PIAnO-Harpsichord
π-N interaction measurement at TRIUMF

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NuFact 2012

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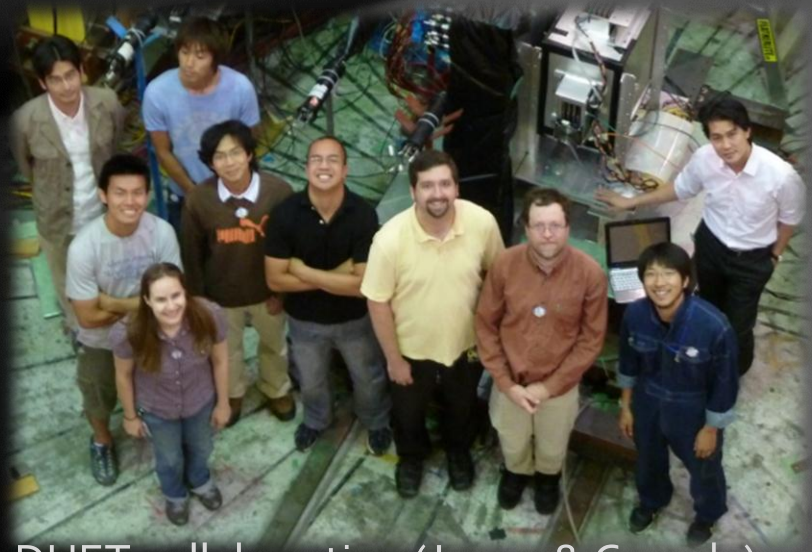
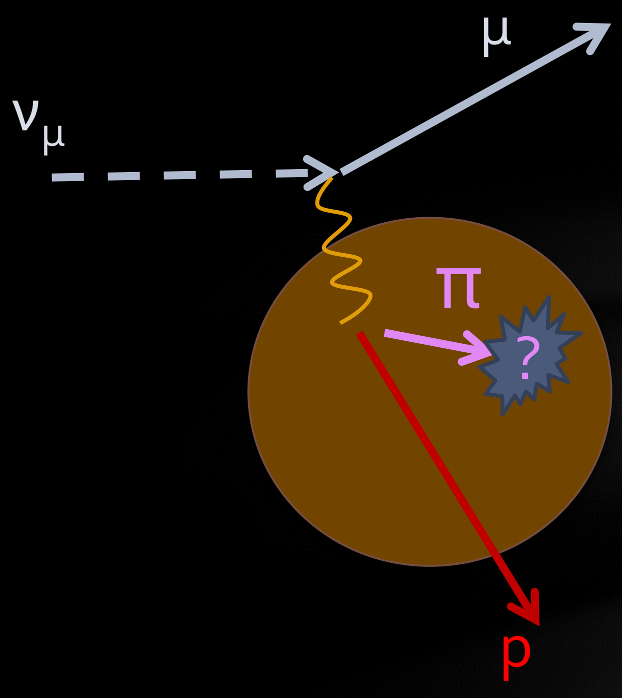
2. Experiment at TRIUMF
3. Event selection
4. Cross section & Systematics



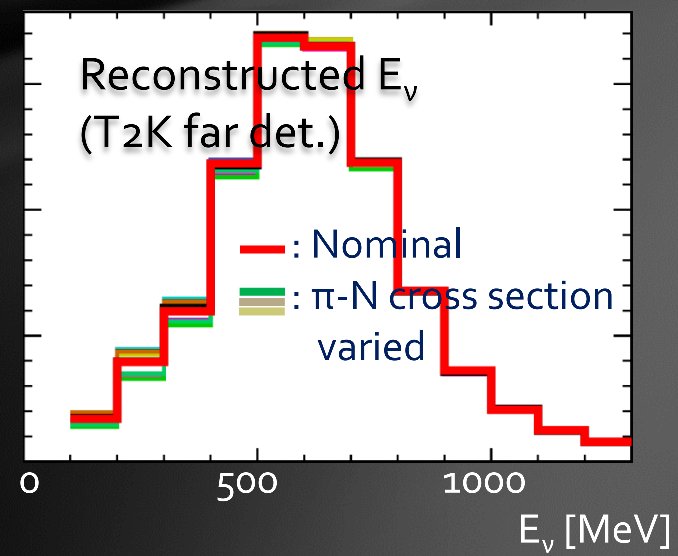
DUET collaboration (Japan & Canada)

π-N interaction: Why important?



Pion production probability is large for ~1Gev neutrino.

Pions are often absorbed by the nucleus
→ Strongly affects the final state and visible energy of an event



π-N cross section uncertainty is key to reduce systematic error for ν measurements.

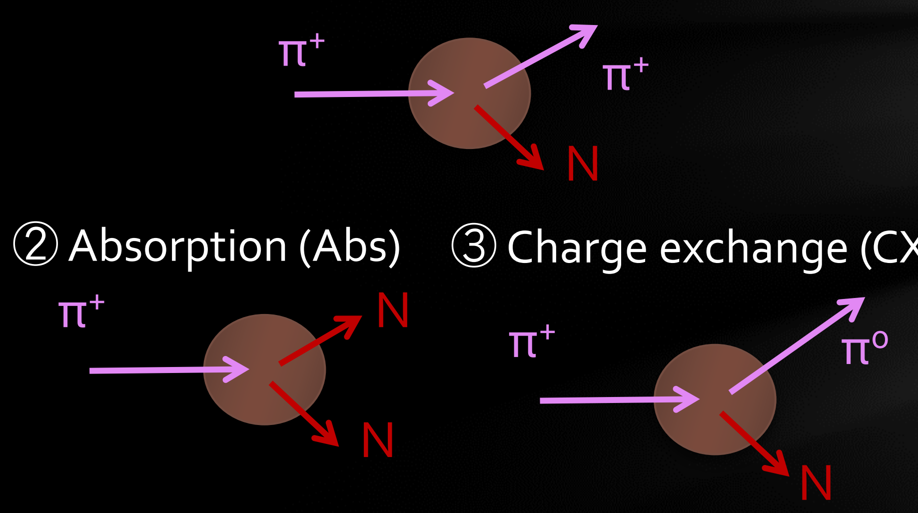
The DUET experiment

Goal: Measure π absorption and π charge exchange cross section with ~10% accuracy.

π interaction modes

① Scattering

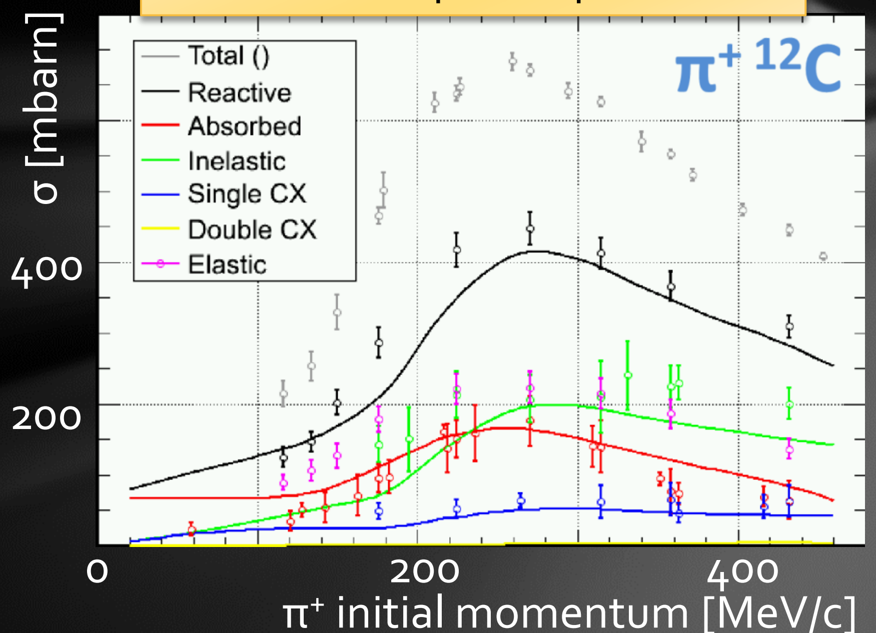
② Absorption (Abs) ③ Charge exchange (CX)



Our signal: Abs & CX → No π^+ in FS

Background: Scattering

Results from past experiments



Cross section uncertainty in the past experiment is large

Preliminary result for Abs+CX measurement will be presented in this talk

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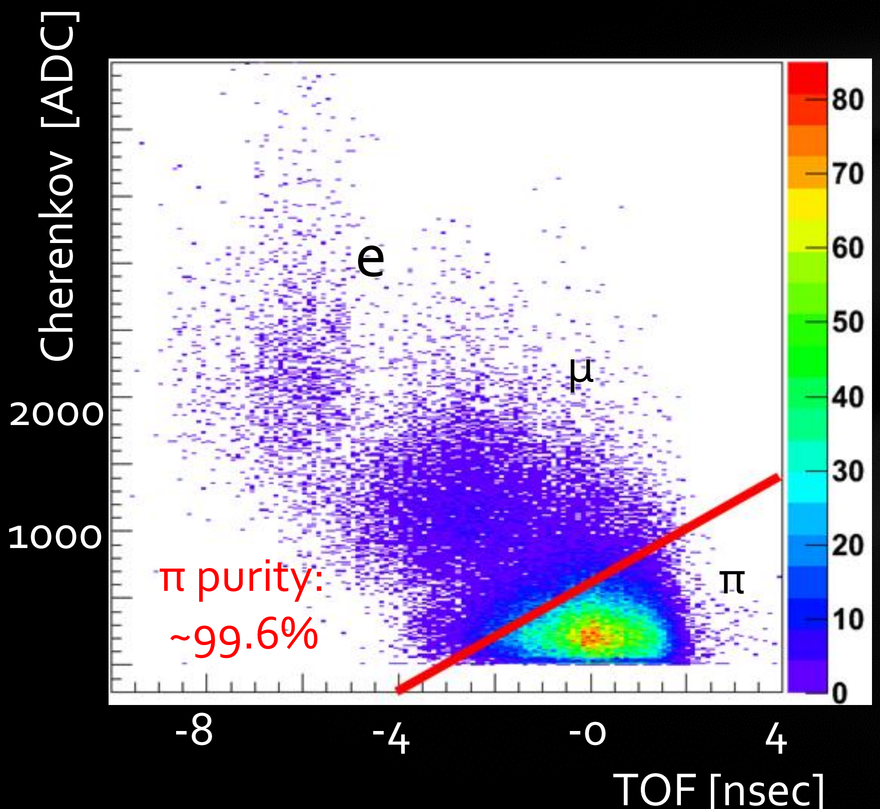
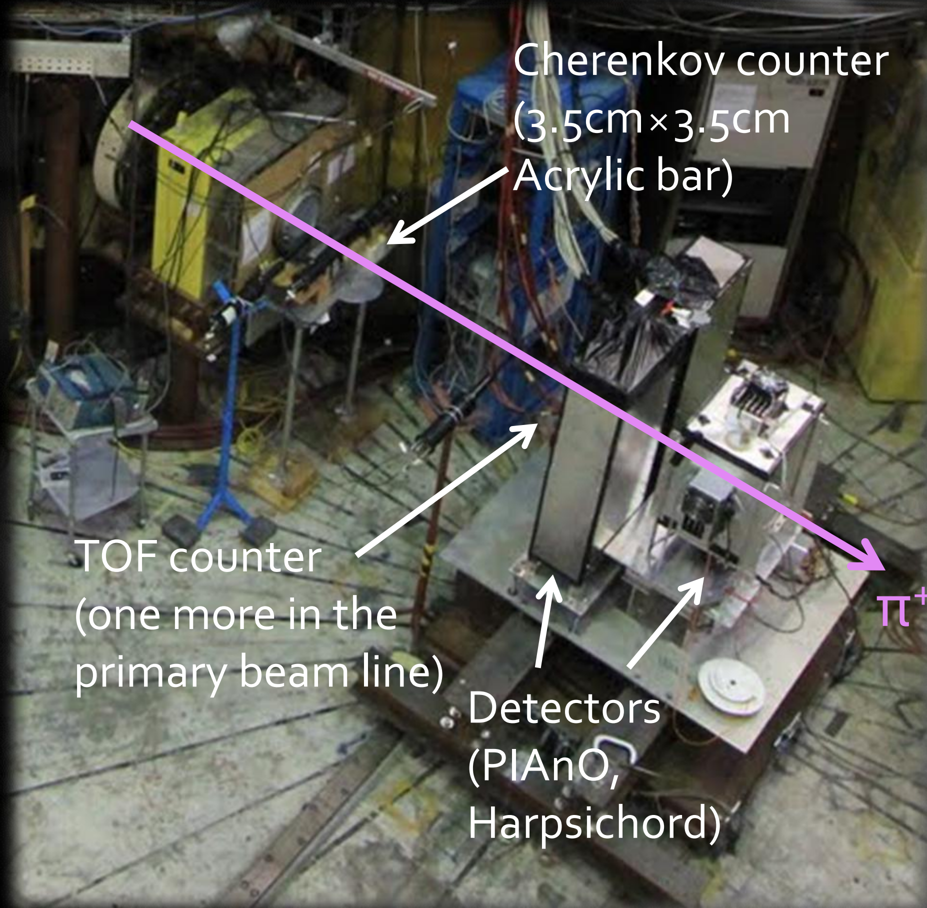
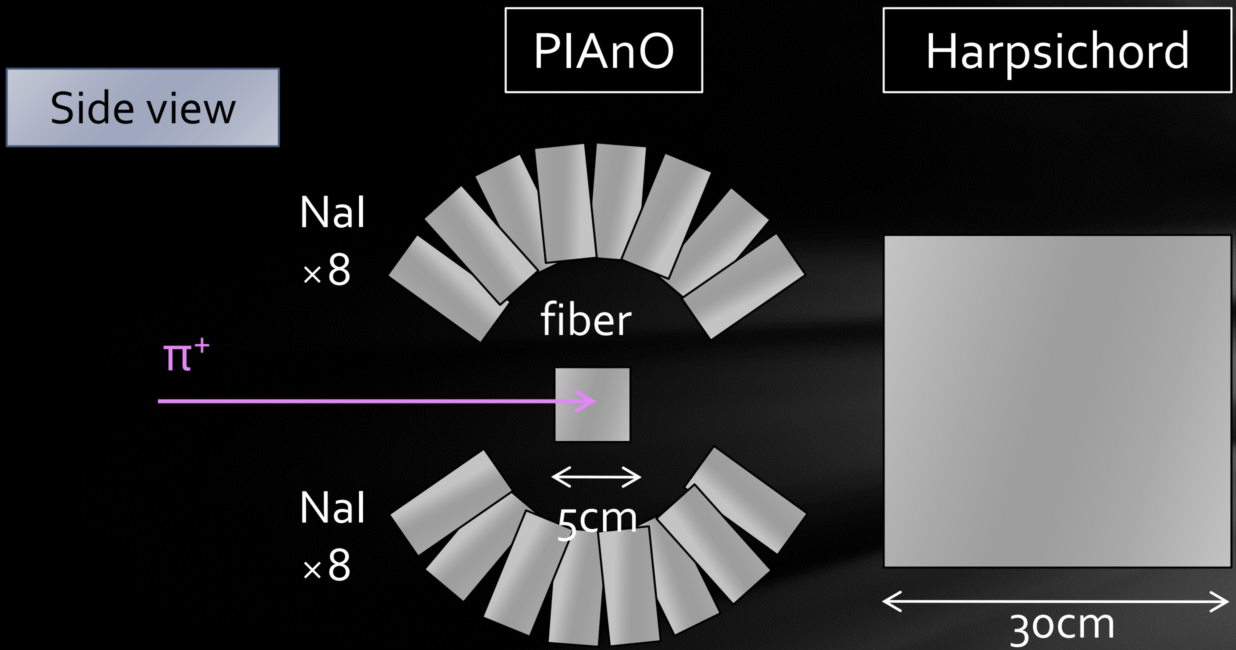
TRIUMF M11 beamline

- Secondary beam line with momentum tunable with $\Delta p_{\pi} < 5\%$ in the range from 150 to 375MeV/c .
- Beam PID with TOF & Cherenkov counter





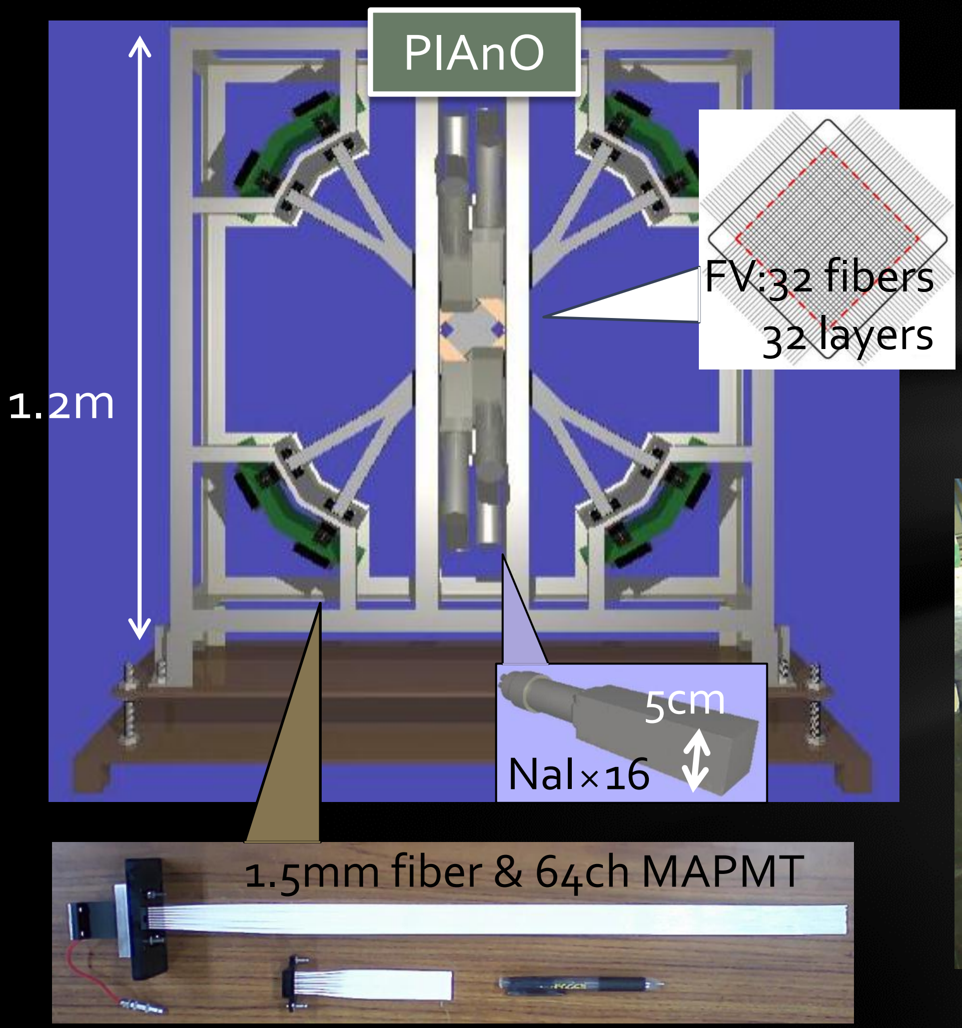
Detector setup



PIAnO : Scintillating fibers and NaI
Harpsichord: Scintillator bars + Lead sheets

Charged tracks emerging from the interaction vertex are detected by full active scintillating fiber detector. NaI and Harpsichord, surrounding the fiber, detects the γ-rays from CX π^0.

PIAnO & Harpsichord



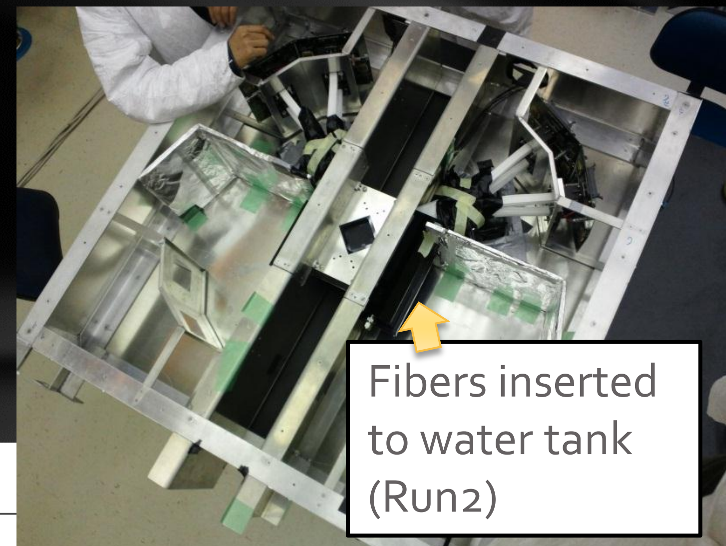
1cm scintillator bars
& Photon detector (MPPC)
+ 1.3mm lead sheets

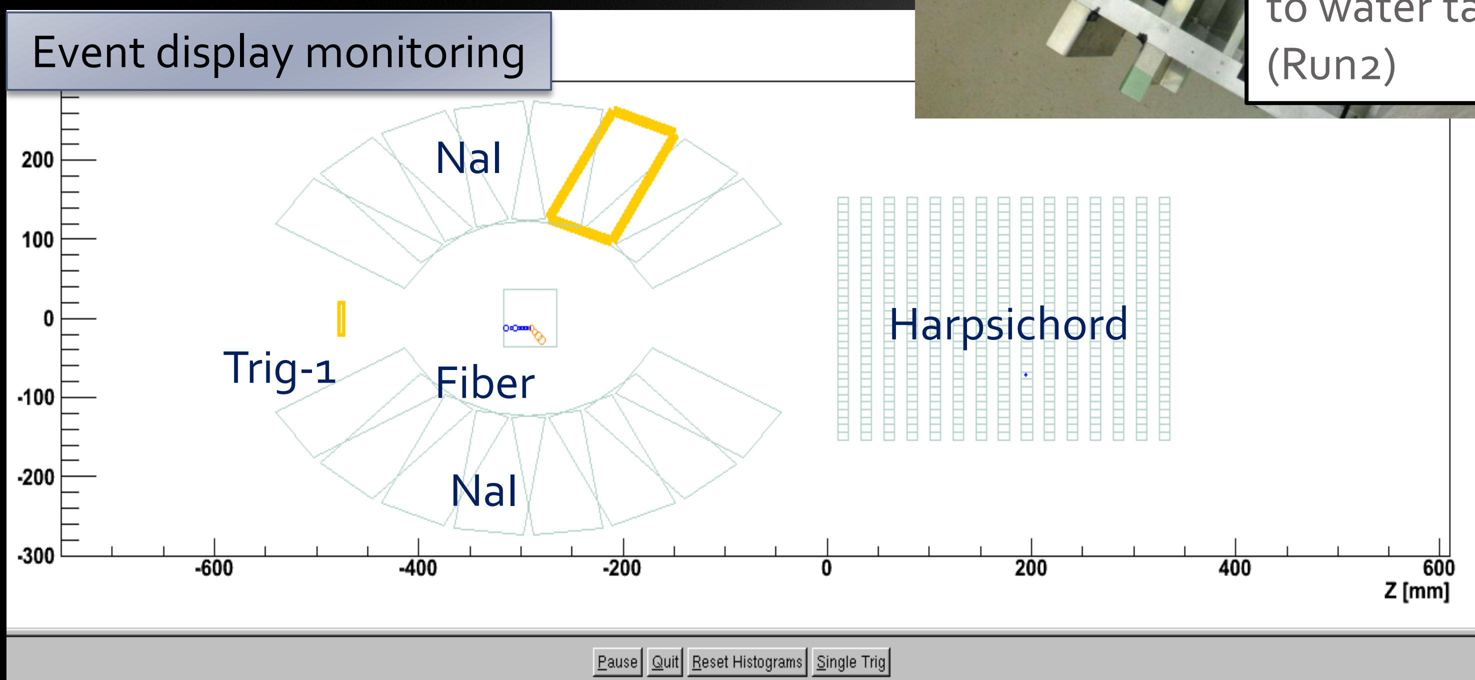
Only the Fiber analysis result (Abs+CX) will be shown for this talk

Data taking summary

Run1 (2010): p_{π} = 150MeV/c ~ 375MeV/c
(25MeV/c step)
Run2 (2011): 200MeV/c, 275MeV/c, 325MeV/c
with additional water tank target

Preliminary analysis result for Run1 250MeV/c data will be presented.





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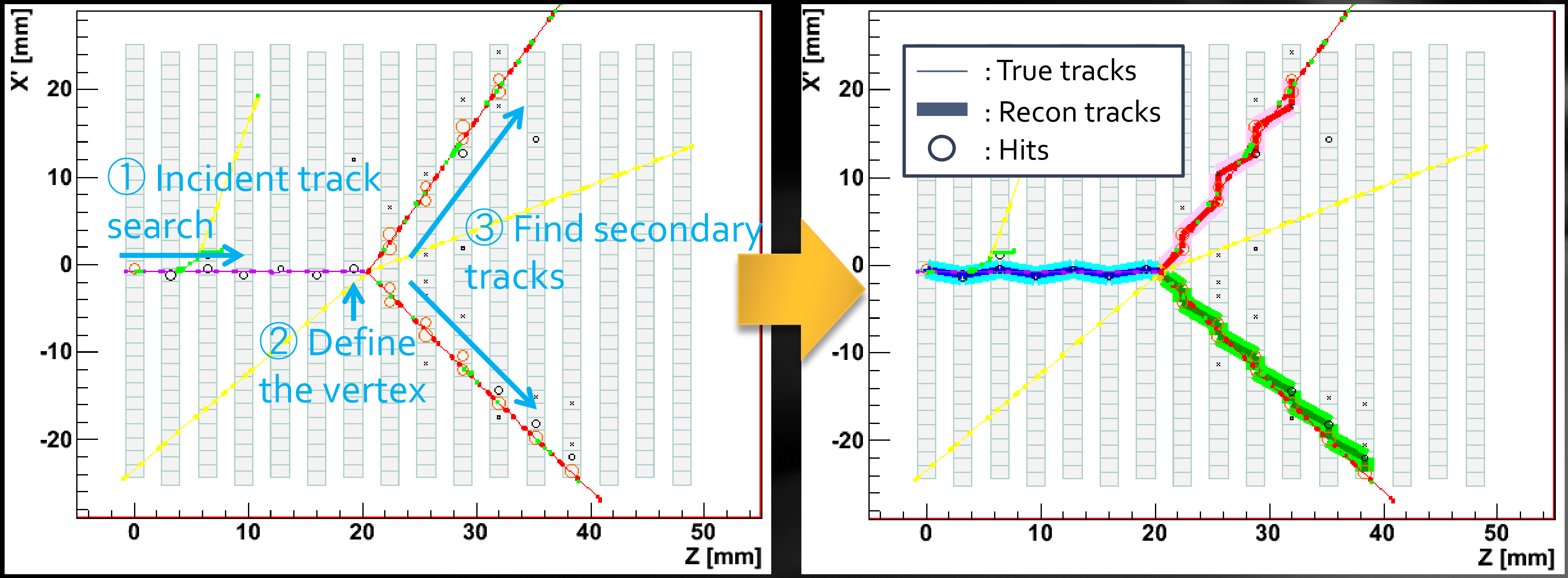
Track & Vertex reconstruction



① Search the incident track by looking for horizontal hits starting from most upstream layers.

② Find the vertex position around the end of the incident track.
Vertex point : The point where you can track max num of hits with straight line.

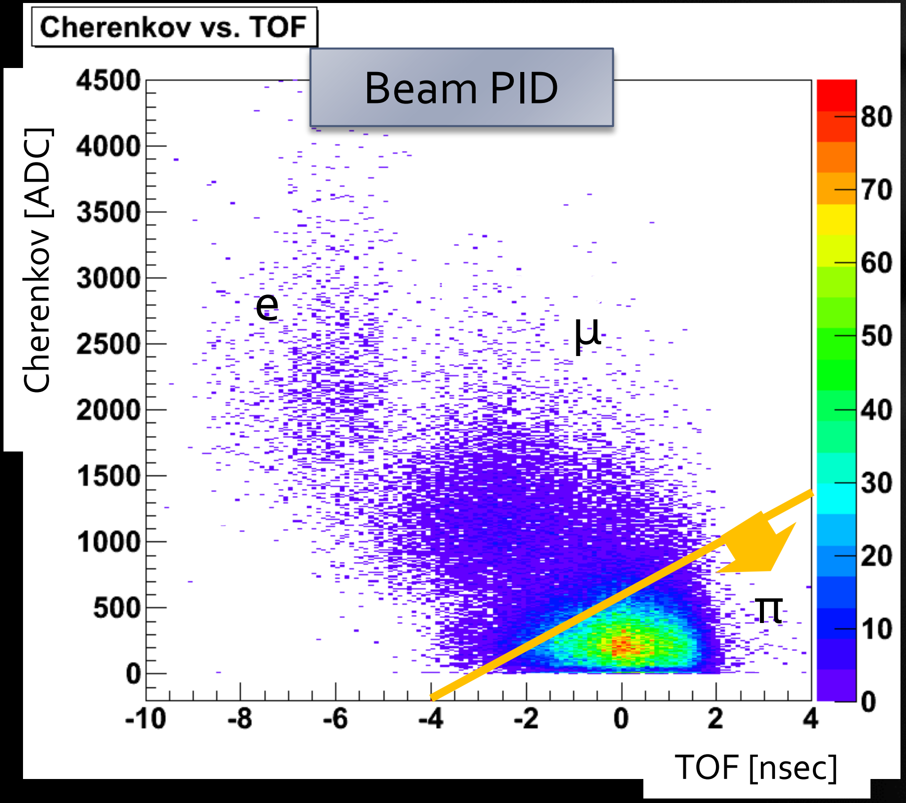
③ Find secondary straight tracks starting from the vertex. (≧3hits required)

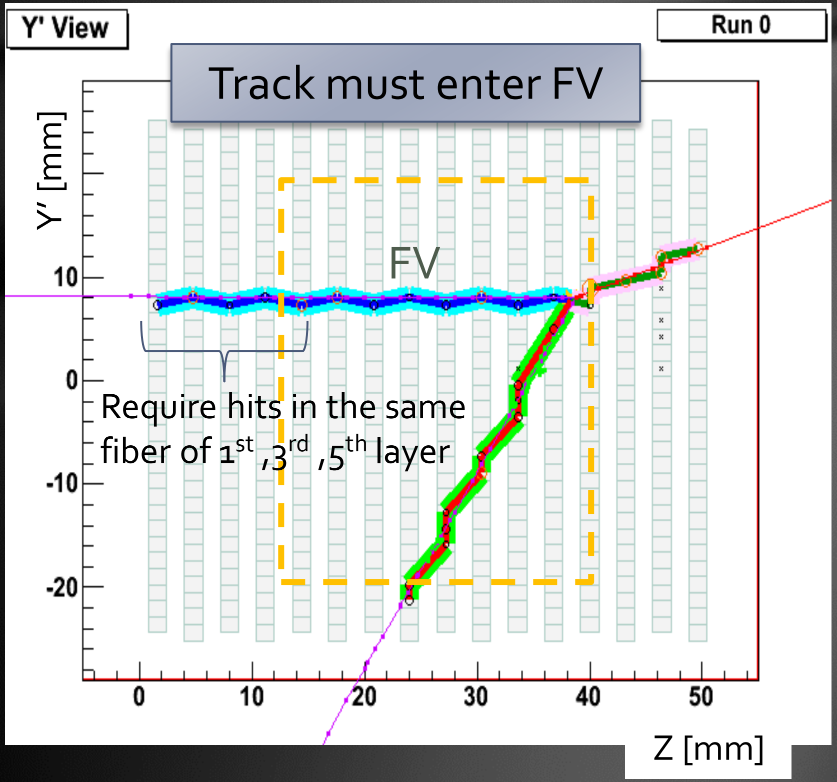
④ Combine X and Y tracks into 3D track by checking the track start/end position.

Event selection

① Good incident cut

Beam particle must be π, straightly entering FV.
→ Beam PID & Upstream hits requirement

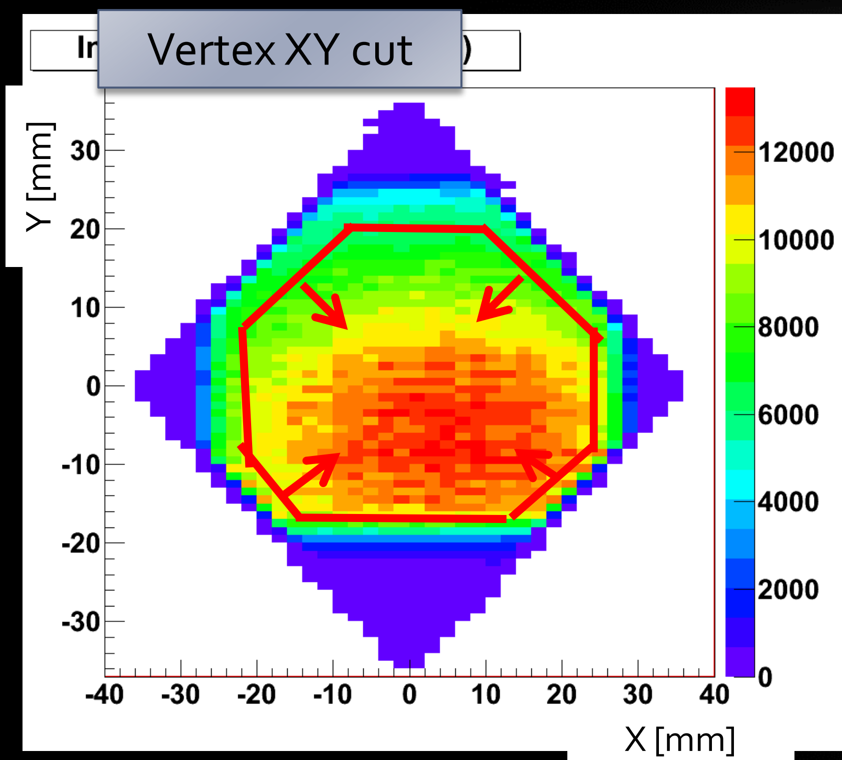


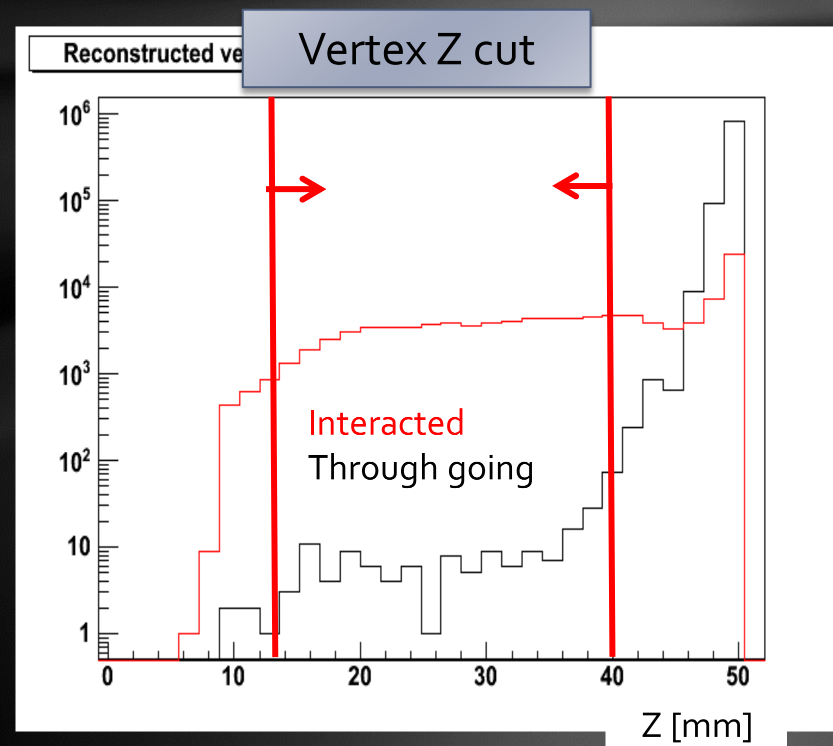


Event selection

② Vertex in FV cut

Reconstruct the interaction vertex.
Require that the vertex position is in FV.



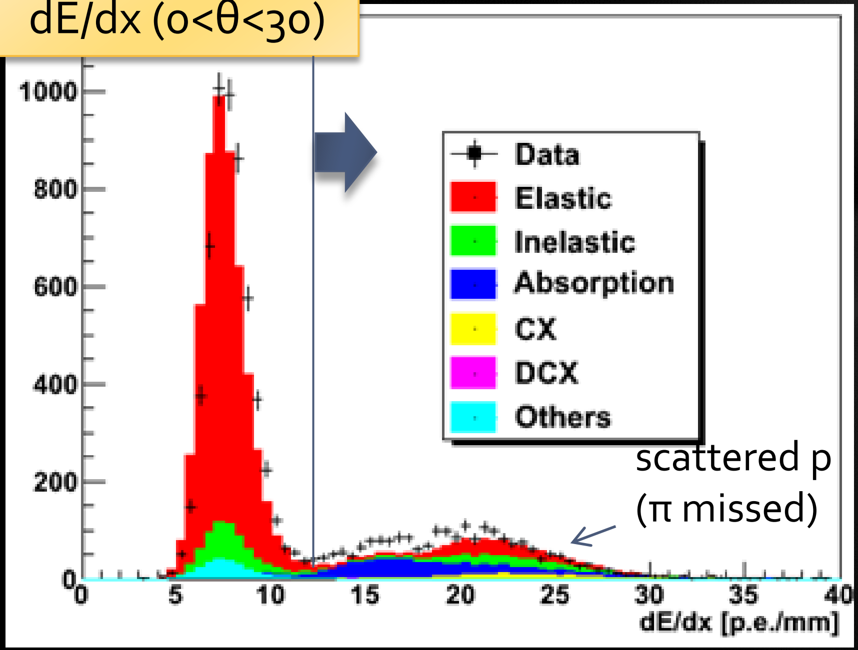


Event selection

③ No FS π^+ cut

Cut the event if there are any π-like track.
We identify the final state particles by dE/dx cut.
Tracks are divided in different angle samples (0<θ<30, … , 150<θ<180).
Different dE/dx threshold is applied for different angle track.

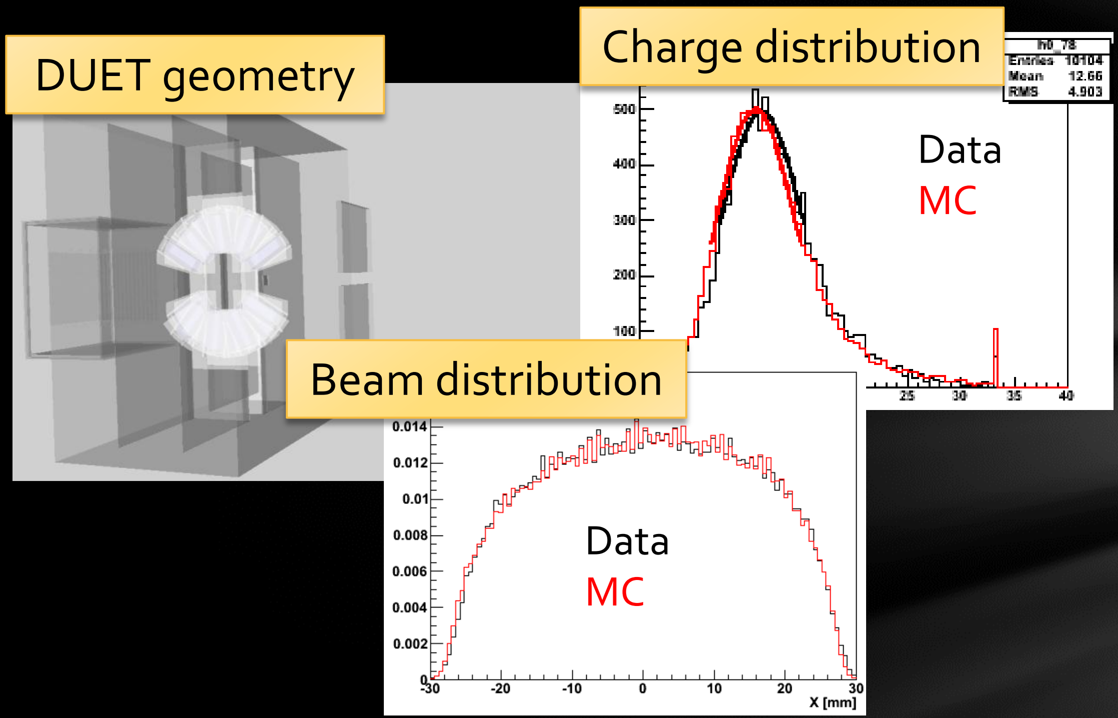
dE/dx (0<θ<30)

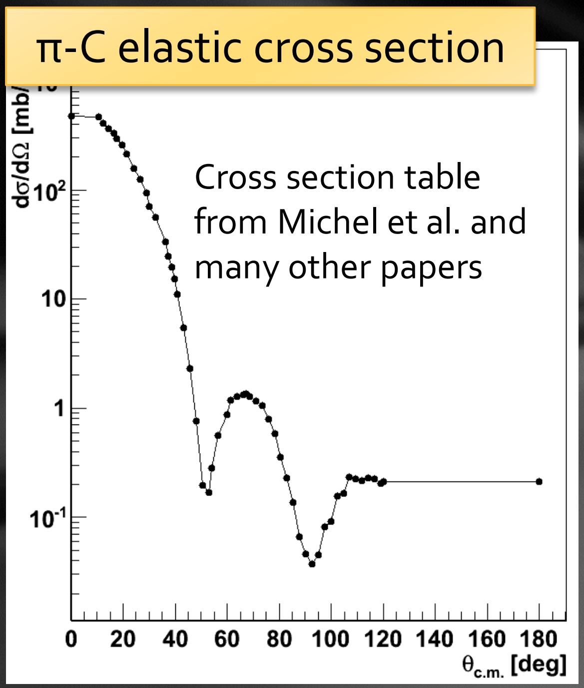


Event reduction

	Data	MC
Good incident cut	316301	1101543
Vertex in FV cut	24575	88401
No FS π cut	8555	27376

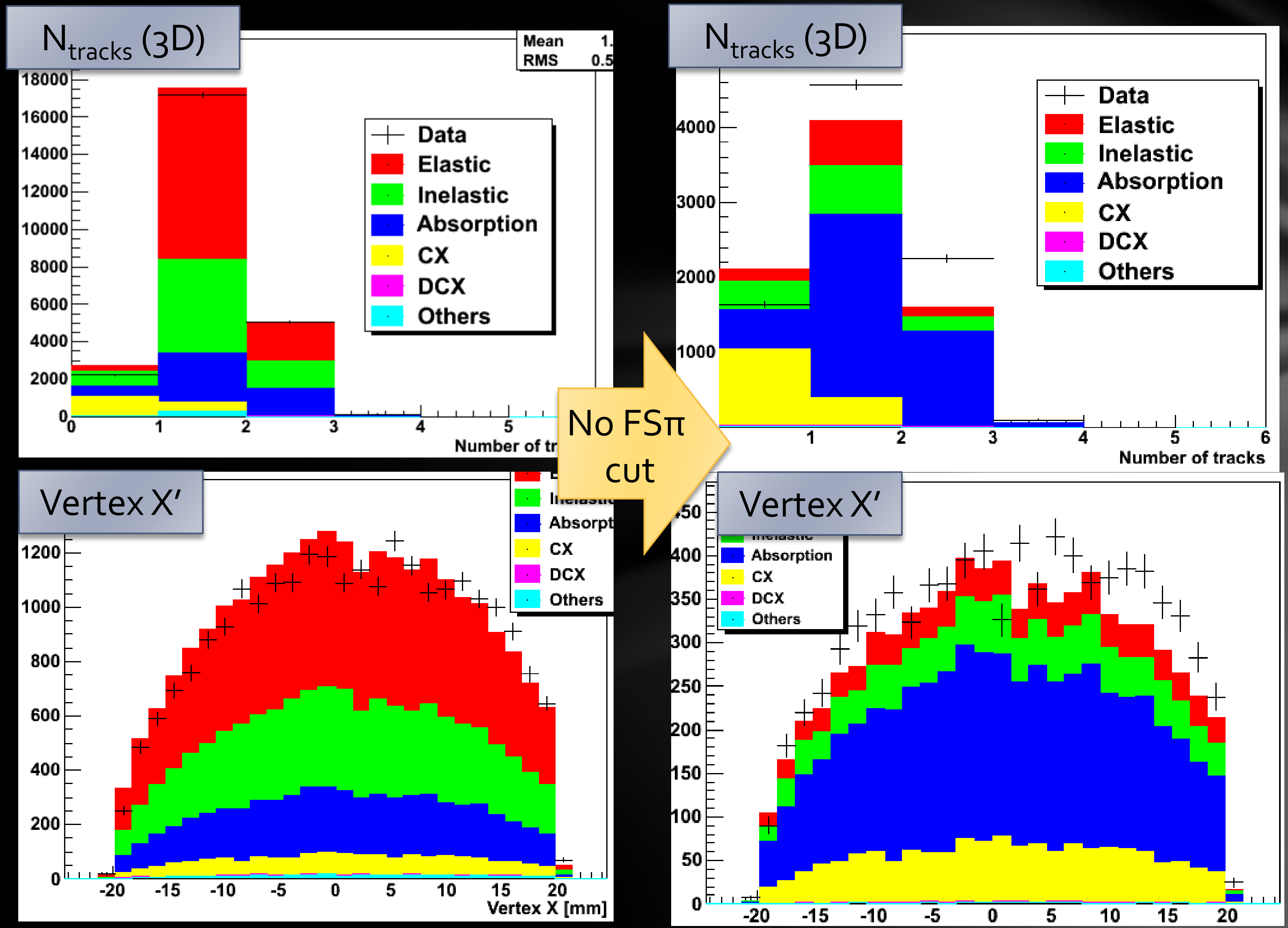
Geant4 simulation





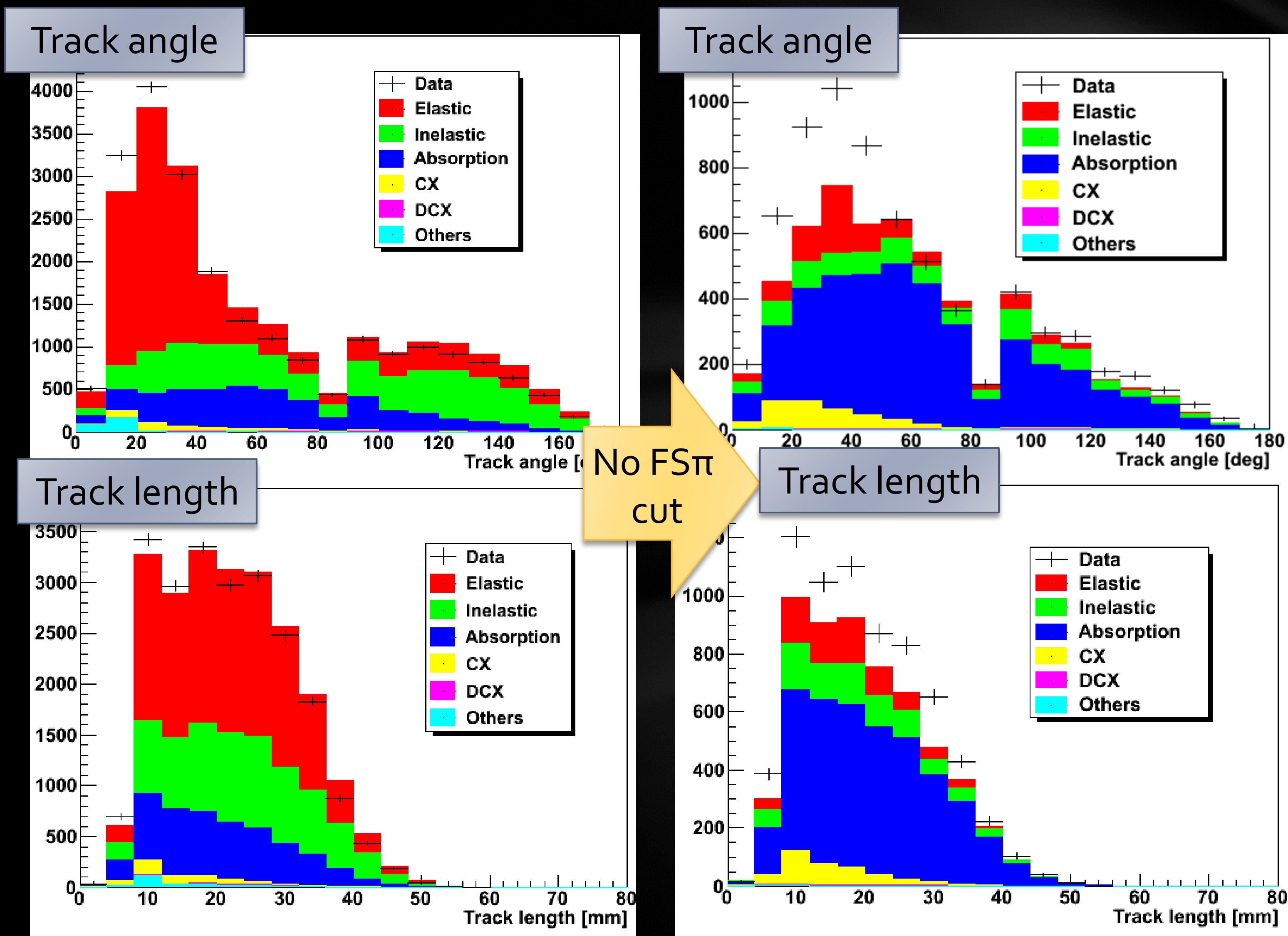
- We use Geant4 (release9.4 patch02) to simulate the detector response and physics. For the physics list, we use QGSP_BERT.
- Detector materials, charge distribution, beam distribution etc. are implemented so that they agree with Data.
- π-C and π-H elastic scattering cross sections are also tuned by using simple linear interpolation from past experiments.

Basic distributions ①



Normalized by number of incident π

Basic distributions ②



Normalized by number of incident π

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Cross section calculation

We calculate the Abs+CX cross section by this formula:

Num of selected events (Data)

Num of selected BG events (MC)

$$\sigma_{Data} = \sigma_{MC} \times \frac{(N_{Sel\_Data} - N_{Sel\_BG\_MC})}{N_{Sel\_AbsCX\_MC}}$$

Abs+CX cross section (MC)

Num of selected Abs+CX events (MC)

For actual calculation, we apply some corrections for the interaction in other nuclei (O, Ti).

Systematic error table

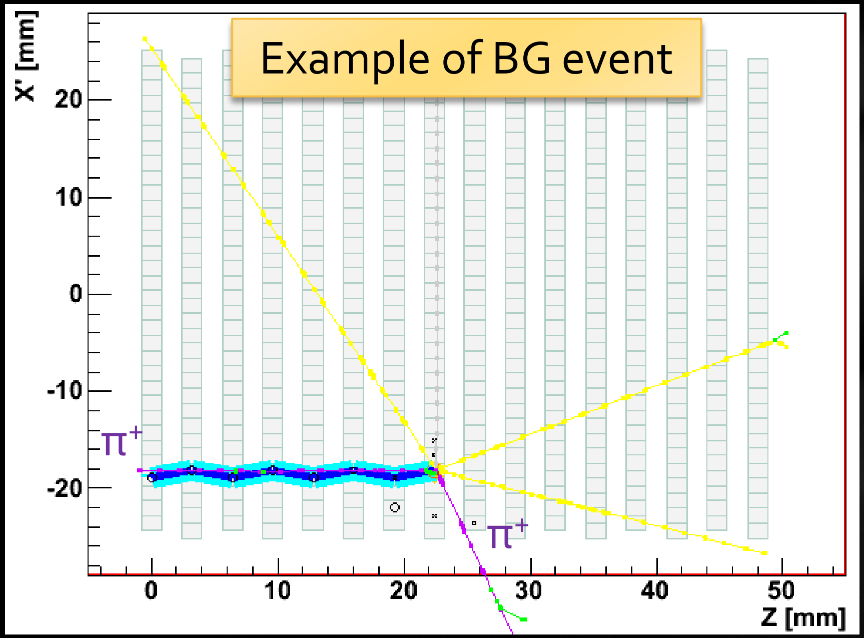
Preliminary

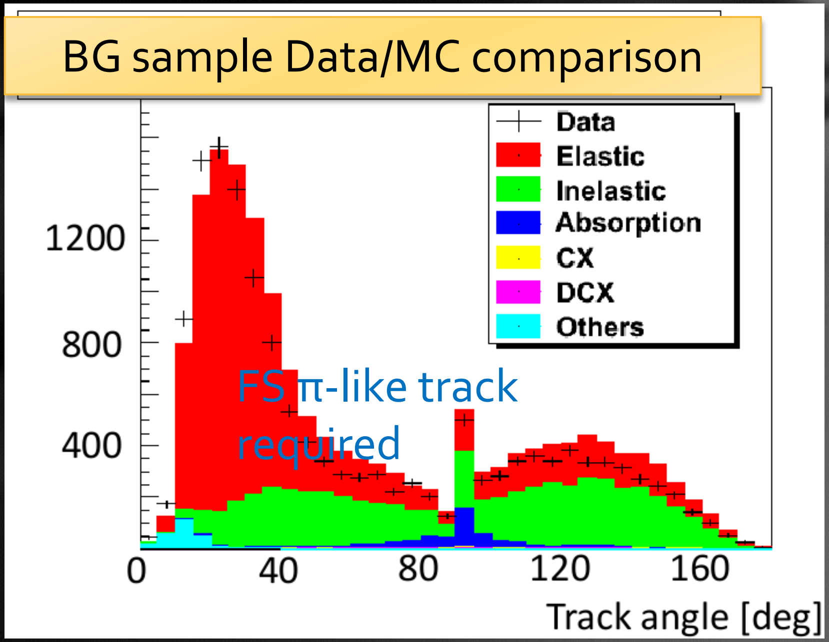
Error source	Method for estimation	Error
(I) Efficiency: Abs+CX model effect to vtxInFV cut	Reweight final state proton angular distribution	0.89%
No FS π cut efficiency	dE/dx difference in X and Y projection etc.	1.40%
Vertex resolution	Test different FV definitions	4.60%
(II) Backgrounds: Scattering model	BG sample Data/MC comparison	5.18%
Impurity of control sample	Cross section uncertainty in past experiments	0.79%
(III) Detector response: Charge distribution	Fluctuate the charge distribution	Under estimate
Crosstalk	Fluctuate the crosstalk probability	Under estimate
(IV) Beam: μ/e contamination	Estimate from Cherenkov & TOF data	0.84%
Momentum	Fluctuate the within error	+3.35% -3.97%
Profile	Fluctuate the within error	2.93%
(V) Number of target nuclei	Estimate from measurement	1.14%

Some of these will be explained in the following slides.

Background uncertainty

The background for Abs+CX events are elastic/inelastic scattering events.
BG error is related to detector response and physics model.



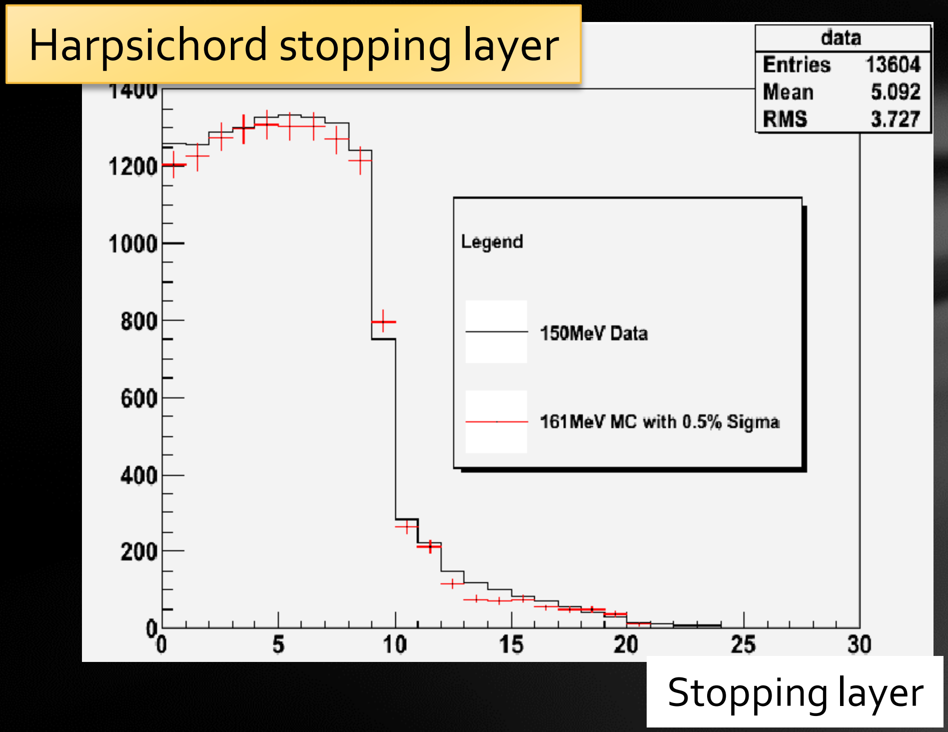


π track is sometimes not detected because of it's angle and vertex position
→ Dominant type of BG

Error for the physics model is evaluated from Data/MC diff in BG control sample.

Momentum uncertainty

Incident π^+ momentum uncertainty is measured by Harpsichord stopping range. Momentum error is ~4%.



This momentum error corresponds to ~3% error in expected number of Abs+CX events. This error is expected to become smaller by doing more sophisticated fit for stopping layer distribution.

Preliminary result

This is the preliminary result for p_π = 235MeV/c.

Number of events after cut (Data)	8555 events
Estimated BG after cut (MC)	2536.77 events
Estimated Abs+CX events after cut	5285.66 events
Cross section in MC	191.11 mbarn

$$\sigma_{Data} = \sigma_{MC} \times \frac{N_{Sel\_Data} - N_{Sel\_BG\_MC}}{N_{Sel\_AbsCX\_MC}}$$

$$= 191.11 \times \frac{8555 - 2536.77}{5285.66}$$

= 218.5 ± 3.8 (stat) [mbarn]
(syst. error not included)

Preliminary

(Past experiment: 213.3±24.9 [mbarn] (Ashery et al.))

Summary

- π-N interaction uncertainty is the key to reduce the systematic error for the ν measurements.
- We measured pion Absorption & Charge exchange cross section at TRIUMF M11 beam line.
- Preliminary result for 250MeV/c is presented, and it is consistent with past experiments. This result will be finalized soon with remaining systematic errors.
- The analysis for other momentum, and for Abs/CX separate measurement, are ongoing.
- We will summarize our result and apply this for T2K oscillation measurement.

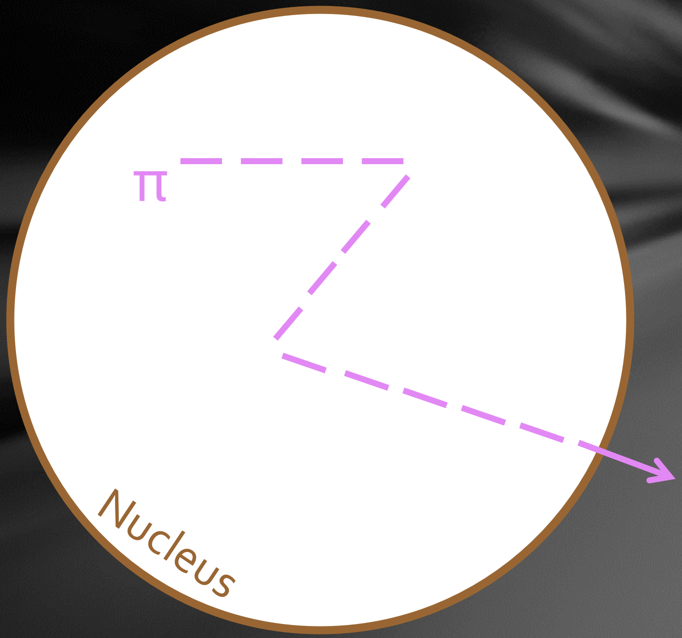
Backup slides

Neutrino interaction simulation

We use “NEUT” for simulating neutrino interaction and final state hadron interaction .

For p_π < 500MeV/c, NEUT simulates the pion interaction probability per step through the nucleus. (Salcedo et al., Nucl. Phys. A 484:557, 1988.)

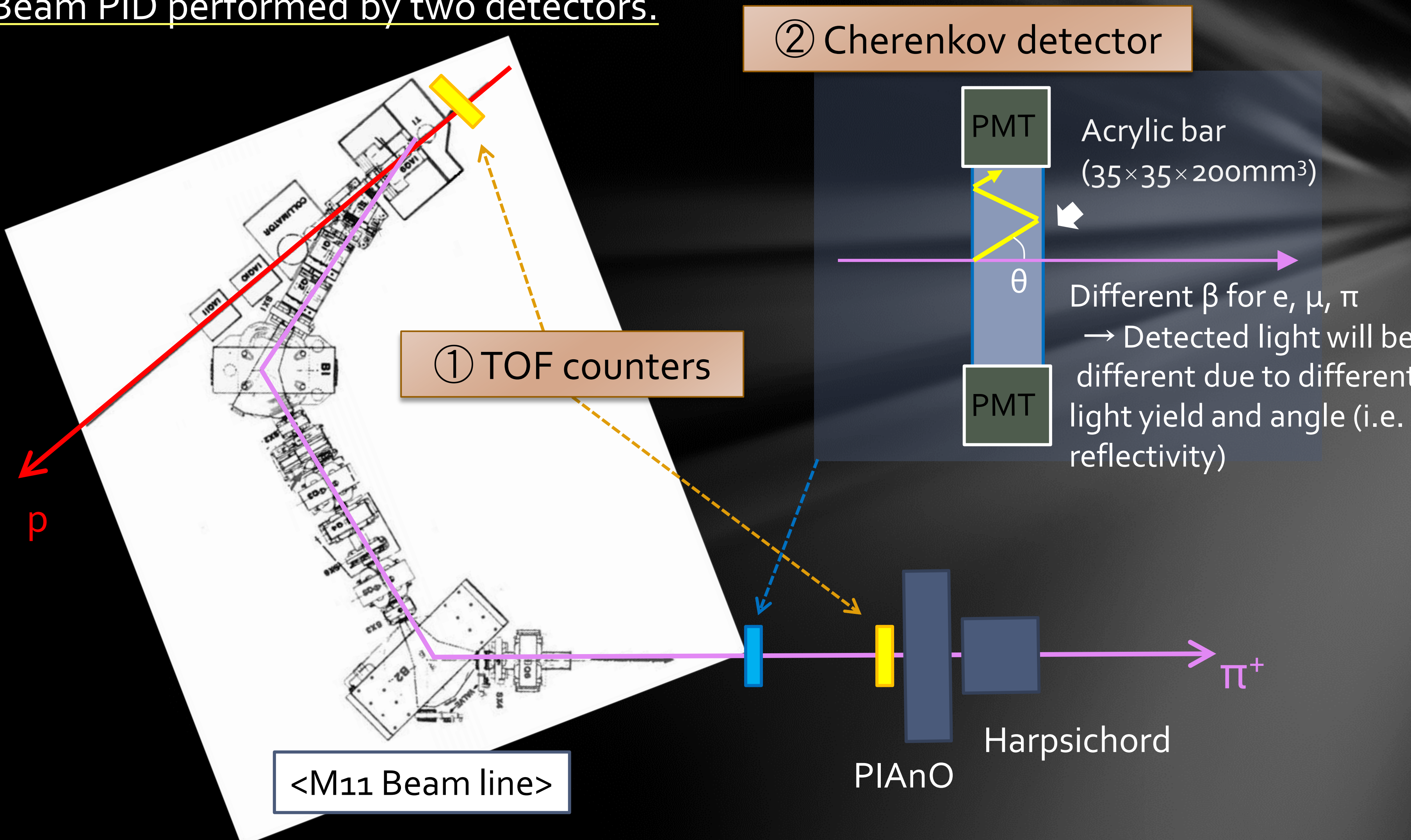
Interaction probability at each step is calculated by using Δ-hole model. Microscopic interaction probability is tuned so that it agree with past π-N scattering data.



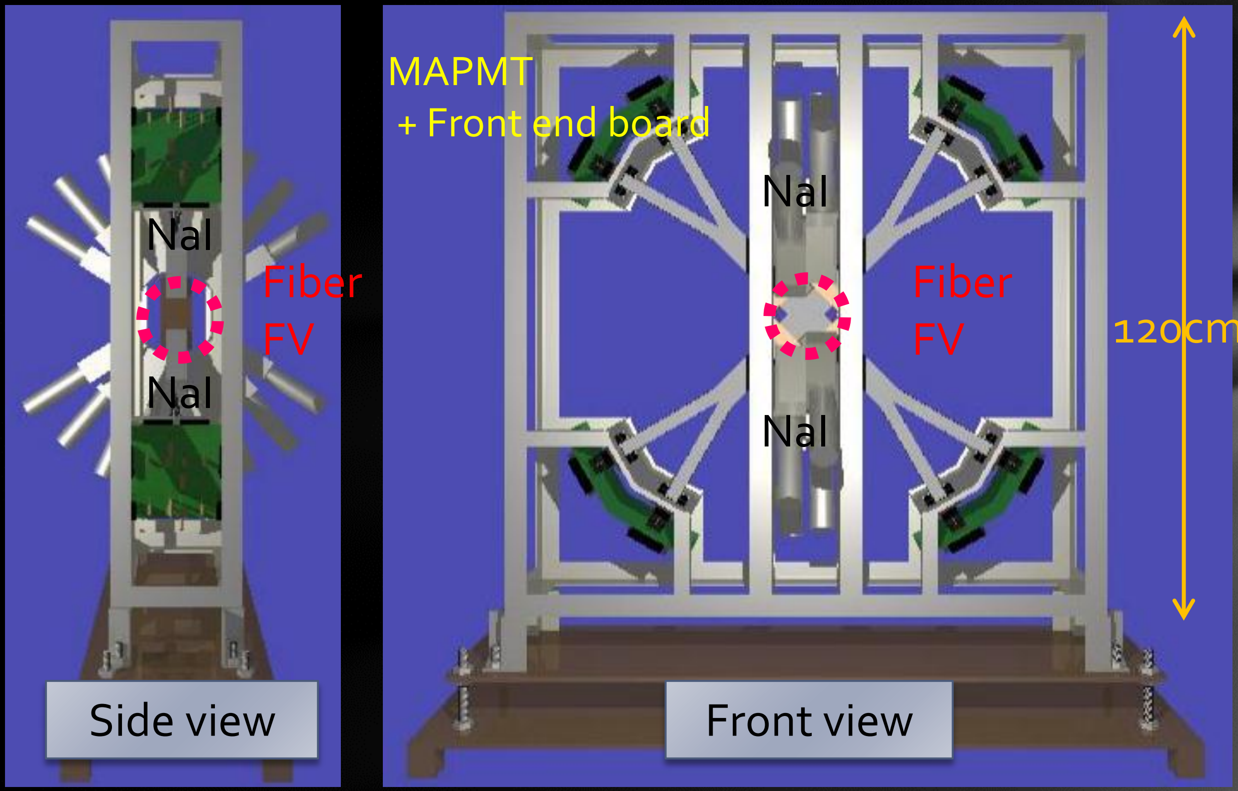
→ We want to validate and reduce the systematic errors for this model, by reducing the π-N scattering cross section uncertainty

Beam PID

Beam PID performed by two detectors.



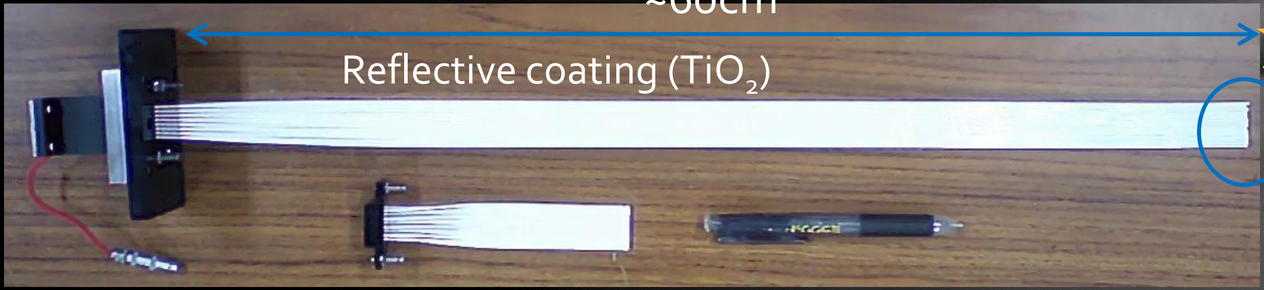
PIAnO detector

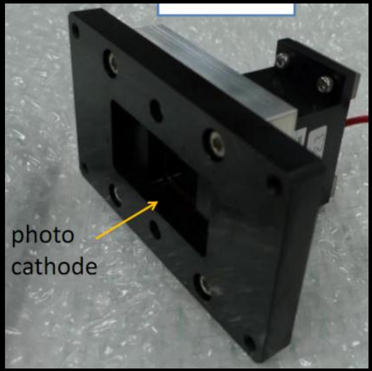


- Scintillating light are read out by MAPMT × 16
- Fiber × 1024 ch, NaI × 16ch
- Fiber main volume: 48mm × 48mm × 48mm

Fiber + MAPMT

Scintillating Fiber: 1.5mm × 1.5mm × 60cm
Kuraray SCSF-78SJ

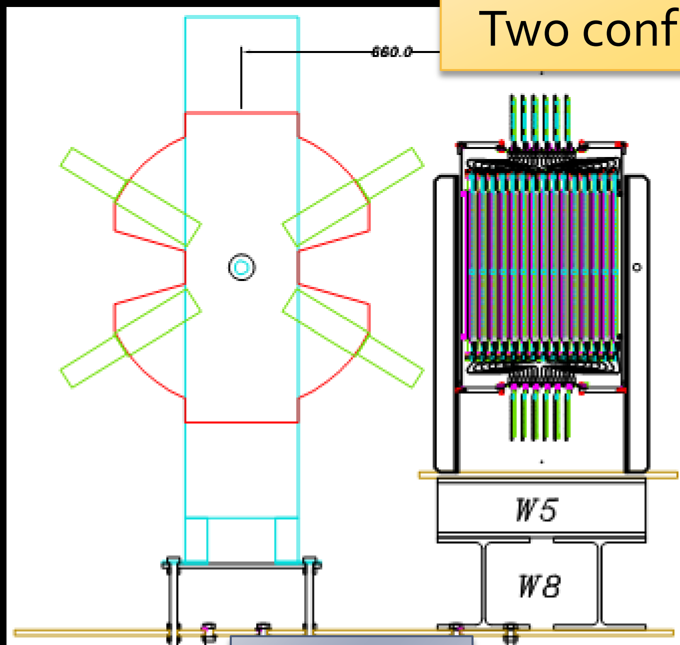




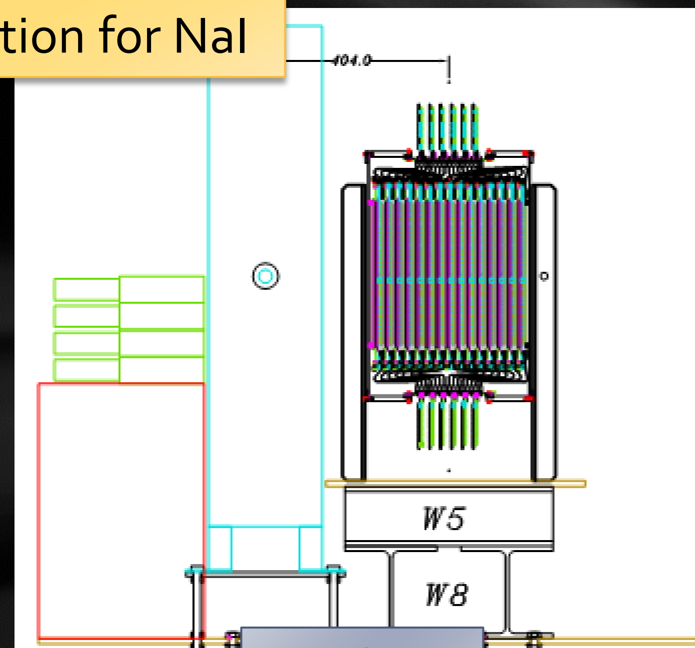
MAPMT : Hamamatsu H8804 64ch
Used in K2K, SciBooNe.
Also use same electronics for readout.
~12p.e. / MIP, crosstalk ~2.5%

NaI detector

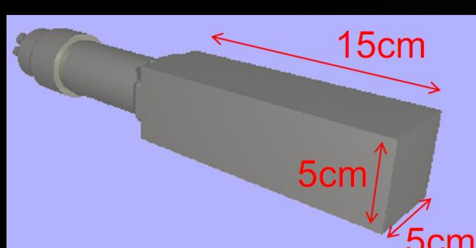
Two configuration for NaI



Config. 1

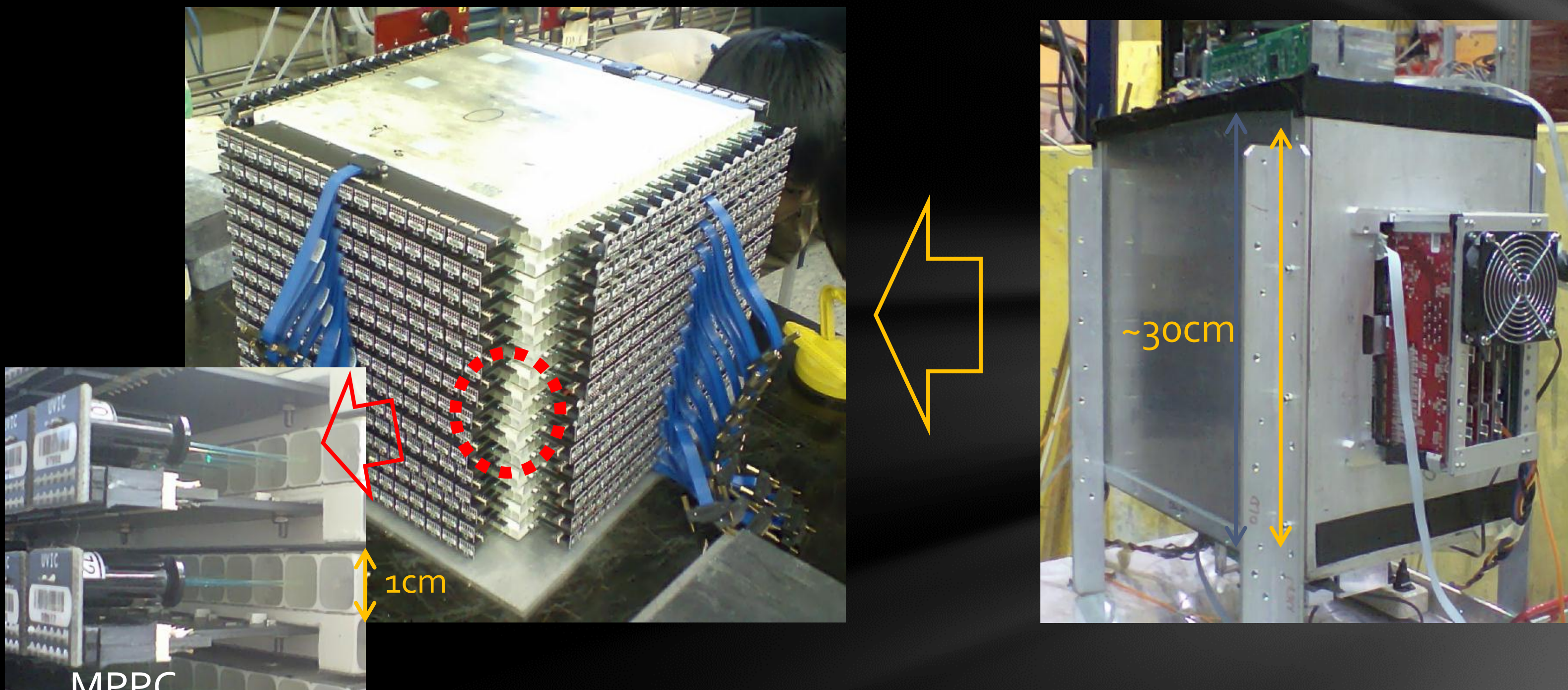


Config. 2



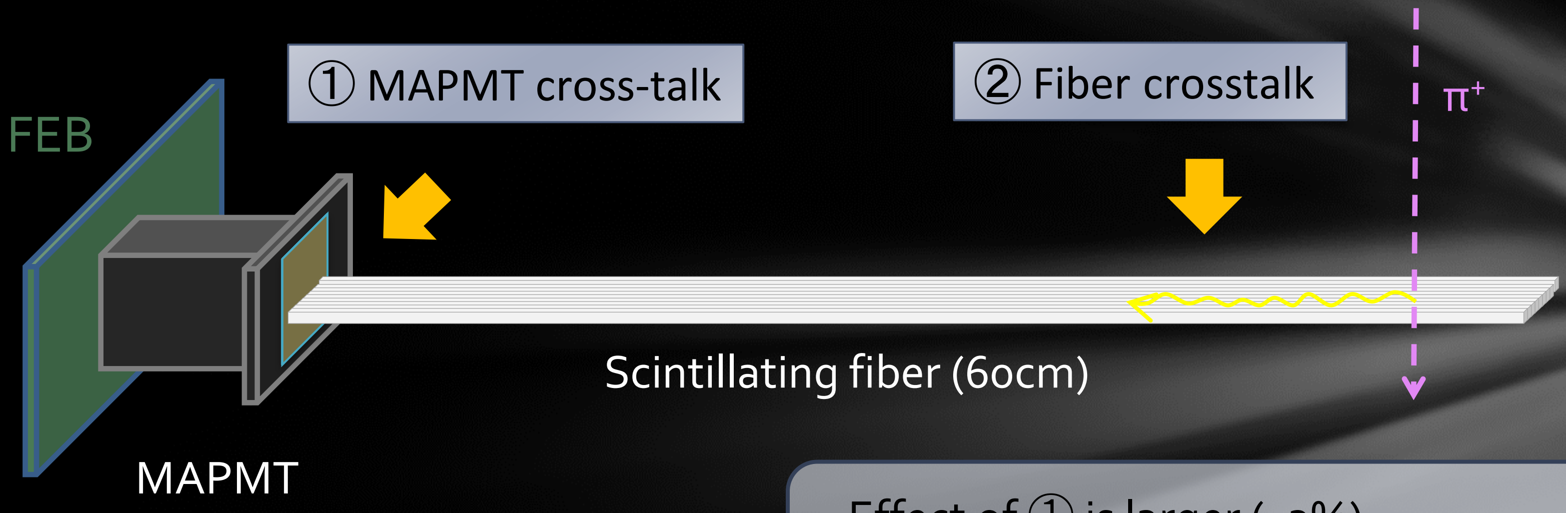
Config.1 ⇒ Check γ angular distribution
Config.2 ⇒ γ detection efficiency by placing gamma detectors closer to the fiber FV

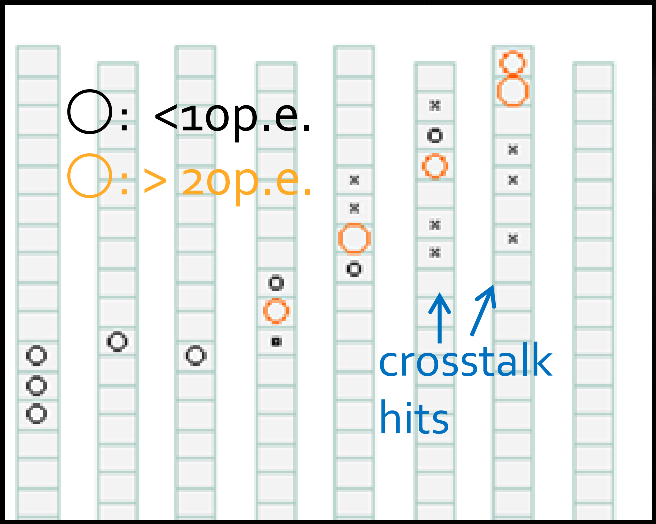
Harpsichord detector



- Sandwich of scintillating bar layer and lead sheets (~1.3mm thick)
- Scintillating bar consists of 32bars, 1cm × 1cm × 30cm each.
- Each bar are read out by MPPC (Multi-Pixel Photon Counter) via wavelength shifting fiber.
- Lead sheets can be removed for incident beam range measurement.

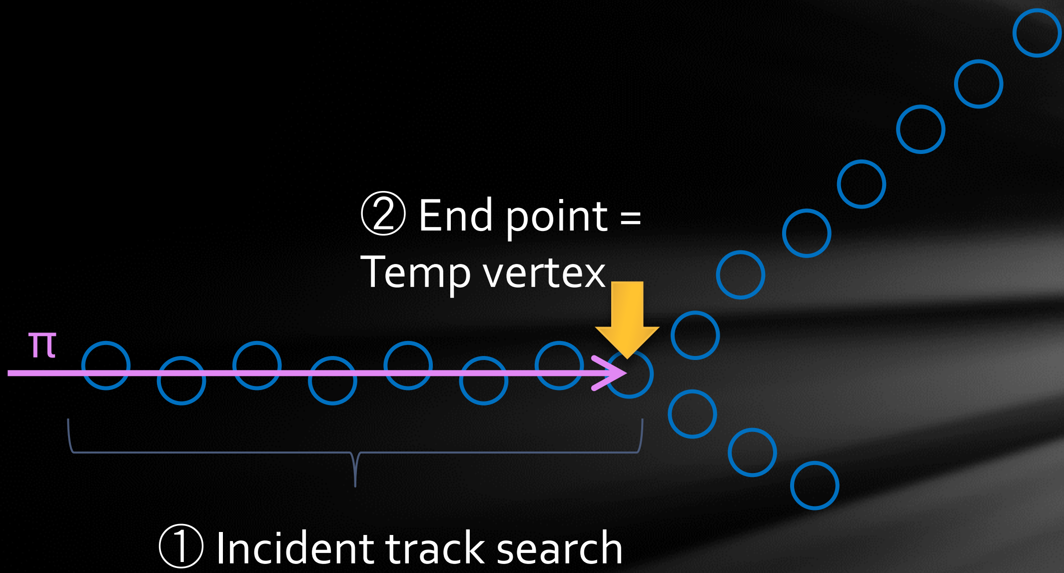
Crosstalk hits





- Effect of ① is larger (~3%).
  Cross talk hits appears around large hits.
  → Small hits (<10p.e.) adjacent to the large hits (>20p.e.) are assumed to be crosstalk hits.
- Fibers with crosstalk hits are skipped when we search the tracks.
- Fibers are arranged so that the adjacent fiber channels do not lie next to each other when we insert it to MAPMT.

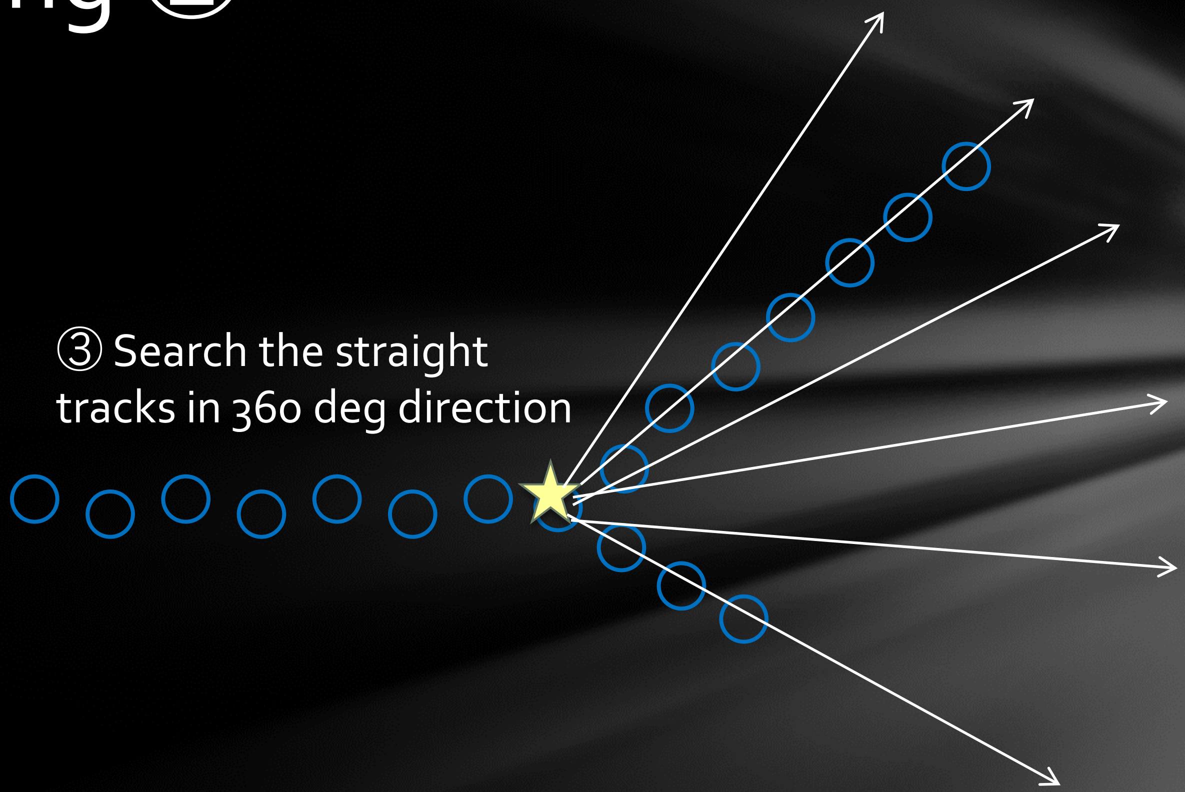
2D tracking ①



Find the best horizontal track by the following method
⇒ Define the end point of the track as the temporary vertex

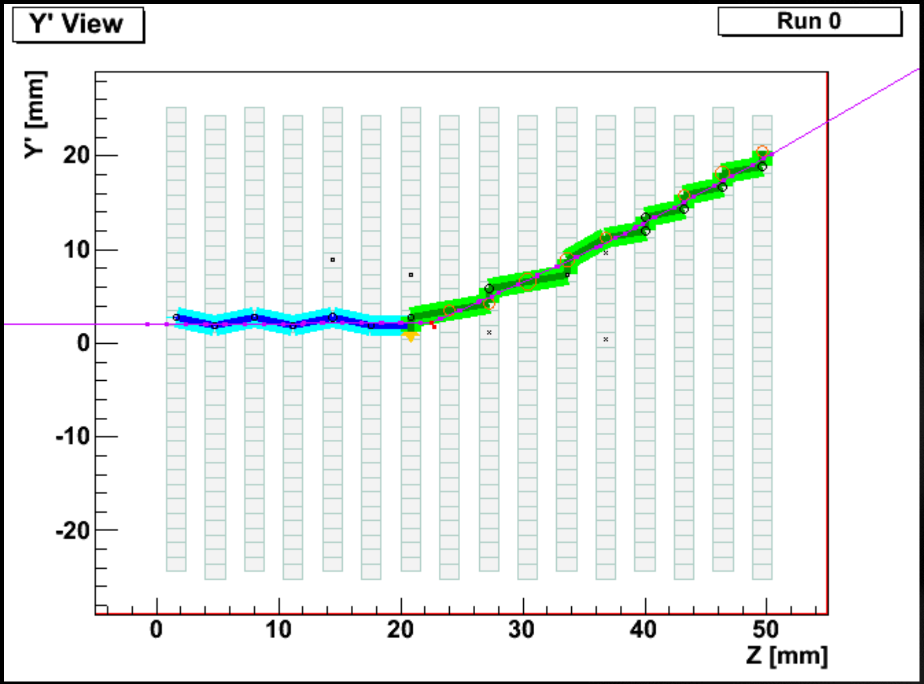
Track search method
- Define the temp track starting point, and search for the hits
- If there are >2fibers skipped, end tracking

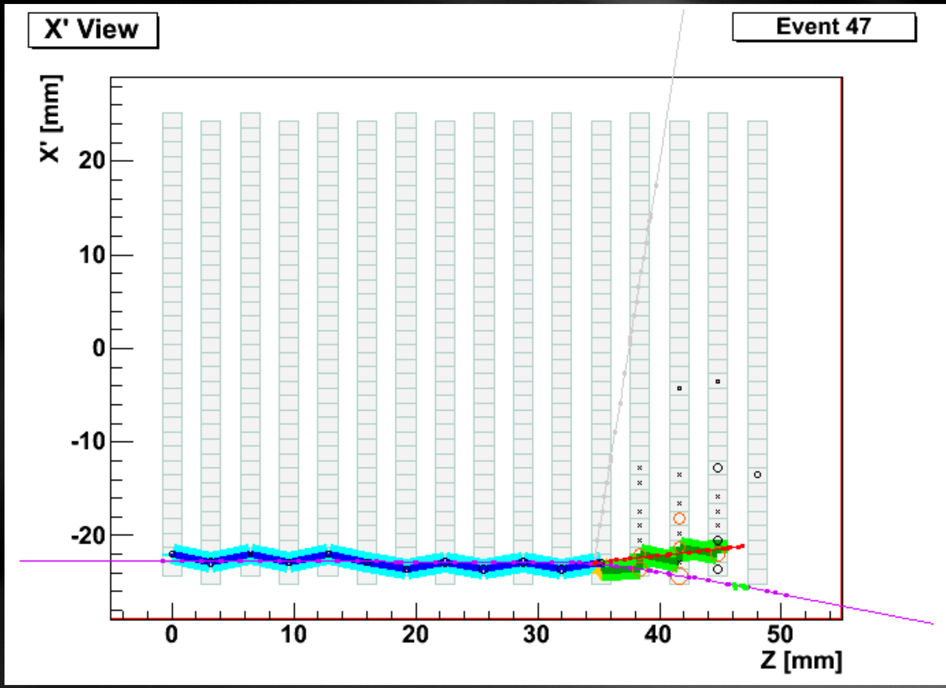
2D tracking ②



- Search the best vertex position around the temporary vertex.
- The best vertex position is the point where you can track maximum number of hits.

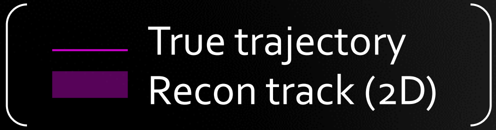
Example of tracking





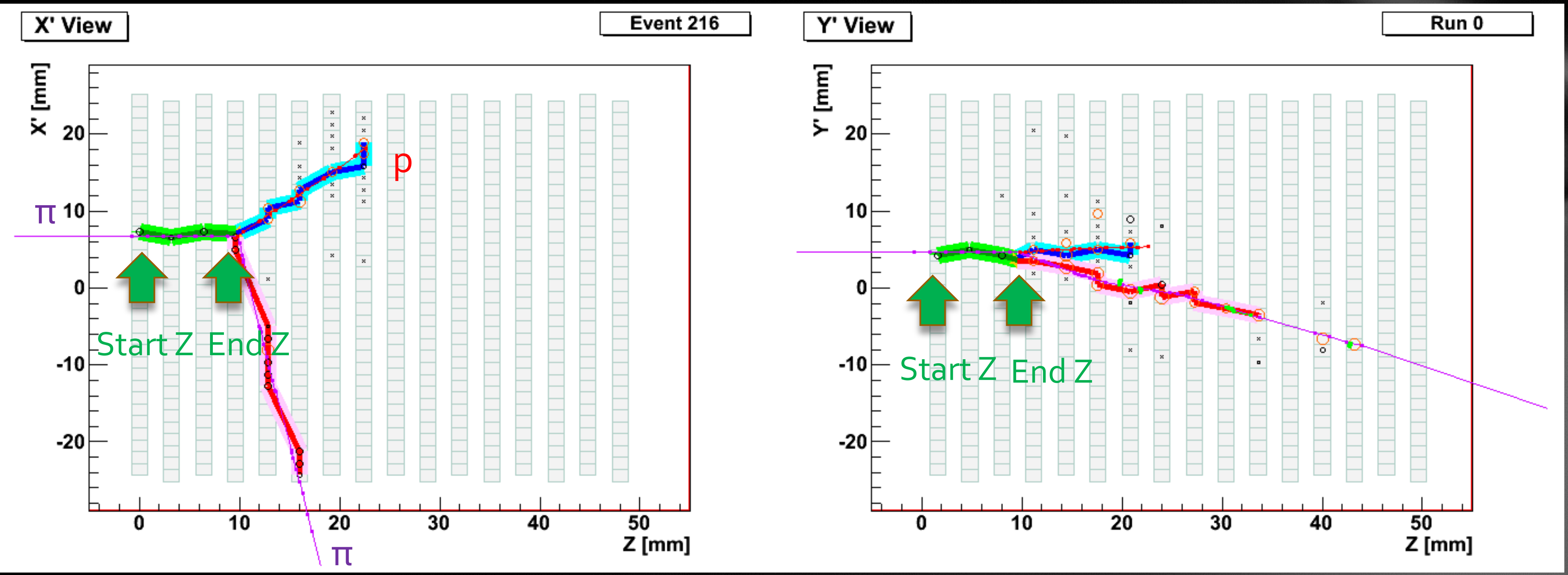
Tracking efficiency: >70%
(For tracks with ≧3 hits)

Tracking fails for very short tracks and low angle tracks.



2D->3D matching

Reconstruct the 3D track from X tracks and Y tracks.

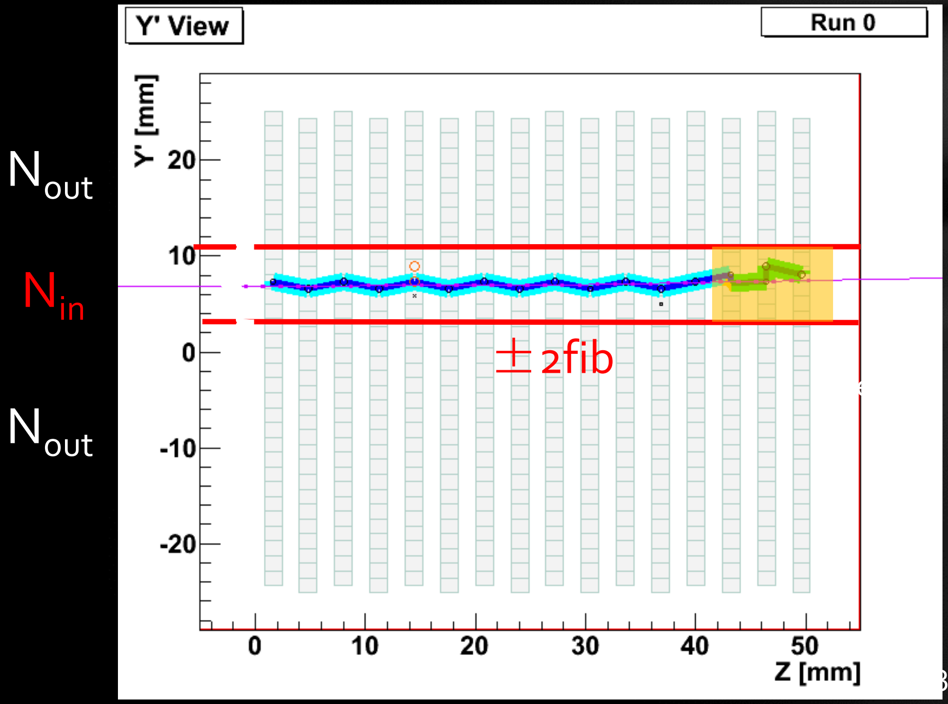


True trajectory
Recon track (2D)
Recon track (3D matched)
(Same color ： Same 3D track)

- Combine the tracks if the track start/end point matches in X and Y.
- The end Z position do not have to match if the track escapes from Fiber crossing region.

Multiple scattering cut

This cut is included in the “vertex in FV cut”.
Sometimes very low angle multiple scattering tracks are reconstructed, but we don’t need to select those.

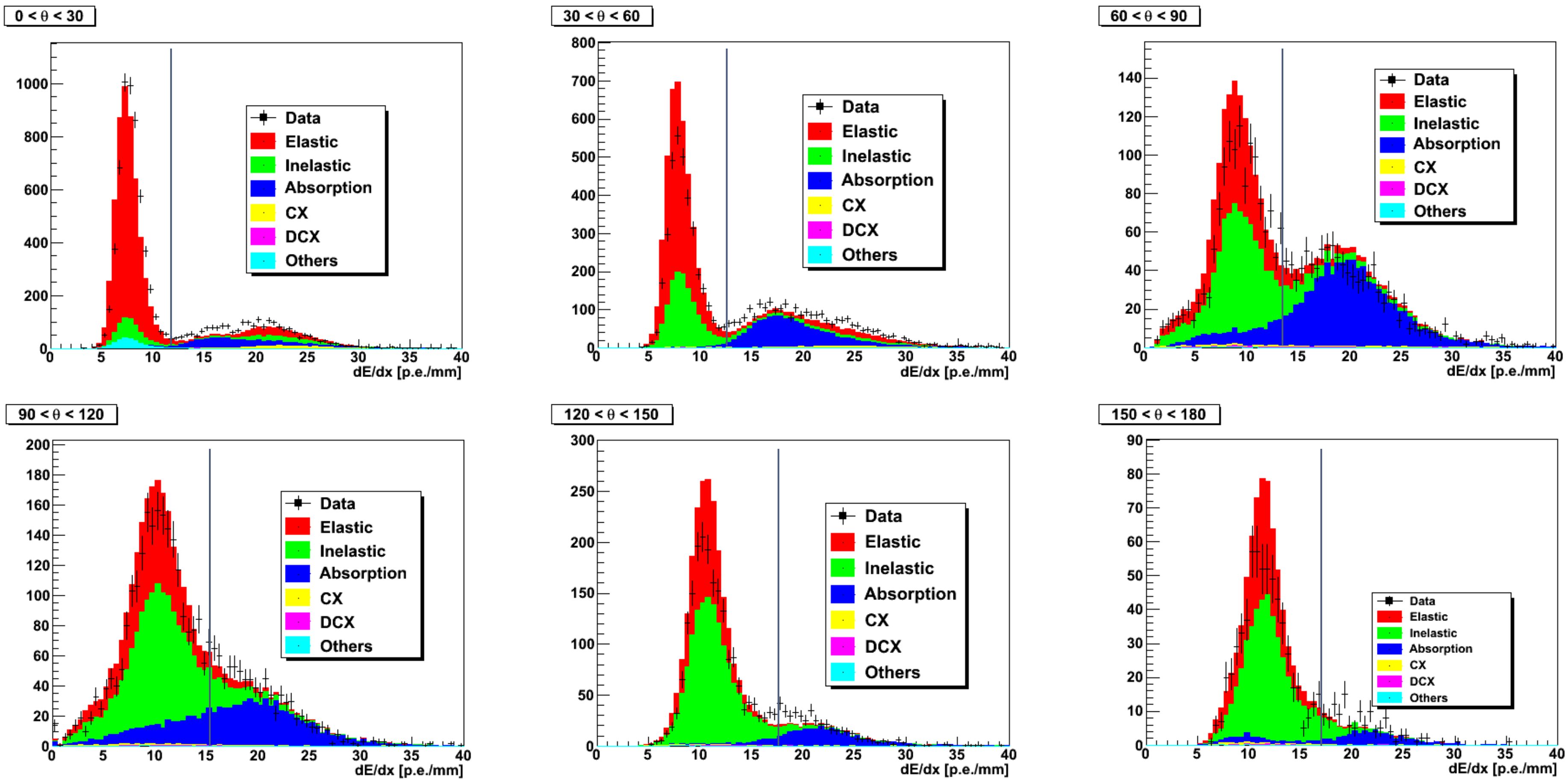


Cut criteria is defined from number of reconstructed hits:

N_{in} >=25 && N_{out}>0

N_{end_X} >=2 && N_{end_Y} >=2

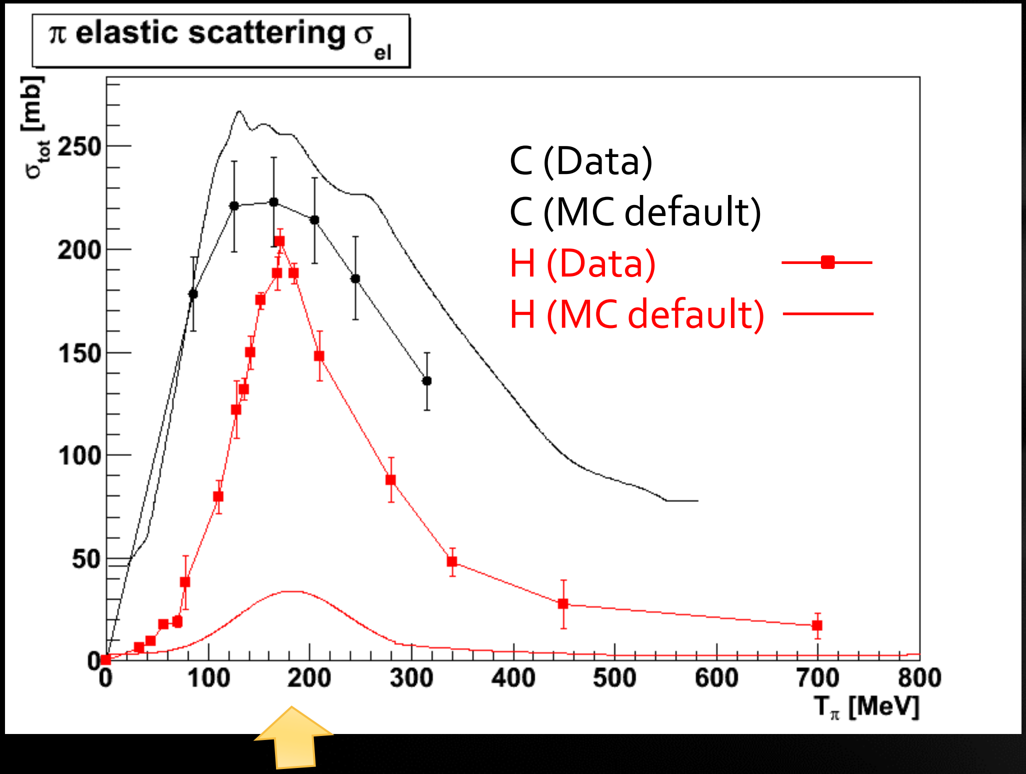
dE/dx distributions



Threshold value depends on angle.

Cross section tuning

① Total cross section

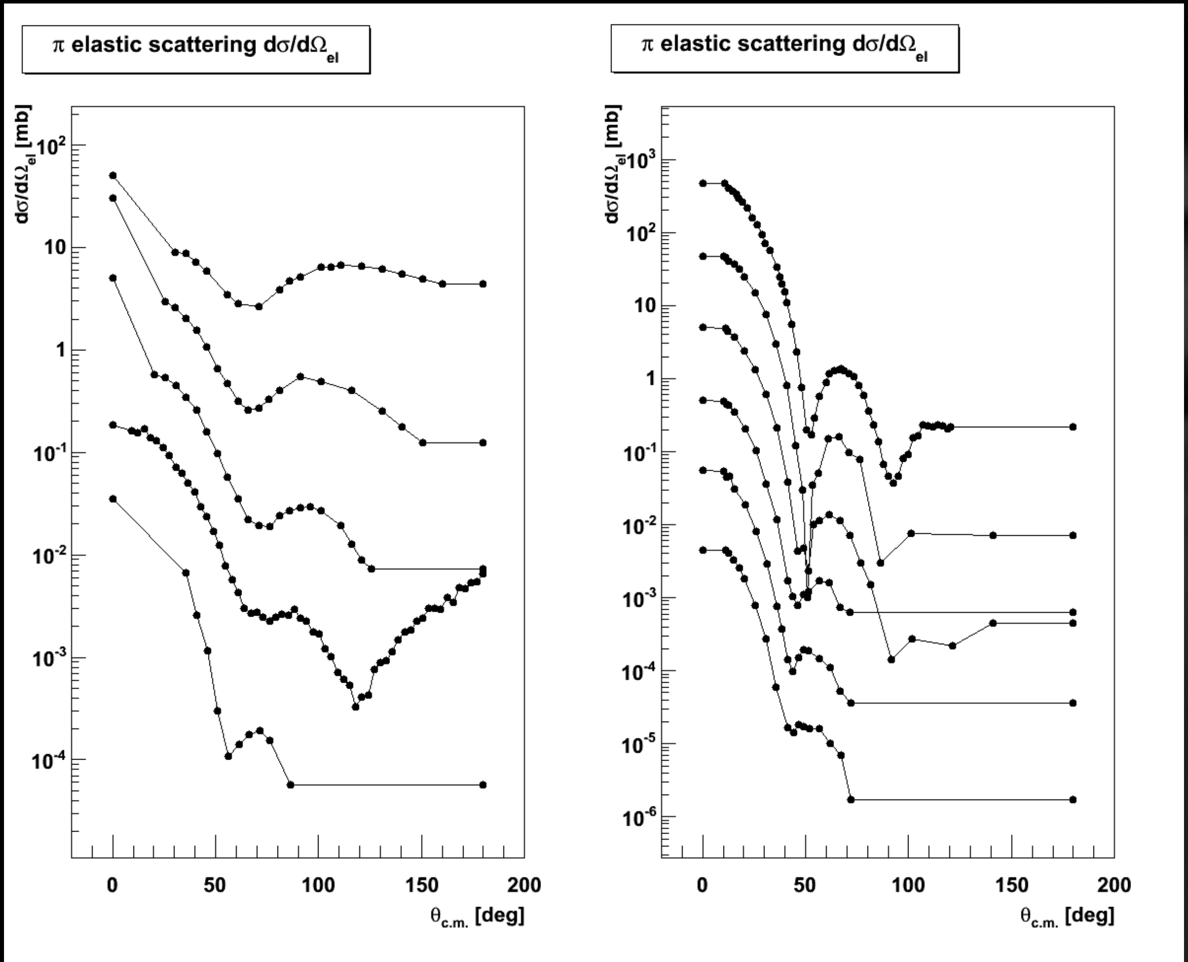


The default (QGSP_BERT) π-H cross section was very small

- Tuned cross section is calculated by interpolating the past experimental data.
  Carbon: D. Ashery, Phys. Rev. C23 2173 (1981)
  Hydrogen: S. L. Leonard, Phys. Rev. 93 568 (1954)
  J. Ashkin, Phys. Rev. 96 1104 (1954)
  H. L. Anderson, Phys. Rev. 91 155 (1953)
  Phys. Rev 100 269 (1955)
  S. J. Lindenbaum, Phys. Rev. 100 306 (1955)
  Phys. Rev. 111 1380 (1958)
- Tune will be applied only for:
  $T_\pi < 315$MeV π-C scattering
  $T_\pi < 700$MeV π-H scattering

cont'd

② Differential cross section



Differential cross section is also tuned according to past experiments.

Carbon: Preedom(50MeV), Amann(67.5MeV), Blecher(80MeV), Antonuk(100MeV), Alden(142MeV), Michael(162MeV), Binon(180,200,230,260,280MeV (π^-))

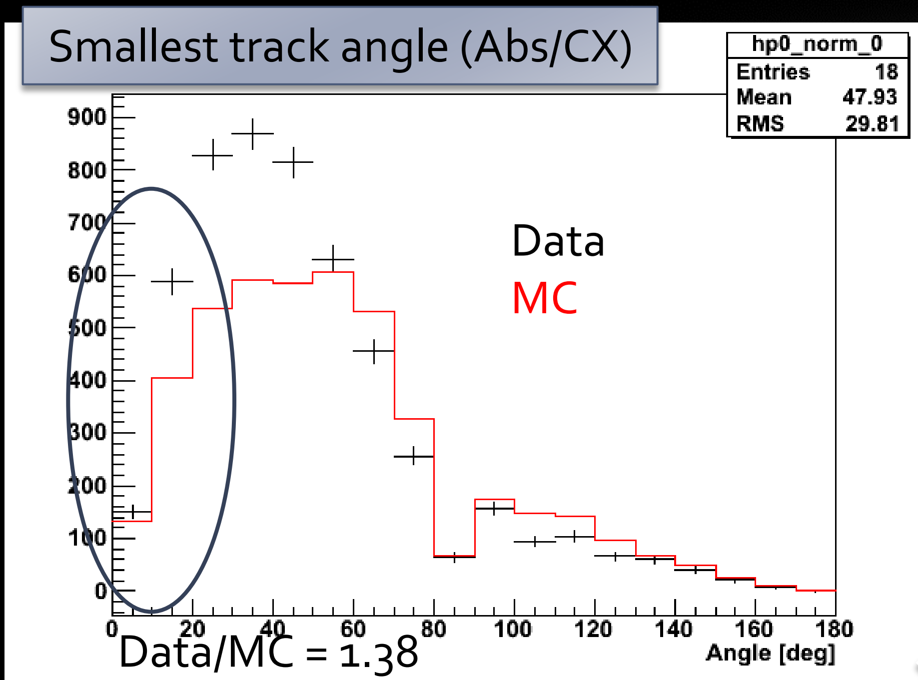
Hydrogen: Frank(49.5MeV, 69MeV), Joram(69MeV), Brack(87.0, 98.0, 116.9, 125.9, 139.0MeV), Bussey(166.0, 194.3, 214.6, 236.3, 263.3, 263.7, 291.4MeV)

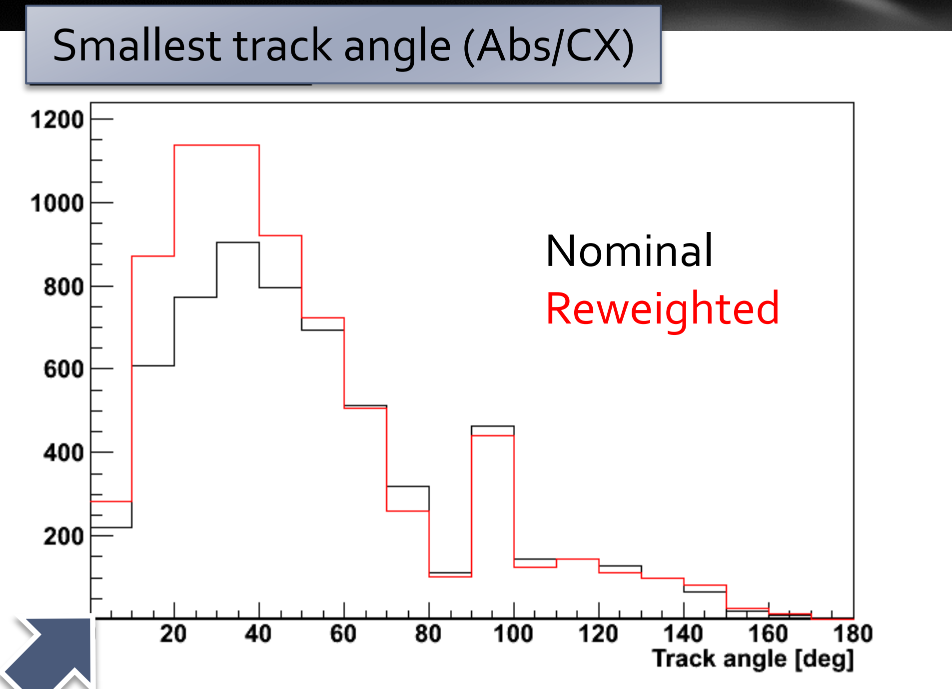
Systematic errors

Event selection efficiency

① Abs+CX model error for Vertex finding efficiency

If the angular distribution of proton track from Absorption/CX is incorrect in the model, vertex finding efficiency will be wrongly estimated. According to the eye scan, forward (θ<20deg) and backward (θ>160deg) are causing the inefficiency.





Estimate this effect with reweighted MC

$\varepsilon_{nominal} / \varepsilon_{reweighted} = 1.011 \rightarrow 1.1\%$

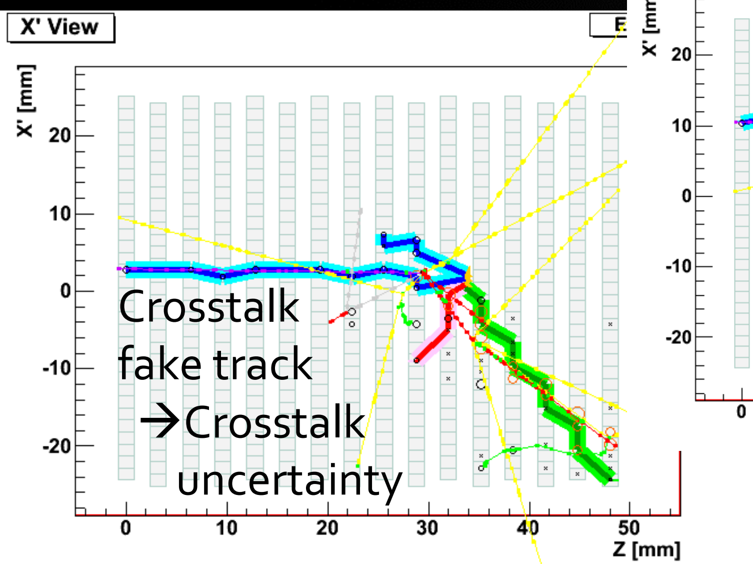
vtxInFV cut: (i)Vertex reconstructed && (ii)Vertex is in FV
(ii) was double-counted with vertex resolution error → Fixed

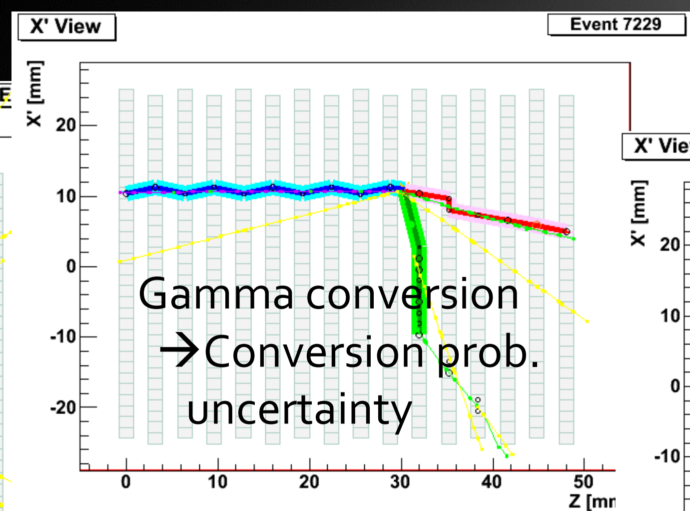
(I) Event selection efficiency

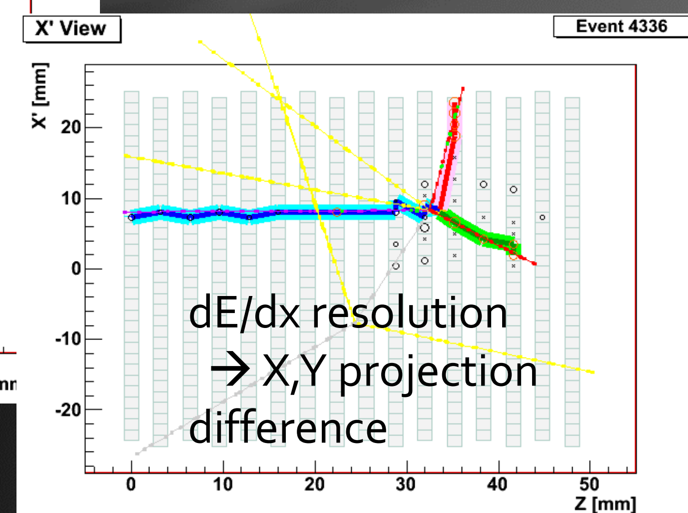
② No FS π cut efficiency error

Bad events which fails the cut (from eye scan in MC):

- (i) dE/dx resolution (44.9%)
- (ii) Crosstalk fake track (33.7%)
- (iii) Gamma conversion (19.1%)
- (iv) High momentum p (2.3%)

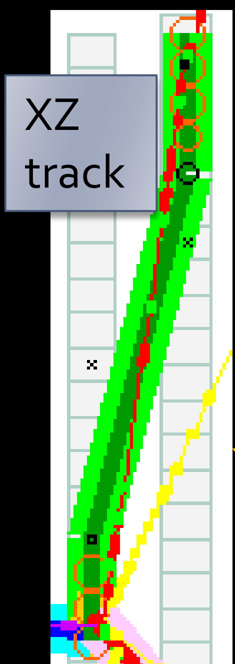


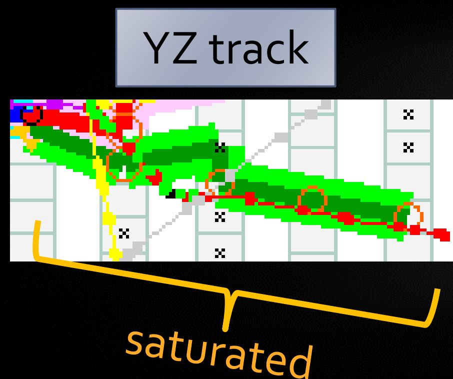




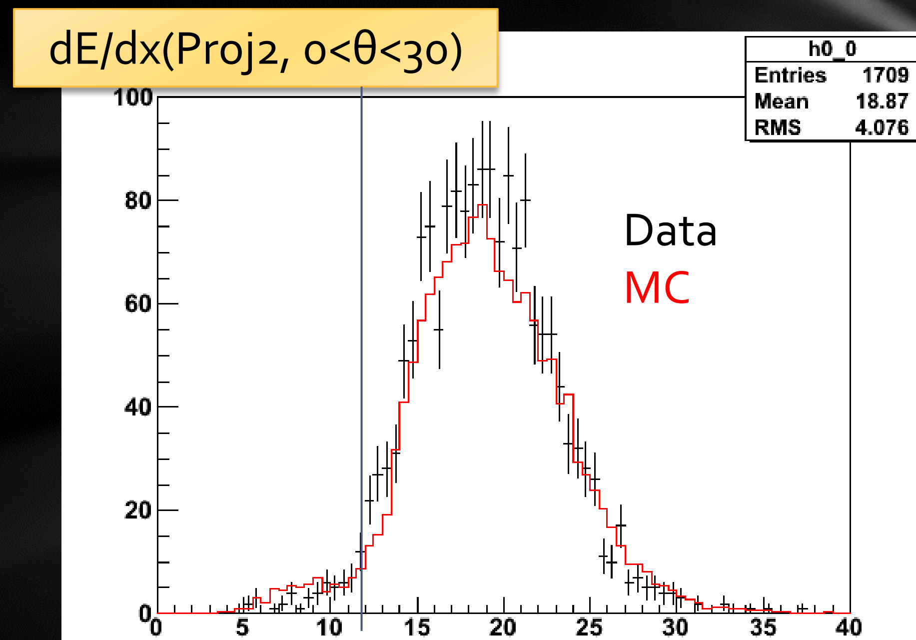
dE/dx resolution uncertainty

Most of the proton tracks are above dE/dx threshold, but sometimes they are misidentified as π due to finite dE/dx resolution.
Uncertainty of this effect is evaluated by dE/dx diff in X and Y projection.





dE/dx is calculated from this projection



We calculate the dE/dx from projection with high angle, to avoid saturation effect.

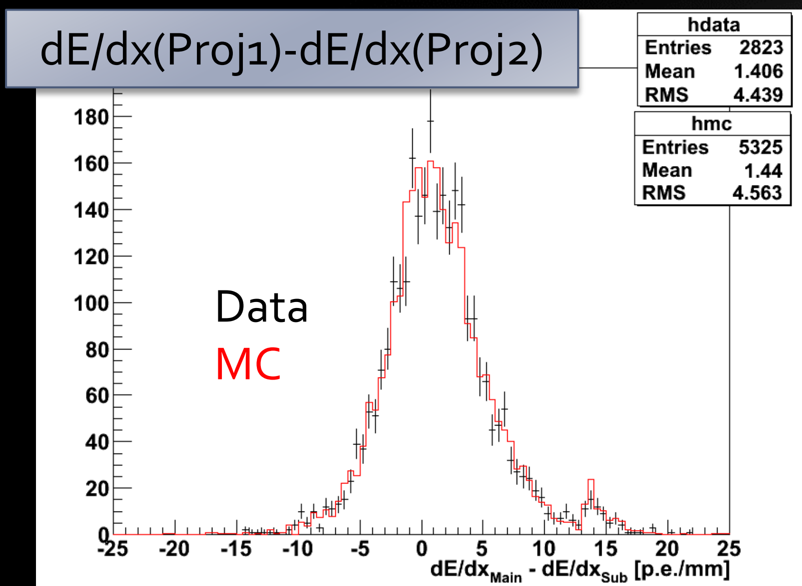
dE/dx cut inefficiency can be evaluated by the probability to fail the dE/dx cut in the other projection.

(I) Event selection efficiency

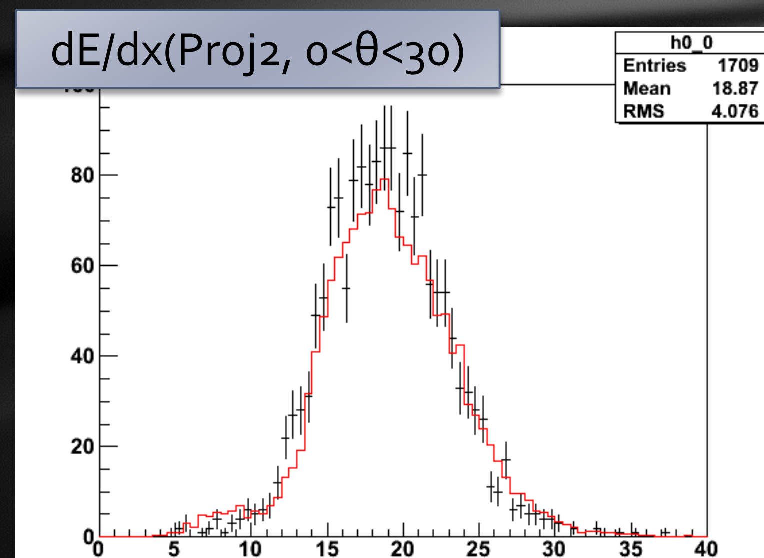
② No FS π cut efficiency error

(i) dE/dx resolution

dE/dx resolution error is calculated by Data/MC diff in the probability to fail the cut in the other projection, which was 9.2%.



The difference of dE/dx in two projection seems to agree very good for Data and MC.



In order to check the dE/dx inefficiency, I checked the dE/dx histogram in the other projection. Here, I could see the difference.

(I) Event selection efficiency

② No FS π cut efficiency error

(i) dE/dx resolution

In order to avoid the saturation effect, I was requiring: Hit per layer diff < 0.3. By requiring this, forward/backward flat tracks were enhanced, which becomes different from the actual proton angular distribution

	Event rate	Ineff (Data)	Ineff (MC)
$0<\theta<30$	33.2%	0.063	0.072
$30<\theta<60$	31.5%	0.090	0.088
$60<\theta<90$	16.2%	0.300	0.262
$90<\theta<120$	9.0%	0.338	0.350
$120<\theta<150$	7.1%	0.362	0.312
$150<\theta<180$	3.0%	0.268	0.316

The actual proton angular distribution is distributed more widely. Data/MC difference was mainly coming from $0<\theta<30$, which is actually only ~30% of all proton tracks.

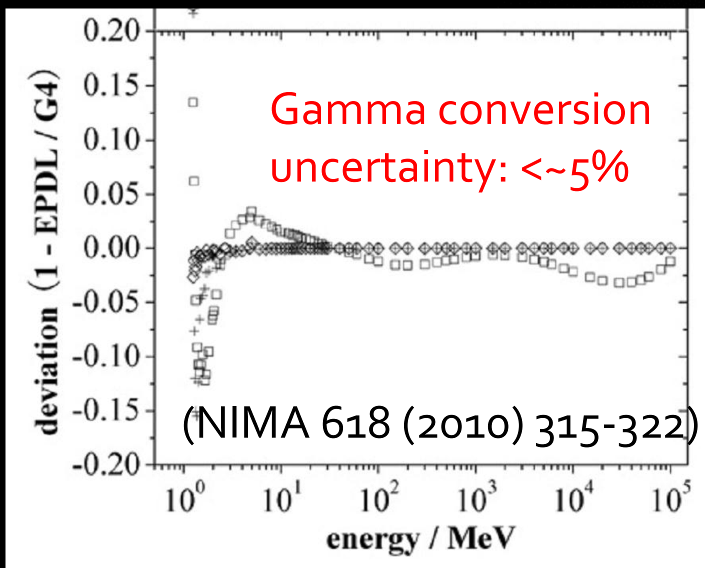
→ Revised Data/MC = 1.0296

$\Delta\sigma = (1-\varepsilon_{vtxInFV})*0.449*0.0296 = 0.22\%$

(I) Event selection efficiency

② No FS π cut efficiency error

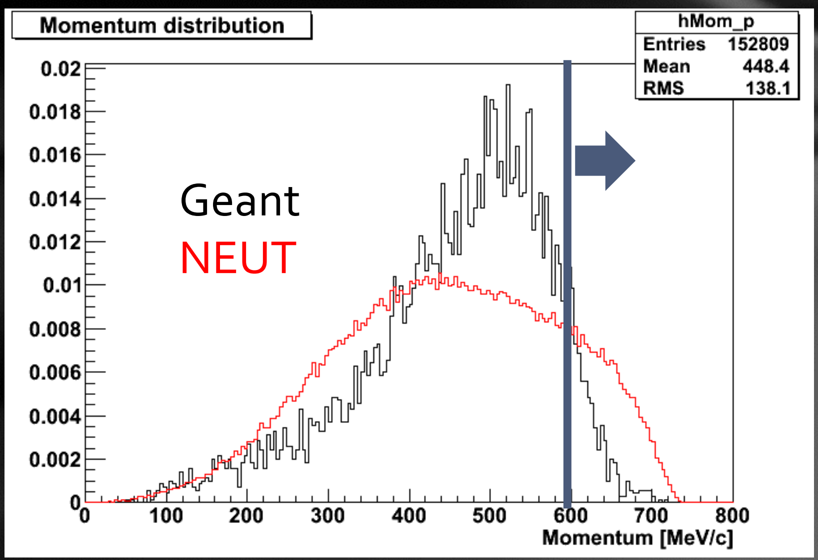
(iii) Gamma conversion (19.1%)



EPDL: Evaluated Photon Data Library
by Lawrence Livermore National Laboratory

$\Delta\sigma = (1-\varepsilon_{vtxInFV})*0.191*0.05 = 0.15\%$

(iv) High momentum p (2.3%)



Uncertainty of high momentum proton events taken from Geant4/NEUT difference:

Geant4/NEUT = 2.32

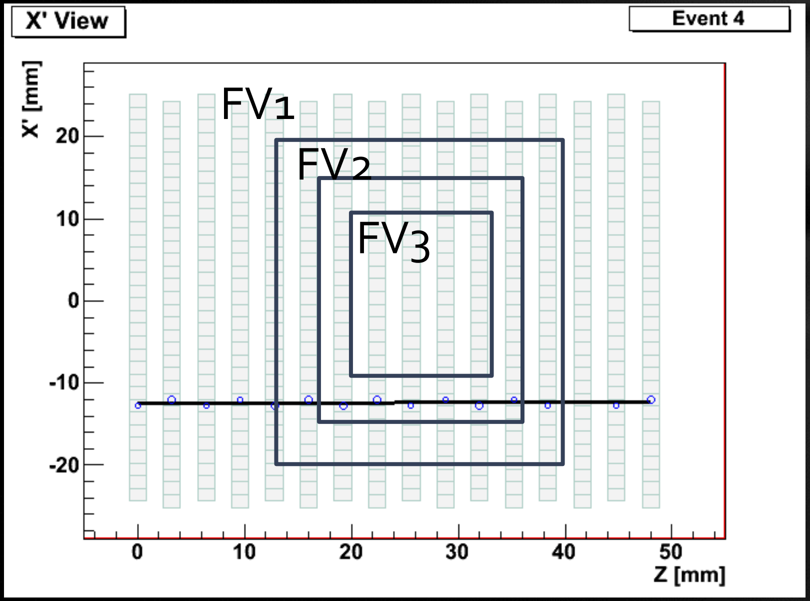
$\Delta\sigma = (1-\varepsilon_{vtxInFV})*0.023*2.32 = 0.85\%$

(possibly improved later by using Harpsichord)

(I) Event selection efficiency

③ Vertex resolution error

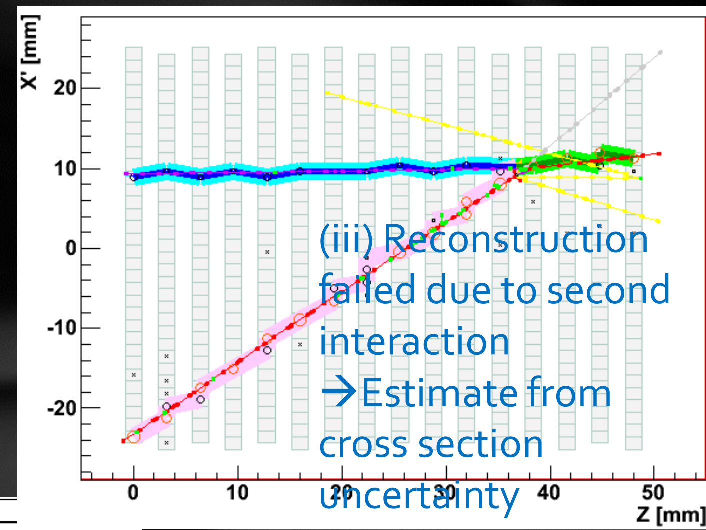
If the vertex resolution in MC is different in Data, the number of events reconstructed inside FV will change.



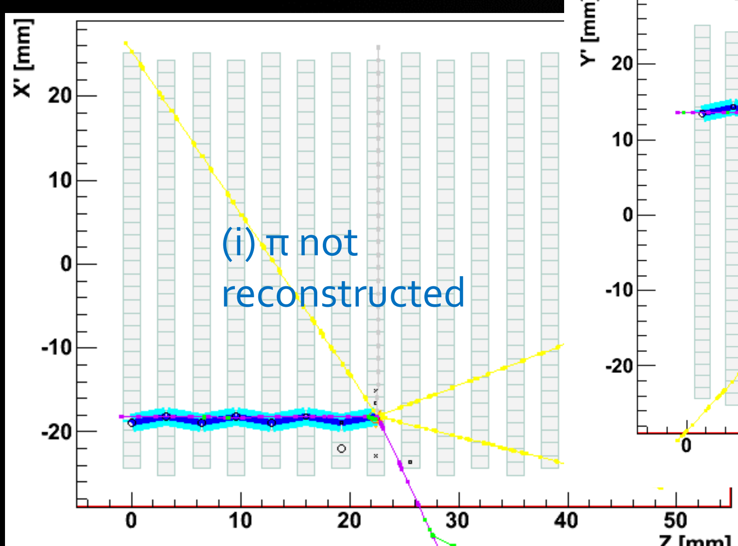
(II) Background estimation

① Scattering model

(i) π recon failure: 56.6%
(ii) dE/dx resolution: 20.5%
(iii) Multiple interaction: 12.3%
(iv) Low momentum π: 10.7%

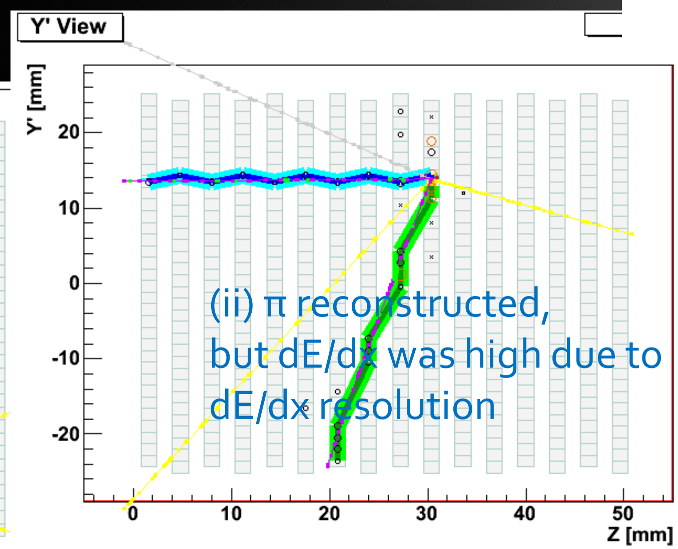


(iii) Reconstruction failed due to second interaction
→ Estimate from cross section uncertainty

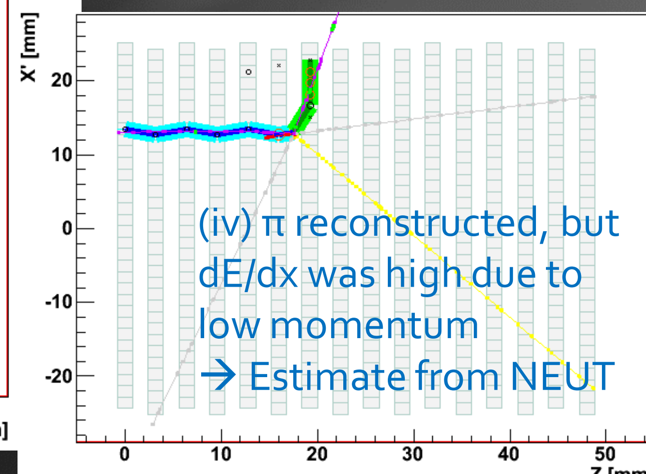


(i) π not reconstructed

→ Estimate from BG sample Data/MC difference



(ii) π reconstructed, but dE/dx was high due to dE/dx resolution

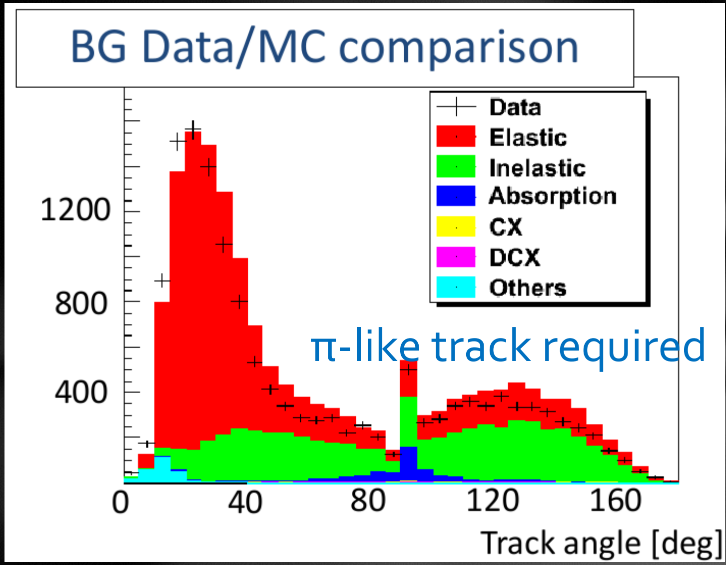


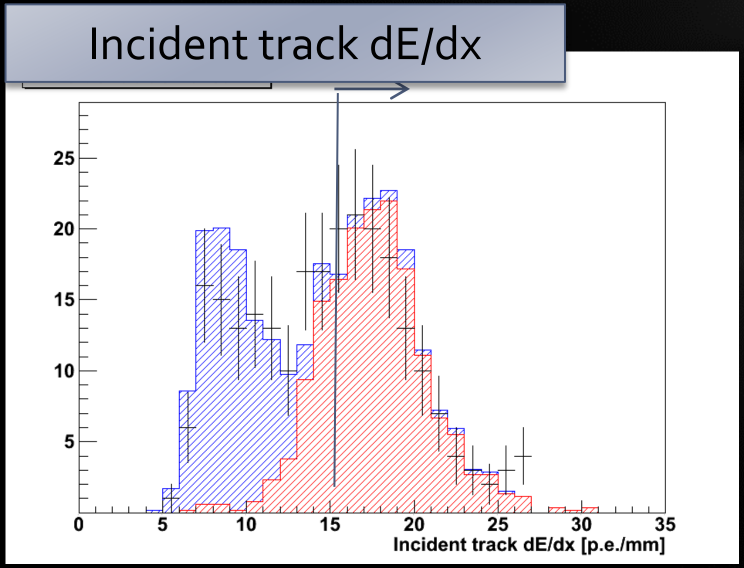
(iv) π reconstructed, but dE/dx was high due to low momentum
→ Estimate from NEUT

(II) Background estimation

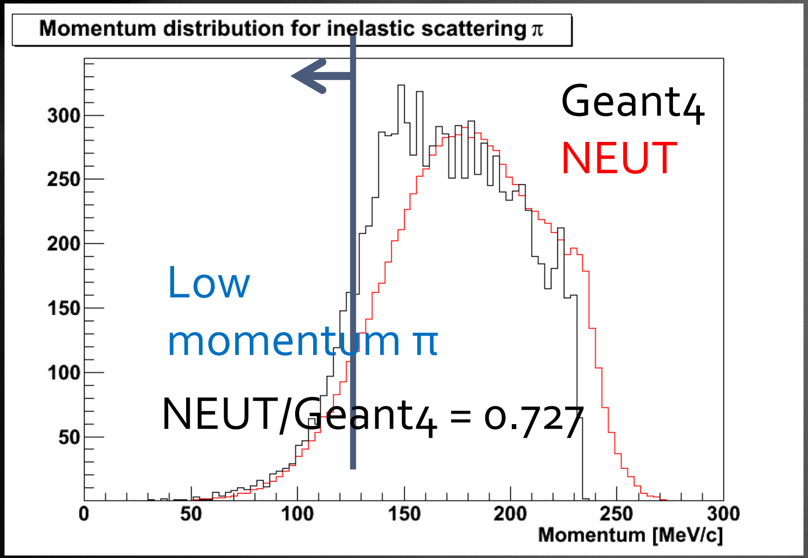
① Scattering model

(i) π recon failure: 56.6%
(ii) dE/dx resolution: 20.5%
(iii) Multiple interaction: 12.3%
(iv) Low momentum π: 10.7%





180deg sample:
Incident track dE/dx is large



(II) Background estimation

① Scattering model

BG type	Number of BG events (normalized to Data)	Error (= Data/MC)	N_{events}* Error
90deg	420.5	-9.2%	±38.7
180deg	124.3	-9.3%	±11.6
Other “π not found” or “dE/dx resolution”			
0 < θ < 30	33.6	+3.5%	±1.2
30 < θ < 60	159.3	-20.7%	±33.0
60 < θ < 90	253.2	-13.5%	±34.2
90 < θ < 120	272.1	-10.5%	±28.6
120 < θ < 150	93.0	-18.6%	±17.3
150 < θ < 180	27.6	-24.7%	±6.8
Low momentum	202.0	-27.2%	±54.9
Total	1585.6		±226.2

(II) Background estimation

① Scattering model

BG type	Number of BG events (normalized to Data)	Error (=xsec uncertainty from Ashery et. al)	N_{events}* Error
Multiple interaction			
Elastic*Elastic	20.1	14.1%	2.8
Elastic*Inelastic	36.1	18.8%	6.8
Elastic*Abs	53.3	21.0%	11.2
Elastic*CX	11.3	51.0%	5.76
Elastic*Decay	8.5	10.0%	0.9
Inelastic*Elastic	0.03	18.8%	0.0
Inelastic*Inelastic	8.6	22.5%	1.9
Inelastic*Abs	38.9	24.4%	9.5
Inelastic*CX	5.4	52.5%	2.8
Inelastic*Decay	66.4	15.9%	10.5
Total	248.6		54.9

(II) Background estimation

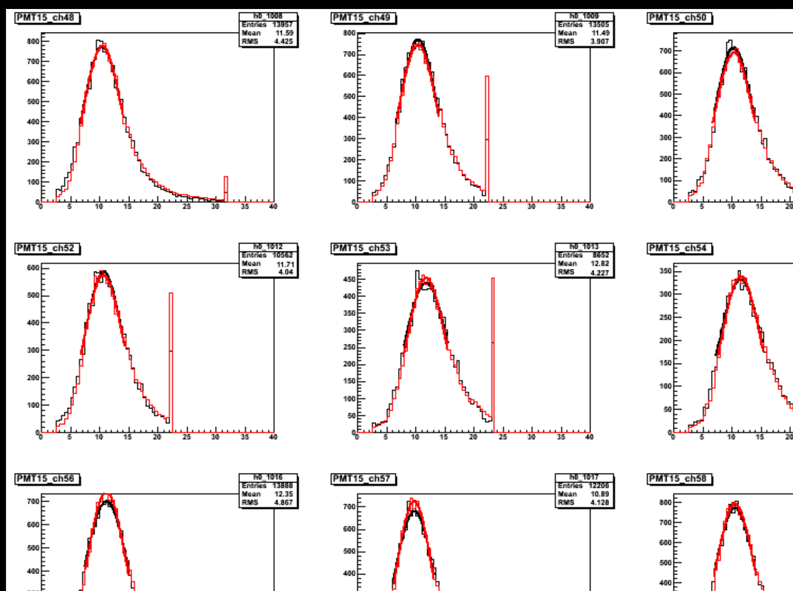
② Impurity of control sample

BG type	Number of events in the control sample	Number of Abs+CX events	N_{AbsCX}* xsec error	Error for Data/MC	Error for BG error
90deg	868.3	313.9	58.1	6.7%	±28.1
180deg	134.6	3.4	0.6	0.5%	±0.6
$0 < \theta < 30$	5187.3	19.5	3.6	0.06%	±0.02
$30 < \theta < 60$	4154.5	40.1	7.4	0.2%	± 0.3
$60 < \theta < 90$	1368.2	181.2	33.5	0.2%	± 6.2
$90 < \theta < 120$	1984.6	276.3	51.1	0.3%	± 7.0
$120 < \theta < 150$	2150.1	51.0	9.4	0.4%	± 0.4
$150 < \theta < 180$	600.1	6.1	1.1	0.2%	± 0.05
Total					±42.7

Total BG uncertainty (① and ②)= ±281.7
(Total BG uncertainty)/(Abs+CX events) = 5.23%

(III) Detector response

① Charge distribution (in progress)



Fluctuate these parameters

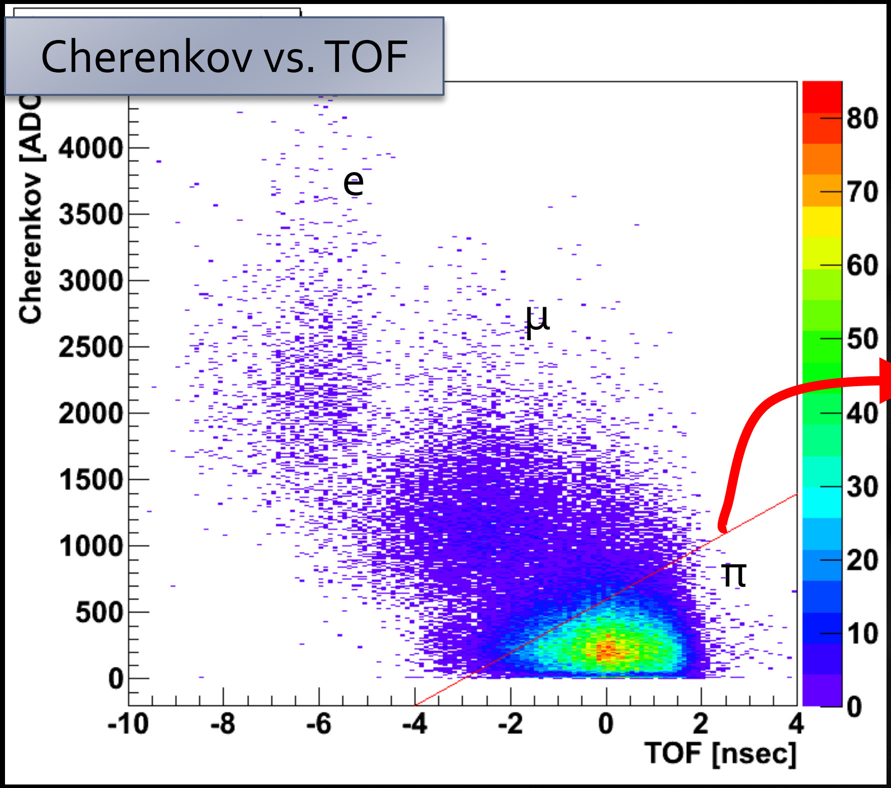
Energy->PE in MC:

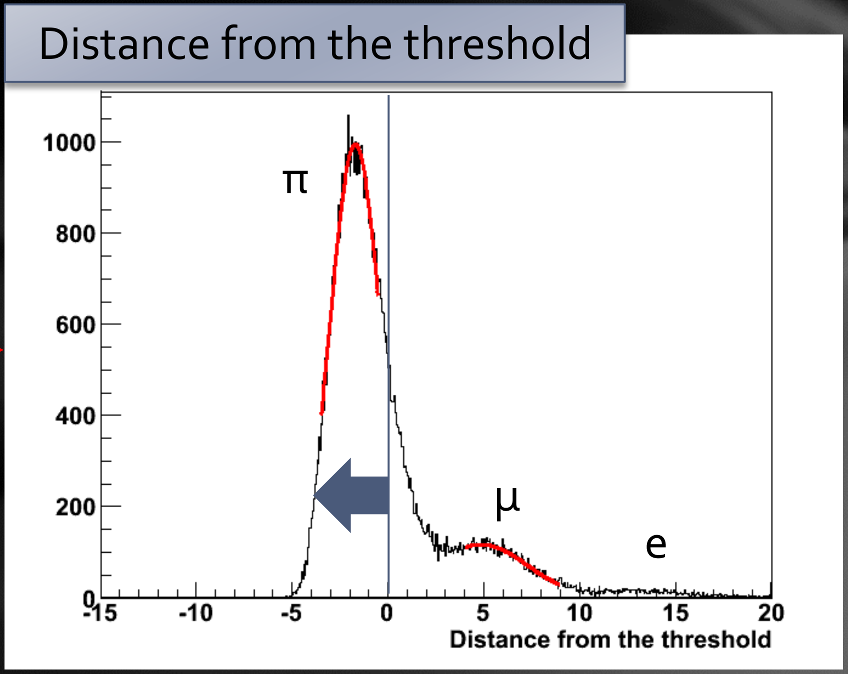
```
PE = Edep*Cony
PE += PMTRES*sqrt(PE)*Gaus(μ=0,σ=1)
for(int ipe = 0 ; ipe < np ; ipe++ )
    PE += h1pe->GetRandom()
```

- Tune charge distribution mean/sigma
- Fluctuate them within error
- Codes are ready, needs few more days for processing

(IV) Beam related errors

① μ/e contamination



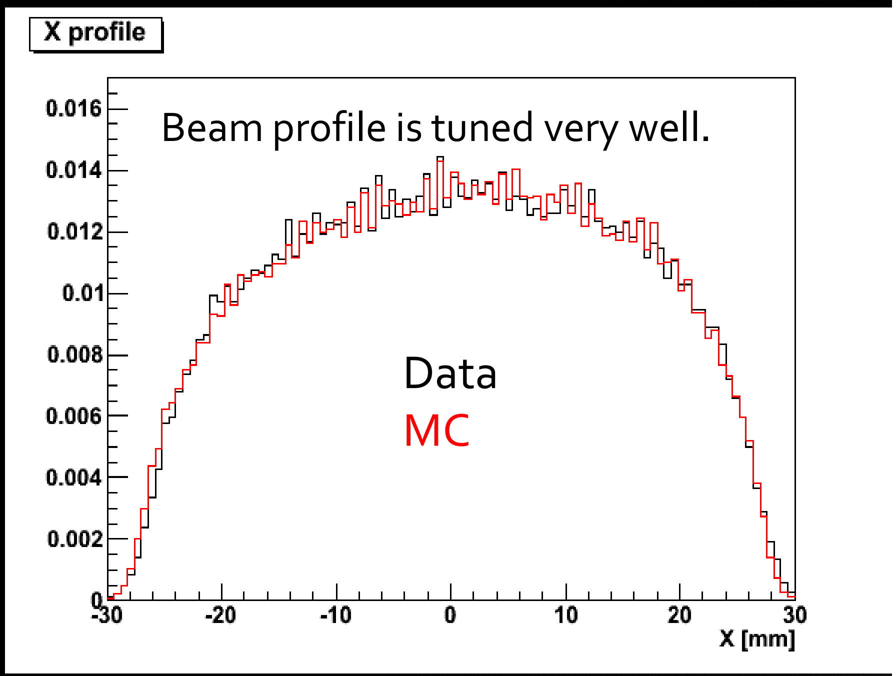


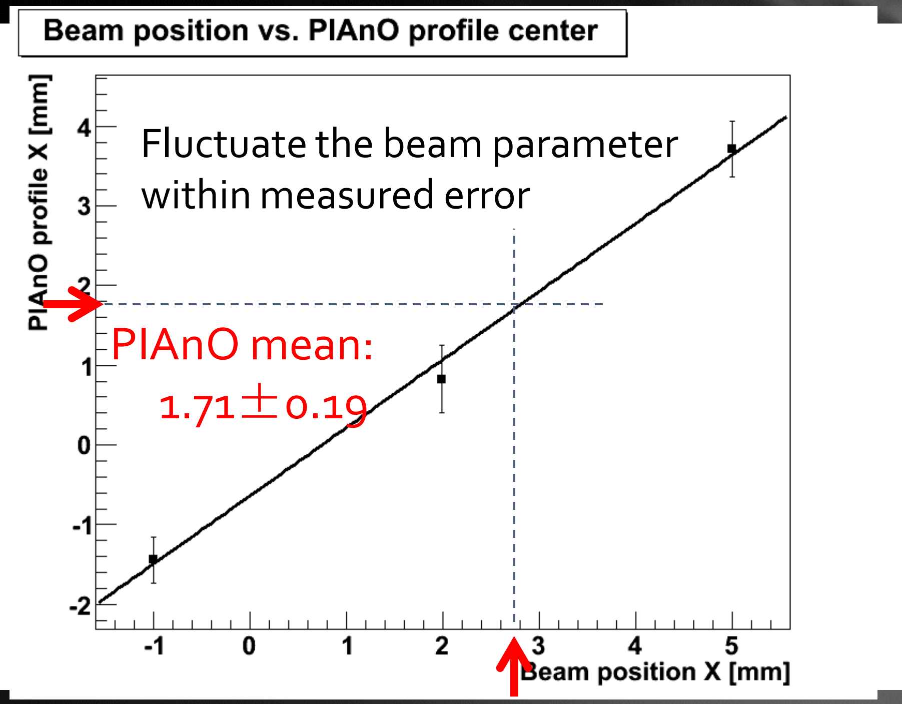
μ contamination: 0.43%

Also, if the pion decay just before entering PIAnO, that event will not be correctly identified. If I generate the pion at S0, 0.84% of incident tracks will be the decay muons. Let's assign that as this number as the systematic error.

(IV) Beam related errors

③ Beam profile





Beam pos mean:
2.745±0.222

Fluctuate the beam parameters within error
→ Do the same cross section measurement
→ Systematic error = $\sigma_{nomi}/\sigma_{fluc}$

(IV) Beam related errors

③ Beam profile

	Change
Mean $+\sigma_X$	-0.48%
$-\sigma_X$	-1.50%
$+\sigma_Y$	+0.35%
$-\sigma_Y$	2.08%

	Change
Sigma $+\sigma_X$	0.79%
$-\sigma_X$	0.36%
$+\sigma_Y$	1.21%

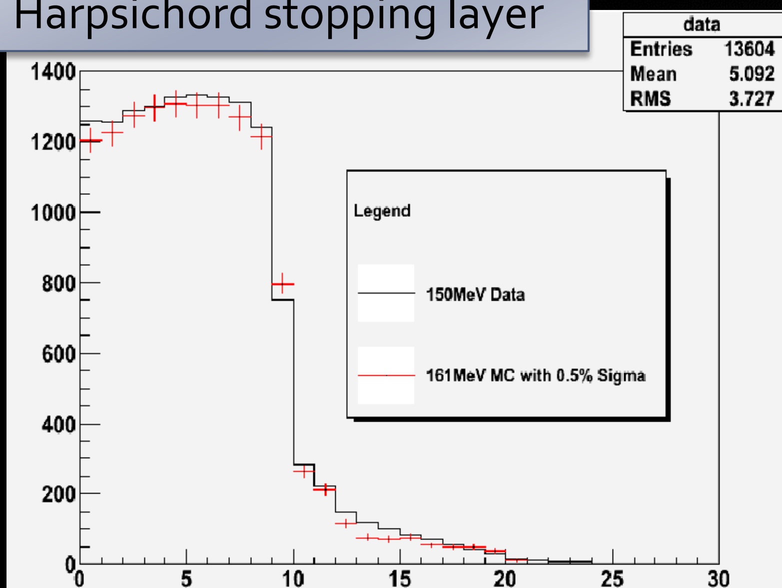
Total error: 2.56%

Total error: 1.43%

(IV) Beam related errors

③ Beam momentum

Harpsichord stopping layer



At 250MeV/c setting:
261.12±8.14 [MeV/c]

As we did for beam profile error, fluctuate the incident pion momentum.

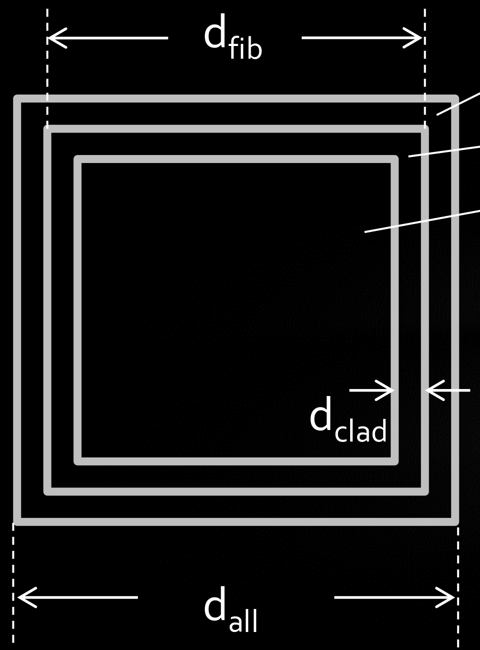
$$\sigma_{Data} = \sigma_{MC} \times \frac{(N_{Sel\_Data} - N_{Sel\_BG\_MC})}{N_{Sel\_AbsCX\_MC}}$$

These numbers will change

	Cross section ratio
+σ	+3.35%
-σ	-3.97%

Consistent with expected cross section change from past experiment: ~3%

(V) Number of target nuclei



Measured values for calculation

Core: Polystyrene (C_8H_8)
density ρ_{core} = 1.05 ± 0.005 [g/cm³]
Clad : PMMA ($C_5H_8O_2$)
density ρ_{clad} = 1.19 ± 0.005 [g/cm³]
Coat: PMMA ($C_5H_8O_2$) 68.7% + TiO_2 31.3%
density ρ_{core} = 2.14 ± 0.02 [g/cm³]

Fiber width d_{fib} = 0.1493 ± 0.0013 [mm]
Clad width d_{clad} = d_{fib}*0.02 ± d_{fib}*0.002 [mm]
Fiber + Coat width d_{all} = 0.1520 ± 0.0016 [mm]

Estimated weight (12fibers) = 17.33 ± 0.08 [g]
Measured weight (12fibers) = 17.35 ± 0.15 [g]

Measured total weight agrees with density*volume.

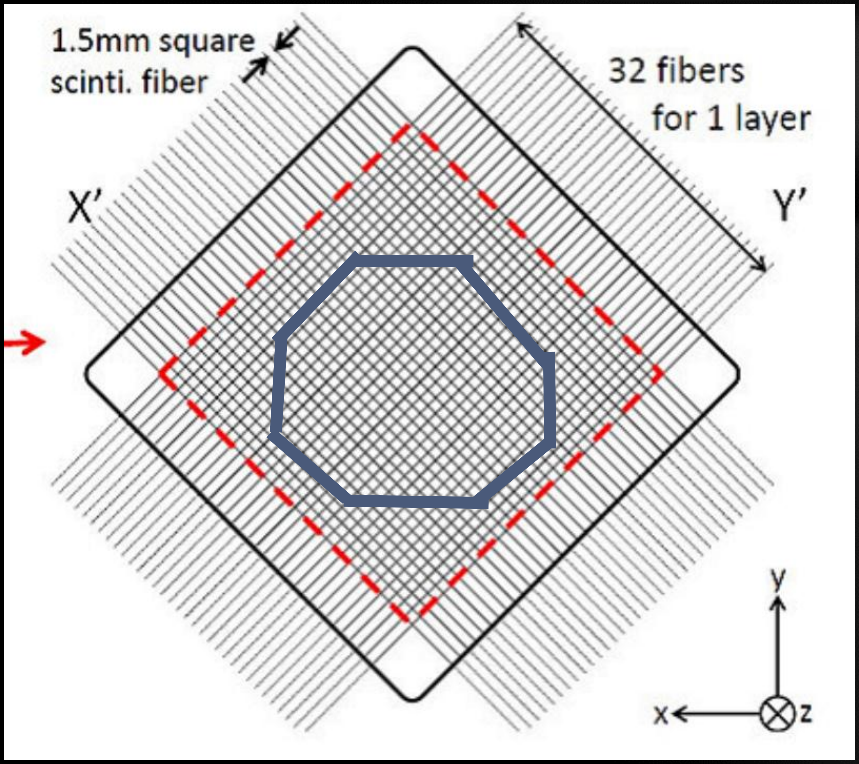
(V) Number of target nuclei

(i) Error for number of C

Number of all nuclei are calculated from all fibers in FV. The uncorrelated errors are canceled out.

Fiducial volume ~ 24fiber*17layers = 408fibers

→ (Total frac error) ~ (Error per fiber)/sqrt(408)



Actual calculation is done by calculating number of nuclei for each fiber in FV.

Total:

C: 1.65 ±0.008 [10^{24}]

H: 1.73± 0.008

O: 0.07± 0.004

Ti: 0.01± 0.002

Error for number of C:

0.49%

(V) Number of target nuclei

(i) Error for number of O, Ti

Cross section calculation formula:

$$\sigma_{Data} = \sigma_{MC} * \frac{N_{AbsCX\_Dat}}{{}^{a}N_{AbsCX\_MC}}$$

Actually, number of observed events includes interaction on O and Ti.

	N_{Nuclei} [10^{22}]	Cross section (MC)	Fraction of events	Cross section (past exp.)
C	4.74±0.22	191.2 [mbarn]	0.905	~ 213.3 ± 24.9
H	5.05±0.32	0	0	0
O	0.27±0.03	267.3	0.072	~ 258.8 ± 40.7
Ti	0.03±0.02	764.8	0.023	~ 580.0 ± 65.4

C: Ashery et al.
O: Ingram et al.
Ti Abs: Nakai et al.
Ti CX: Ashery et al. (see bkup slide)

$$\sigma_{Data} = \sigma_{MC} * \frac{N_{AbsCX\_Data} - N_{O+Ti}}{N_{AbsCX\_MC} - N'_{O+Ti}}$$

Error of this: 1.11%
→ 1.14% in total