Study of hadron interactions as background source in the OPERA experiment

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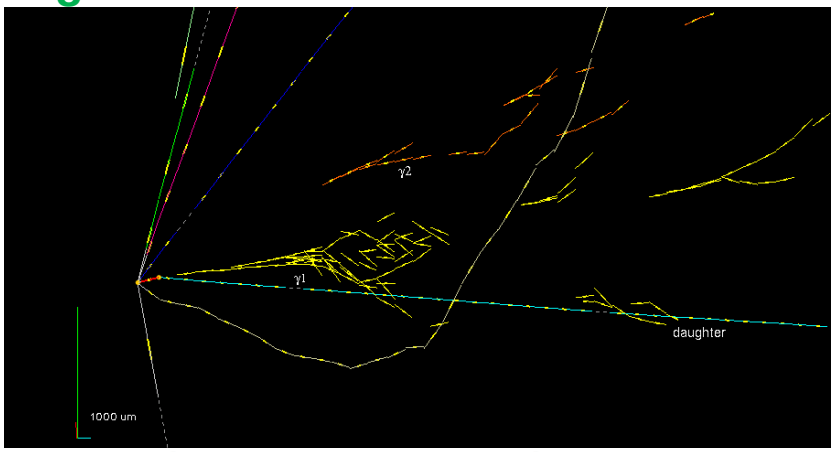
The OPERA experiment

（Oscillation Project with Emulsion tRacking Apparatus）

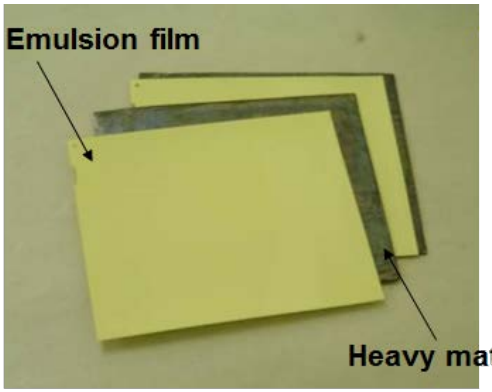
- The **OPERA** experiment was designed **to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode**, i.e., by detecting the τ leptons produced in charged current ν_τ interactions.
- The experiment took data from 2008 to 2012 in the CERN Neutrinos to Gran Sasso beam.
- Given the low background level and the **5 observed candidates**, **the discovery of a ν_τ appearance** in the CNGS neutrino beam has been reported with **a significance of 5.1 σ** [1].

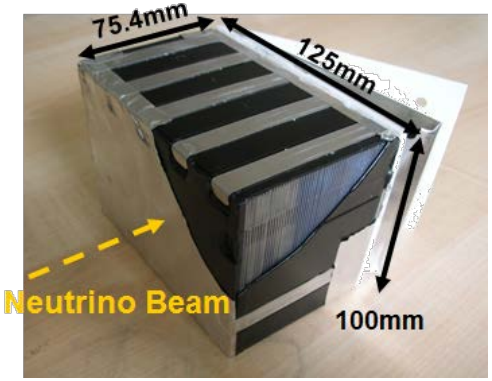


[1] N. Agafonova *et al.* (OPERA Collaboration): Phys. Rev. Lett. 115 (2015) 121802.

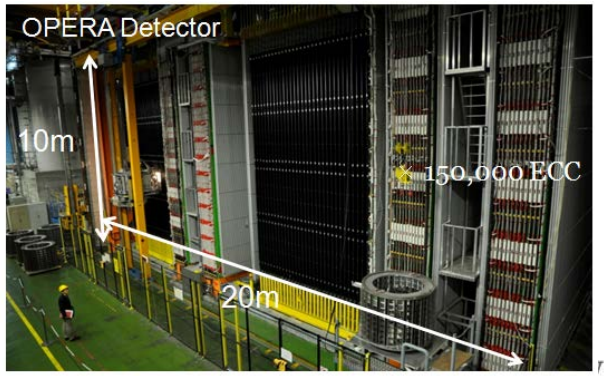
The OPERA detector

- In OPERA, τ **leptons** resulting from the ν_τ interaction are produced in target units called **ECC bricks** made of emulsion films interleaved with lead plates.
- The OPERA target contains **150000 of ECC bricks**, for a total mass of **1.25 kton**, arranged into walls interleaved with plastic scintillator strips.
- The detector is split into **two identical supermodules**, each supermodule containing a **target section** followed by a **magnetic spectrometer** for momentum and charge measurement of penetrating particles.
- **Real time information** from the scintillators and the spectrometers **provide the identification of the bricks** where the neutrino interactions



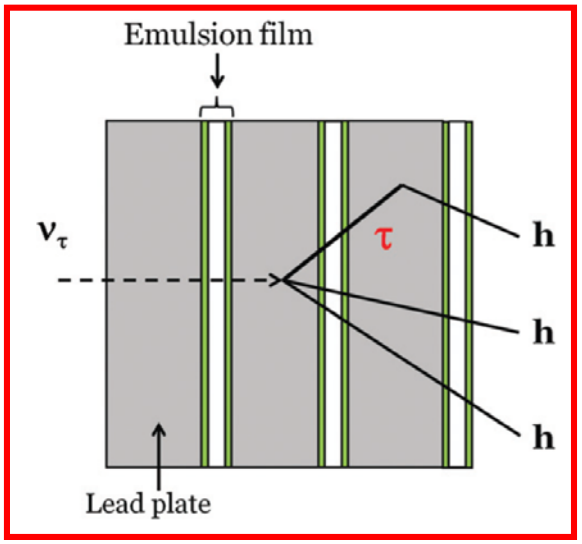


An ECC brick

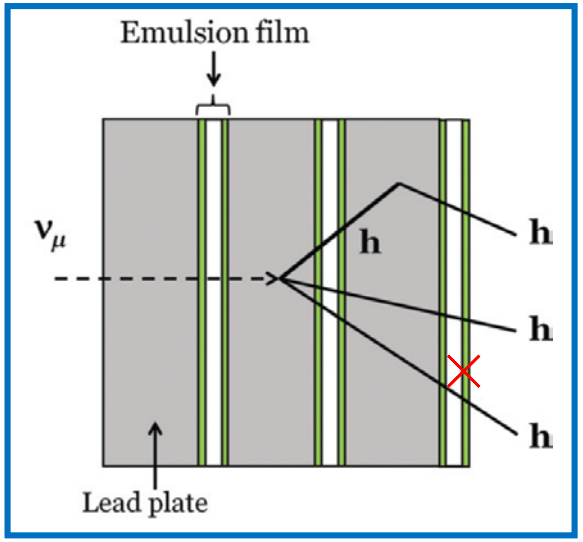


Hadron interaction background

Signal Event



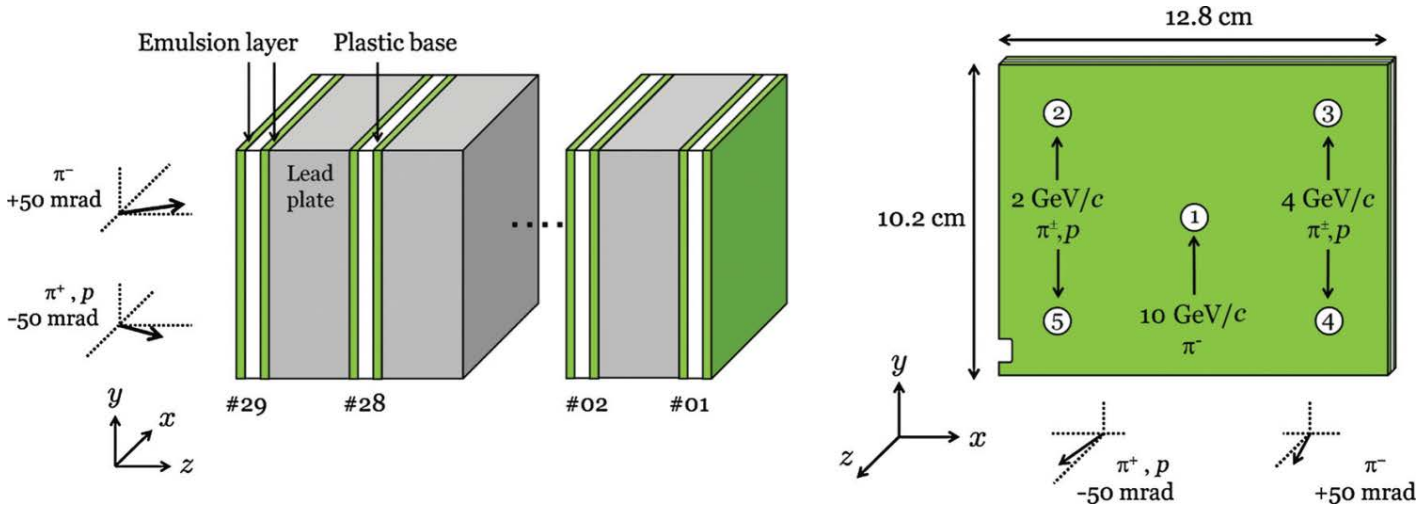
Background



- In the ECC brick, a secondary hadron produced in ν_μ neutral current interactions could interact with the heavy materials and mimic a hadronic decay of the τ lepton.
- Hence such a secondary hadron interaction could be a source of background for τ decays.

Study of hadron interactions as background

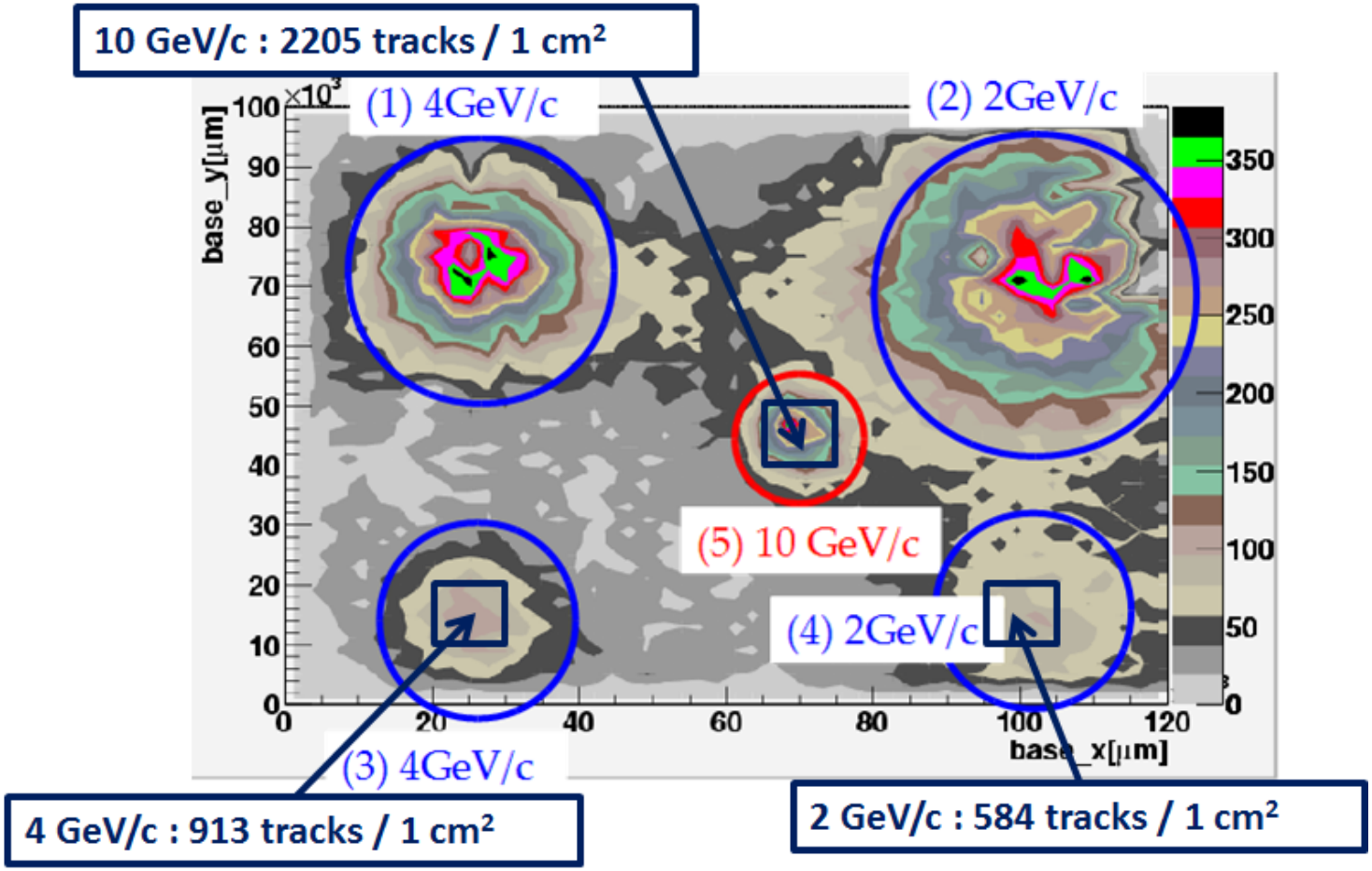
- The dominant background from hadron interactions was evaluated with a FLUKA based Monte Carlo code to be **$(1.9 \pm 0.1) \times 10^{-4}$ per NC event** [1], which must be validated by the experimental data.
  - (About 160 millions of events were simulated where 0.5-15 GeV/c π^+, π^-, K^+, K^- and *p* are impinging on 1 mm of lead. The probability for a background interaction to occur over 2 mm of lead, maximal decay length considered, and to satisfy the selection criteria for reconstruction kink decay topology and its kinematics is be $(1.9 \pm 0.1) \times 10^{-4}$ per NC event.)
- We studied hadron interactions in an ECC brick exposed to 2, 4, and 10GeV/*c* hadron beams and compared the experimental results with those of the Monte Carlo simulation[2] .



[1] N. Agafonova, *et al.*: Phys. Lett. B 691 (2010) 138.
[2] H. Ishida, *et al.*: Prog.Theor.Exp.Phys., 2014 ,093C01(2014).

Beam track reconstruction

- We scanned the whole area of all the emulsion films by using S-UTS.

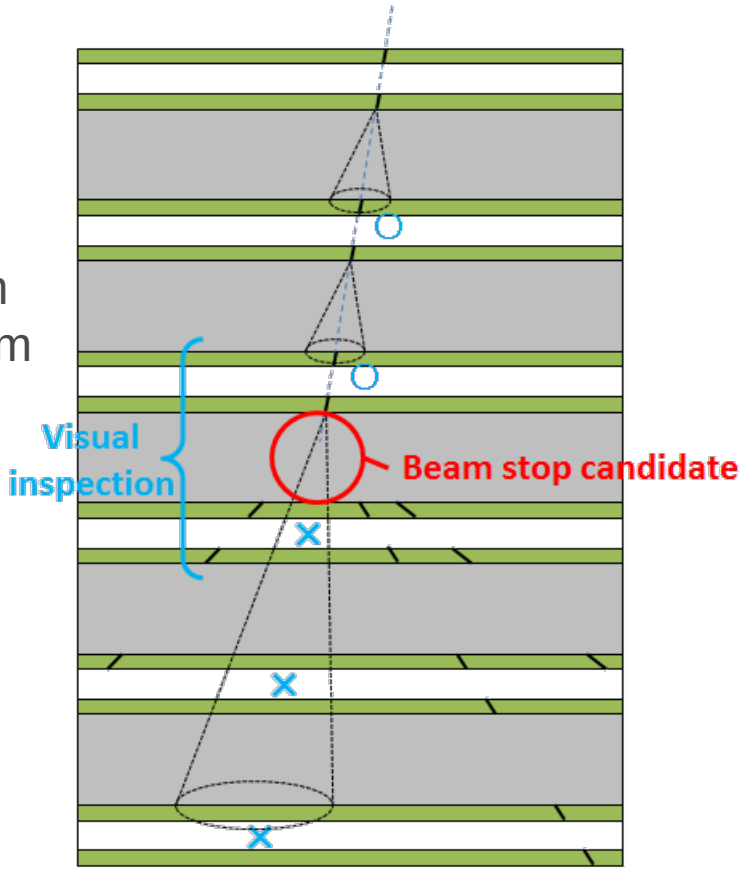


Interaction search

- Beam tracks are followed down from the upstream in the ECC.
- We defined beam stop candidates as follows:

Beam stop candidate
No track found in 3 consecutive films.
(angle difference for connection < 20mrad)

- If the beam-stop candidate found, the last beam track and predicted position in a downstream film are visually inspected.



Secondary particle search

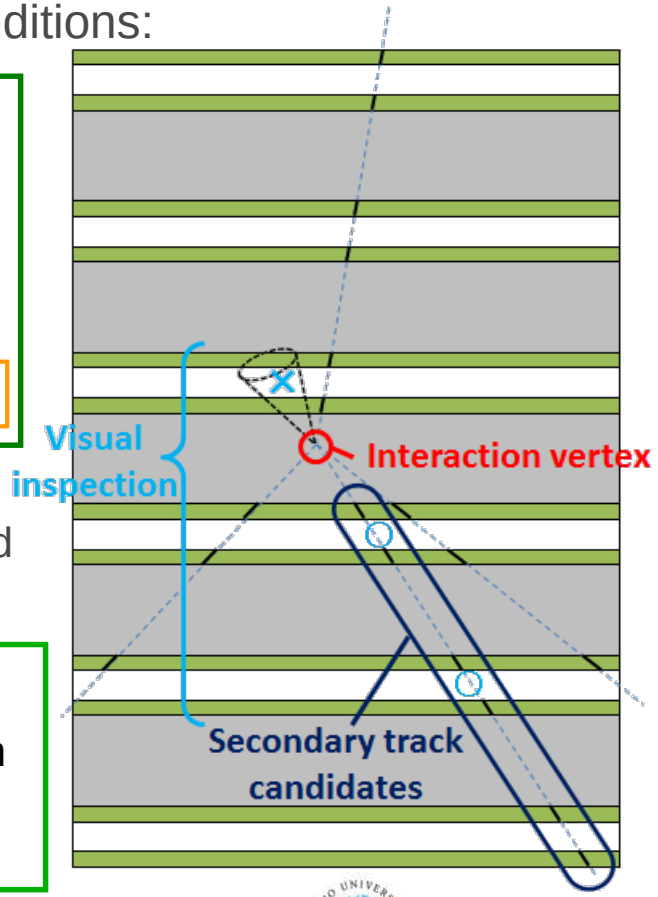
- Each confirmed interaction is subject to the secondary particle track search.
- When a secondary particle candidate is found in at least 1 of the 3 downstream films from the vertex, we required the follow conditions:

Selecting condition

- **IP < 10 + 0.01 x depth (μm)**
- **|tanθ| < 0.6**

Same as those in OPERA

At least 3 tracks in 6 downstream films from the vertex.



- Once a secondary track candidate found, it is checked by visual inspection

Visual inspection

- Passing-through track check in 1 upstream film from the interaction vertex.
- 2 downstream films from the interaction vertex.

Results of the interaction measurements

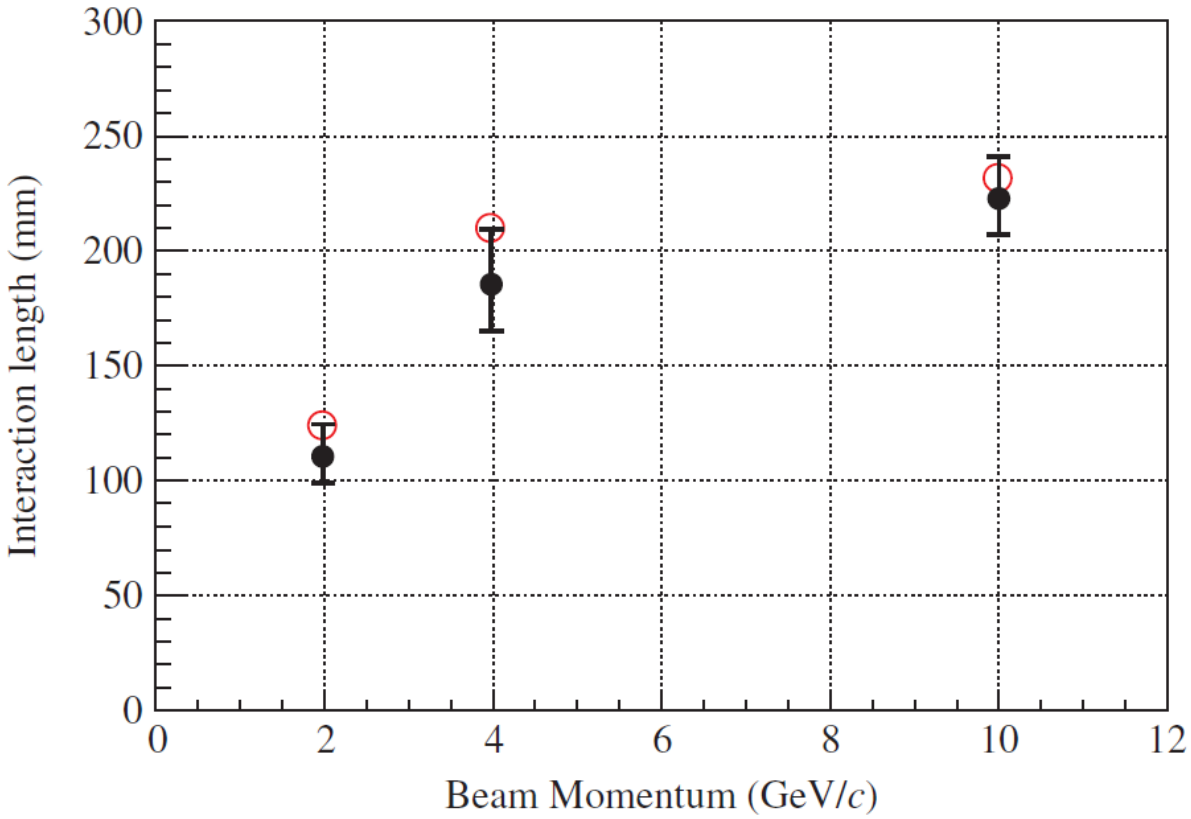
	2GeV	4GeV	10GeV
Number of reconstructed tracks	584 tracks /1 cm^2	913 tracks /1 cm^2	2205 tracks/1 cm^2
Total track length followed in ECC	8.5 m	12.6 m	38.5 m
Number of interactions in ECC	77 events	68 events	173 events
Interaction length In ECC	$109.8\ ^{+14.1}_{-11.4}$ mm	$184.9\ ^{+24.2}_{-20.1}$ mm	$222.5\ ^{+18.4}_{-15.8}$ mm

- In total, 318 interactions were found from the interaction measurements.
- The interaction length, λ, is calculated as follows:

$$\lambda = -\frac{L}{\ln(1-\frac{N}{N_0})}$$

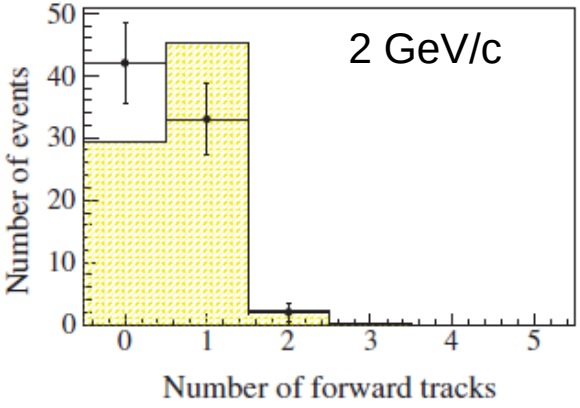
L : thickness of a lead plate and an emulsion film
N : number of interactions found
N_0 : sum of the numbers of followed tracks in all analyzed films.

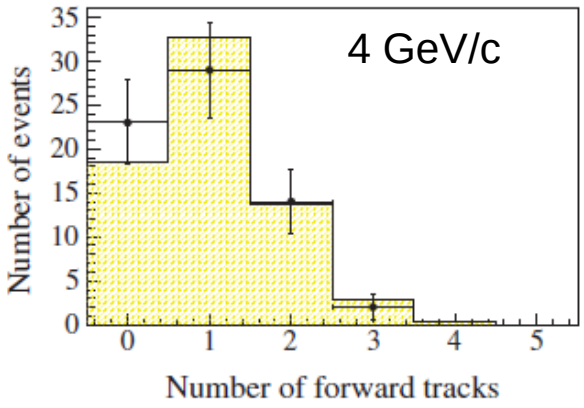
Results of the interaction measurements

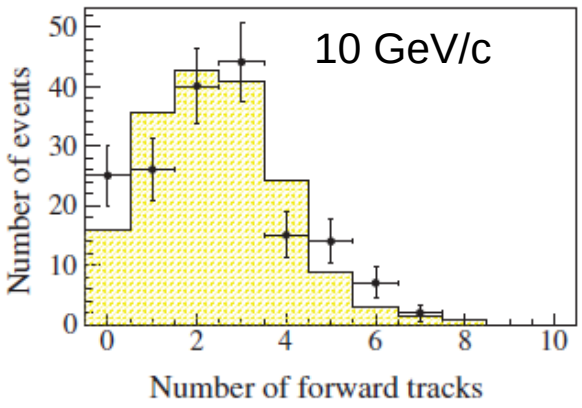


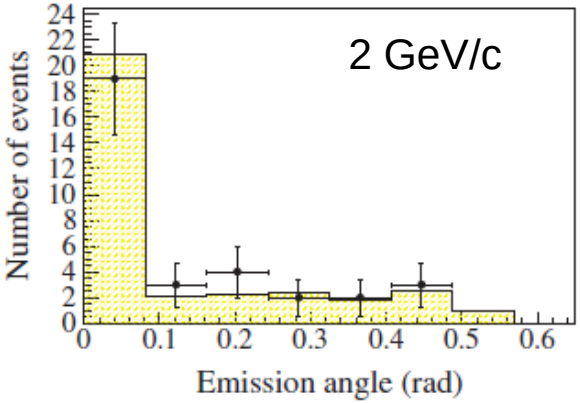
- Momentum dependence of the interaction length is in good agreement with the Monte Carlo simulation within the statistical errors.

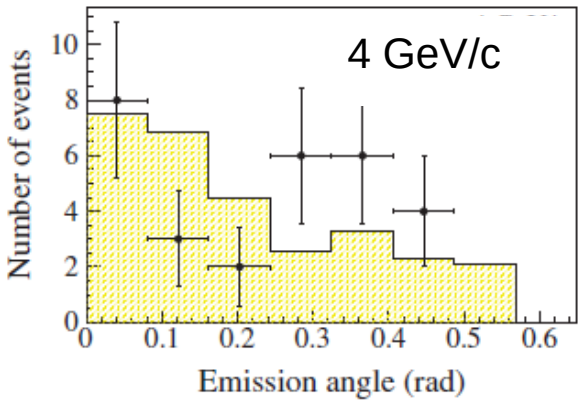
Results of secondary particle search

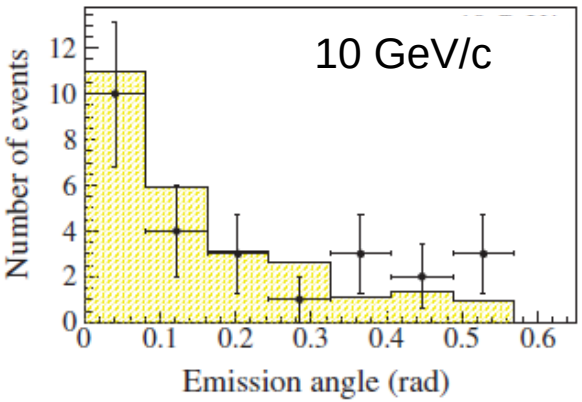












Plots : Experimental data
Histogram : Simulated data

H. Ishida, *et al.*: Prog.Theor.Exp.Phys., 2014 ,093C01(2014).

- The simulation data agree well with the experimental data.

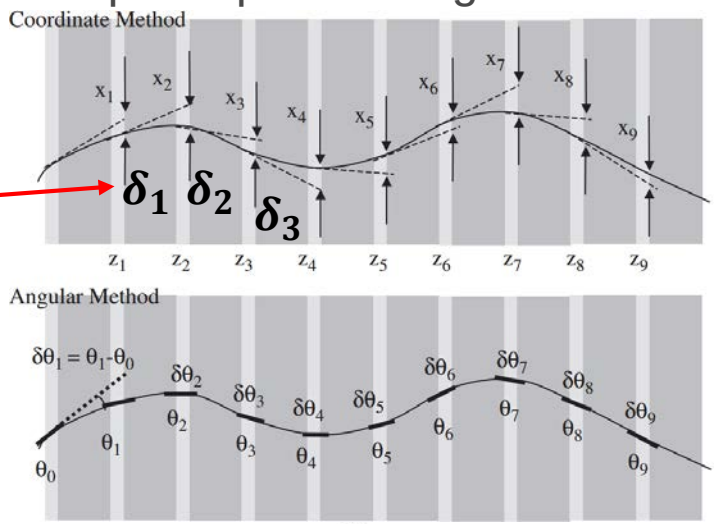
Measurement of secondary particle momentum

- The momenta of secondary tracks are estimated by measuring their multiple Coulomb scattering in the brick.
- There are two methods in the multiple scattering measurements, the angular method[1] and the coordinate method[2].
- The angular method used the angle difference, and the coordinate method used the position displacement between films.
- We use the coordinate method because it is more accurate when a small multiple scattering signal is expected, although it requires precise alignment among the emulsion films.

$$\delta_i = x_{i+2} - x_{i+1} - \frac{x_{i+1} - x_i}{z_{i+1} - z_i} \cdot (z_{i+2} - z_{i+1})$$

$$\langle \delta_i^2 \rangle = \Delta_{\text{sig}}^2 + \langle \epsilon_i^2 \rangle$$

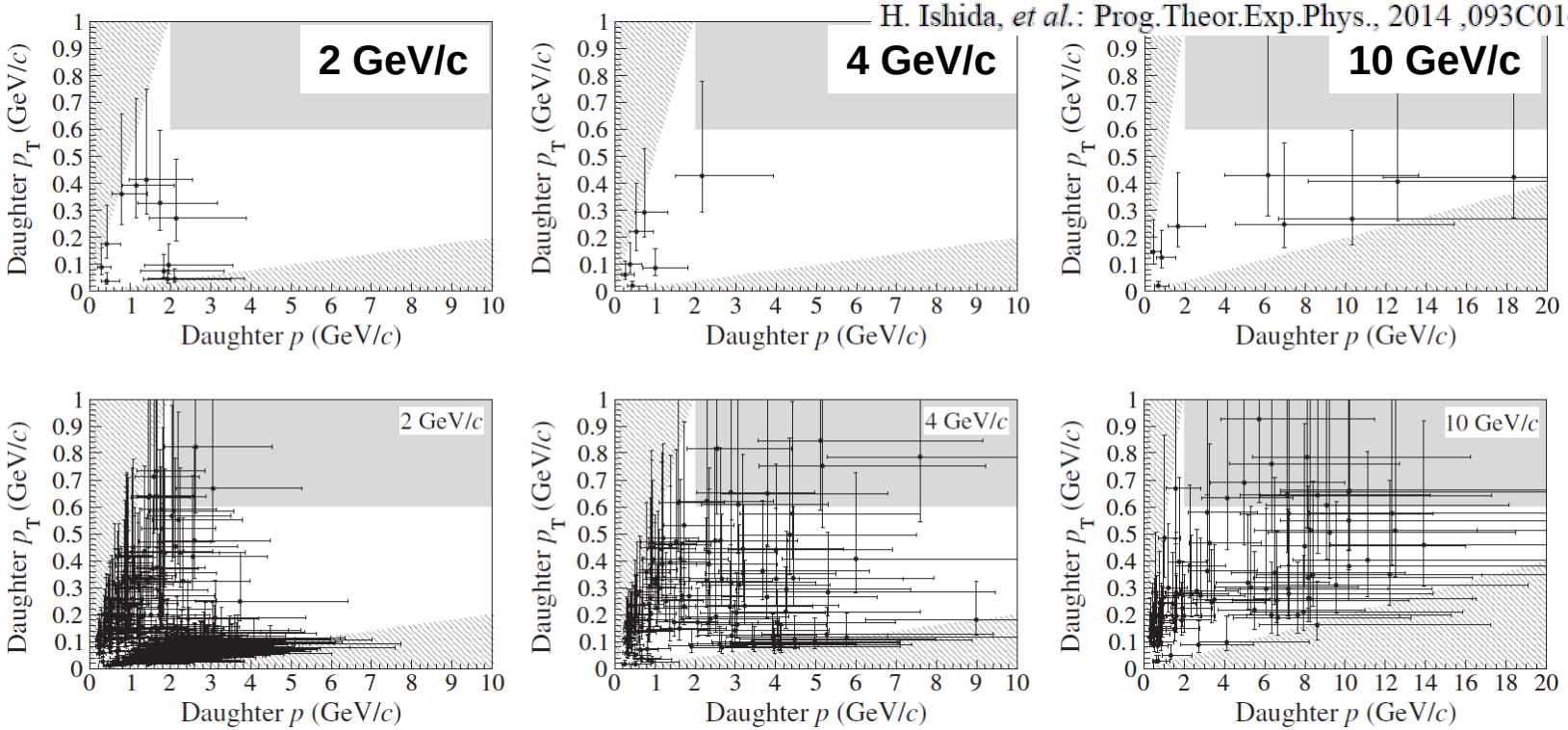
$$\Delta_{\text{sig}} = \frac{t}{2\sqrt{3}} \frac{0.0136\,\text{GeV}}{p\beta c} \cdot \sqrt{\frac{t}{X_0}} \left\{ 1 + 0.038 \ln\left(\frac{t}{X_0}\right) \right\}$$



[1] N. Agafonova, *et al.*: New J. Phys. 14 (2012) 013026.
[2] K.Kodama, *et al.*: Nucl. Instrum. Meth. A, 574 (2007) 192.

Measurement of secondary particle momentum

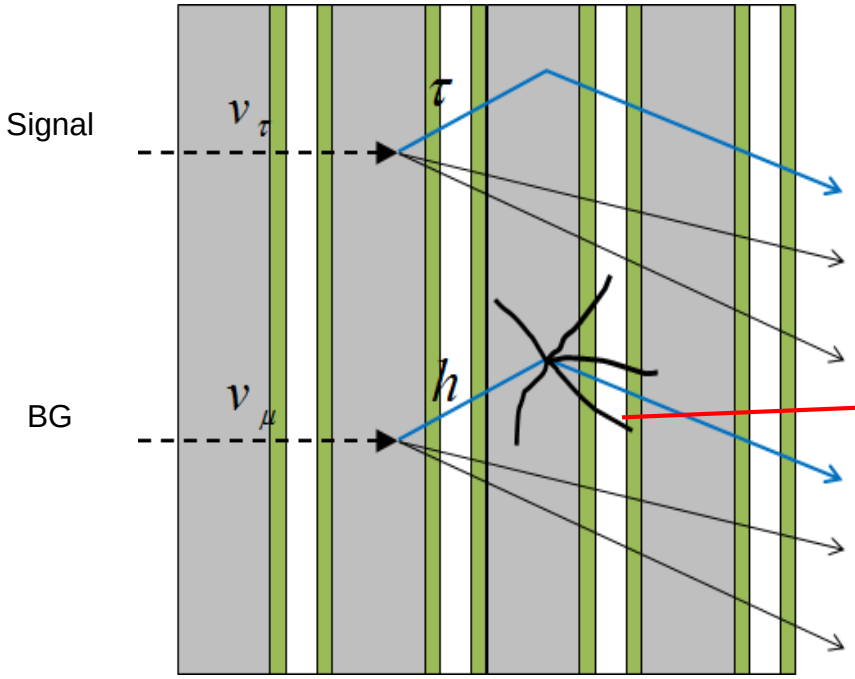
H. Ishida, *et al.*: Prog.Theor.Exp.Phys., 2014 ,093C01(2014).

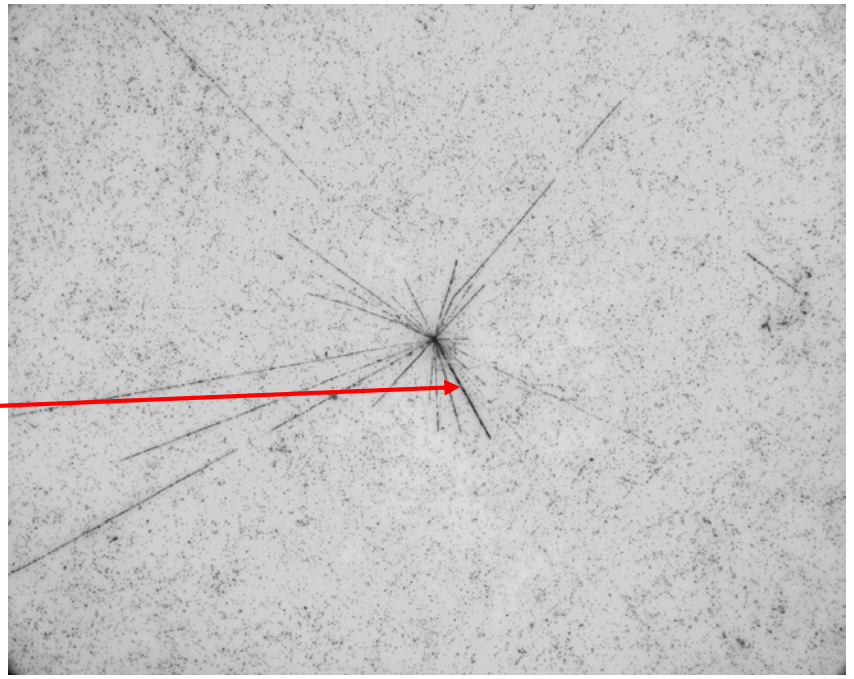


- Comparisons between experimental and MC data show generally good agreement.
- However, statistics are limited because only secondary tracks for which more than 14 lead plates are available as scattering materials are able to be momentum reconstructed.
- Therefore, the final statistics of the tracks in the selection domain are not sufficient to obtain quantitative results on how good the agreement is.

Nuclear Fragments

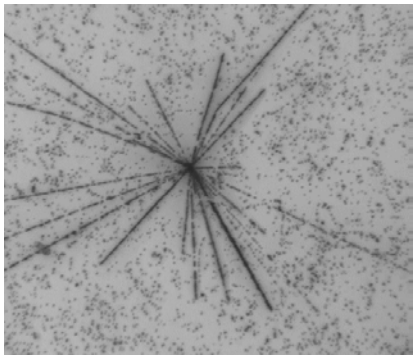
- If a secondary particle has a value of $\beta < 0.7$, the particle is observed as a heavily ionizing track or a nuclear fragment.
- Nuclear fragments emitted from hadron interactions were also sought by a newly developed automatic emulsion scanning system with wider angular acceptance, FTS.

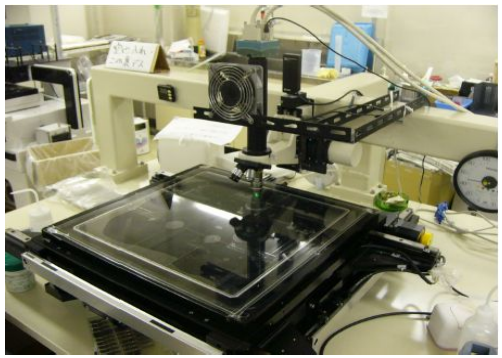


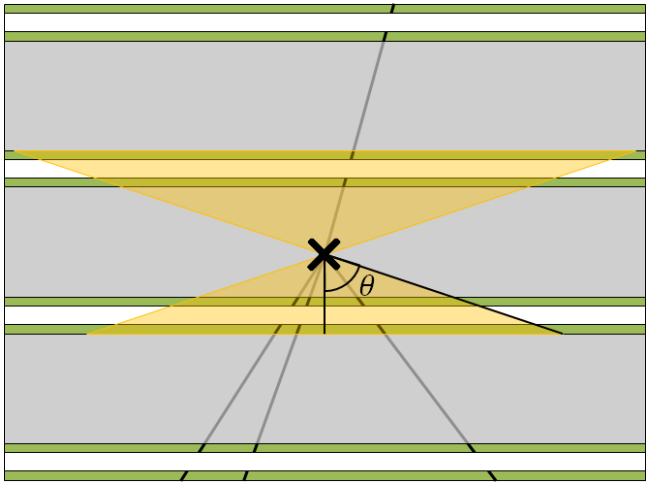


Nuclear fragments search

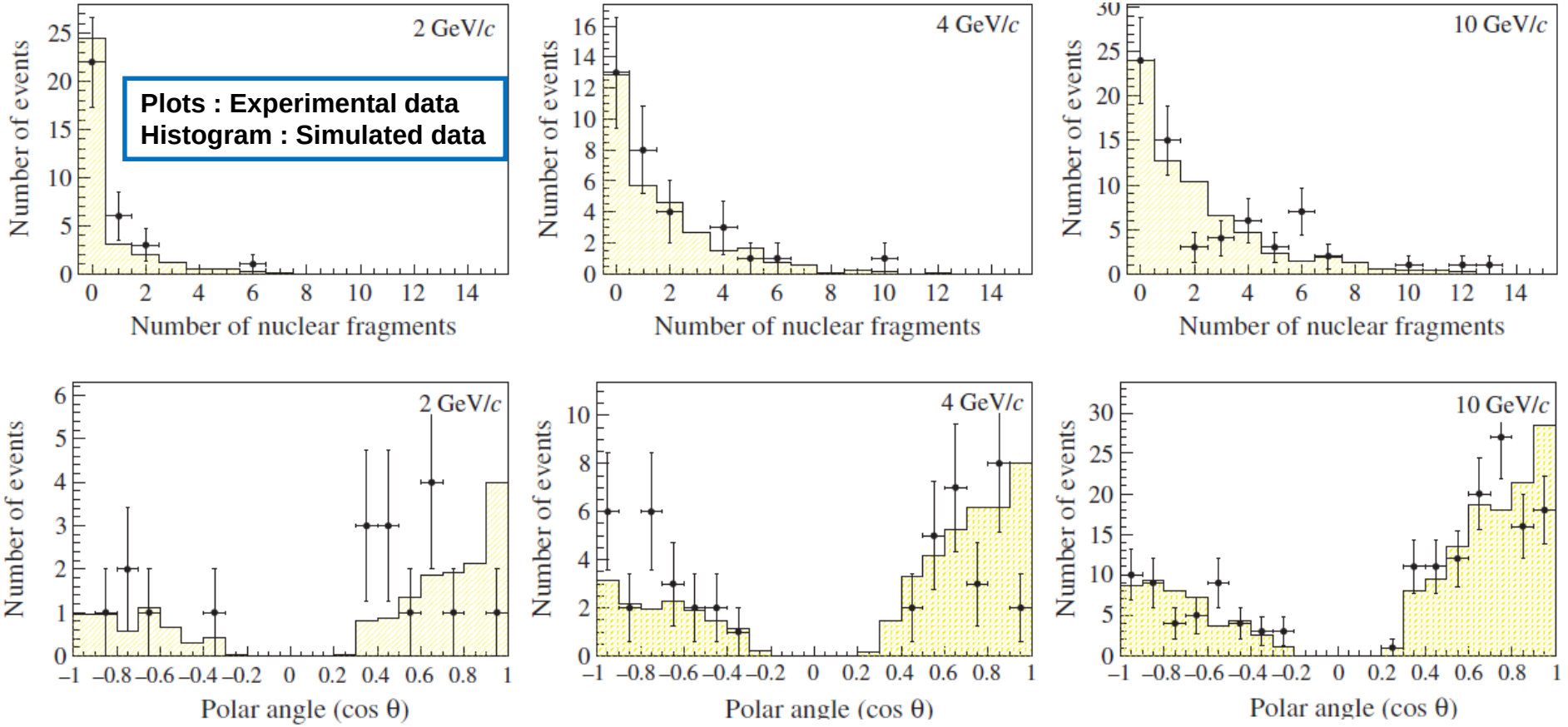
- We scanned upstream and downstream films of the 1 or 3 prong vertex.
- Since most of nuclear fragments are emitted at large angle, scanning was performed by using FTS at Toho University.
  - Angle acceptance : $|\tan\theta| < 3.0$
- Since nuclear fragments are expected to suffer from large multiple scattering, therefore, a loose condition was imposed.
  - IP < 100 μm + 0.01 × depth
- Confirmation of candidates by visual inspection.







Results of nuclear fragments search

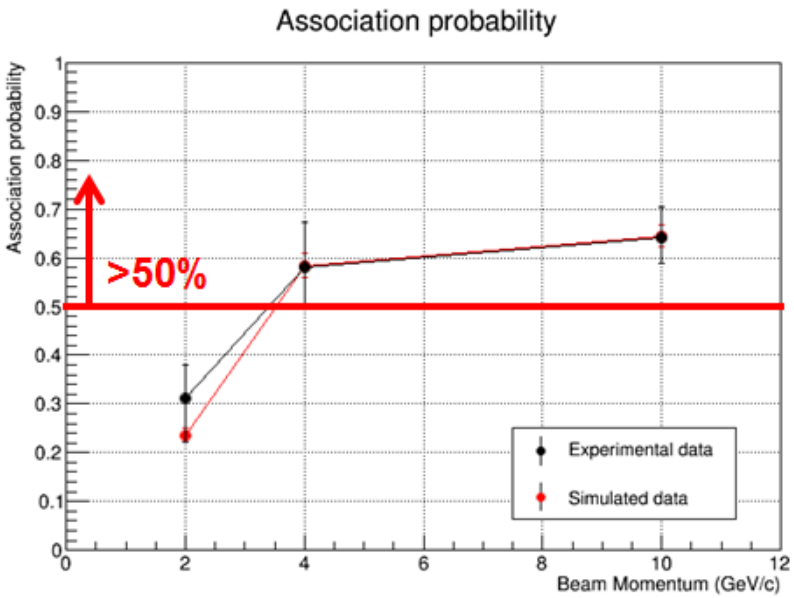


H. Ishida, *et al.*: Prog.Theor.Exp.Phys., 2014 ,093C01(2014).

- Good agreement in the multiplicity and polar angle distributions of nuclear fragments between the experimental data and simulated data.

Nuclear fragments search results

	2 GeV/c		4 GeV/c		10 GeV/c	
	Experimental	MC	Experimental	MC	Experimental	MC
Total events	32	908	31	404	66	460
Associated events	10	213	18	236	42	296
Association probability	$31.3^{+9.1}_{-6.9}\%$	$23.4^{+1.5}_{-1.3}\%$	$58.1^{+8.1}_{-9.1}\%$	$58.4^{+2.4}_{-2.5}\%$	$63.6^{+5.0}_{-5.7}\%$	$64.3^{+2.2}_{-2.3}\%$



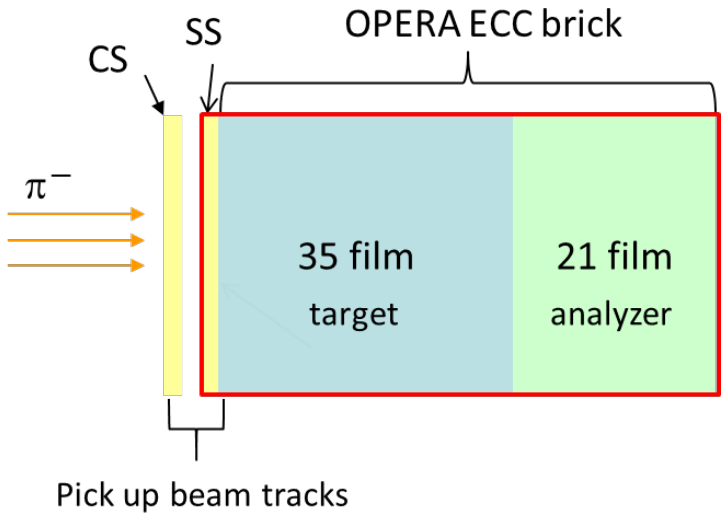
- We measured the probability of the interaction vertices being associated with nuclear fragments and found it to be greater than 50% for beam momentum p > 4 GeV/c.
- The experimental data of the fragment association probability are well reproduced by the simulation with differences less than 10%

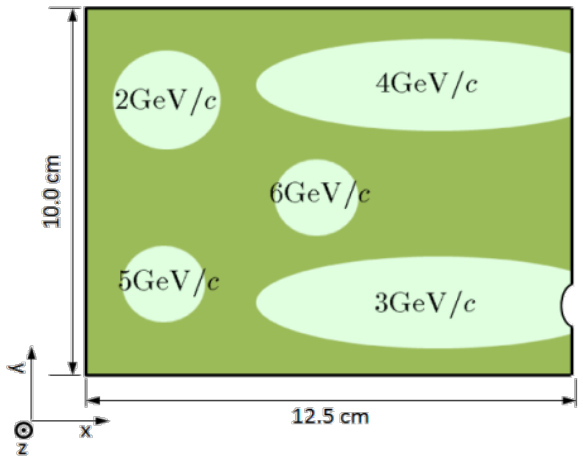
Summary of previous study

- The topological and kinematical characteristics of hadron interactions have been studied by using an ECC brick exposed to 2, 4, and 10 GeV/c π^- beams.
- A total of 318 hadron interactions were found and reconstructed by following 60 m π^- tracks in the brick.
- The charged particle multiplicity of each event and emission angle of each secondary particle were good agreement with a FLUKA MC simulation.
- We measured the probability of the interaction vertices being associated with nuclear fragments and found it to be greater than 50% for p > 4 GeV/c.
- The experimental data of the fragment association probability are well reproduced by the simulation with differences less than 10%.
- Fractions of hadron interactions being in the domain where $\tau \rightarrow$hadron decays are selected are measured and found to be consistent with the simulation at the 30% level.
- However, the final statistics of the measureable secondary track's momentum are not sufficient.

New data set for hadron interaction analysis

- In 2012, we took a new data set for hadron interaction analysis to increase statistics and confirm the agreement with better precision.
- In our plan, the beam interactions are mainly searched in the 35 upstream films, and their secondary particle momenta are measured in the 21 downstream films.
- **More statistics of the momentum measurements of the secondary tracks can be expected.**





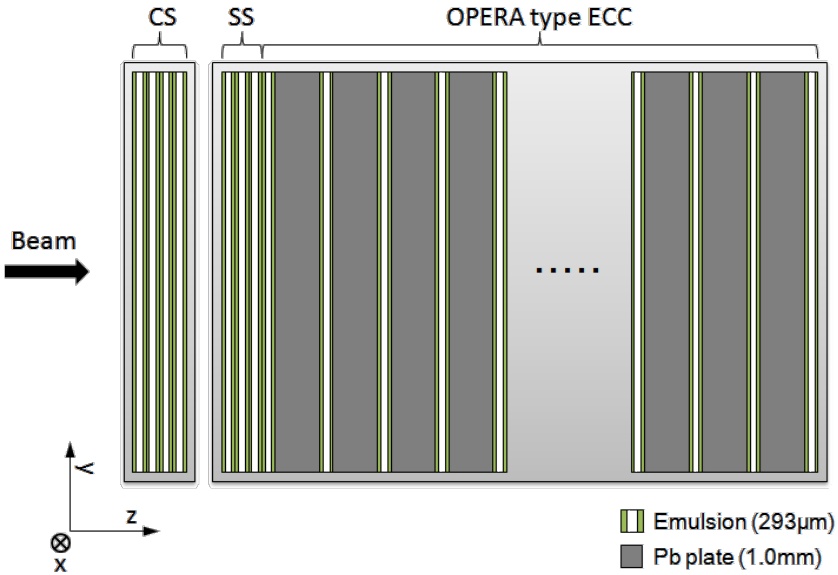
Reconstruction of beam tracks

- In this experiment, Changeable Sheets（CS）and Special Sheets（SS) were placed in the upstream of ECC, CS were changed for each beam exposure.

⇒ At first, beam tracks of each momentum spot are reconstructed on the CS, then they are connected to SS, and finally to the ECC.

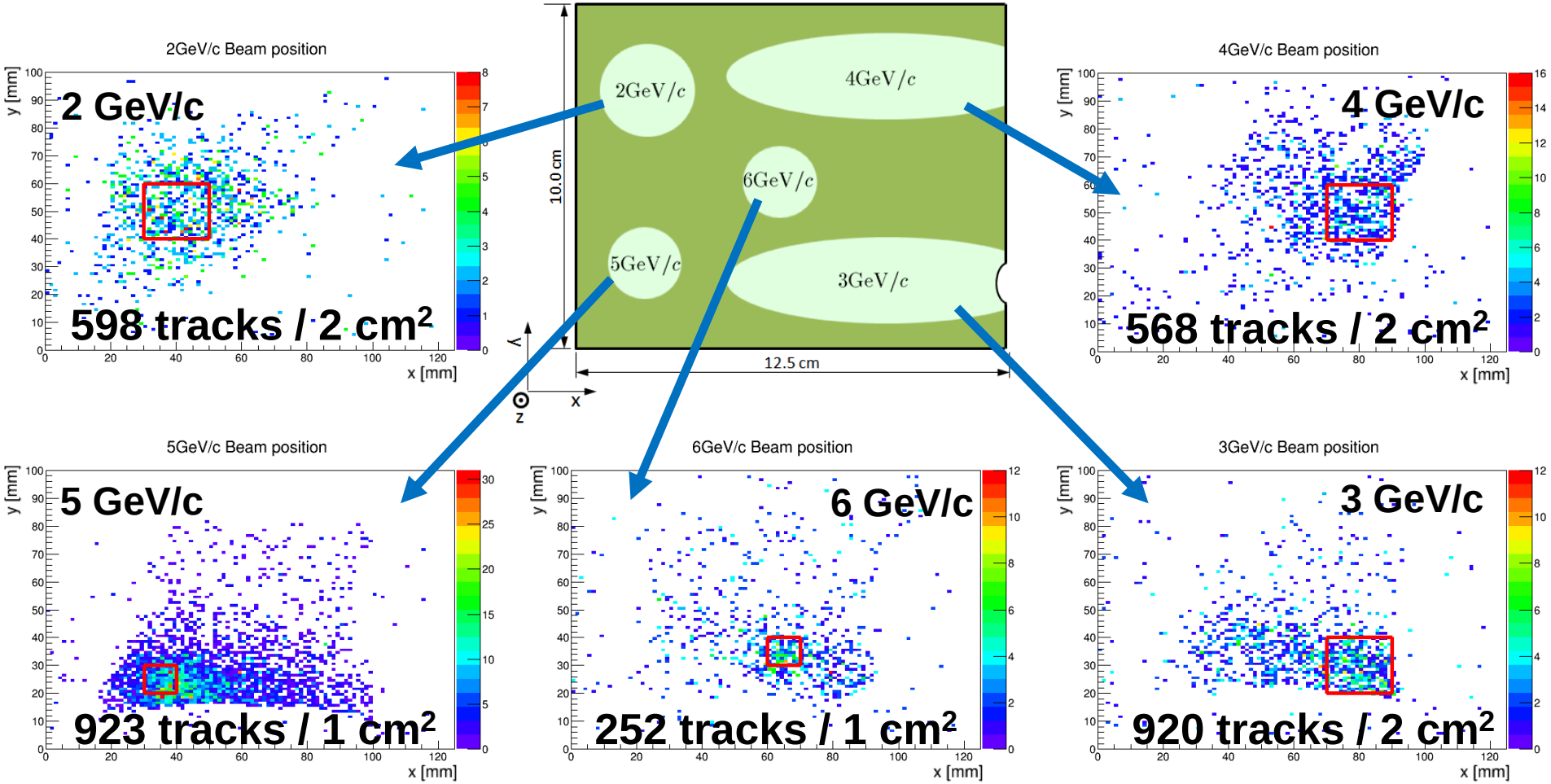
⇒ Even in the ECC area where plural momentum tracks exist, beam tracks of each momentum spot are clearly separated from other momentum beam tracks.

- In this study, reconstructed tracks which contained more than 2 track segments both in CS and SS are treated as beam tracks.



Number of reconstructed Tracks	
2 GeV/c	598 tracks / 2 cm^2
3 GeV/c	920 tracks / 2 cm^2
4 GeV/c	568 tracks / 2 cm^2
5 GeV/c	923 tracks / 1 cm^2
6 GeV/c	252 tracks / 1 cm^2

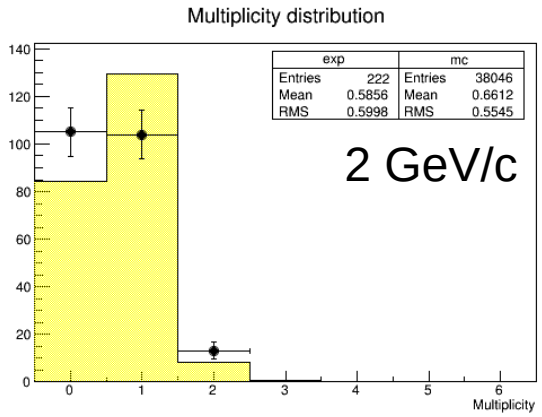
Beam spot positions on the ECC brick

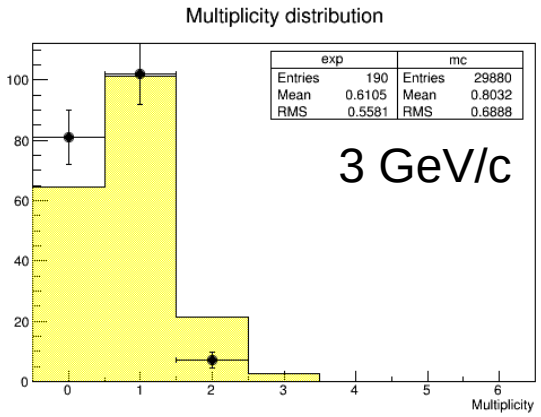


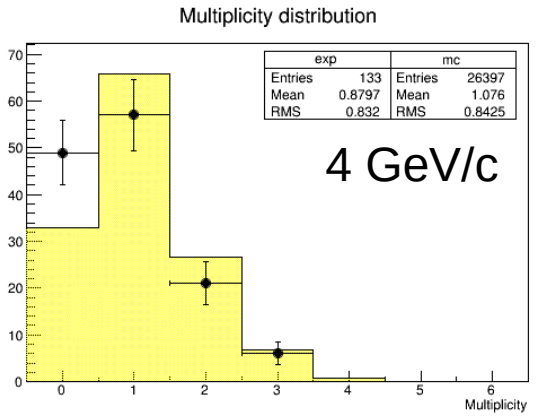
Current status (Secondary tracks)

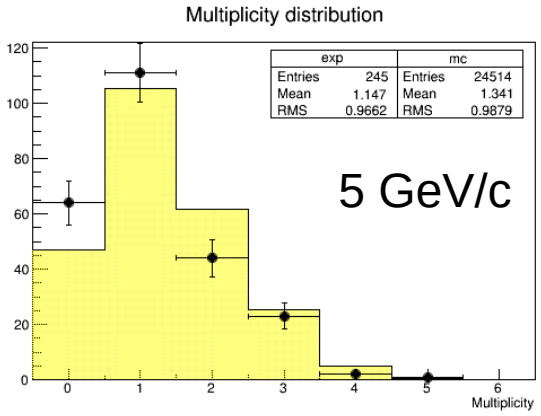
preliminary

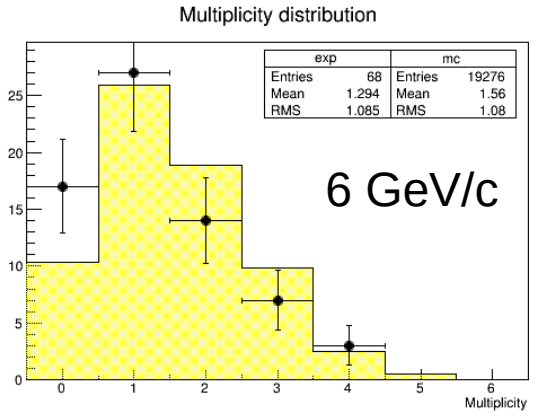
~Multiplicity distributions~









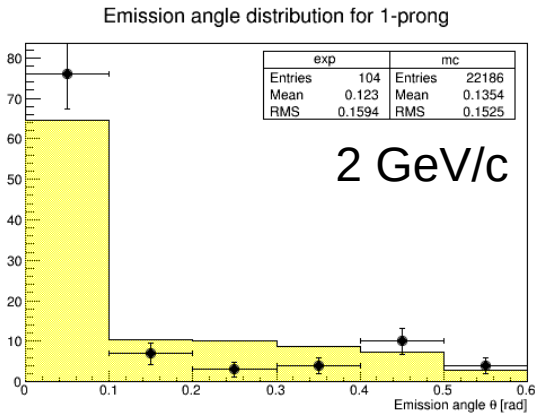


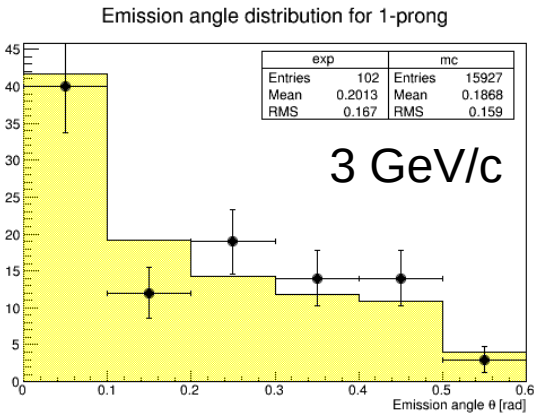
Plots : Experimental data
Histogram : Simulated data

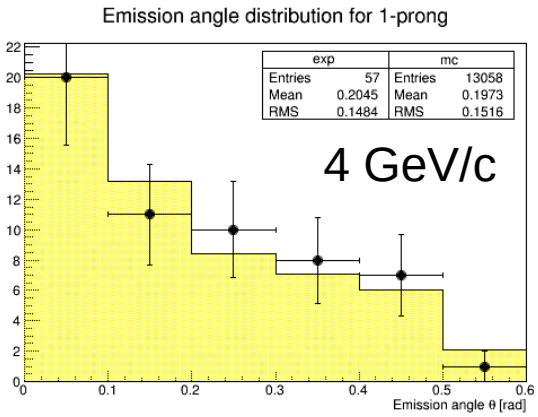
Current status (Secondary tracks)

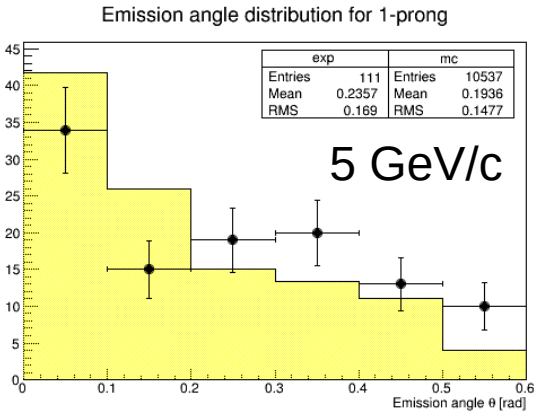
preliminary

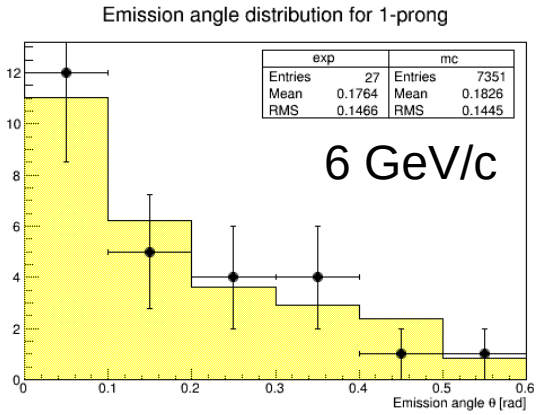
~Emission angle distributions~









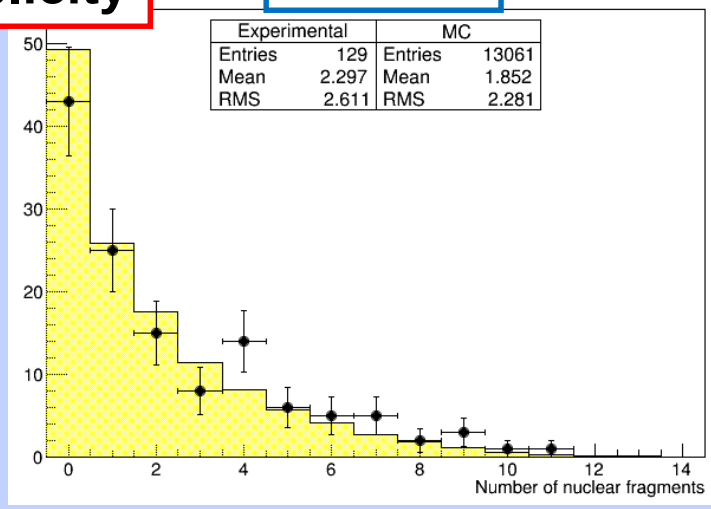


Plots : Experimental data
Histogram : Simulated data

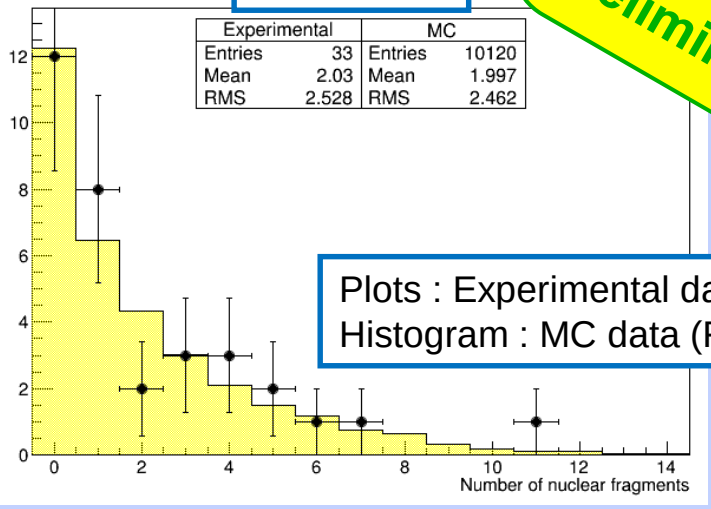
Current status (Nuclear fragments)

Multiplicity

5 GeV/c



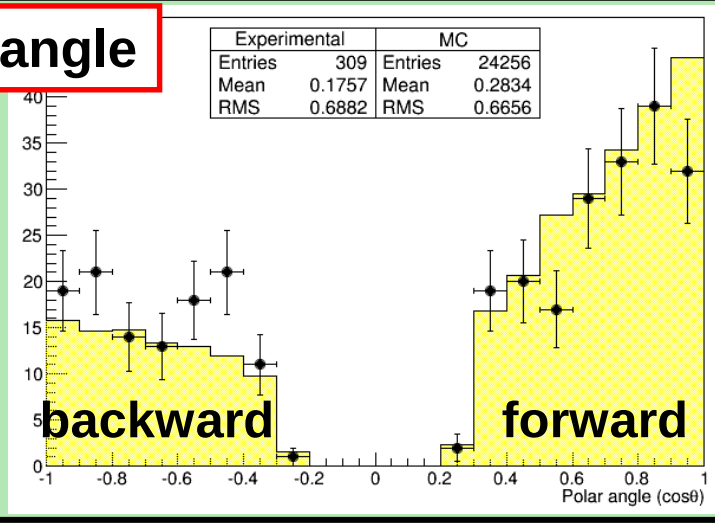
6 GeV/c

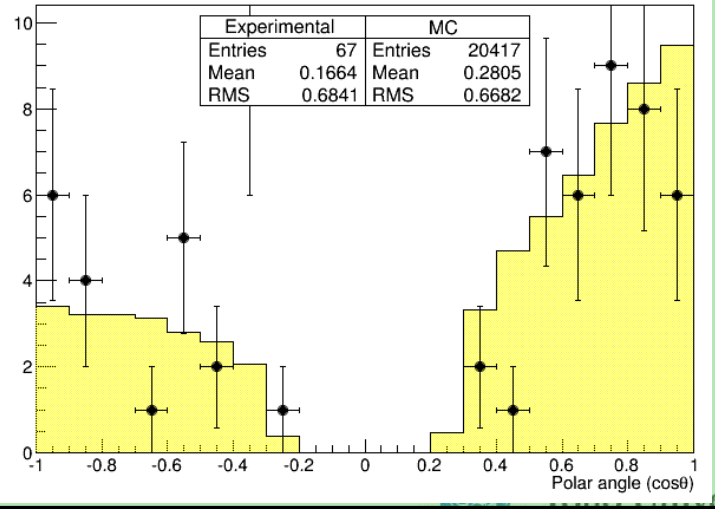


preliminary

Plots : Experimental data
Histogram : MC data (FLUKA)

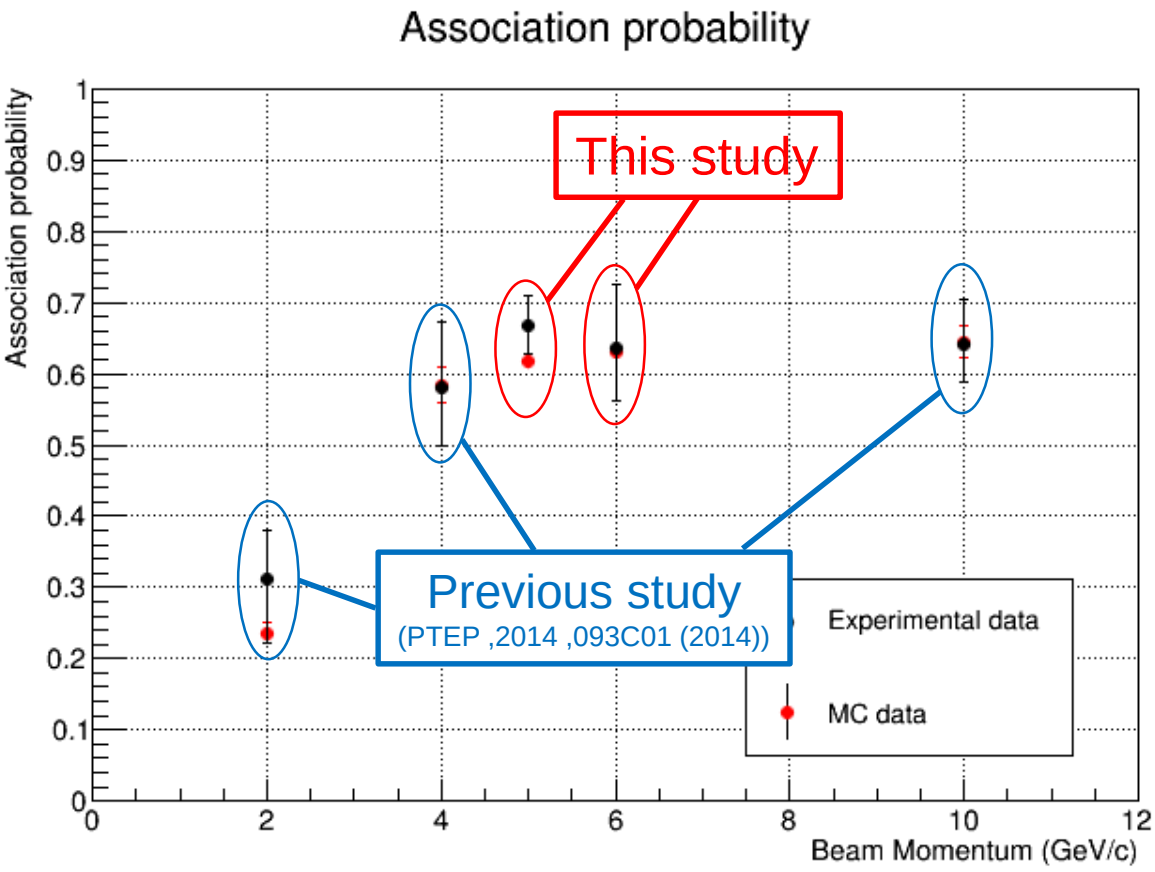
Polar angle





Current status (Nuclear fragments)

preliminary



5 GeV/c

	Experimental	MC
Total events	129	13061
Associated events	86	8079
Association probability	$66.7^{+3.9}_{-4.4}\%$	$61.9^{+0.4}_{-0.4}\%$

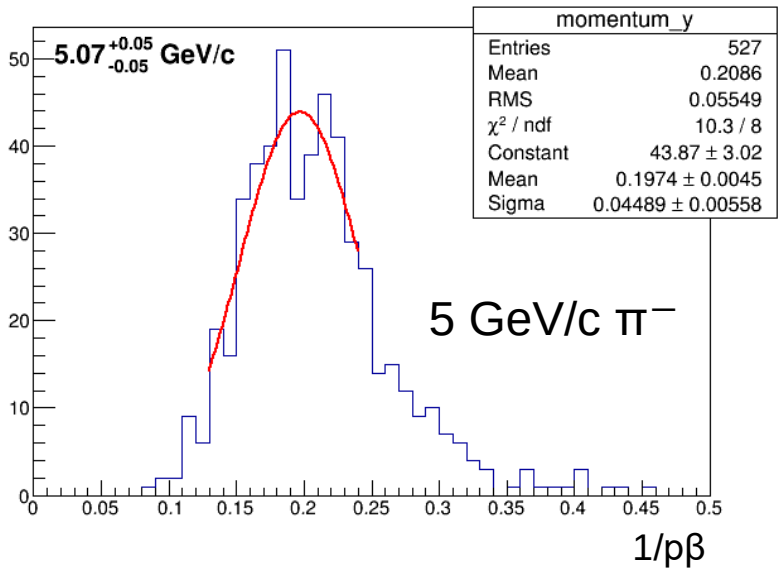
6 GeV/c

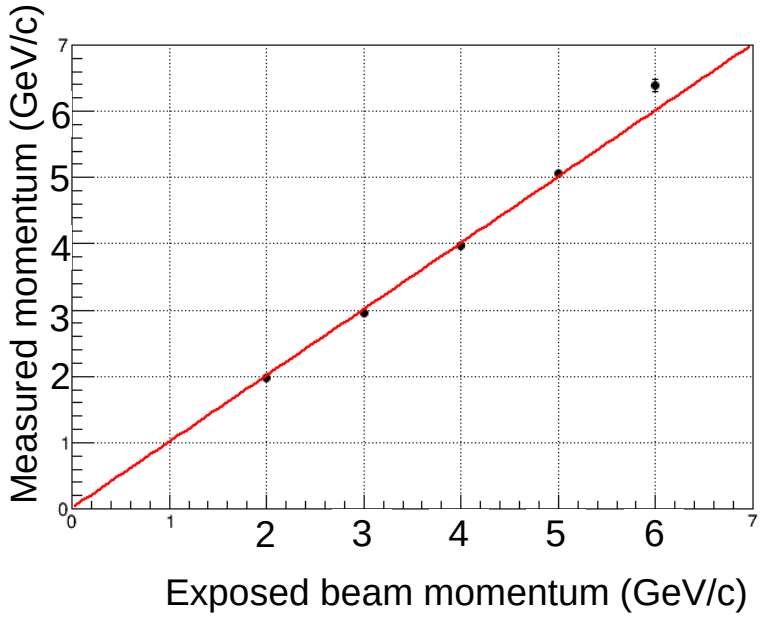
	Experimental	MC
Total events	33	10120
Associated events	21	6371
Association probability	$63.6^{+7.4}_{-8.9}\%$	$63.0^{+0.5}_{-0.5}\%$

- We obtained new beam momentum data of nuclear fragments.
- The MC data agree reasonably well with the experimental data.

Momentum measurement of beam particles

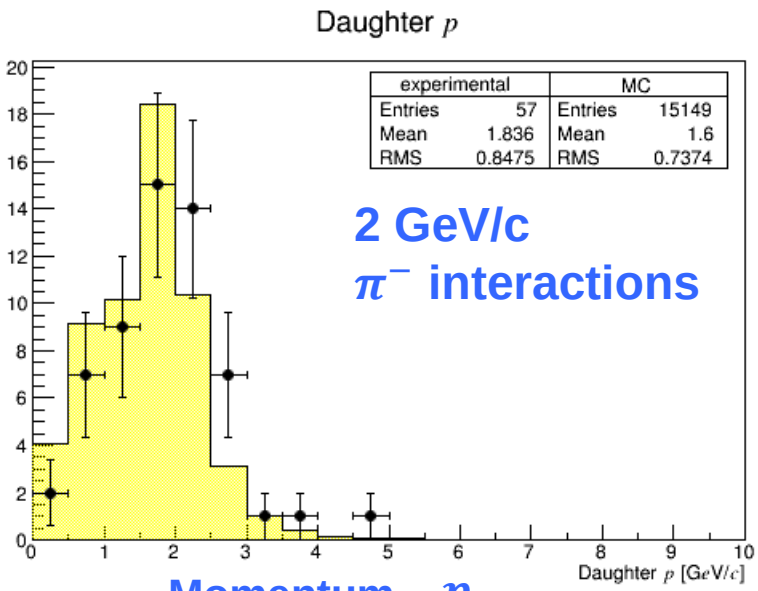
- We applied the coordinate-method to beam particle tracks.
- As a result, average momentum of beam tracks measured by the coordinate method agrees well with each exposed beam momentum.



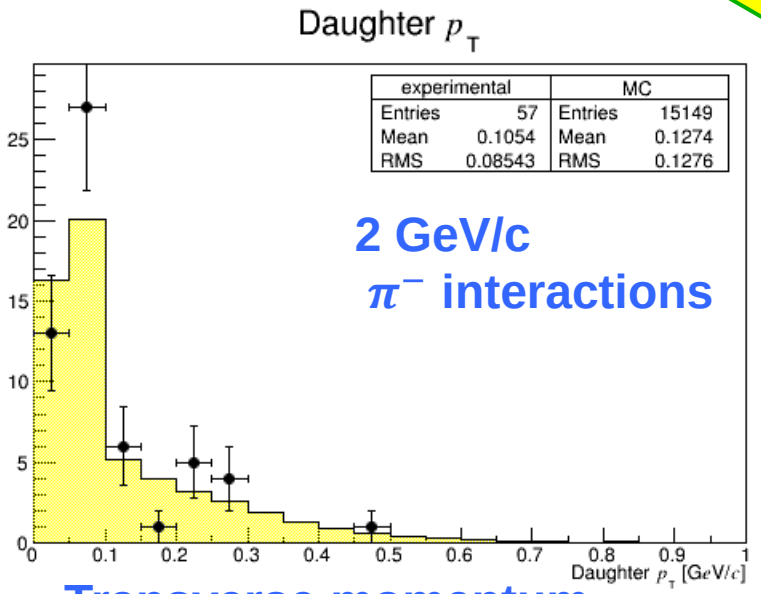


Measurement of secondary particle momentum

Very preliminary



Momentum p



Transverse momentum p_T

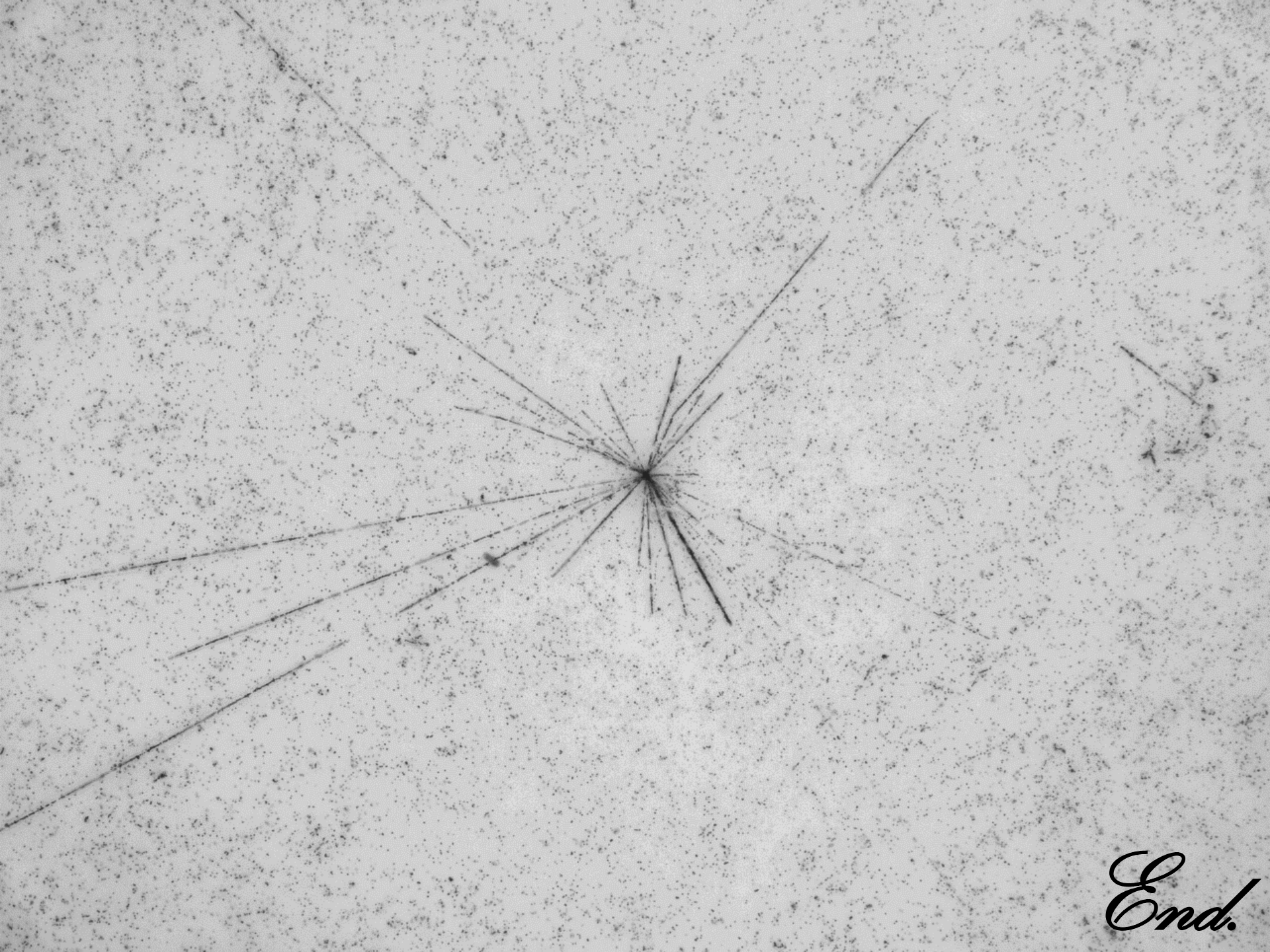
- We started the measurement of secondary particle momentum using the coordinate method.
- Though the detailed analysis are now in progress, the agreement between the experimental data and MC data looks good.

Summary

- Hadron interaction is one of main background sources for τ decay in OPERA.

- In previous study, we analyzed 2, 4, 10 GeV/c π^- interactions in an OPERA-like ECC and compared with a FLUKA based MC simulation.
- We concluded that the agreement between the experimental and simulated data was confirmed at the 30% level, however, the statistics of momentum measurements of secondary tracks were not sufficient yet.

- In 2012, we took a new data set for hadron interaction analysis to increase statistics and confirm the agreement with better precision.
- In this study, 10 times more data than previous one will be obtained.
- New systematic analysis is in progress. We will summarize the results soon.


End.