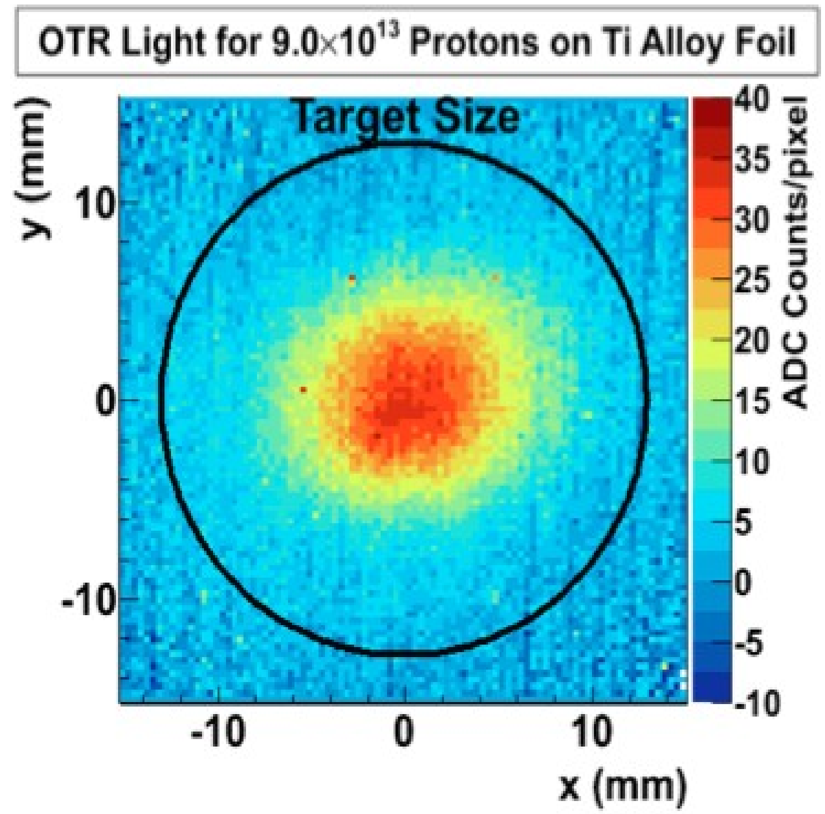
Primary proton beam monitoring





Beam intensity / loss monitoring:

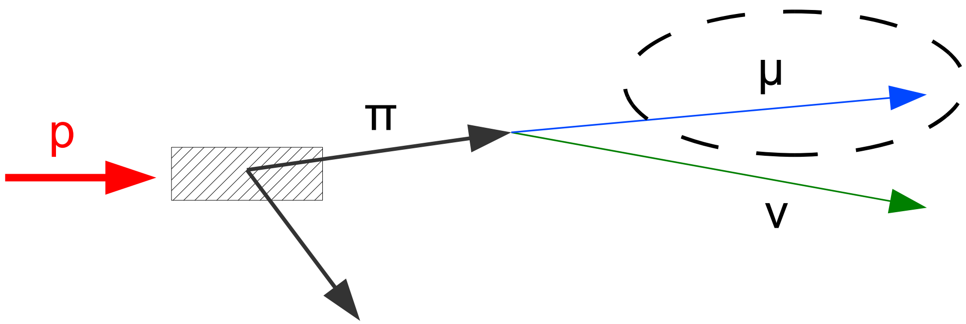
- *5 Current Transformers (CT)*
- *50 Beam Loss Monitors (BLM)*

Beam position & profile monitoring:

- *21 Electro-static monitor (ESM)*
- *19 Segmented Secondary Emission monitor (SSEM)*
- *1 Optical Transition Radiation detector (OTR)*

Run1+2: Stable primary proton beam

Secondary muon beam monitoring

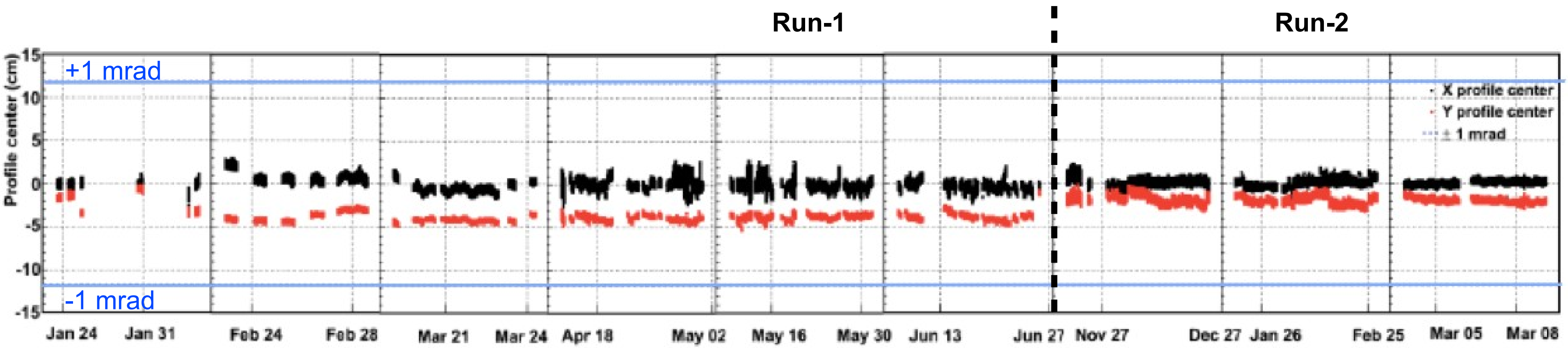


Secondary muon beam monitoring (MUMON) spill-by-spill.

Detector intrinsic resolution < 1.5 mm

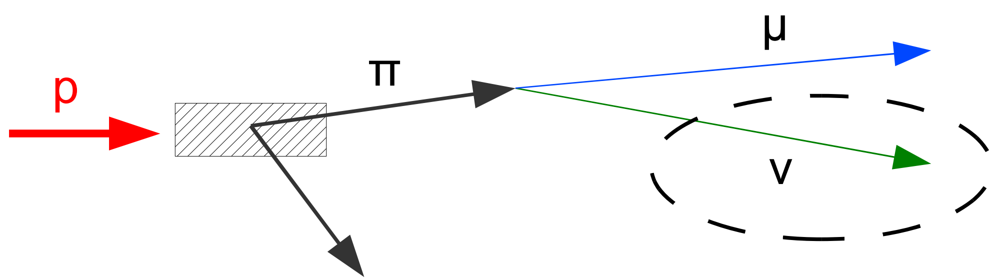
Beam direction is controlled within 1 mrad

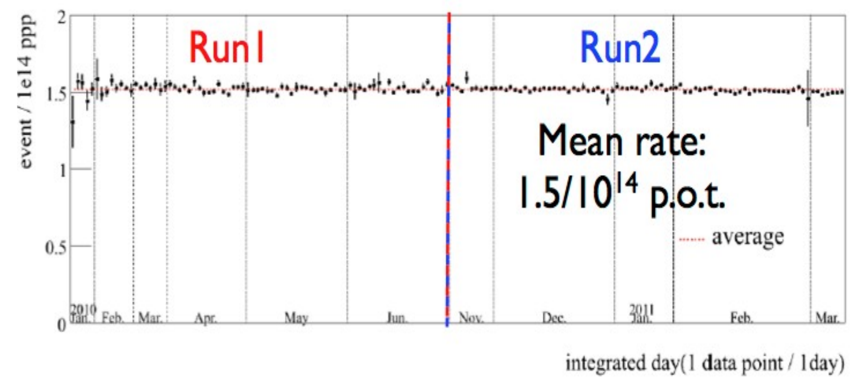
Secondary beam intensity stable to ~1%

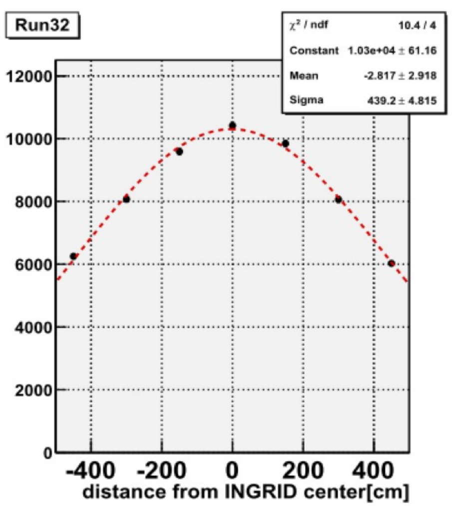


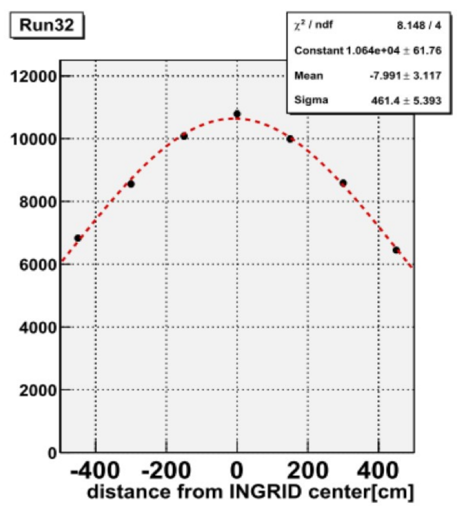
Run1+2: Stable targeting & focusing systems

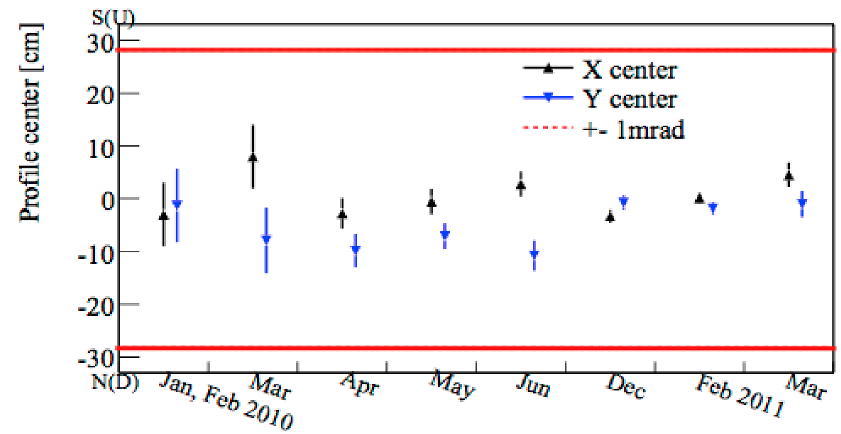
Neutrino beam monitoring





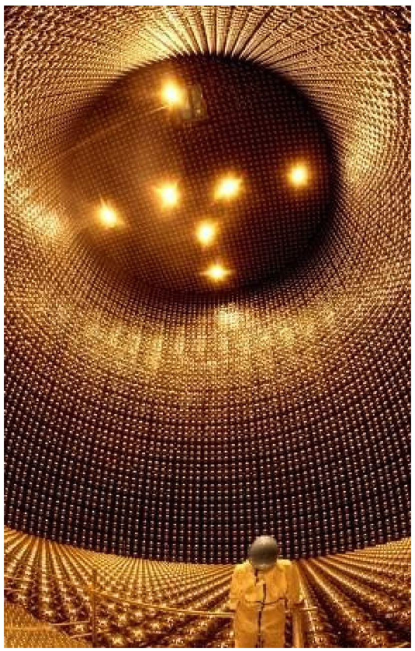


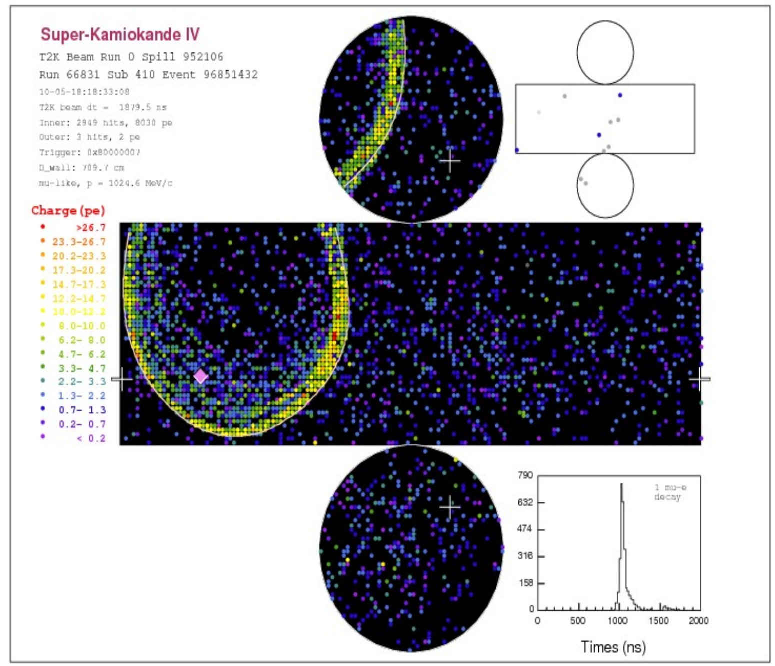




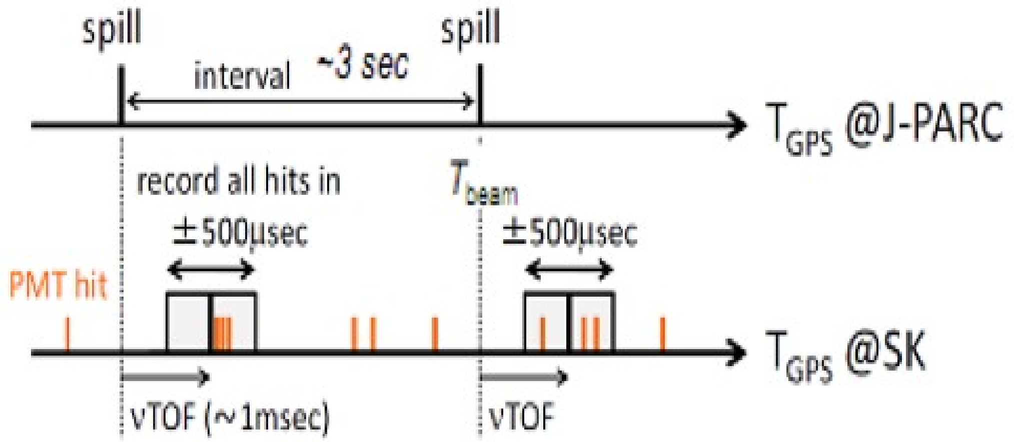
Run1+2: Stable neutrino intensity & direction verified by INGRID

T2K-SuperK event reduction





SuperK – Beam spill time synchronization



Record all hits in +/- 500 μs window around the beam spill arrival to SuperK.

GPS synchronization
for J-PARC and SuperK times

SuperK live-time

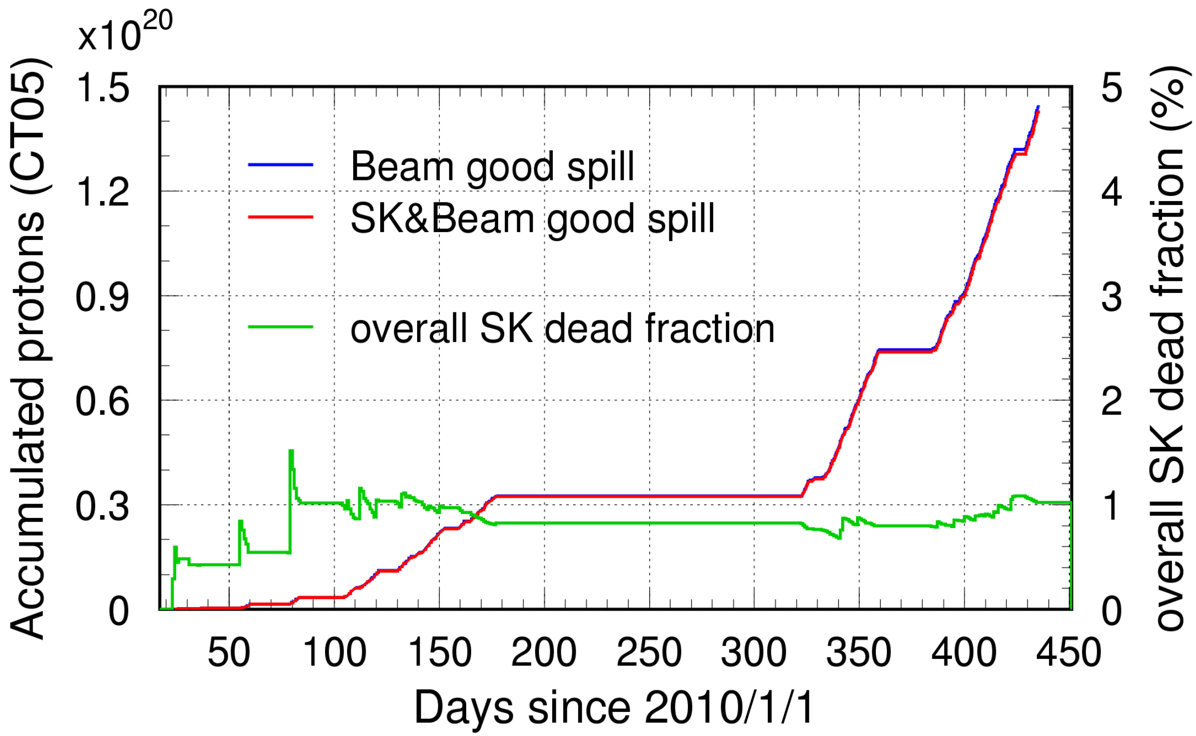
<u>SuperK good spill selection</u>

- SK DAQ alive
- DAQ error check

Checking dark counts in ID and OD

- GPS error check
- Detector status check
- Pre-activity cut

No activity in the 100 μs before beam arri
Removes accidental contamination



Integrated exposure:

- "Beam" good spills → 1.446E+20 POT
- "SK & Beam" good spills → 1.431E+20 POT

SuperK live fraction (for physics) > 99%

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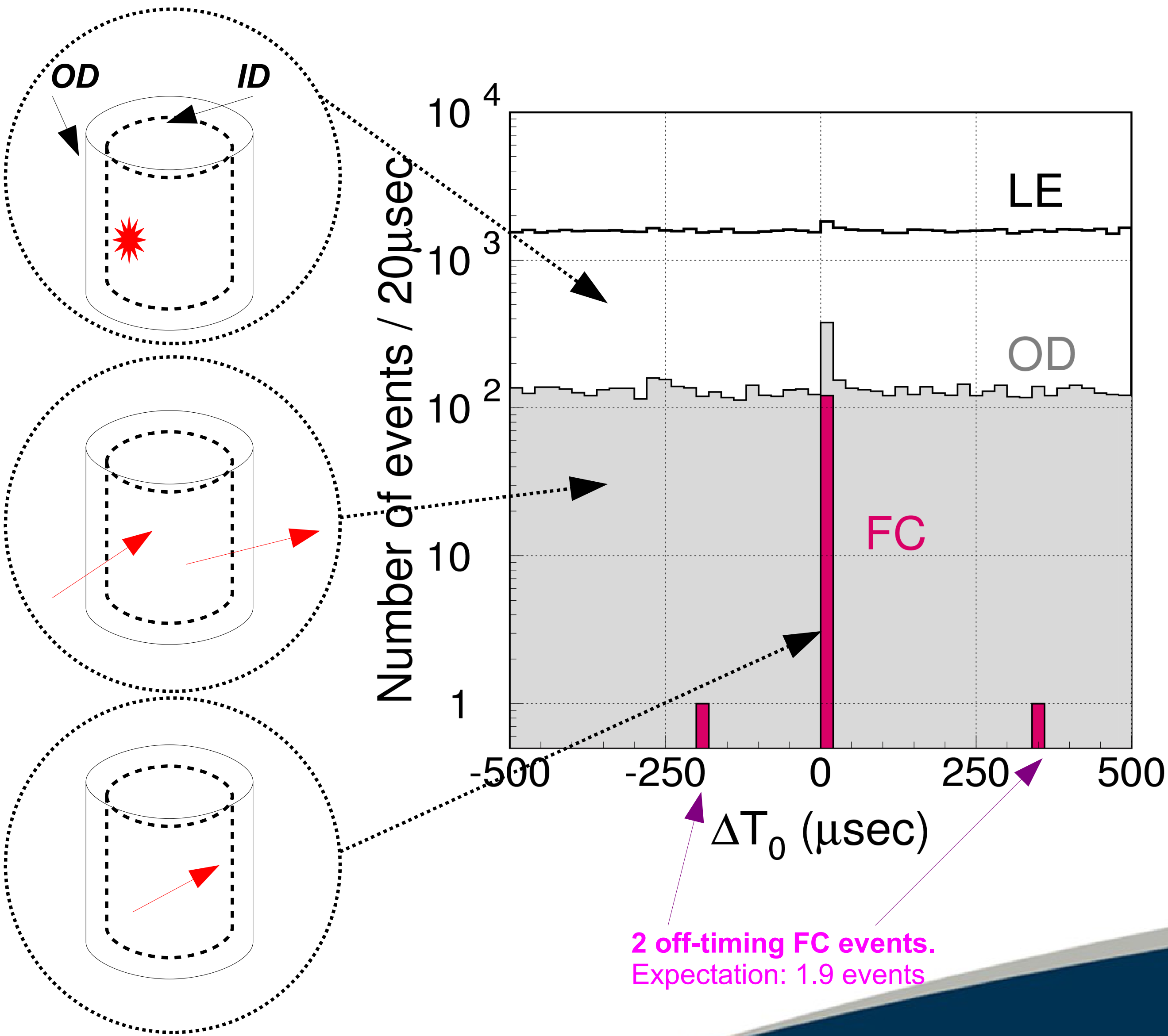
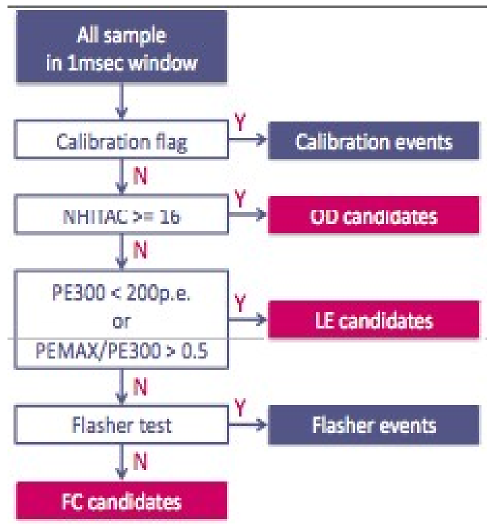
SuperK FC (fully contained) event reduction



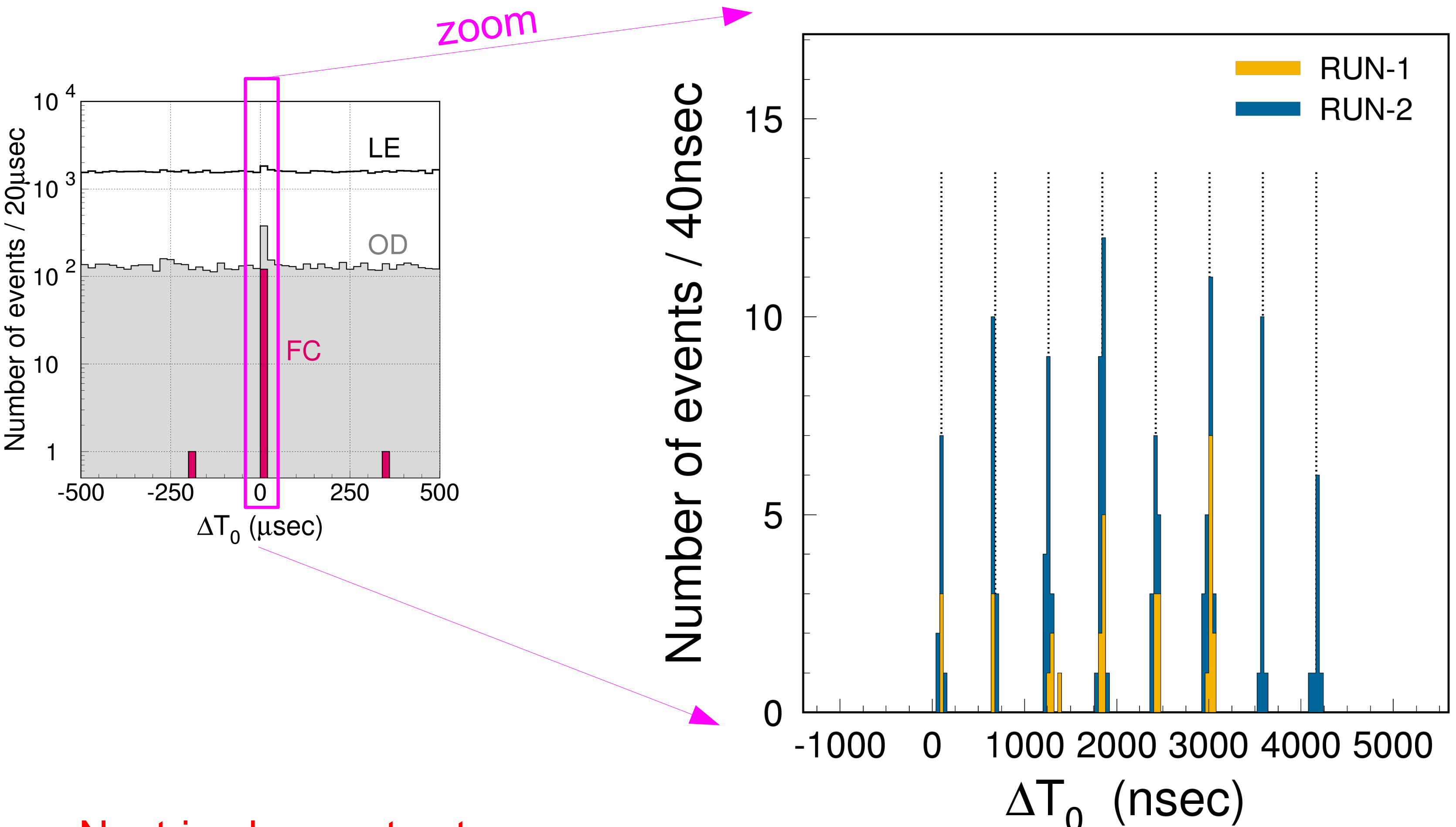


Run-1+2

121 FC neutrino event candidates found

Expected accidental bkg (from dummy spill data): 0.023 events

SuperK FC neutrino event candidate timing

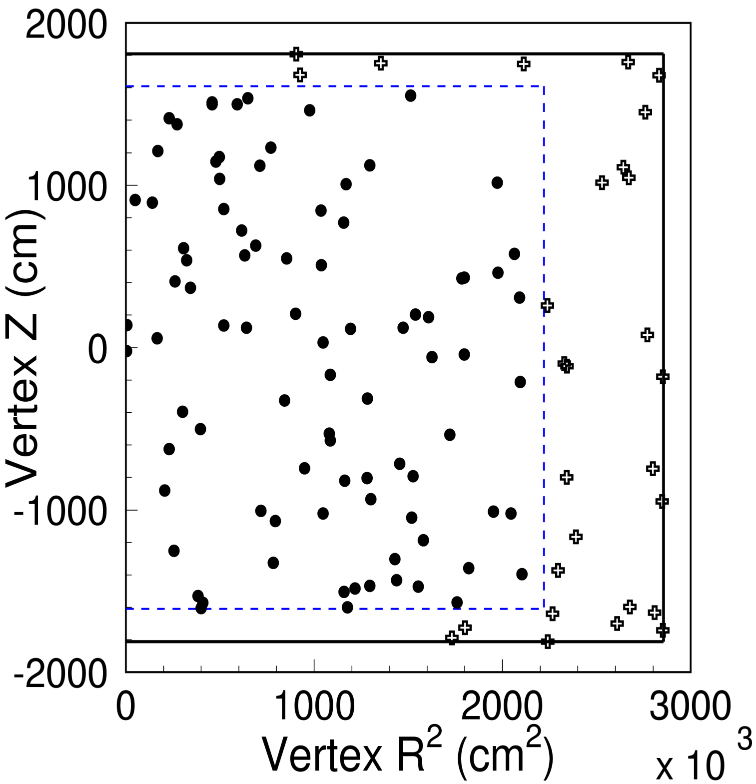


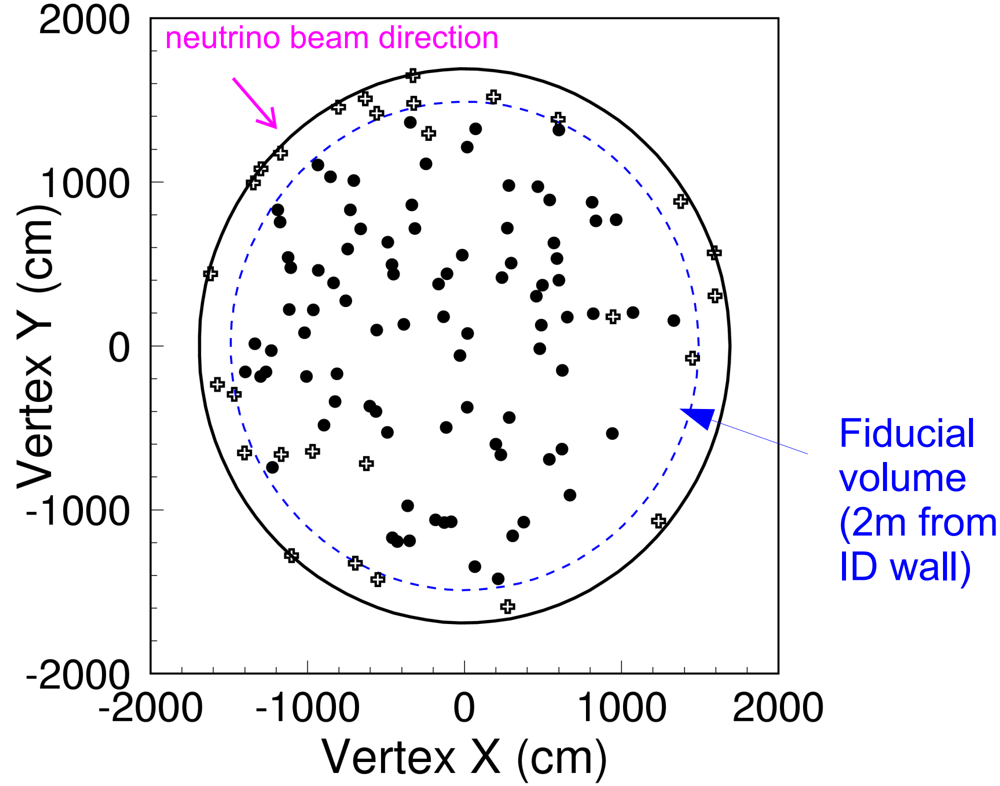
Neutrino beam structure seen with SuperK event candidates!

SuperK FCFV event reduction

FC event candidates
* In fiducial volume (more than 2m away from the ID wall)
* Visible energy > 30 MeV

FC (Fully Contained) FV (Fiducial Volume) event candidates (events used for physics analysis)

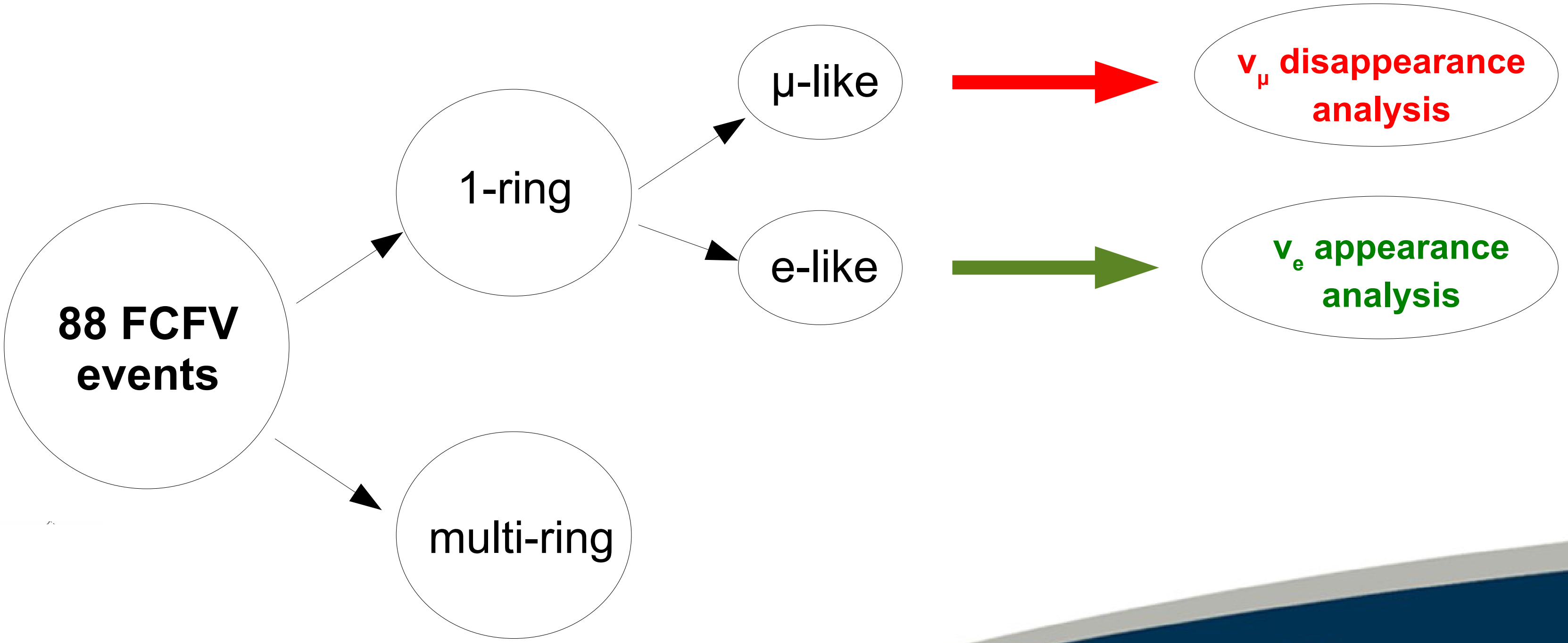




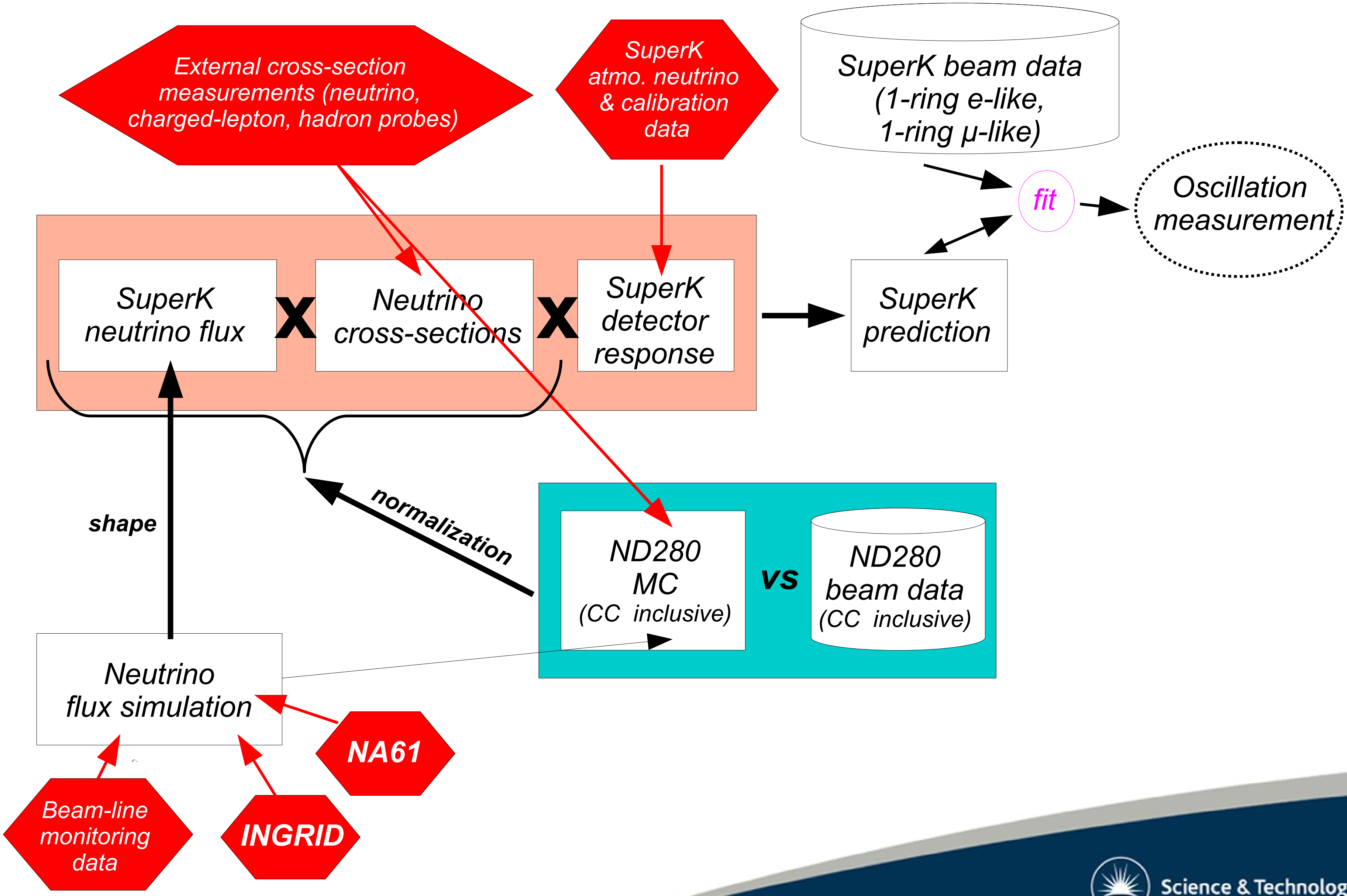
Run-1+2:
88 FCFV neutrino event candidates found

Estimated (from atmospheric neutrino rate) accidental background: 0.0028 events

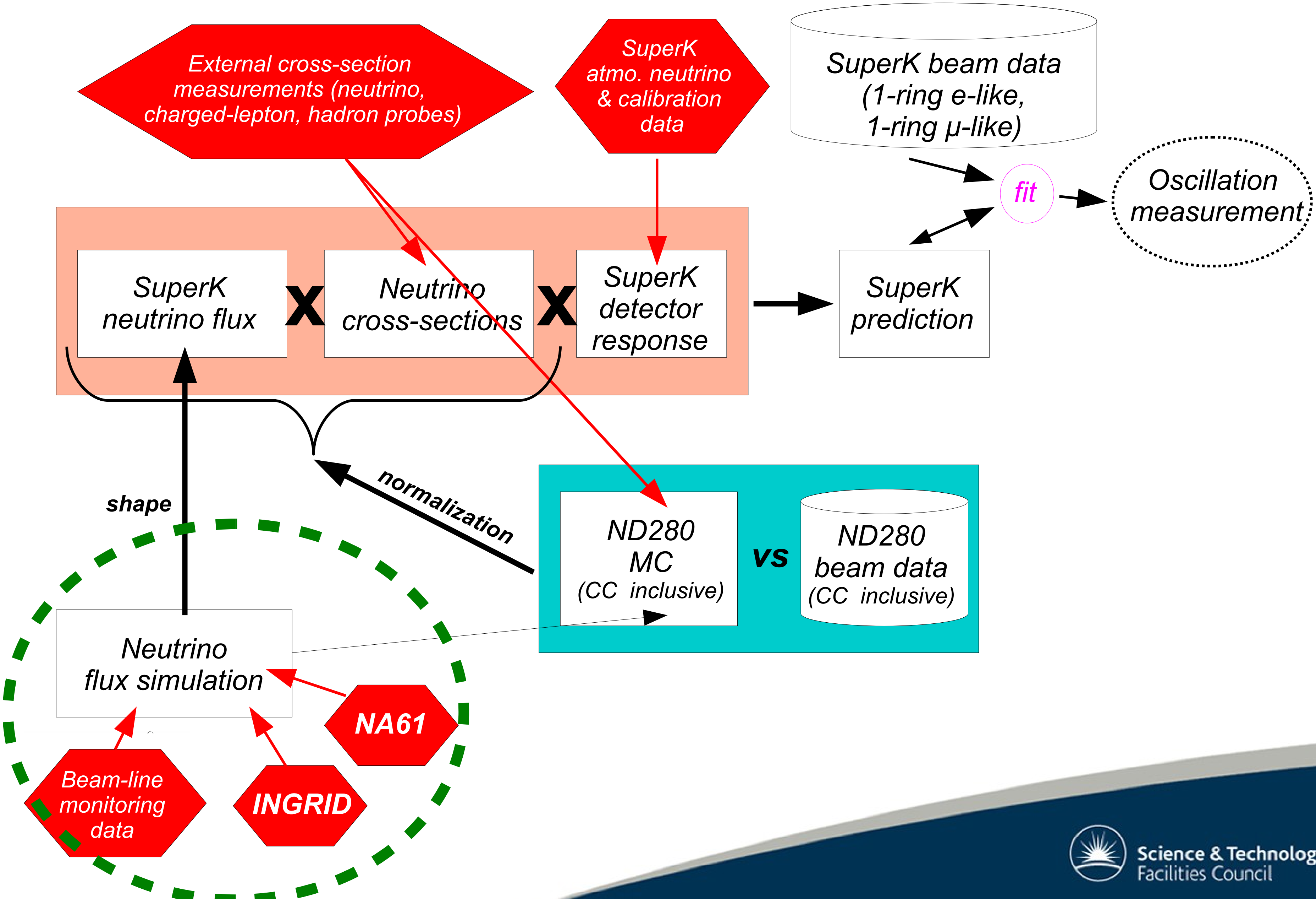
2010 oscillation analysis with Run-1+2 (1.431E+20 POT) data



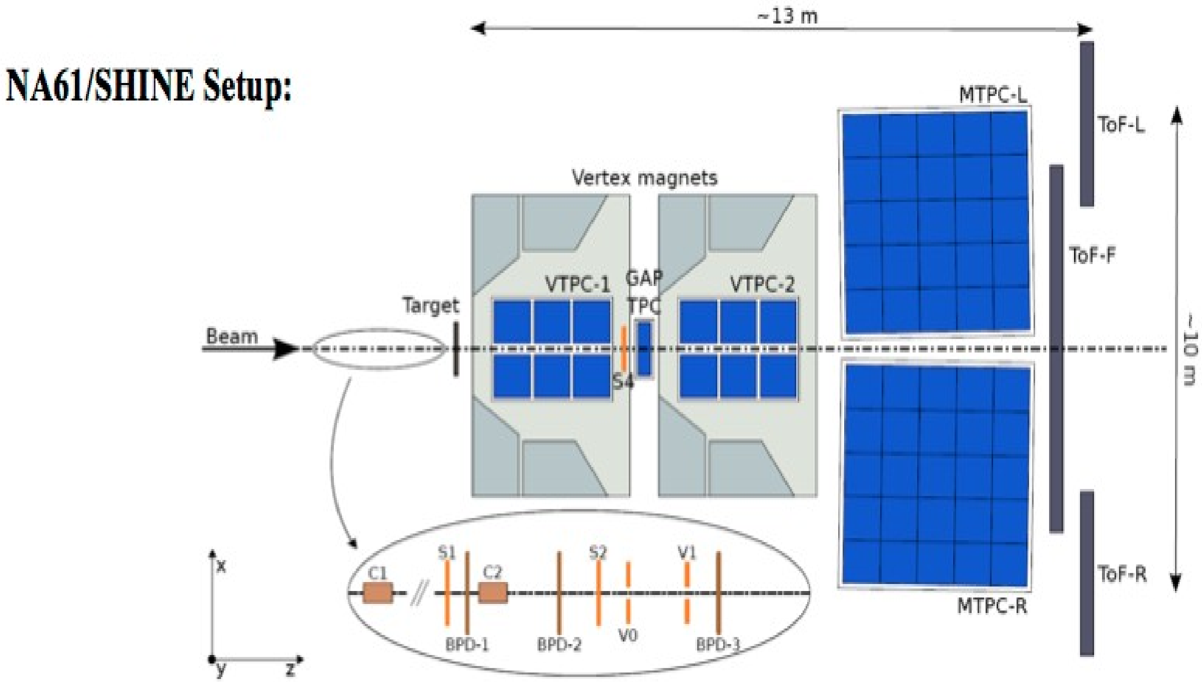
Oscillation Analysis Strategy (2010)



Oscillation Analysis Strategy (2010)



NA61 / SHINE experiment



30 GeV p+C particle yields in
- thin target
- T2K replica target

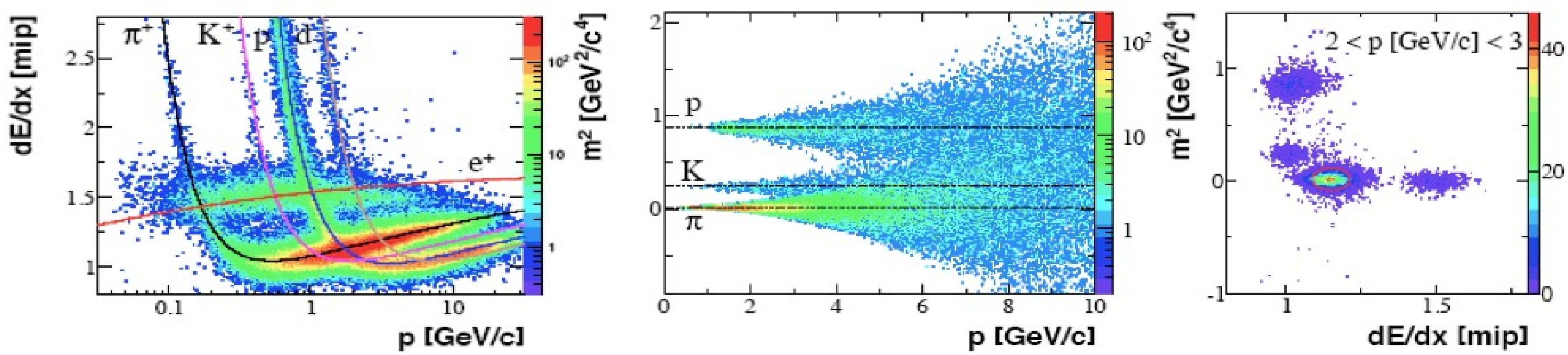
NA61:

- Large acceptance spectrometer

- 5 TPCs
- 2 dipole magnets
- 3 ToFs

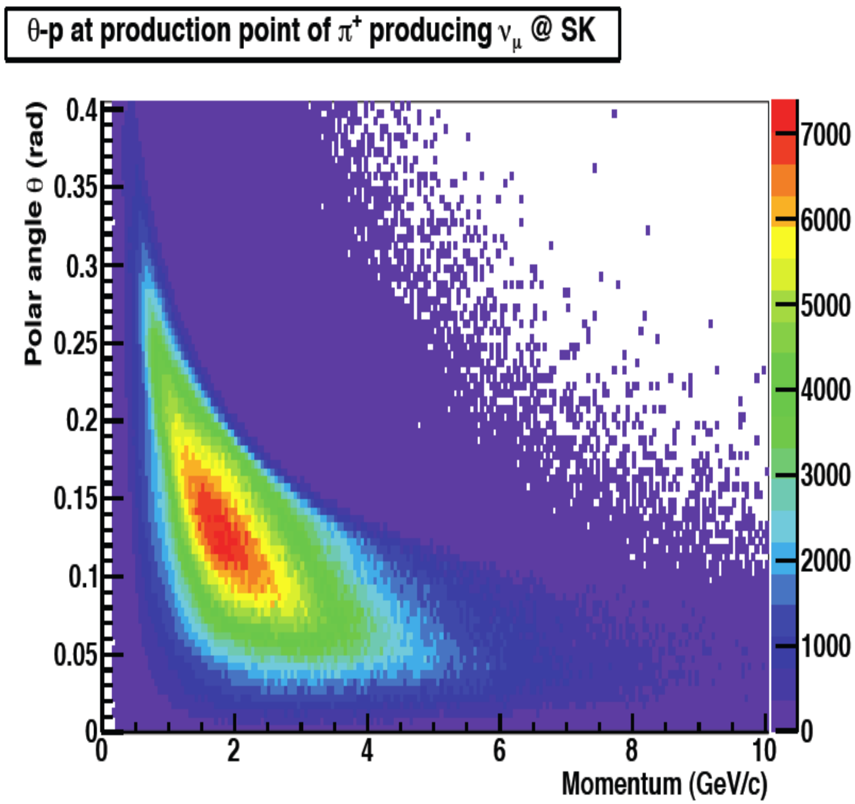
- Good PID and momentum resolution

PID methods

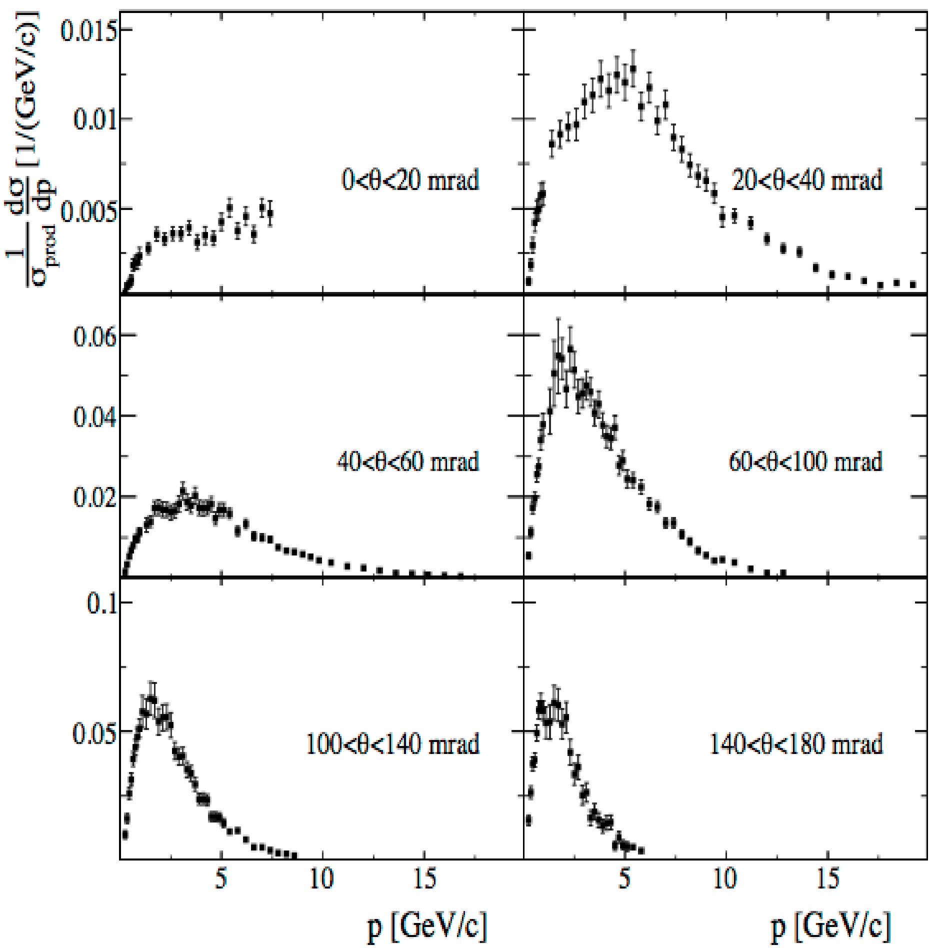


NA61 / SHINE measurements

Full coverage of T2K phase space



N.Abgral et al.,arXiv:1102.0983, submitted to Phys.Rev.C
(~5-10% systematic error and similar statistical error)



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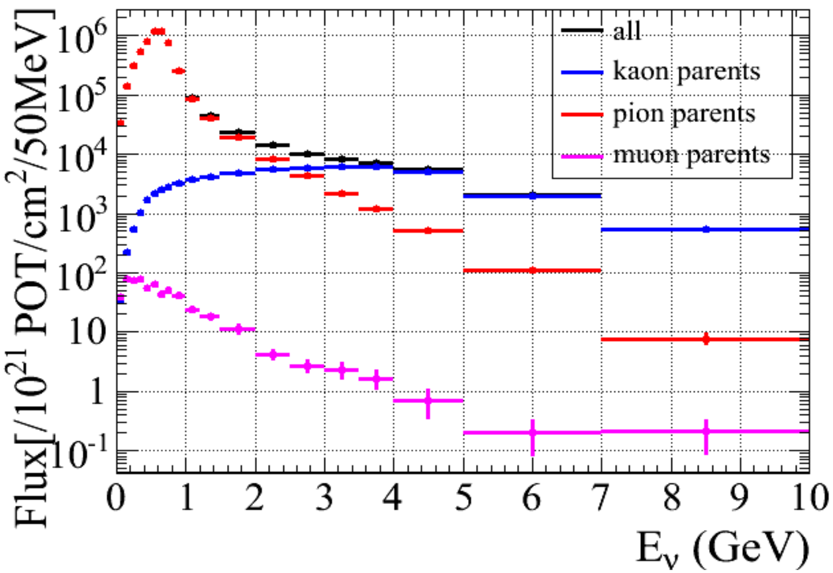
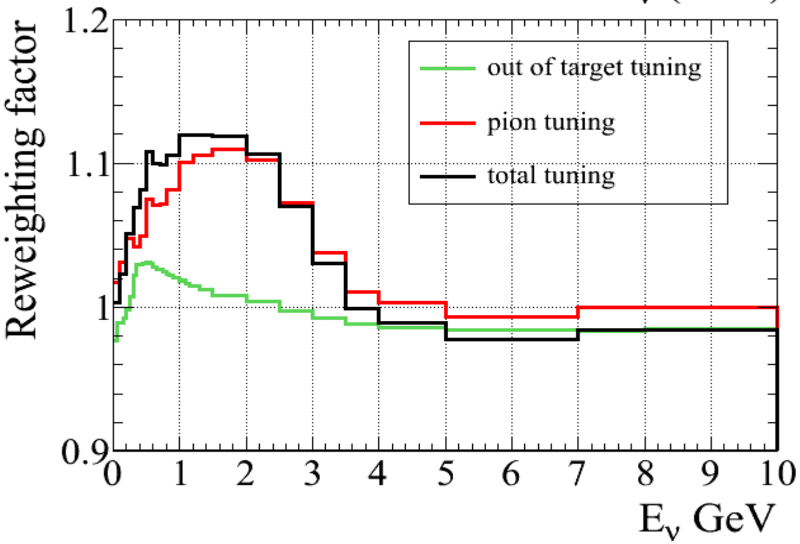
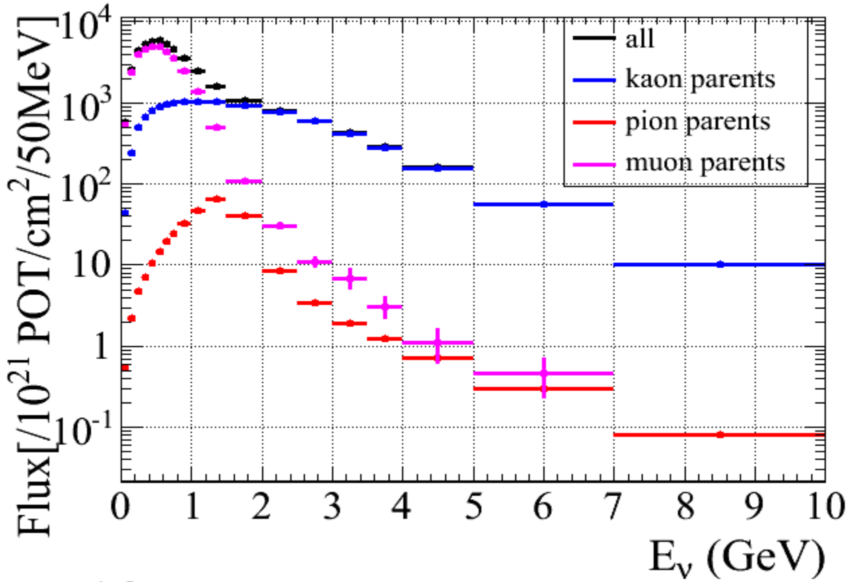
Neutrino flux tuning

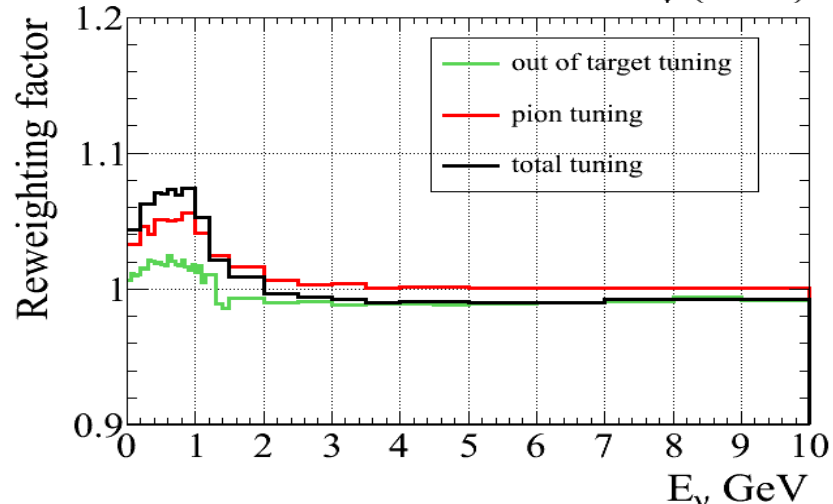
ν_μ at SuperK



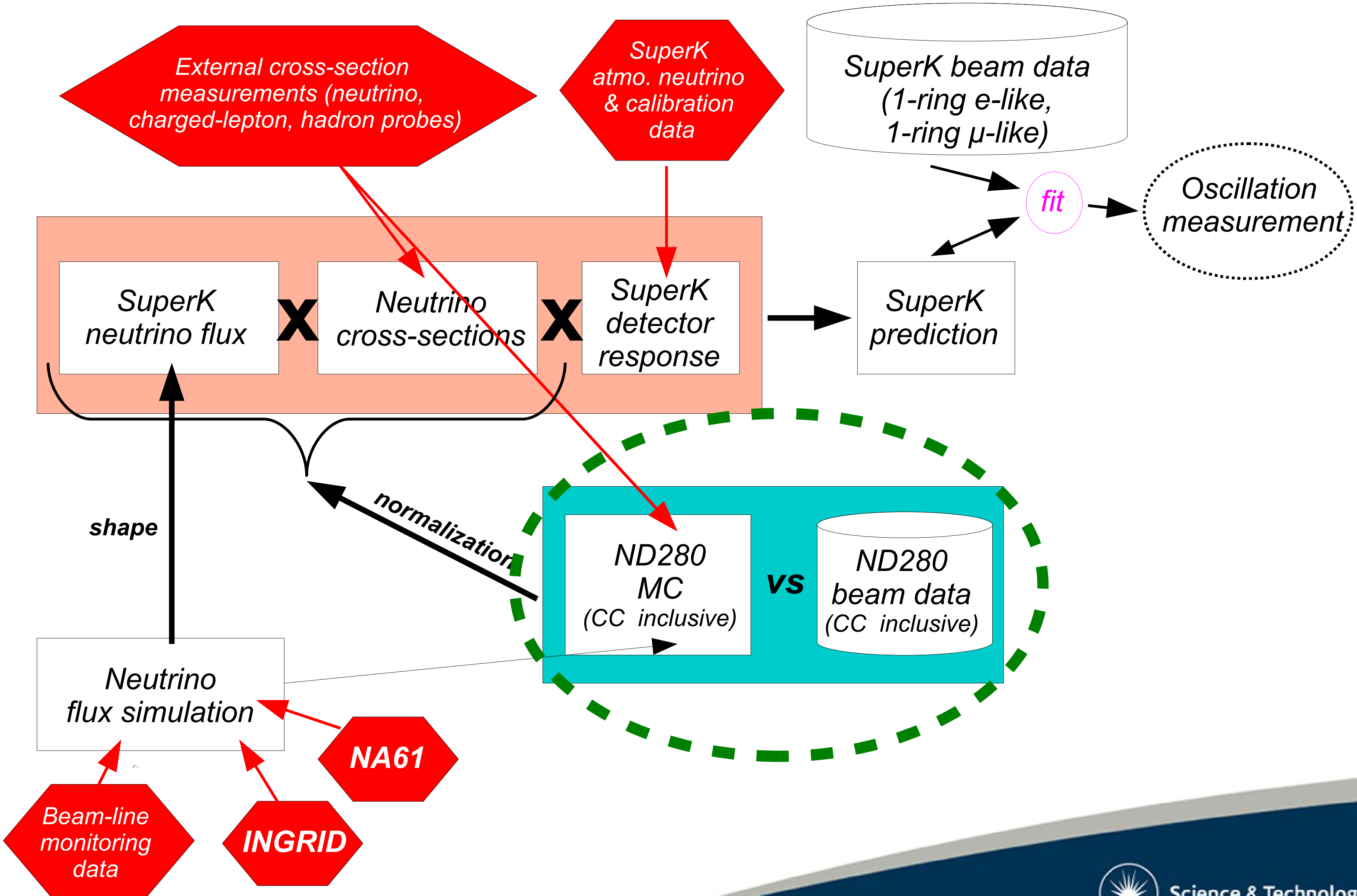


ν_e at SuperK



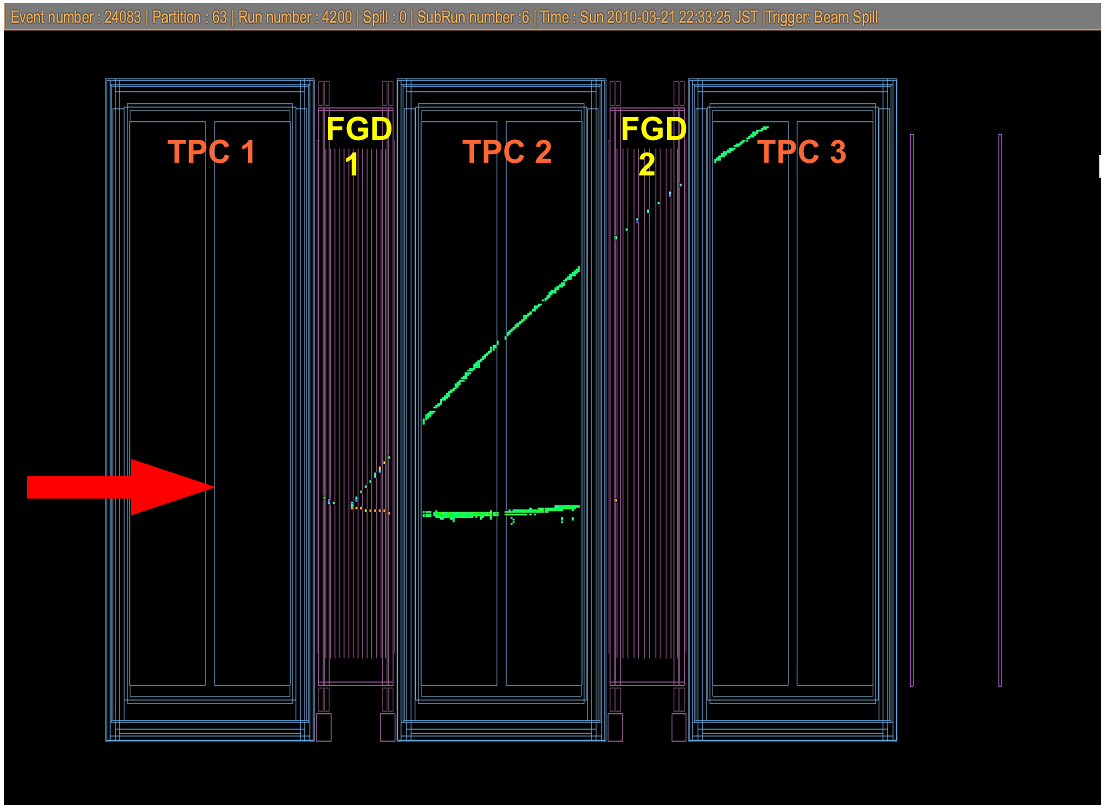


Oscillation Analysis Strategy (2010)



ND280: Inclusive muon neutrino CC analysis

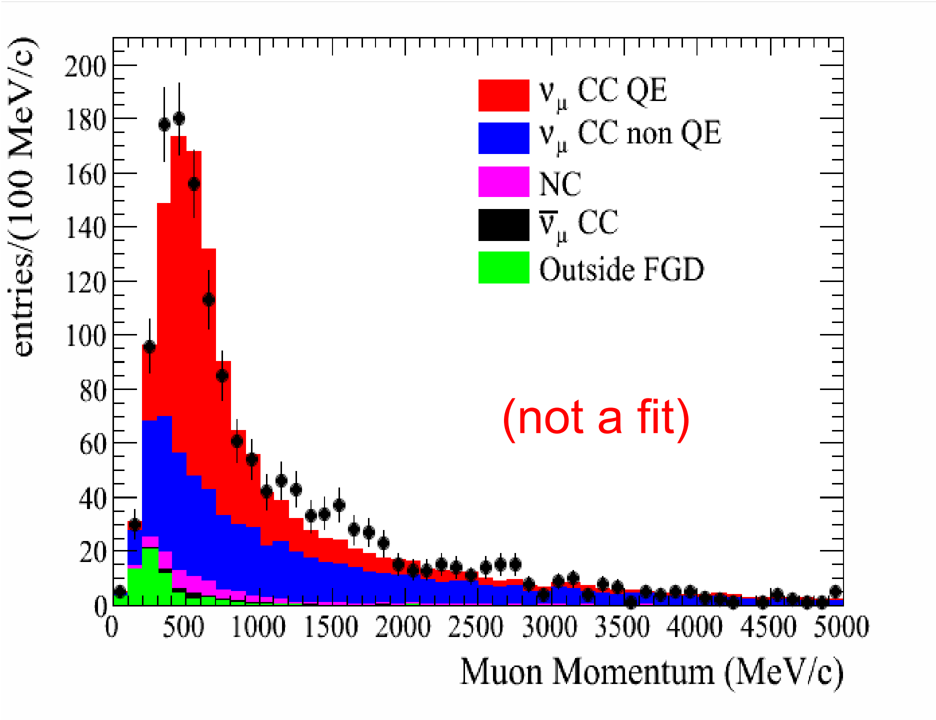
Robust analysis using low-level reconstructed objects (FGD hits and tracks in single TPC)

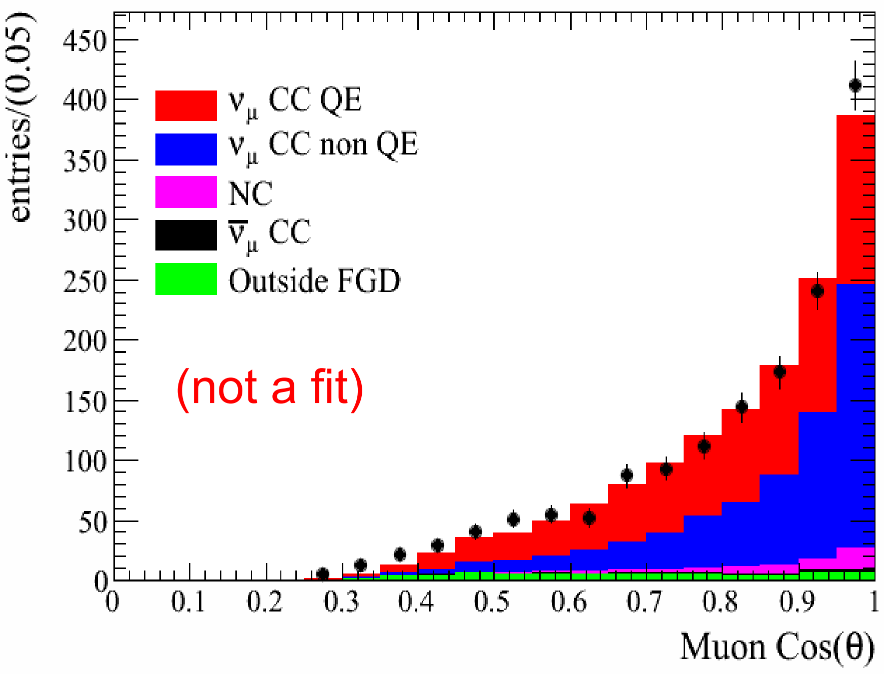


- No tracks in TPC-1
- >= 1 track in TPC-2 with vertex in FGD-1
- No tracks in TPC-2? Repeat with TPC-3 and FGD-2
- Select track with highest momentum
- TPC dE/dx cuts to select muon candidates

High purity: ~90% ν_μ CC (~50% CCQE)

ND280: Inclusive muon-neutrino CC





$$\frac{N_{ND}^{\nu\mu,DATA}}{N_{ND}^{\nu\mu,MC}} = 1.036 \pm 0.028\ (\text{stat.})\ ^{+0.044}_{-0.037} (\text{det. syst.}) \pm 0.038\ (\text{phys. syst.})$$

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Electron-neutrino appearance results

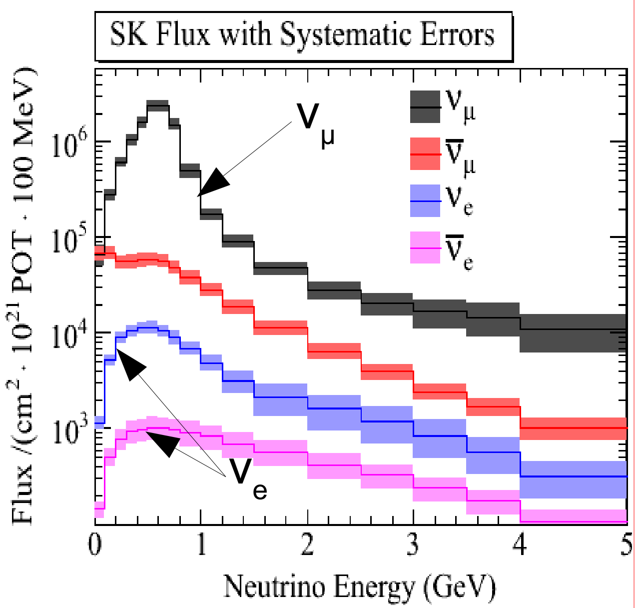
SuperK ν_e event selection: Strategy

Selecting ν_e CCQE events. *A water-Cherenkov detector sees a single e-like (fuzzy) ring*

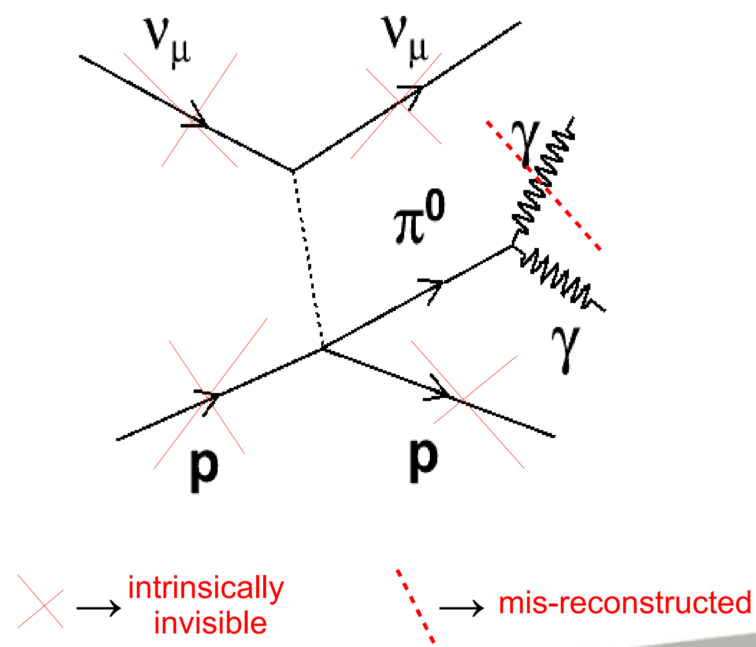
Main backgrounds

Intrinsic ν_e component in beam

$$K_L^0 \to \nu_e + \pi^- + e^+$$
$$K_L^0 \to \bar{\nu_e} + \pi^+ + e^-$$
$$K_L^0 \to \nu_\mu + \pi^- + \mu^+$$
$$K_L^0 \to \bar{\nu_\mu} + \pi^+ + \mu^-$$
$$K^+ \to \nu_\mu + \mu^+$$
$$K^+ \to \nu_e + \pi^0 + e^+$$
$$K^+ \to \nu_\mu + \pi^0 + \mu^+$$
$$K^- \to \bar{\nu_\mu} + \mu^-$$
$$K^- \to \bar{\nu_e} + \pi^0 + e^-$$
$$K^- \to \bar{\nu_\mu} + \pi^0 + \mu^-$$
$$\mu^+ \to \bar{\nu_\mu} + \nu_e + e^+$$
$$\mu^- \to \bar{\nu_e} + \nu_\mu + e^-$$
$$\pi^+ \to \nu_\mu + \mu^+$$
$$\pi^- \to \bar{\nu_\mu} + \mu^-$$



ν_μ NC π^0 with a missed γ



SuperK ν_e event selection: Cut overview

88 FCFV events

Cuts to isolate 1-ring e-like event sample & suppress $\nu_\mu \rightarrow \nu_e$ backgrounds

- Event has 1-ring
- Ring has e-like PID
- Visible energy > 100 MeV
- Decay electron cut
- Invariant mass cut
- Reconstructed energy cut

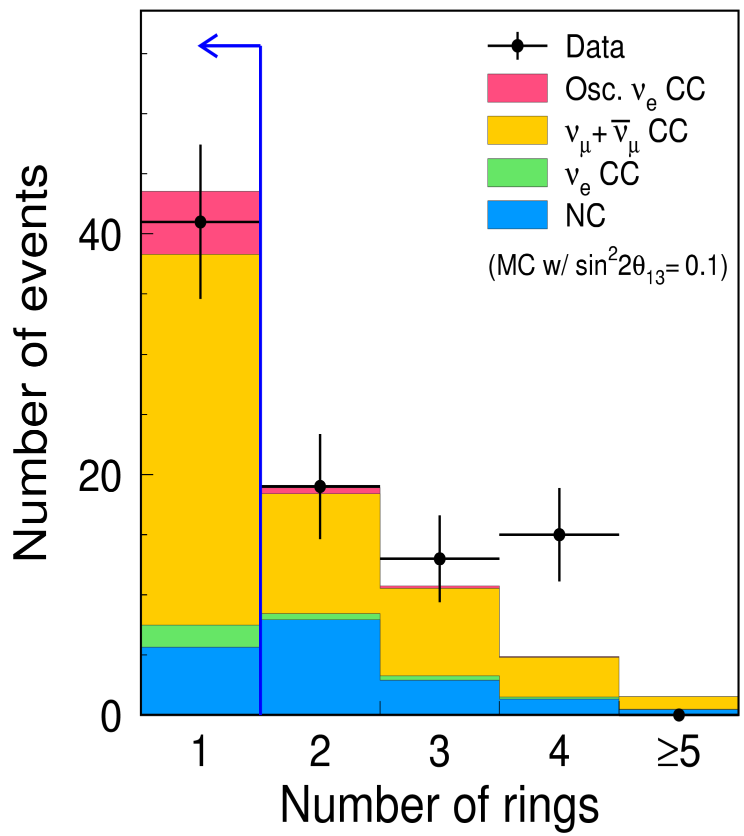
? ν_e event candidates

All cuts were defined <u>before</u> the data-taking operations

SuperK ν_e event selection

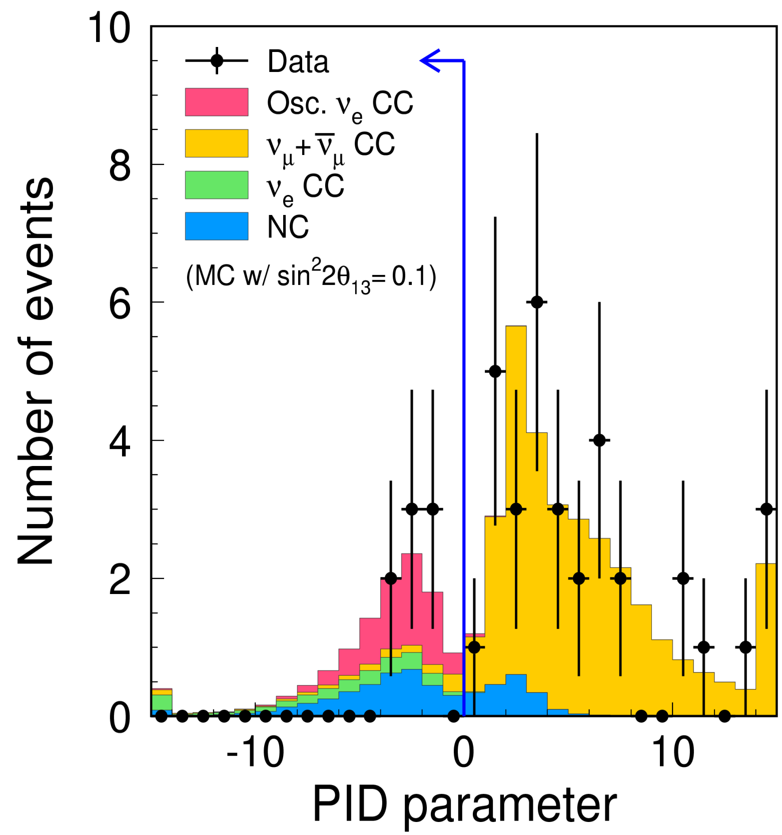
(1) Event has 1-ring

(41 events left after cut)



(2) Ring has e-like PID

(8 events left after cut)



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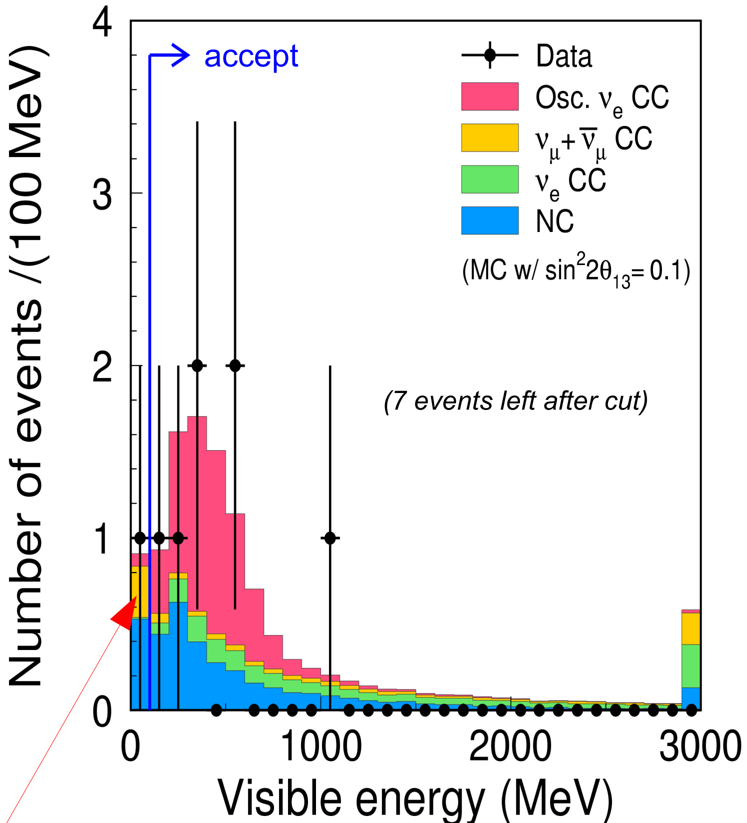
SuperK ν_e event selection

(3) Event has visible energy > 100 MeV

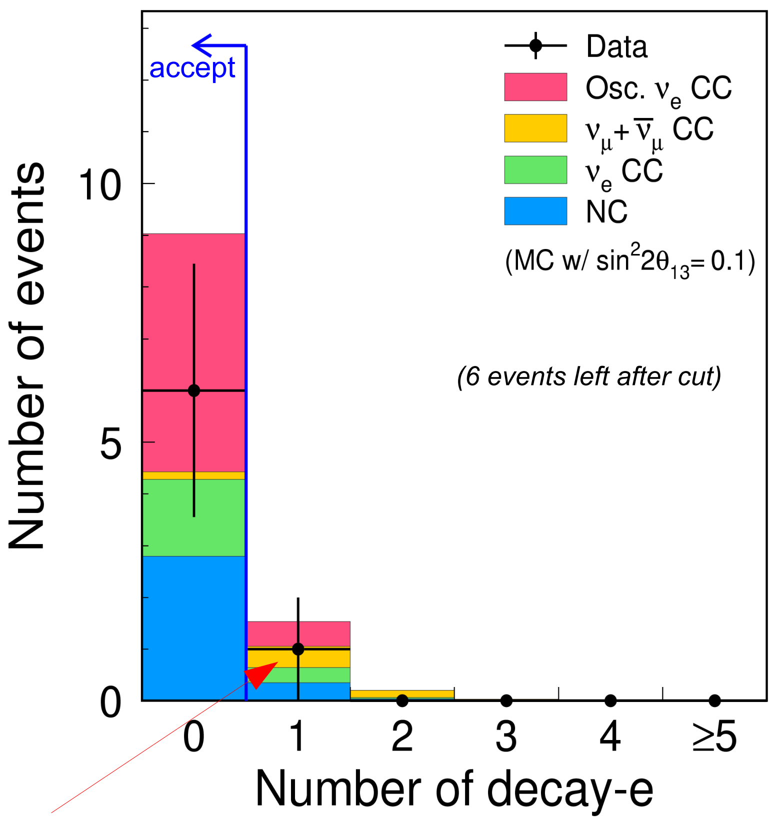
- Cut removes 14% of NC, 30% of ν_μ CC bkg
- 98% signal efficiency



1 candidate rejected

(4) No delayed decay-electron signal

- Rejects events with invisible or mid-ID'ed μ or π
- Cut removes 85% of ν_μ CC bkg
- 90% signal efficiency

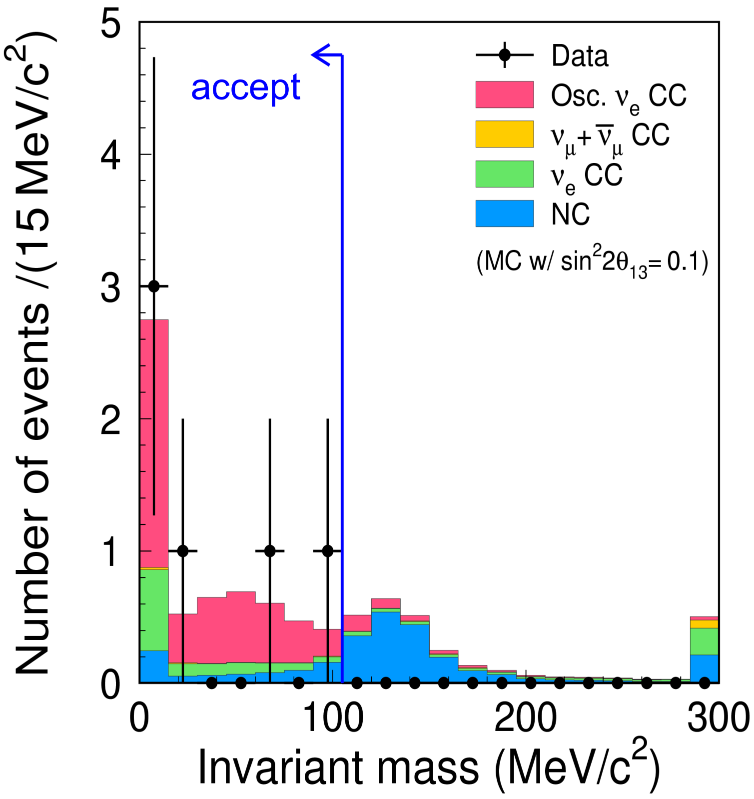


1 candidate rejected

SuperK ν_e event selection

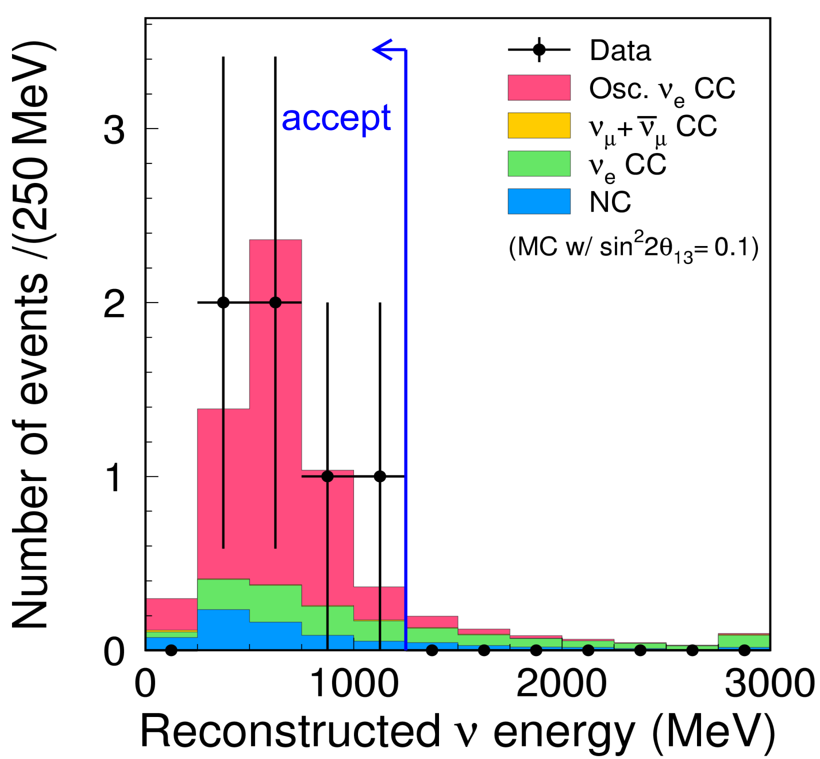
(5) Invariant mass cut (< 105 MeV/c²)
[2-ring assumption, forced 2nd ring]

- Suppresses NC π^0 background.
- Cut removes 71% of NC background
- 91% signal efficiency



(6) Reconstructed energy cut (< 1250 MeV)

- Reduces intrinsic beam contamination from K decays (signal: $\nu_\mu \rightarrow \nu_e$ and ν_μ flux peaks at 600 MeV)
- Cut removes 36% of intrinsic beam ν_e
- 98% signal efficiency



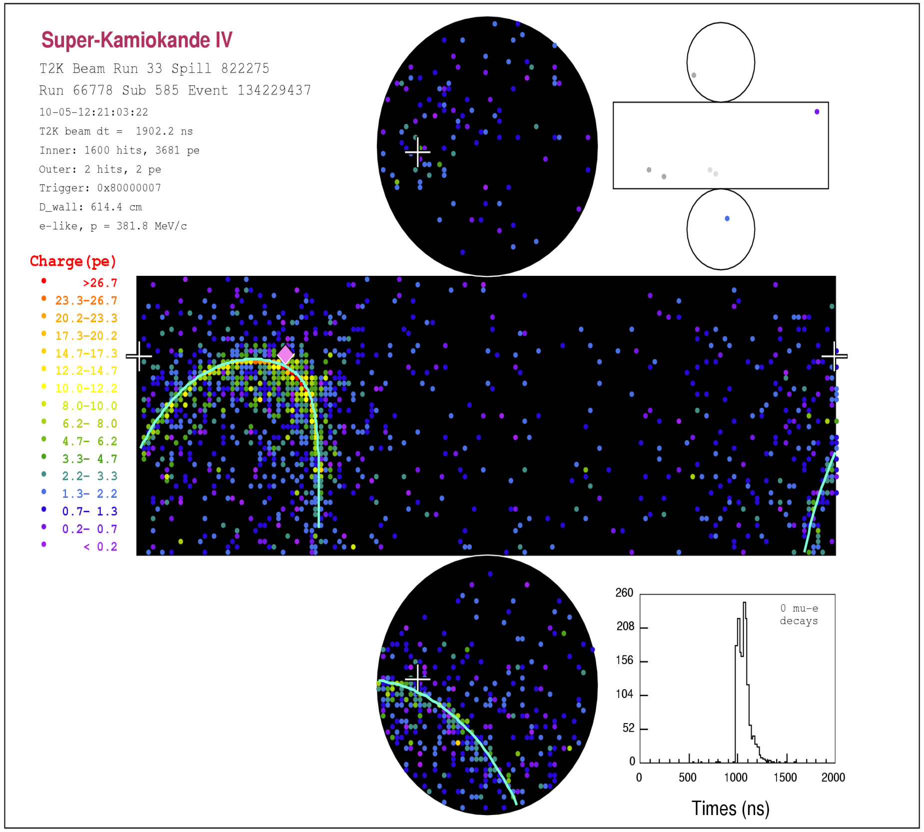
SuperK ν_e event selection

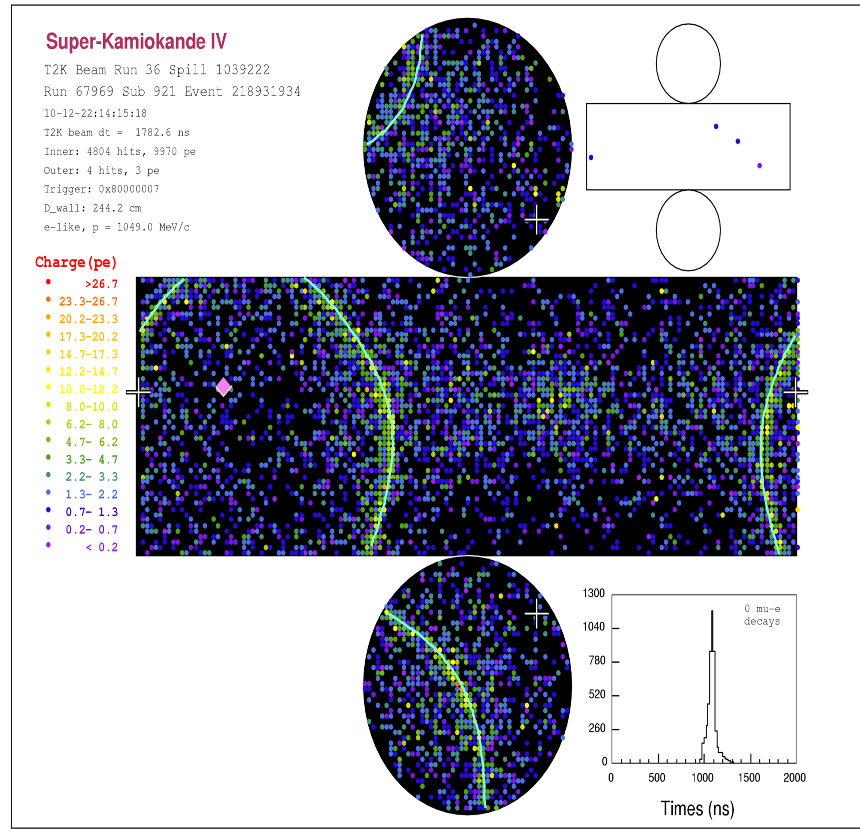
6 ν_e event candidates were found after all cuts!

Signal efficiency: ~66%
Background rejection:

- ~77% for intrinsic beam ν_e
- ~99% for ν_μ NC

MC predicts 1.5 background events





Background-only hypothesis: Systematic study

Error source		N_{ND}	N_{SK}	N_{SK}/N_{ND}
			$\sin^2 2\theta_{13}$=0	
SK Norm.	f^{SKnorm}	$\pm$ 0.0	$\pm$ 1.4	$\pm$ 1.4
SK Energy Scale	f^{Energy}	$\pm$ 0.0	$\pm$ 1.1	$\pm$ 1.1
SK Ring Counting	$f^{N_{ring}}$	$\pm$ 0.0	$\pm$ 8.1	$\pm$ 8.1
SK PID Muon	$f^{PID\mu}$	$\pm$ 0.0	$\pm$ 0.9	$\pm$ 0.9
SK PID Electron	f^{PIDe}	$\pm$ 0.0	$\pm$ 7.8	$\pm$ 7.8
SK POLfit Mass	f^{POLfit}	$\pm$ 0.0	$\pm$ 8.5	$\pm$ 8.5
SK Decay Electron	$f^{N_{dcy}}$	$\pm$ 0.0	$\pm$ 0.3	$\pm$ 0.3
SK π^0 Efficiency	$f^{\pi^0 eff}$	$\pm$ 0.0	$\pm$ 3.4	$\pm$ 3.4
CC QE shape	$f^{CCQEshape}$	$\pm$ 0.0	$\pm$ 3.1	$\pm$ 3.1
CC 1π	$f^{CC1\pi}$	$\pm$ 5.9	$\pm$ 3.7	$\pm$ 2.2
CC Coherentπ	f^{CCcoh}	$\pm$ 3.3	$\pm$ 0.2	$\pm$ 3.1
CC Other	$f^{CCother}$	$\pm$ 4.7	$\pm$ 0.3	$\pm$ 4.4
NC $1\pi^0$	$f^{NC1\pi^0}$	$\pm$ 0.1	$\pm$ 5.4	$\pm$ 5.3
NC Coherentπ	f^{NCcoh}	$<$ 0.1	$\pm$ 2.3	$\pm$ 2.3
NC Other	$f^{NCother}$	$\pm$ 1.1	$\pm$ 3.5	$\pm$ 2.3
$\sigma(\nu_e)$	$f^{\sigma(\nu_e)}$	$<$ 0.1	$\pm$ 3.4	$\pm$ 3.4
FSI	f^{FSI}	$\pm$ 0.0	$\pm$ 10.1	$\pm$ 10.1
Beam Norm.	$f^{\phi}_{SK/ND}$	$\pm$ 15.4	$\pm$ 16.1	$\pm$ 8.5
ND Efficiency	$f^{\epsilon ND}$	$^{+5.6}_{-5.2}$	$\pm$ 0.0	$^{+5.6}_{-5.2}$
Overall Norm.	f^{norm}	$\pm$ 0.0	$\pm$ 0.0	$\pm$ 2.7
Total		$\pm$ 18.4	$\pm$ 25.6	$^{+22.8}_{-22.7}$

Uncertainty on background: ~23%

Expect: 1.5 ± 0.3 (syst) events

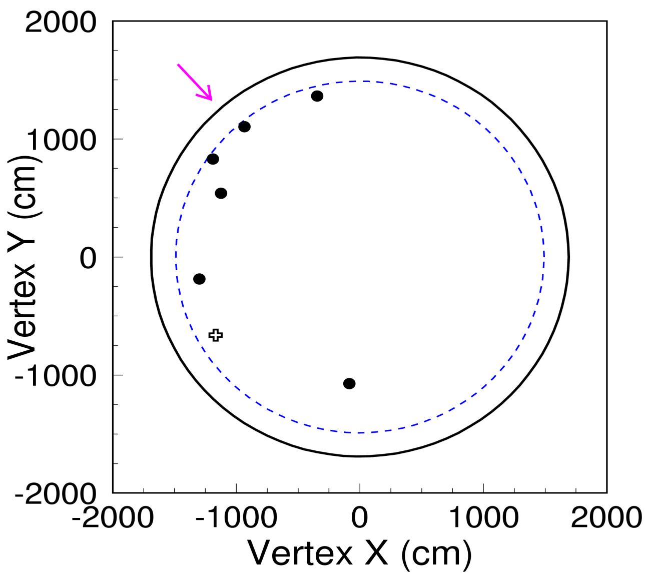
SuperK detector systematics
(dominated by uncertainties in ring-counting, e-like PID and π^0 mass cut efficiency)

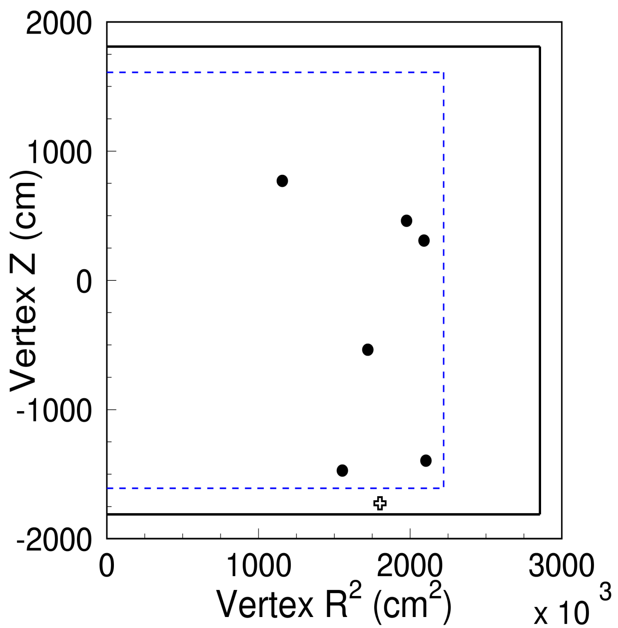
Cross-section systematics
(dominated by $NC\pi^0$ production uncertainties and FSI effects)

Flux systematic
(dominated by hadron-production uncertainties)

$\Delta m^2_{23}=2.4\cdot 10^{-3} eV^2$
$\sin^2 2\theta_{23}=1.0$

Further ν_e candidate event checks





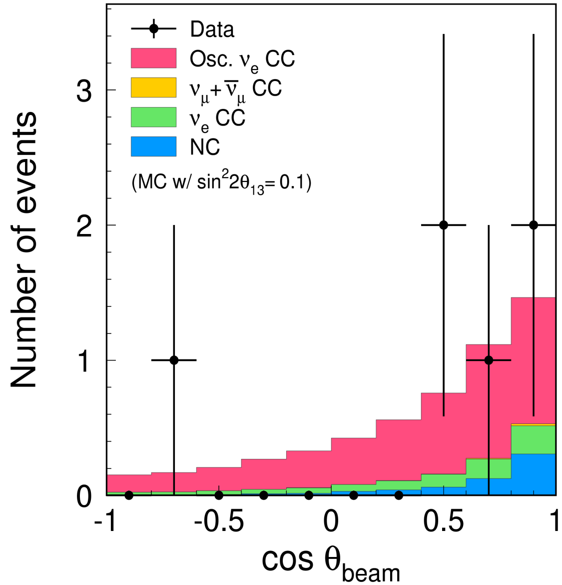
Large R clustering?

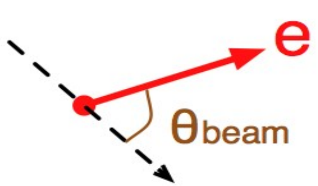
Checked events outside the ID fiducial volume and in OD

→ No indication of unmodelled background

Checked events outside the K.S. test on R^2

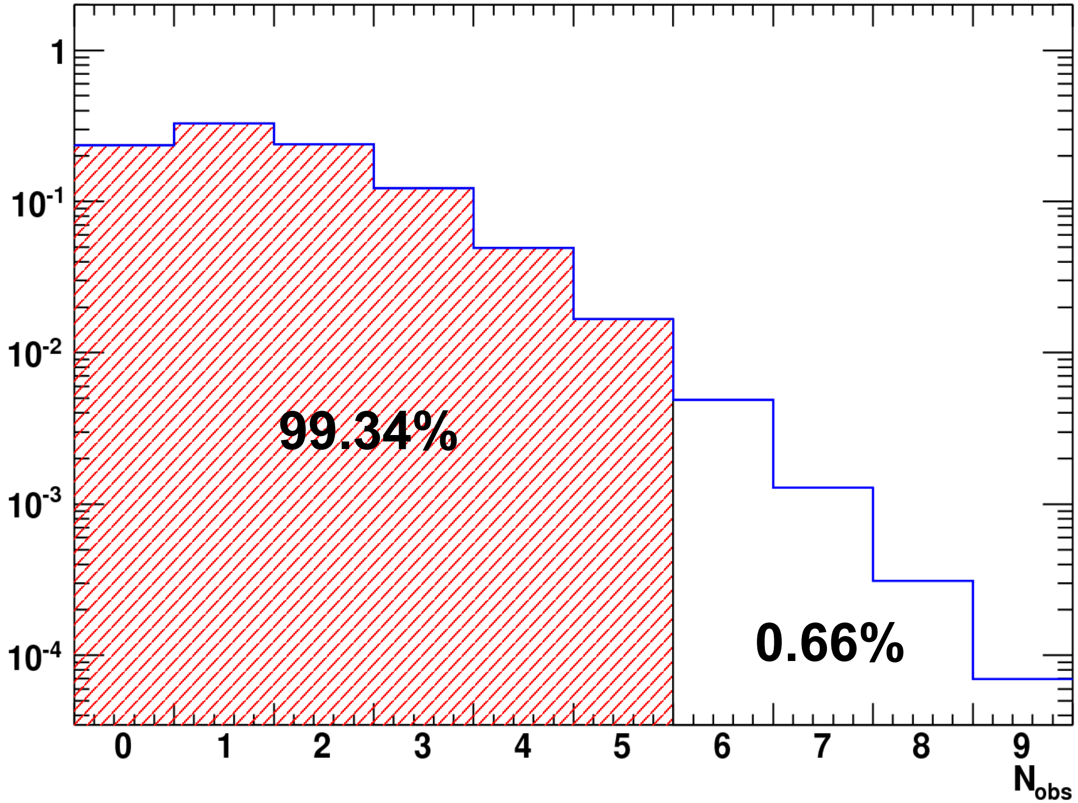
→ p-value 0.03





Background fluctuation?

Distribution of observed number of events
Background-only hypothesis ($\sin^2 2\theta_{13} = 0$)



$\sin^2 2\theta_{13} = 0$ excluded to 99.34% level (2.48σ)

(Normal hierarchy)

$\Delta m^2_{23} = 2.4 \cdot 10^{-3} eV^2$
$\sin^2 2\theta_{23} = 1.0$

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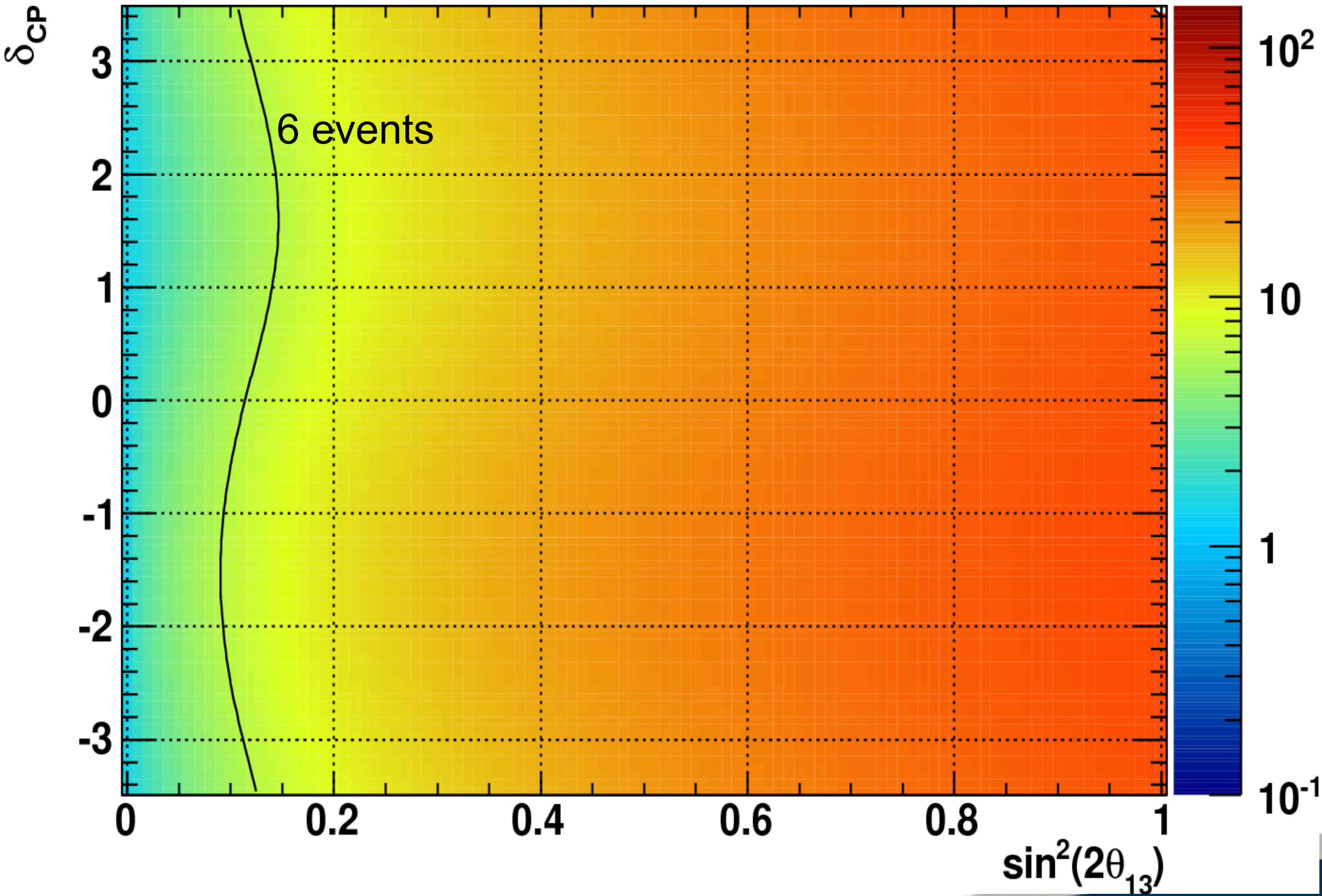
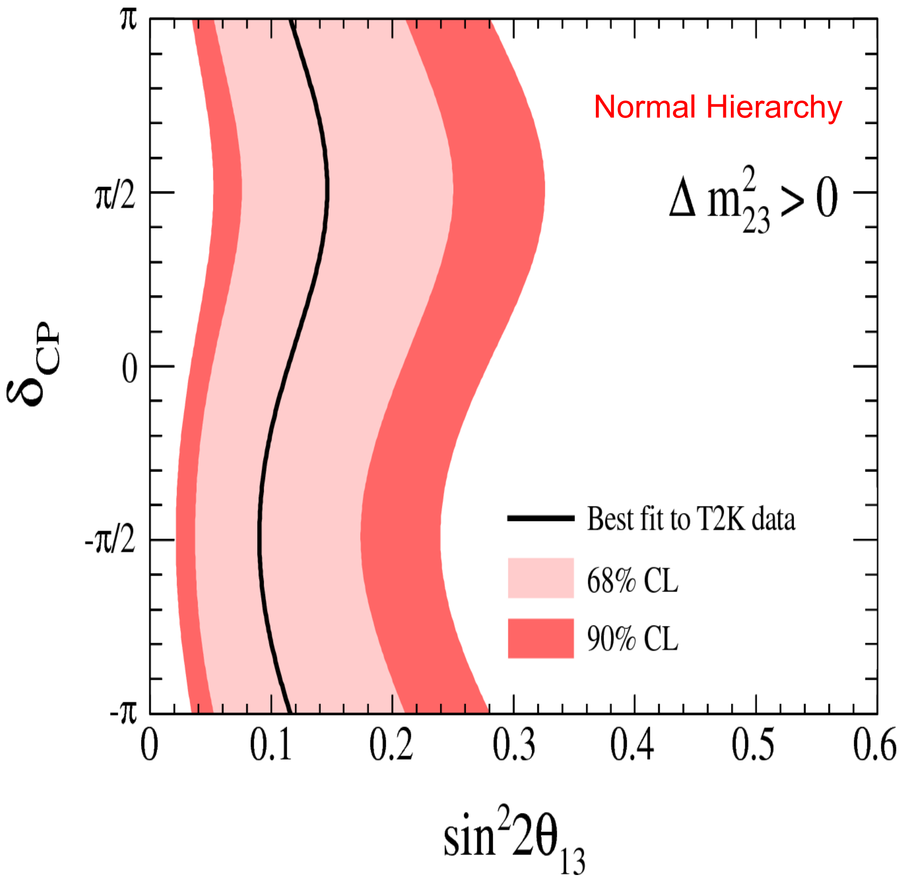
Number of ν_e events allowing for $\nu_\mu \to \nu_e$

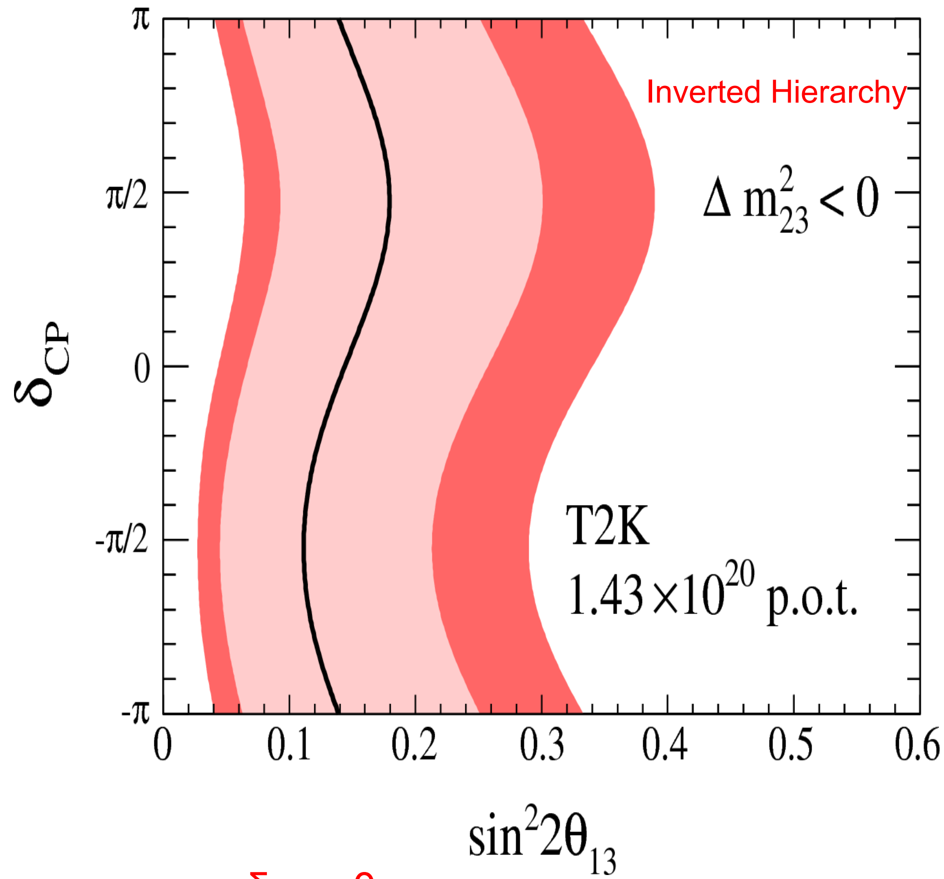


$\Delta m^2_{23} = 2.4 \cdot 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.0$

Allowed regions of $\sin^2 2\theta_{13}$ as function of δ_{CP}





$\delta_{CP} = 0$:

- best-fit $\sin^2 2\theta_{13} \sim 0.11$
- $\sin^2 2\theta_{13}$ 90% CL ~ [0.03 - 0.28]

$\delta_{CP} = 0$:

- best-fit $\sin^2 2\theta_{13} \sim 0.14$
- $\sin^2 2\theta_{13}$ 90% CL ~ [0.04 - 0.34]

$\Delta m^2_{23} = 2.4 \cdot 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.0$

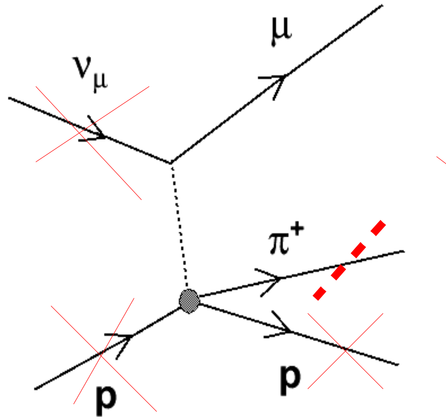
Muon neutrino disappearance results

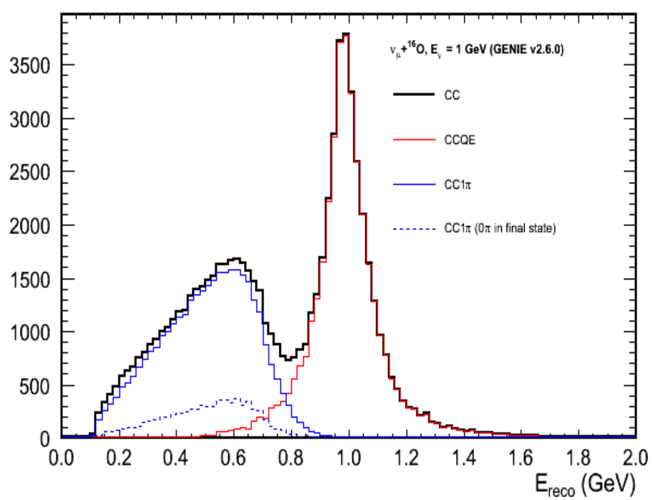
SuperK ν_μ event selection: Strategy

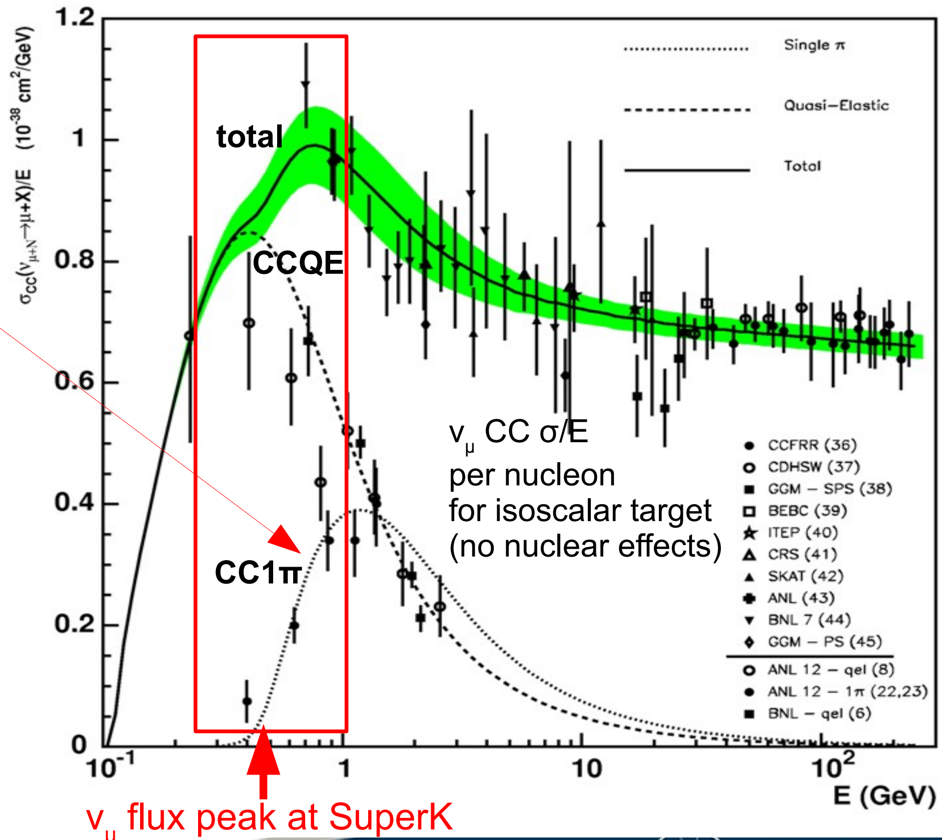
Selecting ν_μ CCQE events. *A water-Cherenkov detector sees a single μ-like (crisp) ring*

Main background: ν_μ CCπ with unidentified π

(Background oscillates too, but energy reconstruction is systematically off due to unaccounted π)







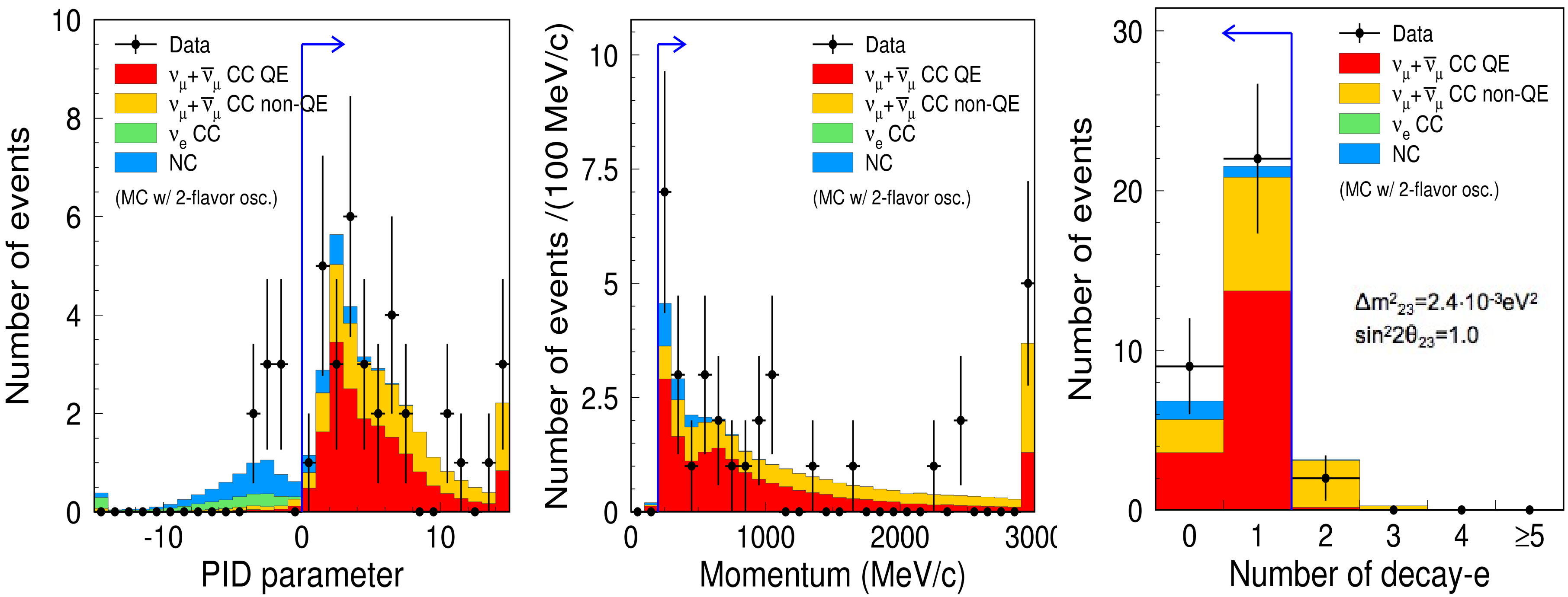
SuperK ν_μ event selection: Cut overview

All cuts were defined before the data-taking operations

88 FCFV events

- Event has 1-ring
- Ring has μ-like PID
- μ momentum > 200 MeV/c
- 0 or 1 delayed electron signals

31 ν_μ event candidates



Expected sample composition: CCQE(61%) CCnQE (32%),NC(6%), ν_e(<1%)

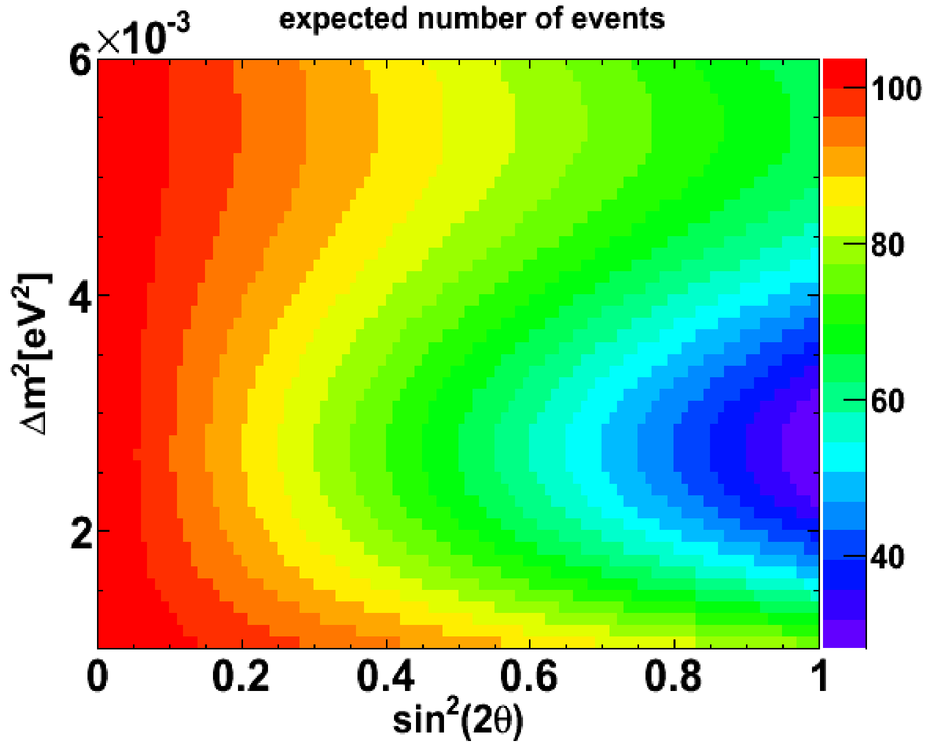
ν_μ-disappearance: MC expectation

In absence of oscillations, expect: **103.6 ± 10.2 (stat) $^{+13.8}_{-13.4}$ (syst)** 1-ring μ-like events

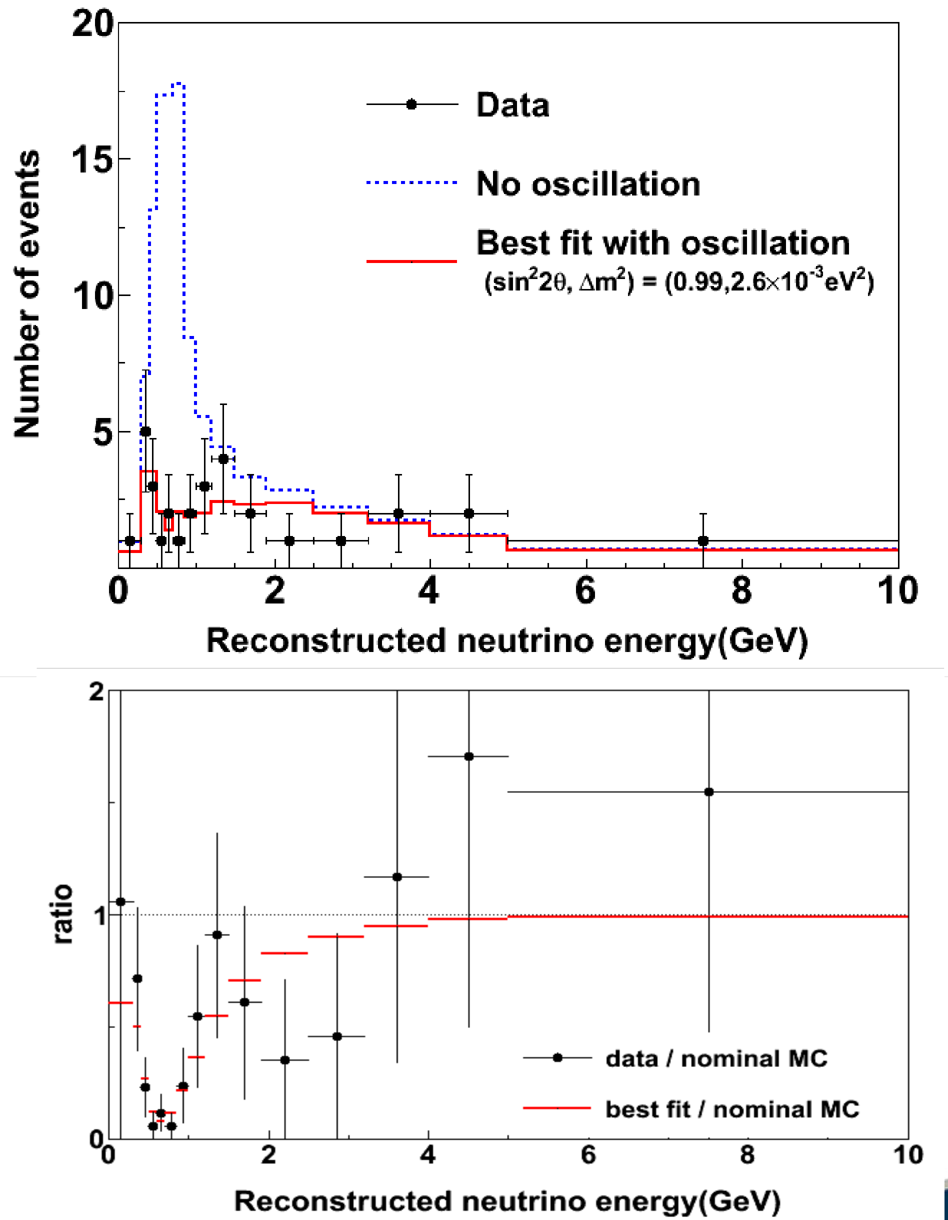
Uncertainty on expected number of events

$N^{SK}_{exp.}$ error table

Error source	$\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$	Null Oscillation
SK Efficiency	+10.3% 10.3%	+5.1% -5.1%
Cross section and FSI	+8.3% -8.1%	+7.8% -7.3%
Beam Flux	+4.8% -4.8%	+6.9% -5.9%
ND Efficiency and Overall Norm.	+6.2% -5.9%	+6.2% -5.9%
Total	+15.4% -15.1%	+13.2% -12.7%



ν_μ-disappearance: Best-fit spectrum



2 independent fitting methods

- Likelihood ratio, w/o systematic param fitting
  $\sin^2(2\theta_{23})=0.98$, $|\Delta m^2_{23}|=2.6\text{x}10^{-3}$ eV^2/c^4
- Ext. max. likelihood ratio, w systematic param fitting
  $\sin^2(2\theta_{23})=0.99$, $|\Delta m^2_{23}|=2.6\text{x}10^{-3}$ eV^2/c^4

Repeated the analysis with 2 different neutrino MC generators (GENIE and NEUT):
Very different cross-section model

Very good consistency between all fits.

A very robust oscillation result!

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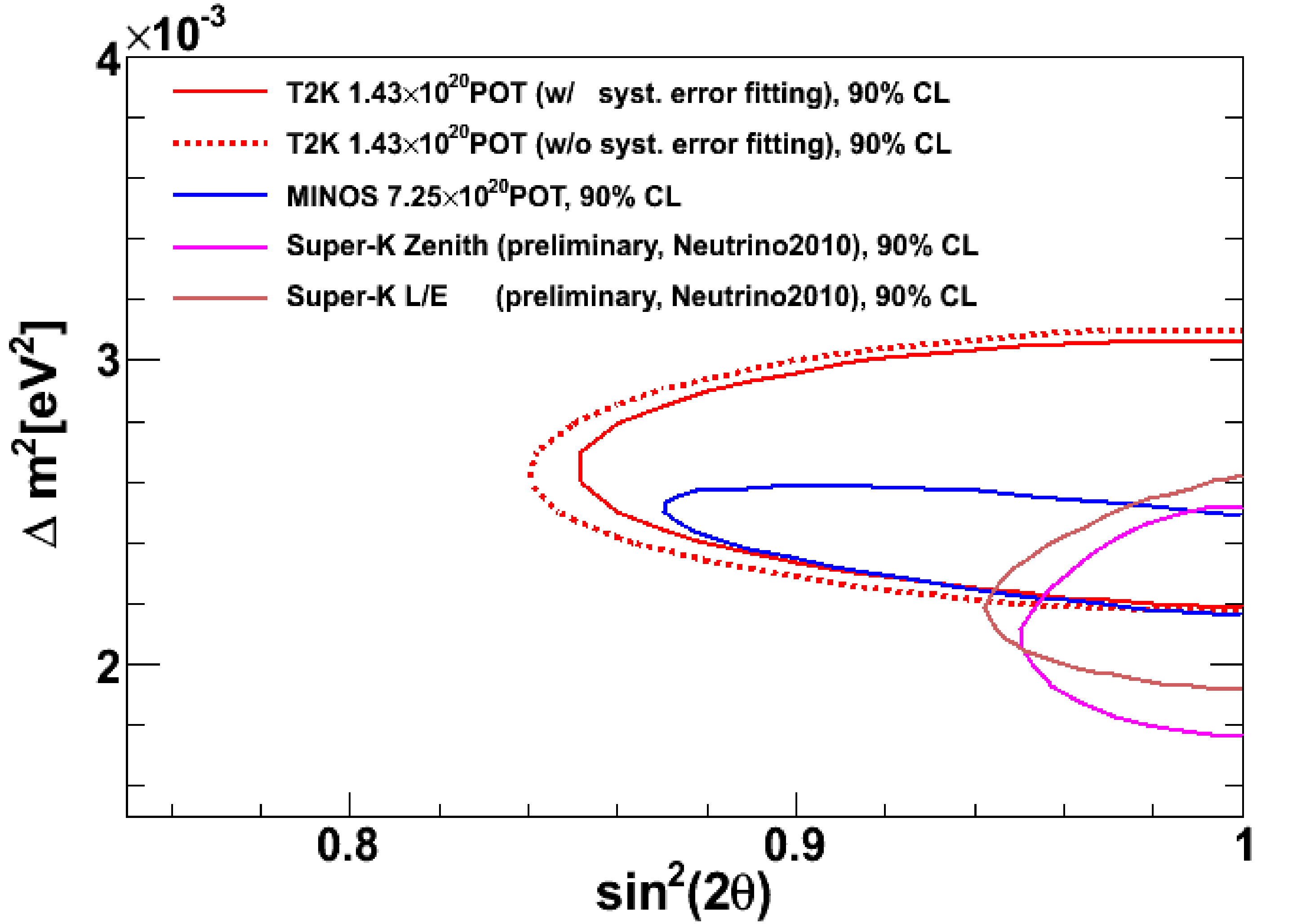
ν_μ-disappearance: Confidence regions

(and comparison with latest MINOS and SuperK results)



Both T2K analyses used the Feldman-Cousins method to construct confidence regions.

Conclusions

Reported results from an initial exposure of 1.431E+20 POT (just **~2%** of expected final exposure)

- **Electron-neutrino appearance:**
  - ***Observed 6 single-ring electron-like event***
  - ***Background (θ_{13}=0) = 1.5 ± 0.3***
  - *θ_{13}=0 excluded to 2.5σ level*
    - *First strong indication for a non-zero θ_{13}*

  - ***3-flavour fit-results***

    For Normal (Inverted) hierarch, δ_{CP} = 0 and global best-fit values of "23"-sector params:
    - *Best-fit value: $\sin^2 2\theta_{13}$ = 0.11 (0.14), 90% CL: 0.03 < $\sin^2 2\theta_{13}$ < 0.28*
    - *90% CL: 0.03 (0.04) < $\sin^2 2\theta_{13}$ < 0.28 (0.34)*

- **Muon-neutrino disappearance:**
  - ***Observed 31 single-ring muon-like events.***
  - ***Without oscillations, expect ~103.6 ± 17.2 events (a ~4σ deficit)***
  - *Consistent with MINOS / K2K / SuperK (atmospheric neutrinos).*

  - ***Effective 2-flavour fit-results:***
    - *Best-fit values: $\mathbf{\sin^2 2\theta_{23}=0.98}$, $|\Delta m^2_{23}|=2.6\times10^{-3}\ eV^2/c^4$*
    - *90% CL : $\mathbf{\sin^2 2\theta_{23}}$ > 0.84, $2.1\times10^{-3}\ eV^2/c^4 < |\Delta m^2_{23}| < 3.1\times10^{-3}\ eV^2/c^4$*

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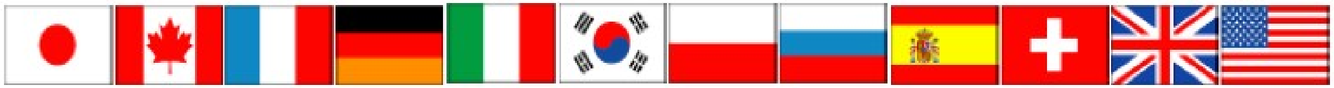
Back-up slides

T2K Collaboration



59 institutions in 12 countries

Canada
TRIUMF
U of Alberta
U of B Columbia
U of Regina
U of Toronto
U of Victoria
York U

France
CEA Saclay
IPN Lyon
LLR E Poly
LPNHE-Paris

Russia
INR

Korea
Chonnam Nat'l U
Dongshin U
Seoul Nat'l U

Spain
IFIC, Valencia
U.A. Barcelona

Poland
A Soltan, Warsaw
HNiewodniczanski
T U Warsaw
U of Silesia
Warsaw U
Wroclaw U

Switzerland
Bern
ETH Zurich
U of Geneva

UK
U of Oxford
Imperial C London
Lancaster U
Queen Mary U of L
Sheffield U
STFC/RAL
STFC/Daresbury
U of Liverpool
U of Warwick

Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe U
Kyoto U
Miyagi U of Ed
Osaka City U
U of Tokyo

Italy
INFN Bari
INFN Roma
Napoli U
Padova U

USA
Boston U
BNL
Colorado State U
Duke U
Louisiana State U
Stony Brook U
U of California, Irvine
U of Colorado
U of Pittsburgh
U of Rochester
U of Washington

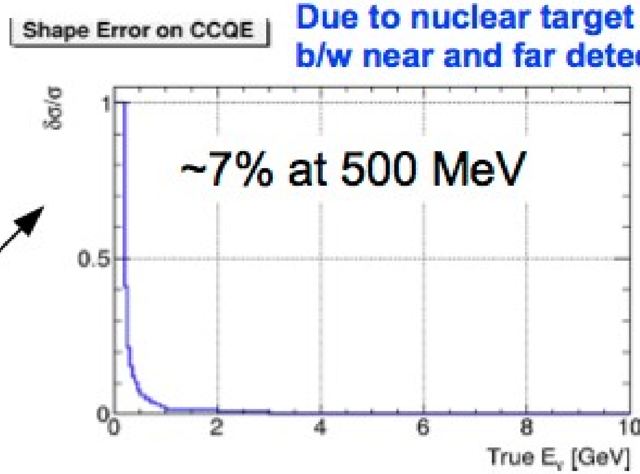
Germany
RWTH Aachen U

ν interaction uncertainty

T2K

- Estimated from parameter variations in MC models and comparisons with data (K2K, MiniBooNE, SciBooNE, MINOS)

Due to nuclear target diff. b/w near and far detector



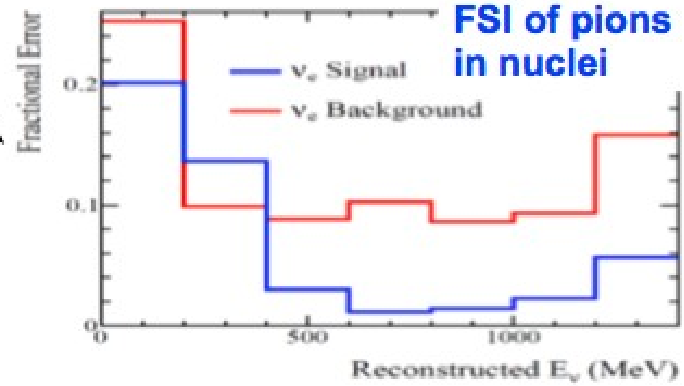
For electron appearance analysis:

Category	Error [%]	
CC QE	Depends on true neutrino energy	
CC 1π	30 (E_ν<2 GeV)	20 (E_ν>2 GeV)
CC coherent π	100	
CC other	30 (E_ν<2 GeV)	25 (E_ν>2 GeV)
NC $1\pi^0$	30 (E_ν<1 GeV)	20 (E_ν>1 GeV)
NC coherent	30	
NC other	30	
FSI error	Depends on reconst. neutrino energy	

$\sigma(\nu_e)/\sigma(\nu_\mu)$: 6%

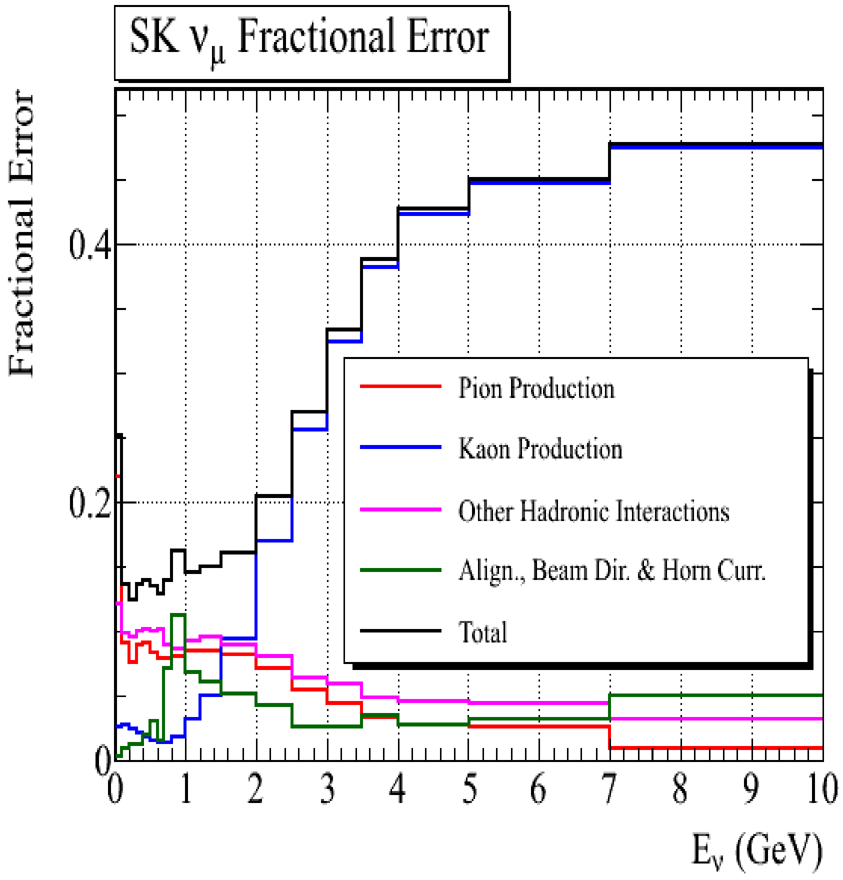
Uncertainties on the ratio relative to CCQE

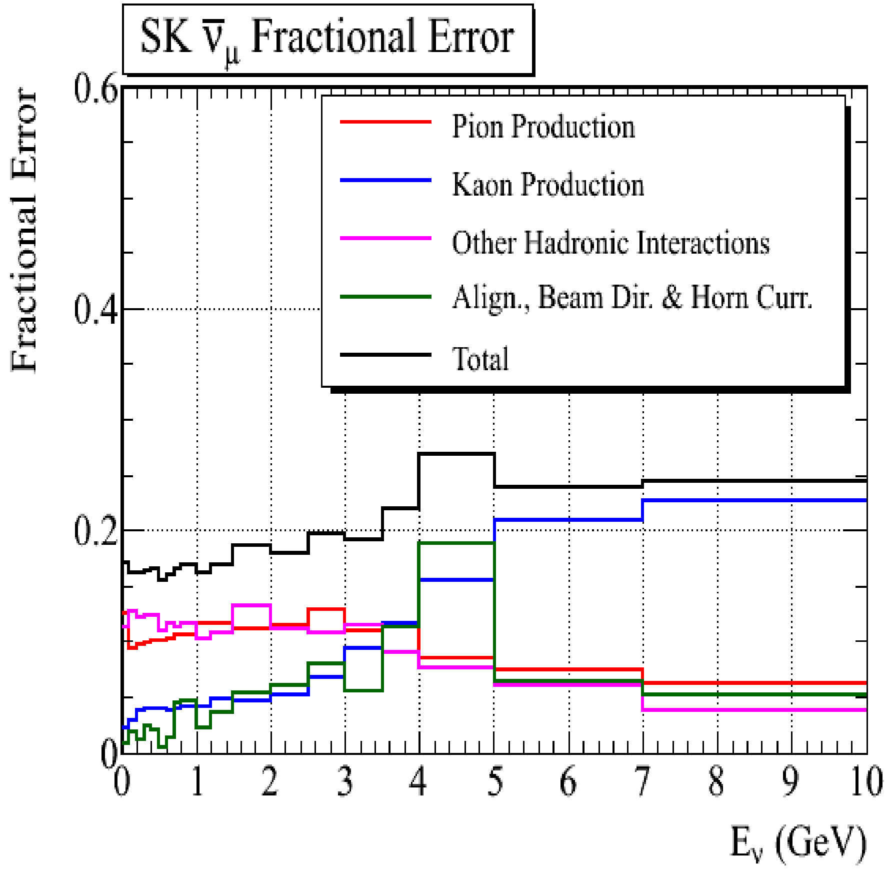
FSI of pions in nuclei



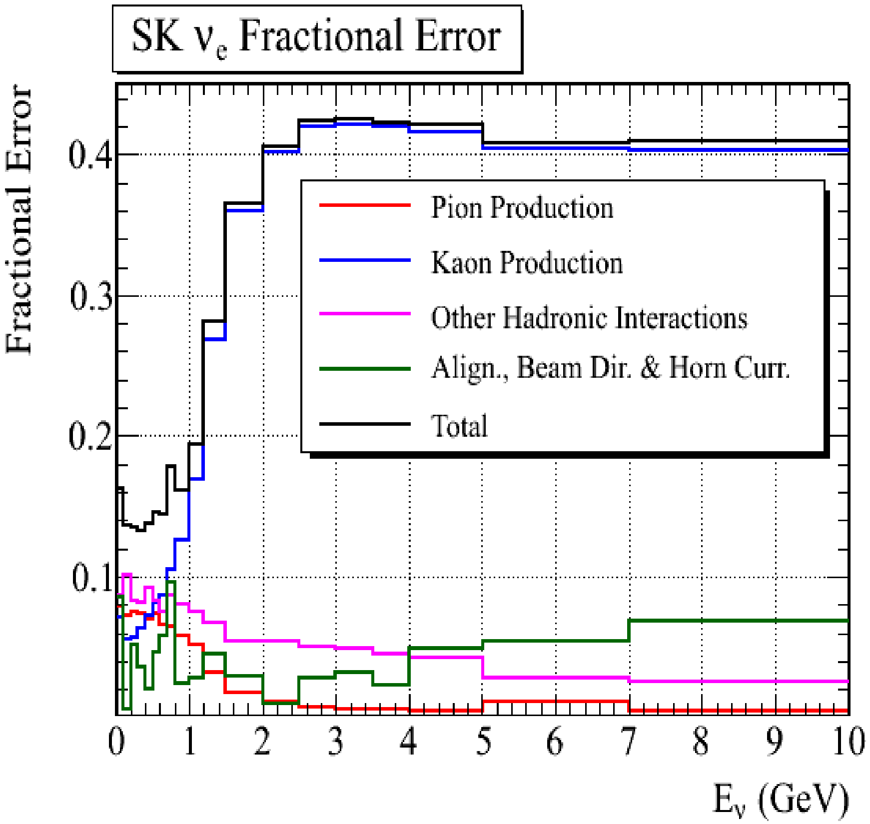
Most errors considered correlated b/w near and far detectors

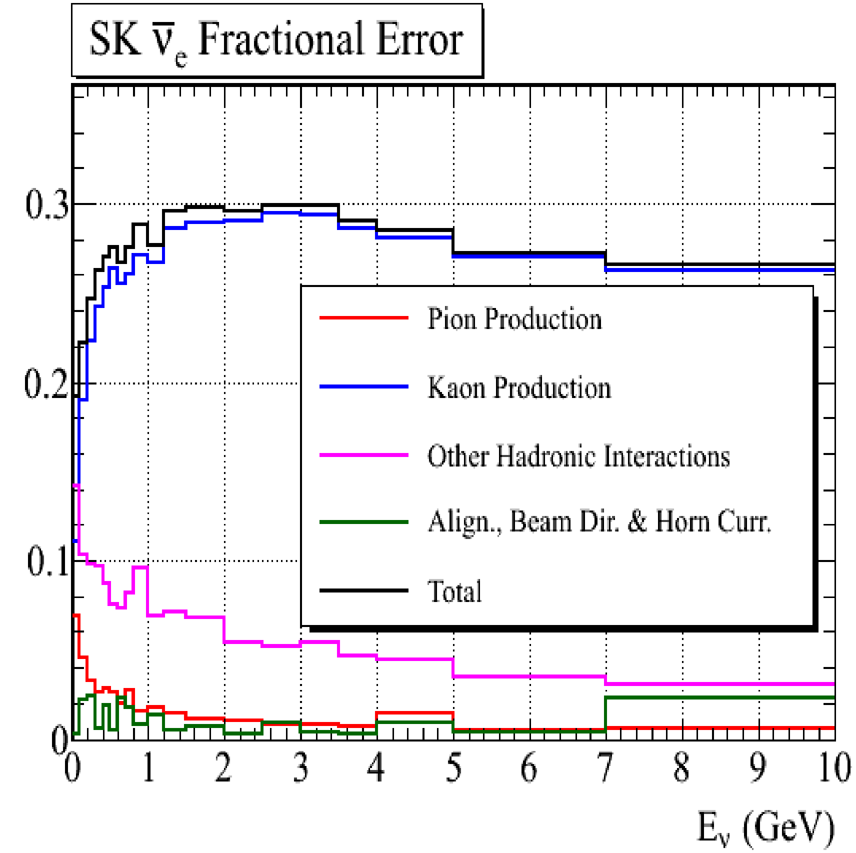
Neutrino flux uncertainties





Neutrino flux uncertainties





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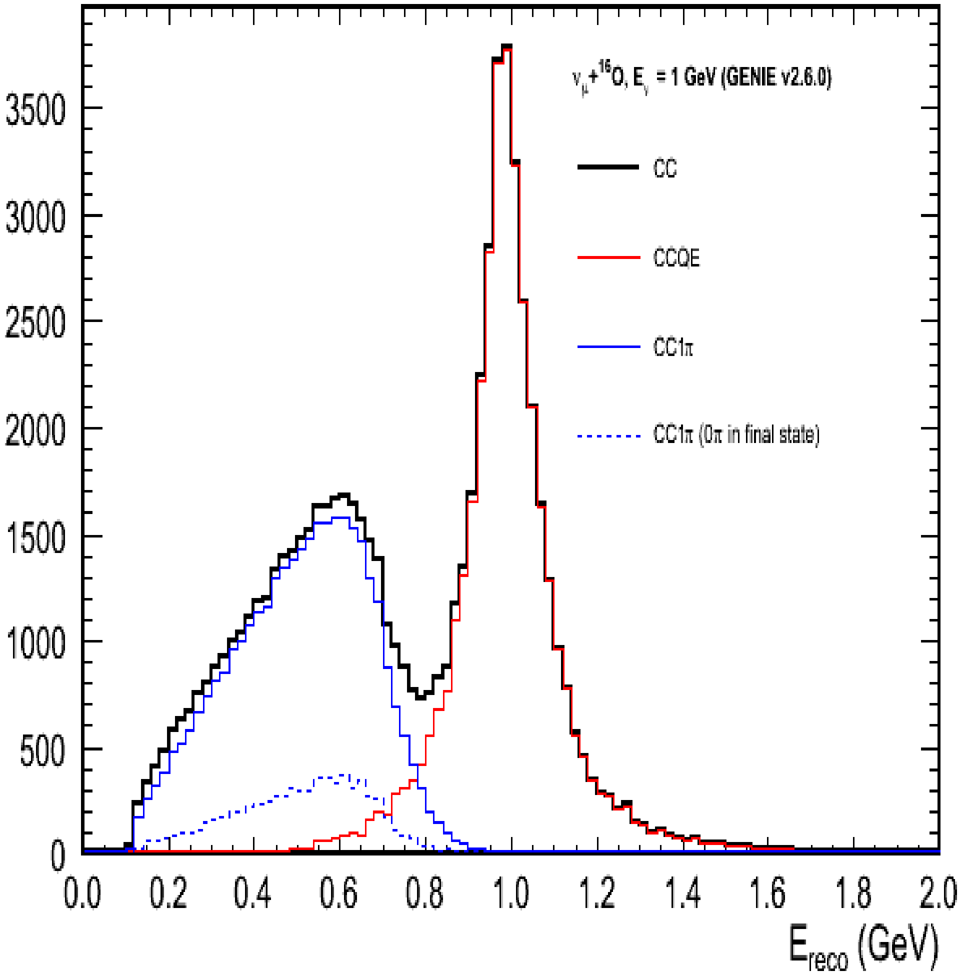
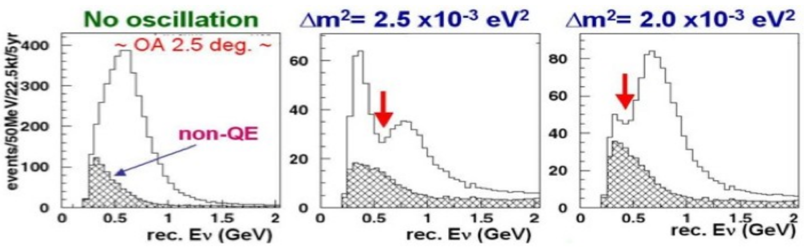
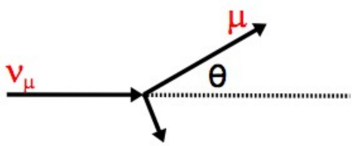
Energy reconstruction for CCQE and non-CCQE







$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\Theta_\mu)}$$

m_N = Neutron mass

E_μ = Muon energy

m_μ = Muon mass

p_μ = Muon momentum

Θ_μ = Muon angle wrt beam

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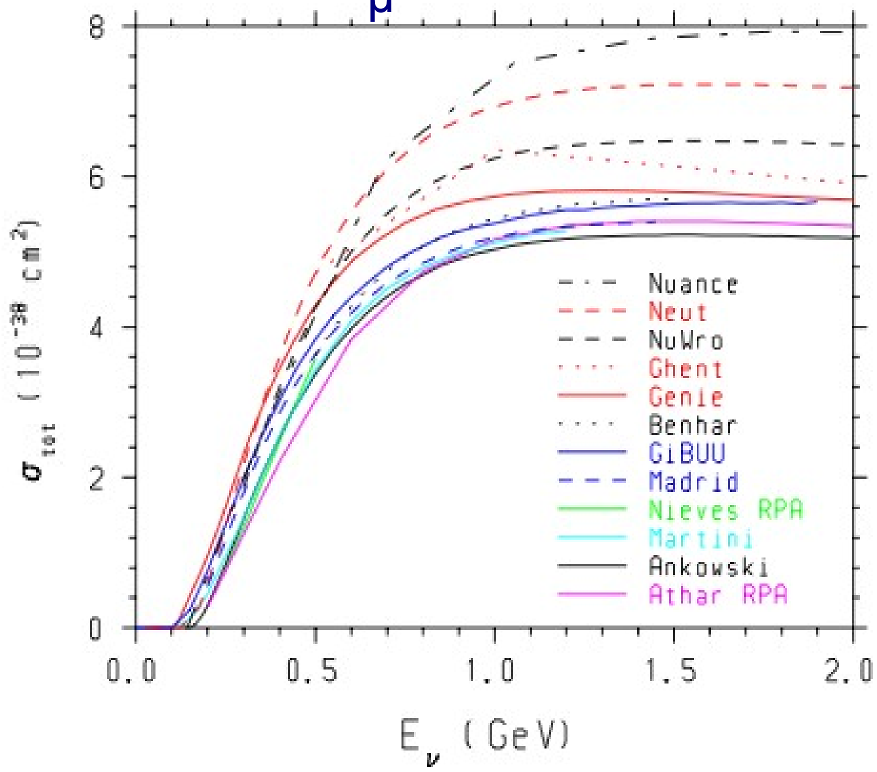
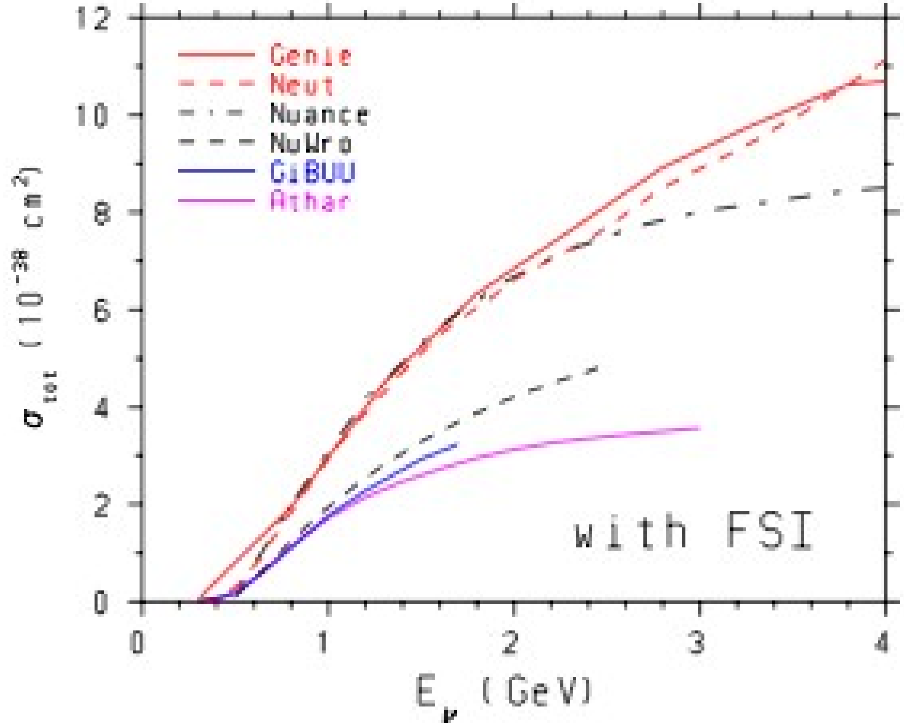
Cross sections – Survey of models

ν_μ CCQE

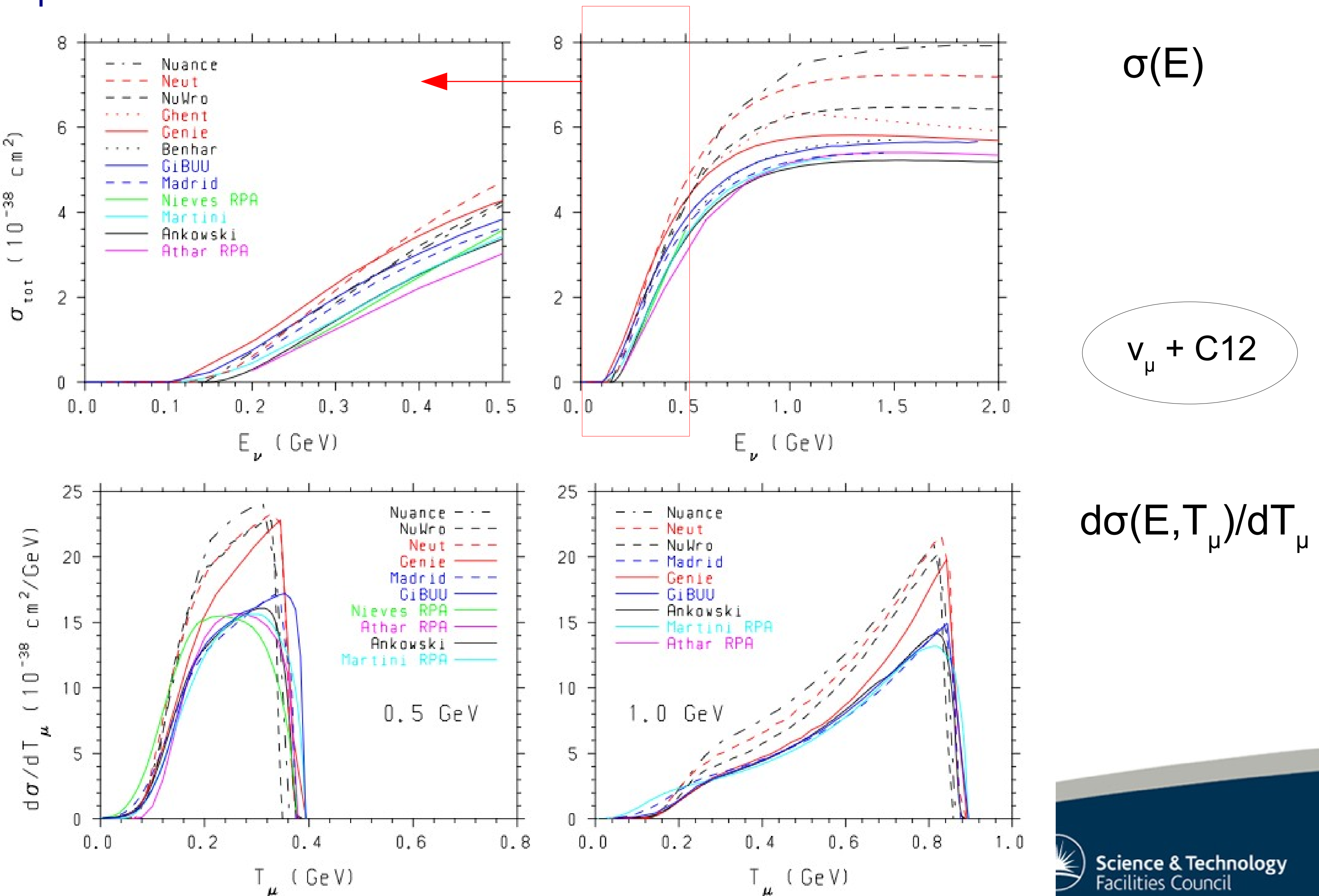


ν_μ CC1π+



ν_μ + C12

ν_μ CCQE cross section – Survey of models



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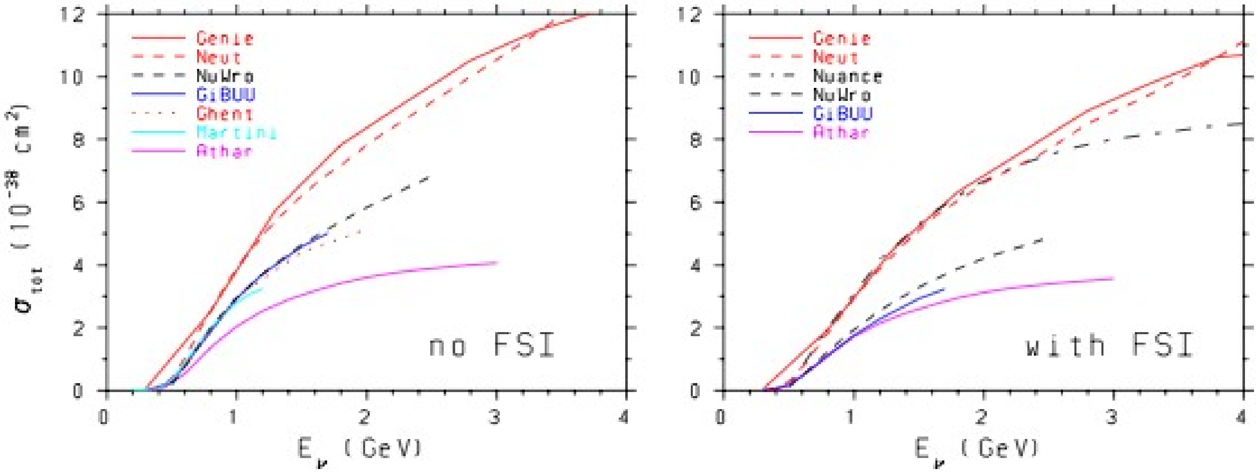
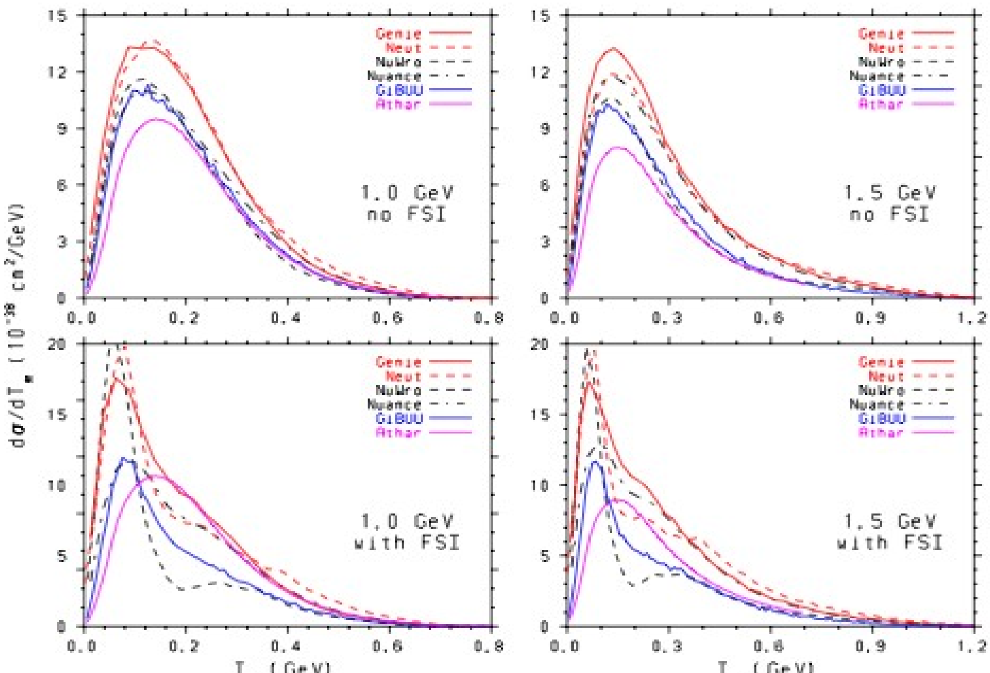
ν_μ CC1π cross section – Survey of models



σ(E)

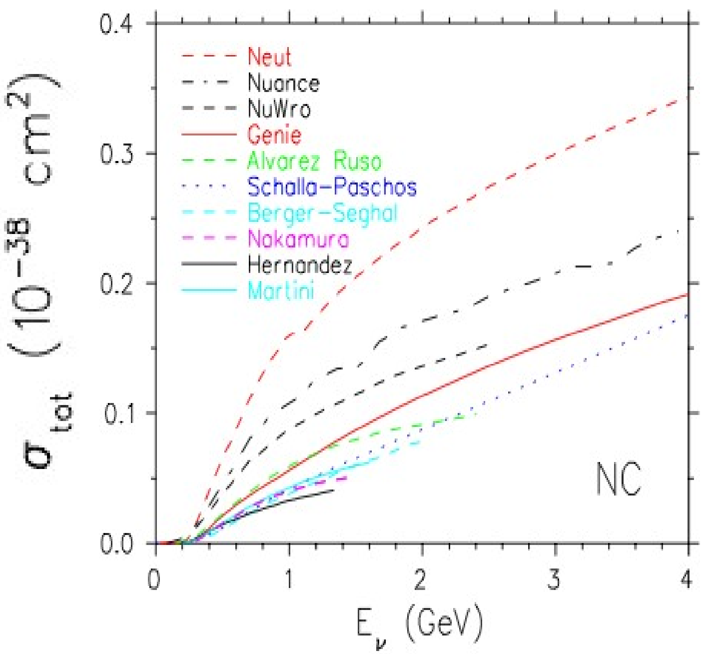
ν_μ + C12

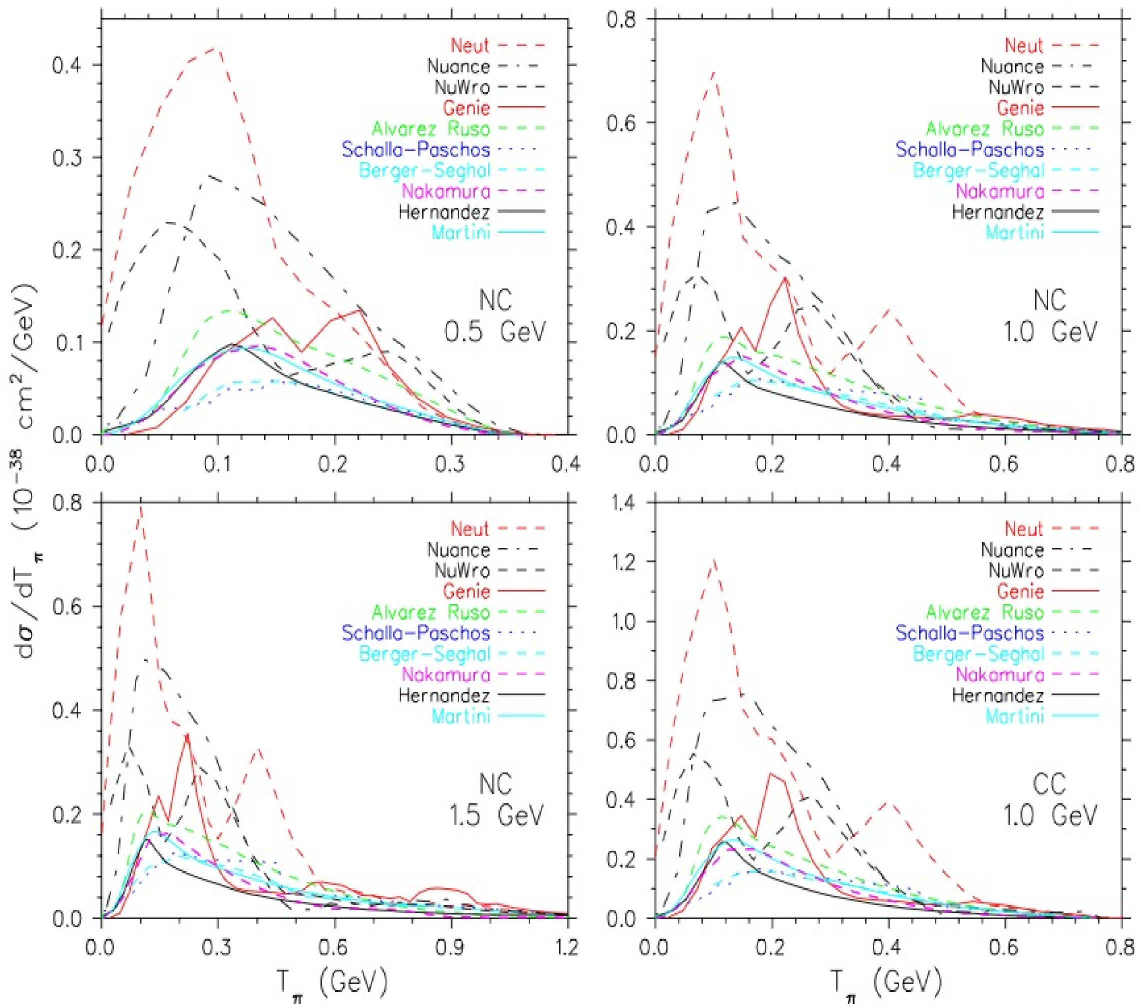


$d\sigma(E,T_\pi)/dT_\pi$

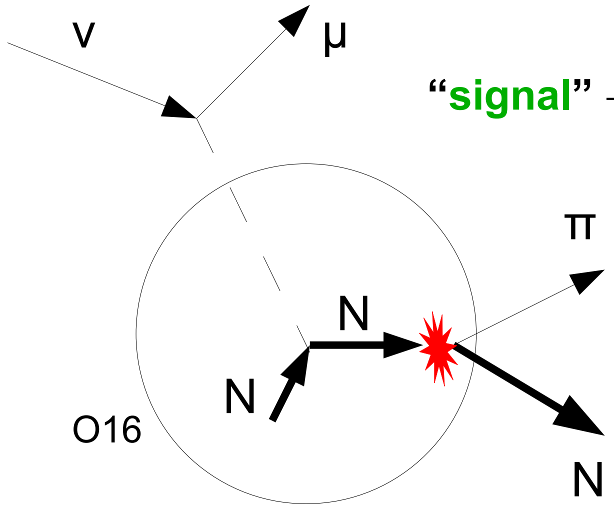
ν_μ NC π^0 (coherent) cross sections – Survey of models

ν_μ + C12

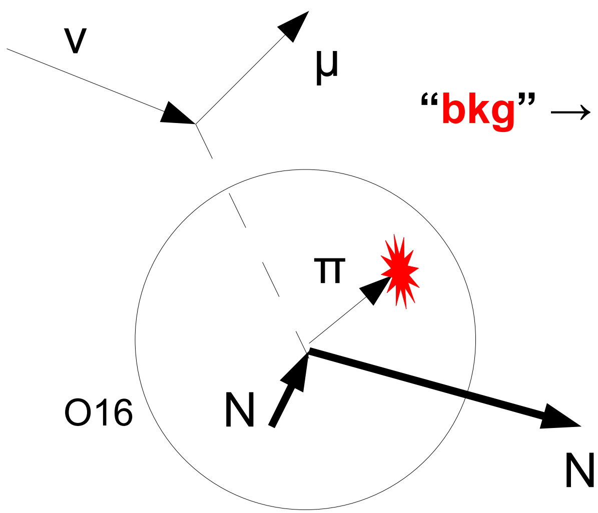




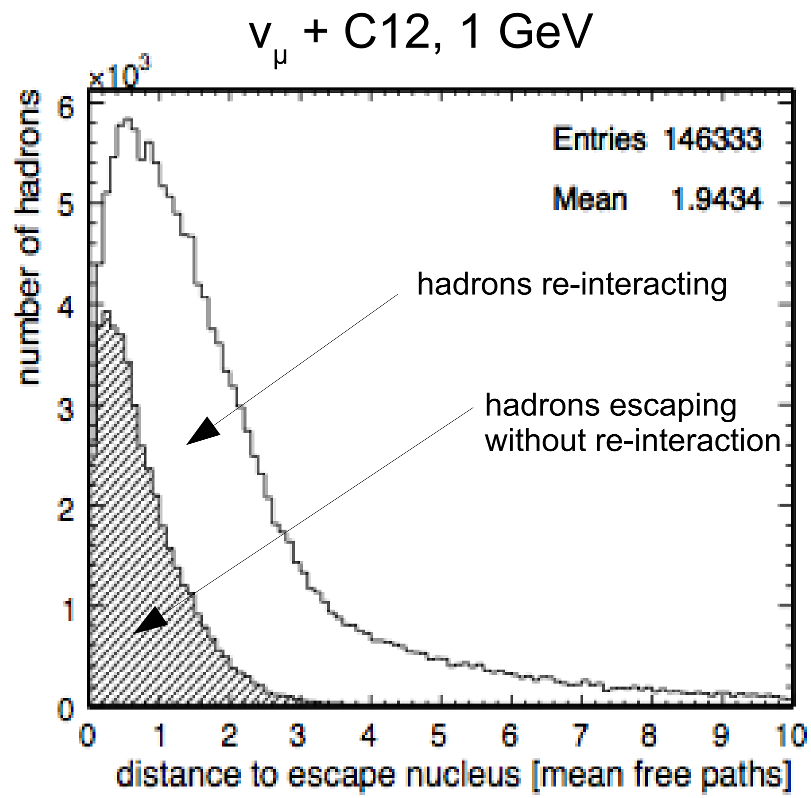
Final State Interactions (FSI)



“signal” → “bkg”



“bkg” → “signal”



~ 2/3 of hadrons re-interact!

FSI effect on final state topologies

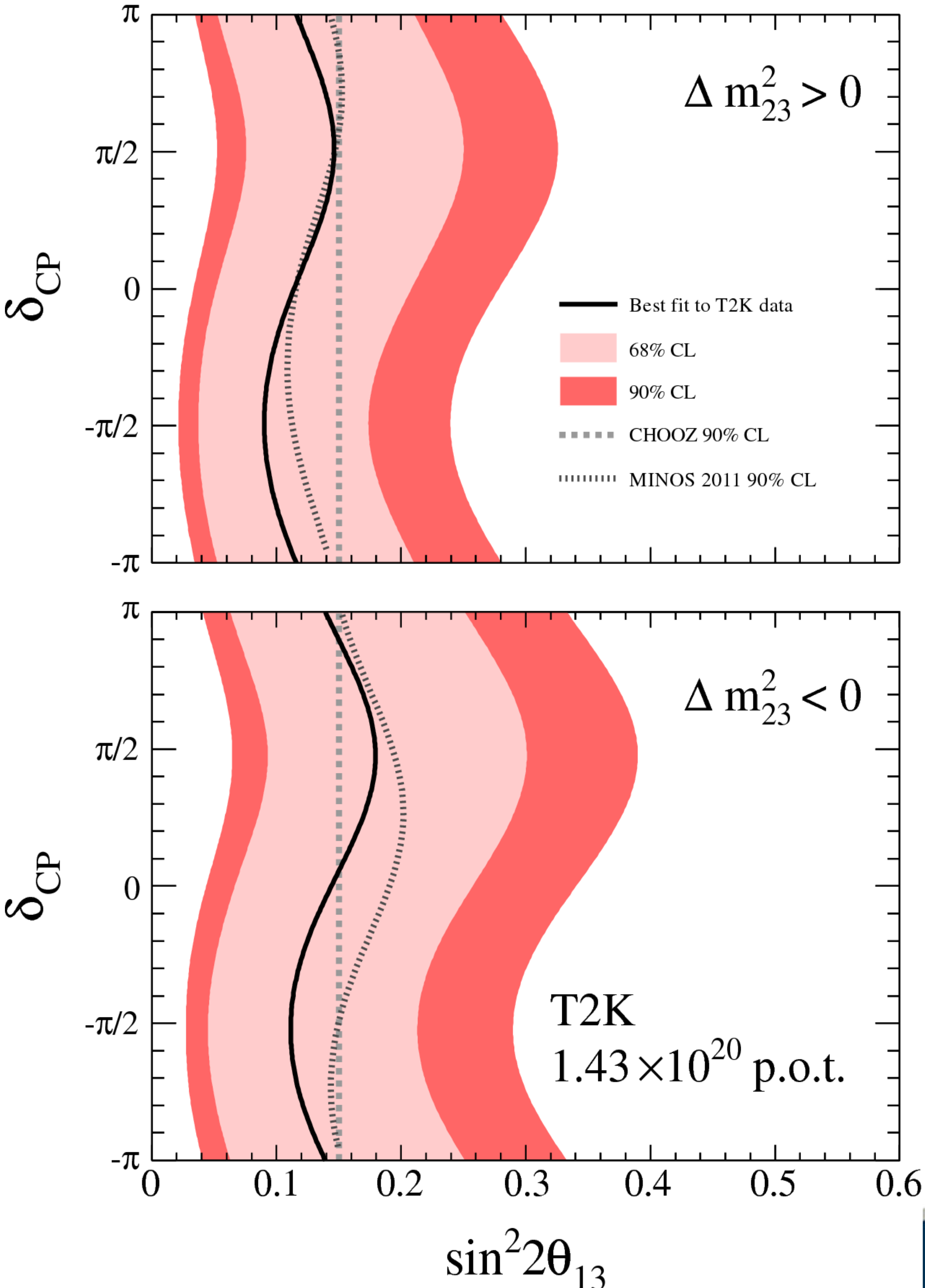
what was generated inside the nucleus

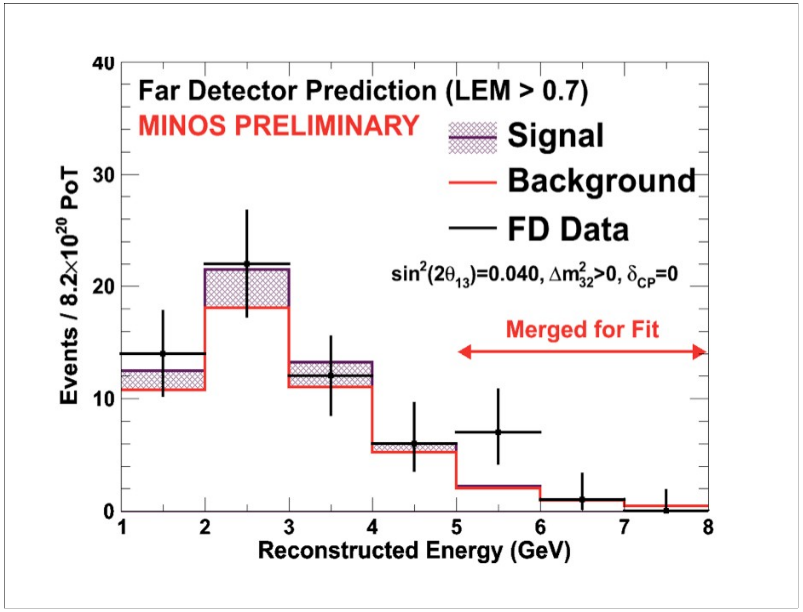
what we could see in a perfect detector

Final-State	Primary Hadronic System									
	$0\pi X$	$1\pi^0 X$	$1\pi^+ X$	$1\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$
$0\pi X$	**293446**	12710	22033	3038	113	51	5	350	57	193
$1\pi^0 X$	1744	**44643**	3836	491	1002	25	1	1622	307	59
$1\pi^+ X$	2590	1065	**82459**	23	14	660	0	1746	5	997
$1\pi^- X$	298	1127	1	**12090**	16	0	46	34	318	1001
$2\pi^0 X$	0	0	0	0	**2761**	2	0	260	40	7
$2\pi^+ X$	57	5	411	0	1	**1999**	0	136	0	12
$2\pi^- X$	0	0	0	1	0	0	**134**	0	31	0
$\pi^0\pi^+ X$	412	869	1128	232	109	106	0	**9837**	15	183
$\pi^0\pi^- X$	0	0	1	0	73	0	8	5	**1808**	154
$\pi^+\pi^- X$	799	7	10	65	0	0	0	139	20	**5643**

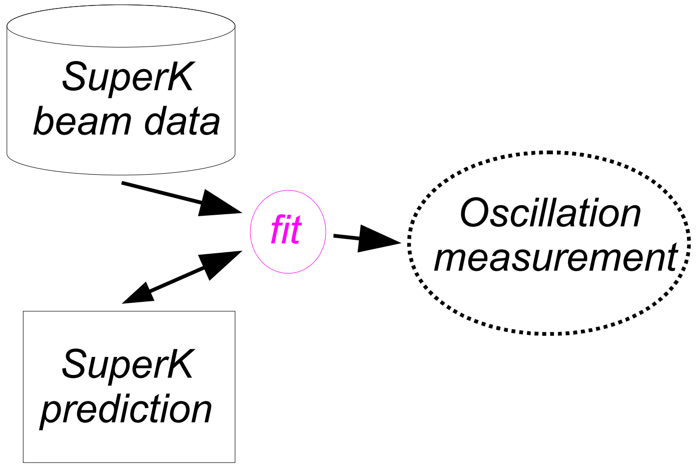
T2K allowed regions of $\sin^2 2\theta_{13}$ as function of δ_{CP}:

Comparison with upper limits from MINOS and CHOOZ.

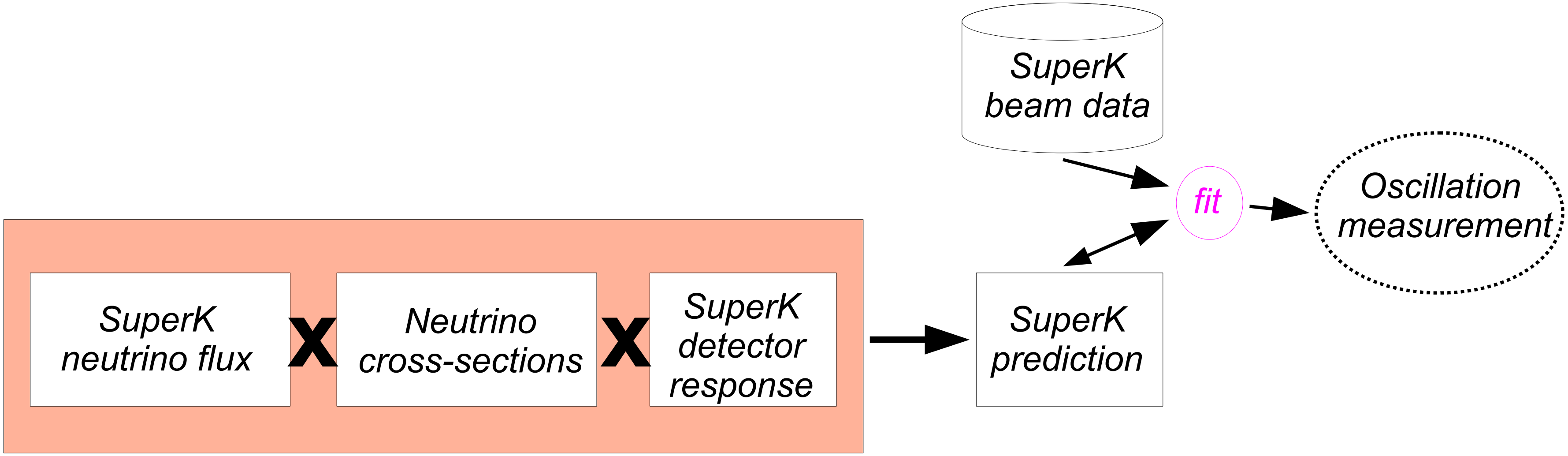




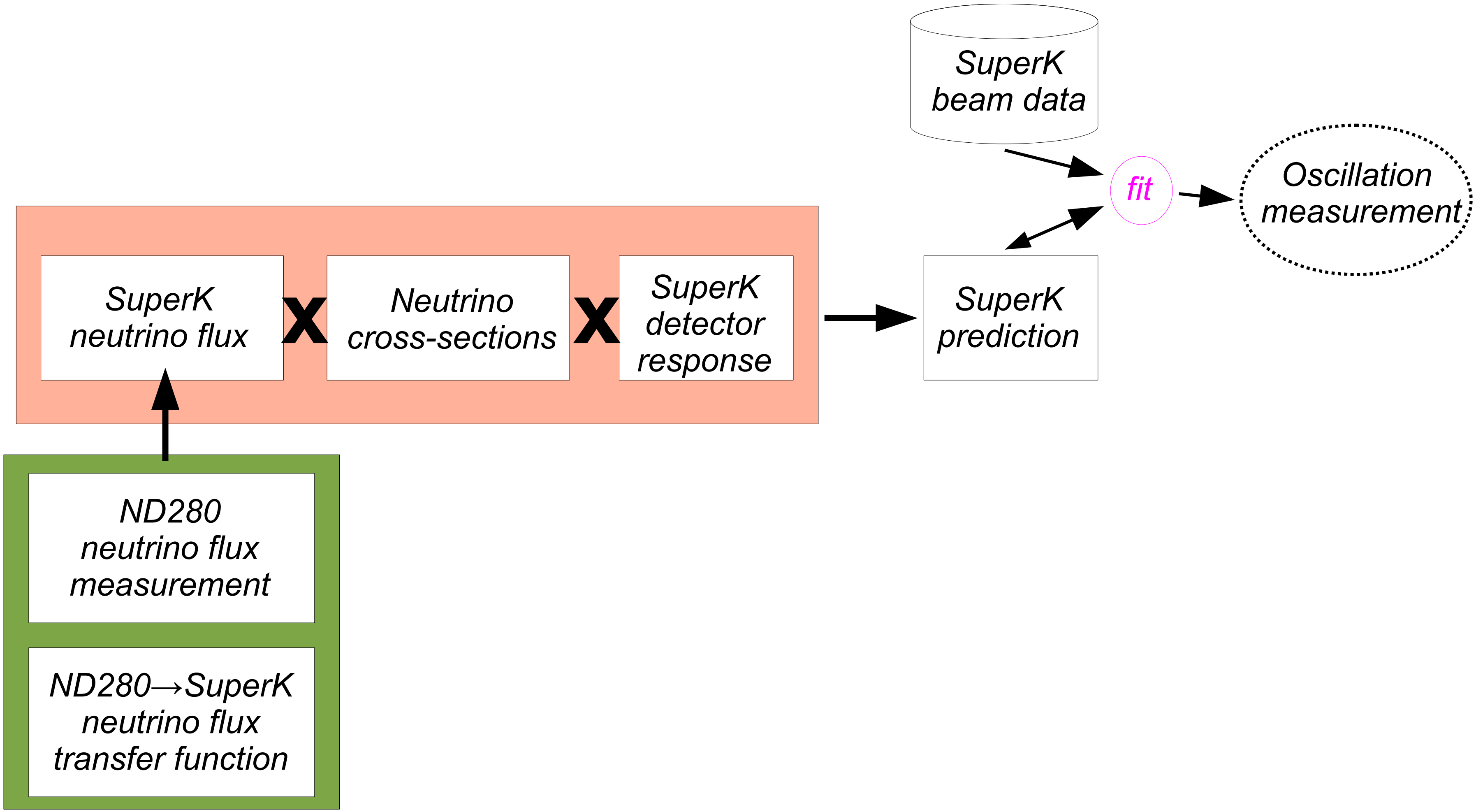
Analysis Flow



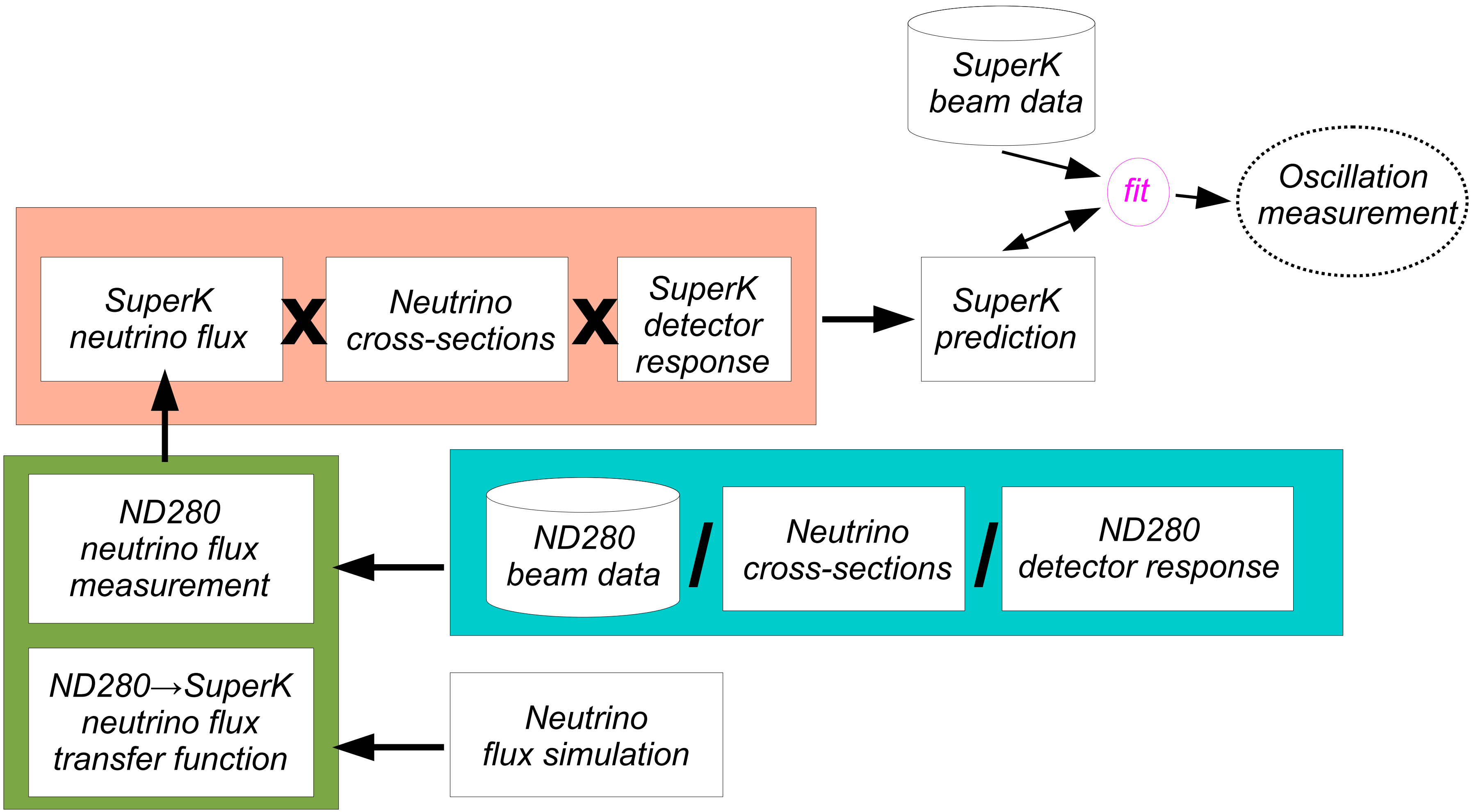
Analysis Flow



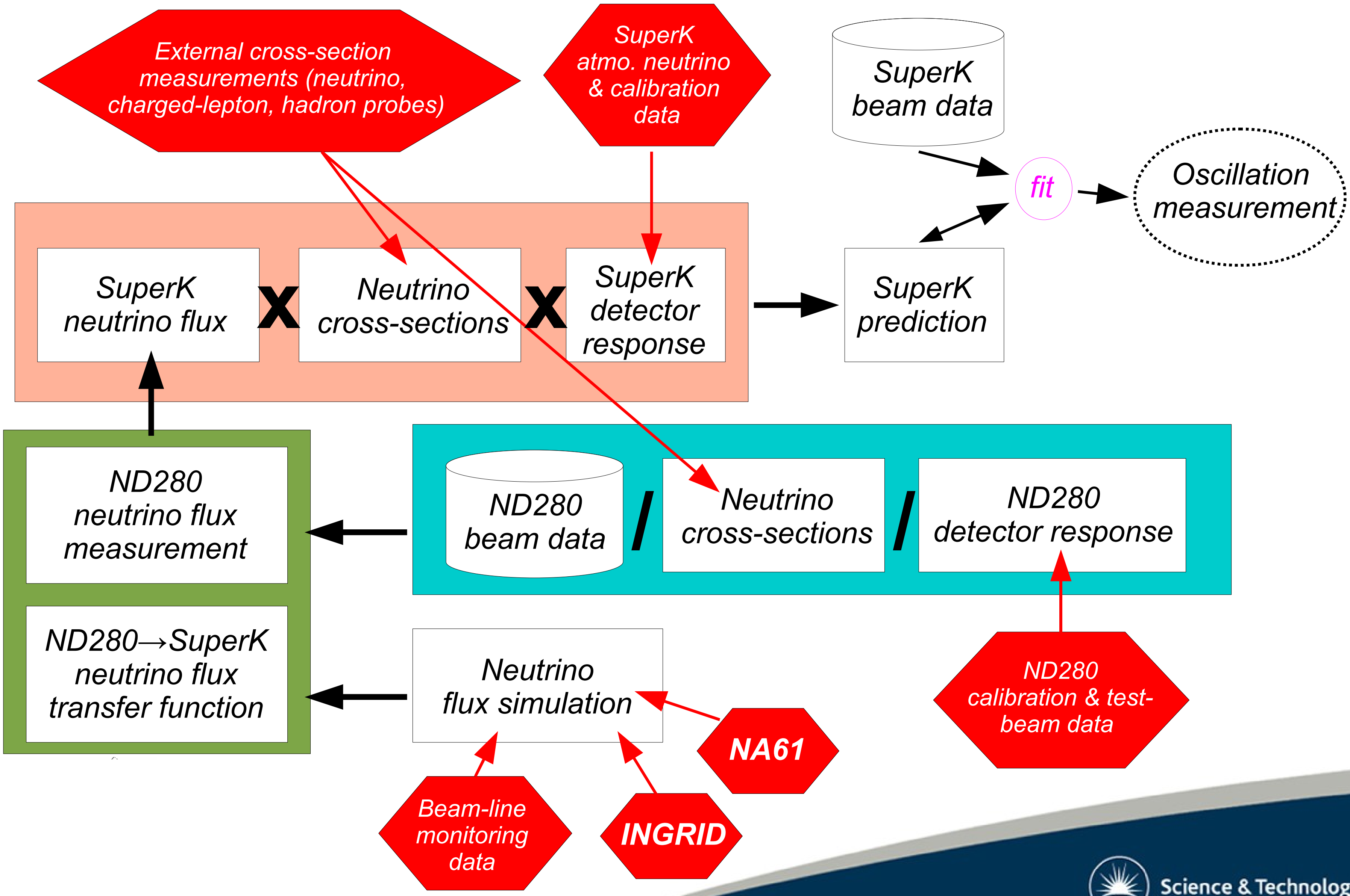
Analysis Flow



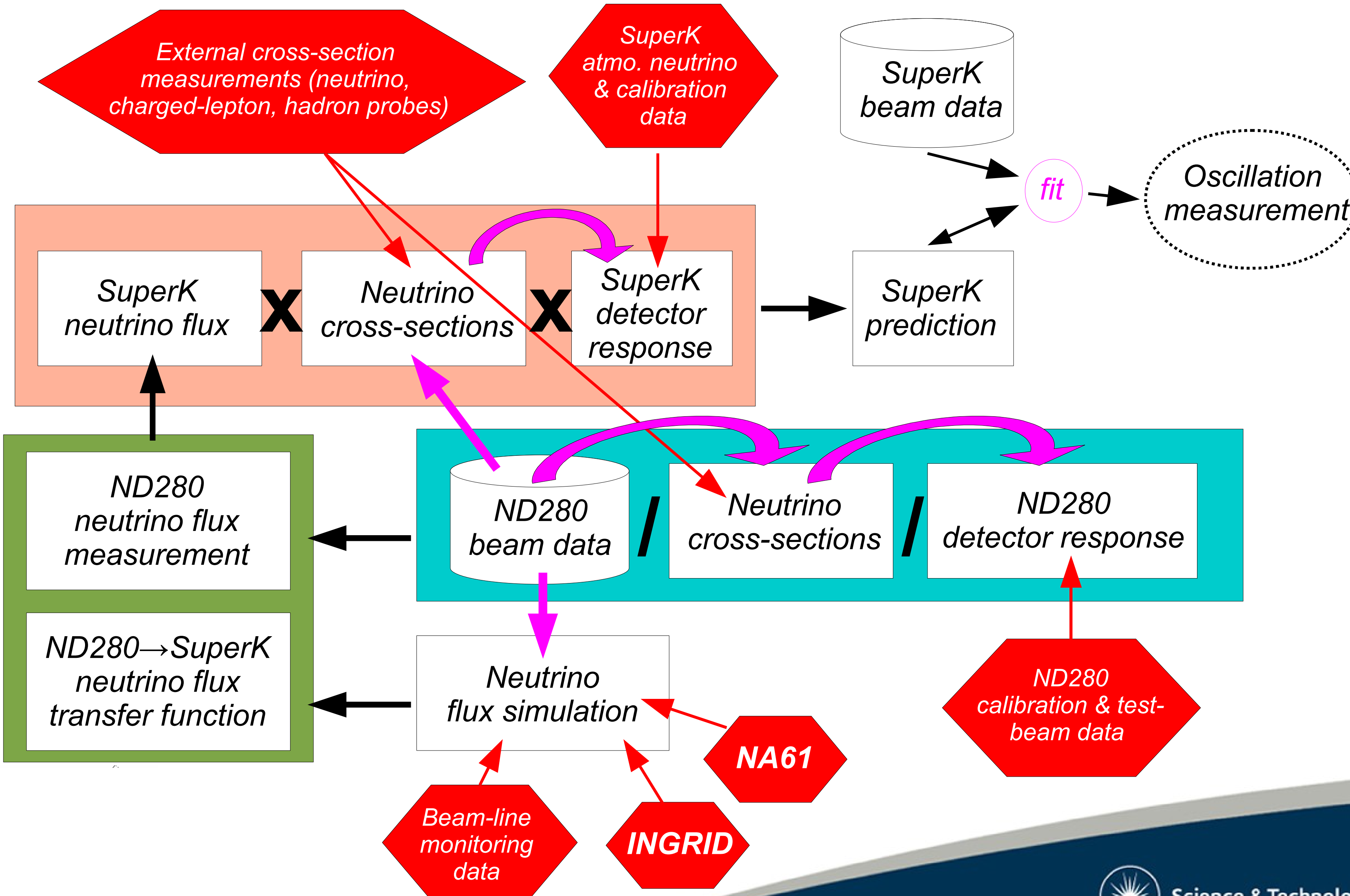
Analysis Flow



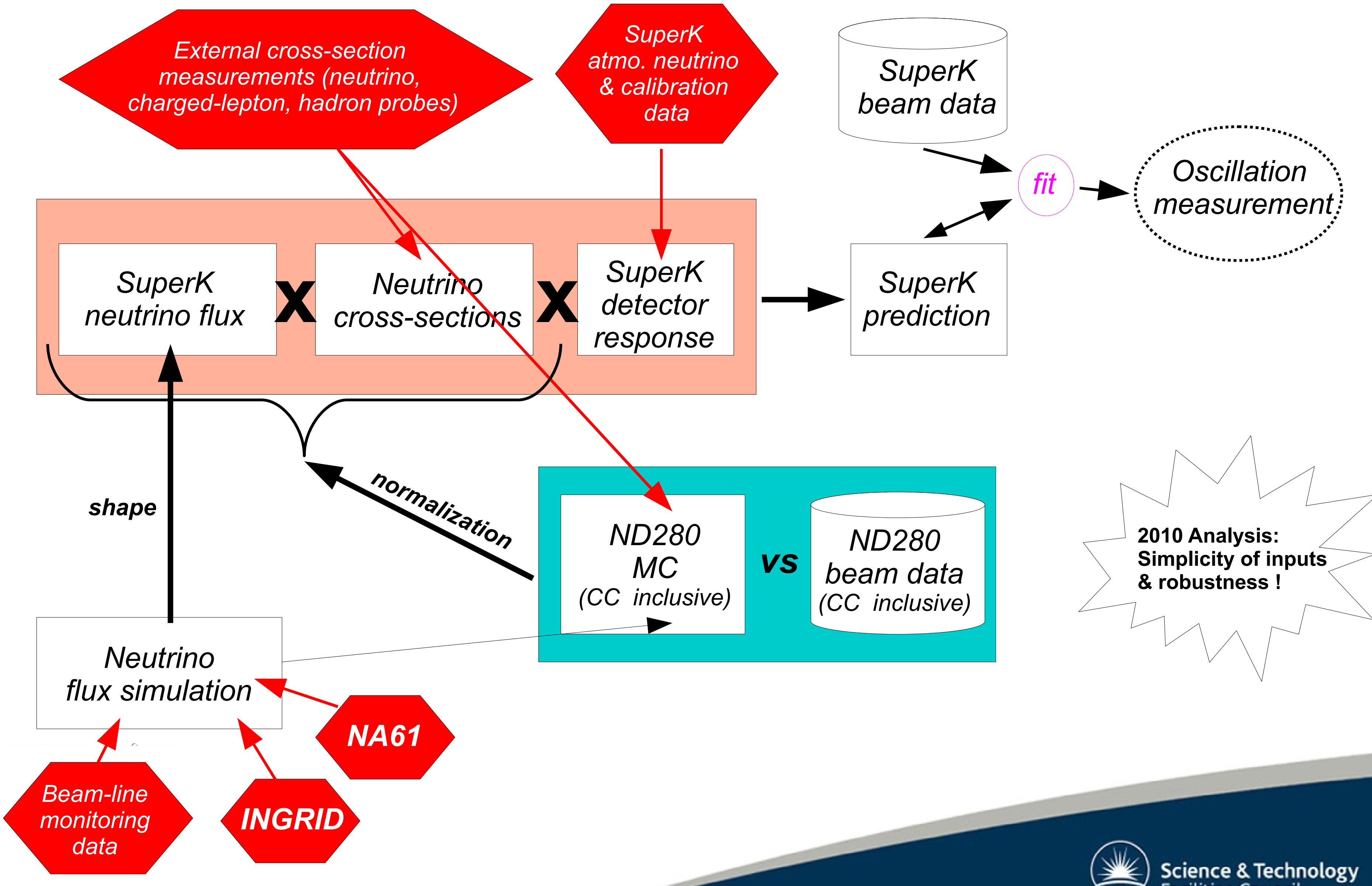
Analysis Flow



Analysis Flow



Analysis Flow (2010)



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