Measurement of $\sigma(\nu_\mu + Fe \rightarrow \mu^- + X)$ Using the MINOS Detector

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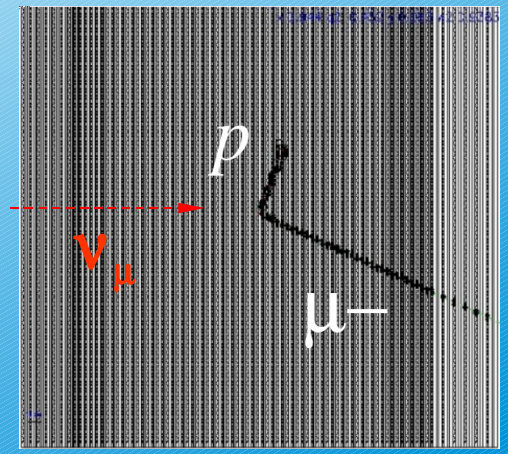
- Neutrino cross sections, σ_ν
- Neutrino flux and uncertantity.
- Use muons to measure the neutrino flux.
- Measurement of the charged current ν_μ cross section.

Types of Neutrino Interactions

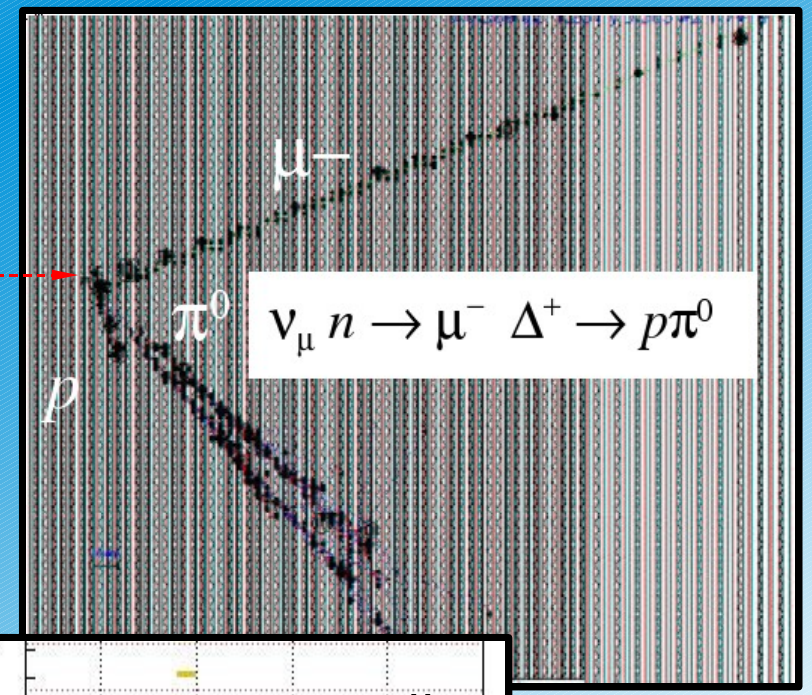
$$\nu_\mu + n \rightarrow \mu^- + p$$

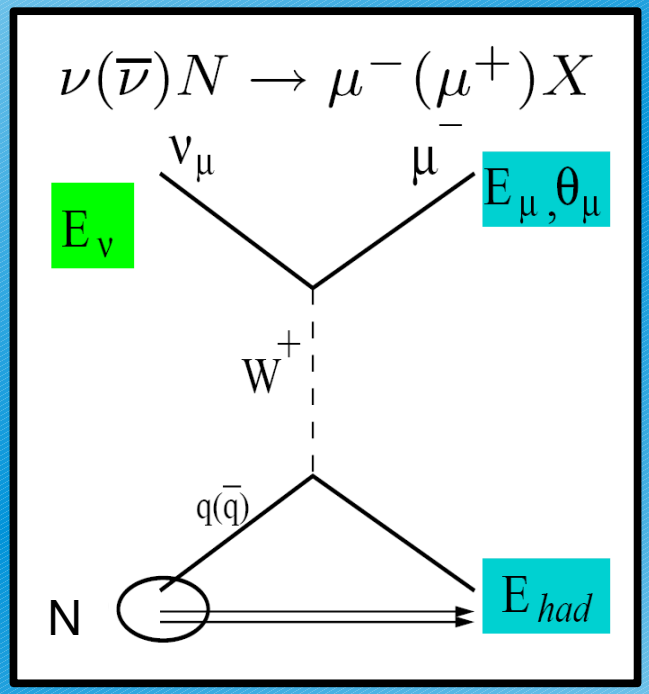
1. Quasi-elastic: ν_μ scatters off nucleons, nucleon remains intact, but a down quark is converted into an up quark



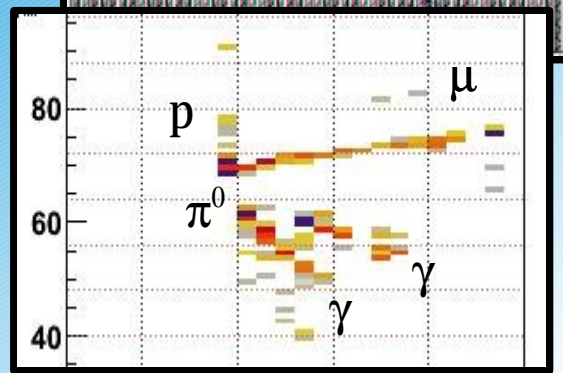
Simulated ν Interactions in MINERνA

2. Resonance: similar to quasi-elastic but the proton is excited and eventually decays to ground state





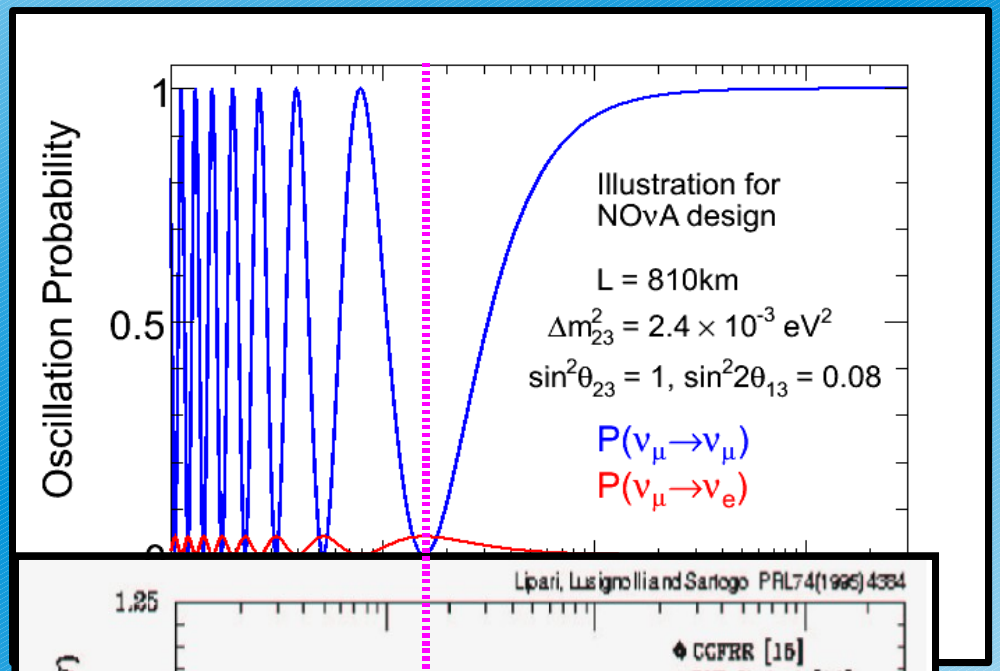
3. DIS: ν_μ scatters off quarks; nucleus breaks up into a shower of hadrons.



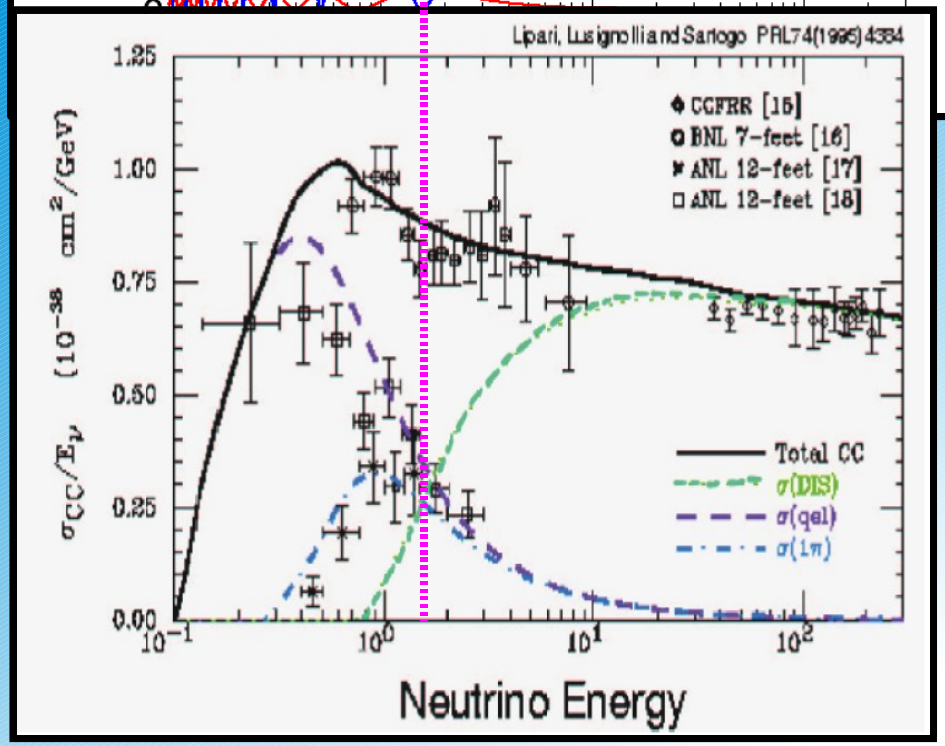
MINERνA Data

Importance of ν Cross Sections, σ_ν

- Tell you the number of ν events to expect to occur in your detector.
- Can't see ν, only see their interaction products. Tell you what you should observe in your detector.



- All neutrino interaction types contribute to neutrino events near the oscillation minimum for ν_μ disappearance and ν_e appearance searches.
- Need precise cross sections for all neutrino interaction types.

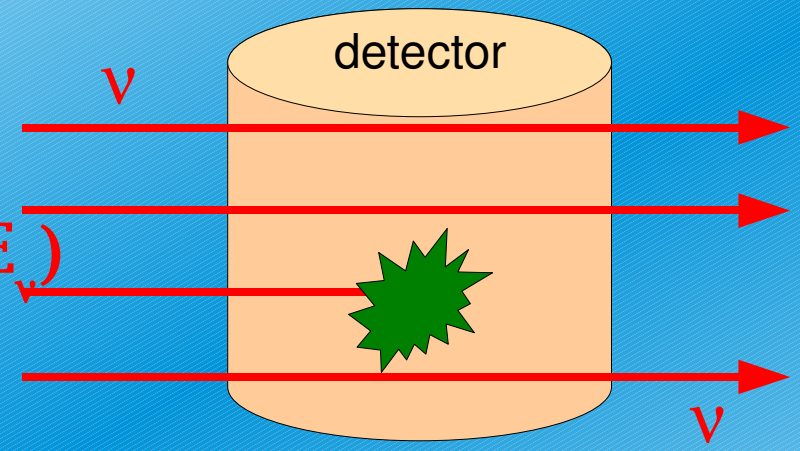


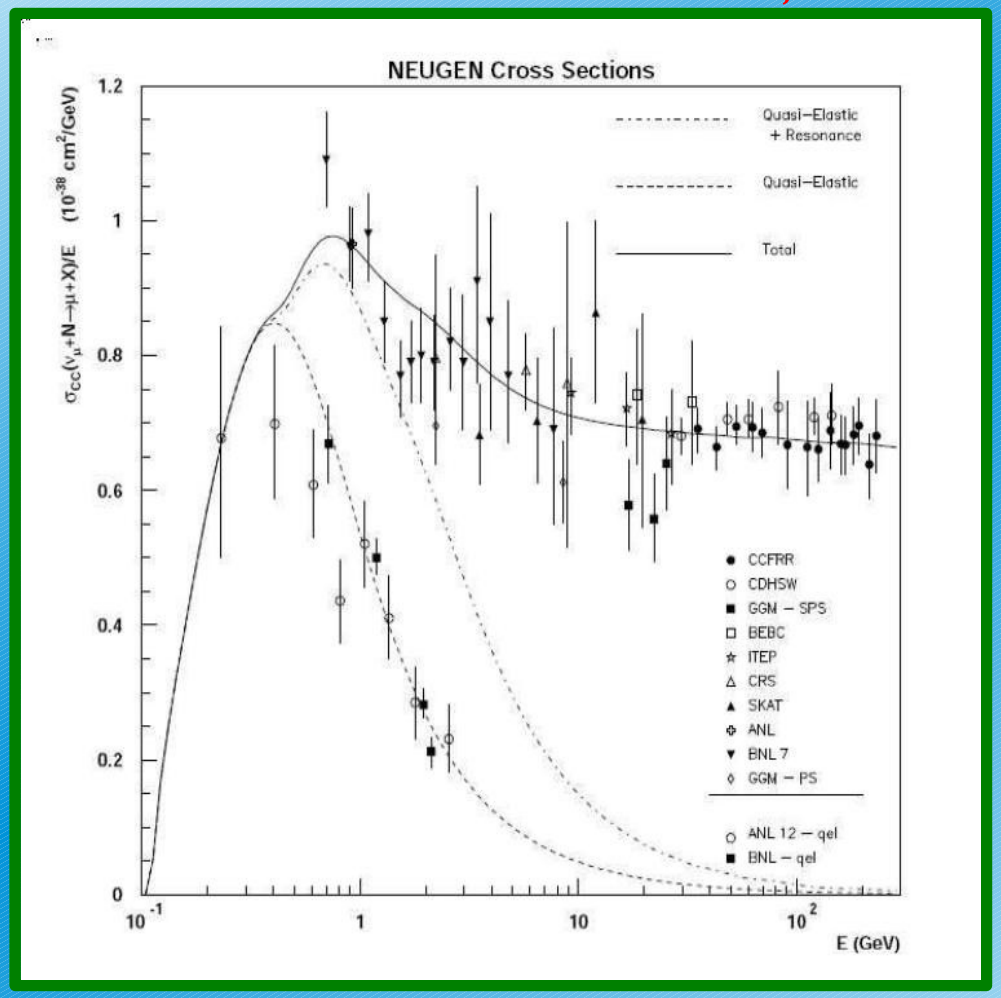
Measuring Absolute σ_ν

$$\sigma(E_\nu) = \frac{N_\nu(E_\nu)}{\phi_\nu(E_\nu)}$$

$N_\nu(E_\nu)$ = # of ν events.

$\phi_\nu(E_\nu)$ = # of ν's at the detector; ν flux.





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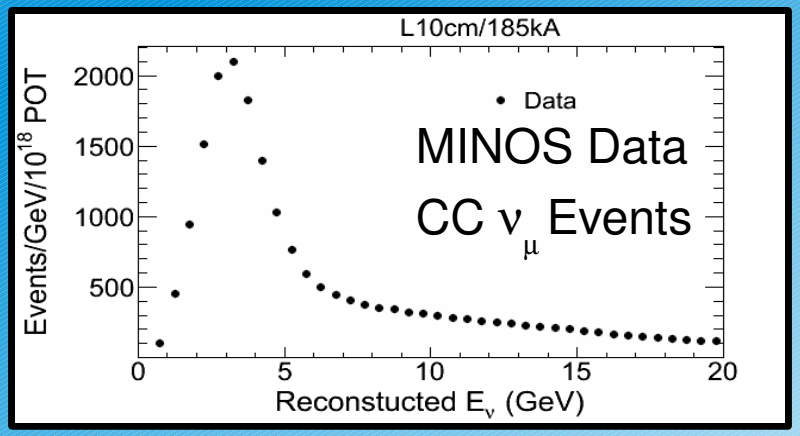
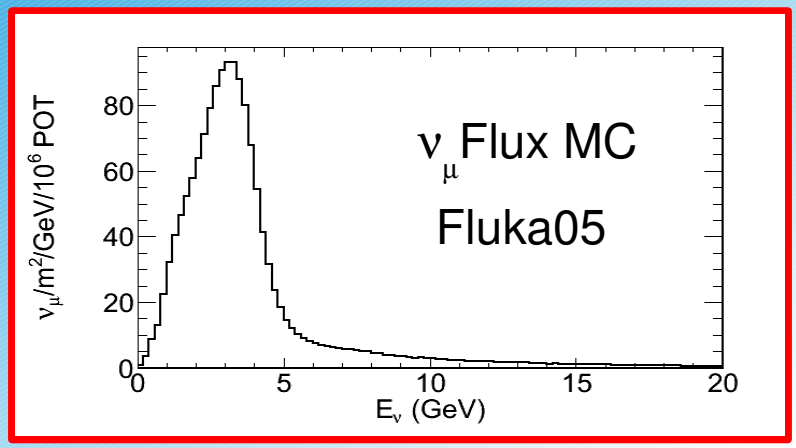
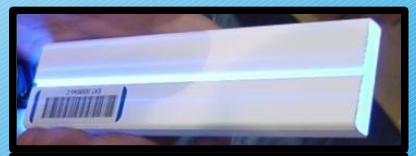
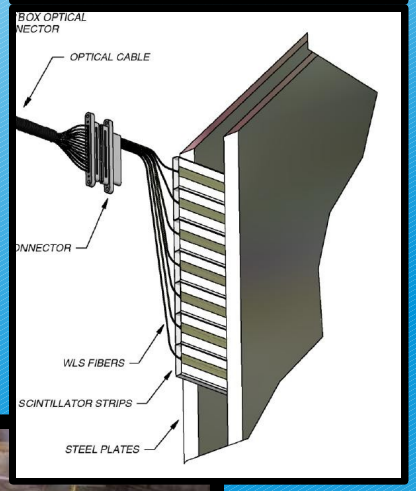


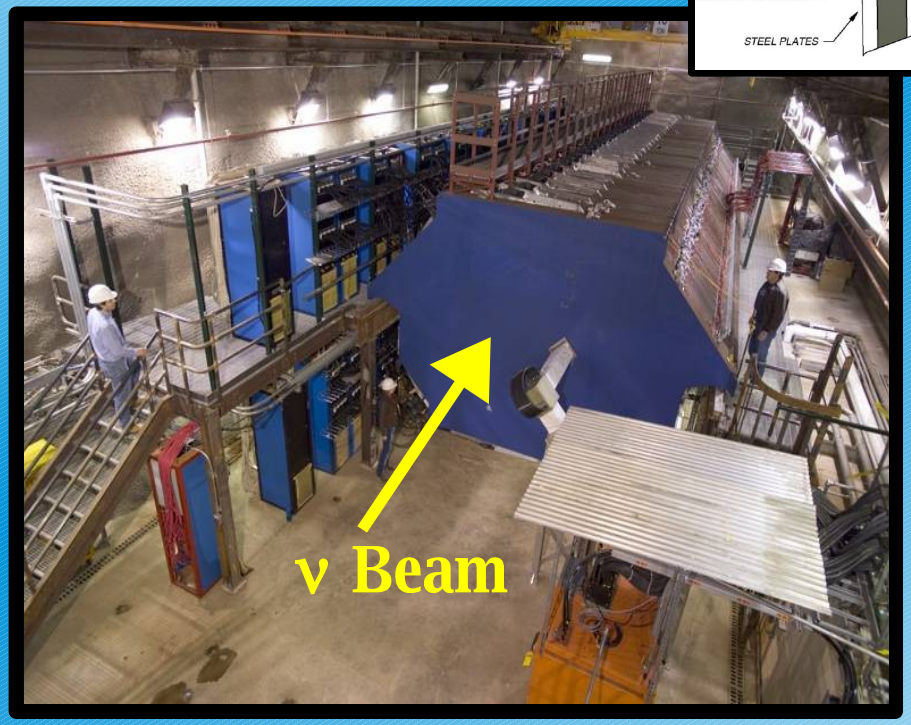


The MINOS Detector

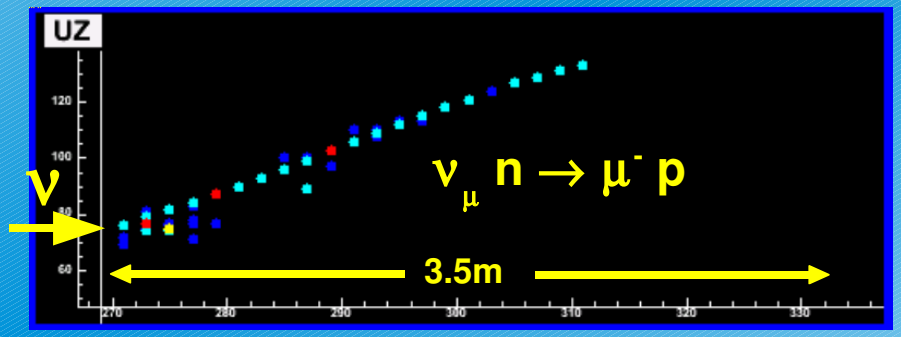
- 980ton Steel + scintillator planes.
- Wavelength shifting fibers + PMTs.





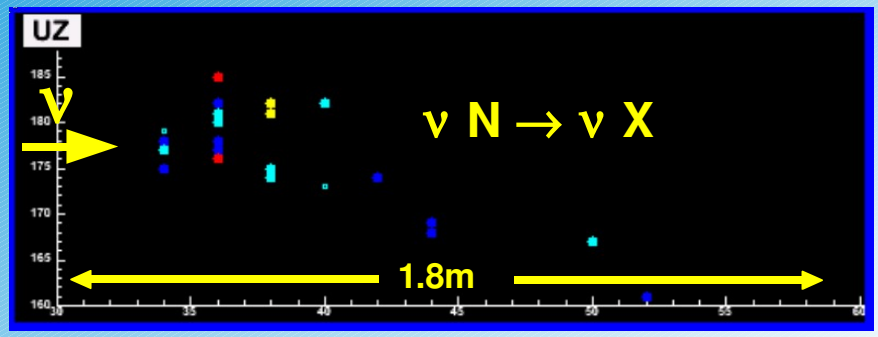


ν_μ CC Event



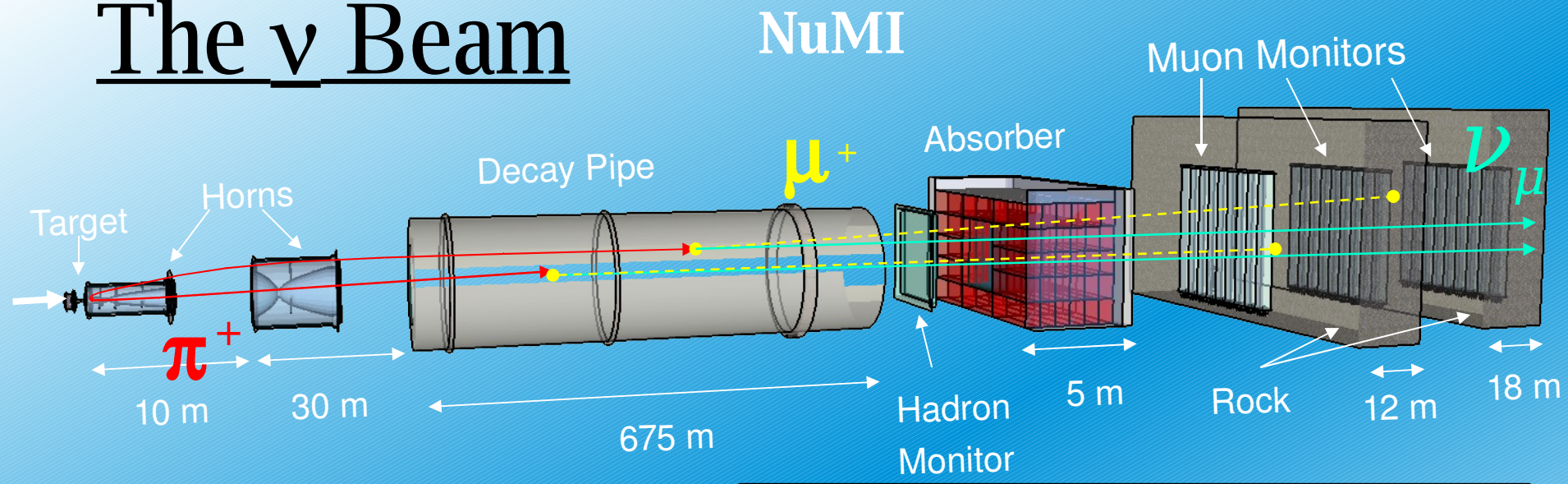
- Long muon track.
- Some hadronic activity at the vertex.

NC Event

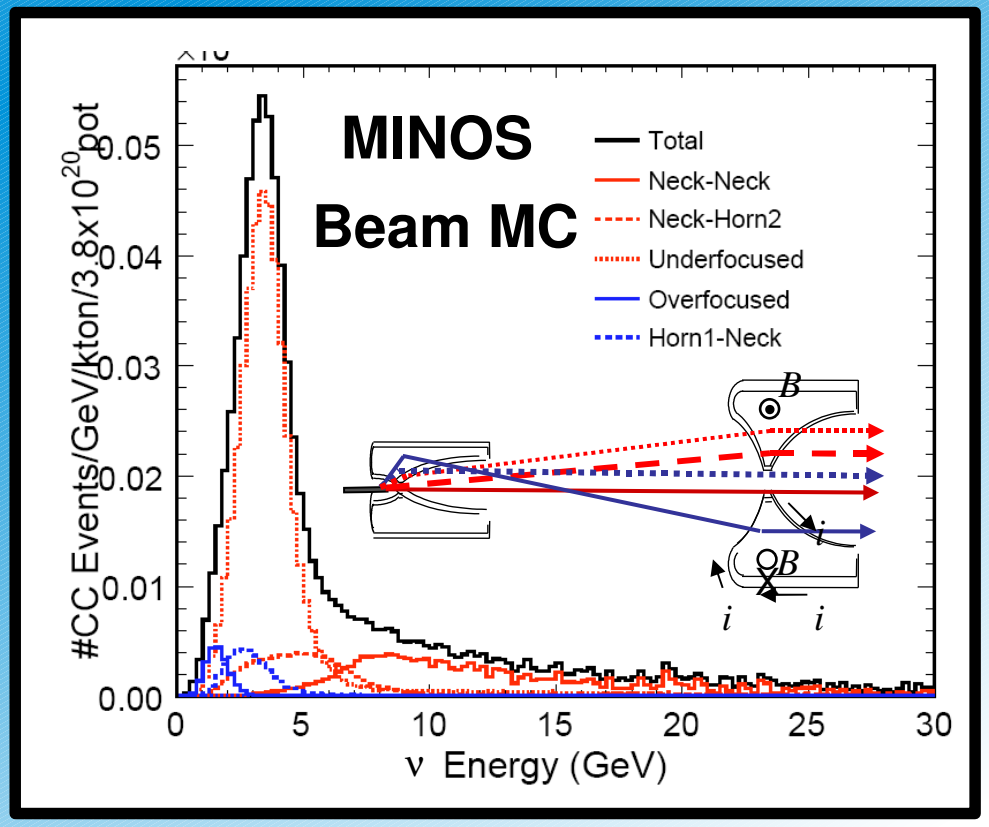


- Short hadronic shower.
- Wide transverse profile.

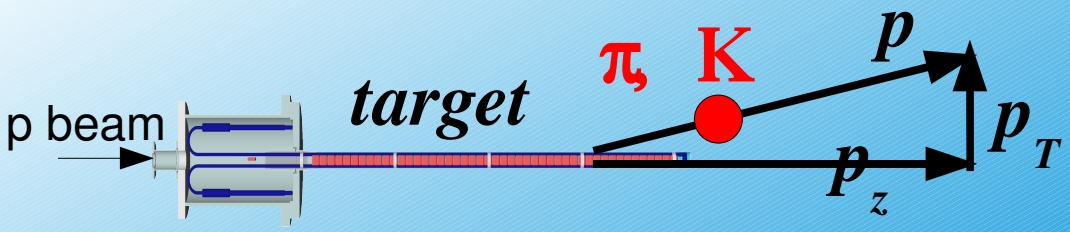
The ν Beam

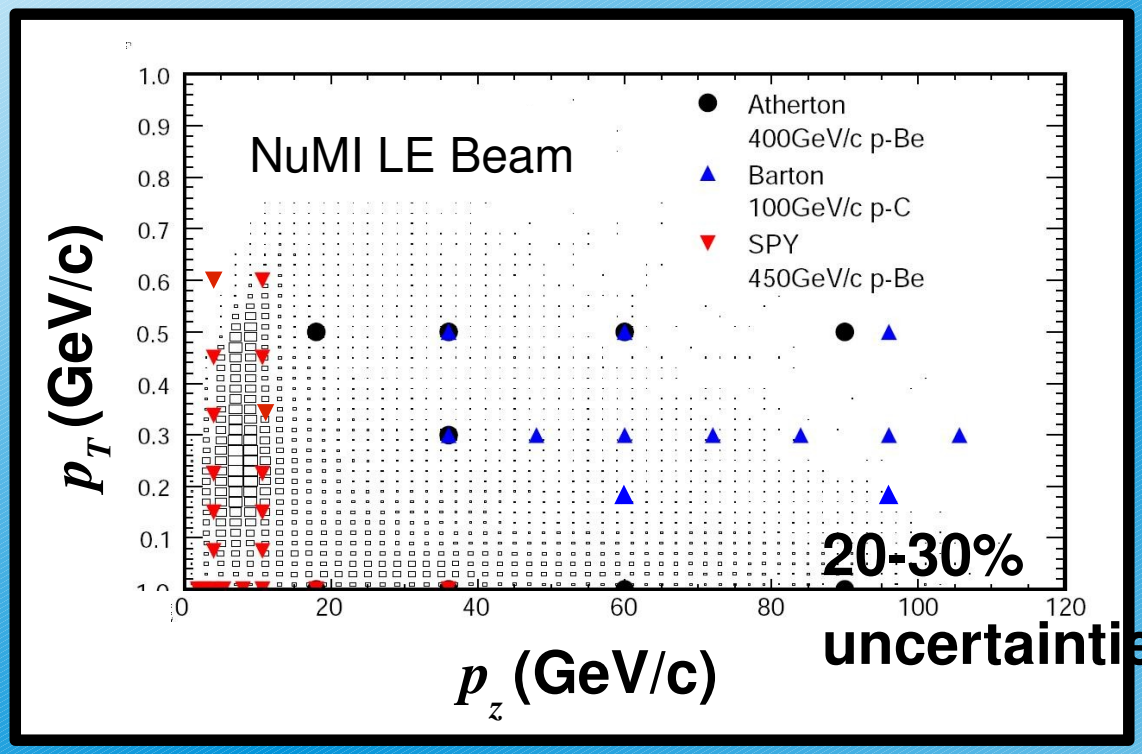


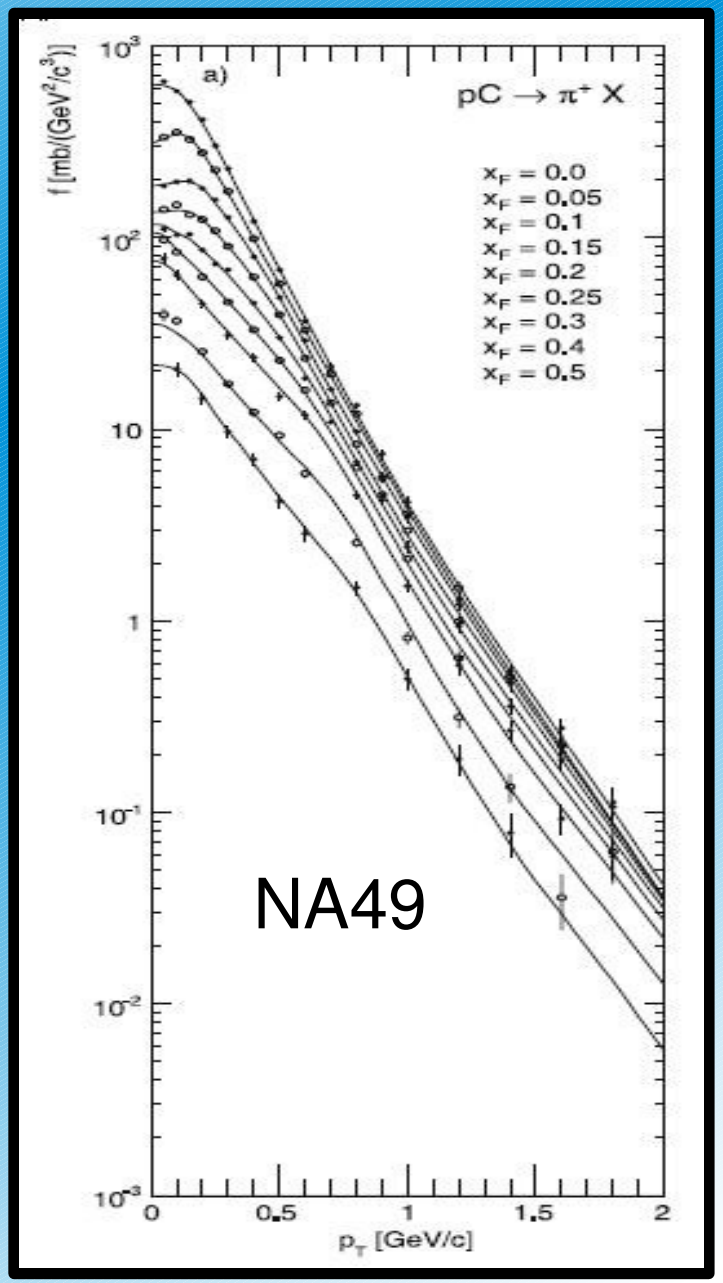
- π and K produced in p+C collisions.
- Point to parallel focusing, $f \propto p$, selects peak energy of the beam.
- π^+ and $K^+ \rightarrow \mu^+\nu_\mu$



Particle Production from the Target



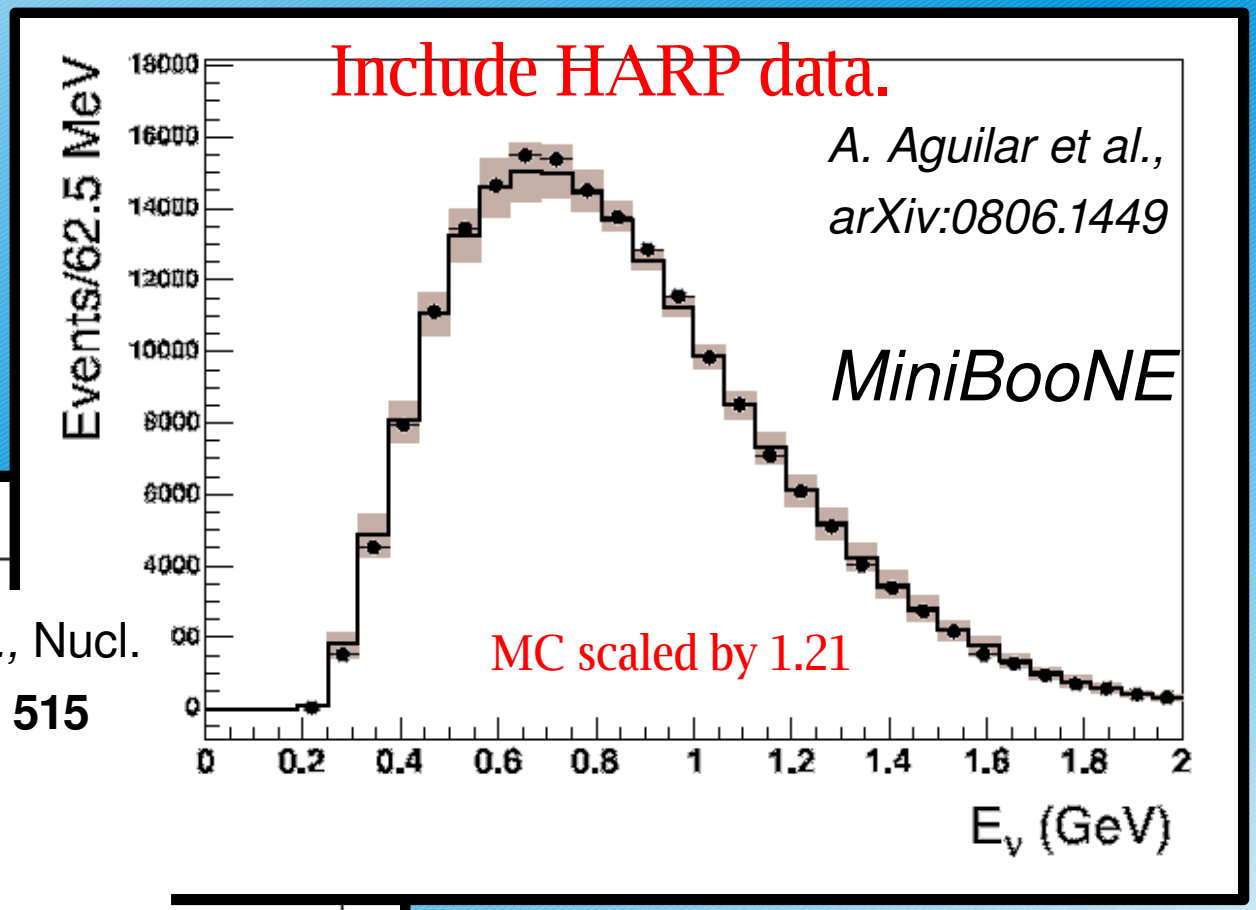


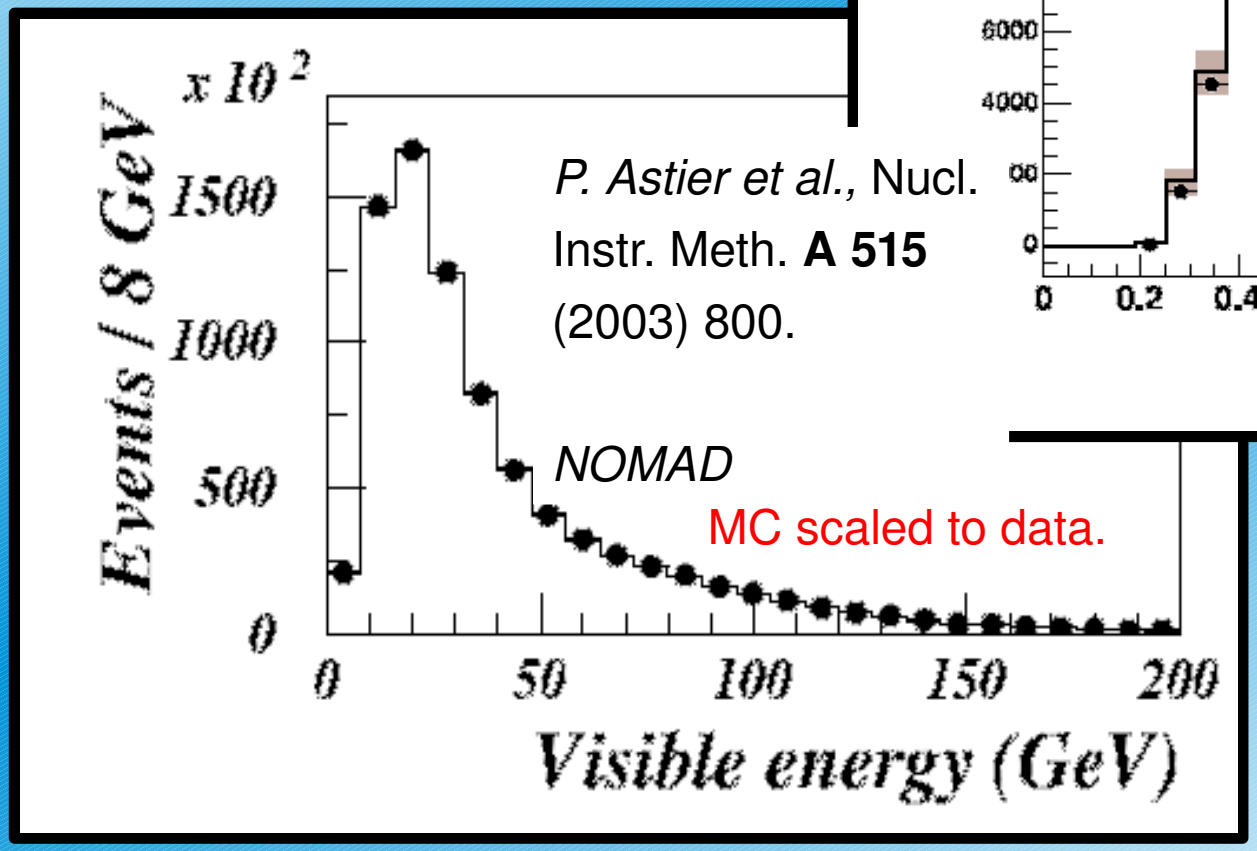


- Most ν experiments use MC tuned to existing hadron production measurements to simulate the production of ν parents in the beam line.

Incorporating Hadron Production

- Shapes seem to agree.

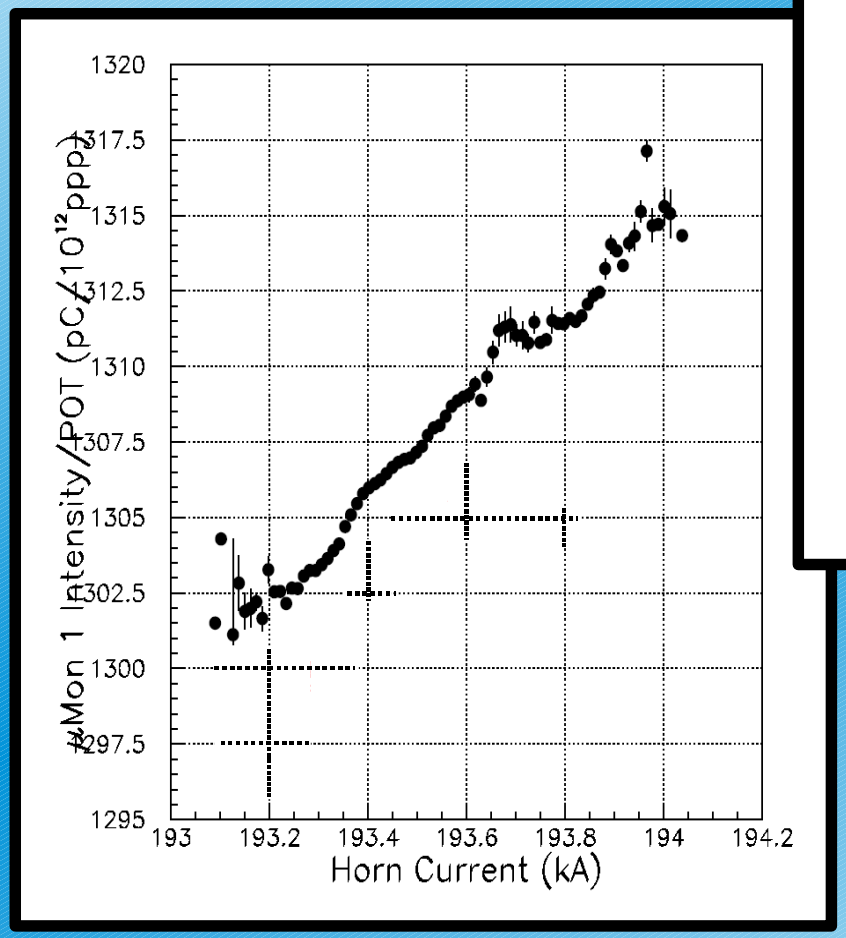


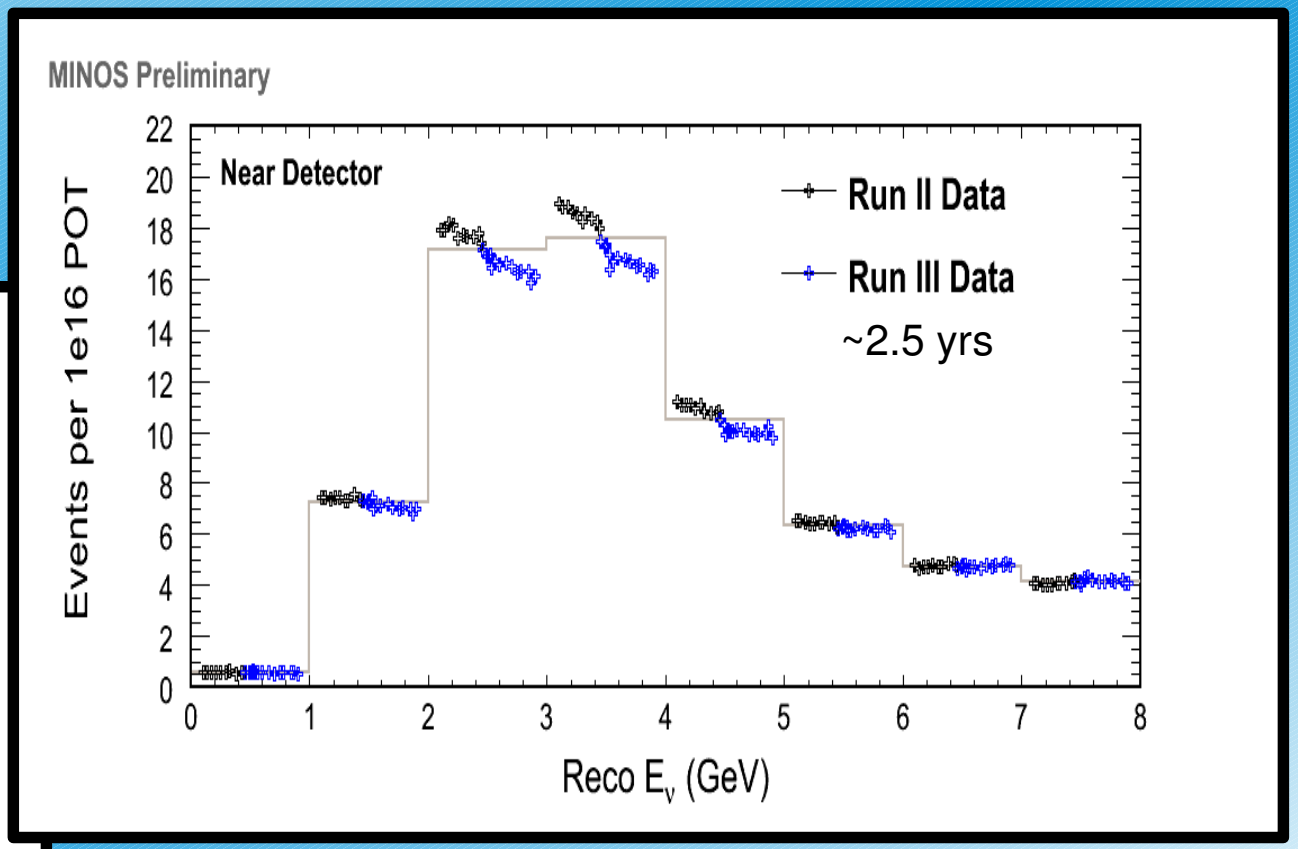


- Normalization seems uncertain.

In situ Flux Variations

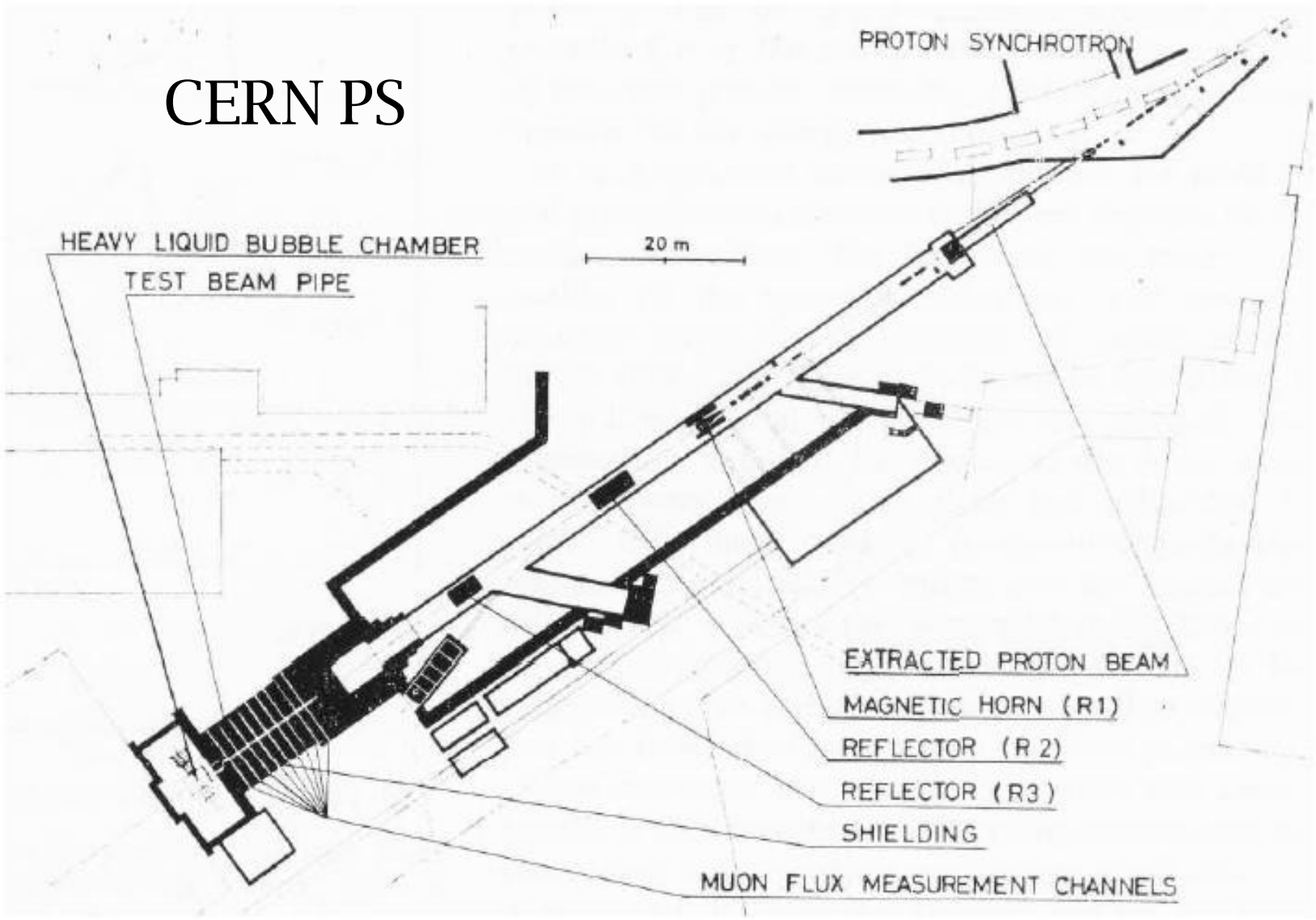
- Flux changes due to horn current variation with temperature.



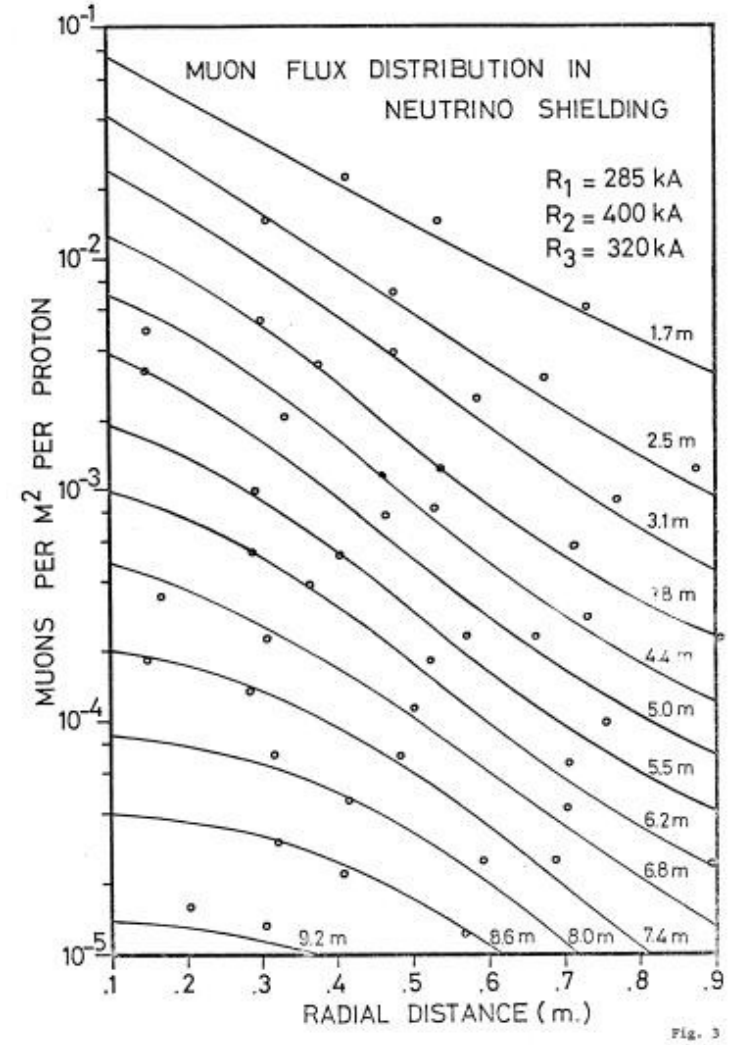


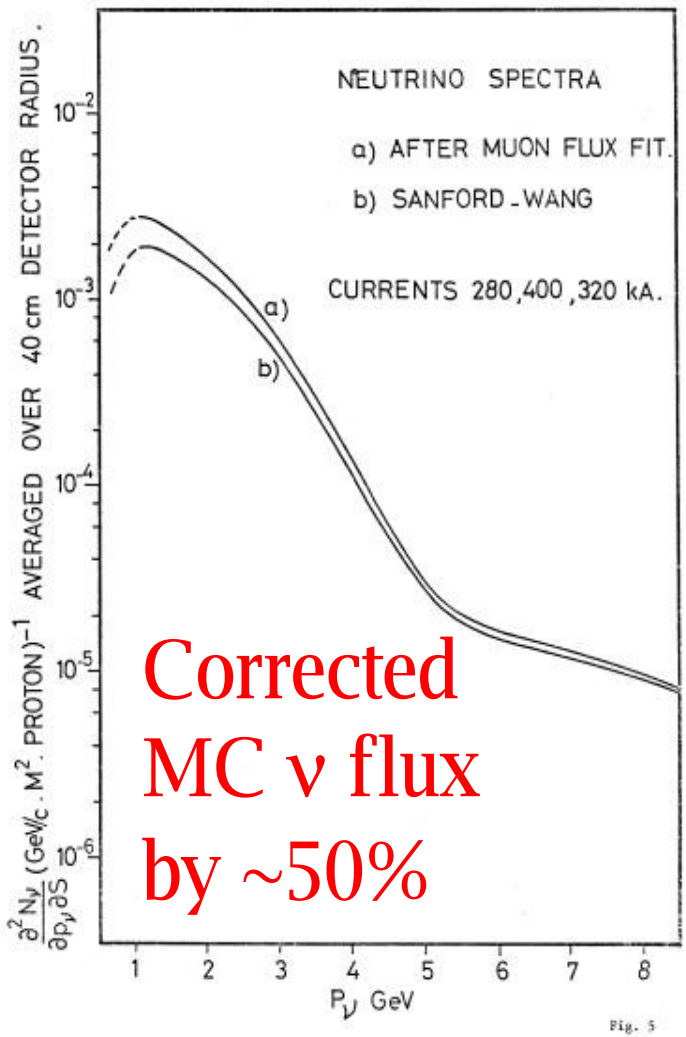
- Target degradation over time.
- Toy MC study is qualitatively consistent with data.

In situ Flux Measurements



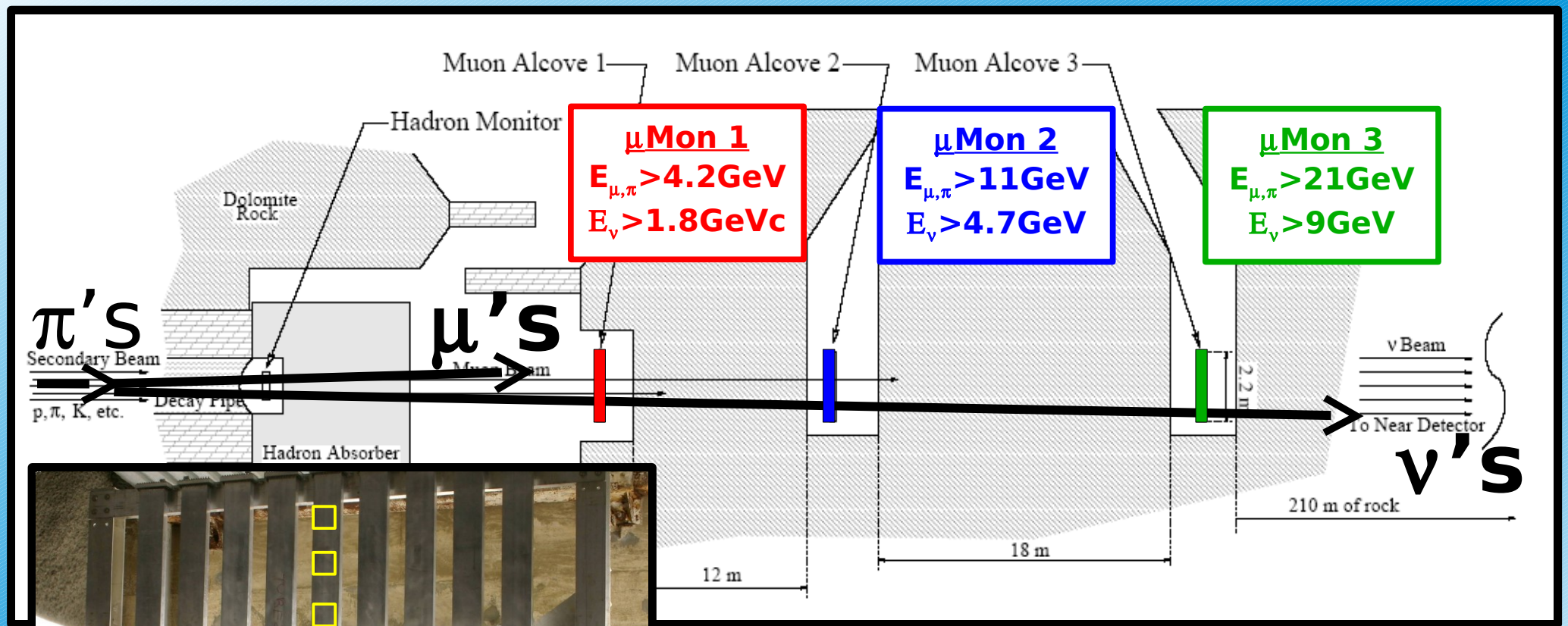
Experience from CERN PS

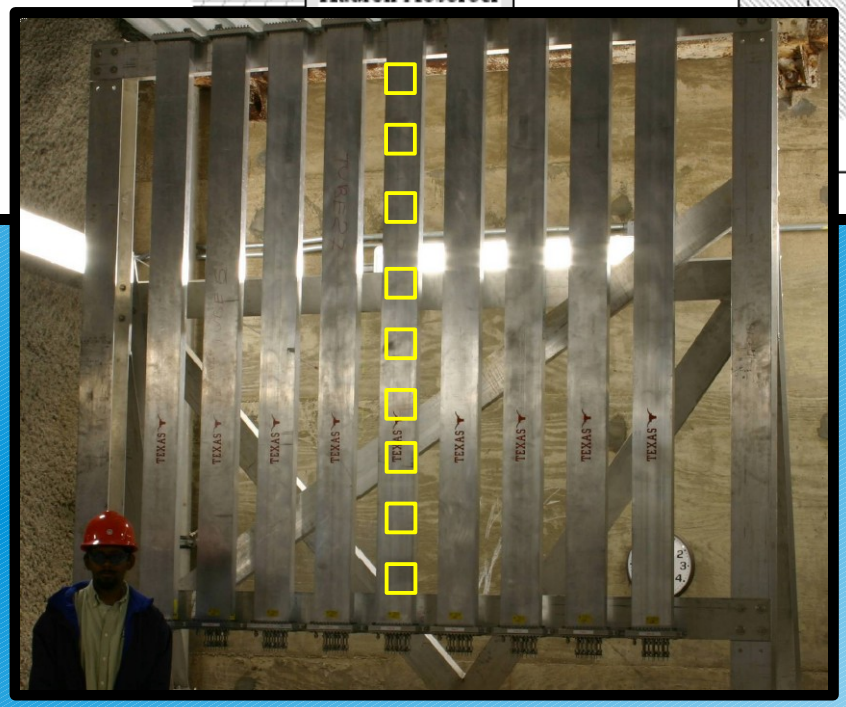




- Originally tuned MC to HP data.
- Flux measurement from μMons indicated ~50% off.
- New HP experiment – agreed with μ tuned ν flux to 15%.

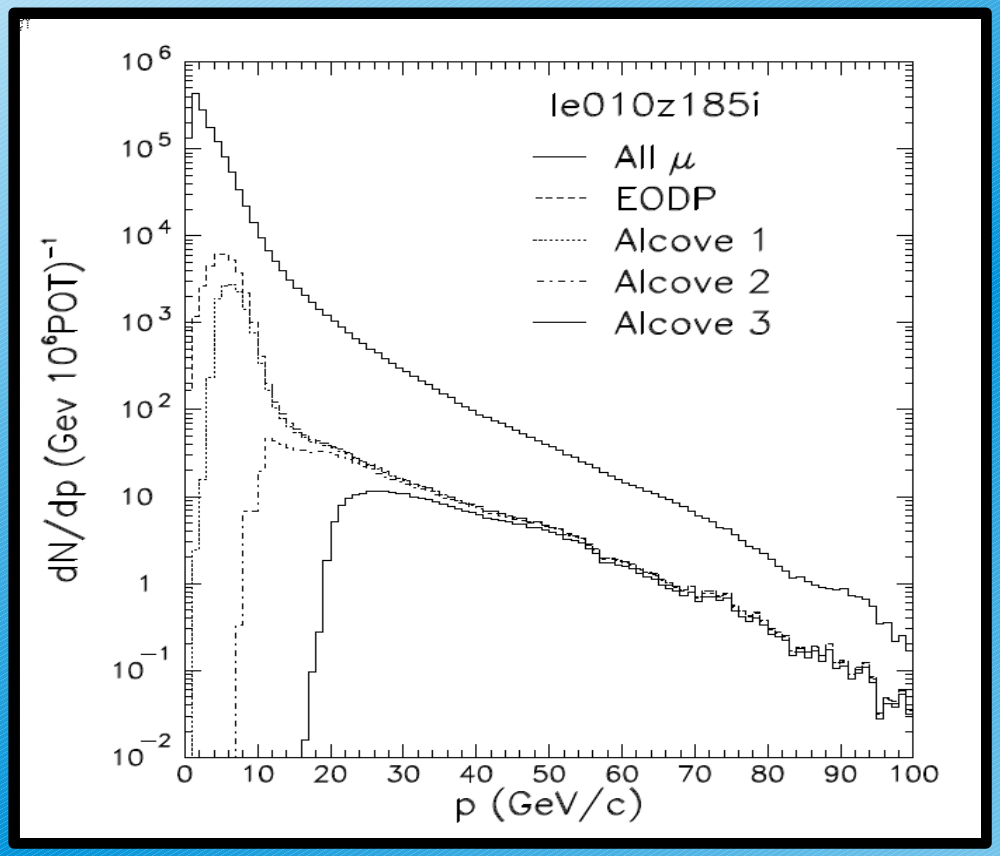
NuMI μ Monitors

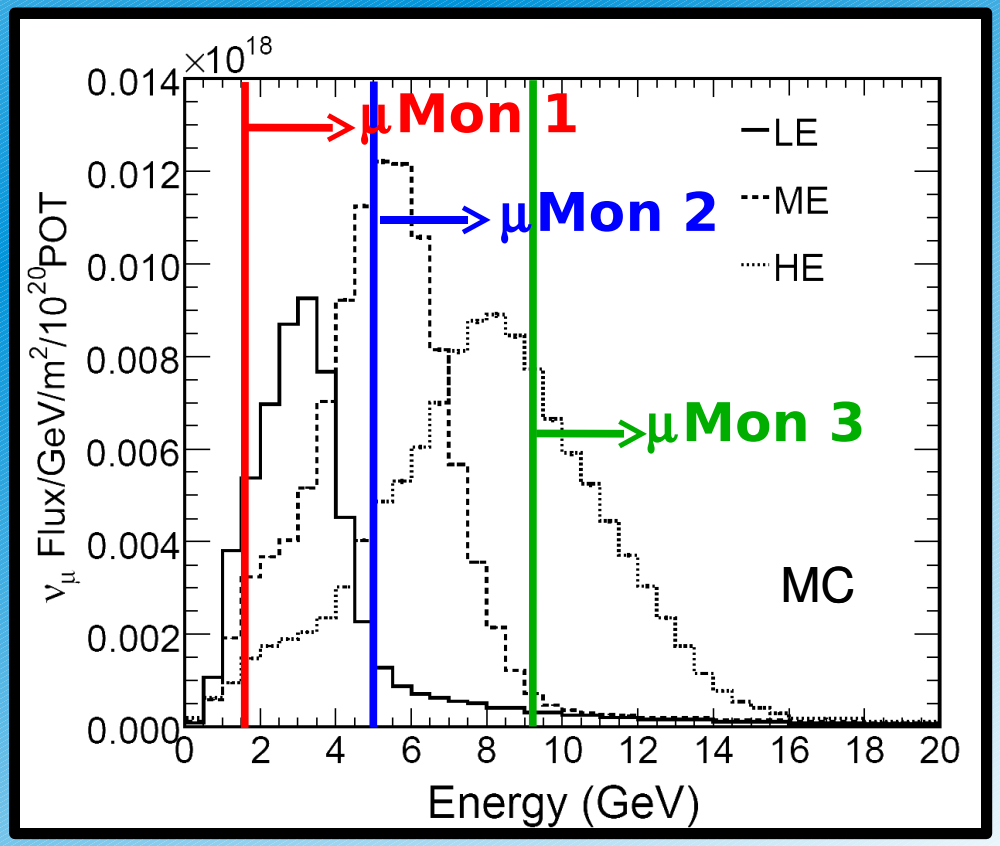




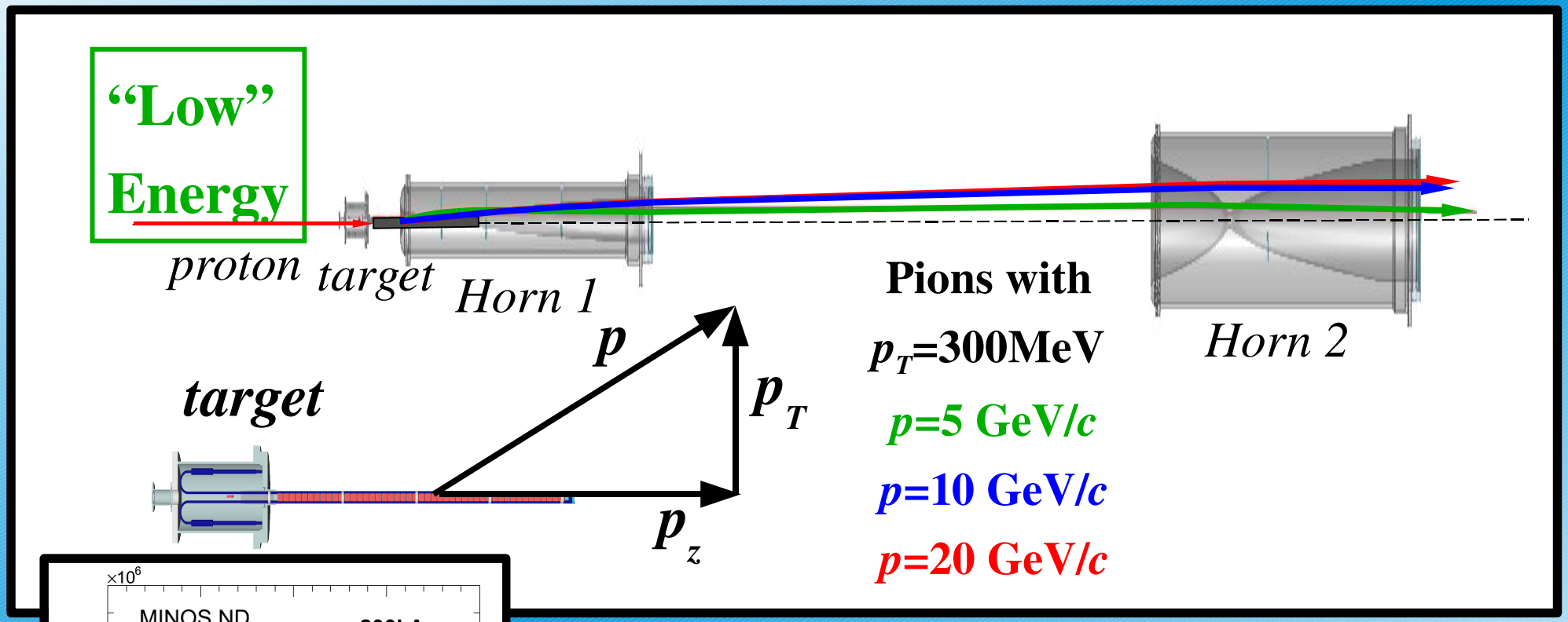
- 3 arrays of ionization chambers.
- Beam μ's ionize He gas. But also, n, δ-rays.
- Signal = ionized electrons.
- Sampling μ flux = Sampling hadrons off target = Sampling ν flux.

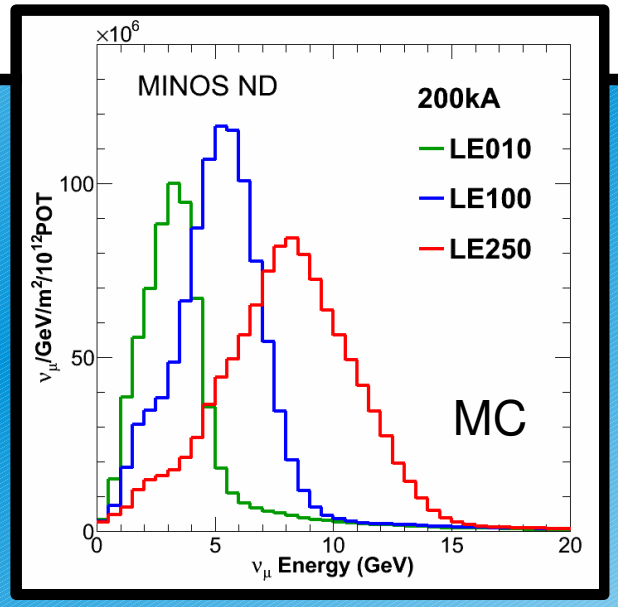
μ's In the μMonitors





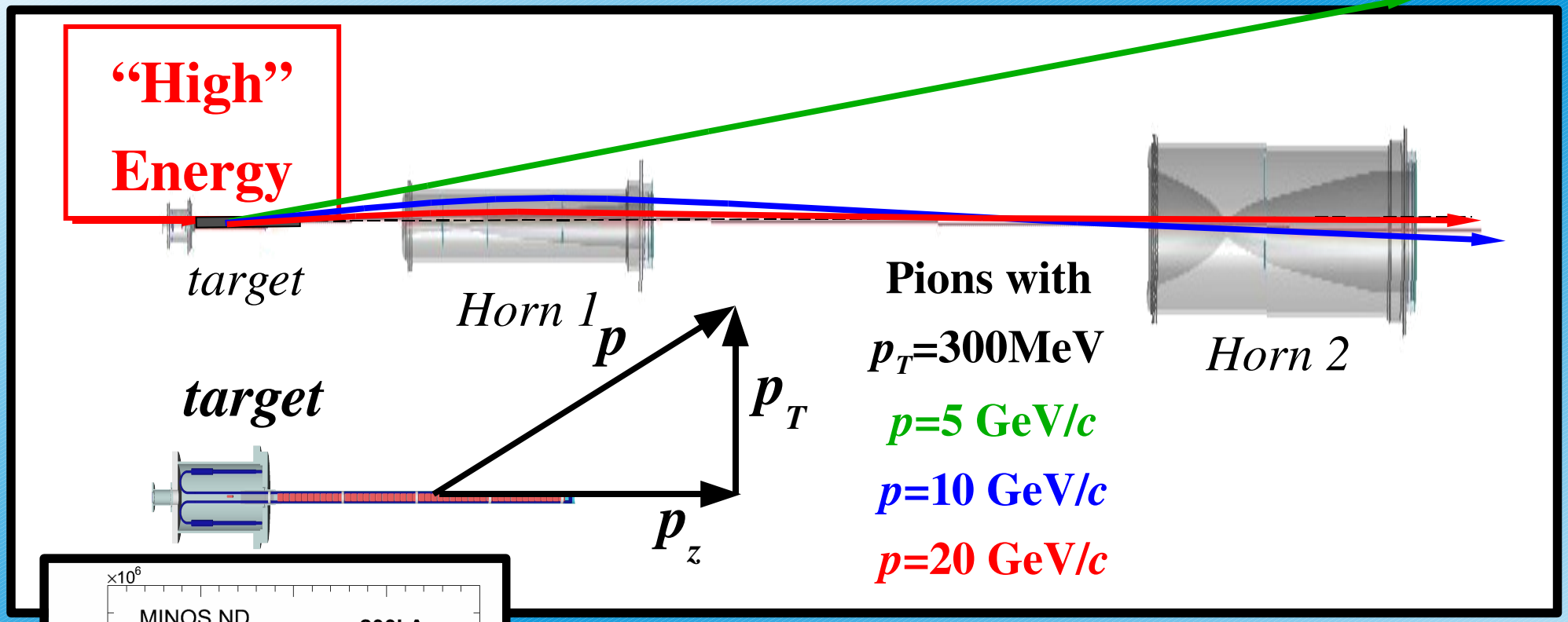
NuMI Variable Energy Beam

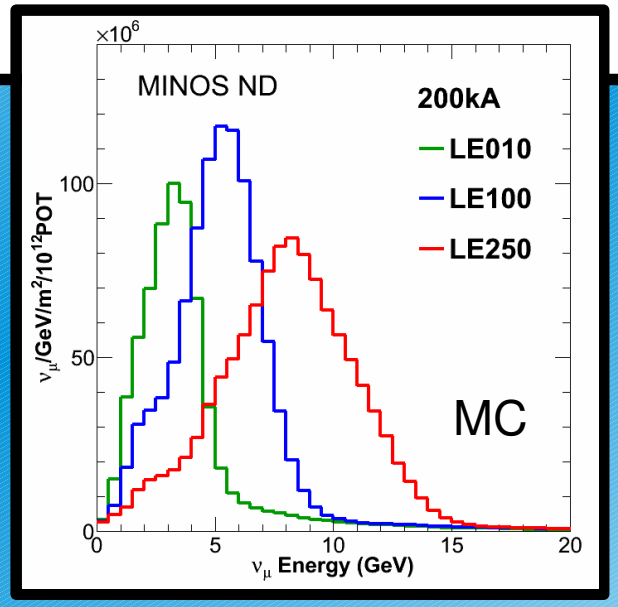




- Hadrons diverge from the target → horns focus hadrons along the beamline.
- Varying target position samples variety of E_π, E_μ and E_ν.

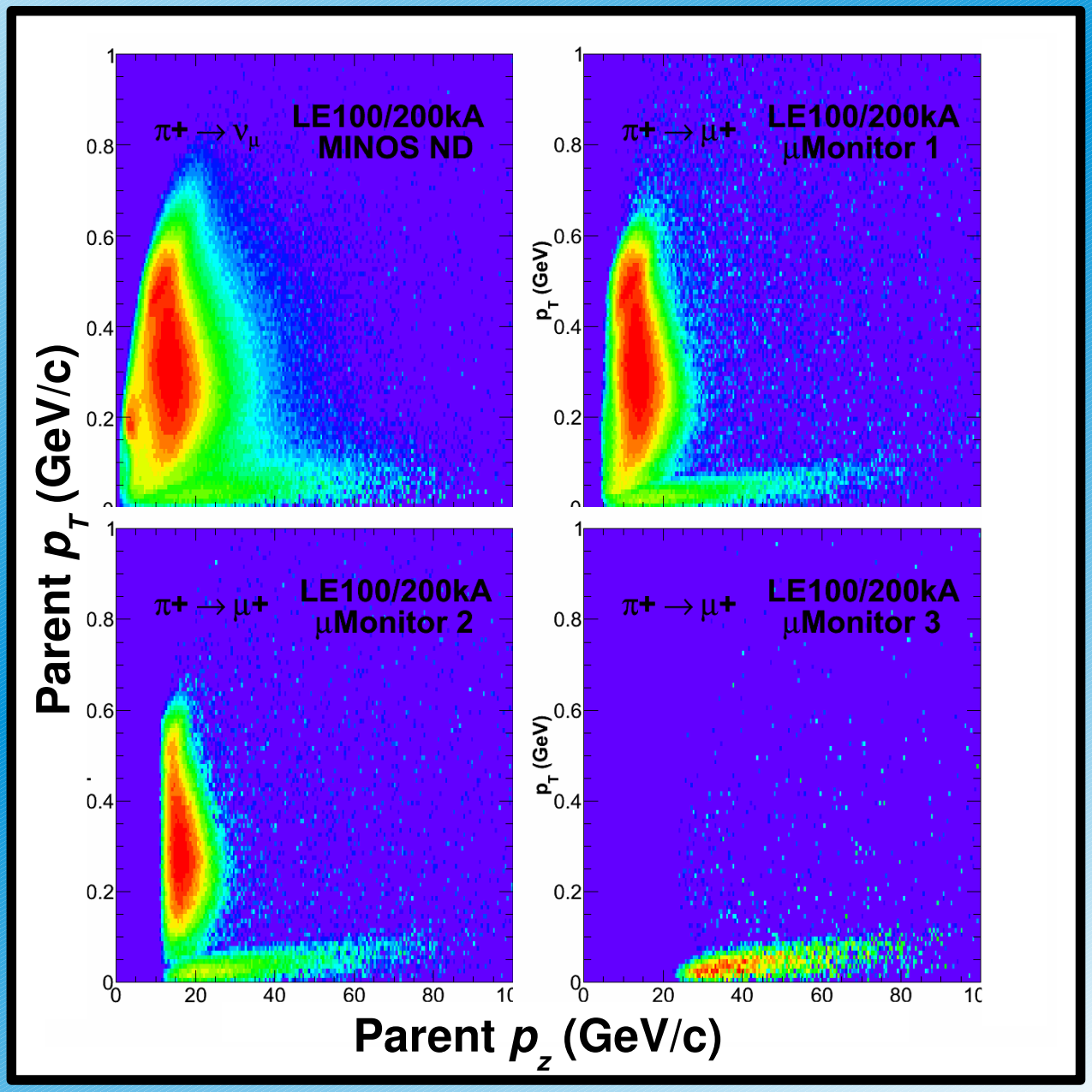
NuMI Variable Beam Energy



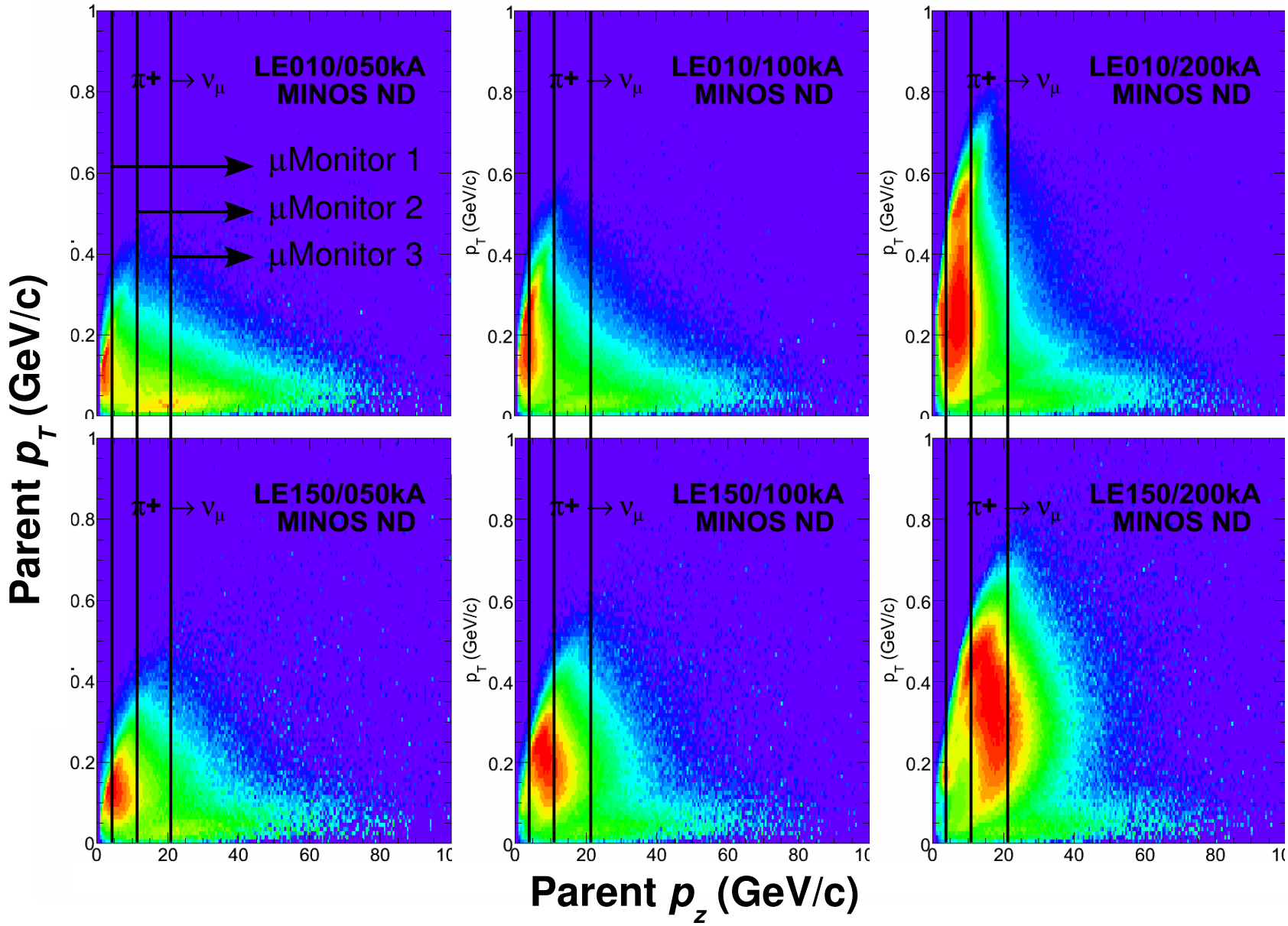


- Varying target position samples variety of E_π E_μ and E_ν.
- Vary target z ⇒ sample p_z. Vary horn current ⇒ sample p_T.

$$\varphi_\nu(E_\nu) \leftrightarrow \varphi_\nu(p_T, p_z)$$

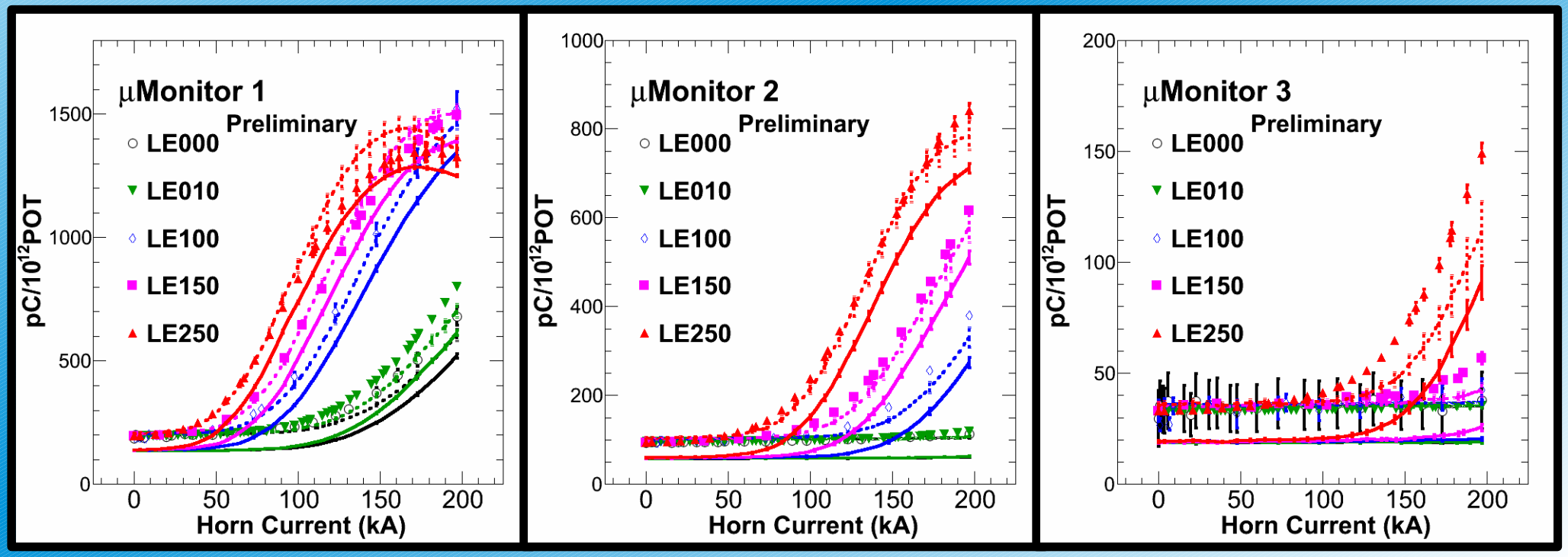


Varying (z_{target}, I_{horn})

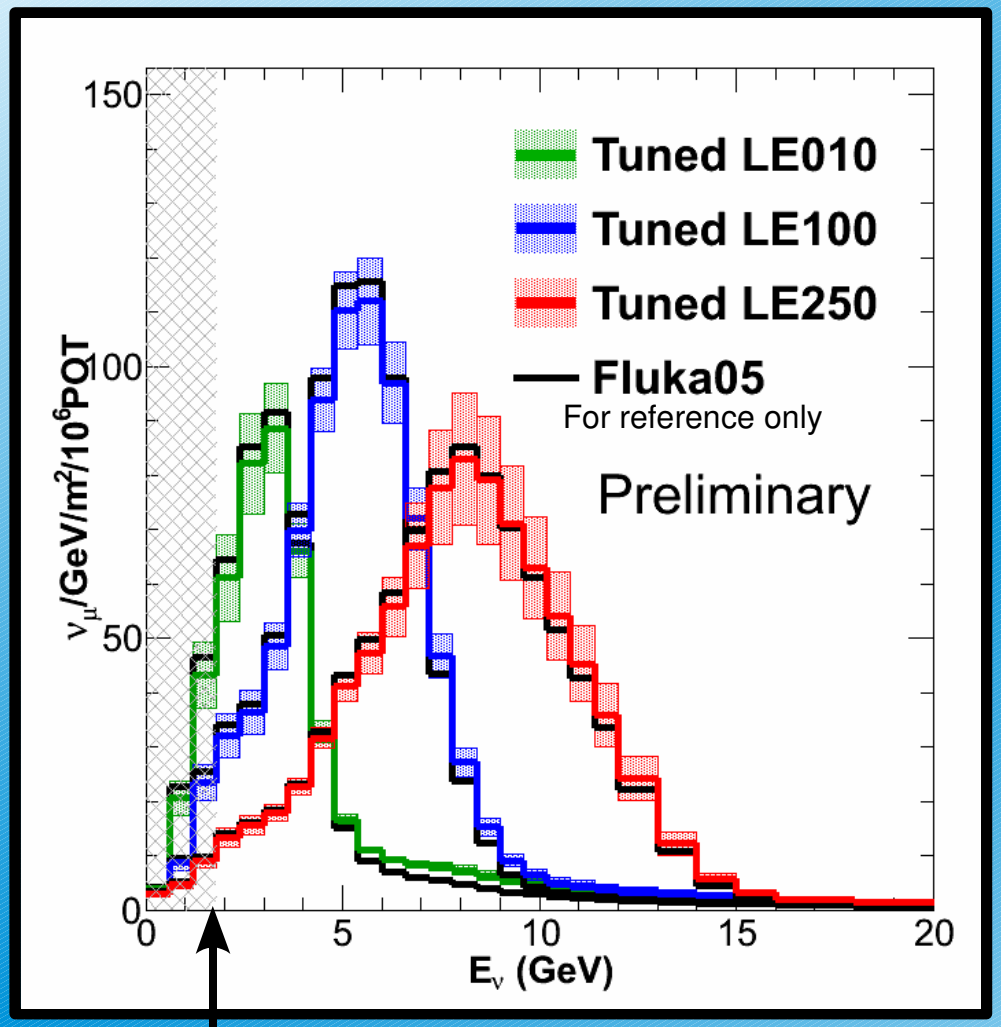


μ Monitor Tuning

- Emperical parameterization for hadron production, f(p_T, p_z).
- Warp p_T and p_z to tune default MC to μ Monitor data.
  - Data — Monte-Carlo - - - Tuned Monte-Carlo



NuMI ν_μ Flux

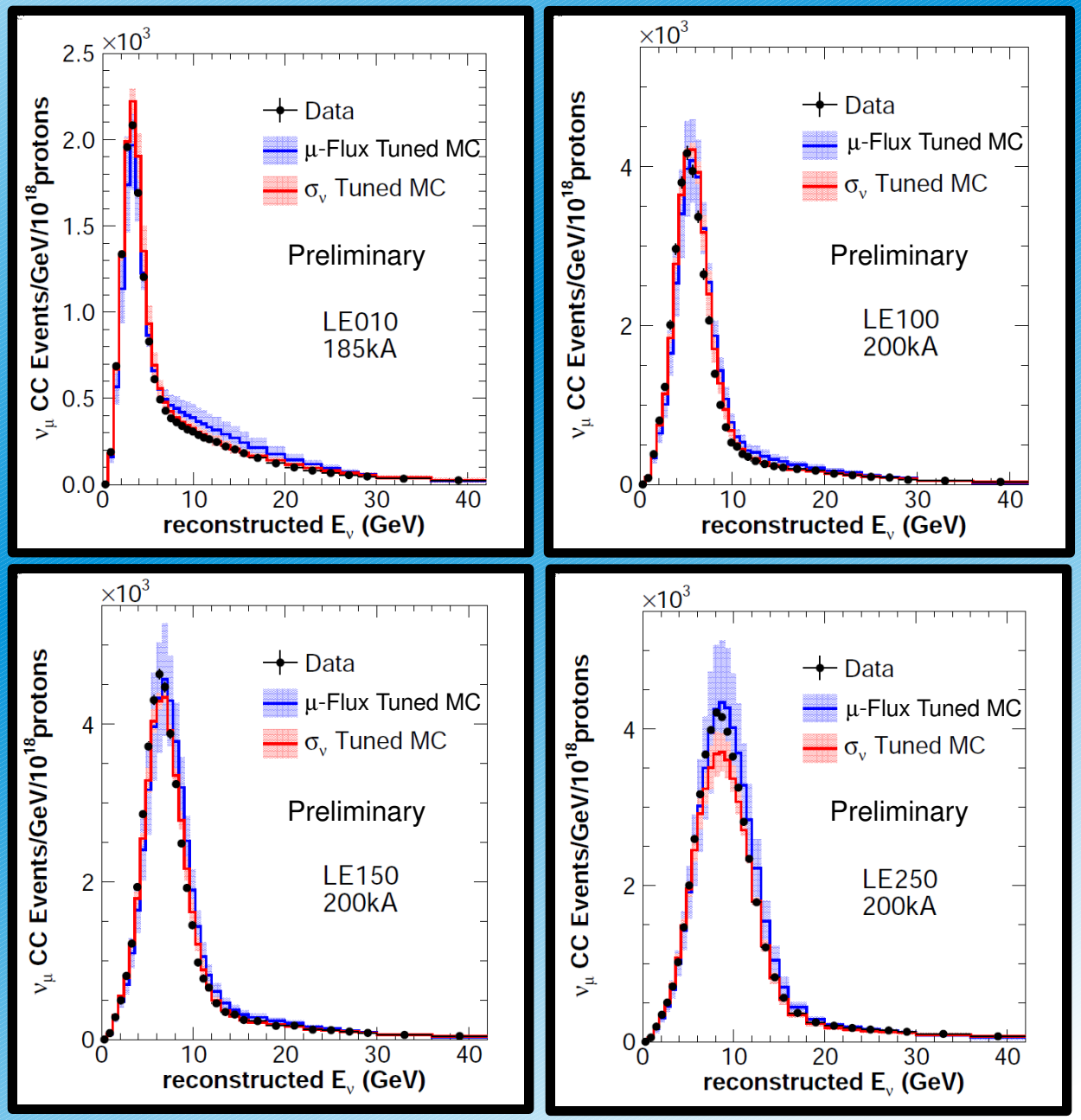


μ Monitor energy threshold.

- Shape only measurement.
- Due to large uncertainty in Muon Monitor Ionization Scale flux requires normalization to MINOS data for $E_\nu > 26$GeV.
- Error bars come from...
  - π+/π- ratio, K/π ratio
  - Non-linearity
  - Backgrounds
- In situ measurement; accounts for real beamline conditions.

CC ν_μ inclusive Cross Section

- Want σ(true E_ν)
- Have measured (reconstructed) E_ν in the detector.
- Fit MC CC ν_μ spectrum to Data by assigning parameters in bins of true E_ν.
- The parameters are scale factors on the NEUGEN cross section in MC.
- Fit 4 beams simultaneously.

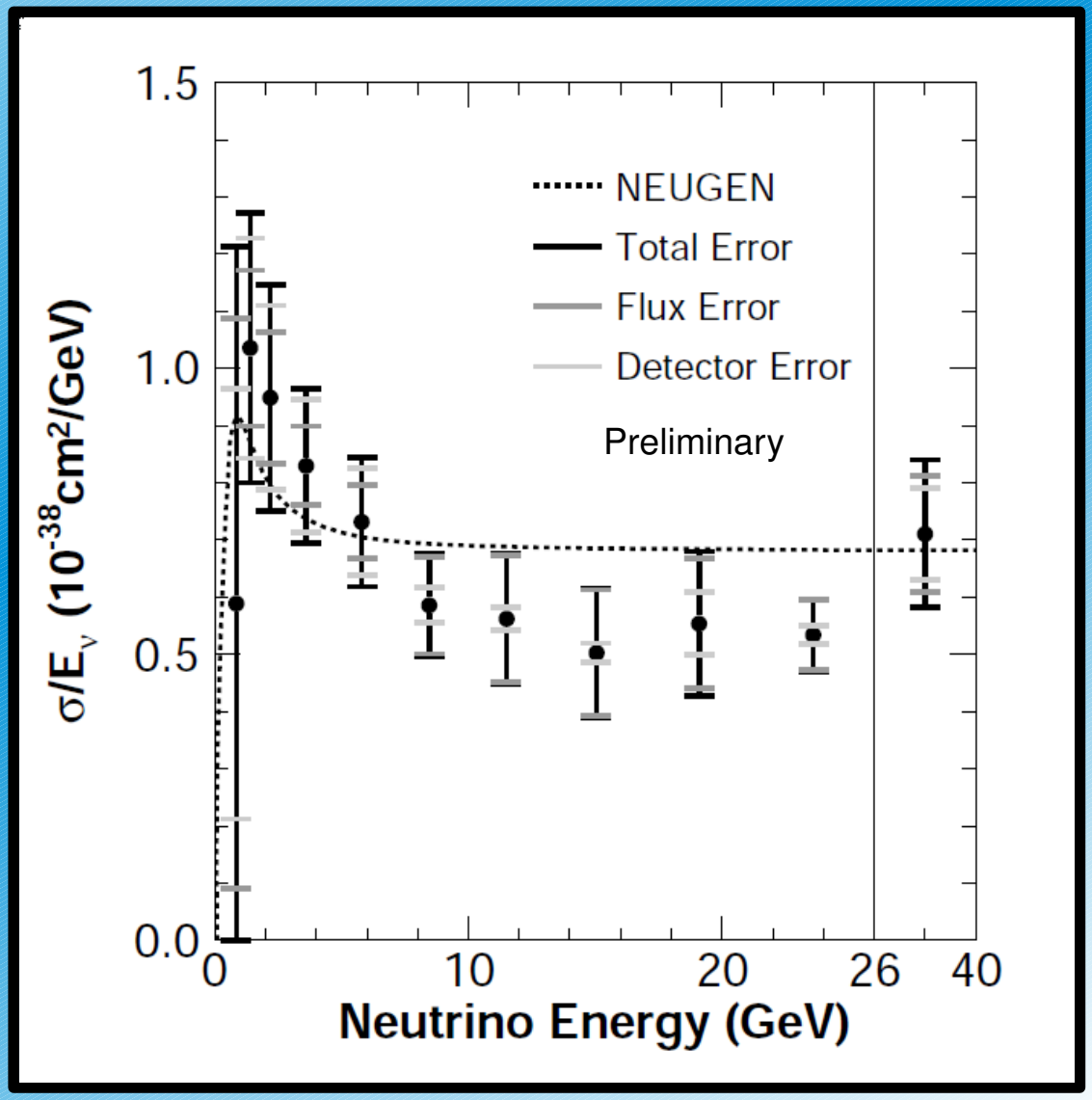


CC ν_μ Inclusive Cross Section

- Detector Error:
  - Hadronic Energy Scale
  - Muon Energy Scale
  - Fiducial Volume
  - Event Selection

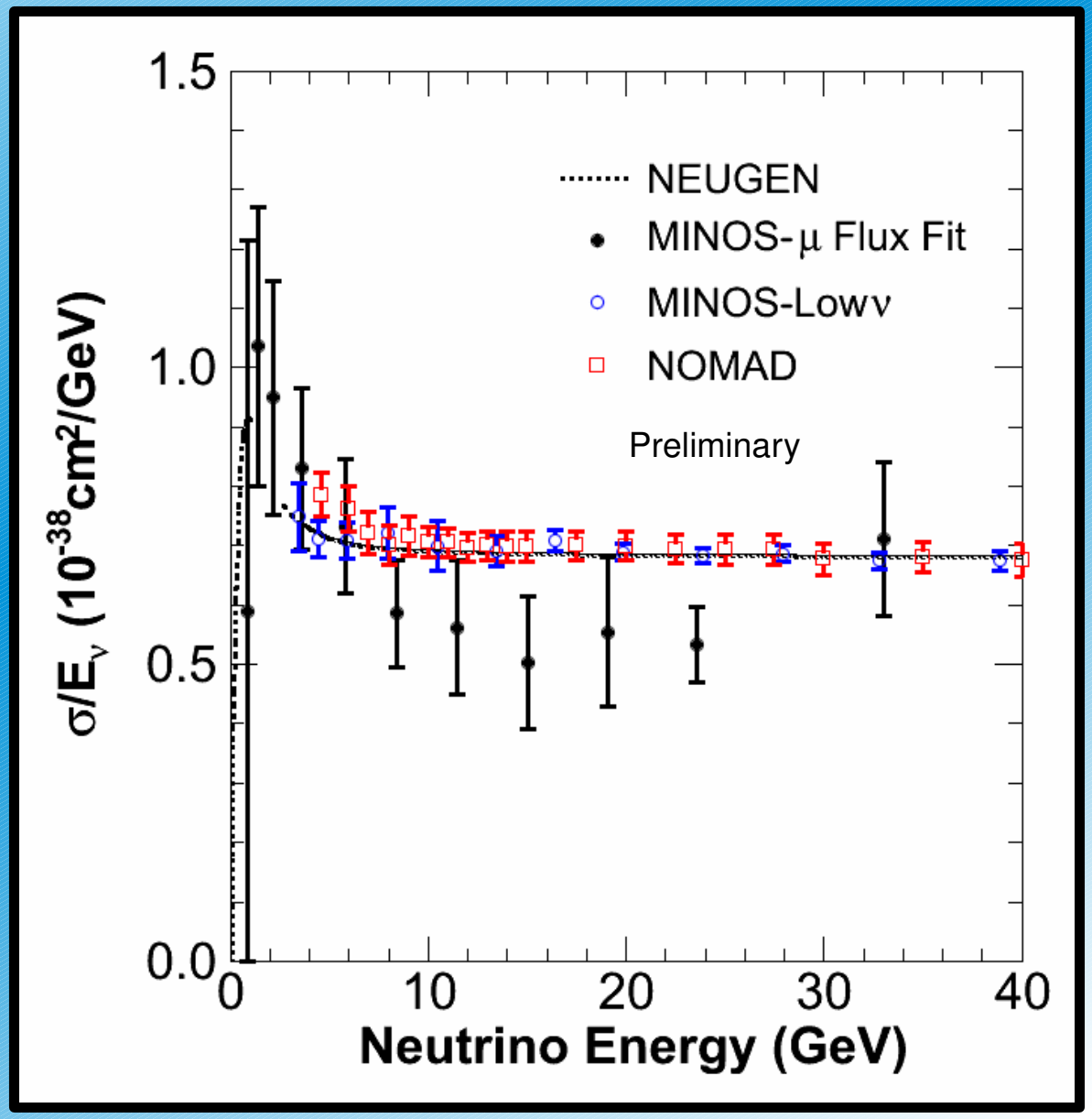
Preliminary

E_ν	σ/E_ν	% Error
0.85	0.59	106.2
1.4	1.04	22.8
2.2	0.95	20.8
3.6	0.83	16.3
5.8	0.73	15.5
8.5	0.59	15.4
11.5	0.56	20.1
15.1	0.50	22.3
19.1	0.55	22.7
23.6	0.53	11.9
33.0	0.71	18.2



Comparison

- MINOS-Low ν: Flux from low hadronic energy transfer neutrino events.
- Nomad: Flux from incorporating hadron production measurements in MC.
- MINOS-μ Flux: In situ flux measurement.
- All normalize cross section at high energies.



Summary

- Over the past several years we have developed a technique to measure neutrino cross sections using a measurement of the muon flux.
- This technique desirable because it provides an in-situ measurement of the flux which accounts for real beamline conditions.
- Agreement between Data and Monte Carlo is improved. The error bars do reflect our best knowledge at this time and account for the uncertainty in this first analysis.
- Have learned where there is room for improvement for a next generation analysis.
  - Understand Muon Monitor Ionization scale
  - Analysis of Delta Ray beam test performed Fall 2009.
  - Improved Monte Carlo which incorporates tertiary particle production.

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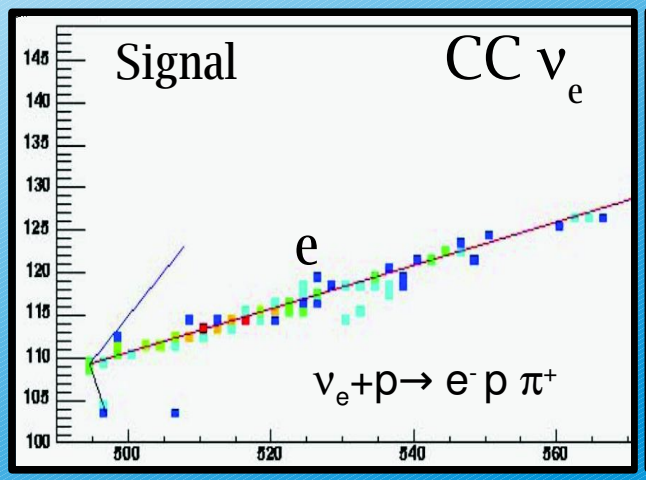
Backup Slides

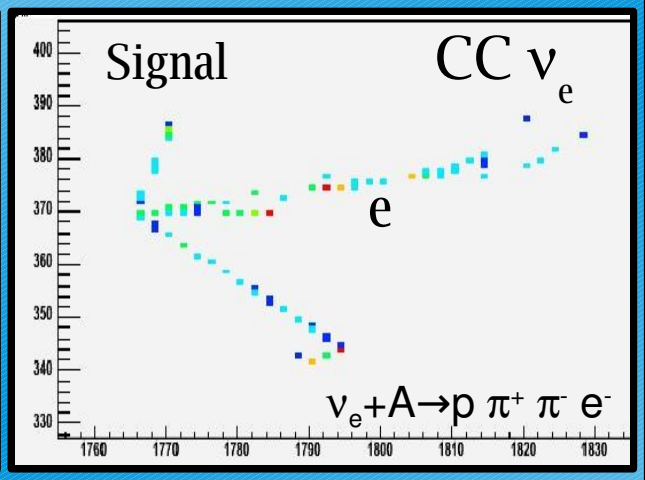
Potential for Event MisID

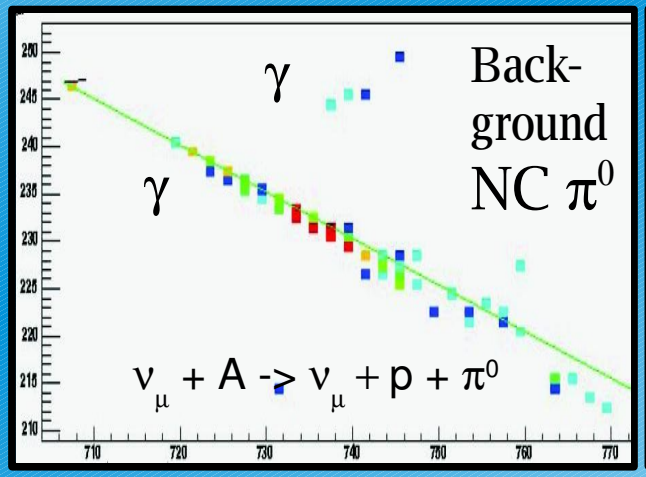
NC pion production $\nu_\mu N \rightarrow \nu_\mu N^* \pi^0 \rightarrow \nu_\mu N \gamma \cancel{\gamma}$

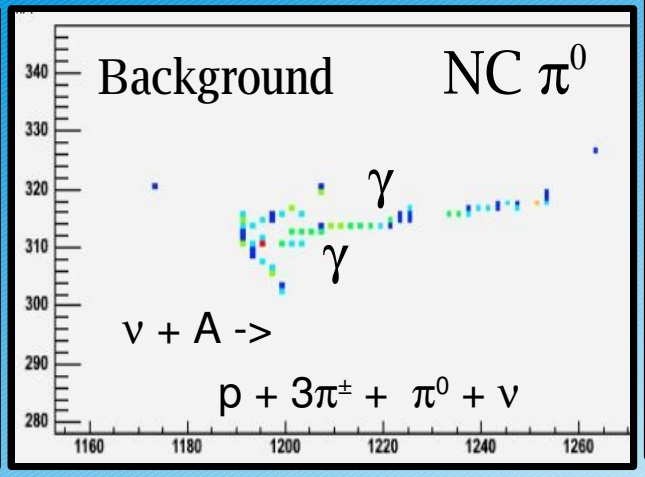
can look like $\nu_e n \rightarrow p e^-$

NOνA

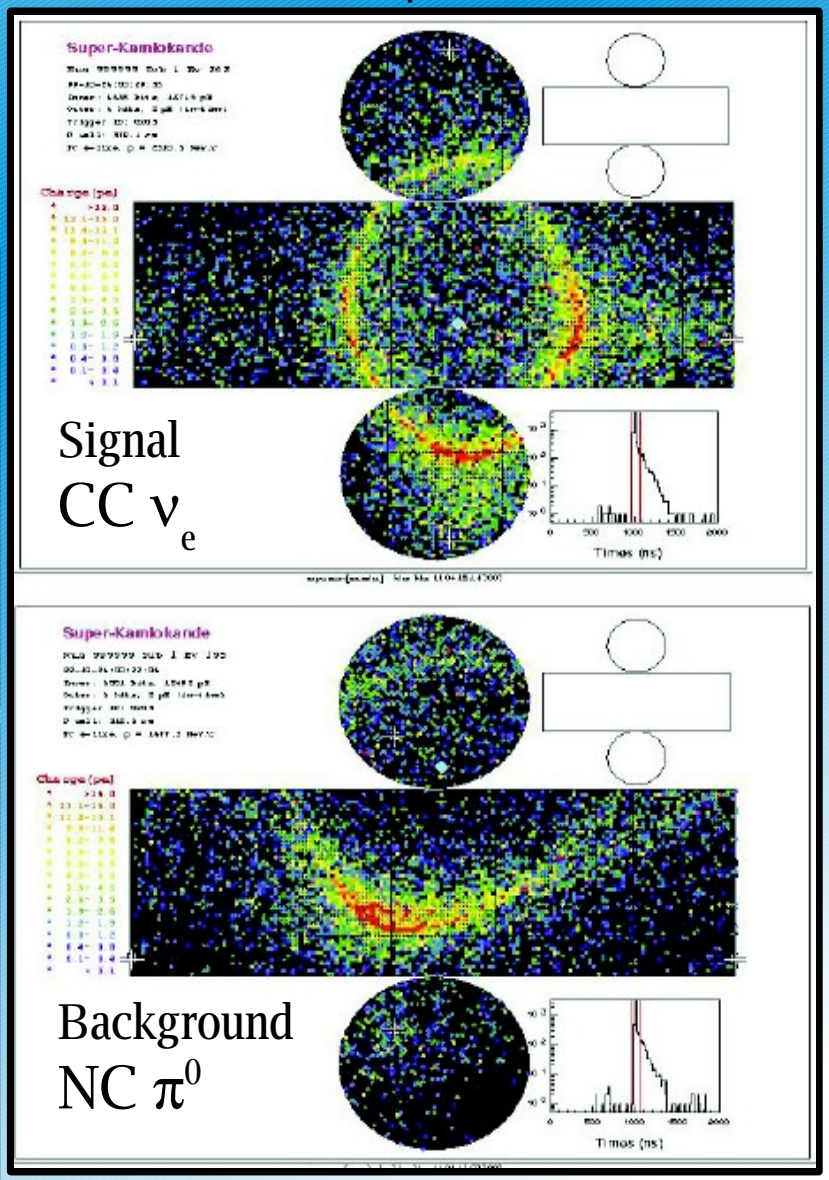








Super-K



Nuclear Effects

- Visible energy in detector is not necessarily = E_ν.

$$E_\nu = E_l + E_{had} + E_{miss}$$

- An example: π absorption and rescattering in the nucleus.

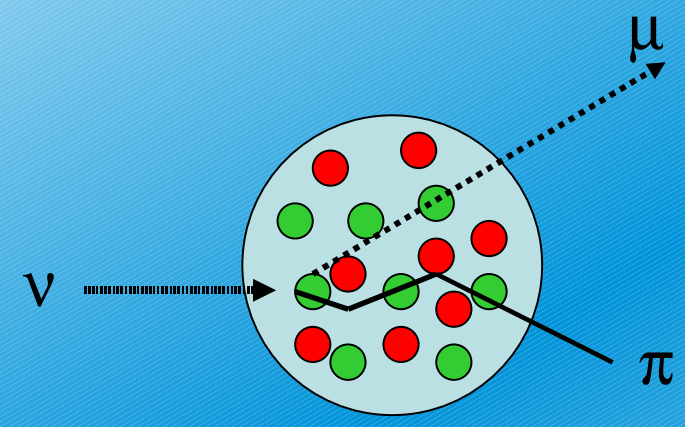
- π energy is missing or is reduced during escape from the nucleus.

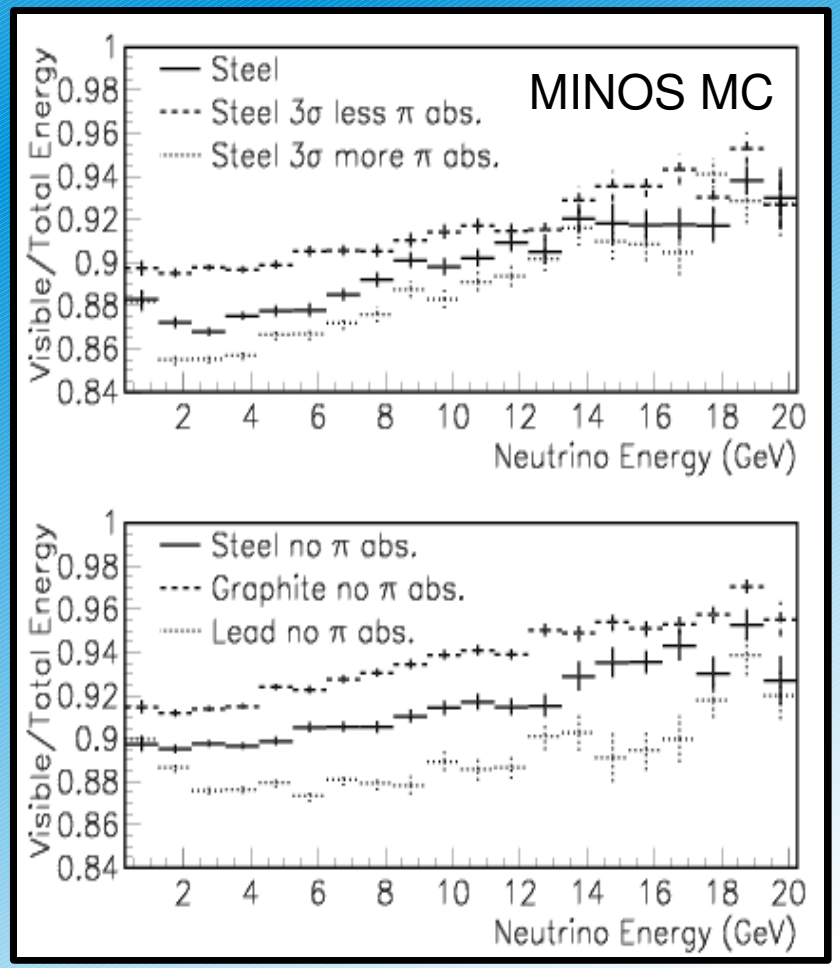
- Example:

  On ^{12}C at E_ν = 1GeV

  ~20% π^0 are absorbed

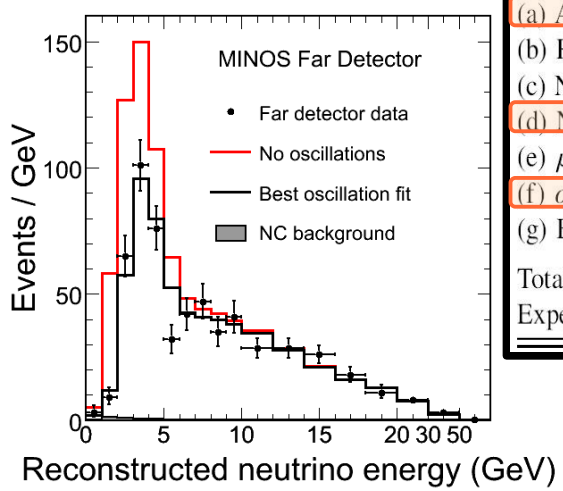
  ~10% π^0 charge exchange ($\pi^0 \rightarrow \pi+, \pi-$)



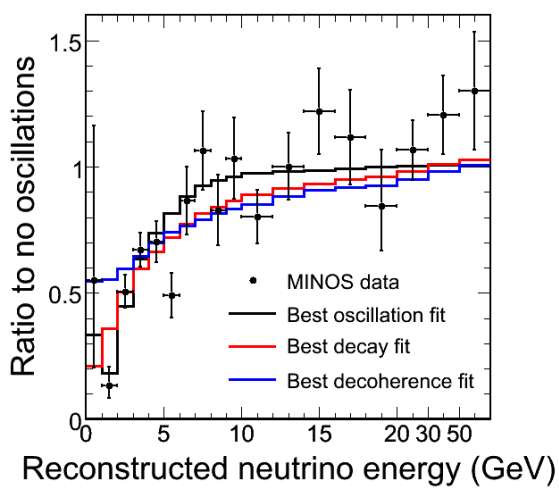


How can better σ_ν measurements help?

MINOS

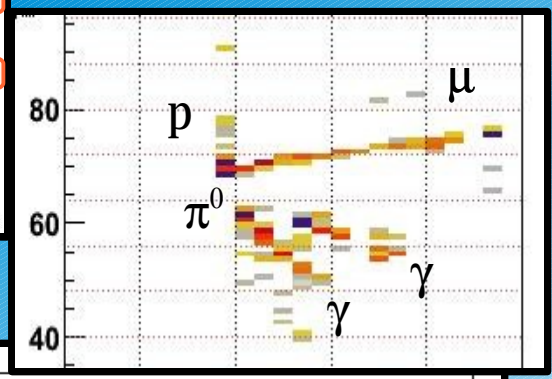


$\Delta m^2 = 2.43 \times 10^{-3}$ eV^2



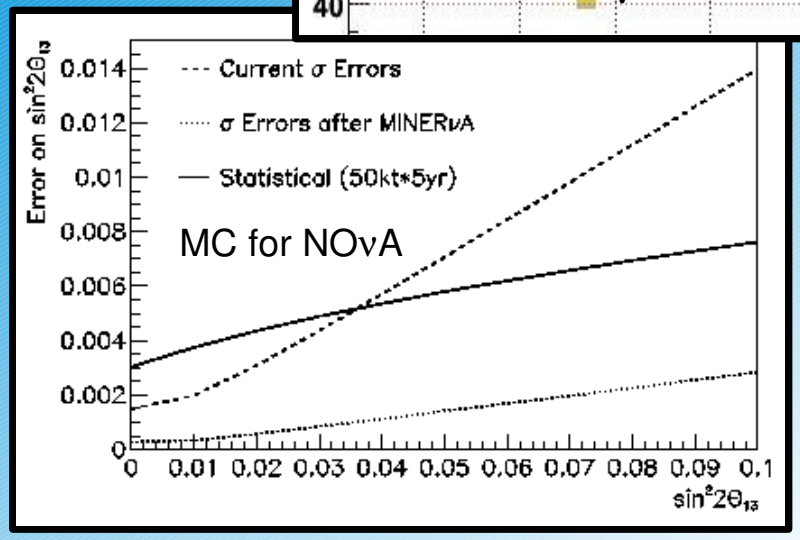
Uncertainty	$\lvert\Delta m^2\rvert$ (10^{-3} eV^2)	$\sin^2(2\theta)$
(a) Absolute hadronic E scale ($\pm$10.3%)	0.052	0.004
(b) Relative hadronic E scale ($\pm$3.3%)	0.027	0.006
(c) Normalization ($\pm$4%)	0.081	0.001
(d) NC contamination ($\pm$50%)	0.021	0.016
(e) μ momentum (range 2%, curvature 3%)	0.032	0.003
(f) $\sigma_\nu(E_\nu < 10$ GeV) ($\pm$12%)	0.006	0.004
(g) Beam flux	0.010	0.000
Total systematic uncertainty	0.108	0.018
Expected statistical uncertainty	0.19	0.09

MINERνA Data



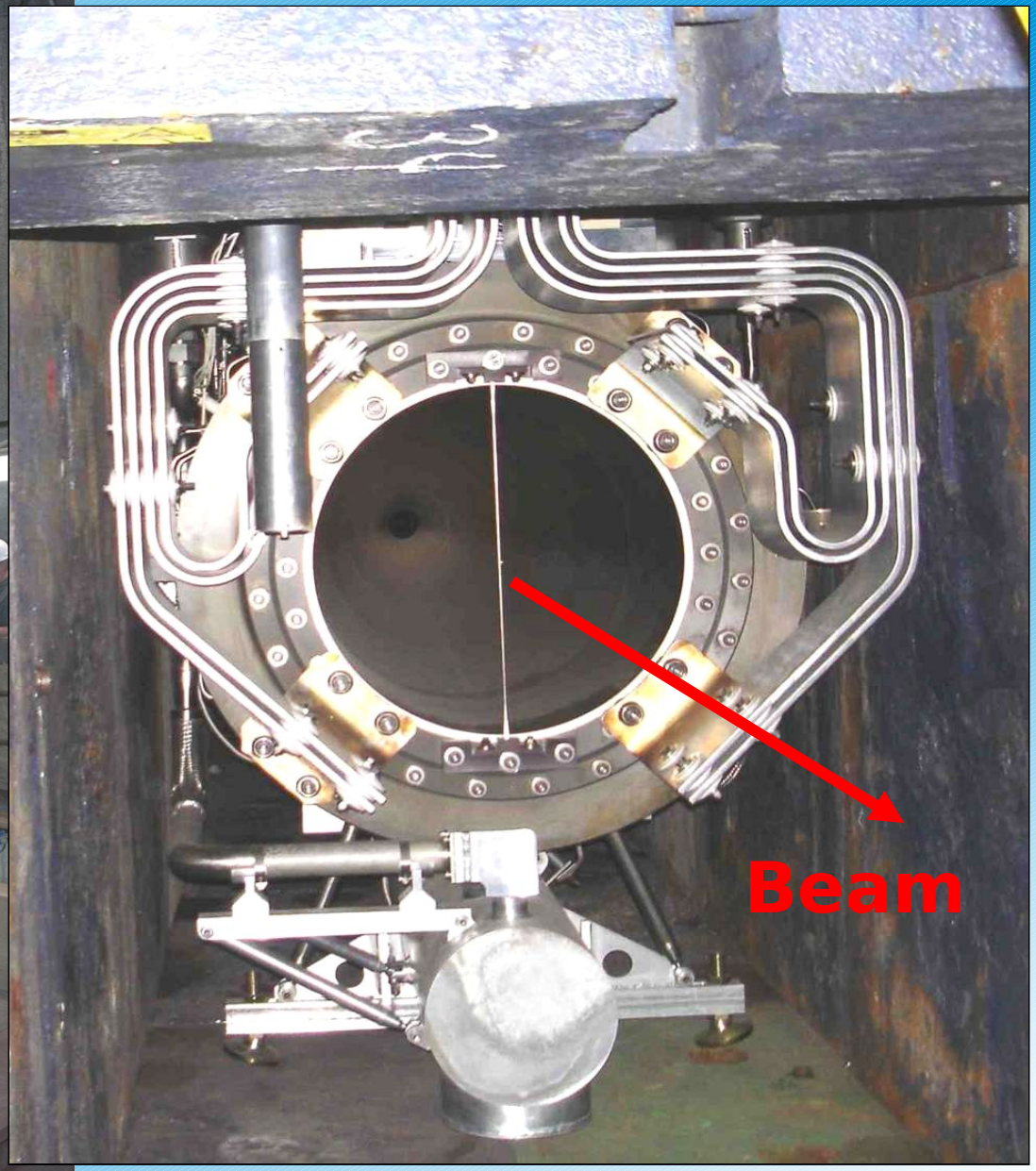
- Significant uncertainty due to Abs E_{Had} scale ⇒ shift Δm^2.
- NC background .

- MINERνA: finely segmented, mutiple nuclear targets.
- Precise σ significantly reduce systematic error on $\sin^2 2\theta_{13}$.



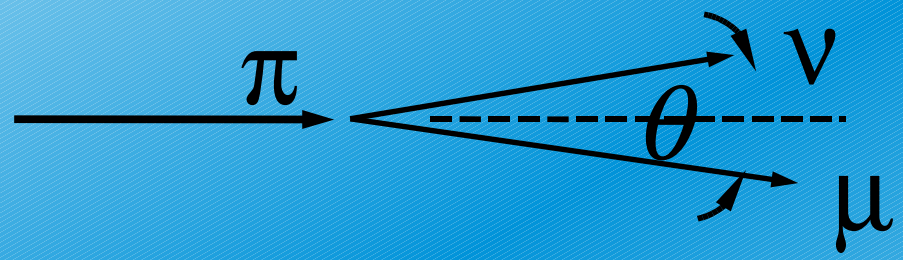
Assume post-MINERνA, σ's known at:
ΔQE = 5%, ΔRES = 5, 10% (CC, NC)
ΔDIS = 5%, ΔCOH_{Fe} = 20%

Horn 2 suspended from shielding module being lowered into shielding pit
During initial installation
30


Beam

Why Focus?

$$\frac{dP}{d\Omega_\nu} = \frac{A}{4\pi z^2}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$



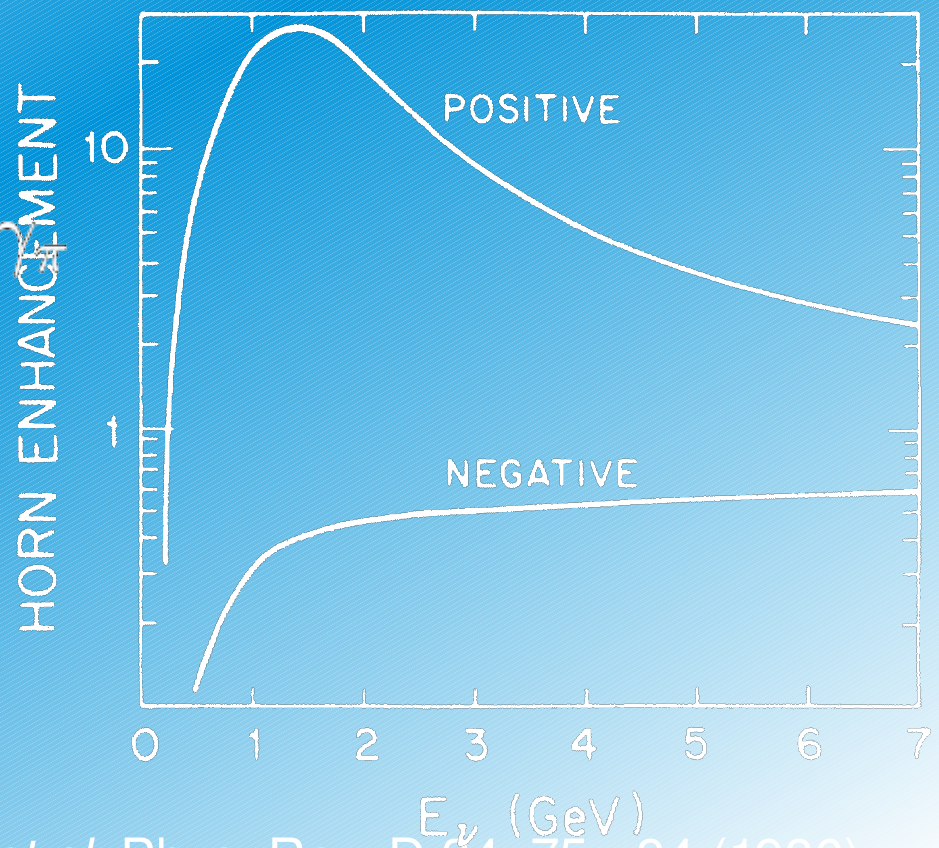
- 'Cocconi divergence'

$$\theta_\pi \sim \langle p_T \rangle / p_L \sim 2m_\pi / E_\pi \sim 2/\gamma_\pi$$

- Neutrino divergence

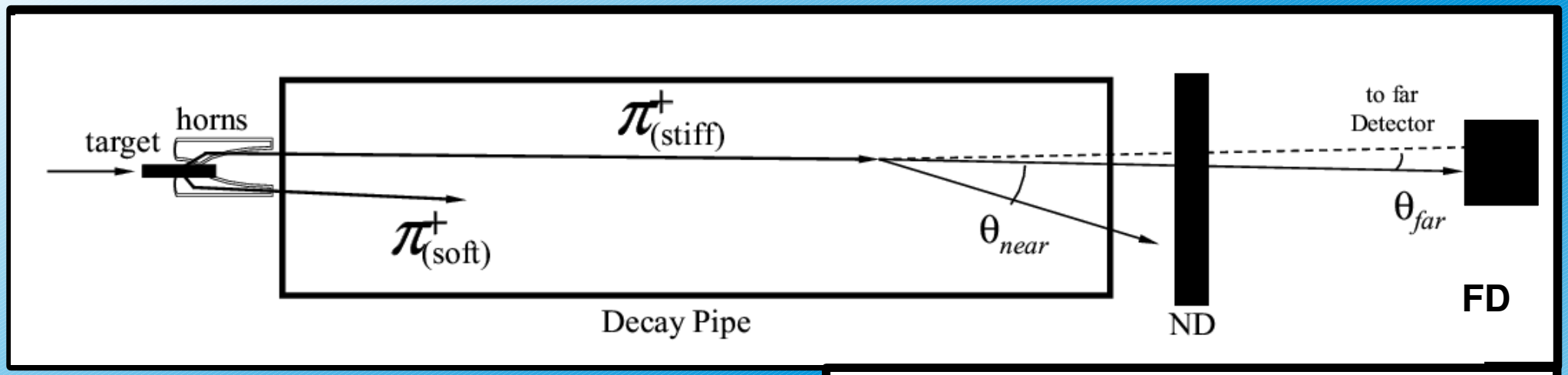
$$\theta_\nu \sim 1/\gamma_\pi$$

- Reduce divergence ~3, flux goes up by ~ 25



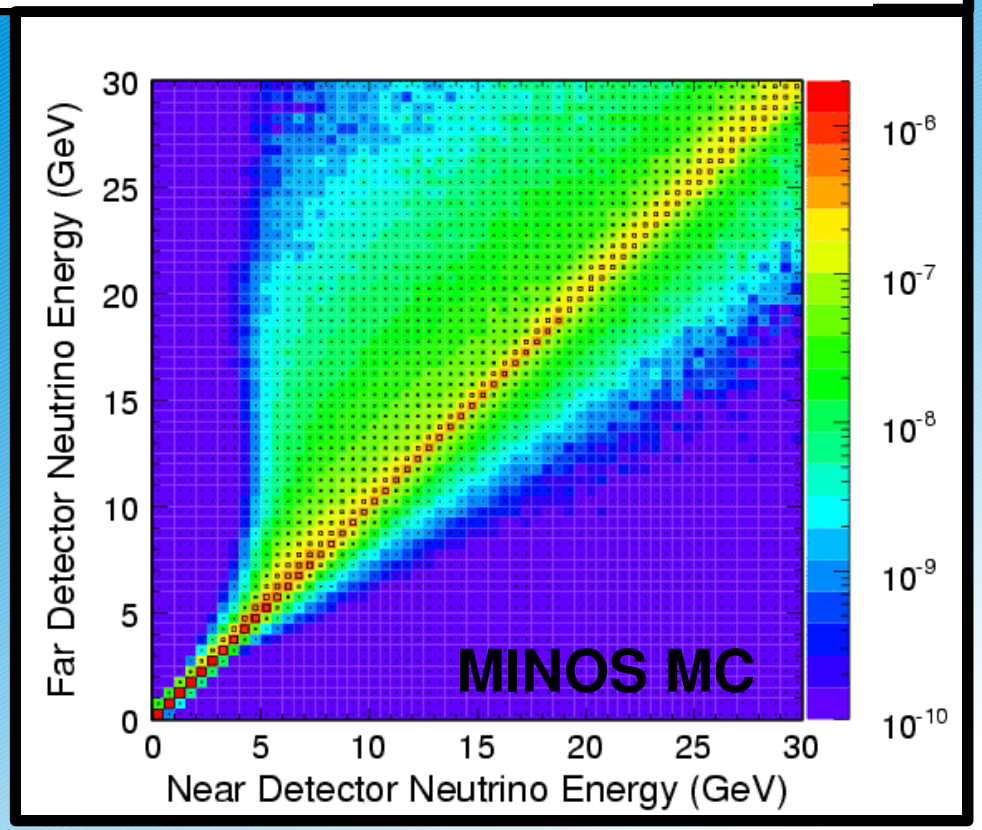
L. Ahrens *et al*, Phys. Rev. D34, 75 - 84 (1986)

Two Detector Experiments



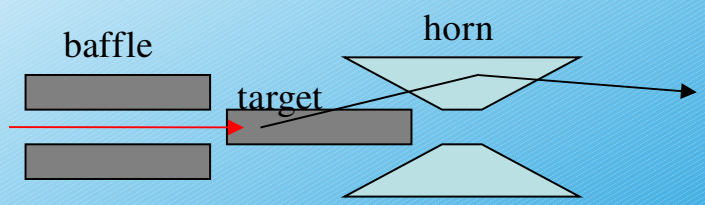
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2} \qquad Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$

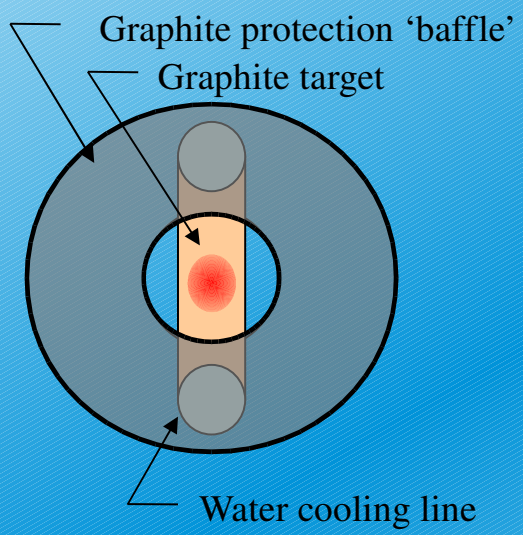
- Flux at ND is from a line source.
- Oscillation experiments use the Near Detector spectrum to predict the far detector spectrum.

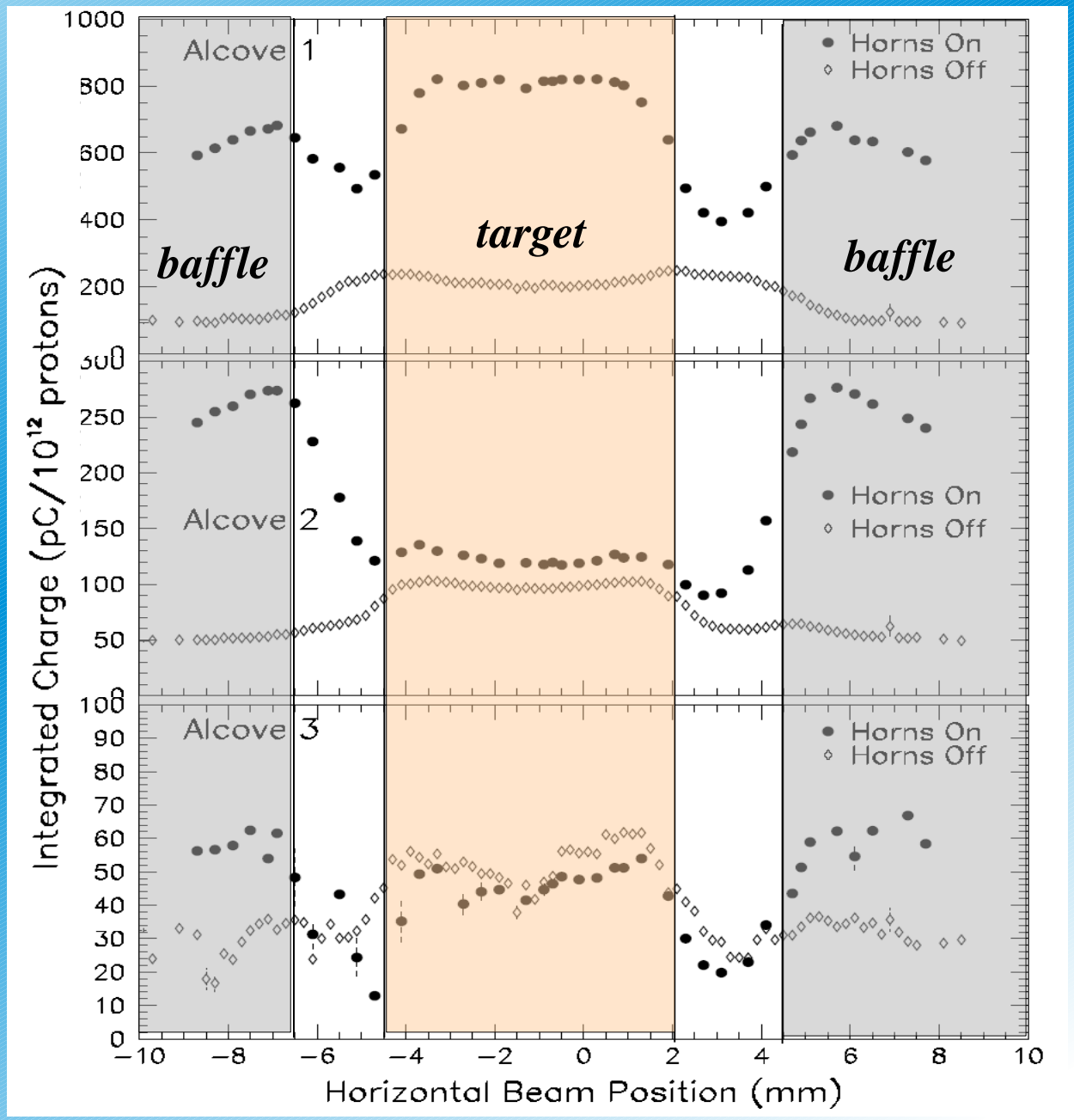


Systematic Errors on the Flux: Targeting

- Targeting.



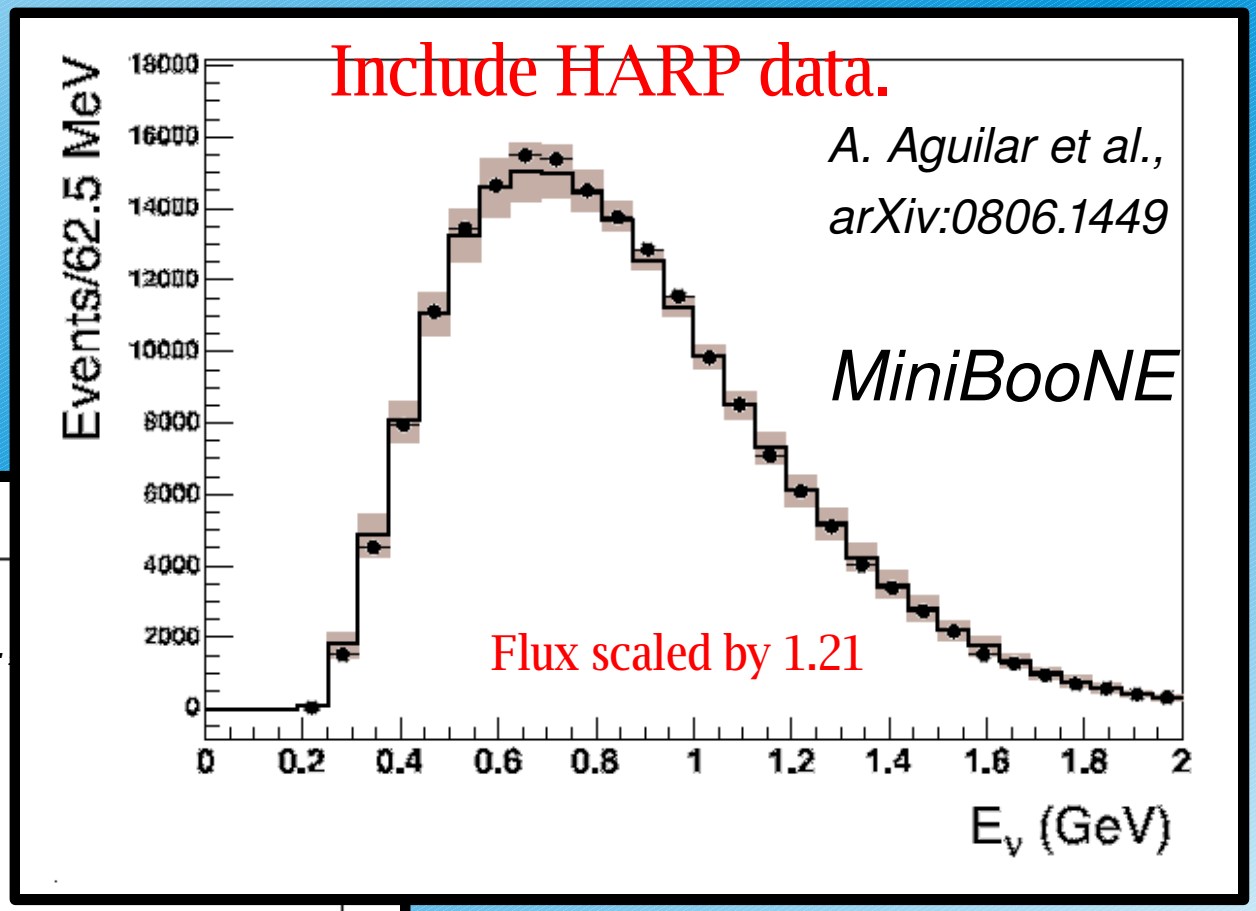


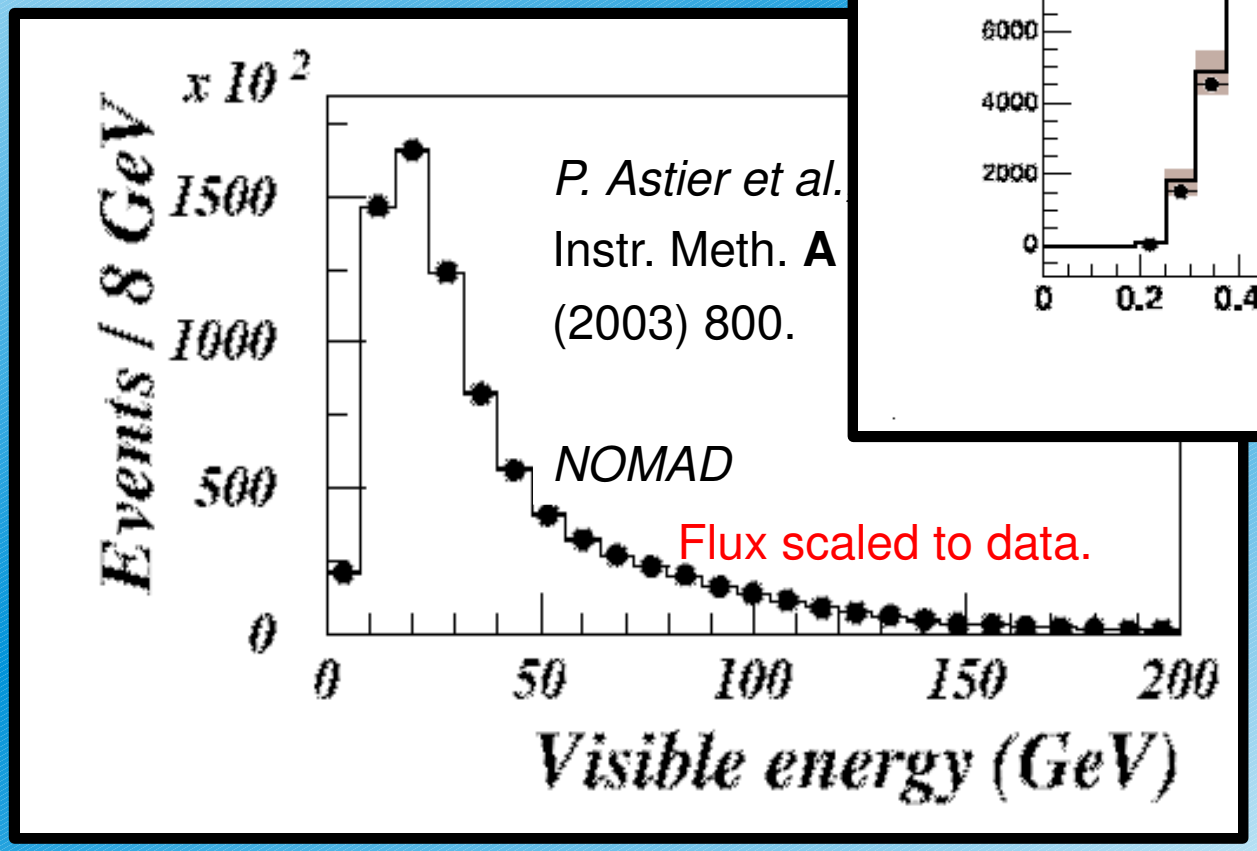


- Flux is sensitive to beam position on the target.

Incorporating Hadron Production

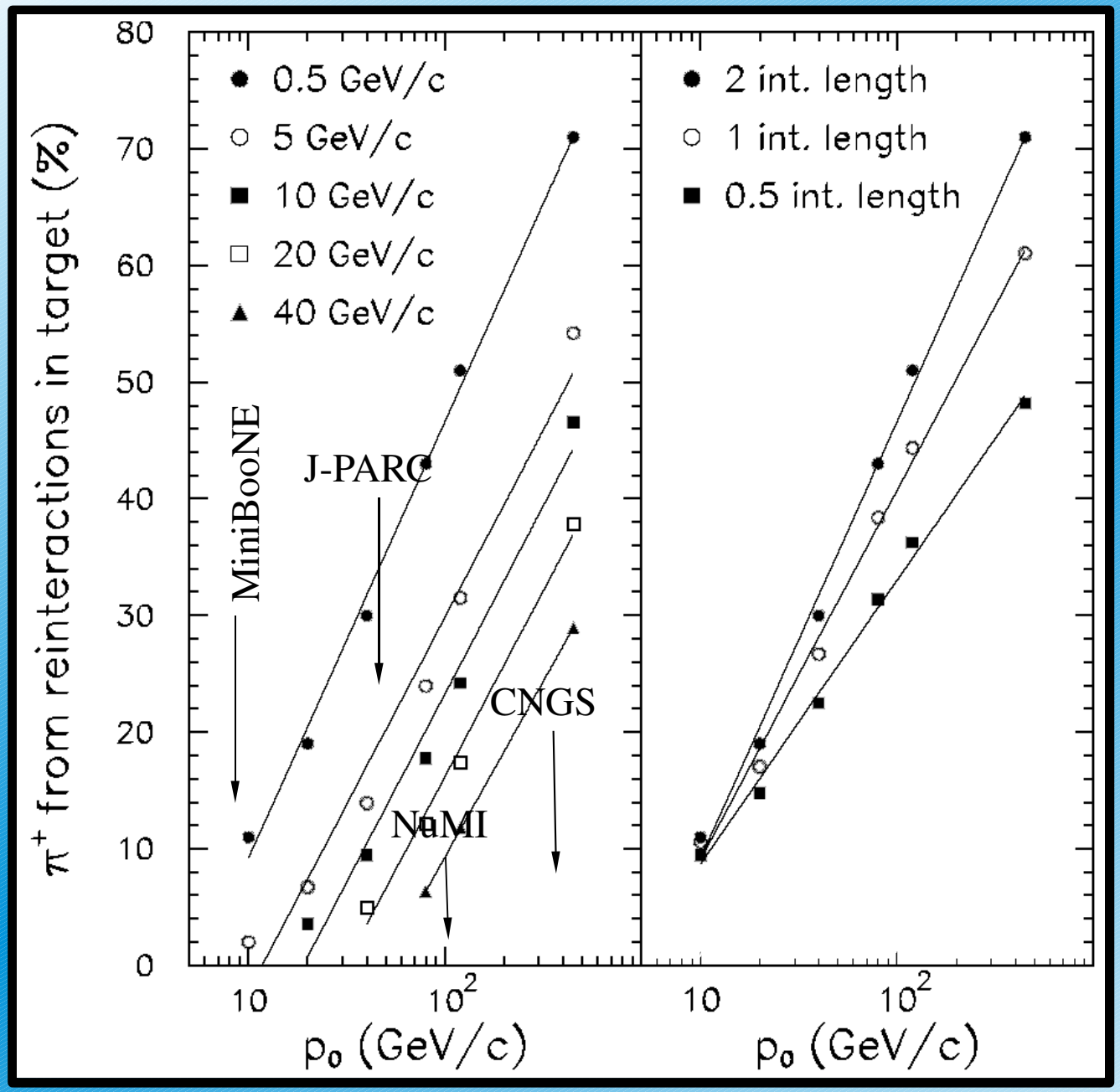
- K2K flux RATIO error is 2-9% after including HARP data.





- Shapes agree well.
- Normalization is uncertain.

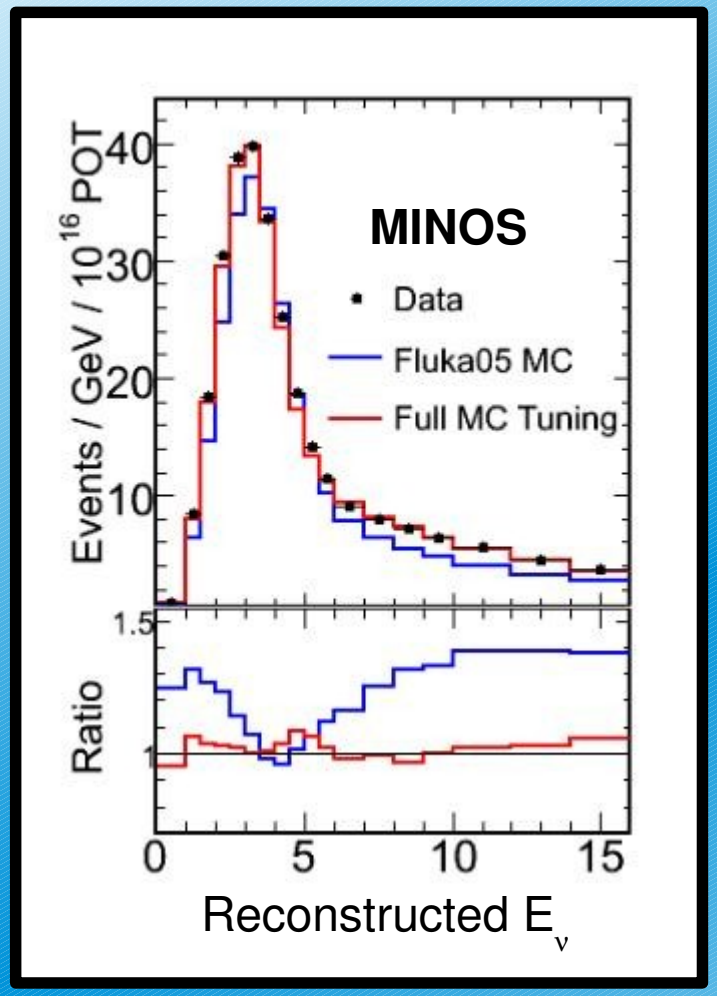
Thick Target Effects

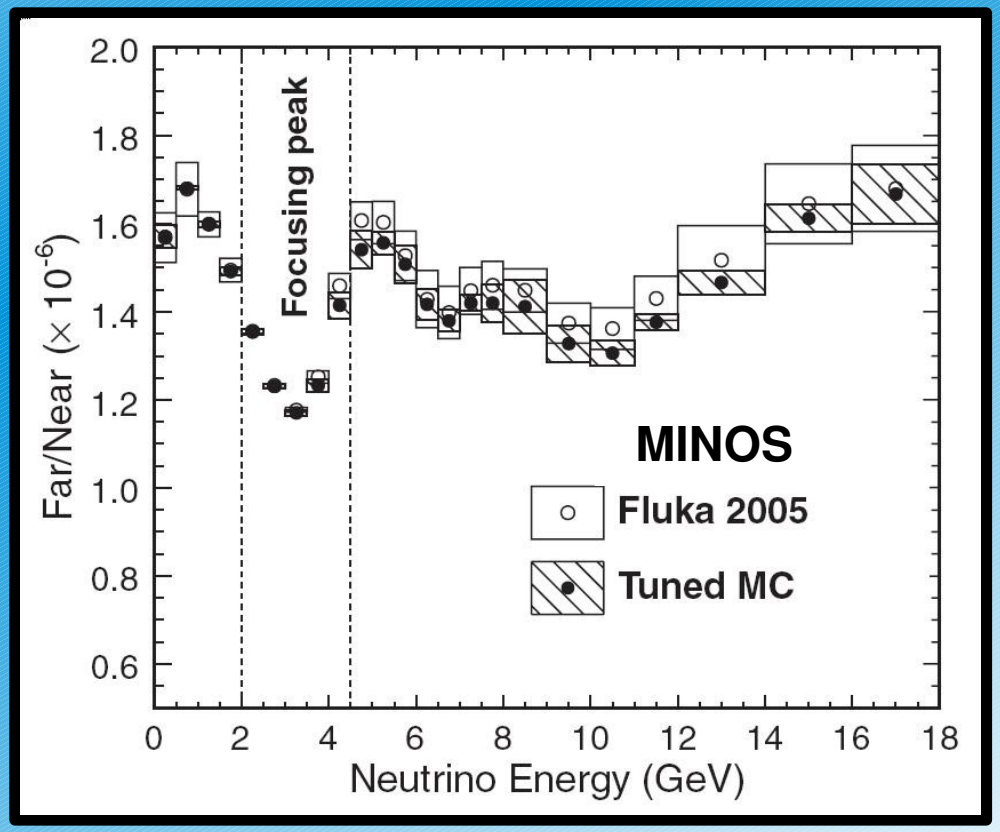


- Most particle production experiments on 'thin' targets.
- Neutrino production target > λ_{int}
- Reinteractions are 20-30% effect for NuMI.

Tuning Hadron Production

- Tune MC to MINOS ND data.
- Reduces error on FD prediction.

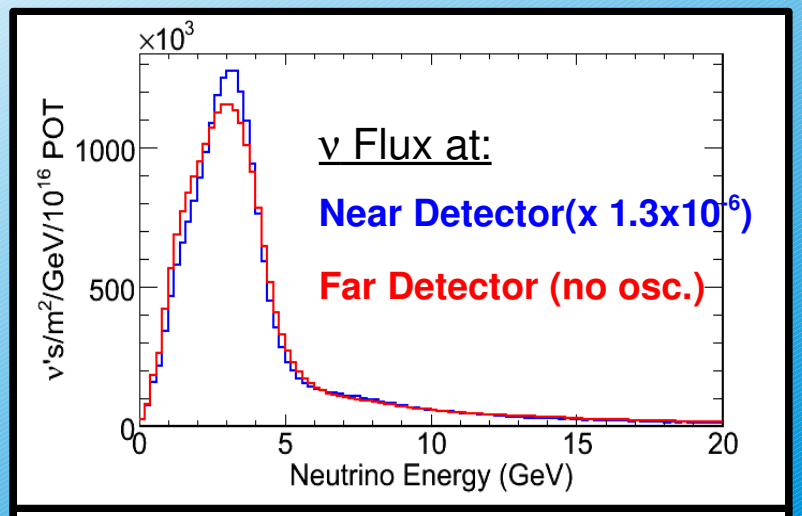


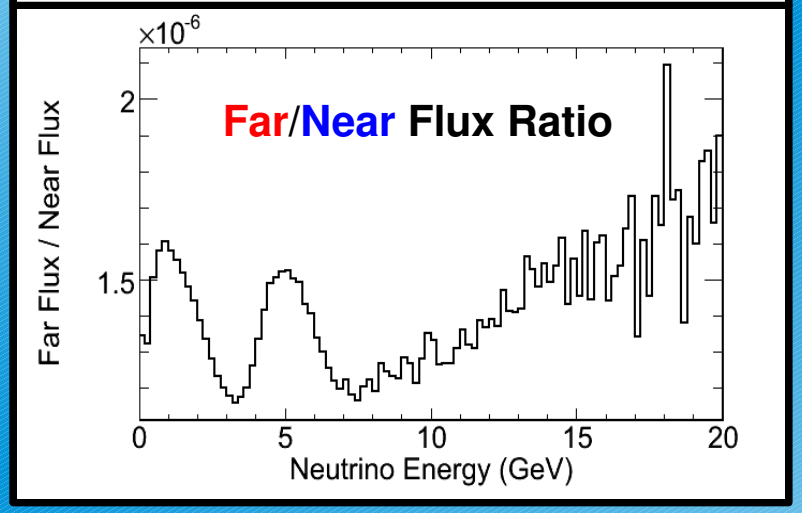


- But must assume knowledge of ν cross-sections.

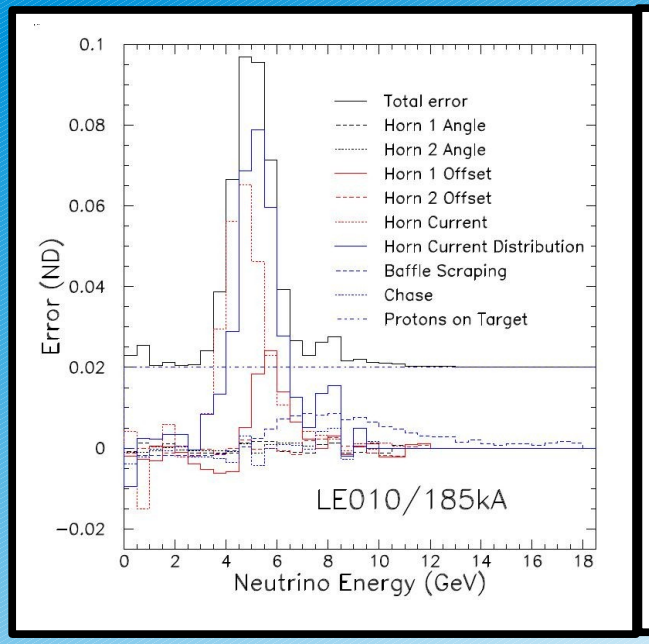
Beam Transportation Uncertainties

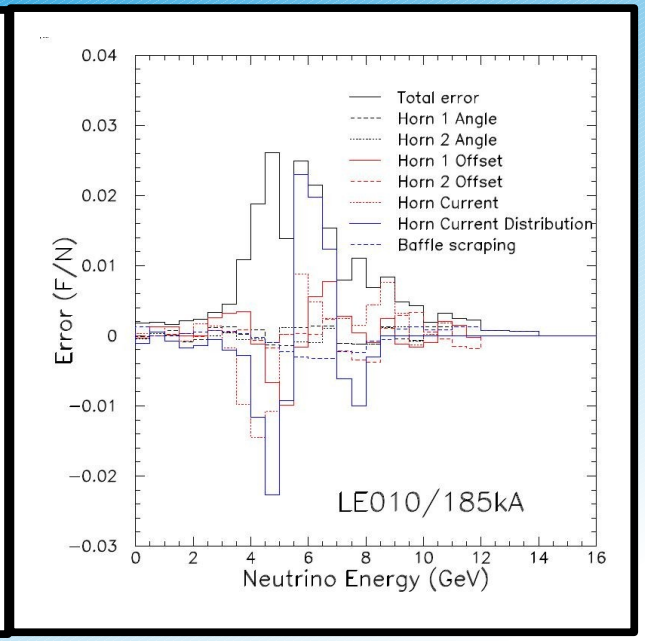
MINOS

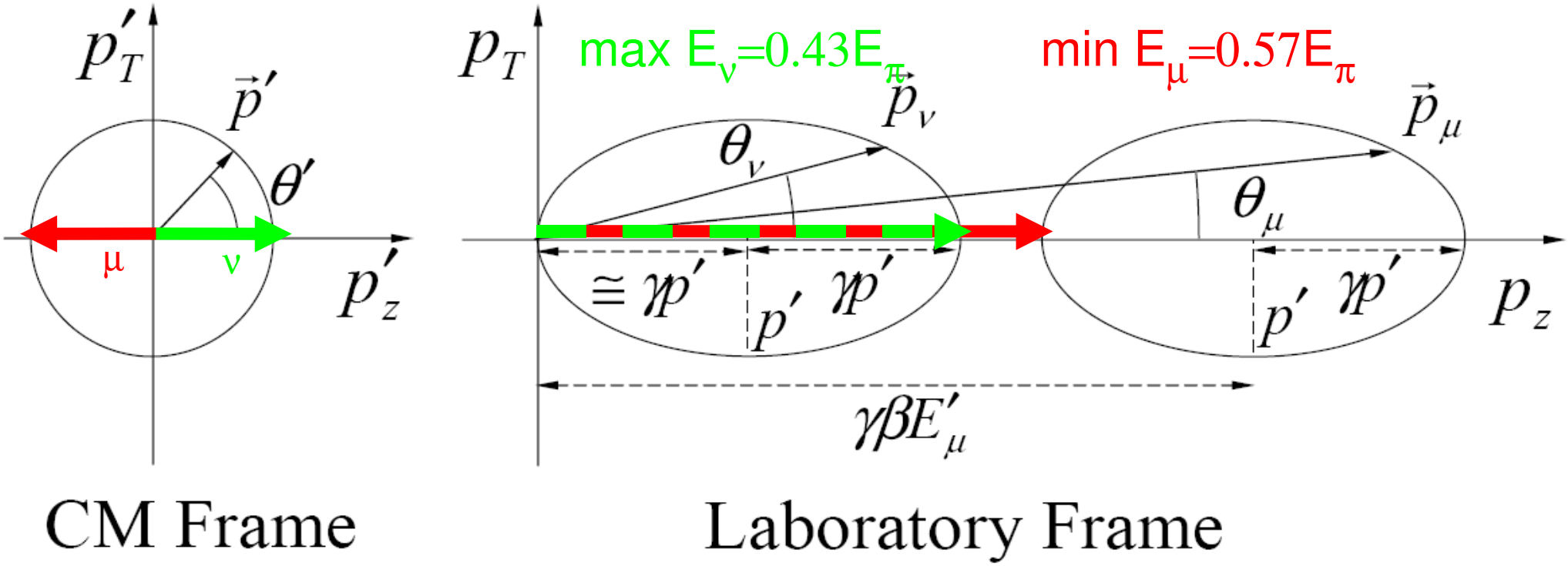




- 2 detector experiments use Near Detector to predict flux at the Far Detector.
- Far Detector flux ≠ Near Detector Flux.
- Flux errors do not completely cancel.





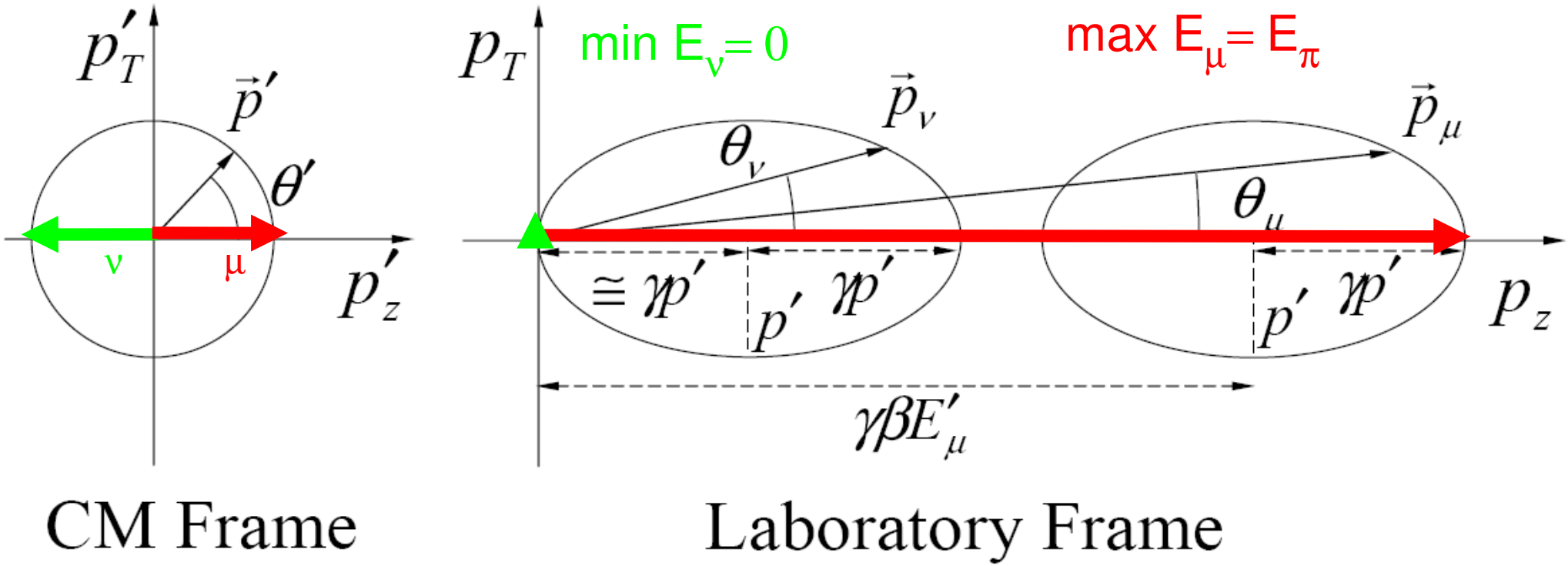


- Neutrinos seen in MINOS and MINERVA come from forward decays in CM frame
- Such decays give highest energy E_ν for given pion energy and lowest energy muons

E_ν	E_μ	E_π
1.6	2.4	4
3	4	7

Seems to imply min E_ν that can be seen by the monitors is 3GeV.

$$E_\nu = \frac{(1 - m_\mu^2/M^2)\,E}{1 - \gamma^2 \tan^2\theta_\nu}$$



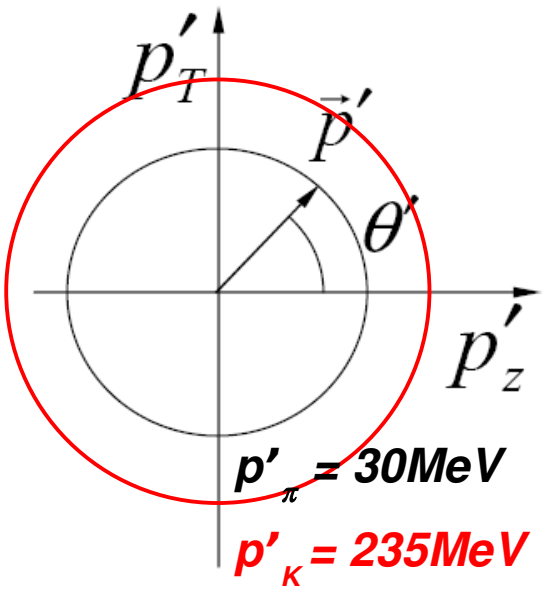
- Forward-going muons give E_ν~0 and E_μ ~E_π
- Muon Monitors can see lower effective pion parent threshold, just not in the same decays as give neutrinos in the ν detectors

	E_ν	E_μ	E_π
Forward ν	1.6	2.4	4
Forward μ	0	4	4

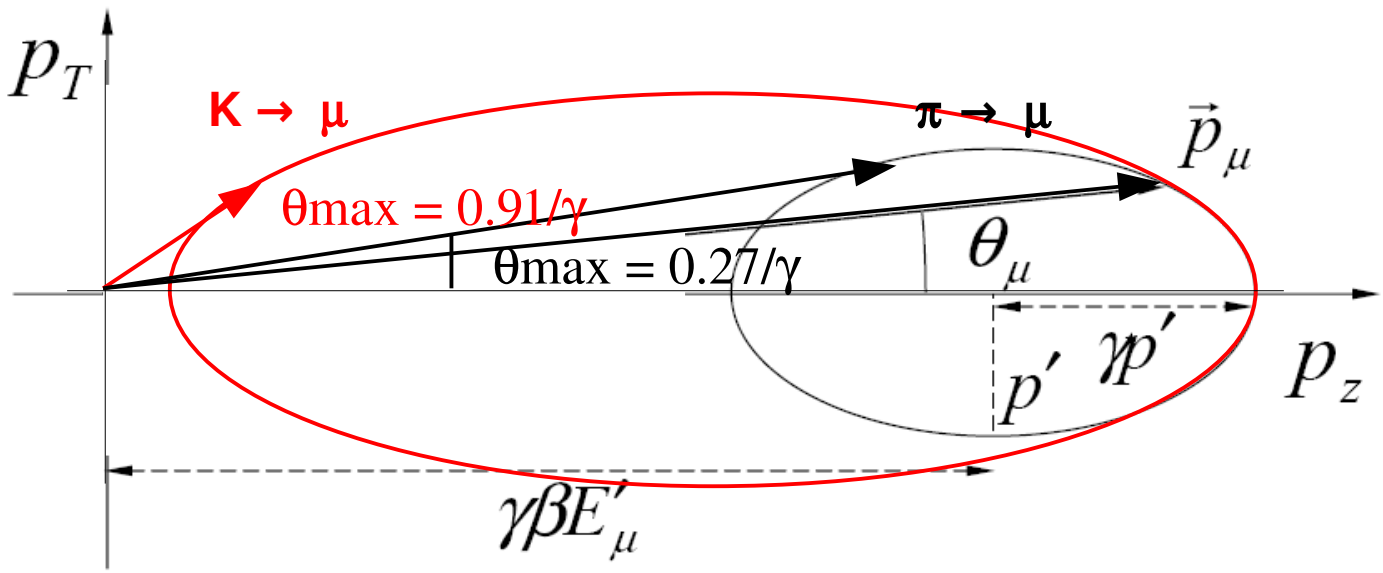
Implies min E_ν that can be seen by the monitors is 1.6 GeV.

$$E_\nu = \frac{(1 - m_\mu^2/M^2)\,E}{1 - \gamma^2 \tan^2\theta_\nu}$$

Kinematics



CM Frame



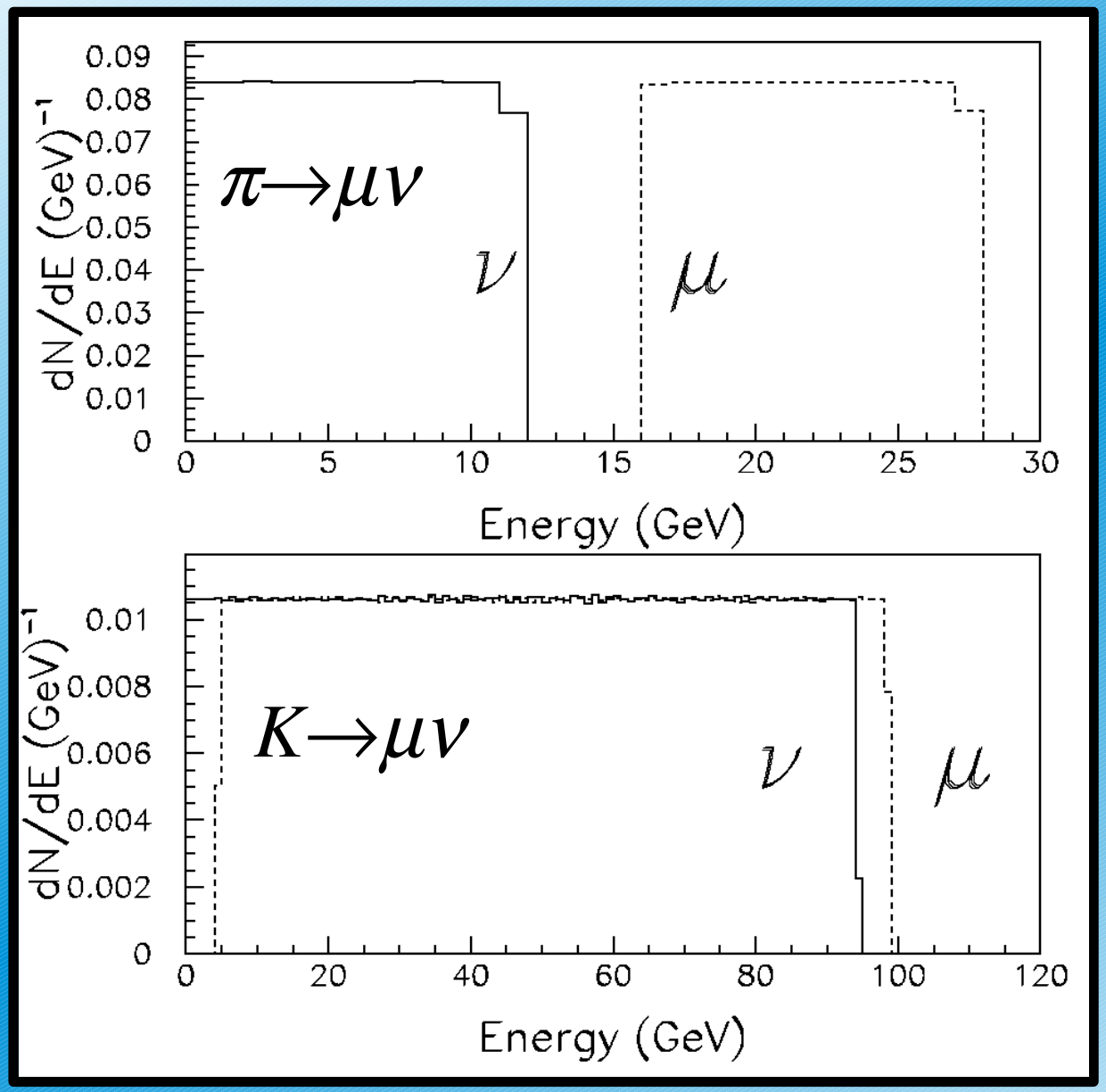
Laboratory Frame

$$p_T'^2 + p_z'^2 = p'^2$$

$$\frac{(p_z - \beta\gamma E')^2}{\gamma^2 p'^2} + \frac{p_T^2}{p'^2} = 1$$

- Larger Kaon mass means muons decay at larger angles than pions.
- Shorter Kaon life time means kaons decay farther upstream than pions.

Flat Energy Spectrum



Just as many high energy μ's as high-energy ν's

$$\frac{dP}{dE_\nu} = \frac{1}{\left(1 - \frac{m_\mu^2}{M^2}\right) E}$$

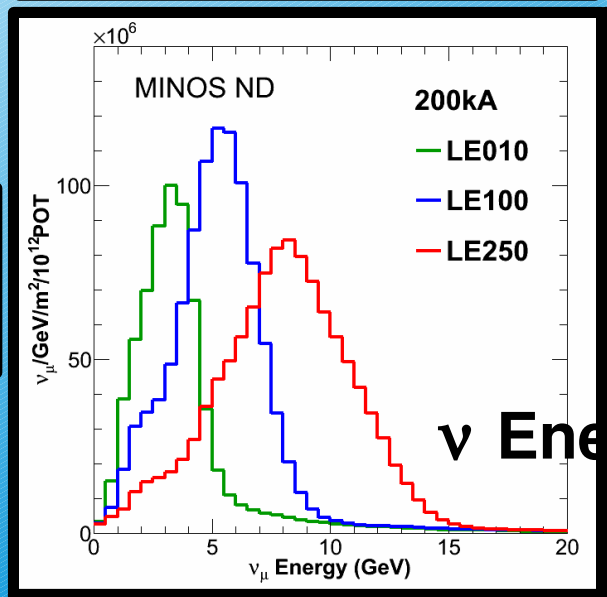
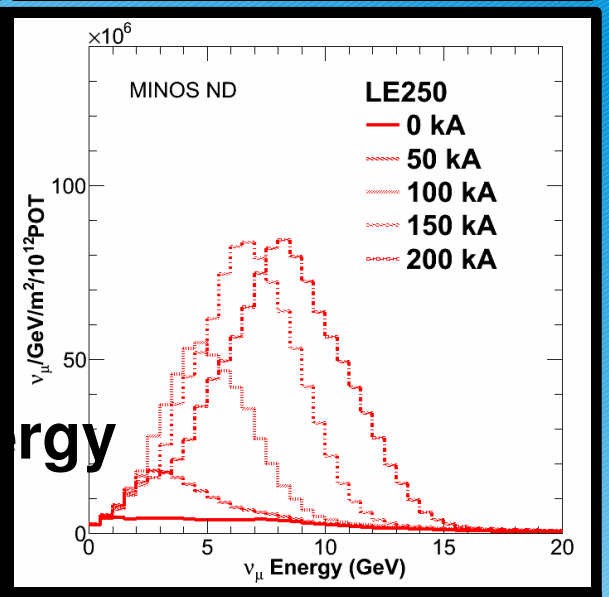
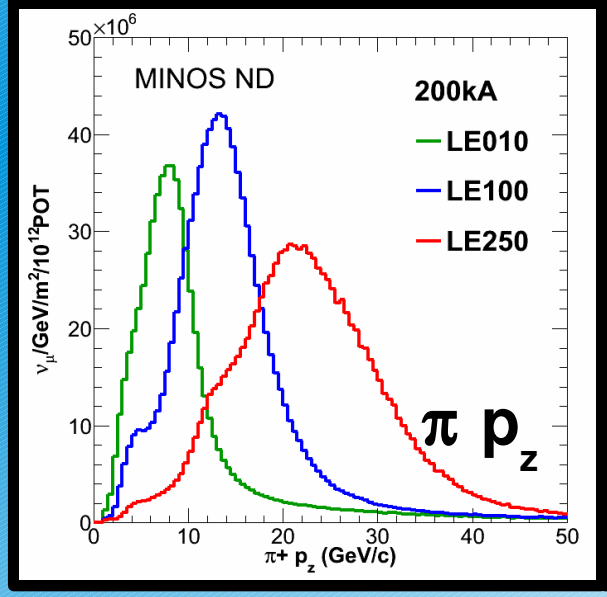
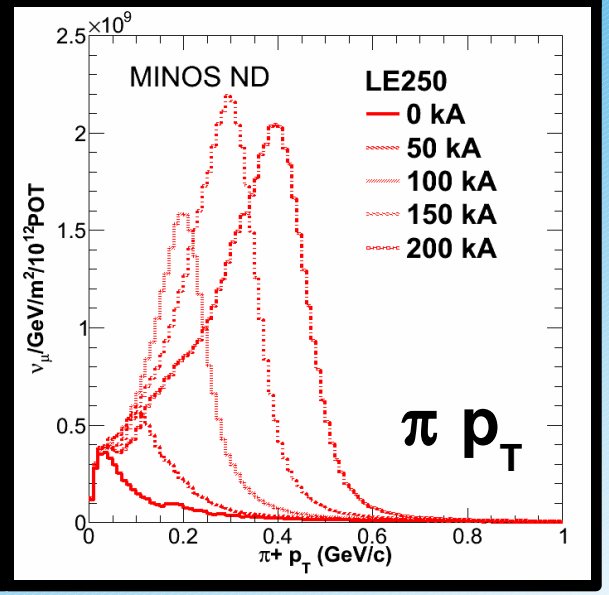
Muon Monitors see only momenta p_μ>4 GeV/c

Such come from E_π>4 GeV

In other decays, such pions give E_ν>1.6 GeV

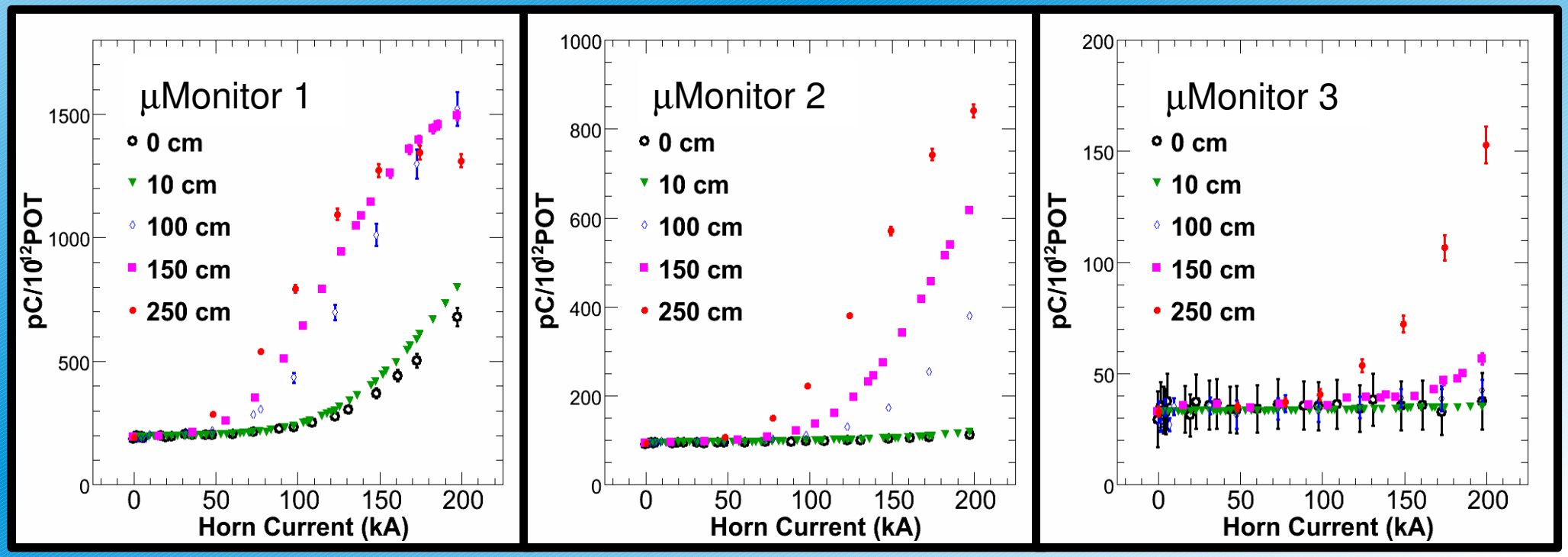
Sets actual "neutrino threshold" of the alcoves

$\varphi_\nu(E_\nu) \leftrightarrow \varphi_\nu(p_T, p_z)$

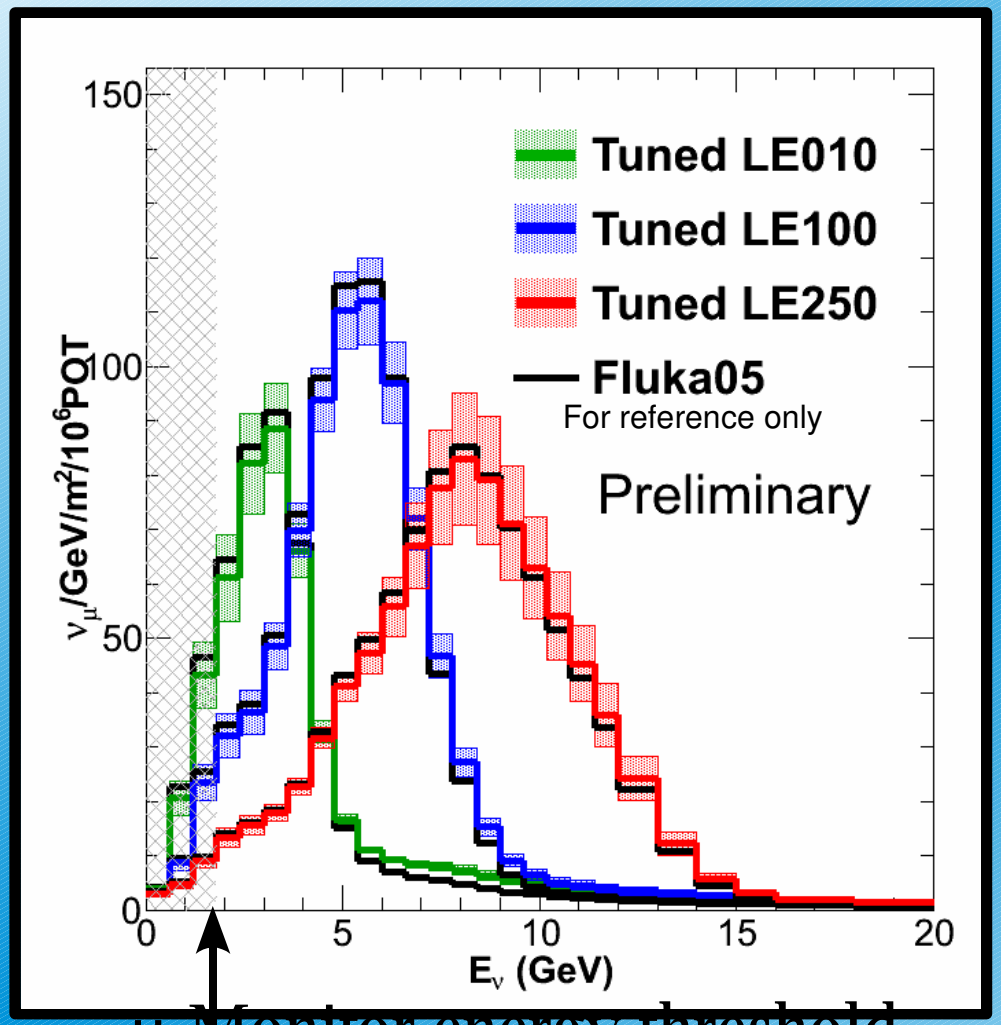
	Vary Target Z	Vary Horn I
$\varphi_\nu(E_\nu)$		
$\varphi_\nu(p_T, p_z)$		

μ Monitor Data

- Must apply corrections to data: pressure, temperature, non-linearity.
- Only want signal pC/10^{12}pot from beam muons.
- Must account for background to signal from, n, δ-rays.



NuMI ν_μ Flux



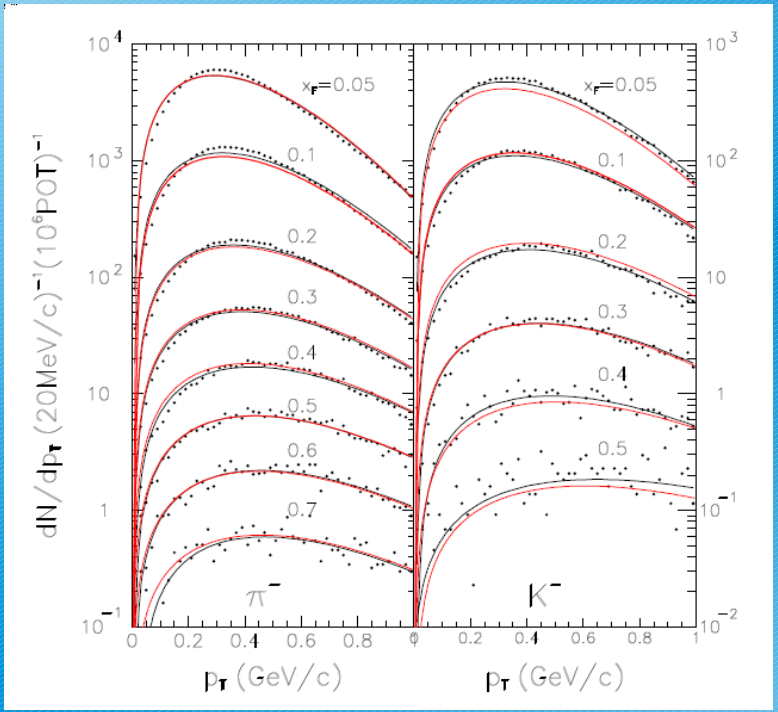
μ Monitor energy threshold.

- Preliminary shape flux measurement.
- Rate measurement is excluded due to uncertainty in pC/μ scale factor and backgrounds from δ-rays.
- In situ measurement; accounts for real beamline conditions.
- Can measure ν cross-sections:

$$\sigma_\nu(E_\nu) = \frac{N_\nu(E_\nu)}{\varphi_\nu(E_\nu)}$$

Eq. 1 $$\frac{d^2N}{dx_F dp_T} = [A + Bp_T] * \exp(-Cp_T^{3/2})$$

Fig. 1

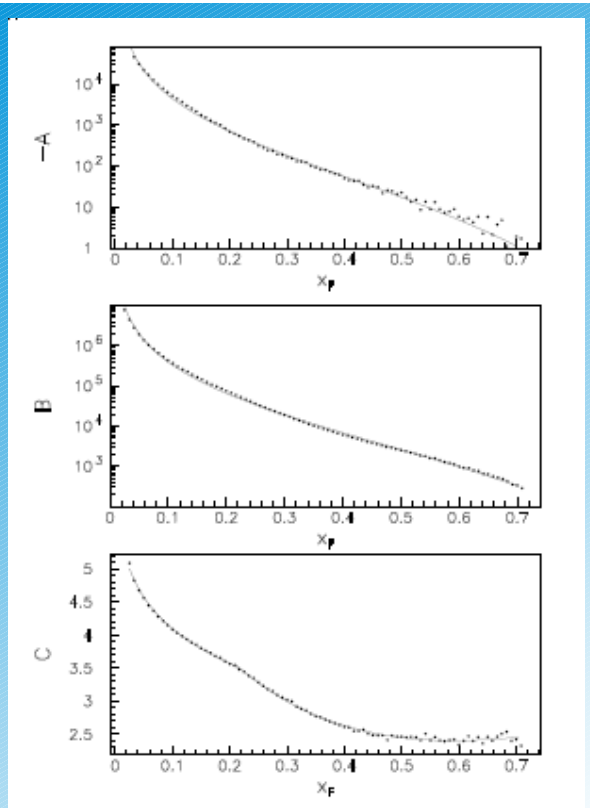


Black curve is fit using Eq 1. Red curve is fit using the fit from Fig 2 with Eq 2.

Eq. 2

$$\begin{aligned} A(x_F) &= a_1 * (1. - x_F)^{a_2} * (1. + a_3 * x_F) * x_F^{-a_4} \\ B(x_F) &= b_1 * (1. - x_F)^{b_2} * (1. + b_3 * x_F) * x_F^{-b_4} \\ C(x_F) &= c_1/x_F^{c_2} + c_3 \quad (\text{for} \quad x_F < 0.22) \\ &= c_1/e^{(x_F - c_3)c_2} + (c_4 x_F) + c_5 \quad (\text{for} \quad x_F > 0.22) \end{aligned}$$

Fig. 2



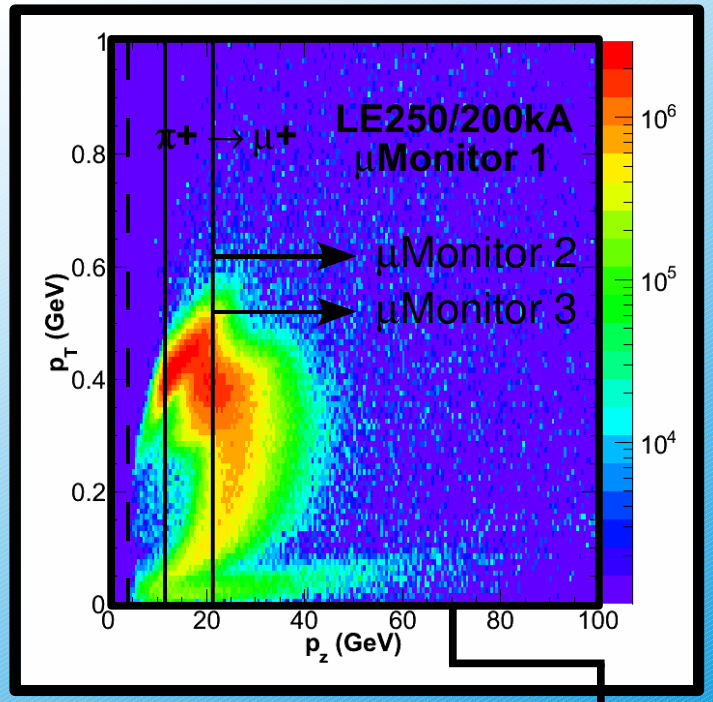
Points are coeffs obtained when fitting Fig 1 to Eq 1. Curves are fit to Eq 2.

$$\begin{aligned} A'(x_F) &= (p_1 + p_2 x_F) A(x_F) \\ B'(x_F) &= (p_3 + p_4 x_F) B(x_F) \\ C'(x_F) &= (p_5 + p_6 x_F) C(x_F) \end{aligned}$$

Rescale the A, B and C parameters

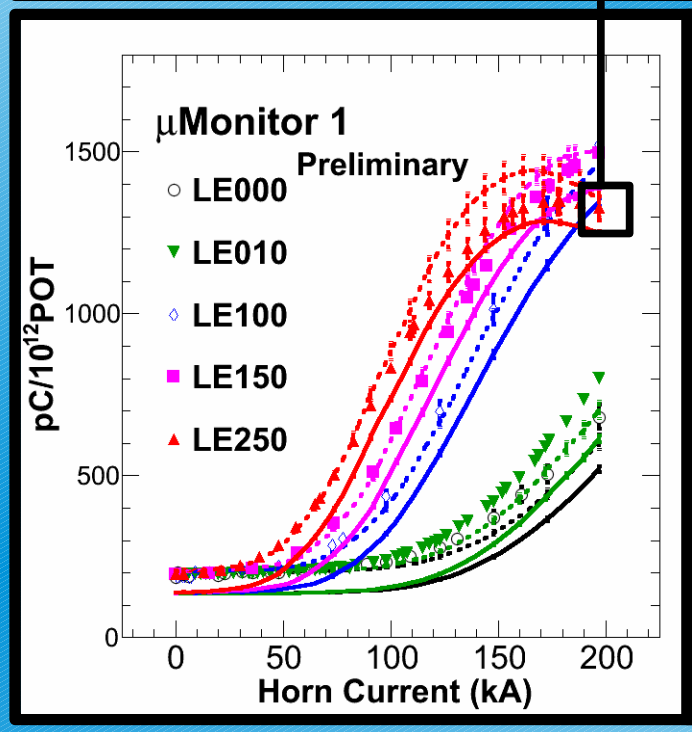
$$W(\pi^+/K^+) = \frac{[A' + B'p_T] \times \exp(-C'p_T^{3/2})}{[A + Bp_T] \times \exp(-Cp_T^{3/2})}$$

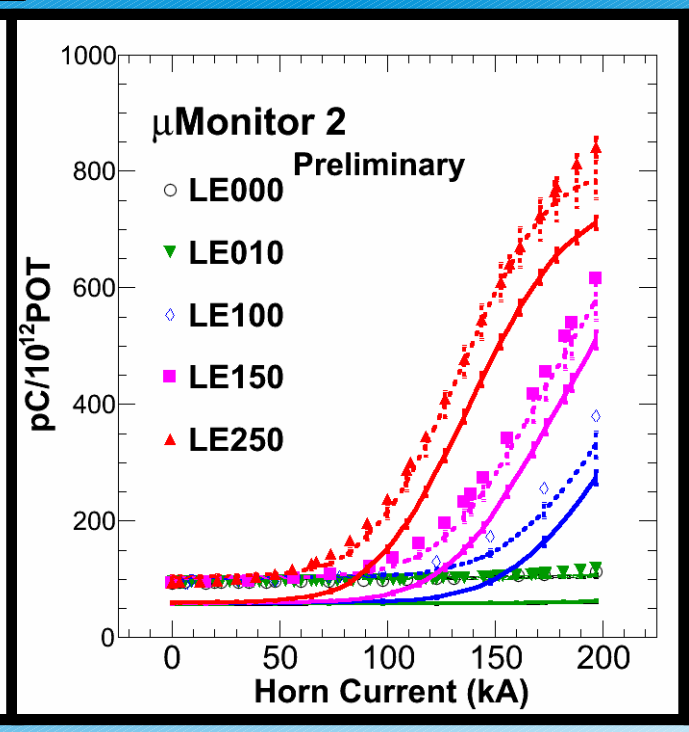
μ Monitor Tuning

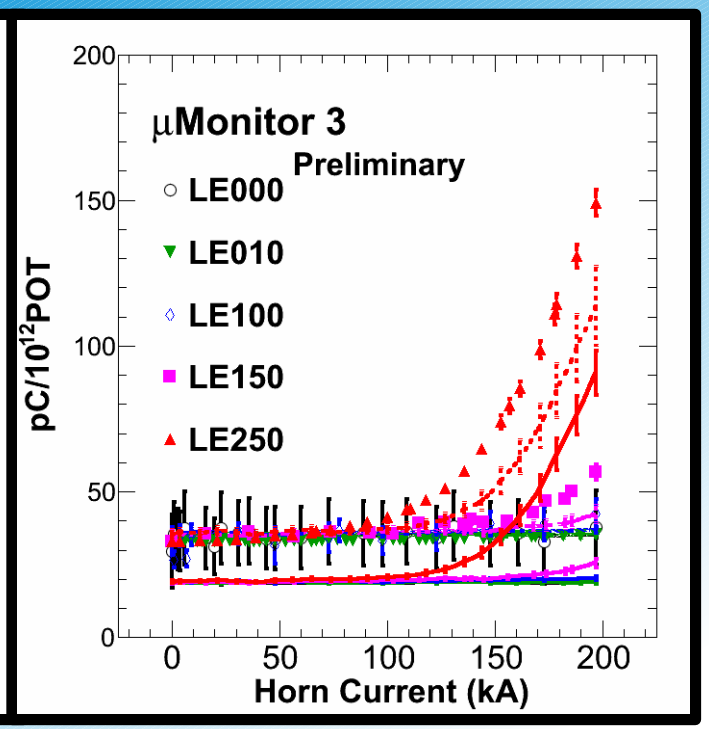


- Emperical parameterization for hadron production, f(p_T, p_z). Warp p_T and p_z to tune default MC to μ Monitor data.

• Data — Monte-Carlo — - - - Tuned Monte-Carlo

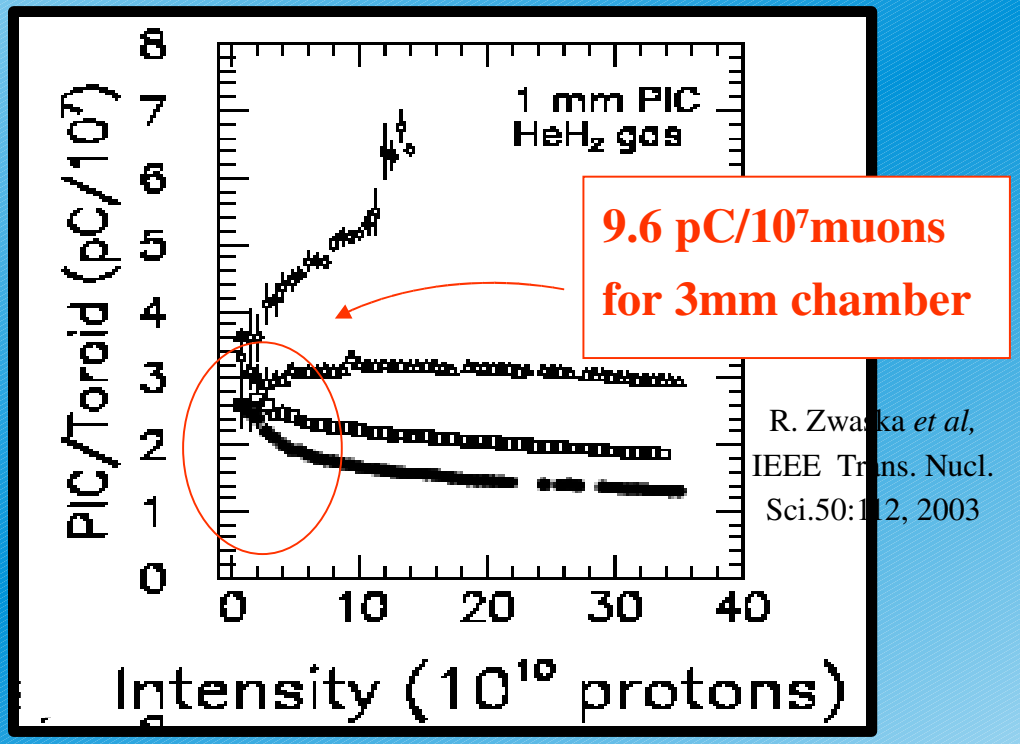






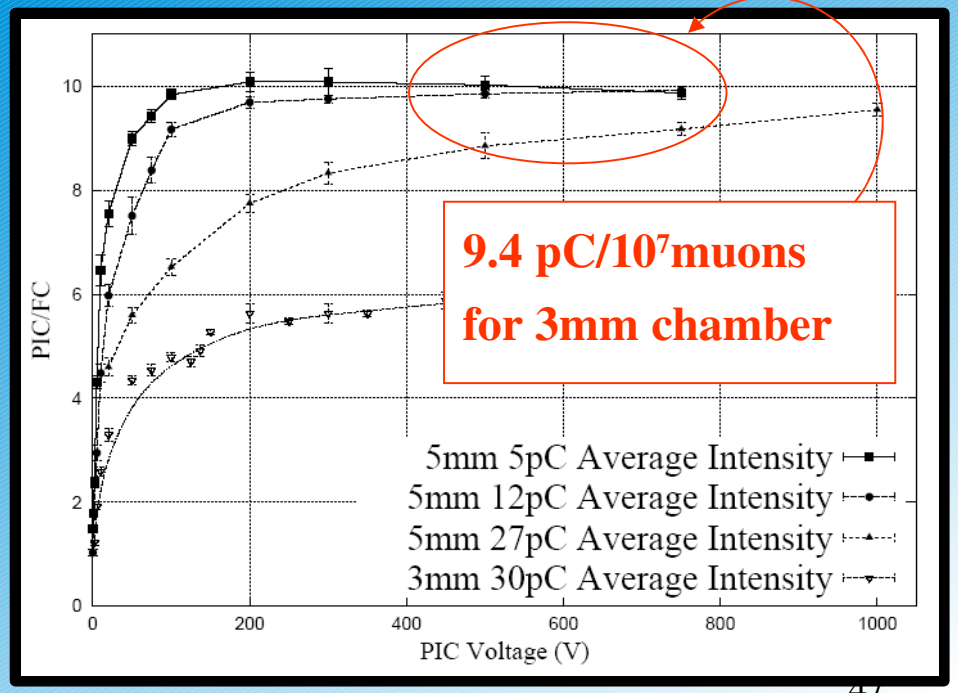
Charge per Muon

- Would like to know pCoul/muon passing through the chambers.
- This is non-trivial for two reasons
  - He gas is easily contaminated (20ppm O_2 causes 5-10% variation in this scale factor)
- Taking (*dE/dx*) for a minimum-ionizing particle and *w*=42 eV/ion-pair, can calculate ionization per muon. Some texts claim *w*=31 eV/i.p. for 'dirty' He. Using that, we'd expect approximately 5.5 pC/10^7muons.
- We have two beam tests (BNL e- beam, FNAL p beam) which made measurements of this quantity in He gas of unknown quality (cylinder gas of 99.995% purity, but chamber contamination?). These might actually be well-translated to present gas system. I will scale them to the expectation for a 3mm gap chamber (like μMons)



9.6 pC/10^7muons for 3mm chamber

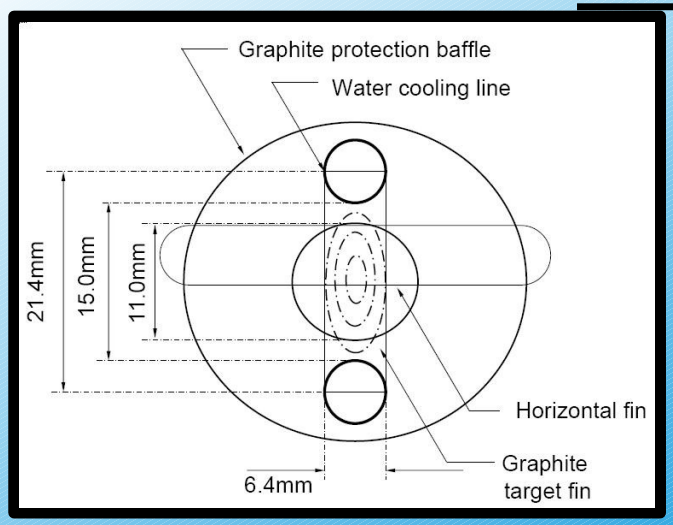
R. Zwaska *et al*, IEEE Trans. Nucl. Sci.50:112, 2003



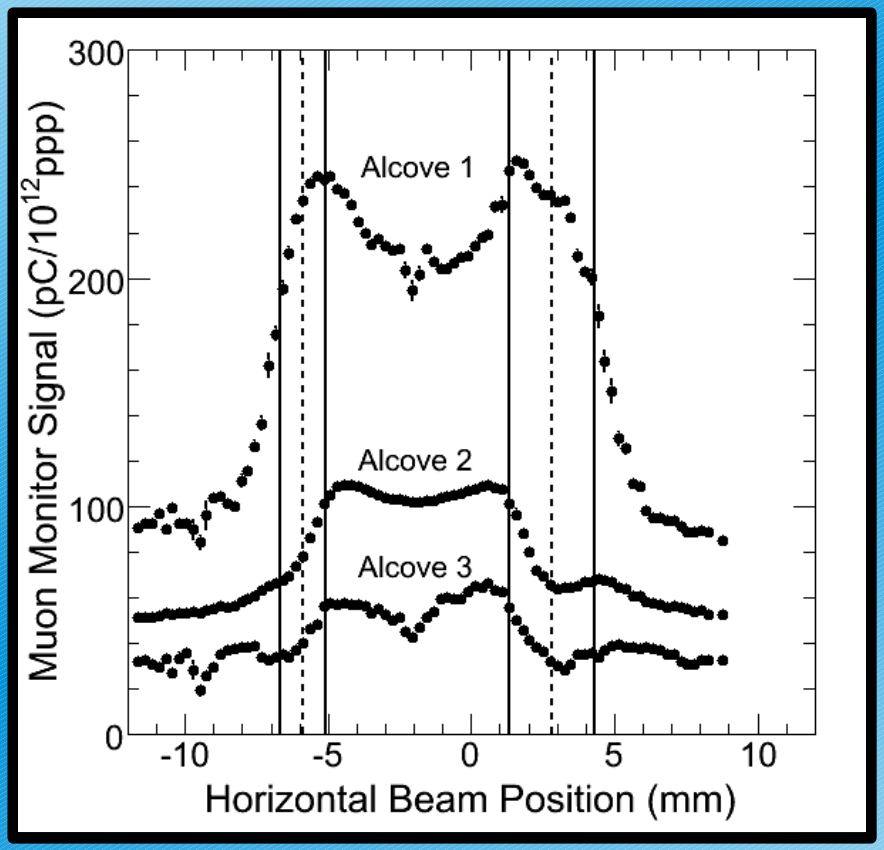
9.4 pC/10^7muons for 3mm chamber

D. Naples *et al*, Nucl.Instrum.Meth.A496:293-304,2003

Dump Backgrounds

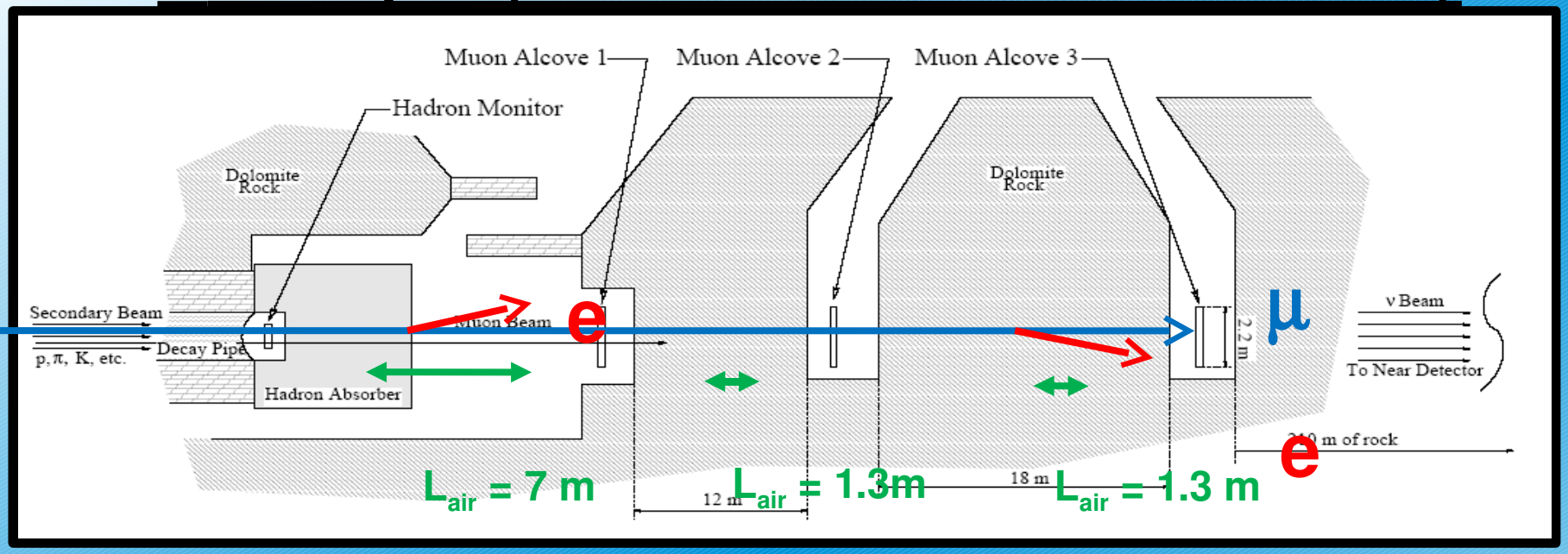


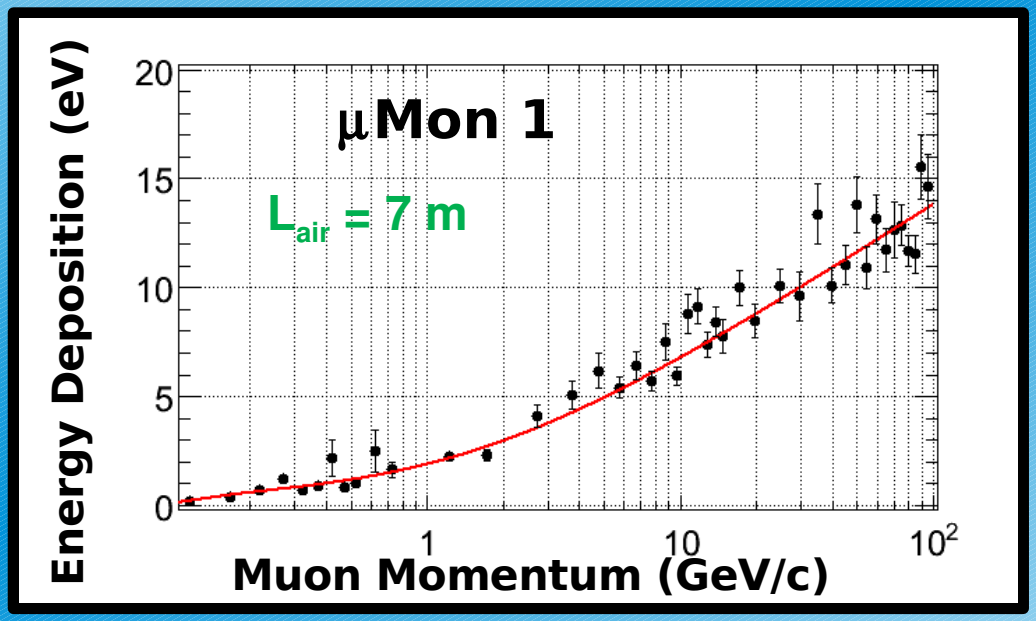
- 13.5% of proton beam doesn't interact in NuMI target ⇒ transported to absorber creating muons, neutrons, gammas.
- Measurements from No-Target spills
- Measurements from Target Scans.
- Take average.

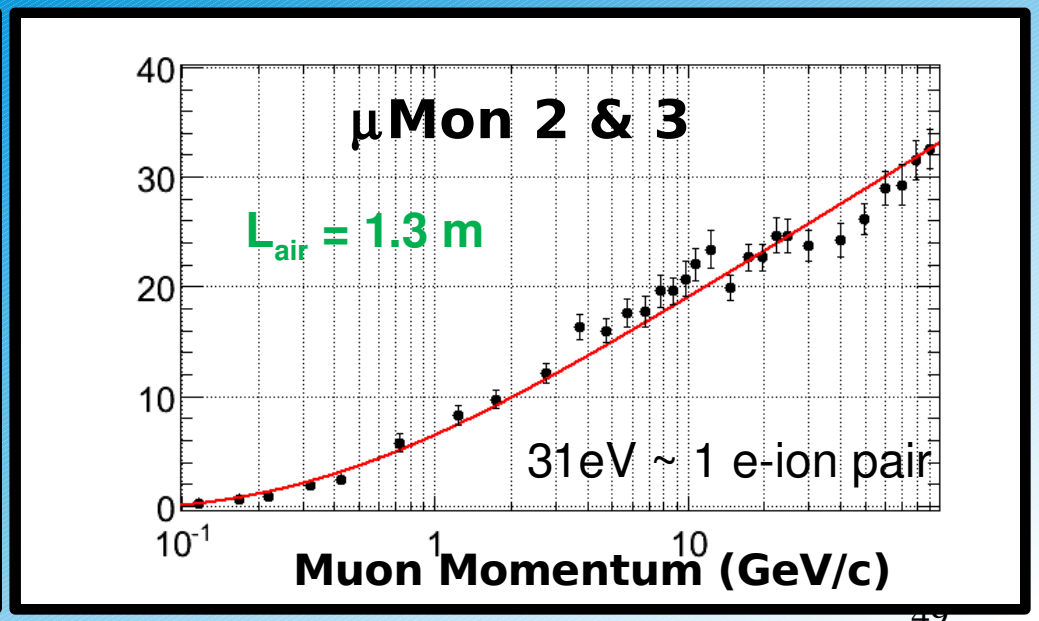


Muon Alcove	Signal Before Gas Corrections ($pC/10^{12}$ ppp)	Signal After Gas Corrections ($pC/10^{12}$ ppp)	Extrapolated to 13.5% Unreacted Proton Beam
	Data from No-Target Spills (Section 4.1)		
1	270 ± 22	251 ± 21	34 ± 3
2	59 ± 5	54 ± 5	7.3 ± 1
3	20 ± 15	12 ± 9	1.6 ± 1.2
	Data from Target Scans (Section 4.2)		
1	236 ± 13	223 ± 16	30 ± 2
2	63 ± 4	58 ± 4	7.8 ± 0.5
3	29 ± 2	20 ± 3	2.7 ± 0.4

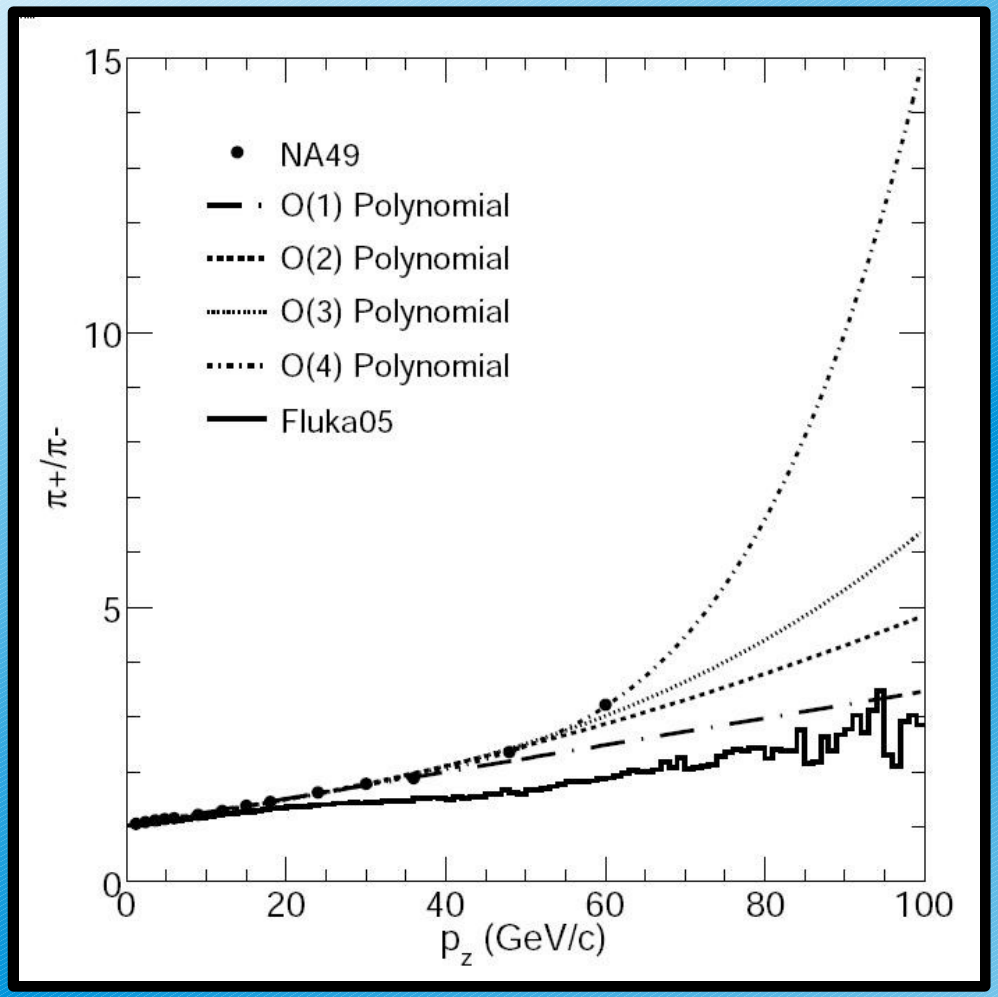
δ-Rays (Knock-On Electrons)







Uncertainties



- Particle Ratios.
  - π+/π-
  - K+/π+.
- Data corrections.
- pC/μ conversion factor .
- Backgrounds.
  - Dump.
  - δ-rays.