Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Booster Neutrino Beam

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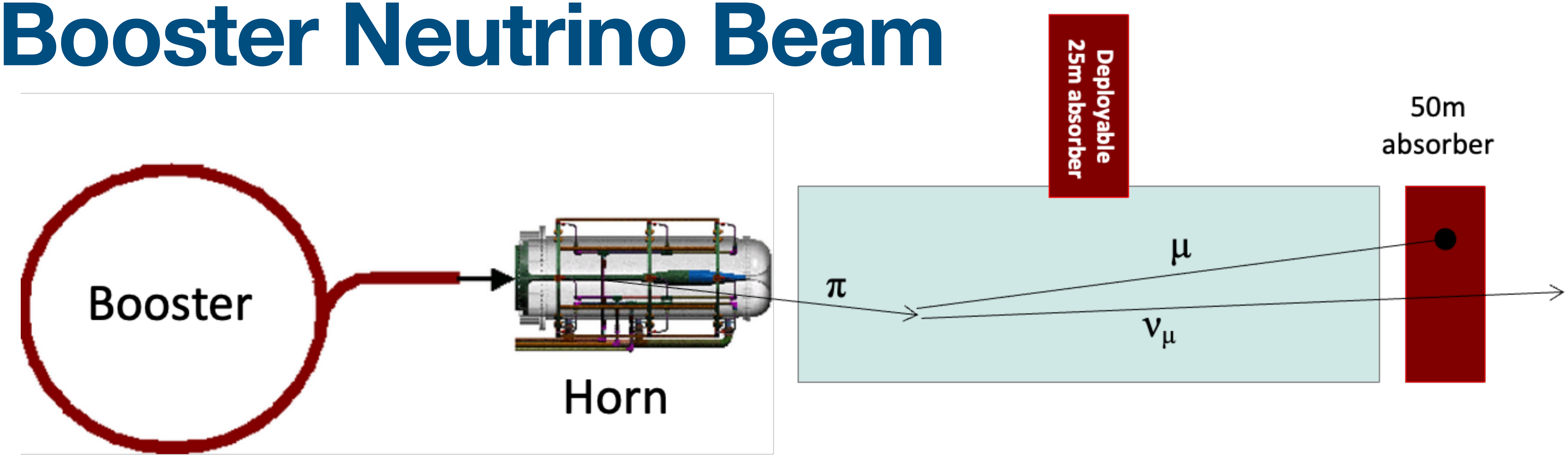
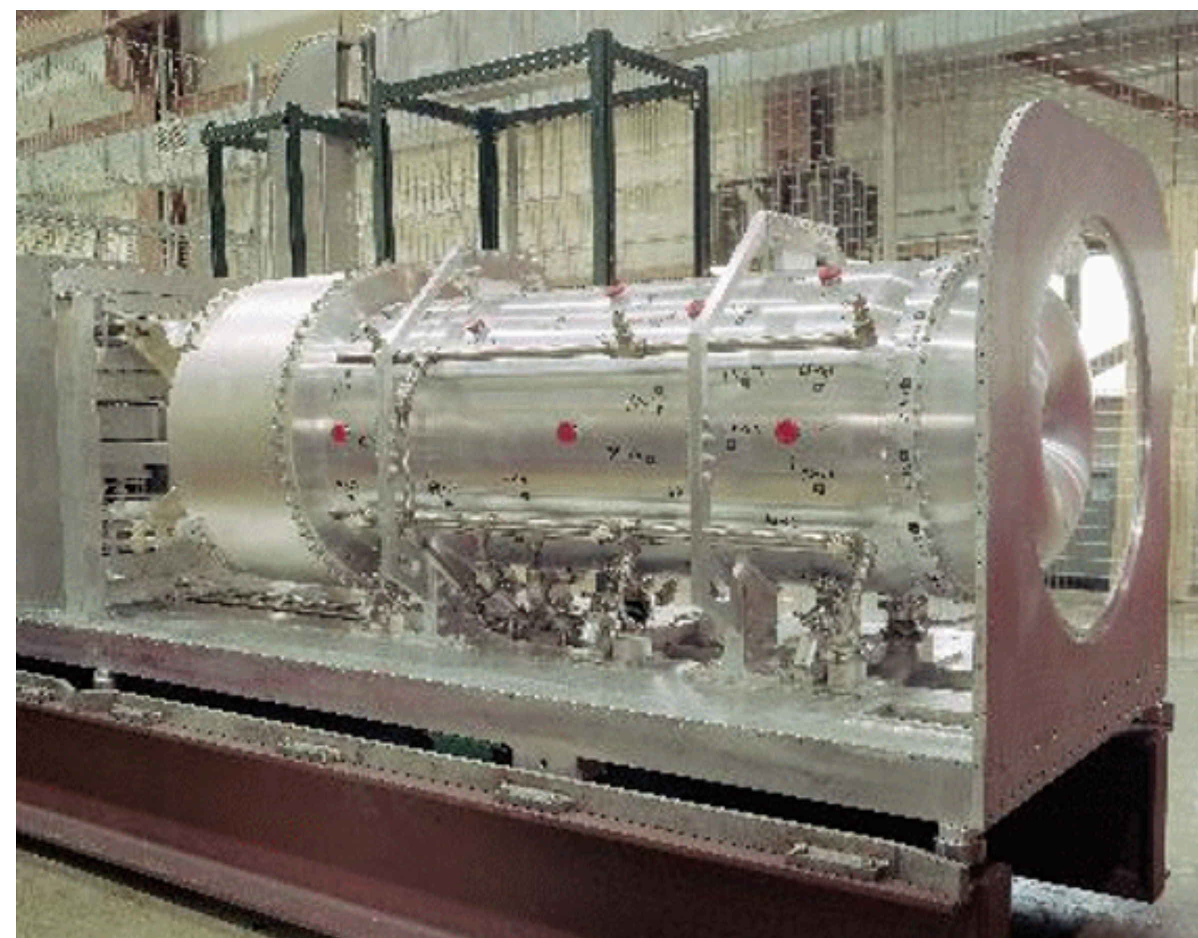
Booster Neutrino Beam

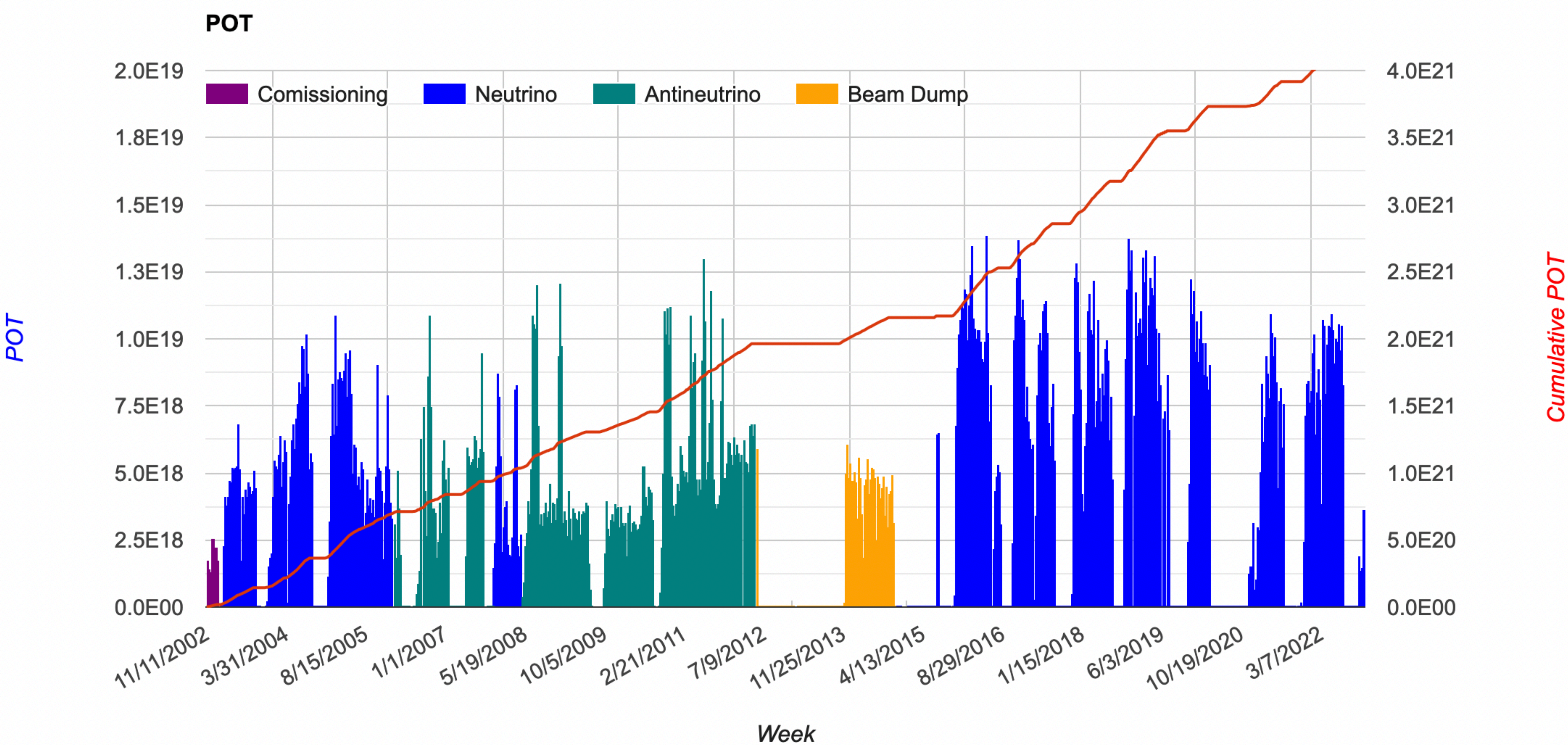


- 8 GeV protons from Booster
    - 4-5e12 PPP
    - Up to 5Hz average rate
- 1.7 int. length Be target
- Horn
    - Neutrino & Antineutrino mode ±170kA
    - Horn off run
- 50m long decay pipe

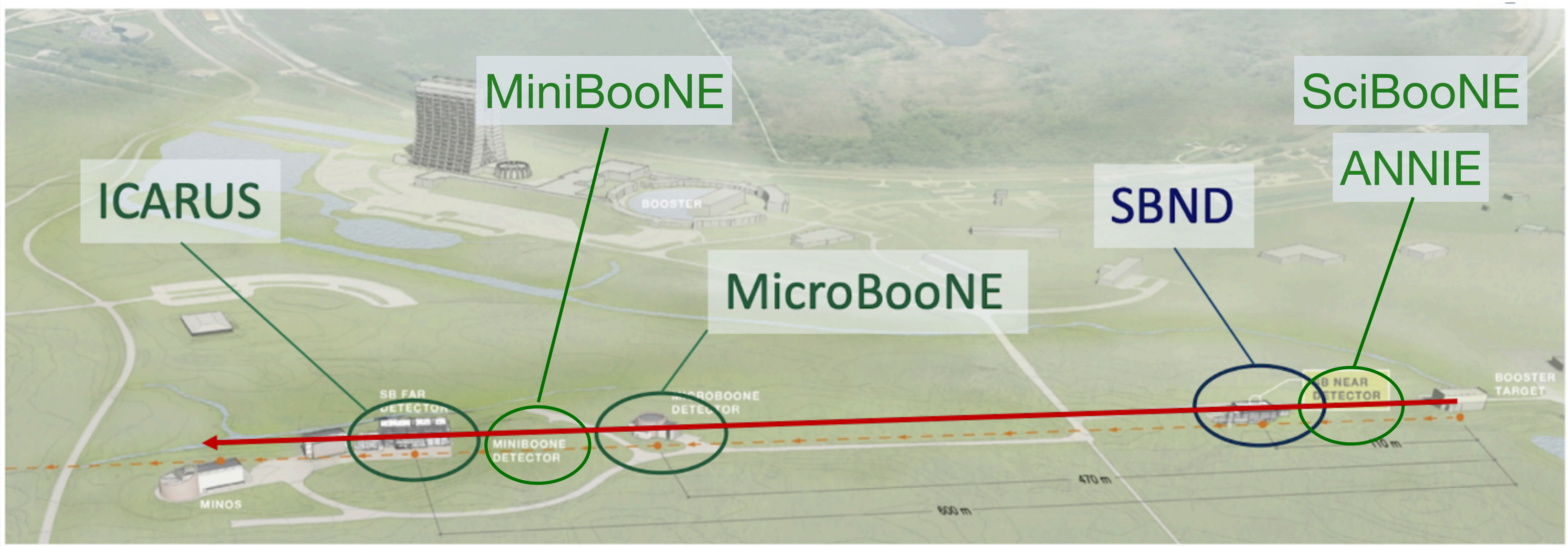


20 years of running

- Beamline commissioned exactly 20 years ago!

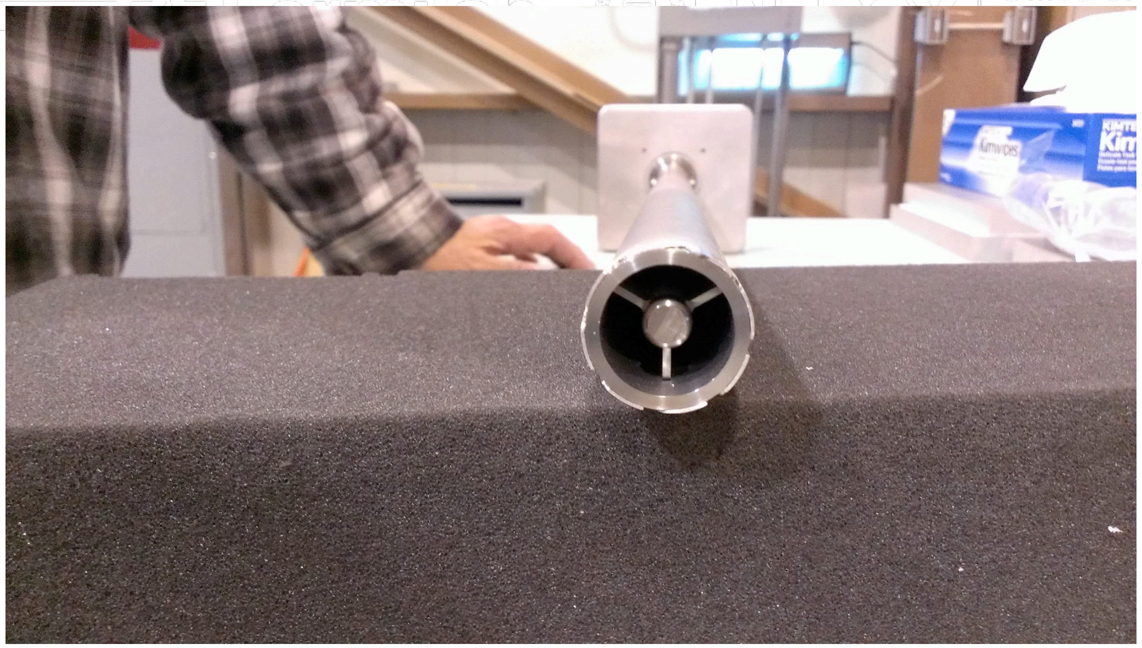


Experiments

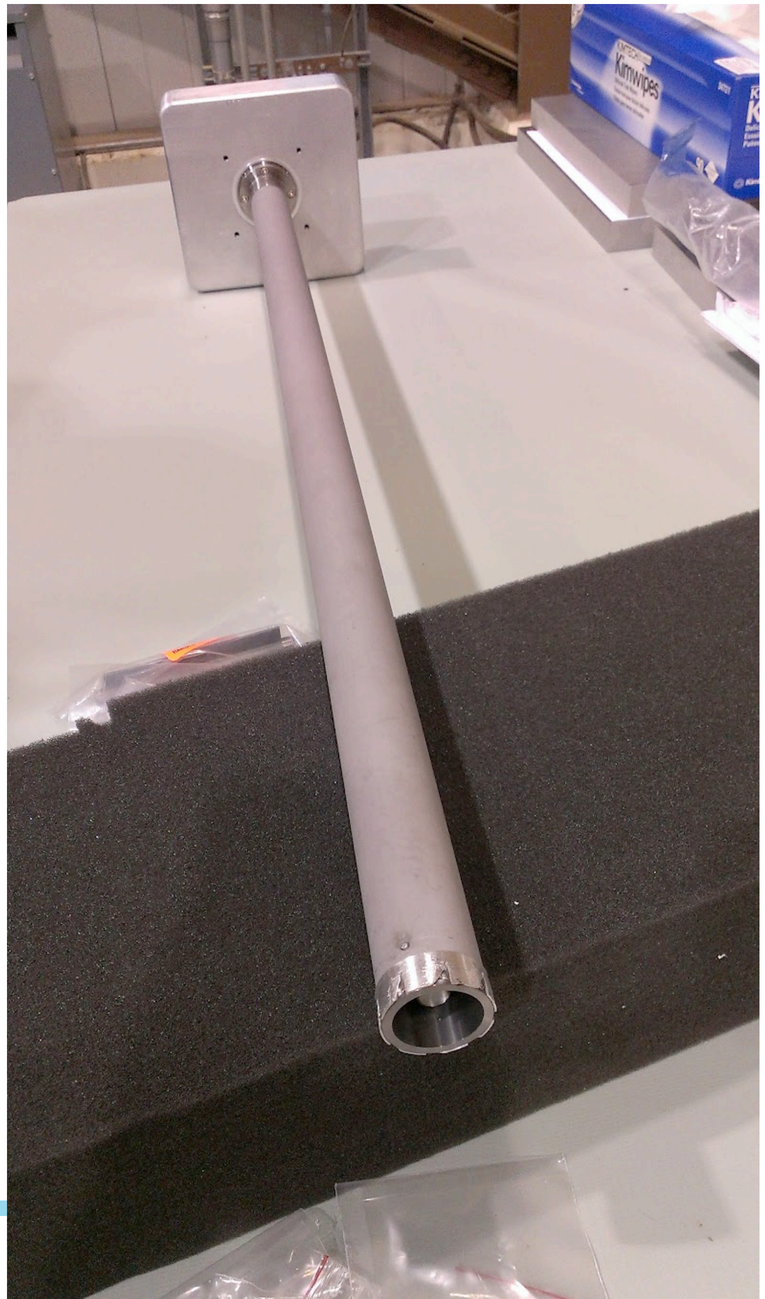


- Broad physics program using BNB
  - Sterile neutrinos
  - Exotic BSM models (explain MiniBooNE low energy excess)
  - Neutrino cross sections
  - Dark matter searches

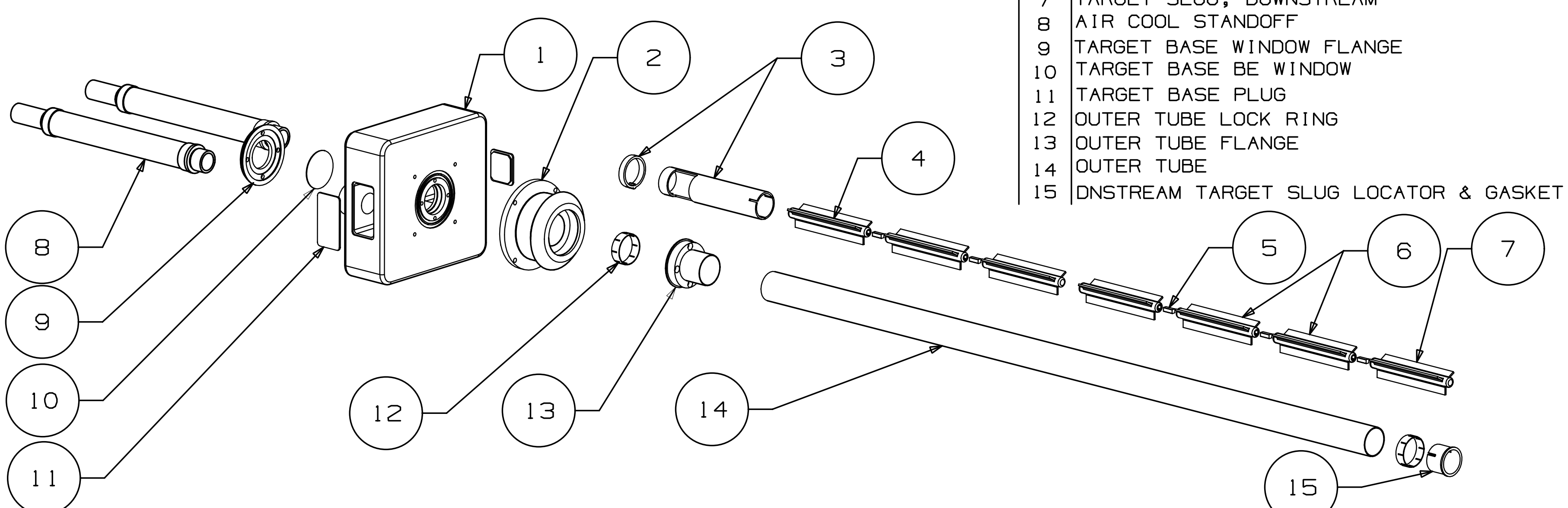
BNB target



- Berrylium target made of 7 cylindrical slugs
  - 10.2cm long 0.48cm radius
  - Held within Be outer tube with 3 fins
- Air cooled

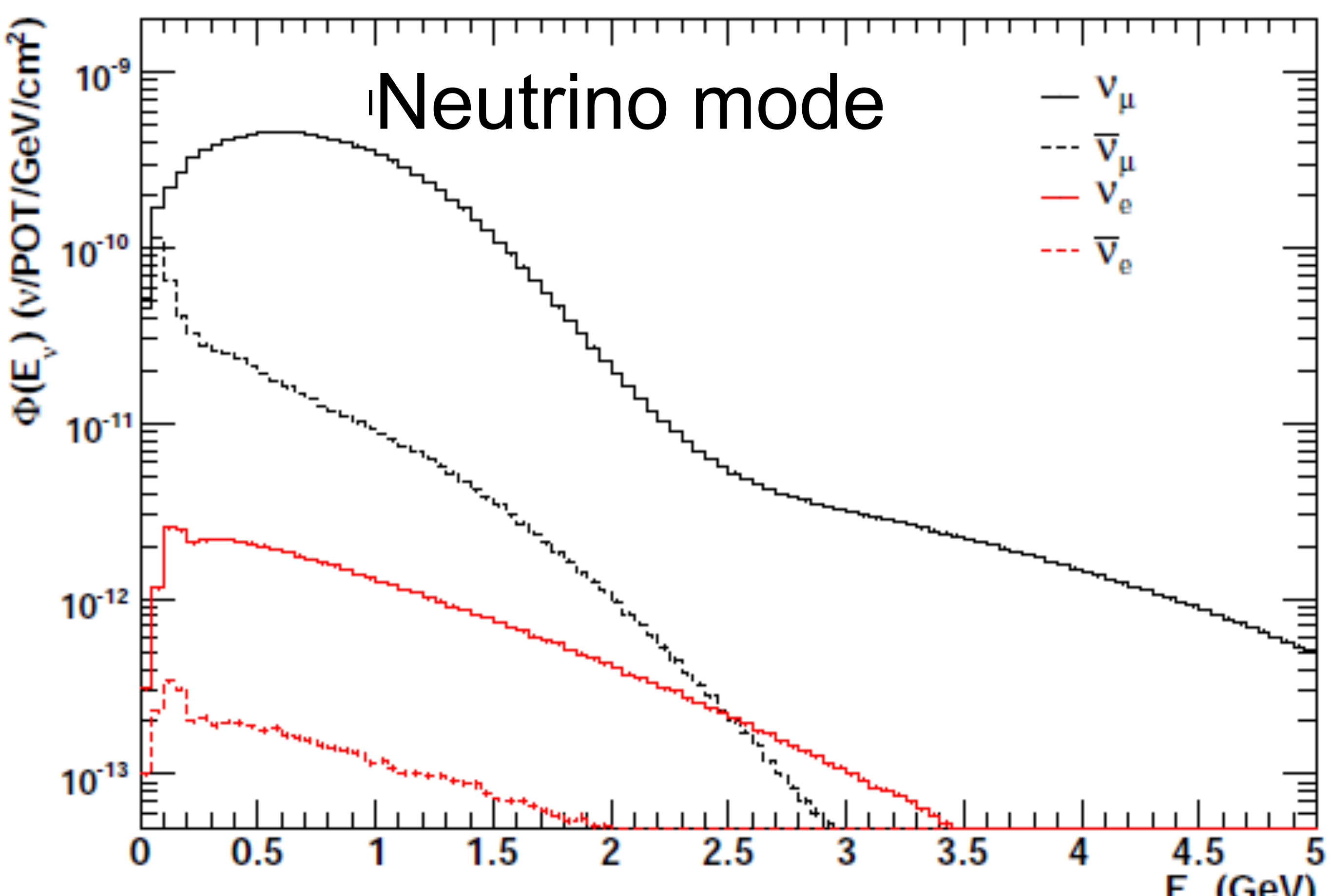


1	TARGET BASE BLOCK
2	BELLOWS CONTACT ASSEMBLY
3	UPSTREAM TARGET SLUG LOCATOR & RING
4	TARGET SLUG, UPSTREAM
5	TARGET SLUG PIN
6	TARGET SLUG, MIDDLE
7	TARGET SLUG, DOWNSTREAM
8	AIR COOL STANDOFF
9	TARGET BASE WINDOW FLANGE
10	TARGET BASE BE WINDOW
11	TARGET BASE PLUG
12	OUTER TUBE LOCK RING
13	OUTER TUBE FLANGE
14	OUTER TUBE
15	DNSTREAM TARGET SLUG LOCATOR & GASKET



Neutrino Flux Prediction

- Geant4 based MC used to predict the flux
- Hadron production cross sections tuned to external data
- Proton, pion cross sections on Be, Al tuned



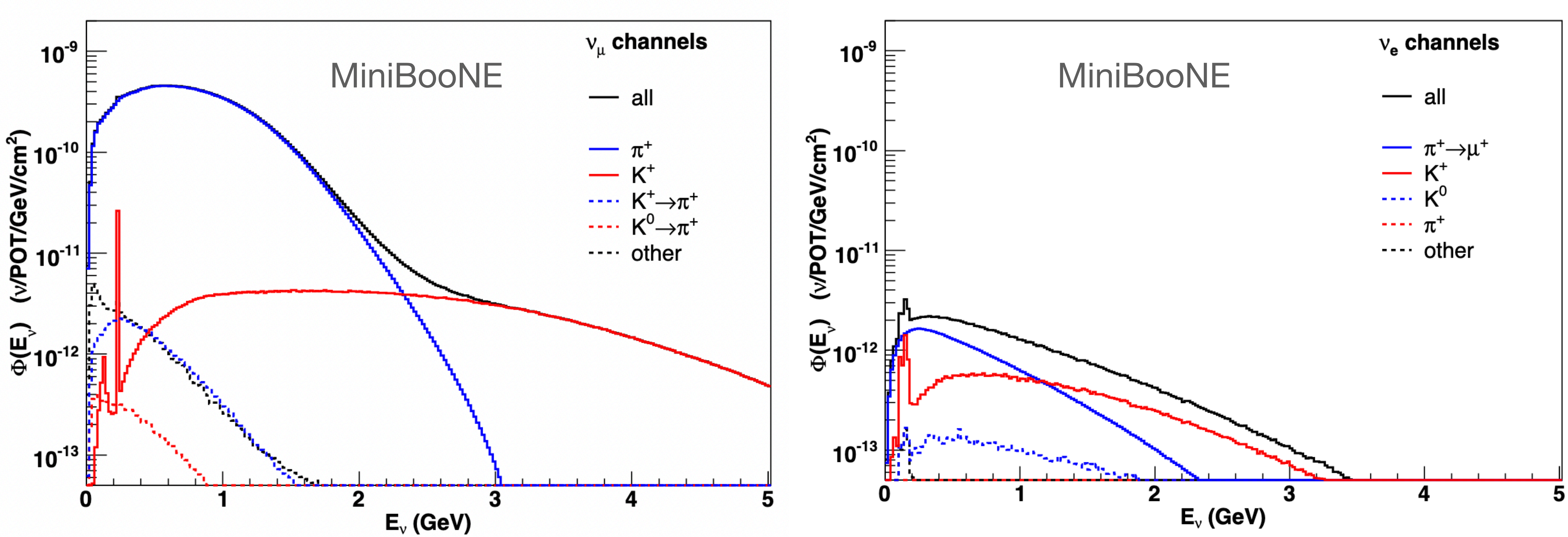
Phys. Rev. D79, 072002 (2009)

	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%

Neutrino Flux Prediction (cont'd)

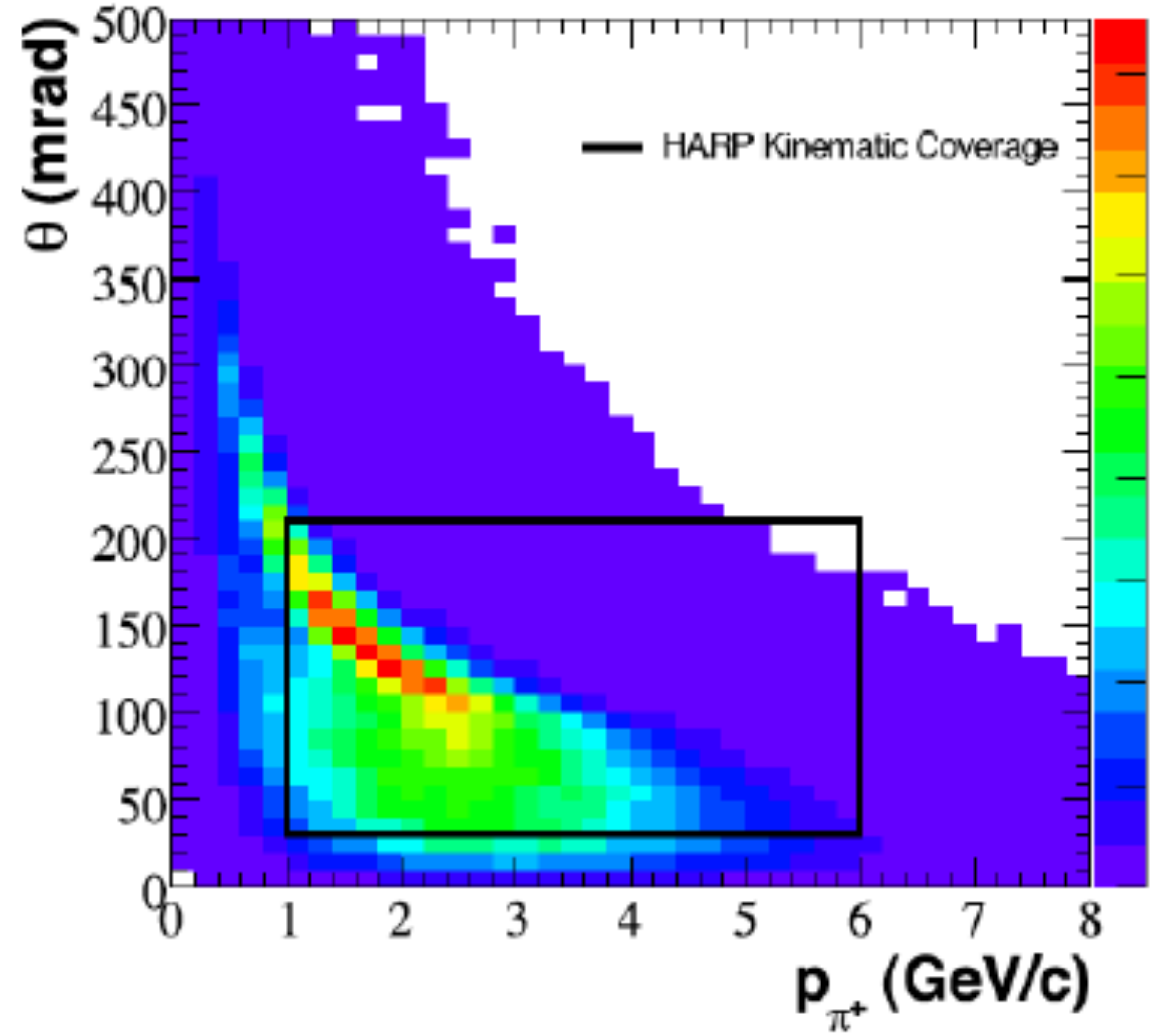
- Flux broken by neutrino parent
- ν_es from π->μ->ν_e highly correlated with ν_μs. Used to constrain systematics in ν_e related analyses

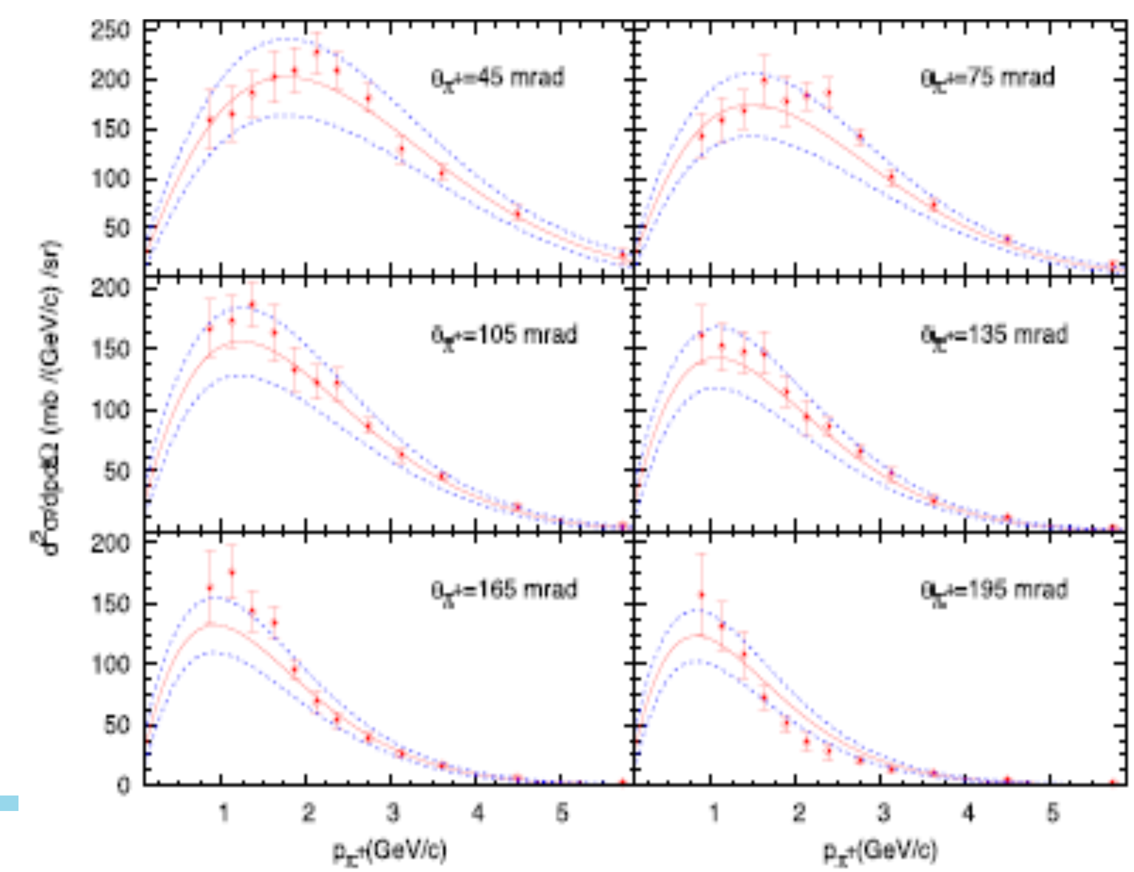


Phys. Rev. D79, 072002 (2009)

Pion production

- Sanford-Wang fits
- HARP (thin target)
  - 8.89GeV p on Be target
  - P = 0.75 – 6.5 GeV/c,
  - θ = 30 – 210 mrad
- E910
  - 6.4, 12.3, 17.5 GeV/c
  - P=0.4 – 5.6 GeV/C,
  - θ = 18 – 400 mrad
- Fits done both for pi+ and pi-

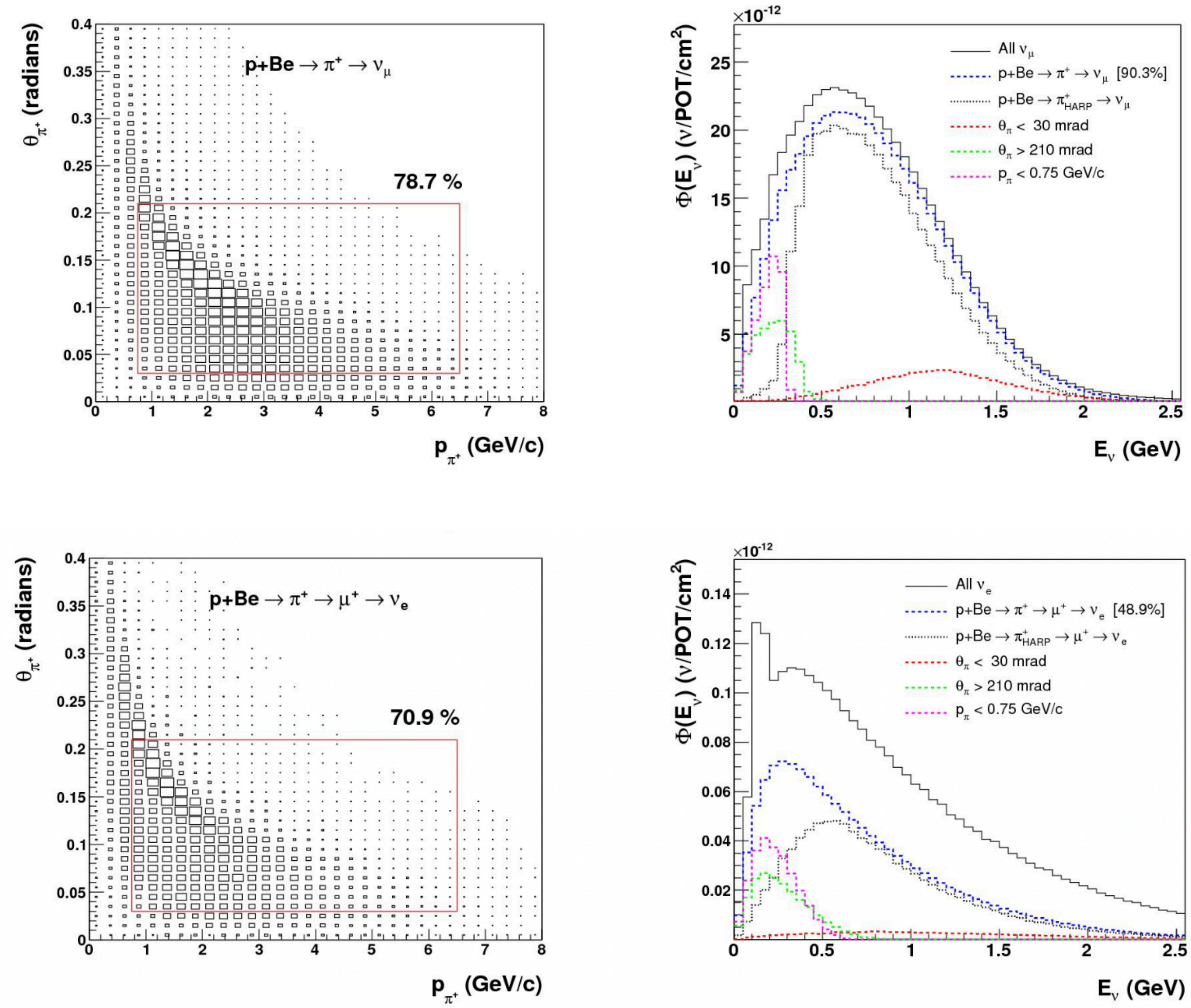




Phys. Rev. D79, 072002 (2009)

HARP coverage

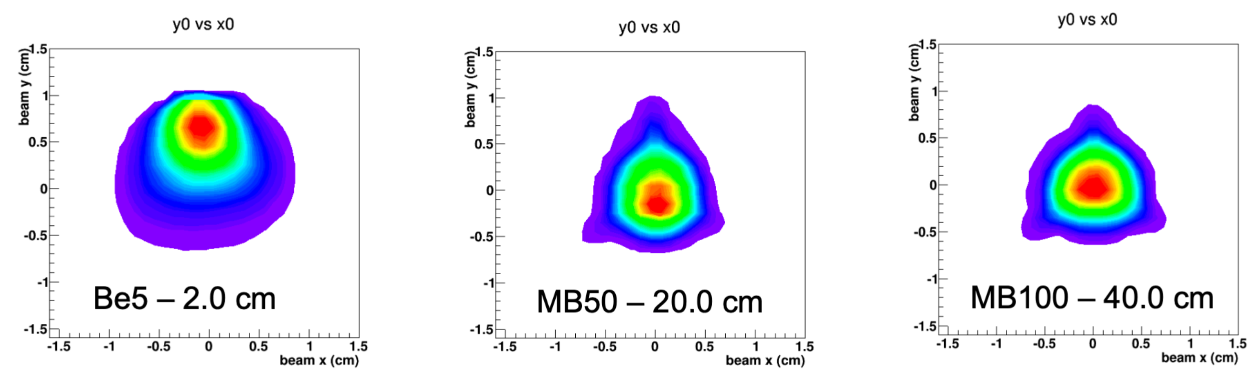
- 90.3% of ν_μs from primary pion production in the target
  - 78.7% covered by HARP
- 48.9% of ν_es from primary pion production
  - 70.9% covered by HARP



D. Schmitz, FERMILAB-THESIS-2008-26

HARP Thick Target Data

- Not directly used in flux prediction, simulation tuned to HARP thin target data
- Cross checks done with thick target data sets
- Good agreement with simulation
  - Double ratios at 2% level



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

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

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

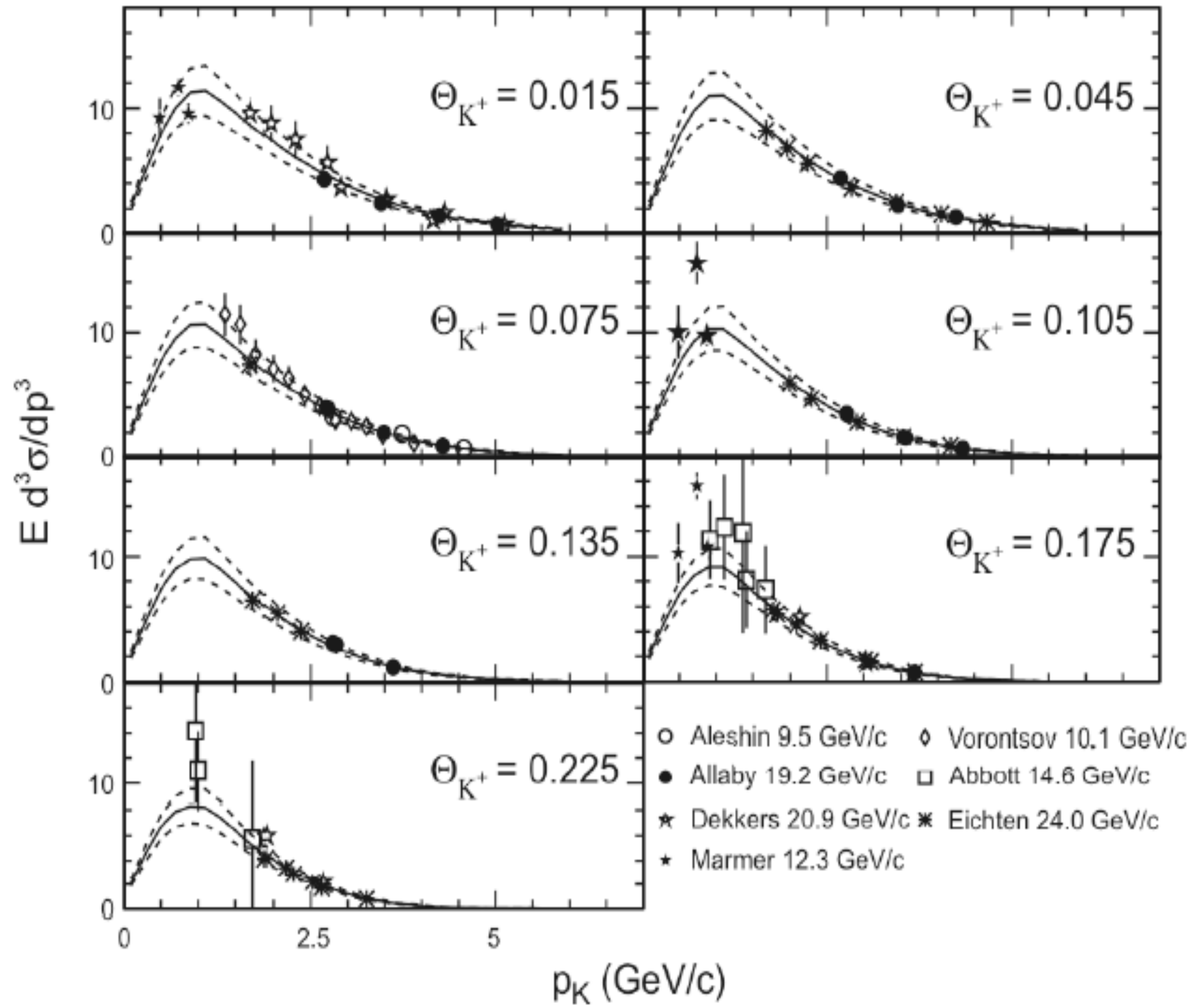
DATA	Beam radius cut (reduce the edge effect)	P.O.T
MB100	0.4 cm	622791
MB50	0.4 cm	814749
Empty	0.4 cm	475776
Be5	1.0 cm	13070000
Empty	1.0 cm	1990000

A. Wickremasinghe, FERMILAB-THESIS-2015-23

K^+ and K^0_L Production

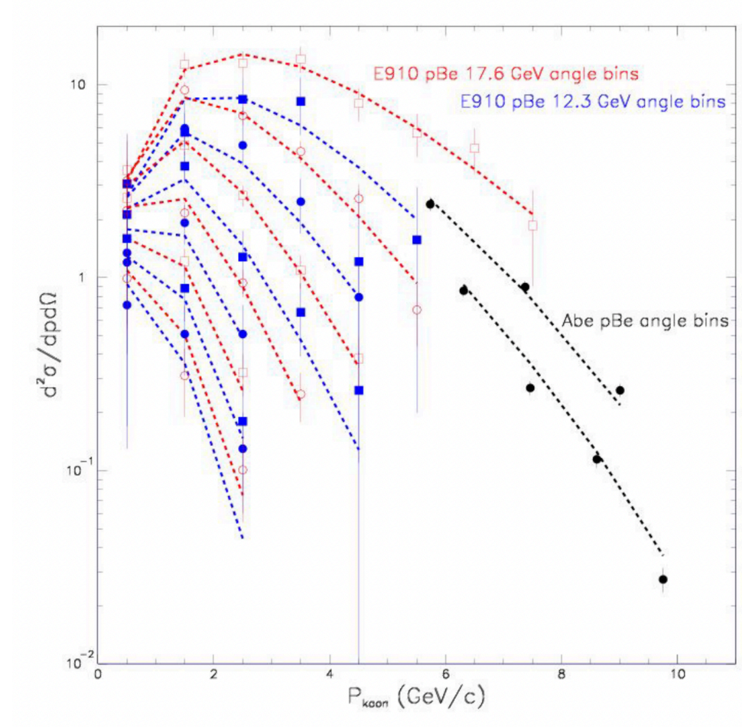
- Feynman scaling based parameterization used to fit world K+ production data
- Datasets scaled to 8.89GeV cover 1.2< $P_K^{8.89}$ [GeV /c] <5.5
- Some of the datasets had issues with normalization

  Phys. Rev. D84 114021 (2011)



- Sanford-Wang fits to K^0_S production data from BNL E910 (p_{beam} = 12.3 and 17.5 GeV/c) and KEK Abe et al. (12.3 GeV/c)
  - Most relevant forward production not fully covered

  Phys. Rev. D79, 072002 (2009)

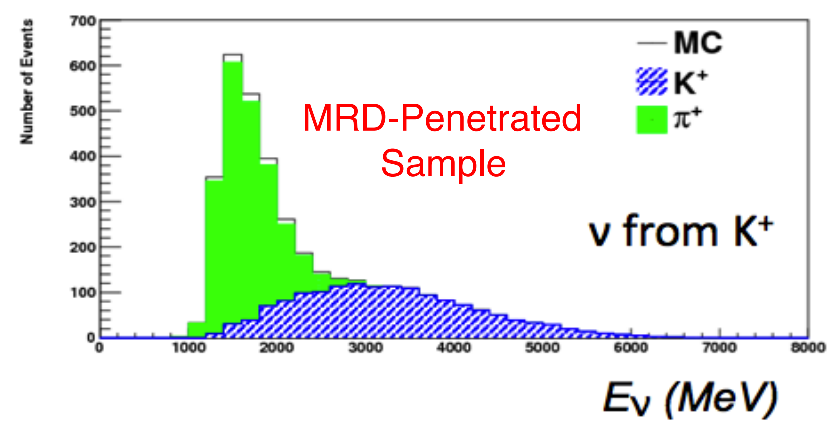


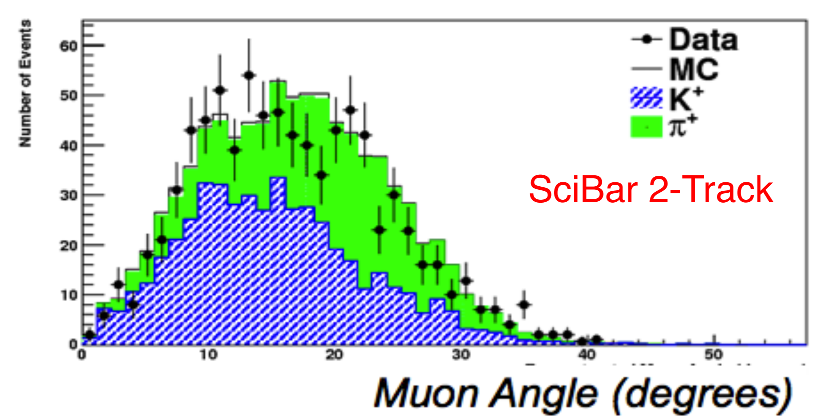
Fermilab

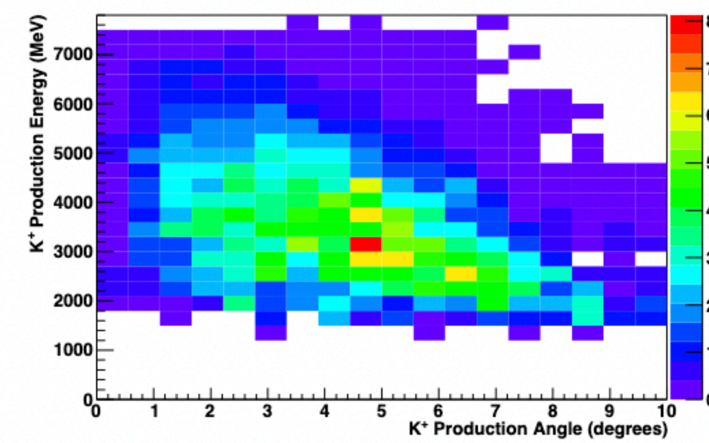
K+ in BNB

- Kaon production further constrained by SciBooNE measurements
- High energy neutrinos from K+
- Found production to be 0.85+-0.12 relative to the global fit to kaons
- Joint fit to global K+ data and SciBooNE

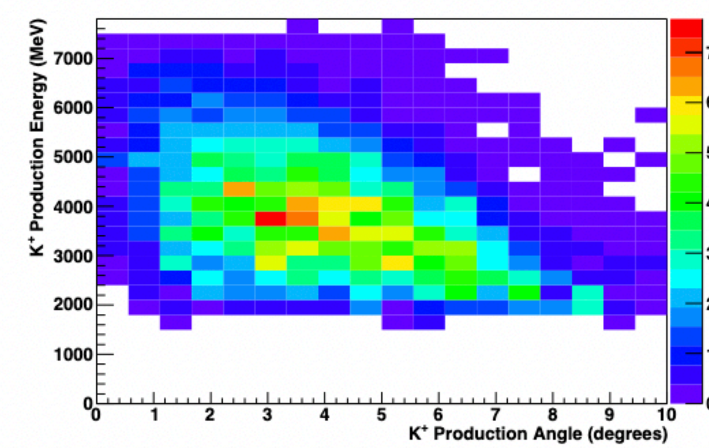
Phys.Rev.D84,012009 (2011)



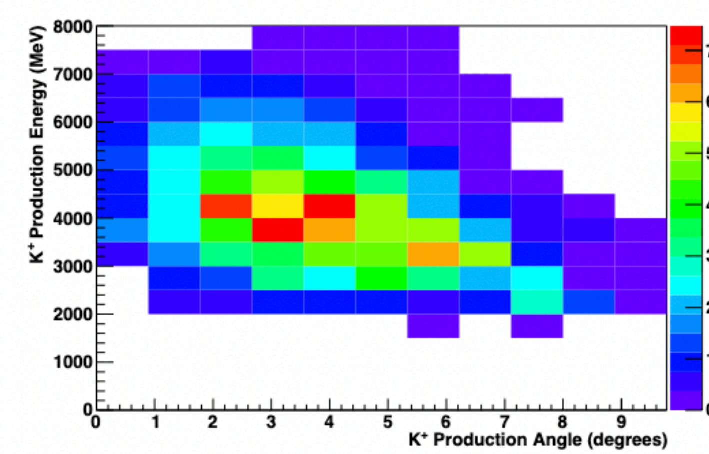




(a) 1-Track Sample



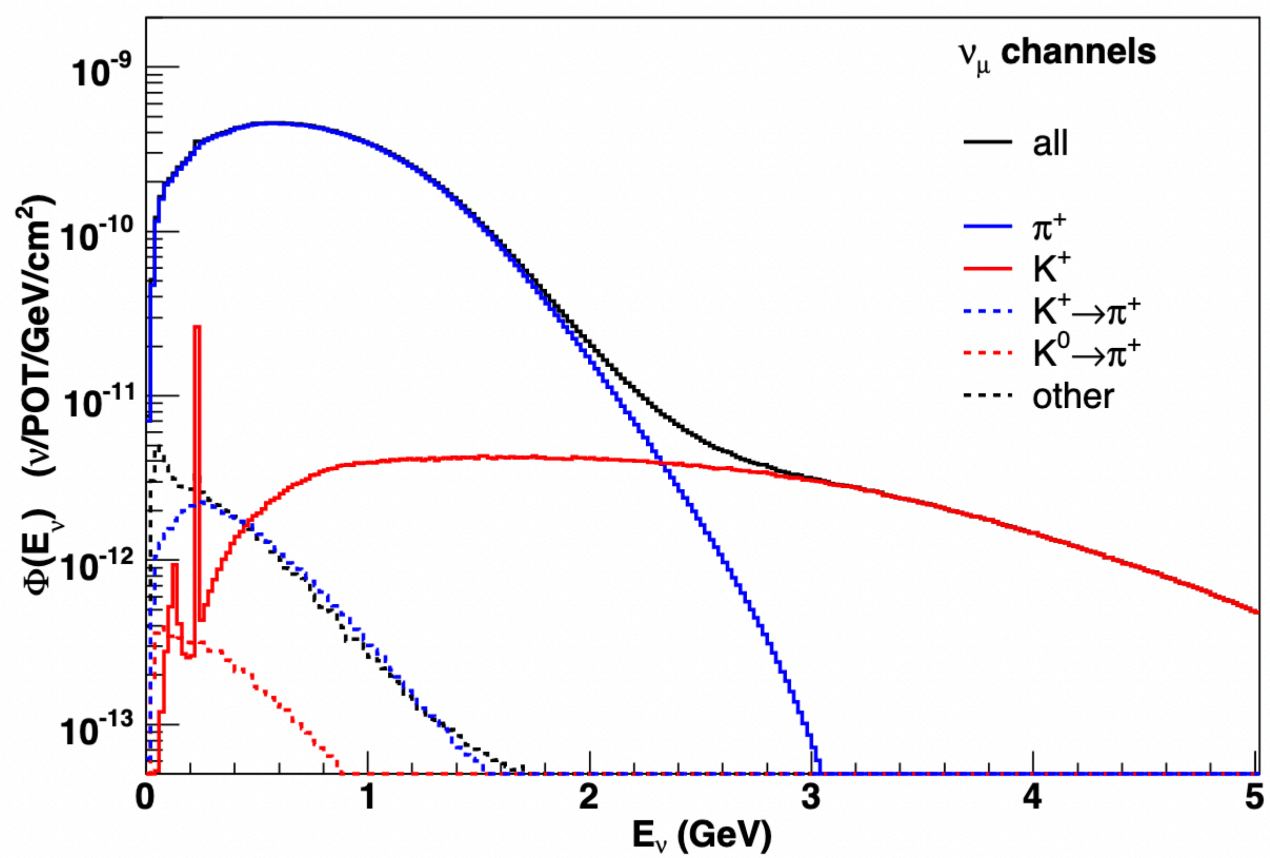
(b) 2-Track Sample



(c) 3-Track Sample

Other particles

- Proton, neutron and K- production in p+Be modeled using the MARS hadronic interaction package
- Overall contribution to neutrino flux small
- HARP proton production data not used
  - Not covering fully the relevant phase space - O(1%) of ν_μ/ν_e flux in neutrino mode
  - Proton production becomes more relevant if probing further into lower energies with better detectors

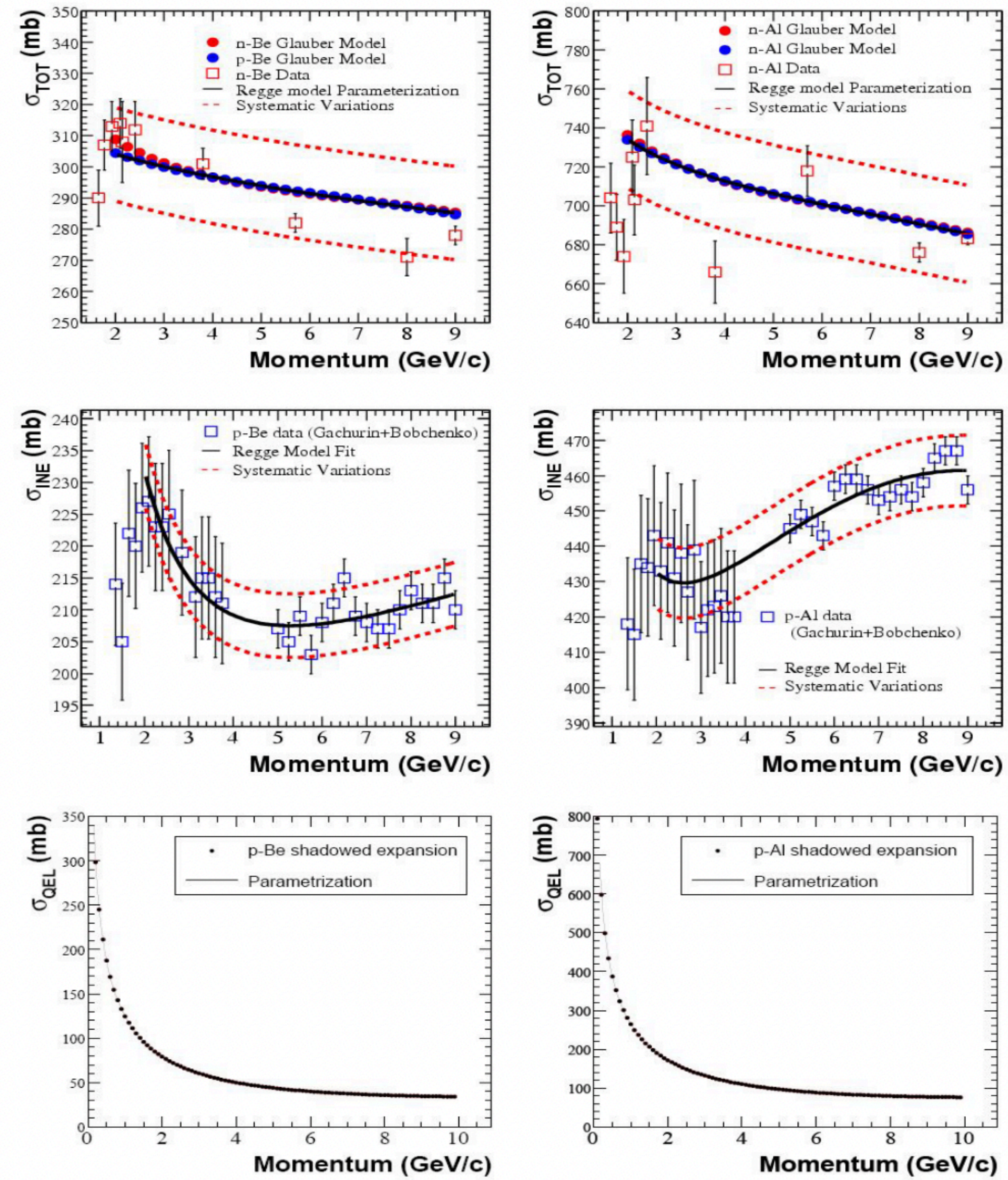


Hadronic interactions

- Where possible measured cross sections used
- QEL largest effect

	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)

	$\Delta\sigma_{TOT}$ (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



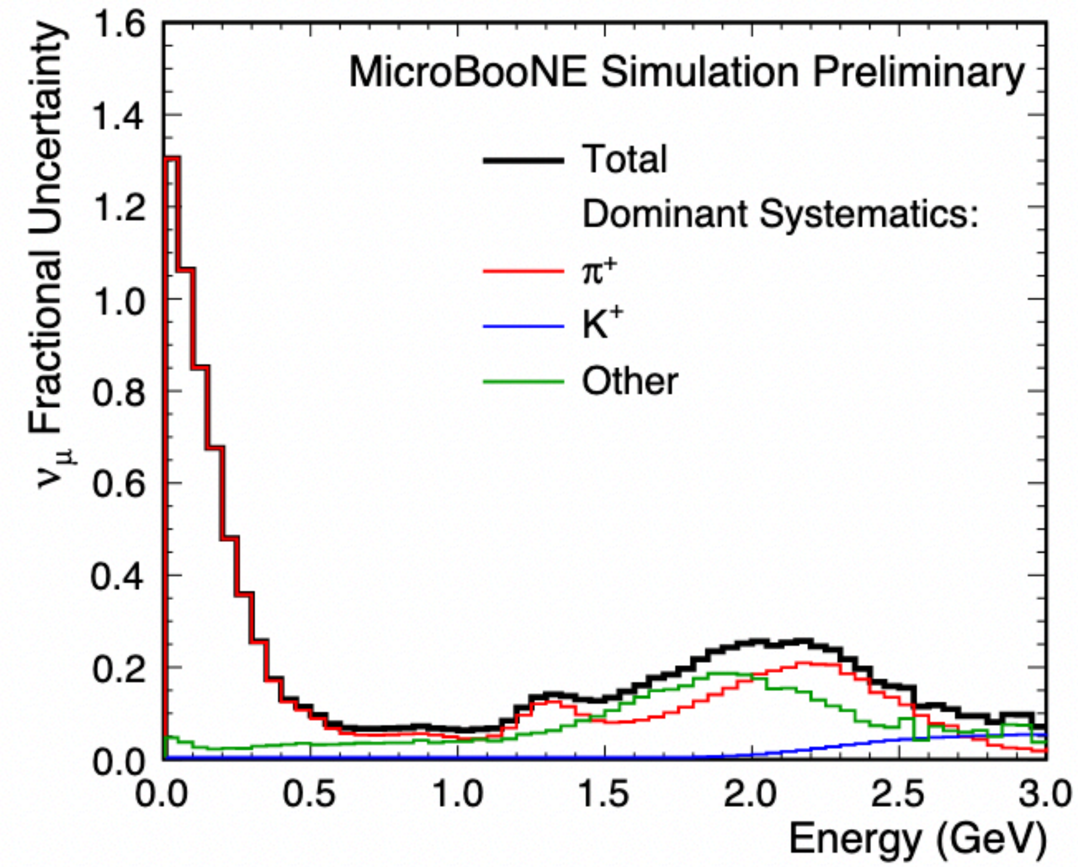
Phys. Rev. D79, 072002 (2009)

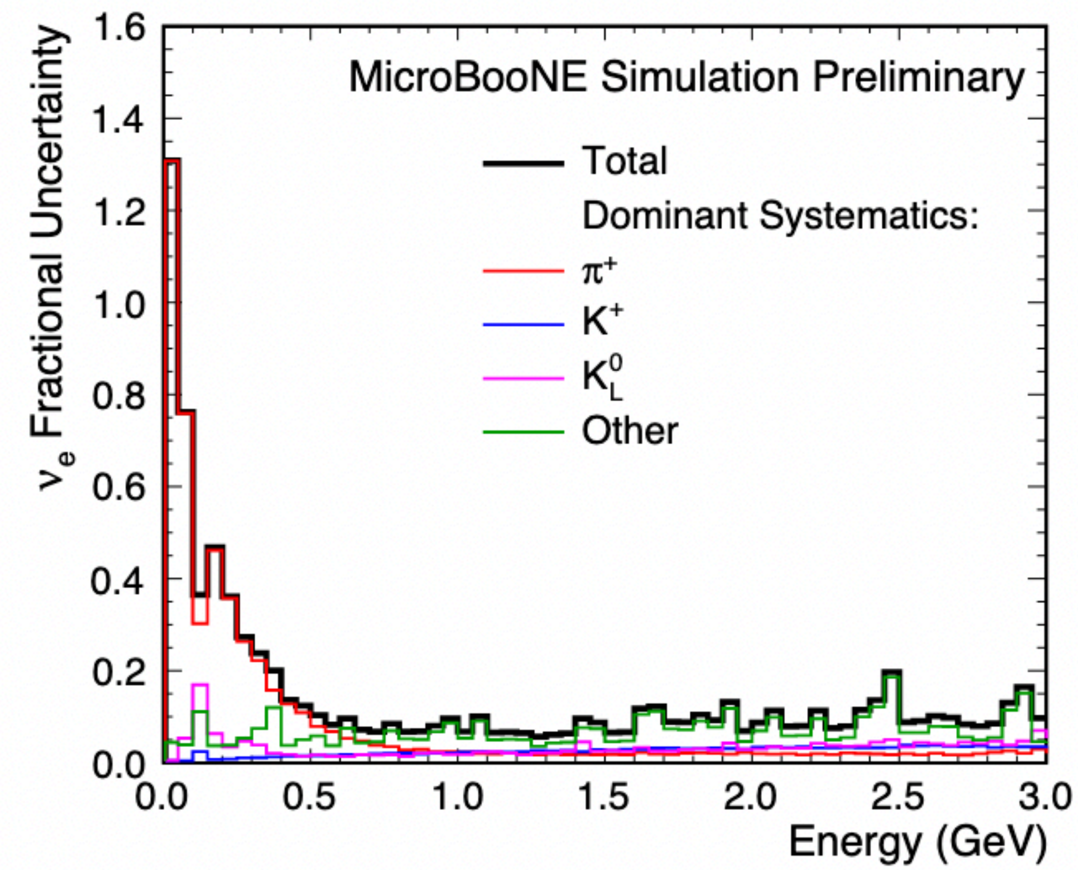
D. Schmitz, FERMILAB-THESIS-2008-26

Systematic errors

- Full propagation of HARP errors using splines (many universes)
- Kaon production errors from parameterization fit parameter errors (many universes)
- Other parameters varied +-1 sigma

Systematic	$\nu_\mu/\%$	$\bar{\nu}_\mu/\%$	$\nu_e/\%$	$\bar{\nu}_e/\%$
Proton delivery	2.0	2.0	2.0	2.0
π^+	11.7	1.0	10.7	0.03
π^-	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^0_L	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

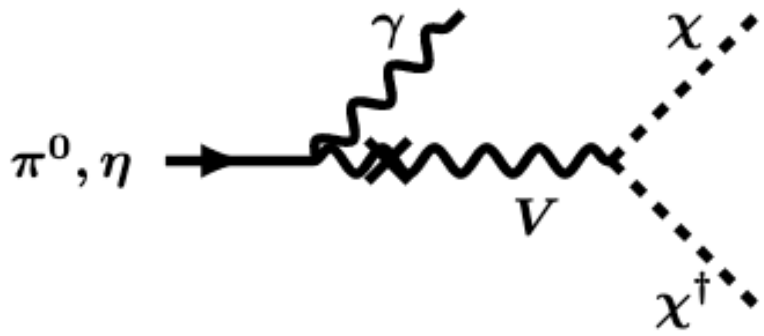


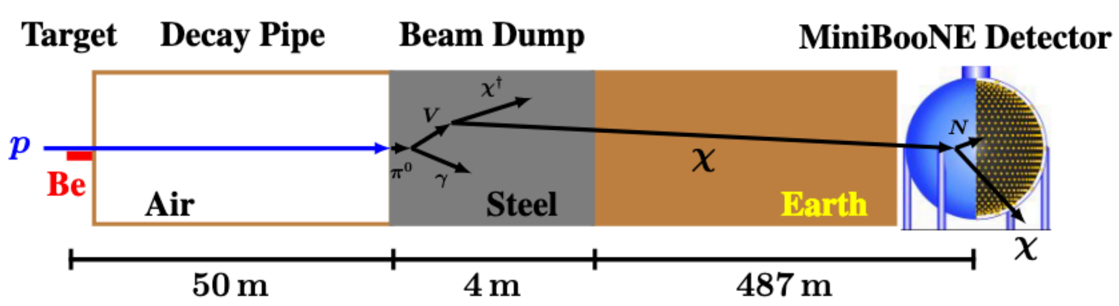


MICROBOONE-NOTE-1031-PUB

Dark Matter Searches

- Searching for dark matter production in the BNB
- π^0 production important for these analyses
  - Not important for neutrino related analysis, so not typically included in beam simulation
  - Averaged π^+/π^-
- To further improve sensitivity MiniBooNE ran in beam off-target mode
  - Steer beam directly to absorber (steel) missing the target
  - Neutrinos background for this search

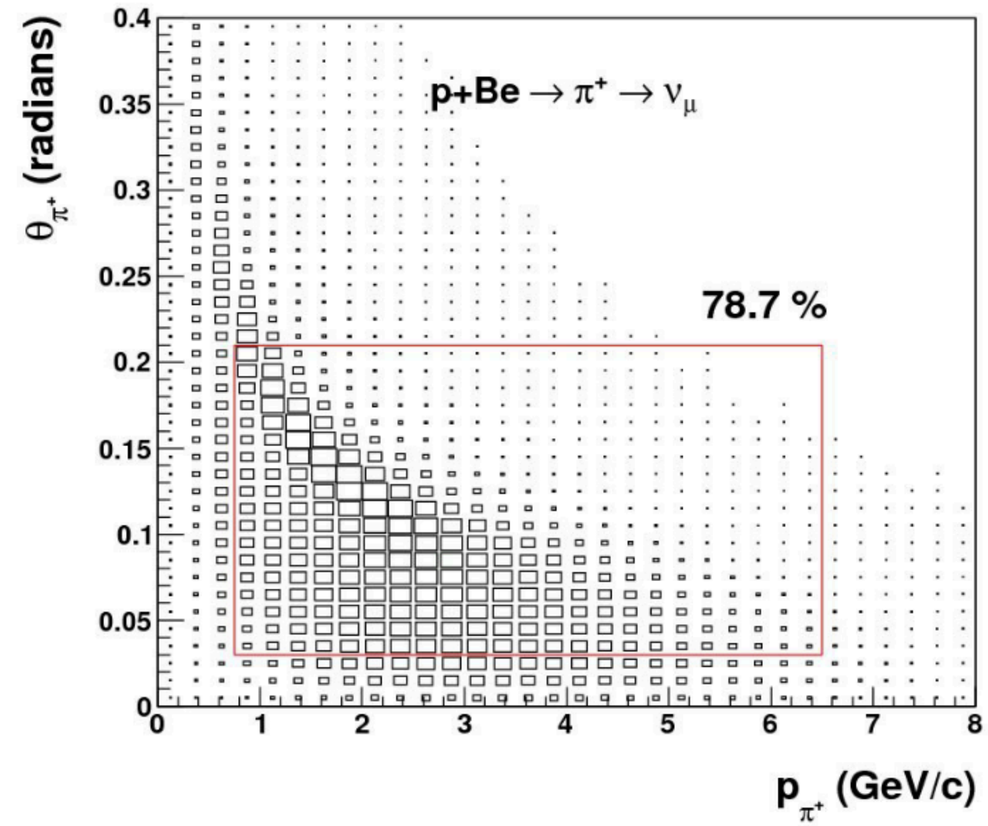


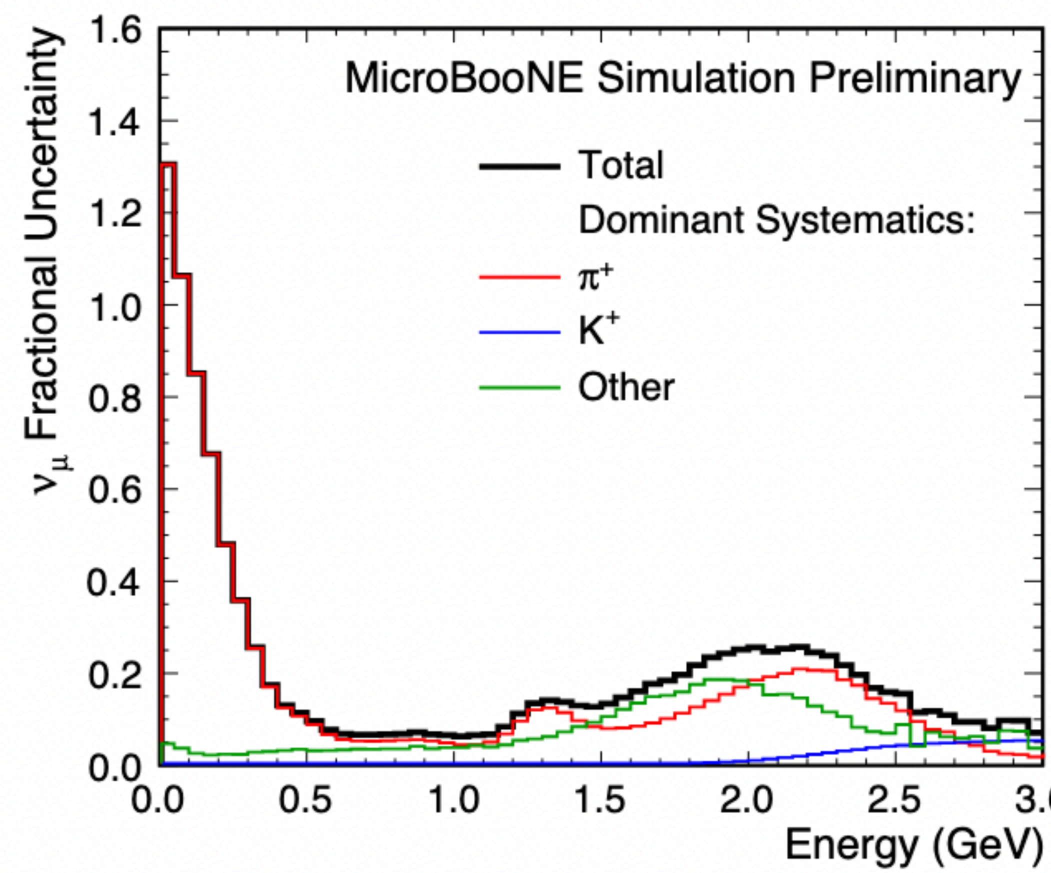


Phys. Rev. D 98, 112004 (2018)

Conclusion

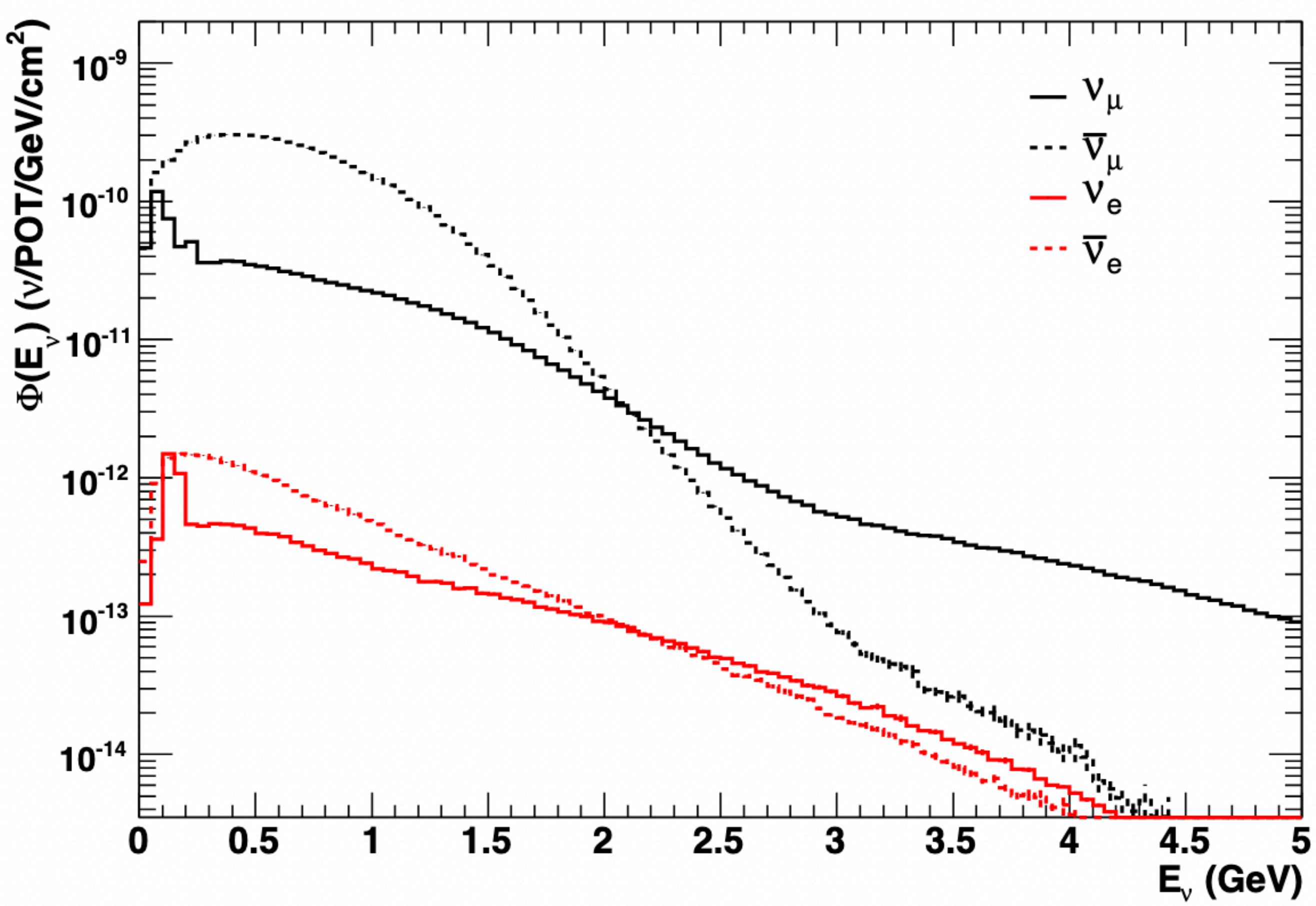
- Several possible measurements to improve BNB flux
- Pion production data below 750 MeV/c and angles out to 350 or 400 mrad for p+Be interactions at 8 GeV (where we currently have no data from HARP)
- New pion production data in the bulk of the phase space with total uncertainties at the ~5% level beyond the existing HARP data (errors at 7-10% level)
- New measurements of kaon production (K+,K-,K0) for p+Be at 8 GeV would be useful
    - Currently scaling from higher energies
- Possibly replica target data though secondary reinteractions smaller effect on BNB (compared to NuMI/DUNE)





Backup

Antineutrino mode flux



	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%