Fermilab Neutrino Beams

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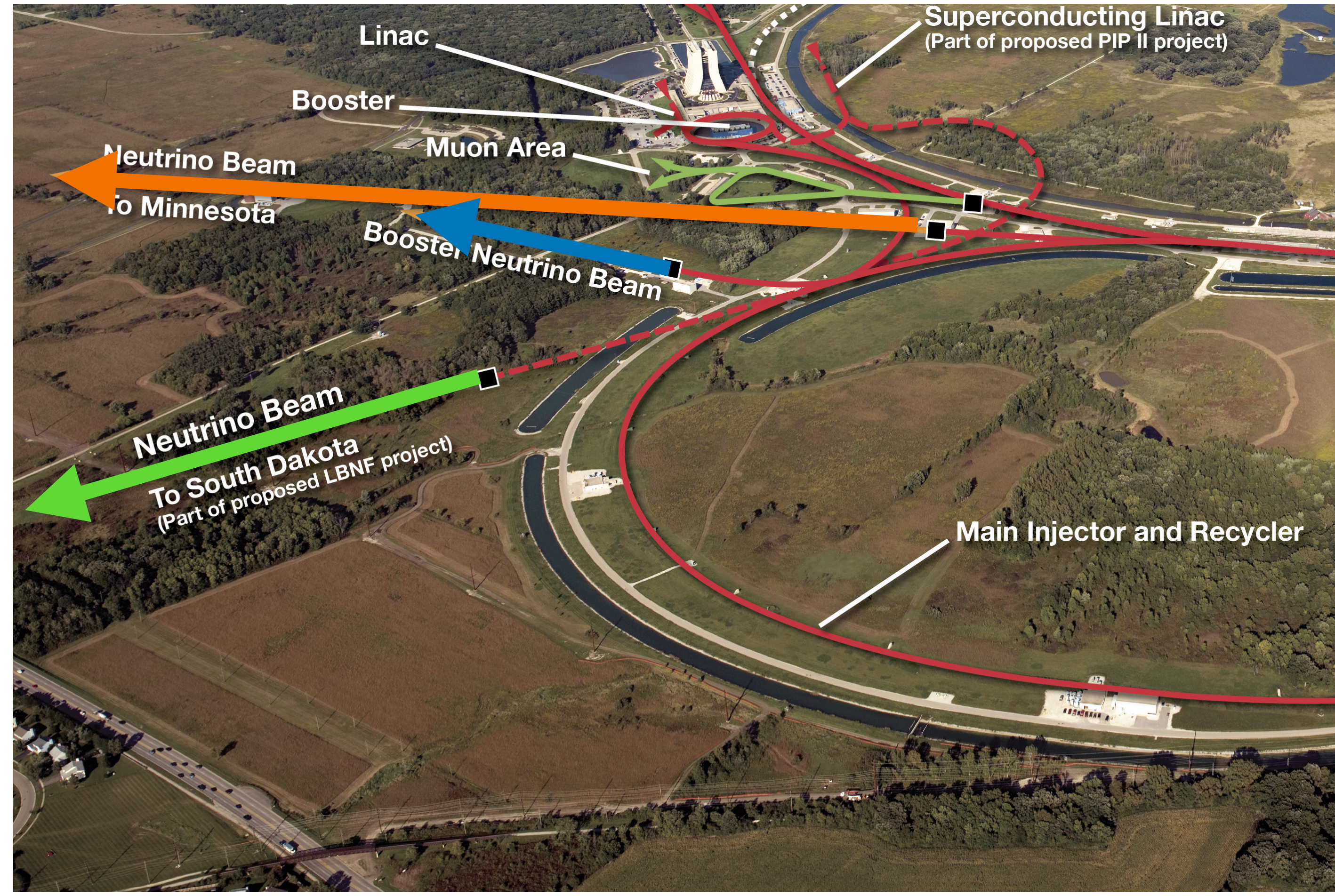
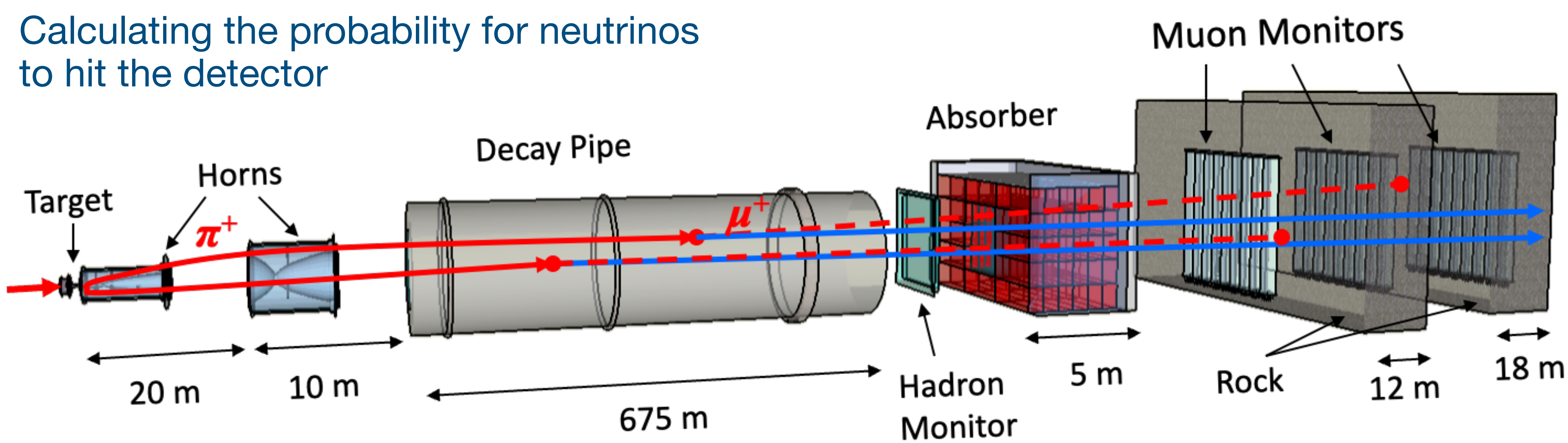
NuINT 2024, April 16 2024

Fermilab Neutrino beams

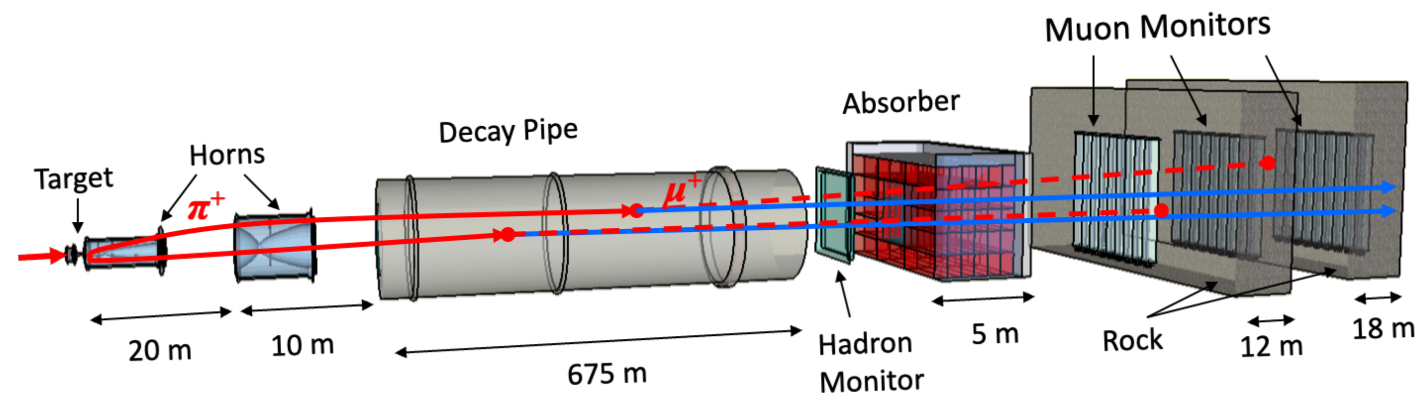
- BNB, NuMI, LBNF
- Conventional neutrino beams
  - Target, focusing horn(s), decay region, absorber, detector(s)
- Flux calculation requires
  - Simulating meson production
  - Tracking particles through magnetic fields and downstream material down to their decay point
  - Calculating the probability for neutrinos to hit the detector

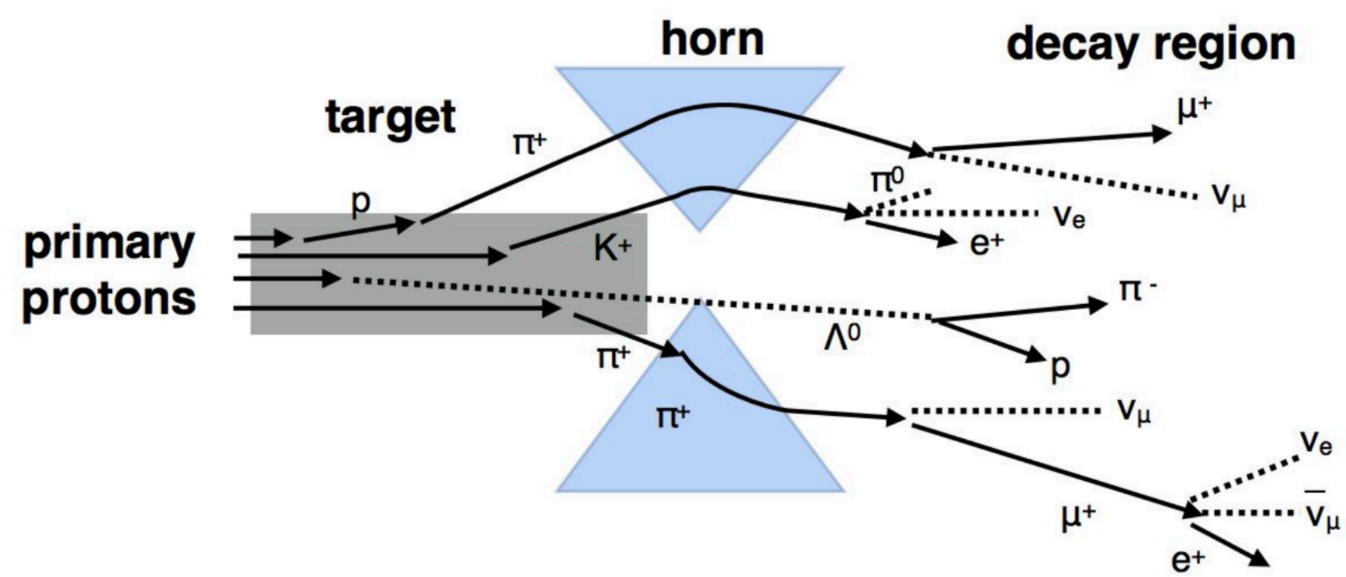




Flux prediction

- All 3 beam lines use geant4 based simulations for flux prediction (fluka also used in past for NuMI target or with flugg - g4/fluka interface)
- Define beamline geometry (including magnetic fields)
- Define Physics
  - Particles and processes (models, cross sections)
- Track particles and record all events producing neutrinos

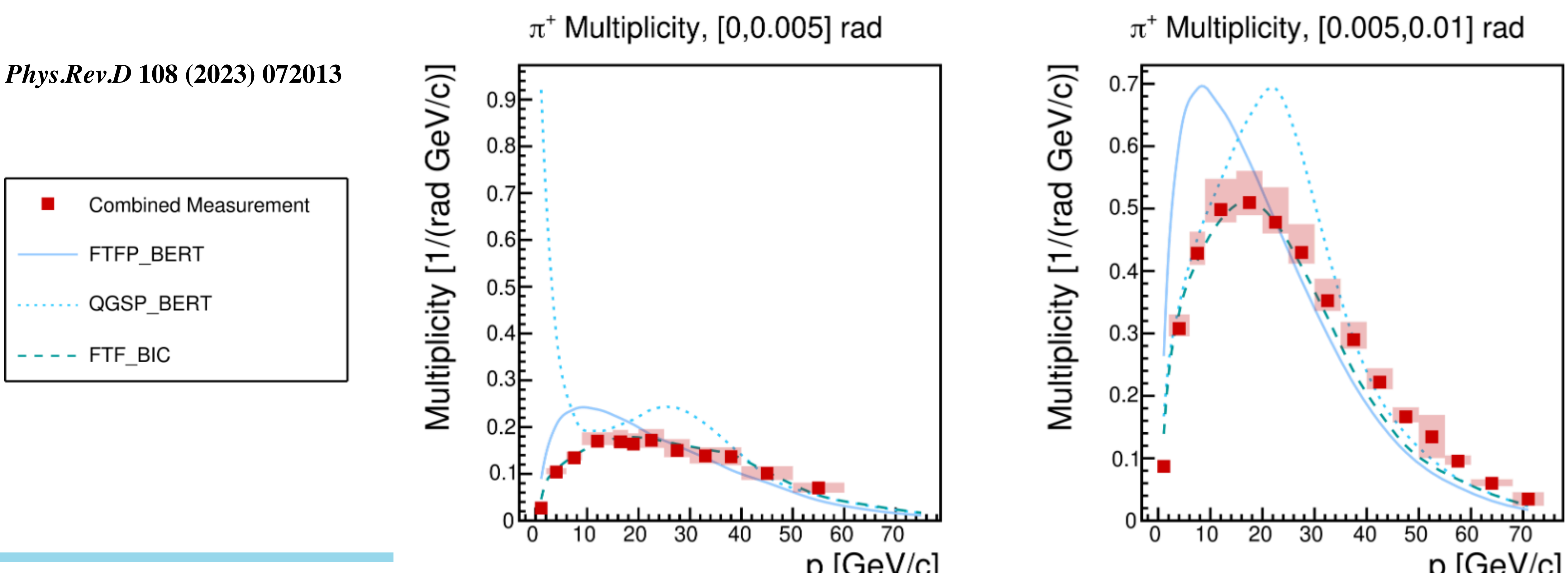




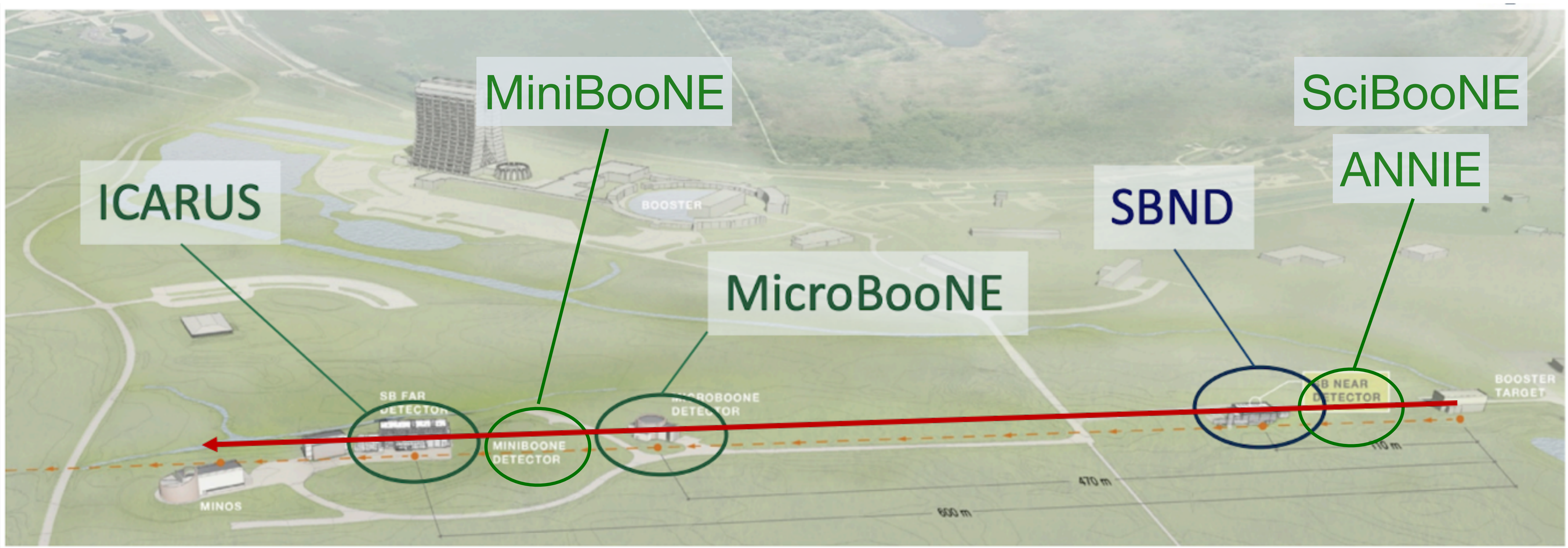
Tuning Beam MC

- Geant4 models improving over the years, but deviations from data persist
- 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

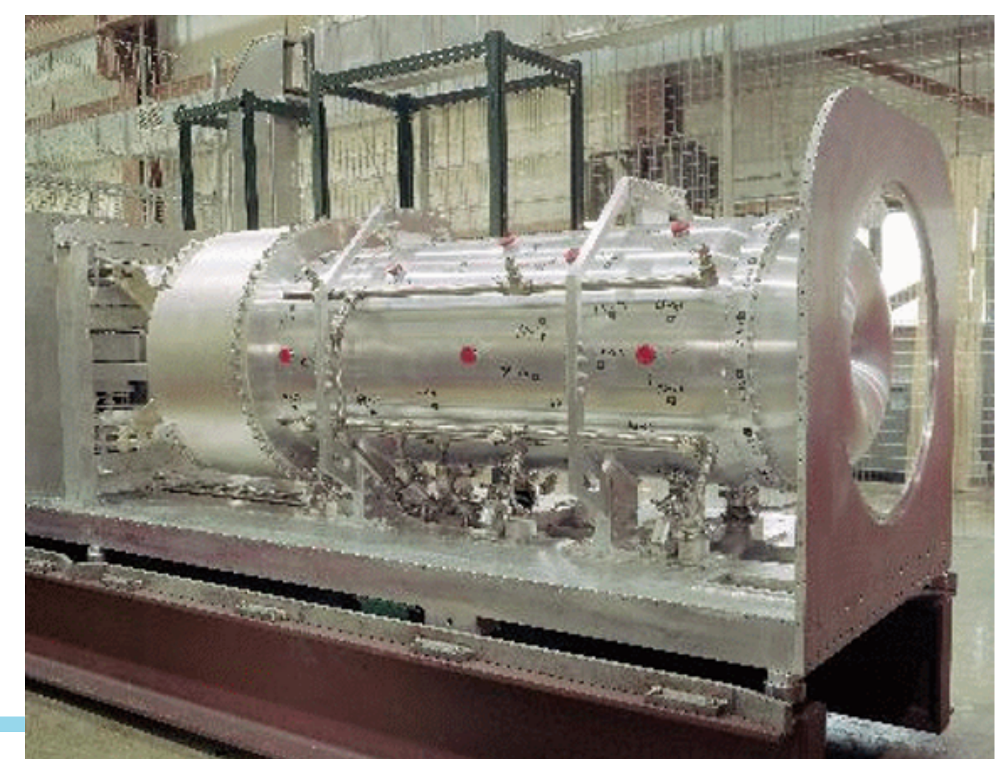
***Phys.Rev.D* 108 (2023) 072013**



Booster Neutrino Beam

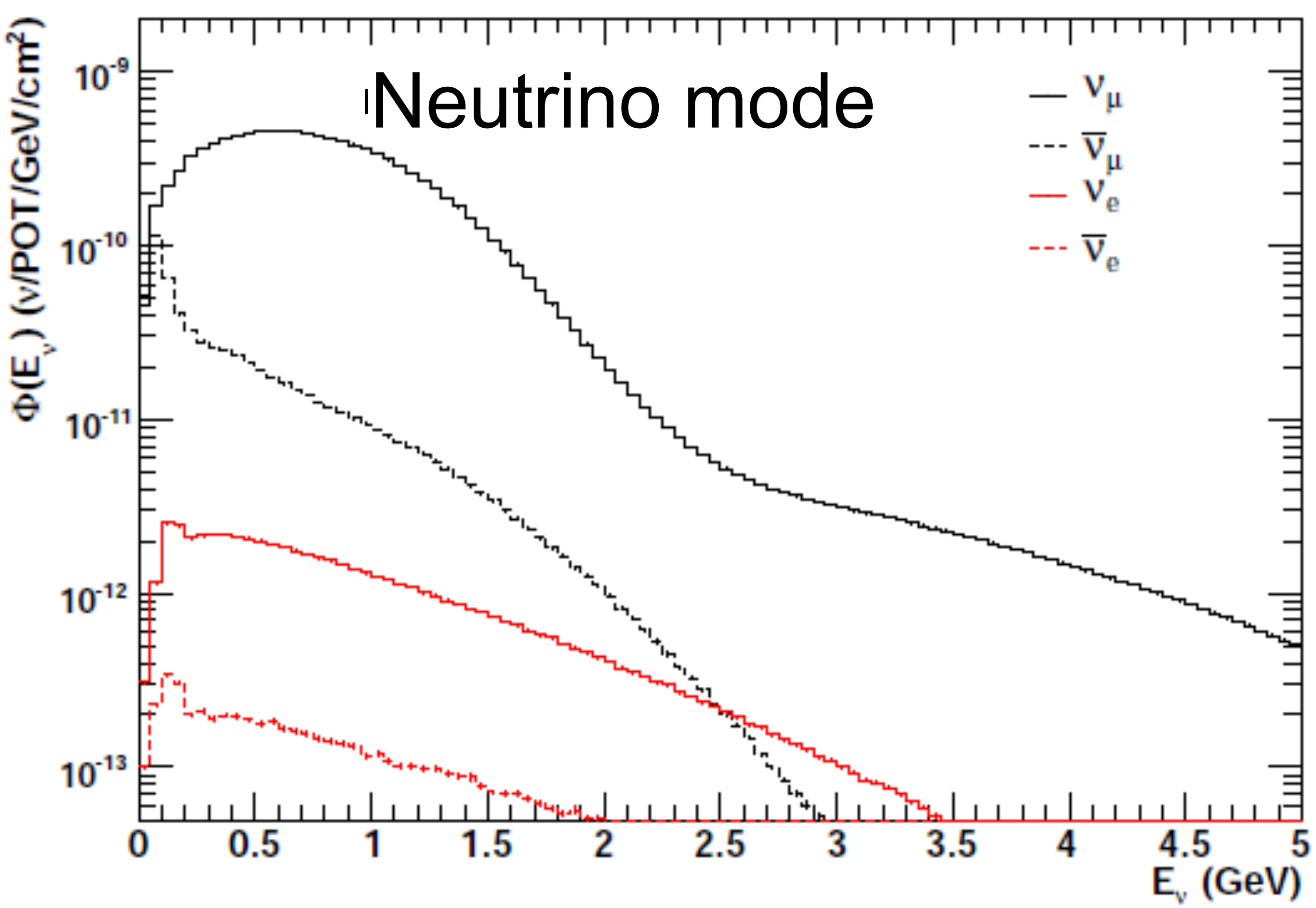


- 8 GeV protons from Booster
- 1.7 int. length Be target
- Single Horn
  - Neutrino & Antineutrino mode ±174kA
- 50m long decay pipe



Neutrino Flux Prediction

- Geant4 based simulation
- Hadron production cross sections tuned to external data
- Proton, pion cross sections on Be, Al tuned



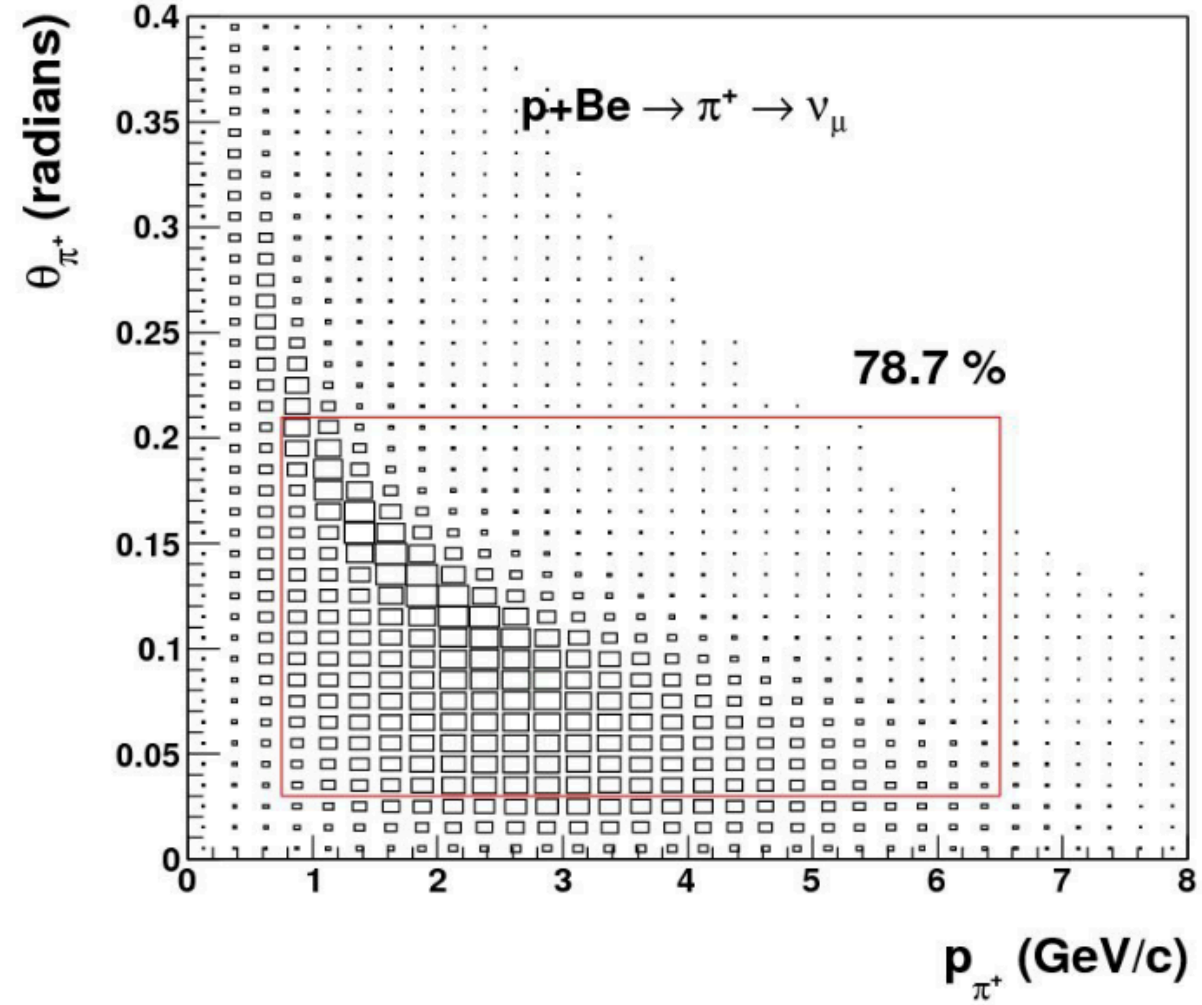
Phys. Rev. D79, 072002 (2009)

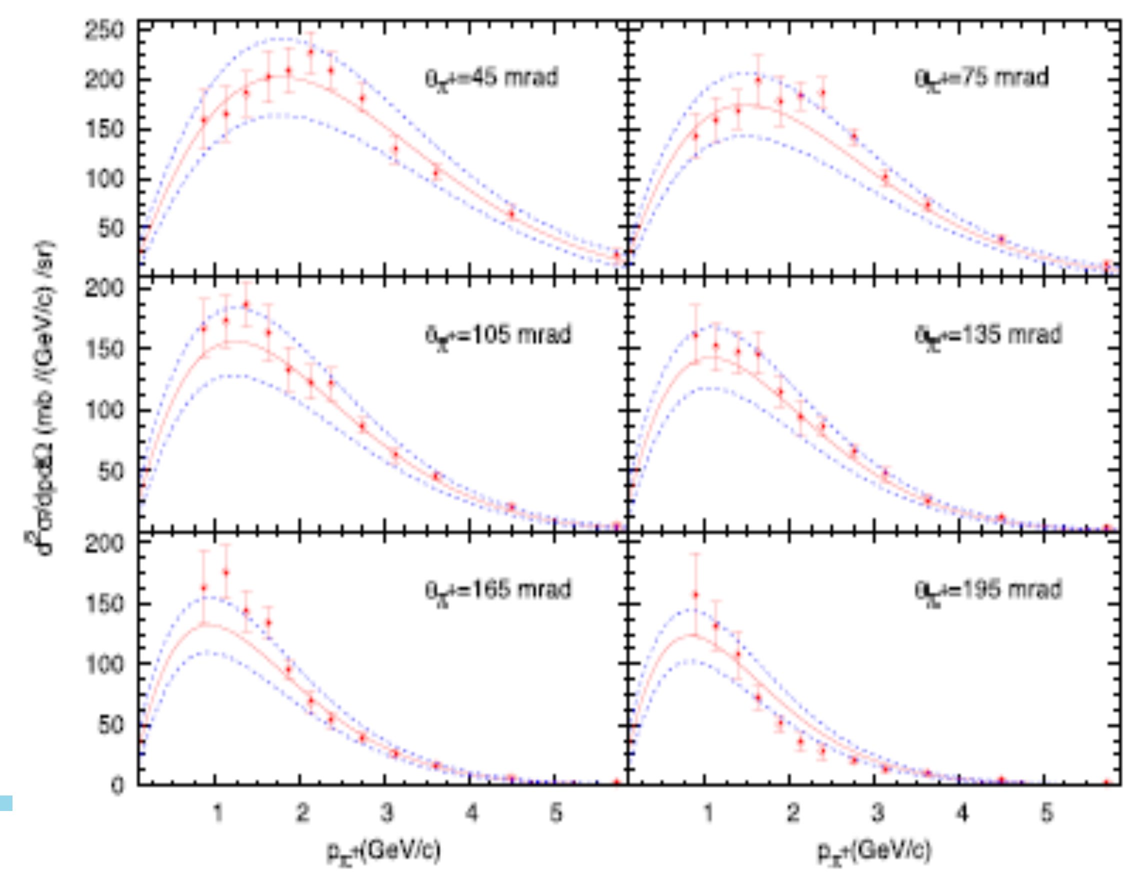
	ν_μ		$\overline{\nu}_\mu$	
Flux (ν/ cm^2/POT)		5.19×10^{-10}		3.26×10^{-11}
Frac. of Total		93.6%		5.86%
Composition	π^+:	96.72%	π^-:	89.74%
	K^+:	2.65%	$\pi^+ \to \mu^+$:	4.54%
	$K^+ \to \pi^+$:	0.26%	K^-:	0.51%
	$K^0 \to \pi^+$:	0.04%	K^0:	0.44%
	K^0:	0.03%	$K^0 \to \pi^-$:	0.24%
	$\pi^- \to \mu^-$: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

Pion production

- 90% of ν_μs come from primary pion production in the target
- HARP measurement (8 GeV protons on Be target) covers ~78.7% of relevant pion production
- Sanford-Wang fits HARP (and E910 data)
- Fits done both for pi+ and pi-
- HARP systematic error propagated by using splines through HARP data taking into account the full error matrix





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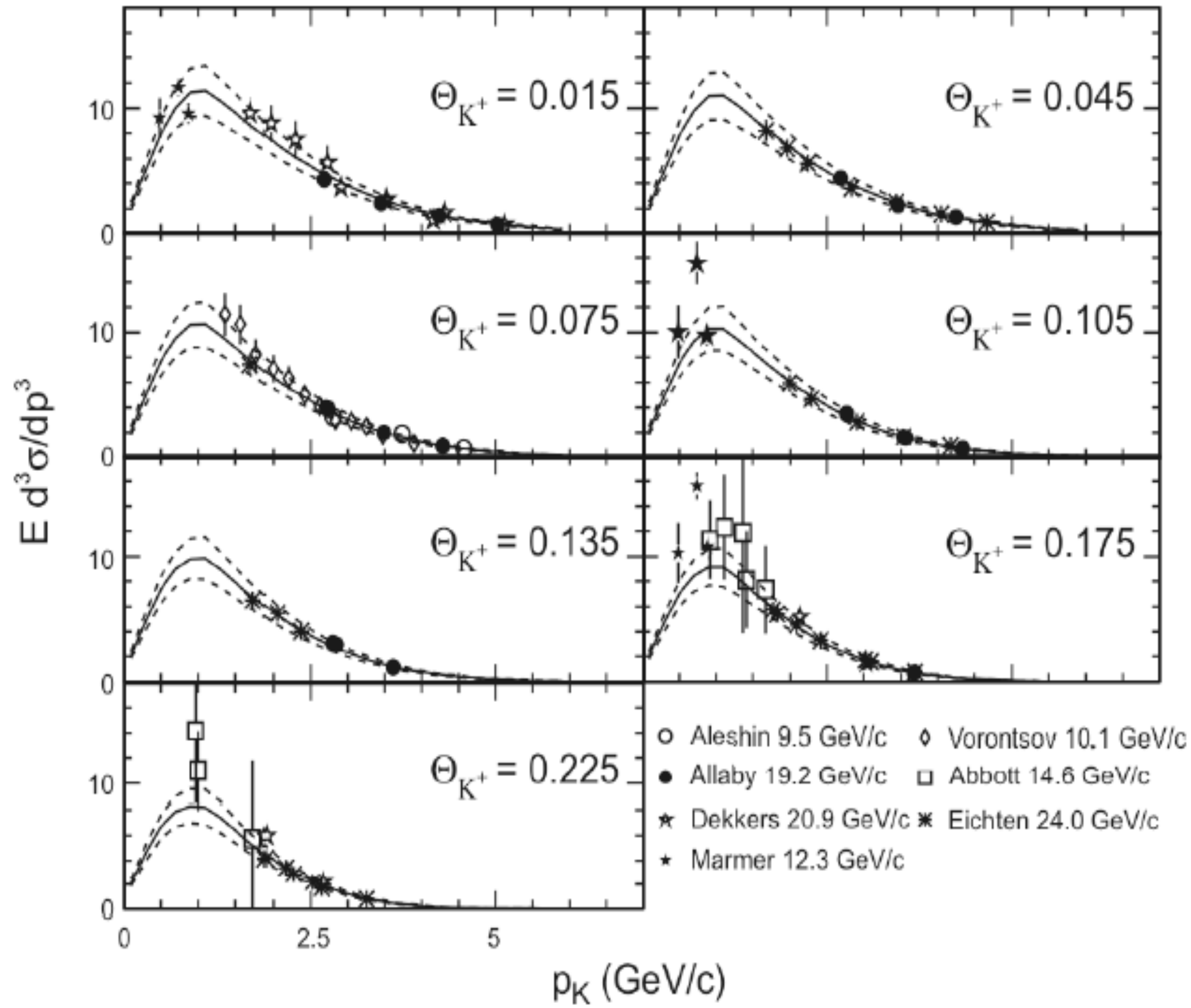
K^+ and K^0_L Production

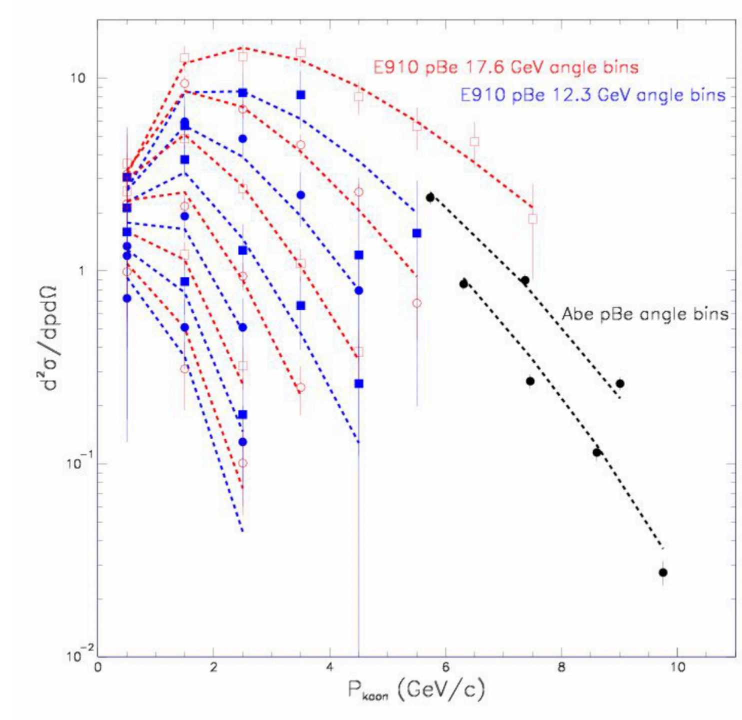
- Feynman scaling parameterization used to fit world K+ production data
- Datasets scaled to 8.89GeV cover 1.2< $P_K^{8.89}$ [GeV /c] <5.5
- Some of the datasets had issues with normalization

Phys. Rev. D84 114021 (2011)



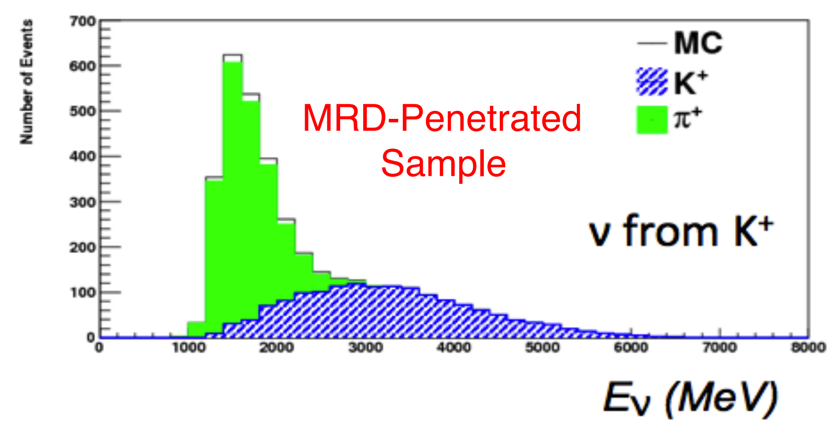
- Sanford-Wang fits to K^0_S production data from BNL E910 (p_{beam} = 12.3 and 17.5 GeV/c) and KEK Abe et al. (12.3 GeV/c)
  - Most relevant forward production not fully covered

Phys. Rev. D79, 072002 (2009)



Using neutrinos to constrain flux

- 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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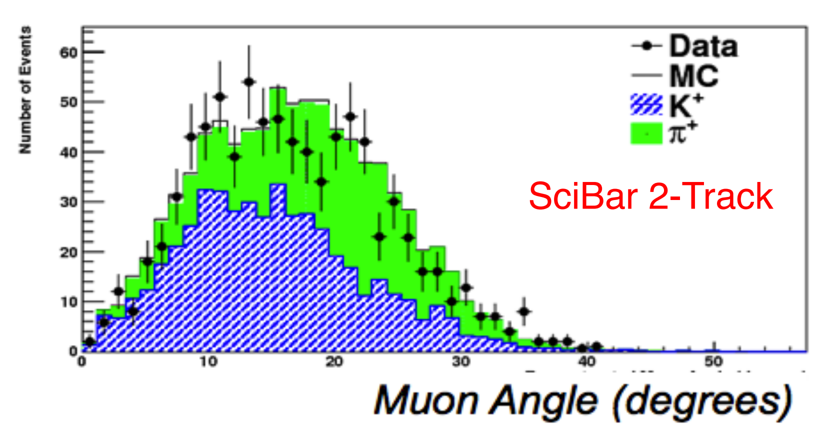
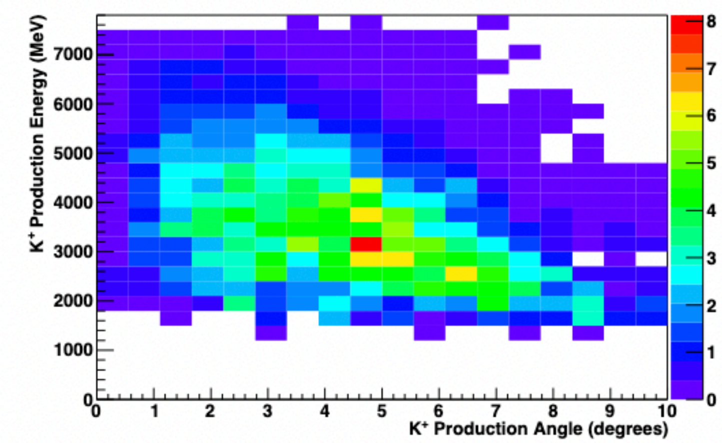
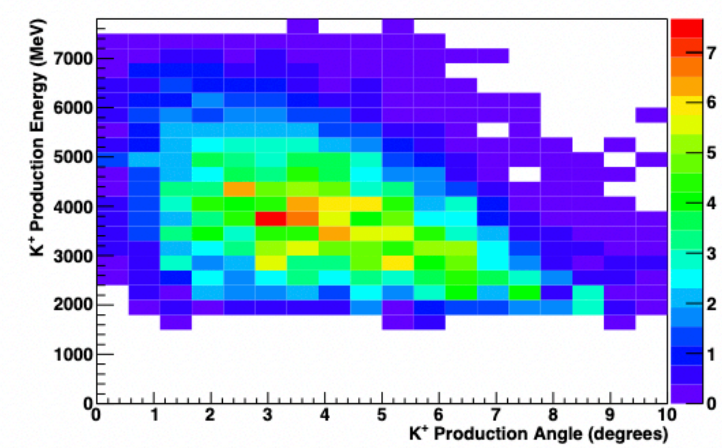
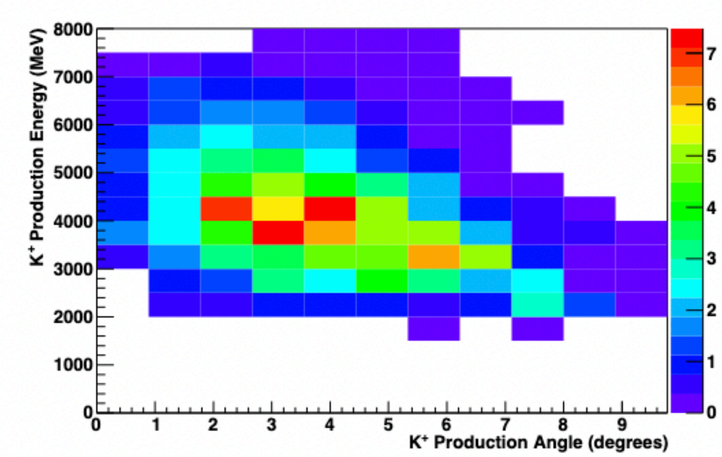




(a) 1-Track Sample



(b) 2-Track Sample



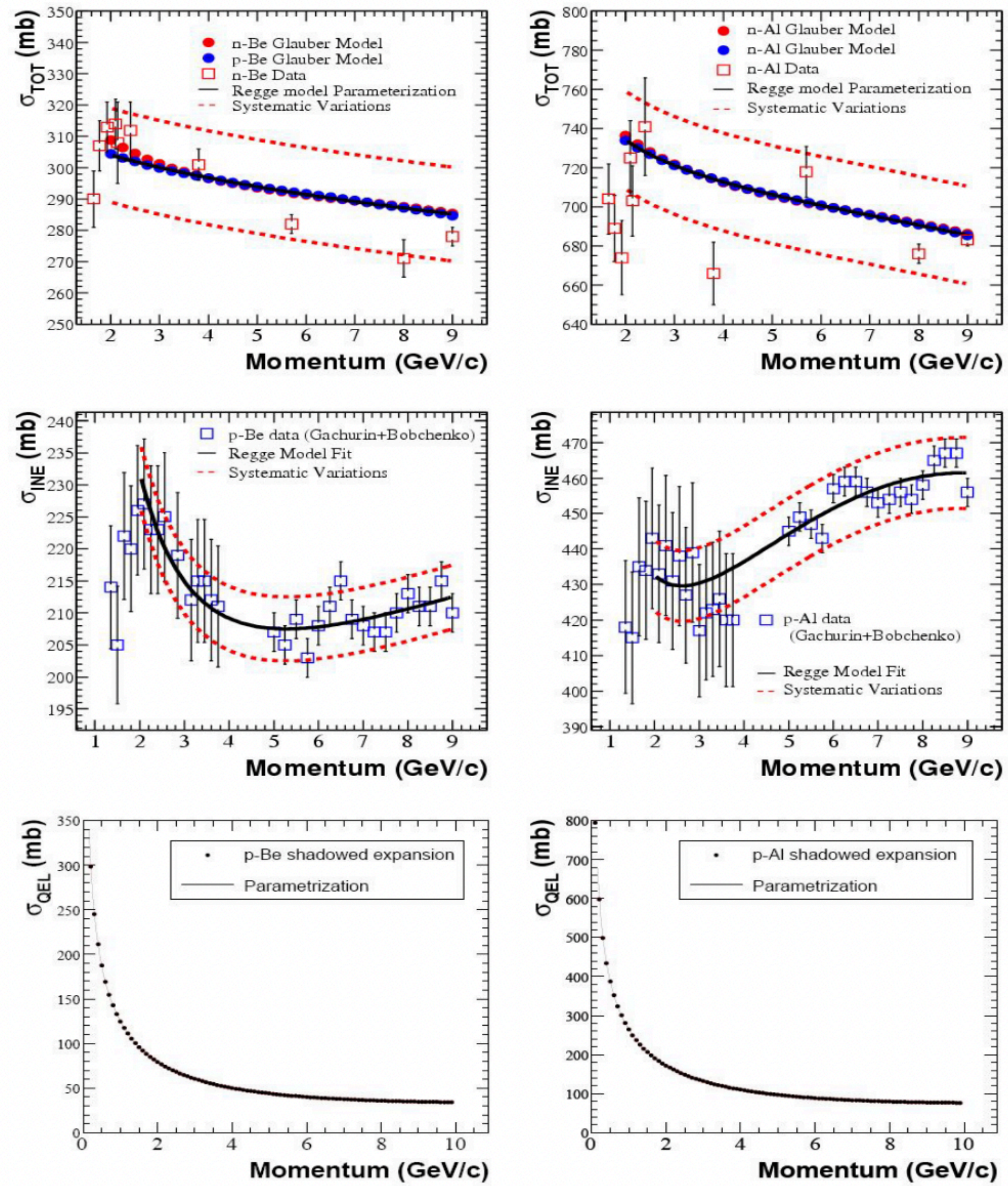
(c) 3-Track Sample

Hadronic interactions

- Measured cross sections used where available
- QEL uncertainties 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



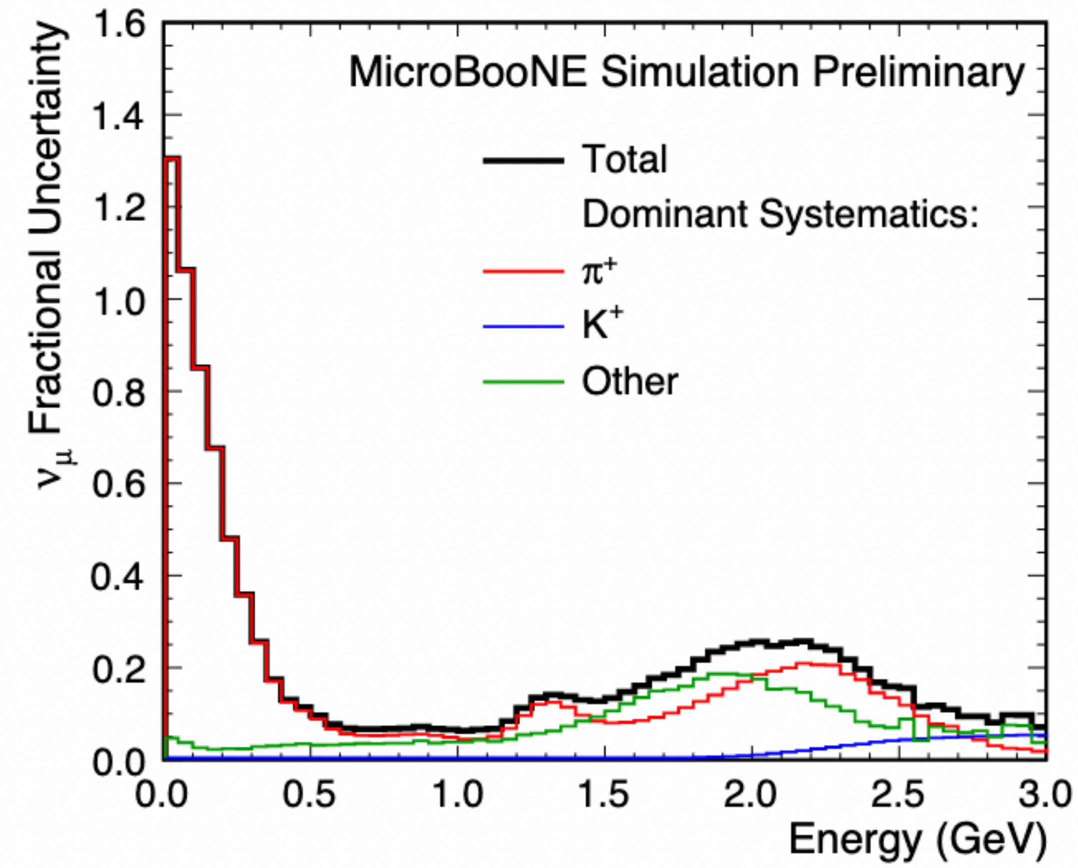
Phys. Rev. D79, 072002 (2009)

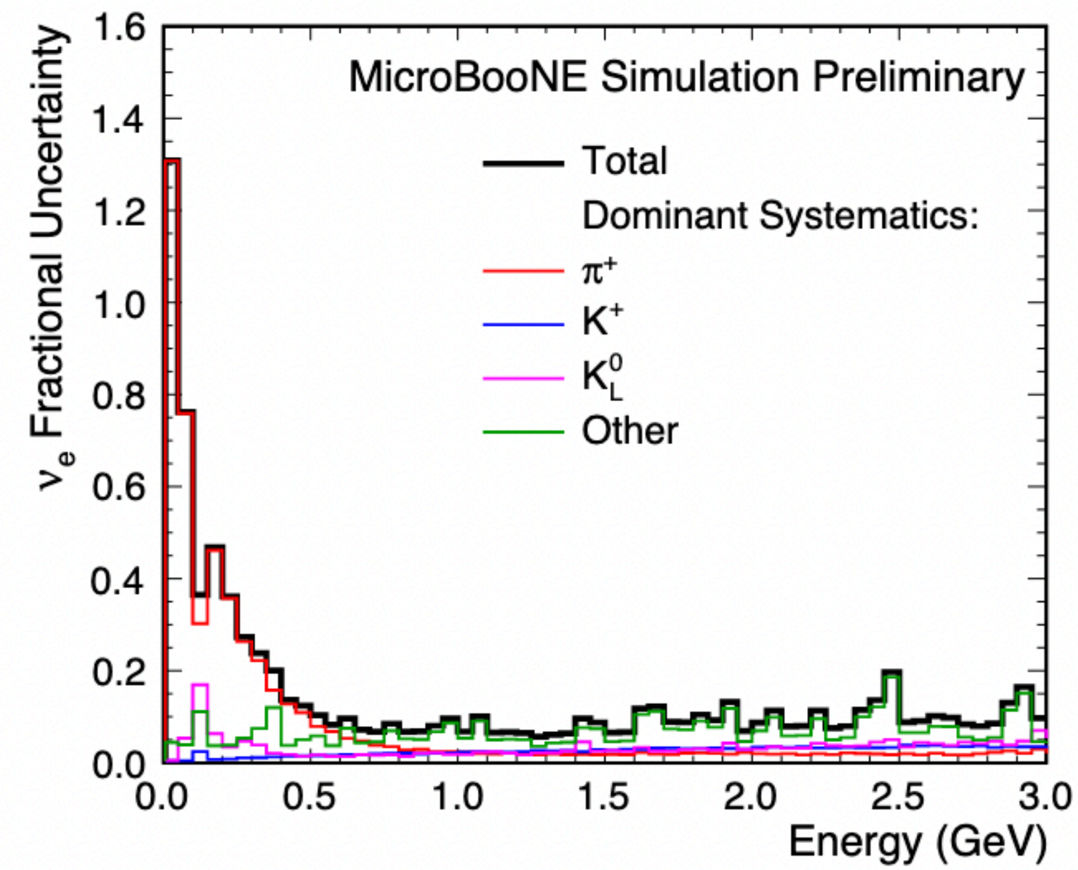
D. Schmitz, FERMILAB-THESIS-2008-26

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_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

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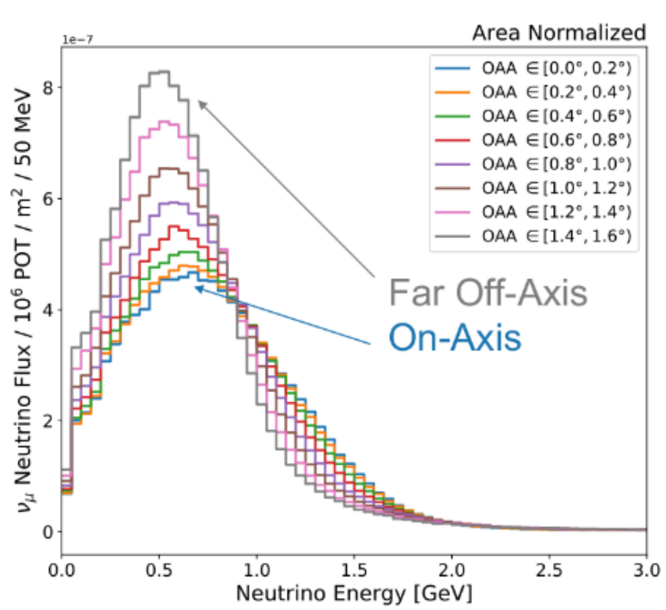
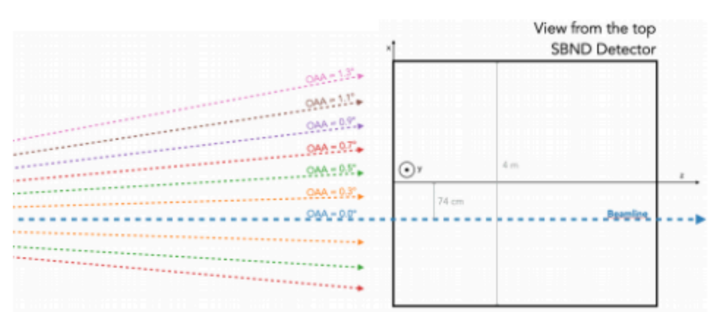
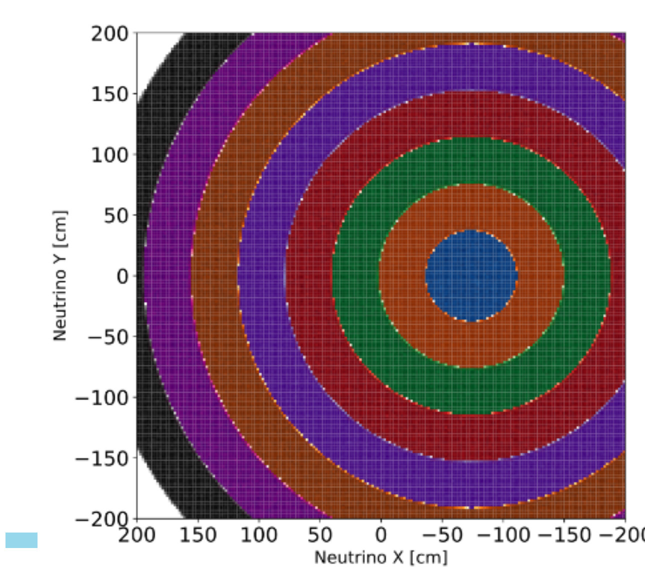
Future development

- Upgrading g4bnb simulation
  - Primary production constrained with same existing data
  - More modern, better geant4 models for reinteractions
  - Adding new data
- Constraints using neutrino data
  - PRISM (Ioana's talk yesterday, Moon's talk on Wednesday)



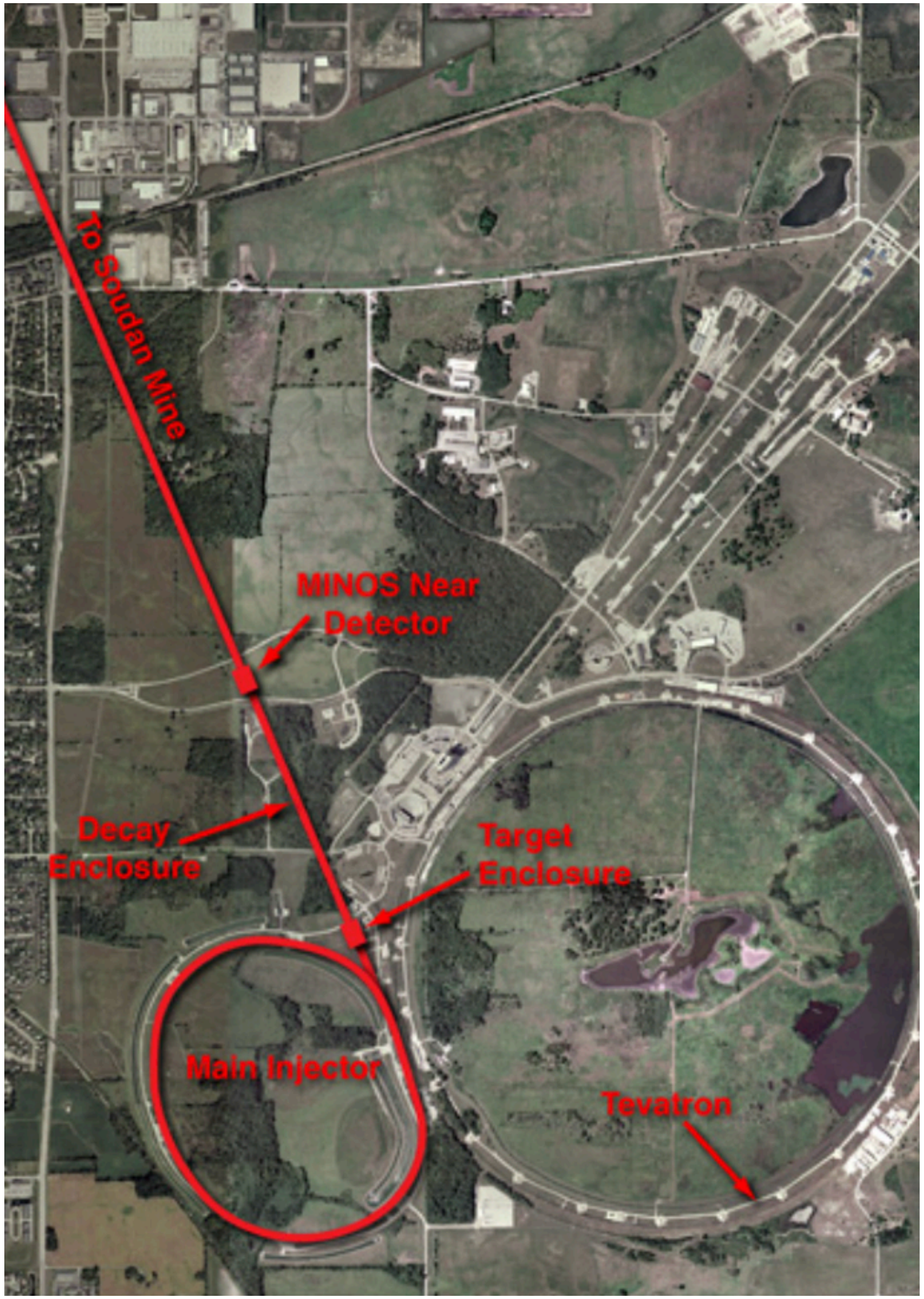


Pictures from: M. Del Tutto and V. Pandey - NuSTEC CEWG Meeting, June 3, 2021



NuMI Beam

- 120 GeV protons from Main Injector
- 2 int. lengths graphite target
- Two magnetic horns
  - Neutrino & anti-neutrino mode
- 675m long decay pipe
- Low Energy and Medium Energy running
- Argoneut, MINERvA, MINOS, NOvA
- MicroBooNE, ICARUS - far off axis



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

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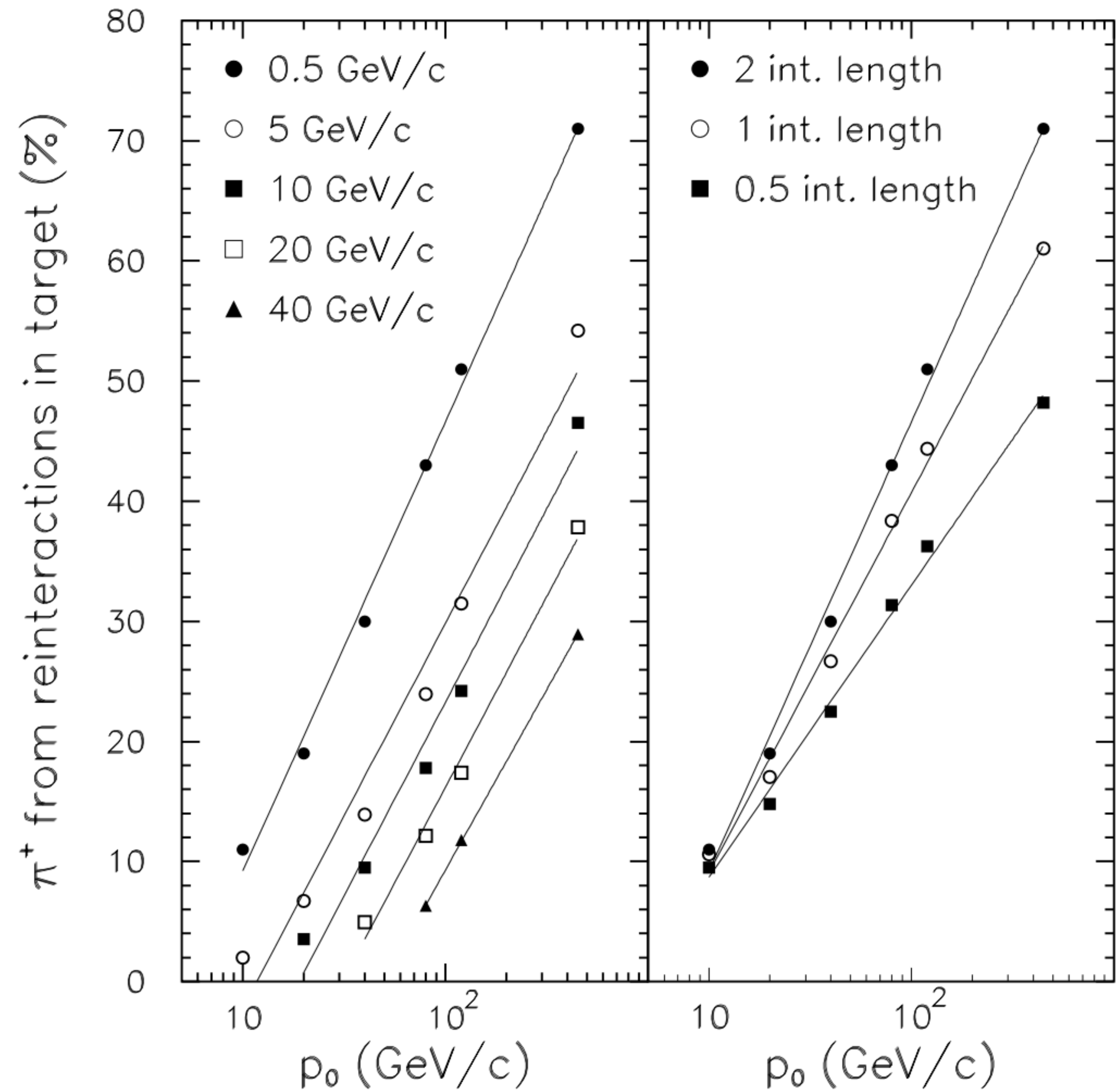
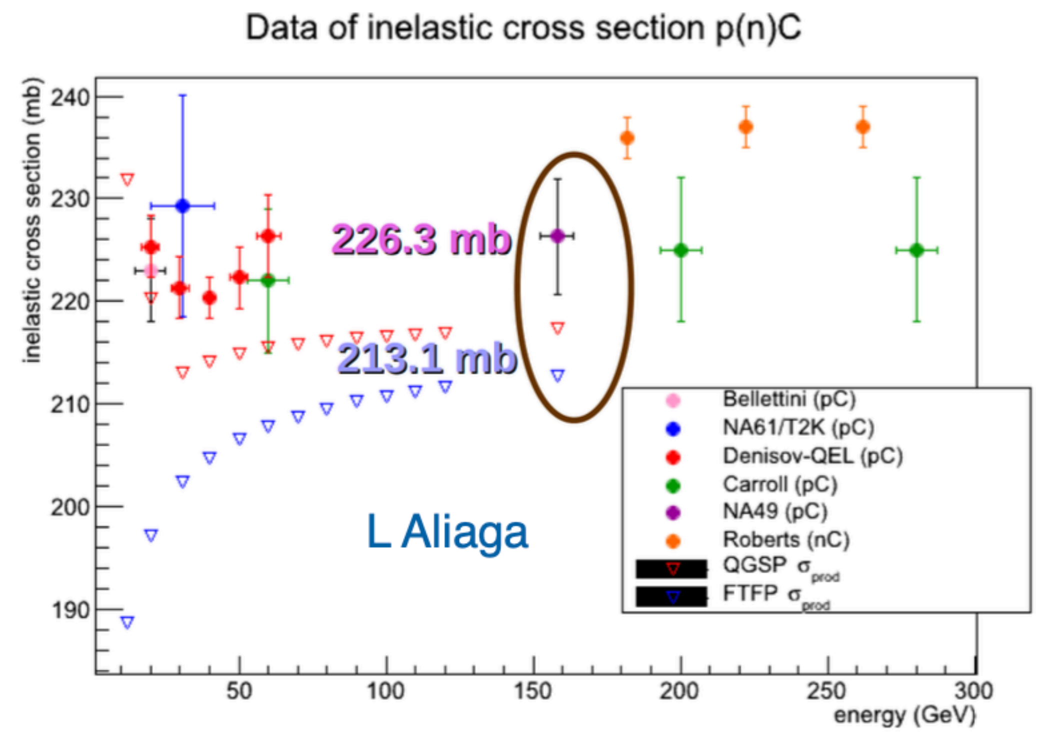


NuMI beam simulation (g4numi)

- Geant4 based simulation
- Using PPFX package to constrain models to external hadron production data
  - Developed for MINERvA and now used by all experiments seeing NuMI neutrinos
- Correcting the simulation through reweighing
  - Keep complete information about cascades leading to a neutrino
- Interactions are weighted by:



$$w_{HP} = \frac{f_{Data}(x_F, p_T, E = 158GeV) \times scale(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}$$

$$f = E\frac{d^3\sigma}{dp^3}$$

- Scale determined by fluka to enable scaling NA49 to lower proton momenta
- Second weight is applied to account for exponential decay of beam

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

Phys. Rev. D 94, 092005 (2016)

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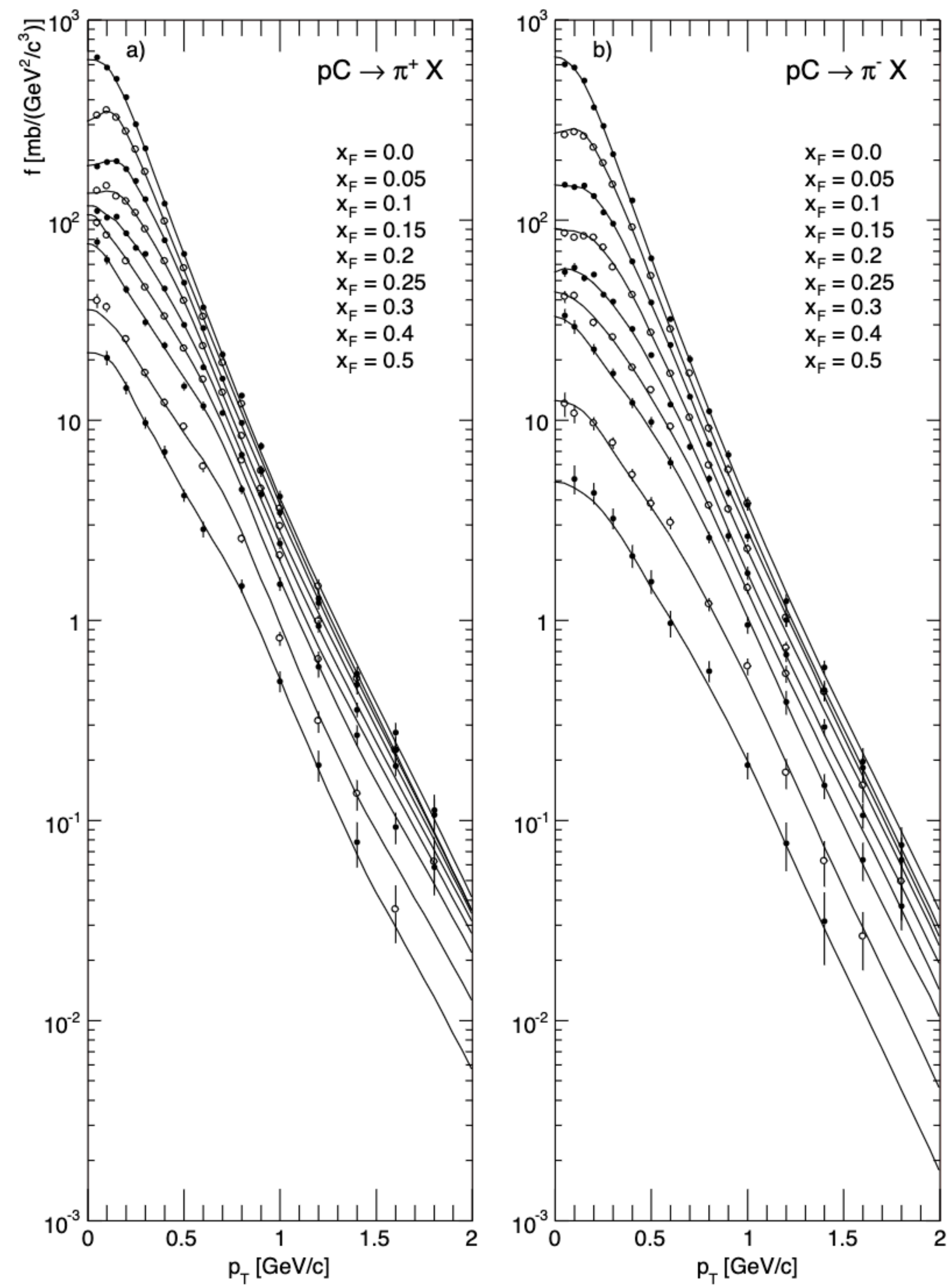
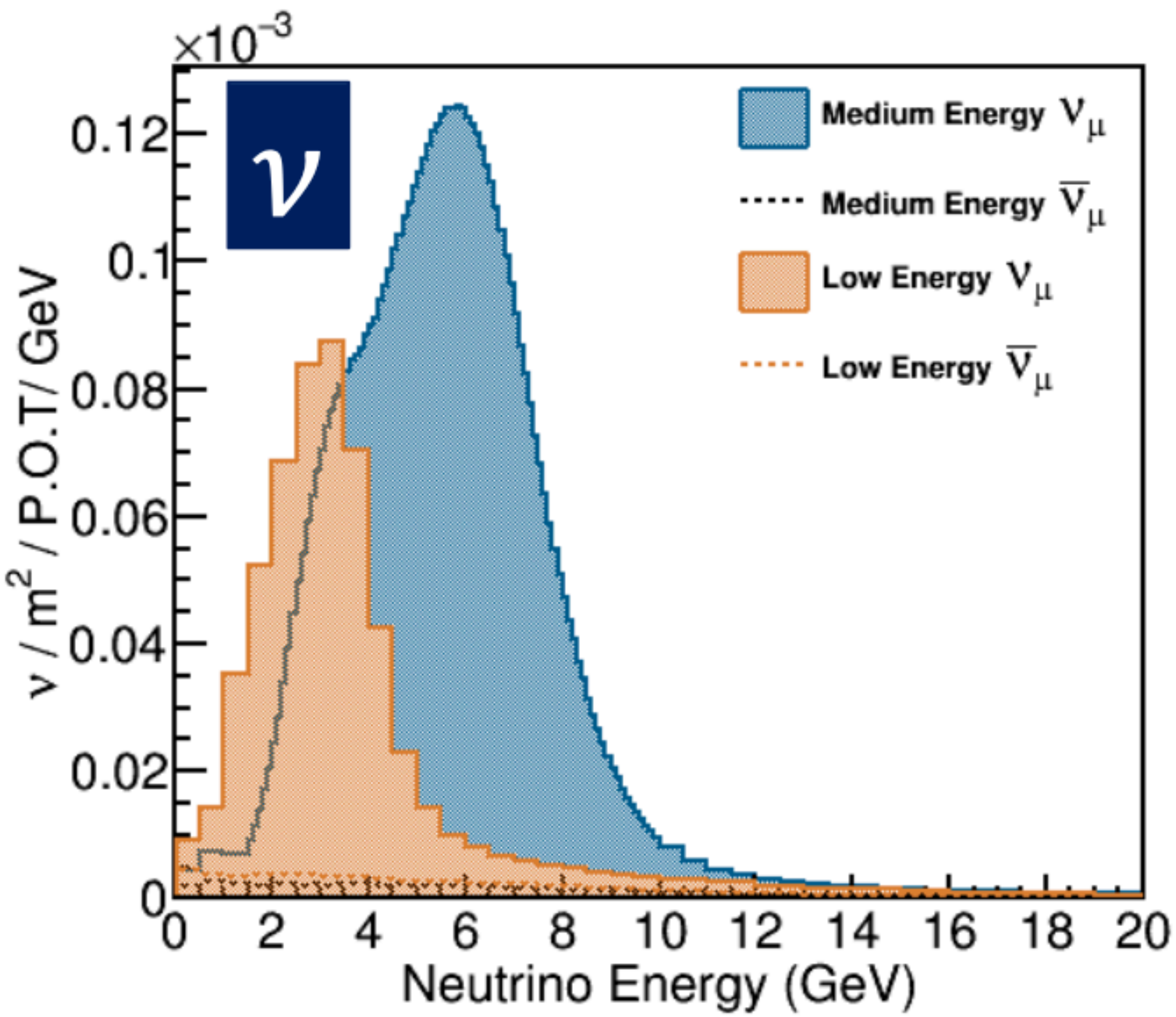
PPFX External data

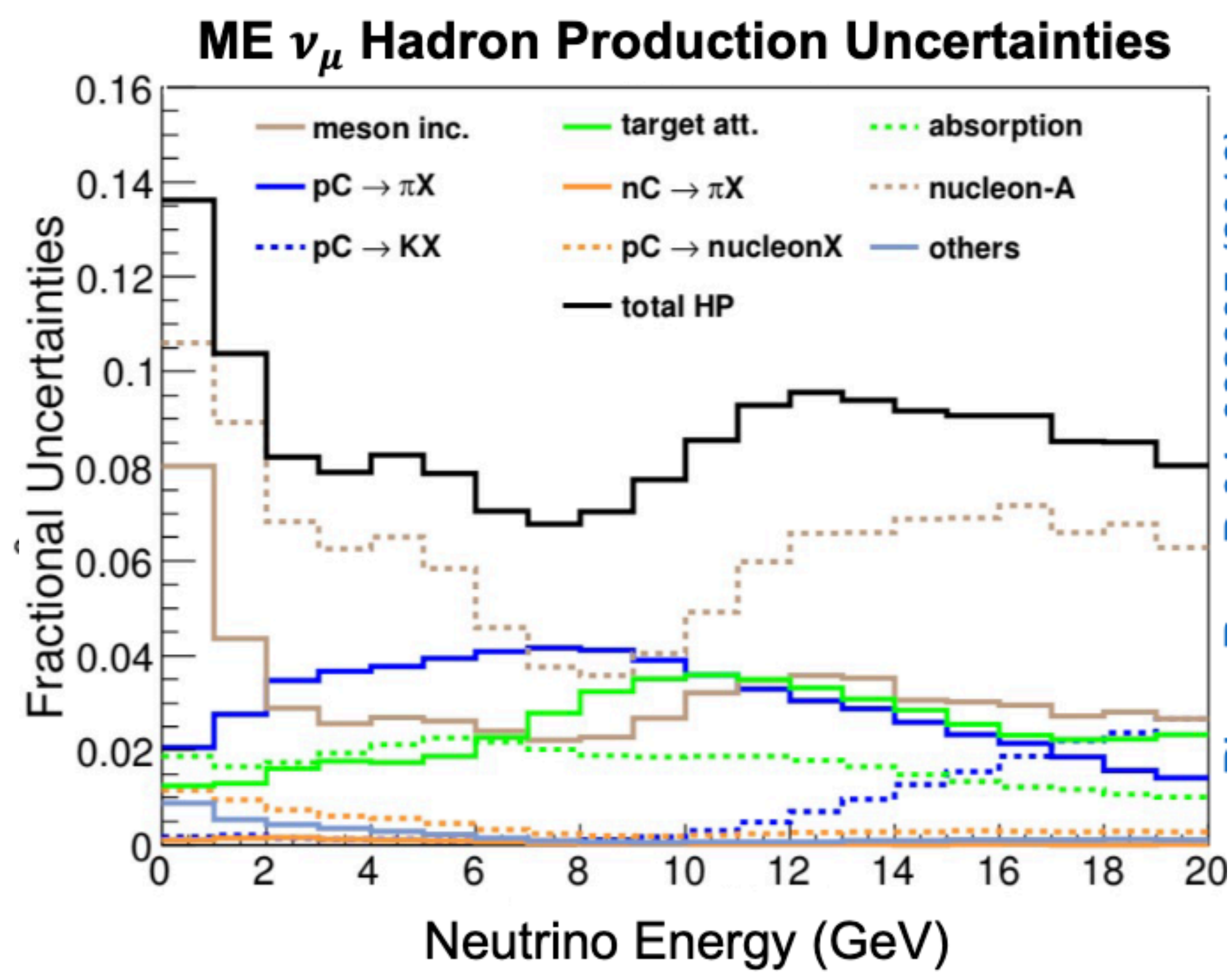
- Data sets currently used:
  - NA49 158 GeV protons (Eur.Phys.J.C49: 897-917, 2007, Eur. Phys. J. C73, 2364 (2013))
  - Barton et. al. 100 GeV protons (Phys. Rev. D 27, 2580) NA49 pC → K±X (G.Tinti Thesis)
  - MIPP K/pi ratios (A.V. Lebedev Thesis)
- Extensions of data:
  - pC → π+X cross section assumed 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 and uncertainties

- Systematics evaluated using multiple universes technique
- Large 40% uncertainty assumed for processes not covered by data



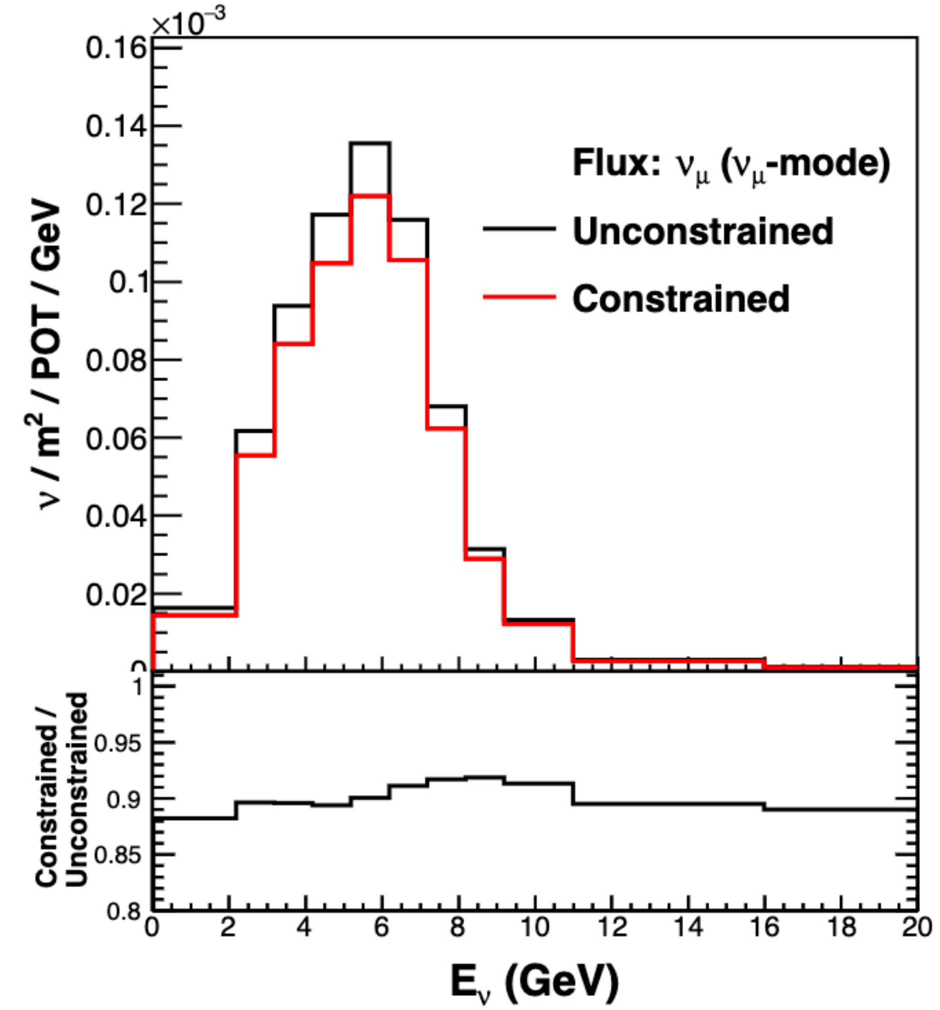


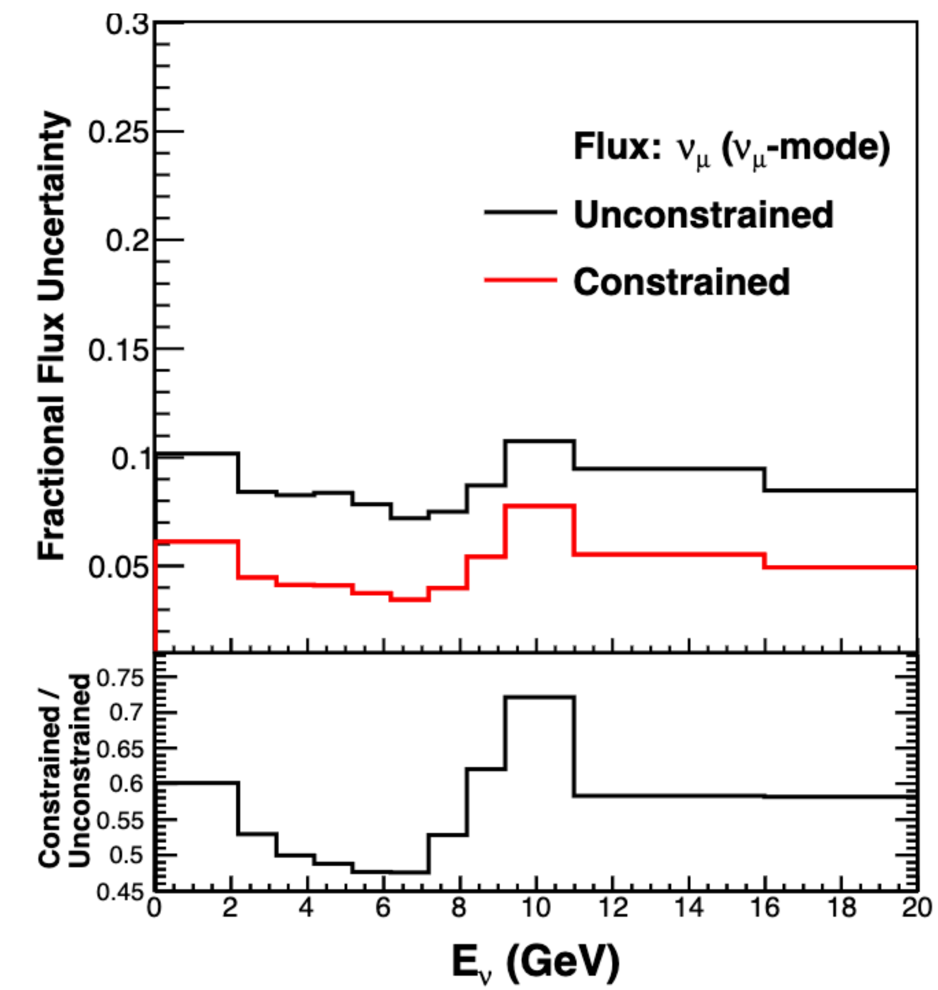
Additional constraints

- Minerva uses in-situ measurements to further constrain the flux:
    - ν+e scattering (talk by Luis)
    - Inverse Muon Decay
    - (Low hadronic recoil)

	$\bar{\nu}_\mu$-mode				ν_μ-mode			
	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_μ	ν_e	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
a priori	7.76	7.81	11.1	11.9	7.62	7.52	12.2	11.7
ν_μ-mode νe^-	6.11	5.81	6.30	8.50	3.90	3.94	8.37	8.68
$\bar{\nu}_\mu$-mode νe^-	4.92	4.98	8.07	9.19	5.88	5.68	8.36	8.64
combined νe^-	4.68	4.62	5.56	7.80	3.56	3.58	7.15	7.84
combined νe^- + IMD	4.66	4.56	5.20	6.08	3.27	3.22	6.98	7.54

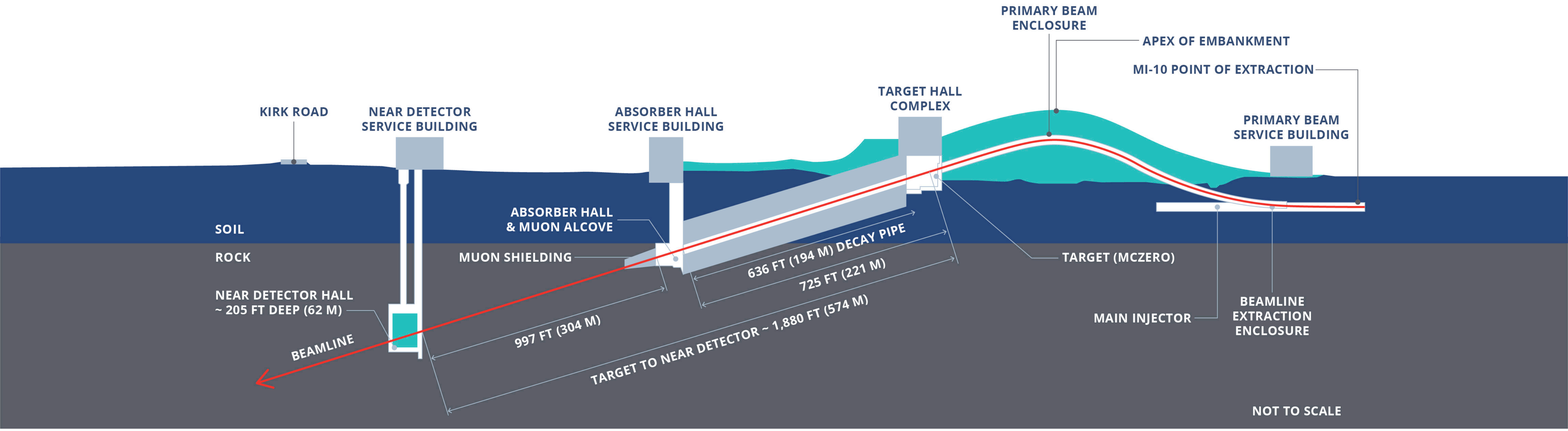
Phys.Rev.D 107 (2023) 1, 012001





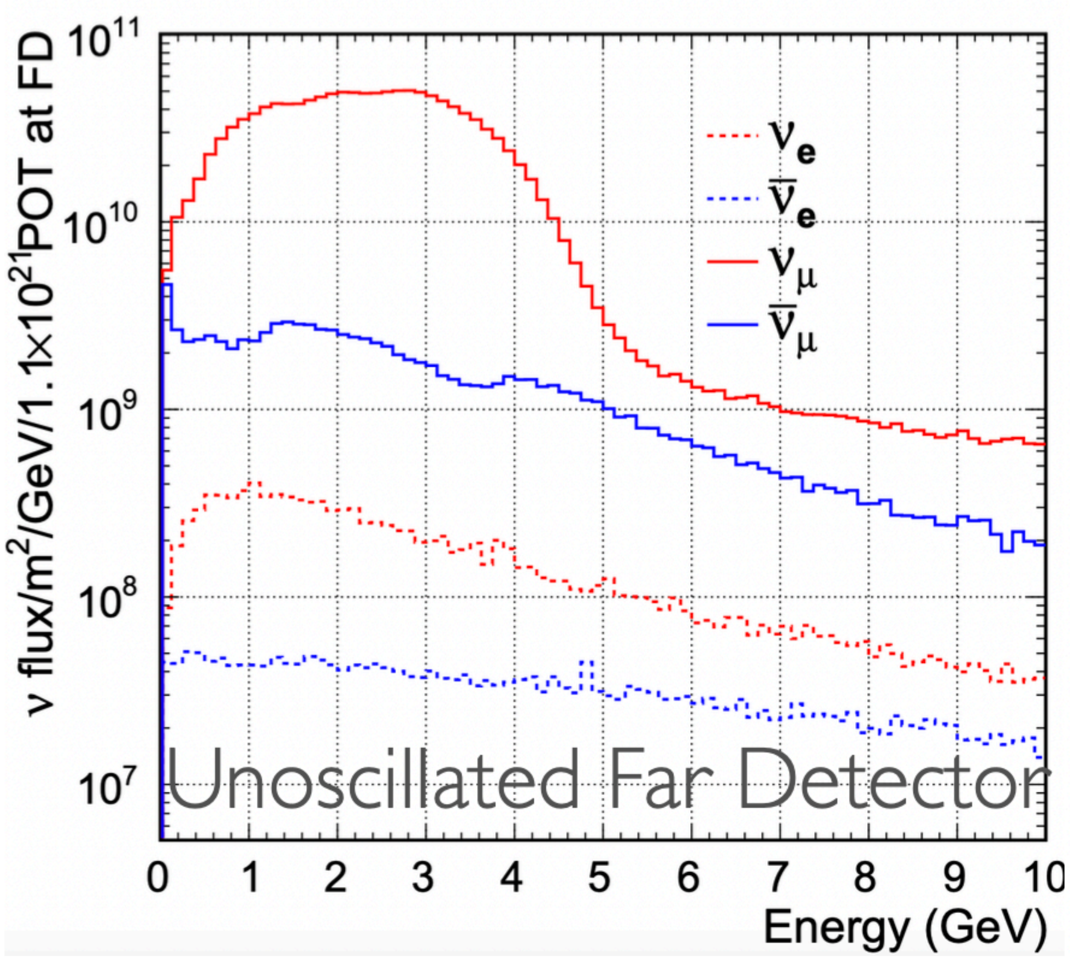
LBNF

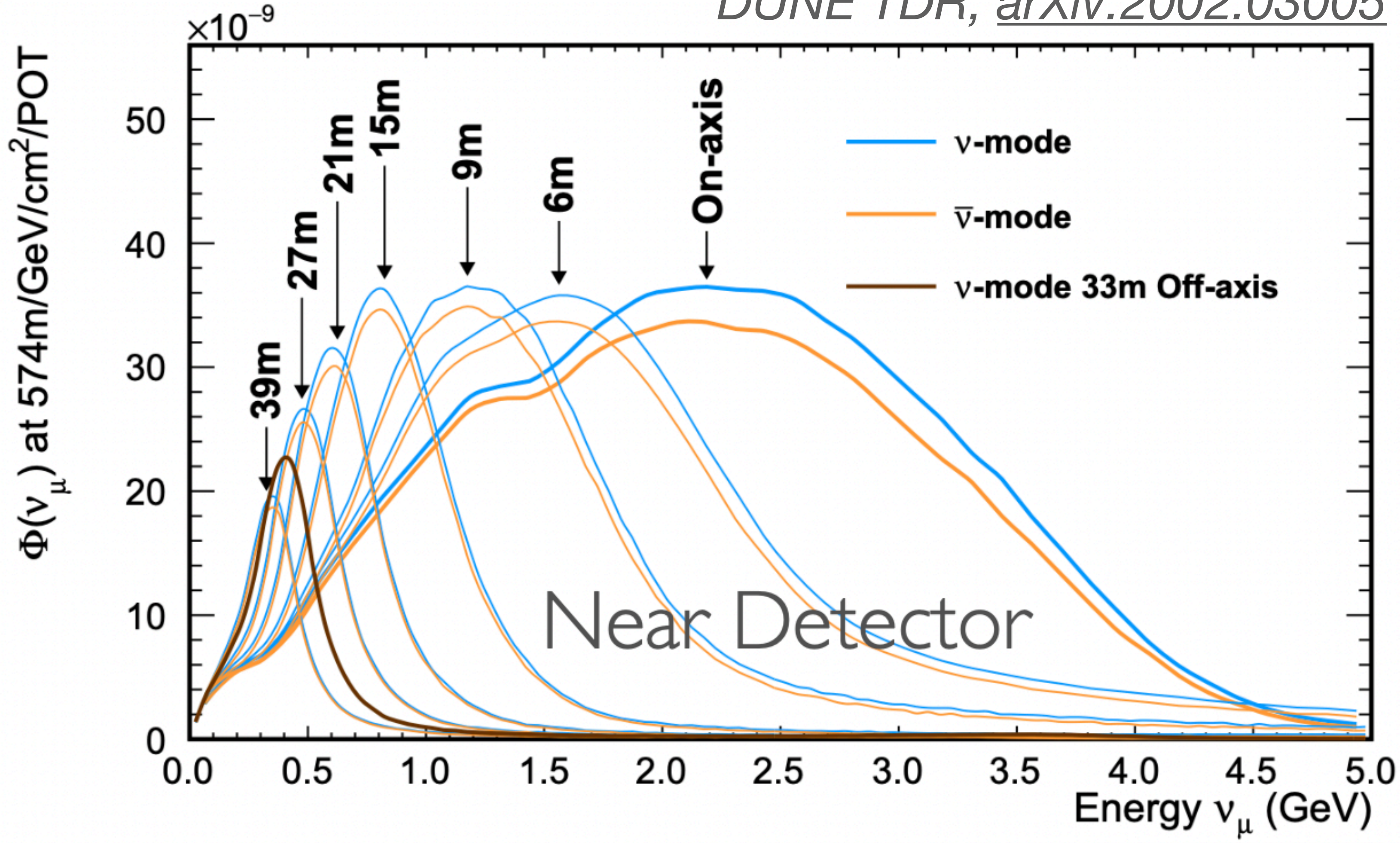
- 120 GeV protons on 3 int. lengths long graphite target
- 3 horns
    - Polarity can be switched to produce neutrino or antineutrino enhanced beam
- 221m long decay region
- Optimized beam design for sensitivity to CP-violation



LBNF simulation (g4lbnf)

DUNE TDR, arXiv:2002.03005

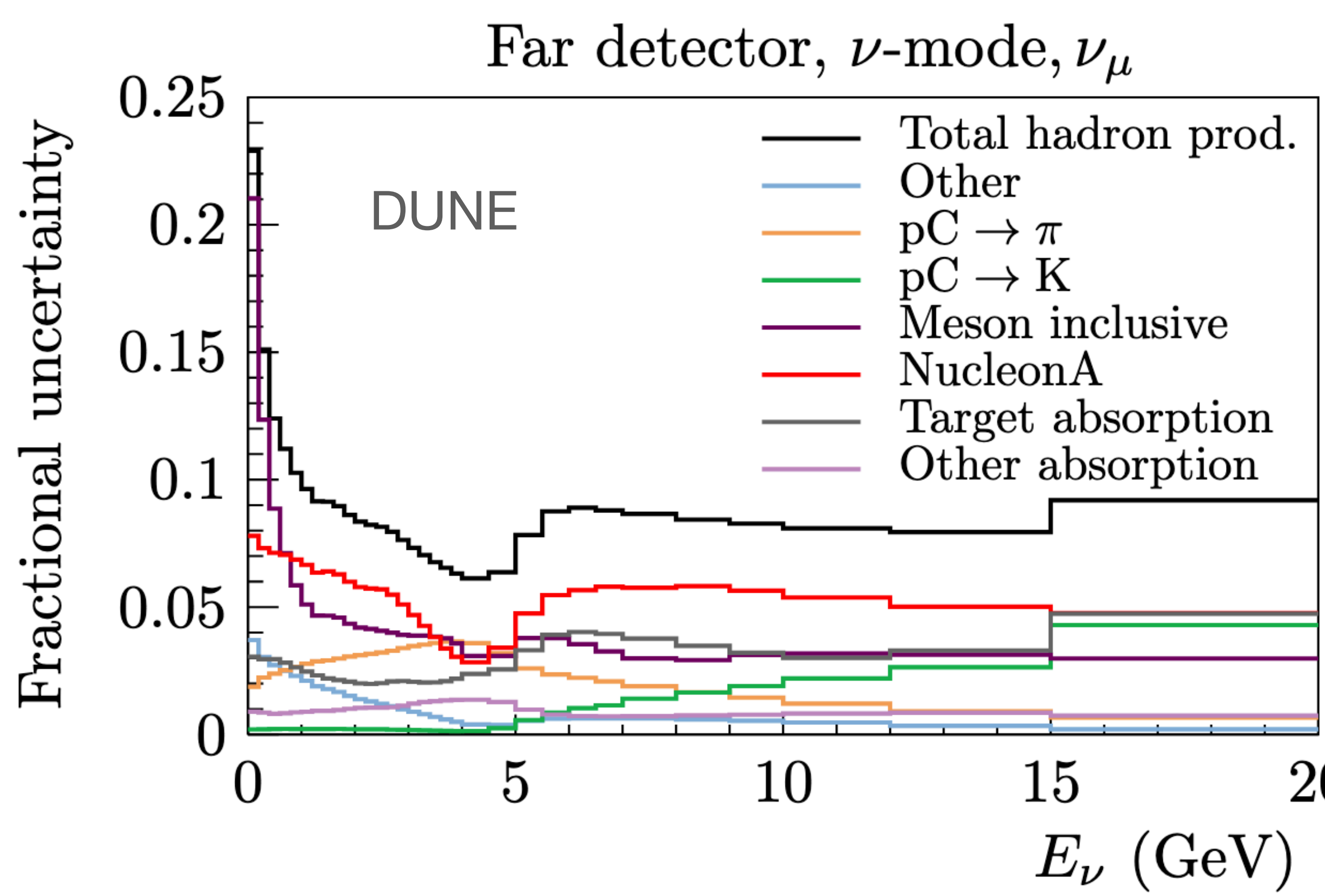




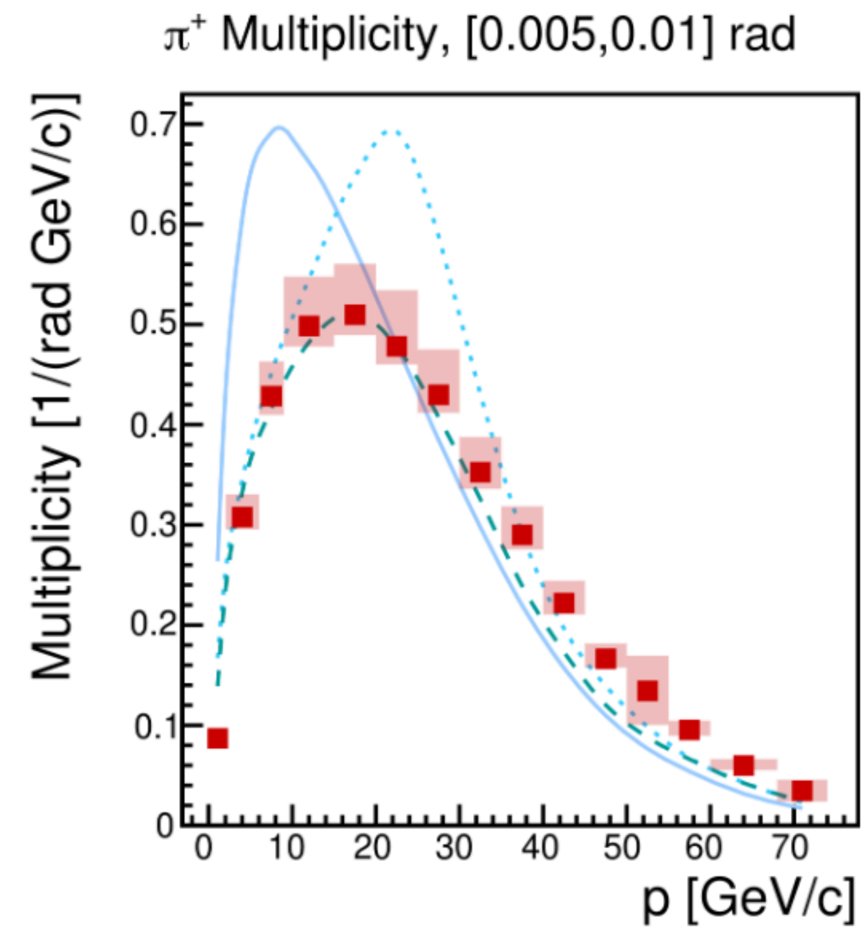
- Need very precise flux prediction to achieve the DUNE precision measurements
  - Most detailed geometry so far
  - Need more external data to constrain the geant4 models
- Need flux at near, far detector and various off-axis locations for PRISM analysis and correlations between all of them

Systematic errors (Hadron Production)

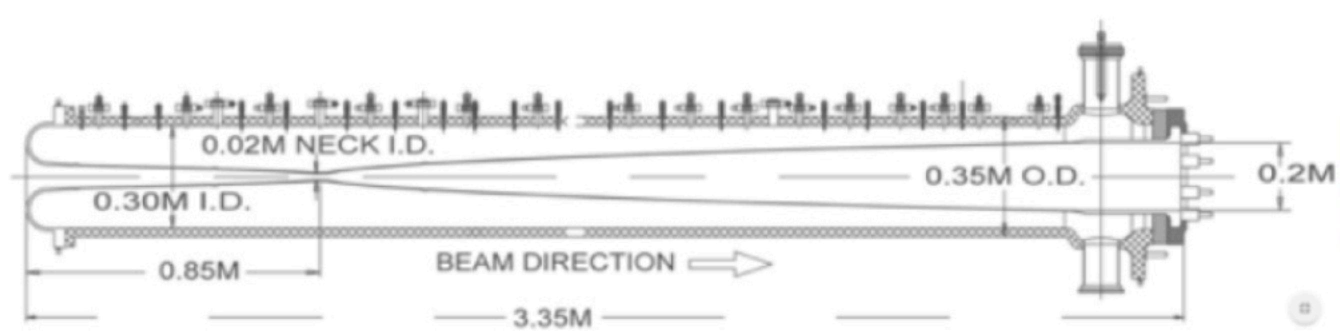
- Using ppfx to propagate the errors
  - Data cross sections varied according to their uncertainties (taking into account correlations)
- Large 40% uncertainty assumed for processes not covered by data



Future work NuMI/LBNF

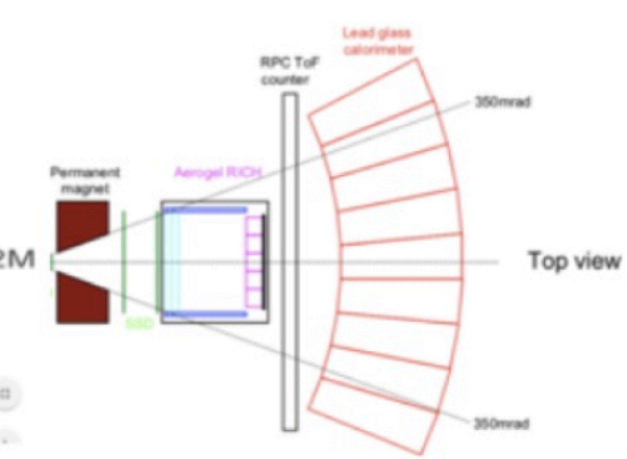


- Update geant4 version
- Geometry updates to g4lbnf as engineering being finalized
- Adding new data to PPFX
    - NA61 (Andrew's talk)
    - Emphatic (Leo's talk, Robert's poster)
- First measurement of hadron production behind horn with EMPHATIC



L. Fields

NuMI Horn 1



EMPHATIC

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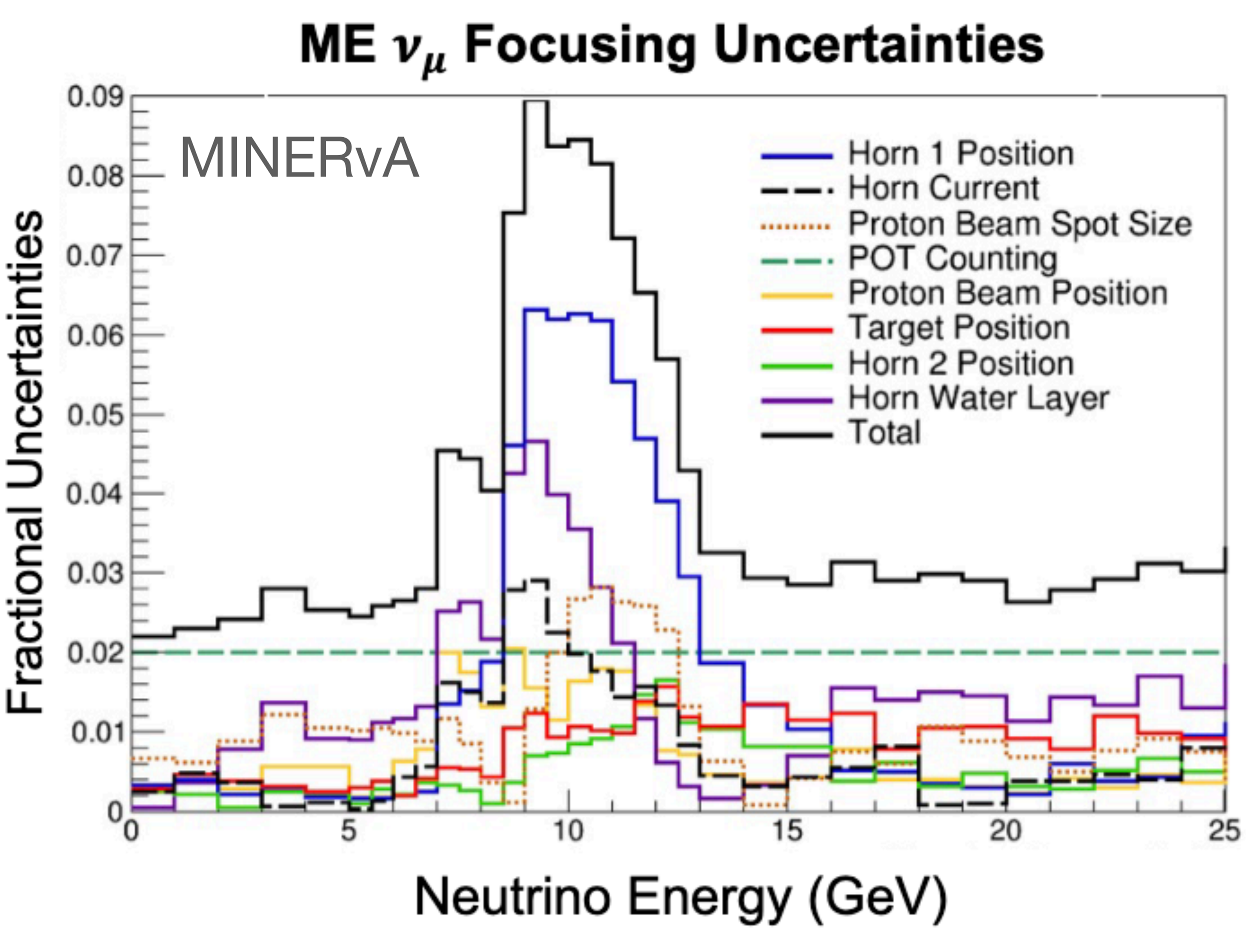
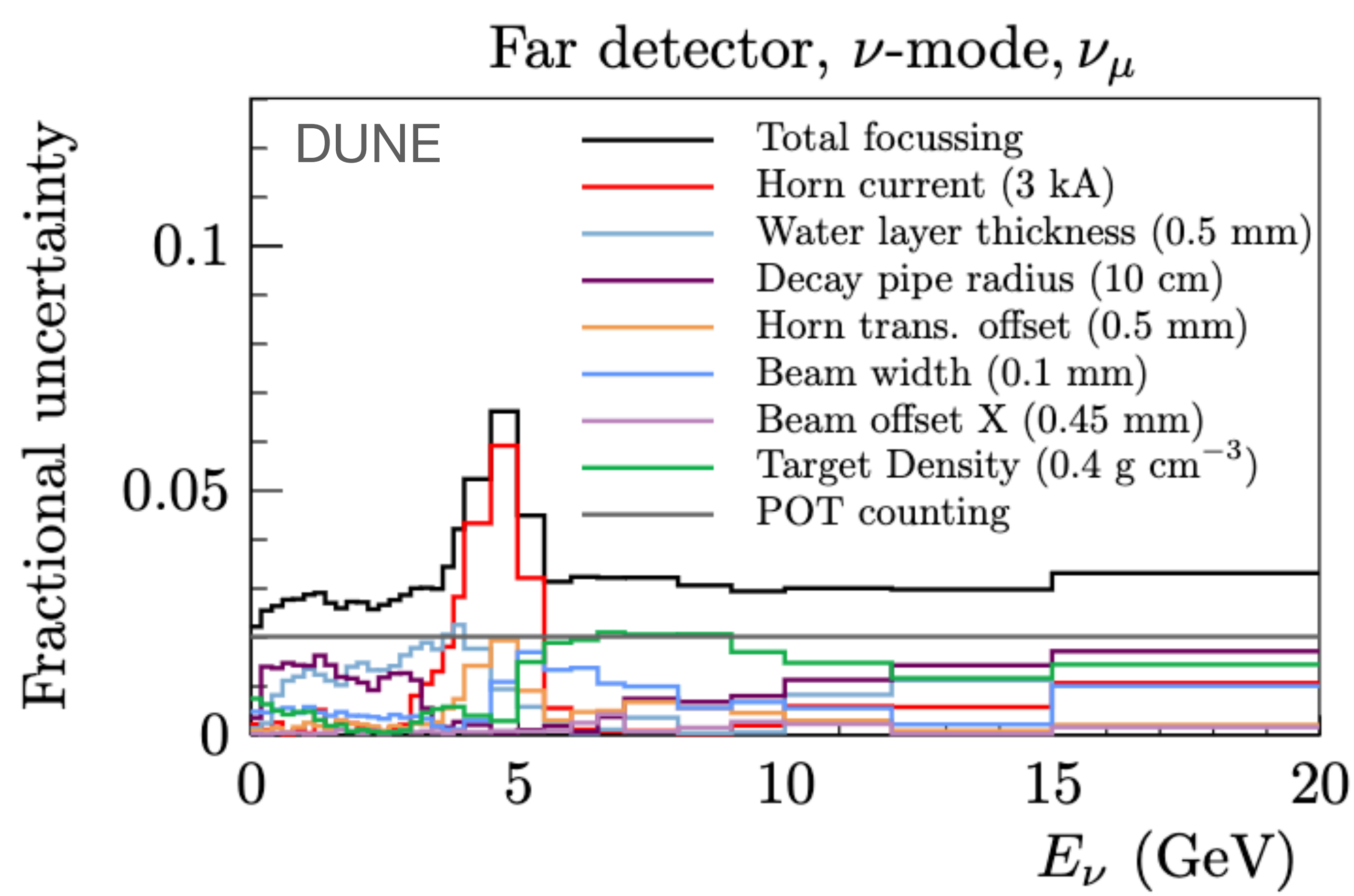
Focusing uncertainties

- Additional uncertainty due to various misalignments in the beamline/geometry mismatches, beamline instrumentation miscalibrations
- Becoming more and more important as hadron production errors get more constrained
- Need good beam monitoring to constrain these errors





Conclusion

- Geant4 based simulations used to predict flux for BNB, NuMI and LBNF
- Additional tuning done to match external data where available
- Systematic errors propagated from hadron production experiments
- Data from neutrino detectors used to further constrain flux
- Focusing uncertainties getting more important as hadron production gets more constrained