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Update of hadron interaction analysis

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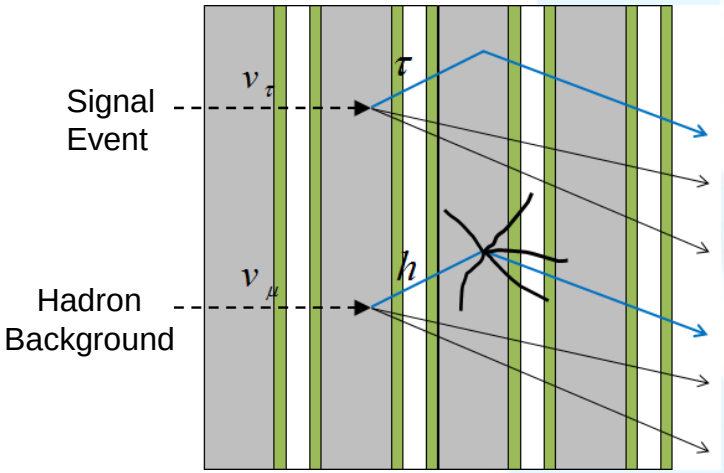
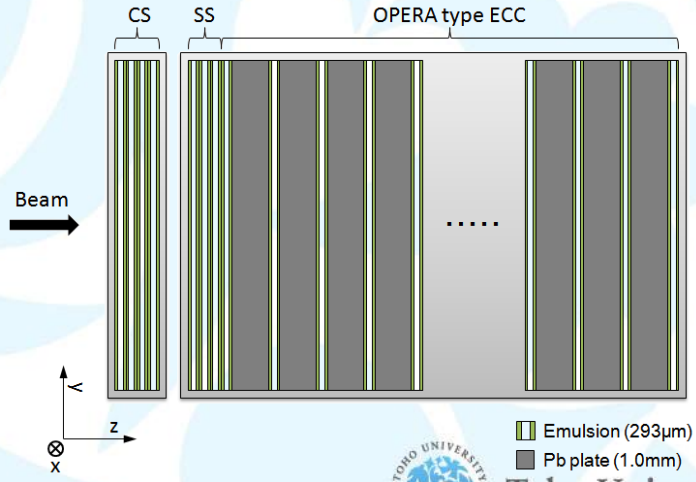
Introduction

- Hadron interaction is one of the main background source of tau decay in OPERA.
- In previous study, we analyzed 2, 4, 10 GeV/c π^- interaction in OPERA ECC and compared with a FLUKA based MC simulation.
- We concluded the agreement between the experimental data has been confirmed at the 30% level.
- In 2012, we took a new data set for hadron interaction analysis to increase statistics and confirm the agreement with better precision.





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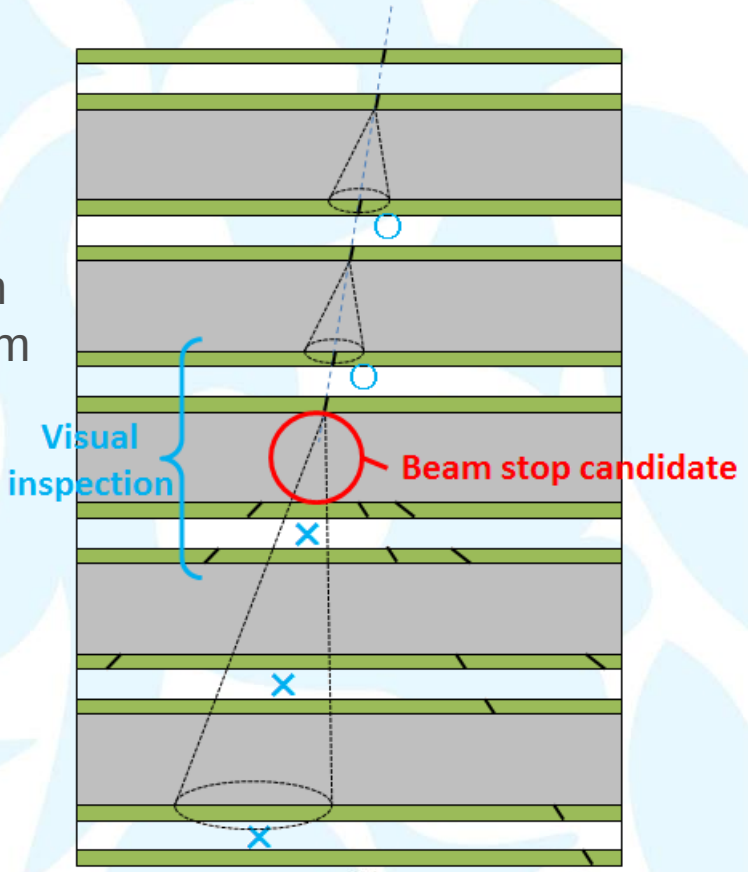
Interaction search

- 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.



Interaction search

Interaction search status

Beam momentum	2 GeV/*c*	3 GeV/*c*	4 GeV/*c*	5 GeV/*c*	6 GeV/*c*
Number of reconstructed tracks	538 /4cm^2	899 /4cm^2	547 /4cm^2	864 /1cm^2	239 /1cm^2
Number of manual checked films	51 films	51 films	51 films	51 films	51 films
Number of found interactions	213 events	239 events	127 events	233 events	61 events

- Interaction search has been finished in all momentum area.

Secondary particle search

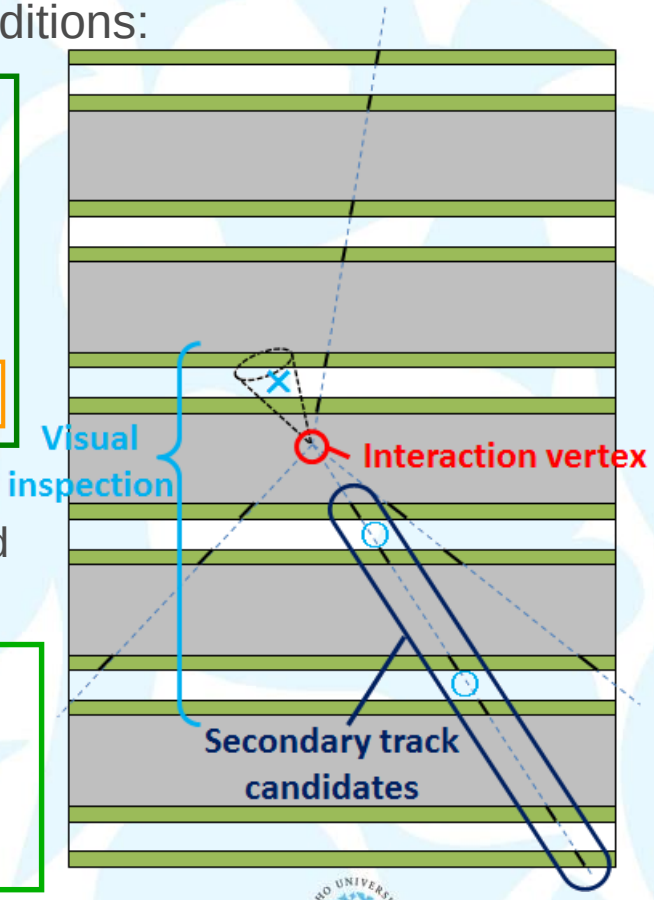
- Each confirmed interaction is subject to the secondary particle track search.
- When a secondary particle candidate is found in at least 1 of the 3 downstream films from the vertex, we required the follow conditions:

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.

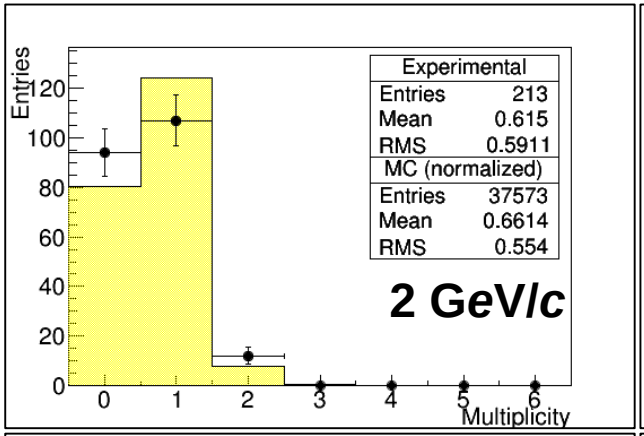


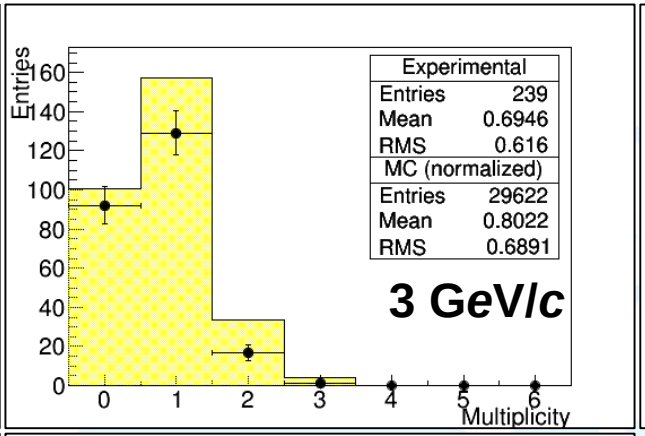
- Once a secondary track candidate found, it is checked by visual inspection

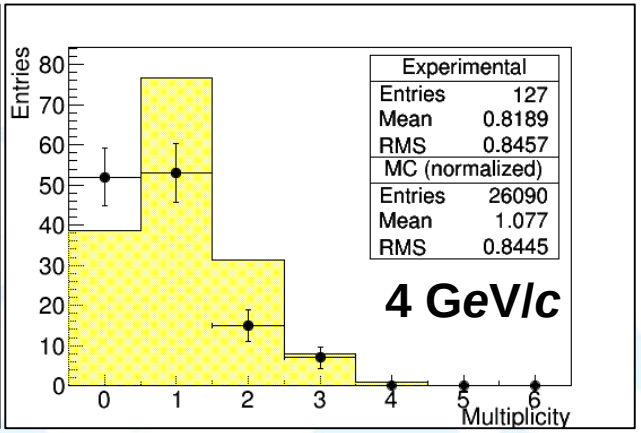
Visual inspection

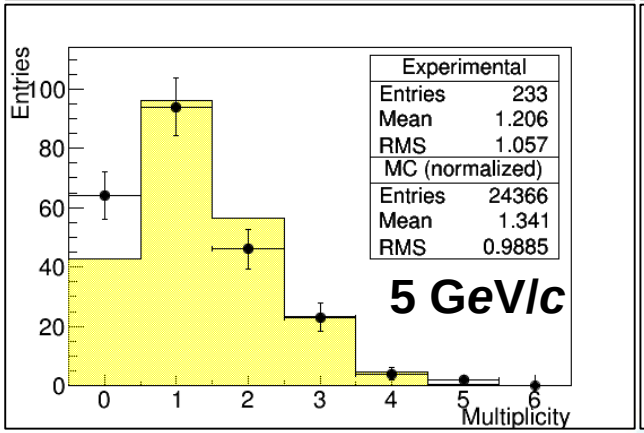
- Passing-through track check in 1 upstream film from the interaction vertex.
- 2 downstream films from the interaction vertex.

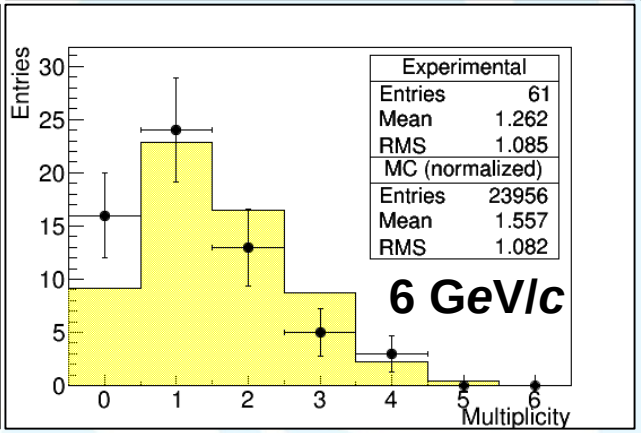
Secondary particle multiplicity





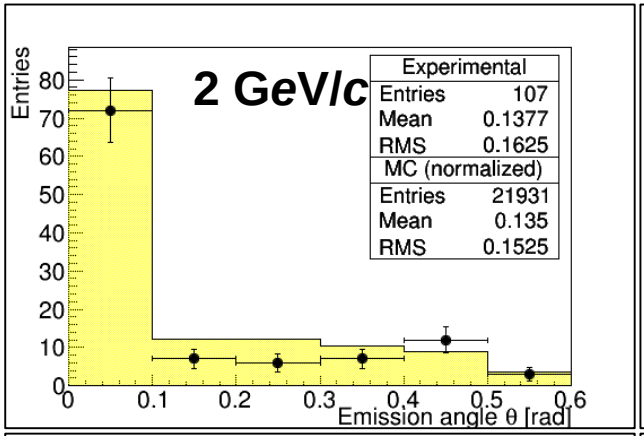


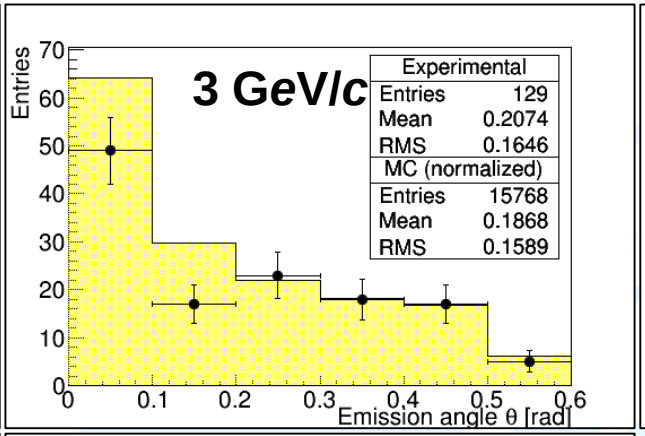


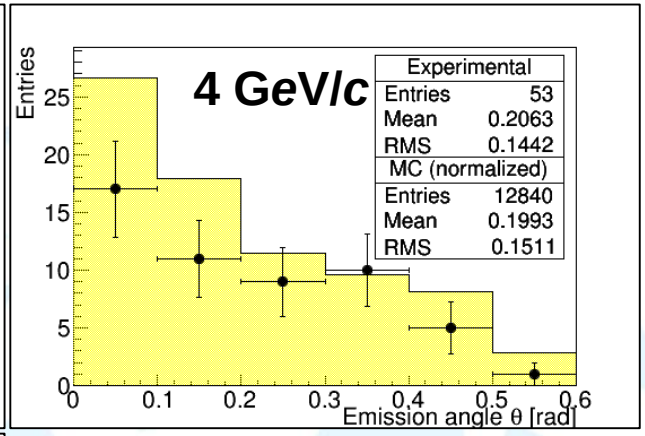


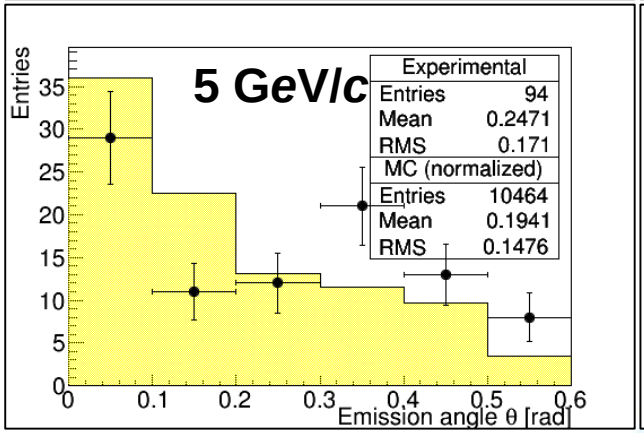
Plots : Experimental data
Histogram : Simulated data

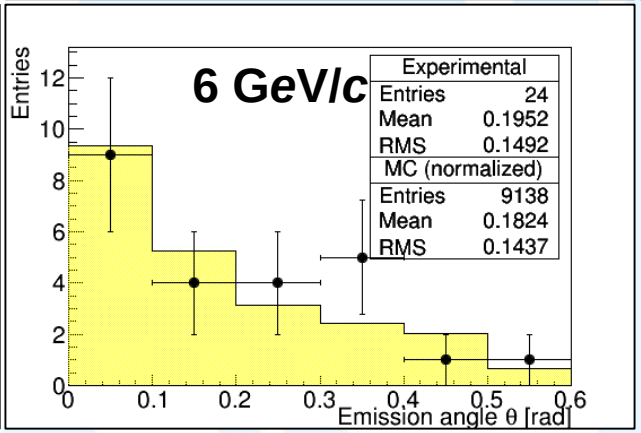
Secondary particle emission angle











Plots : Experimental data
Histogram : Simulated data

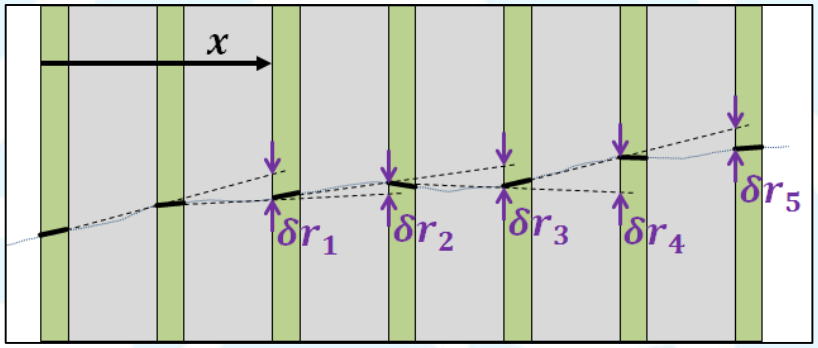
Measurement of secondary particle momentum

- The momenta of secondary tracks are estimated by measuring their multiple Coulomb scattering in the brick.
- We use the coordinate method because it is more accurate when a small multiple scattering signal is expected.

Momentum measurable tracks

At least 14 emulsion films are available for the position measurements.

$$\sigma_r = \sqrt{\frac{\sum \delta r_i^2}{n}} = \frac{1}{2\sqrt{3}} \frac{0.0136\,\mathrm{GeV}/c}{pc\beta} x \sqrt{\frac{x}{X_0}} \left\{ 1 + 0.038\, ln\left(\frac{x}{X_0}\right) \right\}$$



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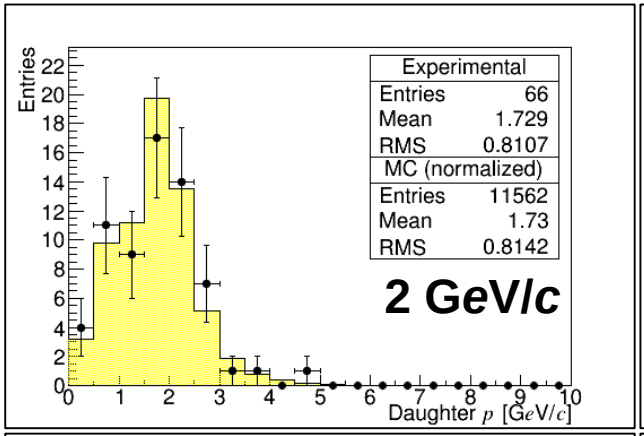
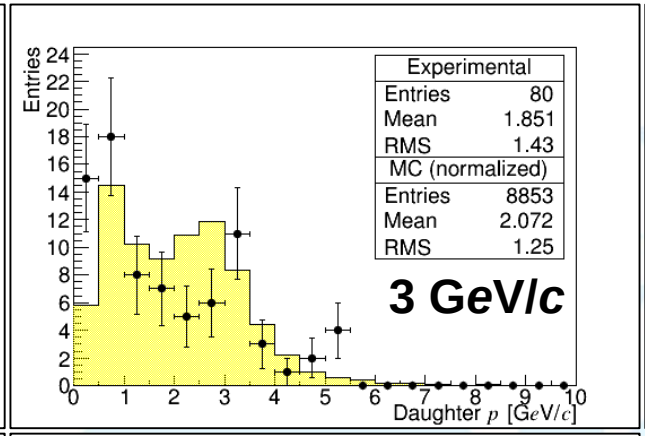
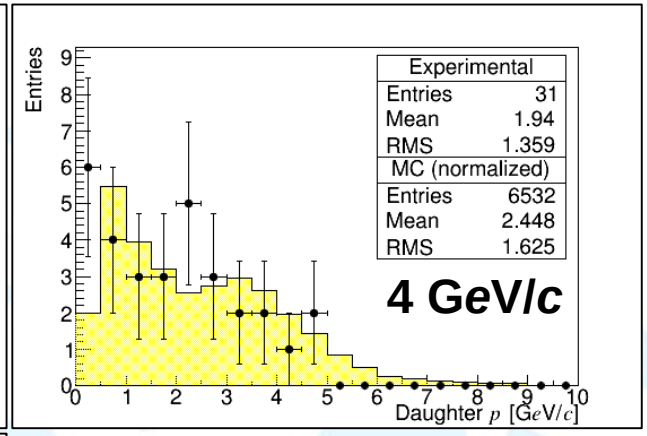
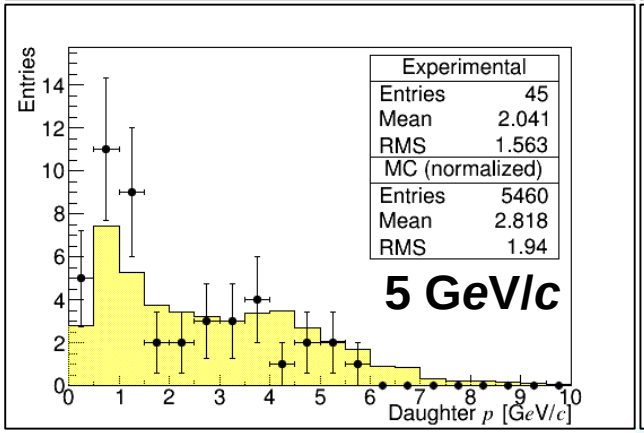
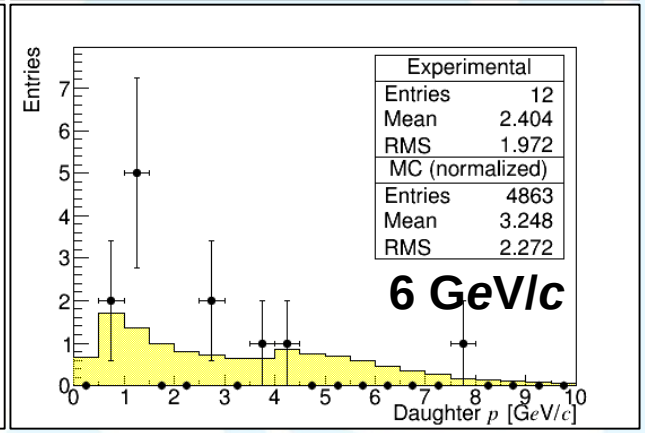
Secondary particle *p*





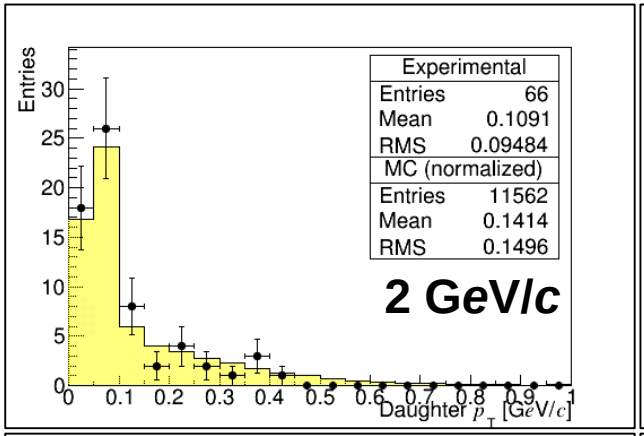


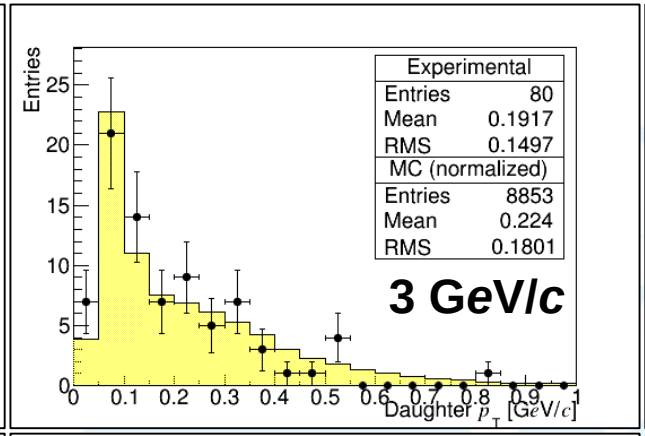


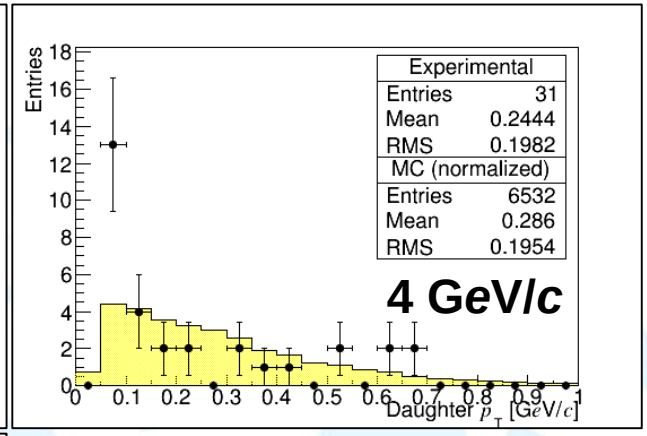


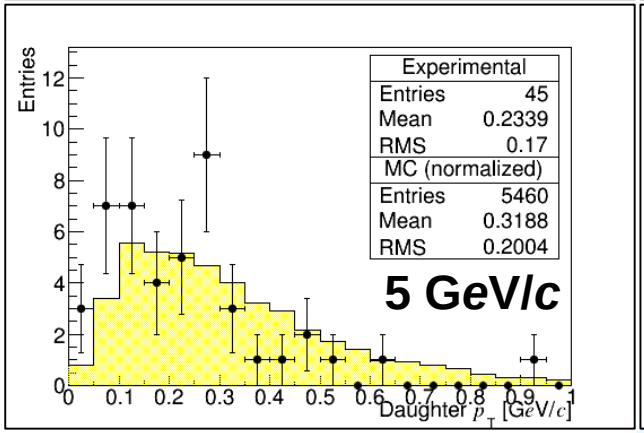
Plots : Experimental data
Histogram : Simulated data

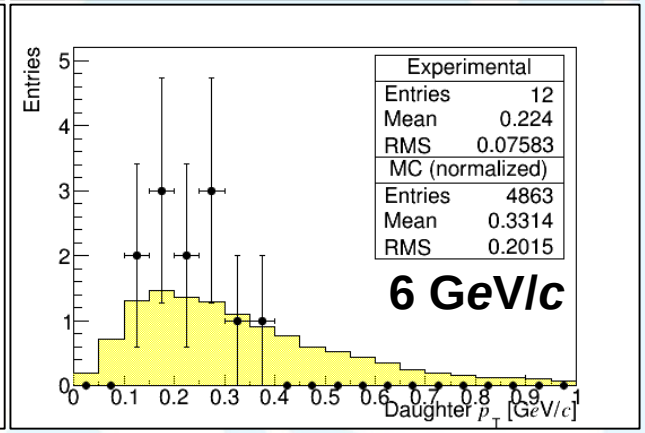
Secondary particle p_T





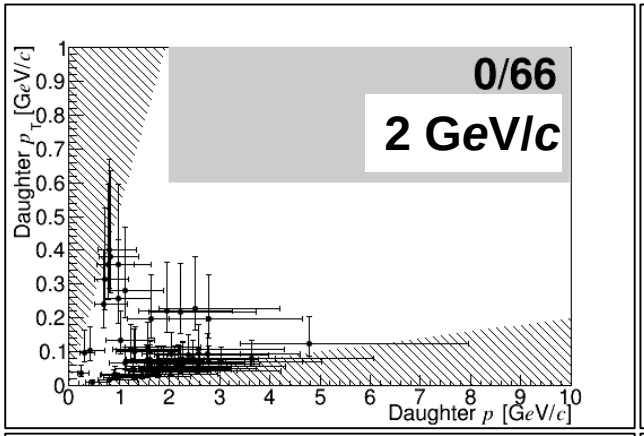


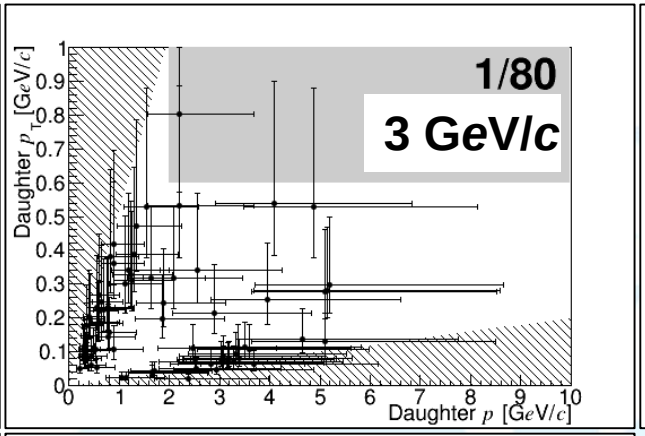


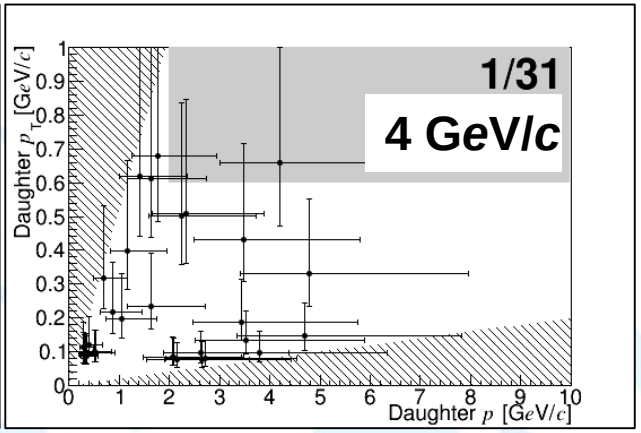


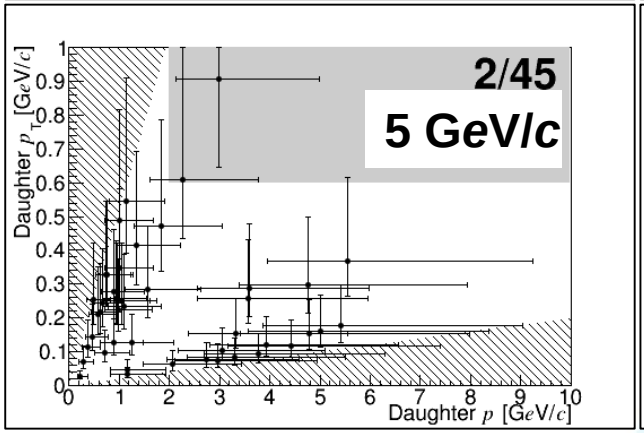
Plots : Experimental data
Histogram : Simulated data

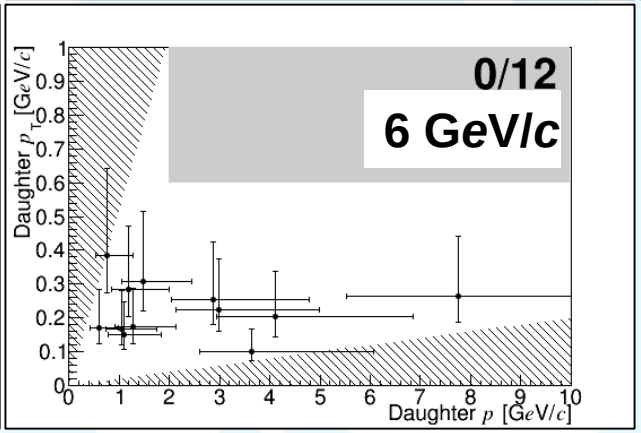
p_T vs. p plot











Plots : Experimental data
Histogram : Simulated data

Statistics of kinematical analysis

Numbers of secondary tracks for which the momentum is measurable

Momentum	2	3	4	5	6	10	Analyzed events
Previous study	12	-	7	-	-	10	29
This study	66	80	31	45	12	-	~234 (~8.1x)

- **More than 8 times the previous data were obtained .**

Upper limits are at 90% C.L.

p > 2 GeV/c, p_T > 0.6 GeV/c ("Golden analysis")

Momentum [GeV/c]	Data			MC		
	Tracks p measurable	Tracks in selection	Fraction [%]	Tracks p measurable	Tracks in selection	Fraction [%]
2	66	0	< 3.38	15393	151	$0.98^{+0.09}_{-0.07}$
3	80	1	$1.25^{+2.76}_{-0.68}$	11594	373	$3.22^{+0.17}_{-0.16}$
4	31	1	$3.23^{+6.71}_{-1.00}$	8747	555	$6.35^{+0.27}_{-0.25}$
5	45	2	$4.44^{+5.36}_{-1.44}$	7142	623	$8.72^{+0.35}_{-0.32}$
6	12	0	< 16.25	6277	641	$10.21^{+0.39}_{-0.37}$

p > 1 GeV/c, p_T > 0.15 GeV/c ("Minimum bias analysis")

Momentum [GeV/c]	Data			MC		
	Tracks p measurable	Tracks in selection	Fraction [%]	Tracks p measurable	Tracks in selection	Fraction [%]
2	66	13	$9.1^{+4.8}_{-2.4}$	15393	3217	$16.2^{+0.3}_{-0.3}$
3	80	27	$26.3^{+5.5}_{-4.3}$	11594	5037	$35.4^{+0.4}_{-0.4}$
4	31	14	$38.7^{+9.2}_{-7.8}$	8747	5343	$52.1^{+0.5}_{-0.5}$
5	45	22	$40.0^{+7.6}_{-6.7}$	7142	5042	$62.1^{+0.6}_{-0.6}$
6	12	10	$66.7^{+10.3}_{-15.2}$	6277	4684	$67.3^{+0.6}_{-0.6}$

Goodness of agreement between Data and MC

- The numbers of secondary particles in the selection domain are too few to evaluate the goodness of the agreement between the Data and the MC.
- We consider an alternative method to estimate the goodness of the agreement same as previous study.
- We select 1-prong hadron interaction events with θ_{kink} cut, which correspond to p_T cut.

$$p_T = p \cdot \sin\theta_{\mathrm{kink}} \sim p \cdot \theta_{\mathrm{kink}} > 0.6 \ \mathrm{GeV}/c \ \text{ or } 0.15 \ \mathrm{GeV}/c$$

Goodness of agreement between Data and MC

***p* > 2 GeV/*c*, p_T > 0.6 GeV/*c* ("Golden analysis")**

***p* [GeV/*c*]**		**2**	**3**	**4**	**5**	**6**
θ_{kink} cut [mrad]		**300**	**200**	**150**	**120**	**100**
Tracks	Data	**22**	**63**	**31**	**61**	**15**
	MC (normalized)	**22.6**	**51.3**	**32.5**	**56.5**	**13.8**
δ_{sys} [%]		**-2.8**	**+22.9**	**-4.7**	**+8.0**	**+9.0**
δ_{stat} [%]		**±21.3**	**±12.6**	**±18.0**	**±12.8**	**±25.8**

$$\delta_{\mathrm{sys}} = \frac{N_{\mathrm{Data}} - N_{\mathrm{MC}}}{N_{\mathrm{MC}}}$$

$$\delta_{\mathrm{stat}} = \frac{1}{\sqrt{N_{\mathrm{Data}}}}$$

- Relative differences δ_{sys} are around 25% and can be understood within the statistical errors δ_{stat}

Goodness of agreement between Data and MC

p > 1 GeV/c, p_T > 0.15 GeV/c ("Minimum bias analysis")

p [GeV/c]		2	3	4	5	6
θ_{kink} cut [mrad]		75	50	37.5	30	25
Tracks	Data	40	93	43	83	23
	MC (normalized)	49.4	86.1	52.8	93.3	22.5
δ_{sys} [%]		-19.0	+8.1	-18.5	-11.0	+2.1
δ_{stat} [%]		±15.8	±10.4	±15.3	±11.0	±20.9

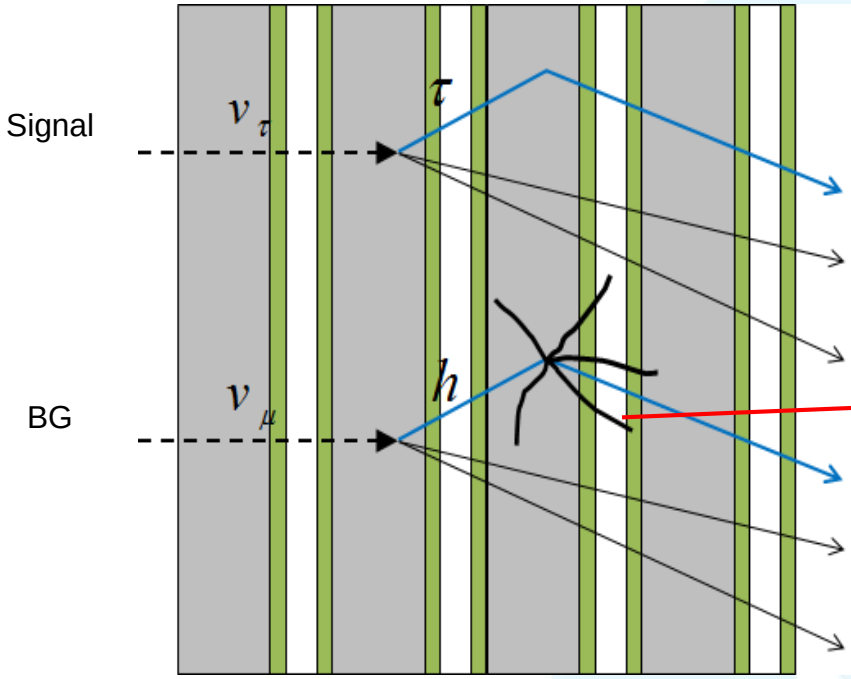
$$\delta_{\mathrm{sys}} = \frac{N_{\mathrm{Data}} - N_{\mathrm{MC}}}{N_{\mathrm{MC}}}$$

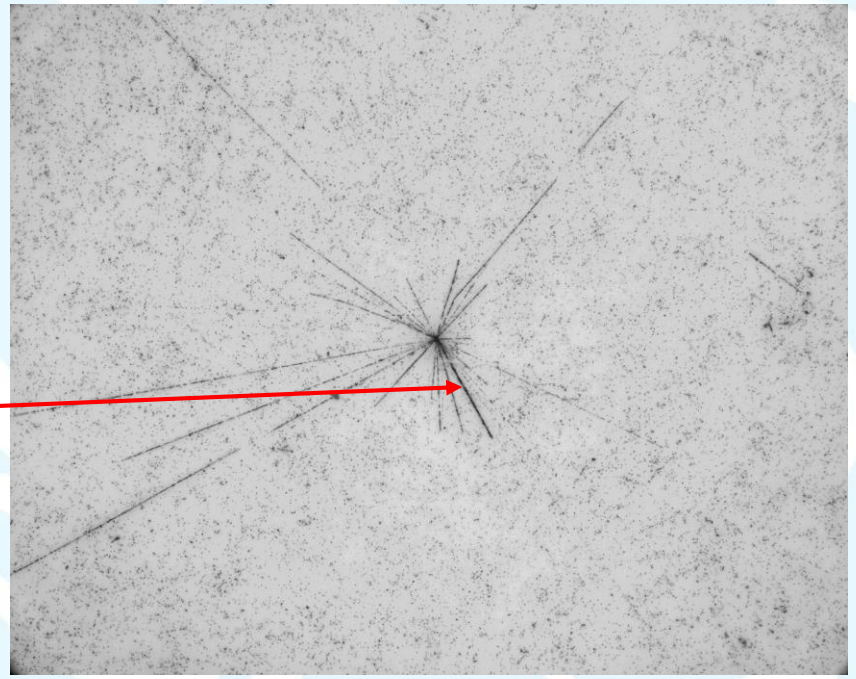
$$\delta_{\mathrm{stat}} = \frac{1}{\sqrt{N_{\mathrm{Data}}}}$$

- Relative differences δ_{sys} are around 20% and can be understood within the statistical errors δ_{stat}

Nuclear Fragments

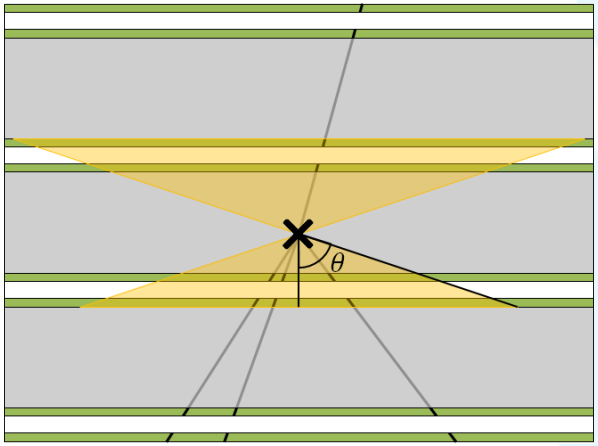
- If a secondary particle has a value of $\beta < 0.7$, the particle is observed as a heavily ionizing track or a nuclear fragment.
- Nuclear fragments emitted from hadron interactions were also sought by a newly developed automatic emulsion scanning system with wider angular acceptance, FTS.

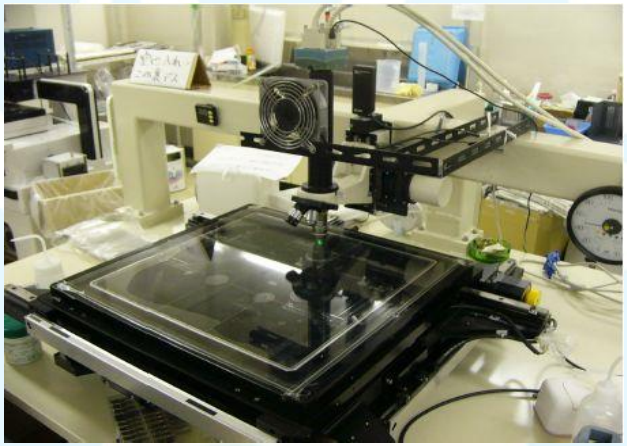


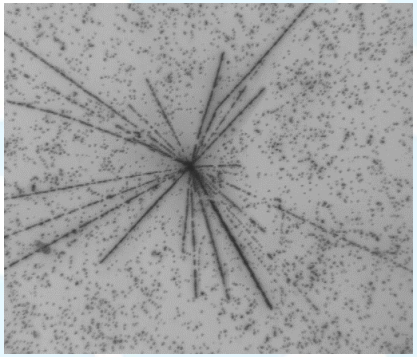


Nuclear fragments search

- 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.







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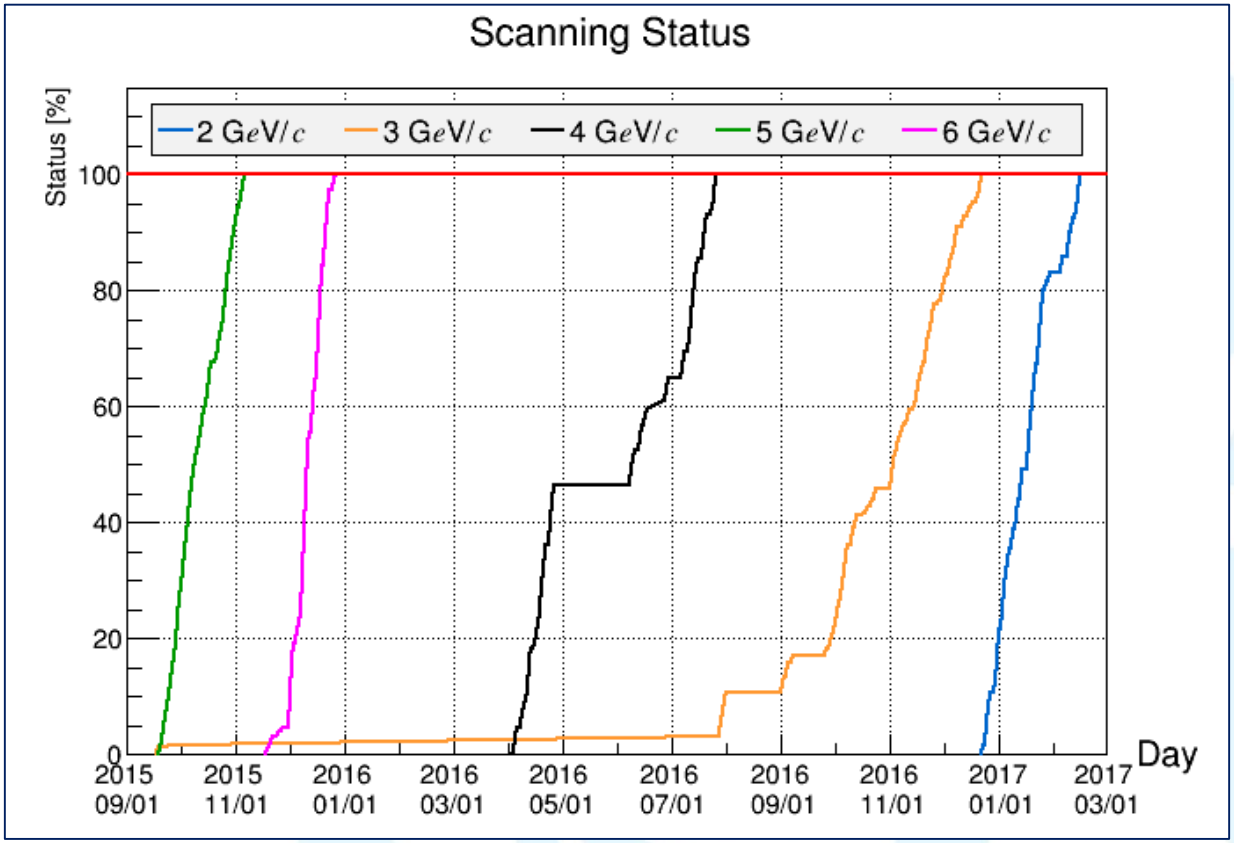
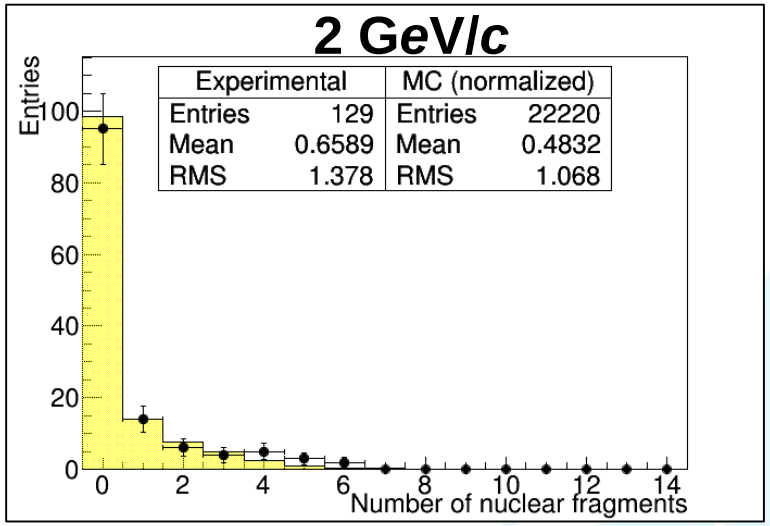
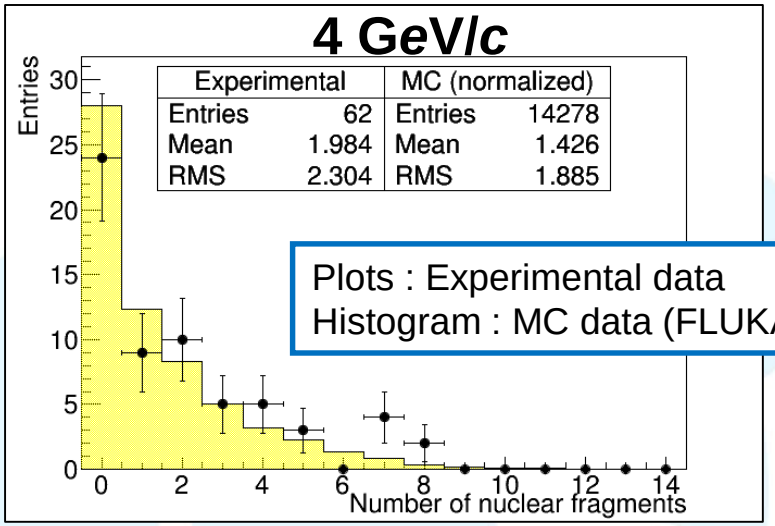
Scanning status



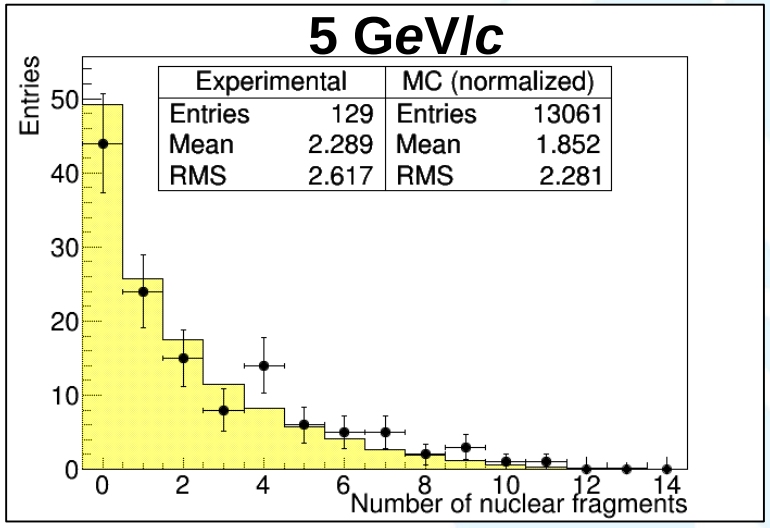
- We finished large angle track scan of all hadron interactions.

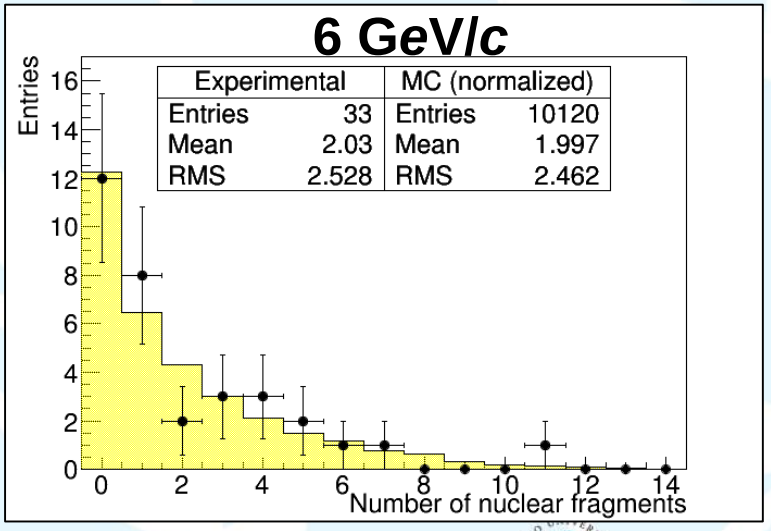
Results (Multiplicity distribution)





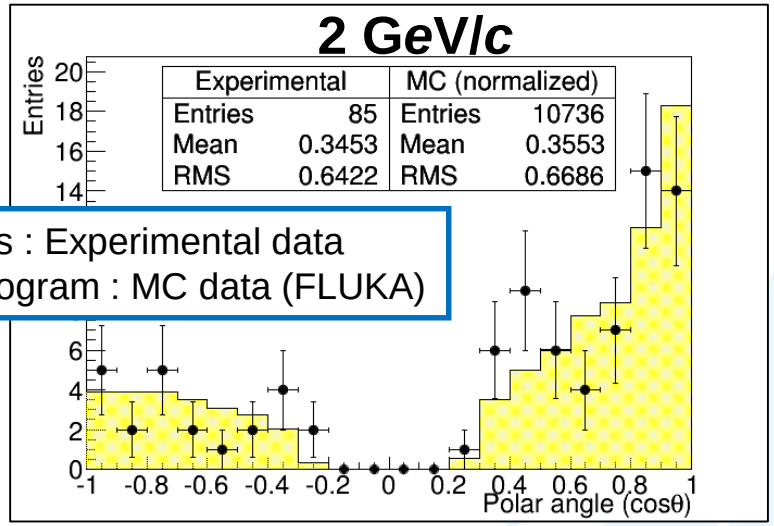
Plots : Experimental data
Histogram : MC data (FLUKA)

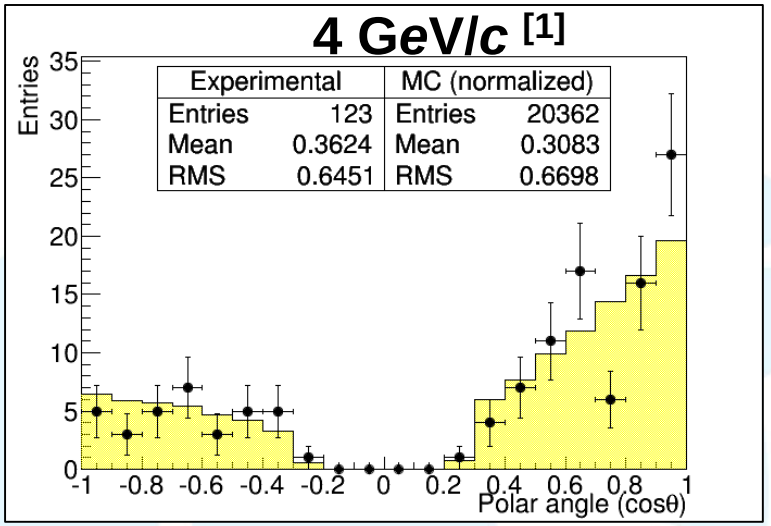


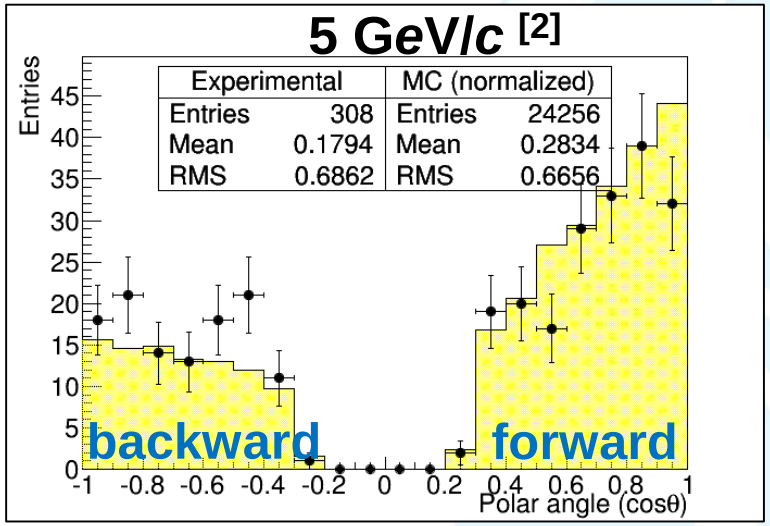


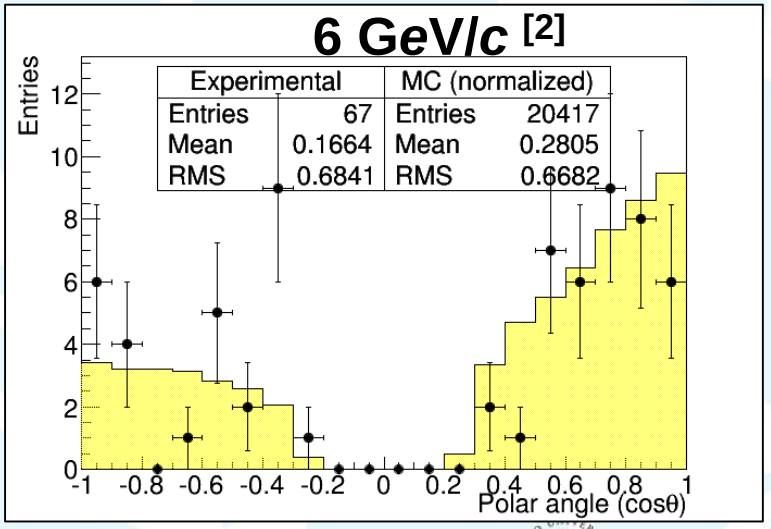
Results (Emission angle distribution)

Plots : Experimental data
Histogram : MC data (FLUKA)

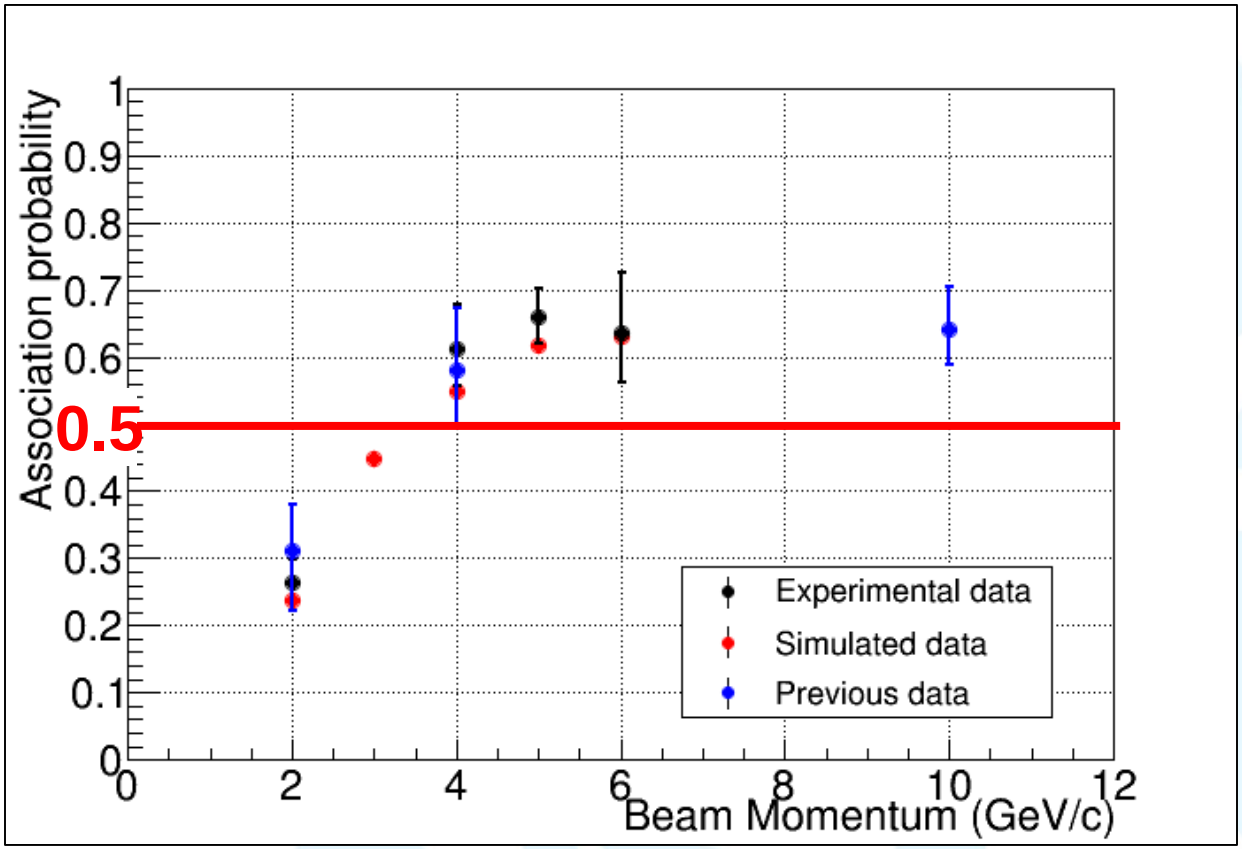








Results (Association probability)



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

Summary

Interaction & Secondary particle search

- We finished the analysis of interaction & secondary particle search for all hadron beam interaction.
- MC data agree roughly well with the experimental data.

Nuclear fragments search

- Except for 3 GeV/c, manual check of nuclear fragments candidate have been done.
- These results agree reasonably well.

Momentum measurement and agreement between Data and MC

- We started the measurement of secondary particle momenta.
- We obtained more than 8 times the previous data.
- Relative differences δ_{sys} are around 20% and can be understood within the statistical errors δ_{stat}.