NuINT 2017
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PION SCATTERING, FINAL STATE INTERACTIONS **(FSI)**, AND SECONDARY INTERACTIONS **(SI)**

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Outline

- What are Final State Interactions (FSI) and Secondary Interactions (SI)?
  - What impact do they have on ~GeV neutrino experiments?

- How are these interactions simulated?
  - How have we improved these simulations?

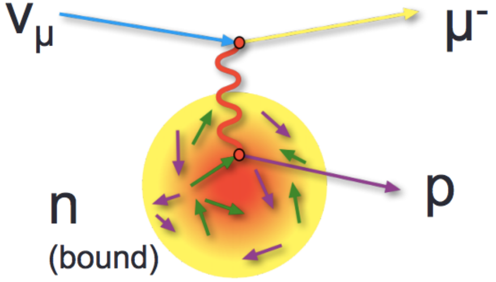
- Ideas for the future

GeV ν Interactions

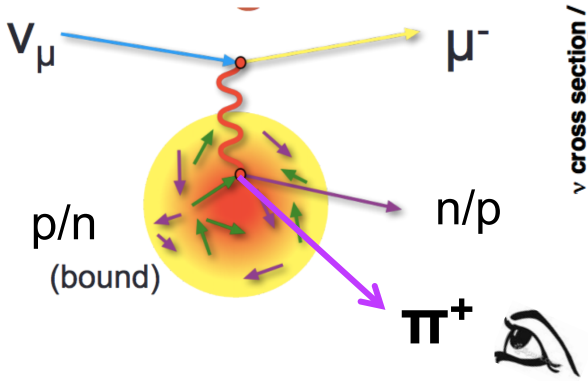
- Reconstructing the ν flavour and its energy is fundamental
  - For both oscillation and cross section analyses

CCQE Interaction

Interaction producing π_s **(Resonance, DIS)**



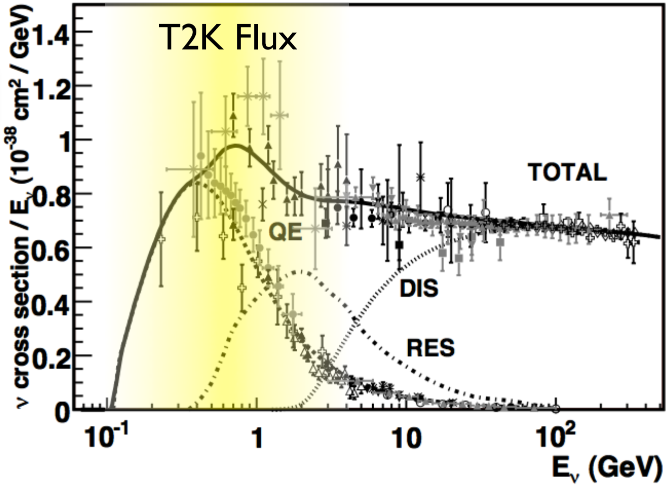
(drawings courtesy G. Perdue)



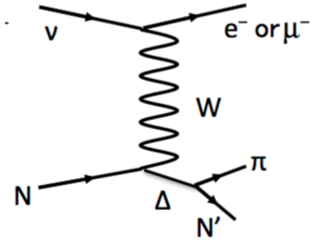
$$E_\nu^{\mathrm{rec}} = \frac{2(M_N - E_B)E_\mu - \left(E_B^2 - 2M_N E_B + m_\mu^2\right)}{2\left[(M_N - E_B) - E_\mu + |\mathbf{k}'|\cos\theta_\mu\right]}$$

$$E_\nu = \frac{m_l^2 + m_{\pi^+}^2 - 2m_N(E_l + E_{\pi^+}) + 2\boldsymbol{p}_l \cdot \boldsymbol{p}_{\pi^+}}{2(E_l + E_{\pi^+} - |\boldsymbol{p}_l|\cos\theta_{\nu l} - |\boldsymbol{p}_{\pi^+}|\cos\theta_{\nu\pi^+} - m_N)}$$

E_ν^{rec} from lepton kinematics

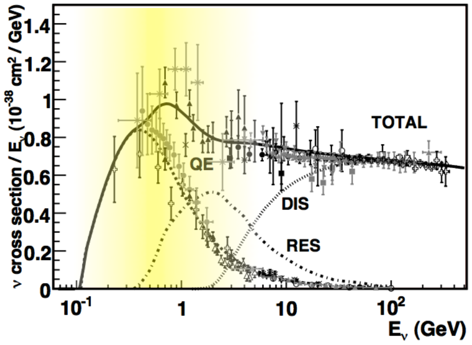


CC1π Resonance Production



GeV ν Interactions

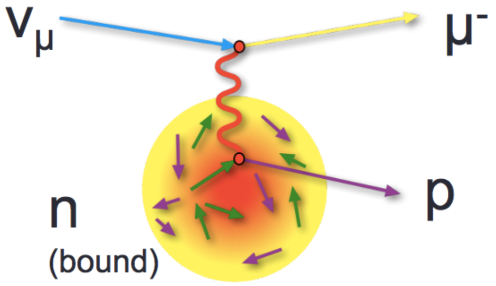
- Reconstructing the ν flavour and its energy is fundamental
  - For both oscillation and cross section analyses

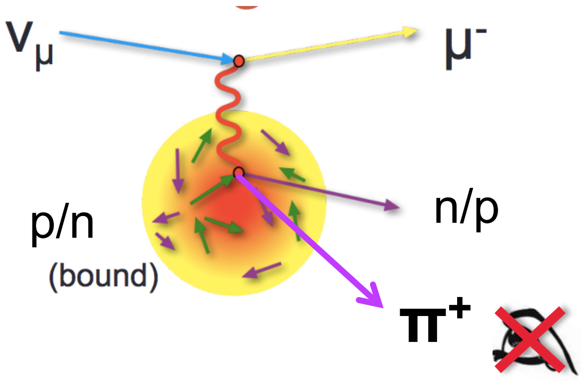


CCQE Interaction

Interaction producing π_s **(Resonance, DIS)**

(drawings courtesy G. Perdue)





$$E_\nu^{\mathrm{rec}} = \frac{2(M_N - E_B)E_\mu - (E_B^2 - 2M_N E_B + m_\mu^2)}{2\left[(M_N - E_B) - E_\mu + |\mathbf{k}'|\cos\theta_\mu\right]}$$

E_ν^{rec} from lepton kinematics

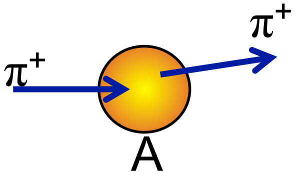
CCQE-like event!

Pions can interact:

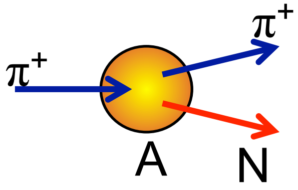
- Inside the nucleus:
  Final State Interactions
- Outside the nucleus:
  Secondary Interactions

How do these sub-GeV pions interact on nuclei?

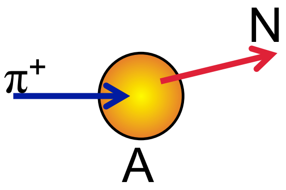
1. Elastic Scattering



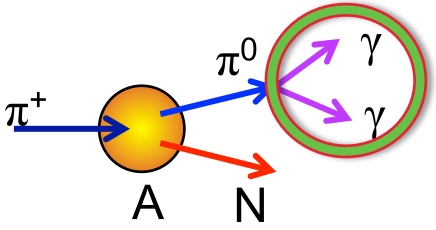
2. Quasi-elastic Scattering



3. Absorption (**ABS**)

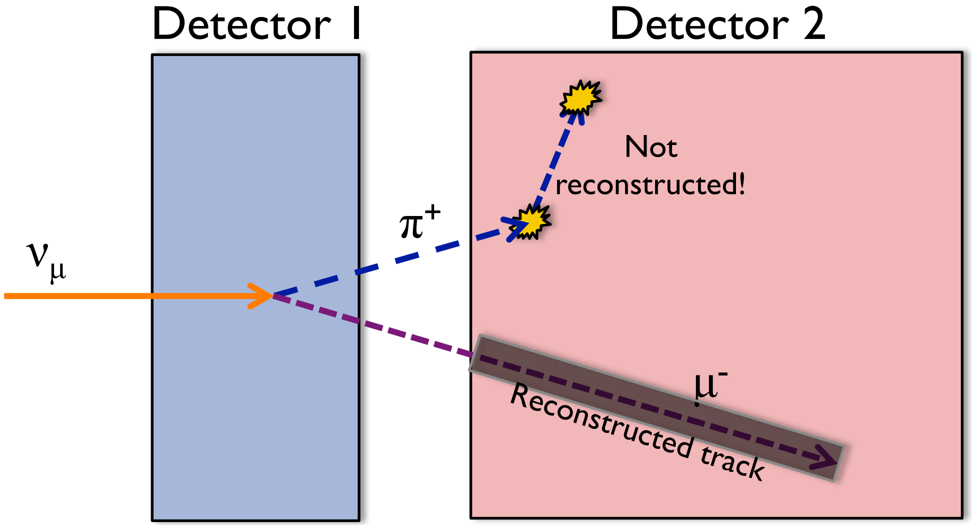


4. Charge Exchange (**CX**)



Secondary Interactions (SI)

- ❖ Interactions outside the nucleus → anywhere in the detectors
- ❖ Could mean that the pion is not detected or that it is mis-reconstructed

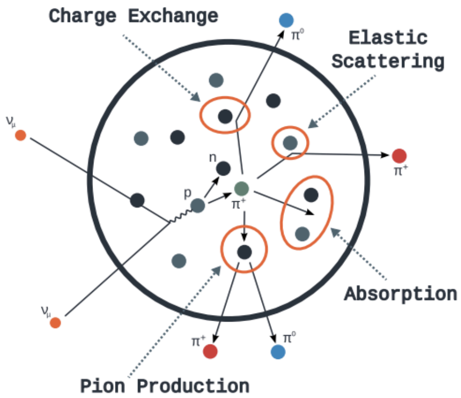


This is a dominant "detector" systematic for the near detector at T2K!

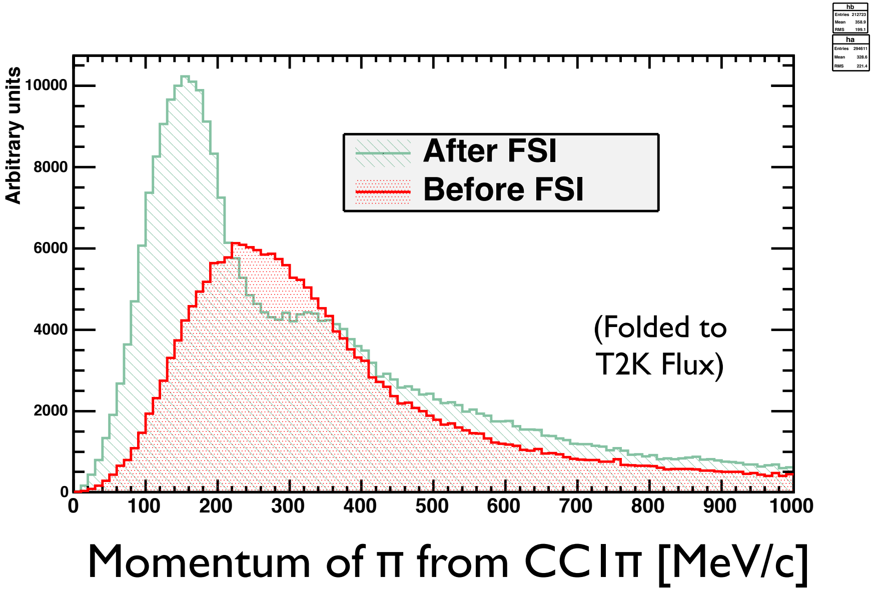
Final State Interactions (FSI)

❖ If the pion interacts inside the nucleus it might not even be able to exit!

- What T2K measures is a combination of FSI and other potential nuclear effects:
    - Fermi momentum of initial nucleon
    - Formation zone effects
    - The actual π production model kinematics
- Very hard to isolate each effect!



Taken from: *T. Golan, What is inside MC generators … and why it is wrong* . Talk at NuSTEC 2015, Okayama



Final State Interactions (FSI)

Combined Analysis of Neutrino and
Antineutrino Oscillations at T2K

Phys. Rev. Lett. 118, 151801 (2017)

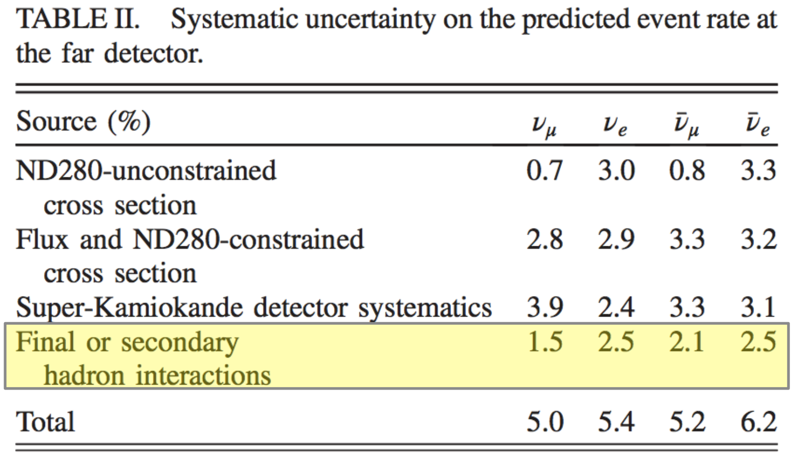
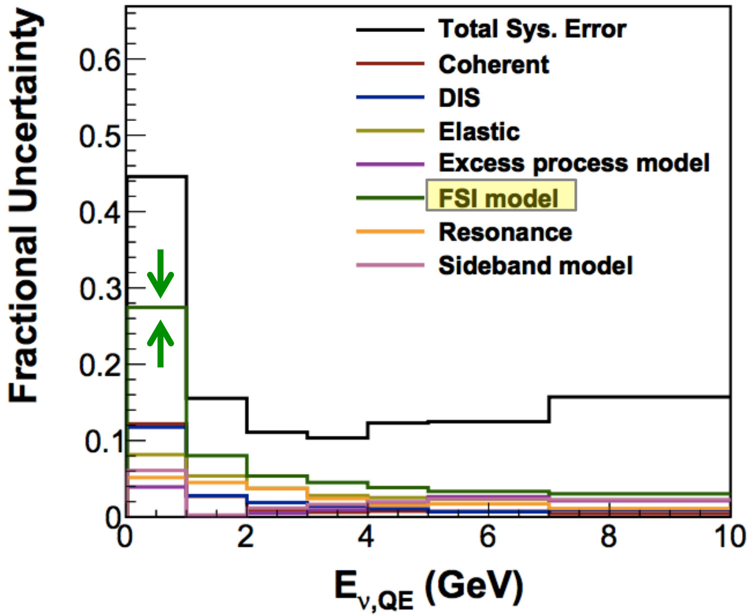


TABLE II. Systematic uncertainty on the predicted event rate at the far detector.

Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

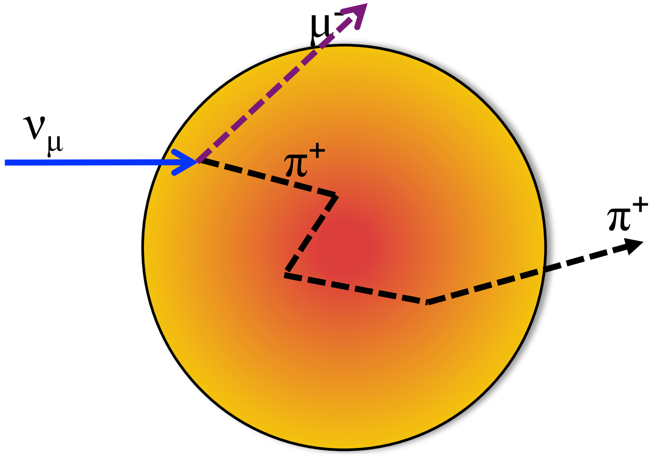
MINERvA CCQE nue

J. Wolcott, FERMILAB-THESIS-2015-26

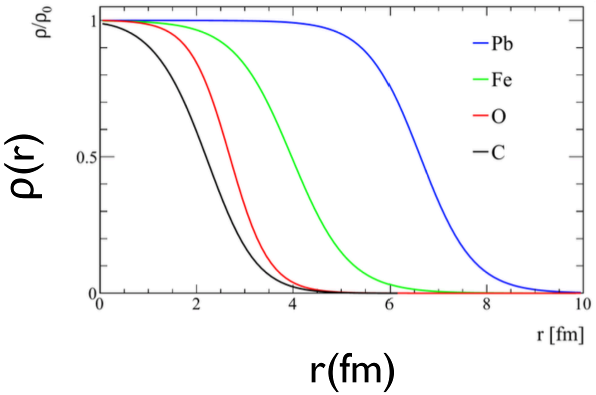


How are FSI/SI simulated?

❖ NEUT, NuWro, GENIE hN, FLUKA, Geant4 use Intra-Nuclear **Cascade Models**



- Particles are stepped within the nucleus
- At each step within the nuclear radius the mean free path is calculated:
  - $\lambda_{step}(r) = [\sigma_{microsopic}\rho(r)]^{-1}$
  - Using Monte Carlo method decide if interaction takes place
  - If not, continue to next step



- A-dependence introduced through $\rho(r)$
  - Three-parameter Fermi model for Oxygen,
  - Two-parameter Fermi model for other nuclei

$$\frac{\rho(r)}{\rho_0} = \frac{1 + w\frac{r^2}{c^2}}{1 + \exp\left(\frac{r-c}{\alpha}\right)}$$

Options for $\sigma_{\mathrm{microsopic}}$

Oset, Salcedo, et al. model

E. Oset, L.L. Salcedo and D. Strottman, Phys. Lett. **B165** (1985) 13

L.L. Salcedo, E. Oset, M. J. Vicente-Vacas, C. Garcia-Recio, Nucl. Phys. **A484** (1988) 557-592

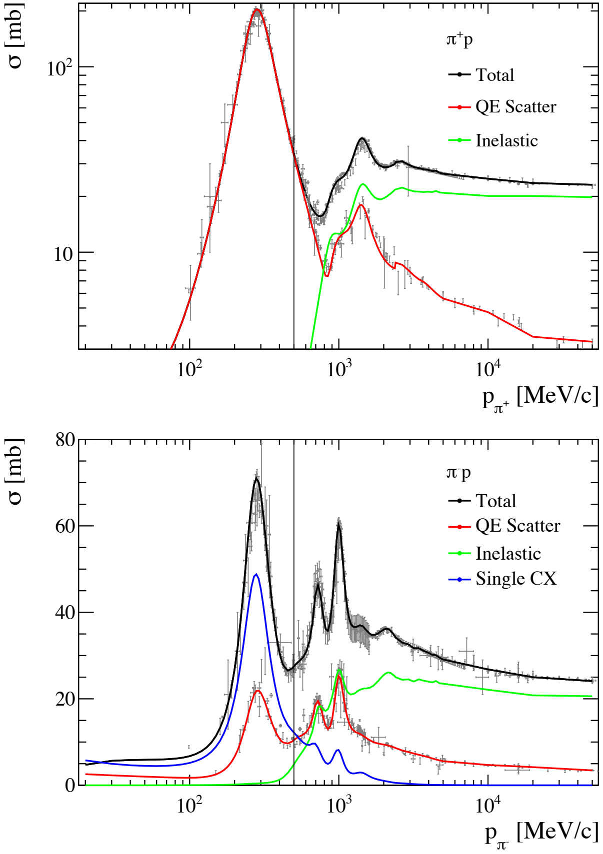
- ❖ Used by NEUT (below 500 MeV/c), NuWro and GENIE hN
- ❖ Computational many-body calculation in infinite nuclear matter + local density approximation
  - Accounts for Δ(1232) spectral function in the medium

See talk "Nuclear Effects in Pion Production/ Resonance Region" by J. Nieves

Used by NEUT above 400 MeV/c

π-N data (SAID) or π-A data directly

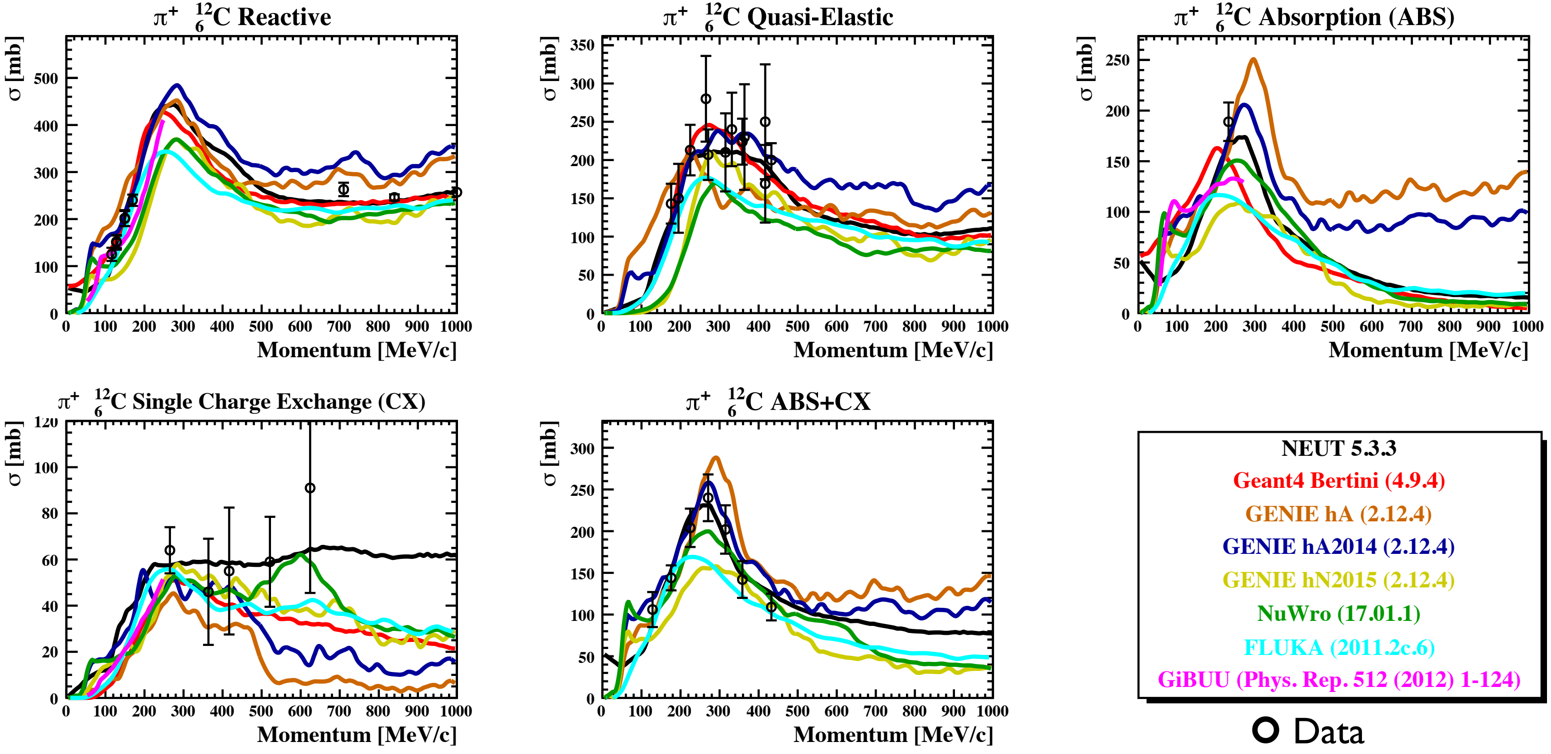
R. Workman et al., SAID Partial Wave Analysis Program



Many cascades…

A. Fiorentini, M. Yu

- Can use data to tune and select models
- Large uncertainties and scarce data → Need more data!!!


π^+ ${}^{12}_{6}$C Reactive

π^+ ${}^{12}_{6}$C Quasi-Elastic

π^+ ${}^{12}_{6}$C Absorption (ABS)

π^+ ${}^{12}_{6}$C Single Charge Exchange (CX)

π^+ ${}^{12}_{6}$C ABS+CX

DUET

(DUAL USE EXPERIMENT AT TRIUMF)

GOAL: MEASURE π^+-C ABSORPTION AND CHARGE EXCHANGE CROSS SECTIONS

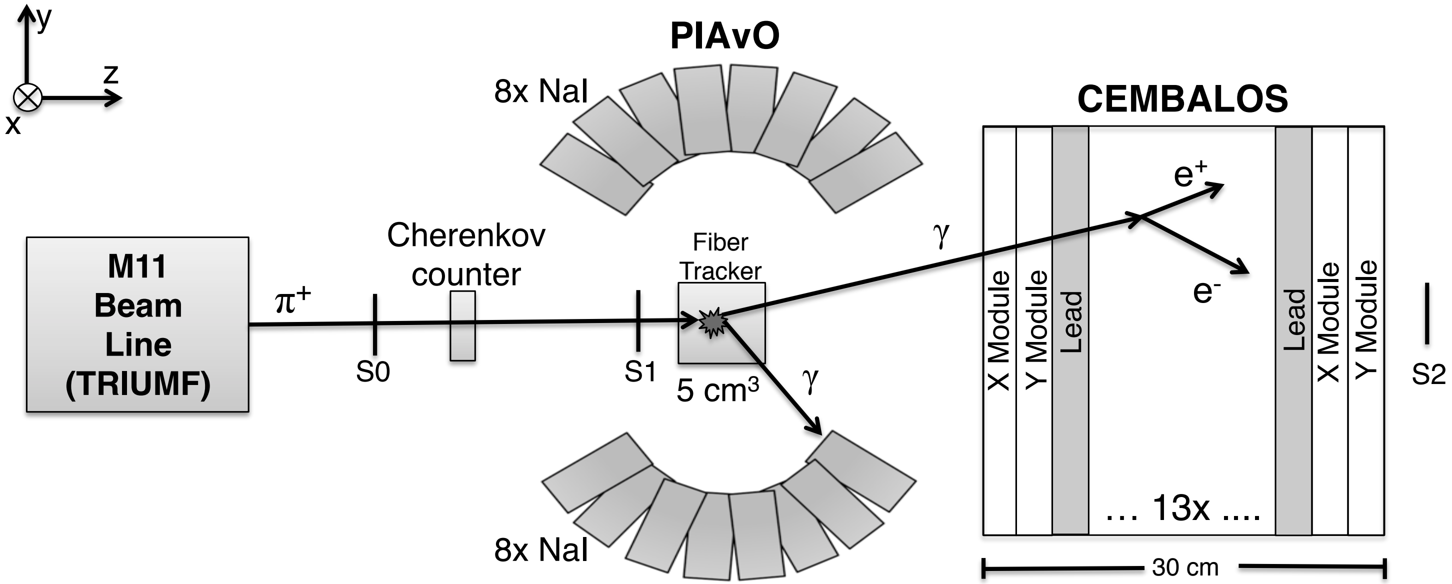
Detector setup: DUET

❖ Main Components:

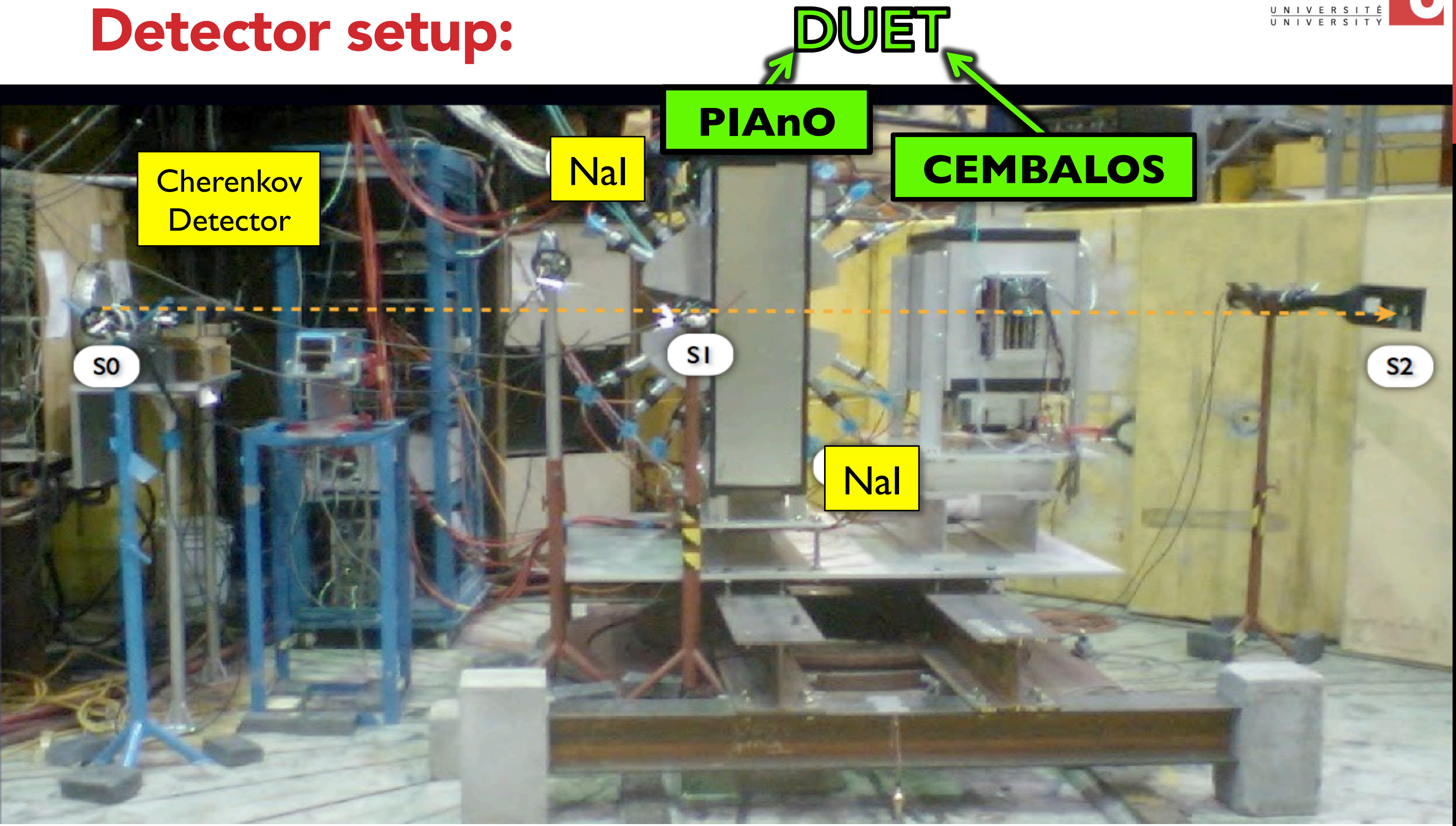
Japan **PIAnO**: (5 cm)^3 scintillating fiber tracker (Full active target) + NaI crystals

CEMBALOS: Miniature Fine Grained Detector

- FGD (NSERC funded) built by Canada
- Scintillating bars + Lead layers

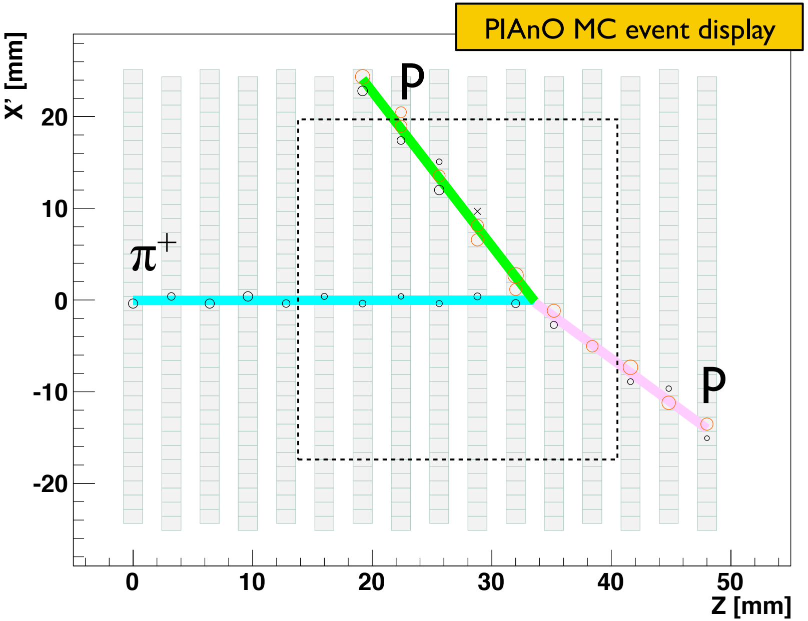


Detector setup:



PIAnO

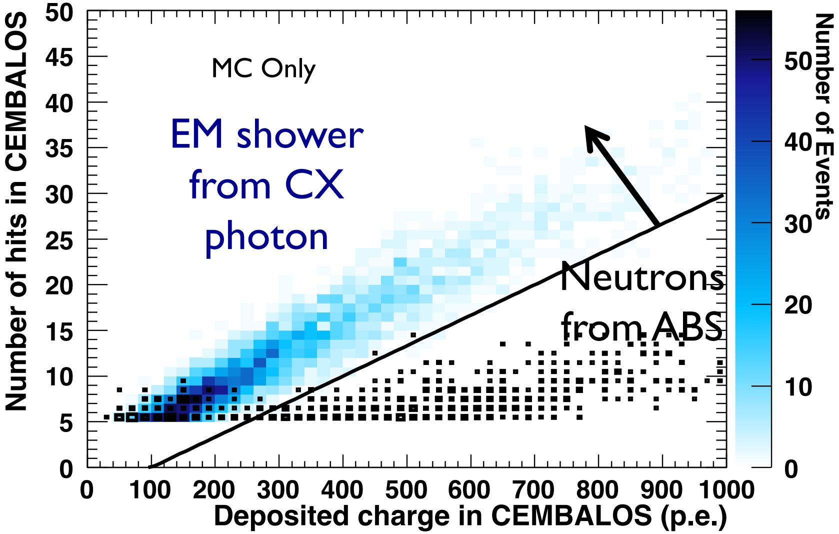
- Excellent track and vertex reconstruction and PID thanks to high granularity



Sample π^+ ABS interaction in PIAnO

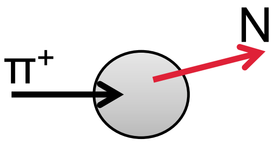
CEMBALOS

- Able to separate photons and neutrons using charge multiplicity and overall deposition

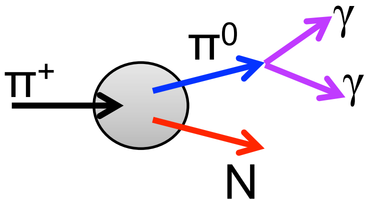


Two DUET publications

Absorption (Abs)

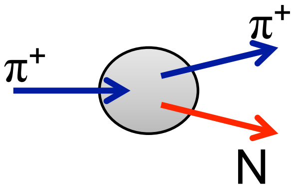


Charge Exchange (CX)



1. Combined ABS+CX using PIAnO

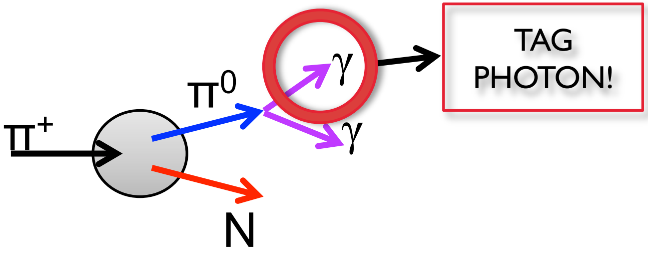
Reject:



Phys. Rev. C **92**, 035205 (2015)

Presented at NuINT 2015

2. Separate ABS, CX using CEMBALOS



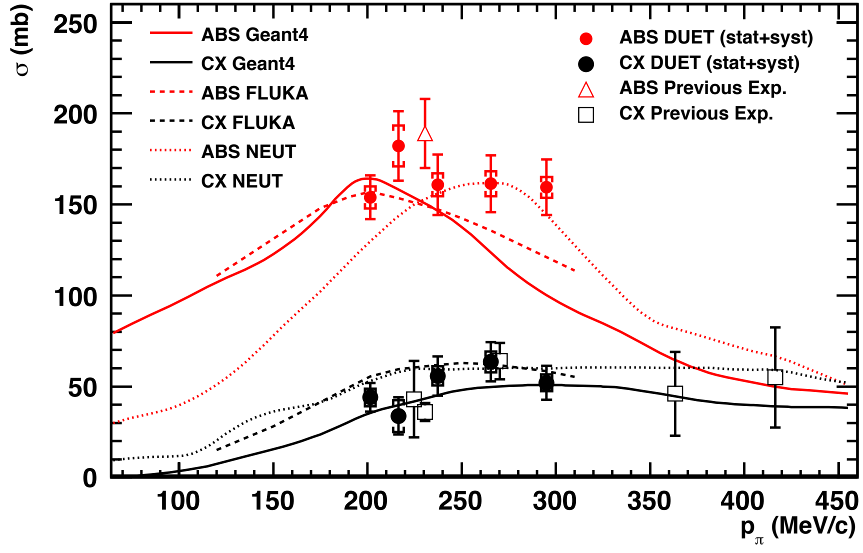
Phys. Rev. C **95**, 045203 (2017)

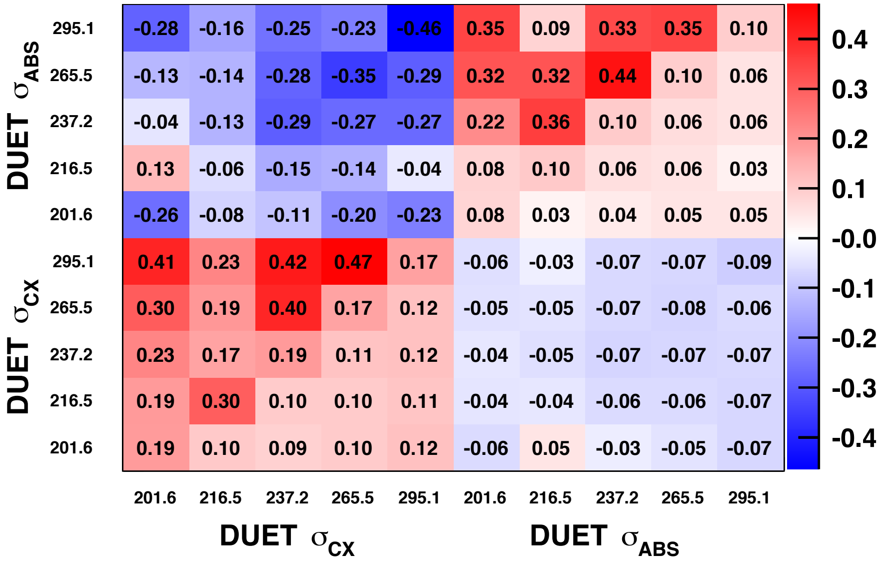
ABS, CX Cross Section Result (2017)

Phys. Rev. C **95**, 045203 (2017)

Similarly sized error bars,
but extended coverage in Δ region

Covariance Matrix:
Important for Fitting Models to Data





		DUET σ_{CX}					DUET σ_{ABS}				
		201.6	216.5	237.2	265.5	295.1	201.6	216.5	237.2	265.5	295.1
DUET σ_{ABS}	295.1	-0.28	-0.16	-0.25	-0.23	-0.46	0.35	0.09	0.33	0.35	0.10
	265.5	-0.13	-0.14	-0.28	-0.35	-0.29	0.32	0.32	0.44	0.10	0.06
	237.2	-0.04	-0.13	-0.29	-0.27	-0.27	0.22	0.36	0.10	0.06	0.06
	216.5	0.13	-0.06	-0.15	-0.14	-0.04	0.08	0.10	0.06	0.06	0.03
	201.6	-0.26	-0.08	-0.11	-0.20	-0.23	0.08	0.03	0.04	0.05	0.05
DUET σ_{CX}	295.1	0.41	0.23	0.42	0.47	0.17	-0.06	-0.03	-0.07	-0.07	-0.09
	265.5	0.30	0.19	0.40	0.17	0.12	-0.05	-0.05	-0.07	-0.08	-0.06
	237.2	0.23	0.17	0.19	0.11	0.12	-0.04	-0.05	-0.07	-0.07	-0.07
	216.5	0.19	0.30	0.10	0.10	0.11	-0.04	-0.04	-0.06	-0.06	-0.07
	201.6	0.19	0.10	0.09	0.10	0.12	-0.06	0.05	-0.03	-0.05	-0.07

TUNING THE NEUT CASCADE MODEL

WITH HELP AND GUIDANCE FROM:

T. FEUSELS, A. FIORENTINI

T2K NIWG CONVENERS: S. BOLOGNESI, Y. HAYATO, K. MCFARLAND, C. WILKINSON

Overview

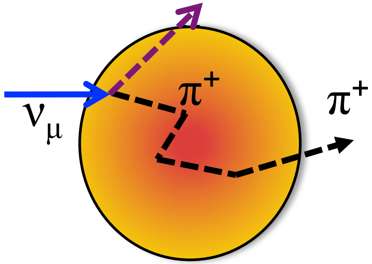
Goal:

Global fit to pion-nucleus scattering data

- Using ad-hoc parameters in the NEUT cascade model that scale the microscopic scaling cross sections at each step
  - Only controls the fate of the pion (not the kinematics)

The π-A macroscopic cross sections (σ^{NEUT}) depend on f_{FSI}

$$\lambda_{step}(r) = f_{FSI}\,[\sigma_{microscopic}\rho(r)]^{-1}$$



Parameter f_{FSI}	Description	p_π Region (MeV/c)
FEFABS	Absorption	< 500
FEFQE	Quasi-elastic scatter	< 500
FEFCX	Single charge exchange	< 500
FEFQEH	Quasi-elastic scatter	> 400
FEFINEL	Hadron (N+nπ) production	> 400

*These same parameters are used in T2K analysis to propagate FSI and SI errors

Summary of π-A scattering data

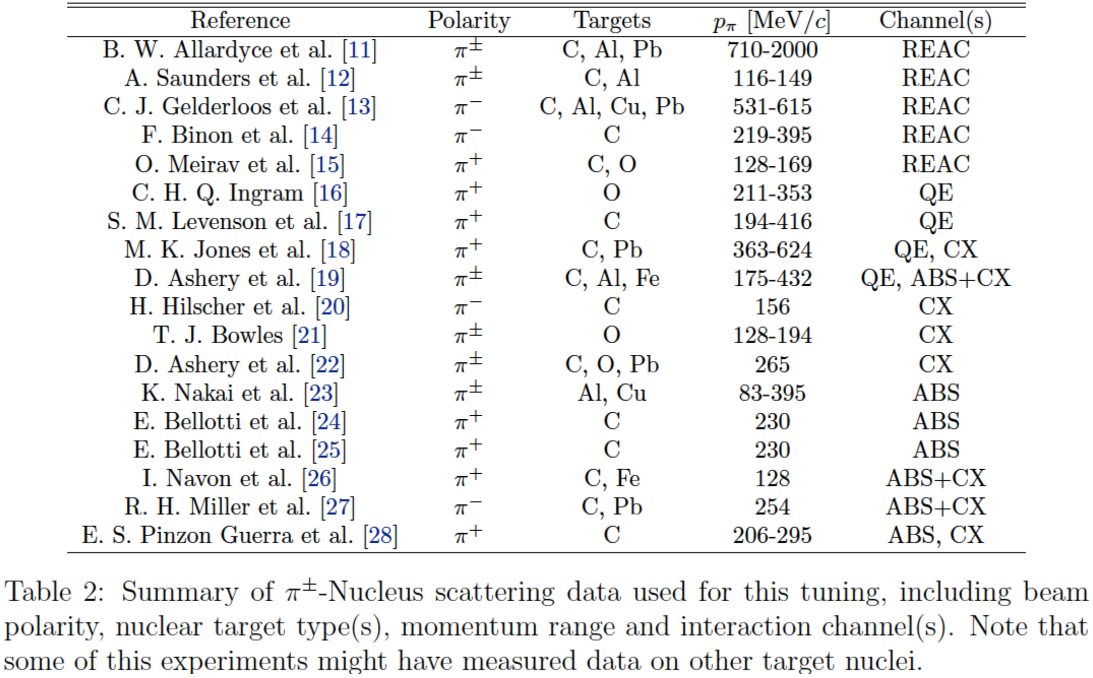
- Total (integrated) and inclusive cross section data

- Light and heavy nuclei:
  - Carbon, oxygen, aluminum
  - Iron, copper, lead

- Five channels:
  - Quasi-elastic (QE)
  - Absorption(ABS)
  - Charge exchange (CX)
  - ABS+CX
  - Reactive: QE+ABS+CX+ Double CX + Hadron Production

- From ~100 to 2000 MeV/c

Data spanning five decades!



Reference	Polarity	Targets	p_π [MeV/c]	Channel(s)
B. W. Allardyce et al. [11]	$\pi^\pm$	C, Al, Pb	710-2000	REAC
A. Saunders et al. [12]	$\pi^\pm$	C, Al	116-149	REAC
C. J. Gelderloos et al. [13]	π^-	C, Al, Cu, Pb	531-615	REAC
F. Binon et al. [14]	π^-	C	219-395	REAC
O. Meirav et al. [15]	π^+	C, O	128-169	REAC
C. H. Q. Ingram [16]	π^+	O	211-353	QE
S. M. Levenson et al. [17]	π^+	C	194-416	QE
M. K. Jones et al. [18]	π^+	C, Pb	363-624	QE, CX
D. Ashery et al. [19]	$\pi^\pm$	C, Al, Fe	175-432	QE, ABS+CX
H. Hilscher et al. [20]	π^-	C	156	CX
T. J. Bowles [21]	$\pi^\pm$	O	128-194	CX
D. Ashery et al. [22]	$\pi^\pm$	C, O, Pb	265	CX
K. Nakai et al. [23]	$\pi^\pm$	Al, Cu	83-395	ABS
E. Bellotti et al. [24]	π^+	C	230	ABS
E. Bellotti et al. [25]	π^+	C	230	ABS
I. Navon et al. [26]	π^+	C, Fe	128	ABS+CX
R. H. Miller et al. [27]	π^-	C, Pb	254	ABS+CX
E. S. Pinzon Guerra et al. [28]	π^+	C	206-295	ABS, CX

Table 2: Summary of $\pi^\pm$-Nucleus scattering data used for this tuning, including beam polarity, nuclear target type(s), momentum range and interaction channel(s). Note that some of this experiments might have measured data on other target nuclei.

Fit description

- Minimize the following chi-square

$$\chi^2 = \sum_{i}^{\text{Datasets}} \sum_{j}^{n_i} \frac{1}{n_i} \left(\frac{\sigma_j^{\text{Data}} - \sigma_j^{\text{NEUT}}(f_{FSI})}{\Delta\sigma_j^{\text{Data}}} \right)^2$$

Fit description

- Minimize the following chi-square

$$\chi^2 = \sum_i^{\text{Datasets}} \left(\sum_j^{n_i} \frac{1}{n_i} \left(\frac{\sigma_j^{\text{Data}} - \lambda_i^{-1} \sigma_j^{\text{NEUT}}(f_{FSI})}{\Delta\sigma_j^{\text{Data}}} \right)^2 + \left(\frac{\lambda_i - 1}{\epsilon} \right)^2 \right)$$

Fit description

- Minimize the following chi-square

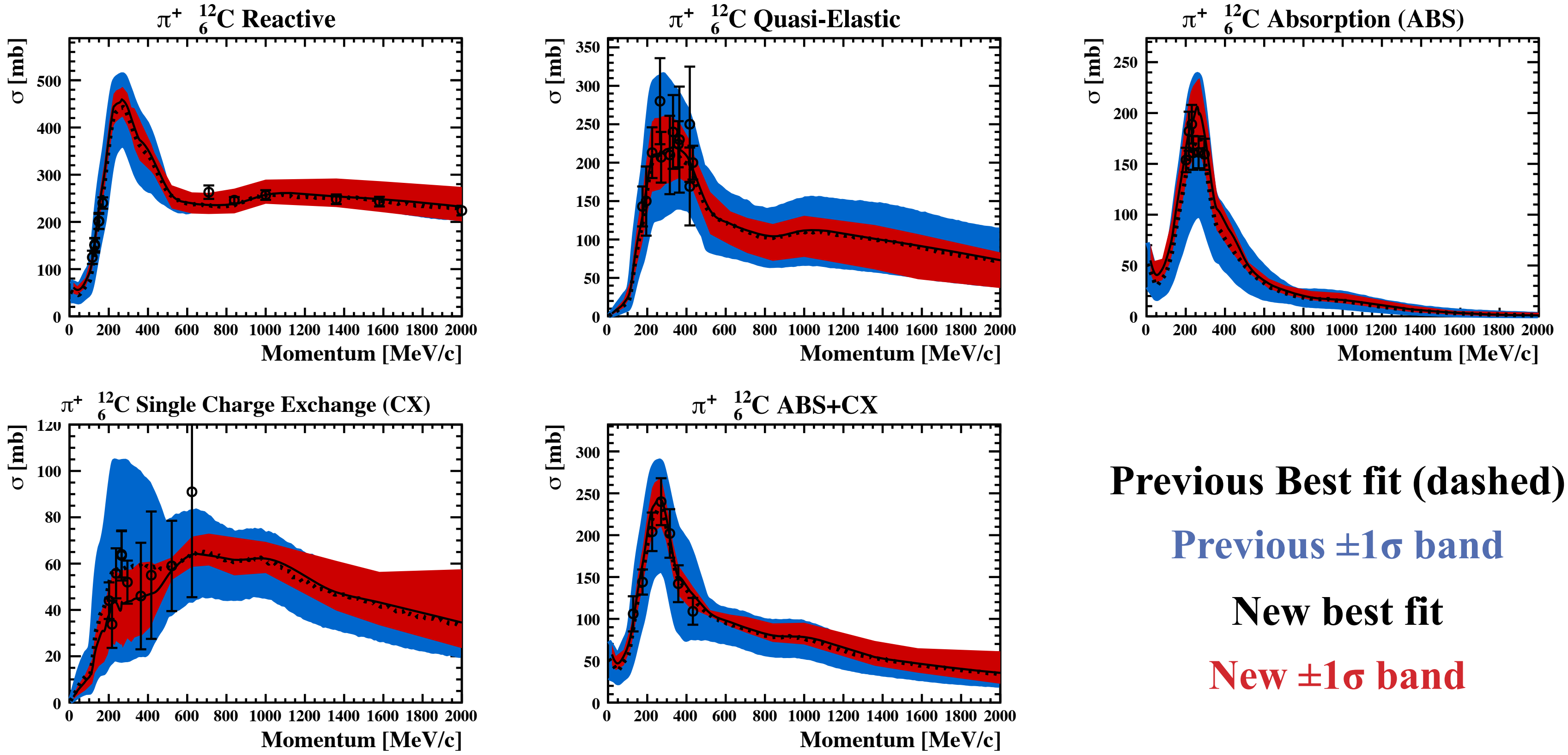
$$\chi^2 = \sum_i^{\text{Datasets}} \left(\sum_j^{n_i} \frac{1}{n_i} \left(\frac{\sigma_j^{\text{Data}} - \lambda_i^{-1} \sigma_j^{\text{NEUT}}(f_{FSI})}{\Delta\sigma_j^{\text{Data}}} \right)^2 + \left(\frac{\lambda_i - 1}{\epsilon} \right)^2 \right)$$

$$+ \sum_{i,j}^{10} \left(\sigma_i^{\text{DUET}} - \sigma_i^{\text{NEUT}}(f_{FSI})\right) \left(V_{ij}^{-1}\right)^{\text{DUET}} \left(\sigma_j^{\text{DUET}} - \sigma_j^{\text{NEUT}}(f_{FSI})\right)$$

- An additional overall scaling factor was introduced to increase the coverage of the external data
- Minuit provides best fit and correlations

Fit result (π^+-${}^{12}_{6}$C)

- Smaller error bands than previous tuning



Previous Best fit (dashed)

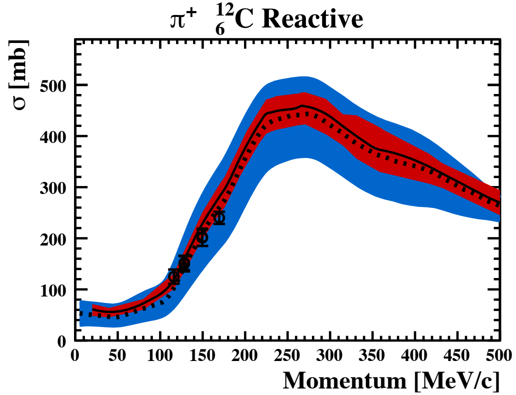
Previous ±1σ band

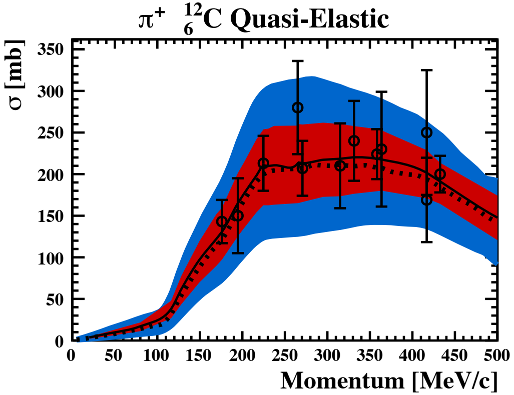
New best fit

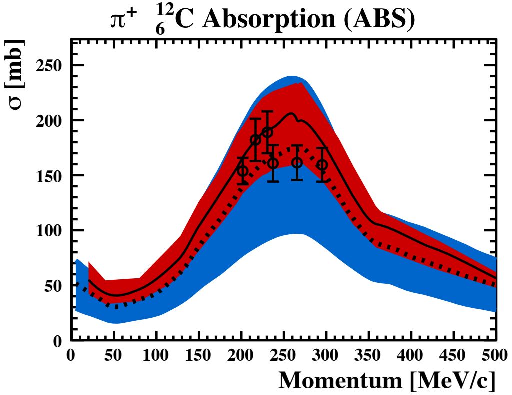
New ±1σ band

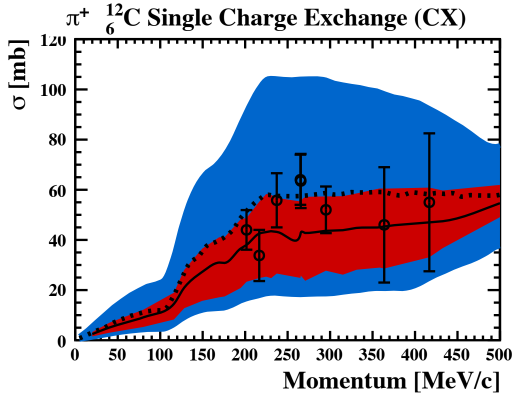
Fit result (π^+-${}^{12}_{6}$C) – 0 to 500 MeV/c

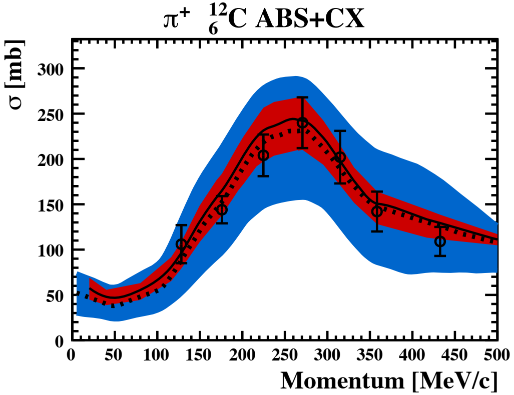
- ❖ Smaller error bands than previous tuning











Previous Best fit (dashed)

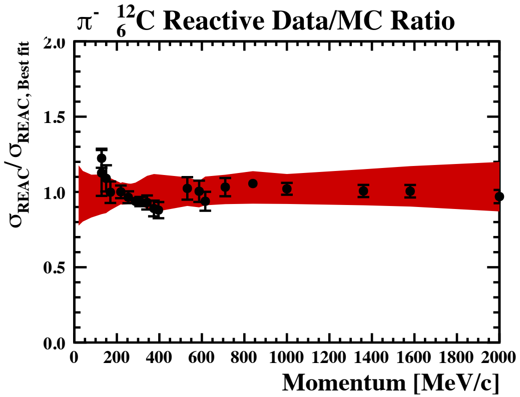
Previous ±1σ band

New best fit

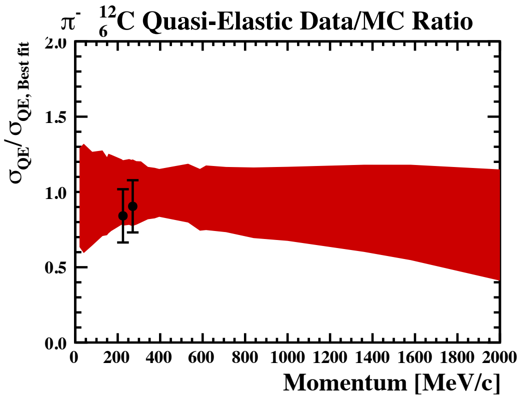
New ±1σ band

Fit result (π^{-}-$^{12}_{6}$C) – Data/MC Ratio

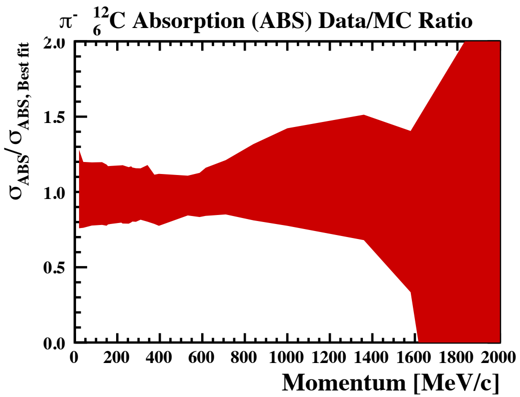
❖ External data appropriately covered by uncertainty band



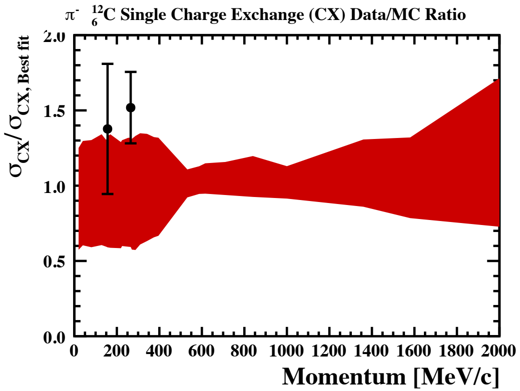
π^{-} $^{12}_{6}$C Reactive Data/MC Ratio



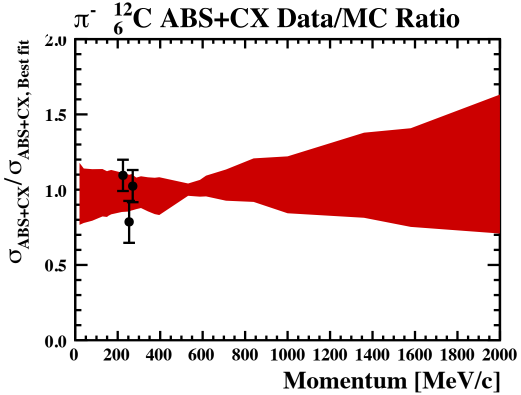
π^{-} $^{12}_{6}$C Quasi-Elastic Data/MC Ratio



π^{-} $^{12}_{6}$C Absorption (ABS) Data/MC Ratio



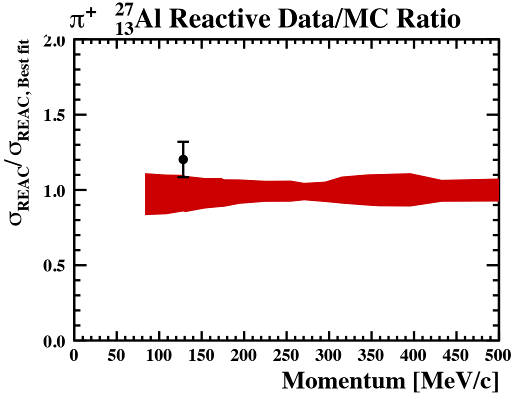
π^{-} $^{12}_{6}$C Single Charge Exchange (CX) Data/MC Ratio

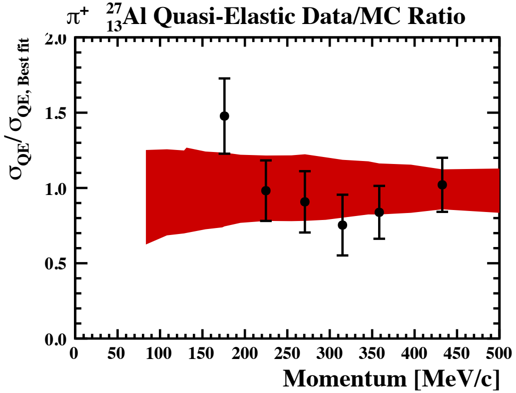


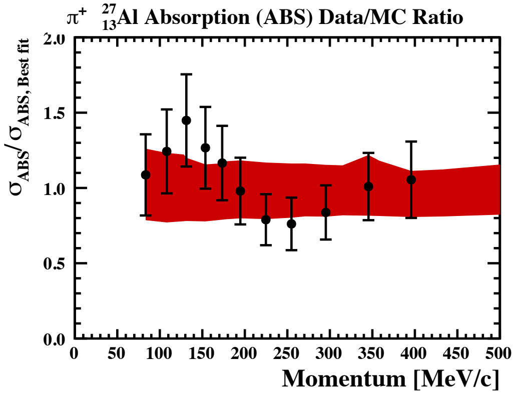
π^{-} $^{12}_{6}$C ABS+CX Data/MC Ratio

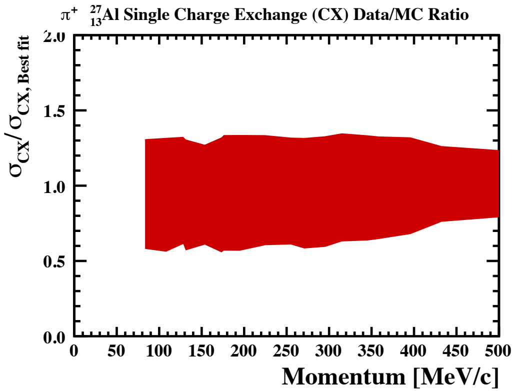
Fit result (π^+-$^{27}_{13}$Al) – Data/MC Ratio

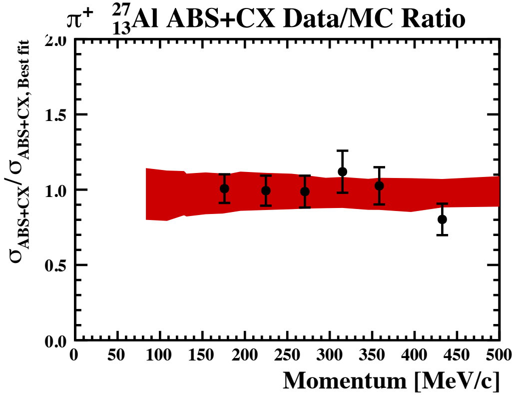
- ❖ External data appropriately covered by uncertainty band


π^+ $^{27}_{13}$Al Reactive Data/MC Ratio


π^+ $^{27}_{13}$Al Quasi-Elastic Data/MC Ratio

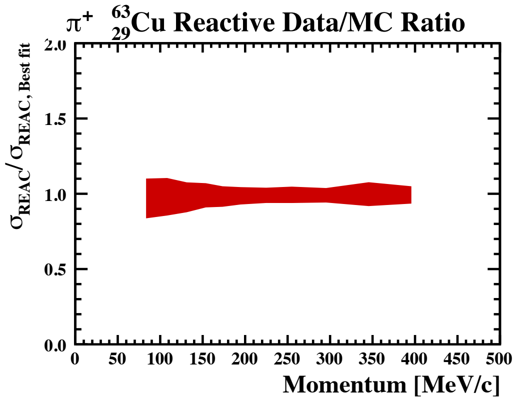

π^+ $^{27}_{13}$Al Absorption (ABS) Data/MC Ratio

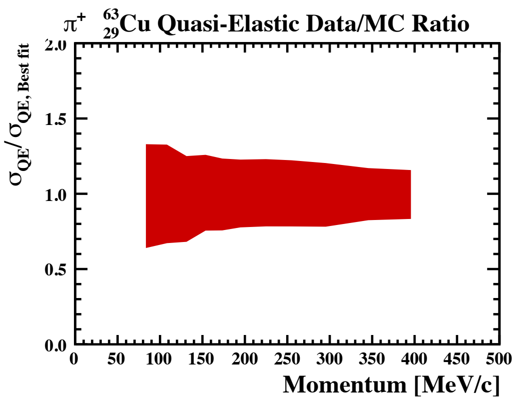

π^+ $^{27}_{13}$Al Single Charge Exchange (CX) Data/MC Ratio

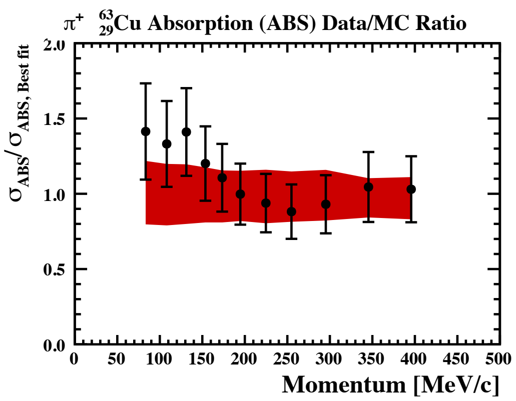

π^+ $^{27}_{13}$Al ABS+CX Data/MC Ratio

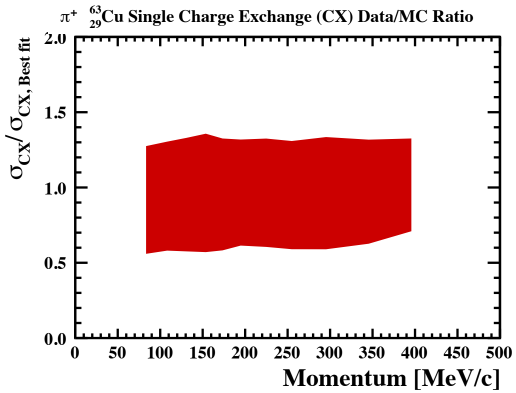
Fit result (π^+-$^{63}_{29}$Cu) – Data/MC Ratio

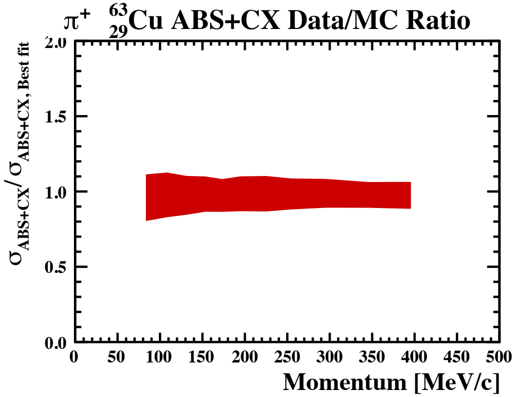
- External data appropriately covered by uncertainty band











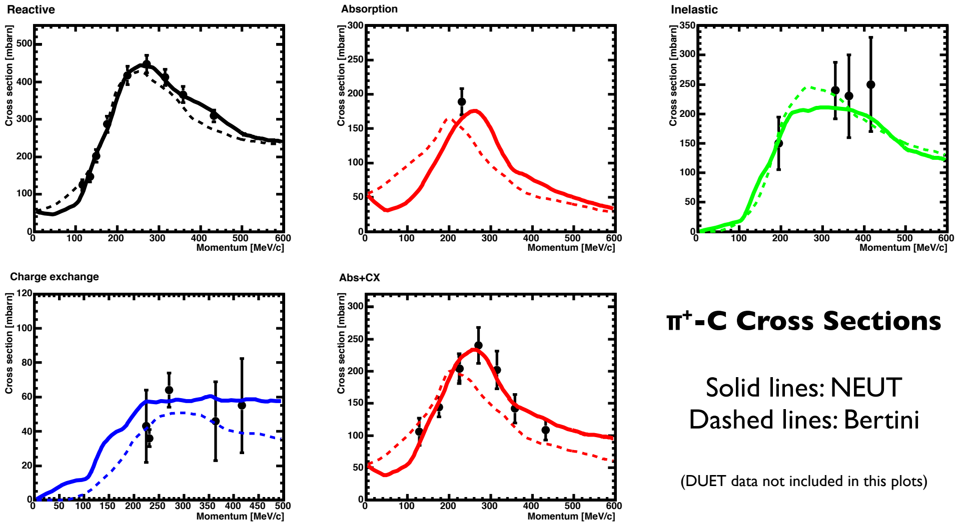
Plan to use these
reduced FSI errors
for T2K 2018 results

Also use NEUT tuning for SI…

- ❖ See "Constraining pion secondary interaction systematic uncertainties at T2K" (Poster-53, Mitchell Yu)

1. Replace Geant4 Bertini model with this tuned NEUT model
2. Use a sample of pions in the near detector to further constrain these parameters

- ❖ Expect significant (~50%) reduction in uncertainties



π^+-C Cross Sections

Solid lines: NEUT
Dashed lines: Bertini

(DUET data not included in this plots)

(Side note) π-A elastic modeling

Important lesson from DUET:

- Large mis-modeling of ^{1}H and ^{12}C elastic interactions in Geant4.9.X
    - Used by ND280 simulation
    - FGD is mostly C_8H_8

- π^+-H has been fixed by Geant in recent version 4.10.X

Phys. Rev. C **92**, 035205 (2015)

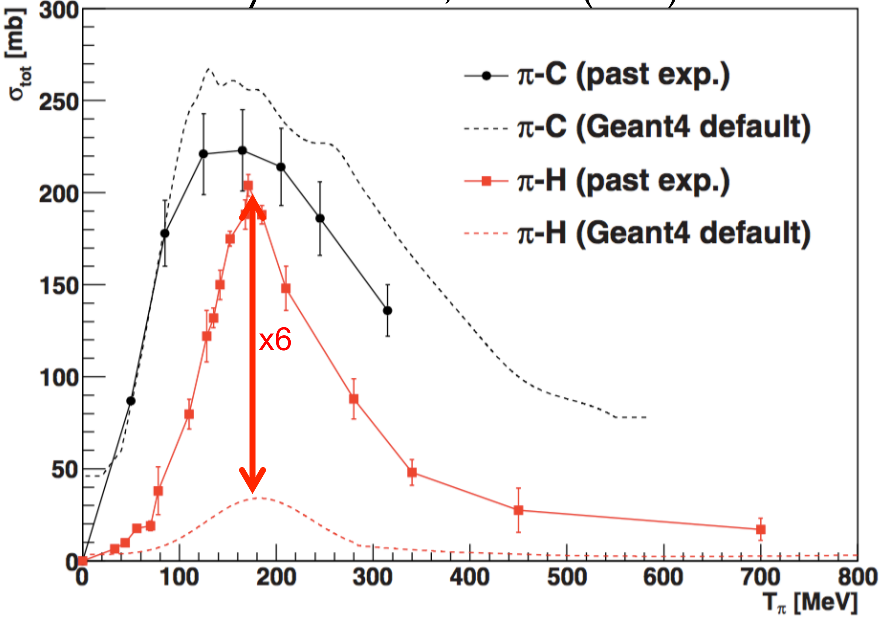


FIG. 16. (Color online) Comparison of elastic inclusive cross section between the previous experiments (summarized in Table IV) and the default GEANT4. The cross sections are plotted as a function of pion kinetic energy.

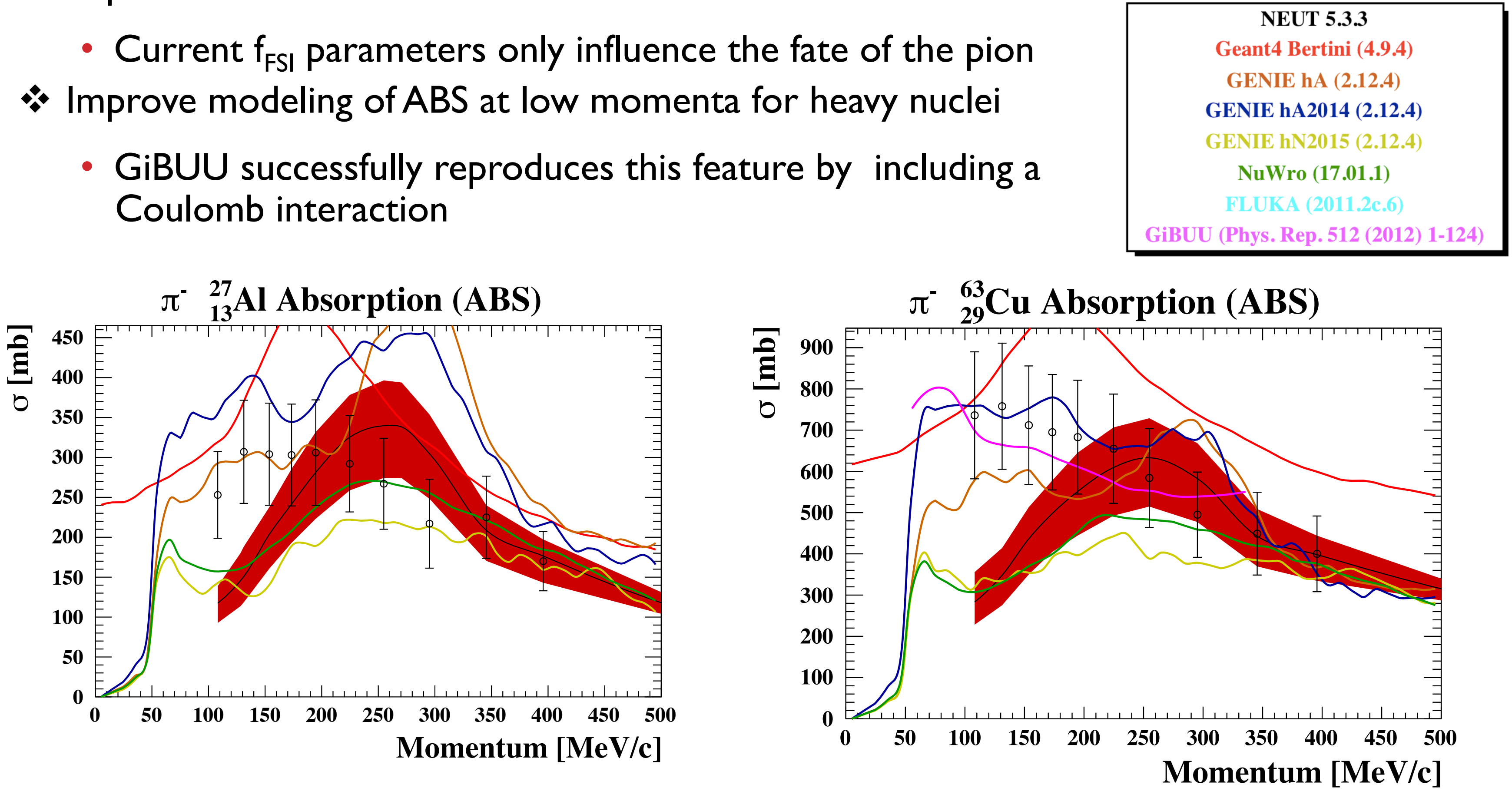
IDEAS FOR THE FUTURE

IMPROVEMENTS TO THE NEUT CASCADE MODEL

INVESTIGATE FSI VS. SI?

NEUT Cascade Improvements

- Improve π Kinematics and tune to differential data
  - Current f_{FSI} parameters only influence the fate of the pion
- Improve modeling of ABS at low momenta for heavy nuclei
  - GiBUU successfully reproduces this feature by including a Coulomb interaction



FSI vs. SI? Pion photo-production

- Exploring how to investigate difference between FSI and SI
  - Surface interactions and deep in-medium effects
  - Expected to be a second order effect
- γA → π looks promising!
  - Similar to neutrino scattering in that the pion is produced within the nucleus
- NEUT has a cascade simulation for this process
  - But is not sophisticated. Need input from experts
- See talk on Pion Photo-production by Astrid Hiller

P. de Perio, PhD Thesis, U. of Toronto

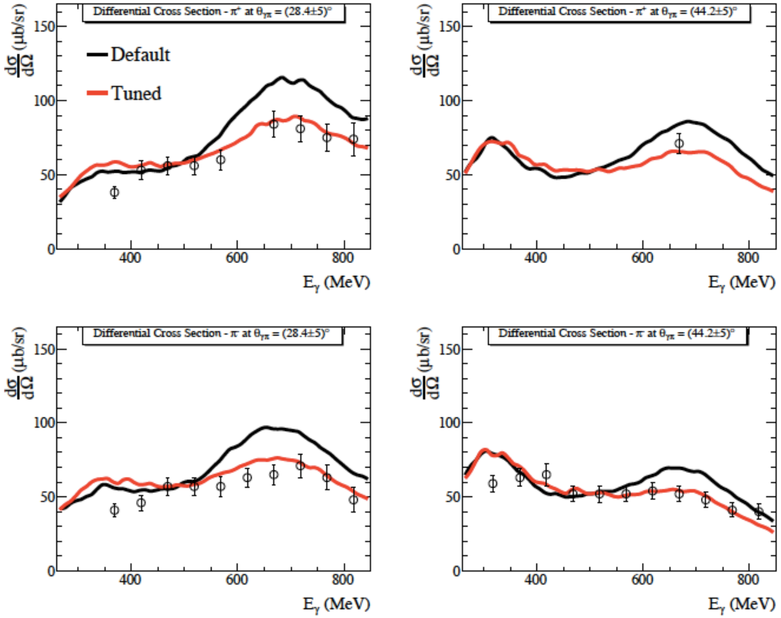


Figure 6.10: Default (black) and tuned (red) NEUT predictions for $\frac{d\sigma}{d\Omega}$ of π^+ (top) and π^- (bottom) photoproduction from carbon, as a function of incoming photon energy. Two outgoing angles are considered: $\theta_{\gamma\pi} = 28.4^\circ$ (left) and $\theta_{\gamma\pi} = 44.2^\circ$ (right). Data points are from [195].

Summary

- ❖ Final State Interactions (FSI) and Secondary Interactions (SI) are important and difficult sources of systematic uncertainty for GeV neutrino experiments

- ❖ DUET measured π^+-^{12}C ABS and CX cross-sections
  - Phys. Rev. C **95**, 045203 (2017)

- ❖ Carried out a global fit to π-A scattering data
  - Will lead to reduced FSI errors

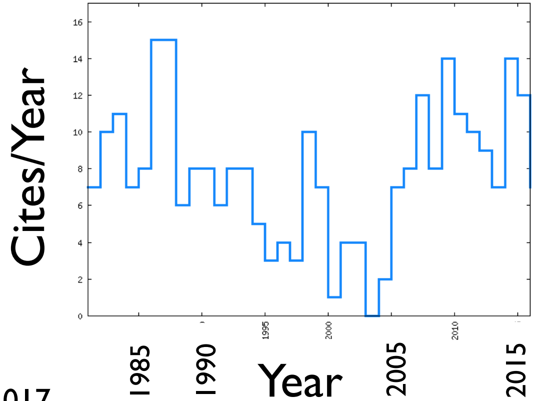
- ❖ Pion photo-production could be a test bench for future improvements of cascade models

BACKUP

π-A as a Probe of Nuclear Structure

- Strong interactions are governed by QCD
  - Structure of atomic nuclei and constituents nucleons are fully described by interactions of quarks and gluons
- Color confinement suggests that interactions between nucleons can be described by colorless particles
  - Effective theories based on interactions of nucleons and mesons can be constructed to describe nuclear structure
- Many papers around the 1980's
  - Both theory and experiment
  - Resurgence in late 2000's
    - Accelerator ν experiments!
      - T2K, NoVA, MiniBoone, Minerva, etc.

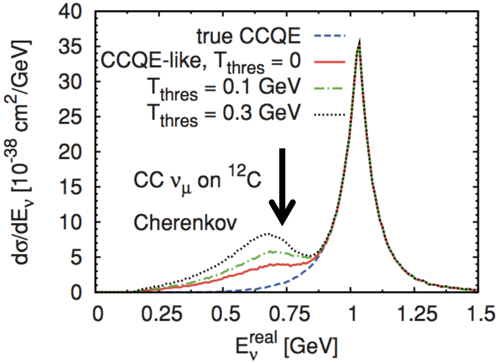
True Absorption and Scattering of Pions on Nuclei
Ashery, D. et al. PRC 23 (1981) 2173-2185



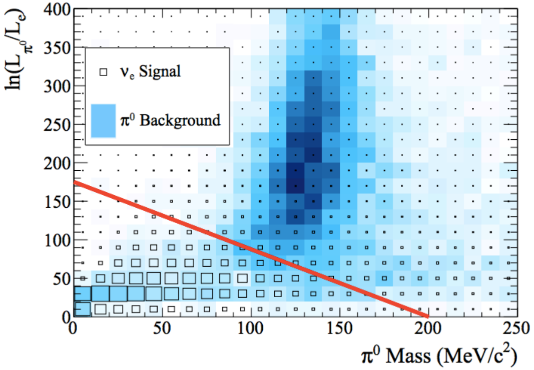
Effects of π FSI/SI

1. E_ν^{rec} smearing

T. Leitner & U. Mosel. PRC 81, 064614 (2010)

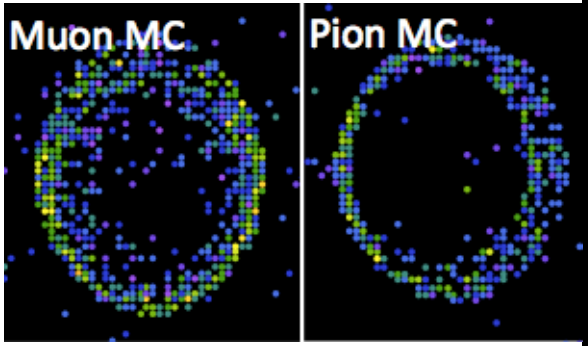


3. π^0 Background to ν_e appearance [PRL 112, 061802 (2014)]



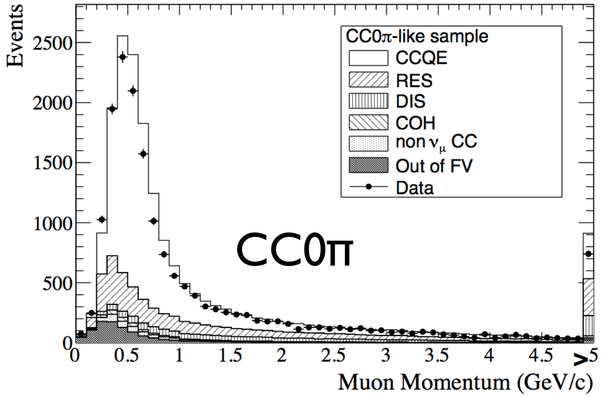
4. π Reconstruction @ SK

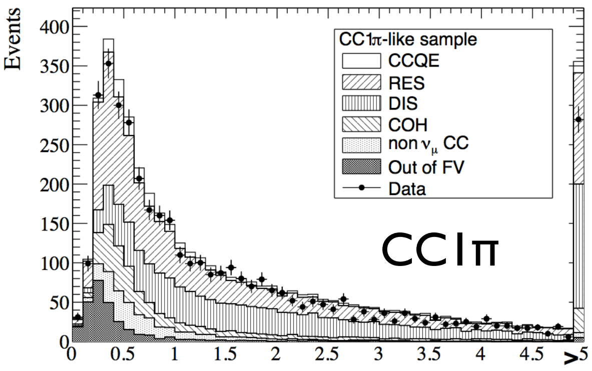
"Identifying CC1π at SK", S. Berkman, CAP 2014

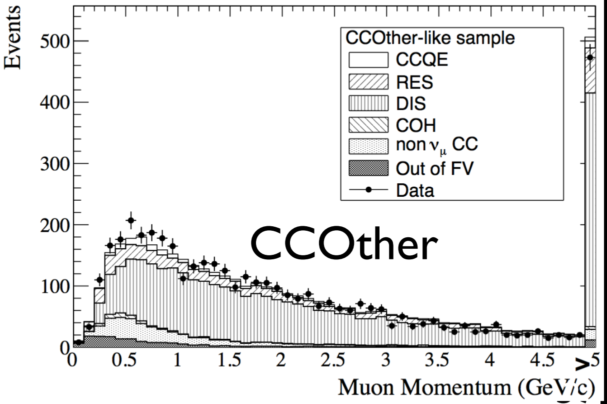


2. Selections based on Final State Topologies

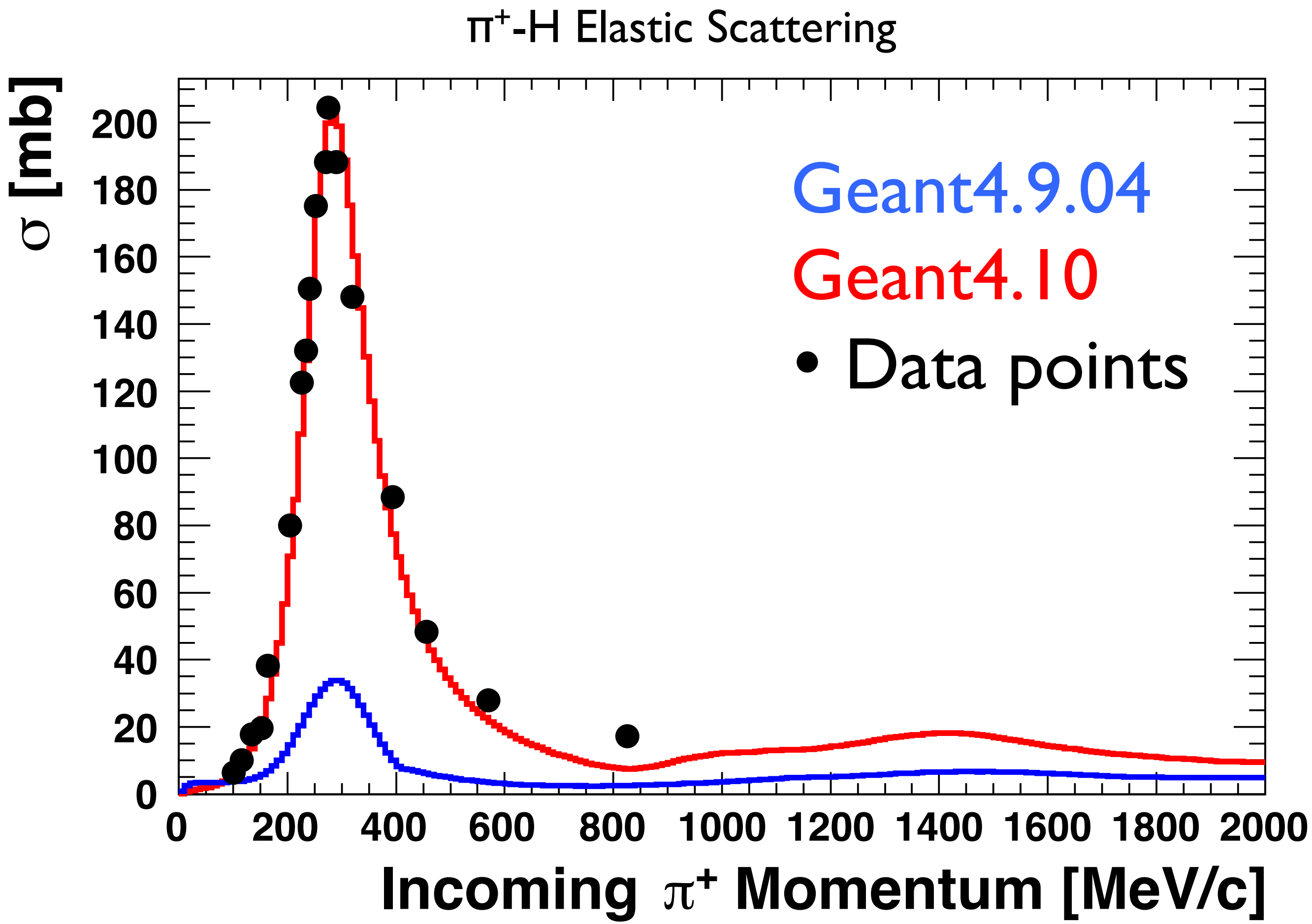
- T2K Near Detector selection to constrain Oscillation Analysis [PRD 91, 072010 (2015)]







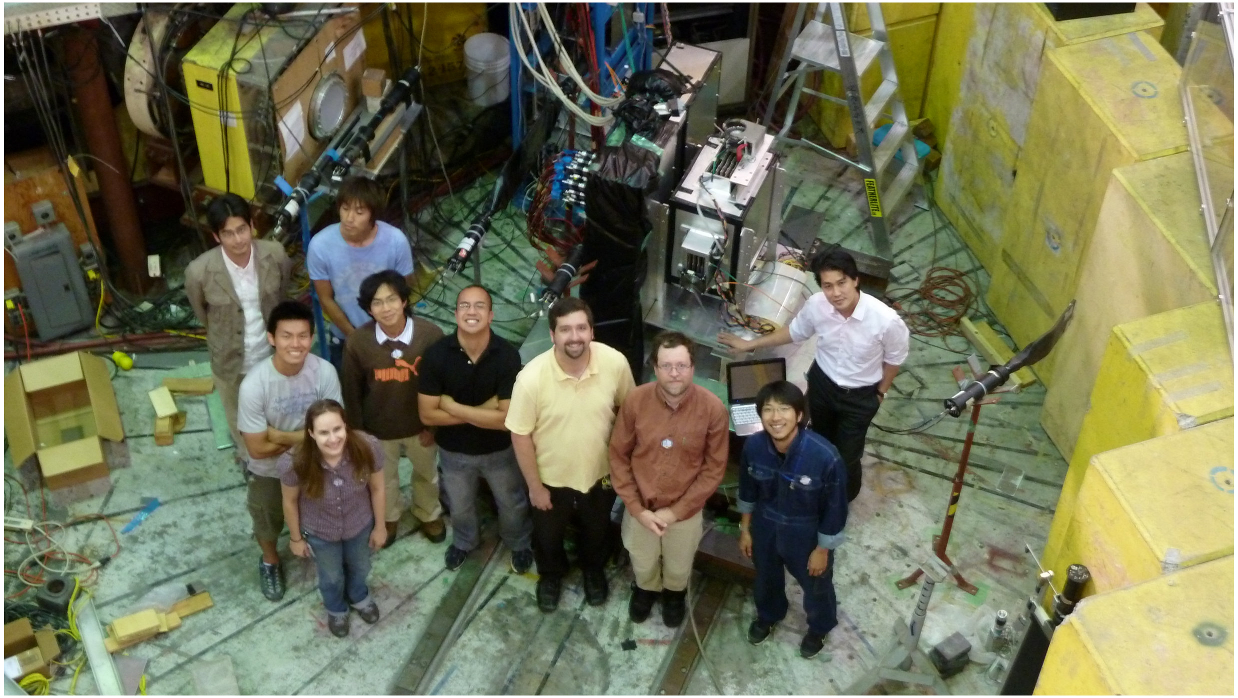
Fixing π-A elastic modeling



Elder Pinzon (York U.) – NuINT 2017

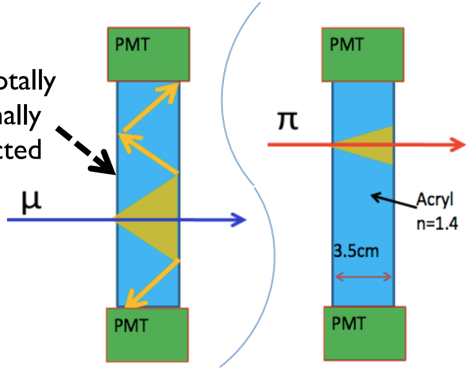
DUET Collaboration

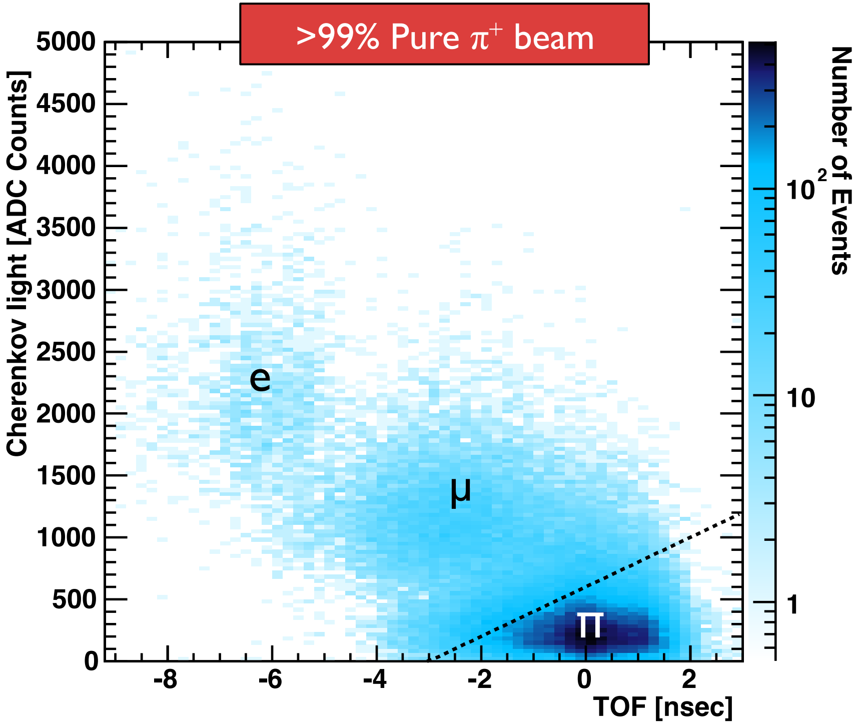
- A subset of members of the T2K experiment from Japanese and North American institutions
- Data taken over the summers of 2010~2012
- ~1 million π^+ triggers for five momentum setting



TRIUMF M11 Beam line

- M11 secondary beam line delivered e, μ, p and π with momentum tunable in the range from 150 MeV/c to 375MeV/c.
- Recorded data at 5 π^+ momenta
- Beam PID from Time Of Flight (TOF)
  - ~15 m between production point and Scintillation counter near target.
- Above 225 MeV/c use Cherenkov detector to select pions.

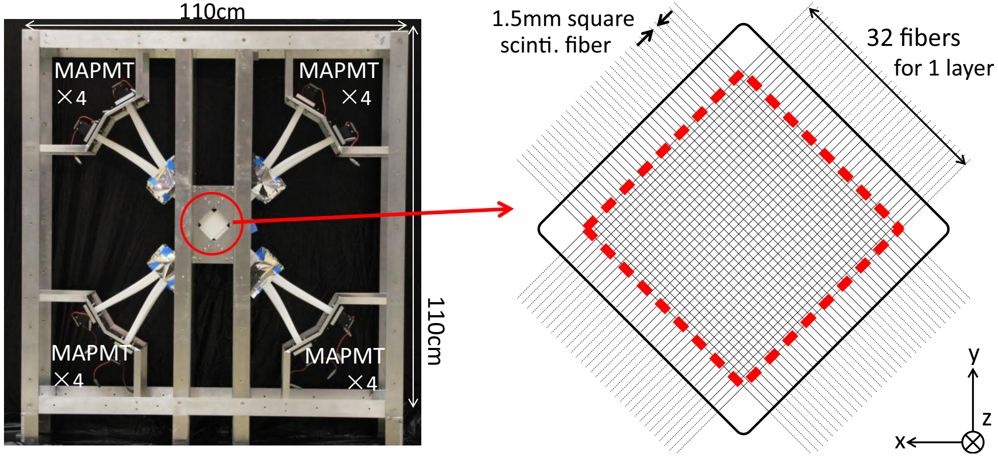



>99% Pure π^+ beam

PIAnO Fibers

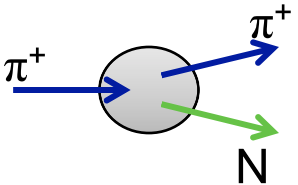
- 16 horizontal and 16 vertical layers with 32 CH fibers each (1.5mm x 1.5mm x 60cm)
- Read by 16 MAPMTs (from K2K) and digitized by FADCs
- Provides precise tracking and dQ/dx measurements of particles in the final state
- Full Geant4 simulation
  - Includes TiO2 fiber coating and support structure

(**PI**on detector for **A**nalysis of neutrino **O**scillation)

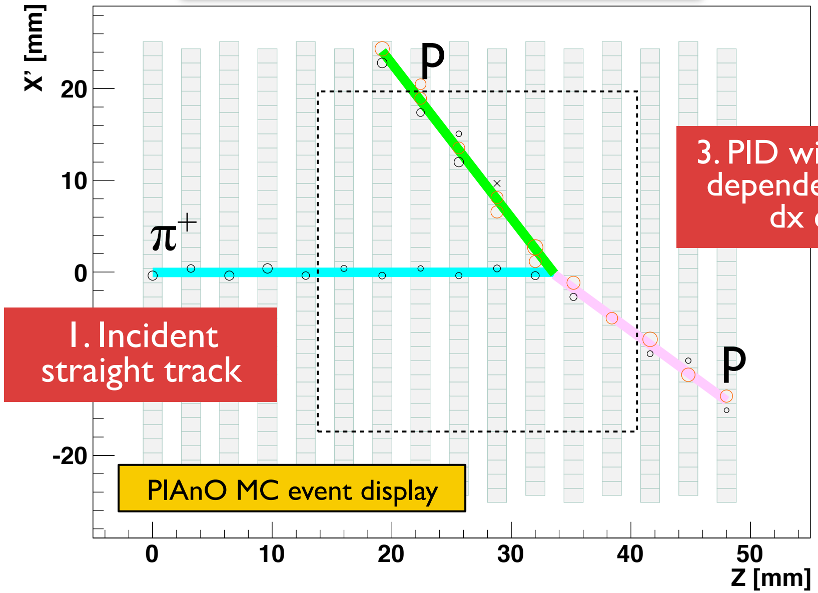


Event Selection: No π^+ in final state

Reject:



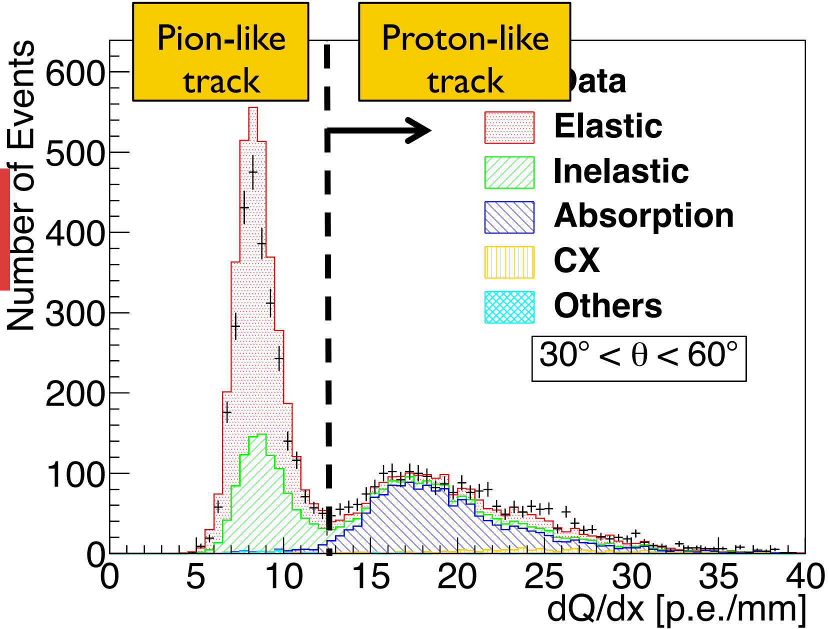
2. Vertex inside PIAnO's Fiducial Volume



1. Incident straight track

3. PID with angle dependent dQ/dx cut

Sample π^+ ABS interaction in PIAnO

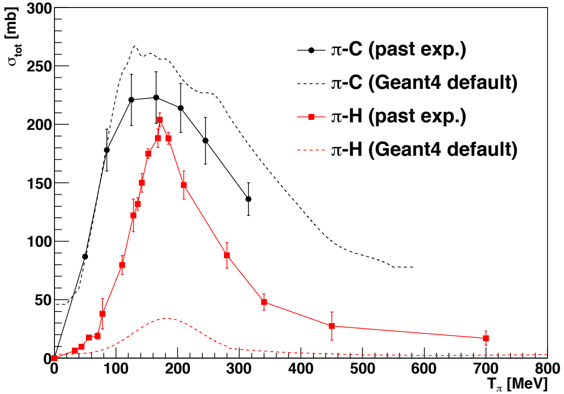


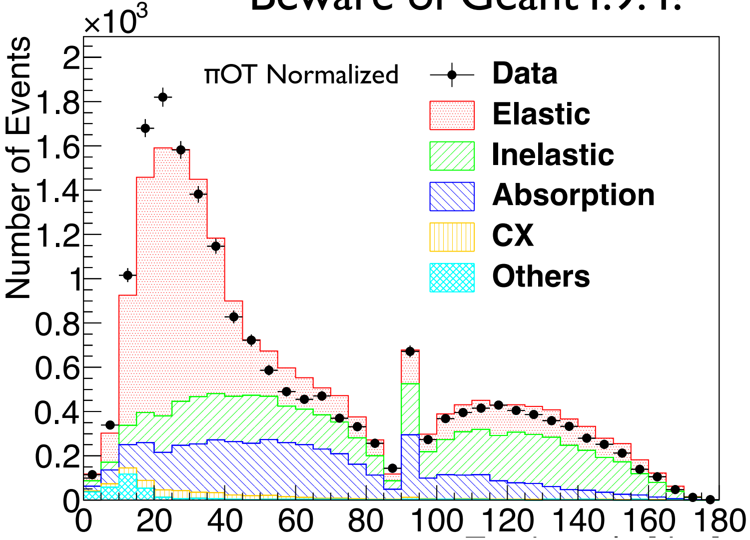
Example of dQ/dx distribution

Event Selection: Data vs. MC comparisons

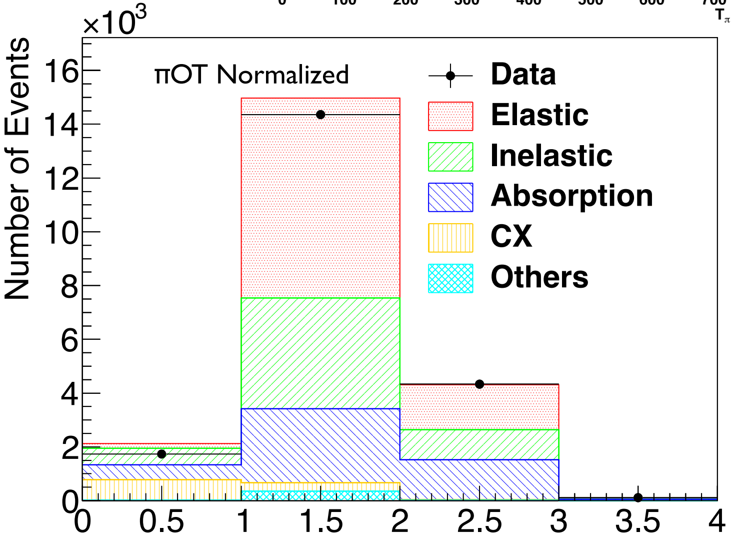
❖ Good agreement of distributions before applying the "no π^+ in final state" cut:

- Large Geant4 mis-modeling of ^{1}H and ^{12}C elastic interactions →
  - Beware of Geant4.9.4!





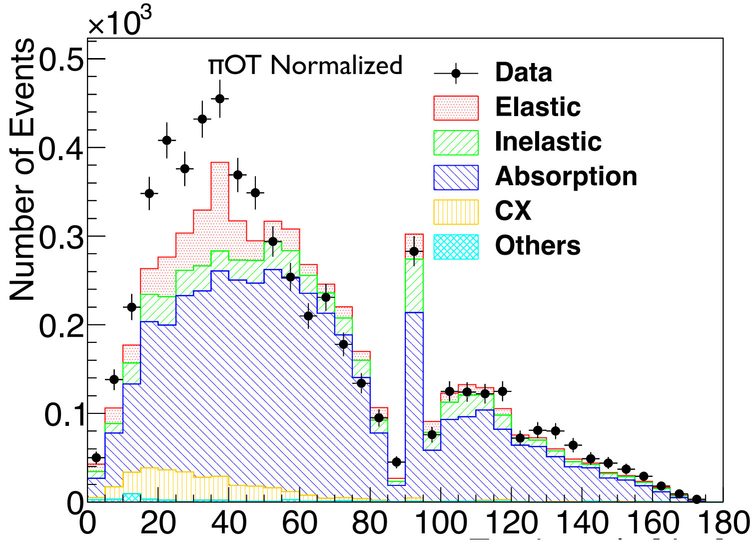
Reconstructed track Polar Angle [deg]



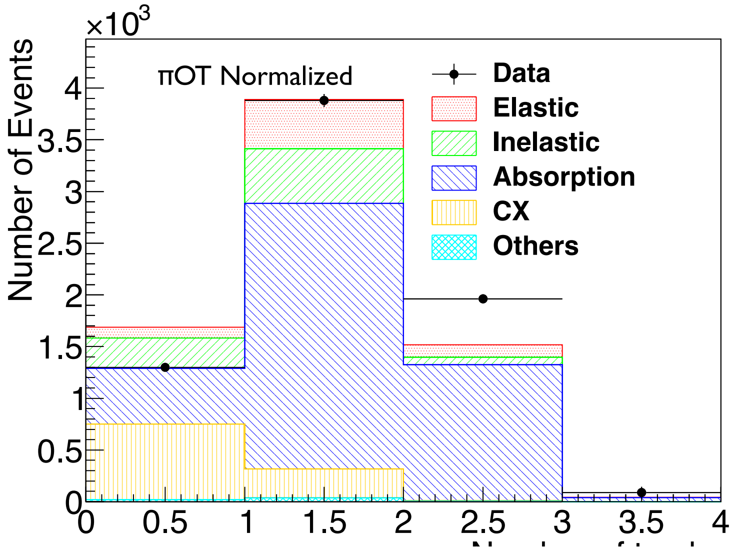
Number of reconstructed tracks

Event Selection: Data vs. MC comparisons

- For 238MeV/c π⁺ data set, the efficiency is 79.8% and the purity is 76.8%.
- ~7000 events selected on each momentum data set after all cuts are applied.

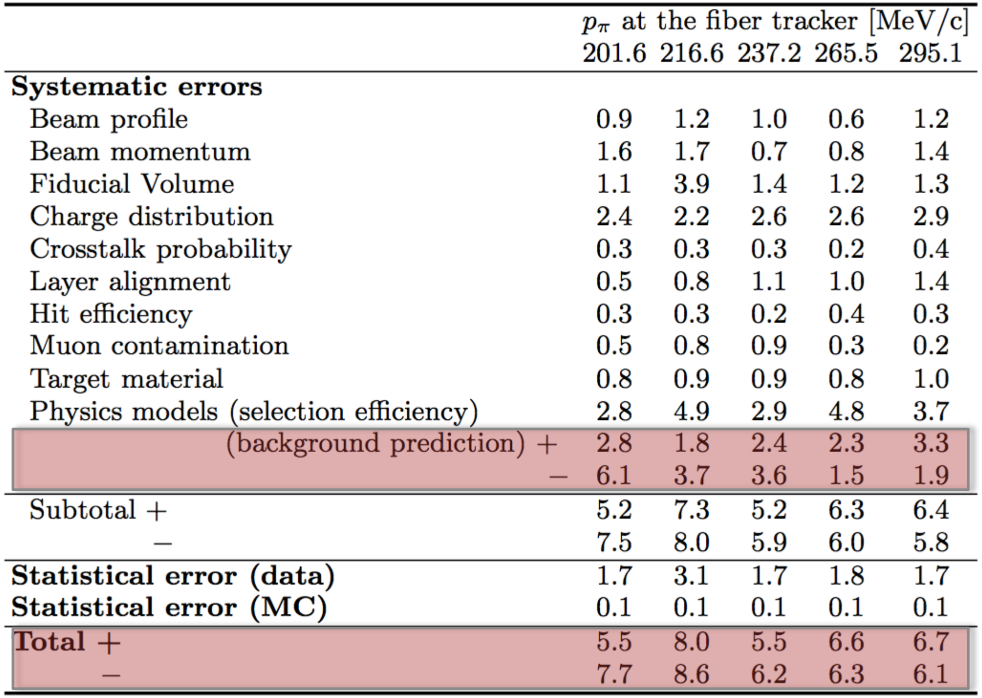


Reconstructed track Polar Angle [deg]



Number of reconstructed tracks

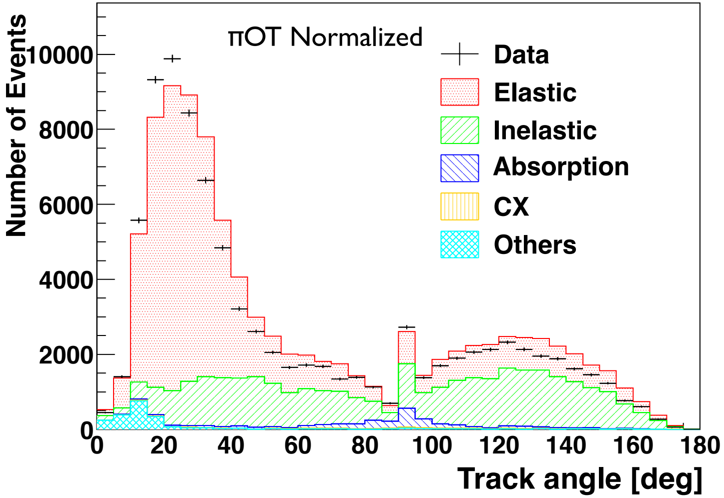
Uncertainties



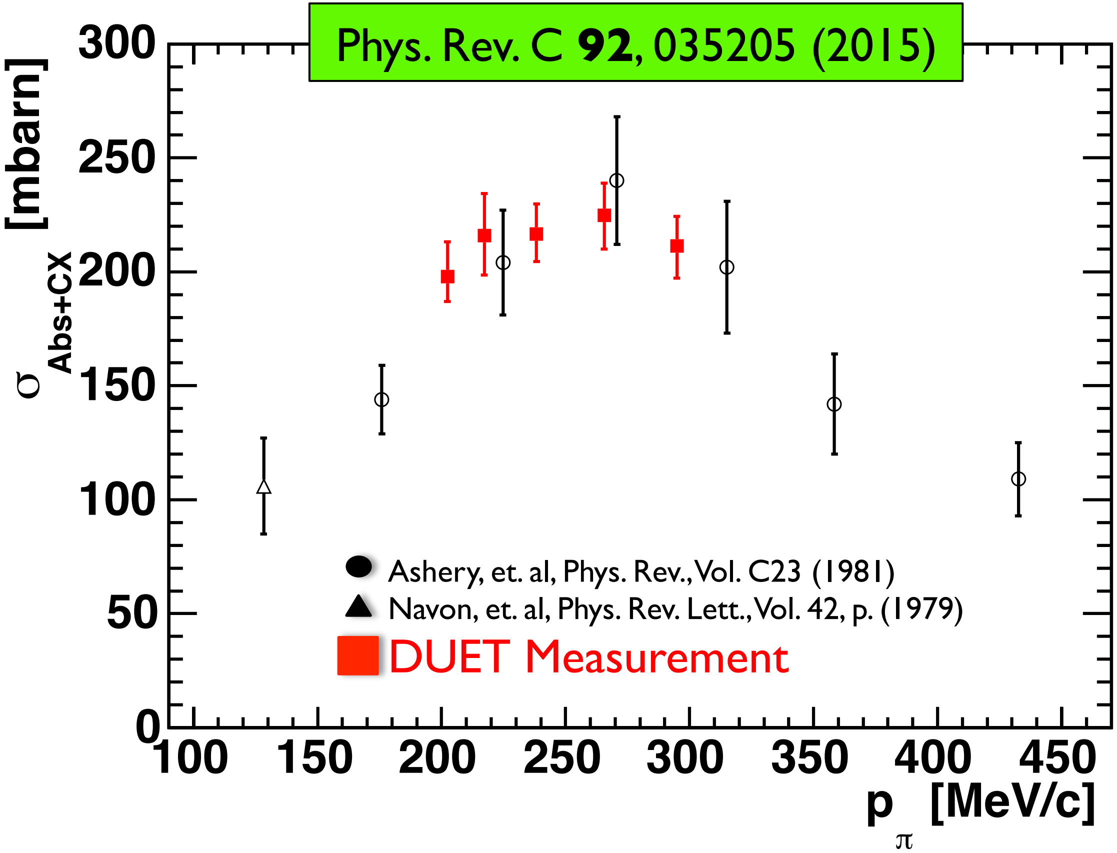
	p_π at the fiber tracker [MeV/c]				
	201.6	216.6	237.2	265.5	295.1
Systematic errors					
Beam profile	0.9	1.2	1.0	0.6	1.2
Beam momentum	1.6	1.7	0.7	0.8	1.4
Fiducial Volume	1.1	3.9	1.4	1.2	1.3
Charge distribution	2.4	2.2	2.6	2.6	2.9
Crosstalk probability	0.3	0.3	0.3	0.2	0.4
Layer alignment	0.5	0.8	1.1	1.0	1.4
Hit efficiency	0.3	0.3	0.2	0.4	0.3
Muon contamination	0.5	0.8	0.9	0.3	0.2
Target material	0.8	0.9	0.9	0.8	1.0
Physics models (selection efficiency)	2.8	4.9	2.9	4.8	3.7
(background prediction) +	2.8	1.8	2.4	2.3	3.3
−	6.1	3.7	3.6	1.5	1.9
Subtotal +	5.2	7.3	5.2	6.3	6.4
−	7.5	8.0	5.9	6.0	5.8
Statistical error (data)	1.7	3.1	1.7	1.8	1.7
Statistical error (MC)	0.1	0.1	0.1	0.1	0.1
Total +	5.5	8.0	5.5	6.6	6.7
−	7.7	8.6	6.2	6.3	6.1

Dominant systematic error is background estimation.

Error is estimated from Data/MC comparisons of a BG enhanced sample



ABS+CX Cross Section Result (2015)

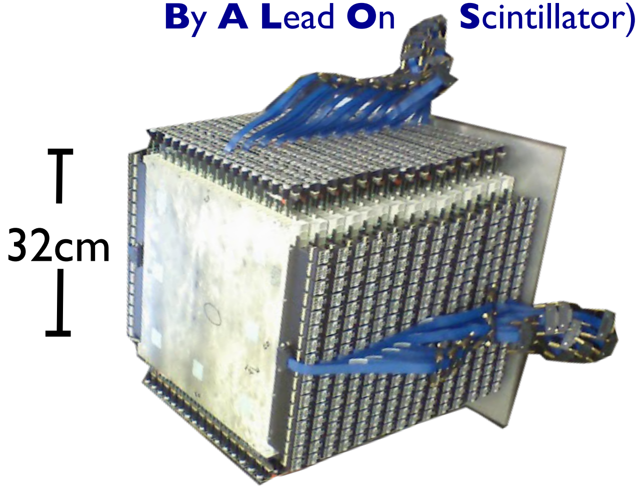


Good agreement and much smaller errors (~20% → ~7%)

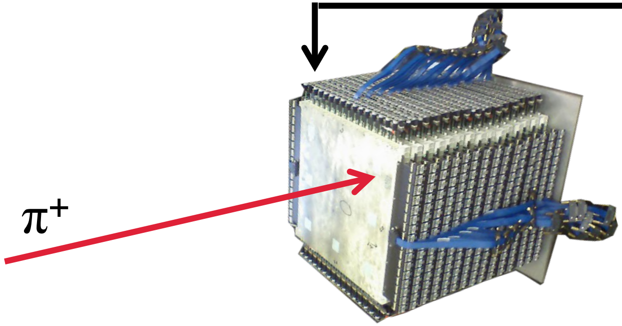
CEMBALOS

(**C**harge **E**xchange **M**easurement **B**y **A** **L**ead **O**n **S**cintillator)

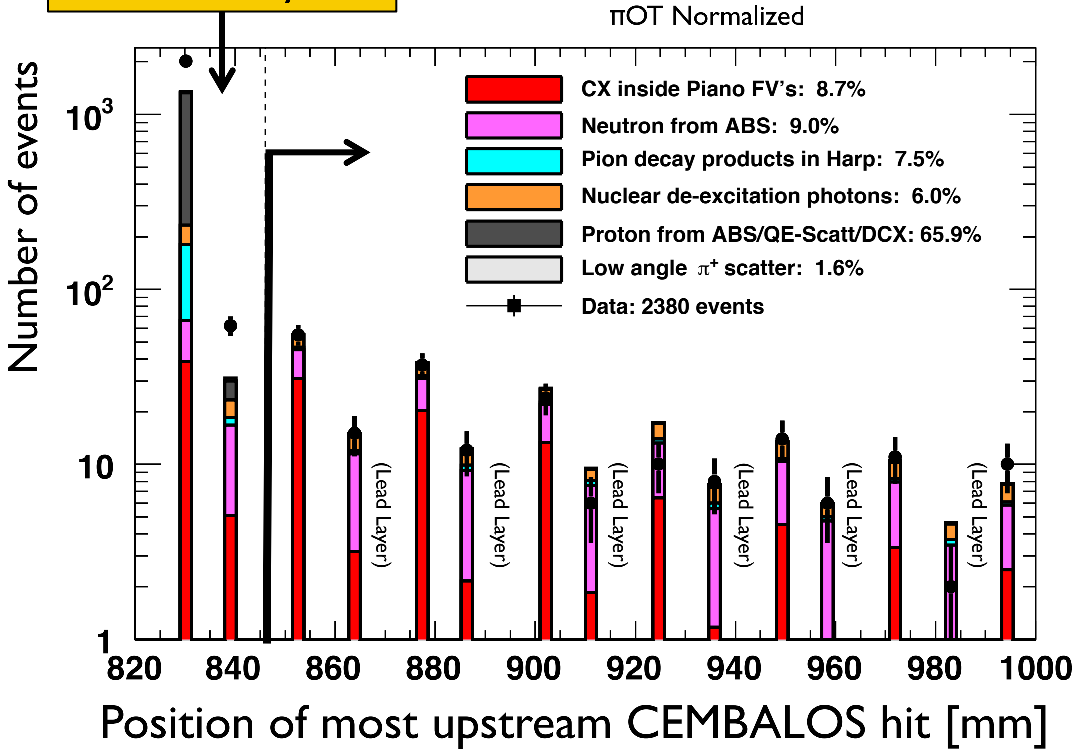
- 8 horizontal and 8 vertical scintillating layers with 32 polystyrene bars each
  - 1/6 x 1/6 of FGD
- Light from scintillation bar + Wave Length Shifting fibers read out by MPPCs
- ~1.5mm Lead layers interspersed to increase photon conversion
- Also used for FGD reconstruction studies: “Harpsichord”
  - **HA**dron **R**econstruction HaRpsi CHordance **S**tudies **I**n **CH** **O**n **R**educed **D**etector



CX Event Selection: Using CEMBALOS

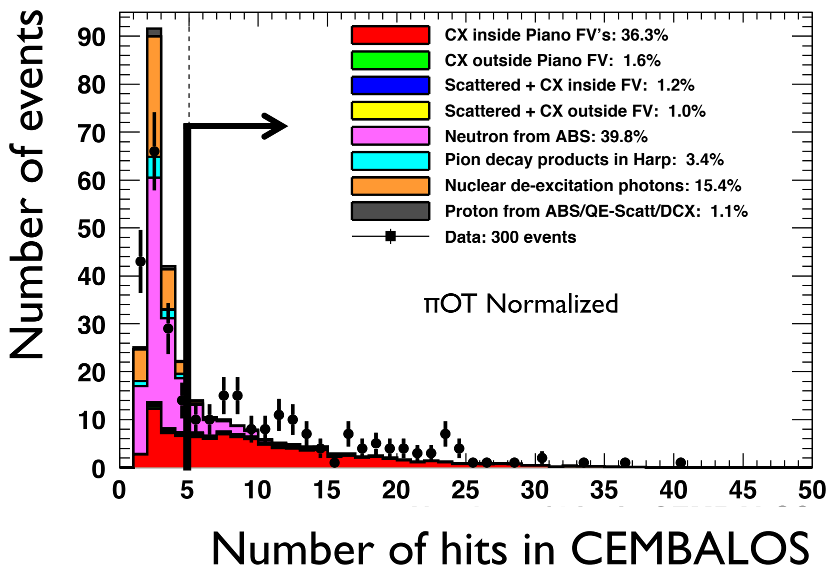


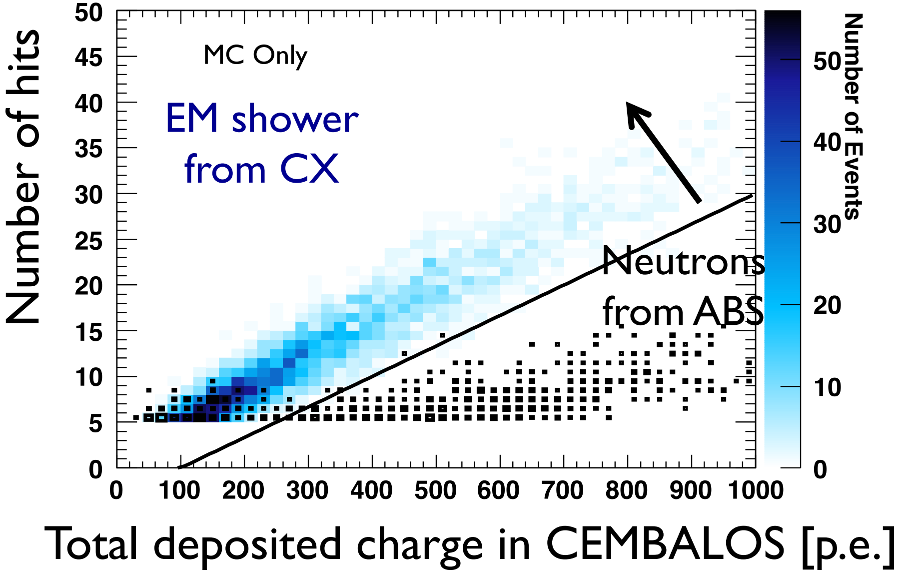
First two layers



- Charged **pions** and **protons** immediately leave a signal in the scintillating detector
- **Photons** are neutral, so they must interact before they can be detected
- The **first two layers** are used as a **veto cut** in order to remove charged background

CX Event Selection: Neutron Rejection





- **Neutrons** will also mostly make hits after the first two layers
- Use number of hits and total charge deposited to remove most of background

Efficiency = $\dfrac{\text{Selected CX events}}{\text{True CX events}} \approx 6\%$

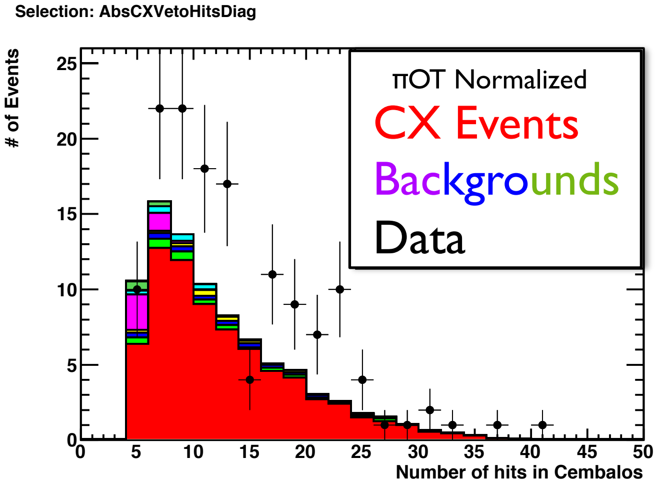
Purity = $\dfrac{\text{Selected CX events}}{\text{Total selected events}} \approx 87\%$

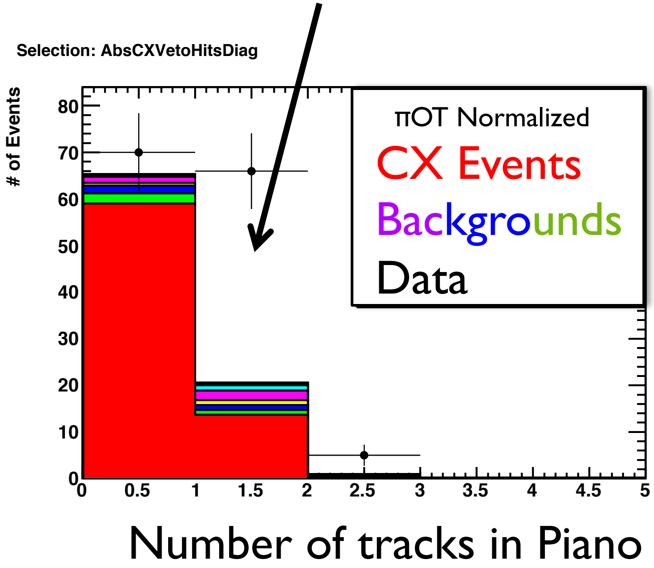
- **~100 events in data sample**

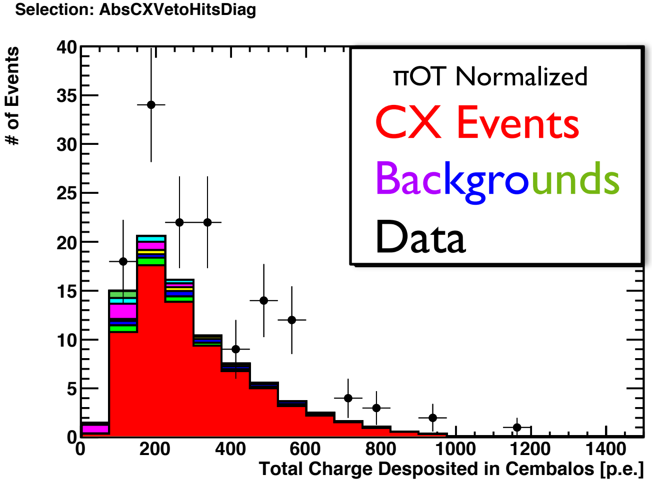
(~20 for 216.6 MeV/c)

CX Event Selection: Data vs. MC

- Data event rate clearly higher than Geant4 Monte Carlo
- Indication of mis-modeling of nucleon ejection multiplicity and/or momentum

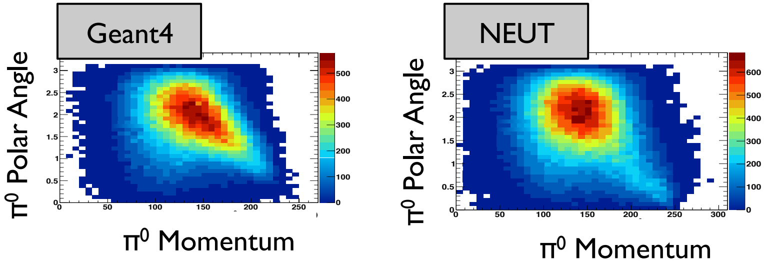


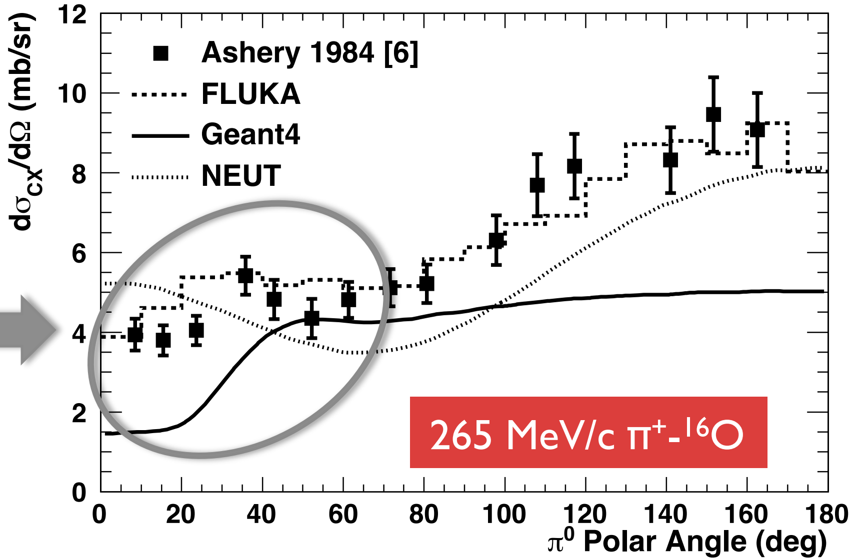




CX Modeling

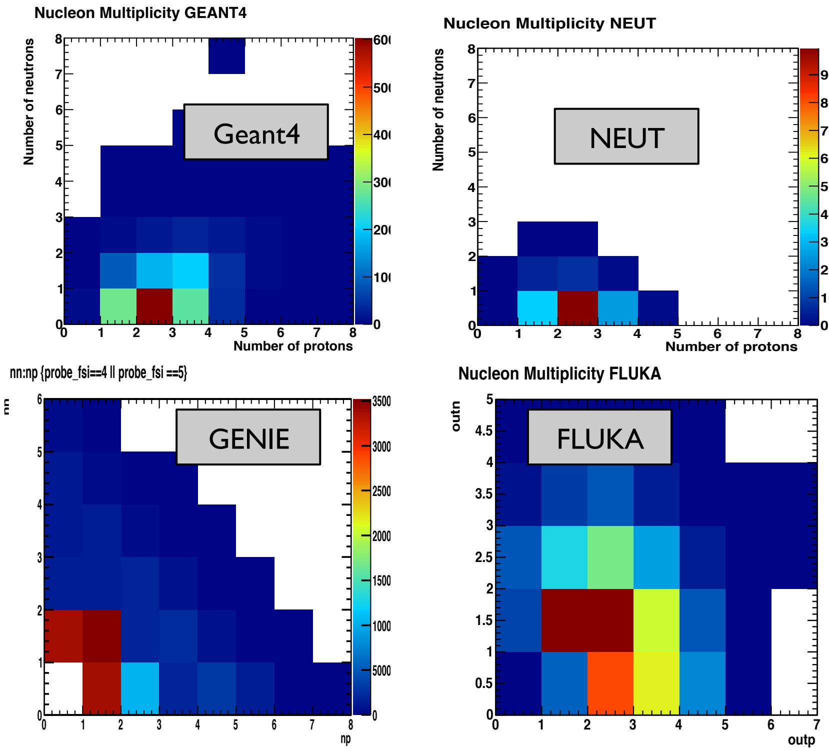
- The kinematics of the outgoing π^0 is not well known
- Few differential cross section measurements
  - D. Ashery et al., "Inclusive pion single-charge-exchange reactions," Phys. Rev. C, 30(3):946 (1984).
- Discrepancy among models is largest in the forward region, where CEMBALOS is more sensitive
  - In particular Geant4 shows the largest disagreement





Nucleon ejection (ABS background)

- Very large difference among models for both:
  - # nucleons ejected
  - Kinematics
- NEUT is the only model with some public information on the model:
  - R. Tacik, AIP Conf. Proc. 1405, 229 (2011)
  - Tuned to π-{N,Ar} data
- High purity of CX selection means this effect is not dominant
  - But it still troubling



σ_{CX}, σ_{ABS} Extraction

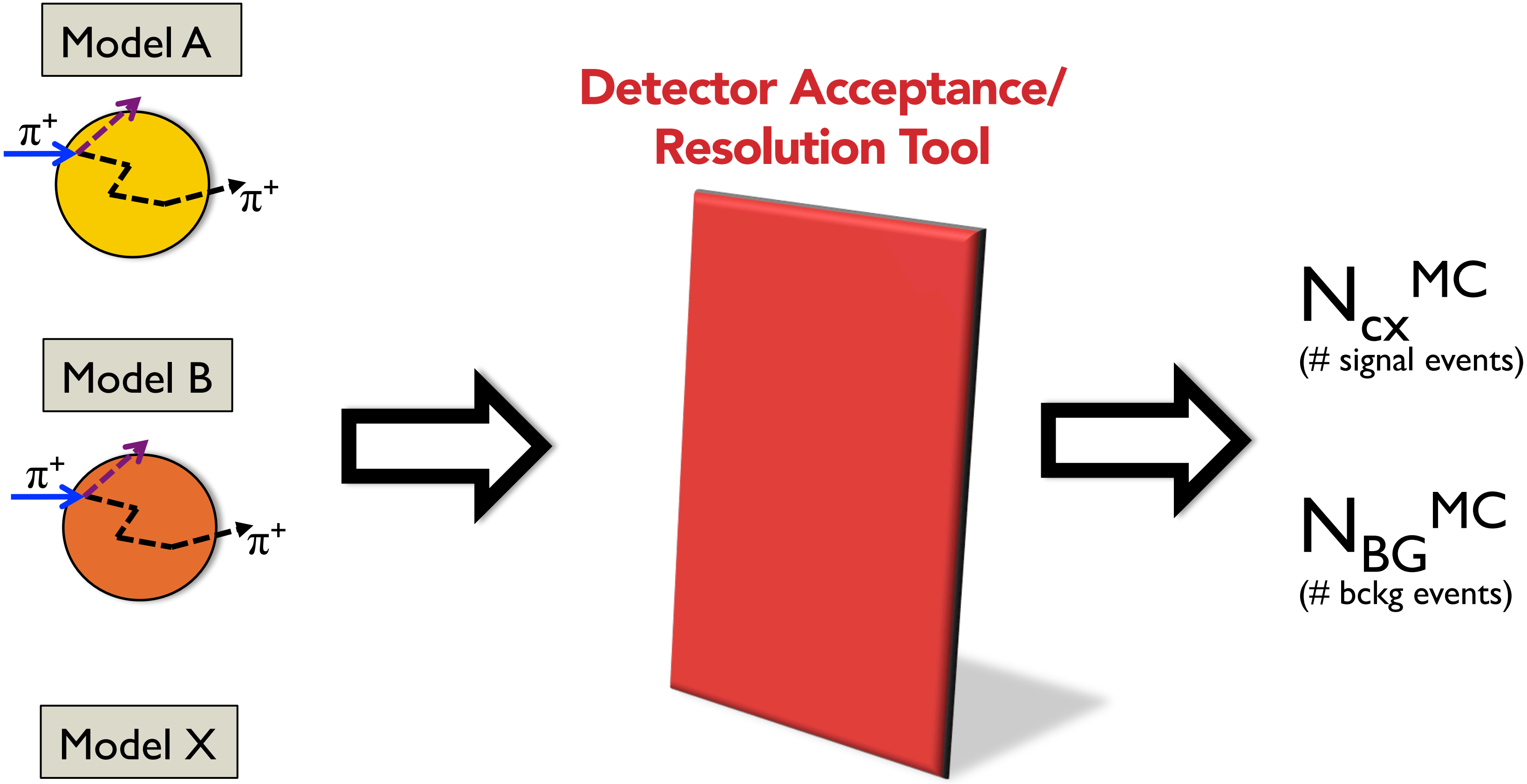
- Formulae for calculation are:

$$\sigma_{\mathrm{CX}} = \sigma_{\mathrm{CX}}^{\mathrm{MC}} \times \frac{N_{\mathrm{Data}} - N_{\mathrm{BG}}^{\mathrm{MC}}}{N_{\mathrm{CX}}^{\mathrm{MC}}} \tag{1}$$

$$\sigma_{\mathrm{ABS}} = \sigma_{\mathrm{ABS+CX}} - \sigma_{\mathrm{CX}} \tag{2}$$

- Want to try out other models:
  - For each model estimate:
    1. N_{cx}^{MC} (# of signal events)
    2. N_{BG}^{MC} (# of background events)
- One option is to re-write the simulation using each package
  - A more general (reasonable) one is:

Detector Acceptance/ Resolution Tool



Model A

Model B

Model X

N_{cx}^{MC}

(# signal events)

N_{BG}^{MC}

(# bckg events)

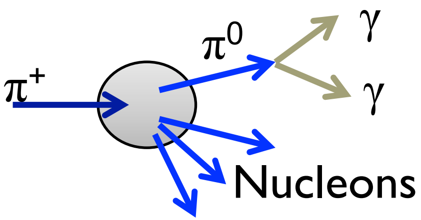
Adapted from: M. Wascko, Neutrino Nucleus Cross Section Experiments. Talk presented at PhyStat-Nu 2016

"Efficiencies" Scheme

π^0 and nucleon kinematics dependant selection efficiencies

→ Apply directly to the "model" from generators

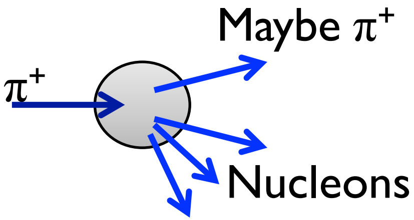
❖ **Sample Signal Event**



❖ Signal event will be selected if:

- π^0 is selected → $\varepsilon_{sel}(\pi^0)$
- Ejected proton is NOT mis-reconstructed in Piano as a pion-like track → ε_{rej}(p misreco)
- Ejected nucleons (proton or neutron) fire the veto cut → ε_{rej}(p/n fires veto)

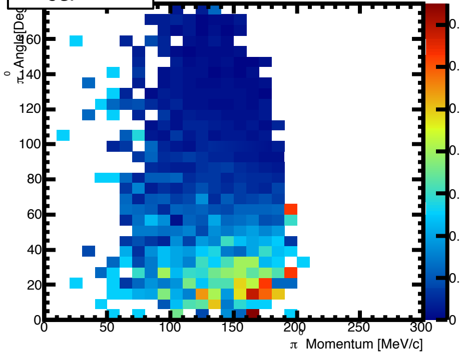
- **Sample Background Event**



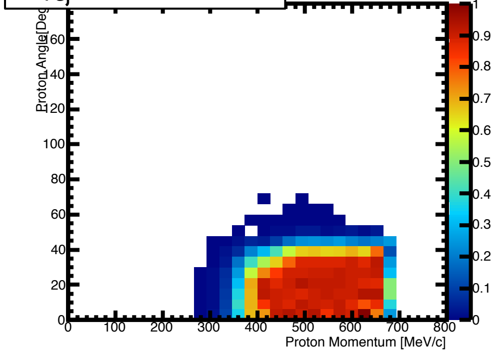
- Background event will be selected if:
  - Neutron is selected → ε_{sel}(n)
  - π^+ is mis-reconstructed as proton → ε_{rej}(π^+ misreco)
  - Ejected proton is NOT mis-reconstructed in Piano as a pion-like track → ε_{rej}(p misreco)
  - Ejected nucleons (proton or neutron) or π^+ fire the veto cut → ε_{rej}(π^+/p/n fires veto)

Selection and Rejection Efficiencies

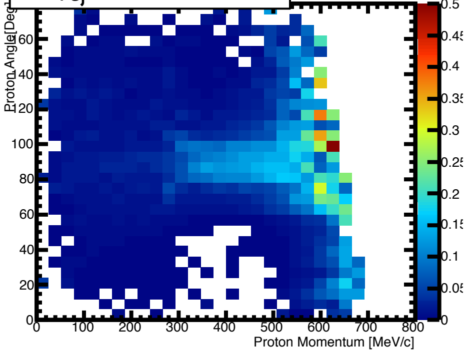
- Binned in true Momentum and Angle of corresponding particle
- Calculated using the full Geant4 DUET simulation



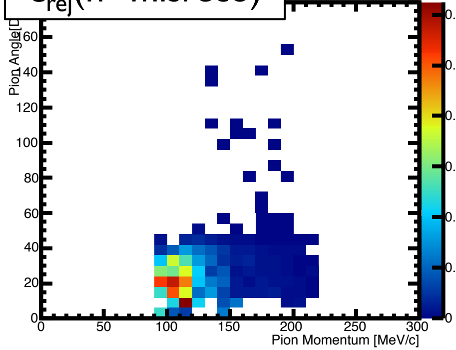
$\varepsilon_{sel}(\pi^0)$



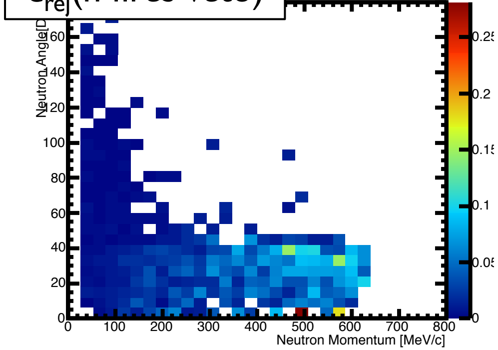
ε_{rej}(p fires veto)



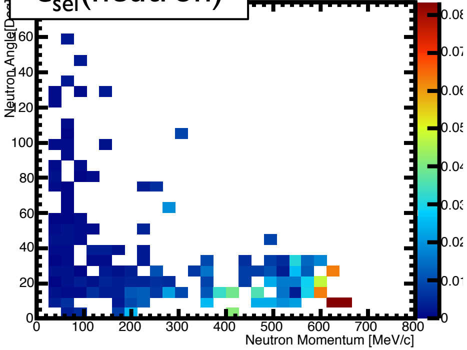
ε_{rej}(p misreco)



$\varepsilon_{rej}(\pi^+$ misreco)



ε_{rej}(n fires veto)



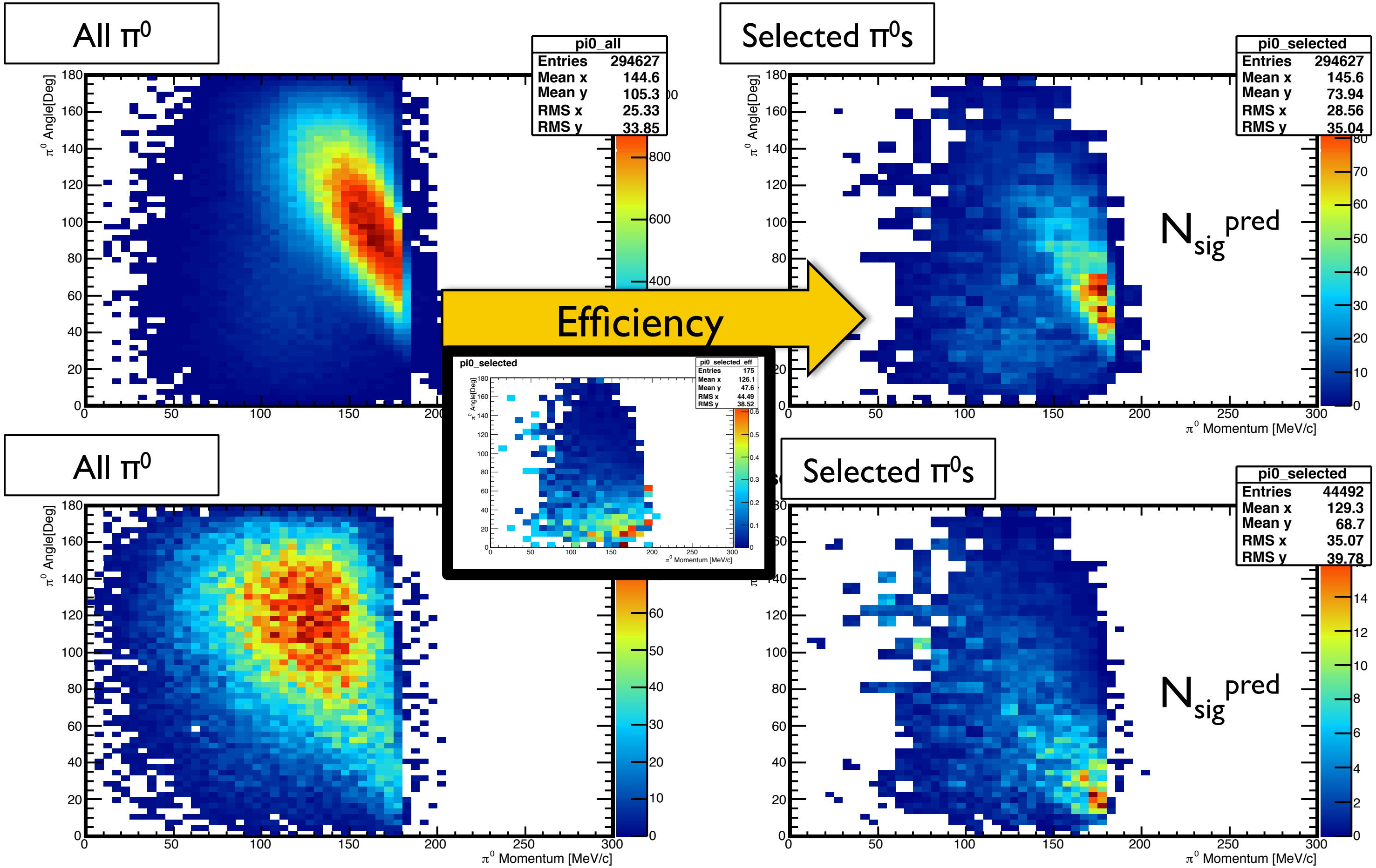
ε_{sel}(neutron)

Example: 201.6 MeV/c

Geant4 Model

(as cross-check)

FLUKA



All π^0

Selected π^0s

Efficiency

N_{sig}^{pred}

All π^0

Selected π^0s

N_{sig}^{pred}

Applying it

- Large differences at low momentum
- Decided to use FLUKA as our nominal model for DUET result
- Scheme can be applied to new models when they become available

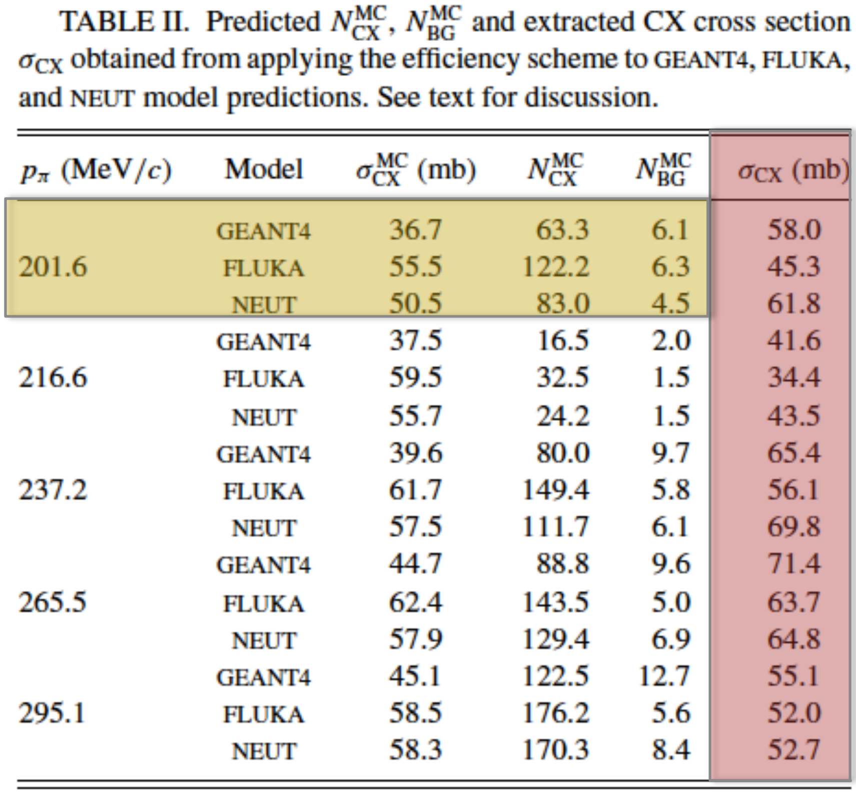


TABLE II. Predicted $N_{\mathrm{CX}}^{\mathrm{MC}}$, $N_{\mathrm{BG}}^{\mathrm{MC}}$ and extracted CX cross section σ_{CX} obtained from applying the efficiency scheme to GEANT4, FLUKA, and NEUT model predictions. See text for discussion.

p_π (MeV/c)	Model	$\sigma_{\mathrm{CX}}^{\mathrm{MC}}$ (mb)	$N_{\mathrm{CX}}^{\mathrm{MC}}$	$N_{\mathrm{BG}}^{\mathrm{MC}}$	σ_{CX} (mb)
201.6	GEANT4	36.7	63.3	6.1	58.0
	FLUKA	55.5	122.2	6.3	45.3
	NEUT	50.5	83.0	4.5	61.8
216.6	GEANT4	37.5	16.5	2.0	41.6
	FLUKA	59.5	32.5	1.5	34.4
	NEUT	55.7	24.2	1.5	43.5
237.2	GEANT4	39.6	80.0	9.7	65.4
	FLUKA	61.7	149.4	5.8	56.1
	NEUT	57.5	111.7	6.1	69.8
265.5	GEANT4	44.7	88.8	9.6	71.4
	FLUKA	62.4	143.5	5.0	63.7
	NEUT	57.9	129.4	6.9	64.8
295.1	GEANT4	45.1	122.5	12.7	55.1
	FLUKA	58.5	176.2	5.6	52.0
	NEUT	58.3	170.3	8.4	52.7

Uncertainties

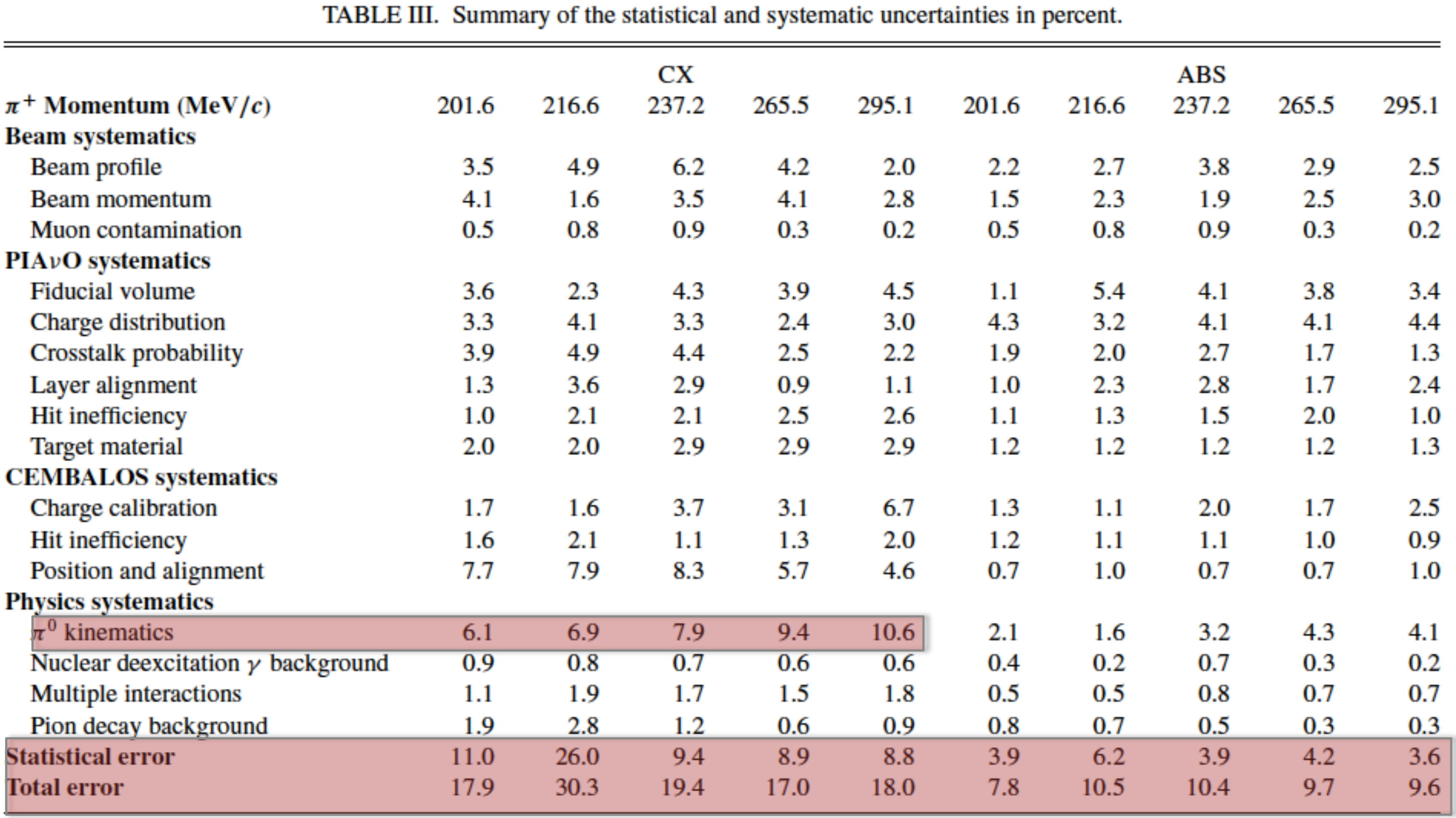


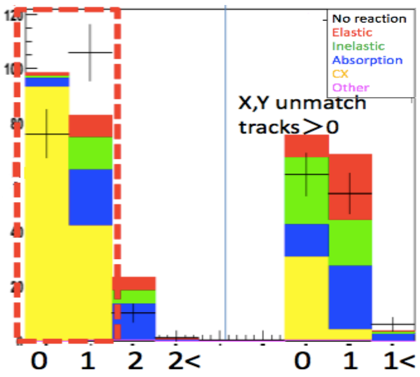
TABLE III. Summary of the statistical and systematic uncertainties in percent.

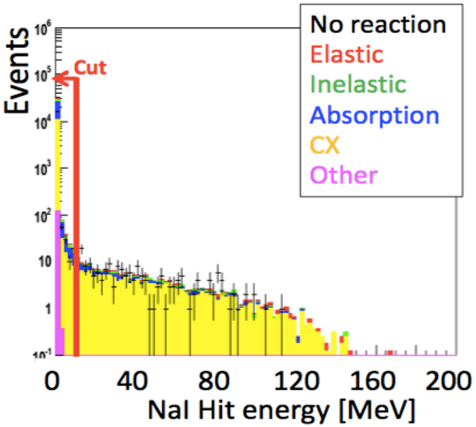
	CX					ABS				
π^+ **Momentum (MeV/c)**	201.6	216.6	237.2	265.5	295.1	201.6	216.6	237.2	265.5	295.1
Beam systematics										
Beam profile	3.5	4.9	6.2	4.2	2.0	2.2	2.7	3.8	2.9	2.5
Beam momentum	4.1	1.6	3.5	4.1	2.8	1.5	2.3	1.9	2.5	3.0
Muon contamination	0.5	0.8	0.9	0.3	0.2	0.5	0.8	0.9	0.3	0.2
PIAνO systematics										
Fiducial volume	3.6	2.3	4.3	3.9	4.5	1.1	5.4	4.1	3.8	3.4
Charge distribution	3.3	4.1	3.3	2.4	3.0	4.3	3.2	4.1	4.1	4.4
Crosstalk probability	3.9	4.9	4.4	2.5	2.2	1.9	2.0	2.7	1.7	1.3
Layer alignment	1.3	3.6	2.9	0.9	1.1	1.0	2.3	2.8	1.7	2.4
Hit inefficiency	1.0	2.1	2.1	2.5	2.6	1.1	1.3	1.5	2.0	1.0
Target material	2.0	2.0	2.9	2.9	2.9	1.2	1.2	1.2	1.2	1.3
CEMBALOS systematics										
Charge calibration	1.7	1.6	3.7	3.1	6.7	1.3	1.1	2.0	1.7	2.5
Hit inefficiency	1.6	2.1	1.1	1.3	2.0	1.2	1.1	1.1	1.0	0.9
Position and alignment	7.7	7.9	8.3	5.7	4.6	0.7	1.0	0.7	0.7	1.0
Physics systematics										
π^0 kinematics	6.1	6.9	7.9	9.4	10.6	2.1	1.6	3.2	4.3	4.1
Nuclear deexcitation γ background	0.9	0.8	0.7	0.6	0.6	0.4	0.2	0.7	0.3	0.2
Multiple interactions	1.1	1.9	1.7	1.5	1.8	0.5	0.5	0.8	0.7	0.7
Pion decay background	1.9	2.8	1.2	0.6	0.9	0.8	0.7	0.5	0.3	0.3
Statistical error	11.0	26.0	9.4	8.9	8.8	3.9	6.2	3.9	4.2	3.6
Total error	17.9	30.3	19.4	17.0	18.0	7.8	10.5	10.4	9.7	9.6

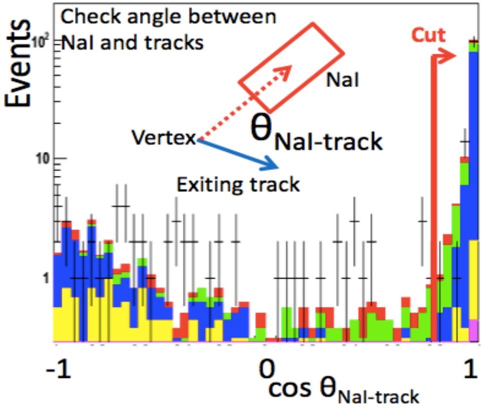
CX Event Selection: Using NaI Crystals

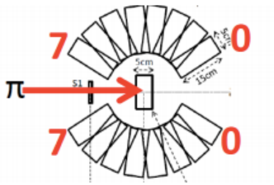
M. Ikeda, ICCR

All plots normalized to # of incident pions



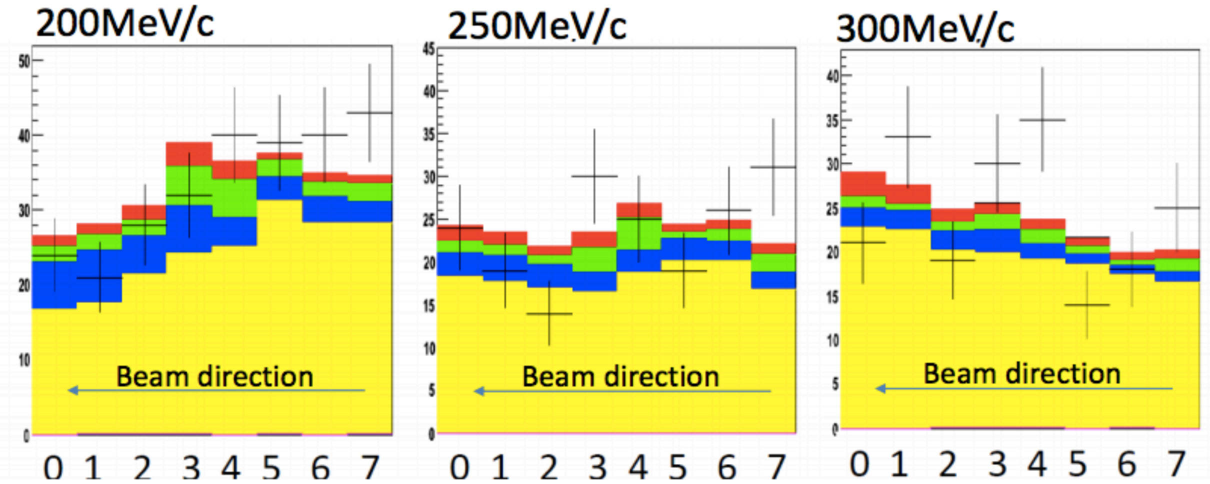






Selection Criteria:

1. 0 or 1 3D Piano tracks
2. NaI Hit Energy10 MeV in NaI Crystals
3. Reject if Piano track points to NaI Crystal



- ❖ π^0 Angular distribution reweighted to FLUKA
- ❖ Confirmed momentum dependence of CX photon angle

CX Analysis Systematics

1. π^+ Beam Systematics
   - Profile and Momentum
   - Muon Contamination
2. PIAnO detector systematics
   - Fiducial volume, target material, charge simulation, alignment

Estimation procedures inherited from ABS+CX analysis

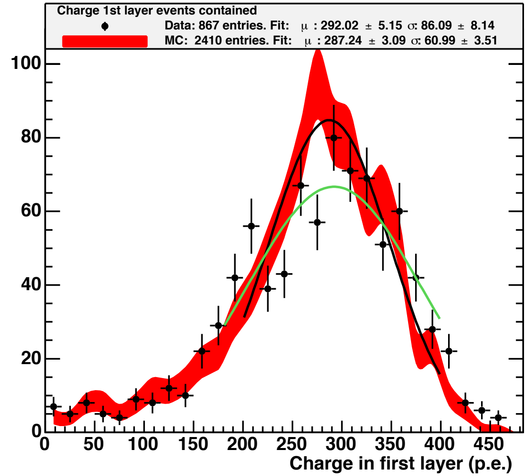
3. Cembalos Detector Systematics
   - Alignment and charge simulation
4. CX Physics Systematics
   - π^0 kinematics (Using Ashery 1984 data)
   - Selection Background

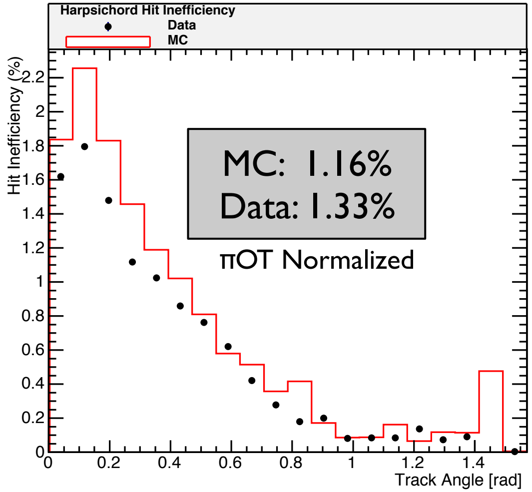
Cembalos Detector Systematics

1. **Detector Alignment (5~8%)**
   - ±5mm shifts of the (x,y,z) position of Cembalos in the Monte Carlo

2. **Charge Simulation (3~5%)**
   - Charge calibration tuning was conducted previously using through going muon sample (peaked around 40 p.e.)
   - A stopping proton control sample was developed for higher charger deposition
   - Systematic is calculated from 10000 toy MC where charge in event is varied following a Gaussian ($\mu=1, \sigma=0.2$)

3. **Hit inefficiency (1~2%)**
   - Missing hits in the middle of Cembalos reconstructed tracks are counted and compared between Data/MC
   - Systematic is calculated from 10000 toy MC where hits are randomly deleted following the Data/MC difference





MC: 1.16%
Data: 1.33%

πOT Normalized

"π entering ND280 tracker" sample

- Select CC1π events where the π track starts upstream of the ND280 tracker (FGD + TPC)
- Follow their secondary interactions elsewhere
- ~3000 events in Data (6.1x10^{20} POT)
- Difficult to convert to a cross-section measurement
  - Studying how to use this sample