Impact of Res+ modelling to the sub-GeV global neutrino oscillation program

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Sub-GeV neutrino oscillation experiments

Short-baseline

- **MiniBooNE**
- **MicroBooNE**
- SBN(**SBND**/MicroBooNE/ICARUS
- ND280 (T2K)

Long-baseline

- **ND280/T2K**
- T2K2
- HK

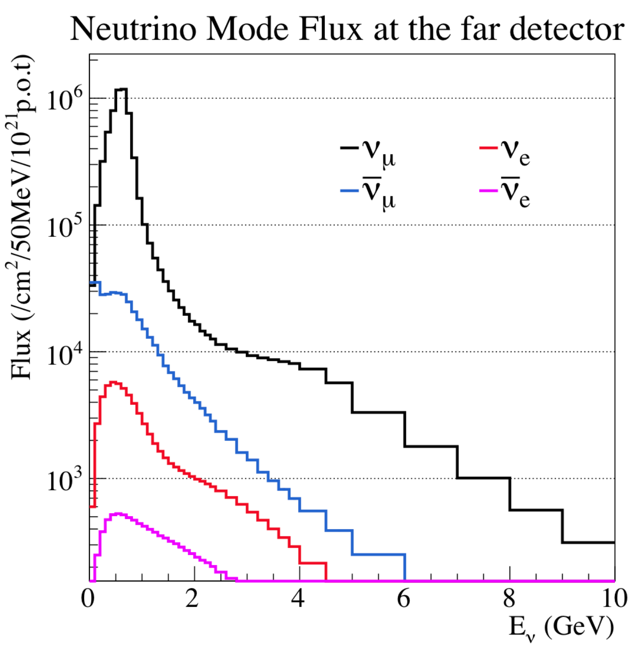
Outline:

- Pion processes in sub GeV region
- Monte Carlo generators
- T2K approach
- MiniBooNE approach
- MicroBooNE/SBN

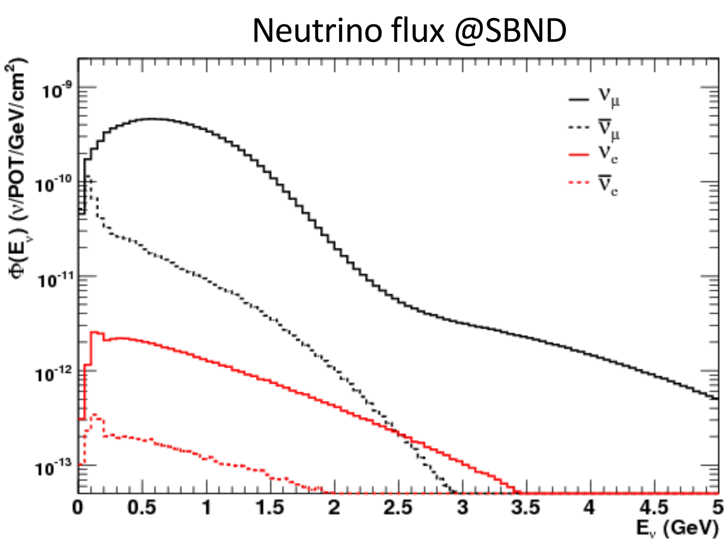
T2K and BNB fluxes

- The two sub-GeV neutrino beams (BNB and T2K) have very similar medium energy
- The flux for T2K is narrower due to the off-axis effect.

T2K beam

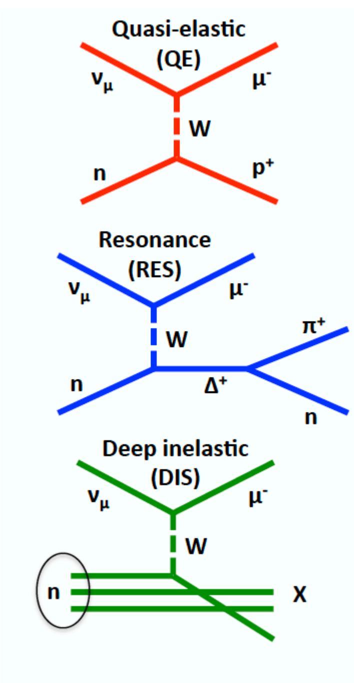


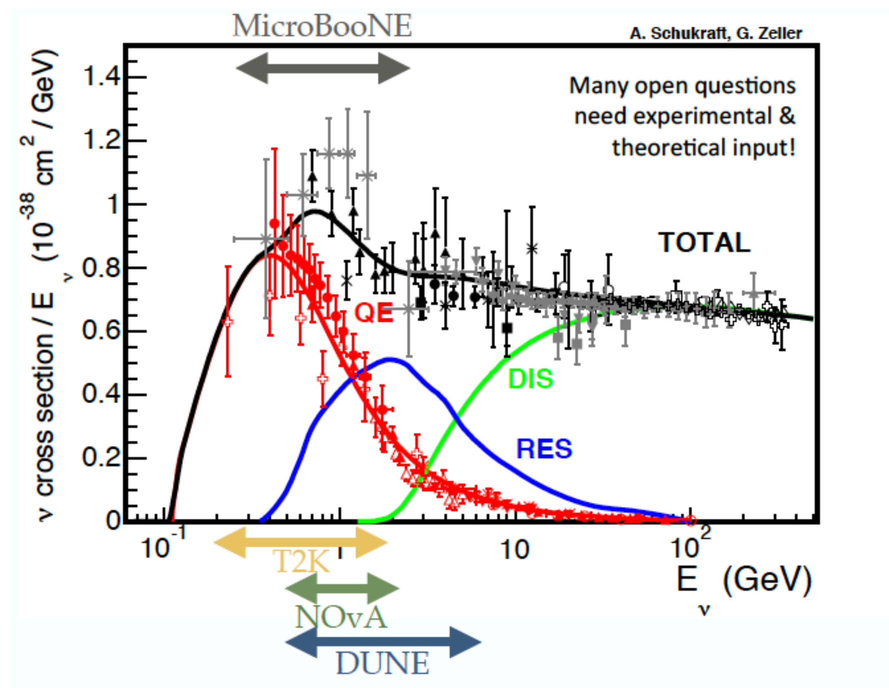
BNB beam



Neutrino interactions (simplified)

- For BNB and T2K the dominant interaction channel is quasi-elastic scattering
- Pion production channels contribute less than 25%





Pion production channels

- **In the sub-GeV region the only relevant resonance is Δ.**

Neutrino CC channels

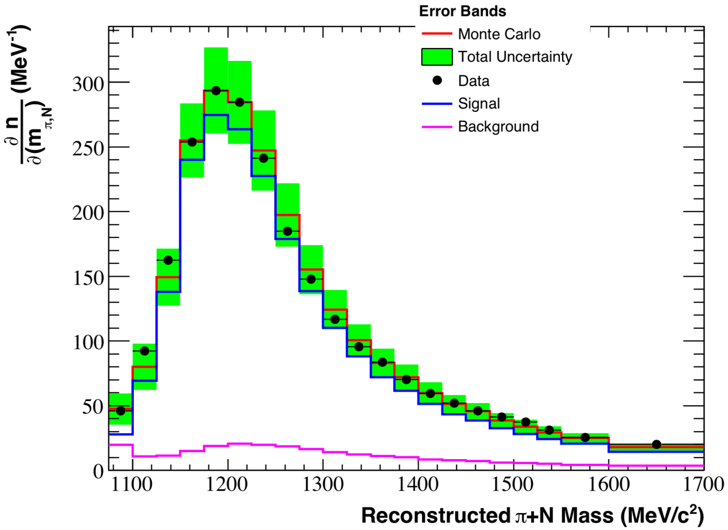
$$\nu + p \rightarrow \mu^- + (\Delta^{++} \hookrightarrow p + \pi^+)$$
$$\nu + n \rightarrow \mu^- + (\Delta^{+} \hookrightarrow p + \pi^0)$$
$$\nu + n \rightarrow \mu^- + (\Delta^{+} \hookrightarrow n + \pi^+)$$

anti-neutrino CC channels

$$\bar{\nu} + p \rightarrow \mu^+ + (\Delta^{0} \hookrightarrow n + \pi^0)$$
$$\bar{\nu} + p \rightarrow \mu^+ + (\Delta^{0} \hookrightarrow p + \pi^-)$$
$$\bar{\nu} + n \rightarrow \mu^+ + (\Delta^{-} \hookrightarrow n + \pi^-)$$

NC channels

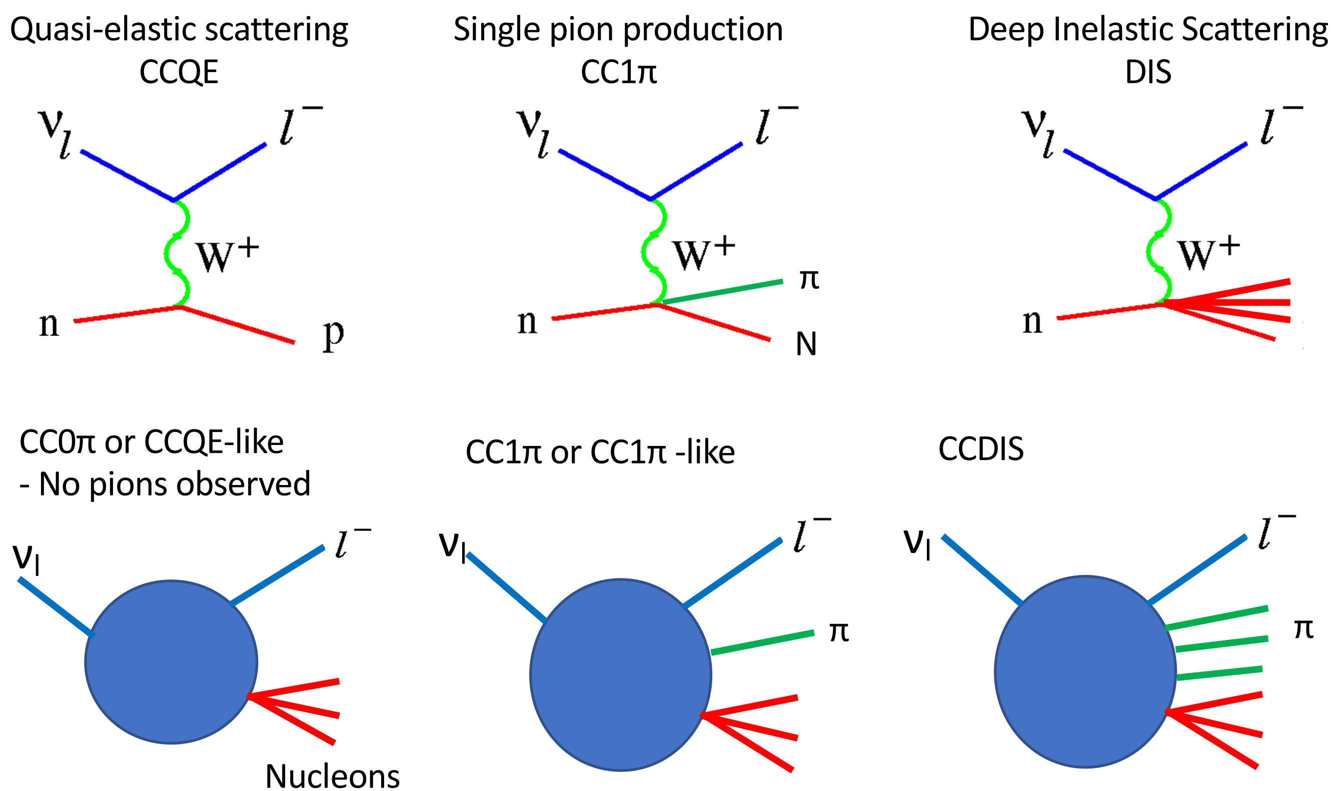
$$\nu(\bar{\nu}) + p \rightarrow \nu(\bar{\nu}) + (\Delta^{+} \hookrightarrow p + \pi^0)$$
$$\nu(\bar{\nu}) + p \rightarrow \nu(\bar{\nu}) + (\Delta^{+} \hookrightarrow n + \pi^+)$$
$$\nu(\bar{\nu}) + n \rightarrow \nu(\bar{\nu}) + (\Delta^{0} \hookrightarrow p + \pi^-)$$
$$\nu(\bar{\nu}) + n \rightarrow \nu(\bar{\nu}) + (\Delta^{0} \hookrightarrow n + \pi^0)$$



MiniBooNE, PRD83:052007,2011

Neutrino-nucleus cross section

- Topology-based measurements make the picture more (less) complicated



Pion production models

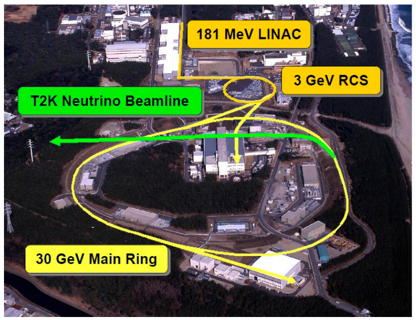
- The Monte Carlo generators & Experiments

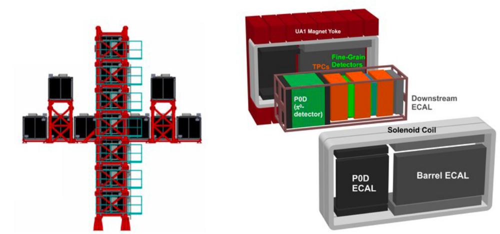
generator	Experiments	Resonance model	Coherent model	FSI
NUANCE	MiniBooNE	Rein-Sehgal KNL-BRS	Rein-Sehgal	Cascade
GENIE	MicroBooNE, T2K, SBN	Rein-Sehgal KNL-BRS	Rein-Sehgal Bergel-Sehgal	INTRANUKE/hA
NEUT	T2K	Rein-Sehgal with MB form factors (Graczyk-Sobczyk)	Rein-Sehgal Bergel-Sehgal	Hybrid Oset et al. & exp. based
NuWro	T2K, MicroBooNE	Home-grown	Rein-Sehgal Bergel-Sehgal	Cascade

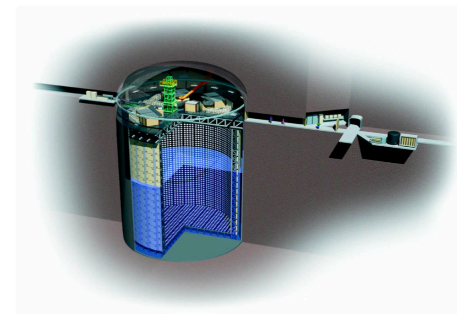
- Each generator has different approach to the transition region between RES and DIS
- Variety of models for interactions and nuclear effects are crucial for experiments
- The same models could give different prediction in the MC generators due to implementation approaches

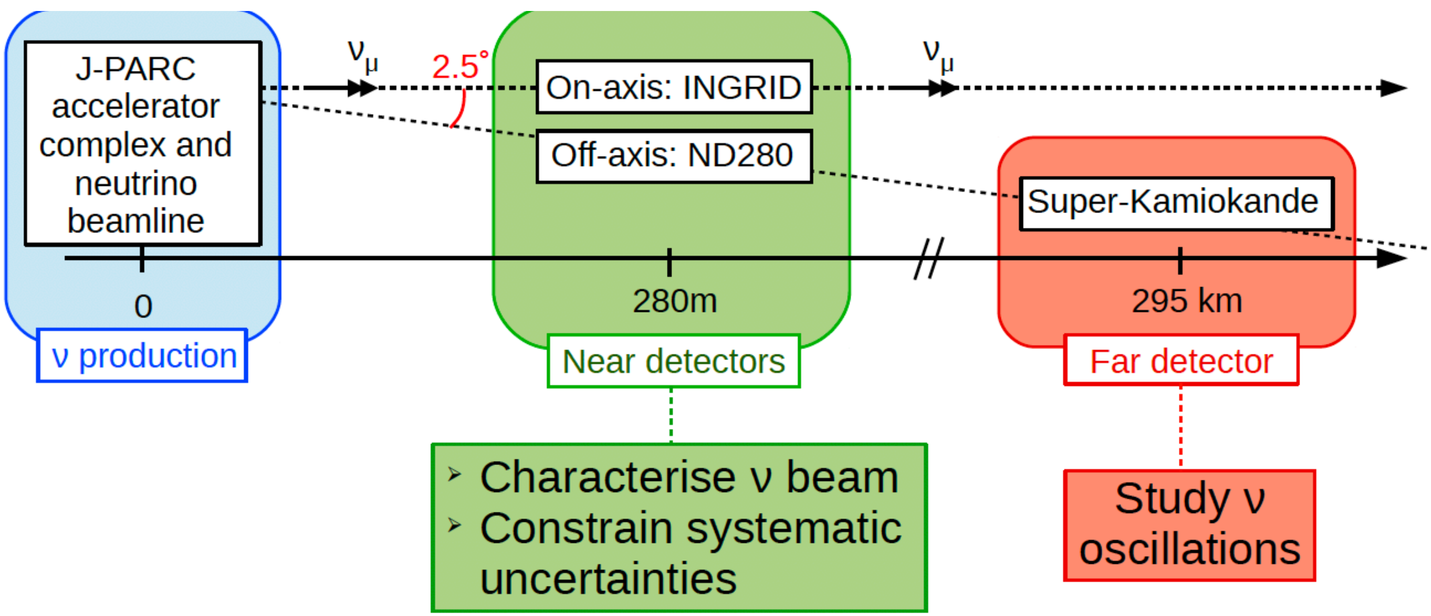
KNL-BRS: Kuzmin-Naumov-Lubushkin-Berger-Sehgal with axial form factor fit to MiniBooNE data
Graczyk-Sobczyk: relation between form factors and helicity amplitudes

The T2K experiment approach



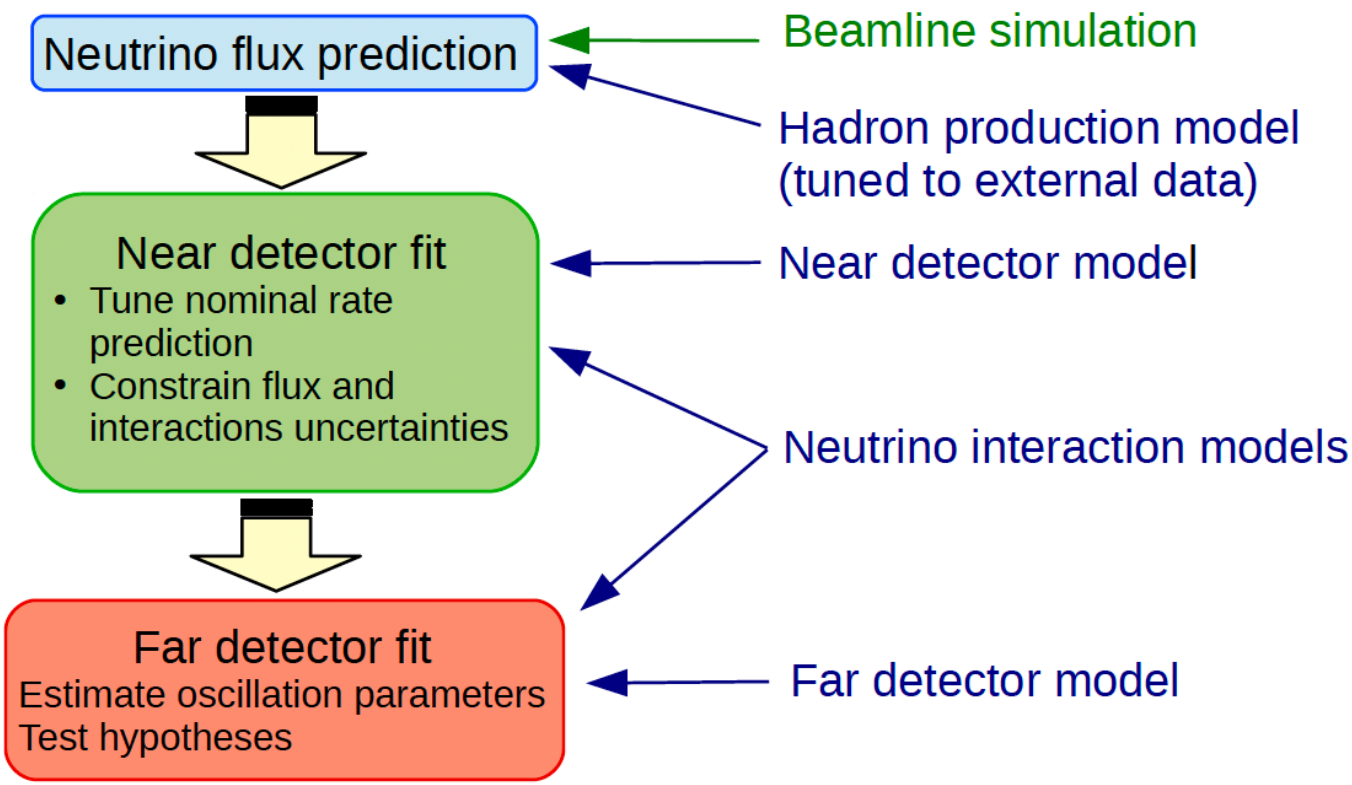






T2K Oscillation Analysis Overview

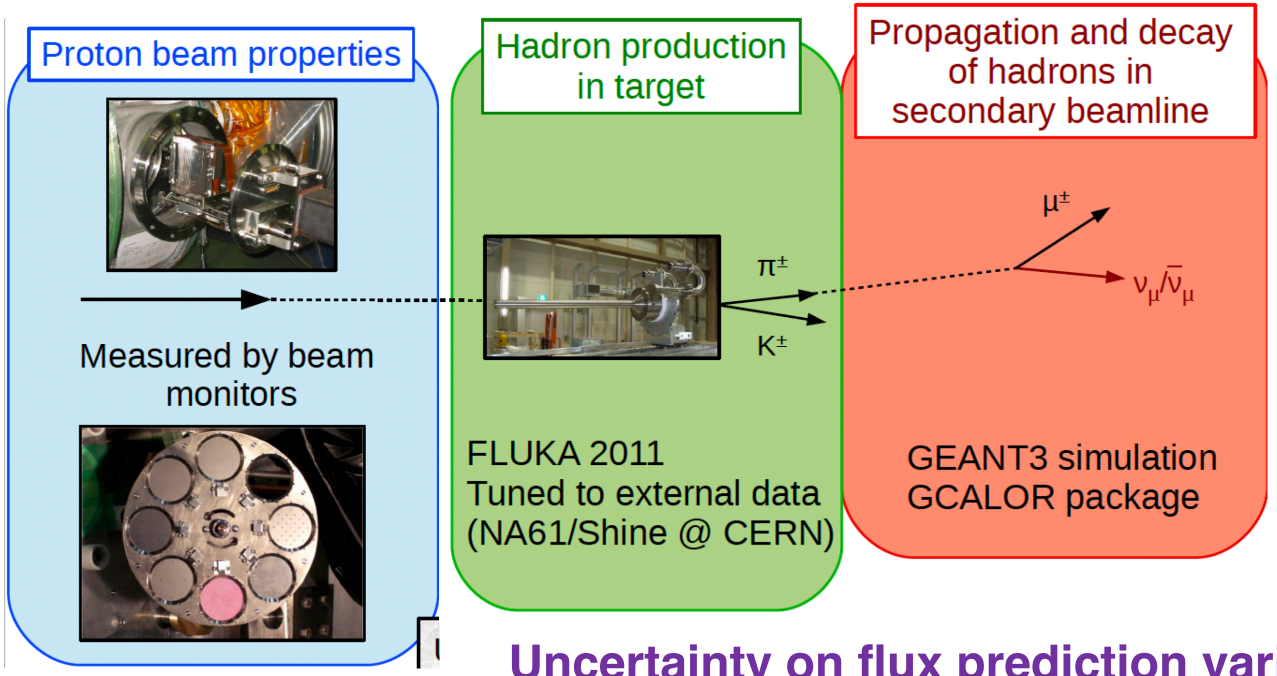
Likelihood analysis: compare observed data at the far detector to predictions based on a model of the experiment to make measurements



(Near and far detector fits can be done sequentially or simultaneously)

T2K Oscillation Analysis
Neutrino flux prediction

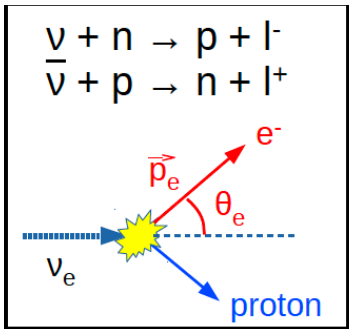
Neutrino flux predicted using a series of simulations



Uncertainty on flux prediction varies between 8 and 12%, depending on neutrino flavour and energy

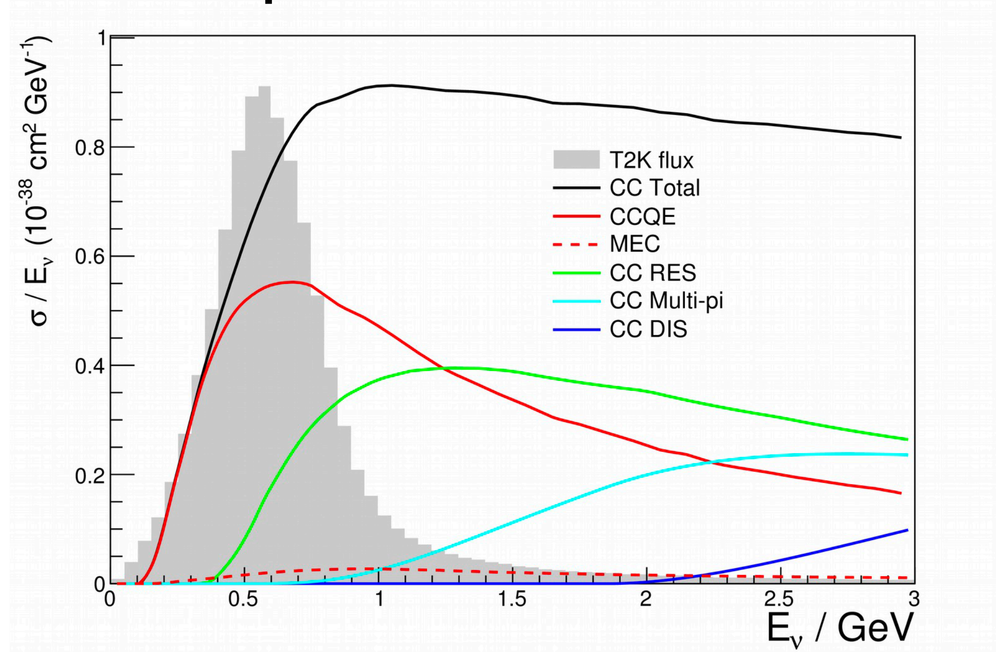
T2K Oscillation Analysis
Neutrino interaction model

Dominant interaction mode is CCQE



Other interactions can populate region of interest

Select interaction models using external data
➢ Nominal predictions from NEUT 5.3.2

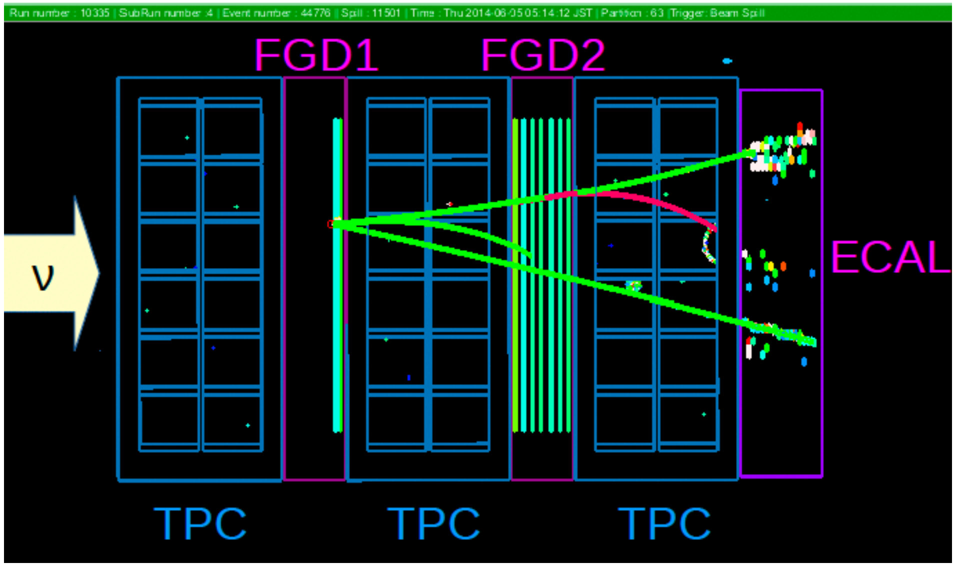


Uncertainties on model parameters (e.g. M_A, p_F,…)
➢ Additional uncertainties for certain modes (shape, normalization)
➢ "Simulated Data Studies" (SDS) for alternative models and uncertainties that could not be implemented

Near detector analysis event selection

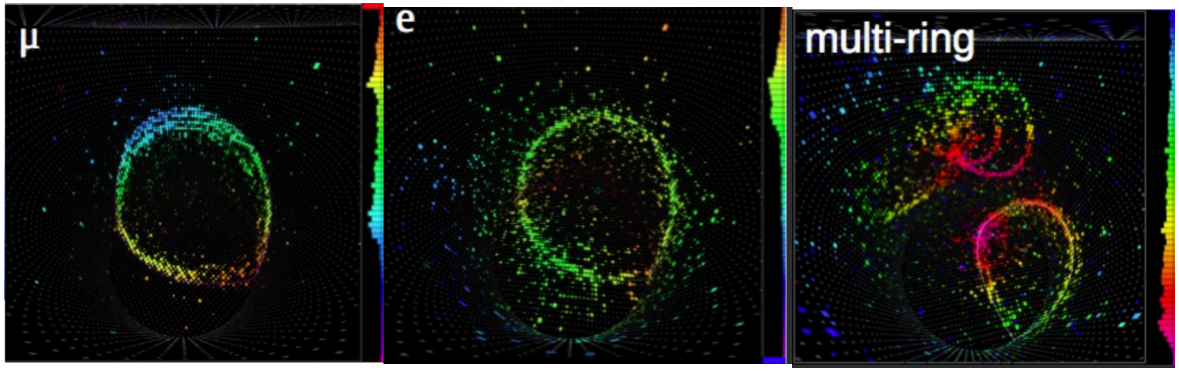
Select CC ν_μ interactions, categorize into samples

- Enriched in different type of interactions
- Interactions on different targets (FGD1: CH target, FGD2: 42% water)
- additional samples for wrong sign background in ν-mode



Far detector selections:

- 1-ring, CCQE-enriched sample
- $CC1\pi^+$ sample (ν_e appearance)

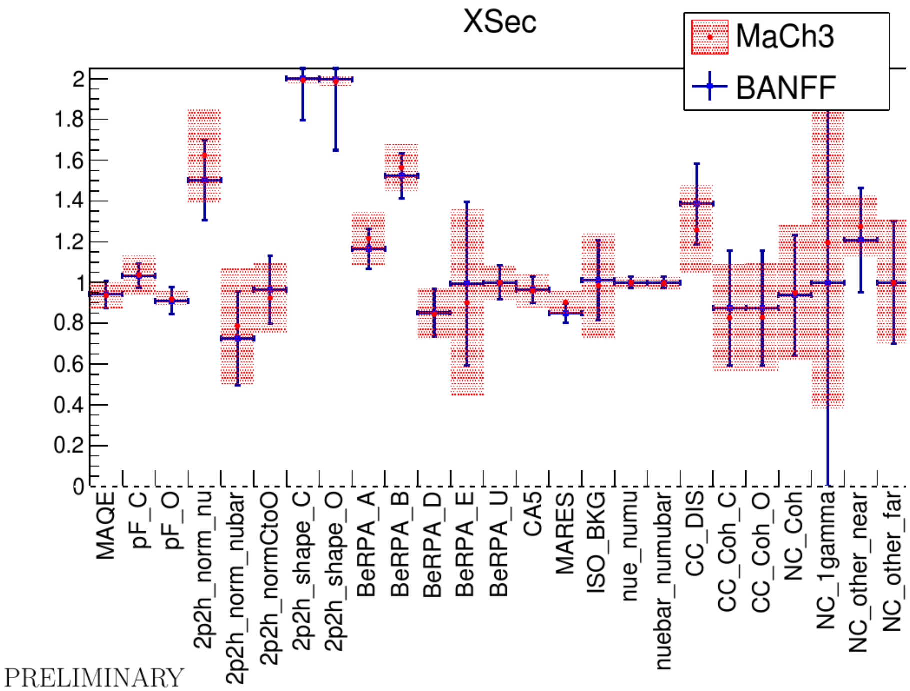


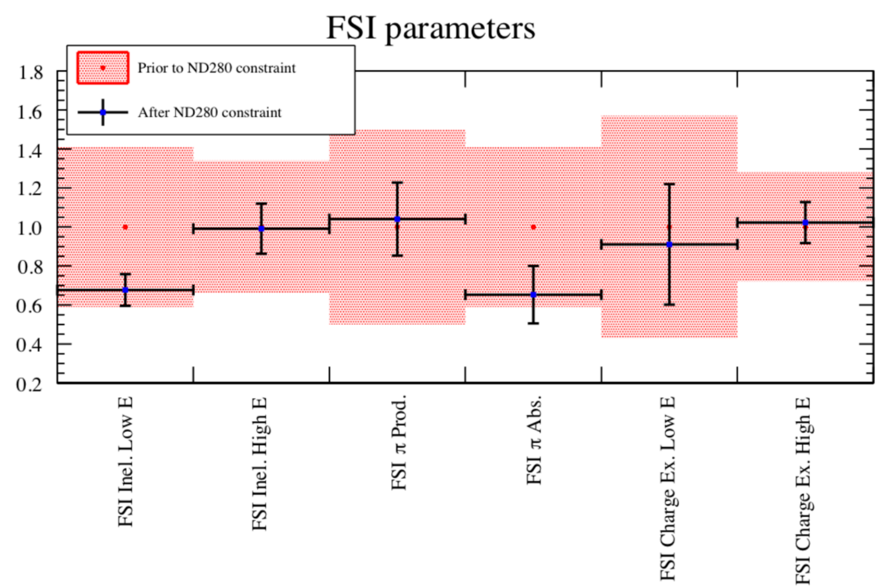
Near detector analysis Fits

The magic happens during the near detector analysis fitting

2 different fitters giving consistent results:

- "Mach3": MCMC based marginalization to obtain posterior probabilities
- "BANFF": gradient descent

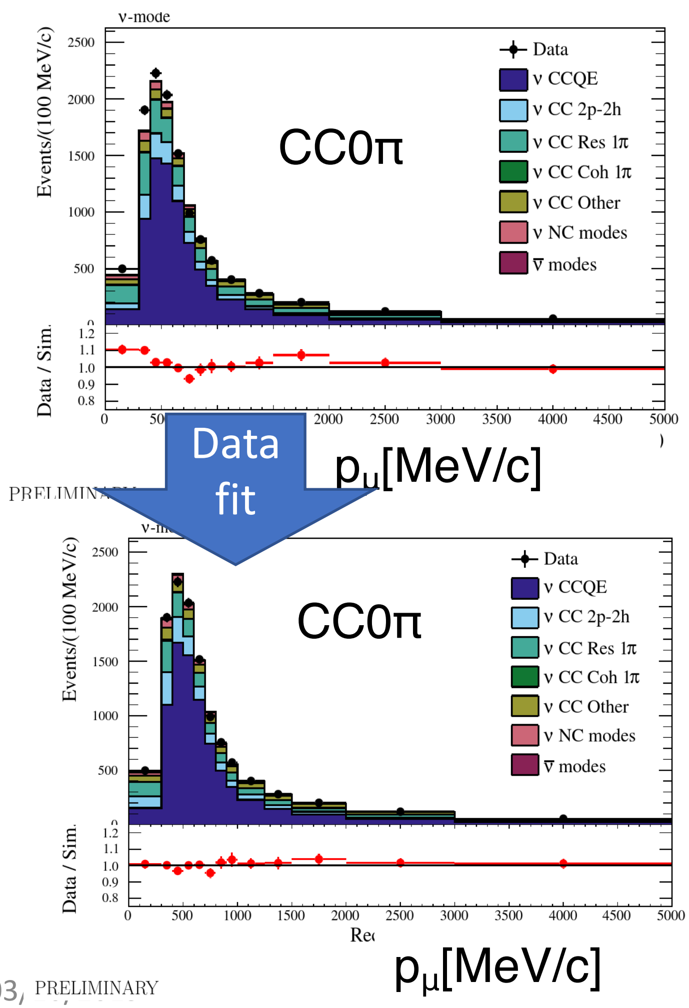


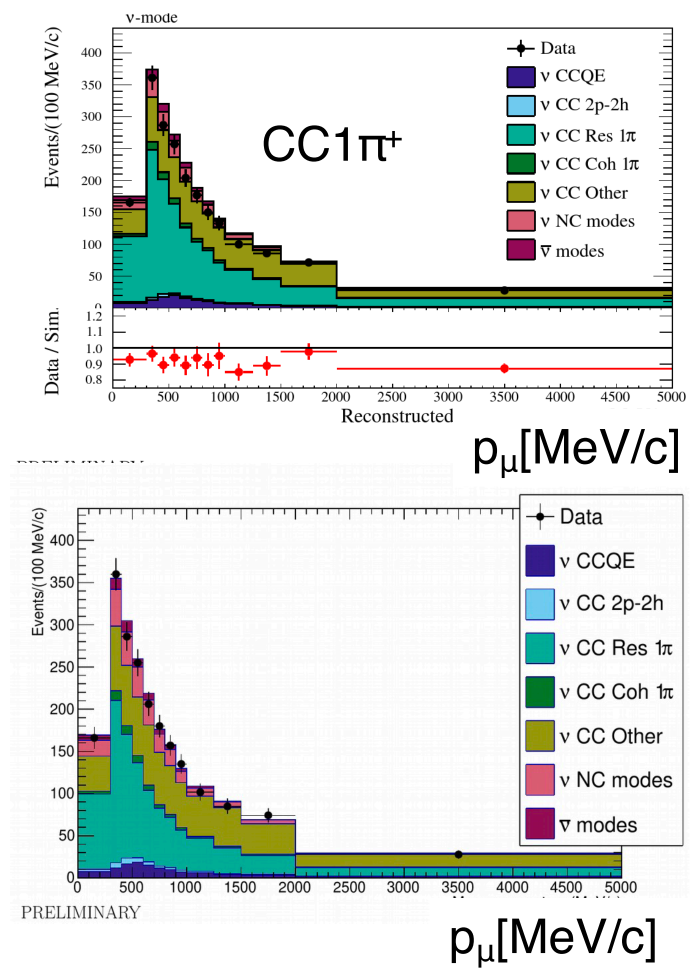


Anti-correlations between postfit flux and interaction uncertainties

Near detector analysis event selection

FGD1 samples (MC tuned with ND fit)

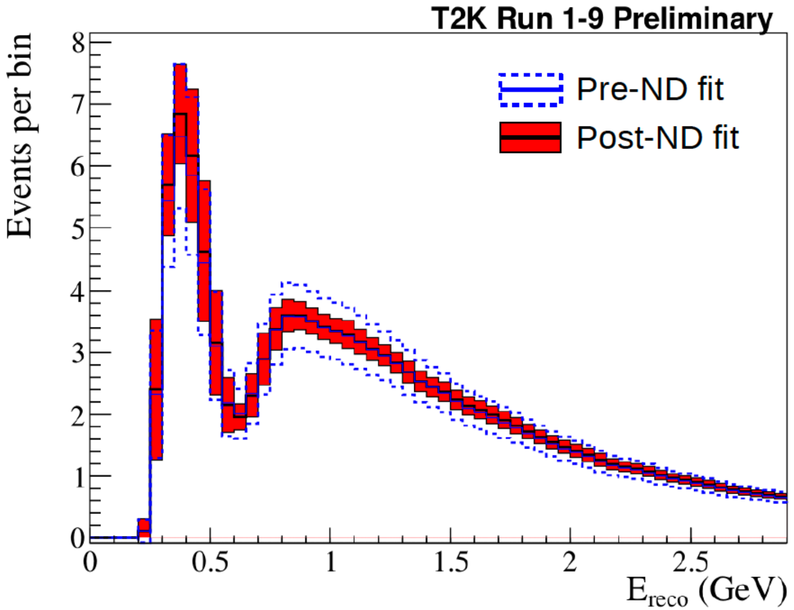




Near detector analysis reduction of uncertainties

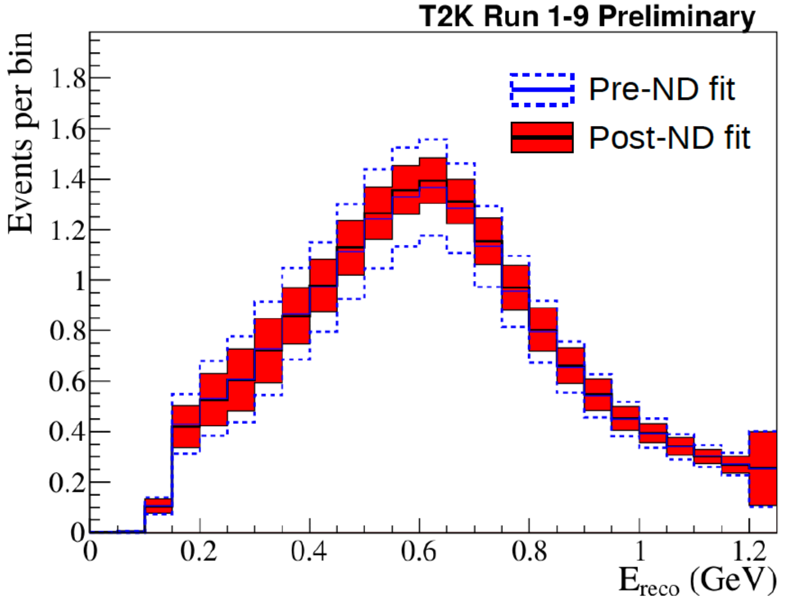
Near detector fit shifts the nominal predictions at the far detector, and reduces the flux and cross-section uncertainties

1 ring μ-like ($\bar{\nu}$-mode)



$\Delta N_{SK}/N_{SK}$: 12.5% → 4.4%

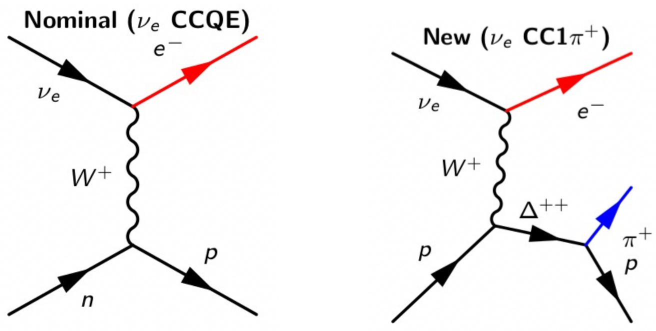
1 ring e-like ($\bar{\nu}$-mode)



$\Delta N_{SK}/N_{SK}$: 14.4% → 7.1%

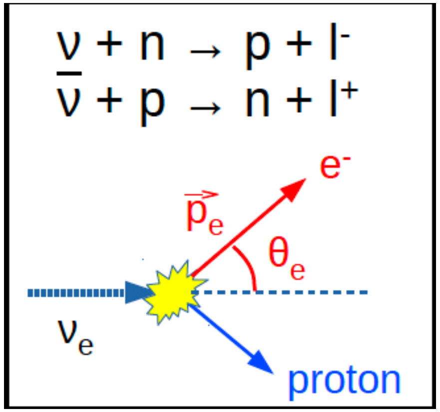
CC1π^+ as signal events

- The T2K also included the CC1π^+ in the ν_e appearance analysis
- Far detector analysis Energy reconstruction use similar approach for resonant pion production with p→Δ^{++}



- Knowing ν direction we can

reconstruct Eν from lepton (p,θ)



Observed number of events

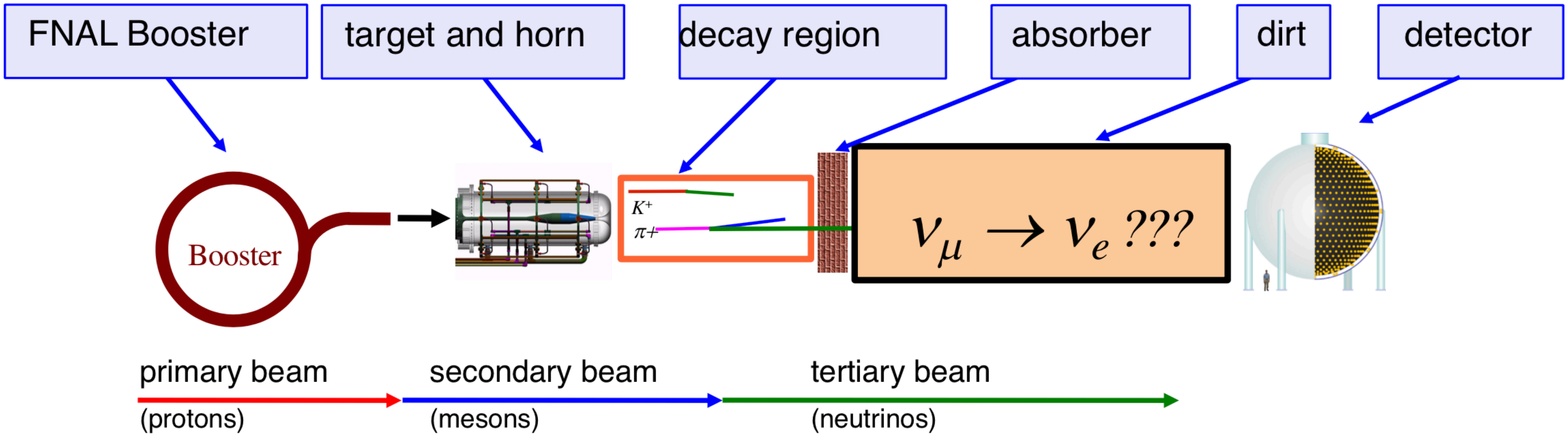
- The T2K in the full dataset (run 1-9) observed:
  - Excess of events in the neutrino mode sample targeting the CC1π^+ events
  - Small deficit in the neutrino mode 1-ring muon-like sample

Sample	δ=-π/2 MC	δ=0 MC	δ=π/2 MC	δ=π MC	Observed
ν-mode 1Re	74.46	62.26	50.59	62.78	**75**
ν-mode 1Rμ	272.34	271.97	272.30	272.74	**243**
$\bar{\nu}$-mode 1Re	17.15	19.57	21.75	19.33	**15**
$\bar{\nu}$-mode 1Rμ	139.47	139.12	139.47	139.82	**140**
ν-mode e-like CC1π	7.02	6.10	4.94	5.87	**15**

MiniBooNE

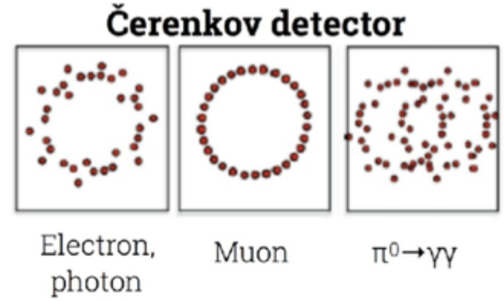
$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + \boxed{e^-}$$

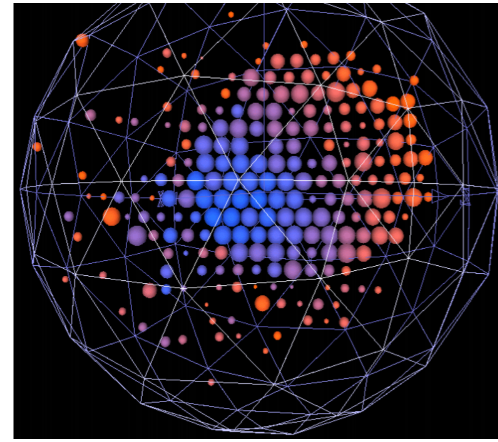
$$\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow n + \boxed{e^+}$$



MiniBooNE is looking for the single isolated electron-like events, which is the signature of ν_e events

MiniBooNE detector

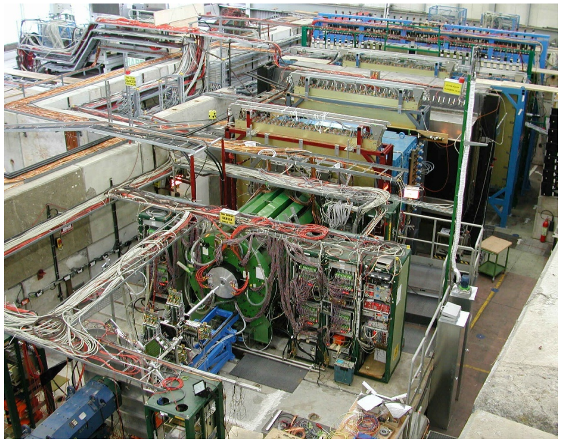




- 541 meters downstream of target
- 12 meter diameter sphere (10 meter "fiducial" volume)
- Filled with 800 t of pure mineral oil (CH2) (Fiducial mass: 450 t)
- 1280 inner phototubes and 240 veto phototubes

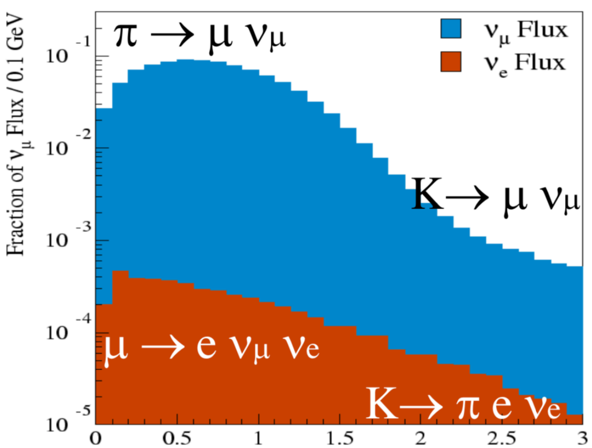
MiniBooNE approach- Neutrino beam

HARP experiment (CERN)



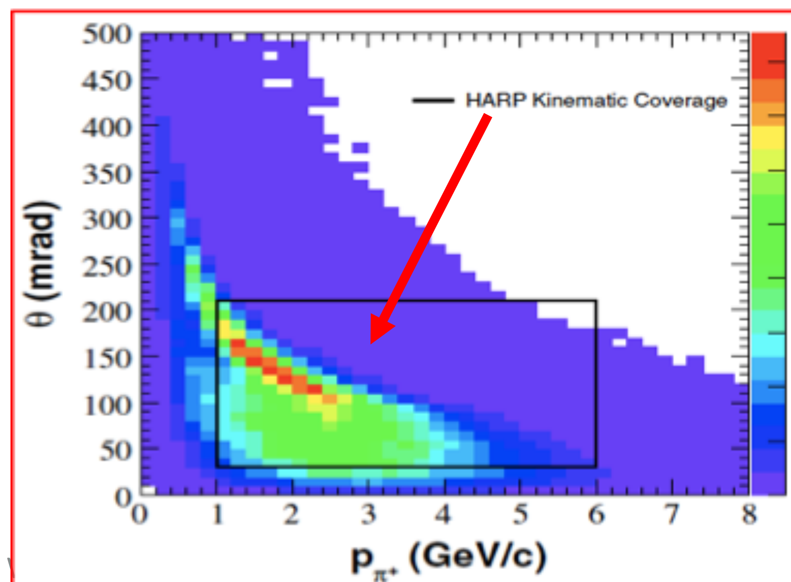
Modelling of meson production is based on the measurement done by HARP collaboration.

- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum - >80% coverage for π^+



Estimation of intrinsic ν_e is crucial for MiniBooNE, but for for this talk

MiniBooNE simulation

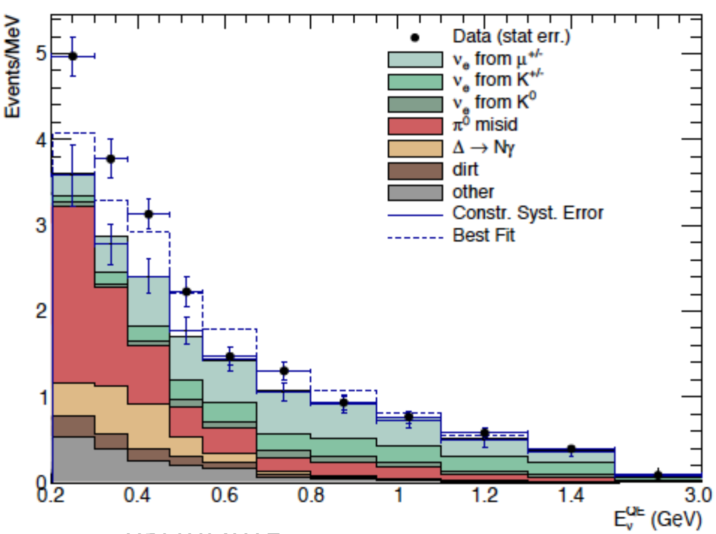


MiniBooNE approach- *in situ* constraints

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

misID

intrinsic



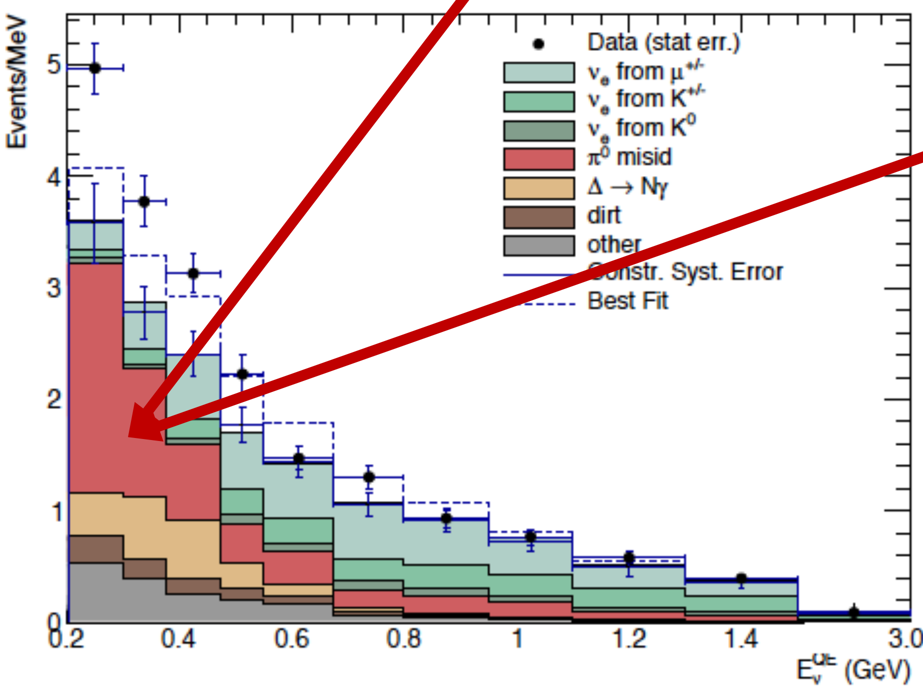
Internal background constraints

- All backgrounds are internally constrained
  - intrinsic (beam ν_e) = flat
  - misID (gamma) = accumulate at low E

- Here let's focus on the misID channels with pions
- Almost 50% of the background come form resonance excitation channels.

NC π^0

Asymmetric π^0 decay is constrained from measured CC π^0 rate ($\pi^0 \rightarrow \gamma$)



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γ from π^0 constraint

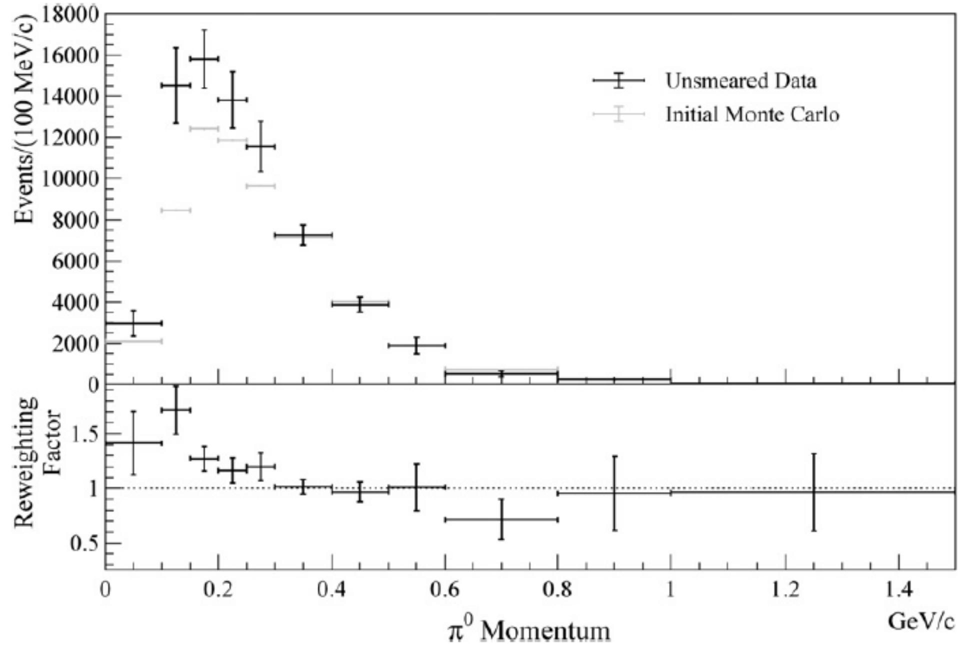
- $\pi^0 \rightarrow \gamma\gamma$
  - not background, we can measure and rejected
- $\pi^0 \rightarrow \gamma$
  - misID background, we cannot measure

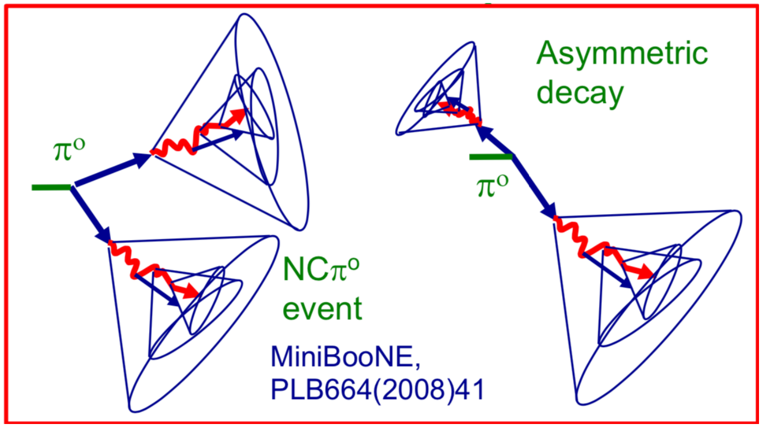
The biggest systematics is production rate of π^0 , because once you find that, the chance to make a single gamma ray is predictable.

We measure π^0 production rate, and correct simulation with function of π^0 momentum

Better understanding of the π^0 would help to disambiguate it from the nuclear effects.

π^0 momentum data-MC comparison





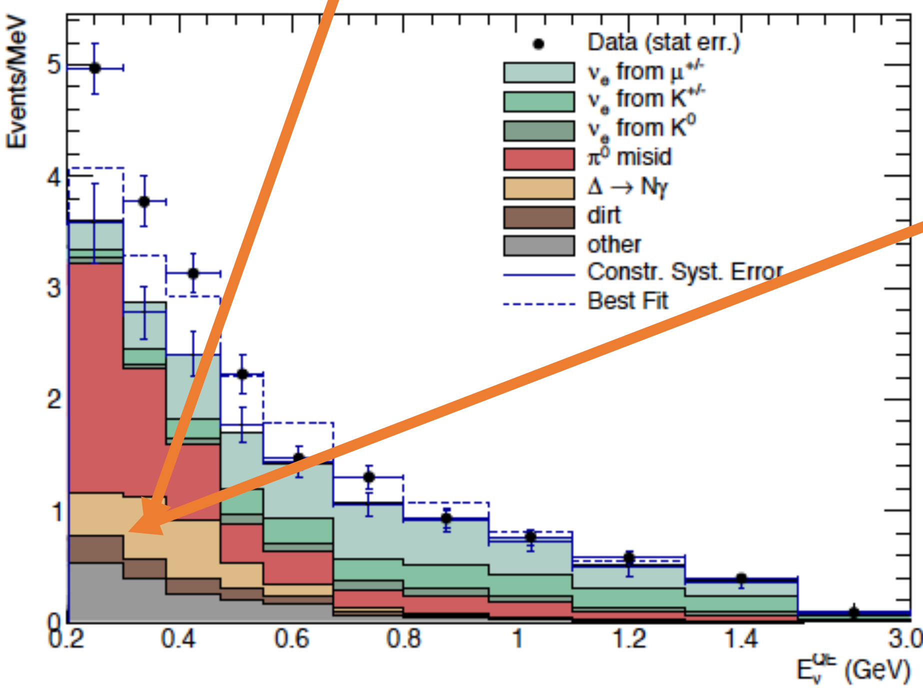
NCγ constraint

Δ resonance rate is constrained from measured NCπ^0 rate

A simple estimation more or less agree with modern calculations (later)

$$\frac{N(\Delta \to N\gamma)}{N(\Delta \to N\pi^o)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^o}\varepsilon}$$

$\Gamma\gamma/\Gamma\pi$: NCγ to NCπ branching ratio
π^o fraction (=2/3)
ε: π escaping factor



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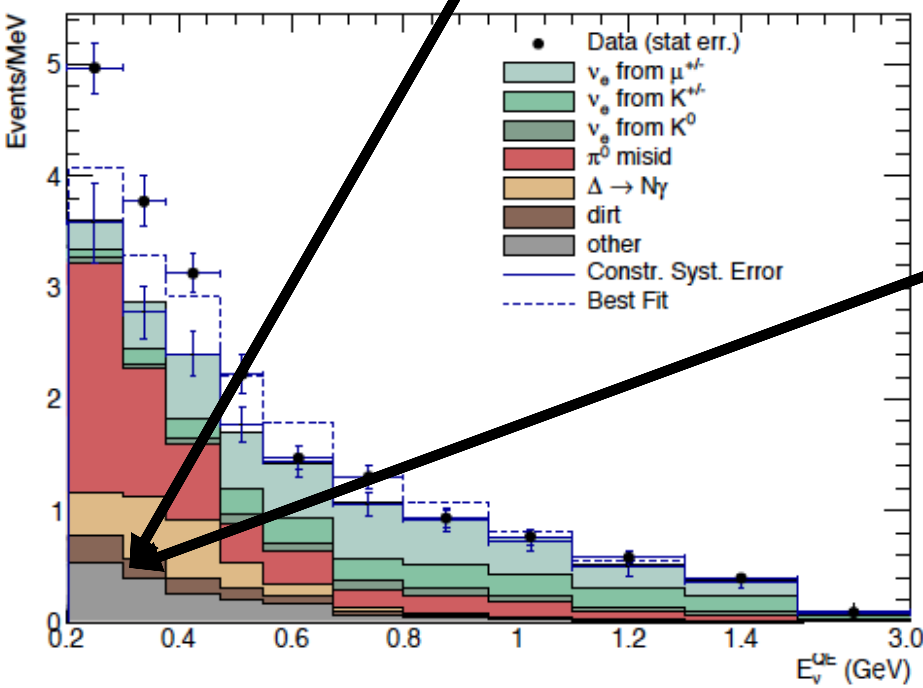
External γ constraint

Dirt (external) rate is measured from dirt data sample



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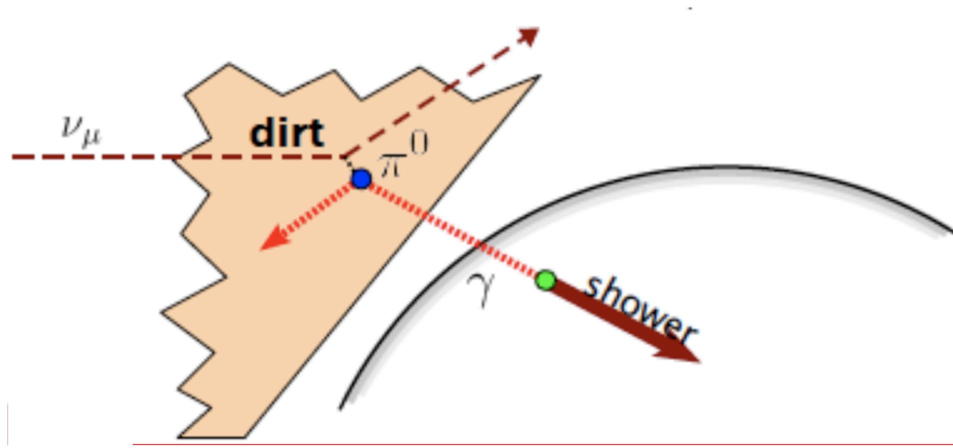
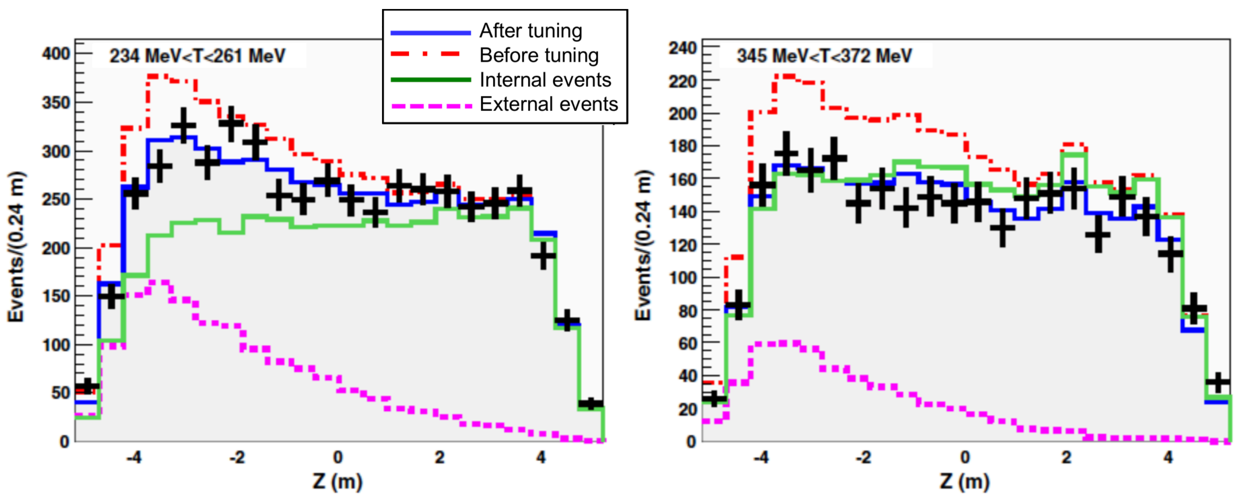
External γ constraint

- MiniBooNE detector has a simple geometry - Spherical Cherenkov detector
  - Homogeneous, large active veto
- We have number of internal measurement to understand distributions of external events.

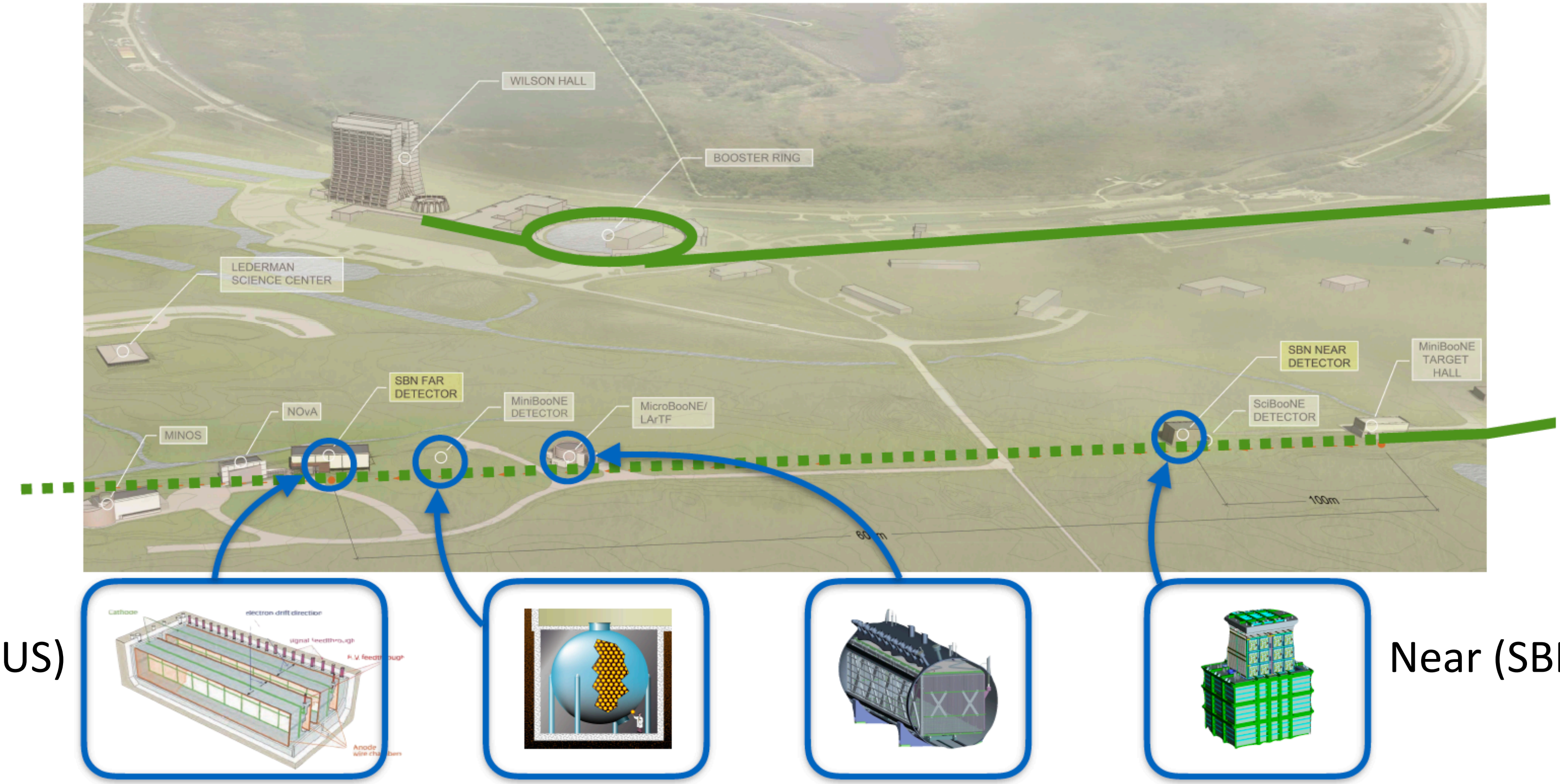




NC elastic candidates with function of Z

Mis-modelling of external background is visible

SBN (Short-baseline neutrino) programme



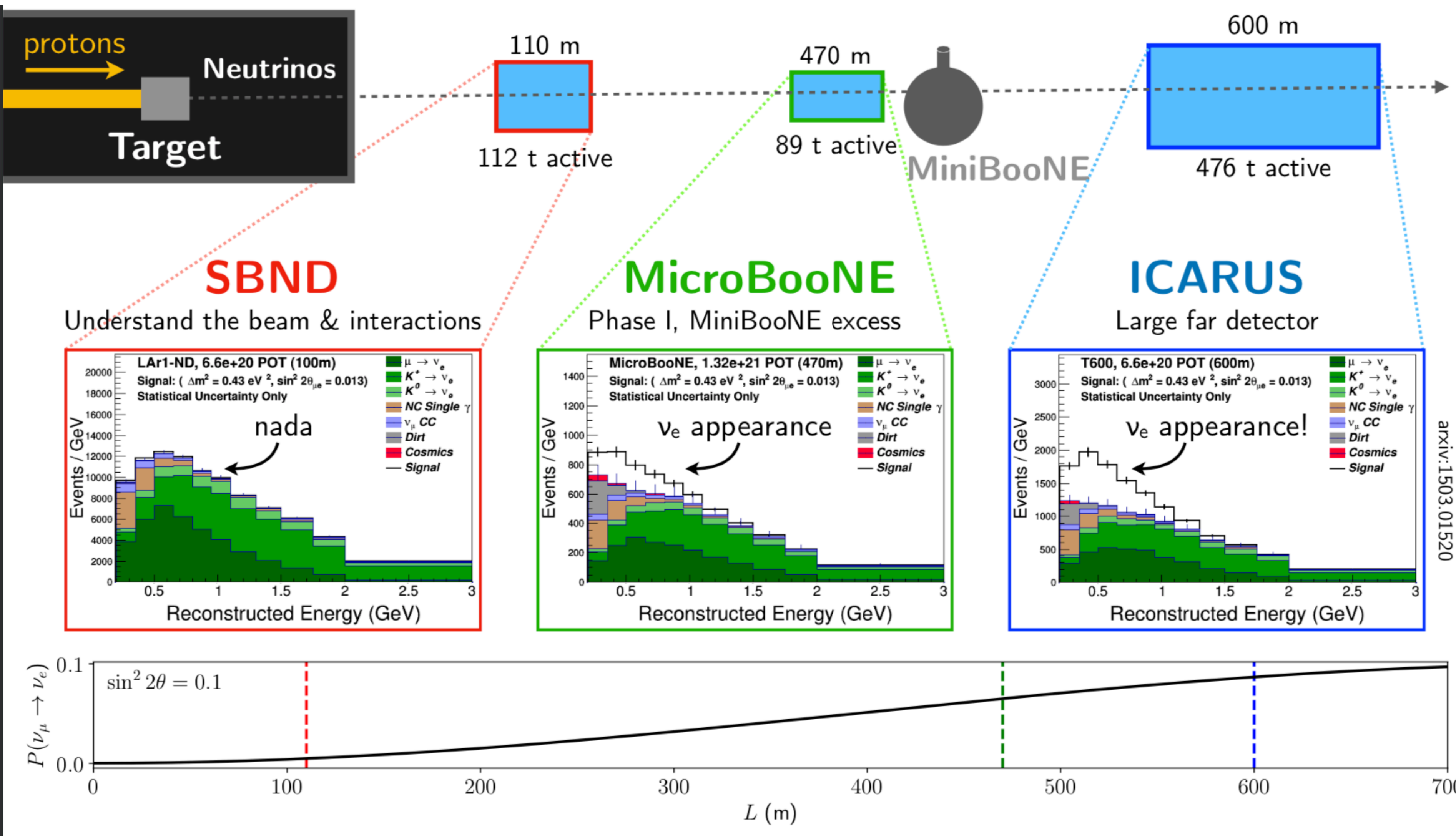
Far (ICARUS)

Near (SBND)

Middle (MicroBooNE)

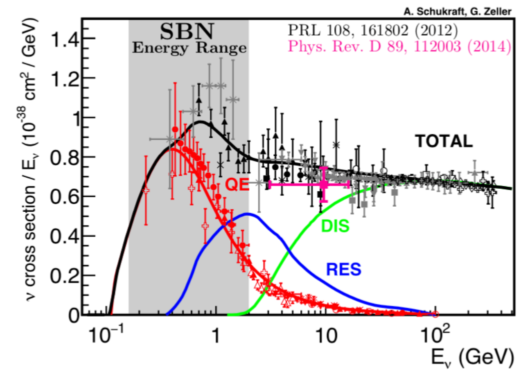
- Three liquid argon TPCs in the Fermilab Booster Neutrino Beam
  - Same argon target, functionally similar detectors
  - Definitive test of LSND oscillations using three baselines
  - Simultaneous ν_μ disappearance and ν_e appearance searches

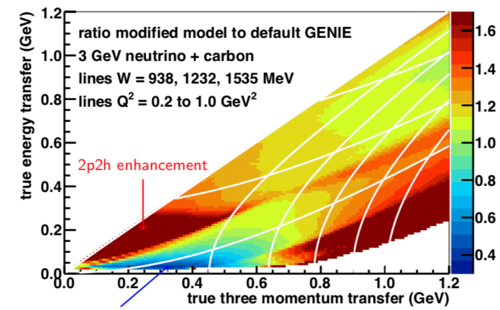
The Short-Baseline Neutrino Program



Interaction Modelling & Uncertainties

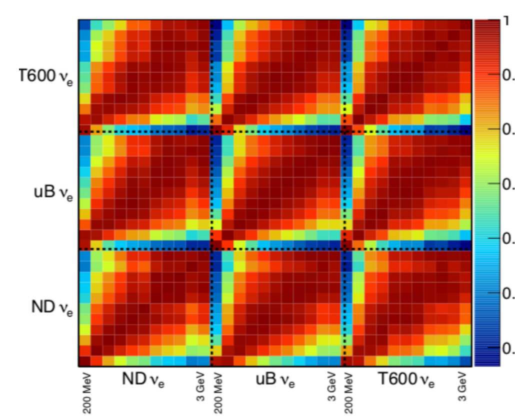
- Ongoing efforts to include state-of-the art models, multiple generators
- Updated tunes for deuterium bubble chamber reanalyses
- Integrating Ar cross section measurements into oscillation analysis
- GENIE cross section, hadronization, resonance decay, FSI uncertainties
- RPA and Valencia MEC uncertainties (cf. MINERvA, NOvA)
- Alternate FSI models (full vs. effective nuclear cascade)
- Alternate MEC models (Valencia vs. empirical tuned on e scattering)
- Second class currents, radiative corrections, C/Ar, ν_e/ν_μ





P. Rodrigues (MINERvA), FNAL JETP 12/15

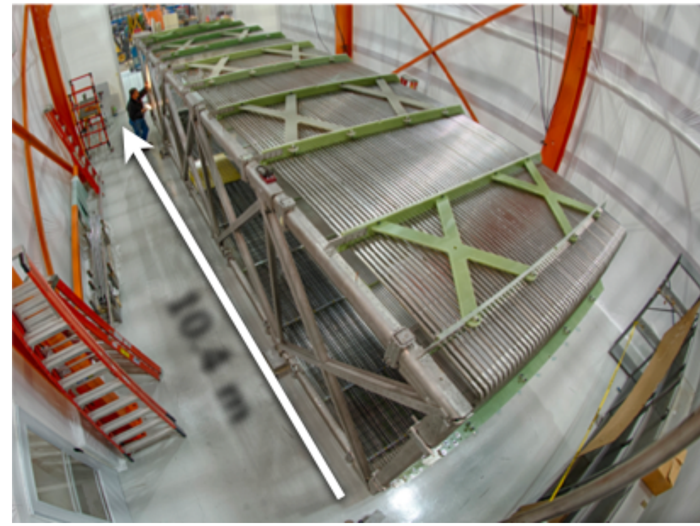
GENIE Correlations arxiv:1503.01520

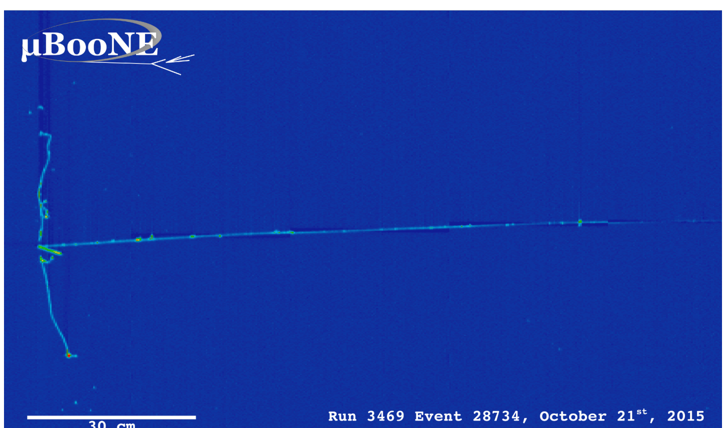


MicroBooNE

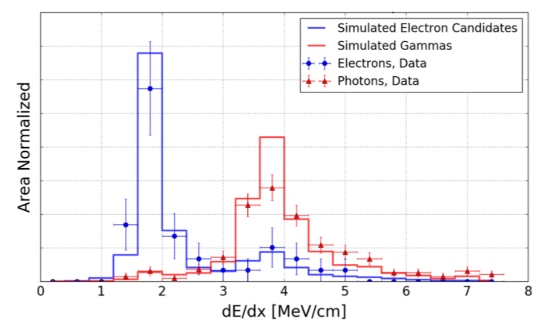
- Determine the nature of MiniBooNE excess (e or γ)
  - Similar baseline to MiniBooNE (470 m)
  - 89 tons active LAr mass

- Why Lar TPC?
  - Detailed imaging of neutrino interactions
  - Superb e/γ separation





dE/dx e/γ
in ArgoNeut



PRD 95, 072005 (2017)

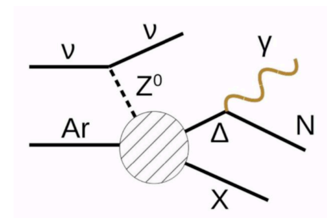
MicroBooNE (Low Energy Excess)

- **Parallel *e*-like Excess Analysis Efforts:**
  - Multiple reconstruction and selection techniques

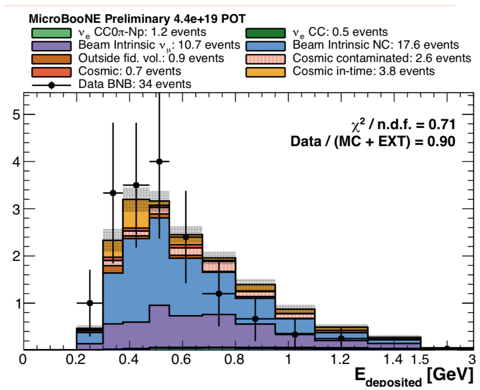
Pandora-Based CC0π*Np* Selection

- **Sideband checks in place to ensure backgrounds understood**

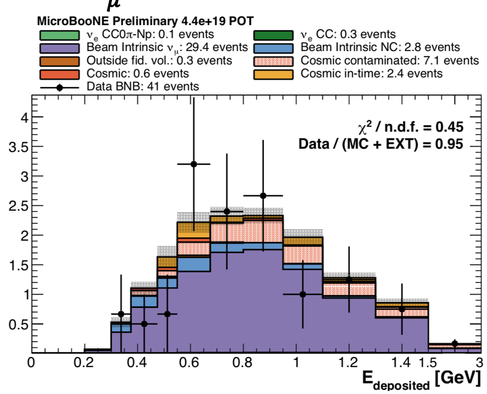
Search for **single photon events** consistent with originating from a **resonant Δ radiative decay** (~0.5% of Δ decays)



π^0 Enhanced Sideband

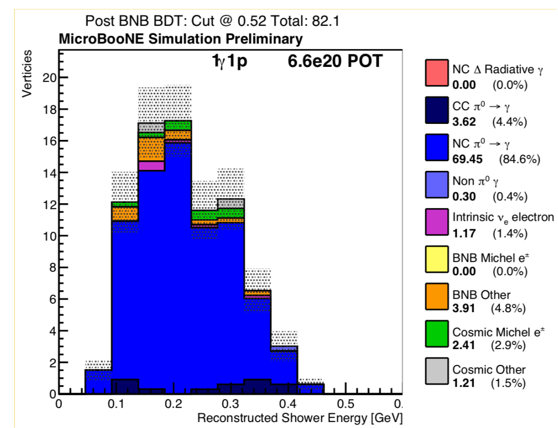


CC ν_μ Enhanced Sideband



MicroBooNE-NOTE-1038-PUB

Single Photon 1γ1p Selection



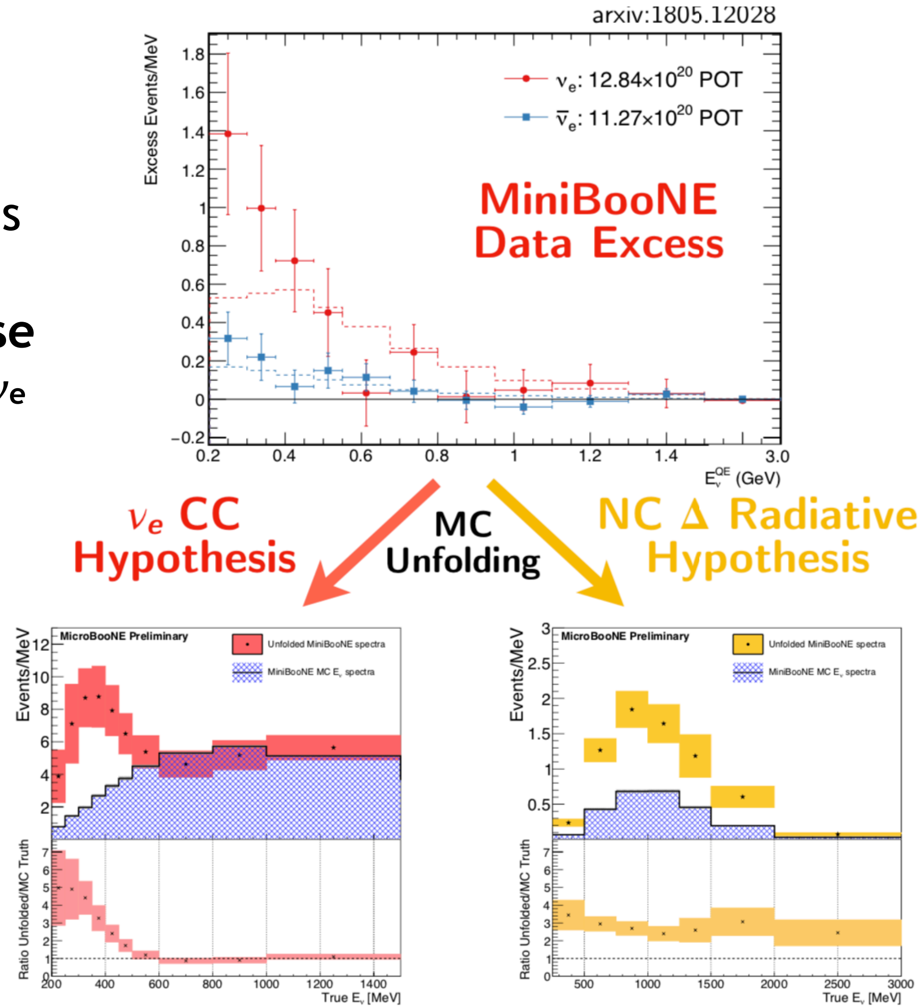
MicroBooNE-NOTE-1041-PUB

MicroBooNE (Low Energy Excess)

Assuming the LEE is due to an energy dependent **increase in the rate of CC ν_e** events

For ν_e:

- $\nu_e + Ar \rightarrow e^- + 1\,p$ (1e1p)
- $\nu_e + Ar \rightarrow e^- + N\,p$ (1eNp)
- $\nu_e + Ar \rightarrow e^- + X$ (incl.)



MICROBOONE-NOTE-1043-PUB
(N.B. using previous MiniBooNE results)

Assuming the LEE is due to an increase in the rate of **NC resonant Δ with subsequent radiative decays**

For NC $\Delta \rightarrow N\gamma$:

- $\nu + Ar \rightarrow \gamma + 1\,p$ ($1\gamma1p$)
- $\nu + Ar \rightarrow \gamma + 0\,p$ ($1\gamma0p$)

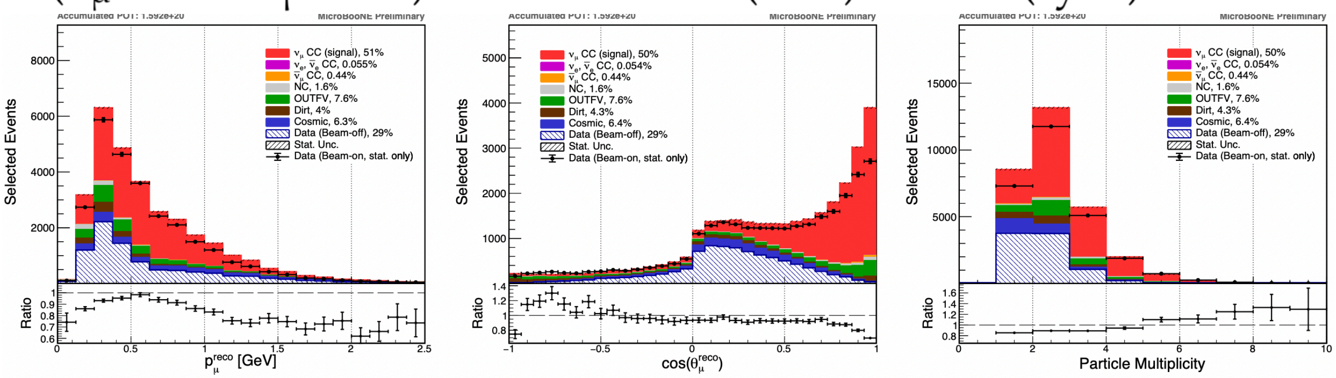
MicroBooNE Cross section program

Friday: Kirsty Duffy, MicroBooNE capabilities, measurements and plans

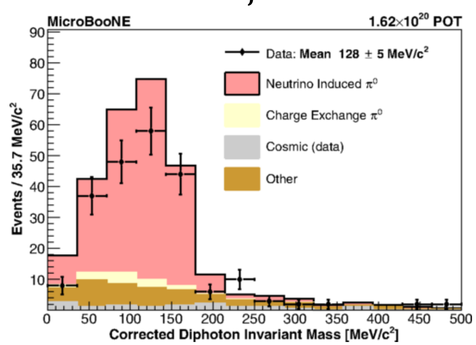
- The MicroBooNE has a similar approach to MiniBooNE to make *in situ* measurement to constraint background.
- Huge advantage over MiniBooNE as can tell 1γ from 1 e events.

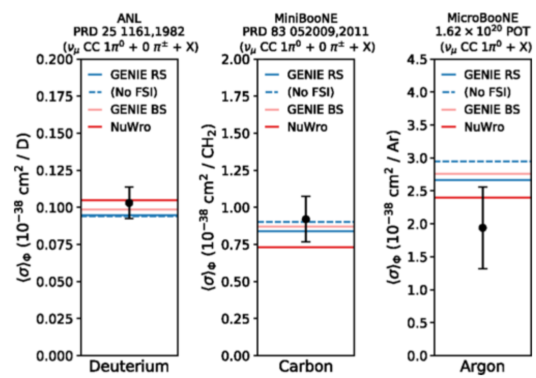
CC inclusive PRL123, 13180 MICROBOONE-NOTE-1045-PUB

$$\sigma(\nu_\mu + Ar \rightarrow \mu^- + X) = 0.693 \pm 0.010\ (\text{stat.}) \pm 0.165\ (\text{syst.}) \times 10^{-38}\ \text{cm}^2$$



CC π^0 Phys. Rev. D 99, 091102

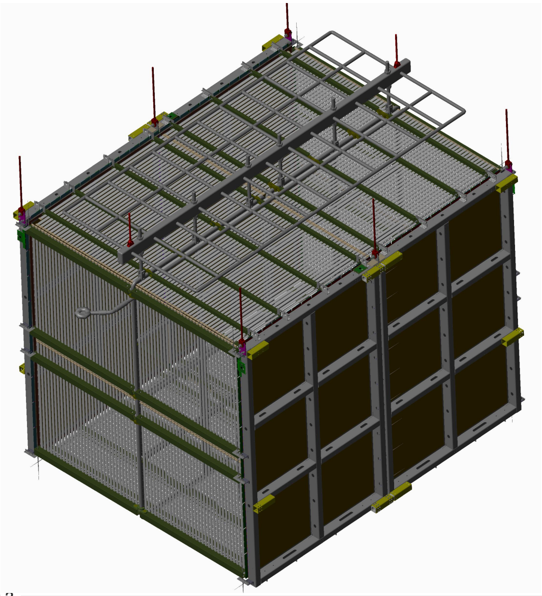


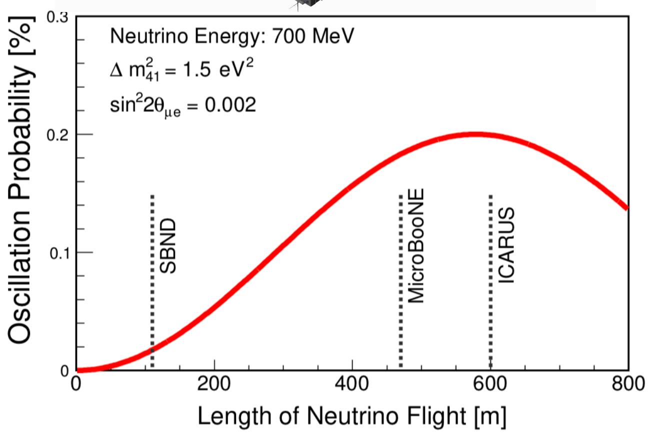


SBND - The Short-Baseline Near Detector

- 110m from the target
- 113 tons of active mass
- Two TPCs with the same central cathode

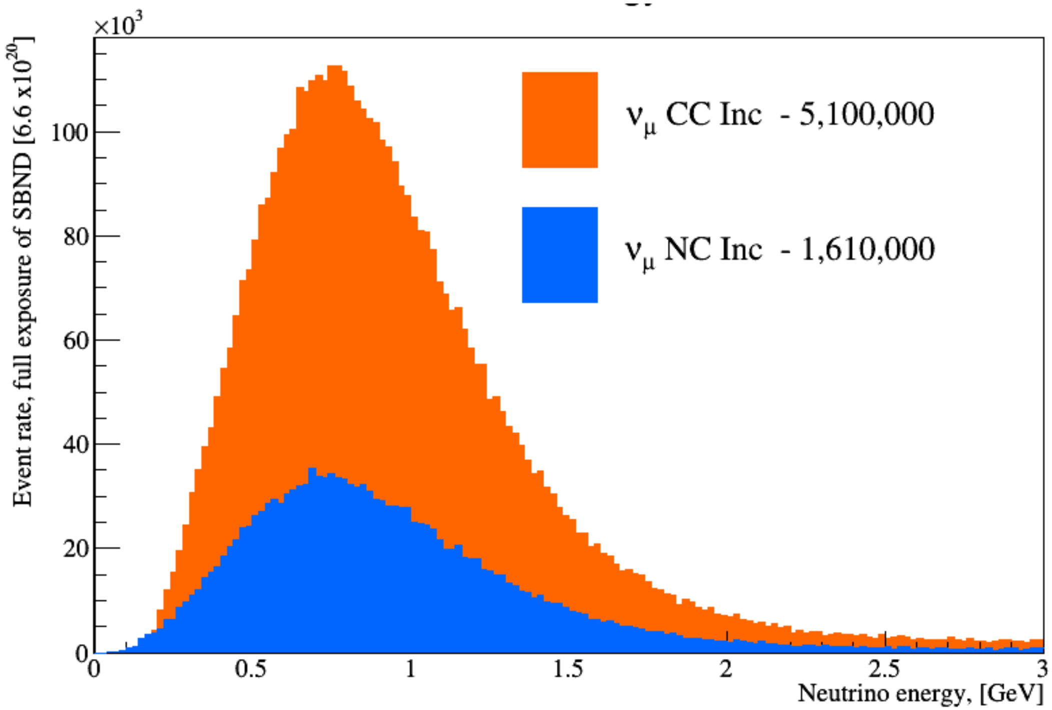
- SBND's role in SBN program is to measure the unoscillated neutrino flux
  - Crucial for the sensitivity of oscillation measurement
  - Highly correlated interactions in near and far detectors
    - Same detector technology and target for three detectors
    - Decreases effects of neutrino flux and neutrino interaction uncertainties on the measurement
  - Controls systematic uncertainties for sterile neutrino search
-





SBND physics: neutrino-argon interactions

- SBND will provide the world's highest statistics cross-section measurements on liquid argon

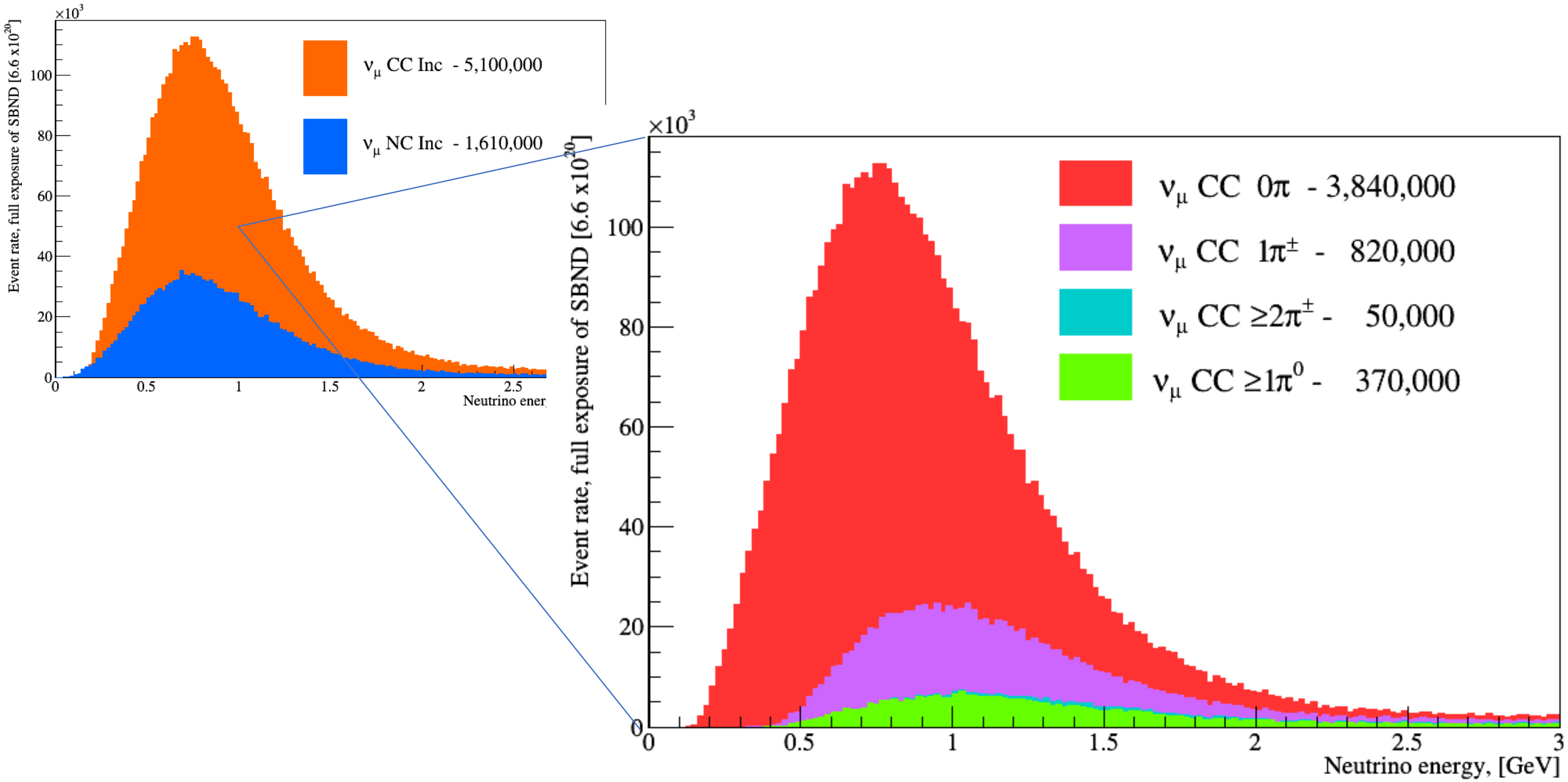


7 million ν_μ interactions in 3 years

[P. Machado et al, arXiv:1903.04608v1]

50,000 ν_e interactions in 3 years – Also crucial for DUNE

SBND physics: neutrino-argon interactions



- High interaction rate and LAr TPC technology allows precision measurements of exclusive event topologies
- Can quantify nuclear effects in ν-Ar scattering with ν_μ and ν_e CC 0π
- Direct experimental quantification of nuclear effects and impact on rates, final states and kinematics
  - SBND data will inform neutrino MC generators and discriminate between final state interaction models
  - Especially important in low energy (1GeV) regime

Summary

- All experiments rely on good modelling of neutrino interactions
  - Not only pion production
  - Nuclear effects & scattering in the nucleus
- Theory and MC developers should provide a reasonable set of values of parameters and their "reasonable" variations
- Upcoming high-statistics data from LArTPCs and ND280 will allow for better understanding of pion production with heavy nuclei