Simulation & Beam Transport Systematics of Neutrino Flux in NOvA

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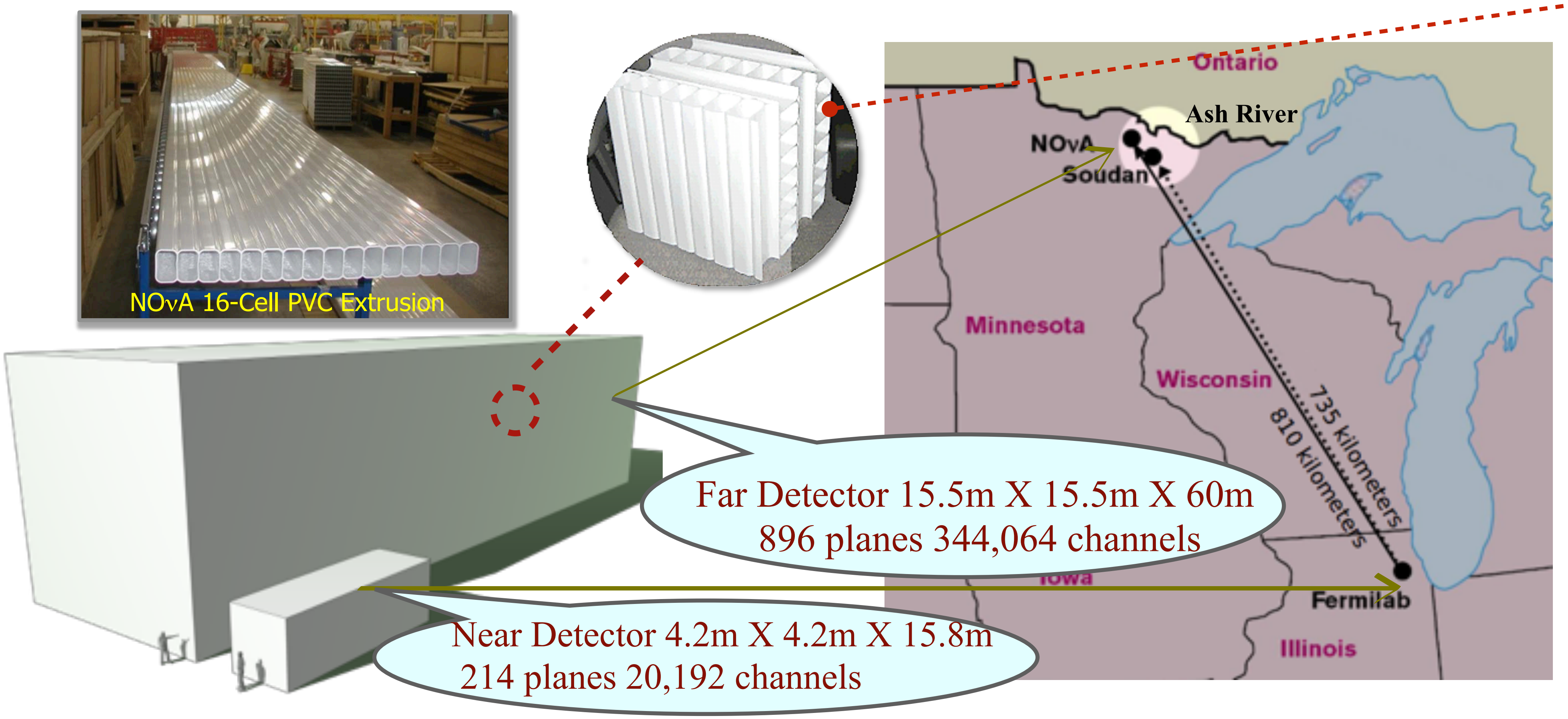
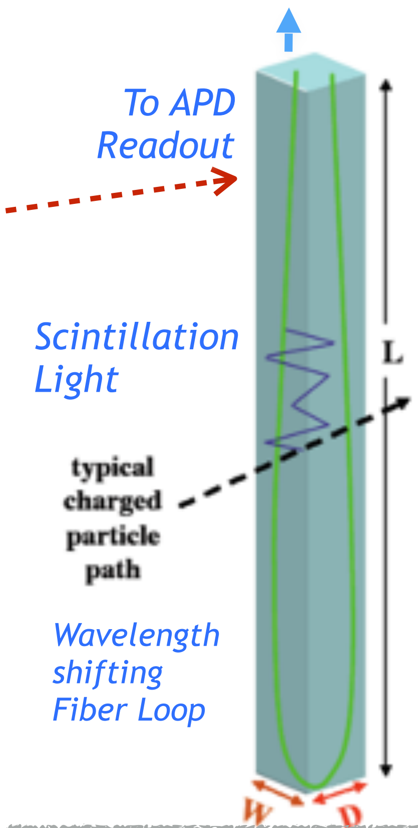
NOvA:

NuMI: Neutrinos at the Main Injector (ν_μ) , Off-Axis: narrow band beam (2 GeV), ν_e Appearance

- NOvA can observe oscillations in two channels using a predominantly ν_μ beam:
    1. ν_e appearance
    2. ν_μ disappearance
- The Near Detector (ND), 1km from the source, used to measure composition of the un-oscillated beam
- Far Detector (FD), 810km from the source, observes the oscillated spectra

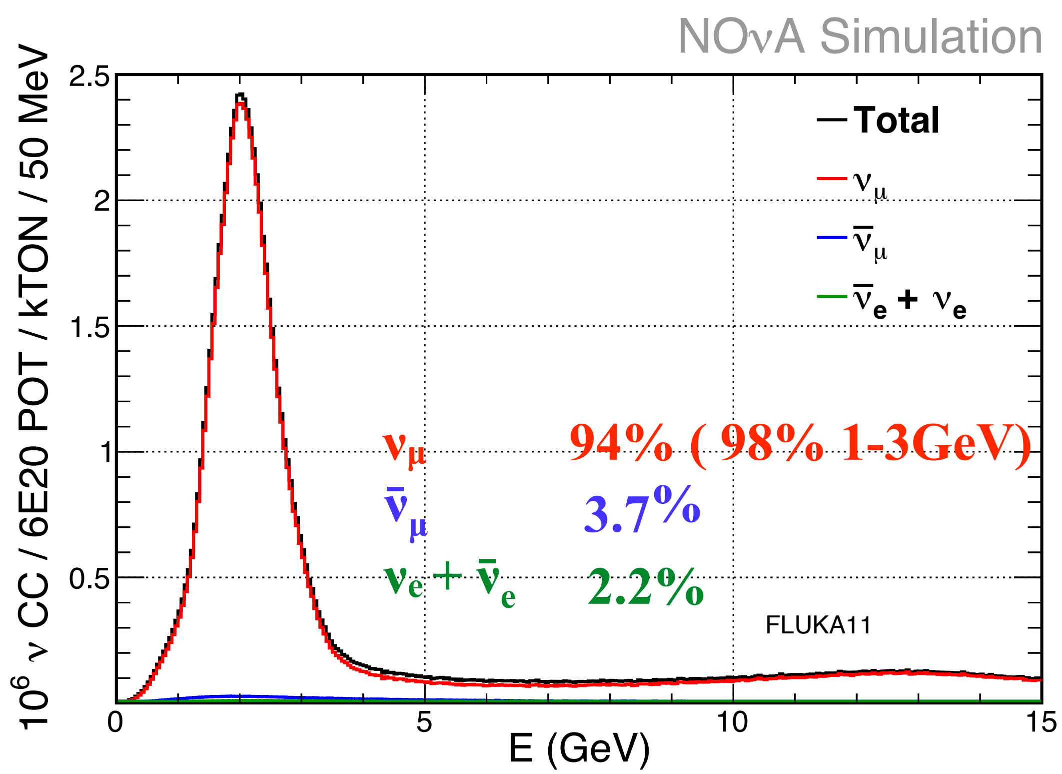




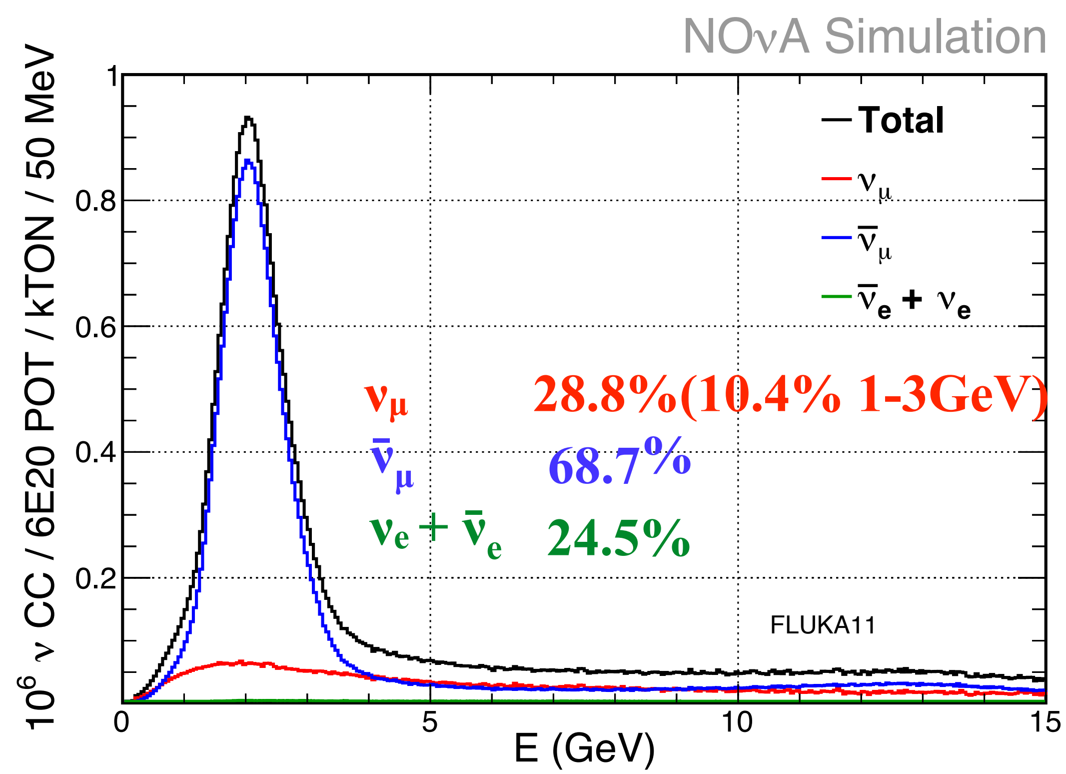
Extruded plastic (PVC) cell filled with Liquid Scintillator instrumented with λ-shifting fiber and APDs

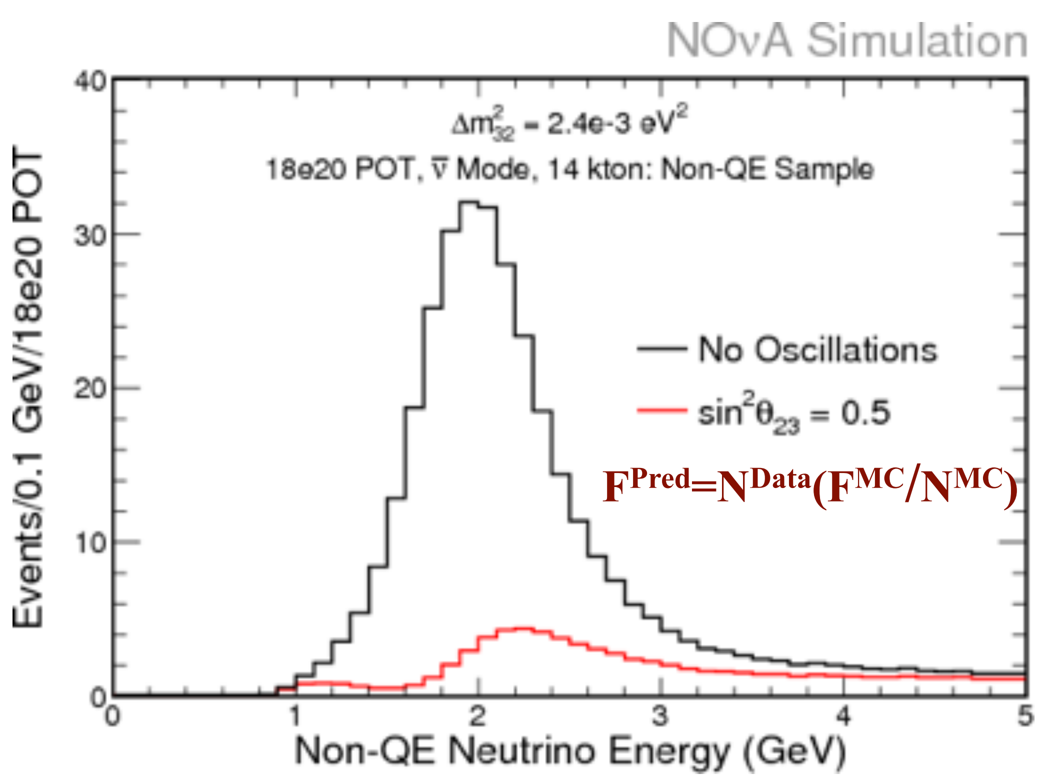
Motivation

Neutrino mode: horns focus positives



Anti-neutrino mode: horns focus negatives

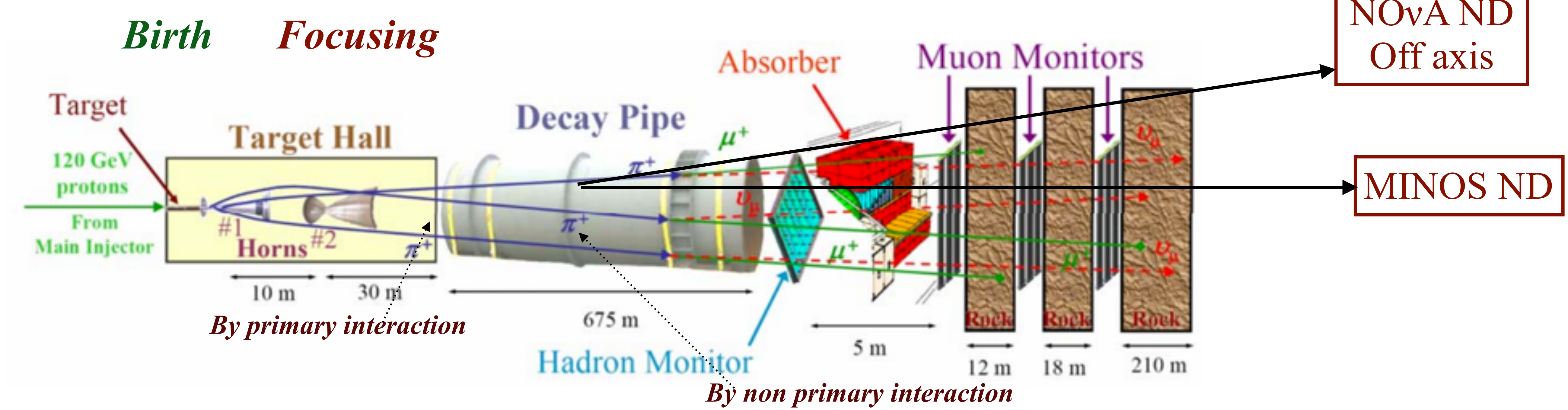




- The sensitivity of the oscillation studies critically depends upon precise prediction of un-oscillated ν_μ, $\bar{\nu}_\mu$, $\nu_e+\bar{\nu}_e$ flux-ratio: FD/ND(E_ν).
- Uncertainties in FD/ND come from the proton-nucleon hadron production and the beam transport simulation — the focus of this talk.
- Needed are data-driven methods to constrain the uncertainties. The most important is the NOvA-ND data. Other constraints include MINOS, NDOS (Near Detector Prototype On Surface) data, and Hadron-production data (MIPP, NA49...)

Beam Transport Systematic Variations

The 'Standard Flux' is based on FLUKA 2011.2b.6 (Flugg 2009-3d)



A. Horn Current
B. Beam spot size
C. Horn1 & Horn 2 position
D. Target position shift
E. Shifted beam positions on Target
F. B-field modeling in skin of horn: Exponential Magnetic field

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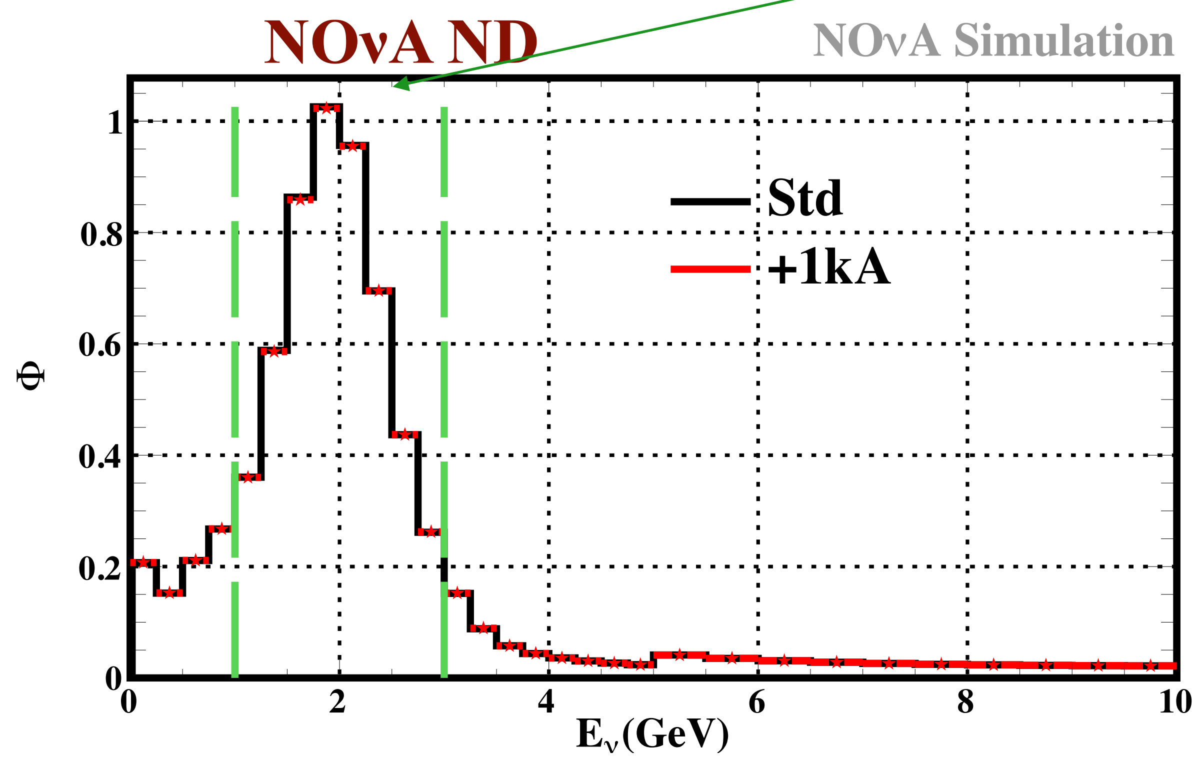
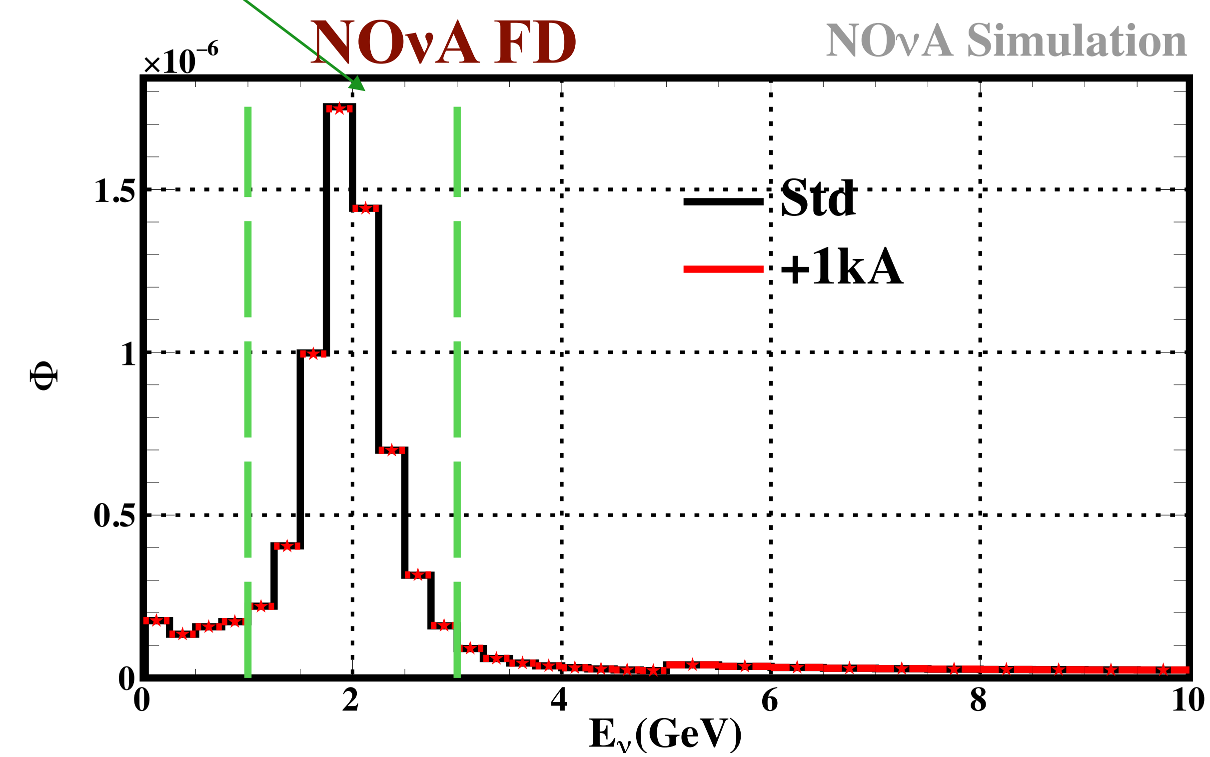
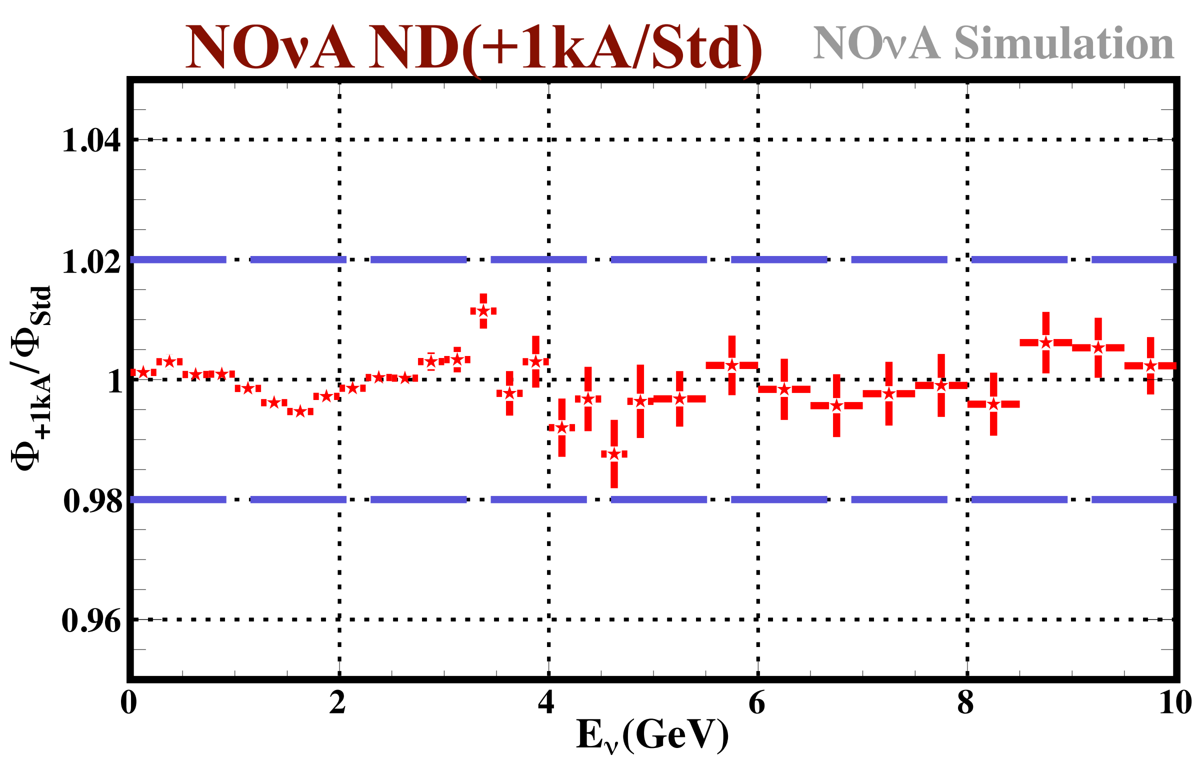
G. Different hadron production model(FTFP_BERT using G4NuMI with geant4_9_6_p03b)

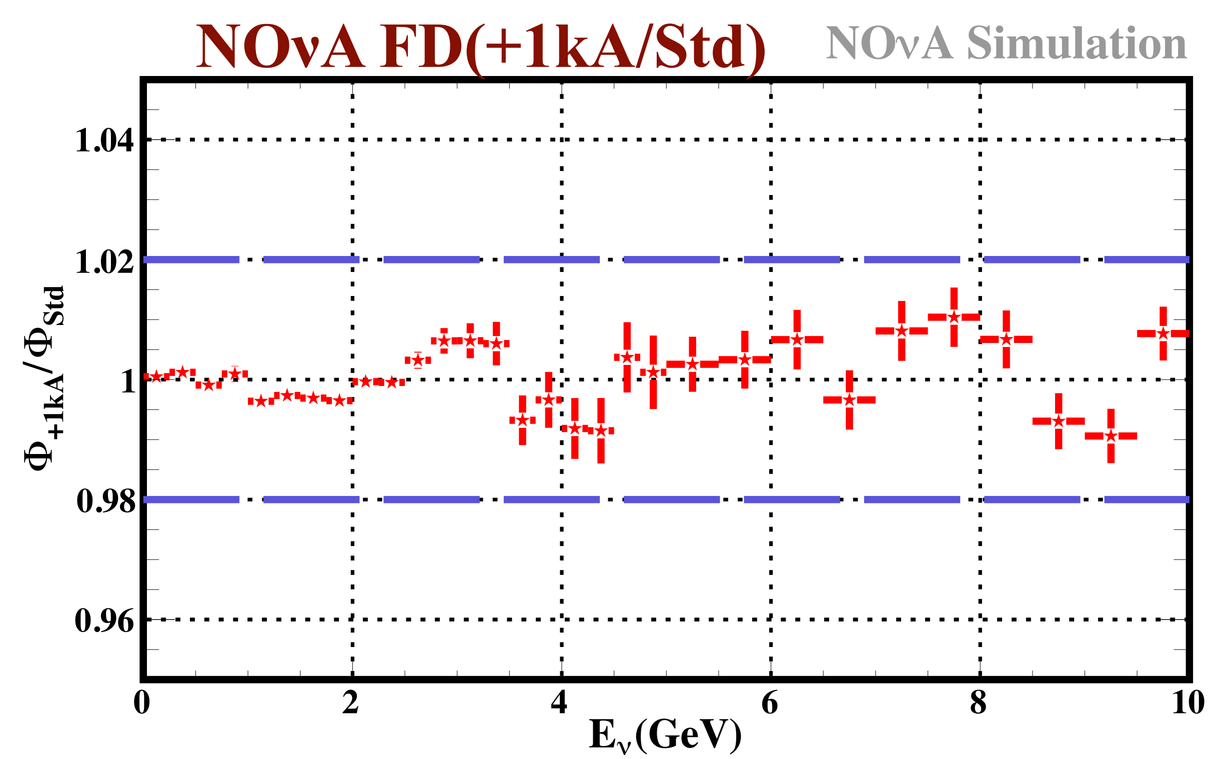
An example of Beam-Transport parameter variation
Horn Current Variation +1kA:

Oscillation region

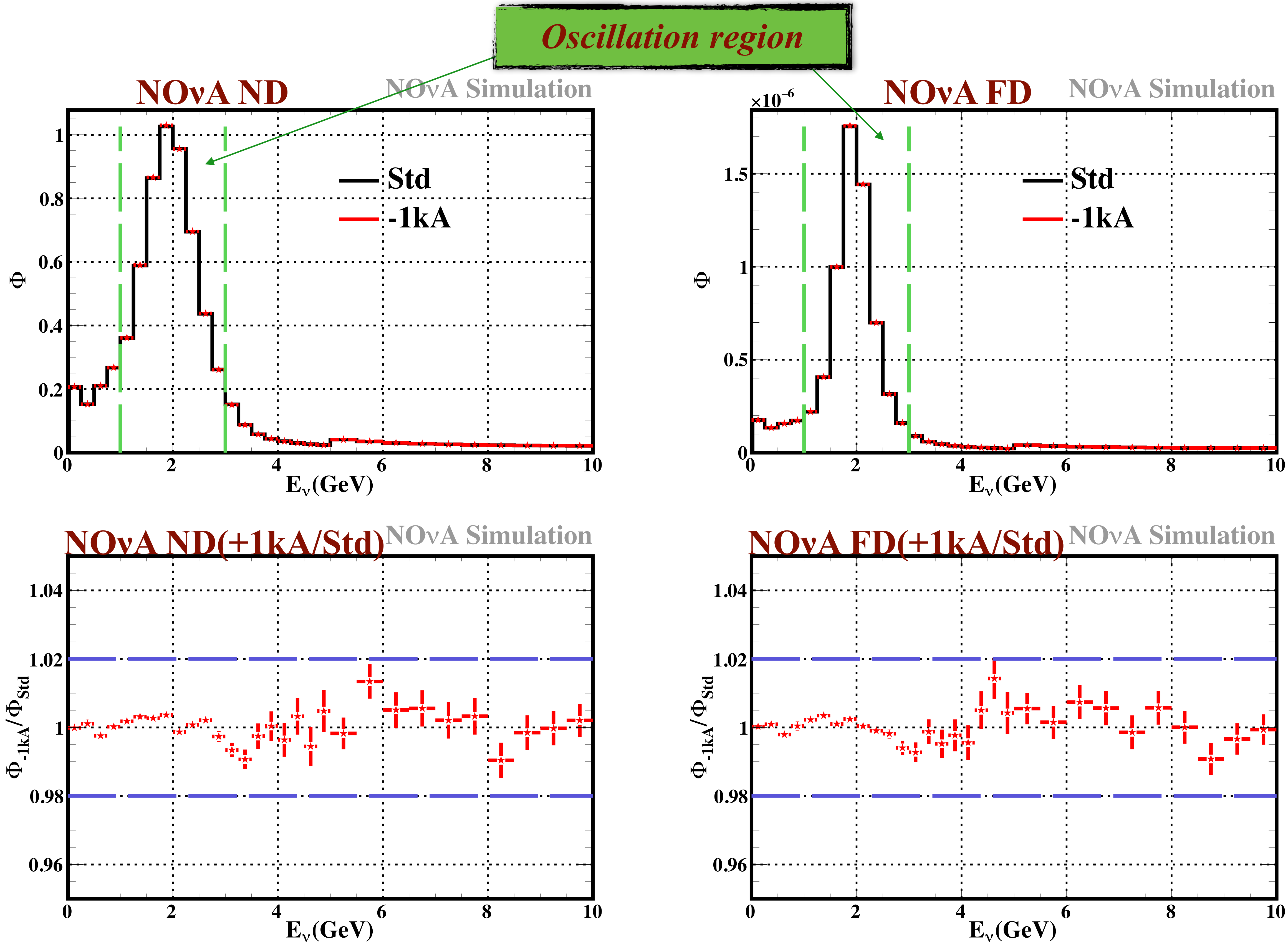


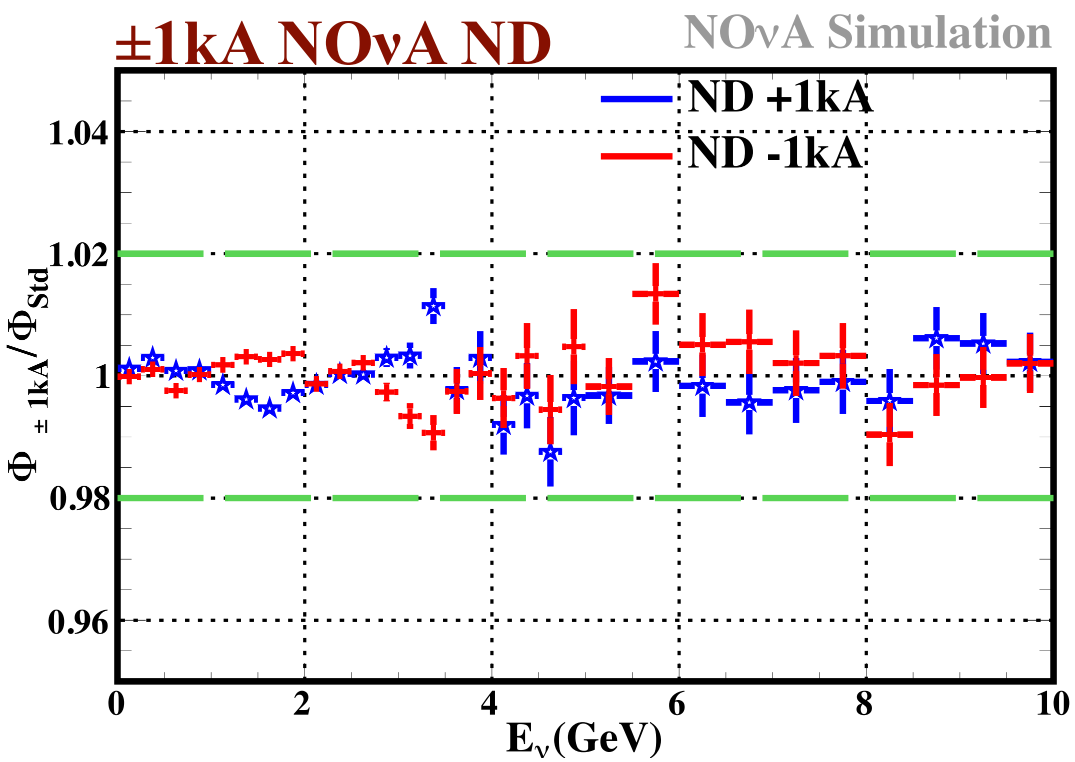


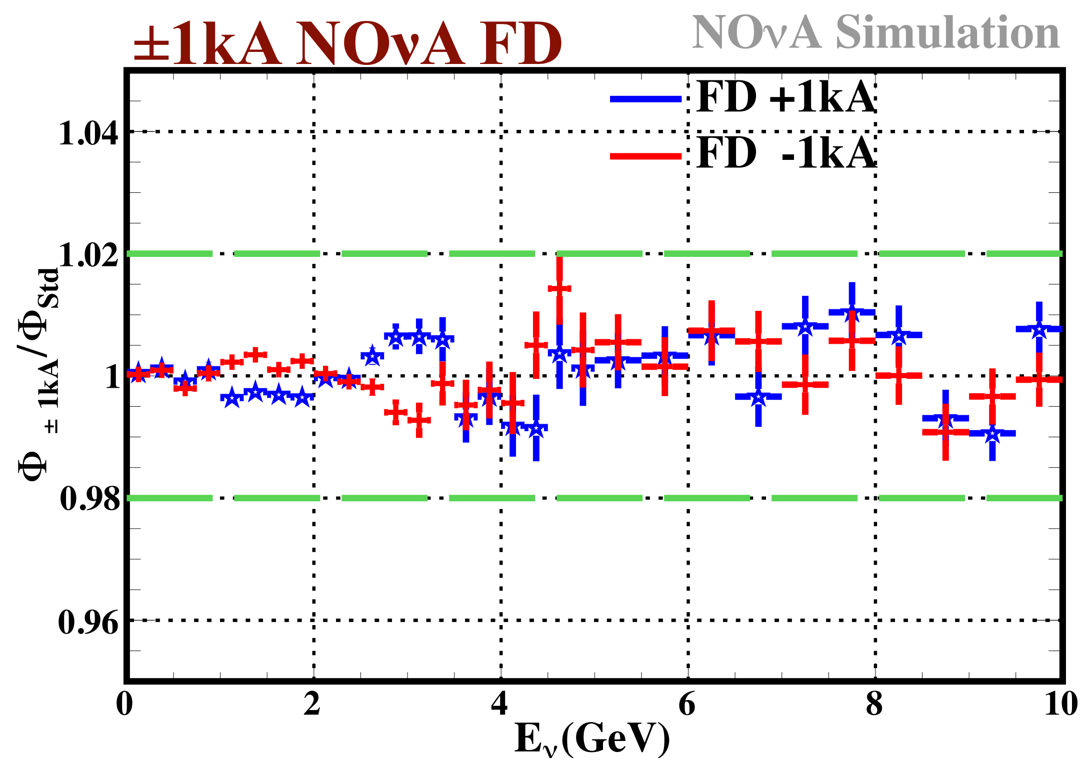


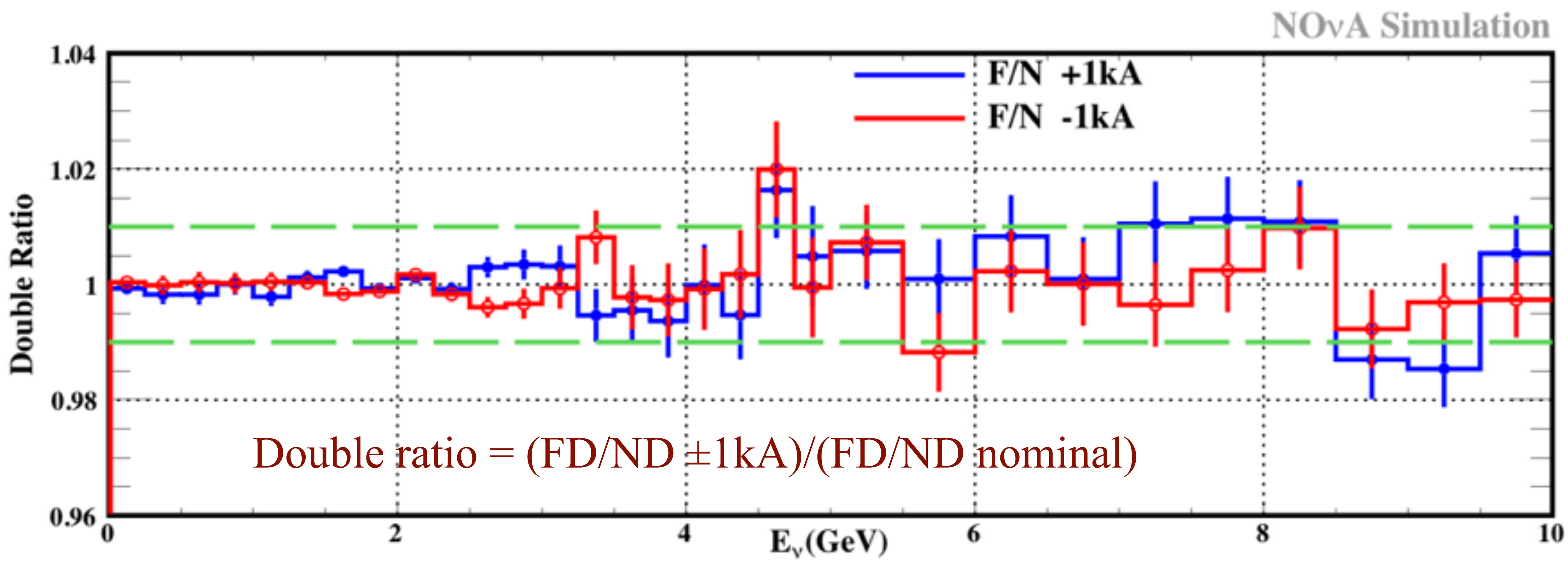


Horn Current Variation -1kA:



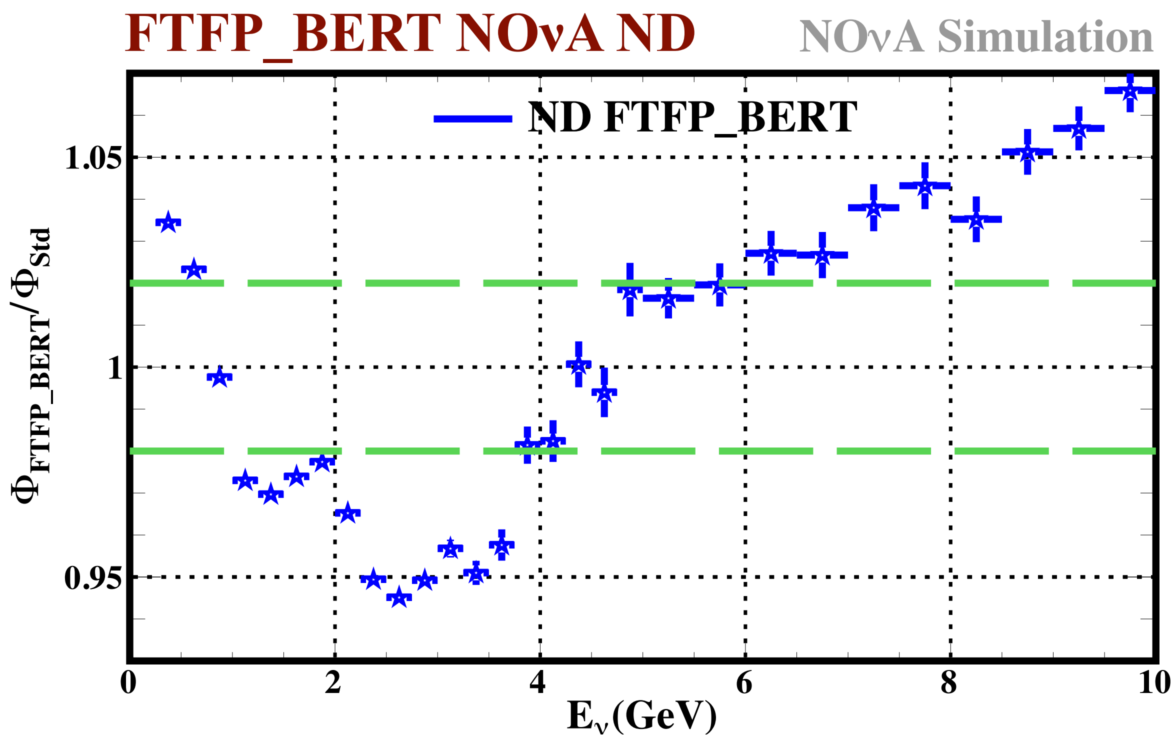


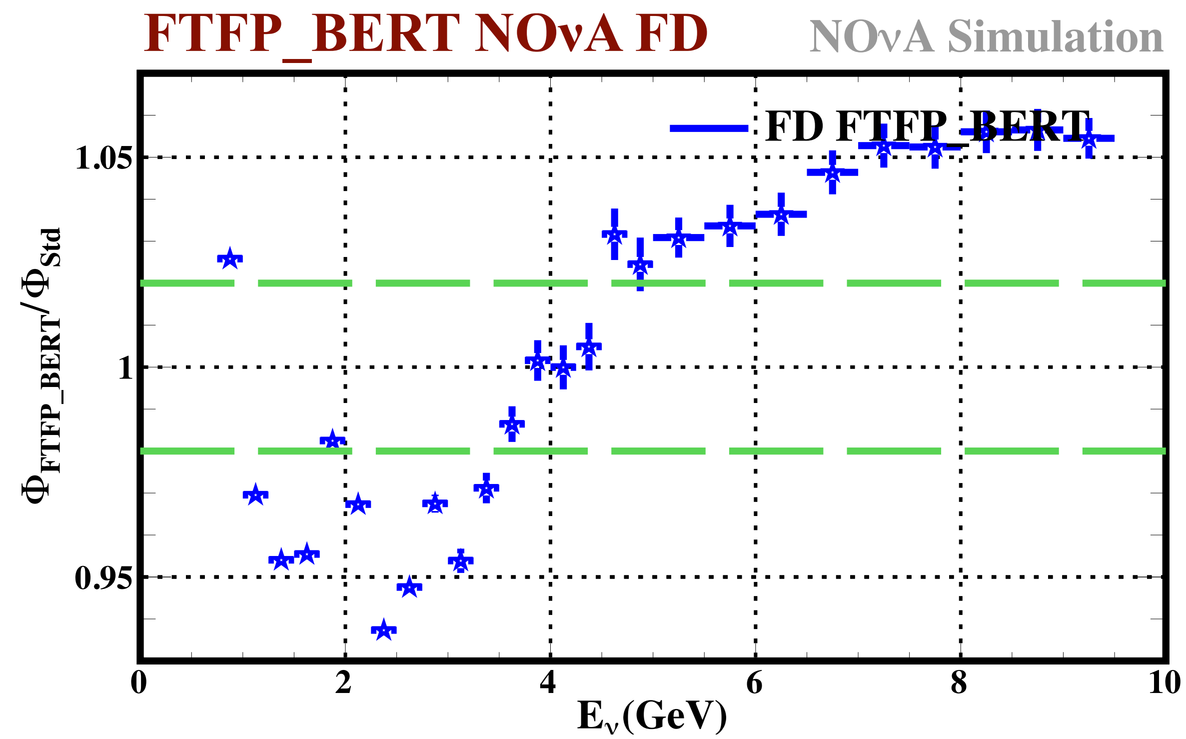


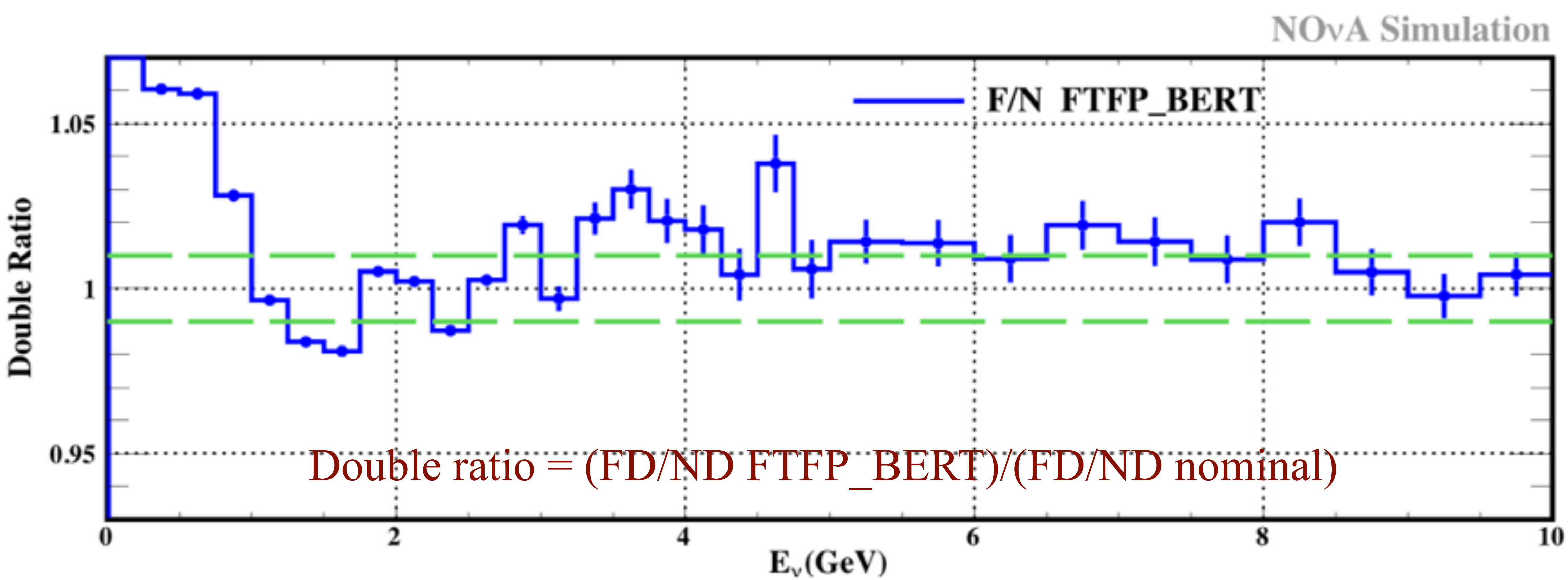


This is one example of beam transport systematic, similarly we conducted this exercise for various systematics on slide 4.

FTFP_BERT (different hadron-production model) -vs- Fluka







Variation in #-ν_μ at NOvA ND &FD

δ(%) ν_μ at NOvA ND

Model	Delta(%)
Std	0.00
+1kA	-0.20
-1kA	0.16
BposX+.5mm	-0.66
BposX-.5mm	0.26
BposY+.5mm	0.13
BposY-.5mm	-0.35
BmSptp +.2mm in X & Y	-0.77
BmSptm -.2mm in X & Y	0.29
H1 +2mm X & Y	-0.44
H1 -2mm X & Y	-1.70
H2 +2mm in X & Y	-0.51
H2 -2mm in X & Y	0.37
Exp B field	-4.30
Target position +2mm	-0.08
FTFP	-3.65

δ(%) ν_μ at NOvA FD

Model	Delta(%)
Std	0.00
+1kA	-0.16
-1kA	0.10
BposX+.5mm	-0.68
BposX-.5mm	0.24
BposY+.5mm	0.18
BposY-.5mm	-0.45
BmSptp +.2mm in X & Y	-0.81
BmSptm -.2mm in X & Y	0.29
H1 +2mm X & Y	-0.39
H1 -2mm X & Y	-1.79
H2 +2mm in X & Y	-0.47
H2 -2mm in X & Y	0.30
Exp B field	-4.32
Target position +2mm	-0.09
FTFP	-3.76

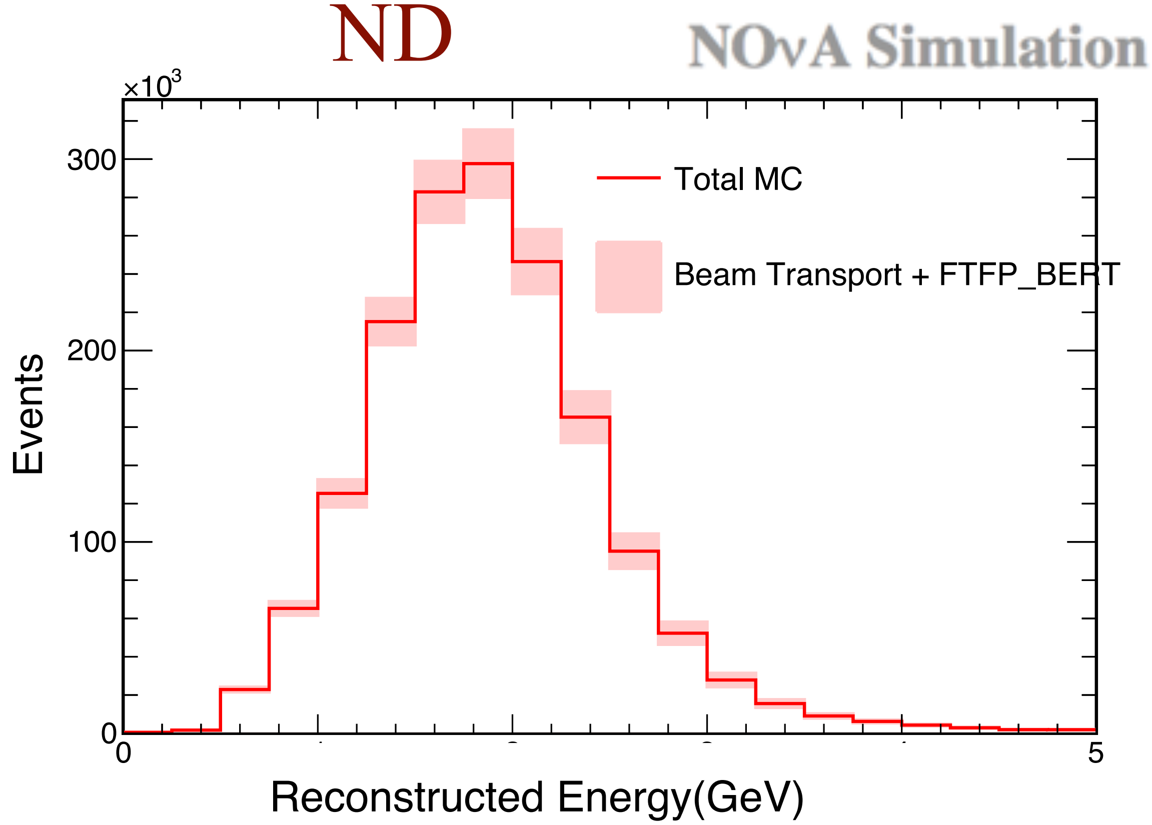
δ(%) is ~3%, Energy variation <.5%

of ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ from π^+, K^+, K^0 in $0<E\nu<10$ GeV & $1<E\nu<3$ GeV

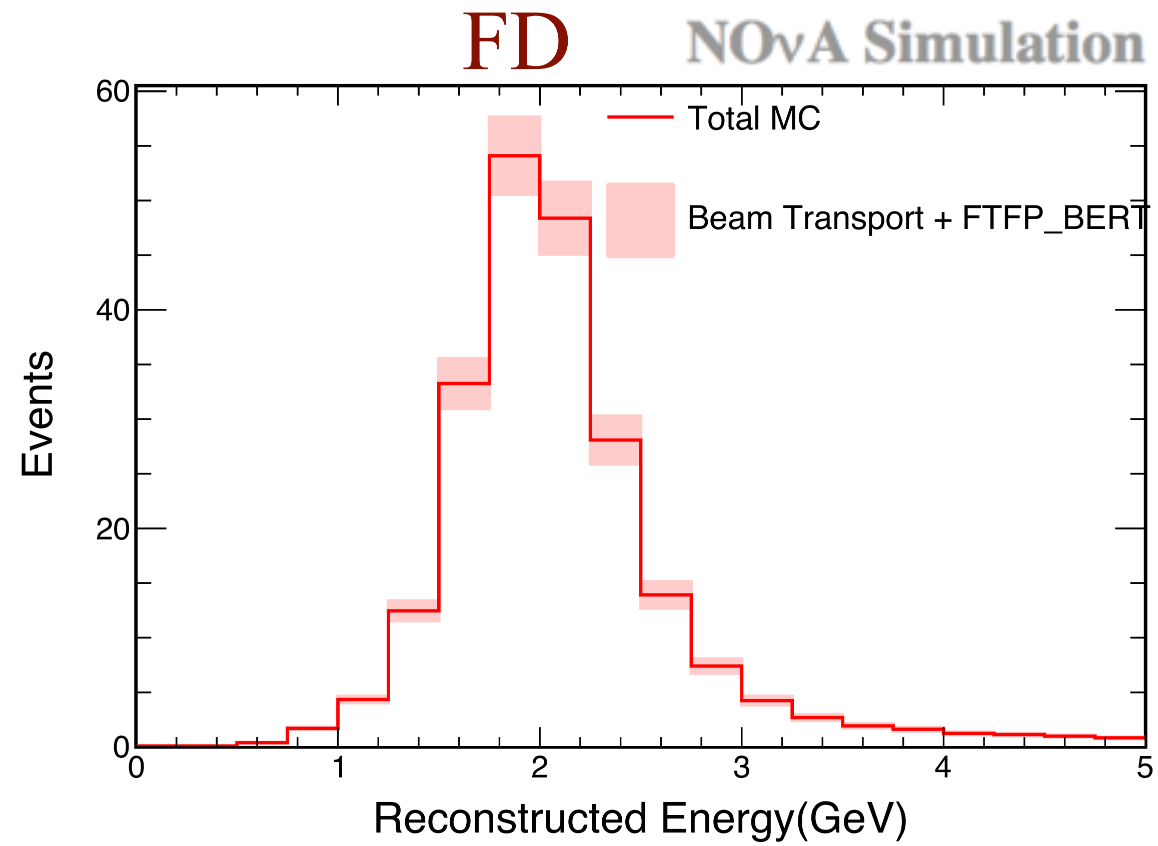
Average-E_ν and RMS for $0<E\nu<10$ and $1<E\nu<3$

Beam Transport Errors, including Hadro-Production Flux Uncertainty on Reconstructed neutrino energy[GeV] in NOvA ND & FD for 6e20 POT

ND



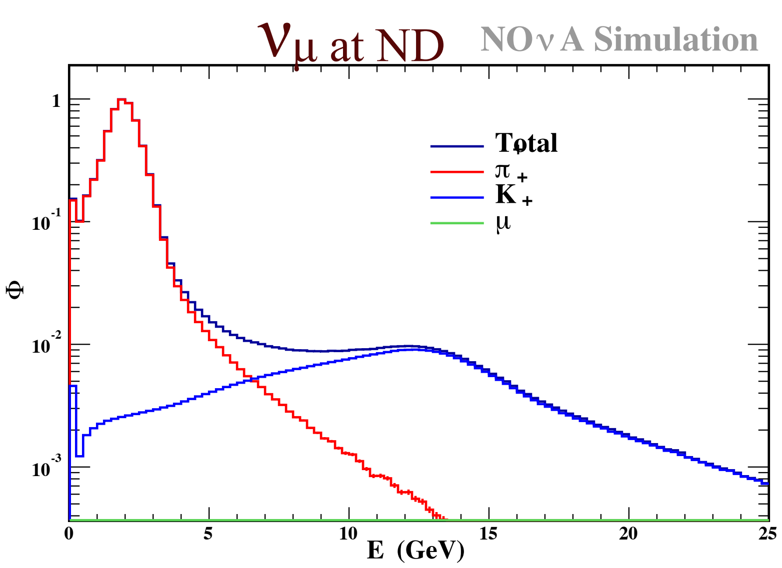
FD

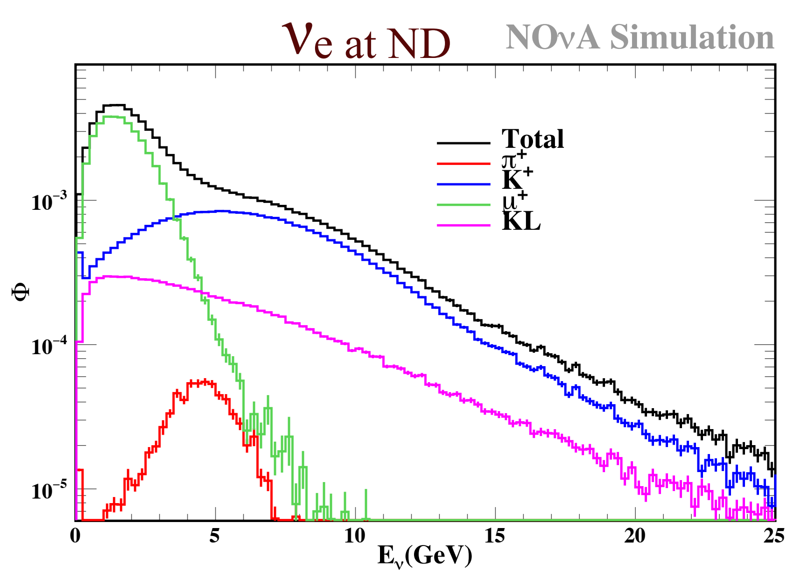


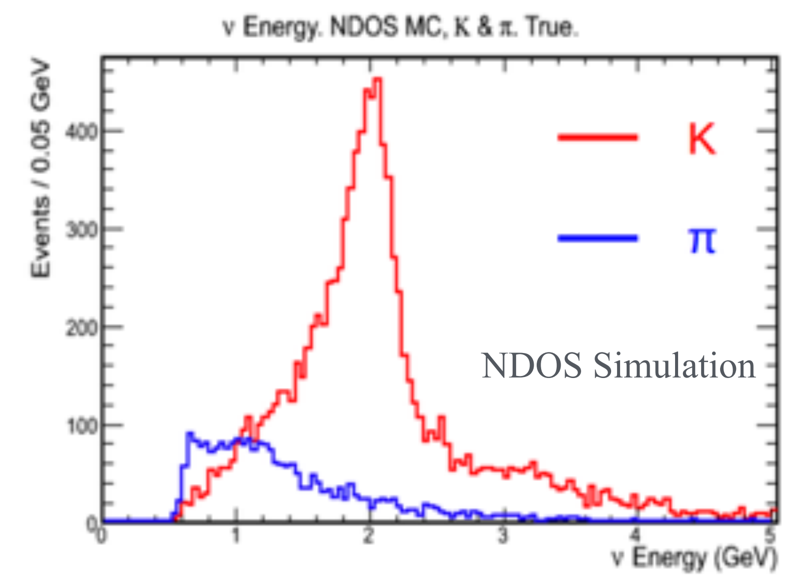
The error band represents a ±1 sigma shift of all beam systematics: Hadro-production model(different MC based physics list FTFP_BERT), Spot size, Beam position on the target (X/Y), Target position, Horn current, Horn-positions, & the modeling of horn's B-field.

Future Plan!

- We have shown systematic uncertainties from Beam Transport and hadron production model
- Need to constrain by Data.
- $\pi \rightarrow \nu_\mu + \mu$; 97% of ν_μ at the ND are from the π which be constrained by ND-Data







- ν_e constrains:
  - Use the NDOS(NOvA prototype detector on surface ~110 mrad Off-axis) data to constrain K^+(for ν_e) since above 1.5GeV 92% of ν at NDOS from K
  - Use ND-Data (E_ν>7.5 GeV) to constrain K^+ (for ν_e)
  - Use ND-Data (0.5<Eν<5) to constrain $\pi^+ \Leftrightarrow \mu^+$ (for ν_e) i.e $\pi \rightarrow \nu_\mu + \mu \rightarrow \nu_\mu + e^+ \nu_e$
- Analysis of Neutrino-electron (Atomic) NC scattering to yield the absolute flux

Summary:

- We evaluated the flux systematic errors arising from the uncertainties in the beam transport & hadro-production model: $\delta(\%)$ for ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ is ~3% for ND & FD(1-3GeV)
  Energy variation for ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ <1% for ND & FD(1-3GeV)
- Constraints by data… in progress.


Thank you!
ROBERT RAT

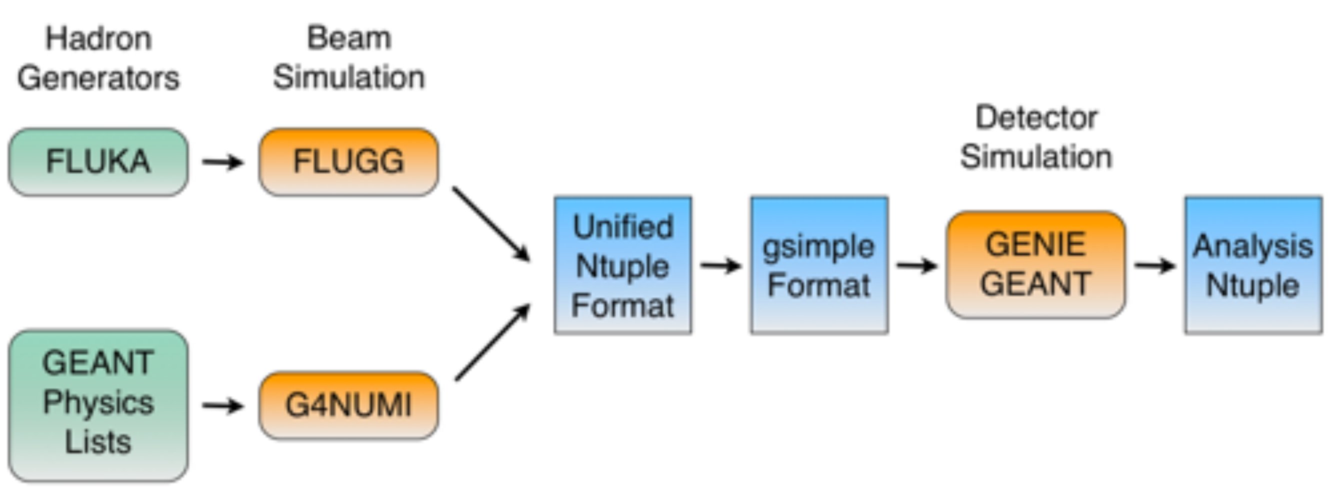
Backup!

FLUGG -vs- G4NuMI

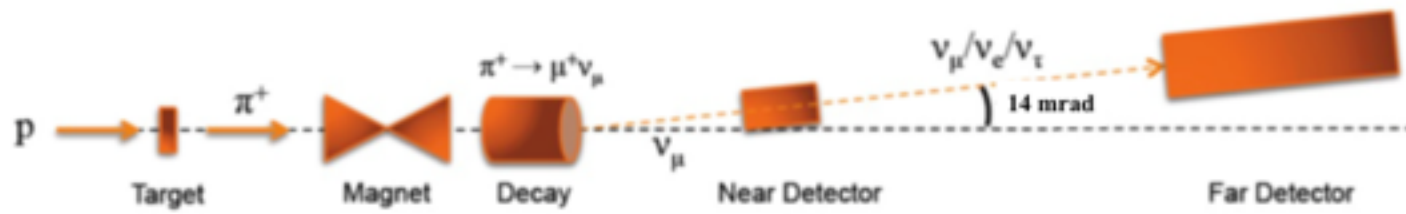
FLUGG = Fluka using GEANT4 geometry files
http://www.fluka.org/content/tools/flugg/

G4NUMI is a Geant4-based simulation of the NUMI beam. We know what physics G4NUMI simulates(QGSP, FTFP…)

- Two alternative hadron production models:
  - GEANT - open code, but hadron production is tuned more for showers
  - FLUKA - best data agreement with neutrino experiments, closed code
- Both simulation chains share the same G4 target/beamline geometry
- Simulation output in unified ntuple format, containing full ancestry information



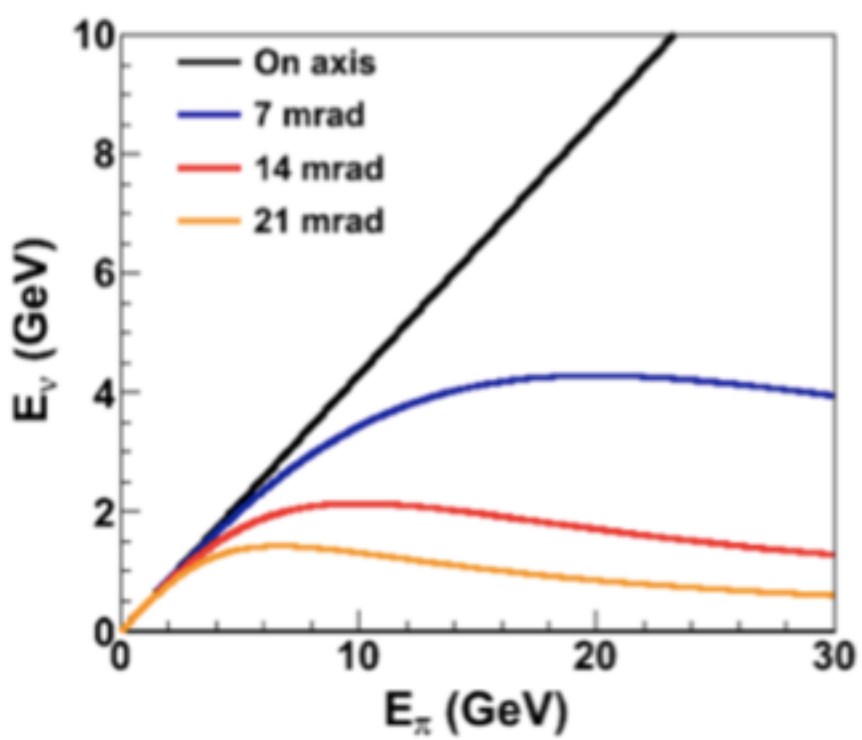
Why off-axis?

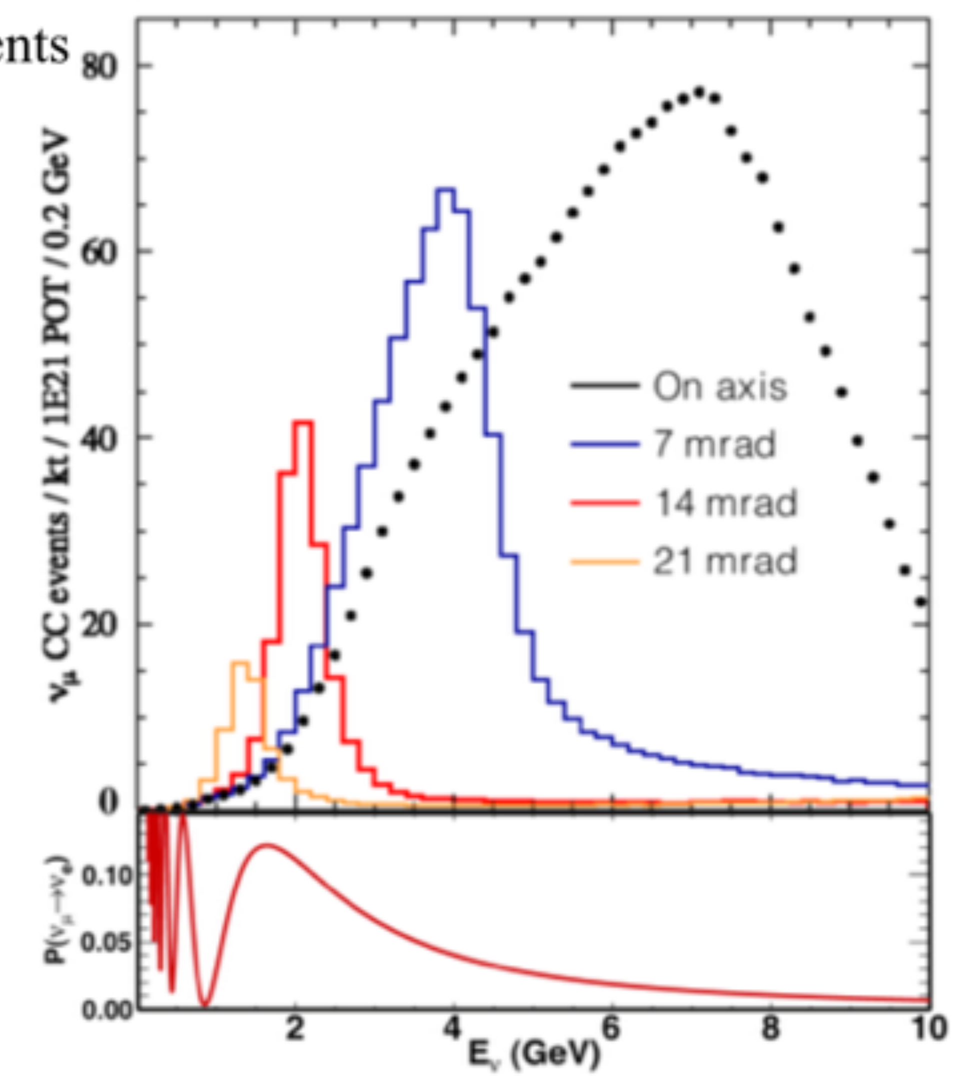


At 14 mrad off-axis, narrow band beam peaked at E_ν=2GeV

- The peak of the beam coincides with the oscillation maximum for electron neutrino appearance for the 810 km distance
- Removes high energy NC background events

$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$





Downstream of Primary Target C, hadrons encounter different A's ... C—He-Al--Fe--N--H--O---Si----- etc

Need to know ν_μ-contamination in "ν_μ bar-beam" :

- Negative focusing (π^-,K^-) (RHC- Reverse Horn Current)
- Positive focusing(π^+,K^+) (FHC- Forward Horn Current)

i.e Large contamination of ν_μ in RHC setting, to a lesser extent there exist ν_μ bar contamination in ν_μ beam.

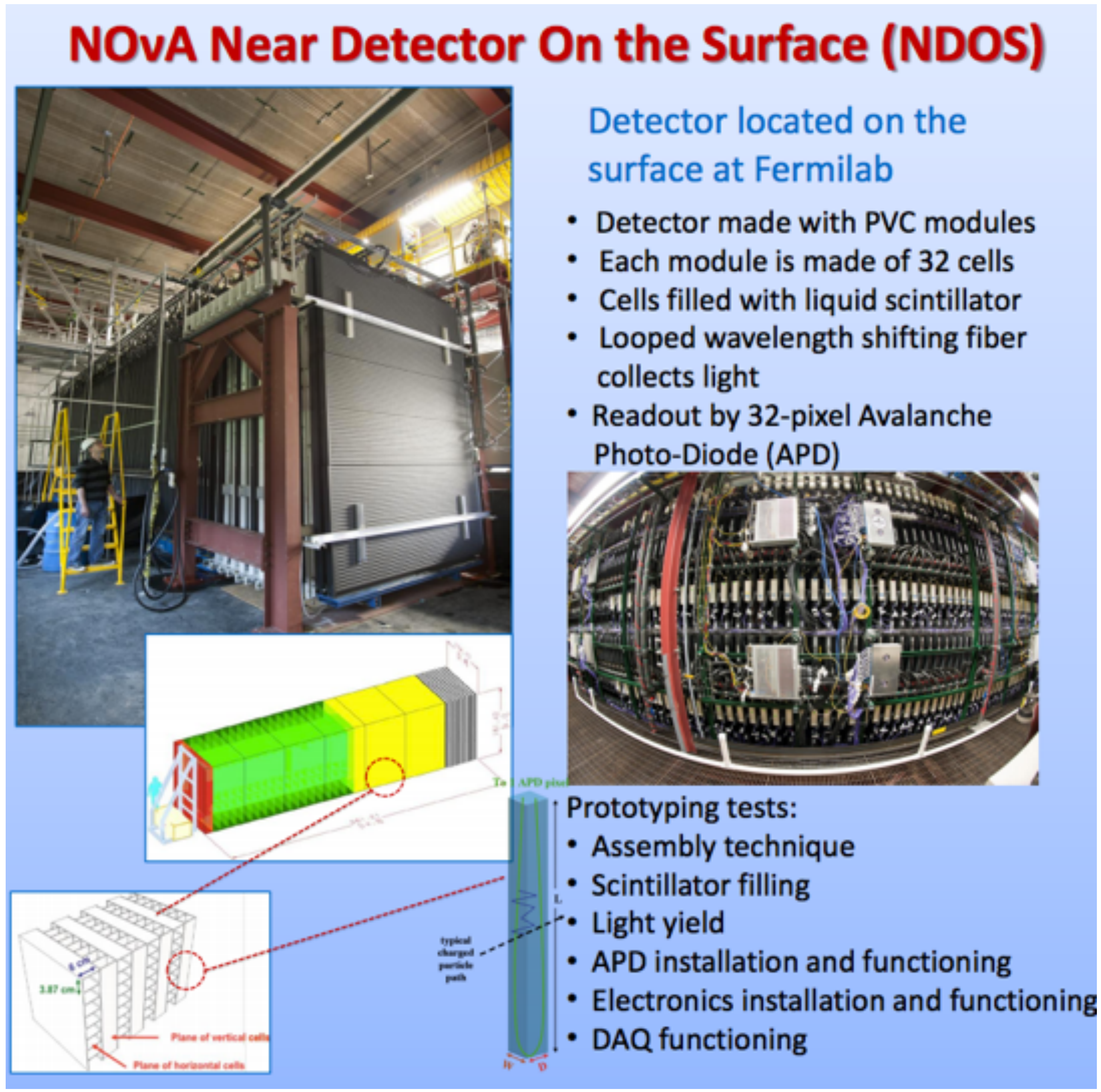
Most of contamination is because of production in secondary nuclear elements. Some results with G4NuMI(FTFP):

π- in Negative focusing

Element		
Carbon	83.7	35.9
Iron	5.12	30.9
Aluminium	4.21	12
Nitrogen	2.94	11.4
Helium	2.27	6.93
Oxygen	1.65	2.68
Beryllium	0.118	0.11
Hydrogen	0.009	0.049
Chromium	0.008	0.016
Silicon	0.004	0.005
Magnesium	0.003	0.003

NDOS

NDOS is ~6.1^0 off axis of the NuMI beam



#ν_μ at NOvA ND (1-3GeV)

Model/Parents	π^+	K^+	μ^-	Rest	Total
Std	4.92E+00	2.07E-02	5.60E-04	1.79E-03	4.94E+00
+1kA	4.91E+00	2.07E-02	5.30E-04	1.79E-03	4.93E+00
-1kA	4.93E+00	2.06E-02	5.30E-04	1.80E-03	4.95E+00
BposX+.5mm	4.89E+00	2.07E-02	5.20E-04	1.80E-03	4.91E+00
BposX-.5mm	4.93E+00	2.07E-02	5.70E-04	1.80E-03	4.95E+00
BposY+.5mm	4.92E+00	2.07E-02	5.50E-04	1.80E-03	4.95E+00
BposY-.5mm	4.90E+00	2.06E-02	5.50E-04	1.78E-03	4.92E+00
BmSptp +.2mm	4.88E+00	2.08E-02	5.50E-04	1.81E-03	4.90E+00
BmSptm -.2mm	4.93E+00	2.06E-02	5.40E-04	1.78E-03	4.96E+00
H1 +2mm X & Y	4.90E+00	2.06E-02	5.40E-04	1.79E-03	4.92E+00
H1 -2mm X & Y	4.83E+00	2.07E-02	5.40E-04	1.79E-03	4.86E+00
H2 +2mm in X &	4.89E+00	2.06E-02	5.70E-04	1.79E-03	4.92E+00
H2 -2mm in X &	4.94E+00	2.06E-02	5.60E-04	1.78E-03	4.96E+00
Exp B field	4.71E+00	1.97E-02	5.20E-04	1.72E-03	4.73E+00
Target position	4.91E+00	2.06E-02	5.10E-04	1.79E-03	4.94E+00
FTFP	4.74E+00	1.93E-02	5.40E-04	1.99E-03	4.76E+00

Summary:

Variation in #-ν_μ and Energy(Mean & RMS(1-3GeV))at NOvA ND

δ(%) ν_μ at NOvA ND

Model	Delta(%)
Std	0.00
+1kA	-0.20
-1kA	0.16
BposX+.5mm	-0.66
BposX-.5mm	0.26
BposY+.5mm	0.13
BposY-.5mm	-0.35
BmSptp +.2mm in X & Y	-0.77
BmSptm -.2mm in X & Y	0.29
H1 +2mm X & Y	-0.44
H1 -2mm X & Y	-1.70
H2 +2mm in X & Y	-0.51
H2 -2mm in X & Y	0.37
Exp B field	-4.30
Target position +2mm	-0.08
FTFP	-3.65

RMS & Mean

Model	RMS(GeV)	Mean(GeV)
Std	0.46	1.96
+1kA	0.46	1.96
-1kA	0.46	1.96
BposX+.5mm	0.46	1.95
BposX-.5mm	0.46	1.96
BposY+.5mm	0.46	1.96
BposY-.5mm	0.46	1.96
BmSptp +.2mm in X & Y	0.46	1.96
BmSptm -.2mm in X & Y	0.46	1.96
H1 +2mm X & Y	0.46	1.96
H1 -2mm X & Y	0.46	1.95
H2 +2mm in X & Y	0.46	1.95
H2 -2mm in X & Y	0.46	1.96
Exp B field	0.46	1.96
Target position +2mm	0.46	1.96
FTFP	0.46	1.95

δ(%) is ~3%, Energy variation <.5%