Effects on the Flux due to Variations of the Decay Pipe Geometry

Pierce Weatherly

April 15, 2021

Last update

- Looked at smaller variations at effect decay pipe radius variations (dR) has on flux

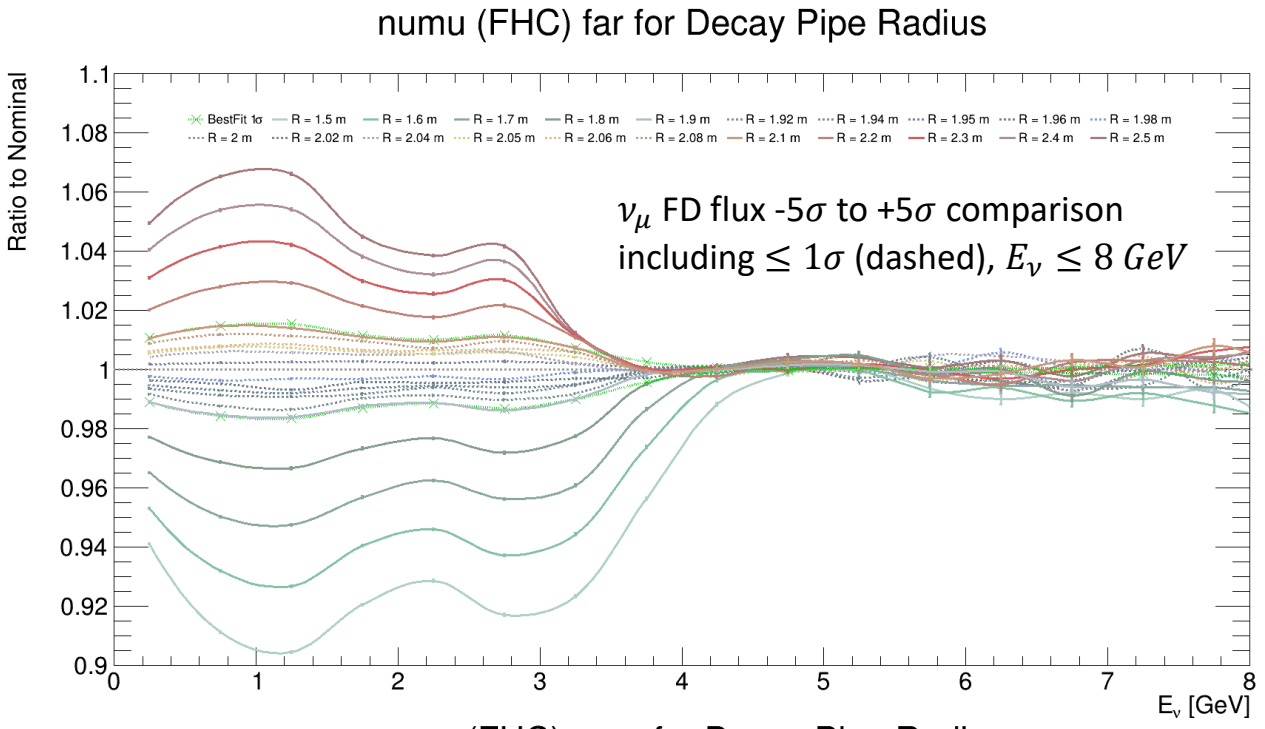
- Homework: Look at effects other variations in the decay pipe geometry can have on flux using 2.5 cm as 1-sigma value for variation.
  - Transverse offset of the decay pipe in x, y
  - Tilting the upstream end of the decay pipe while keeping the downstream end on-axis.
  - Decay pipe with elliptical cross-section
  - “Bowed” decay pipe
    - Pipe split into 3 segments
  - For comparison, uncertainty for dR = 2.5 cm will be graphed in plots

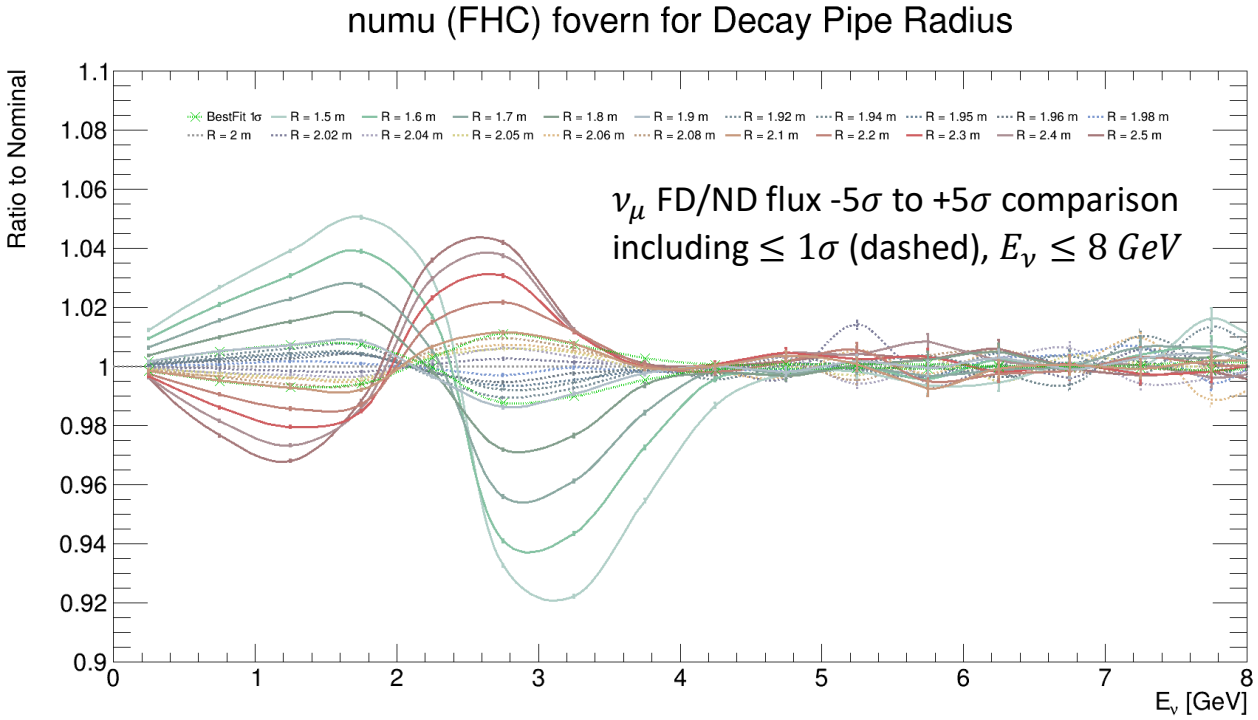
Reminder from previous update

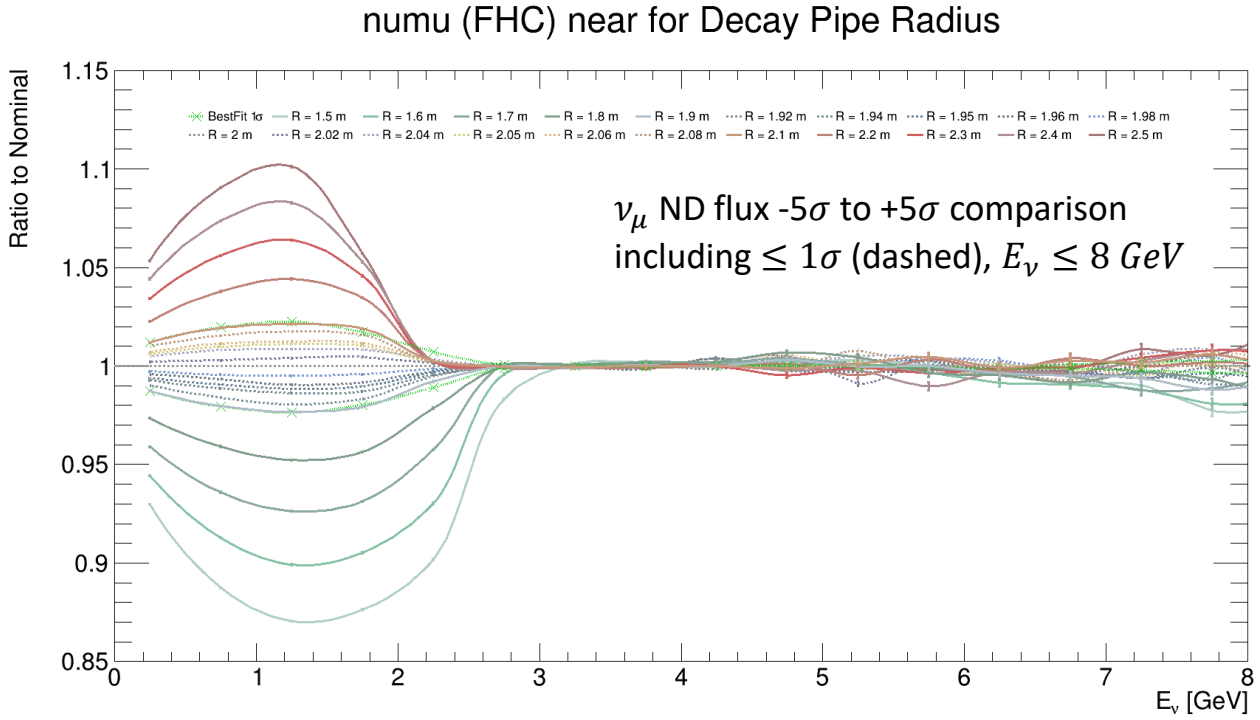
- Smaller step dR study

Flux Ratios to Nominal Simulation: -5σ to 5σ, $d\sigma$ = 1σ & $\pm$0.2, $\pm$0.4, $\pm$0.5, $\pm$0.6, $\pm$0.8σ

- Fits are performed in each energy bin on the data from these plots (including errors)

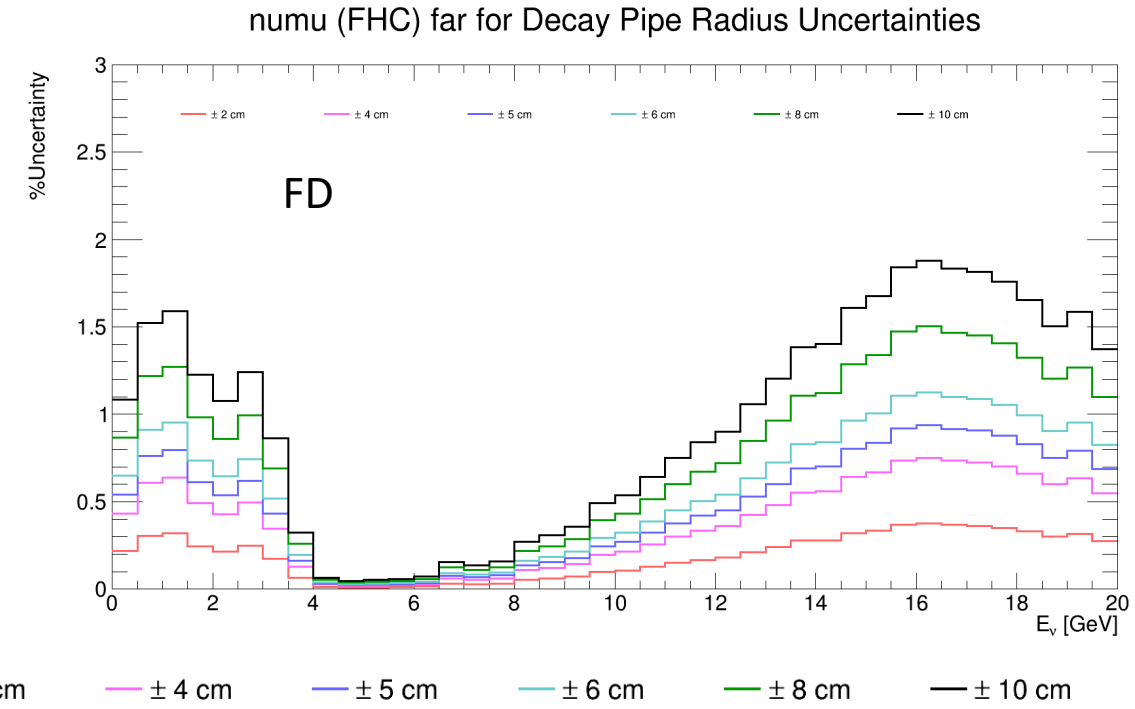


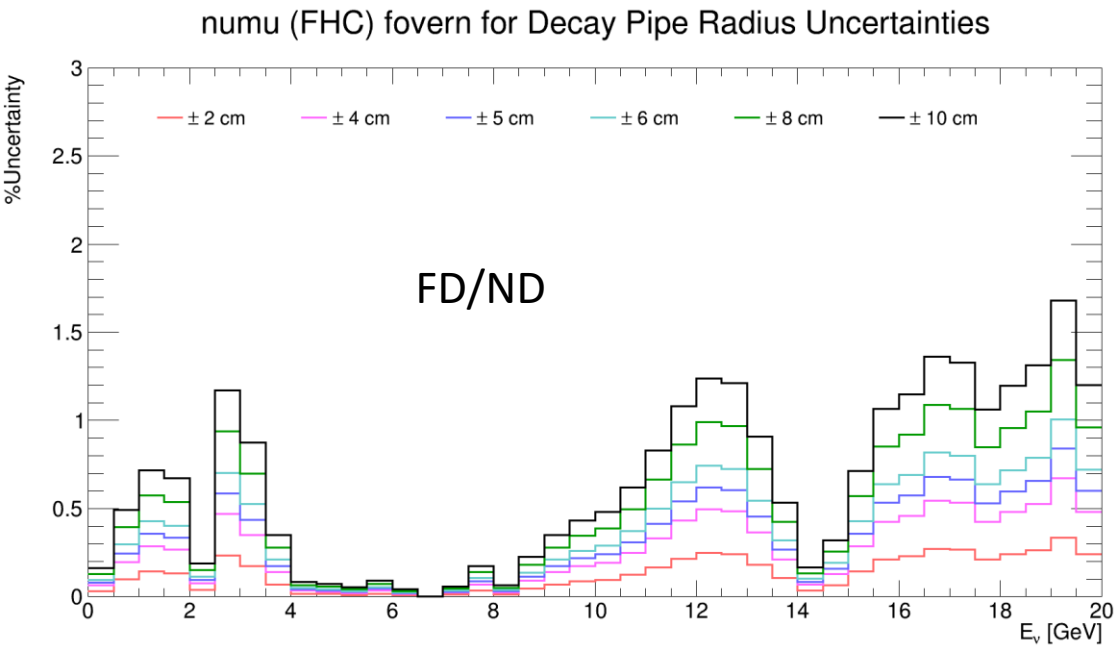


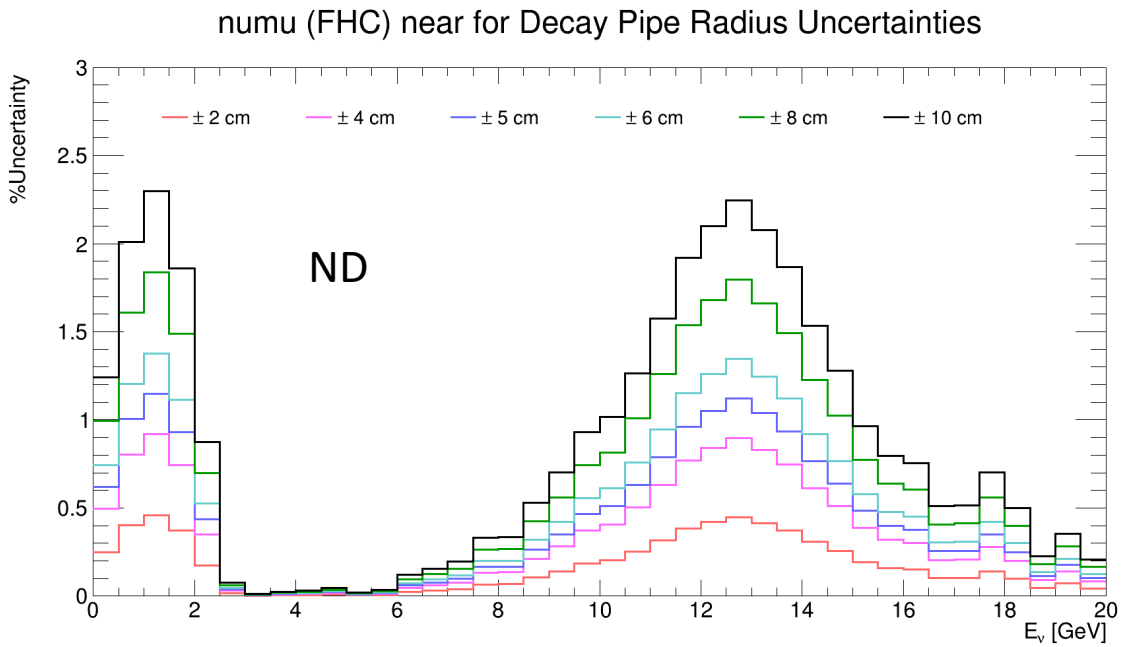


Extracted Uncert & Sim Details

- This page: %Uncertainties for FD, ND, FD/ND
- Large plots on following pages
- $\pm 1\sigma$ has > 1e9 PoT
- -5σ to 5σ samples ~ 0.5e9 PoT,
- Sub-1σ samples
  - $\pm 0.2, \pm 0.4, \pm 0.6, \pm 0.8\ \sigma$ samples generated with 0.25e9 PoT each
  - $\pm 0.5\sigma$ have 0.5e9 PoT

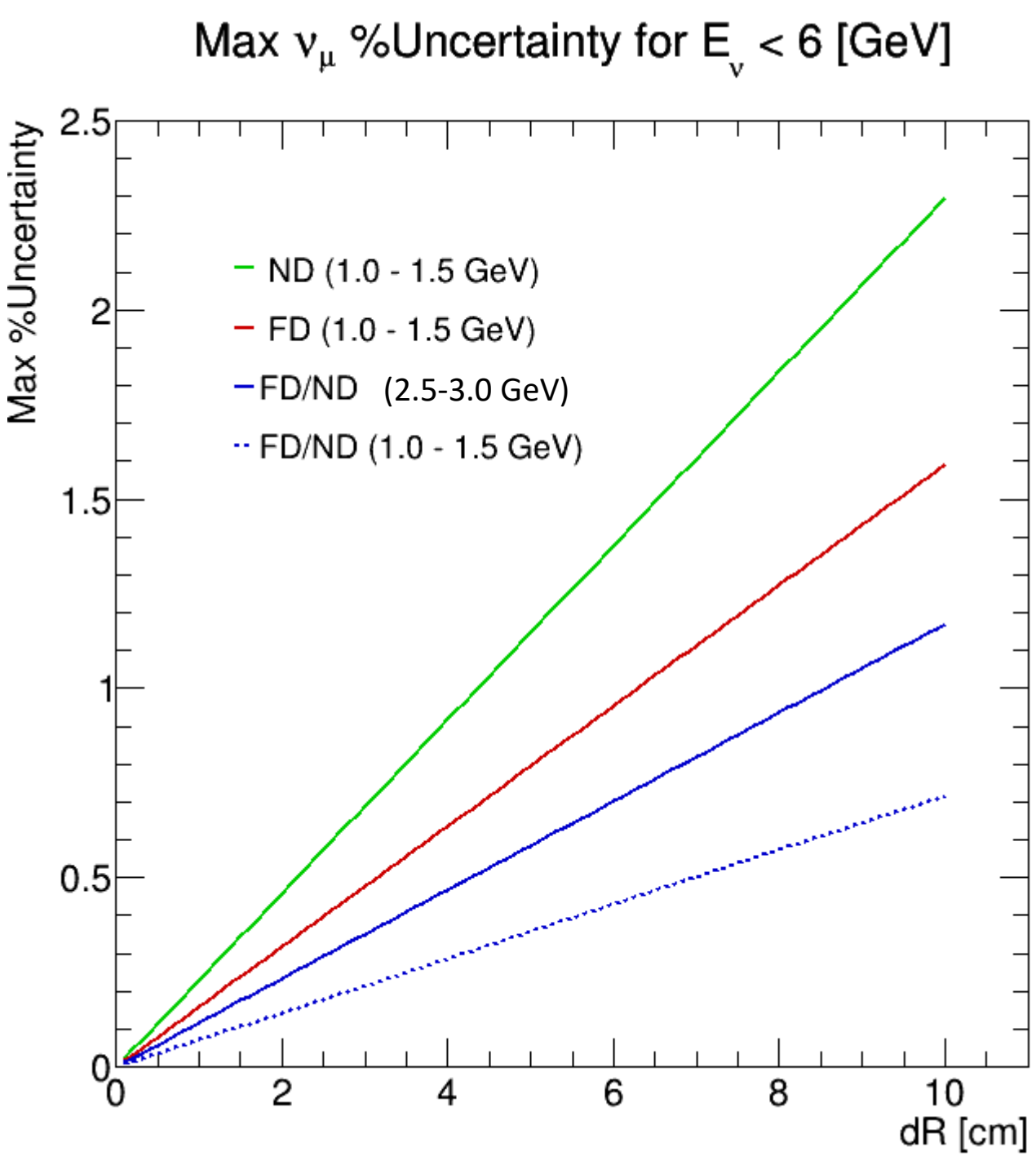






Max %Uncertainty(dR) in Flux ROI

- R_0= 2.0 m, 1σ = 10 cm
- -5σ – +5σ & Sub-1σ samples:
  - $\pm$0.2, $\pm$0.4, $\pm$0.5, $\pm$0.6, $\pm$0.8 σ (2-8 cm)
- Fit in σ for each energy bin with all simulations
  - Include Sub-1σ simulation samples
    - 1σ sample has very high stats (>1e9), so no significant change to best fit after including
- Result (right)
  - extract values from fit (1 mm steps)
  - All 4 are very shallow P_2's
  - 2.5 cm: 0.18/0.29/0.40/0.58



This Update

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  - Transverse offset of the decay pipe in x, y
  - Tilting the upstream end of the decay pipe while keeping the downstream end on-axis.
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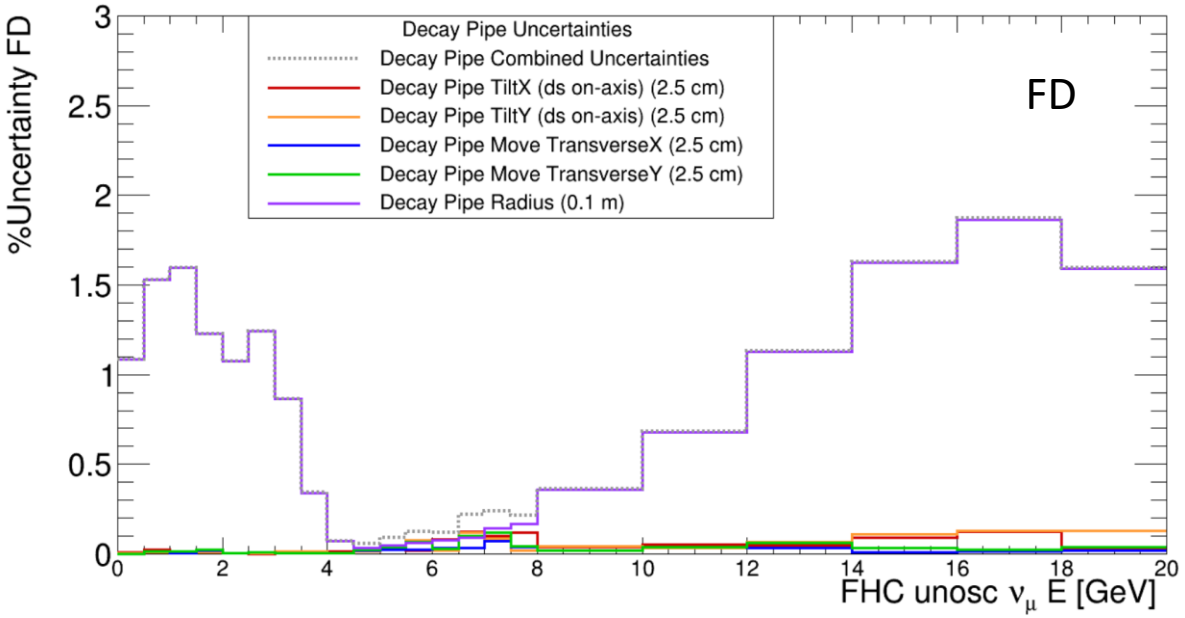
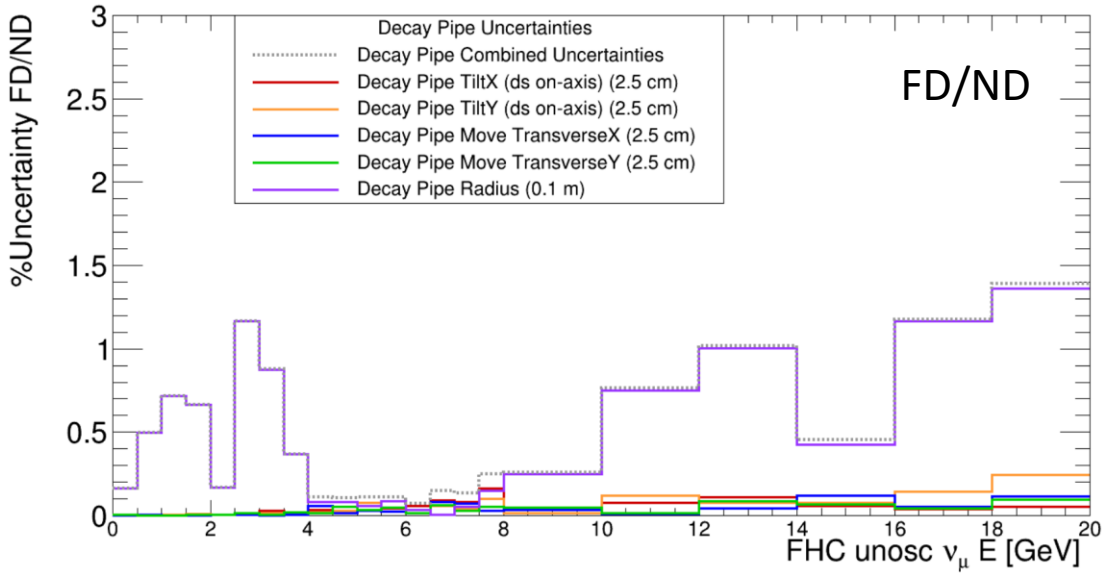
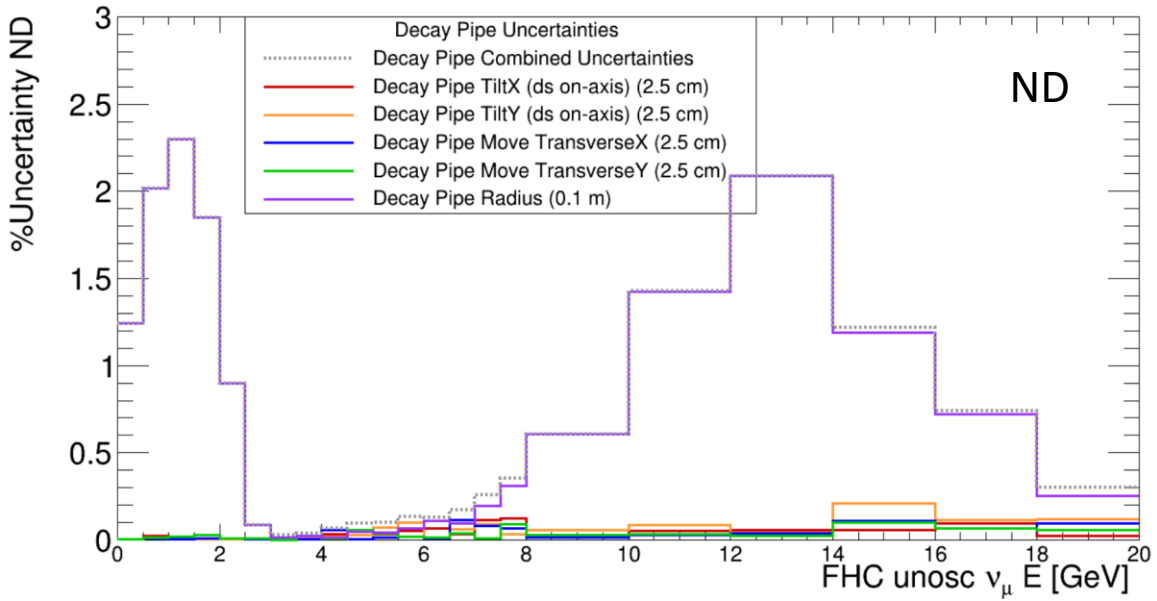
Tilt (DSoA), Transverse Offset (movement) of Pipe

- Very minimal contribution below 4 GeV, small contribution in general for all 4 of these uncertainty sources.







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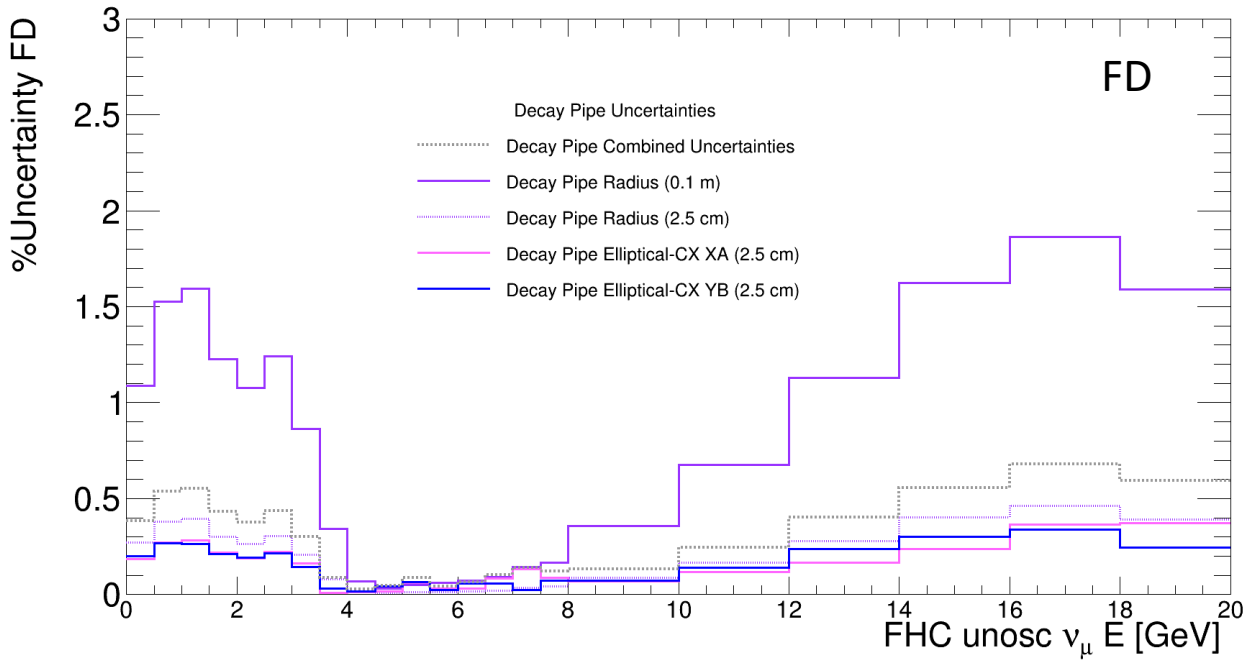
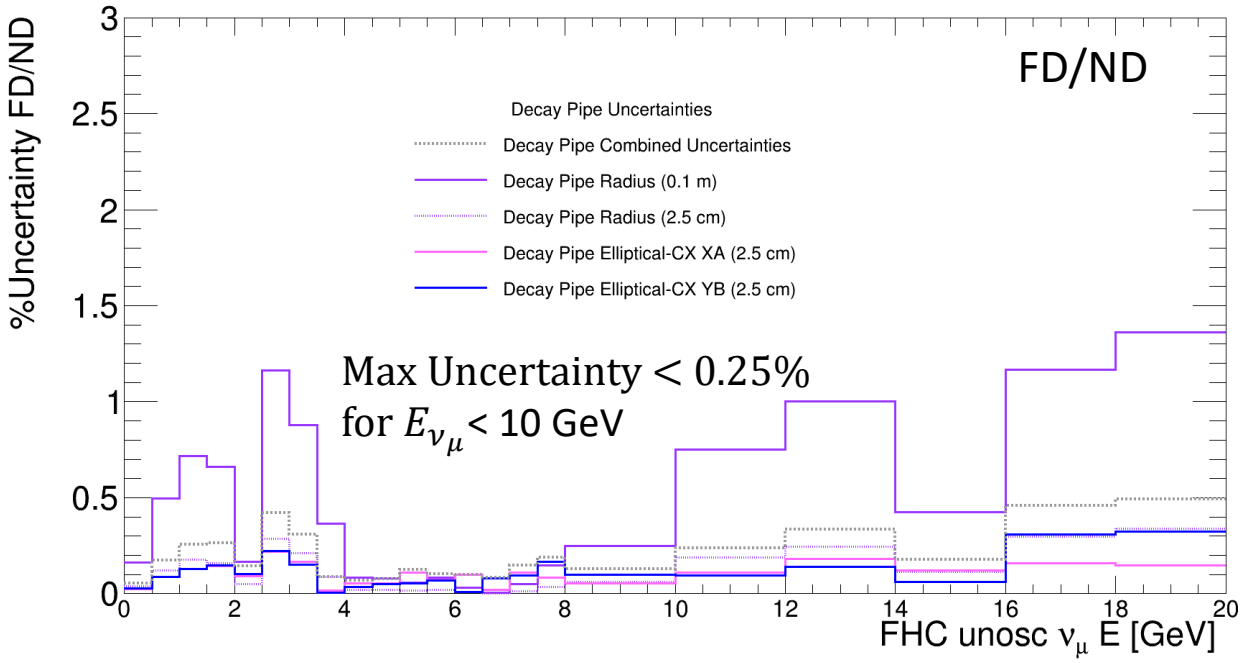
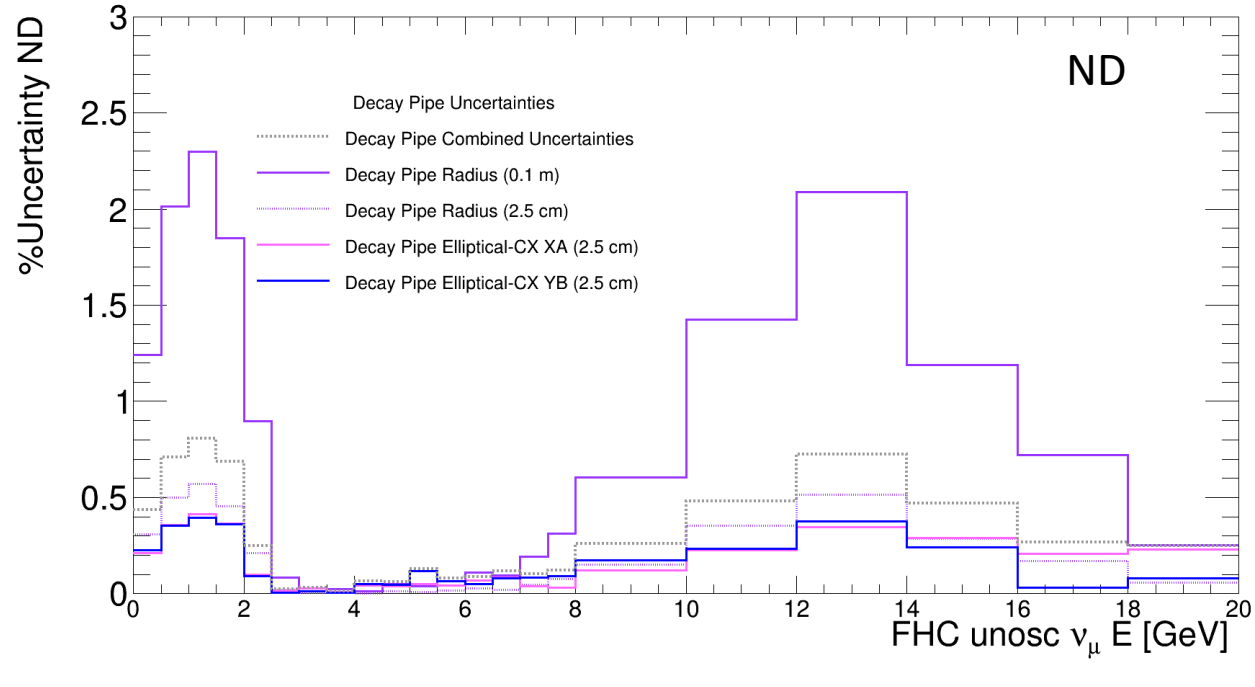
Elliptical Deformation in the Decay Pipe CX

- G4 commands enabled for macros & x,y independently set
- Below 4 GeV, uncertainties caused by deformation in x & y are similar
  - Follow trend of dR
- Between 4 and 8 GeV, uncertainties are small, but behavior does not follow each other as well.







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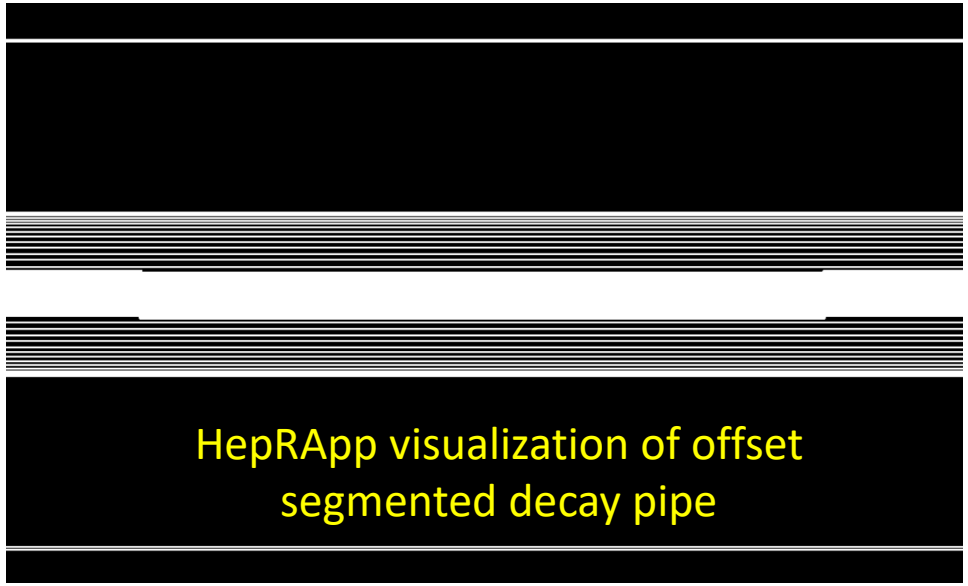
Bowed Decay Pipe

- Suggestion was to offset all segments of the pipe 2.5 cm from the beamline axis
  - Shift the upstream and downstream segments opposite the middle segment: $\mp 2.5, \pm 2.5, \mp 2.5$ cm
  - Did this for x & y independently
    - Results: averaged $\pm 1\sigma$ simulations (5e8 PoT)

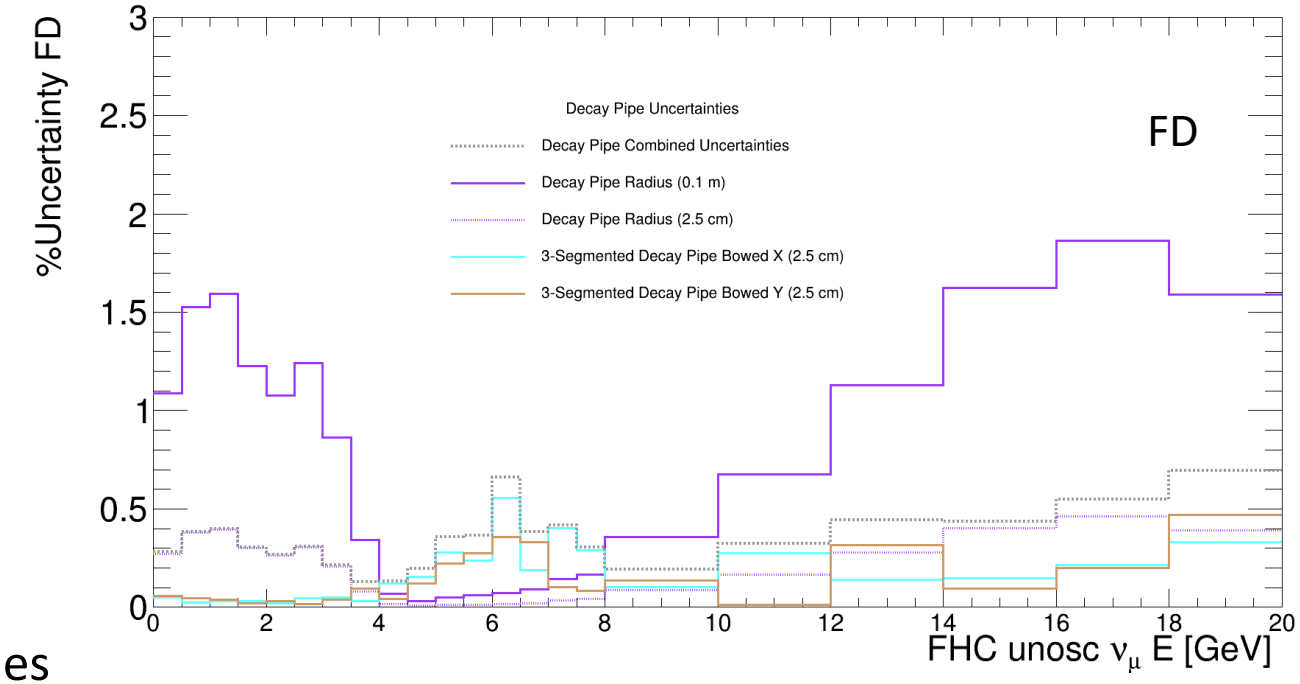


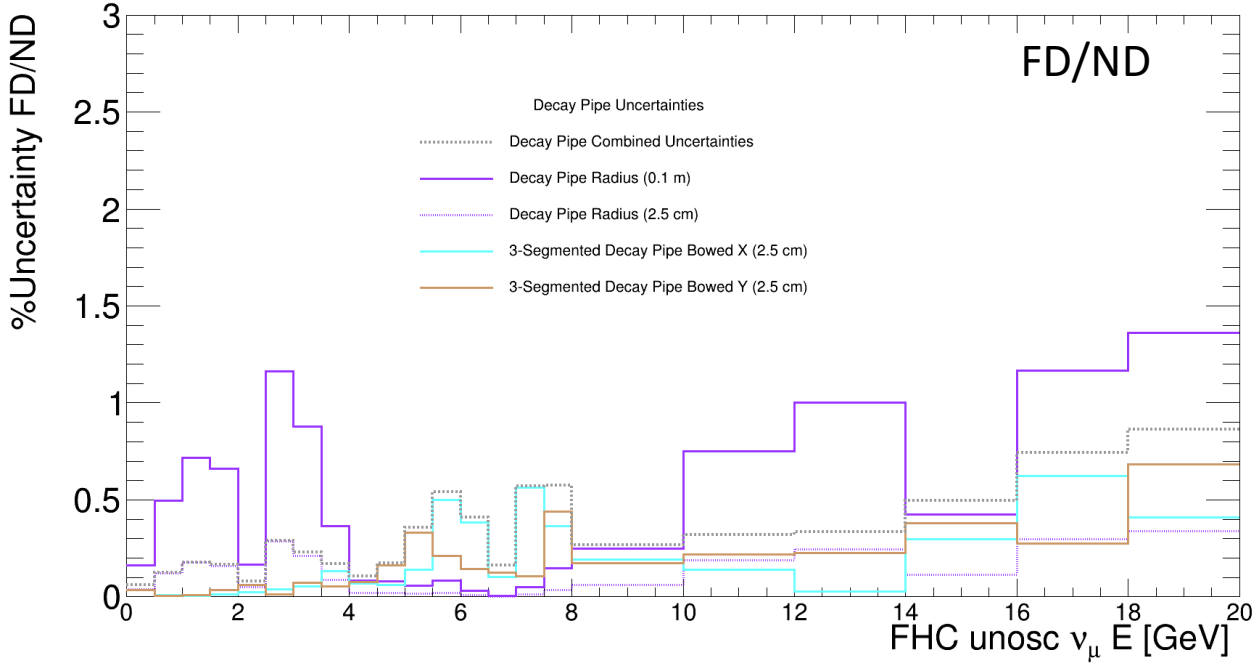
HepRApp visualization of offset segmented decay pipe

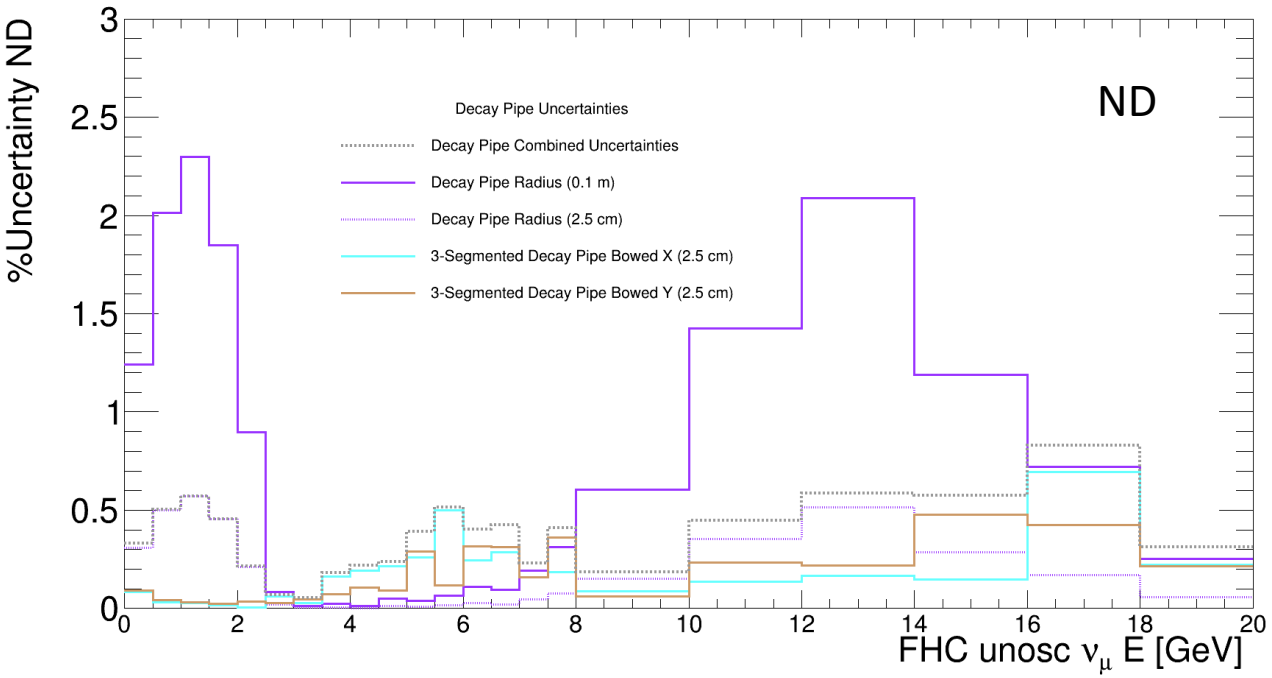
- G4 Implementation:
  - The concrete enclosure of the decay pipe is hollowed out and the pipe is constructed via G4 unions of the segmented pieces from outside to inside components.
  - The user can specify via G4 commands in the macro how far off-axis each piece can be translated (in x&y), but the internal pieces cannot be shifted outside of the concrete enclosure.
  - The external geometry of the concrete is left undisturbed.
  - The whole pipe should still be surveyable (translateable/tilted).
  - Elliptical geometry options are not enabled for segmented decay pipe.
    - Elliptical cross-section pipe is constructed in a similar (but simpler) manner

Bowed Decay Pipe Uncertainties

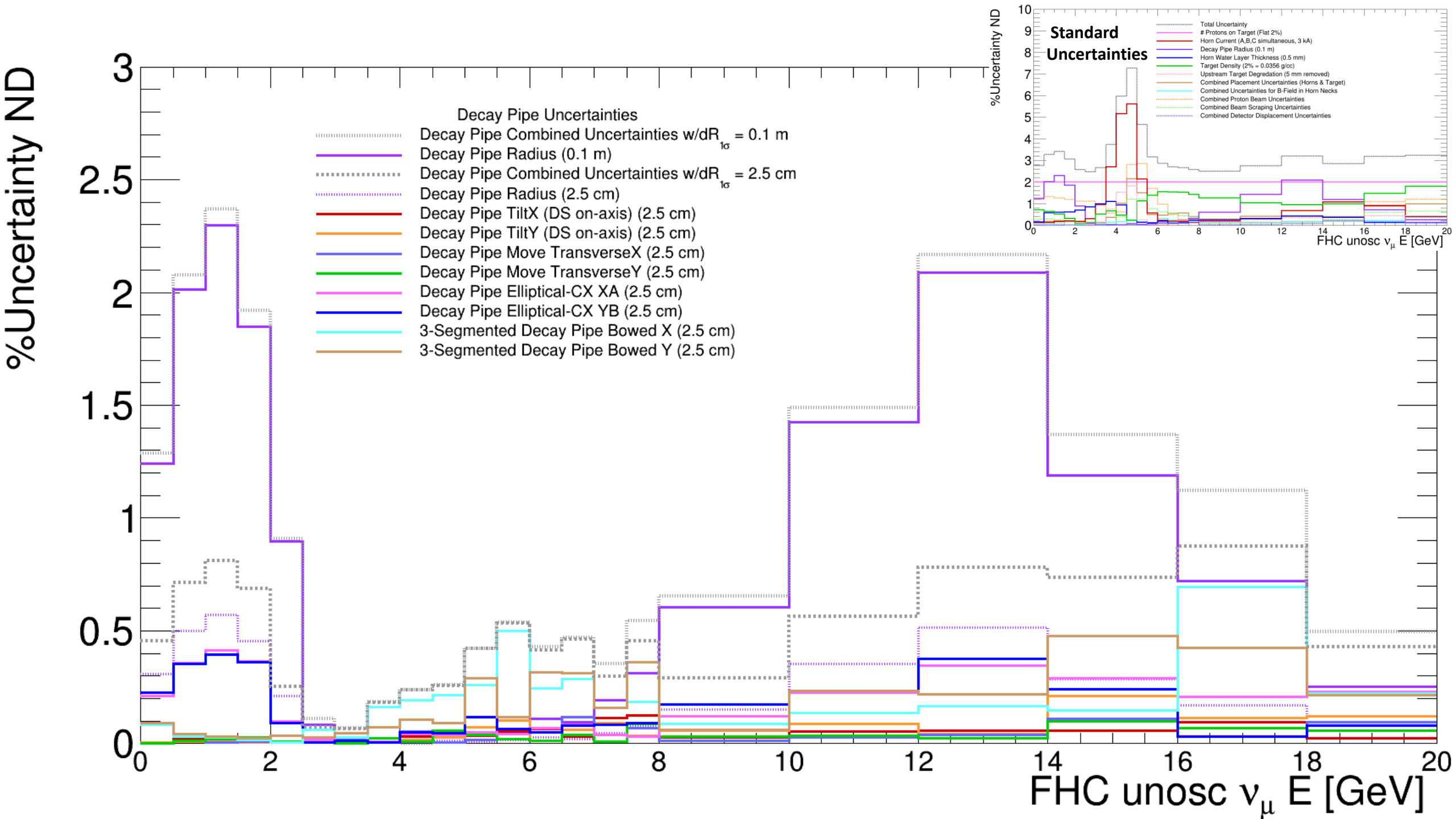
- Small/minimal effect below 4 GeV
- Bow in x vs y has different behavior above 4 GeV
  - Horn Current and Proton Beam uncertainties dominant in this region for FD/ND ratio

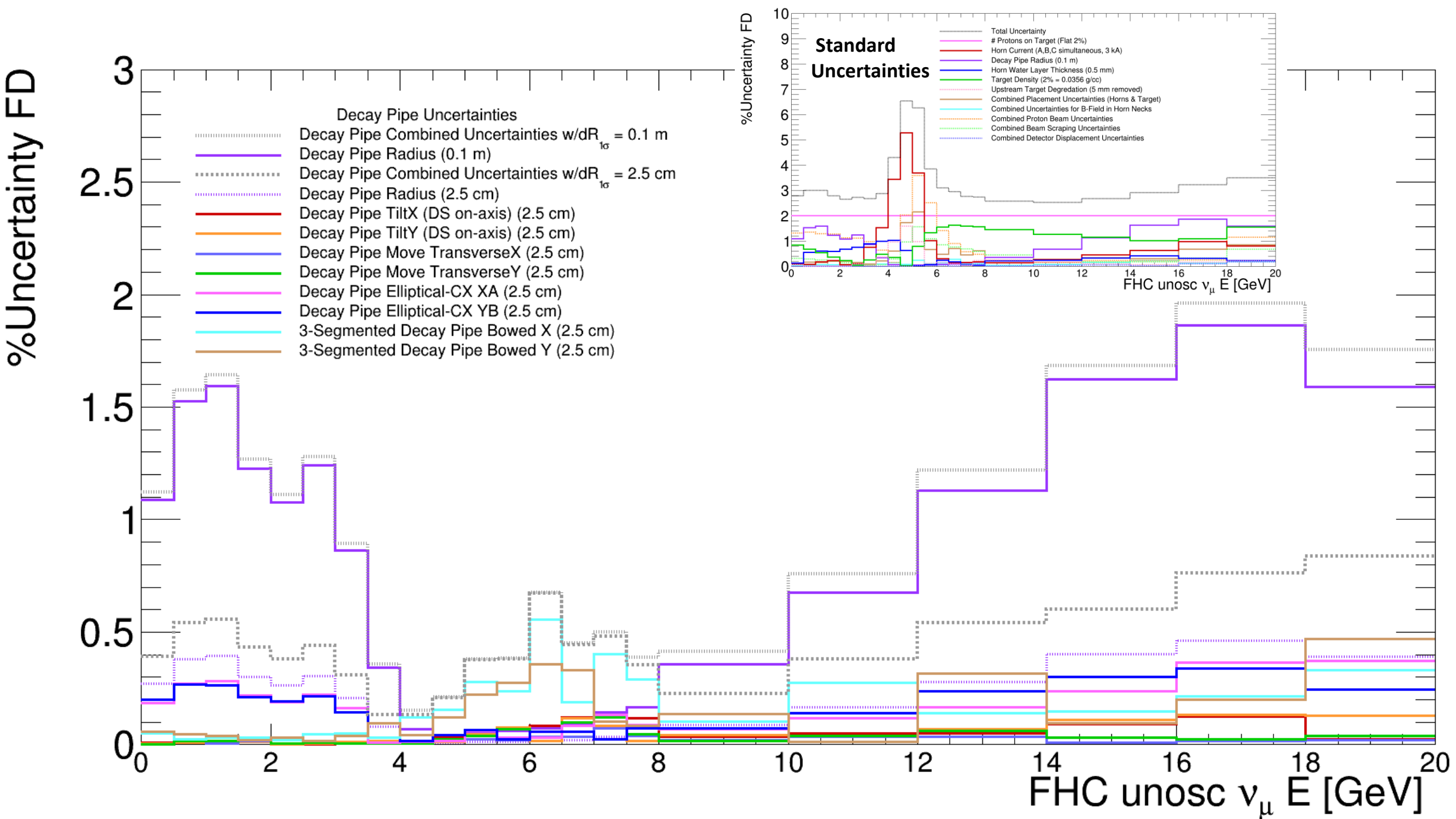






All “new” Decay Pipe Systematics


%Uncertainty ND
FHC unosc ν_μ E [GeV]
Decay Pipe Uncertainties
Decay Pipe Combined Uncertainties w/dR$_{1\sigma}$ = 0.1 m
Decay Pipe Radius (0.1 m)
Decay Pipe Combined Uncertainties w/dR$_{1\sigma}$ = 2.5 cm
Decay Pipe Radius (2.5 cm)
Decay Pipe TiltX (DS on-axis) (2.5 cm)
Decay Pipe TiltY (DS on-axis) (2.5 cm)
Decay Pipe Move TransverseX (2.5 cm)
Decay Pipe Move TransverseY (2.5 cm)
Decay Pipe Elliptical-CX XA (2.5 cm)
Decay Pipe Elliptical-CX YB (2.5 cm)
3-Segmented Decay Pipe Bowed X (2.5 cm)
3-Segmented Decay Pipe Bowed Y (2.5 cm)
Standard Uncertainties
%Uncertainty ND
FHC unosc ν_μ E [GeV]
Total Uncertainty
Protons on Target (Flat 2%)
Horn Current (A,B,C simultaneous, 3 kA)
Decay Pipe Radius (0.1 m)
Horn Water Layer Thickness (0.5 mm)
Target Density (2% = 0.0356 g/cc)
Upstream Target Degredation (5 mm removed)
Combined Placement Uncertainties (Horns & Target)
Combined Uncertainties for B-Field in Horn Necks
Combined Proton Beam Uncertainties
Combined Beam Scraping Uncertainties
Combined Detector Displacement Uncertainties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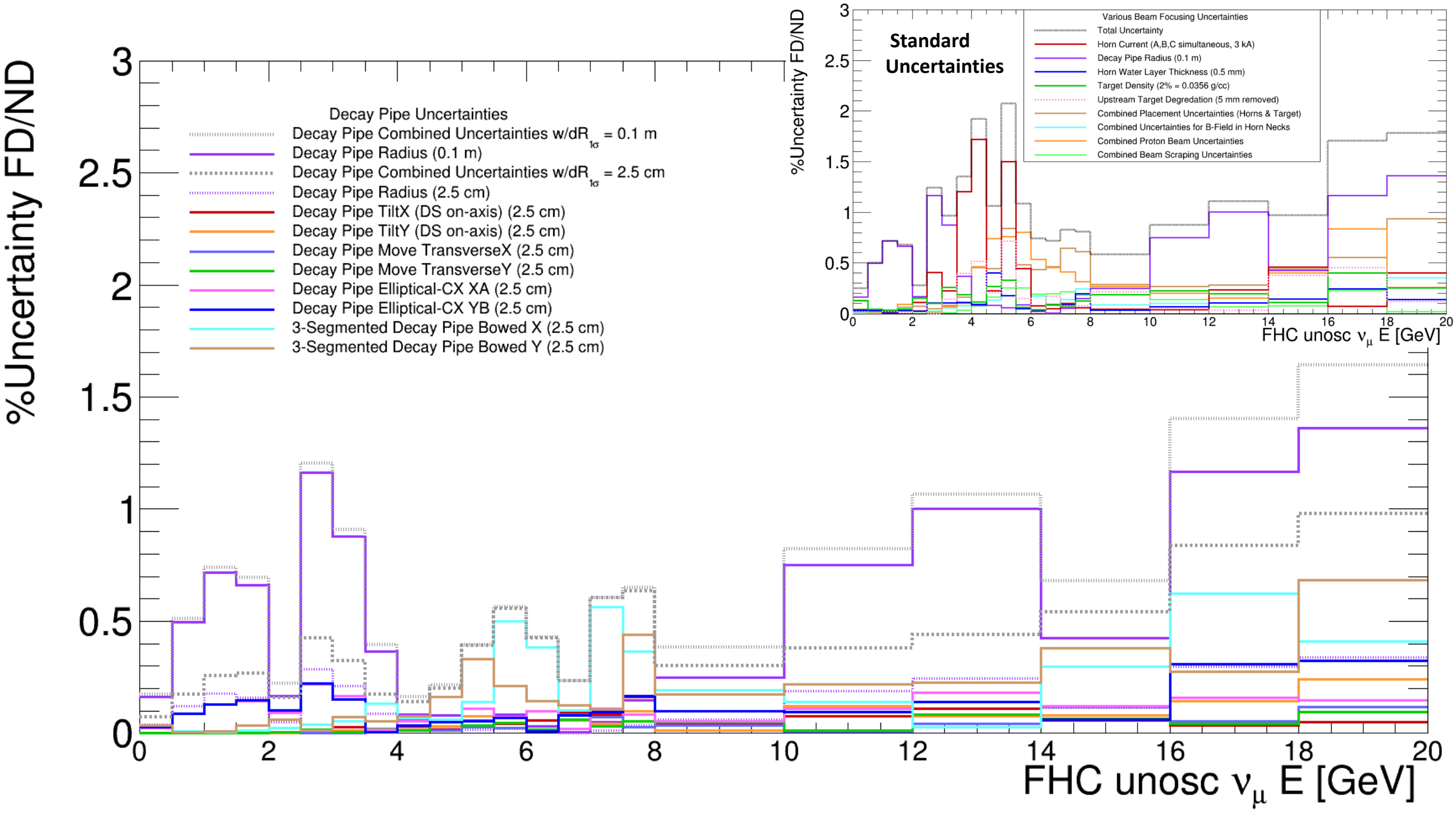
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Standard Uncertainties
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Total Uncertainty
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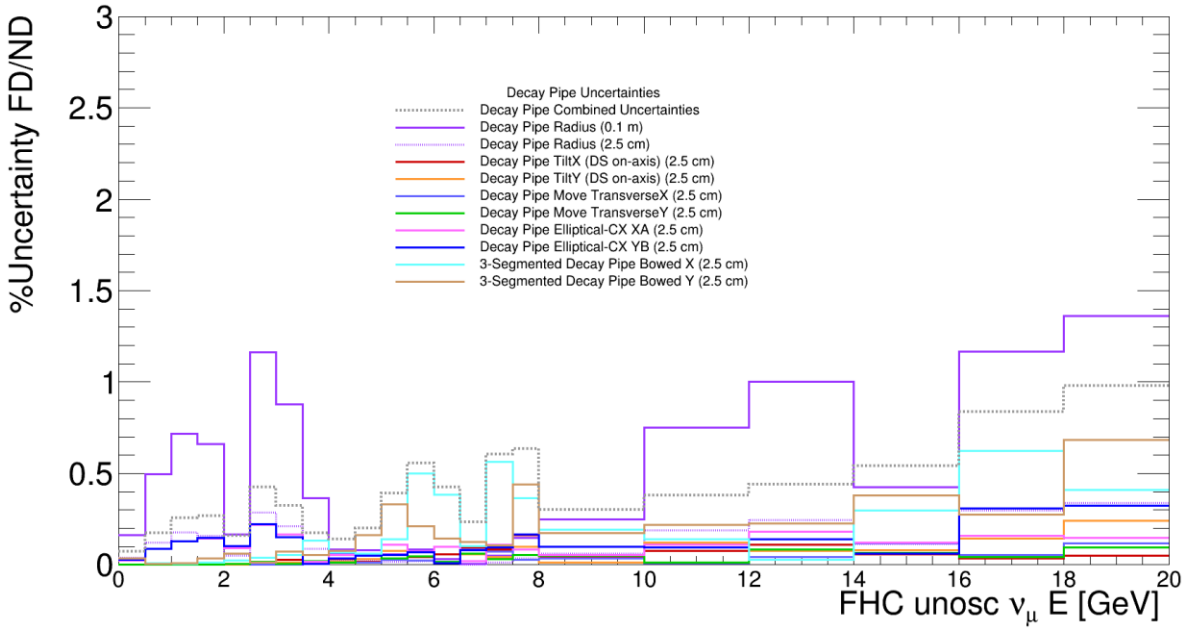
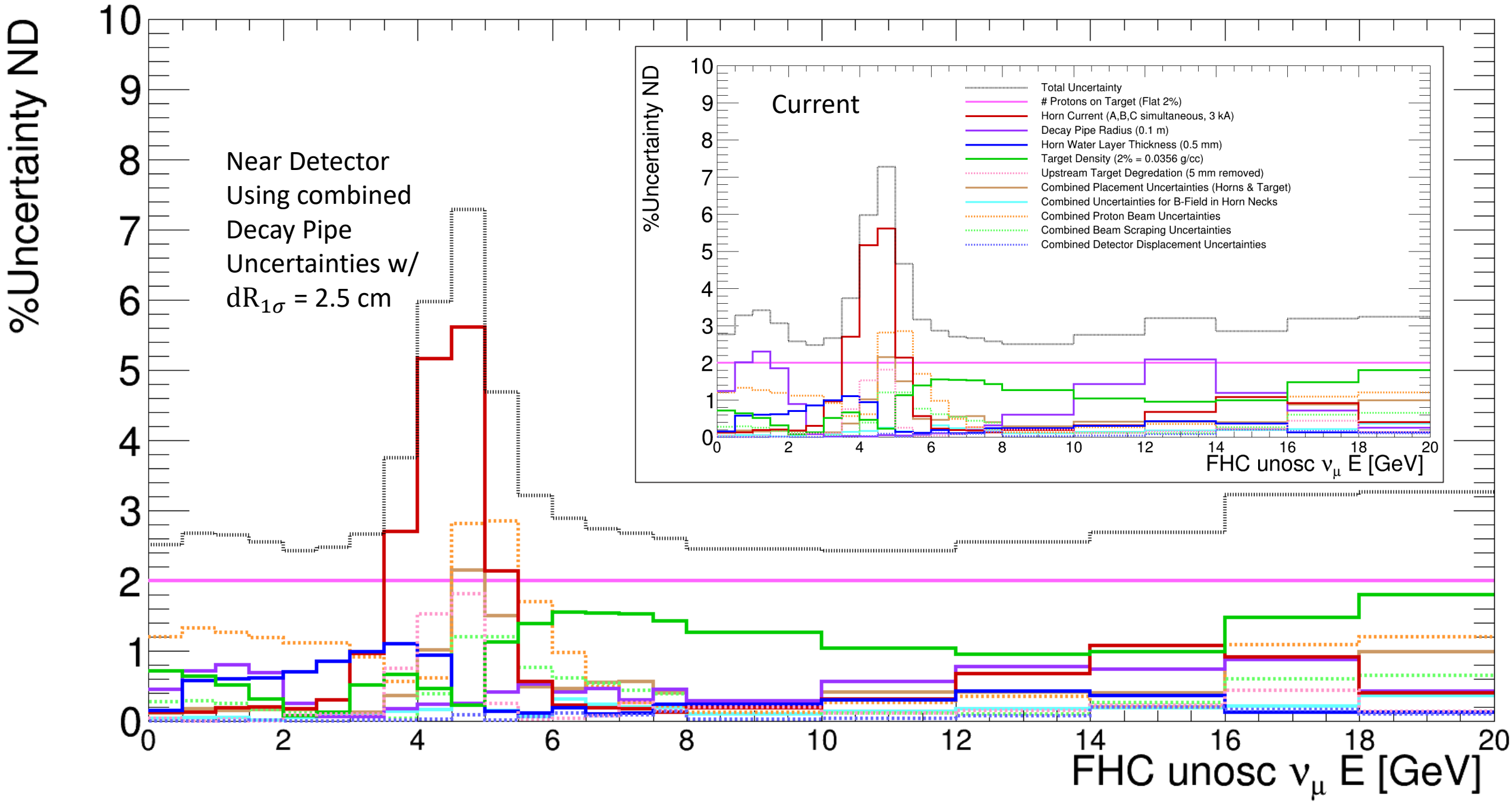
Discussion



- Consistent (longitudinal) deviations from standard decay pipe cross-section are most impactful to FD/ND flux ratio
  - Below 3.5 GeV, Elliptical CX is most impactful “new” uncertainty
- Is 1σ = 2.5 cm reasonable for these tolerances?
  - Is 1σ = 10 cm for dR reasonable or is 2.5 cm more reasonable?
- Which (if any) of these new uncertainties do we wish to include?
  - Should we consider the dR to be uncorrelated with the elliptical deformations?
- Different version(s) of the segmented pipe geometry desired?
  - How many actual segments will the pipe be constructed from?
- Any other uncertainties that should be simulated?


%Uncertainty ND
Near Detector
Using combined
Decay Pipe
Uncertainties w/
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FHC unosc ν_μ E [GeV]
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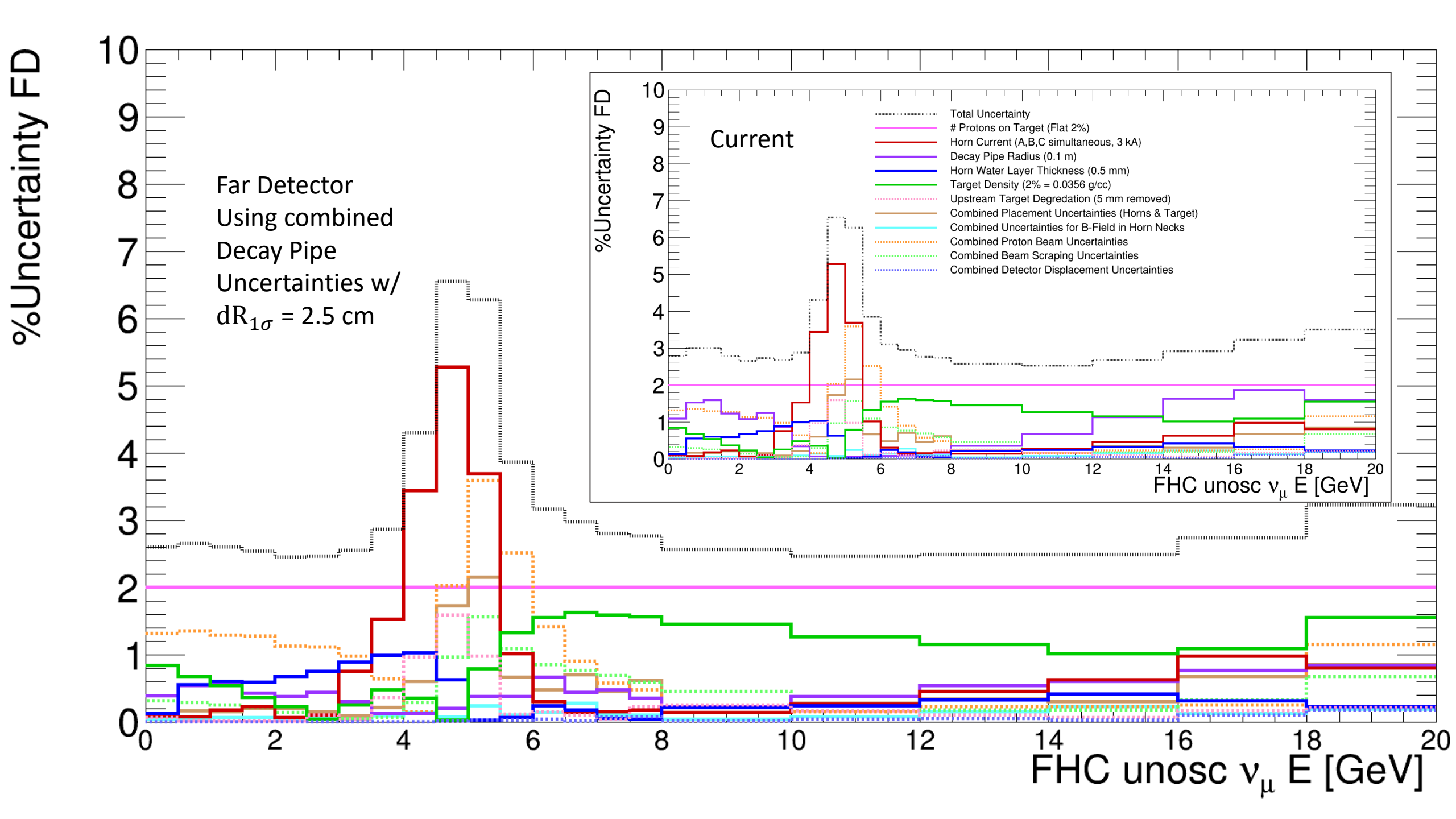
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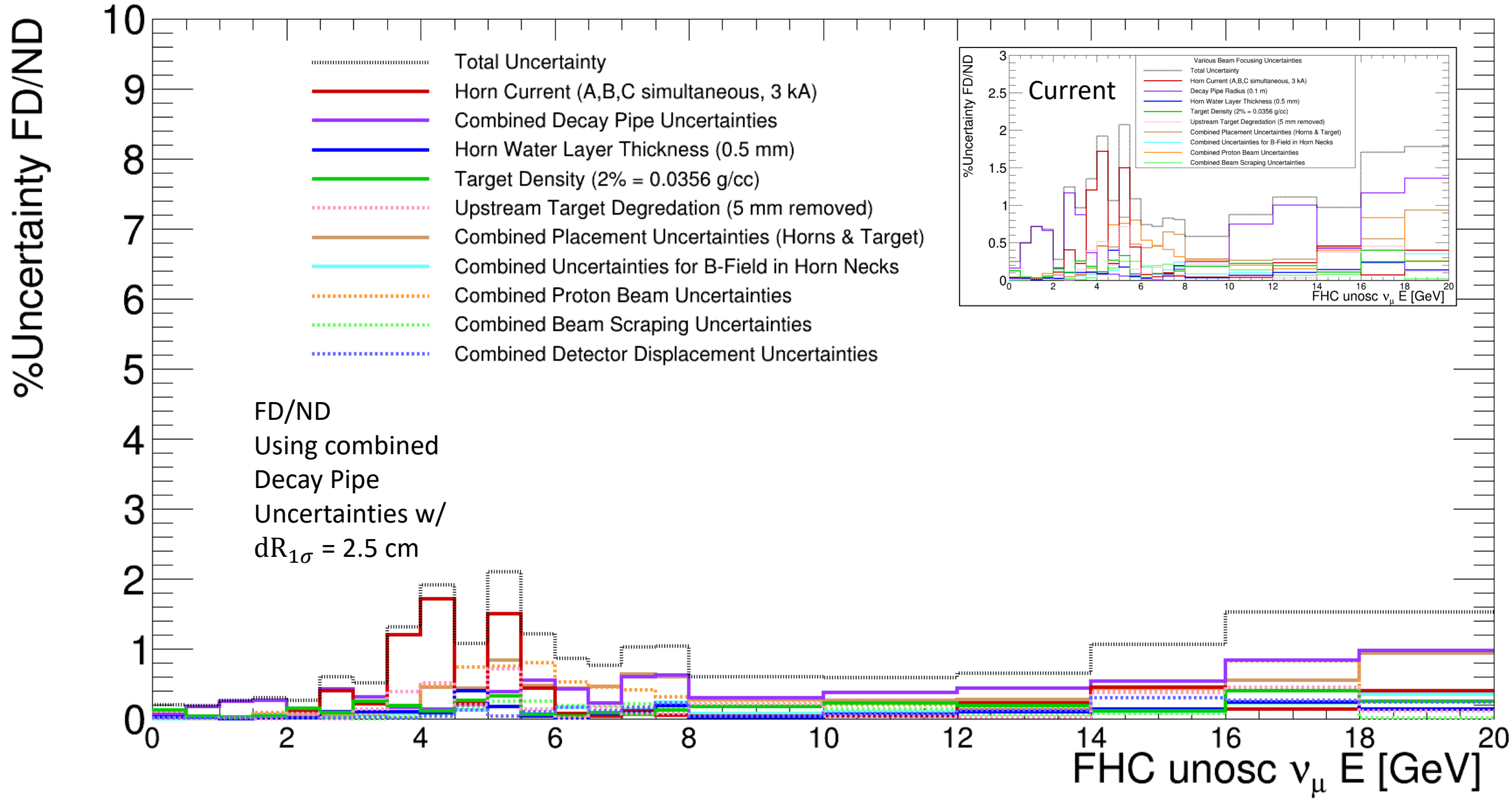
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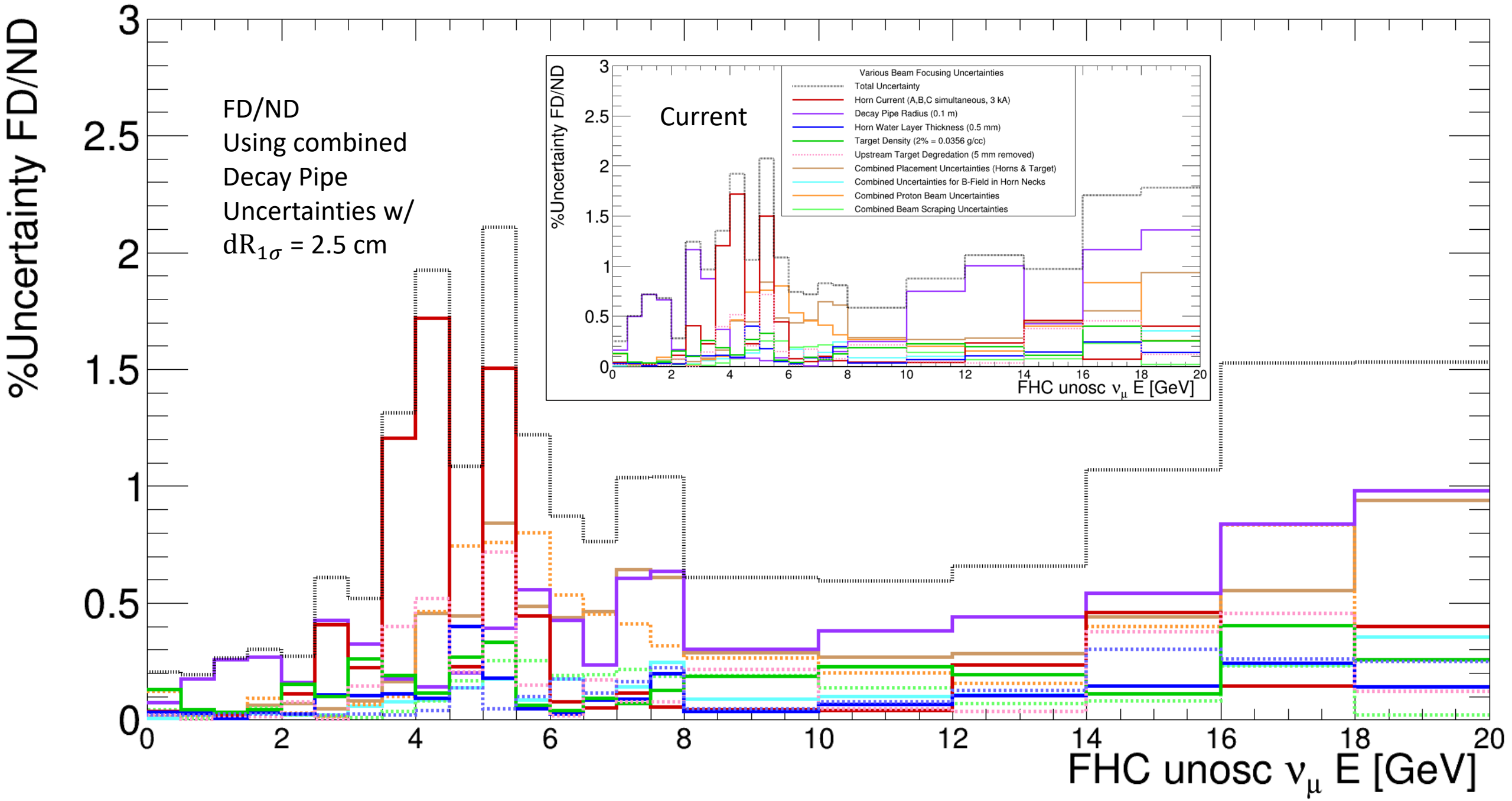
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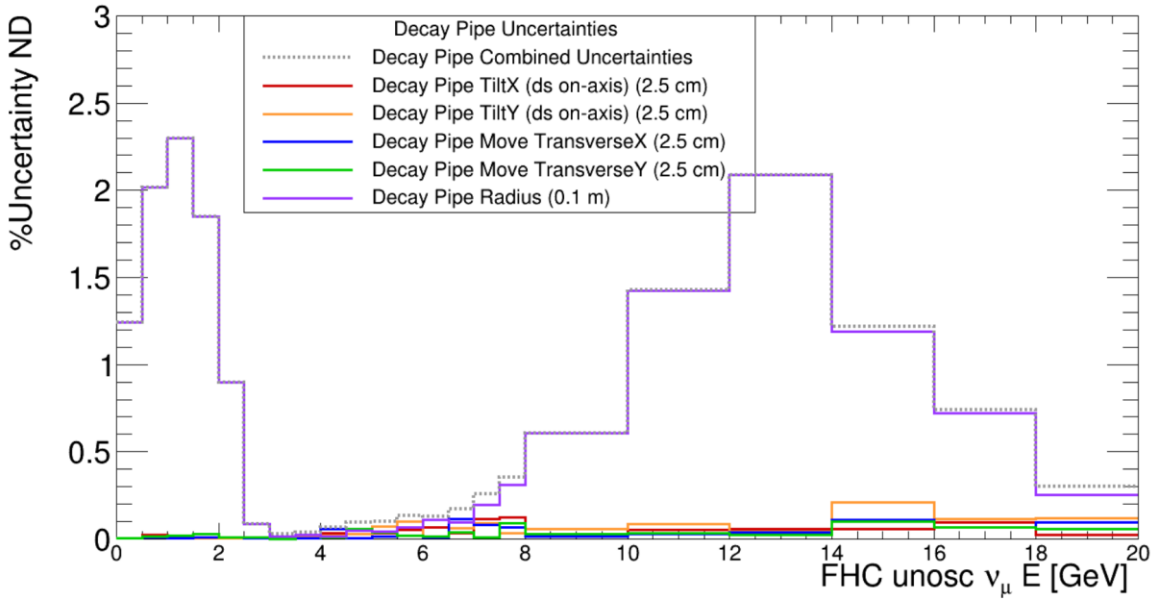
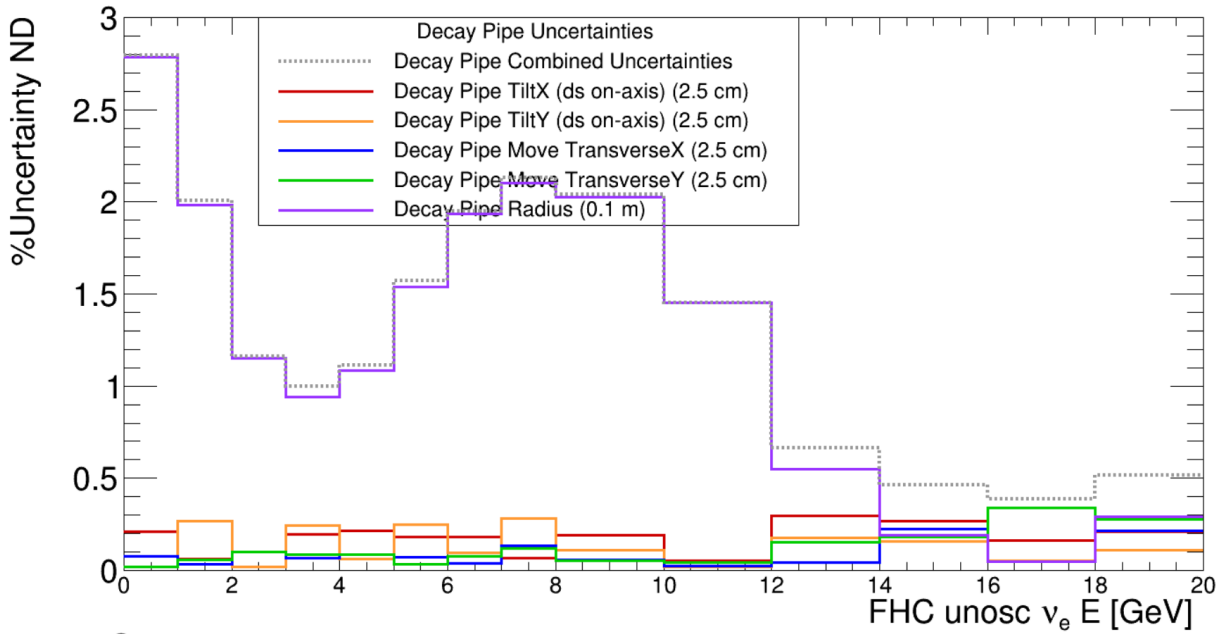
Backup

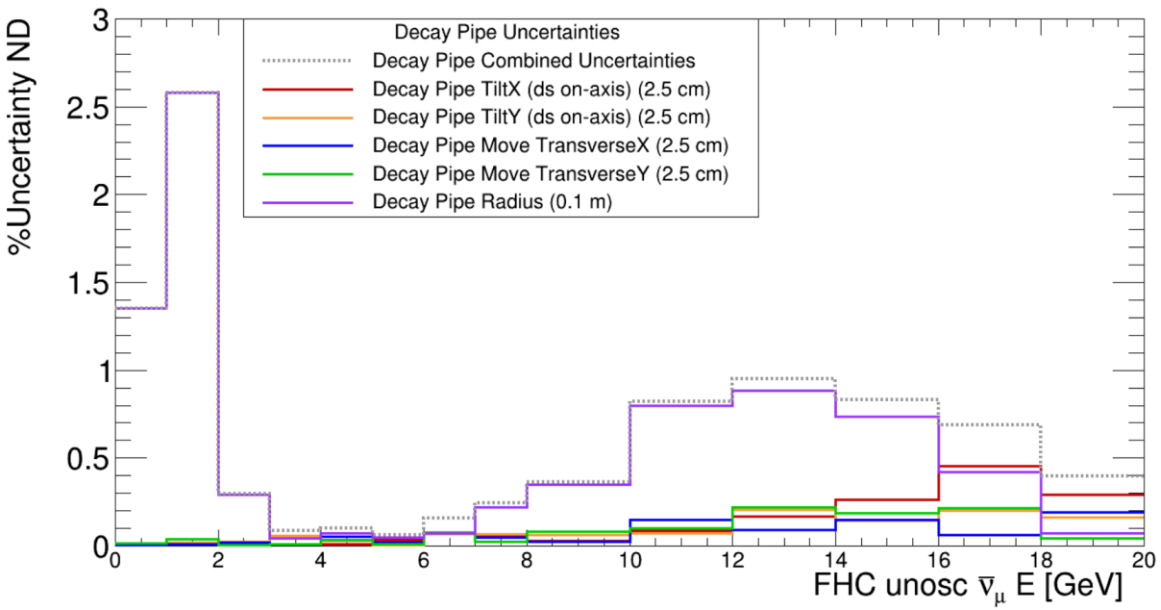
- Previous Talk

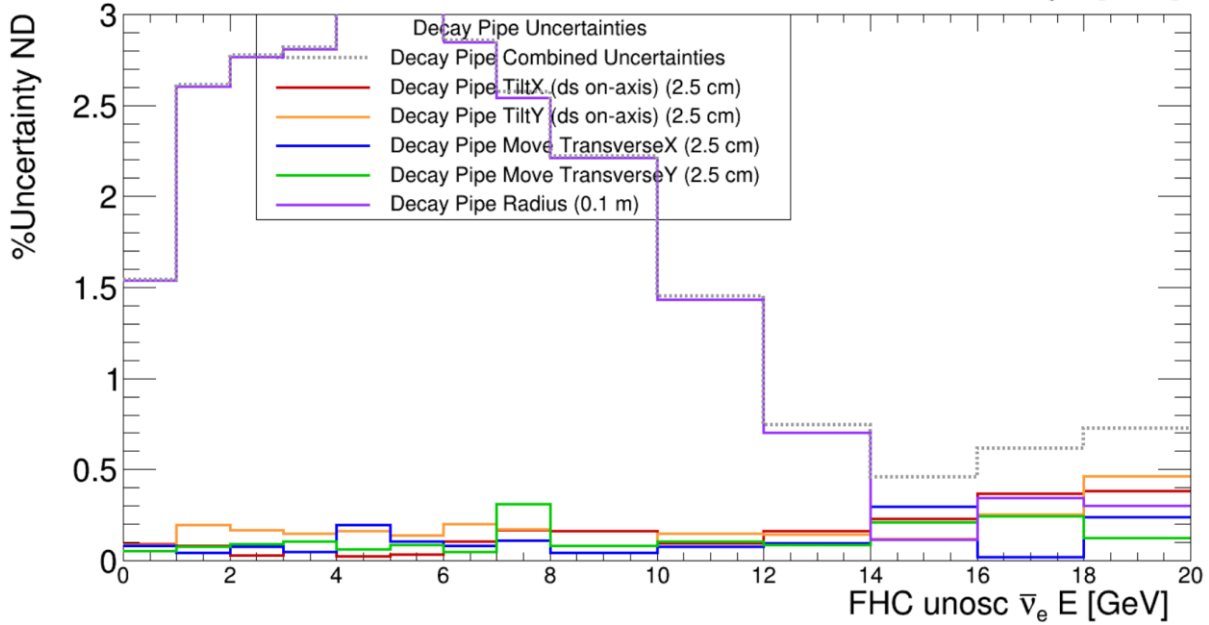
Tilt (DSoA) & Transverse Movement

ND Flux '1σ uncertainties'

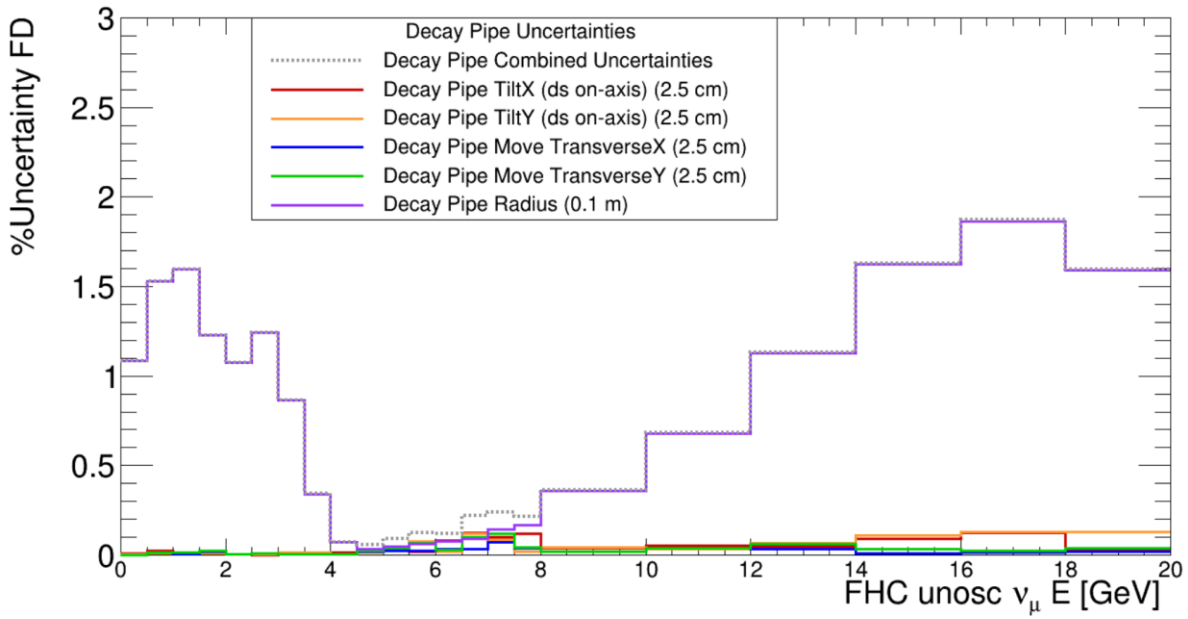


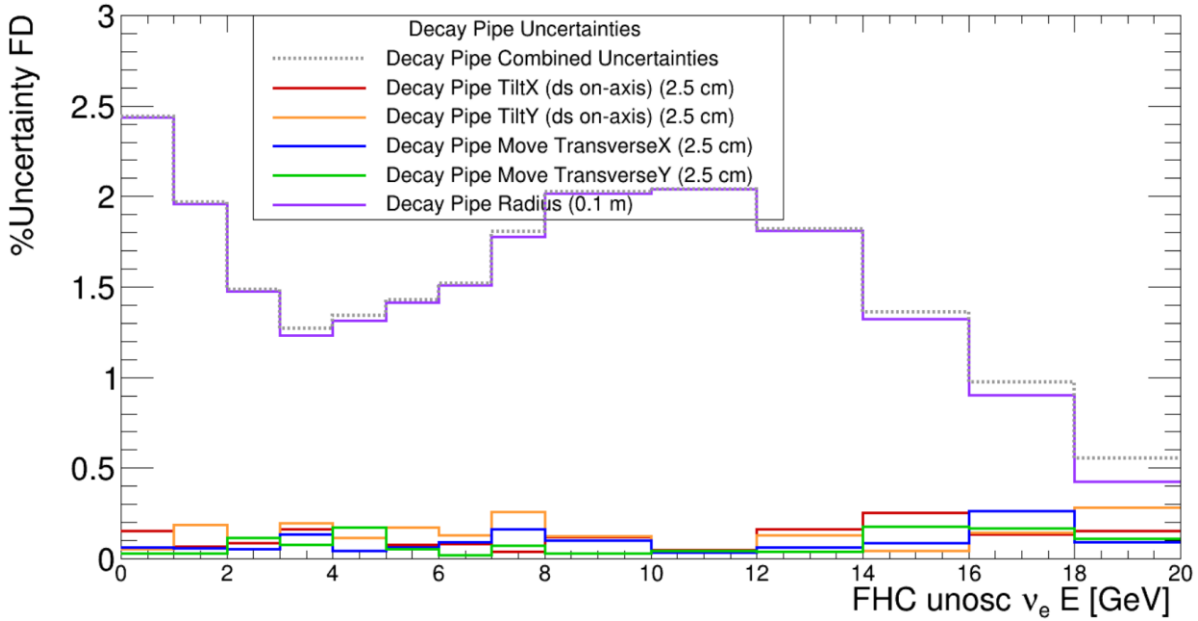


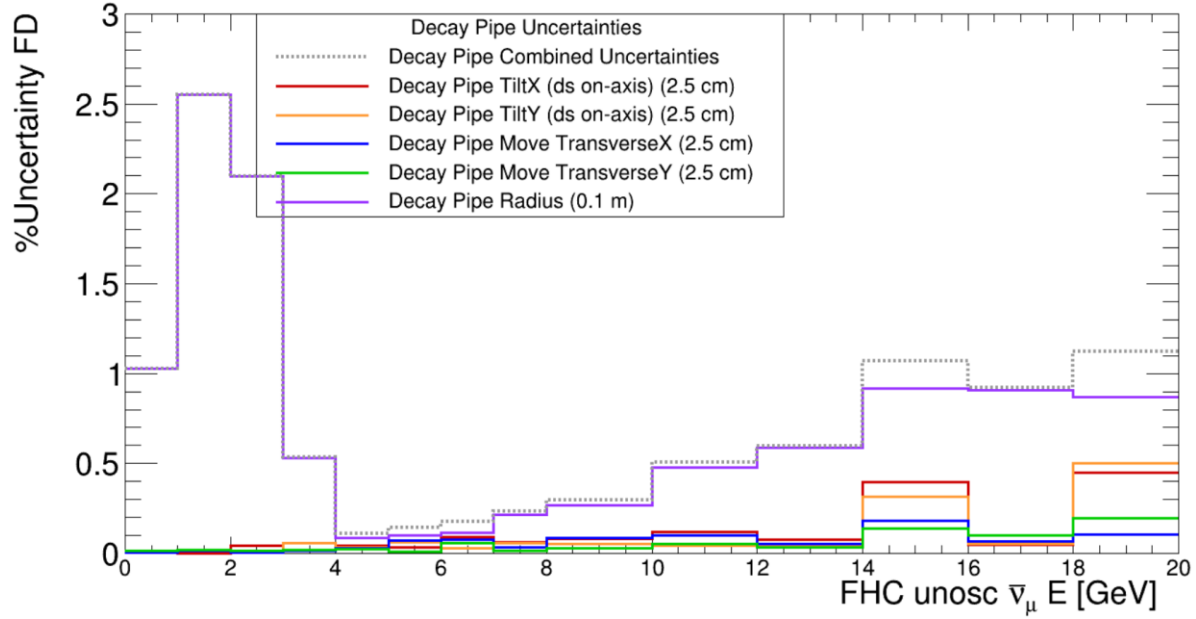


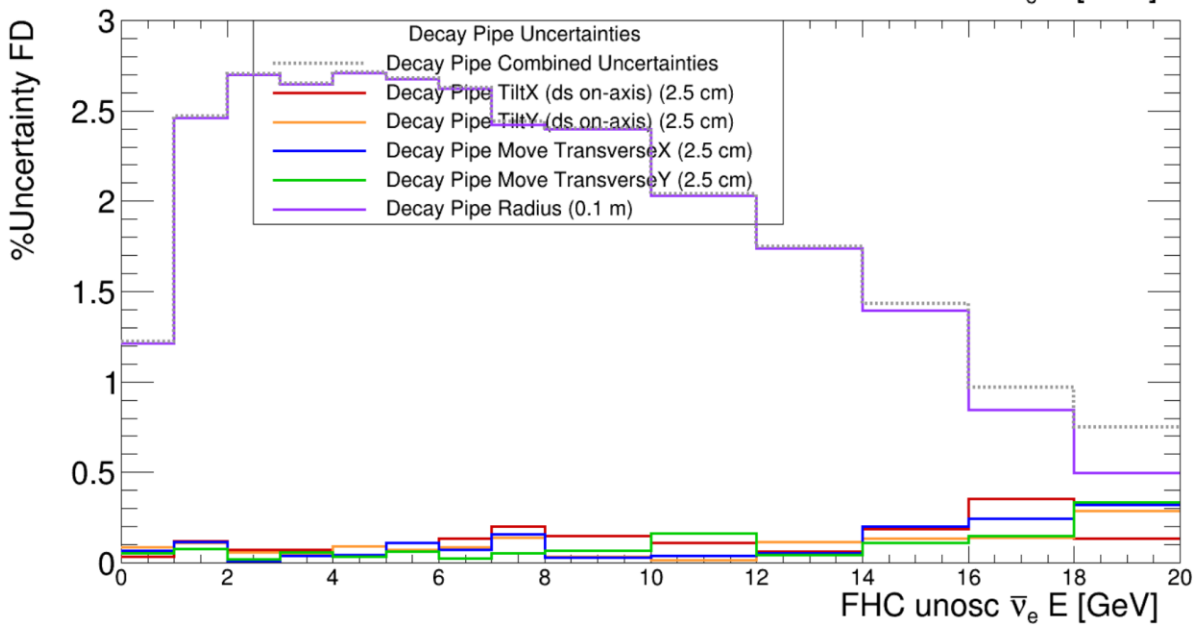


FD Flux ‘1σ uncertainties’

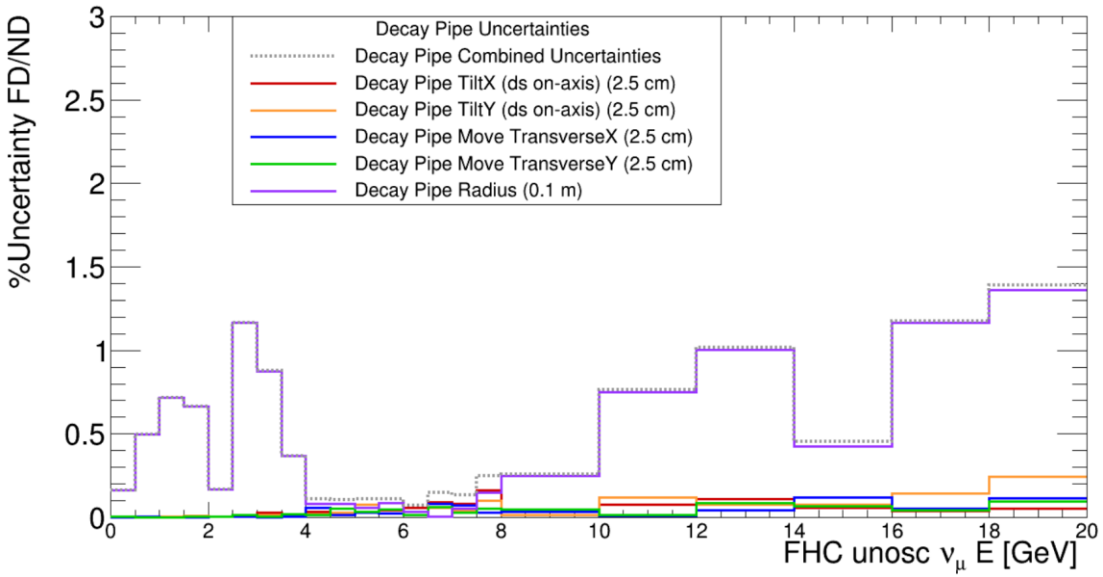


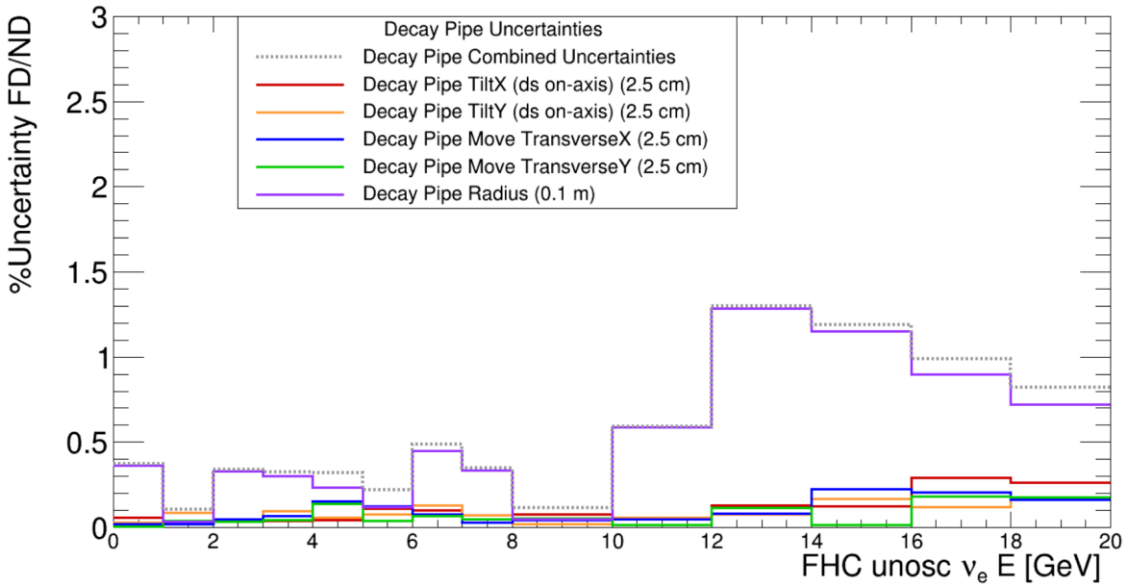


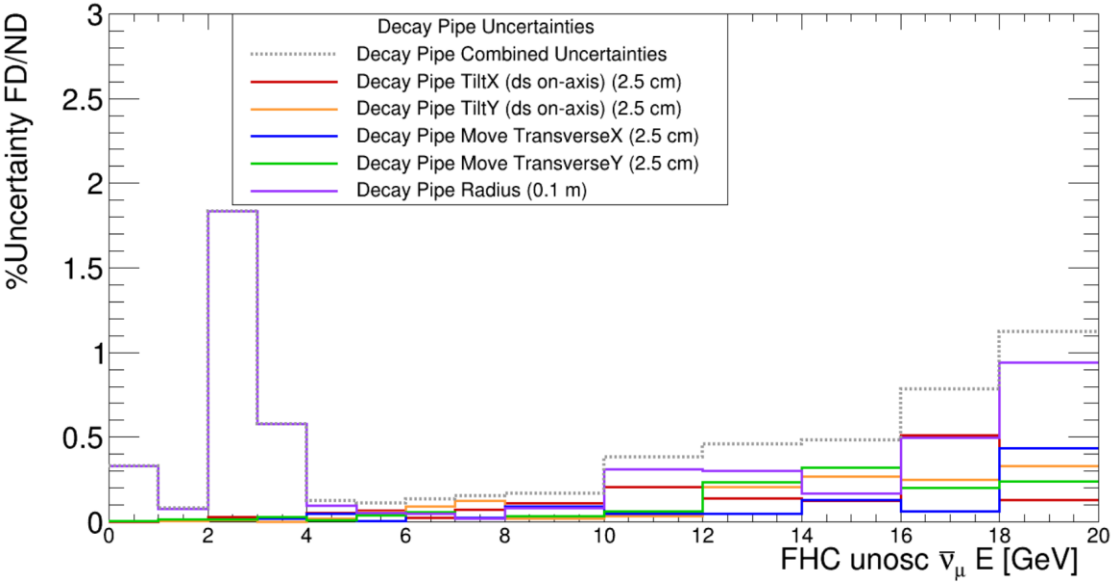


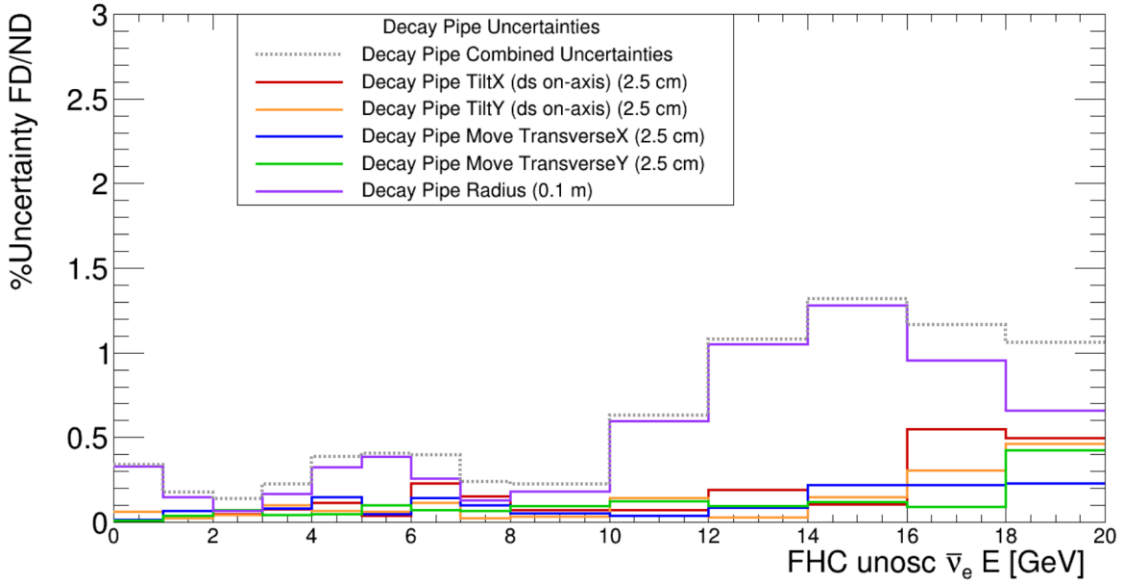


FD/ND Flux '1σ uncertainties'



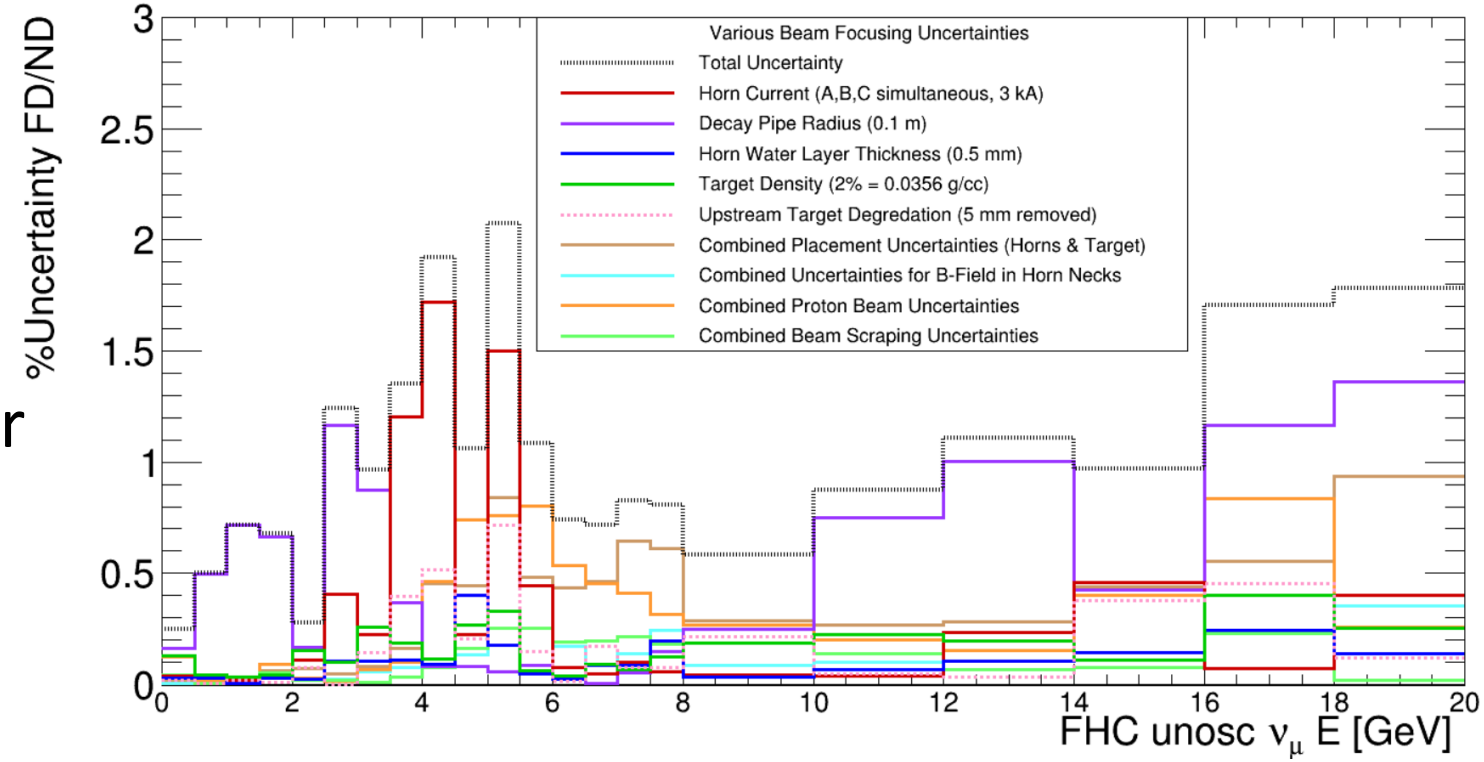






Motivation/Goal

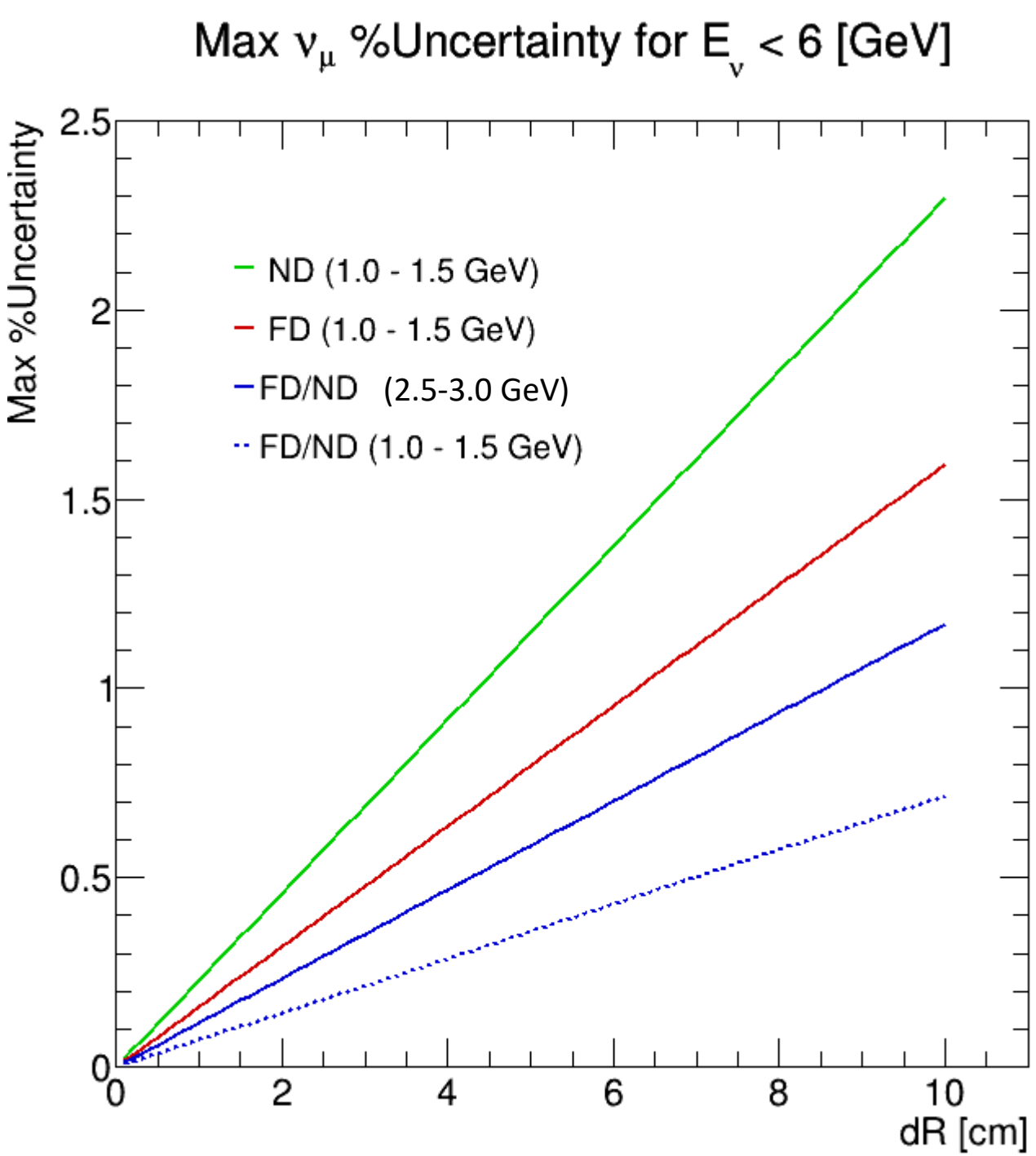
- Decay Pipe is a significant systematic uncertainty source in beam focusing uncertainties for primary physics region.
- Uncertainties are for Unoscillated ν_μ flux



- Asked to see how uniform we need the decay pipe to be to reduce uncertainty.
  - In terms of deviation in “decay pipe radius” dR
    - “Radius” is a stand in for multiple deformation effects of the pipe
  - Find an acceptable level of deviation in muon neutrino flux, corresponding dR value, that fits within engineering budget/constraints

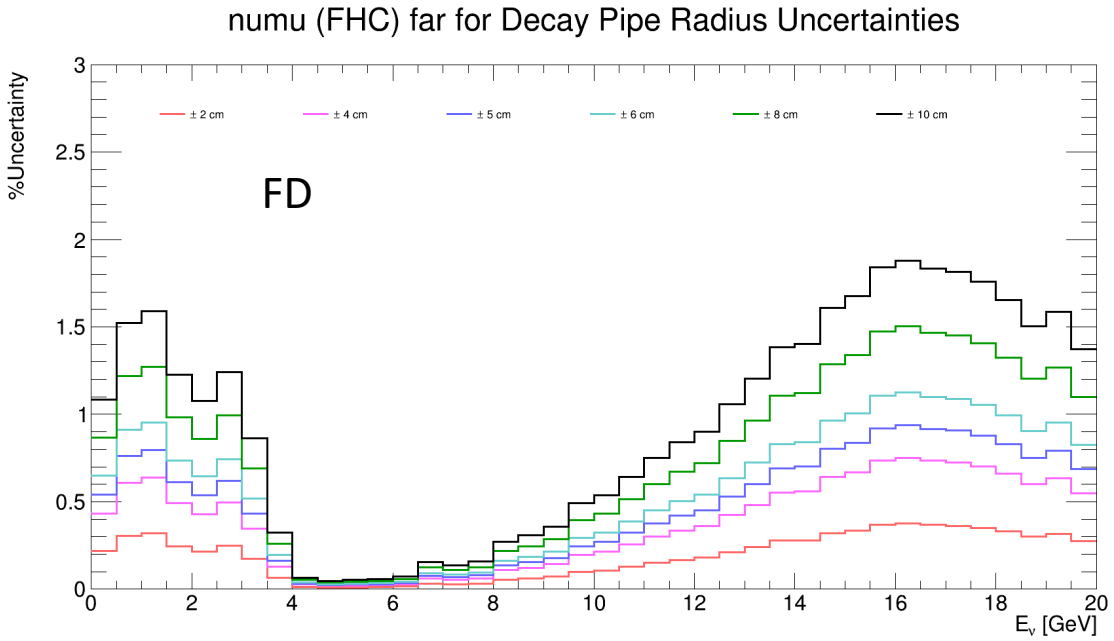
Max %Uncertainty(dR) in Flux ROI

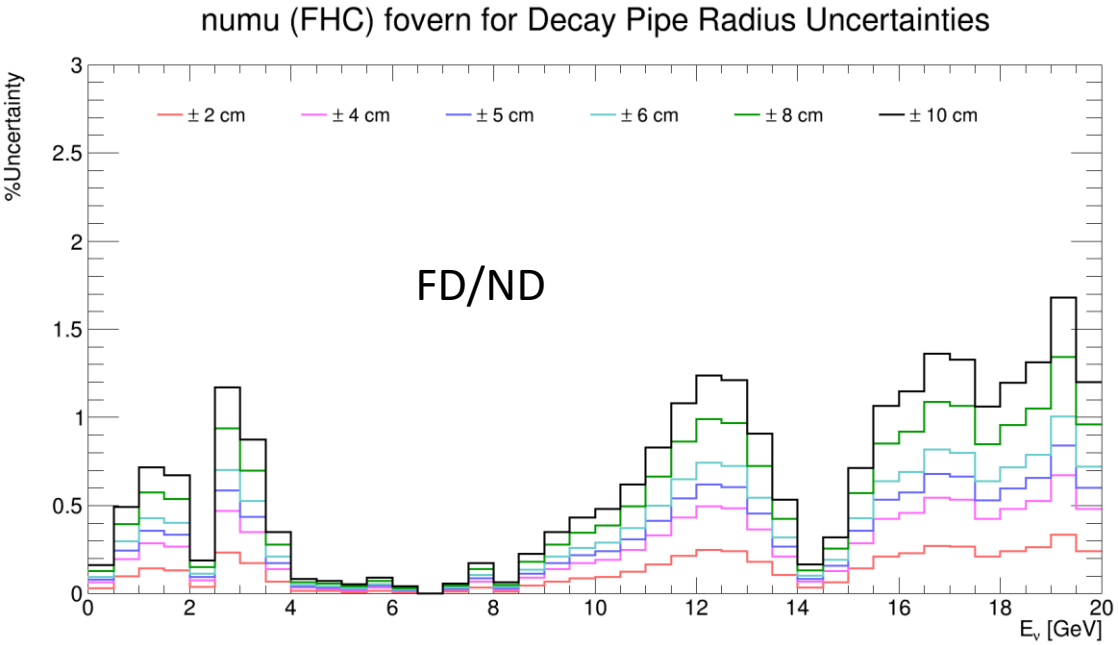
- R_0= 2.0 m, 1σ = 10 cm
- -5σ – +5σ & Sub-1σ samples:
  - $\pm$0.2, $\pm$0.4, $\pm$0.5, $\pm$0.6, $\pm$0.8 σ (2-8 cm)
- Fit in σ for each energy bin with all simulations
  - Include Sub-1σ simulation samples
    - 1σ sample has very high stats (>1e9), so no significant change to best fit after including
- Result (right)
  - extract values from fit (1 mm steps)
  - All 4 are very shallow P_2's
  - 2.5 cm: 0.18/0.29/0.40/0.58

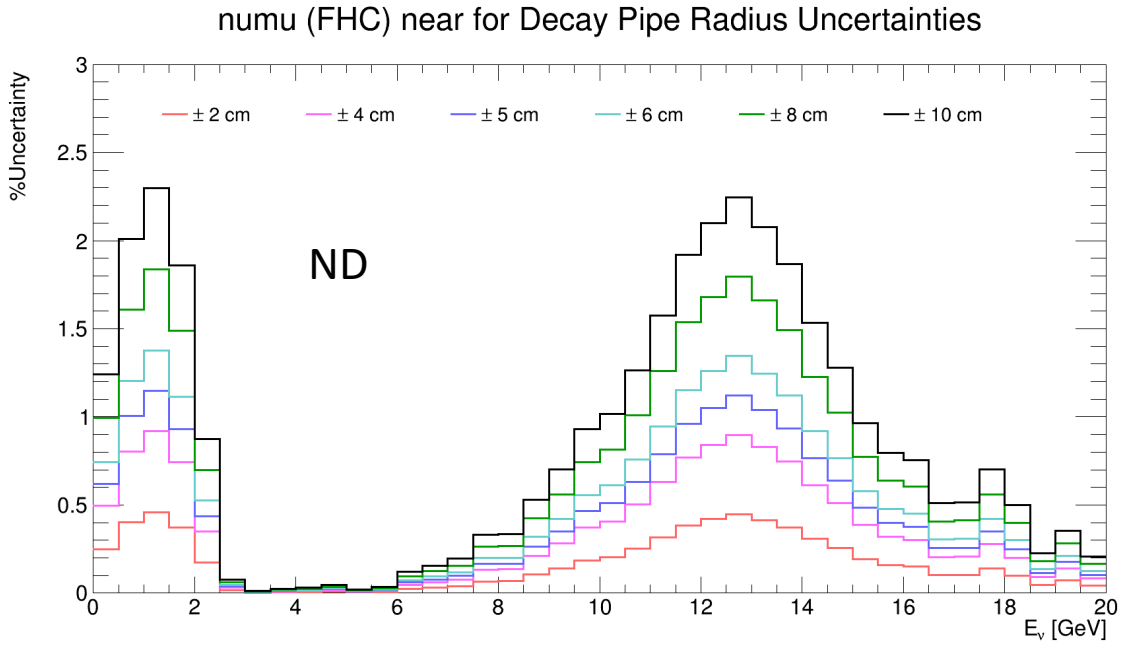


Details

- This page: %Uncertainties for FD, ND, FD/ND
- Large plots on following pages
- $\pm 1\sigma$ has > 1e9 PoT
- -5σ to 5σ samples ~ 0.5e9 PoT,
- Sub-1σ samples
  - $\pm 0.2, \pm 0.4, \pm 0.6, \pm 0.8\ \sigma$ samples generated with 0.25e9 PoT each
  - $\pm 0.5\sigma$ have 0.5e9 PoT

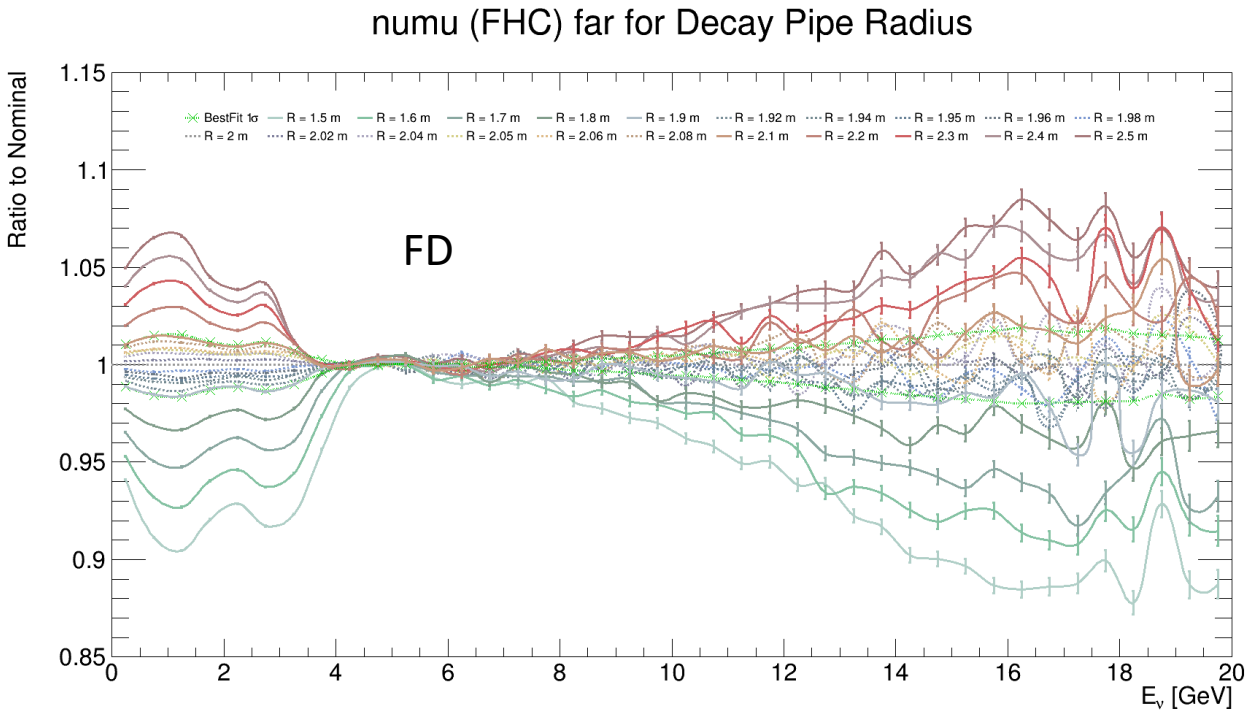


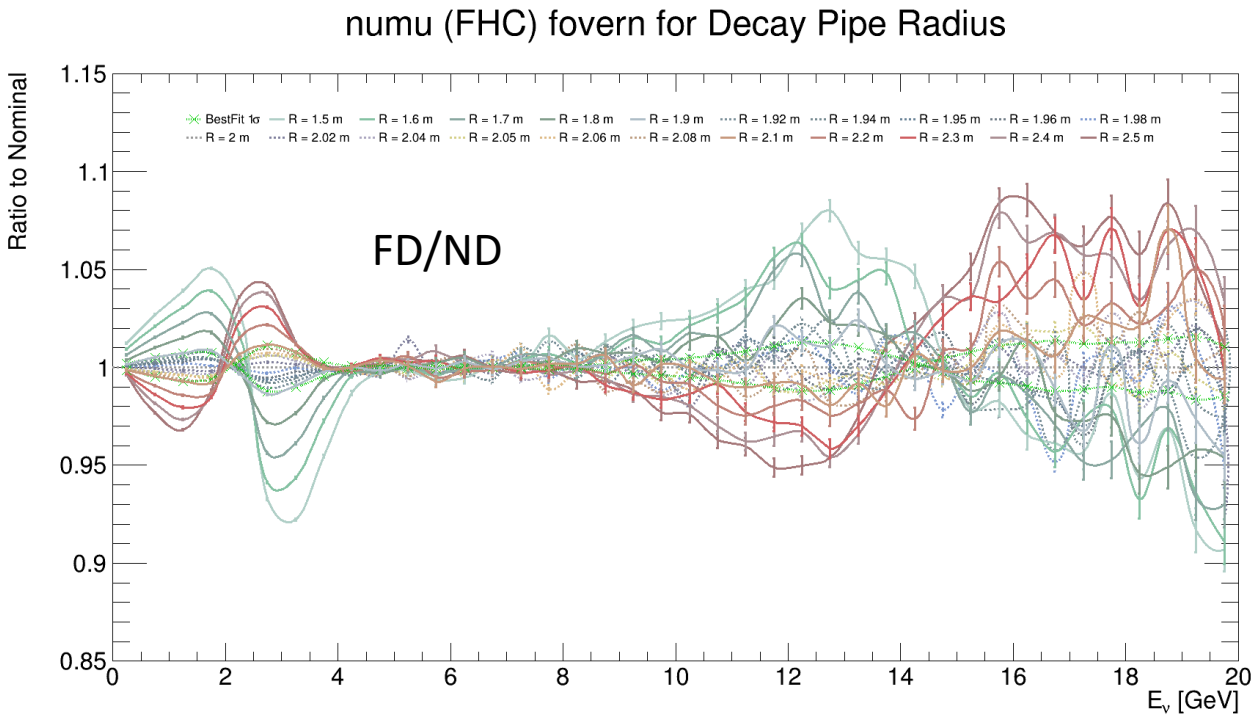


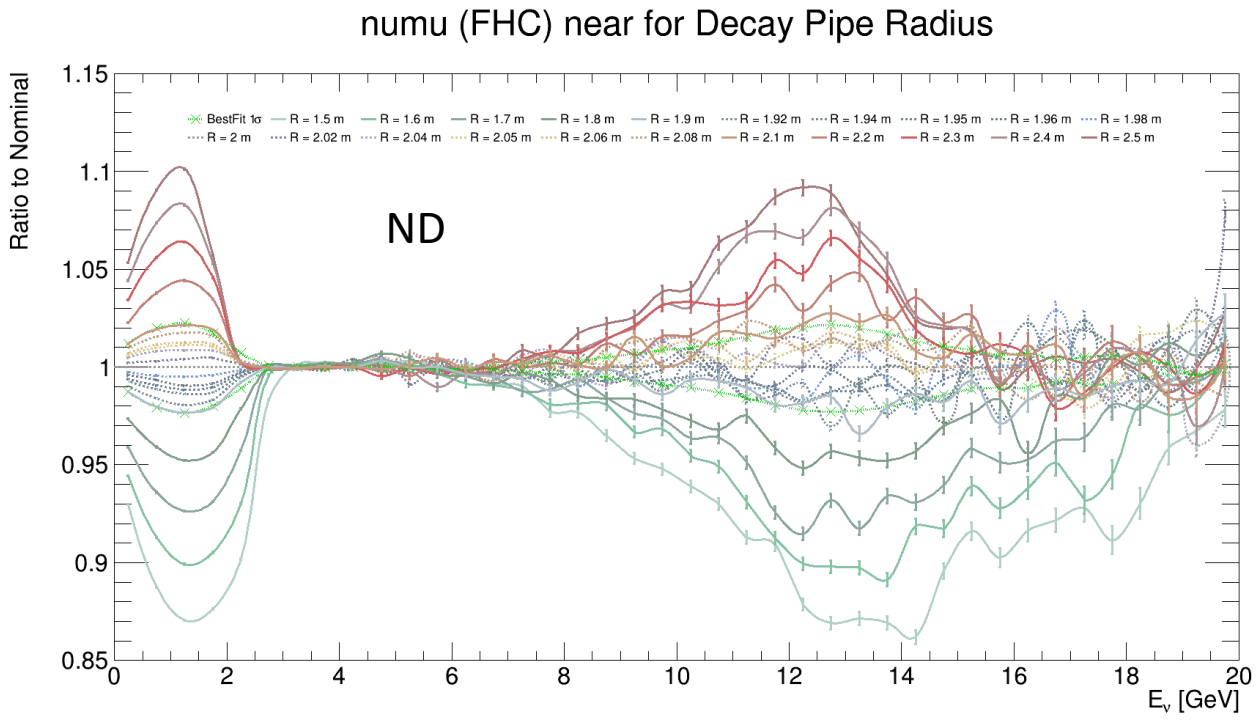


Flux Ratios to Nominal Simulation: -5σ to 5σ, $d\sigma$ = 1σ & $\pm$0.2, $\pm$0.4, $\pm$0.5, $\pm$0.6, $\pm$0.8σ

- Fits are performed in each energy bin on the data from these plots (including errors)

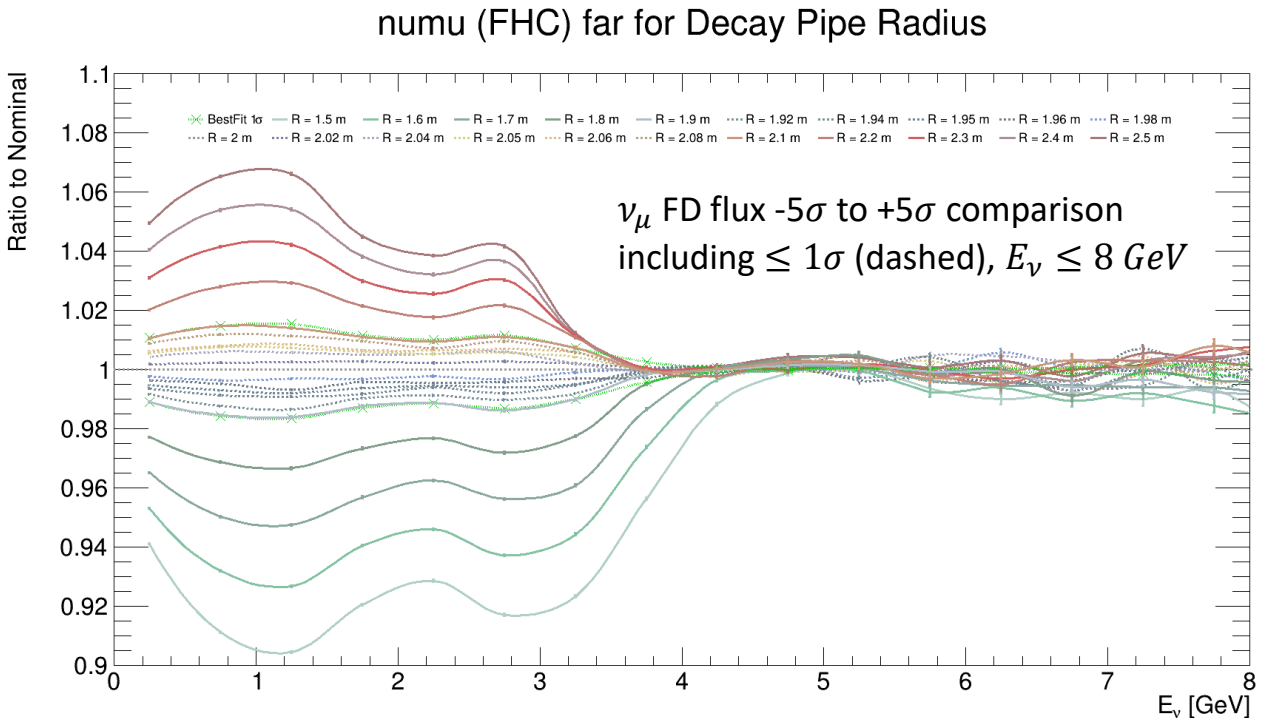


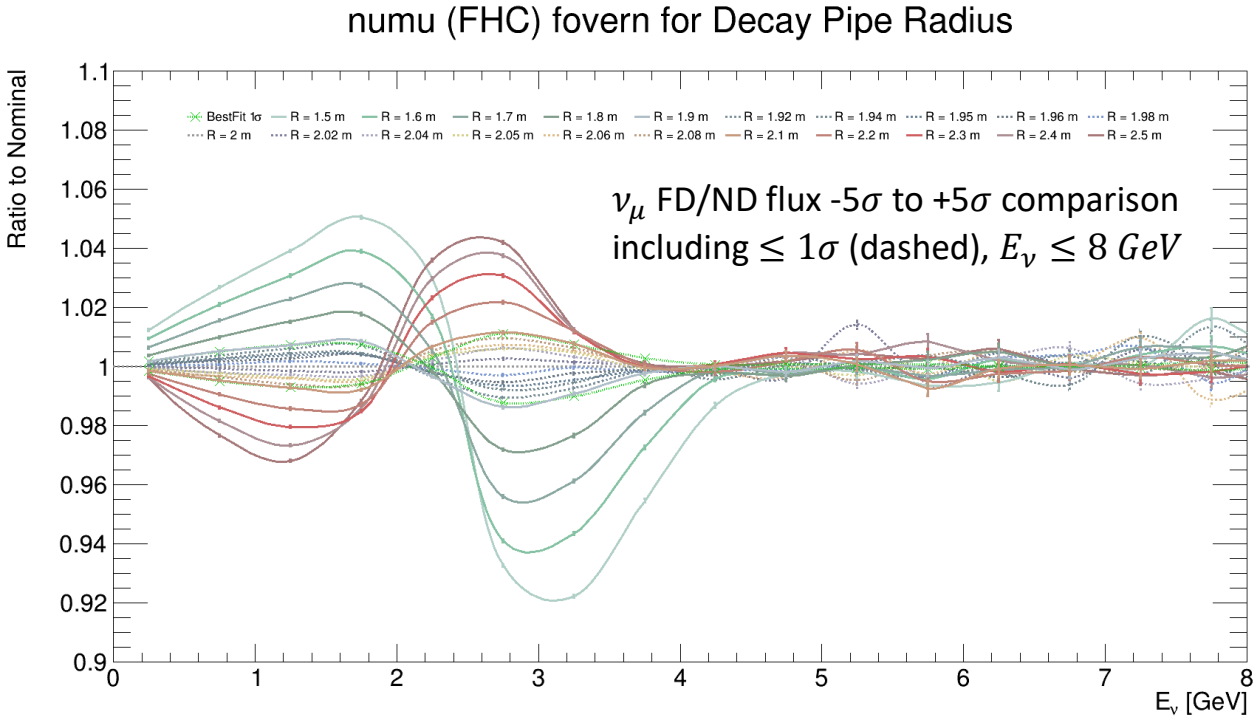


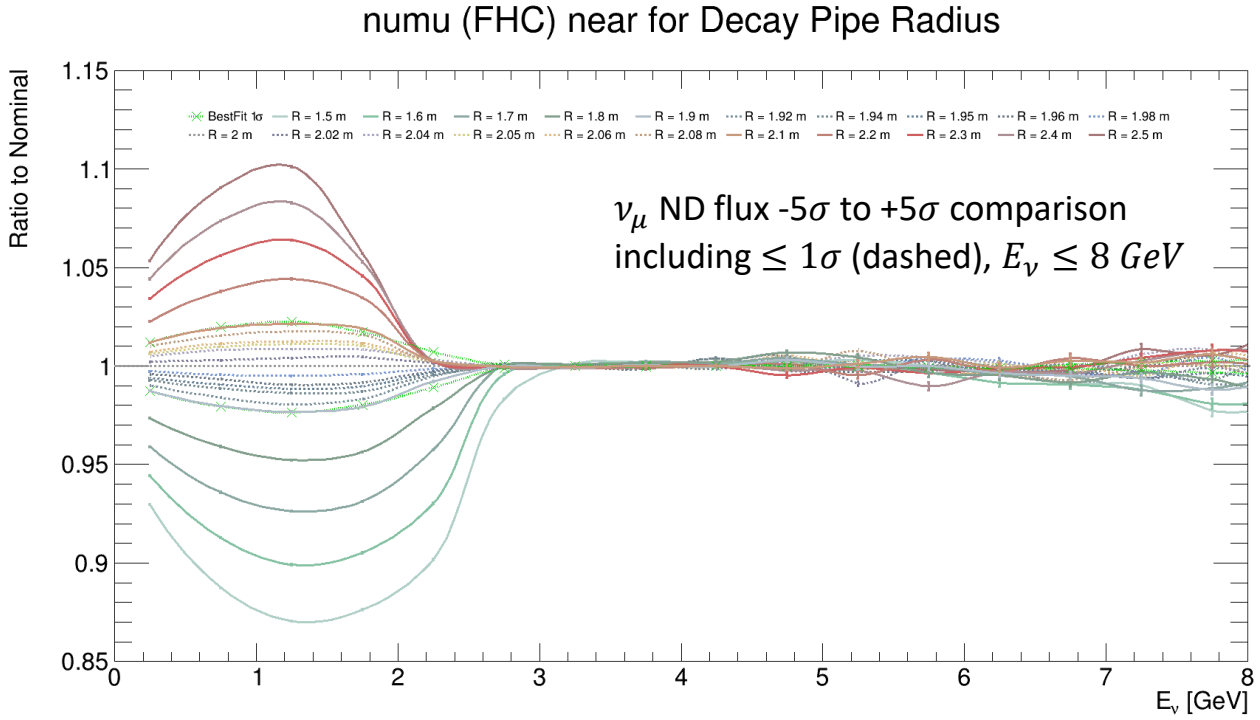


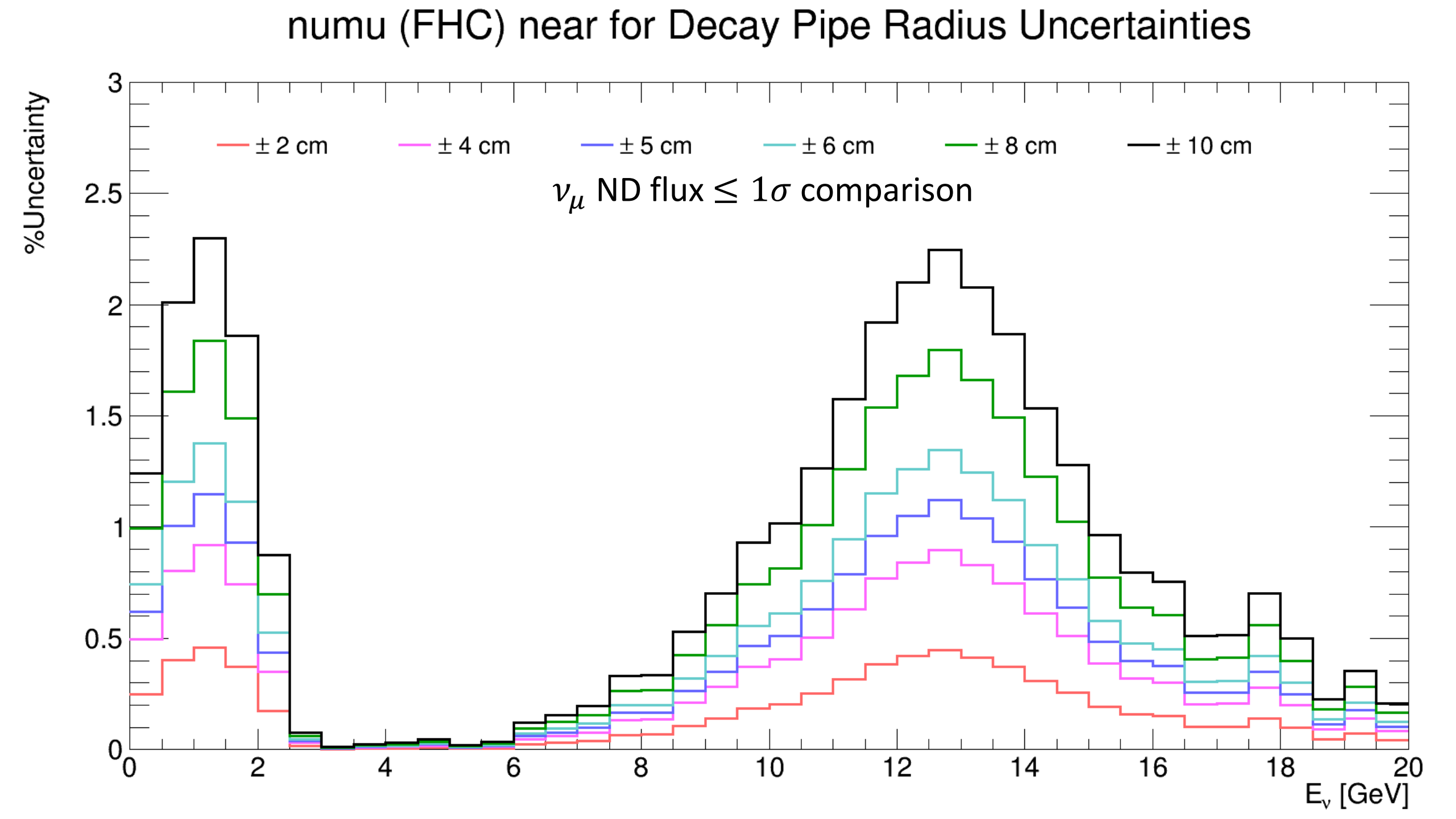
Flux Ratios to Nominal Simulation: -5σ to 5σ, $d\sigma$ = 1σ & $\pm$0.2, $\pm$0.4, $\pm$0.5, $\pm$0.6, $\pm$0.8σ

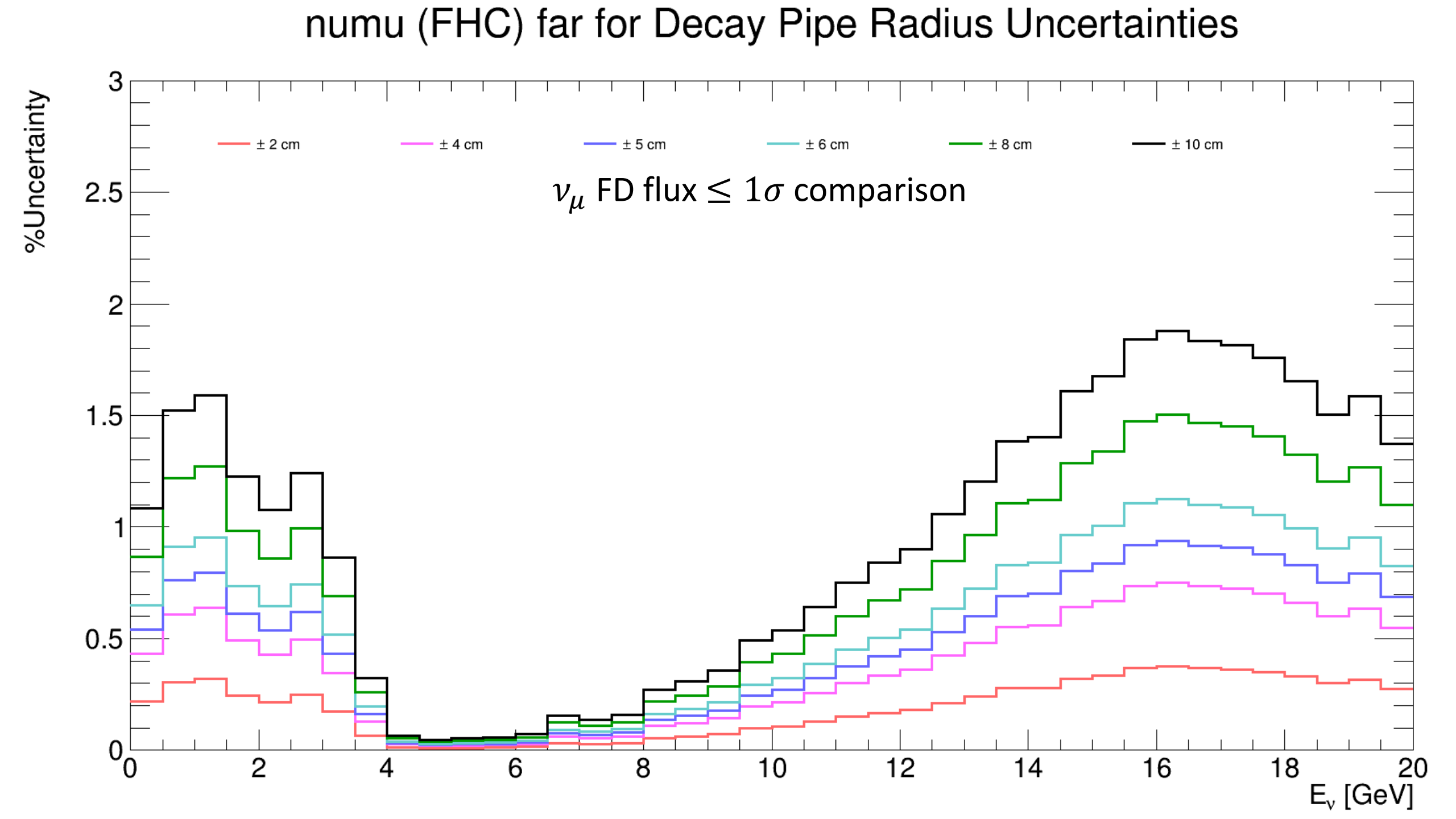
- Fits are performed in each energy bin on the data from these plots (including errors)

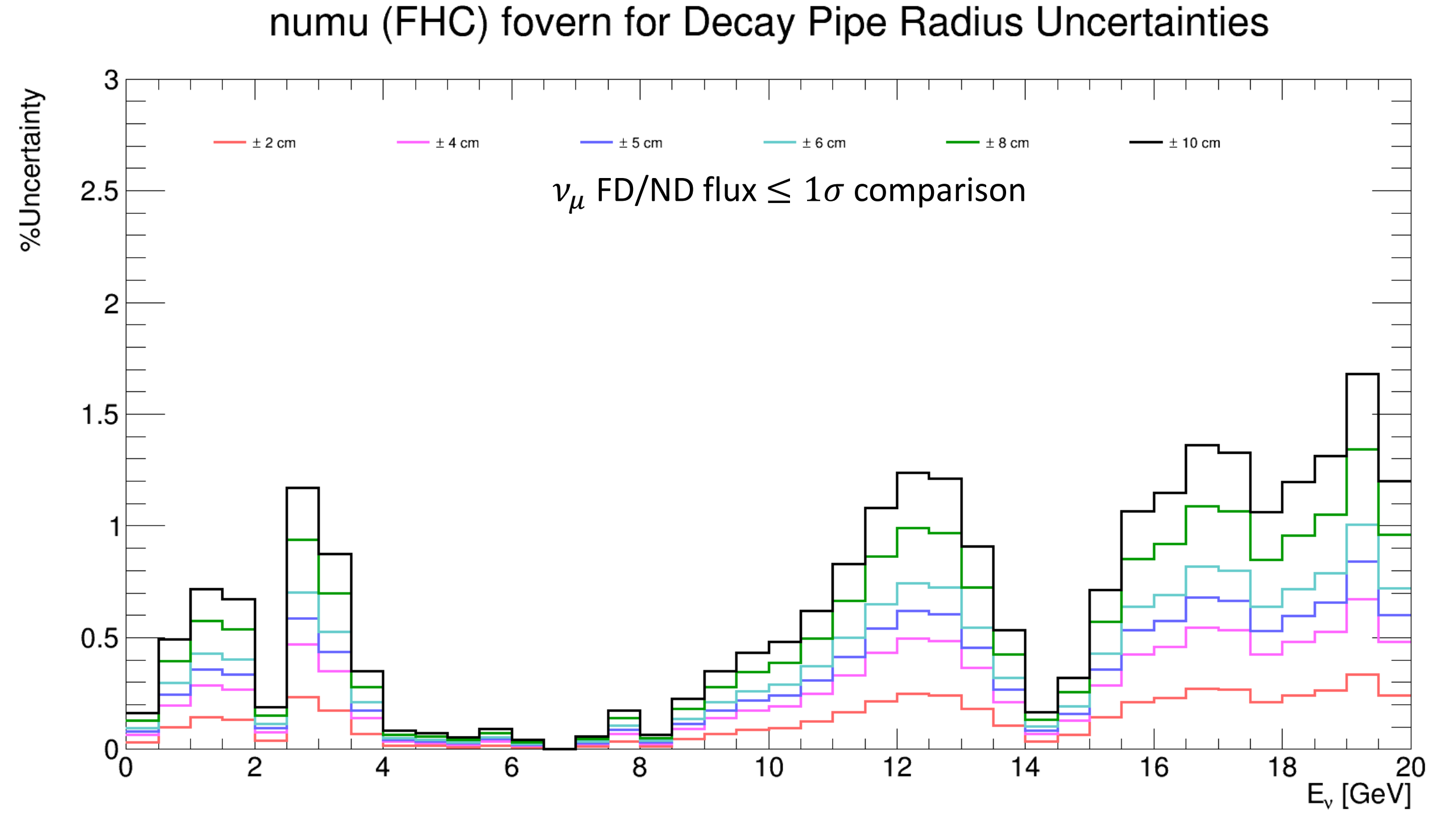


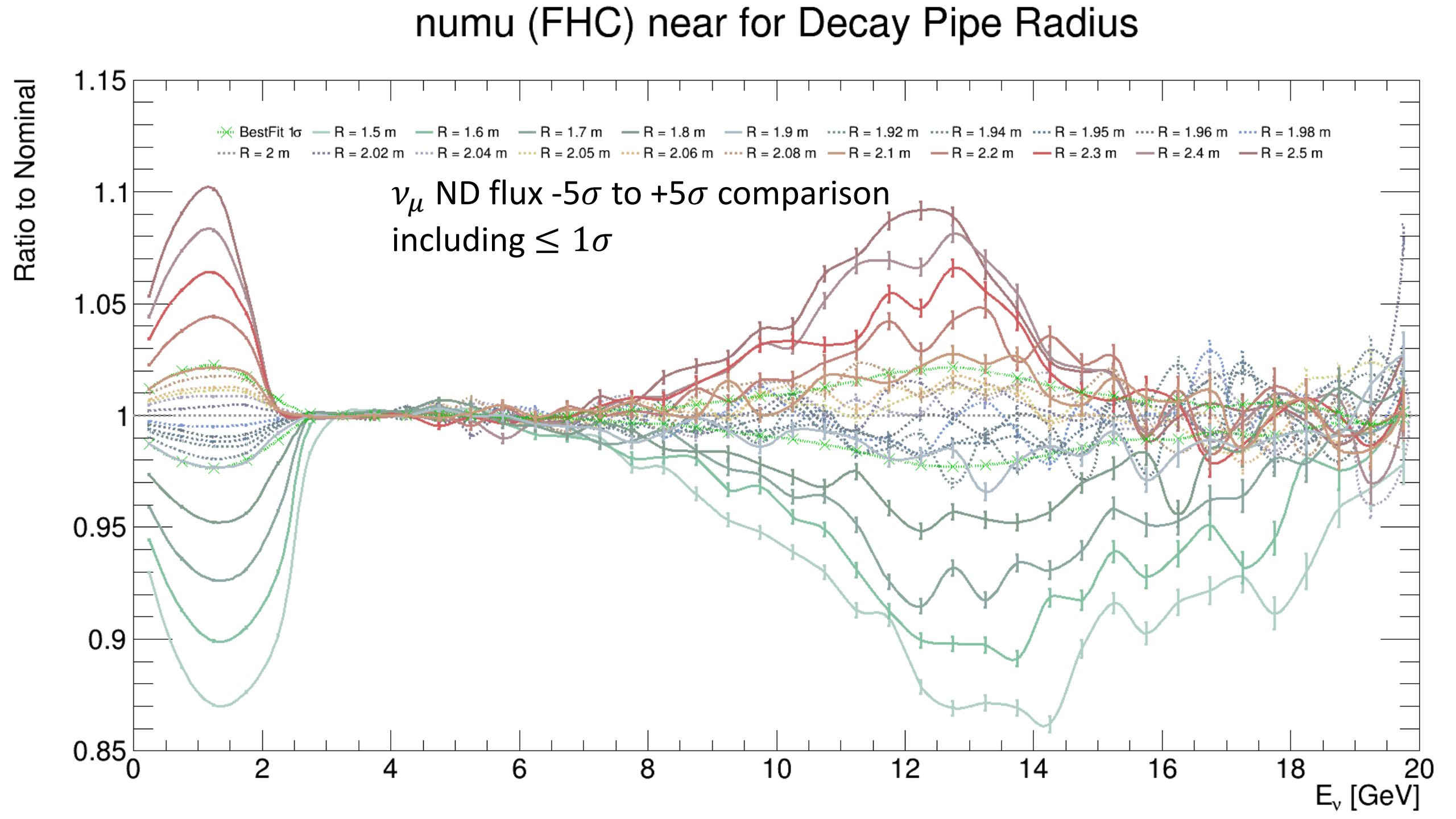




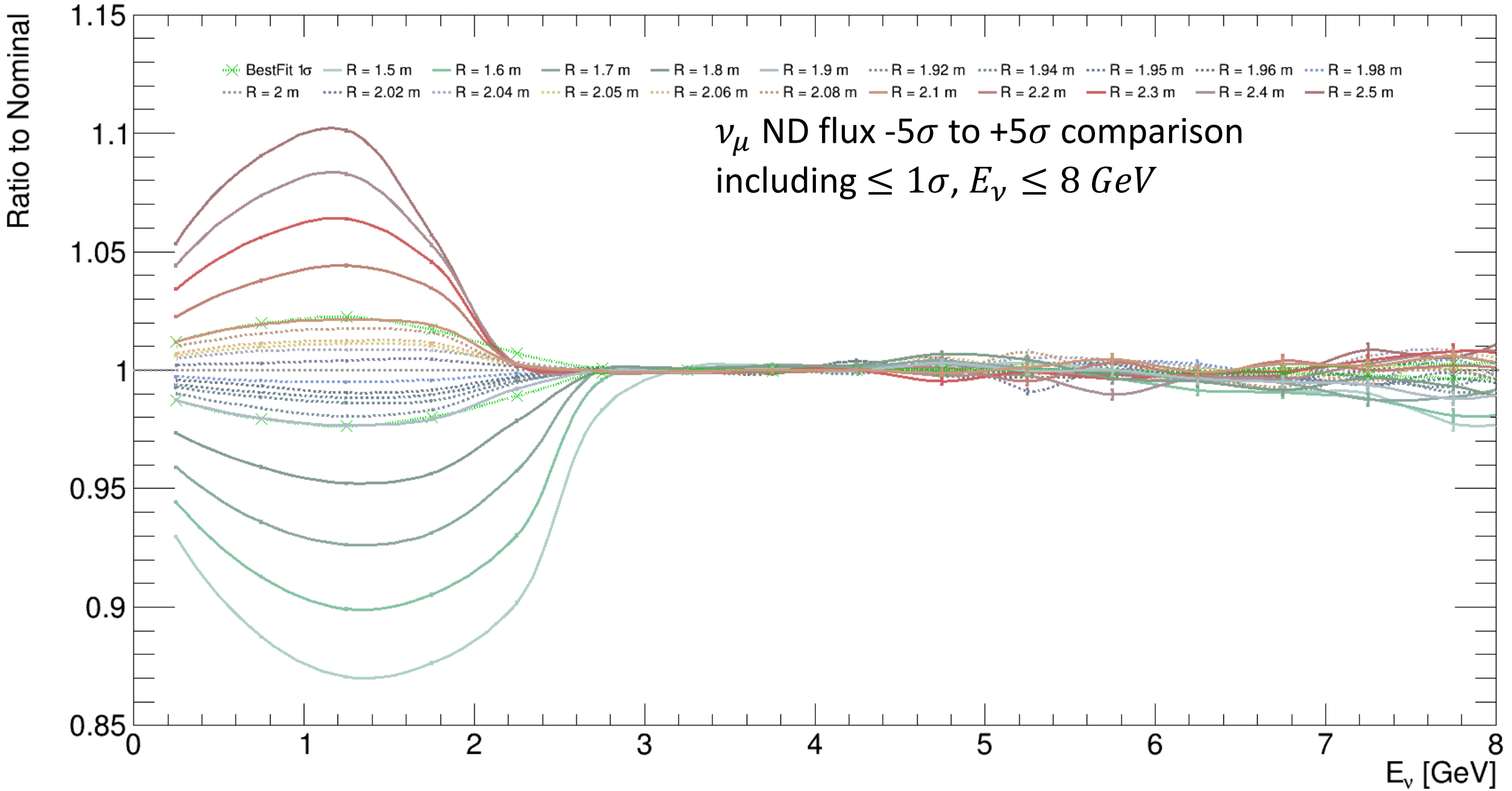

numu (FHC) near for Decay Pipe Radius Uncertainties
± 2 cm
± 4 cm
± 5 cm
± 6 cm
± 8 cm
± 10 cm
ν_μ ND flux $\leq 1\sigma$ comparison
%Uncertainty
E_ν [GeV]
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
14
16
18
20

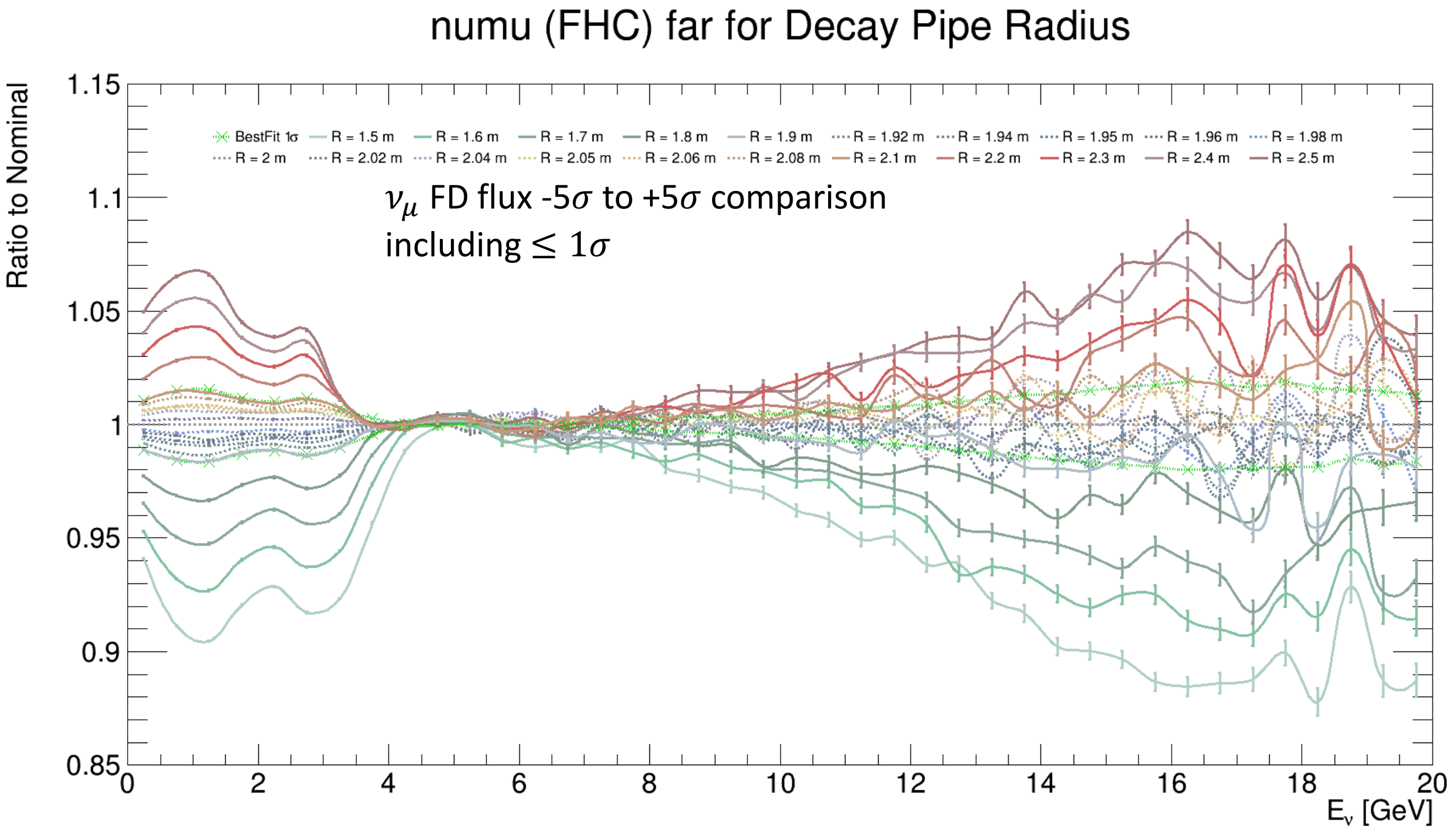

numu (FHC) far for Decay Pipe Radius Uncertainties
%Uncertainty
± 2 cm
± 4 cm
± 5 cm
± 6 cm
± 8 cm
± 10 cm
ν_μ FD flux $\leq 1\sigma$ comparison
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]

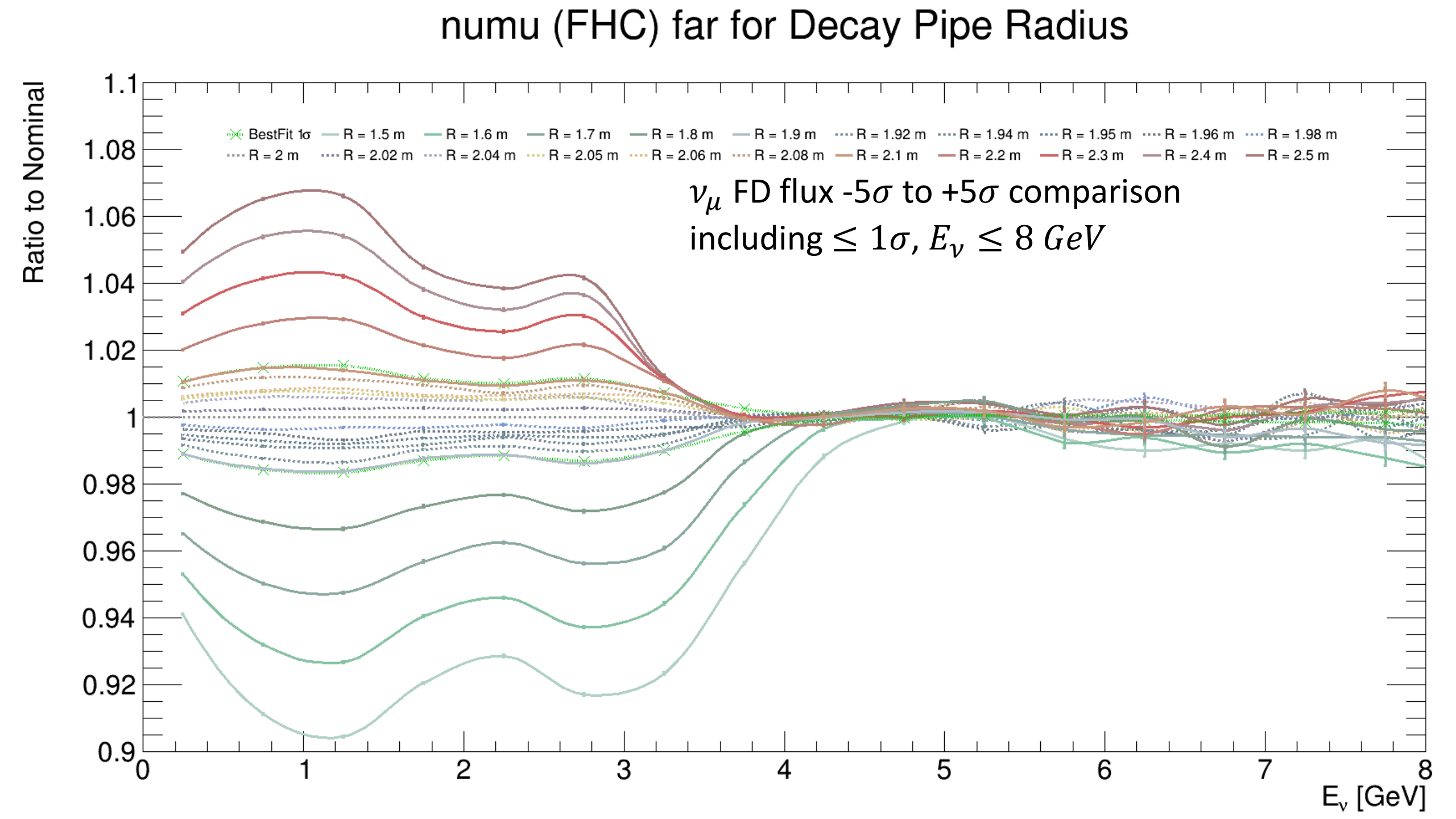

numu (FHC) fovern for Decay Pipe Radius Uncertainties
%Uncertainty
± 2 cm
± 4 cm
± 5 cm
± 6 cm
± 8 cm
± 10 cm
ν_μ FD/ND flux $\leq 1\sigma$ comparison
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]

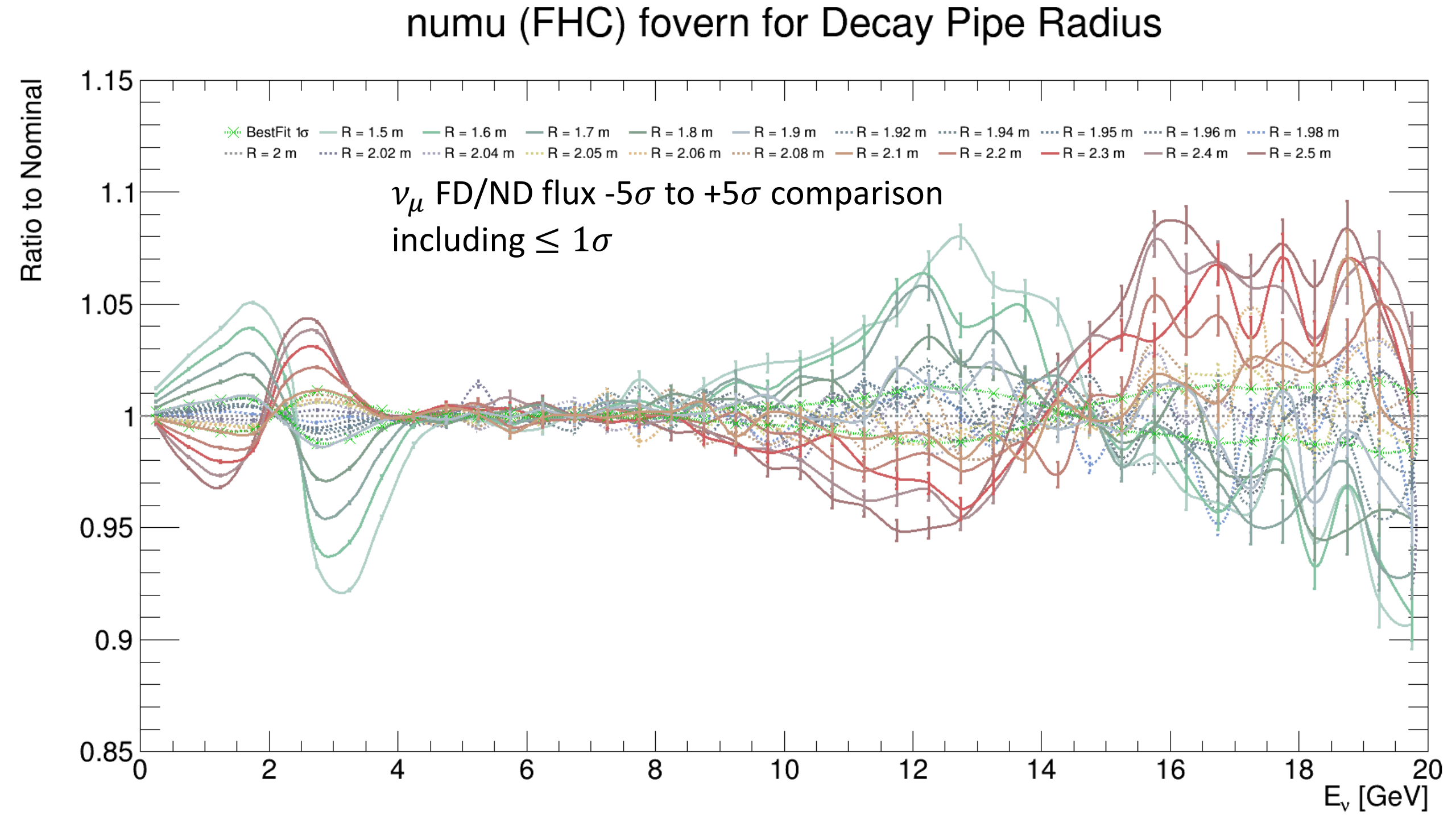

numu (FHC) near for Decay Pipe Radius
Ratio to Nominal
1.15
1.1
1.05
1
0.95
0.9
0.85
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]
BestFit 1σ
R = 1.5 m
R = 1.6 m
R = 1.7 m
R = 1.8 m
R = 1.9 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.1 m
R = 2.2 m
R = 2.3 m
R = 2.4 m
R = 2.5 m
ν_μ ND flux -5σ to +5σ comparison
including $\leq 1\sigma$

numu (FHC) near for Decay Pipe Radius

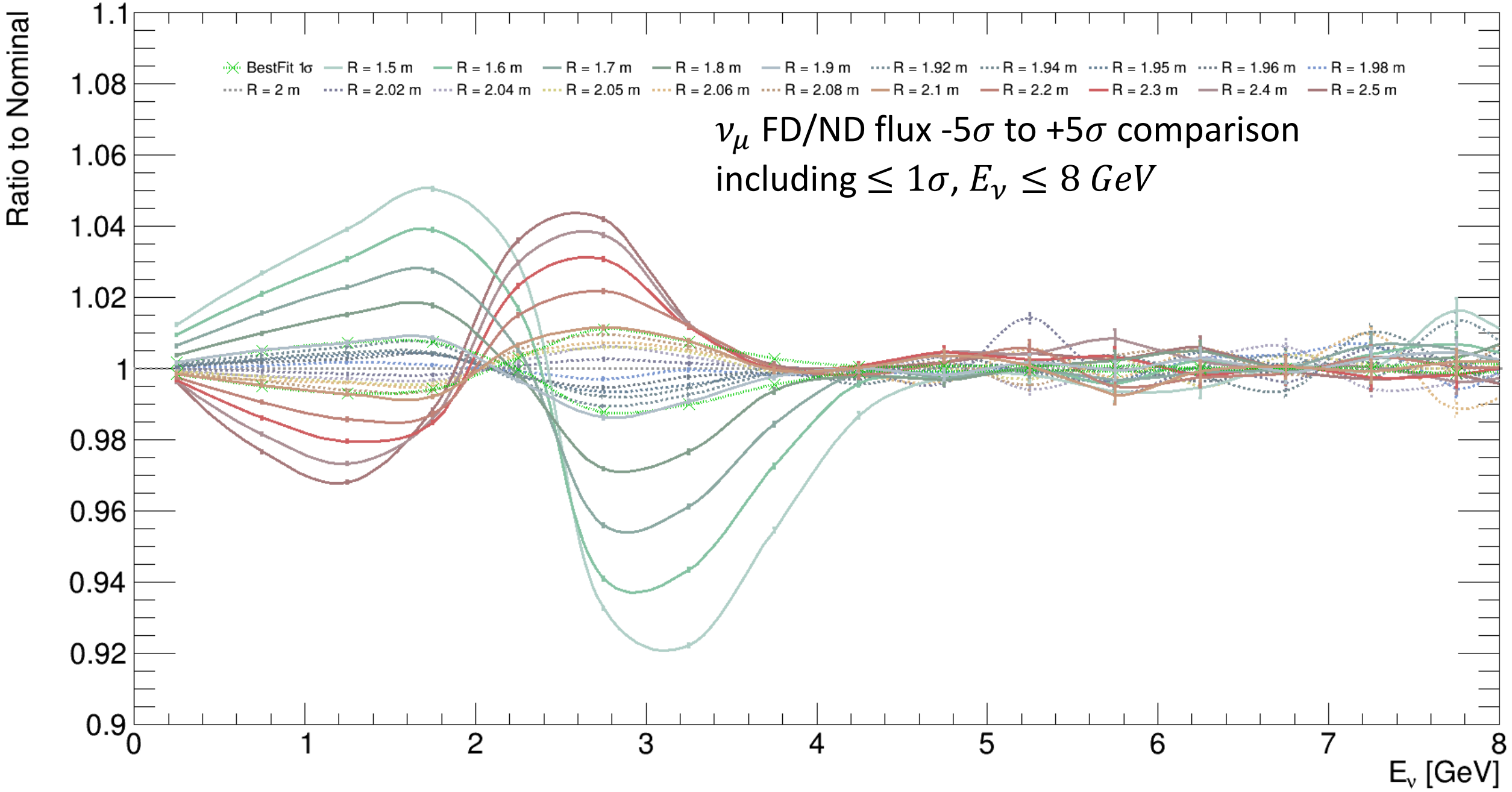



numu (FHC) far for Decay Pipe Radius
Ratio to Nominal
1.15
1.1
1.05
1
0.95
0.9
0.85
0
2
4
6
8
10
12
14
16
18
20
E$_\nu$ [GeV]
BestFit 1σ
R = 1.5 m
R = 1.6 m
R = 1.7 m
R = 1.8 m
R = 1.9 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.1 m
R = 2.2 m
R = 2.3 m
R = 2.4 m
R = 2.5 m
ν_μ FD flux -5σ to +5σ comparison
including $\leq 1\sigma$

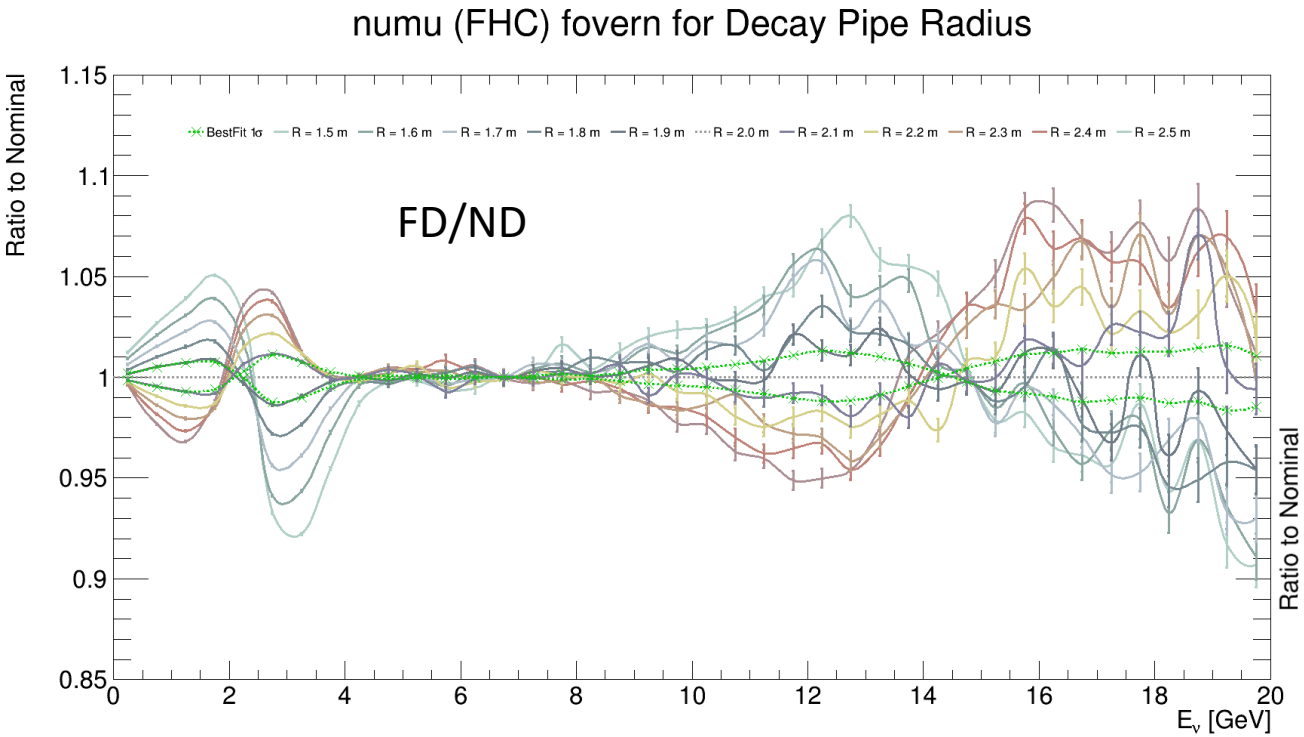

numu (FHC) far for Decay Pipe Radius
Ratio to Nominal
BestFit 1σ
R = 1.5 m
R = 1.6 m
R = 1.7 m
R = 1.8 m
R = 1.9 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.1 m
R = 2.2 m
R = 2.3 m
R = 2.4 m
R = 2.5 m
ν_μ FD flux -5σ to +5σ comparison
including $\leq 1\sigma$, $E_\nu \leq 8\ GeV$
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0
1
2
3
4
5
6
7
8
E_ν [GeV]

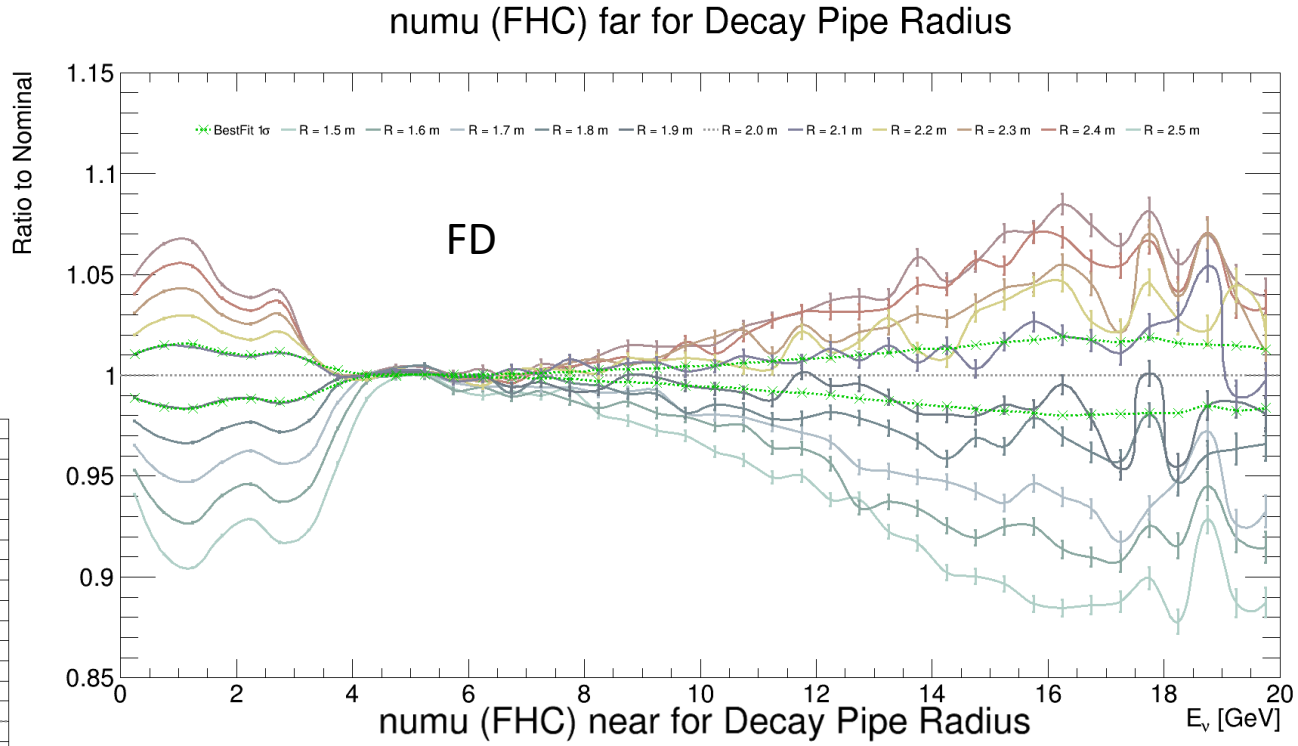

numu (FHC) fovern for Decay Pipe Radius
Ratio to Nominal
BestFit 1σ
R = 1.5 m
R = 1.6 m
R = 1.7 m
R = 1.8 m
R = 1.9 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.1 m
R = 2.2 m
R = 2.3 m
R = 2.4 m
R = 2.5 m
ν_μ FD/ND flux -5σ to +5σ comparison
including $\leq 1\sigma$
1.15
1.1
1.05
1
0.95
0.9
0.85
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]

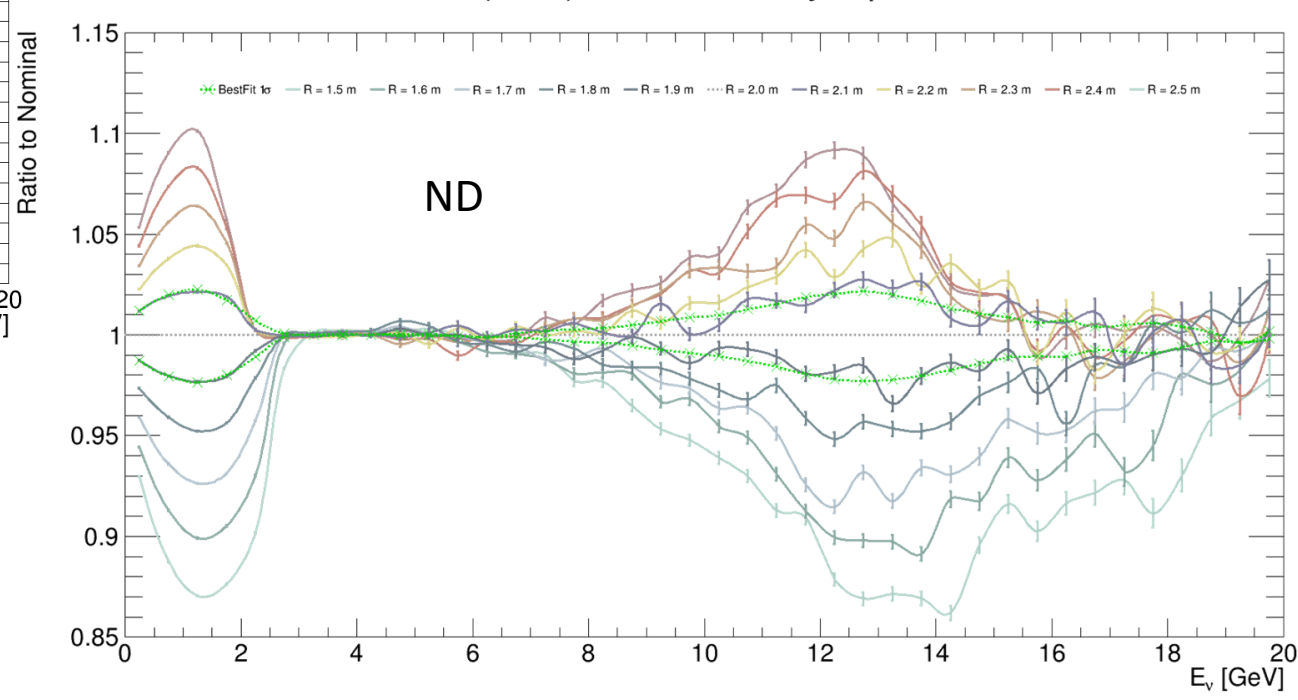
numu (FHC) fovern for Decay Pipe Radius

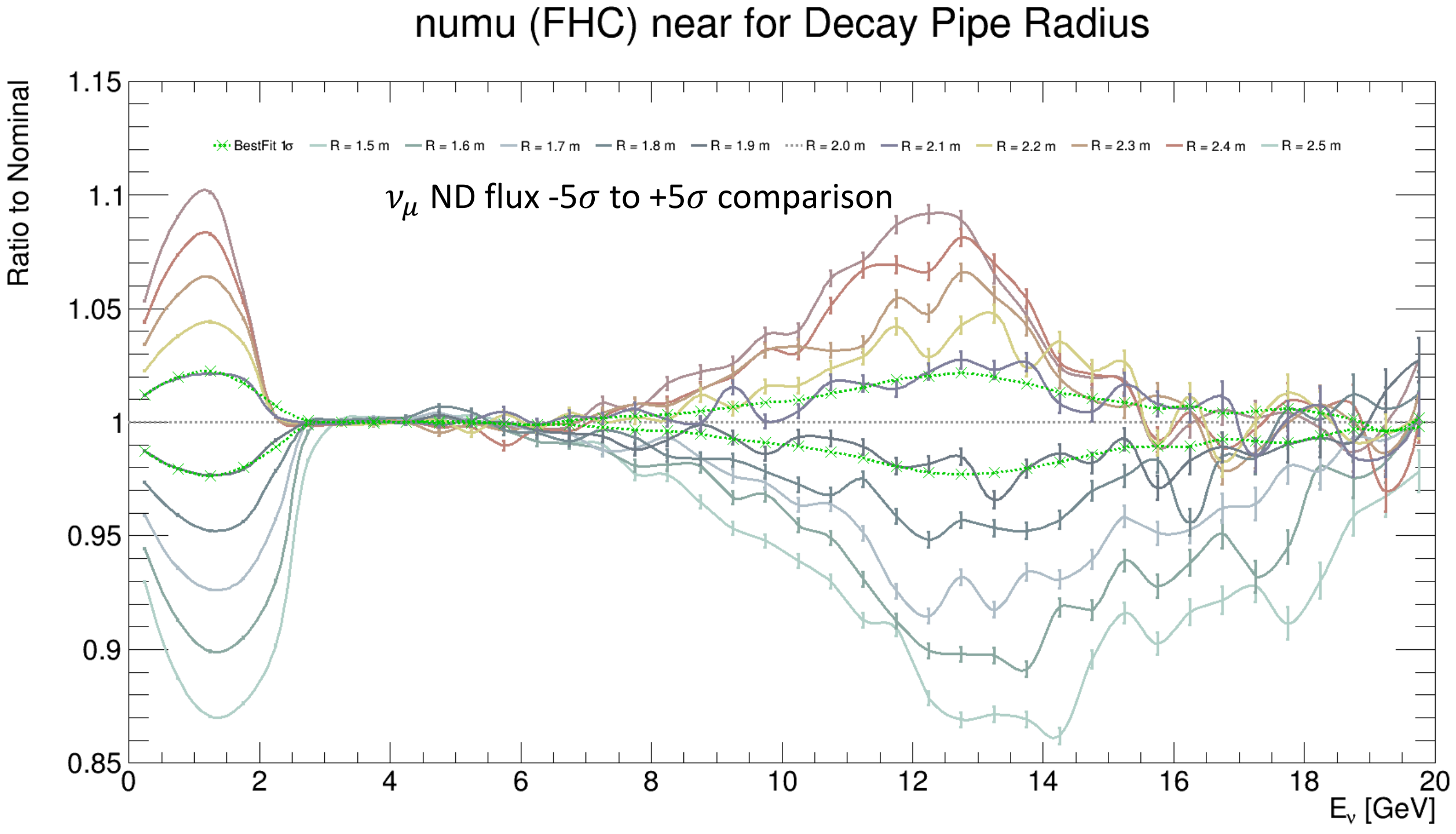


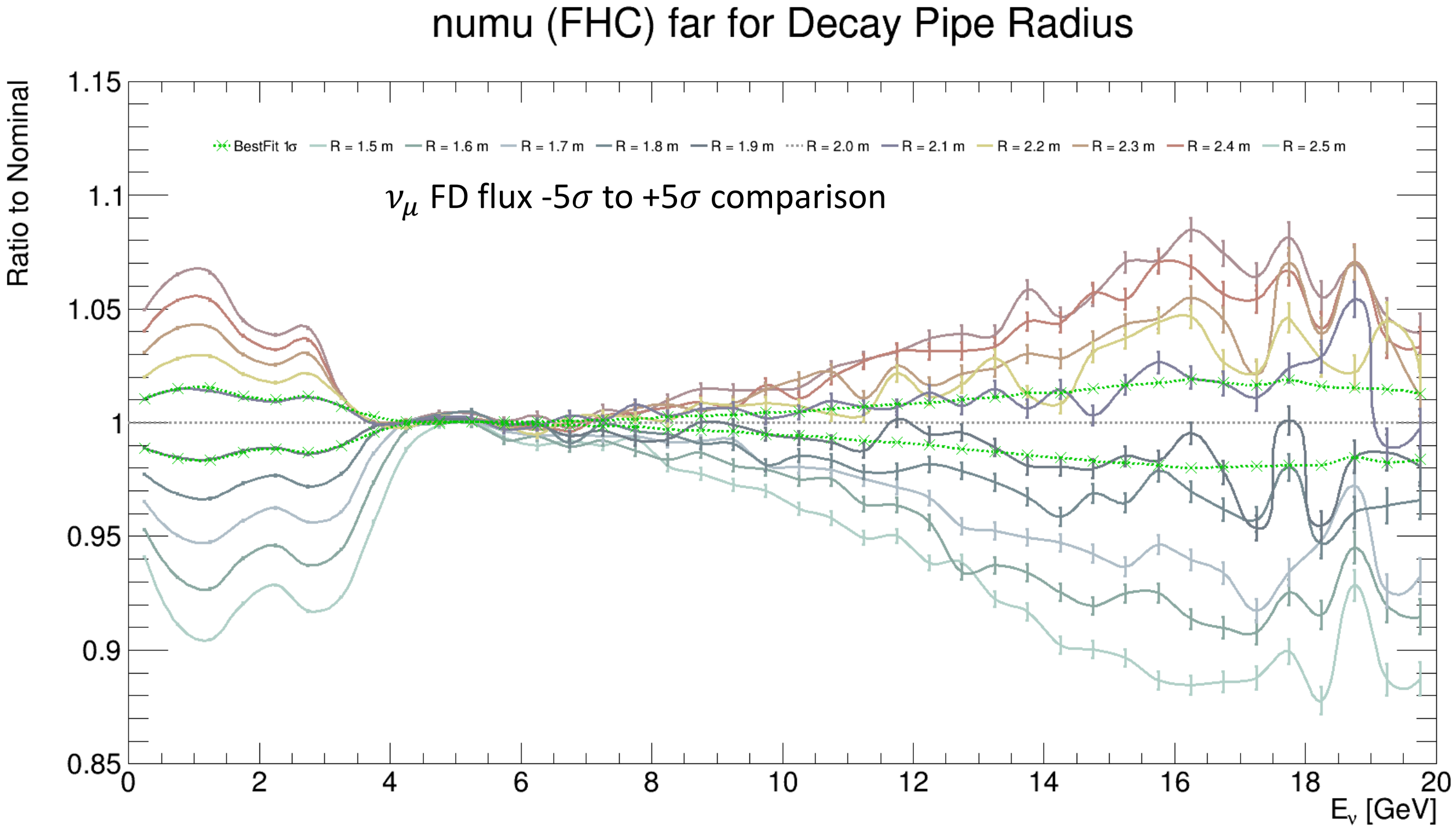
-5σ to 5σ, $d\sigma$ = 1σ

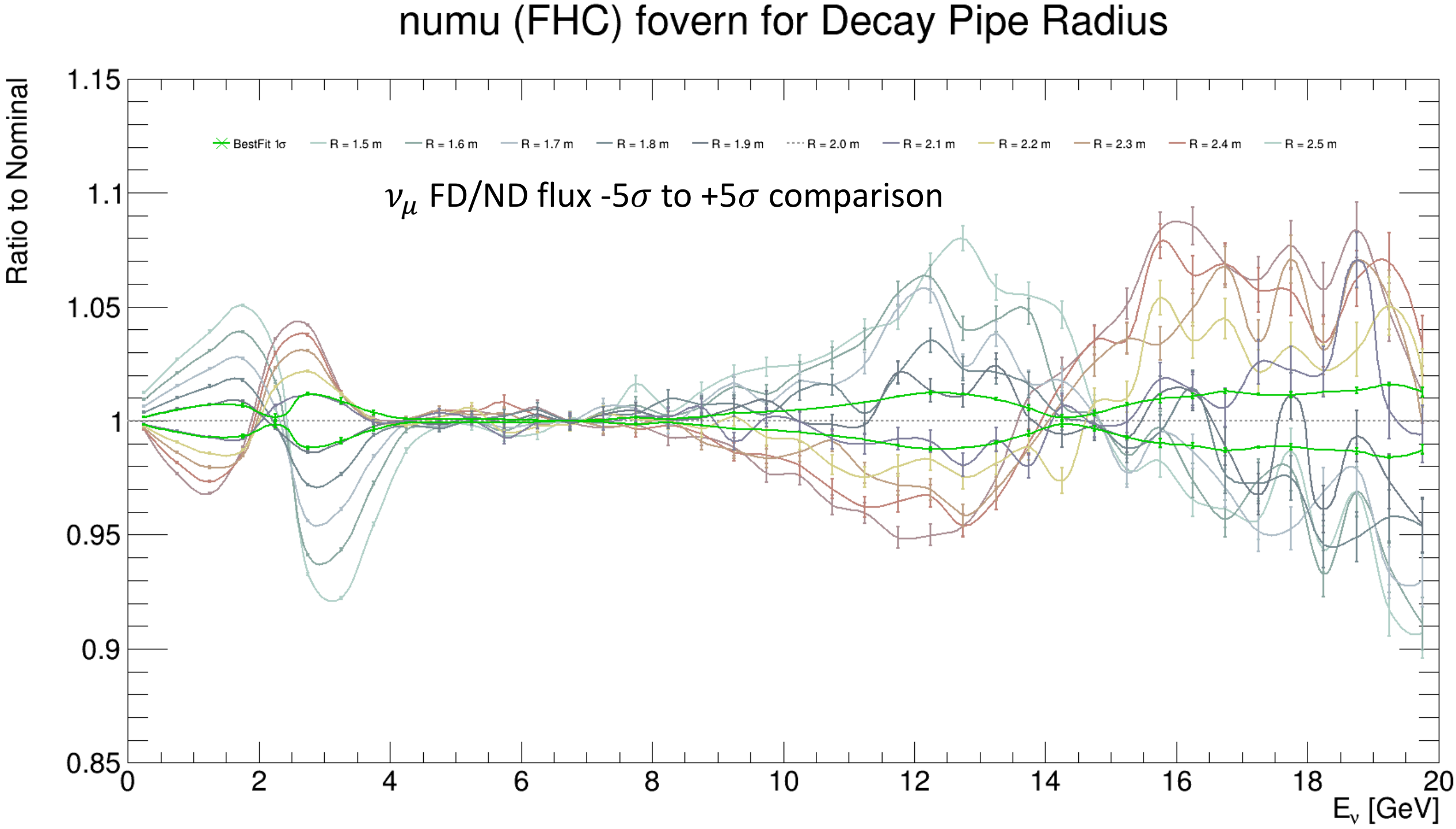




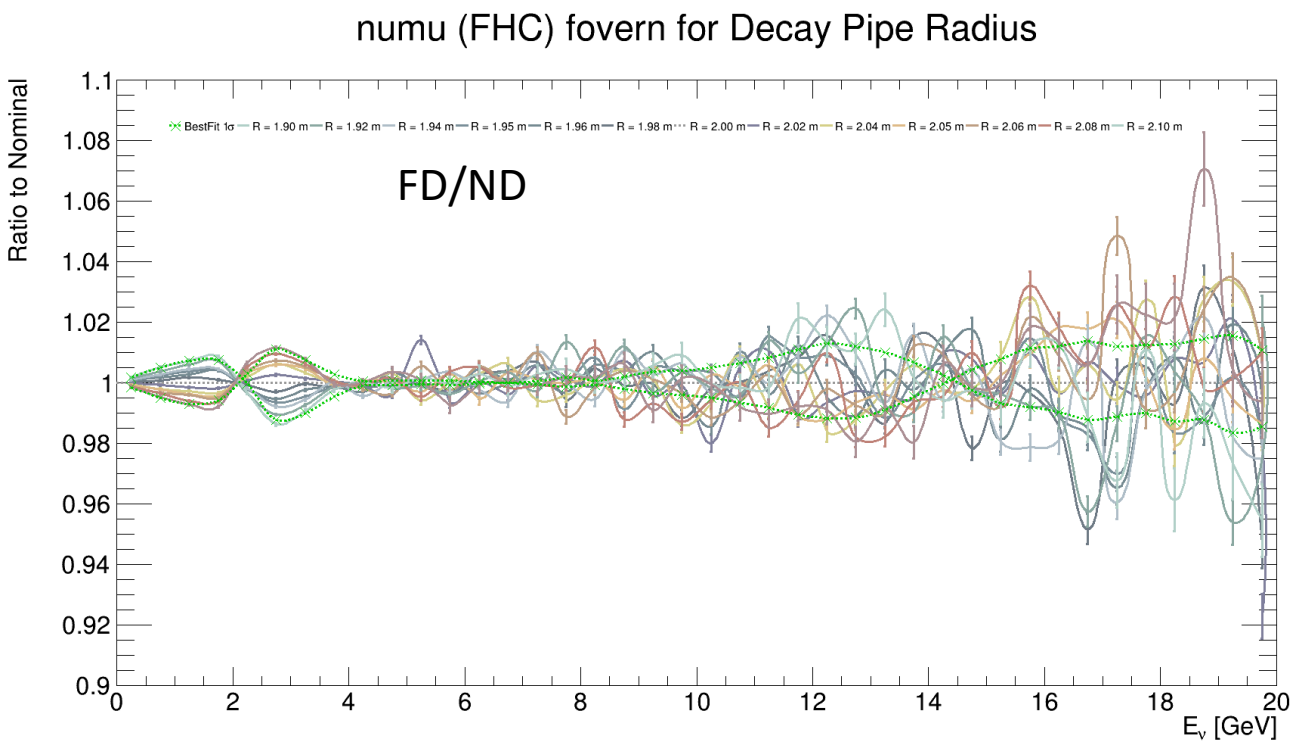


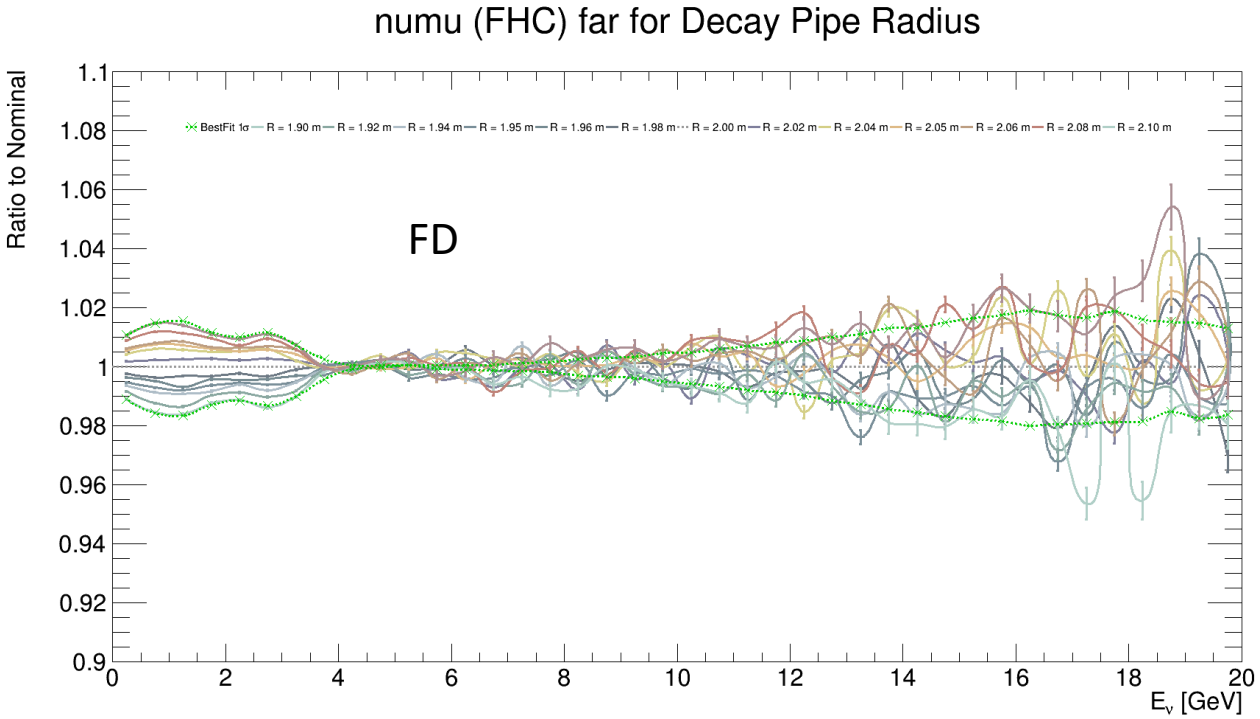

numu (FHC) near for Decay Pipe Radius
Ratio to Nominal
BestFit 1σ
R = 1.5 m
R = 1.6 m
R = 1.7 m
R = 1.8 m
R = 1.9 m
R = 2.0 m
R = 2.1 m
R = 2.2 m
R = 2.3 m
R = 2.4 m
R = 2.5 m
ν_μ ND flux -5σ to +5σ comparison
1.15
1.1
1.05
1
0.95
0.9
0.85
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]

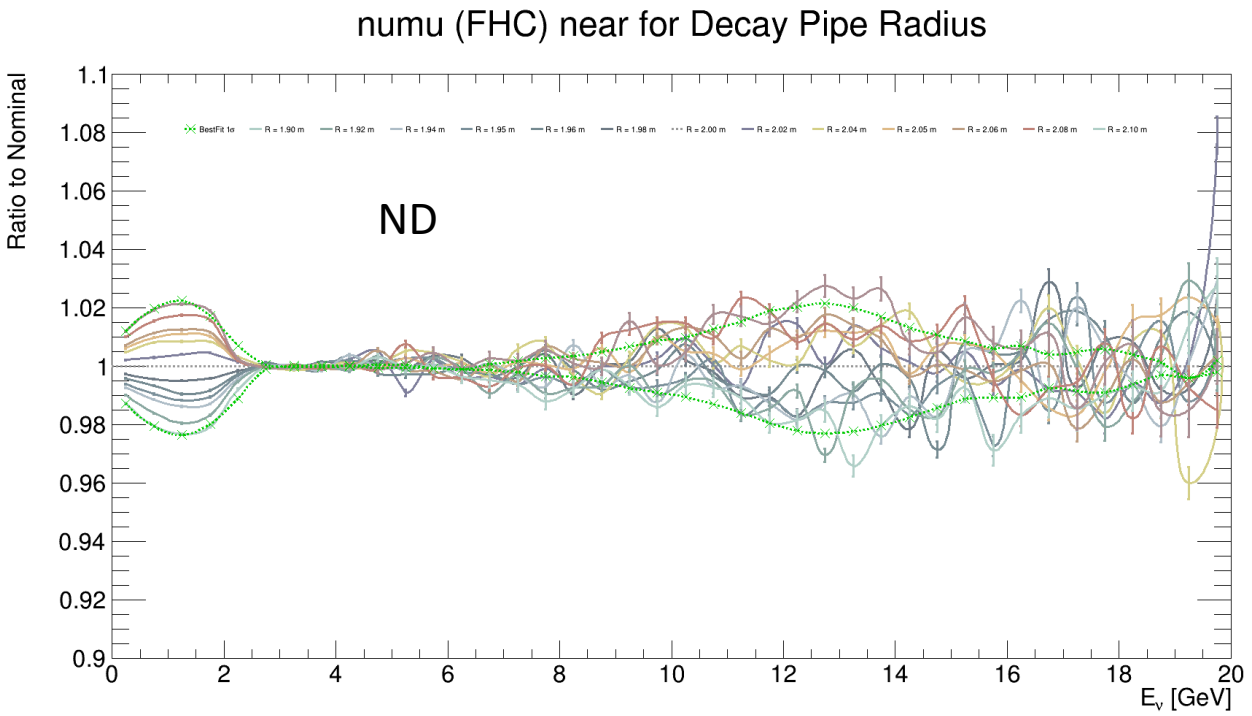

numu (FHC) far for Decay Pipe Radius
ν_μ FD flux -5σ to +5σ comparison
BestFit 1σ
R = 1.5 m
R = 1.6 m
R = 1.7 m
R = 1.8 m
R = 1.9 m
R = 2.0 m
R = 2.1 m
R = 2.2 m
R = 2.3 m
R = 2.4 m
R = 2.5 m
Ratio to Nominal
1.15
1.1
1.05
1
0.95
0.9
0.85
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]


numu (FHC) fovern for Decay Pipe Radius
ν_μ FD/ND flux -5σ to +5σ comparison
BestFit 1σ
R = 1.5 m
R = 1.6 m
R = 1.7 m
R = 1.8 m
R = 1.9 m
R = 2.0 m
R = 2.1 m
R = 2.2 m
R = 2.3 m
R = 2.4 m
R = 2.5 m
Ratio to Nominal
1.15
1.1
1.05
1
0.95
0.9
0.85
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]

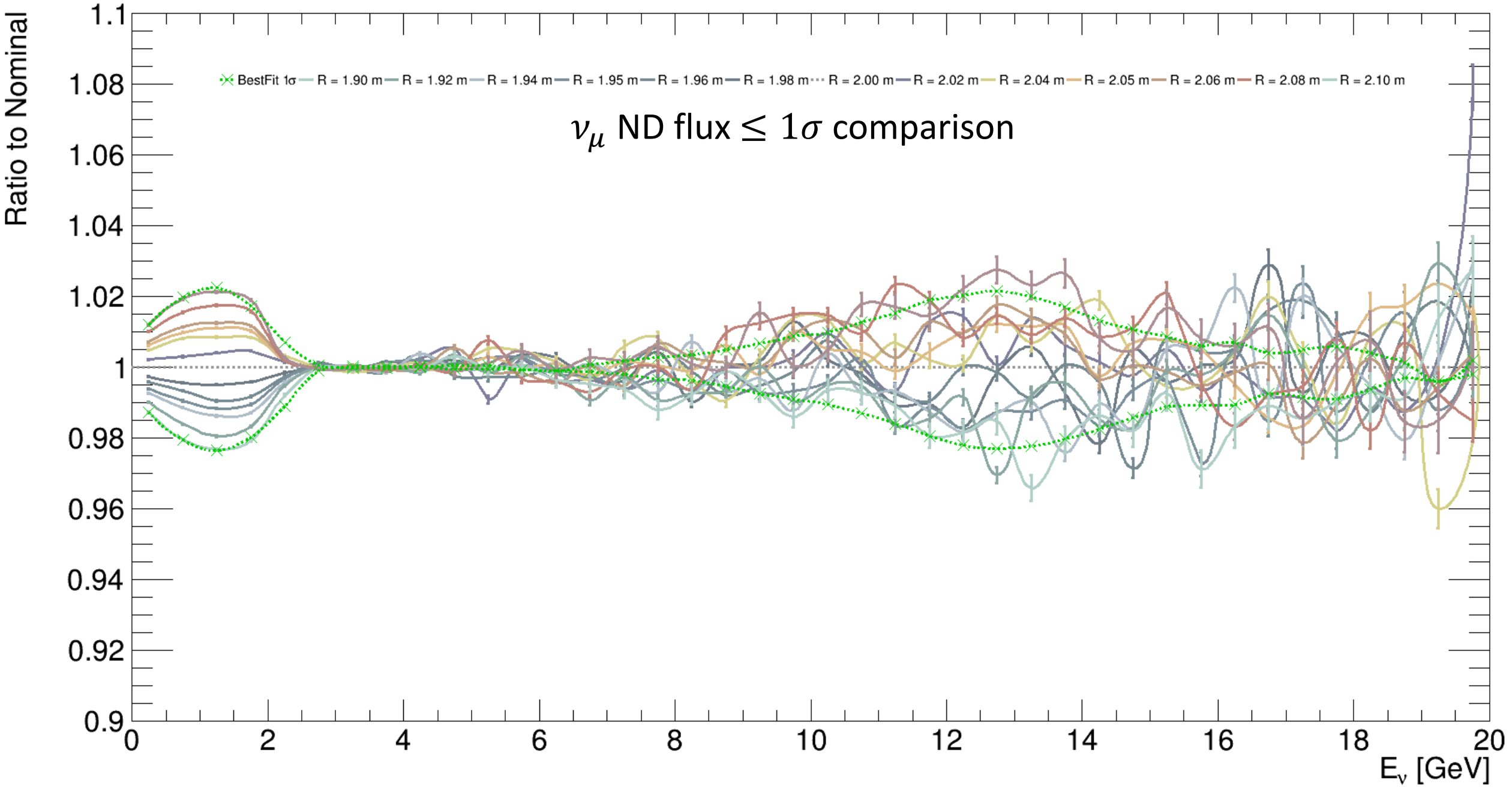
$\leq 1\sigma$ simulations
$\pm 0.2, \pm 0.4, \pm 0.5, \pm 0.6, \pm 0.8\sigma$

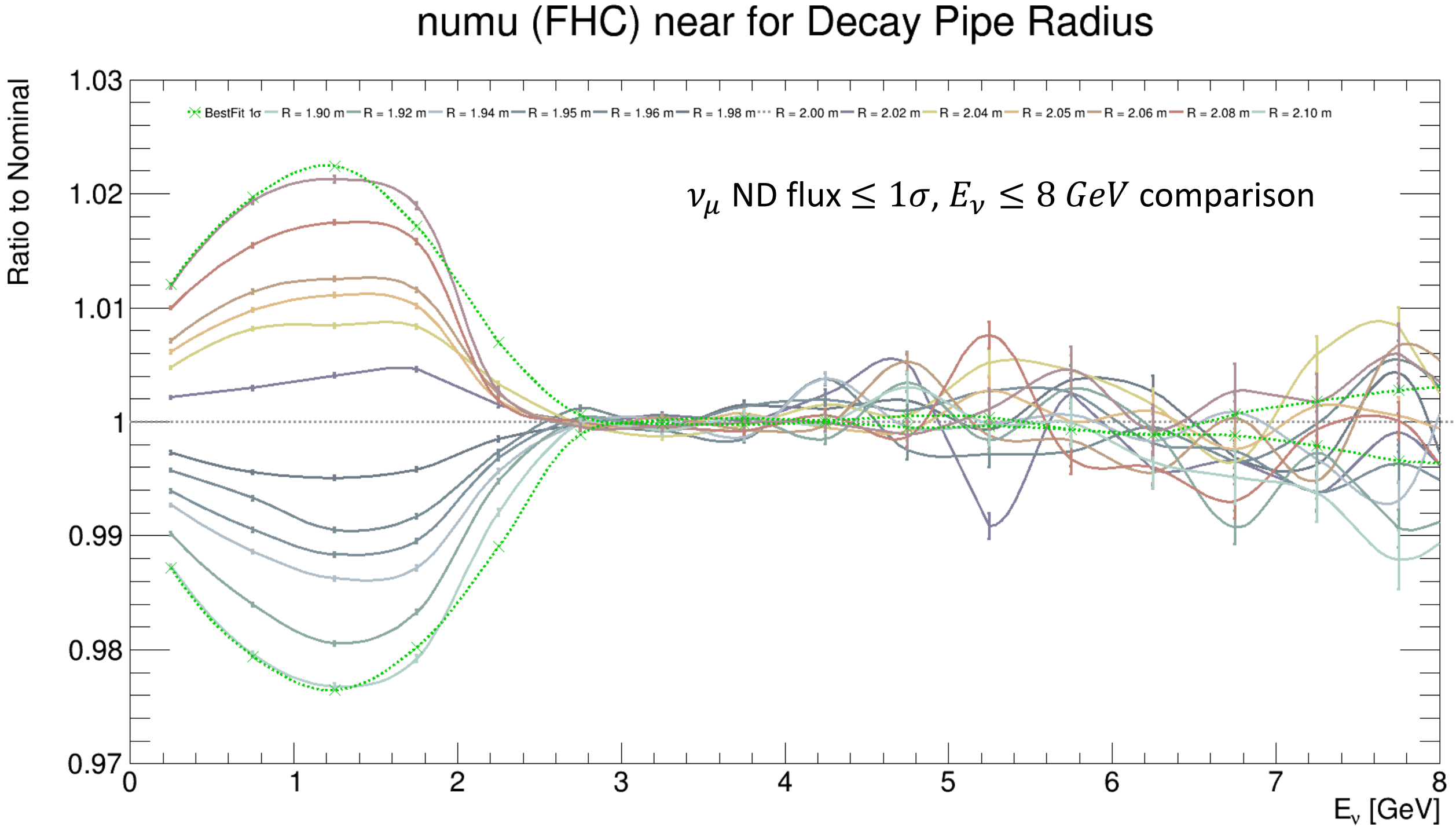


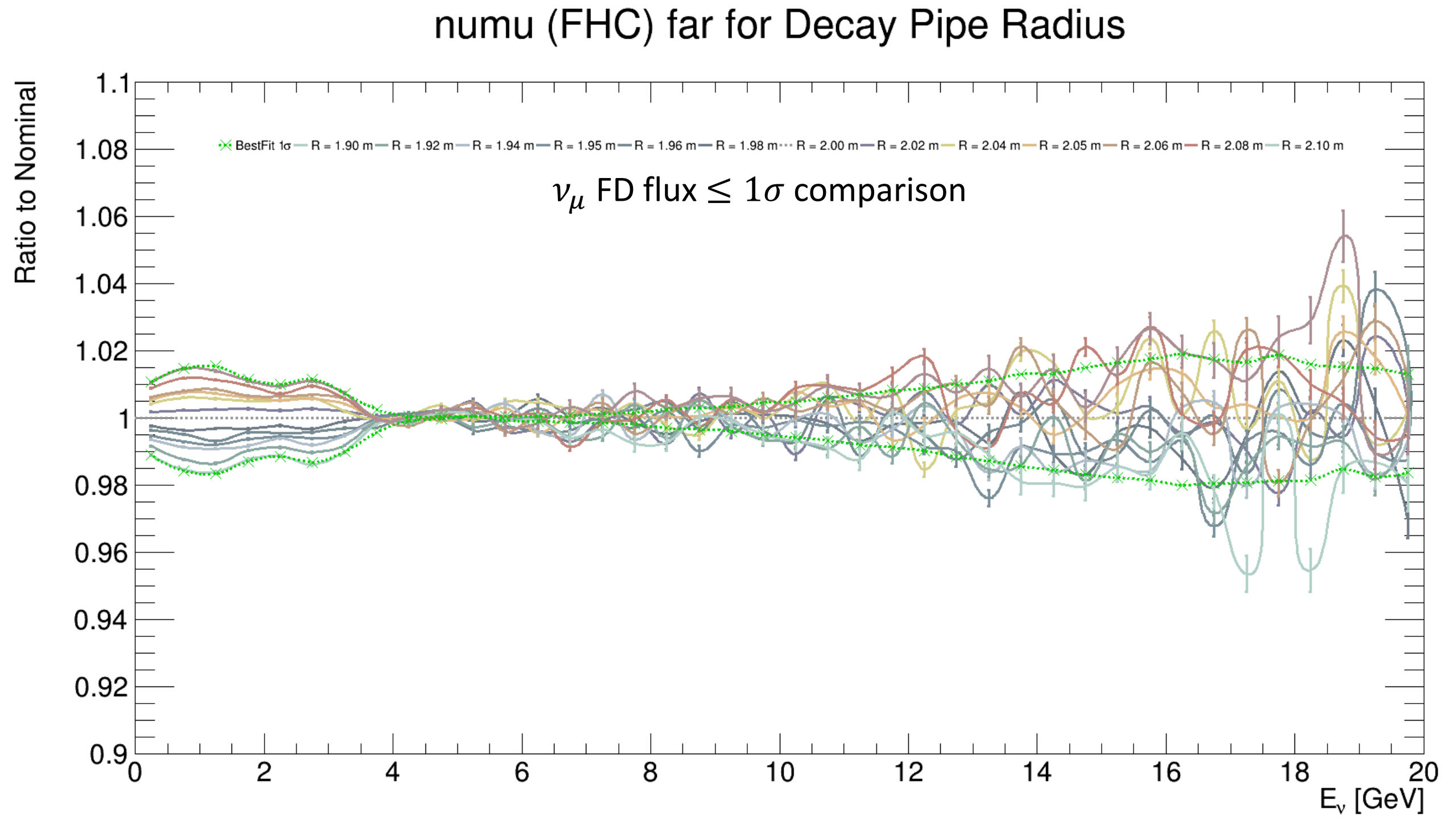




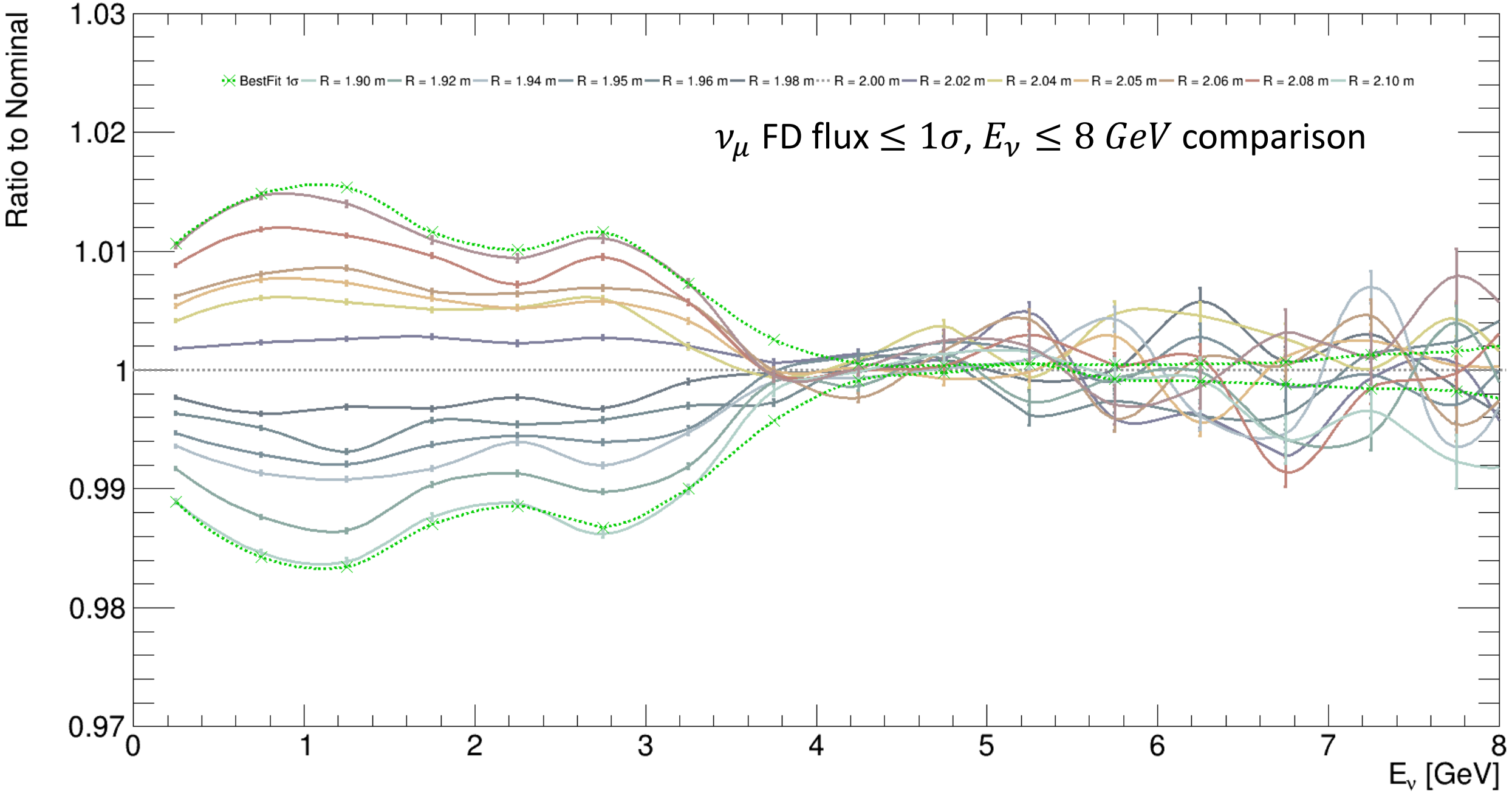
numu (FHC) near for Decay Pipe Radius

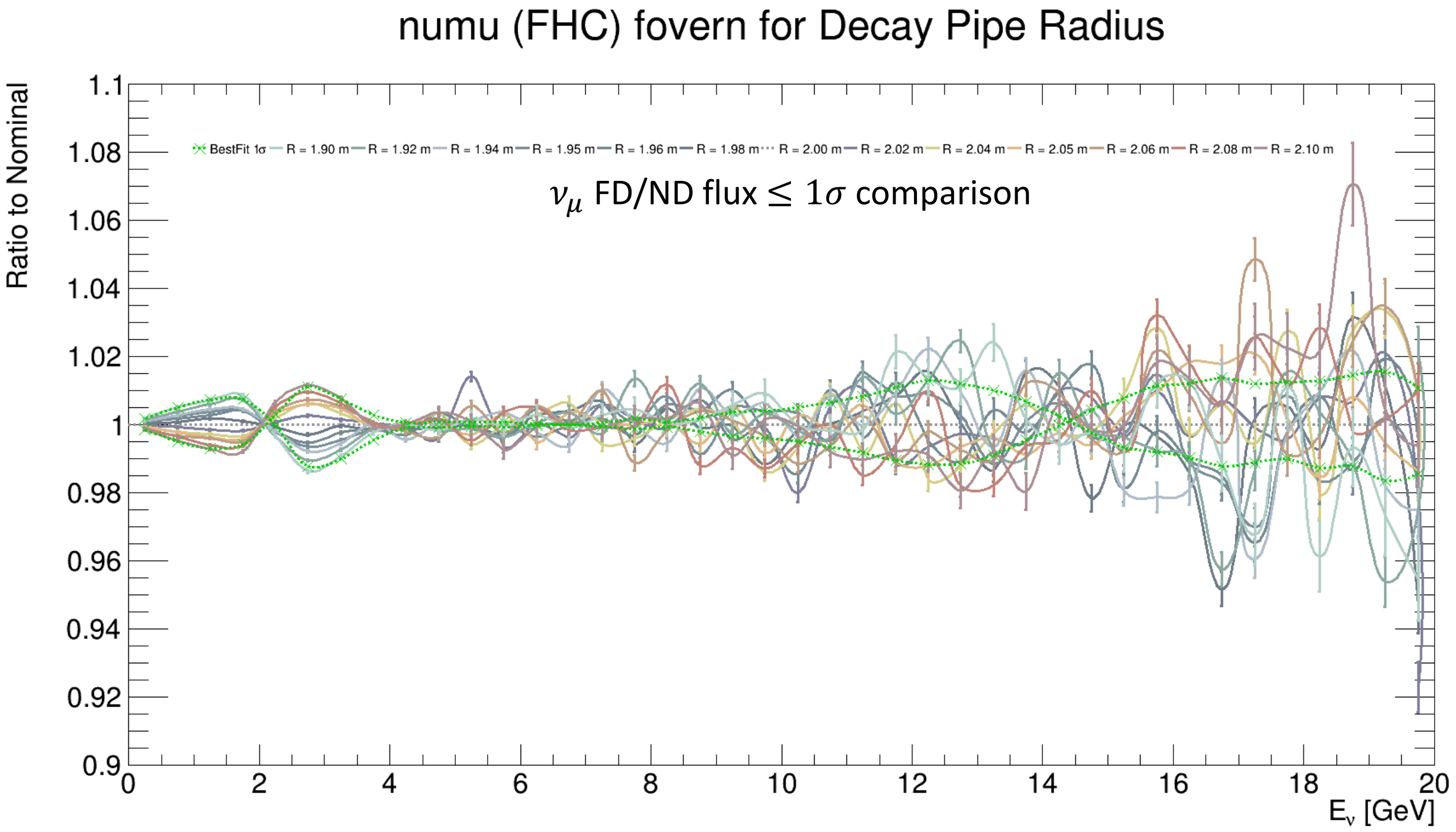


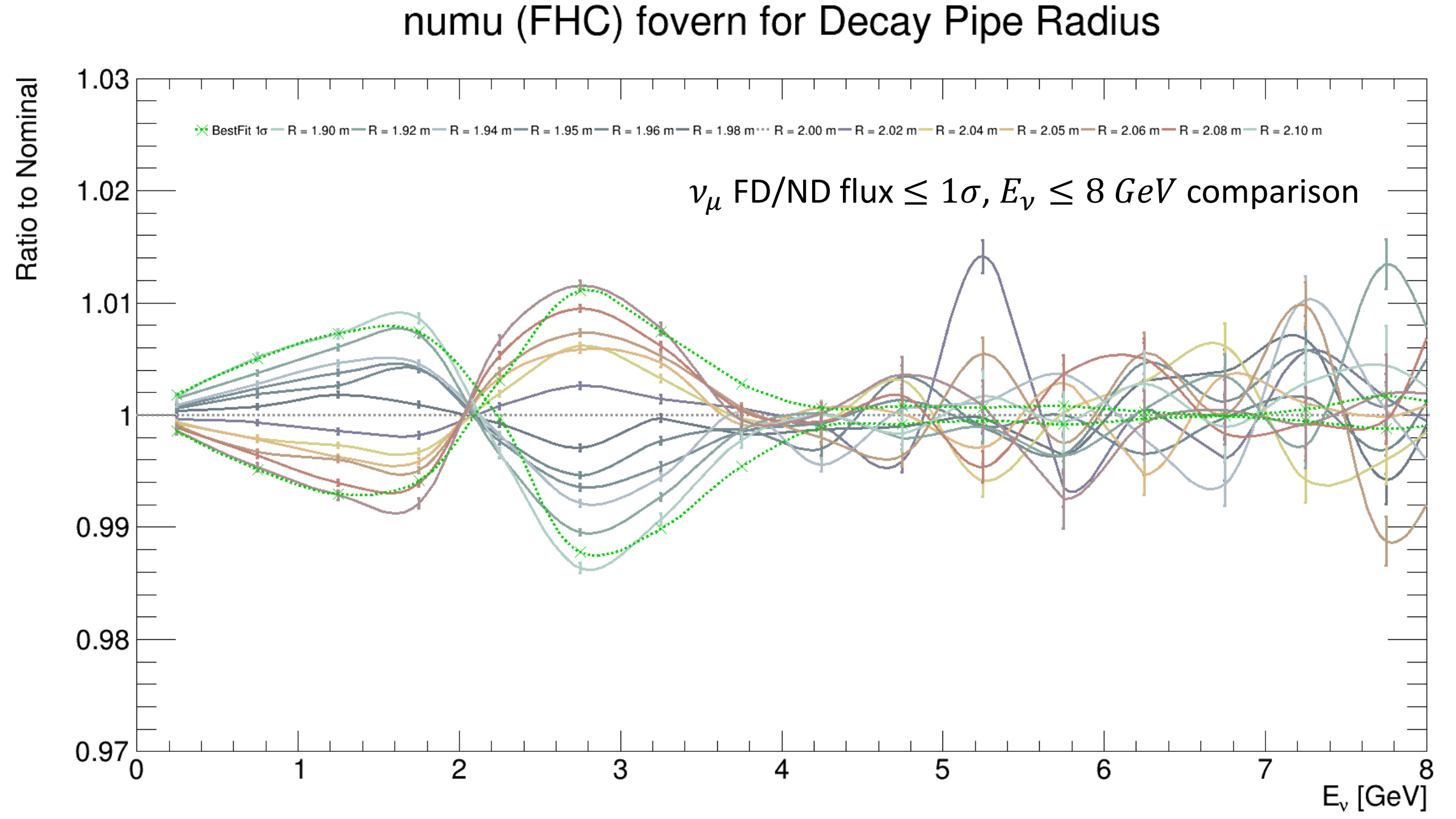

numu (FHC) near for Decay Pipe Radius
Ratio to Nominal
BestFit 1σ
R = 1.90 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2.00 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.10 m
ν_μ ND flux $\leq 1\sigma$, $E_\nu \leq 8\ GeV$ comparison
1.03
1.02
1.01
1
0.99
0.98
0.97
0
1
2
3
4
5
6
7
8
E_ν [GeV]

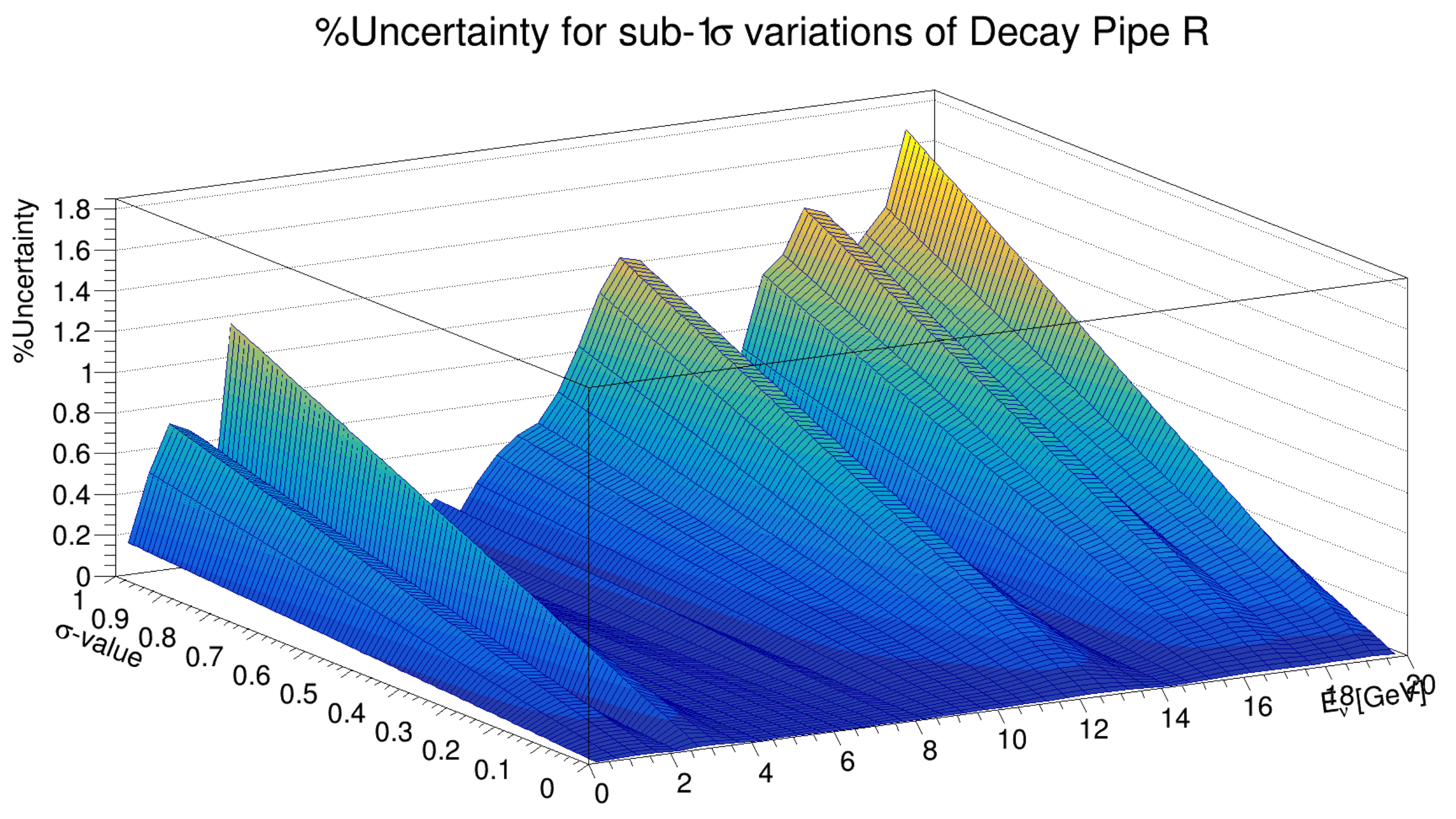

numu (FHC) far for Decay Pipe Radius
ν_μ FD flux $\leq 1\sigma$ comparison
Ratio to Nominal
BestFit 1σ
R = 1.90 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2.00 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.10 m
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]

numu (FHC) far for Decay Pipe Radius




numu (FHC) fovern for Decay Pipe Radius
Ratio to Nominal
BestFit 1σ
R = 1.90 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2.00 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.10 m
ν_μ FD/ND flux $\leq 1\sigma$ comparison
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0
2
4
6
8
10
12
14
16
18
20
E_ν [GeV]


numu (FHC) fovern for Decay Pipe Radius
Ratio to Nominal
BestFit 1σ
R = 1.90 m
R = 1.92 m
R = 1.94 m
R = 1.95 m
R = 1.96 m
R = 1.98 m
R = 2.00 m
R = 2.02 m
R = 2.04 m
R = 2.05 m
R = 2.06 m
R = 2.08 m
R = 2.10 m
ν_μ FD/ND flux $\leq 1\sigma$, $E_\nu \leq 8\ GeV$ comparison
1.03
1.02
1.01
1
0.99
0.98
0.97
0
1
2
3
4
5
6
7
8
E_ν [GeV]


%Uncertainty for sub-1σ variations of Decay Pipe R
%Uncertainty
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
σ-value
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
E_{ν} [GeV]