Optimizing LBNF for $\nu_\mu \to \nu_\tau$ Appearance

Mary Bishai
for the Beam Interface Group

September 13, 2016

Outline

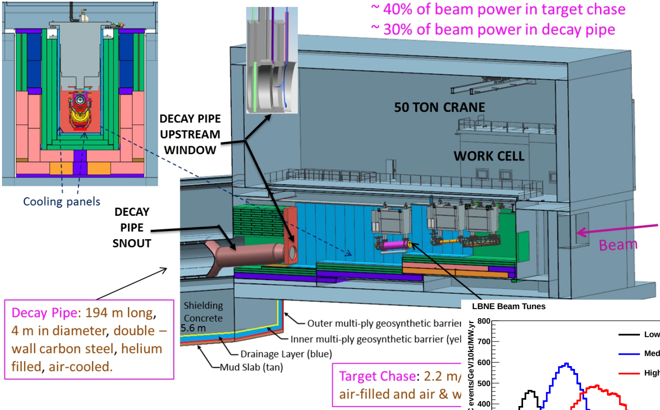
Global Science Requirements of the Beam

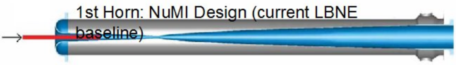
From DocDB 112, DUNE/LBNF's formal requirement document:

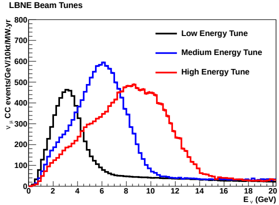
Glo-Sci-13 The neutrino beam spectrum shall cover the energy region of the first two oscillation maxima affected by muon-neutrino conversion from the atmospheric parameters.
Glo-sci-60 The neutrino beam spectrum shall extend beyond the first maximum to higher energies, while maintaining a high signal to background ratio to obtain the maximum number of charged current signal events. [We have not specified what range of energies...!!]
Glo-Sci-14 The neutrino beam spectrum shall be tunable so that beam with both lower peak energy (below the first oscillation node) and higher peak energy (significantly higher than the first oscillation node) can be achieved without substantial downtime that reduces the overall exposure.

The LBNF Beamline CDR Design

Advanced conceptual design with upgraded NuMI-style focusing. Horn location fixed but *tunable* by using movable target:

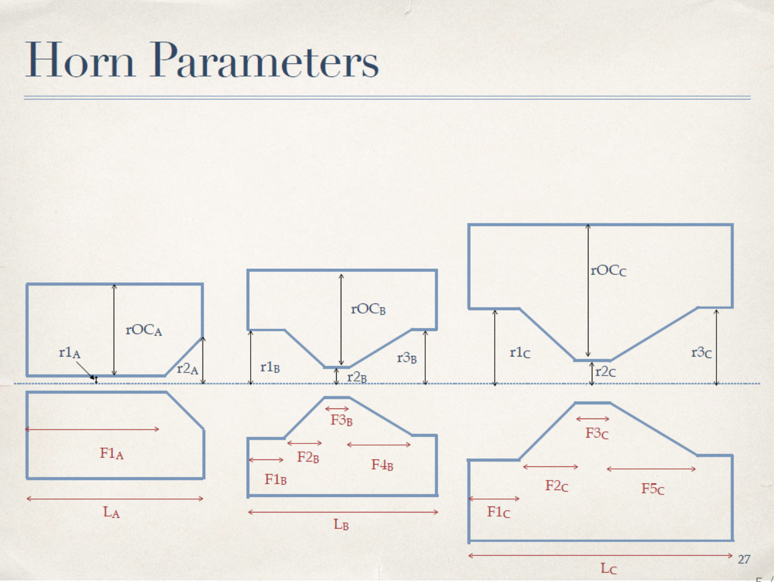






Optimization of Focusing System Geometry for CPV

Laura Fields



Optimization of Focusing System Geometry for CPV

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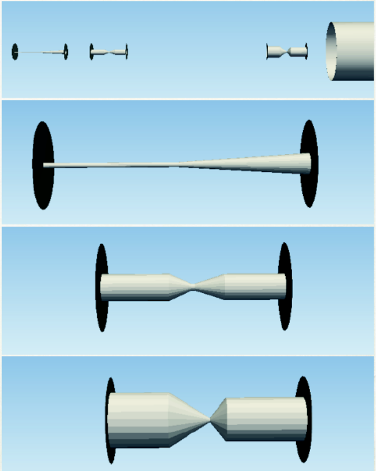
Cylindrical Target Optimization Results

Parameter	Lower Limit	Upper Limit	Unit	
Horn A: L_A	1000	4500	mm	3717
Horn A: $F1_A$	1	99	%	51
Horn A: $r1_A$	20	50	mm	33
Horn A: $r2_A$	20	200	mm	147
Horn A rOC_A	200	650	mm	630
Horn B: L_B	2000	4500	mm	2551
Horn B: $F1_B$	0	100	%	37
Horn B: $F2_B$	0	100	%	12
Horn B: $F3_B$	0	100	%	2
Horn B: $F4_B$	0	100	%	16
Horn B: $R1_B$	50	200	mm	186
Horn B: $R2_B$	20	50	mm	47
Horn B: $R3_B$	50	200	mm	179
Horn B: ROC_B	200	650	mm	633
HornB: Z position	2000	17000	mm	5453
Horn C: L_C	2000	4500	mm	2694
Horn C: $F1_C$	0	100	%	30
Horn C: $F2_C$	0	100	%	21
Horn C: $F3_C$	0	100	%	2
Horn C: $F4_C$	0	100	%	9
Horn C: $R1_C$	50	550	mm	388
Horn C: $R2_C$	20	50	mm	26
Horn C: $R3_C$	50	550	mm	306
Horn C: ROC_C	550	650	mm	620
Horn C: Z Position	4000	19000	mm	17836
Target Length	0.5	2.0	m	1.98
Beam spot size	1.6	2.5	mm	2.1
Target Radius	9	15	mm	7.8
Proton Energy	60	120	GeV	108
Horn Current	150	300	kA	270



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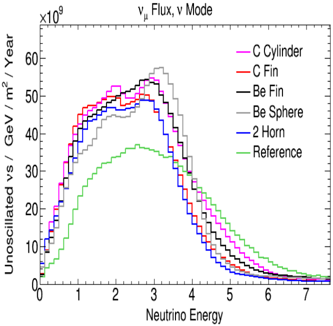
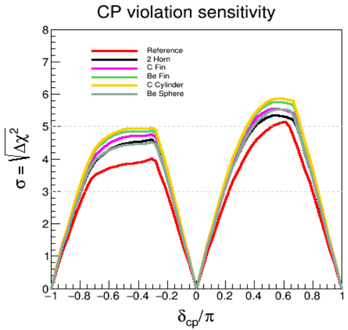




BOTF result: Significant gain in flux $<$ 3 GeV $=$ CPV gain

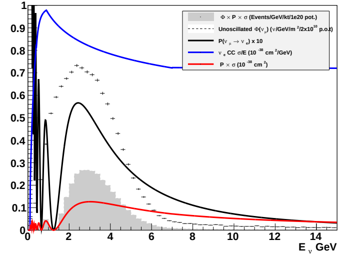
Optimization of Focusing System Geometry for CPV

The optimized horn design for CPV is not tunable ! BUT the target chase, horn carrier systems, strip lines ...etc could be designed to allow for flexibility in deploying either a tunable focusing system (like NuMI) or the CPV optimized focusing system. DUNE has to be explicit about requesting this from the LBNF design team. Tunable focusing is a requirement!.

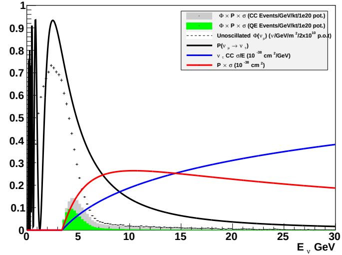
$\nu_\mu \rightarrow \nu_\tau$ Appearance Fundamentals

LBNF reference design (NuMI focusing) low energy tune

$\nu_\mu \rightarrow \nu_e$ Appearance at 1300 km



$\nu_\mu \rightarrow \nu_\tau$ Appearance at 1300 km

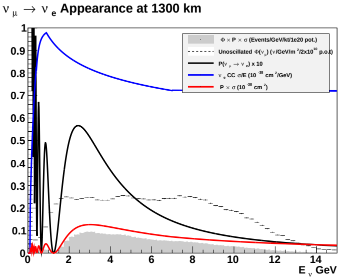


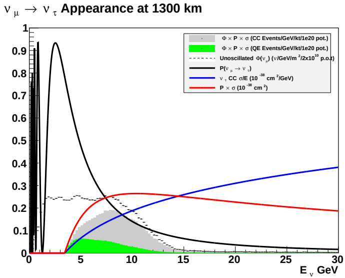
$\nu_\mu \rightarrow \nu_e$ 310 events **$\nu_\mu \rightarrow \nu_\tau$ 190 events**

in 40 ktons, 1 year at 1.2 MW

$\nu_\mu \rightarrow \nu_\tau$ Appearance Fundamentals

LBNF reference design (NuMI focusing) higher energy tune

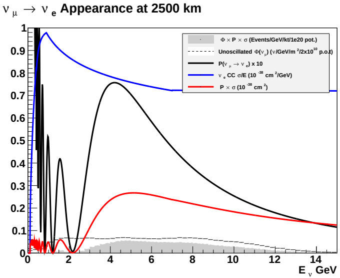


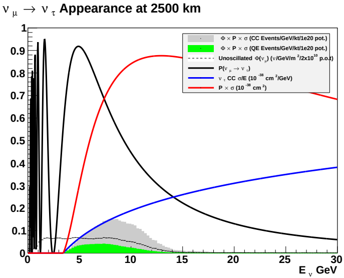


$\nu_\mu \rightarrow \nu_e$ 230 events **$\nu_\mu \rightarrow \nu_\tau$ 530 events**
in 40 ktons, 1 year at 1.2 MW at 1300km

$\nu_\mu \rightarrow \nu_\tau$ Appearance Fundamentals

LBNF reference design (NuMI focusing) higher energy tune

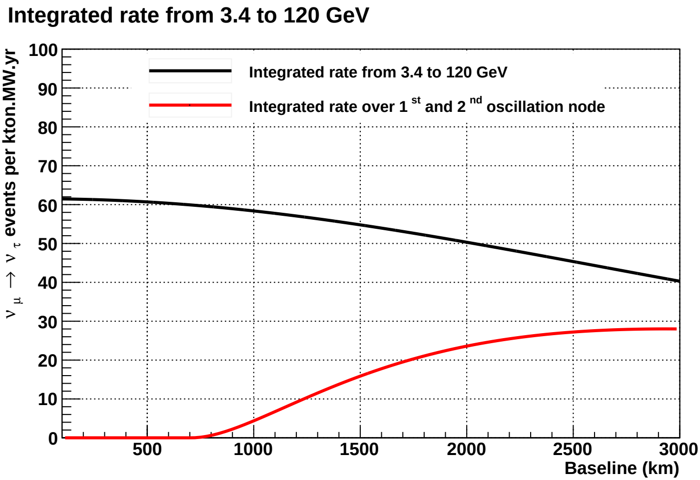




$\nu_\mu \rightarrow \nu_e$ 150 events **$\nu_\mu \rightarrow \nu_\tau$ 410 events**
in 40 ktons, 1 year at 1.2 MW at 2500km

Are we at the right baseline?

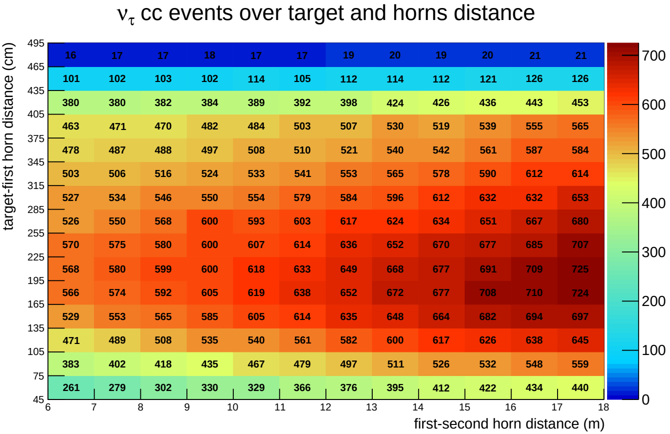
Rates with a 120 GeV perfect focused beam and a 400m decay channel:



Depends on how you focus !!. Baseline is not a fundamental limitation.

Optimize LBNF Reference Design for ν_τ

From Letizia Parato (G4LBNF, detailed geometry, GENIE cross-sections):



Need to push the horns as further away as possible

Optimize LBNF Reference Design for ν_τ

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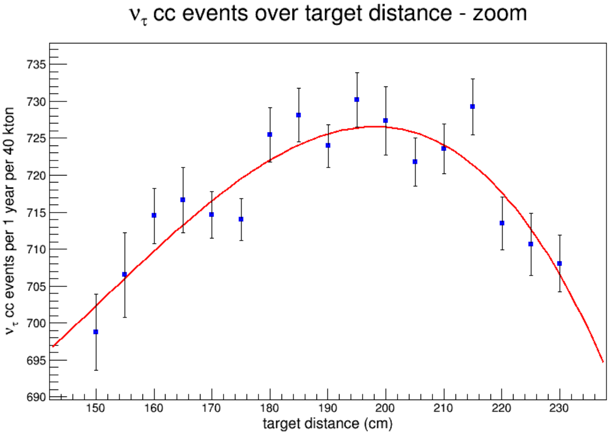

A target ∼ 2 m away from NuMI Horn 1 is optimal

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Optimize LBNF Reference Design for ν_τ

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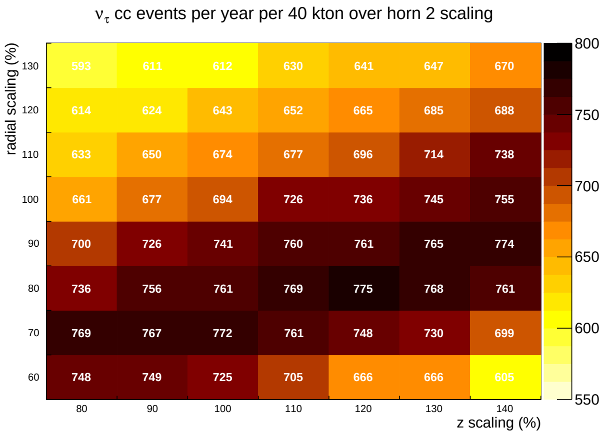
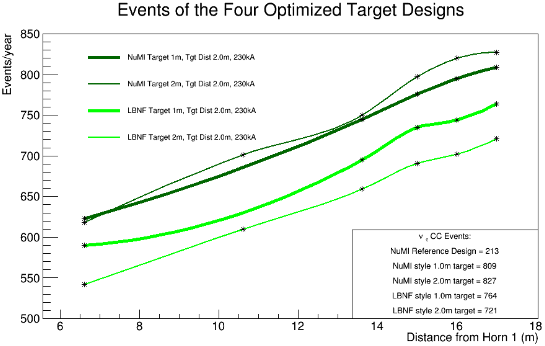


Further optimization of horns increases yield.

From Michael Dolce (G4LBNE v2, simplified geometry, GLoBeS cross-sections):

NuMI target: 120 GeV σ_p = 1.5mm; graphite box 1.754 g/cm^3; 6.4mm W x 20mm H x 0.9538m or 2.3719m L

LBNF target: 120 GeV σ_p = 1.7mm; graphite box 1.754 g/cm^3; 10mm W x 20.73mm H x 0.9538m or 2.3719m L



Need a target that produces more pions from primary p^+ interactions.

Optimize LBNF Reference Design for ν_τ

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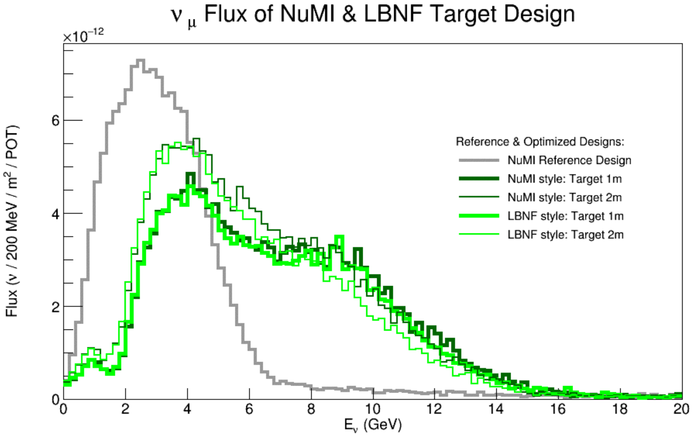

Optimize LBNF Reference Design for ν_τ

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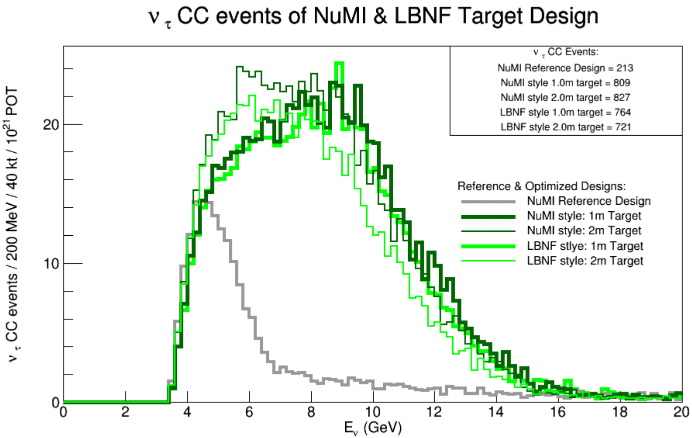

Summary and Conclusions

- **A TUNABLE beam with a high energy tune is a requirement that is met with the reference NuMI-like LBNF design but not with the 3-horn optimized design for CPV.**
- **By varying the tune of the reference LBNF 2-horn design (NuMI-like), we can increase the number of ν_τ appearance events from 130 CC events with the optimized 3-horn design ($\sim$ 200 with the reference LBNF design) to $\sim$ 720 CC events per 40 kton-year !**
- **2 completely independent studies by Letizia Parato and Michael Dolce indicate that for the reference LBNF NuMI-like focusing system, the optimal tune for ν_τ apperance is with the horns the maximum distance apart allowed by the expanded chase $\sim$ 17m, 230kA and a target 2m from Horn 1.**
- **Preliminary studies indicate target optimization is needed to increase the number of pions from primary proton interactions. Challenge at 1.2MW or higher.**

Further Studies

- **Explore whether a combination of NuMI-style horns and the horns from the LBNF optimized design can also be used - for e.g. use optimized Horn C instead of NuMI Horn 2, This would reduce the number of horn designs needed.**
- **Apply machine learning techniques to the double parabolic horn designs to optimize for ν_τ appearance. This requires development of a metric that takes into account smearing and backgrounds to ν_τ appearance not just number of events.**
- **Co-ordinate with the BSM and Long-Baseline PWG on the final design high energy focusing system that expands the physics reach beyond ν_τ appearance as well.**