Increased Neutrino Yield with the new NOvA Target Design Simulation Study

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On behalf of NOvA Collaboration

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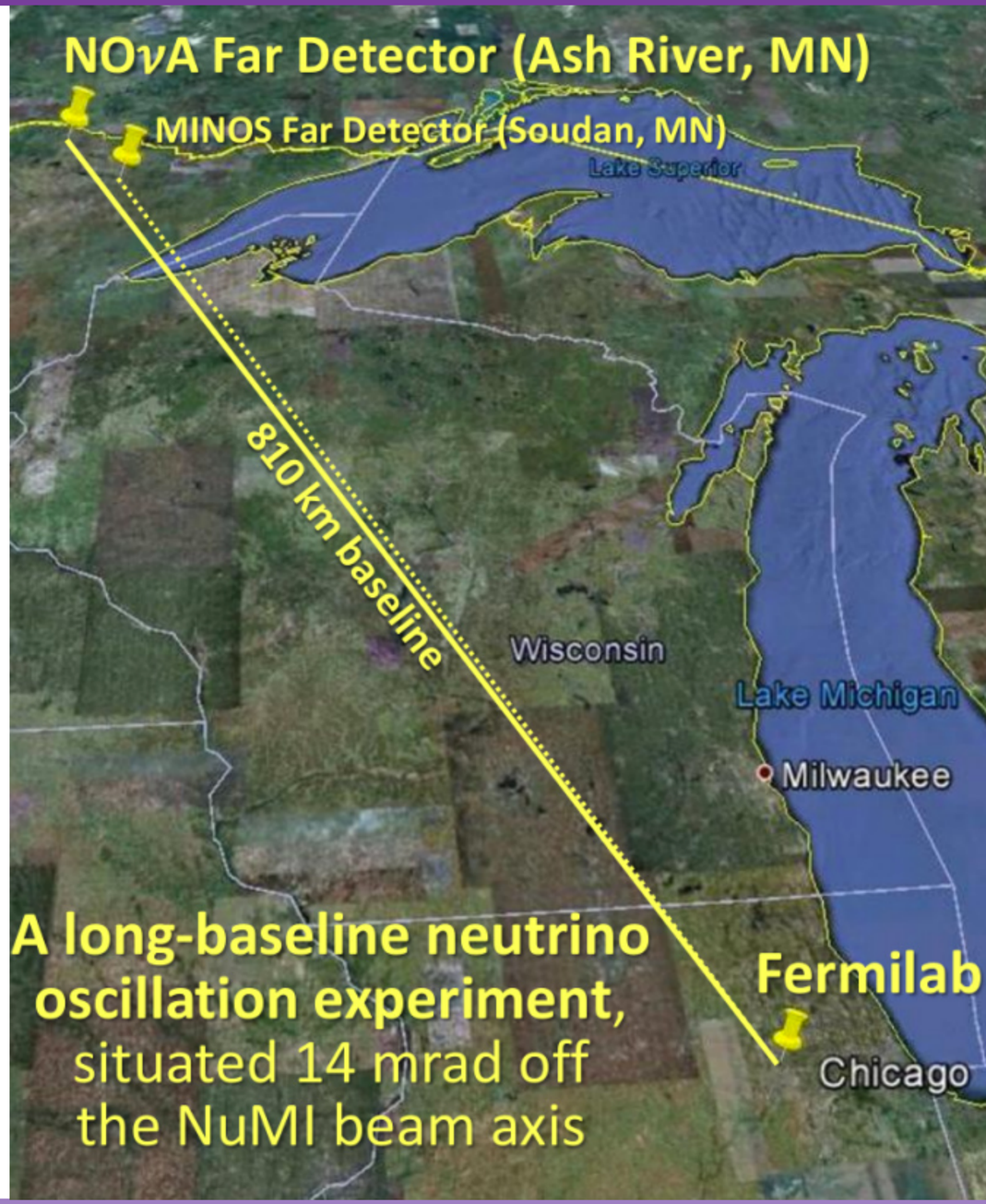
NOvA (NuMI Off-Axis ν_e Appearance)

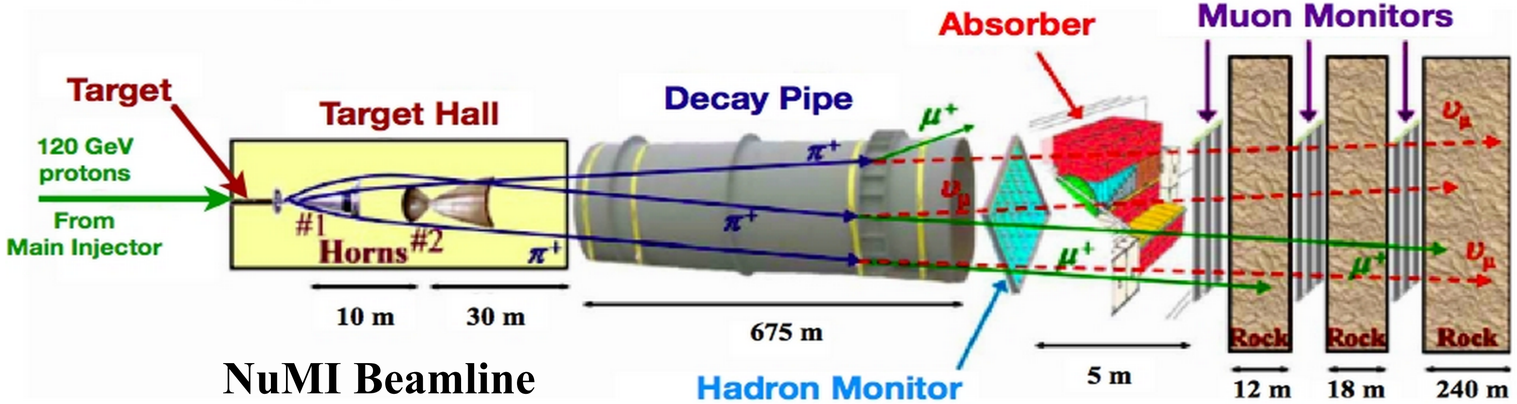
- NOvA looks primarily for the ν_e appearance and ν_μ disappearance using two detectors: the Near Detector (ND) & the Far Detector (FD).

- Using ν_e appearance and ν_μ disappearance
  Determine the ν mass hierarchy.
  Measure θ_{13}.
  Search for CP violation.
  Determine the θ_{23} octant (muon-tau asymmetry in neutrino mixing).
  Precise measurement of atmospheric parameters θ_{23} and $|\Delta m^2_{atm}|$.

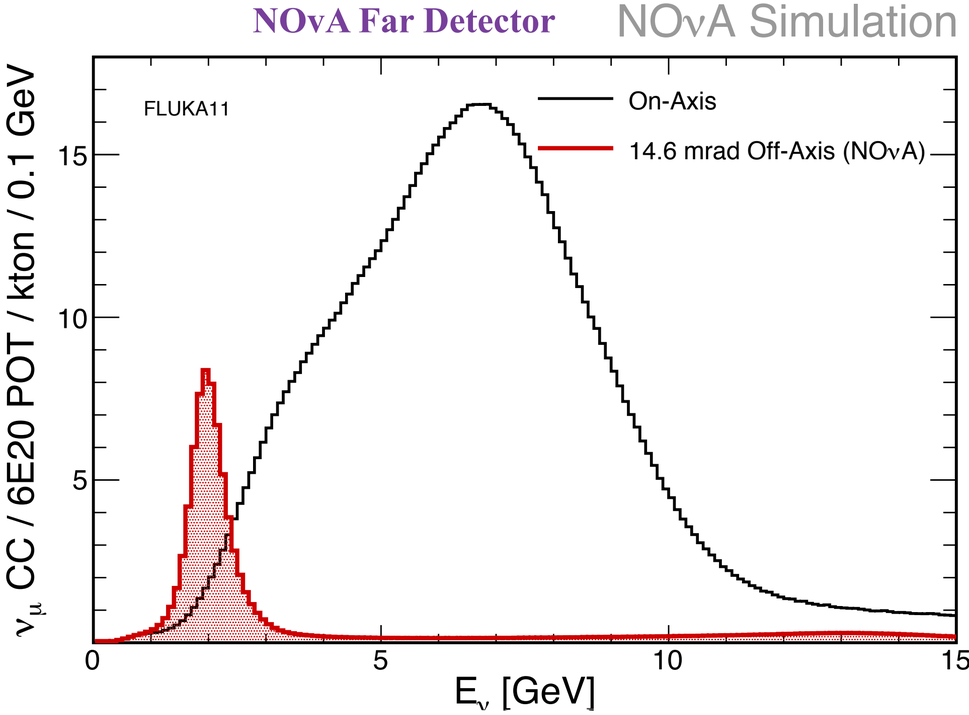
- Also…
  Neutrino cross sections at the NOvA ND
  Sterile neutrinos
  Supernova neutrinos
  other exotica



The NuMI (Neutrinos at the Main Injector) Beam Line



NuMI Beamline

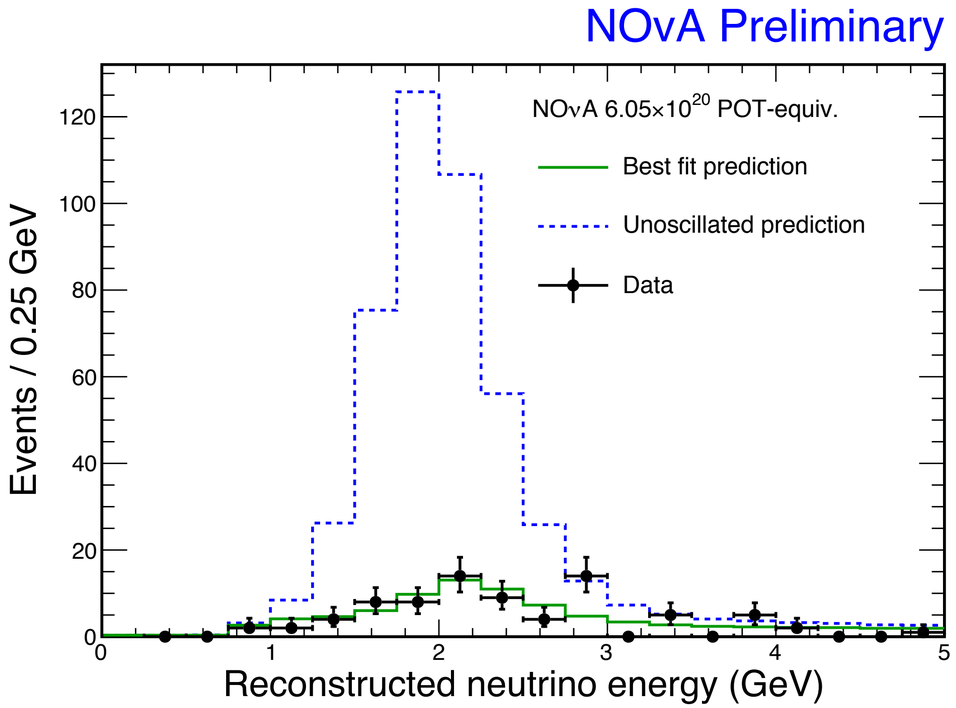


The NOvA off-axis position selects quasi mono energetic neutrino beam of 2 GeV where it gives the highest probability of oscillation.

- 120 GeV proton beam from the Main Injector collides with a graphite target, resulting in the production of many secondary (short-lived) particles (e.g pions and kaons).
- These particles are focused by a set of two magnetic horns: The Horn2 is 19.18m away from the Horn1. They afterwards decay to neutrinos in a decay pipe filled with He.
- At the end of the NuMI beam line, we get an almost pure ν_μ beam.

Motivation

- NOvA FD observed few events with exposure of 6.05 e20 POTs.
- **We need more events, more POTs.**



Event yield for NOvA

The Event yield for the NuMI off-axis NOvA neutrino experiment is :

Upgraded to 700kW for NOvA Off-Axis

Running time

Detector mass

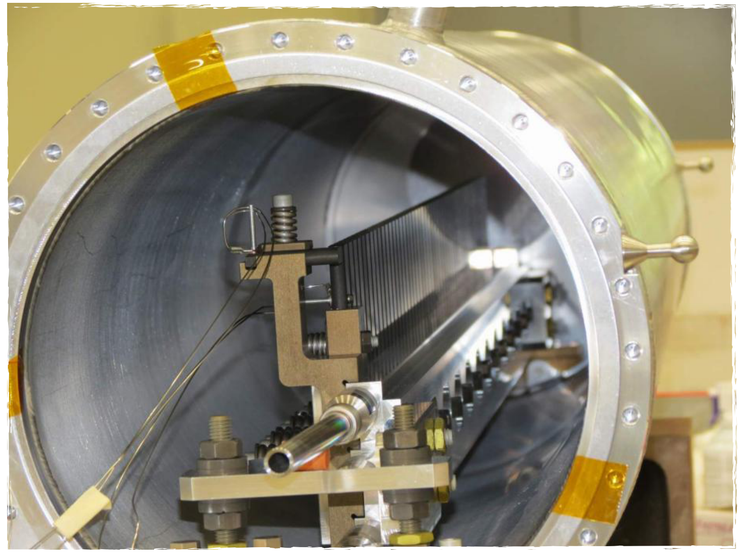
Event Yield (N) ∝ (Beam Power)(time) **(ν per proton)** * **M(ε)** → Detector efficiency

We focus on the efficiency (**ν per proton**) of the ***NuMI Target and Horn system*** to produce useful neutrinos (in energy range 1-3 GeV) in the NOvA detector.

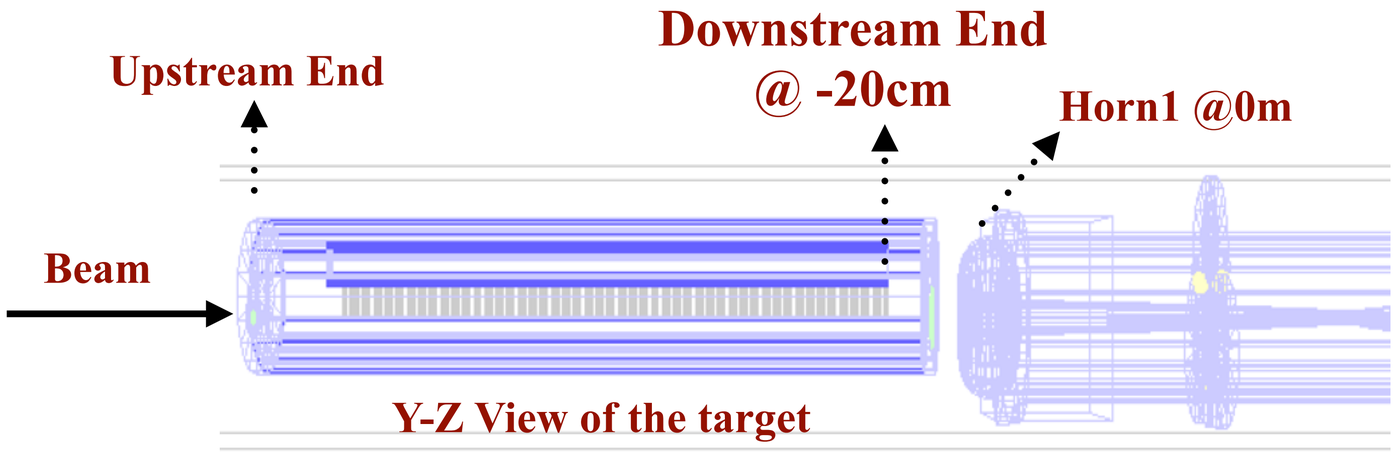
- ***Getting 10% more ν per proton means 10% more event yield as if the experiment had a detector of 10% larger mass or 10% more beam power (770kW) :*** **Interesting!**
- **So, we investigate different ways to optimize the neutrino yield per proton on the target, hence the event yield (N) of the experiment.**

NuMI Target & Horn system for NOvA

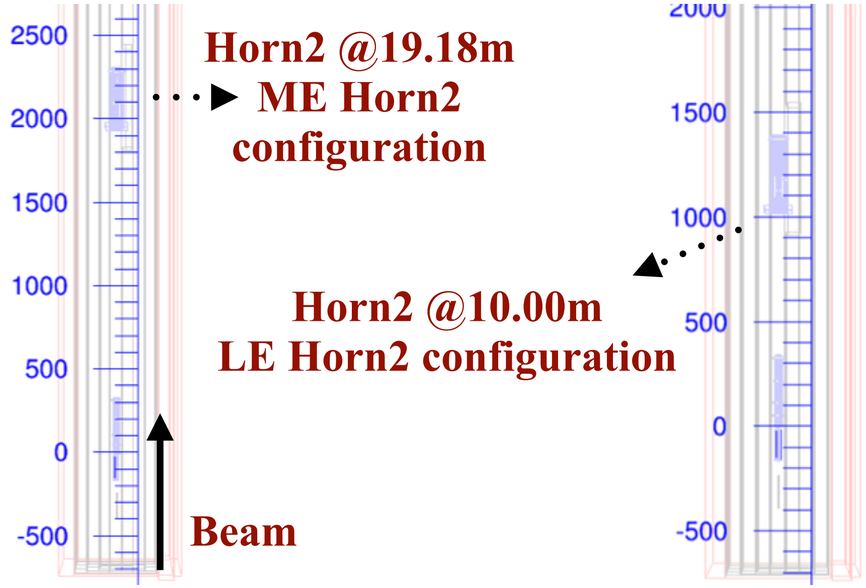
- The NOvA target consists of 48 graphite fins (+2 budal monitors) with a total target length of 122.5 cm.



The NOvA Target

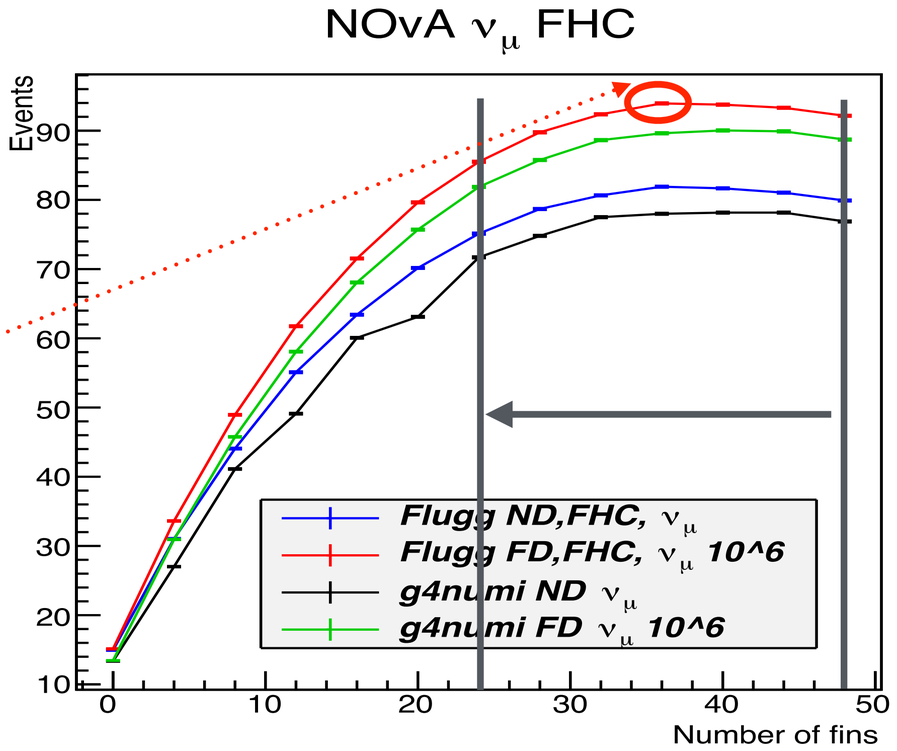


- Medium Energy Horn2 configuration (ME): The Horn2 is at 19.18m w.r.t the Horn1: s*tandard configuration for NOvA.*
- Low Energy Horn2 configuration (LE): The Horn2 is at 10.0m w.r.t the Horn1: *used in past by MINOS On-Axis Experiment.*



Study of neutrino yield

- Longer targets & targets with gaps : observed few ν_μ events.
- Reduce the number of fins from the upstream part of the NOvA target, making a shorter target : observed maximum ν_μ yield with 36-fins target.
- Using half of the target (24 fins), ***neutrino flux is reduced by just 5% at the FD*** as compared to the whole 48 fins target.
- **The number of protons** surviving a 24 fins target (λ ~1.25) is **~30% : WASTE of protons!**



Events are in 1-3 GeV Energy Range
FLUGG & G4NuMI Simulations

We have investigated if we can use these protons elsewhere to get the increased neutrino yield!!

Idea is to extend the target inside the Horn1!

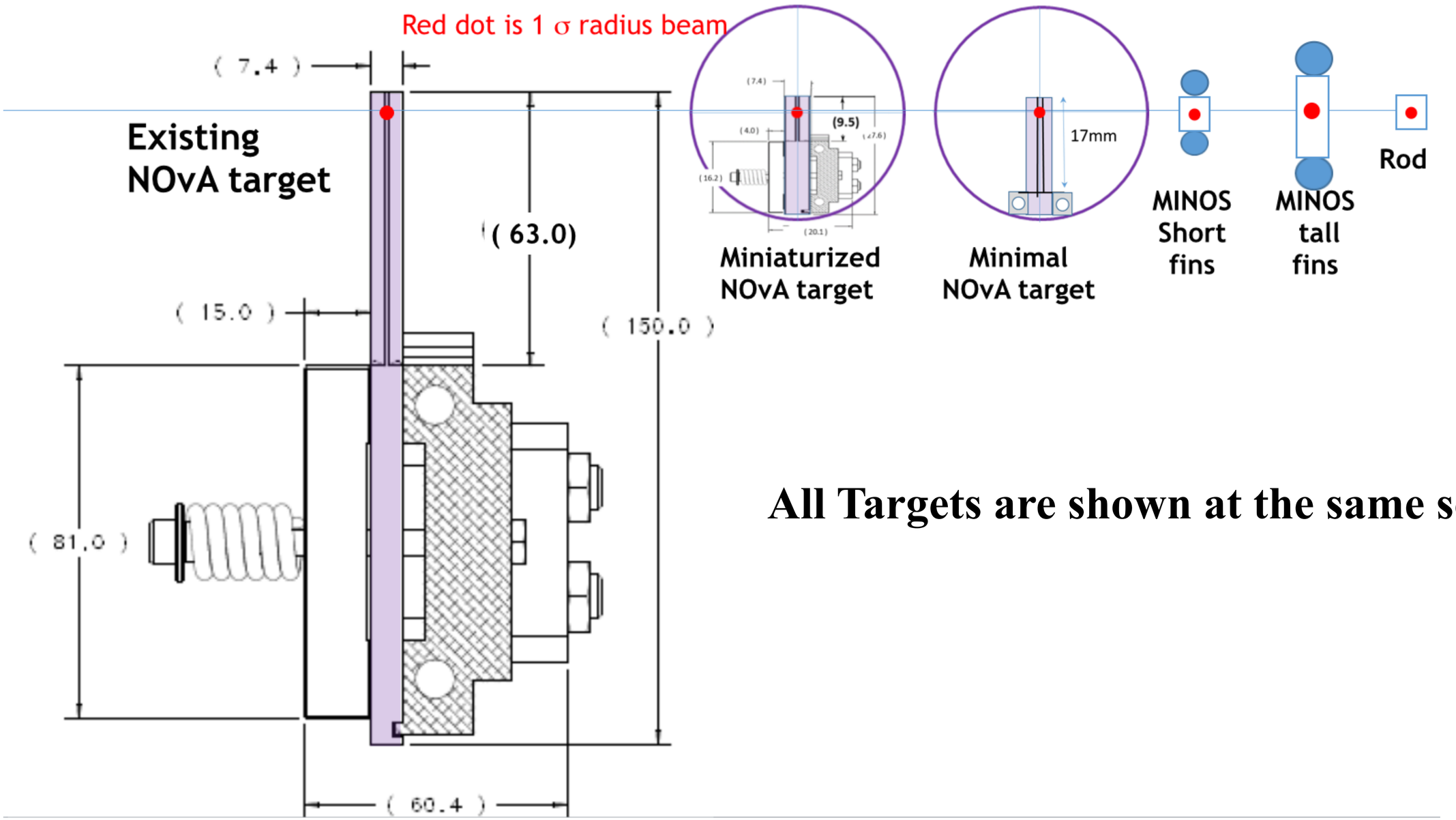
Various Targets

- In this study, various targets are simulated to see the effect on neutrino yield.

1. Standard NOvA target (63 mm high Fins) → Real
2. MINOS tall fins target (18 mm high Fins, 120cm long, *longer than the default MINOS target ~97cm*) → Almost Real
3. MINOS short fins target (7.4 mm high Fins) → Concept
4. Miniaturized NOvA target (9.5 mm high Fins) → Concept
5. Minimal NOvA target (17 mm high Fins) → Concept
6. Simple rod (7.4 mm high fins) → Idealized Concept

All targets are ~122cm long.

X-Y View (Beam View Of the Targets)



All Targets are shown at the same scale

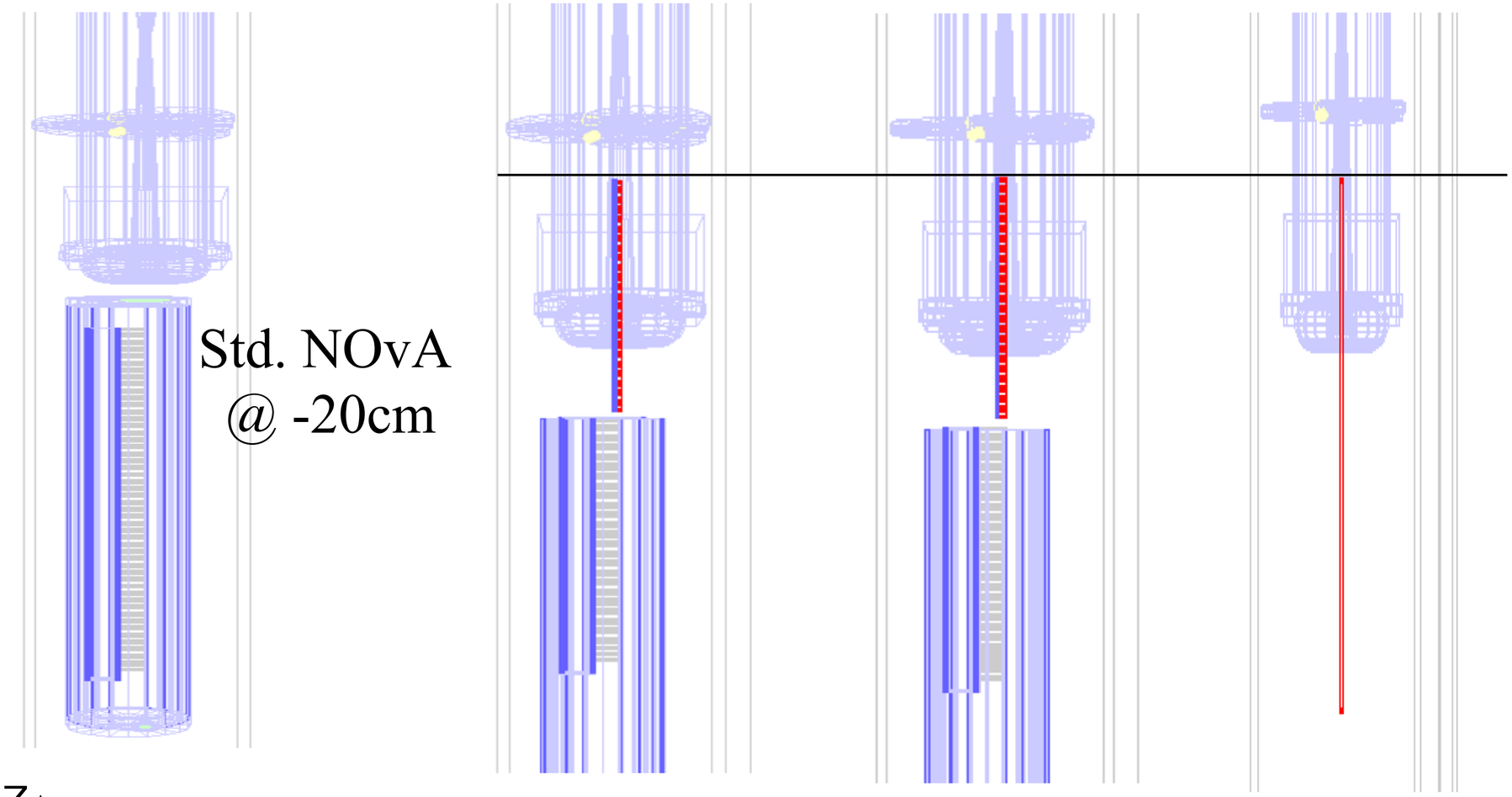
Y-Z View of the Targets

NOvA Standard

NOvA Miniaturized

NOvA Minimal

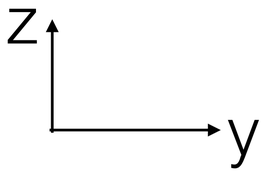
Rod



Std. NOvA @ -20cm

All targets (~122cm) ending @40cm

Rod is the idealized concept so there is not any supporting structure, cooling tubes, Be window…



Details of the targets are in backup slides.

Strategy

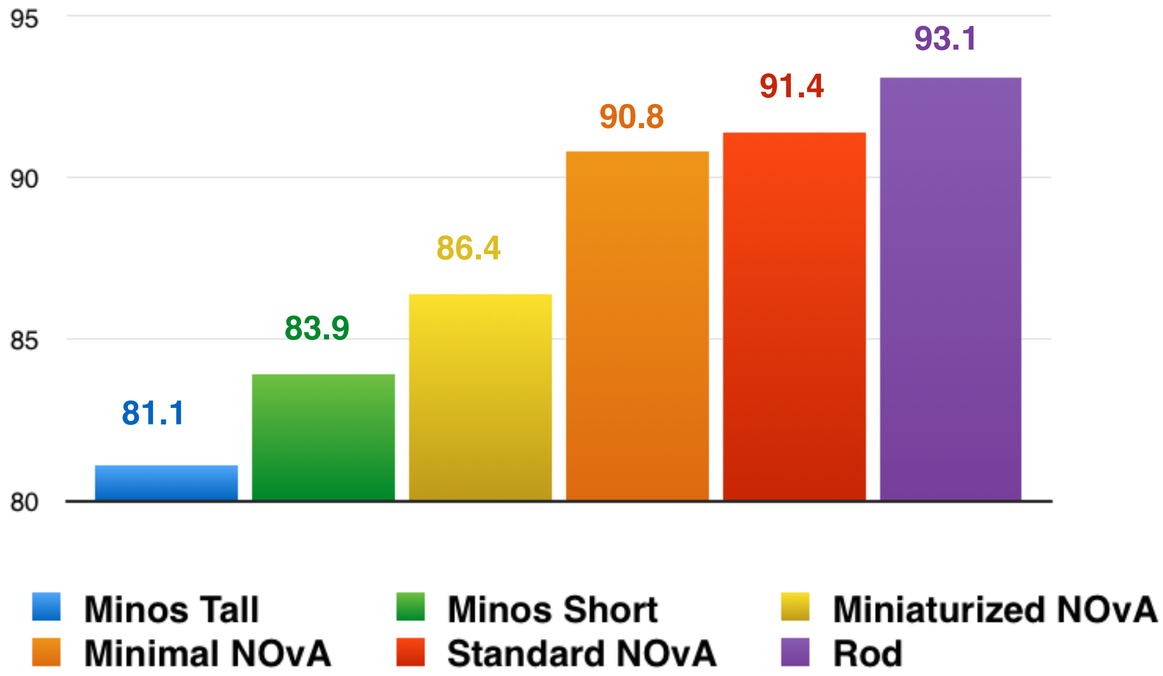
Using FLUGG software

- Simulate targets at target position -20 cm.
- Simulate various targets at different positions to find the best possible target position.
- Simulate targets at the best target position.

Simulation Results with different Targets (Targets Length ~122cm)

Target Downstream end @ -20 cm

ν_μ Event yield (Un-oscillated ν_μ) for FD in 1-3 GeV energy range



At -20cm, Standard NOvA target is the best target..
(Rod is the ideal one…).

Choosing the best target position and configuration

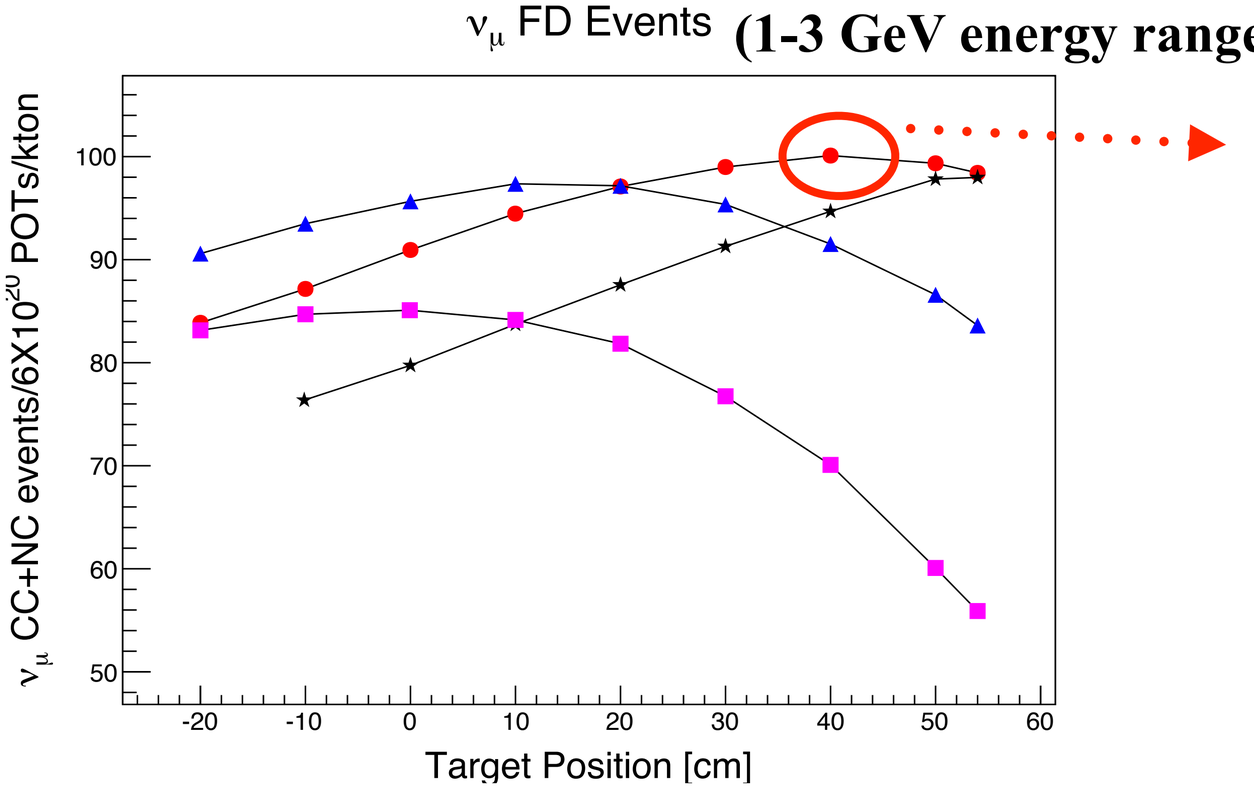
- Simulate Minos short target of different lengths at various target positions.

Magenta: 24 fins
~64cm long

Blue: 36 fins
~93cm long

Red: 48 fins
~122 cm long

Black: 60 fins
~147cm long



48 fins target (~122cm long) configuration **@40cm** position seems to be the best one.

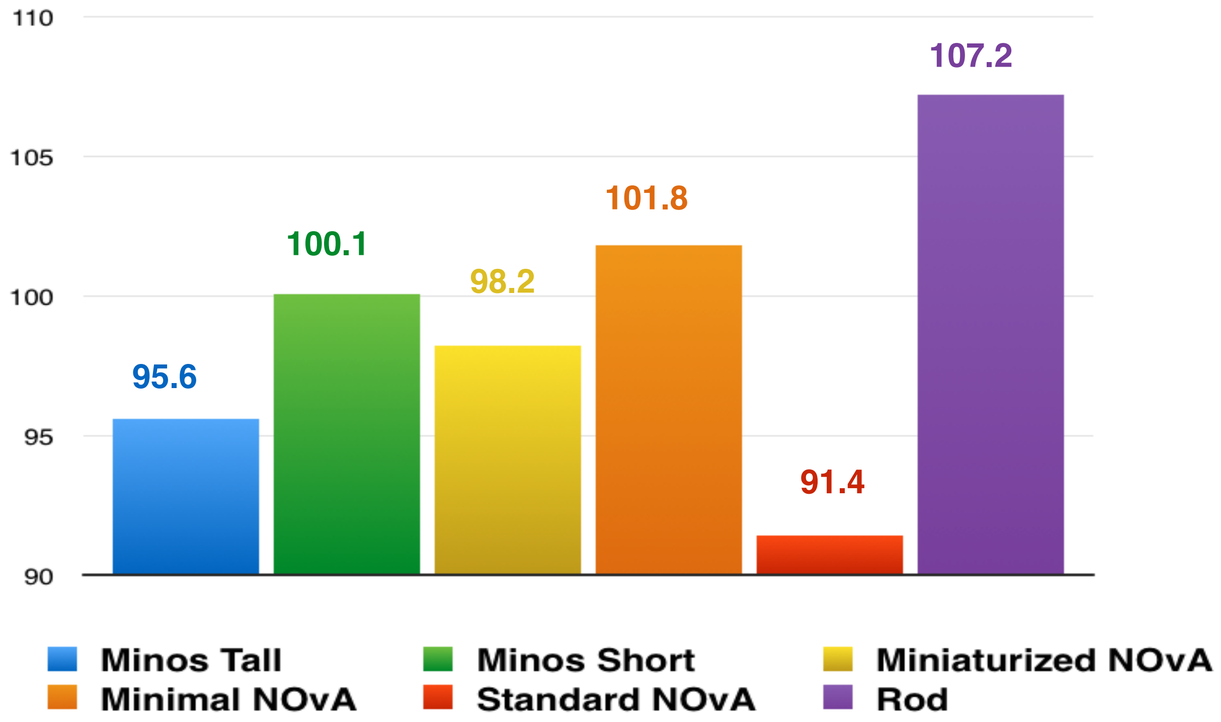
- We checked this further using different targets and they all showed maximum yield with **target positioned @+40cm (inside the Horn1).**

Simulation Results with different Targets (Targets Length ~122cm)

Target Downstream end @ +40cm

Std. NOvA is always @-20cm

ν_μ Event yield (Un-oscillated ν_μ) for FD in 1-3 GeV energy range



NOTE:

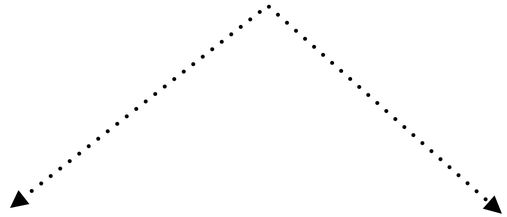
We are back to 48 fins target configuration and are not wasting protons.

At +40cm, NOvA Minimal target proves to be the best target configuration.

Event gain with Minimal NOvA is 11.4% as compare to the Std. NOvA.

Minimal NOvA Target simulation

Minimal NOvA target @+40 cm inside the Horn1



Graphite fins

- **ME Horn2 Configuration (Horn2 @19.18m) *FHC & RHC**
- **LE Horn2 Configuration (Horn2 @10.0m) *FHC & RHC**

Beryllium fins

- **ME Horn2 Configuration (Horn2 @19.18m) *FHC & RHC**
- **LE Horn2 Configuration (Horn2 @10.0m) *FHC & RHC**

Compare these results with the **Std. NOvA target**

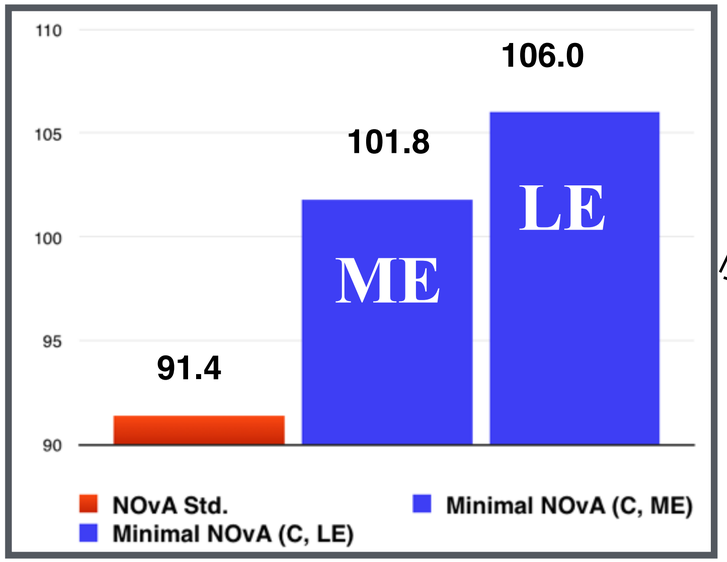
**FHC: Forward Horn Current, 200kA (focussing π^+)*

**RHC: Reverse Horn Current, -200kA (focussing π^-)*

Results (Std. NOvA & *graphite fins* Minimal NOvA target: FHC)

(FHC)

FD Events are in 1-3 GeV Energy range



Red: *Standard NOvA*

Blue: Graphite (C) Fins Minimal NOvA Target

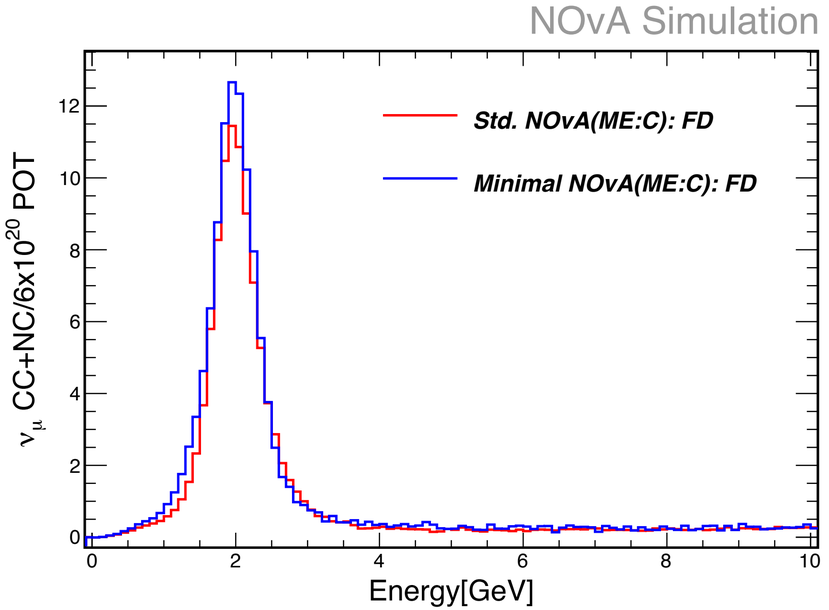
ME Horn2 configuration *(Horn2 @19.18m)*

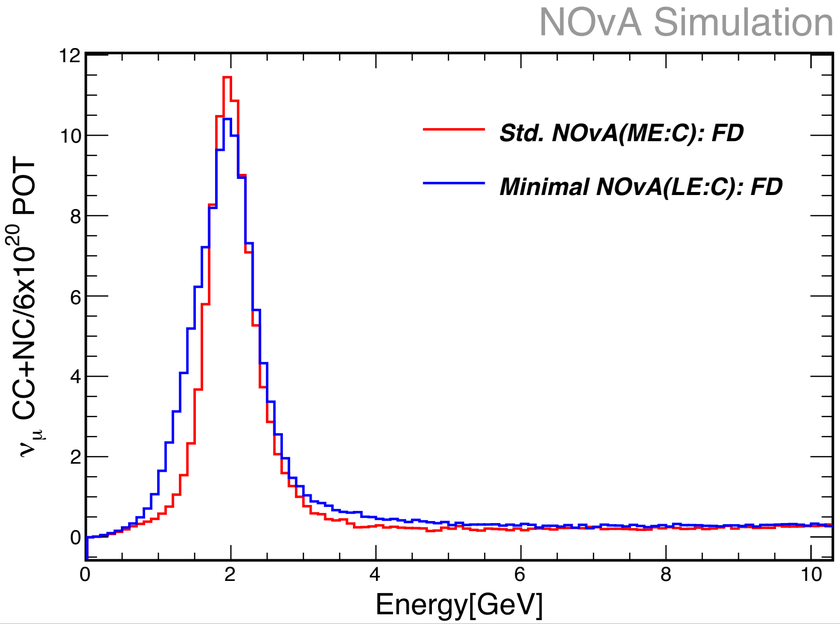
11.4 % gain with Minimal NOvA Target

LE Horn2 configuration *(Horn2 @10.0m)*

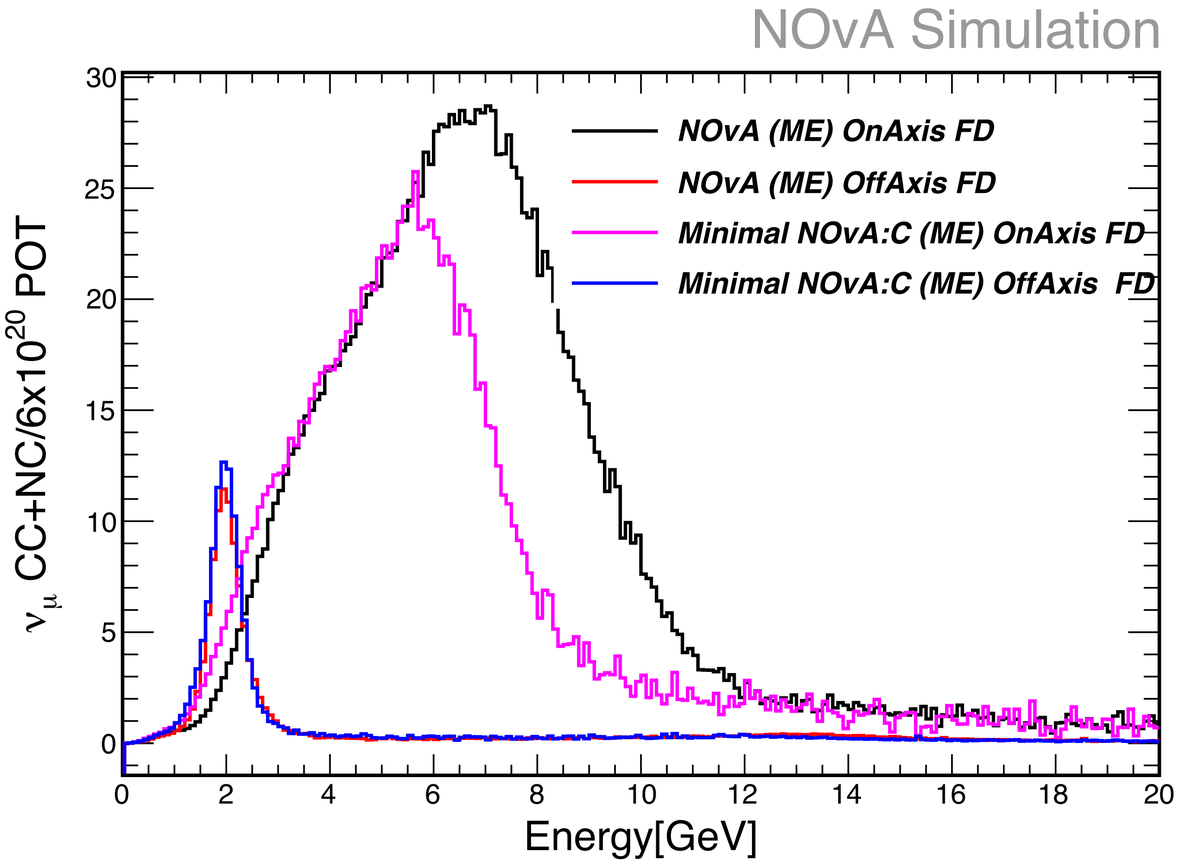
15.9 % gain with Minimal NOvA Target

% is w.r.t Std.NOvA





On-axis behavior is very different from Off-axis behavior

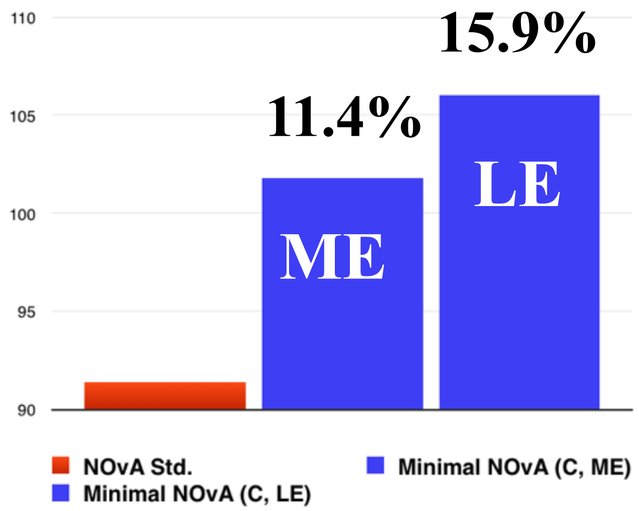


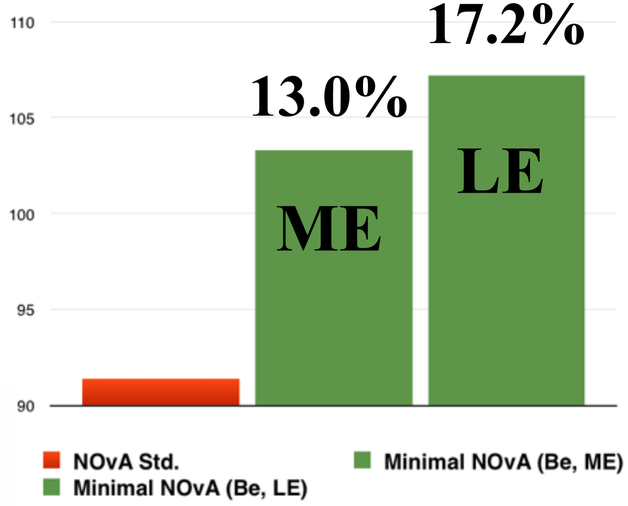
- **Off-axis spectra** is fairly constant (no shift in the peak), just the number of events changes.
- **On-axis spectra** for **Standard NOvA** shifts towards higher energy as compare to the on-axis spectra for Minimal NOvA because we have removed the fins from upstream part in Minimal NOvA which leads to higher energies.

Results: *(FD Events: in 1-3 GeV Energy range)*

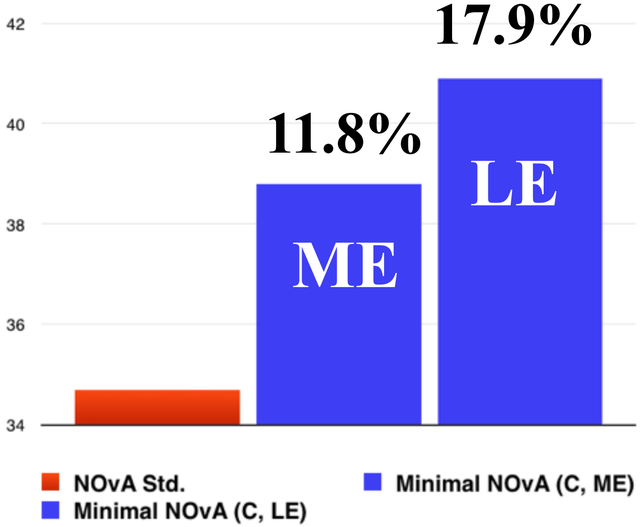
% is the gain w.r.t Std. NOvA target

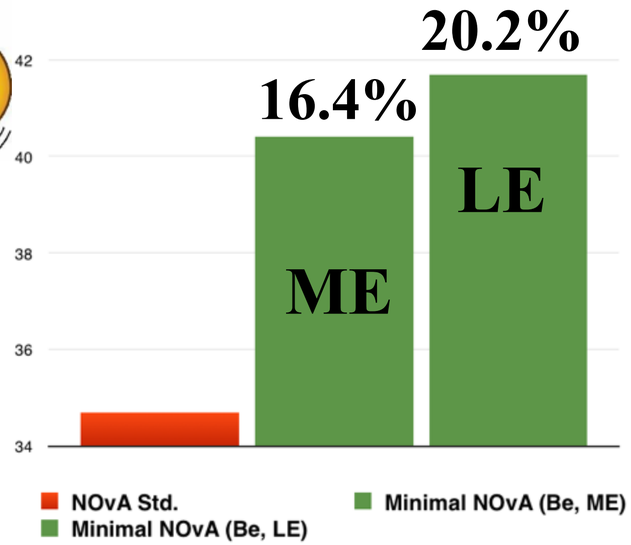
(FHC)





(RHC)





Red: ***Standard NOvA***

Blue: Graphite (C) Fins Minimal NOvA Target

Green: ***Be Fins Minimal NOvA Target***

Horn2 configuration

ME: Horn2 @+19.18m

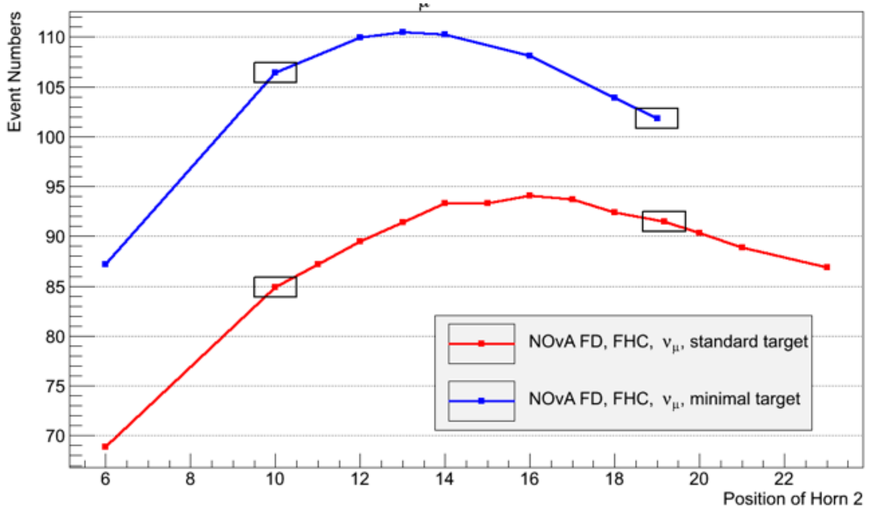
LE : Horn2 @+10m

Horn2 Scan using Minimal NOvA Target

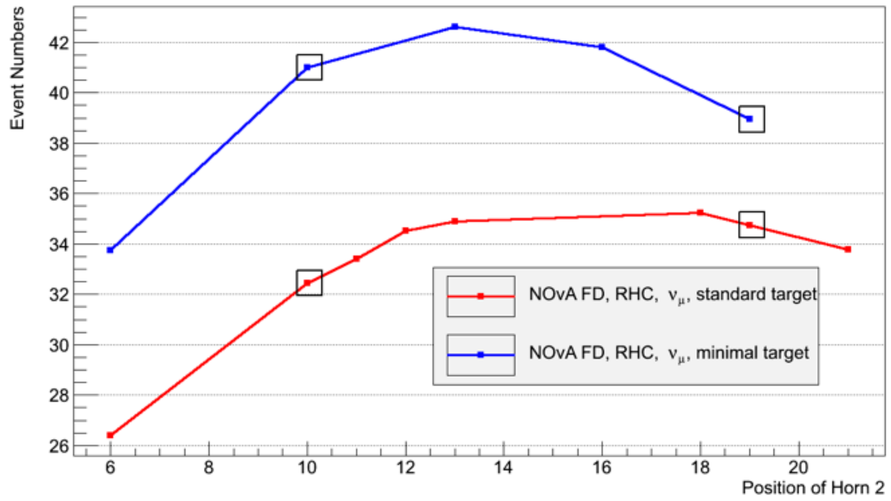
J. Tripathi

ν_μ yield for FD in 1-3 GeV energy range

FHC



RHC



Red: *Standard NOvA*

Blue: Graphite (C) Fins Minimal NOvA Target

- Plot shows that the Minimal NOvA performs better at all the horn2 positions as compare to the Std. NOvA with the maximum yield placing **horn2 @13m both in FHC and RHC beam configuration.** ***This requires new stripline.***

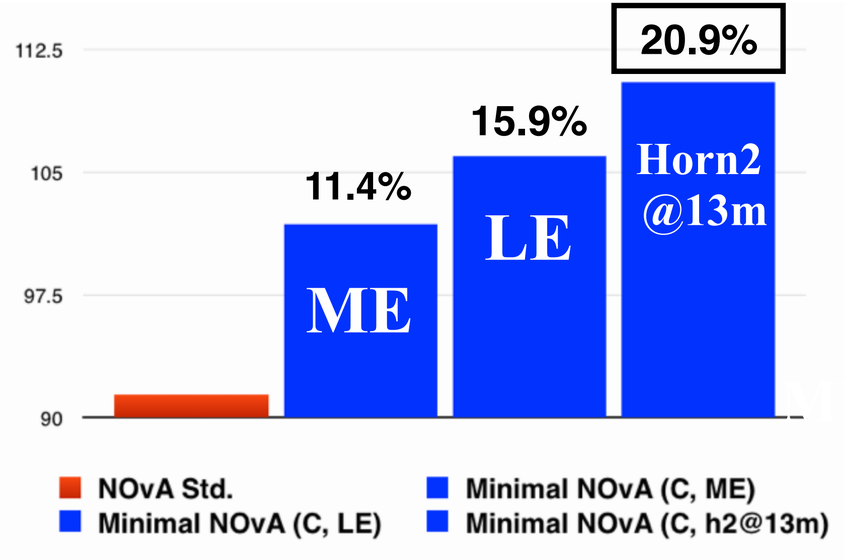
Comparison

FD Events are in 1-3 GeV Energy range

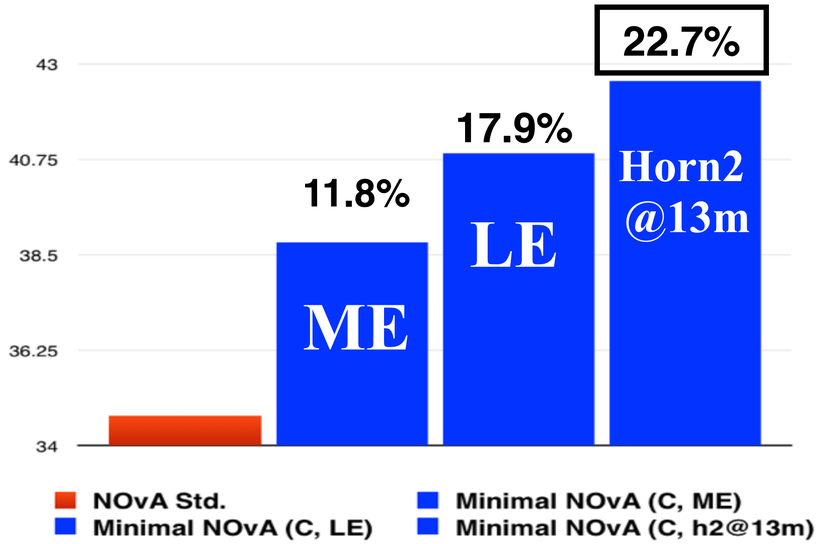
Red: *Standard NOvA*

Blue: Graphite (C) Fins Minimal NOvA Target

(FHC)



(RHC)



- Anti-neutrino yield in RHC case is only 38% of the neutrino yield in FHC case. **We really need more events.**

Technical challenges of the target design

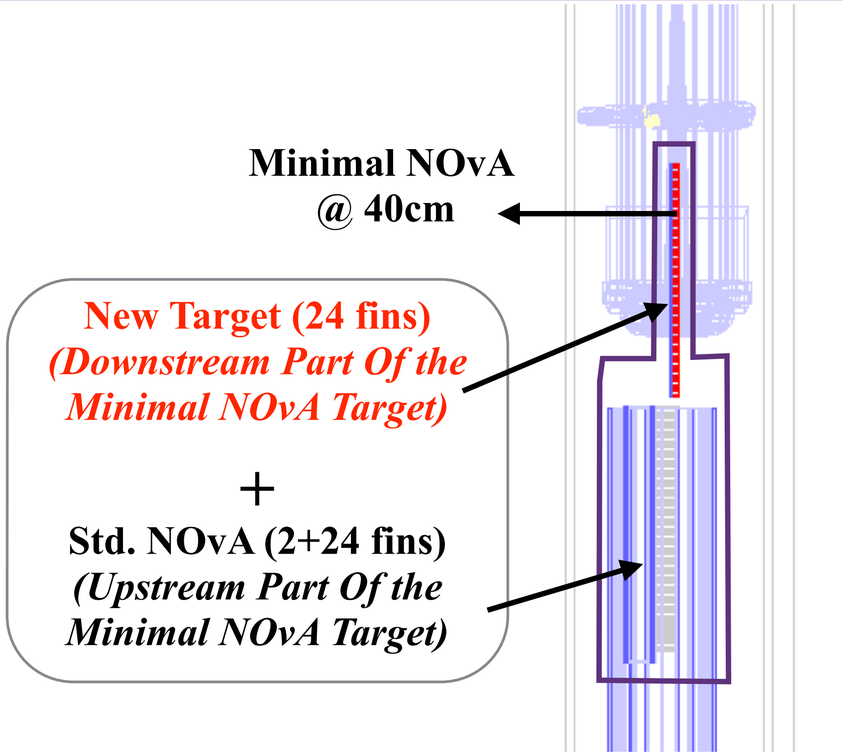
- Minimal NOvA target requires an engineering design .

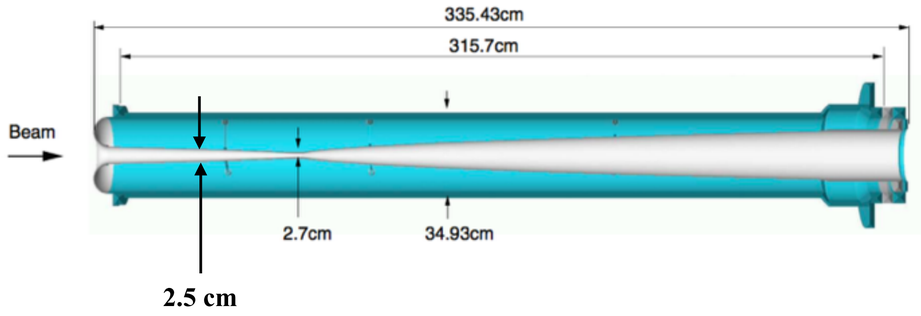
  - *To connect the upstream part of target (Std. NOvA with 24 fins) to the new target (which goes inside the Horn1) would be challenging.*

  - *We had removed Be window and target downstream flange from the standard NOvA target to avoid overlapping MC sections in FLUGG.*

  - *The radius of the surrounding tube of the **new target part** (which goes inside the Horn1) is 2.15 cm and at +40 cm w.r.t Horn1 inner conductor of Horn1 is 2.54 cm. So, ~4mm radial clearance between this **new target** and the Horn1.*

  - *Heating/Cooling of the Horn1 inner conductor should be considered but the downstream part of the target requires less cooling as compared to the upstream part because of lesser interactions in the downstream part of the target.*

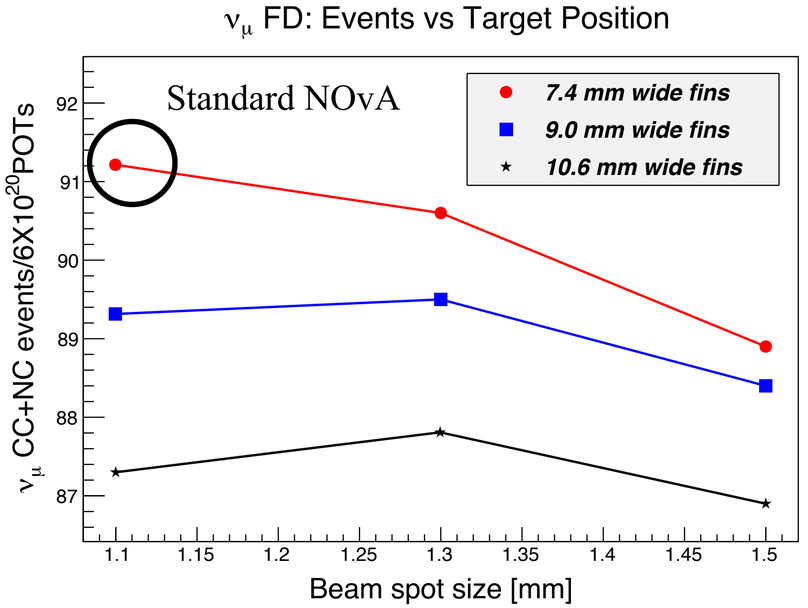




Proton Improvement Plan (PIP-I+) Proposal

M. Convery

- Aim of PIP-I+ is to **increase the NuMI intensity to 1.2MW** which requires a target station that is robust at 1MW.
  - B. Zwaska, K. Yonehara and Cory F. Crowley estimated that wider beam spot would be required at 900kW beam power.
  - This is probably required to keep the heating under control.
- So, we performed the simulation changing the beam spot size from 1.1mm to 1.5 mm and target fin width from 7.4mm to 9.0mm saw ***3% reduction in neutrino yield w.r.t standard.***
- We simulated 7.4mm, 9.0mm, 10.6mm wider fins with 3 different beam spot size 1.1mm, 1.3mm and 1.5mm to see the effect on neutrino yield. →



Summary & Conclusions

- We have studied the different targets design for the NuMI off-axis NOvA to optimize the neutrino and anti-neutrino yield at ND and FD.
- **Minimal NOvA target always performs better for all horn configurations with 21% (23%) gain in the neutrino (anti-neutrino) yield w.r.t the Std. NOvA:** ***(best case)***
- Beam intensity effects are additive. So, **Increased beam power (~30%) with the new target inside the Horn1 (~21%)** could lead to **~50% more neutrinos** to the NOvA.
  - *This depends on FEA thermal analysis of the target heating/cooling and of the inner conductor Horn1 heating/cooling under these conditions.*

Thank you!

Back-up

Targets Specification

Standard NOvA

	2+48 Fins (Graphite)
Length	24 mm
Width	7.4 mm
Height	63 mm
Pitch	0.5 mm

- With cooling tubes only on bottom
- With supporting structure (pressing plates, cooling plates)

MINOS Tall Fins

1+49 Fins (Graphite)
24 mm
7.4 mm
18 mm
0.5 mm

- With cooling tubes on both top and bottom
- With supporting structure (pressing plates, cooling plates)

Fins are of same height (18 mm) as in default MINOS.

MINOS Short Fins

1+49 Fins (Graphite)
24 mm
7.4 mm
7.4 mm
0.5 mm

- With cooling tubes on both top and bottom
- With supporting structure (pressing plates, cooling plates)

There is a tube filled with Helium (He) surrounding these targets (but there is no tube material to hold the He in place)

Miniaturized NOvA

Minimal NOvA

Simple Rod

No need to change the NOvA target design upstream of the Horn1, only the part that goes inside the horn1. "NOvA Target design is quite robust as proved by the first NOvA target"

	2+24 Std.	24 New
Length	24 mm	24 mm
Width	7.4 mm	7.4 mm
Height	63 mm	9.5 mm
Total H	150 mm	19.5 mm
Pitch	0.5 mm	0.5 mm

2+24 Std.	24 New
24 mm	24 mm
7.4 mm	7.4 mm
63 mm	17 mm
150 mm	19.5 mm
0.5 mm	0.5 mm

1 Elongated Fin
Length = 122 cm
Width = 7.4 mm
Height = 7.4 mm

- With cooling tubes (squeezed) only on bottom.
- With supporting structure (pressing plates, cooling plates)
- No Be window & No TargetDownstream Flange

- With cooling tubes far away from the target fin.
- With supporting structure (pressing plates, cooling plates)
- No Be window & No TargetDownstream Flange.

No cooling tubes

No supporting structure (pressing plates, cooling plates)

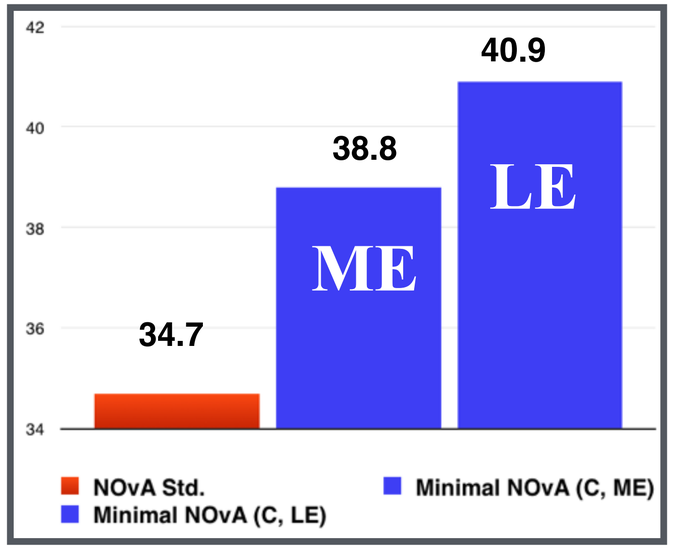
No Be window & TargetDownstream Flange

A Real Engineering design would be required to connect the 24 old to the 24 new fins.

Results (Std. NOvA & Minimal NOvA target: RHC)

(RHC)

FD Events are in 1-3 GeV Energy range



Std.NOvA & Minimal NOvA :

ME Horn2 configuration

11.8 % gain with Minimal NOvA Target

Std.NOvA & Minimal NOvA :

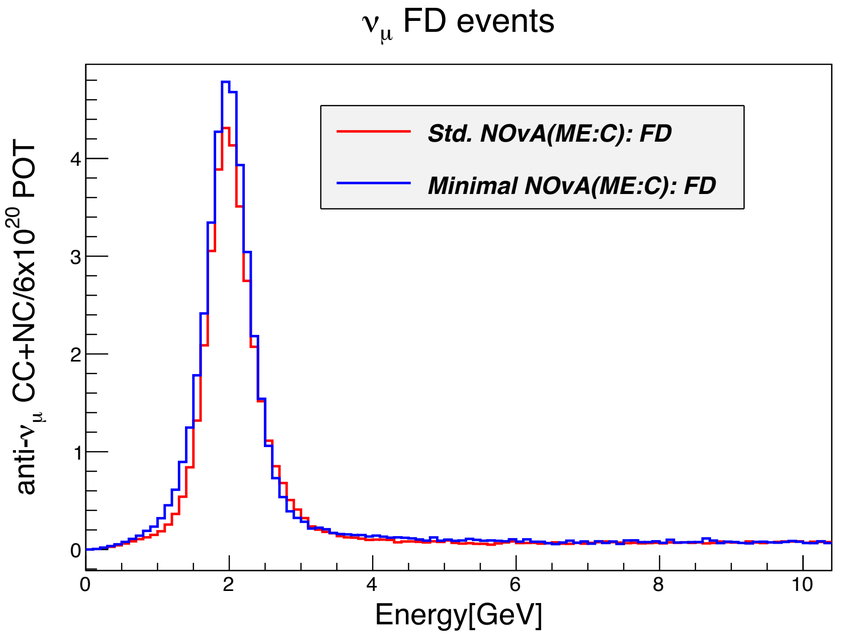
LE Horn2 configuration

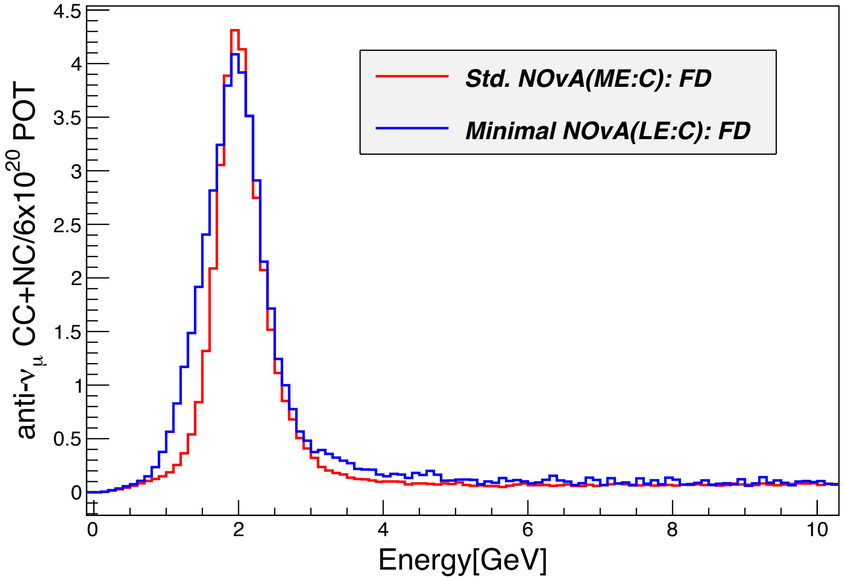
17.9 % gain with Minimal NOvA Target

% is w.r.t Std.NOvA

Red: *Standard NOvA*

Blue: Graphite (C) Fins Minimal NOvA Target

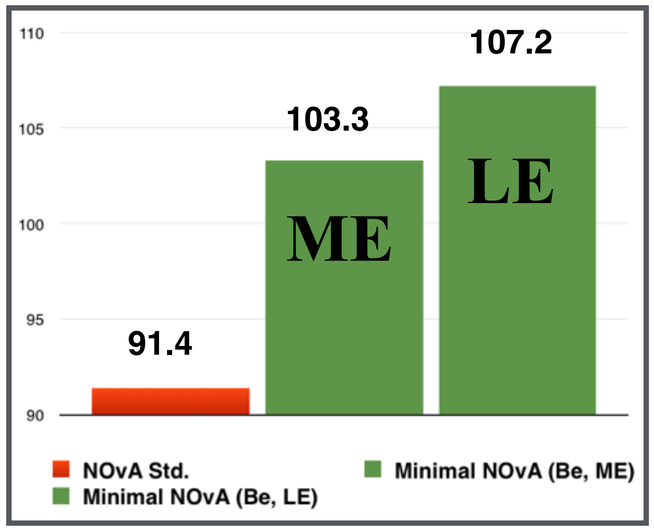




Results (Std. NOvA & Minimal NOvA target: FHC)

(FHC)

FD Events are in 1-3 GeV Energy range



Red: *Standard NOvA*

Green: *Be Fins Minimal NOvA Target*

Std.NOvA & Minimal NOvA :

ME Horn2 configuration

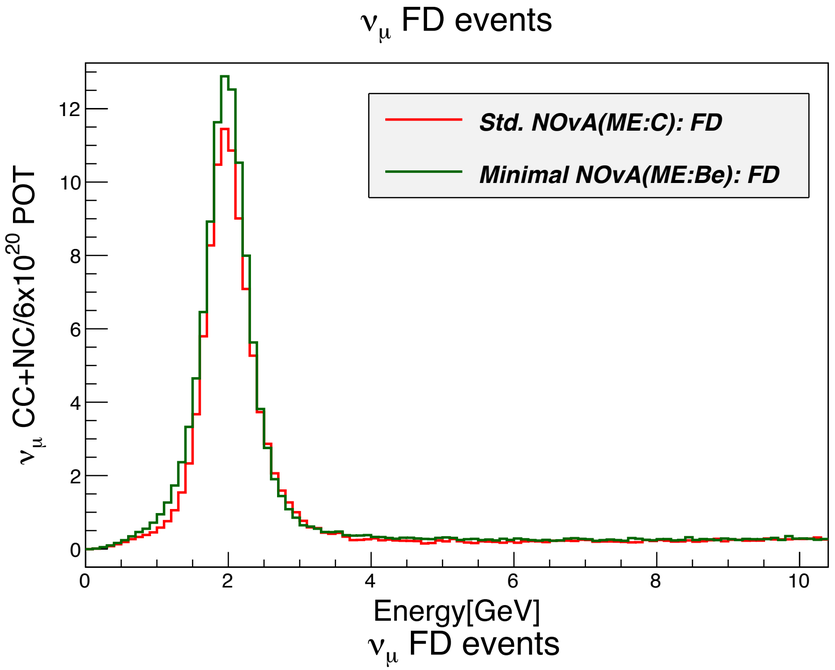
13.0 % gain with Minimal NOvA Target

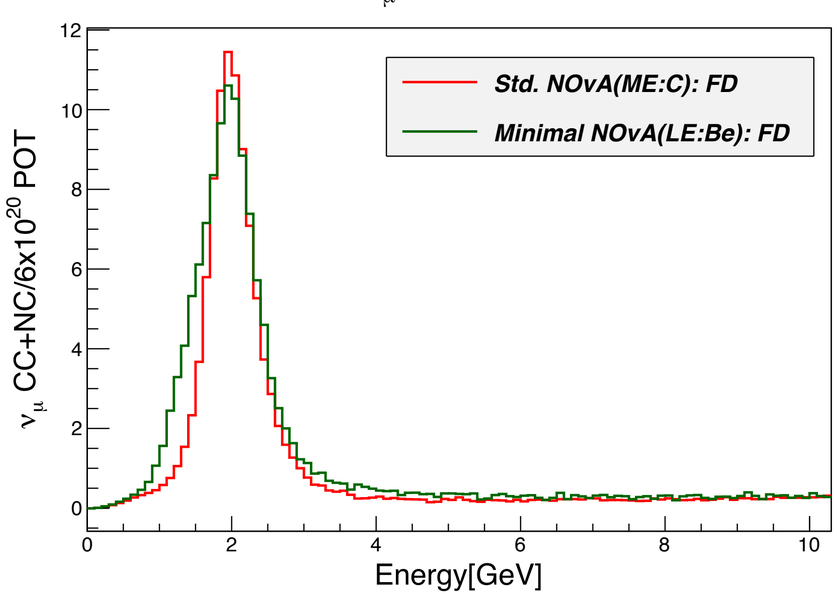
Std.NOvA & Minimal NOvA :

LE Horn2 configuration

17.2 % gain with Minimal NOvA Target

% is w.r.t Std.NOvA

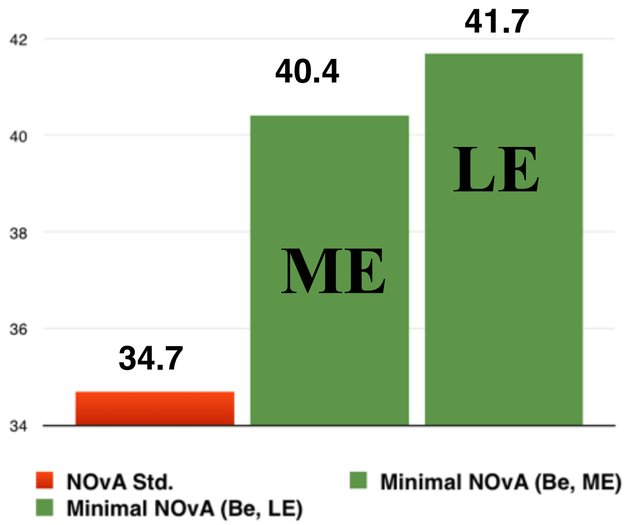




Results (Std. NOvA & Minimal NOvA target: RHC)

(RHC)

FD Events are in 1-3 GeV Energy range



Red: *Standard NOvA*

Green: *Be Fins Minimal NOvA Target*

Std.NOvA & Minimal NOvA :

ME Horn2 configuration

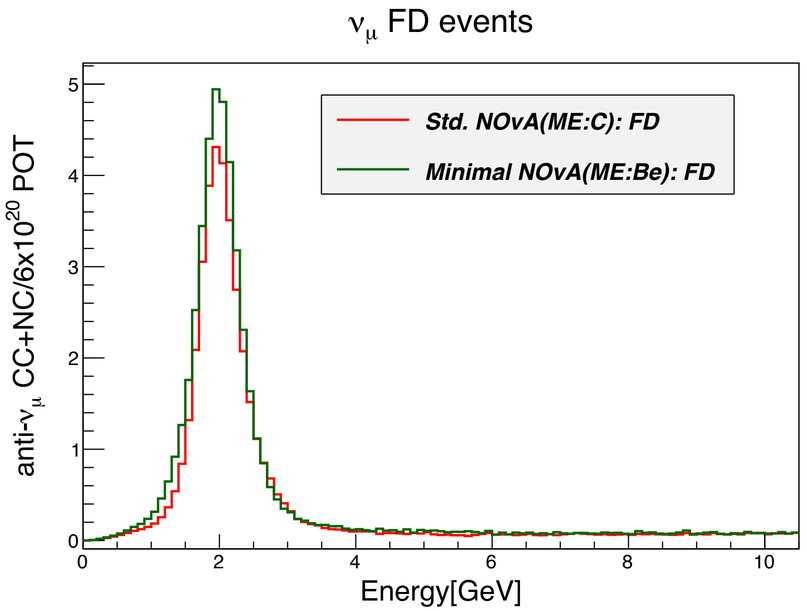
16.4 % gain with Minimal NOvA Target

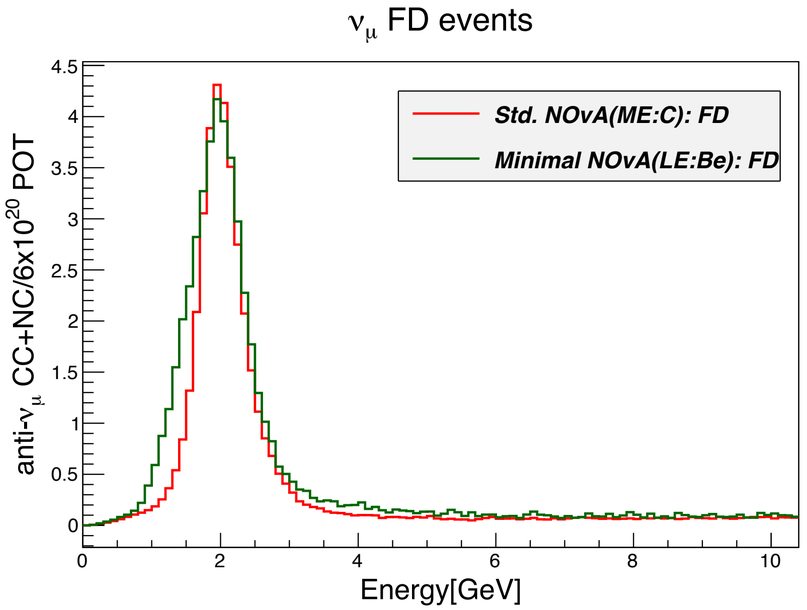
Std.NOvA & Minimal NOvA :

LE Horn2 configuration

20.2 % gain with Minimal NOvA Target

% is w.r.t Std.NOvA

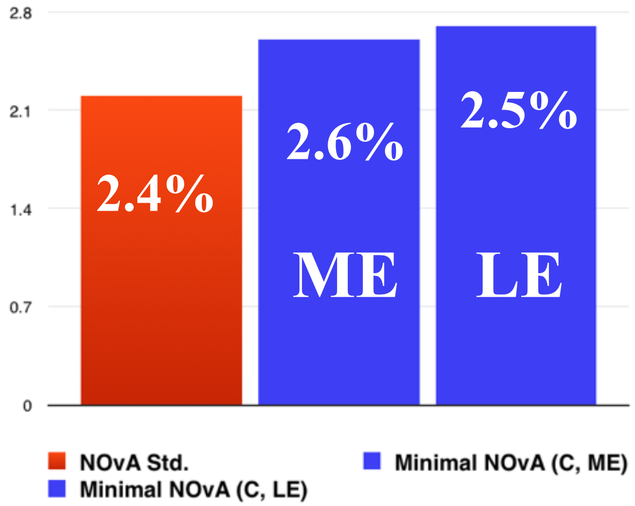


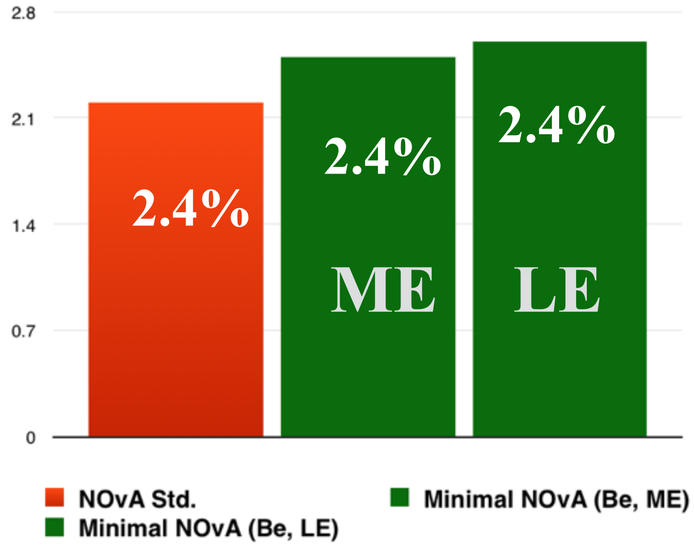


Background to the Event Yield

% here is w.r.t ν_μ yield

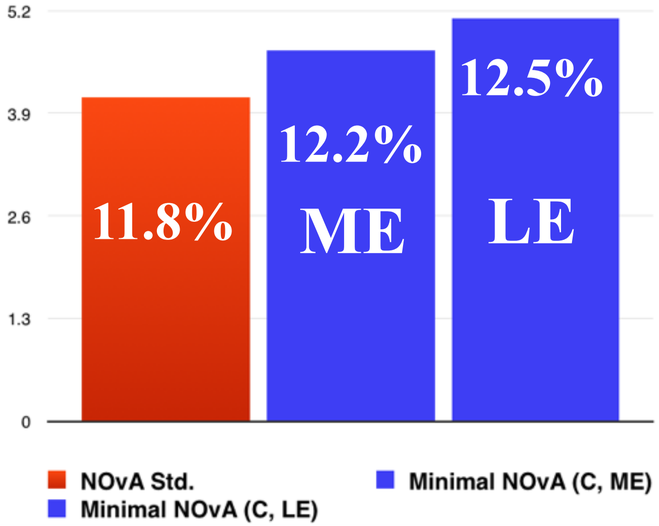
(FHC)

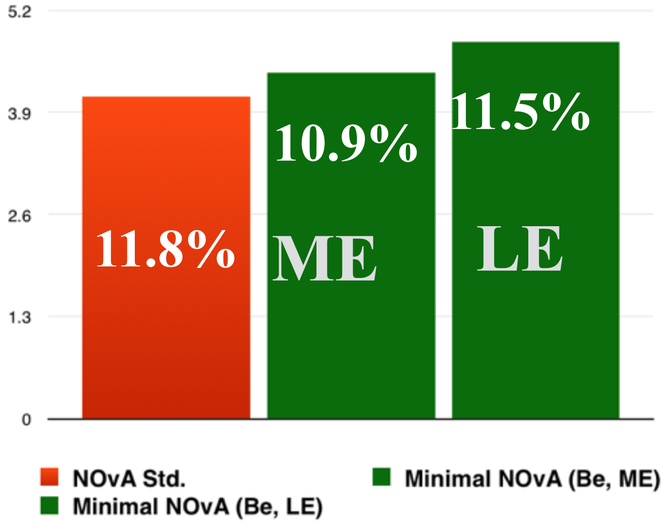




NOT BAD

(RHC)





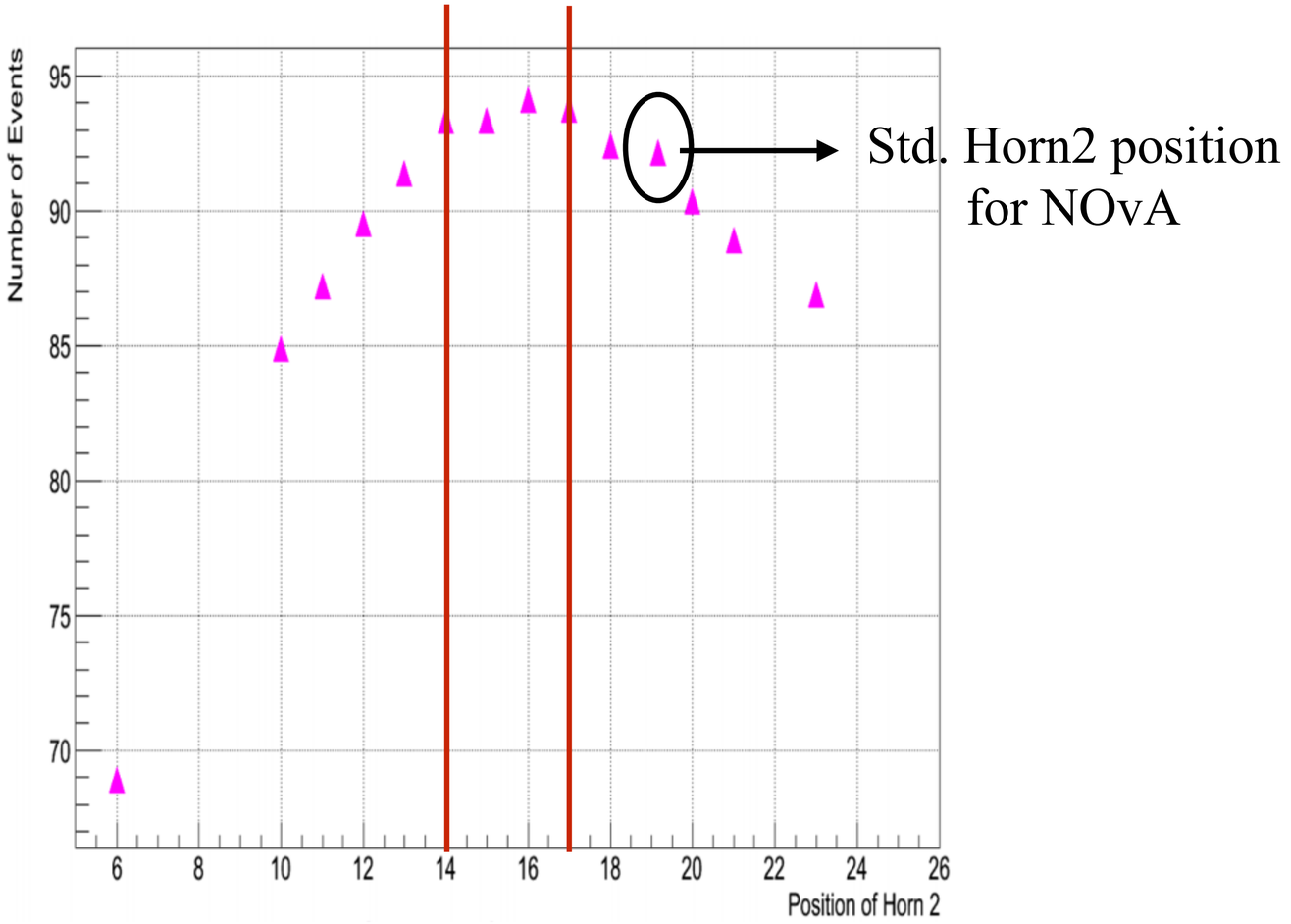
Can we get even better neutrino yield ??

J. Tripathi

- Plot shows more neutrino yield with horn2 placed somewhere between 14m and 17m as compared to the Standard horn2 position (@ +19.12m)
- Same study was performed using the ***Minimal NOvA Target (with Graphite Fins)*** to see the effect on the neutrino yield.

Reminder

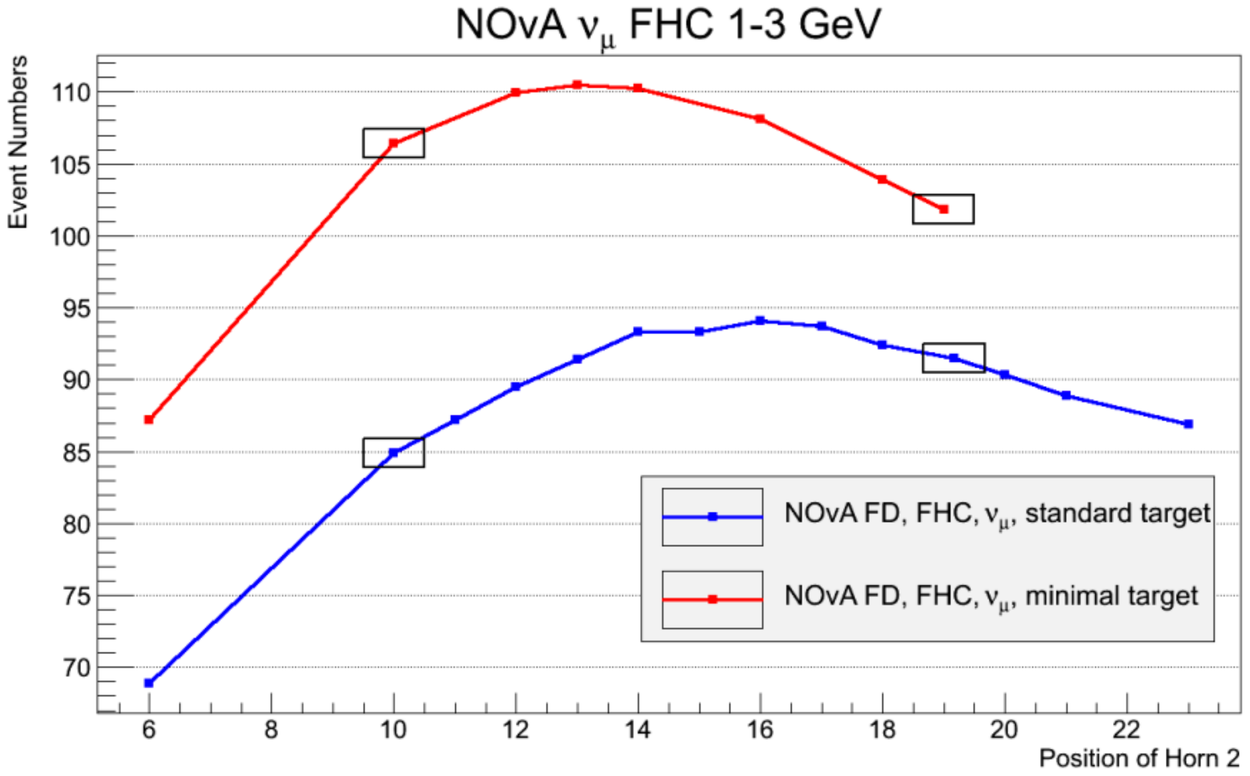
Horn2 Configuration
ME: horn2 @+19.18m
LE: horn2 @+10m



Number of neutrino events at NOvA FD in energy range 1-3 GeV for different horn2 positions..

Horn2 Scan using Minimal NOvA Target

- For Std. NOvA, ME performs always better.
- **For Minimal NOvA, LE performs better**… May be because the target is half inserted inside the horn1 allowing low energy pions (4-6 GeV) to get focused and those low energy pions prefer a closer position of horn2 (as in MINOS On-Axis), but not too close as we may lose higher energy pions (8-10 GeV) due to over focusing (as they get focused nicely by the horn1)



ν_μ Event yield (Un-oscillated ν_μ) for FD in 1-3 GeV energy range

Costs:
Thanks to John W.Cooper (NOvA Project Manager) for providing these figures

For a new target:

WBS 2.0.3.2.1 ME Target, Carrier & Baffle (For new target design, should be able to use existing MINOS carriage)

Materials and Services	= $ 455,455
Personnel Costs	= $ 997,578
TOTAL COST	= $1,972,667

This included all the design, construction, and installation of the existing NOvA target built by the NOvA Project

For Horn 2 in a new position:

WBS 2.0.3.3.2.1 Stripline Extension

Materials and Services	= $ 125,935
Personnel Costs	= $ 207,276
SUBTOTAL COST	= $ 333,211

WBS 2.0.3.3.2.2 Shielding Reconfiguration

Materials and Services	= $ 346,661
Personnel Costs	= $ 545,659
SUBTOTAL COST	= $ 892,319
TOTAL COST	= $1,225,530

This included all the design, construction, and installation of a new stripline based on the move of Horn 2 from 10m to 19m in the NOvA Project.