



# Physics impact of LBNF target outer container & support fins

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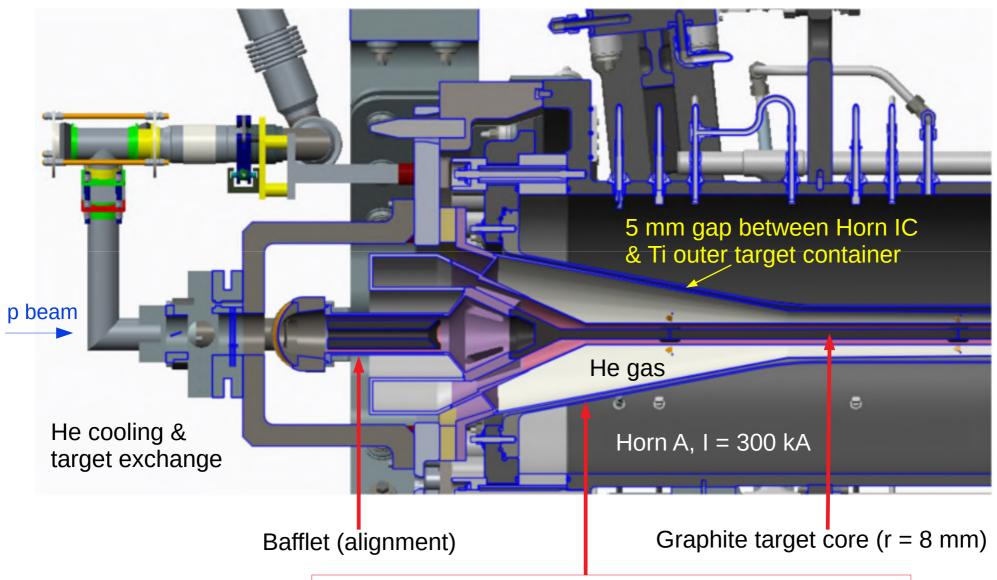
23 June 2022

DUNE-doc-25880

#### Introduction

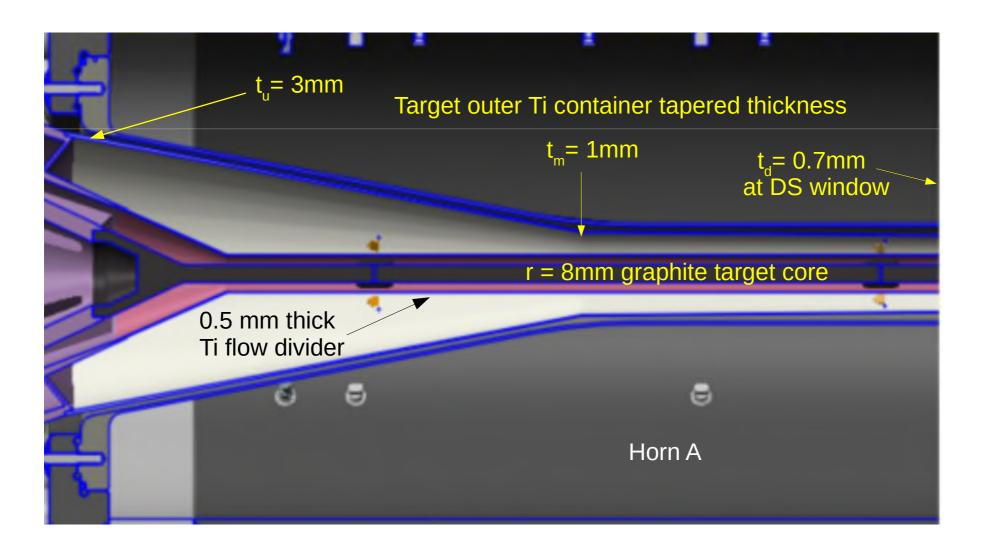
- Geant4 simulations of LBNF beamline: graphite target & 3 focusing horns
  - Cantilevered target, double-cone Ti support structure with He cooling
  - Proton beam: 120 GeV, 1.2 MW; QGSP\_BERT hadronic model
  - Target core:  $\mathbf{r} = \mathbf{8} \ \mathbf{mm}$ ,  $\mathbf{L} = \mathbf{1.5} \ \mathbf{m}$  (prototype) &  $\mathbf{1.8} \ \mathbf{m}$  (aspiration)
- Overview of physics impact when we vary:
  - Outer titanium container thickness (0 to 2.5 mm in 0.5 mm steps)
  - Amount of material in the titanium target support fins (±45 & ±135 deg)
- Plots of unoscillated ν signal & bkgnd fluxes extrapolated to far detector
- Plots of CP sensitivity & exposure (run time x far detector 40 kt mass)
  - GLoBES, NuFit 4.0 parameters, normal neutrino mass ordering

### Target and Horn A integration

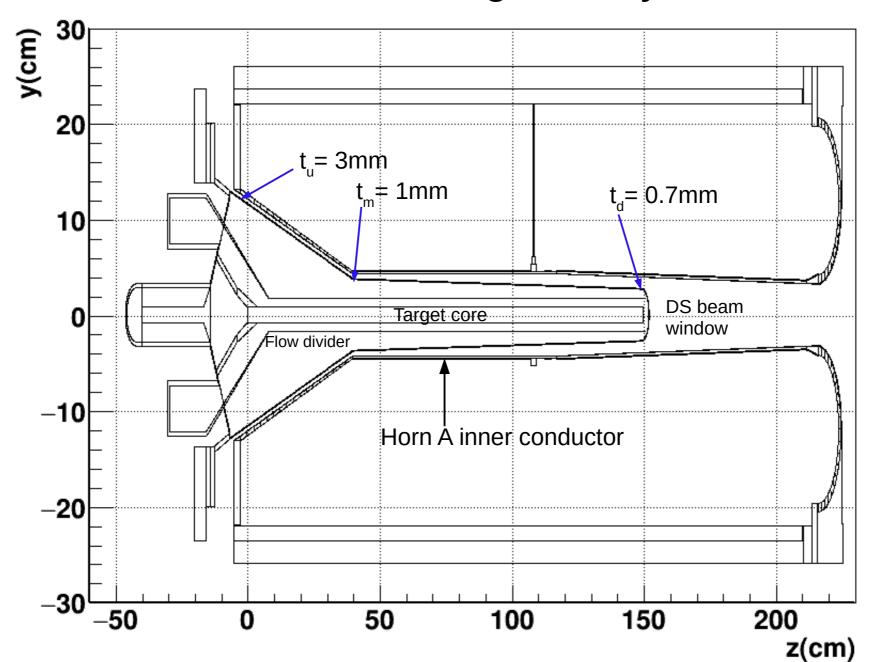


Courtesy RAL High Power Targets Group Horn A inner conductor cone ( $r_{base}$ = 14cm,  $L_z$ = 40cm) to allow space for upstream target support structure

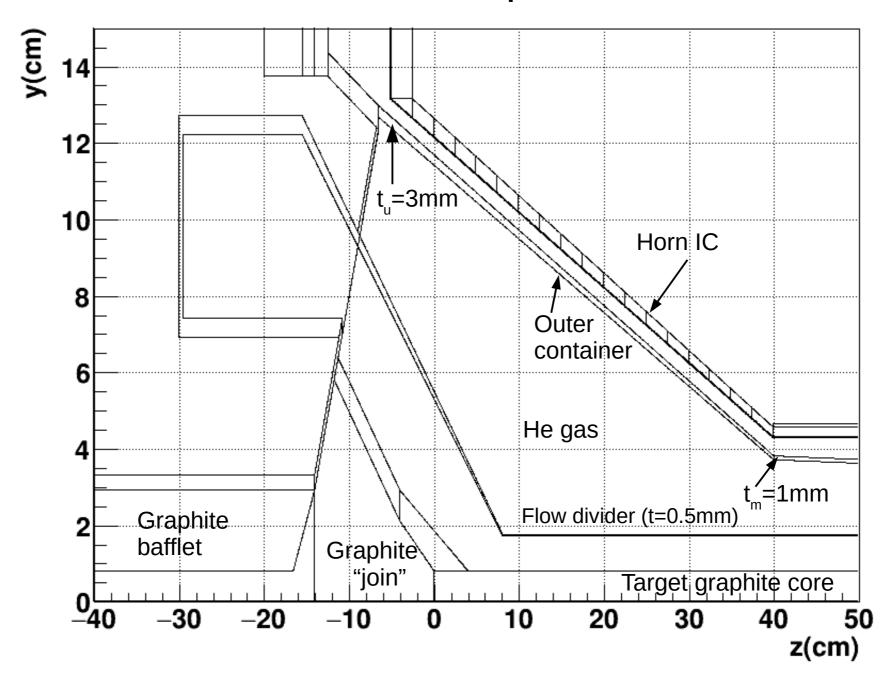
## Target detail: tapered outer container (titanium)



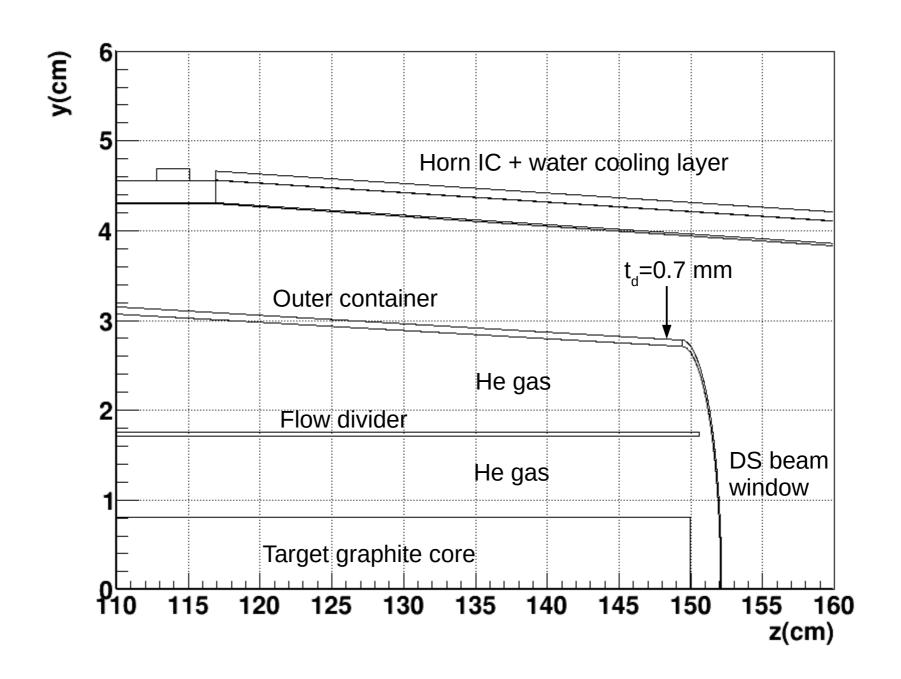
## Geant4 geometry



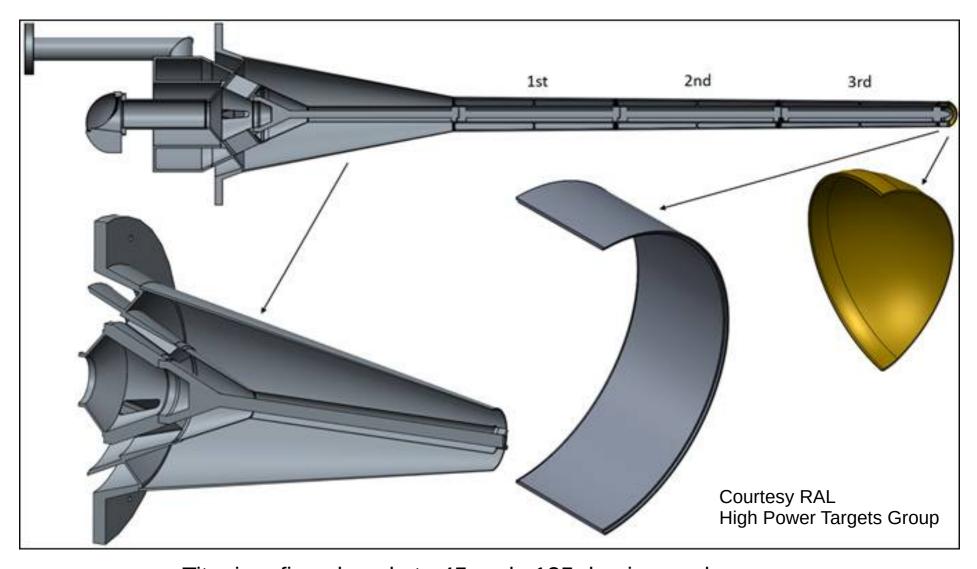
## Outer container upstream detail



#### Outer container downstream detail

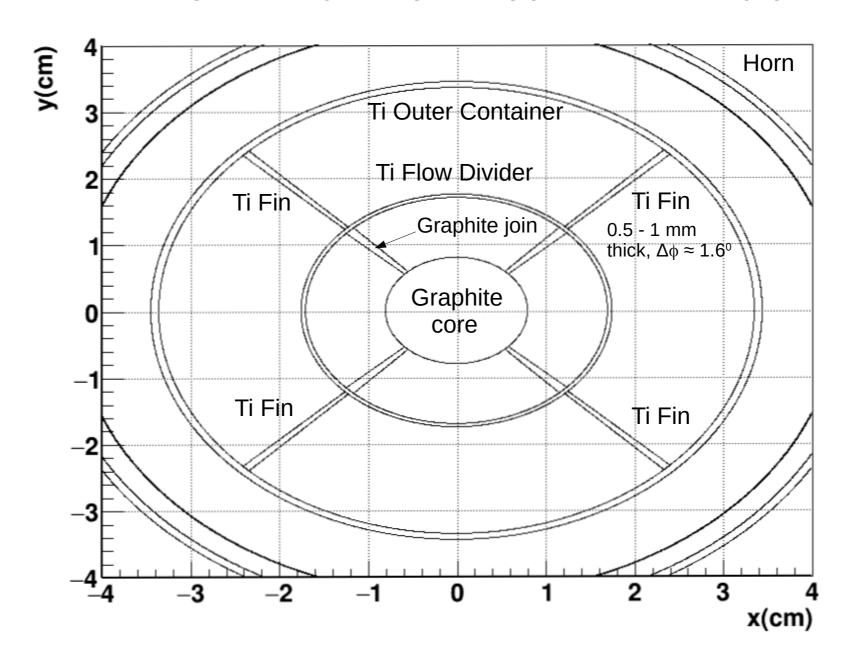


## Target titanium support fins

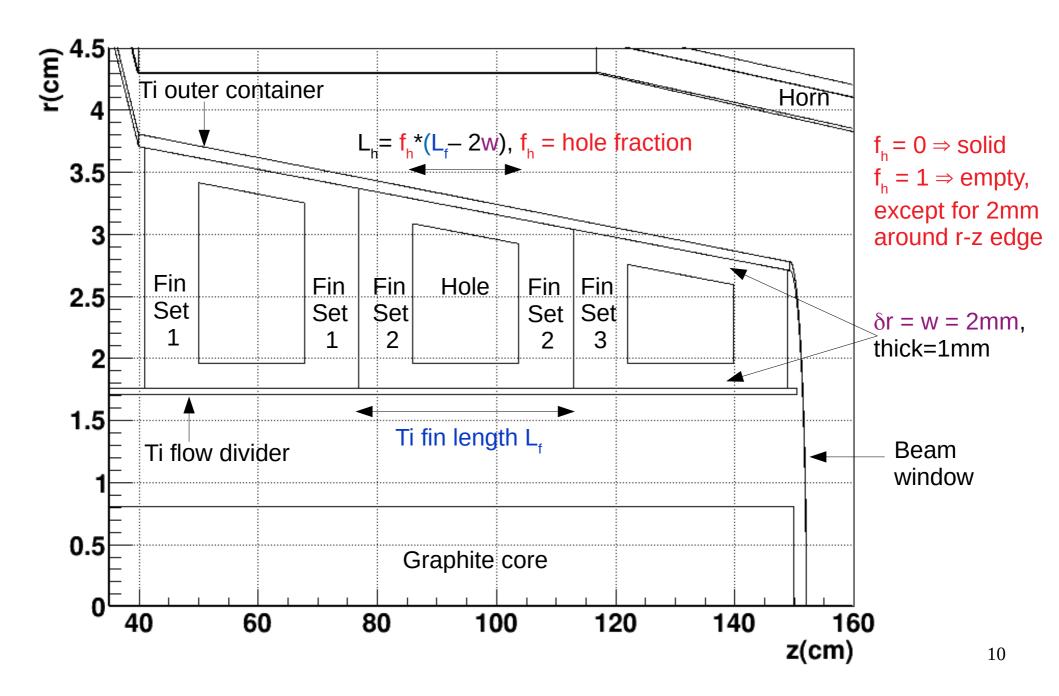


Titanium fins placed at ±45 and ±135 deg in x-y plane 0.5 to 1 mm thick, fully extending along beam z axis 3 equal sections starting from end of upstream cone region

#### Geant4 geometry: target support fins in x-y plane



## Creating holes in fin supports: r-z plane view



## Neutrino Flux Spectra at Far Detector

- Nominal histos:  $t_u = 3$  mm,  $t_m = 1$  mm,  $t_d = 0.7$  mm container taper
- All other histos:  $t_u = t_m = t_d = t_{oc} = 0$  to 2.5 mm, in 0.5 mm steps
- For L = 1.5 m and 1.8 m core target lengths
- Target support fin hole fractions:
  - **0.0** (solid)
  - 0.5 (half solid)
  - **1.0** (2 mm edges only)
- Neutrino & anti-neutrino running
- Unoscillated fluxes extrapolated to far detector

L = 1.5 m,  $f_h$  = 0 (solid fins) signal mode:  $v_{\mu}$  (left) & anti- $v_{\mu}$  (right) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm \_\_\_\_ 1.0 mm 1.0 mm 50×10<sup>-12</sup> ---- 2.5 mm 1.5 mm 2.0 mm - 2.5 mm 1.5 mm 2.0 mm 45 40 40 Unosc  $\overline{v}_{\mu}s$  / GeV / m² / POT Unosc  $v_{\mu}s$  / GeV / m $^2$  / POT 35 30 30 25 25 20 20 15 15 10 10 2 5  $\overline{v}_{\mu}$  Energy (GeV)  $v_u$  Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.5 mm 0.0 mm ---- 1.0 mm 0.0 mm – 0.5 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm ---- 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.1 1.1  $t_{oc} = 0 \text{ mm}$  $t_{oc} = 0 \text{ mm}$ t<sub>oc</sub>= 2.5 mm  $t_{oc}$ = 2.5 mm

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ν<sub>u</sub> Energy (GeV)

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 $\overline{v}_{u}$  Energy (GeV)

L = 1.5 m,  $f_h$  = 0.5 (half solid) signal mode:  $v_{\mu}$  (left) & anti- $v_{\mu}$  (right) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm \_\_\_ 1.0 mm 0.5 mm 50×10<sup>-12</sup> 2.0 mm — 2.5 mm 1.5 mm - 2.5 mm 1.5 mm 2.0 mm 45 40 40 Unosc  $\overline{v}_{\mu}s$  / GeV / m² / POT Unosc  $v_{\mu}s$  / GeV / m $^2$  / POT 35 30 30 25 25 20 20 15 15 10 10 2 5  $\overline{v}_{\mu}$  Energy (GeV)  $v_{\mu}$  Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm 0.5 mm — 1.0 mm 0.0 mm – 0.5 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm —— 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.1 1.1  $t_{oc} = 0 \text{ mm}$  $t_{oc} = 0 \text{ mm}$ t<sub>oc</sub>= 2.5 mm  $t_{oc}$ = 2.5 mm 0.85 0 0.85 1 2 5 5 6

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ν<sub>u</sub> Energy (GeV)

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L = 1.5 m,  $f_h$  = 0 (solid fins) wrong sign bkg: anti- $v_{\mu}$  (left) &  $v_{\mu}$  (right) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm - 0.5 mm --- 1.0 mm 0.0 mm 8×10<sup>-12</sup> 8×10<sup>-12</sup> 2.0 mm --- 2.5 mm 1.5 mm 2.0 mm — 2.5 mm 1.5 mm 6 6 Unosc  $\overline{v}_{\mu}s$  / GeV / m² / POT Unosc  $v_{\mu}s$  / GeV / m² / POT 5 6 2 5 ν<sub>u</sub> Energy (GeV)  $\overline{v}_{\mu}$  Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.5 mm 0.0 mm ---- 1.0 mm 0.0 mm – 0.5 mm — 1.0 mm 1.5 mm 2.0 mm ---- 2.5 mm 1.5 mm 2.0 mm —— 2.5 mm 1.04 1.04 Unosc binned flux ratio wrt nominal 6.0 86.0 86.0 86.0 Unosc binned flux ratio wrt nominal 1.02 0.96 0.96 0.94 0.92 0.92

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ν<sub>u</sub> Energy (GeV)

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 $\overline{v}_{u}$  Energy (GeV)

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ν<sub>u</sub> Energy (GeV)

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L = 1.8 m,  $f_h$  = 0.5 (half solid) wrong sign bkg: anti- $v_{\mu}$  (left) &  $v_{\mu}$  (right) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm 0.5 mm \_\_\_ 1.0 mm 0.0 mm 8×10<sup>-12</sup> \_ 2.0 mm 2.0 mm — 2.5 mm 1.5 mm - 2.5 mm 1.5 mm 6 6 Unosc  $\overline{v}_{\mu}s$  / GeV / m² / POT Unosc  $v_{\mu}s$  / GeV / m² / POT 5 6 2 5 ν<sub>u</sub> Energy (GeV)  $\overline{v}_{\mu}$  Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.5 mm 0.0 mm — 1.0 mm 0.0 mm — 0.5 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm —— 2.5 mm 1.5 mm 2.0 mm —— 2.5 mm 1.04 1.04 Unosc binned flux ratio wrt nominal 6.0 86.0 86.0 86.0 Unosc binned flux ratio wrt nominal 86.0 86.0 86.0 86.0 0.92 0.92

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ν<sub>u</sub> Energy (GeV)

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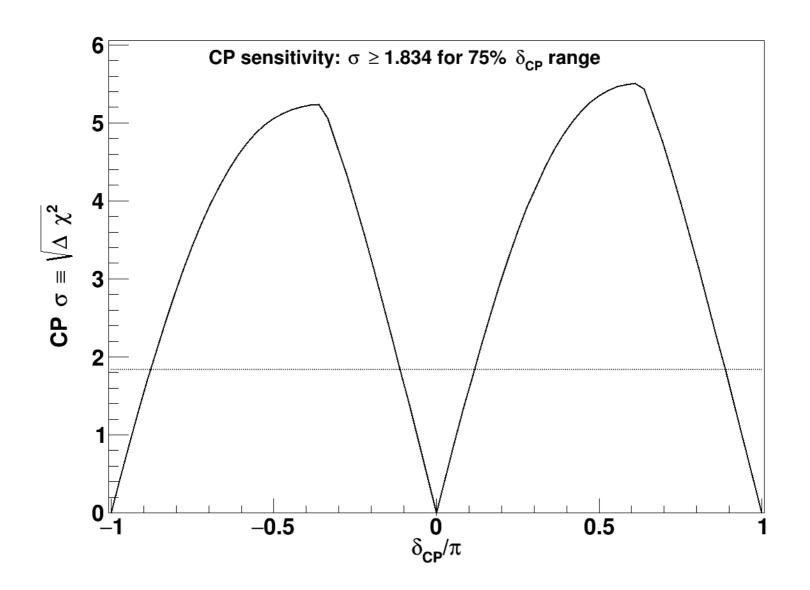
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L = 1.8 m,  $f_h$  = 1.0 (fin edge) wrong sign bkg: anti- $v_{\mu}$  (left) &  $v_{\mu}$  (right) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm 0.5 mm \_\_\_ 1.0 mm 0.0 mm 8×10<sup>-12</sup> 2.0 mm — 2.5 mm 1.5 mm - 2.5 mm 1.5 mm – 2.0 mm 6 6 Unosc  $\overline{v}_{\mu}s$  / GeV / m² / POT Unosc  $v_{\mu}s$  / GeV / m² / POT 5 6 2 5 ν<sub>u</sub> Energy (GeV)  $\overline{v}_{\mu}$  Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.5 mm 0.0 mm — 1.0 mm 0.0 mm — 0.5 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm —— 2.5 mm 1.5 mm 2.0 mm —— 2.5 mm 1.04 1.04 Unosc binned flux ratio wrt nominal 6.0 86.0 86.0 86.0 0.92 0.92 2 5 2 3 5 6 3

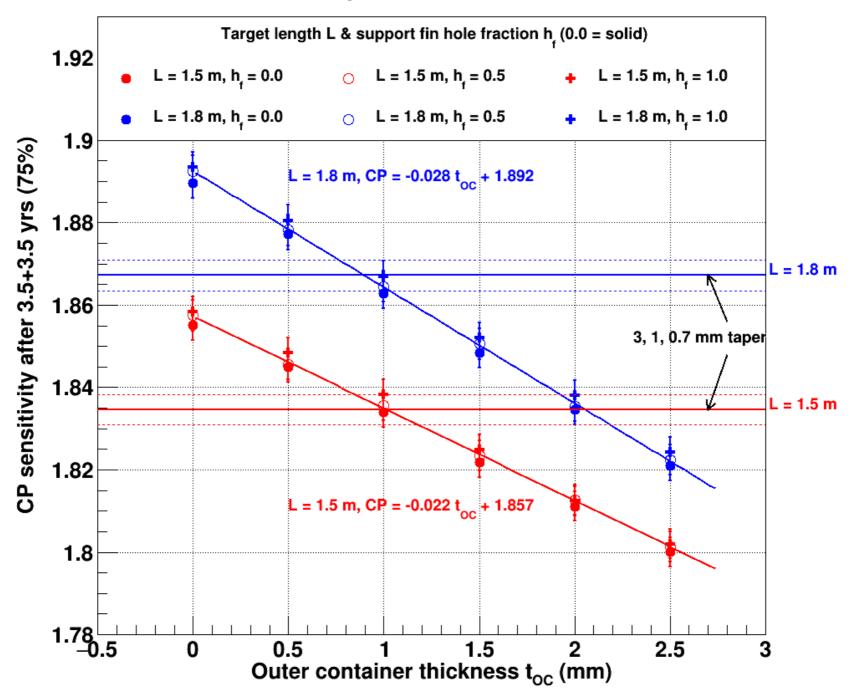
 $\overline{v}_{u}$  Energy (GeV)

ν<sub>u</sub> Energy (GeV)

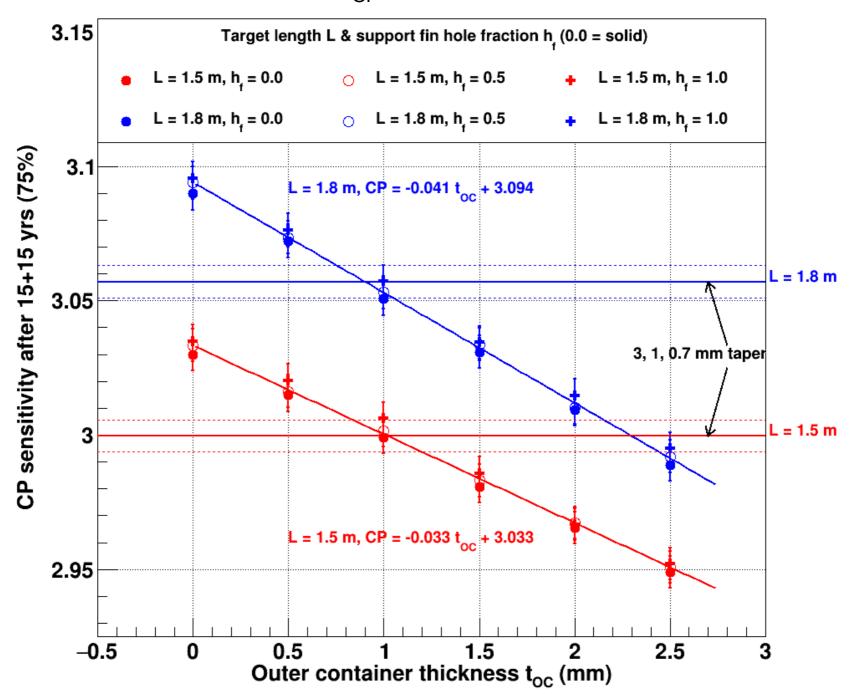
**CP sensitivity** for L = 1.5 m,  $t_{oc}$ = 1 mm (solid fins) 3.5 v + 3.5 anti-v run years, 1.2 MW, 1.1x10<sup>21</sup> POT/year



### CP sensitivities (75% $\delta_{\rm CP}$ range, 3.5+3.5 run yrs, 1.2 MW)

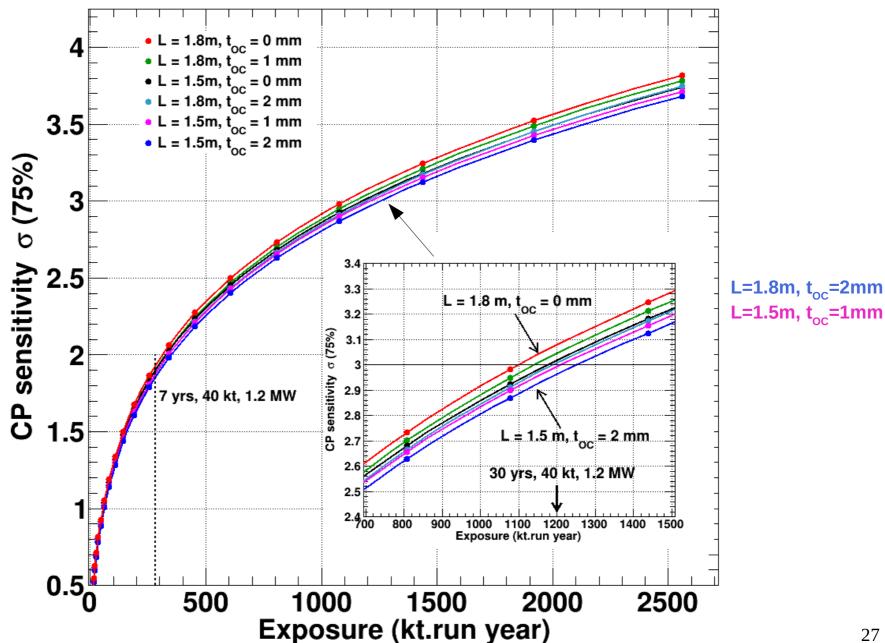


### CP sensitivities (75% $\delta_{\rm CP}$ range, 15+15 run yrs, 1.2 MW)



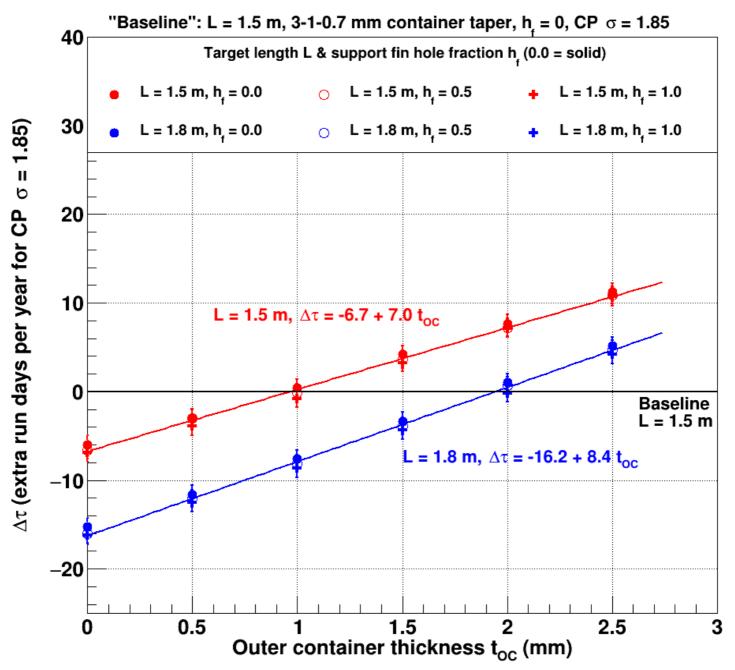
#### CP sensitivity vs exposure (solid support fins)

1.2 MW, 40kt far detector, 56% run efficiency; 1 run year = 204.5 calendar days

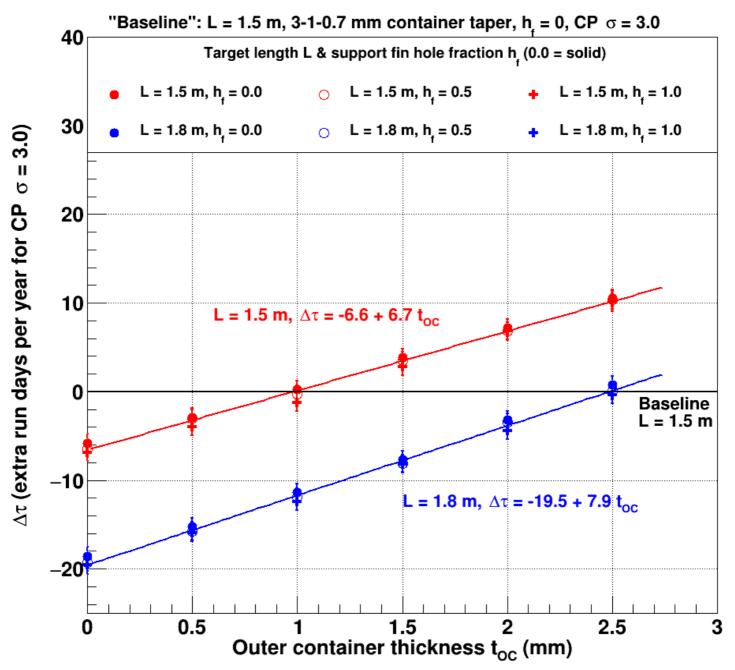


detector mass (40 kt) x run time

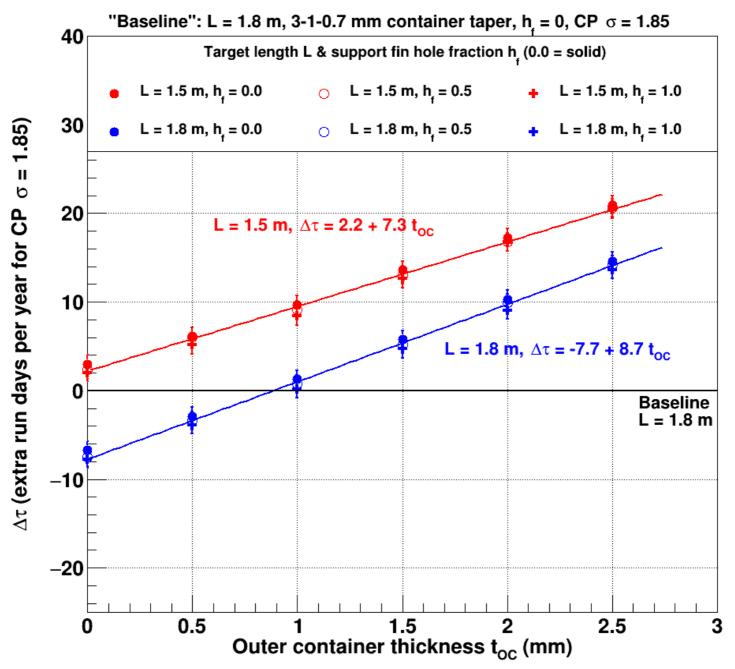
#### Extra run days per year to match L = 1.5 m, CP $\sigma = 1.85$



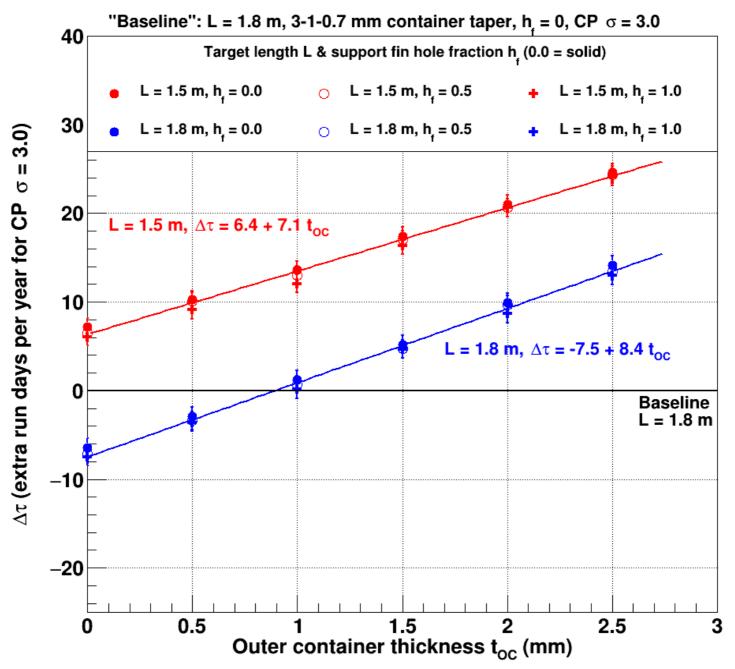
#### Extra run days per year to match L = 1.5 m, CP $\sigma = 3.0$



#### Extra run days per year to match L = 1.8 m, CP $\sigma = 1.85$



#### Extra run days per year to match L = 1.8 m, CP $\sigma = 3.0$



## Summary

- Investigated physics performance, varying:
  - outer container thickness (0 to 2.5 mm in 0.5 mm steps): dominant effect
  - target support fin material (solid, half-solid or 2 mm edge): small changes
- Performance gets worse as outer container thickness increases
  - More transverse material to scatter  $\pi$  away from horn focusing trajectories
  - All  $\pi$  have to pass through the container (or the DS beam window)
  - Need outer container thickness as thin as practicable (within engineering constraints)
    - 3 to 1 to 0.7 mm taper is probably a good compromise (approx equivalent to  $t_{oc} = 1$  mm)
- Small performance changes with material fraction for ~1 mm thick target support fins (±45, ±135 deg)
  - Only  $\pi$  trajectories near these angles are affected (within approx ±1 deg arc span)
  - Slightly better performance with less material: introduce holes along the fins (also good for cooling)
- Increasing container thickness  $t_{\rm OC}$  from 1 to 2.5 mm:
  - Binned signal neutrino flux spectrum decreases by 5% to 10% (E<sub>v</sub> = 2 to 4 GeV)
  - Wrong sign backgrounds change by ~±2%, sometimes more
- CP sensitivity (1.2 MW, 40 kt far detector) vs outer container thickness toc: linear dependence
  - L = 1.8 m with  $t_{oc}$  = 2 2.5 mm equivalent to L = 1.5 m with  $t_{oc}$  = 1 mm (CP  $\sigma$  = 1.85 3.00)

L = 1.5 m,  $f_h$  = 0 (solid fins)  $v_e$  bkg:  $v_\mu$  (left) & anti- $v_\mu$  (right) running Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm --- 1.0 mm 0.0 mm 0.7×10<sup>-12</sup> 2.0 mm ---- 2.5 mm 1.5 mm - 2.5 mm 1.5 mm 2.0 mm 0.6 0.6 Unosc  $\overline{v}_e s$  / GeV / m² / POT Unosc  $v_e s$  / GeV / m<sup>2</sup> / POT 0.5 0.3 0.3 0.1 0.1 5 6 2 5  $\overline{v}_e$  Energy (GeV) ve Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.5 mm 0.0 mm ---- 1.0 mm 0.0 mm — 0.5 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm --- 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.2 1.2 1.15 1.15 Unosc binned flux ratio wrt nominal 6.0 co. 1 co. 1.1 co. 50 co. Unosc binned flux ratio wrt nominal 0.85 0.85 5

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 $\overline{v}_e$  Energy (GeV)

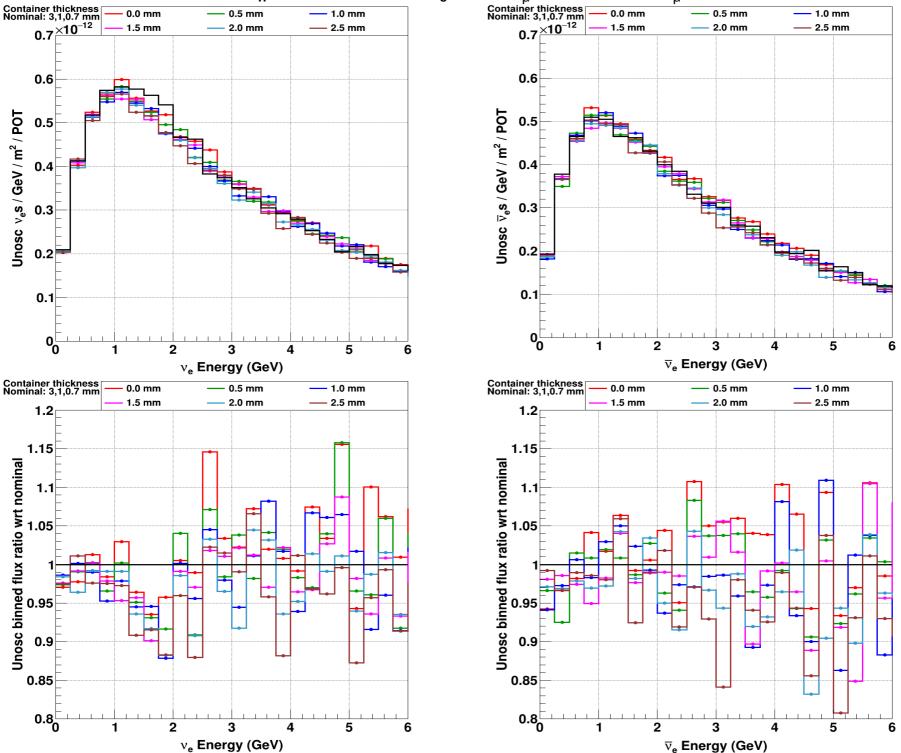
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3 ν<sub>e</sub> Energy (GeV)

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L = 1.5 m,  $f_h$  = 1 (fin edge)  $v_e$  bkg:  $v_\mu$  (left) & anti- $v_\mu$  (right) running



L = 1.8 m,  $f_h$  = 0 (solid fins)  $v_e$  bkg:  $v_\mu$  (left) & anti- $v_\mu$  (right) running Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm — 1.0 mm 0.0 mm 0.5 mm 0.7×10<sup>-12</sup> 0.7×10<sup>-12</sup> —— 2.5 mm 1.5 mm - 2.5 mm 1.5 mm 2.0 mm 2.0 mm 0.6 0.6 Unosc  $\overline{v}_e s$  / GeV / m² / POT Unosc  $v_e s$  / GeV / m<sup>2</sup> / POT 0.5 0.4 0.3 0.3 0.1 0.1 5 6 2 5  $\overline{v}_e$  Energy (GeV) ve Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.5 mm 0.0 mm — 1.0 mm 0.0 mm — 0.5 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm —— 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.2 1.2 1.15 1.15 Unosc binned flux ratio wrt nominal 6.0 co. 1 co. 1.1 co. 50 co. 0.85 0.85

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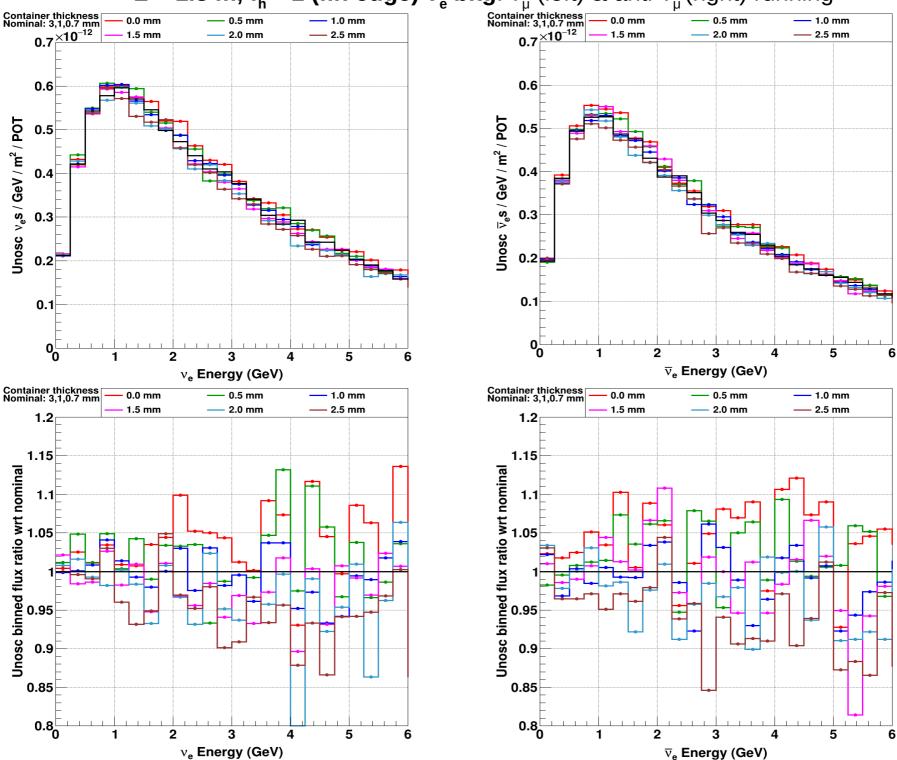
 $\overline{v}_e$  Energy (GeV)

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L = 1.8 m,  $f_h$  = 1 (fin edge)  $v_e$  bkg:  $v_\mu$  (left) & anti- $v_\mu$  (right) running



L = 1.5 m,  $f_h$  = 0 (solid fins) anti- $v_e$  bkg:  $v_\mu$  (left) & anti- $v_\mu$  (right) running Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm - 0.5 mm --- 1.0 mm 0.0 mm 1.0 mm <u>×1</u>0<sup>-12</sup> ×10<sup>-12</sup> --- 2.5 mm 1.5 mm \_ 2.0 mm - 2.5 mm 1.5 mm 2.0 mm 0.12 0.12 0.1 0. Unosc √es / GeV / m² / POT 00 90'0 90'0 80'0 Unosc v<sub>e</sub>s / GeV / m<sup>2</sup> / POT 90.0 90.0 90.0 0.02 0.02 5 6 2 4 5 ν<sub>e</sub> Energy (GeV) v̄<sub>e</sub> Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm – 0.5 mm 0.0 mm 0.5 mm ---- 1.0 mm 0.0 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm --- 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.2 1.2 1.15 1.15 0.85 0.85 0.8 2 5 2 3 5 6

1

3 ⊽<sub>e</sub> Energy (GeV)

ve Energy (GeV)

L = 1.5 m,  $f_h$  = 1 (fin edge) anti- $v_e$  bkg:  $v_{\mu}$  (left) & anti- $v_{\mu}$  (right) running Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm \_\_\_ 1.0 mm 0.0 mm 0.5 mm <u>×1</u>0<sup>-12</sup> ×10<sup>-12</sup> —— 2.5 mm - 2.0 mm - 2.5 mm 1.5 mm 2.0 mm 1.5 mm 0.12 0.12 0. Unosc v<sub>e</sub>s / GeV / m<sup>2</sup> / POT 90.0 90.0 90.0 Unosc √es / GeV / m² / POT 00 90'0 90'0 80'0 0.02 0.02 5 6 2 4 5 ν<sub>e</sub> Energy (GeV) v̄<sub>e</sub> Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm - 0.5 mm 0.0 mm 0.5 mm — 1.0 mm 0.0 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm —— 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.2 1.2 1.15 1.15 Unosc binned flux ratio wrt nominal 0.95 0.9 0.85 0.85 2 5 2 3 5 6 1 3

 $\overline{v}_e$  Energy (GeV)

ve Energy (GeV)

L = 1.8 m,  $f_h$  = 0 (solid fins) anti- $v_e$  bkg:  $v_\mu$  (left) & anti- $v_\mu$  (right) running Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm — 1.0 mm 0.0 mm 1.0 mm 0.5 mm <u>×1</u>0<sup>-12</sup> ×10<sup>-12</sup> —— 2.5 mm 1.5 mm \_ 2.0 mm - 2.5 mm 1.5 mm 2.0 mm 0.12 0.12 0.1 Unosc √es / GeV / m² / POT 00 90'0 90'0 80'0 Unosc v<sub>e</sub>s / GeV / m<sup>2</sup> / POT 90.0 90.0 90.0 0.02 0.02 5 6 2 4 5 ν<sub>e</sub> Energy (GeV) v̄<sub>e</sub> Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm - 0.5 mm 0.0 mm 0.5 mm — 1.0 mm 0.0 mm \_\_\_ 1.0 mm 1.5 mm 2.0 mm —— 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.2 1.2 1.15 1.15 Unosc binned flux ratio wrt nominal 6.0 co. 1 co. 1.1 co. 50 co. 0.85 0.85

2

3

ν<sub>e</sub> Energy (GeV)

2

3

⊽<sub>e</sub> Energy (GeV)

1

5

6

L = 1.8 m,  $f_h$  = 1 (fin edge) anti- $v_e$  bkg:  $v_{\mu}$  (left) & anti- $v_{\mu}$  (right) running Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm 0.0 mm \_\_\_ 1.0 mm 0.0 mm 0.5 mm <u>×1</u>0<sup>-12</sup> <u>×1</u>0<sup>-12</sup> —— 2.5 mm 1.5 mm - 2.0 mm - 2.5 mm 1.5 mm 2.0 mm 0.12 0.12 0.1 Unosc √es / GeV / m² / POT 00 90'0 90'0 80'0 Unosc v<sub>e</sub>s / GeV / m<sup>2</sup> / POT 90.0 90.0 90.0 0.02 0.02 5 6 2 4 5 ν<sub>e</sub> Energy (GeV) v̄<sub>e</sub> Energy (GeV) Container thickness Nominal: 3,1,0.7 mm Container thickness Nominal: 3,1,0.7 mm - 0.5 mm 0.0 mm 0.5 mm — 1.0 mm 0.0 mm — 1.0 mm 1.5 mm 2.0 mm —— 2.5 mm 1.5 mm 2.0 mm – 2.5 mm 1.2 1.2 1.15 1.15 Unosc binned flux ratio wrt nominal 6.0 co. 1 co. 50 co. 6.0 c 0.85 0.85 2 5 2 3 5 6 1 3

⊽<sub>e</sub> Energy (GeV)

40

ν<sub>e</sub> Energy (GeV)