*International Workshop on Frontiers in Electroweak Interactions of Leptons and Hadrons*

**Aligarh, India**

November 2016

# π-NUCLEUS SCATTERING CROSS SECTIONS

## THE DUET EXPERIMENT

ELDER PINZON

YORK UNIVERSITY

PHYSICS & ASTRONOMY

YORK U

# Outline

❖ Why measure π-Nucleus **(π-A)** scattering cross sections?

- …in the 21st century?

❖ How are these interactions modeled and simulated?

- Oset et al model
- Intra-nuclear Cascade models

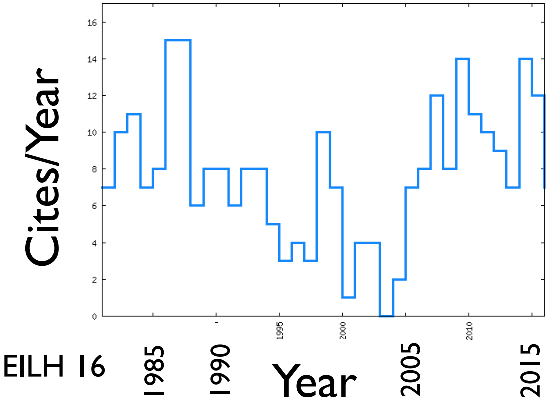
❖ The DUET Experiment ($\pi^+$-$^{12}C$ scattering)

1. arXiv:1506.07783: Phys. Rev. C 92, 035205
2. New analysis to be submitted soon

# π-A as a Probe of Nuclear Structure

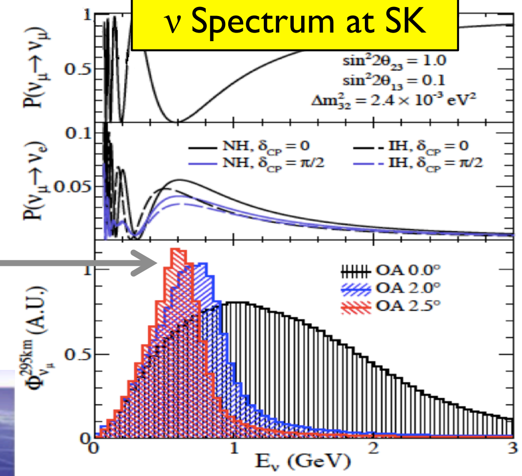
- Strong interactions are governed by QCD
  - Structure of atomic nuclei and constituents nucleons are fully described by interactions of quarks and gluons
- Color confinement suggests that interactions between nucleons can be described by colorless particles
  - Effective theories based on interactions 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.

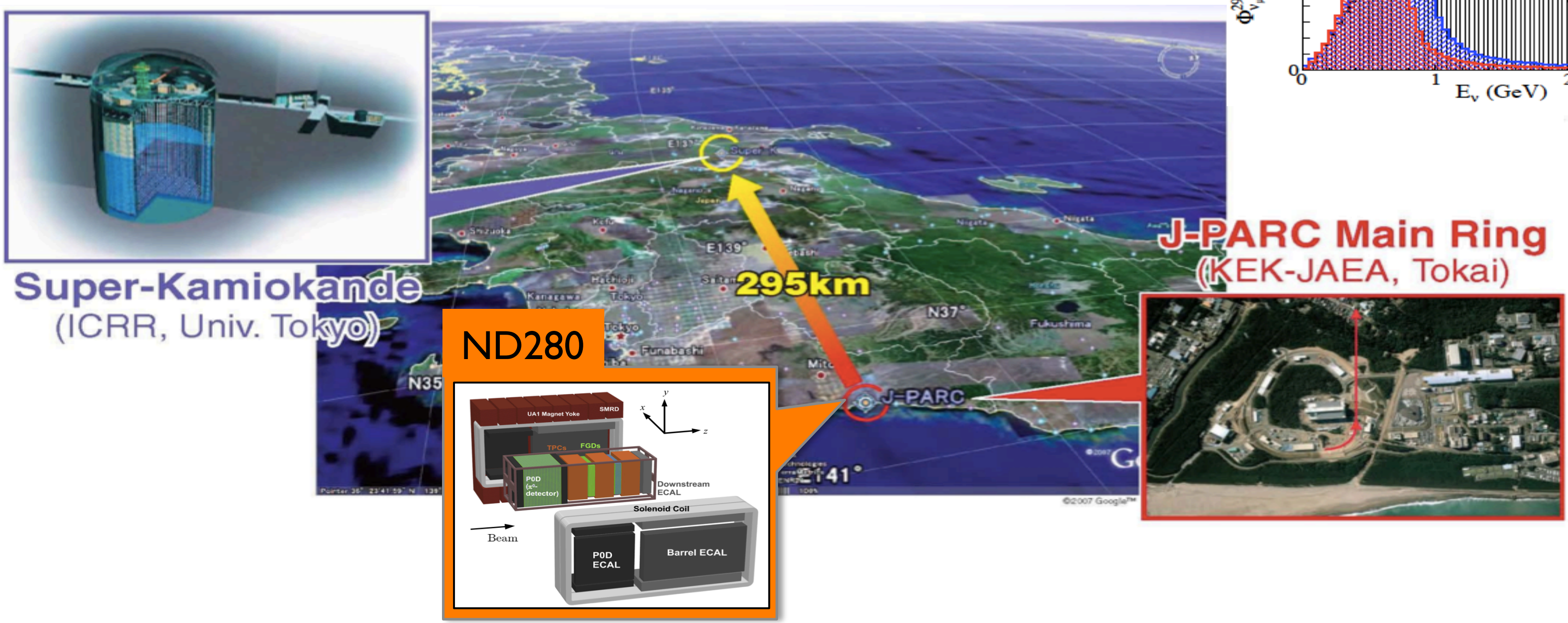
True Absorption and Scattering of Pions on Nuclei
Ashery, D. et al. PRC 23 (1981) 2173-2185



# T2K Experiment

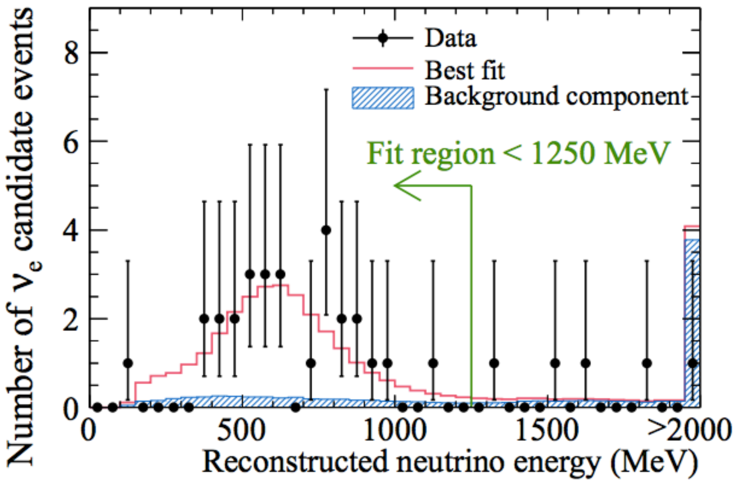
- Tokai-to-Kamioka
- $\nu_\mu$ (anti-$\nu_\mu$) beam peaked at 0.6 GeV
- Near detector (ND280) located at 280 m in Tokai
- Far detector (Super-Kamiokande) at 295 km in Kamioka



# T2K: 2015 Breakthrough prize

- 2011-2013: Observation of $\nu_e$ appearance
  - 28 events (4.9 expected) for 7.3σ significance
    - PRL107 (2011) 041801, PRD 88 (2013) 3, 032002, PRL 112 (2014) 061802
- 2014: Most precise measurement of $\theta_{23}$ from $\nu_\mu$ disappearance:
  - PRL 112 (2014) 18, 181801

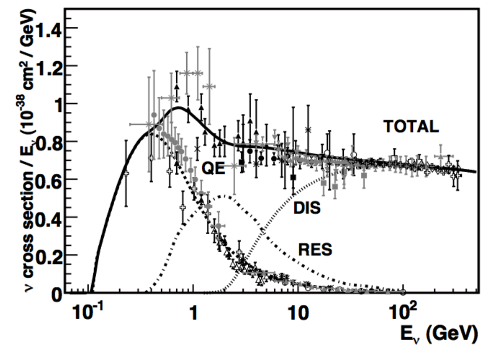



- As long baseline experiments enter the precision era
  - Understanding and reducing systematic uncertainties becomes even more important

# GeV ν Experiments on Nuclear Targets

❖ Reconstructing the ν flavour and its energy is fundamental for accelerator ν experiments

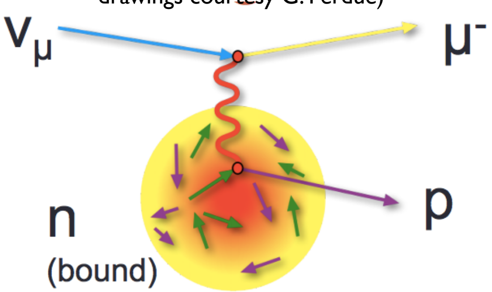
- For both oscillation and cross section analyses

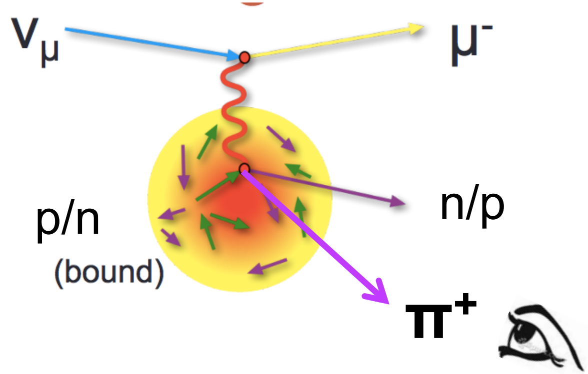



**CCQE Interaction.**
**Golden channel**

**$CC1\pi^+$ Interaction.**
**(RES, DIS)**

drawings courtesy G. Perdue)




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

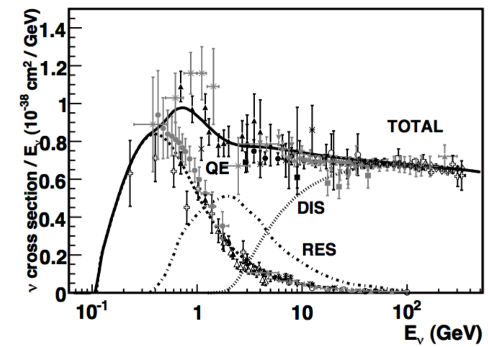
$$E_\nu = \frac{1}{2}\frac{2M_N E_\mu + M_f^2 - M_N^2 - m_\mu^2}{M_N - E_\mu + \cos\theta_\mu\sqrt{E_\mu^2 - m_\mu^2}}$$

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

# GeV ν Experiments on Nuclear Targets

❖ Reconstructing the ν flavour and its energy is fundamental for accelerator ν experiments

- For both oscillation and cross section analyses




**CCQE Interaction.**
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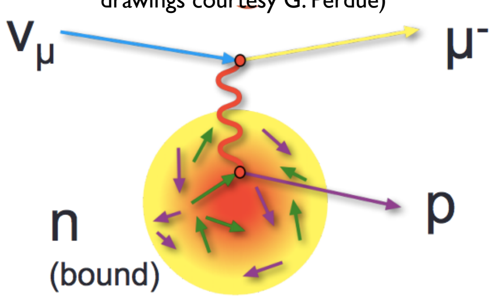


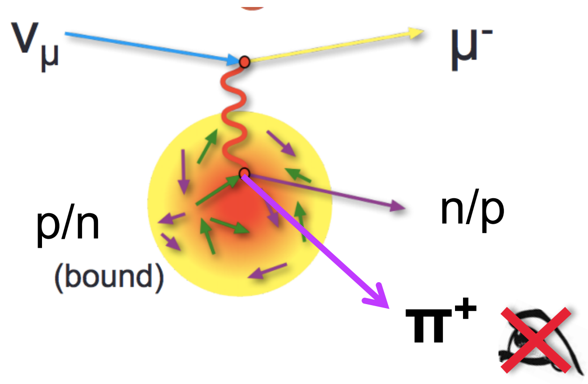


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$E_\nu^{rec}$ from lepton kinematics

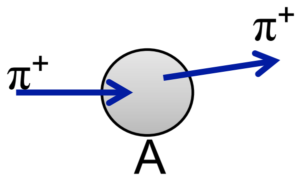
**CCQE-like event!**

Pions can interact:

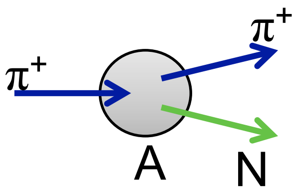
- Inside the nucleus:
  **Final State Interactions**
- Outside the nucleus:
  ***Secondary Interactions***

# How do these sub-GeV pions interact?

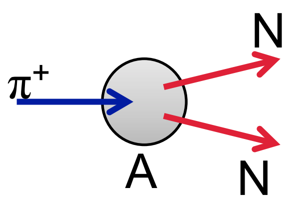
1. Elastic Scattering



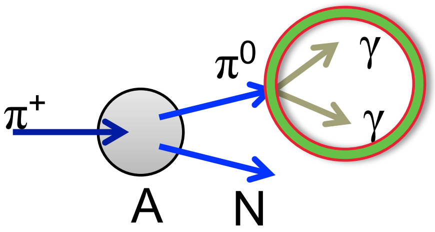

2. Quasi-elastic Scattering




3. Absorption (**ABS**)



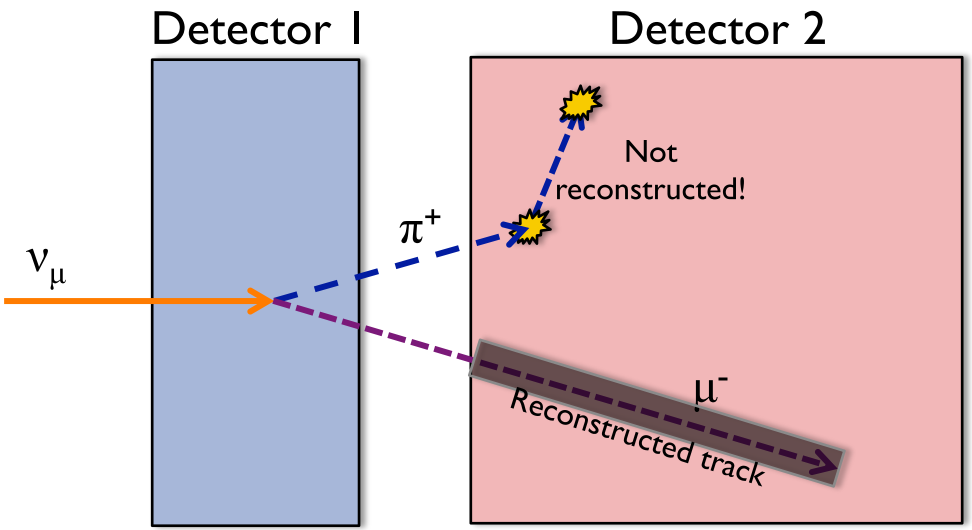

4. Charge Exchange (**CX**)



# 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



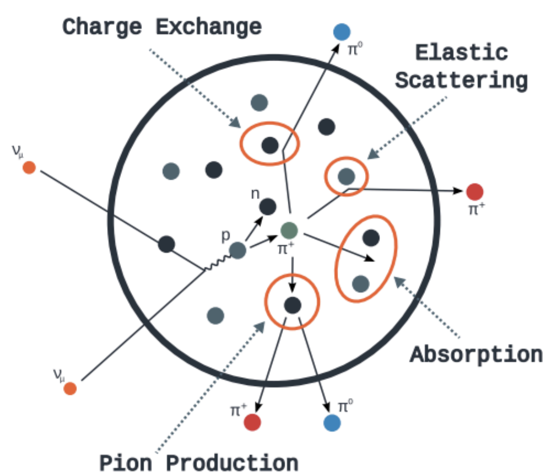

❖ Currently largest systematic for the near detector at T2K!

- (Mostly due to large mis-modeling of π interactions by Geant4)

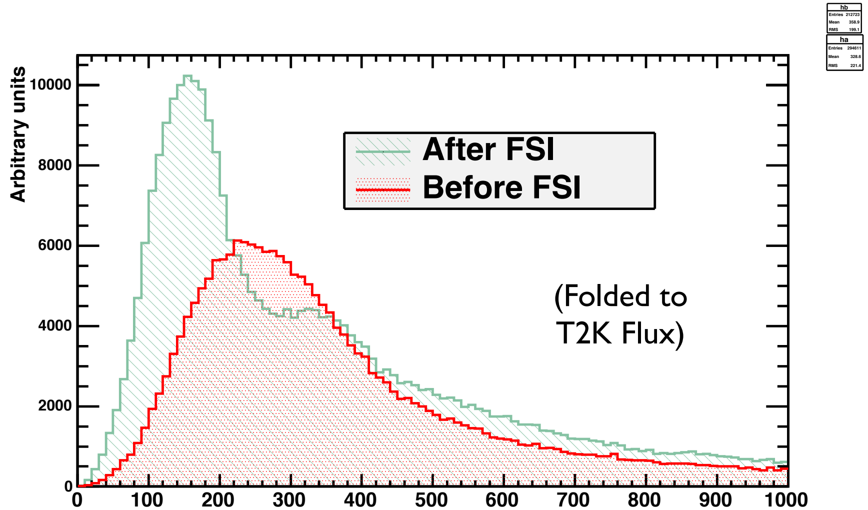
# Final State Interactions (FSI)

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

- Very hard to isolate from other nuclear effects:
  - Fermi momentum of initial nucleon
  - **Formation zone effects**
  - **Or even the actual CC1π model kinematic**




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

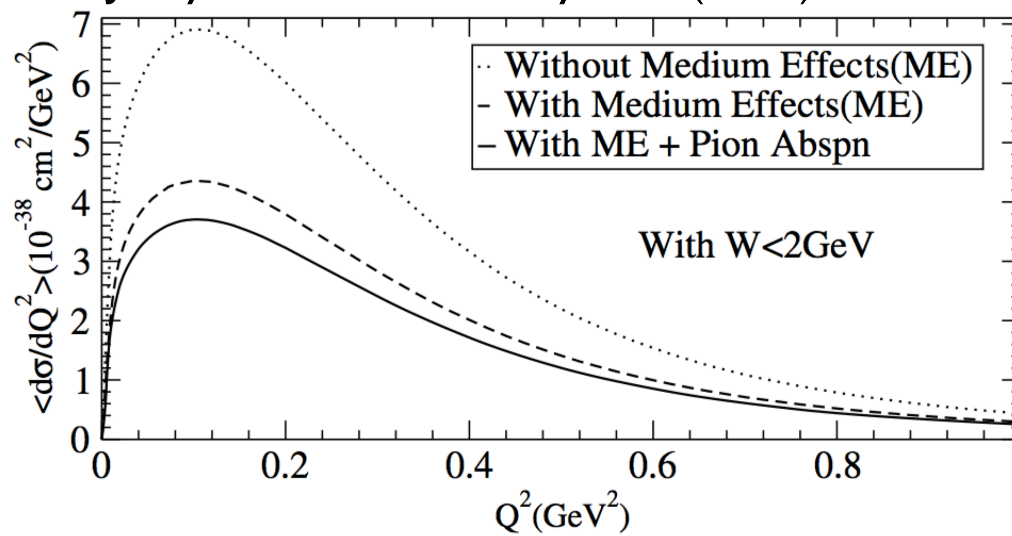



Momentum of π from CC1π [MeV/c]

# Singh, Athar, et al CC1π model

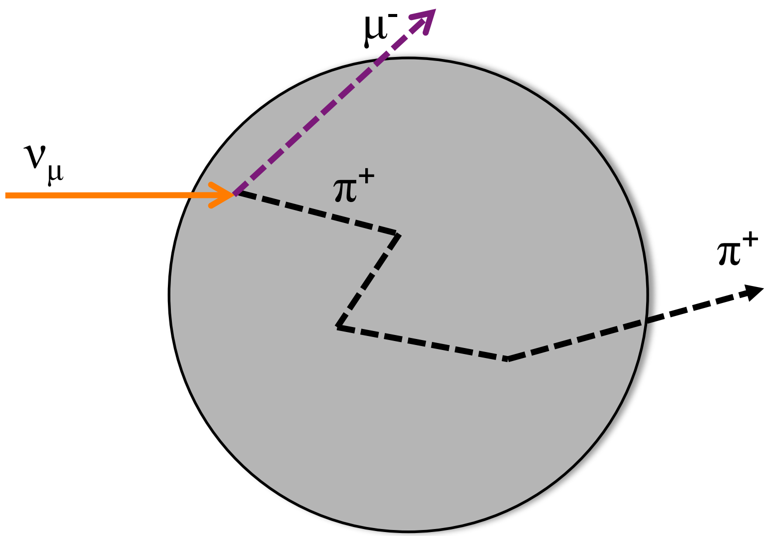
- Extensive work on CCQE, CC1π modeling at GeV scale
- Nuclear medium effects
  - Modifications of Δ properties in the medium
- Additional terms:
  - Non-resonant backgrounds
  - Higher order resonances
- Anti-ν induced CC hyperon production
  - J. Phys. G: Nucl. Part. Phys. 42 (2015) 055107
- Now being implemented in NEUT for T2K

J. Phys. G: Nucl. Part. Phys. **37** (2010) 015005

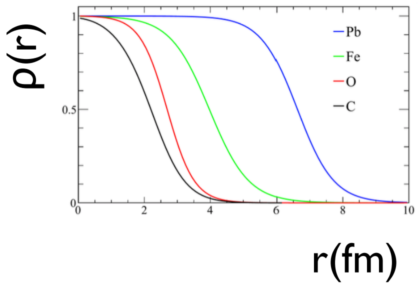


# How are FSI/SI simulated?

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




- Particles assumed to be classical
- At each step within the nuclear radius the mean free path is calculated:
  - $\lambda(r) = [\sigma\rho(r)]^{-1}$
  - Using Monte Carlo method decide if interaction takes place
  - If not, continue to next step!



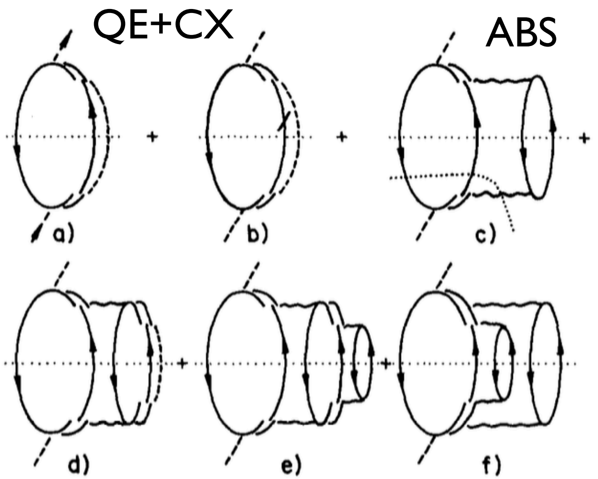

The density is modeled using a Woods-Saxon potential

- Main ingredients are the nuclear density model ($\rho(r)$) and the microscopic interaction probabilities ($\sigma$)

# E. Oset, L.L. Salcedo, et al model

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

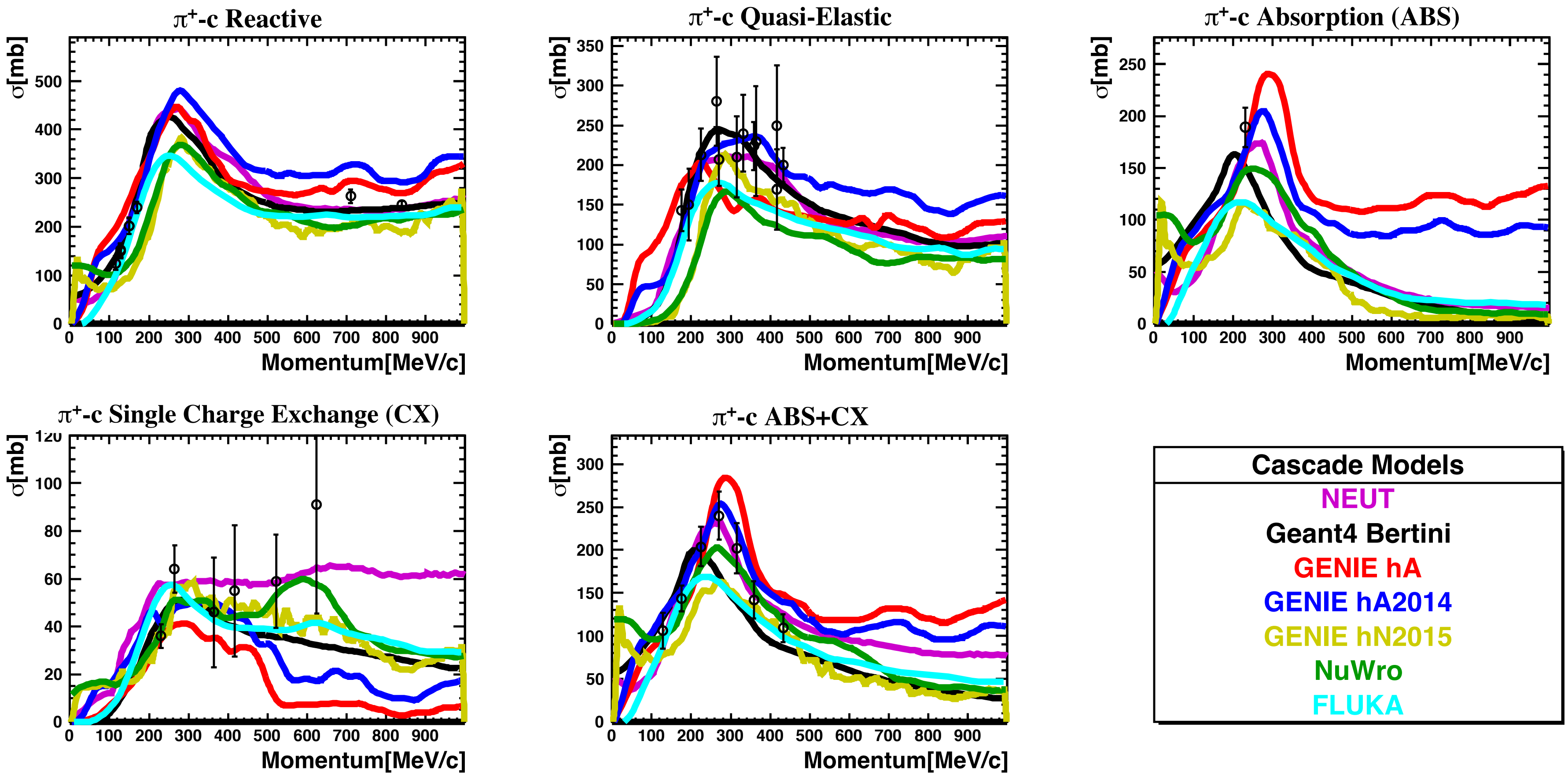
- Used by NEUT, NuWro and GENIE hN
- Computational many-body calculation in infinite nuclear matter + local density approximation
- π-A scattering is represented as a wave in a complex optical potential
  - The individual channel contributions (Elastic, QE, ABS etc.) are obtained from separating the real and complex parts of the potential and calculating the corresponding Feynman diagrams




Diagrams contributing to π-A optical potential

# Many cascades…

❖ Large uncertainties and scarce data → Need more data!!!



# THE DUET EXPERIMENT @ TRIUMF

(Canada's national laboratory for nuclear and particle physics)

MEASURE $\pi^+$ ABSORPTION CROSS SECTION WITH ~10% ACCURACY AND CHARGE EXCHANGE WITH ~20% ACCURACY

# DUET Collaboration

- A subset of members of the T2K experiment from Japanese and North American institutions


K. Ieki,[1] E. S. Pinzon Guerra,[2] S. Berkman,[3] S. Bhadra,[2] C. Cao,[3] P. de Perio,[4] Y. Hayato,[5] M. Ikeda,[5] Y. Kanazawa,[6] J. Kim,[3] P. Kitching,[7] K. Mahn,[8] T. Nakaya,[1] M. Nicholson,[7] K. Olchanski,[7] S. Rettie,[3,7] H. A. Tanaka,[3] S. Tobayama,[3] M. J. Wilking,[9] T. Yamauchi,[1] S. Yen,[7] and M. Yokoyama[6]

(DUET Collaboration)

[1]*Kyoto University, Department of Physics, Kyoto, Japan*

[2]*York University, Department of Physics and Astronomy, Toronto, Ontario, Canada*

[3]*University of British Columbia, Department of Physics and Astronomy, Vancouver, British Columbia, Canada*

[4]*University of Toronto, Department of Physics, Toronto, Ontario, Canada*

[5]*University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan*

[6]*University of Tokyo, Department of Physics, Tokyo, Japan*

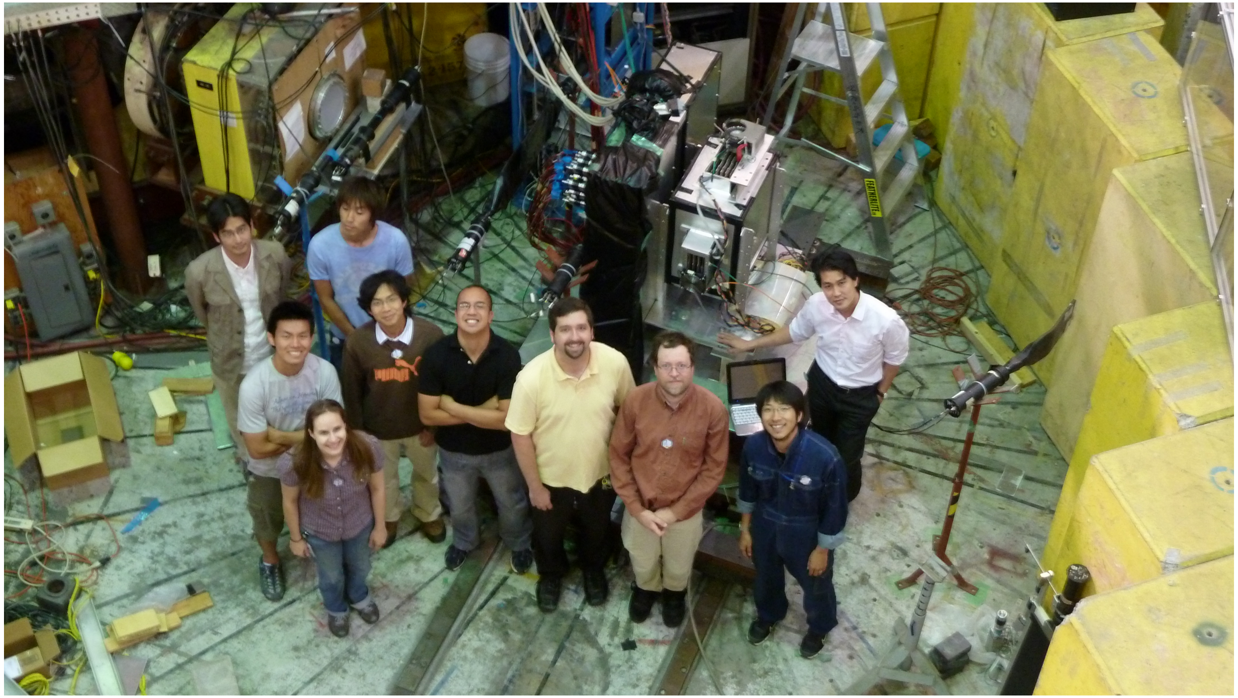
[7]*TRIUMF, Vancouver, British Columbia, Canada*

[8]*Michigan State University, Department of Physics and Astronomy, East Lansing, Michigan, USA*

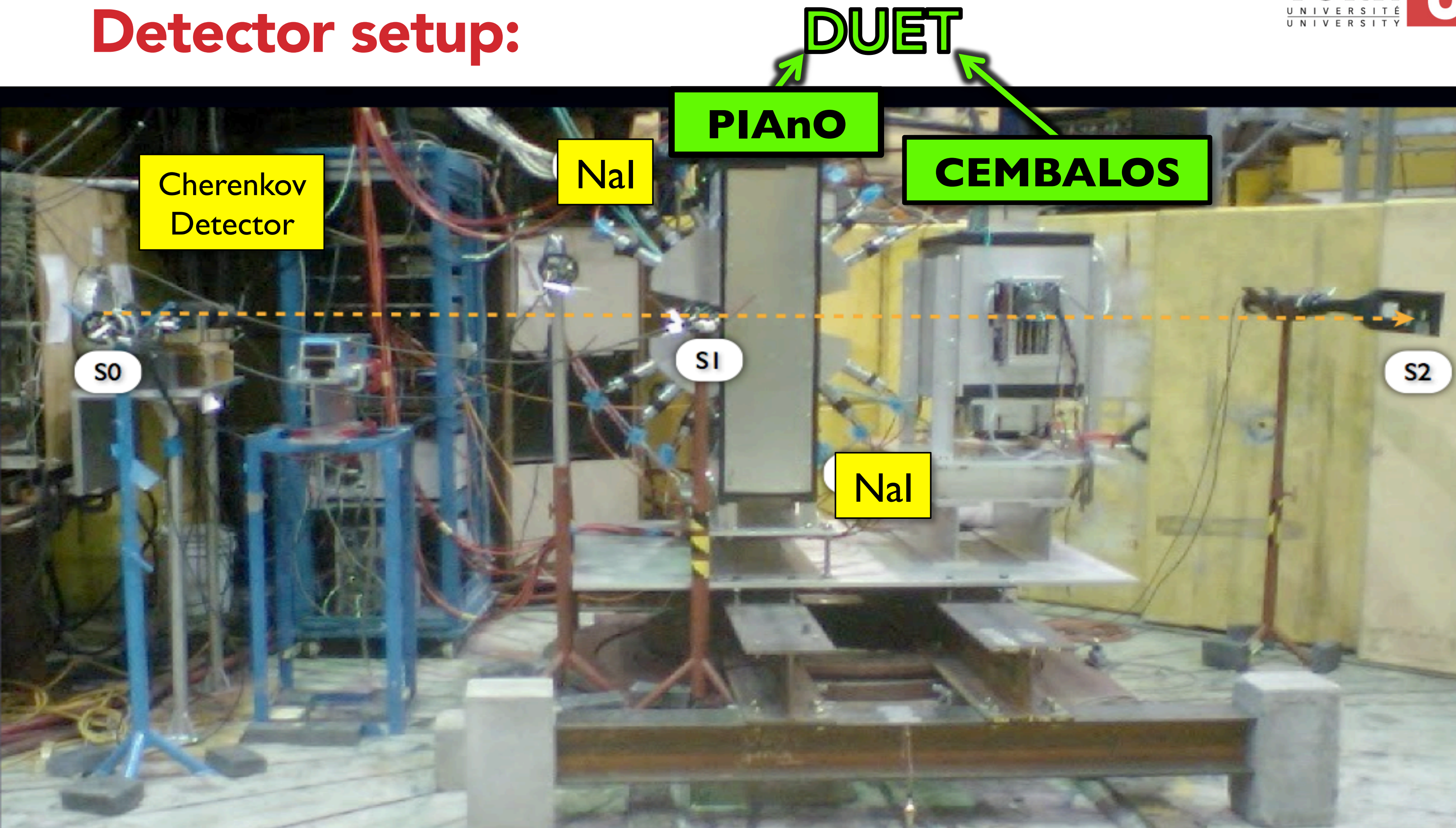
[9]*State University of New York at Stony Brook, Department of Physics and Astronomy, Stony Brook, New York, USA*

# Data taking

- ❖ Data taken in summers of 2010~2012
- ❖ ~1 million $\pi^+$ triggers for each momentum setting

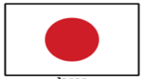


# Detector setup:



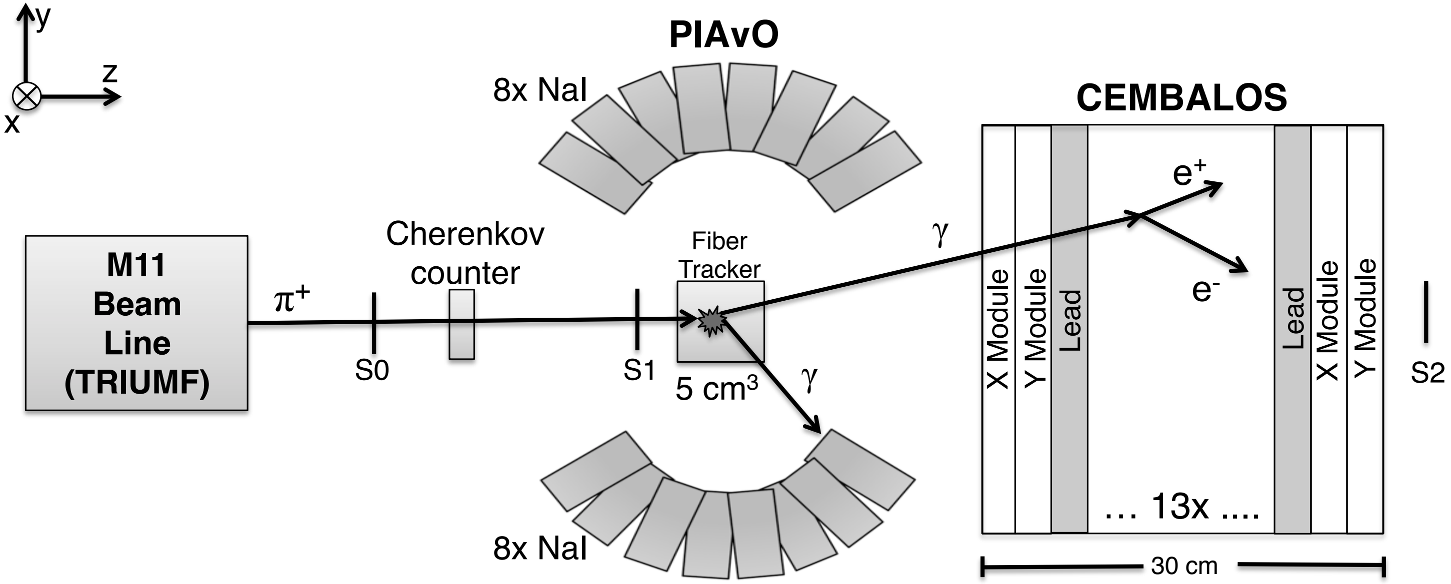
# Detector setup: DUET

❖ Main Components:



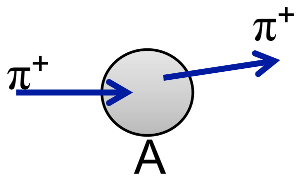

**PIAnO**: 5 $cm^3$ scintillating fiber tracker (Full active target) + NaI crystals

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

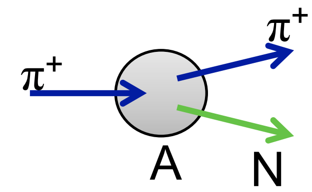


# Sub-GeV Pion Inelastic Interaction Modes

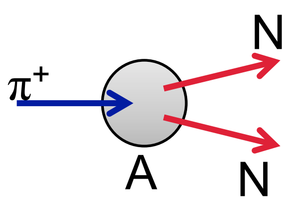
1. Elastic Scattering



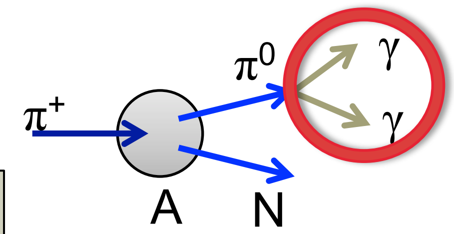

2. Quasi-elastic Scattering




3. Absorption (ABS)




4. Charge Exchange (CX)




Can measure combined ABS+CX

No $\pi^+$ in final state

# Sub-GeV Pion Inelastic Interaction Modes

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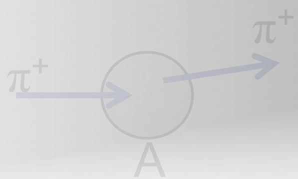
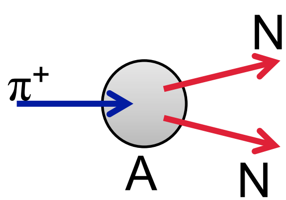



2. Quasi-elastic Scattering


Reject $\pi^+$ in final state

3. Absorption (ABS)

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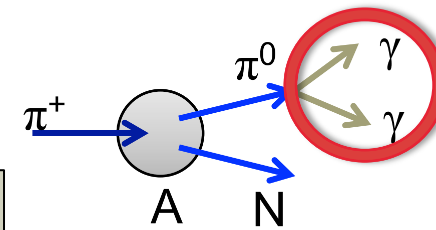
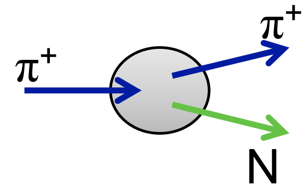



Can measure combined ABS+CX

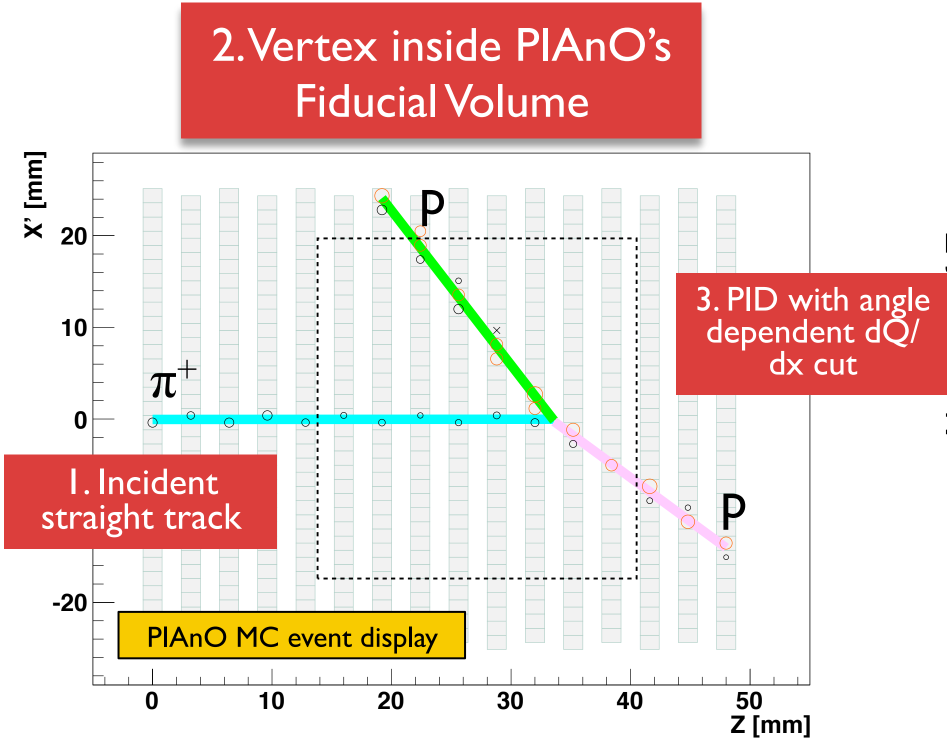
No $\pi^+$ in final state

# Combined ABS+CX selection using PIAnO

Reject: 

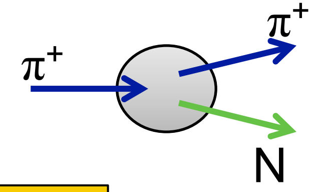

Phys. Rev. C **92**, 035205 (2015)

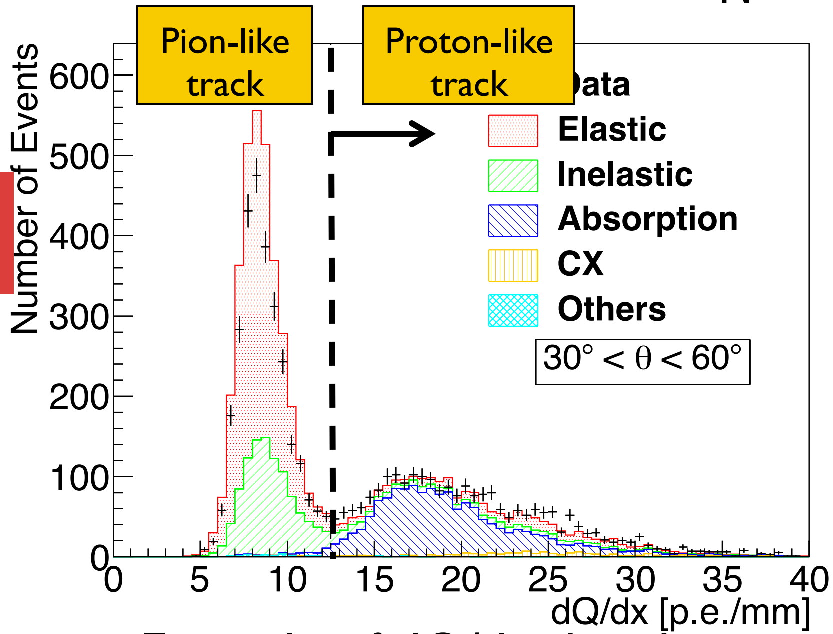
# Event Selection: No $\pi^+$ in final state




Sample $\pi^+$ ABS interaction in PIAnO

Reject:



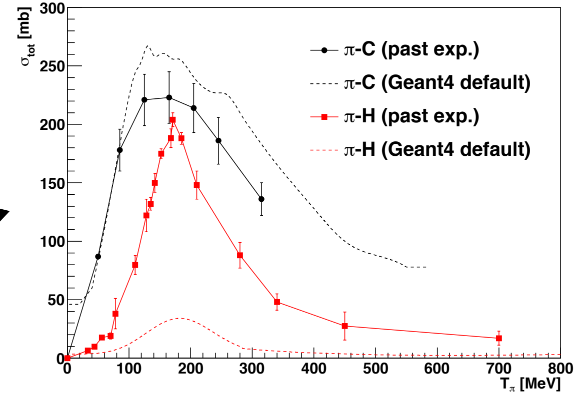



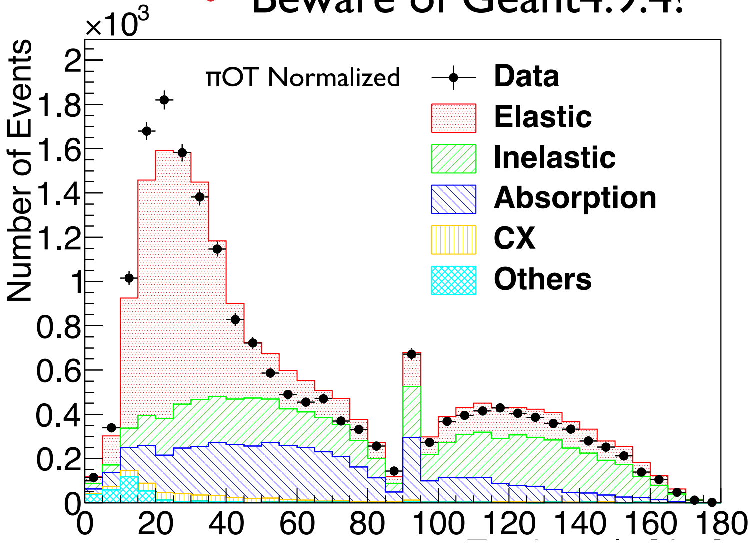

Example of dQ/dx distribution

# Event Selection: Data vs. MC comparisons

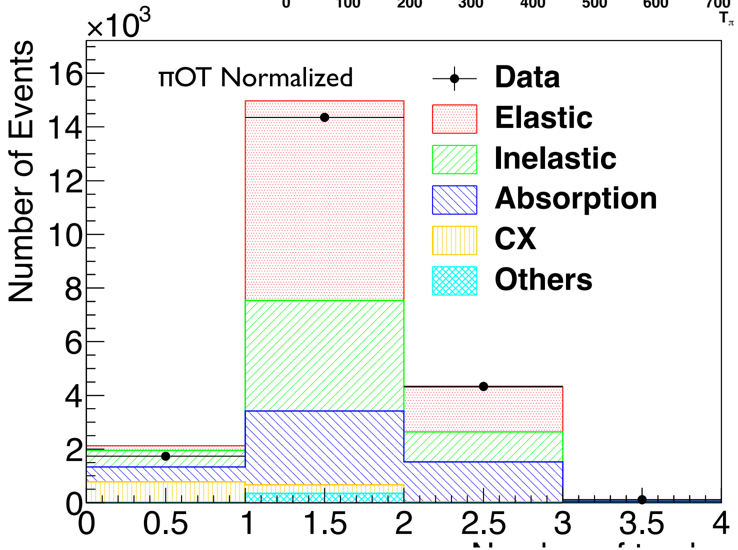
❖ Good agreement of distributions before applying the "no π⁺ in final state" cut:

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



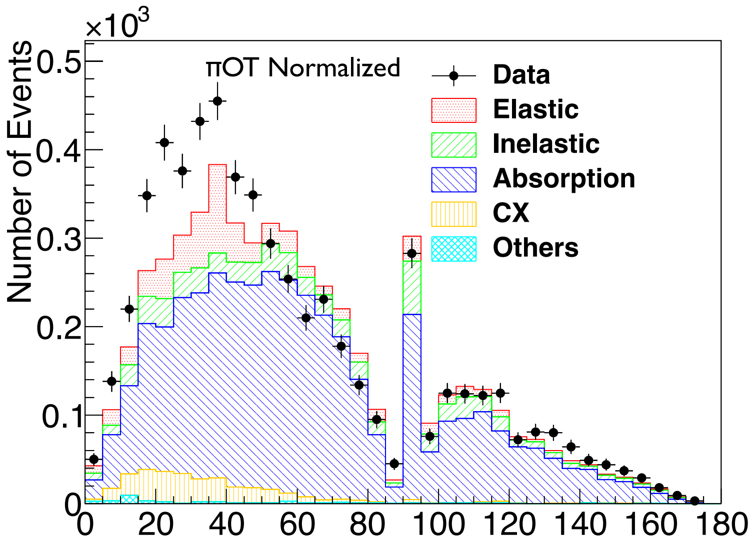

Reconstructed track Polar Angle [deg]



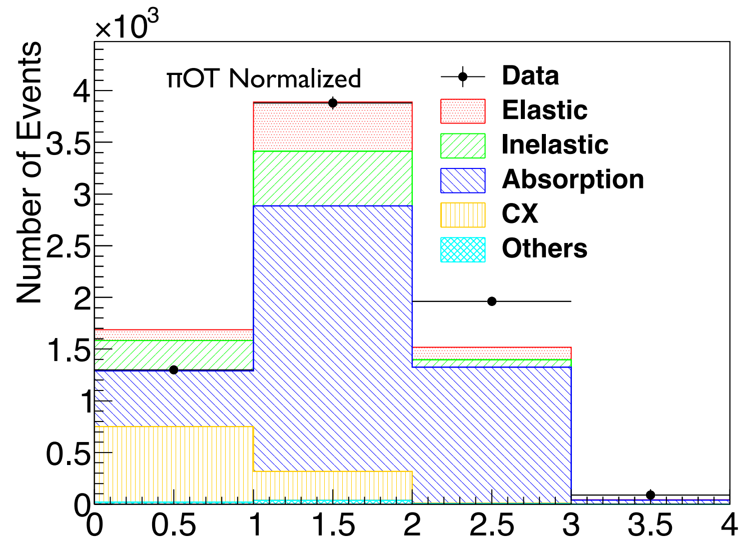

Number of reconstructed tracks

# Event Selection: Data vs. MC comparisons

- For 238MeV/c $\pi^+$ 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.




Reconstructed track Polar Angle [deg]



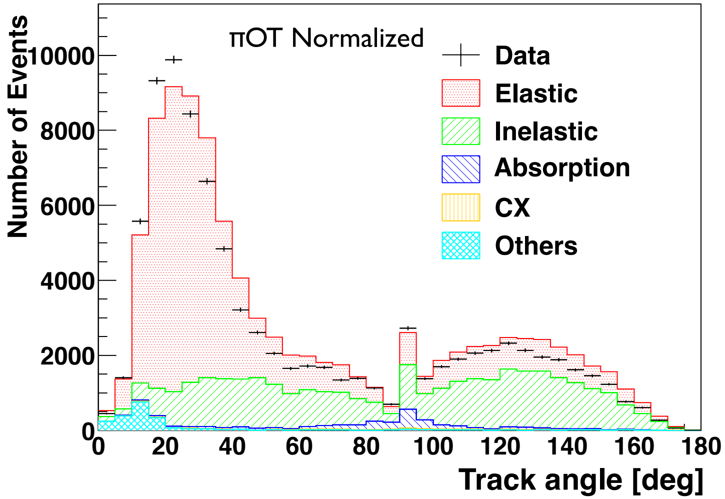

Number of reconstructed tracks

# Uncertainties

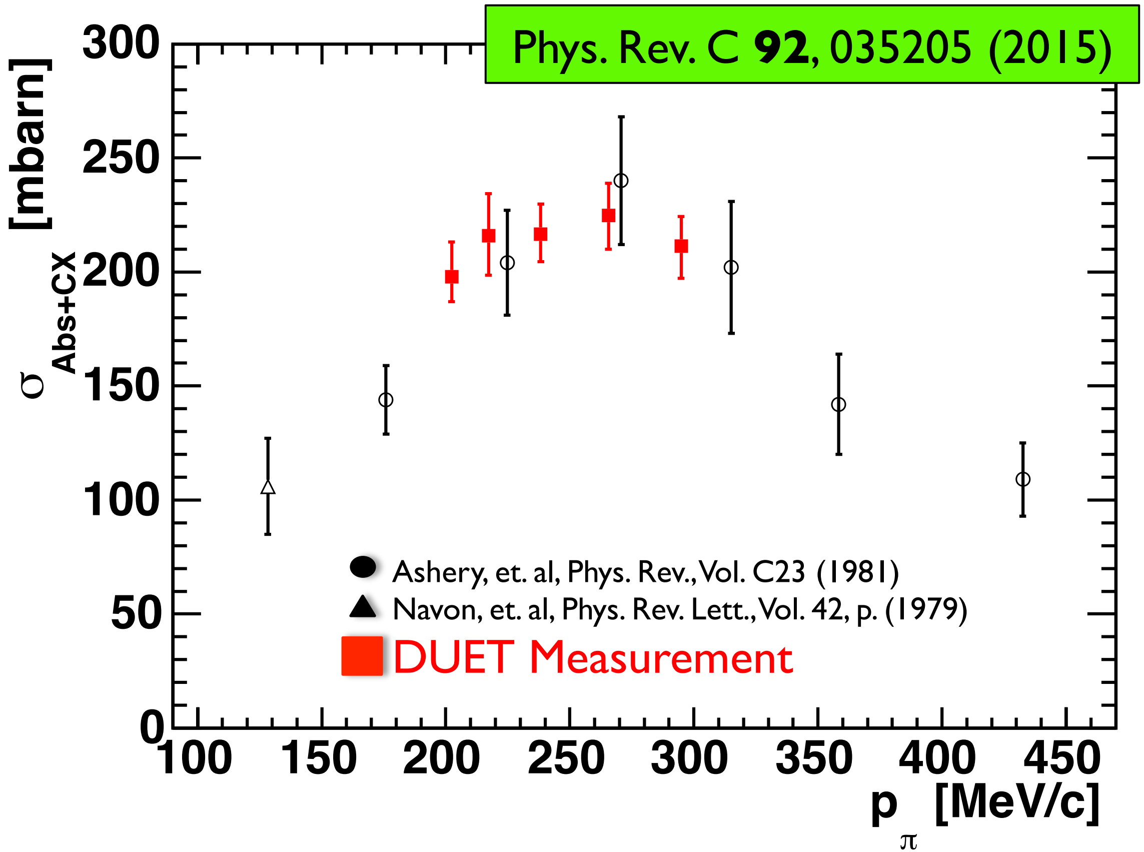
| | $p_\pi$ at the fiber tracker [MeV/c] | | | | |
|---|---|---|---|---|---|
| | 201.6 | 216.6 | 237.2 | 265.5 | 295.1 |
| **Systematic errors** | | | | | |
| Beam profile | 0.9 | 1.2 | 1.0 | 0.6 | 1.2 |
| Beam momentum | 1.6 | 1.7 | 0.7 | 0.8 | 1.4 |
| Fiducial Volume | 1.1 | 3.9 | 1.4 | 1.2 | 1.3 |
| 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

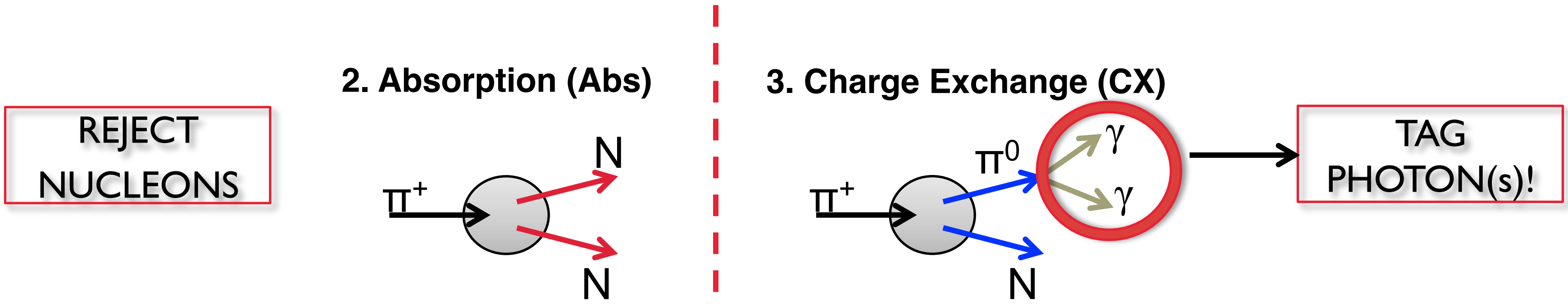


# ABS+CX Cross Section Result




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

# Extracting the CX cross section



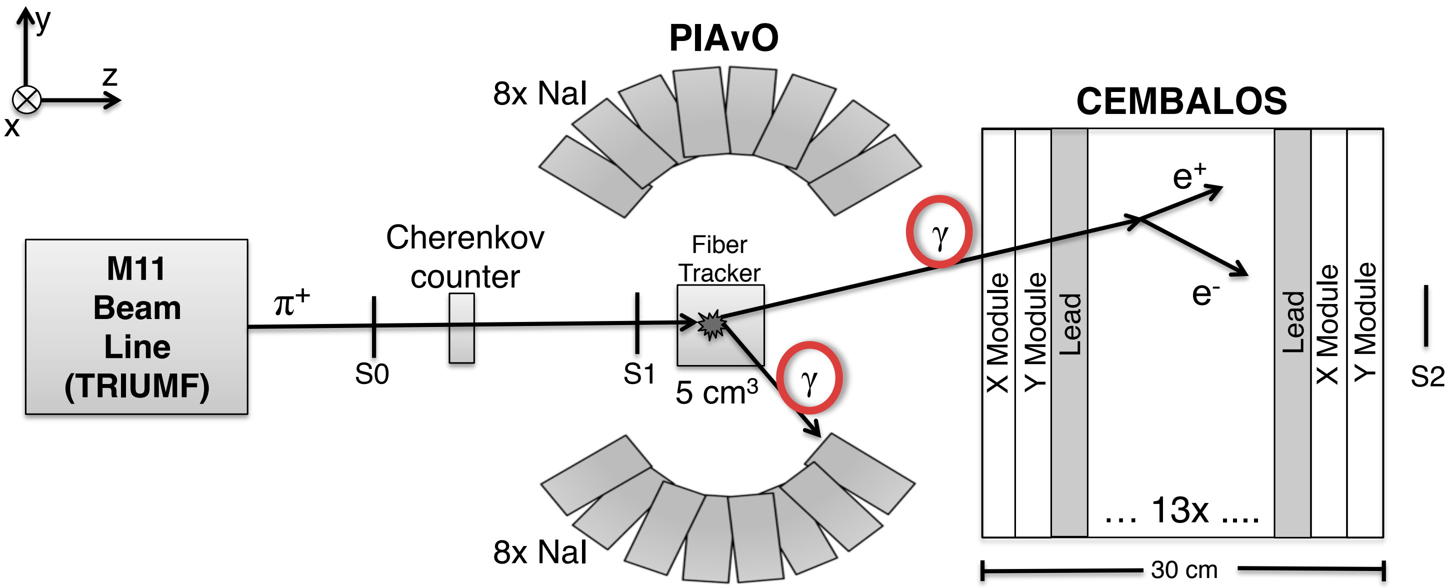
# Detector setup: DUET

❖ Main Components:

Japan

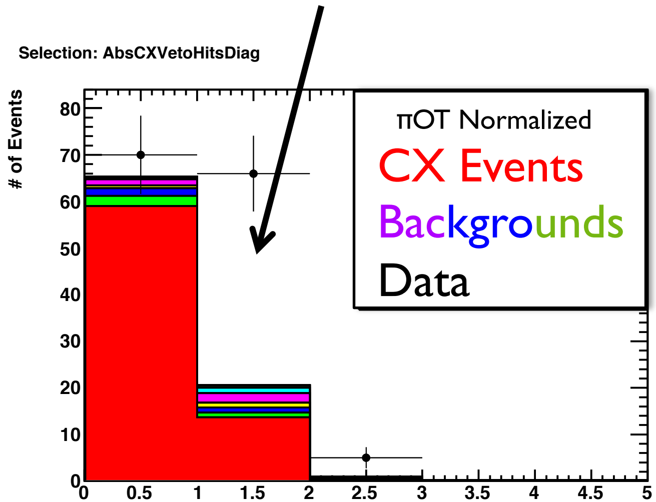
**PIAnO**: 5 cm$^3$ scintillating fiber tracker (Full active target) + NaI crystals

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

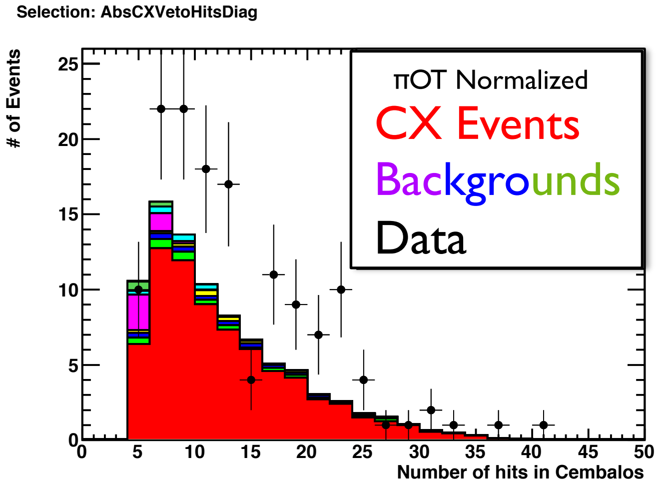


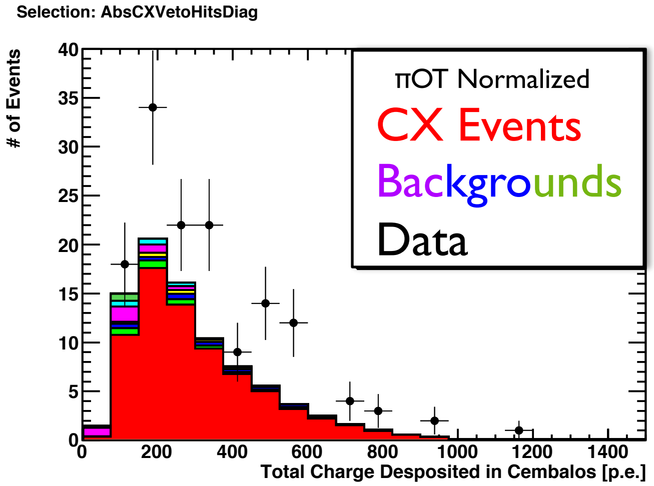
# CX Event Selection: Data vs. MC

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



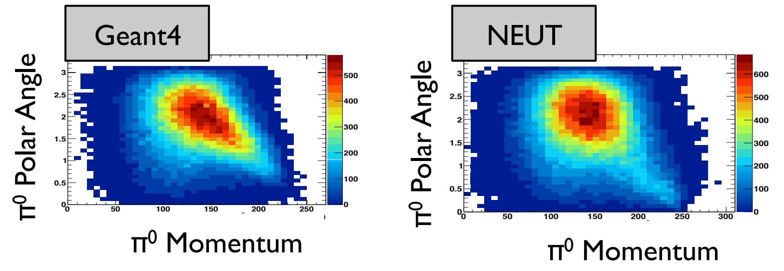

Number of tracks in Piano

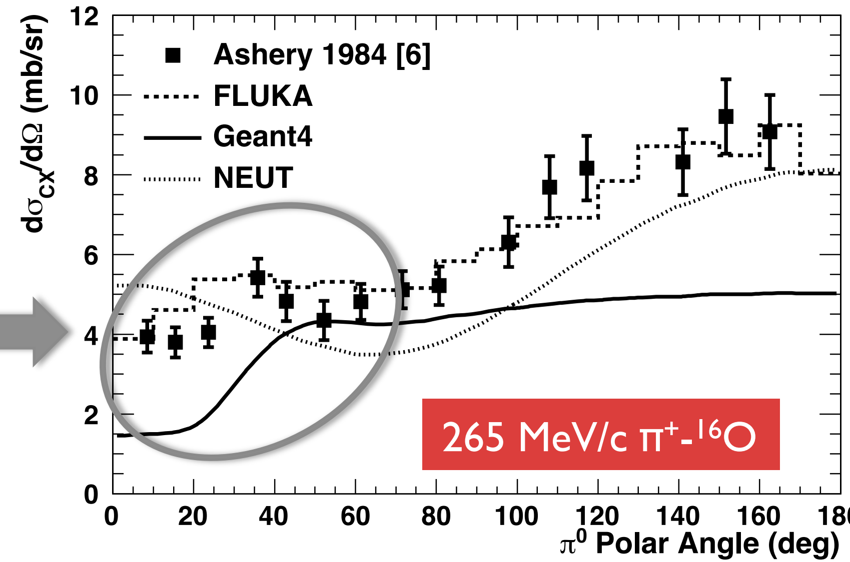


# CX Modeling

- 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



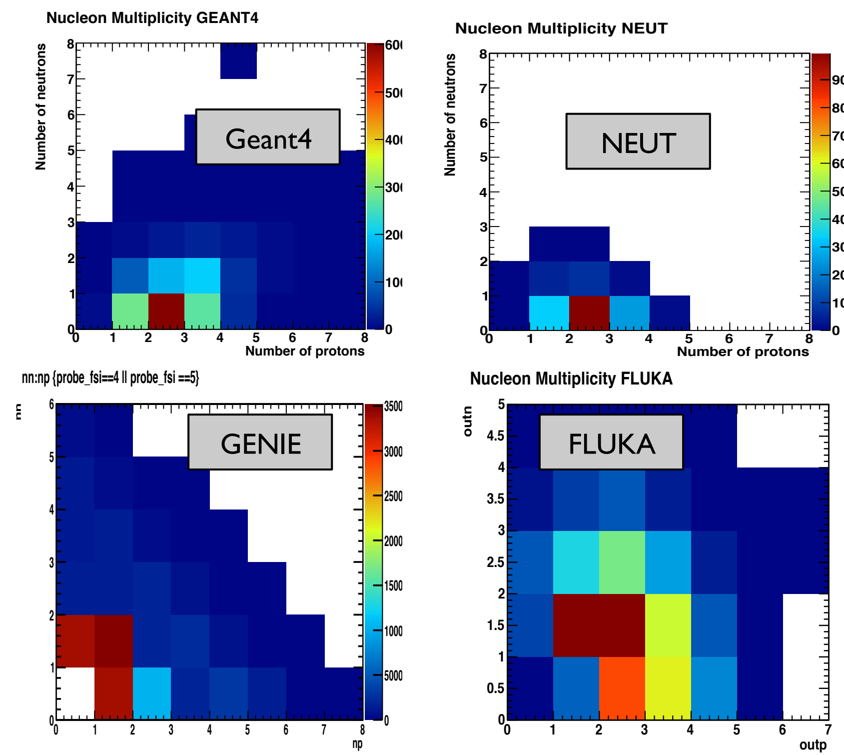



# Nucleon ejection (ABS background)

- ❖ 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 π-{N,Ar} data

- ❖ High purity of CX selection means this effect is not dominant
  - But it still troubling



# $\sigma_{CX}$, $\sigma_{ABS}$ 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:

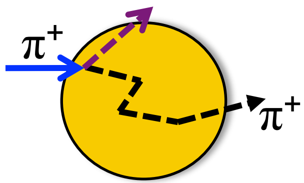
- For each model estimate:
  1. $N_{cx}^{MC}$ (# of signal events)
  2. $N_{BG}^{MC}$ (# of background events)

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

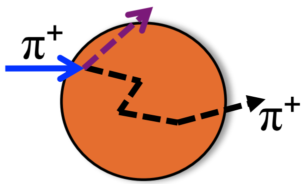
- A more general (reasonable) one is:

# Detector Acceptance/ Resolution Tool

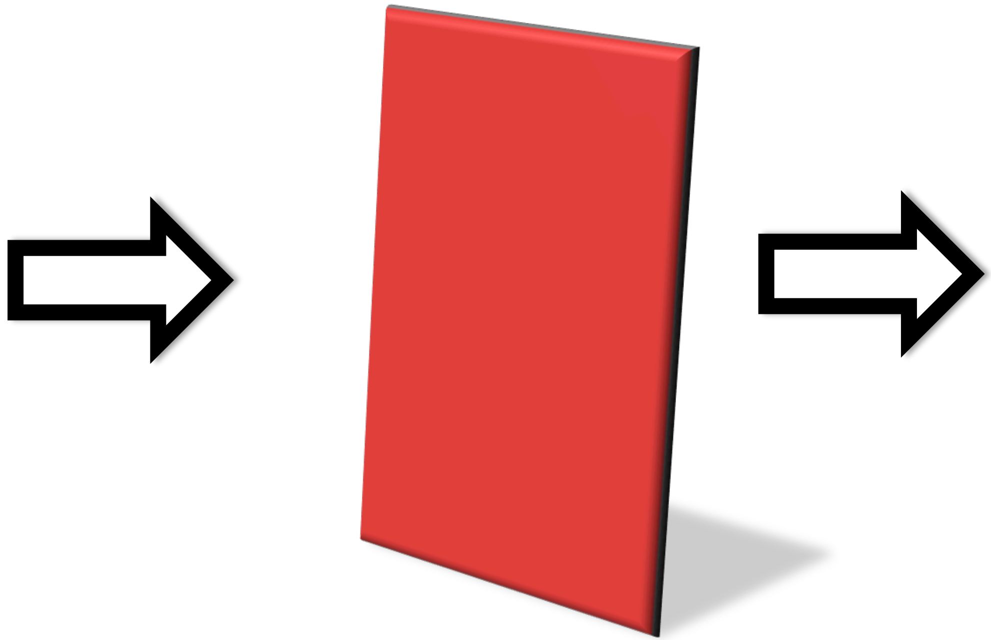
Model A




Model B




Model X



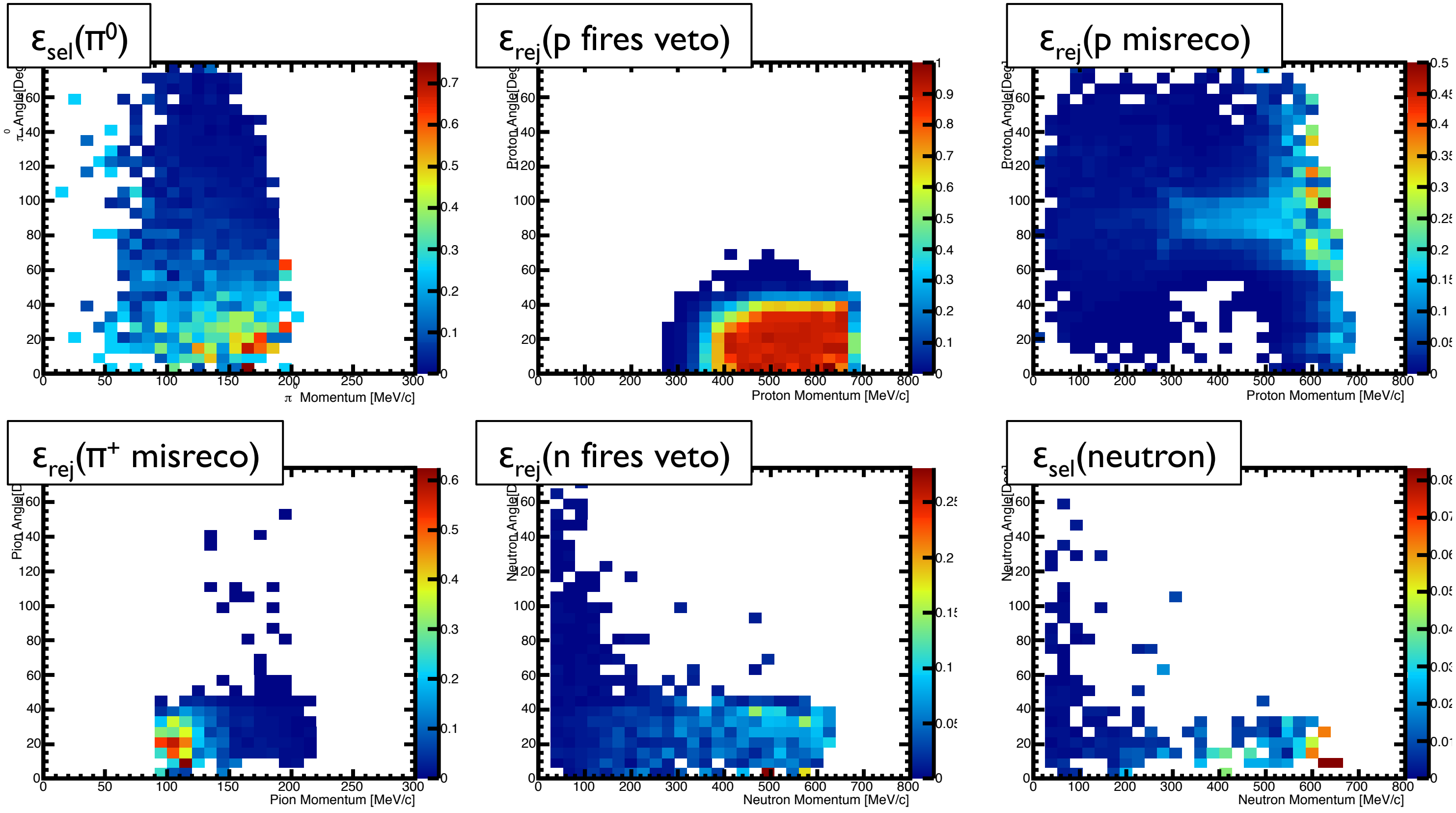
$N_{cx}^{MC}$
(# signal events)

$N_{BG}^{MC}$
(# bckg events)

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

# Selection and Rejection Efficiencies

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

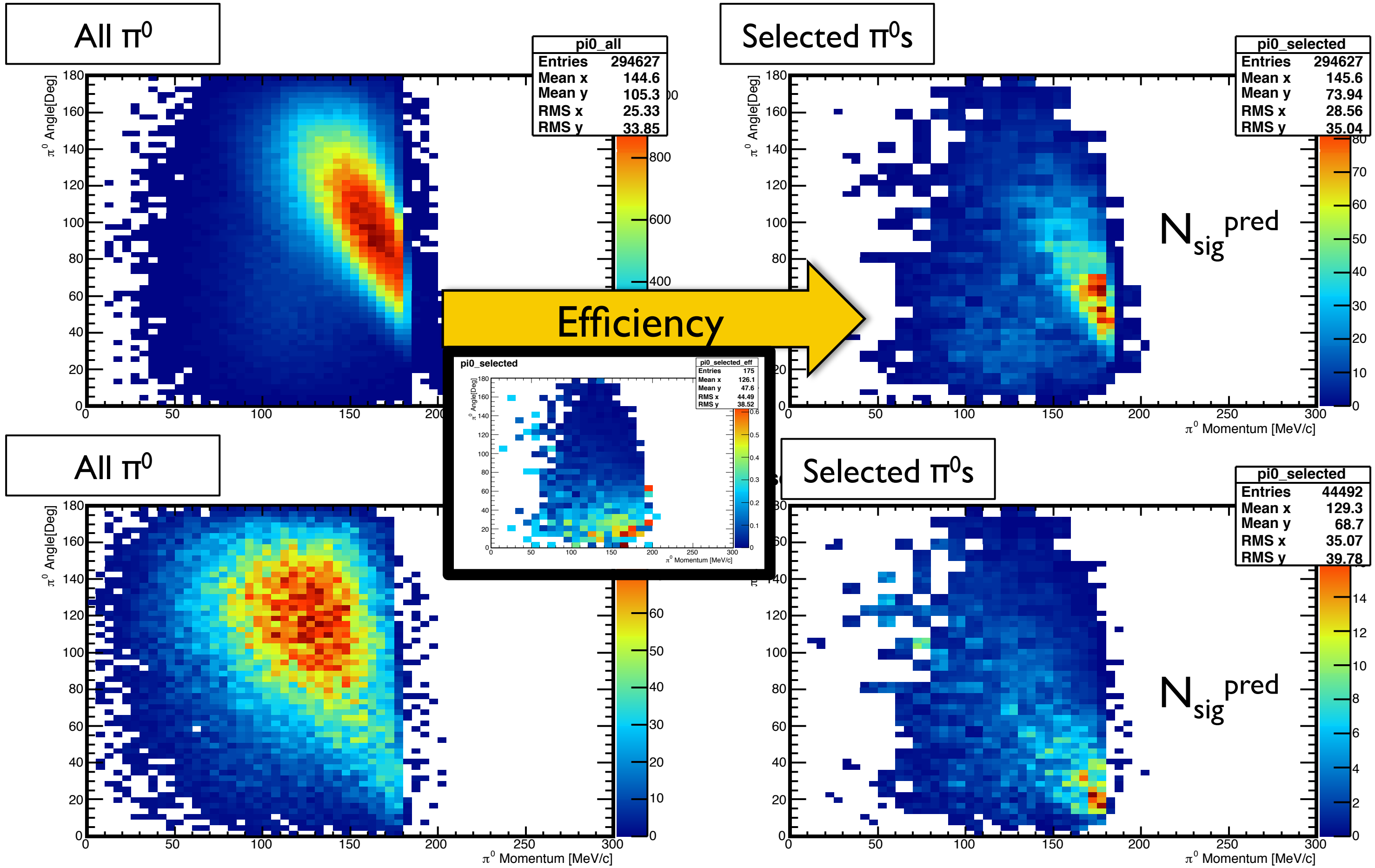


# Example: 201.6 MeV/c

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

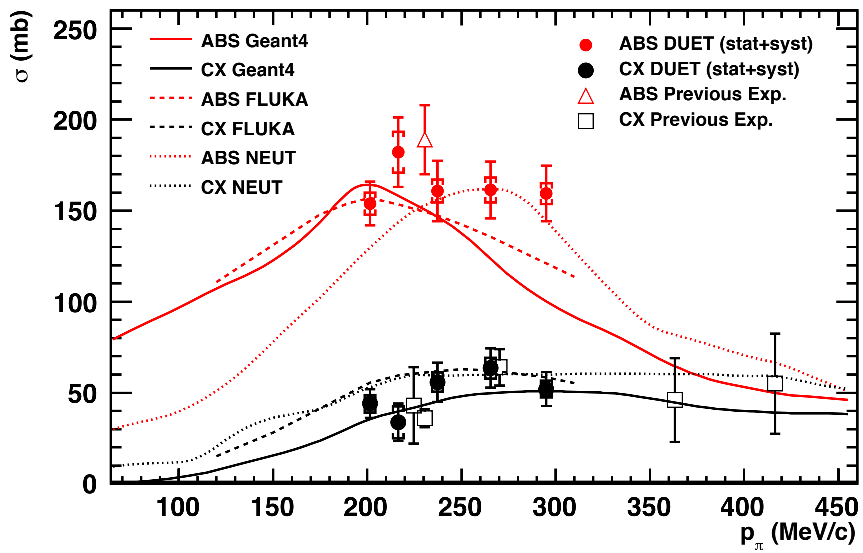
| $p_\pi$ [MeV/$c$] | Model | $\sigma_{CX}^{MC}$ [mb] | $N_{\mathrm{CX}}^{\mathrm{MC}}$ | $N_{\mathrm{BG}}^{\mathrm{MC}}$ | $\sigma_{CX}$ [mb] |
|---|---|---|---|---|---|
| 201.6 | GEANT4 | 36.7 | 63.3 | 6.1 | 58.0 |
| | FLUKA | 55.5 | 122.2 | 6.3 | 45.3 |
| | NEUT | 50.5 | 83.0 | 4.5 | 61.8 |
| 216.6 | 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

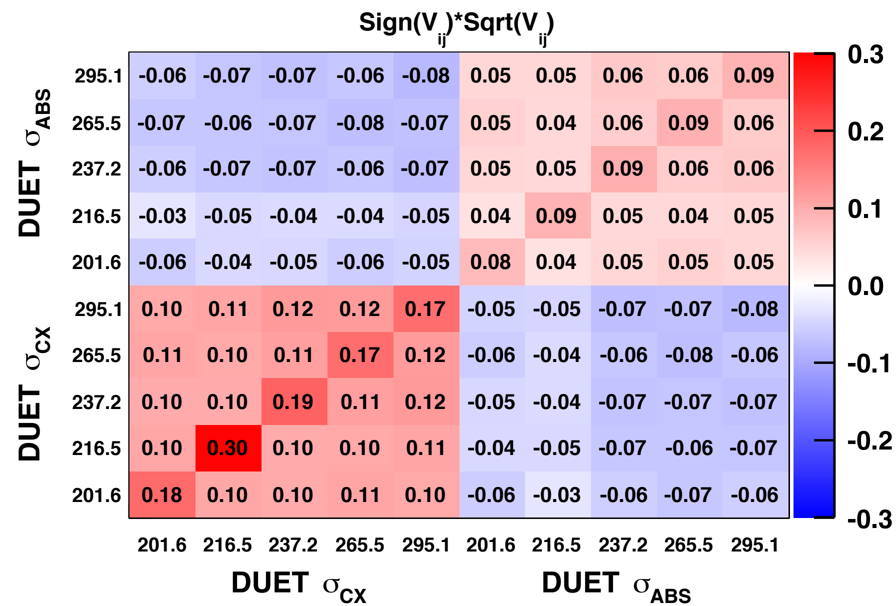
| | CX | | | | | ABS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $\pi^+$ **Momentum [MeV/c]** | 201.6 | 216.6 | 237.2 | 265.5 | 295.1 | 201.6 | 216.6 | 237.2 | 265.5 | 295.1 |
| **Beam Systematics** | | | | | | | | | | |
| Beam profile | 3.5 | 4.9 | 6.2 | 4.2 | 2.0 | 2.2 | 2.7 | 3.8 | 2.9 | 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 |
| **Pia$\nu$o 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 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 |
| **Harpsichord Systematics** | | | | | | | | | | |
| Harpsichord Charge | 1.7 | 1.6 | 3.7 | 3.1 | 6.7 | 1.3 | 1.1 | 2.0 | 1.7 | 2.5 |
| Harpsichord Hit Inefficiency | 1.6 | 2.1 | 1.1 | 1.3 | 2.0 | 1.2 | 1.1 | 1.1 | 1.0 | 0.9 |
| Harpsichord Alignment | 7.7 | 7.9 | 8.3 | 5.7 | 4.6 | 0.7 | 1.0 | 0.7 | 0.7 | 1.0 |
| **Physics Systematics** | | | | | | | | | | |
| 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 |
| **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 | 8.0 | 11.0 | 10.5 | 9.8 | 9.8 |

# ABS, CX Result

Similarly sized error bars,
but extended coverage in Δ region




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



# Final Remarks

- DUET measured $\pi^+$-$^{12}C$ interaction cross-sections
  - Using the M11 pion beam line at TRIUMF

- First paper reported a combined Absorption + Charge Exchange cross section consistent with previous results and have much smaller errors (~20% → ~7%)
  - **Phys. Rev. C 92, 035205**

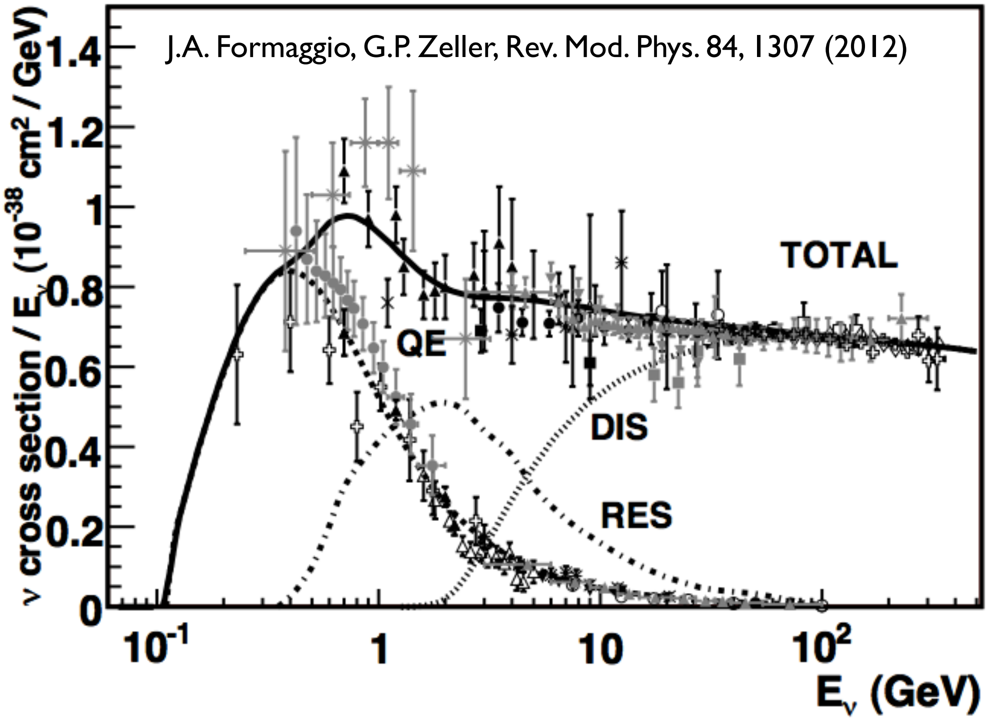
- New results with separate Absorption and Charge Exchange cross sections
  - To be submitted soon

- This will feed into a better model of pion Final State Interactions and Secondary Interactions
  - Reduce systematics for current and future neutrino experiments

# BACKUP

# GeV ν Experiments on Nuclear Targets

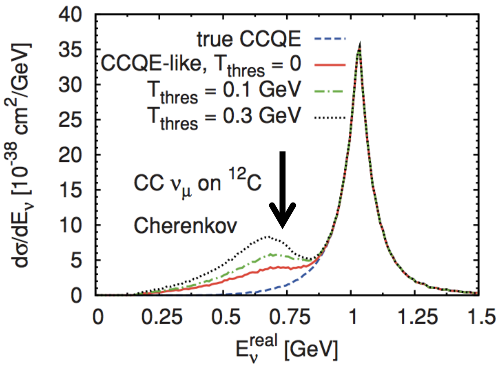
- Reconstructing the ν flavour and its energy is fundamental for accelerator ν experiments
  - For both oscillation and cross section analyses



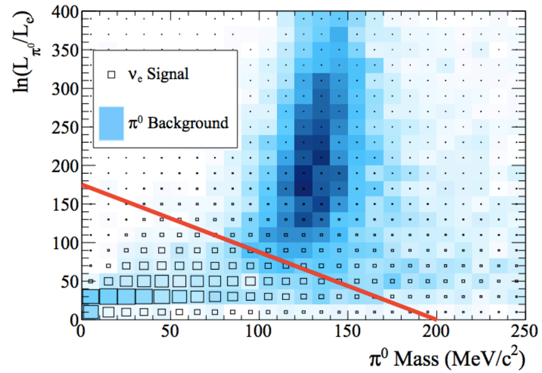
# Effects of π FSI/SI

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

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

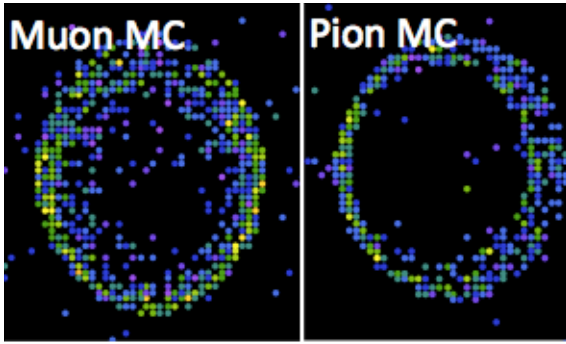



## 3. $\pi^0$ Background to $\nu_e$ appearance [PRL 112, 061802 (2014)]



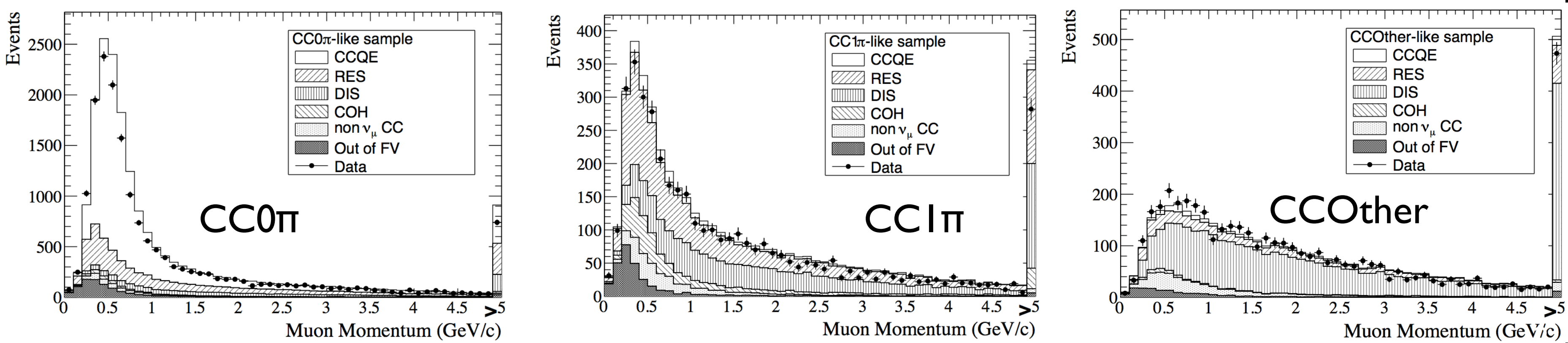

## 4. π Reconstruction @ SK

"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]



# TRIUMF

- Canada's national laboratory for nuclear and particle physics research and accelerator-based science.

- Located on the campus of the University of British Columbia in Vancouver.
- At its core is a 500 MeV cyclotron that delivers a beam of primary protons
  - Magnet diameter: 18 m
  - In operation for 40+ years
- Multiple secondary beam lines give life to many experiments and diverse applications

Cyclotron magnet and staff, 1972

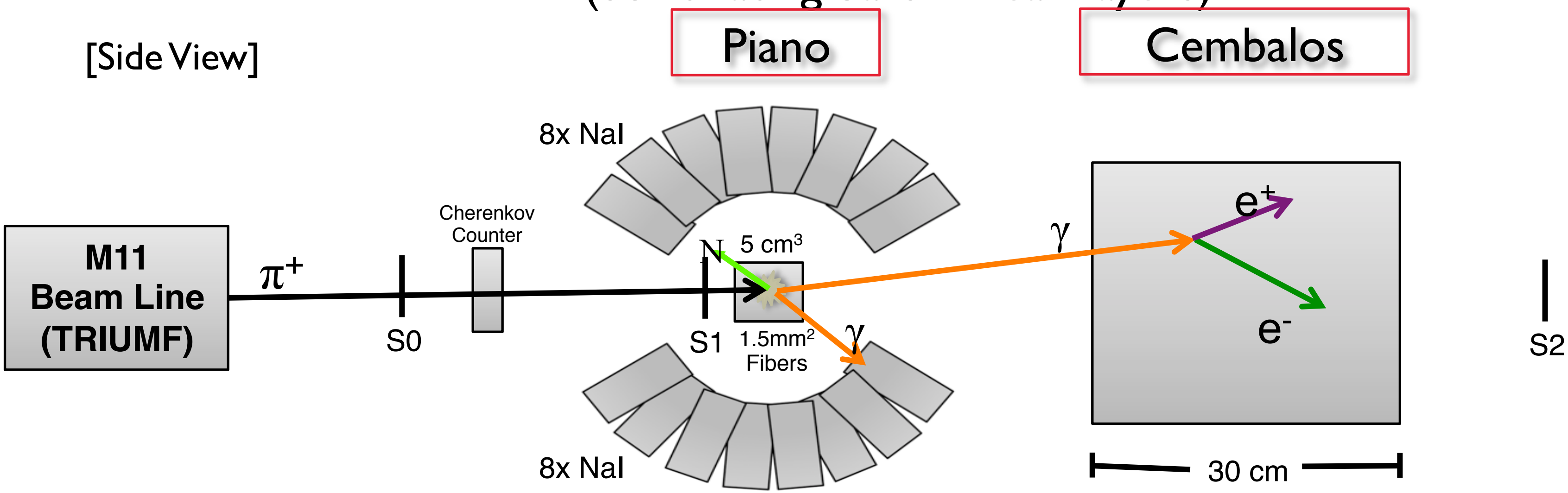
# Detector setup: DUET

❖ Main Components:

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

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

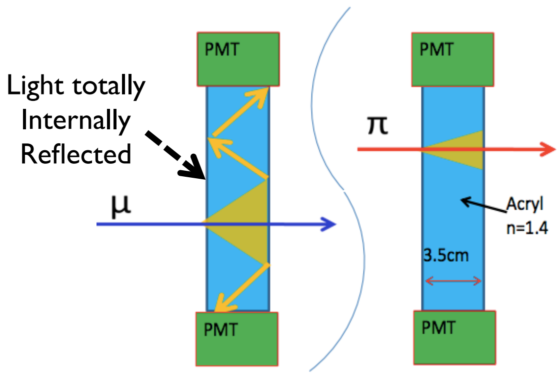
[Side View]

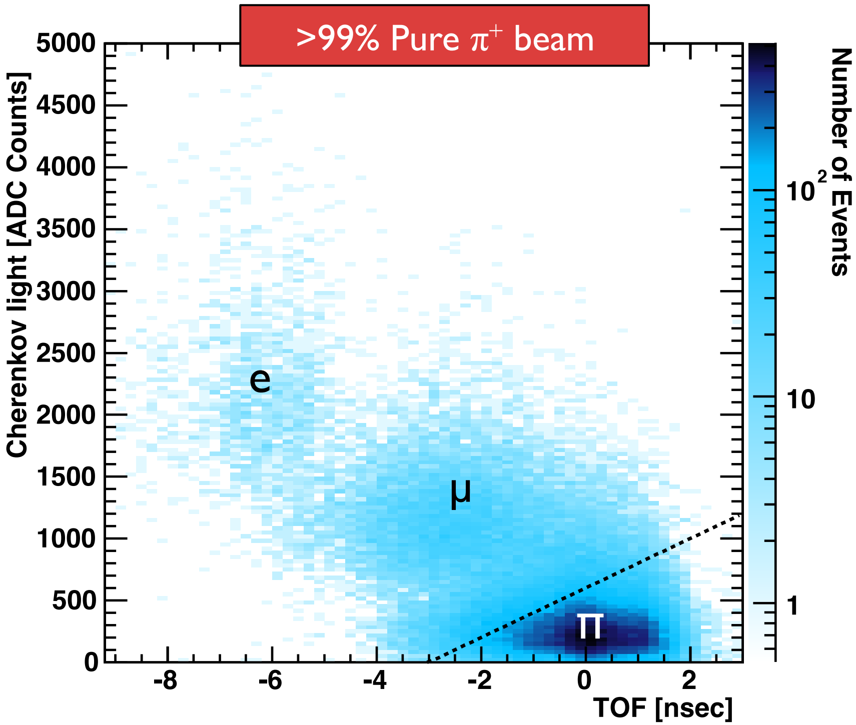



Sample CX Interaction

# 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 $\pi^+$ 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.

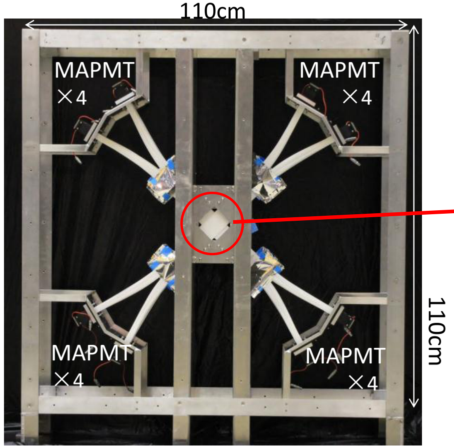


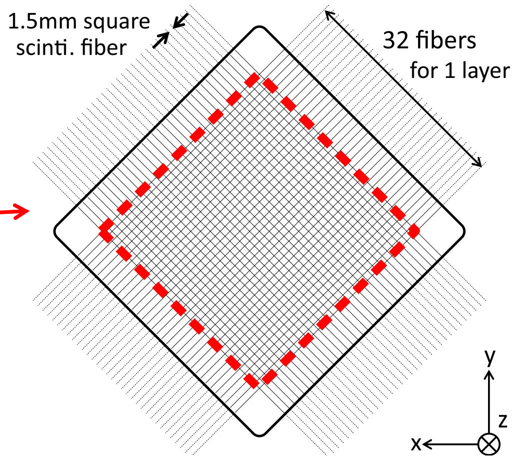



# PIAnO Fibers

- 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 TiO2 fiber coating and support structure

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

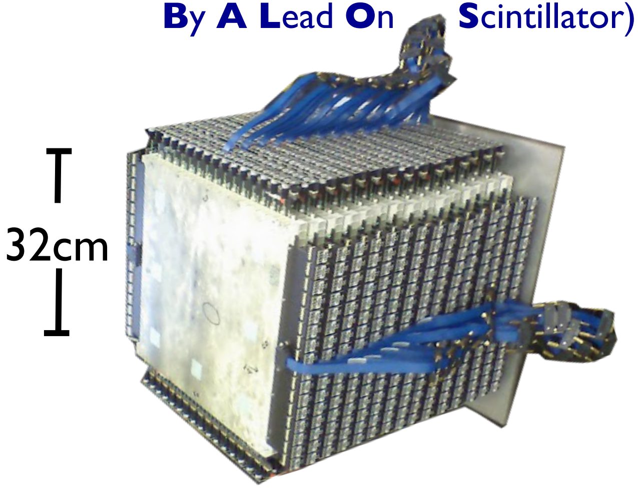


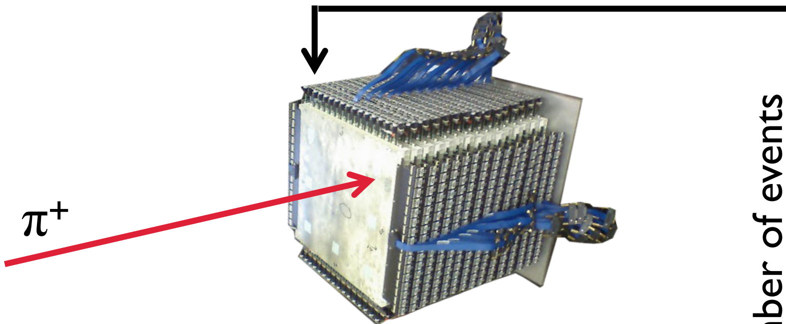
# CEMBALOS

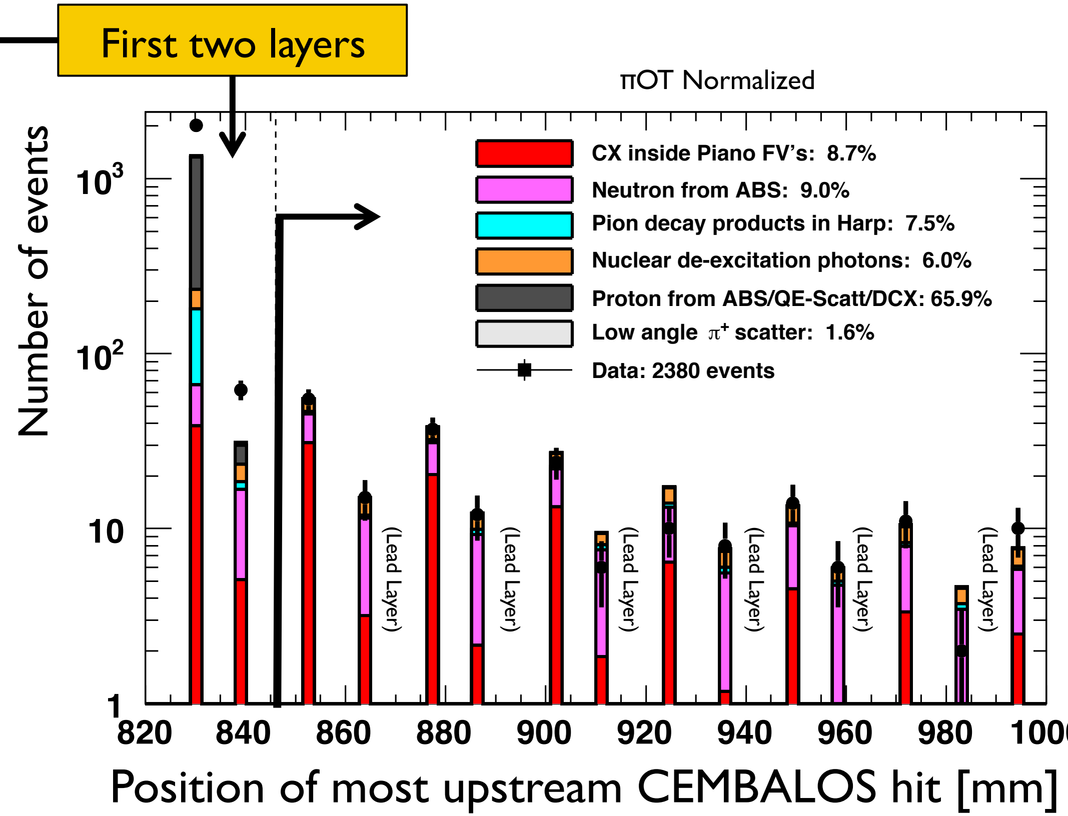
(**C**harge **E**xchange **M**easurement **B**y **A** **L**ead **O**n **S**cintillator)

- 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



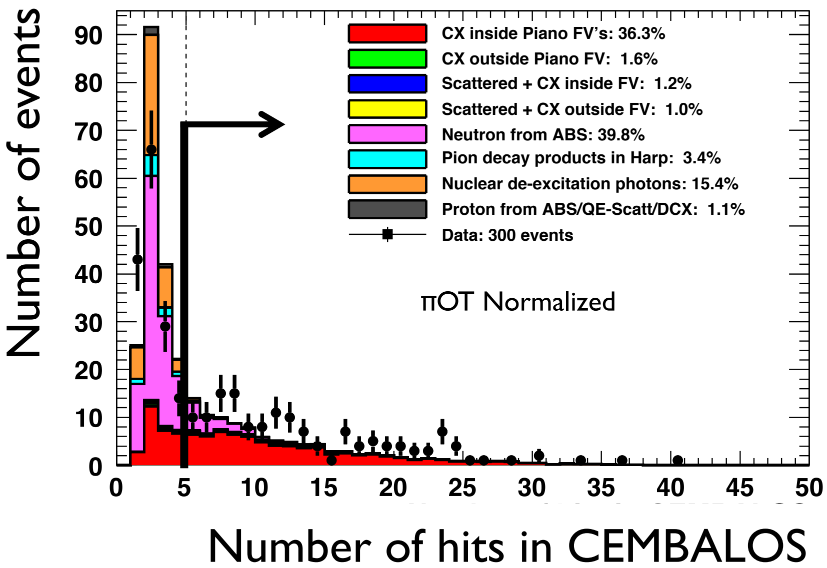

# CX Event Selection: Using CEMBALOS

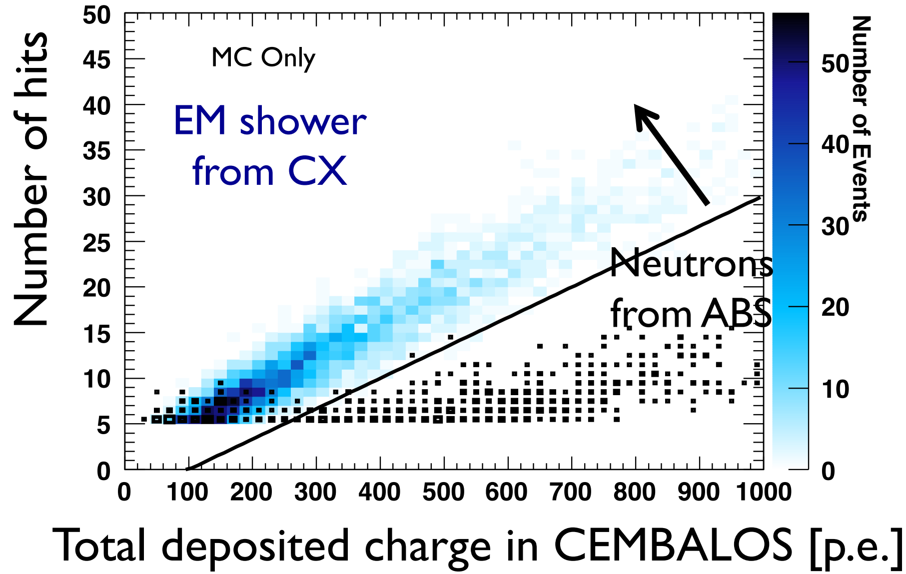



- Charged **pions** and **protons** immediately leave a signal in the scintillating detector
- **Photons** are neutral, so they must interact before they can be detected
- The **first two layers** are used as a **veto cut** in order to remove charged background

# 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

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

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

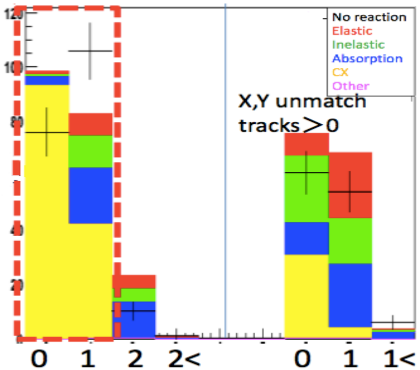
- **~100 events in data sample**

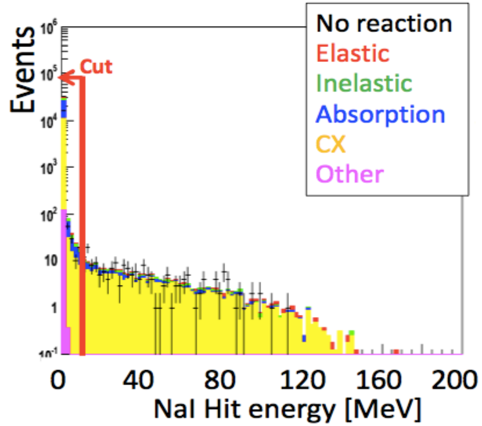
**(~20 for 216.6 MeV/c)**

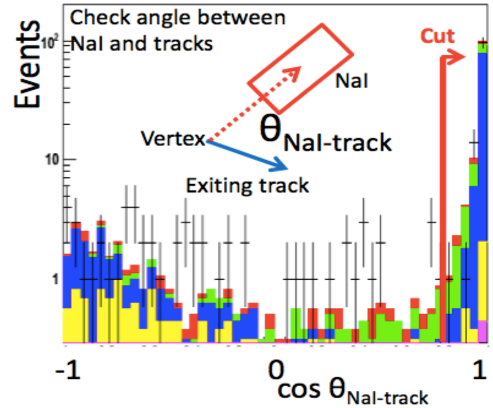
# CX Event Selection: Using NaI Crystals

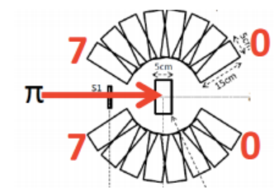
M. Ikeda, ICCR

All plots normalized to # of incident pions



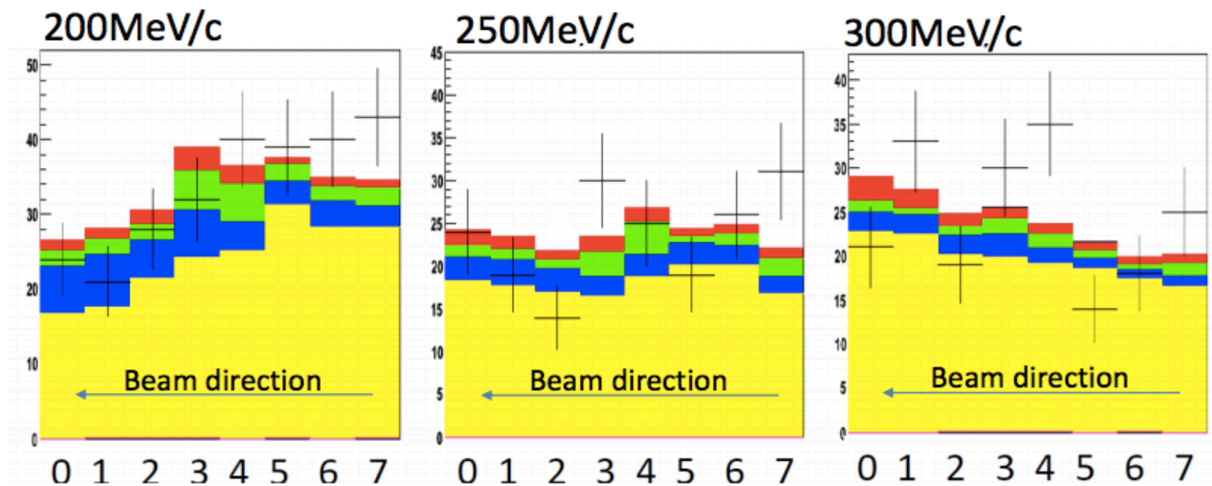




**Selection Criteria:**

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

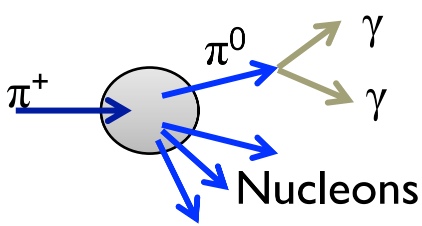



- ❖ $\pi^0$ Angular distribution reweighted to FLUKA
- ❖ Confirmed momentum dependence of CX photon angle

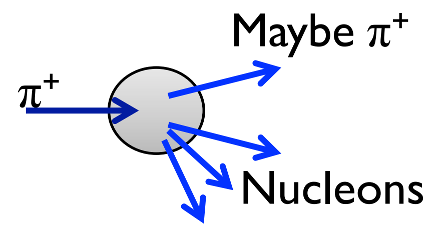
# "Efficiencies" Scheme

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

- **Sample Signal Event**




- **Sample Background Event**




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

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

# Applying to thin target

$$\sigma_{\mathrm{CX}} = \sigma_{\mathrm{CX}}^{\mathrm{MC}} \times \frac{N_{\mathrm{Data}} - N_{\mathrm{BG}}^{\mathrm{MC}}}{N_{\mathrm{CX}}^{\mathrm{MC}}} \times \frac{1 - R_{\mathrm{TiO_2}}^{\mathrm{Data}}}{1 - R_{\mathrm{TiO_2}}^{\mathrm{MC}}} \times \frac{1}{1 - f_{\mu}}, \quad (1)$$

(Model-G4)/G4 *100

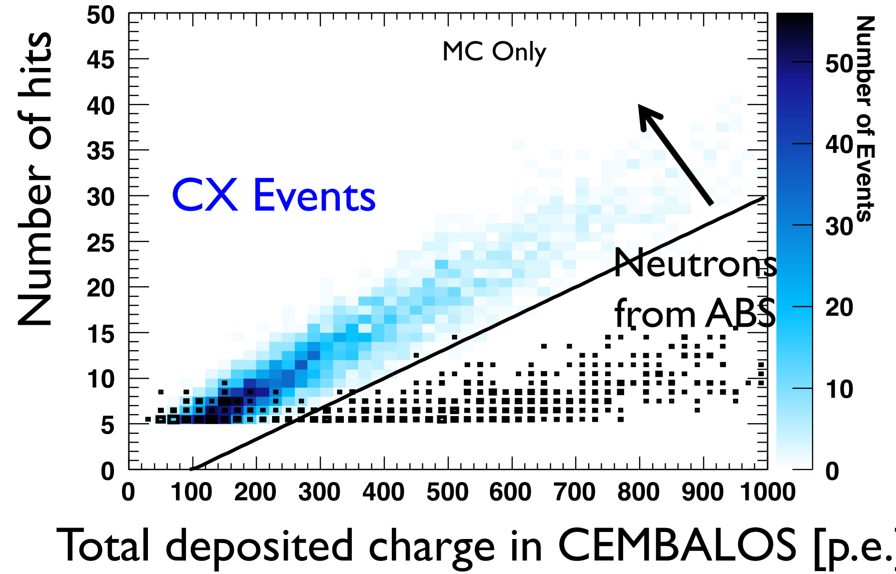
| Model | $p_{\pi^+}$ (MeV) | Incident | $\sigma_{CX}^{pred}$ (mb) | $N_{sig}^{pred}$ | $N_{BG}^{pred}$ | $\sigma_{CX}$ (mb) | $\Delta_{G4}$ |
|---|---|---|---|---|---|---|---|
| DUET | 200 | 1.387e+07 | 34.3 | 60.4 | 8.7 | 59.1 | 2.0 |
| Geant4 | 200 | 8.000e+08 | 36.7 | 63.3 | 6.1 | 58.0 | 0.0 |
| FLUKA | 200 | 8.000e+07 | 55.5 | 122.2 | 6.3 | 45.3 | -21.9 |
| NEUT | 200 | 4.000e+08 | 50.5 | 83.0 | 4.5 | 61.8 | 6.7 |
| DUET | 225 | 1.027e+07 | 34.9 | 15.8 | 2.4 | 42.5 | 2.2 |
| Geant4 | 225 | 8.000e+08 | 37.5 | 16.5 | 2.0 | 41.6 | 0.0 |
| FLUKA | 225 | 8.000e+07 | 59.5 | 32.5 | 1.5 | 34.4 | -17.2 |
| NEUT | 225 | 8.000e+08 | 55.7 | 24.2 | 1.5 | 43.5 | 4.6 |
| DUET | 250 | 1.130e+07 | 36.8 | 75.9 | 11.1 | 68.2 | 4.3 |
| Geant4 | 250 | 8.000e+08 | 39.6 | 80.0 | 9.7 | 65.4 | 0.0 |
| FLUKA | 250 | 8.000e+07 | 61.7 | 149.4 | 5.8 | 56.1 | -14.1 |
| NEUT | 250 | 8.000e+08 | 57.5 | 111.7 | 6.1 | 69.8 | 6.8 |
| DUET | 275 | 1.253e+07 | 41.3 | 87.1 | 10.5 | 72.4 | 1.4 |
| Geant4 | 275 | 8.000e+08 | 44.7 | 88.8 | 9.6 | 71.4 | 0.0 |
| FLUKA | 275 | 8.000e+07 | 62.4 | 143.5 | 5.0 | 63.7 | -10.8 |
| NEUT | 275 | 8.000e+08 | 57.9 | 129.4 | 6.9 | 64.8 | -9.3 |
| DUET | 300 | 1.407e+07 | 41.6 | 119.4 | 12.8 | 56.5 | 2.5 |
| Geant4 | 300 | 8.000e+08 | 45.1 | 122.5 | 12.7 | 55.1 | 0.0 |
| FLUKA | 300 | 8.000e+07 | 58.5 | 176.2 | 5.6 | 52.0 | -5.7 |
| NEUT | 300 | 8.000e+08 | 58.3 | 170.3 | 8.4 | 52.7 | -4.5 |

Difference between DUET and Geant4 gives an idea of validity of scheme

6% ~ 22% Not included as systematic

# CX Event Selection: Using CEMBALOS

- Judicious cuts to remove charged background:
  - QE π 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




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

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

# 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

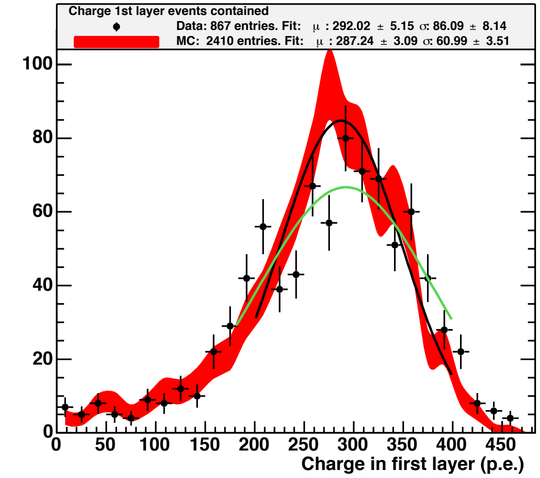
} Estimation procedures inherited from ABS+CX analysis

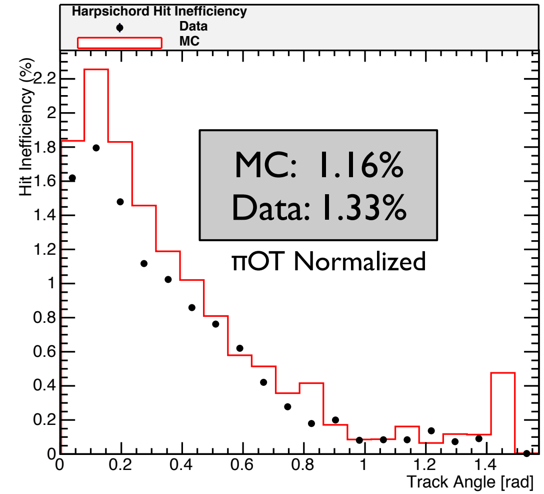
# Cembalos Detector Systematics

1. **Detector Alignment (5~8%)**
   - ±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

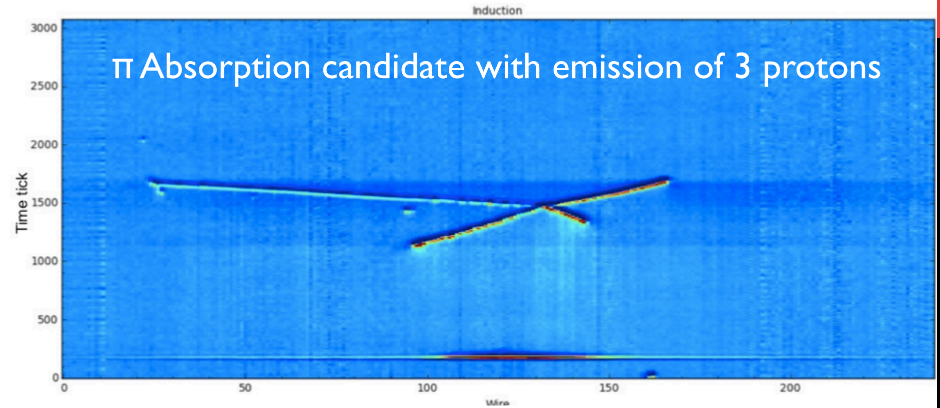


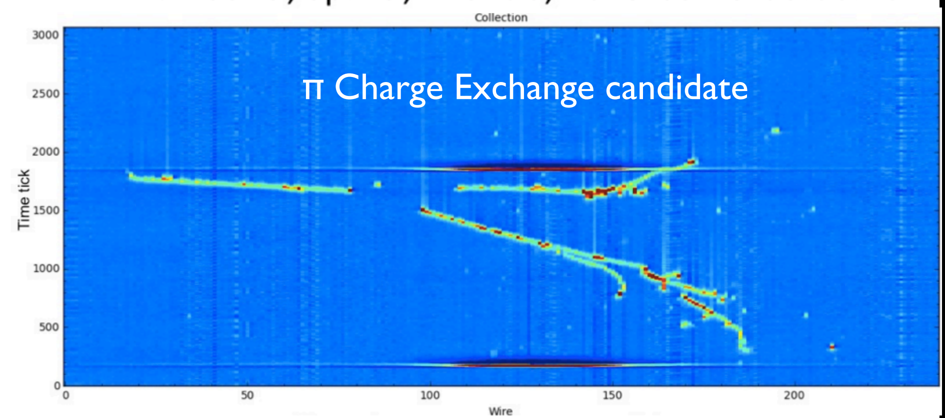
# π±-Argon measurements

- Liquid Argon detectors are an option for future long baseline experiments
  - π±-Ar measurements are necessary
- LArIAT shows promising π± interaction reconstruction capabilities
  - ArgoNEUT cryostat + LArTPC + improvements @ Fermilab Test Beam Facility (0.2~2GeV/c)
- Developing pion identification algorithms
- Total and Reactive cross sections already being prepared!

LArIAT TPC readout
Run 5979; Spill 58; Event 0; 2015-05-29 00:49:49




LArIAT TPC readout
Run 5979; Spill 9; Event 0; 2015-05-29 00:00:40




[http://lariat.fnal.gov/eventgallery.html]