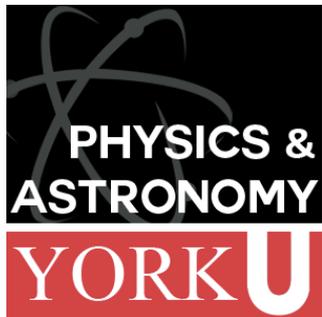


**Workshop on  
Neutrino-nucleus  
interaction in a few  
GeV region**

**KEK Tokai Campus**  
November 2017

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



**ELDER PINZON**

**YORK UNIVERSITY**

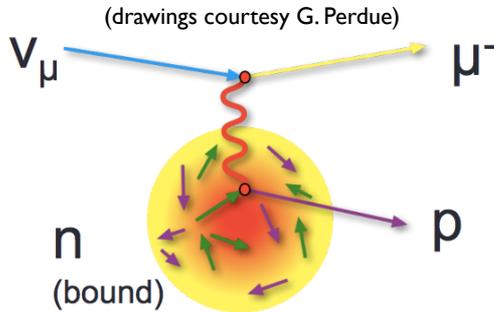
- ❖ What are Final State Interactions (FSI) and Secondary Interactions (SI)?
  - What impact do they have on  $\sim$ GeV neutrino experiments?
- ❖ How are these interactions simulated?
  - How have we improved these simulations?
  - DUET Experiment

# GeV $\nu$ Interactions

❖ Reconstructing the  $\nu$  flavour and its energy is fundamental

- For both oscillation and cross section analyses

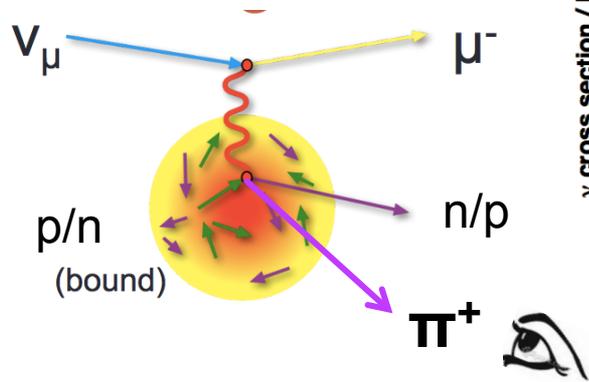
## CCQE Interaction



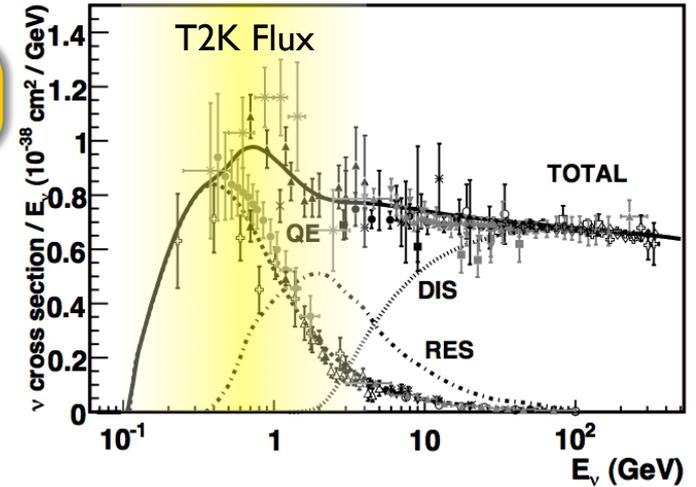
$$E_{\nu}^{\text{rec}} = \frac{2(M_N - E_B)E_{\mu} - (E_B^2 - 2M_N E_B + m_{\mu}^2)}{2[(M_N - E_B) - E_{\mu} + |\mathbf{k}'| \cos \theta_{\mu}]}$$

$E_{\nu}^{\text{rec}}$  from lepton kinematics

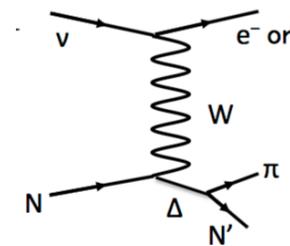
## Interaction producing $\pi_S$ (Resonance, DIS)



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



### CC $\Delta$ Resonance Production

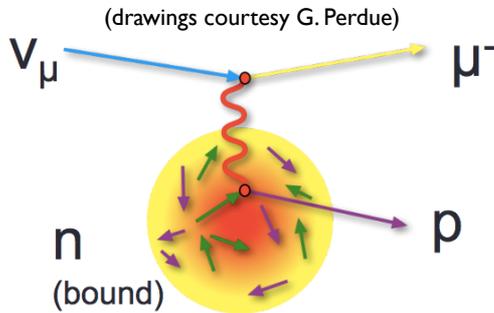


# GeV $\nu$ Interactions

❖ Reconstructing the  $\nu$  flavour and its energy is fundamental

- For both oscillation and cross section analyses

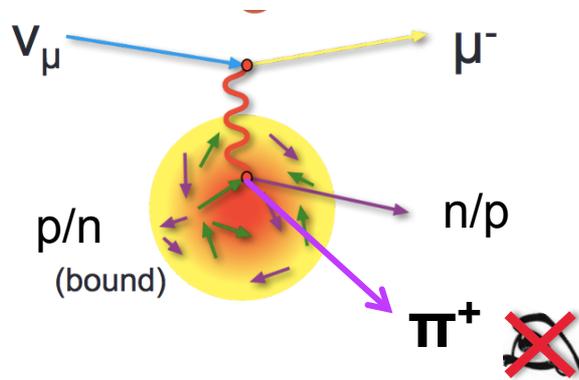
## CCQE Interaction



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

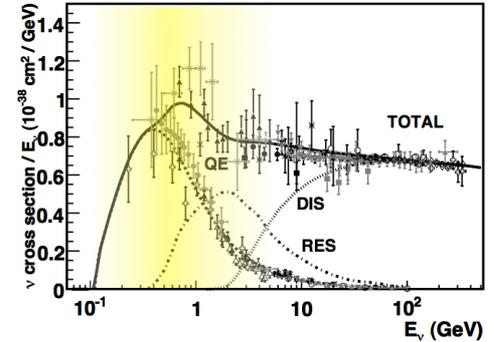
$E_{\nu}^{\text{rec}}$  from lepton kinematics

## Interaction producing $\pi_S$ (Resonance, DIS)



~~$$E_{\nu} = \frac{2(E_{\mu} + E_{\pi}) - (E_{\mu} + E_{\pi})^2 - (E_B + E_B)^2 - (E_B + E_B)^2 + m_{\mu}^2 + m_{\pi}^2}{2(E_{\mu} + E_{\pi}) - (E_{\mu} + E_{\pi})^2 - (E_B + E_B)^2 - (E_B + E_B)^2 + m_{\mu}^2 + m_{\pi}^2} + m_N$$~~

**CCQE-like event!**

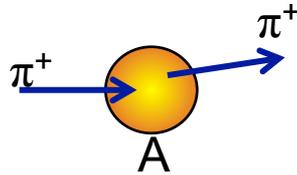


Pions can interact:

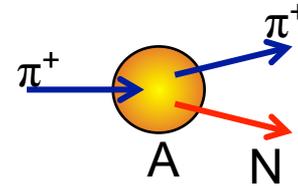
- Inside the nucleus:  
**Final State Interactions**
- Outside the nucleus:  
**Secondary Interactions**

# How do these sub-GeV pions interact on nuclei?

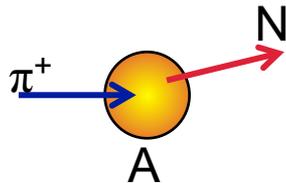
## 1. Elastic Scattering



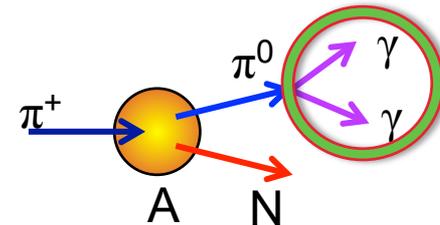
## 2. Quasi-elastic Scattering



## 3. Absorption (**ABS**)

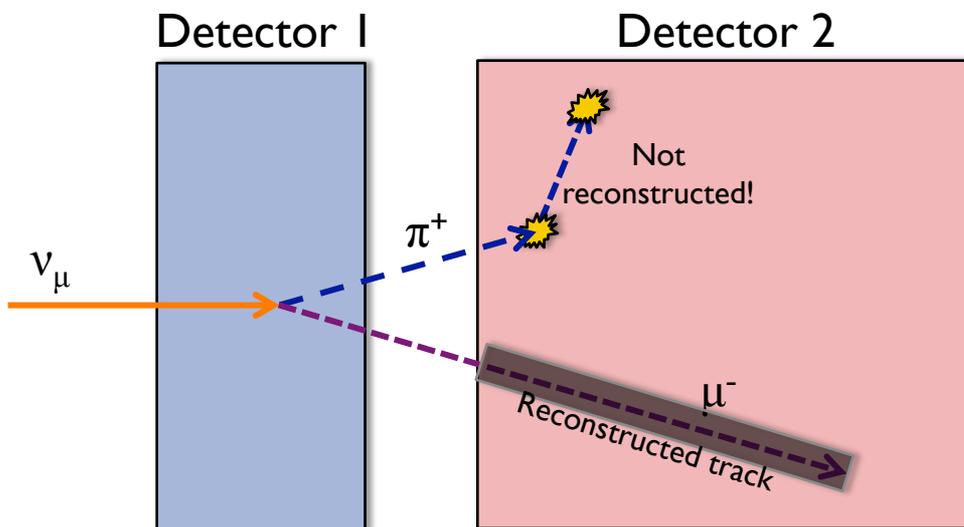


## 4. Charge Exchange (**CX**)



# Secondary Interactions (SI)

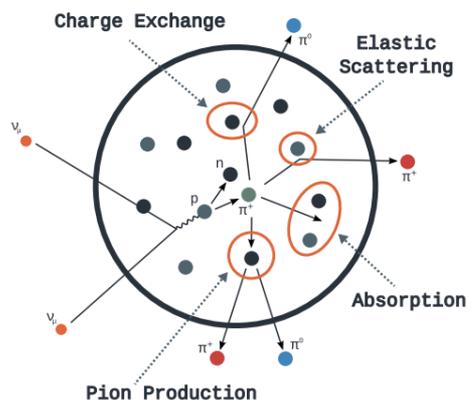
- ❖ Interactions outside the nucleus  $\rightarrow$  anywhere in the detectors
- ❖ Could mean that the pion is not detected or that it is mis-reconstructed



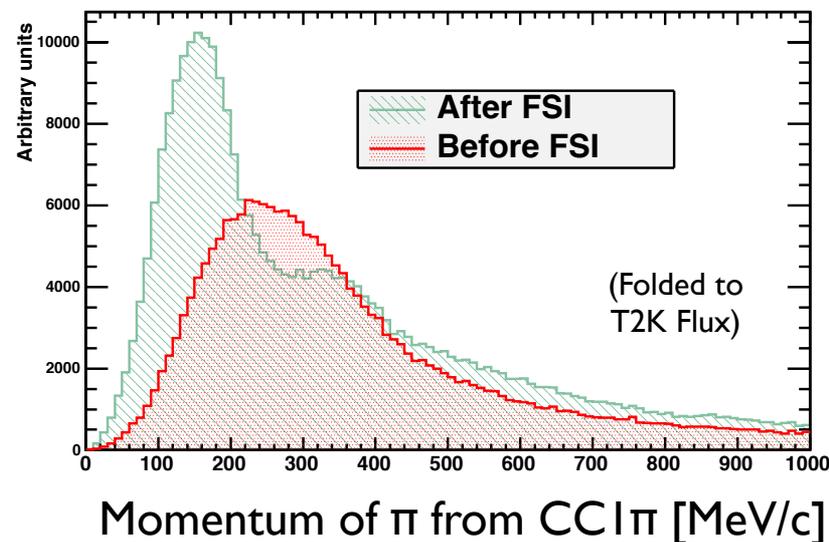
This is a dominant  
“detector” systematic for  
the near detector at T2K!

# 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  $\pi$  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

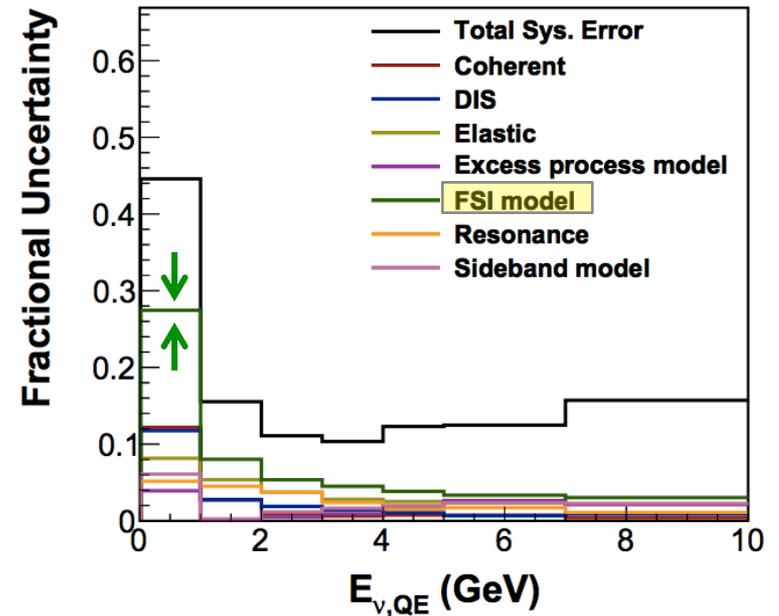
Phys. Rev. Lett. 118, 151801 (2017)

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

Source (%)	$\nu_\mu$	$\nu_e$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
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

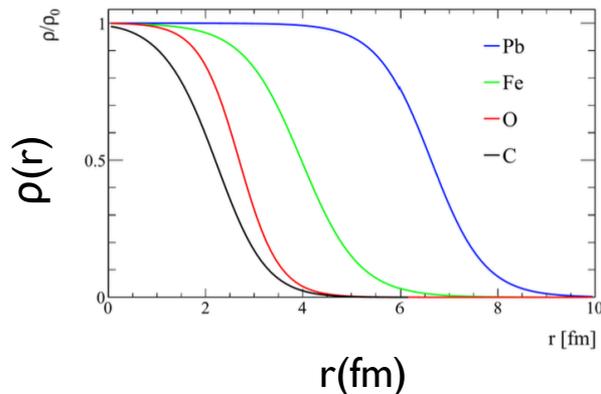
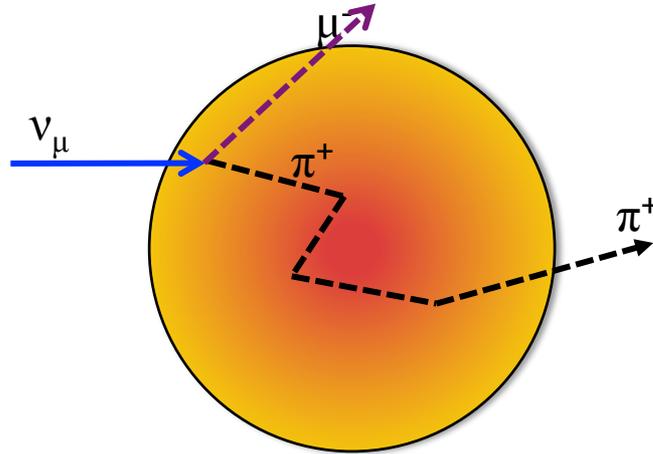
MINERvA CCQE nue

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:
  - $\lambda_{\text{step}}(r) = [\sigma_{\text{microscopic}}\rho(r)]^{-1}$
  - 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 $\sigma_{\text{microscopic}}$

Used by NEUT  
above 400 MeV/c

## Oset, Salcedo, et al. model

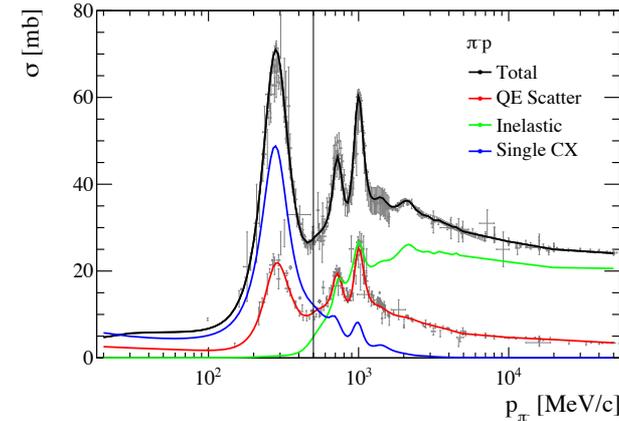
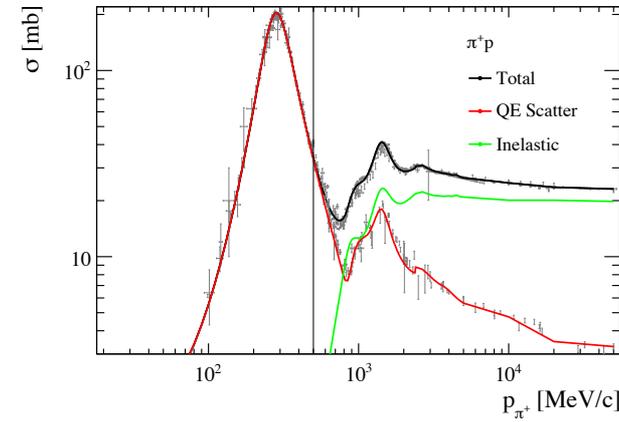
E. Oset, L.L. Salcedo and D. Strottman, Phys. Lett. **B165** (1985) 13

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  $\Delta(1232)$  spectral function in the medium

## $\pi$ -N data (SAID) or $\pi$ -A data directly

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



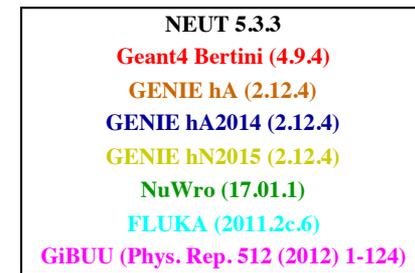
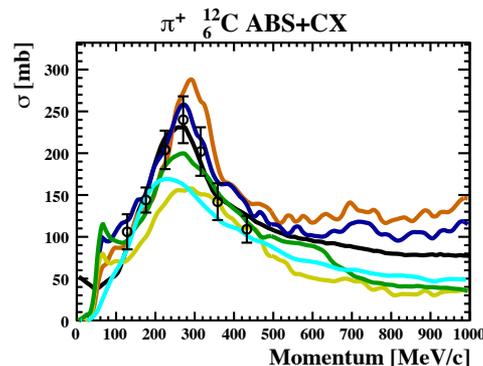
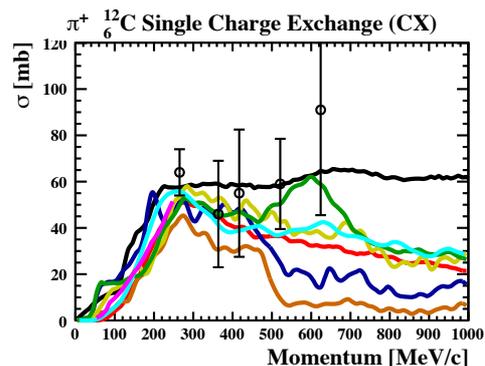
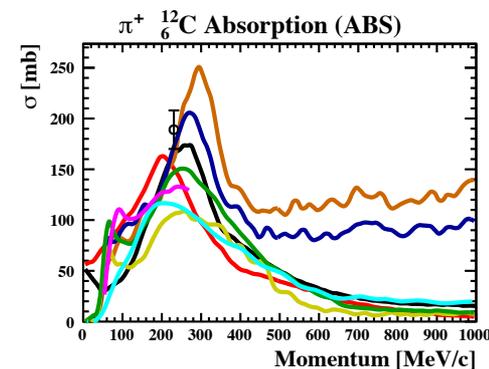
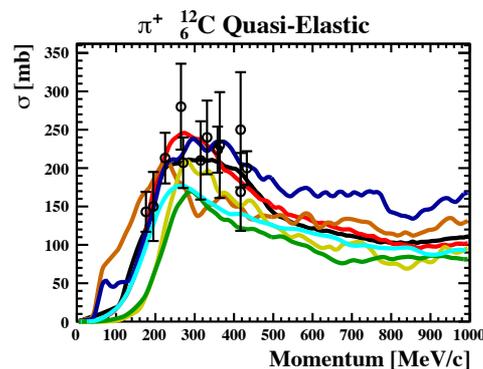
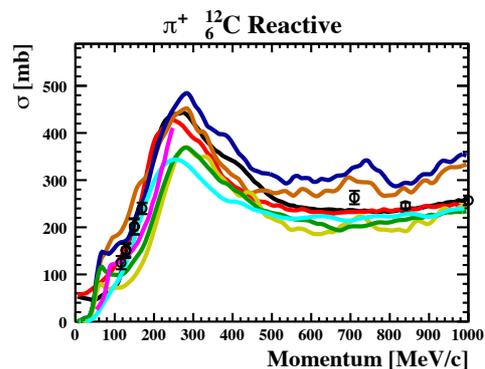
# Models on the market

- ❖ Effective (using interpolations of  $\pi$ -A cross sections directly)
  - GENIE hA: used by NOvA and MINERvA
- ❖ Cascade
  - NEUT: Oset et al. +  $\pi$ -n cross sections
  - NuWro: Oset et al. +  $\pi$ -n cross sections + formation zone effect
  - FLUKA(PEANUT): Oset et al. +  $\pi$ -n cross sections + nuclear thermalization effects
  - Geant4 (Bertini):  $\pi$ -n cross section + pre-equilibrium and evaporation
  - GENIE hN: will use Oset et al.
- ❖ Transport
  - GIBBU: hadronic potentials and the equation of state of nuclear matter within the Boltzmann-Uehling-Uhlenbeck (BUU) theory

# Model comparisons ( $\pi^+$ - $^{12}\text{C}$ )

A. Fiorentini, M. Yu

- ❖ Can use data to tune and select models
- ❖ Large uncertainties and scarce data  $\rightarrow$  Need more data!!!



○ Data

# FSI == SI?

- ❖ In T2K, we have decided that the physics of FSI and SI are the same to first order
  
- ❖ In practice this means:
  1. Use the same model to simulate FSI and SI
  
  2. Use  $\pi$ -A scattering to tune this single model and set its uncertainties

# DUET

(DUAL USE EXPERIMENT AT TRIUMF)

GOAL: MEASURE  $\pi^+$ -C ABSORPTION AND CHARGE EXCHANGE  
CROSS SECTIONS

# Detector setup: DUET

## ❖ Main Components:

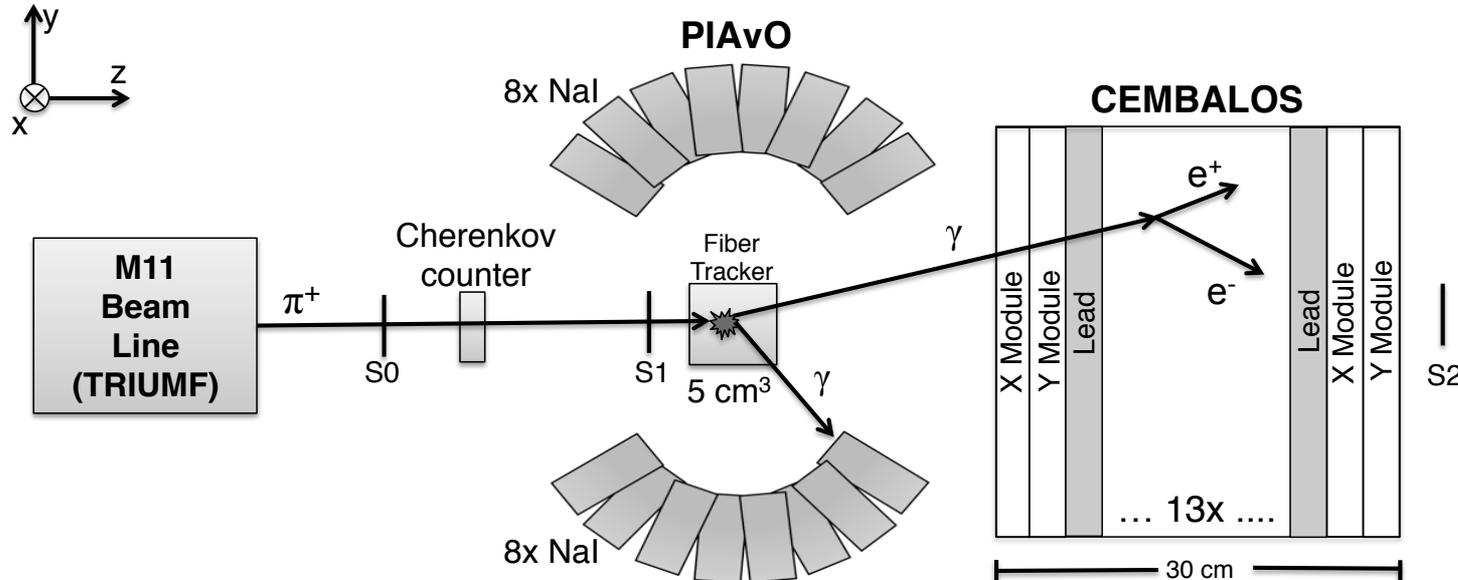


**PIAnO:**  $(5 \text{ cm})^3$  scintillating fiber tracker (Full active target) + NaI crystals

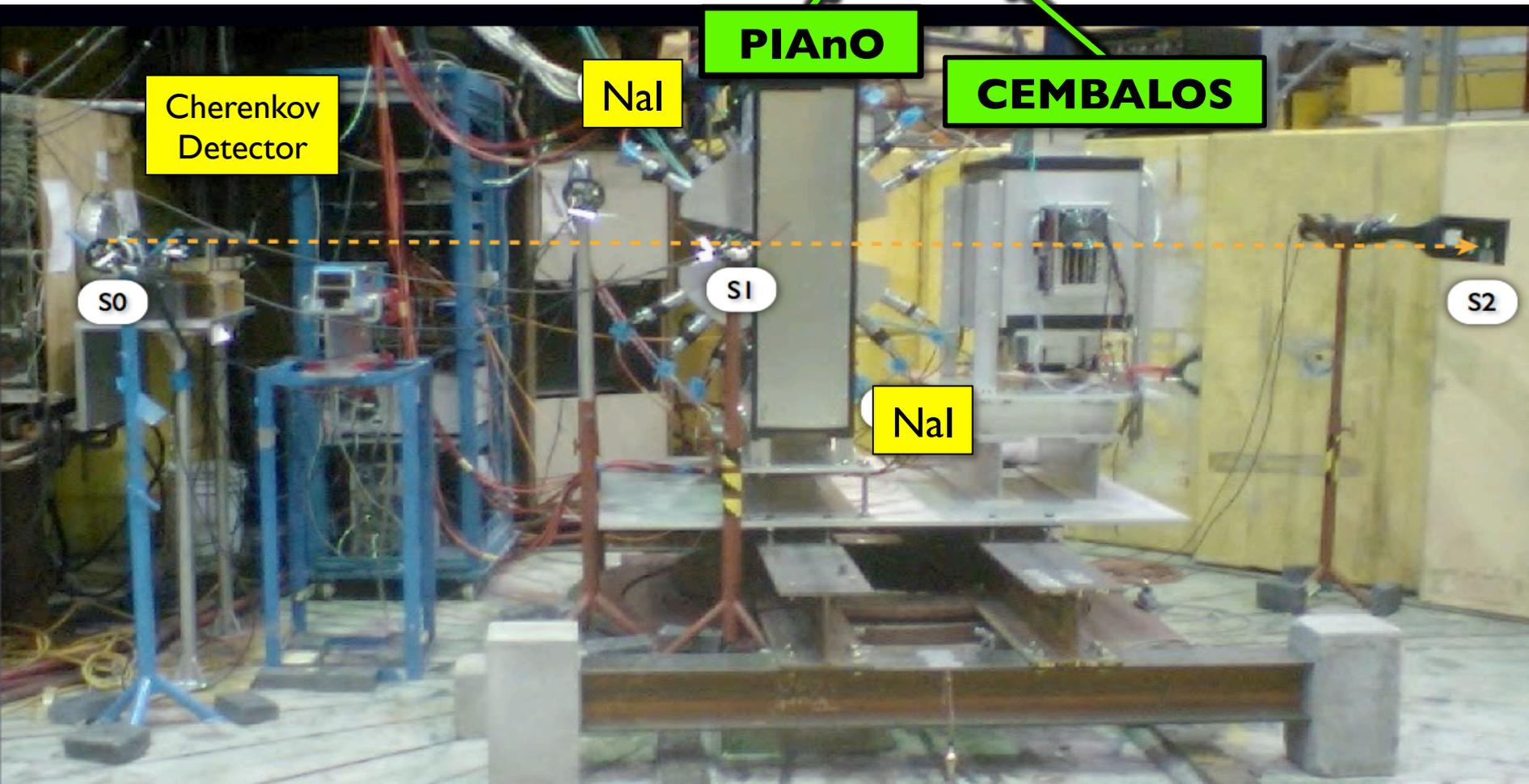


**CEMBALOS:** Miniature Fine Grained Detector

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

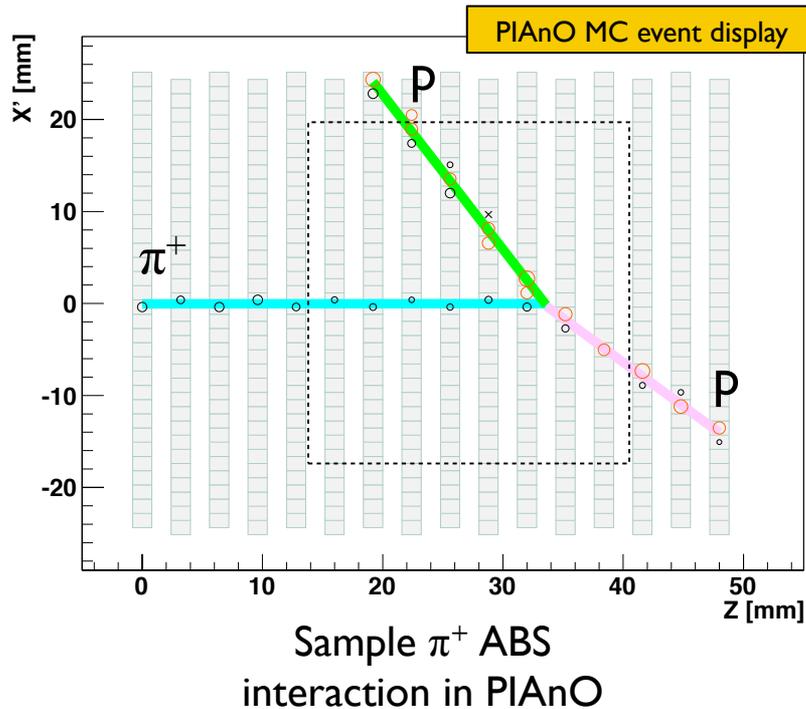


# Detector setup:



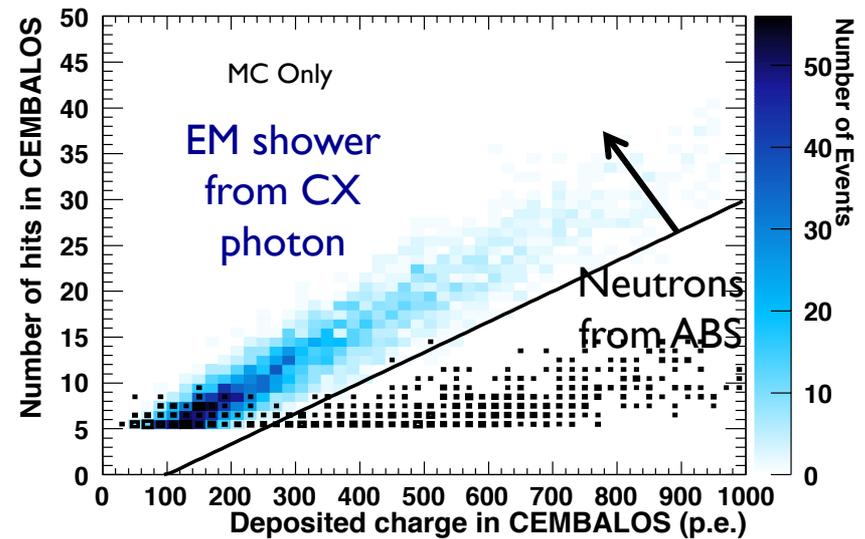
# PIAnO

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



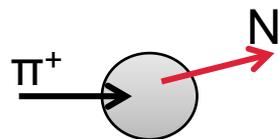
# CEMBALOS

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

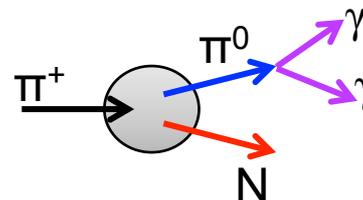


# Two DUET publications

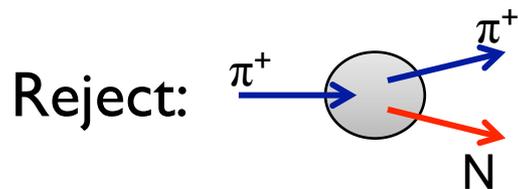
Absorption (Abs)



Charge Exchange (CX)



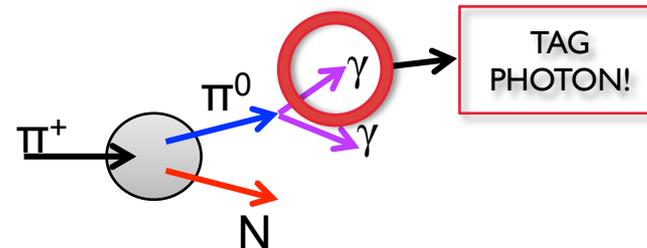
## 1. Combined ABS+CX using PIANO



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

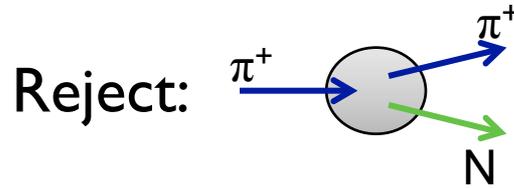
Presented at NuINT 2015

## 2. Separate ABS, CX using CEMBALOS



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

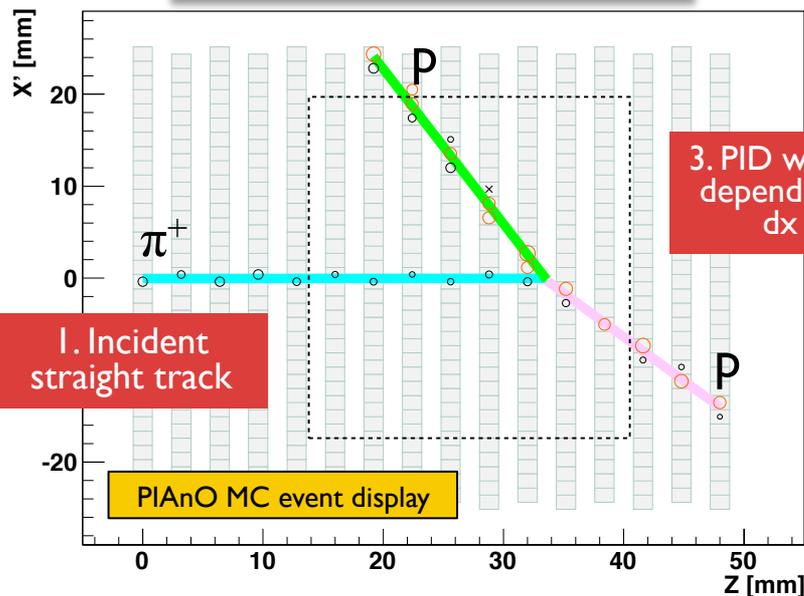
# Combined ABS+CX selection using PIAAnO



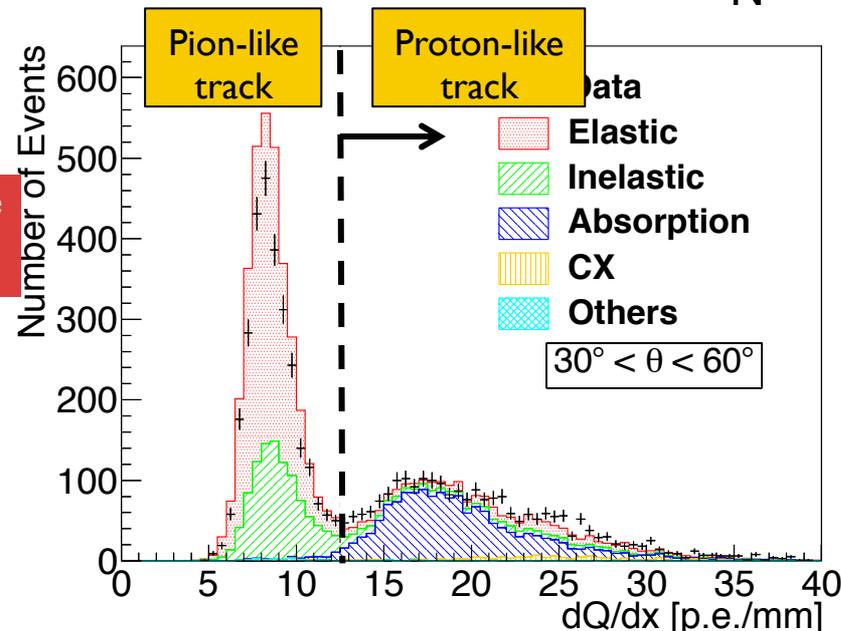
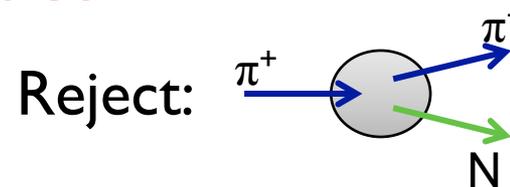
Phys. Rev. C **92**, 035205 (2015)

# Event Selection: No $\pi^+$ in final state

2. Vertex inside PIAAnO's Fiducial Volume



Sample  $\pi^+$  ABS interaction in PIAAnO



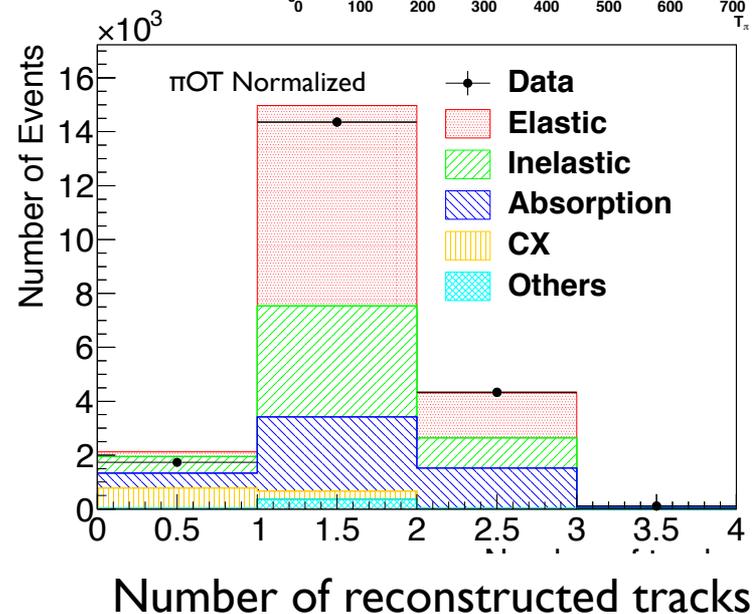
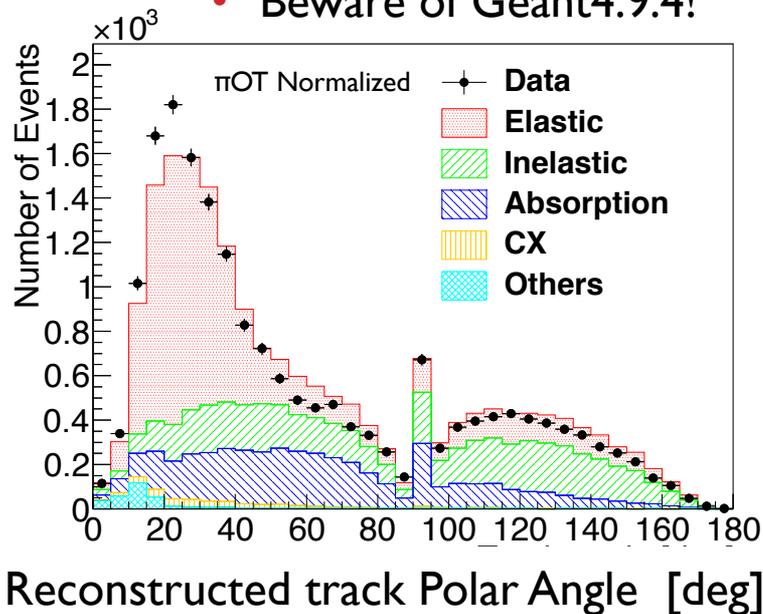
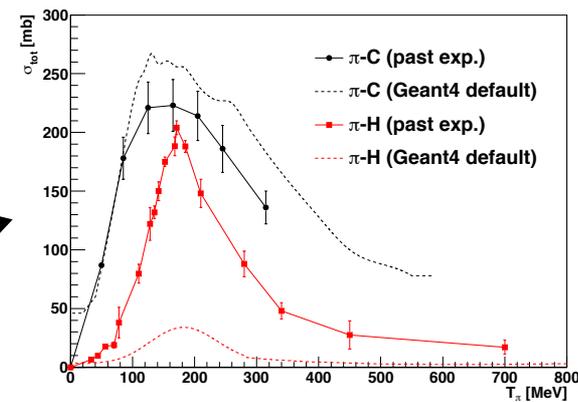
Example of  $dQ/dx$  distribution

# Event Selection: Data vs. MC comparisons

❖ Good agreement of distributions before applying the “no  $\pi^+$  in final state” cut:

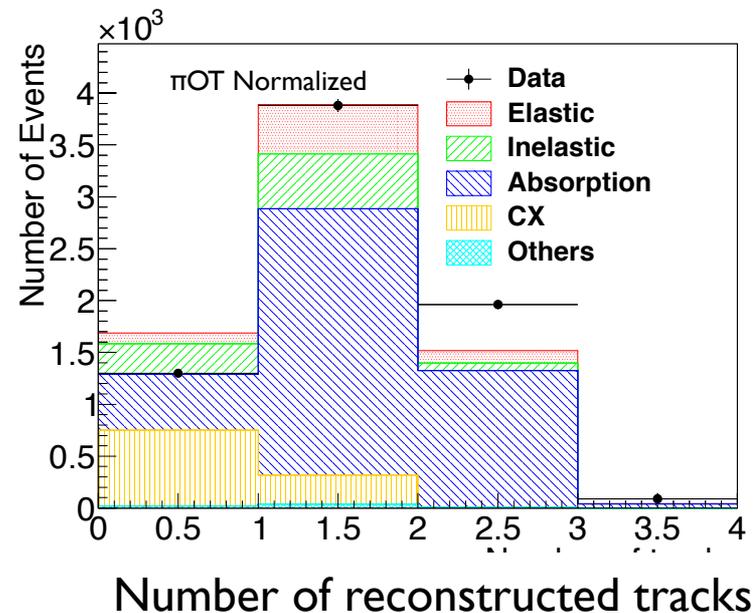
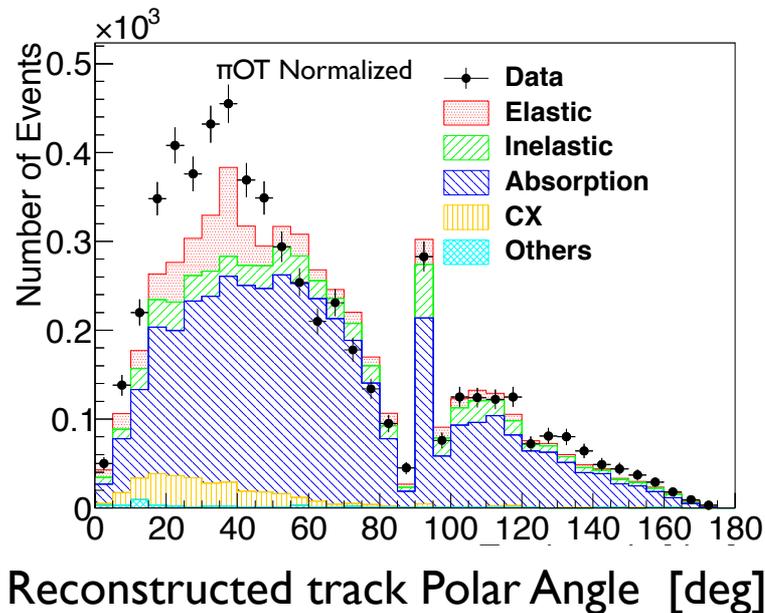
- Large Geant4 mis-modeling of  $^1\text{H}$  and  $^{12}\text{C}$  elastic interactions

• Beware of Geant4.9.4!



# Event Selection: Data vs. MC comparisons

- ❖ For 238MeV/c  $\pi^+$  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.

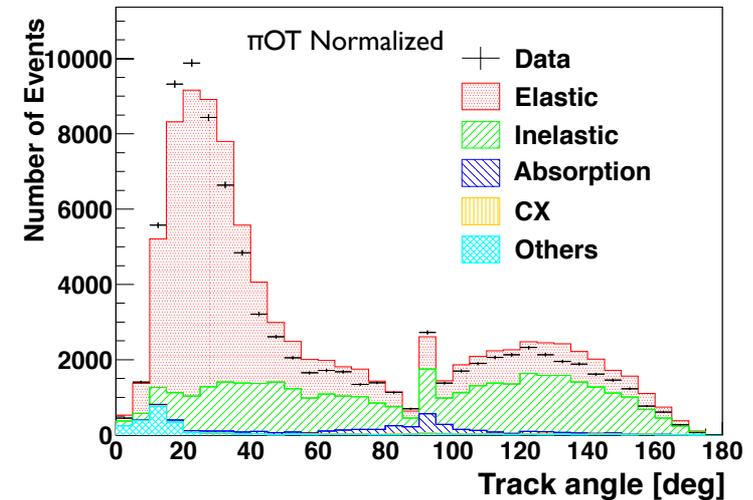


# Uncertainties

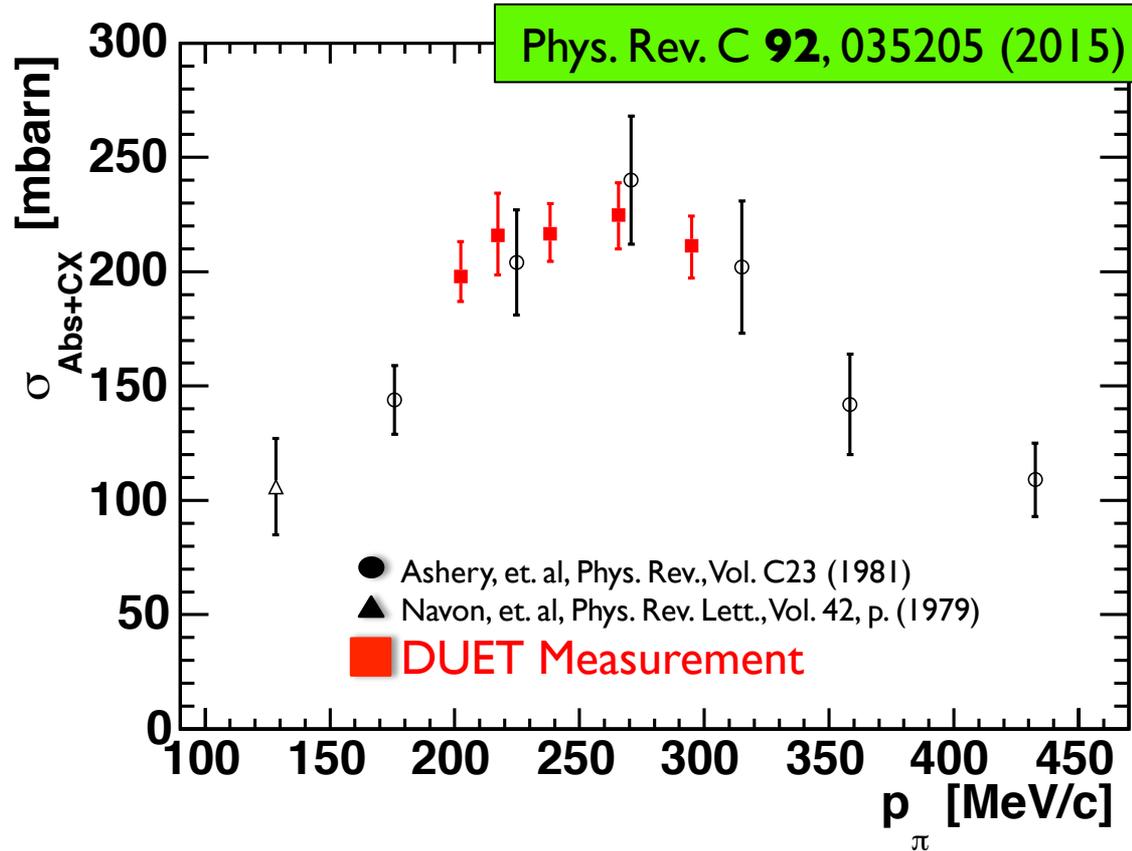
	$p_\pi$ at the fiber tracker [MeV/c]				
	201.6	216.6	237.2	265.5	295.1
<b>Systematic errors</b>					
Beam profile	0.9	1.2	1.0	0.6	1.2
Beam momentum	1.6	1.7	0.7	0.8	1.4
Fiducial Volume	1.1	3.9	1.4	1.2	1.3
Charge distribution	2.4	2.2	2.6	2.6	2.9
Crosstalk probability	0.3	0.3	0.3	0.2	0.4
Layer alignment	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
<b>Statistical error (data)</b>	1.7	3.1	1.7	1.8	1.7
<b>Statistical error (MC)</b>	0.1	0.1	0.1	0.1	0.1
<b>Total +</b>	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

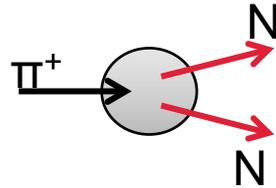


Good agreement and much smaller errors ( $\sim 20\% \rightarrow \sim 7\%$ )

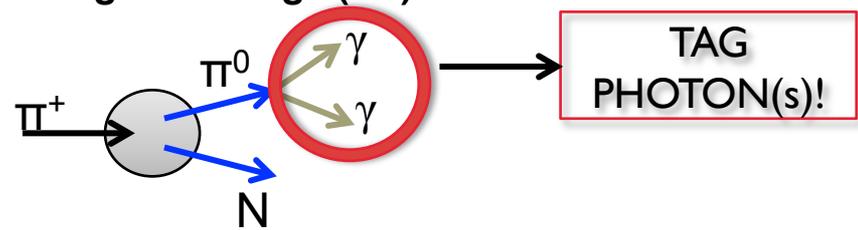
# Extracting the CX cross section

REJECT  
NUCLEONS

2. Absorption (Abs)



3. Charge Exchange (CX)



# Detector setup: DUET

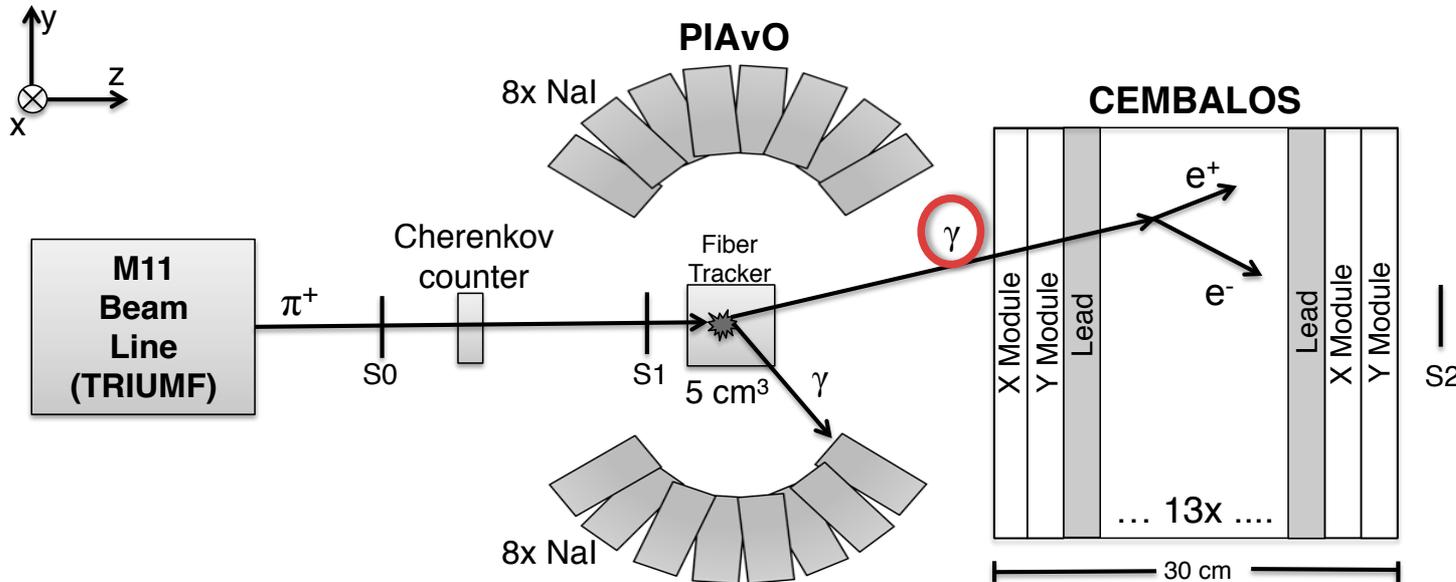
## ❖ Main Components:



**PIAnO**: 5 cm<sup>3</sup> scintillating fiber tracker (Full active target) + NaI crystals

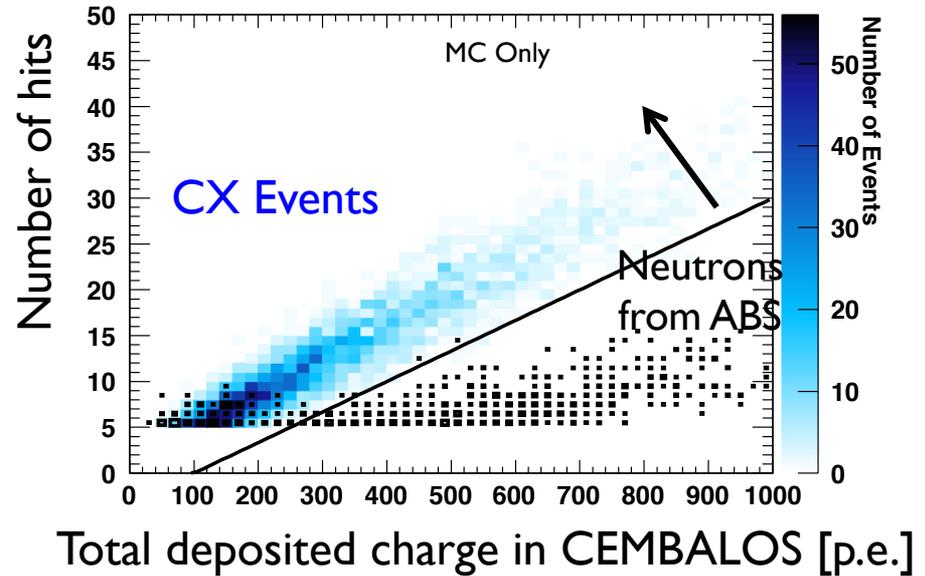


**CEMBALOS**: Miniature Fine Grained Detector (FGD from T2K)  
(Scintillating bars + Lead layers)



# CX Event Selection: Using CEMBALOS

- ❖ Judicious cuts to remove charged background:
  - QE  $\pi$  scatterings
  - Protons from ABS
  
- ❖ And neutral background
  - Neutrons from ABS
  - Gamma rays from nuclear de-excitation
  
- ❖ ~100 events selected for each momentum setting
  - ~20 for 216.6 MeV/c

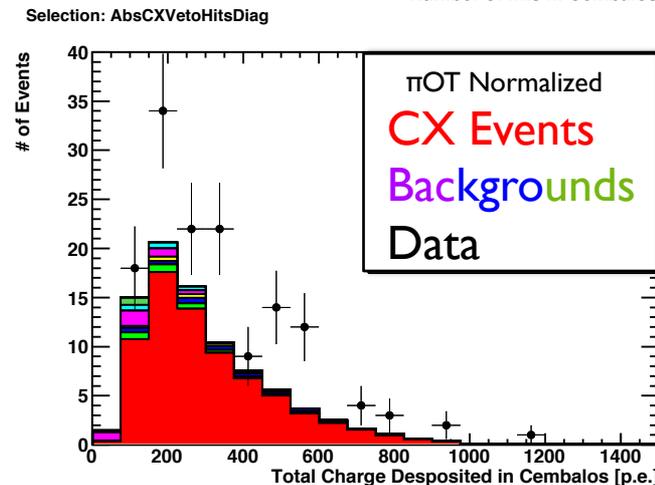
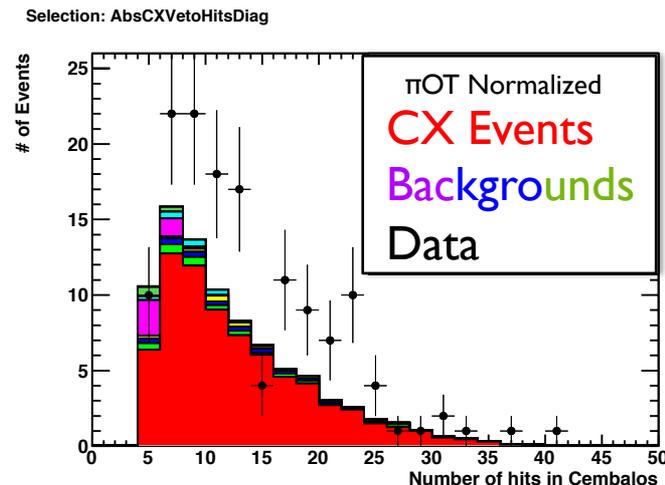
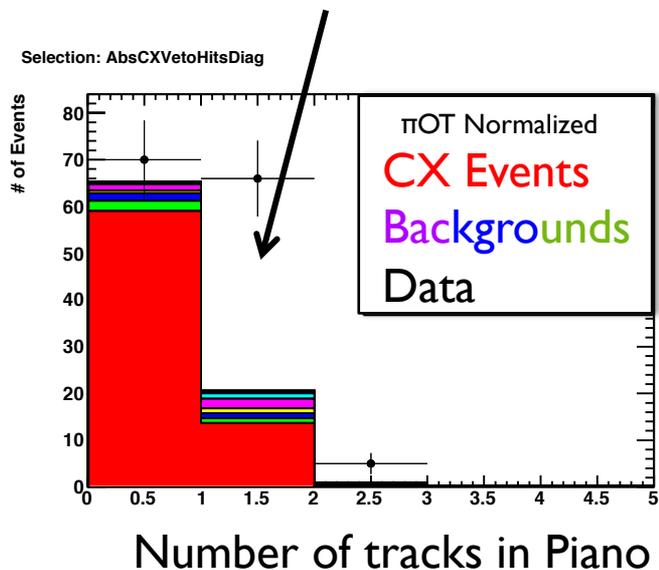


$$\text{Efficiency} = \frac{\text{Selected CX events}}{\text{True CX events}} \approx 6\%$$

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

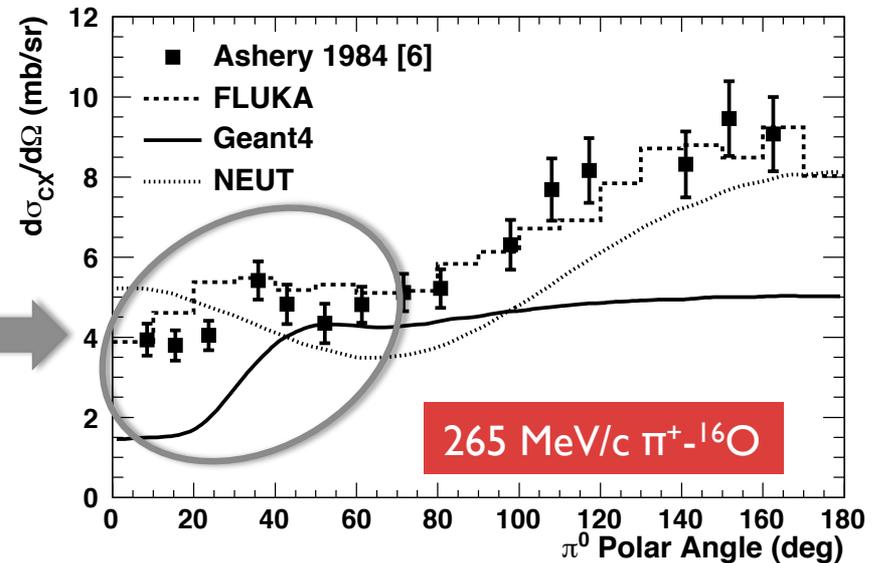
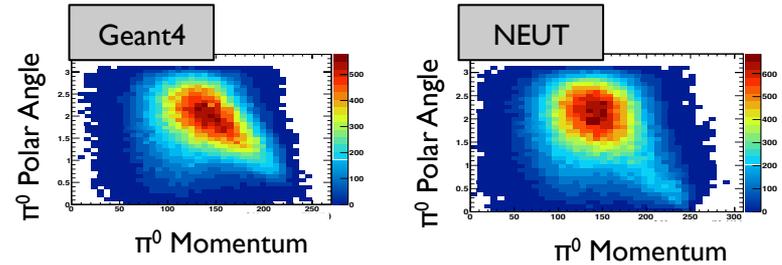
# CX Event Selection: Data vs. MC

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



# CX Modeling

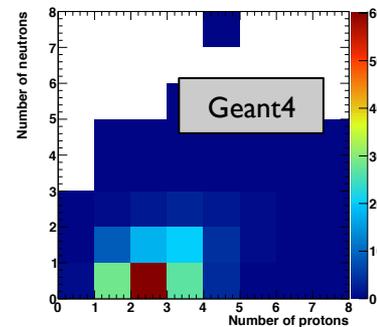
- ❖ The kinematics of the outgoing  $\pi^0$  is not well known
- ❖ Few differential cross section measurements
  - D.Ashery et al., “Inclusive pion single-charge-exchange reactions,” Phys. Rev. C, 30(3):946 (1984).
- ❖ Large discrepancy among models in the forward region, where CEMBALOS is more sensitive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



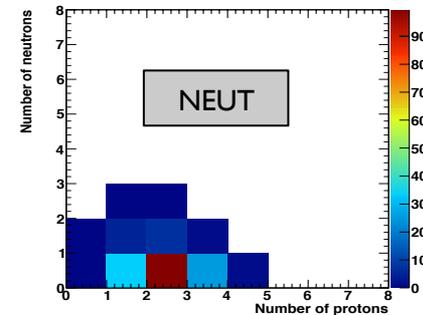
# Nucleon ejection (ABS background)

- ❖ 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  $\pi$ -{N,Ar} data
  
- ❖ High purity of CX selection means this effect is not dominant
  - But it still troubling

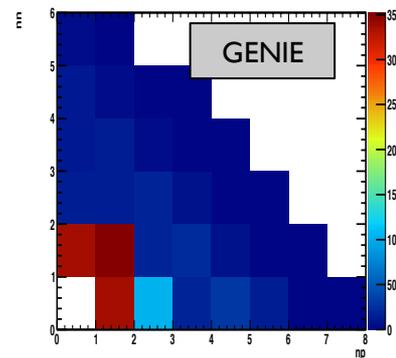
Nucleon Multiplicity GEANT4



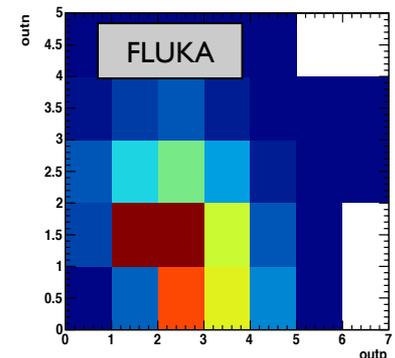
Nucleon Multiplicity NEUT



nn:np (probe\_fsi==4 || probe\_fsi==5)



Nucleon Multiplicity FLUKA



# Selecting the model

- ❖ Implemented a selection/rejection efficiency-based algorithm to switch from Geant4 to other models
- ❖ Large differences at low momentum
- ❖ Decided to use FLUKA as our nominal model for DUET result

$p_\pi$ [MeV/c]	Model	$\sigma_{CX}^{MC}$ [mb]	$N_{CX}^{MC}$	$N_{BG}^{MC}$	$\sigma_{CX}$ [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

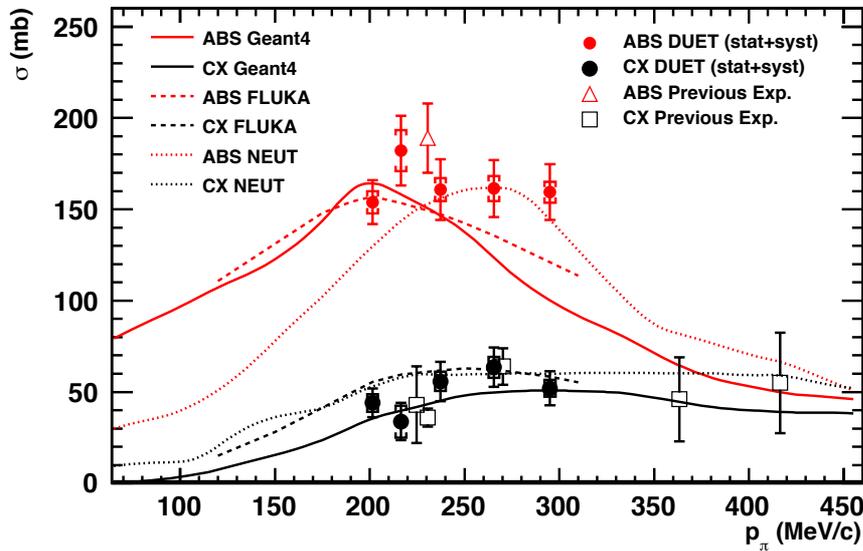
# Uncertainties

$\pi^+$ Momentum [MeV/c]	CX					ABS				
	201.6	216.6	237.2	265.5	295.1	201.6	216.6	237.2	265.5	295.1
<b>Beam Systematics</b>										
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
<b>Pi<math>\nu</math>o Systematics</b>										
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 efficiency	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
<b>Harpichord Systematics</b>										
Harpichord Charge	1.7	1.6	3.7	3.1	6.7	1.3	1.1	2.0	1.7	2.5
Harpichord Hit Inefficiency	1.6	2.1	1.1	1.3	2.0	1.2	1.1	1.1	1.0	0.9
Harpichord Alignment	7.7	7.9	8.3	5.7	4.6	0.7	1.0	0.7	0.7	1.0
<b>Physics Systematics</b>										
Ashery	6.1	6.9	7.9	9.4	10.6	2.1	1.6	3.2	4.3	4.1
Multiple Interactions	1.1	1.9	1.7	1.5	1.8	1.1	1.9	1.7	1.5	1.8
Pion Decay Background	1.9	2.8	1.2	0.6	0.9	1.9	2.8	1.2	0.6	0.9
<b>Statistical error</b>	11.0	26.0	9.4	8.9	8.8	3.9	6.2	3.9	4.2	3.6
<b>Total error</b>	17.9	30.3	19.4	17.0	18.0	8.0	11.0	10.5	9.8	9.8

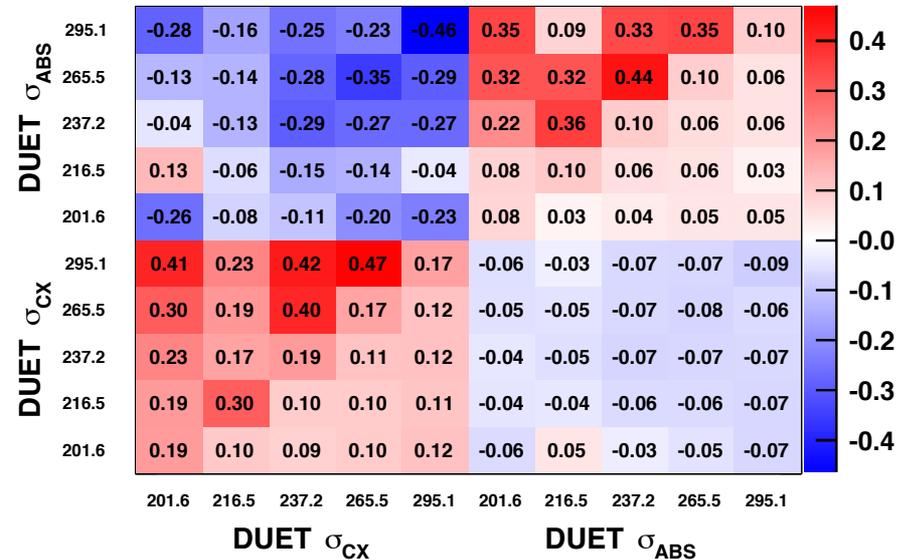
# ABS, CX Cross Section Result (2017)

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

Similarly sized error bars,  
but extended coverage in  $\Delta$  region



**Covariance Matrix:**  
Important for Fitting Models to Data



# 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

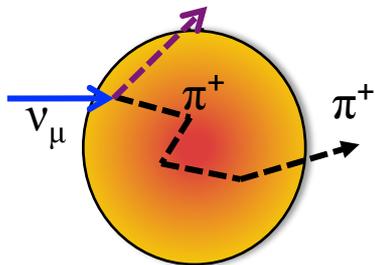
## Goal:

### 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  $\pi$ -A macroscopic cross sections ( $\sigma^{\text{NEUT}}$ ) depend on  $f_{\text{FSI}}$

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



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

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

# Summary of $\pi$ -A scattering data

❖ Total (integrated) and inclusive cross section data

## Data spanning five decades!

❖ 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  $\sim 100$  to 2000 MeV/c

Reference	Polarity	Targets	$p_\pi$ [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]	$\pi^-$	C, Al, Cu, Pb	531-615	REAC
F. Binon et al. [14]	$\pi^-$	C	219-395	REAC
O. Meirav et al. [15]	$\pi^+$	C, O	128-169	REAC
C. H. Q. Ingram [16]	$\pi^+$	O	211-353	QE
S. M. Levenson et al. [17]	$\pi^+$	C	194-416	QE
M. K. Jones et al. [18]	$\pi^+$	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]	$\pi^-$	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]	$\pi^+$	C	230	ABS
E. Bellotti et al. [25]	$\pi^+$	C	230	ABS
I. Navon et al. [26]	$\pi^+$	C, Fe	128	ABS+CX
R. H. Miller et al. [27]	$\pi^-$	C, Pb	254	ABS+CX
E. S. Pinzon Guerra et al. [28]	$\pi^+$	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 these 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

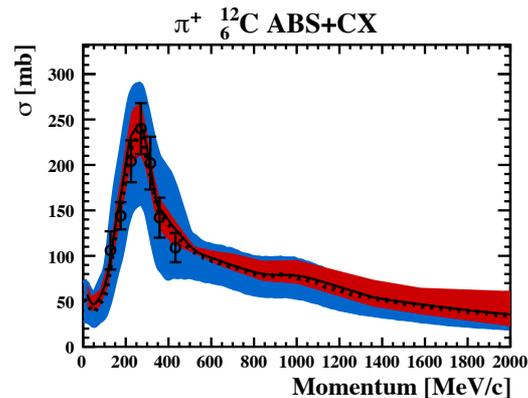
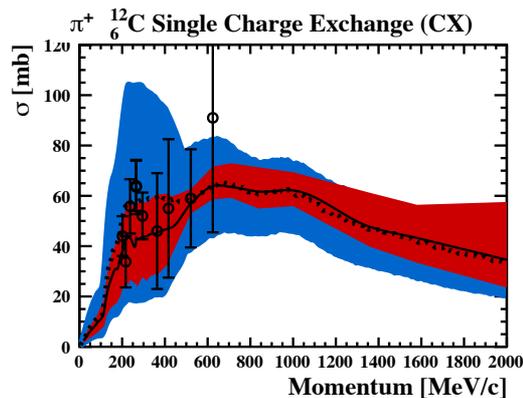
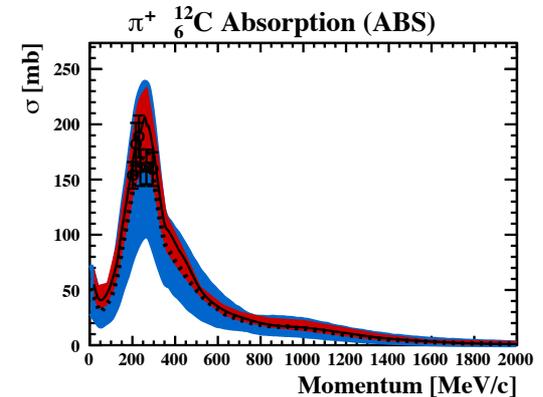
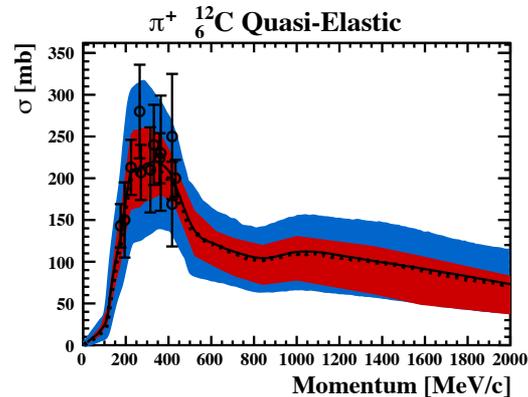
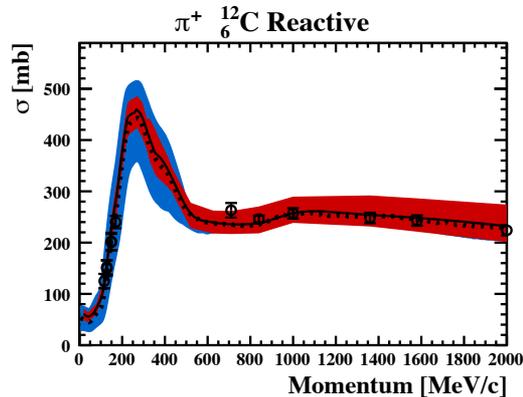
$$\chi^2 = \sum_i^{\text{Datasets}} \left( \sum_j^{n_i} \frac{1}{n_i} \left( \frac{\sigma_j^{\text{Data}} - \lambda_i^{-1} \sigma_j^{\text{NEUT}}(f_{FSI})}{\Delta \sigma_j^{\text{Data}}} \right)^2 + \left( \frac{\lambda_i - 1}{\epsilon} \right)^2 \right) + \sum_{i,j}^{10} (\sigma_i^{\text{DUET}} - \sigma_i^{\text{NEUT}}(f_{FSI})) (V_{ij}^{-1})^{\text{DUET}} (\sigma_j^{\text{DUET}} - \sigma_j^{\text{NEUT}}(f_{FSI}))$$

❖ An additional overall scaling factor was introduced to increase the coverage of the external data

❖ Minuit provides best fit and correlations

# Fit result ( $\pi^+ - {}^{12}_6\text{C}$ )

❖ Smaller error bands than previous tuning (includes some error scaling)



Previous Best fit (dashed)

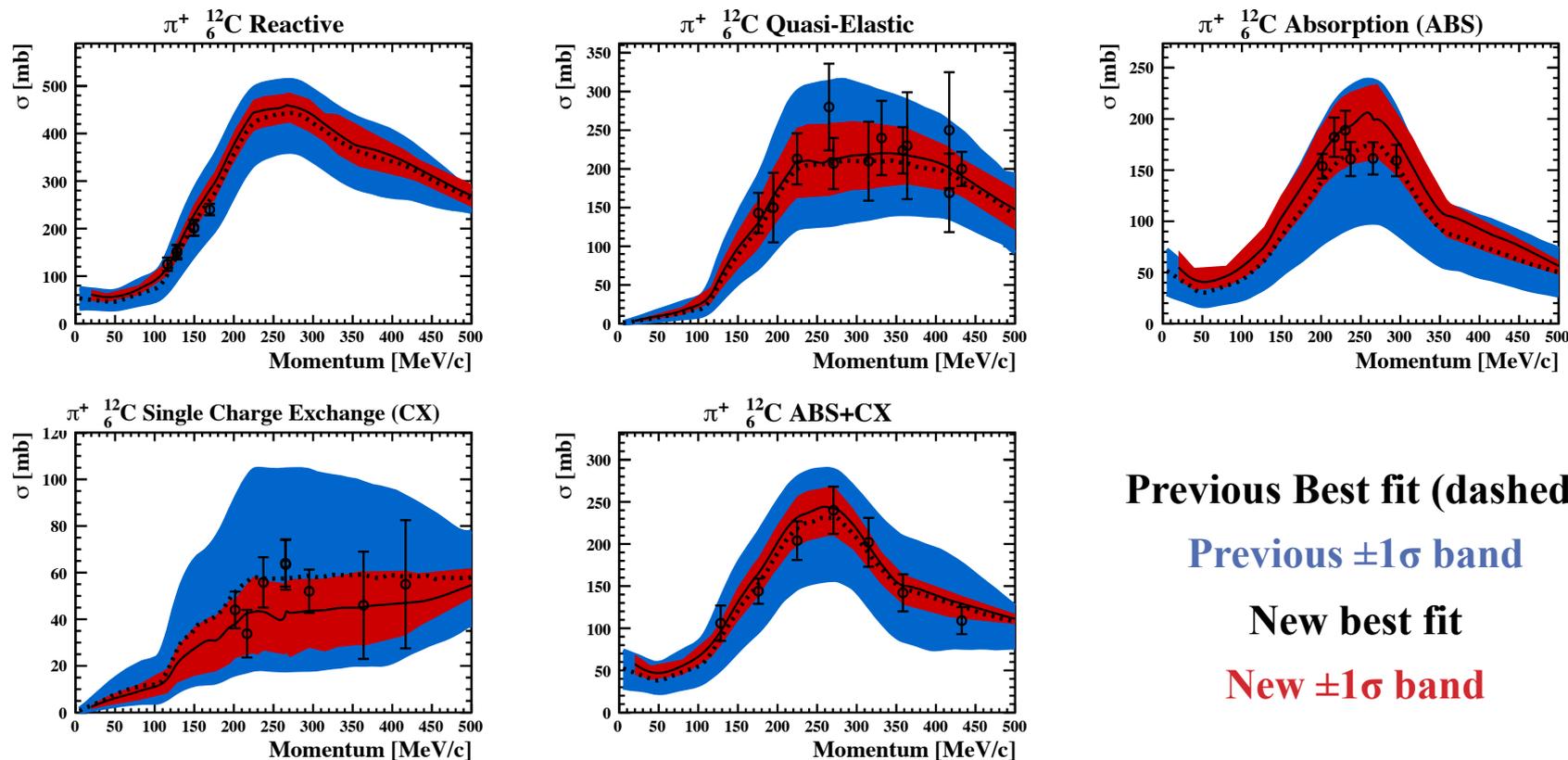
Previous  $\pm 1\sigma$  band

New best fit

New  $\pm 1\sigma$  band

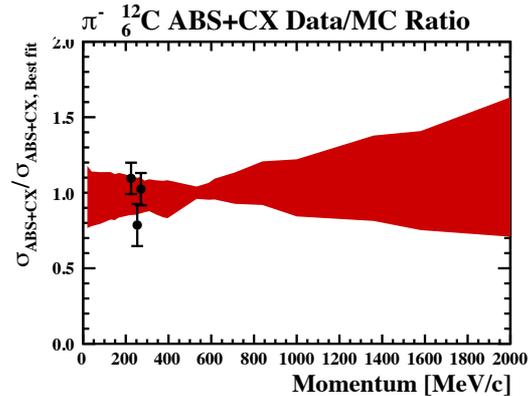
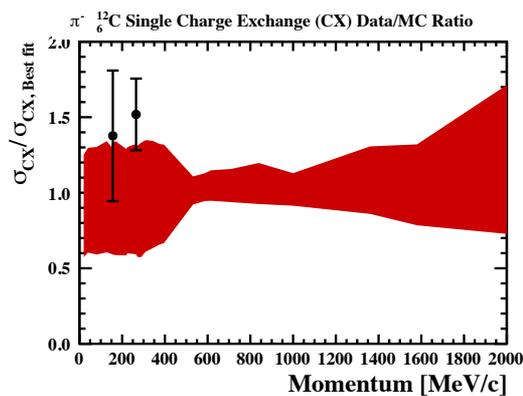
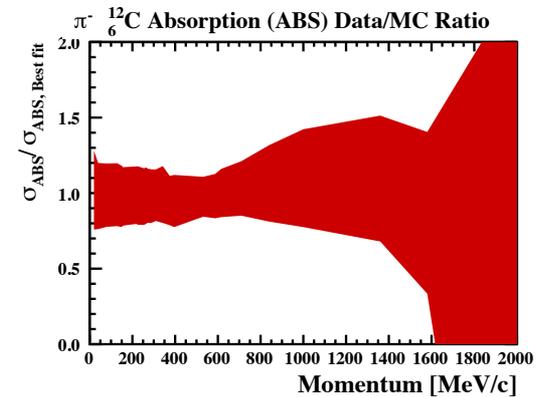
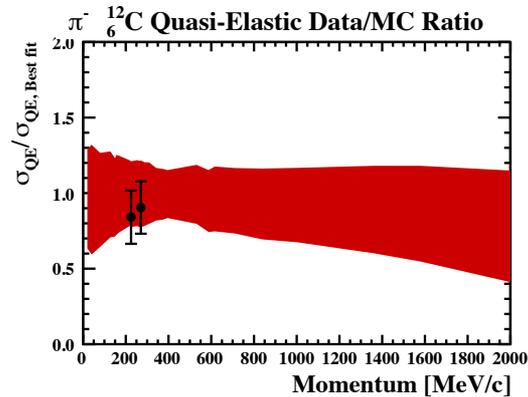
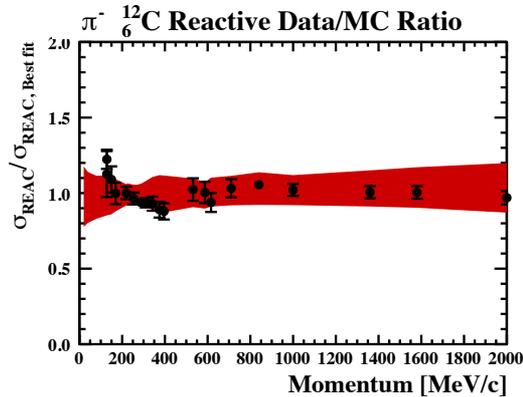
# Fit result ( $\pi^+ - {}^{12}_6\text{C}$ ) – 0 to 500 MeV/c

❖ Smaller error bands than previous tuning (includes some error scaling)



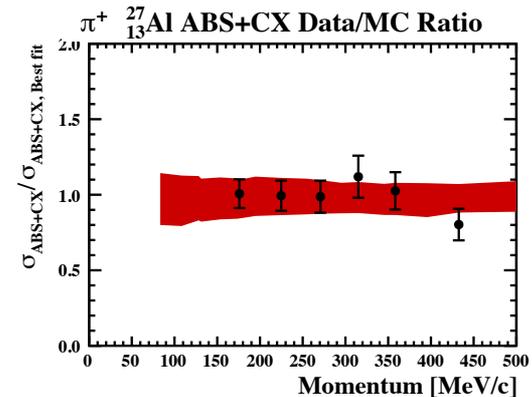
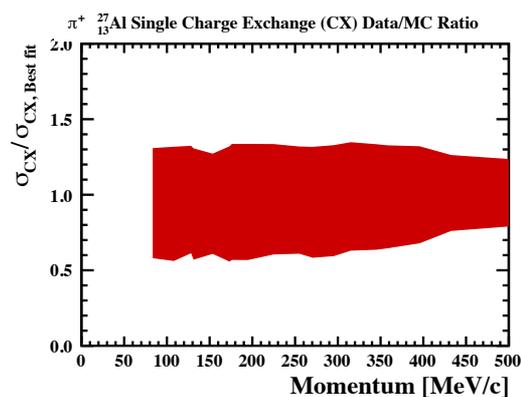
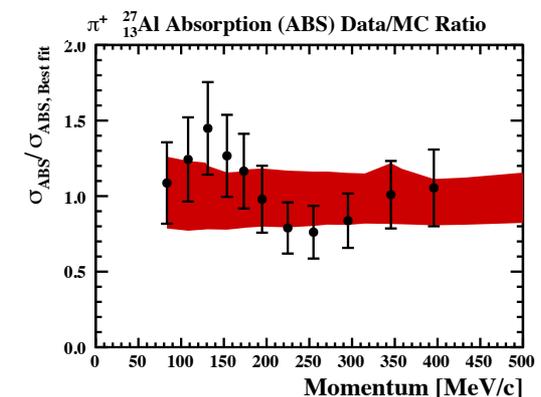
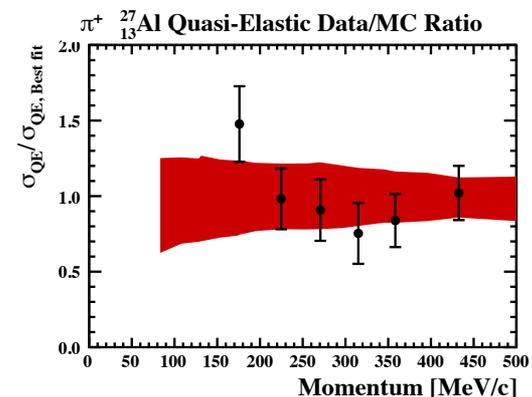
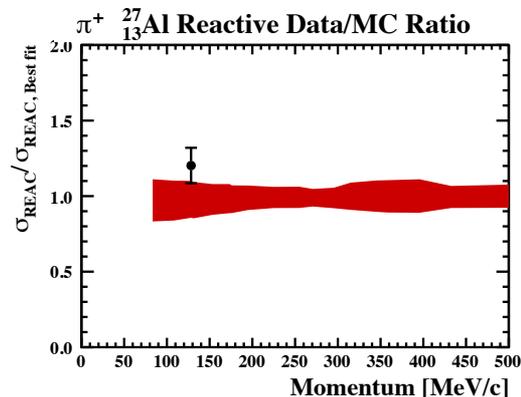
# Fit result ( $\pi^-$ - $^{12}_6\text{C}$ ) – Data/MC Ratio

❖ External data appropriately covered by uncertainty band



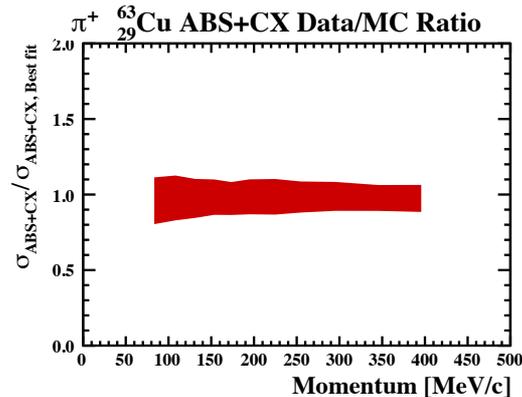
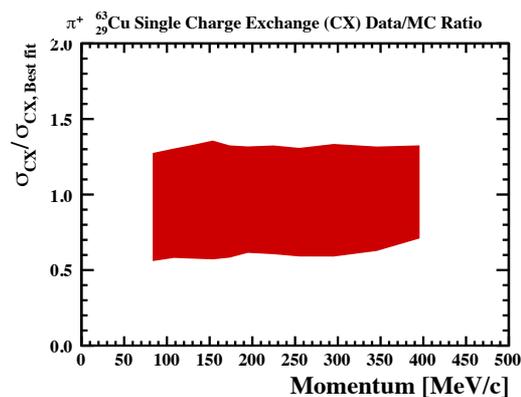
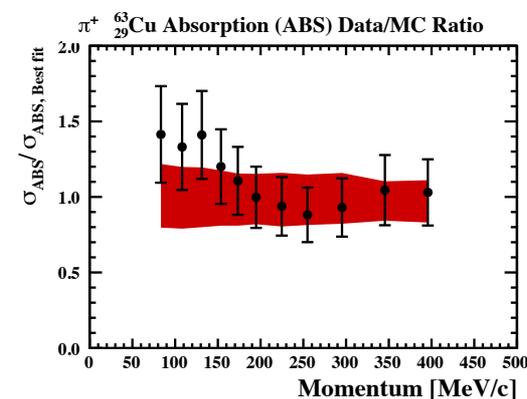
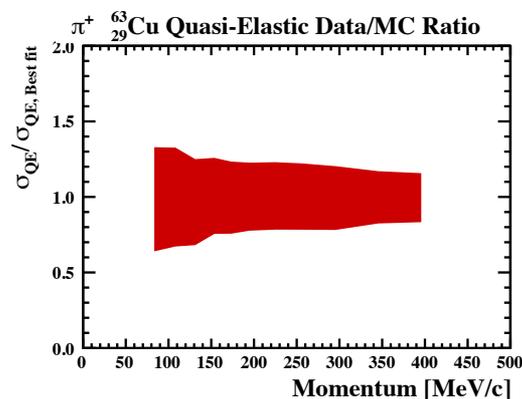
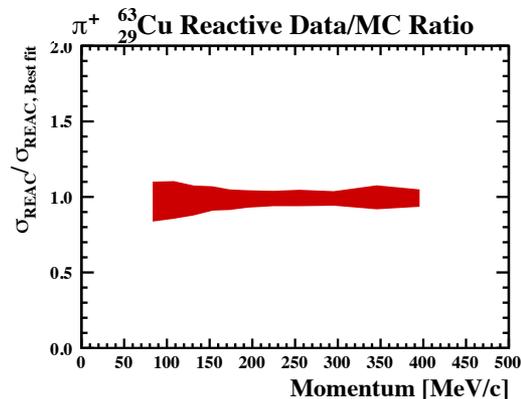
# Fit result ( $\pi^+$ - $^{27}_{13}\text{Al}$ ) – Data/MC Ratio

❖ External data appropriately covered by uncertainty band



# Fit result ( $\pi^+$ - $^{63}_{29}\text{Cu}$ ) – Data/MC Ratio

❖ External data appropriately covered by uncertainty band



Plan to use these  
reduced FSI errors  
for T2K 2018 results

# IDEAS FOR THE FUTURE

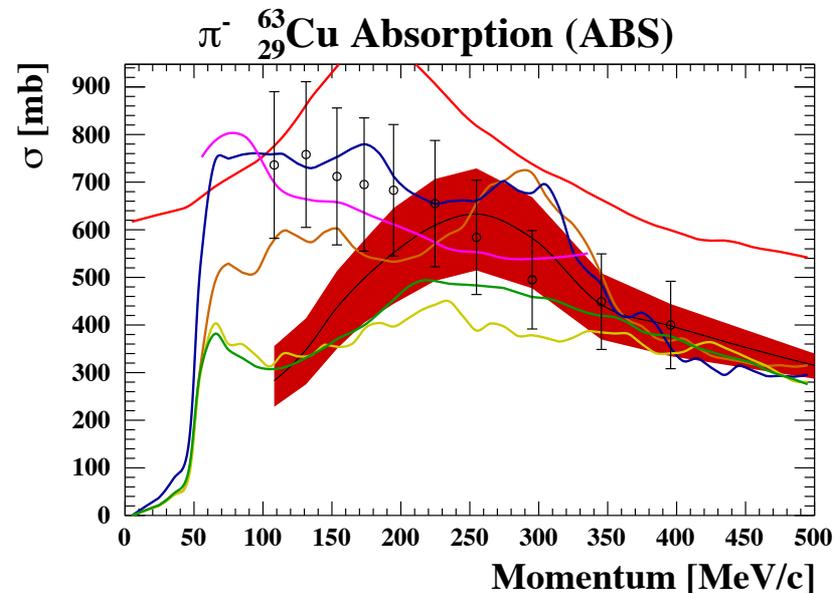
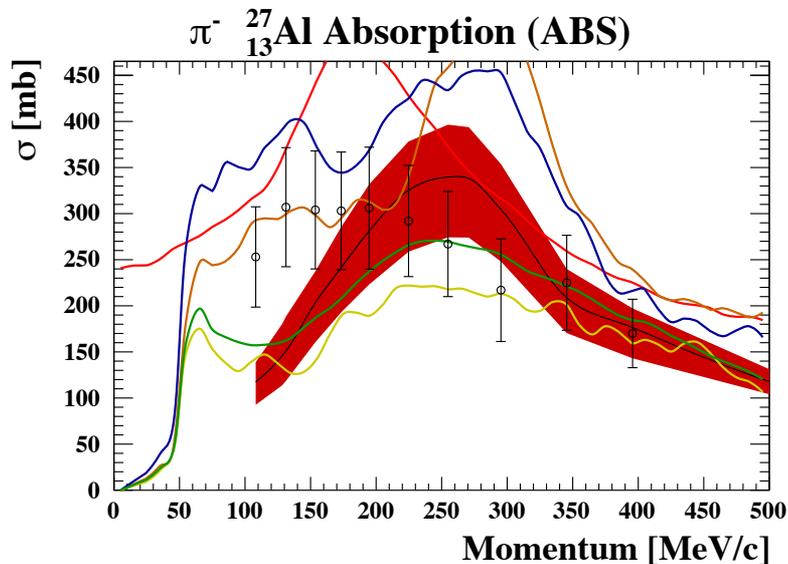
IMPROVEMENTS TO THE NEUT CASCADE MODEL

INVESTIGATE FSI VS. SI?

# NEUT Cascade Improvements

- ❖ Improve  $\pi$  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

NEUT 5.3.3	
Geant4 Bertini	(4.9.4)
GENIE hA	(2.12.4)
GENIE hA2014	(2.12.4)
GENIE hN2015	(2.12.4)
NuWro	(17.01.1)
FLUKA	(2011.2c.6)
GiBUU	(Phys. Rep. 512 (2012) 1-124)



# 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
  
- ❖  $\gamma A \rightarrow \pi$  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

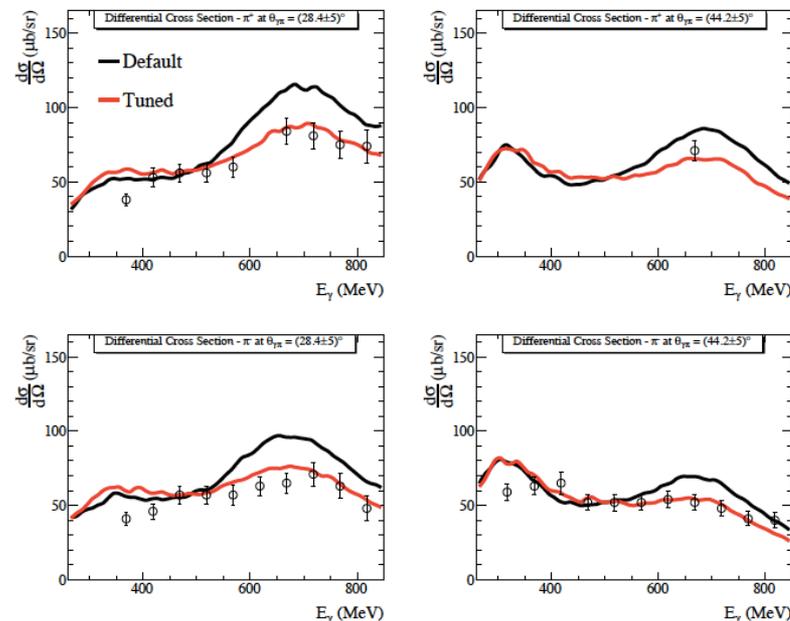


Figure 6.10: Default (black) and tuned (red) NEUT predictions for  $\frac{d\sigma}{d\Omega}$  of  $\pi^+$  (top) and  $\pi^-$  (bottom) photo-production from carbon, as a function of incoming photon energy. Two outgoing angles are considered:  $\theta_{\gamma\pi} = 28.4^\circ$  (left) and  $\theta_{\gamma\pi}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

# Summary

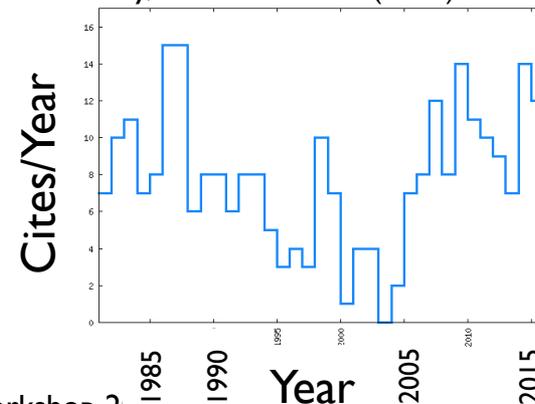
- ❖ Final State Interactions (FSI) and Secondary Interactions (SI) are important and difficult sources of systematic uncertainty for GeV neutrino experiments
- ❖ DUET measured  $\pi^+-^{12}\text{C}$  ABS and CX cross-sections
  - Phys. Rev. C **95**, 045203 (2017)
- ❖ Carried out a global fit to  $\pi$ -A scattering data
  - Will lead to reduced FSI and SI uncertainties in T2K analyses
- ❖ Pion photo-production could be a test bench for future improvements of cascade models

**BACKUP**

# $\pi$ -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  $\nu$  experiments!
    - **T2K**, NoVA, MiniBoone, Minerva, etc.

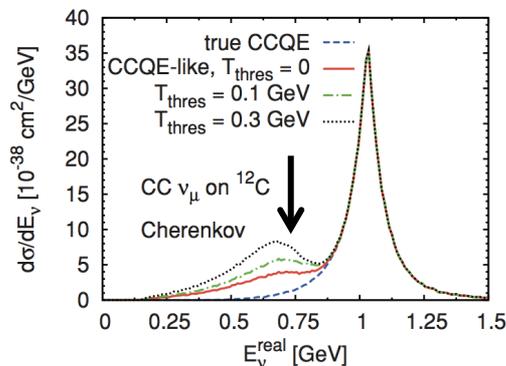
True Absorption and Scattering of Pions on Nuclei  
Ashery, D. et al. PRC 23 (1981) 2173-2185



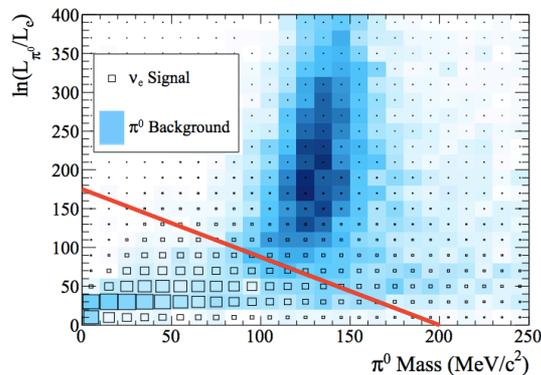
# Effects of $\pi$ FSI/SI

## 1. $E_\nu^{\text{rec}}$ smearing

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

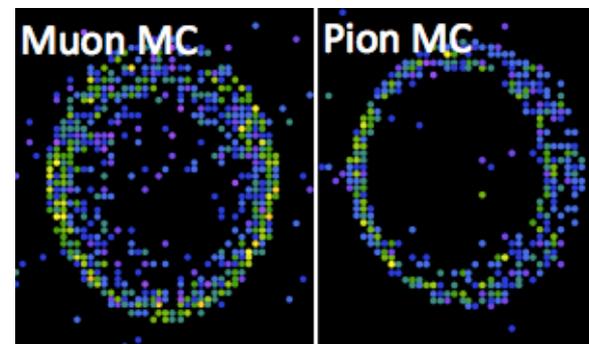


## 3. $\pi^0$ Background to $\nu_e$ appearance [PRL 112, 061802 (2014)]



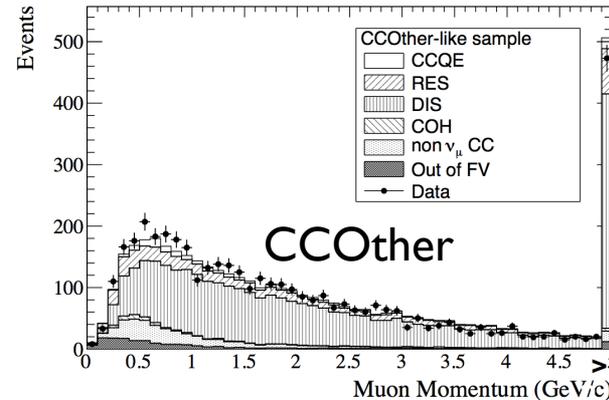
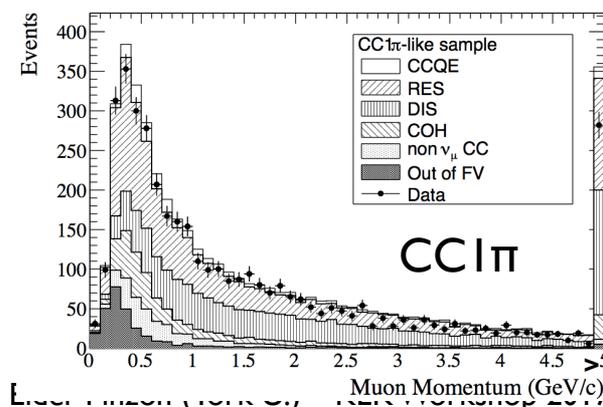
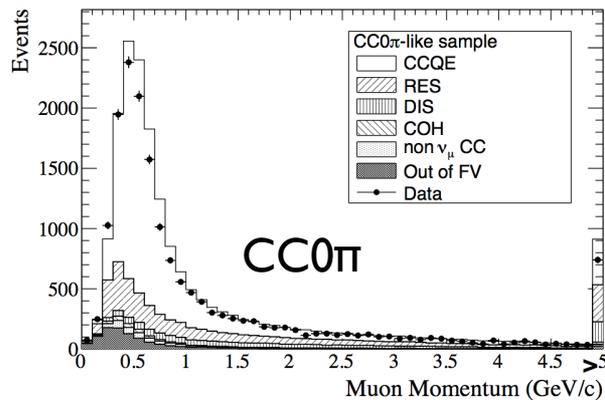
## 4. $\pi$ Reconstruction @ SK

“Identifying CC  $\pi$  at SK”, S. Berkman, CAP 2014



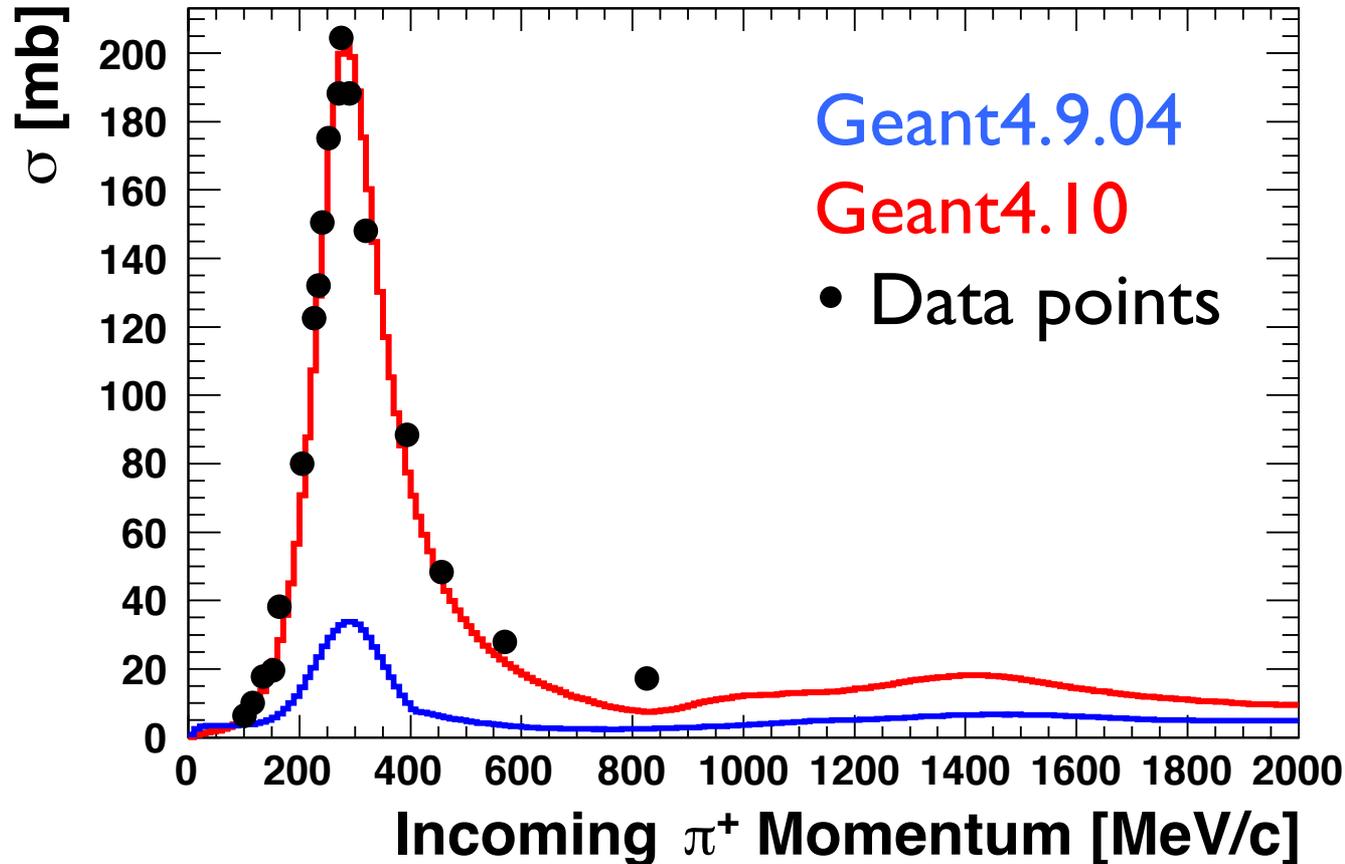
## 2. Selections based on Final State Topologies

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



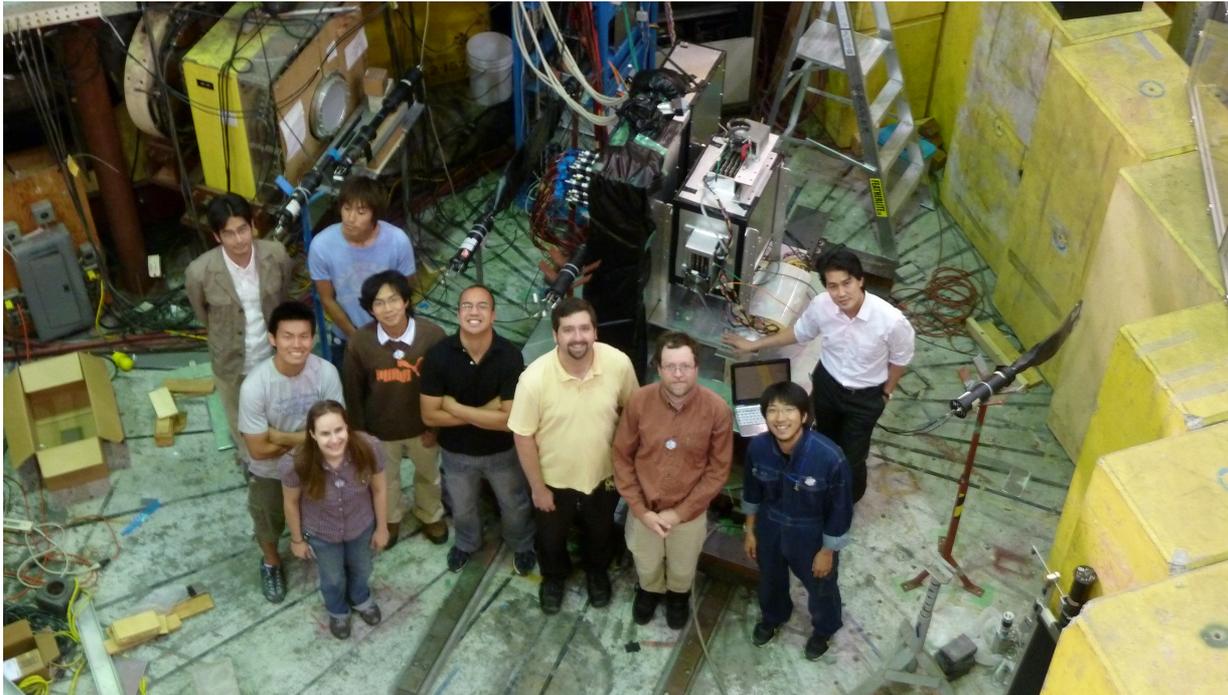
# Fixing $\pi$ -A elastic modeling

$\pi^+$ -H Elastic Scattering



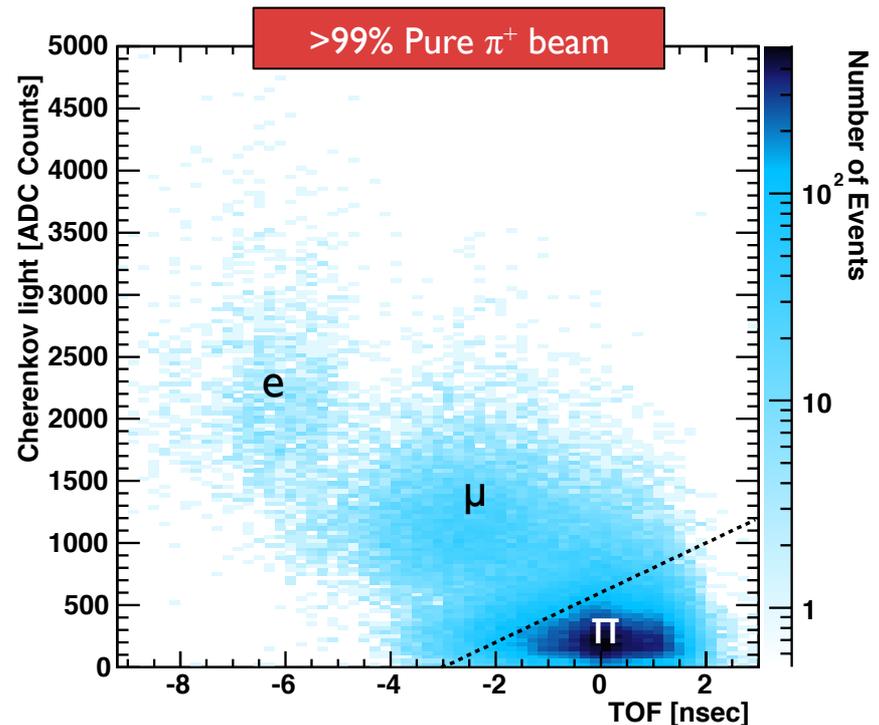
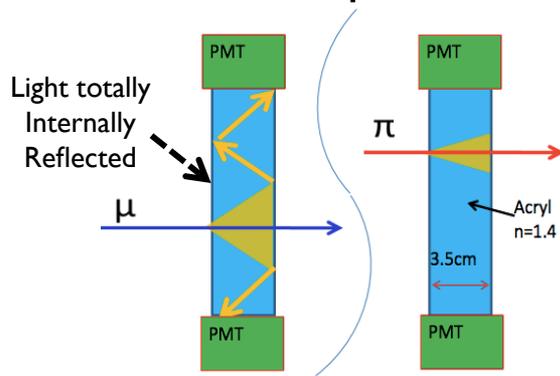
# DUET Collaboration

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



# TRIUMF M11 Beam line

- ❖ M11 secondary beam line delivered e,  $\mu$ , p and  $\pi$  with momentum tunable in the range from 150 MeV/c to 375 MeV/c.
- ❖ Recorded data at 5  $\pi^+$  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.

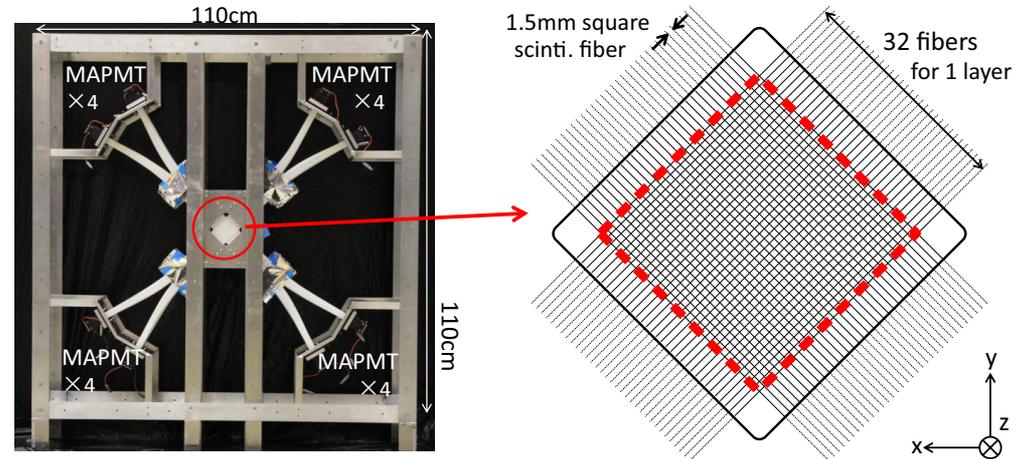


# PIAnO Fibers

- ❖ 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 TiO<sub>2</sub> fiber coating and support structure

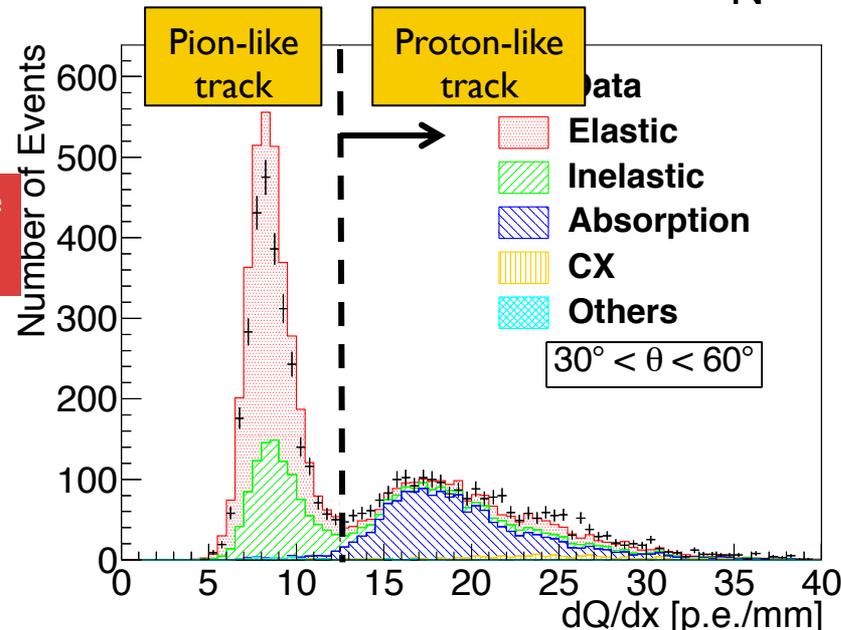
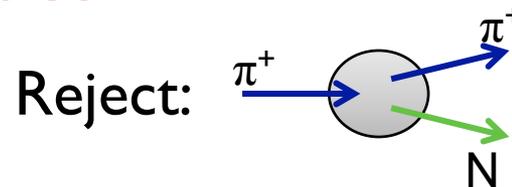
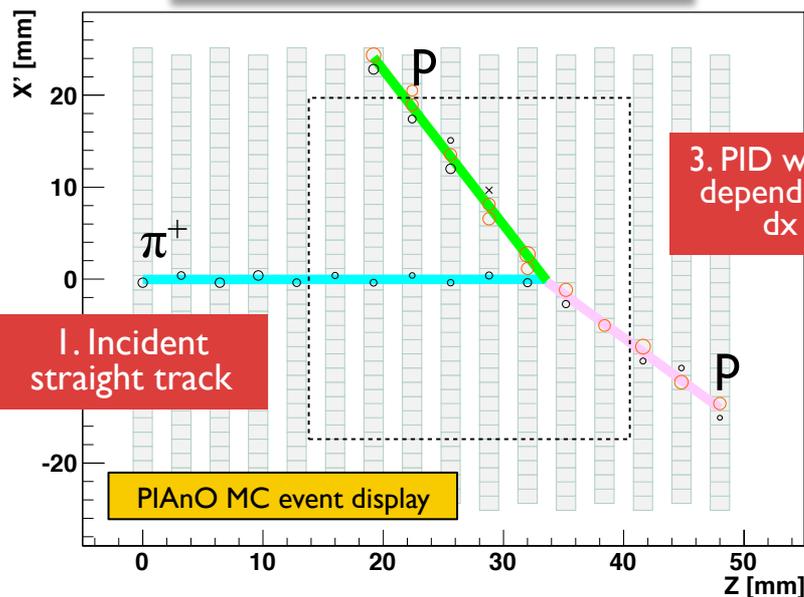


## (Pion detector for Analysis of neutrino Oscillation)



# Event Selection: No $\pi^+$ in final state

2. Vertex inside PIAAnO's Fiducial Volume



Example of  $dQ/dx$  distribution

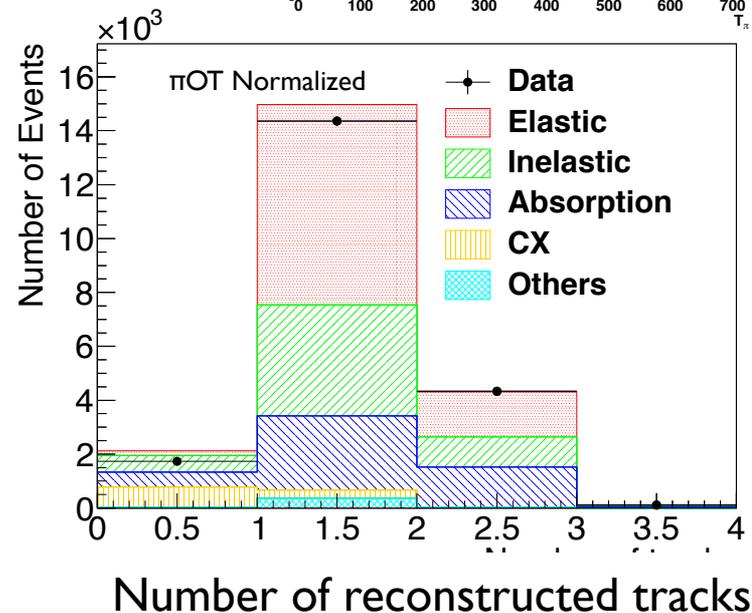
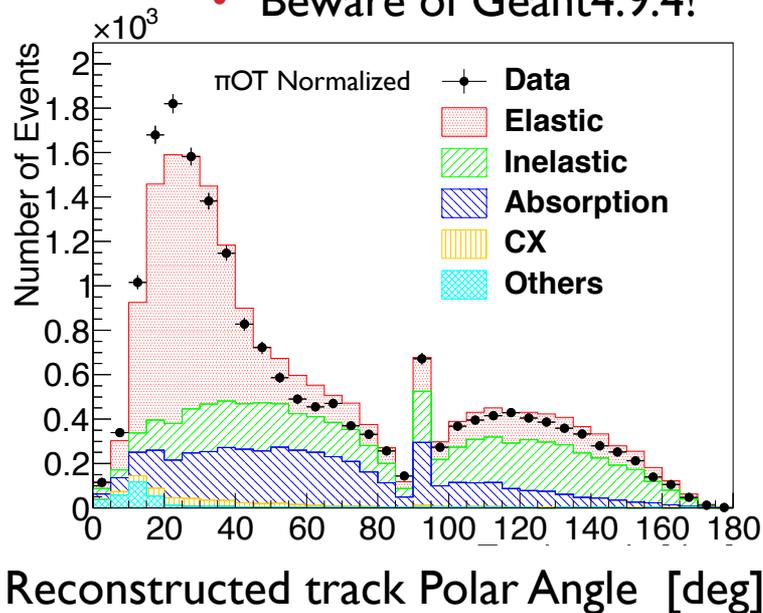
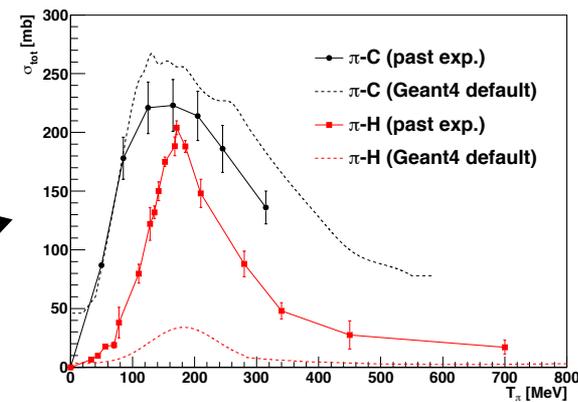
Sample  $\pi^+$  ABS interaction in PIAAnO

# Event Selection: Data vs. MC comparisons

❖ Good agreement of distributions before applying the “no  $\pi^+$  in final state” cut:

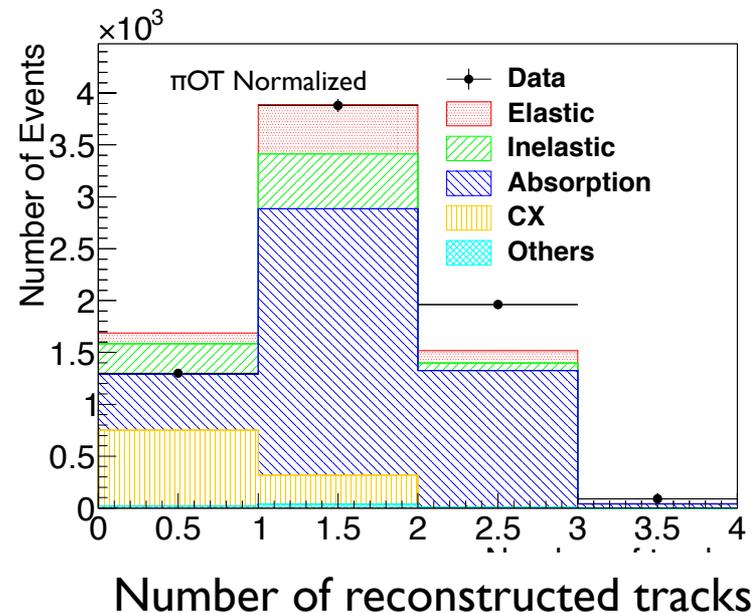
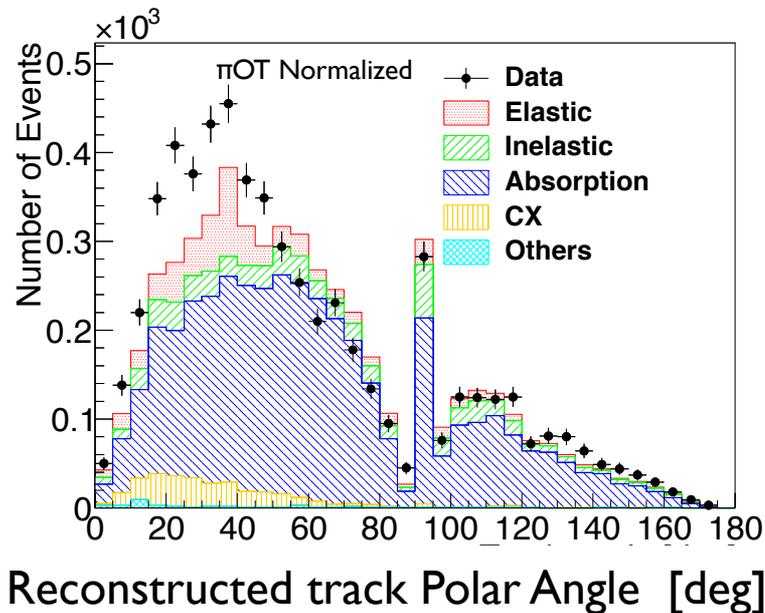
- Large Geant4 mis-modeling of  $^1\text{H}$  and  $^{12}\text{C}$  elastic interactions

• Beware of Geant4.9.4!



# Event Selection: Data vs. MC comparisons

- ❖ For 238MeV/c  $\pi^+$  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.

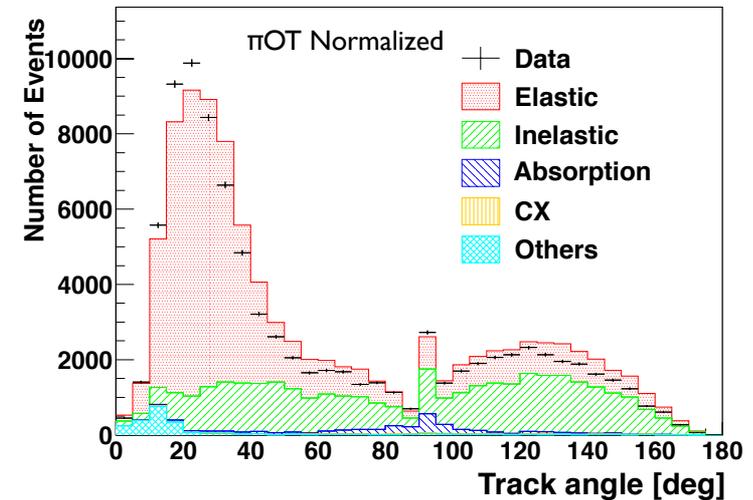


# Uncertainties

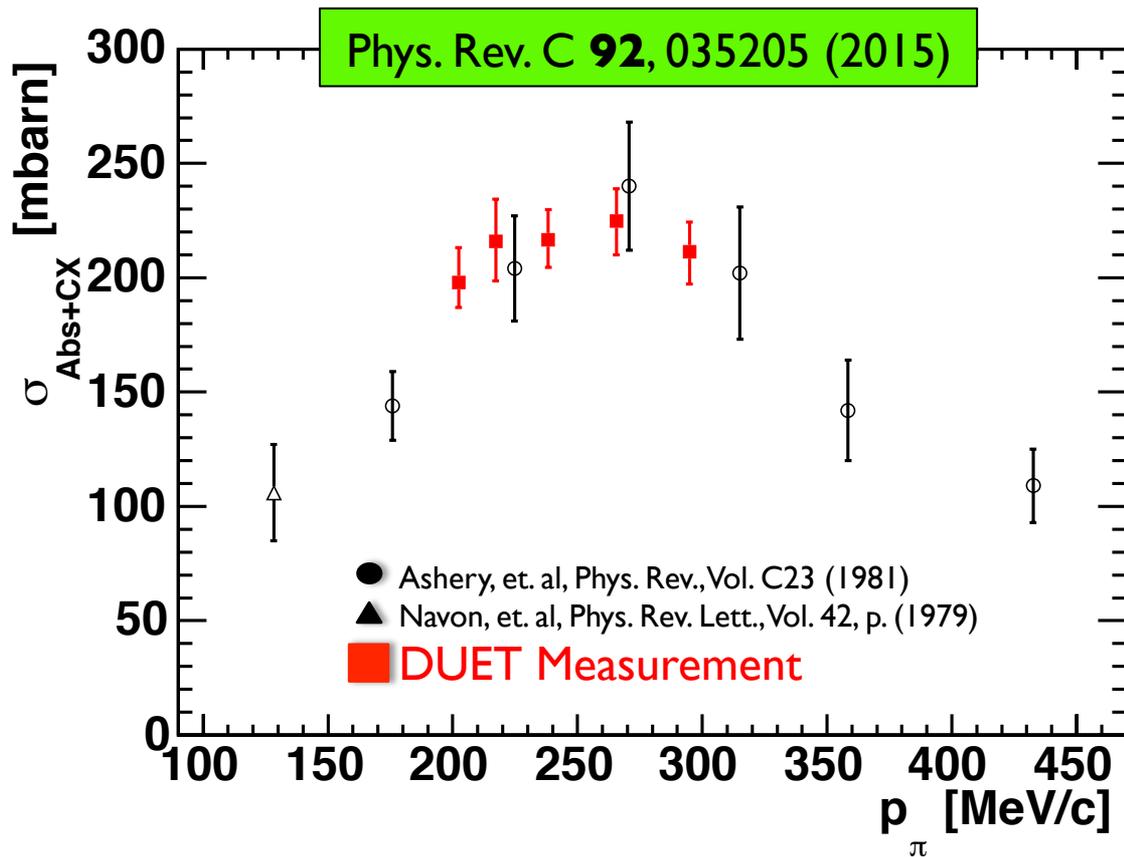
	$p_\pi$ at the fiber tracker [MeV/c]				
	201.6	216.6	237.2	265.5	295.1
<b>Systematic errors</b>					
Beam profile	0.9	1.2	1.0	0.6	1.2
Beam momentum	1.6	1.7	0.7	0.8	1.4
Fiducial Volume	1.1	3.9	1.4	1.2	1.3
Charge distribution	2.4	2.2	2.6	2.6	2.9
Crosstalk probability	0.3	0.3	0.3	0.2	0.4
Layer alignment	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
<b>Statistical error (data)</b>	1.7	3.1	1.7	1.8	1.7
<b>Statistical error (MC)</b>	0.1	0.1	0.1	0.1	0.1
<b>Total +</b>	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 ( $\sim 20\% \rightarrow \sim 7\%$ )

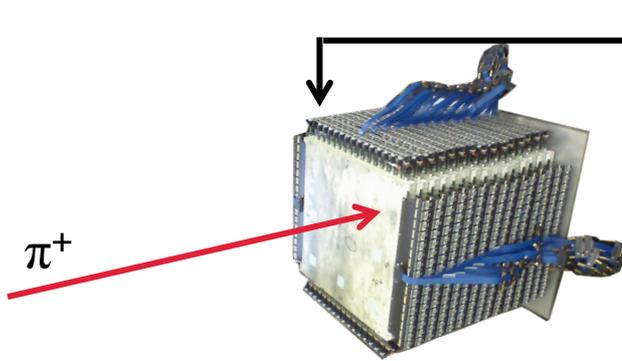
# CEMBALOS

- ❖ 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: “Harpichord”
  - **HA**dron **R**econstruction **CH**ordance **S**tudies **I**n **CH** **O**n **R**educed **D**etector

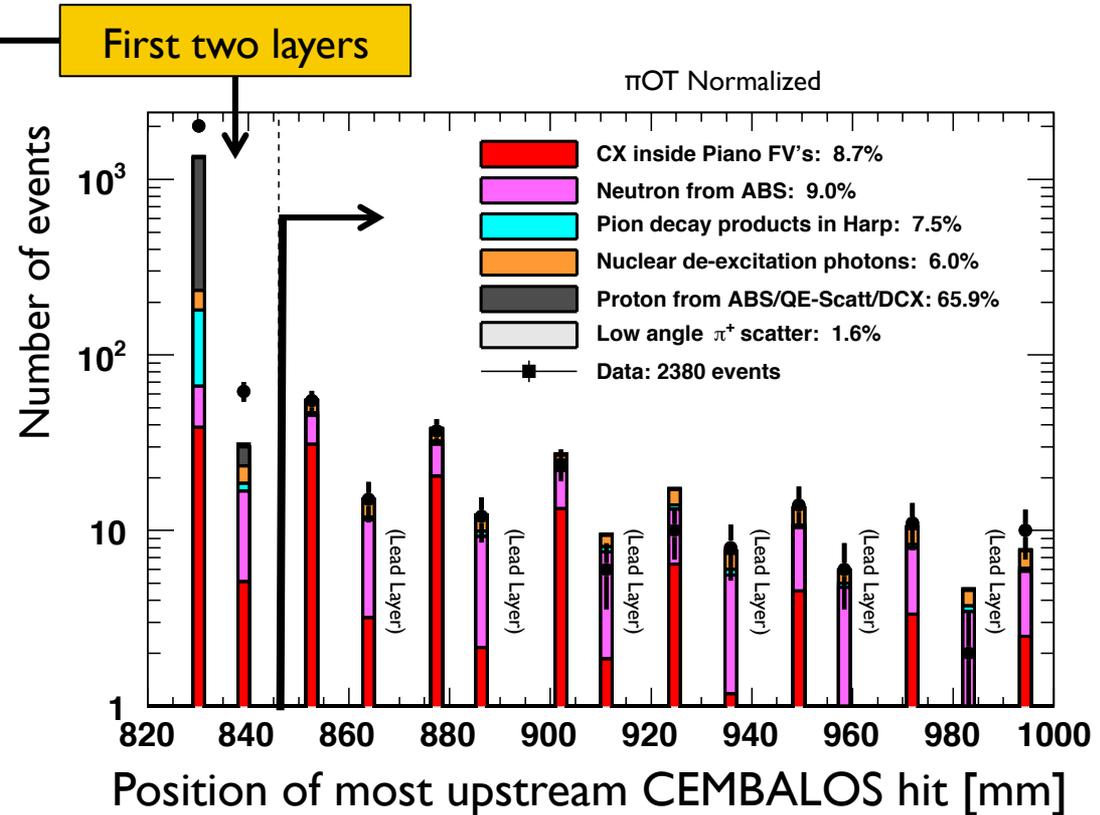
(Charge Exchange Measurement By A Lead On Scintillator)



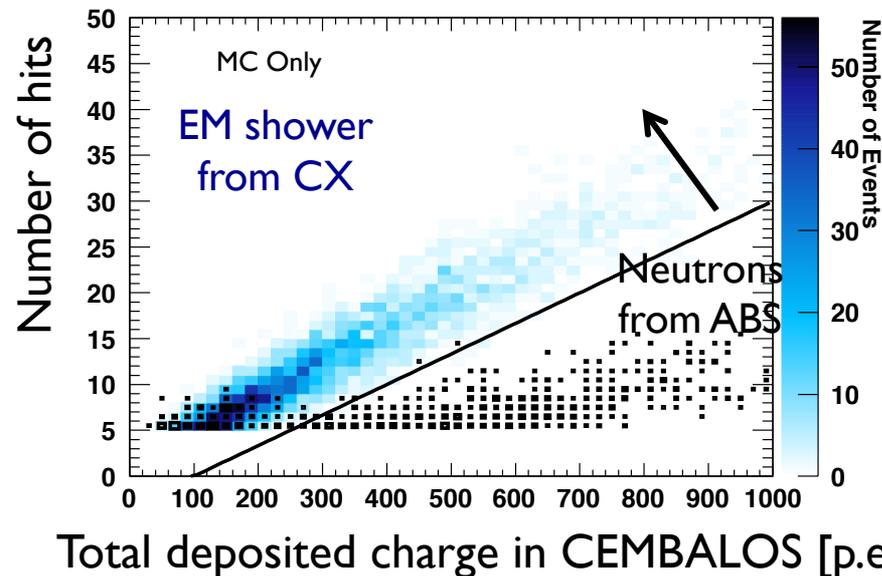
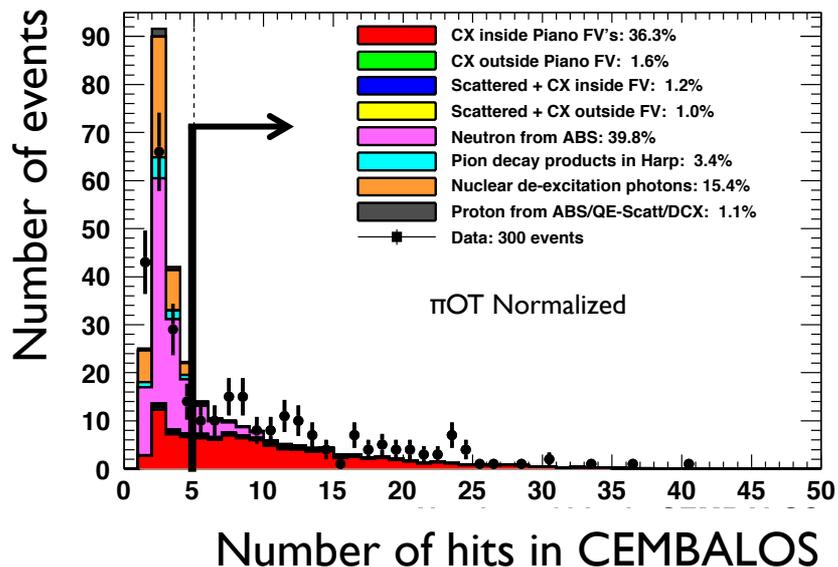
# CX Event Selection: Using CEMBALOS



- 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

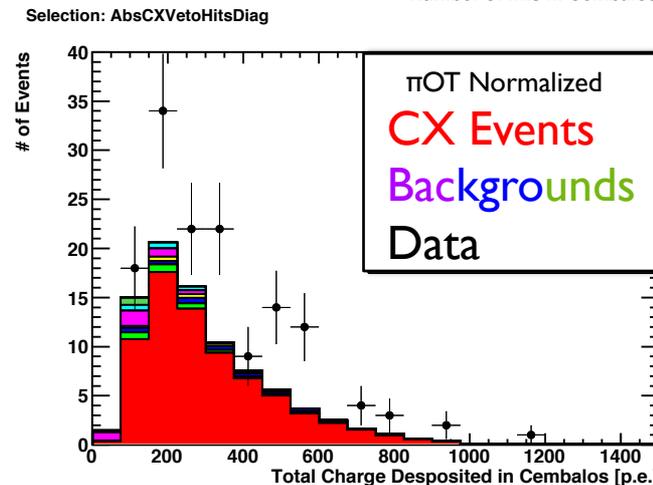
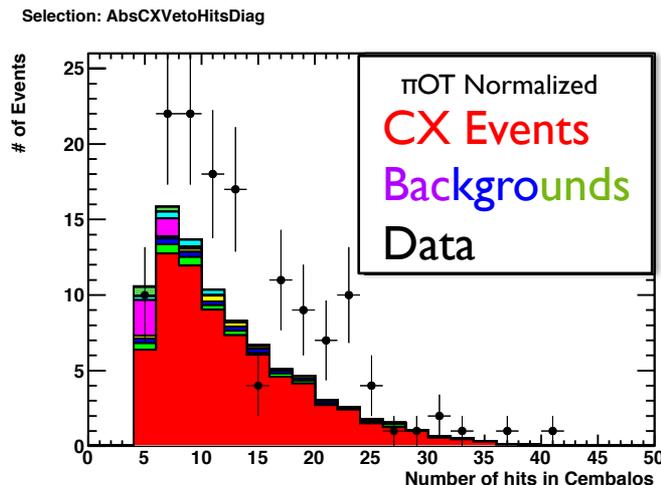
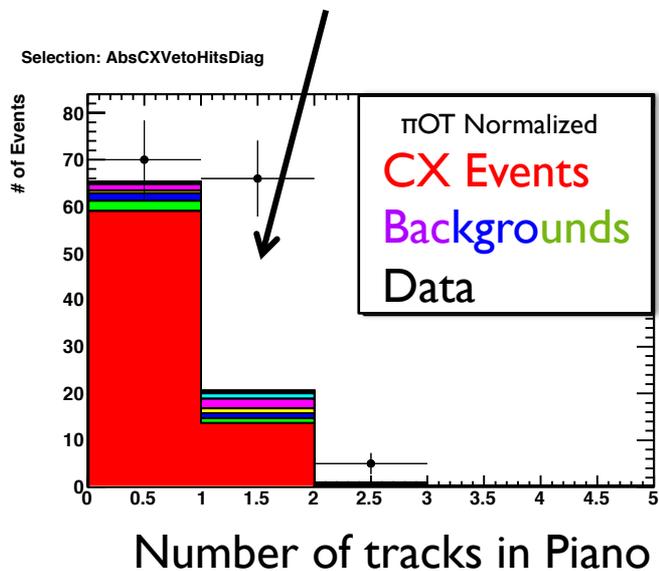
$$\text{Efficiency} = \frac{\text{Selected CX events}}{\text{True CX events}} \approx 6\%$$

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

- **~100 events in data sample**  
(~20 for 216.6 MeV/c)

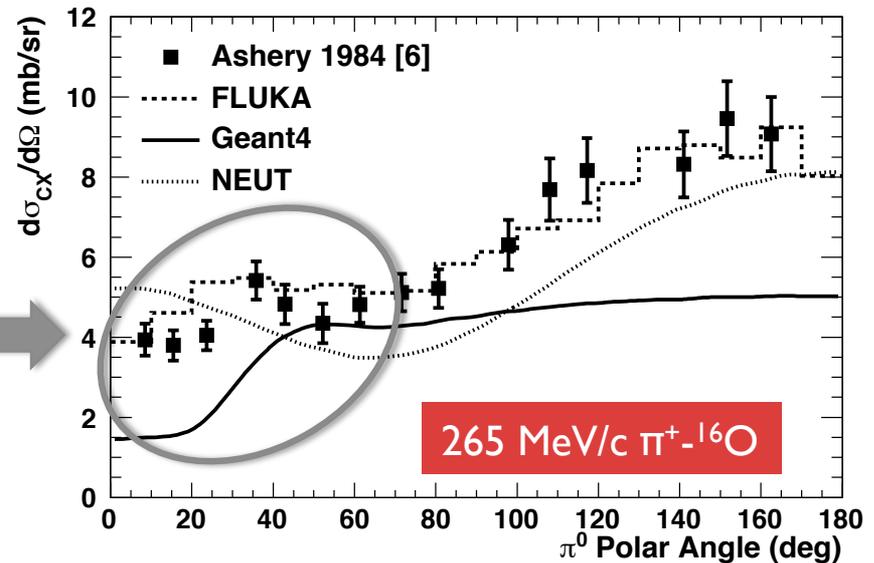
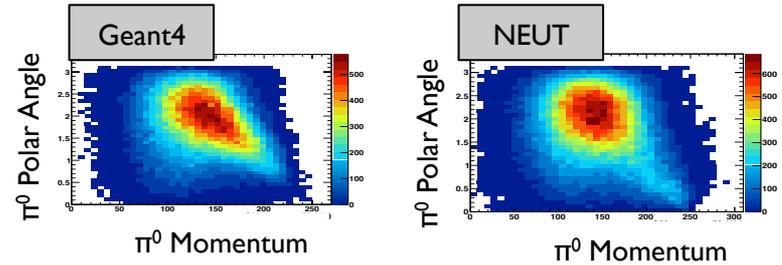
# CX Event Selection: Data vs. MC

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



# CX Modeling

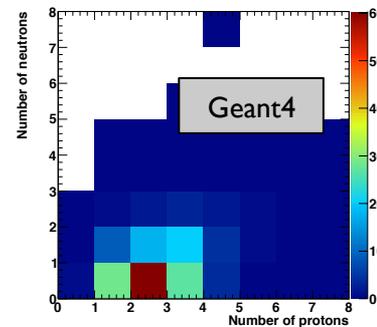
- ❖ The kinematics of the outgoing  $\pi^0$  is not well known
- ❖ Few differential cross section measurements
  - D.Ashery et al., “Inclusive pion single-charge-exchange reactions,” Phys. Rev. C, 30(3):946 (1984).
- ❖ Discrepancy among models is largest in the forward region, where CEMBALOS is more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



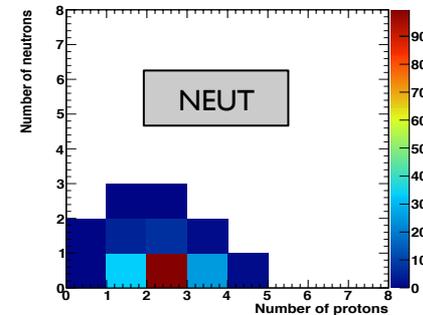
# Nucleon ejection (ABS background)

- ❖ 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  $\pi$ -{N,Ar} data
  
- ❖ High purity of CX selection means this effect is not dominant
  - But it still troubling

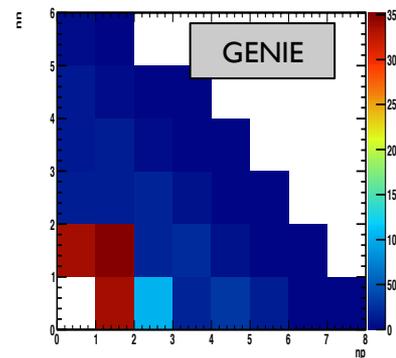
Nucleon Multiplicity GEANT4



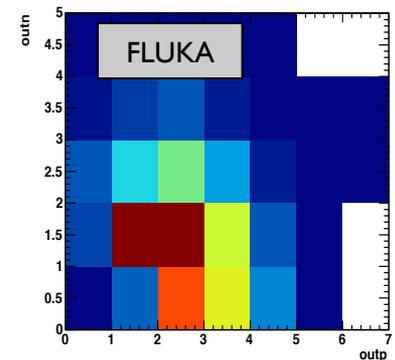
Nucleon Multiplicity NEUT



nn:np (probe\_fsi==4 || probe\_fsi==5)



Nucleon Multiplicity FLUKA



# $\sigma_{\text{CX}}, \sigma_{\text{ABS}}$ Extraction

❖ Formulae for calculation are:

$$\sigma_{\text{CX}} = \sigma_{\text{CX}}^{\text{MC}} \times \frac{N_{\text{Data}} - N_{\text{BG}}^{\text{MC}}}{N_{\text{CX}}^{\text{MC}}} \quad (1)$$

$$\sigma_{\text{ABS}} = \sigma_{\text{ABS+CX}} - \sigma_{\text{CX}} \quad (2)$$

❖ Want to try out other models:

- For each model estimate:

1.  $N_{\text{CX}}^{\text{MC}}$  (# of signal events)
2.  $N_{\text{BG}}^{\text{MC}}$  (# of background events)

❖ One option is to re-write the simulation using each package

- A more general (reasonable) one is:

# $\sigma_{\text{CX}}, \sigma_{\text{ABS}}$ Extraction

❖ Formulae for calculation are:

$$\sigma_{\text{CX}} = \sigma_{\text{CX}}^{\text{MC}} \times \frac{N_{\text{Data}} - N_{\text{BG}}^{\text{MC}}}{N_{\text{CX}}^{\text{MC}}} \quad (1)$$

$$\sigma_{\text{ABS}} = \sigma_{\text{ABS+CX}} - \sigma_{\text{CX}} \quad (2)$$

❖ Want to try out other models:

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  1.  $N_{\text{CX}}^{\text{MC}}$  (# of signal events)
  2.  $N_{\text{BG}}^{\text{MC}}$  (# of background events)

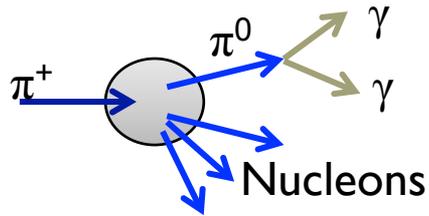
❖ One option is to re-write the simulation using each package

- A more general (reasonable) one is:

# "Efficiencies" Scheme

$\pi^0$  and nucleon kinematics dependant selection efficiencies  
 → Apply directly to the "model" from generators

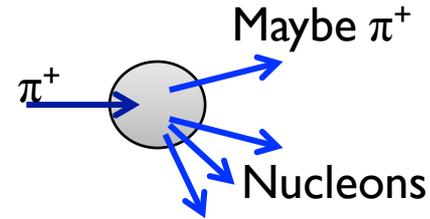
## ❖ Sample Signal Event



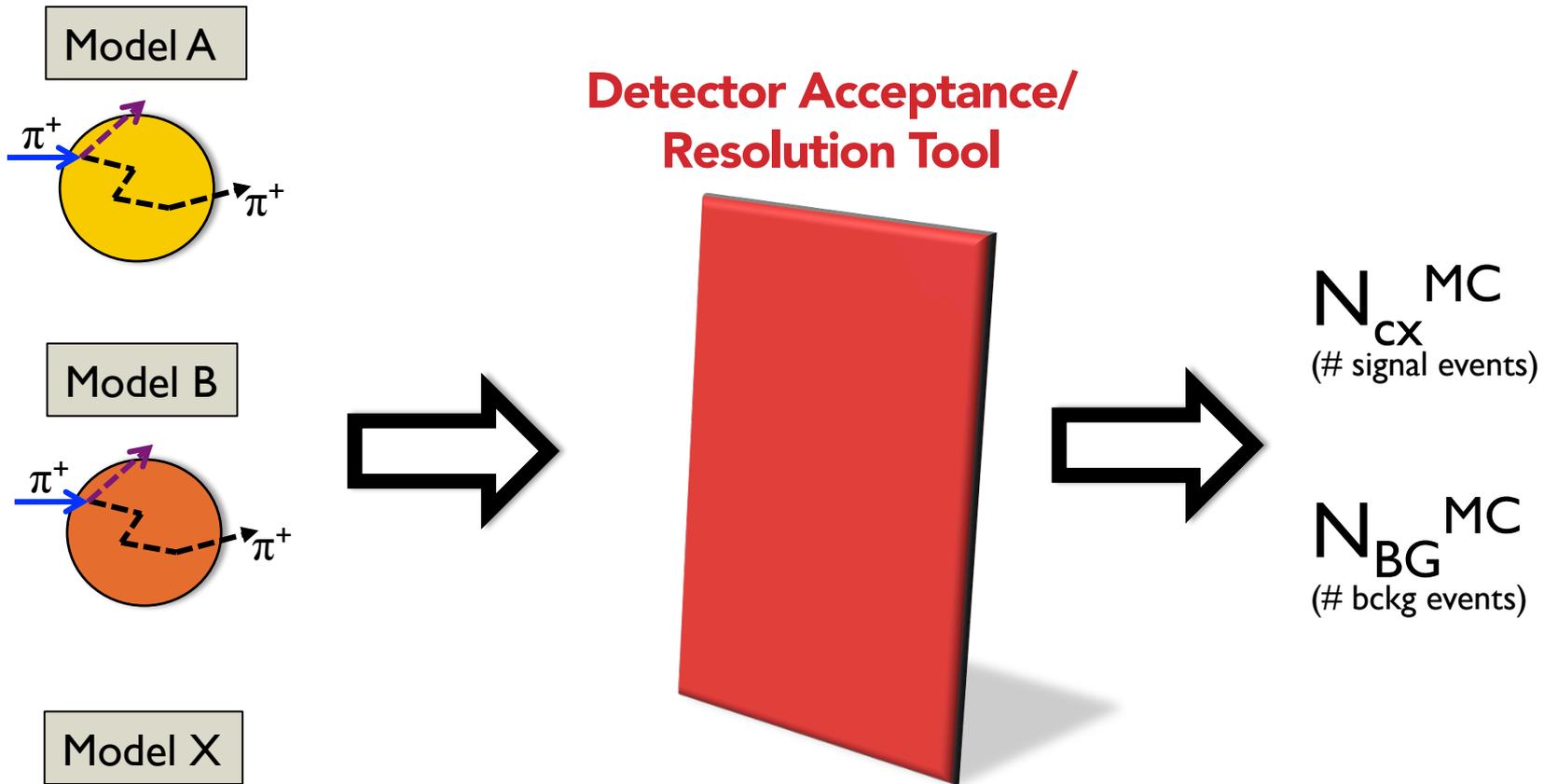
## ❖ Signal event will be selected if:

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

## • Sample Background Event



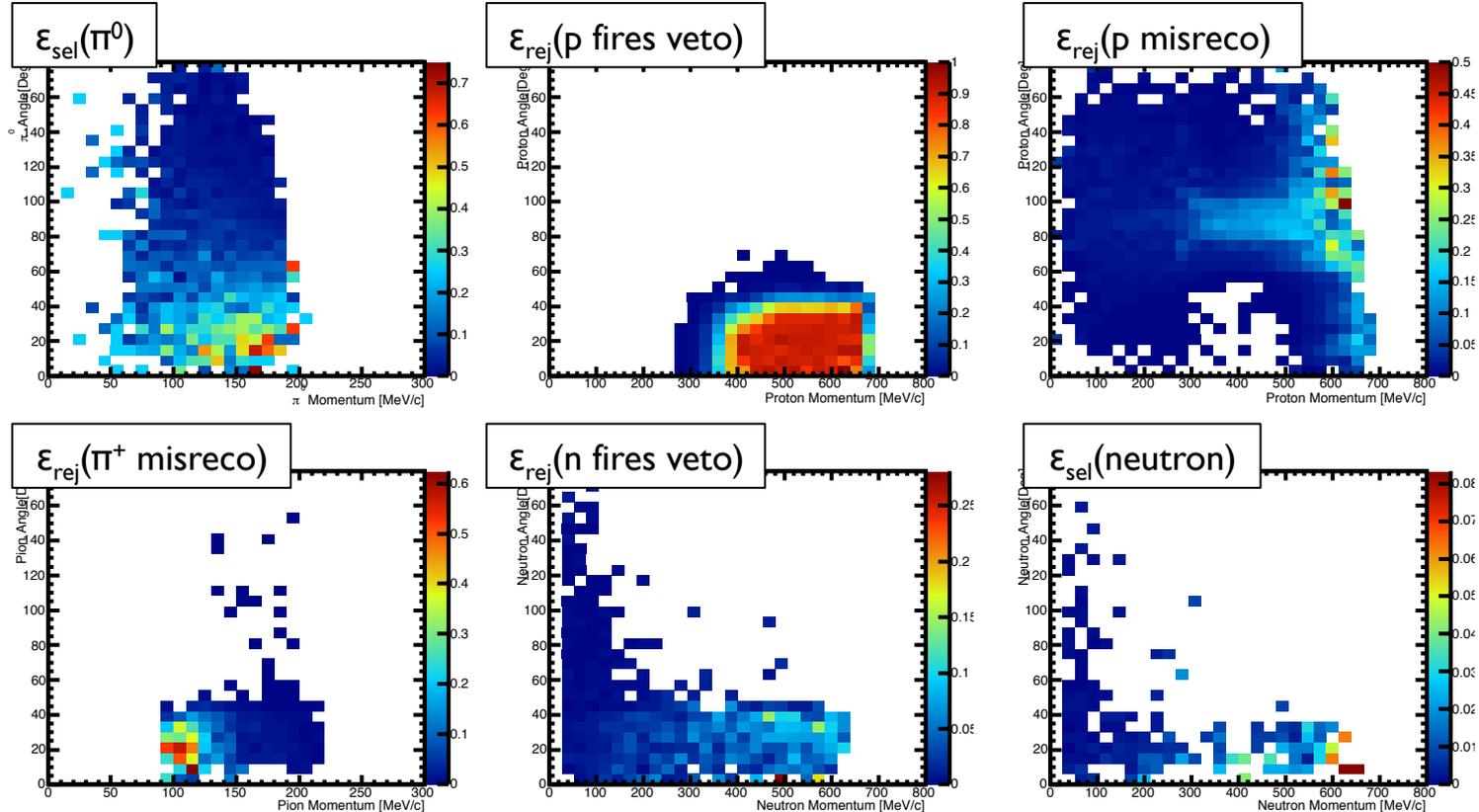
- Background event will be selected if:
  - Neutron is selected  $\rightarrow \epsilon_{sel}(n)$
  - $\pi^+$  is mis-reconstructed as proton  $\rightarrow \epsilon_{rej}(\pi^+ \text{ misreco})$
  - Ejected proton is NOT mis-reconstructed in Piano as a pion-like track  $\rightarrow \epsilon_{rej}(p \text{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



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

# Selection and Rejection Efficiencies

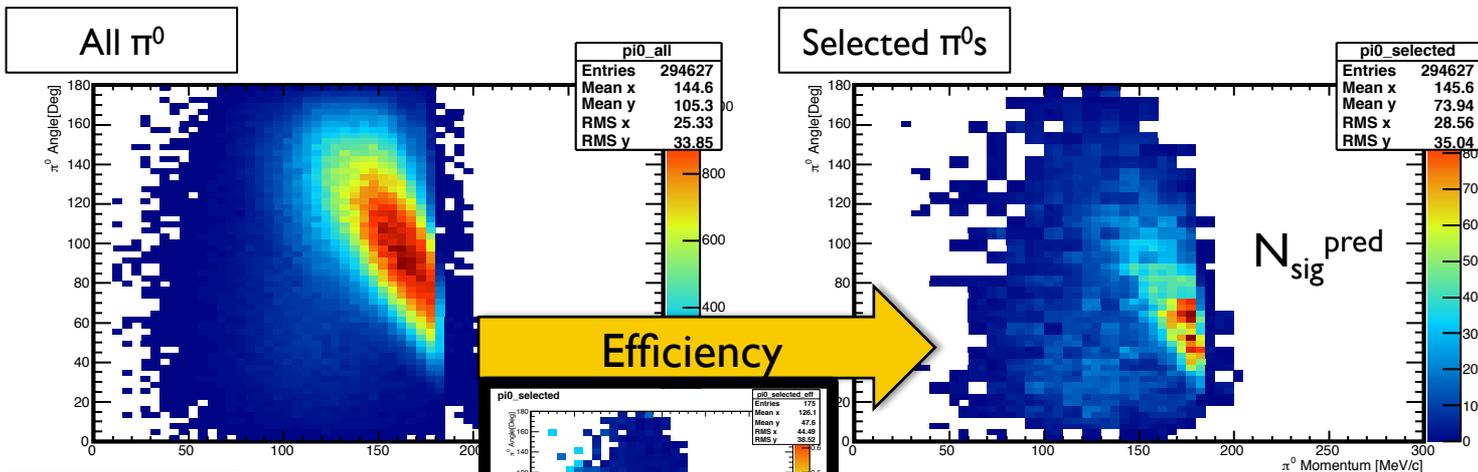
- ❖ Binned in true Momentum and Angle of corresponding particle
- ❖ Calculated using the full Geant4 DUET simulation



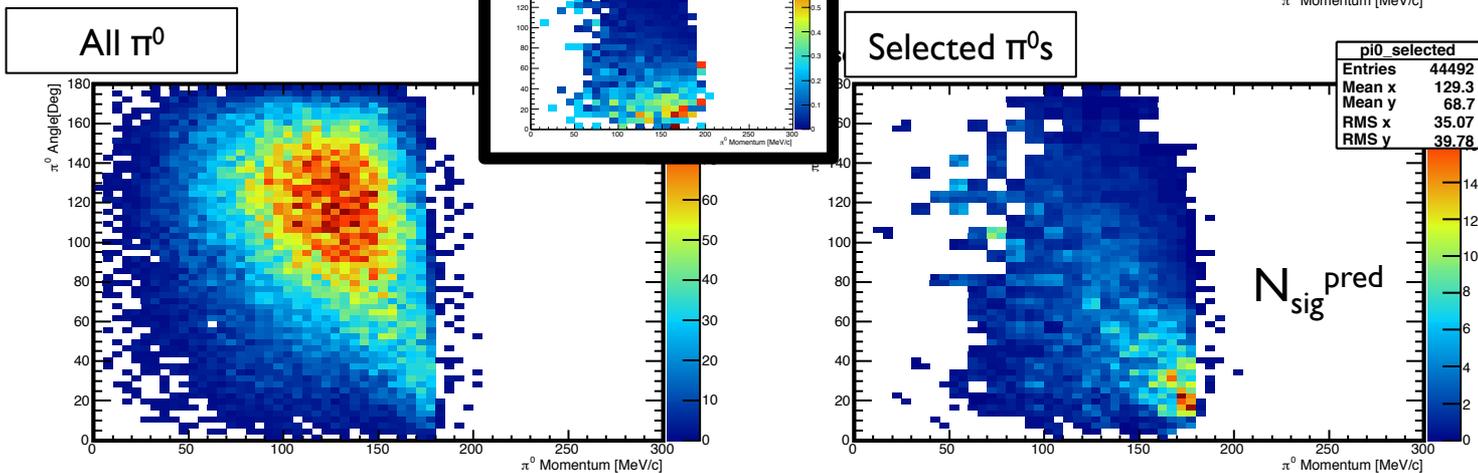
# Example: 201.6 MeV/c

Geant4  
Model

(as cross-check)



FLUKA



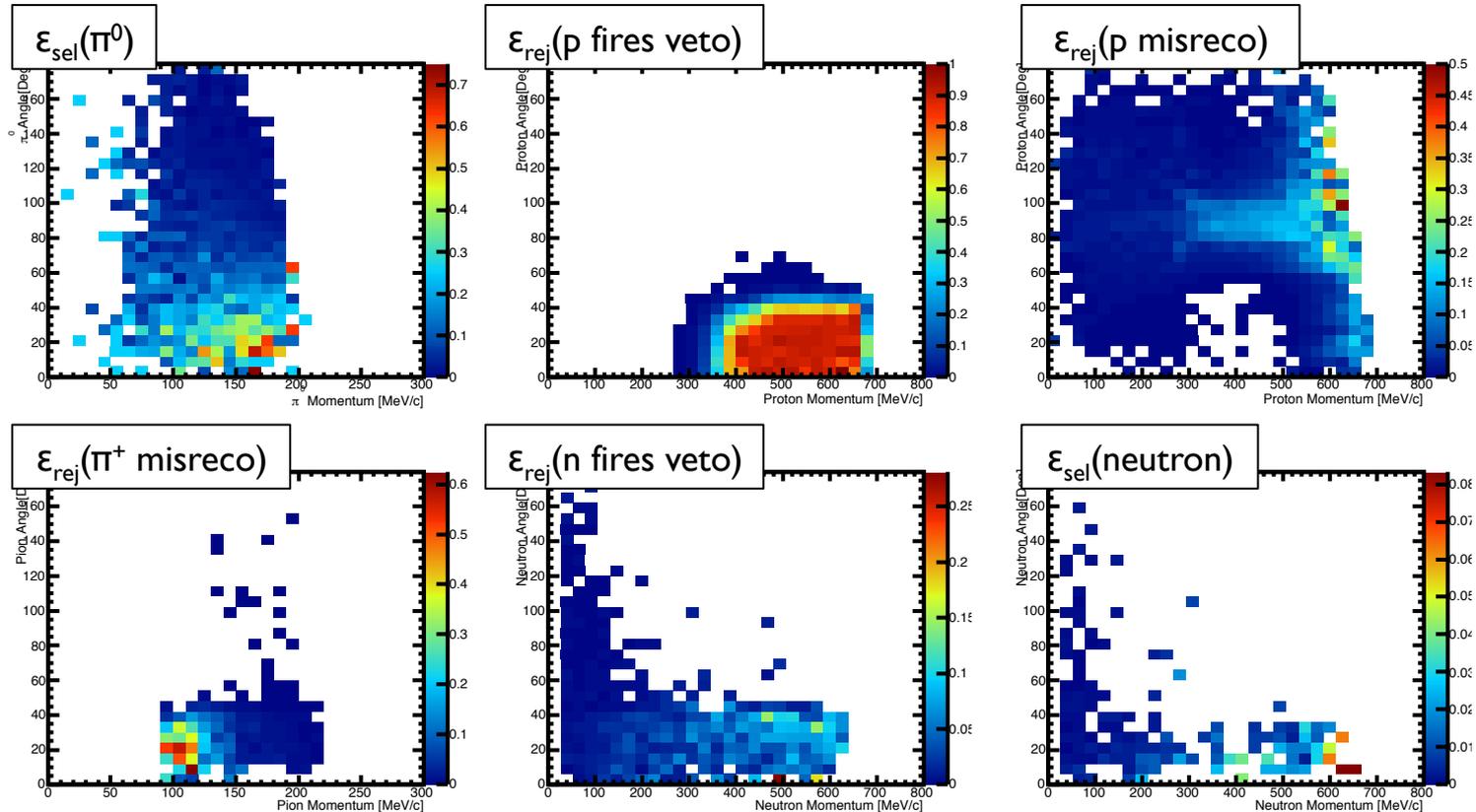
# Applying it

- ❖ 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

$p_\pi$ [MeV/c]	Model	$\sigma_{CX}^{MC}$ [mb]	$N_{CX}^{MC}$	$N_{BG}^{MC}$	$\sigma_{CX}$ [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

# Selection and Rejection Efficiencies

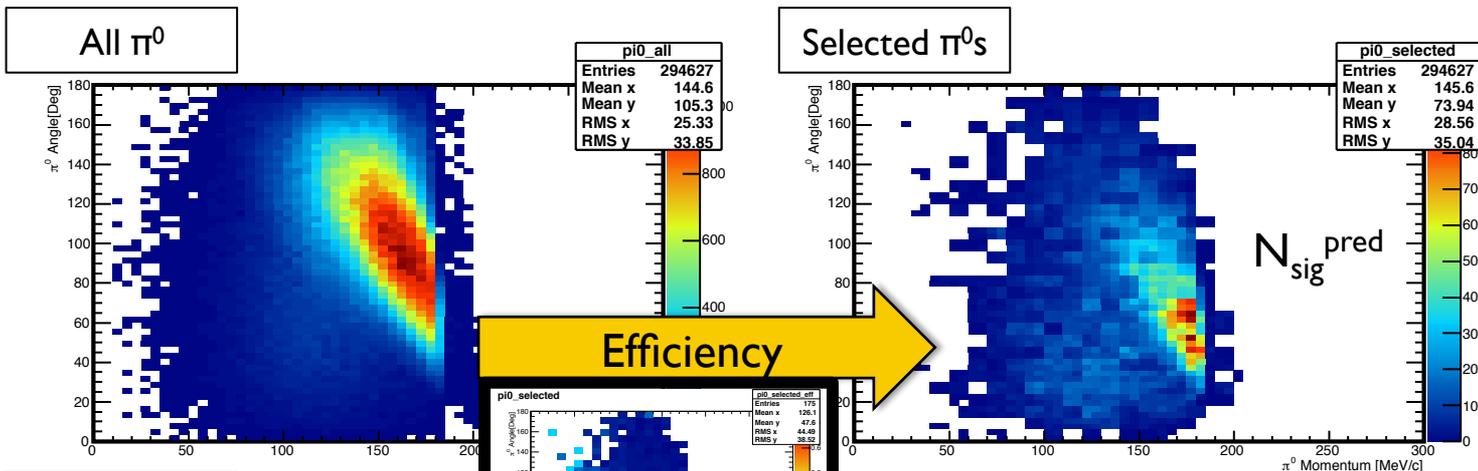
- ❖ Binned in true Momentum and Angle of corresponding particle
- ❖ Calculated using the full Geant4 DUET simulation



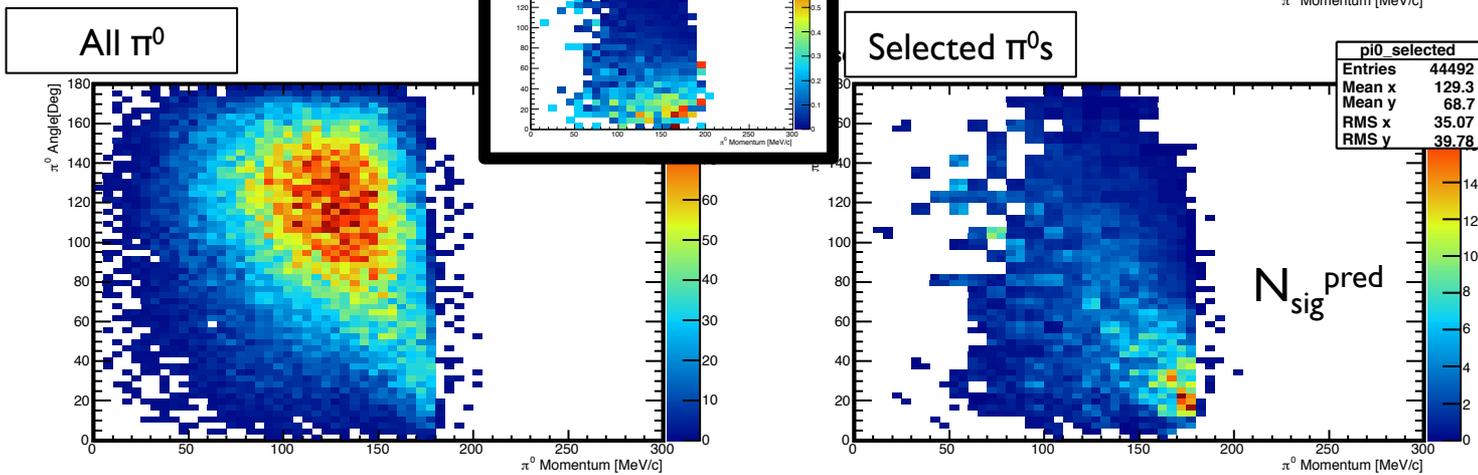
# Example: 201.6 MeV/c

Geant4  
Model

(as cross-check)



FLUKA



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

$p_\pi$ (MeV/c)	Model	$\sigma_{CX}^{MC}$ (mb)	$N_{CX}^{MC}$	$N_{BG}^{MC}$	$\sigma_{CX}$ (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
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	NEUT	55.7	24.2	1.5	43.5
237.2	GEANT4	39.6	80.0	9.7	65.4
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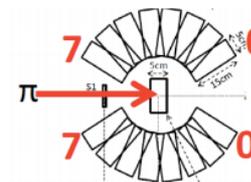
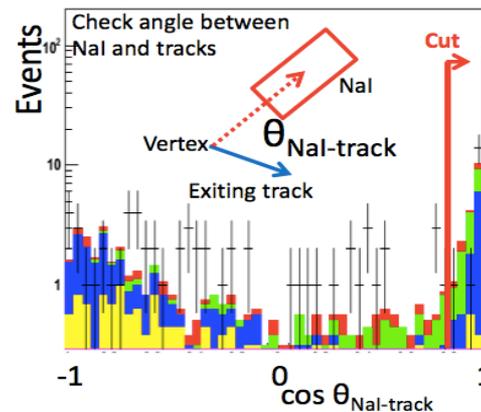
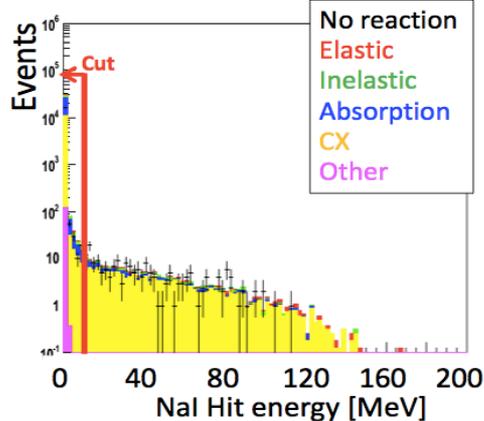
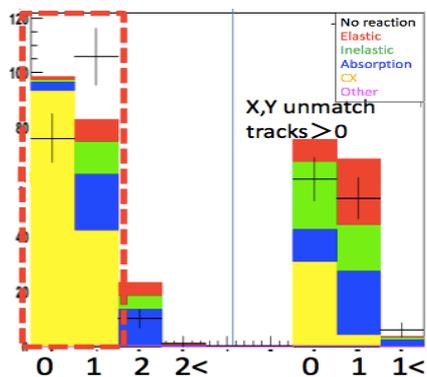
TABLE III. Summary of the statistical and systematic uncertainties in percent.

	CX					ABS				
	201.6	216.6	237.2	265.5	295.1	201.6	216.6	237.2	265.5	295.1
$\pi^+$ Momentum (MeV/c)										
<b>Beam systematics</b>										
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
<b>PIA<math>\nu</math>O systematics</b>										
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
<b>CEMBALOS systematics</b>										
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
<b>Physics systematics</b>										
$\pi^0$ kinematics	6.1	6.9	7.9	9.4	10.6	2.1	1.6	3.2	4.3	4.1
Nuclear deexcitation $\gamma$ 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
<b>Statistical error</b>	11.0	26.0	9.4	8.9	8.8	3.9	6.2	3.9	4.2	3.6
<b>Total error</b>	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

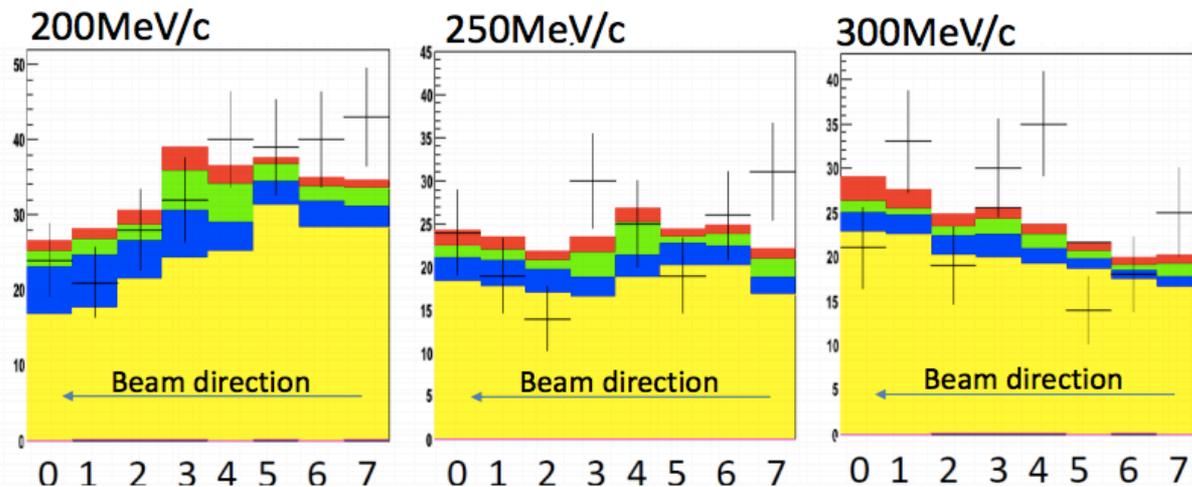
All plots normalized to # of incident pions



## Selection Criteria:

1. 0 or 1 3D Piano tracks
2. NaI Hit Energy > 10 MeV in NaI Crystals
3. Reject if Piano track points to NaI Crystal

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



# CX Analysis Systematics

## 1. $\pi^+$ Beam Systematics

- Profile and Momentum
- Muon Contamination

## 2. PIANO detector systematics

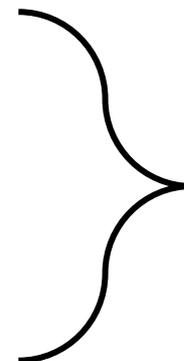
- Fiducial volume, target material, charge simulation, alignment

## 3. Cembalos Detector Systematics

- Alignment and charge simulation

## 4. CX Physics Systematics

- $\pi^0$  kinematics (Using Ashery 1984 data)
- Selection Background



Estimation procedures  
inherited from ABS+CX  
analysis

# Cembalos Detector Systematics

## 1. Detector Alignment (5~8%)

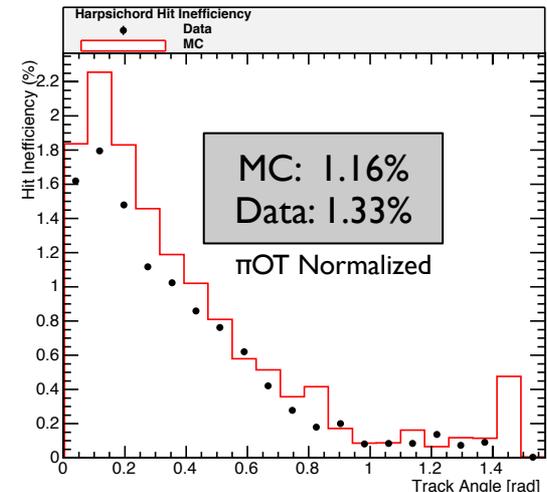
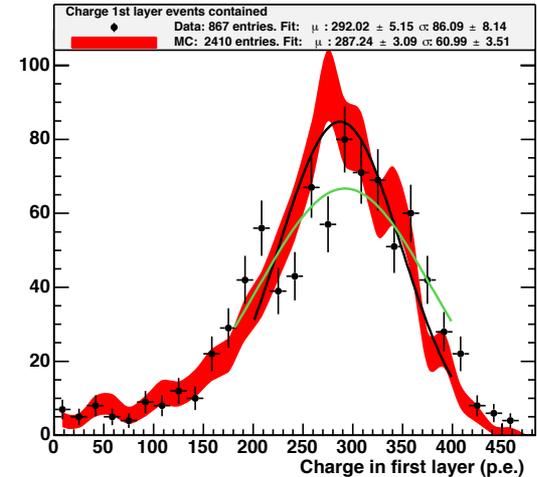
- $\pm 5\text{mm}$  shifts of the (x,y,z) position of Cembalos in the Monte Carlo

## 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%)

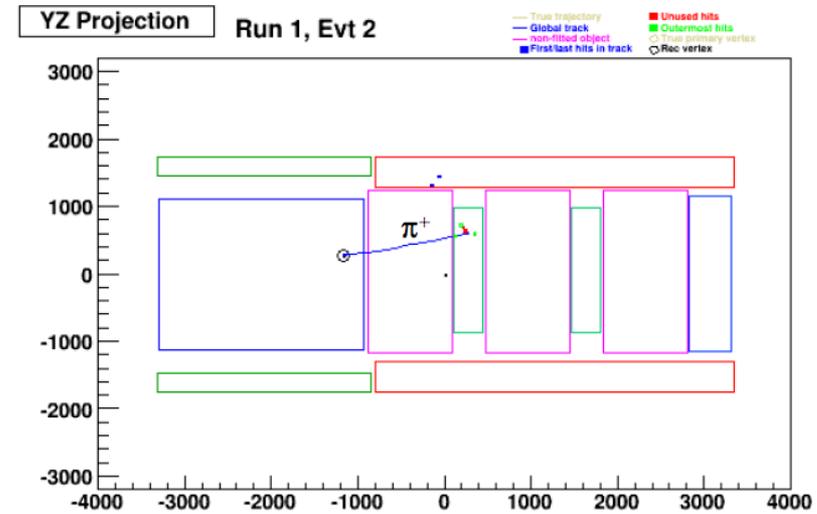
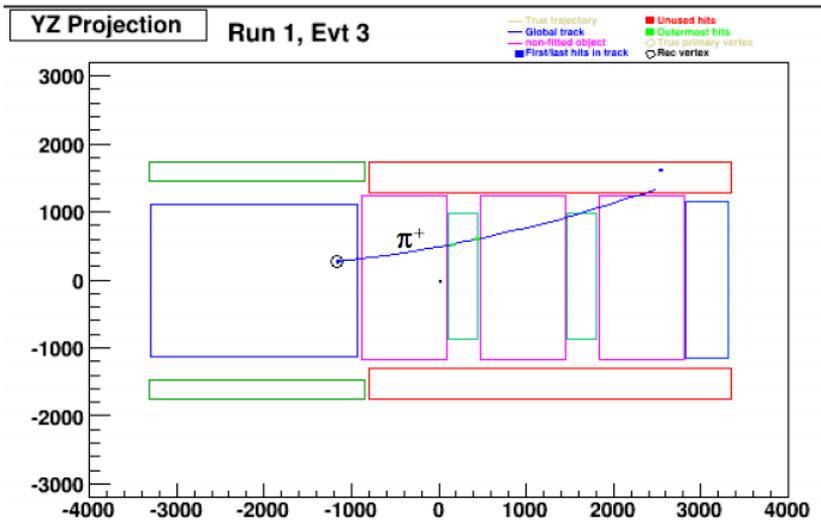
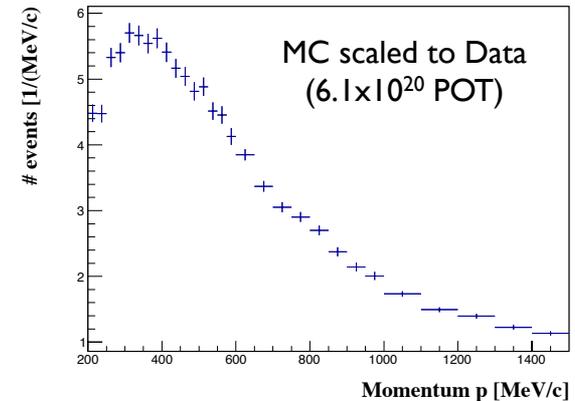
- Missing hits in the middle of Cembalos reconstructed tracks are counted and compared between Data/MC
- Systematic is calculated from 10000 toy MC where hits are randomly deleted following the Data/MC difference



# " $\pi$ entering ND280 tracker" sample

- ❖ Select CC  $\pi$  events where the  $\pi$  track starts upstream of the ND280 tracker (FGD + TPC)
- ❖ Follow their secondary interactions elsewhere
- ❖ ~3000 events in Data ( $6.1 \times 10^{20}$  POT)
- ❖ Difficult to convert to a cross-section measurement
  - Studying how to use this sample

TPC1 pion sample momentum distribution



# Tuning fit result

❖ Compared to previous tuning fit (only used  $\pi^+$ -C data)

Scaling Parameter	Previous tuning	This work
QE Scattering (low energy)	$1.0 \pm 0.41$	$1.069 \pm 0.313$
Absorption	$1.1 \pm 0.41$	$1.404 \pm 0.432$
Charge Exchange	$1.0 \pm 0.57$	$0.697 \pm 0.305$
Pion production	$1.0 \pm 0.5$	$1.002 \pm 1.101$
QE Scattering (high energy)	$1.8 \pm 0.34$	$1.824 \pm 0.859$
Charge Exchange (high energy)	$1.8 \pm 0.28$	1.8 (Fixed)

# Error scaling

- ❖ Decided to come up with a simple method to inflate the errors on the FSI parameters

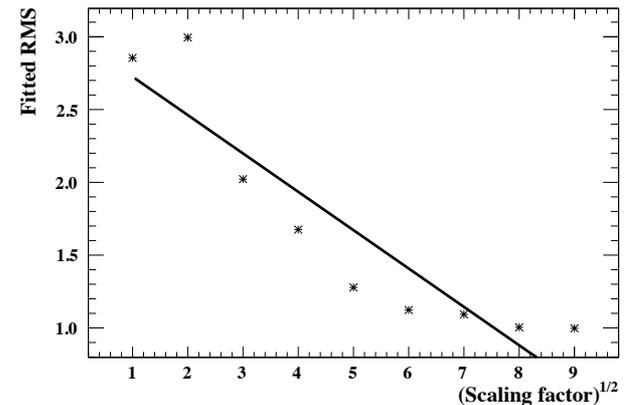
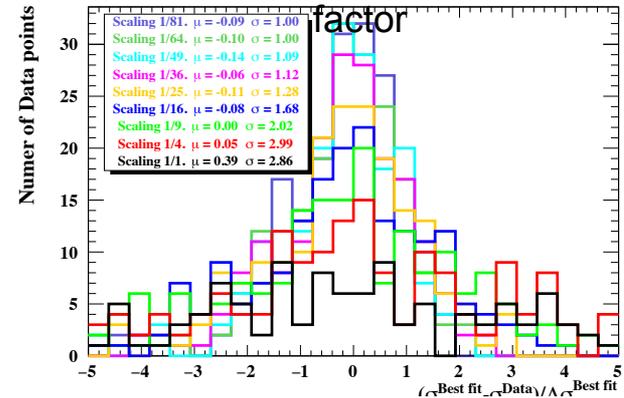
$$\chi^2(f_{FSI}) = \frac{\chi^2(f_{FSI})}{\text{Scaling factor}}$$

- ❖ The following metric was calculated for each data point and used for comparison:

$$\Psi = \frac{\sigma_j^{\text{Bestfit}}(f_{FSI}) - \sigma_j^{\text{Data}}}{\Delta\sigma_j^{\text{Bestfit}}(f_{FSI})}$$

- ❖ Choose factor such that this distribution has a width of 1.0
  - Ensures coverage of 66% of the datasets

Each color corresponds to a value of the scaling

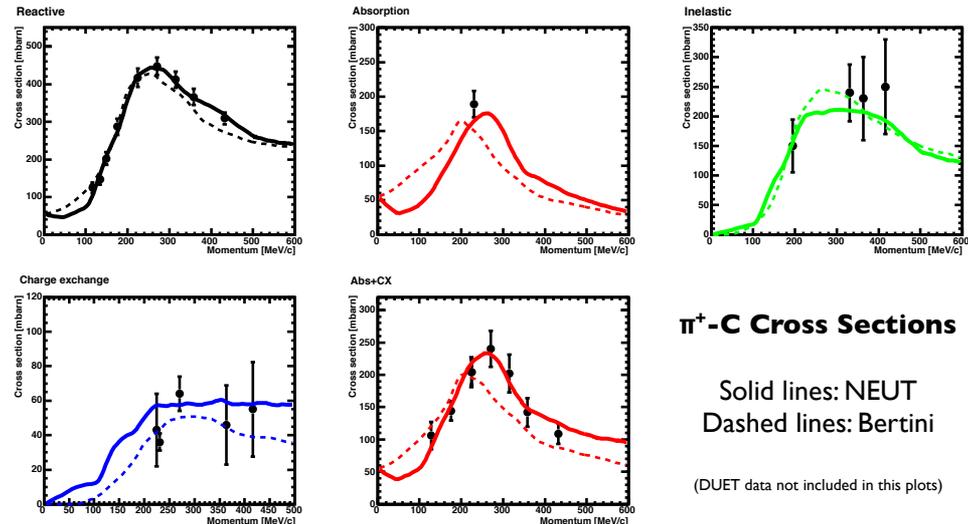


# Also use NEUT tuning for SI...

❖ See “Constraining pion secondary interaction systematic uncertainties at T2K” (Mitchell Yu, NuINT17 Poster)

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



**$\pi^+$ -C Cross Sections**

Solid lines: NEUT  
Dashed lines: Bertini

(DUET data not included in this plots)

# (Side note) $\pi$ -A elastic modeling

## Important lesson from DUET:

- ❖ Large mis-modeling of  $^1\text{H}$  and  $^{12}\text{C}$  elastic interactions in Geant4.9.X
  - ❖ Used by ND280 simulation
  - ❖ FGD is mostly  $\text{C}_8\text{H}_8$
  
- ❖  $\pi^+$ -H has been fixed by Geant in recent version 4.10.X

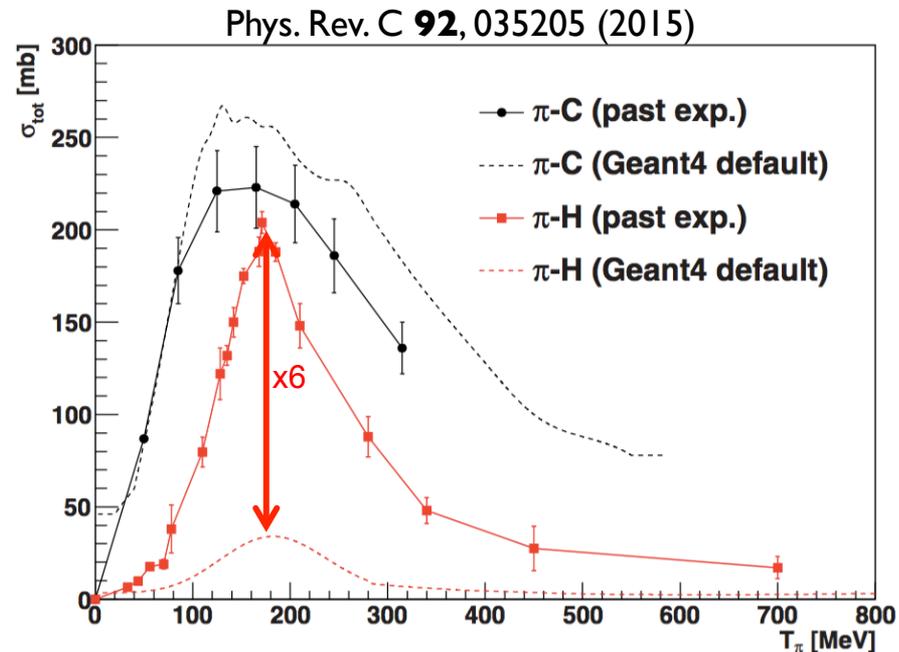


FIG. 16. (Color online) Comparison of elastic inclusive cross section between the previous experiments (summarized in Table IV) and the default GEANT4. The cross sections are plotted as a function of pion kinetic energy.