Neutrino Beam Flux Systematics

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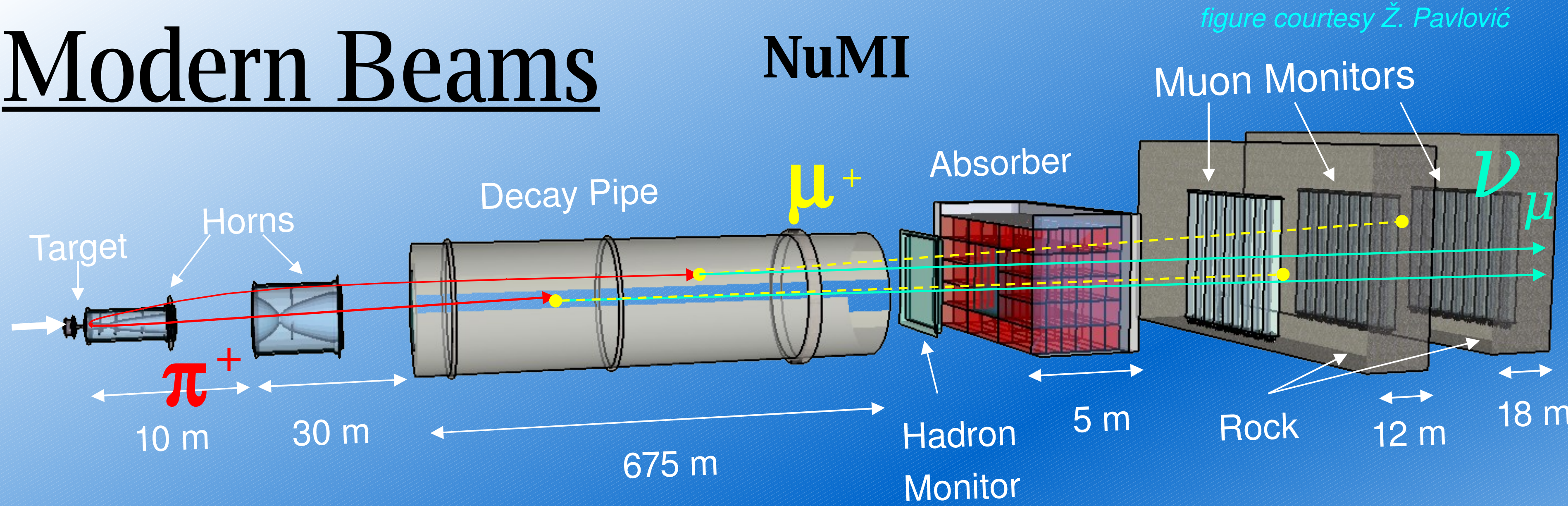
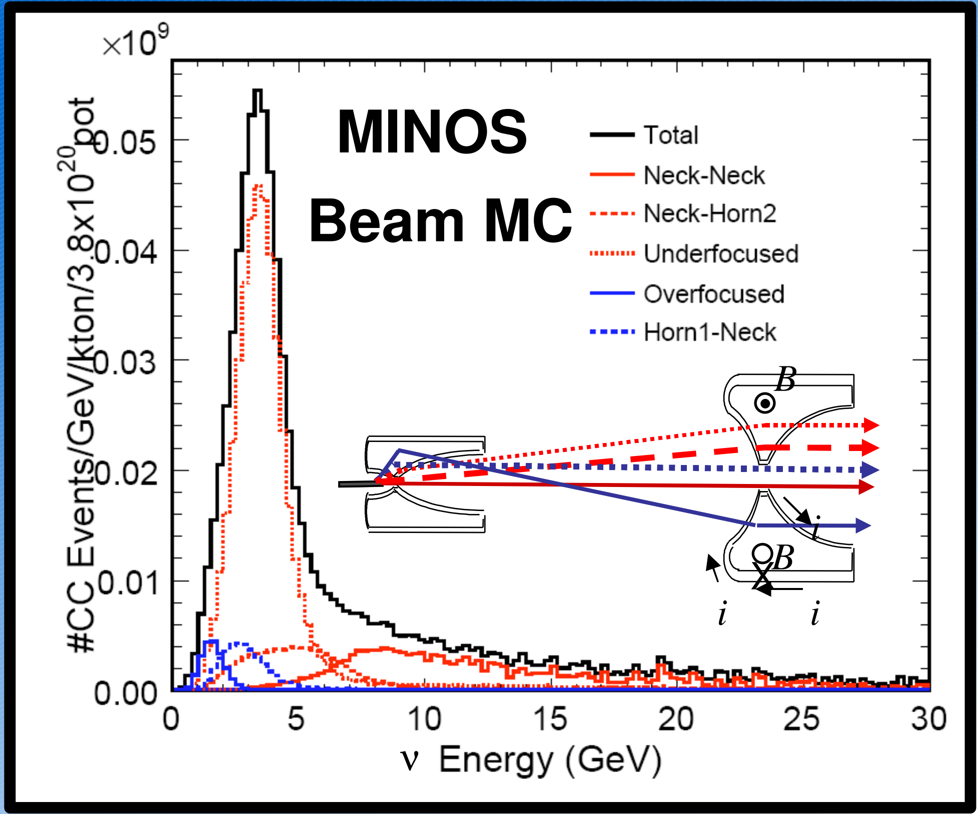
NuFact 2009

- Modern ν Beams.
- Systematic Flux Errors.
  - Beam transportation.
  - Hadron Production.
  - Other.
- Flux Measurements.
- Flux measurement from the NuMI μMonitors.

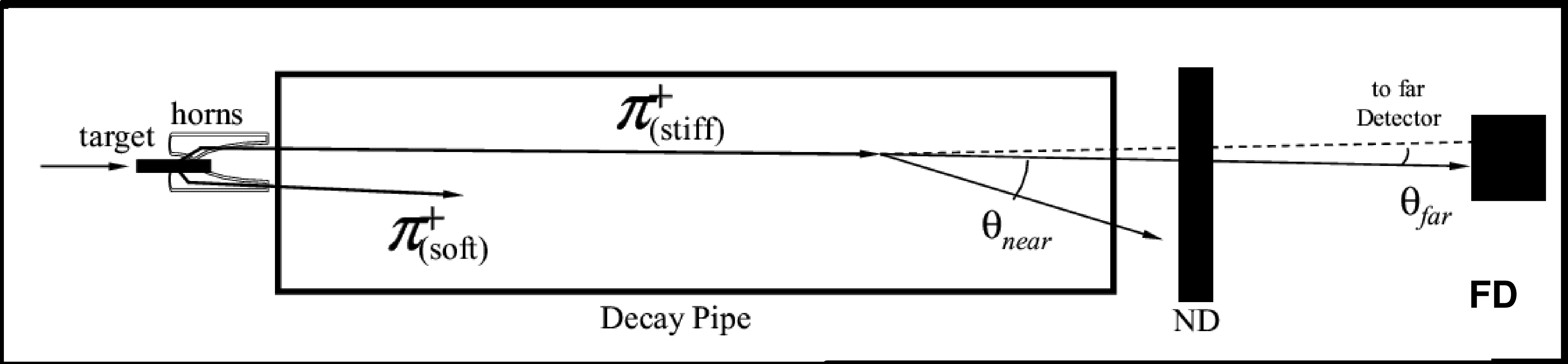
Modern Beams



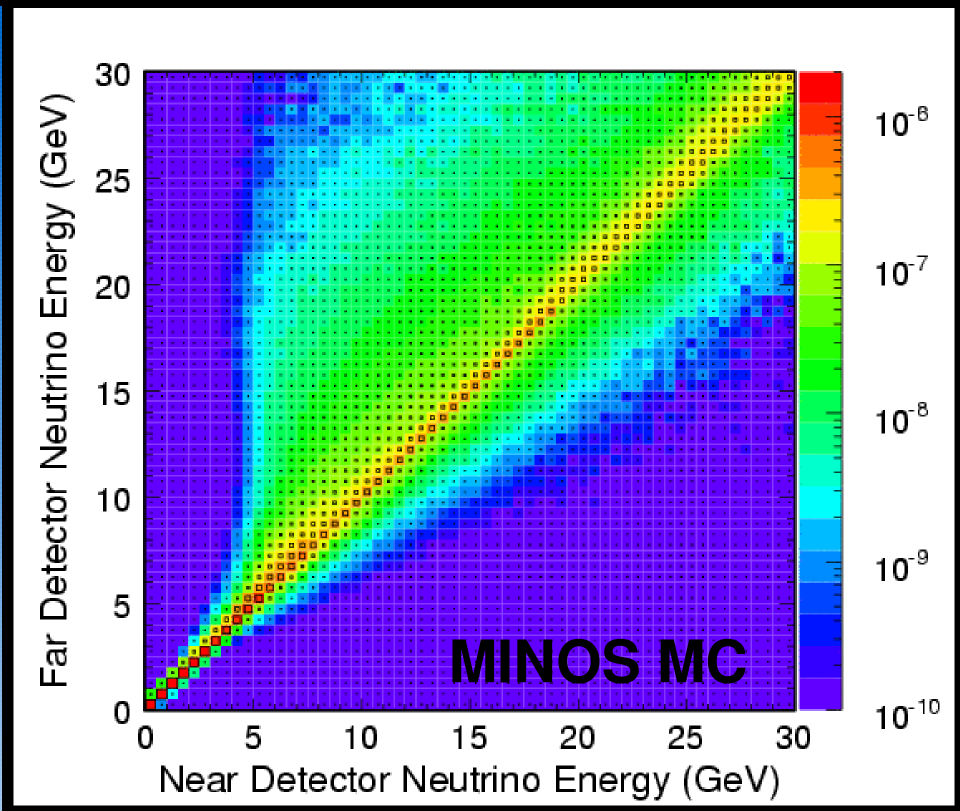
- Point to parallel focusing, $f \propto p$, selects peak energy of the beam.
- Magnetic horn focusing increases the flux of neutrinos to downstream detectors by ~ 25.



Two Detector Experiments



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

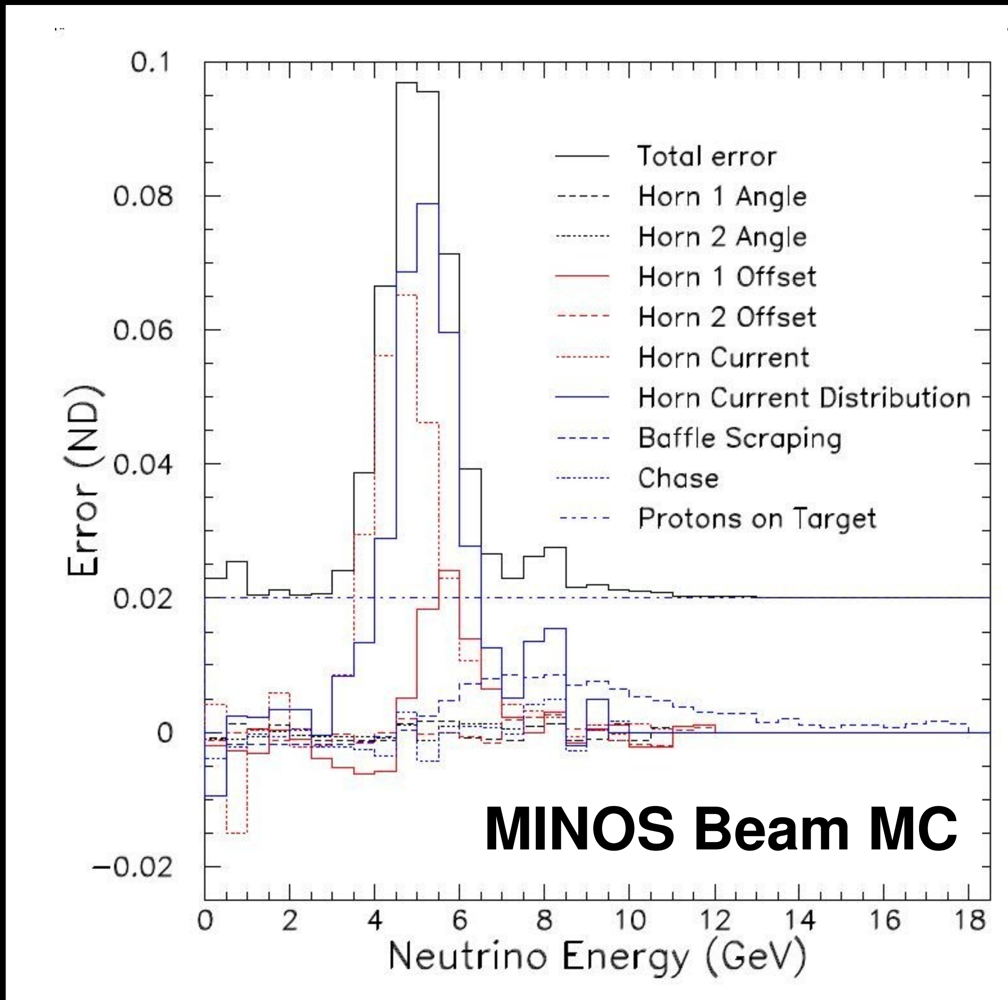


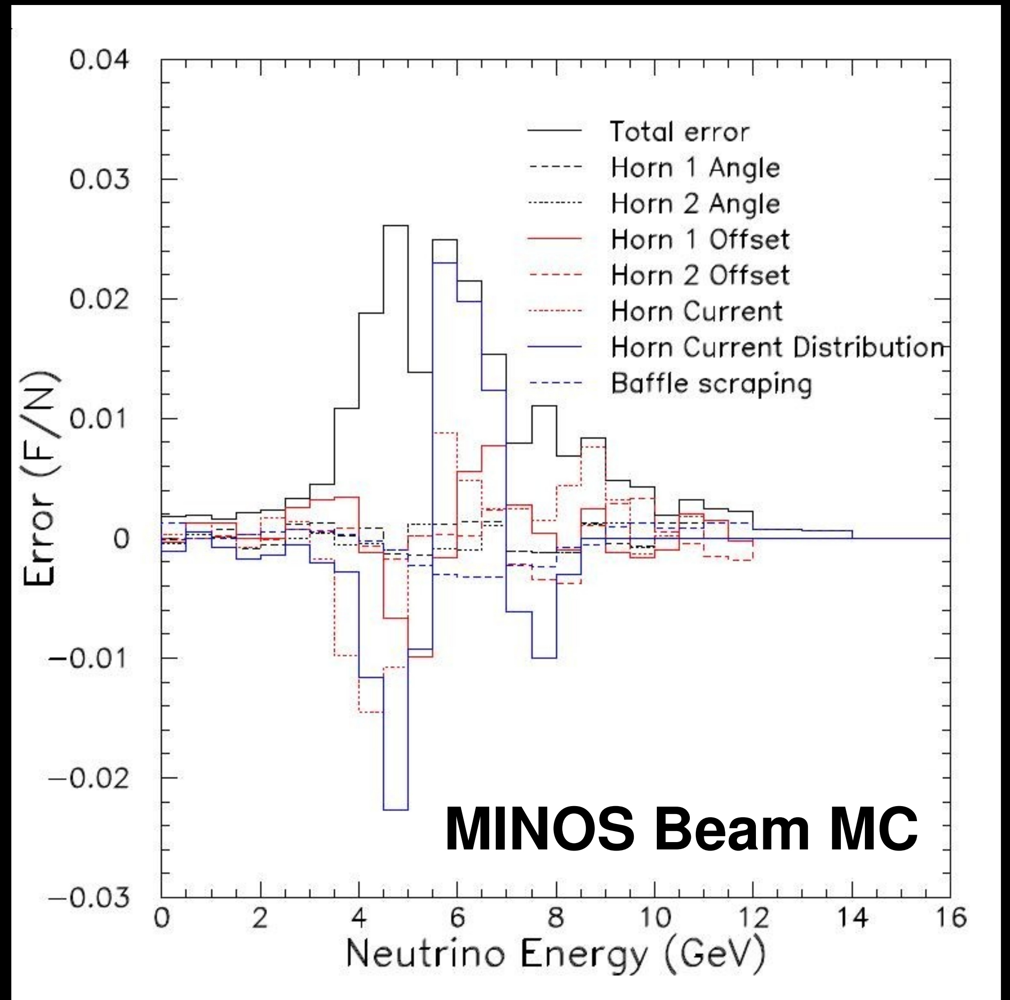
- ➢ Flux at ND is from a line source.
- ➢ Oscillation experiments use the Near Detector spectrum to predict the far detector spectrum.

Systematic Errors on the Flux: Beam Transportation

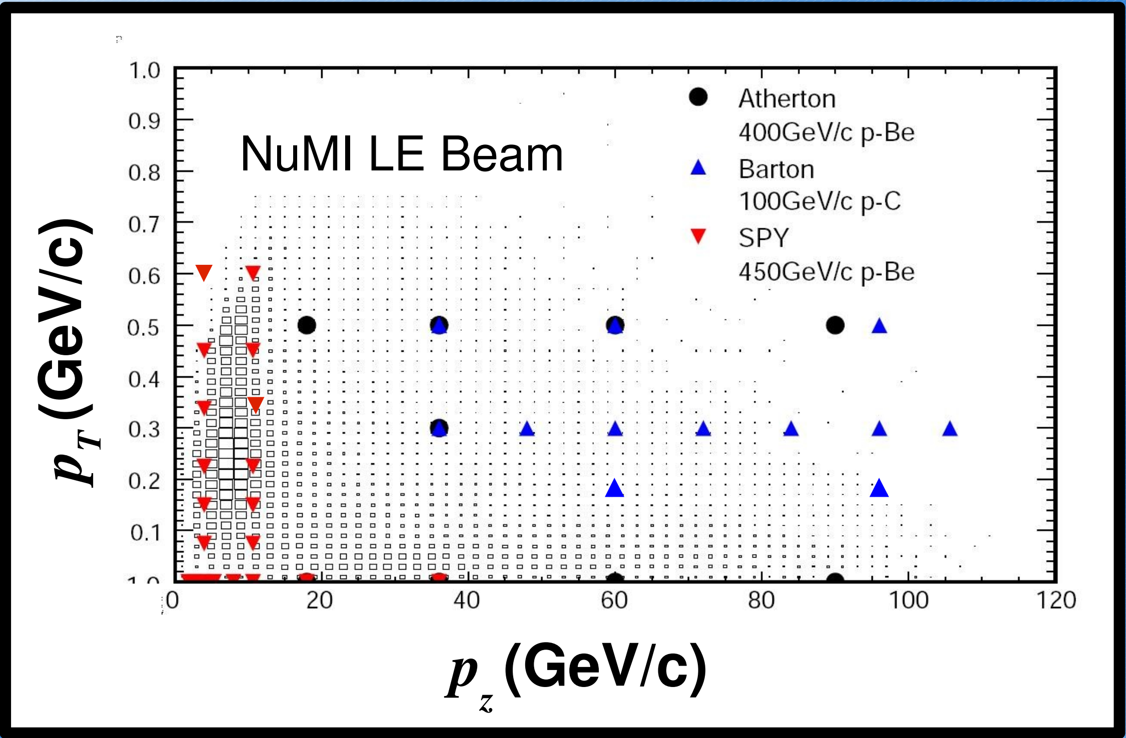
Most important for cross section experiments

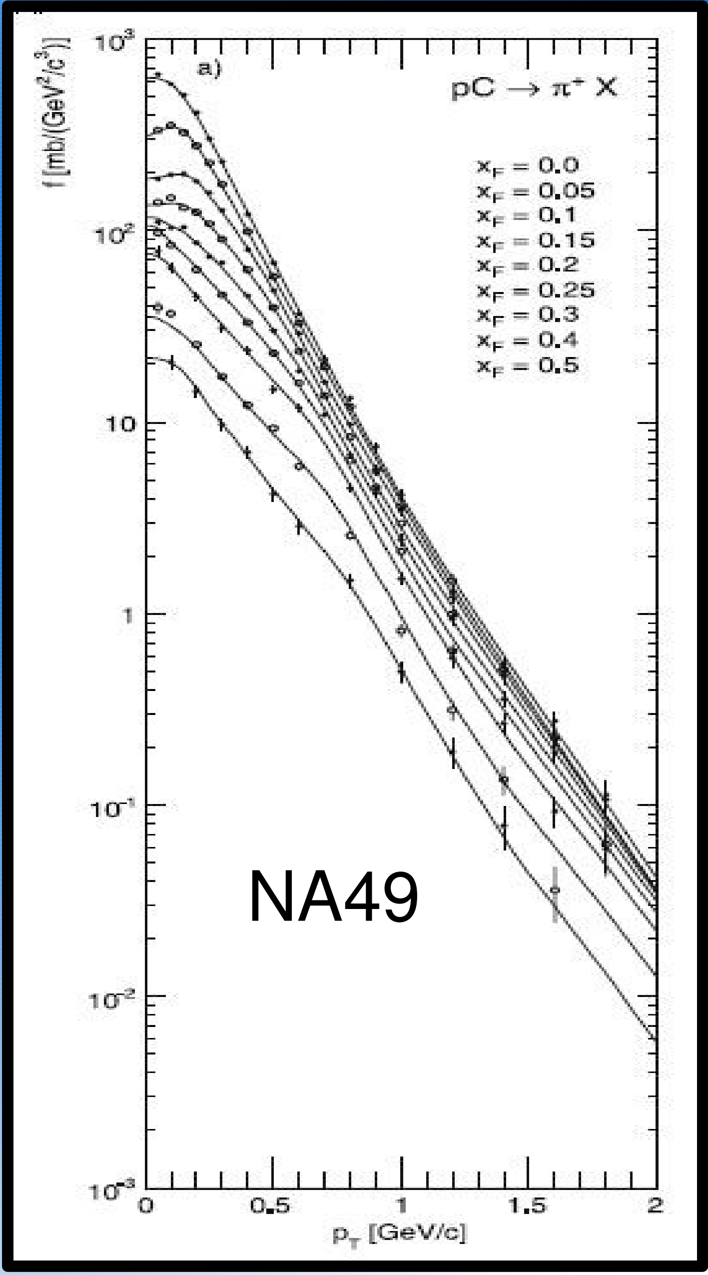
Important for oscillation experiments





Systematic Errors on the Flux: Hadron Production

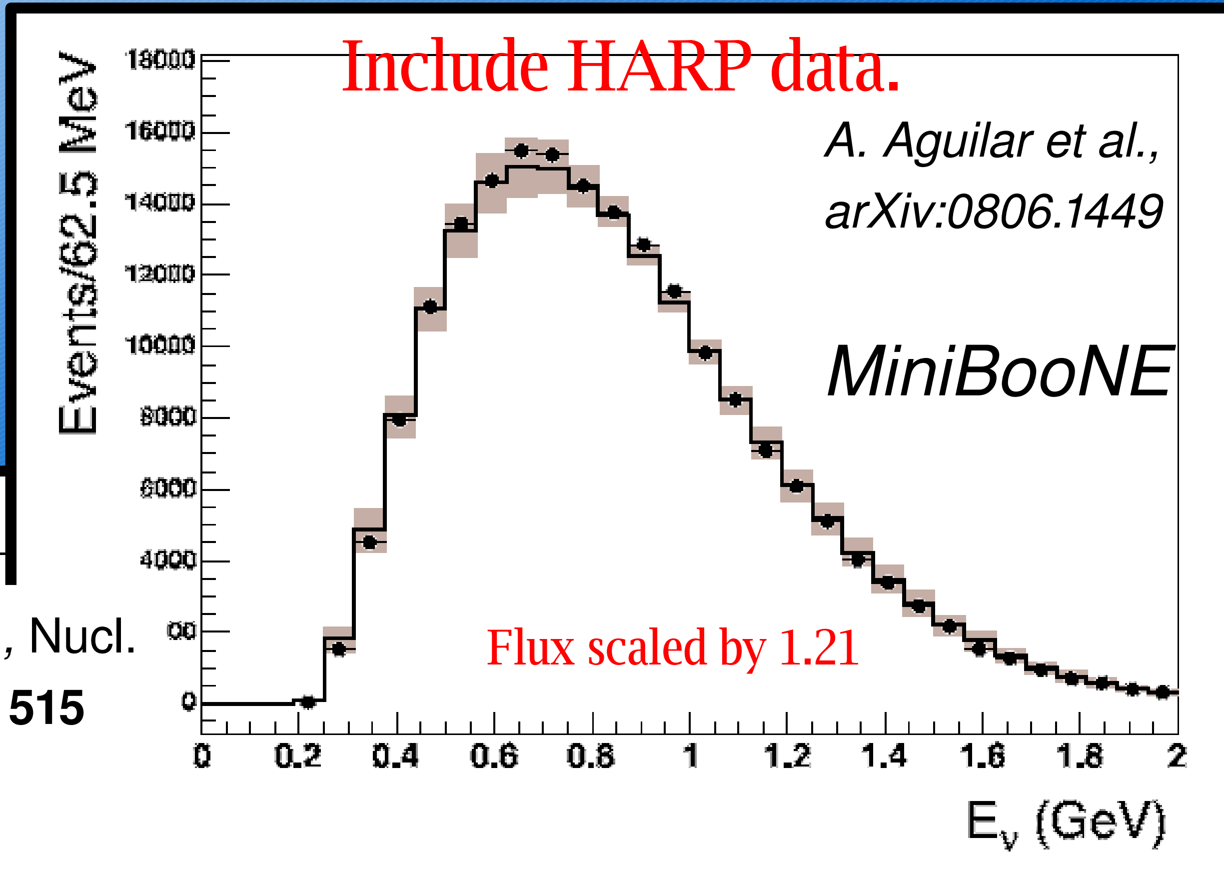


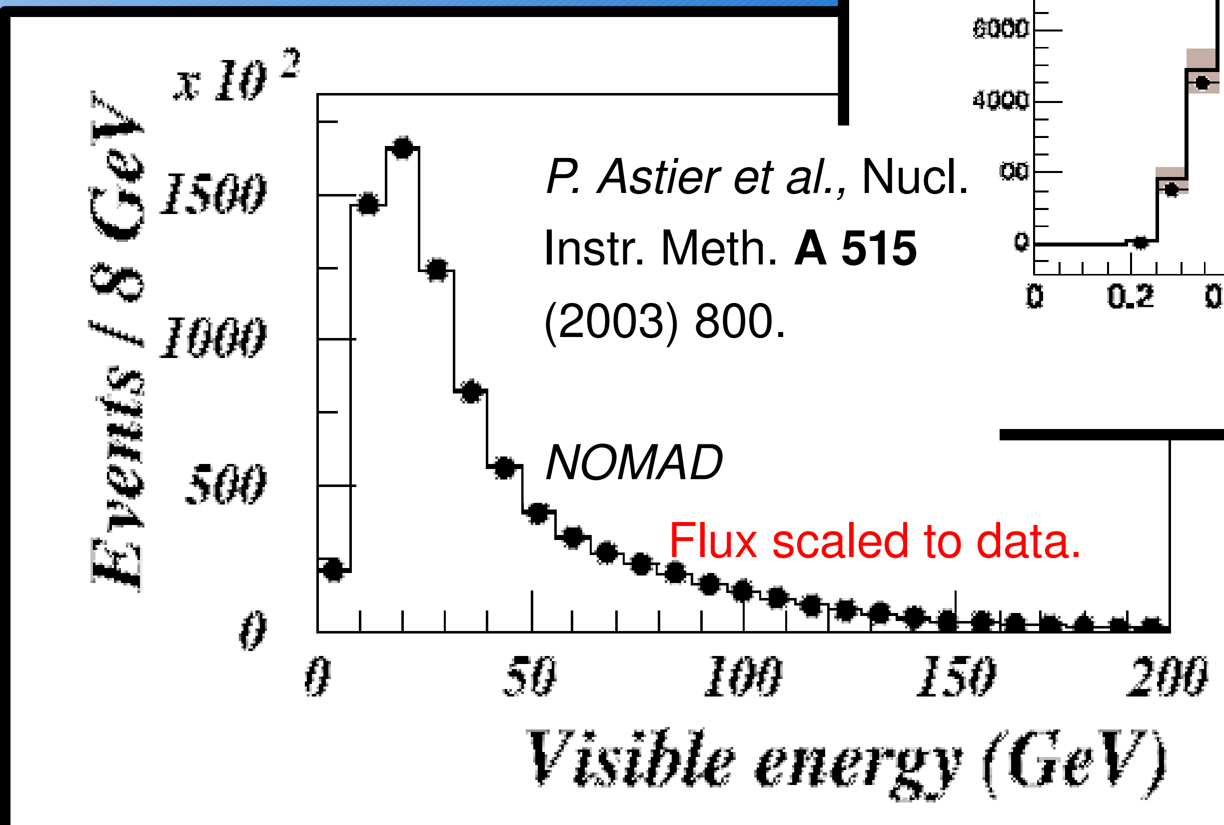


- Most neutrino experiments use MC tuned to existing hadron production measurements to simulate the production of neutrino parents in the beam line.

Incorporating Hadron Production

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

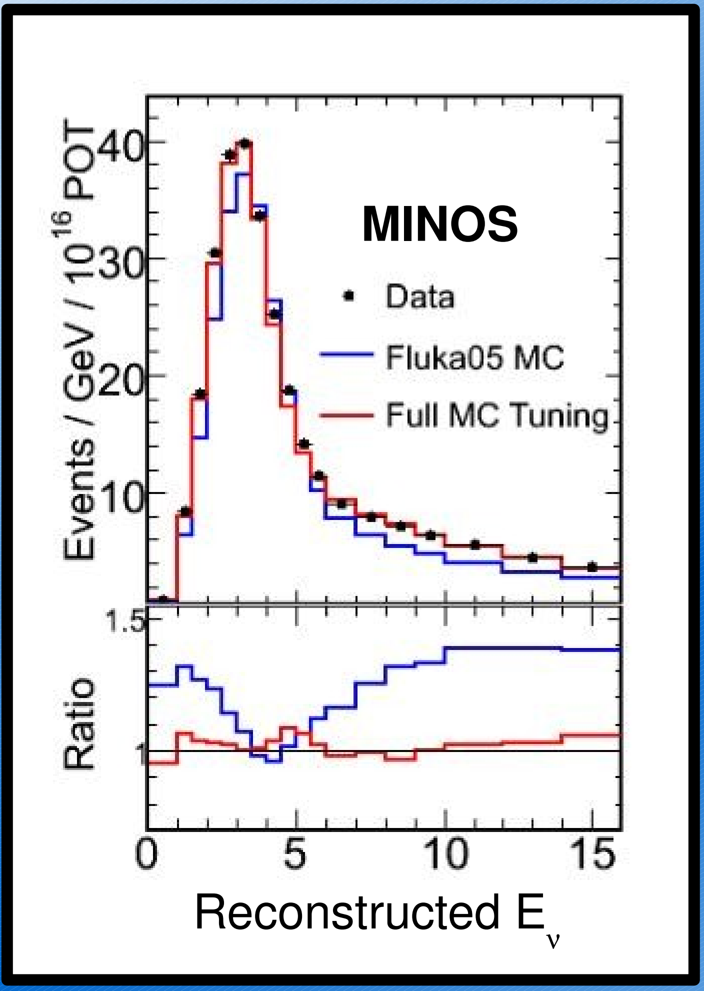


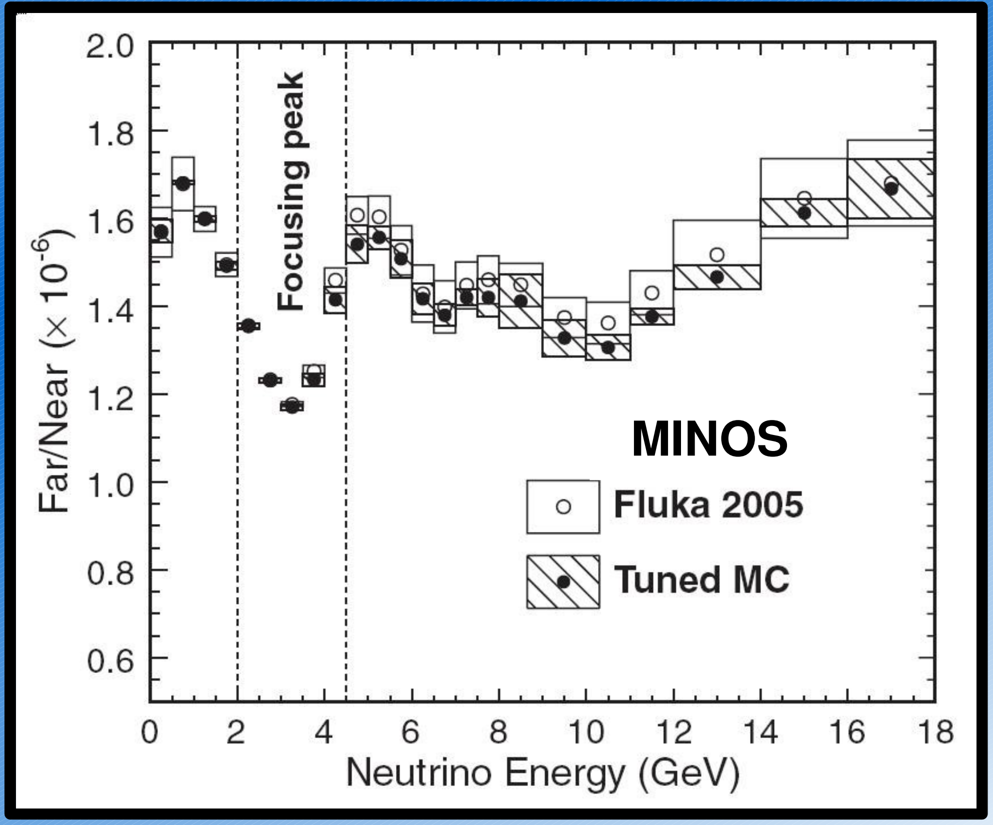


- Shapes agree well.
- Normalization is still questionable.

Tuning Hadron Production

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

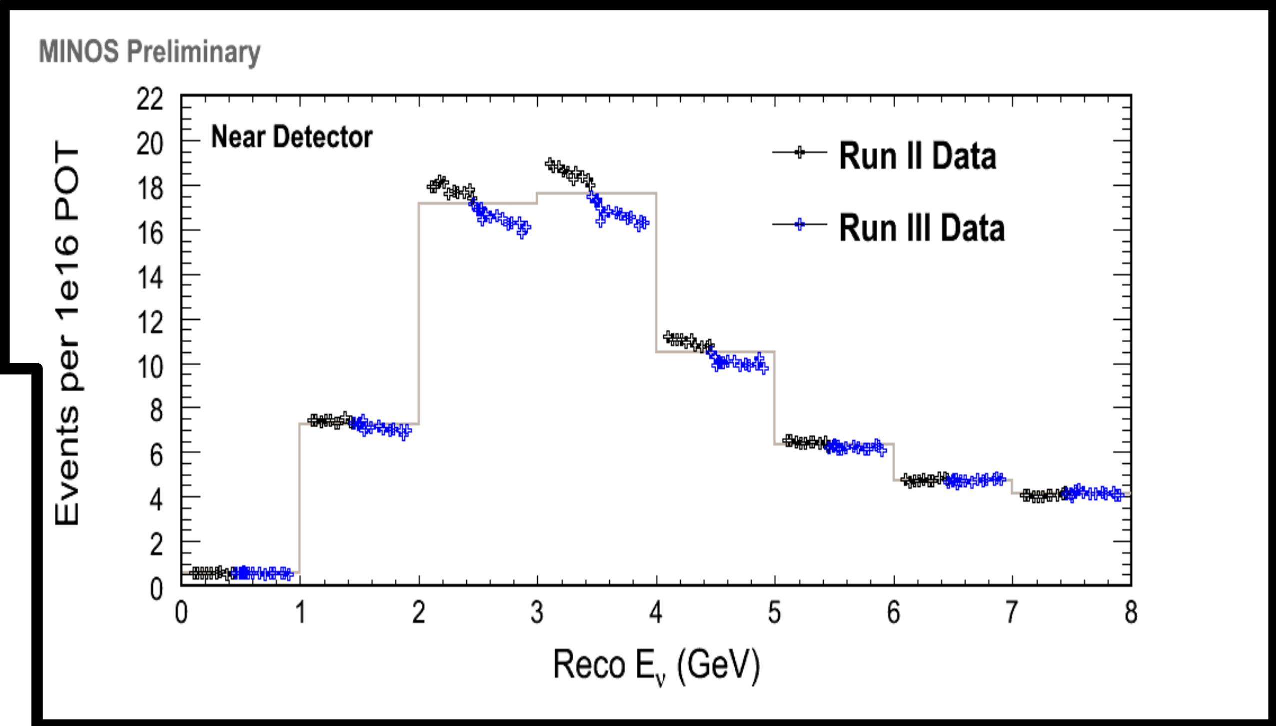


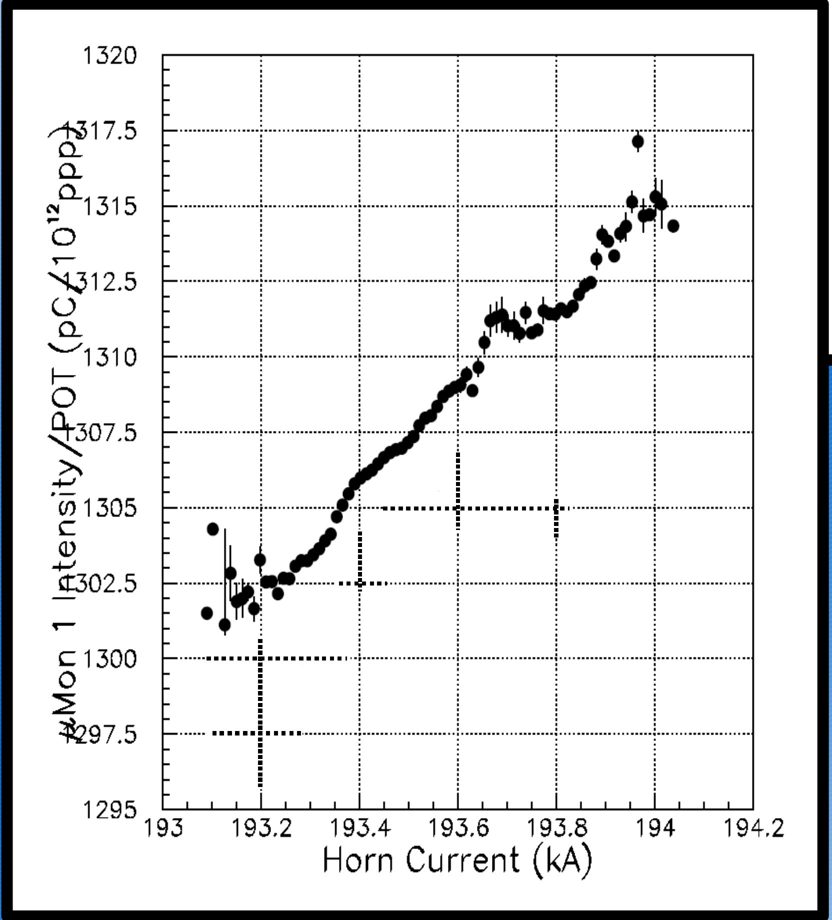


- But must assume knowledge of ν cross-sections.

Systematic Errors on the Flux: Other

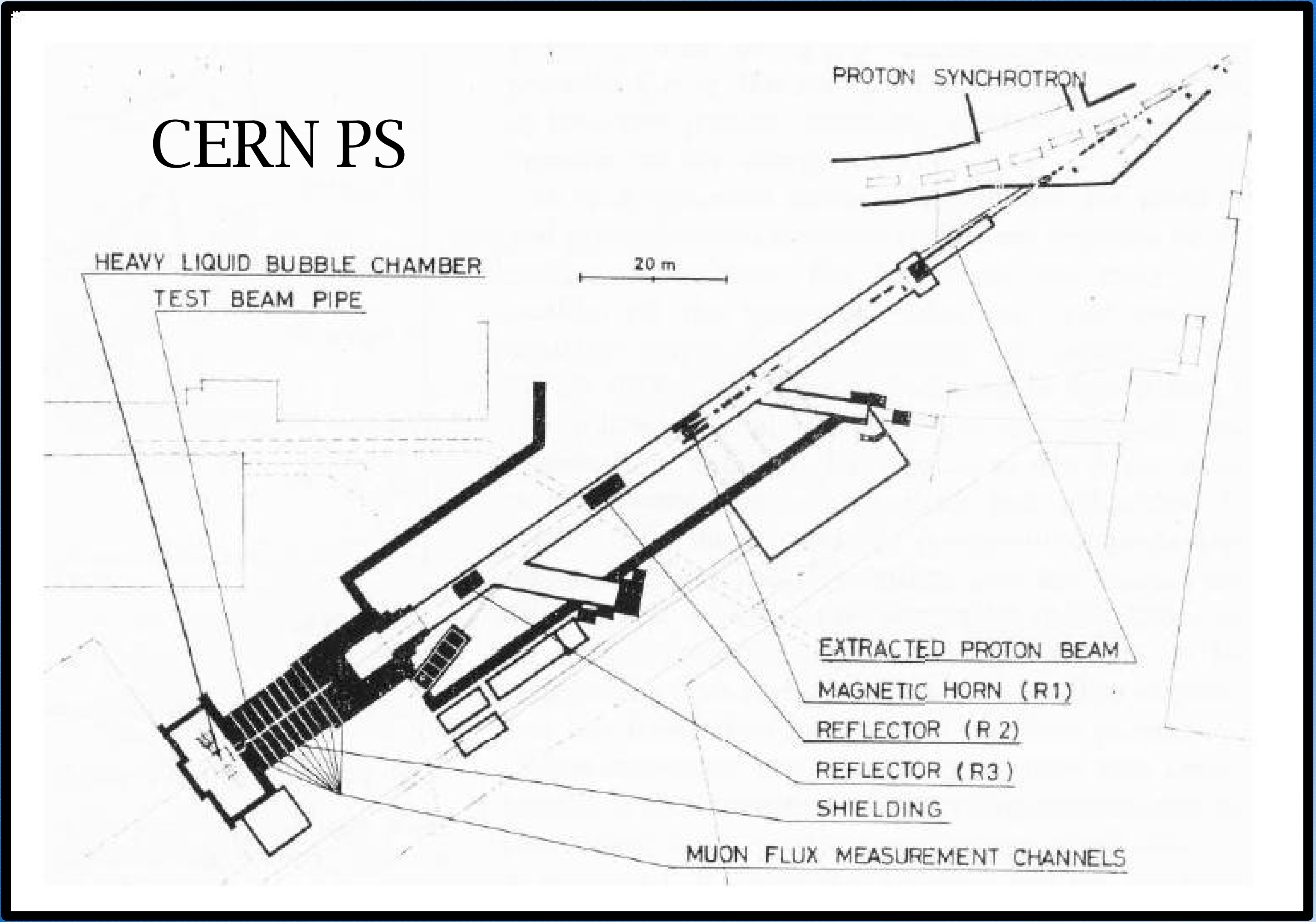
- Flux changes due to horn current variation with temperature.





- Possible target degradation over time.
- Also have downstream interactions on rock and concrete which are not covered in hadron production experiments.

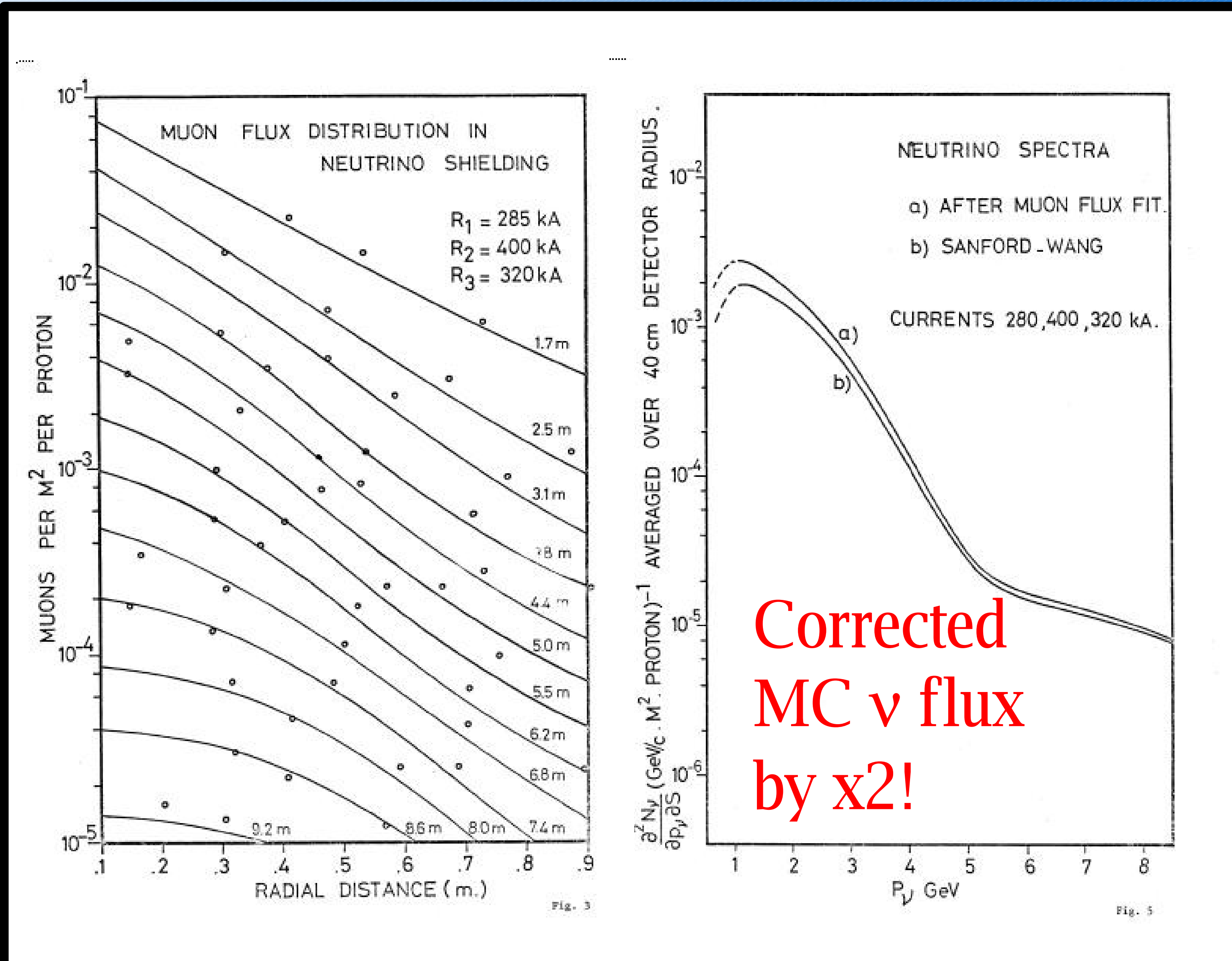
In situ Flux Measurements



- BNL
- CERN-PS, WANF
- IHEP
- FNAL E616
- Typical ~20%

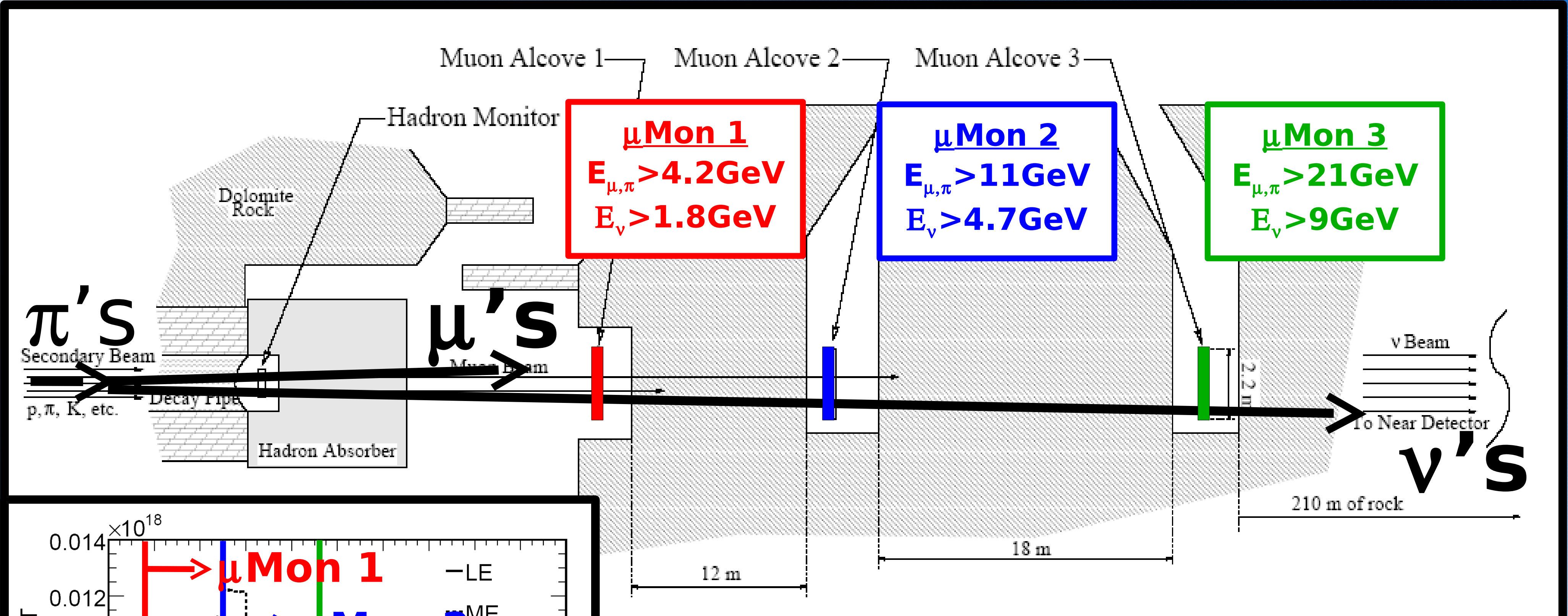
- Not an easy measurement.

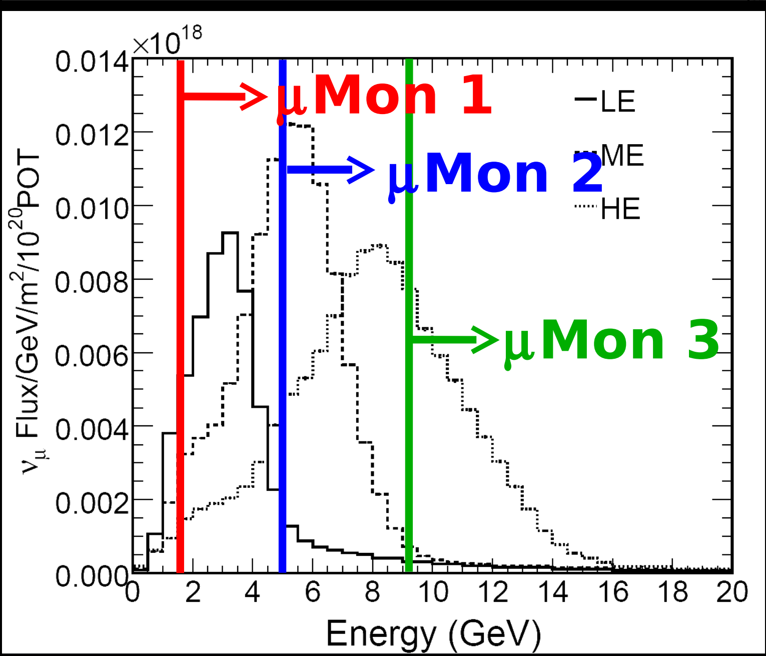
Experience from CERN PS



- Originally tuned MC to HP data.
- Flux measurement from μMons indicated x2 off.
- New HP experiment – agreed with μ tuned ν flux to 15%.

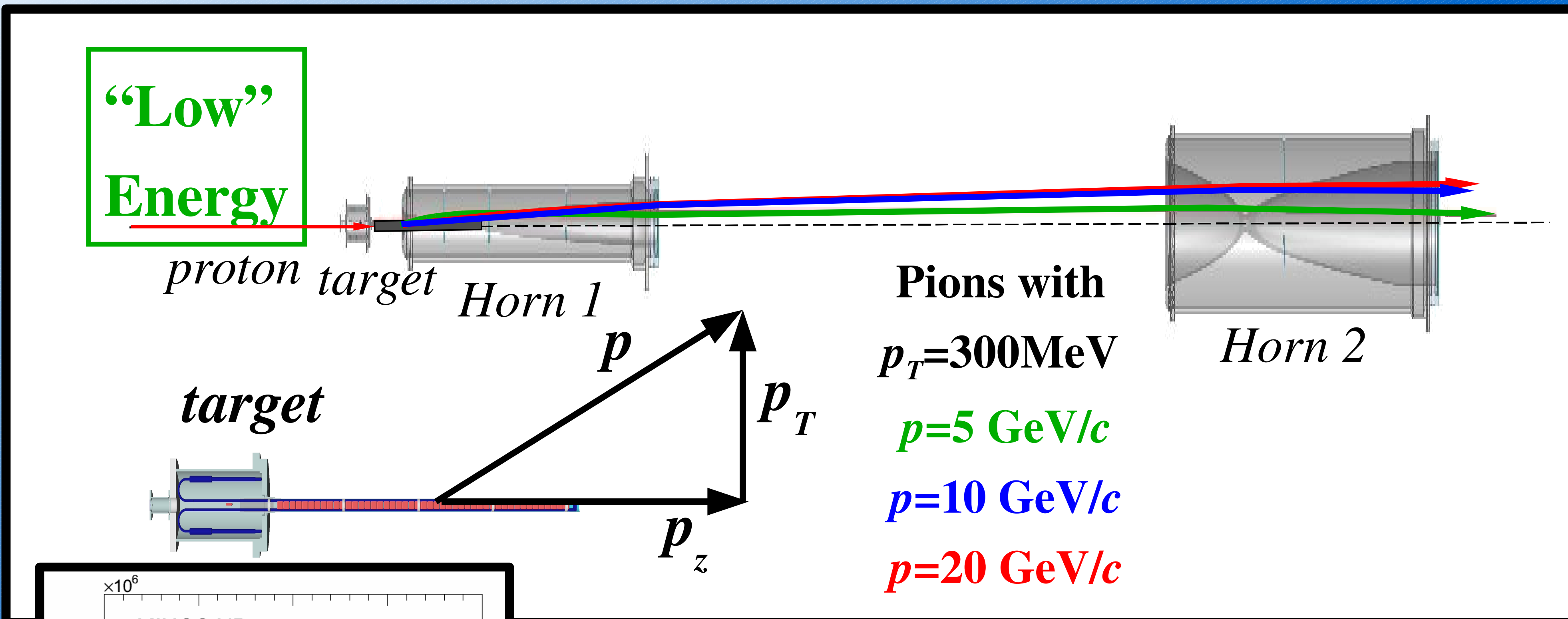
NuMI Flux Measurement

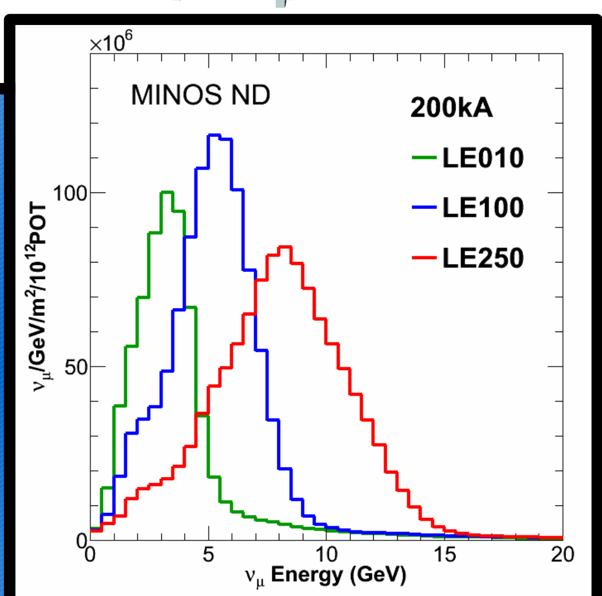




- 3 arrays of ionization chambers; Signal = ionized electrons.
- Sampling μ flux = Sampling hadrons off target = Sampling ν flux.
- Sample different energy regions of the flux.

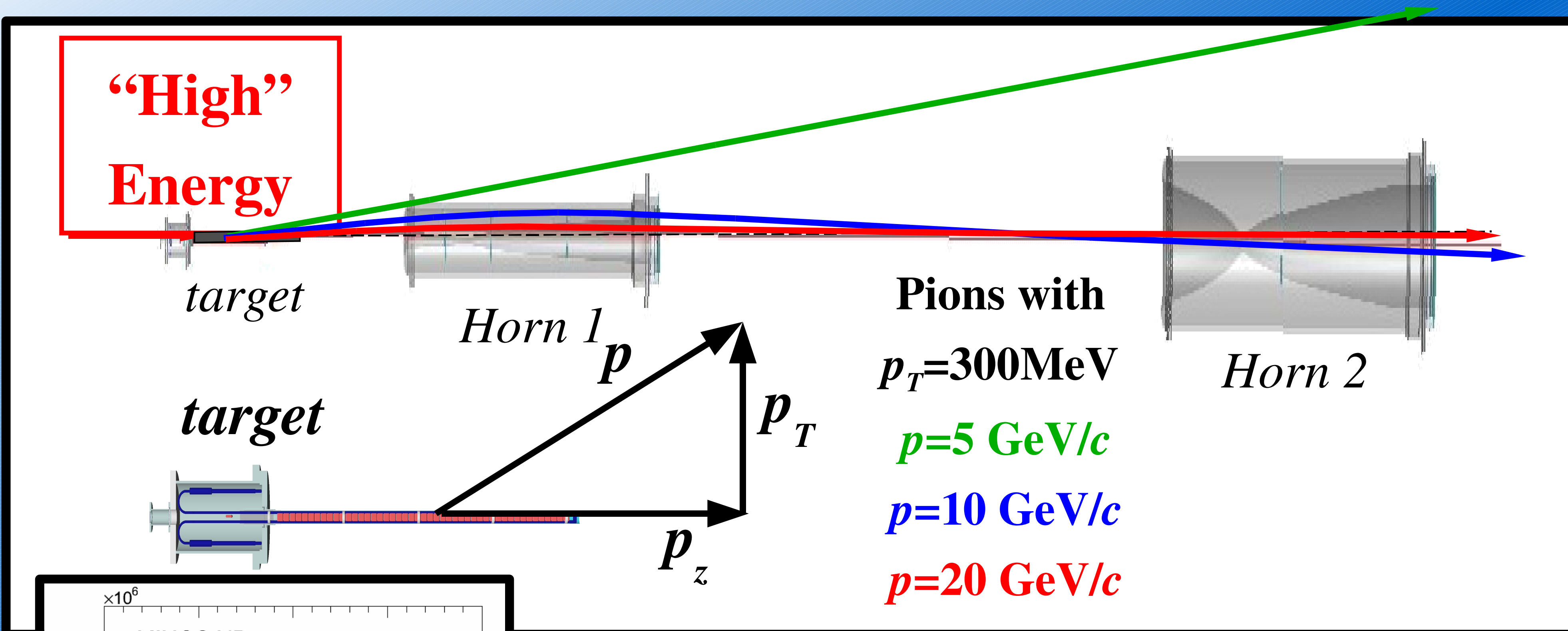
NuMI Variable Beam Energy

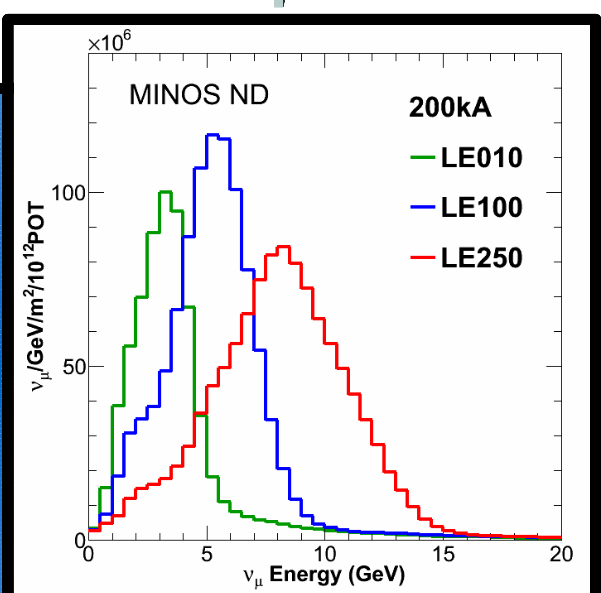




- Hadrons diverge from the target → horns focus hadrons along the beamline.
- Varying target position samples variety of E_π, E_μ and E_ν.

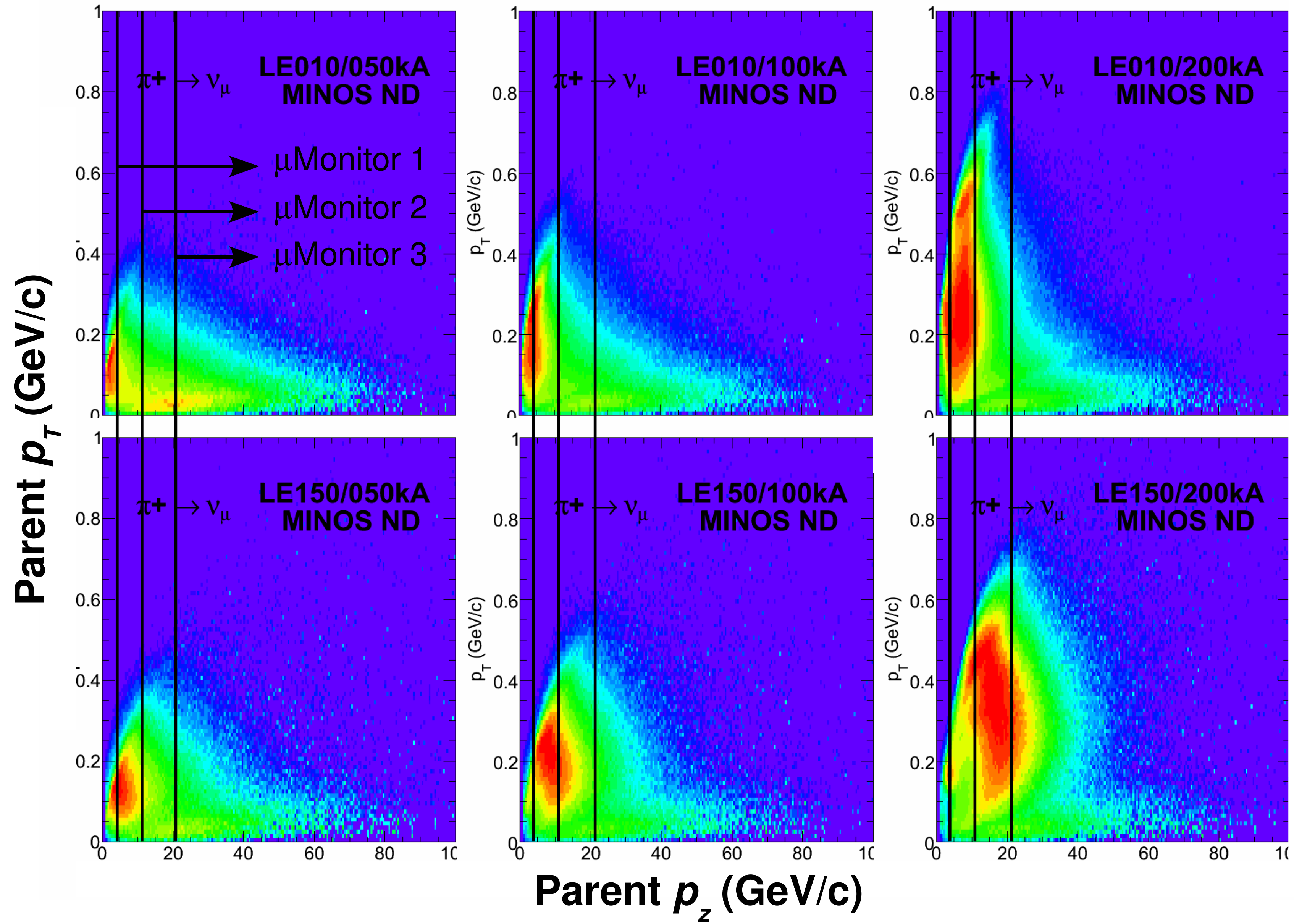
NuMI Variable Beam Energy





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

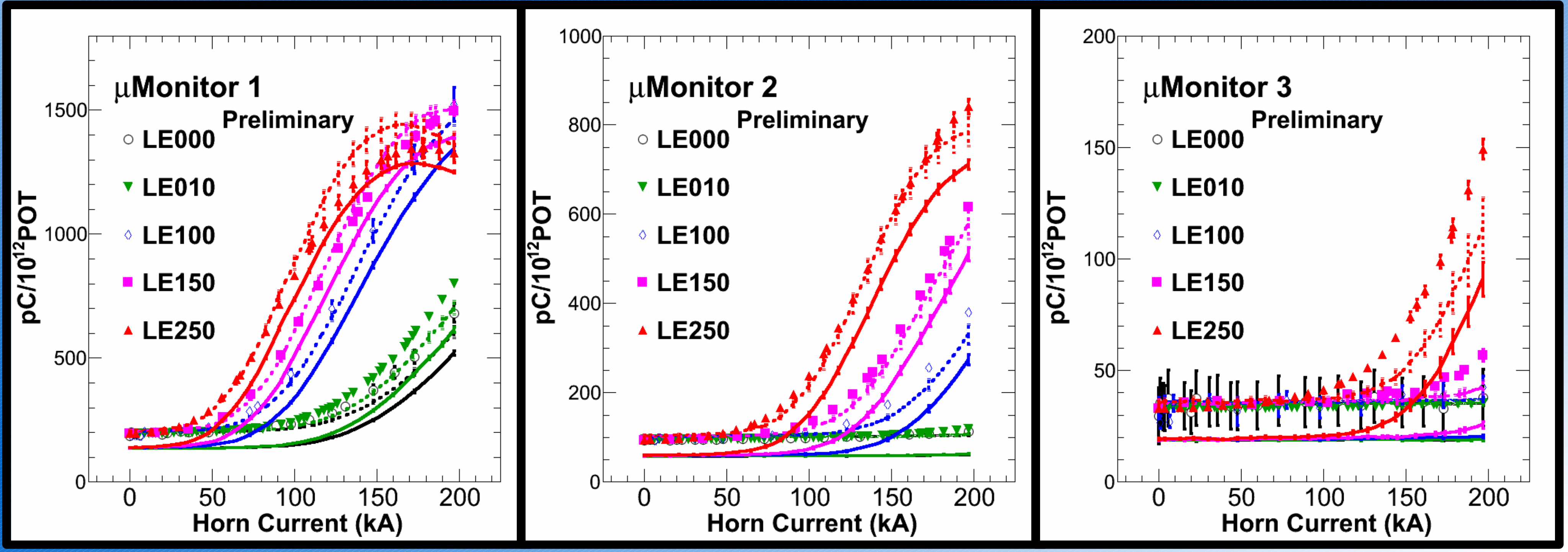
$\varphi_\nu(E_\nu) \leftrightarrow \varphi_\nu(p_T, p_z)$



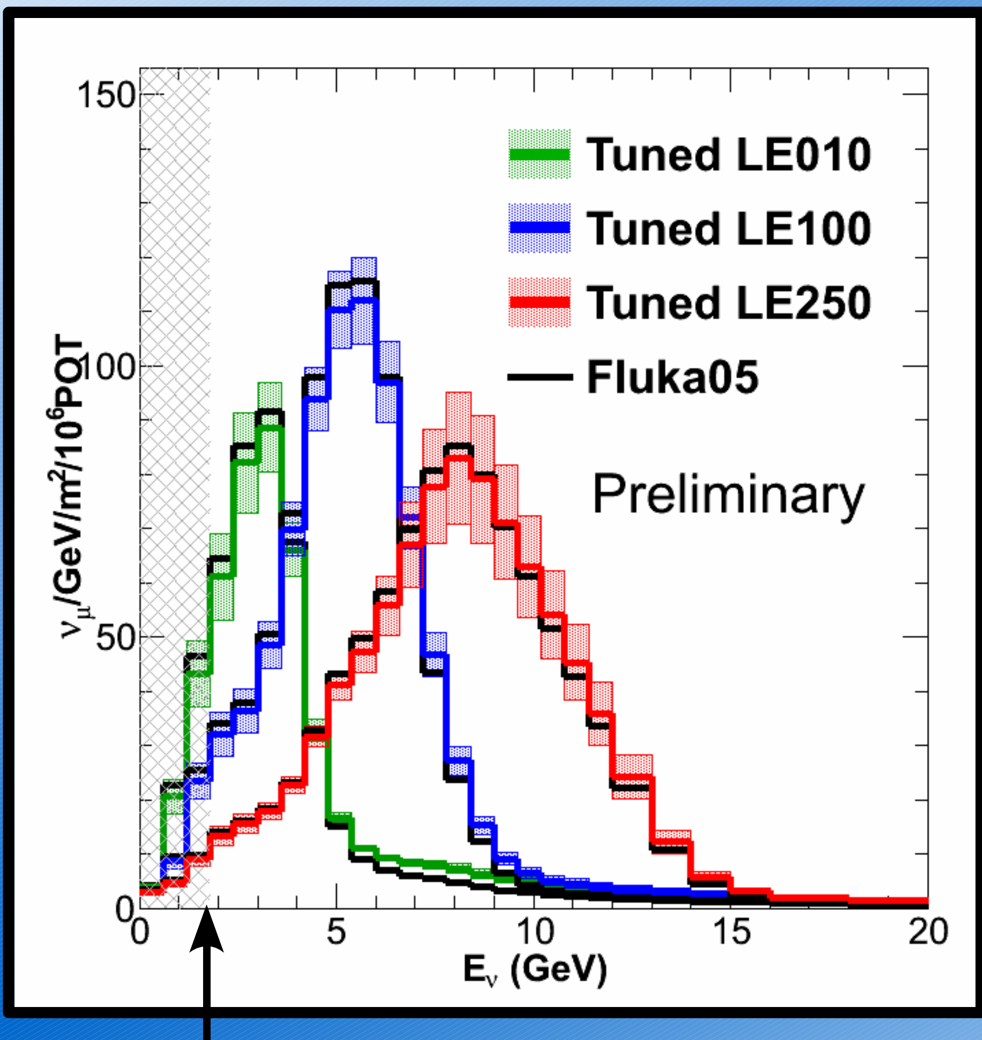
μ Monitor Tuning

- 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.

- 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:

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

Summary

- Flux uncertainties/normalization particularly important for neutrino cross section experiments; but absolute fluxes benefit everyone.
- Unexpected/Unknown *In situ* effects can add uncertainty to flux predictions.
- *In situ* NuMI Flux measurement has been made.
- ν cross sections to follow.

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- S. Kopp, "*Accelerator Neutrino Beams*," *Phys. Rep.* 439, 101 (2007).
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- E. H. M. Heijne, ``Muon Flux Measurement With Silicon Detectors In The Cern Neutrino Beams," CERN-YELLOW-83-06.
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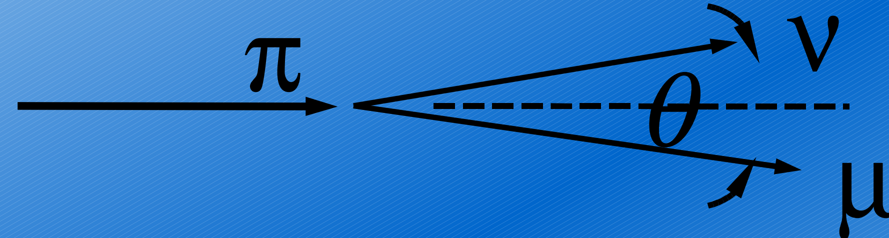
- R. Blair, et al., ``Monitoring And Calibration System For Neutrino Flux Measurement In A High-Energy Dichromatic Beam," Nucl. Instrum. Meth. A **226**, 281 (1984).

Backup Slides

Why Focus?

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



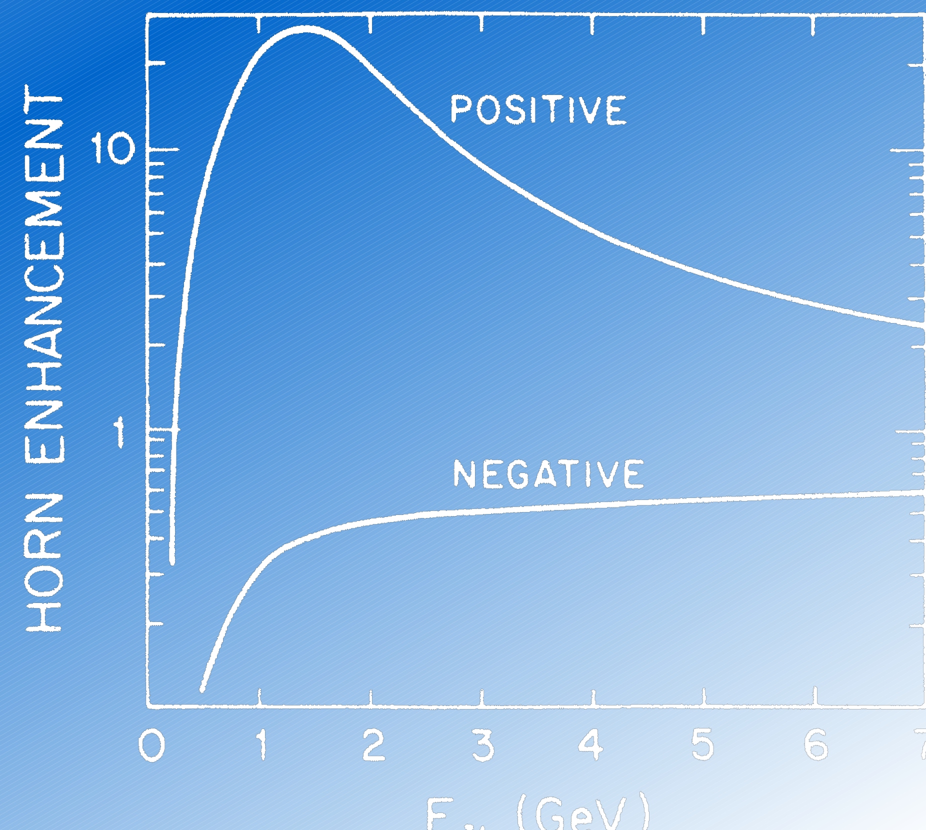
- 'Cocconi divergence'

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

- Neutrino divergence

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

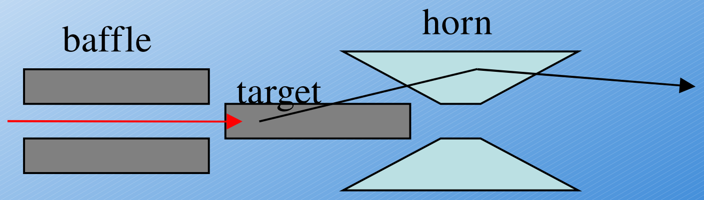
- Reduce divergence ~3, flux goes up by ~ 25

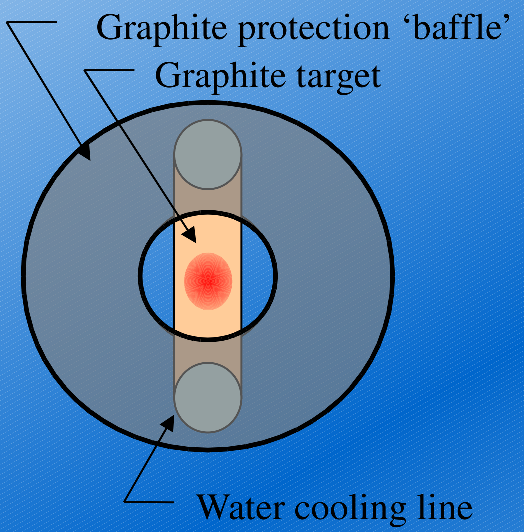


L. Ahrens *et al*, Phys. Rev. D 34, 75 - 84 (1986)

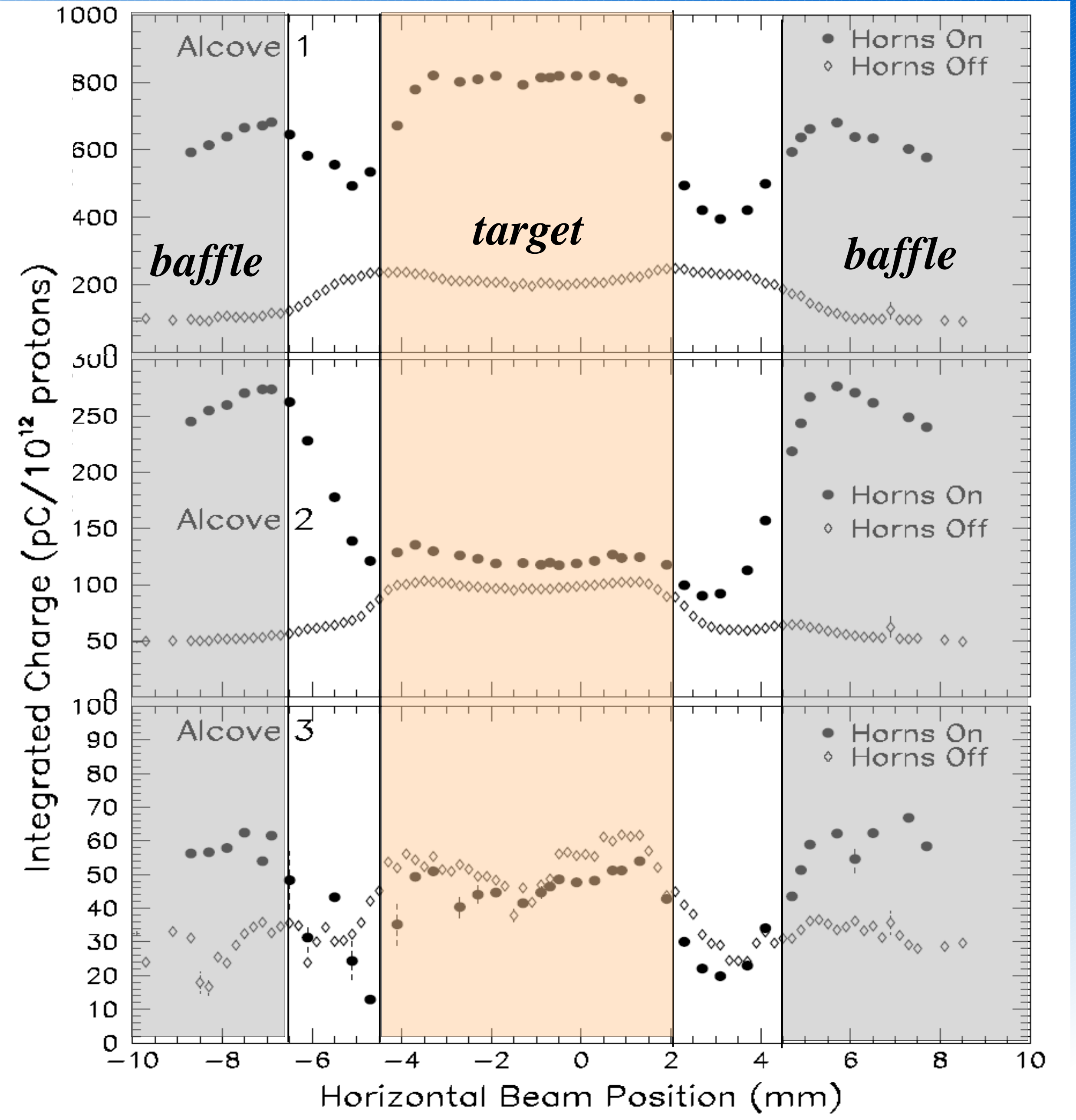
Systematic Errors on the Flux: Targeting

➢ Targeting.

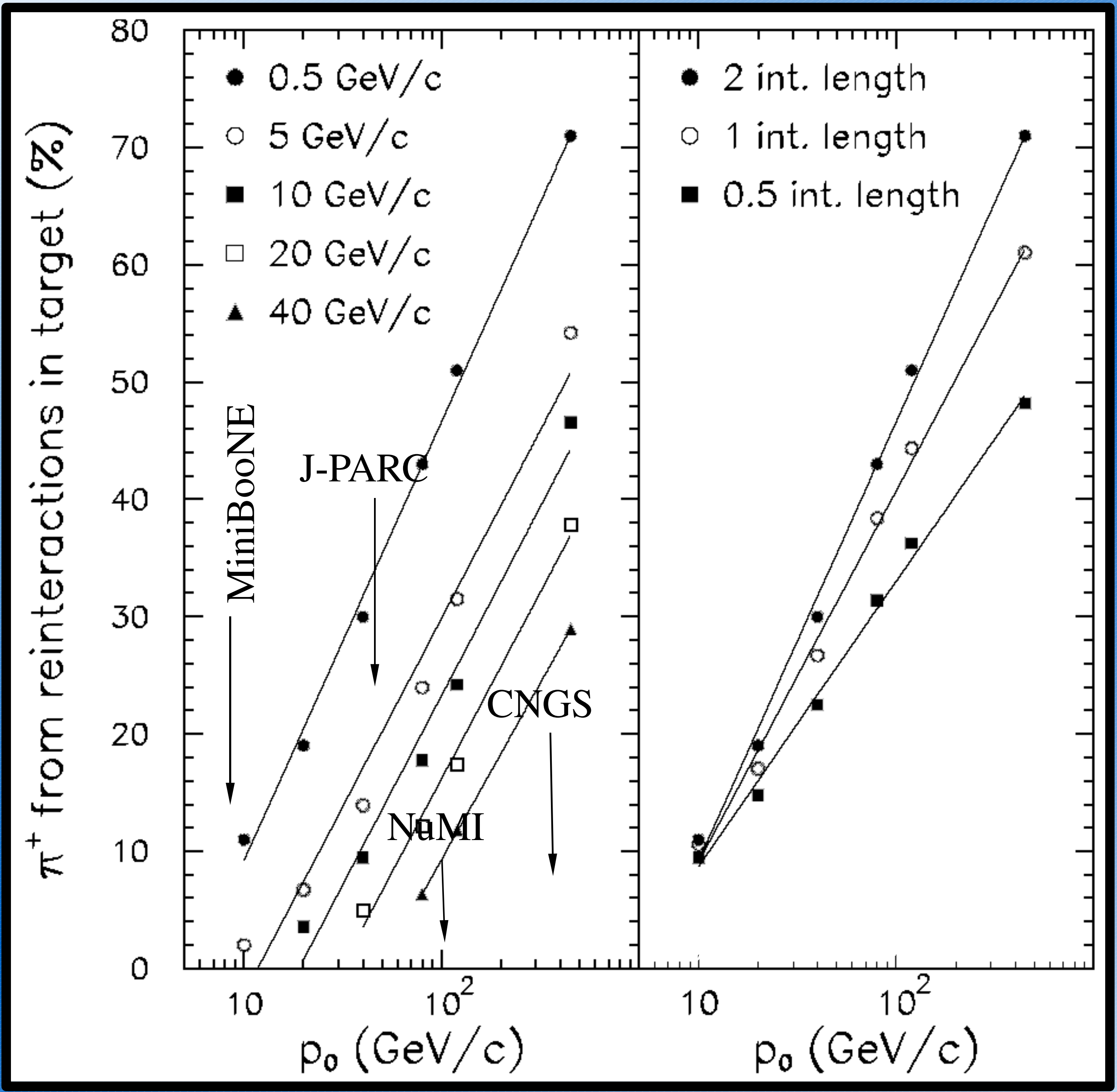




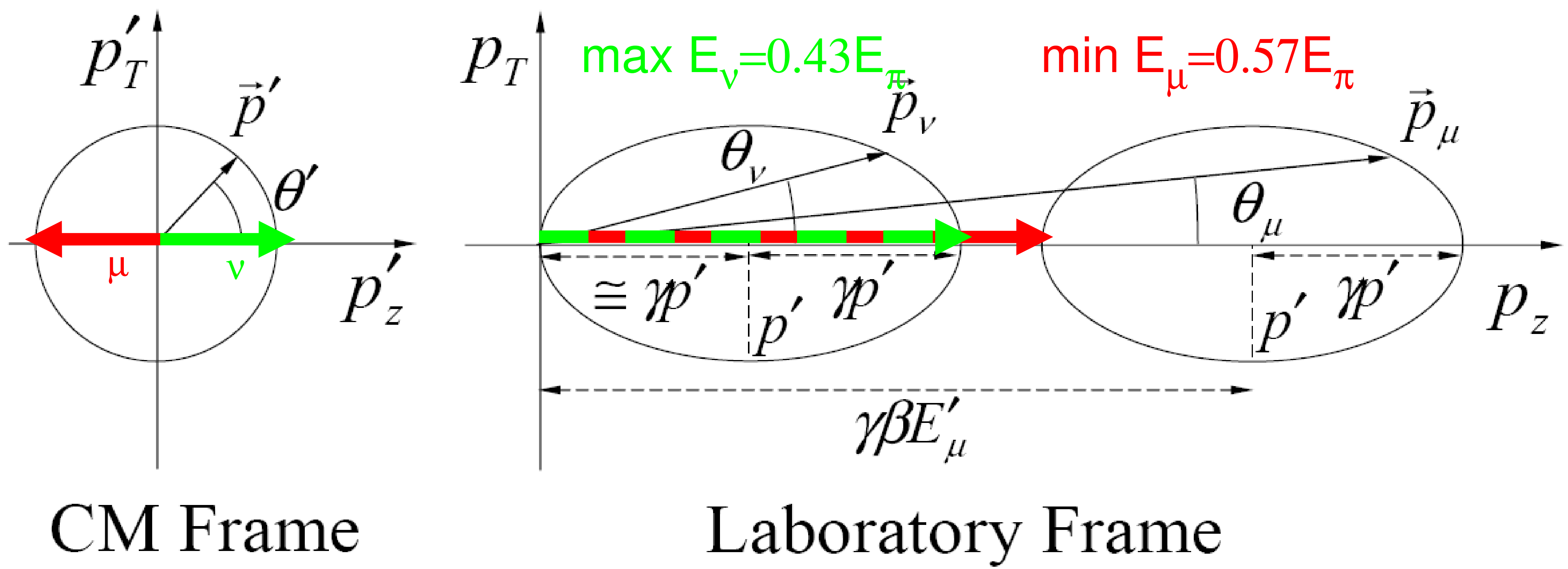
➢ Flux is sensitive to beam position on the target.



Thick Target Effects



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

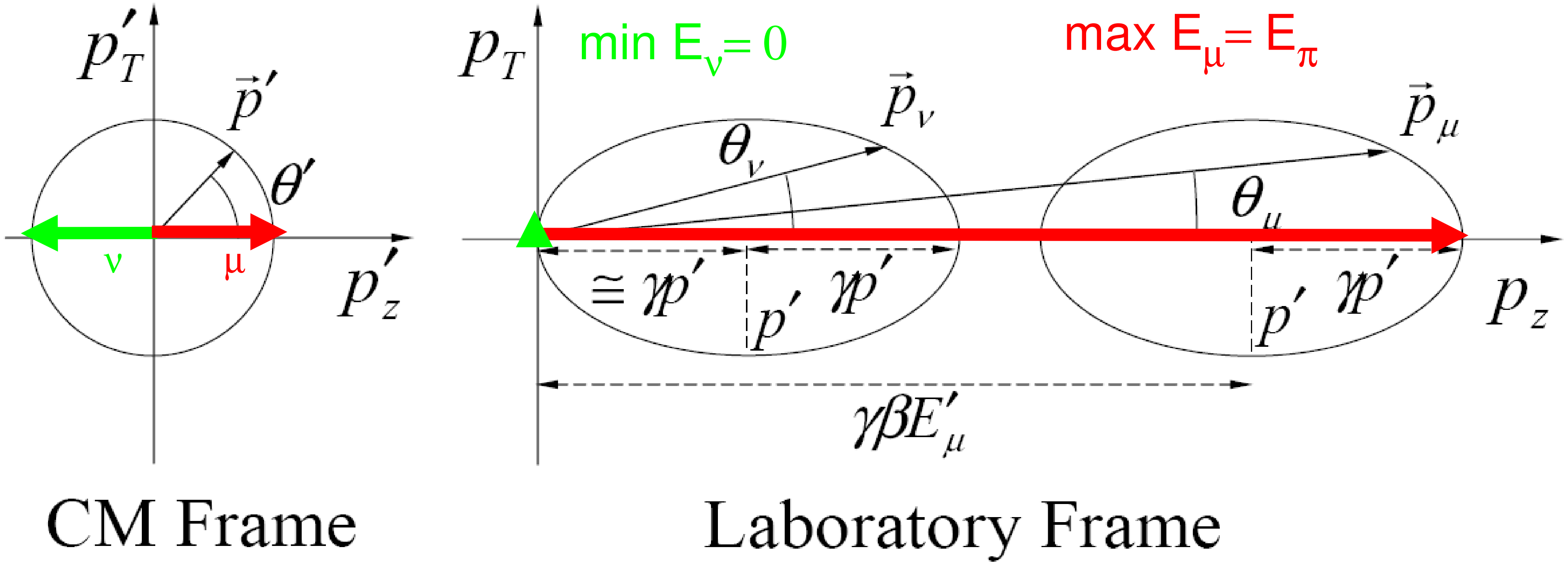


- Neutrinos seen in MINOS and MINERVA come from forward decays in CM frame
- Such decays give highest energy E_ν for given pion energy and lowest energy muons

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.

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



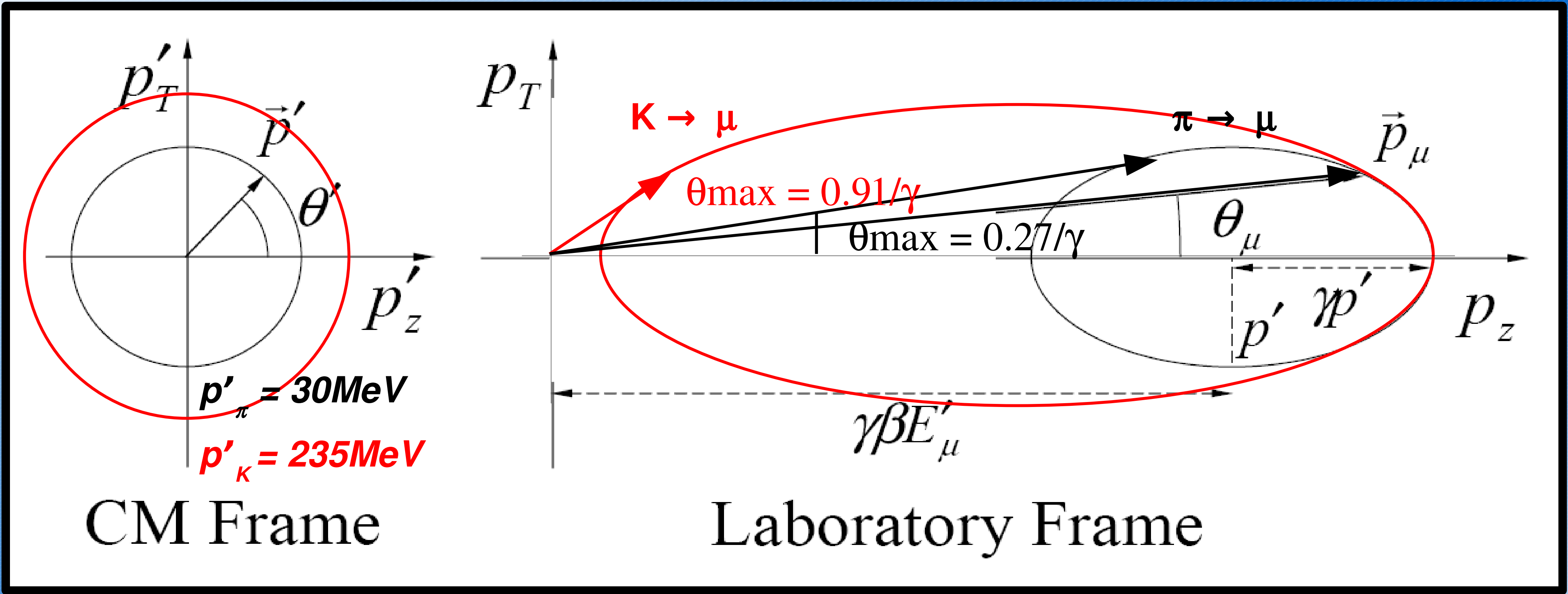
- Forward-going muons give E_ν ~0 and E_μ ~E_π
- Muon Monitors can see lower effective pion parent threshold, just not in the same decays as give neutrinos in the ν detectors

	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

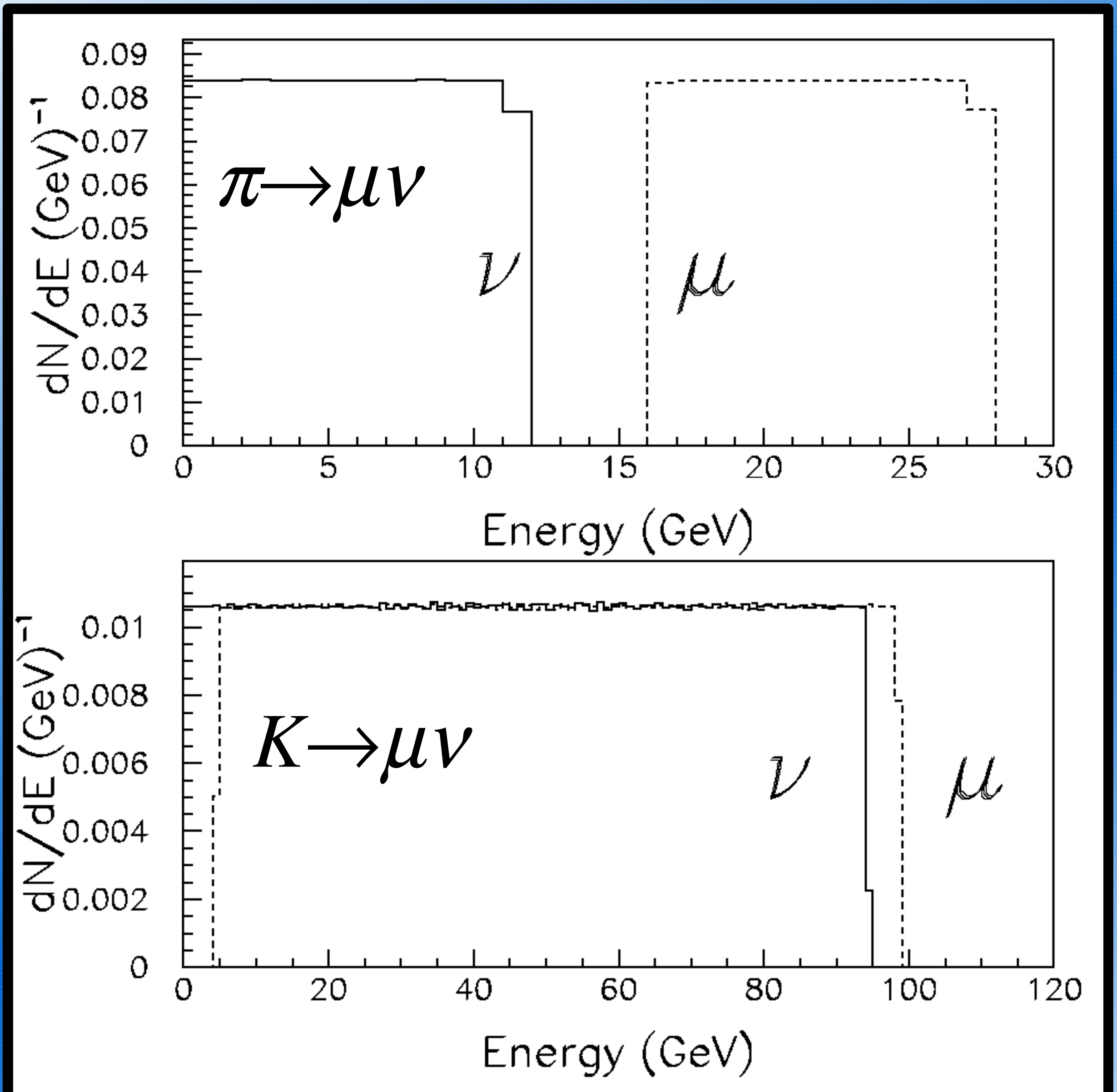


$$p_T'^2 + p_z'^2 = p'^2$$

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

- 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

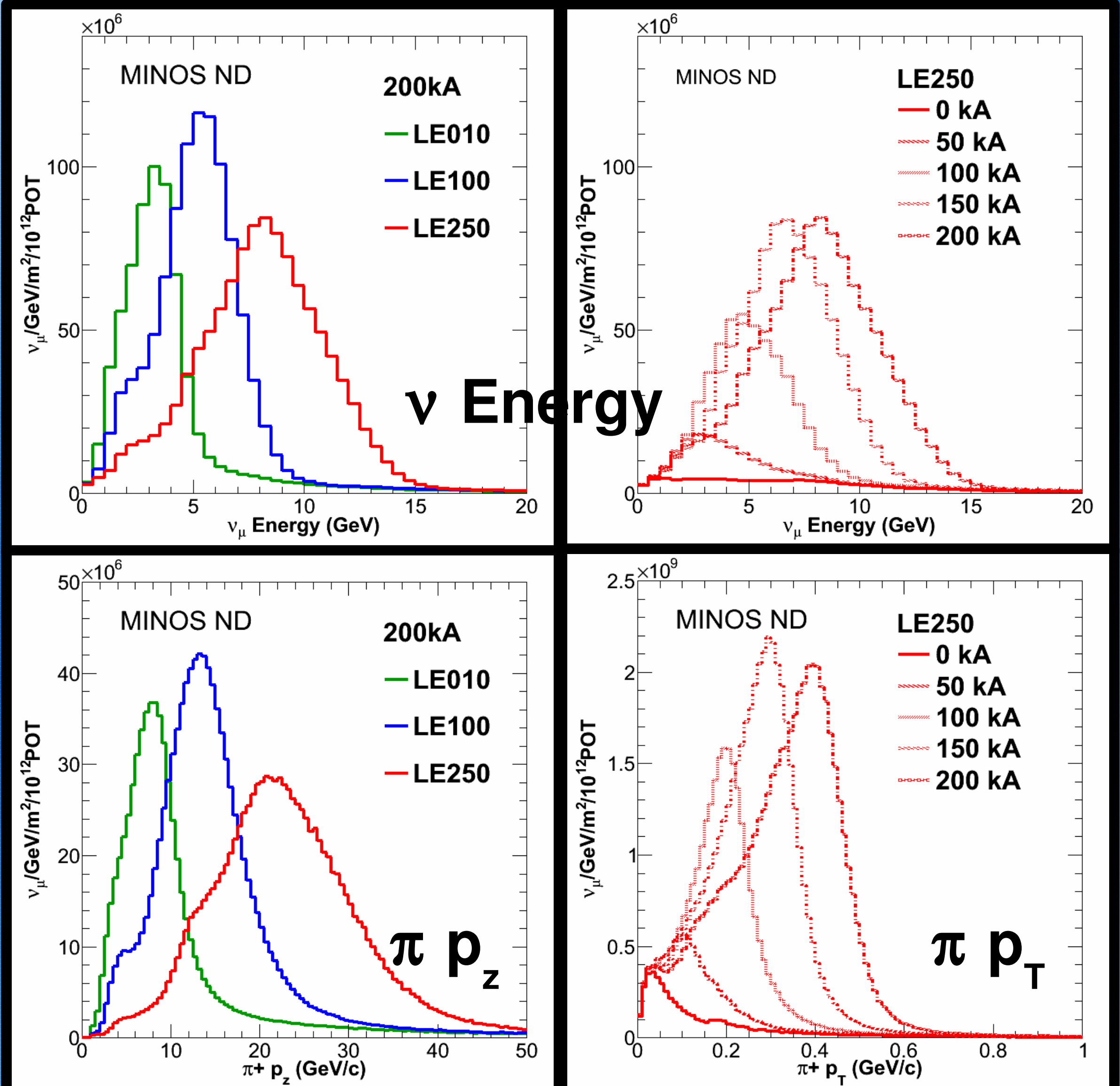
Such come from E_π>4 GeV

In other decays, such pions give E_ν>1.6 GeV

Sets actual "neutrino threshold" of the alcoves

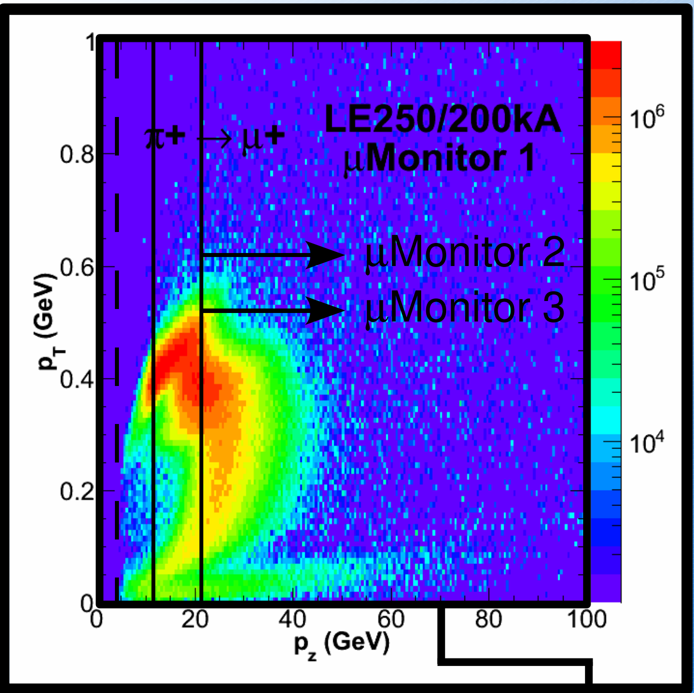
$\varphi_\nu(E_\nu) \leftrightarrow \varphi_\nu(p_T, p_z)$

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



μ Monitor Tuning

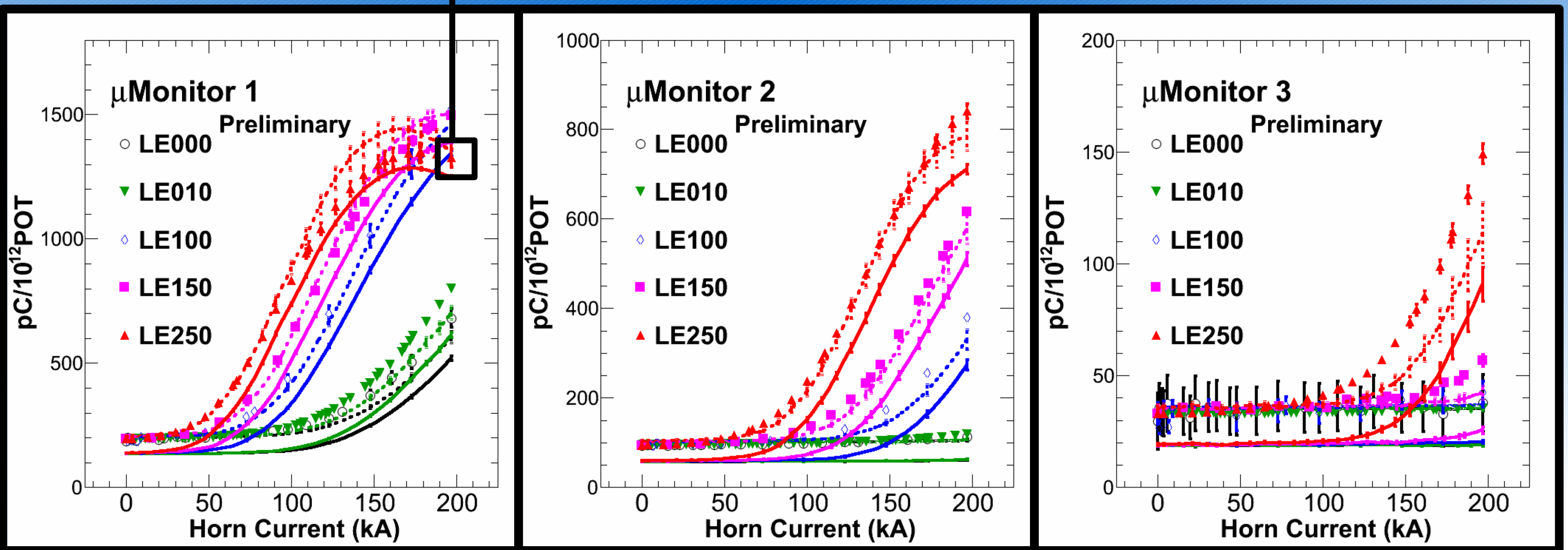
➤ Emperical parameterization for hadron production, f(p_T, p_z). Warp p_T and p_z to tune default MC to μ Monitor data.



• Data

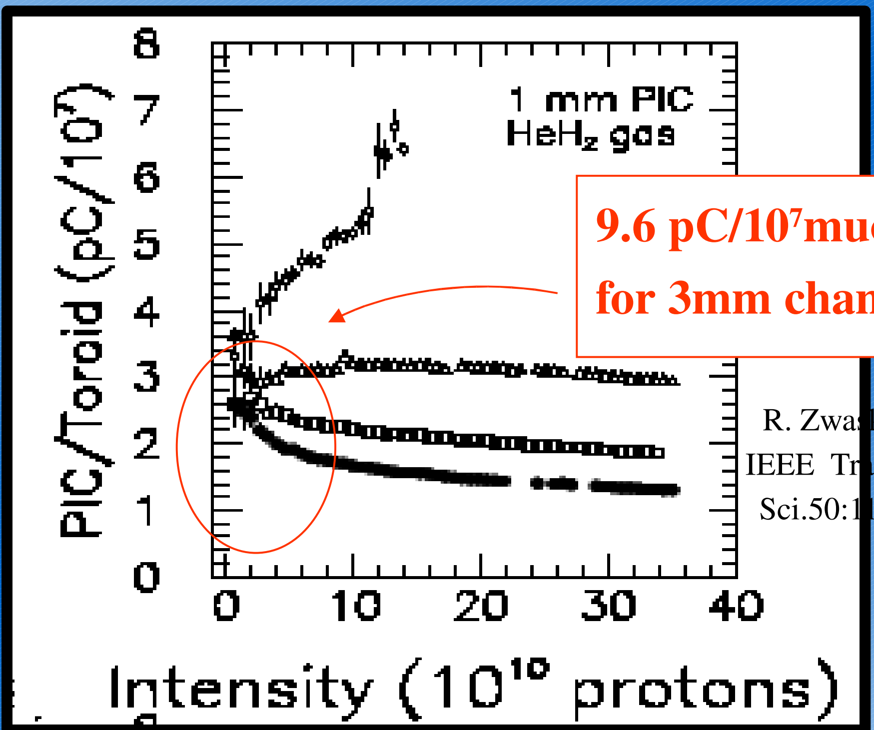
Monte-Carlo (solid line)

Tuned Monte-Carlo (dashed line)

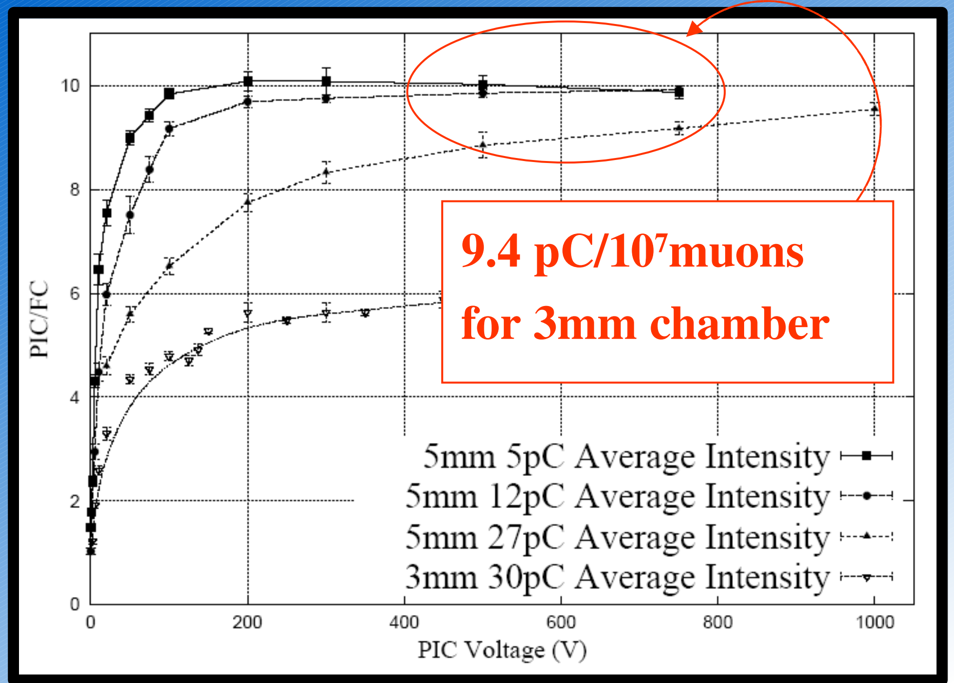


Charge per Muon

- 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)

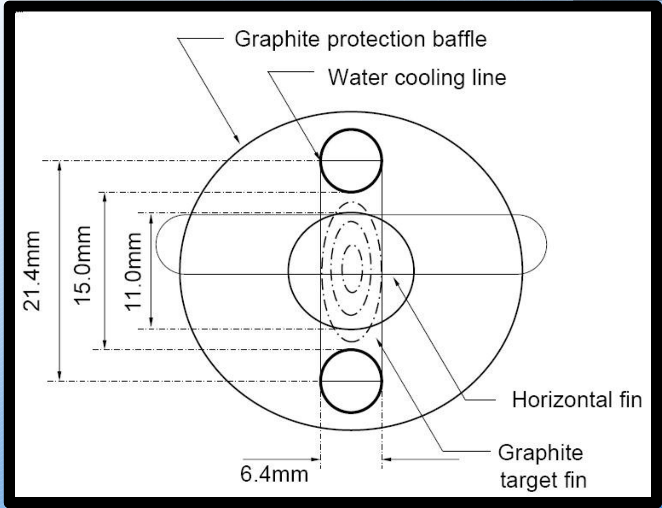


R. Zwaska *et al*, IEEE Trans. Nucl. Sci.50:1112, 2003

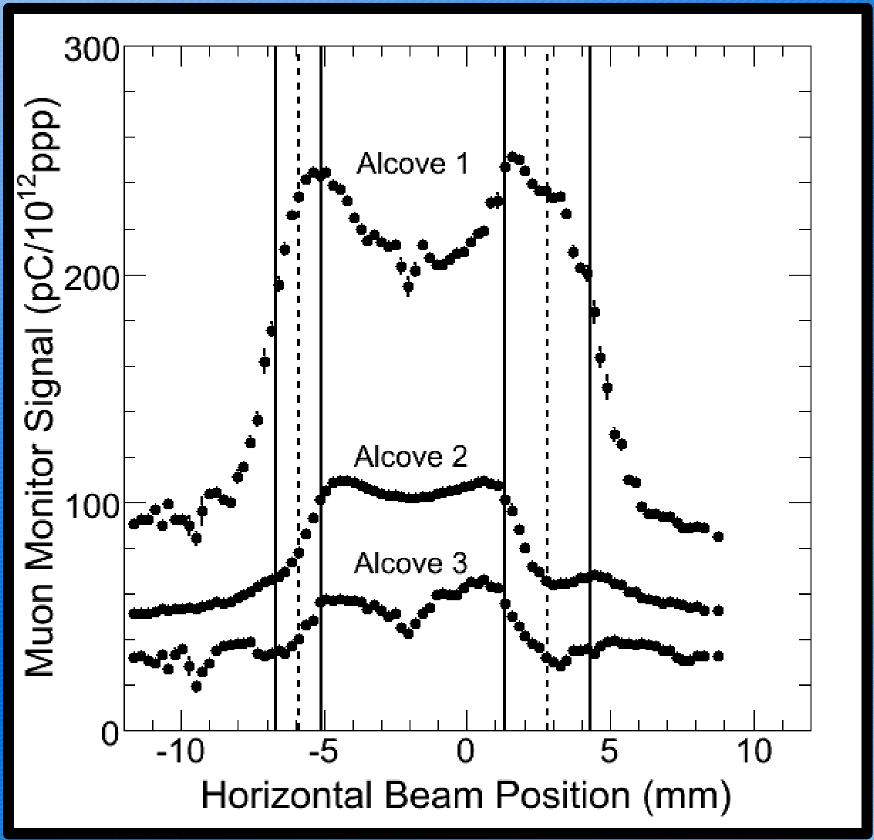


D. Naples *et al*, Nucl.Instrum.Meth.A496:293-304,2003

Dump Backgrounds

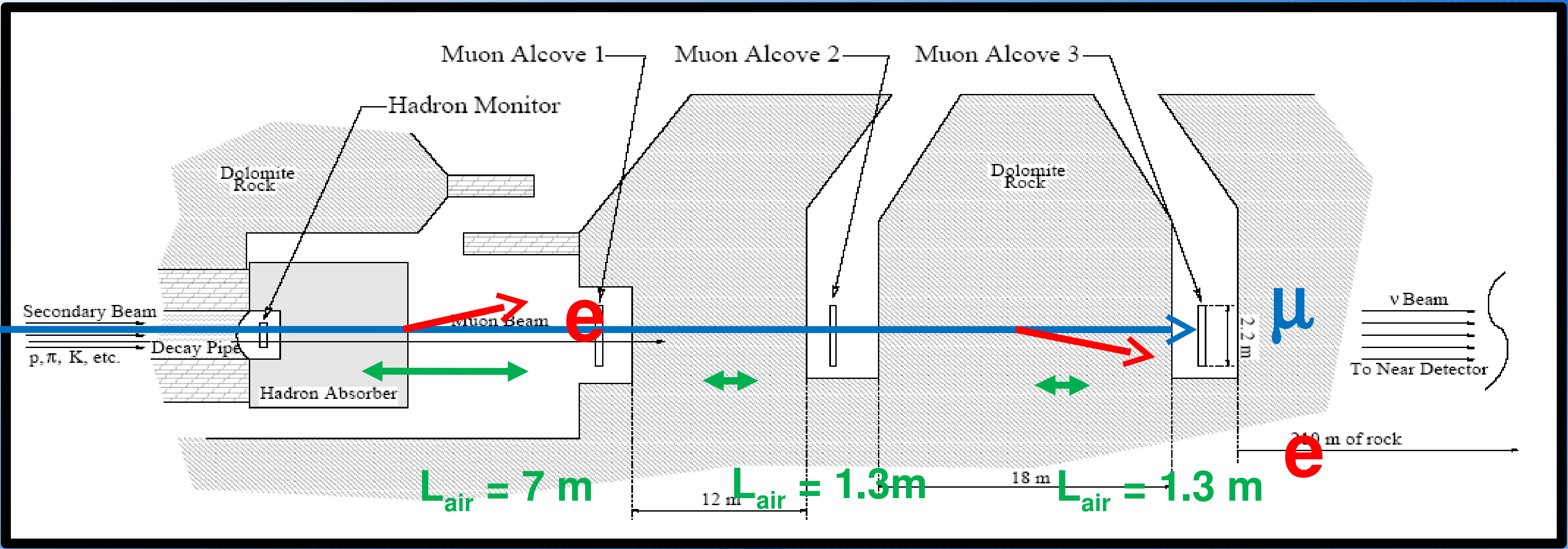


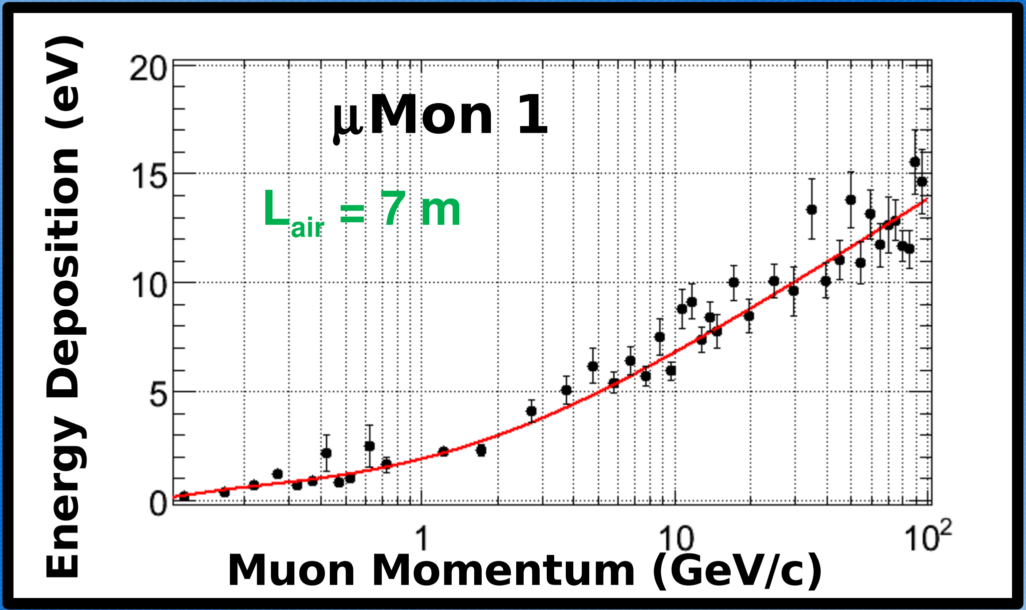
- 13.5% of proton beam doesn't interact in NuMI target ⇒ transported to absorber creating muons, neutrons, gammas.
- Measurements from No-Target spills
- Measurements from Target Scans.
- Take average.

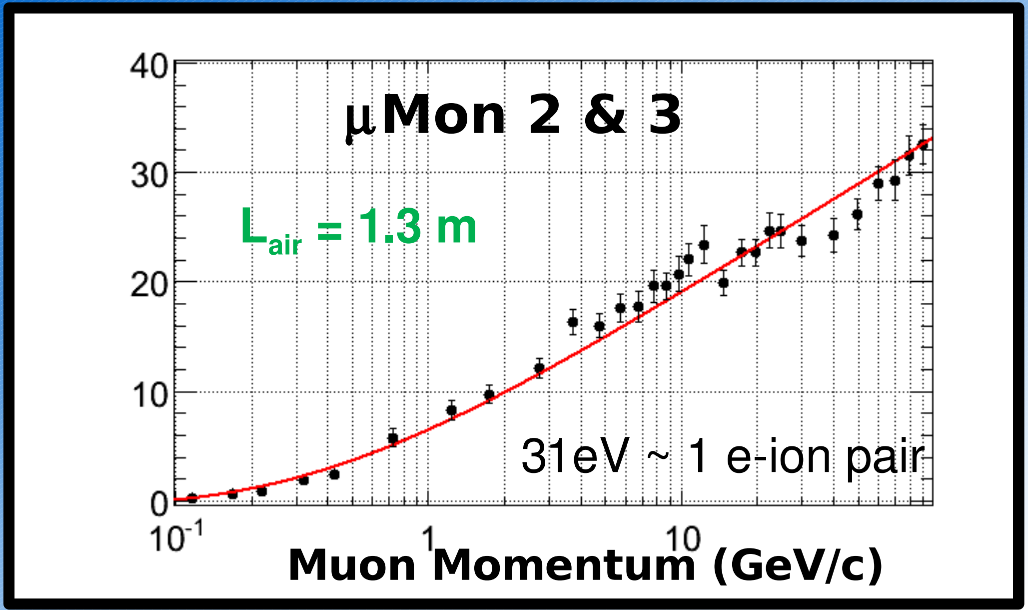


Muon Alcove	Signal Before Gas Corrections ($pC/10^{12}$ ppp)	Signal After Gas Corrections ($pC/10^{12}$ ppp)	Extrapolated to 13.5% Unreacted Proton Beam
	Data from No-Target Spills (Section 4.1)		
1	270 ± 22	251 ± 21	34 ± 3
2	59 ± 5	54 ± 5	7.3 ± 1
3	20 ± 15	12 ± 9	1.6 ± 1.2
	Data from Target Scans (Section 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

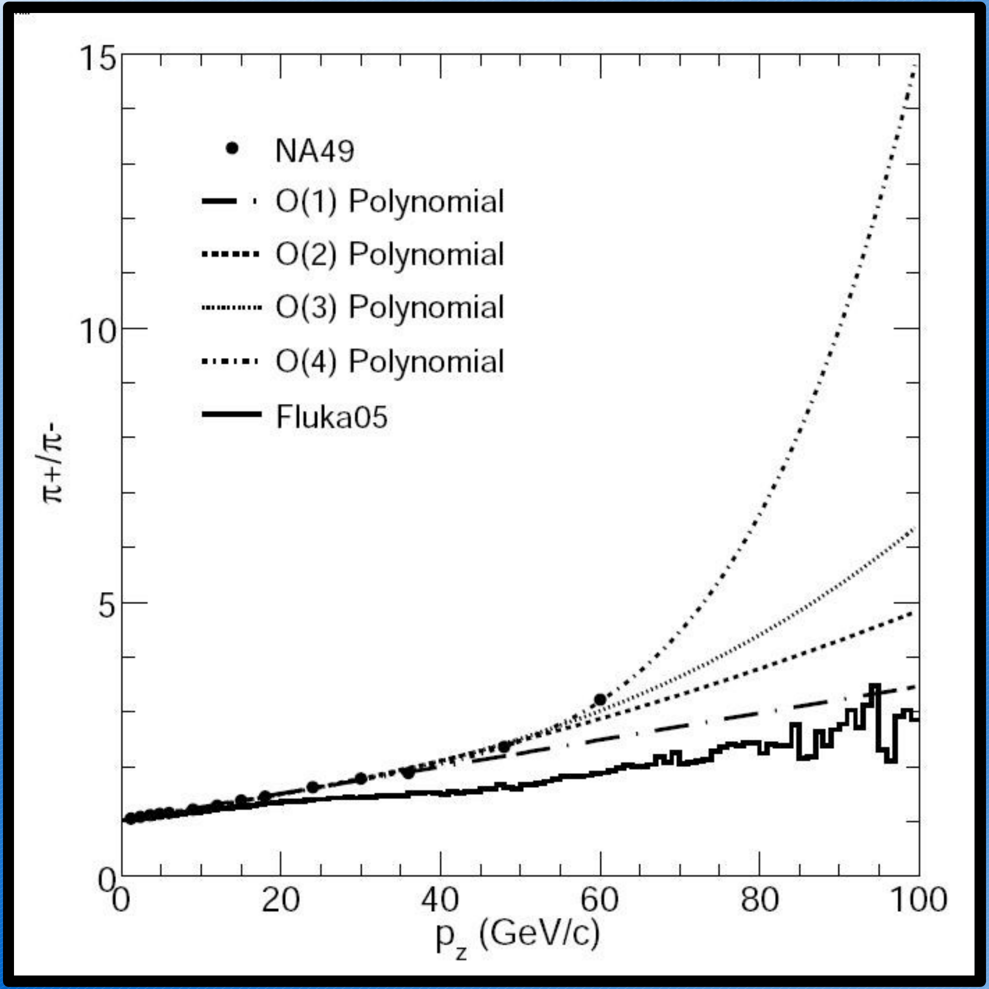
δ-Rays (Knock-On Electrons)







Uncertainties



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