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νFact02
@Imperial College
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Translation from Near to Far at K2K

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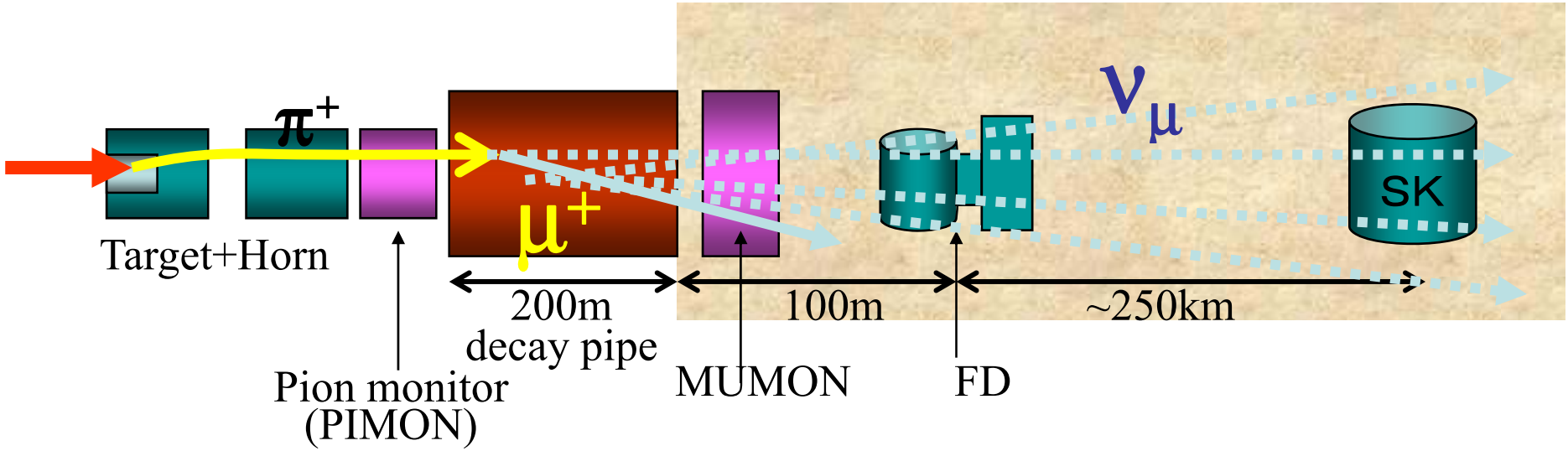
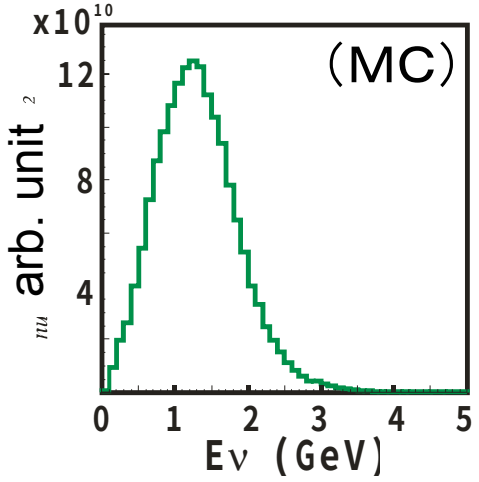
for K2K beam monitor group
(K.Nishikawa, T.Hasegawa, T.Inagaki, T.Maruyama, T.Nakaya, ...)

Especially for T.Maruyama(KEK→Chicago) who played major role in PIMON construction/measurement/analysis

Strategy of K2K

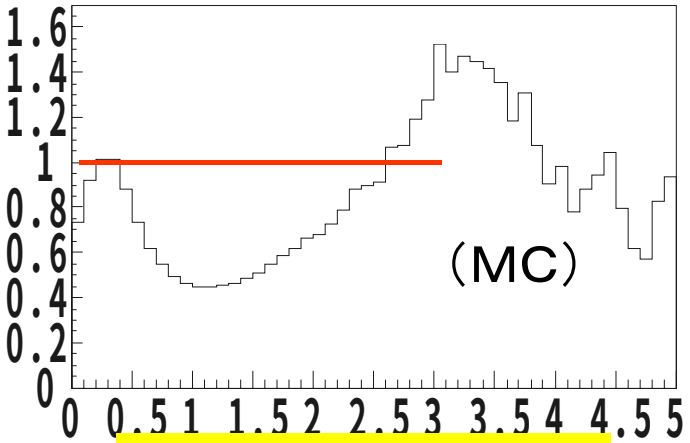


ν_μ spectrum@production



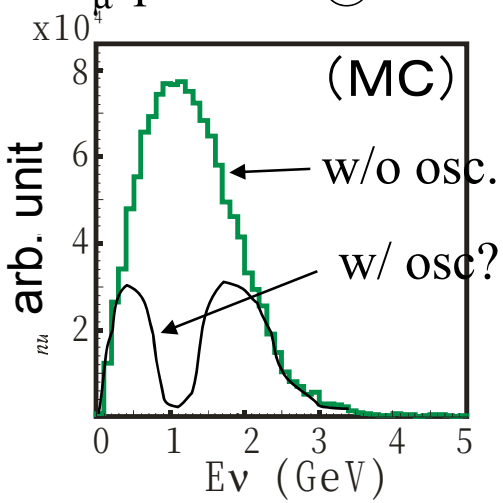
measure w/ FD

Extrapolate by multiplying ratio(≠0)



measured by PIMON

$\nu_\mu$spectrum @SK



What's new in the treatment of far/near extrapolation

- Before
  - Observable for osc. analysis:
    - total # of events
  - added syst. error from each energy bins linearly (= 100% positive correlation) to be safe.
- New
  - Observables for osc. analysis
    - total # of events,
    - E_ν^{rec} spec. shape for 1-ring μ-like events
  - **Correlation for far/near ratio btw energy bins are taken into account**

Far/Near ratio in oscillation analysis (method1)

Maximum Likelihood Method

$$L_{tot} = L_{norm}(f) \cdot L_{shape}(f) \cdot L_{syst}(f)$$

systematics parameters

$$f = (f_{\Phi}, f_{nQE}, f_{\mathrm{F/N}}, f_{\varepsilon sk}, f_{Esk}, f_{n6}, f_{n11})$$

spec

nQE/QE

Far/near

ε_{SK}(efficiency)

SK Enegry scale

Overall Norm Error

For Jun99 and Nov99-

Normalization term

$$L_{norm} = Poisson(N_{obs}, N_{\exp}(f))$$

$$N_{\exp} = N_{KT}^{obs} \cdot \frac{N_{SK}^{MC}(f, P_{osc})}{N_{KT}^{MC}(f)}$$

$$= N_{KT}^{obs} \cdot \frac{\sum_{i,j} f_{\Phi i} \boxed{f_{F/Ni}} \cdot \Phi_{SK}^{MC}(E_i) P(\Delta m^2, \sin^2 2\theta) \cdot (f_j \sigma_{ij}) \cdot \varepsilon_{ij}^{SK}}{\sum_{i,j} f_{\Phi i} \cdot \Phi_{KT}^{MC}(E_i) \cdot (f_j \sigma_{ij}) \cdot \varepsilon_{ij}^{KT}}$$

i: energy bin index

j: processes (=QE, nQE)

Spectrum meas. in FD($f_{\Phi i}$) cancels first order but far/near ratio $f_{F/N}$ does not.

E_ν^{rec} spectrum shape term for FC 1Rμ

$$L_{shape} \equiv \prod_{i=1}^{29} P(E_i^{rec})$$

Total 29 events
for **Nov99~** data

P: reconstructed Eν distribution for 1Rμ (gen'ed by using MC)

$$P\left(E_\nu^{rec}\right) = \int \Phi_{SK}\left(E_\nu^{true}\right) \cdot \left[\begin{array}{l} \sigma_{QE}\left(E_\nu^{true}\right) \cdot \varepsilon_{QE}^{1R\mu}\left(E_\nu^{true}\right) \cdot r_{QE}\left(E_\nu^{rec}, E_\nu^{true}\right) \\ + f_{nQE}\sigma_{nQE}\left(E_\nu^{true}\right) \cdot \varepsilon_{nQE}^{1R\mu}\left(E_\nu^{true}\right) \cdot r_{nQE}\left(E_\nu^{rec}, E_\nu^{true}\right) \end{array}\right] dE_\nu^{true}$$

Detector response from MC

$$\Phi_{SK}\left(E_\nu^{true}\right) = \left(f_\Phi^{meas}\Phi_{FD}^{MC}\right) \cdot \left(f_{F/N}R\right) \cdot P_{osc}\left(\sin^2 2\theta, \Delta m^2\right)$$

Systematic constraint term

$$L_{syst} \equiv \exp\left(-\Delta f^{T}_{\Phi,nQE}\cdot M^{-1}_{FD}\cdot \Delta f_{\Phi,nQE}/2\right)$$
$$\times\exp\left(-\Delta f^{T}_{F/N}\cdot M^{-1}_{F/N}\cdot \Delta f_{F/N}/2\right)$$
$$\times\exp\left(-\Delta f^{T}_{\varepsilon SK}\cdot M^{-1}_{\varepsilon SK}\cdot \Delta f_{\varepsilon SK}/2\right)$$
$$\times\exp\left(-f^{2}_{n6}/2\sigma^{2}_{n6}\right)\cdot\exp\left(-f^{2}_{n11}/2\sigma^{2}_{n11}\right)$$
$$\times\exp\left(-\Delta f^{2}_{Esk}/2\sigma^{2}_{Esk}\right)$$

Far/near ratio

$$\Delta f \equiv f - 1$$

M_{FD}, $\boldsymbol{M_{\pi}}$, M_{SK}: error matrix of syst. errors.

σ_{n6}: overall norm. err. for Jun99 (=+0.80–0.68 evts)

σ_{n11}:overall norm. err. for Nov99~ (=5.34%)

σ_{Esk}: SK Enery scale error (3%)

Qeustions

- Central values of far/near ratio (relative to MC prediction)

$$f_{\mathrm{F/Ni}}$$

- Correlation of far/near ratio btw. energy bins (error matrix)

$$M_{\pi}$$

A tool:Pion Monitor (PIMON)

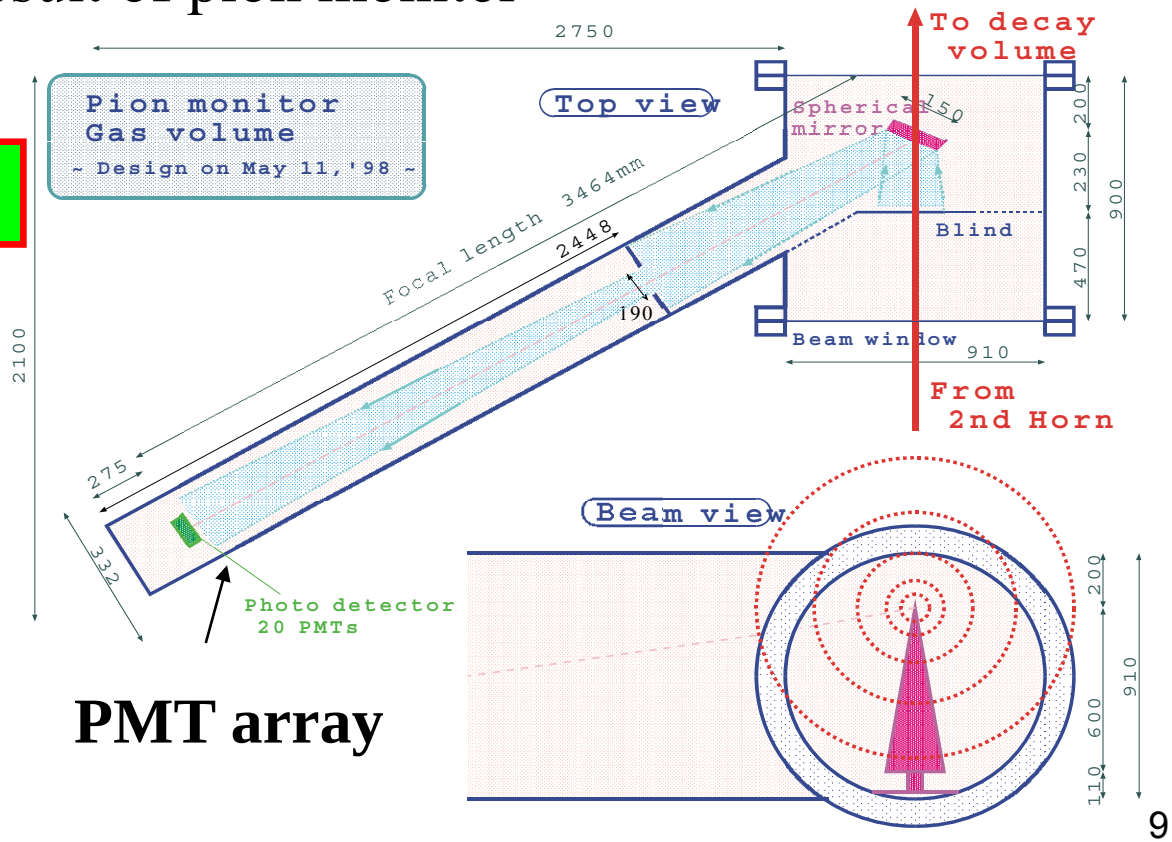
$N(p_\pi, \theta_\pi)$ → Neutrino flux $\Phi(E_\nu)$ at any distance
using **only decay kinematics**

$$R(E_\nu) \equiv \Phi_{SK}(E_\nu) / \Phi_{FD}(E_\nu)$$

as a result of pion monitor

Gas Cherenkov detector

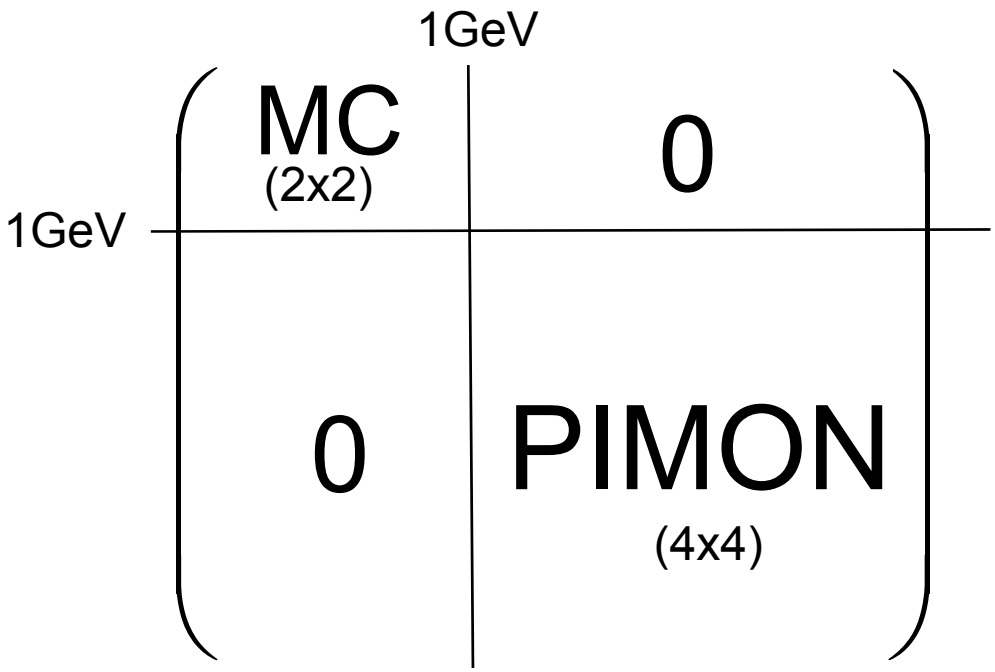
to avoid signal from
12GeV protons
→ insensitive to p_π
<2GeV (E_ν<1GeV)



PMT array

Strategy to obtain $f_{F/N}$, error matrix

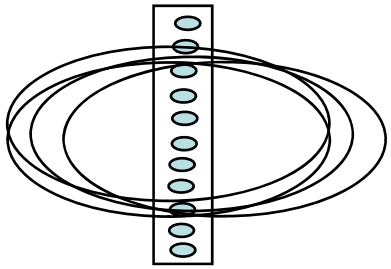
- Above 1GeV ➔ PIMON
- Below 1GeV ➔ Beam MC(Sanford-Wang parameterization fitted to previous data) validated by PIMON measurement at >1GeV
- Error matrix

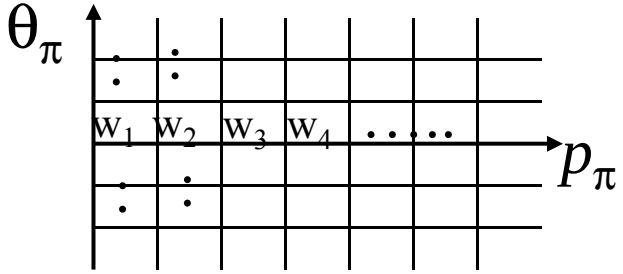


MC part:
Fit previous pion production data below ~2GeV/c
move paraemters within error
→ get error matrix

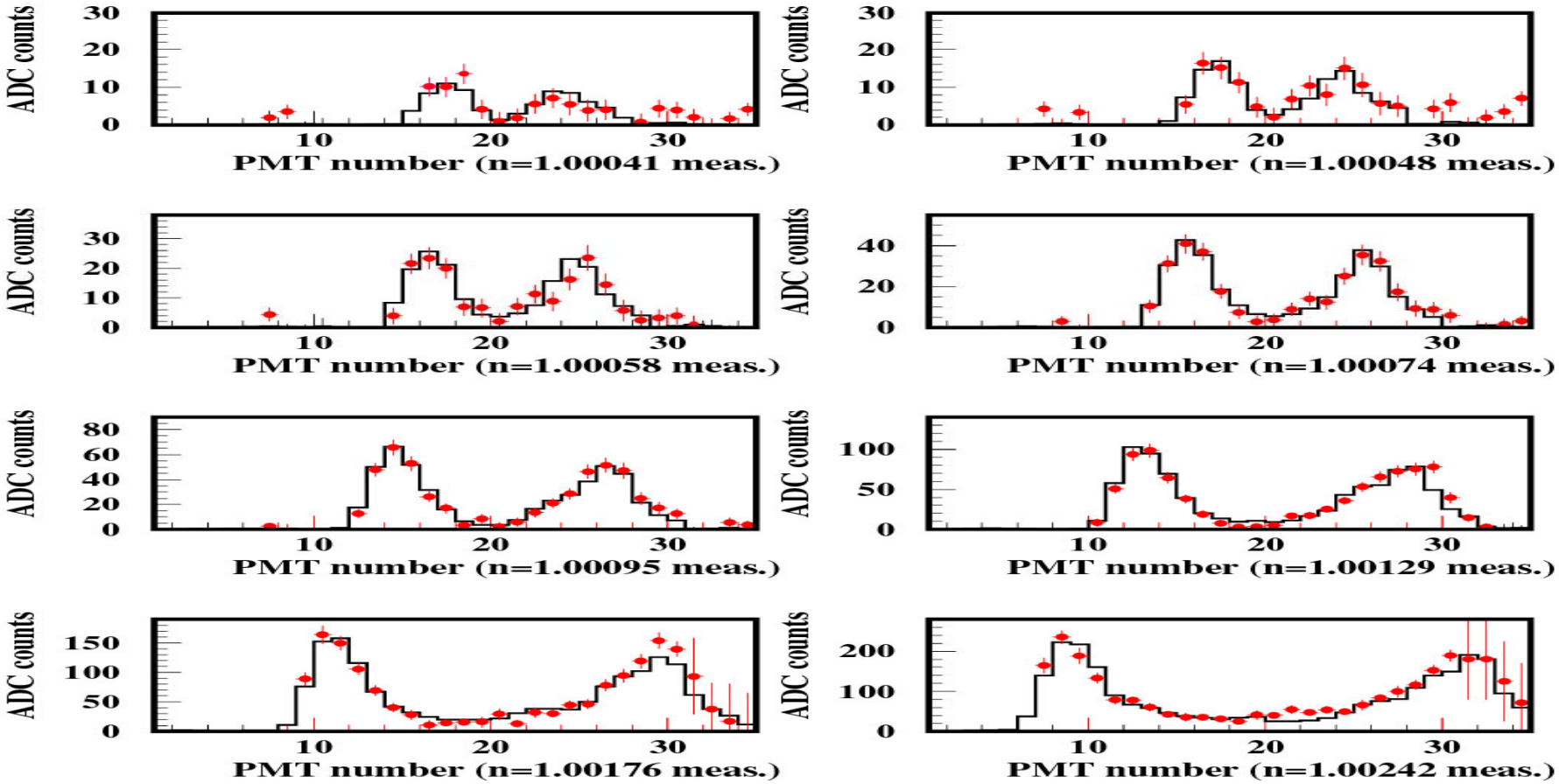
No correlation w/ PIMON part

Pion Monitor Results

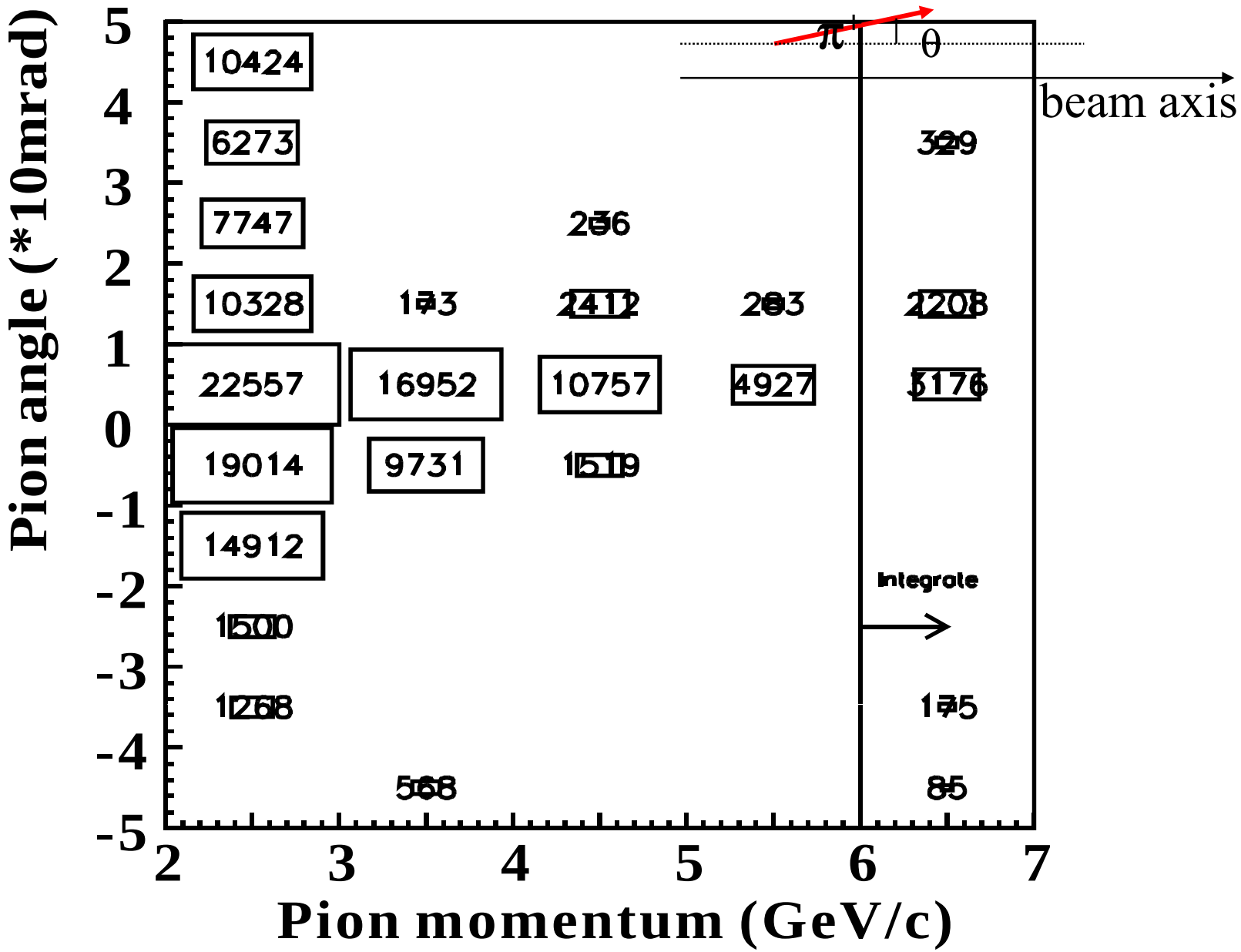




Pion Monitor Fitting (November)



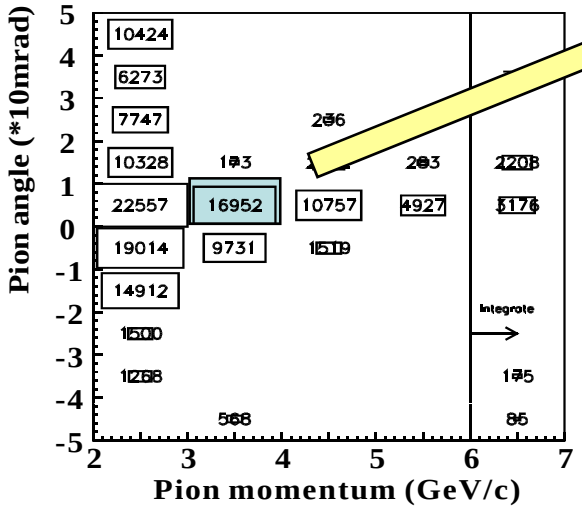
Pion Monitor Result(relative weight)



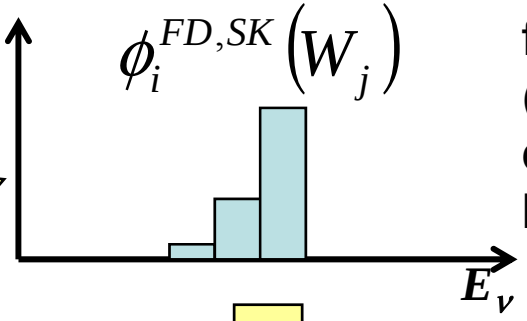
Pion distribution to far/near ratio (incl. error matrix)

From PIMON fitting

Relative weight W_i(i=1~50)



$$\phi_i^{FD,SK}(W_j)$$



Contribution to ν flux from each p-θ bin (by MC. To 1st order, depend only on decay kinematics &geometry

$$\Phi_i^{FD,SK} = \sum_{j=1}^{50} \phi_i^{FD,SK}(W_j)$$

FD,SK flux

$$R_i = \Phi_i^{SK}(W) / \Phi_i^{FD}(W)$$

Ratio as func. of weights

$$U_{ij} = \frac{dR_j}{dW_i}$$

Dependence of R on W (50x4 matrix)

50x50 error matrix on weight

$$E_{ij}^{\pi}$$

$$E^R = U^T \cdot E^\pi \cdot U$$

(4x4) (4x50) (50x50) (50x4)

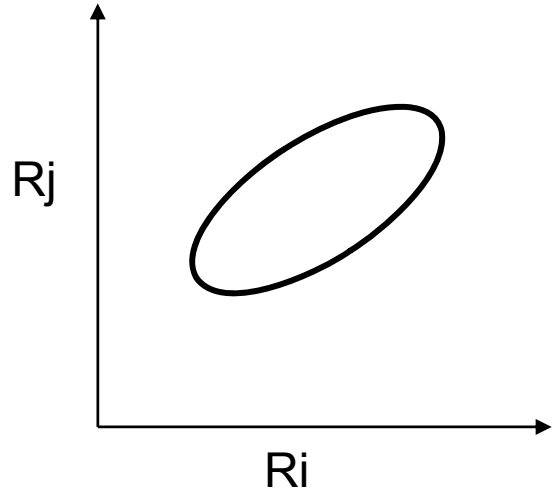
Error matrix transformation from π weight → far/near ratio

Other systematic errros

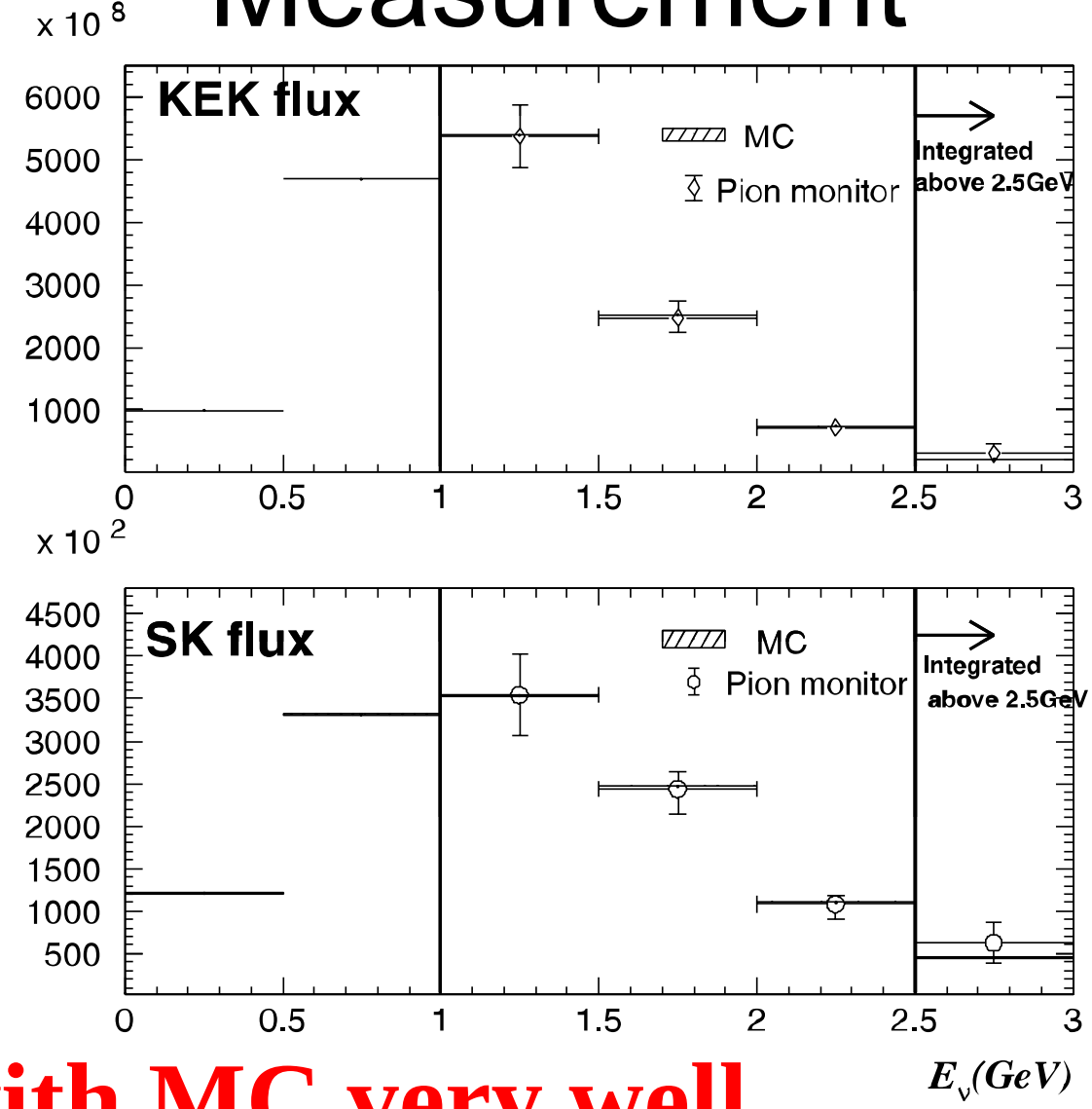
Errors on spectrum ratio (Nov.)
Fitting error
PMT saturation correction PMT relative gain correction Mirror reflectivity Refractive index measurement Wave length dep. of the ref. index
Low and high beam intensity Pion monitor alignment Injection point of protons Beam stability (pion monitor run) Horn magnetic field uncertainty
Subtraction of BKG radiation component Subtraction of EM shower component Fitting method Pion beam profile (fitting function) Pion decay before pion monitor Pion beam profile (pion absorption) Bin size of pion kinematics
Beam stability (normal run)
Hadron model (MC)
Total

← treated in matrix form as described

1. move syst. parameter within error
2. Check correlation btw energy bins

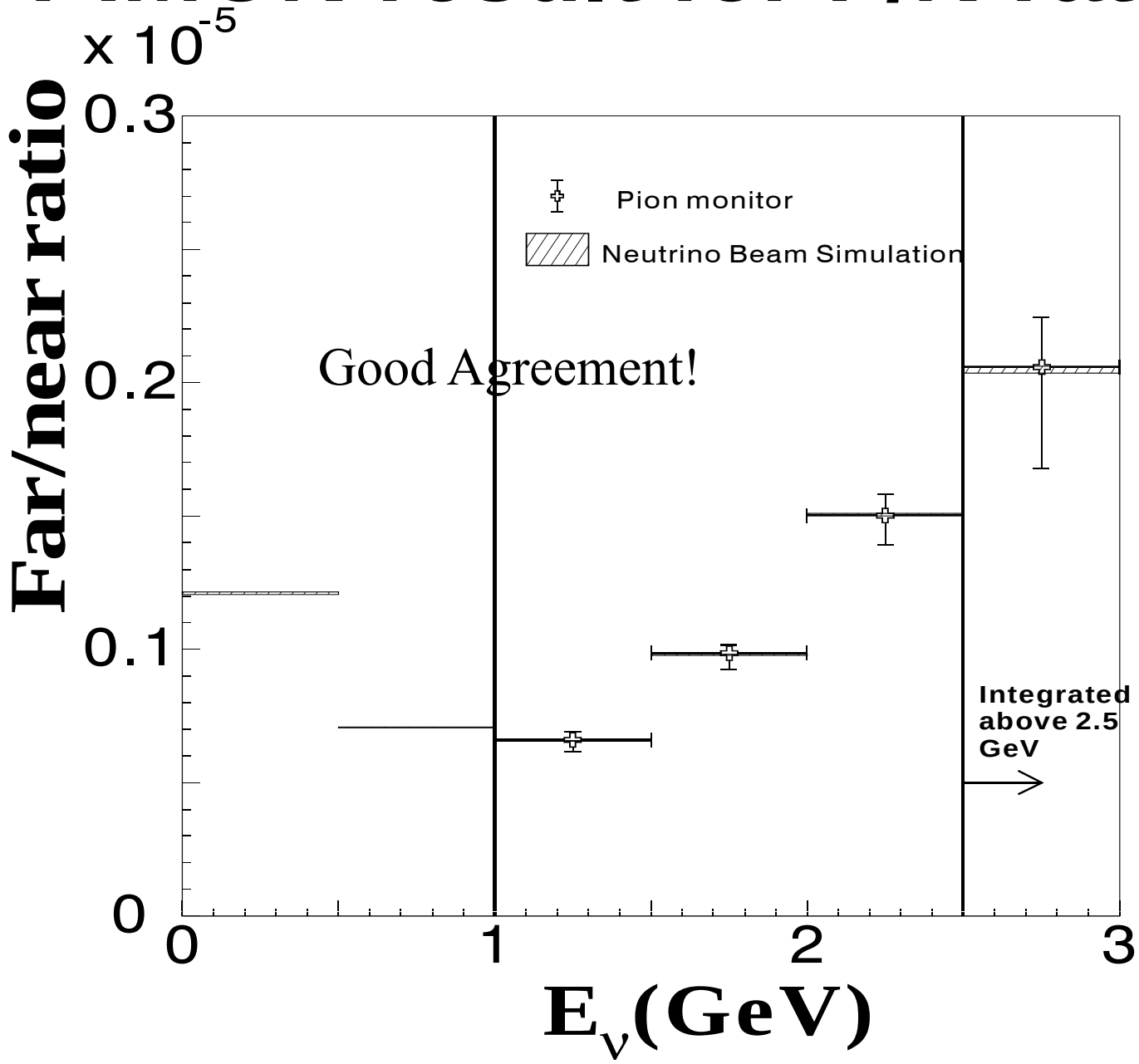


ν_μ spectra from Pion Monitor Measurement



Agree with MC very well.

PIMON result for F/N ratio



Far/Near Error Matrix

"sqrt" of error matrix (%)

$$\mathrm{sign}\left(M_{ij}\right)\cdot\sqrt{\left|M_{ij}\right|}$$

********** SQRT(FAR/NEAR ERROR MATRIX) (%) **********

2.5696	-1.6432	0.0000	0.0000	0.0000	0.0000
-1.6432	4.2591	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	6.5322	2.3973	-1.7861	-4.0187
0.0000	0.0000	2.3973	10.4307	9.5315	4.9528
0.0000	0.0000	-1.7861	9.5315	11.0833	7.2229
0.0000	0.0000	-4.0187	4.9528	7.2229	12.1552
0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-

Beam MC

PIMON

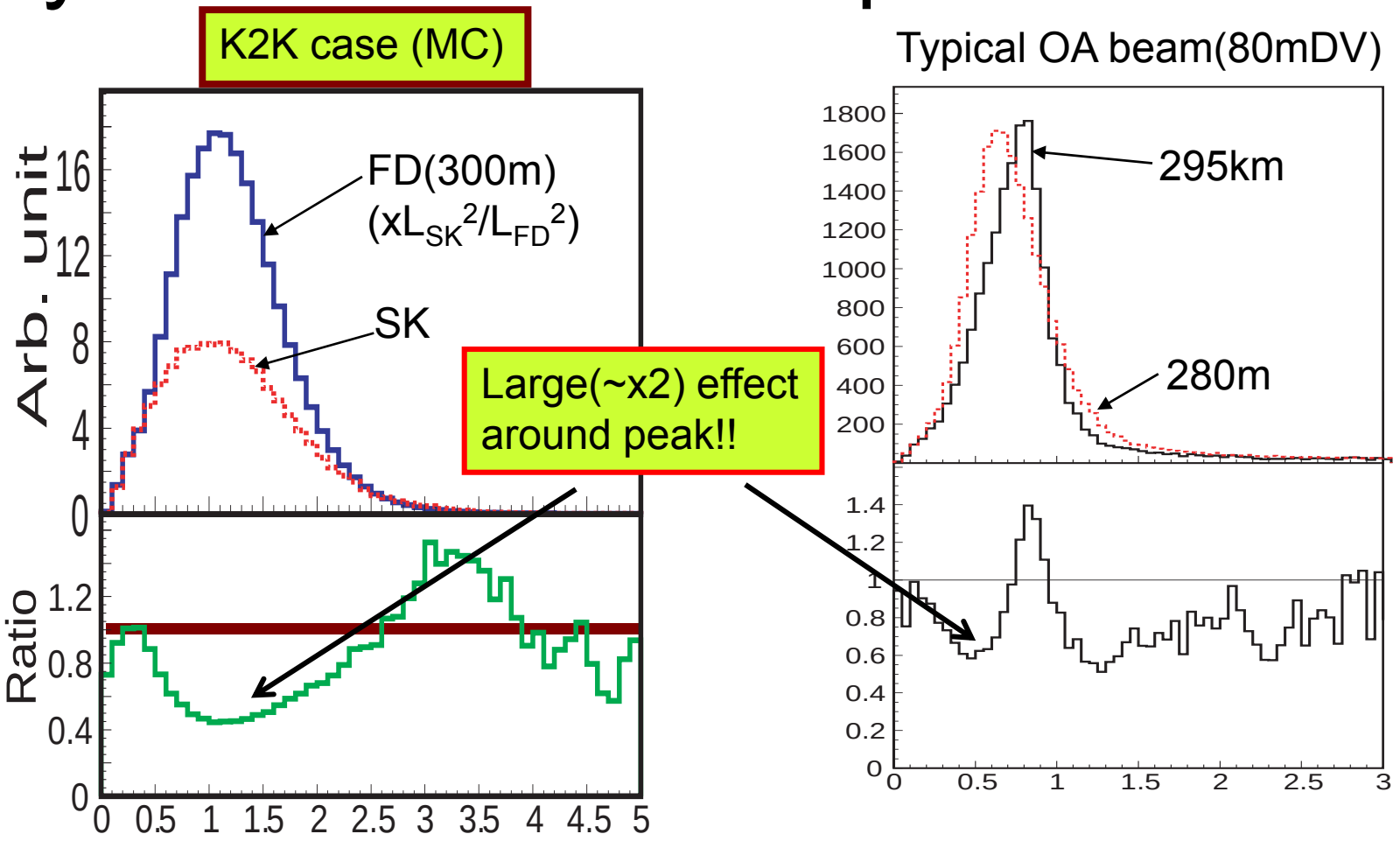
Summary of systematic errors on total # of events w/o osc.

Center: 80.1evts		(%)
Jun99 (4.55evts)	Total	+1.0% –0.9%
Nov99~ (75.5evts)	Spectrum	+0.6% –0.6%
	nQE/QE	+0.5% –1.1%
	Far/Near	+4.9% –5.0%
	Norm	5.0%
Total		**+7.7%** **–6.7%**

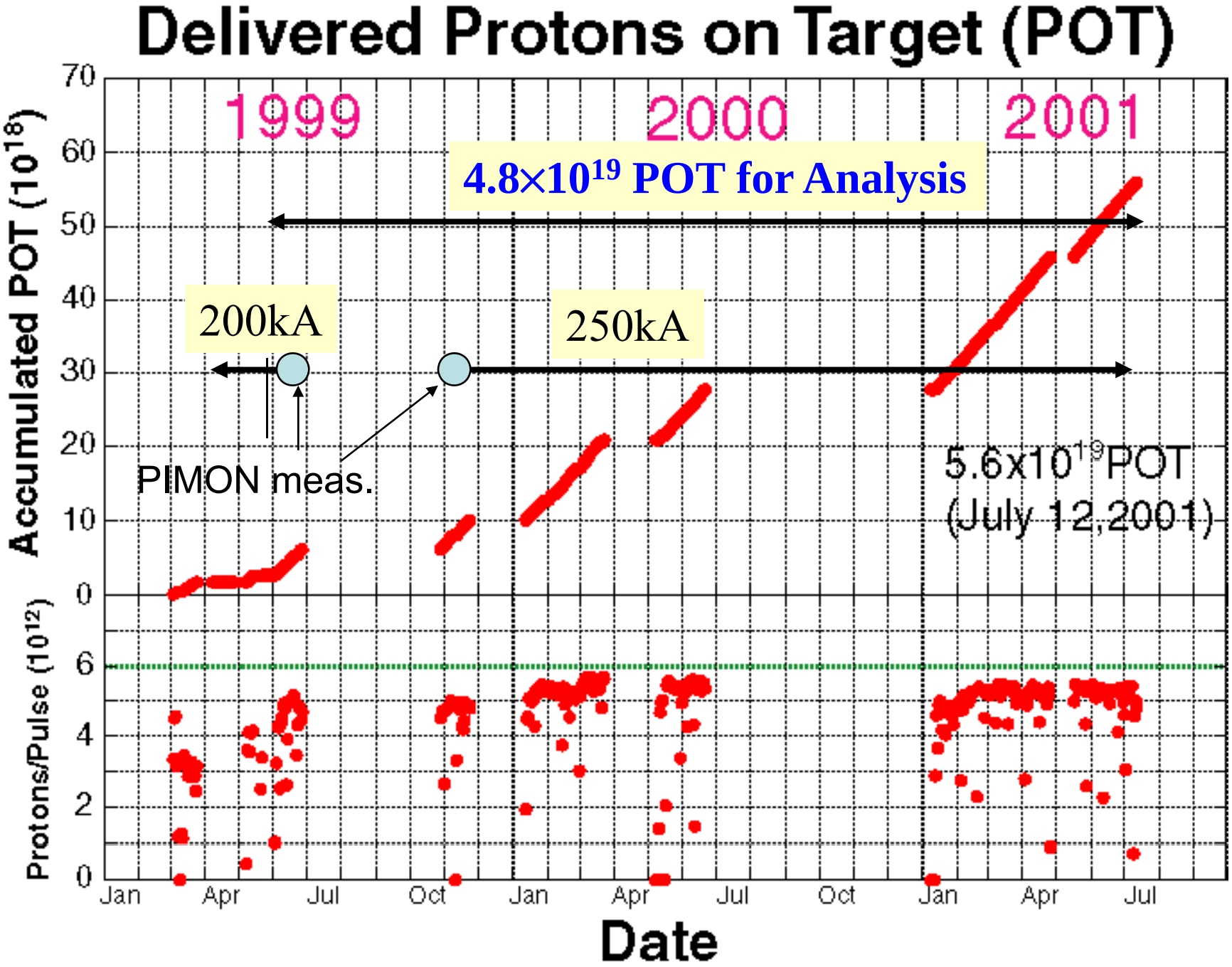
Summary

- K2K uses pion distribution measured in-situ(>1GeV) and beam MC(<1GeV) for spectrum extrapolation
- The beam MC is validated by the PIMON measurements
- Correlation of far/near ratio btw energy bins is taken into account (instead of linear sum = 100% positive correlation
- Still far/near ratio is major source of systematic error
- Expect precise data from HARP (measurement in Aug.26~). Many many thanks to HARP collaborators

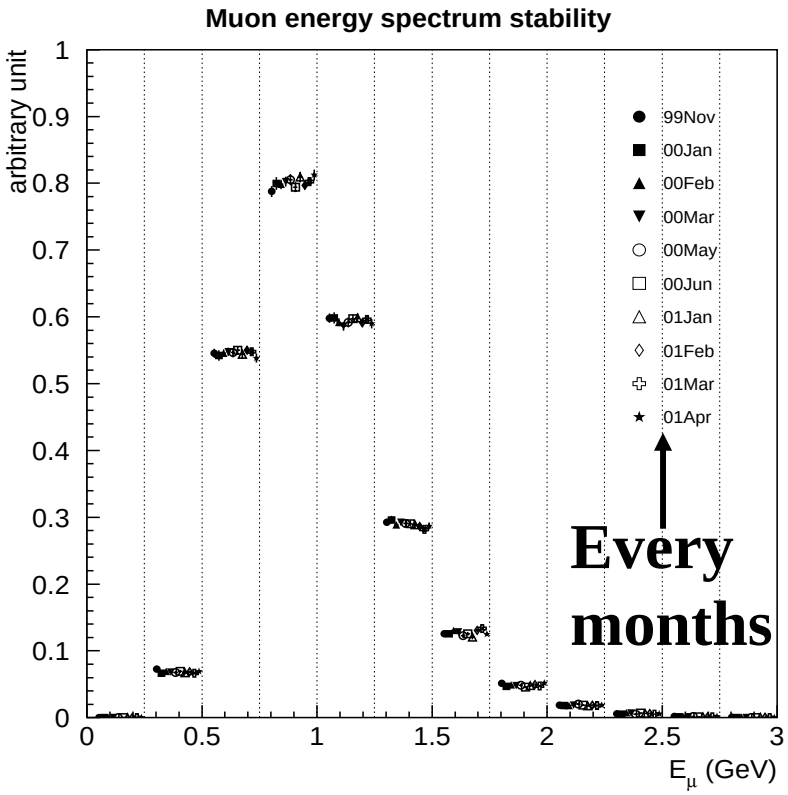
Syst. error: far/near spectrum diff.

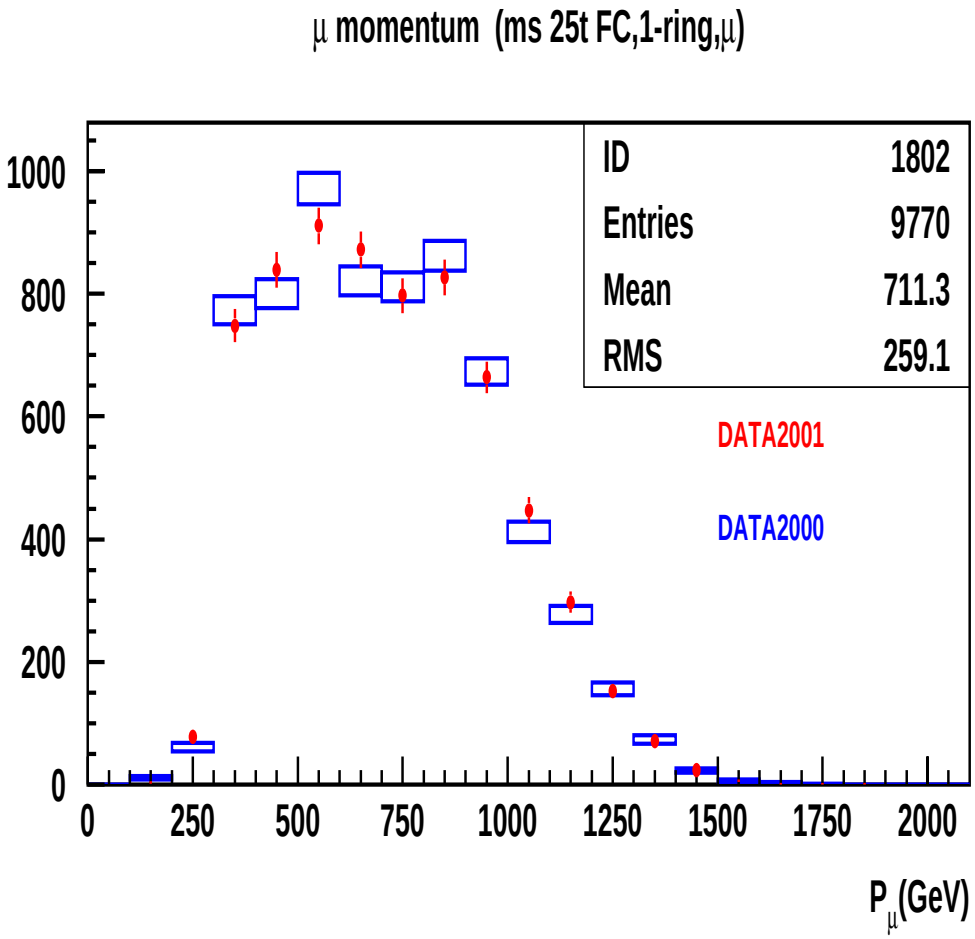


Important not only for ν_μ disappearance,
but also **for sig/BG estimation for ν_e search**


Delivered Protons on Target (POT)
1999
2000
2001
4.8×10^19 POT for Analysis
200kA
250kA
PIMON meas.
5.6x10^19 POT
(July 12,2001)
Accumulated POT (10^18)
Protons/Pulse (10^12)
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Date

Stability of μ–Energy Spectrum

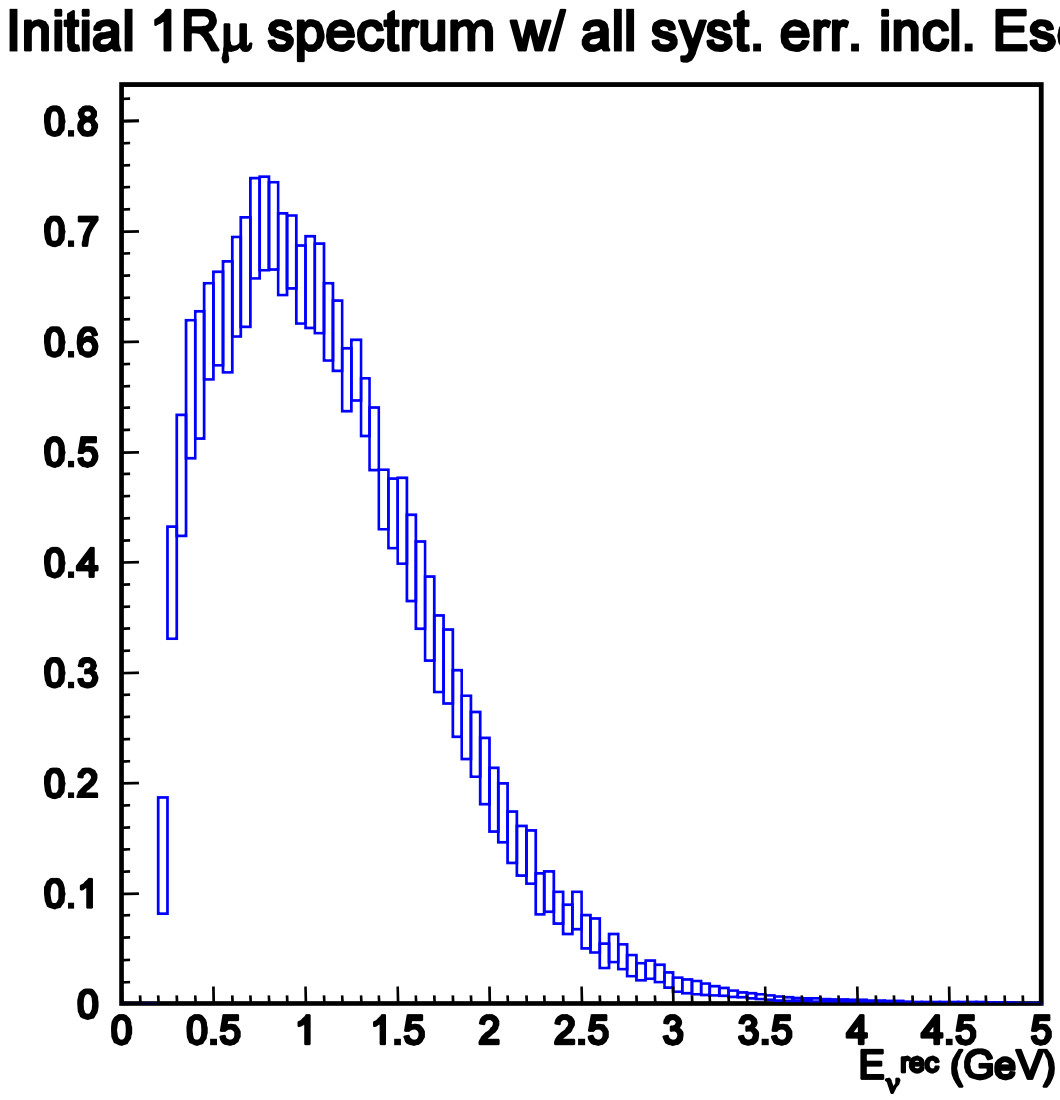




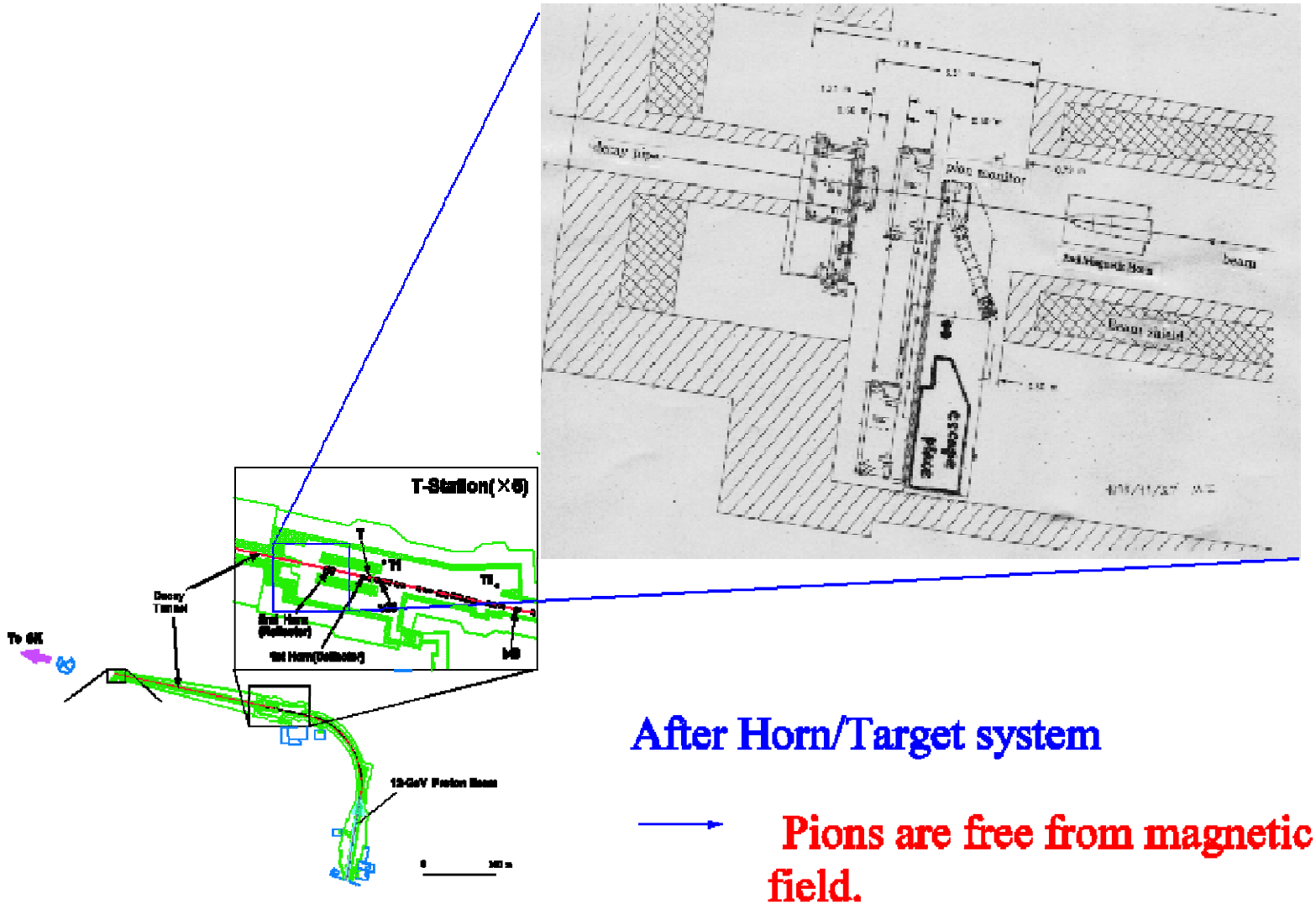
Muon Energy of MRD events

Muon Energy in KT on ’01, ‘00

Exp'ed E_ν^{rec} spectrum for 1Rμ estimated by FD measurements



PIMON in target station



After Horn/Target system

→ Pions are free from magnetic field.
(decay with well known kinematics)

Pion monitor analysis
(using θ_π- P_π plane)

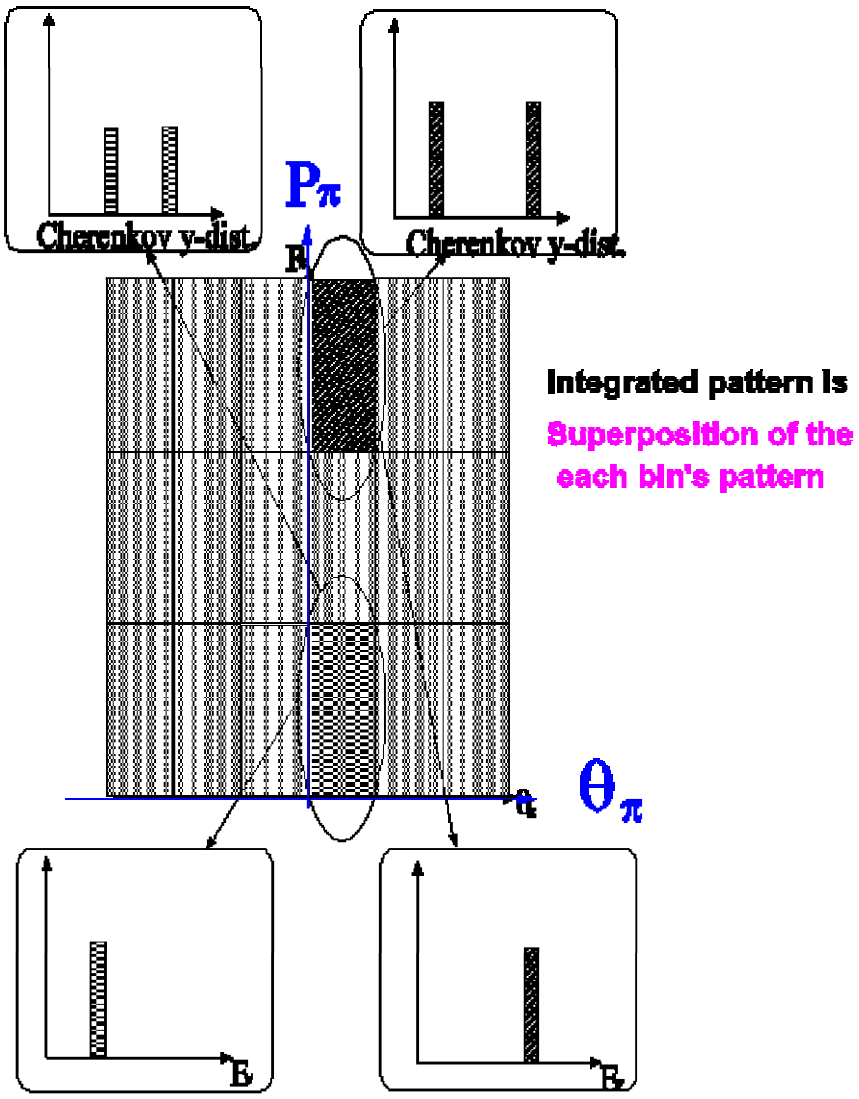
A. 50 kinematic bins are prepared in θ_π- P_π plane.

-50 < θ_π < 50mrad
(10mrad step: 10bins)

2 < P_π < 10 GeV/c
(2~6: 1 GeV/c step: 4bins
>6 : integrated : 1bin)

B. Reconstruct pion kinematics using fit. (each bin has each Cherenkov photon dist.)

C. Predict neutrino spectrum from pion kinematics.
(Each bin has each neutrino energy)



K2K osc. analysis overview