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Measurement of Momentum Spectrum of Cosmic Rays for Precise Muon Radiography

The J-PARC T60 experiment is performed to study the low energy neutrino nucleus interactions using an emulsion-based detector at J-PARC.

Using this detector, we have observed cosmic-ray particles and performed the momentum measurements at J-PARC.

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Toho University, Nihon University and Nagoya University

Introduction

1) Muon radiography is a technique, by using natural cosmic-ray muons, to investigate the inside of a large structure that X-ray or neutrons cannot penetrate.
2) Among various particle detectors, nuclear emulsion films have an advantage of unbeatable resolution for position and slope measurements of charged particle tracks with no dead time.
3) Furthermore they are compact and can be used in remote and harsh environments because they do not require power supply.
4) Therefore it can be said that emulsion films are a sort of ultimate innovative-energy-saving particle detectors.
5) To obtain precise material density of the structure, a precise muon flux with momentum spectrum has to be known beforehand.
6) Furthermore, momentum measurement of cosmic-ray particles is effective to reduce background due to low energy particles, such as electrons/positrons, and protons.
7) Momentum measurement in emulsions is thus important.

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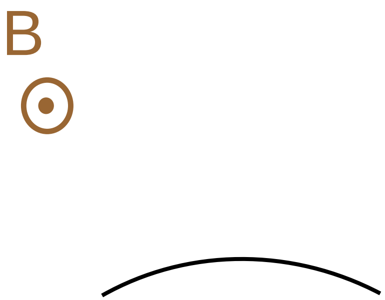
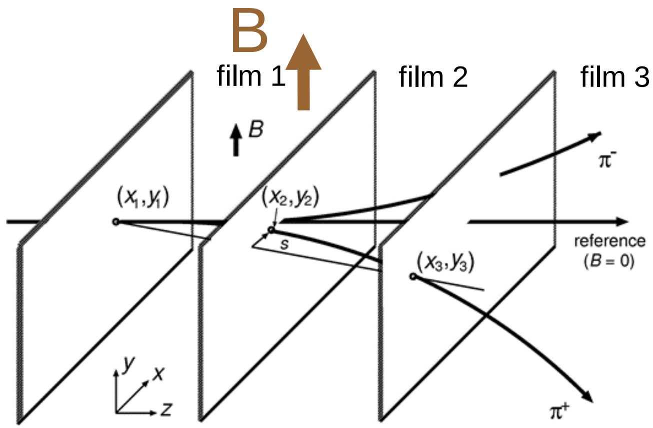
Methods of momentum measurement in emulsion detectors

1) Emulsion Spectrometer in a magnetic field





$$p = e\,B\,r = e\,B \cdot \frac{L}{\theta}$$

$$s = r\left(1 - \cos\frac{\theta}{2}\right) = 2\,r\,\sin^2\frac{\theta}{4}$$

$$= \frac{r\,\theta^2}{8} = \frac{r}{8}\cdot\left(\frac{eBL}{p}\right)^2 = \frac{eBL^2}{8p}$$

If B is measured in Tesla, L in meters and p in GeV/c, the sagitta is given by

$$s = \frac{0.3\,B\,L^2}{8p}$$

The determination of sagitta requires at least three position measurements, x_1, x_2 and x_3.

Trajectory of a charged particle in a magnet

$$s = x_2 - \frac{x_1 + x_3}{2}$$

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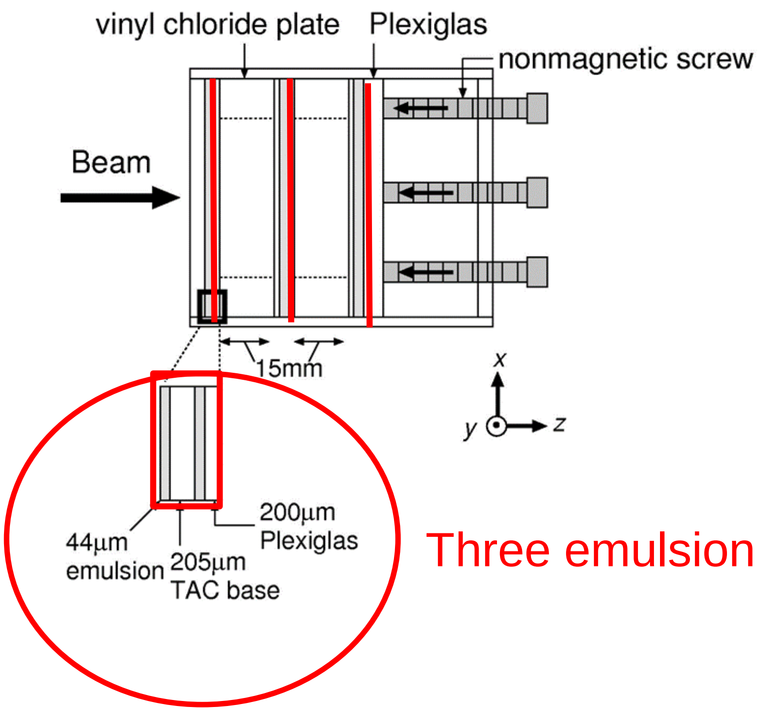
Methods of momentum measurement in emulsion detectors

1) Emulsion Spectrometer in a magnetic field

Intrinsic performance of the emulsion spectrometer was already demonstrated by a test beam experiment performed at KEK.



Three emulsion films

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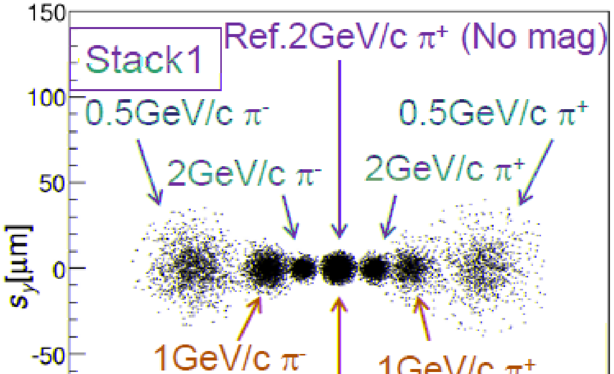
Methods of momentum measurement in emulsion detectors

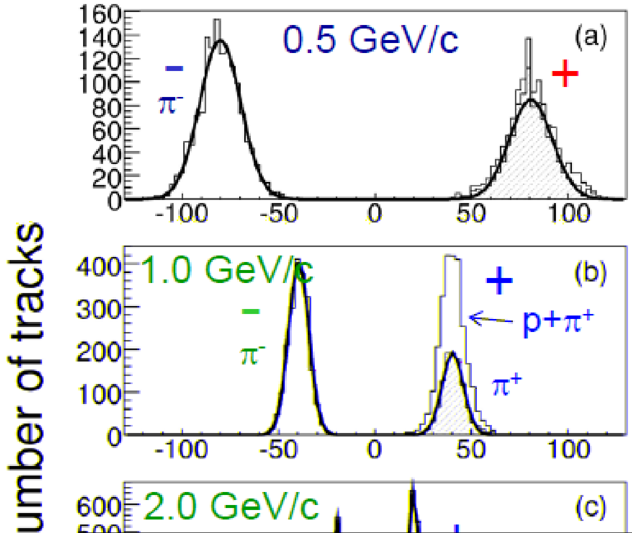
1) Emulsion Spectrometer in a magnetic field

Results from the test beam experiment

C. Fukushima et al., Nucl. Instr. and Meth. A 592 (2008) 56-62.

2D sagitta values of 0.5, 1.0 and 2.0 GeV/c charged particles





0.5 GeV/c π^+ and π^-

1.0 GeV/c π^+ and π^-

[redacted]

2.0 GeV/c π^+ and π^-

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Methods of momentum measurement in emulsion detectors

1) Emulsion Spectrometer in a magnetic field

This test beam experiment and its simulation study clearly demonstrated that the Compact Emulsion Spectrometer(CES) has excellent intrinsic performance, where the accuracy of track position measurement is about 1 μm.

Therefore, CES can be widely used in a variety of experiments.
However uniform magnetic field in a relatively large volume may be a limitation for practical use. And also, there are some practical problems which may deteriorate its intrinsic performance in each case.

Fabrication of emulsion stacks as Compact Emulsion Spectrometer(CES)

- Planarity of emulsion films
- Deformation of emulsion films
- Alignment among emulsion films

→ Various R&D and tests are ongoing e.g. SHiP test beam experiments.

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These problems will be overcome in the near future.

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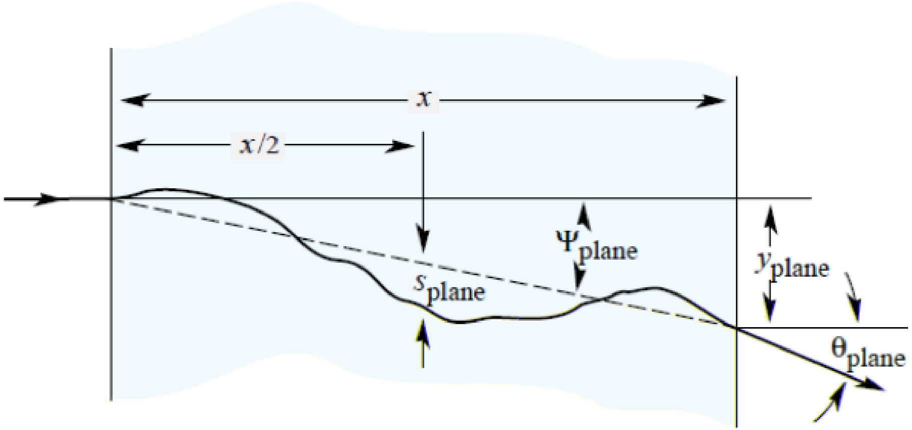
Methods of momentum measurement in emulsion detectors

2) Multiple Coulomb scattering method (the angular method)

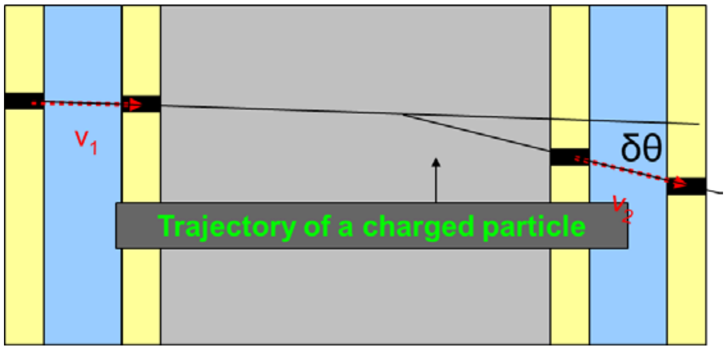


Multiple scattering distribution is well represented by a Gaussian distribution with an rms width:

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

C. Patrignani *et al*. (PDG), Chin. Phys. C, 100001 (2016).

In a real experiment, the track angle measurements are repeated for many films.



- Distribution of many measured angle differences $\delta\theta$
- σ (rms width) of the distribution is given by the above θ_0

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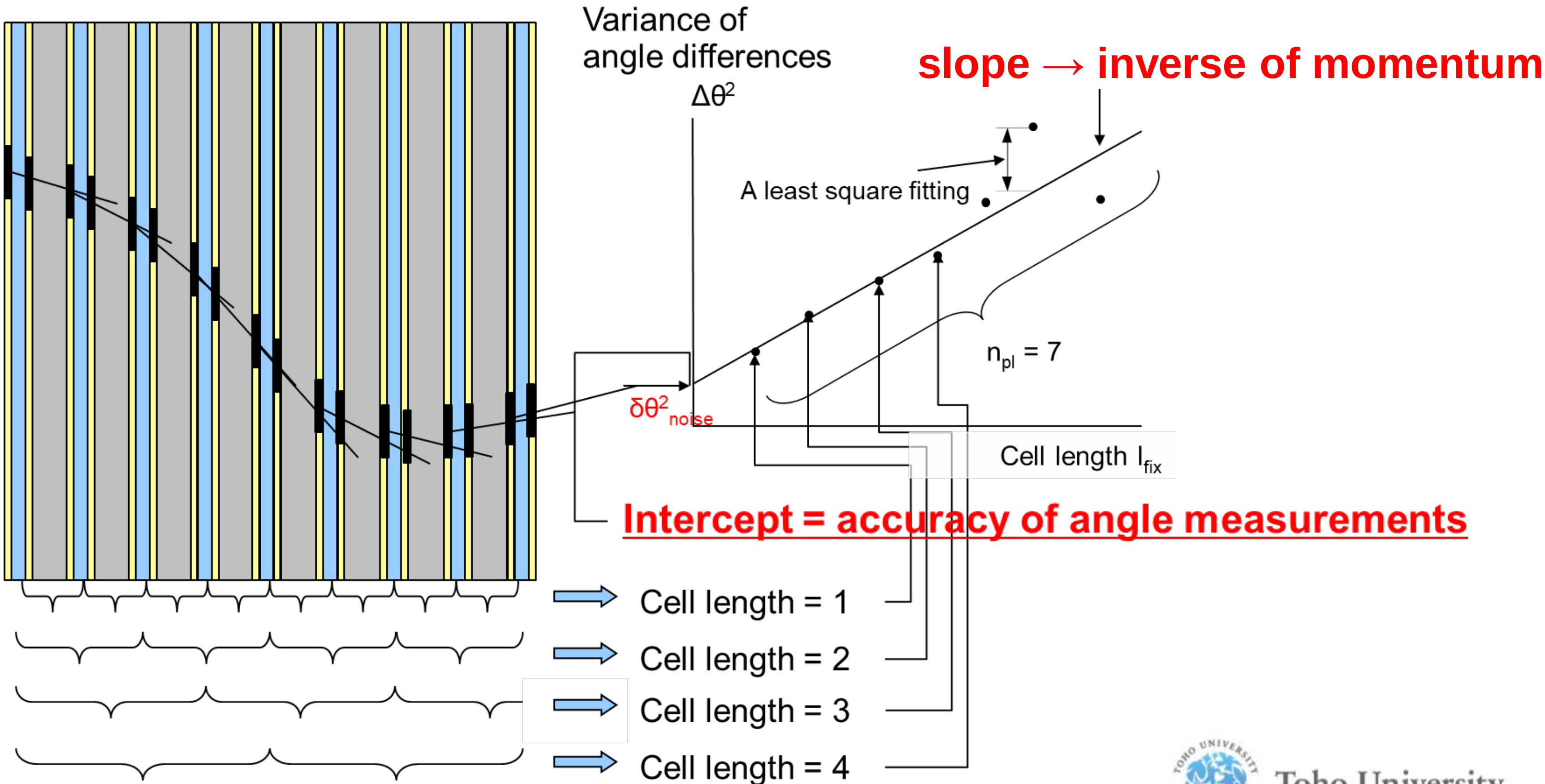
Methods of momentum measurement in emulsion detectors

2) Multiple Coulomb scattering method (the angular method)



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Methods of momentum measurement in emulsion detectors

2) Multiple Coulomb scattering method (the angular method)

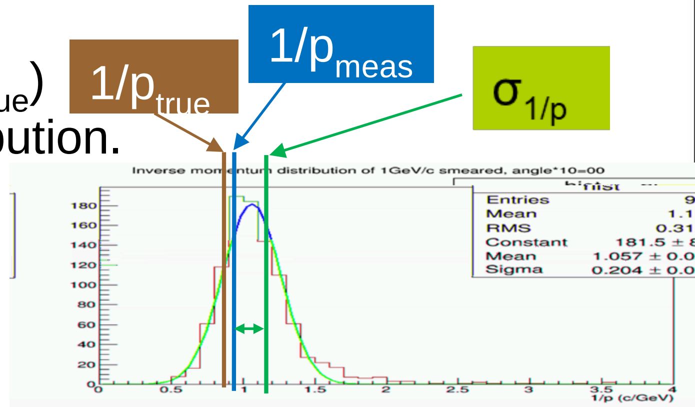
Multiple scattering distribution is well represented by the Gaussian distribution:

$$\theta_0 = \frac{13.6(MeV)}{p\beta} z \sqrt{\frac{x}{X_0}} \left\{ 1 + 0.038 \ln\left(\frac{x}{X_0}\right) \right\}$$

Since each angle difference corresponds to an estimate of 1/p, the distribution of 1/p estimates for each track is approximately given by the Gaussian distribution.

Systematic error is defined by $(1/p_{meas} - 1/p_{true}) / (1/p_{true})$ where $1/p_{meas}$ is fitted mean of the measured 1/p distribution.

Statistical error is defined by (fitted σ)/ $(1/p_{true})$



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Study of multiple Coulomb scattering methods
(the angular method) for momentum measurement

with a Geant 4-based Monte Carlo simulation

MC study

T. Matsuo

Incident beam: 0.1, 0.2, 0.5, 1.0, 1.5, 2.0, 3.0 GeV/c muons with slopes of $\tan\theta_x$ = 0, 0.5, 1.0, 1.5

Target and detector: an ECC brick which is made of 40 steel plates of 0.5mm thickness interleaved with 41 emulsion films of two 60 μm-thick emulsion layers on both sides of a 180 μm-thick polystyrene base

Statistics: $10^3 - 10^5$ muons each

Smearing: $\tan\theta_x$= 0.00212, 0.00362, 0.00513, 0.00663
for $\tan\theta_x$ = 0, 0.5, 1.0, 1.5, respectively
$\tan\theta_y$= 0.00212

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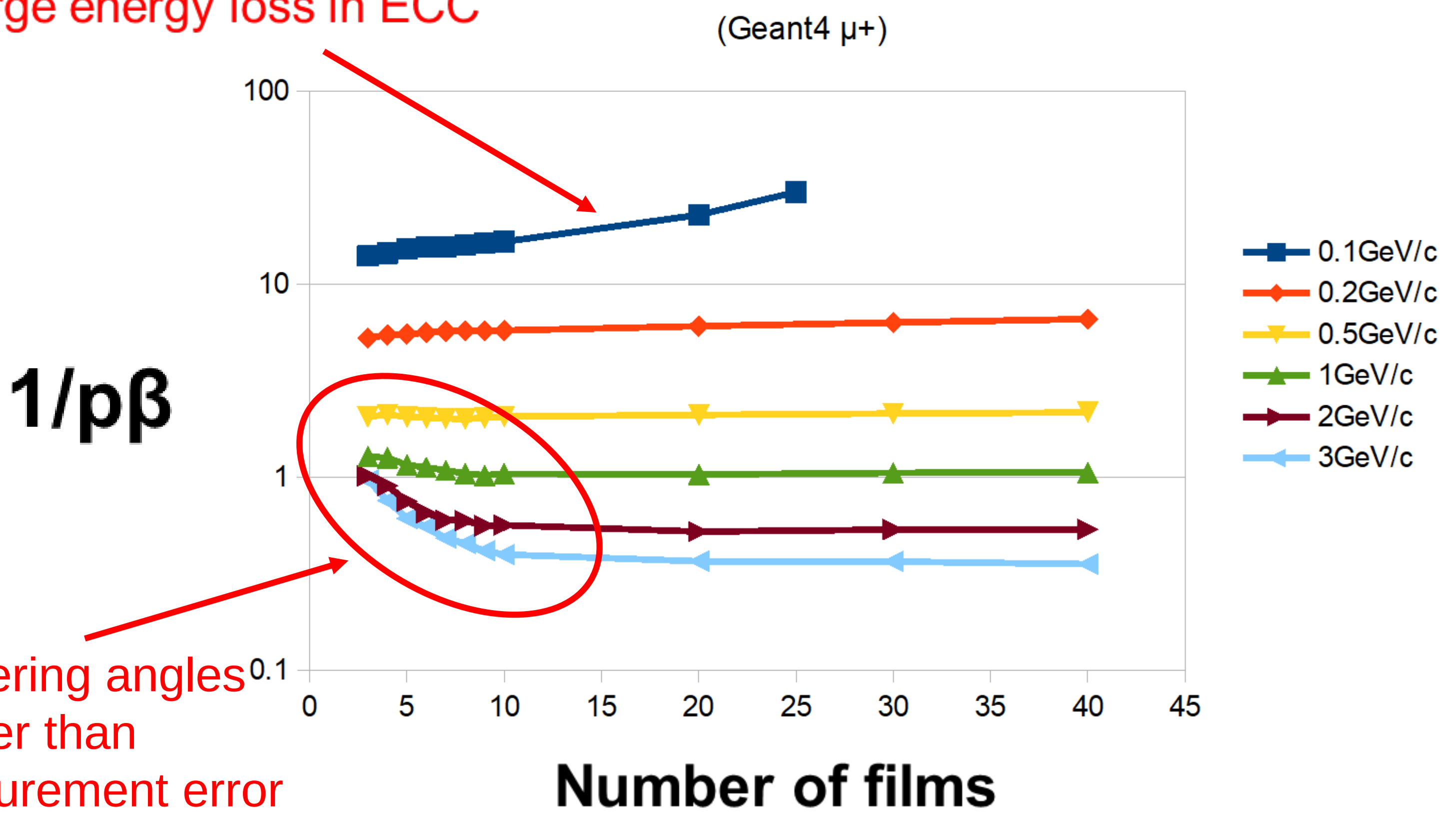
Study of multiple Coulomb scattering methods
(the angular method) for momentum measurement
with a Geant 4-based Monte Carlo simulation

MC study

T. Matsuo

1/pβ vs. number of films

Large energy loss in ECC



Scattering angles smaller than measurement error

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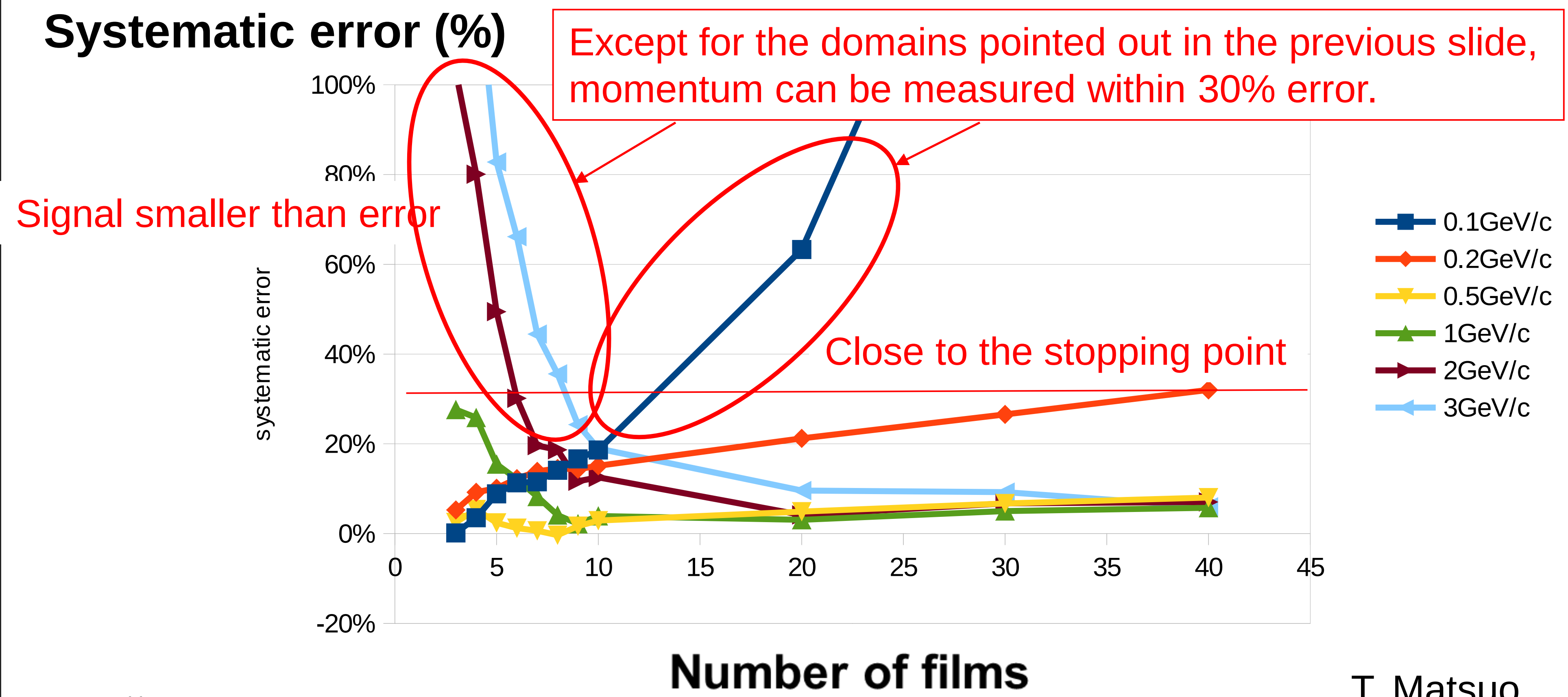
Study of multiple Coulomb scattering methods
(the angular method) for momentum measurement
with a Geant 4-based Monte Carlo simulation

MC study

Systematic error vs. number of films



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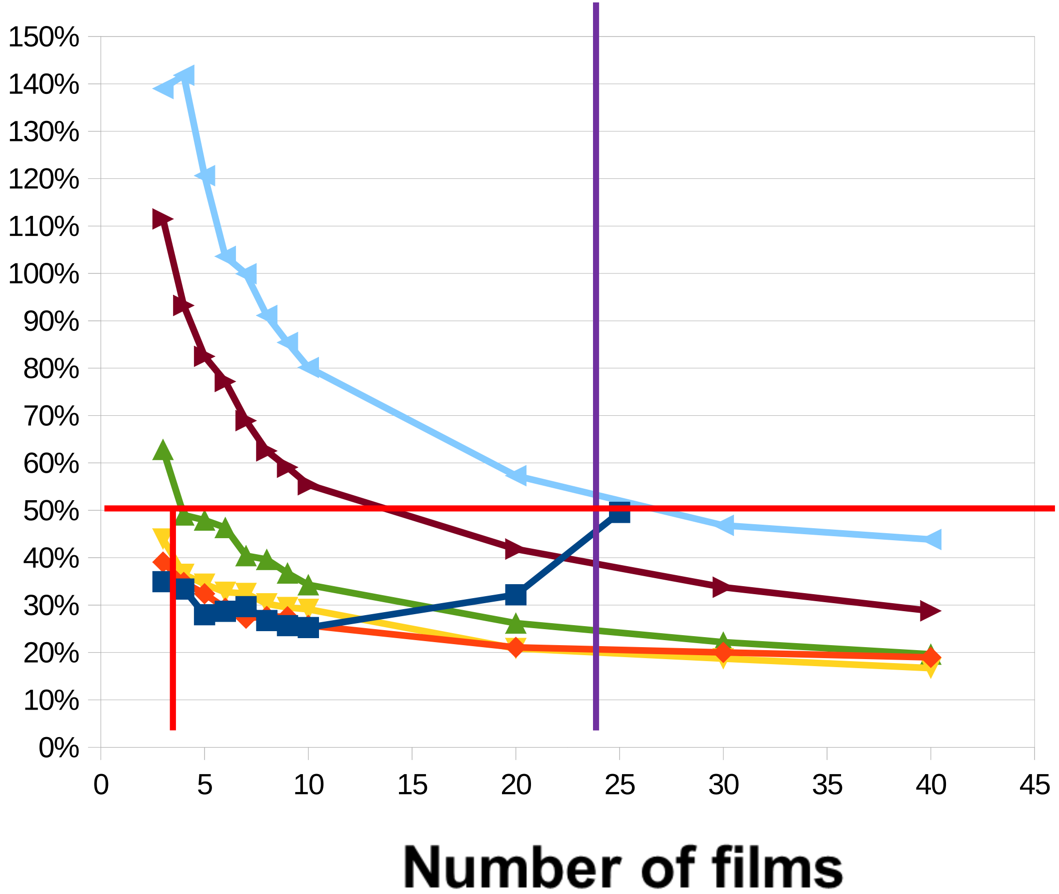
Study of multiple Coulomb scattering methods
(the angular method) for momentum measurement
with a Geant 4-based Monte Carlo simulation

MC study

Statistical error vs. number of films



- Using 23 films,
Momentum can be measured within 50% error for 0.1 – 2 GeV/c

- Using only 3 films,
momentum can be measured within 50% error for 0.1–0.5GeV/c.

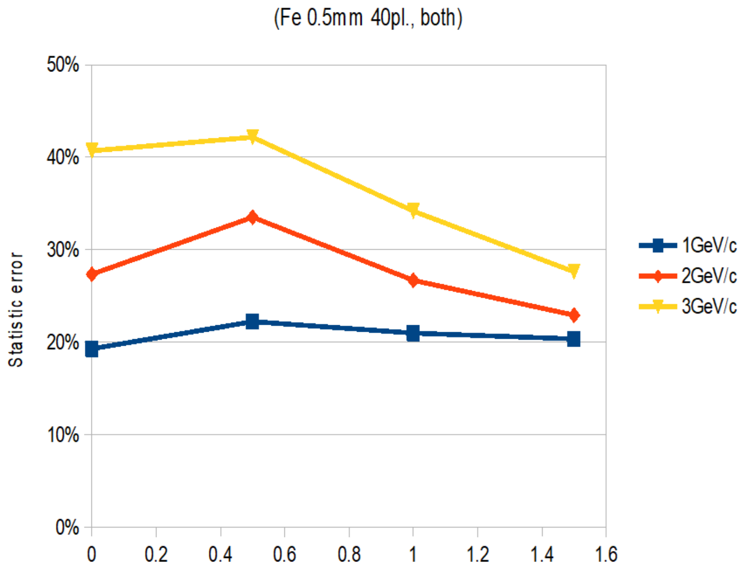
T. Matsuo
Toho University

Study of multiple Coulomb scattering methods
(the angular method) for momentum measurement
with a Geant 4-based Monte Carlo simulation

MC study

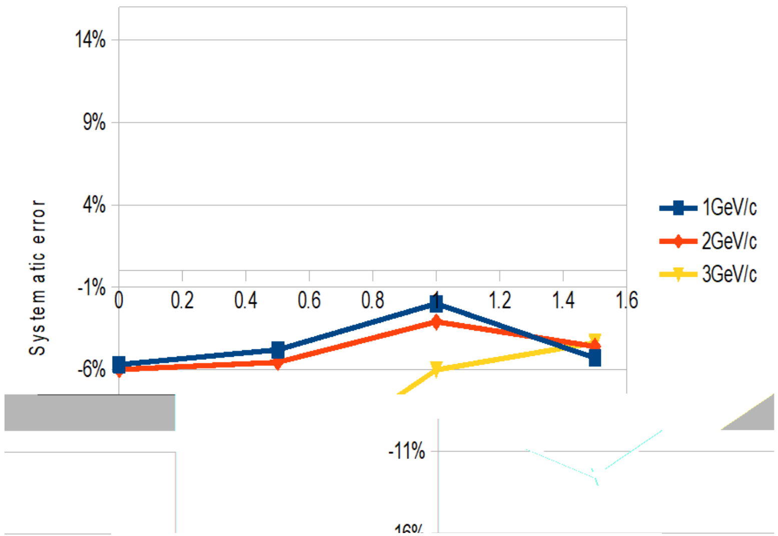
Statistical and Systematic errors vs. incident slopes

Statistical error (%)



Incident slope (|tan θ|)

Systematic error(%)



Incident slope (|tan θ|)

For incident slopes of tan theta = 0 to 1.5, changes of both statistical and systematic errors are small (less than 10%).

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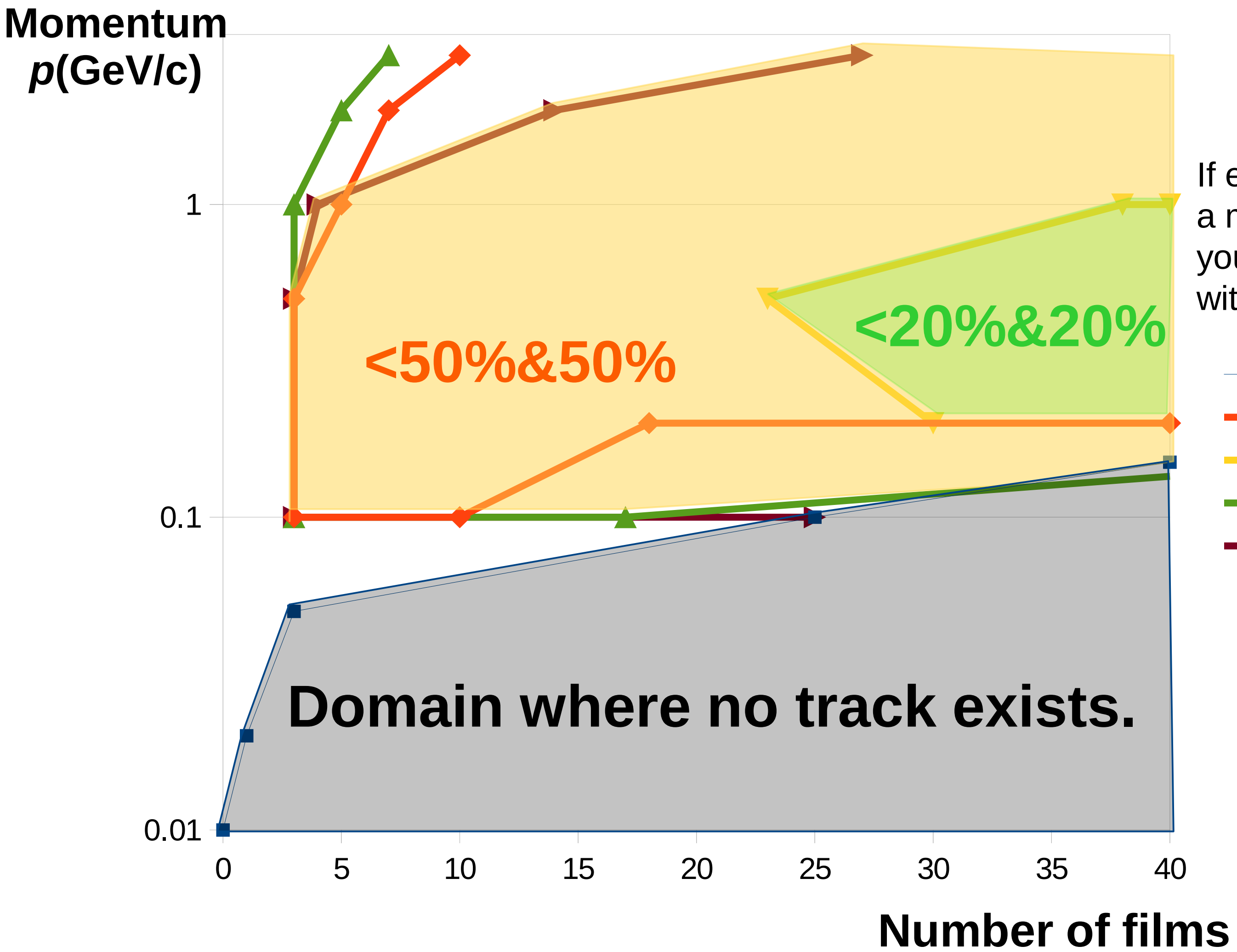
Domain where *p* can be measured with a certain accuracy in a plot of *p* vs. number of films



Preliminary

MC study

If enough films can be used for a moderate momentum particle, you can estimate its momentum with an accuracy less than 20%

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The J-PARC T60 experiment (NINJA)

Neutrino **I**nteraction research with **N**uclear emulsion and **J**-PARC **A**ccelerator

The J-PARC T60 experiment is performed to study the low energy neutrino-nucleus interactions using an emulsion-based detector at J-PARC.

T2K near detector hall

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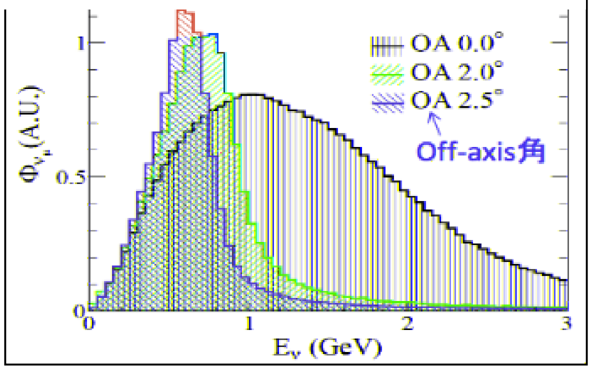
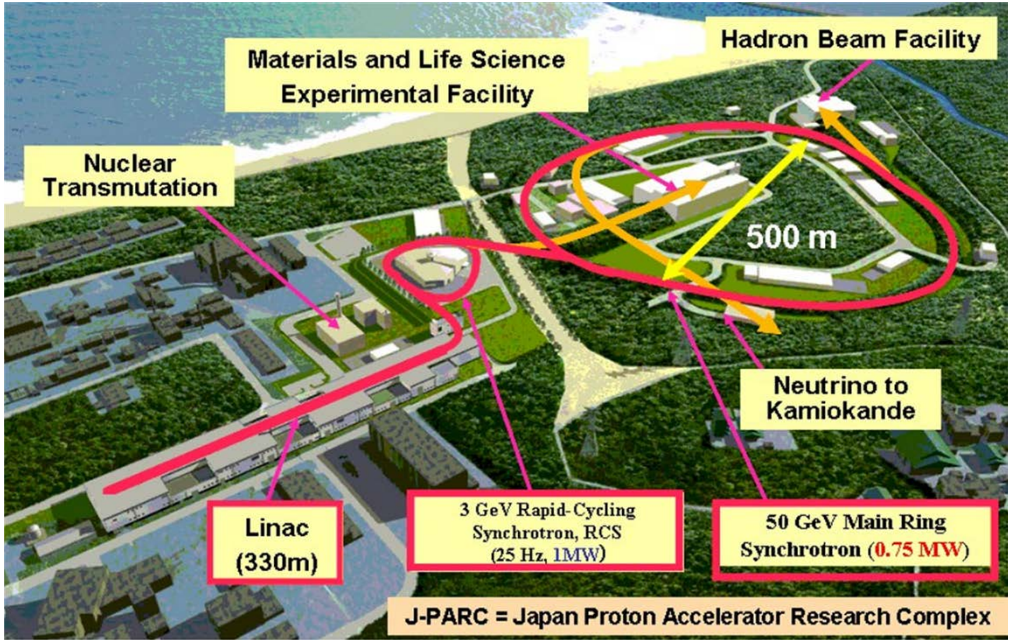
Neutrino energy spectrum

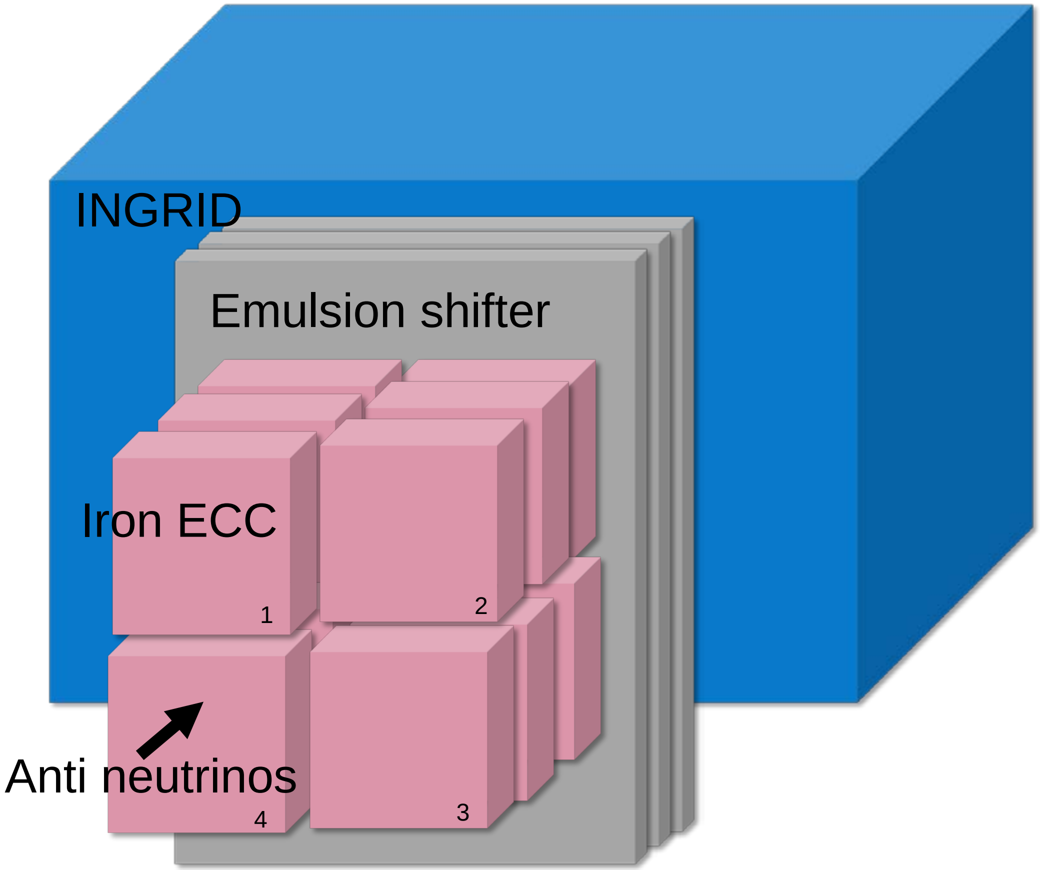




The J-PARC T60 experiment (NINJA)

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

The J-PARC T60 experiment is performed to study the low energy neutrino nucleus interactions using an emulsion-based detector at J-PARC.



Detector Run: Jan.31 – May 27, 2016
Anti-neutrino beam: 4 * 10^{20} POT
On Axis in the T2K near detector hall

Structure of ECC brick
25cm long * 25cm wide
22 0.5mm-thick iron plates
interleaved with 23 emulsion films
12 ECC bricks
Target mass: 60 kg in total

Expected number of events:
$\sim$ ν_μ
$\sim$ ν

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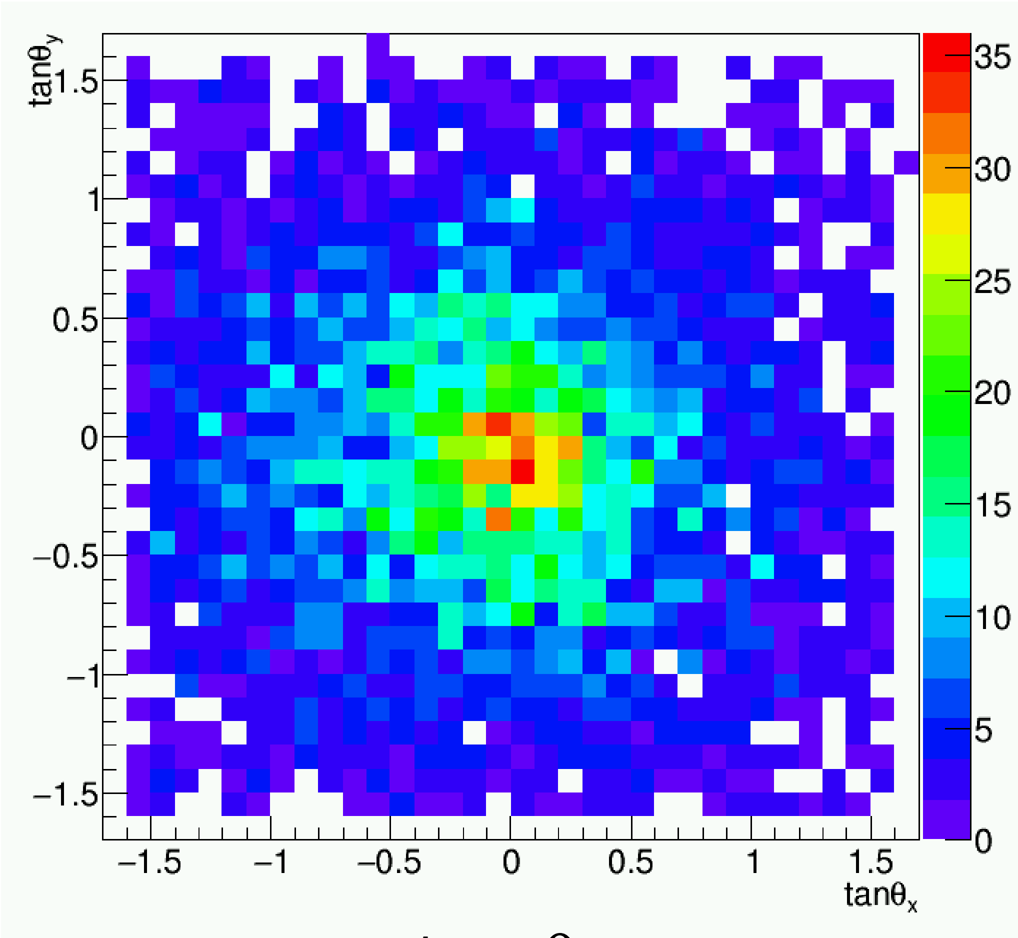
Slope distribution of real data in T60(NINJA)

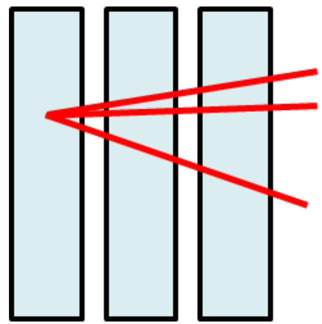
Secondary particles produced in ν-nucleus interactions

$\tan\theta_y$



$\tan\theta_x$

Experimental data



Secondary particles
from multi-prong vertices

H. Oshima
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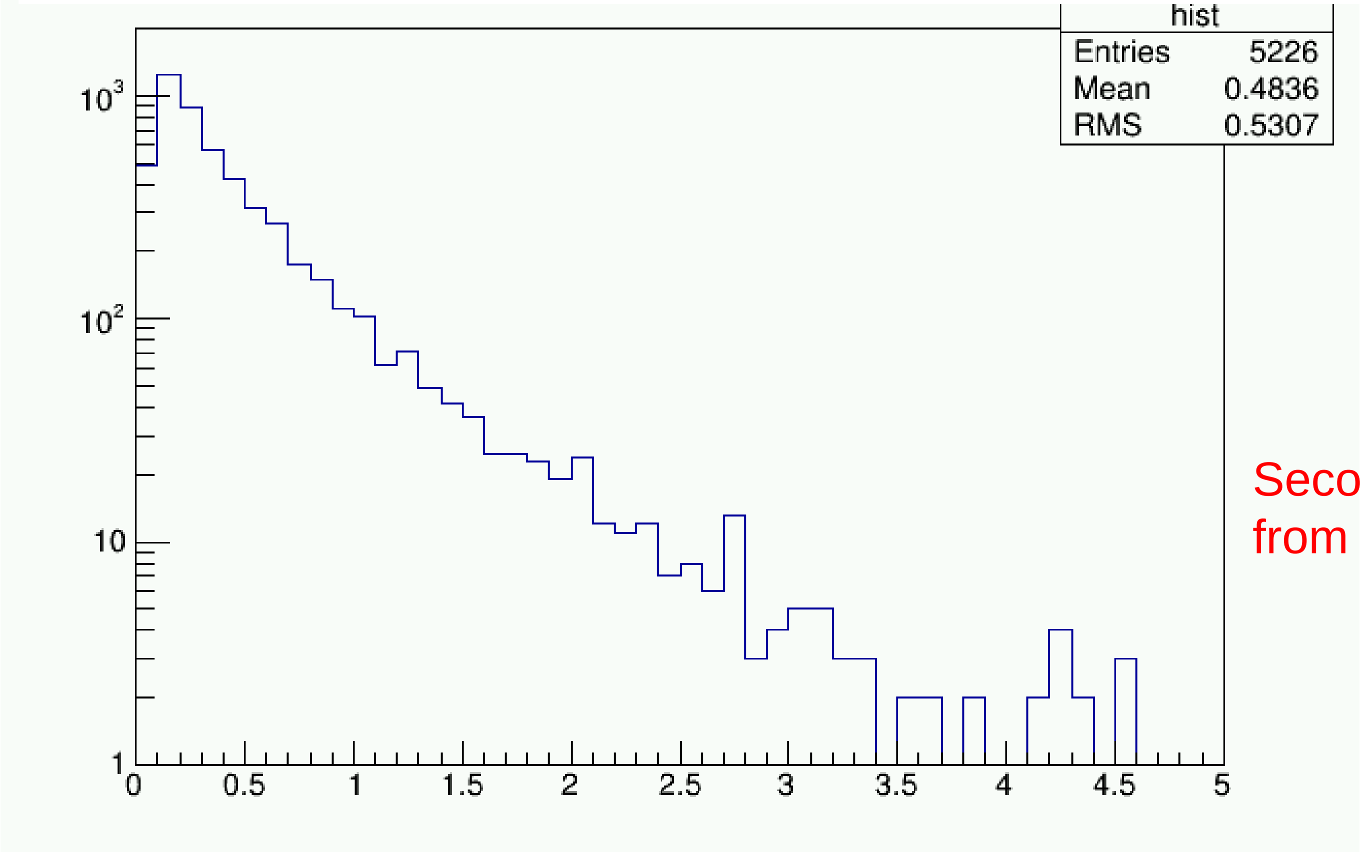
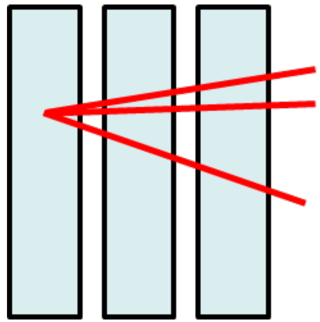
Momentum of real data in T60 (NINJA)

Secondary particles produced in ν-nucleus interactions



Momentum *p*(GeV/c)

Experimental data



Secondary particles
from multi-prong vertices

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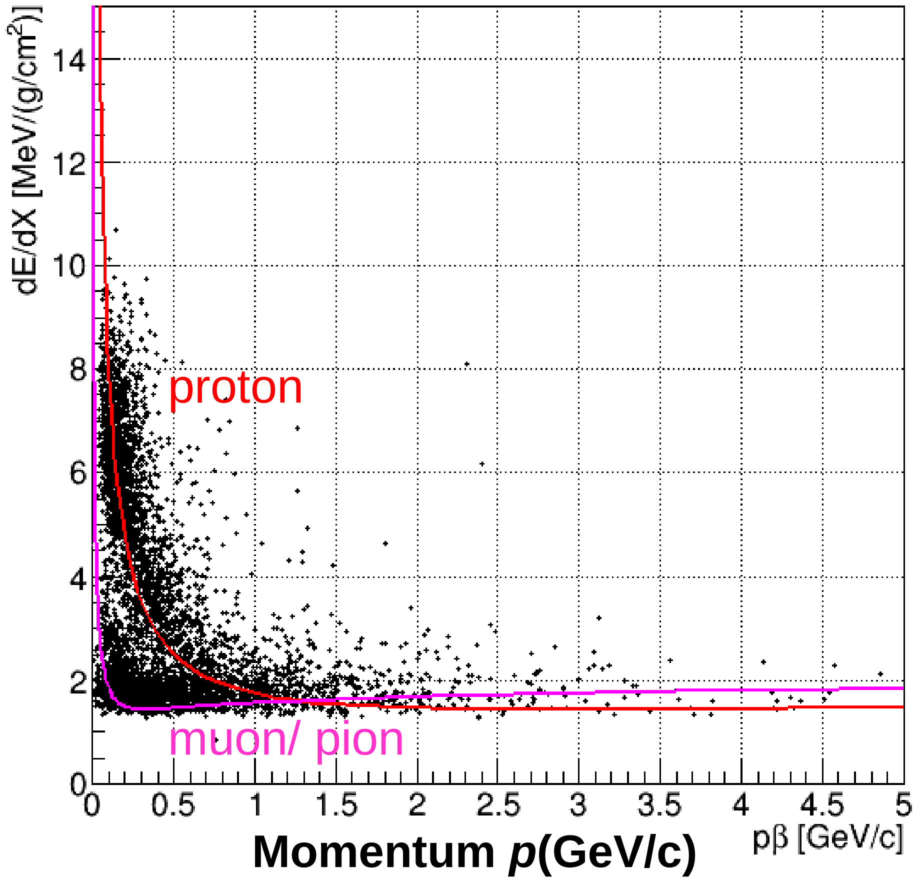
Momentum of real data in T60 (NINJA)

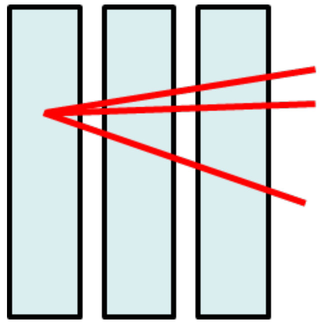
Secondary particles produced in ν-nucleus interactions

dE/dx



Experimental data

Mostly μ, π, proton



Secondary particles
from multi-prong vertices

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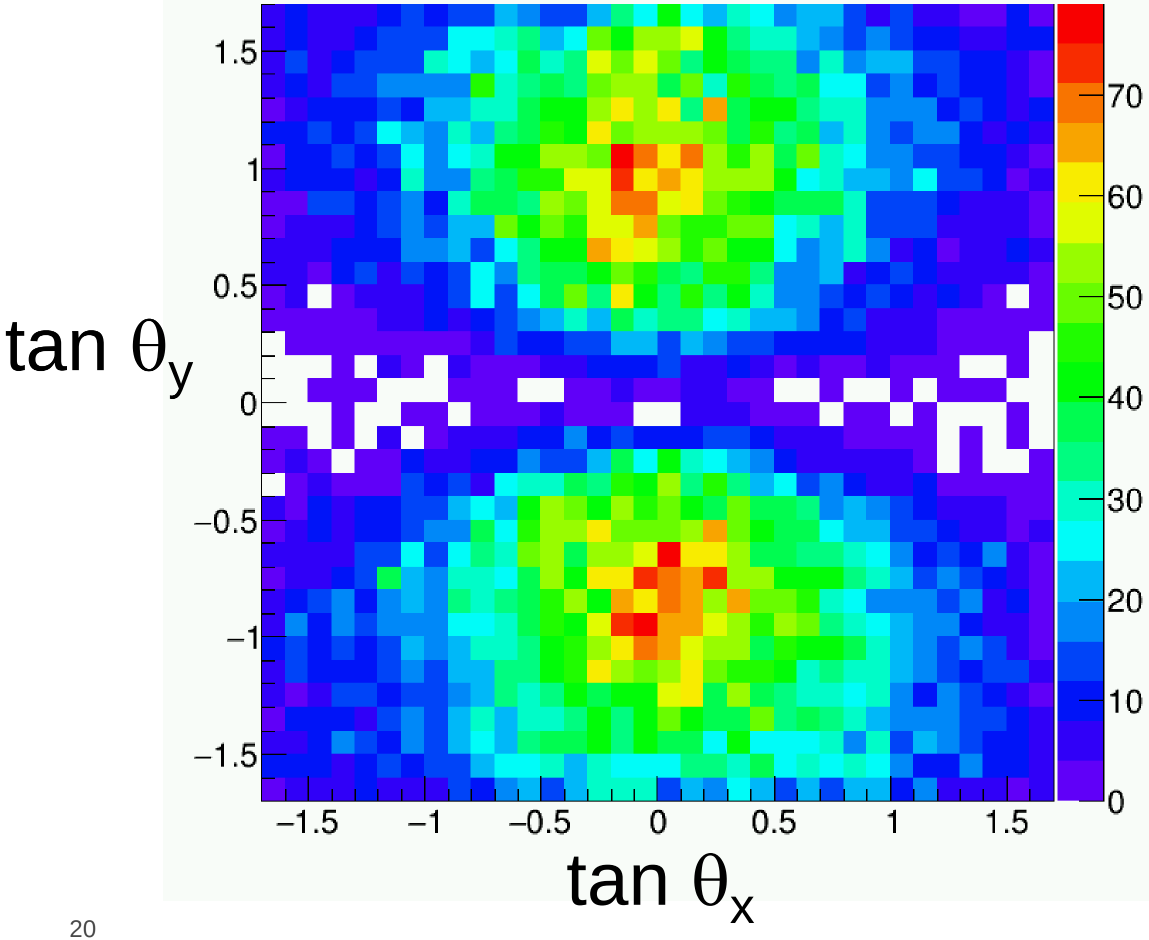
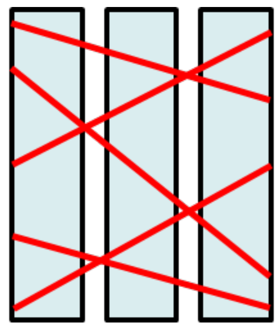
Slope distribution of real data in T60(NINJA)

Observed slope distribution of penetrating tracks

Mostly cosmic-ray particles



Experimental data



Particle tracks penetrating at least plural stacks

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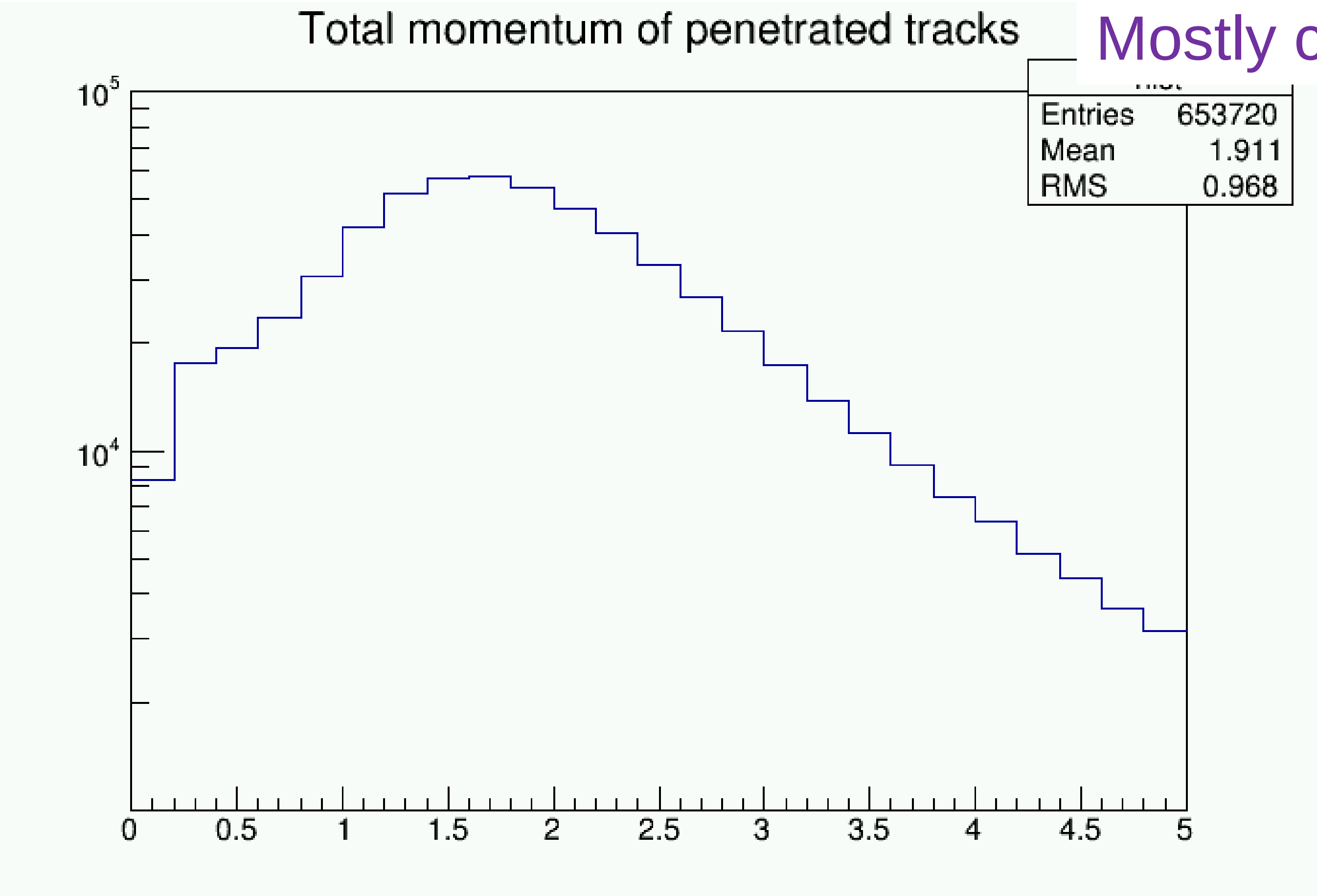
$p\beta$ distribution of real data in T60 (NINJA)

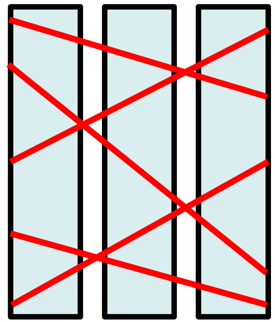
Observed momentum distribution of penetrating tracks

Mostly cosmic-ray particles



Momentum $p\beta$ (GeV/c)

Experimental data



Particle tracks penetrating at least plural stacks

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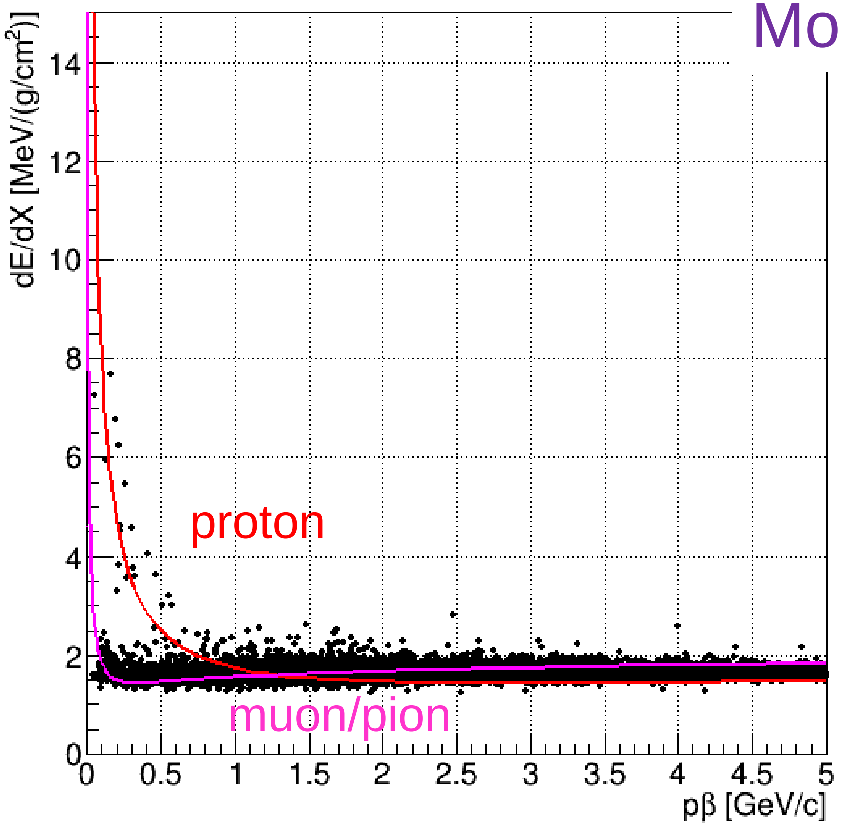
dE/dx vs. *pβ* of real data in T60 (NINJA)

Observed scatter plot *dE/dx* vs. *pβ* of penetrating tracks

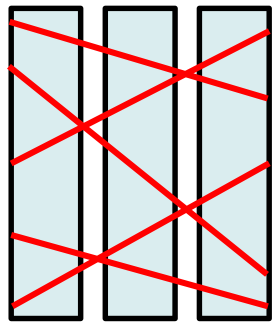
Mostly cosmic-ray particles

dE/dx



Momentum *pβ* (GeV/c)

Experimental data



Particle tracks penetrating at least plural stacks

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Summary and Outlook

- **We have studied momentum measurement by MCS (Angular method) in an ECC brick (0.5mm-thick iron plate ECC) using a Geant4-based MC simulation.**

MC study

- **By this MC study, the followings are found.**

  - For 0.1 to 2 GeV/c charged particles, momentum can be measured with an error less than 50% using 23 films (1 ECC stack in RUN6).

- **- For 0.1 to 0.5 GeV/c charged particles, momentum can be measured with an error less than 50% using only 3 films.**

  - For incident slopes of tanθ = 0 to 1.5, changes of both systematic and statistic errors are small (less than 10%).

- **We have applied this method to real data in J-PARC T60 experiment.**

  - Momentum measurement of secondary particles in ν-nucleus interactions, and penetrating muons (cosmic-ray particles).

- **If we can apply this method to real data in a test beam experiment, the above results with MC will be confirmed.**

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