Imperial College London

Cross Section Measurements in T2K

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15th September 2012

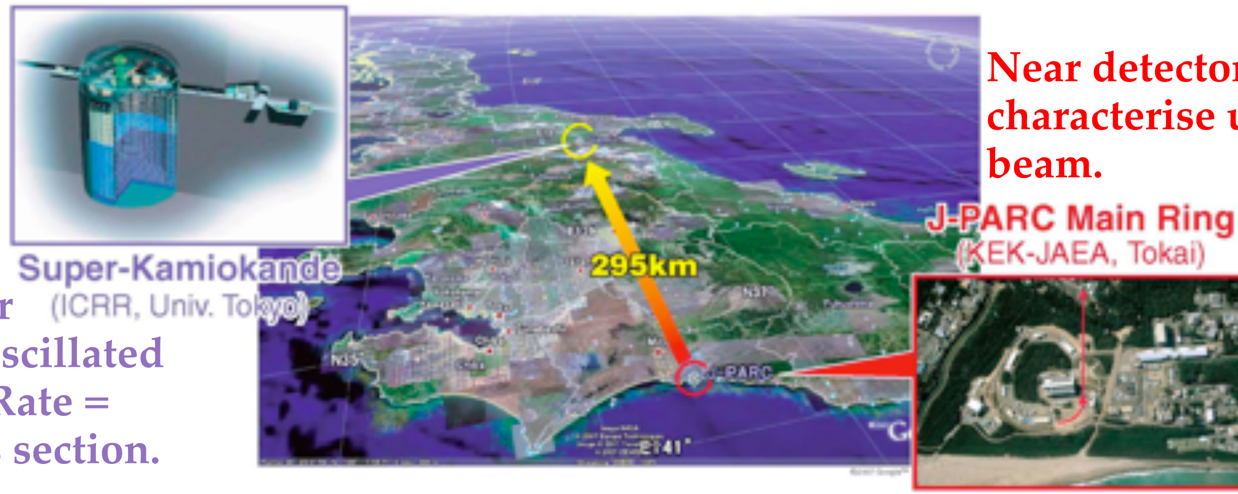
Outline of talk:

- *Overview of T2K and motivation for cross section measurements.*
- *The T2K near detector and event selections.*
- *First cross section results for charge current inclusive scattering.*

The T2K (Tokai-to-Kamioka) experiment

First off-axis long-baseline ν-oscillation experiment:

- Measure $\nu_\mu \rightarrow \nu_e$ appearance and precision ν_μ disappearance.
- ν_μ beam (~1% ν_e) with peak ~ 600 MeV → oscillation max @ far detector.



Near detectors @ 280 m characterise un-oscillated beam.

Far detector measures oscillated spectrum: Rate = flux × cross section.

Full T2K description: Nucl.Instrum.Meth. A659, 106 (2011), 1106.1238

In 2011 using (Run 1+2):

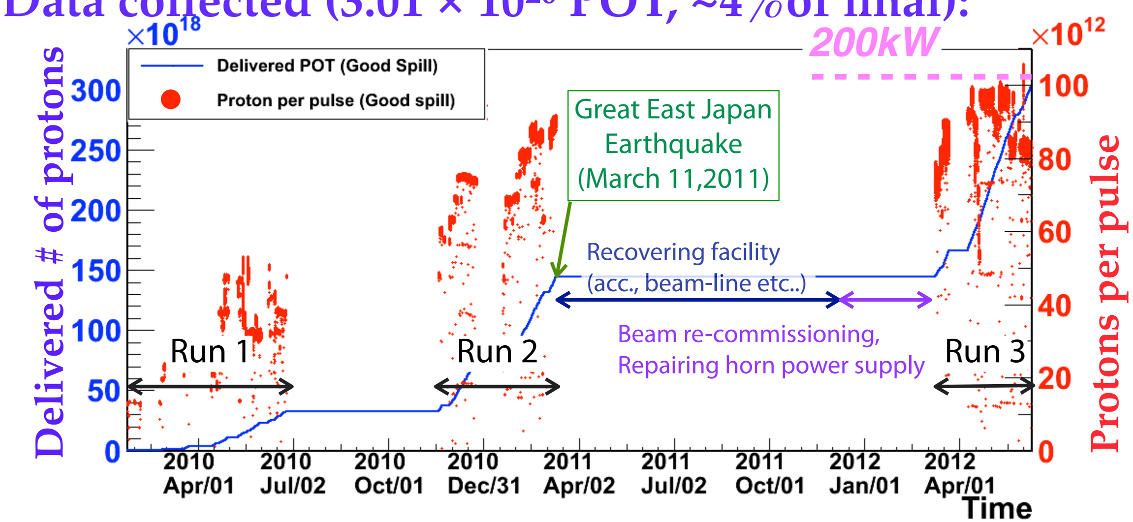
- **First indication of non-zero θ_{13} at 2.5σ significance** (Phys.Rev.Lett.107:041801,2011).
- **Also first off-axis ν_μ disappearance result** (Phys.Rev.D.85:031103,2012).

Earlier this year (Run 1+2+3):

- **Non-zero θ_{13} at 3.2σ!**

Covered in plenary talk by Gabriella Catanesi.

Data collected (3.01×10^{20} POT, ~4% of final):

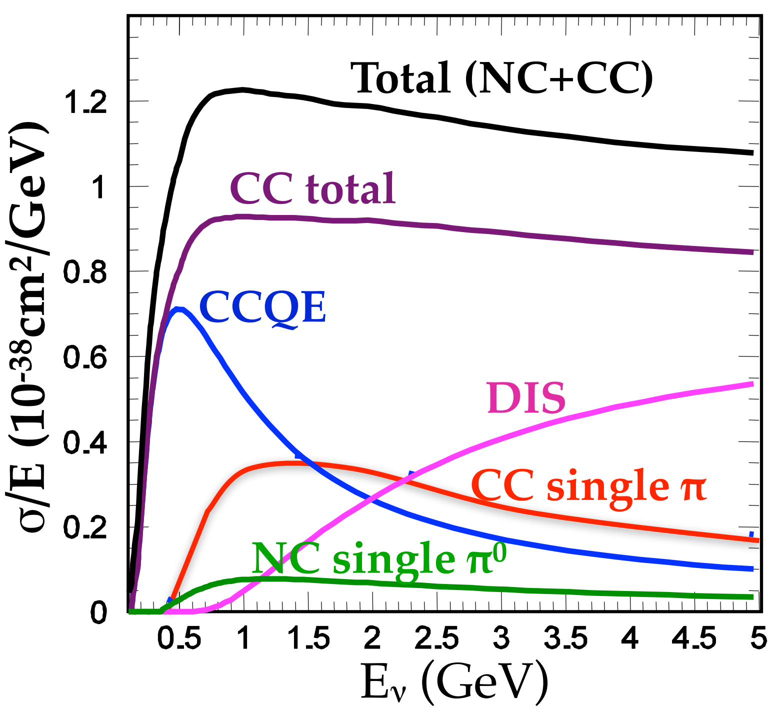


Motivation for cross section measurements

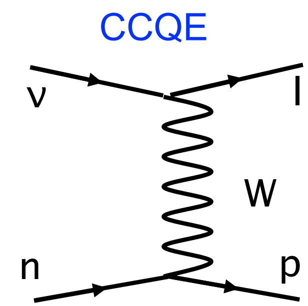
T2K now entering precision phase:

- At ~1 GeV ν cross sections poorly known. Not much data and need better theoretical models*.
- **Cross section measurements at T2K are important for both T2K and other experiments.**

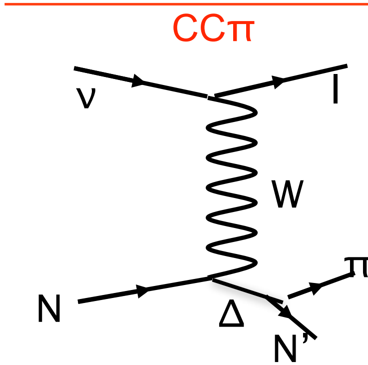
~1GeV → transition between CCQE, RES and DIS

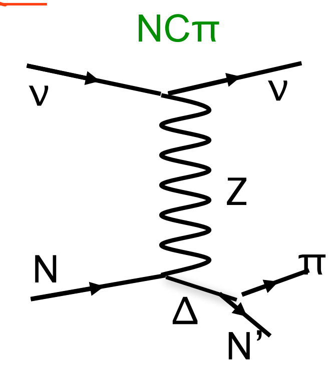


Signal is:



Mis-reconstruct as CCQE:





Lepton kinematics → E_ν:

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

+ DIS and other inelastic processes.

+ Final state interactions.

+ Nuclear modelling.

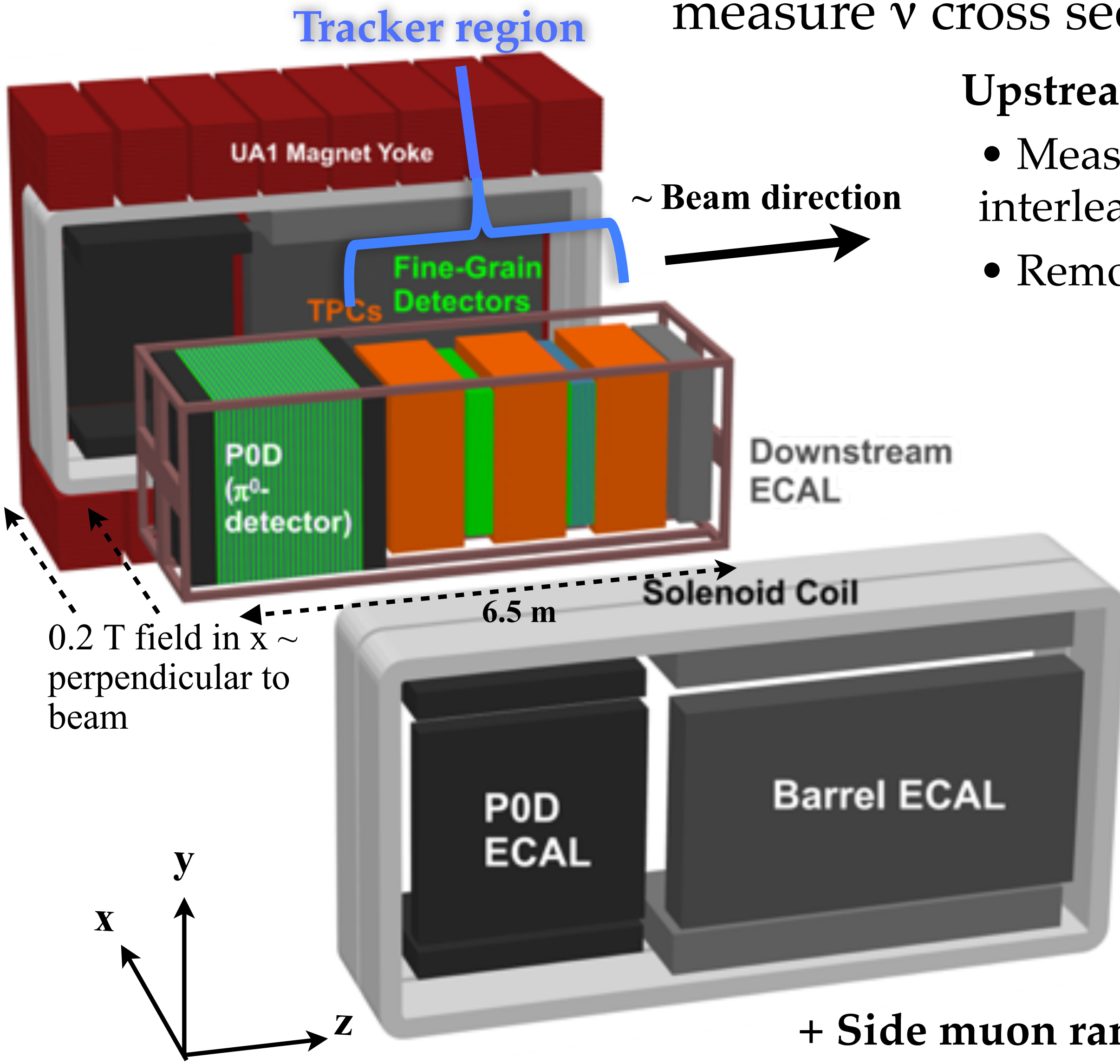
T2K uses two MC generators to simulate ν-interactions :

- **NEUT**: **Acta Phys. Polon. B40 (2009) 2477–2489.**
- **GENIE**: **Nucl. Instrum. Meth. A614 (2010) 87–104.**

* *Good summary of neutrino nucleus interactions:* ***Ann.Rev.Nucl.Part.Sci. 61 (2011) 355-378.***

The T2K off-axis near detector (ND280)

280m downstream of beam production → characterise beam before osc and measure ν cross sections.



Upstream is P0D:

- Measure π^0s (plastic scintillator planes interleaved with brass and lead, ~13.3 tons).
- Removable H_2O targets (~2.8 tons).

Downstream is tracker:

Measure charged current interactions:

- **2 FGDs:**
  - 1.1 tons each, Carbon + H_2O targets.
  - Tracking and PID.
- **3 TPCs:**
  - Tracking, momentum and PID.

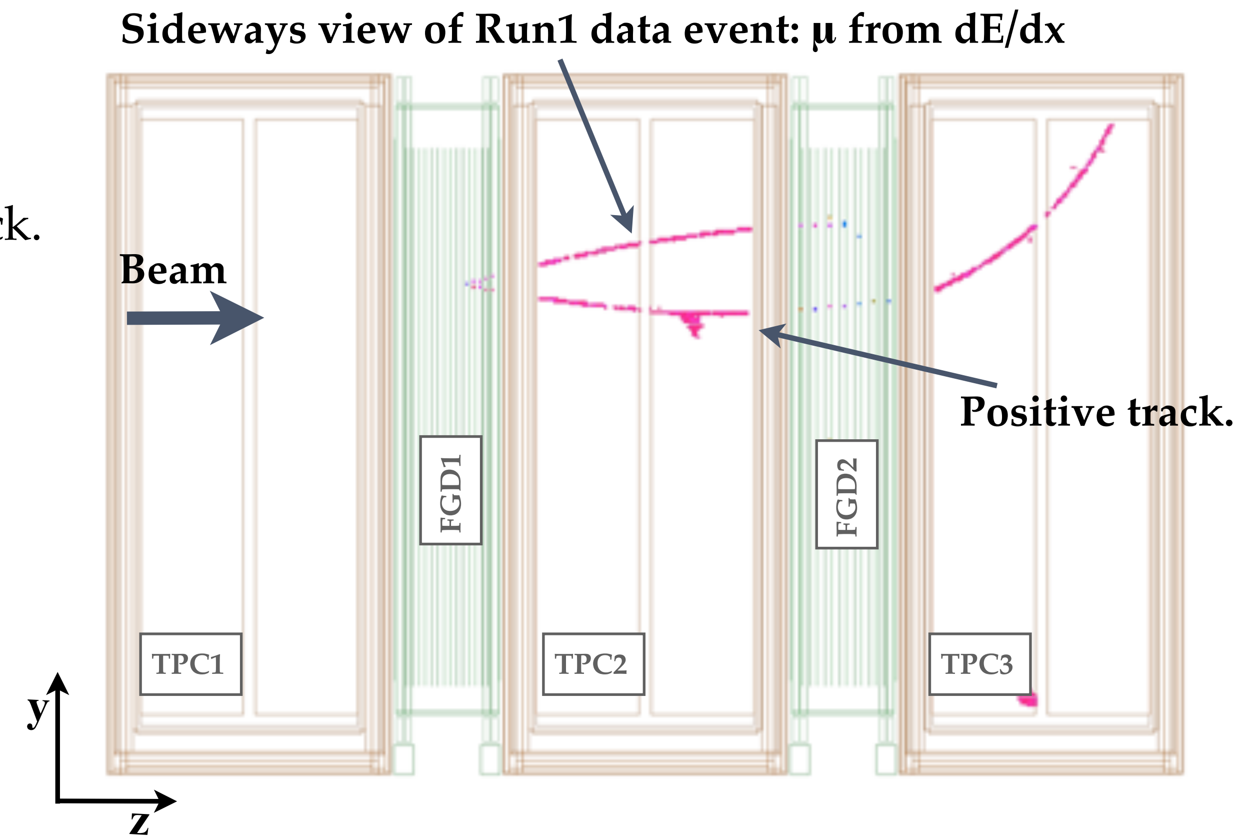
ECals surround P0D and tracker:

- Provide tracking and PID.

+ Side muon range detector (SMRD): Embedded in magnet yoke.

Tracker-based ν_μ selection

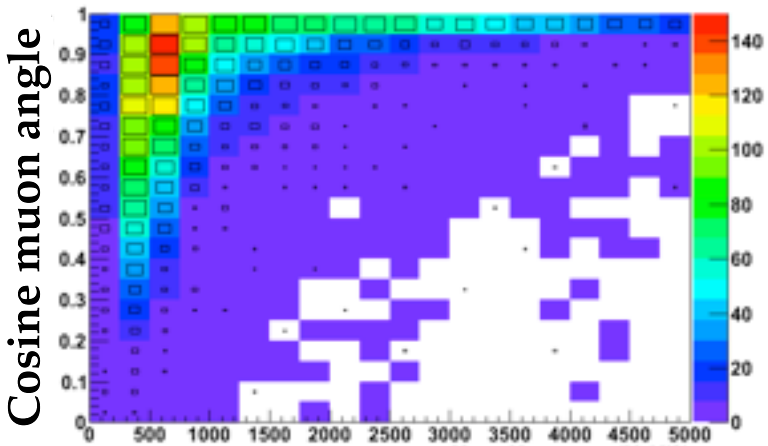
- **Select ν_μ-CC in FGD1:**
  - Negative TPC-FGD1 matched track.
  - Forward-going.
  - TPC1 veto.
  - TPC PID: dE/dx → muon.
- **Subdivide into CCQE-like:**
  - Only 1 TPC-FGD matched track.
  - No Michel electron signal in FGD1.
- **And all else = CCnQE-like.**



Binned output in terms of reconstructed lepton angle and momentum.

Results for Run 1+2 data

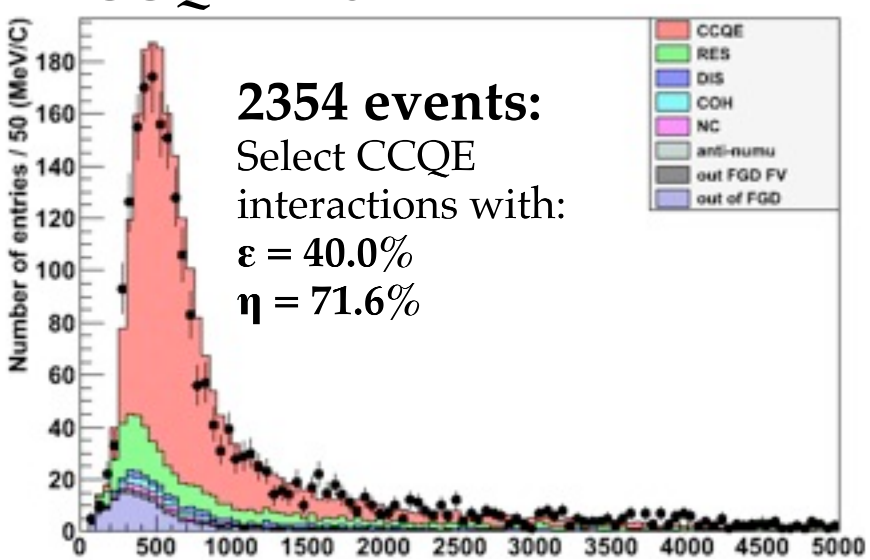
Select 4485 ν_μ CC candidates in FGD1:



Muon momentum (MeV/c)

- 1.08×10^{20} POT.
- Efficiency ~40% (forward peaked acceptance.)
- ~13% BG contamination:
  - 9% Non-FGD:
    - 7% Outside-FGD.
    - 1% Outside FV but inside FGD.
    - 1% Outside magnet.
  - 3% NC.
  - 1% CC ν_e or anti-ν_e/ν_μ.

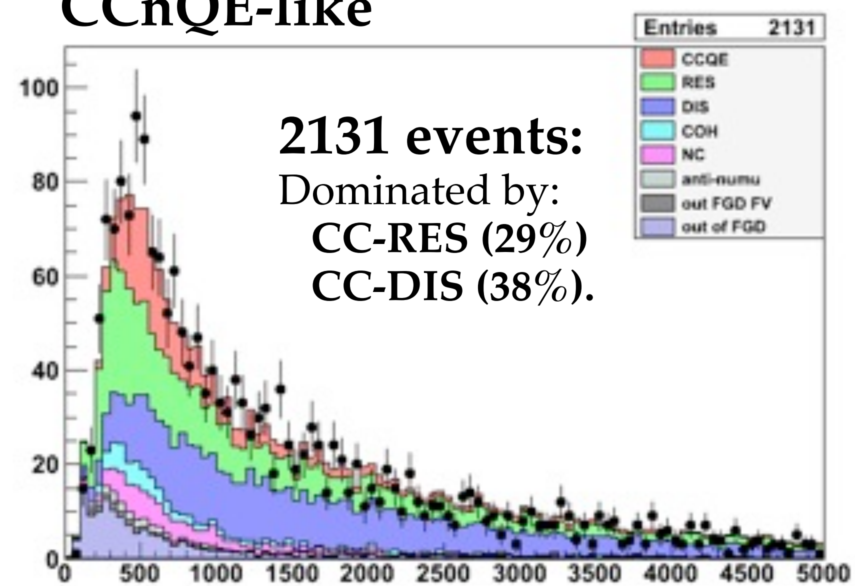
CCQE-like



2354 events:
Select CCQE interactions with:
ε = 40.0%
η = 71.6%

Muon momentum(MeV/c)

CCnQE-like



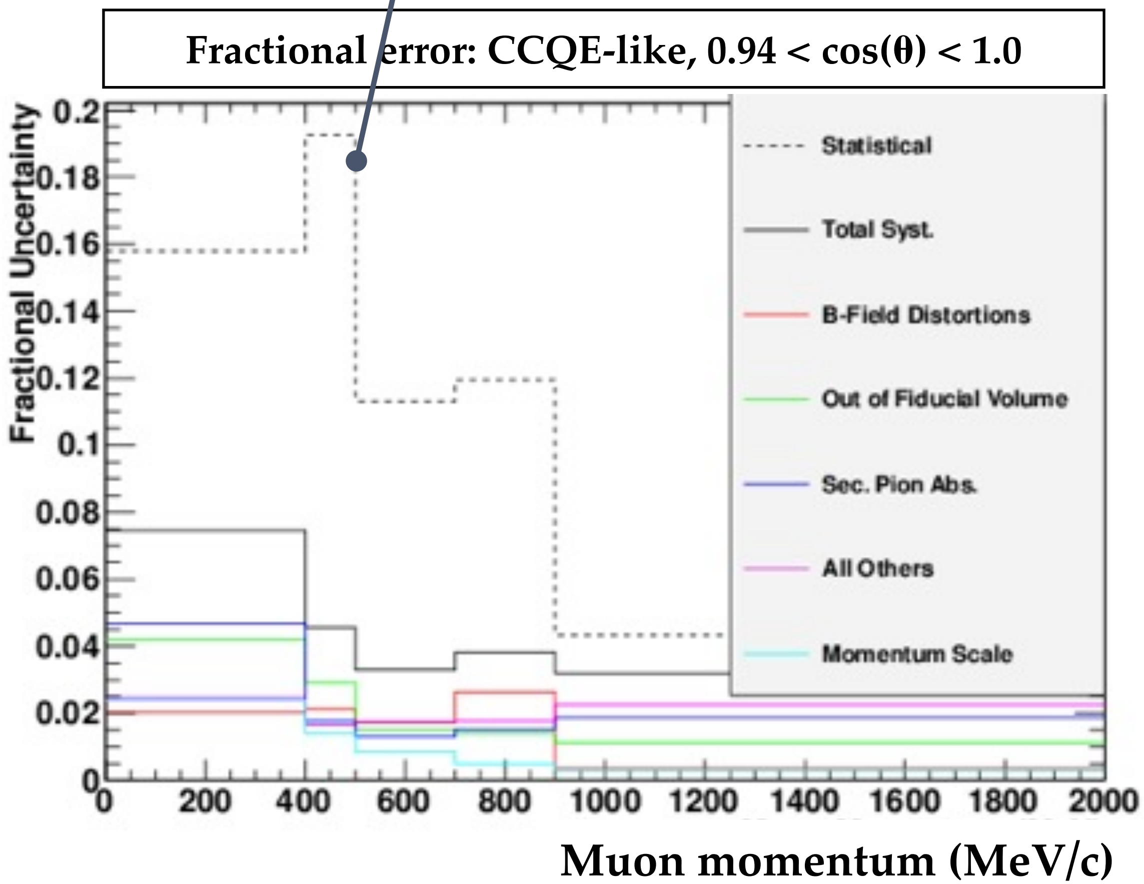
2131 events:
Dominated by:
CC-RES (29%)
CC-DIS (38%).

Muon momentum (MeV/c)

ν_μ detector systematics

- Many considered - dominant sources:
  - **Magnetic field distortions** (scale, non-linearities, mis-alignments):
    - Momentum bias, track matching and TPC-PID.
  - **Out of fiducial volume events**:
    - Mis-reconstruct incoming particle stopping in FGD as outgoing.
    - Reconstruction failures break through-going.
    - Neutral particles from outside tracker.
  - **Secondary pion absorption in detector:**
    - Migration between CCQE and CCnQE.

Stat errors dominate

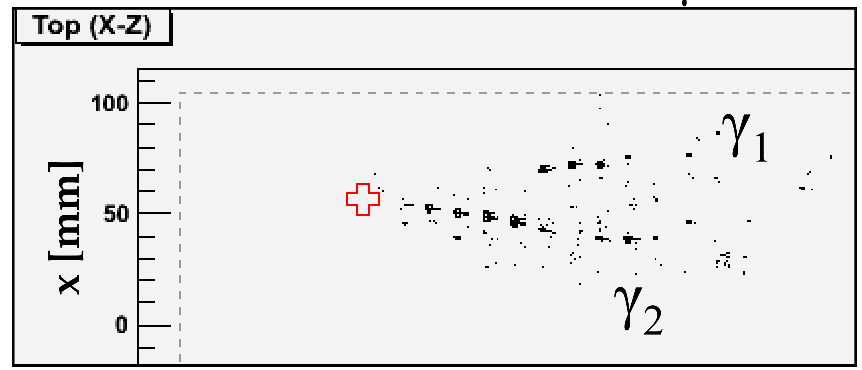


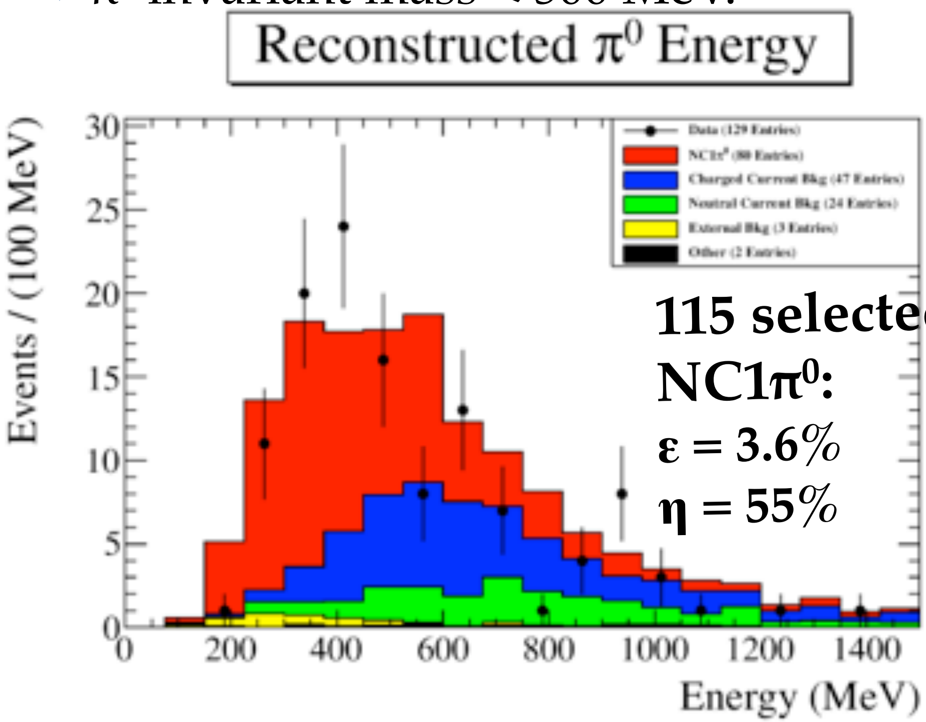
Other ND280 samples: P0D NC-π^0

Look for 2 γ's from π^0 decay:

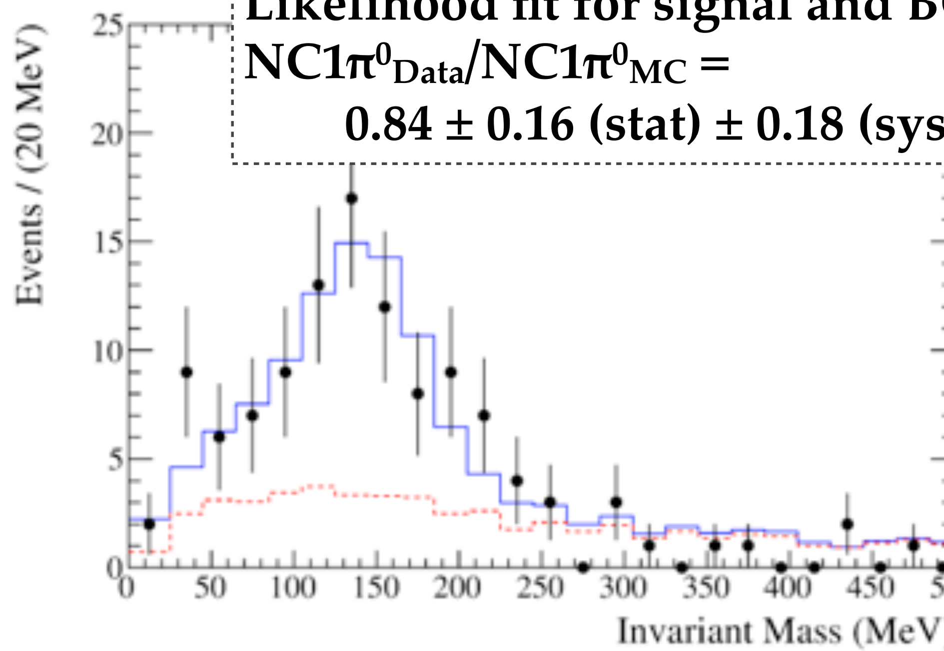
- Vertex in P0D FV (***H_2O ~1900 kg, Scintillator ~2675 kg and Brass ~740 kg).***
- No μ-like tracks.
- 2 EM-like ($\pi^0 \rightarrow 2\gamma$) in forward dir.
- Energy based PID for μ/EM separation.
- π^0 invariant mass < 500 MeV.

MC simulation of energy deposits for NCπ^0 interaction → 2γ.





115 selected NC1π^0:
ε = 3.6%
η = 55%



Likelihood fit for signal and BG:
$NC1\pi^0_{Data}/NC1\pi^0_{MC}$ =
0.84 ± 0.16 (stat) ± 0.18 (syst)

Plus many other (CC and NC) Tracker, P0D and ECal selections in development.

T2K's first cross section measurement

ν_μ-CC differential cross section

- Use tracker-based ν_μ CC inclusive (CCQE-like + CCnQE-like).
- Flux averaged double differential cross section:

$$\langle \frac{\partial^2 \sigma}{\partial p_\mu \partial \cos\theta_\mu} \rangle_{kl} = \frac{\widehat{N}_{kl}}{T\phi \Delta p_{\mu,k} \Delta \cos\theta_{\mu,l}}$$

- N_{kl} = number of events in true p_μ bin k and true θ_μ bin l:
  - Inferred from reconstructed kinematics using unfolding algorithm.
- T is the number of target nucleons/nuclei.
- ϕ is the integrated flux at the near detector.
- $\Delta p_{\mu,k}$ and $\Delta \cos\theta_{\mu,l}$ are bin widths.

Unfolding algorithm

- Bayesian unfolding method to infer # events in true bin t_k:

$$N_{t_k} = \frac{1}{\epsilon_k} \sum_{j=1}^{n_r} P(t_k|r_j) \times (N_{r_j}^{meas} - \frac{n_{POT}^{Data}}{n_{POT}^{MC}} \times B_{r_j})$$

Efficiency for reconstructing CC inclusive event in true bin k.

Sum over n_r reconstructed bins (0 → 19).

Unsmearing matrix: Gives probability of event in true bin t_k given event in reconstructed bin r_j(details on next slide).

Measured number of events in reconstructed bin r_j.

Purity correction based on MC prediction of BG.

The Unsmearing matrix

- Bayes' theorem → probability event in true bin t_k given in reco bin r_j:

$$P(t_k|r_j) = \frac{P(r_j|t_k)P(t_k)}{\sum_{\alpha=1}^{n_t} P(r_j|t_\alpha)P(t_\alpha)}$$

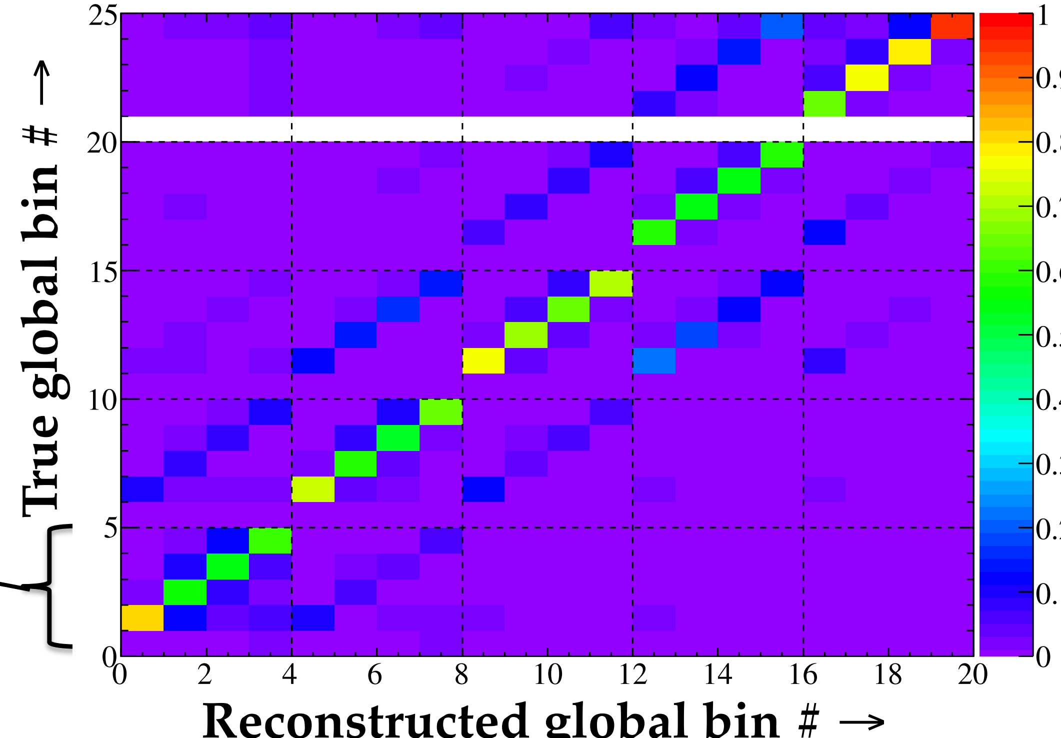
Directly from MC.

Unsmearing matrix for NEUT MC for ν_μ CC (CCQE-like + CCnQE-like):

Binning convention:

- 5 bins p_μ (GeV):
  - *0→0.4→0.5→0.7→0.9→∞*
- 4/5 bins $\cos(\theta_\mu)$:
  - *Reco:-1→0.84→0.9→0.94→1.0*
  - *True:-1→0→0.84→0.9→0.94→1.0*

20(25) global bins in increasing (true) momentum/angle: single momentum bin subdivided into angular bins.



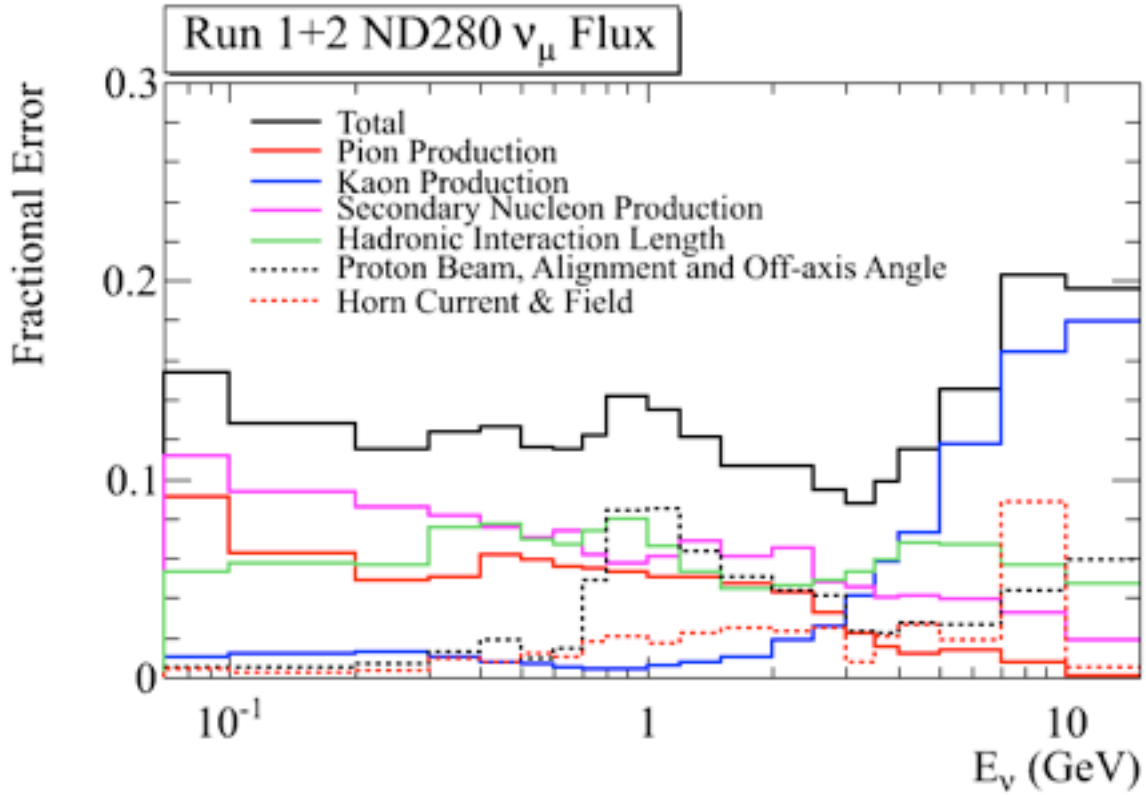
Neutrino interaction modelling uncertainties

- Rely on neutrino interaction MC for prediction of BGs and efficiency corrections.
- Parameterisation of NEUT MC and uncertainties from fits/comparisons to external data.

	Parameter	E_ν Range	Nominal	Error	CCQE	CCnQE	Total
QE shape and normalisation	M_A^{QE}	all	1.21 GeV/c^2	0.45	15.5%	5.2%	10.5%
	CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11	6.7%	1.5%	4.2%
	CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30	6.7%	1.5%	4.2%
	CCQE E3	$E_\nu > 3.5$	1.0	0.30	6.7%	1.5%	4.2%
Nuclear model	p_F ^{12}C	all	217 MeV/c	30	1.6%	0.2%	0.8%
	SF ^{12}C	all	0 (off)	1 (on)	0.9%	0.8%	0.6%
1π production shape and normalisation.	M_A^{RES}	all	1.16 GeV/c^2	0.11	3.7%	6.0%	4.8%
	CC1π E1	$0 < E_\nu < 2.5$	1.63	0.43	3.7%	6.0%	4.8%
	NC1π^0	all	1.19	0.43	3.7%	6.0%	4.8%
	CC1π E2	$E_\nu > 2.5$	1.0	0.40	1.9%	4.8%	3.2%
	CC Coherent	all	1.0	1.0	1.7%	3.9%	2.7%
Other (DIS, COH, NC)	CC Oth shp	all	0.0	0.40	0.7%	3.5%	2.0%
	NC Other	all	1.0	0.30	0.5%	1.6%	1.0%
	W Shape	all	87.7 MeV/c^2	45.3	0.6%	2.2%	0.9%
Final state interactions	FSI	all	Section 2.1		0.5%	0.7%	0.2%
	Total				17.0%	10.1%	12.8%

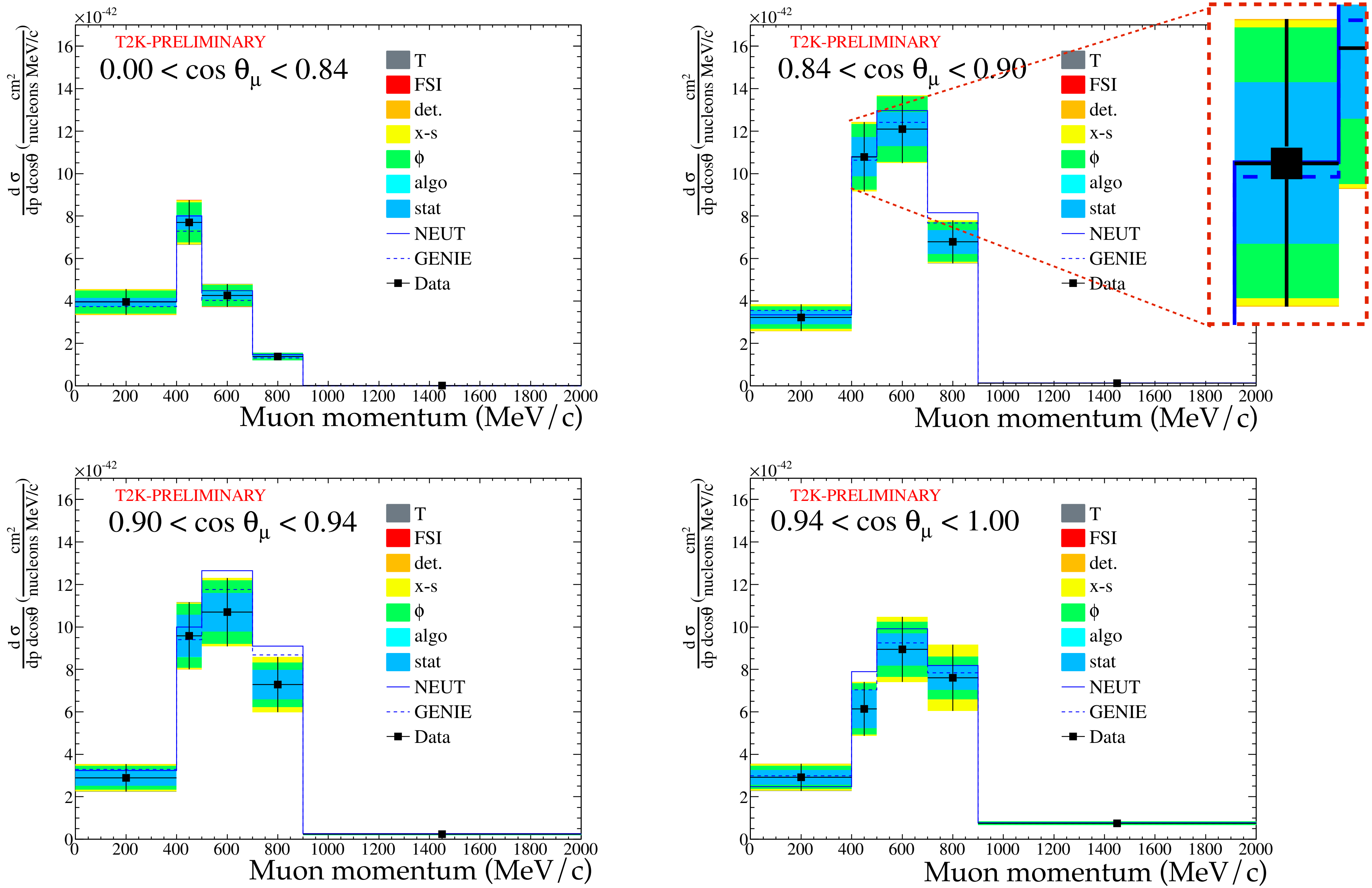
Flux, detector and statistical uncertainties

- **Flux:**
  - Based on fits/constraints to NA61(π and K) and external hadron production data + beam run conditions.
- **Detector:**
  - Described earlier - use combined CCQE-like and CCnQE-like covariance matrices.
- **Statistical:**
  - Toy-experiments where fake data and MC are fluctuated according to poisson statistics.



Reweighting methods + Cholesky decomposition → account for correlations.

Differential cross section results



Integrated cross section

T2K measured (unfolded with NEUT):

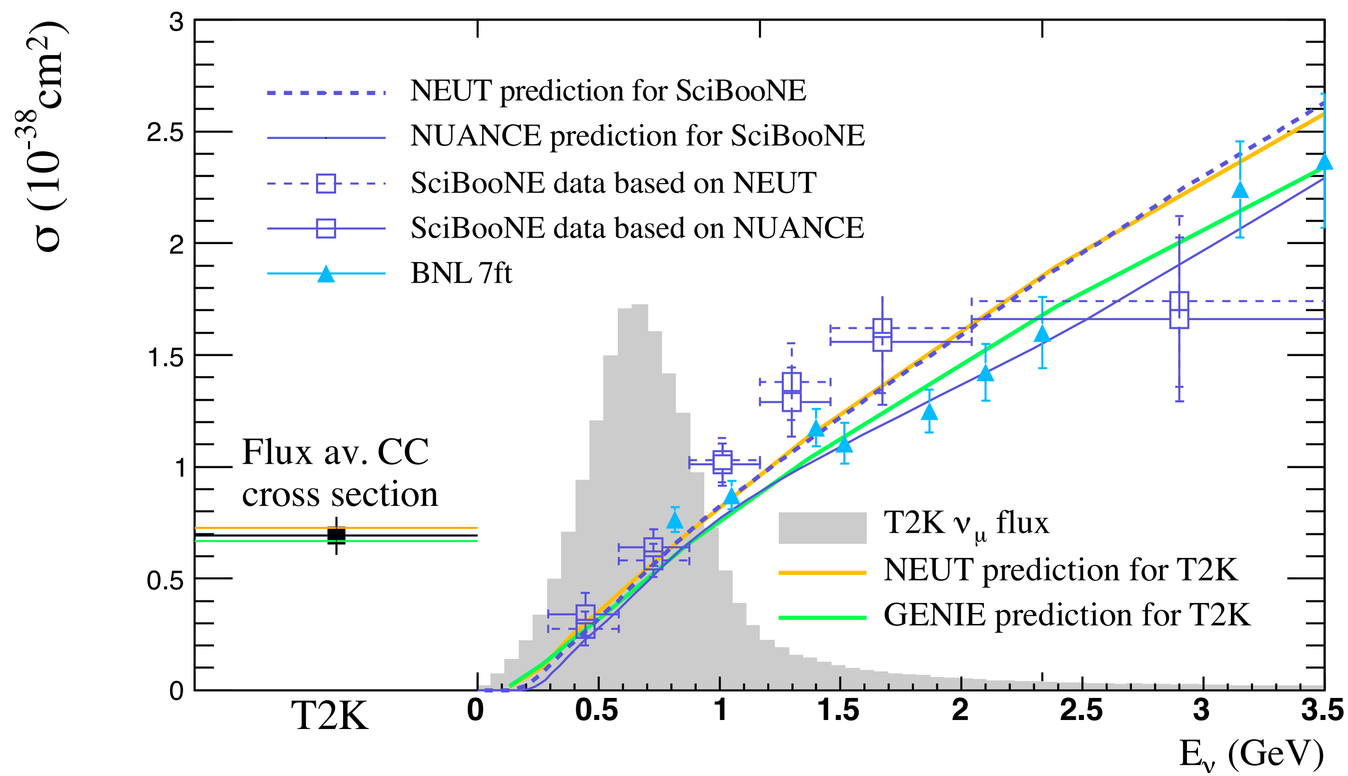
$$\langle \sigma_{CC} \rangle_\phi = (6.93 \pm 0.13(stat) \pm 0.85(syst)) \times 10^{-39} \mathrm{cm}^2/\mathrm{nucleon}$$

MC:

$$\langle \sigma_{CC}^{\mathrm{NEUT}} \rangle_\phi = 7.26 \times 10^{-39} \mathrm{cm}^2/\mathrm{nucleon}$$

$$\langle \sigma_{CC}^{\mathrm{GENIE}} \rangle_\phi = 6.68 \times 10^{-39} \mathrm{cm}^2/\mathrm{nucleon}$$

Compare to other experiments by showing w.r.t T2K flux (mean energy 0.85 GeV) →

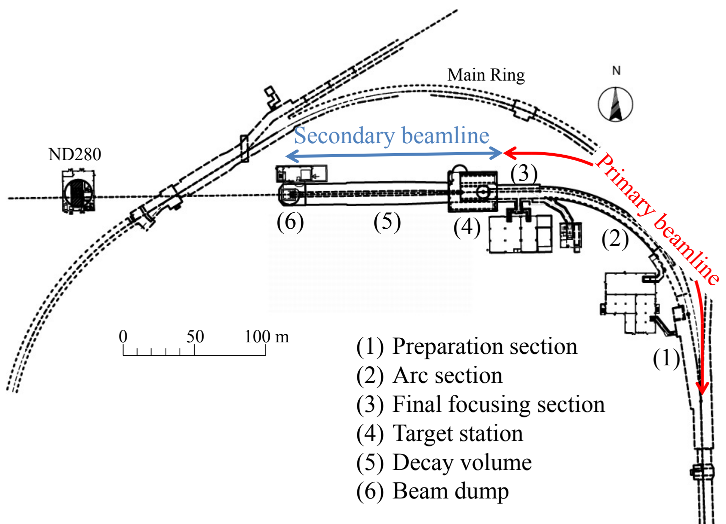


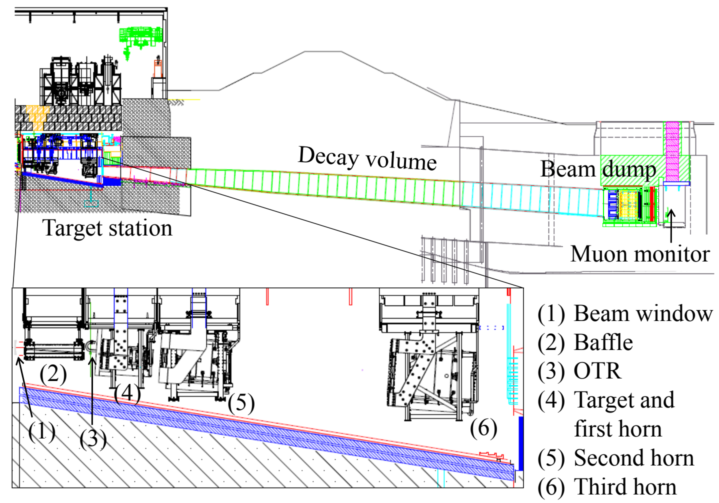
Summary and outlook

- Cross section measurements at ND280 important for T2K and other beam experiments.
- Selections developed at ND280 → constrains rate at far detector as well as checks on BG rates.
- First ν_μ CC inclusive cross section result from ND280.
- Cross section publications under preparation.
- Only 4% of final data:
  - More cross section measurements expected (NCπ0, CC-1π, etc...).

BACKUP SLIDES

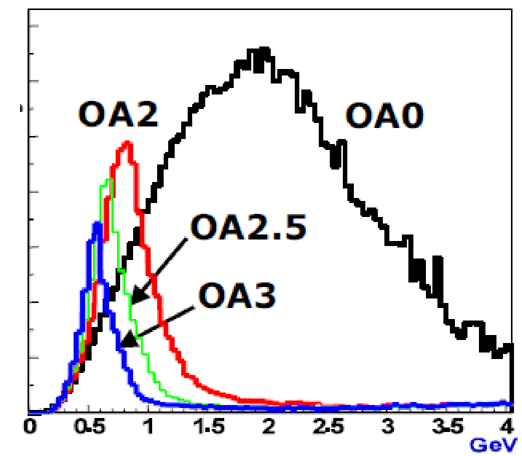
The T2K neutrino beam

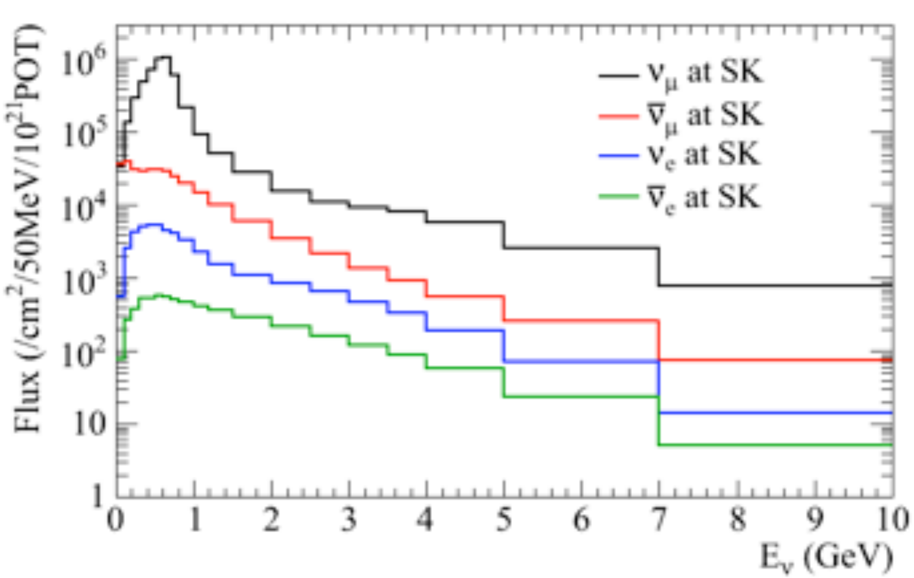


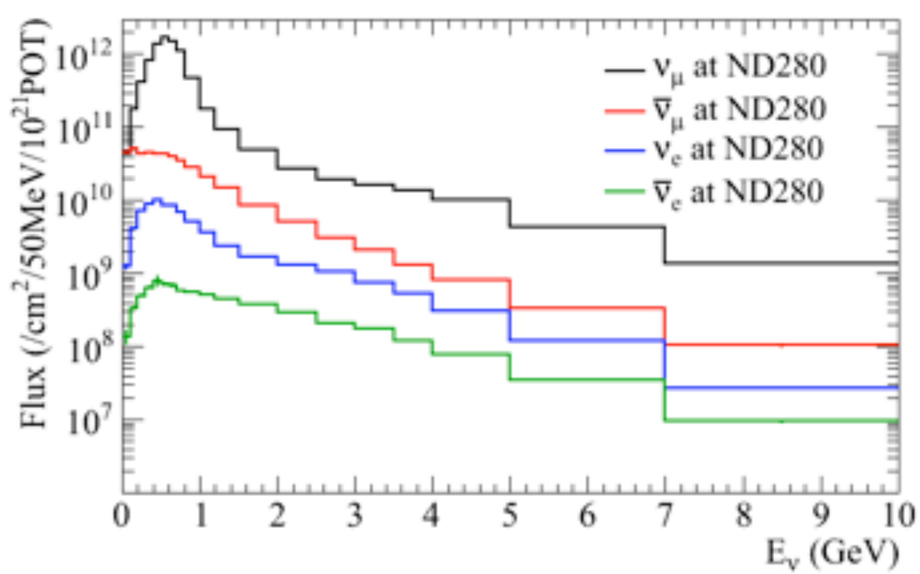


30 GeV protons @ 200 kW

Off-axis @ far detector:
- Narrow band.
- Peak @ osc maximum.

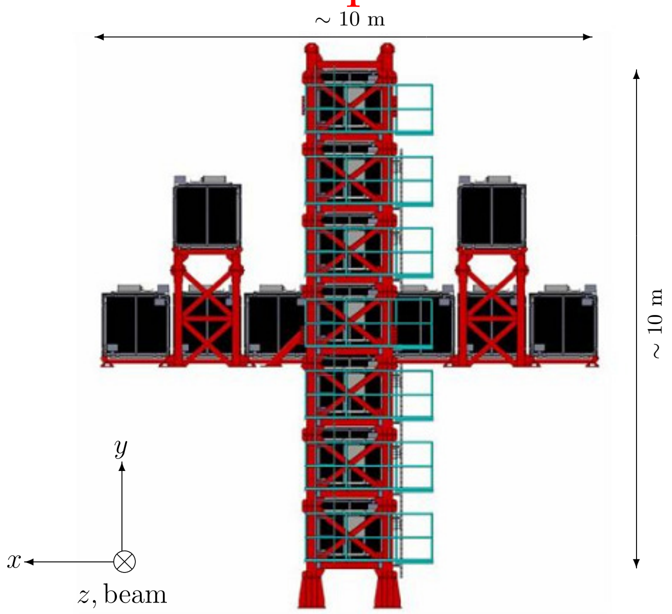




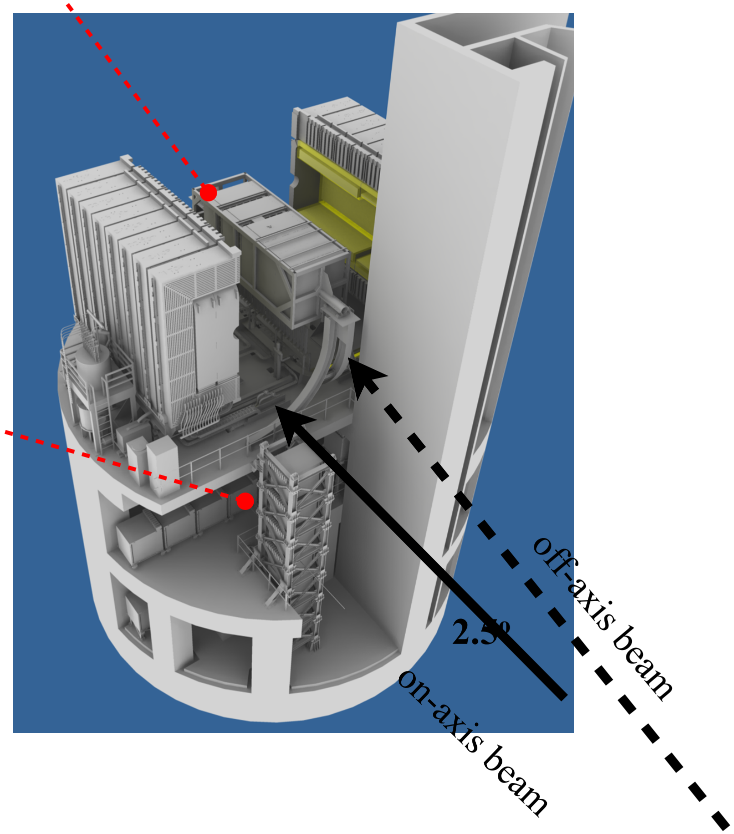


The T2K near detector suite @ 280 m

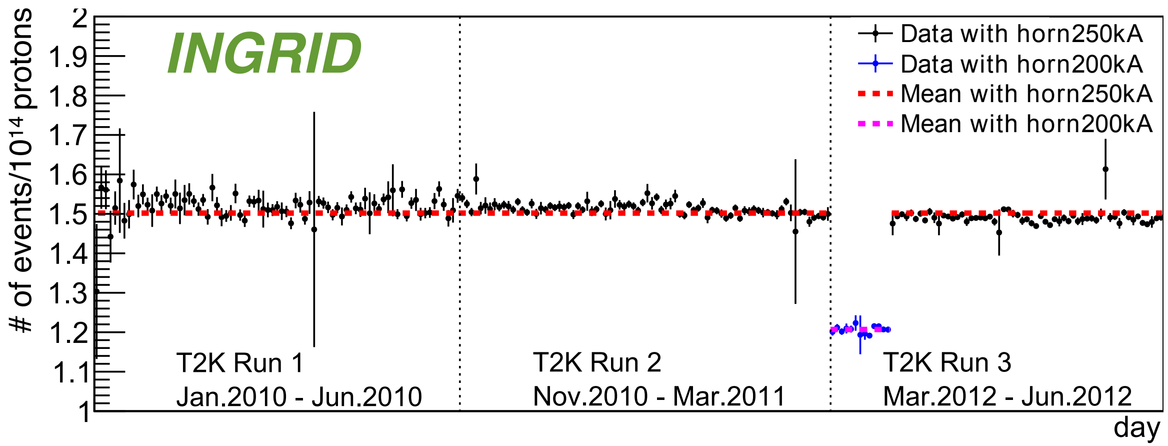
INGRID: beam profile and rate.



ND280: beam composition, off-axis rate and BG processes.



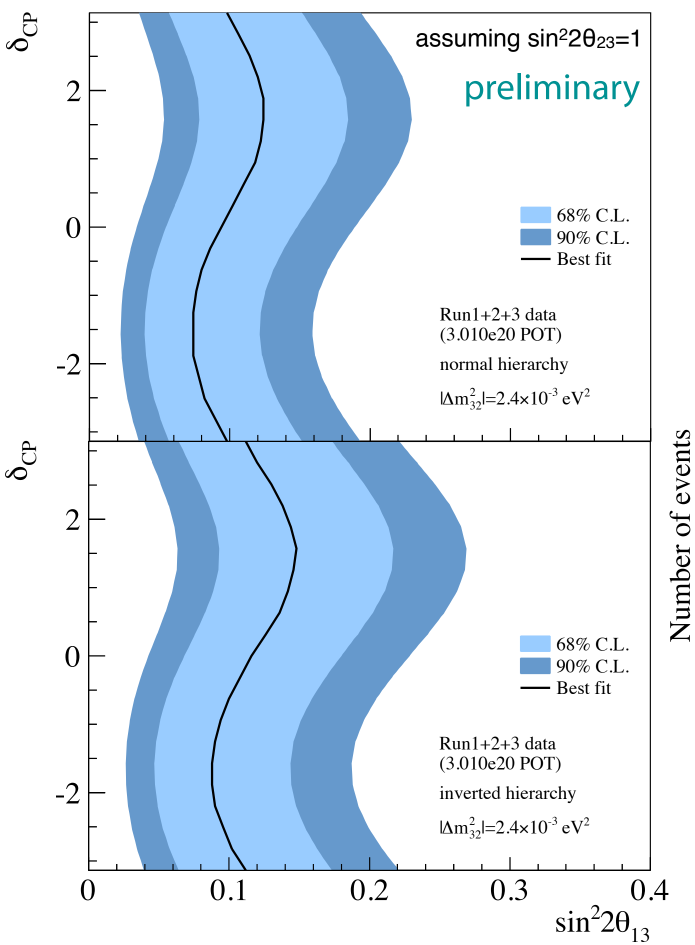
Measurement of beam stability:

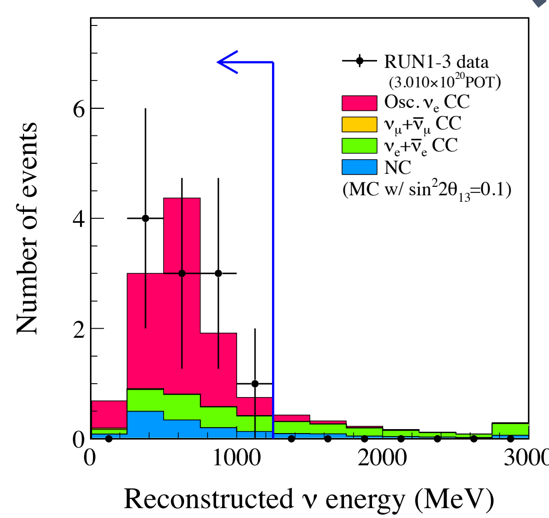


Recent T2K physics results

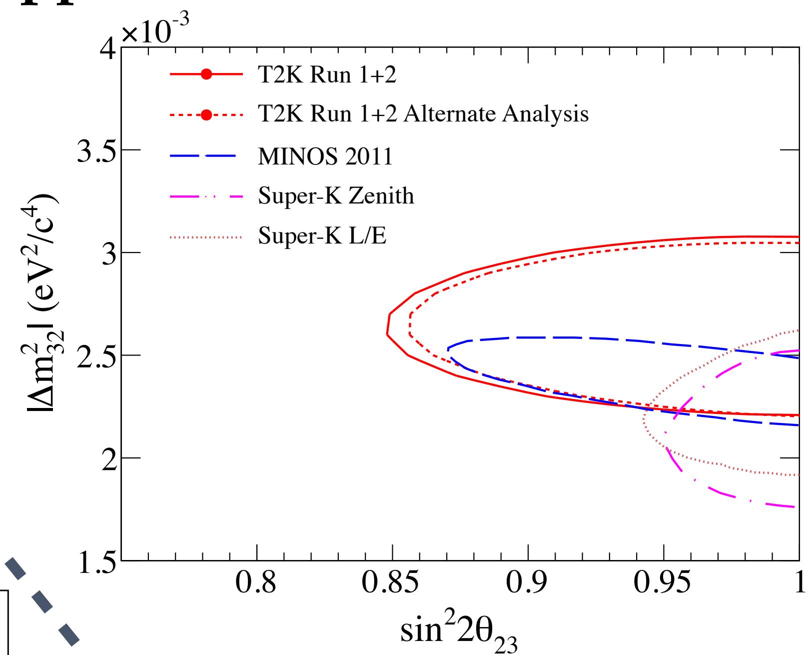
ν_e appearance results with Run 1 + 2 + 3:

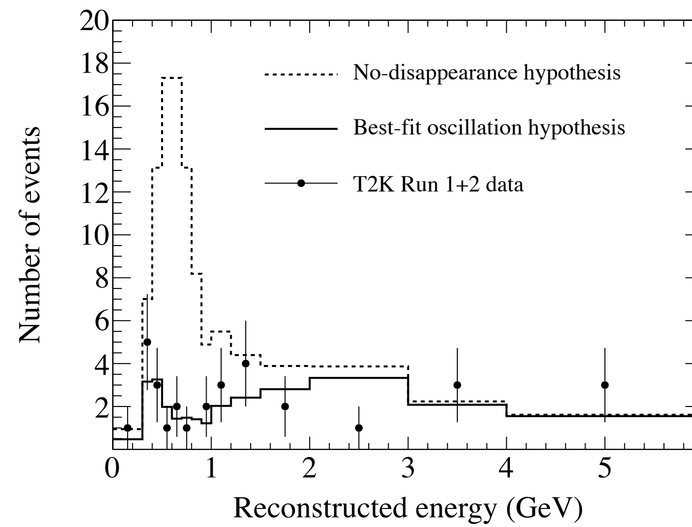
- **Non-zero θ_{13} at 3.2σ!**





ν_μ-disappearance with Run 1 + 2:



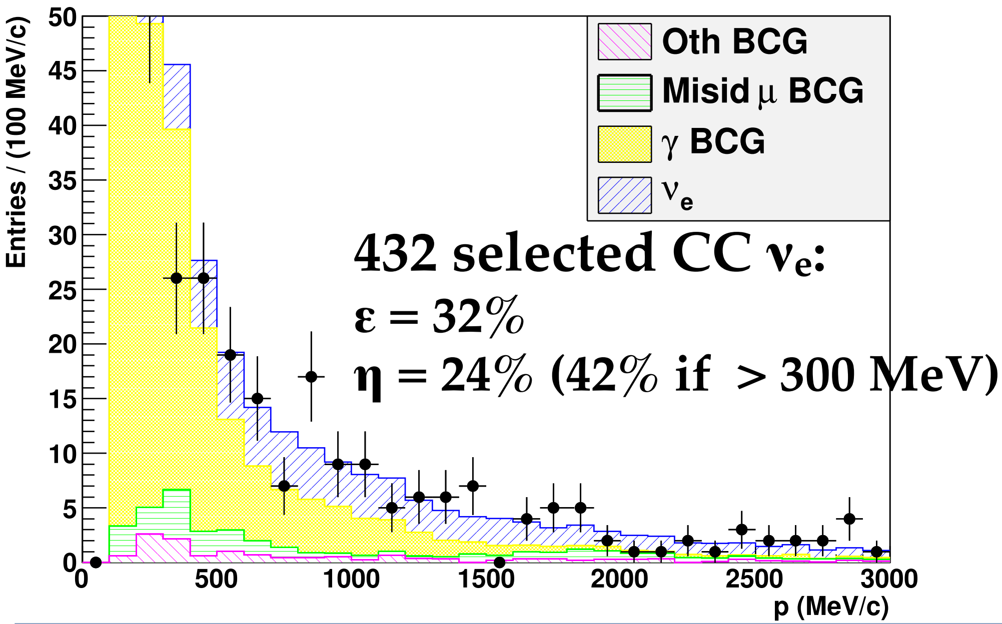


ND280 ν_e selections

Measure beam ν_e contamination → ν_e appearance BG.

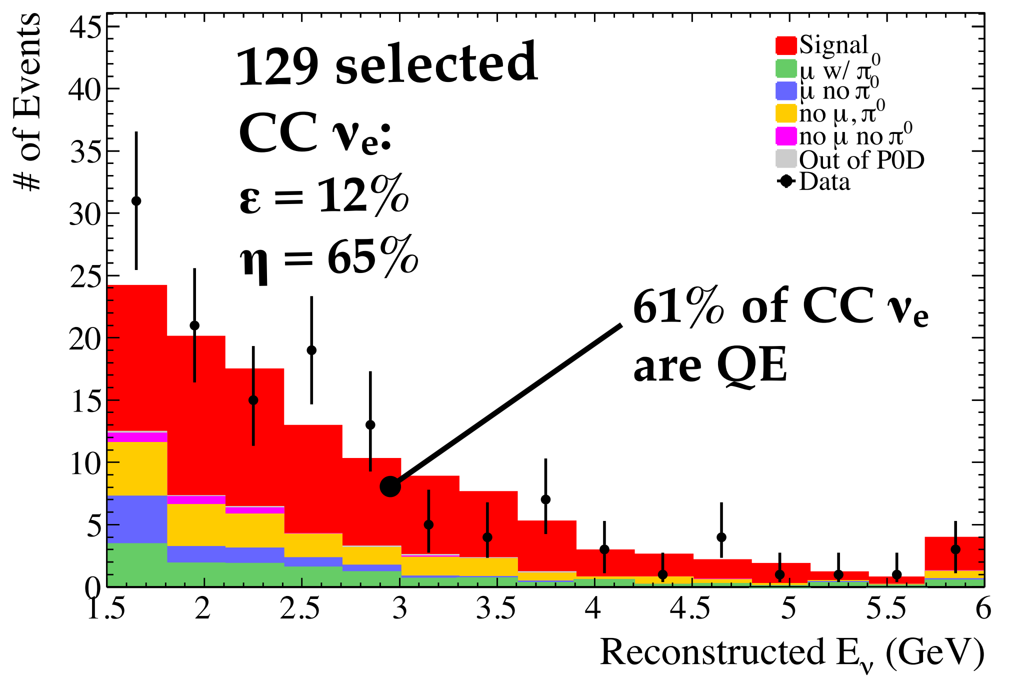
Tracker ν_e:

- Select tracks in FGD1 FV as in Tracker-ν_μ.
- TPC and ECal PID select electrons.
- Very challenging as ~1% νe comp to BG:
  - Large amount of μ's from ν_μ interactions.
  - Large amount of e+/e- (γ-conversion in FGD).
- Fit to extract Data/MC scale factor:
  - **$f(\nu_e) = 0.845 \pm 0.15(\text{stat}) \pm 0.11(\text{syst})$**



P0D high energy ν_e:

- Run 1+2 water-in (8.6×10^{19} POT).
- Single P0D track in FV.
- Track width > 1mm (reject MIP-like).
- No additional low-pT (reject π^0 γ's).
- Reco Eν > 1.5 GeV (assume QE-kinematics).

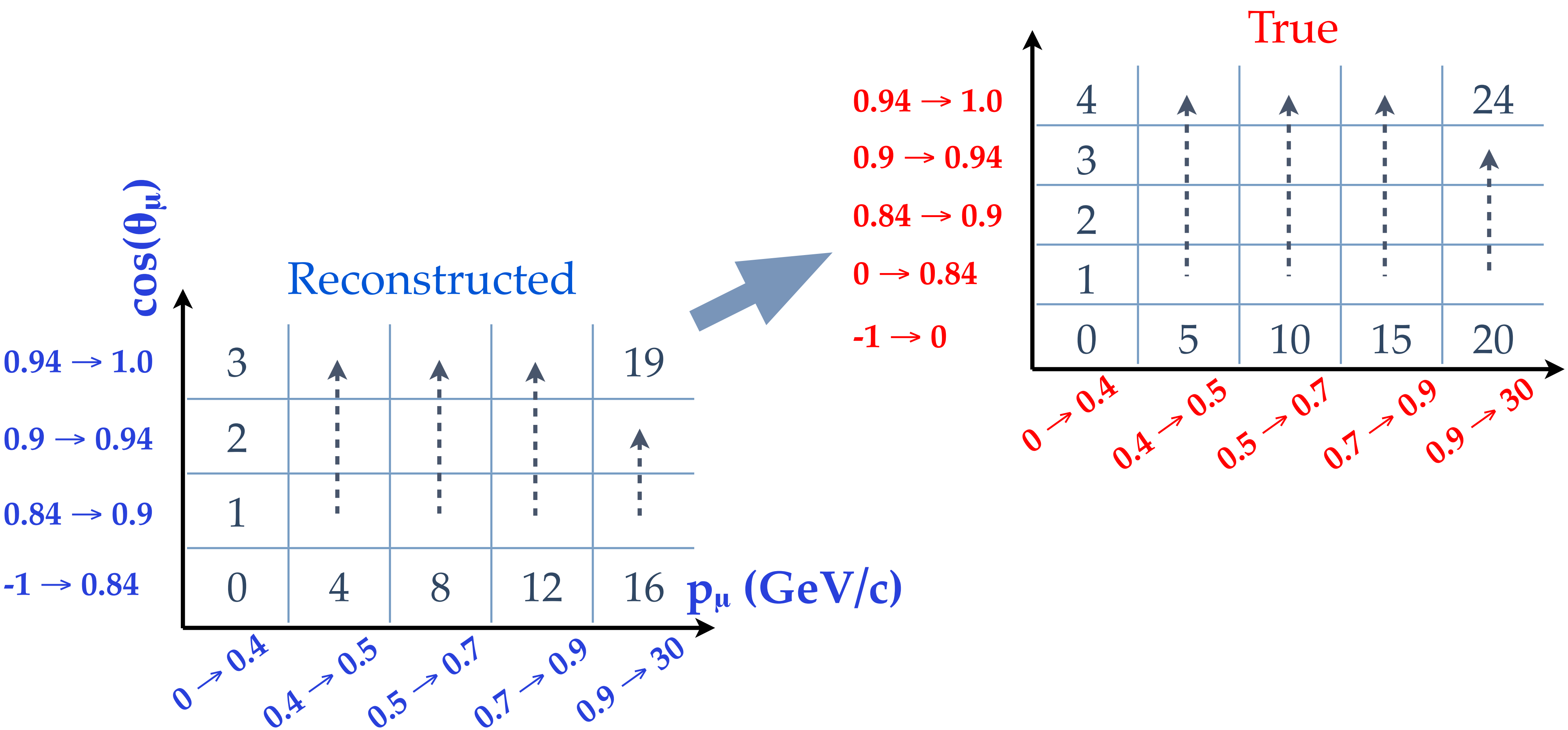


Tracker-based CC ν_μ cuts

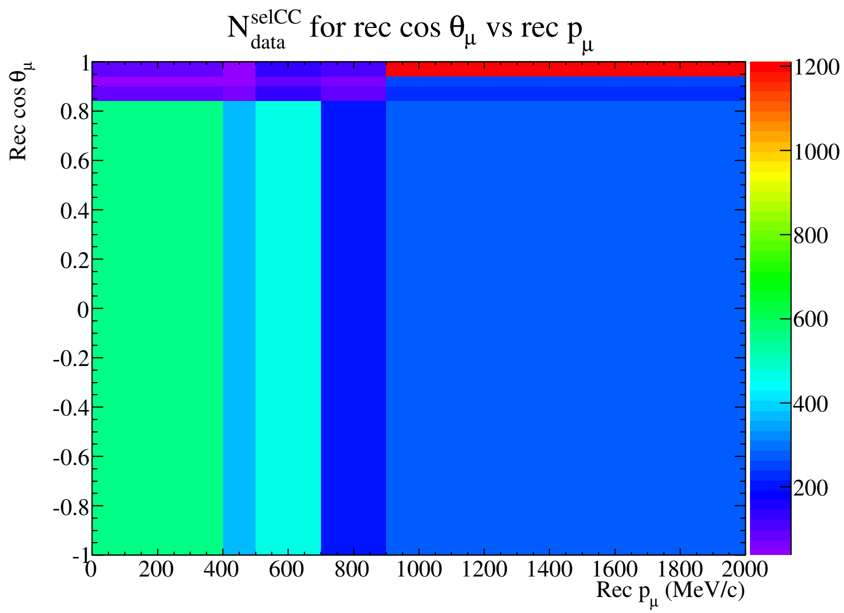
Cut	Data Run1	MC Run1	Data Run2	MC Run2
CC Inclusive Selection				
Good negative track in FV	2479	2347.9	6358	6148.8
Upstream TPC veto	1741	1800.7	4502	4749.6
PID cut	1202	1266.2	3283	3440.6
CCQE Sub-Sample Selection				
TPC-FGD track = 1	664	727.4	1853	1989.9
No Michel electron	619	676.0	1735	1858.8

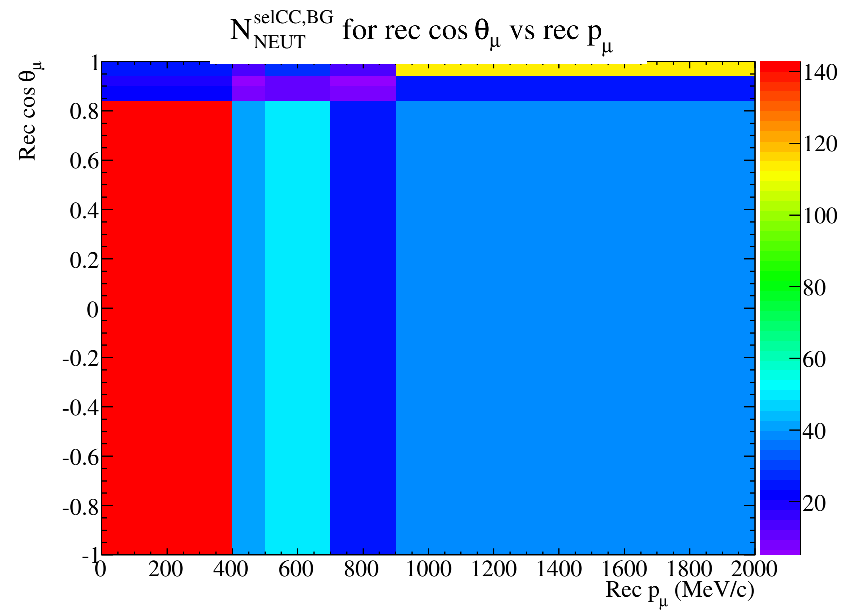
ν_μ-CC Binned in terms inferred p_μ and cos

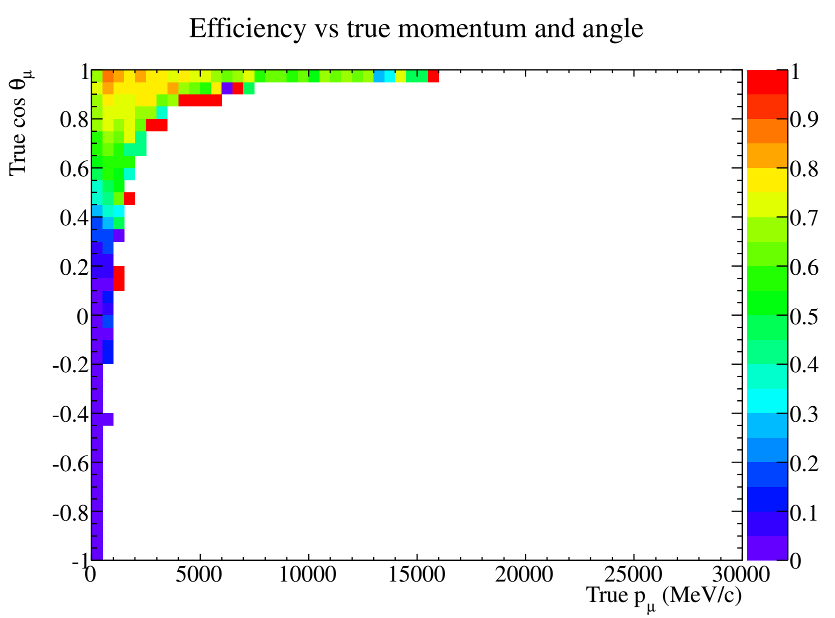
- Same binning as output of ν_μ-CC-Inclusive.
- Additional cos(θ) bin when going from reconstructed to true.

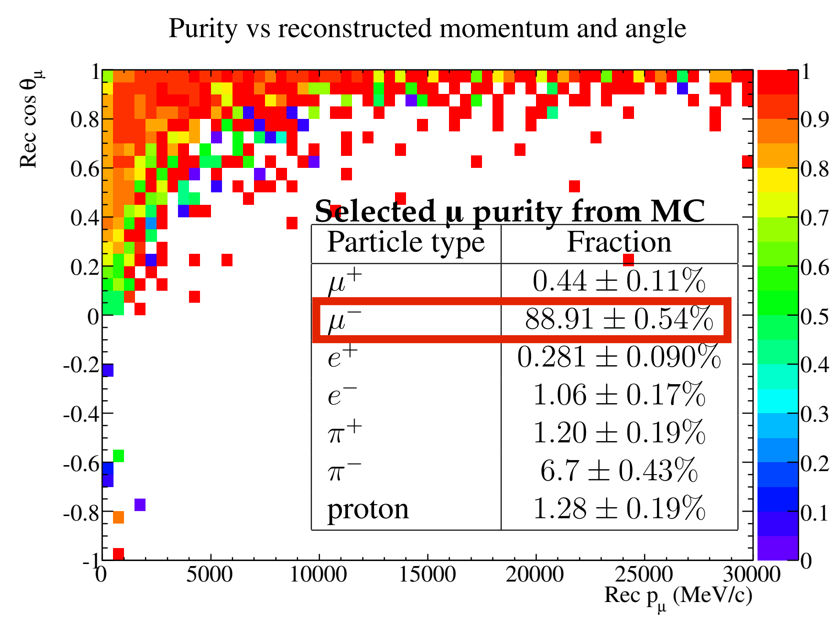


Tracker-based CC ν_μ selected events









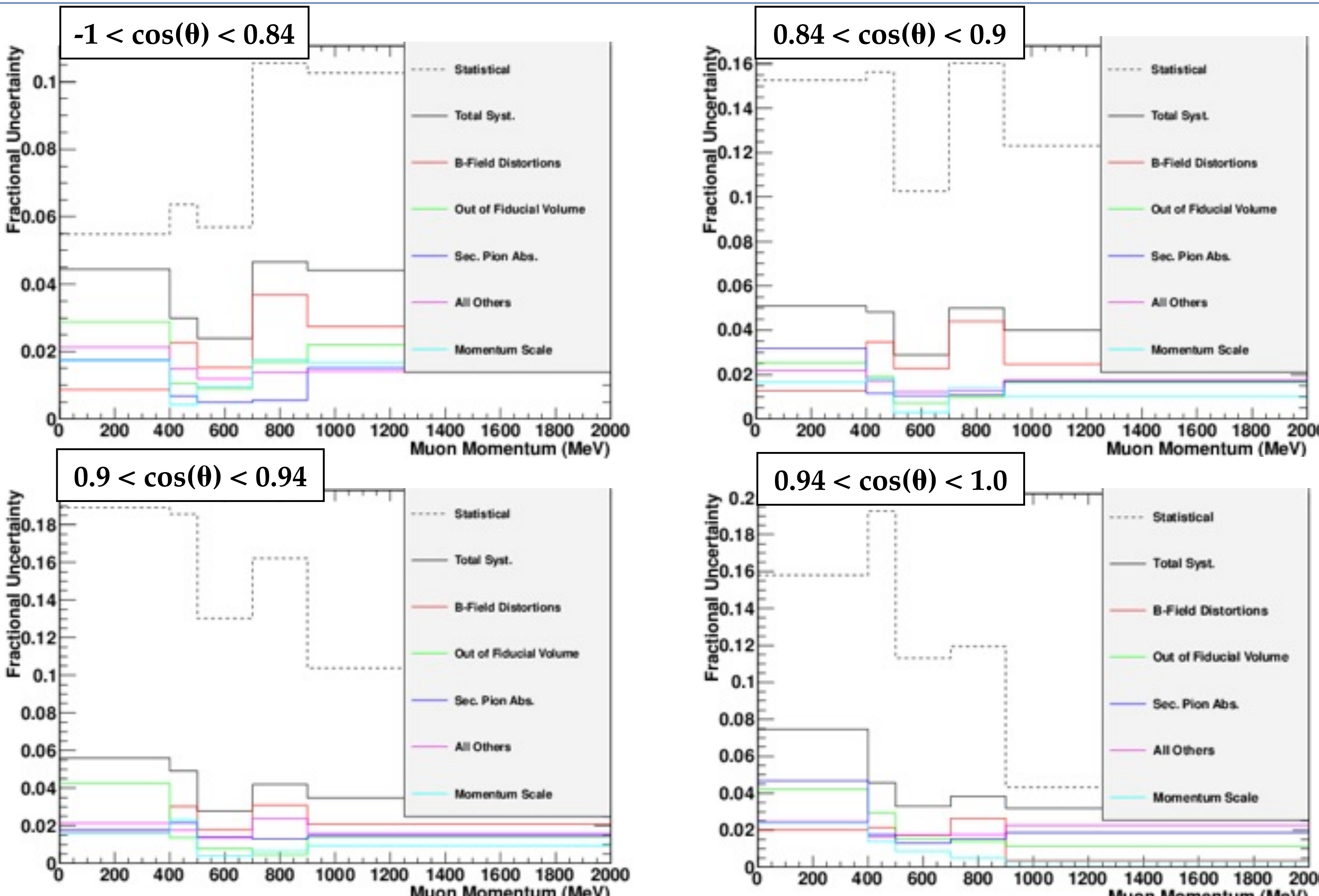
Selected μ purity from MC

Particle type	Fraction
μ^+	$0.44 \pm 0.11\%$
μ^-	$88.91 \pm 0.54\%$
e^+	$0.281 \pm 0.090\%$
e^-	$1.06 \pm 0.17\%$
π^+	$1.20 \pm 0.19\%$
π^-	$6.7 \pm 0.43\%$
proton	$1.28 \pm 0.19\%$

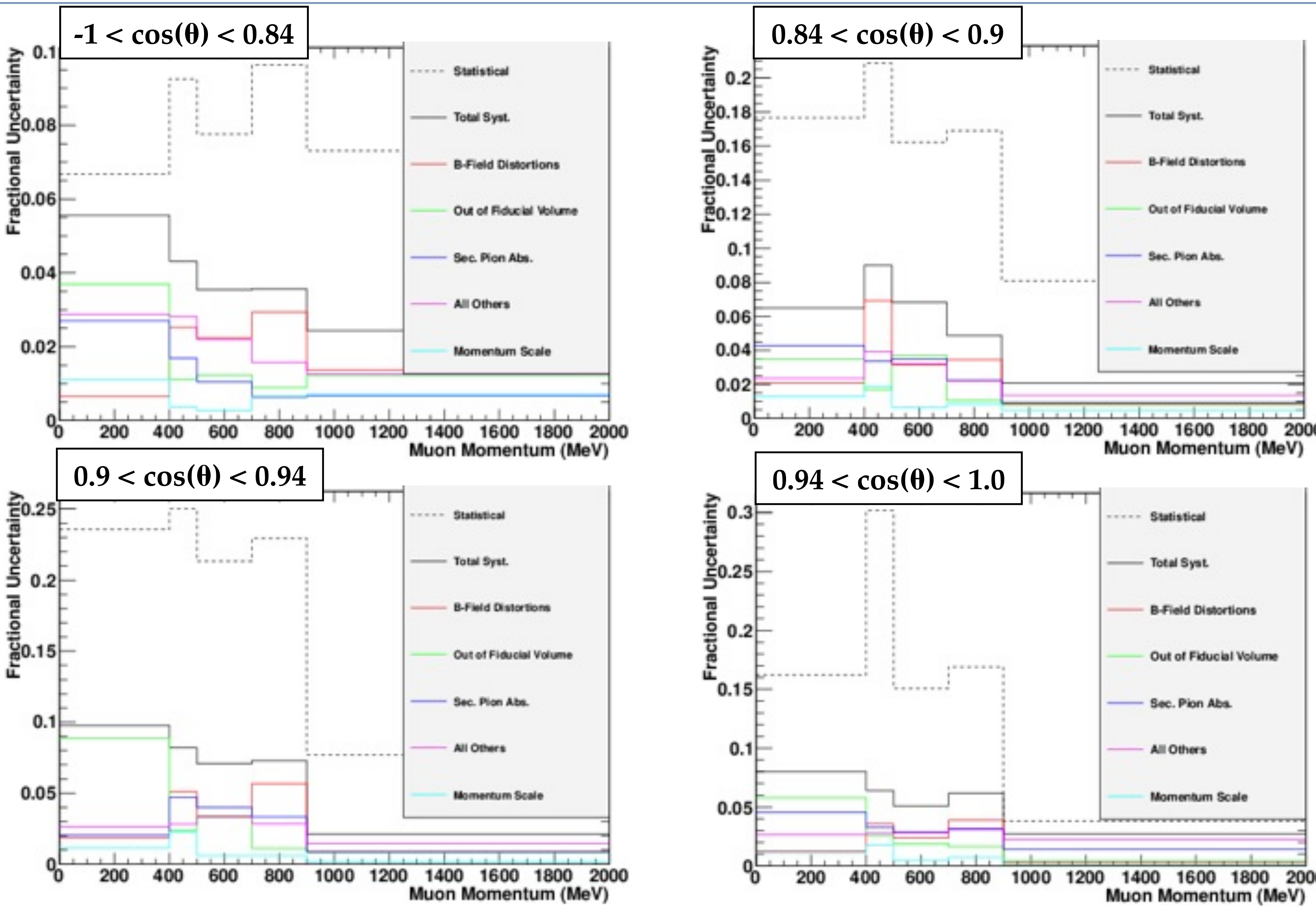
ν_μ selection detector systematics table

Systematics	Sample	Error (%)
Pion re-interaction	Special MC	3.0
Track quality	Beam data/MC	0.1
TPC single track eff.	Beam data/MC	0.5
TPC double track eff.	Beam data/MC	0.6
TPC particle ID (PID)	Beam data/MC	0.1
TPC momentum scale	External measurements	0.5
TPC mom. distortion	Special MC	~1-7
TPC mom. resolution	Beam data/MC	2.0
TPC-FGD match. eff.	Sand interact. + cosmics	<1
Fiducial mass	External measurements	0.7
Charge mis-ID	Beam data/MC	<0.3
Michel electron eff.	Cosmics	0.5
Cosmic rays	Special MC	0.1
Sand interactions	Special MC	1.5
Out-of-fiducial volume	Several samples	~1-9
Pileup	Beam data/MC	0.2
Track Multiplicity external bkgd	Beam data/MC	1.5

ν_μ CCQE-like main systematics



ν_μ CCnQE-like main systematics



ν_μ CC differential cross section uncertainties

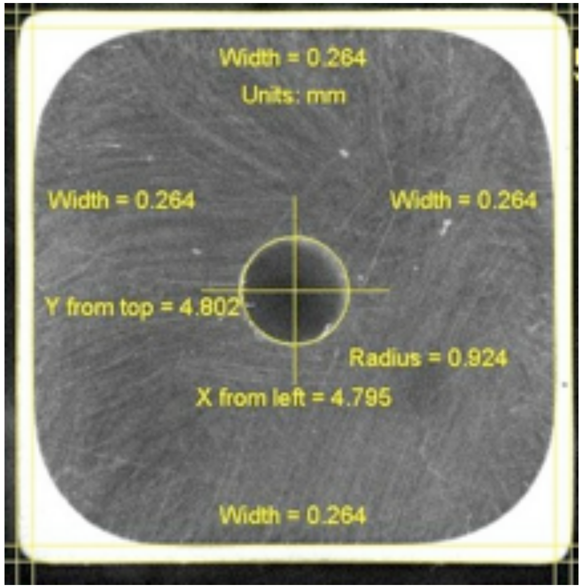
P_μ (GeV/c)	$\cos\theta_\mu$	algo. (%)	ϕ (%)	x-s (%)	det. (%)	FSI (%)	syst (%)	stat (%)	tot (%)
$[0.0, 0.4]$	$[-1, 0]$	0.03	11.92	15.45	2.97	0.96	19.78	2.86	19.98
	$[0, 0.84]$	0.10	12.82	5.44	3.70	1.23	14.49	5.03	15.34
	$[0.84, 0.9]$	0.06	13.17	10.25	2.67	1.35	16.98	9.37	19.39
	$[0.9, 0.94]$	0.06	13.95	10.02	4.73	3.32	18.14	11.82	21.65
	$[0.94, 1]$	0.24	14.00	11.09	4.49	2.57	18.61	13.78	23.16
$[0.4, 0.5]$	$[-1, 0]$	0.98	12.05	48.06	2.79	0.47	49.64	3.52	49.77
	$[0, 0.84]$	0.13	11.39	5.68	1.31	0.34	12.83	4.27	13.52
	$[0.84, 0.9]$	0.18	11.41	4.96	0.94	0.38	12.51	8.55	15.15
	$[0.9, 0.94]$	0.90	11.71	4.90	1.19	0.44	12.82	9.97	16.24
	$[0.94, 1]$	0.34	13.12	6.25	2.06	0.83	14.73	11.42	18.64
$[0.5, 0.7]$	$[-1, 0]$	7.15	11.22	47.37	1.97	0.63	49.25	30.30	57.83
	$[0, 0.84]$	0.10	11.12	3.76	1.10	0.37	11.83	3.86	12.44
	$[0.84, 0.9]$	0.10	10.87	3.25	0.79	0.29	11.41	6.18	12.98
	$[0.9, 0.94]$	0.55	11.06	5.62	0.76	0.32	12.48	7.18	14.39
	$[0.94, 1]$	0.22	11.71	9.15	0.98	0.24	14.92	7.67	16.77
$[0.7, 0.9]$	$[-1, 0]$	3.18	13.48	101.82	1.59	0.48	102.77	28.89	106.75
	$[0, 0.84]$	0.19	11.35	2.93	1.14	0.41	11.81	5.23	12.92
	$[0.84, 0.9]$	0.23	10.93	5.84	0.83	0.19	12.45	6.85	14.21
	$[0.9, 0.94]$	0.04	10.75	10.59	0.95	0.40	15.15	7.57	16.94
	$[0.94, 1]$	0.03	11.01	15.59	0.79	0.30	19.13	6.90	20.34
$[0.9, 30.0]$	$[-1, 0]$	-	-	-	-	-	-	-	-
	$[0, 0.84]$	0.20	11.83	4.97	1.46	0.69	12.97	5.88	14.24
	$[0.84, 0.9]$	0.07	11.30	2.31	0.89	0.26	11.60	6.05	13.09
	$[0.9, 0.94]$	0.05	11.09	2.08	0.72	0.36	11.34	5.33	12.53
	$[0.94, 1]$	0.09	10.90	2.25	0.75	0.26	11.19	2.97	11.58

Elemental breakdown of FGD1 module

- Approximately: 86% C, ~4% O, 7% H, O(1%) Ti, Si, N.
- Detailed calculation of FGD module masses and comparison to measured values → mass uncertainty = 0.67%.
- As CC-Inclusive do not distinguish between protons and neutrons → calculate total number of nucleons.

Stacked scintillator XY modules for FGD1

30 alternating X Y layers:
192 bars/layer



Cross check of model independence

- As p_μ and θ_μ parameterise efficiency to reconstruct CC-Inclusive event → expect model independent, i.e. do not depend on which MC is used to unfold - see good agreement: