

# Energy calibration

**for higher energy physics analyses  
(atmospheric and accelerator neutrino oscillation,  
proton decay, etc.)**

S.Mine(UCI)

- Review of SK calibration
- Toward HK

# Momentum (energy) reconstruction (SK-IV)

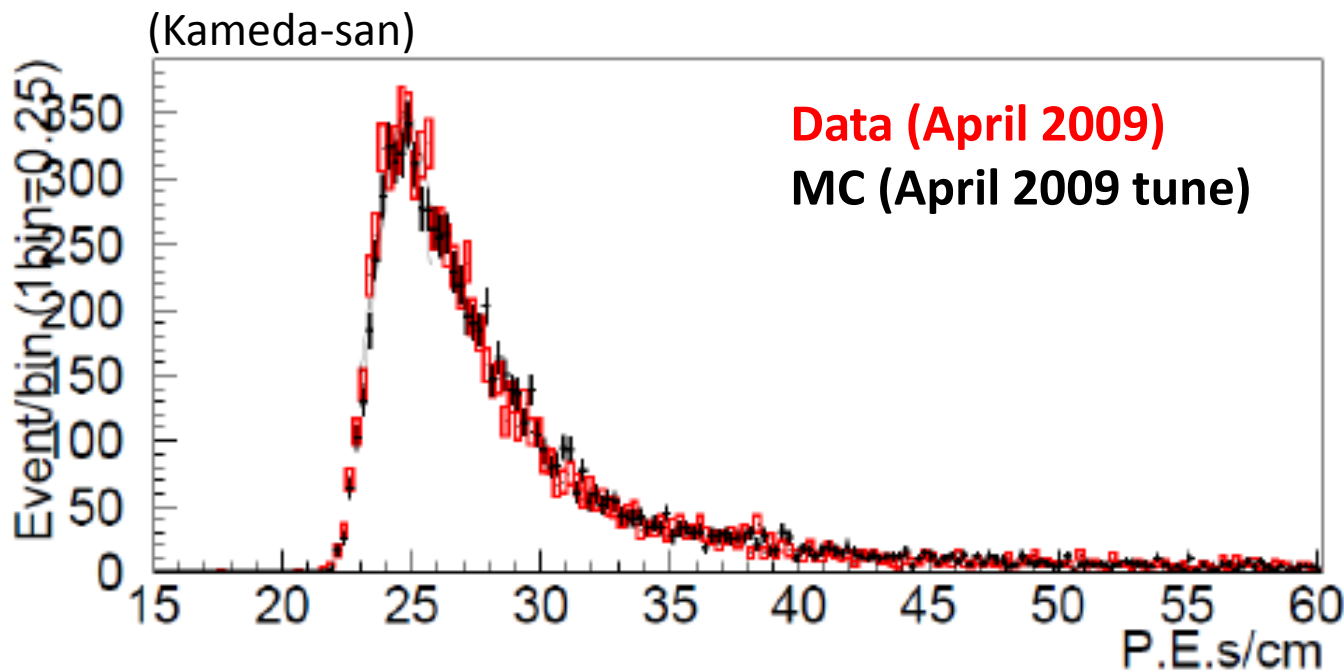
$$\begin{aligned}
 & \text{corrected charge } RTOT = \frac{\text{PMT gain correction } G_{MC}}{G_{data}(t)} \\
 & \times \left[ \alpha \times \sum_{\theta_{i,n} < 70^\circ, -50ns < t_i < 250ns} \left( \text{observed PMT charge } q_{i,n} \times \text{light attenuation correction } \exp\left(\frac{r_i}{L'(t)}\right) \times \text{PMT acceptance correction } \frac{\cos(\theta_i)}{f(\theta)} \right) \right. \\
 & \quad \left. - \sum_{\theta_{i,n} < 70^\circ} S_i(L_{scat}, L'_{attn}(t)) - \sum_{\theta_{i,n} < 70^\circ} R_i(L'(t)) \right] \\
 & \quad \text{scattered light subtraction} \qquad \qquad \qquad \text{reflected light subtraction}
 \end{aligned}$$

- Conversion from *RTOT* to momentum is done by using momentum table generated with MC for each particle type

# Energy calibration procedure

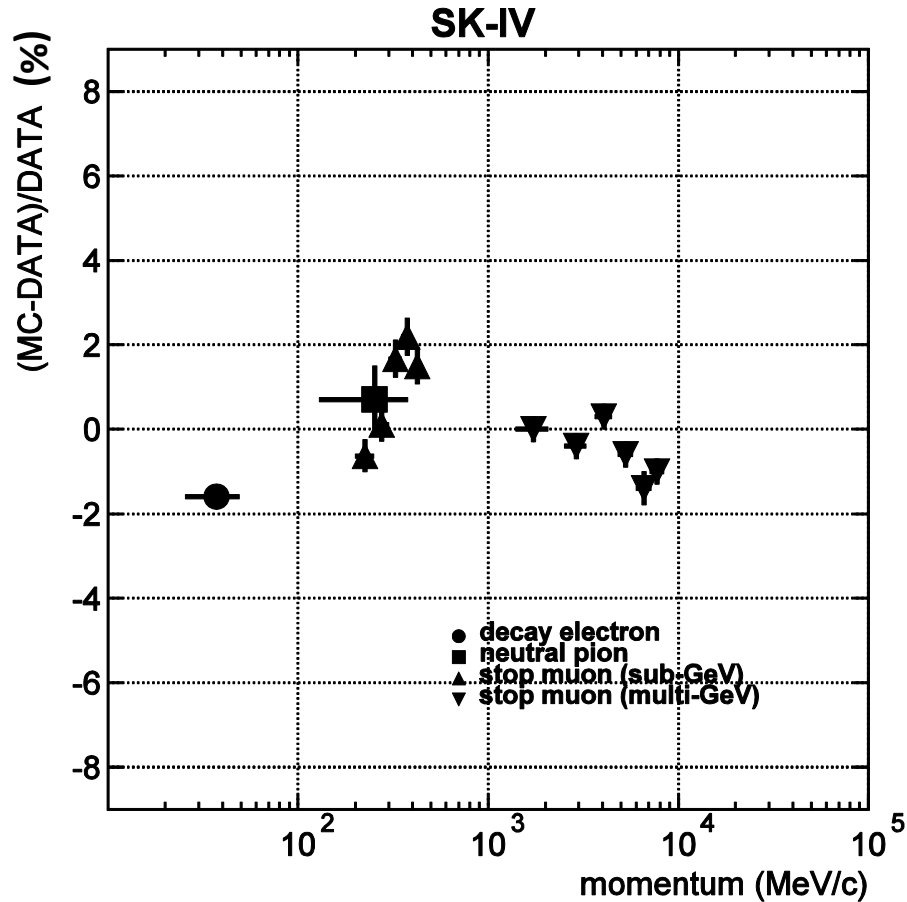
- Initial SK detector simulator (SKDETSIM) tune (see detail in Hide,Hiro's talks)
  - QE, SPE shape, Q-linearity, etc. for each PMT
  - Light scattering/absorption in water, reflection at PMT/blacksheet
- Global photon detection efficiency tune in SKDETSIM using cosmic ray through going muons
- The energy scale check with cosmic ray stopping muons, decay electrons, and  $\pi^0$ s from atm.- $\nu$  interactions
  - Global momentum scale tune typically done at end of each SK experiment (*not done yet in SK-IV*)

# Cosmic ray thru- $\mu$ charge / track



Data(pe/cm)	MC(pe/cm)	(MC-Data) / Data
$24.75 \pm 0.08$	$24.71 \pm 0.05$	$-0.2 \pm 0.4\%$

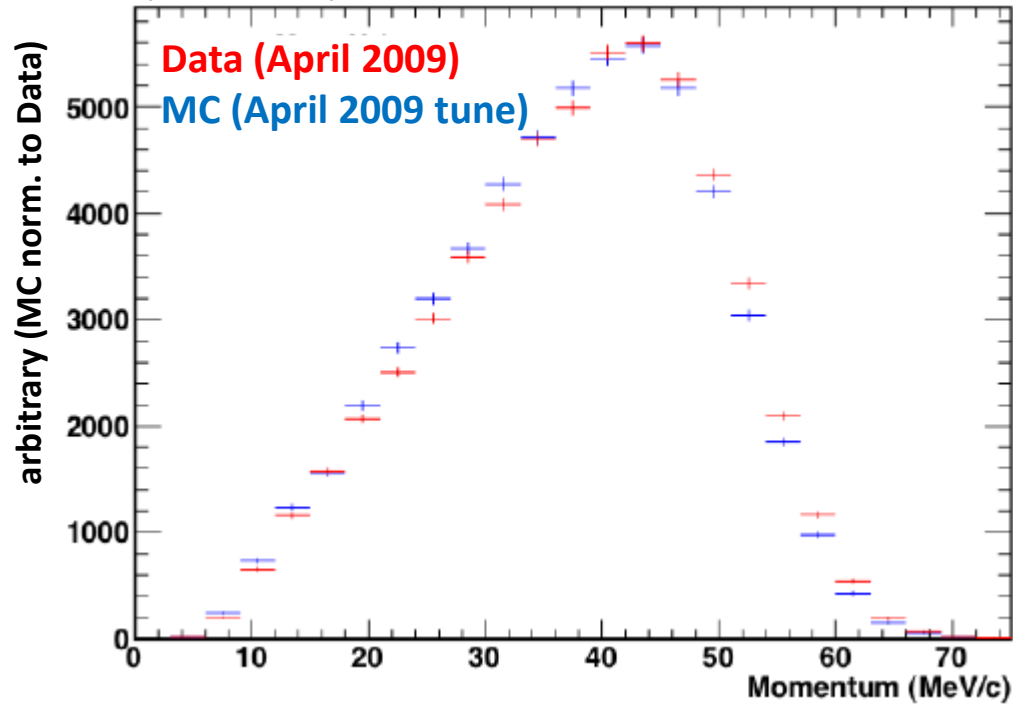
# Absolute energy scale check in SK-IV



**absolute  
scale error:  
2.2%**

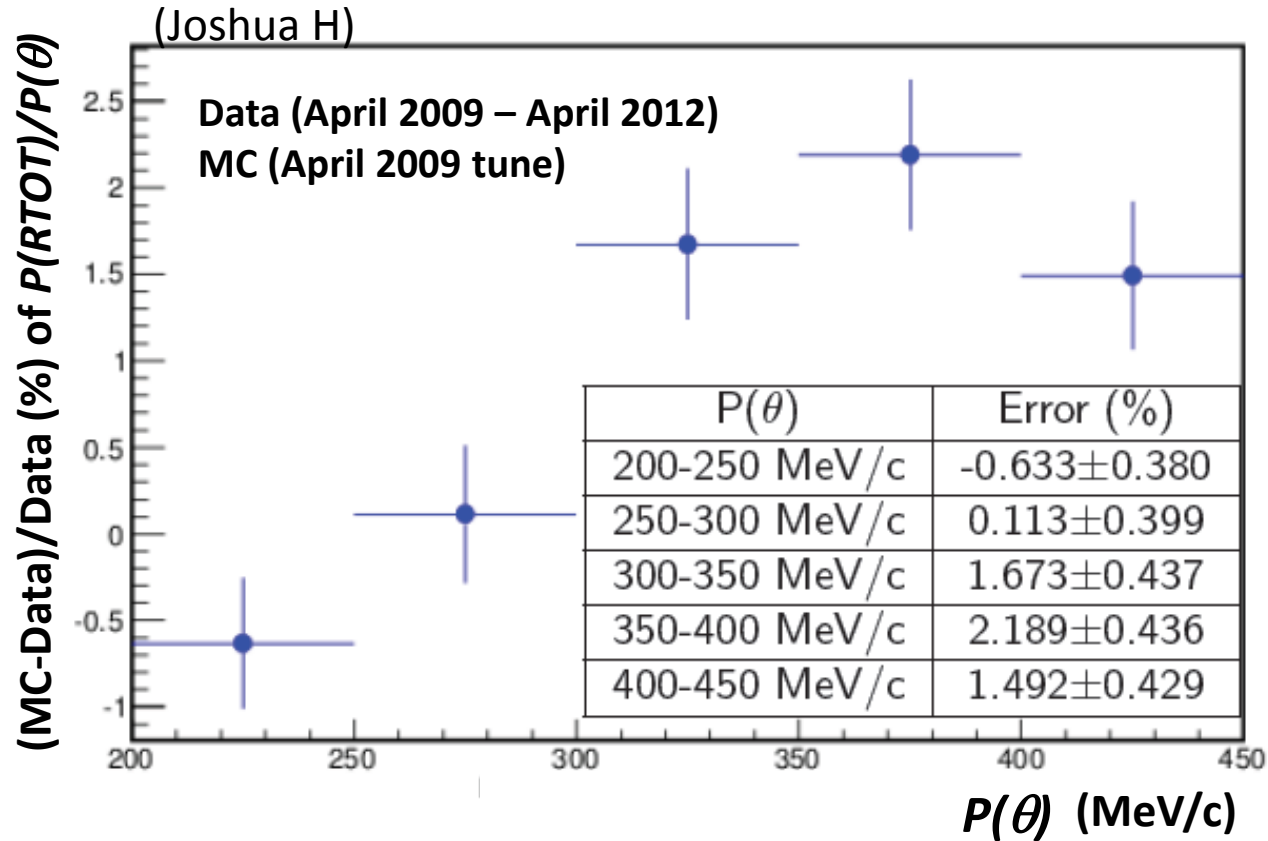
# Decay electron

(Joshua A)



Data(MeV/c)	MC(MeV/c)	(MC-Data) / Data
$37.78 \pm 0.05$	$37.18 \pm 0.05$	$-1.6 \pm 0.2\%$

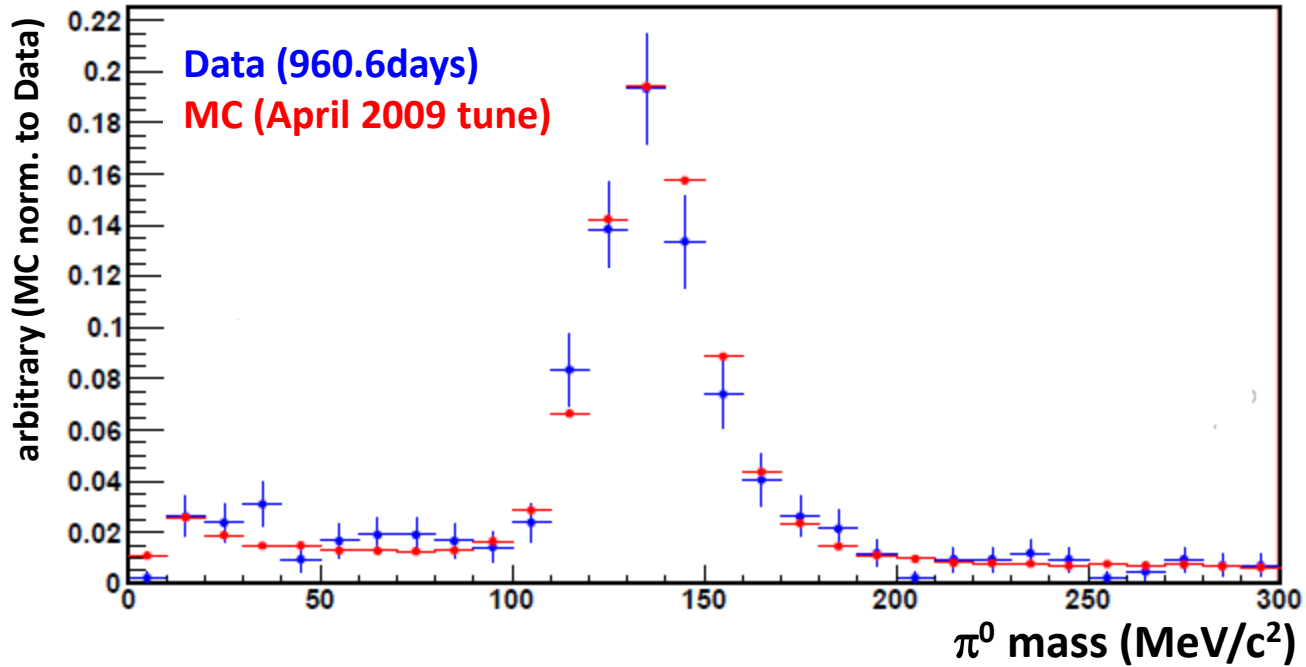
# Sub-GeV stop- $\mu$



$$P(\theta) = \frac{m}{\sqrt{n^2 \cos^2 \theta - 1}}$$

# $\pi^0$

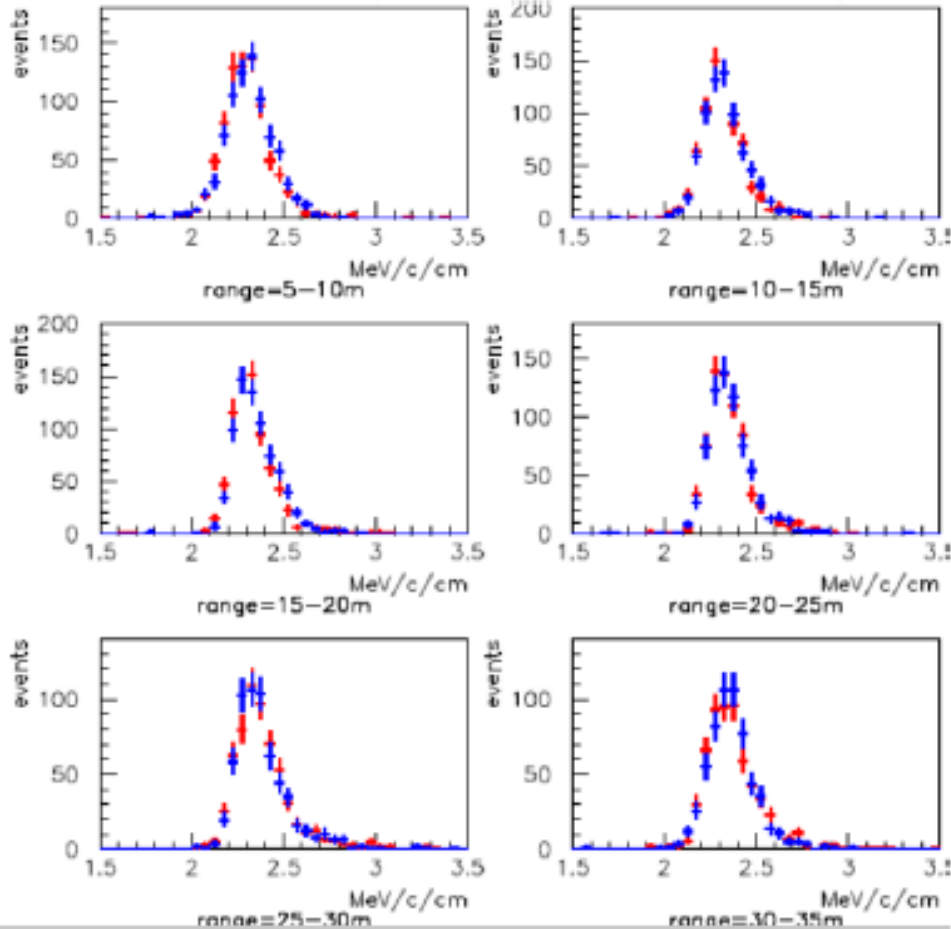
(Joshua H)



Data(MeV/c <sup>2</sup> )	MC(MeV/c <sup>2</sup> )	(MC-Data) / Data
<b>136.10 ± 1.10</b>	<b>137.08 ± 0.08</b>	<b>0.7 ± 0.8%</b>



# Multi-GeV stop- $\mu$

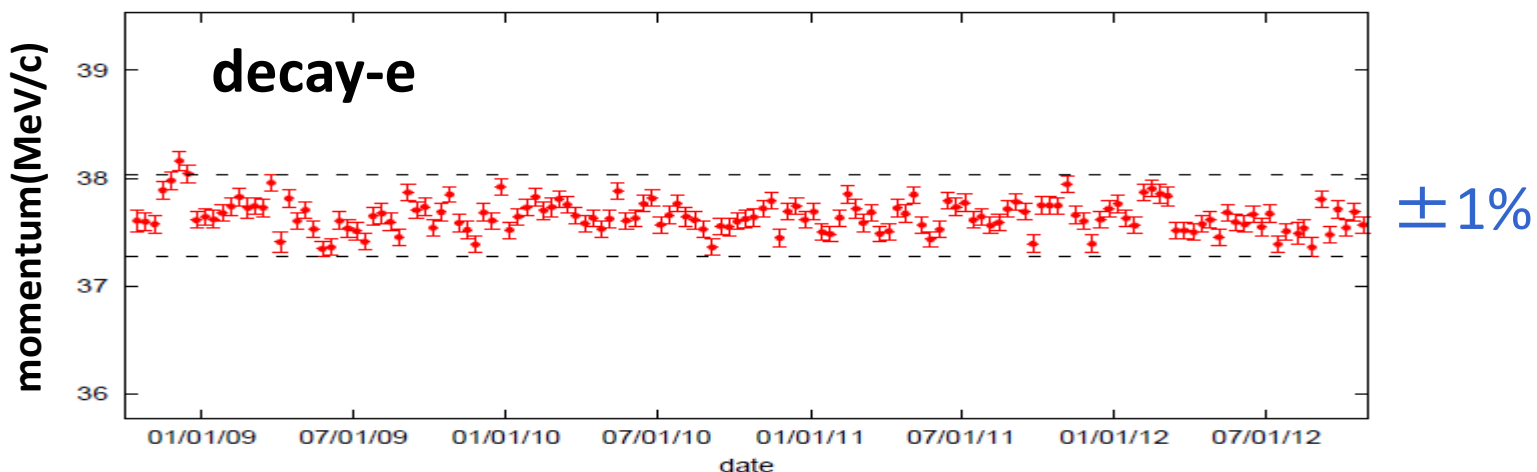
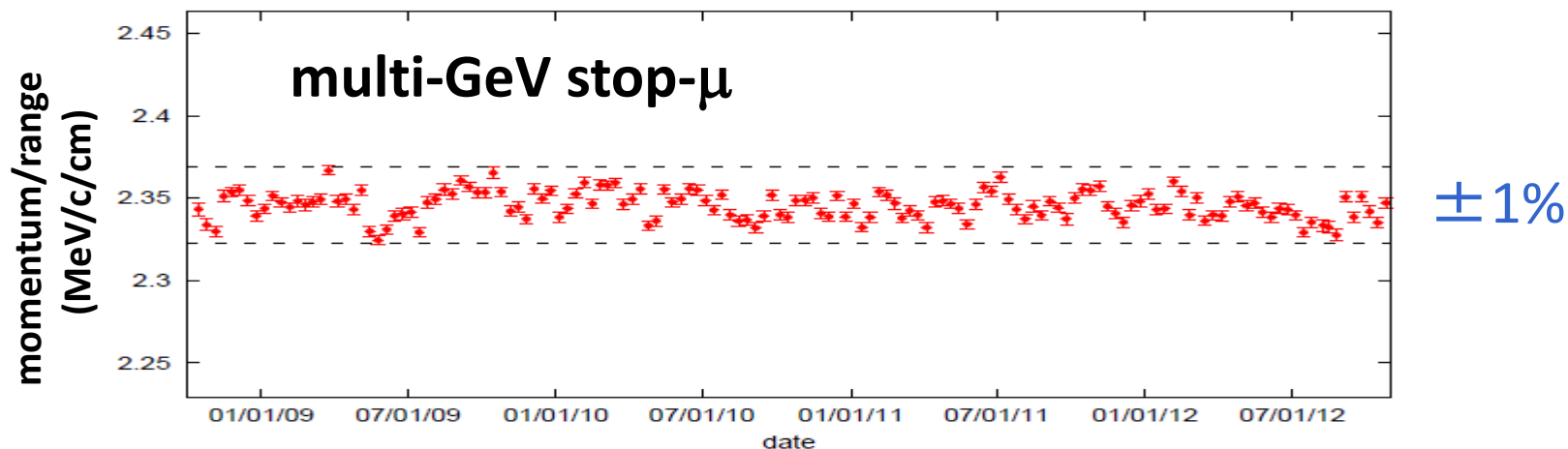


**Data (April 2009)**  
**MC (April 2009 tune)**

Range (m)	MC $\frac{\text{Momentum}}{\text{Range}}$	DATA $\frac{\text{Momentum}}{\text{Range}}$	$\frac{\text{MC} - \text{DATA}}{\text{DATA}}$ (%)
5-10	2.315 $\pm 0.005$	2.316 $\pm 0.005$	0.0 $\pm 0.3$
10-15	2.322 $\pm 0.005$	2.331 $\pm 0.004$	-0.4 $\pm 0.3$
15-20	2.345 $\pm 0.005$	2.339 $\pm 0.004$	0.3 $\pm 0.3$
20-25	2.343 $\pm 0.005$	2.358 $\pm 0.003$	-0.6 $\pm 0.3$
25-30	2.355 $\pm 0.006$	2.388 $\pm 0.006$	-1.4 $\pm 0.4$
30-35	2.353 $\pm 0.005$	2.377 $\pm 0.005$	-1.0 $\pm 0.3$

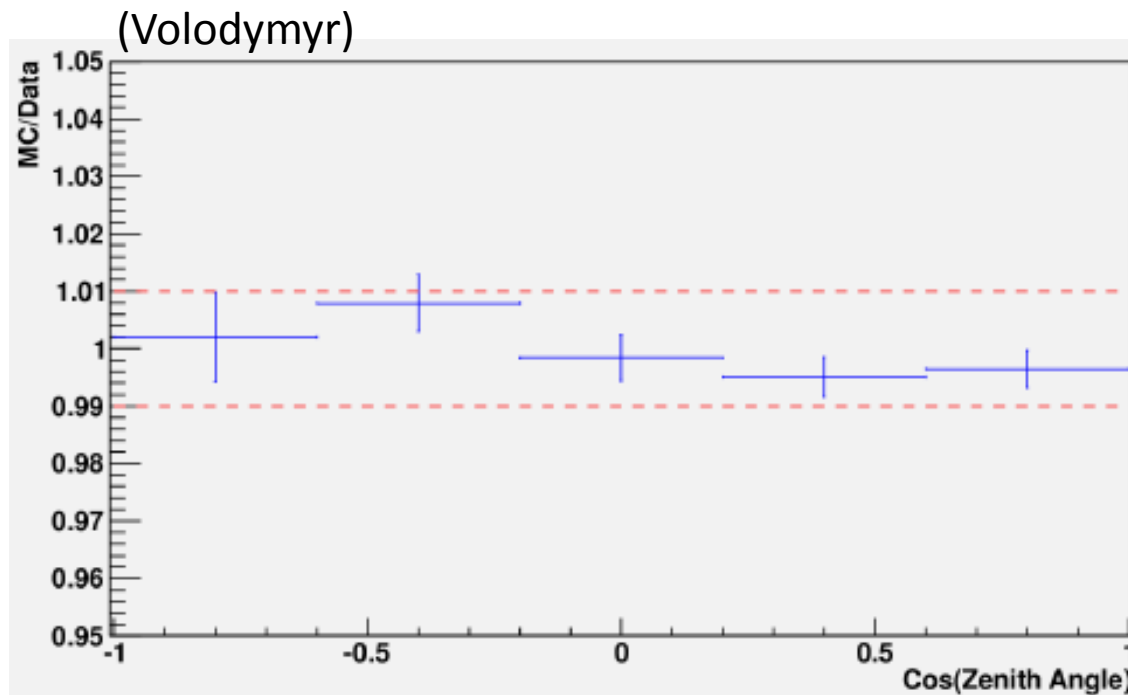
# Time variation of momentum

(entire SK-IV period)



- RMS/Mean: 0.35/0.39% for stop- $\mu$ /decay-e, respectively

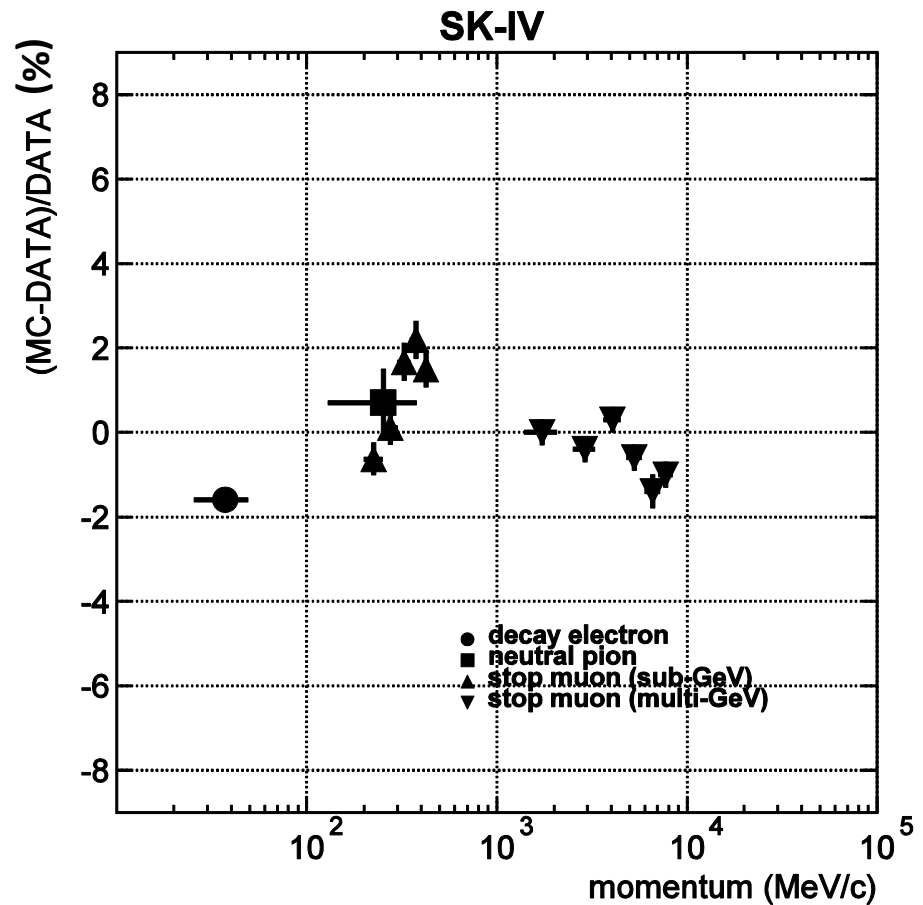
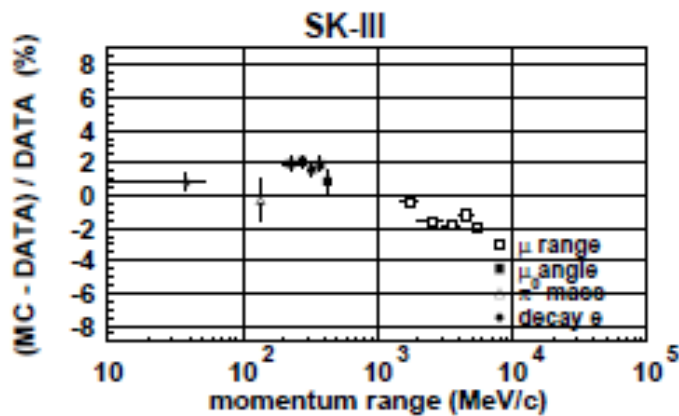
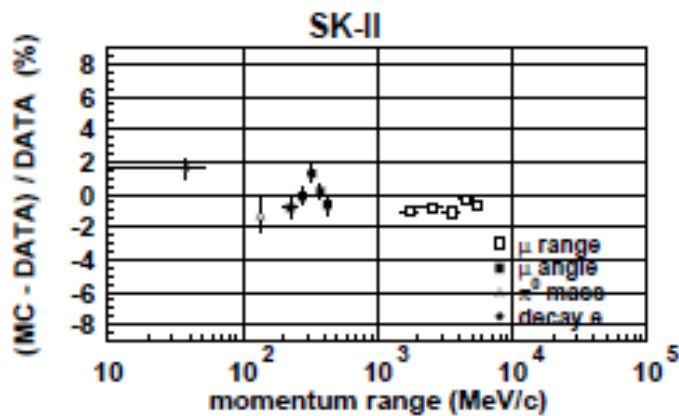
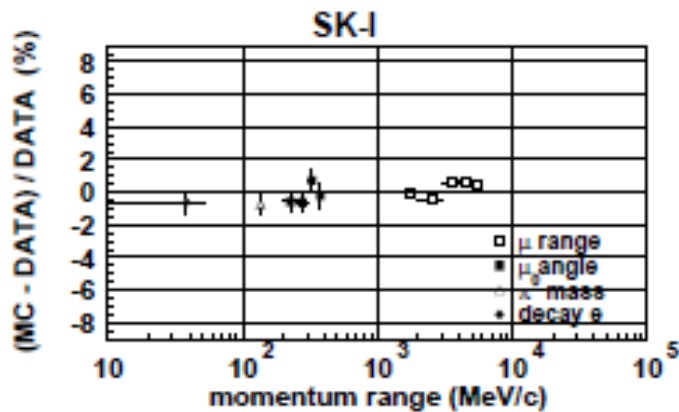
# Detector uniformity check in SK-IV (decay electron)



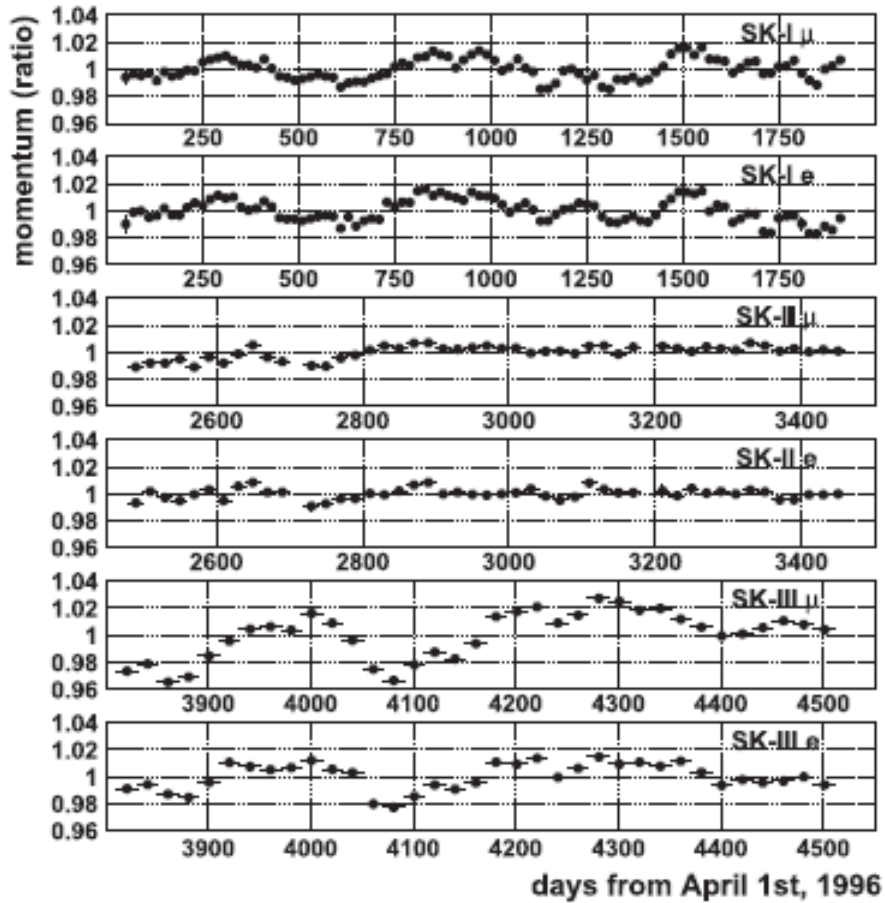
**detector  
uniformity;  
0.8%**

# Summary of energy scale error in SK-IV

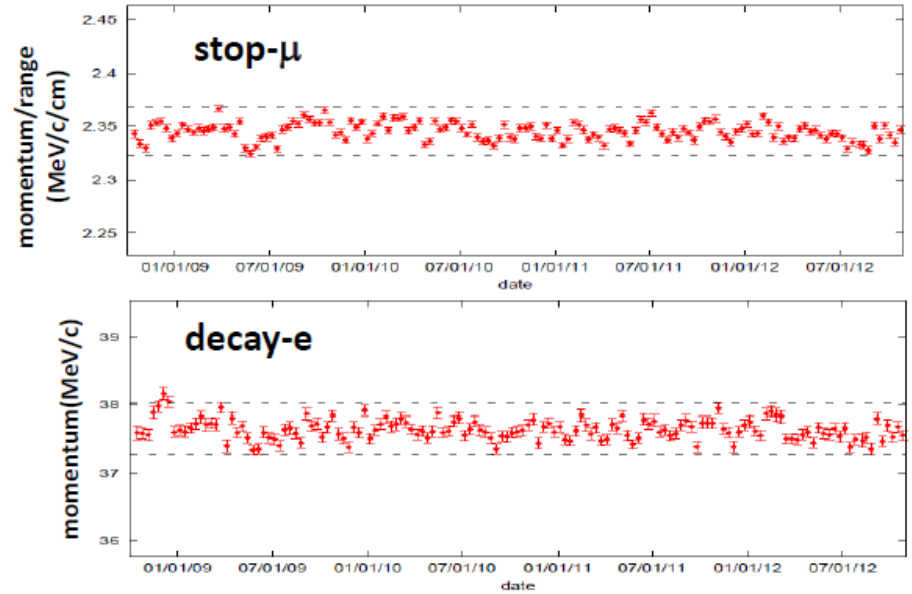
- **total error (quad. sum of abs. + time variation): 2.2%**
  - **absolute: 2.2%**
  - **time variation: 0.39%**
- **detector uniformity: 0.8%**



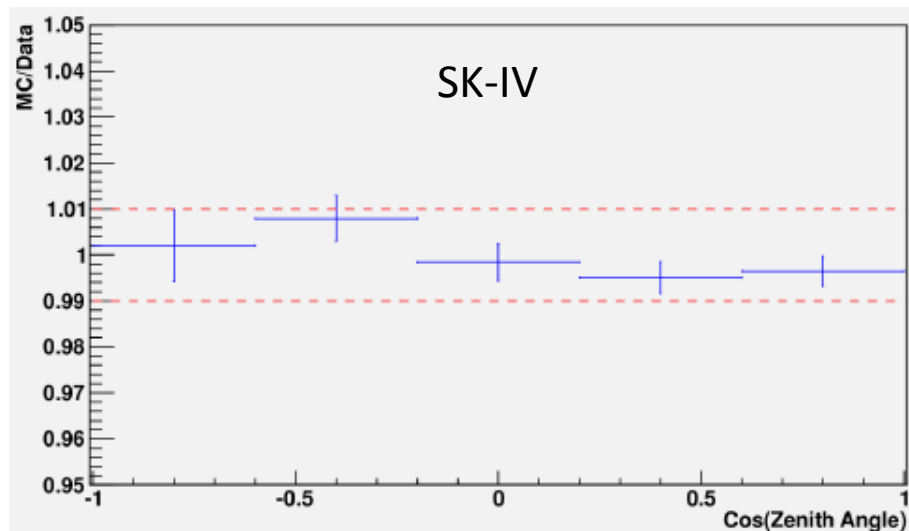
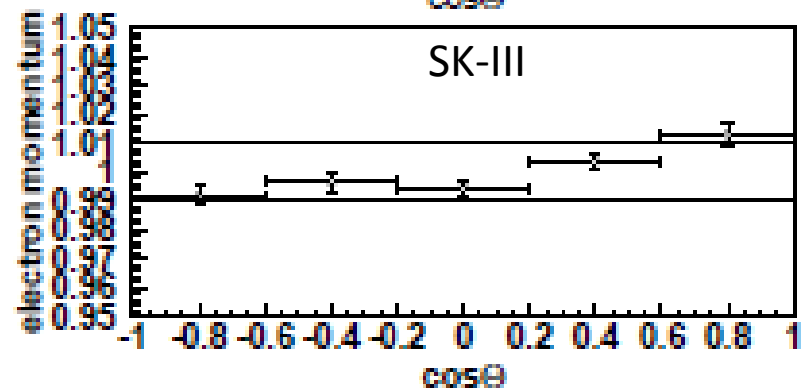
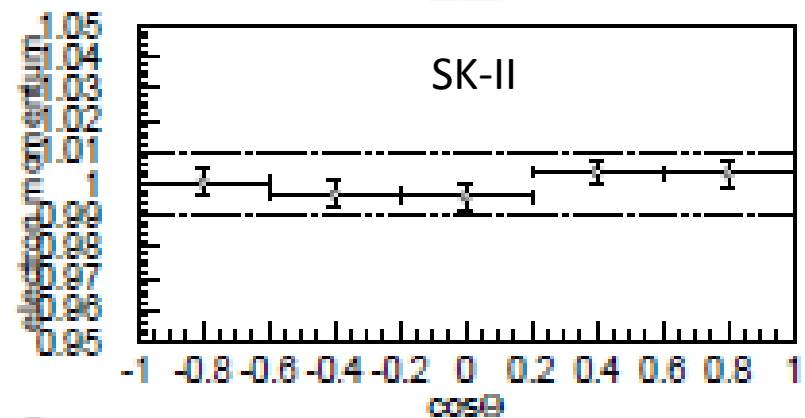
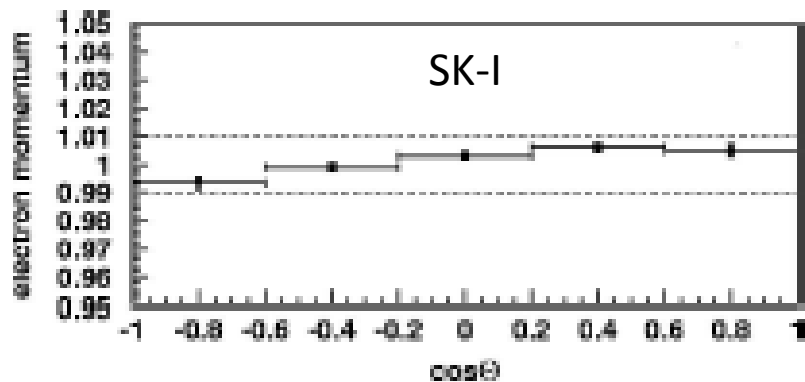
detector	absolute scale error
SK-I	0.74%
SK-II	1.6%
SK-III	2.1%
SK-IV	2.2%



(entire SK-IV period)



detector	time variation
SK-I	0.88%
SK-II	0.55%
SK-III	1.8%
SK-IV	0.39%



detector	detector uniformity
SK-I	0.6%
SK-II	0.6%
SK-III	1.3%
SK-IV	0.8%

# Toward HK

- Should achieve SK detector level (1%) in HK
- No major concern in HK detector design?
  - similar calibration hardware expected at HK
  - cosmic ray muon rate (especially for longer detector axis)?
- Understanding of scattering/absorption of light in water, charge profile, attenuation length, etc. are important.
- Any improvement of momentum reconstruction would reduced energy scale error
  - time variation correction, etc.
  - fiTQun or any new momentum reconstruction