Measurements of π Absorption and Charge Exchange Cross Sections on nuclear targets DUET Experiment (π^{+}-^{12}C)

Elder Pinzon (York U.)
for the DUET Collaboration

NuInt15
Osaka, Japan

HAdron Reconstruction Performance
Studies In CH On Reduced Detector

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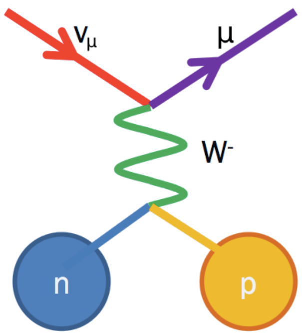
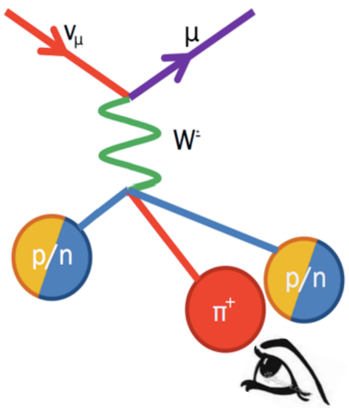
Pions in ν Interactions

Neutrino flavour and energy reconstruction is fundamental for oscillation and cross section analyses

CCQE Interaction.
Golden channel



CC1π⁺ Interaction.
(RES, DIS)



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

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

E_ν^{rec} from lepton kinematics

Pions in ν Interactions

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CCQE Interaction.
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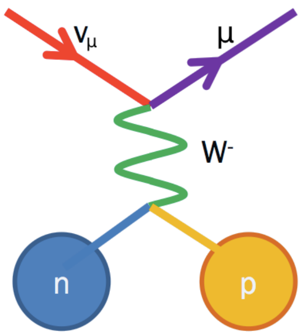

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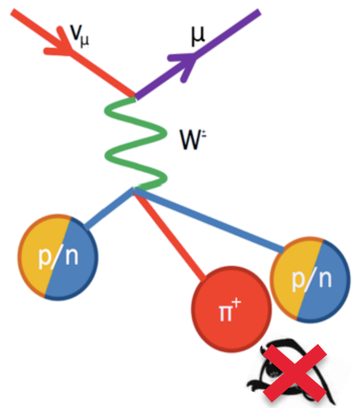
E_ν^{rec} from lepton kinematics

CC1π^+ Interaction.
(RES, DIS)



CCQE-like event!

Pions can interact:

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

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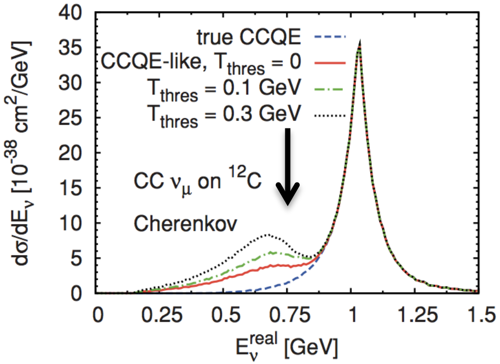
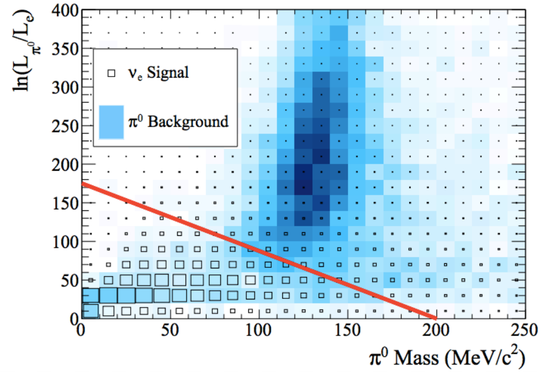
Effect of π FSI/SI

1. E_ν^{rec} smearing

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

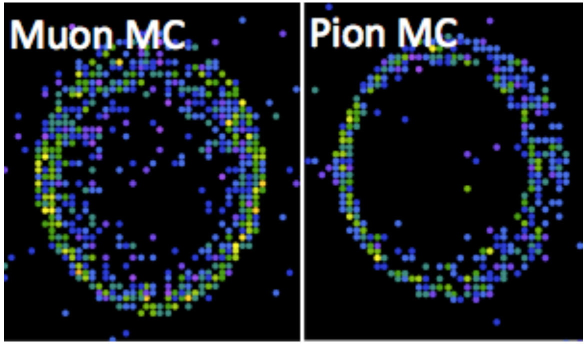


3. π^0 Background to ν_e appearance [PRL 112, 061802 (2014)]



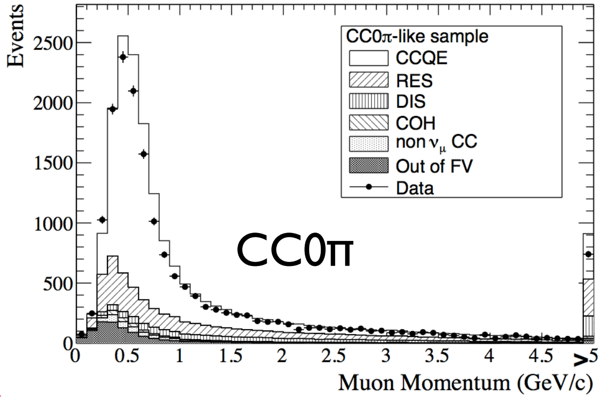
4. π Reconstruction @ SK

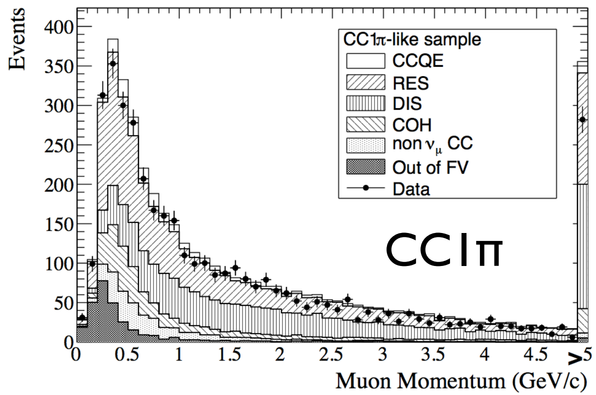
"Identifying CC1π at SK", S. Berkman, CAP 2014

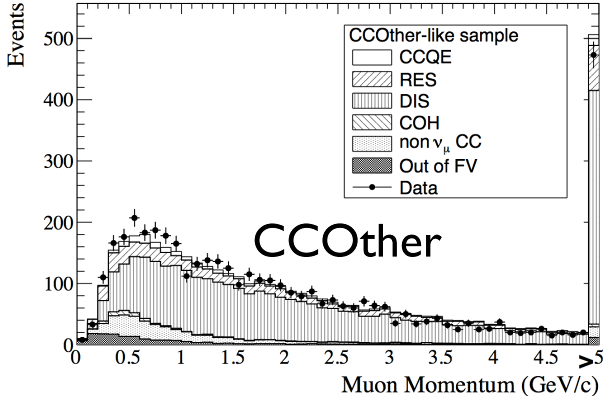


2. Selections based on Final State Topologies

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

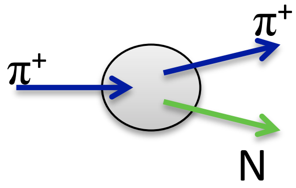




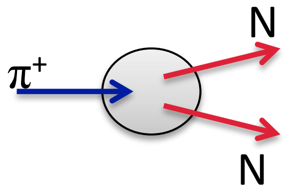


Sub-GeV Pion Inelastic Interaction Modes

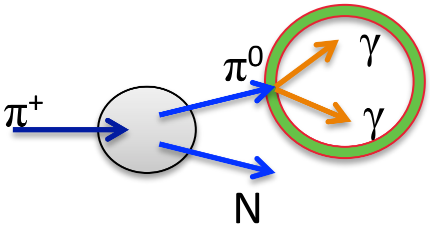
1. Quasi-elastic Scattering



2. Absorption (ABS)



3. Charge Exchange (CX)



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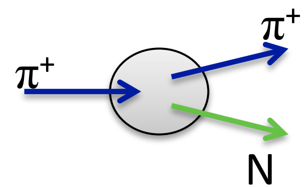

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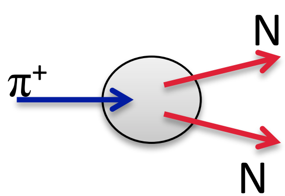

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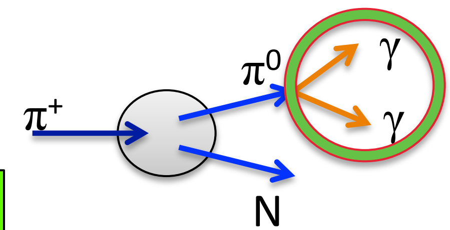
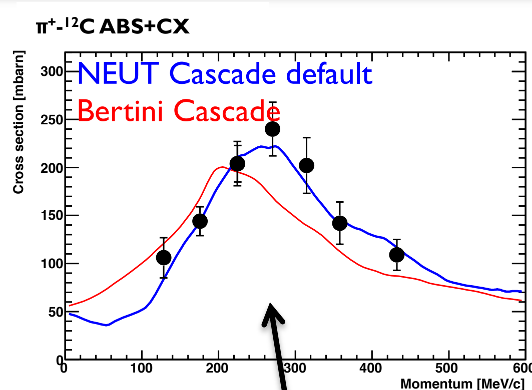


Can measure combined ABS+CX

No π^+ in final state

Sub-GeV Pion Inelastic Interaction Modes



Previous measurements:
Ashery et al., Phys. Rev. **C23**, 2173 (1981)
Bellotti et al., Nuovo Cimento **14A**, 567 (1973)
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NEUT Cascade:
Salcedo, et al., Nucl. Phys. **A484** (1988) 557-592

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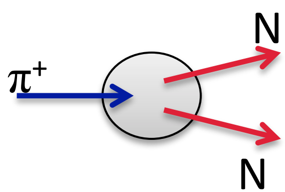

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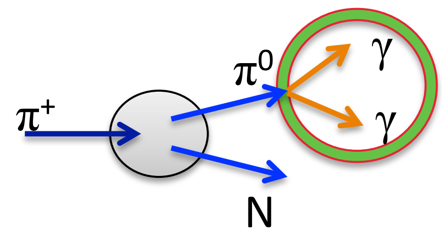

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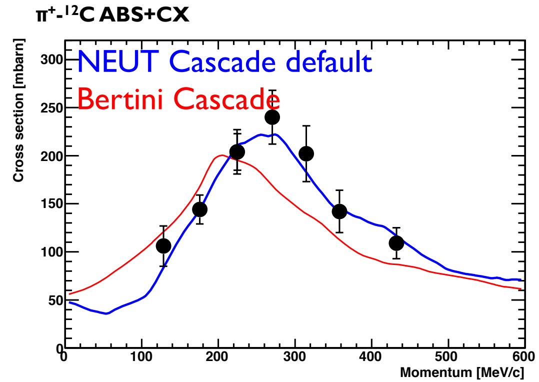

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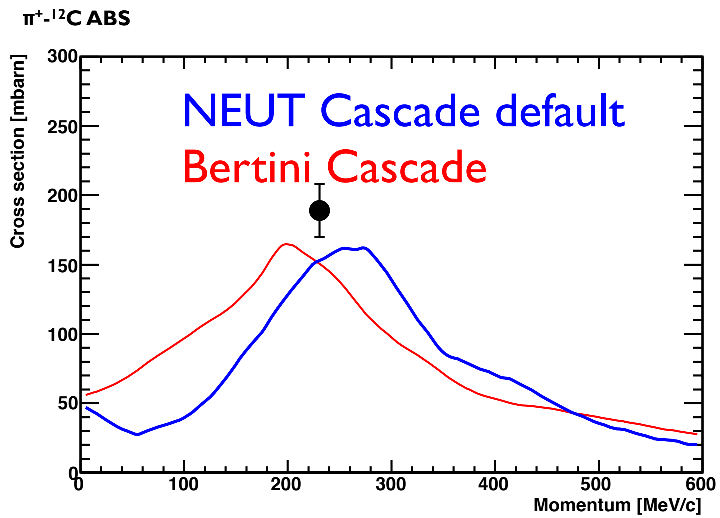

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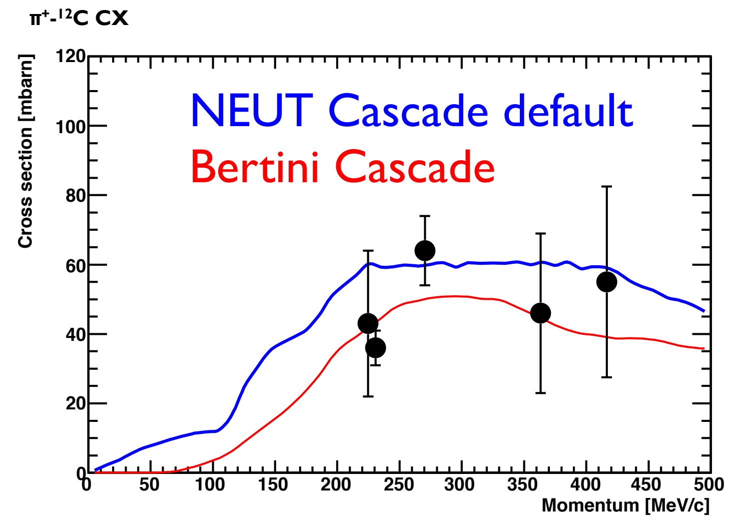


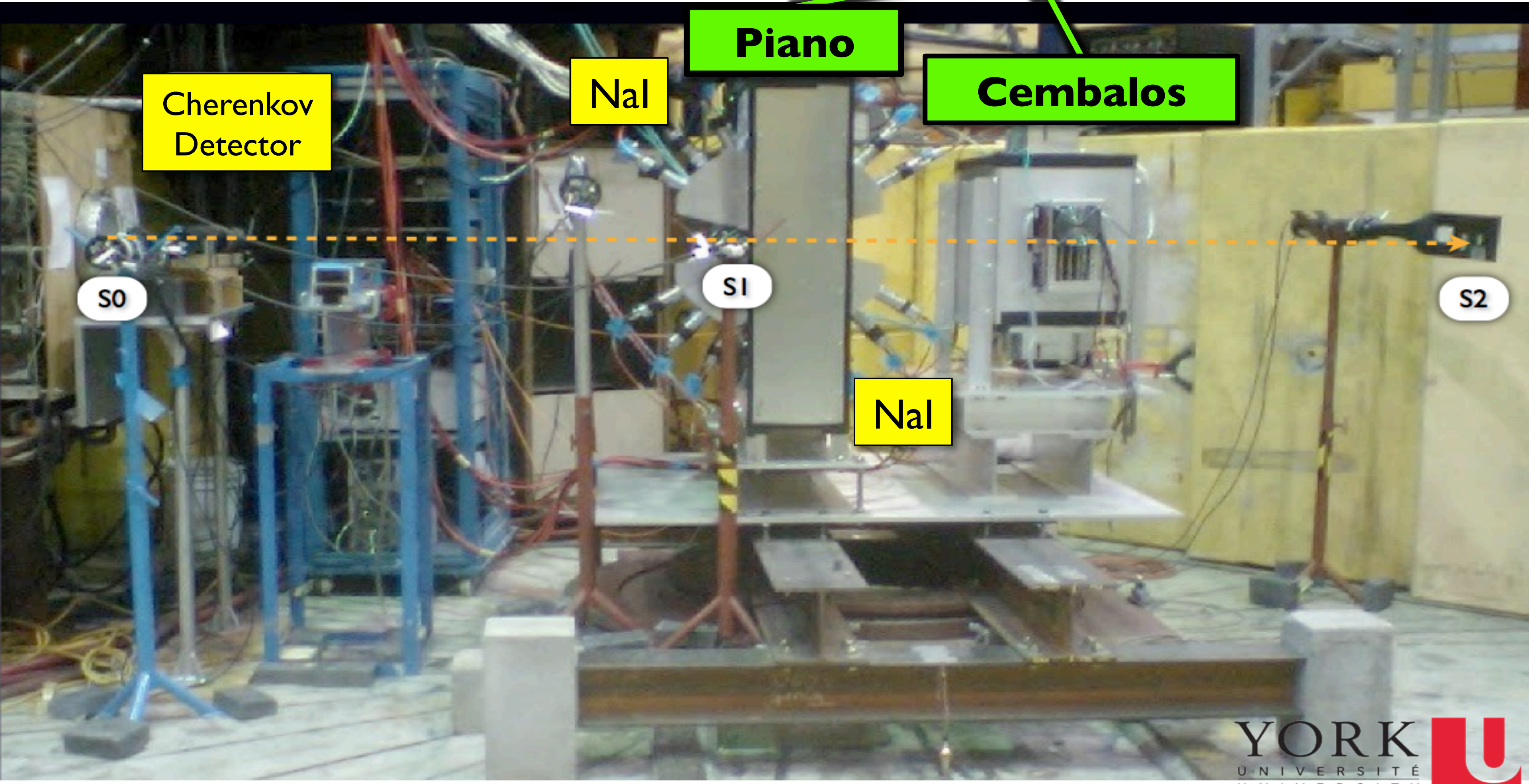
DUET Experiment

GOAL

Measure π^+ Absorption cross section with ~10% accuracy and Charge Exchange with ~20% accuracy

Use TRIUMF M11 beam line

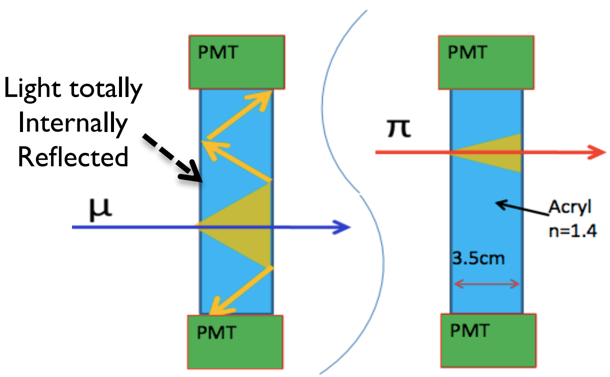
Detector setup: DUET

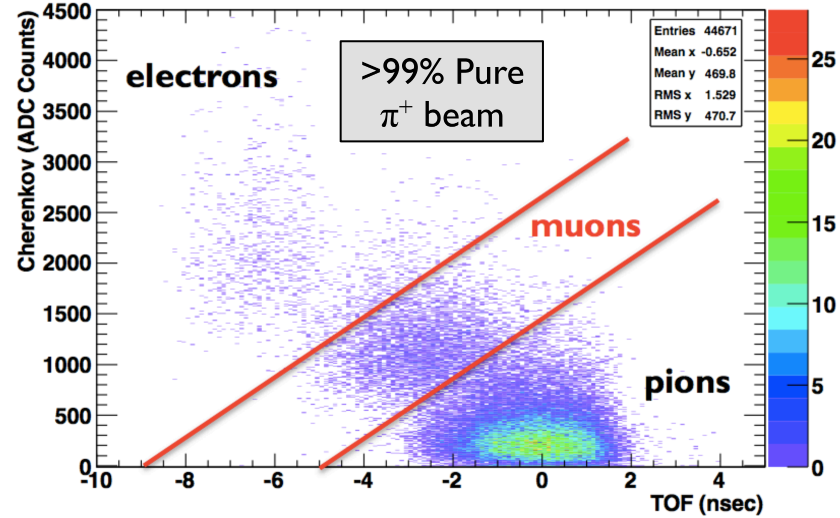


TRIUMF M11 Beam line

- TRIUMF Cyclotron produces 500 MeV/c primary proton beam
- Secondary beam line with momentum tunable in the range from 150 MeV/c to 375MeV/c delivers e, μ, p and π.

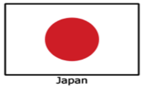
- Beam PID from Time Of Flight (TOF) counters.
- Above 225 MeV/c use Cherenkov detector to select pions.





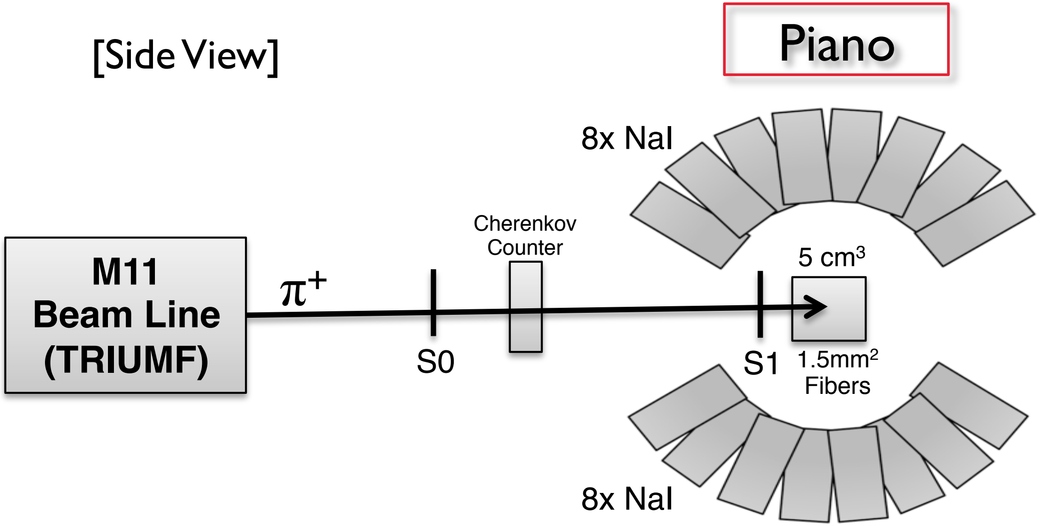
Detector setup: DUET

- Main Components:



Piano: 5 cm³ scintillating fiber tracker (Full active target) + NaI crystals

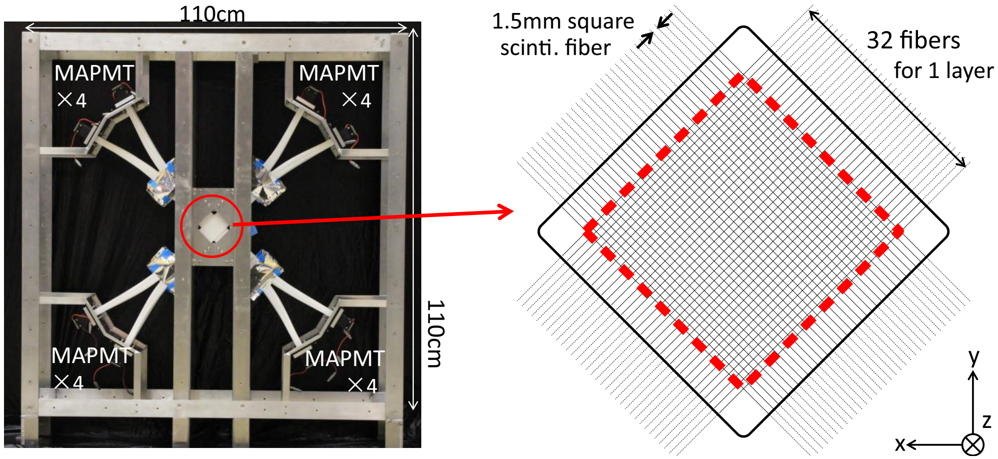
[Side View]



Piano Fibers

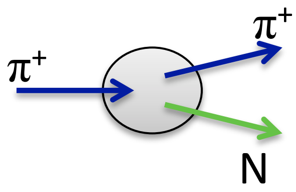
- 16 horizontal and 16 vertical layers with 32 CH fibers each (1.5mm x 1.5mm x 60cm)
- Read by 16 MAPMTs (from K2K) and digitized by FADCs
- Provides precise tracking and dQ/dx measurements of particles in the final state
- Full Geant4 simulation
  - Includes TiO_2 fiber coating and support structure

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



Combined ABS+CX Selection using Piano

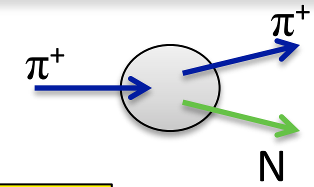
Reject:



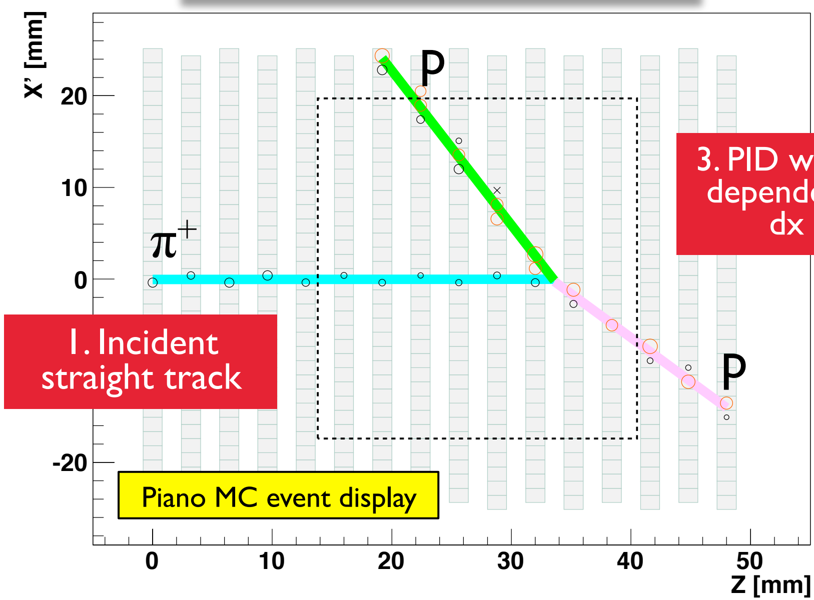
Phys. Rev. C **92**, 035205 (2015)

Event Selection: No π^+ in final state

Reject:



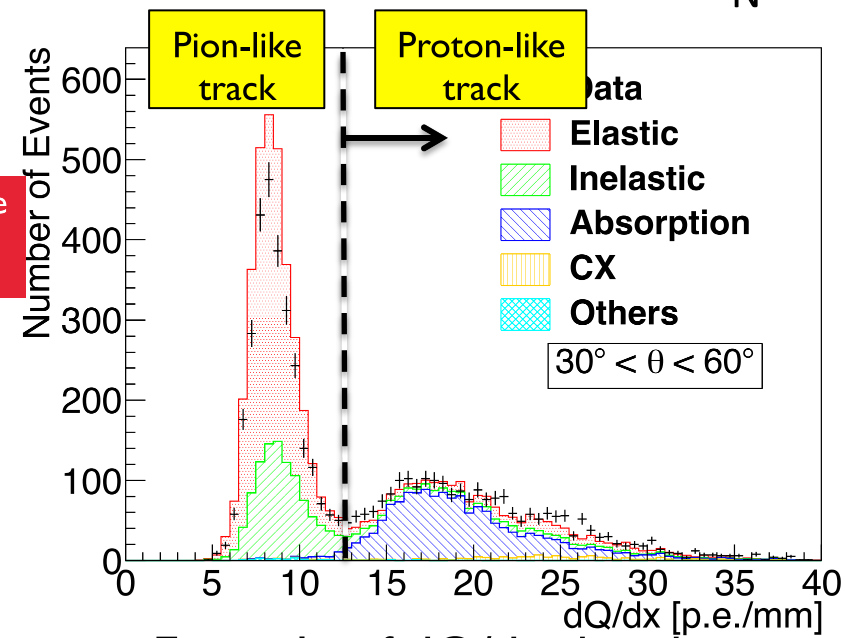
2. Vertex inside Piano's Fiducial Volume



1. Incident straight track

3. PID with angle dependent dQ/dx cut

Sample π^+ absorption interaction in **Piano**



Example of dQ/dx distribution

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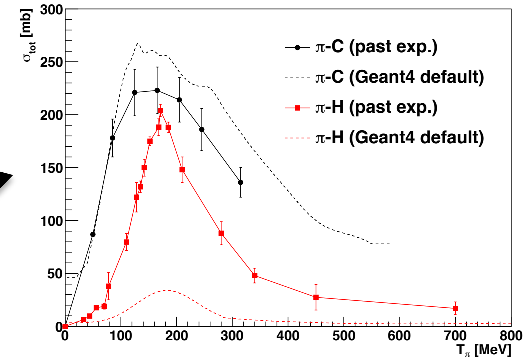
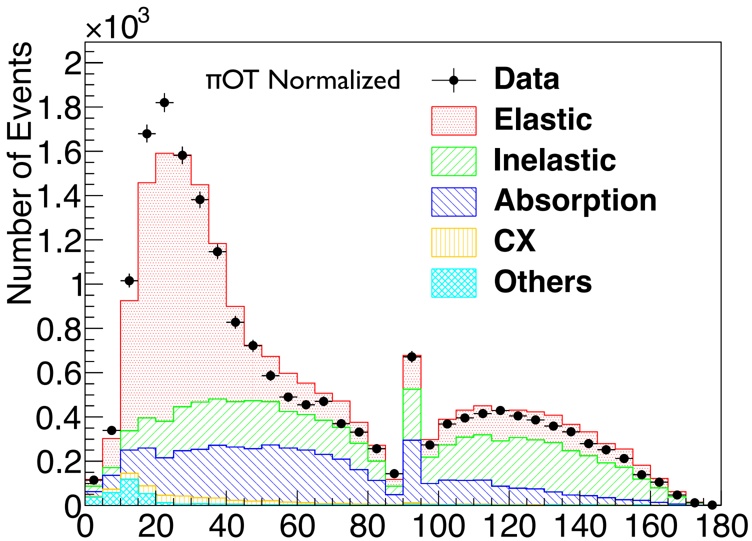
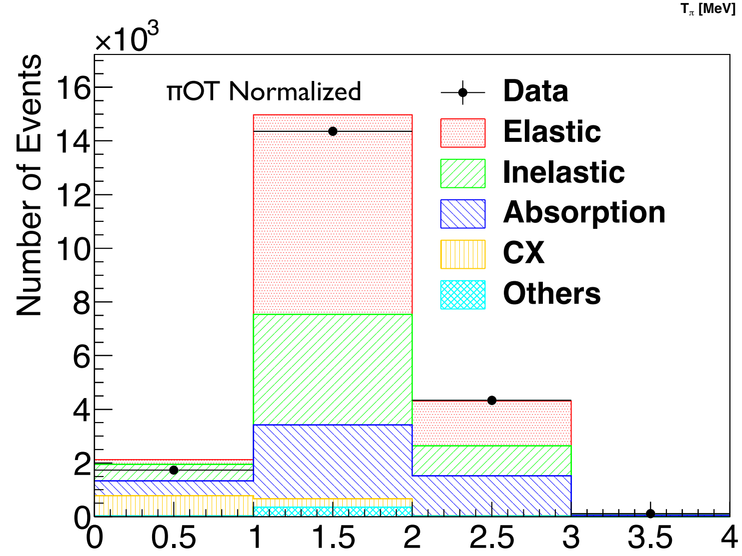
Event Selection: Data/MC comparisons

- Good agreement of distributions before applying the "no π^+ in final state" cut:
  - Tuning of ^{1}H and ^{12}C elastic scattering cross section in Geant4 was necessary





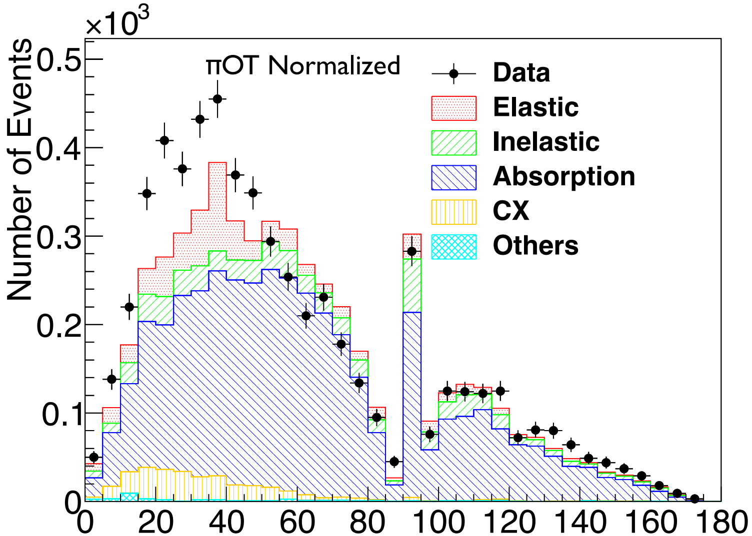
Reconstructed track Polar Angle [deg]



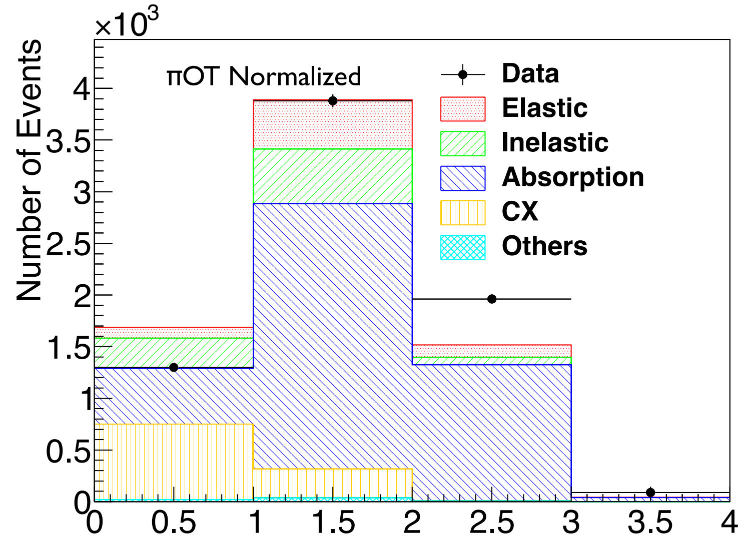
Number of reconstructed tracks

Event Selection: Data/MC comparisons

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



Reconstructed track Polar Angle [deg]



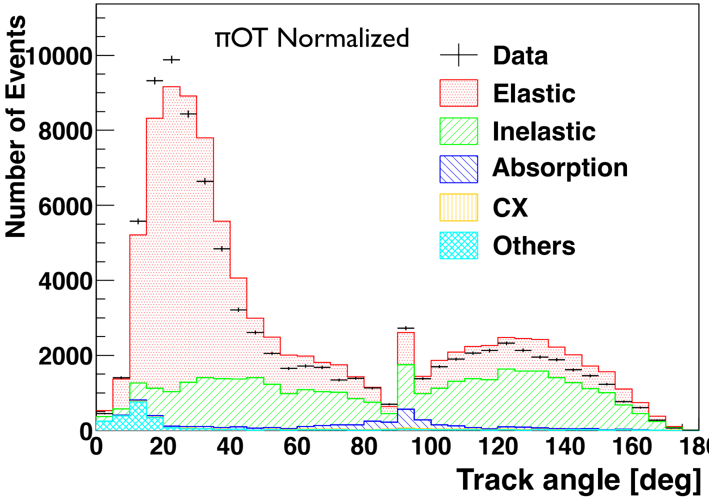
Number of reconstructed tracks

Uncertainties

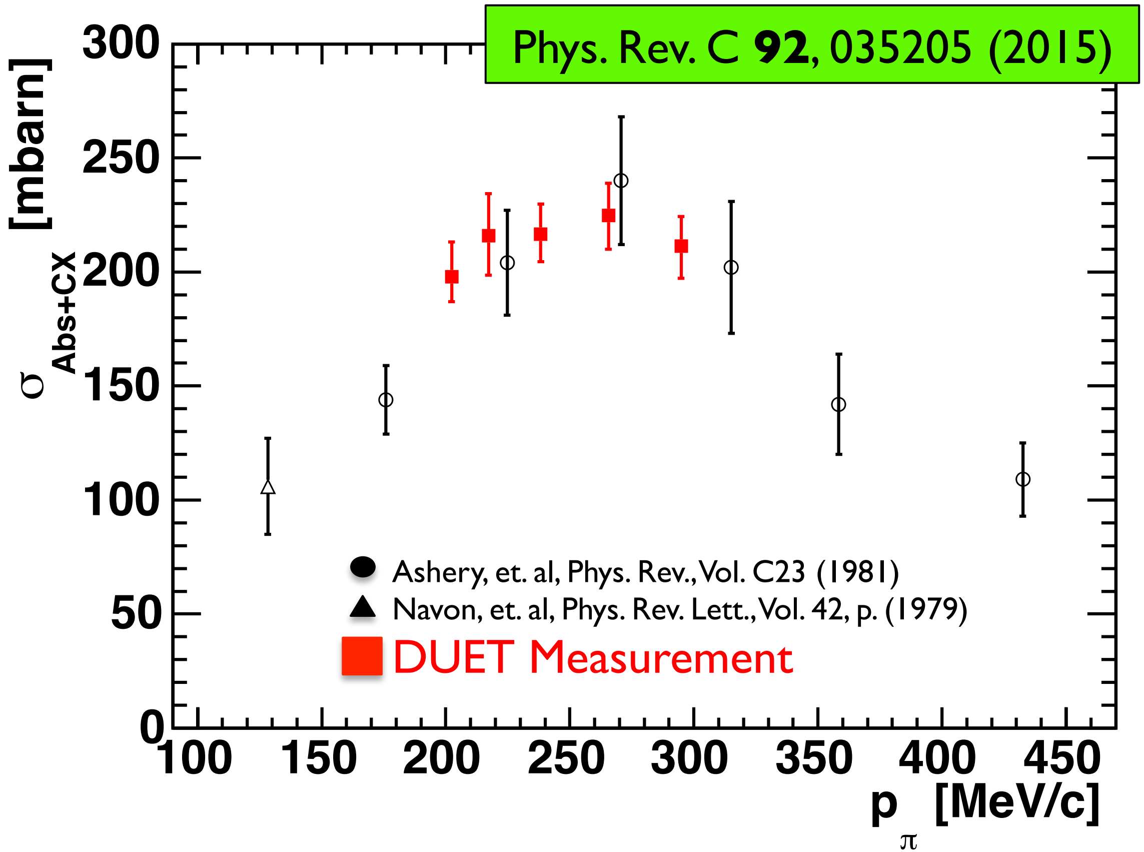
	p_π at the fiber tracker [MeV/c]				
	201.6	216.6	237.2	265.5	295.1
Systematic errors					
Beam profile	0.9	1.2	1.0	0.6	1.2
Beam momentum	1.6	1.7	0.7	0.8	1.4
Fiducial Volume	1.1	3.9	1.4	1.2	1.3
Charge distribution	2.4	2.2	2.6	2.6	2.9
Crosstalk probability	0.3	0.3	0.3	0.2	0.4
Layer alignment	0.5	0.8	1.1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

Dominant systematic error is background estimation.

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



Abs+CX Cross Section Result



$$\sigma_{\mathrm{ABS+CX}} = \sigma^{pred}_{\mathrm{ABS+CX}} \times \frac{N_{\mathrm{data}} - N^{pred}_{\mathrm{BG}}}{N^{pred}_{\mathrm{sig}}} \times \frac{1 - R^{data}_{\mathrm{TiO}}}{1 - R^{\mathrm{MC}}_{\mathrm{TiO}}} \times \frac{1}{1 - f_\mu}$$

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

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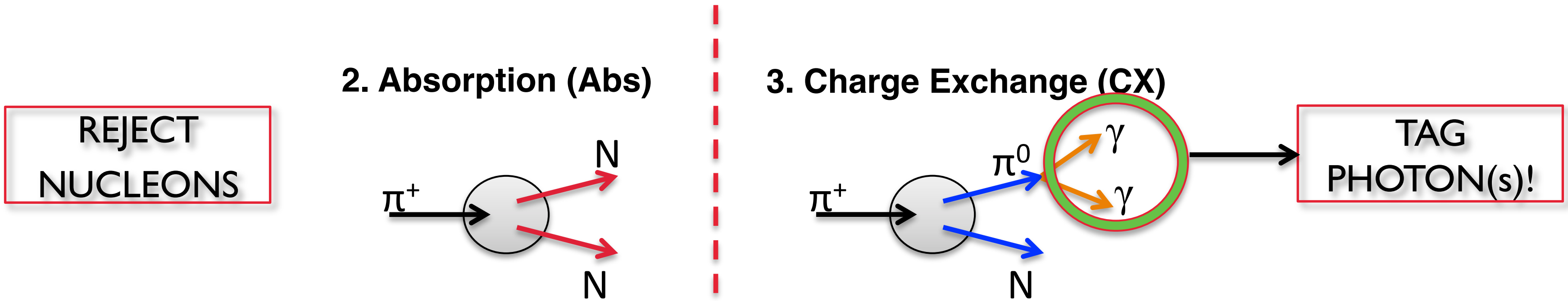
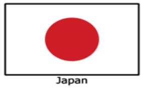
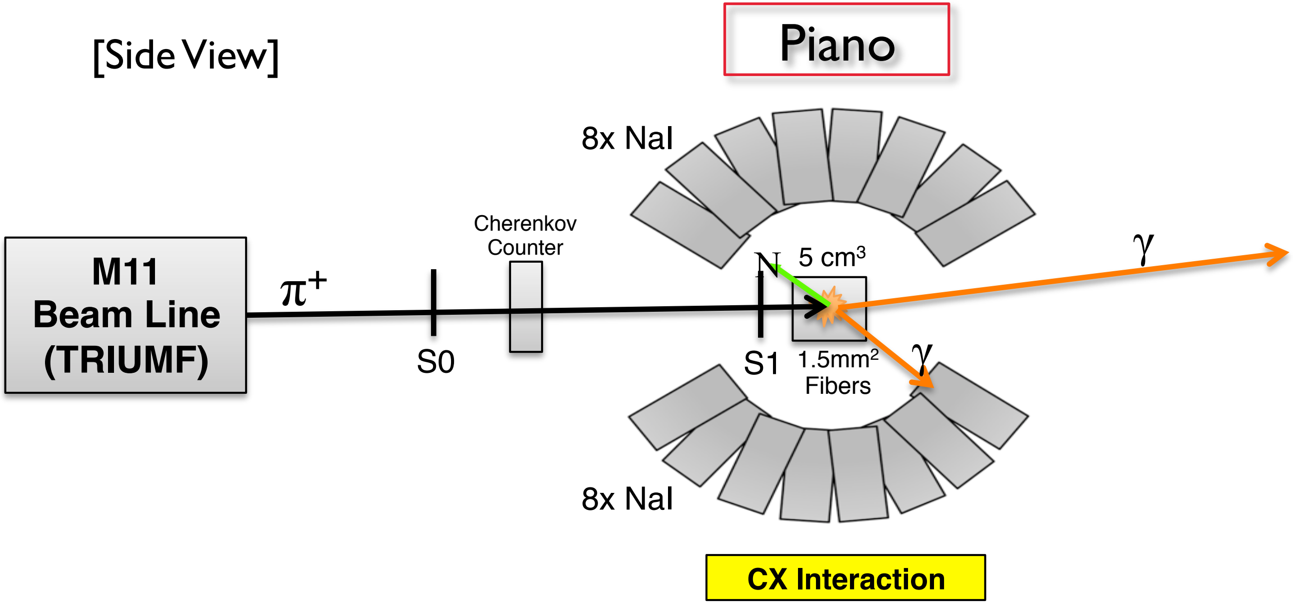
Extracting the Charge Exchange cross section



- Main Components:



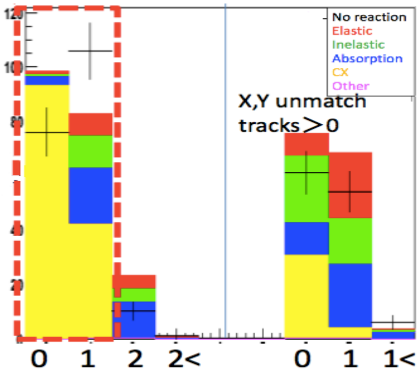
Piano: 5 cm^3 scintillating fiber tracker (Full active target) + **NaI crystals**

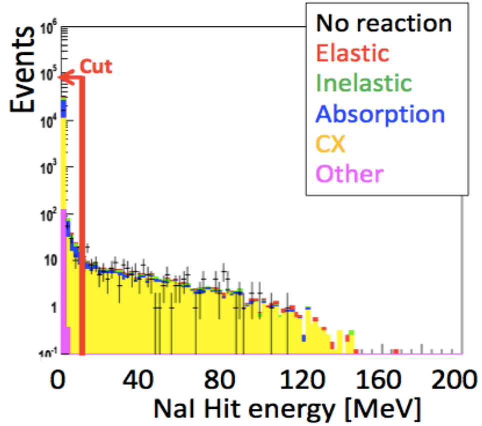


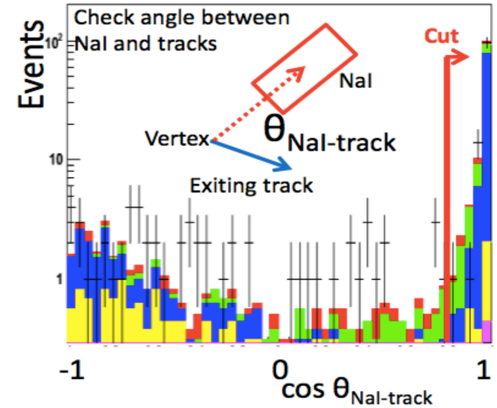
CX Event Selection: Using NaI Crystals

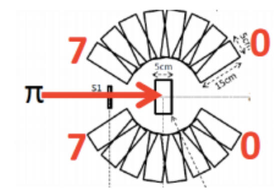
M. Ikeda, ICCR

All plots normalized to # of incident pions





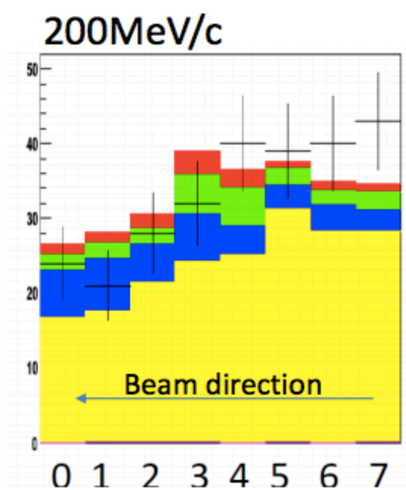


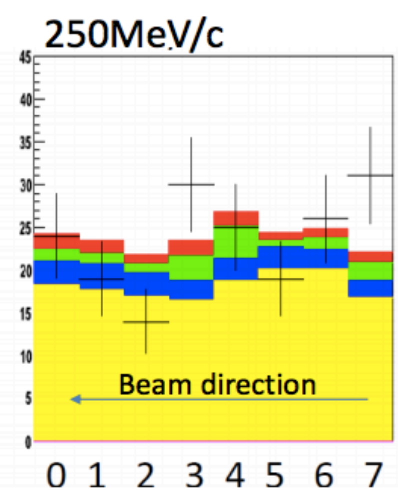


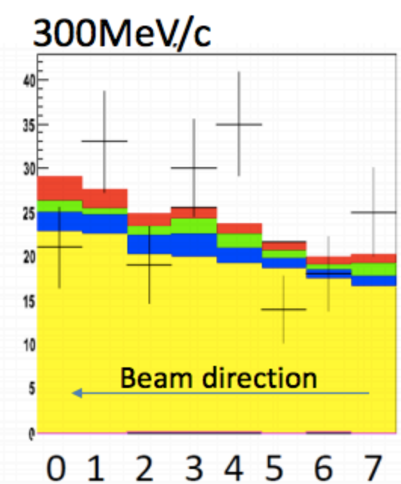
Selection Criteria:

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

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

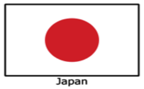






Detector setup: DUET

- Main Components:



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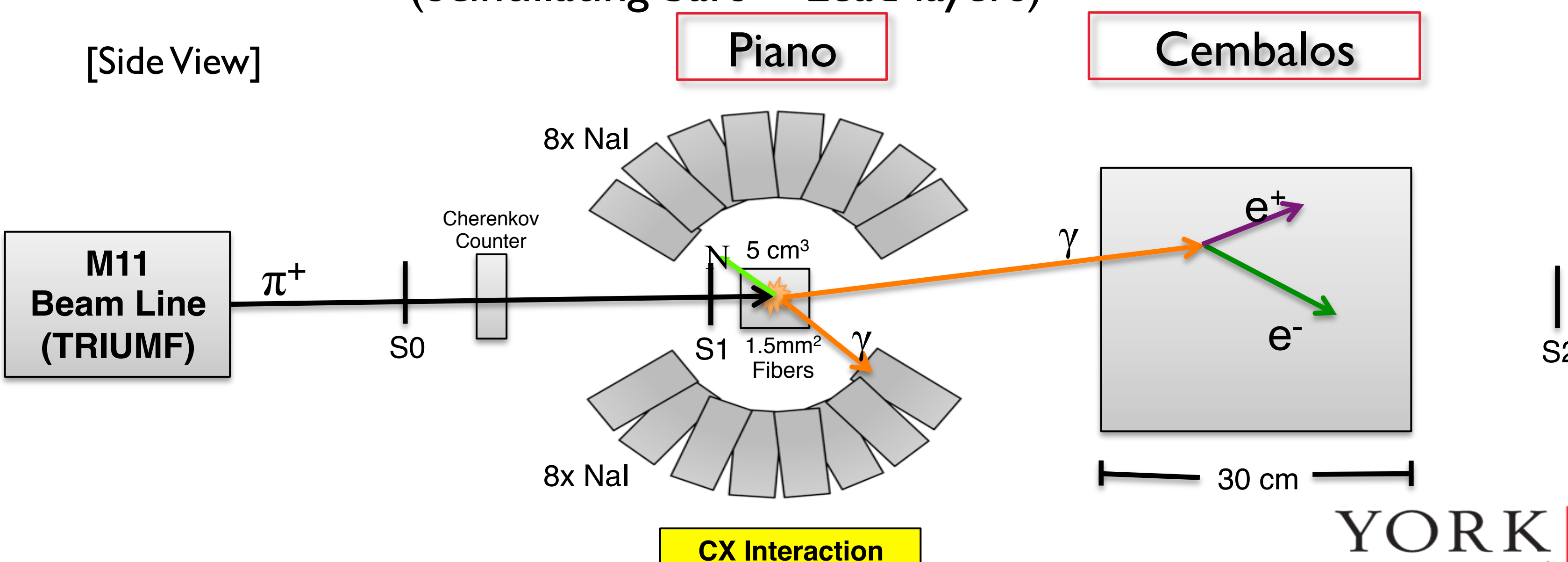
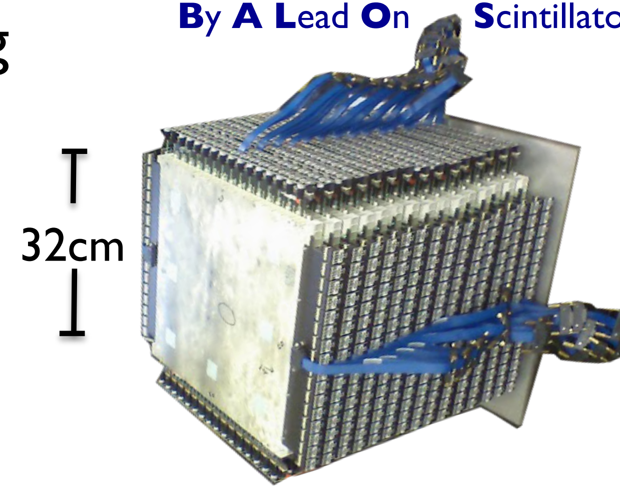
Cembalos: **Miniature Fine Grained Detector (FGD from T2K)** (Scintillating bars + Lead layers)



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" HaRpsi CHord
  - **HA**dron **R**econstruction **P**erformance **S**tudies **I**n **CH** **O**n **R**educed **D**etector



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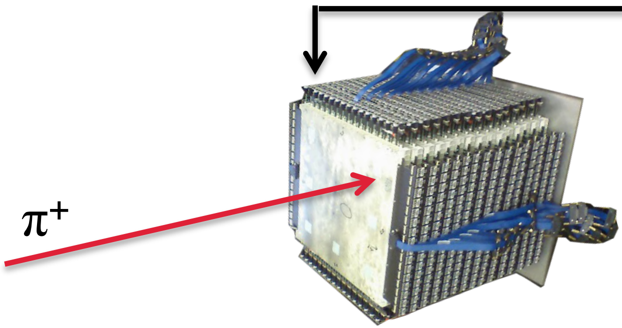
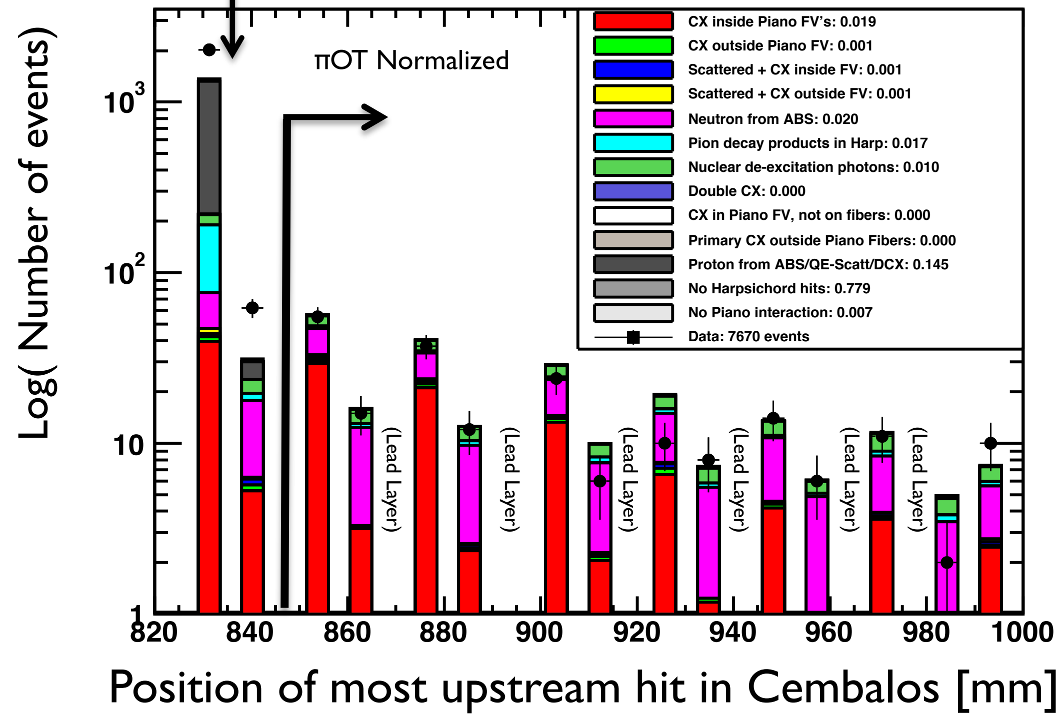
CX Event Selection: Using Cembalos

First two layers

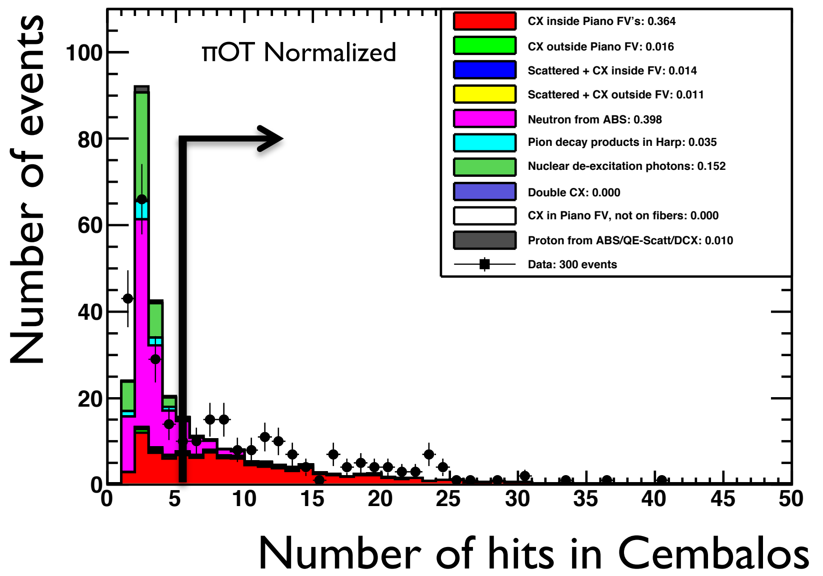


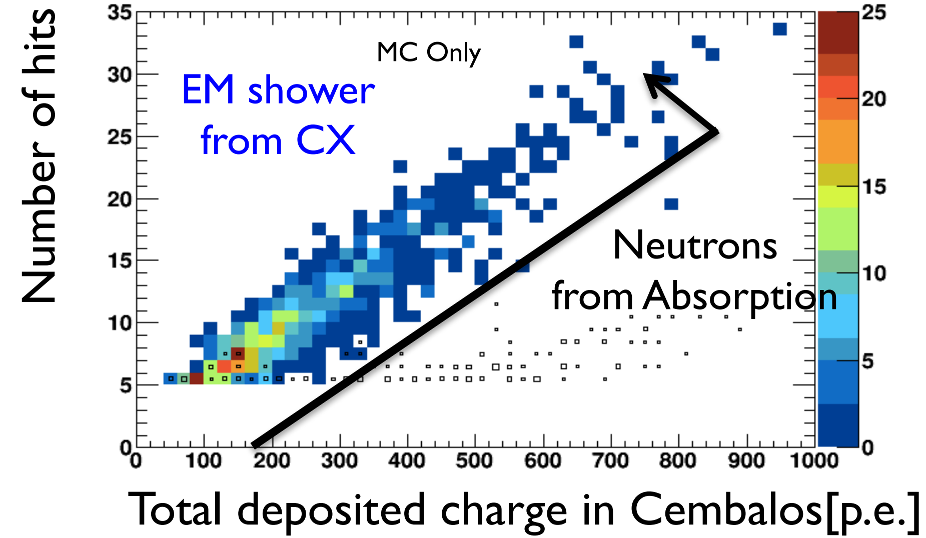
- Charged **pions** and **protons** immediately leave a signal in the scintillating detector
- **Photons** are neutral, so they must interact before they can be detected
- The **first two layers** are used as a **veto cut** in order to remove charged background



CX Event Selection: Neutron Rejection

Selection: Abs+CX+Veto





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

$$\textbf{Efficiency} = \frac{\text{Selected CX events}}{\text{True CX events}} \approx 5\%$$

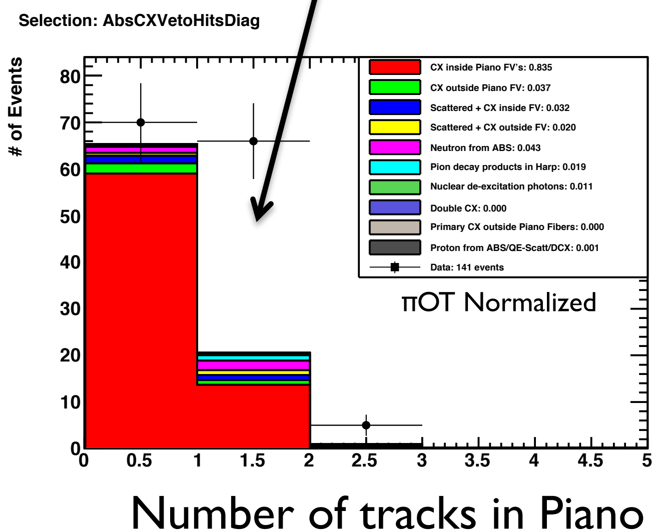
$$\textbf{Purity} = \frac{\text{Selected CX events}}{\text{Total selected events}} \approx 88\%$$

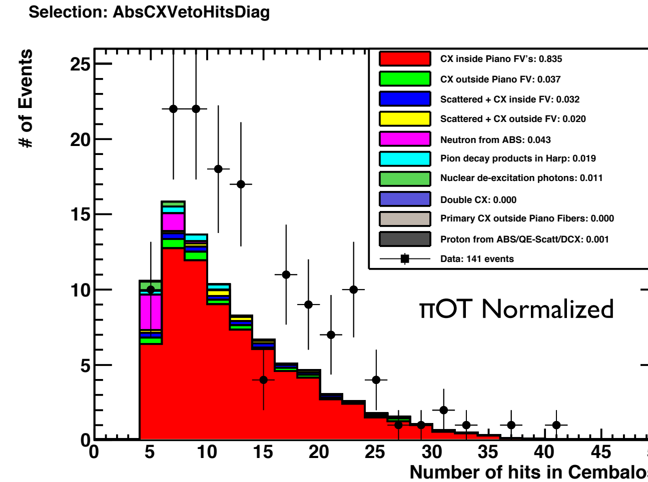
- **~100 events in data sample**

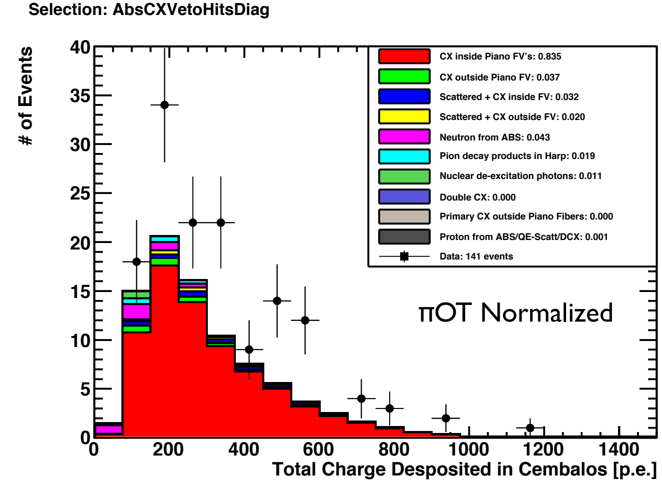
(~20 for 216.6 MeV/c)

CX Event Selection: Data/MC

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







CX Analysis Systematics

1. π^+ 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
   - π^0 kinematics
   - ABS an CX Nucleon ejection
   - Selection Background

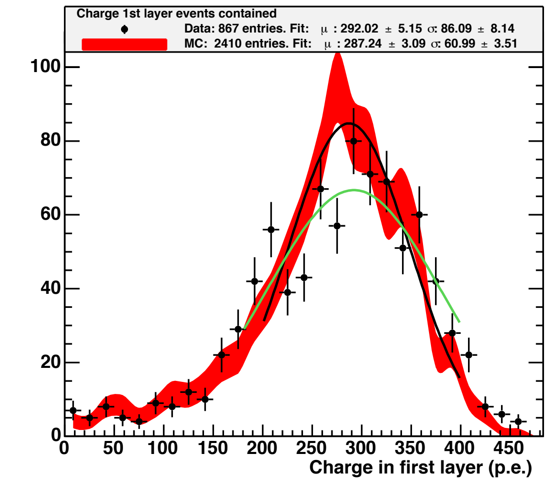
Estimation procedures inherited from ABS+CX analysis

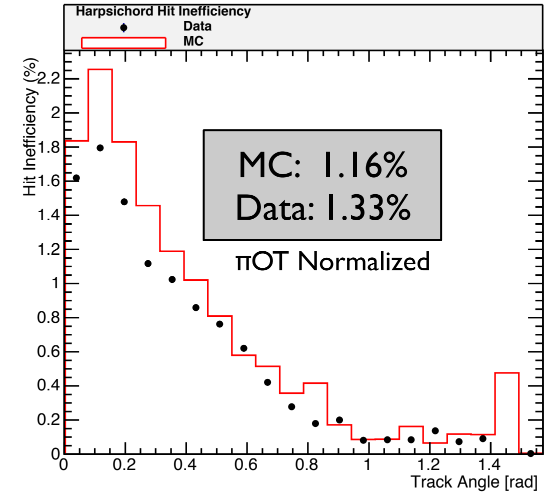
Cembalos Detector Systematics

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 (μ=1, σ=0.2)

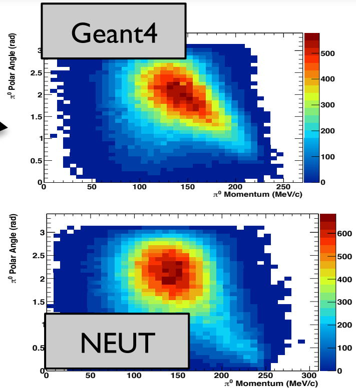
3. **Hit inefficiency (1~2%)**
   – Missing hits in the middle of Cembalos reconstructed tracks are counted and compared between Data/MC
   – Systematic is calculated from 10000 toy MC where hits are randomly deleted following the Data/MC difference

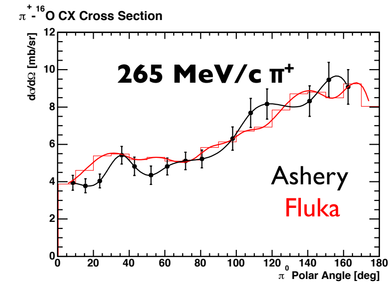




Physics Model Systematics

1. **π^0 Kinematics**
   – Large difference between models (FLUKA angular distribution closest to data)
   – Reweighting scheme was investigated → 10~15% effect (large/not trusted)

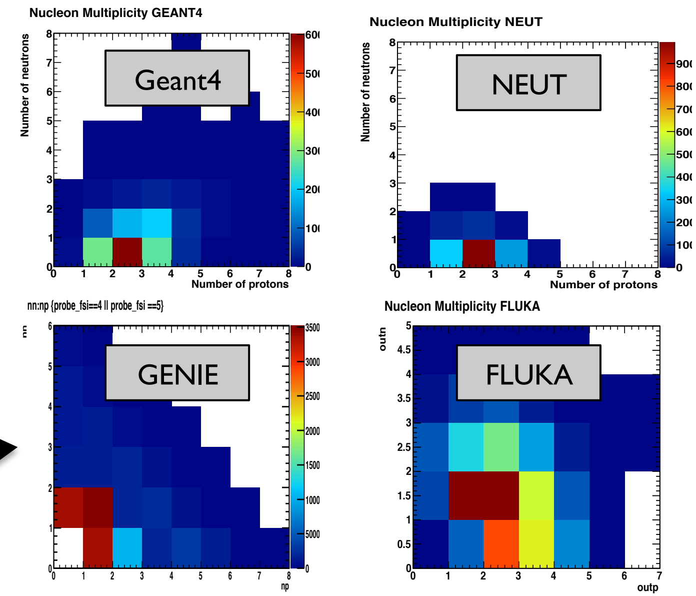




2. **Nucleon Ejection**
   – Largest background are neutrons from ABS.
   – Very large differences among models!

Thin target π^+-C simulations

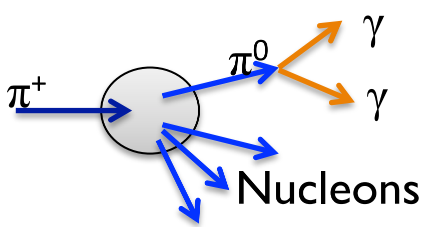
(Hard to run full DUET simulation using each generator)



"Efficiencies" Scheme

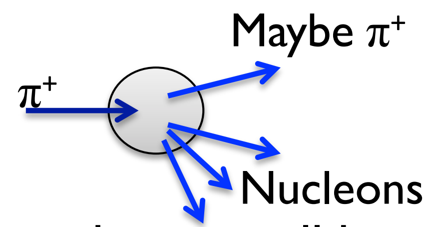
New approach : π^0 and nucleon kinematics dependant selection efficiencies
→ Apply to interactions from thin target simulations (i.e., directly to the "model")

- **Sample Signal Event**



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

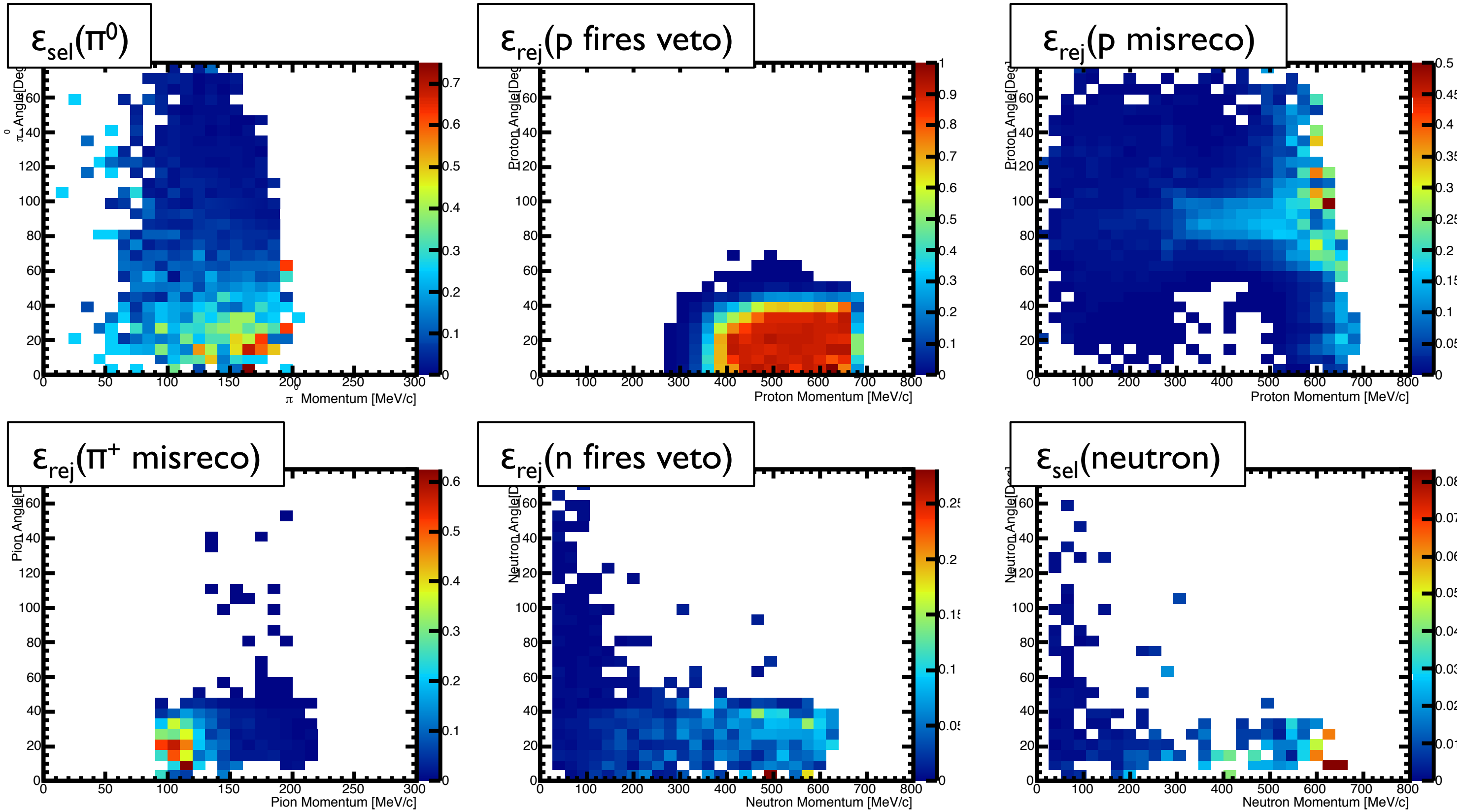
- **Sample Background Event**



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

Selection and Rejection Efficiencies

- Binned in Momentum and Angle
- Calculated using the full Geant4 DUET simulation

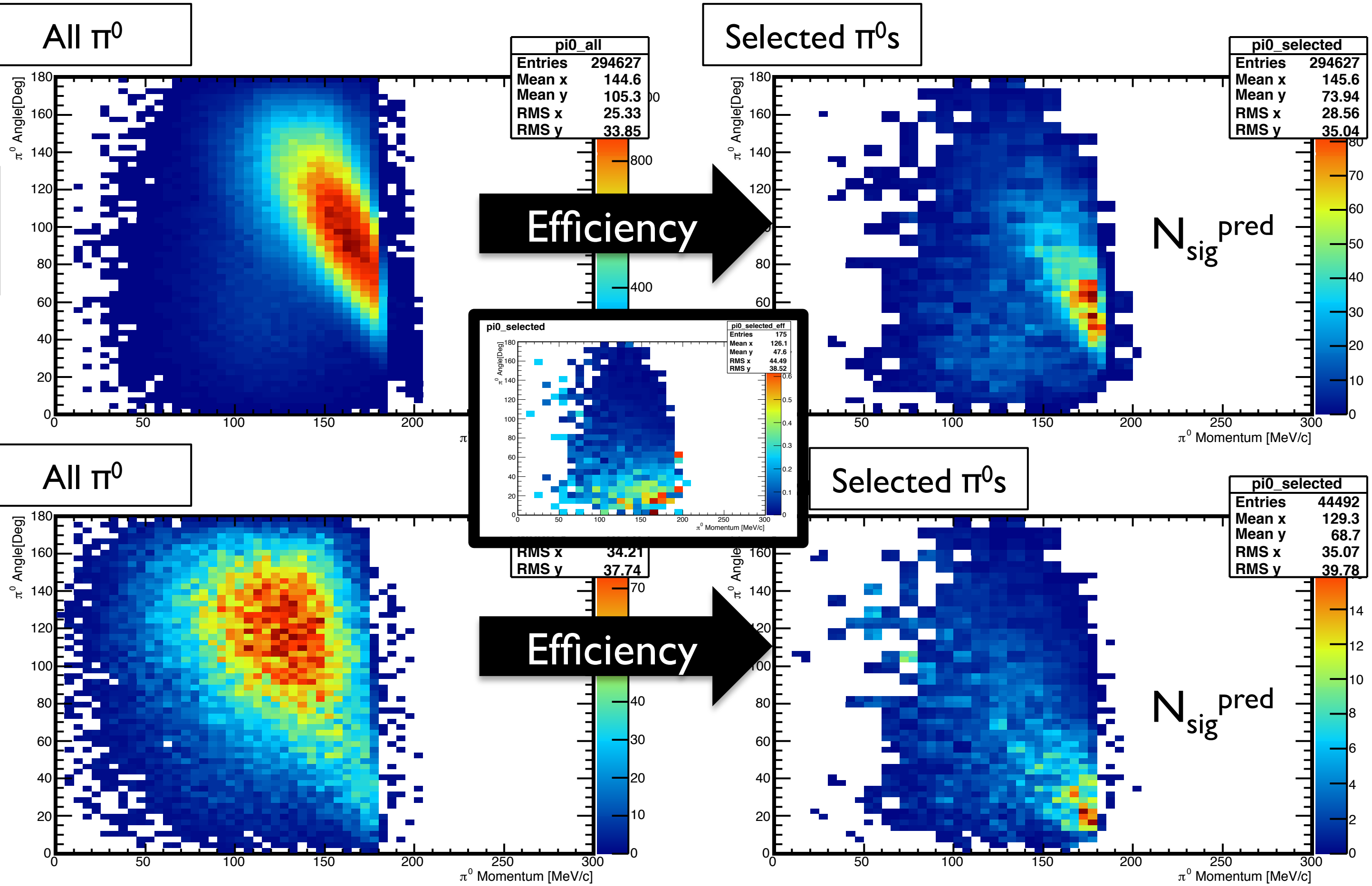


Example: 200 MeV/c

Geant4 Thin Target

(as cross-check)

FLUKA



Applying to thin target

$$\sigma(\mathrm{ABS+CX}) = \sigma(\mathrm{ABS+CX})_{pred} \times \frac{N_{\mathrm{data}} - N^{pred}_{\mathrm{BG}}}{N^{pred}_{\mathrm{sig}}} \times \frac{1 - R^{data}_{\mathrm{TiO}}}{1 - R^{\mathrm{MC}}_{\mathrm{TiO}}} \times \frac{1}{1 - f_\mu}$$

(Model-G4)/G4 *100

Model	p_{π^+} (MeV)	Incident	σ^{pred}_{CX} (mb)	N^{pred}_{sig}	N^{pred}_{BG}	σ_{CX} (mb)	Δ_{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

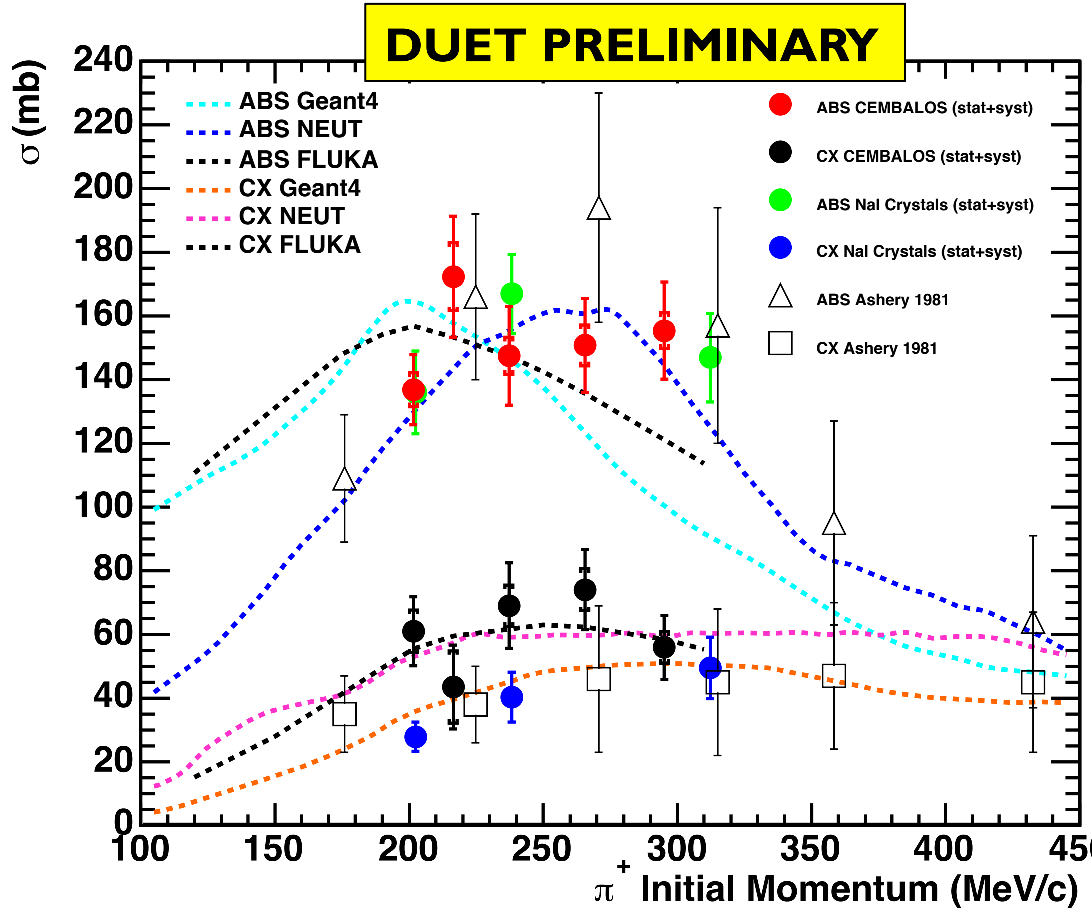
6% ~ 22% Not included as systematic

Uncertainties

	CX					ABS				
π^+ Momentum [MeV/c]	201.6	216.6	237.2	265.5	295.1	201.6	216.6	237.2	265.5	295.1
Beam Systematics										
Beam profile	3.5	4.9	6.2	4.2	2.0	2.2	2.7	3.8	2.9	2.5
Beam momentum	4.1	1.6	3.5	4.1	2.8	1.5	2.3	1.9	2.5	3.0
Muon Contamination	0.5	0.8	0.9	0.3	0.2	0.5	0.8	0.9	0.3	0.2
Piaνo Systematics										
Fiducial Volume	3.6	2.3	4.3	3.9	4.5	1.1	5.4	4.1	3.8	3.4
Charge distribution	3.3	4.1	3.3	2.4	3.0	4.3	3.2	4.1	4.1	4.4
Crosstalk probability	3.9	4.9	4.4	2.5	2.2	1.9	2.0	2.7	1.7	1.3
Layer alignment	1.3	3.6	2.9	0.9	1.1	1.0	2.3	2.8	1.7	2.4
Hit 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

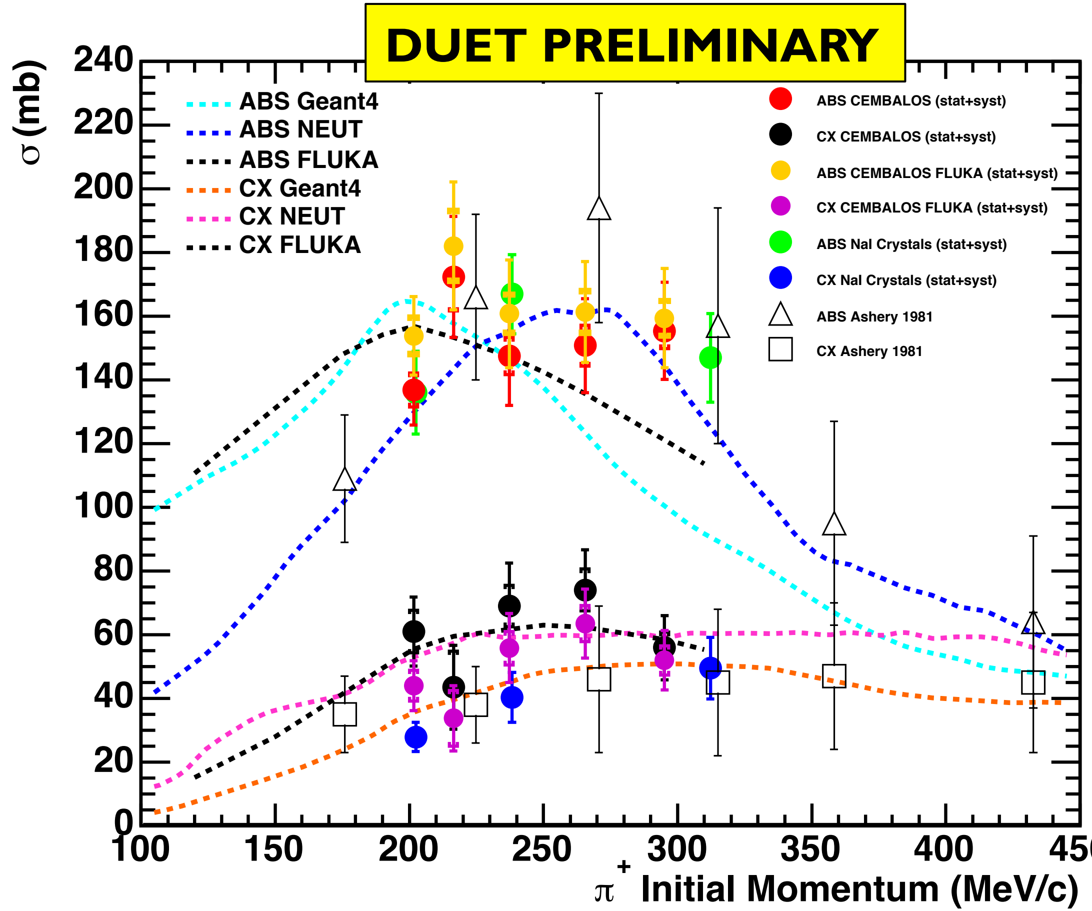
Preliminary Result

- **Preliminary**
- Plan is to also release covariance matrix
- Large discrepancy with NaI Crystals result
  - Different polar angle coverage
  - Uses FLUKA π^0 Angular Distribution
  - Investigating



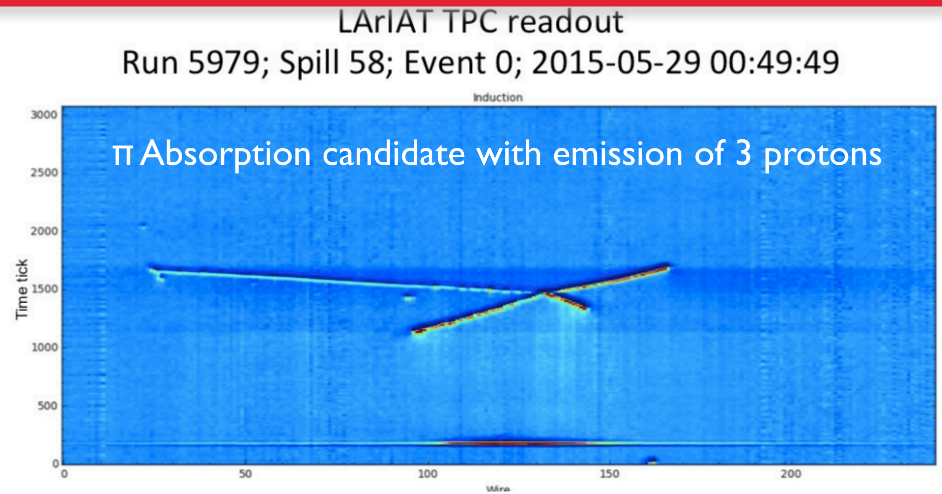
Preliminary Result

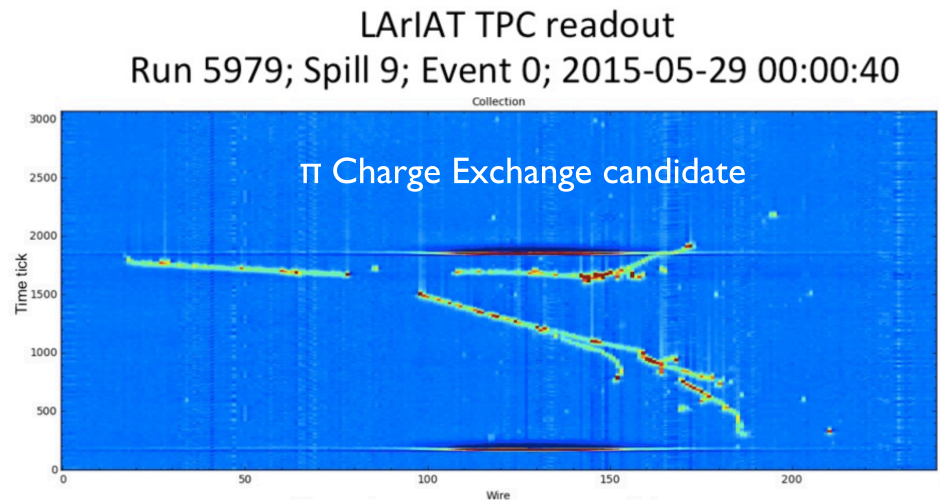
- **Preliminary**
- Plan is to also release covariance matrix
- Large discrepancy with NaI Crystals result
  - Different polar angle coverage
  - Uses FLUKA π^0 Angular Distribution
  - Investigating
- Cannot be fully explained by Geant4-FLUKA difference



$\pi^{\pm}$-Argon measurements

- Liquid Argon detectors are an option for future long baseline experiments
  - $\pi^{\pm}$-Ar measurements are necessary
- LArIAT shows promising $\pi^{\pm}$ 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!

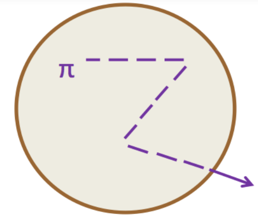




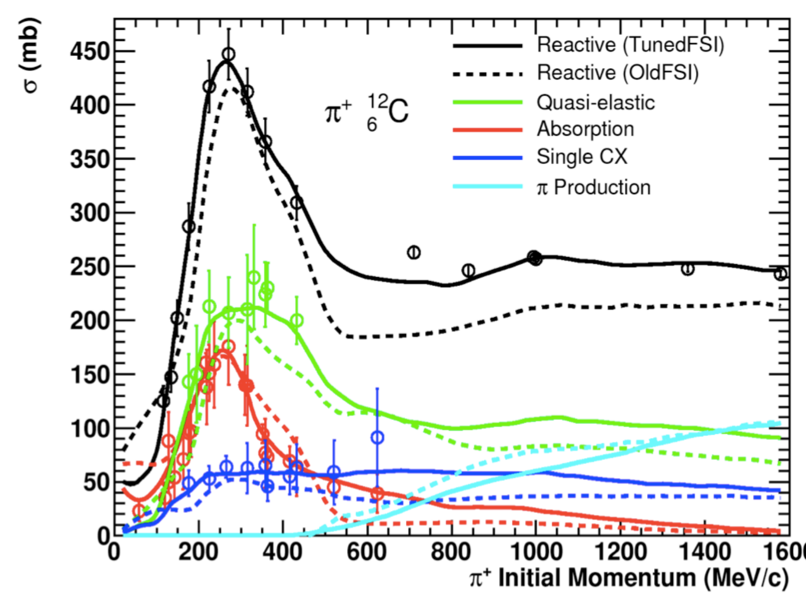
[http://lariat.fnal.gov/eventgallery.html]

Improving FSI/SI Uncertainties

- NEUT FSI model simulates pion interaction by stepping through the nuclear medium (cascade)
  - The interaction probability in each step is defined by the microscopic Scattering, ABS and CX cross sections
- The microscopic cross sections are tuned so that the resulting Scat, ABS and CX cross sections agree with external data
  - $\pm 1\sigma$ from fit are propagated to T2K's Near and Far Detectors observables through reweighting for uncertainty estimation
- Will add DUET data for tuning



"NEUT Pion FSI", P. de Perio, NuInt11



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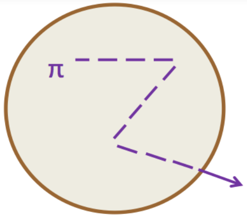

"NEUT Pion FSI", P. de Perio, NuInt11

- SI uncertainty for T2K's Near Detector is estimated using Geant4
- Preparing a Geant4 to NEUT interface for pion inelastic interactions
- Consistent treatment of FSI and SI across T2K detectors

Final Remarks

- DUET measures π^+-^{12}C interaction cross-sections using the M11 pion beam line at TRIUMF
  - Also took data with water target (π-^{16}O)

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

- Work for a separate charge exchange measurement is ongoing
  - Preliminary results with full systematics
  - Investigating possible differential CX measurement

- **LArIAT will measure π-Ar cross sections!**

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

YORK UNIVERSITÉ UNIVERSITY

[Backup]

DUET Collaboration

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

Analysis Outline

Using Piano fibers

Measure Abs+CX cross section
[No π^+ in final state]

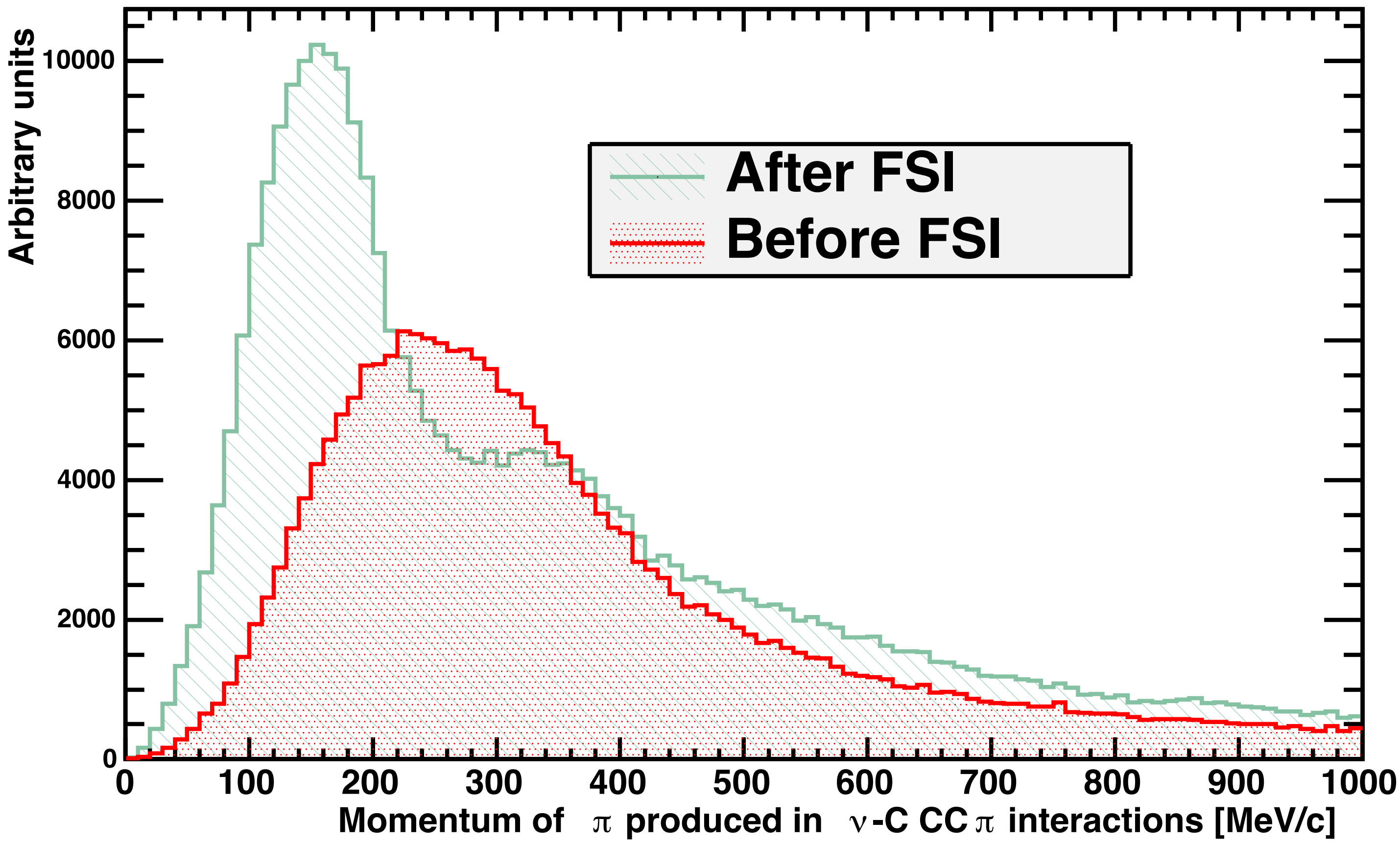
Using NaI detectors and Cembalos

Measure CX cross section
[Tag photon(s) from π^0]

Feed into FSI & Secondary Interaction models

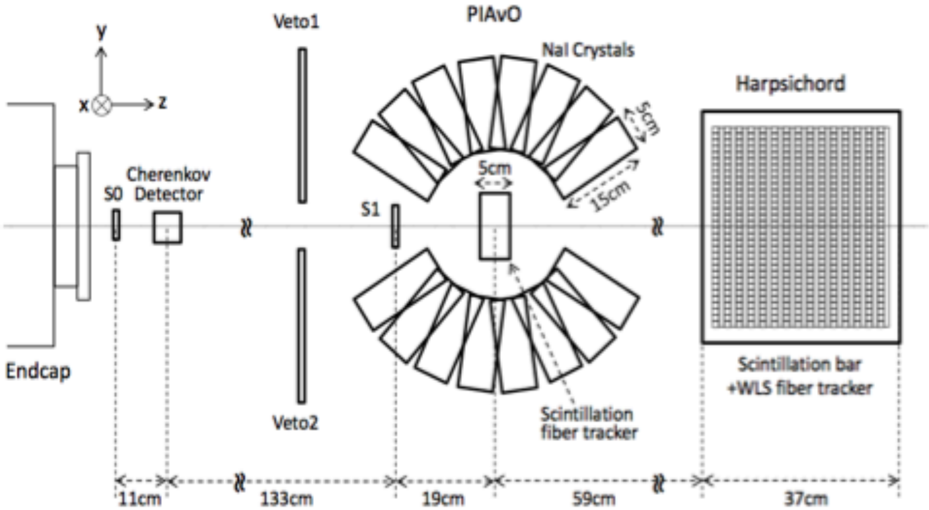
Improve Systematics

FSI effect

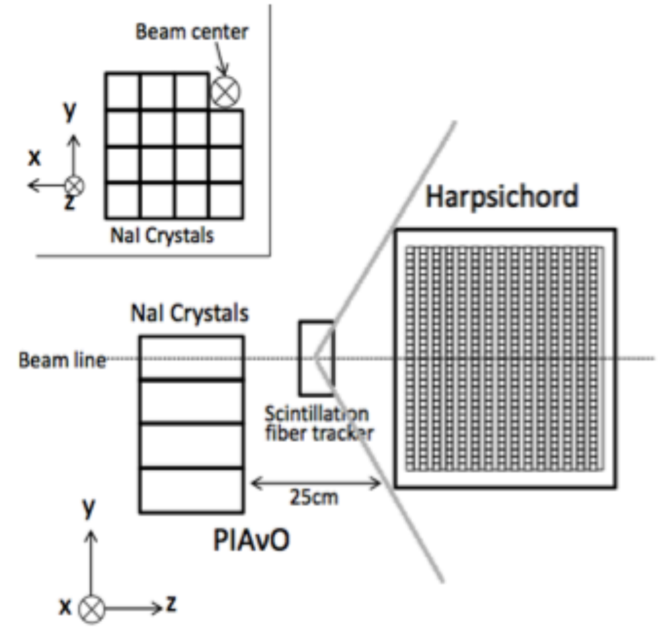


Arbitrary units
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
700
800
900
1000
Momentum of π produced in ν-C CCπ interactions [MeV/c]
After FSI
Before FSI

DUET Experiment

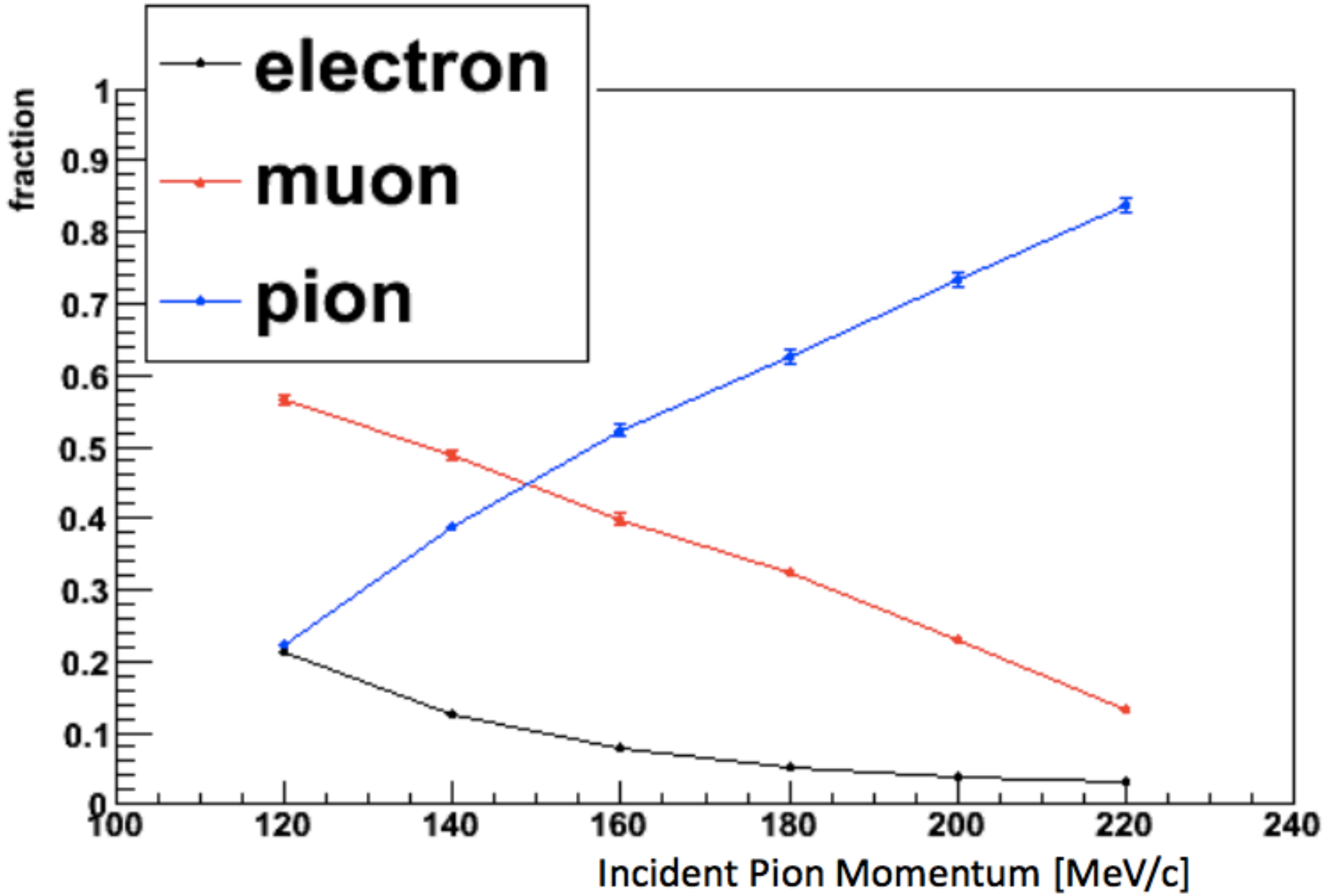


(a) Piaνo and Harpsichord in configuration 1. The angular distribution of photons can be measured using the NaI detectors.

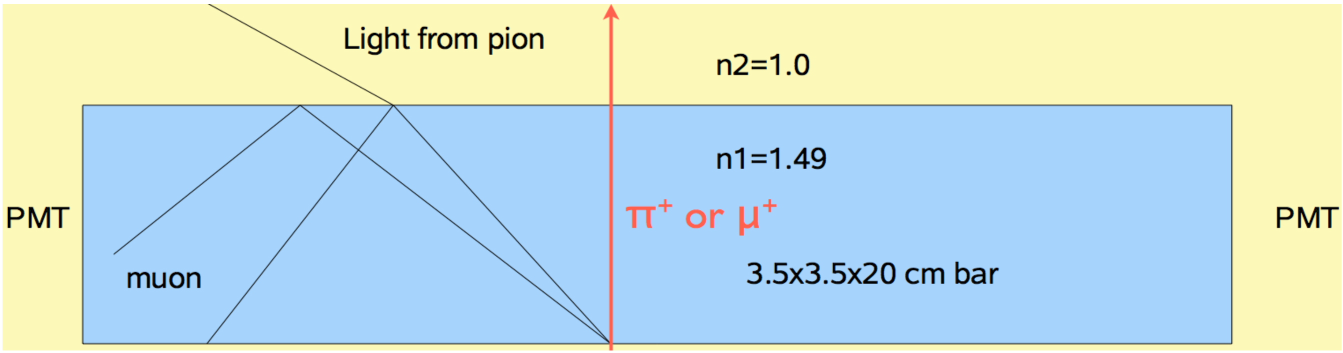


(b) Piaνo and Harpsichord in configuration 2. Lead layers are added to Harpsichord to increase photon conversion.

Beam particle fraction

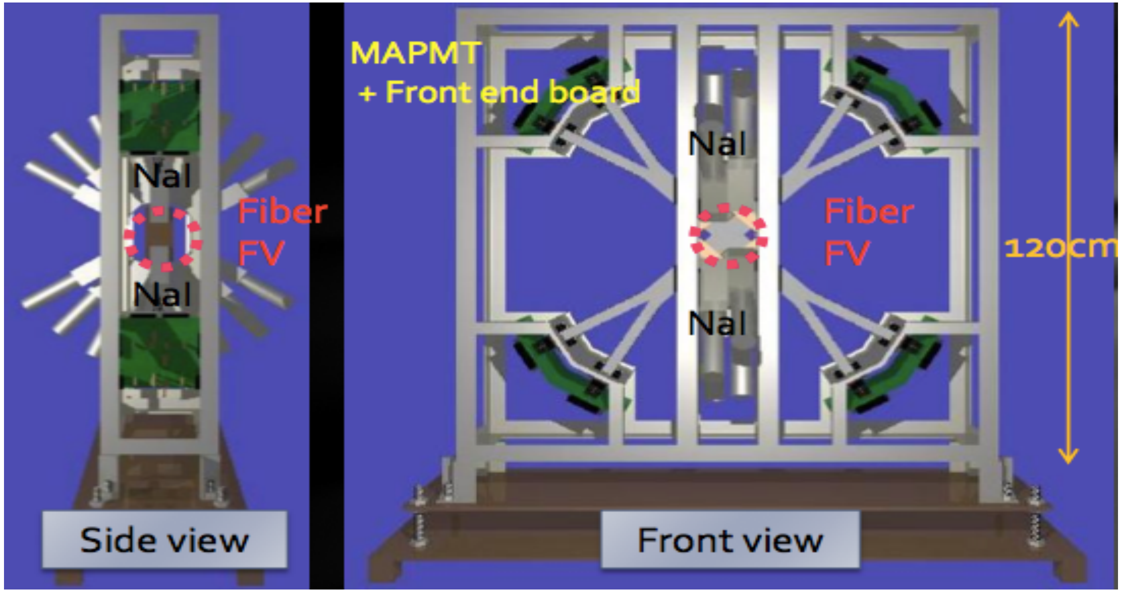


Cherenkov Counter



- TOF is not enough to separate pions and muons above 200MeV/c
- Different β for e, μ, π → Detected light will be different due to different light yield and angle

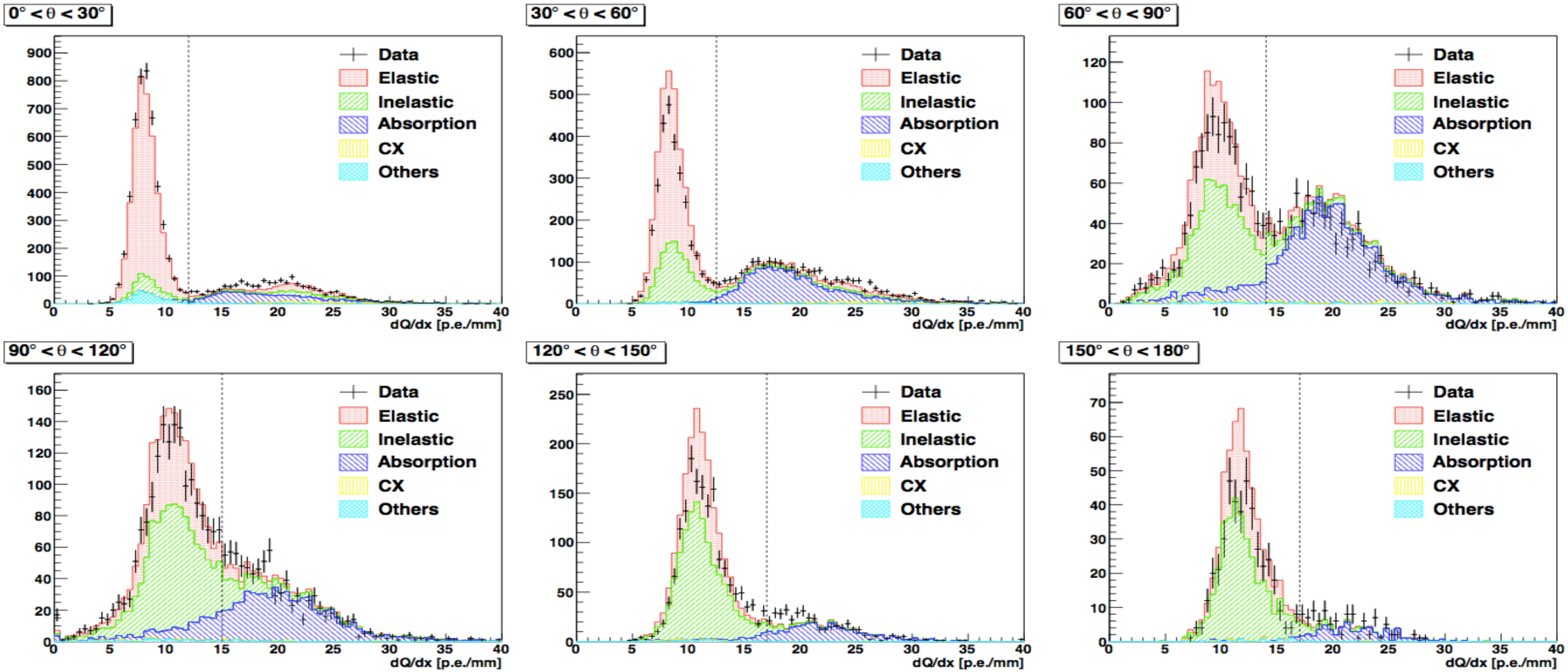
Piano



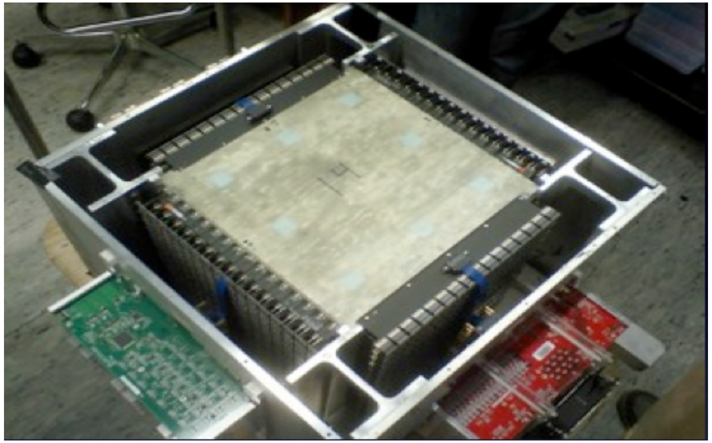
- Scintillating light are read out by MAPMT×16
- Fiber×1024 ch, NaI×16ch
- Fiber main volume: 48mm×48mm×48mm

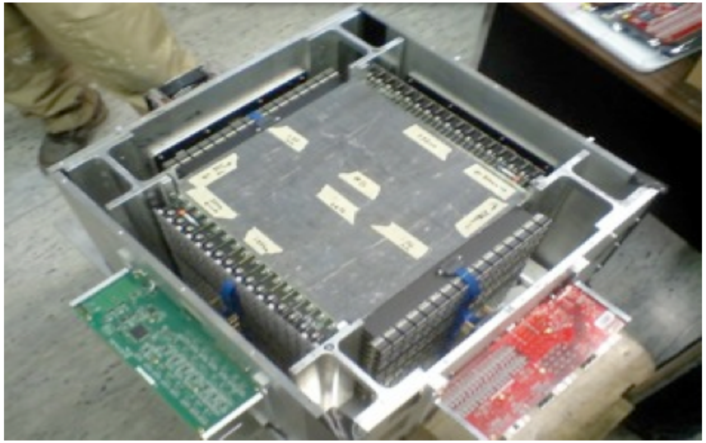
dE/dx Distributions

- Used for PID in Piano's fibers



Harpsichord

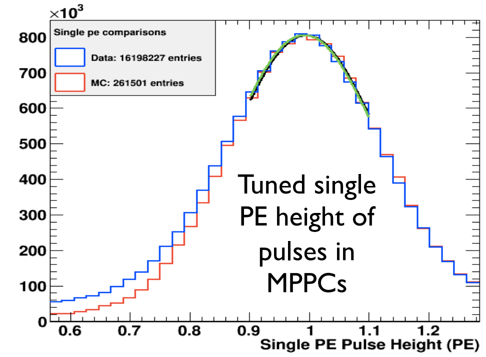


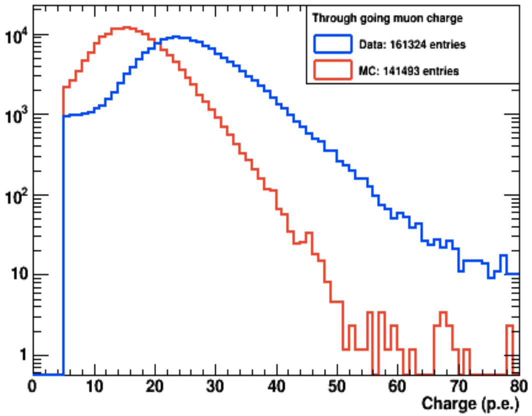


- Harpsichord
  - 1/6 X 1/6 scale FGD
  - Same numbers of layers, electronics as FGD
- Cembalos
  - Added lead layers between XY scintillator modules
  - Increased photon conversion

Cembalos Simulation Validation

- Cembalos GEANT4 simulation is based on the FGD (from T2K):
  - Only geometrical and calibration-related modifications
  - Need to validate simulation
- Use muons (MIPs) traversing the detector as control sample
- Tune MC and electronics simulation parameters to match Data vs. MC deposited charge distributions

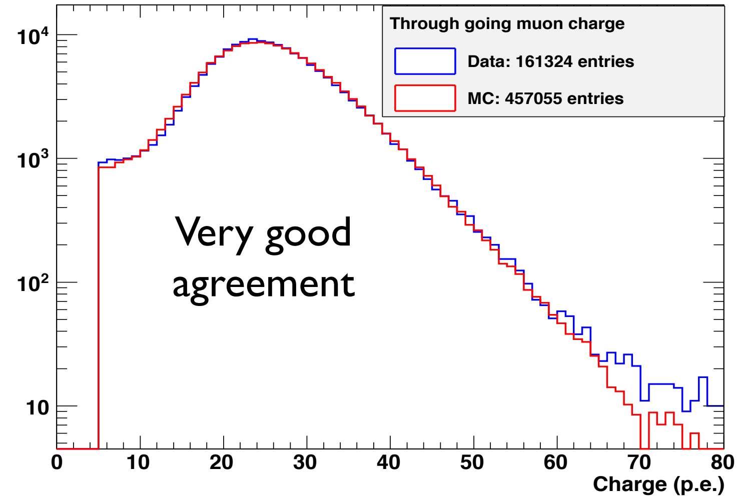




Some tuned parameters:
- MPPC waveform parameters
- MPPC ADC to p.e. factor

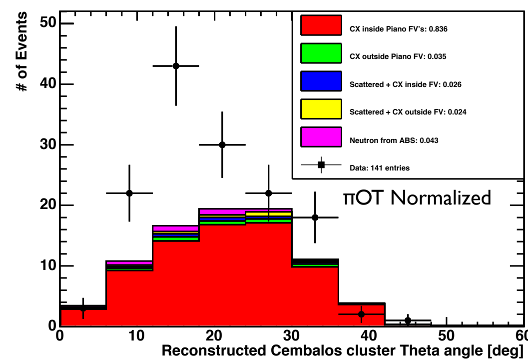
Tuning

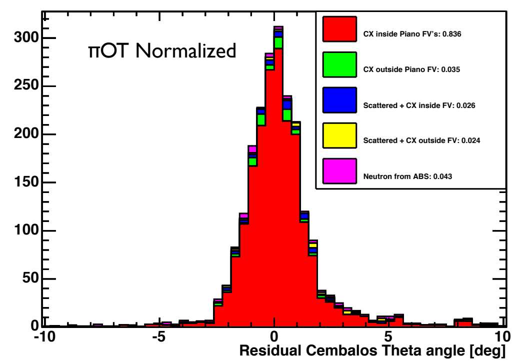
- MeV to p.e. factor
- Mirrored end of fibers



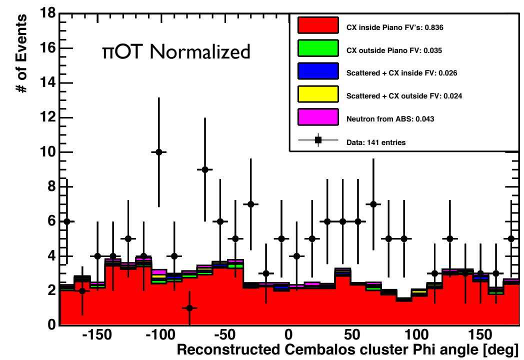
Cembalos photon direction Reconstruction

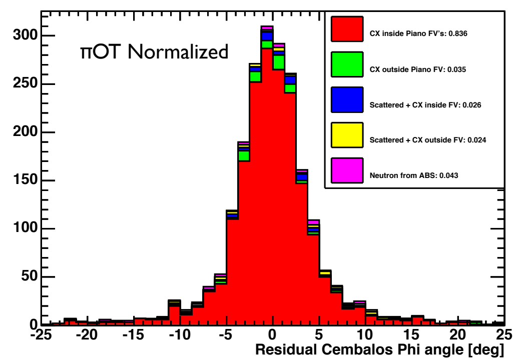
- Reconstruct CX photon direction from Piano vertex and position of hit clusters in Cembalos
- Good resolution (<5°)



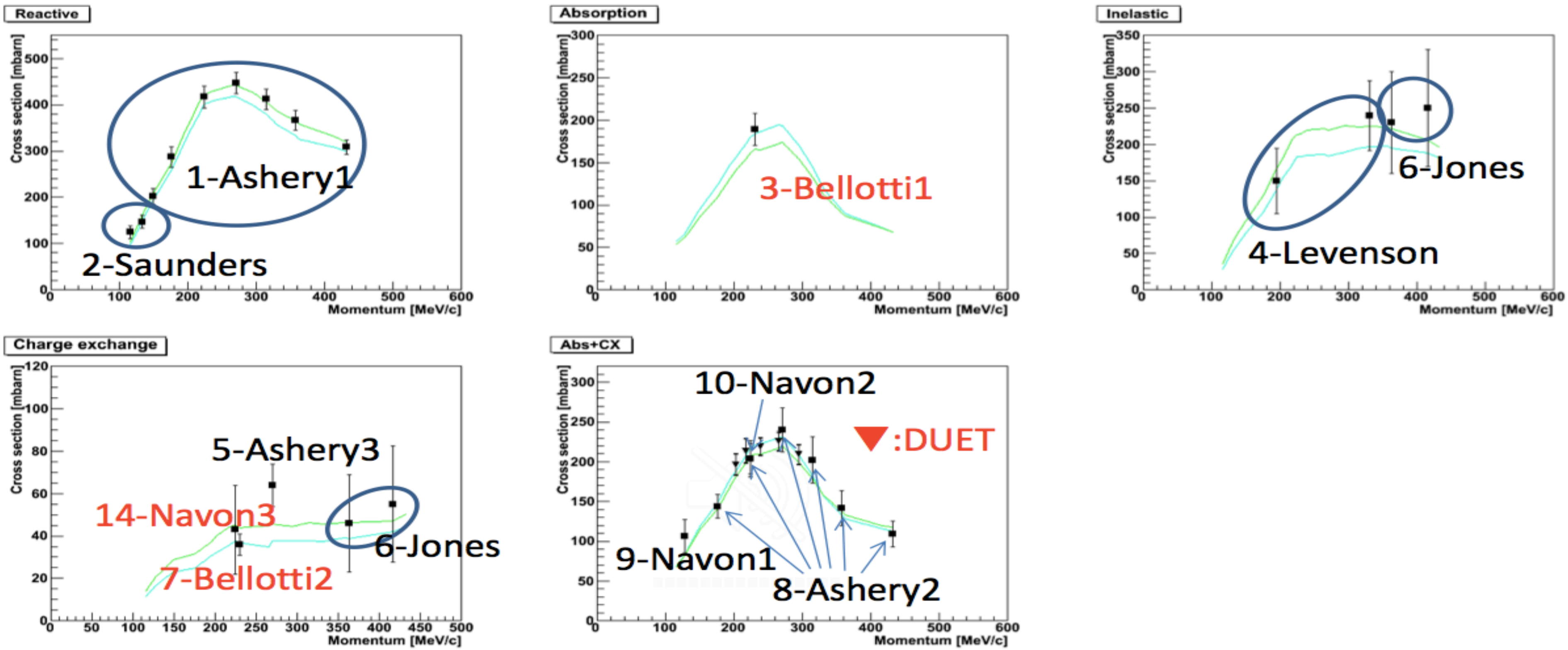


- Investigating if differential cross section measurement is possible
- Unify NaI Crystals and Cembalos analyses
  - Reduce model dependence



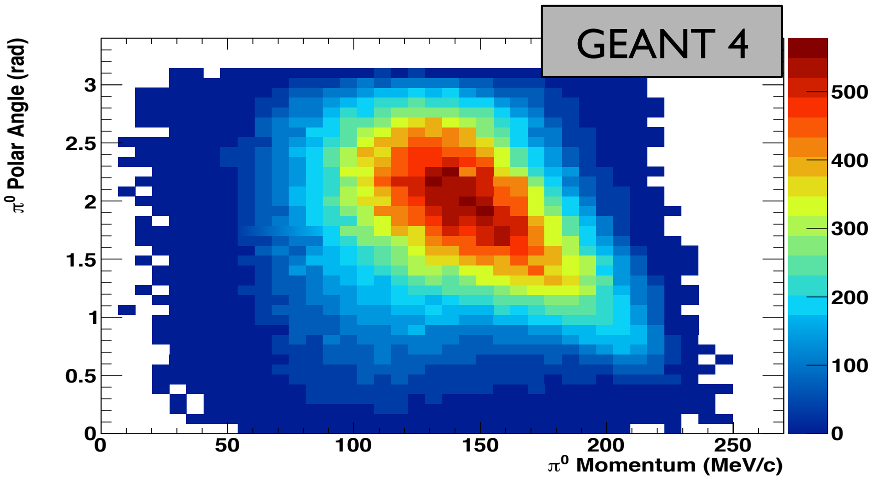


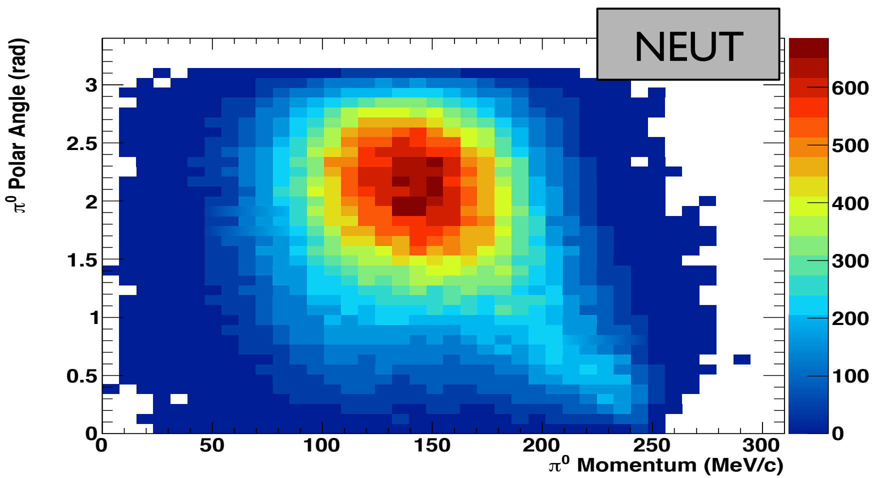
Previous experiments



p-theta for π^0's

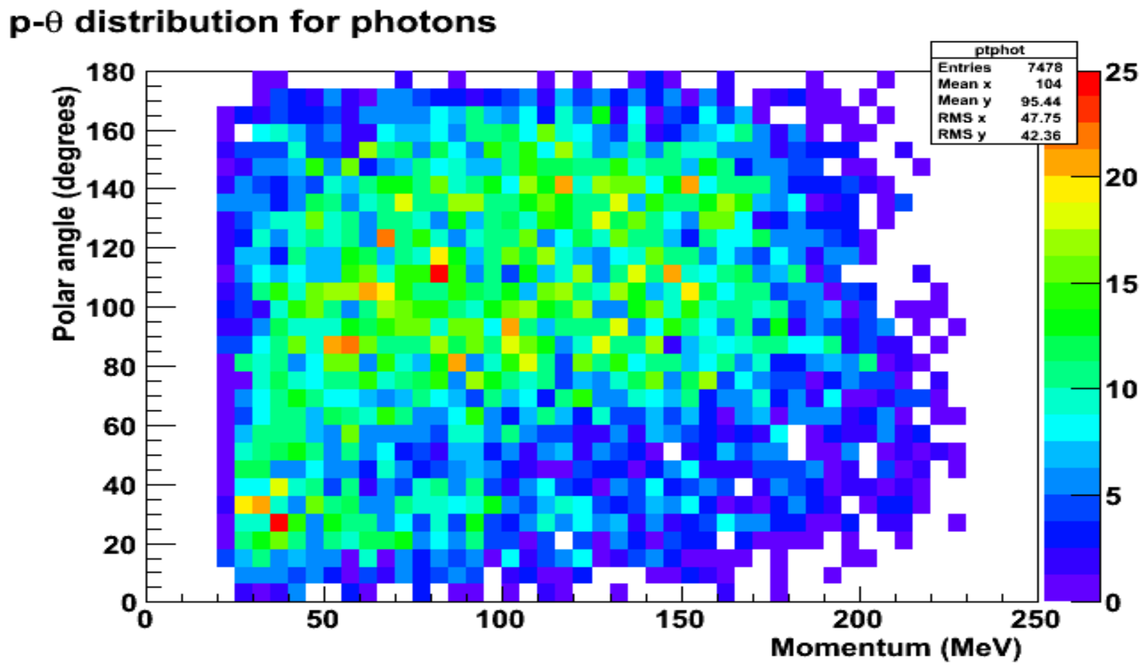
- GEANT4 (QGSP-BERT) and NEUT
- Initial 250 MeV/c π^+





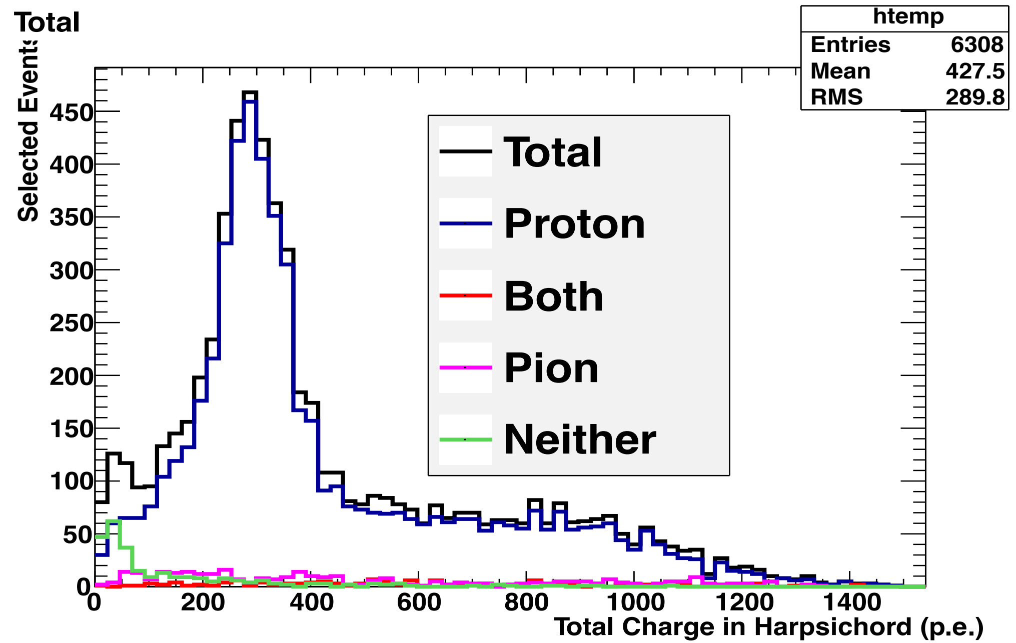
p-theta for CX Photons

- GEANT4



Proton selection (Control sample)

- Selection:
  - Good incident pi+
    - TOF + Cherenkov
    - Straight incoming Piano track
  - Vertex in FV
  - Not low scattering pi+
  - Reconstructed proton track in Piano
  - Hits in Harpsichord



Not stacked, just plotted on top of each other

- From MC:
  - 88.4% proton hitting Harpsichord
  - 5.2% pion hitting Harpsichord
  - 4.2% neither proton nor pion hitting Harpsichord
  - 2.1% both proton and pion hitting Harpsichord