Neutrino Beam Simulation

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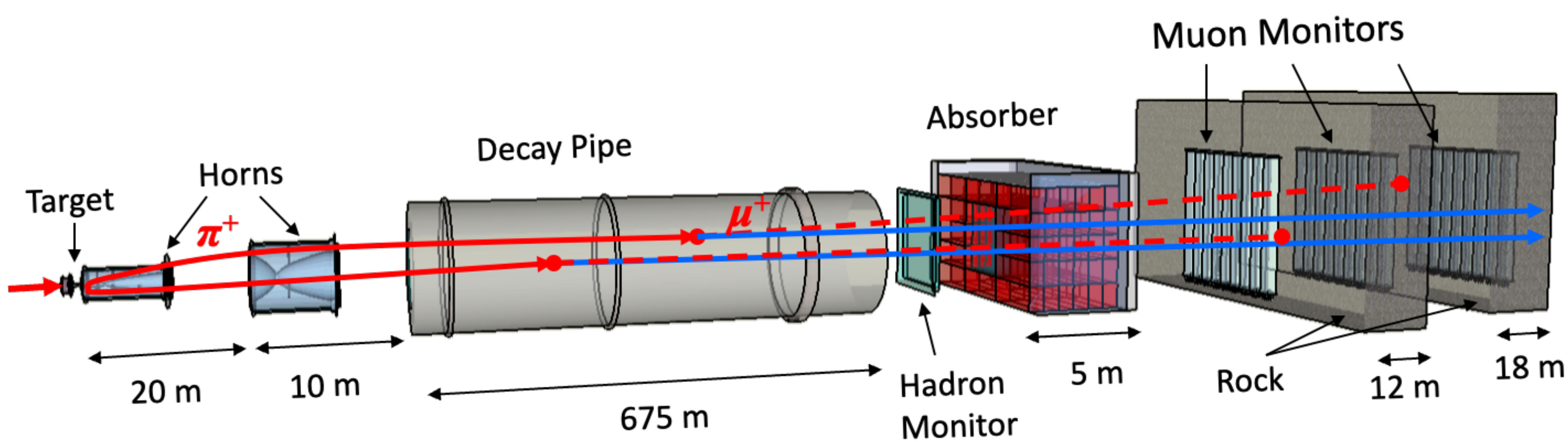
Path to Dark Sector Discoveries at Neutrino Experiments,
Colorado State University, June 2023

Fermilab Neutrino beams

- BNB, NuMI, LBNF
- Target, N focusing horn(s), decay region, absorber, detector(s)
  - Need to simulate meson production, track particles through magnetic fields down to their decay point, and calculate the probability for neutrino to hit the detector

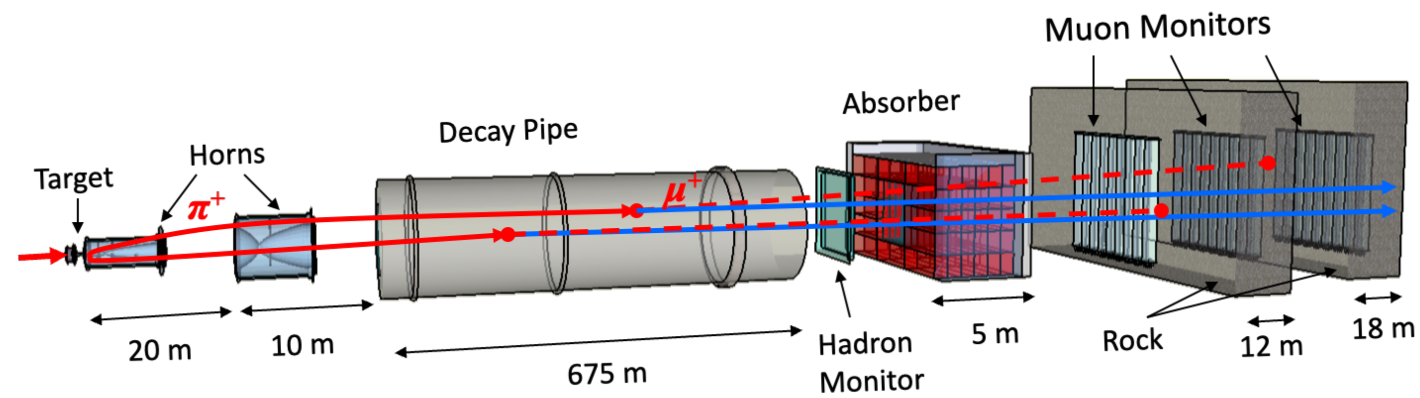


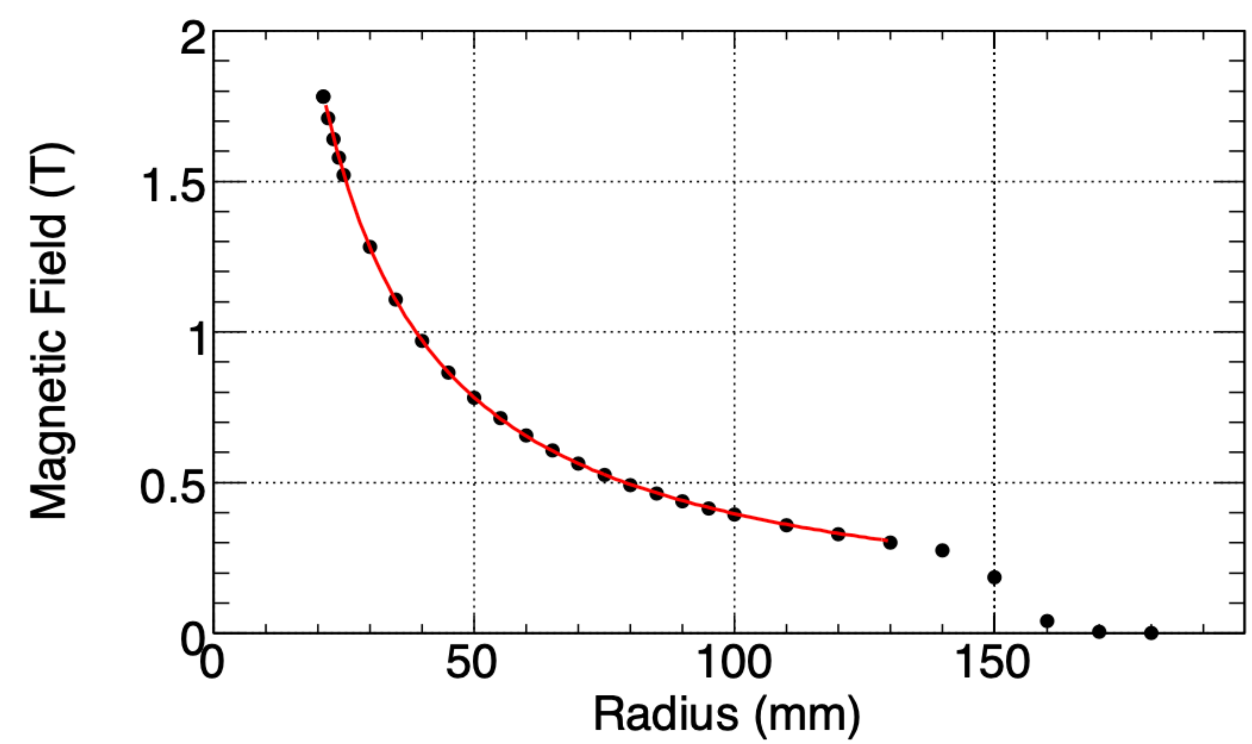
Calculating neutrino flux

- Over the years the simulations have evolved and there were several simulations in use
- Fast parametric Monte Carlo
  - Used in early days of BNB/NuMI
  - Not great for predicting flux, but good to study relative impact of geometry change
- Detailed simulations
  - Past based on GEANT3/4, Fluka, Mars or some combination
  - Current simulations based on GEANT4

Geant4 simulation

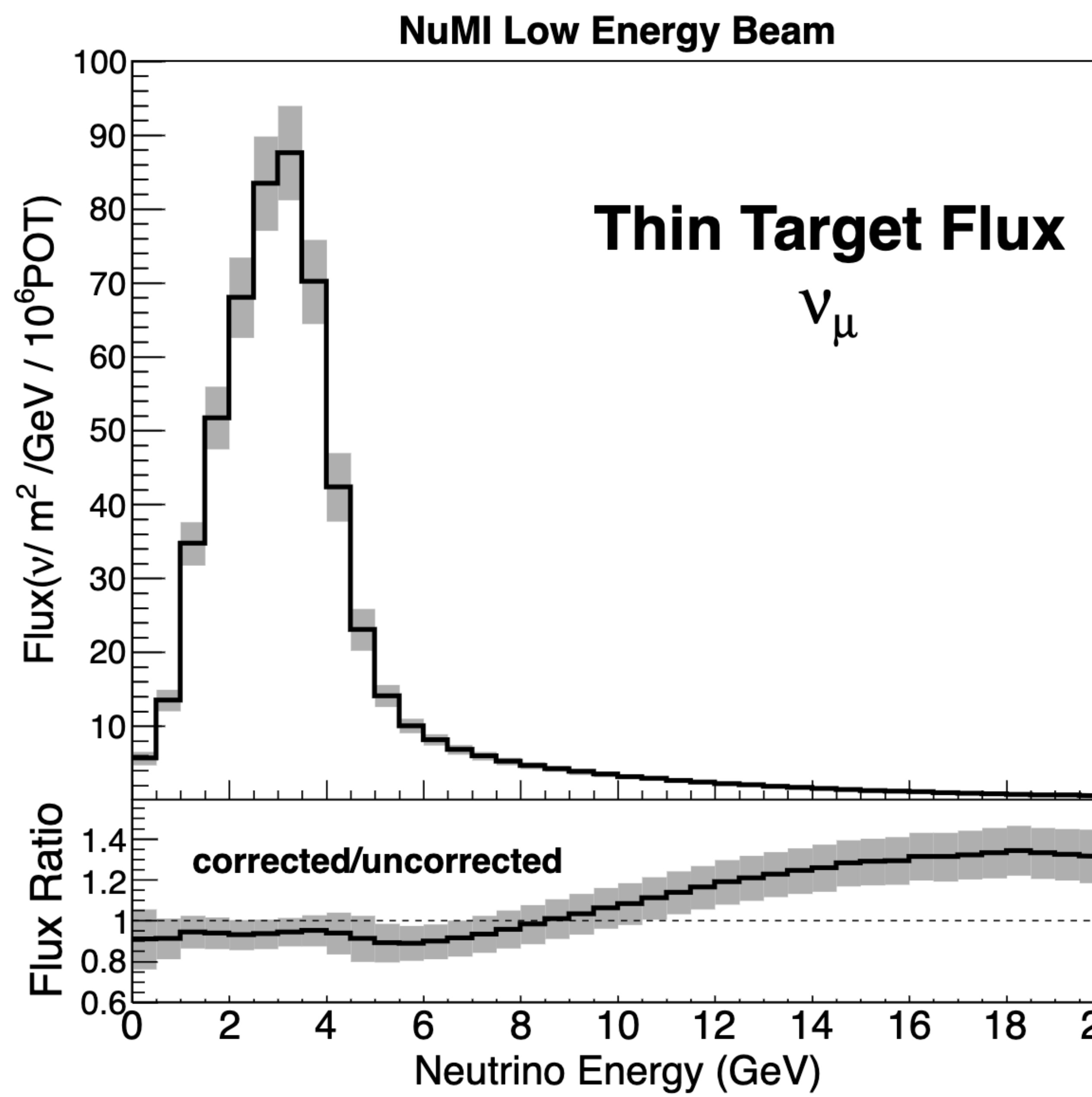
- Define beamline geometry (including magnetic fields)
- Define Physics
    - particles and processes (models, cross sections)
- Define tracking cuts
- Track particles and record all events producing neutrinos



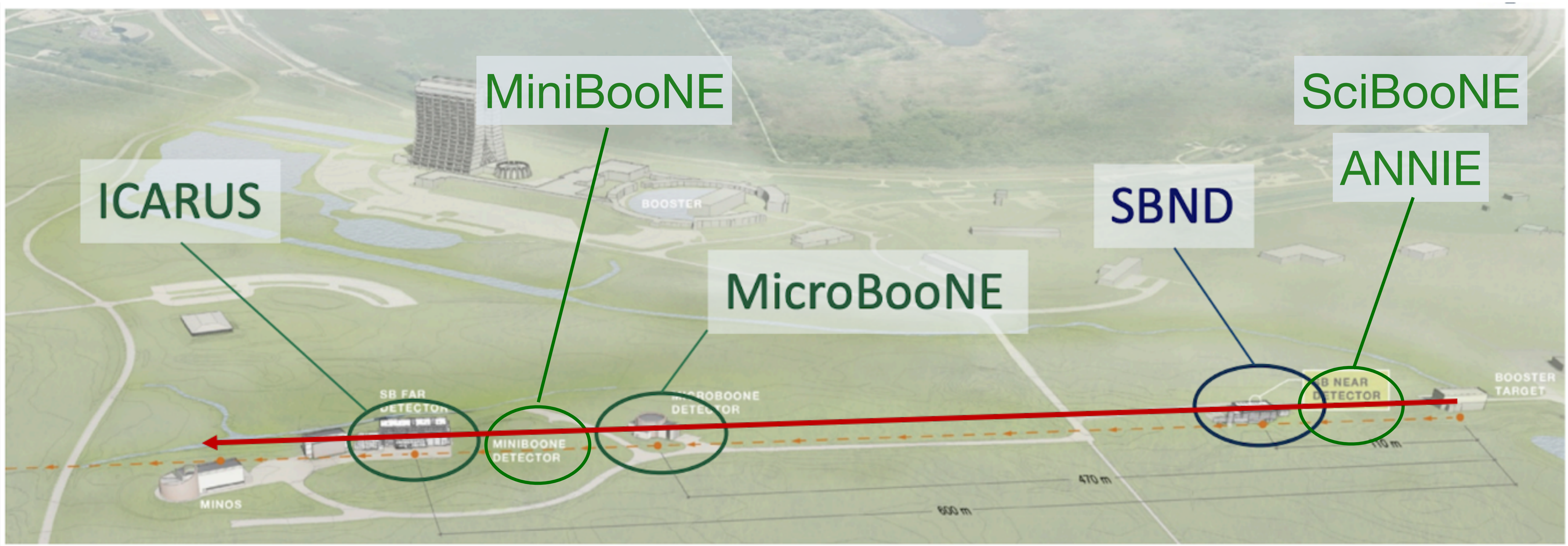


Tuning GEANT4

- Models improving over the years, but many differ from data
- Not expecting perfect match to data for all the processes that matter for neutrino flux
- Tuning done by modifying the geant4 models and/or reweighing
  - Using external data that covers the phase space relevant for neutrino flux

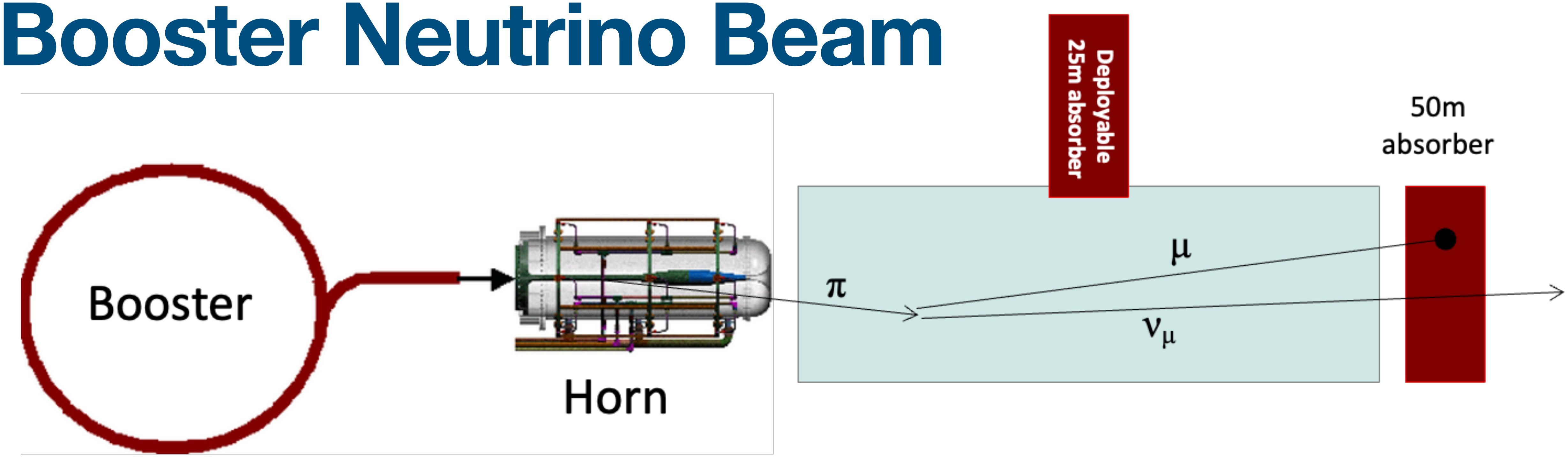


Booster Neutrino Beam

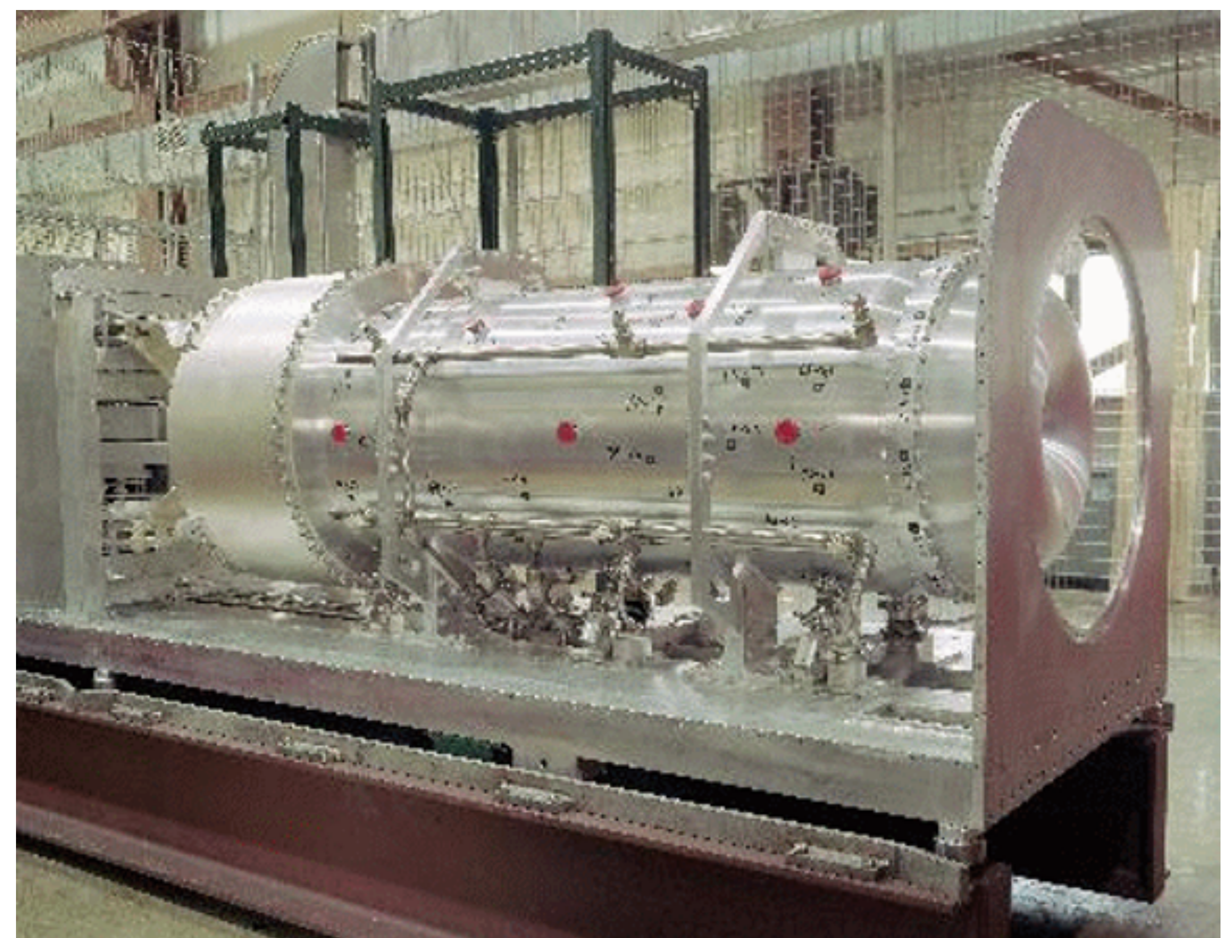


- Broad physics program using BNB
  - Sterile neutrinos
  - Neutrino cross sections
  - Exotic BSM models (explain MiniBooNE low energy excess)
  - Dark matter searches

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

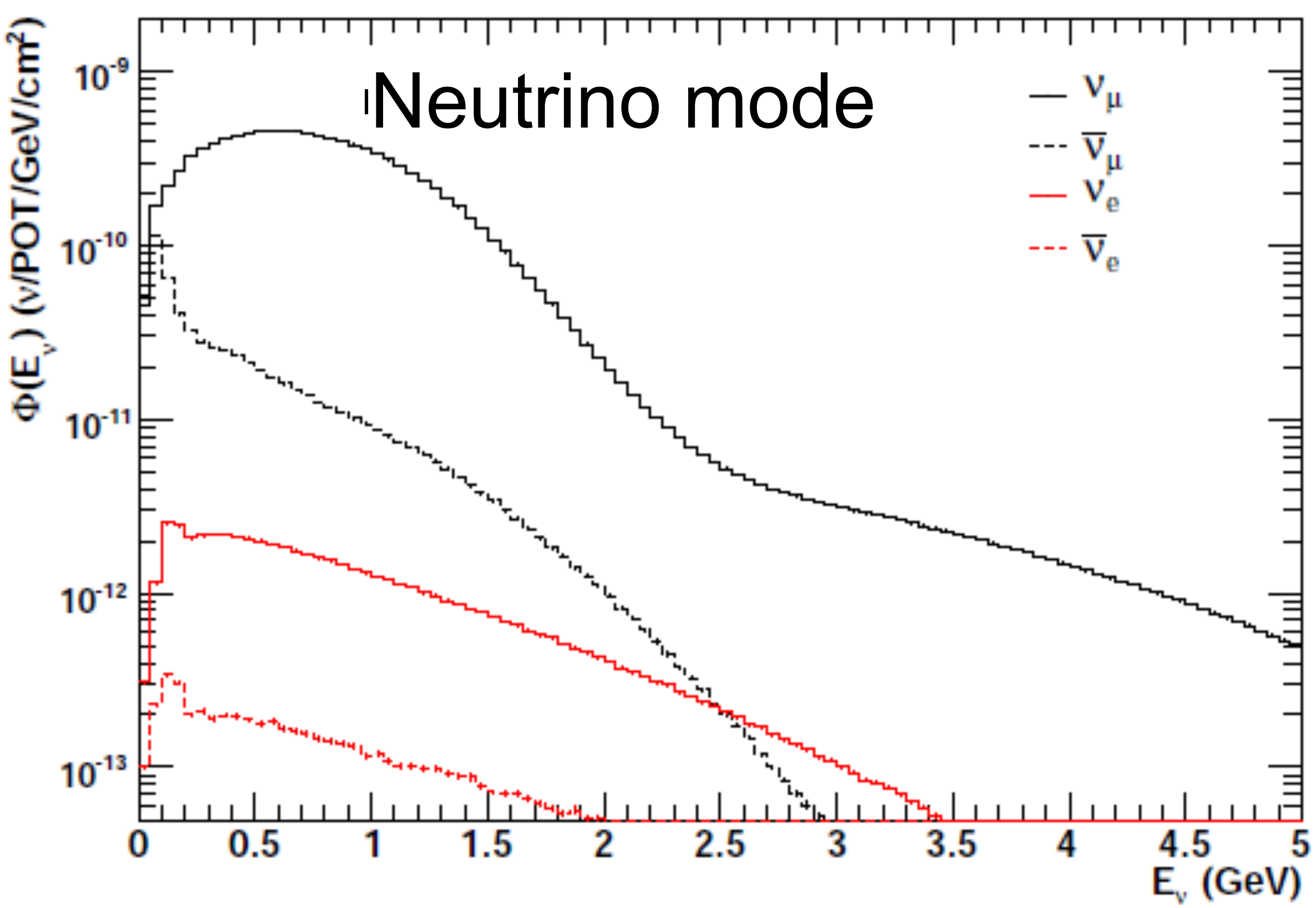


BNB Flux simulation (BooNEG4Beam)

- Geant4 based simulation (g4.8.1)
- Currently default for all SBN experiments
- Ongoing work on upgraded version using more recent version of geant4 - g4bnb
    - Using same external data constraints

Neutrino Flux Prediction

- Default simulation developed to mainly support the sterile neutrino searches and neutrino cross sections
- Hadron production cross sections tuned to external data
- Proton, pion cross sections on Be, Al tuned



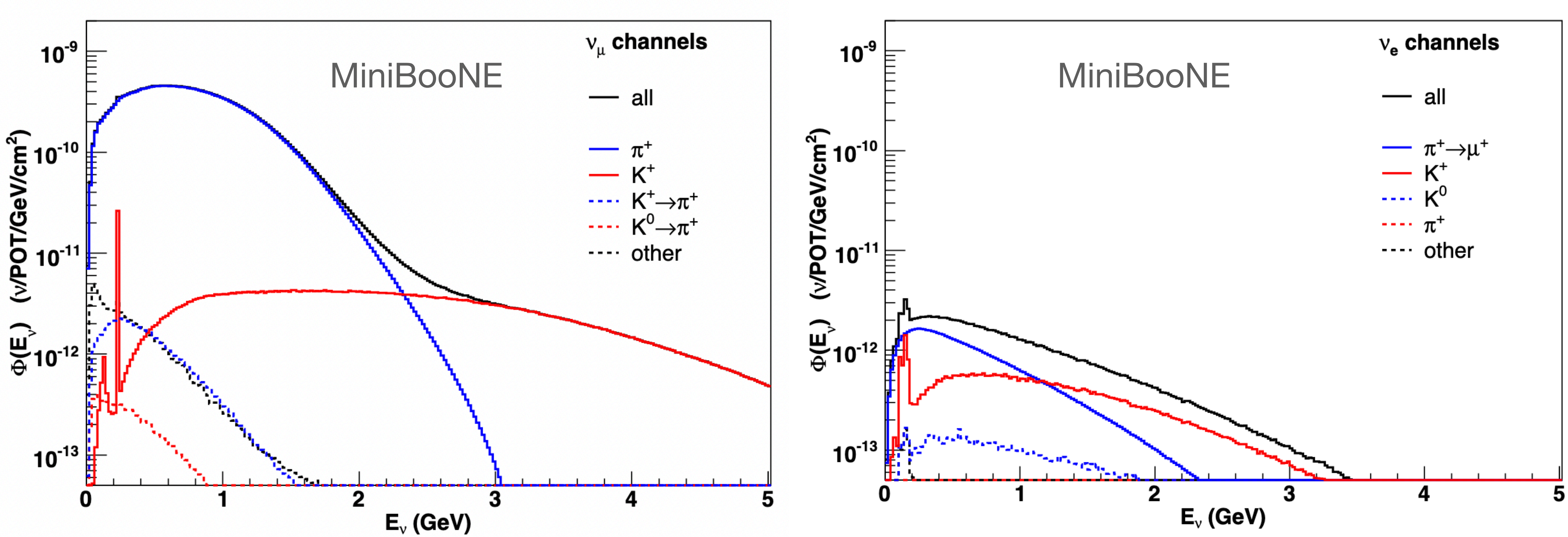
Phys. Rev. D79, 072002 (2009)

	ν_μ		$\bar{\nu}_\mu$	
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		$\bar{\nu}_e$	
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_L^0:	70.65%
	K^+:	37.28%	$\pi^- \to \mu^-$	19.33%
	K_L^0:	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



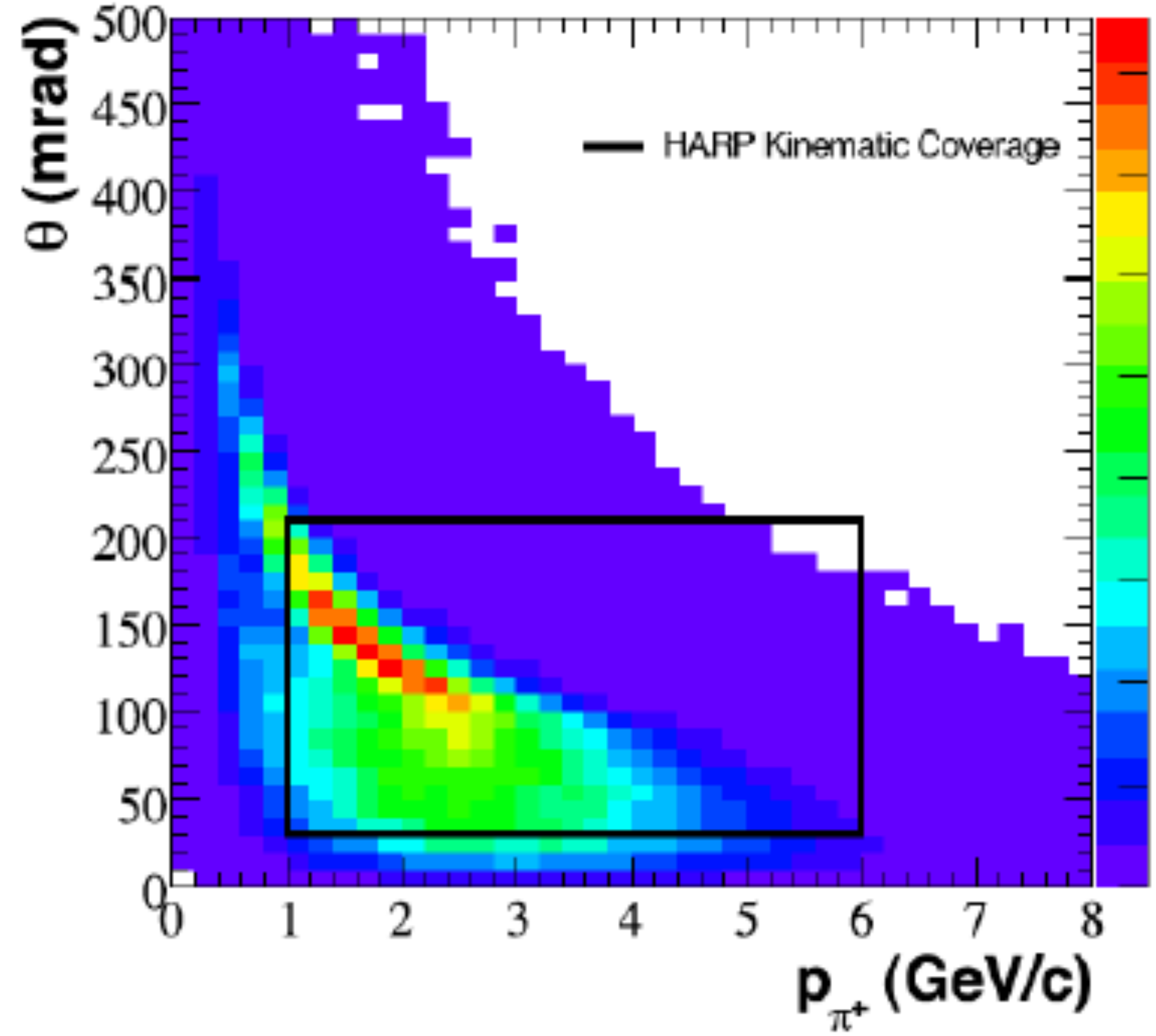
Phys. Rev. D79, 072002 (2009)

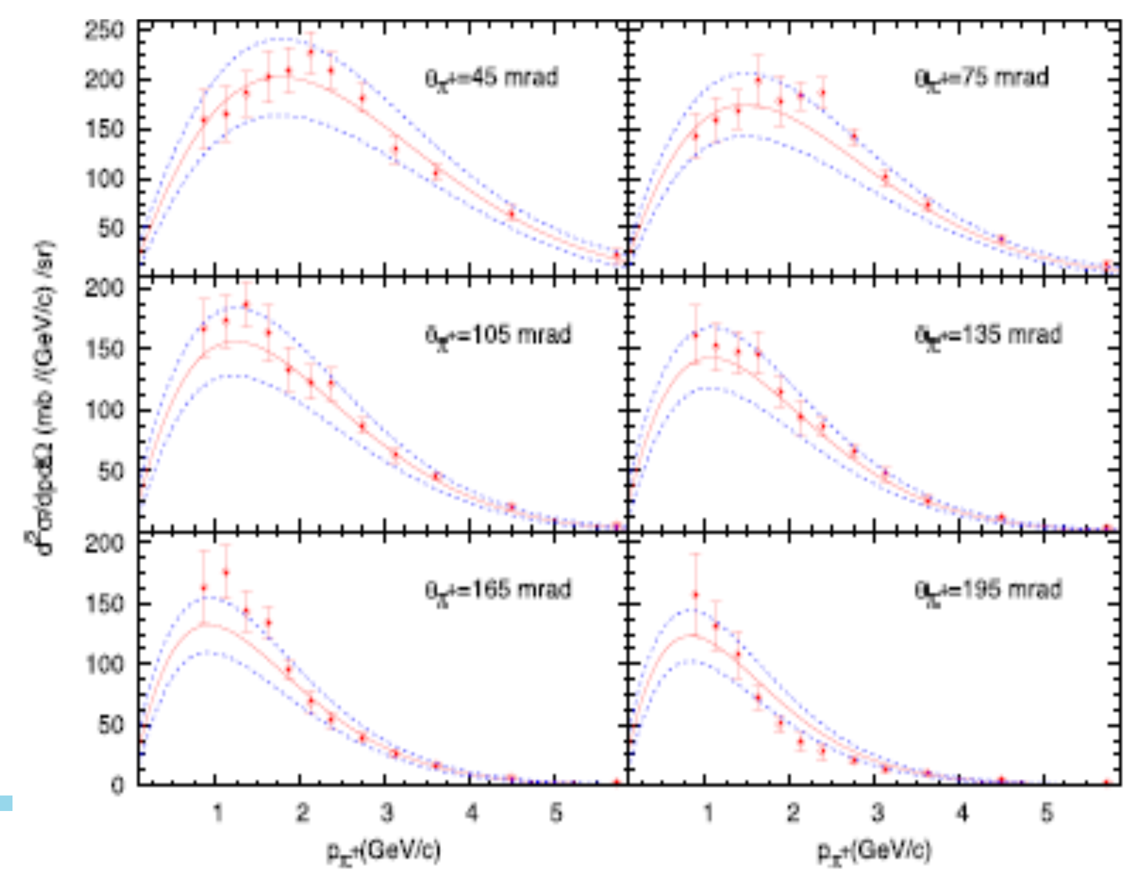
Pion production

- 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-

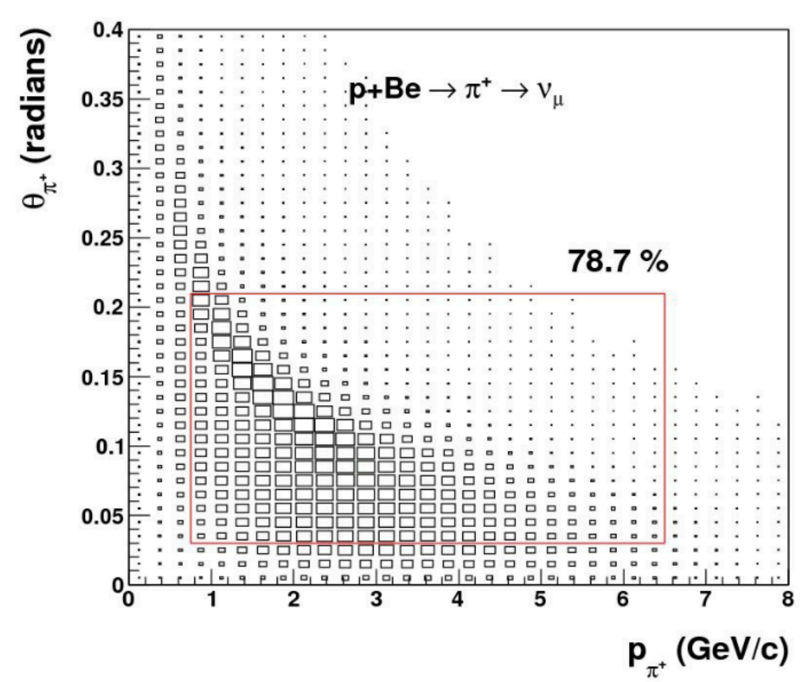
Phys. Rev. D79, 072002 (2009)

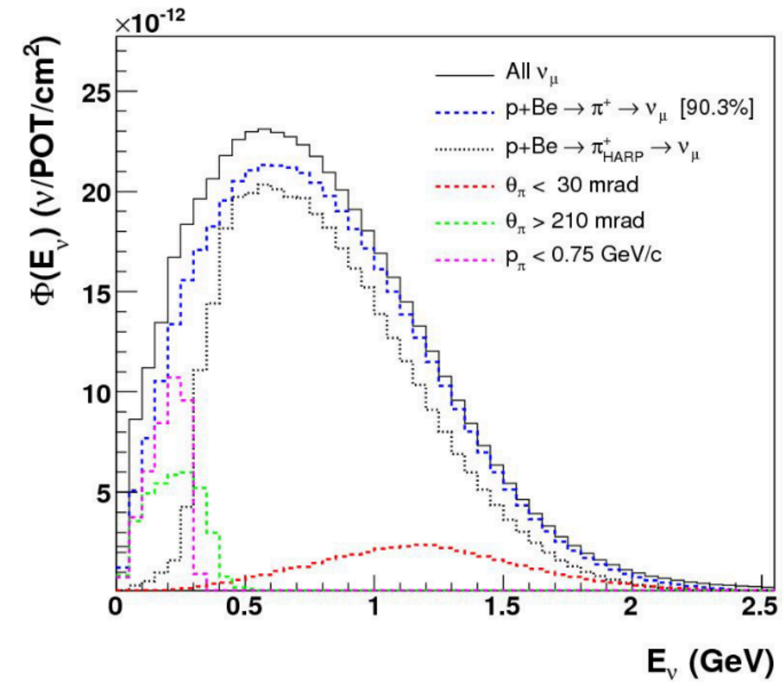


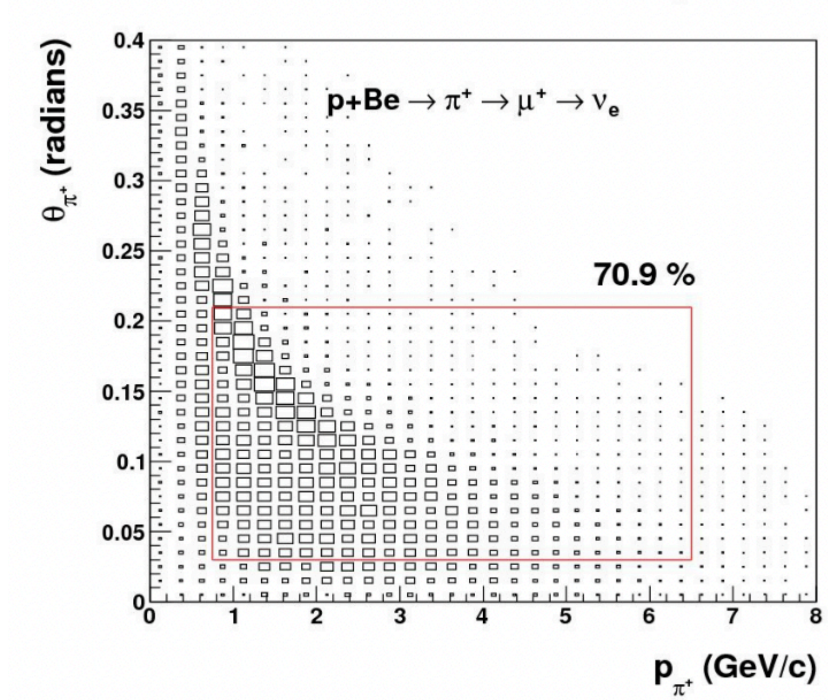


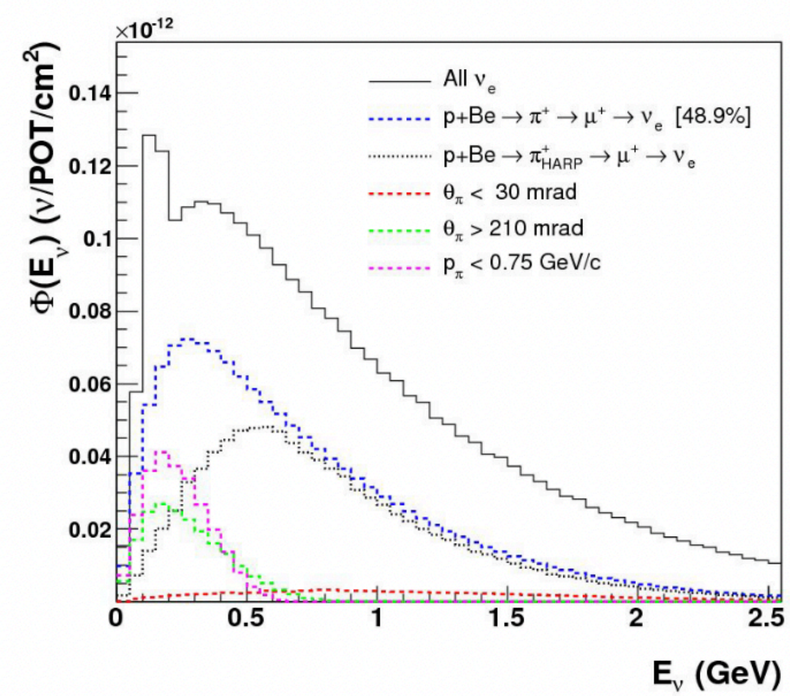
HARP coverage

- 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









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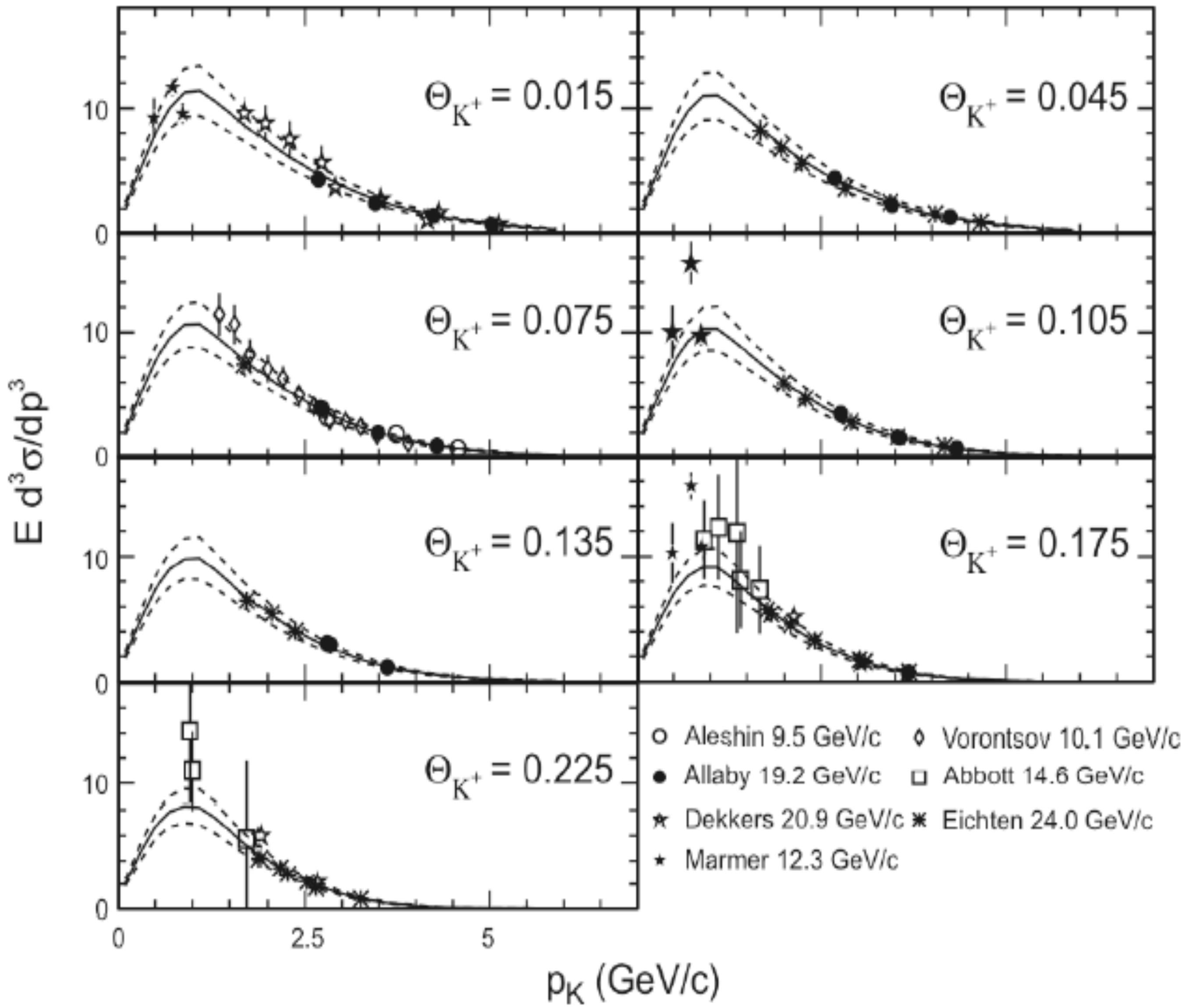
K^+ and K^0_L Production

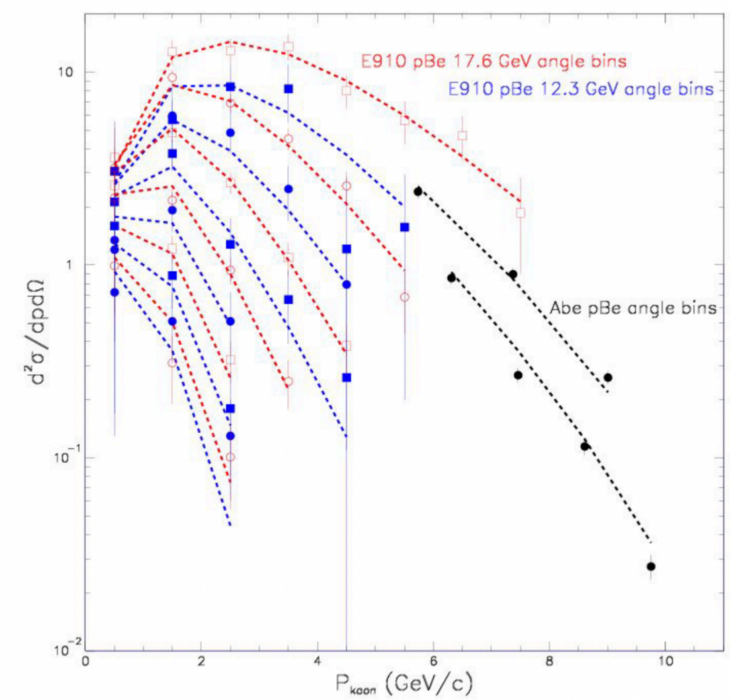
- Feynman scaling based parameterization used to fit world K+ production data
- Datasets scaled to 8.89GeV cover 1.2< $P_K^{8.89}$ [GeV /c] <5.5
- Some of the datasets had issues with normalization

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)

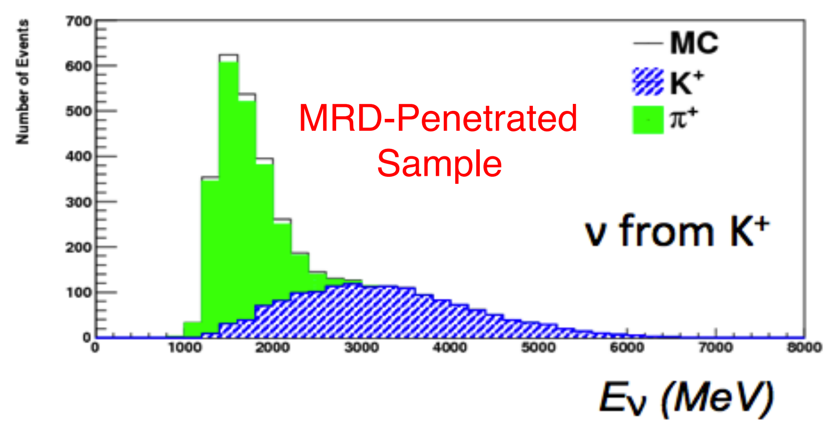


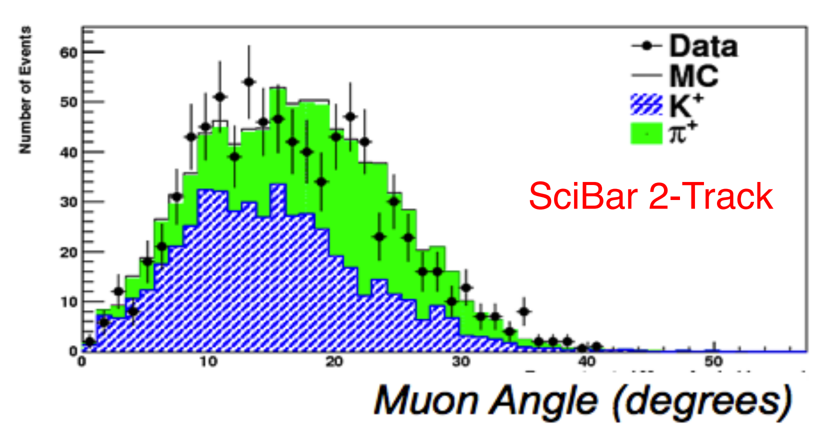


Fermilab

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





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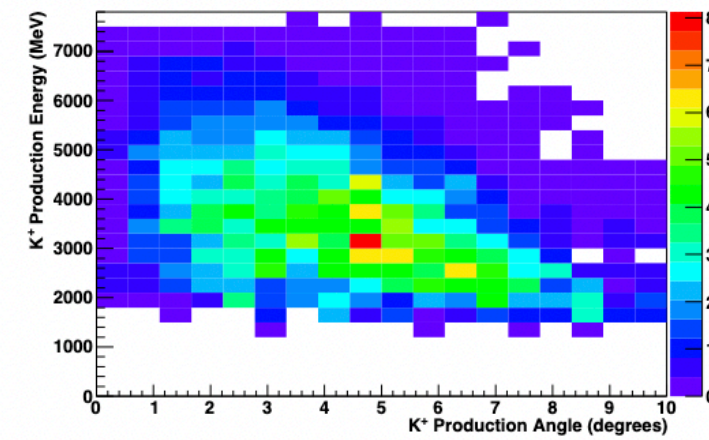
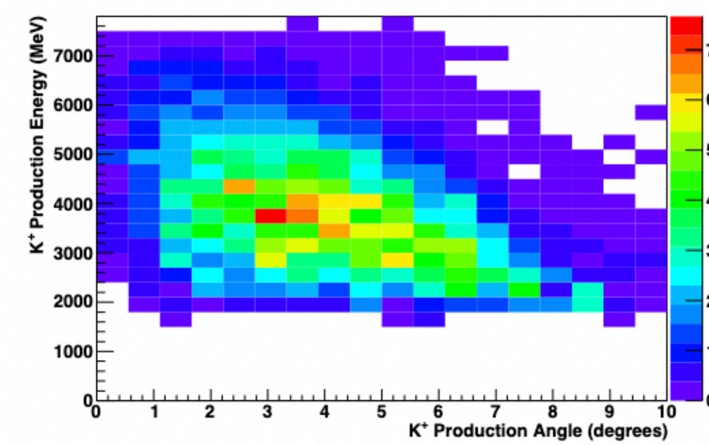
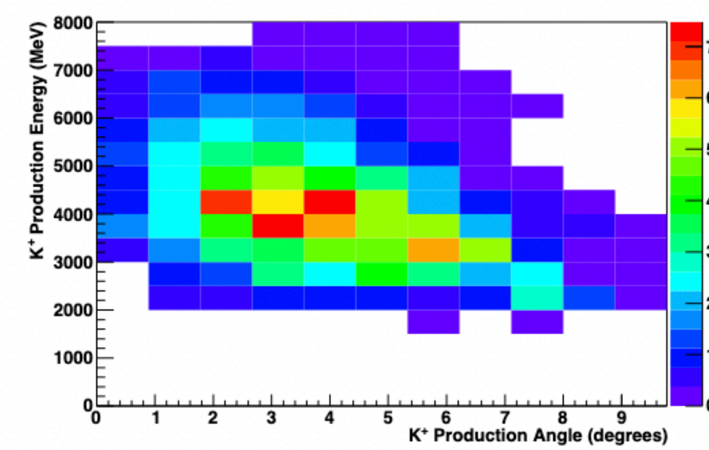


(a) 1-Track Sample



(b) 2-Track Sample



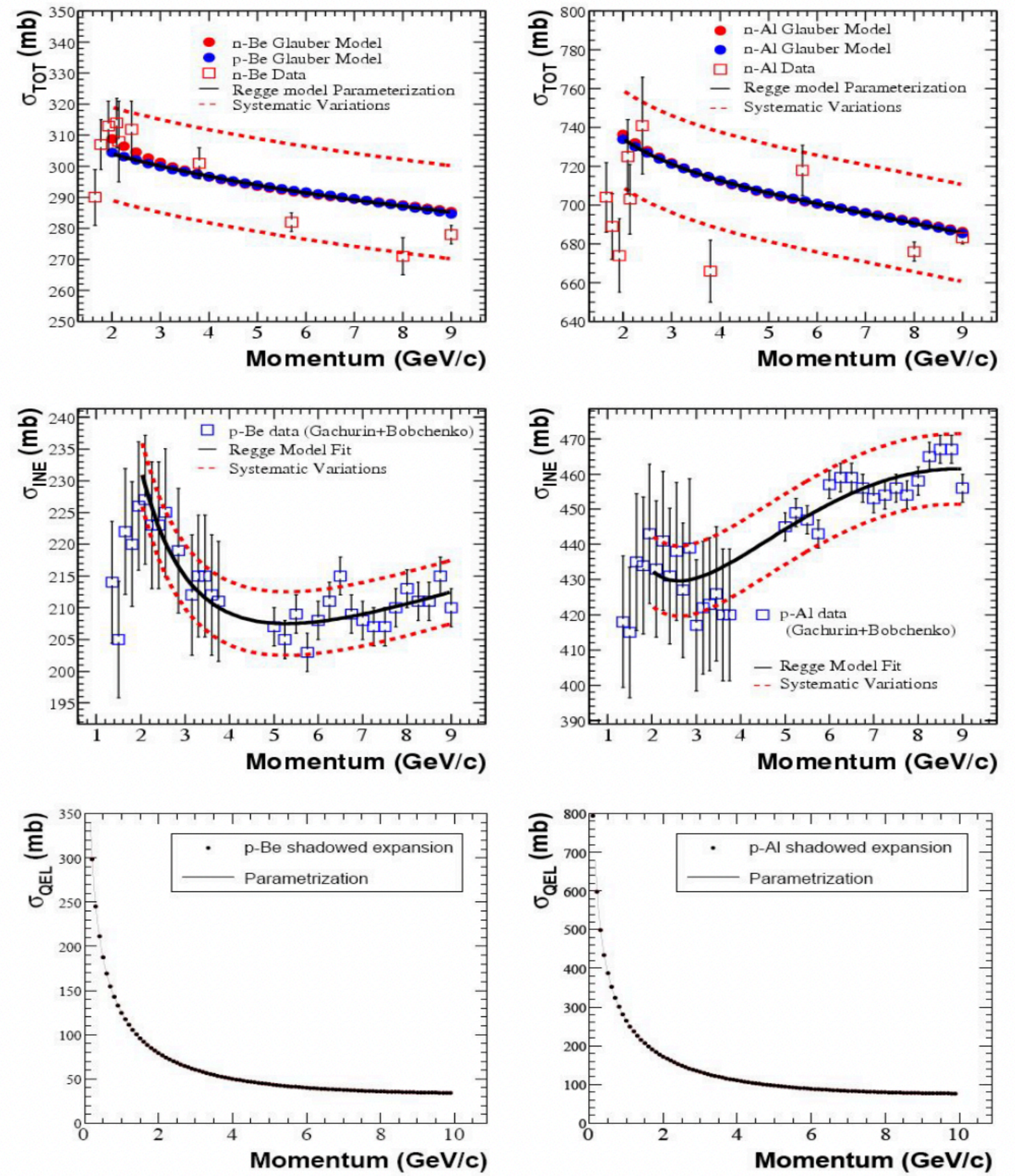
(c) 3-Track Sample

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 (checked with data)	Data ($p < 0.6/0.8$ GeV/c) 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)

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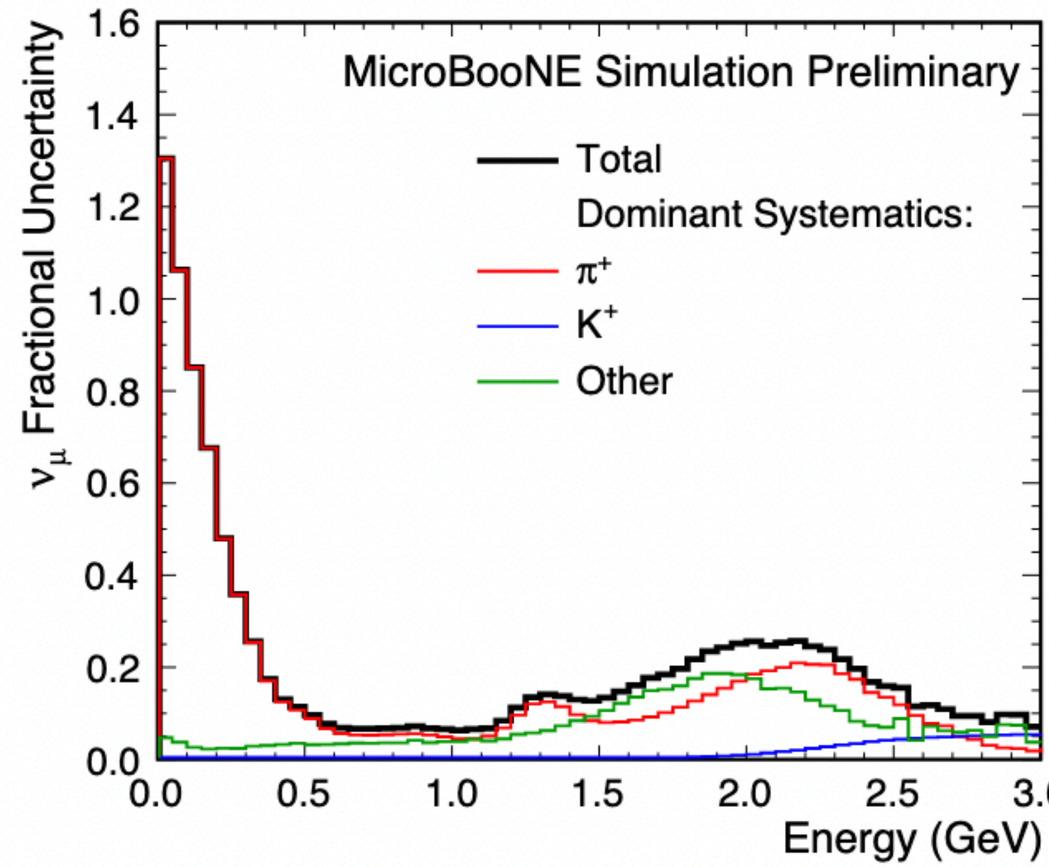
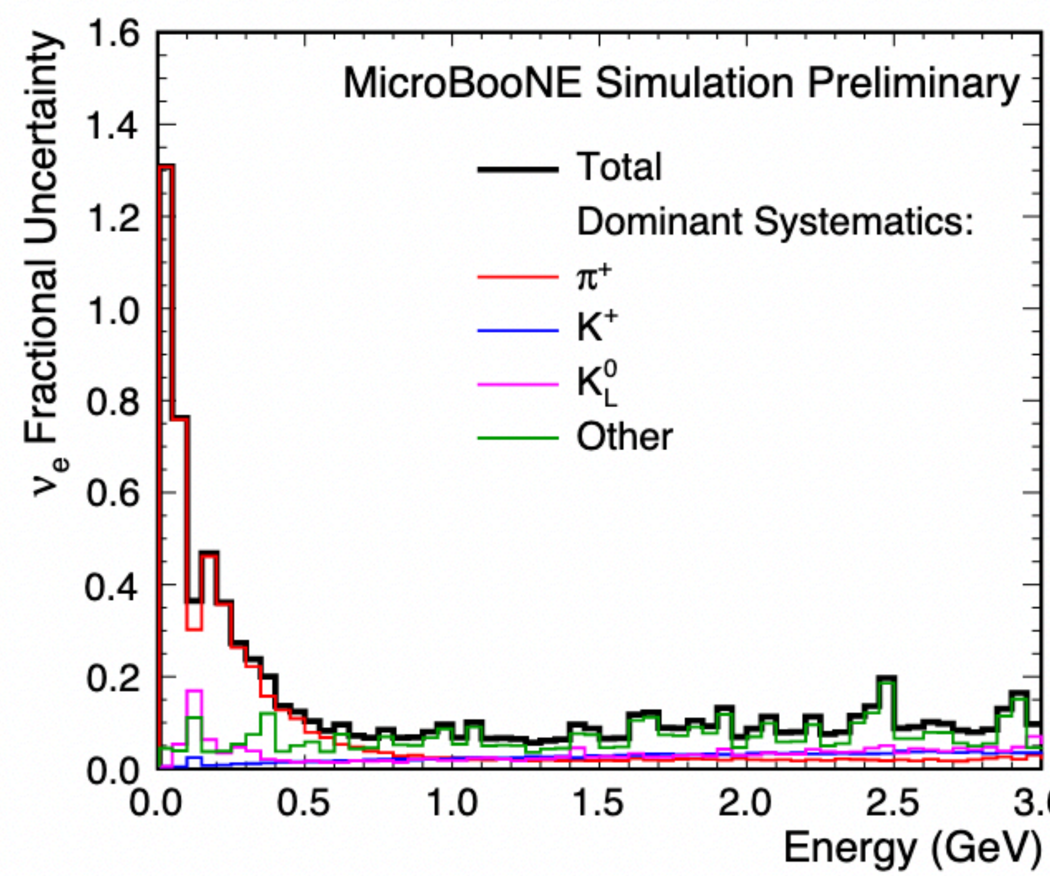
Systematic errors

- 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_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

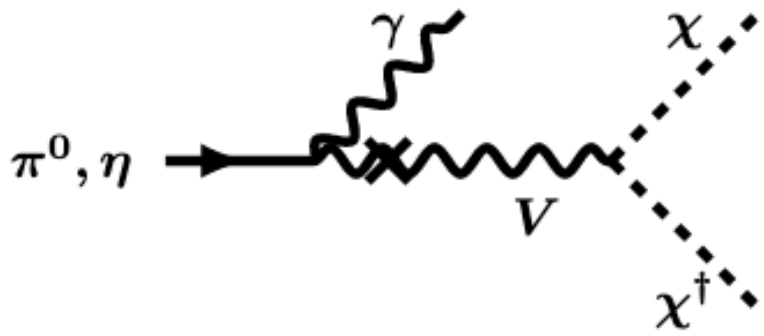


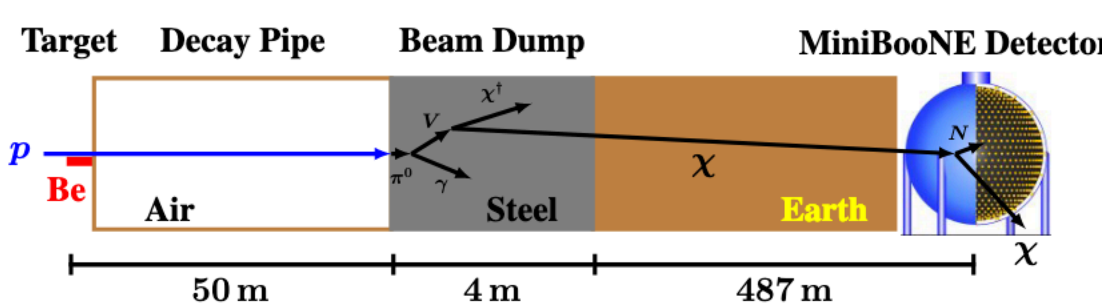


MICROBOONE-NOTE-1031-PUB

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
  - Required revisiting of the beam MC
    - Interactions in absorber not covered by external production data
    - Geometry details irrelevant for neutrino run, but significant when beam off-target

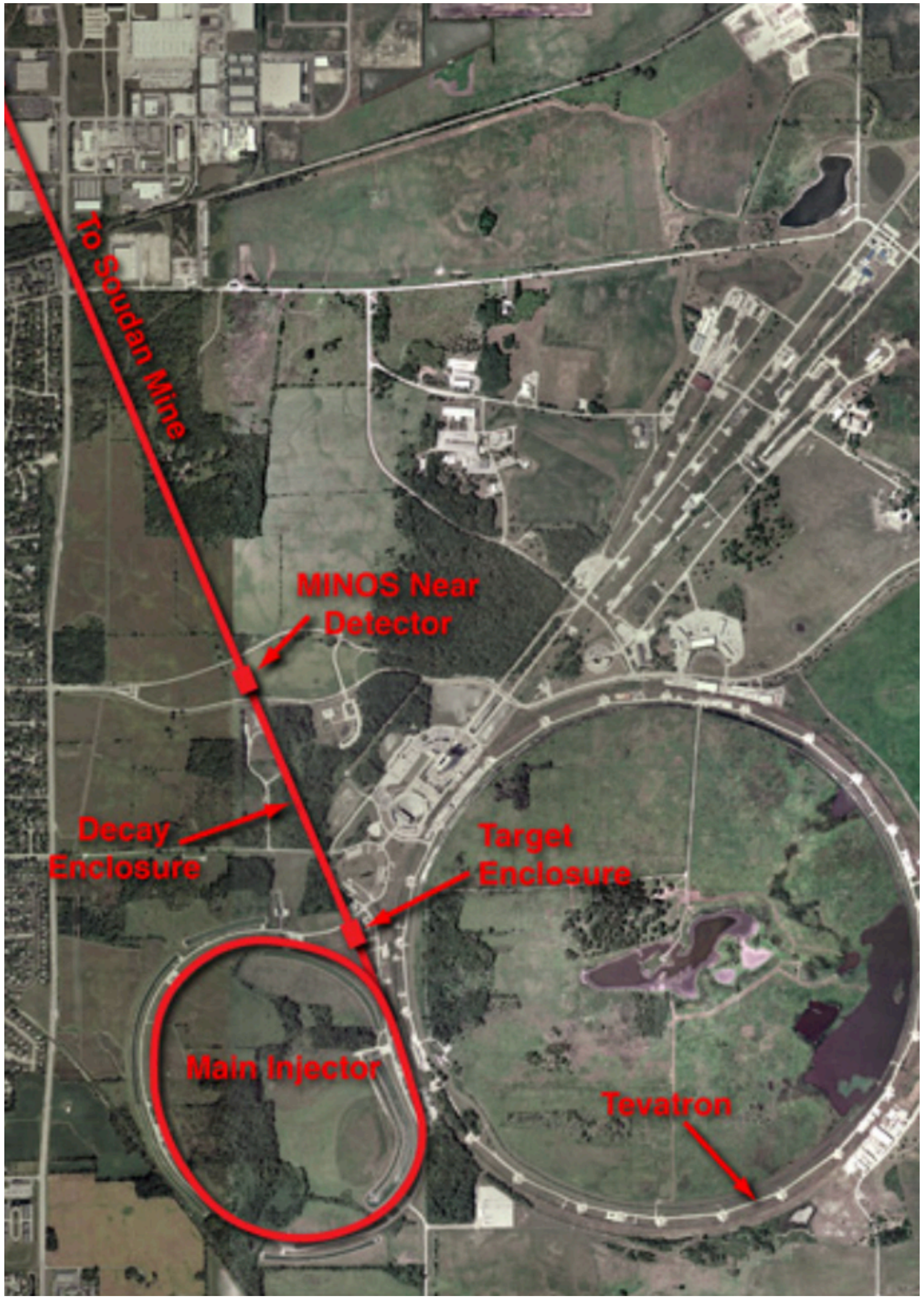




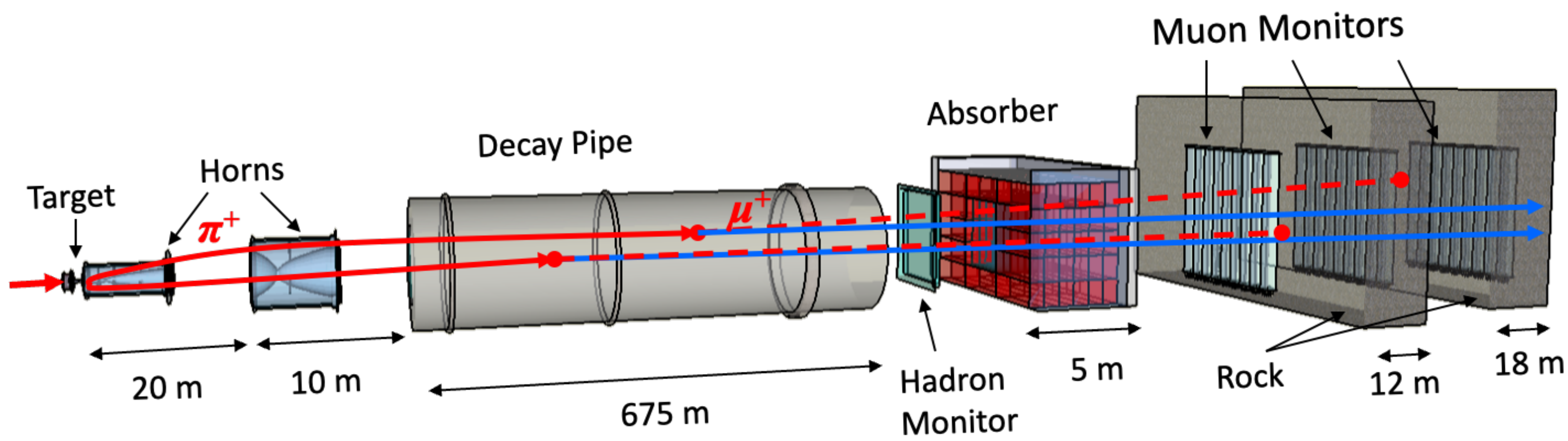
Phys. Rev. D 98, 112004 (2018)

NuMI Beam

- 120 GeV protons from Main Injector
- Graphite target
- Two magnetic horns
    - Neutrino & anti-neutrino mode
- 675m long decay pipe
- Argoneut, MINERvA, MINOS, NOvA



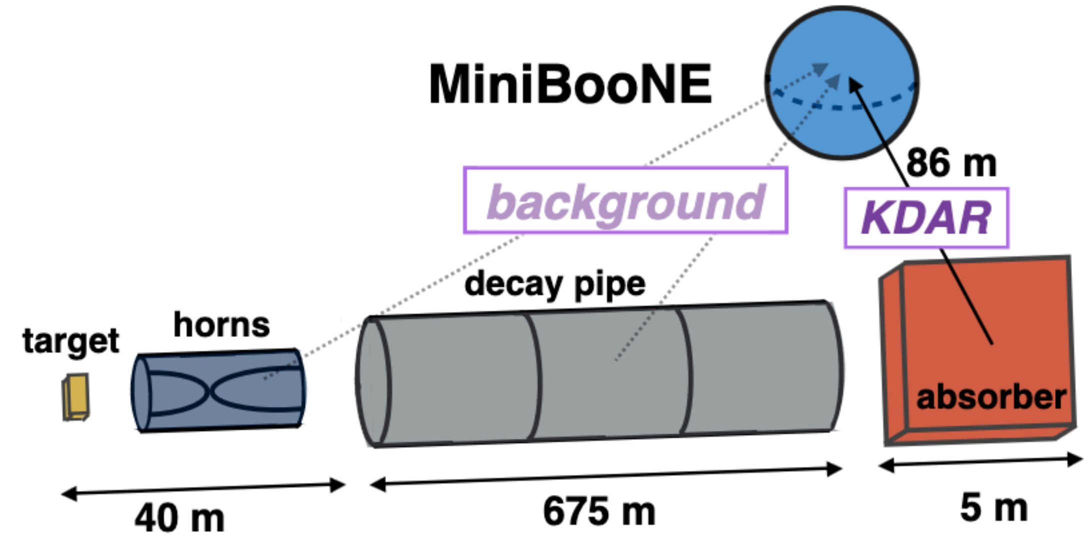
NuMI beam simulation (g4numi)

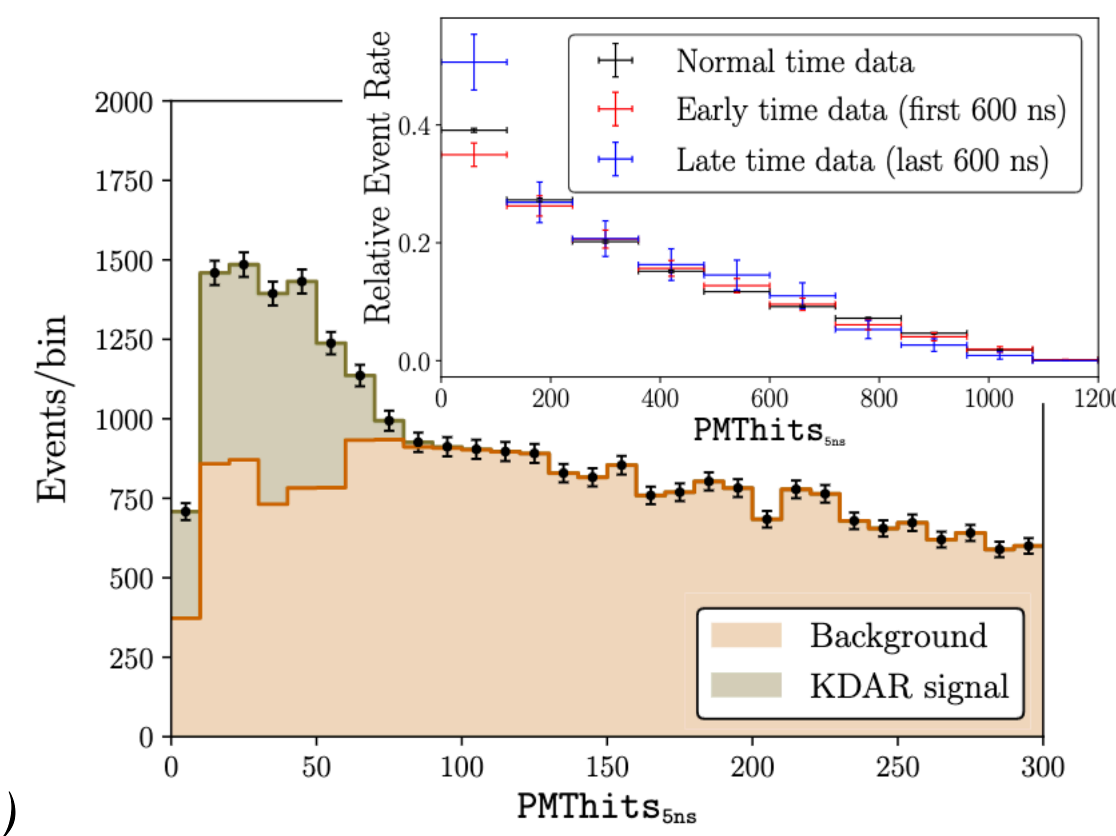


- Geant4 based simulation
- Using PPFX package to constrain geant4 models to external hadron production data
  - p+C production in the target
  - Downstream reinteractions where data is available

NuMI KDAR in MiniBooNE

- More exotic searches may require some additional checks
- Searching for KDAR in NuMI absorber with MiniBooNE detector required additional simulations of production/ stopping kaons in the absorber: geant4, fluka, mars
- Production varied significantly 0.06–0.12 KDAR νμ/proton on target

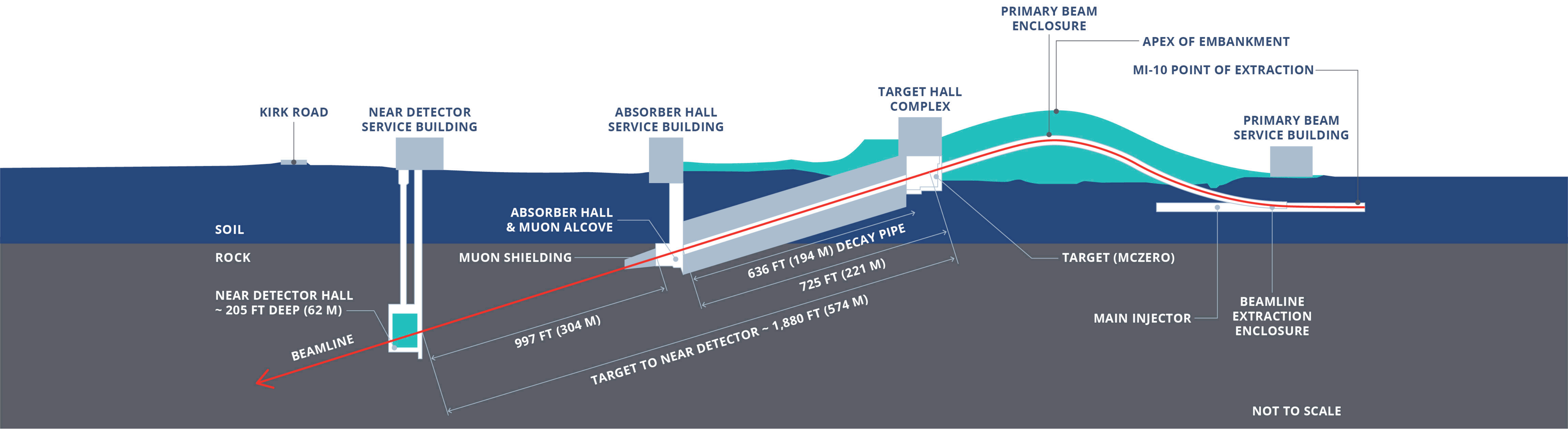




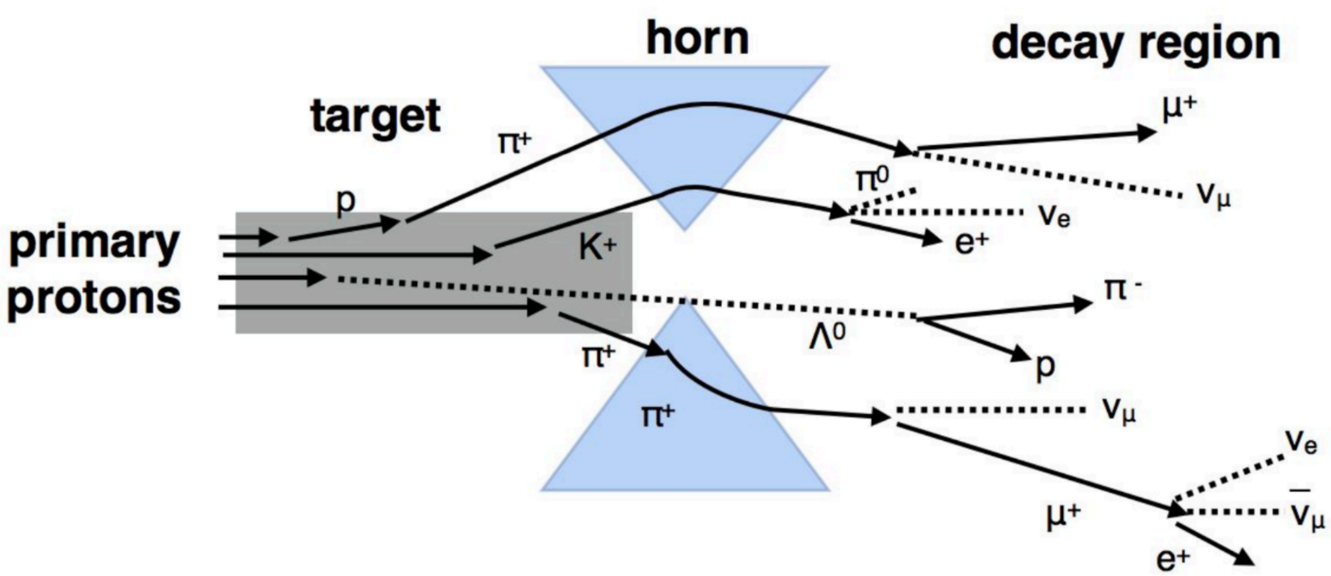
Phys. Rev. Lett. 120, 141802 (2018)

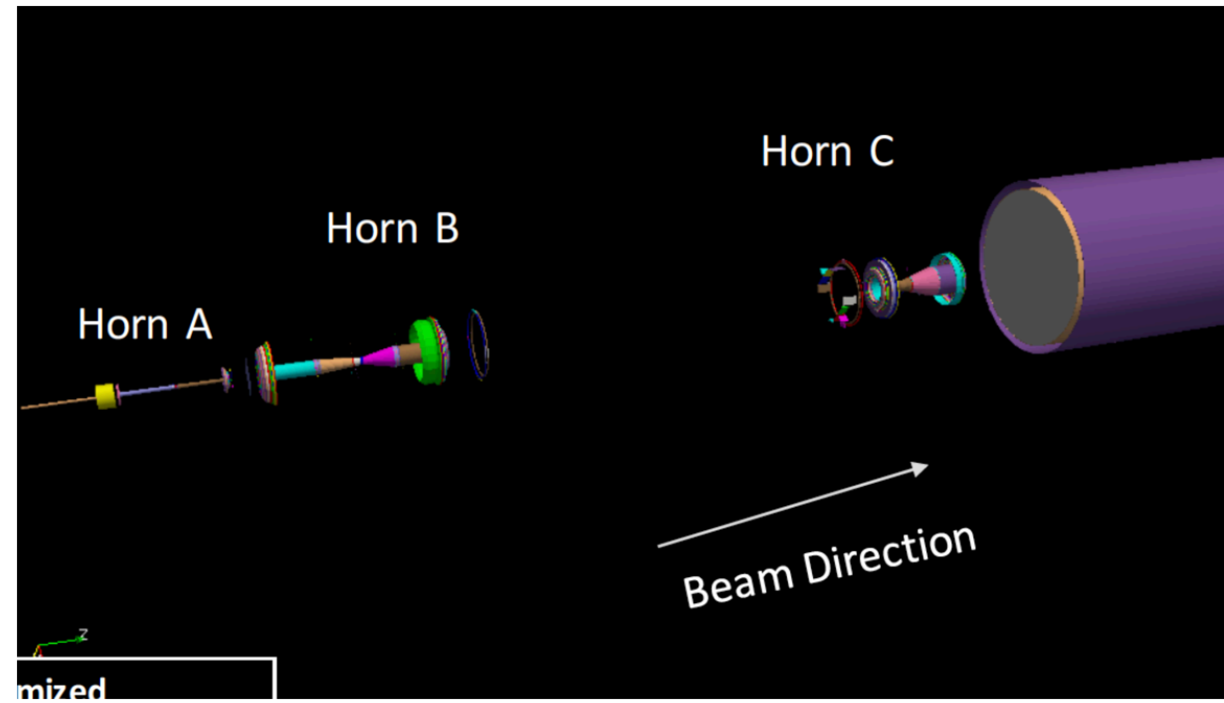
LBNF

- 120 GeV protons on long graphite target
- 3 horns
  - Polarity can be switched to produce neutrino or antineutrino enhanced beam
- 221m long decay region
- Optimized for sensitivity to CP-violation



LBNF simulation (g4lbnf)

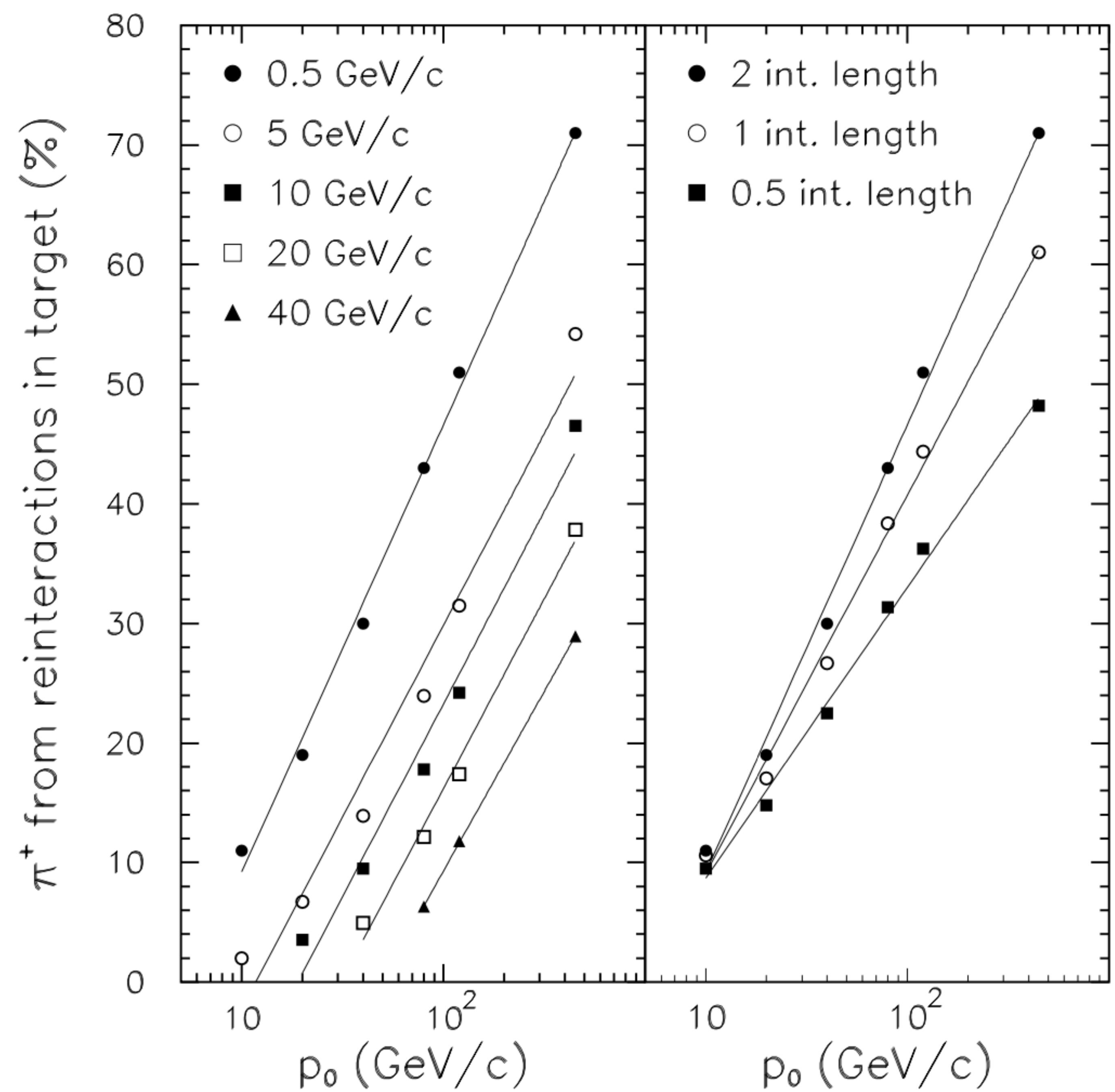




- Using Geant4 version 10.3.p03 with the QGSP_BERT Physics List
- Simulate primary interactions of 120 GeV protons on the LBNF target, reinteractions in the target, other materials and decays to neutrinos
- Need very precise flux prediction to achieve the DUNE precision measurements of neutrino oscillation parameters and search for CP-violation and a variety of BSM physics
  - Most detailed geometry so far
  - Use more external data to constrain the geant4 models

Reinteractions

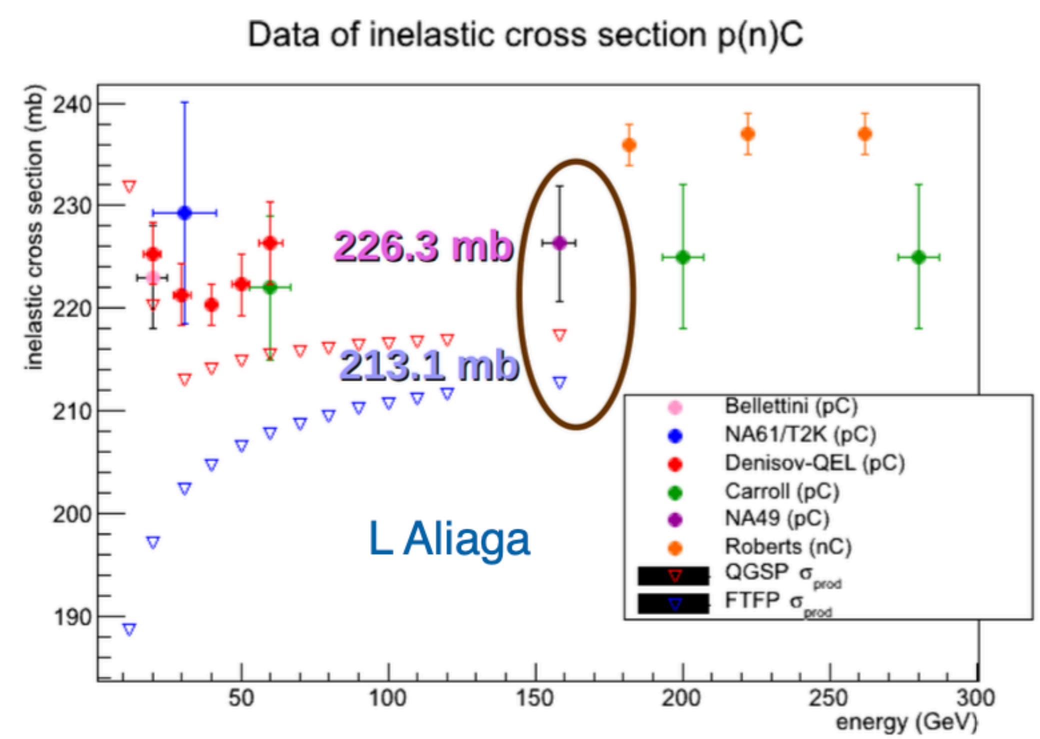
- Tertiary production becomes more important for higher energy beams
- In addition to p+C production data, need to constrain reinteractions currently not covered by data to achieve ultimate precision
-



PPFX

- Correcting the simulation through reweighing
- Using PPFX package developed for MINERvA and used by experiments using NuMI beam
- Requires complete information about cascades leading to a neutrino
- Interactions are weighted by:

$$w_{HP} = \frac{f_{Data}(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)} \qquad f = E\frac{d^3\sigma}{dp^3}$$



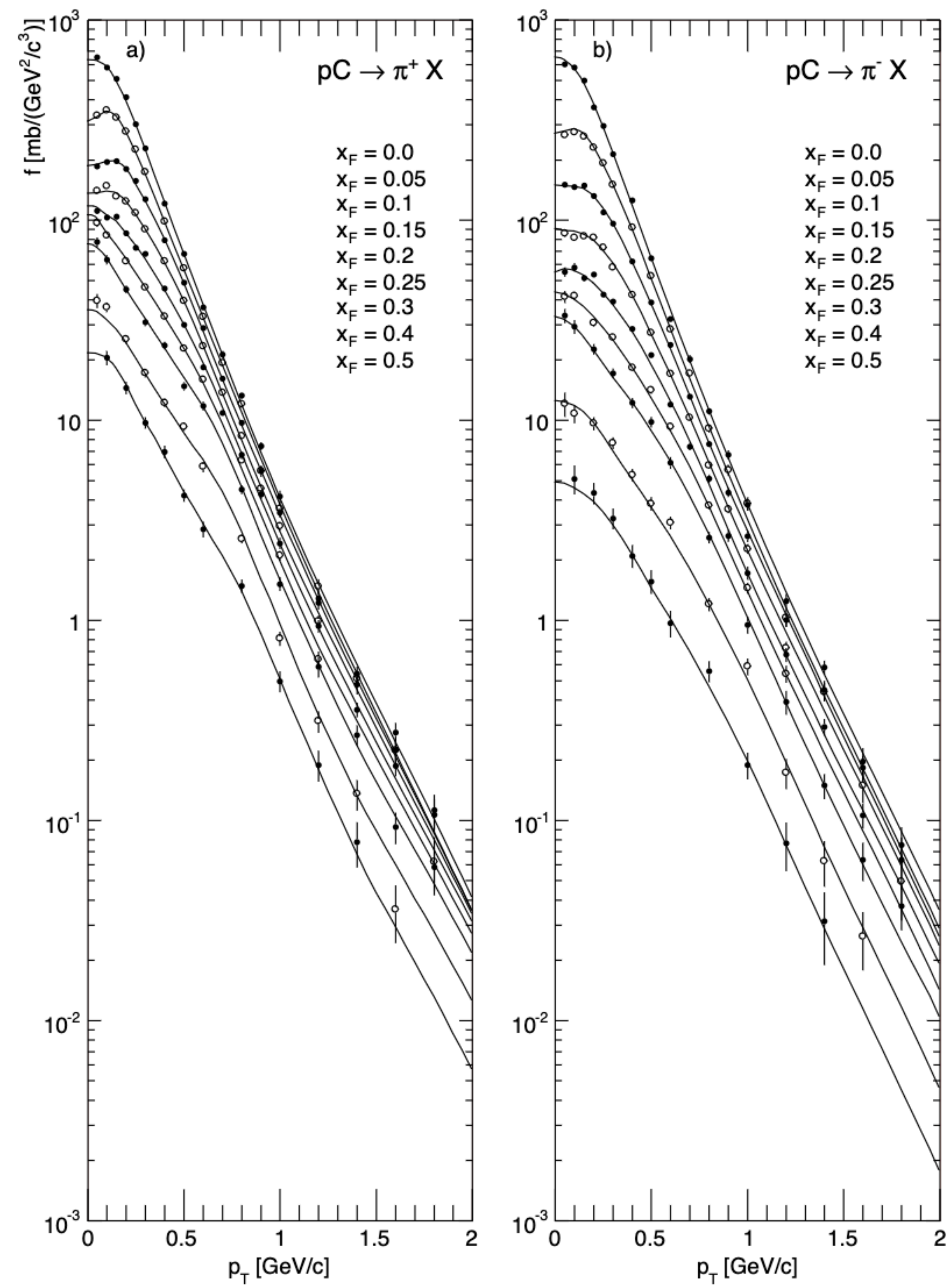
- Second weight is applied to account for exponential decay of beam

$$w_{att} = e^{-L\rho(\sigma_{Data} - \sigma_{MC})}$$

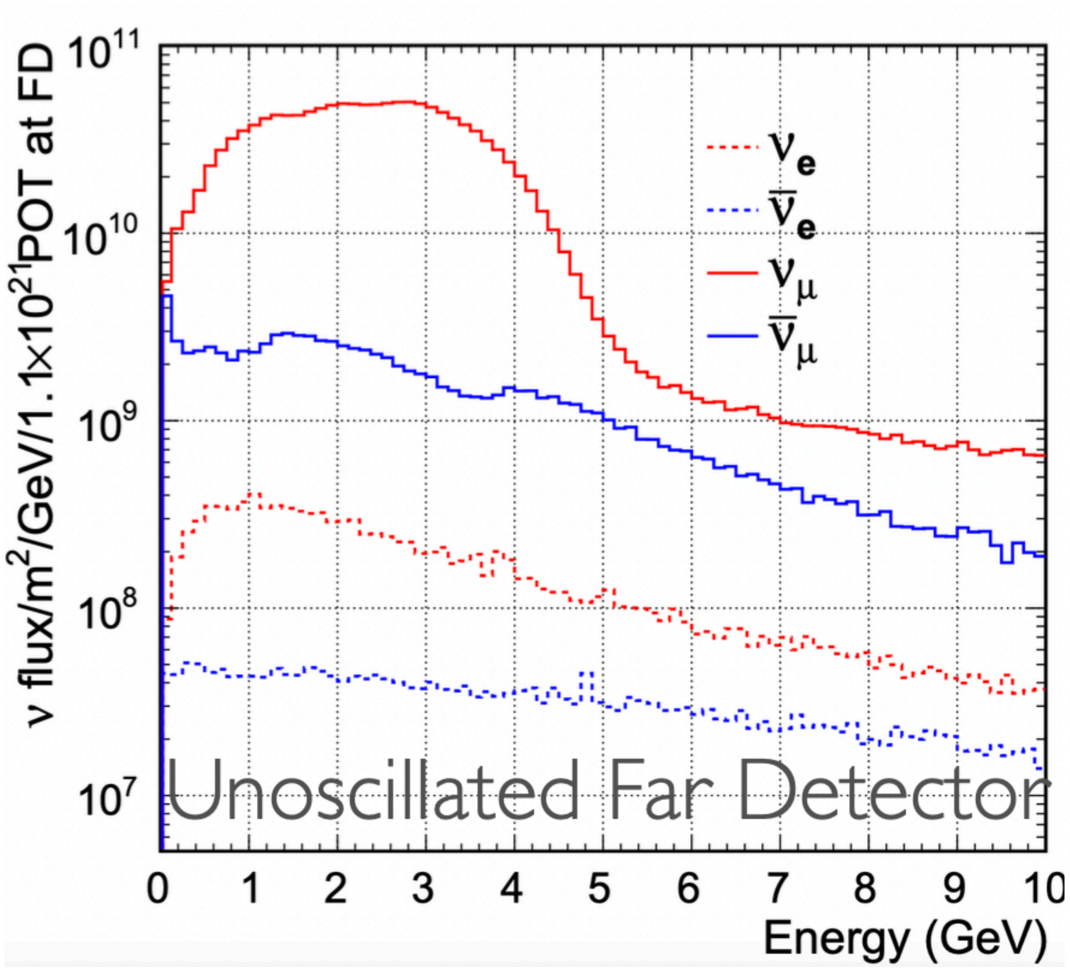
- Under development for DUNE

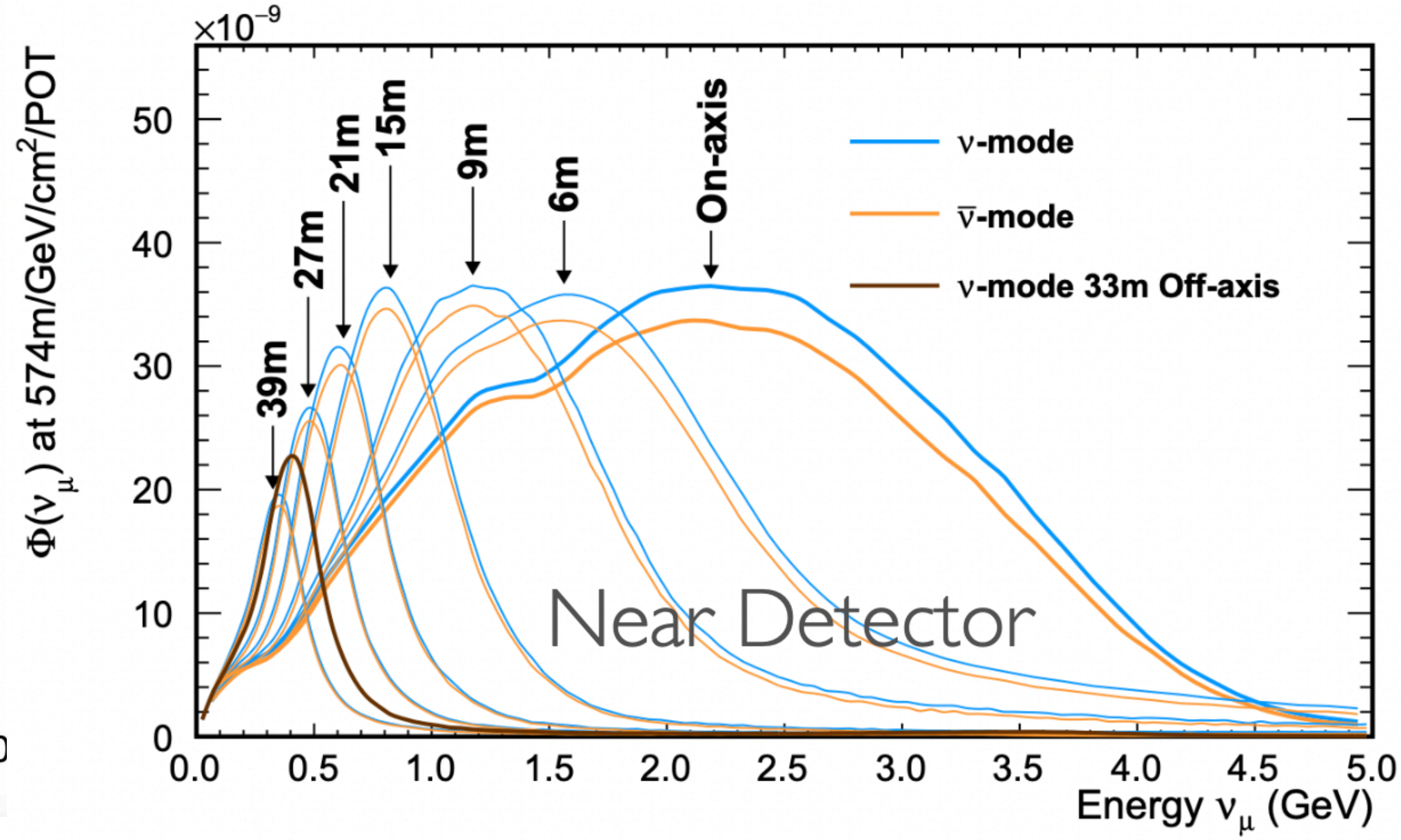
PPFX External data

- Data sets currently used:
  - NA49 158 GeV protons (Eur.Phys.J.C49: 897-917, 2007, Eur. Phys. J. C73, 2364 (2013))
  - Barton et. al. 100 GeV protons (Phys. Rev. D 27, 2580) NA49 pC → K±X (G.Tinti Thesis)
  - MIPP K/pi ratios (A.V. Lebedev Thesis)
  - Incorporation of new NA61 and EMPHATIC data is ongoing
- Extensions of data:
  - pC → π+X cross section assumed to be the same as nC → π−X and vice versa (isospin symmetry)
  - Carbon data used for other nuclei
  - 158 GeV proton data used for incident energies between 12 and 120 GeV, with scaling taken from Fluka



Predicted flux



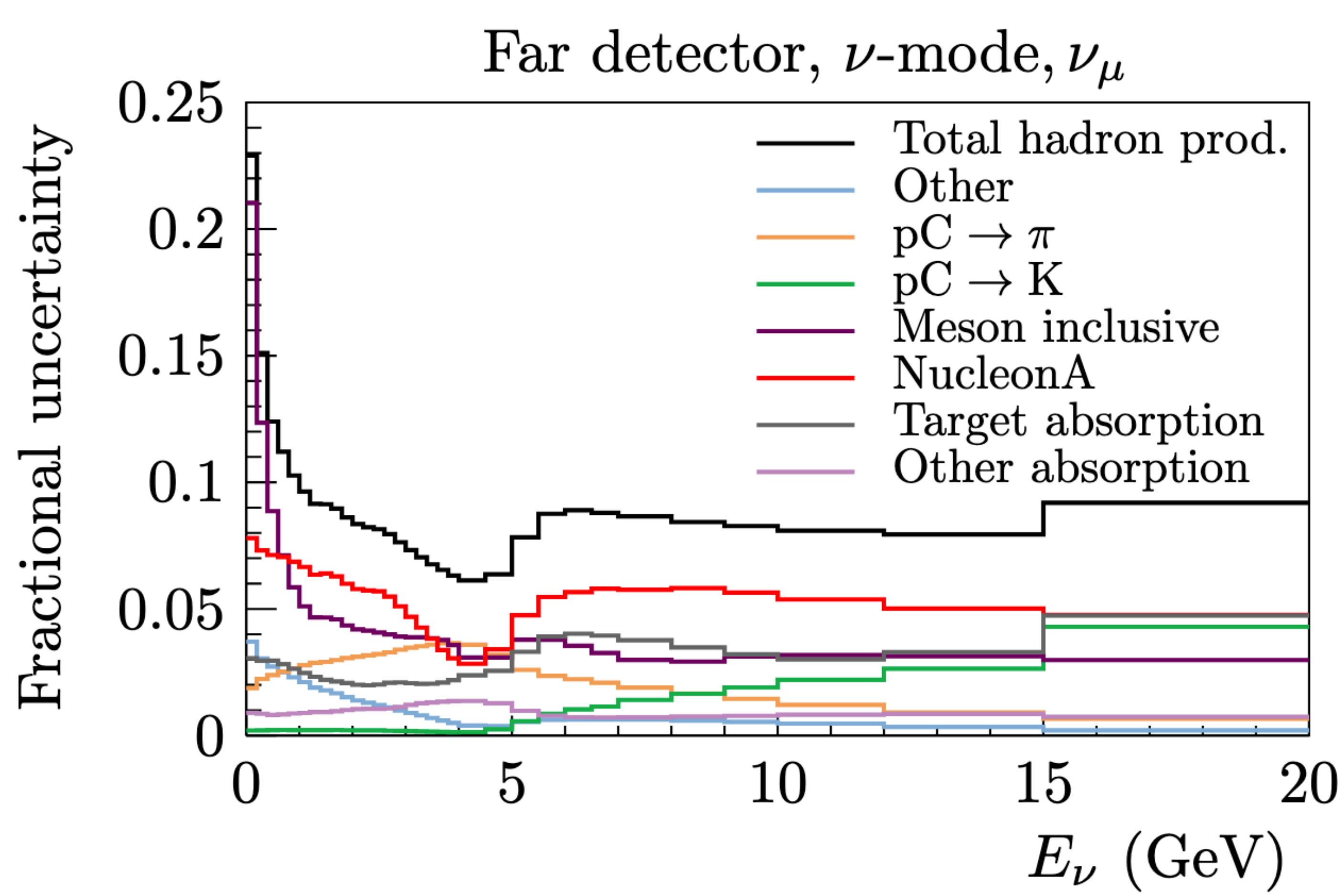


DUNE TDR, arXiv:2002.03005

- Predicting neutrino flux at far detector, near detector and off axis locations

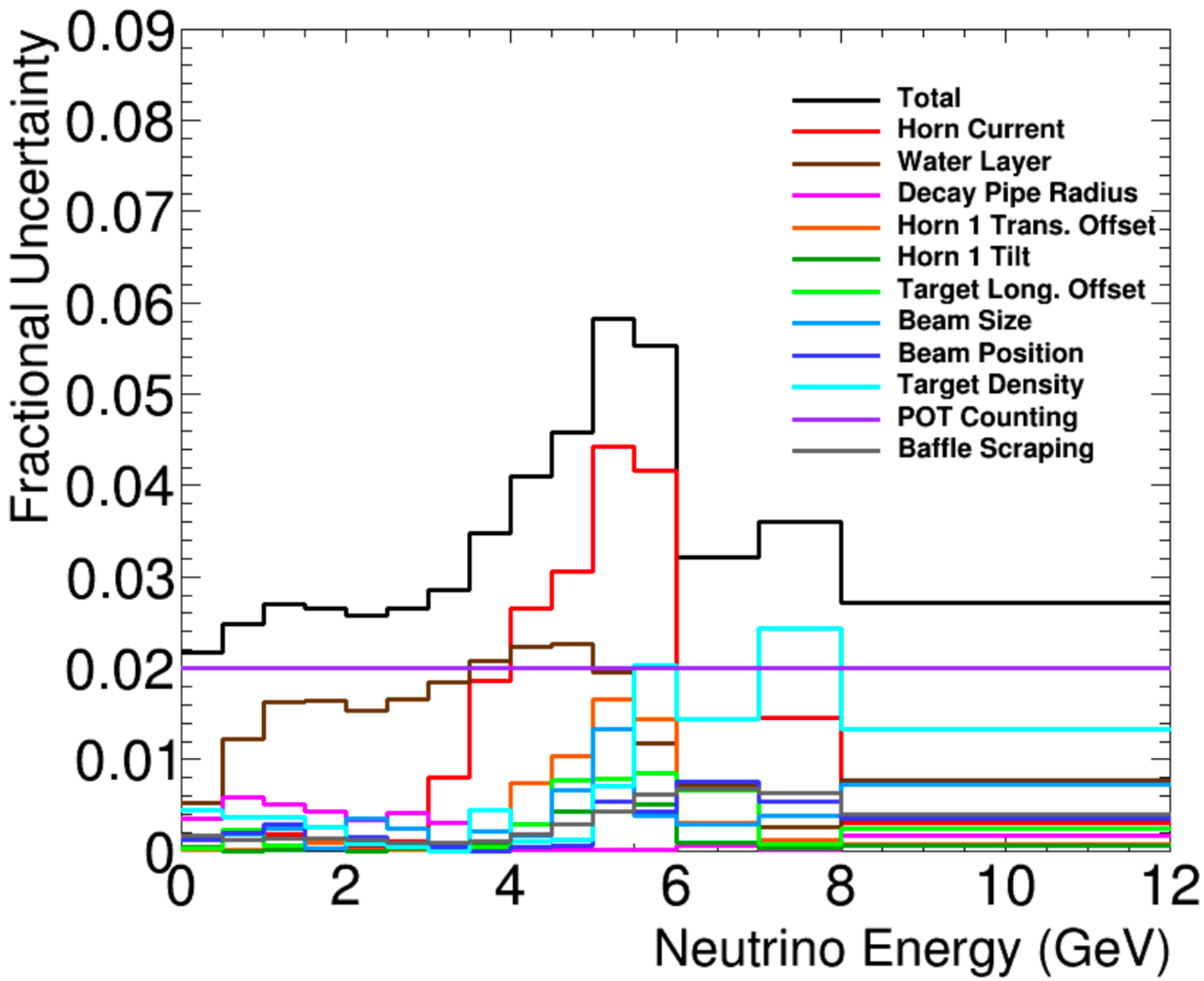
Systematic errors (Hadron Production)

- Equally important to understand systematic errors and correlations
- Using ppfx to propagate the errors
  - Data cross sections varied according to their uncertainties (taking into account correlations)
- Large 40% uncertainty assumed for processes not covered by data



Systematic errors (Focusing)

- Additional uncertainty due to various misalignments
- Running simulation with various alignment parameters varied

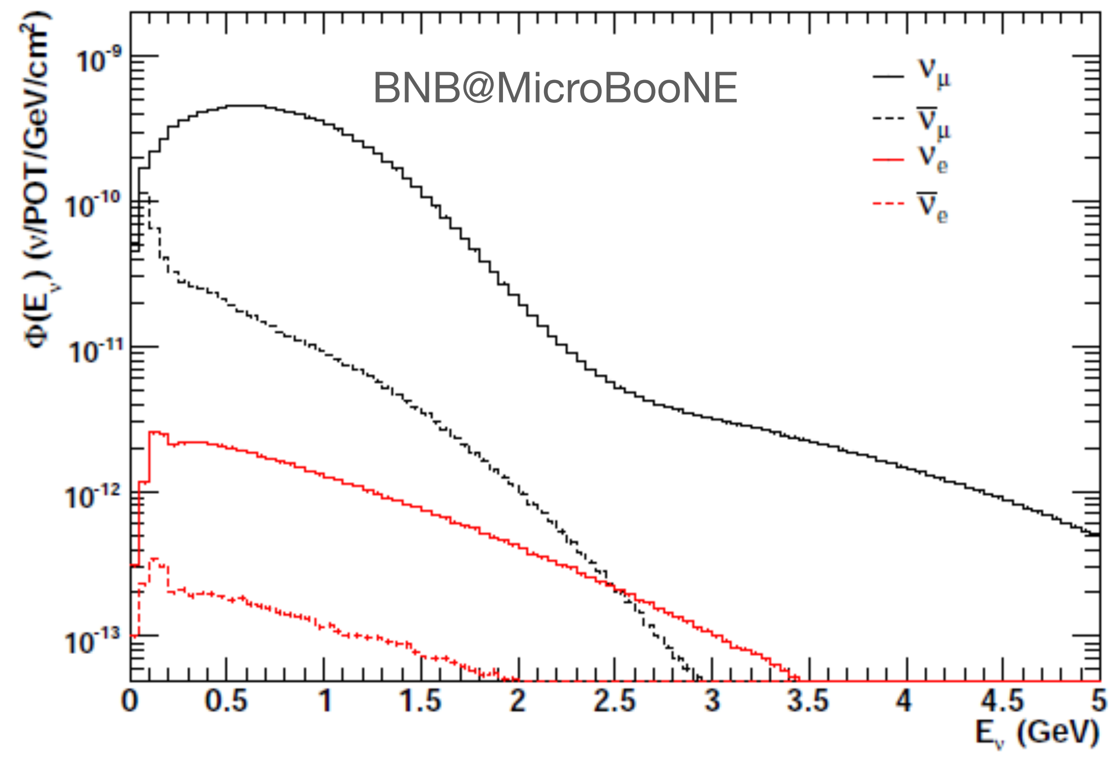


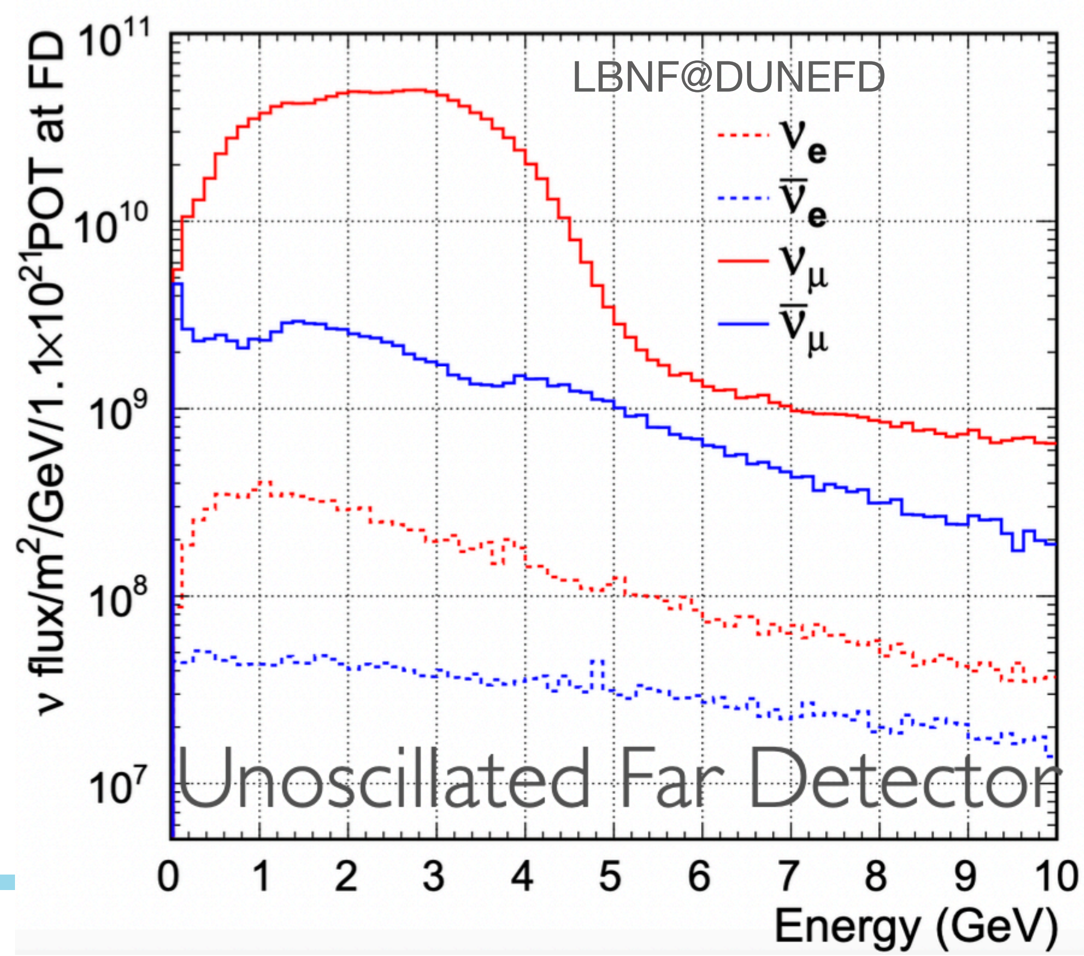
Neutrino flux calculation

- Beam MC saves events that produce a neutrino at the end of the chain
- There is an additional step between the beam MC and event generator (GENIE)
- Flux calculated at the window in front of the detector
  - Redecay
  - Weight event by probability that neutrino will hit detector
  - This step also includes weight rejection to produce unweighted events

Conclusion

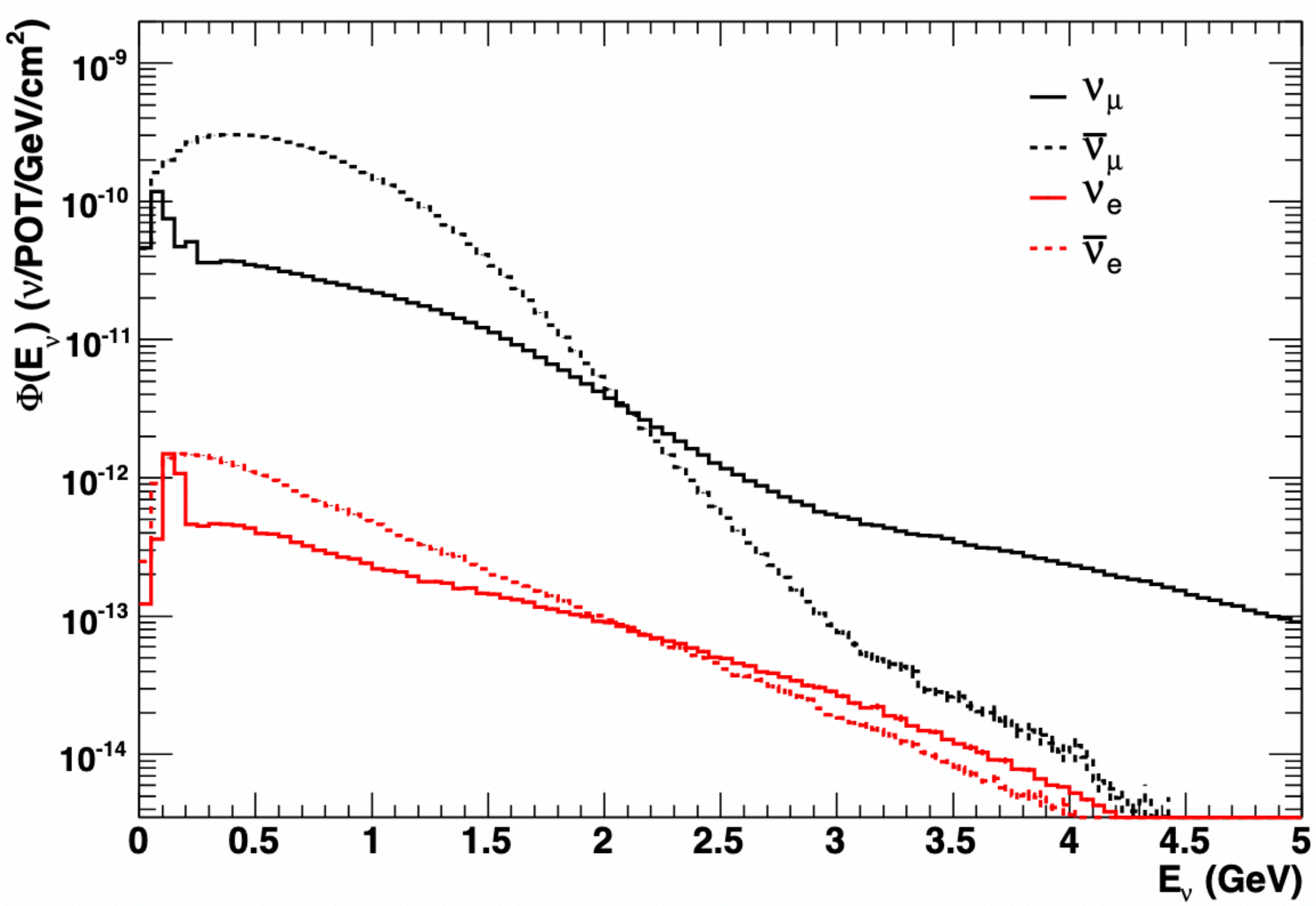
- Geant4 based simulations used to predict flux for BNB, NuMI and LBNF
- Simulation typically focused on neutrino flux
    - By default not tracking particles irrelevant for neutrino production
- Additional tuning done to match external data where available
    - Driven by what is relevant for given physics analysis (typically oscillation and cross-section analyses)
    - Note that this is sometimes included in geant4, and sometimes a separate step





Backup

BNB Antineutrino mode flux

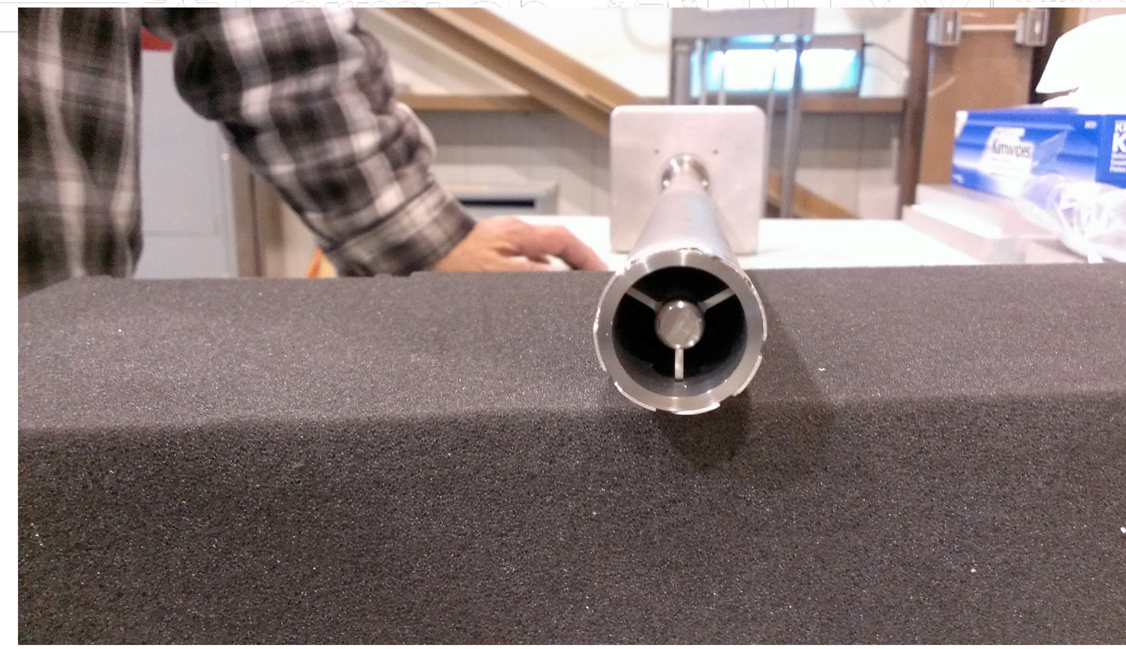


	ν_μ		$\overline{\nu}_\mu$	
Flux (ν/ cm^2/POT)		5.42×10^{-11}		2.93×10^{-10}
Frac. of Total		15.71%		83.73%
Composition	π^+:	88.79%	π^-:	98.4%
	K^+:	7.53%	K^-:	0.18%
	$\pi^- \to \mu^-$:	1.77%	$K^0 \to \pi^-$:	0.05%
	K^0:	0.26%	K^0:	0.05%
	Other:	2.00%	$\pi^+ \to \mu^+$:	0.03%
			$K^- \to \pi^-$:	0.02%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

BNB target

- Beryllium 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