Honda flux

Sato (Nagoya U.)

14, Sep., 2019 @ Diffuse Workshop on Global Fit

contents

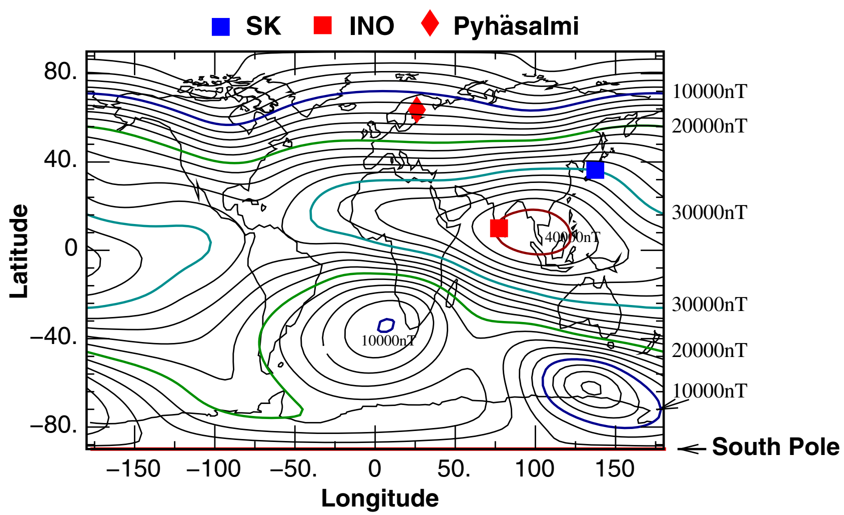
- ATMNC : atm. ν flux calculation code
- attempt to handle had. int. uncertainty by Nagoya group
- ongoing status

Honda's ATMNC

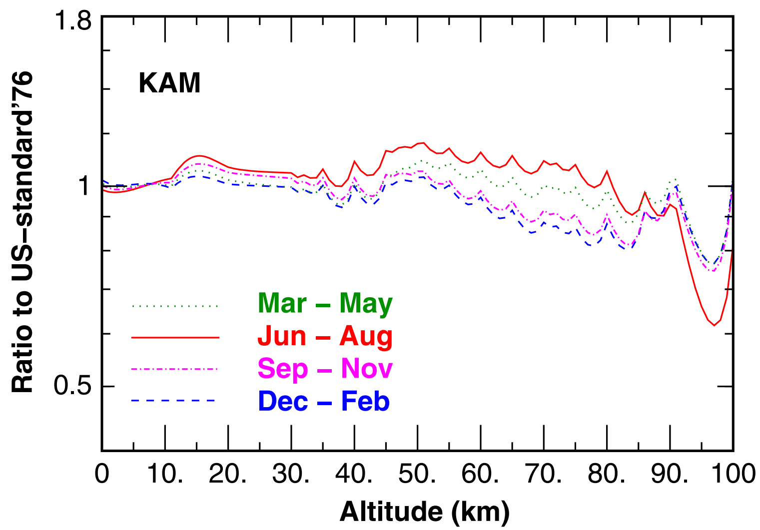
ATMNC: **ATM**ospheric **M**uon **N**eutrino **C**alculation code

developed by M. Honda (U of Tokyo, ICRR)
[PRD 83, 123001(2011) and references in it]

- used in Super-Kamiokande atm. ν analysis
- Full & 3D simulation
- several ideas for high speed computation



geomagnetic field based on **IGRF** model



air density profile based on **NRLMSISE-00**

- for each month to handle seasonal variation

hadronic interaction in ATMNC

ATMNC adopts ***inclusive*** code for speed-up

Beam experiment for hadronic interaction measurement is usually *inclusive*

target **unknown**

$p + A \rightarrow h_{out} + X$

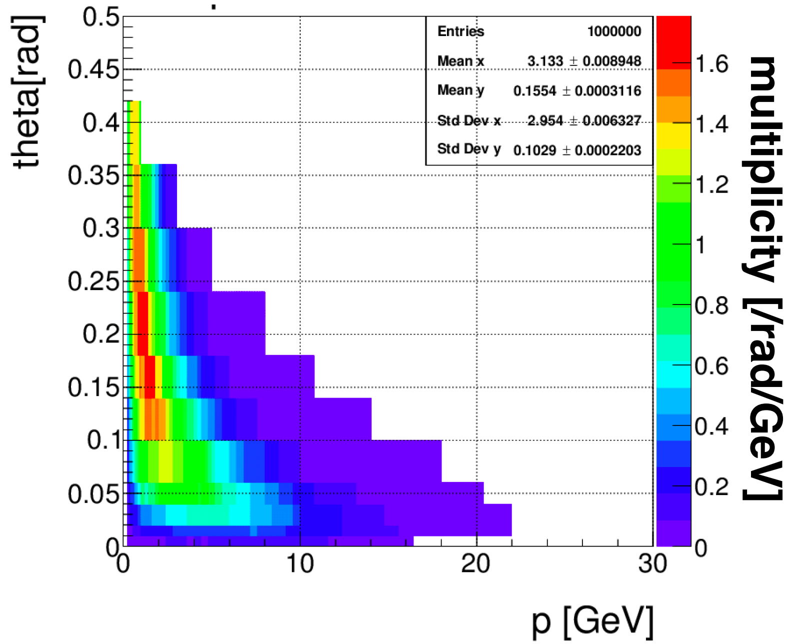
beam particle **observable**

→ only see $\mathbf{h_{out}}$, ignore **X**

what they measure

- multiplicity $\mathbf{n(p_{in})}$ of h_{out}
- $\mathbf{p_{out}}$ distribution of h_{out}
- $\boldsymbol{\theta_{out}}$ distribution of h_{out}

p_{out}-θ_{out} distribution of $p+C \rightarrow \pi^+ + X$ (p=31GeV, from NA61/SHINE)



Hadronic interaction in ATMNC is also *inclusive* cont.

ignore ↓

h_{in} + Air → h_{out} + X

(h_{out} : $\pi^{+,-,0}$, $K^{+,-,0}$, p, n, $\bar{p}$, $\bar{n}$)

ex) π^+ production from p + A

1) generate $N_{\pi+}(p_{in})$ π^+s

2) p_{out} of each π^+ are randomly sampled from E_{out}/E_{in} distribution

3) projectile angle of the π^+ is also sampled from cosθ distribution

… also the same for other particles

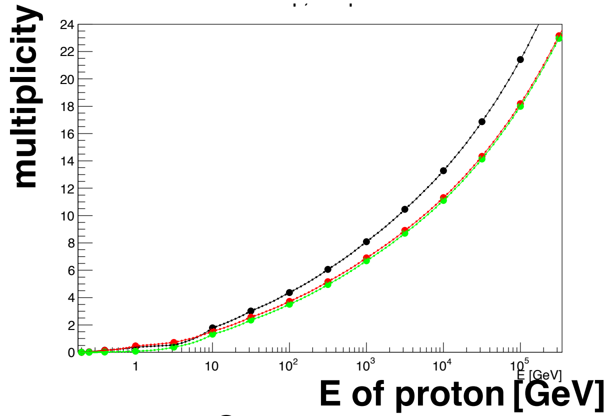
- not correct for single CR event

→ by **accumulating statistics**, **correct flux** is reproduced

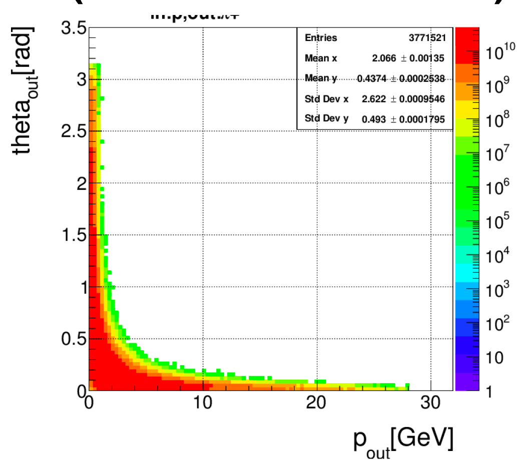
pre-simulated tables

$N(E_{in})$, $E_{out}(E_{in})$, $\theta(E_{in},E_{out})$

multiplicity ($N_{\pi+}$)
for p+air→$\pi^{+,-,0}$ + X



p_{out}-θ_{out}
for p+air→π^+ + X
(visualize as 2D hist.)



o *inclusive* cont.

- made from event generator
  - **JAM** (E_{inc}<$\mathbf{E_{JAM}}$ = 31.6 GeV)
    K. Niita et al., Radiat. Meas. 41, 1080 (2006)
  - **dpmjet3** (E_{inc}>E_{JAM})

multiplicity table, E_{out}/E_{in} table

for **every combination of h_{in} x h_{out}**
- h = p,n,p,n,$\pi^{+,-,0}$,$K^{+,-,0}$ +(e,γ for JAM h_{out})

for **each E_{in}**
- 25 division from 0.1GeV—E_{JAM}
- 10 division from E_{JAM}—10^3 TeV
  - equal space in log scale

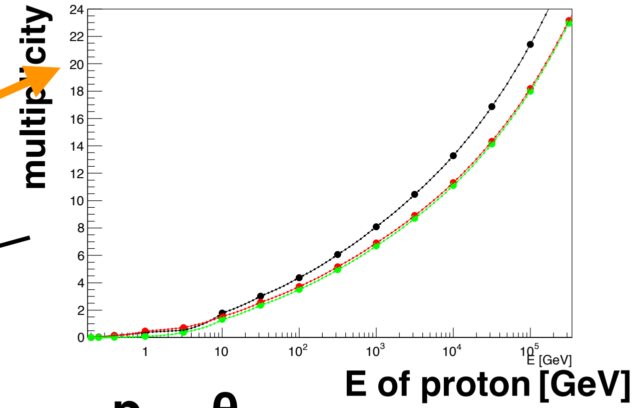
cosθ_{out} table

for **every combination of h_{in} x h_{out}**
- h = p,n,p,n,$\pi^{+,-,0}$,$K^{+,-,0}$ +(e,γ for JAM h_{out})

for **each E_{in} & E_{out}**
- 13 division for E_{in}
- 40 division for E_{out}
  - equal space in log scale

pre-simulated tables

multiplicity ($N_{\pi+}$)
for p+air→π^+ + X



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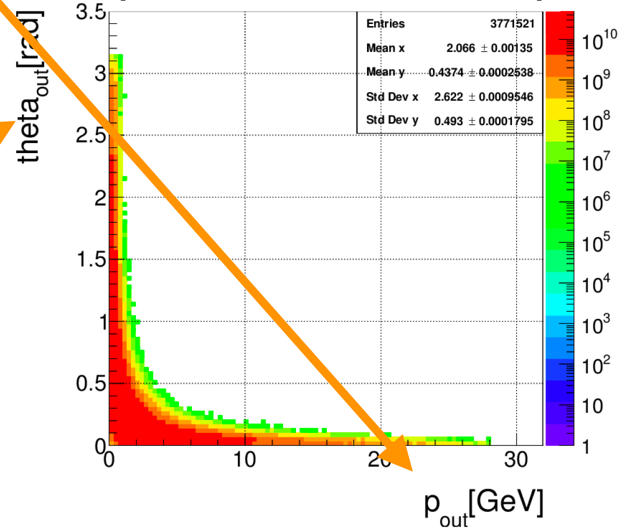
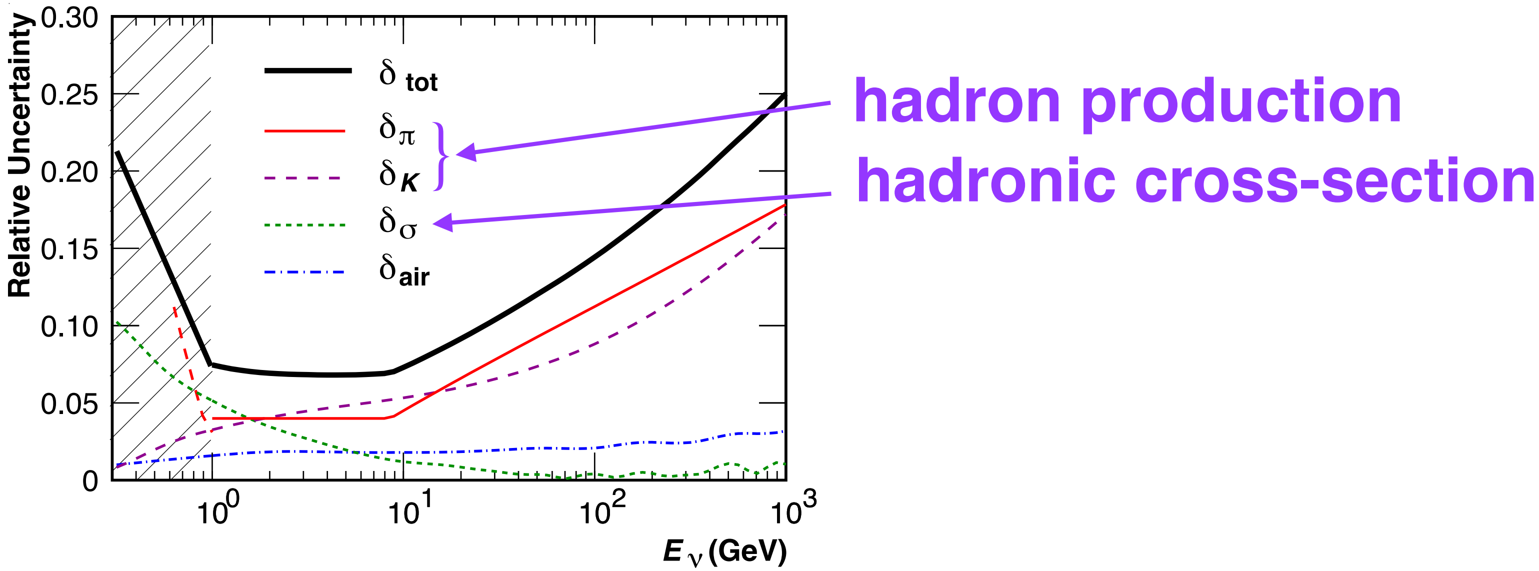


...**ct flux** is reproduced

uncertainty of ATMNC flux

uncertainty of ATMNC flux

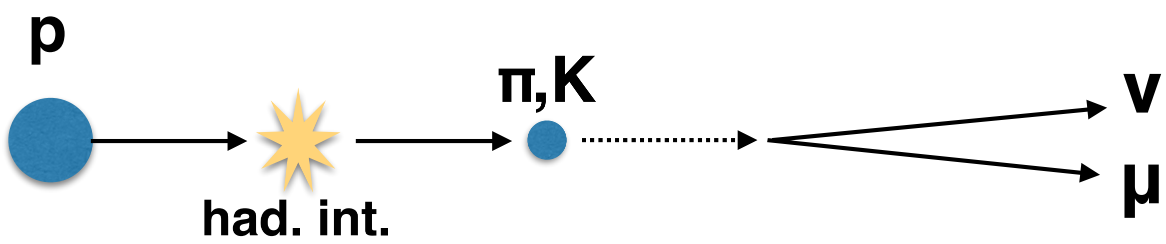
[M. Honda et. al, PRD75, 043006(2007)]



dominant uncertainty of ATMNC comes from the **uncertainty of hadronic interaction**

hadron interaction uncertainty

- Honda-san's study using cosmic-ray muon flux



μ & ν are produced in the same mechanism

→ response of μ flux to the change of hadron interaction strongly correlated to response of ν flux

$$\frac{\Delta\phi_{\mu}}{\phi_{\mu}} \simeq \frac{\Delta\phi_{\nu_\mu}}{\phi_{\nu_\mu}} \simeq \frac{\Delta\phi_{\nu_e}}{\phi_{\nu_e}}$$

Unfortunately, μ correlated to <1GeV ν has too low energy to observe at ground level

→ large uncertainty in <1 GeV

*In TAUP2019 Honda-san shows the possibility that μ at ~4500 m altitude covers the phase space of low-E ν
[arXiv:1908.08765 (astro-ph.HE)]

activity of Nagoya group

to reduce the uncertainty

Nagoya group
Y. Itow
H. Menjo
K. Sato

start the study to incorporate the **hadron production measurement by beam experiment** into ATMNC directly

- Since this April

several measurement are conducted/planned
(mainly for long-baseline ν experiment)

HARP, BNL, NA61/SHINE, EMPHATIC …

→ reflect these measurement by **referring the method used in T2K**

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Maybe the measurement data is insufficient but…

- **will complement the phase space where Honda-san's muon study does not covered**
- **can reveal which phase space is important for atm. ν simulation, and feed back to the future beam experiment**

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a common treatment of sys. error of hadronic interaction
→ can discuss correlation of sys. error between T2K and SK,HK

Maybe the measurement data is insufficient but…

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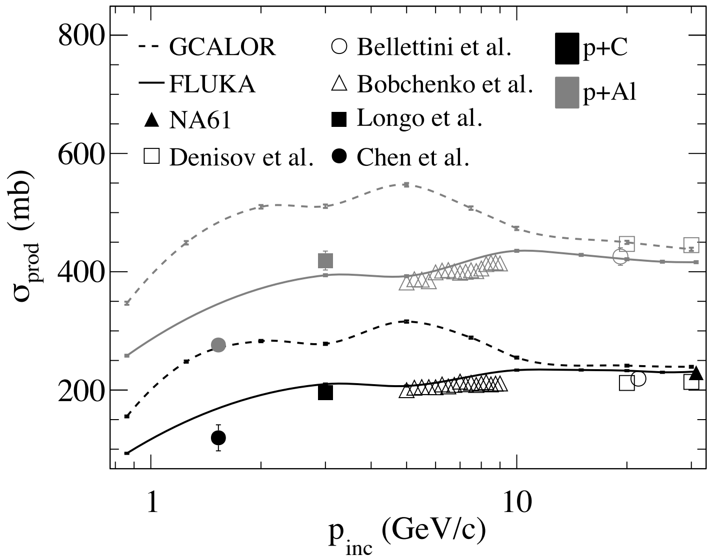
- **can reveal which phase space is important for atm. ν simulation, and feed back to the beam experiment**

weighting method in T2K

They correct their MC by applying weight. **[ref: PRD 87, 012001 (2013)]**

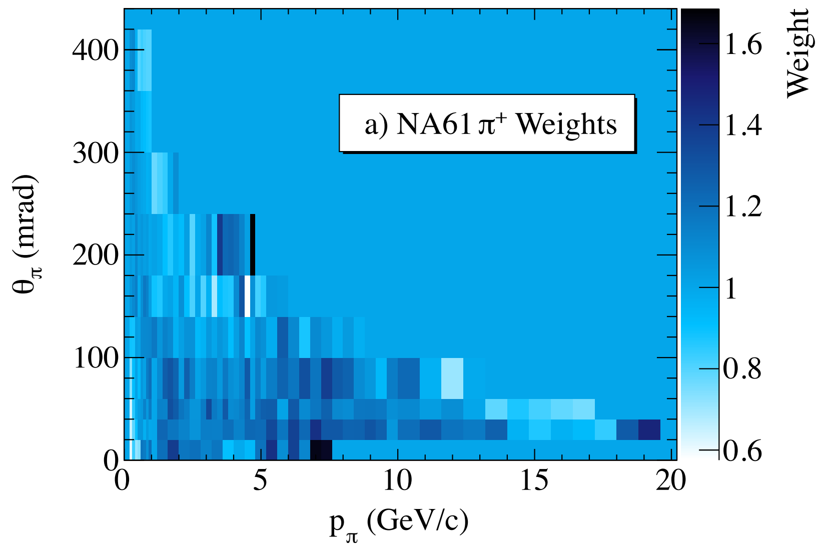
[from the T2K paper]

had.-production cross-section of p + C,Al



[from the T2K paper]

weight for p + C → π^+ + X



atom density **flight length**

$$P = \exp(-\sigma\rho L) \times \sigma_{prod}\rho\Delta L$$

$$W = \frac{P_{Data}}{P_{MC}} = \frac{\sigma_{Data}}{\sigma_{MC}} \exp\{-L\rho\left(\sigma_{Data} - \sigma_{MC}\right)\}$$

multiplicity at (p_{out},θ_{out}) [1/GeV/rad]

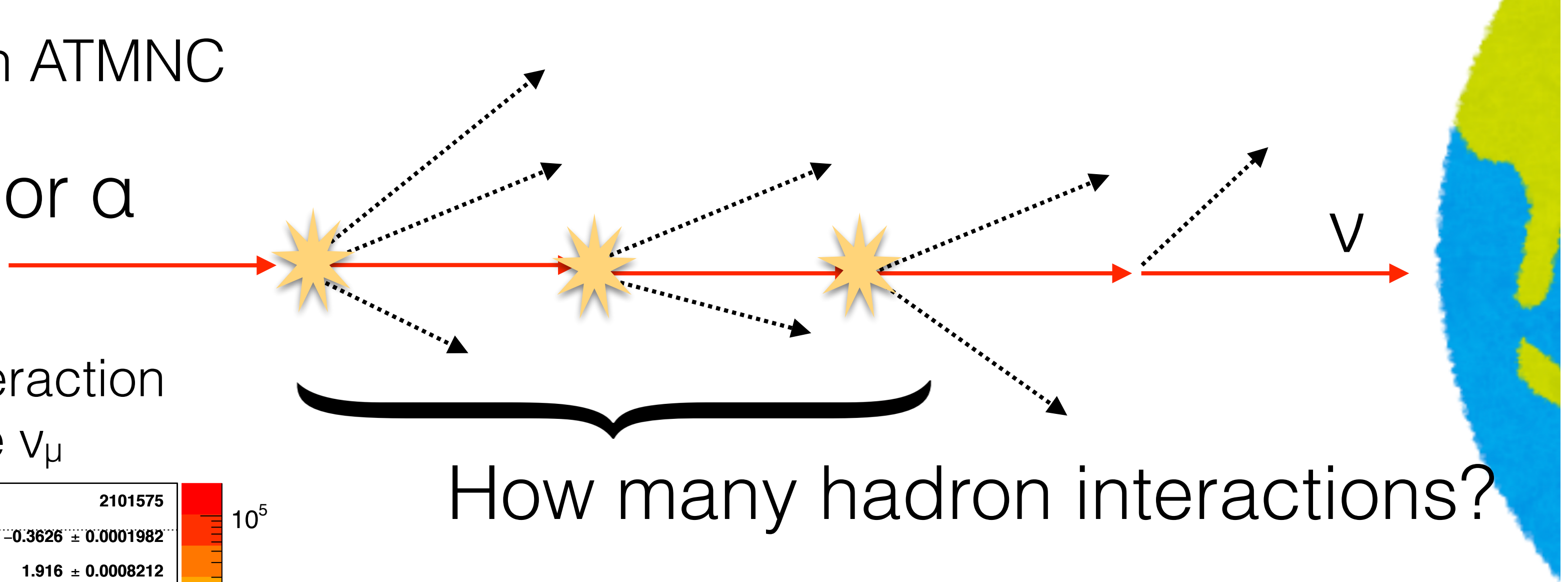
$$W = \frac{\left(\frac{dn}{dpd\theta}\right)_{Data}}{\left(\frac{dn}{dpd\theta}\right)_{MC}}$$

requirement for beam measurement

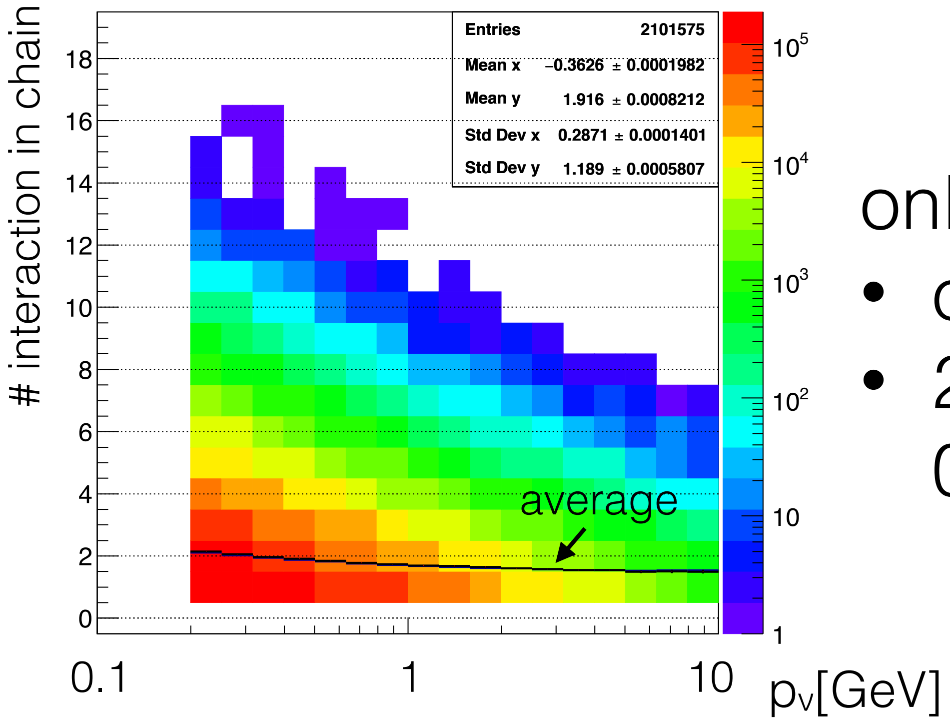
check what beam measurement is needed for atm. ν production

• beamE? • kind of beam particle (h_{in}) and observable particle (h_{out})?

simulation with ATMNC



# of hadron interaction to produce ν_μ



only a few between the 1ry and ν

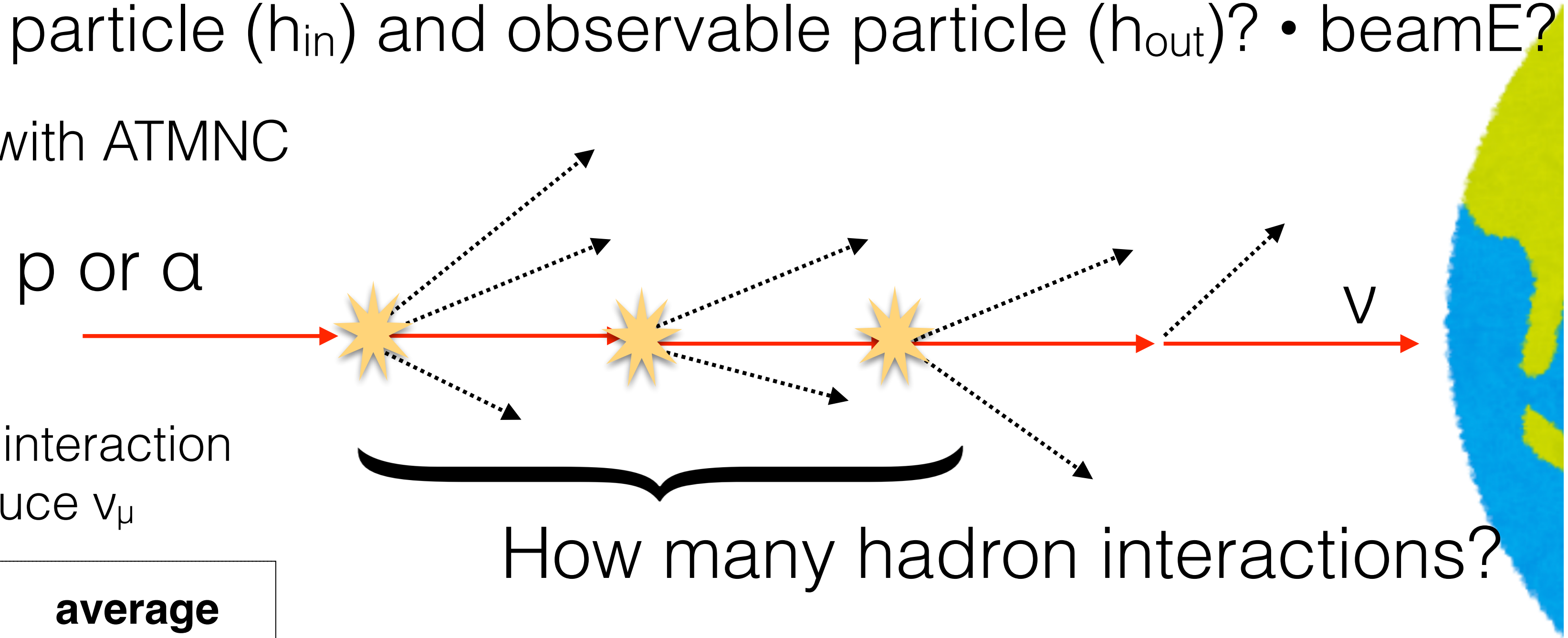
- of course 1ry interact once
- 2nd, 3rd,… hadrons also induce 0.5-1.2 times interaction

requirement for beam measurement

check what beam measurement is needed for atm. ν production

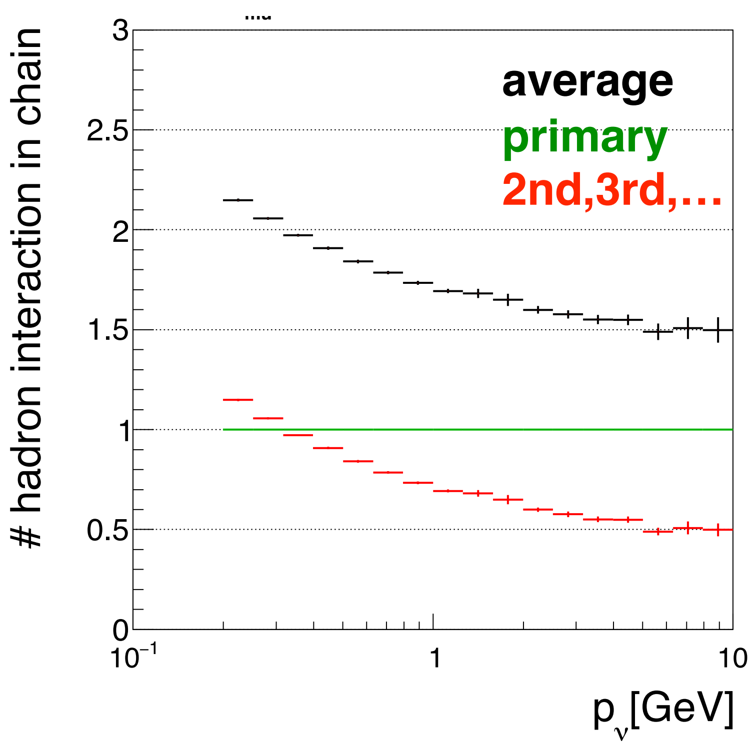
- kind of beam particle (h_{in}) and observable particle (h_{out})? • beamE?

simulation with ATMNC



How many hadron interactions?

# of hadron interaction to produce ν_μ

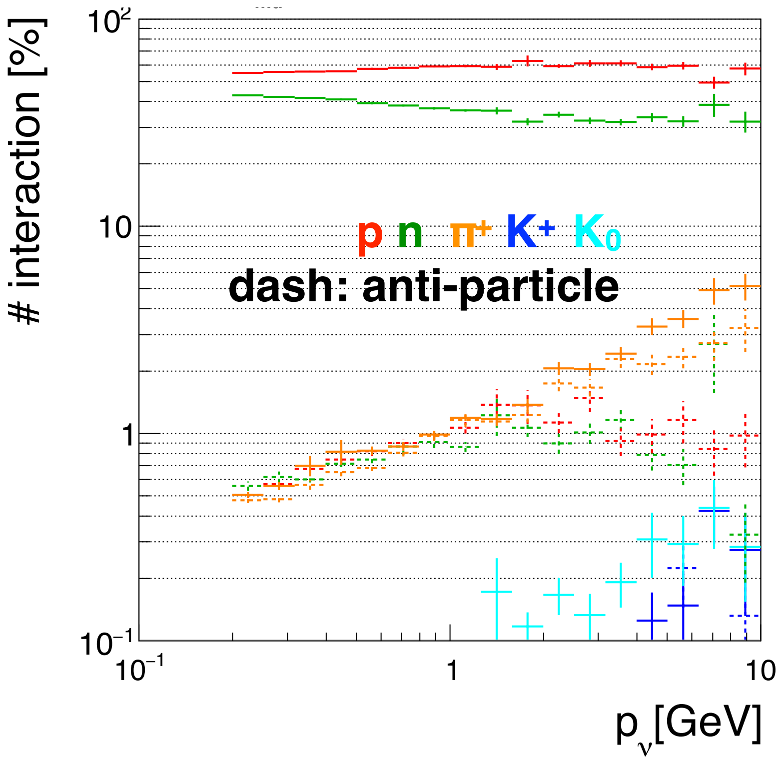


only a few between the 1ry and ν

- of course 1ry interact once
- 2nd, 3rd,… hadrons also induce 0.5-1.2 times interaction

cont.

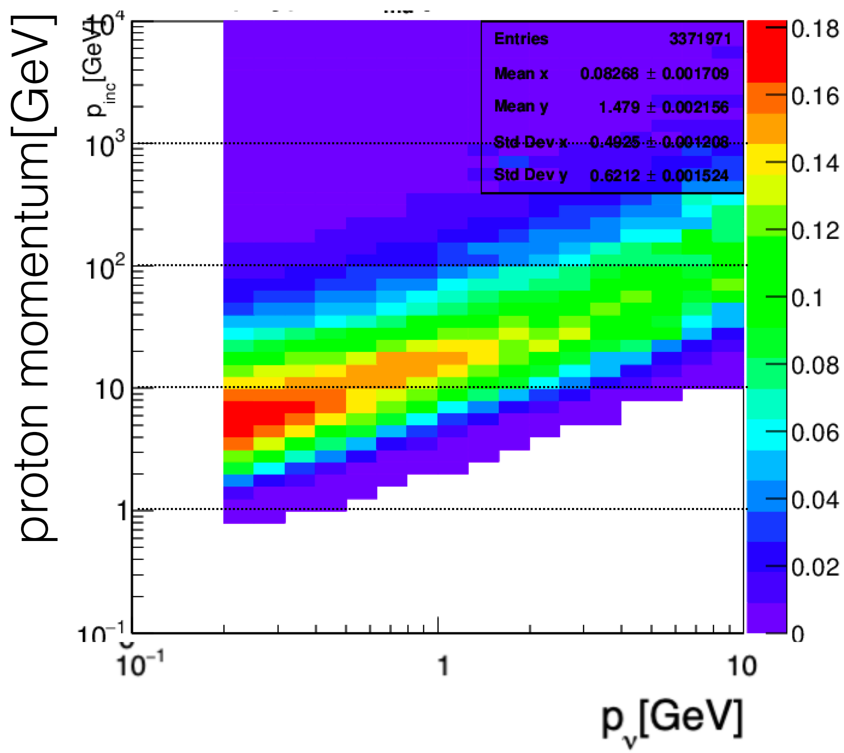
particle type of 2,3,…-th hadron causing hadronic interaction



In sub- or multi- GeV region, p,n is dominant

beam particle : p

incident p,n momentum involved in hadron interaction in ν_μ chain

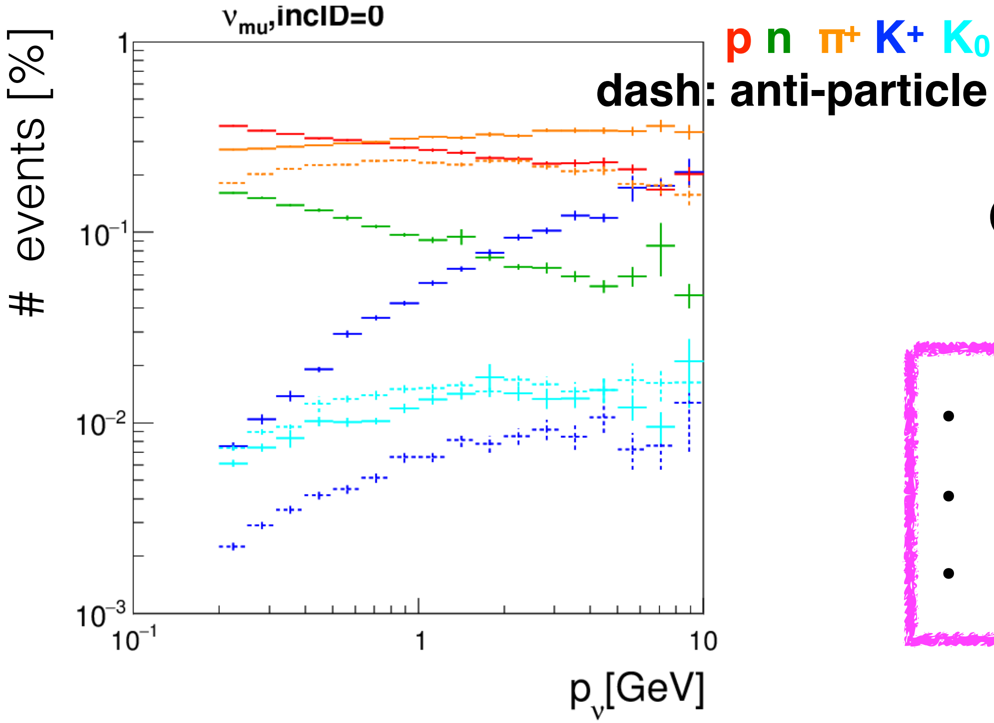


peak of the incident p & n momentum ranges 5—100 GeV

beam energy : ~5—100 GeV

suitable beam measurement

particle emitted from hadron interaction in ν_μ chain (incident particle: proton)



kind of emitted particle

- π^{+-},p,n
- K^{+-} also contributes

observed particle : $\pi^{\pm}$, $K^{\pm}$, p

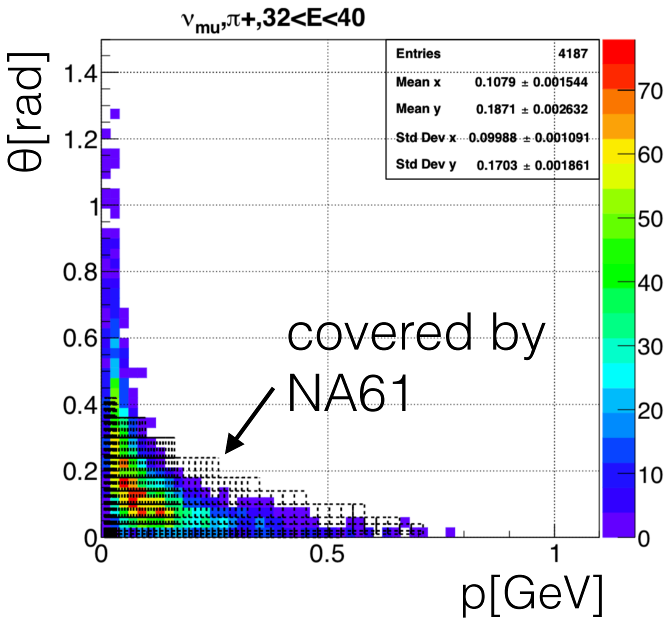
- **beam particle: p**
- **observed particle: p,π,K**
- **beam energy: ~5—100 GeV**

	target	beam P [GeV]	h_{out}	ref.
HARP	Be	8.9	π^+	Eur. Phys. J. C52(2007)
HARP	C	12	π^+,π^-	Astr. Phys. 29 (2008) 257
NA61/SHINE	C	31	p,π^{+-},K^{+-}	Eur. Phy. J. C76 (2016)
BNL	Be	6.4,12.3,17.5	π^+,π^-	PRC77 015209 (2008)

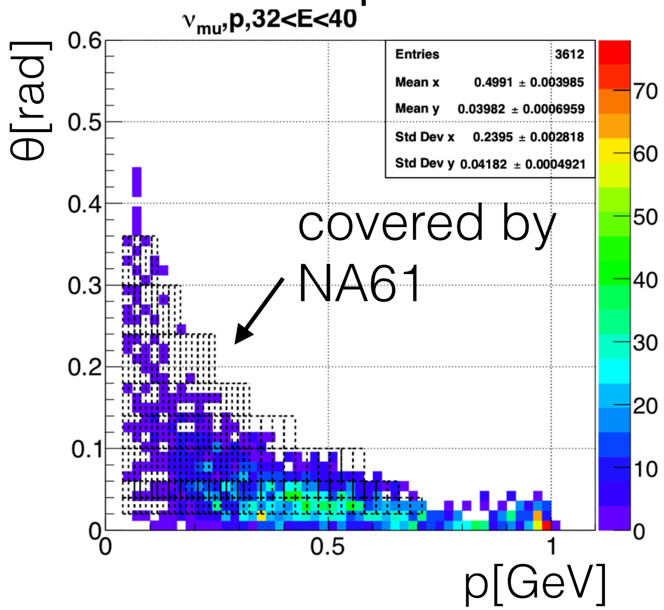
Does measurement cover phase space?

$32 < p_{in} < 40$ GeV

$h_{out} = \pi^+$

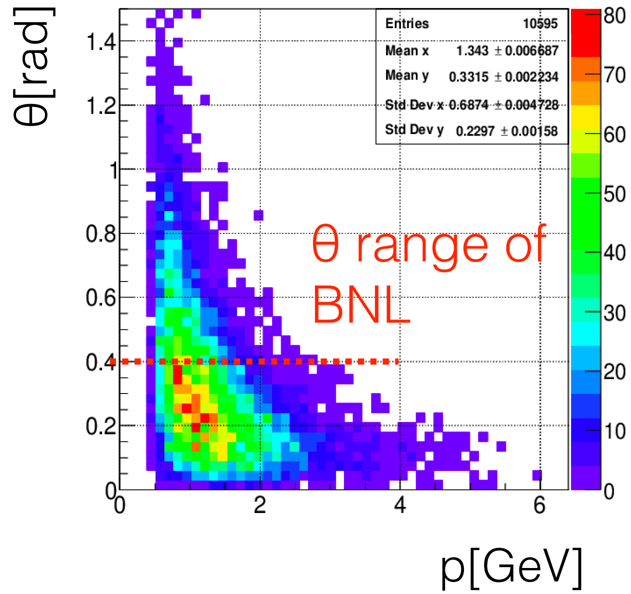


h_{out} = proton



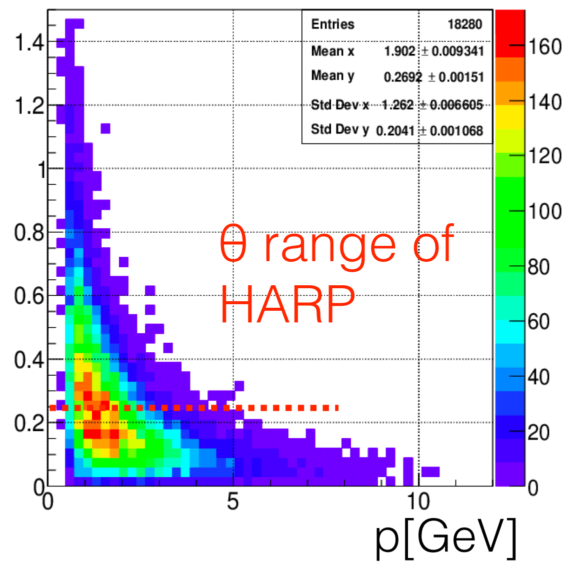
$4 < p_{in} < 8$ GeV

$X_{out} = \pi^+$



$8 < p_{in} < 14$ GeV

$X_{out} = \pi^+$



We need some parameterization

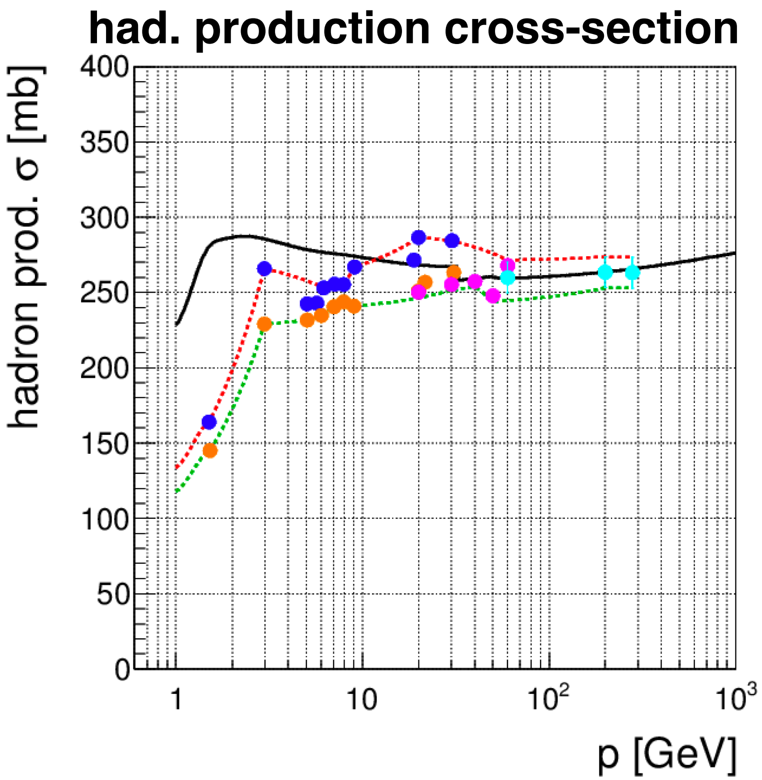
- to cover phase space
- to scale to different incident energy

current status

apply weighting method to ATMNC

Weighting online is too time-consuming
→ restore h_{in}, $\mathbf{p}_{in}$, h_{out}, $\mathbf{p}_{out}$, $\mathbf{x}_{vtx}$ of all hadron interaction related to ν hitting the detector
→ apply weight at offline

Now finished to implement the weight for cross-section

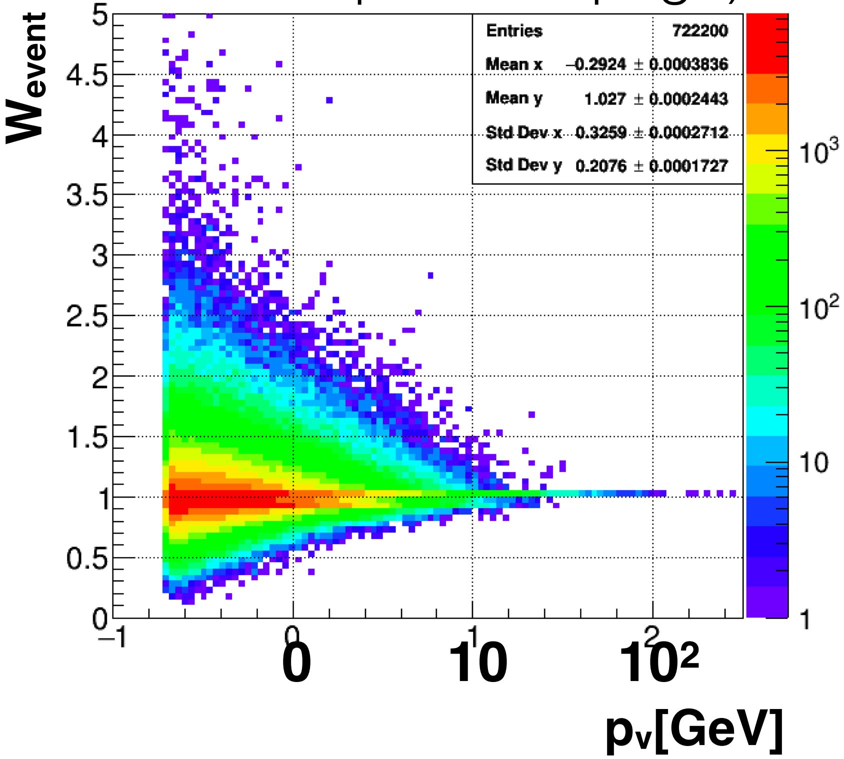


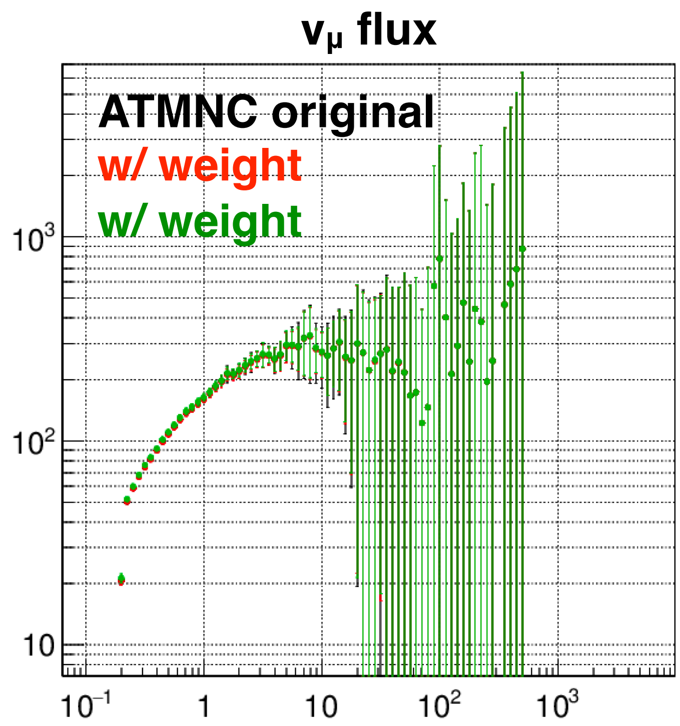
ATMNC (=σ_{MC})
p+Al data (from T2K paper [PRD 87, 012001 (2013)])
p+C data (from T2K paper [PRD 87, 012001 (2013)])
Denisov et. al. [Nucl. Phys. B61, 62 (1973)]
Carroll et. al. [PLB80, 3 (1979)]
--- & --- :to calculate weight (=σ_{Data})

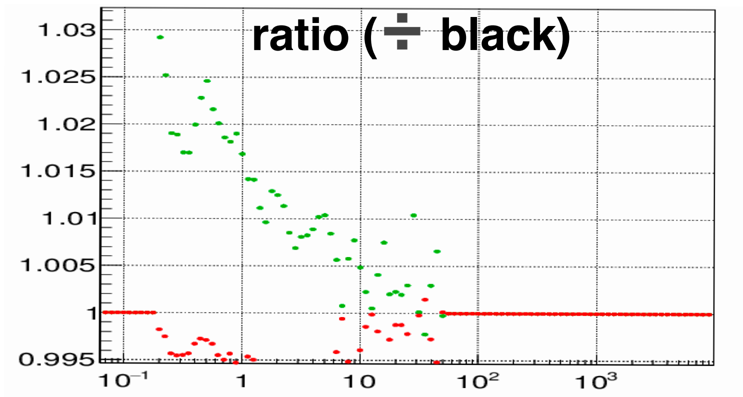
$$W = \frac{\sigma_{Data}}{\sigma_{MC}} \exp\{-L\,(<\rho\sigma_{Data}> - <\rho\sigma_{MC}>)\}$$

impact of the weight for cross-section

weight (based on the green line in the previous page)

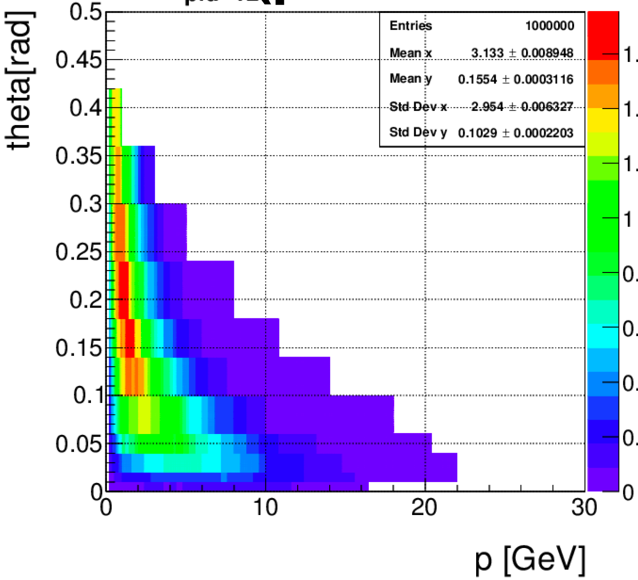






next step: weight for p-θ

NA61 (p_{beam}=31GeV)



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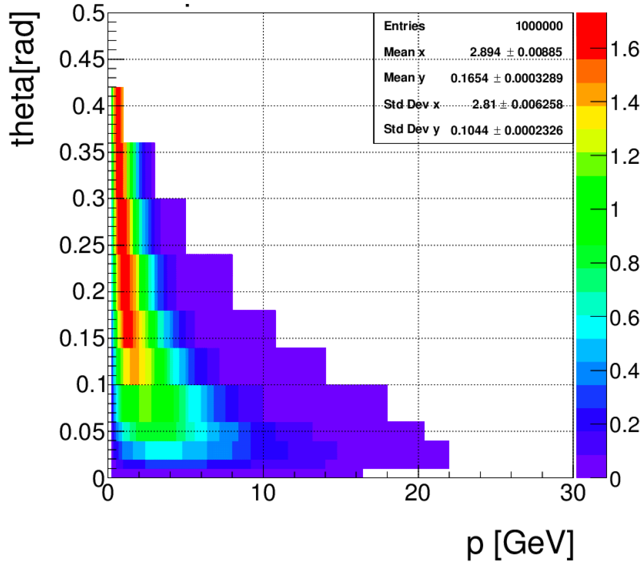
ATMNC (p_{in}=31GeV)



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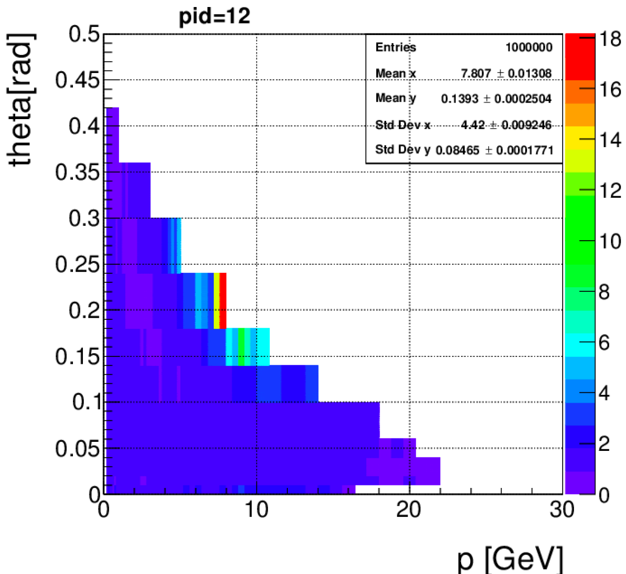
Weight table (NA61 / ATMNC)



to do (in the next 1-2 months)

- make tables for HARP & BNL
  - parameterization to cover shortage of measured phase space
- scale to different beam energy

Then, evaluate how the uncertainty of beam experiment measurement propagate to ν flux uncertainty.

summary

- Honda's ATMNC
  - Full & 3D simulation code to calculate atm. ν flux
  - inclusive hadron interaction for speed up
  - main uncertainty comes from hadronic interaction
- activity of Nagoya group
  - incorporate the beam measurement for hadron production into ATMNC
    - implementing T2K-style weight
      - enables common treatment of the sys. uncertainty of hadronic interaction between T2K and SK
- current status
  - check the required phase space
  - implement the weight for cross section
  - now preparing the weight for p-θ distribution