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CC1π + CC coherent results from T2K (on and off-axis)

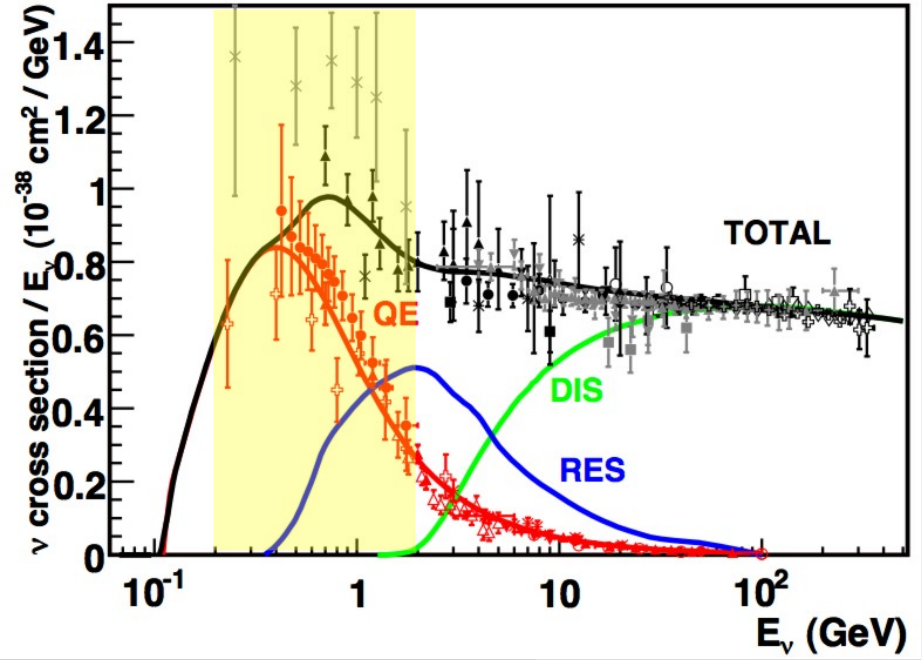
Martti Nirkko, for the T2K collaboration

NuFact15, Rio de Janeiro (Brazil)

12th August 2015

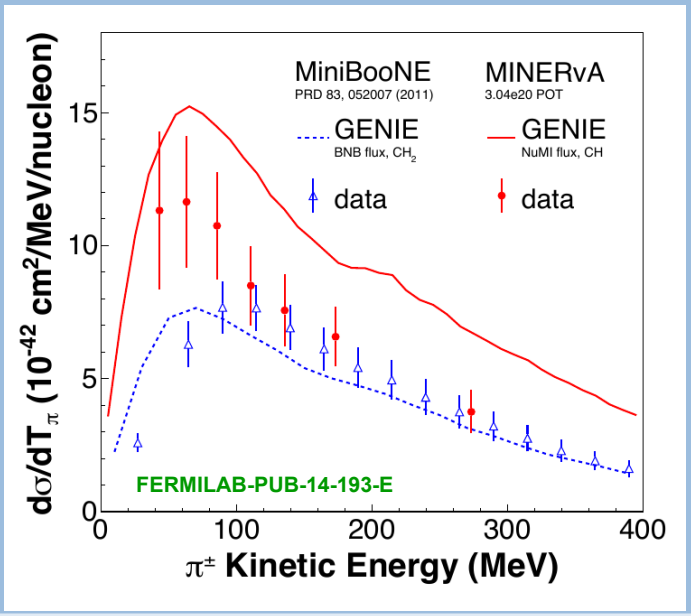
Motivation

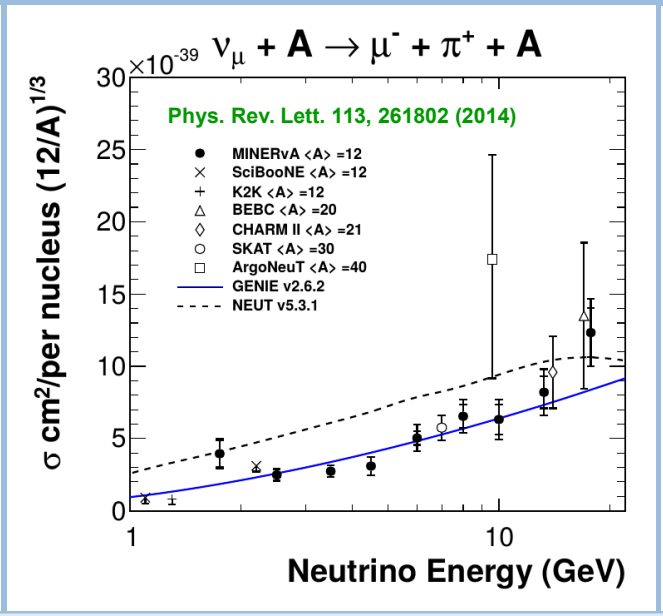
- Oscillation experiments demand a good knowledge of how neutrinos interact with matter to reduce systematic effects
- Measured cross sections from other experiments show discrepancies with most common theoretical models
- Data taken with the T2K near detector (ND280) cover most of the critical energy region (0.2 ~ 2.0 GeV, highlighted) →
- This talk: focus on **resonant** and **coherent** contributions

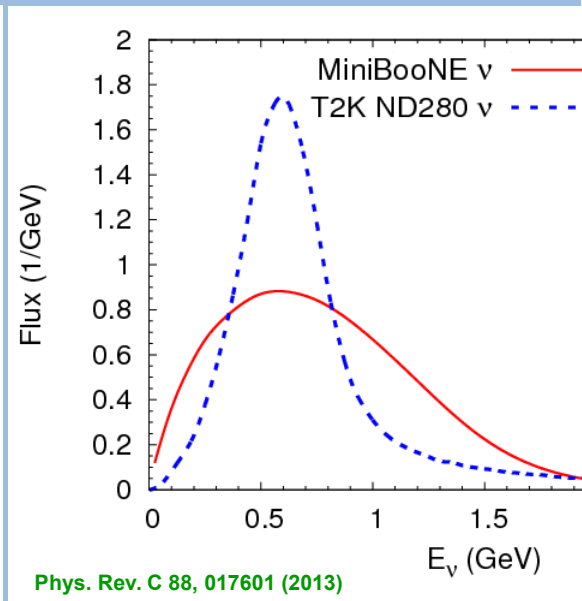


Motivation

- Disagreements between experiments for CC-1π measurement (left)
- Extend CC-coh data to lower (~1 GeV) neutrino energies (center)
- T2K flux peaked at ~0.6 GeV, same as MiniBooNE (right)
  - Can provide complementary measurement







T2K experiment

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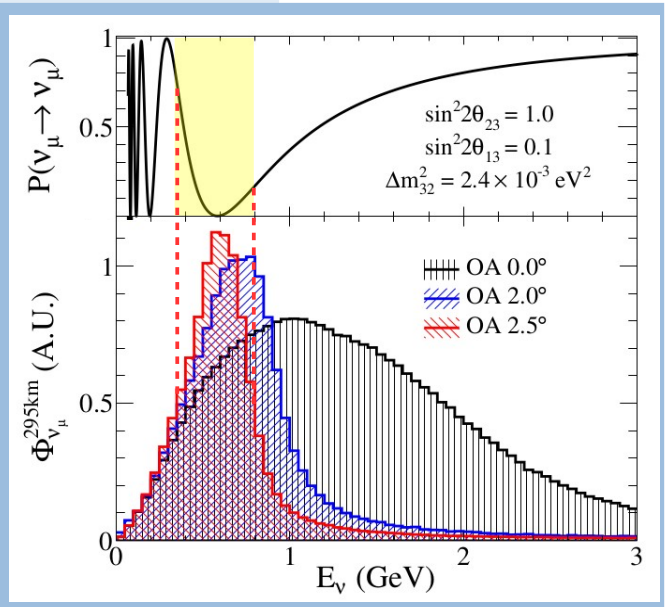
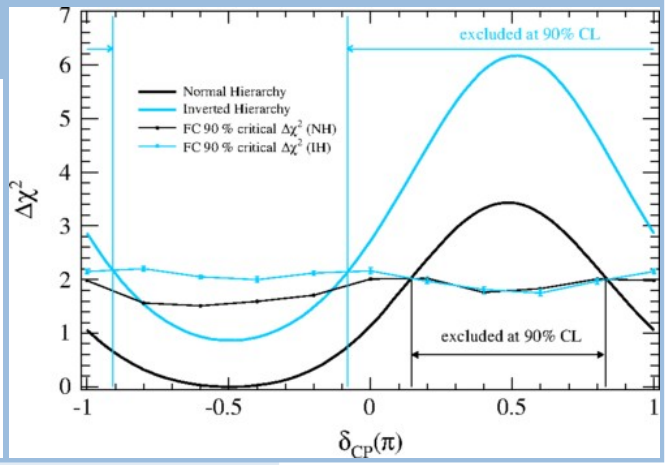
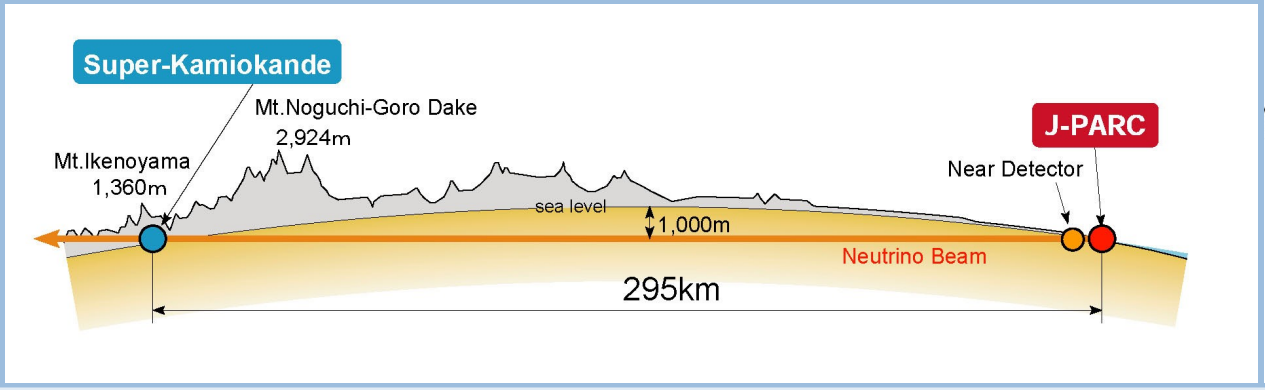
- Long-baseline ν oscillation experiment ($L/E \approx 500$ km/GeV) located in Japan.
- Main goals are to measure
  - ν_e appearance (θ_{13})
  - ν_μ disappearance (θ_{23}, $|\Delta m^2_{32}|$)
  - CP violation (δ_{CP})
  - **ν cross sections**

first indication...



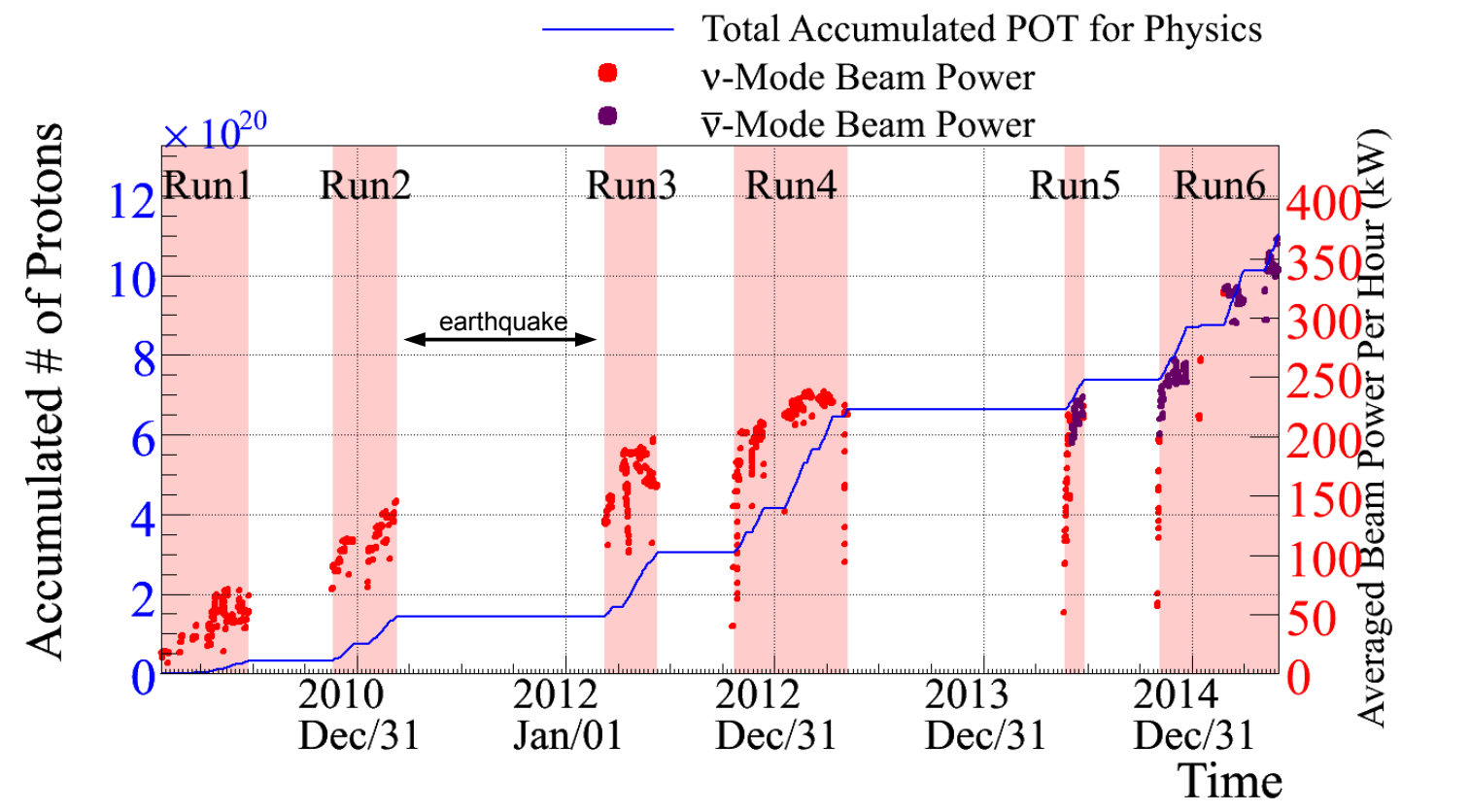




Phys. Rev. D 91, 072010 (2015)

Collected data in T2K

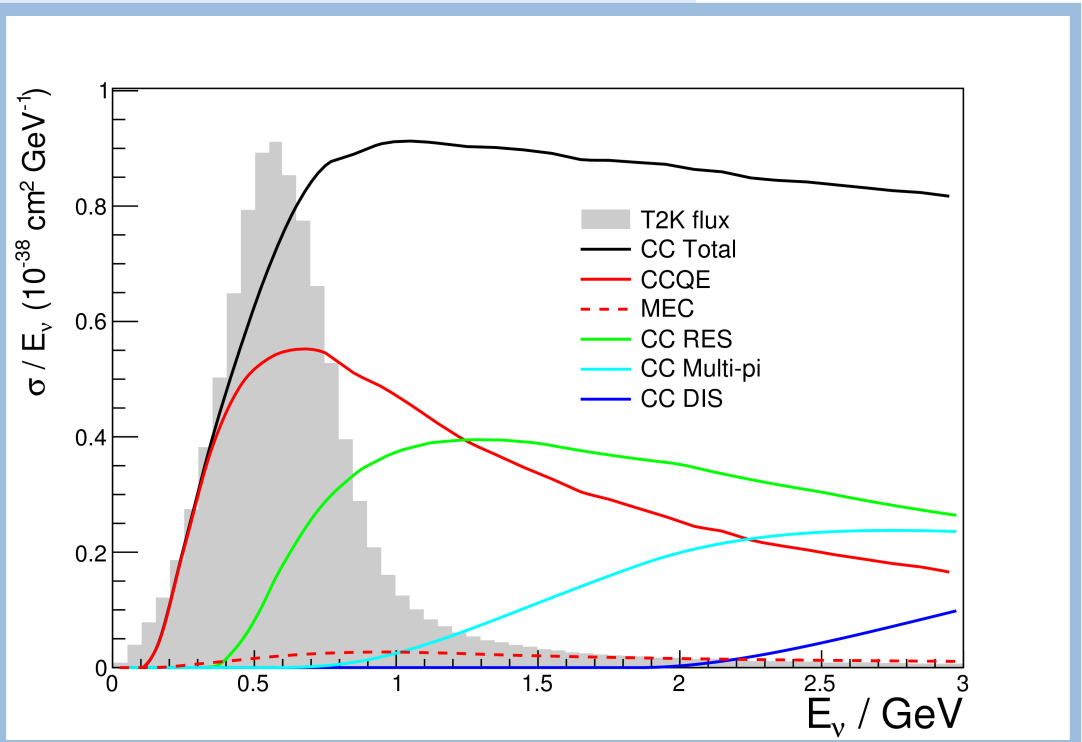
> Recently exceeded 10^{21} POT (68% ν-mode, 32% $\bar{\nu}$-mode)

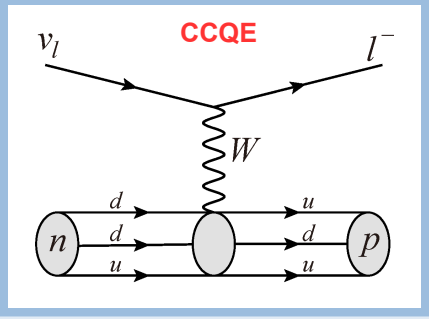


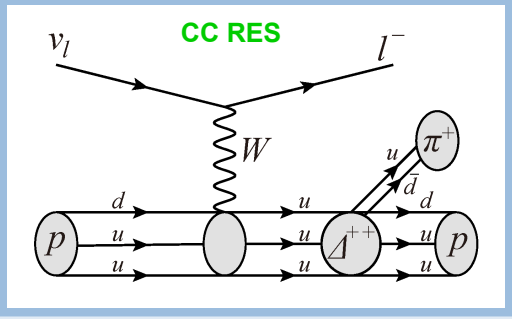
Neutrino interactions in T2K

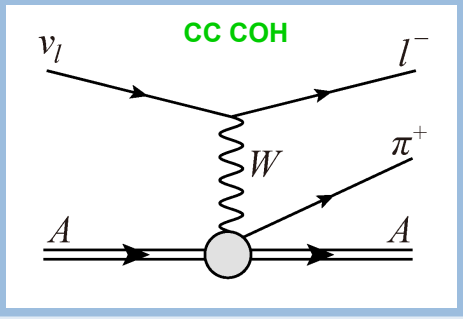
- Quasi-elastic (CCQE)
- Resonant (CC RES)
- Coherent (CC COH)
- Deep inelastic (CC DIS)

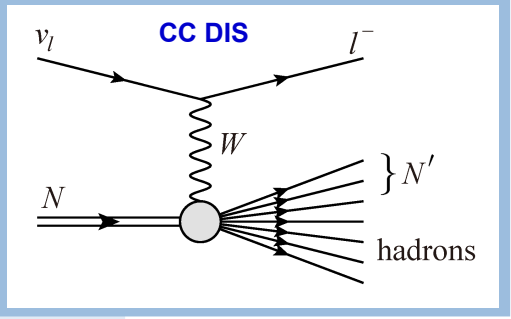
- Neutral current (NC …)
- Similar for ν_e, $\bar{\nu}_e$, $\bar{\nu}_\mu$



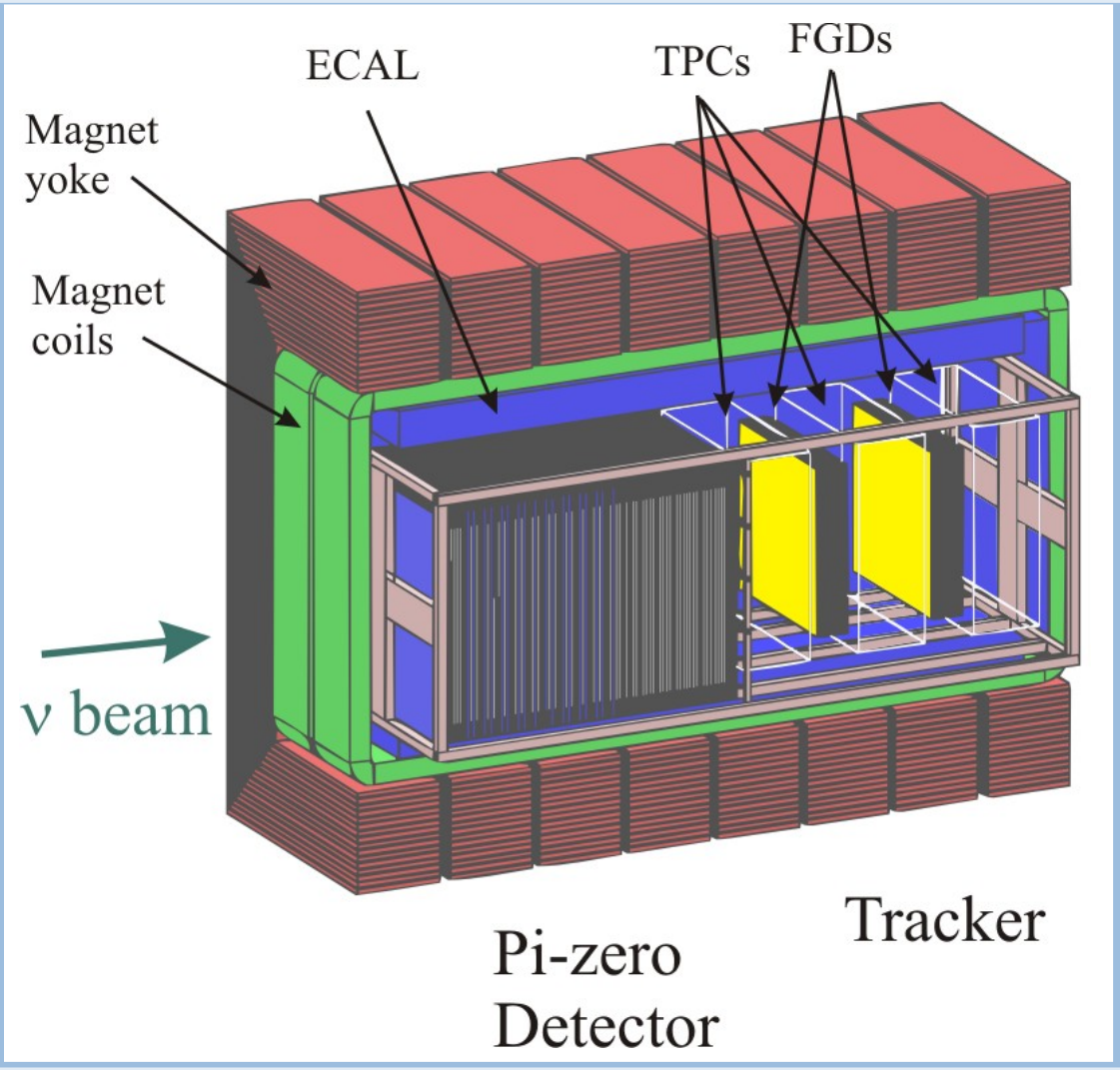








ND280 detector (off-axis)



Designed to measure

- > ν_μ flux
- > ν_e contamination
- > **ν cross-sections!**

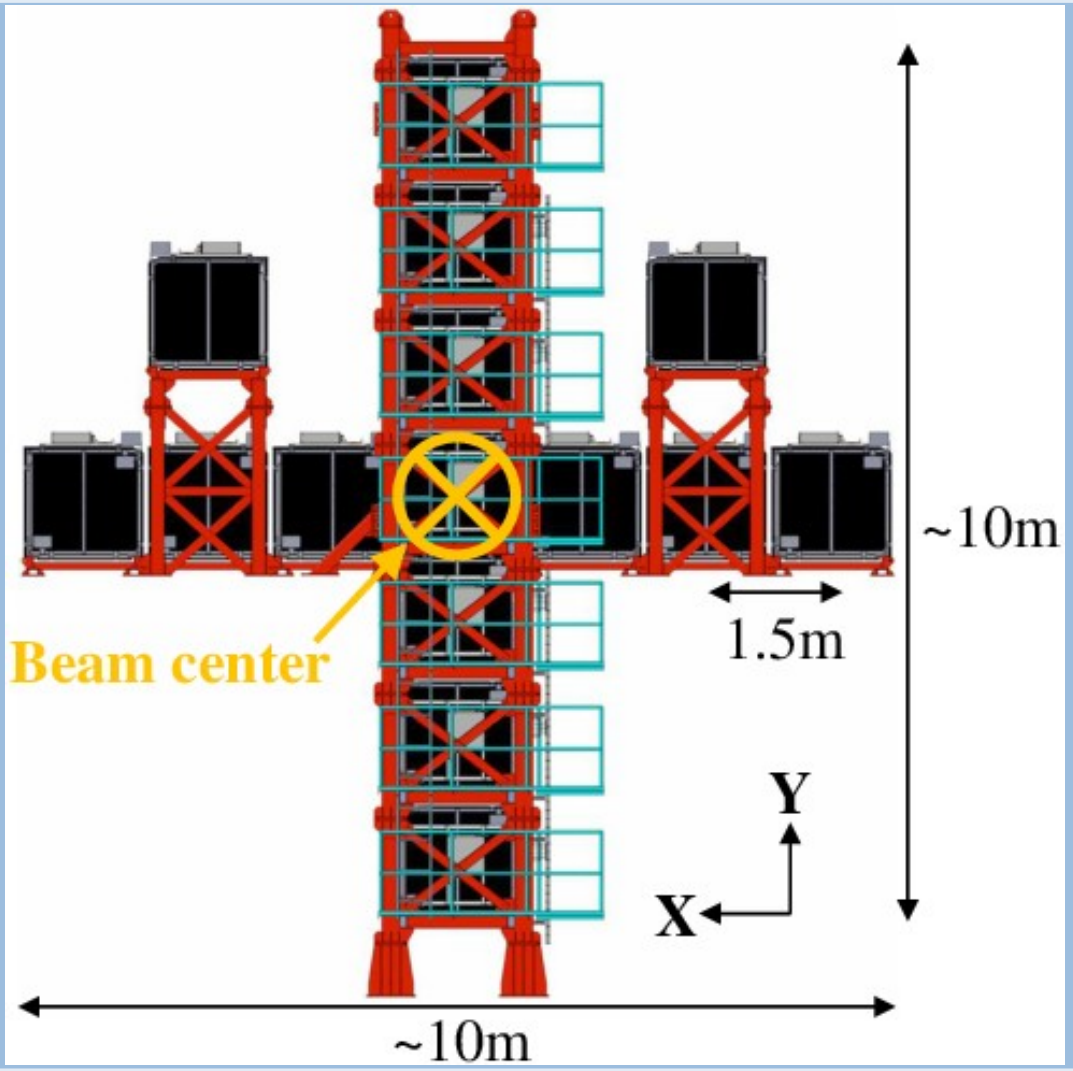
Multi-purpose detector

- > Fine-grained det. → x_0
- > Time-projection ch. → $^{dE}/_{dx}$
- > El.mag. calorimeters → E
- > Magnet (0.2 T) → p, q

Main target materials

- > Scintillator (FGD1) → ^{12}C
- > Water (P0D, FGD2) → ^{16}O

INGRID detector (on-axis)



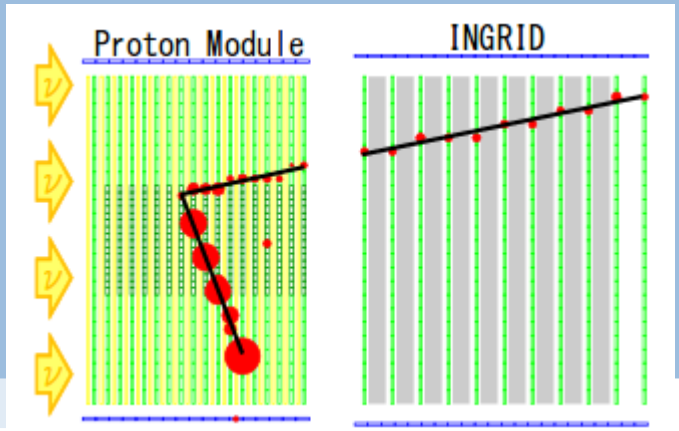
Designed to measure

- > ν beam direction & profile

16 “sandwich” modules

- > Scintillator trackers → ^{12}C
- > Iron plates → ^{54}Fe

Proton module (scintillator only) used for xsec measurements



Interaction topologies at T2K

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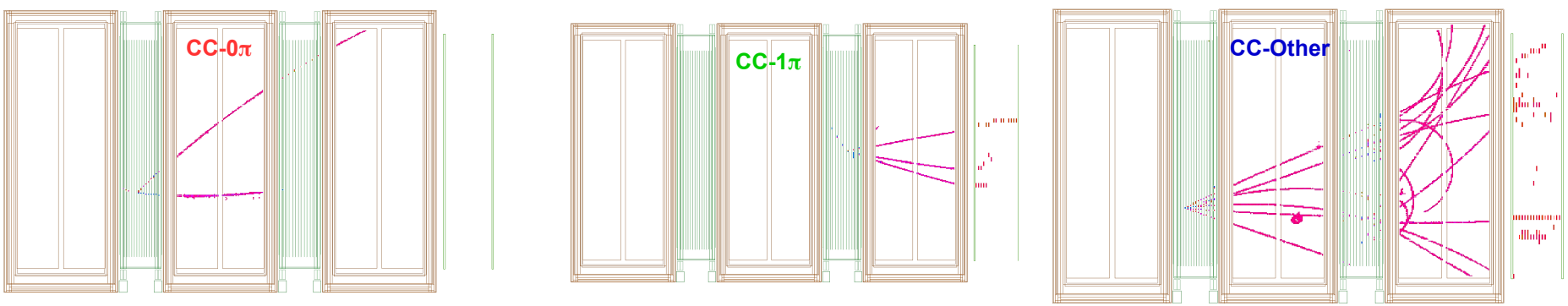
- There is no way to look "into" the nucleus during a ν interaction
- Nuclear effects (e.g. FSI) affect particle composition and kinematics
- Define interaction by **final state topology** rather than reaction type
- CC-Inclusive split into 3 topologies according to number of pions
  - CC-0π $\nu_\mu + N \rightarrow \mu^- + N'$ (~64% CCQE)
  - CC-1π $\nu_\mu + N \rightarrow \mu^- + \pi^+ + N'$ (~40% CC RES)
  - CC-Other $\nu_\mu + N \rightarrow \mu^- + n\pi^{\pm,0} + N'$ (~68% CC DIS)



Cross-section analyses at T2K

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> Current single and coherent pion analyses at the near detector site:

Target	CC-1π	CC-coh
Scintillator (CH)	FGD1	FGD1
		INGRID → on-axis
Water (H_2O)	FGD2	-
	P0D	

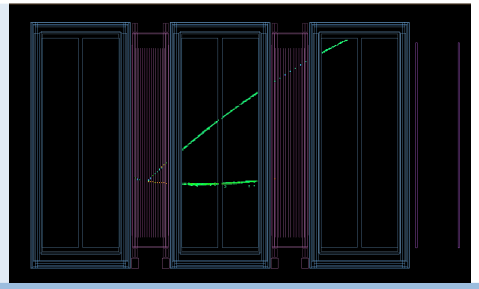
CC-1K
FGD1

Legend:
Under review (no data shown)
Publication in preparation

> Other studies on the way, but will focus on more mature analyses

> For more information about oscillation and cross section analyses, see talks by A. Furmanski, S. Bolognesi, K. Duffy, K. Mahn!

Typical event selection



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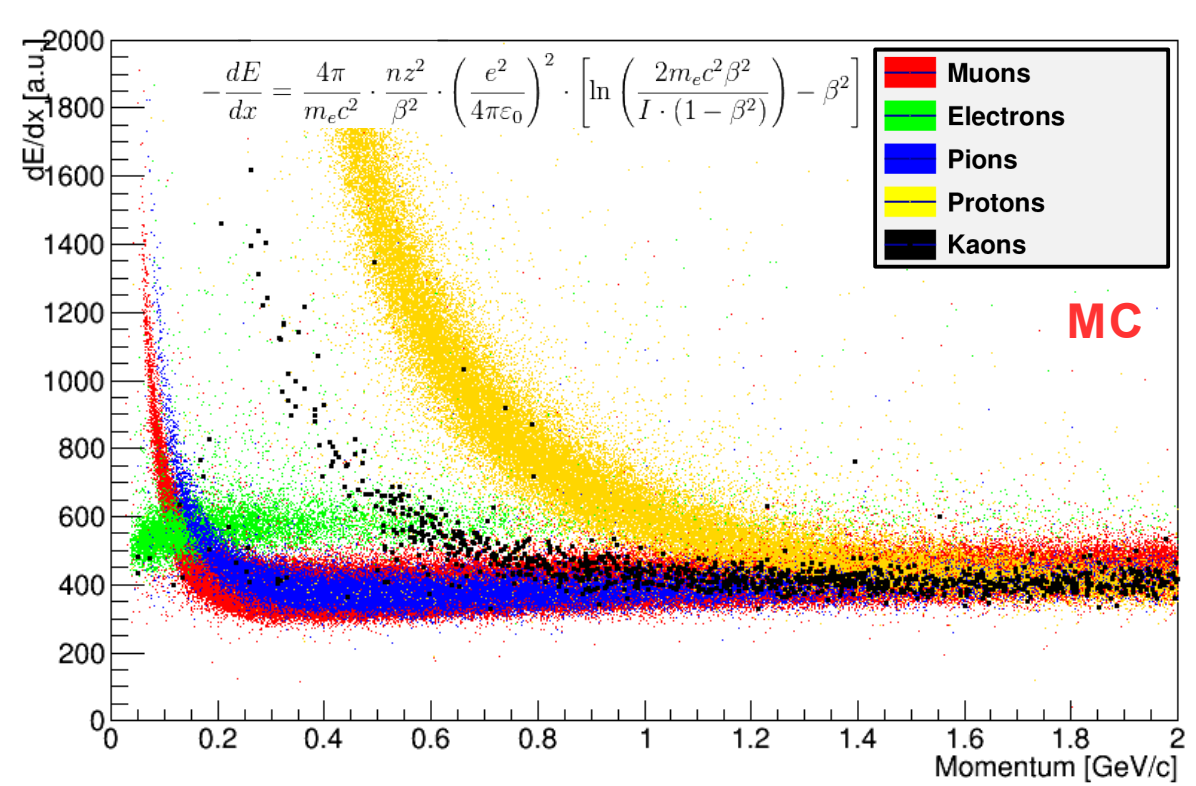
- Select muon candidate (CC-inclusive)
  - Highest momentum negative (HMN) track with good quality
  - Starting point inside fiducial volume of subdetector
  - PID cuts require track to be MIP-like (assume HMN track is muon)
- Select pion candidate (CC-1π / CC-coh)
  - Positive track with good quality in fiducial volume
  - PID cuts require track to be pion-like
  - No other (pion-like) tracks in event
- More individual cuts are applied in specific analyses

Particle ID using Bethe-Bloch

- Tracks are assigned a likelihood for each particle hypothesis
- Likelihood calculated via dE/dx pull variables for given momentum
  - Here: reconstructed variables in the TPCs using NEUT MC

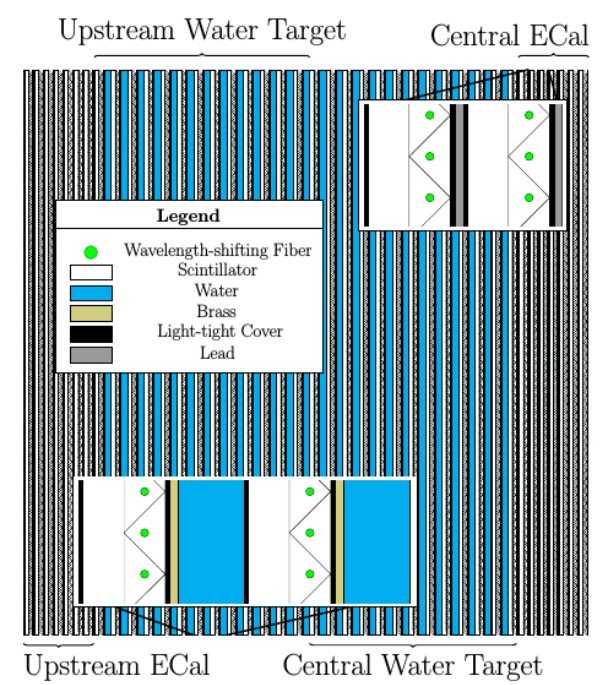


CC-1π in water (P0D)

- Select events with exactly two (contained) tracks in fiducial volume
  - Starting points close to reconstructed vertex
  - dE/dx pull variables match muon/pion hypothesis
  - Contained tracks must have delayed Michel cluster
- Different data runs with “water-in” and “water-out” configurations
- Background reduction through **water subtraction technique**:

Event rate “water-in” $s_w = s_w^{H_2O} + s_w^{scint}$ **Event rate “water-out”**

Event rate in water



CC-1π in water (P0D)

- T2K NEUT prediction ***before*** FSI agrees with MiniBooNE data
- Results currently under internal review
- Efforts to extend result into a differential xsec measurement
- Efforts to include other topologies (1 track, >2 tracks)
- Perform background fits using sidebands (in progress)

CC-1π in water (FGD2)

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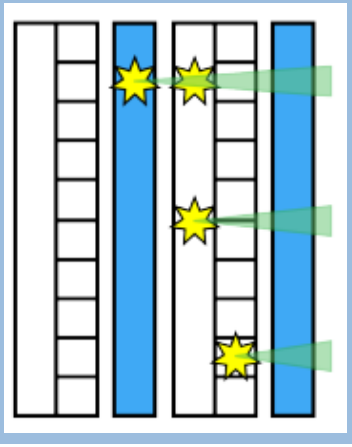
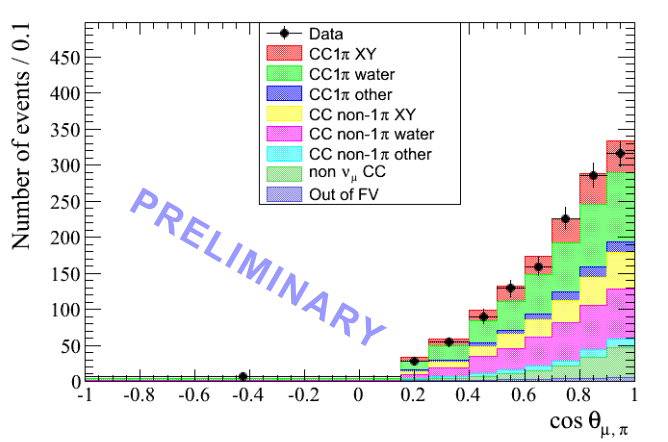
- CC-Inclusive selection with good-quality positive TPC track
  - Track must be pion-like (with no other pion-like tracks in event)
  - Reject events containing π^0 (ECal)
  - Muon candidate starts in x-layer of scintillator → intrinsic background from carbon interactions!
- Main backgrounds are carbon and CC non-1π interactions
- Two sidebands to control backgrounds:
  - CC-1π scintillator sample (y-layer)
  - CC-Other water-enhanced sample





CC-1π in water (FGD2)

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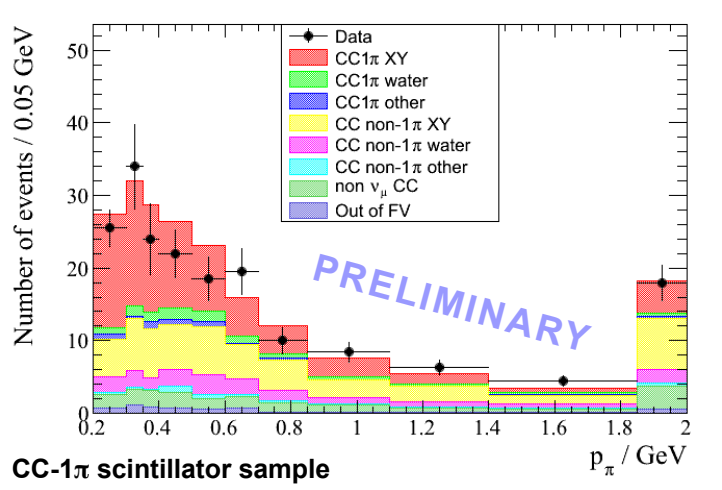
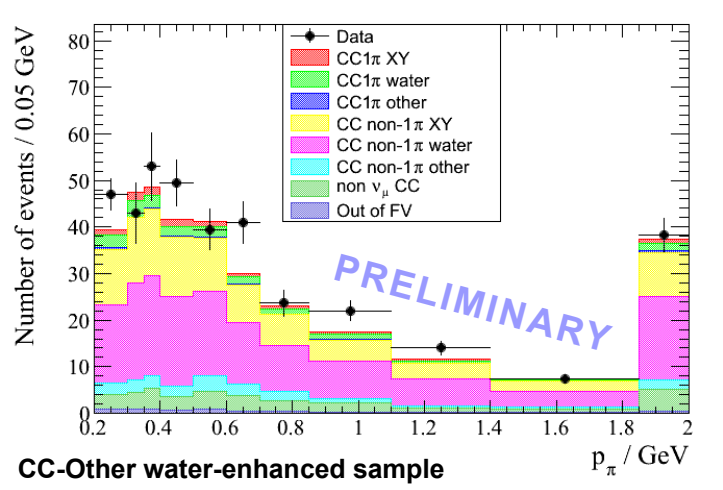
> MC background agreement with data (pion momentum shown):



CC-1π scintillator sample



CC-Other water-enhanced sample

> Flux-integrated differential cross-section obtained using **Bayesian unfolding method*** to estimate number of true signal events:

* G. D'Agostini, NIM A 362 487-498 (1995)

$$\left\langle \frac{\partial \sigma}{\partial X} \right\rangle_k = \frac{N_k^{unfolded}}{\epsilon_k N_{targets} \Phi \Delta X_k}$$

# of true signal events in bin k

detection efficiency in bin k

# of target nucleons

integrated ν flux

width of bin k

CC-1π in water (FGD2)

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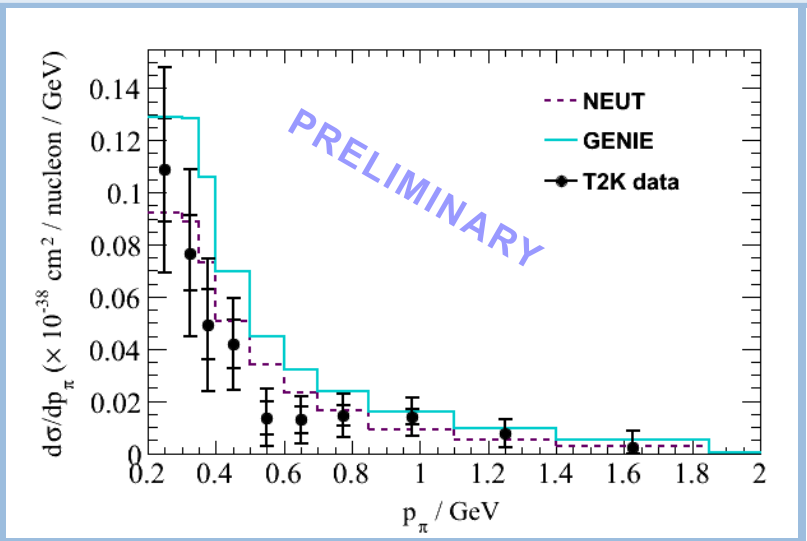

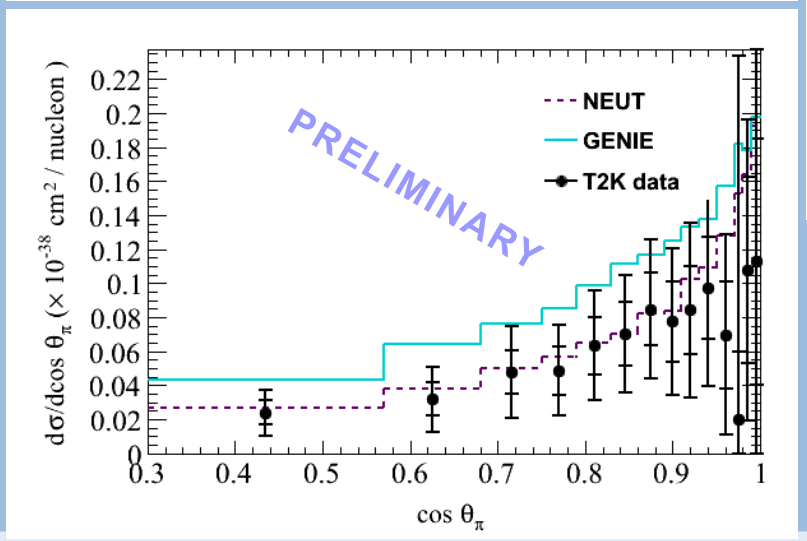

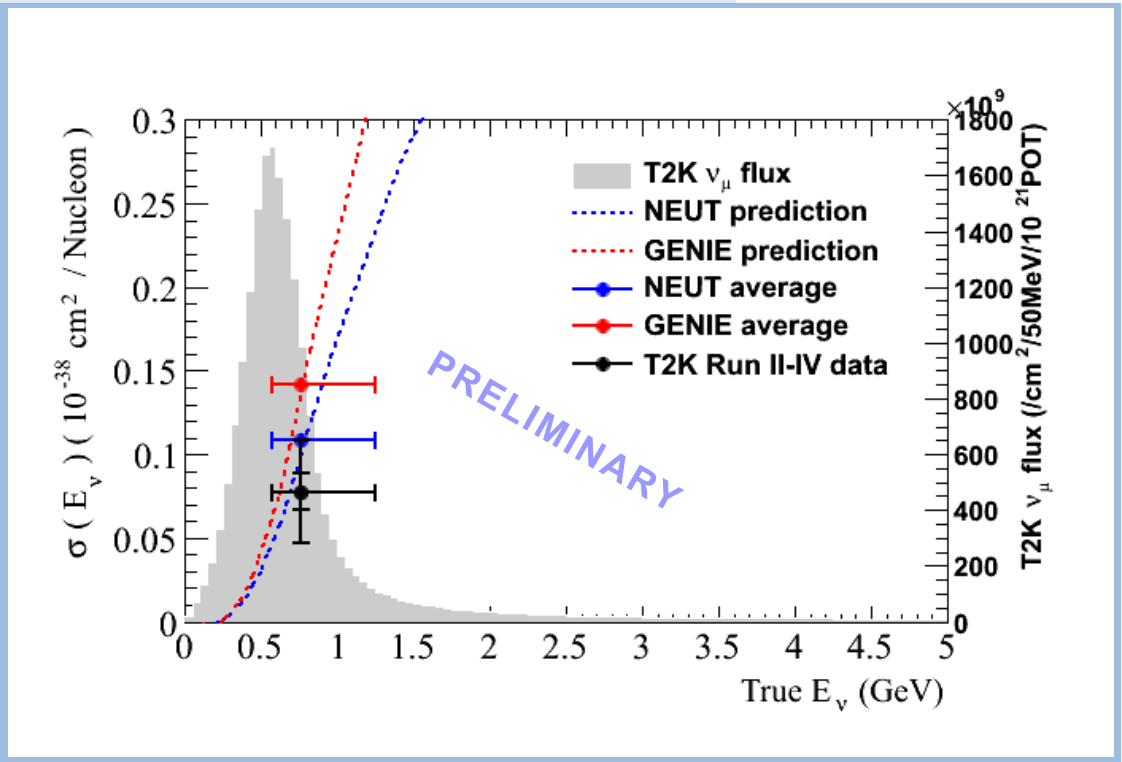

- Pion kinematics: Both generators seem to overestimate this channel!
- Total xsec 1.5 sigma lower than GENIE

CC-1π in carbon (FGD1)

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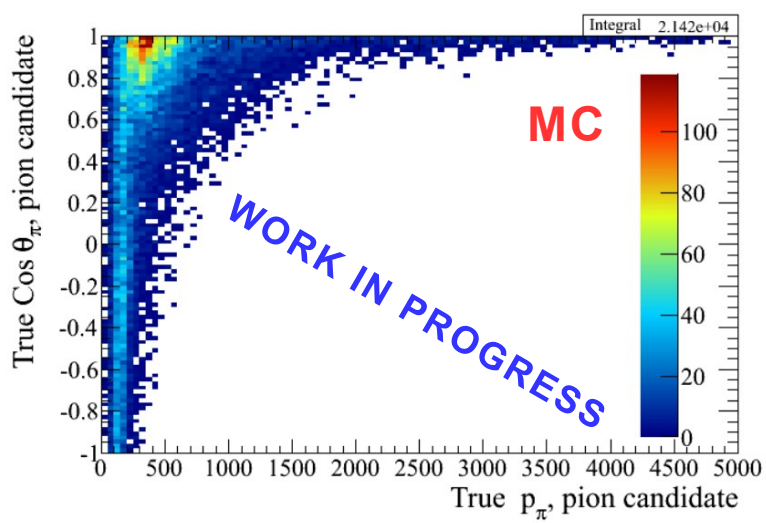
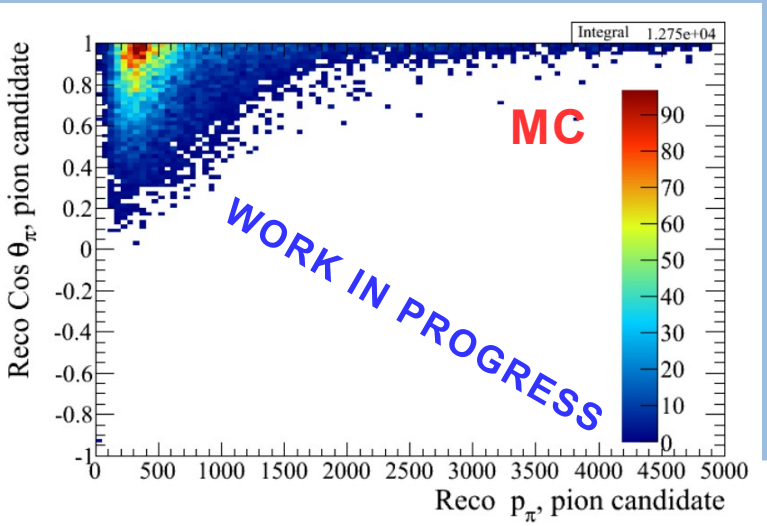
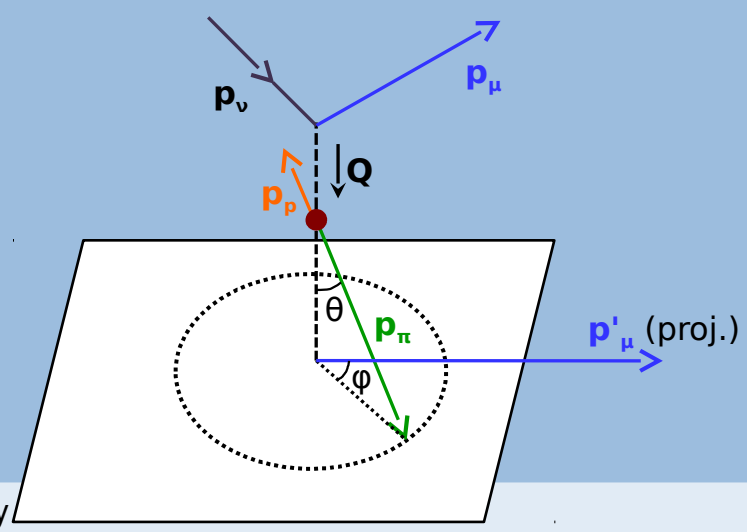
- Selection based on CC-Inclusive sample, with additional cuts:
  - Require 1 π^+ (TPC track with pion PID / Michel electron from decay)
  - Require no π^- in TPC, no π^0 in TPC or ECal
- Measured muon & **pion kinematics**, but also neutrino energy E_ν, momentum transfer Q^2, invariant mass W and special angular variables $\theta_{\mu\pi}$, θ_{planar}, ϕ_{planar} (see next slide)

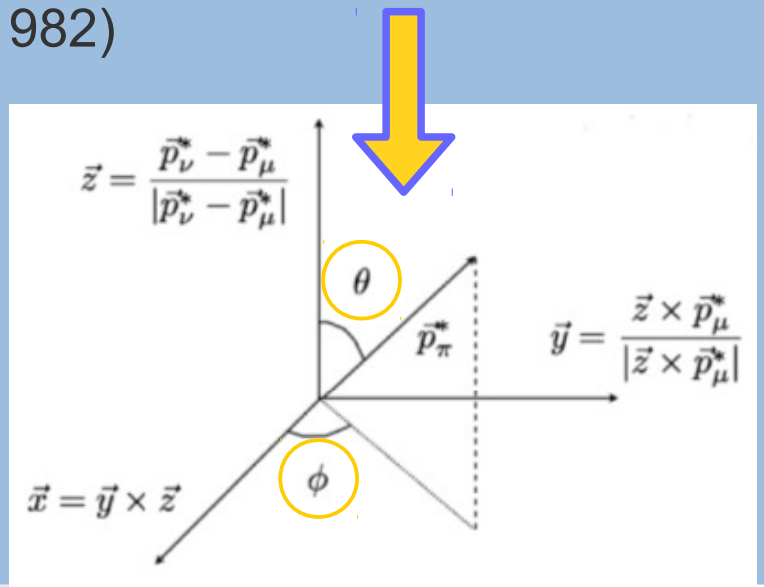




CC-1π – special angular variables

- Specific angular variables were chosen to better understand properties of the Δ^{++} decay:
  - Angle between muon and pion in lab $\theta_{\mu\pi}$
  - Angle between pion and 3-mom transfer in lab $\theta_{|Q_3|\pi}$
  - Angles in the *Adler system* (Δ rest frame) θ_{planar} ϕ_{planar}
- Compare **planar angles** to ANL data (1982)





CC-1π in carbon (FGD1)

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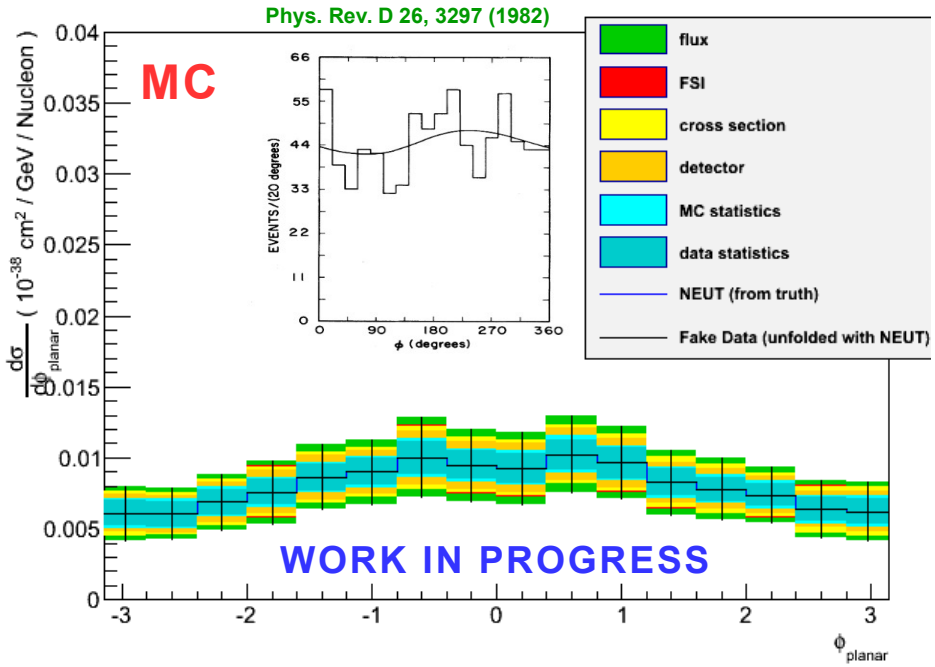
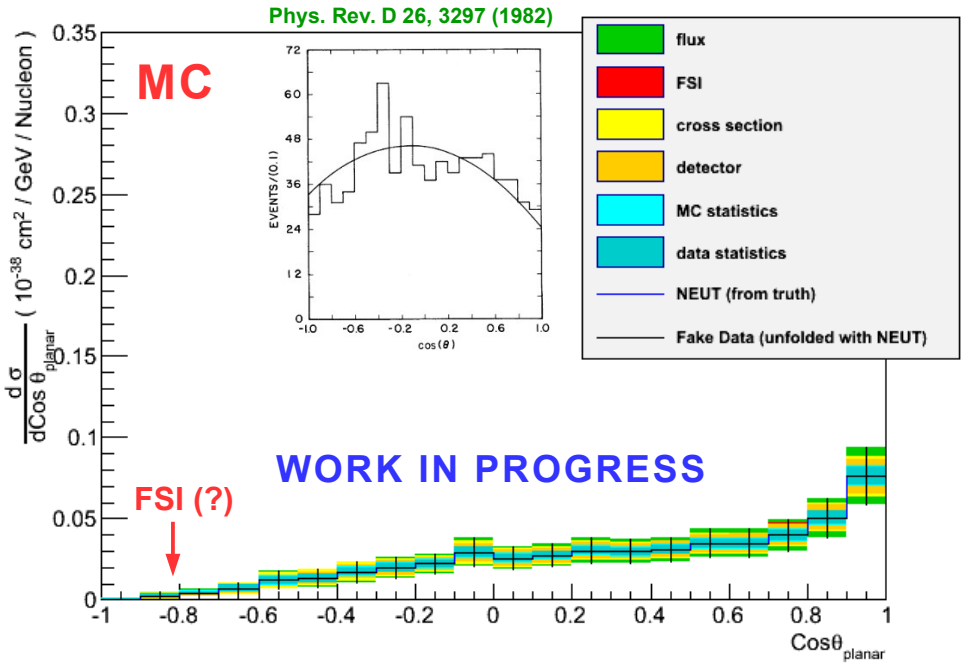
> NEUT MC pion angular estimations within Rein-Sehgal model
  - ϕ_{planar} seems relatively flat, similar shape to ANL expected
  - $\cos(\theta_{planar})$ highly sensitive to nuclear effects (low momentum pions), different shape from ANL (deuterium target) expected





CC-coh in carbon (FGD1)

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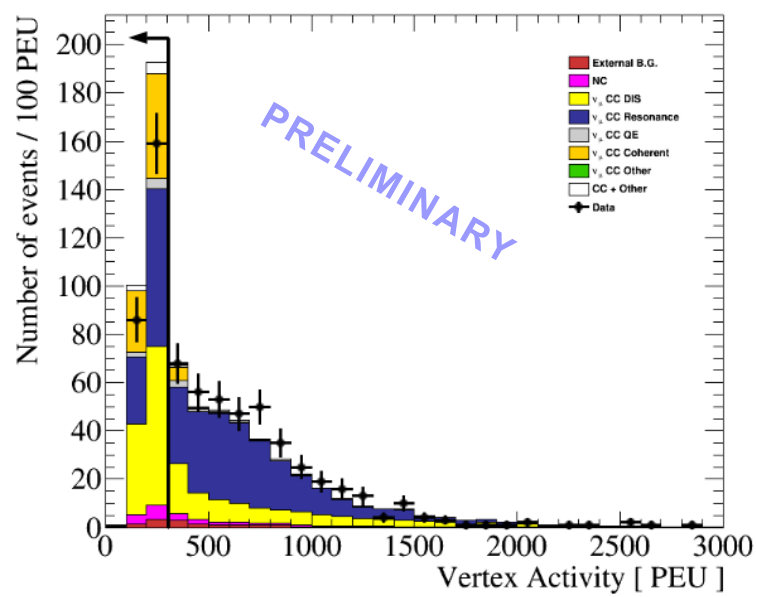
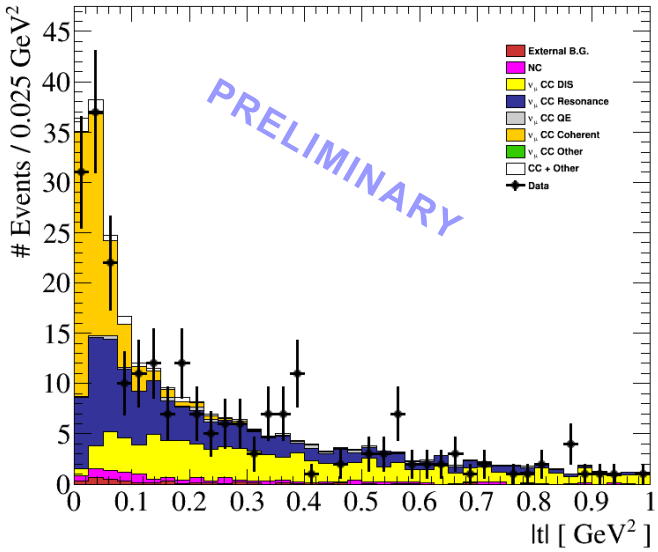
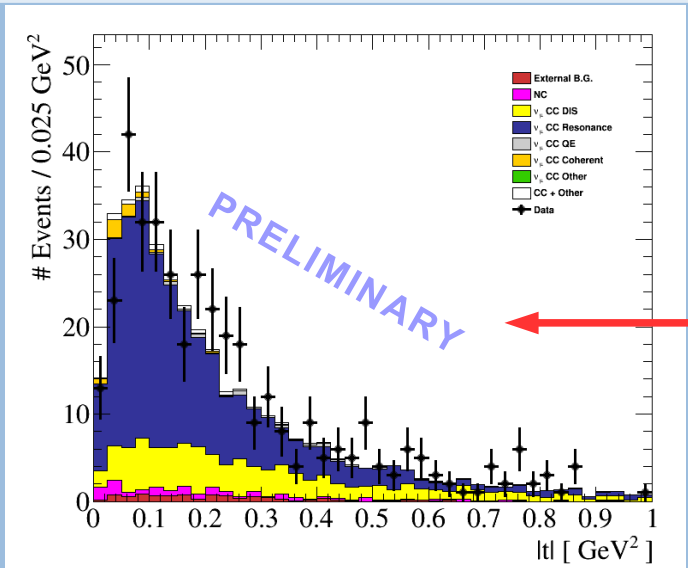
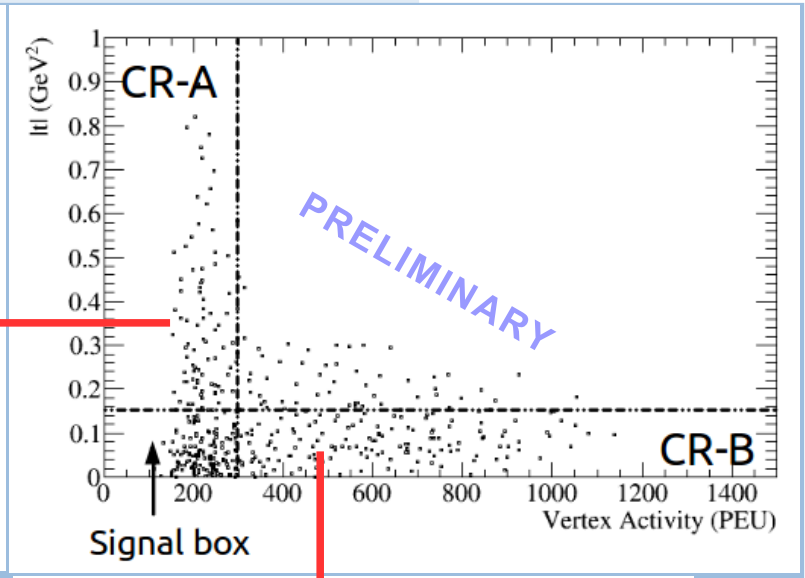
- CC-Inclusive selection with exactly one other positive track
  - Track must have good quality, be pion-like and <u>not</u> proton-like
  - Require both tracks to be associated to same vertex
- Use additional variables to discriminate coherent interactions
  - Low vertex activity: $VA < 300$ PEU
  - Low 4-mom transfer to nucleus: $|t| < 0.15$ GeV

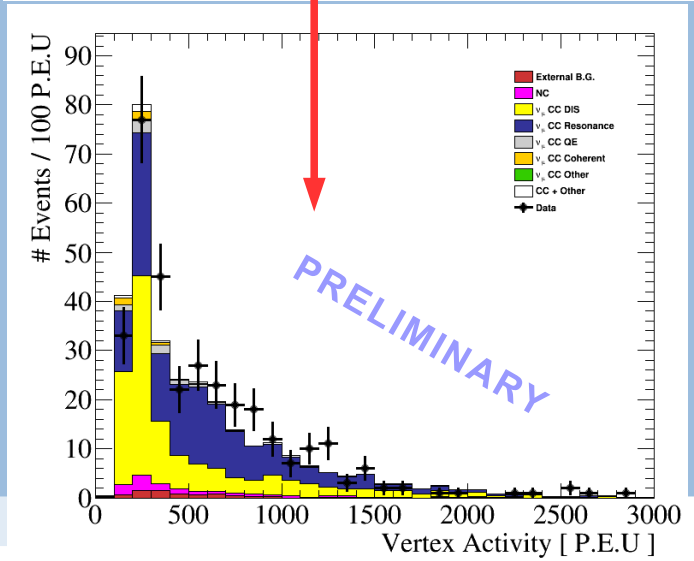




CC-coh in carbon (FGD1)



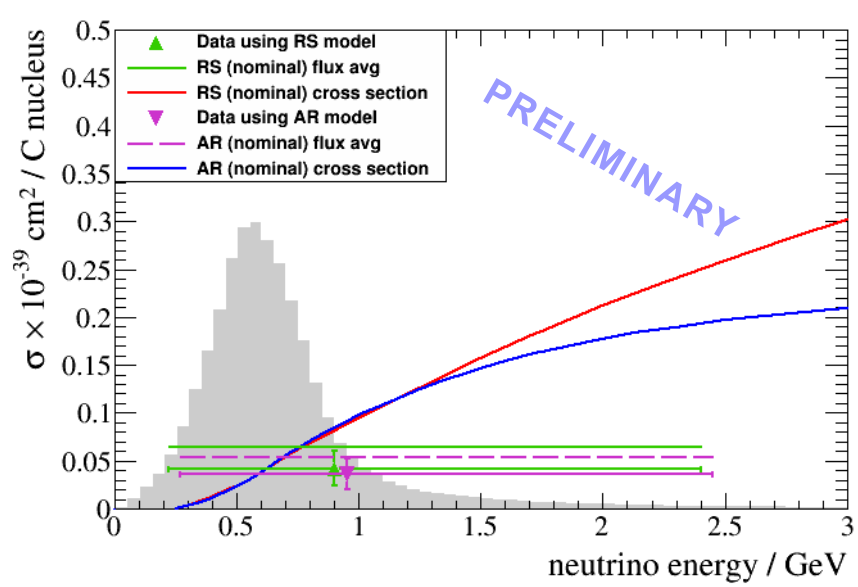


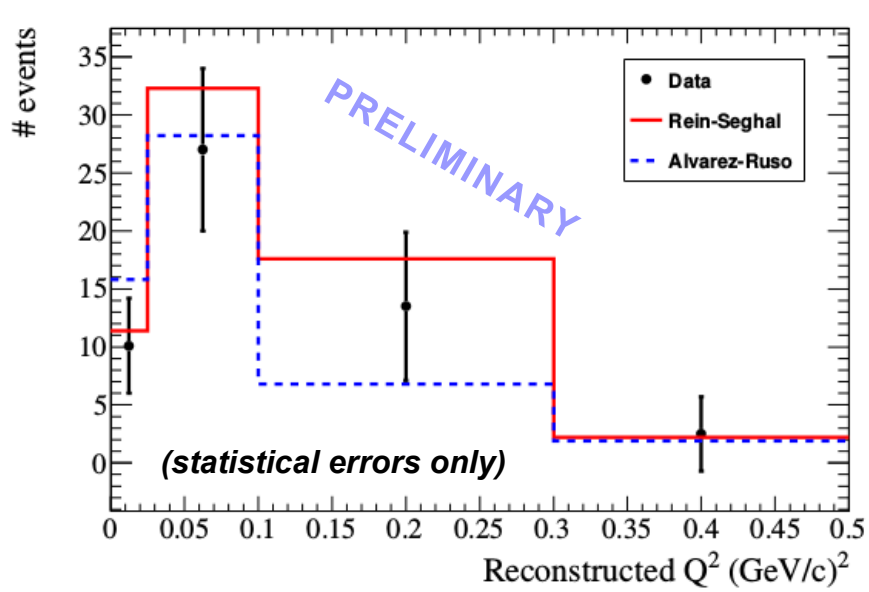


- Control samples outside signal region to constrain background
  → mainly CC-RES, some CC-DIS
- Simultaneous fit of background parameters and binned signal xsec

CC-coh in carbon (FGD1)

- Excess of 55 ± 20 events observed with a significance of 2.7 σ
- Xsec calculated using two coherent production models in GENIE:
  - Rein-Seghal model $\langle \sigma_{CC;Coh;C} \rangle_{RS} = (3.8 \pm 1.0(stat)^{+1.4}_{-1.3}(sys)) \times 10^{-40}\ \mathrm{cm}^2/^{12}C$ nucleus
  - Alvarez-Ruso model $\langle \sigma_{CC;Coh;C} \rangle_{AR} = (3.3 \pm 0.9(stat)^{+1.3}_{-1.2}(sys)) \times 10^{-40}\ \mathrm{cm}^2/^{12}C$ nucleus
- Currently lack the statistical power to distinguish between them





CC-coh in carbon (INGRID)

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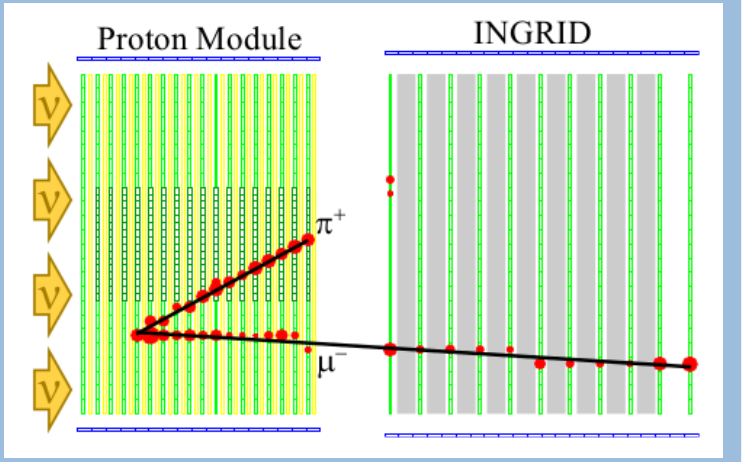
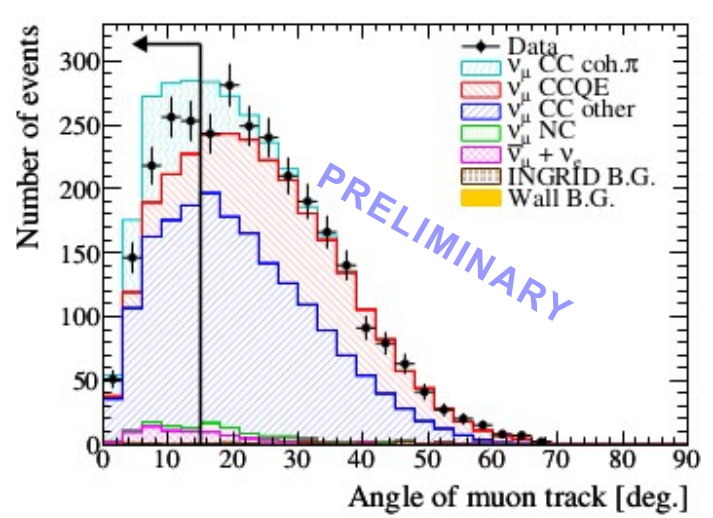
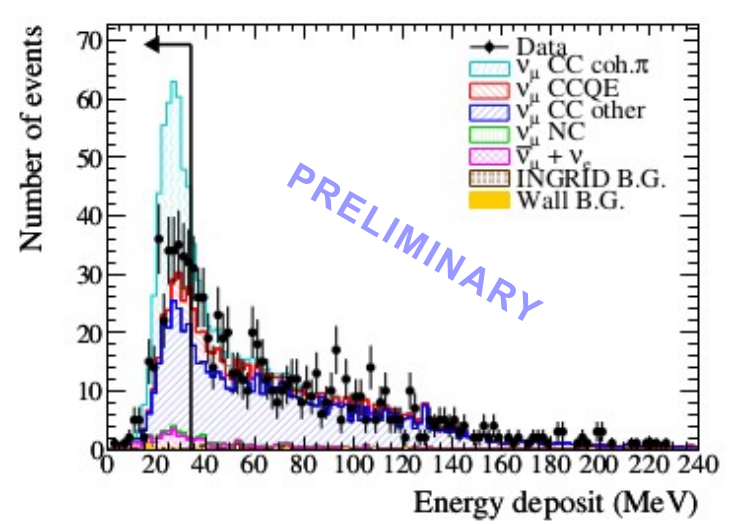
> CC-Inclusive selection with exactly two tracks from vertex:
  - Tracks match muon / pion PID using dE/dx method
  - Forward going muon ($\theta_\mu < 15°$) due to small Q^2 in CC-coh
  - Low vertex activity (VA < 34 MeV) → reject below-threshold protons







CC-coh in carbon (INGRID)

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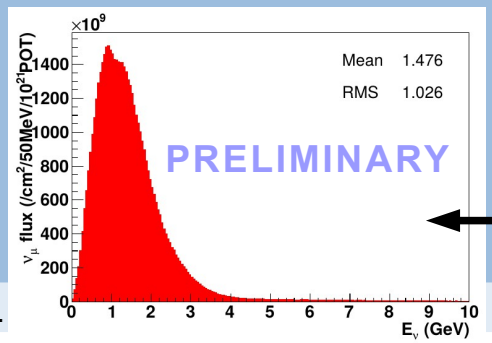
- Background components:
  - CC-coh events on other nuclei
  - CC non-coherent events
  - NC events
  - $\bar{\nu}_\mu$ and ν_e events from beam contamination
  - ν events in the material surrounding the detector
- Uses background subtraction to calculate xsec: model-dependant due to MC-based assumption on signal purity



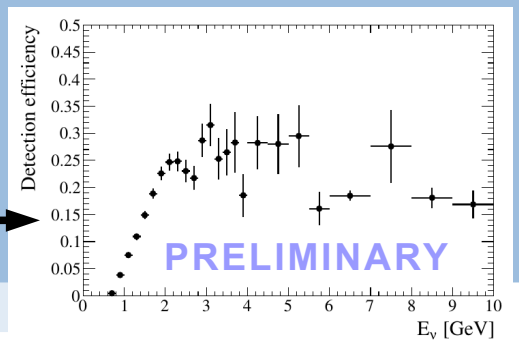
$$\sigma_{CCcoh.\pi} = \frac{N_{sel} - N_{BG}}{\phi T \varepsilon}$$

# of signal events

integrated ν flux

# of target nucleons

detection efficiency



CC-coh in carbon (INGRID)

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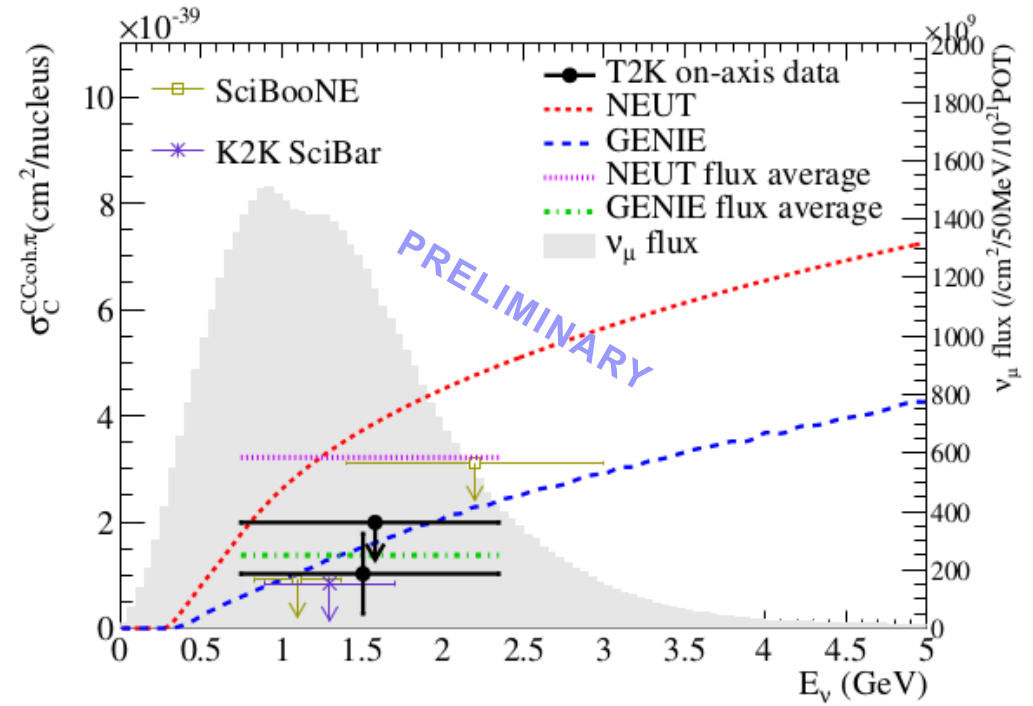
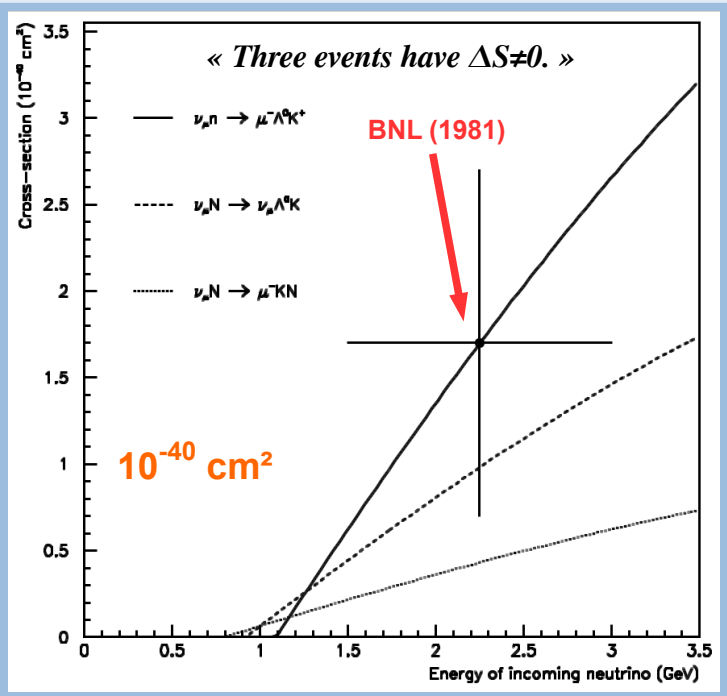
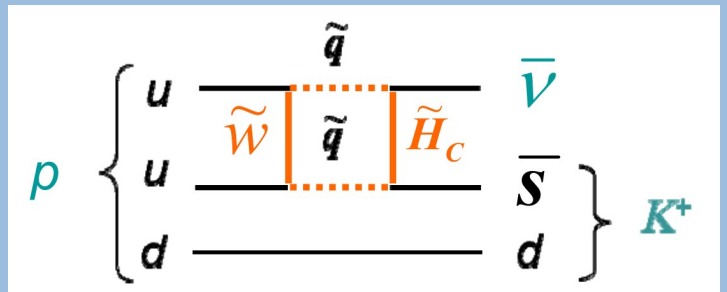
- On-axis result: $\sigma_{CCcoh.\pi} = (1.0267 \pm 0.2455(stat.)^{+0.7028}_{-0.6769}(syst.)) \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleus}.$
- Upper limit: $\sigma_{CCcoh.\pi} < 1.9808 \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleus}.$ (90% C.L.)
- Consistent with GENIE, but ~40% below NEUT prediction
  → mainly due to differences in pion-nucleon cross section



Kaon production



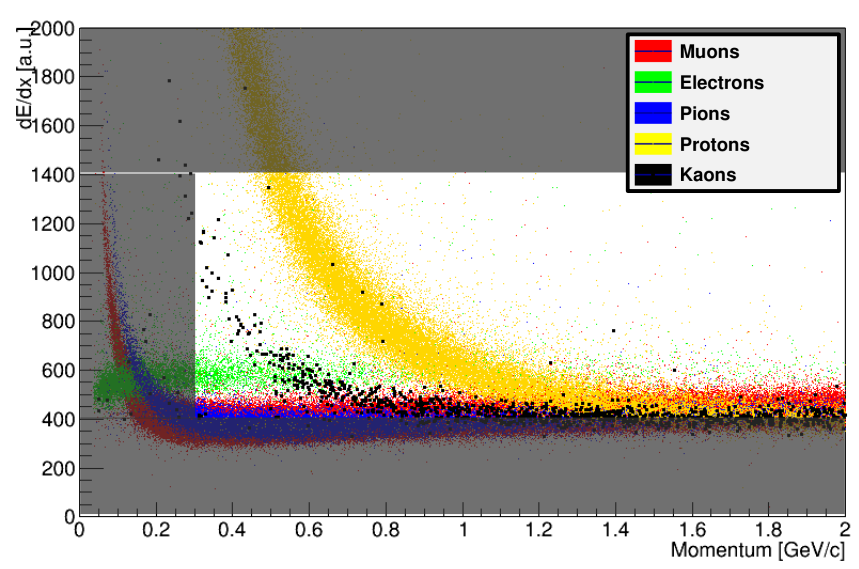


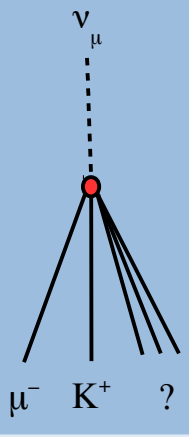
SUSY favored, $\tau > 5.9 \cdot 10^{33}$ y (90%)

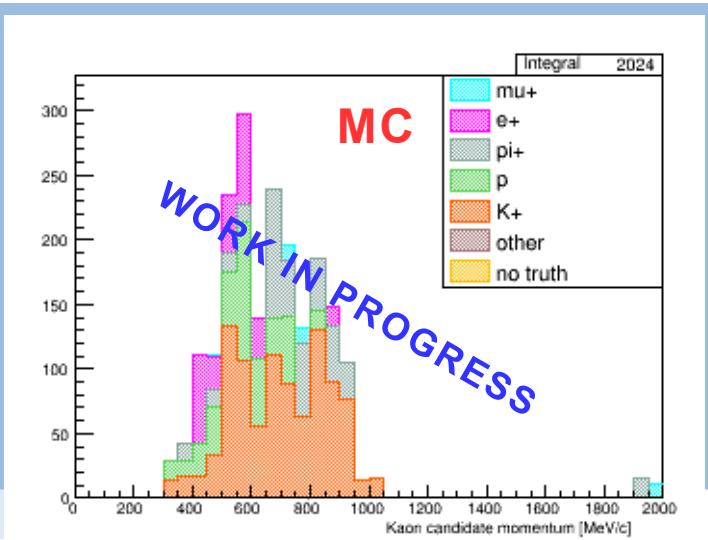
- Similar to CC-1π^+ channels, there exist various CC-1K^+ channels (with strangeness conserved or violated)
- Almost no data available at ~1 GeV
- First analyses on the way at MINERvA, see previous talk by M. Carneiro
- Complementary analyses can be performed at T2K
- Important background to proton decay
- Relevance to nuclear models

Kaon production in carbon

- First attempt at T2K to measure strangeness at ND280
- GENIE 2.9.0 includes new model for single kaon production
- Inclusive CC selection with K^+ performed with restricted phase space in momentum and dE/dx
- Efficiency ~5%, purity ~40%, expect 7.2 events / 10^{20} POT
- Statistically limited, will expect upper limit measurement







Other ongoing analyses

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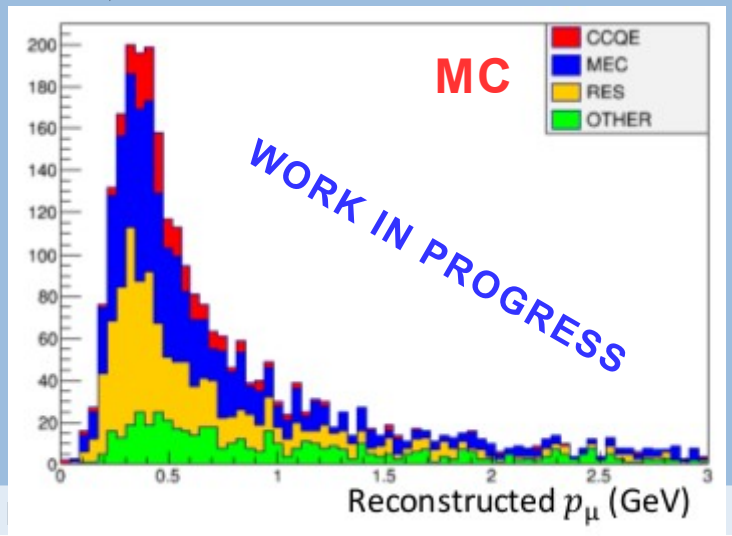
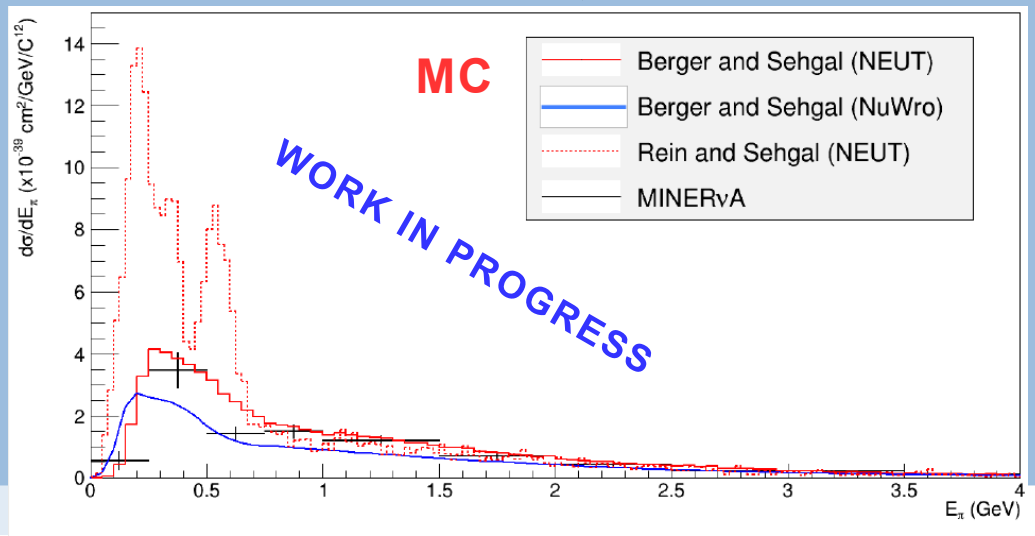
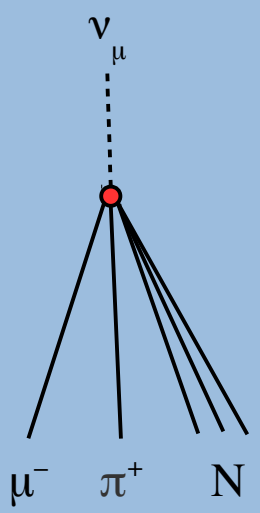
> Many other analyses on the way – some non-inclusive examples:
  - CC-coh cross section in FGD2
  - CC1π^+ studies at Super-Kamiokande
  - Δ-resonances for transverse analysis
  - MEC contribution using transverse variables
  - Improvements to NEUT model in CC-coh





Summary

- Various T2K cross section measurements on the way
  - Differential cross sections when possible
- First exclusive topologies being studied:
  - CC-1π & CC-coh presented in this talk →
  - CC-0π presented by A. Furmanski (Monday)
- CC-1π results provide insights into nuclear effects
  - Some interesting discrepancies from MC
- CC-coh results statistics limited, expect upper limit measurements



Thank you!

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Backup

Definition of RES / COH interactions

- "A **coherent** neutrino-nucleus interaction is defined as one which leaves the nucleus in the same quantum state as it was initially. The nucleus' constituents must retain their identity, and the nucleus cannot be excited or fragmented, though it can recoil, nor can any quantum numbers be transferred to any of the nucleons." - T2K-TN-191

- In a **resonant** neutrino-nucleus interaction, a nucleon is excited into a resonant state (baryon resonance). The outgoing final-state particles are then produced from the decay of this resonance.

Acceptance for CC1pi in water (example)

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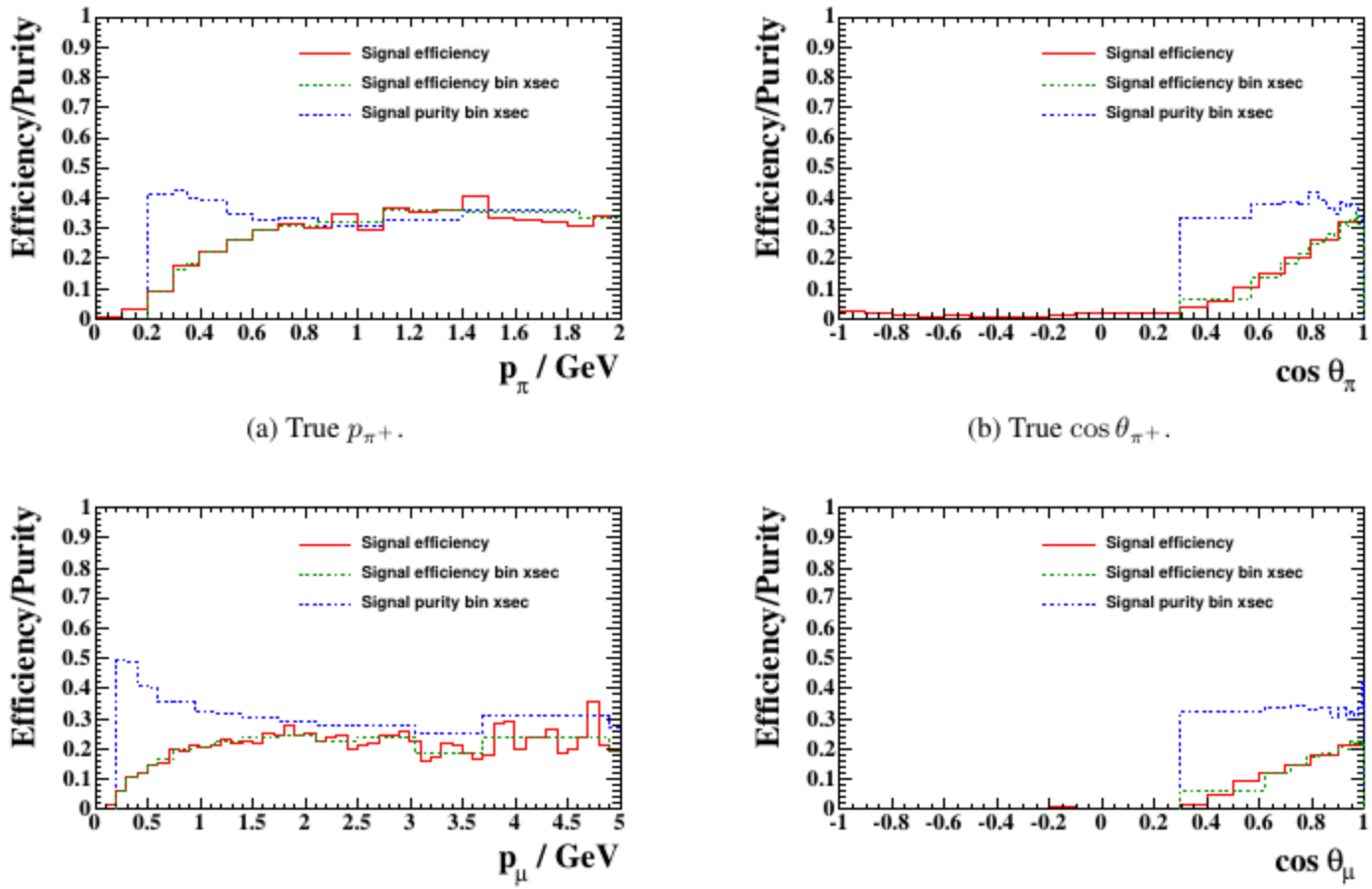
> Restricted phase space: Only forward going pions above ~200 MeV/c



(a) True p_{π^+}.

(b) True $\cos\theta_{\pi^+}$.

(c) True p_{μ^-}.

(d) True $\cos\theta_{\mu^-}$.

Systematics

- CC1pi in water (example)
- Dominant errors:
  - Data stats
  - **Theory (!)**
  - Pion SI

	p_{π^+}	$\cos\theta_{\pi^+}$	p_{μ^-}	$\cos\theta_{\mu^-}$	$\cos\theta_{\mu^+,\pi^+}$
Flux-averaged σ	3.222	3.133	2.981	2.772	3.118
Total stat. error	0.422	0.437	0.433	0.442	0.441
Total syst. error	1.441	1.701	1.473	1.253	1.670
Total error	1.501	1.756	1.535	1.328	1.727
Fractional uncertainties in %					
Data statistics	12.48	13.34	13.96	15.28	13.53
MC statistics	3.93	4.12	4.06	4.58	4.17
Theory cross-section	32.02	40.64	34.89	35.34	41.09
FSI	6.97	7.95	7.42	16.11	7.10
Flux	29.51	33.87	32.97	21.58	32.21
B field distortion	0.18	0.07	0.26	0.10	0.09
TPC charge confusion	0.18	0.07	0.25	0.10	0.10
FGD2 backward migrations	0.56	0.35	0.42	0.86	0.38
FGD2 forward migrations	1.13	0.77	0.82	0.89	0.72
FGD mass scintillator	0.28	0.42	0.34	0.51	0.42
FGD mass water	0.78	0.79	0.82	0.87	0.82
TPC momentum resolution	1.37	0.76	1.57	1.03	0.75
TPC momentum scale	0.44	0.48	0.45	0.61	0.38
Out of FV	0.47	0.35	0.82	1.04	0.32
ECal PID	0.09	0.11	0.08	0.08	0.07
Pile up	0.35	0.36	0.38	0.40	0.36
ECal reconstruction	0.40	0.47	0.38	0.54	0.54
Pion secondary interactions	6.88	8.98	8.66	7.77	9.11
TPC quality cut	negl	negl	negl	negl	negl
TPC-FGD matching efficiency	0.03	0.03	0.02	0.03	0.03
TPC PID	1.08	1.36	0.81	1.97	2.24
TPC track efficiency	0.33	0.23	0.26	0.41	0.25
Übermerging	negl	negl	negl	negl	negl

How are K^+ produced?

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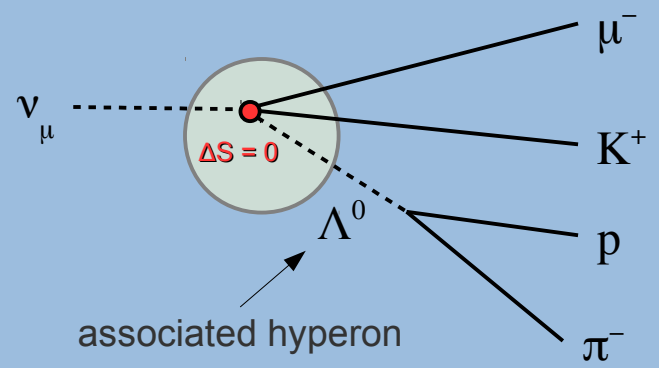
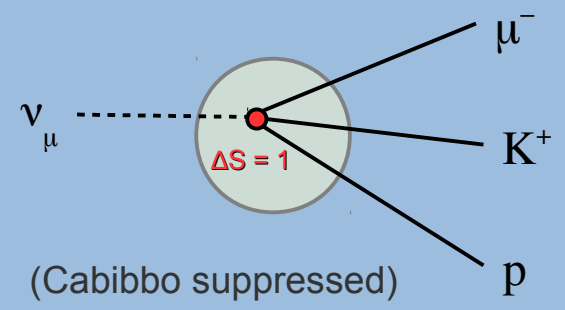
> Associated kaon production

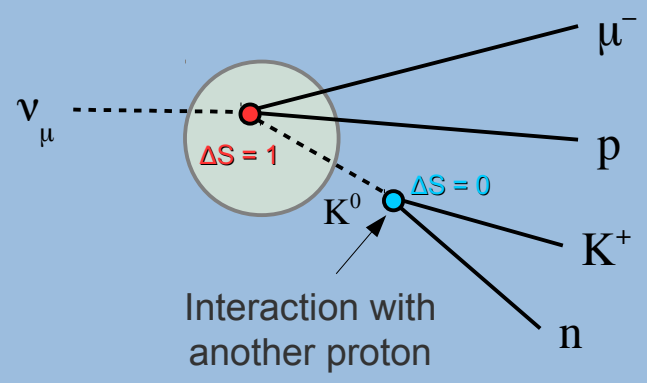
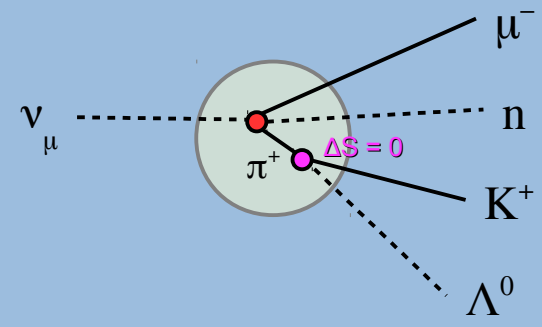


Single kaon production



NEW in GENIE v2.9.0 (Apr 2015)

> Secondary K^0 interaction



Single pion FSI