Neutrino Flux Studies at NOvA

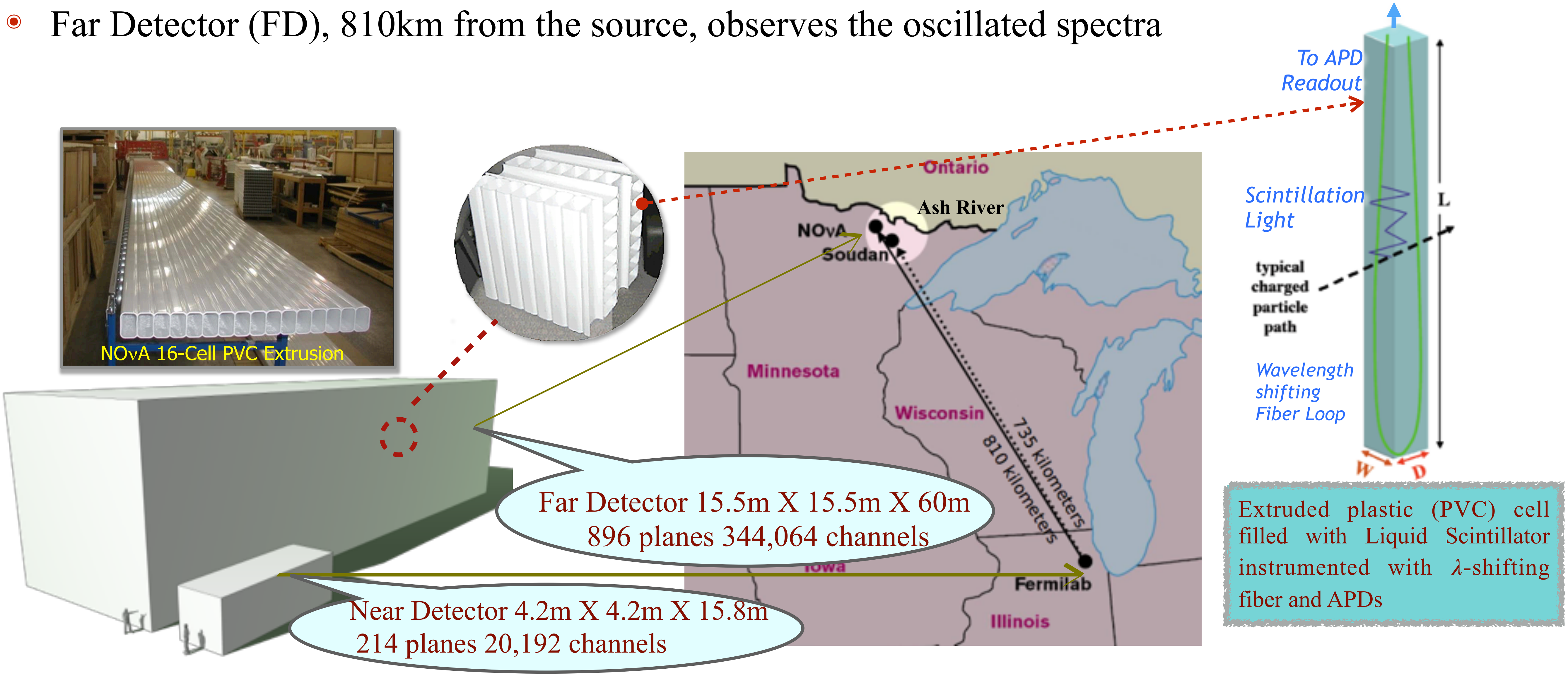
Kuldeep K. Maan[1], H.Duyang[2], Sanjib R. Mishra[2] & Vipin Bhatnagar[1]
Panjab University Chandigarh[1], University of South Carolina[2]

For the NOvA Collaboration
DPF 2015 in ANN ARBOR, MI
August 4-8, 2015

NOνA:

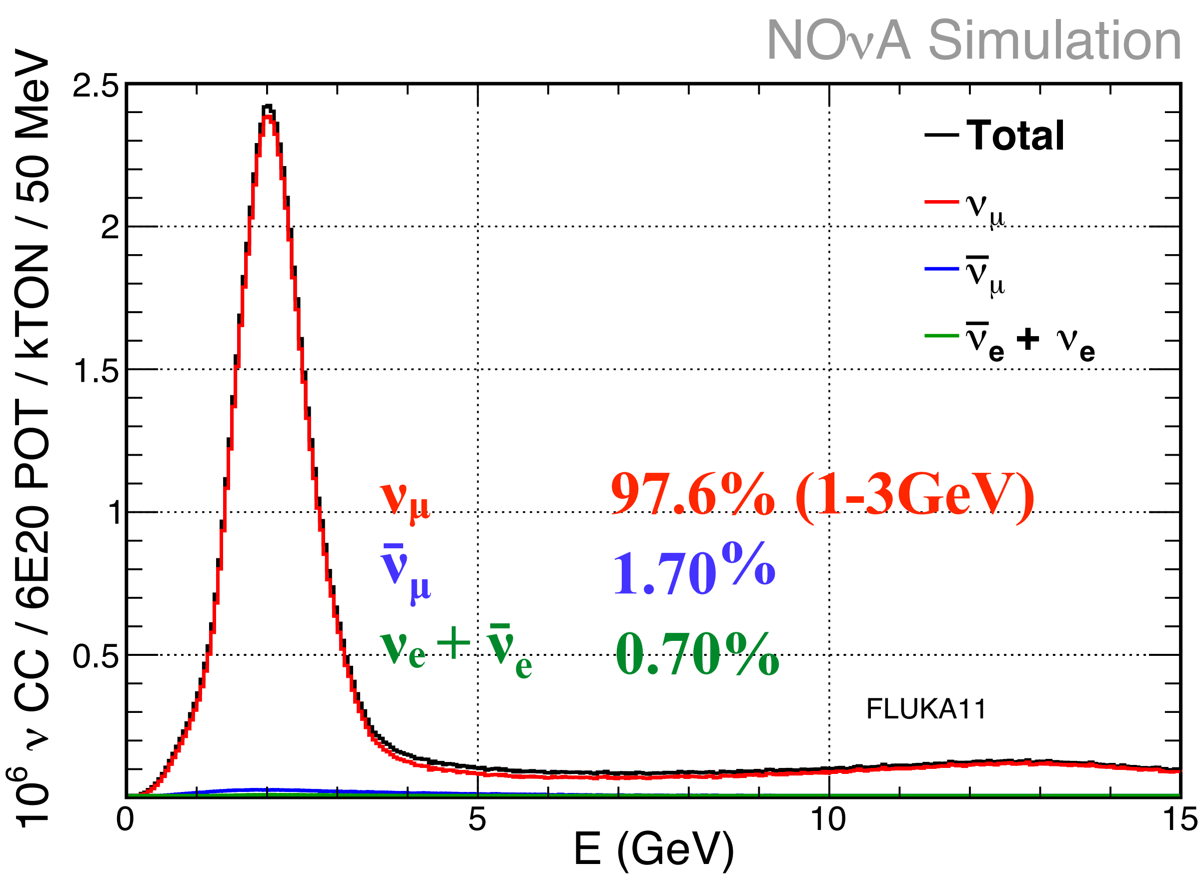
NuMI: Neutrinos at the Main Injector (ν_μ) , Off-Axis: narrow band beam (2 GeV), ν_e Appearance

- NOνA 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

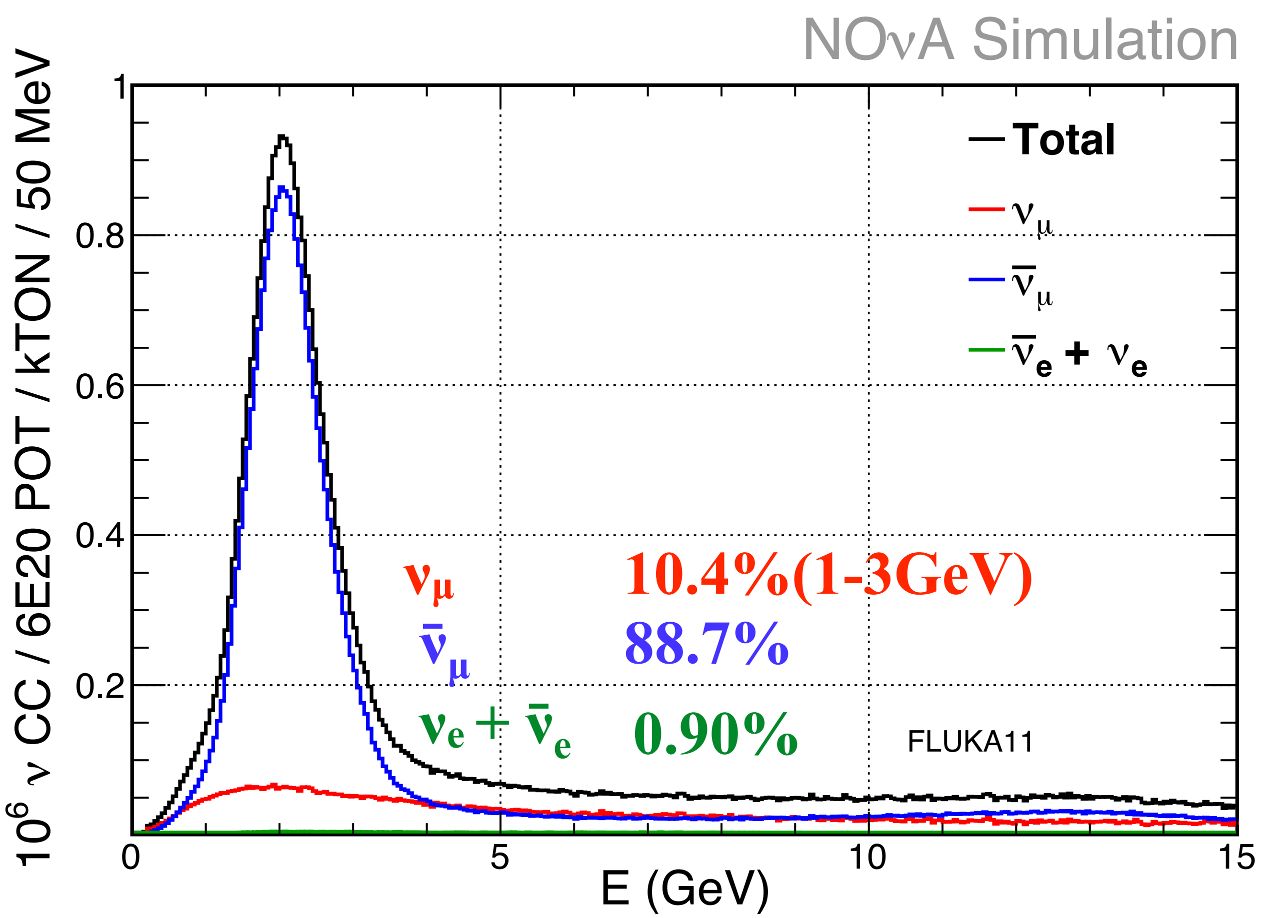


Motivation

Neutrino mode: horns focus positives

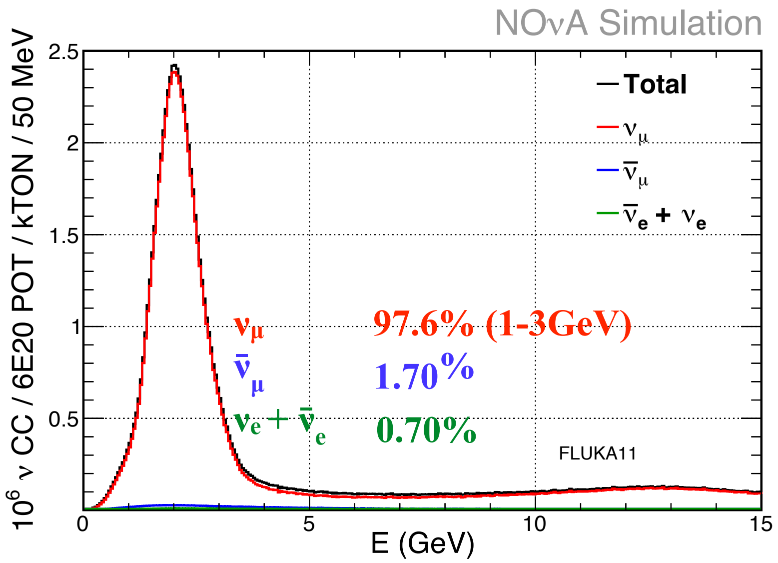


Anti-neutrino mode: horns focus negatives

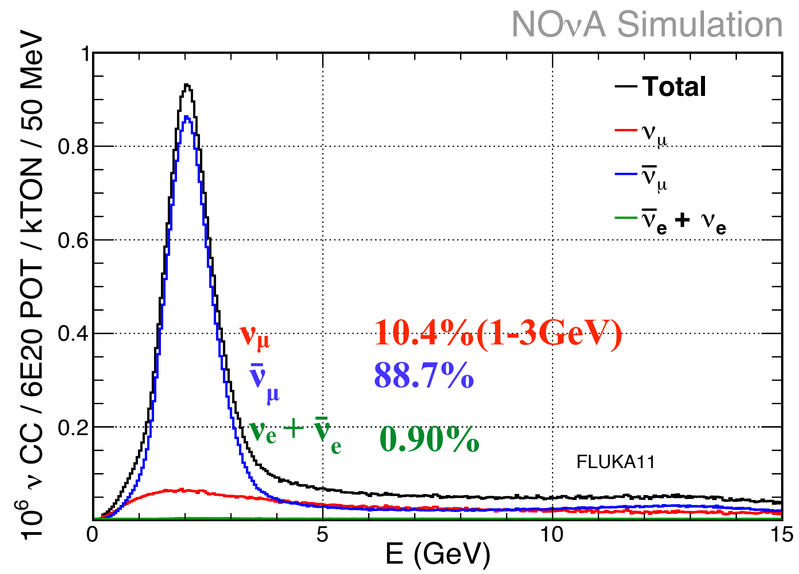


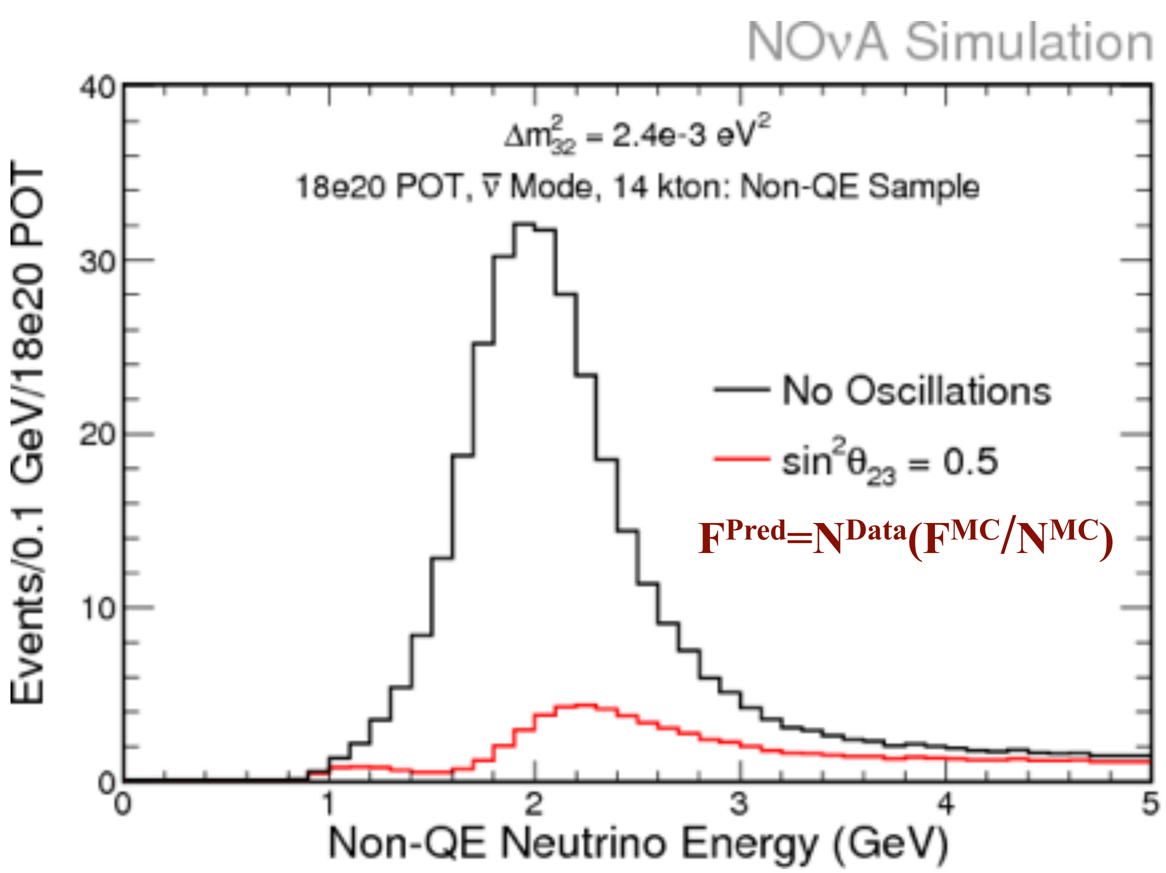
Motivation

Neutrino mode: horns focus positives



Anti-neutrino mode: horns focus negatives

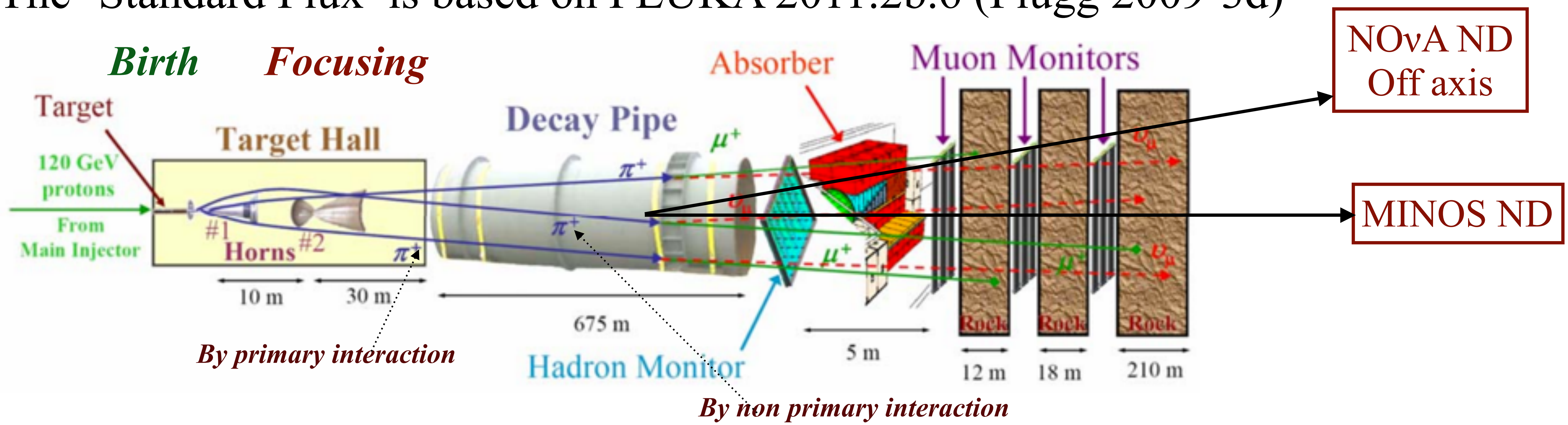




- The sensitivity of the oscillation studies critically depends upon precise prediction of un-oscillated ν_μ, $\bar{\nu}_\mu$, $\nu_e+\bar{\nu}_e$ flux-ratio: FD/ND(E_ν).
- Uncertainties in FD/ND come from the proton-nucleon hadron production and the beam transport simulation
- Needed are data-driven 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)



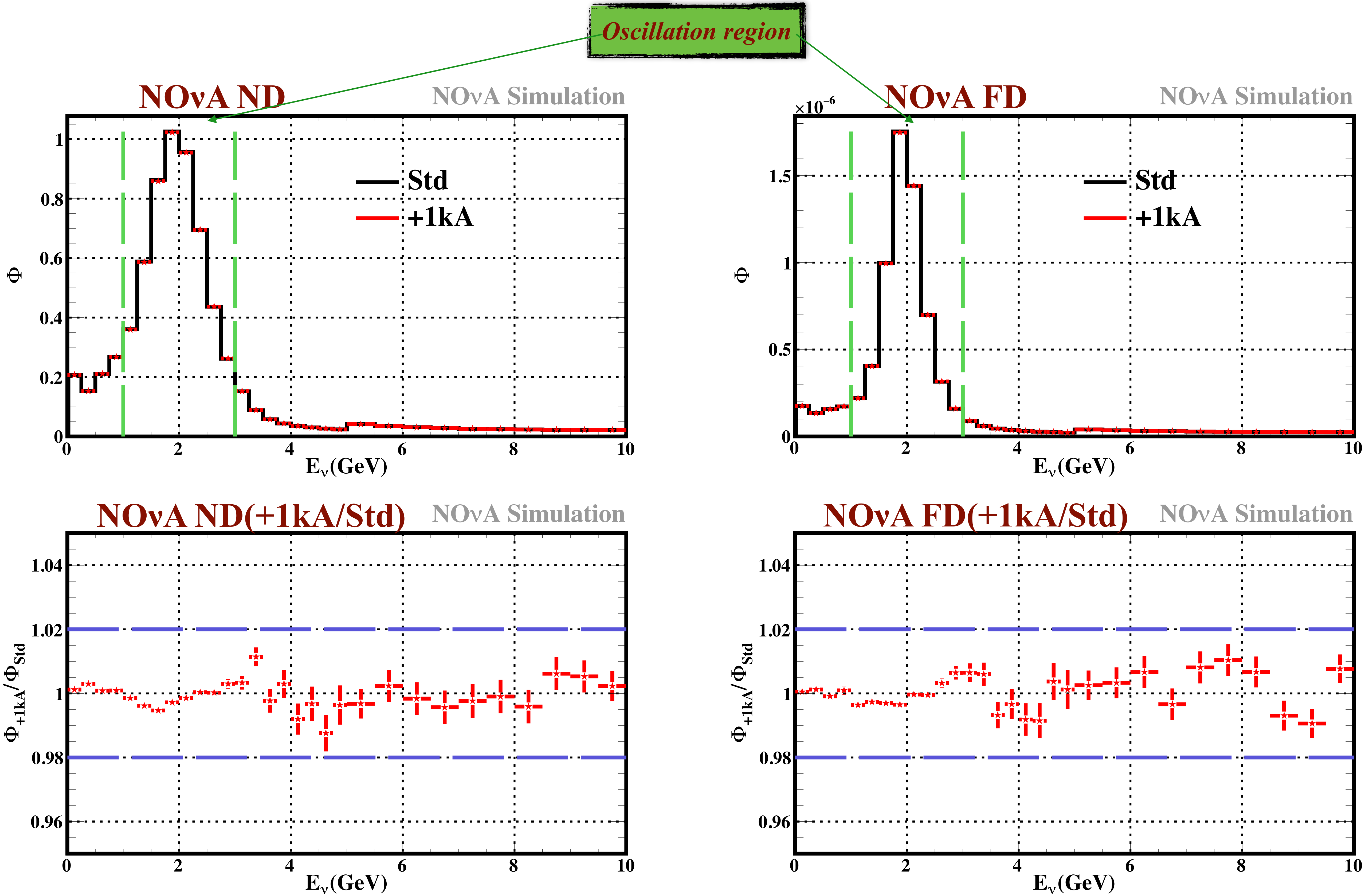
A. Horn Current
B. Beam spot size
C. Horn1 & Horn 2 position
D. Target position shift
E. Shifted beam positions on Target
F. B-field modeling in skin of horn: Exponential Magnetic field

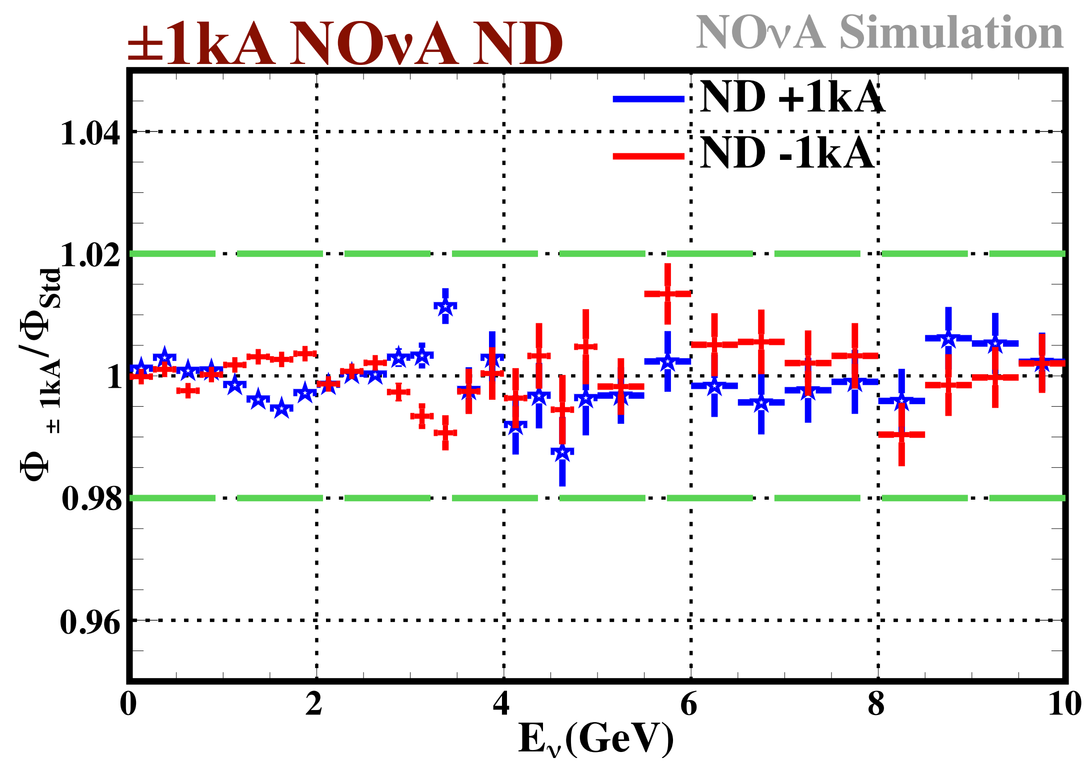
---

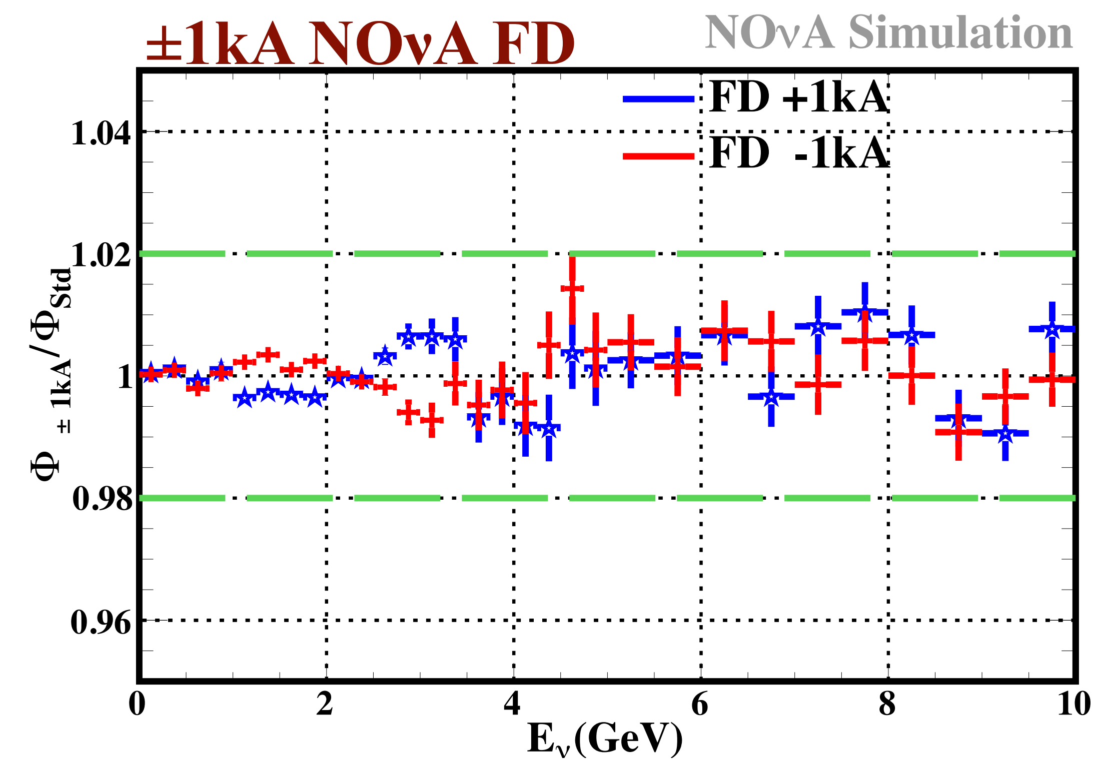
G. Different hadron production model(FTFP_BERT using G4NuMI with geant4_9_6_p03b)

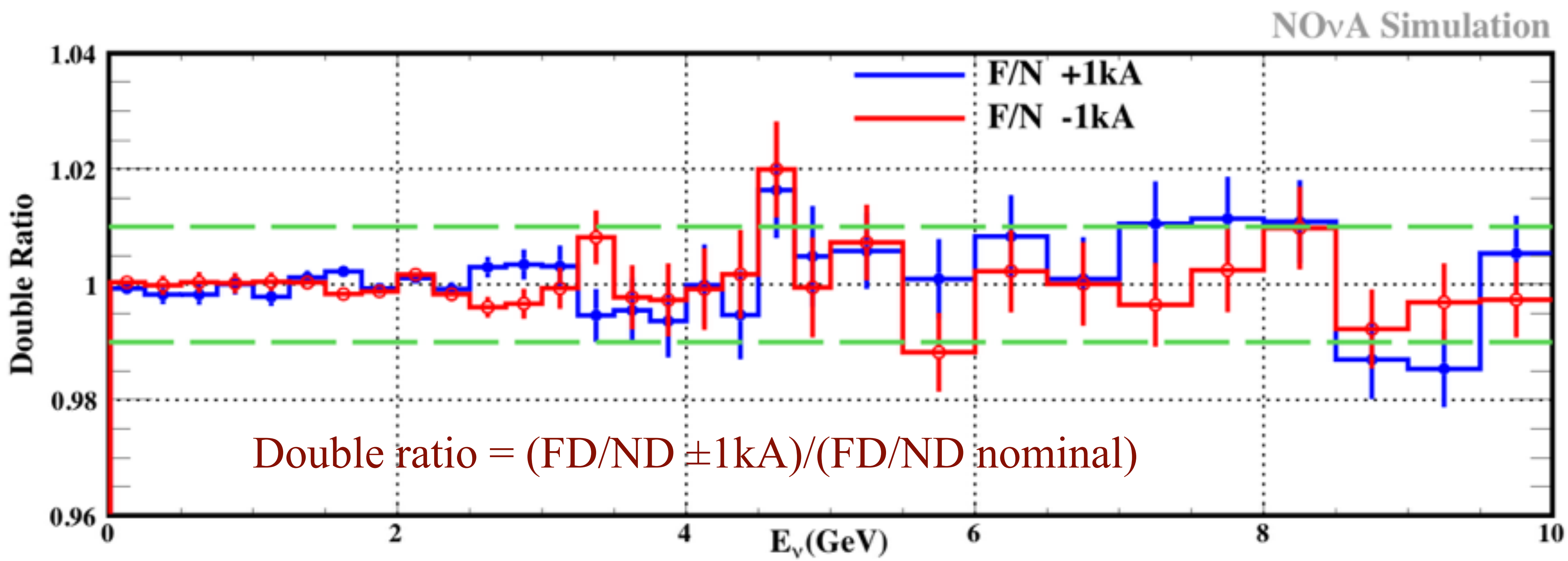
An example of Beam-Transport parameter variation

Horn Current Variation +1kA:



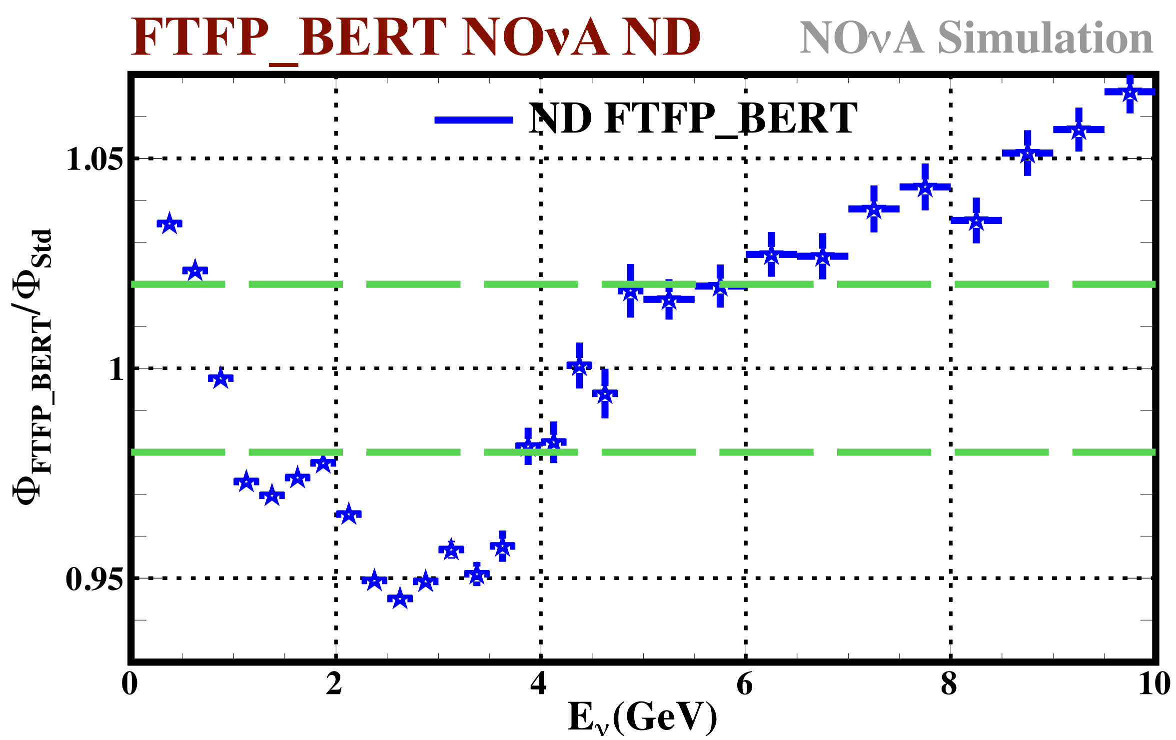


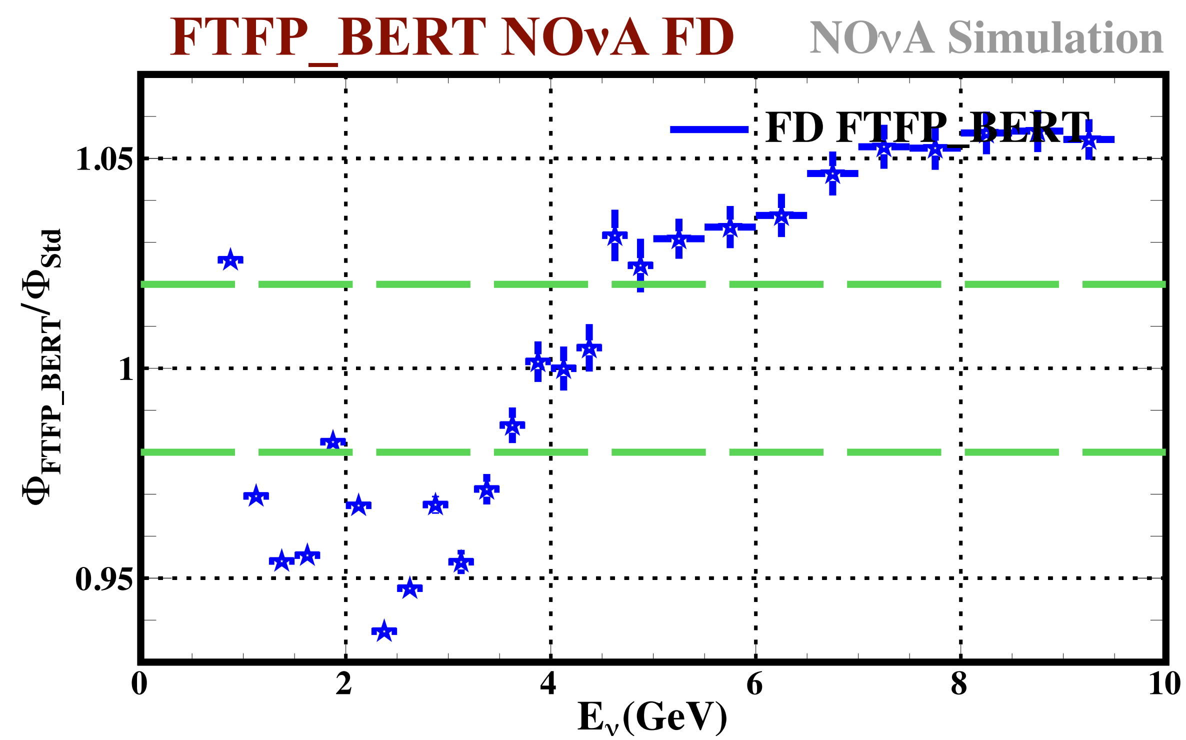


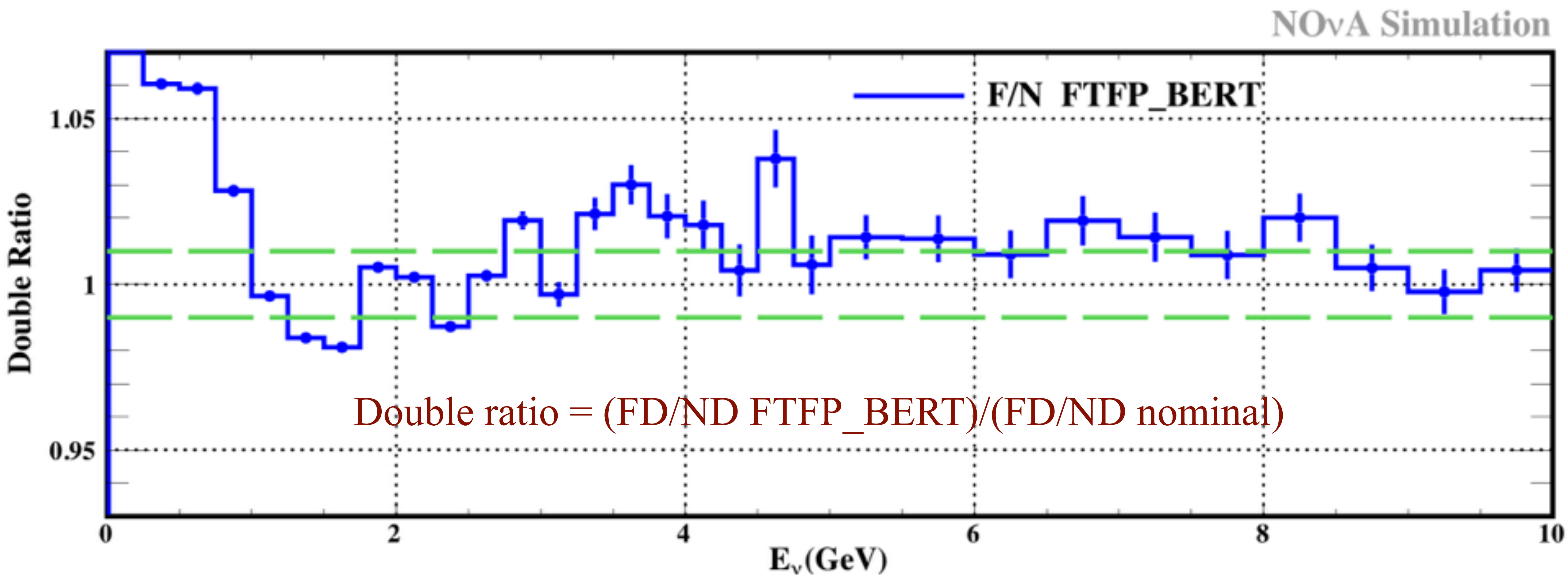


This is one example of beam transport systematic, similarly we conducted this exercise for various systematics on slide 5.

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







Double ratio = (FD/ND FTFP_BERT)/(FD/ND nominal)

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

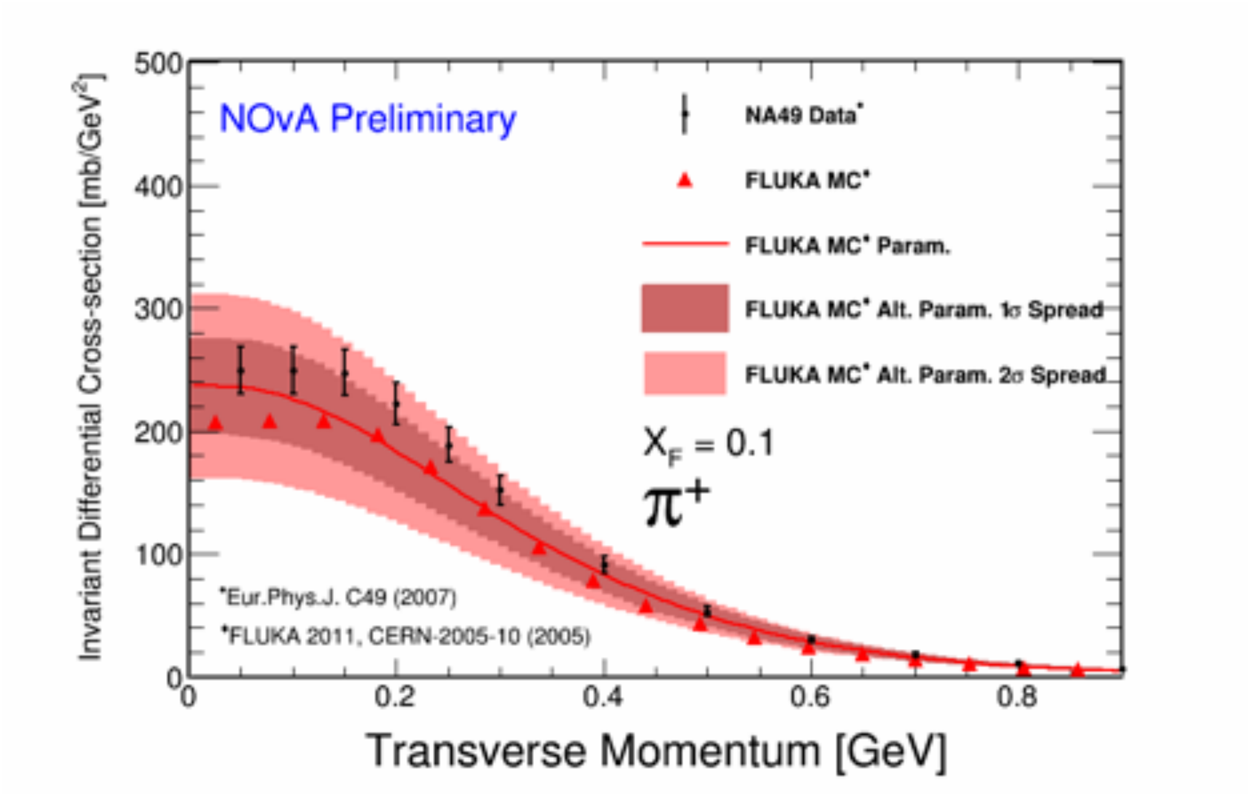
Model	Delta(%)
Std	0.00
+1kA	-0.16
-1kA	0.10
BposX+.5mm	-0.68
BposX-.5mm	0.24
BposY+.5mm	0.18
BposY-.5mm	-0.45
BmSptp +.2mm in X & Y	-0.81
BmSptm -.2mm in X & Y	0.29
H1 +2mm X & Y	-0.39
H1 -2mm X & Y	-1.79
H2 +2mm in X & Y	-0.47
H2 -2mm in X & Y	0.30
Exp B field	-4.32
Target position +2mm	-0.09
FTFP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

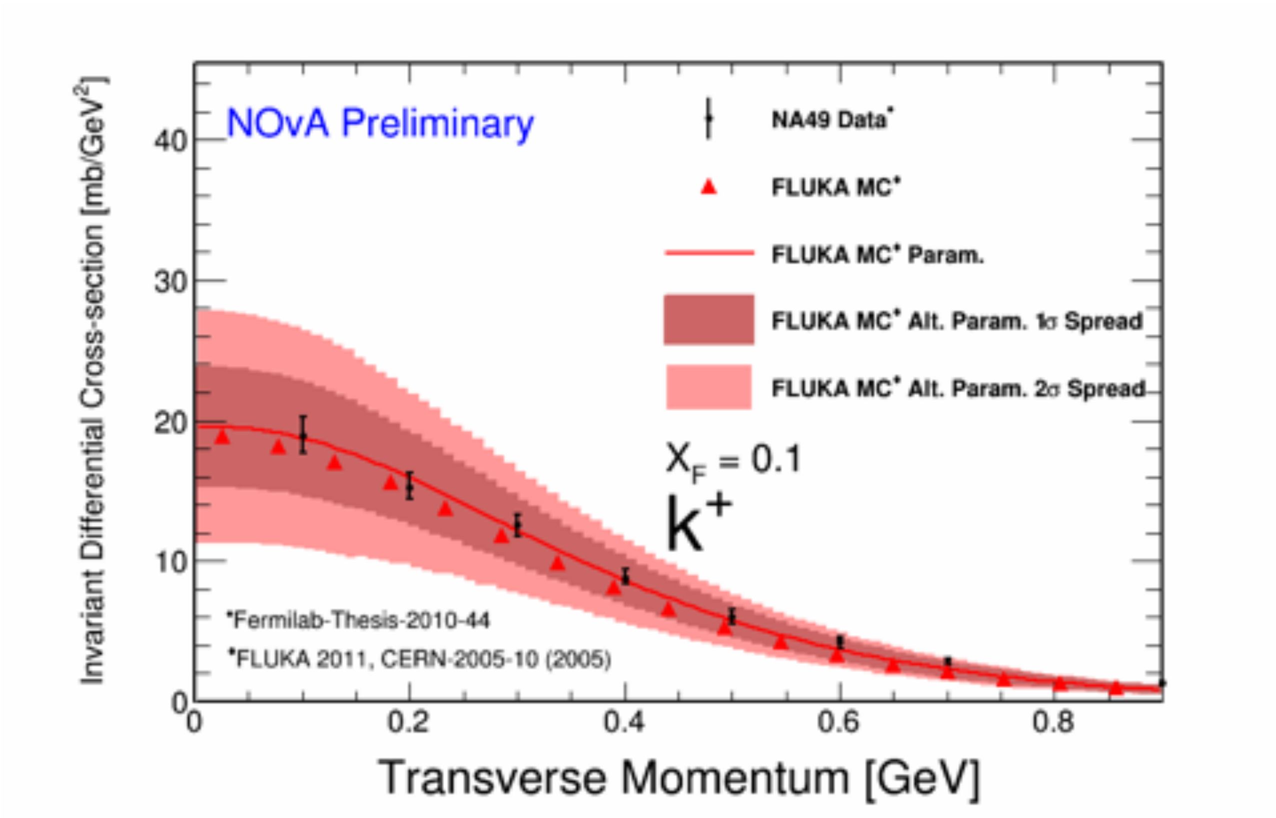
δ(%) is ~3%, Energy variation <.5%

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

Average-E_ν and RMS for 0<Eν<10 GeV & 1<Eν<3 GeV

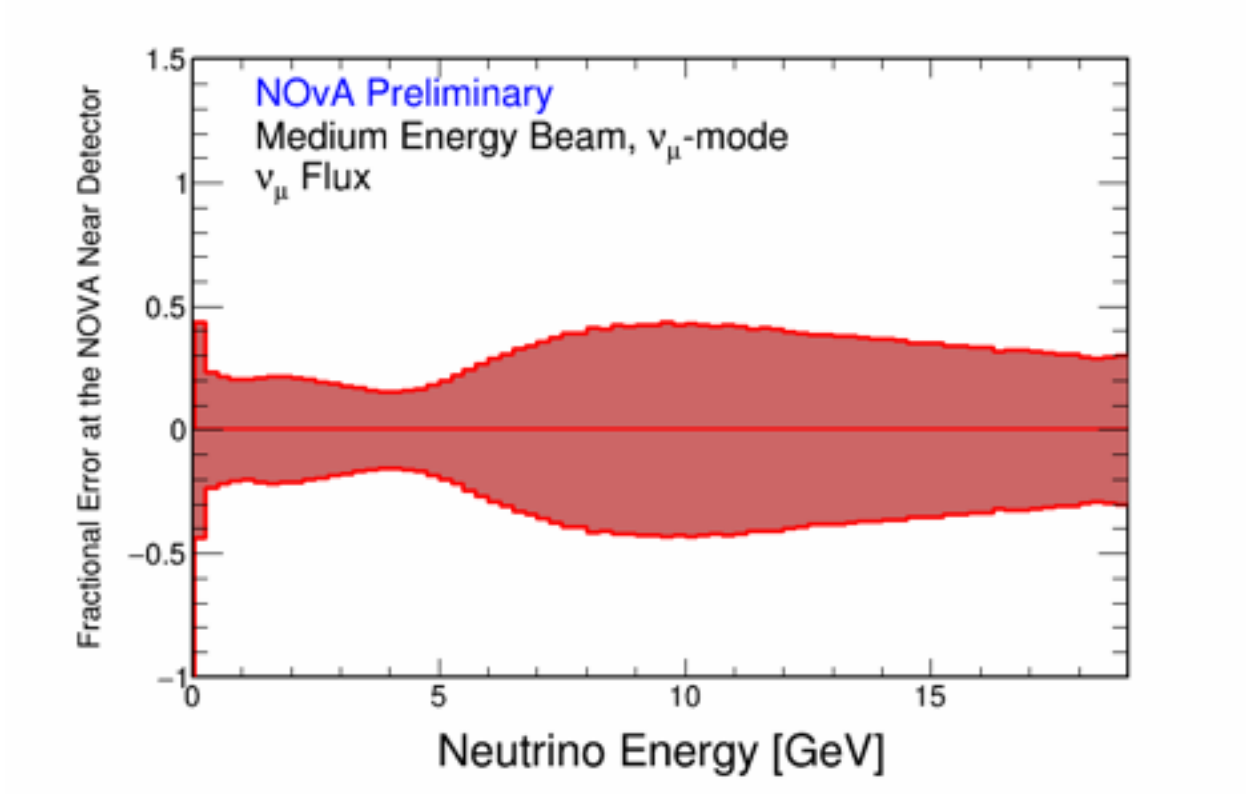
Uncertainties in hadron production based on NA49 data

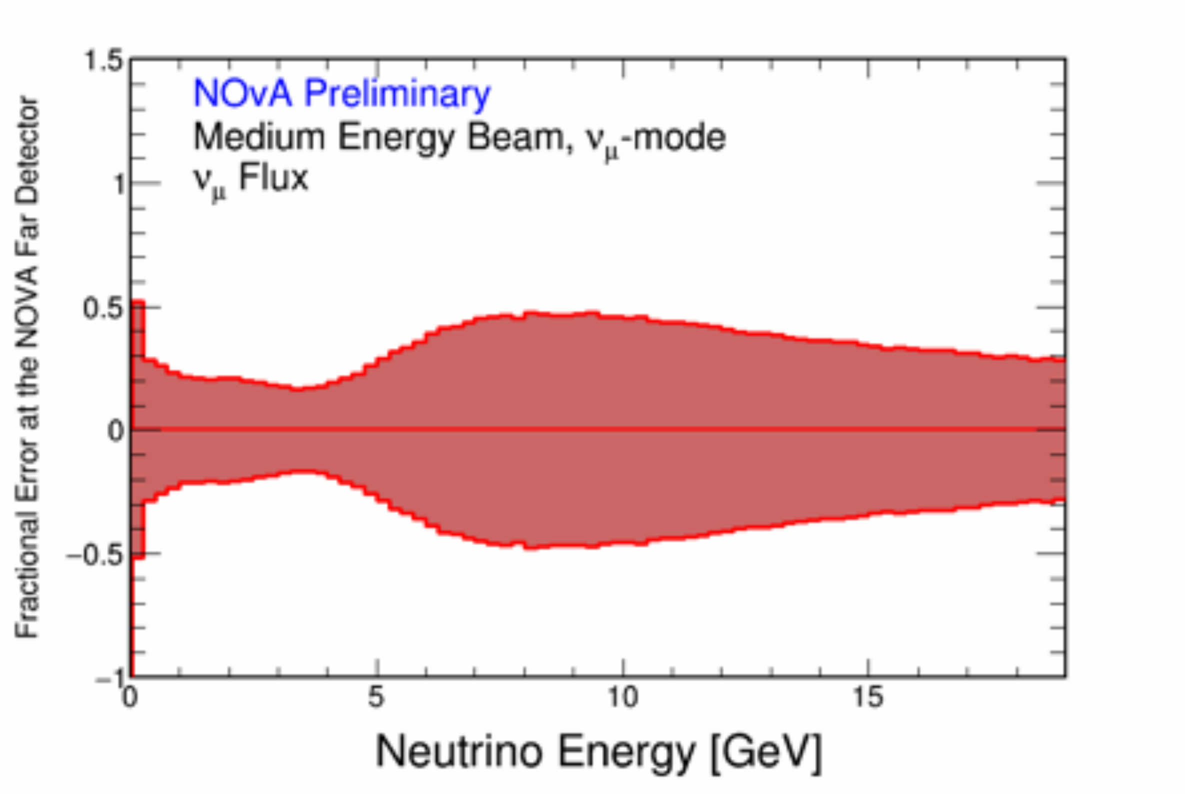


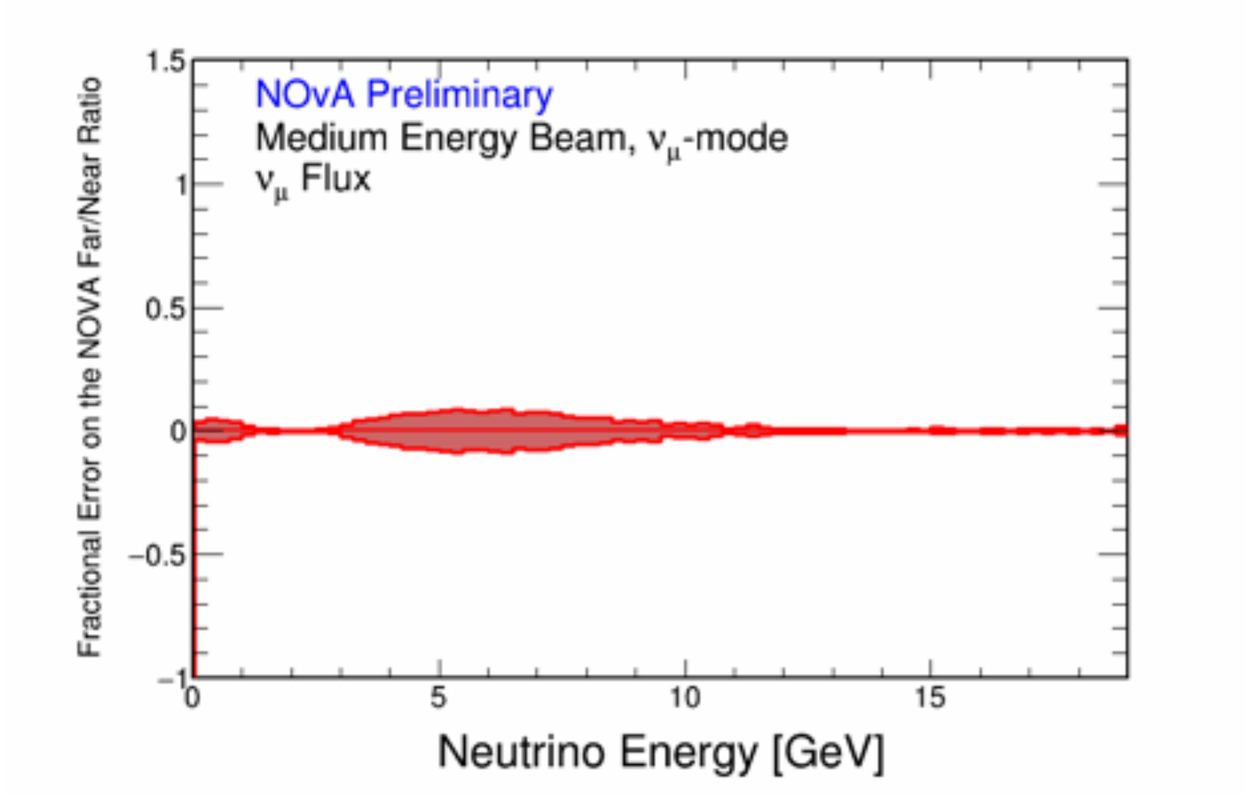


Invariant differential cross section for an X_F of 0.1 and as a function of P_T for Pions & Kaons produced in p+C collisions at 158-GeV/c beam momentum on thin target.

Uncertainties in hadron production based on NA49 data



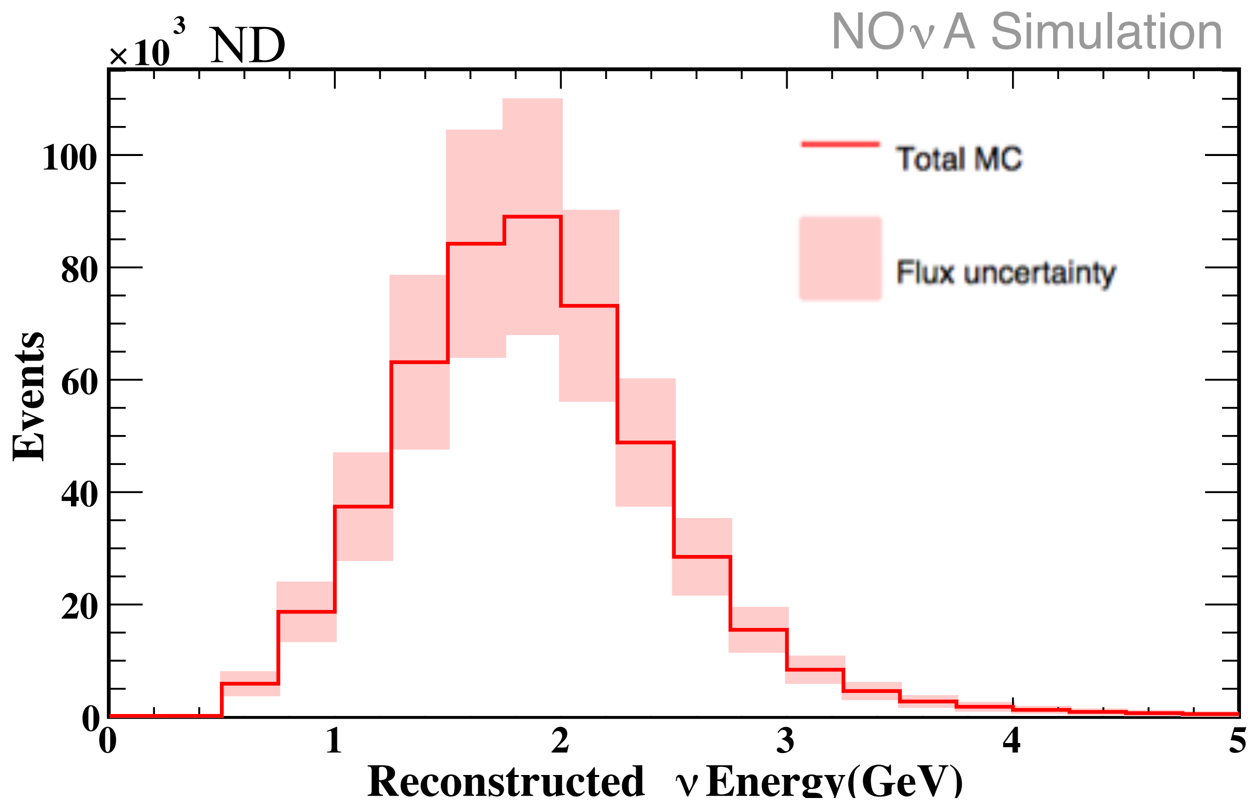


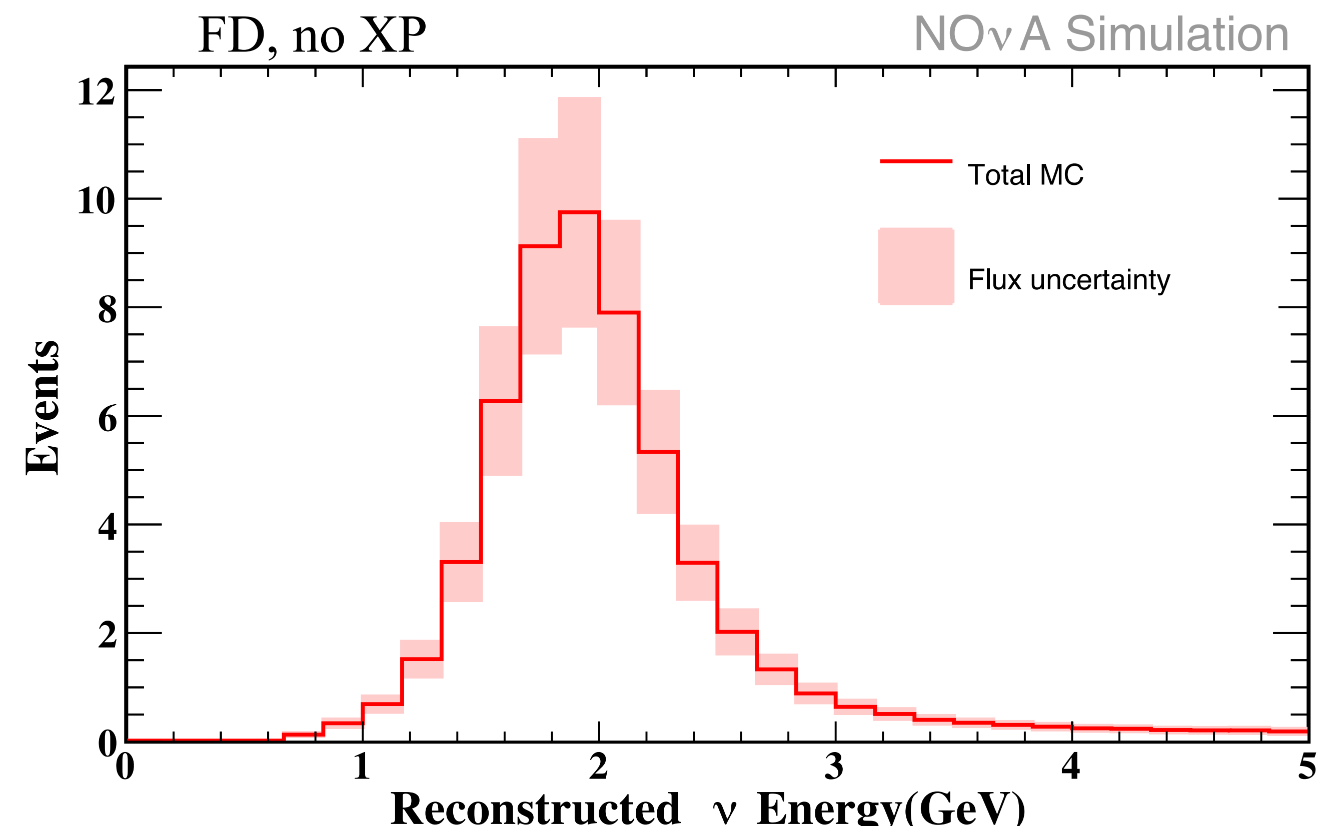


The square root of the diagonal elements of the covariance matrix describing the hadron production uncertainty on the beam ν_μ flux at the ND, FD and FD/ND.

However, based on NA49 data, the variations are larger than that expected by two different models, FTFP and Fluka

Beam Transport Errors, including NA49 Hadroproduction Uncertainty on Reconstructed neutrino energy[GeV] in NOνA ND & FD for 6e20 POT





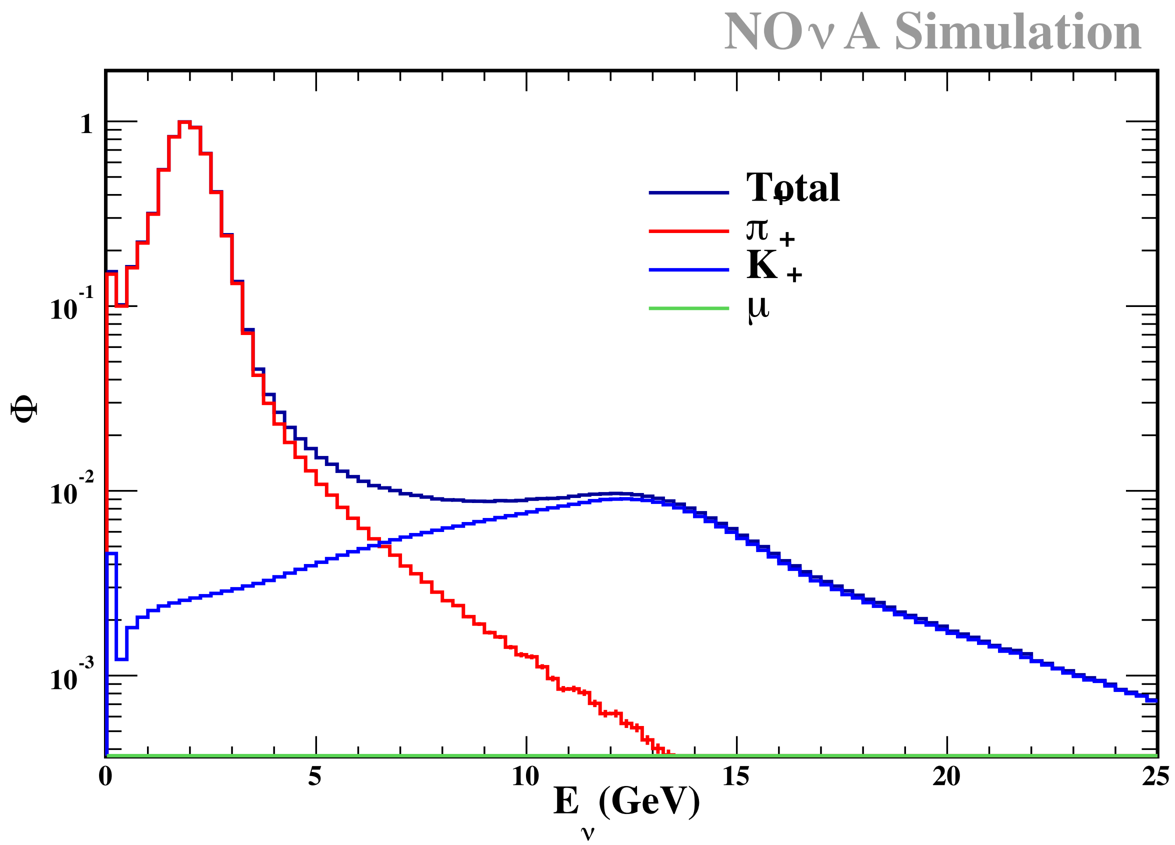
Flux uncertainty is ±23.9%

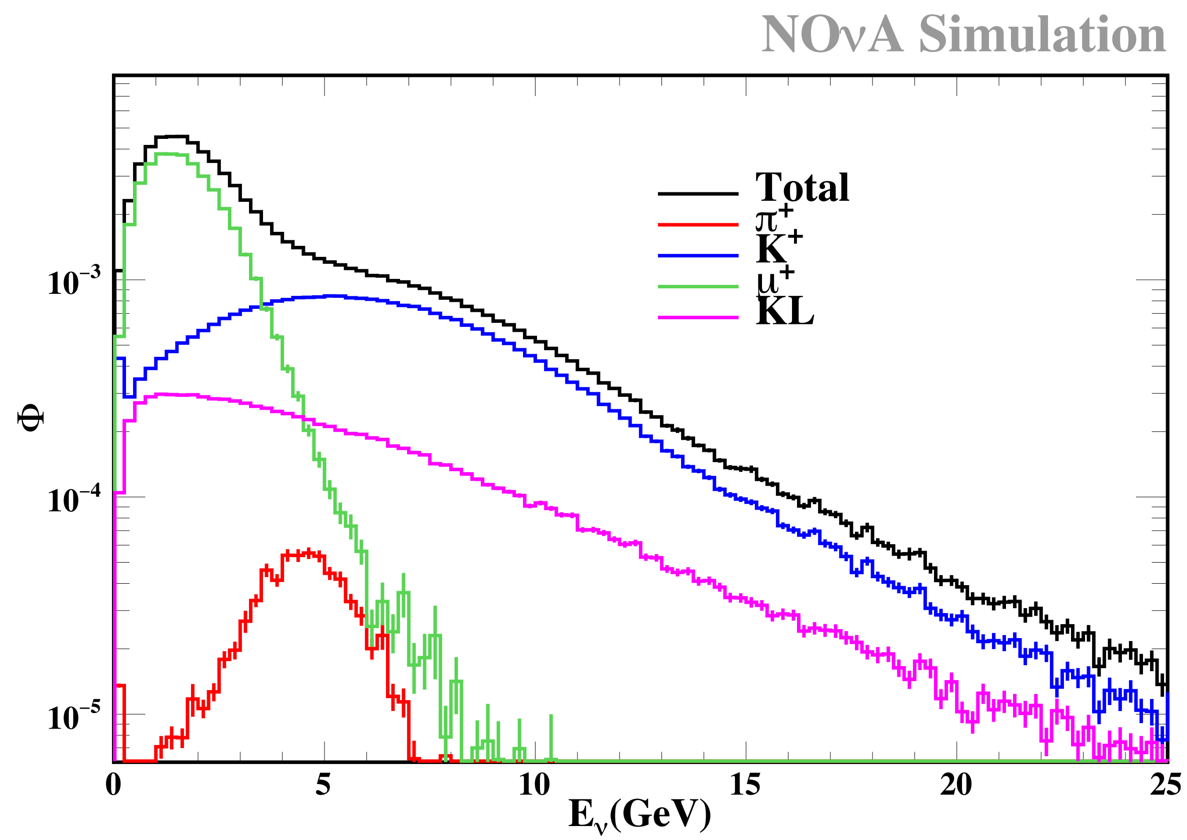
Flux uncertainty is ±20.9%

The error band represents a ±1 sigma shift of all beam systematics: including NA49 Hadroproduction Uncertainty, Spot size, Beam position on the target (X/Y), Target position, Horn current, Horn-positions, & the modeling of horn's B-field.

Constraints using ND Data

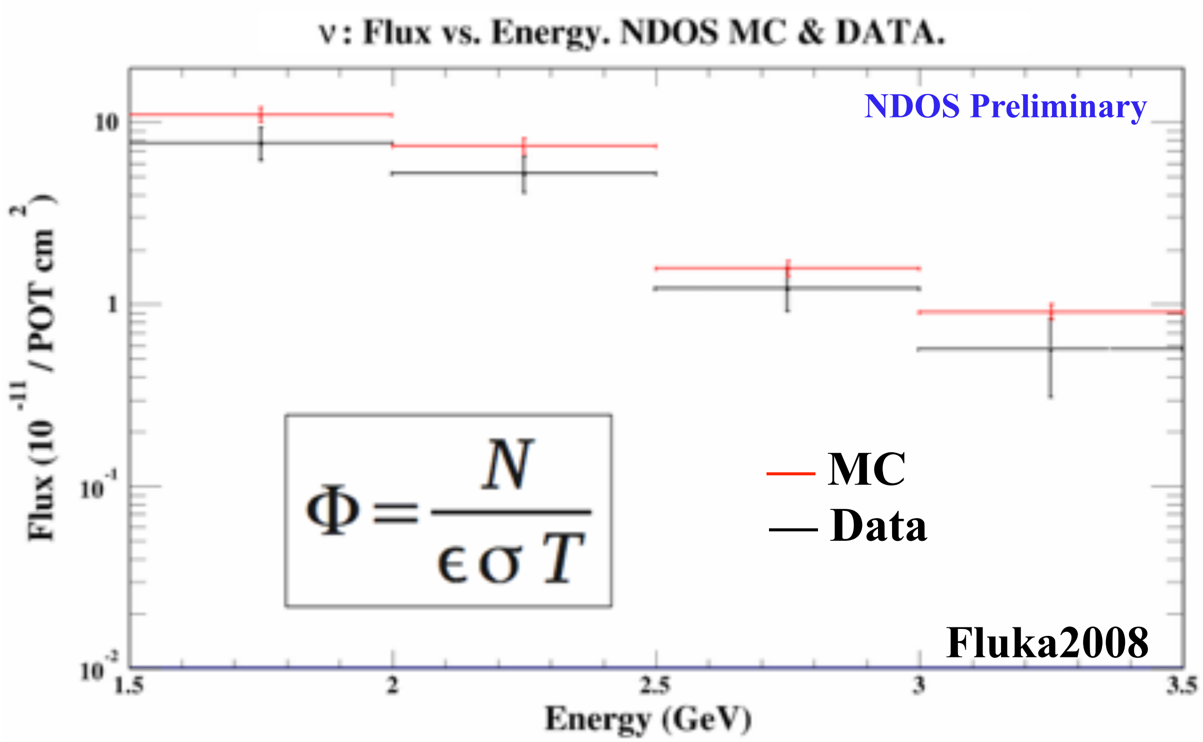
- We have shown systematic uncertainties from Beam Transport and hadron production model
- Need to constrain by Data.
- $\pi \rightarrow \nu_\mu + \mu$; 97% of ν_μ at the ND are from the π which be constrained by ND-Data

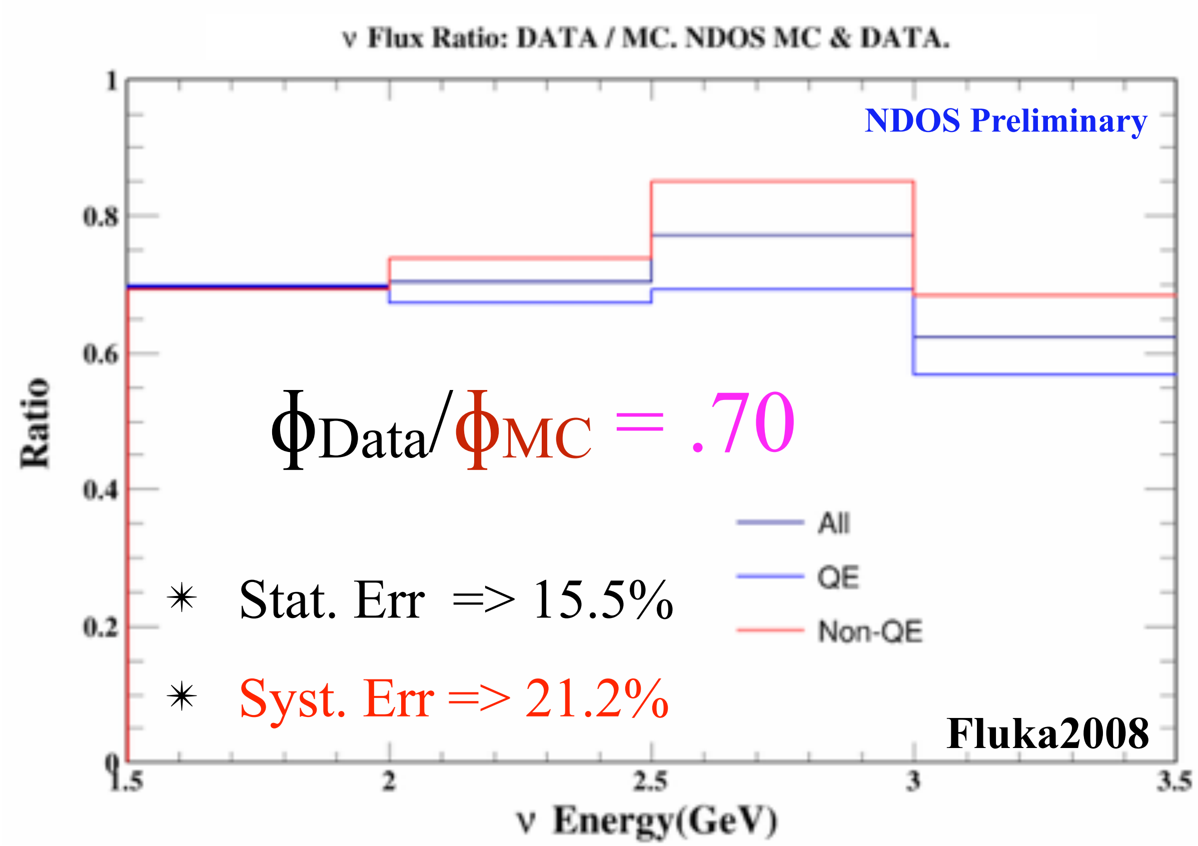


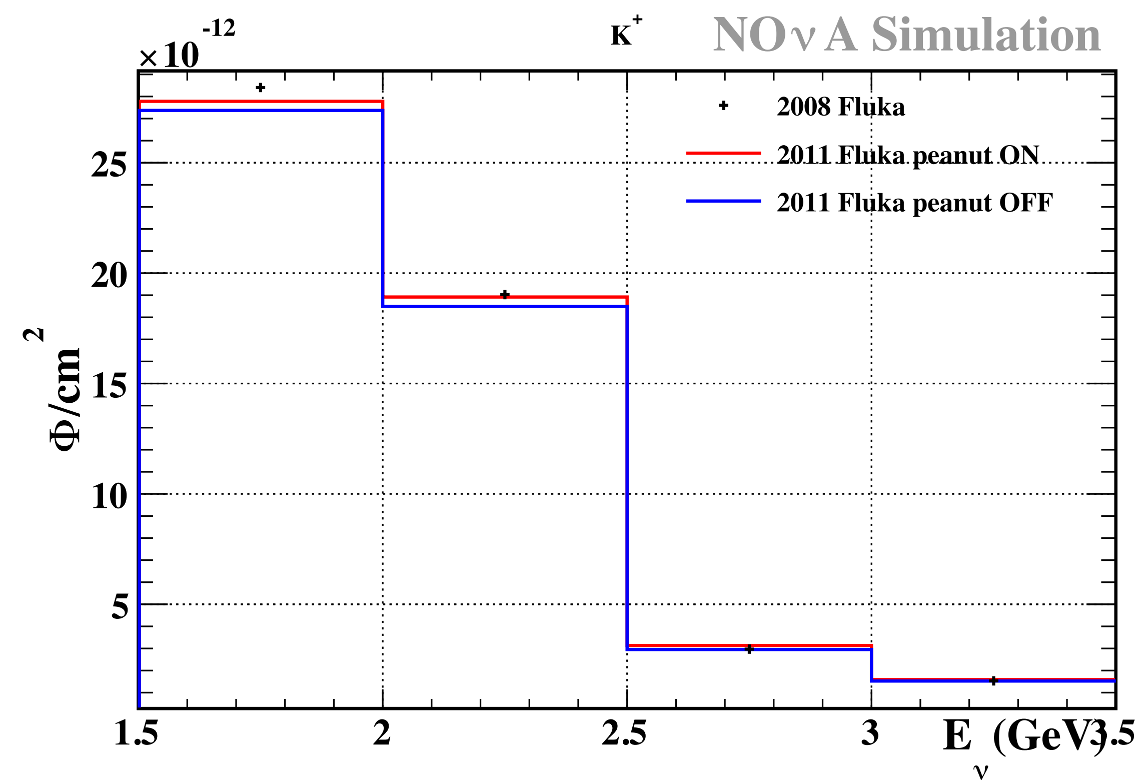


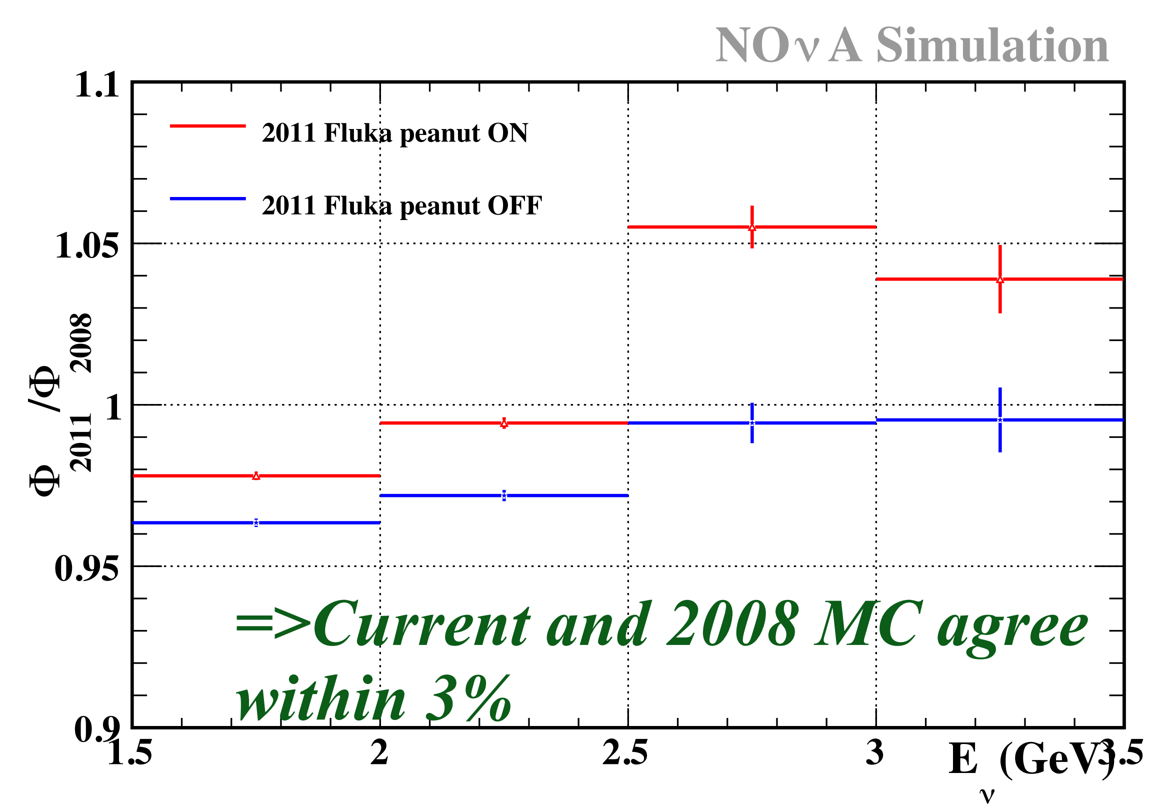
- ν_e constrains:
  - Use ND-Data (E_ν>7.5 GeV) to constrain K^+ (for ν_e)
  - Use ND-Data (0.5<Eν<5) to constrain $\pi^+ \Leftrightarrow \mu^+$ (for ν_e) i.e $\pi \rightarrow \nu_\mu + \mu \rightarrow \nu_\mu + e + \nu_e$
- Analysis of Neutrino-electron (Atomic) NC scattering to yield the absolute flux

Fixing K^+ using Near Detector on Surface (NDOS) Data:
NDOS => ~110 mrad off-axis, Prototype Detector[Plots from E. Arrieta-Diaz, Ph.D. Thesis]

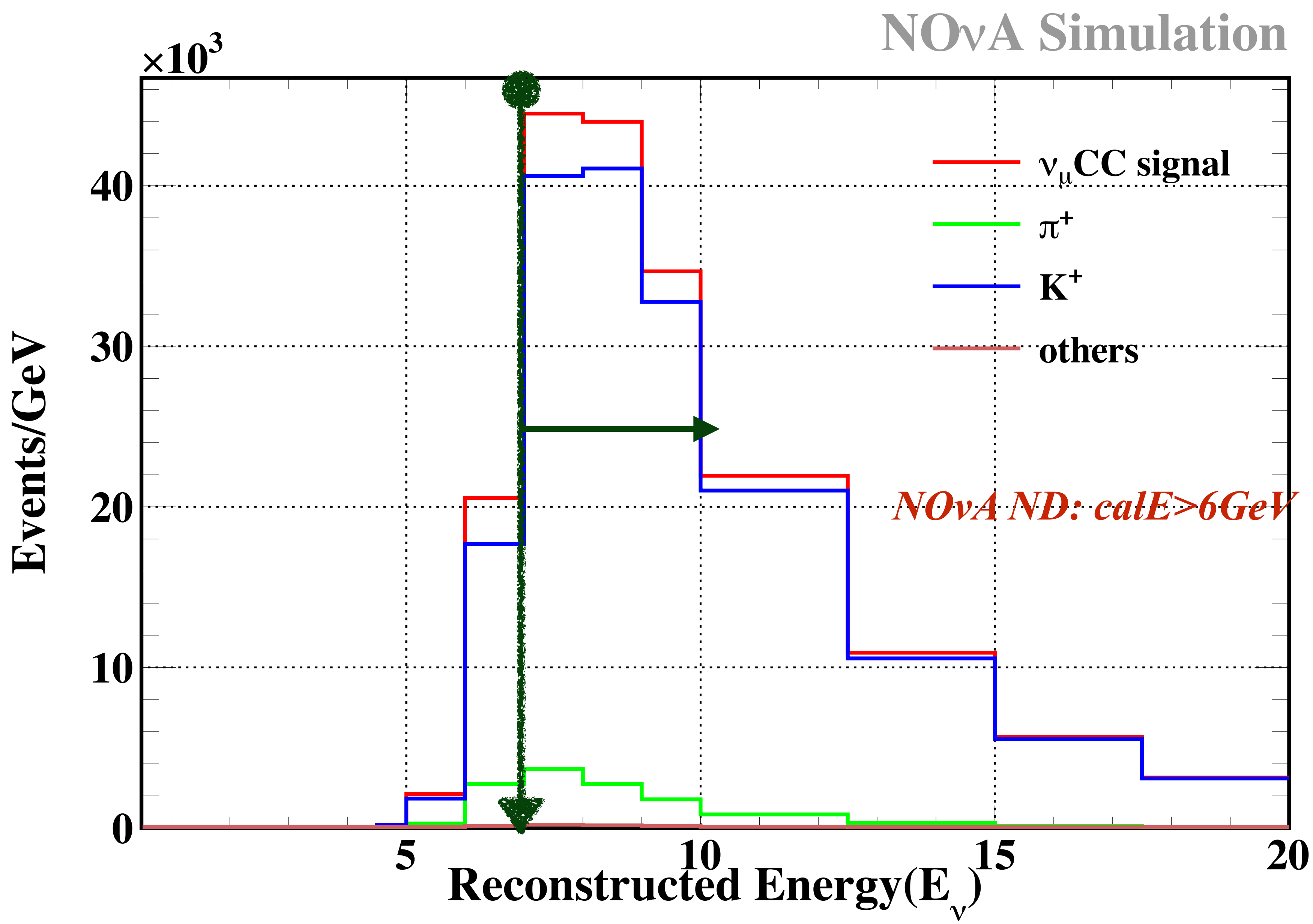








K^+ Constraint using Near Detector (ND) (~14 mad) CC Data



The ND data provide constraint on K^+ (independent of NDOS)

- ND offers better systematics than NDOS
- At higher-energy, e.g. E_ν>7 GeV, CC data dominated by ν's from K+ (see Fig)

Summary:

- We evaluated the flux systematic errors arising from the uncertainties in the beam transport & hadro-production MC 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)
- Data driven constraints:

- K^+ & Π^+ Normalization from CC-Data
- Absolute flux from Nu-Electron NC interaction
- Constraining the shape (relative-flux) using Low-Nu0 method

- … in progress.

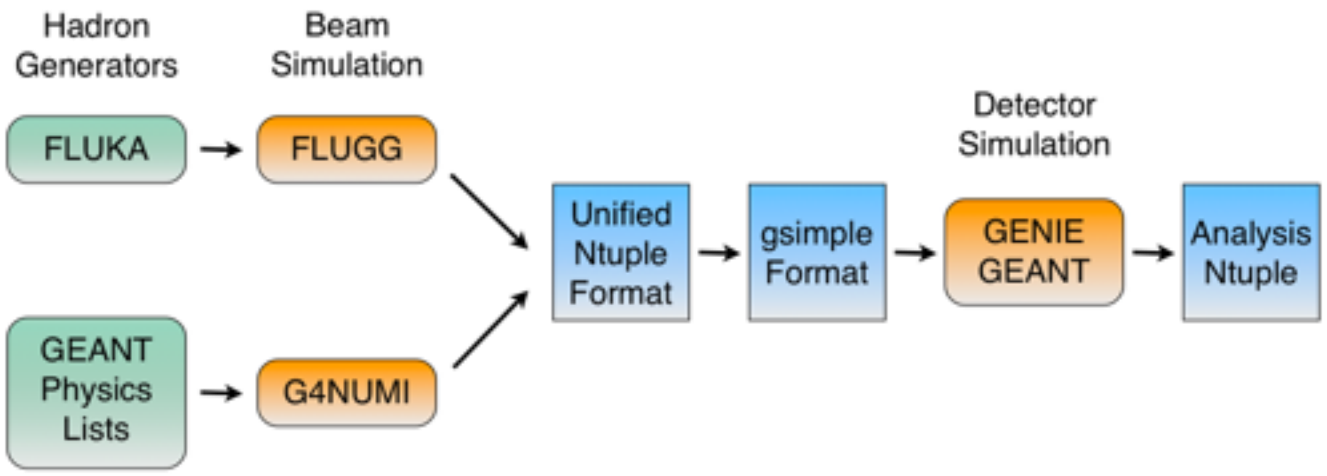
Thank you!

Backup!

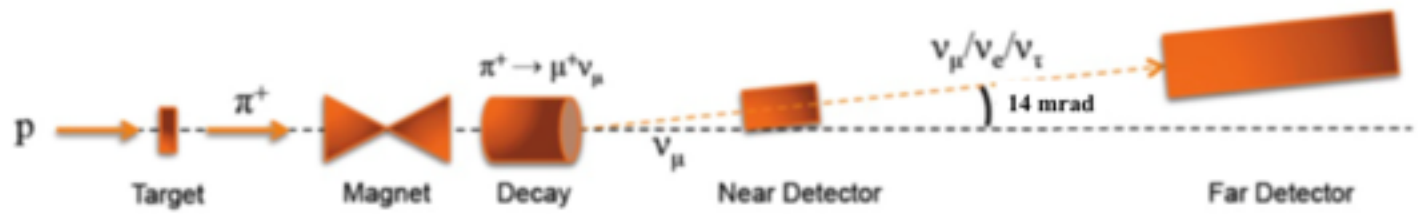
FLUGG -vs- G4NuMI

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



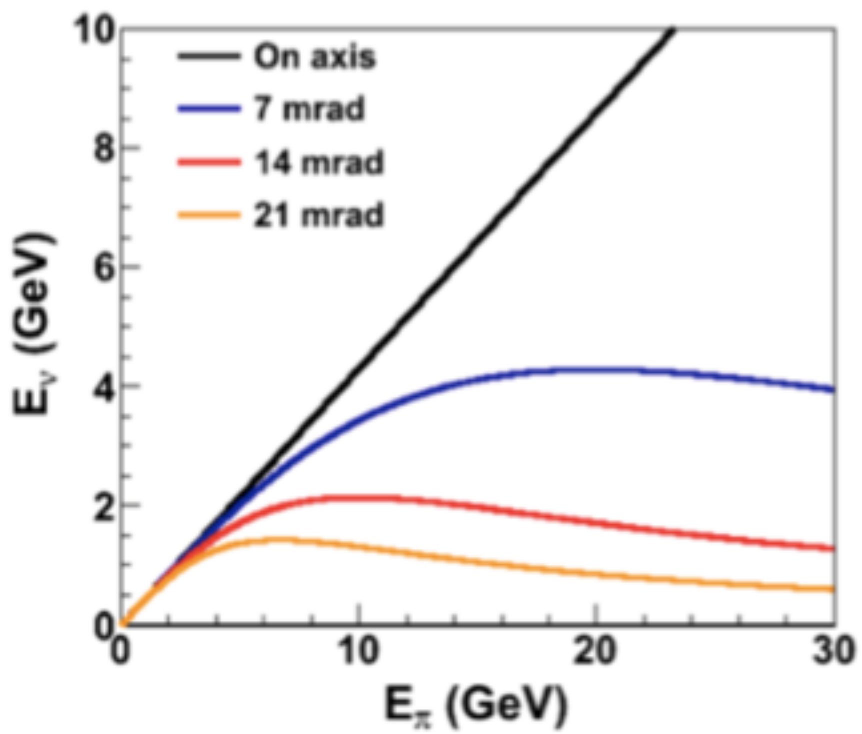
Why off-axis?

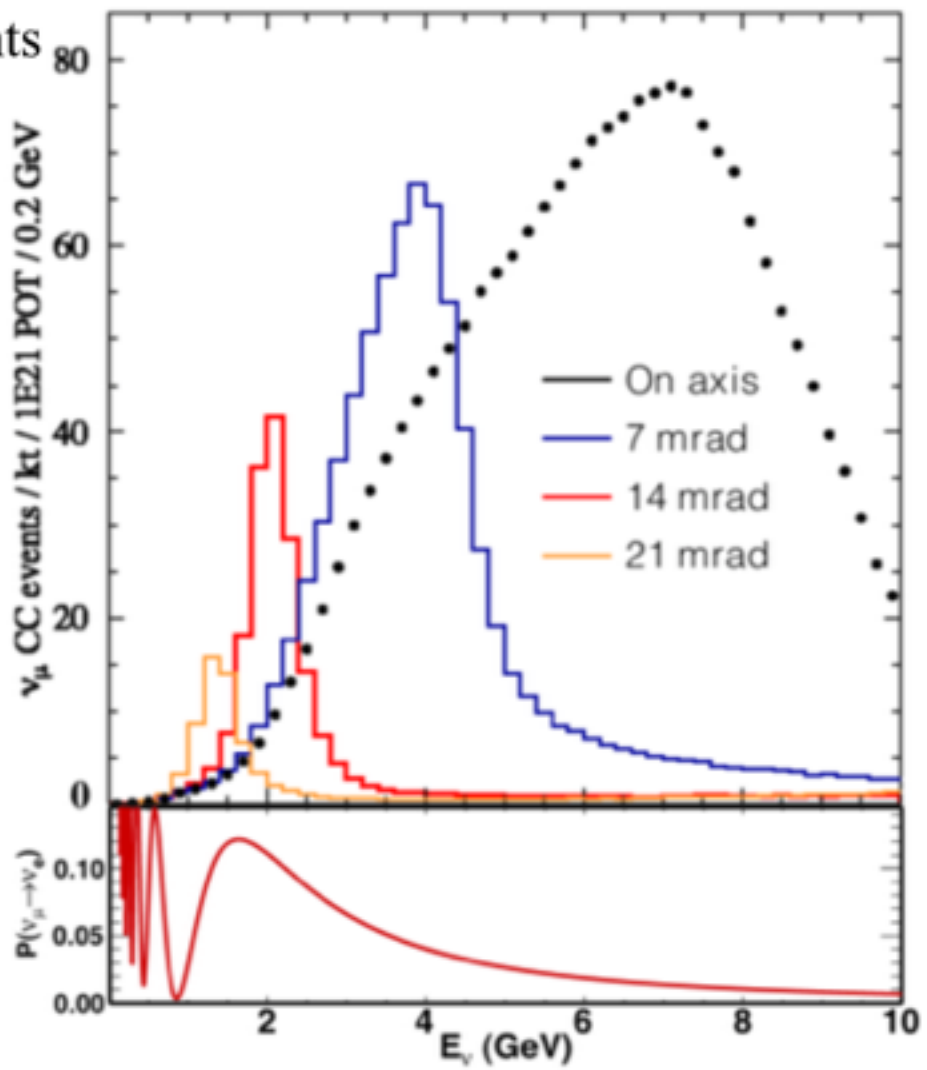


At 14 mrad off-axis, narrow band beam peaked at E_ν=2GeV

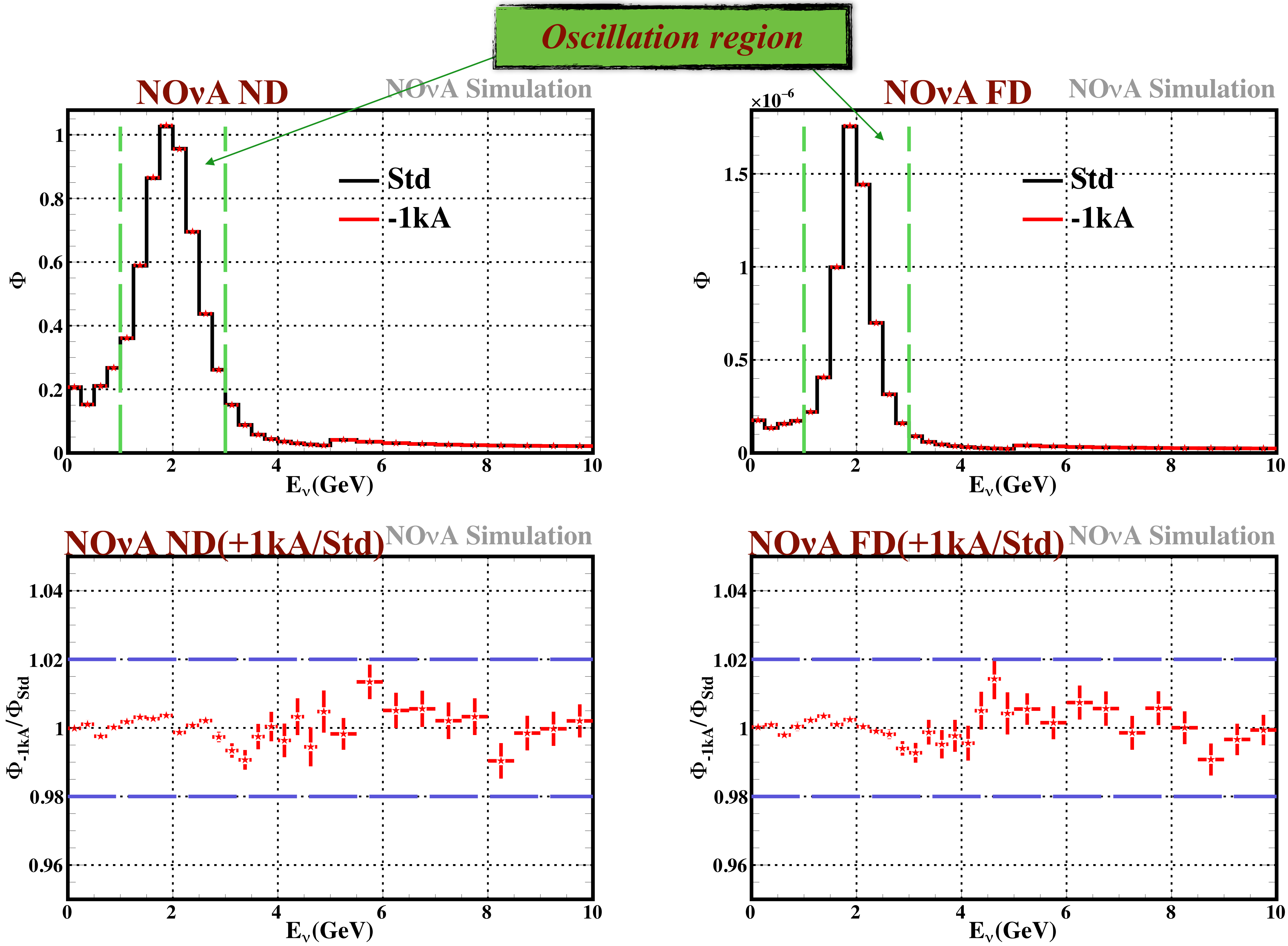
- The peak of the beam coincides with the oscillation maximum for electron neutrino appearance for the 810 km distance
- Removes high energy NC background events

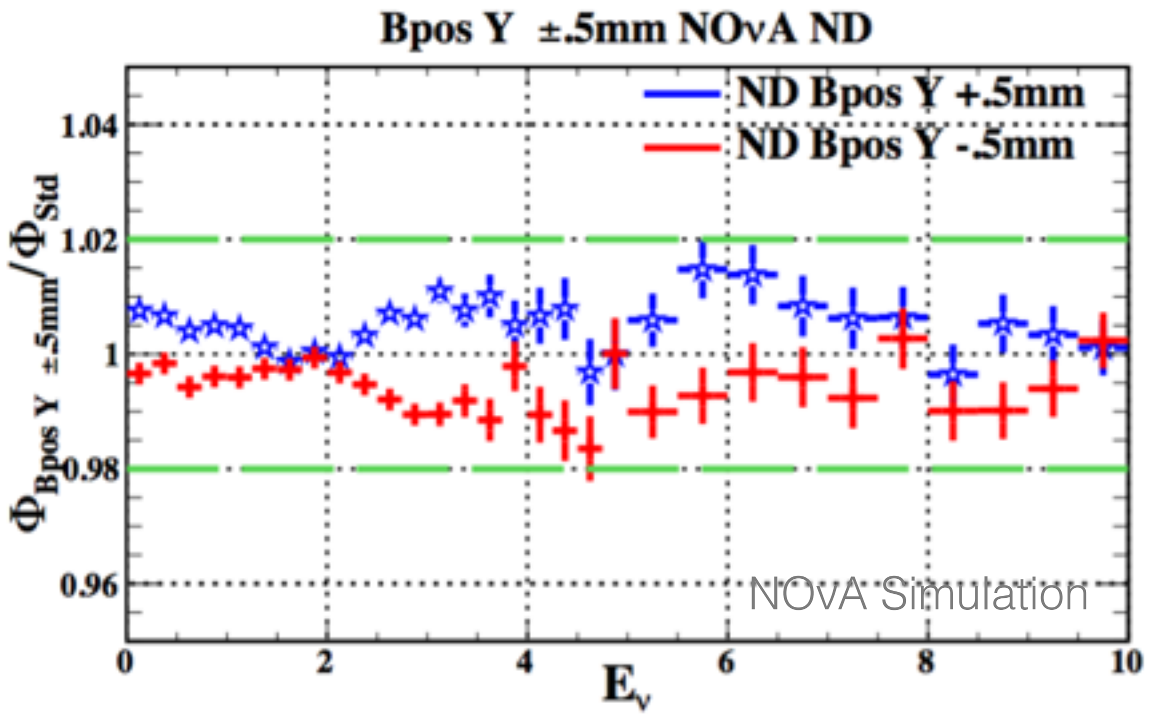
$$E_\nu \approx 0.43\frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

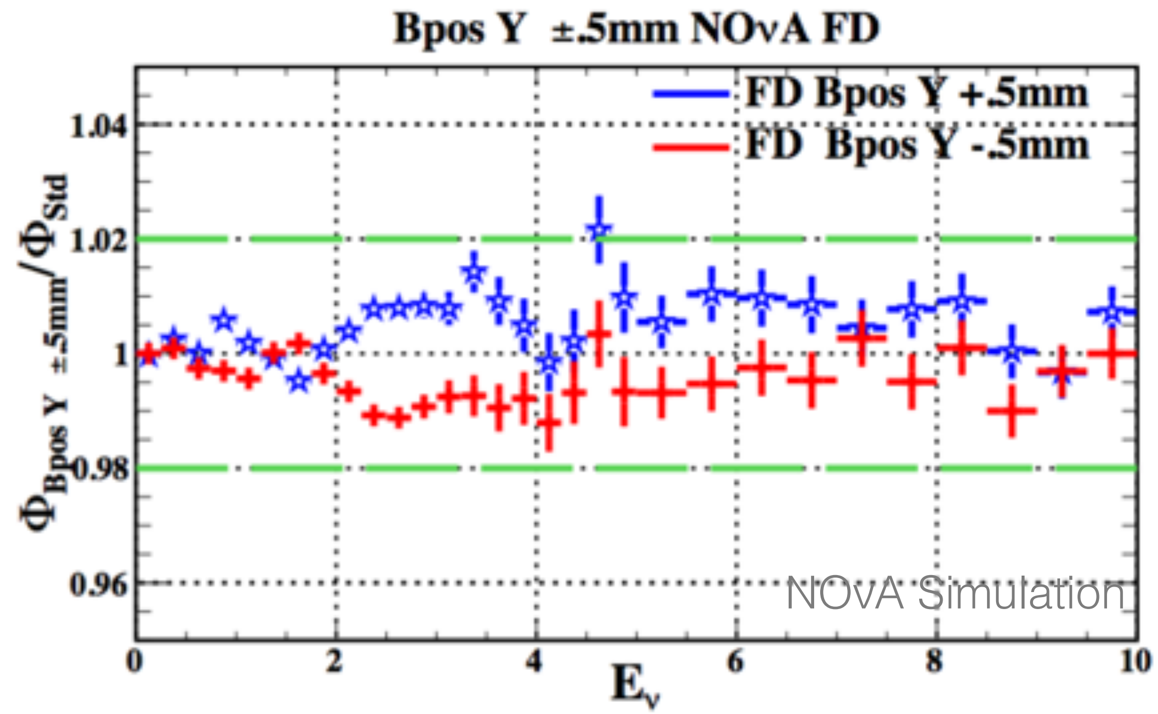


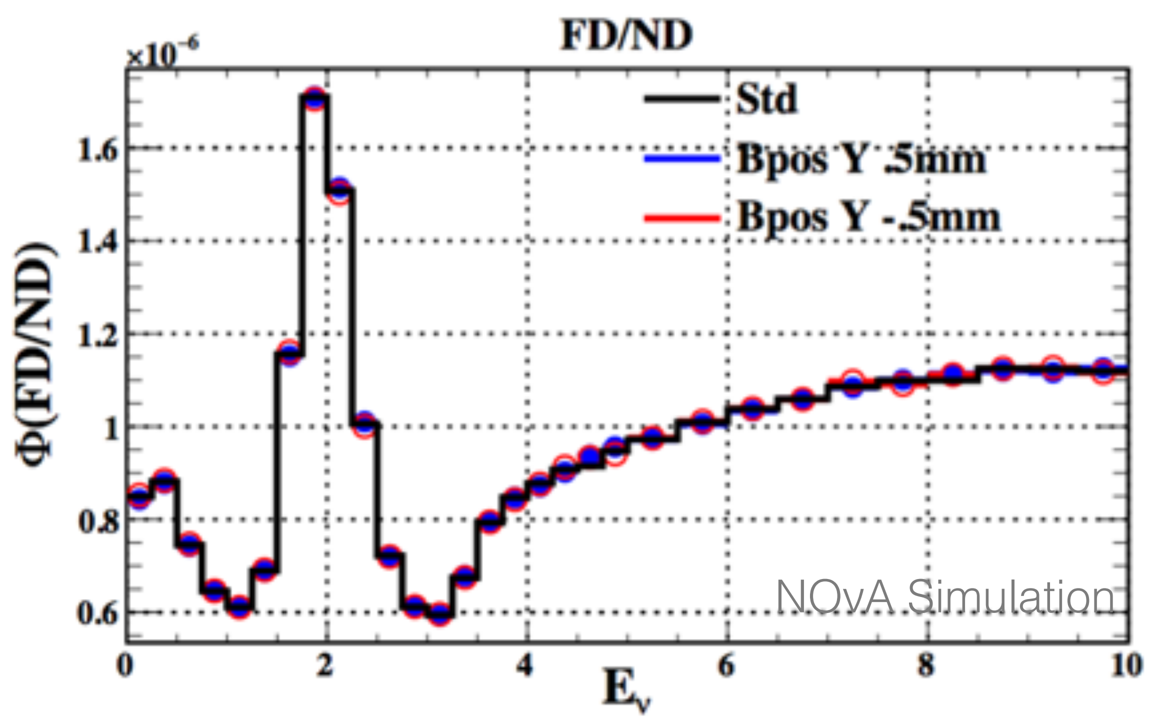


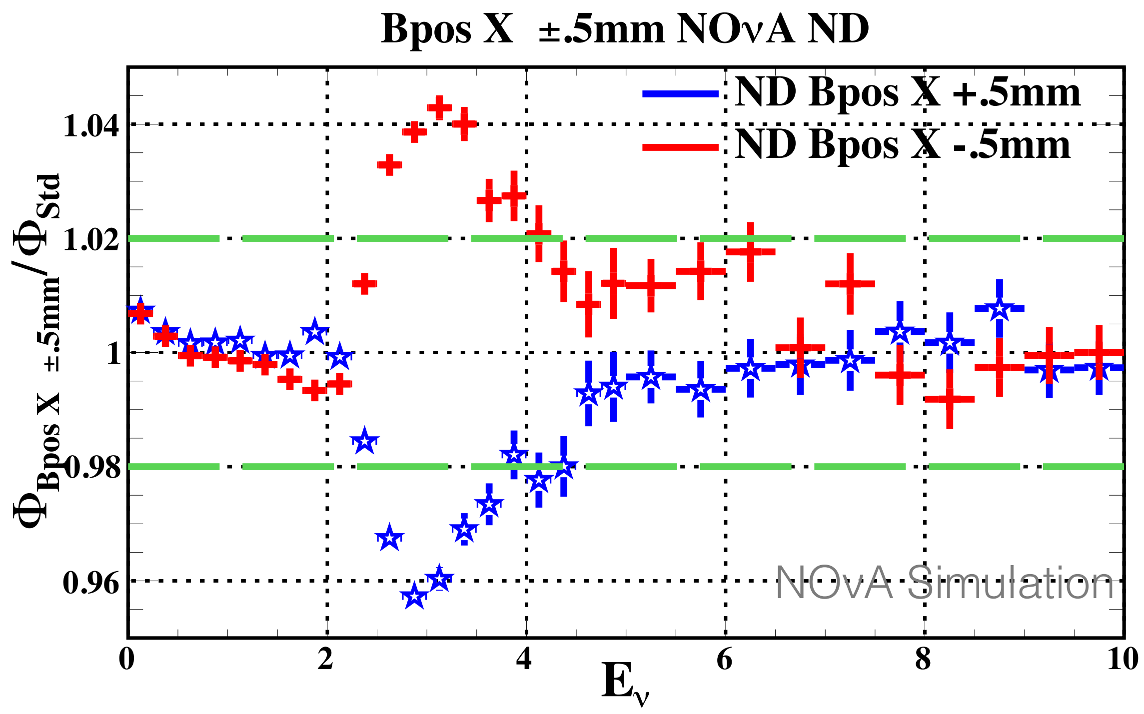
Horn Current Variation -1kA:

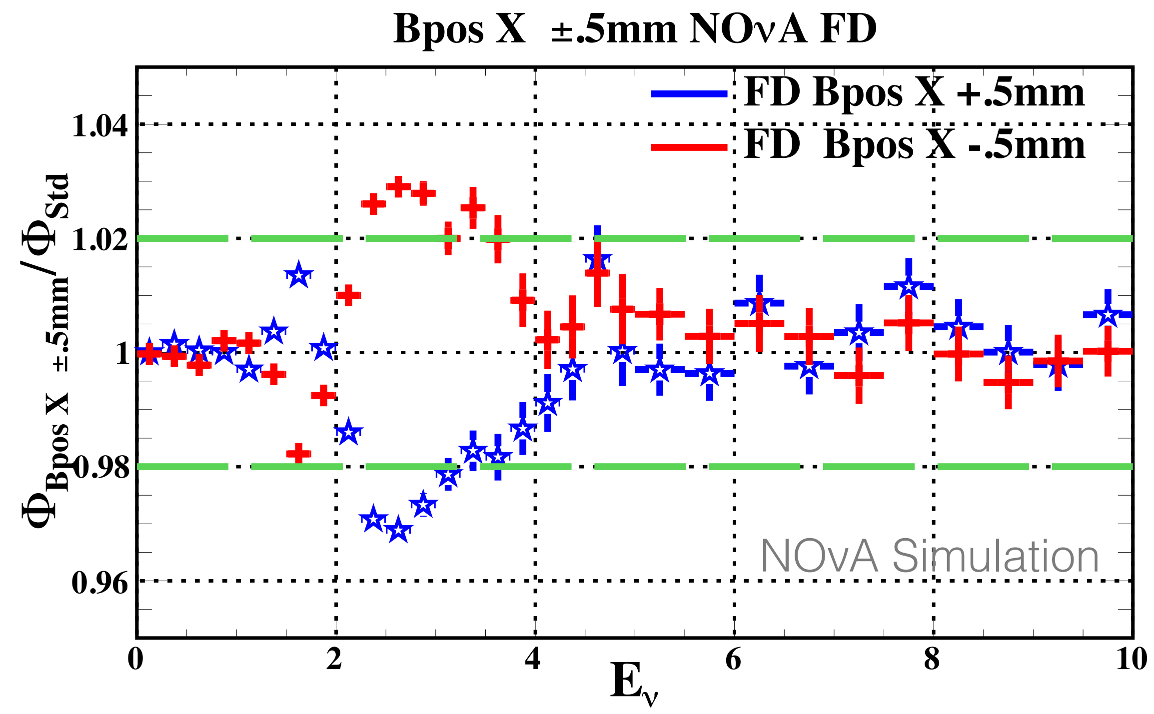


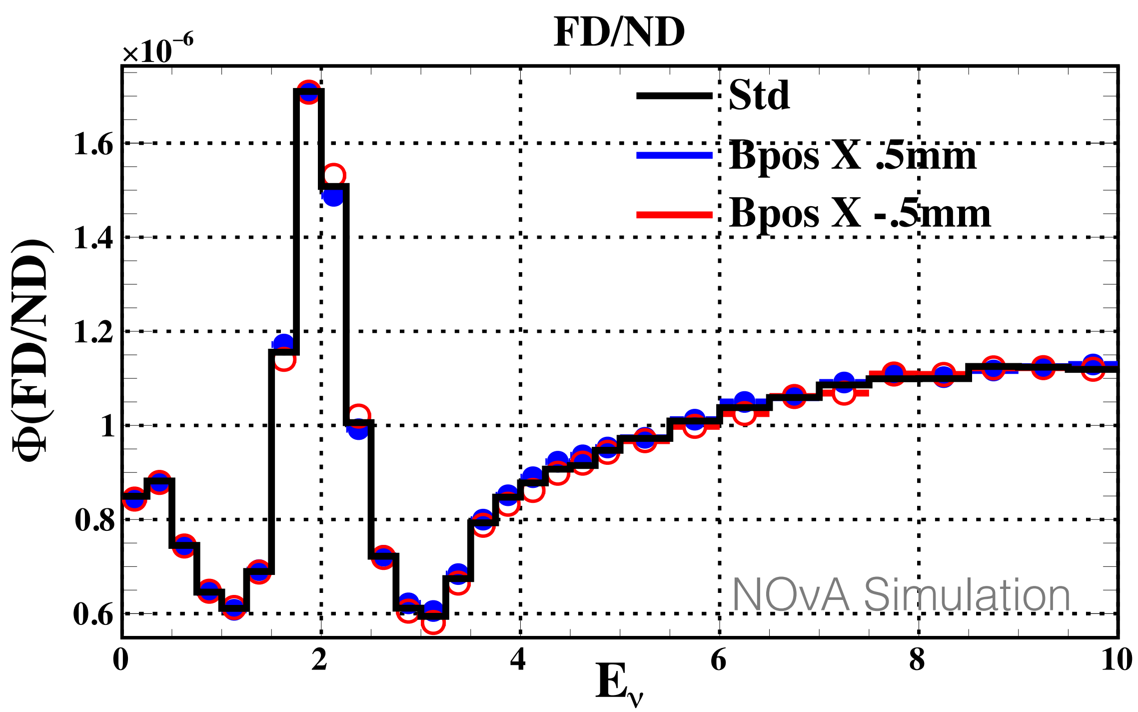

Bpos Y ±.5mm NOvA ND
ND Bpos Y +.5mm
ND Bpos Y -.5mm
$\Phi_{Bpos\ Y\ \pm.5mm}/\Phi_{Std}$
NOvA Simulation
E_ν

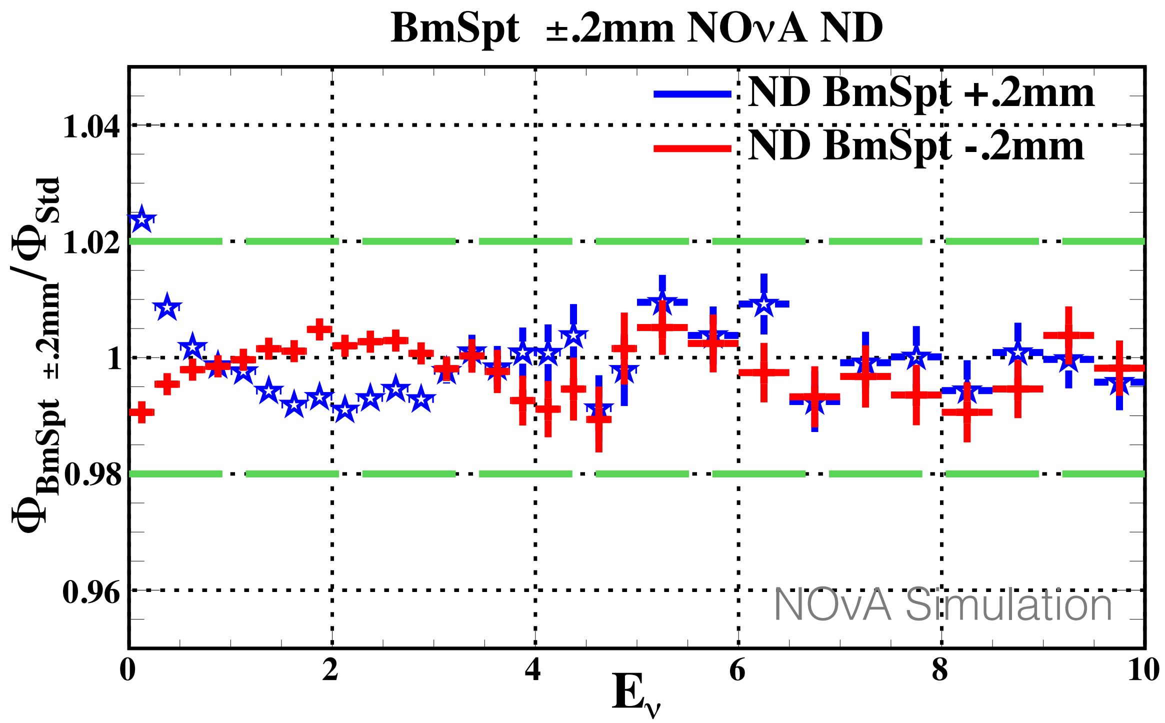

Bpos Y ±.5mm NOvA FD
FD Bpos Y +.5mm
FD Bpos Y -.5mm
$\Phi_{Bpos\ Y\ \pm.5mm}/\Phi_{Std}$
NOvA Simulation
E_ν

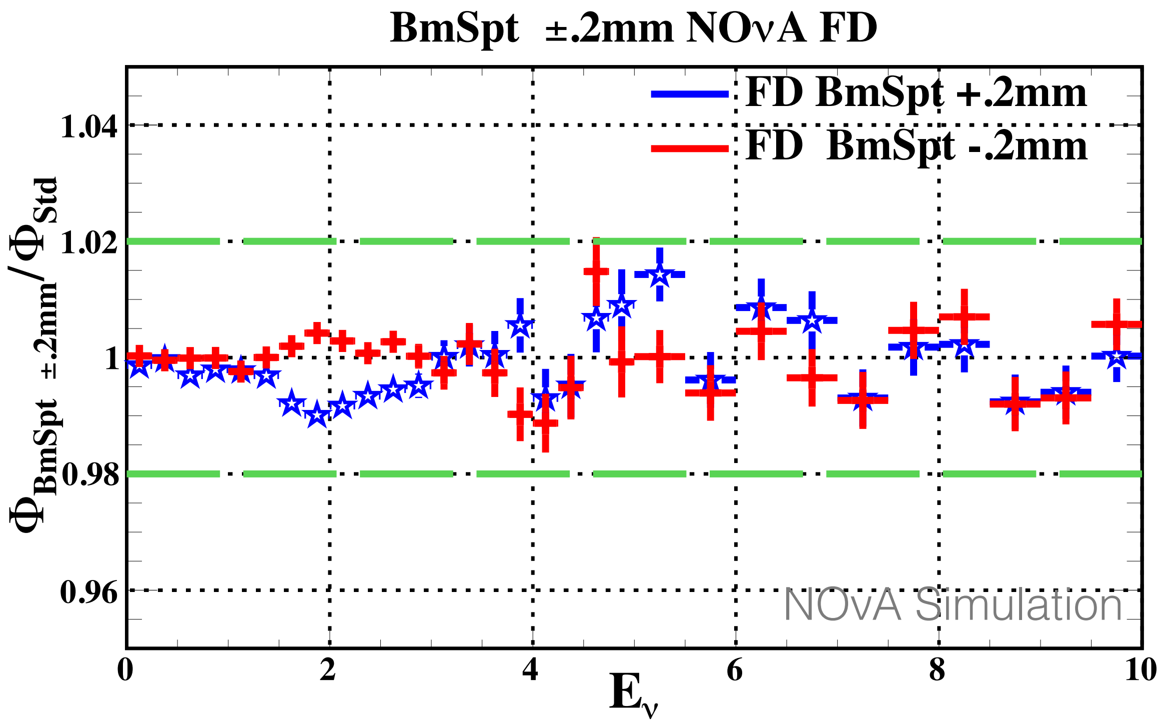

FD/ND
$\times10^{-6}$
Std
Bpos Y .5mm
Bpos Y -.5mm
Φ(FD/ND)
NOvA Simulation
E_ν

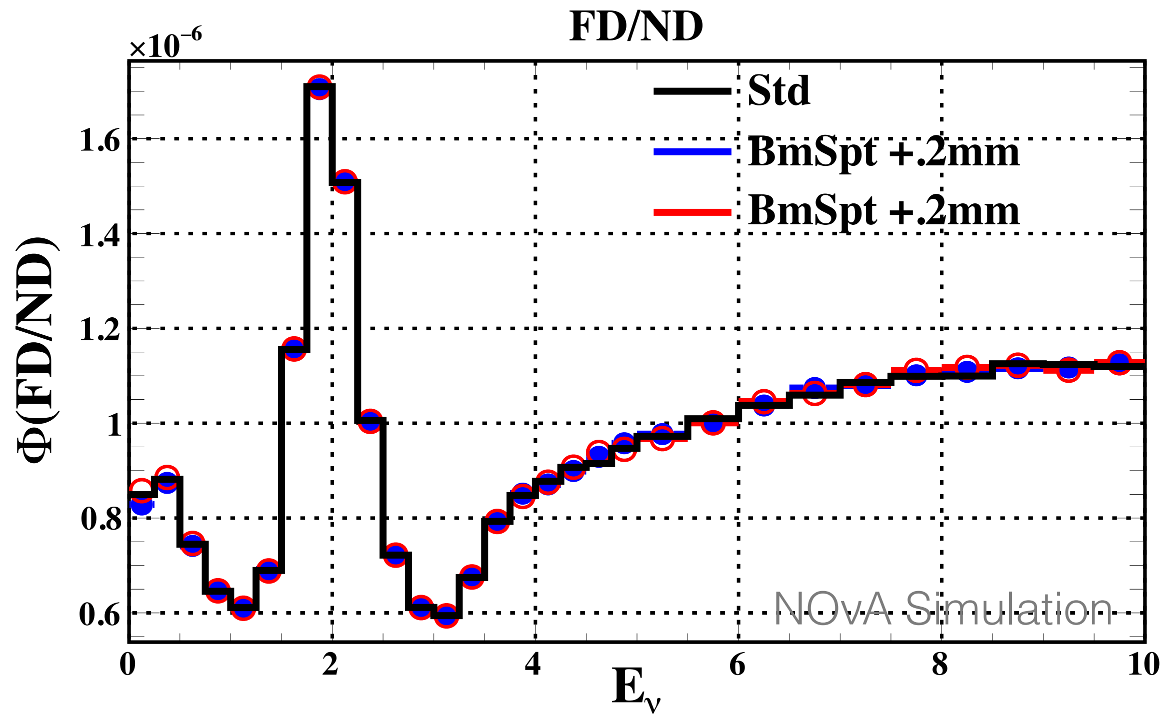

Bpos X ±.5mm NOνA ND
ND Bpos X +.5mm
ND Bpos X -.5mm
$\Phi_{Bpos\ X\ \pm.5mm}/\Phi_{Std}$
1.04
1.02
1
0.98
0.96
NOvA Simulation
0
2
4
6
8
10
E_ν

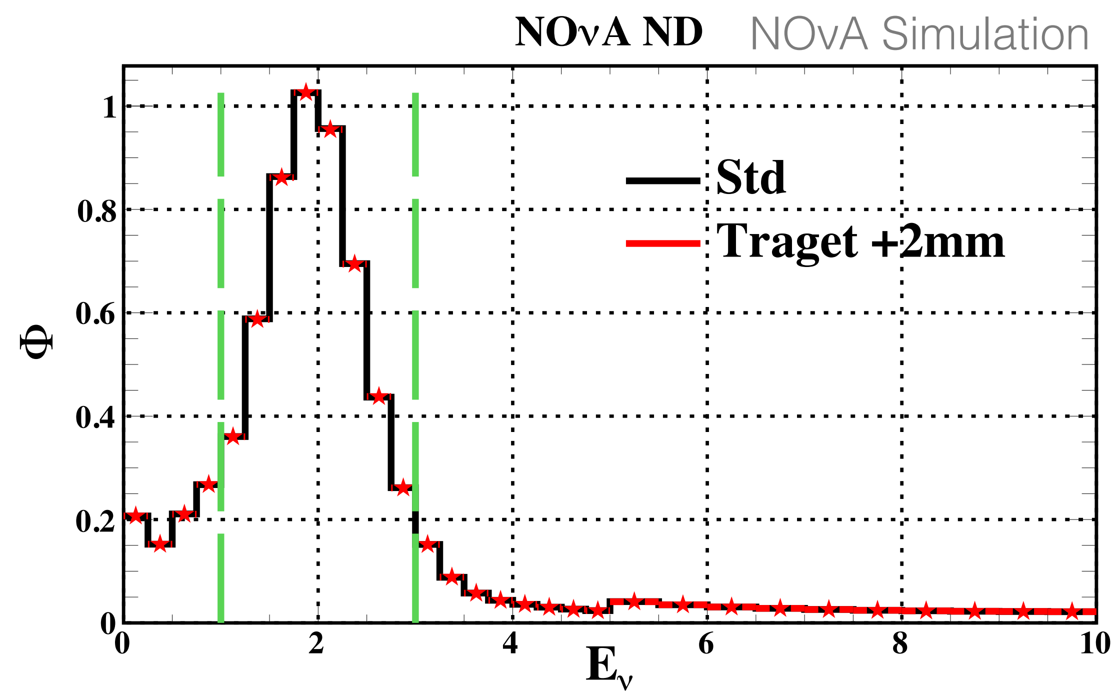

Bpos X ±.5mm NOνA FD
FD Bpos X +.5mm
FD Bpos X -.5mm
$\Phi_{Bpos\ X\ \pm.5mm}/\Phi_{Std}$
1.04
1.02
1
0.98
0.96
NOvA Simulation
0
2
4
6
8
10
E_ν

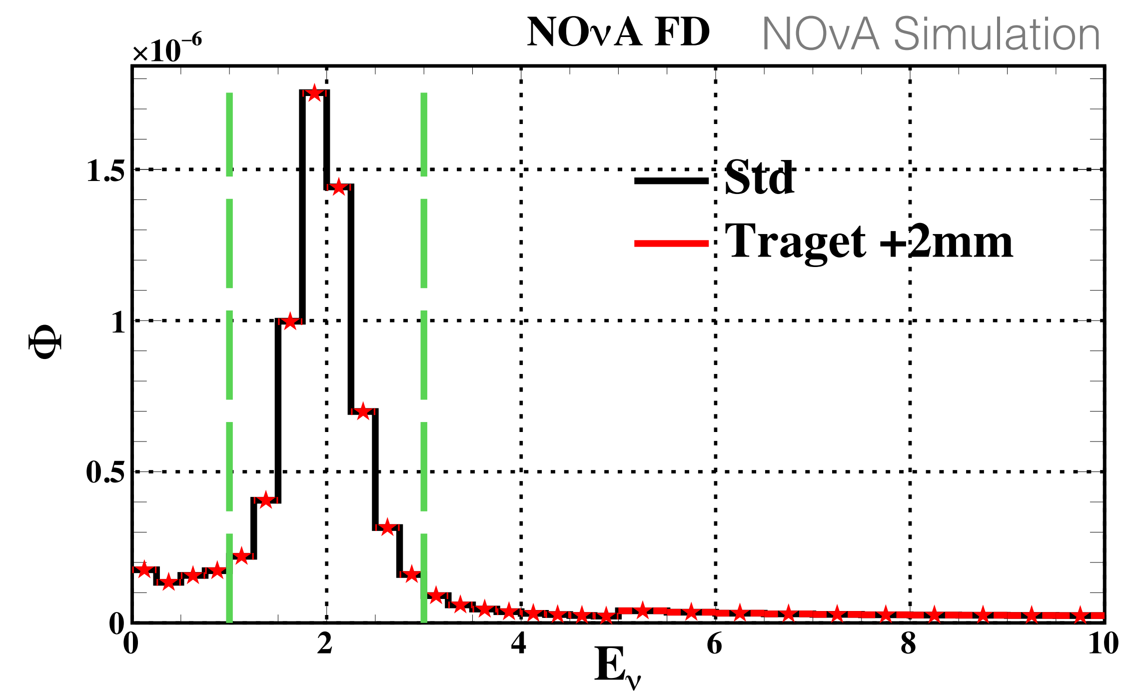

FD/ND
$\times10^{-6}$
Std
Bpos X .5mm
Bpos X -.5mm
Φ(FD/ND)
1.6
1.4
1.2
1
0.8
0.6
NOvA Simulation
0
2
4
6
8
10
E_ν

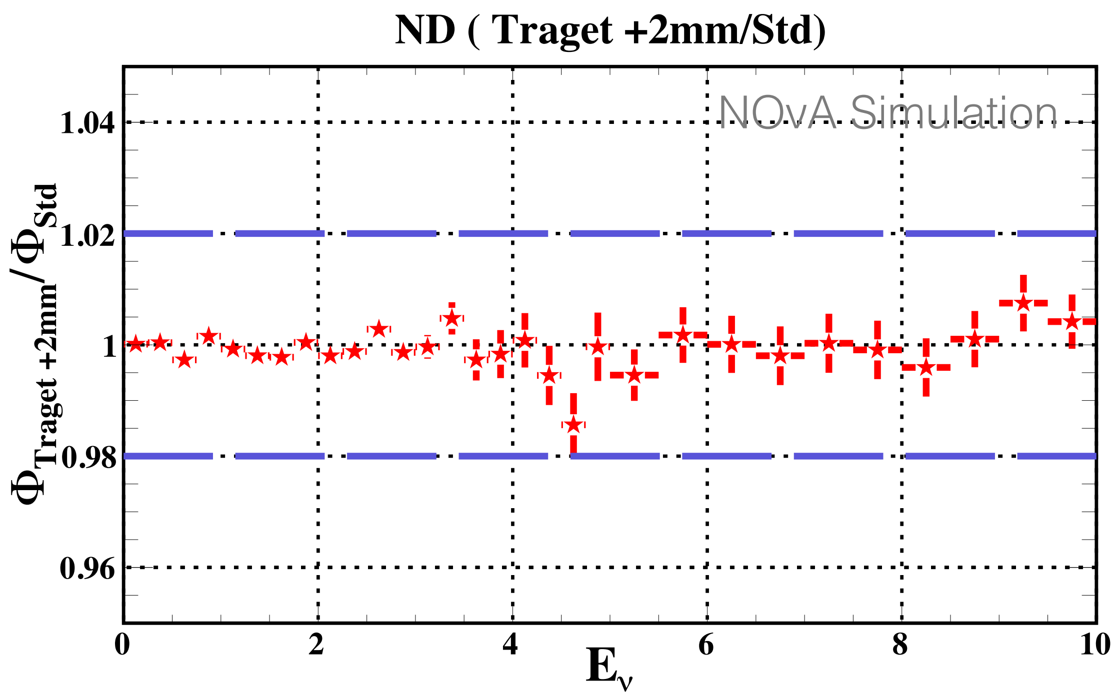

BmSpt ±.2mm NOνA ND
ND BmSpt +.2mm
ND BmSpt -.2mm
Φ_BmSpt ±.2mm/Φ_Std
NOvA Simulation
E_ν

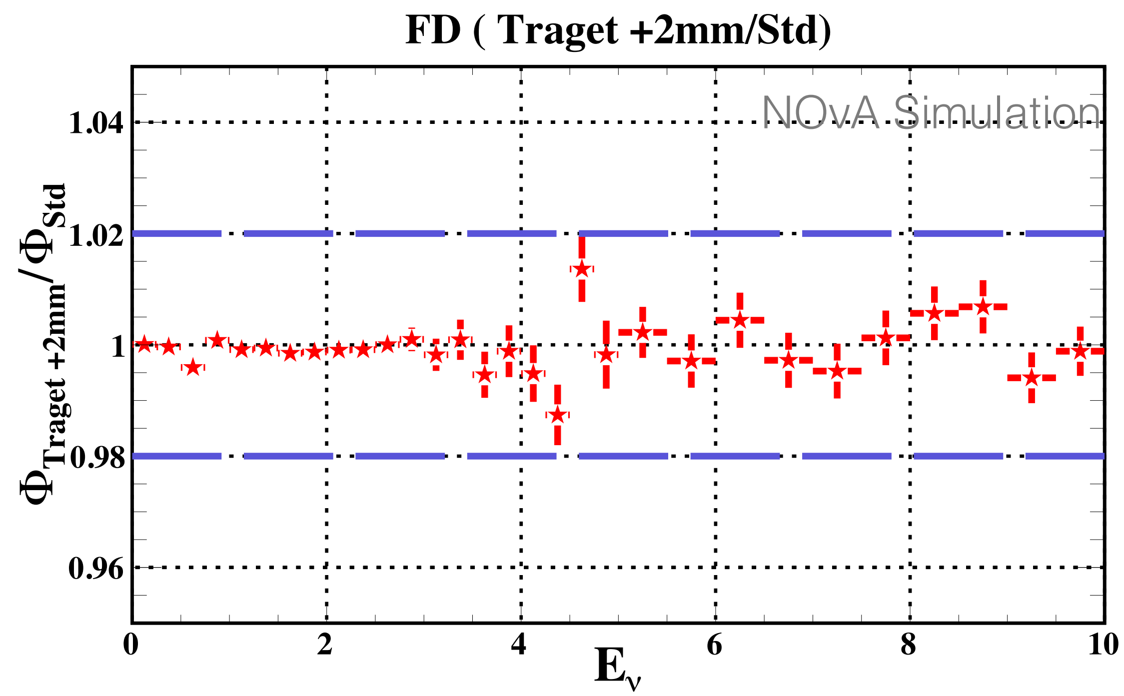

BmSpt ±.2mm NOνA FD
FD BmSpt +.2mm
FD BmSpt -.2mm
Φ_BmSpt ±.2mm/Φ_Std
NOvA Simulation
E_ν

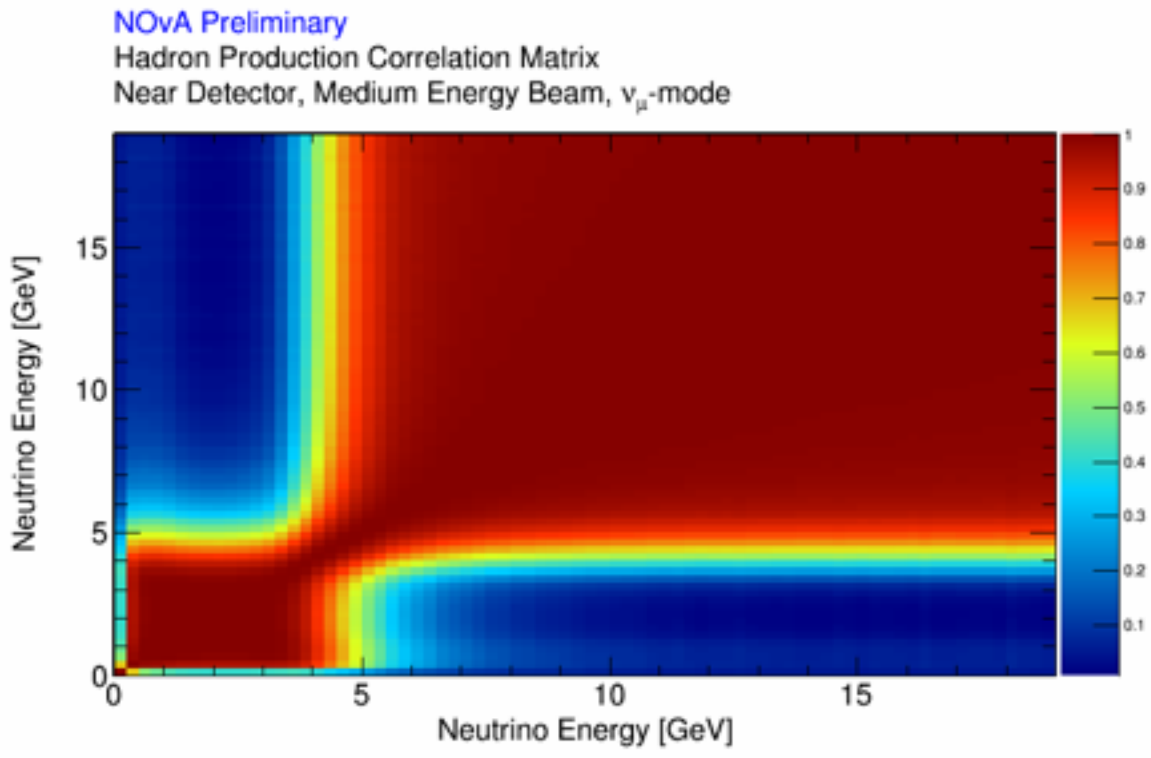

FD/ND
×10⁻⁶
Std
BmSpt +.2mm
BmSpt +.2mm
Φ(FD/ND)
NOvA Simulation
E_ν

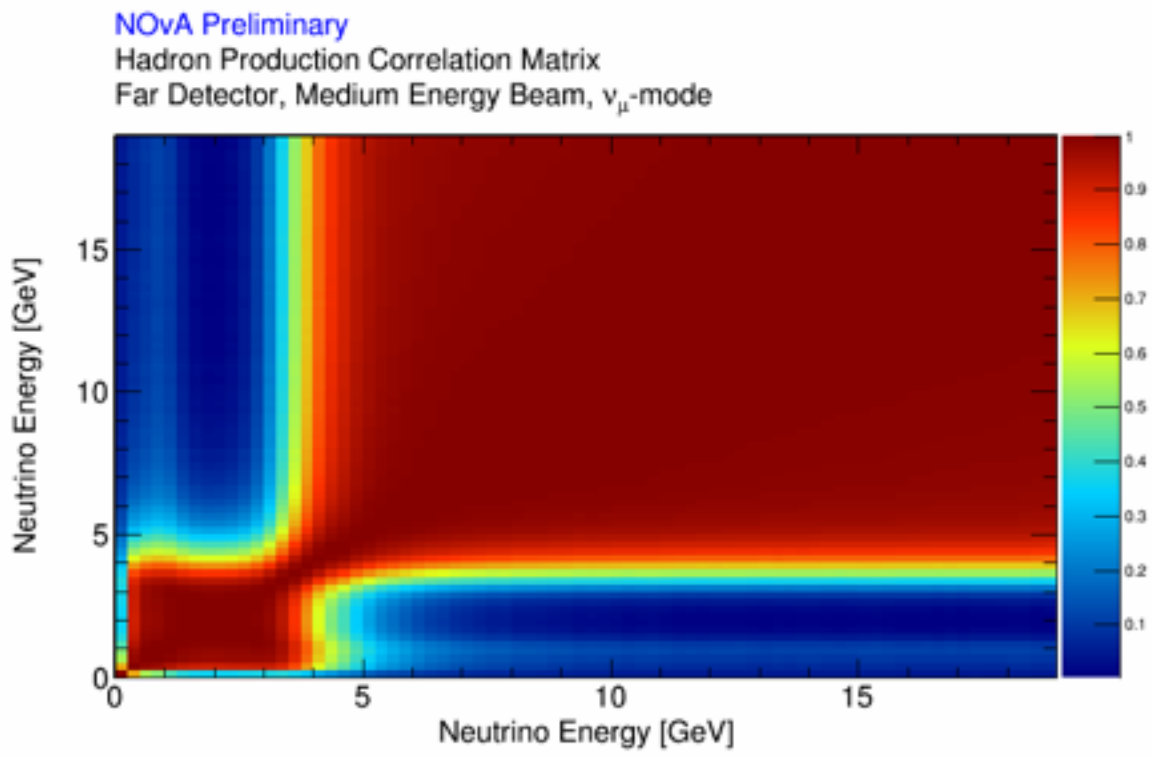

NOνA ND
NOνA Simulation
Std
Traget +2mm
Φ
E_ν
0
0.2
0.4
0.6
0.8
1
2
4
6
8
10

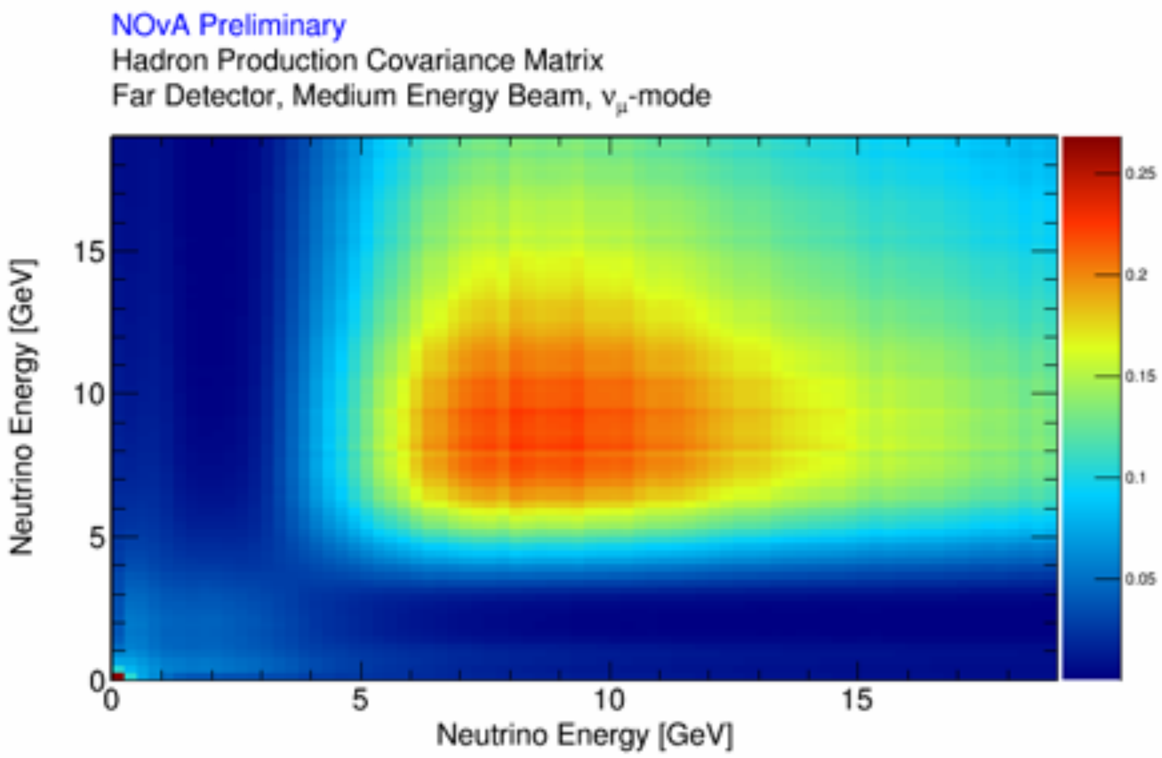

NOνA FD
NOνA Simulation
$\times 10^{-6}$
Std
Traget +2mm
Φ
E_ν
0
0.5
1
1.5
2
4
6
8
10

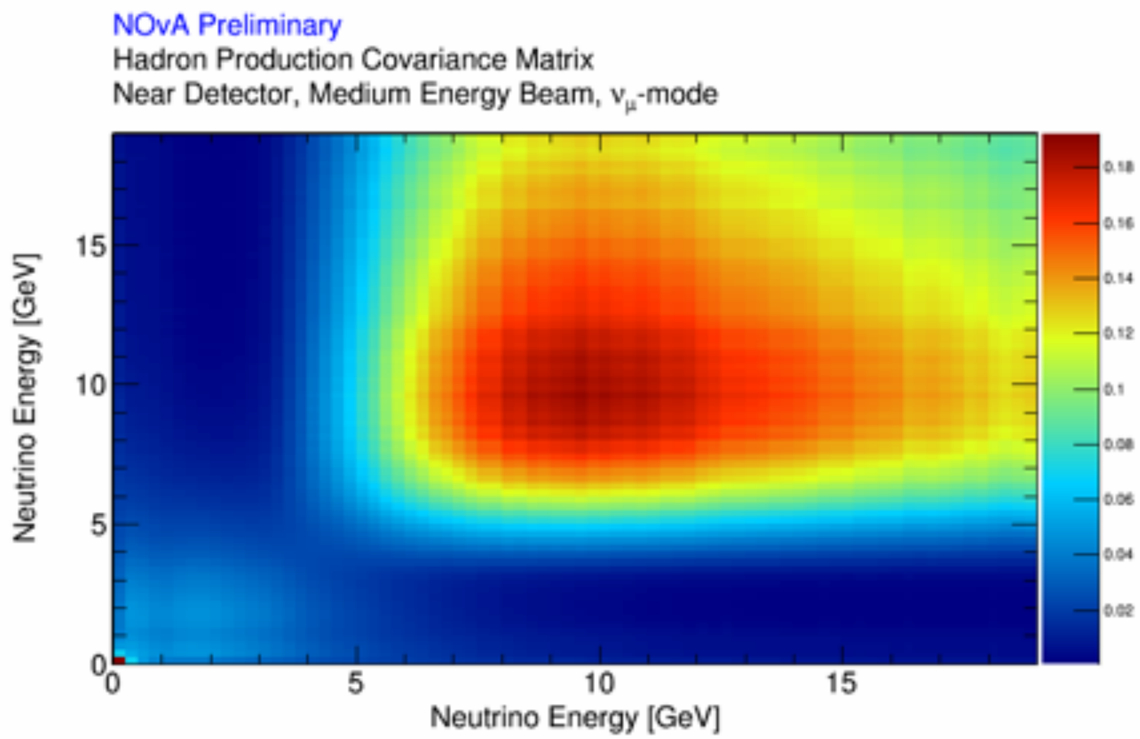

ND (Traget +2mm/Std)
NOνA Simulation
$\Phi_{Traget +2mm}/\Phi_{Std}$
E_ν
0.96
0.98
1
1.02
1.04
0
2
4
6
8
10


FD (Traget +2mm/Std)
NOνA Simulation
$\Phi_{Traget +2mm}/\Phi_{Std}$
E_ν
0.96
0.98
1
1.02
1.04
0
2
4
6
8
10


NOvA Preliminary
Hadron Production Correlation Matrix
Near Detector, Medium Energy Beam, ν_μ-mode
Neutrino Energy [GeV]
Neutrino Energy [GeV]


NOvA Preliminary
Hadron Production Correlation Matrix
Far Detector, Medium Energy Beam, ν_μ-mode
Neutrino Energy [GeV]
Neutrino Energy [GeV]


NOvA Preliminary
Hadron Production Covariance Matrix
Far Detector, Medium Energy Beam, ν_μ-mode
Neutrino Energy [GeV]
Neutrino Energy [GeV]


NOvA Preliminary
Hadron Production Covariance Matrix
Near Detector, Medium Energy Beam, ν_μ-mode
Neutrino Energy [GeV]
Neutrino Energy [GeV]

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	$\prod^+$	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%

K^+ Constraint from NDOS & ND CC Data

From NDOS:

Central Value ⇒ $\varphi_{Data} / \varphi_{MC} = 0.70$

Since the error is 26.4%, suggest ⇒ split the difference

Errors:

✳ Statistical Error => 15.5%

✳ Systematic Errors => 21.21%

(1) Energy

(2) Reconstruction ⇒ 15%

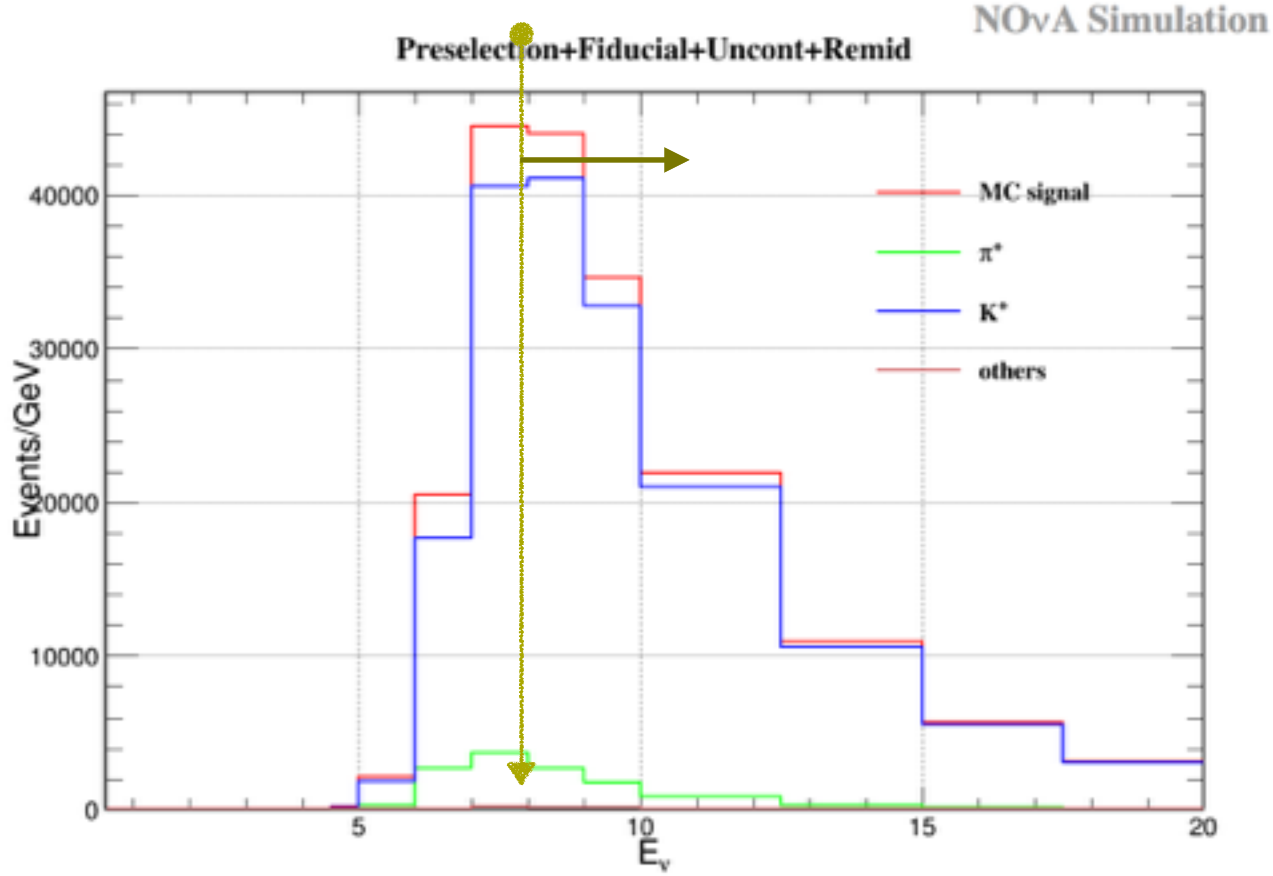
(3) Cross-section ⇒ 10% (Reasonable for K^+/Π^+)

(4) New.vs.OldMC⇒ 3%

✳ Total Error ⇒ 26.27%

Multiply Fluka-K^+ by 0.85

Error on K^+/Π^+ is 26.27%



NOvA ND: calE>6GeV