Implementation of new beam focusing systematics within the PRISM Analysis

Ioana Caracas

on behalf of DUNE – PRISM working group

DUNE LBL Meeting

30.10.2023

Incorporation of beam focusing uncertainties (v3r5p9 release of G4LBNE) within PRISM Analysis

- Focusing uncertainties:
  - the position, geometry, and composition of the beamline components (horns, target, decay pipe, etc)
  - the current or water layer in each horn
  - the geometry of the incident proton beam

- Previous flux focusing systematics (Nov 17) are incomplete and include only 2 horns

- New (not present in the previous releases) uncertainties:
  - tilt of target, horns, decay pipe
  - horns' inner conductor deformations
  - major updates to the decay pipe geometry and positioning

Parameter	1 σ Shift	Notes
Proton Beam Transverse X	0.5 mm	Interaction Position.
Proton Beam Transverse Y	0.5 mm	Updated to 0.5 mm from 4.5 mm in TDR
Proton Beam Angle X	$\delta\theta$ = 70 μrad Φ = 0, π	Proton Beam Angle on target Target Interaction Point fixed to center of target
Proton Beam Angle Y	$\delta\theta$ = 70 μrad Φ =±π/2	
Proton Beam Radius	10% (0.27 mm)	Updated from 1% in the TDR. Change X&Y sigmoid simultaneously
Target Density	2% (0.0356 g/cm^3)	Approximate target degredation
Upstream Target Degredation	5 mm loss	Assume complete loss of target on upstream end; basically a shorter target (by dz) shifted downstream by the loss dz
Target Displace Transverse X	0.5 mm	
Target Displace Transverse Y	0.5 mm	
Target Tilt Transverse X	0.5 mm	
Target Tilt Transverse Y	0.5 mm	
Target Length	1.5 mm (0.01%)	Arbitrarily assumed tolerance
Horn Currents	1% (3 kA)	Simoultaneously change to all 3 Horns; nominal = 300 kA
Horn Water Layer Thickness	0.5 mm	Simultaneous change to all 3 Horns; nominal = 1 mm. Cannot go below 0
Horn A Displace Transverse X	0.5 mm	
Horn A Displace Transverse Y	0.5 mm	
Horn A Displace Longitudinal Z	2.0 mm	
Horn A Tilt Transverse X	0.5 mm	Upstream and downstream ends shifted in opposite directions by tolerance value
Horn A Tilt Transverse Y	0.5 mm	
Horn A Eccentricity X Induced B Field	0.035 mm	Horn A Inner conductor eccentrictiy: Eccentric (off aixs) deformation of inner conductor; induced dipole field in y in field-free region. NuMI Horn 1 tolerance assumed
Horn A Ellipticity X Induced B Field	0.120mm	Elliptical deformation of inner conductor; induced quadrupole field in x-y in field-free region; NuMI Horn1 tolerance assumed
Horn B Displace Transverse X	0.5 mm	
Horn B Displace Transverse Y	0.5 mm	
Horn B Displace Longitudinal Z	3.0 mm	
Horn B Tilt Transverse X	0.5 mm	Upstream and downstream ends shifted in opposite directions by tolerance value
Horn B Tilt Transverse Y	0.5 mm	
Horn B Ellipticity X Induced B Field	0.180 mm	NuMI Horn 2 tolerance assumed
Horn C Displace Transverse X	0.5 mm	
Horn C Displace Transverse Y	0.5 mm	
Horn C Displace Longitudinal Z	3.0 mm	
Horn C Tilt Transverse X	0.5 mm	
Horn C Tilt Transverse Y	0.5 mm	
Horn C Eccentricity X Induced B Field	0.07 mm	NuMI horn 2 tolerance assumed
Horn C Ellipticity X Induced B Field	0.180 mm	NuMI horn 2 tolerance assumed
Decay Pipe Radius	2.0 cm	Changed from 10 cm; nominal = 2 m
Decay Pipe Length	2.5 cm	Same as elongating, since the distance between decay pipe upstream is fixed
Decay Pipe Displace Transverse X	2.5 cm	
Decay Pipe Displace Transverse Y	2.5 cm	
Decay Pipe Tilt X _ DSOA	2.5 cm	Downstream (DS) end fixed to remain on axis
Decay Pipe Tilt Y _ DSOA	2.5 cm	
Decay Pipe Elliptical Cross section X (A)	2.5 cm	Ellipse with A (X-axis) or B (y-axis) varied by tolerance, while other dimension fixed to nominal radius
Decay Pipe Elliptical Cross section Y (B)	2.5 cm	
Decay Pipe Geo B Field	1	Scale-factor value to 1 is 1σ tolerance. Mapped from NuMI decay pipe geo B-field measurements
Decay Pipe Segmented Bowing X	2.5 cm	Decay Pipe segmented in 3 equal pieces; central piece transverse shifted by tolerance
Decay Pipe Segmented Bowing X	2.5 cm	

New Flux Systematics – September 2021

September 2021: 45 flux parameters (beam systs)

→ Investigate the effect each individual parameter has on the PRISM oscillation analysis

10 IMPORTANT (influence the sensitivity substantially)

8 SEMI (influence the oscillation fit much less)

27 NEGLIGIBLE (negligible effect on the oscillation fit)

- Analysis variable **is reconstructed neutrino energy:** EnuReco

  → all of the presented results are obtained by using EnuReco unless stated otherwise

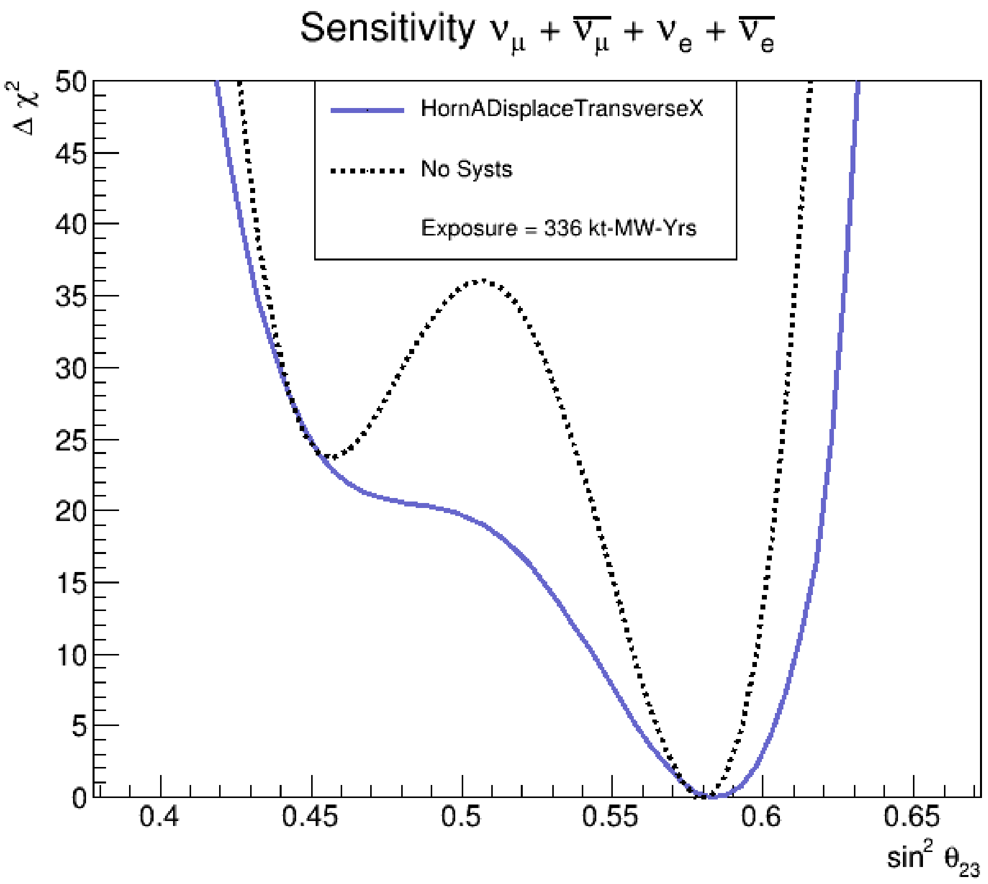
September 2021 flux focusing parameters

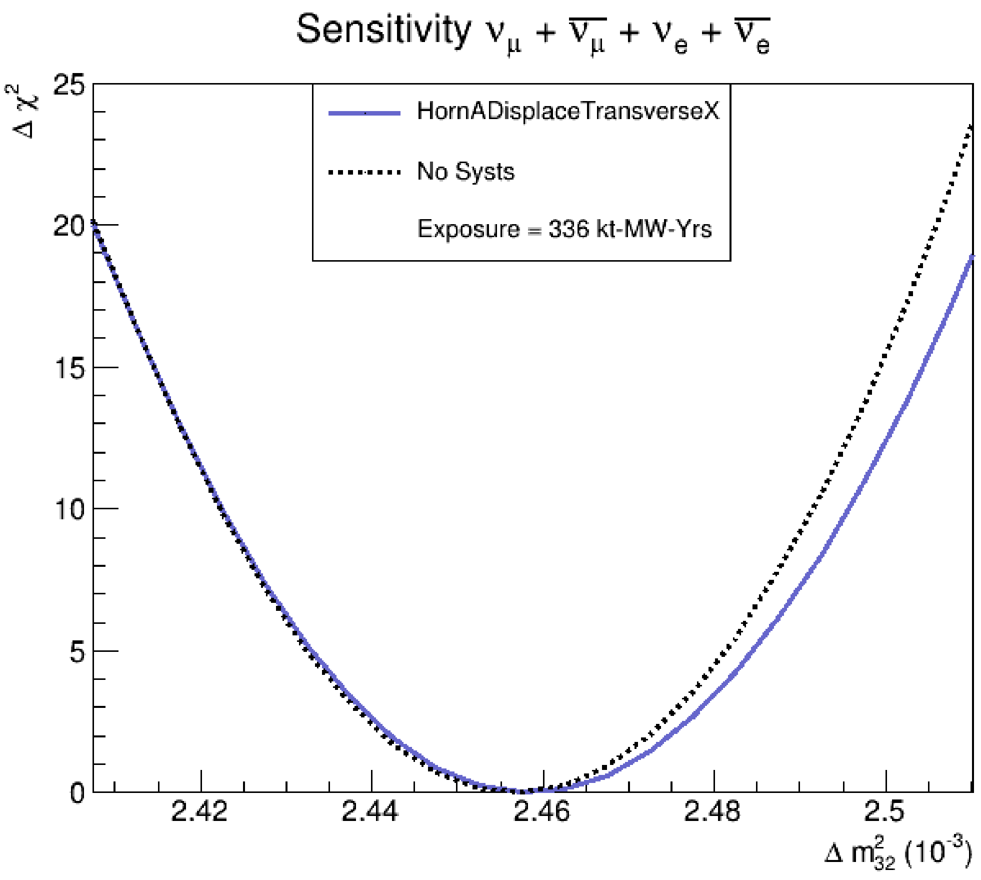
" HornADisplaceTransverseX ",
" HornBDisplaceTransverseX ",
" HornCDisplaceTransverseX ",
" HornADisplaceTransverseY ",
" HornBDisplaceTransverseY ",
" HornCDisplaceTransverseY ",
" DecayPipe3SegmentBowingX ",
" DecayPipe3SegmentBowingY ",
" DecayPipeDisplaceTransverseX ",
" DecayPipeDisplaceTransverseY ",
" DecayPipeEllipticalCrossSectionXA ",
" DecayPipeEllipticalCrossSectionYB ",
" DecayPipeGeoBField ",
" DecayPipeLength ",
" DecayPipeRadius ",
" DecayPipeTiltX_DSOA ",
" DecayPipeTiltY_DSOA ",
" HornADisplaceLongitudinalZ ",
" HornAEccentricityXInducedBField ",
" HornAEllipticityXInducedBField ",
" HornATiltTransverseX ",
" HornATiltTransverseY ",
" HornBDisplaceLongitudinalZ ",
" HornBEllipticityXInducedBField ",
" HornBTiltTransverseX ",
" HornBTiltTransverseY ",
" HornCDisplaceLongitudinalZ ",
" HornCEccentricityXInducedBField ",
" HornCEllipticityXInducedBField ",
" HornCTiltTransverseX ",
" HornCTiltTransverseY ",
" HornCurrent ",
" HornWaterLayerThickness ",
" ProtonBeamAngleX ",
" ProtonBeamAngleY ",
" ProtonBeamRadius ",
" ProtonBeamTransverseX ",
" ProtonBeamTransverseY ",
" TargetDensity ",
" TargetDisplaceTransverseX ",
" TargetDisplaceTransverseY ",
" TargetLength ",
" TargetTiltTransverseX ",
" TargetTiltTransverseY ",
" TargetUpstreamDegredation "

Horn A Displace Transverse X

IMPORTANT

- 1σ shift = 0.5 mm

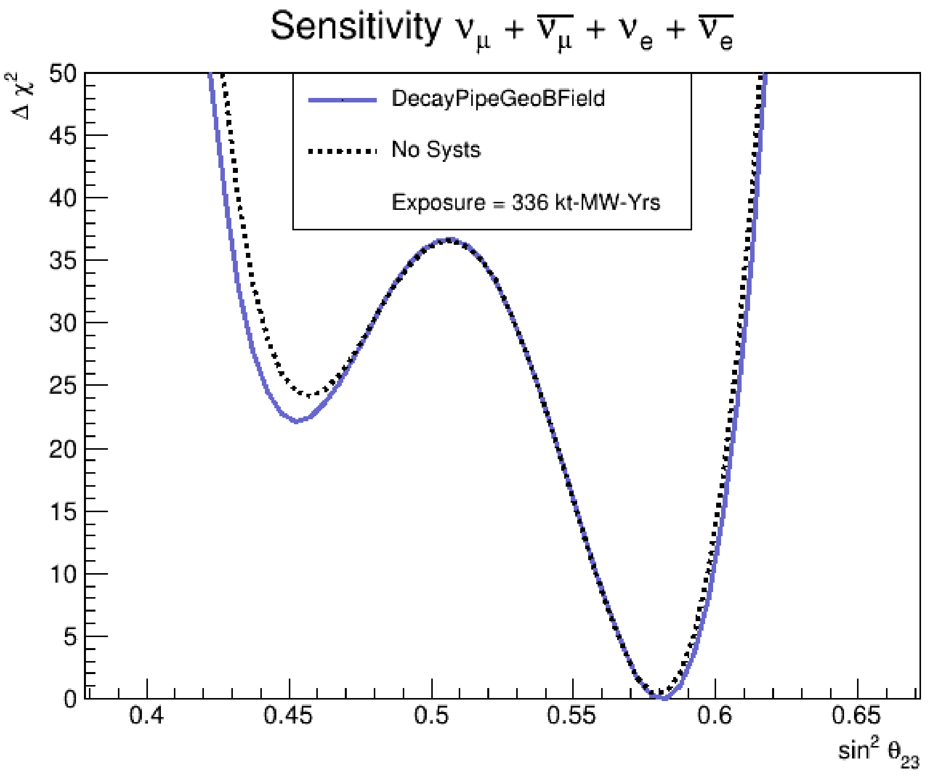


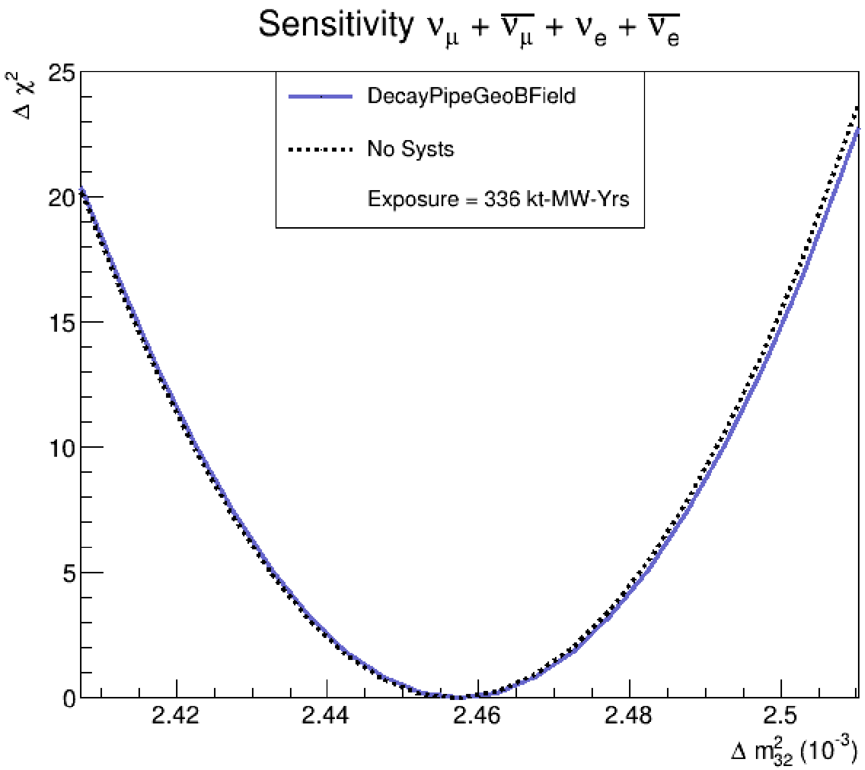


Decay Pipe Geo BField

SEMI

- 1σ shift = 1: scale factor value of 1 is 1σ tolerance
(mapped from NuMI Decay Pipe Geo Bfield measurements)

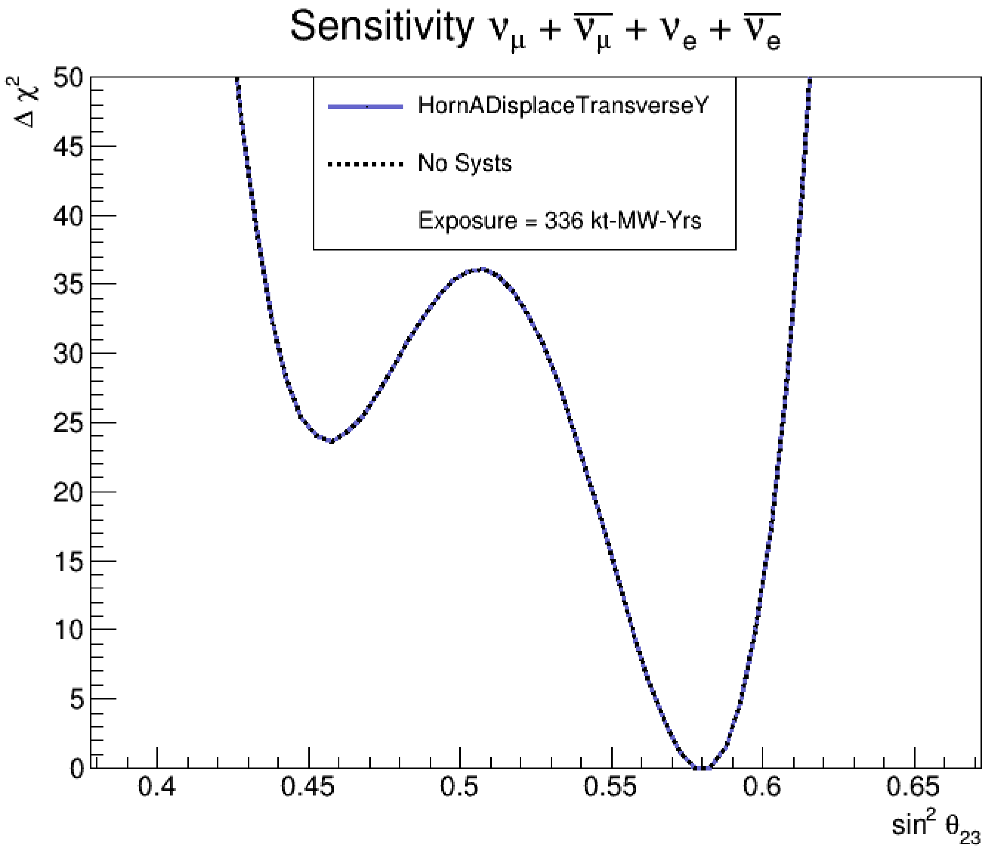


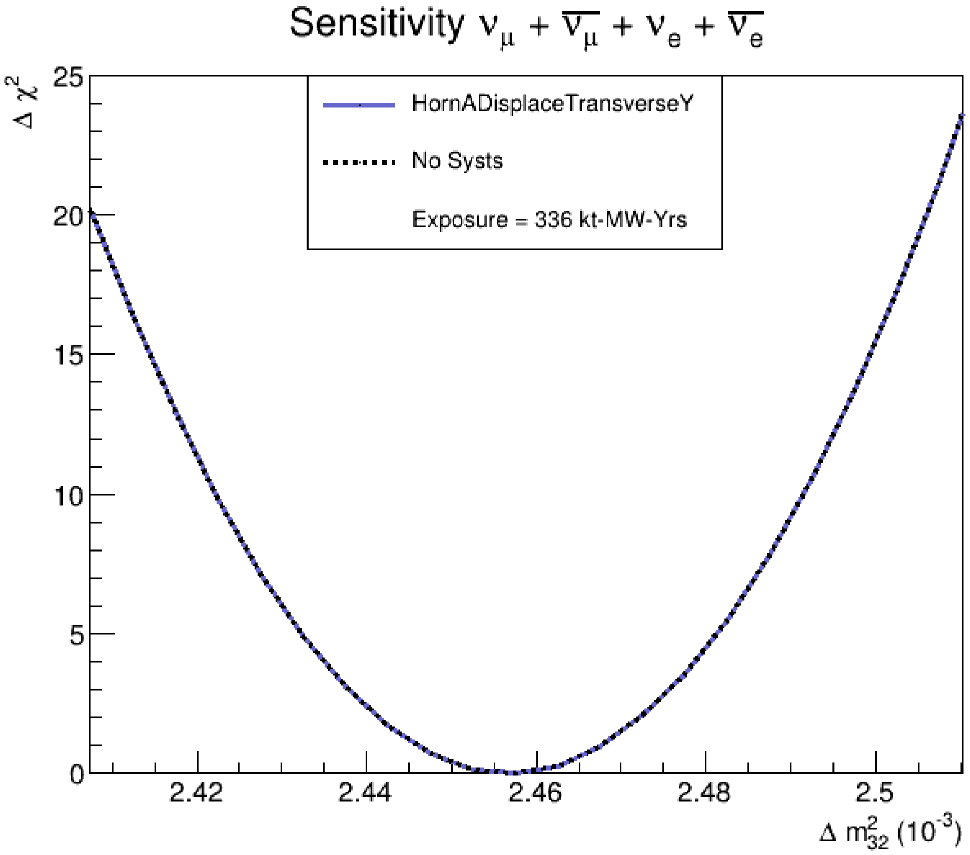


Horn A Displace Transverse Y

NEGLIGIBLE

- 1σ shift = 0.5 mm





New Flux Systematics (Sept 21) – Important parameters

10 IMPORTANT parameters: influence the sensitivity substantially

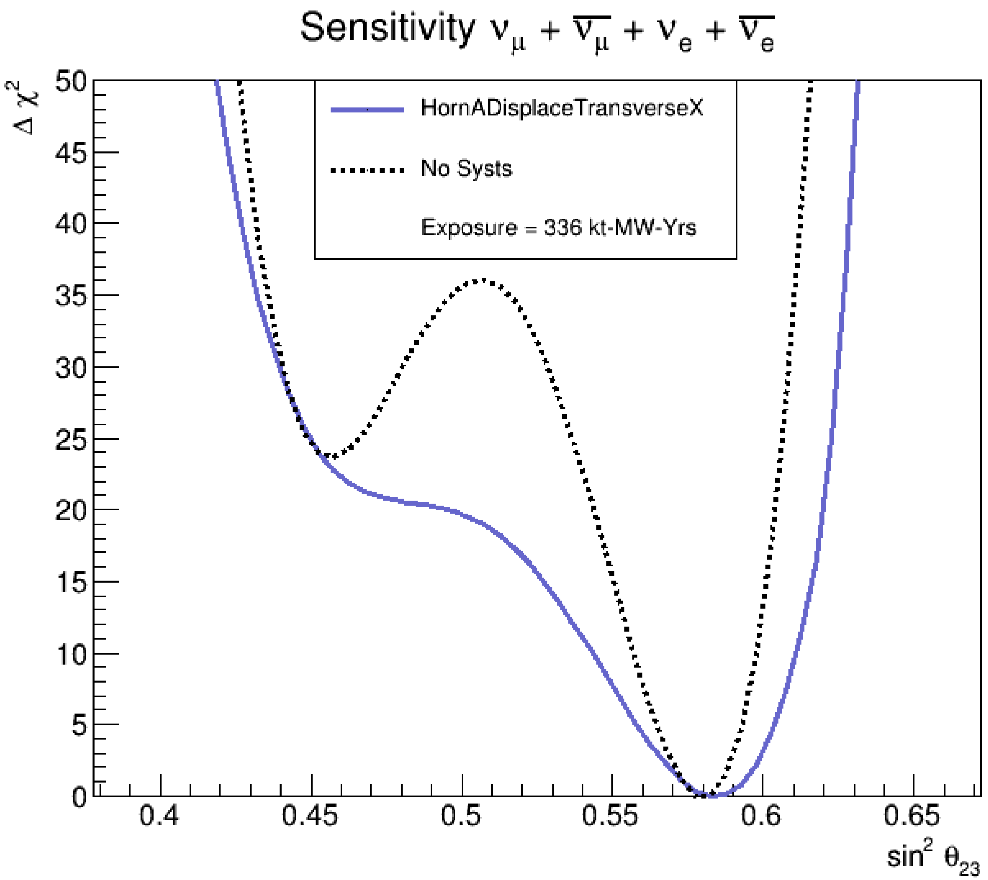
- **HornADisplaceTransverseX**
- HornBDisplaceTransverseX
- HornCDisplaceTransverseX
- HornAEccentricityXInducedBField
- HornCEccentricityXInducedBField
- HornATiltTransverseX
- **HornCurrent**
- **HornWaterLayerThickness**
- ProtonBeamTransverseX
- TargetUpstreamDegredation

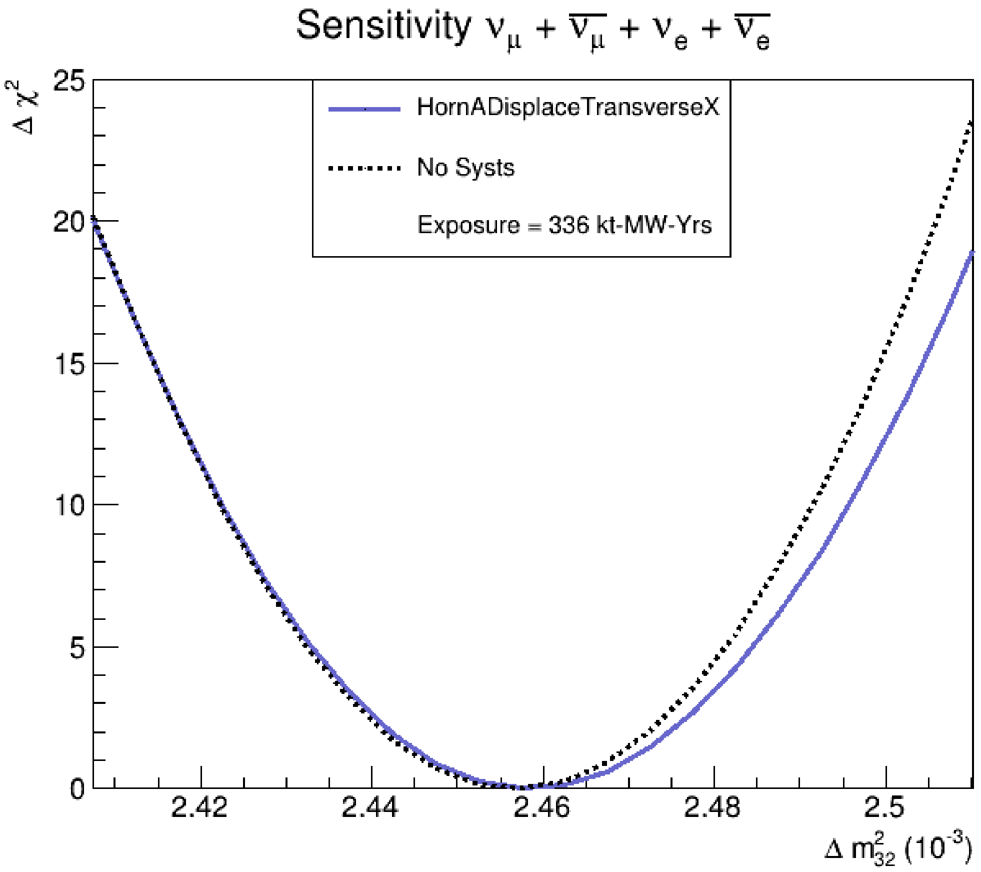
- New uncertainties (not present in TDR): Horn C Displace Transverse, Eccentricity X (both A and C), Horn Tilt (horn A) target upstream degredation

Horn A Displace Transverse X

IMPORTANT

- 1σ shift = 0.5 mm



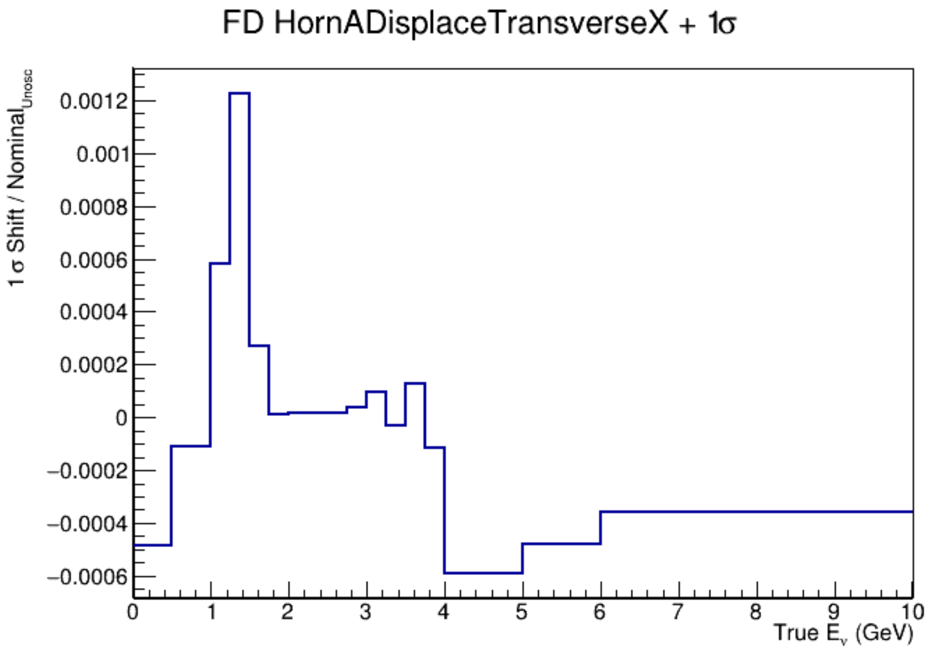


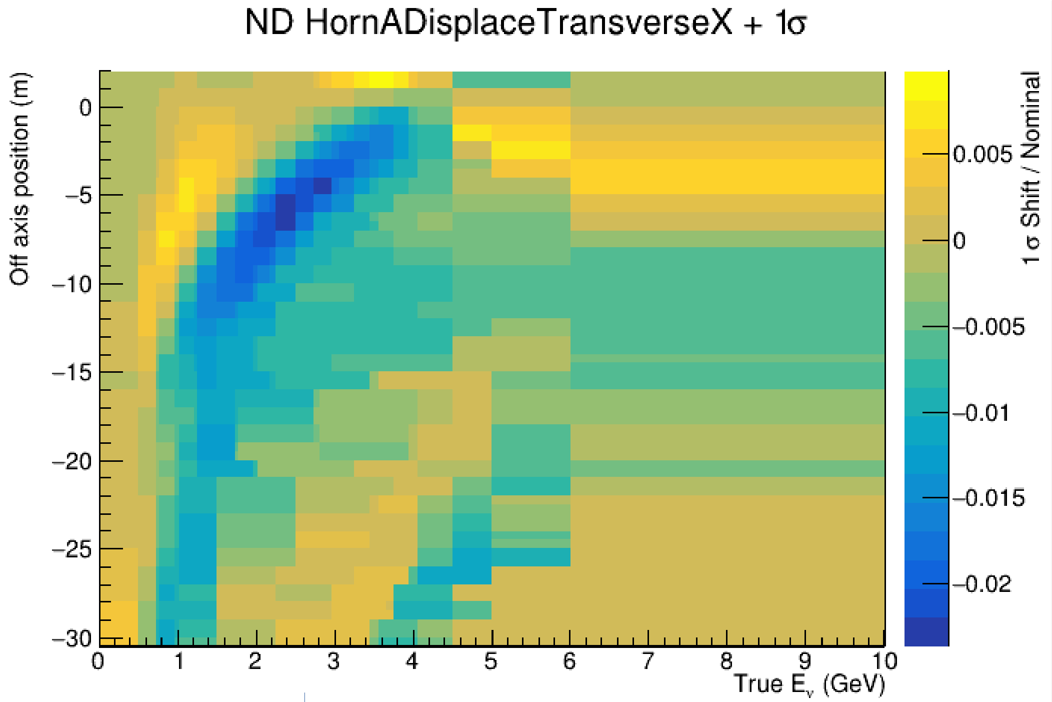
Horn A Displace Transverse X

IMPORTANT

- 1σ shift = 0.5 mm, $\nu_\mu \rightarrow \nu_\mu$ channel

- look at both FD and ND fractional ratios versus energy when the the flux parameter of interest is shifted by 1 σ



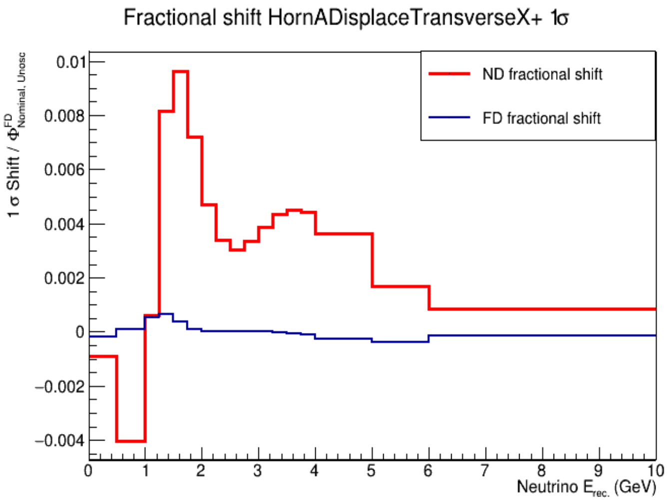


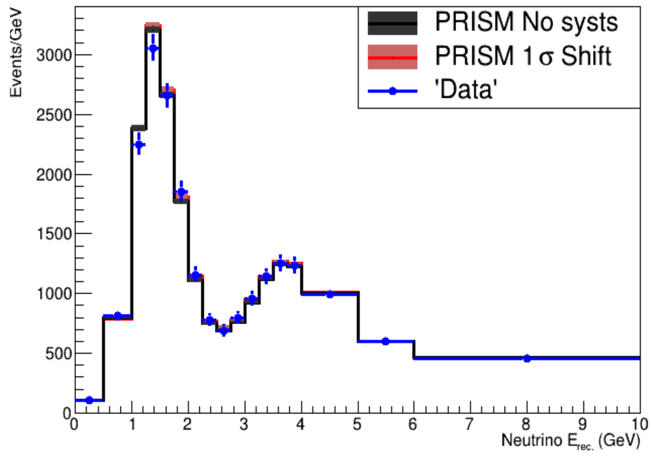
Linearly combine to get the PRISM fractional uncertainty

Horn A Displace Transverse X

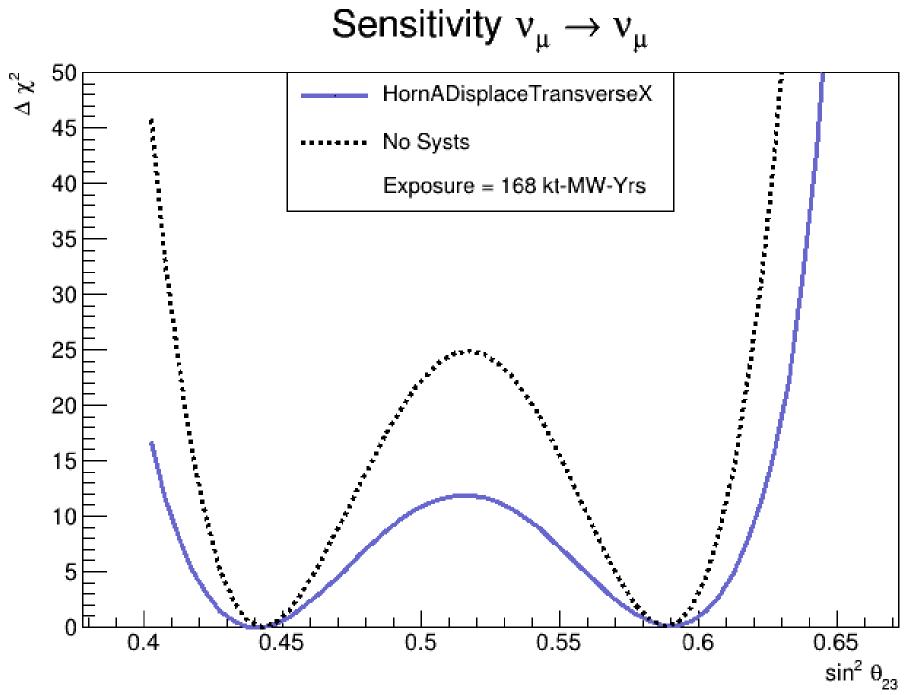
IMPORTANT

- 1σ shift = 0.5 mm, $\nu_\mu \rightarrow \nu_\mu$ channel





- PRISM linear combination (ND) fractional shift is much higher than the oscillated FD one + different energy dependence between ND and FD → impact on the oscillation parameters sensitivity
- uncertainties of < 1% (small difference between nominal and 1 σ shifted prediction) → **why such a high sensitivity reduction?**

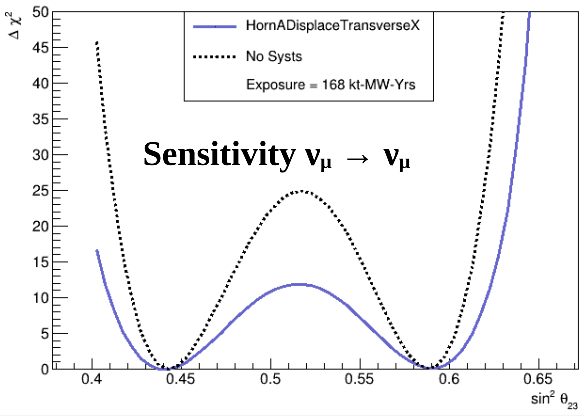


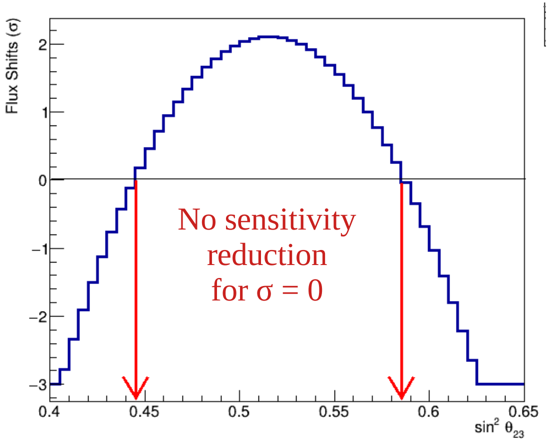
Horn A Displace Transverse X

IMPORTANT

- 1σ shift = 0.5 mm, $\nu_\mu \rightarrow \nu_\mu$ channel

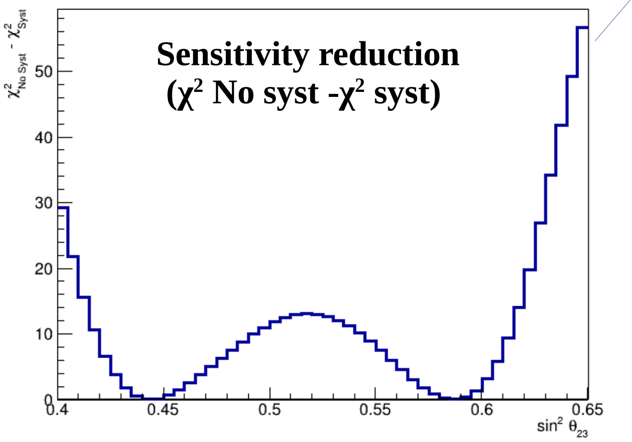
→ investigate sensitivity reduction and systematic shifts corresponding to best χ^2 at each scan parameter

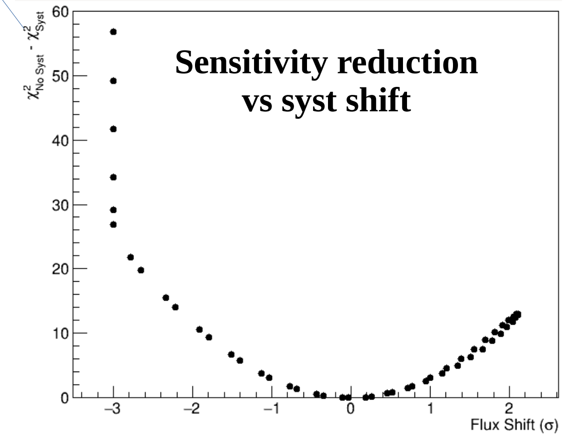




Biggest sensitivity reduction for -3 σ shift

→ why is a -3 σ shift preferred as the best fit?



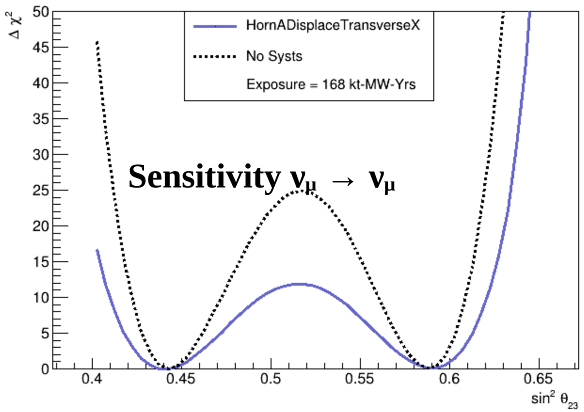


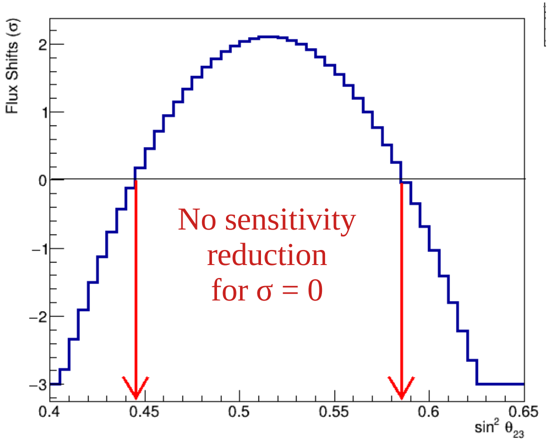
Horn A Displace Transverse X

IMPORTANT

- 1σ shift = 0.5 mm, $\nu_\mu \rightarrow \nu_\mu$ channel

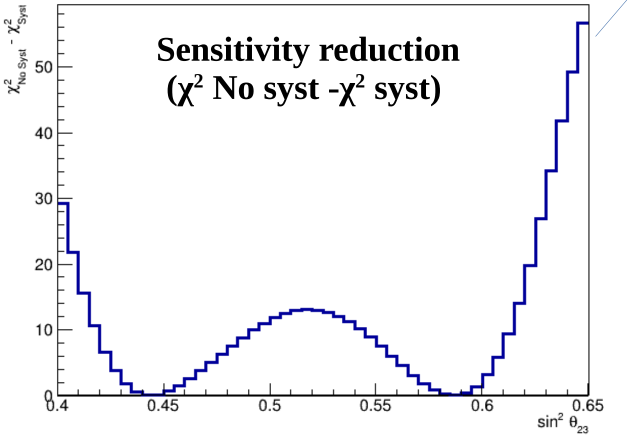
→ investigate sensitivity reduction and systematic shifts corresponding to best χ^2 at each scan parameter





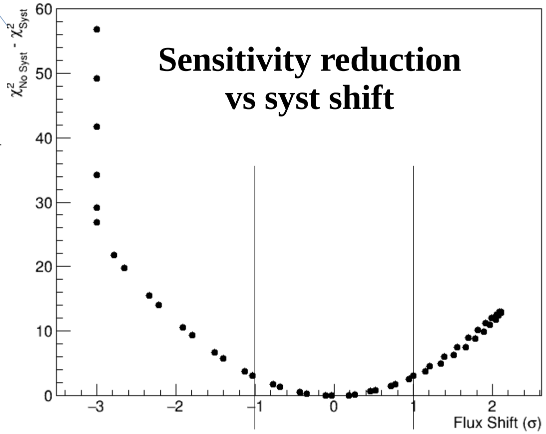
Biggest sensitivity reduction for -3 σ shift

→ why is a -3 σ shift preferred as the best fit?



All of our plots are for +1σ shift and $\sin^2\theta_{23}$ = 0.58 (Asimov) → very small sensitivity reduction

→ check PRISM prediction for some of the angles with a large shift

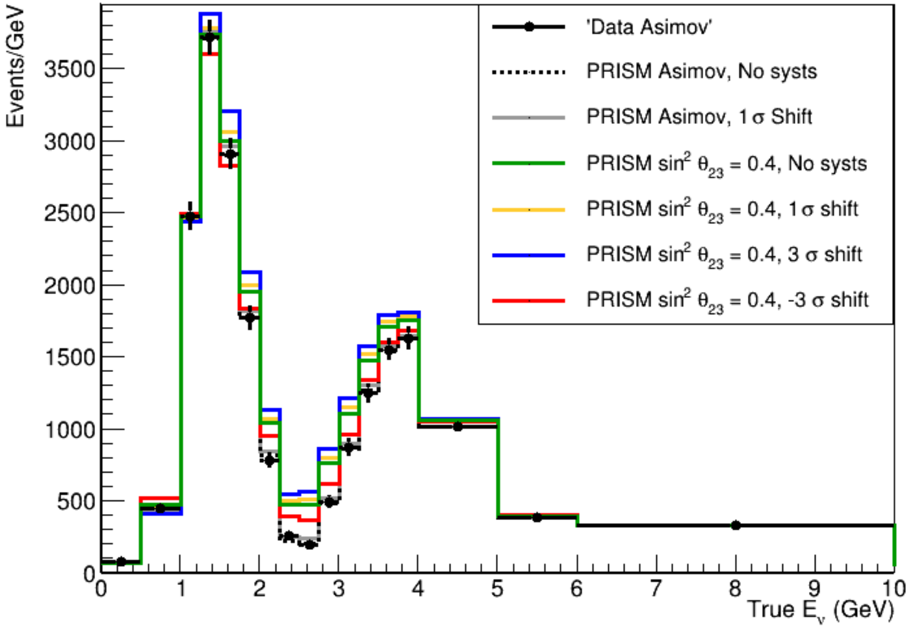


Horn A Displace Transverse X

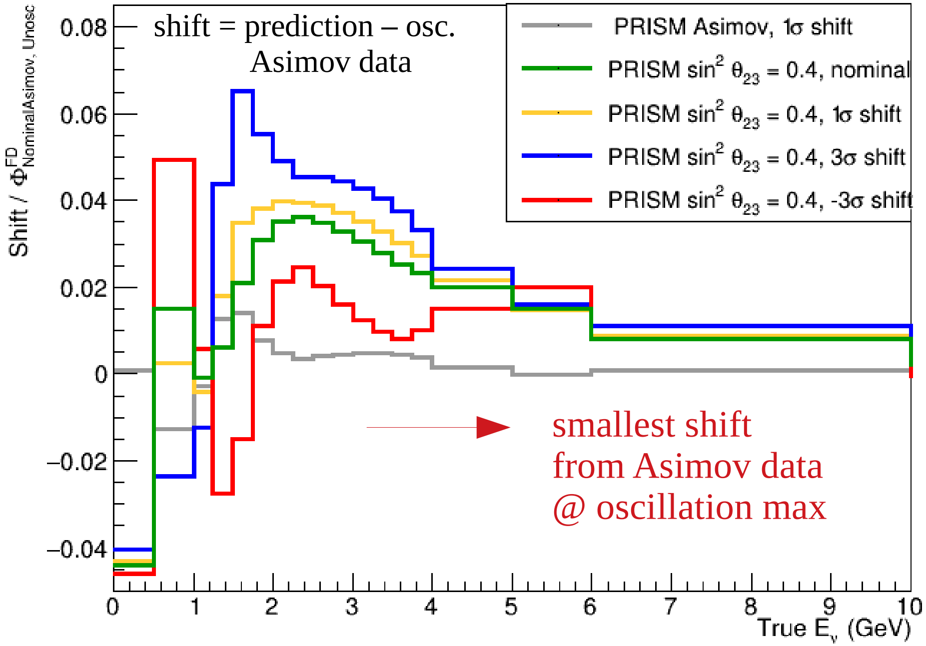
IMPORTANT

→ why is a -3 σ syst. shift preferred as the best fit?

- χ^2 calculation is using Asimov data (PRISM pred – Asimov data), with PRISM pred for different scan parameters
- For a scan parameter of $\mathbf{sin^2\theta_{23} = 0.4}$ the PRISM prediction corresponding to **-3 σ** (value preferred by χ^2) shift is fitting the data (Asimov-like) much better than the nominal PRISM prediction



Shift relative to Asimov data

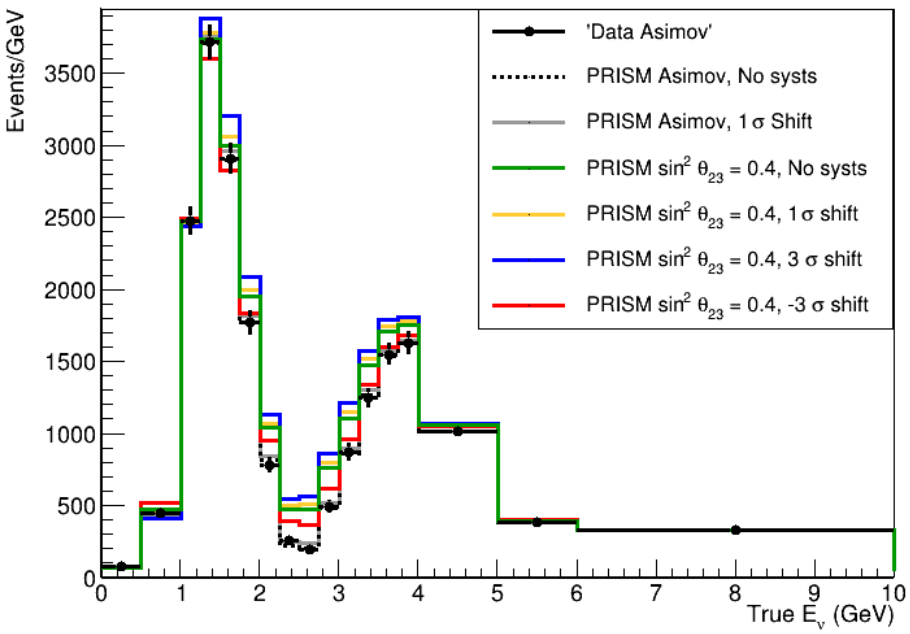


Horn A Displace Transverse X

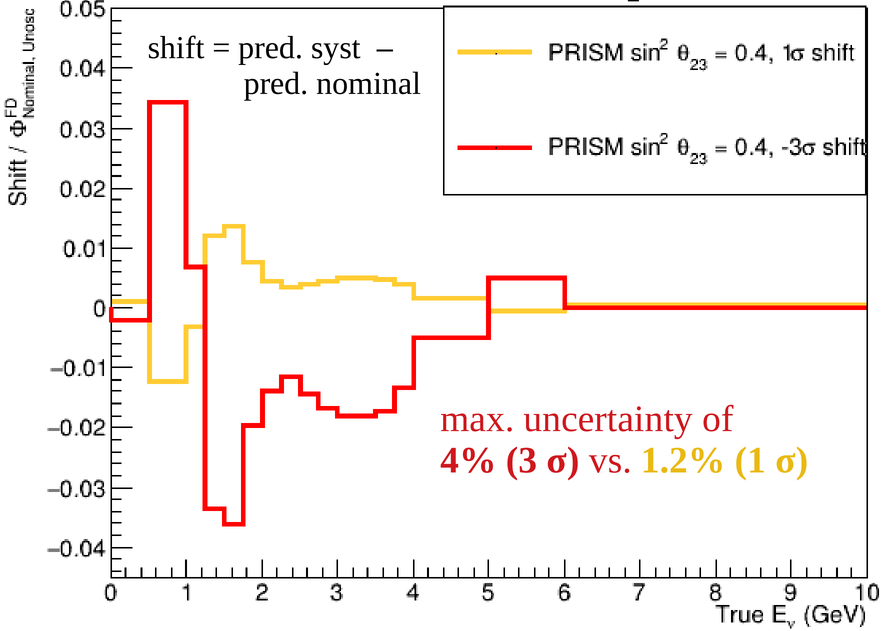
IMPORTANT

→ why is a -3 σ syst. shift preferred as the best fit?

- χ^2 calculation is using Asimov data (PRISM pred – Asimov data), with PRISM pred for different scan parameters
- For a scan parameter of $\sin^2\theta_{23} = 0.4$ the PRISM prediction corresponding to -3 σ (value preferred by χ^2) shift is fitting the data (Asimov-like) much better than the nominal PRISM prediction



Shift relative to Nominal prediction

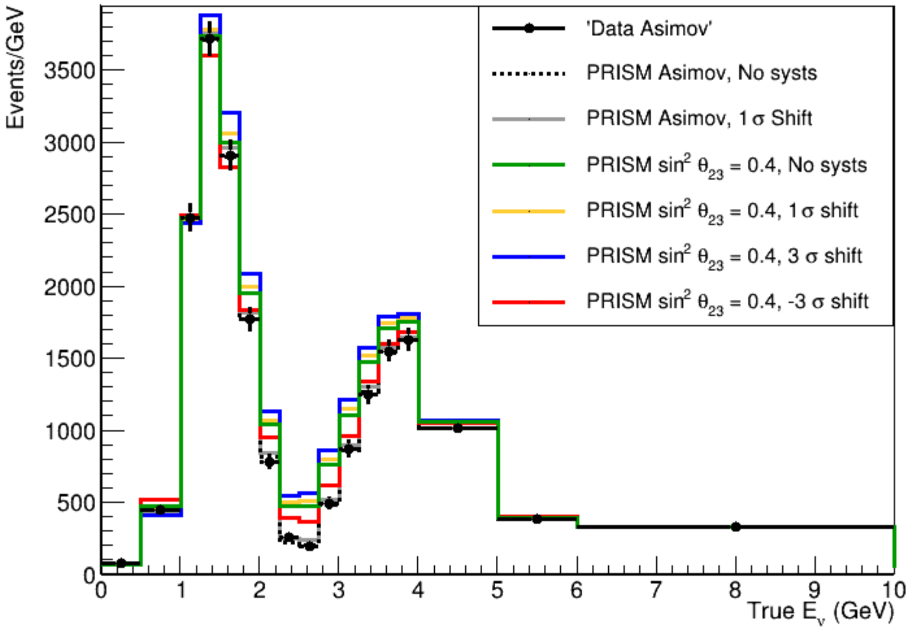


Horn A Displace Transverse X

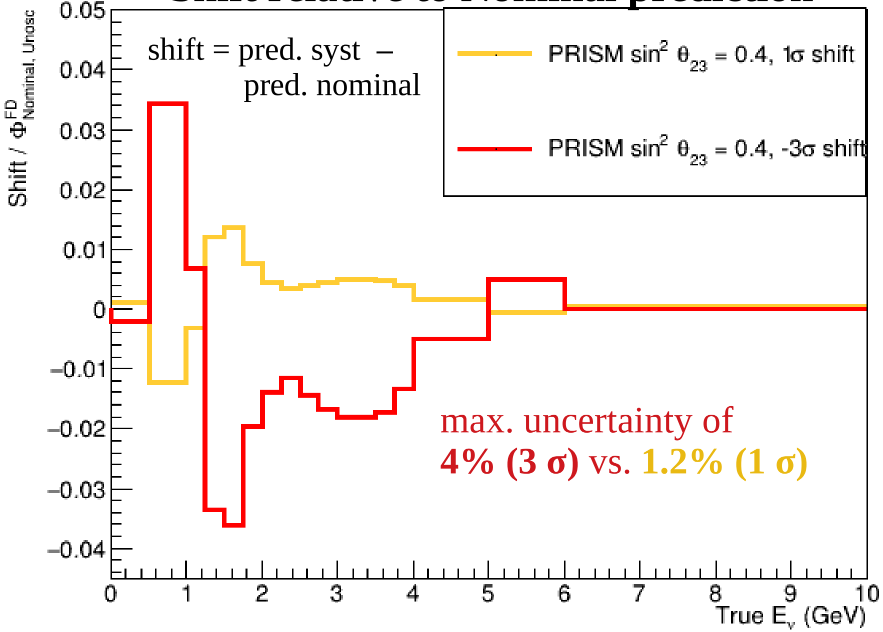
IMPORTANT

→ why is the sensitivity reduced so much given the small fractional shifts?

- χ^2 calculation is using Asimov data (PRISM pred – Asimov data), with PRISM pred for different scan parameters
- For a scan parameter of $\sin^2\theta_{23} = 0.4$ the PRISM prediction corresponding to **-3 σ** (value preferred by χ^2) shift is fitting the data (Asimov-like) much better than the nominal PRISM prediction



Shift relative to Nominal prediction

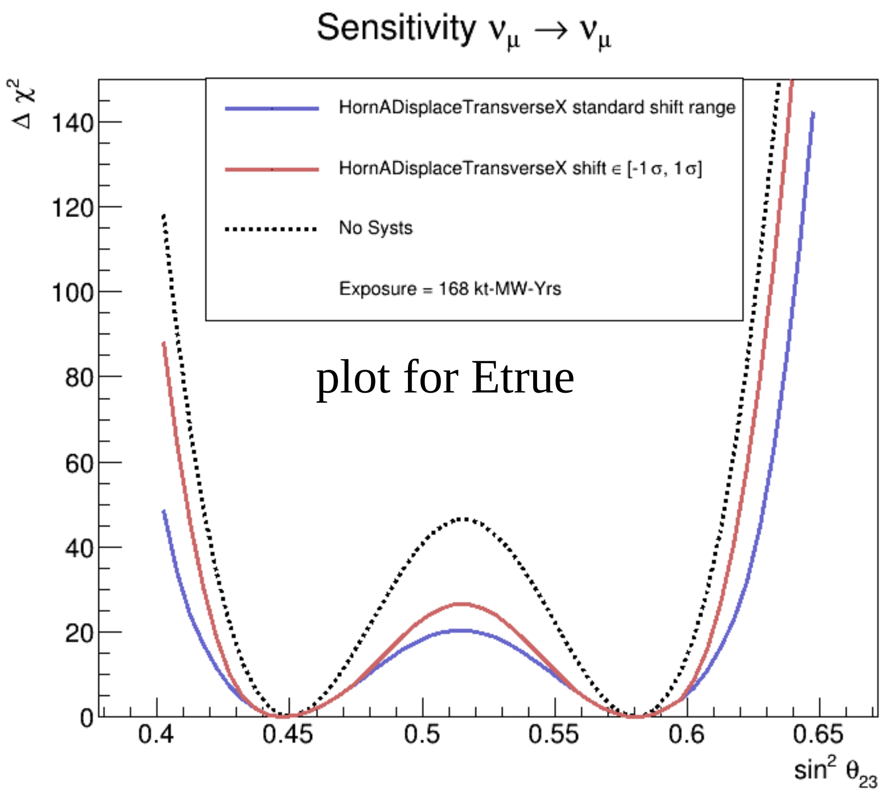


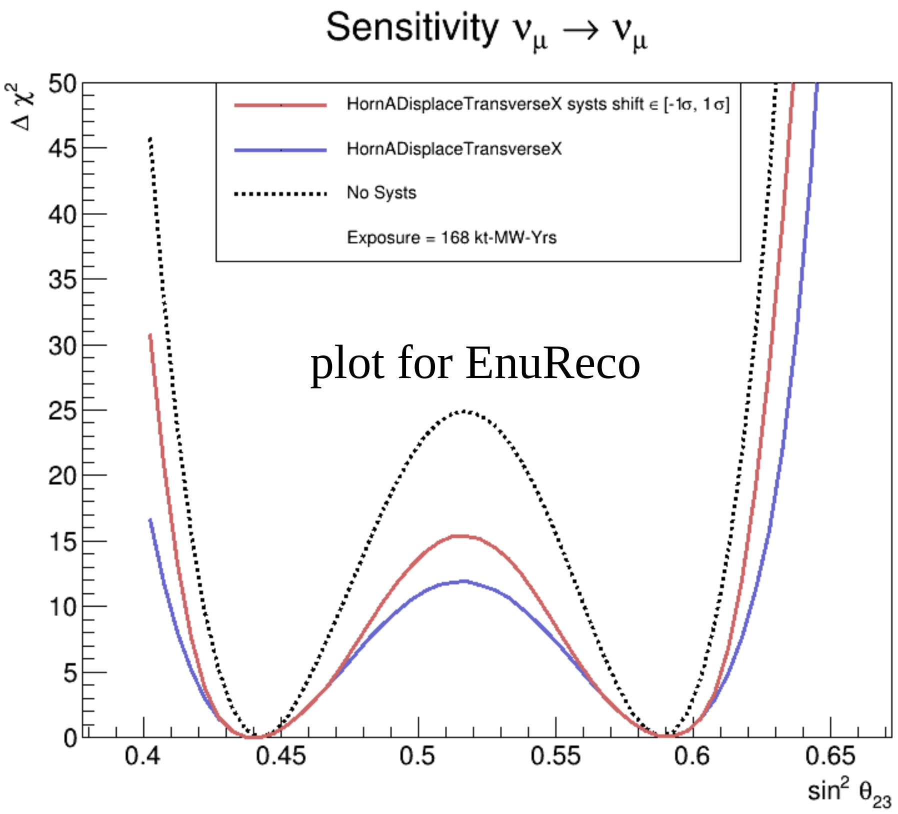
→ Sensitivity reduction due to higher uncertanties (3σ vs 1σ) and much better (lower χ^2) PRISM prediction at 3 σ for the given scan parameter ($\sin^2\theta_{23}$ = 0.4) compared to the nominal

Horn A Displace Transverse X

IMPORTANT

→ limit systematics shift to +/- 1 σ in the fit



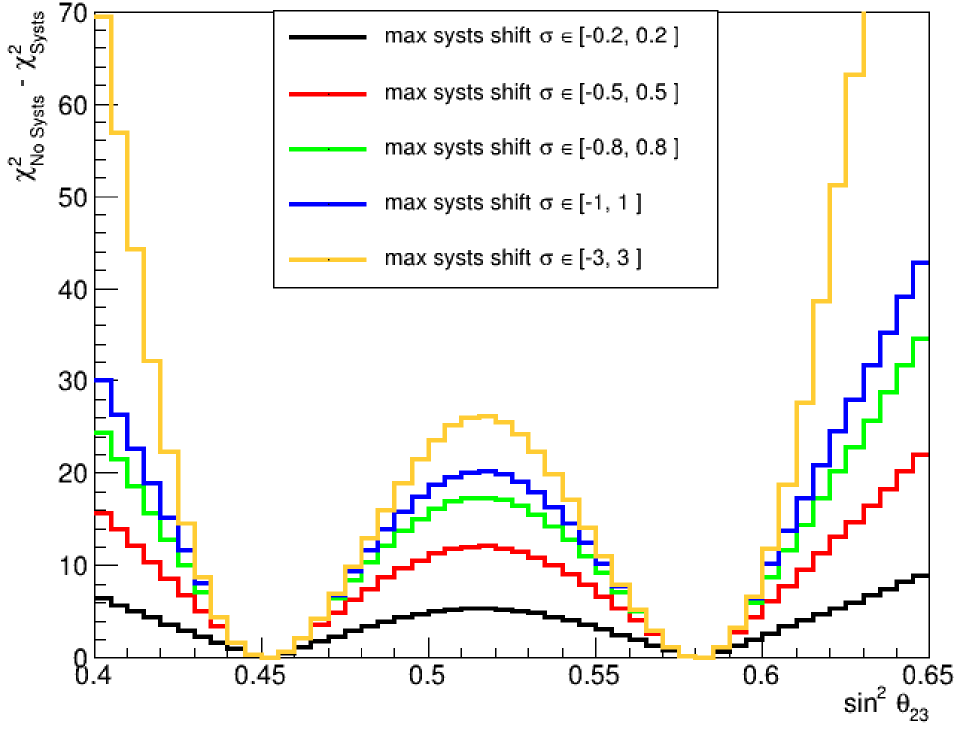


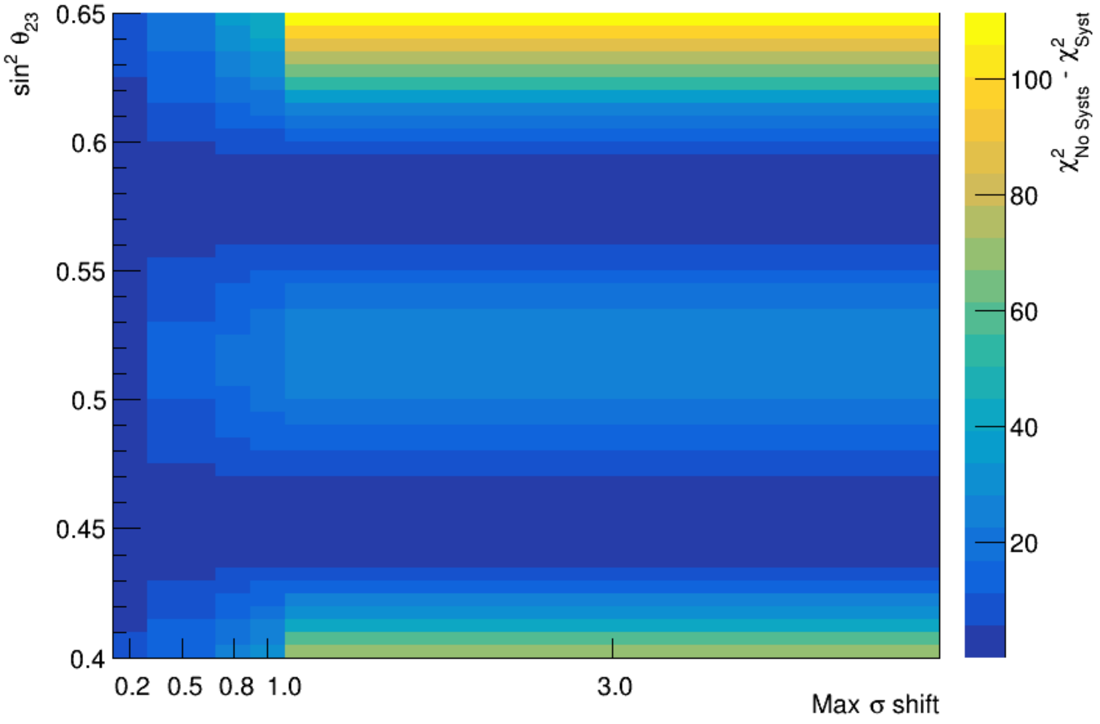
- much smaller sensitivity reduction (specifically at the edges) when limiting the syst shifts to +/- 1σ

Horn A Displace Transverse X

IMPORTANT

- **limit systematics shift to different σ ranges in the fit**





Open questions...

- Horn systematics
  - Eccentricity X Induced Bfield → why so high uncertainty values? (up to 3% for both horn A and horn C – horn B systematics missing for this parameter)

- Target Upstream Degredation (5 mm loss at 1 σ)
  - Uncertainties up to 50% for on-axis at E ≈ 4GeV → is this realistic?

- Decay Pipe Geomagnetic field
  - Relatively high uncertainties: up to 1.5%
  - What is the assumption for uncertainty calculation? (*"Scale-factor of 1 is 1-σ tolerance. Mapped from NuMI Decay Pipe Geo B-Field Measurements"*)

So far...

- Successfully **implemented new beam focusing systematics** (v3r5p9 release of G4LBNE) **within the PRISM Analysis software**
  - energy binning issue solved: uncertainties vs off axis vs energy look smooth and result in correct oscillation fits shape for all parameters
  - no additional biases when true neutrino energy is used
- Identified 10 IMPORTANT parameters which reduce the PRISM sensitivity significantly
  - understand why the sensitivity is reduced so much for certain scan parameters

Still TO DO:

- look at all important parameters and confirm the results obtained from Horn A Displace Transverse X
- talk to the beam group and try to better understand the provided systematics as well as a way of further reducing them

So far...

- Successfully **implemented new beam focusing systematics** (v3r5p9 release of G4LBNE) **within the PRISM Analysis software**
  - energy binning issue solved: uncertainties vs off axis vs energy look smooth and result in correct oscillation fits shape for all parameters
  - no additional biases when true neutrino energy is used
- Identified 10 IMPORTANT parameters which reduce the PRISM sensitivity significantly
  - understand why the sensitivity is reduced so much for certain scan parameters

Still TO DO:

- look at all important parameters and confirm the results obtained from Horn A Displace Transverse X
- talk to the beam group and trying to better understand the provided systematics as well as a way of further reducing them

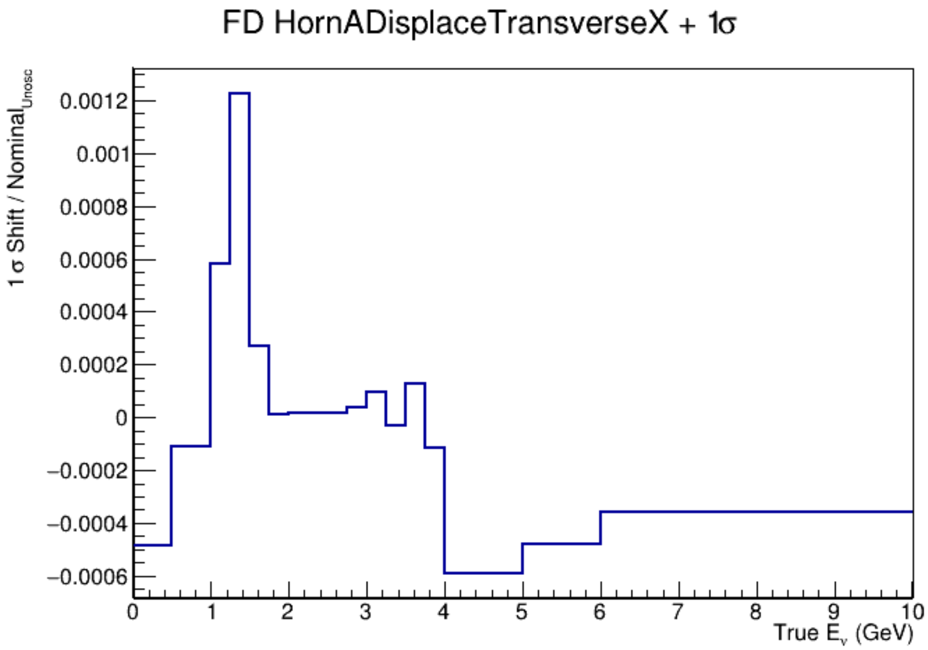
ANY ideas are more than welcome :)

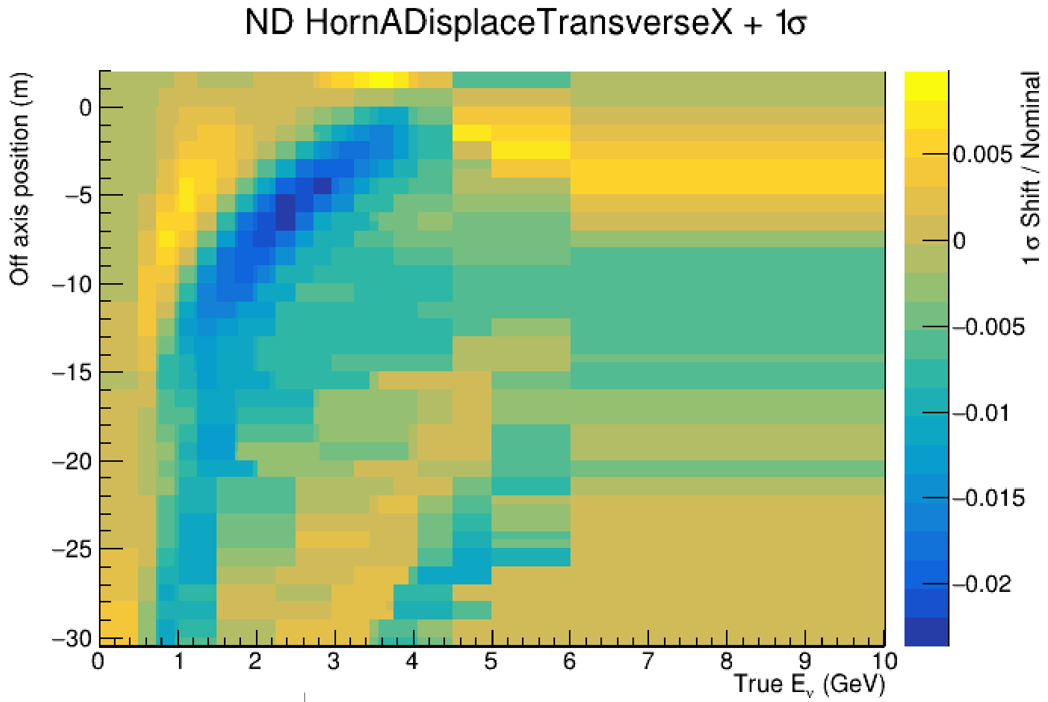
Thank you very much!

Horn A Displace Transverse X

IMPORTANT

- 1σ shift = 0.5 mm
- look at both FD and ND fractional ratios versus energy when the the flux parameter of interest is shifted by 1 σ



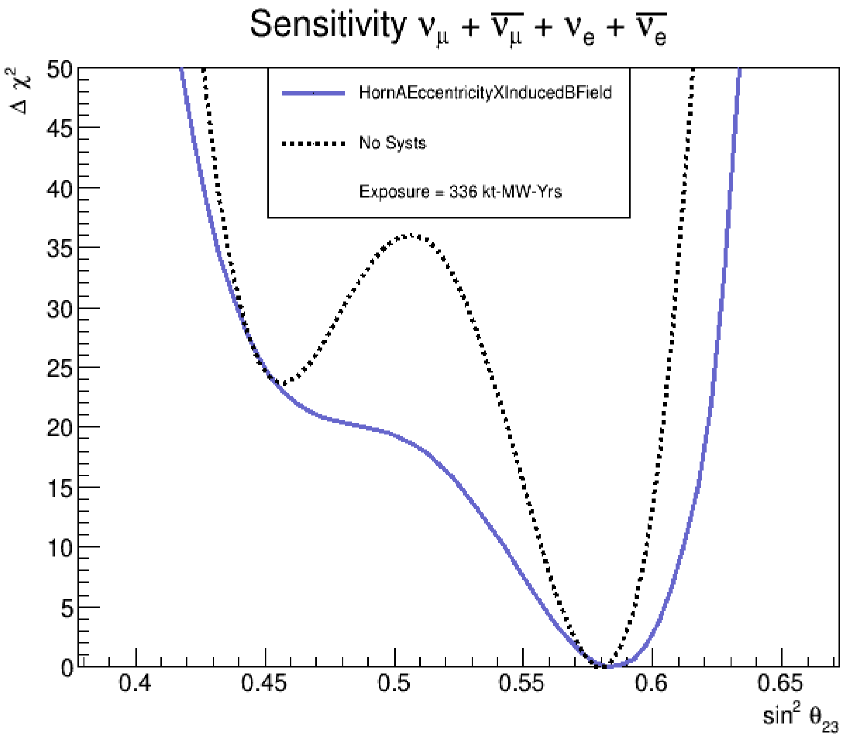


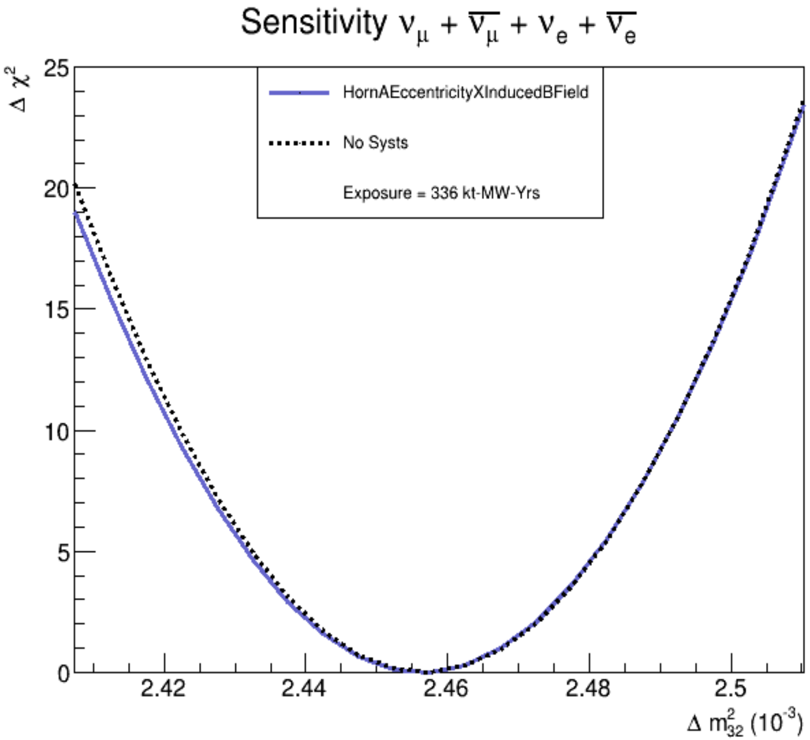
Linearly combine to get the PRISM fractional uncertainty

Horn A Eccentricity X Induced Bfield

IMPORTANT

- 1σ shift = 0.035 mm: NuMi Horn 1 tolerance assumed (off axis deformation of inner conductor)



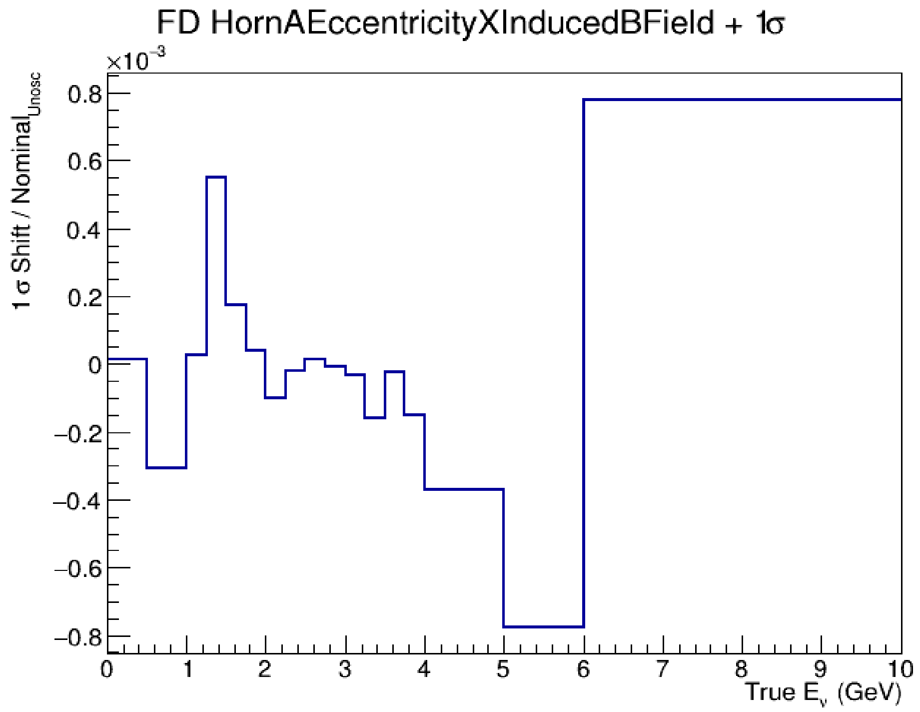


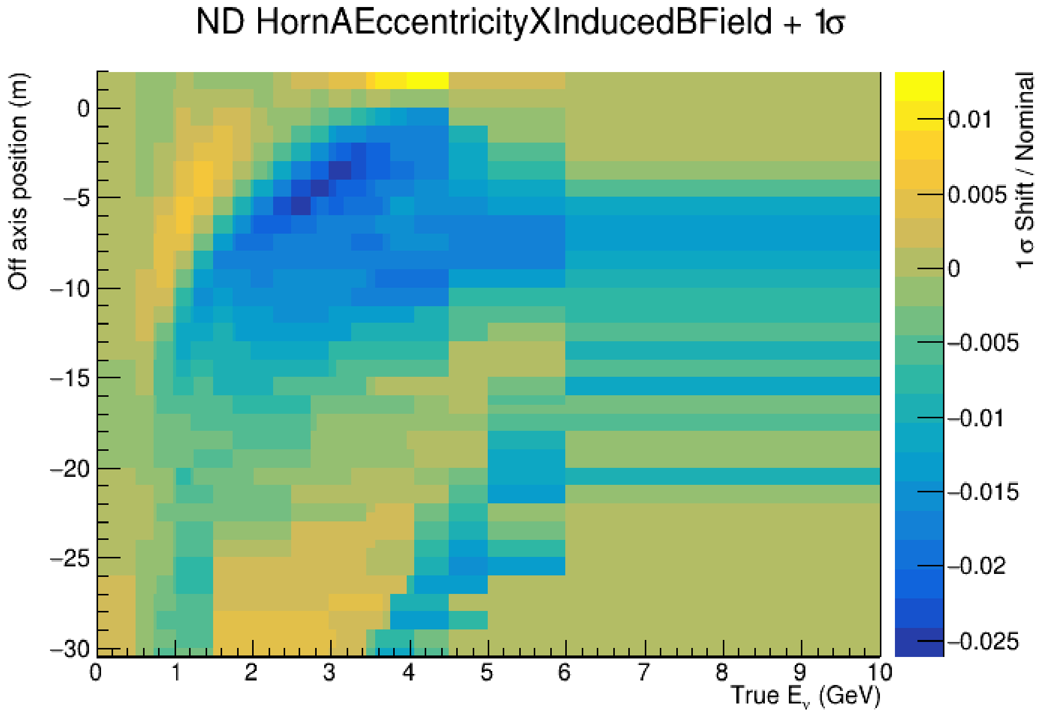
- Parameter previously (Nov17 – TDR) not studied (i.e no syst shift) → significant influence on the sensitivity

Horn A Eccentricity X Induced Bfield

IMPORTANT

- 1σ shift = 0.035 mm: NuMi Horn 1 tolerance assumed (off axis deformation of inner conductor)

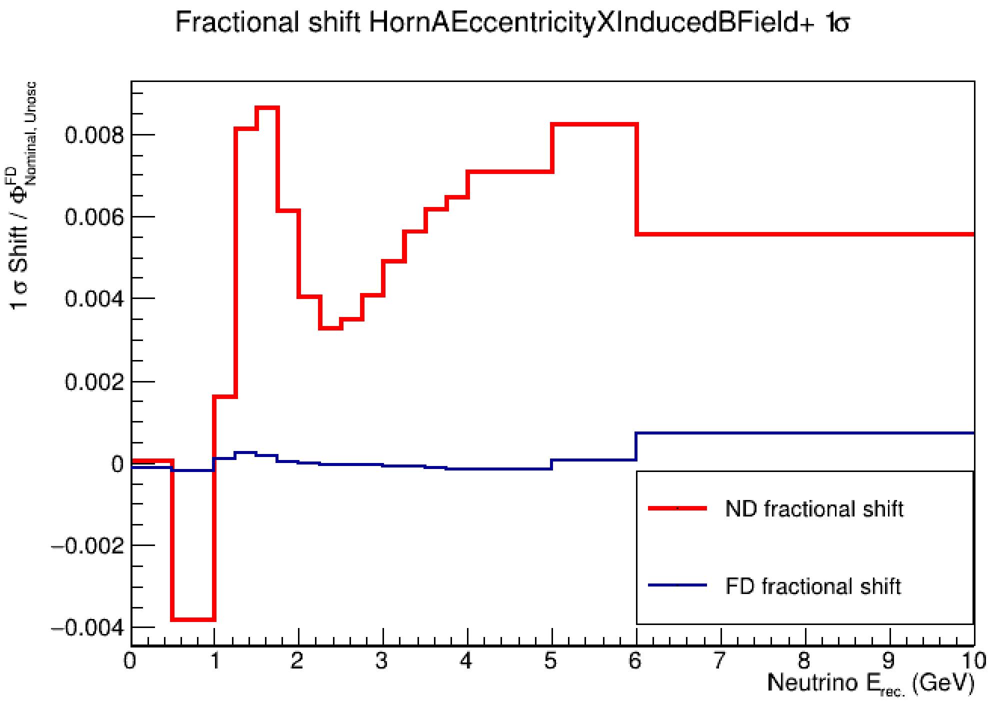


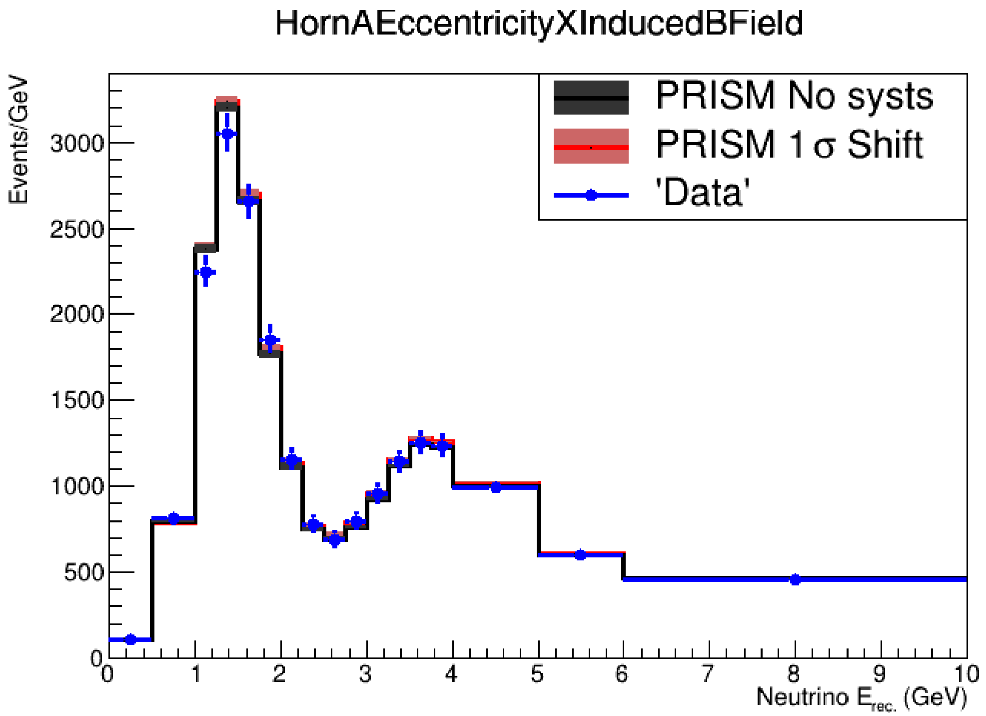


Horn A Eccentricity X Induced Bfield

IMPORTANT

- 1σ shift = 0.035 mm: NuMi Horn 1 tolerance assumed (off axis deformation of inner conductor)

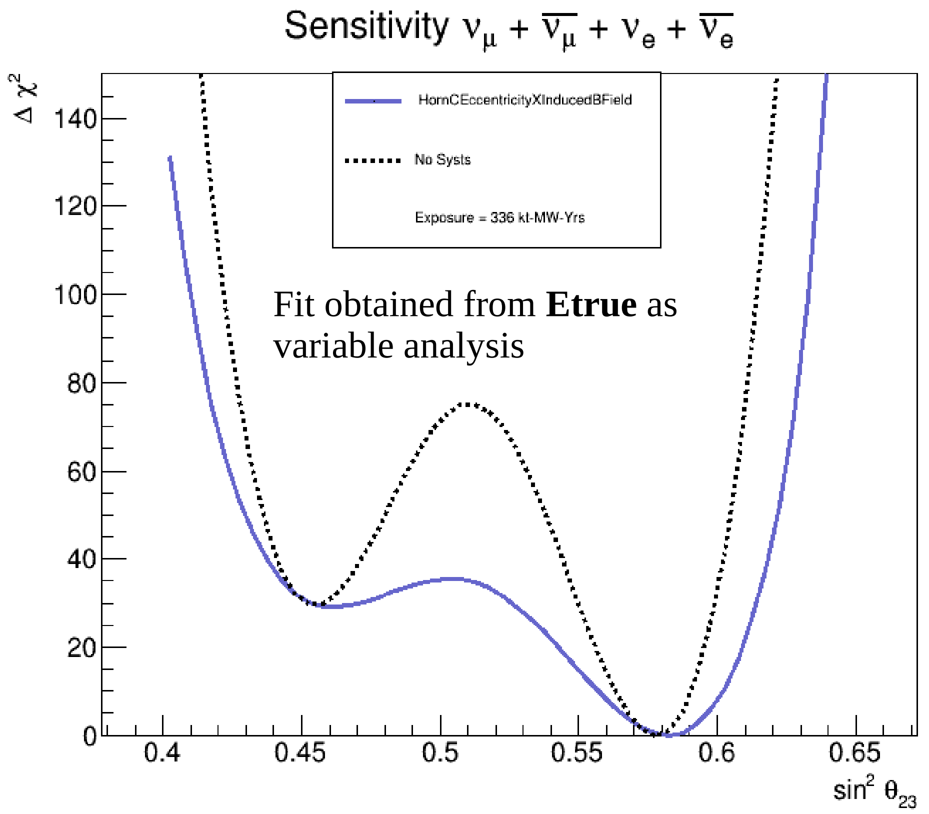


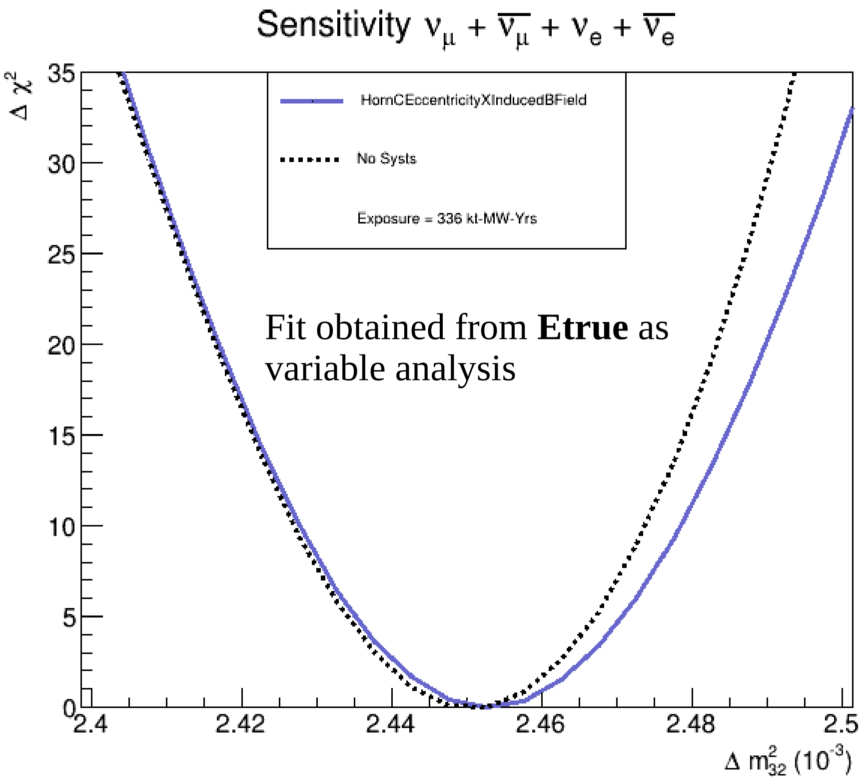


Horn C Eccentricity X Induced Bfield

IMPORTANT

- 1σ shift = 0.07 mm: NuMi Horn 2 tolerance assumed (off axis deformation of inner conductor)

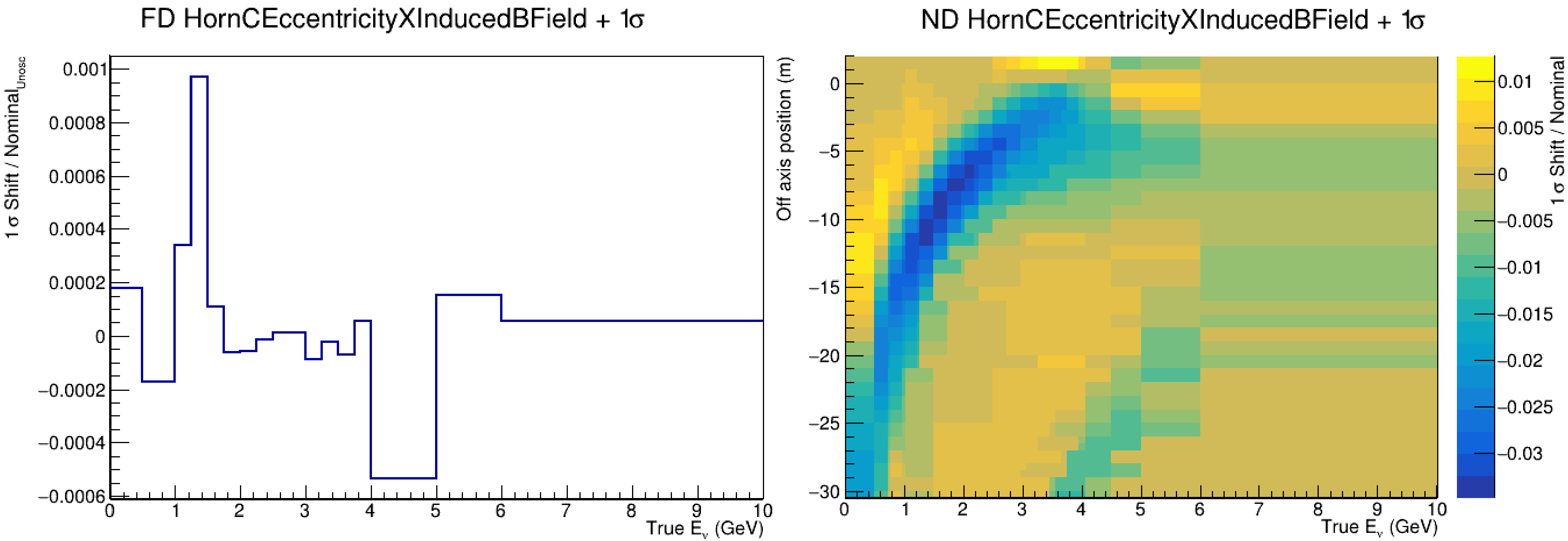




Horn C Eccentricity X Induced Bfield

IMPORTANT

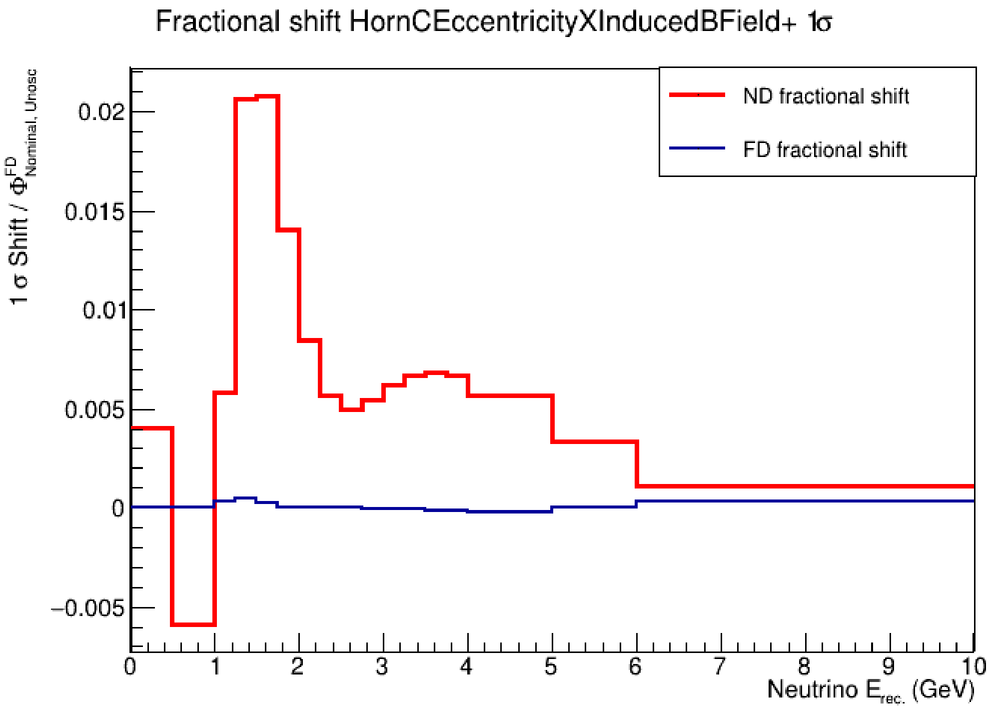
- 1σ shift = 0.07 mm: NuMi Horn 2 tolerance assumed (off axis deformation of inner conductor)

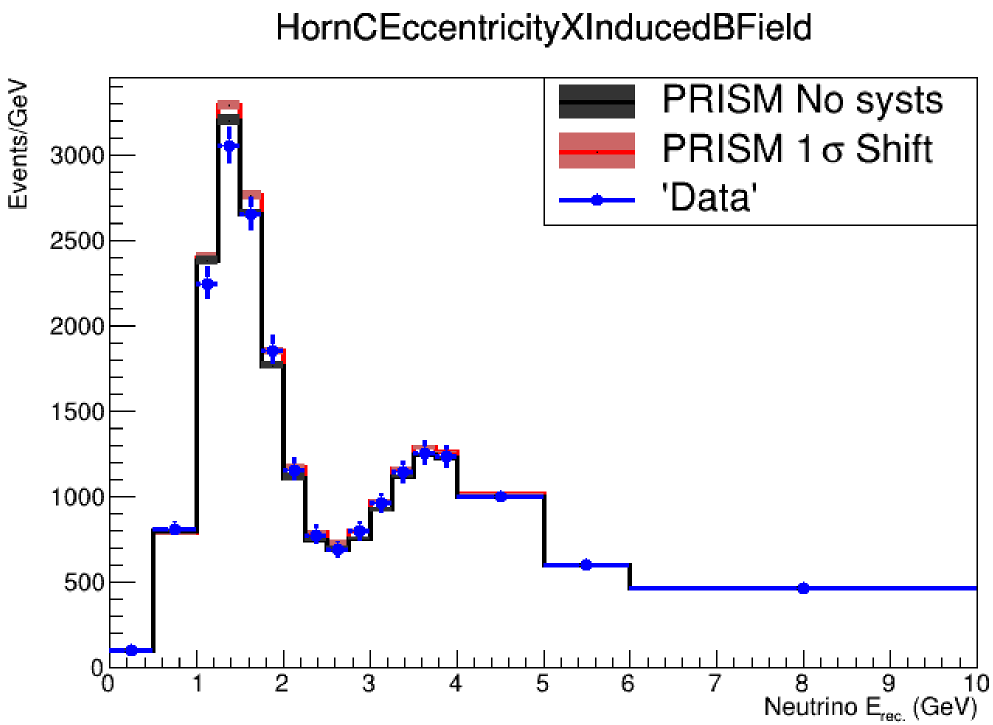


Horn C Eccentricity X Induced Bfield

IMPORTANT

- 1σ shift = 0.07 mm: NuMi Horn 2 tolerance assumed (off axis deformation of inner conductor)



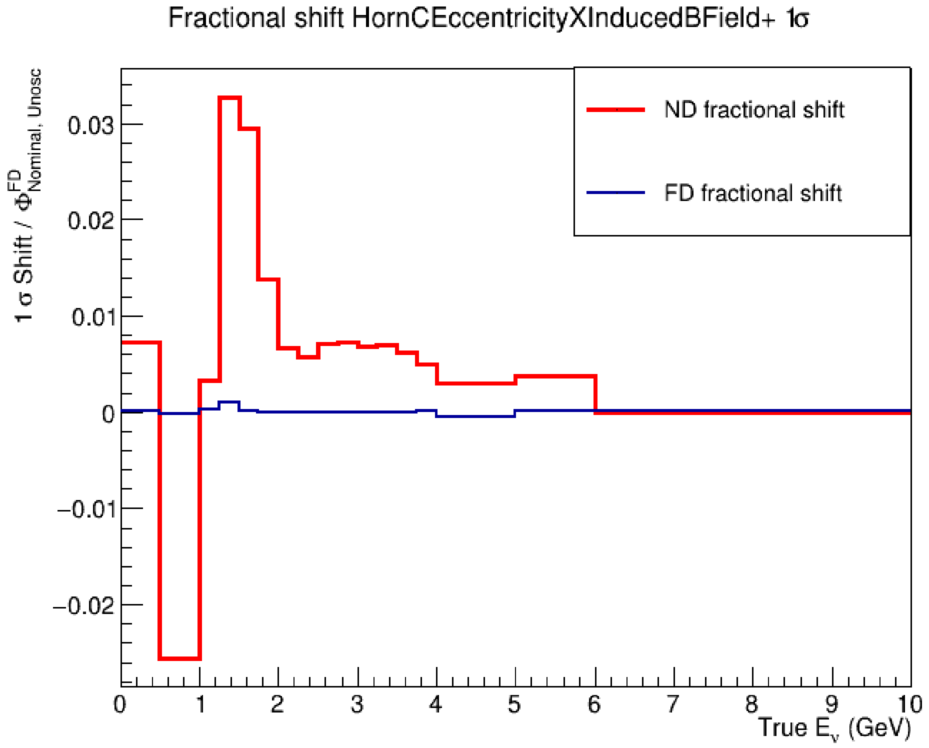


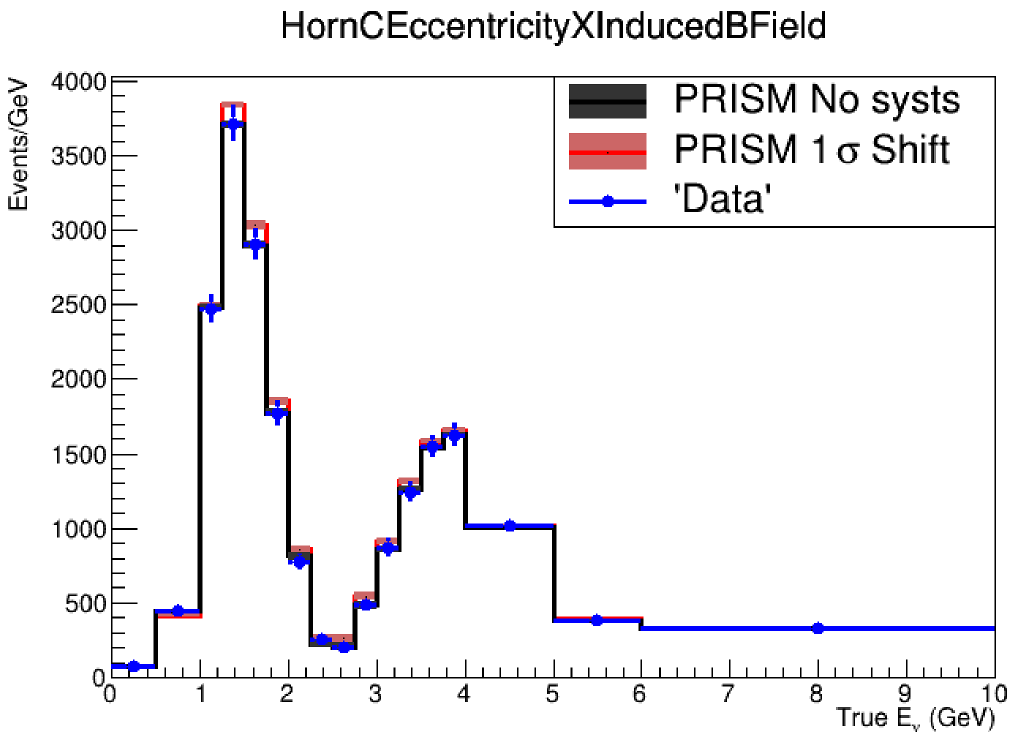
Horn C Eccentricity X Induced Bfield

IMPORTANT

- 1σ shift = 0.07 mm: NuMi Horn 2 tolerance assumed (off axis deformation of inner conductor)

- Results obtained by using true energy **Etrue** as analysis variable



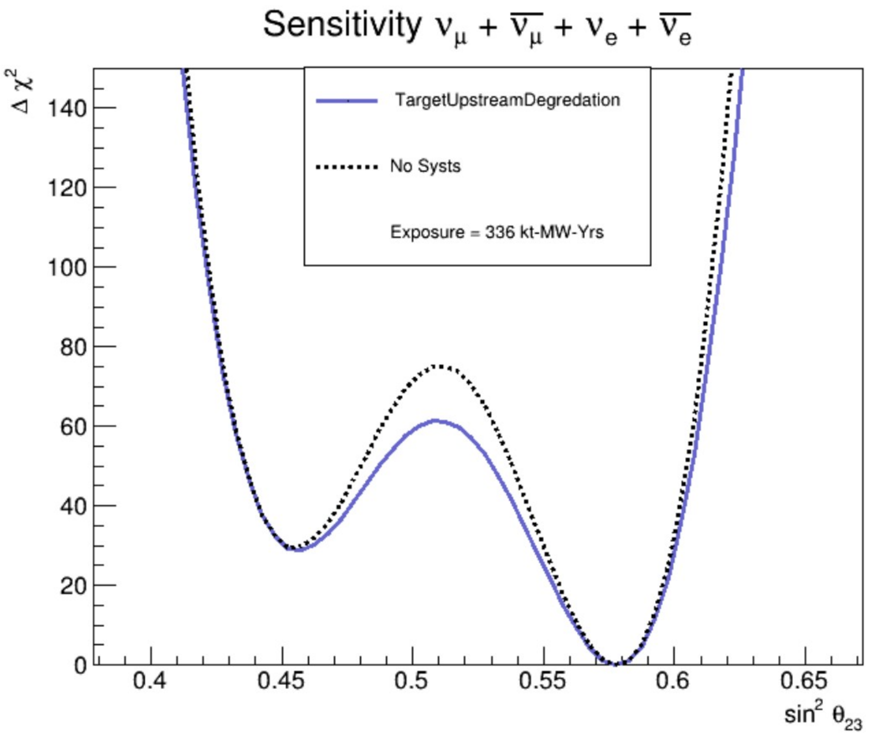


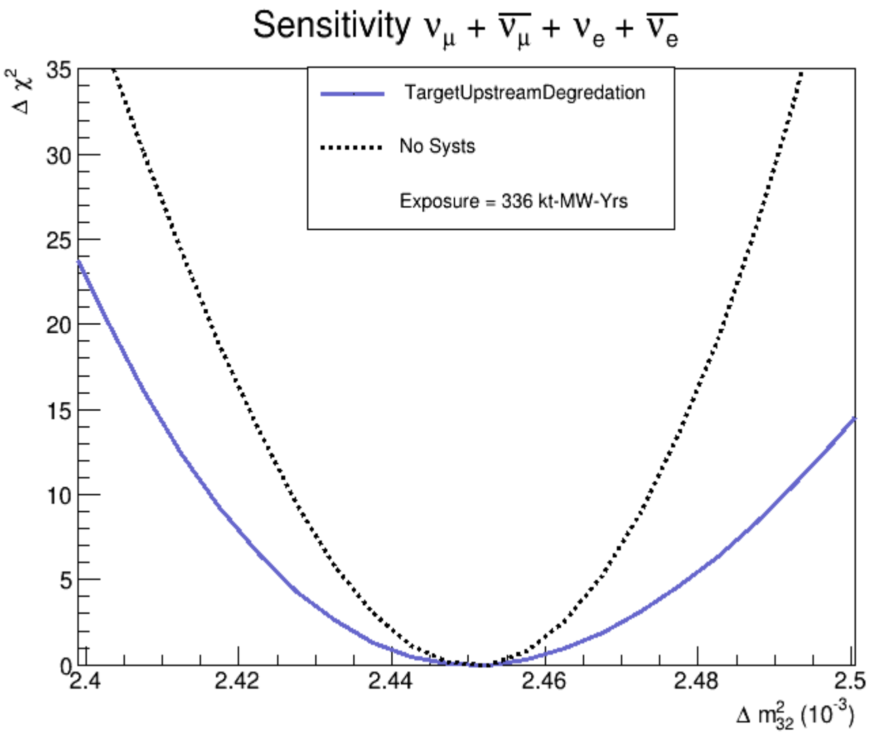
Target Upstream Degradation

IMPORTANT

- 1σ shift = 5 mm loss: assume complete loss of target on upstream end
(a shorter target by dz shifted downstream by the loss dz)

- Results when using true energy **Etrue** as analysis variable

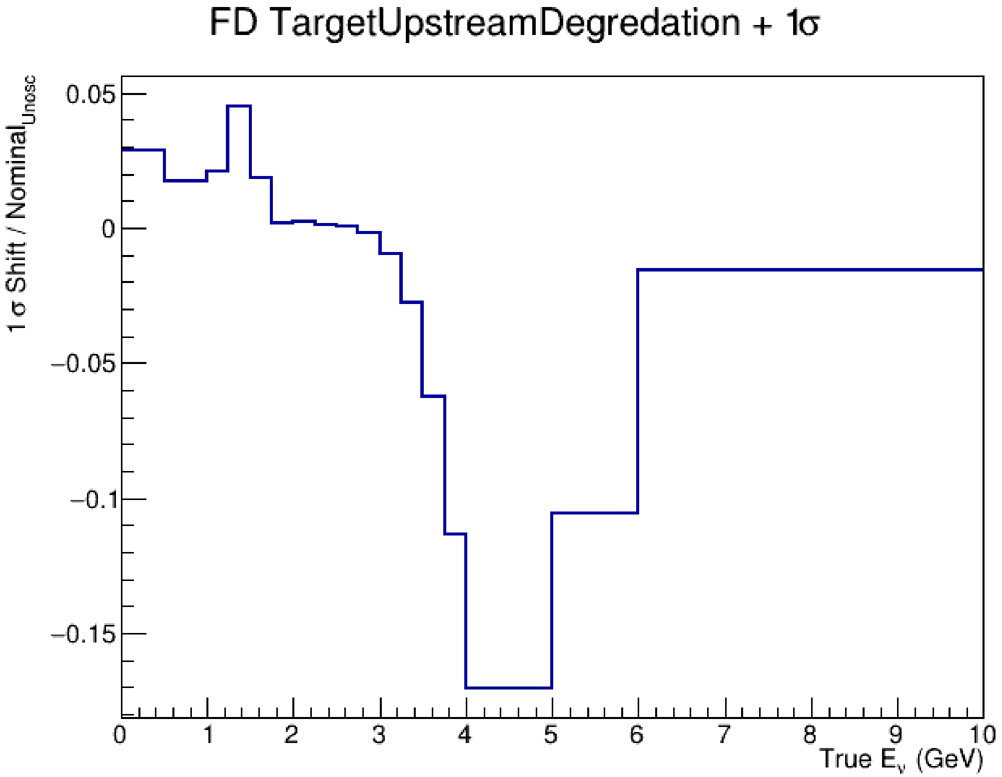


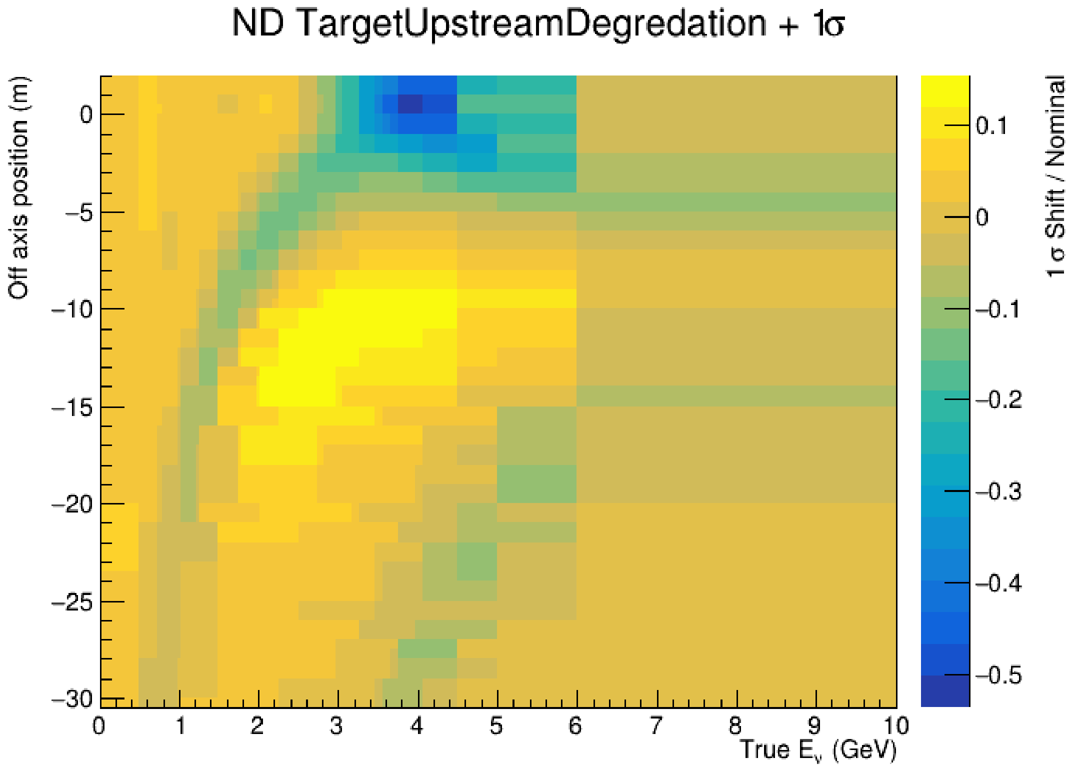


Target Upstream Degradation

IMPORTANT

- 1σ shift = 5 mm loss: assume complete loss of target on upstream end
(a shorter target by dz shifted downstream by the loss dz)



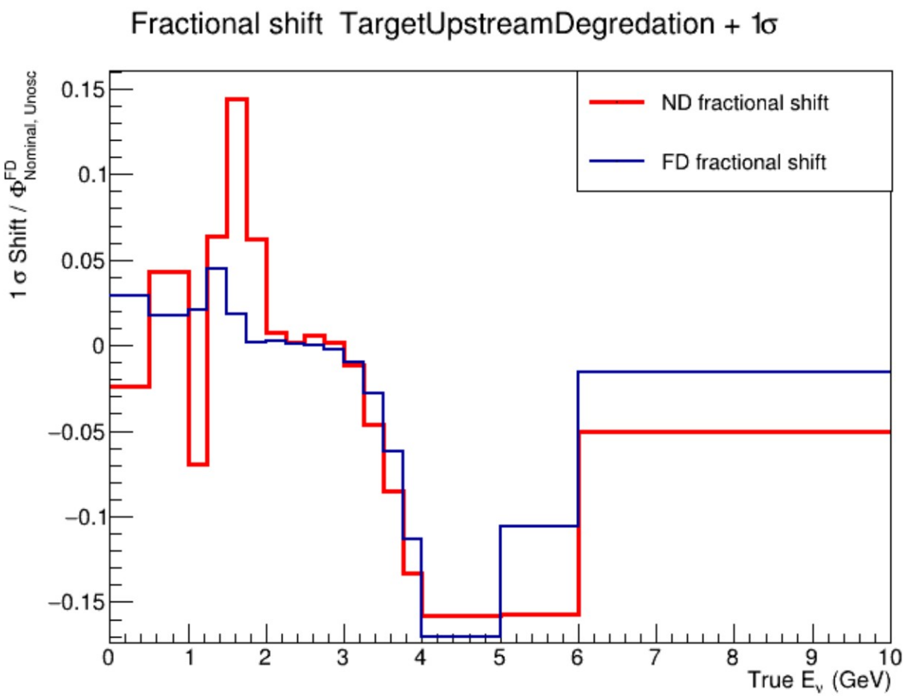


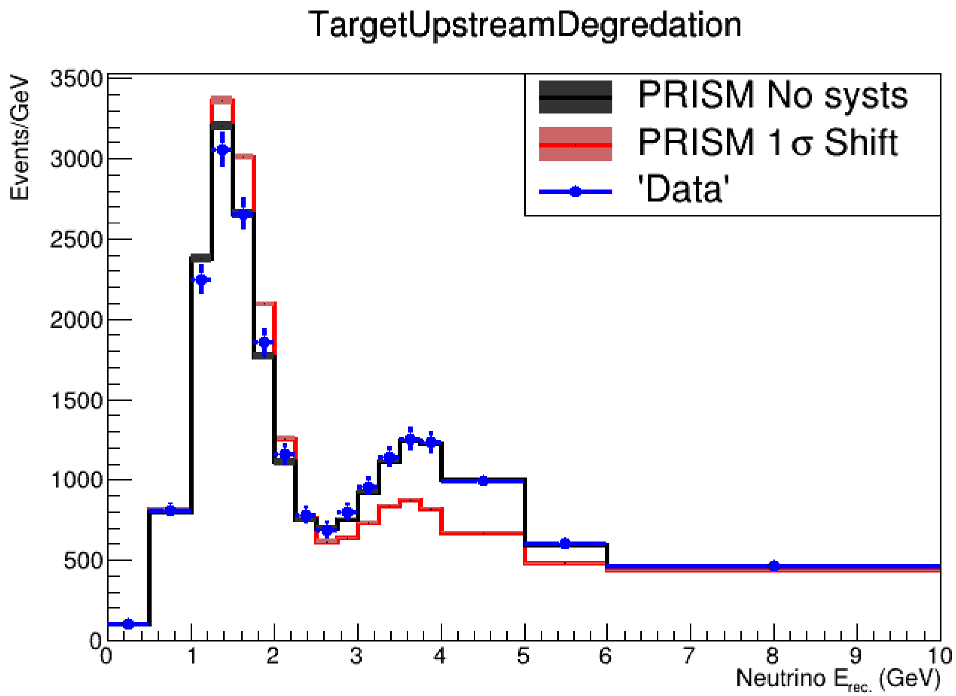
Target Upstream Degredation

IMPORTANT

- 1σ shift = 5 mm loss: assume complete loss of target on upstream end
(a shorter target by dz shifted downstream by the loss dz)

- results when using true energy **Etrue** as analysis variable

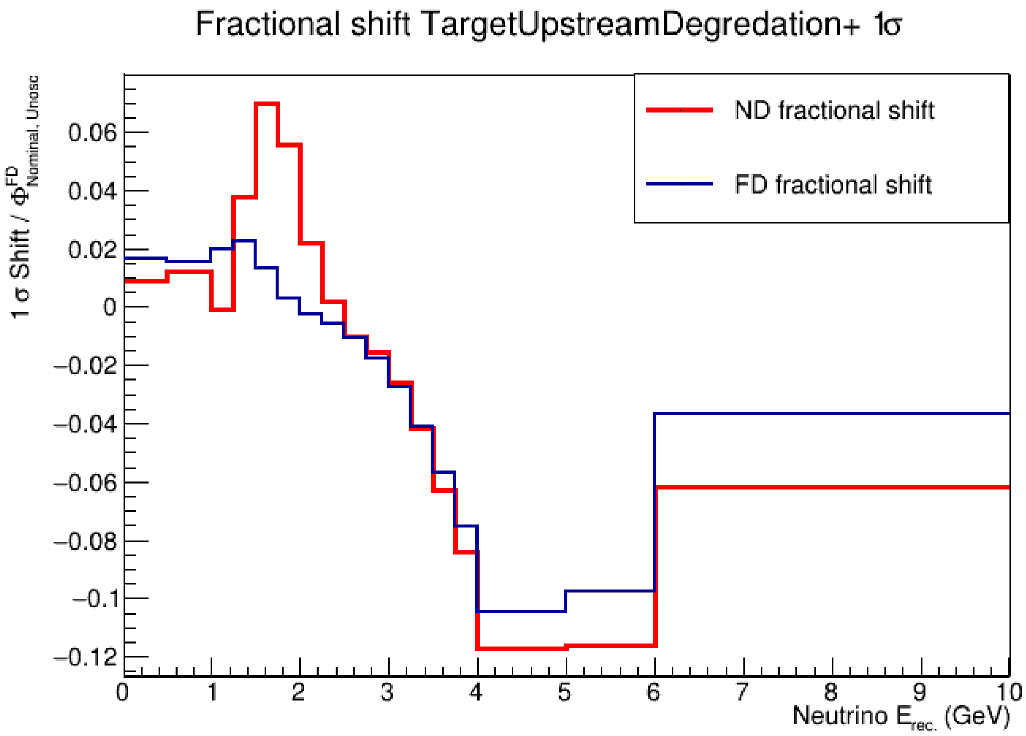


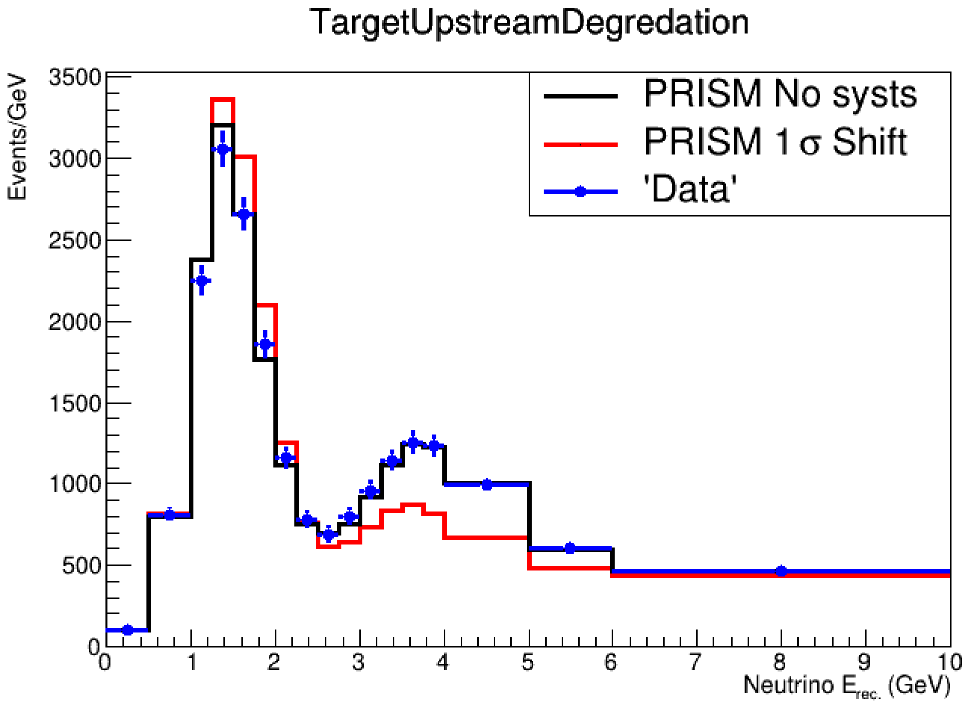


Target Upstream Degredation

IMPORTANT

- 1σ shift = 5 mm loss: assume complete loss of target on upstream end
(a shorter target by dz shifted downstream by the loss dz)



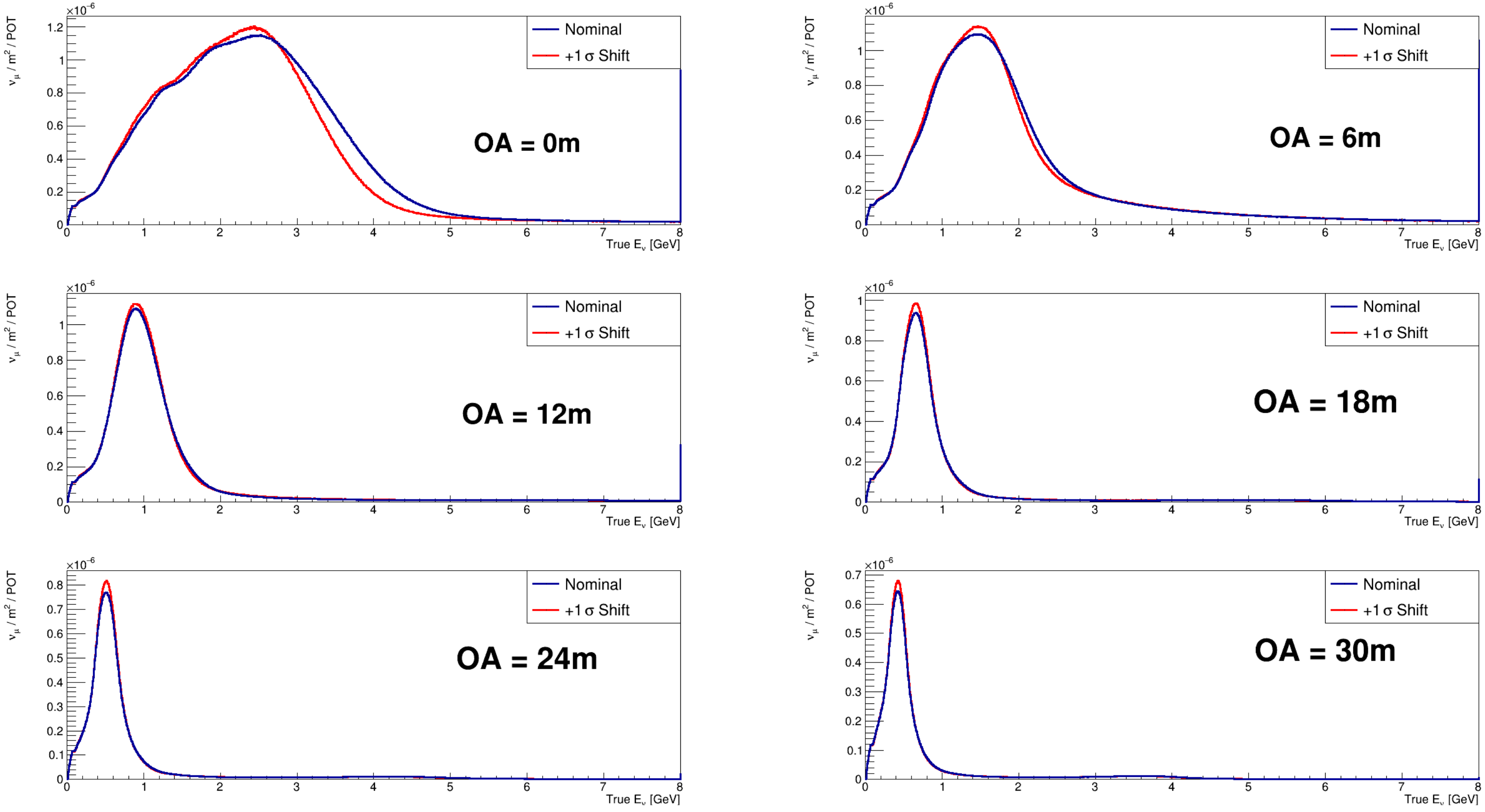


Target Upstream Degradation

IMPORTANT

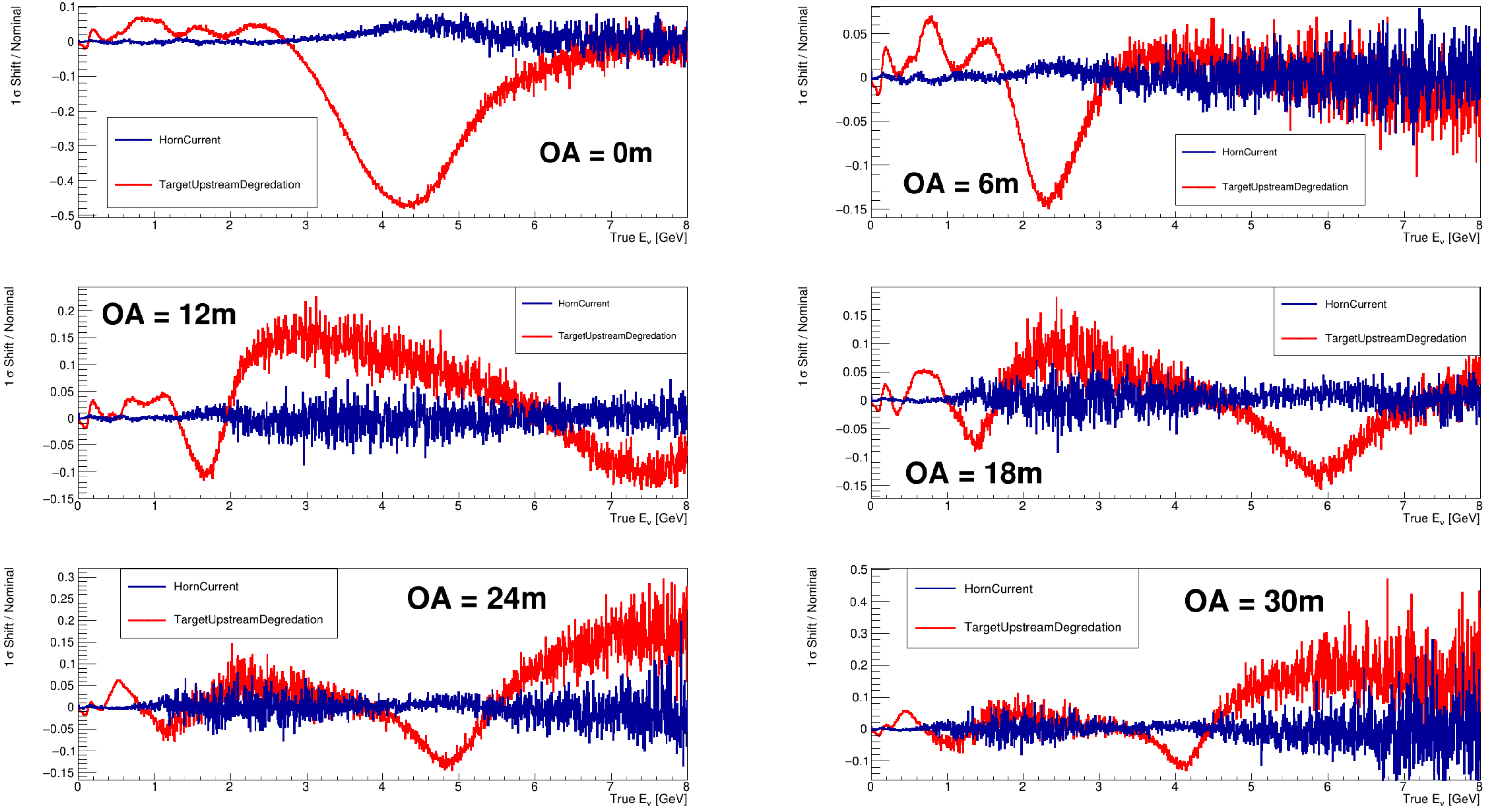
- 1σ shift = 5 mm loss: assume complete loss of target on upstream end

→ cross check with fluxes from the provided root files: visible difference in the shifted flux



Target Upstream Degradation vs HornCurrent

→ fractional error obtained from the flux files (original energy binning)

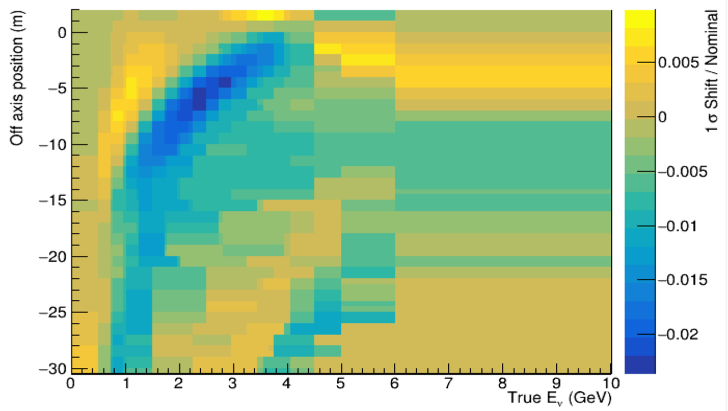


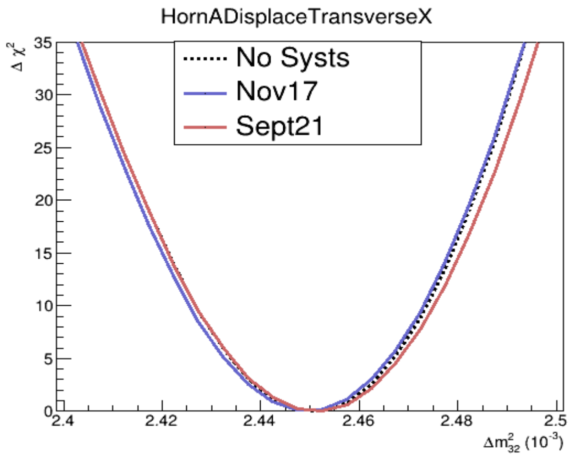
High fractional uncertainties (up to 50%) for TargetUpstreamDegradation parameter are coming from the original root files (not a re-binning issue)

Horn A Displace Transverse X → comparison to Nov17 systs

IMPORTANT

ND HornADisplaceTransverseX + 1σ **Sept 21: 1σ = 0.5mm**





NDHorn1XShift -1σ **Nov17 1σ = 0.5mm**