



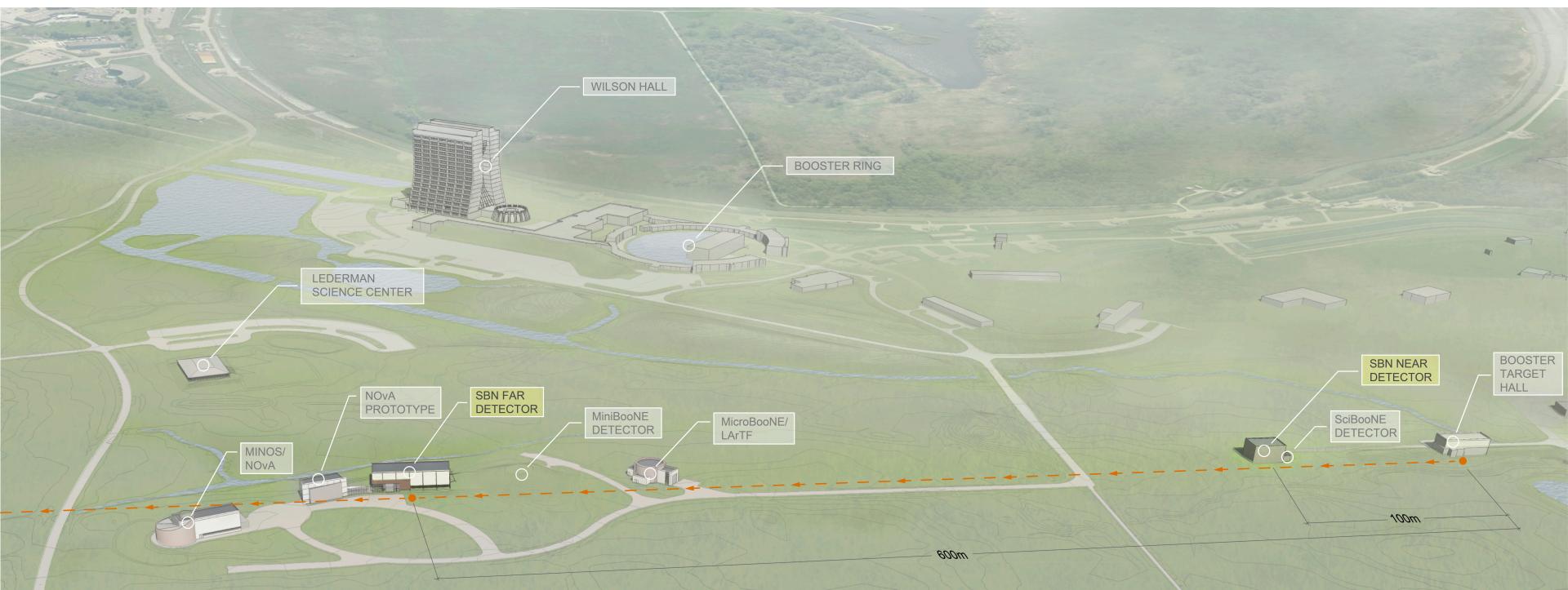
# Booster Neutrino Beam Flux Prediction

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11th International Workshop on Neutrino Beams and Instrumentation

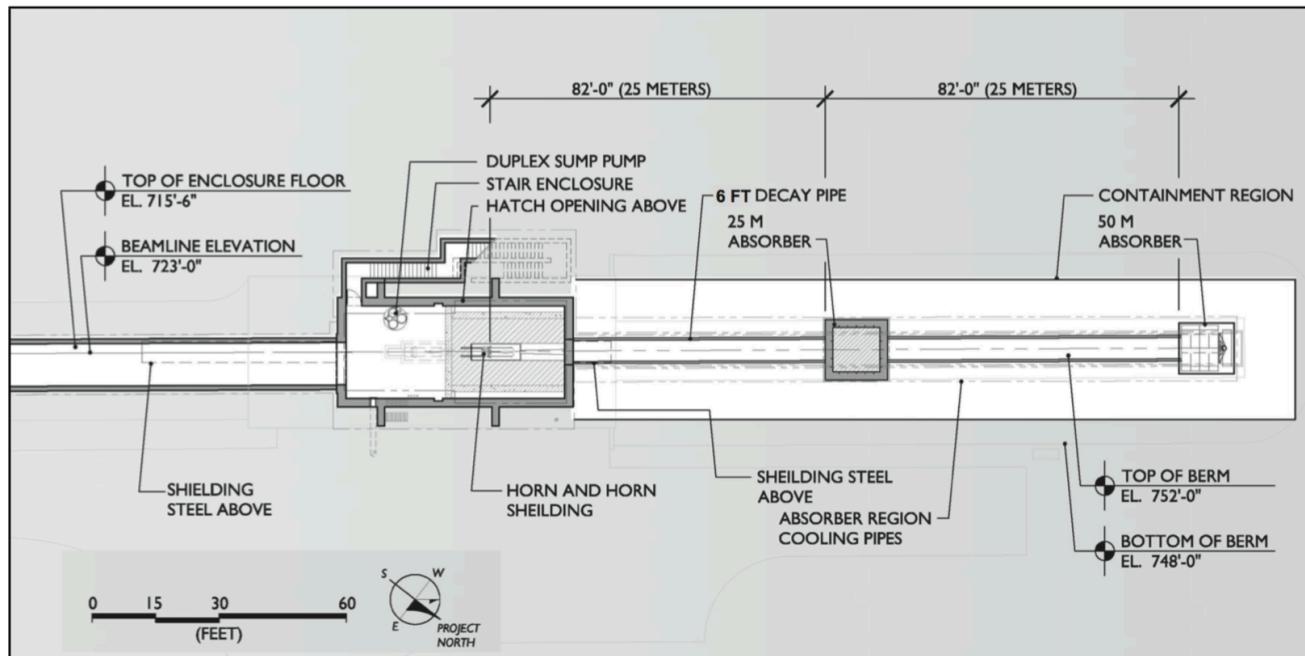
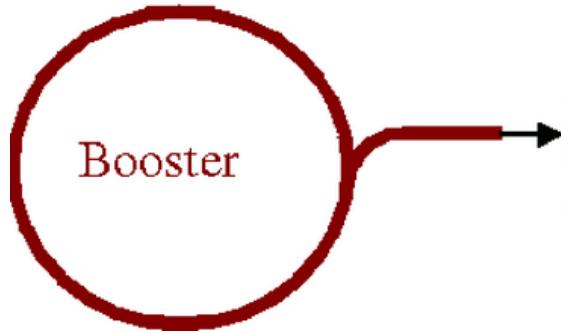
Fermilab, October 2019

# Experiments



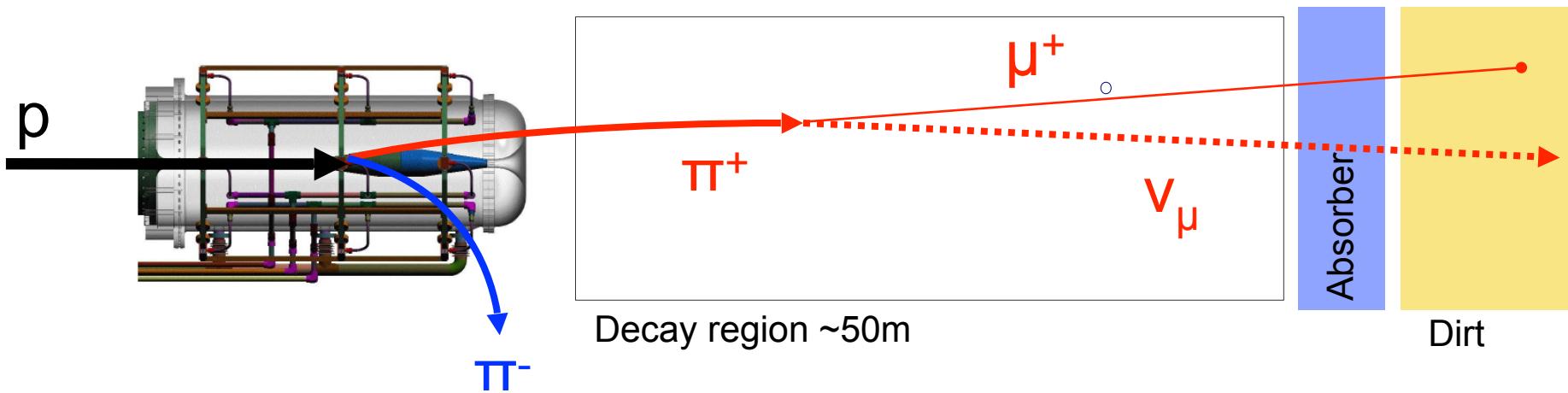
Experiment	Distance from target
ANNIE (SciBooNE)	100m
SBND	110m
MicroBooNE	470m
MiniBooNE	541m
ICARUS	600m

# Booster Neutrino Beamlne



- Conventional horn focused beam
- Single horn, Beryllium target
- 8 GeV protons from Booster (4-5e12 @ up to 5Hz)
- Horn pulsed at ( $\pm$ )174kA (neutrino/anti-neutrino mode)

# Simulation

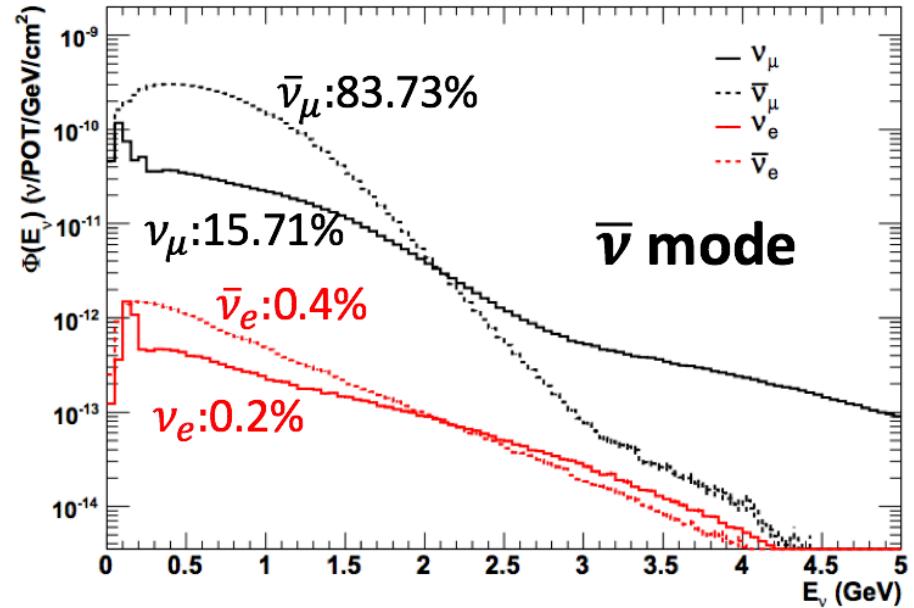
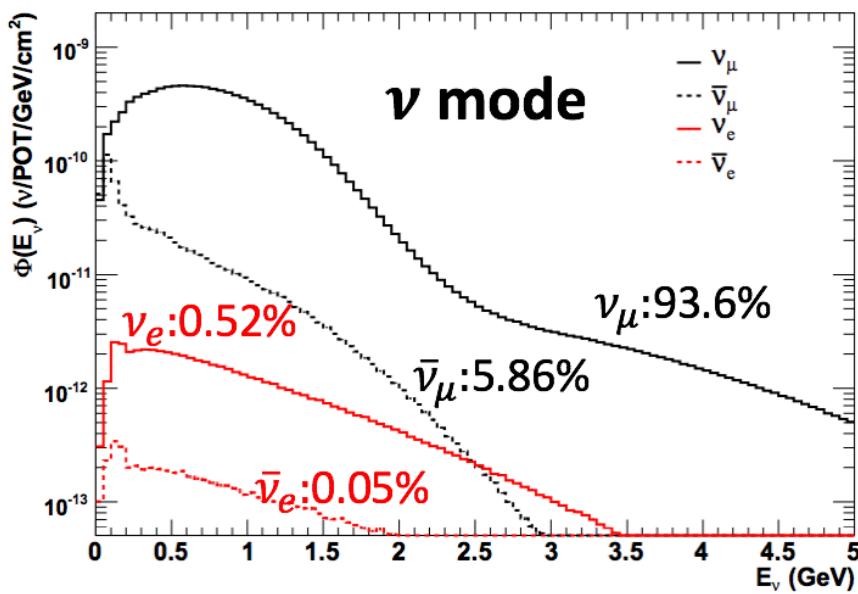


- GEANT4 based simulation
- Detailed description of target, horn, decay region and shielding, and absorber geometries
- Hadron production cross sections tuned to external data
- Nucleon interaction cross sections tuned to available data

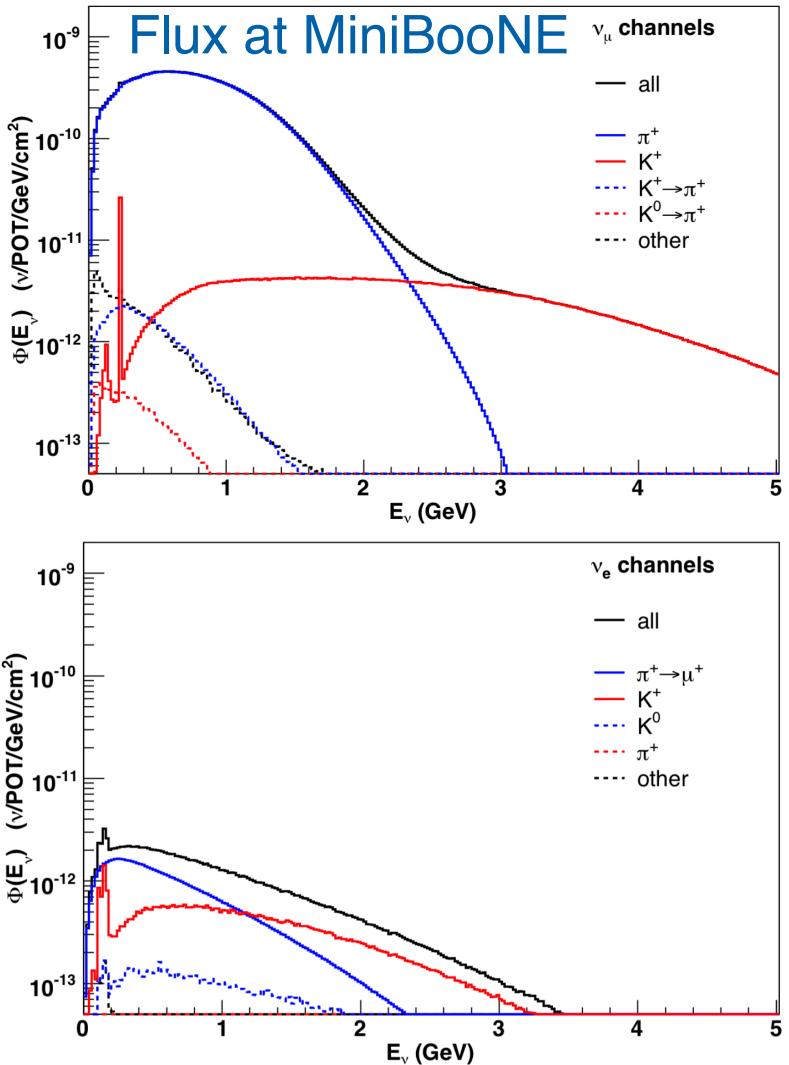
# Neutrino flux

- Predominantly  $\nu_\mu + \bar{\nu}_\mu$  flux (>99%)
- Small ~0.5% intrinsic due component
- Larger wrong sign component in anti-neutrino mode, amplified by higher neutrino cross-sections

Flux at MiniBooNE



# Neutrino parents

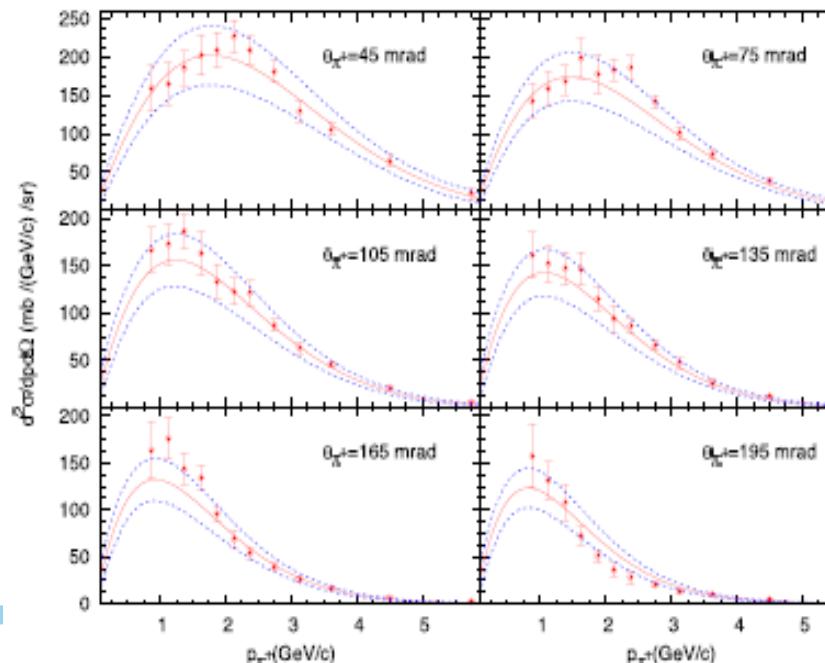
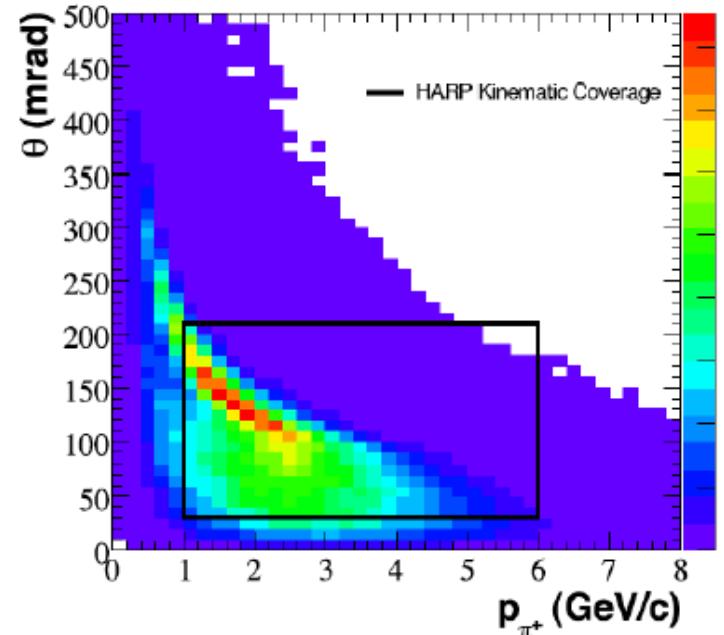


Phys.Rev.D79, 072002 (2009)

	$\nu_\mu$		$\bar{\nu}_\mu$	
Flux ( $\nu / \text{cm}^2/\text{POT}$ )	$5.19 \times 10^{-10}$		$3.26 \times 10^{-11}$	
Frac. of Total	93.6%		5.86%	
Composition	$\pi^+$ :	96.72%	$\pi^-$ :	89.74%
	$K^+$ :	2.65%	$\pi^+ \rightarrow \mu^+$ :	4.54%
	$K^+ \rightarrow \pi^+$ :	0.26%	$K^-$ :	0.51%
	$K^0 \rightarrow \pi^+$ :	0.04%	$K^0$ :	0.44%
	$K^0$ :	0.03%	$K^0 \rightarrow \pi^-$ :	0.24%
	$\pi^- \rightarrow \mu^-$ :	0.01%	$K^+ \rightarrow \mu^+$ :	0.06%
	Other:	0.30%	$K^- \rightarrow \pi^-$ :	0.03%
			Other:	4.43%
	$\nu_e$		$\bar{\nu}_e$	
Flux ( $\nu / \text{cm}^2/\text{POT}$ )	$2.87 \times 10^{-12}$		$3.00 \times 10^{-13}$	
Frac. of Total	0.52%		0.05%	
Composition	$\pi^+ \rightarrow \mu^+$ :	51.64%	$K_L^0$ :	70.65%
	$K^+$ :	37.28%	$\pi^- \rightarrow \mu^-$ :	19.33%
	$K_L^0$ :	7.39%	$K^-$ :	4.07%
	$\pi^+$ :	2.16%	$\pi^-$ :	1.26%
	$K^+ \rightarrow \mu^+$ :	0.69%	$K^- \rightarrow \mu^-$ :	0.07%
	Other:	0.84%	Other:	4.62%

# Pion production

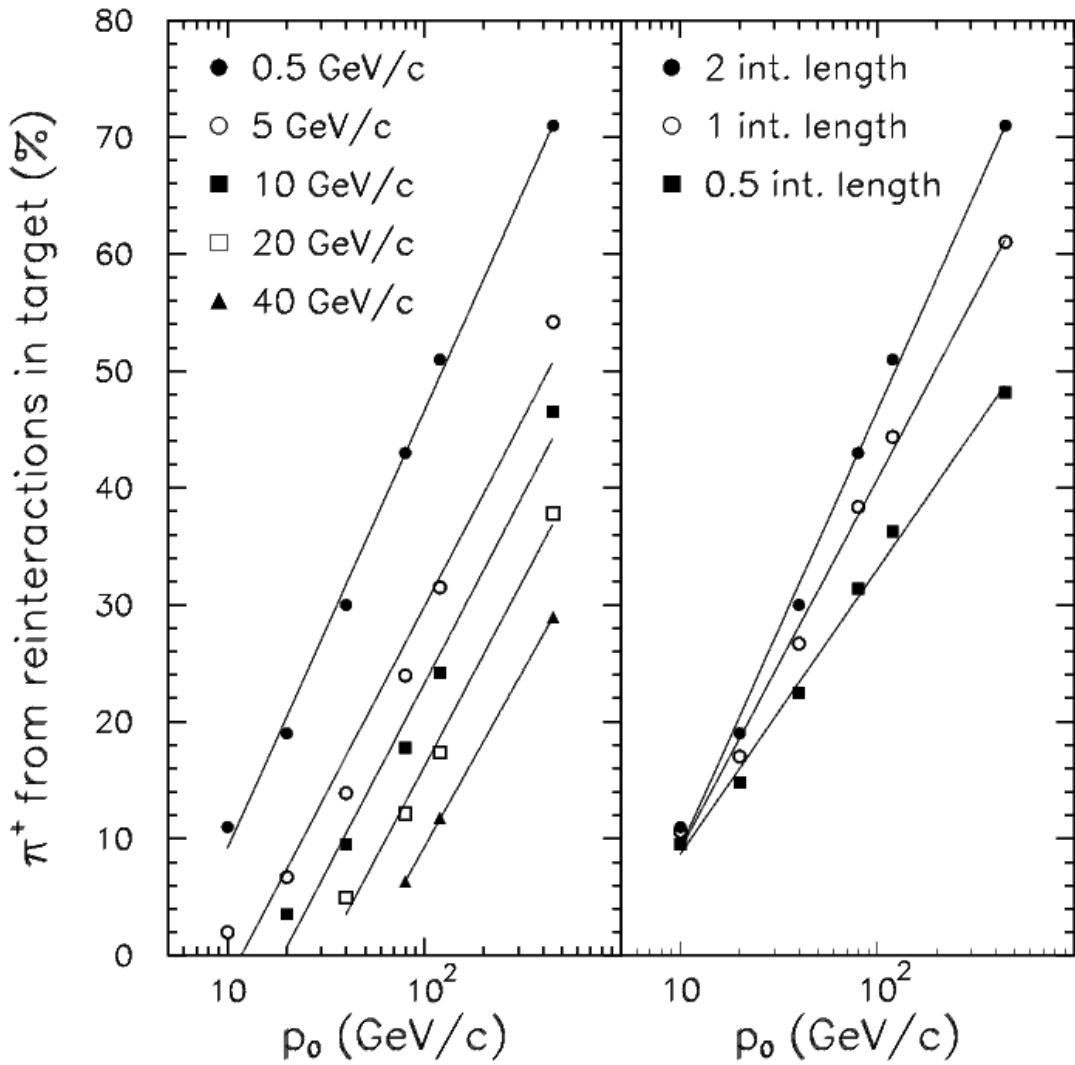
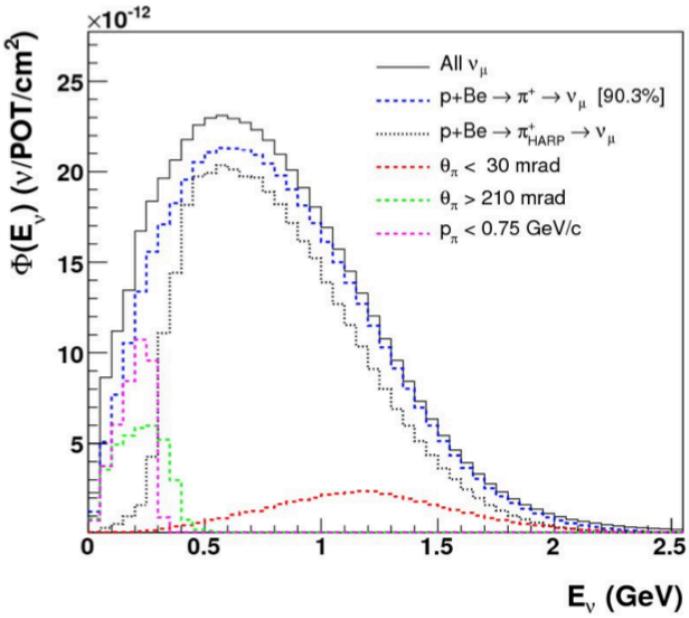
- Sanford Wang fits to positive and negative pion production in proton+Be interactions
- HARP (thin target)
  - 8.89 GeV/c protons
  - $P_\pi = 0.75 - 6.5 \text{ GeV}/c$
  - $\theta_\pi = 30 - 210 \text{ mrad}$
- E910
  - 6.4, 12.3, 17.5 GeV/c protons
  - $P_\pi = 0.4 - 5.6 \text{ GeV}/c$
  - $\theta_\pi = 18 - 400 \text{ mrad}$



Phys.Rev.D79, 072002 (2009)

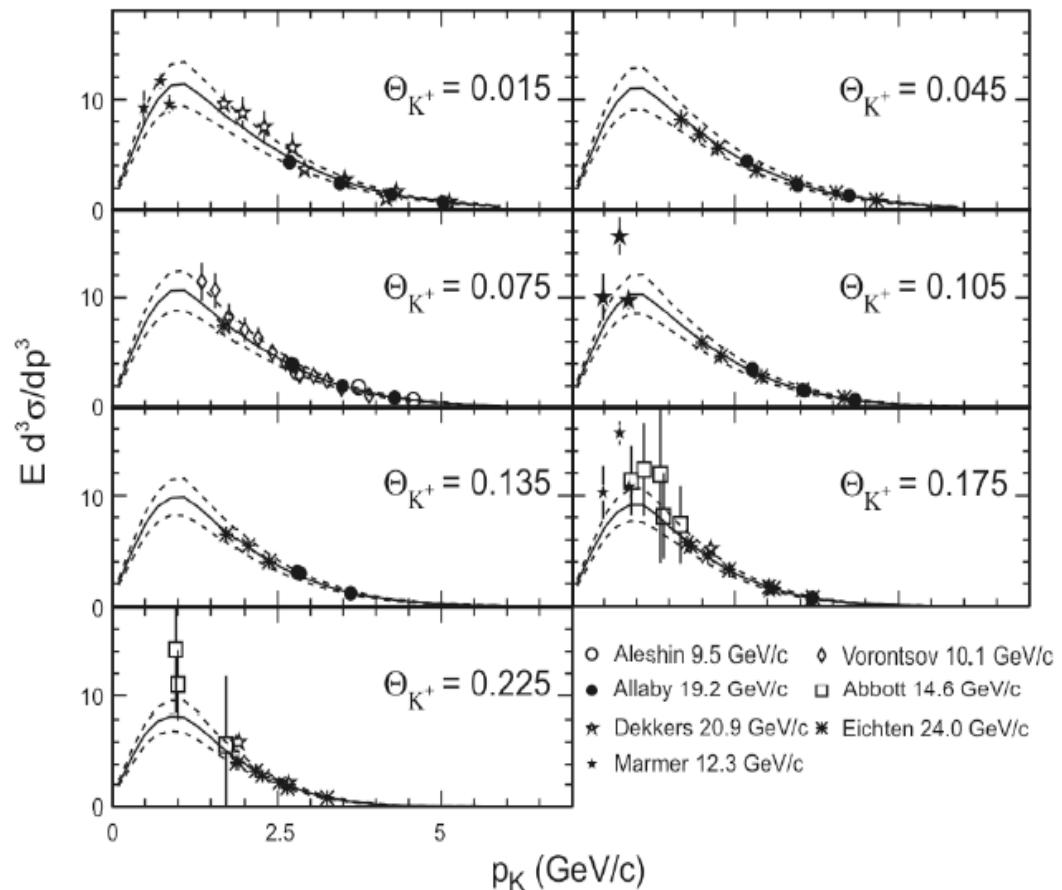
# HARP coverage

- At booster energies about 90% of pions contributing to neutrino flux from primary p+Be interactions



# Kaon production

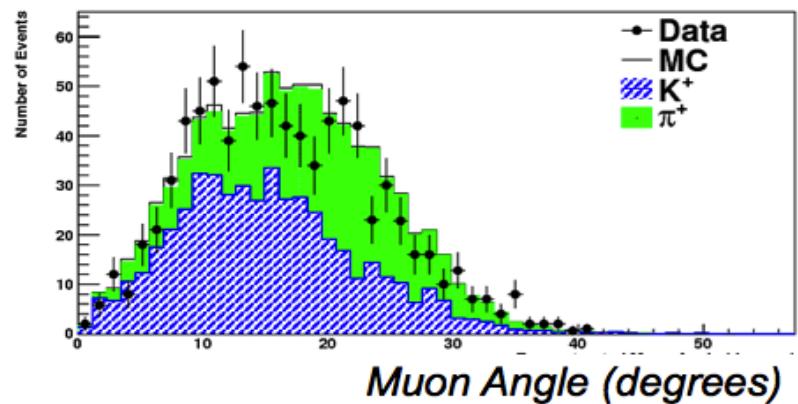
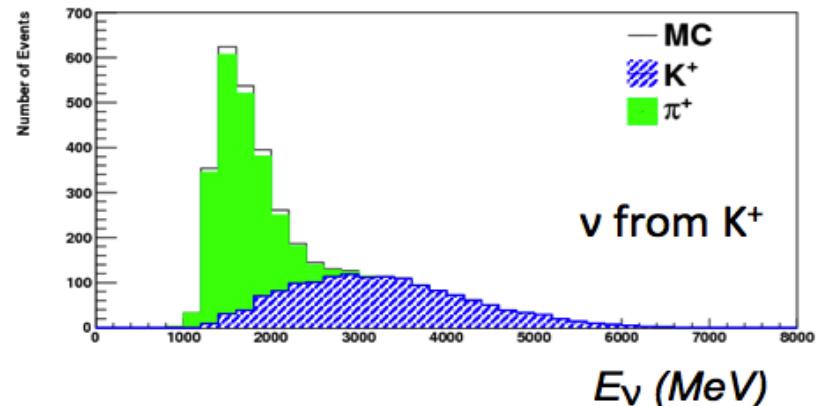
- Feynman scaling based parameterization used to fit world  $K^+$  production data
- For neutral kaons Sanford-Wang fits to  $K^0\bar{K}^0$  production data from BNL E910 and KEK Abe et al.



Phys.Rev.D79, 072002 (2009)

# Kaons in BNB

- Kaon production further constrained by SciBooNE measurements
- Used kaon enhanced sample to constrain kaons contributing to neutrinos (similar coverage as farther on-axis)
- Found production to be  $0.85 \pm 0.12$  relative to the global fit to kaons



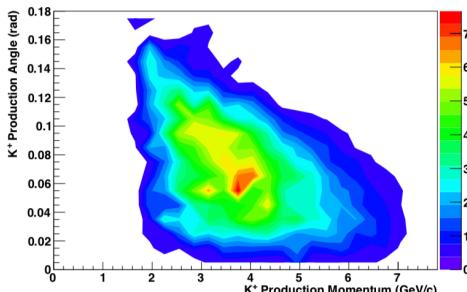
*Phys. Rev.D84, 012009 (2011)*

*Phys. Rev.D84, 114021 (2011)*

# Kaons in BNB

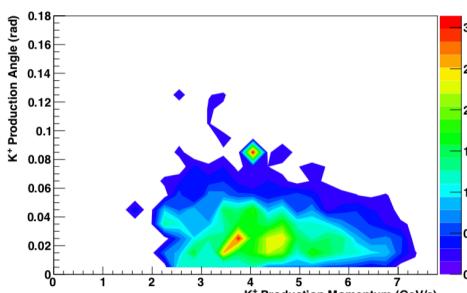
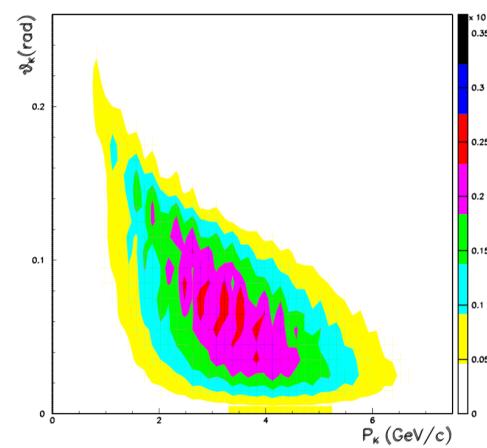
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K@SciBooNE



(a) Neutrino Sample

K@MiniBooNE



(b) Antineutrino Sample

*Phys.Rev.D84,012009 (2011)*

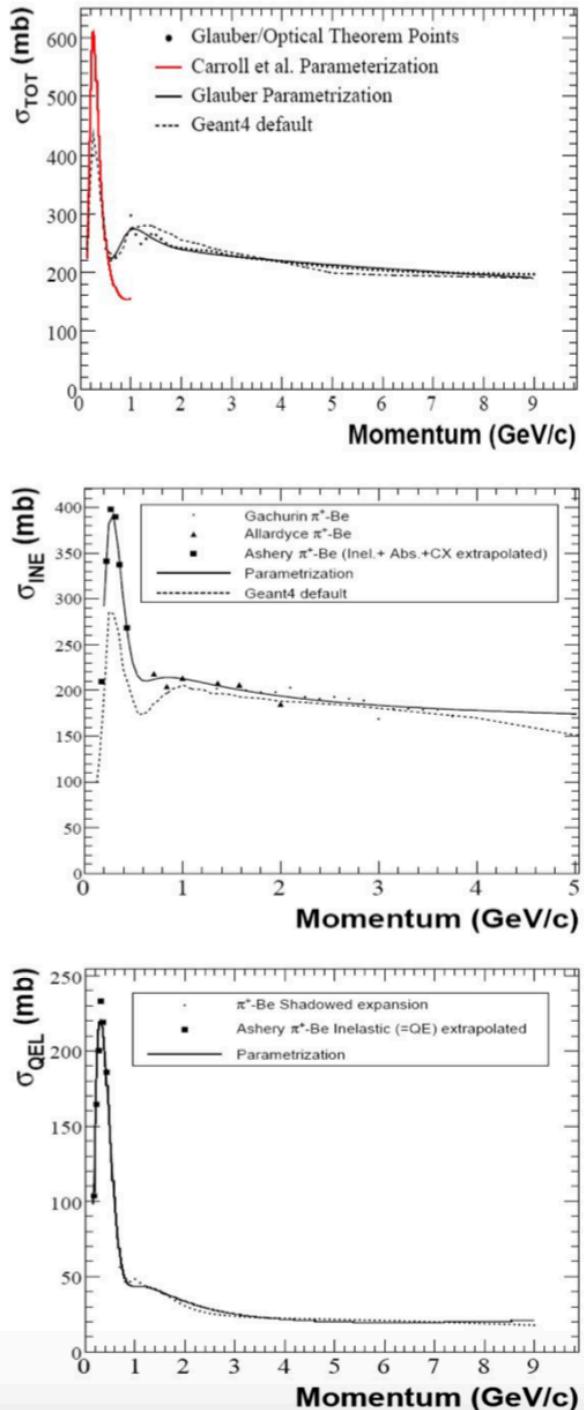
*Phys.Rev.D84,114021 (2011)*



# Hadronic cross-sections

- Total, inelastic, and quasi elastic cross sections for p, n,  $\pi$  on Be and Al constrained with data where available

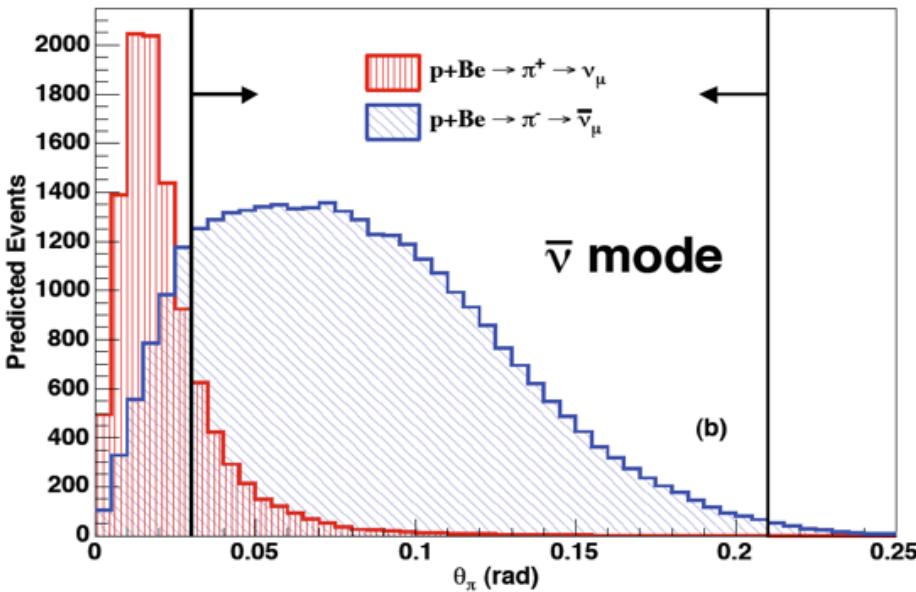
	p-(Be/Al)	n-(Be/Al)	$\pi^\pm$ -(Be/Al)
$\sigma_{TOT}$	Glauber  (checked with data)	Glauber  (same as p-Be/Al)	Data ( $p < 0.6/0.8 \text{ GeV}/c$ )  Glauber ( $p > 0.6/0.8 \text{ GeV}/c$ )
$\sigma_{INE}$	Data	Shadow	Data
$\sigma_{QEL}$	Shadow	Shadow	Data ( $p < 0.5 \text{ GeV}/c$ )  Shadow ( $p > 0.5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



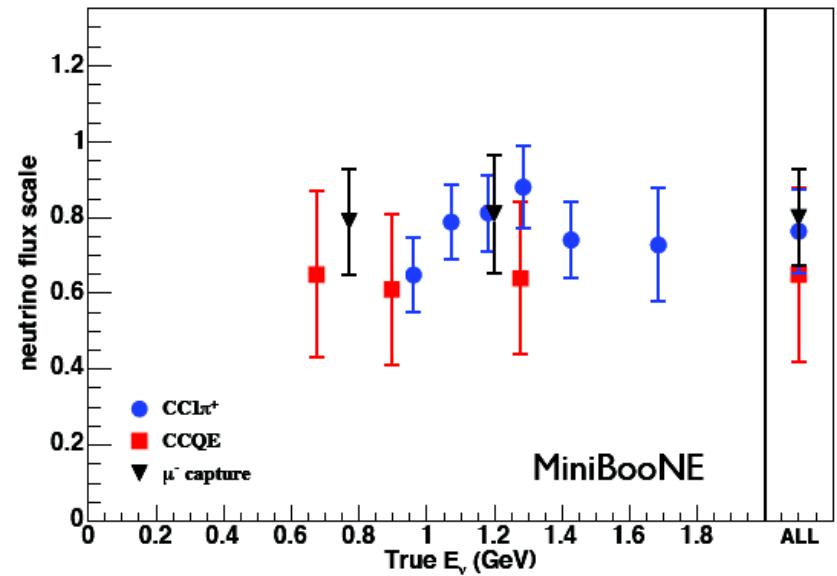
Phys.Rev.D79, 072002 (2009)

# Wrong signs

- Significant  $\nu_\mu$  component in anti-neutrino mode ( $\sim 16\%$ )
- Not constrained well by HARP/E910
- MiniBooNE used in-situ measurement
  - $\nu_\mu$  CCQE angular fit
  - $\text{CC}\pi^+$  rate
  - $\mu^-$  capture

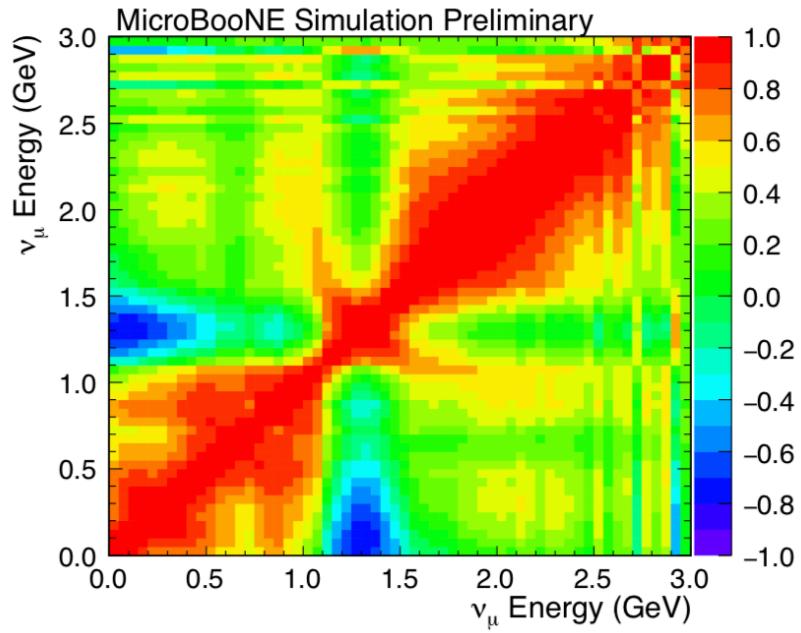


*Phys.Rev.D84,072005 (2011)*



# Flux Uncertainties

- Uncertainties propagated using many MC worlds to build error matrices that capture correlations between bins of neutrino observables
  - spline fits through HARP data
  - correlated parameter variations for kaon fits
  - hadron cross sections on Be and Al
  - horn focusing (current variations, skin depth)
  - POT counting



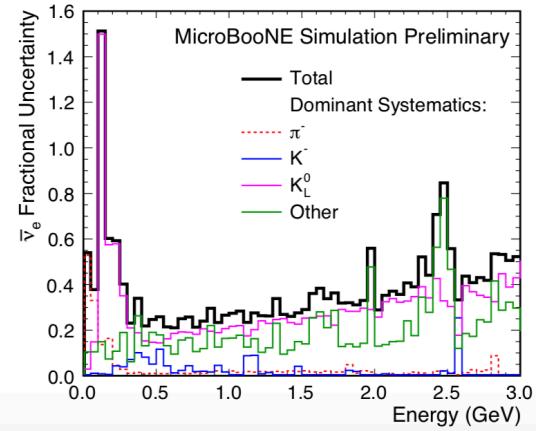
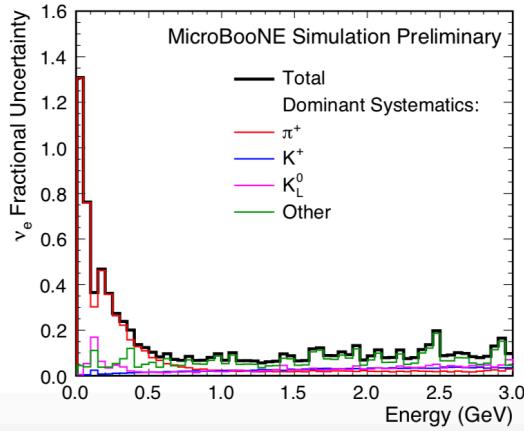
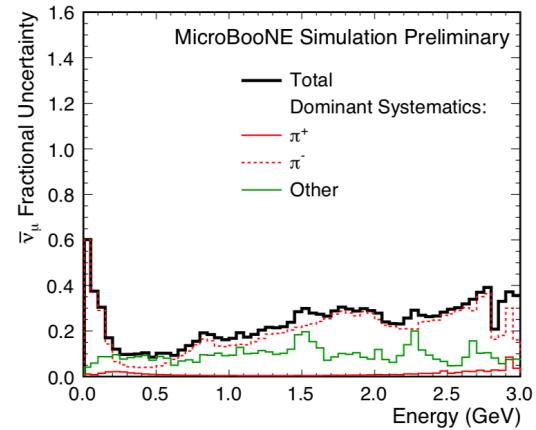
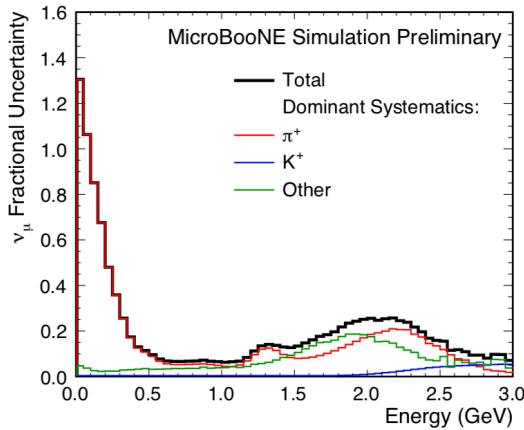
*MICROBOONE-NOTE-1031-PUB*

*Phys.Rev.D79, 072002 (2009)*



# Flux Uncertainties (cont'd)

- Integrated over whole energy range uncertainties at ~10% level



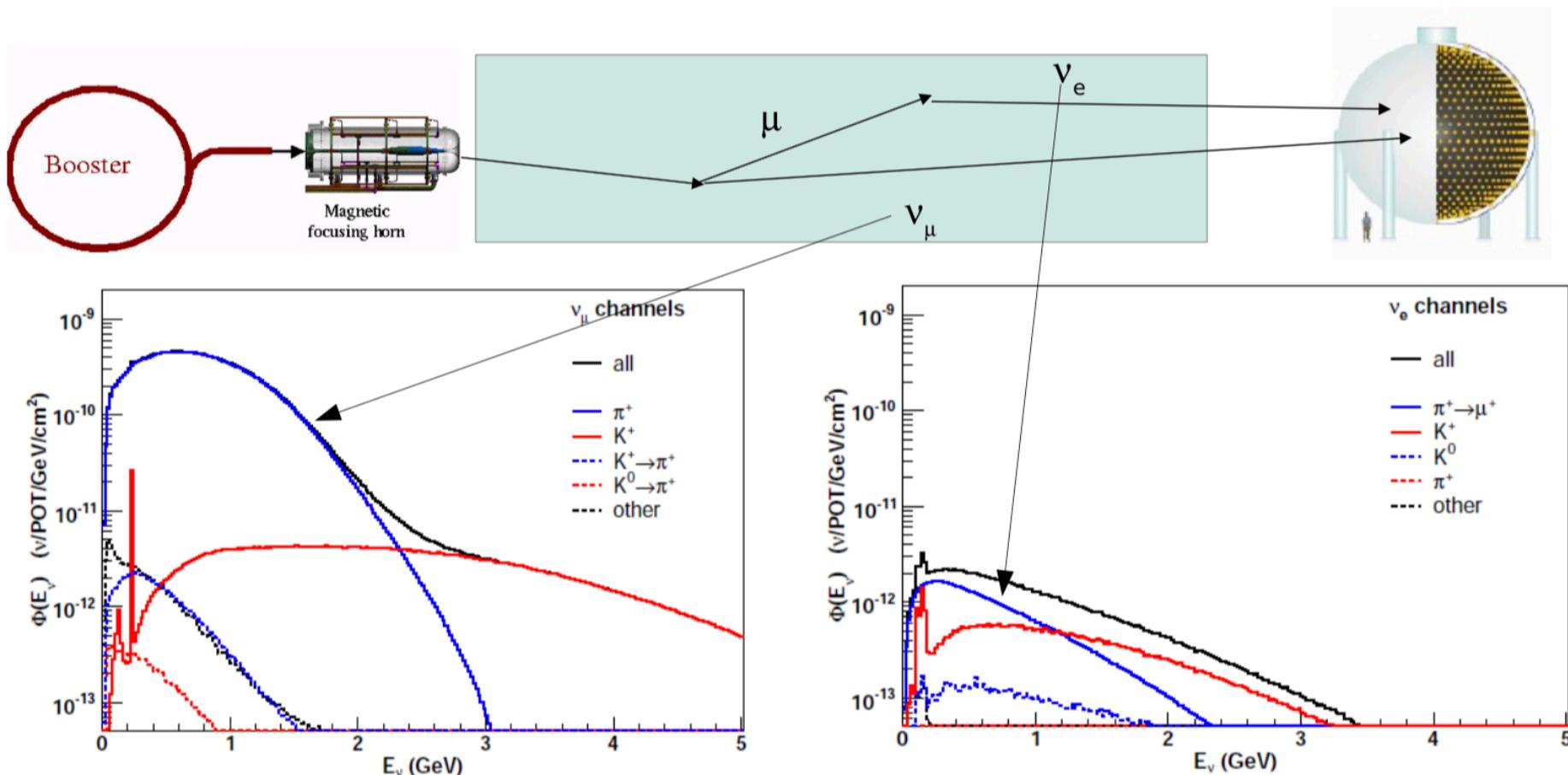
Systematic	$\nu_\mu/\%$	$\bar{\nu}_\mu/\%$	$\nu_e/\%$	$\bar{\nu}_e/\%$
Proton delivery	2.0	2.0	2.0	2.0
$\pi^+$	11.7	1.0	10.7	0.03
$\pi^-$	0.0	11.6	0.0	3.0
$K^+$	0.2	0.1	2.0	0.1
$K^-$	0.0	0.4	0.0	3.0
$K_L^0$	0.0	0.3	2.3	21.4
Other	3.9	6.6	3.2	5.3
Total	12.5	13.5	11.7	22.6

MICROBOONE-NOTE-1031-PUB



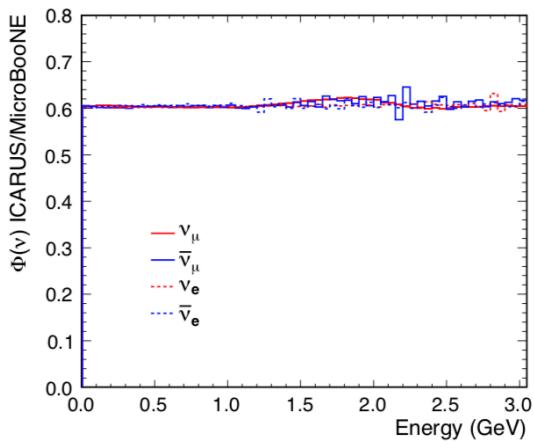
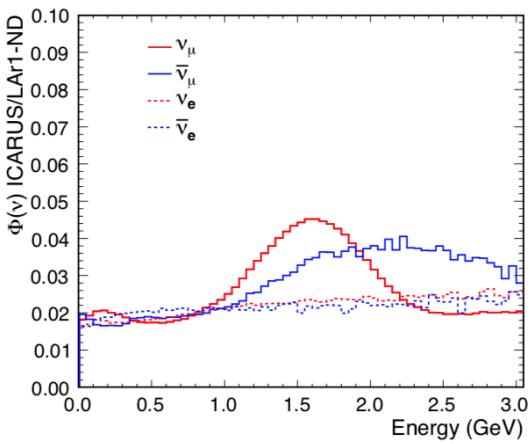
# Single detector

- MiniBooNE and MicroBooNE use high statistics muon neutrino sample to further constrain the intrinsic  $\nu_e$ s

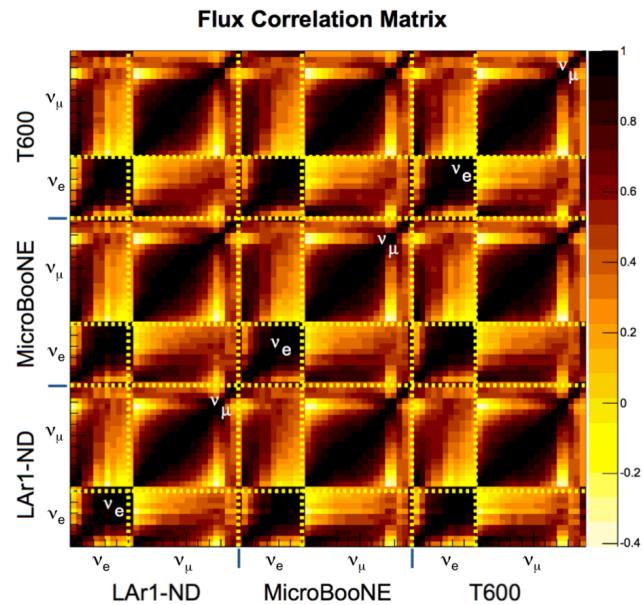


# Multiple detectors

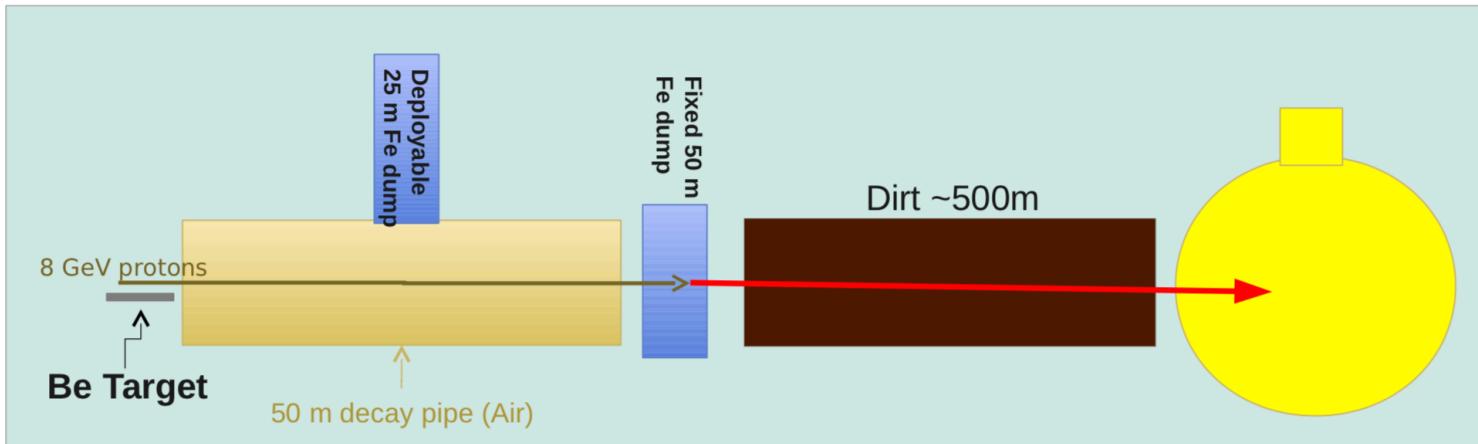
- SBN program includes three detectors - SBND, MicroBooNE, ICARUS
- SBND constraining flux for far detector(s)
- Strong correlations between detectors



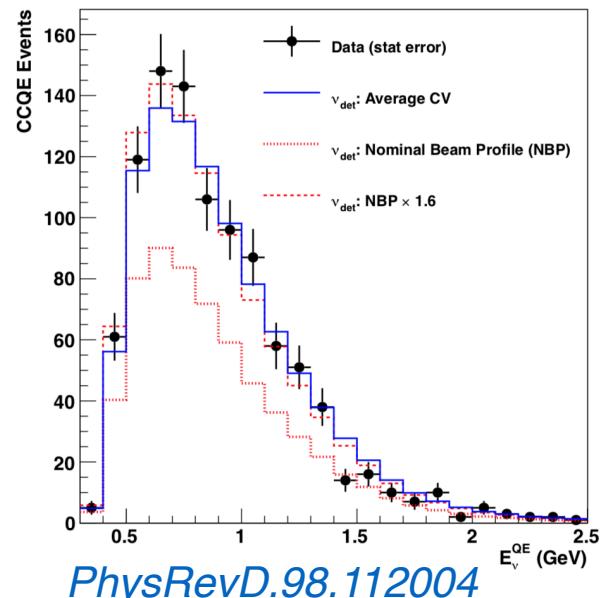
*arXiv:1503.01520*



# Beam dump mode



- Steer beam away from target directly into absorber
- Reduce neutrino flux by  $\sim 50$  times
- Sensitive to beam profile (scraping target)
  - Use  $\nu_\mu$  CCQE to constrain
- MiniBooNE collected  $1.86 \times 10^{20}$  POT



# Conclusion

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- Well understood neutrino flux from Booster Neutrino Beamline
  - constrained using external hadron production measurements
  - years of running experiments (SciBooNE, MiniBooNE, MicroBooNE)
- SBN experiments (SBND, MicroBooNE, ICARUS) revisiting flux prediction and exploring possible improvements

# Flux stability

- MiniBooNE event rates stable throughout 17 years of running
  - Neutrino mode
  - Anti-neutrino mode (2x lower flux, 2-3x lower cross section)
  - Dark matter mode ( $\sim 40$ x lower flux)

