Measurement of π^+ Absorption and Charge Exchange Cross Sections for the T2K Experiment:

DUET Experiment

Elder Pinzon

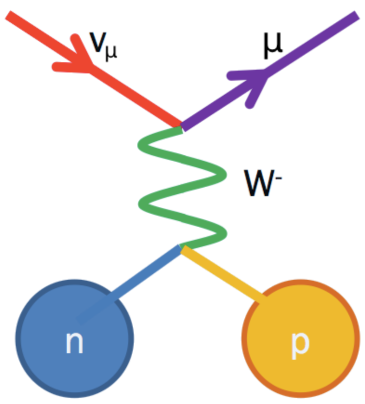
for the DUET Collaboration

Kyoto University, TRIUMF,
UBC, University of Tokyo,
University of Toronto,
York University

HAdron Reconstruction Performance
Studies In CH On Reduced Detector

Pions in ν Interactions

- Neutrino flavour and energy determined from flavour and momentum of outgoing lepton



CCQE Interaction.
Signal event

Use two-body decay kinematics to reconstruct neutrino energy

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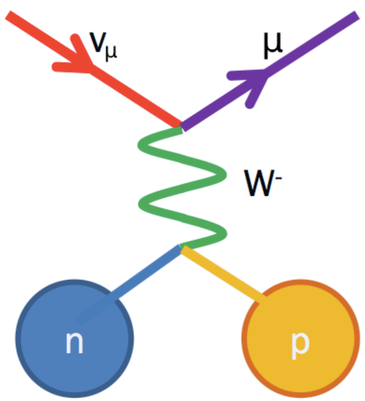

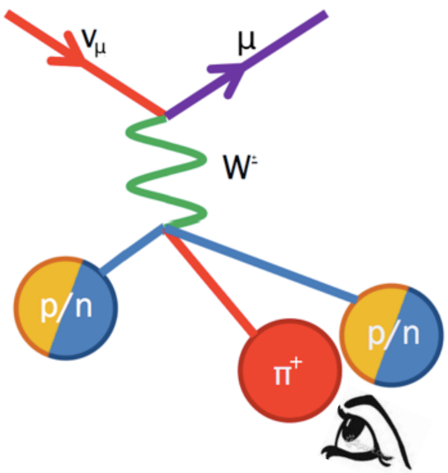

CCQE Interaction.
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CC1π^+ Interaction.
Background

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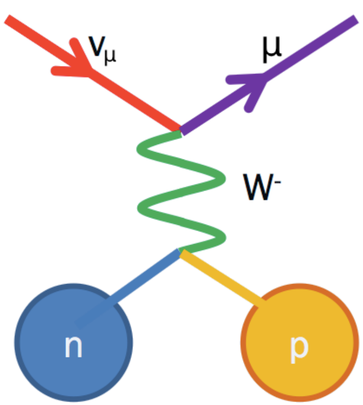

CCQE Interaction.
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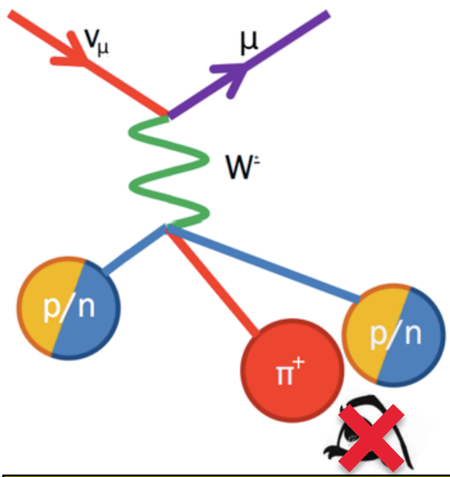
Use two-body decay kinematics to reconstruct neutrino energy



CC1π^+ Interaction.
Background

Unidentified pion leads to wrong reconstructed energy

(FSI+SI)

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

Pions in ν Interactions

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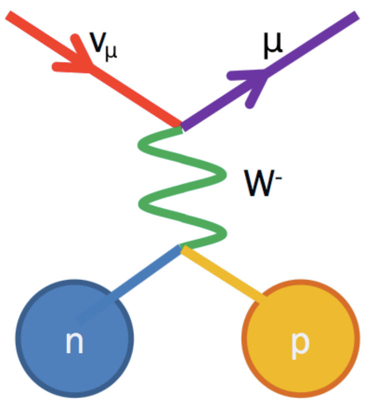

CCQE Interaction.
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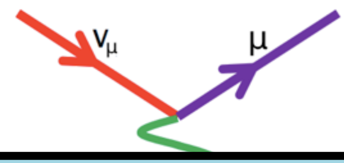
Use two-body decay kinematics to reconstruct neutrino energy



Background

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Phys. Rev. Lett. 112, 181801 (2014)

Source of uncertainty (number of parameters)	$\delta n_{\mathrm{SK}}^{\mathrm{exp}}$ / $n_{\mathrm{SK}}^{\mathrm{exp}}$
ND280-independent cross section (11)	4.9%
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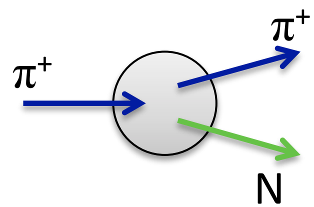
SK detector and FSI+SI systematics (7)	5.6%
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{21}, δ_{CP} (4)	0.2%
Total (45)	8.1%

Measure π^+ interaction cross sections!

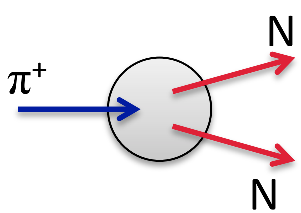
- Inside nucleus:
  Final State Interactions
- Outside nucleus:
  Secondary Interactions

Pion Interaction modes

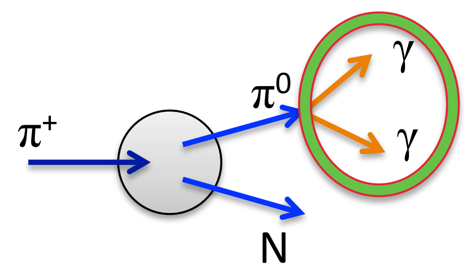
1. Quasi-elastic Scattering



2. Absorption (ABS)



3. Charge Exchange (CX)



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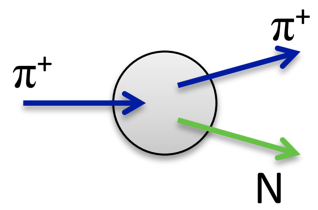

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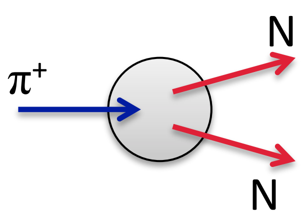

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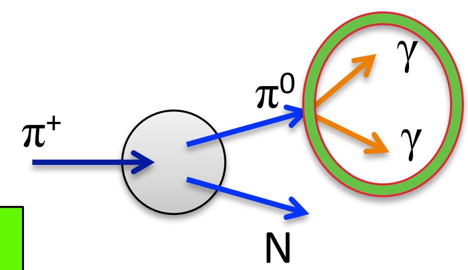

Can measure combined ABS+CX

No π^+ in final state

Pion Interaction modes

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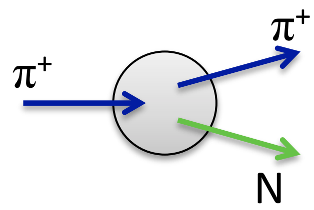

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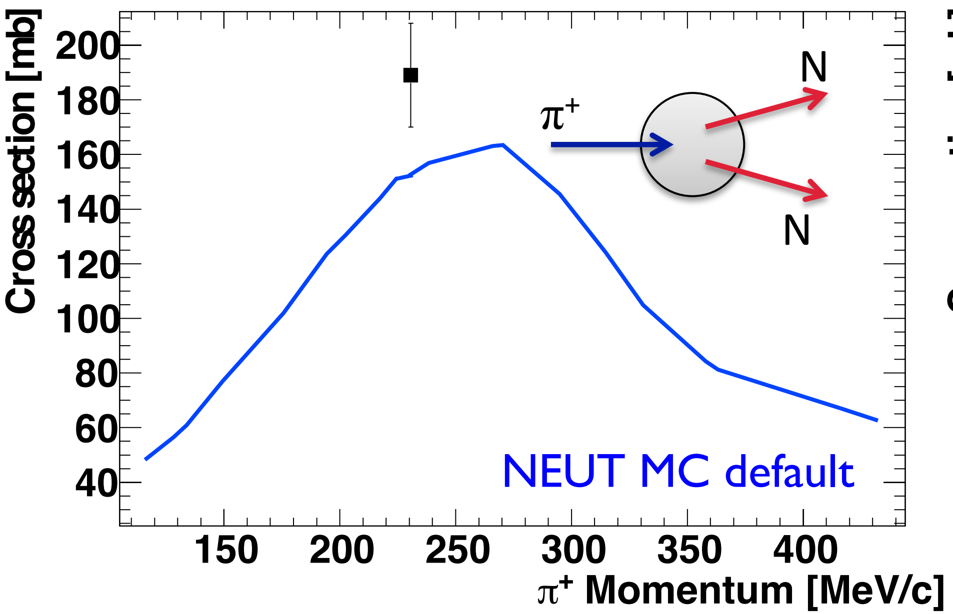

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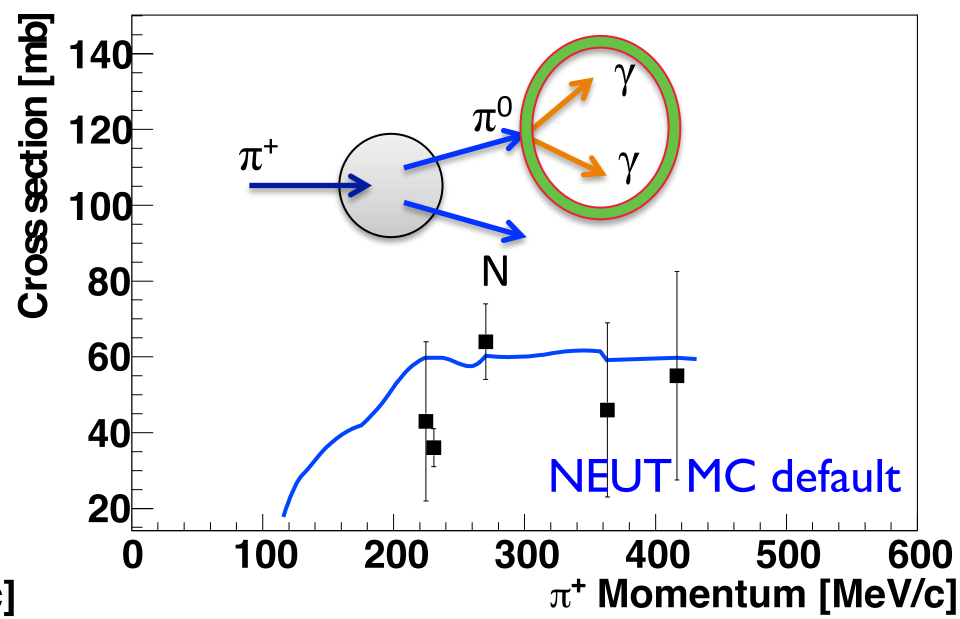


DUET Experiment

GOAL

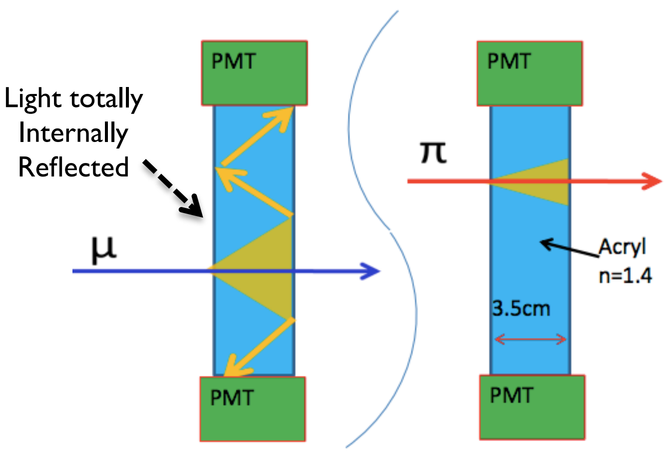
Measure pion absorption cross section with ~10% accuracy and charge exchange with ~20% accuracy

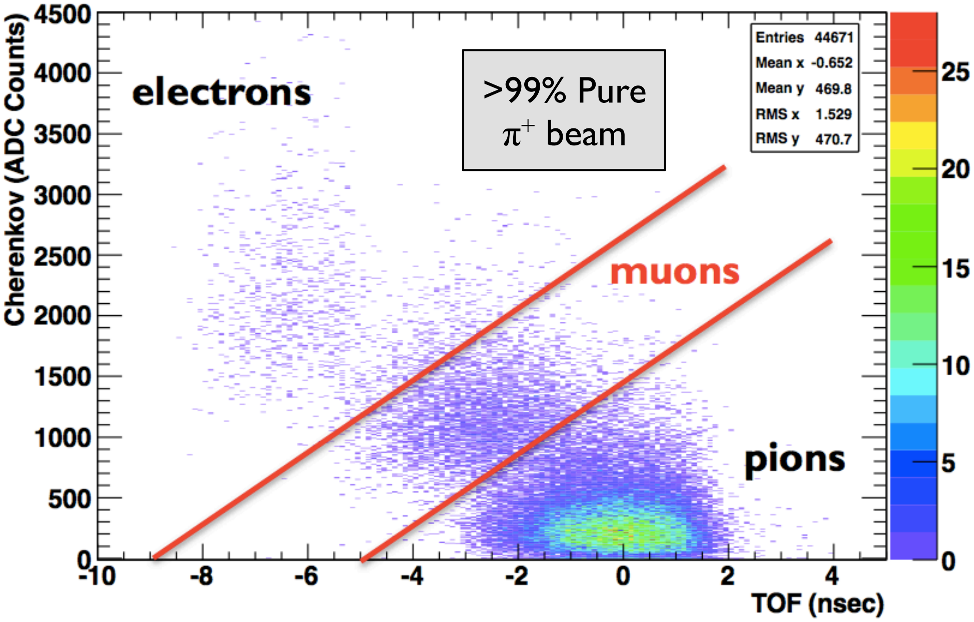
Use TRIUMF M11 beam line

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.



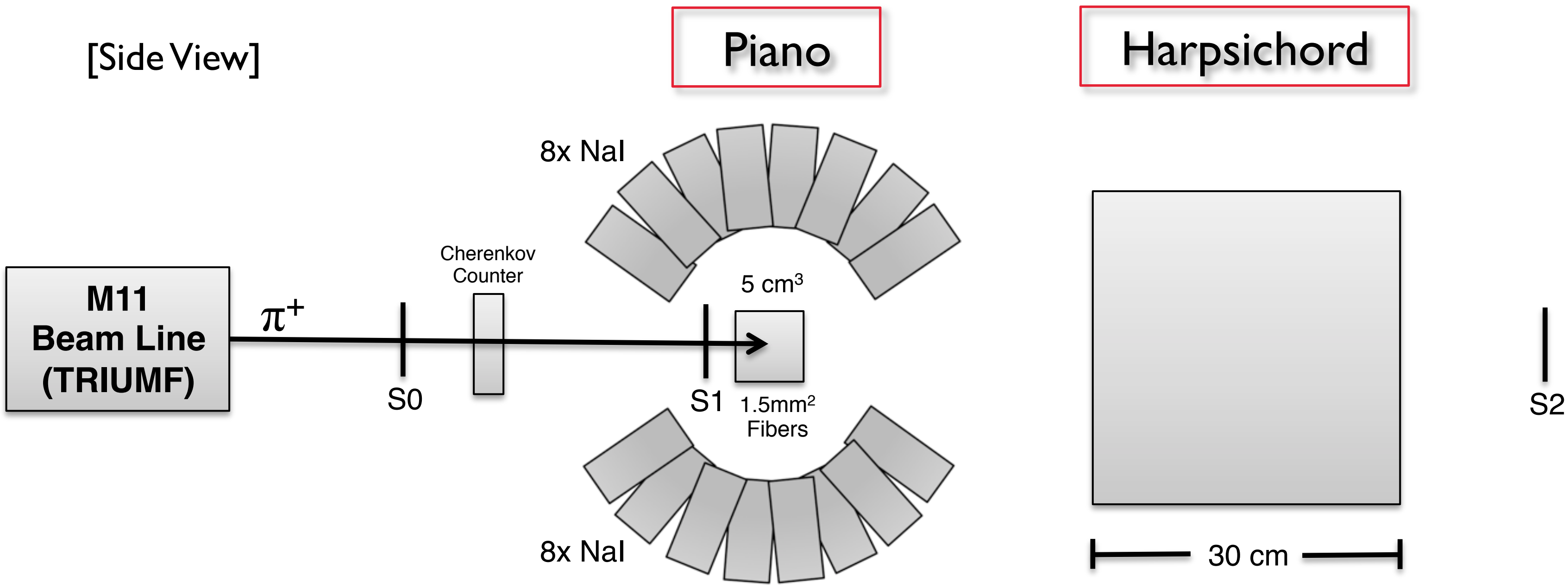


Detector setup: DUET

- Main Components:

Piano: 1.5 mm^2 scintillating fiber tracker (Full active target) + NaI crystals

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



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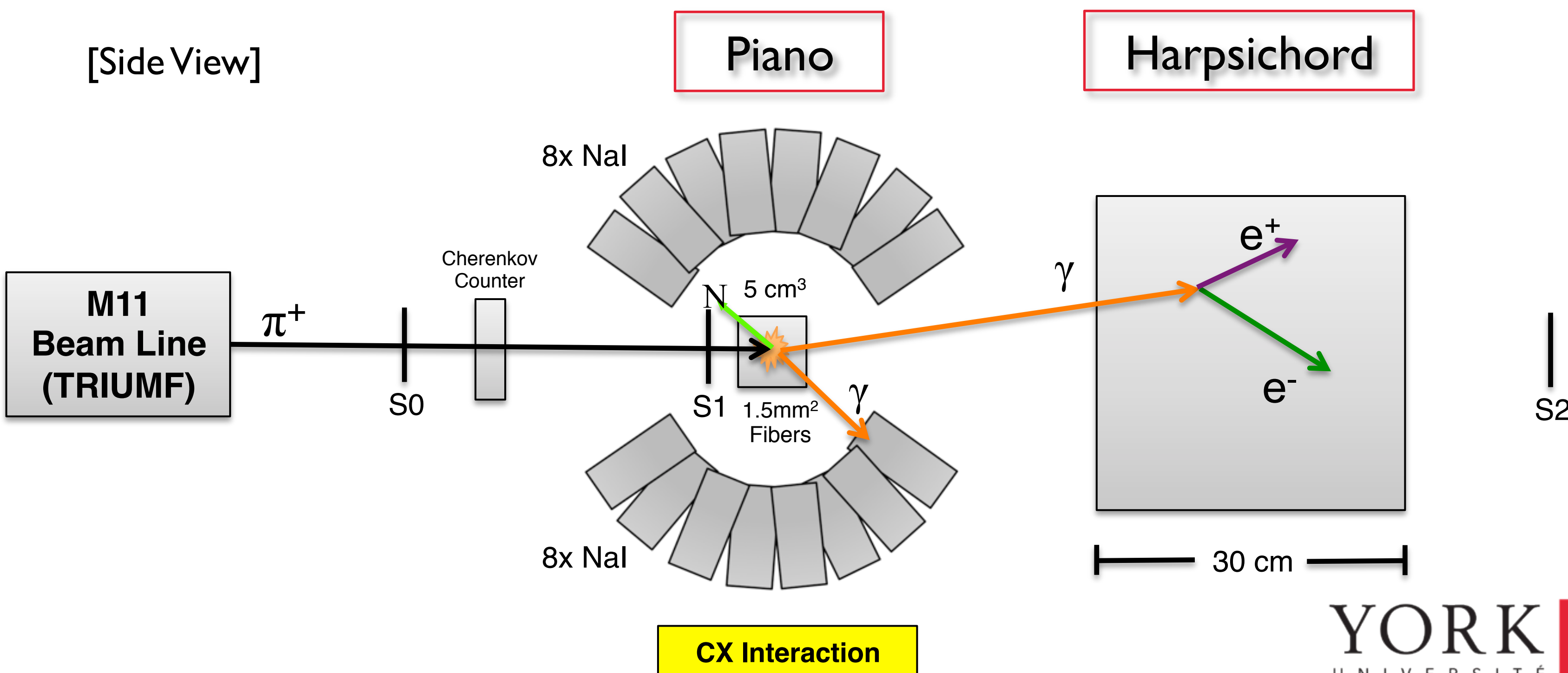

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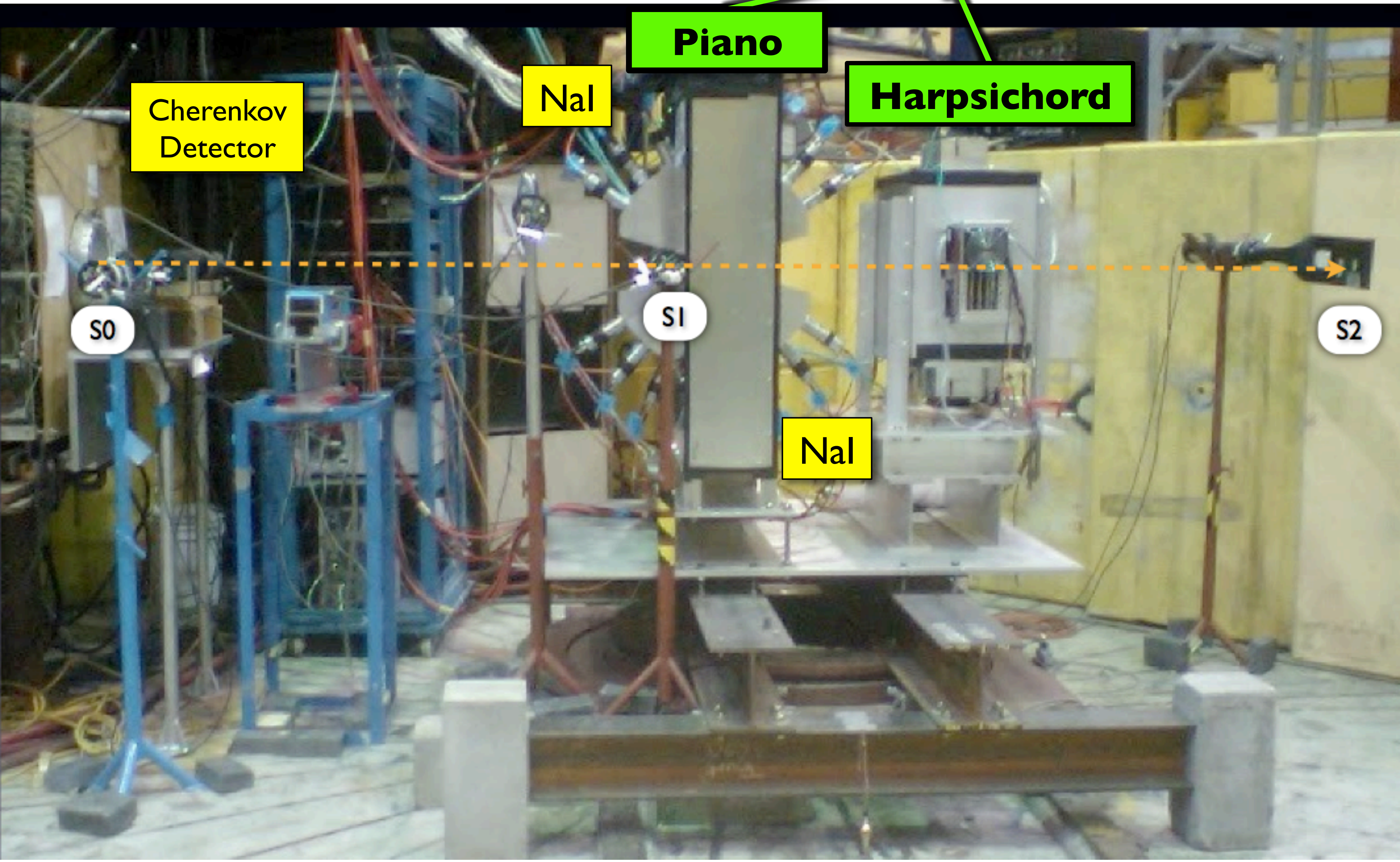

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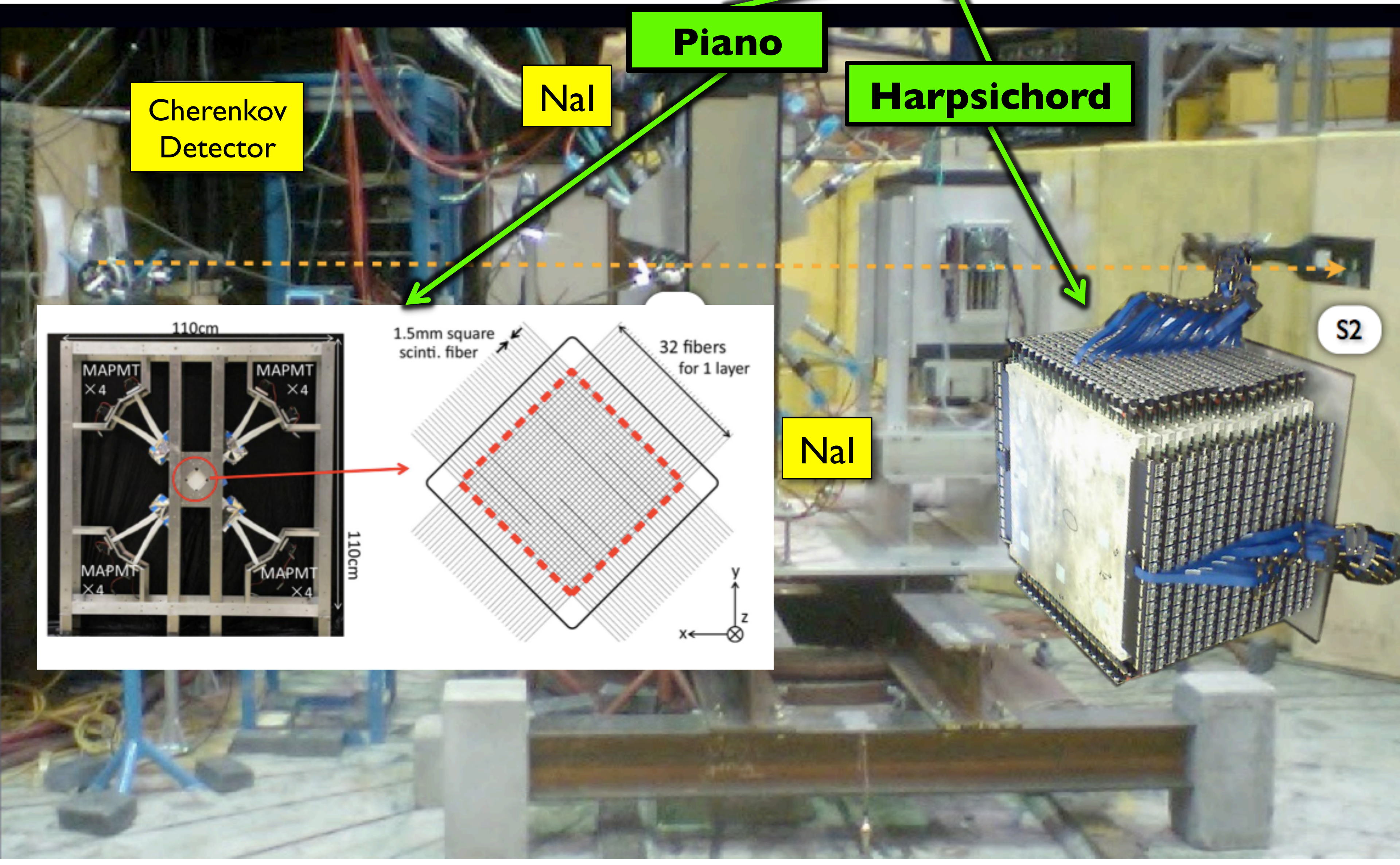


Analysis Outline

Using Piano fibers

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

Using NaI detectors and Harpsichord

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

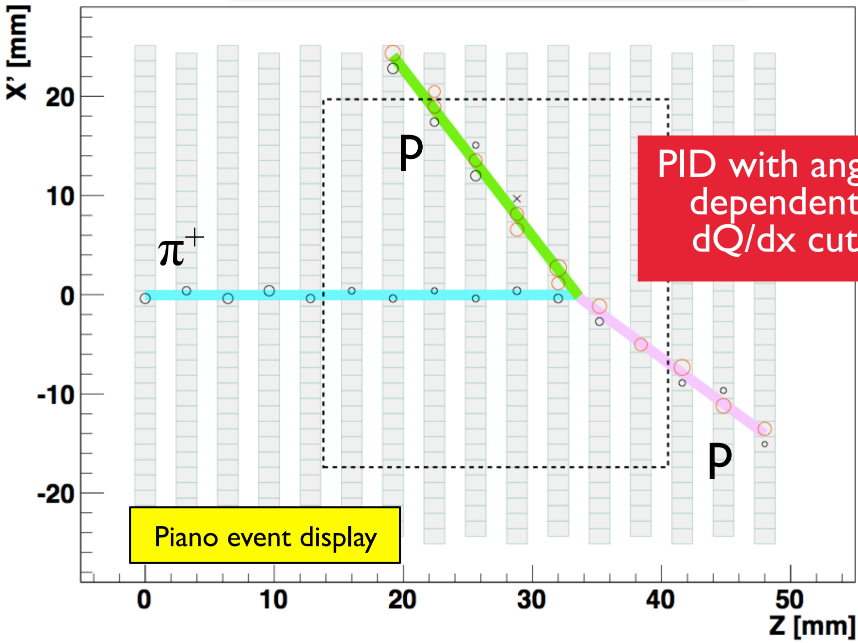
Feed into FSI & Secondary Interaction models

Improve Systematics

Event Selection: No π^+ in final state

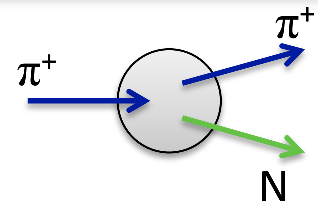
Vertex inside Piano's Fiducial Volume

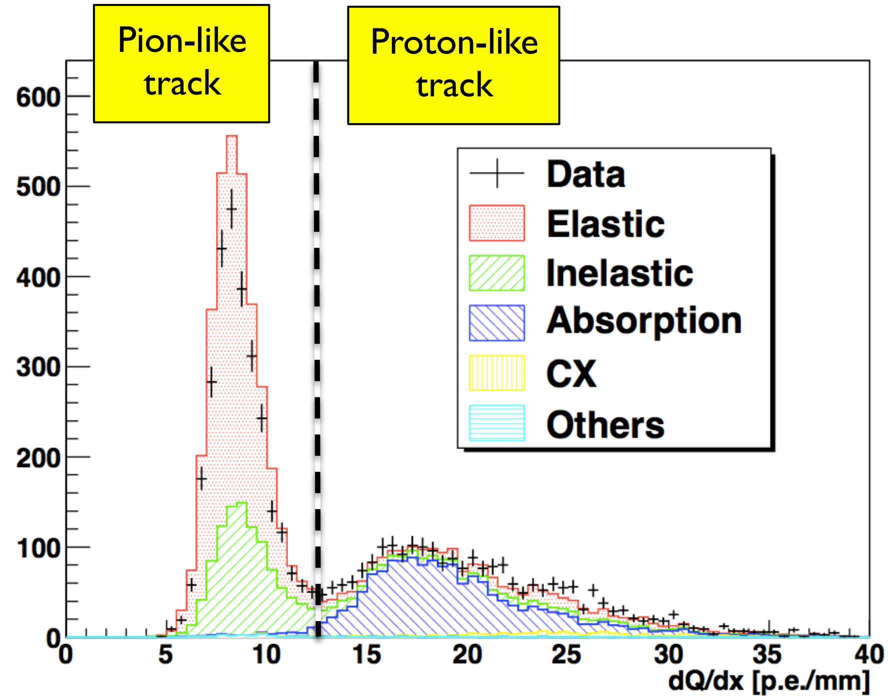
PID with angle dependent dQ/dx cut



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

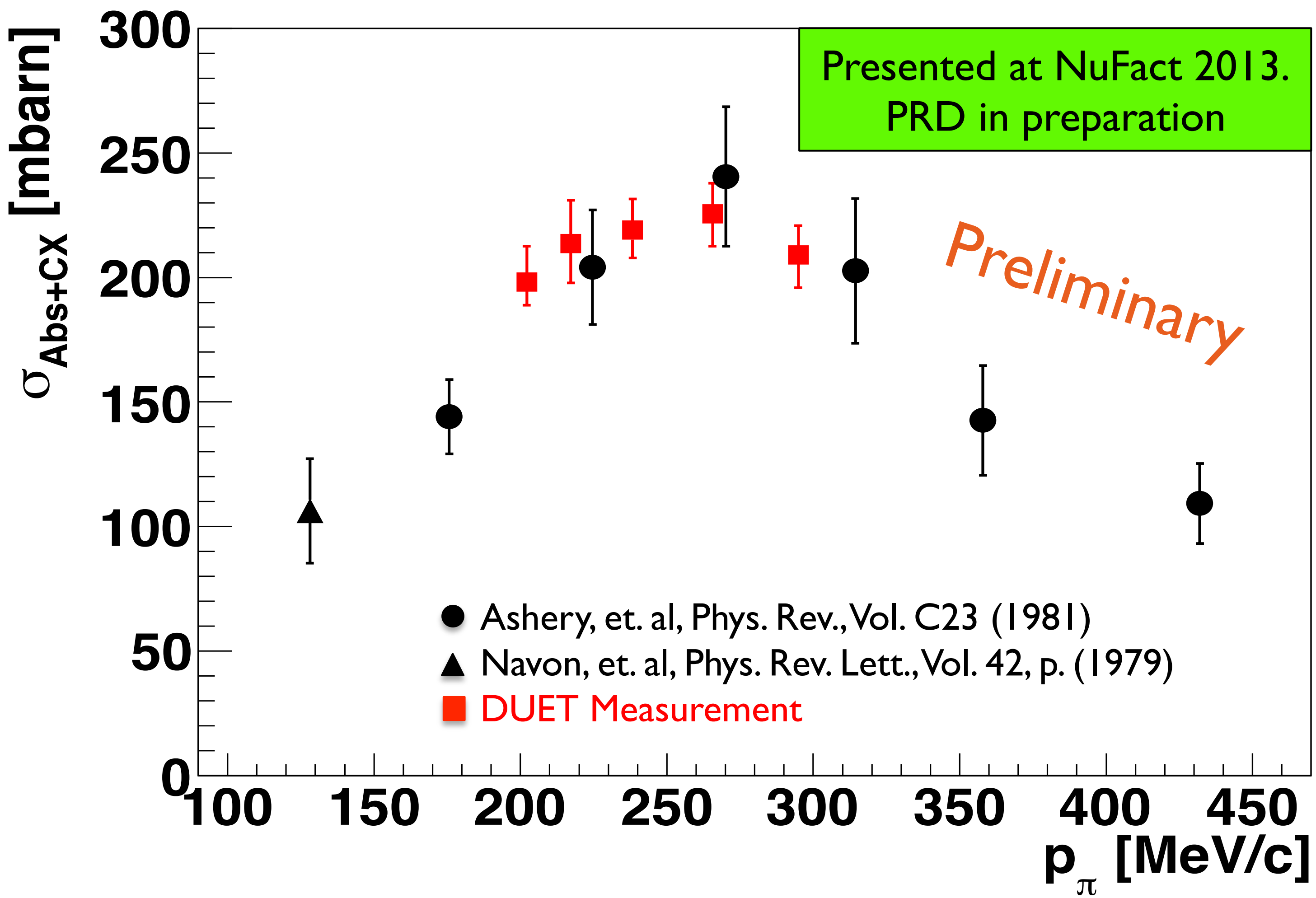
Reject:





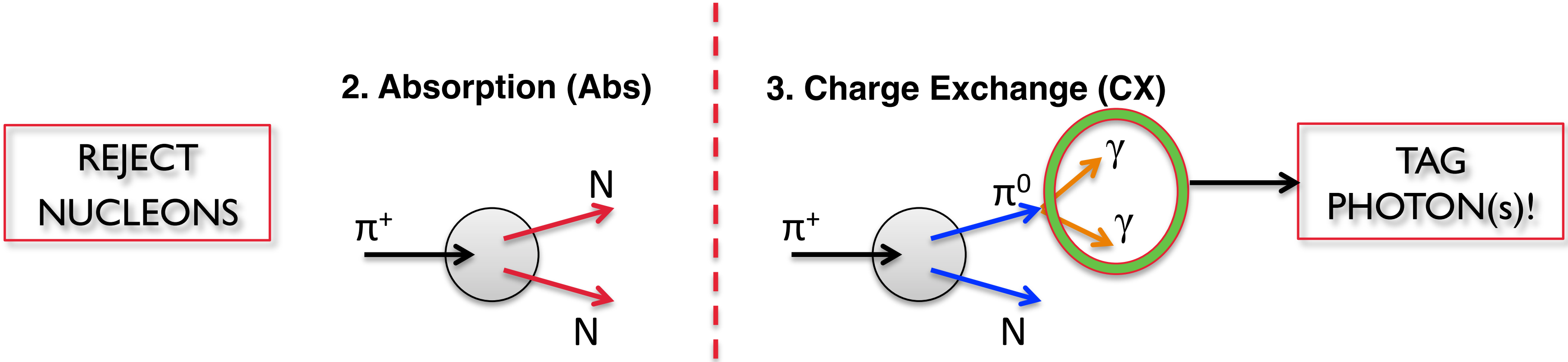
Example of dQ/dx distribution

Abs+CX Cross Section Result



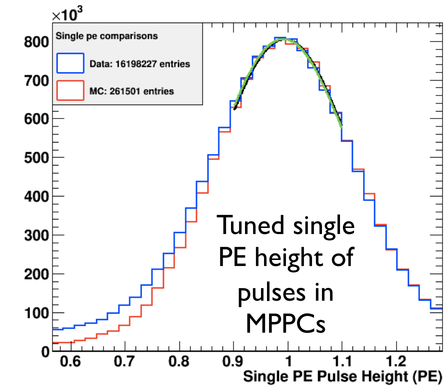
Good agreement and much smaller errors (~20% → ~6%)

Extracting the Charge Exchange cross section

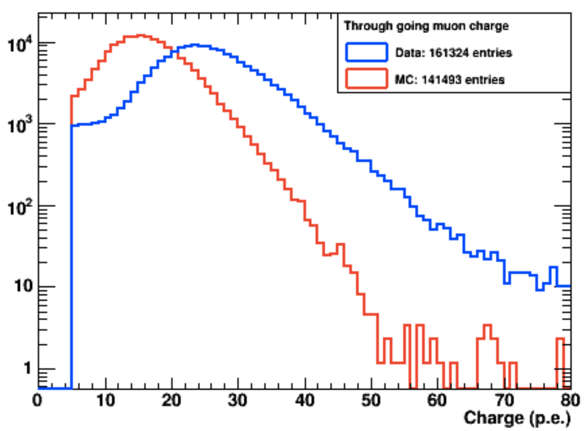


Harpsichord Simulation Validation

- Harpsichord GEANT4 simulation is based on the FGD (from T2K):
  - Only geometrical and calibration-related modifications
  - Need to validate simulation



- Use muons traversing the detector as control sample
- Tune MC and electronics simulation parameters to match Data vs. MC deposited charge distributions

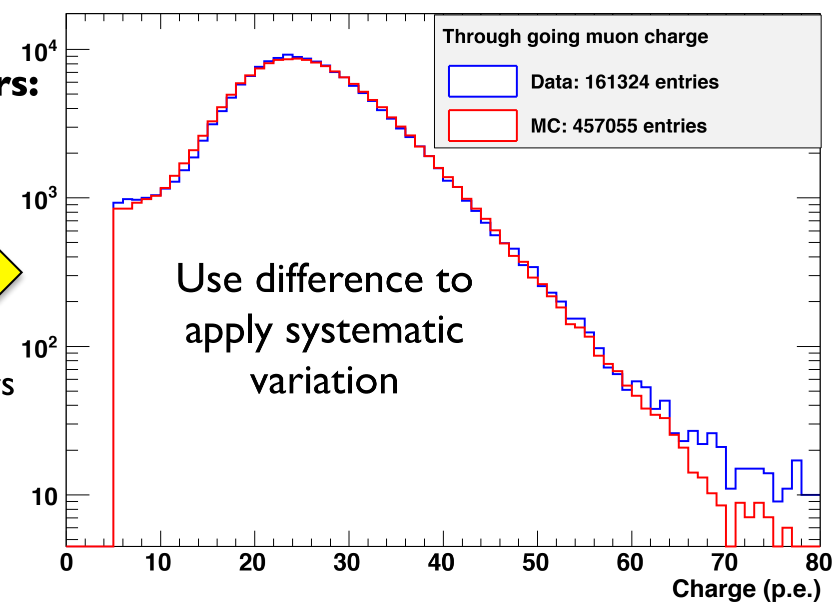


Some tuned parameters:

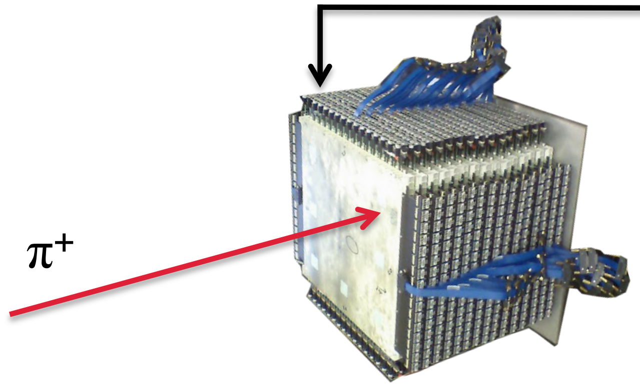
- MeV to p.e. factor
- MPPC ADC to p.e. factor

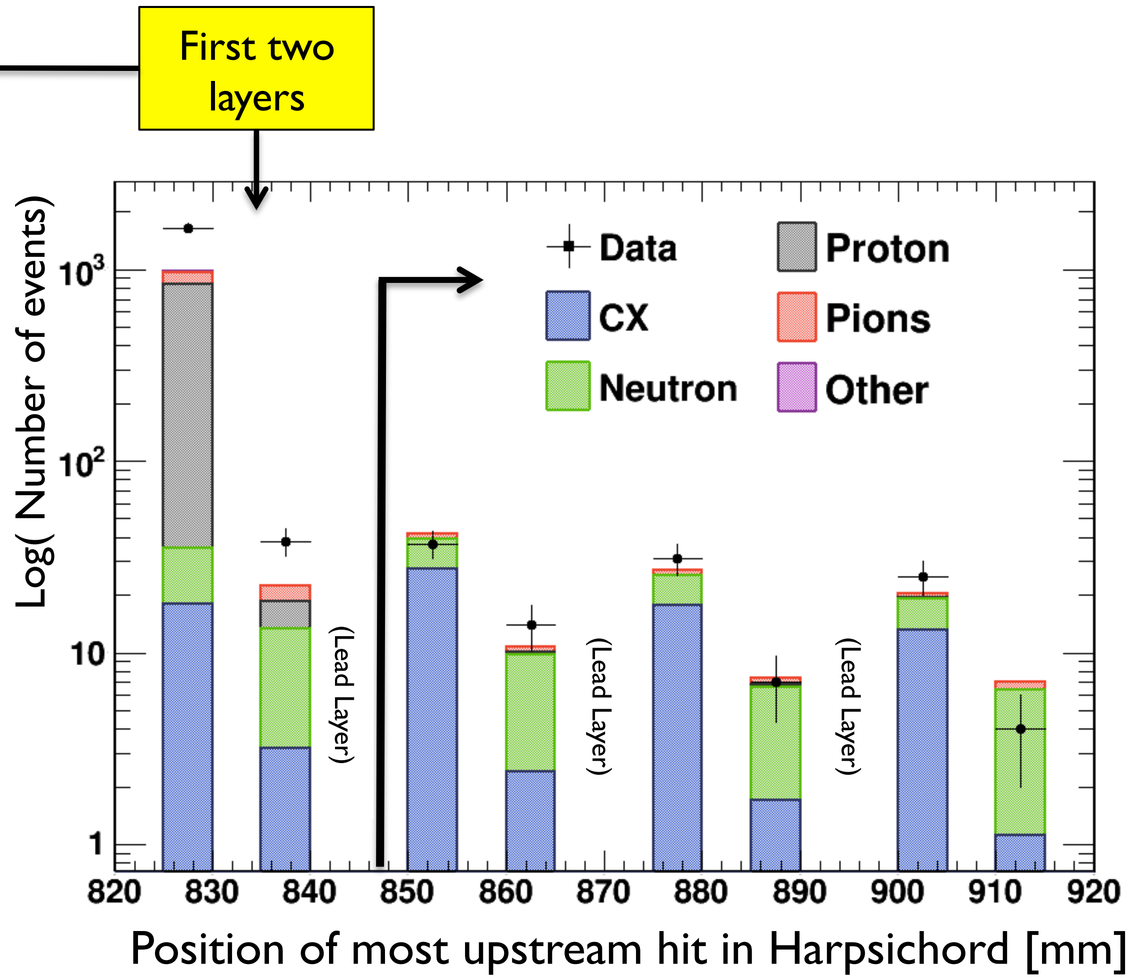
Tuning

- MPPC waveform parameters
- Mirror end of fibers



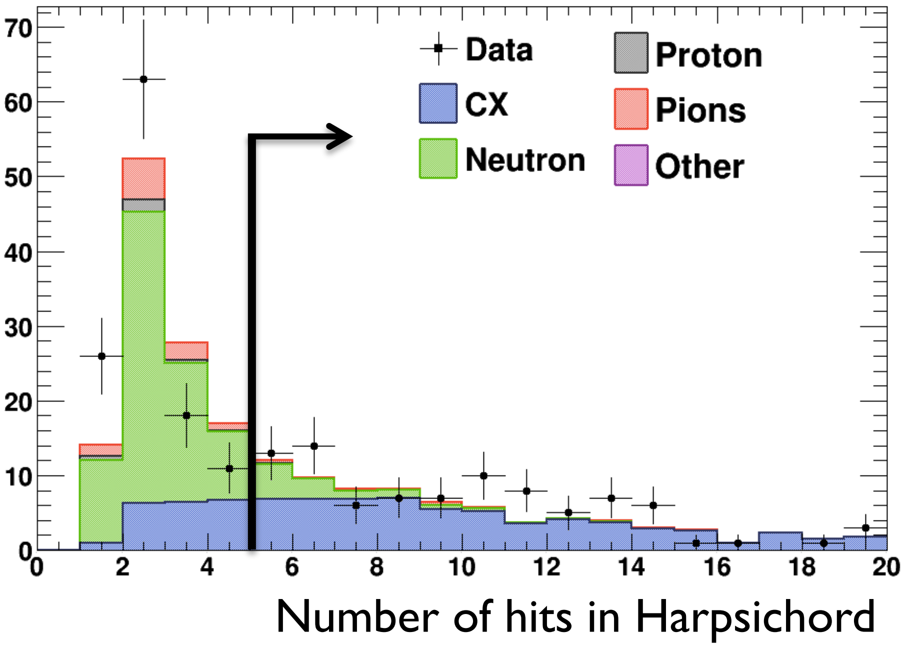
CX Event Selection: Using Harpsichord

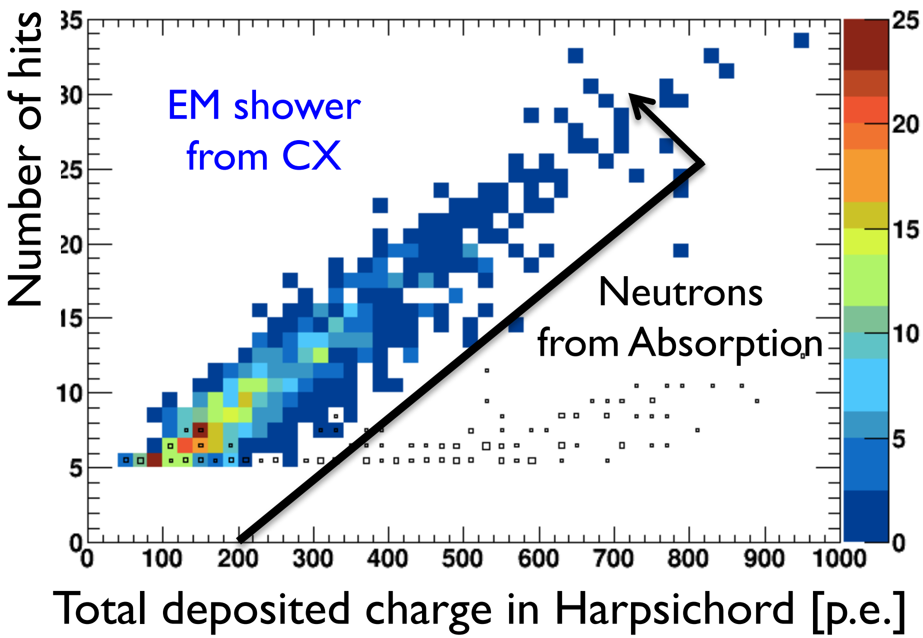




- Charged pions and **protons** immediately leave a signal in the scintillating detector
- Photons are neutral, so they must interact before they can be detected
- The **first two layers** are used as a **veto cut** in order to remove pions and protons.

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

$$\textbf{Efficiency} = \frac{\text{Selected CX events}}{\text{True CX events}} \approx 15\%$$

$$\textbf{Purity} = \frac{\text{Selected CX events}}{\text{Total selected events}} \approx 95\%$$

- Working on sources of systematic error:
  - Charge response
  - π^0 kinematics (opening angle & momentum)

Summary and Outlook

- 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% → ~6%)
  - Paper will be submitted to PRD in the next few weeks
- Work for a separate charge exchange measurement is ongoing
  - Event selection finalized
  - Working on systematic errors
  - Results are coming
- This will feed into a better model of pion Final State Interactions and Secondary Interactions
  - Reduce systematics for current and future neutrino experiments

Thank you

Piano & Harpsichord!

[Backup]

DUET Experiment

ν_μ disappearance systematics

Source of uncertainty (no. of parameters)	$\delta n_{SK}^{exp} / n_{SK}^{exp}$
ND280-independent cross section (11)	4.9%
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SK detector & FSI+SI systematics (7)	5.6%
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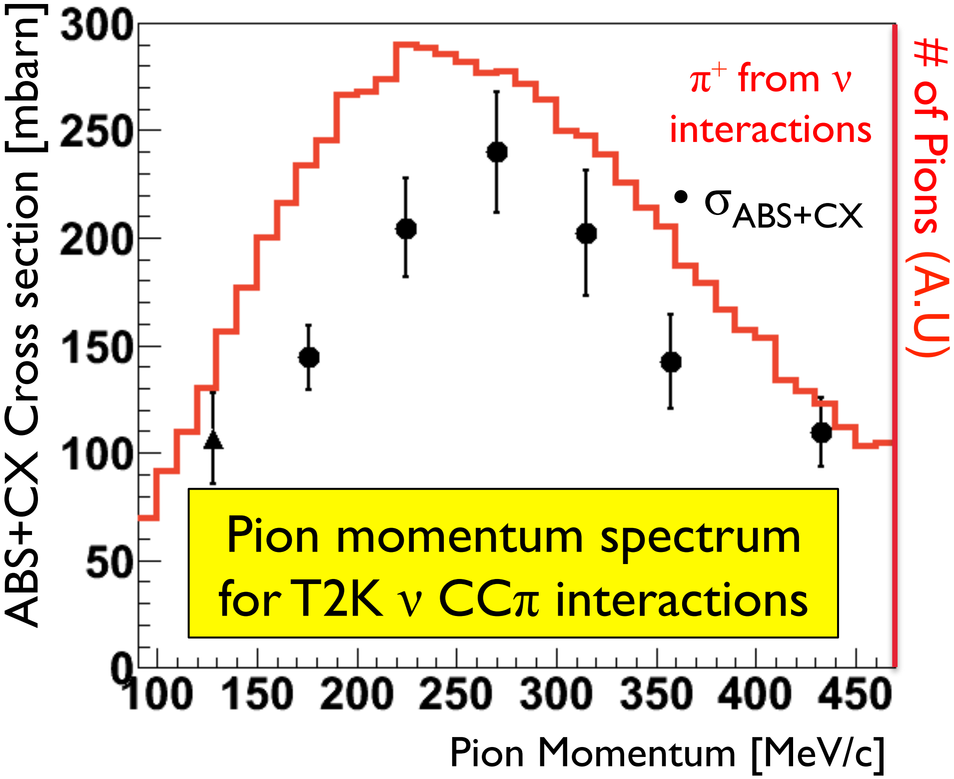
Total (45)	8.1%

Very relevant processes for pions in ν experiments



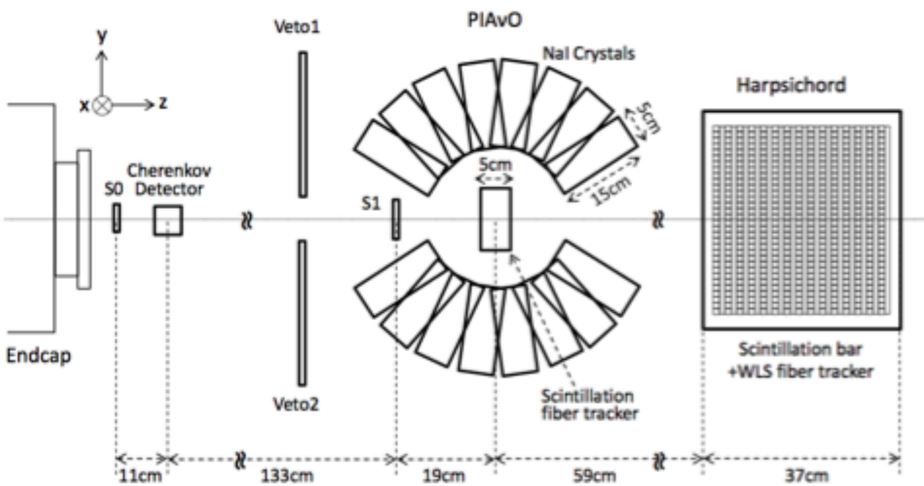
Pion momentum spectrum for T2K ν CCπ interactions

GOAL:

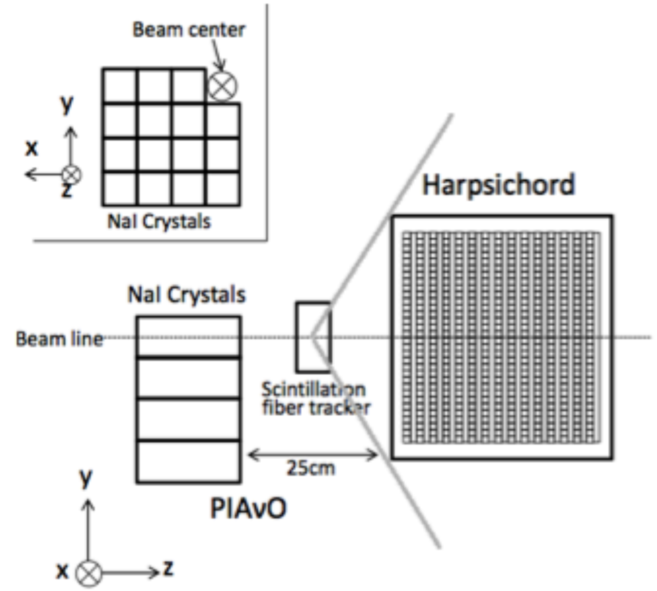
Measure pion absorption with ~10% accuracy and charge exchange with ~20% accuracy

Use TRIUMF M11 beam line

DUET Experiment

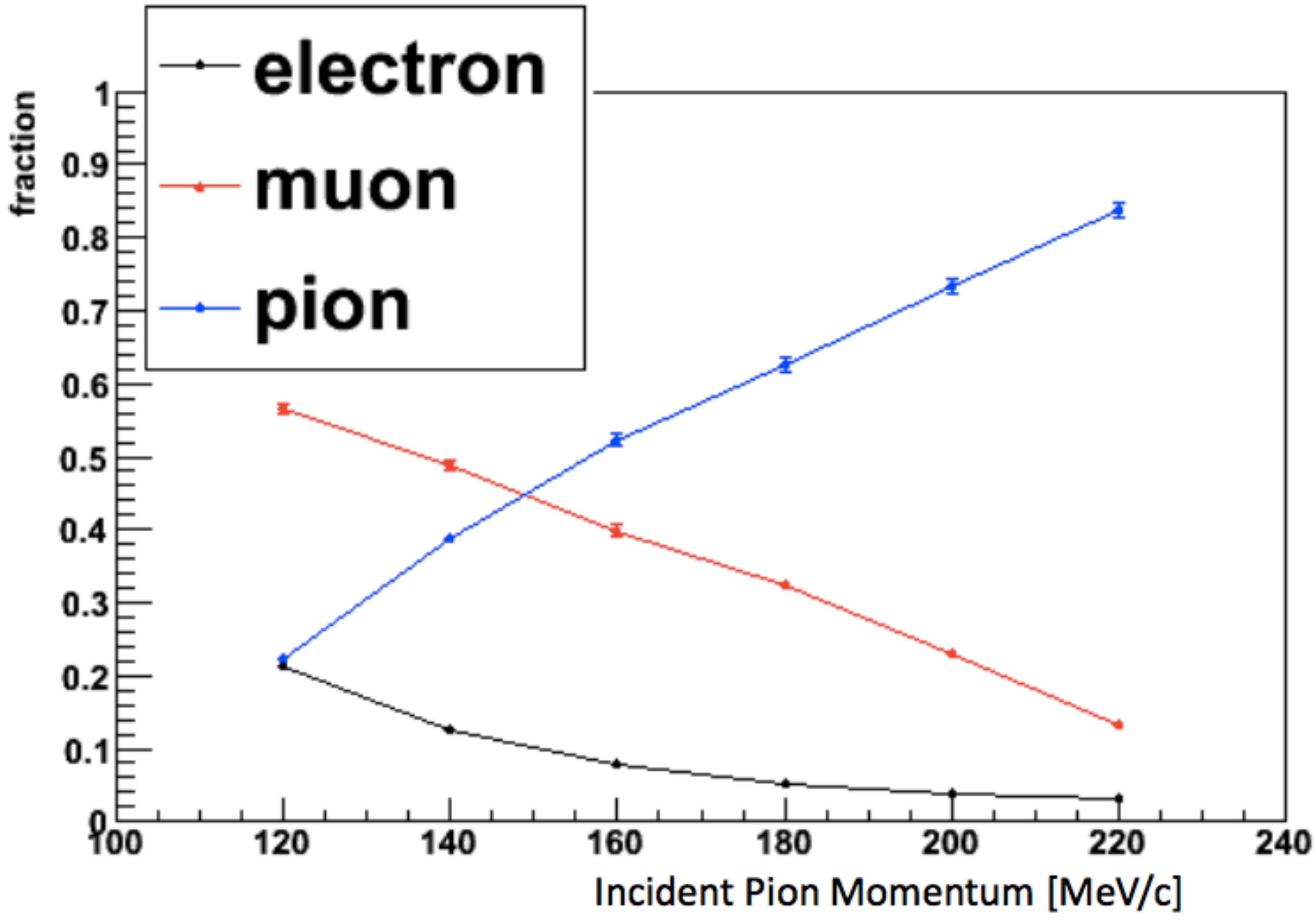


(a) Piaνo and Harpsichord in configuration 1. The angular distribution of photons can be measured using the NaI detectors.

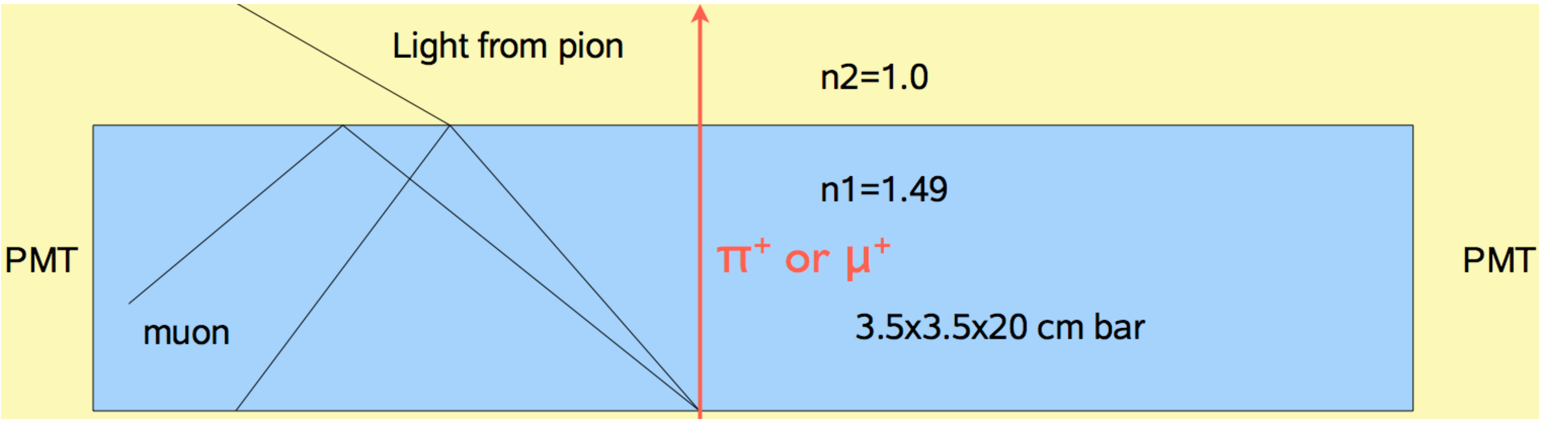


(b) Piaνo and Harpsichord in configuration 2. Lead layers are added to Harpsichord to increase photon conversion.

Beam particle fraction



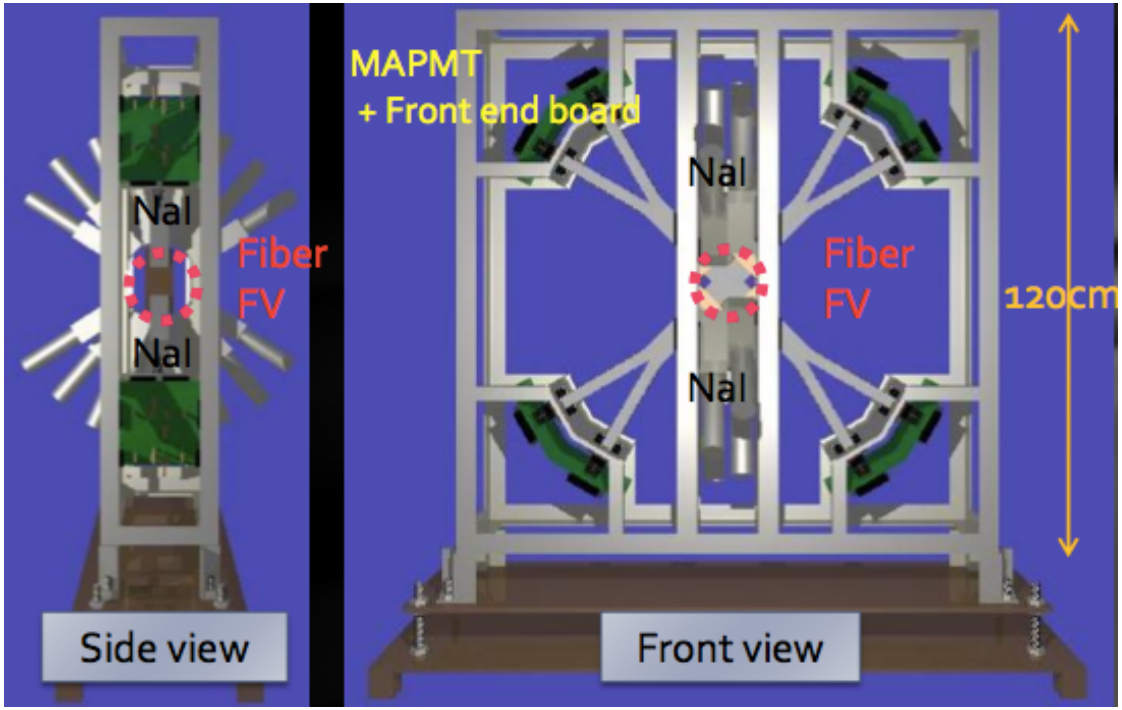
Cherenkov Counter



- TOF is not enough to separate pions and muons above 200MeV/c

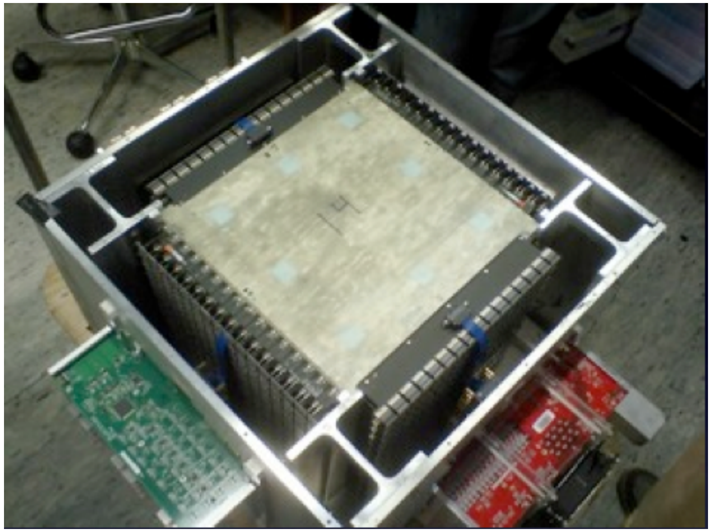
- Different β for e, μ, π → Detected light will be different due to different light yield and angle

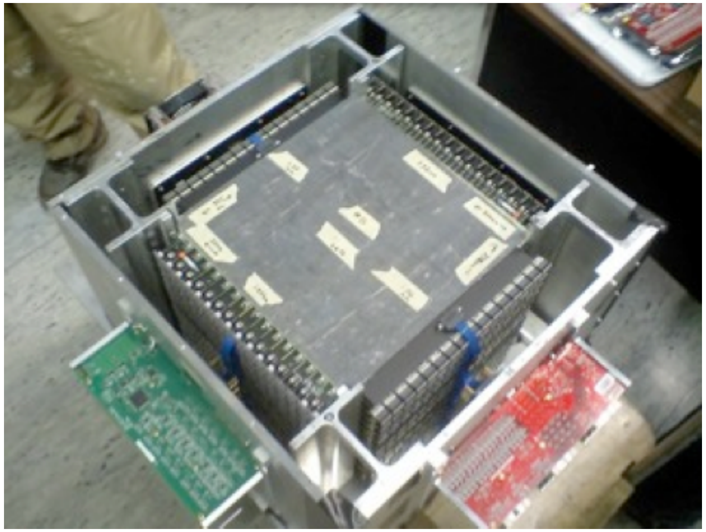
Piano



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

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

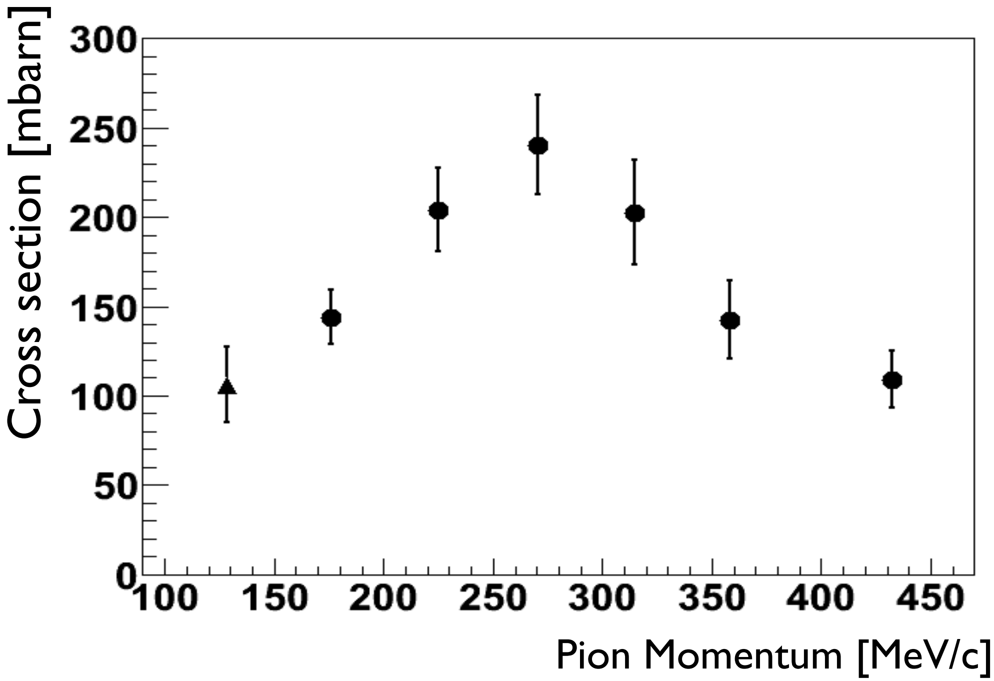
Harpsichord

- Light from scintillation bar + WLS fibers read out by MPPCs

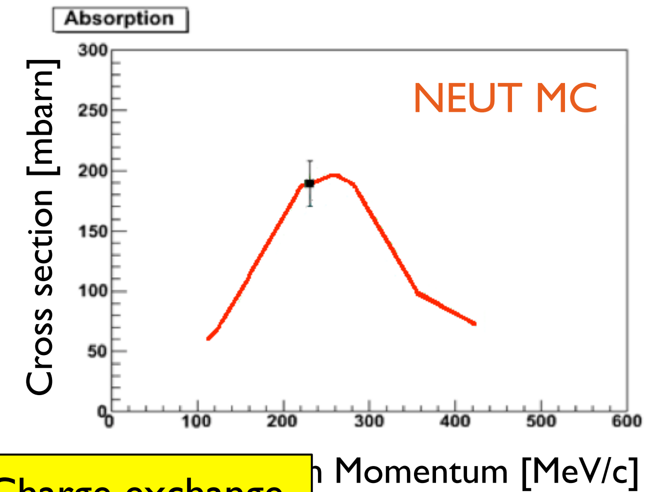
Previous experiments

Ashery et al., Phys. Rev. C23, 2173 (1981)
Bellotti et al., Nuovo Cimento 14A, 567 (1973)
Jones et al., Phys. Rev. C48 2800 (1993)
Navon et al., Phys. Rev. C28, 2548 (1983)

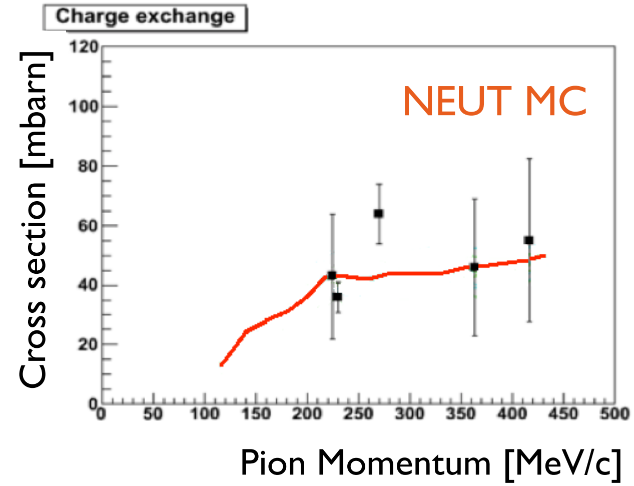
Absorption + Change exchange



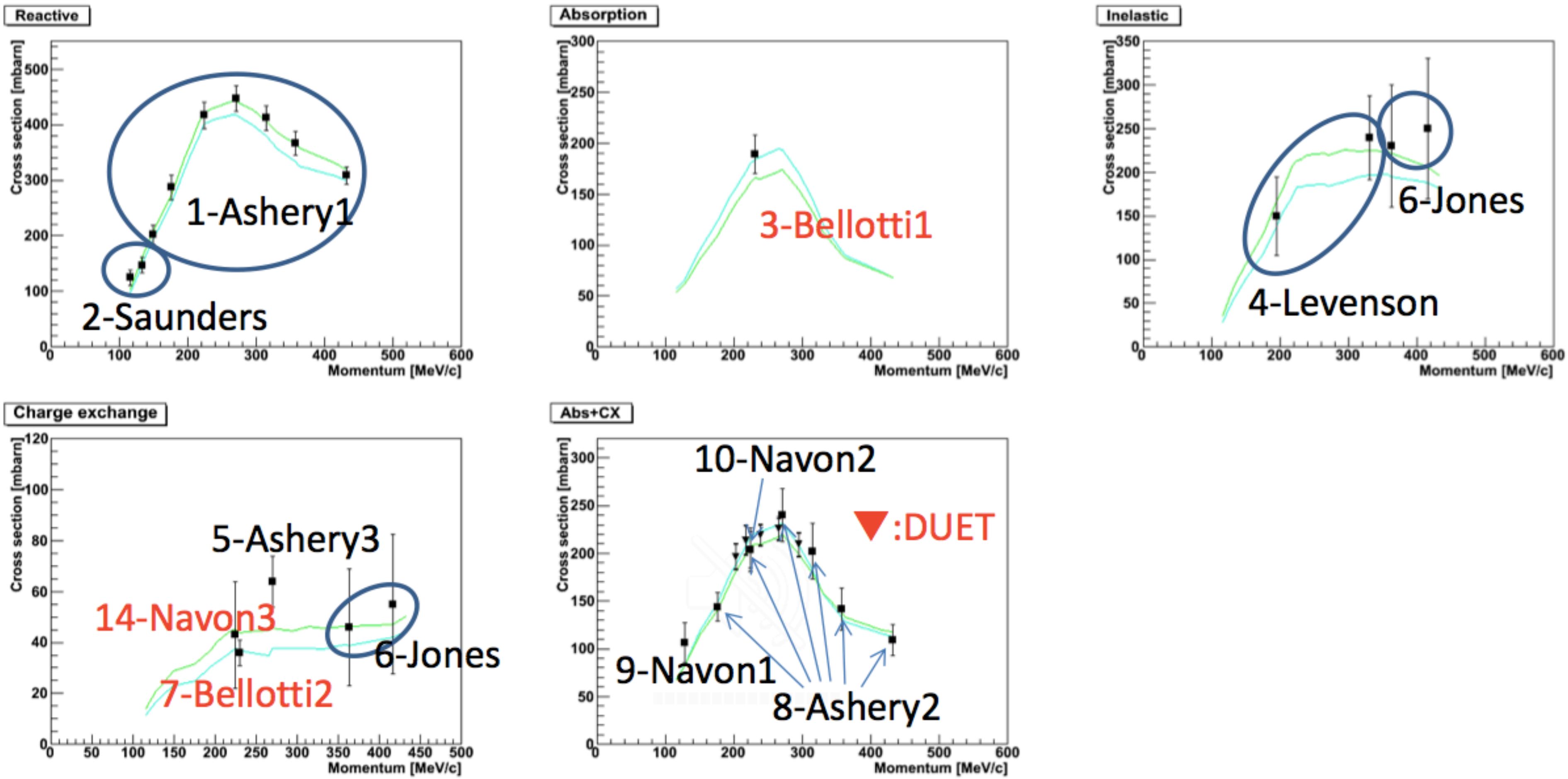
Absorption



Charge exchange

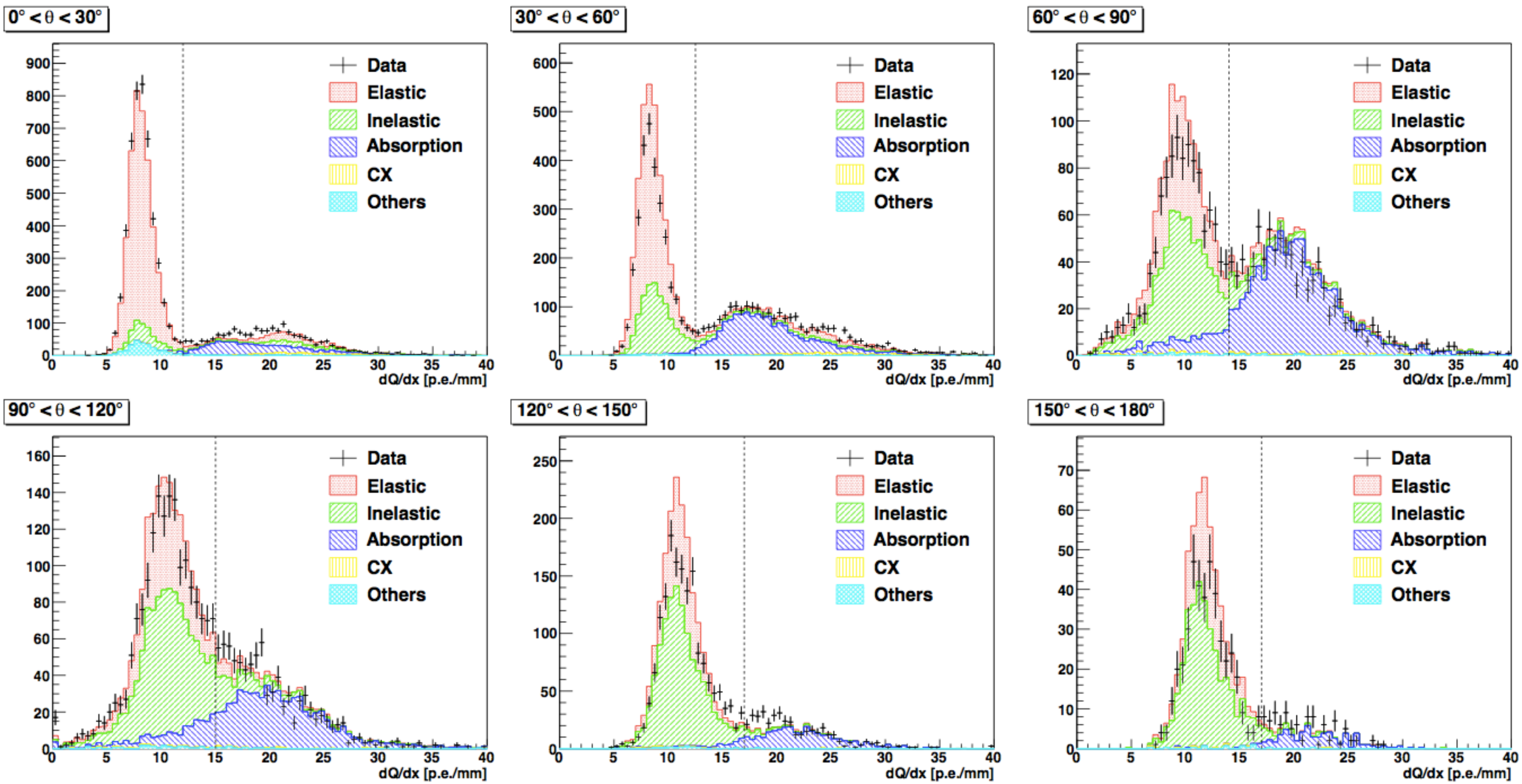


Previous experiments



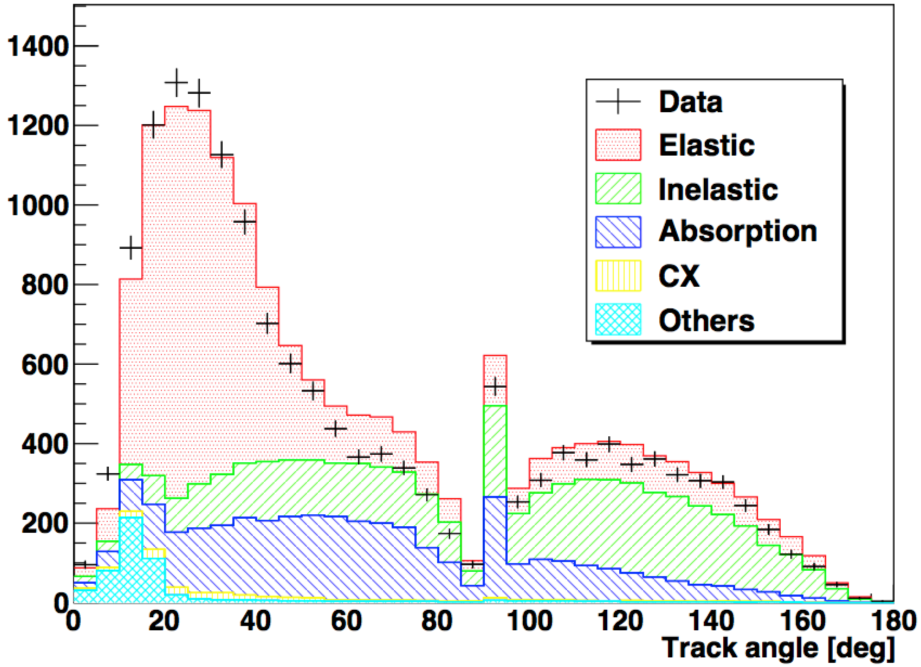
dE/dx Distributions

- Used for PID in Piano's fibers

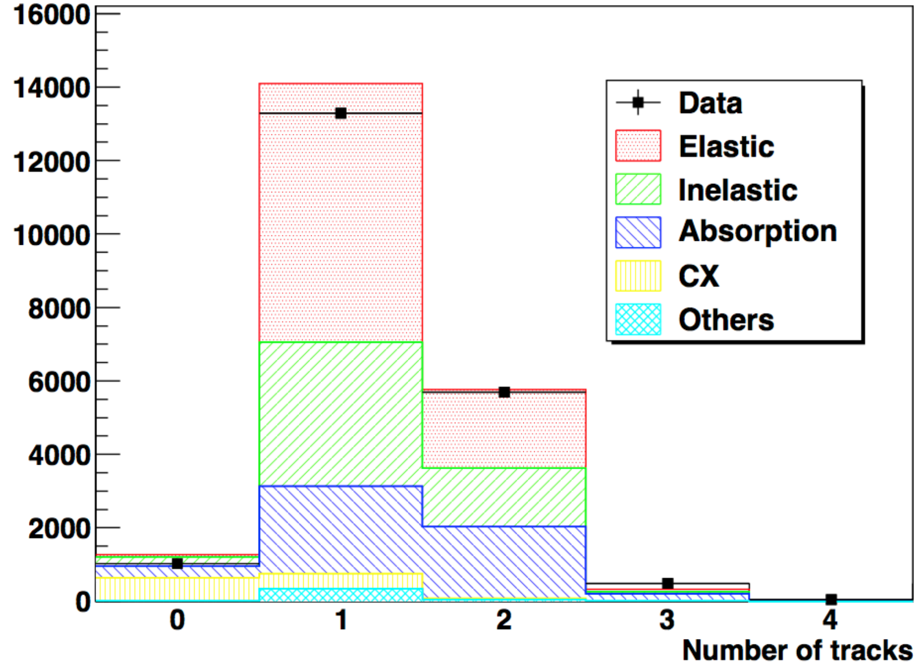


Event Selection: Data/MC comparisons

- Distributions before applying the "no π^+ in final state" cut:
- Good agreement between Data and MC.



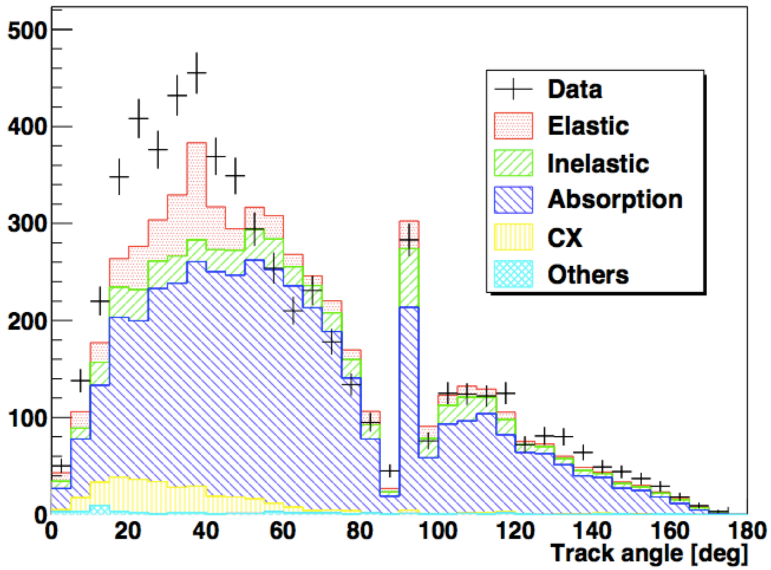
Angular distribution of reconstructed tracks



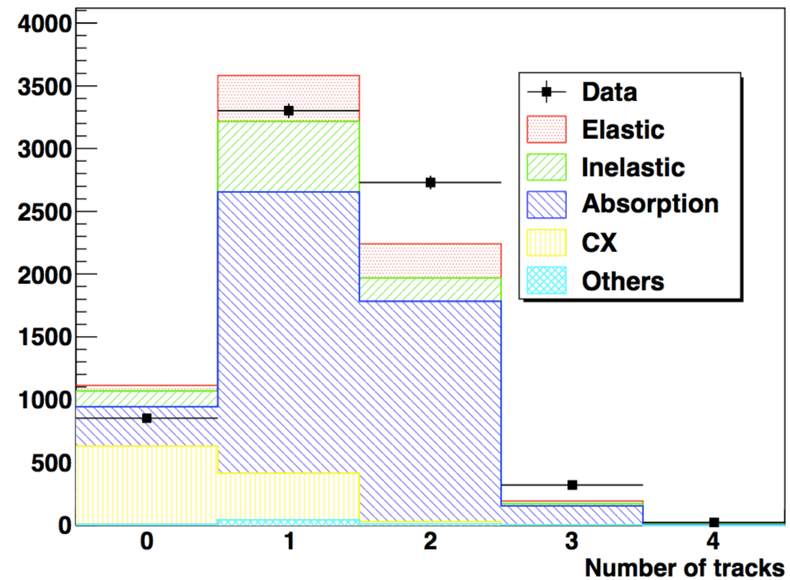
Distribution of number of reconstructed tracks in the final state

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.
- Agreement becomes worse.



Angular distribution of the proton-like track



Distribution of number of reconstructed tracks in the final state

Abs+CX Cross section

- We calculate the Abs+CX cross section using this formula:

Selected events in Data

Selected Background events in MC

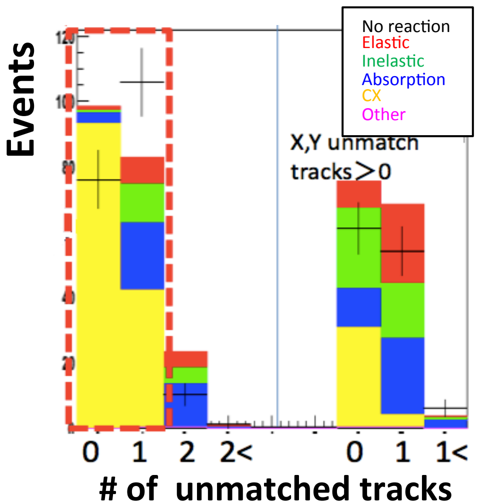
$$\sigma_{\mathrm{DATA}} = \sigma_{\mathrm{MC}} \times \frac{\mathrm{N_D} - \mathrm{N_{BG.MC}}}{\mathrm{N_{MC}}}$$

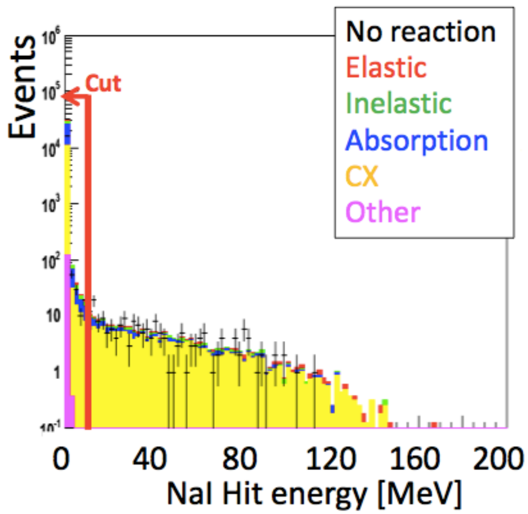
Abs+CX cross section in MC

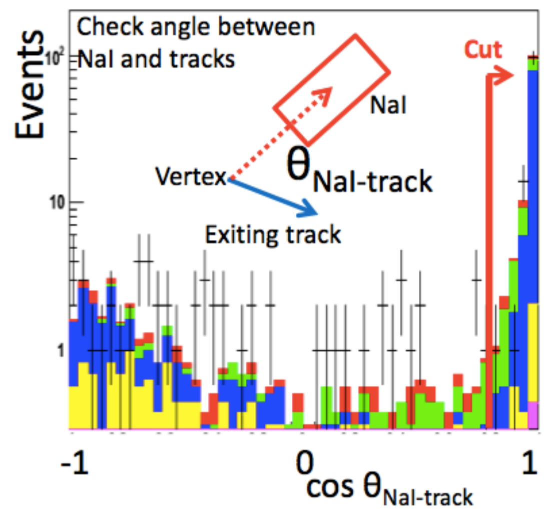
Selected Abs+CX events in MC

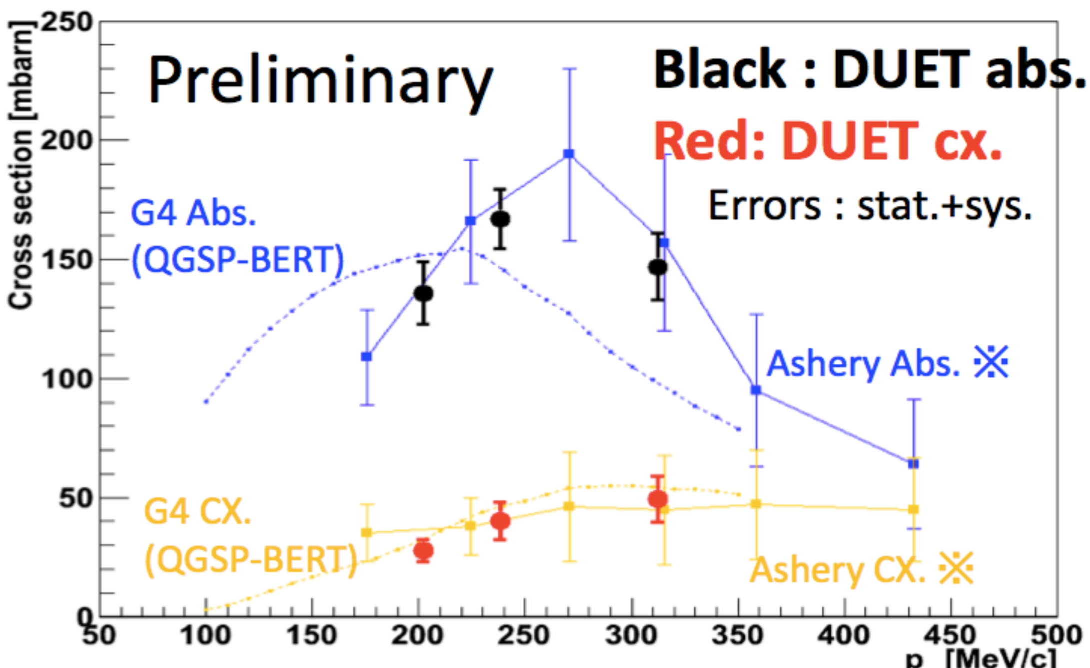
- All systematic errors have been evaluated.
- Corrections for interactions in other nuclei (O,Ti) are also applied.

CX using NaI crystals









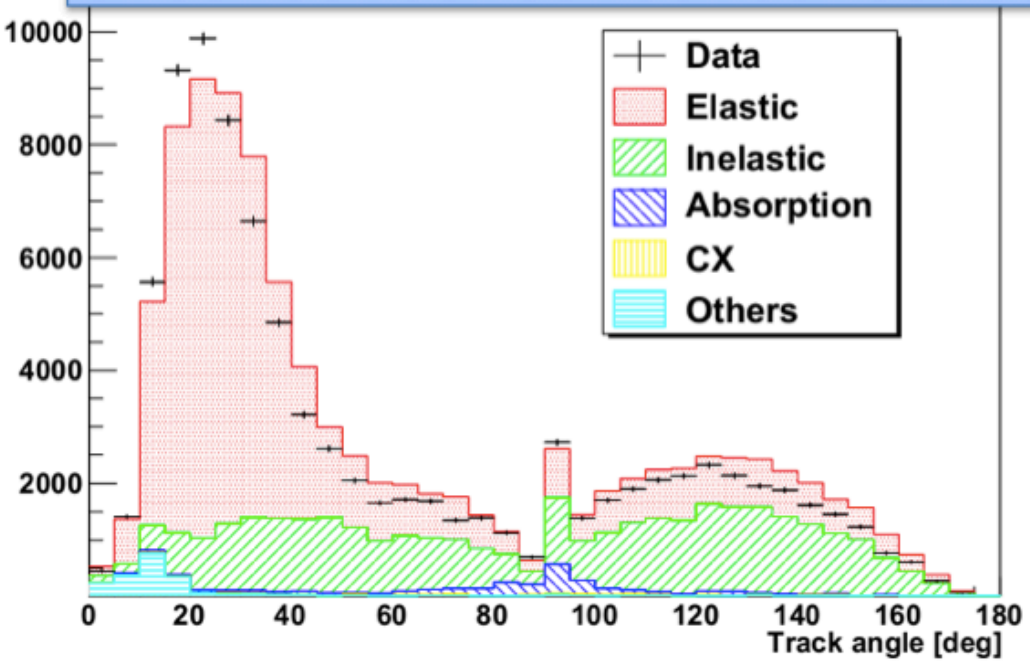
Systematic errors Abs+CX

Systematic error (p_{π}=250MeV/c)

Error source	Error
Profile	1.55%
Momentum	1.34%
FV	1.87%
Charge	0.46%
Crosstalk	0.53%
Alignment	0.82%
Hit efficiency	0.76%
μ contami	0.89%
Target	0.86%
Efficiency	2.42%
Background	2.42%
	-3.57%
Total syst	4.76%
	-5.44%

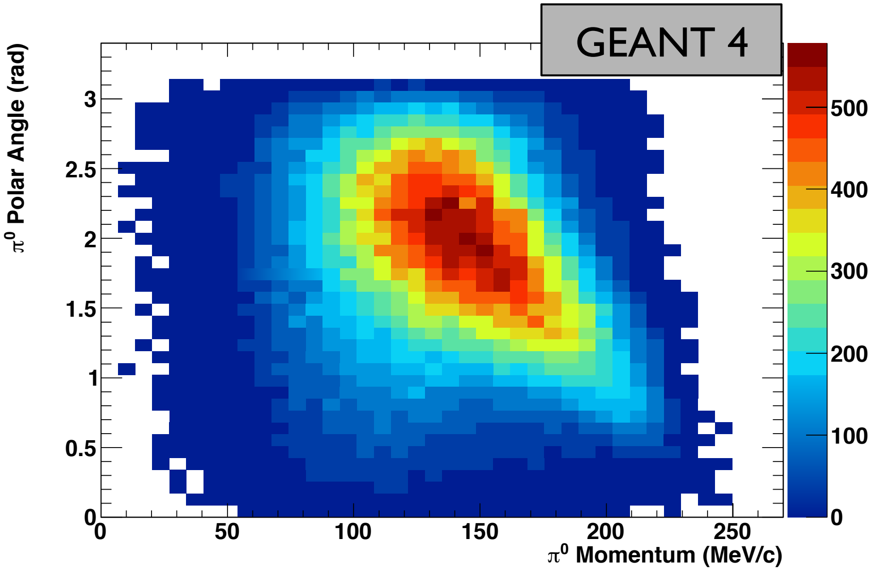
The dominant systematic error comes from BG estimation, and the error is estimated from the Data/MC difference in the BG enhanced sample.

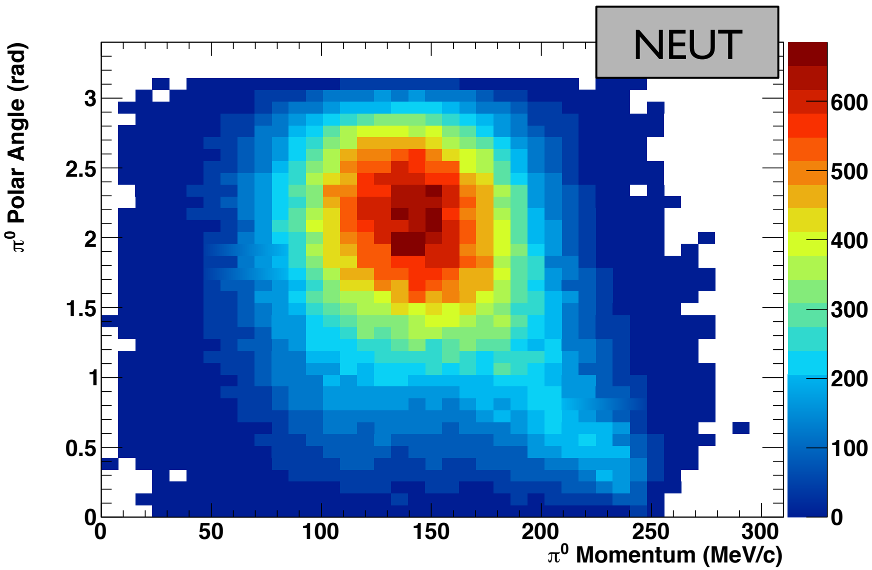
Background sample angular distribution



p-theta for π^0's

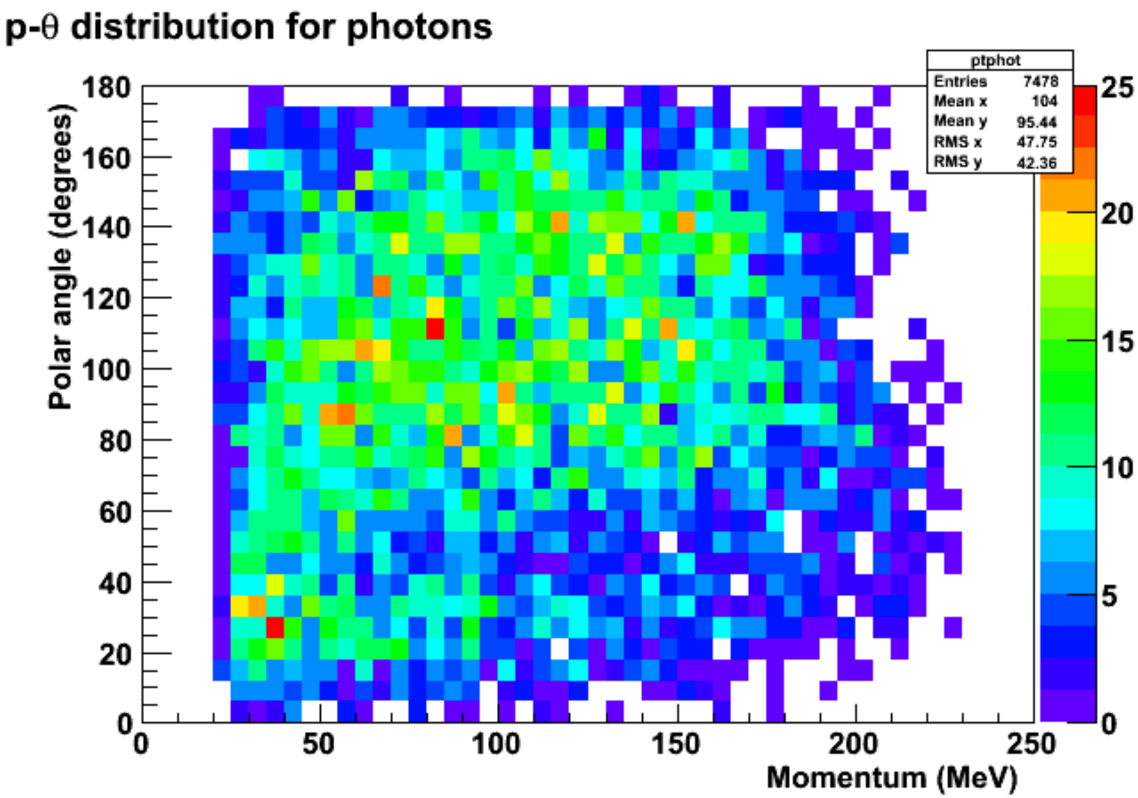
- GEANT4 (QGSP-BERT) and NEUT
- Initial 250 MeV/c π^+



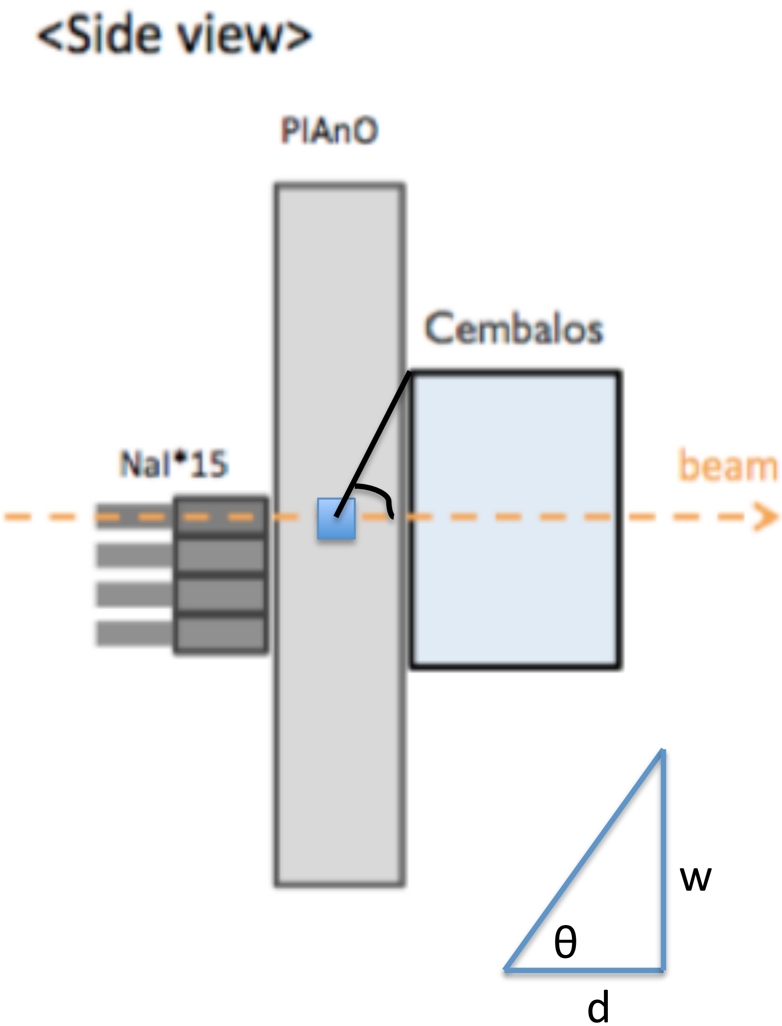


p-theta for CX Photons

- GEANT4



Solid angle subtended



- Rough calculation
  - Take Piano as a point
  - Ignore rectangular shape of Harpsichord
- A cone with opening angle:

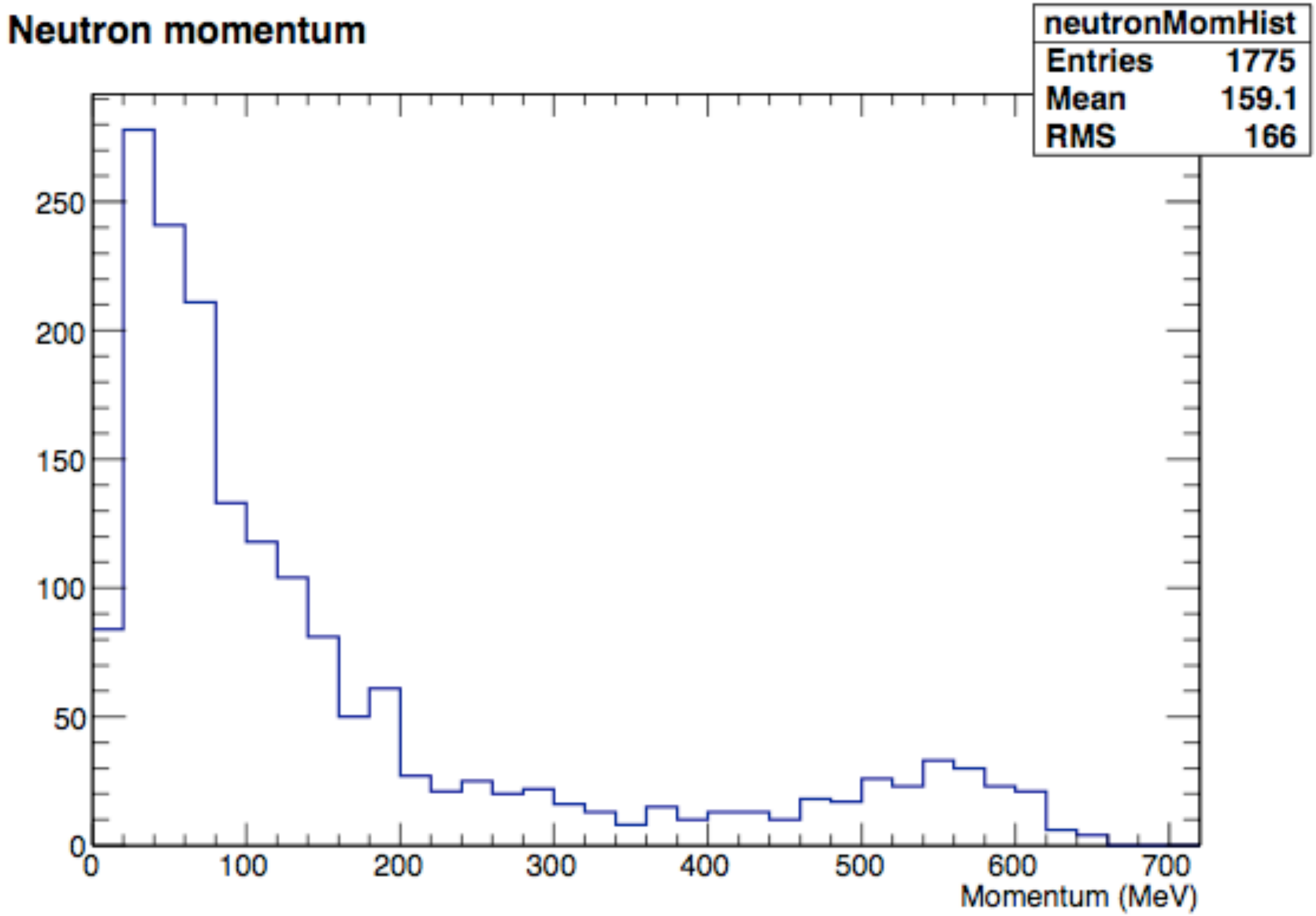
$$\theta = \arctan(w/d) = \arctan(175/190) = 42.6°$$

- The solid angle is:

$$\Omega = 2\pi(1-\cos\theta) = 0.53\pi$$

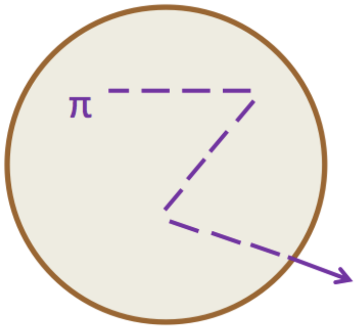
- Or, around 13% of the whole sphere

Neutron momentum



NEUT FSI

- 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/CX cross sections.

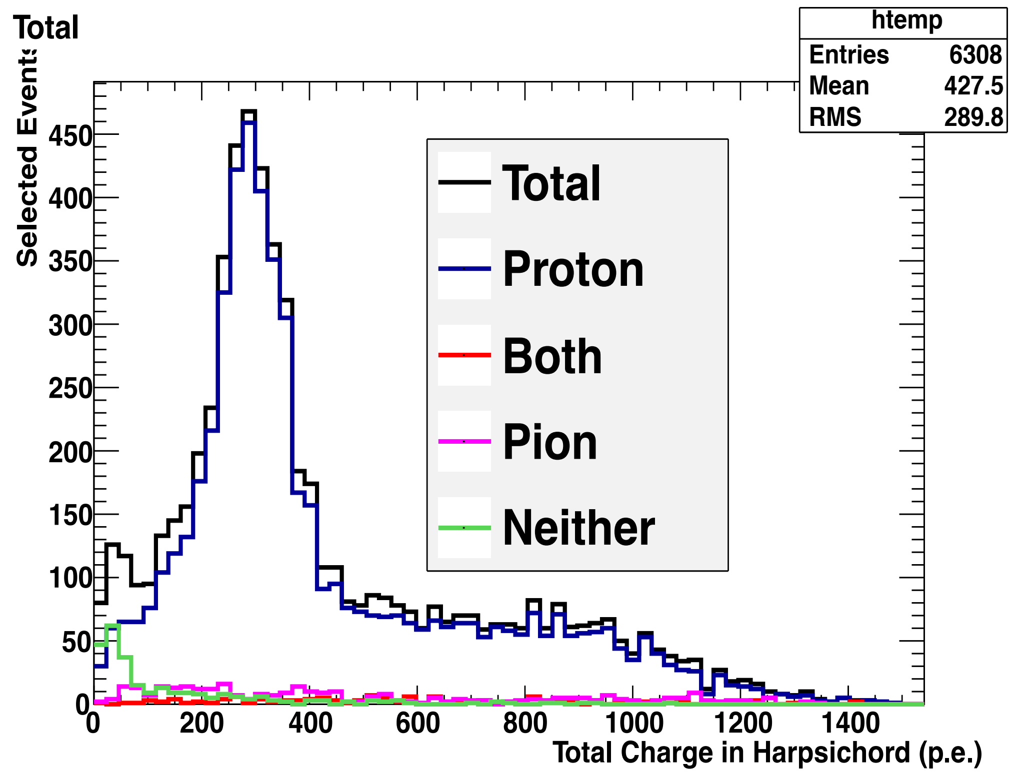


- The microscopic cross sections are tuned so that the resulting Scat/Abs/CX cross section agree with external data.

- Add DUET data for tuning

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

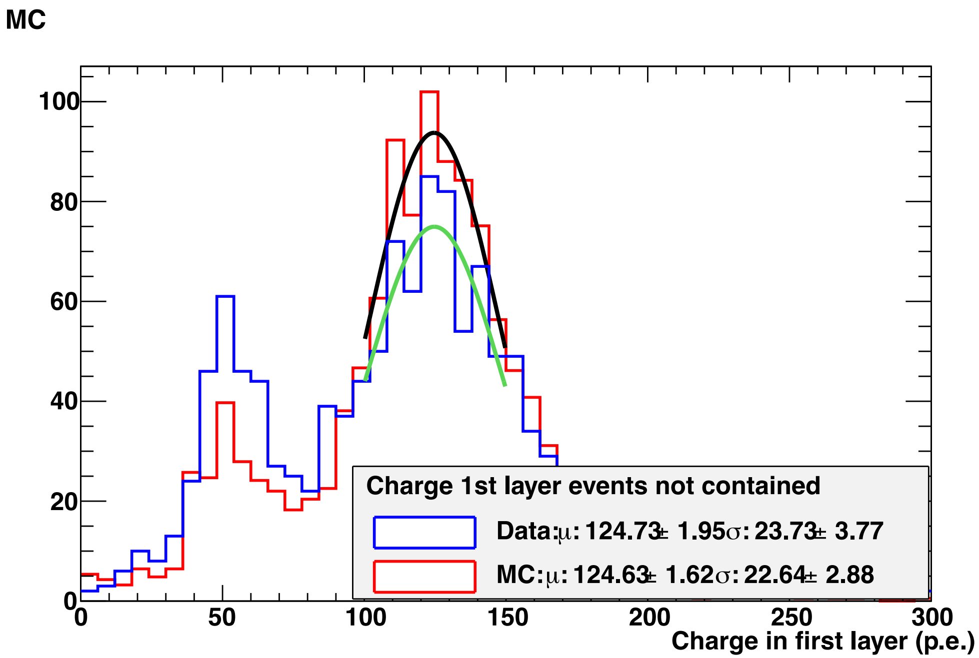


Not stacked, just plotted on top of each other

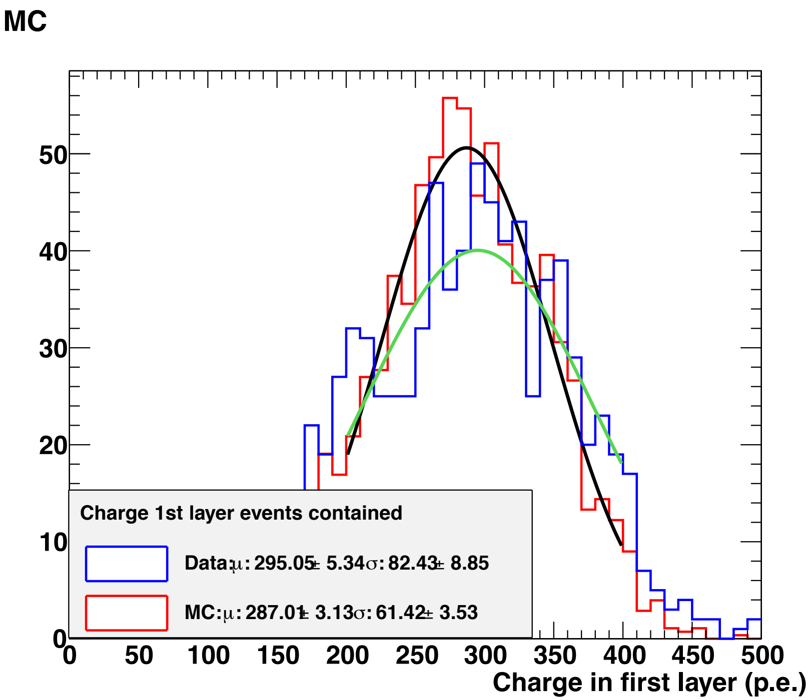
- From MC:
  - 88.4% proton hitting Harpsichord
  - 5.2% pion hitting Harpsichord
  - 4.2% neither proton nor pion hitting Harpsichord
  - 2.1% both proton and pion hitting Harpsichord

Proton selection (Control sample)

Contained in first layer



Not Contained in first layer



Tune FSI Model

- Current: