Physics impact of target & horn design updates

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DUNE-doc-20072

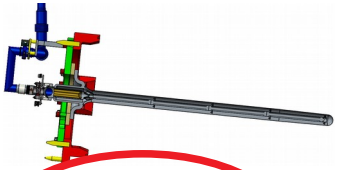
Introduction

- Geant4 simulations of neutrino beamline: graphite target & 3 focusing horns
  - Using geometry based on beam optimization task force (BOTF) report
    - DUNE-doc-2901, Summer 2017
  - 2 m long cylindrical graphite target, extended to 2.2 m: used for TDR fluxes
    - RAL downstream-support (DS) conceptual design: DUNE-doc-5207, Sept. 2017
  - proton beam: 120 GeV, 1.2 MW, 1.1×10^{21} POT/yr; QGSP_BERT hadronic model

- Overview of physics impact of various engineering changes since TDR:
  - Cylindrical graphite target design: cantilever, L = 1.5 – 1.8 m, r = 8 mm = $3\sigma_{beam}$
  - Using cone for upstream horn A inner conductor
    - Allows bigger, stiffer target support (to make target longer)
  - Standardizing horn B and C engineering design
    - Equalization sections, striplines, structural support requirements

- Plots of unoscillated neutrino signal & bkgnd fluxes extrapolated to far detector (40 kt)
- Plots of CP sensitivity and exposure (GLoBES, NuFit 4.0 parameters), using:
  - https://github.com/DUNE/lblpwgtools/tree/master/deprecated/inputs/MVAtoGLoBES/tdr_globes_final

Target concept selection summary: DUNE-doc-15490

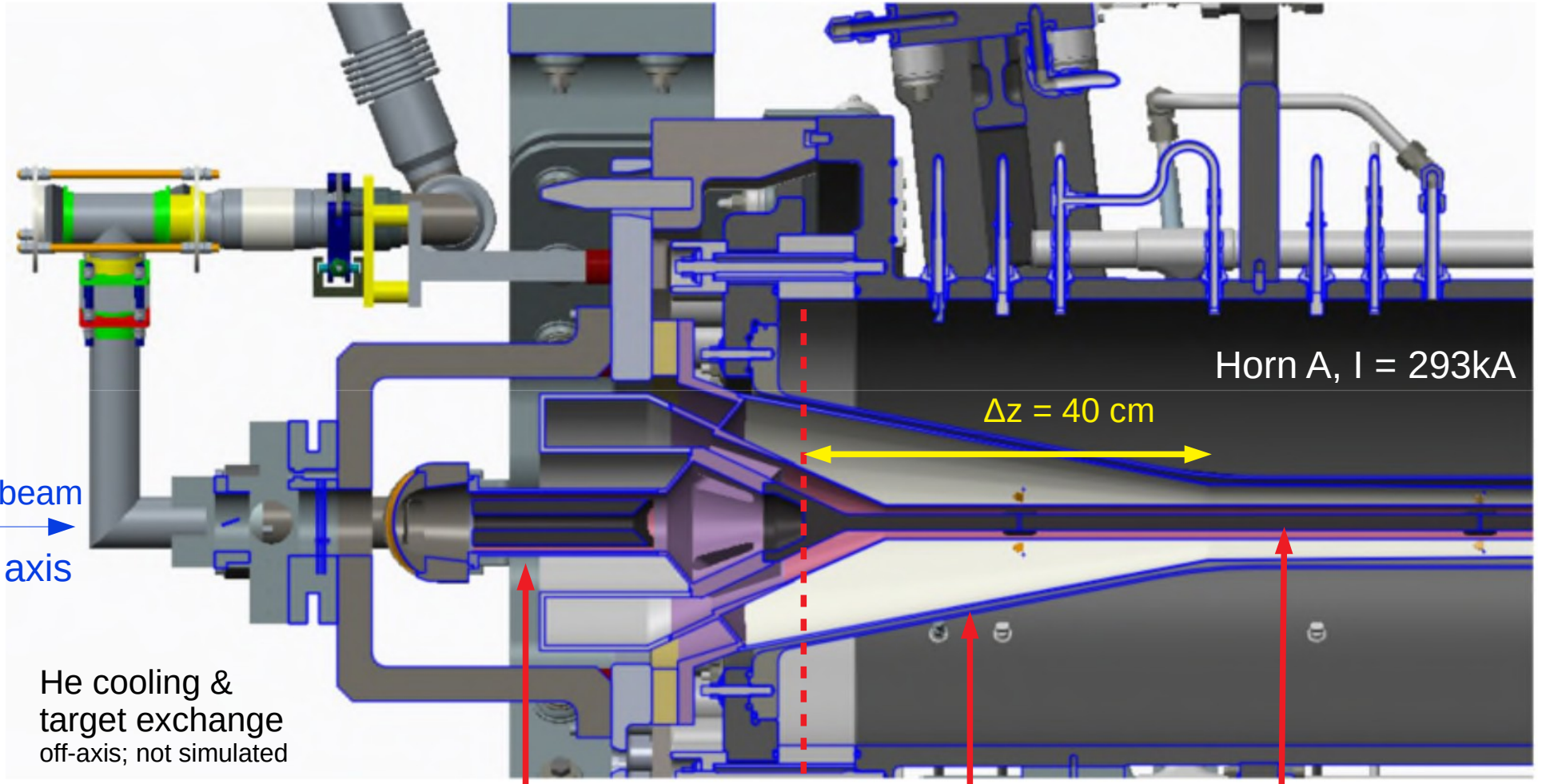
	 **Option 1:1x2m long**	 **Option 2: 2x1m long**	 **Option 3: intermediate cantilever**
Instantaneous physics	Best instantaneous physics.	Needs an extra 19 days/yr to match option 1.	1.5m needs an extra 19 days/yr (13 days/yr at 1.6m).
Engineering performance	High heat load. Unstable until supported.	High heat load but divided between 2 targets	Pushing at the limits on cantilever length.
Manufacturability	Difficult to make long tubes. DS support adds complexity.	2nd target low-mass manifold is complex.	Difficult to make long tubes.
Ease of remote maintenance	≈3 weeks exchange time, DS support adds time and risk.	≈2 weeks exchange time, 2nd target adds some time and risk.	≈1 week exchange time, lowest complexity and risk.
Cost and schedule impacts	DS support somewhat increases cost and time.	2nd target greatly increases cost and time.	Cheapest and fastest to produce.

LBNF target conceptual design selection review: 24 July 2019 @ Fermilab

Target performance = physics x reliability

⇒Consensus to use option 3: cantilever with L = 1.5 m (prototype) up to 1.8 m (goal)

Target and Horn A integration



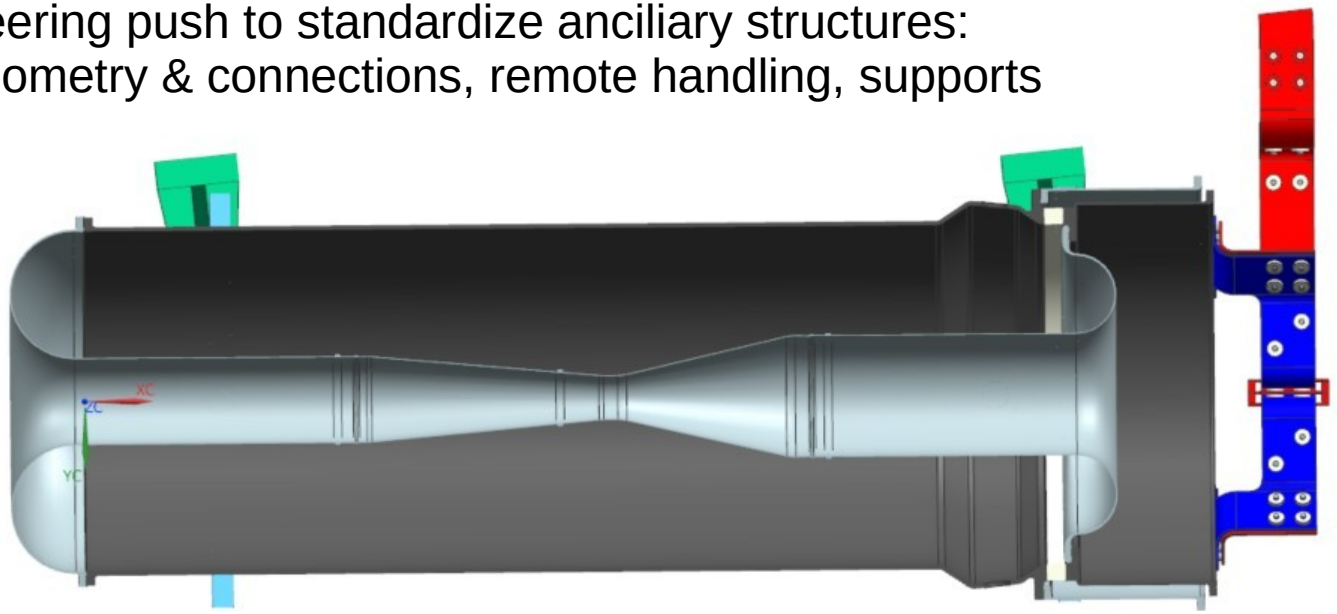
Horn A inner conductor cone (r_{base} = 14 cm, Δz = 40 cm)
to allow space for upstream target support structure

Courtesy RAL
High Power Targets Group

Horn B (& C) standardization

Need to reduce heating of current equalization sections.
Major engineering push to standardize anciliary structures:
stripline geometry & connections, remote handling, supports

TDR
conceptual
engr. design
r_{OC} = 63.4 cm

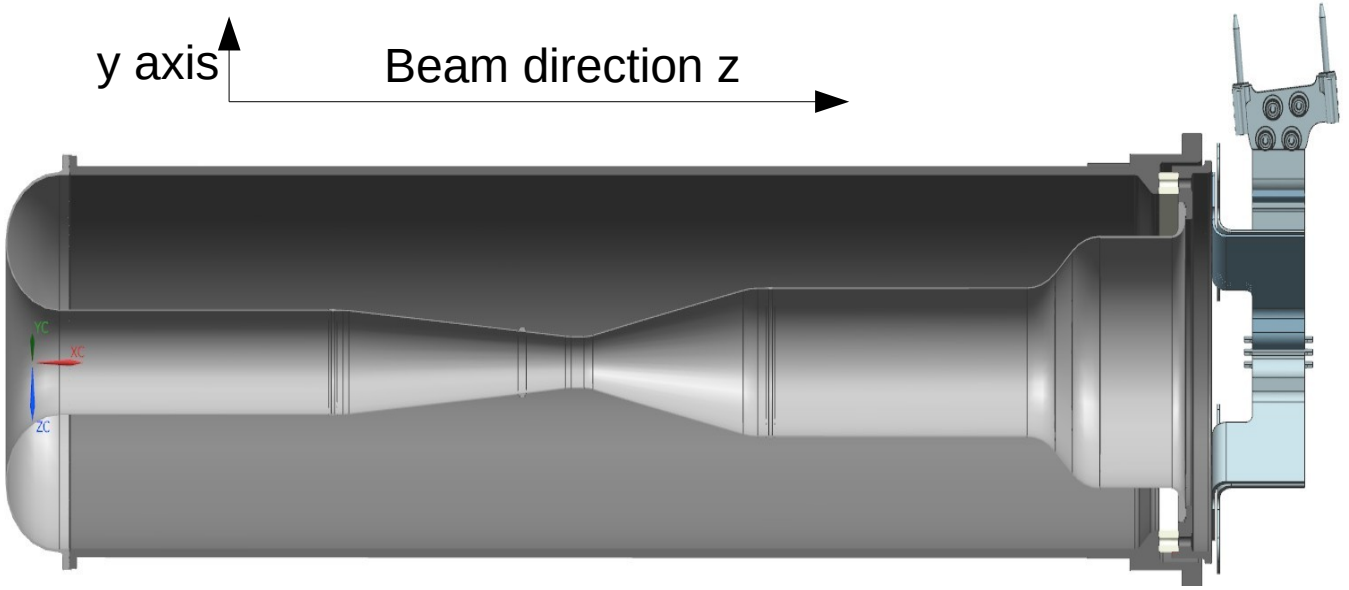


Striplines
not simulated

y axis

Beam direction z

$I_B=I_C$=293kA



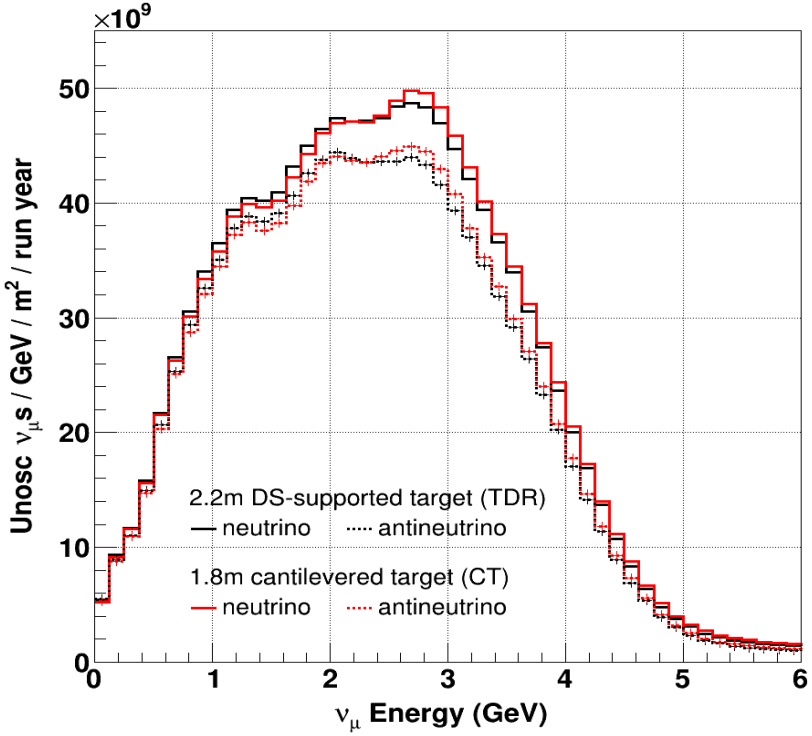
Current
standardized
engr. design
r_{OC} = 60 cm
maximum radius

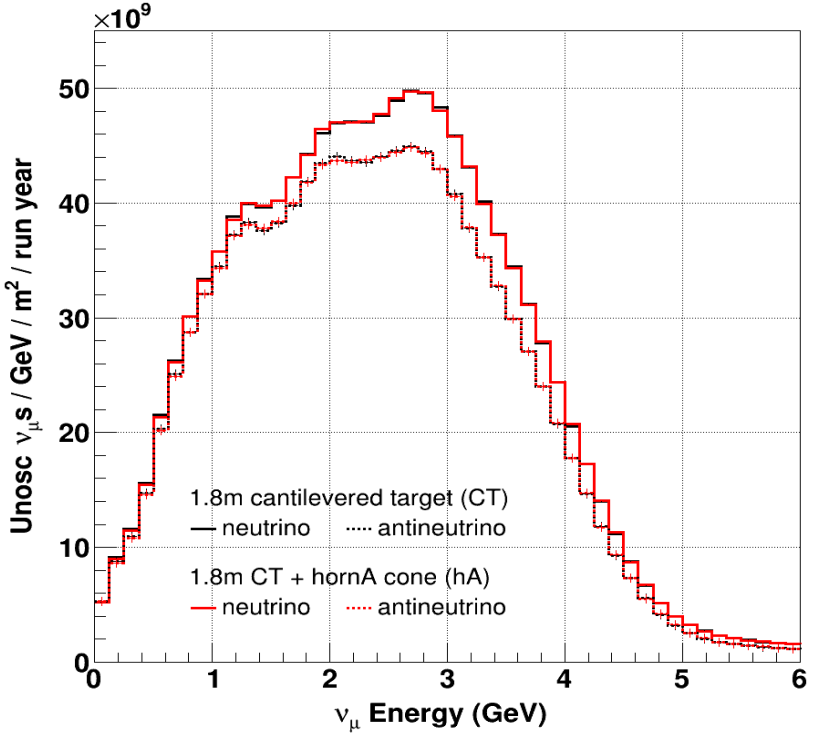
Striplines & **B**
fields included

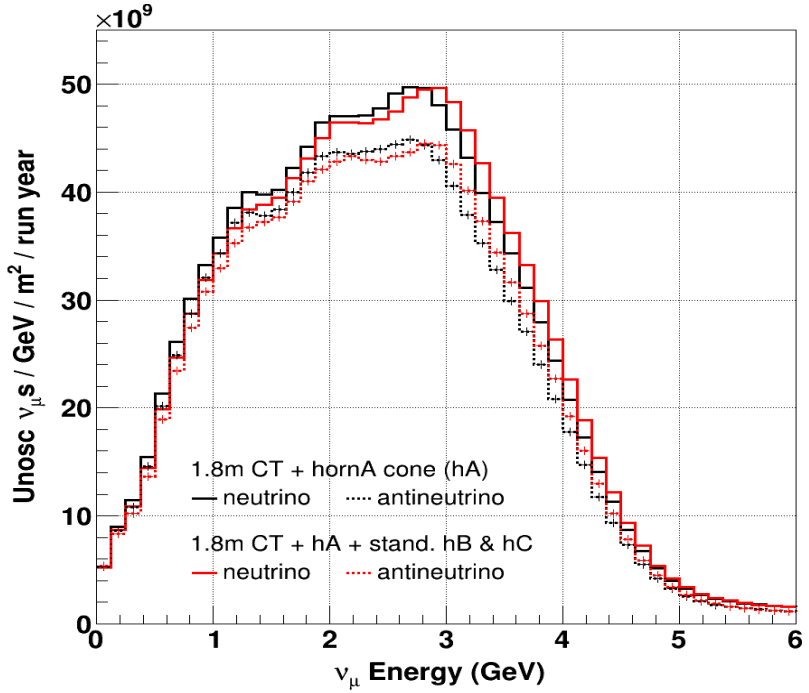
Courtesy Cory Crowley

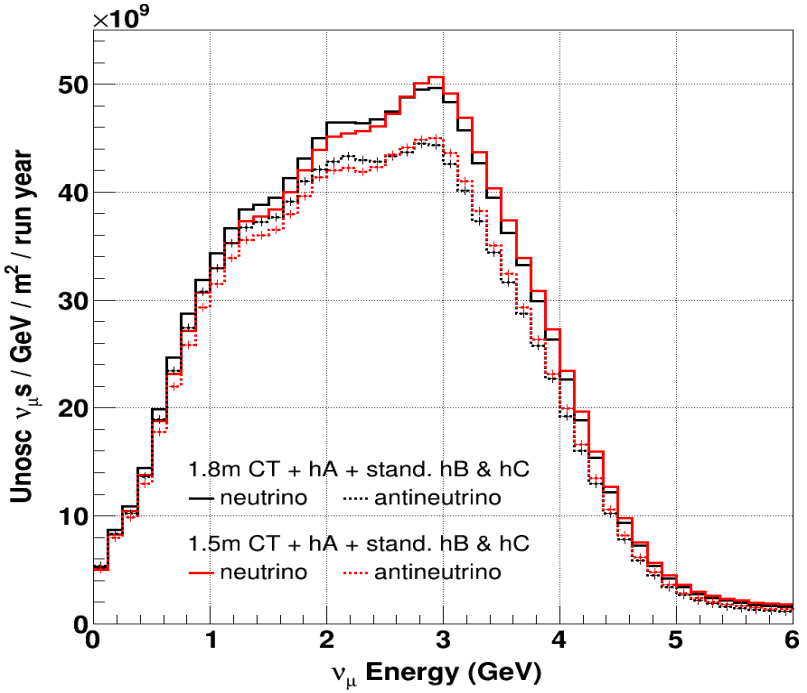
Similar for Horn C (mirror image)

Signal: ν_μ (solid) & anti-ν_μ (dotted)

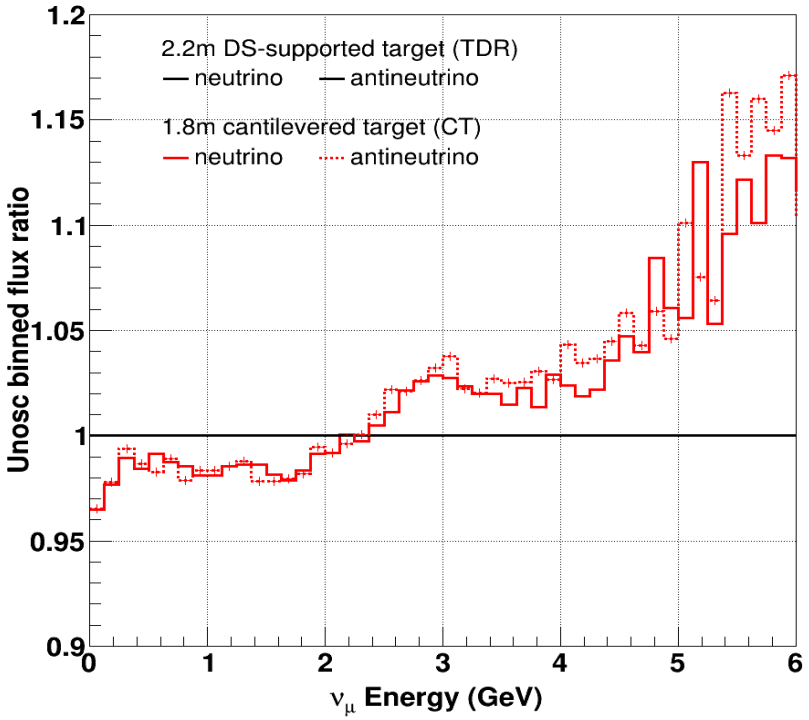


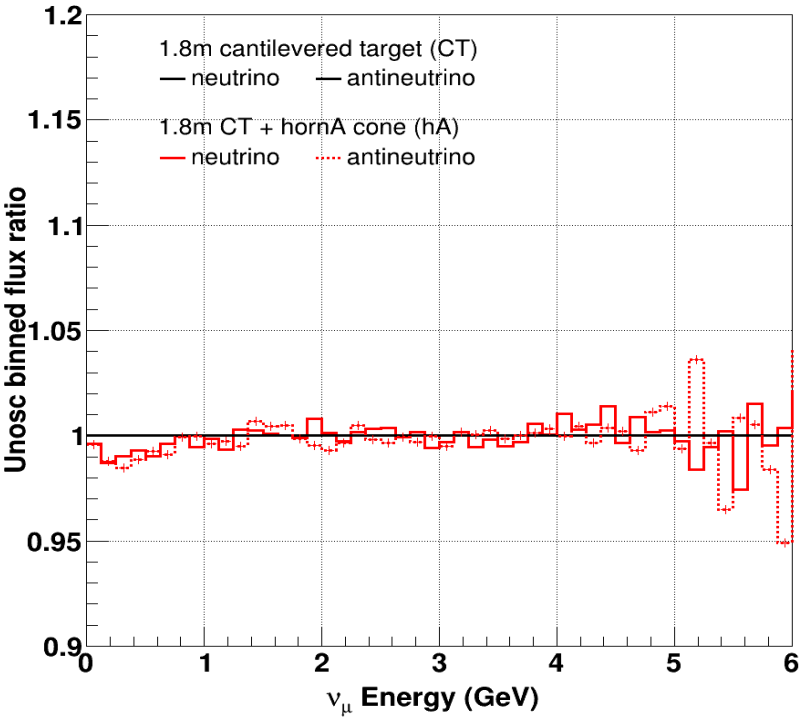


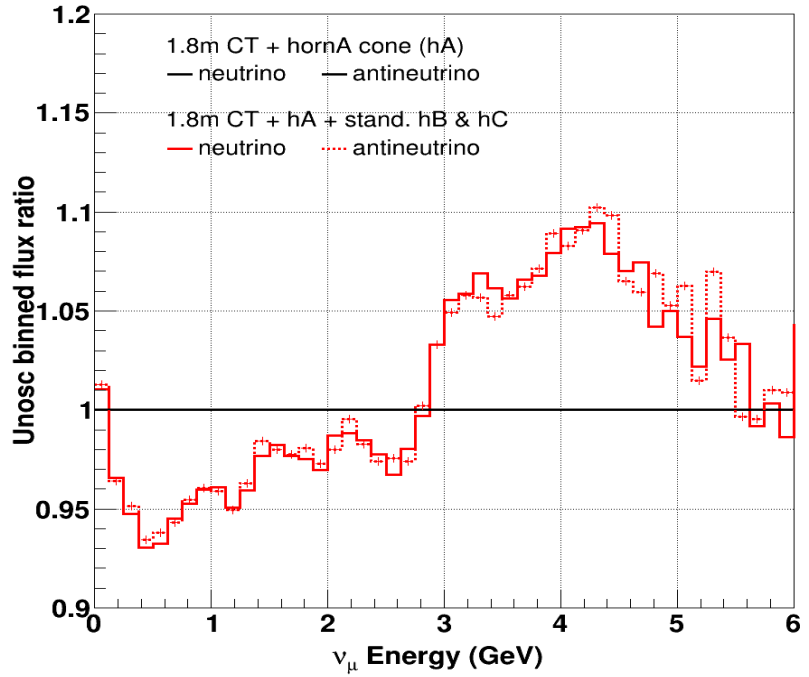


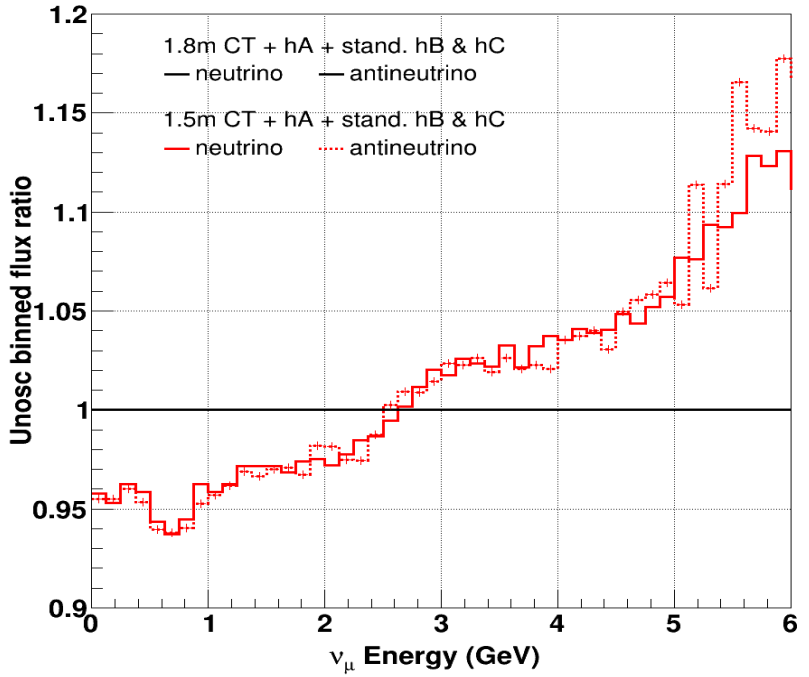


Signal: ν_μ (solid) & anti-ν_μ (dotted)

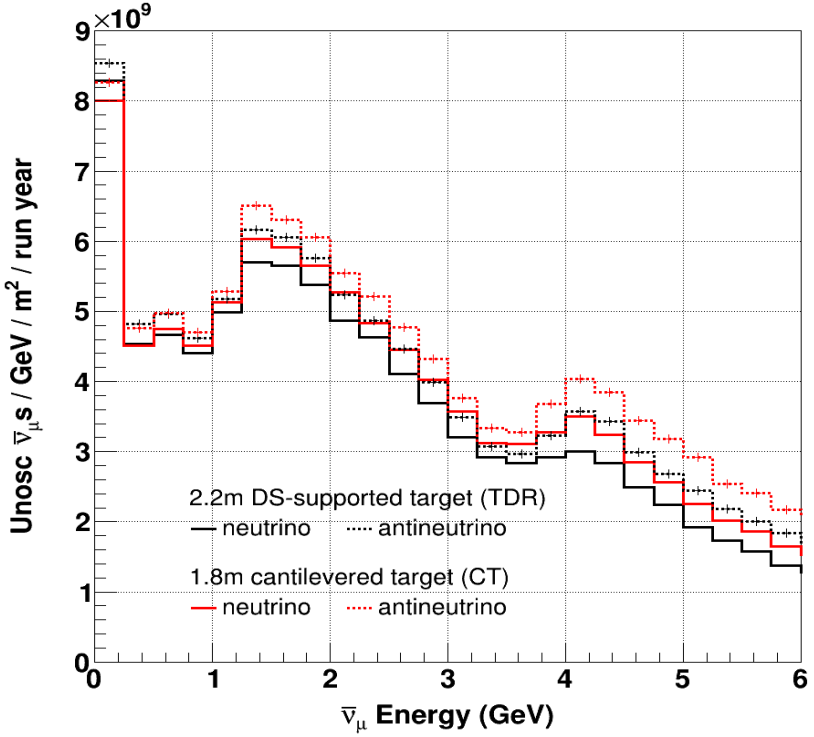


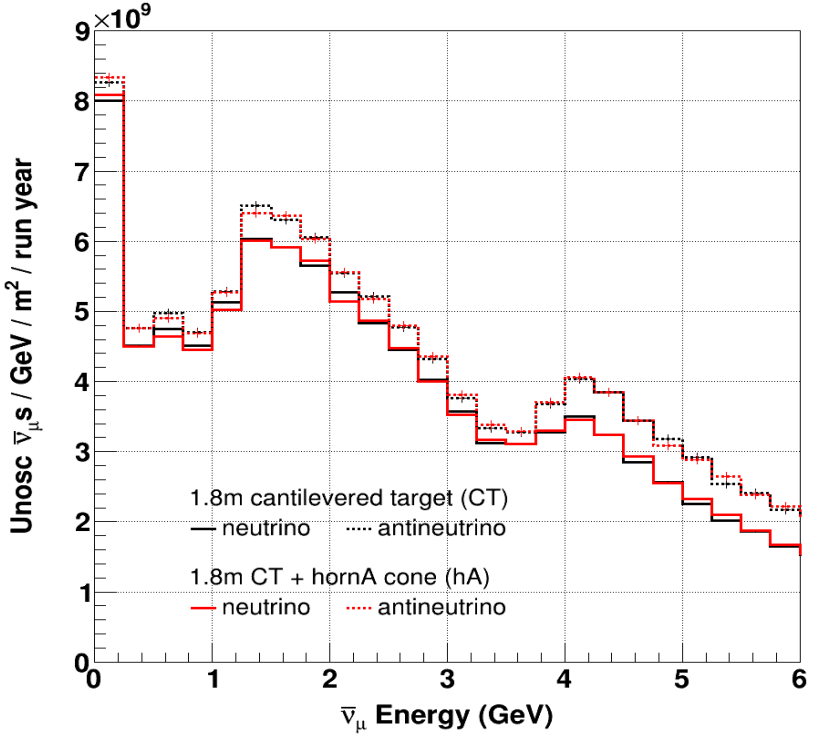


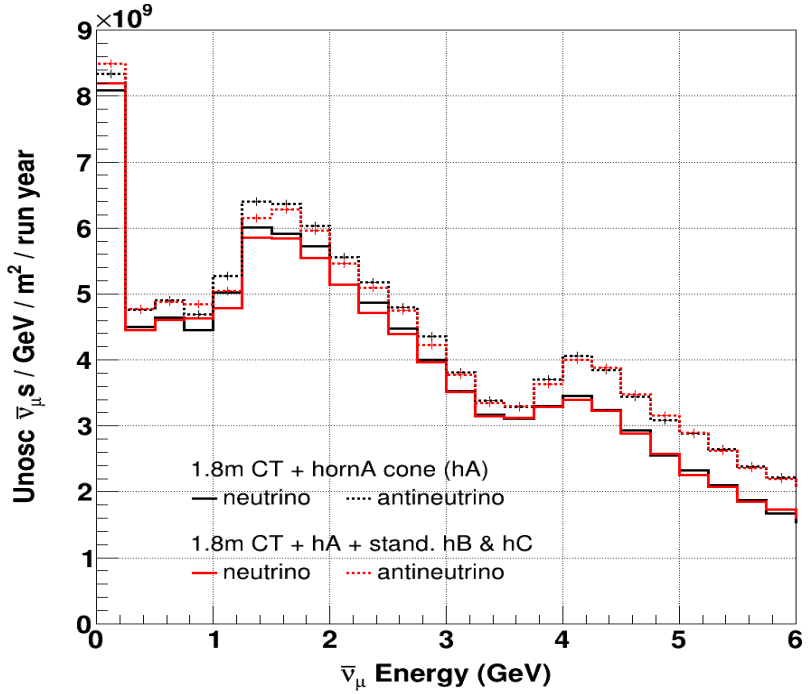


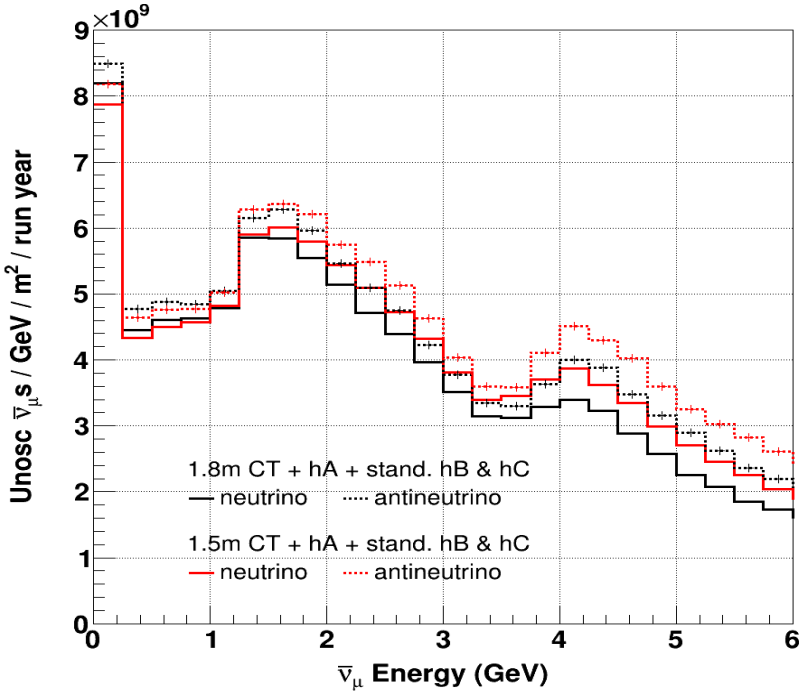


Wrong-sign bkgnd: anti-ν_μ (solid) & ν_μ (dotted)









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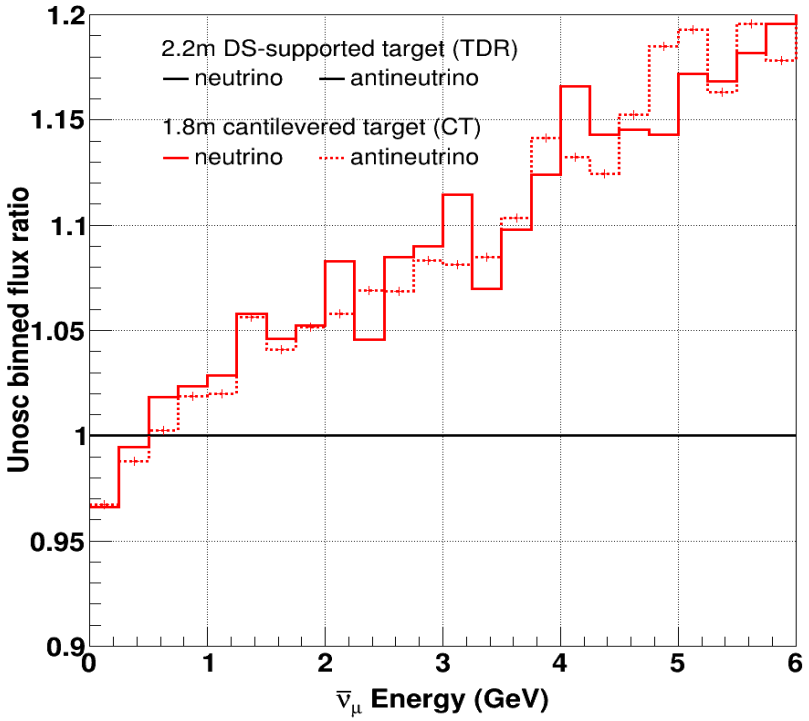
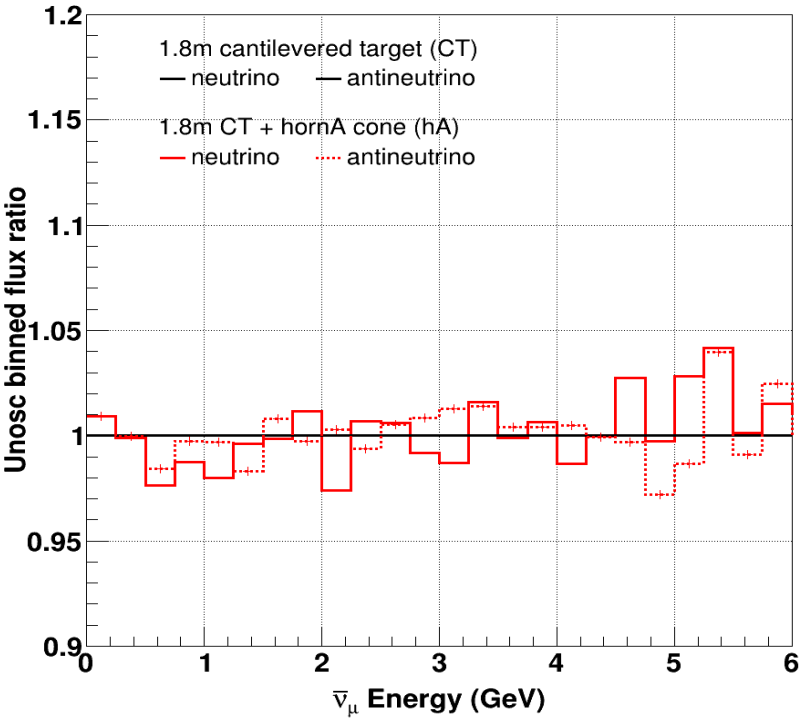
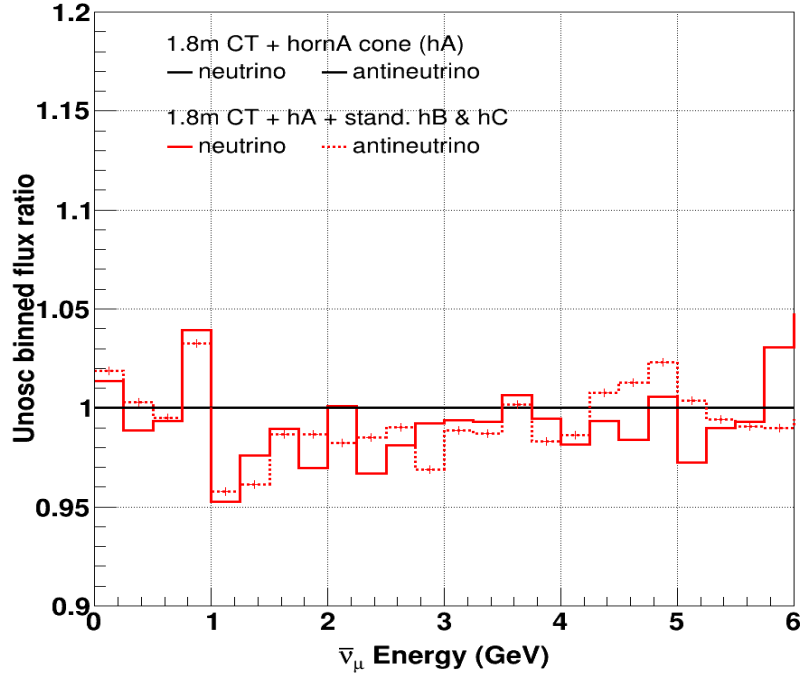
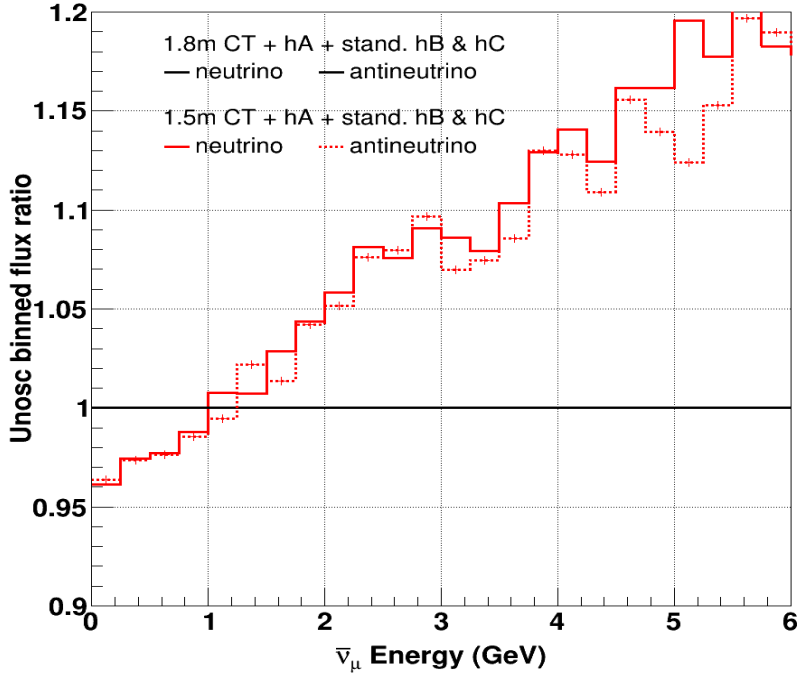
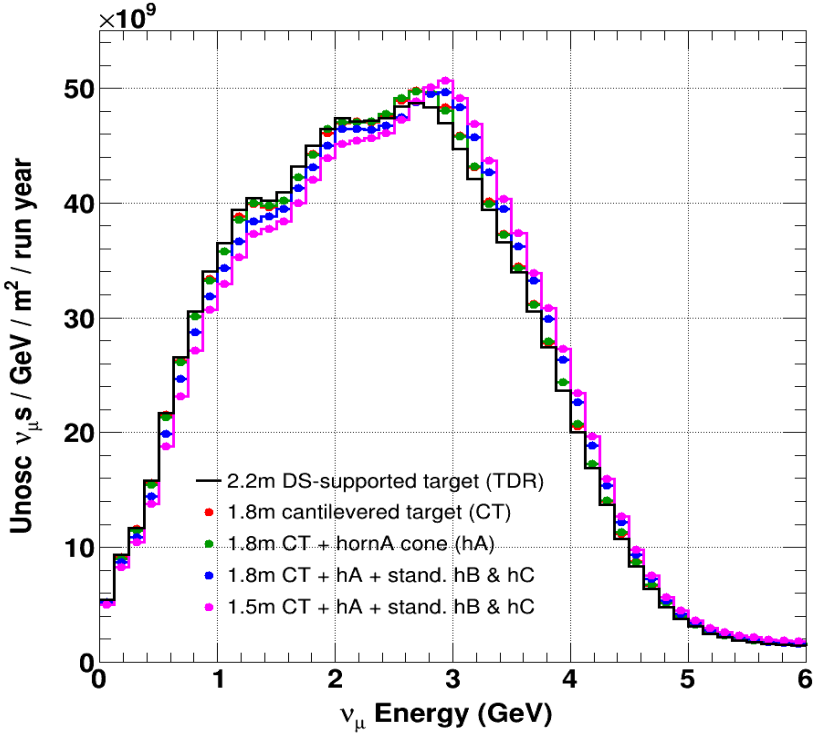


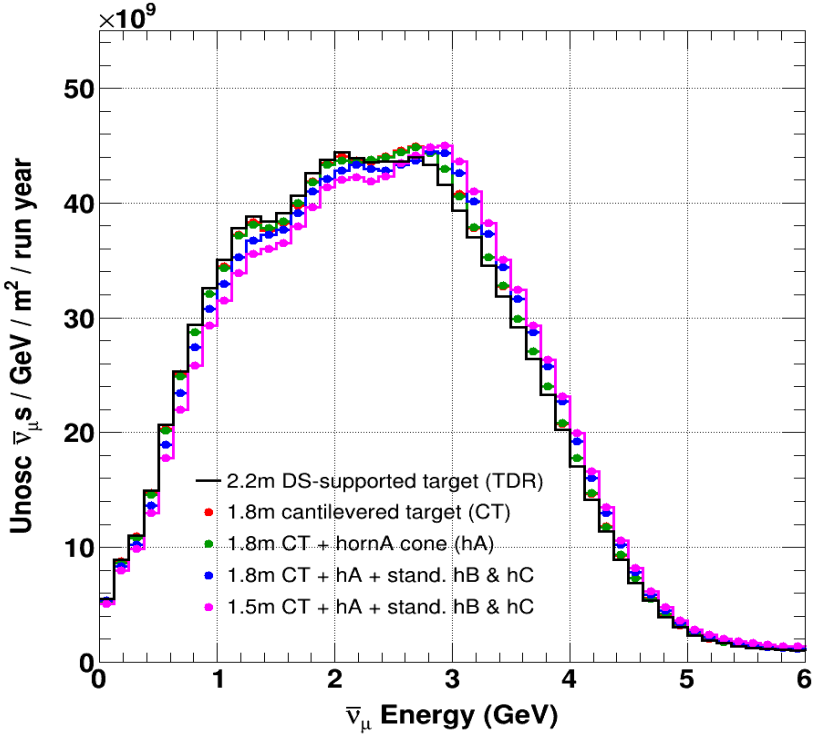


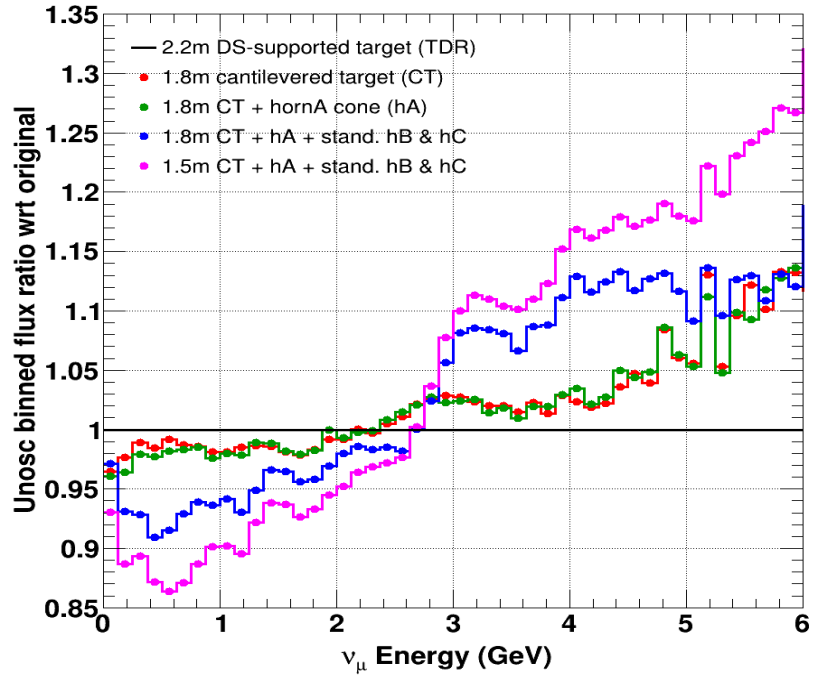


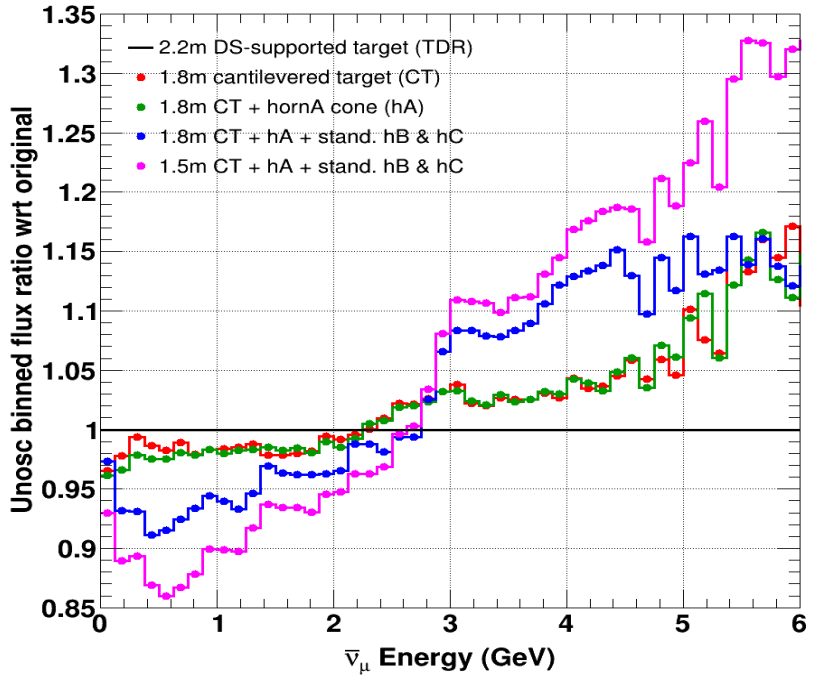


Signal: ν_μ (left) & anti-ν_μ (right)

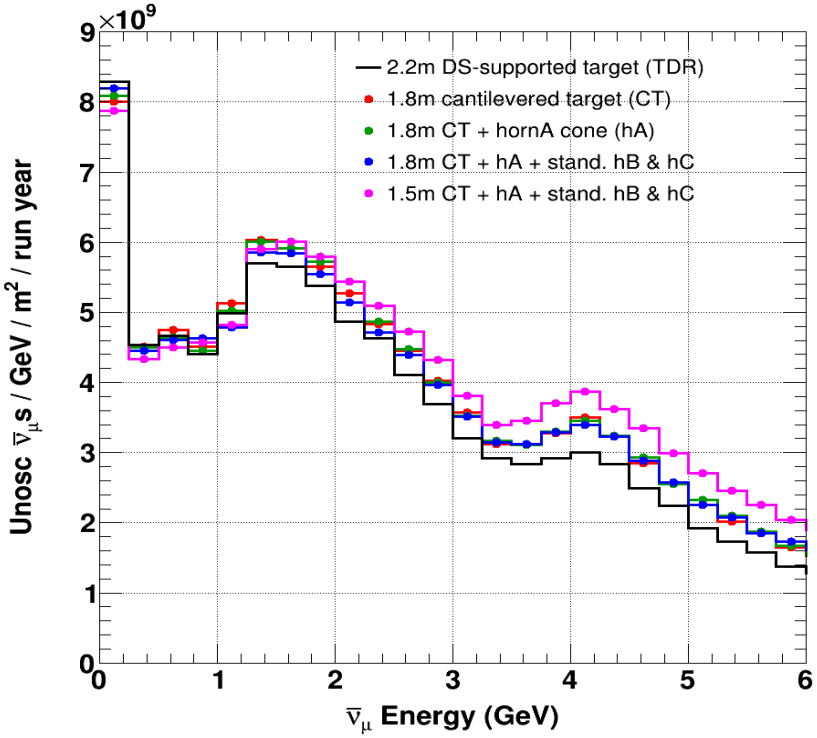


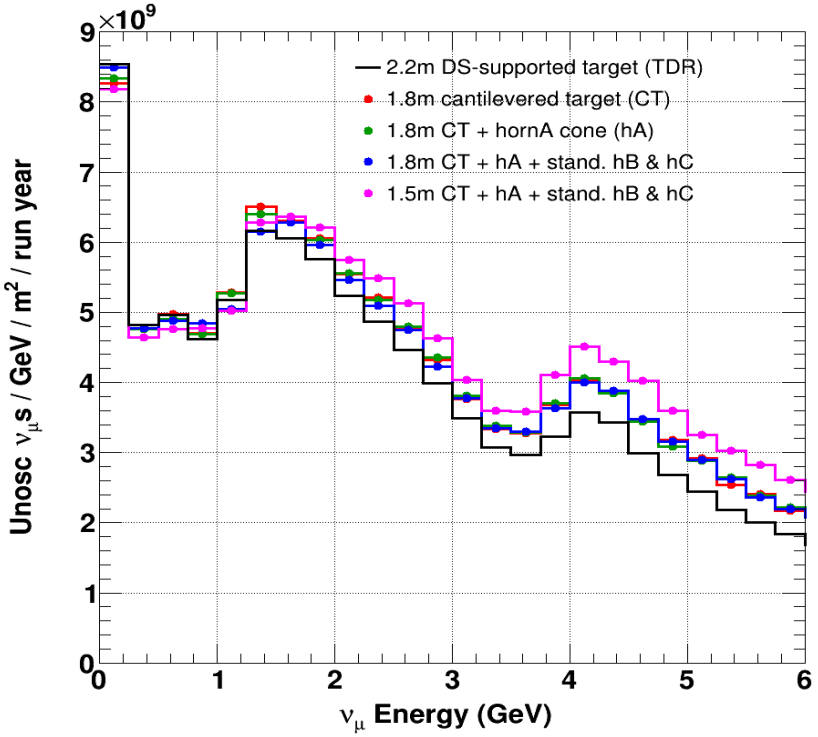


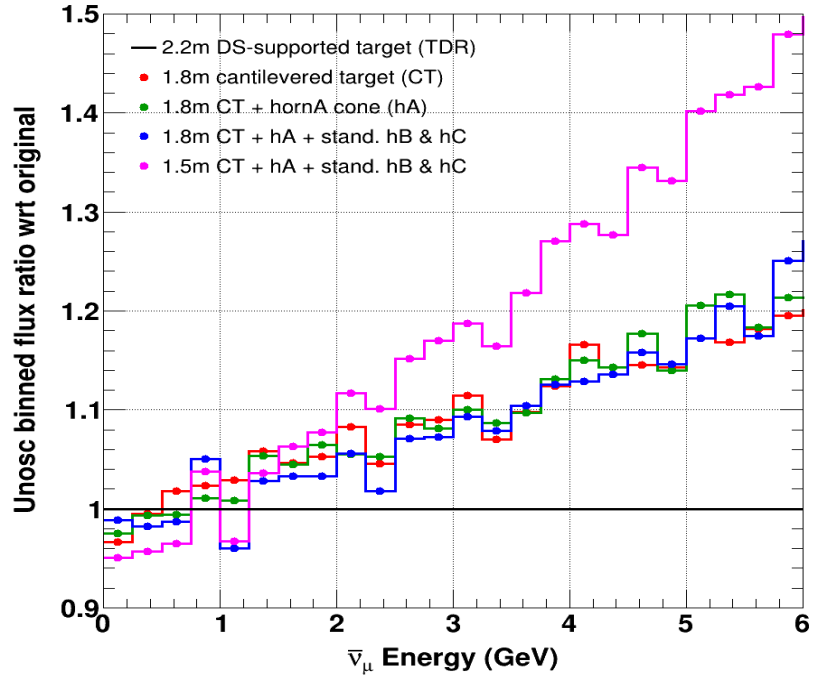


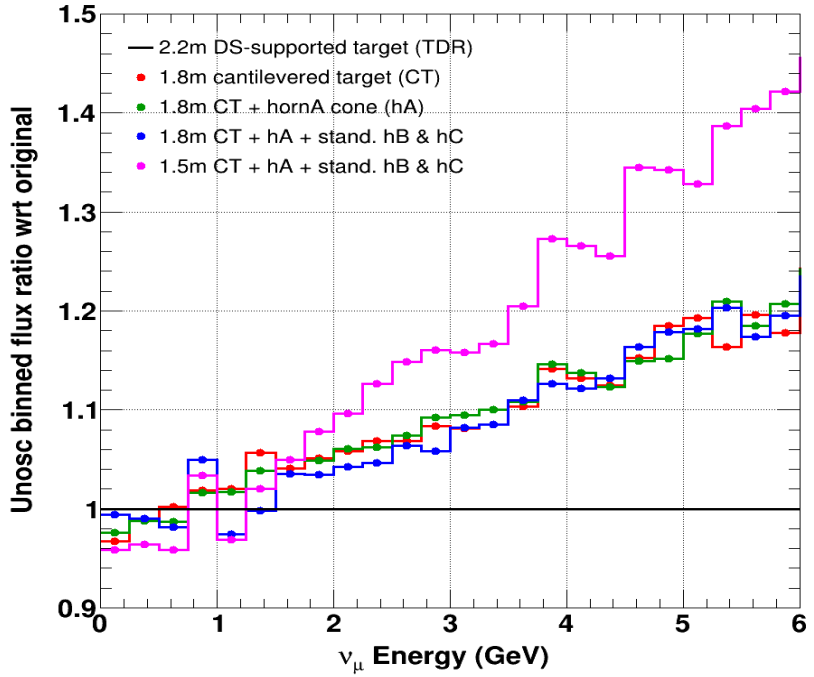


Wrong-sign bkgnd: anti-ν_μ (left) & ν_μ (right)

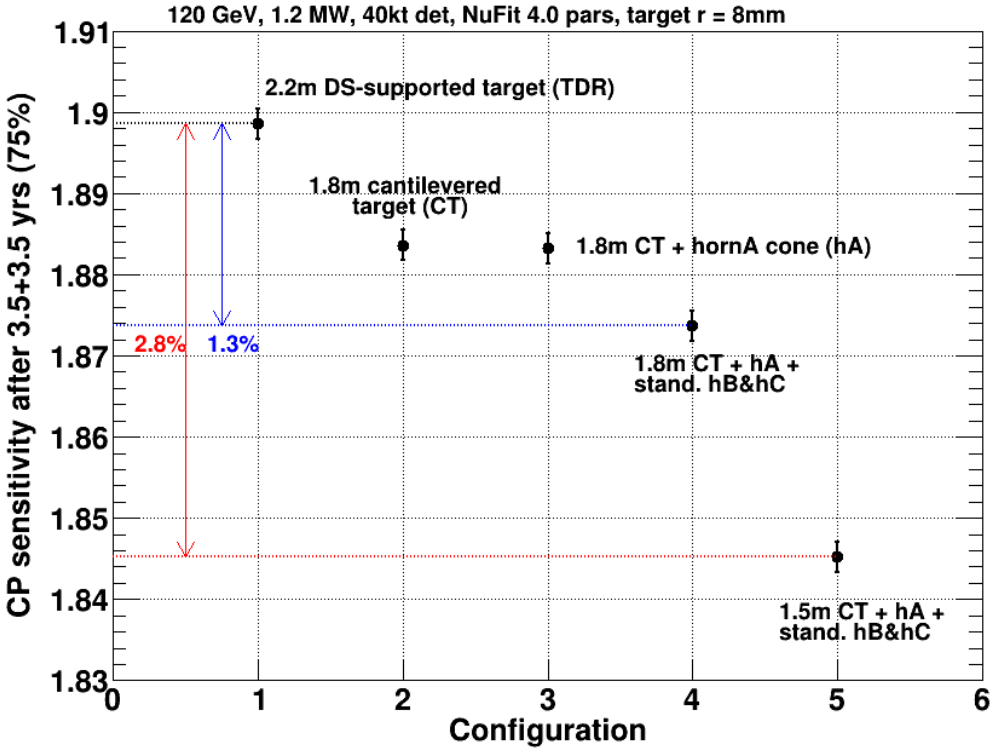


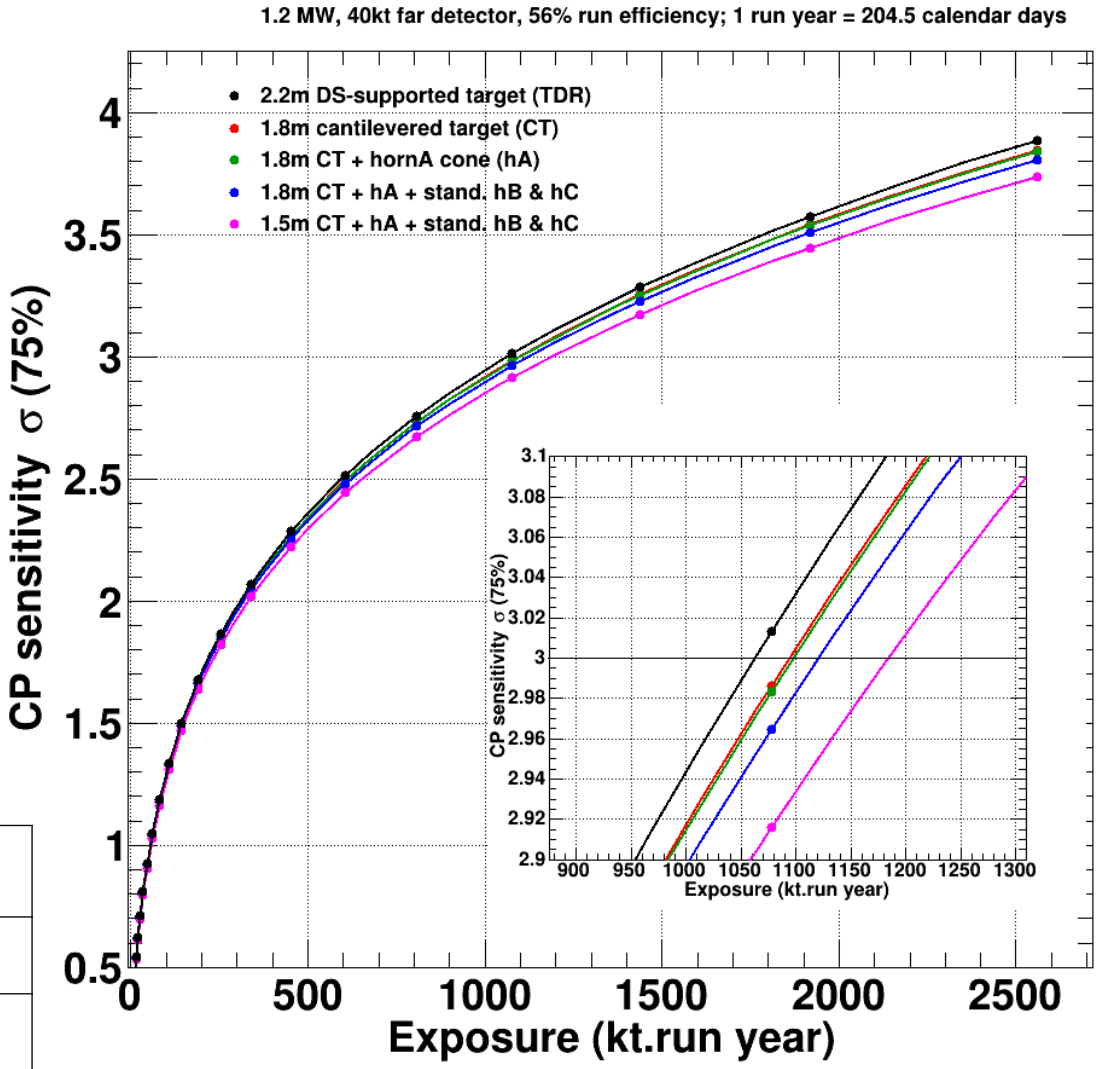






CP sensitivities (75% δ_{CP} range) and exposures





Configuration	Extra time per run year (1 run year = 204.5 days)
1.8m cantilevered target (CT)	6 days (3 %)
1.8m CT + horn A cone (hA)	6 days (3 %)
1.8m CT + hA + standardized horns B & C	11 days (5 %)
1.5m CT + hA + standardized horns B & C	23 days (11 %)

Approx extra time needed to reach **3σ** level of CP exposure performance of TDR 2.2 m target

Excludes target exchange downtime variations

Summary

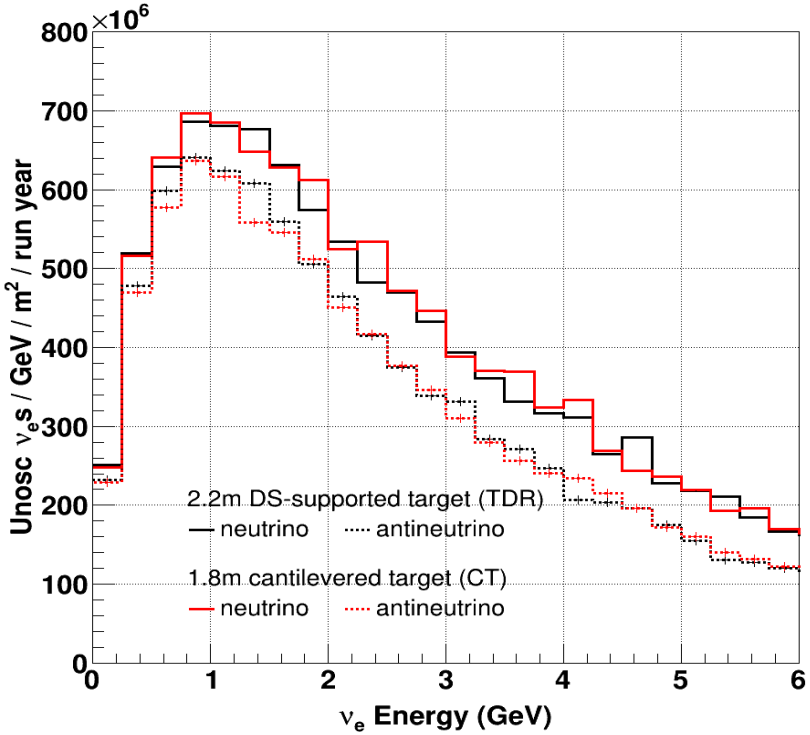
- Evolution of target & horn engineering design has affected physics performance:
  - Loss (gain) of signal flux at low (high) neutrino energy
  - Increase of wrong-sign backgrounds, especially at high energy

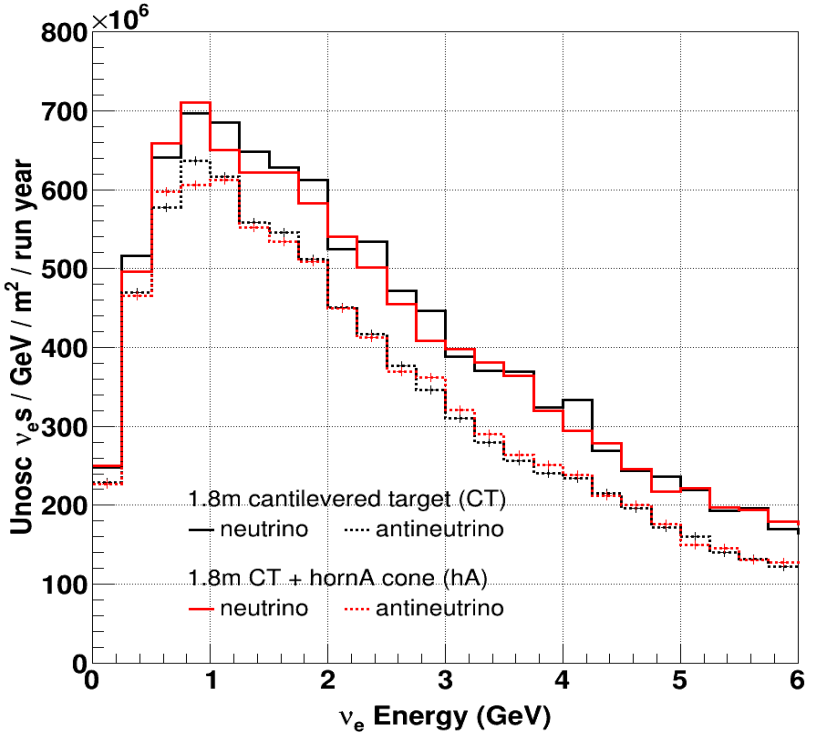
- Biggest change from target length reduction:
  - TDR L = 2.2 m has more engineering (reliability) risks: ~21 days exchange downtime
  - Cantilevered target has lower risk & cost, more reliable: ~7 days exchange downtime
  - Production target (aim) L = 1.8 m needs ~+6 days/run year to match TDR exposure (same horns)
  - Cantilevered L = 1.8 m with standardized horns ~ +11 days/run year to match TDR exposure
    - This is the current target & horn design we are aiming for
  - Initial target prototype, cantilevered L = 1.5 m ~ +23 days/run year to match TDR exposure

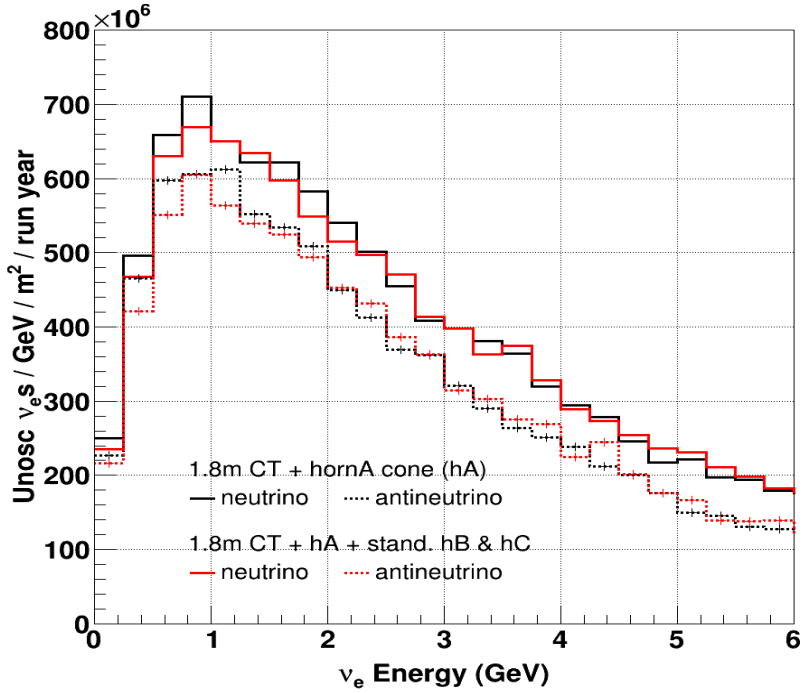
- Horn A upstream inner conductor cone gives no significant change:
  - Potentially allows target length up to 1.8 m ~ $4\lambda_{int}$ (max limit from gravitational bending)

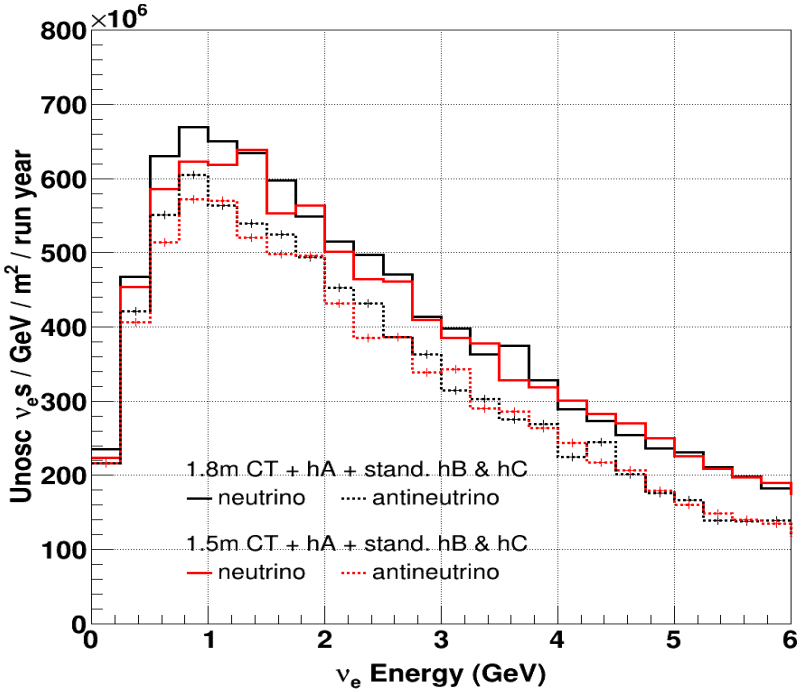
- Horn B & C standardization requirements increase exposure time by an extra ~5 days/run year:
  - Striplines & their B fields give ~1% signal flux reduction (DUNE-doc-19219)
  - Varying horn lengths & foci does not significantly improve performance (DUNE-doc-19885)

$\nu_\mu \rightarrow \nu_e$ (solid) & anti-$\nu_\mu \rightarrow$ anti-ν_e (dotted) bkgnd

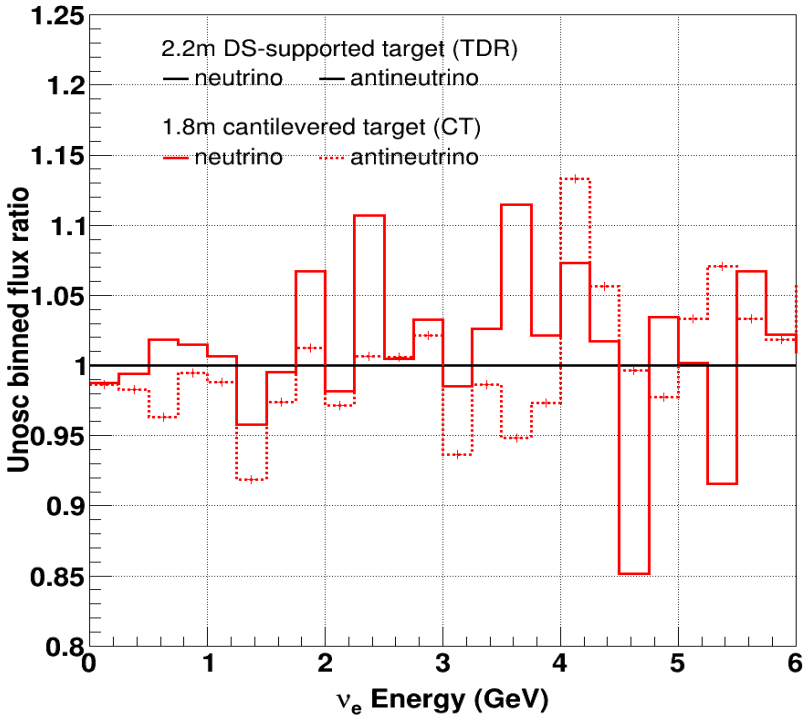


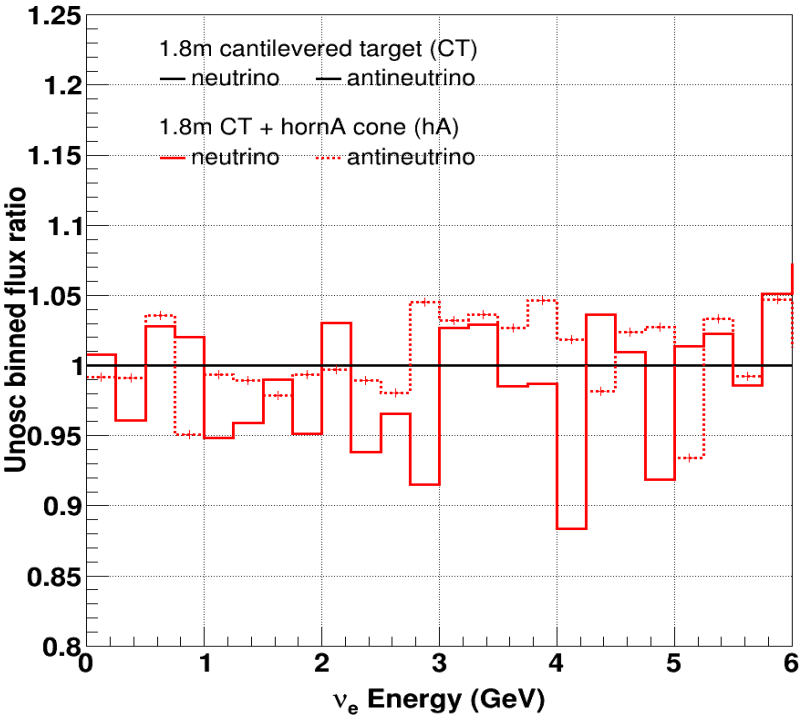


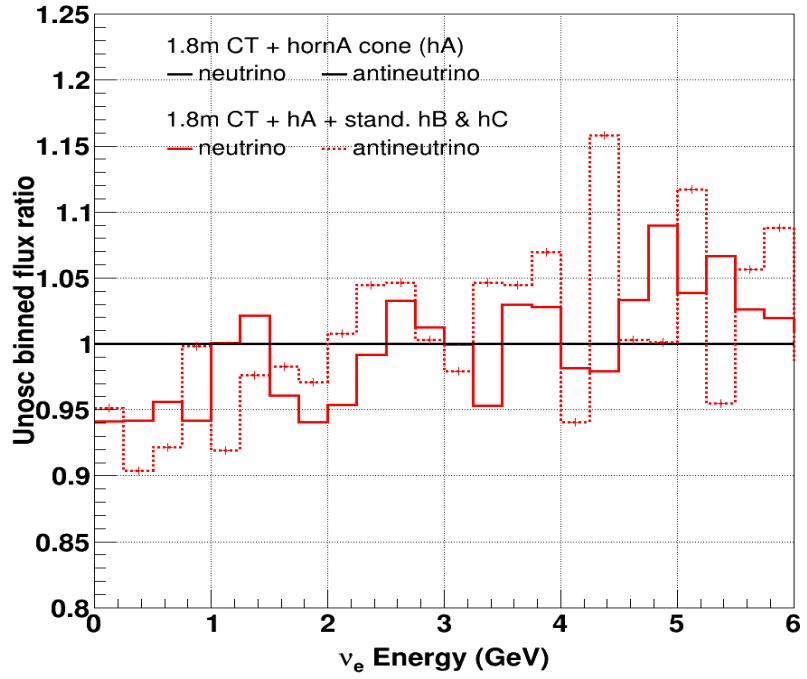


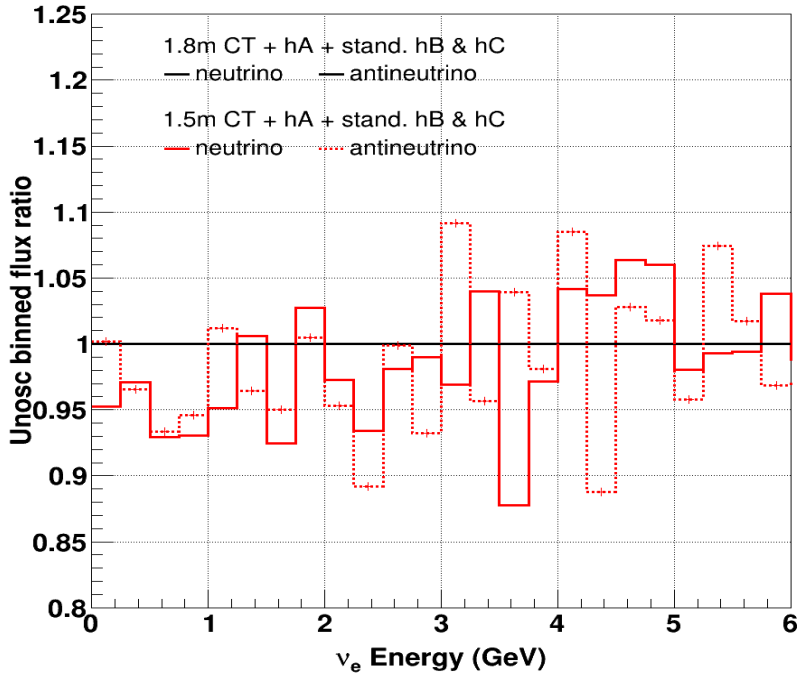


$\nu_\mu \rightarrow \nu_e$ (solid) & anti-$\nu_\mu \rightarrow$ anti-ν_e (dotted) bkgnd

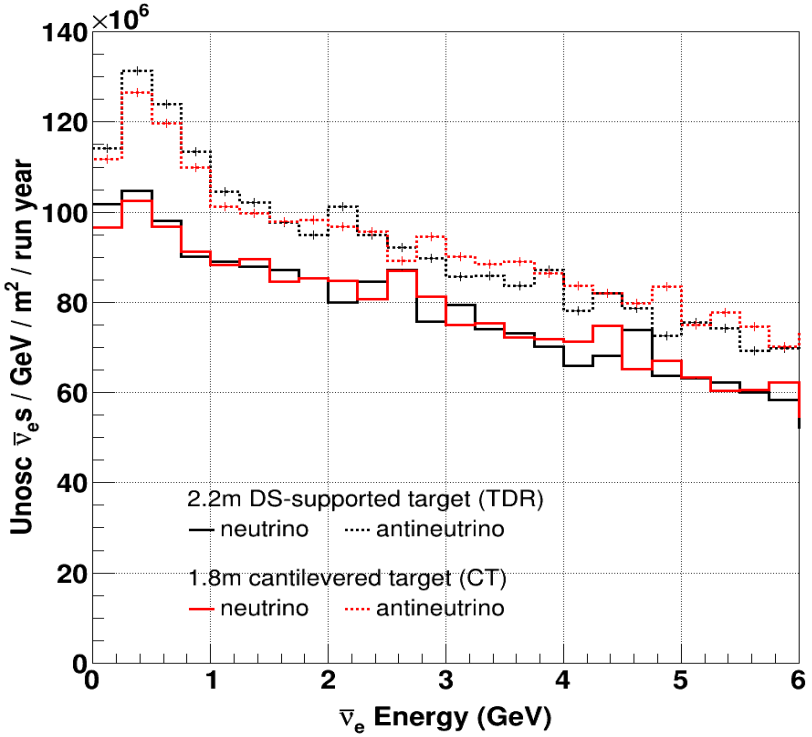


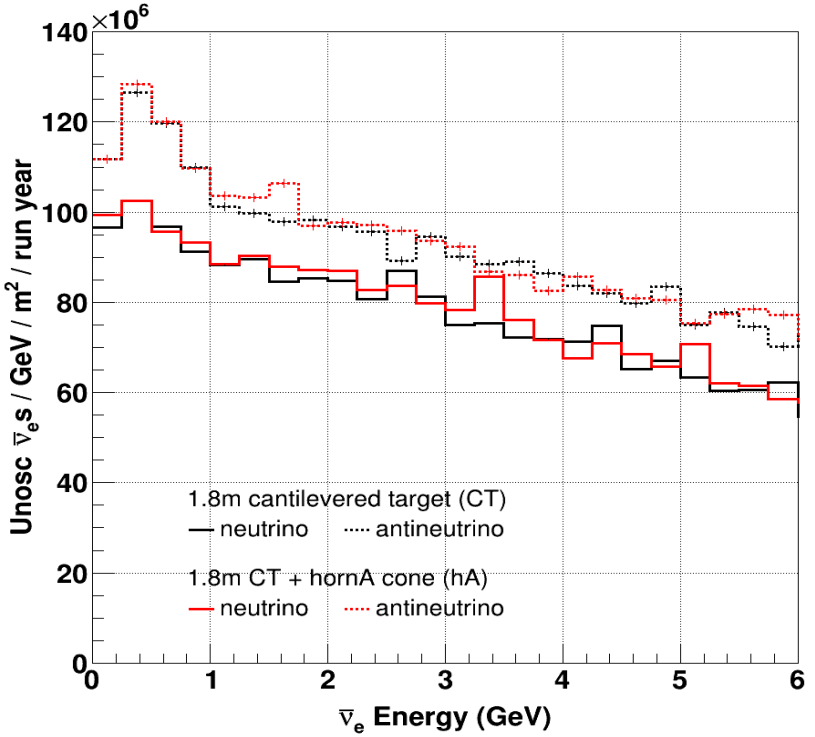


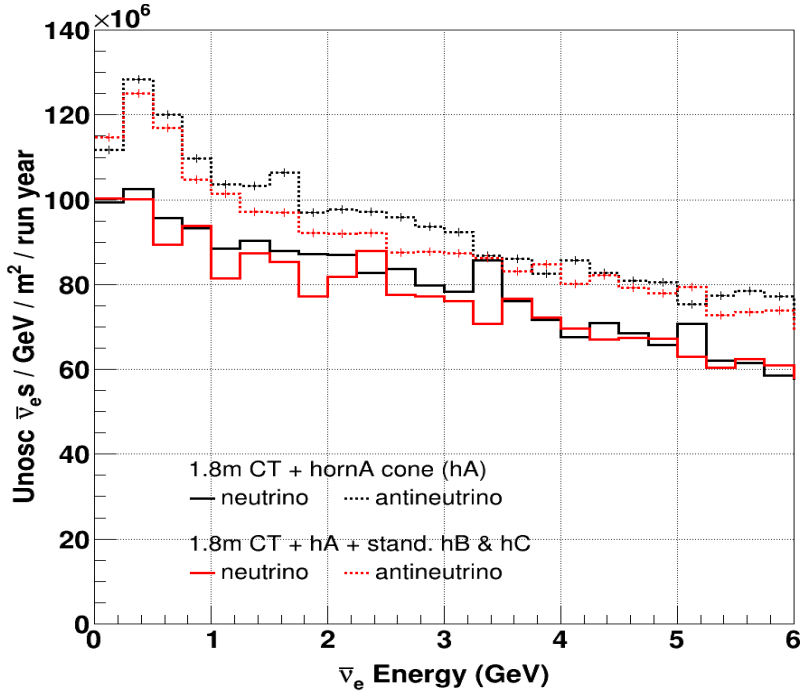


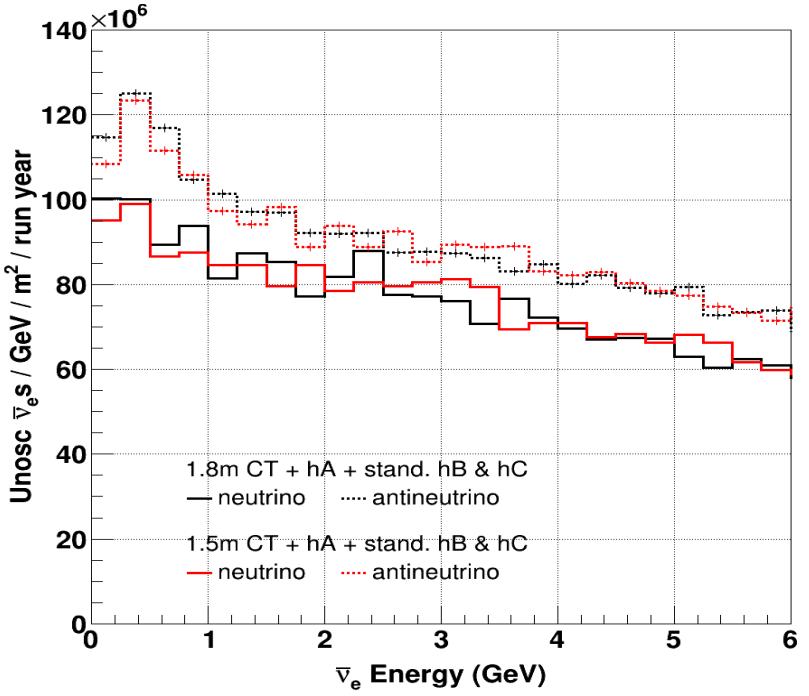


$\nu_\mu \rightarrow$ anti-ν_e (solid) & anti-$\nu_\mu \rightarrow \nu_e$ (dotted) bkgnd

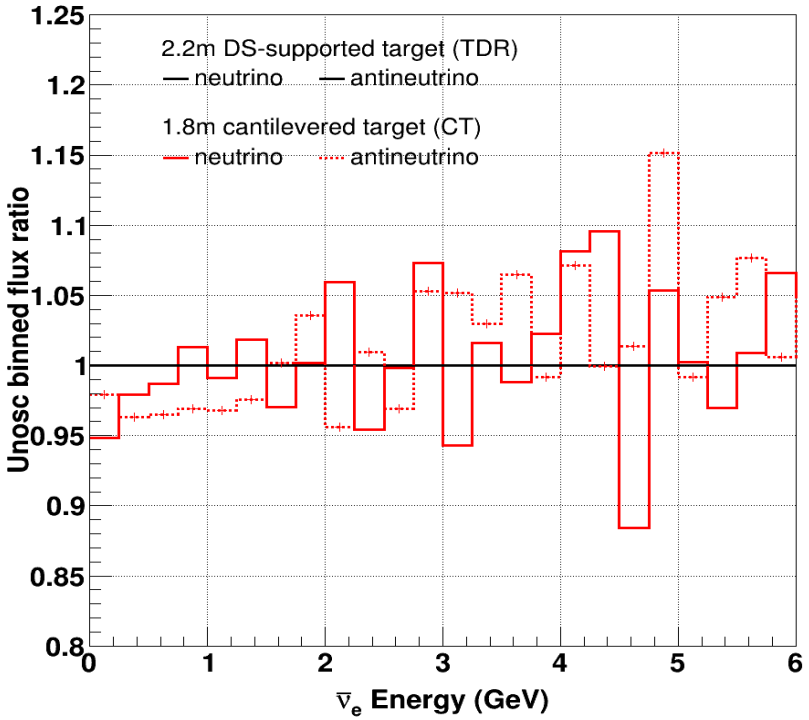


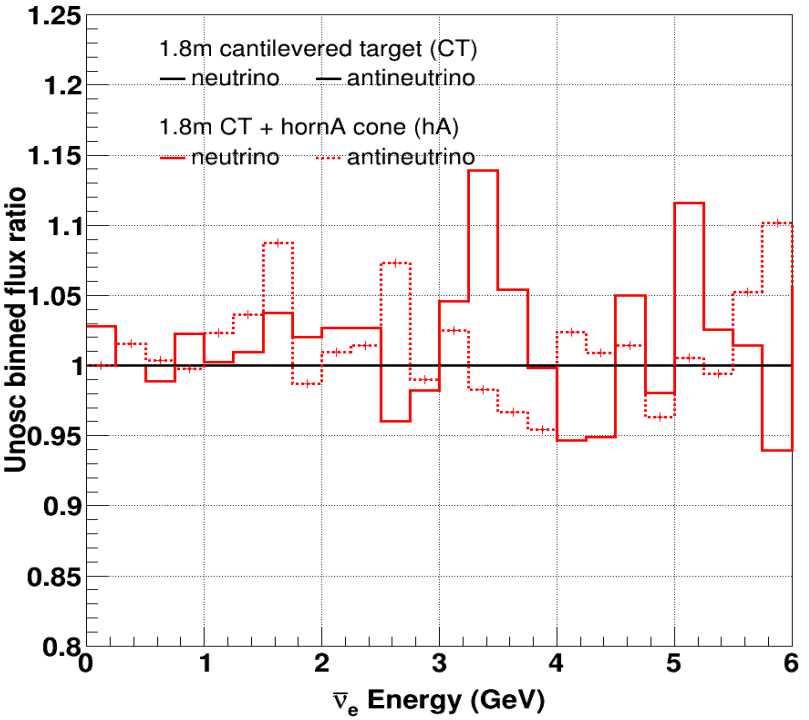


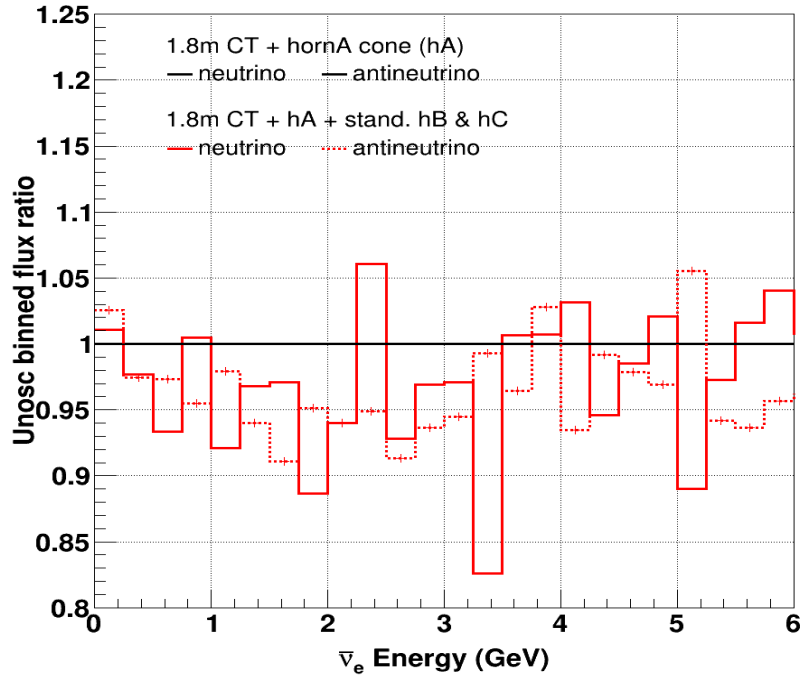


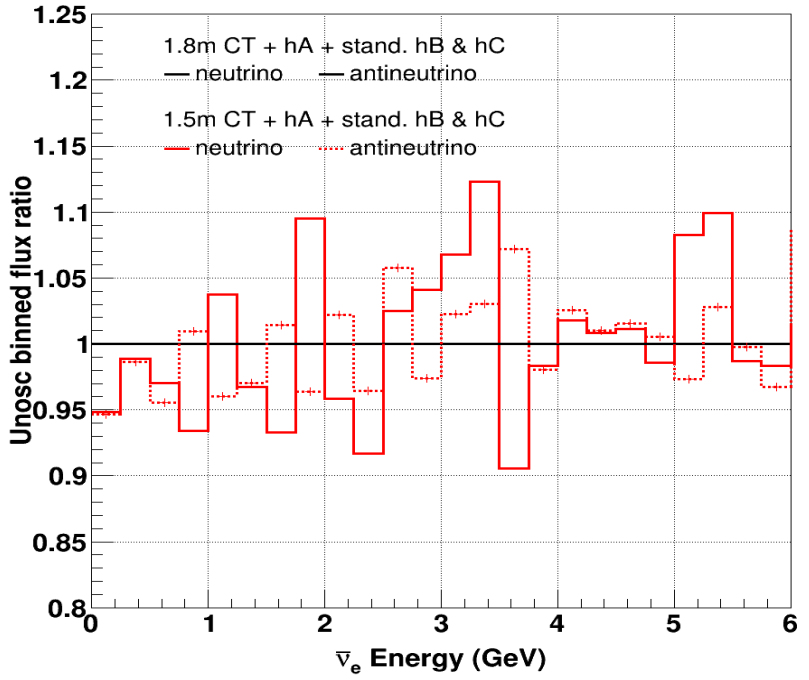


$\nu_\mu \rightarrow$ anti-ν_e (solid) & anti-$\nu_\mu \rightarrow \nu_e$ (dotted) bkgnd









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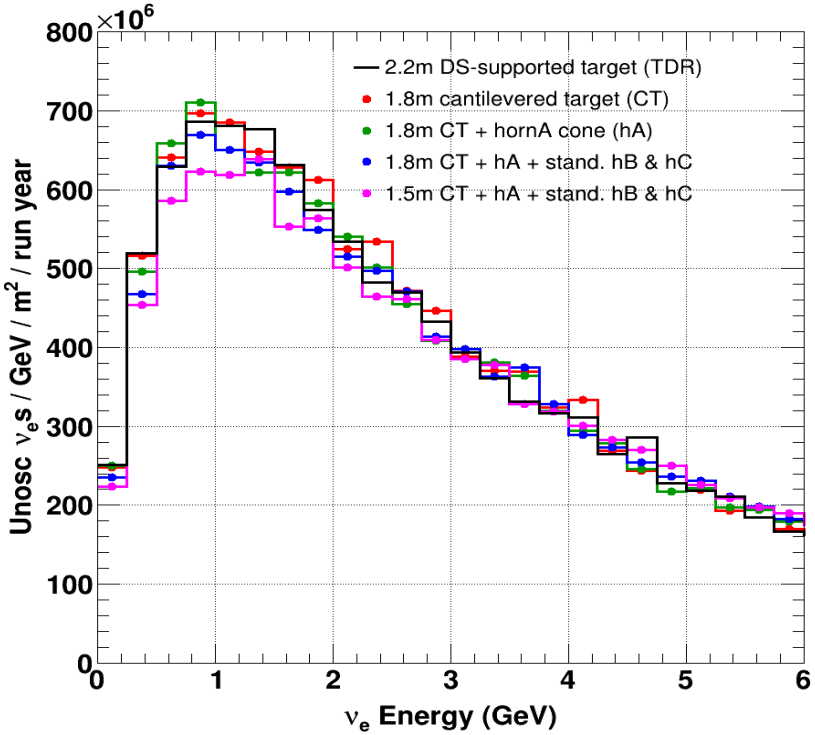
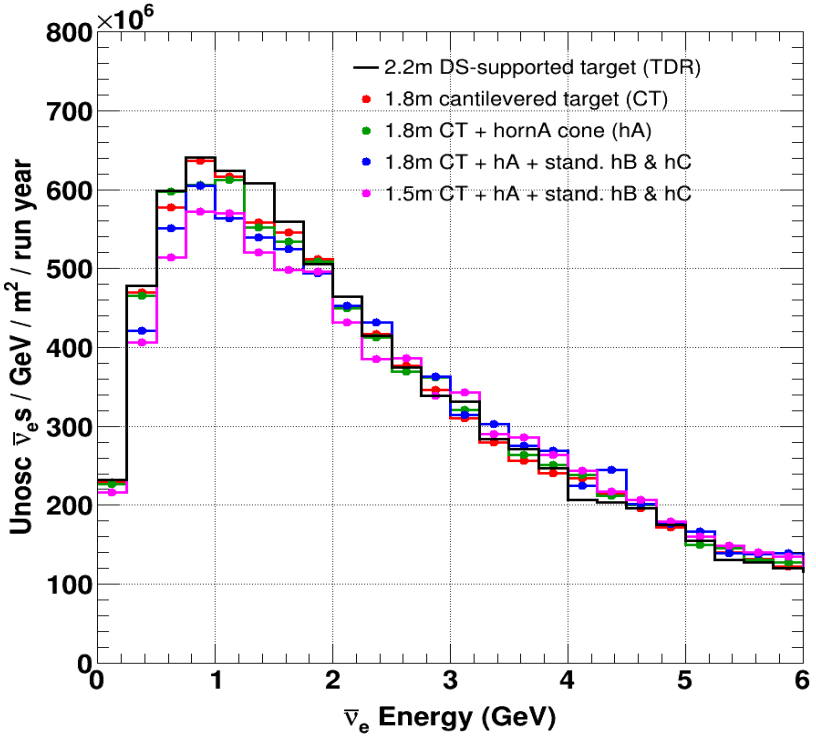
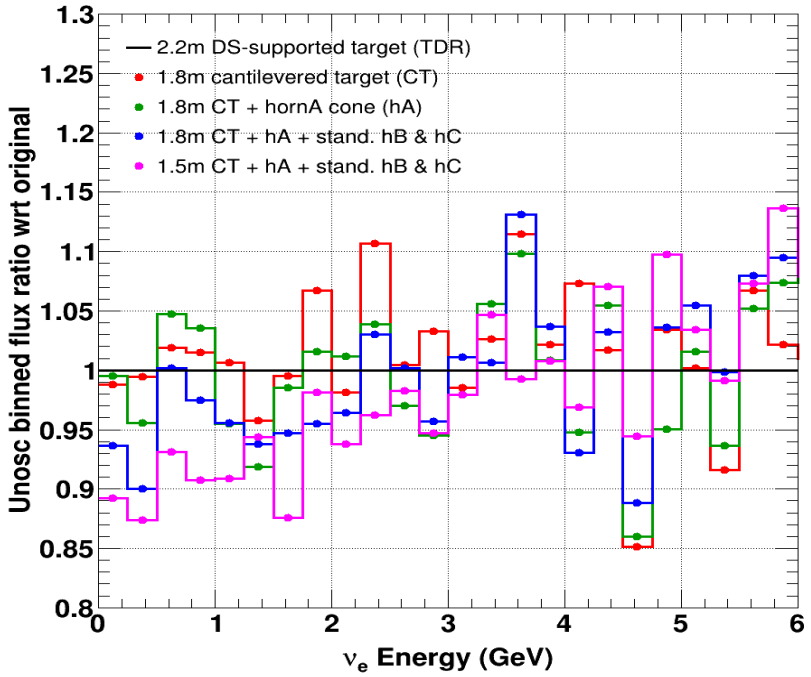
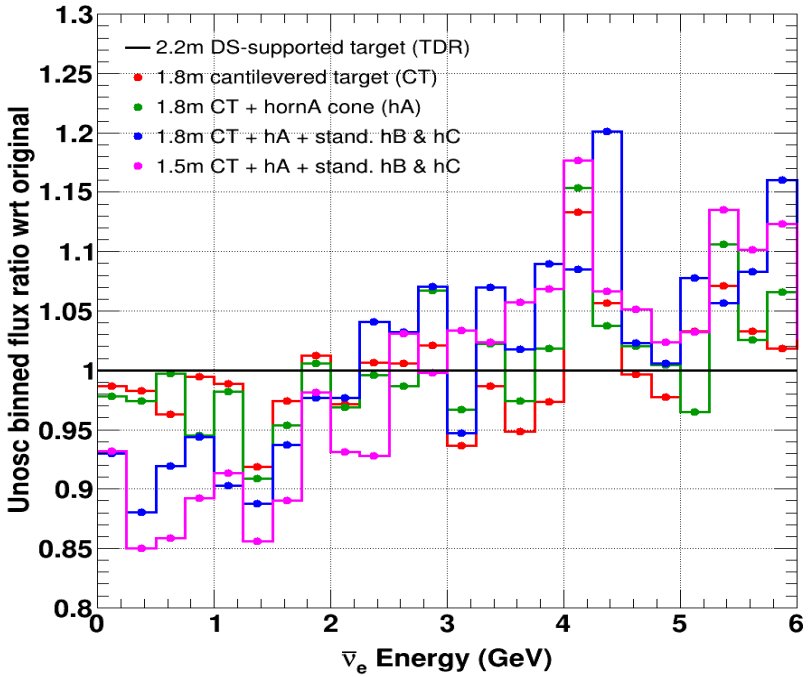
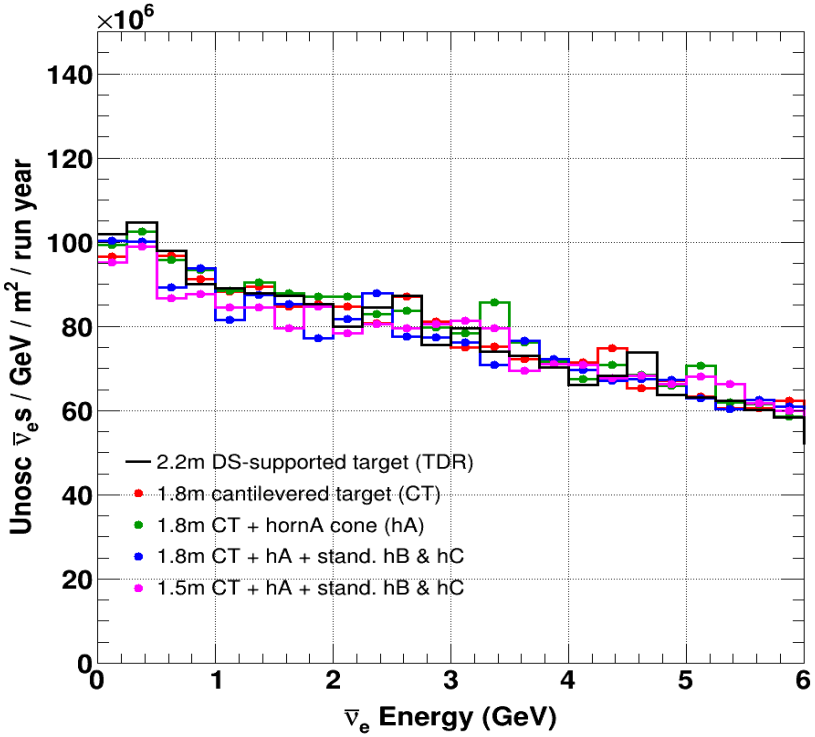


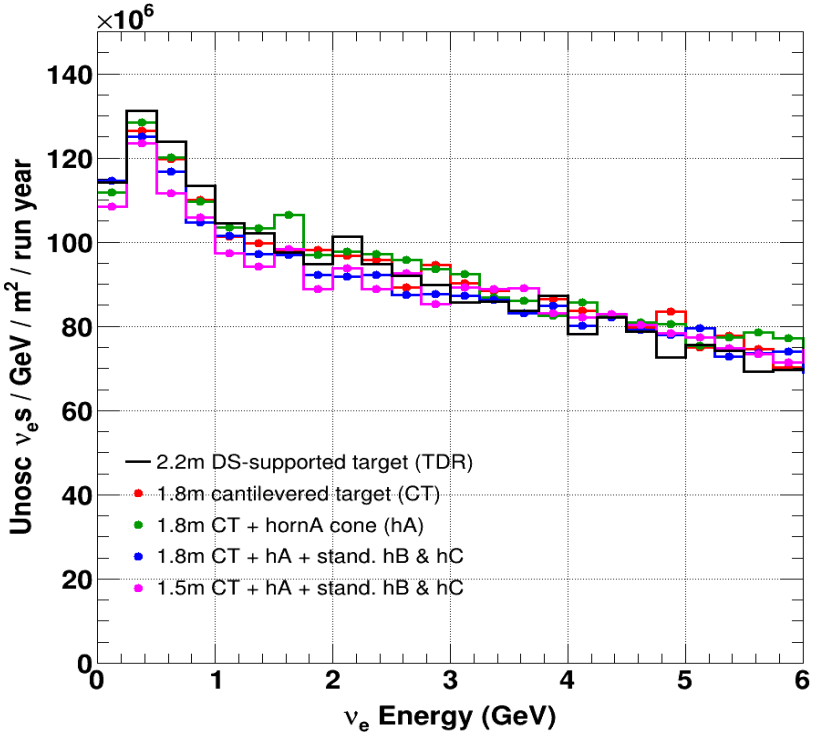


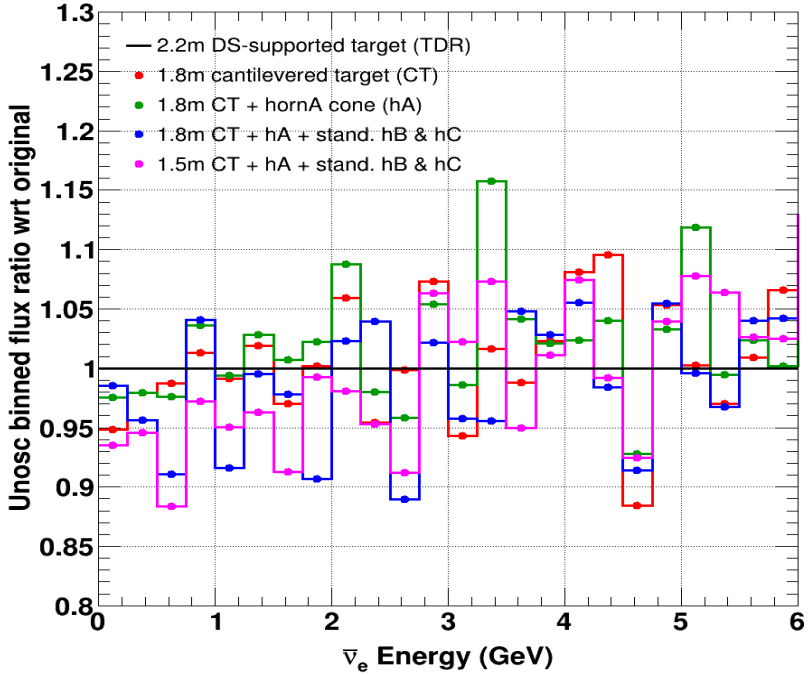


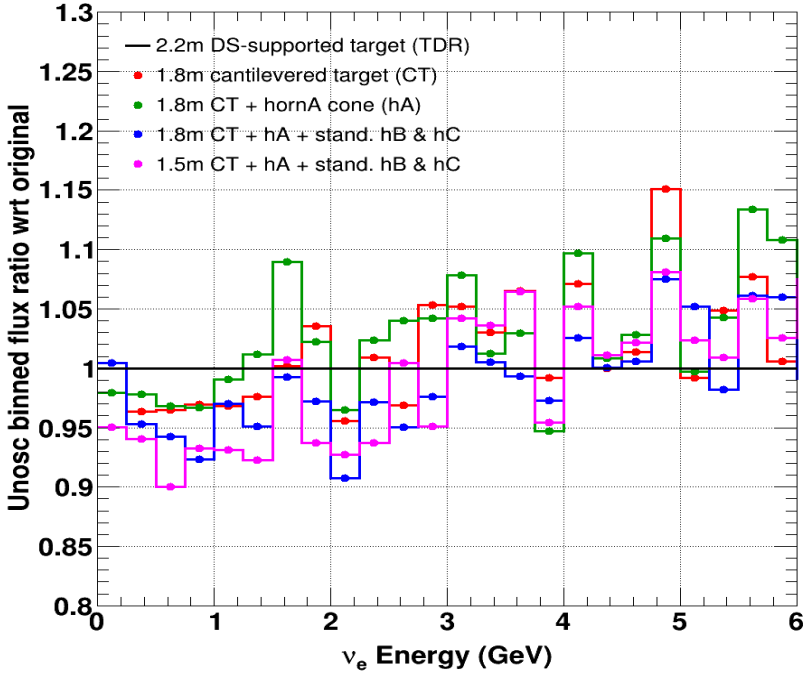


$\nu_\mu \rightarrow$ anti-ν_e (left) & anti-$\nu_\mu \rightarrow \nu_e$ (right) bkgnd

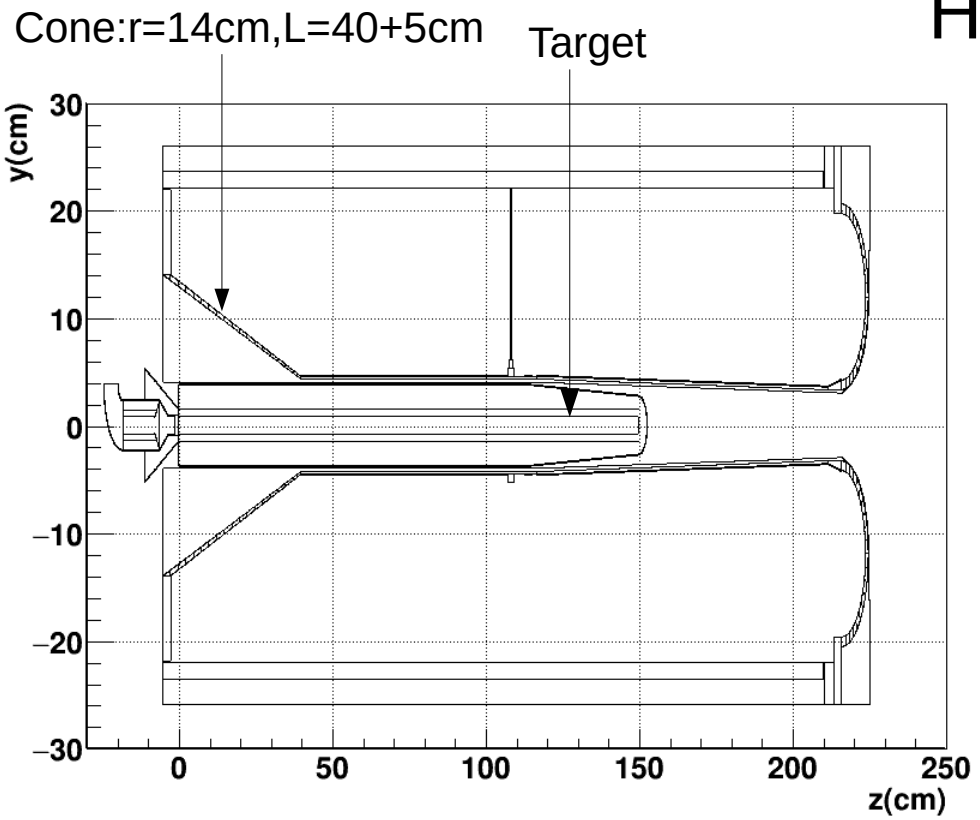


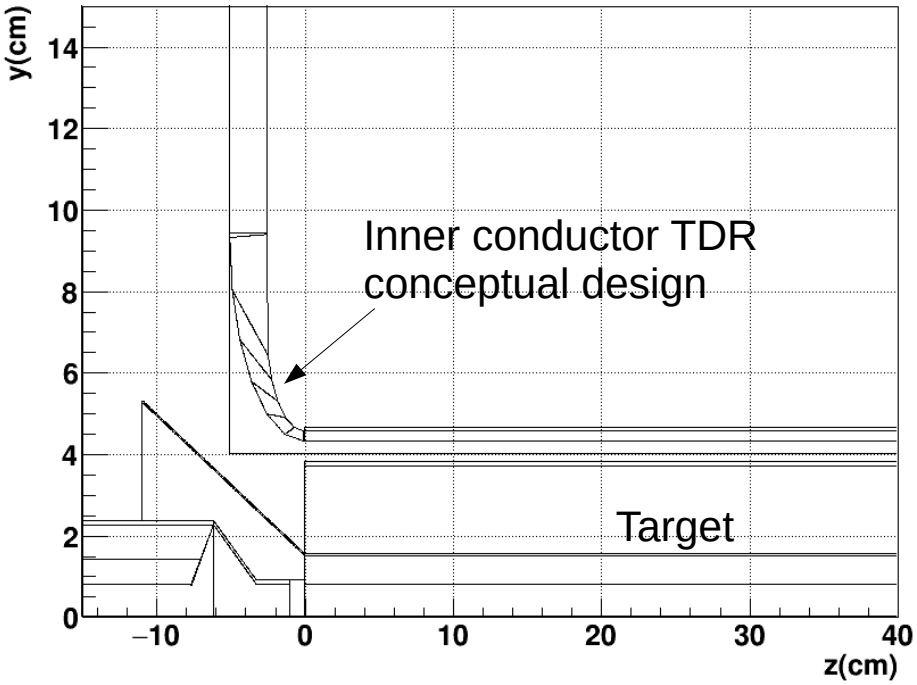


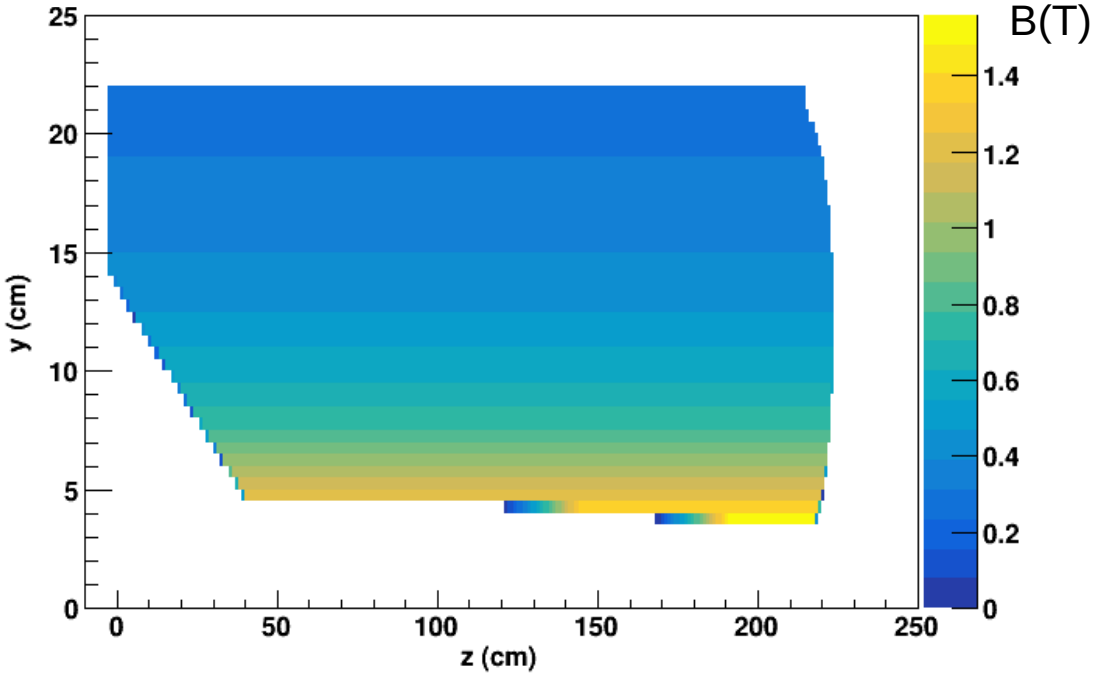




Horn A geometry & B field





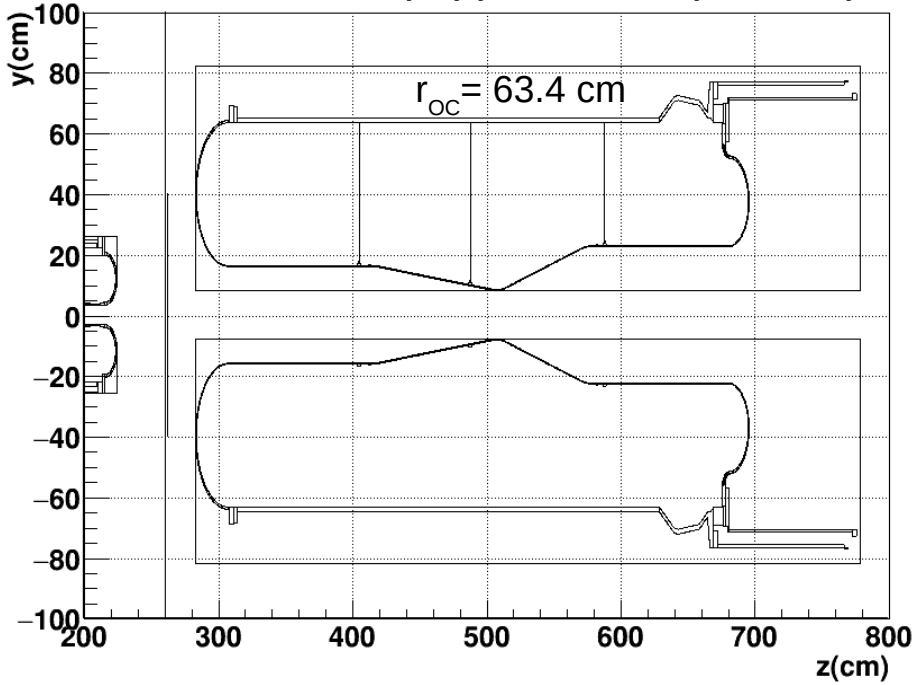


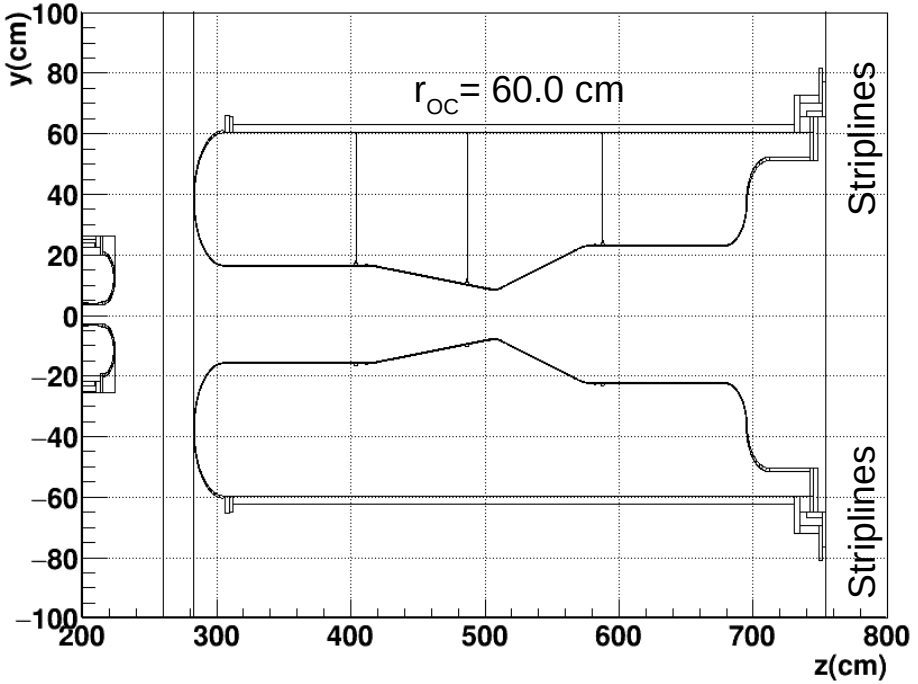
$B = \mu I/2\pi r = 0.02\ [I(kA)/r(cm)]\ T$

$I_A = 293\ kA = I_B = I_C$

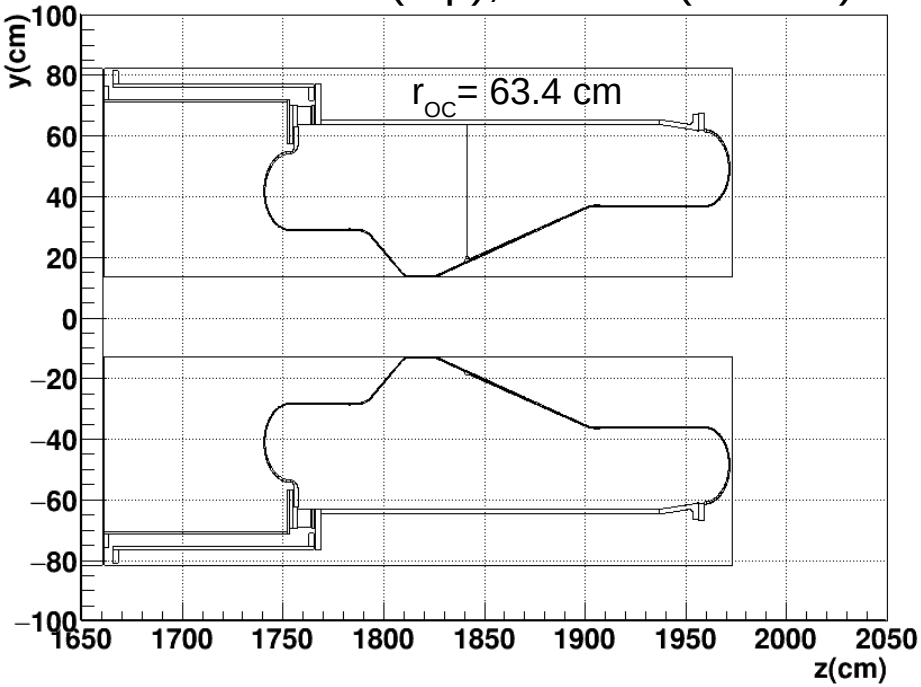
Horn B & C geometry changes

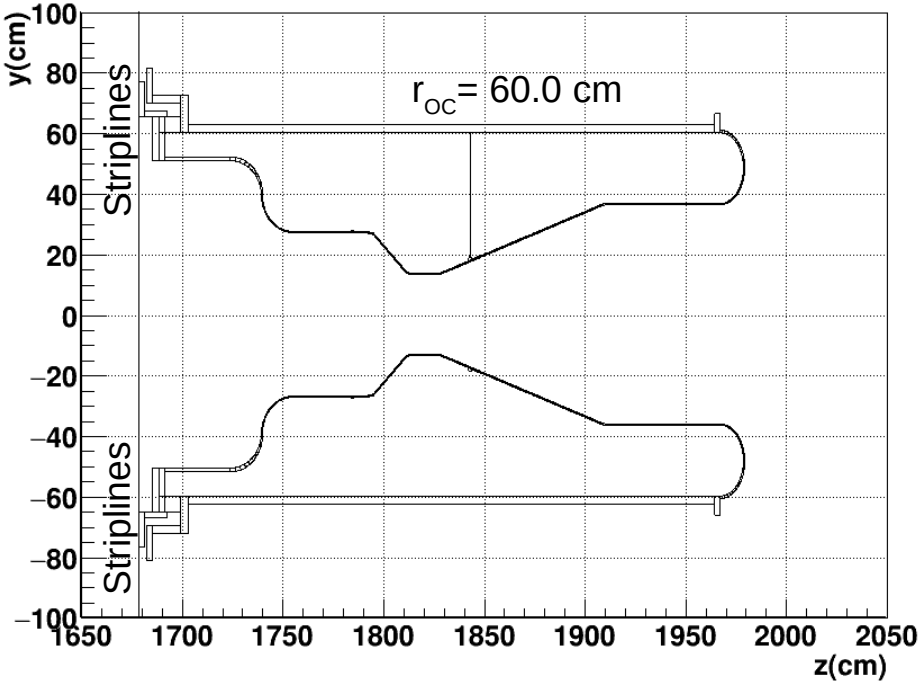
Horn B: TDR (top), current (bottom)



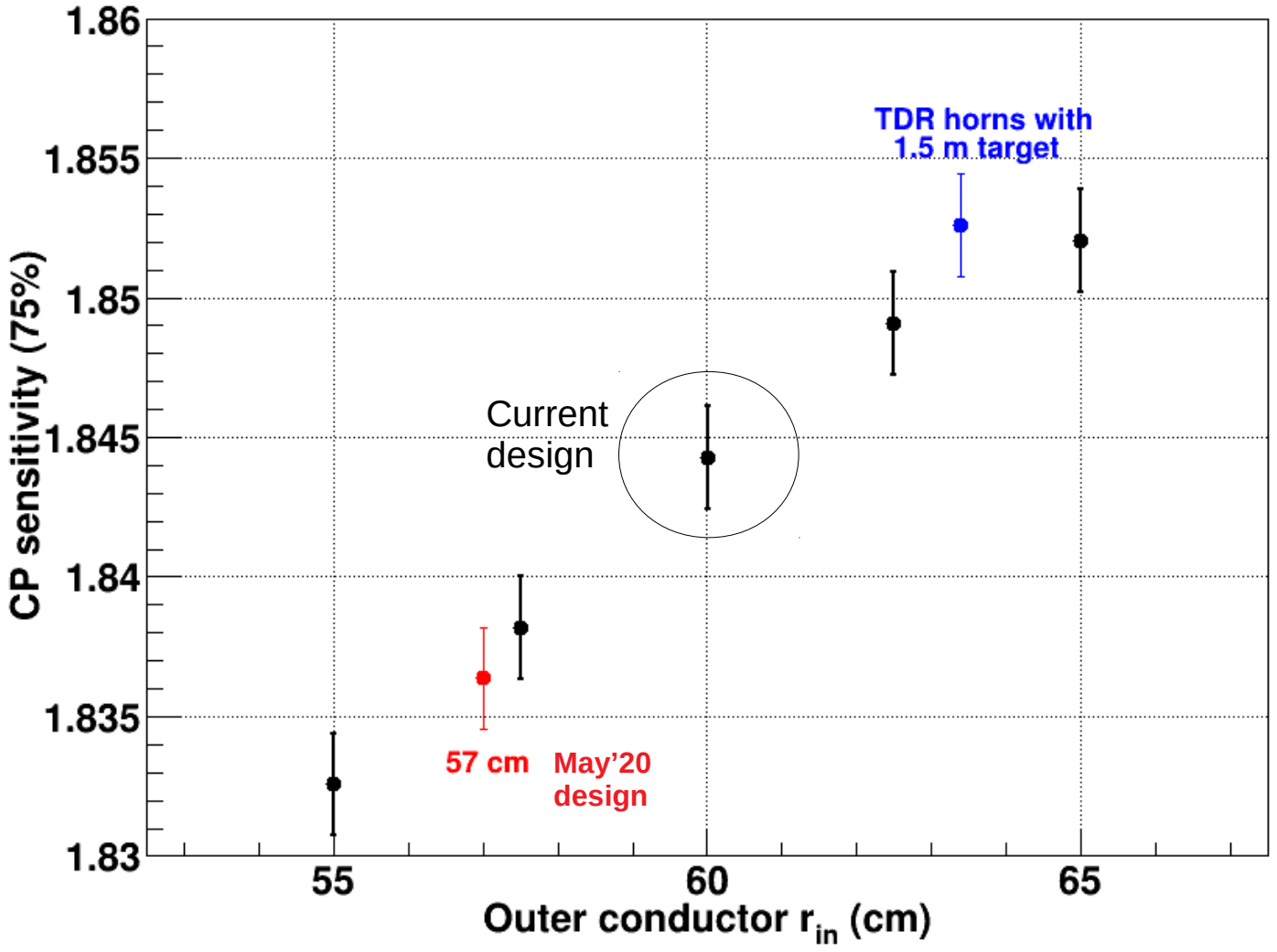


Horn C: TDR (top), current (bottom)



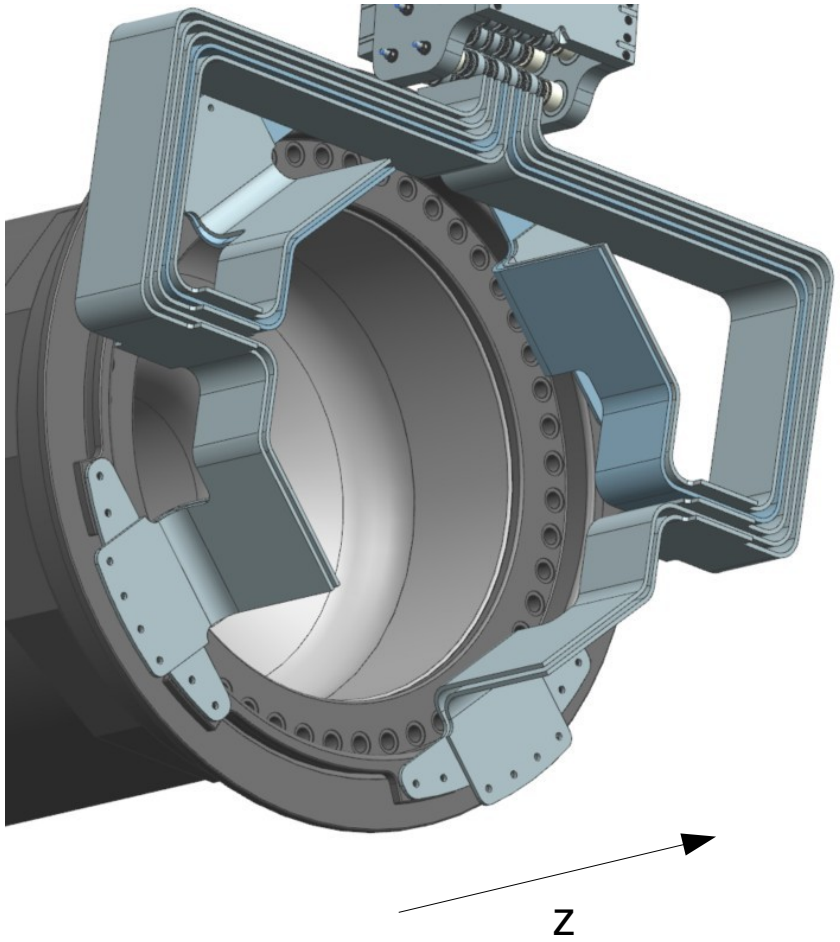


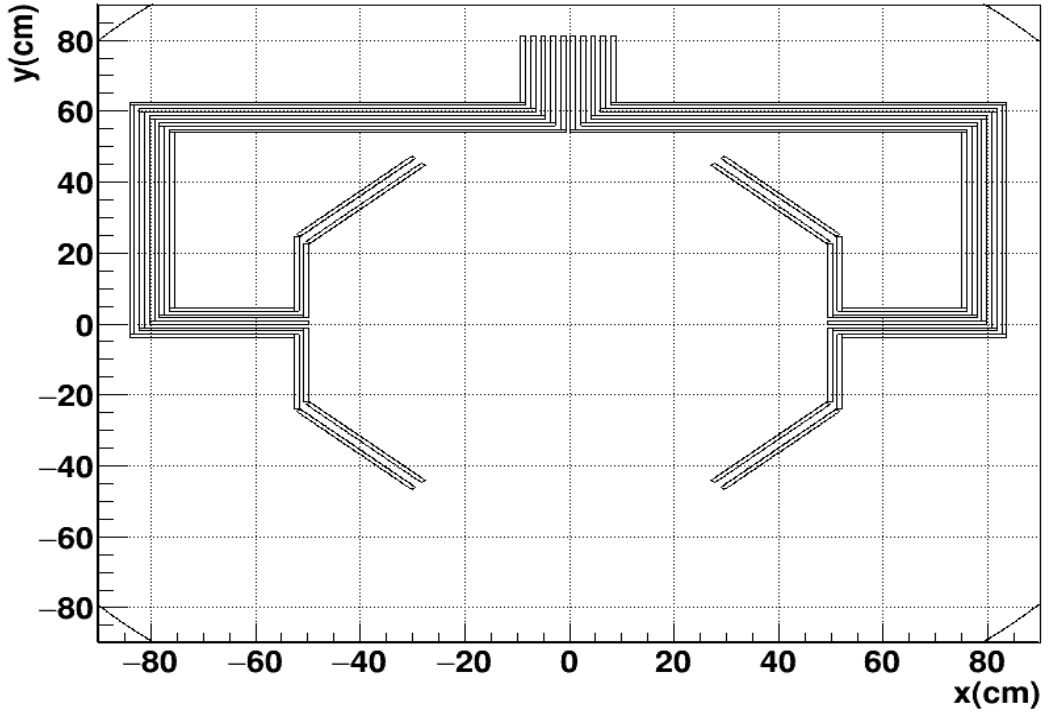
CP sensitivity vs standardized Horn B & C outer conductor inner radius



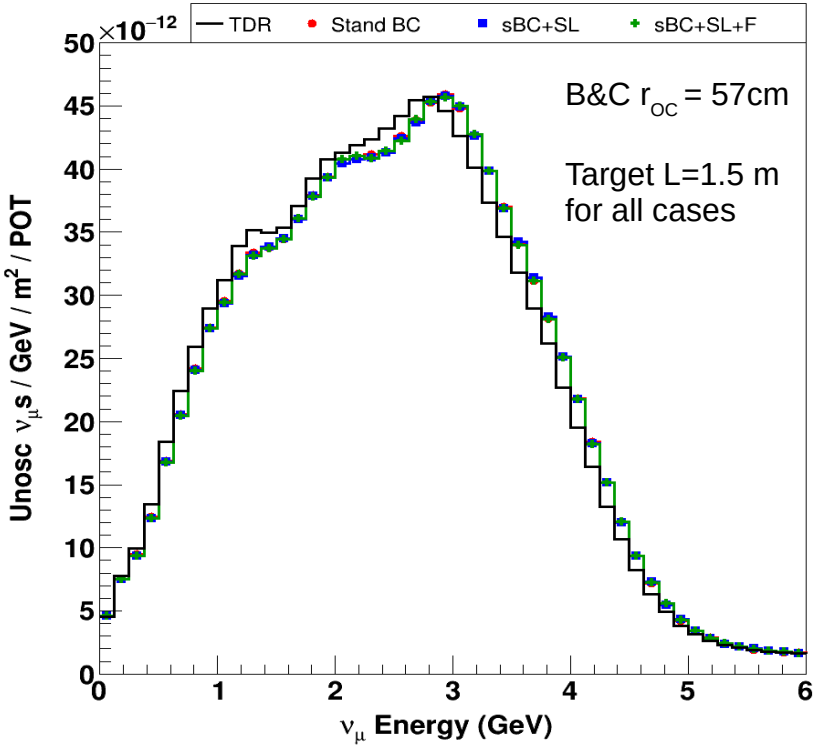
1.5 m cantilever target, horn A cone, DUNE-doc-19219
Horns B & C outer conductor radii are equal

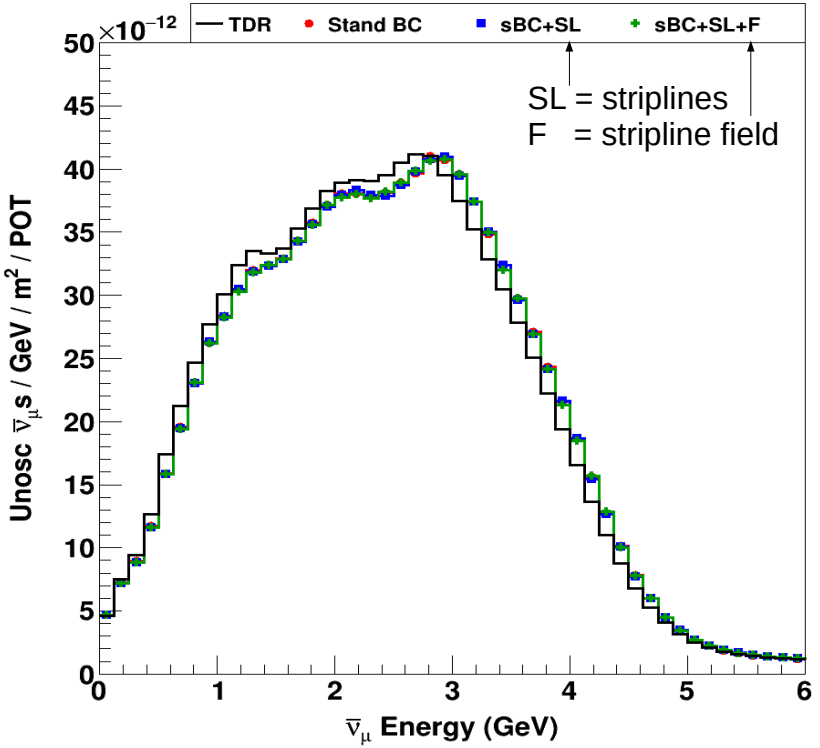
Current Horn B & C striplines

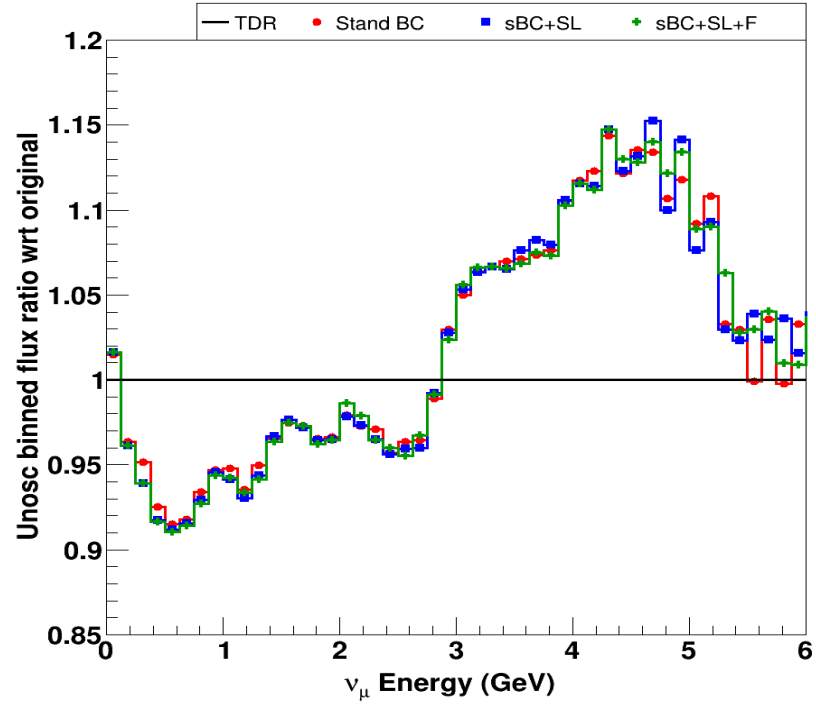


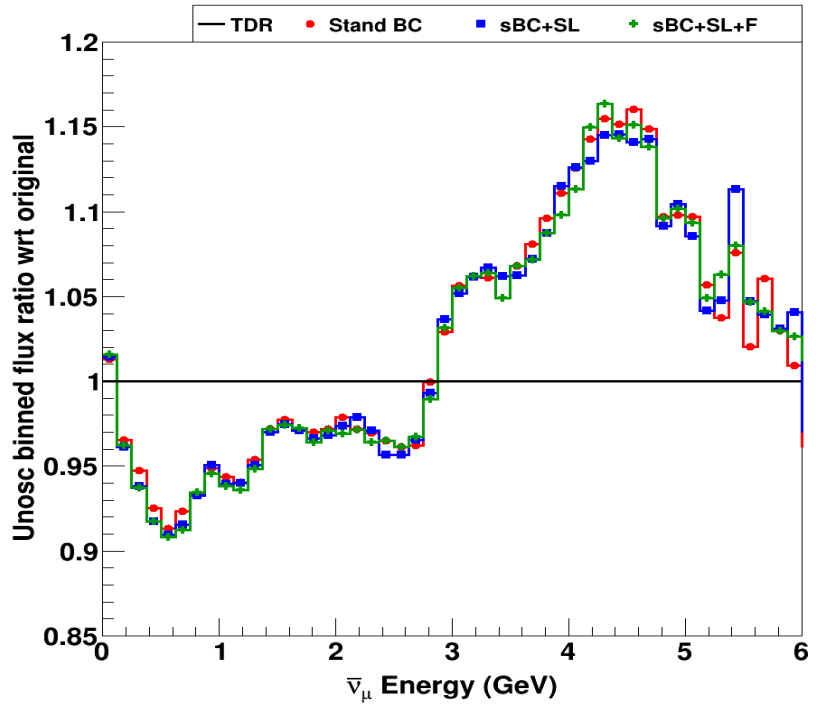


Including Horn B&C striplines: signal ν_μ (left) and anti-ν_μ (right)







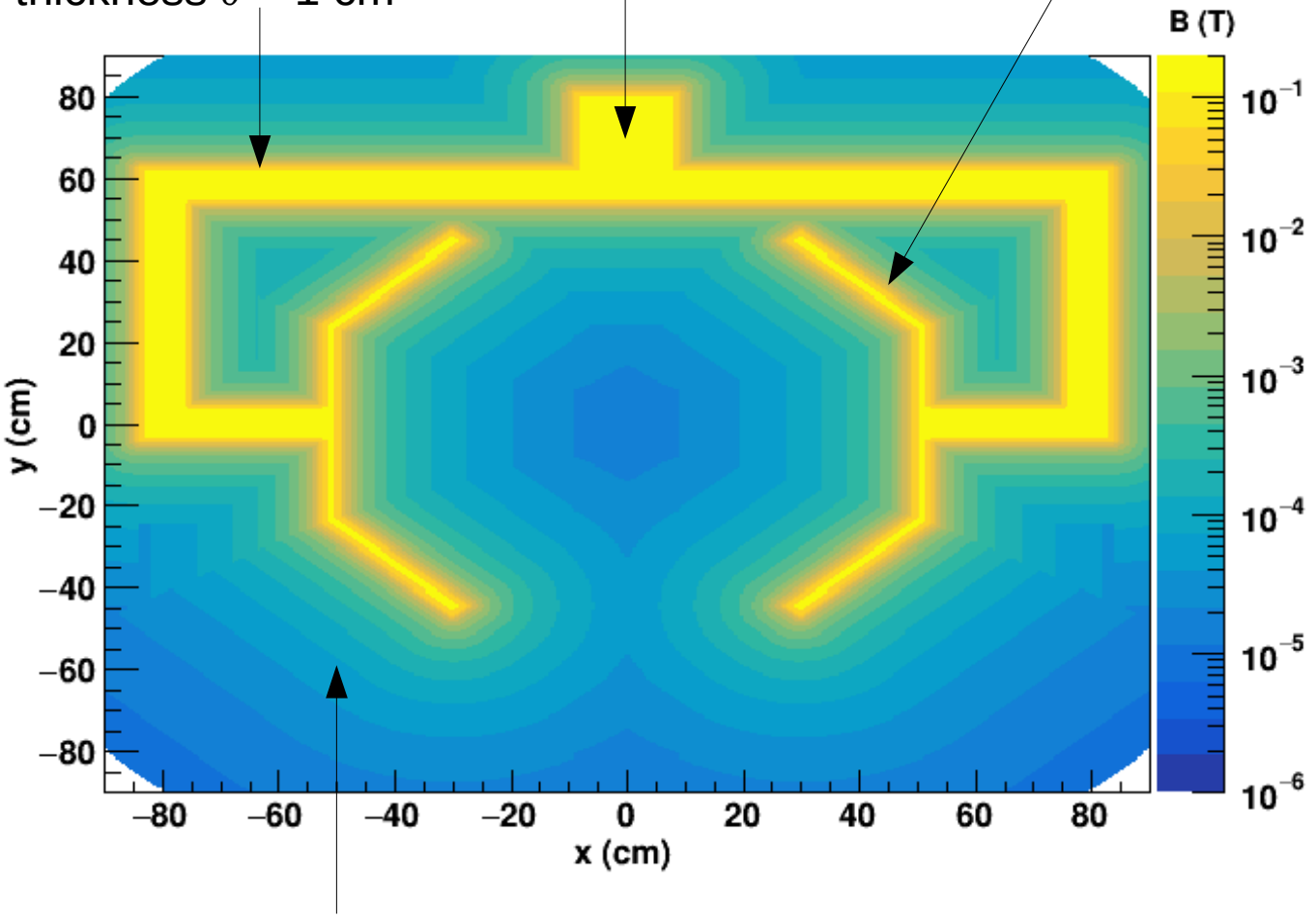


Stripline field

surface B_z = 0.04 T
within thickness δ = 1 cm

Inside B_z = 0.2 T

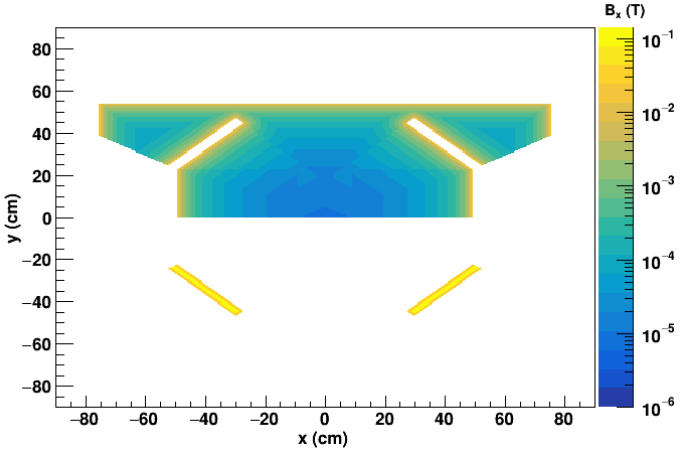
B_x & B_y parallel to planes (I along z)



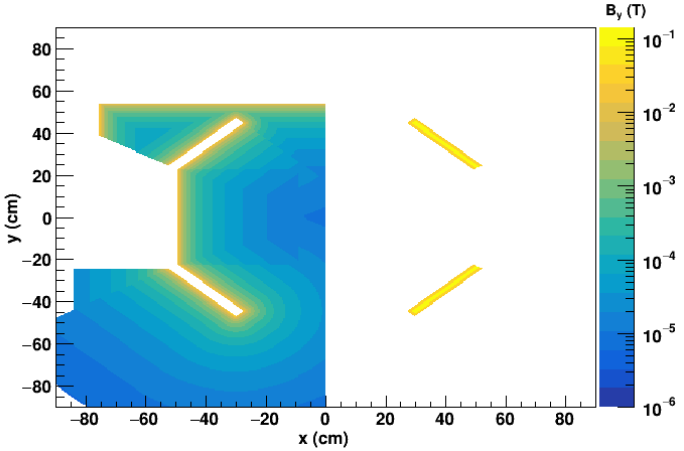
outside dipole $B_{x,y \text{ or } z}$ = 0.04 $[\delta/(r+\delta)]^2$ T, where r = nearest perp. distance from planes

Not a real field map but an approximation

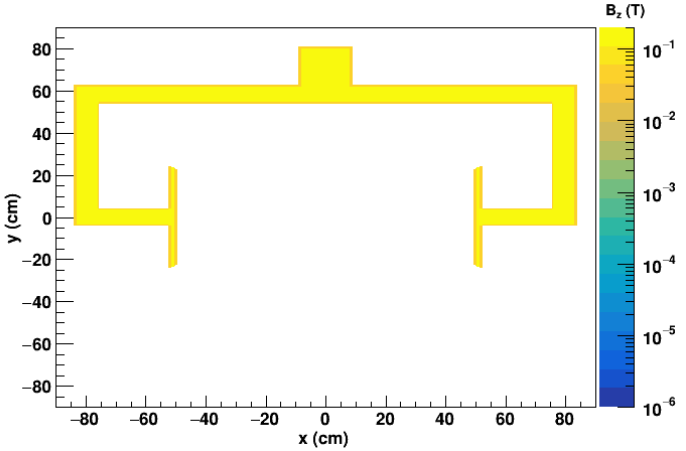
Stripline field components



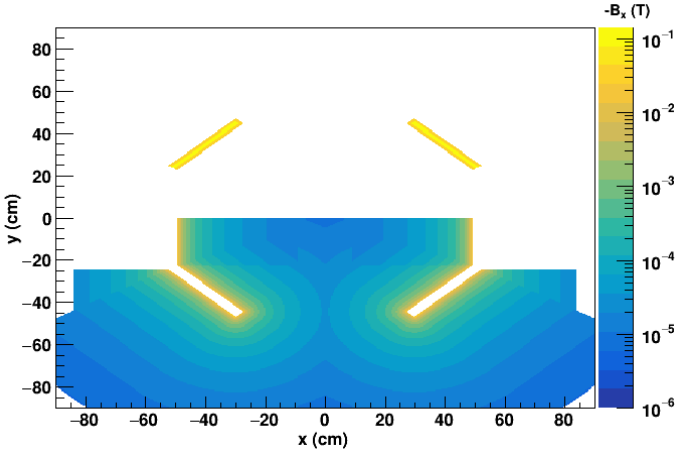
B_x



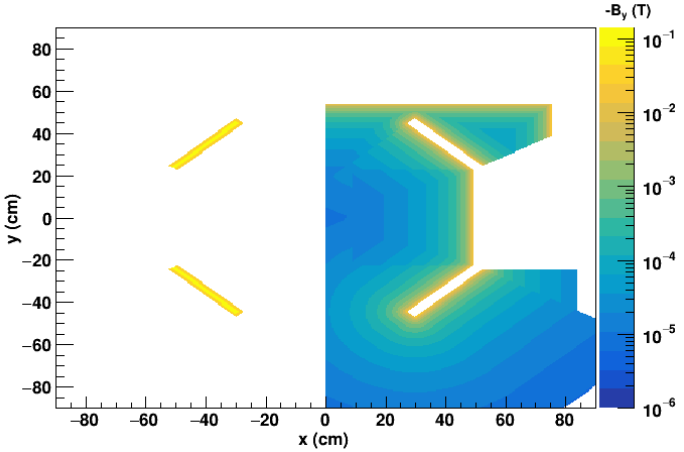
B_y



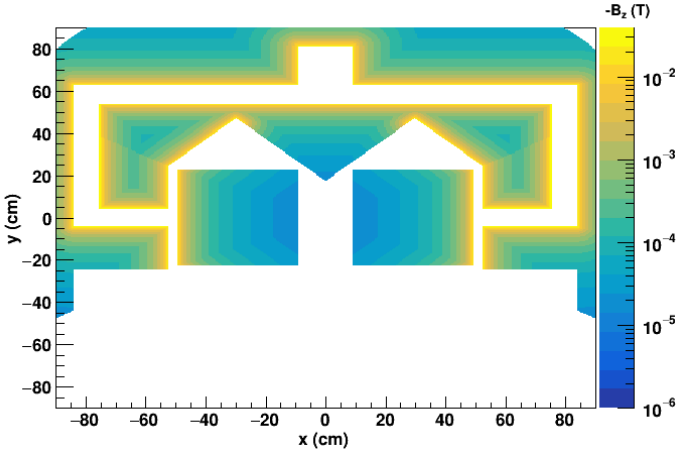
B_z



$-B_x$

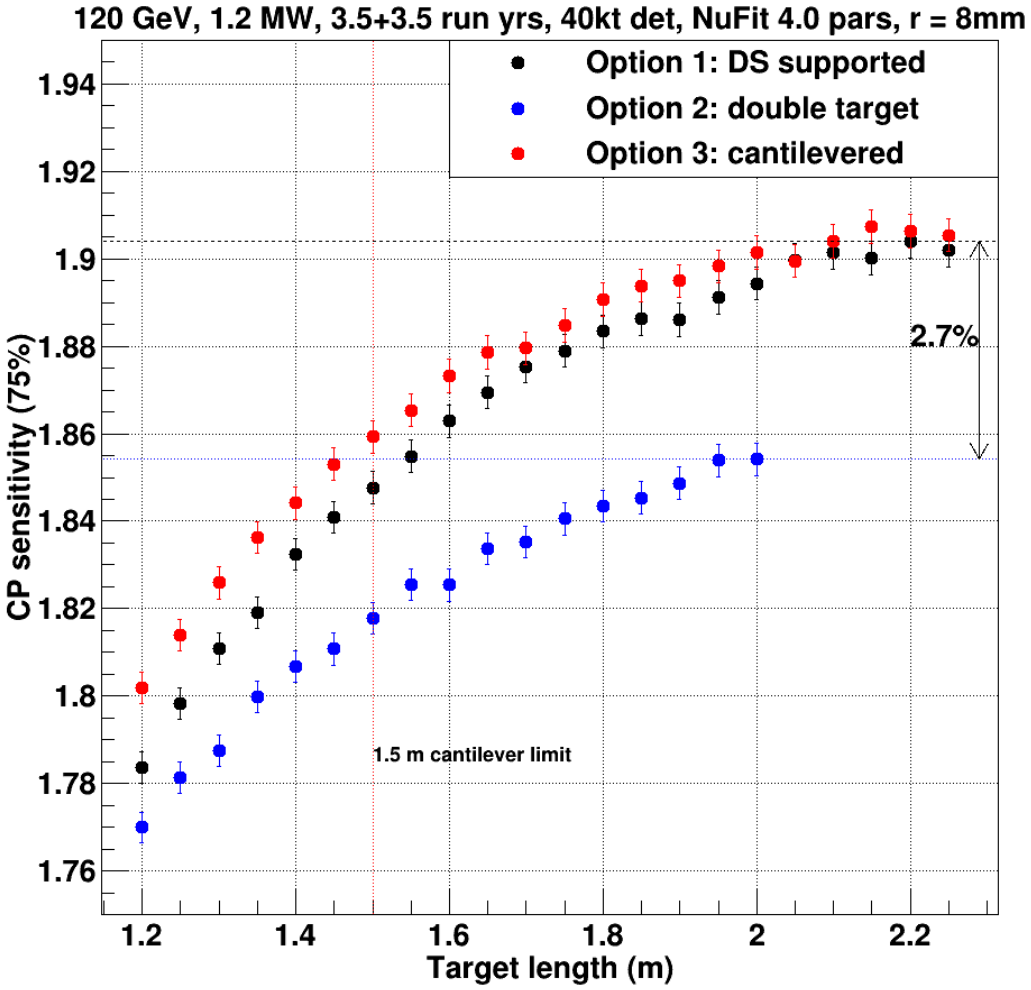


$-B_y$

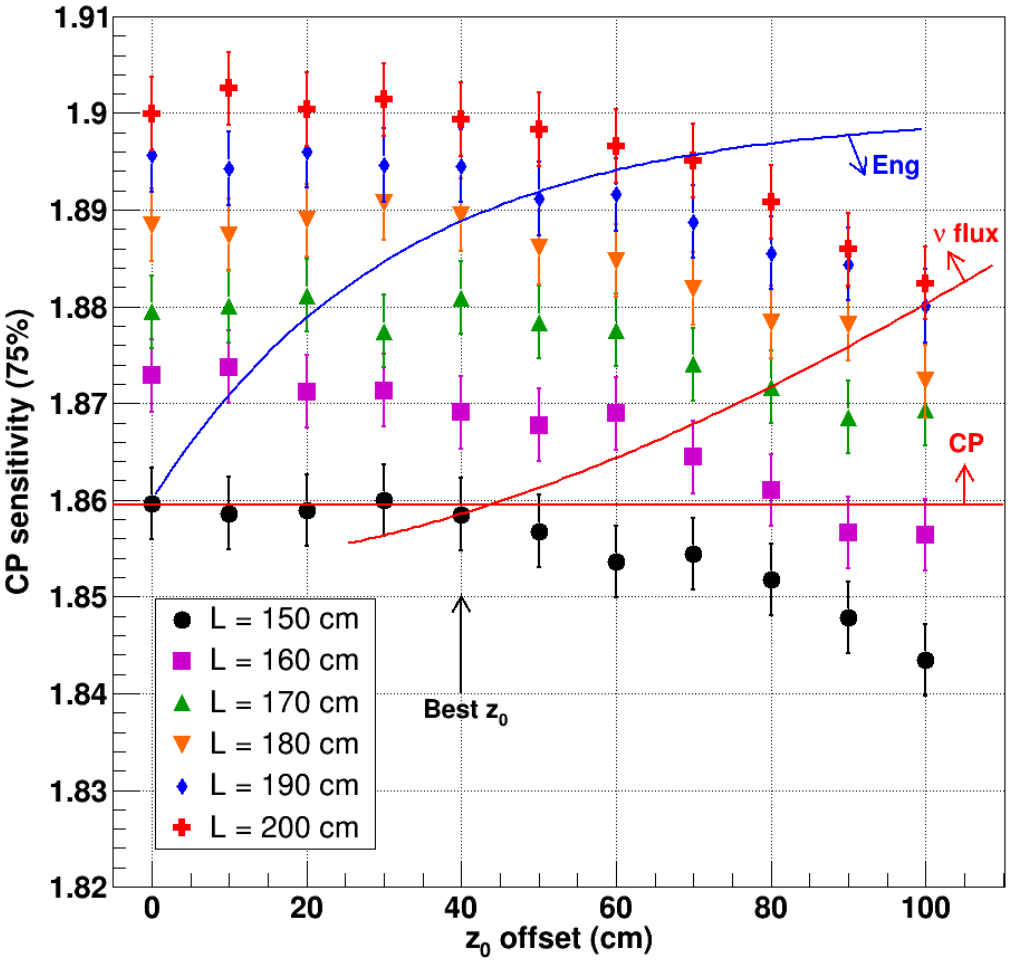


$-B_z$

CP sensitivity vs target length & horn A cone length



TDR horns A, B & C
DUNE-doc-14944



Horn A cone:
r_{base} = 14 cm, $L_z = z_0 + 5$ cm; $z_0 = \Delta z$ from MCZero
1.5 m cantilevered target; TDR horns B & C
DUNE-doc-17052