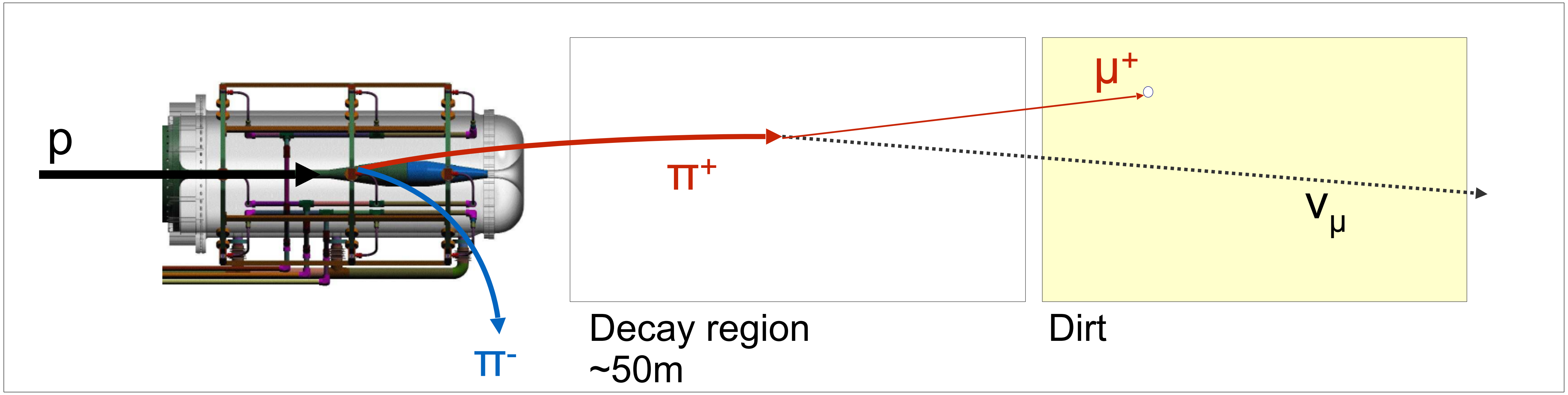
Booster Neutrino Beam

Žarko Pavlović

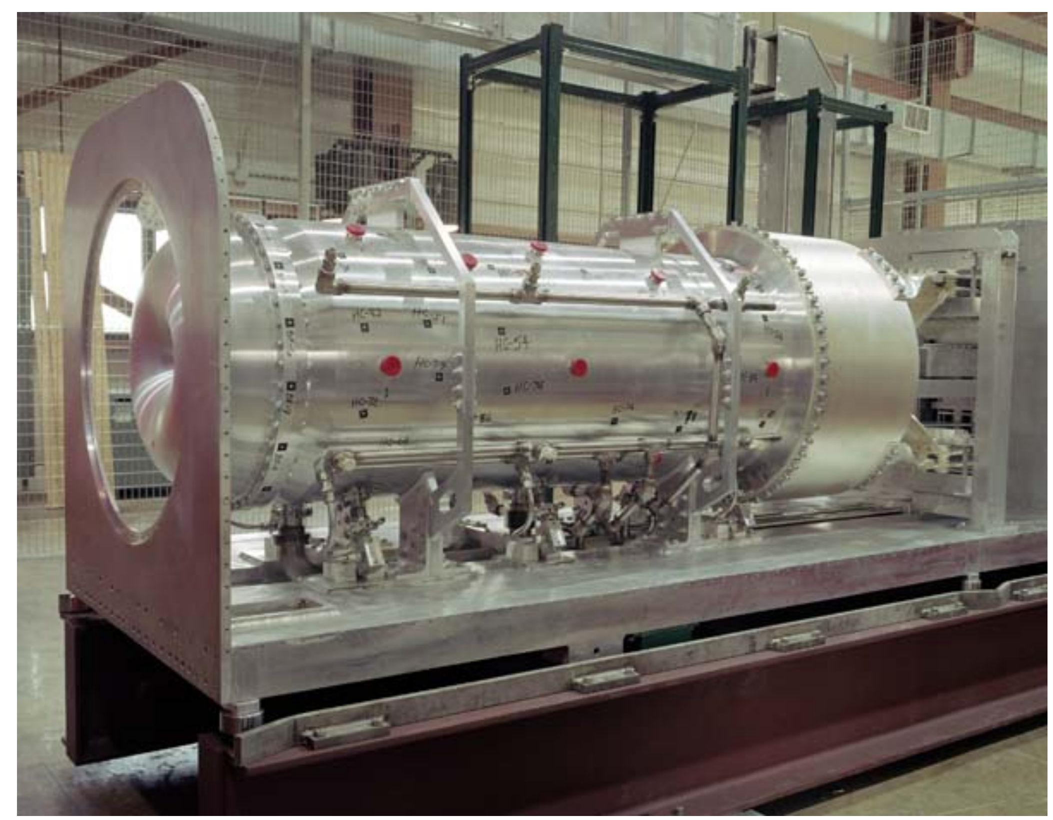
NA61/SHINE at Low Energy

08 December 2020

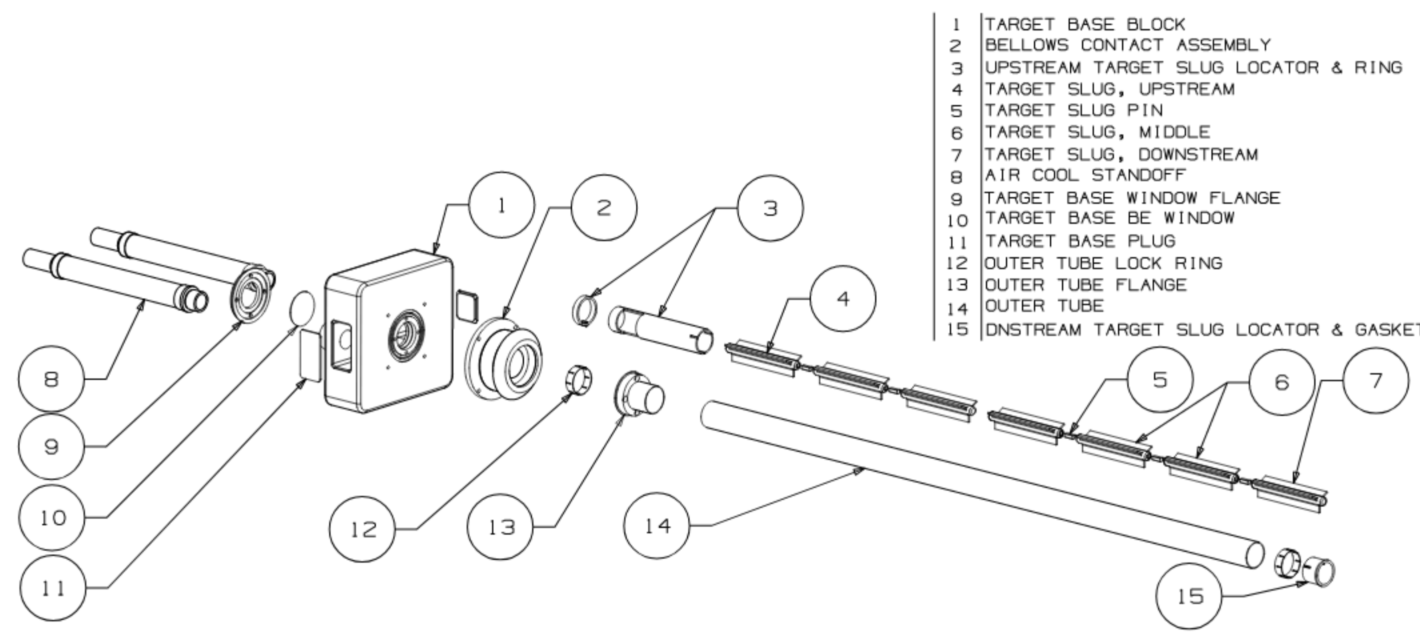
Booster Neutrino Beamline



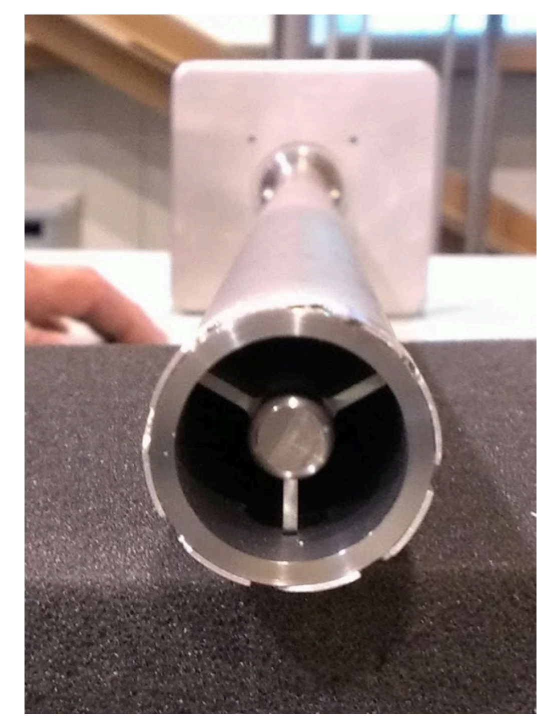
- 8 Gev protons from Booster
  - up to 5Hz and 5e12 protons per pulse
- Beryllium target
- Horn pulsed at 170kA (neutrino and antineutrino mode)
- 50m long decay region



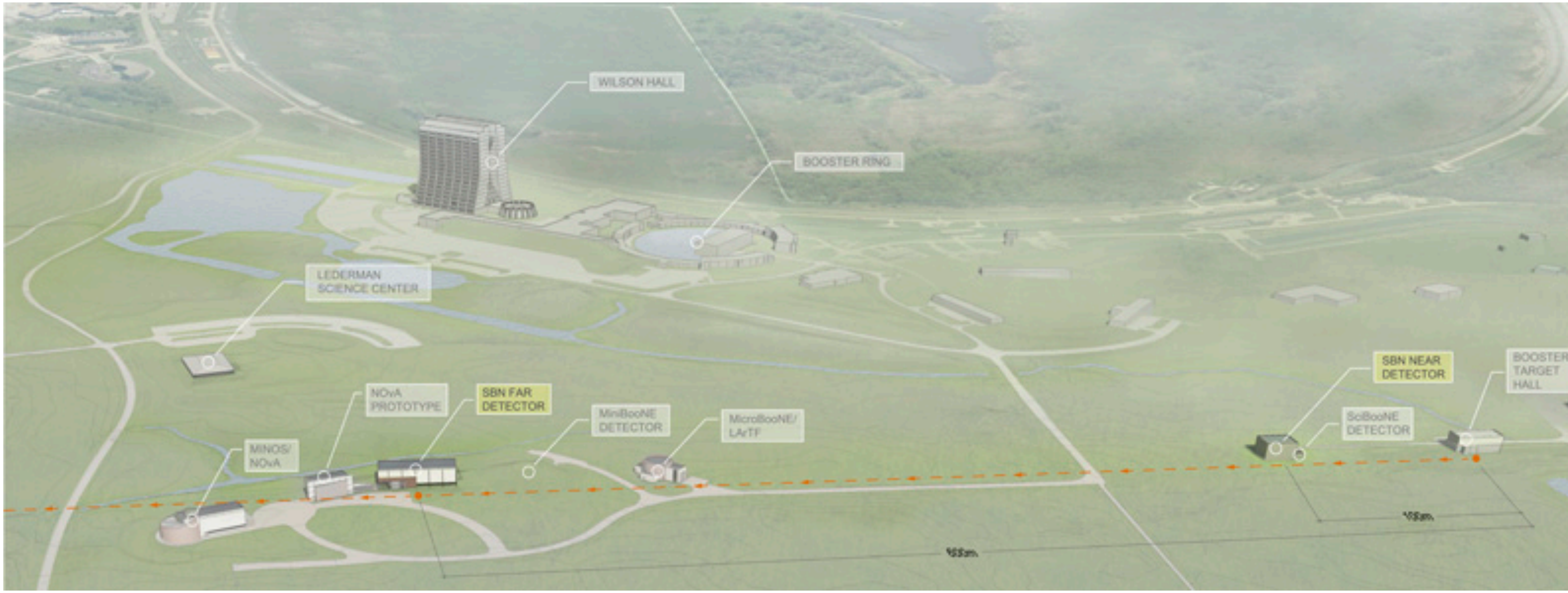
BNB target



- Seven 10.2cm long Beryllium cylindrical slugs with 1cm diameter
- Each slug supported by 3 supporting fins within the Be container
- Air cooled

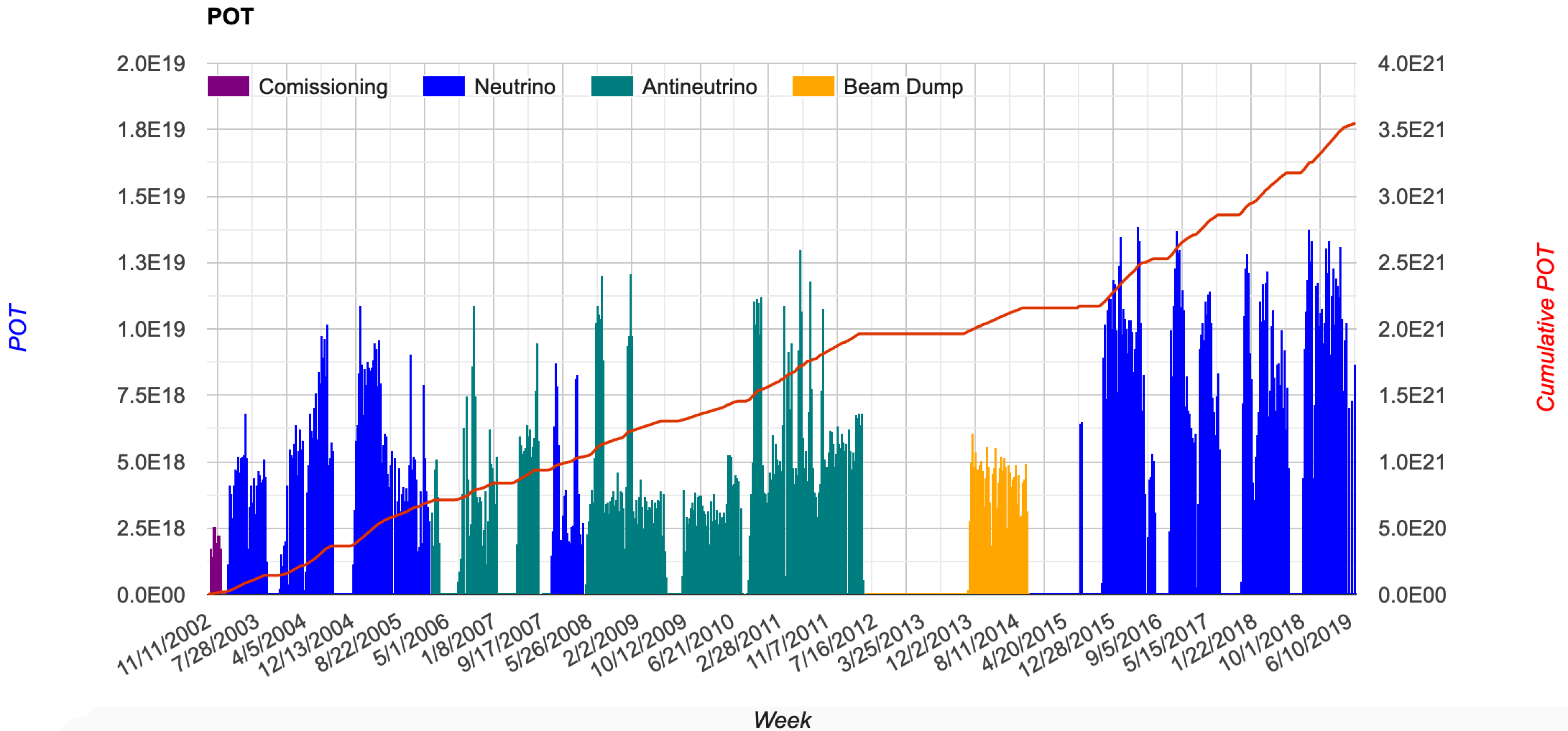


BNB experiments



- Experiments
  - MiniBooNE, SciBooNE, SciBath, MicroBooNE, ANNIE, ICARUS, SBND
- Physics goals
  - Sterile neutrino searches, Neutrino cross sections in 1GeV region, Dark matter searches, neutron flux

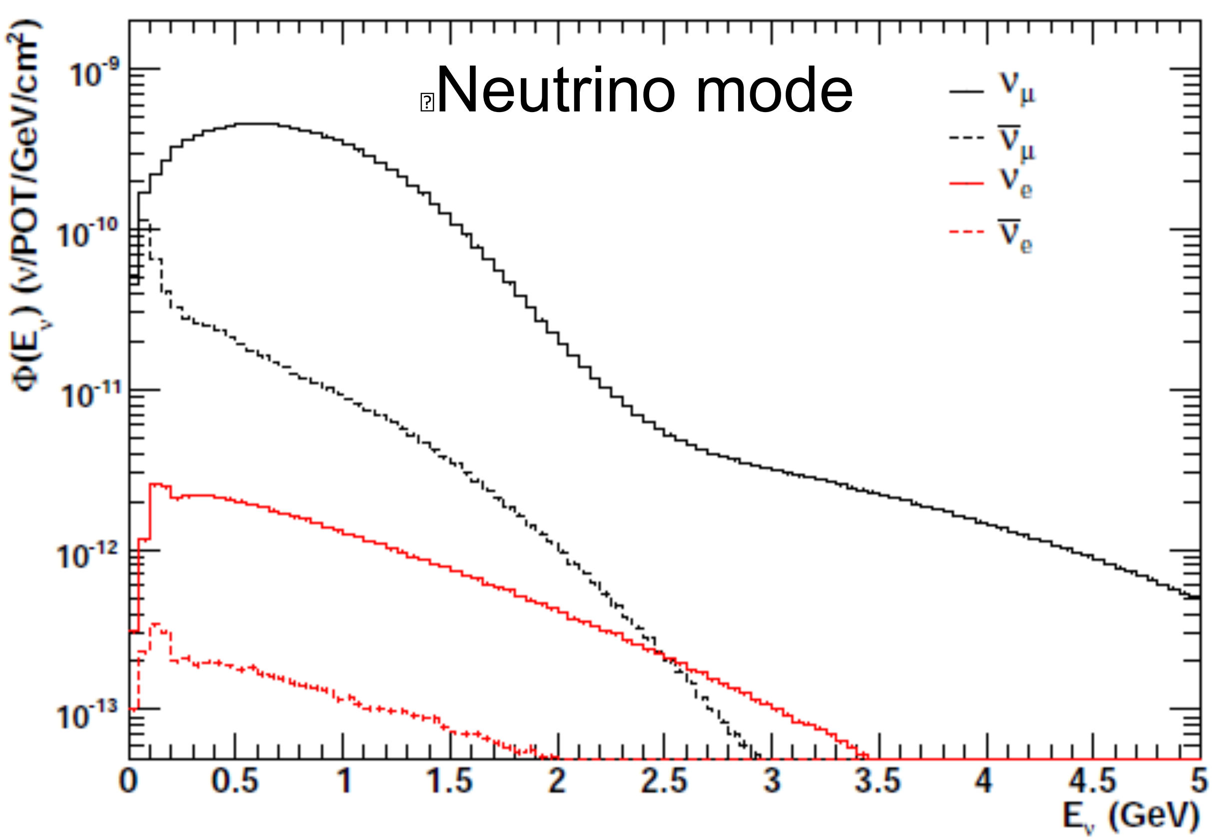
18 years of running



- Still more to come

Neutrino mode flux (MiniBooNE)

- Flux calculation based upon the geant4 simulation
- Many of the processes constrained with external data

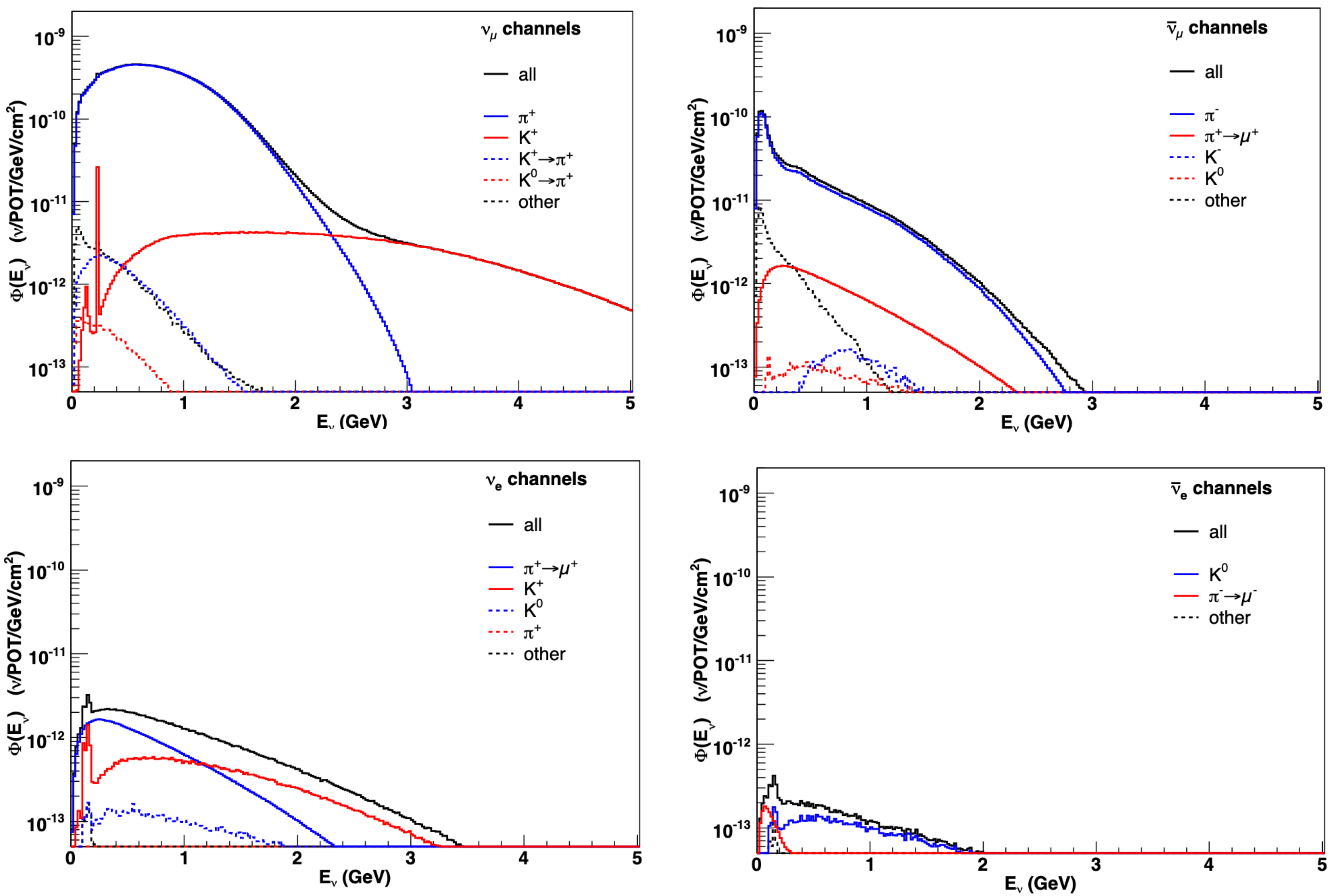


	ν_μ		$\overline{\nu}_\mu$	
Flux (ν/ cm^2/POT)		5.19×10^{-10}		3.26×10^{-11}
Frac. of Total		93.6%		5.86%
Composition	π^+:	96.72%	π^-:	89.74%
	K^+:	2.65%	$\pi^+ \to \mu^+$:	4.54%
	$K^+ \to \pi^+$:	0.26%	K^-:	0.51%
	$K^0 \to \pi^+$:	0.04%	K^0:	0.44%
	K^0:	0.03%	$K^0 \to \pi^-$:	0.24%
	$\pi^- \to \mu^-$:	0.01%	$K^+ \to \mu^+$:	0.06%
	Other:	0.30%	$K^- \to \pi^-$:	0.03%
			Other:	4.43%

	ν_e		$\overline{\nu}_e$	
Flux (ν/ cm^2/POT)		2.87×10^{-12}		3.00×10^{-13}
Frac. of Total		0.52%		0.05%
Composition	$\pi^+ \to \mu^+$:	51.64%	K^0_L:	70.65%
	K^+:	37.28%	$\pi^- \to \mu^-$	19.33%
	K^0_L:	7.39%	K^-:	4.07%
	π^+:	2.16%	π^-:	1.26%
	$K^+ \to \mu^+$:	0.69%	$K^- \to \mu^-$:	0.07%
	Other:	0.84%	Other:	4.62%

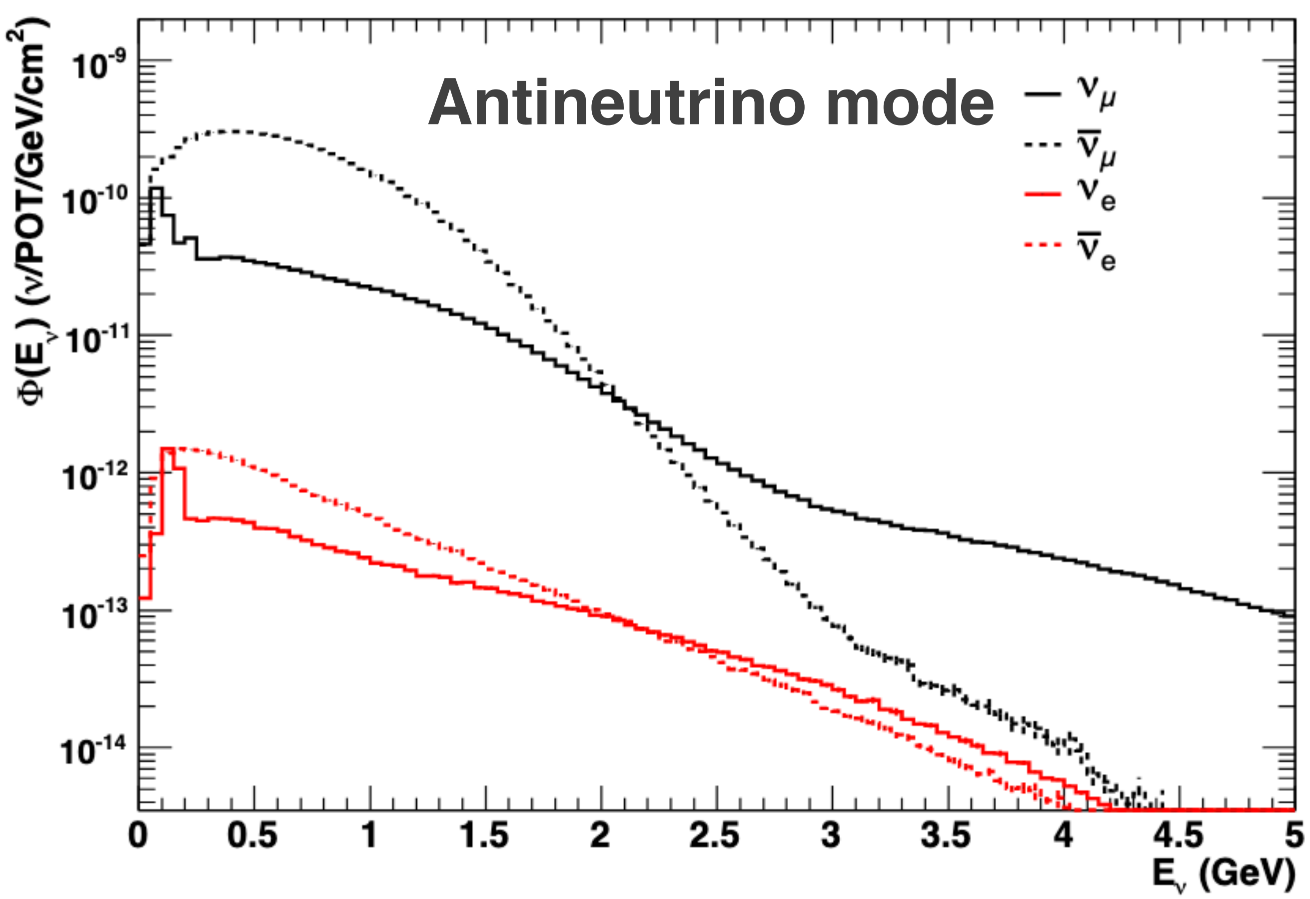
Phys. Rev. D79, 072002 (2009)

Neutrino mode flux (MiniBooNE)



Antineutrino mode flux (MiniBooNE)

- Flux calculation based upon the geant4 simulation
- Processes constrained with data where available
- Notable difference is that ν_μ (wrong sign) much more pronounced

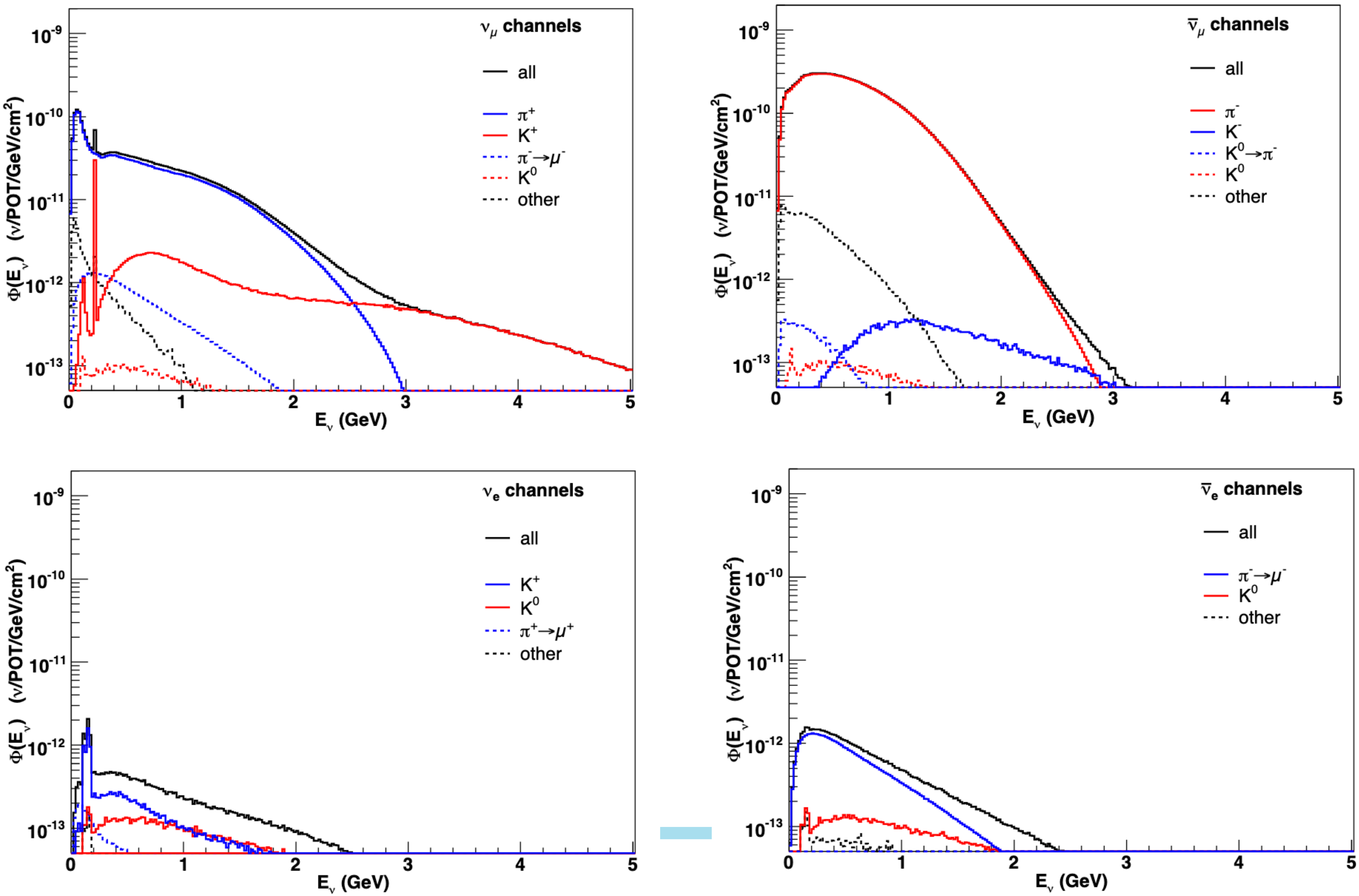


	ν_μ		$\overline{\nu}_\mu$	
Flux (ν/ cm^2/POT)		5.42×10^{-11}		2.93×10^{-10}
Frac. of Total		15.71%		83.73%
Composition	π^+:	88.79%	π^-:	98.4%
	K^+:	7.53%	K^-:	0.18%
	$\pi^- \to \mu^-$:	1.77%	$K^0 \to \pi^-$:	0.05%
	K^0:	0.26%	K^0:	0.05%
	Other:	2.00%	$\pi^+ \to \mu^+$:	0.03%
			$K^- \to \pi^-$:	0.02%
			Other:	1.30%

	ν_e		$\overline{\nu}_e$	
Flux (ν/ cm^2/POT)		6.71×10^{-13}		1.27×10^{-12}
Frac. of Total		0.2%		0.4%
Composition	K^+ :	51.72%	$\pi^- \to \mu^-$:	75.67%
	K^0 :	31.56%	K^0:	16.51%
	$\pi^+ \to \mu^+$	13.30%	K^-:	3.08%
	π^+ :	0.83%	π^-:	2.58%
	$K^+ \to \mu^+$:	0.41%	$K^- \to \mu^-$:	0.06%
	Other:	2.17%	Other	2.10%

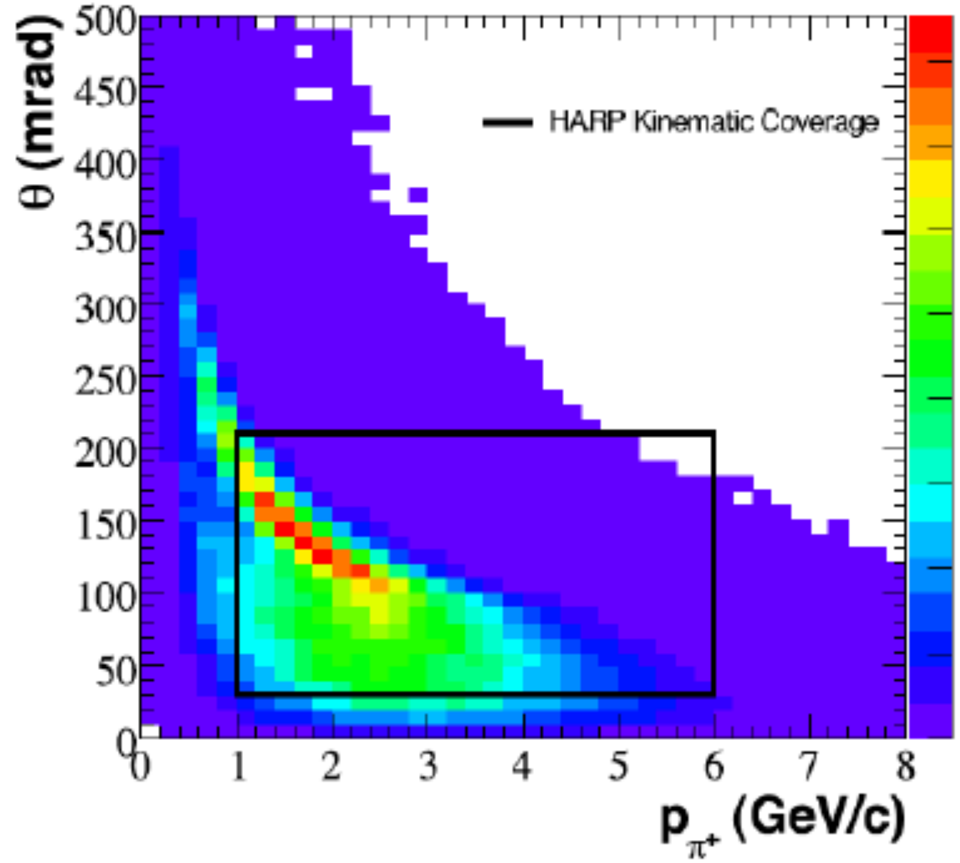
Phys. Rev. D79, 072002 (2009)

Antineutrino mode flux (MiniBooNE)



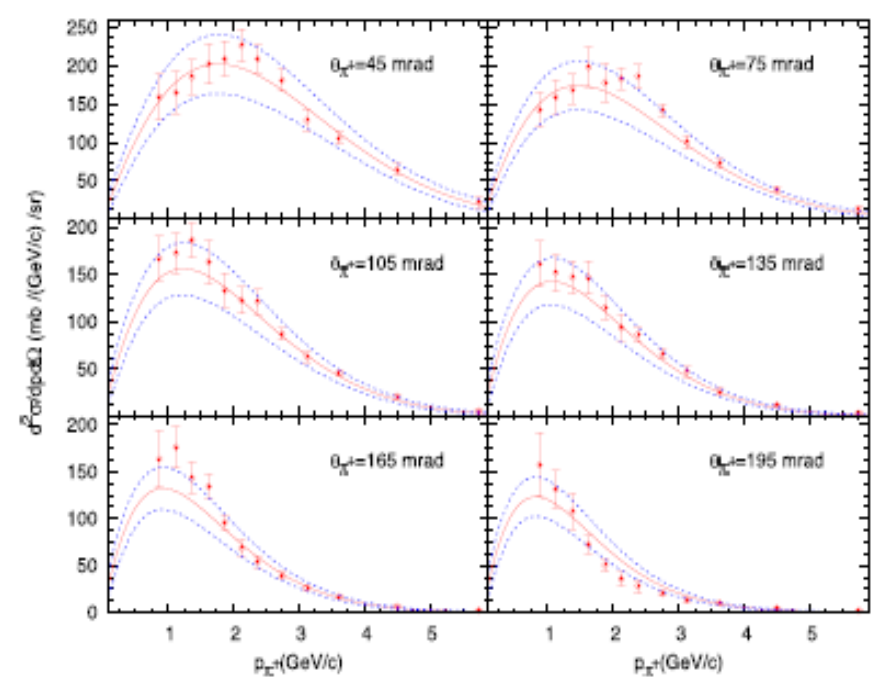
Pion production

- Sanford-Wang fits:
  - HARP (thin target)
    - 8.89GeV p on Be target
    - P = 0.85 - 6.5 GeV/c
    - θ = 30 - 210 mead
  - E910
    - 6.4, 12.3, 17.5 GeV/c
    - P = 0.4 - 5.6 GeV/c
    - θ = 18 - 400 mead



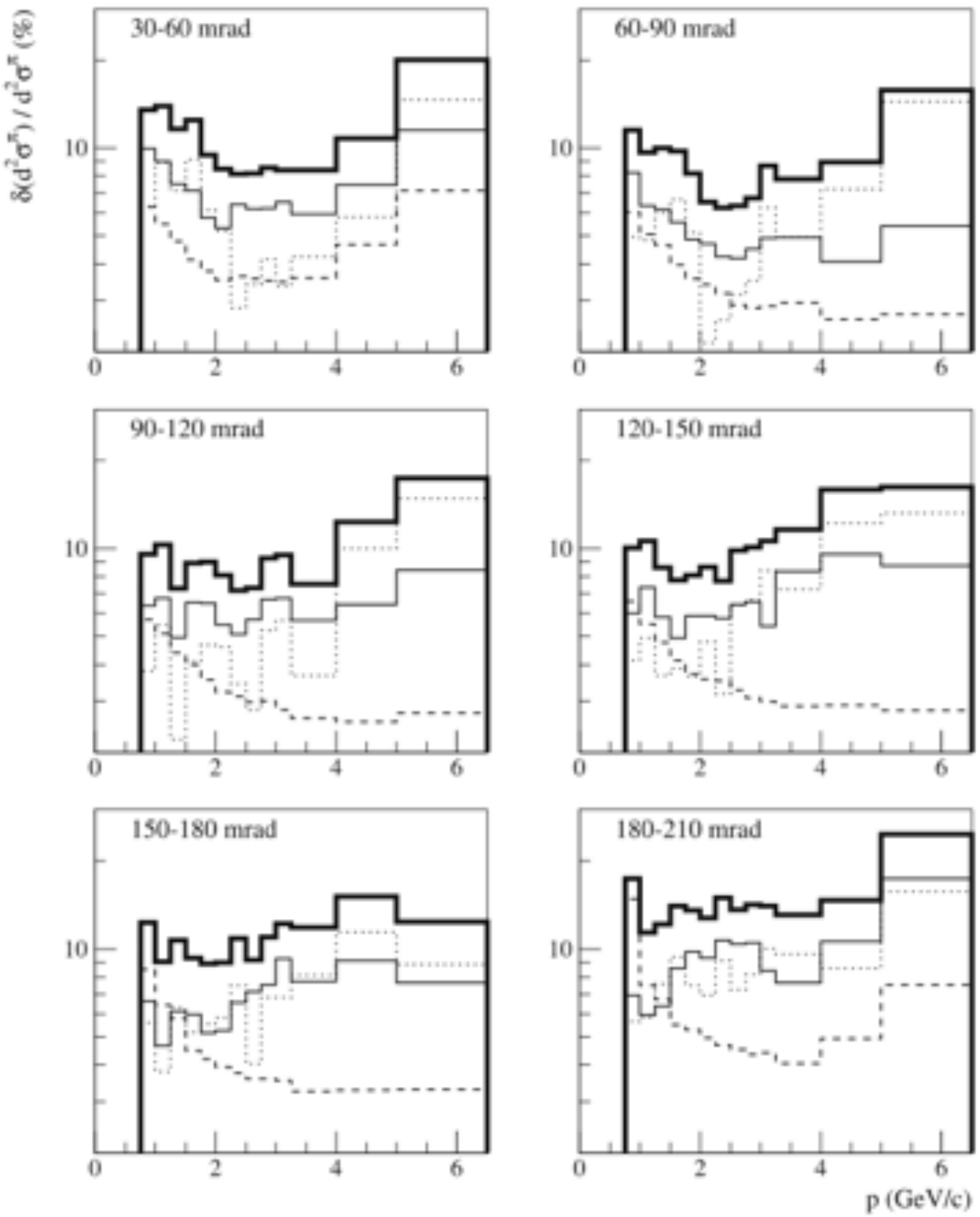
- Fits done both to π^+ and π^- production data

- Harp data covers phase space contributing to 78% of neutrino flux from π^+ (76% from π^- in antineutrino mode)

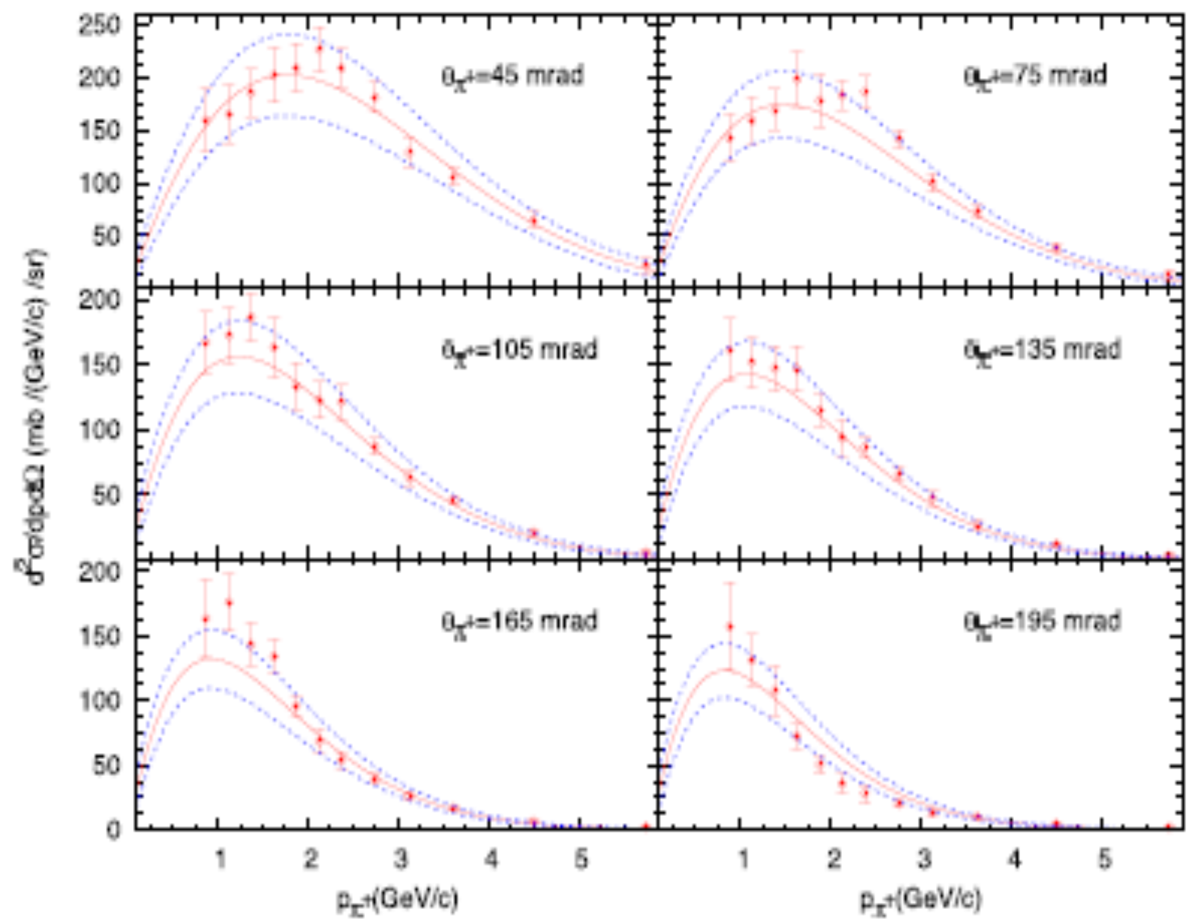


Phys. Rev. D79, 072002 (2009)

HARP



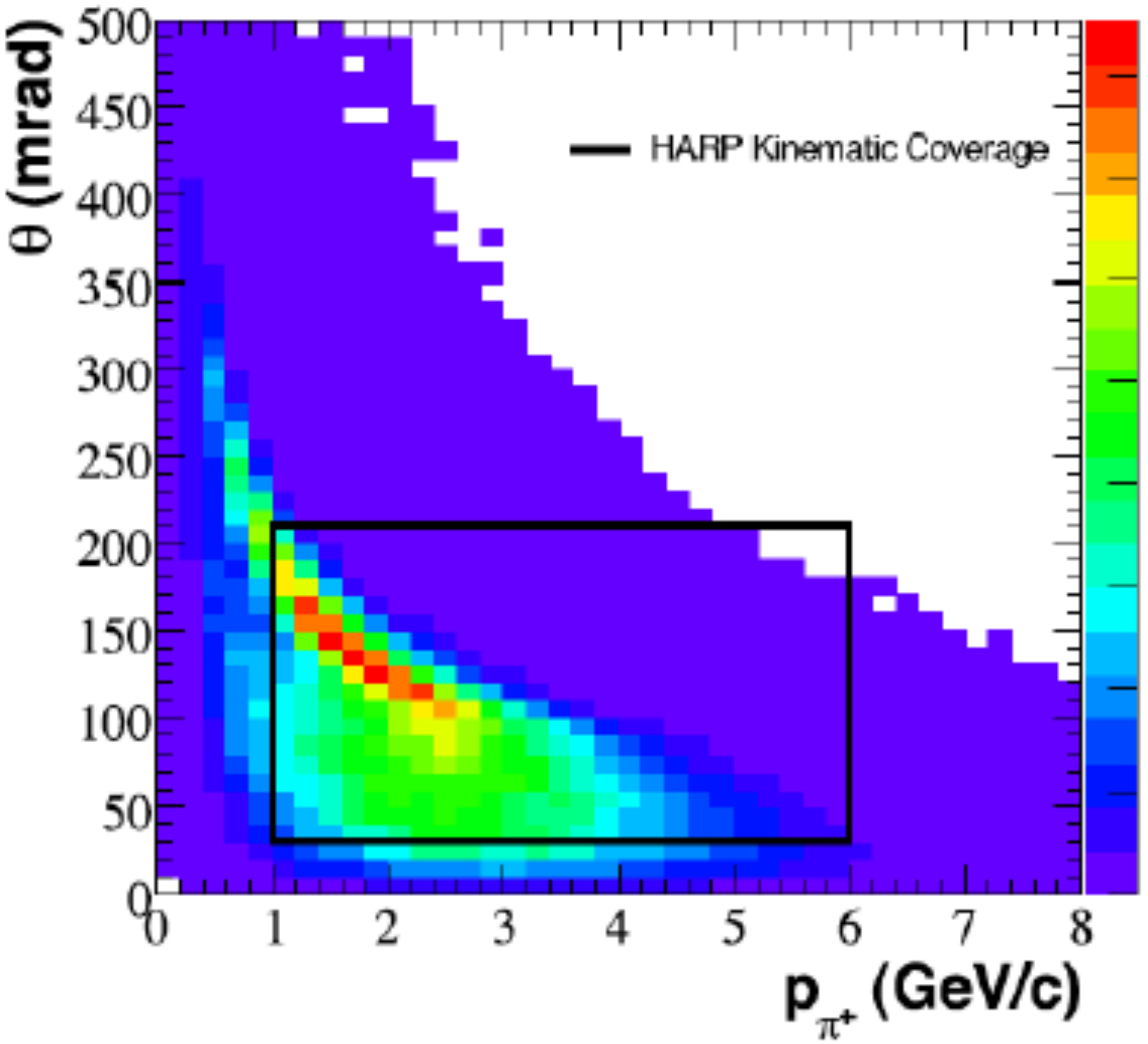
- Probably hard to improve in the region already constrained by HARP

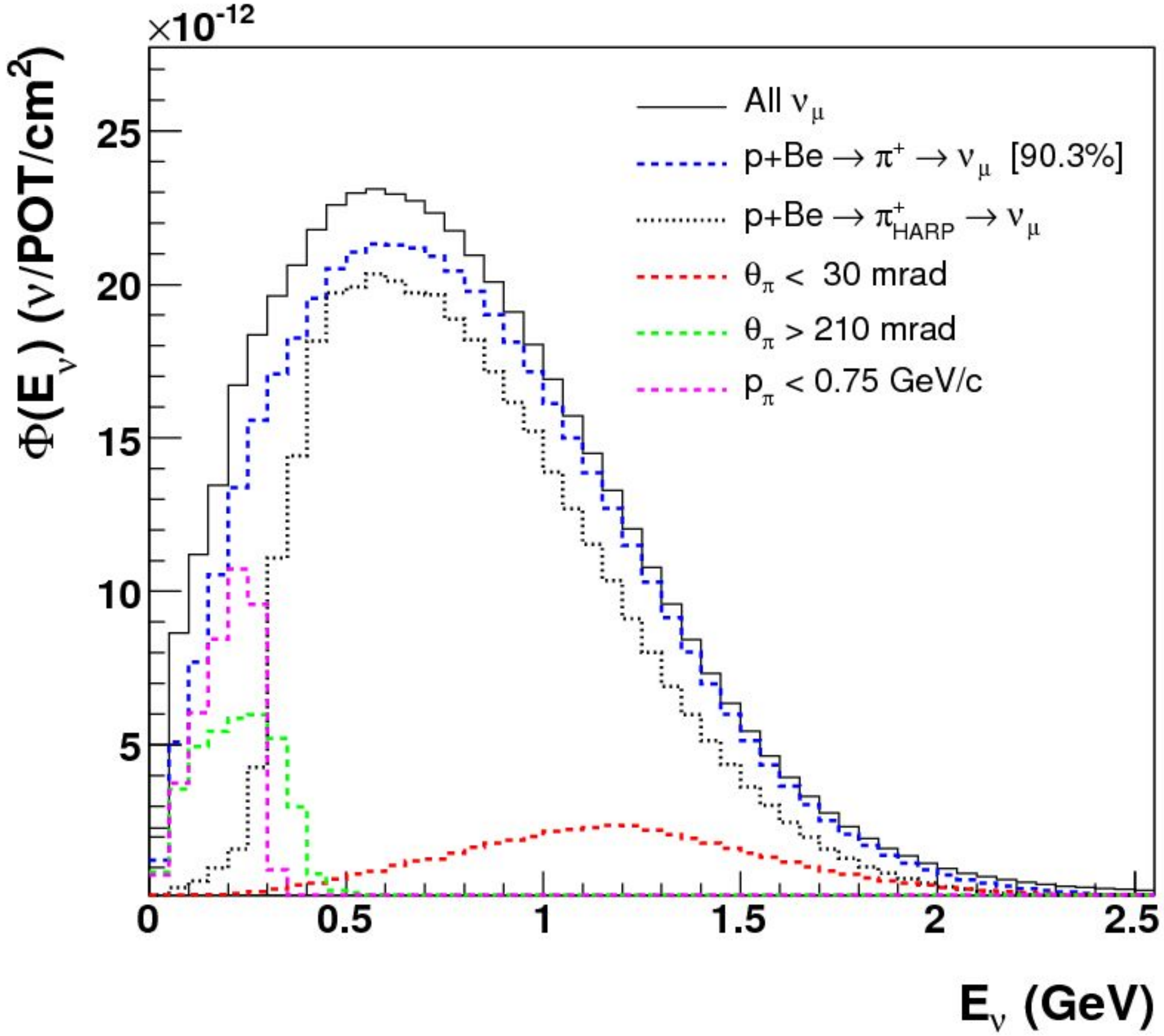


D. Schmitz, PhD thesis

HARP coverage

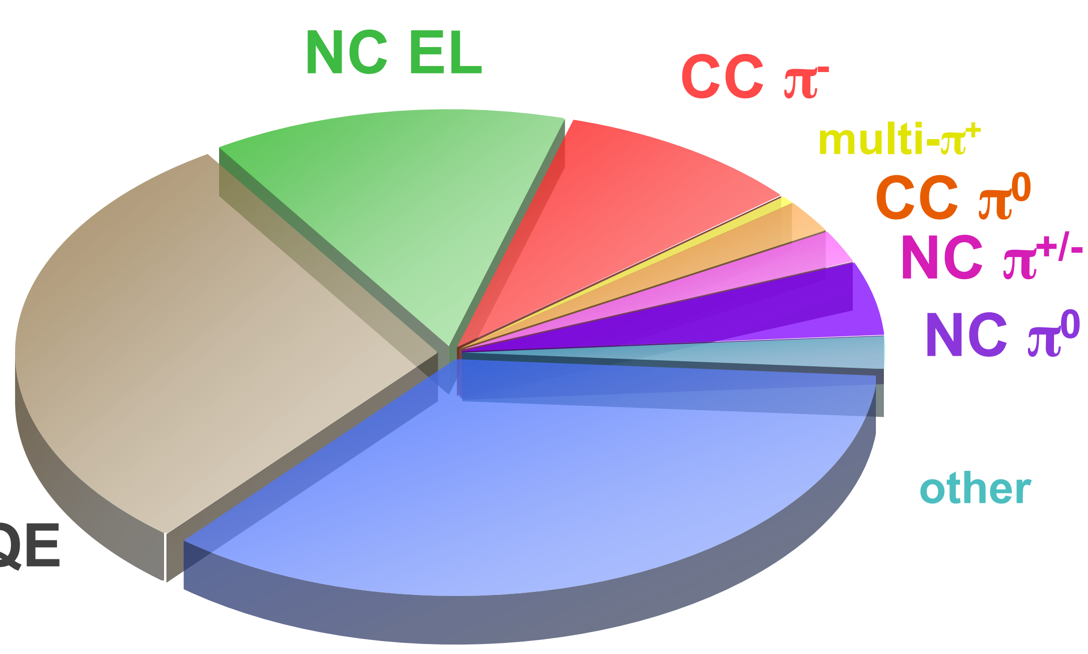
- Neutrino mode
  - 90% of numu flux from p+Be->pi+->numu
  - 78% of flux from pi+ covered by HARP measurement



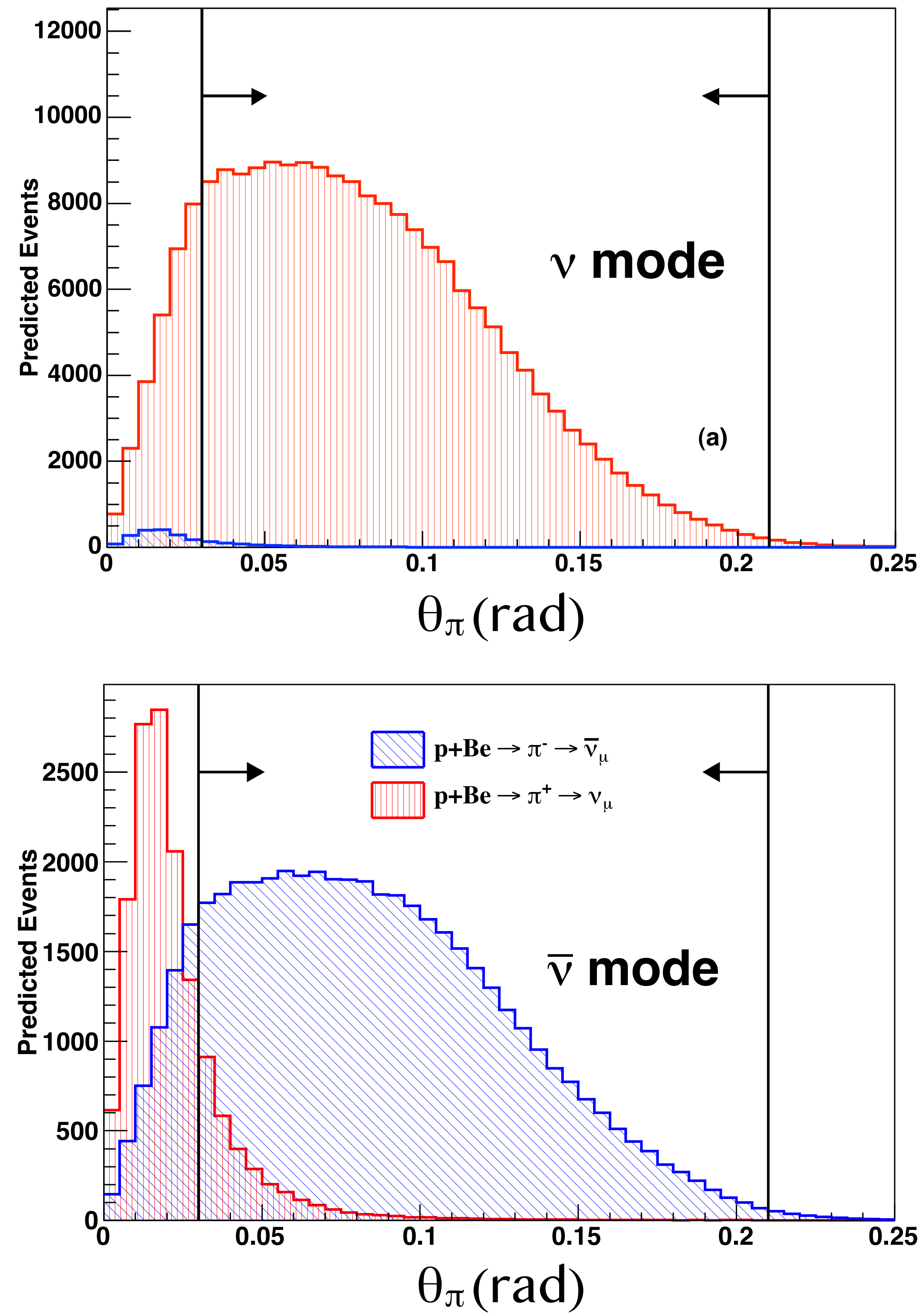


Wrong signs

- In neutrino mode $\bar{\nu}_\mu$ events are not significant, however in antineutrino mode ν_μ events are
- ν_μ parent π^+ contributing to events in antineutrino mode largely not constrained by HARP



Antineutrino mode

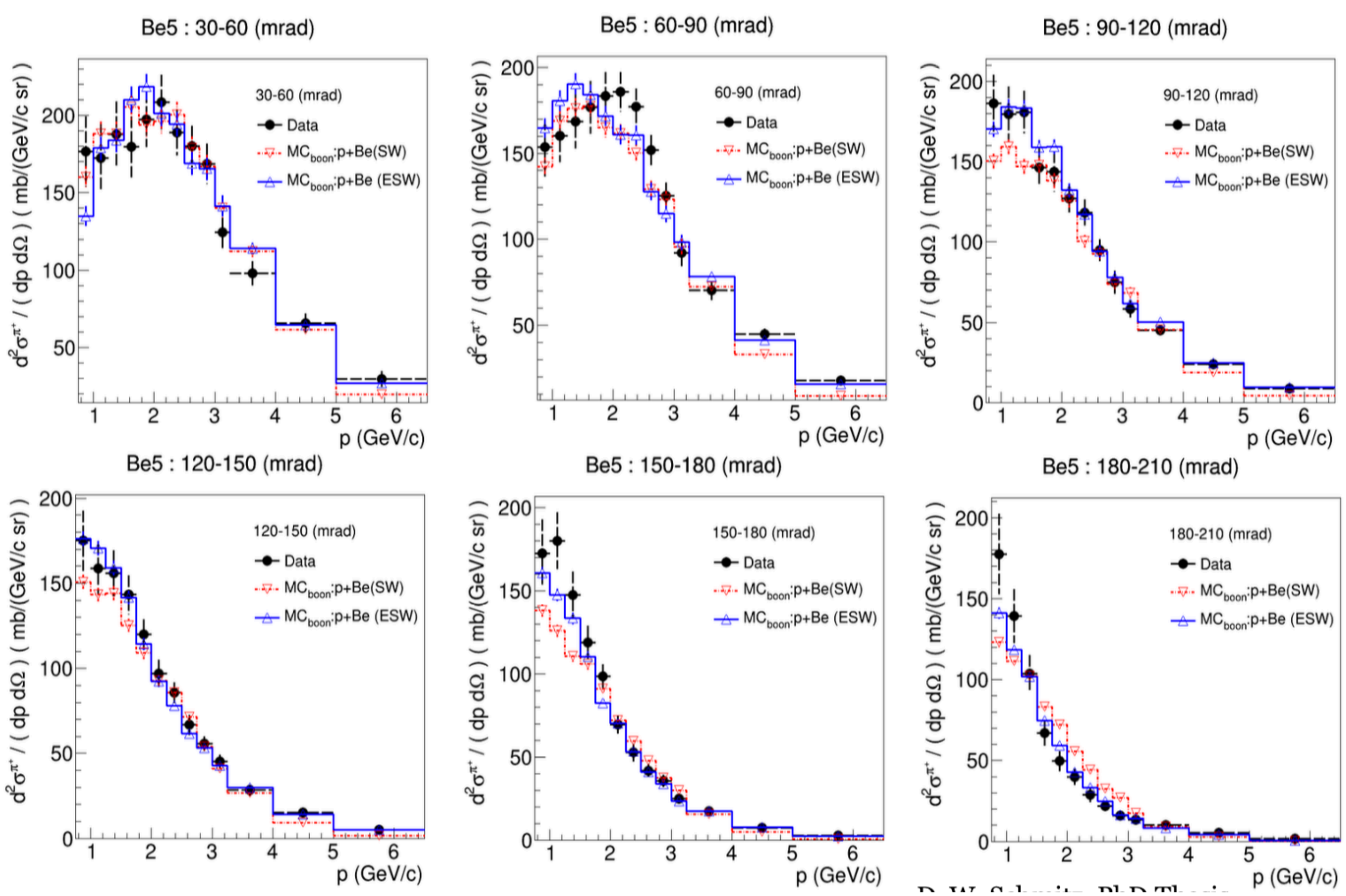


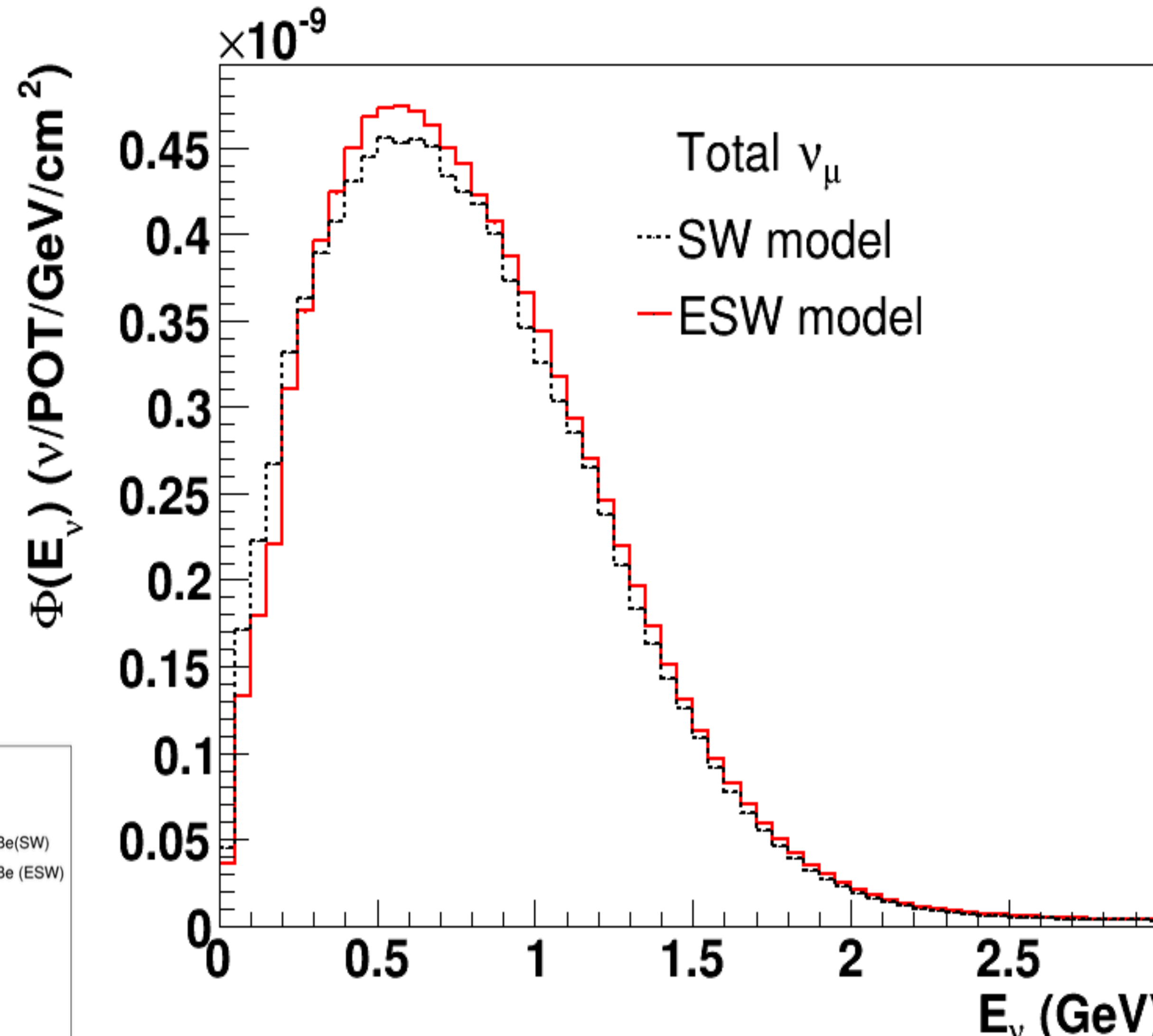
Phys. Rev. D84, 072005 (2011)

Extended Sanford Wang model

- Current BNB simulation based on the old SW parameterization

- Using extended SW model improves fit to HARP data





- Overall 2% change in neutrino flux

M. G. Catanesi, et al., Eur.Phys.J.C C52 (2007) 29-53.

A. Wickremasinghe, PhD thesis

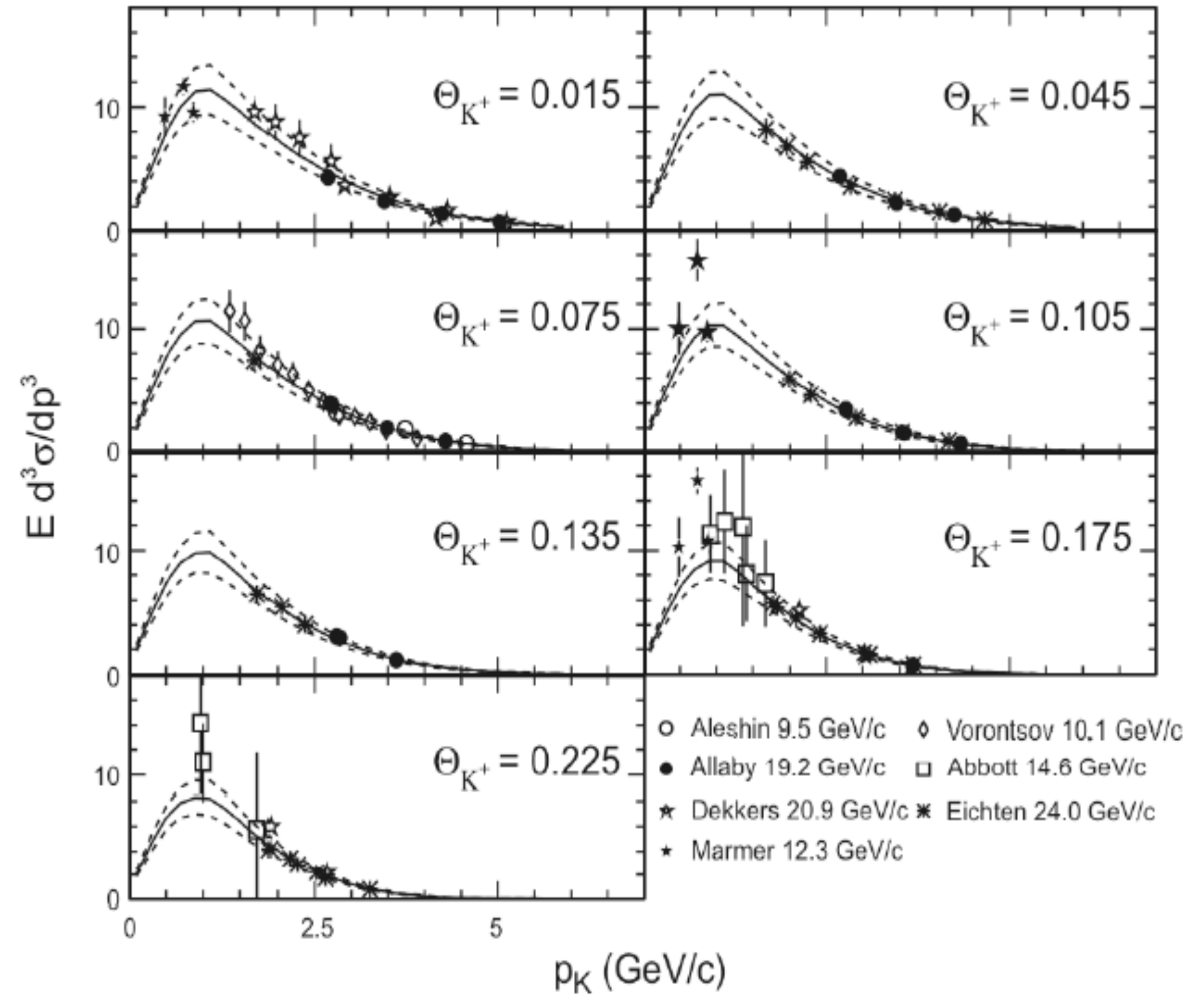
Fermilab

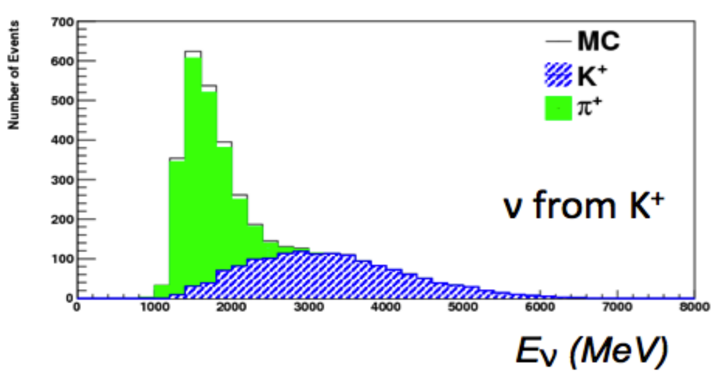
K⁺ production

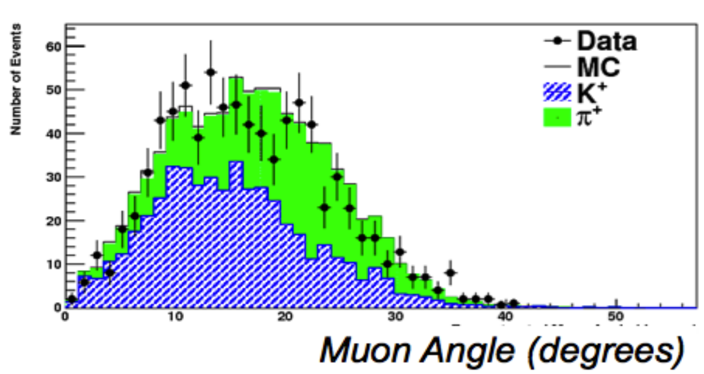
- Global data fit using Feynman scaling based parameterization
- Further constrained by SciBooNE measurement of kaons in BNB

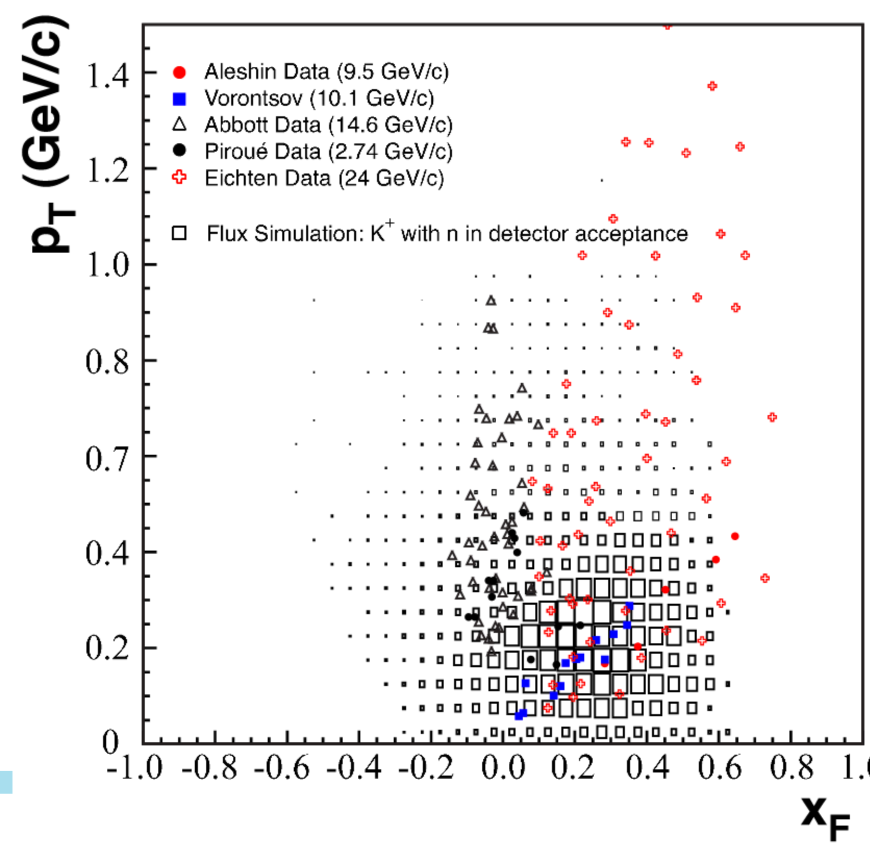
Phys. Rev. D84, 114021 (2011)

Phys. Rev. D84, 012009 (2011)





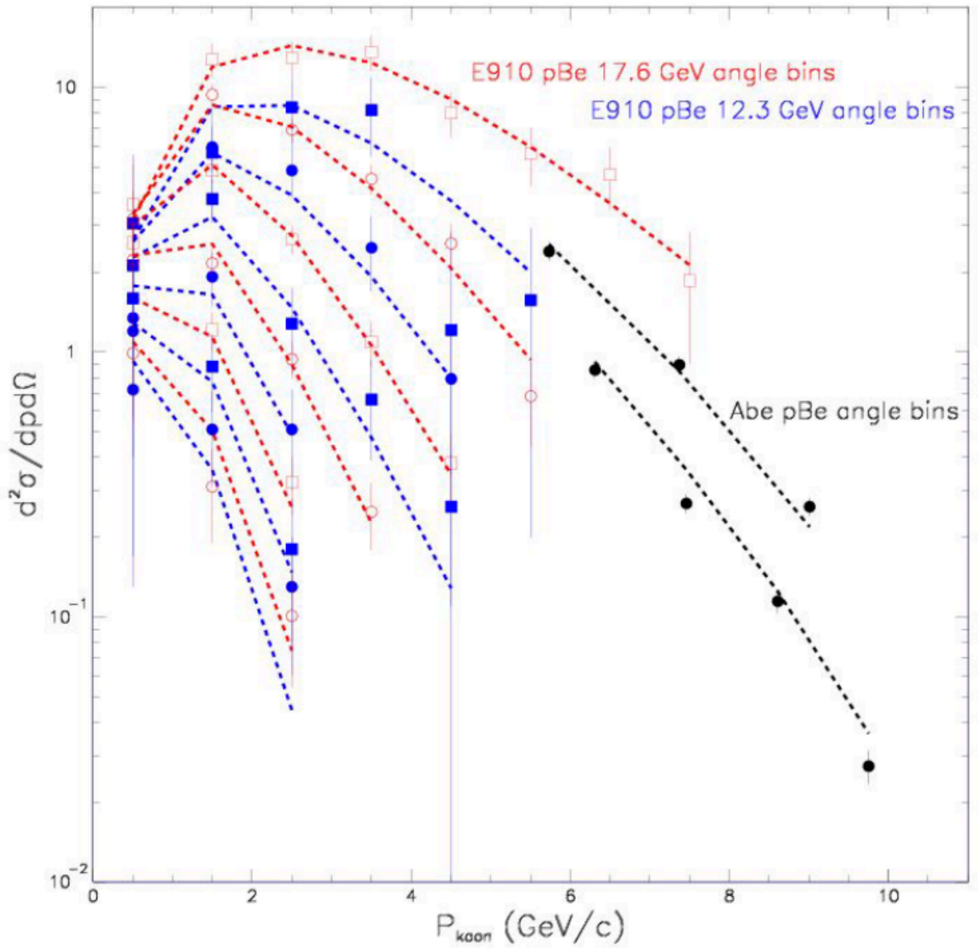




Fermilab

Neutral kaons and K^-

- Sanford-Wang fits to K^0_S production data
  - BNL E910 experiment (p_{beam}= 12.3 and 17.5 GeV/c)
  - KEK Abe et al. (12.3 GeV/c)
- Forward production important and not entirely covered by data, but the two data sets combined constrain the production via SW fit



- K^- production from MARS
  - negligible contribution to neutrino flux

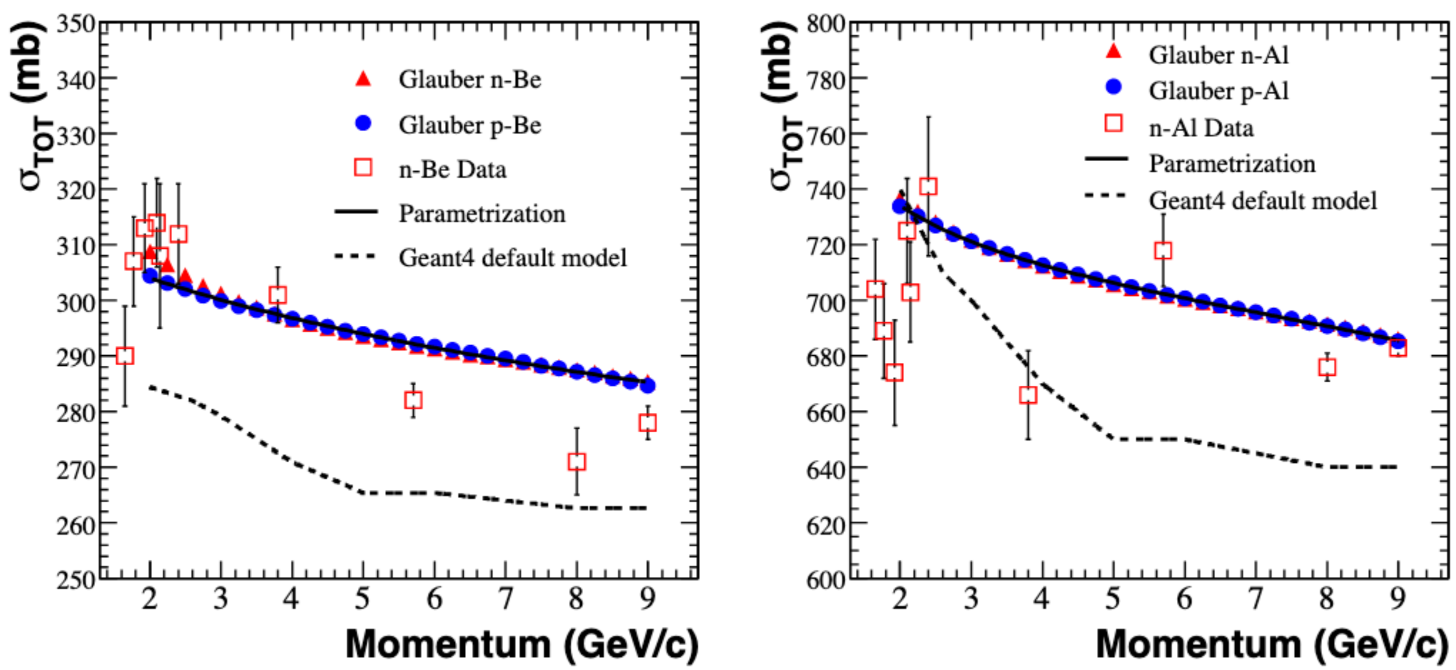
Fermilab

Hadronic interactions

- Hadronic cross sections on beryllium and aluminum constrained with data where available - total, inelastic & quasi-elastic

- Elastic cross section calculated by subtracting measured inelastic from total calculated using Glauber model

	p-(Be/Al)	n-(Be/Al)	$\pi^{\pm}$-(Be/Al)
σ_{TOT}	Glauber	Glauber	Data ($p < 0.6/0.8$ GeV/c)
		(checked with data)	Glauber ($p > 0.6/0.8$ GeV/c)
σ_{INE}	Data	(same as p-Be/Al)	Data
σ_{QEL}	Shadow	Shadow	Data ($p < 0.5$ GeV/c)
			Shadow ($p > 0.5$ GeV/c)

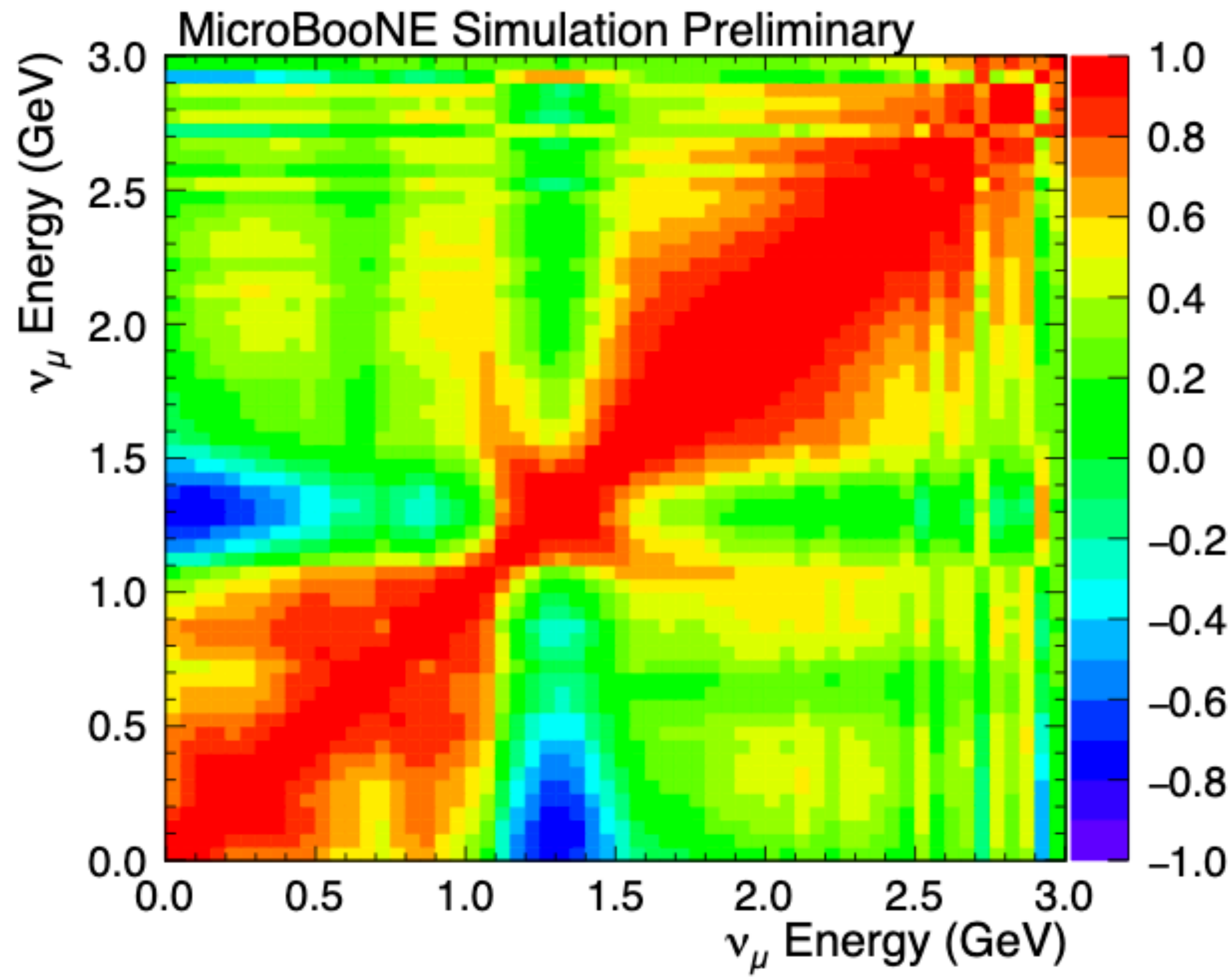


Phys. Rev. D79, 072002 (2009)

Fermilab

Flux uncertainty

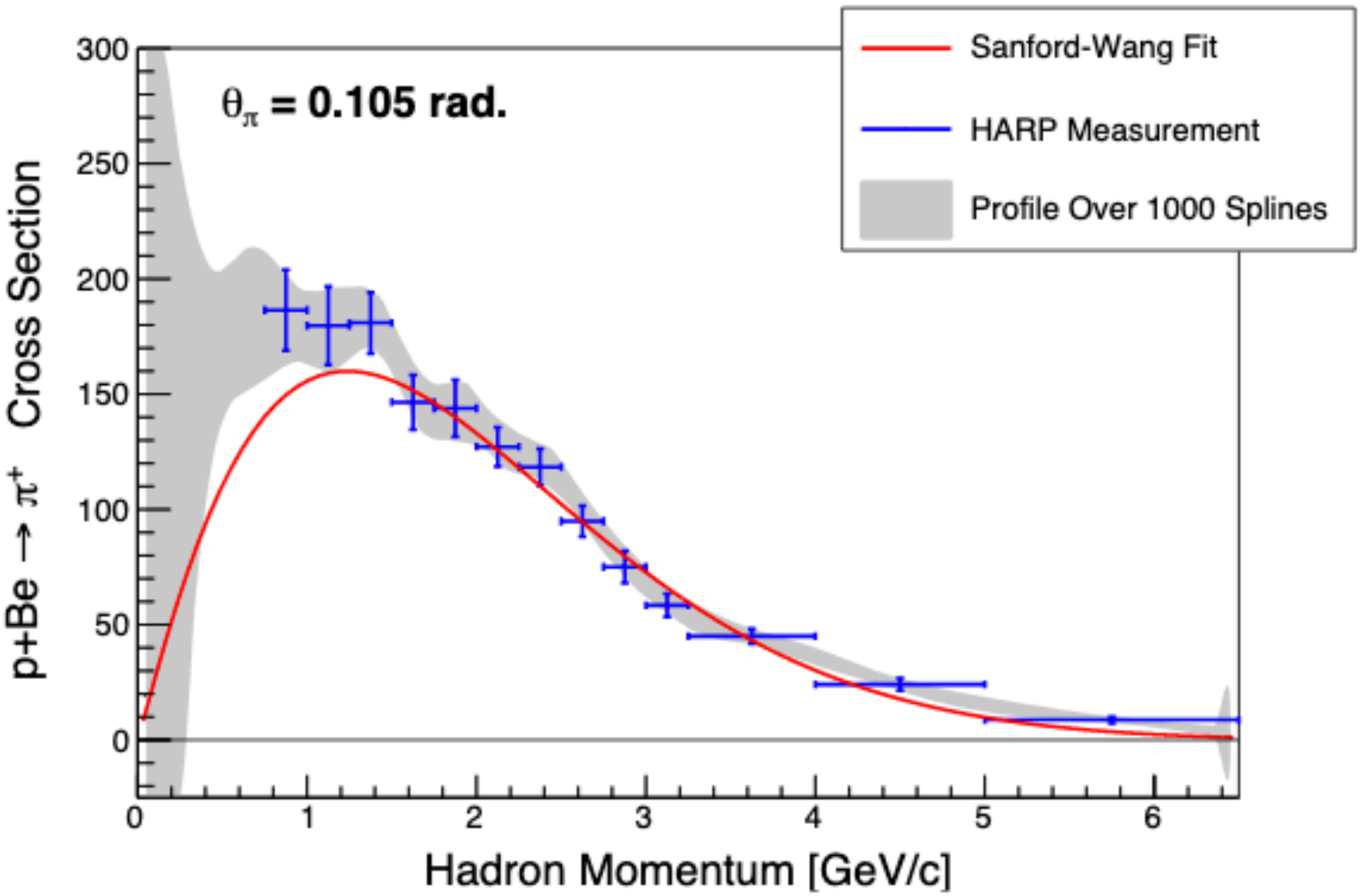
- Propagate uncertainties using many MC worlds to build error matrices that capture correlations between bins of observables
  - Spline fits through HARP data
  - Kaon fits
  - Hadron cross sections on Be and Al
  - Horn Focusing
  - POT counting



MICROBOONE-NOTE-1031-PUB

Spline fits

- HARP data interpolated using splines
- Splines created first in θ at fixed values of p, and then resulting splines interpolated to produce values as a function of p
- Full 78x78 covariance matrix from HARP used to vary measured double differential cross sections
- Splines also used to extrapolate outside the HARP region



Fermilab

Hadronic uncertainty

- σ_{TOT}, σ_{INE}, and σ_{QEL} are separately varied for nucleons on Be and Al, and for pions on Be and Al
- Flat offset is applied to momentum dependent cross section
- Offsets cover deviations of data from used parameterization or model

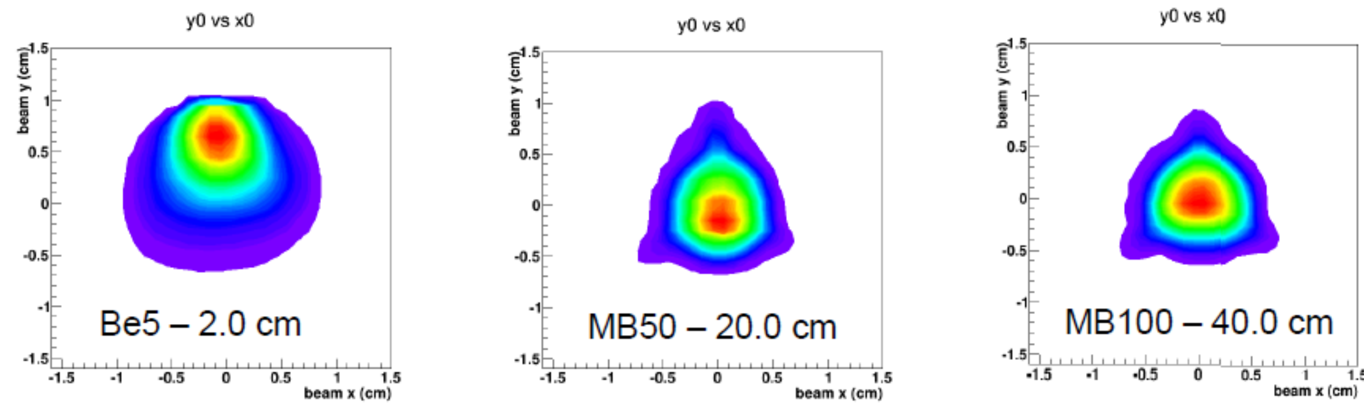
	$\Delta\sigma_{TOT}$ (mb)		$\Delta\sigma_{INE}$ (mb)		$\Delta\sigma_{QEL}$ (mb)	
	Be	Al	Be	Al	Be	Al
(p/n)-(Be/Al)	$\pm$ 15.0	$\pm$25.0	$\pm$ 5	$\pm$10	$\pm$ 20	$\pm$45
$\pi^{\pm}$-(Be/Al)	$\pm$ 11.9	$\pm$28.7	$\pm$ 10	$\pm$20	$\pm$ 11.2	$\pm$25.9

Phys. Rev. D79, 072002 (2009)

HARP thick target analysis

- Not used to constrain the uncertainty, but cross checked simulation

- Double ratios of thin to thick yields data to MC consistent with 1 (+-1-2%) indicating that the simulation does a good job extrapolating to long target



DATA	Beam radius cut (reduce the edge effect)	P.O.T
MB100	0.4 cm	622791
MB50	0.4 cm	814749
Empty	0.4 cm	475776
Be5	1.0 cm	13070000
Empty	1.0 cm	1990000

Be5 to MB50: $$\eta_{MB50} = \left\{ \frac{[d^2N/dpd\Omega]_{50\lambda_I}}{[d^2\sigma/dpd\Omega]_{5\lambda_I}} \right\}^{Data} \cdot \left\{ \frac{[d^2\sigma/dpd\Omega]_{5\lambda_I}}{[d^2N/dpd\Omega]_{50\lambda_I}} \right\}^{MC}$$

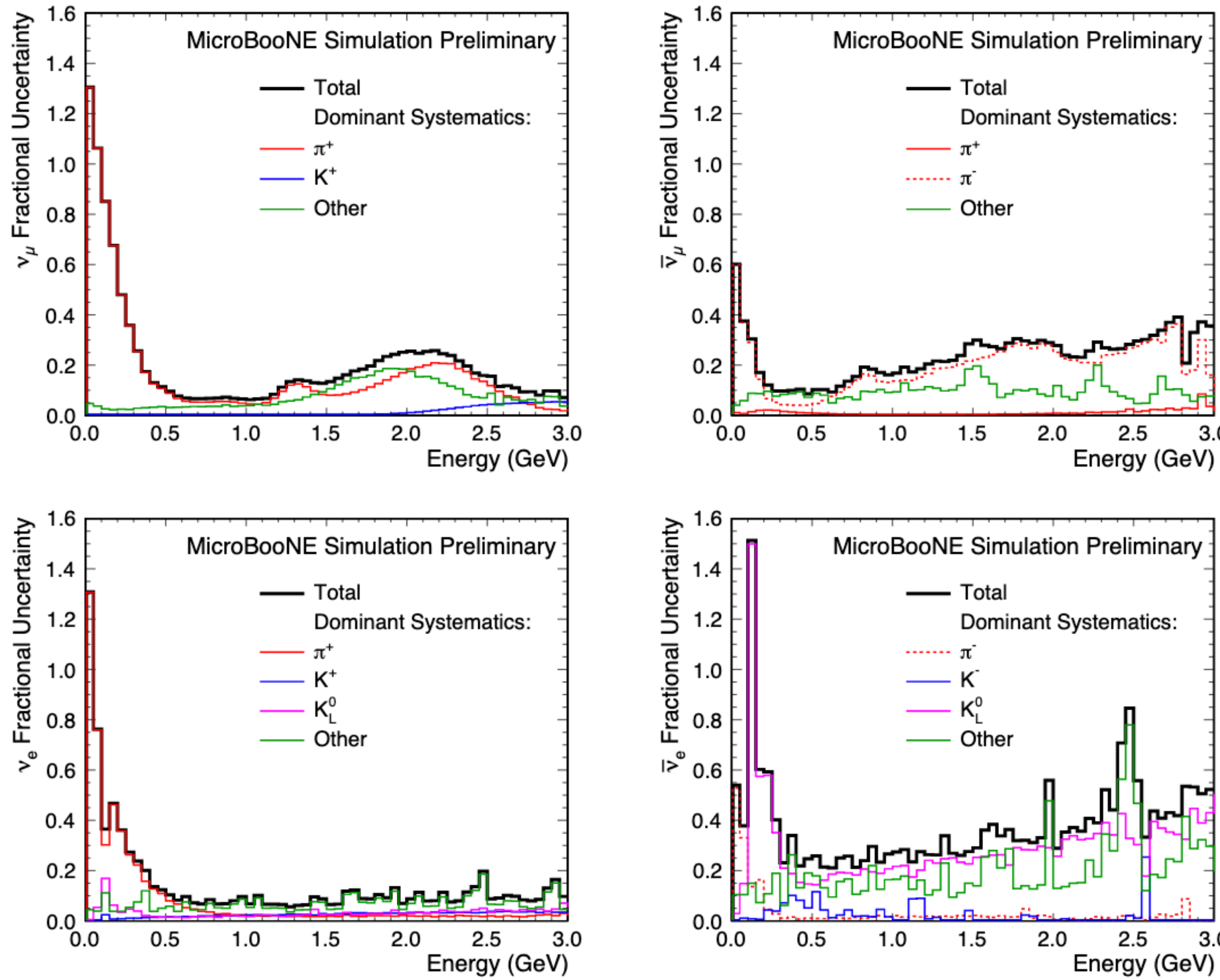
Be5 to MB100: $$\eta_{MB100} = \left\{ \frac{[d^2N/dpd\Omega]_{100\lambda_I}}{[d^2\sigma/dpd\Omega]_{5\lambda_I}} \right\}^{Data} \cdot \left\{ \frac{[d^2\sigma/dpd\Omega]_{5\lambda_I}}{[d^2N/dpd\Omega]_{100\lambda_I}} \right\}^{MC}$$

MB50 to MB100: $$\eta' = \left\{ \frac{[d^2N/dpd\Omega]_{50\lambda_I}}{[d^2N/dpd\Omega]_{100\lambda_I}} \right\}^{Data} \cdot \left\{ \frac{[d^2N/dpd\Omega]_{100\lambda_I}}{[d^2N/dpd\Omega]_{50\lambda_I}} \right\}^{MC}$$

A. Wickremasinghe, PhD thesis

Flux uncertainty

- Dominated by pion production uncertainty
- Other includes: horn current miscalibration, horn current distribution in inner conductor, nucleon+Be/Al cross sections, pion+Be/Al cross sections
- Horn field and Nucleon QE xsec dominate in Other



MICROBOONE-NOTE-1031-PUB

Flux uncertainties (neutrino mode)

- Dominant uncertainty from pion production
- Nucleon QE dominates the nucleon cross section error (mostly flat in energy)

	numu	numubar	nue	nuebar
pi+	11.4	1.2	12.0	0.1
pi-	0.0	11.9	0.0	3.8
K+	0.2	0.1	2.1	0.1
K-	0.0	0.4	0.0	3.4
K0L	0.0	0.3	2.2	22.7
Horn field	2.5	3.3	0.8	0.7
Nucleon	2.7	5.2	3.0	4.9
Pion	1.4	0.9	0.4	0.7
Total	12.1	13.5	12.8	23.8

Conclusion

- BNB flux largely constrained by HARP data
- Errors in the peak ~6-7%, but are large outside the HARP region
- There is opportunity to improve the low/high energy region, wrong sign flux in antineutrino mode