Neutrino Flux Measurement In the DUNE Near Detector

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For the DUNE Collaboration

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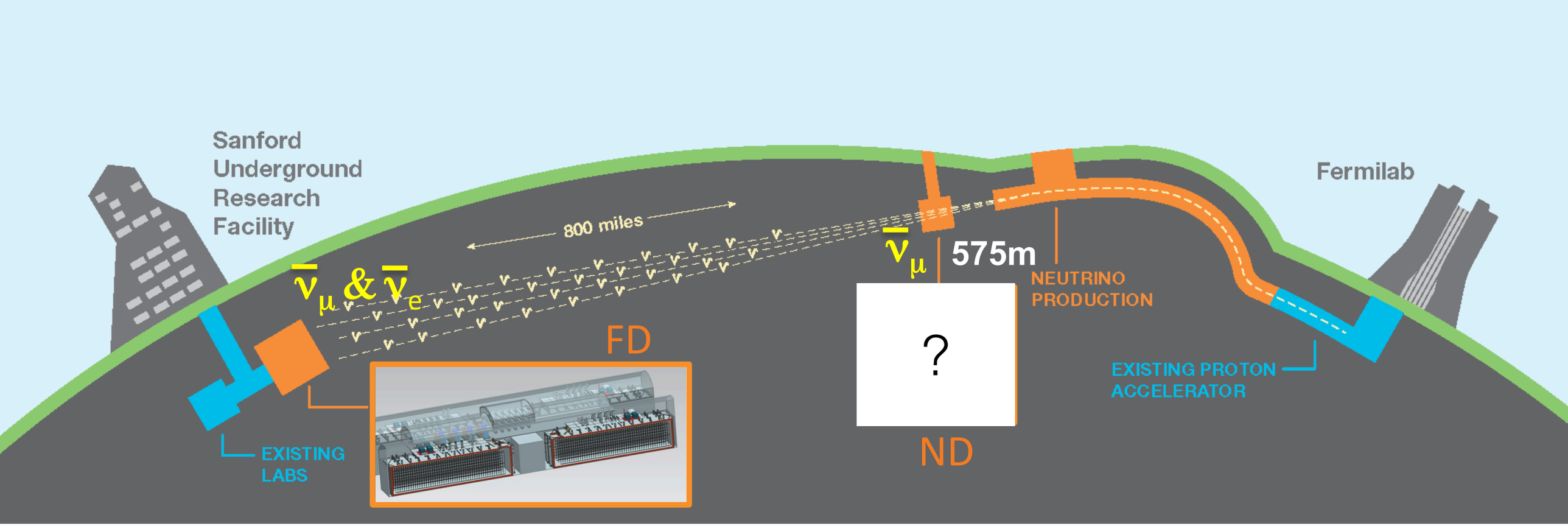
Fermilab

Introduction to DUNE

- DUNE is a long-baseline neutrino experiment aiming to solve mass hierarchy and CP-violation by measuring ν_μ to ν_e/$\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation in one single experiment.
- 40 kton LAr TPC as the far detector in Lead, SD.
- A capable near detector is crucial for DUNE to constrain systematic uncertainties, including flux uncertainty.



Near Detector Options

- Currently we have several ND options under study:
  - LAr TPC
  - Fine-Grained Tracker (FGT, CDR reference design)
  - High-Pressure Ar Gas TPC
  - Scintillating plastic tracker

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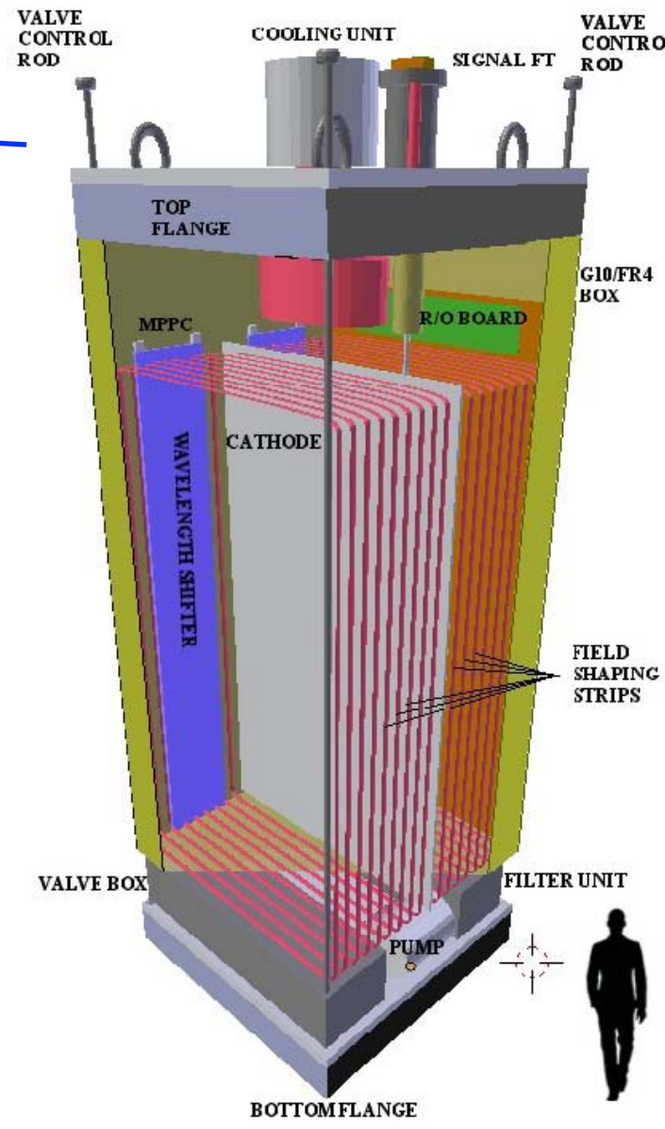

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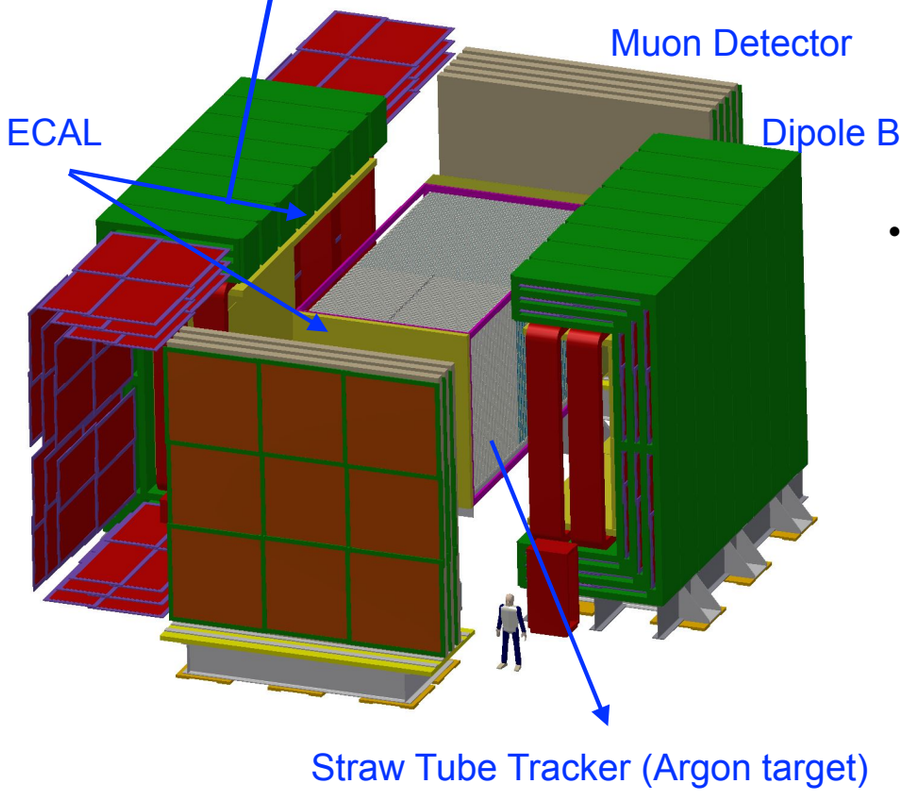

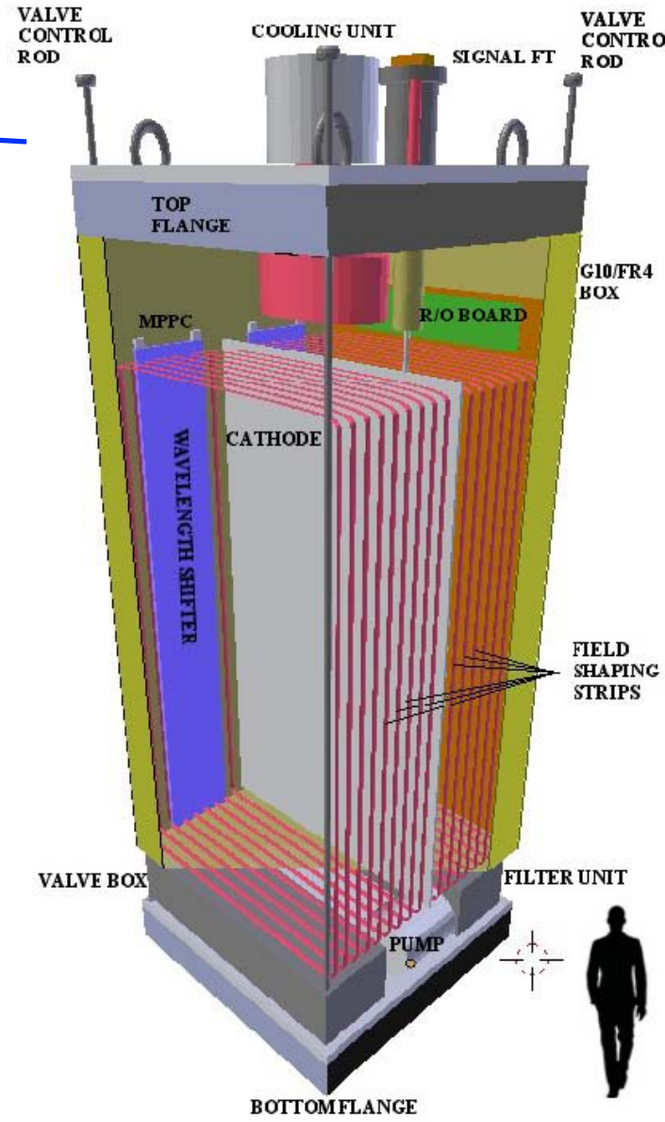

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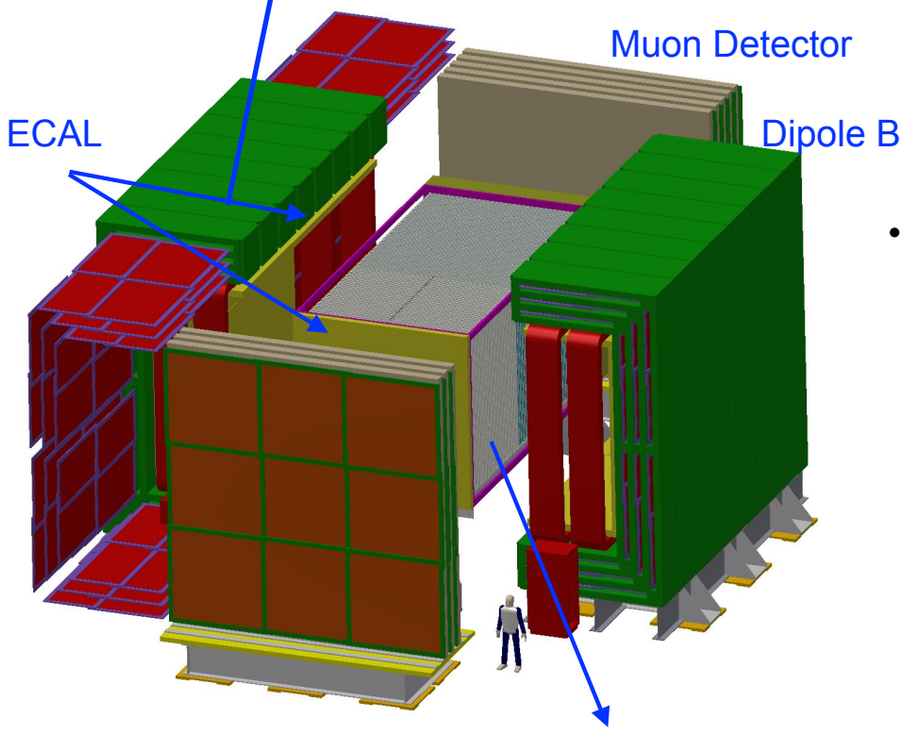

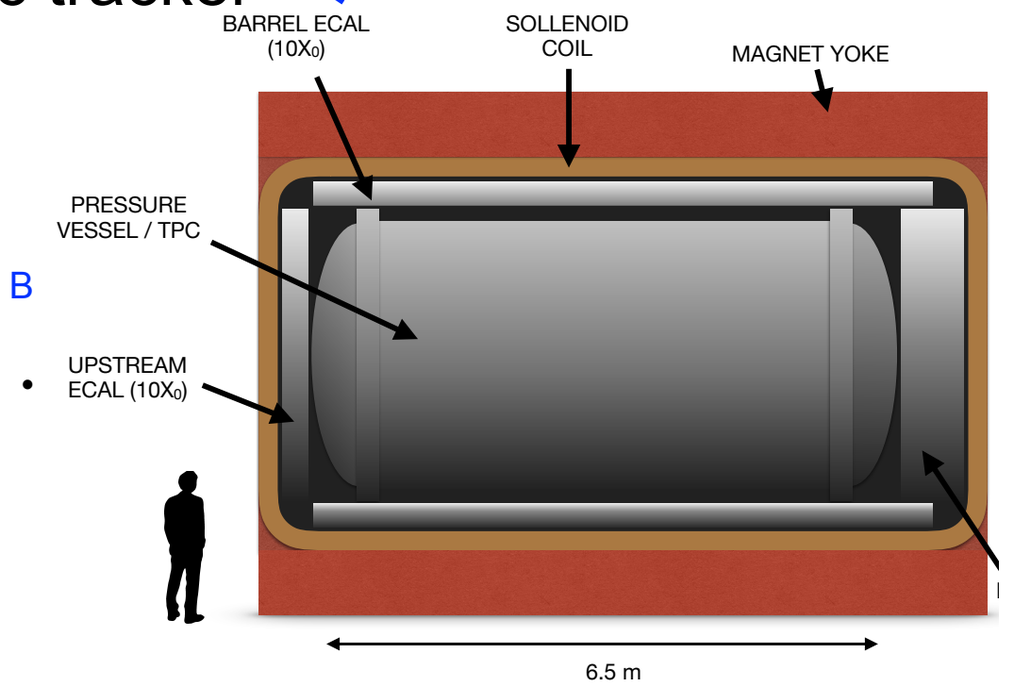

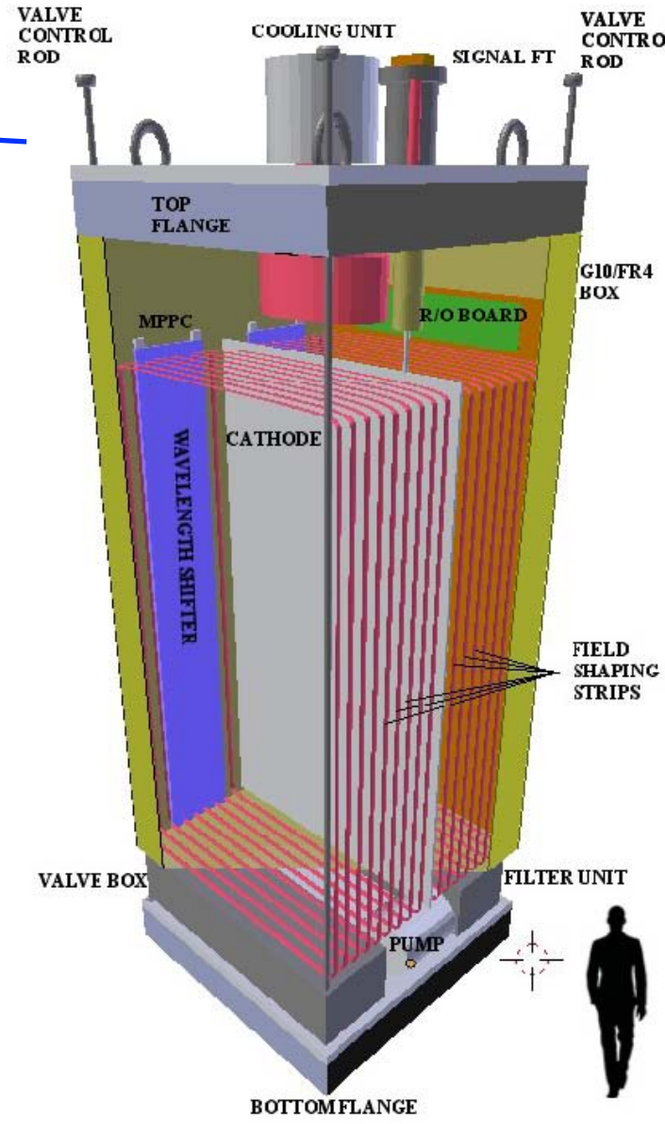

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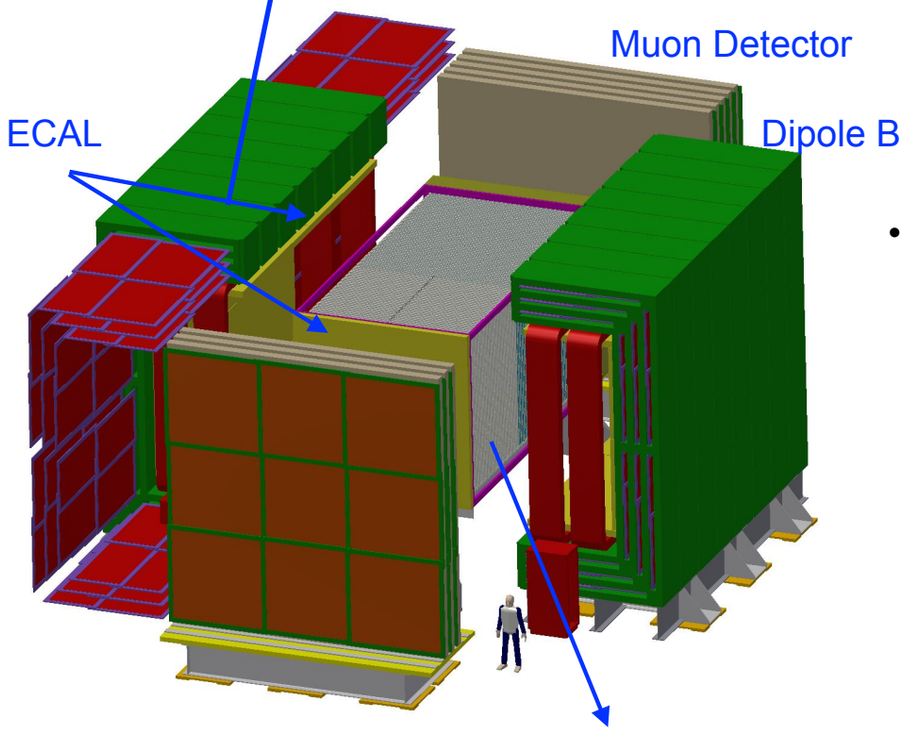
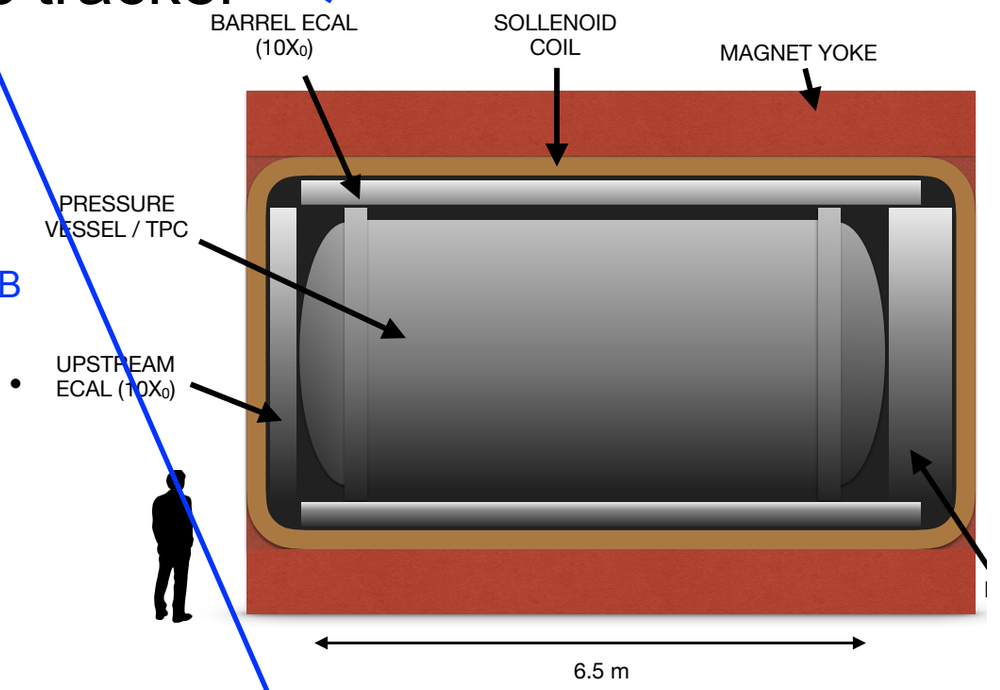
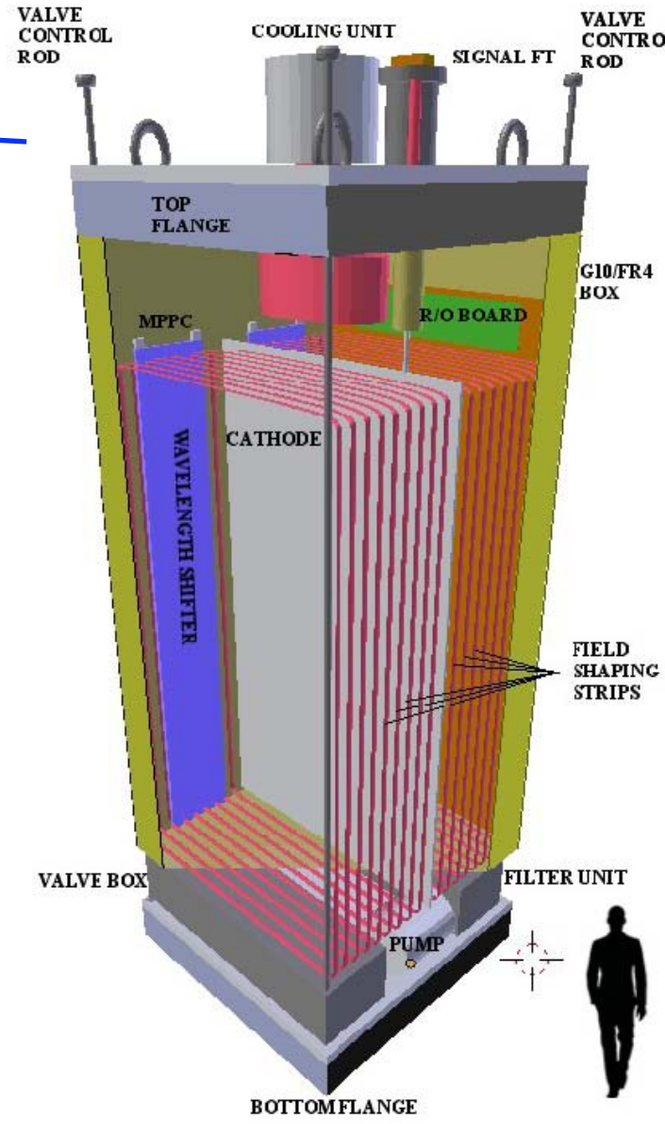
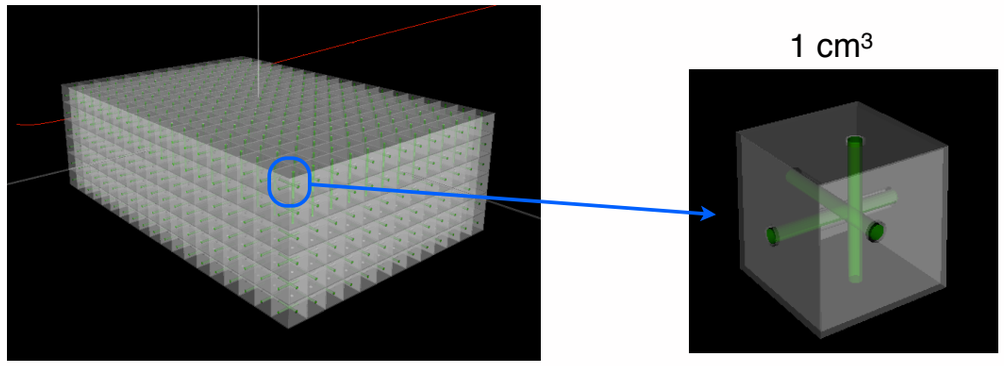
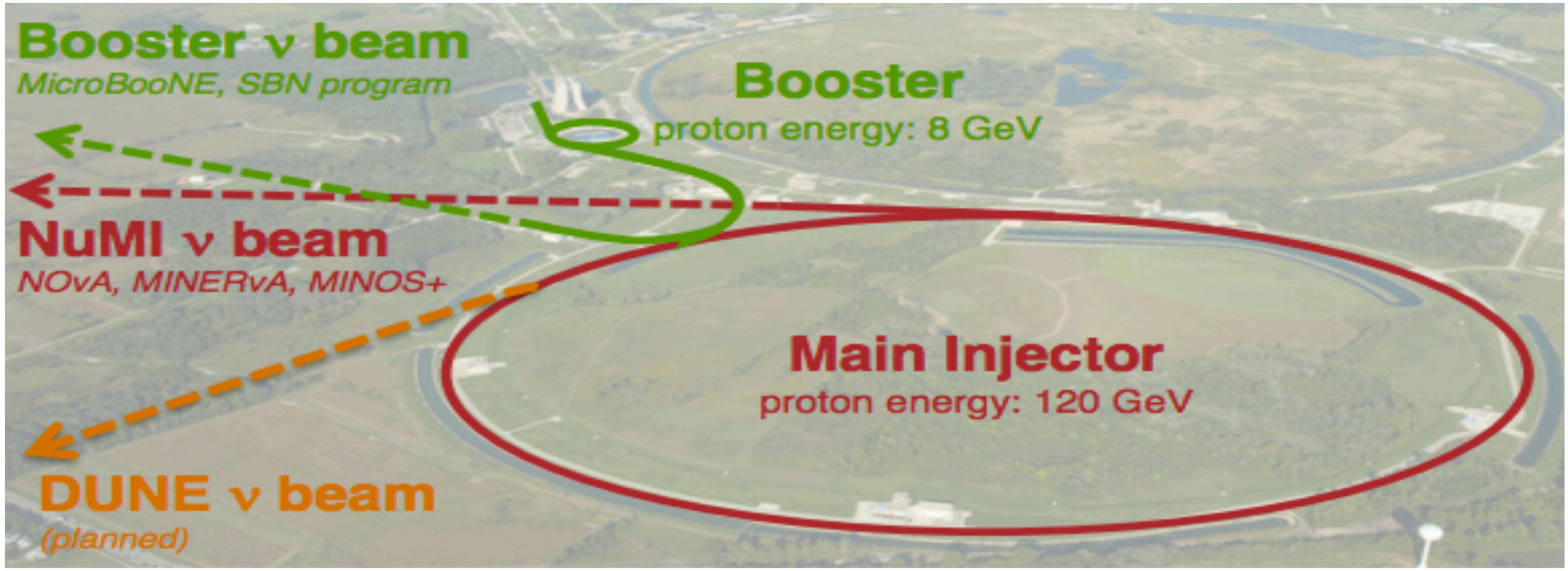


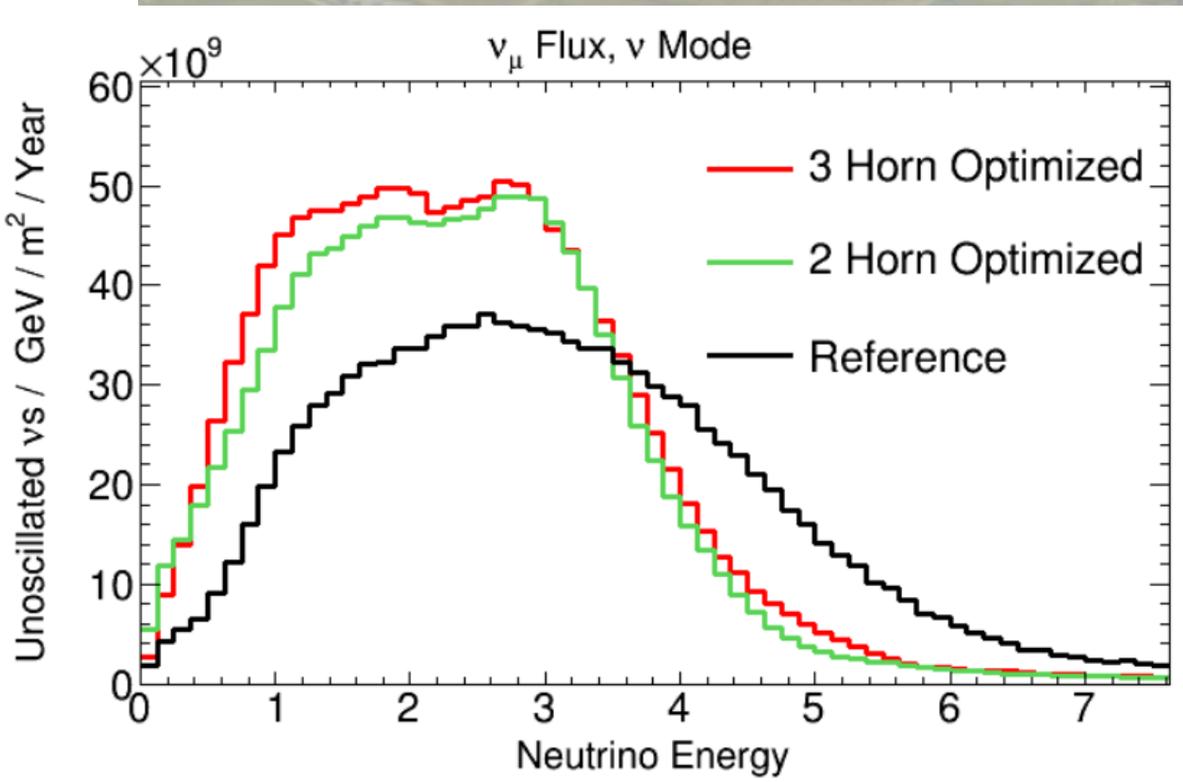






Neutrino Flux at DUNE





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- Flux uncertainty comes from hadron production and beam focusing.

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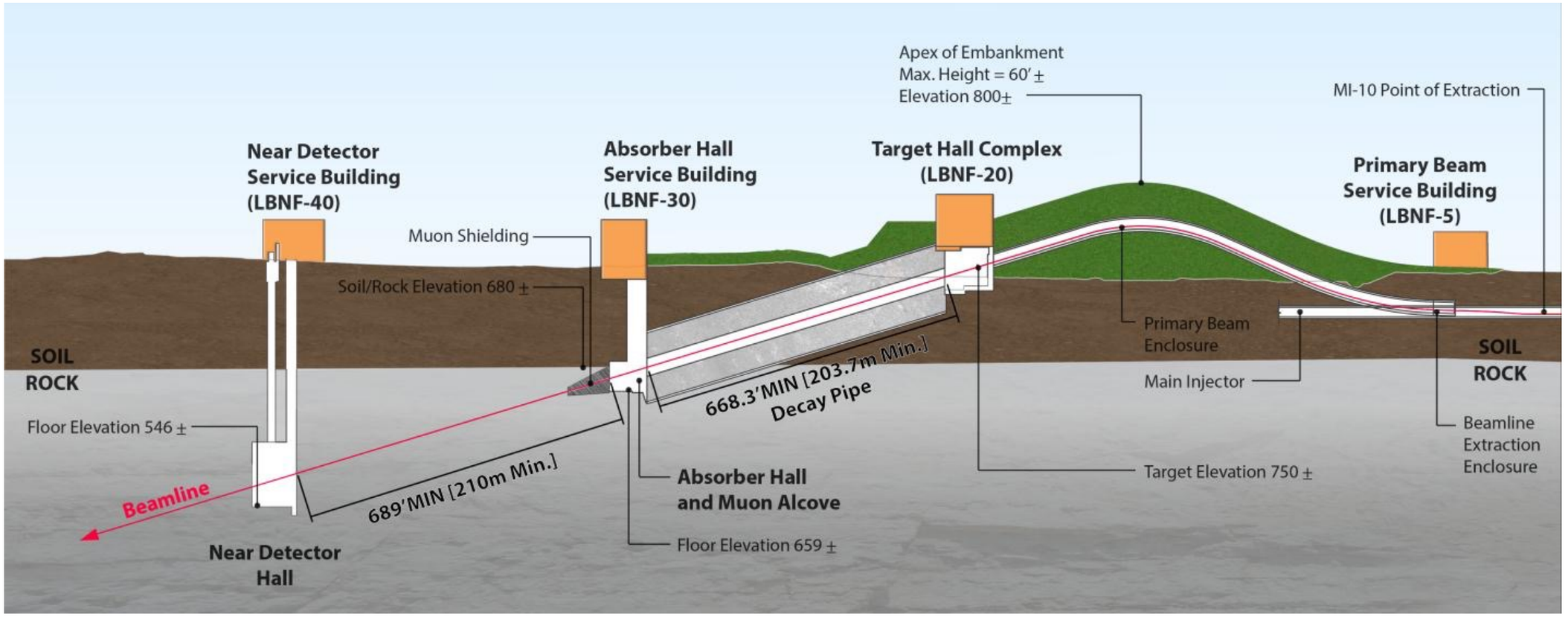

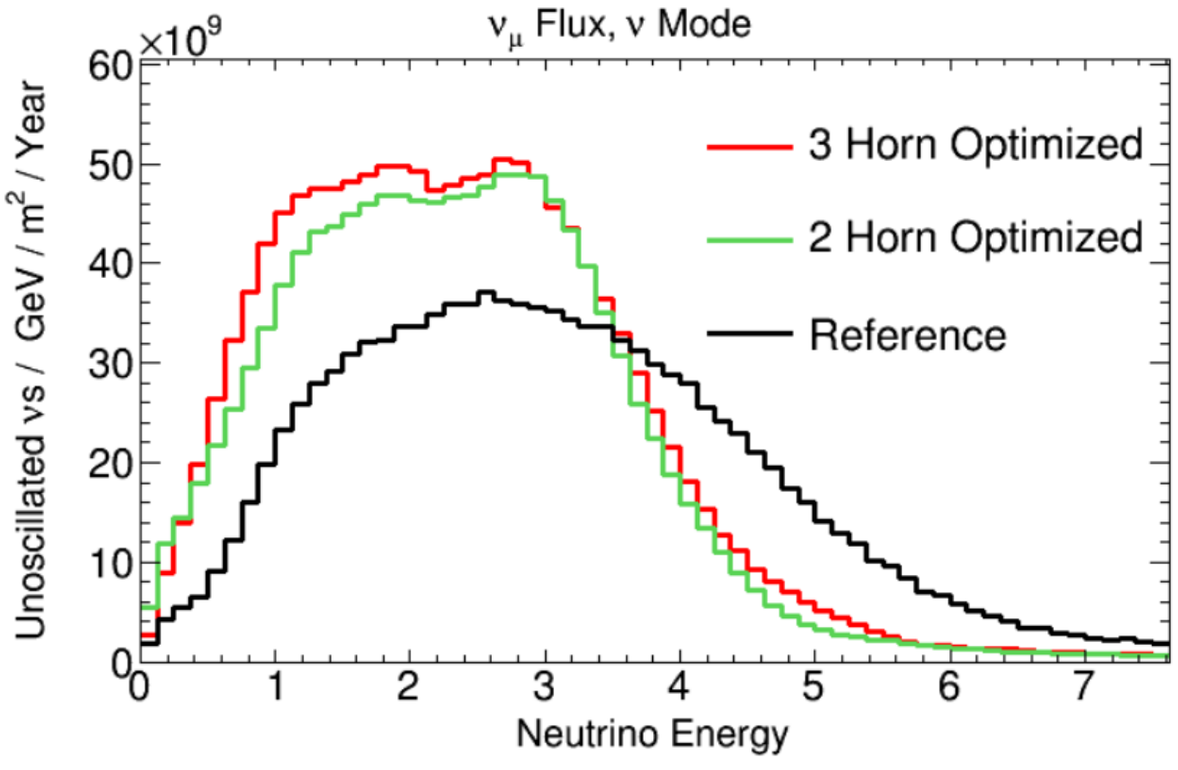

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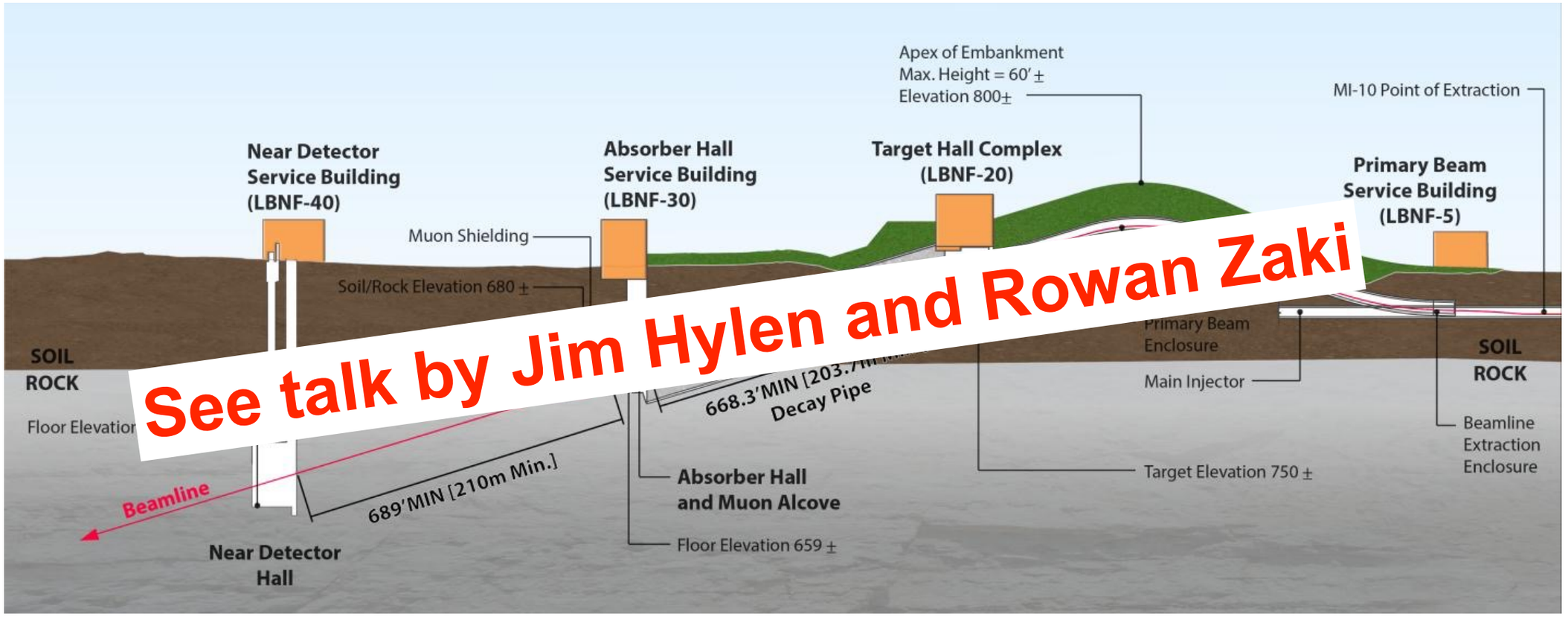
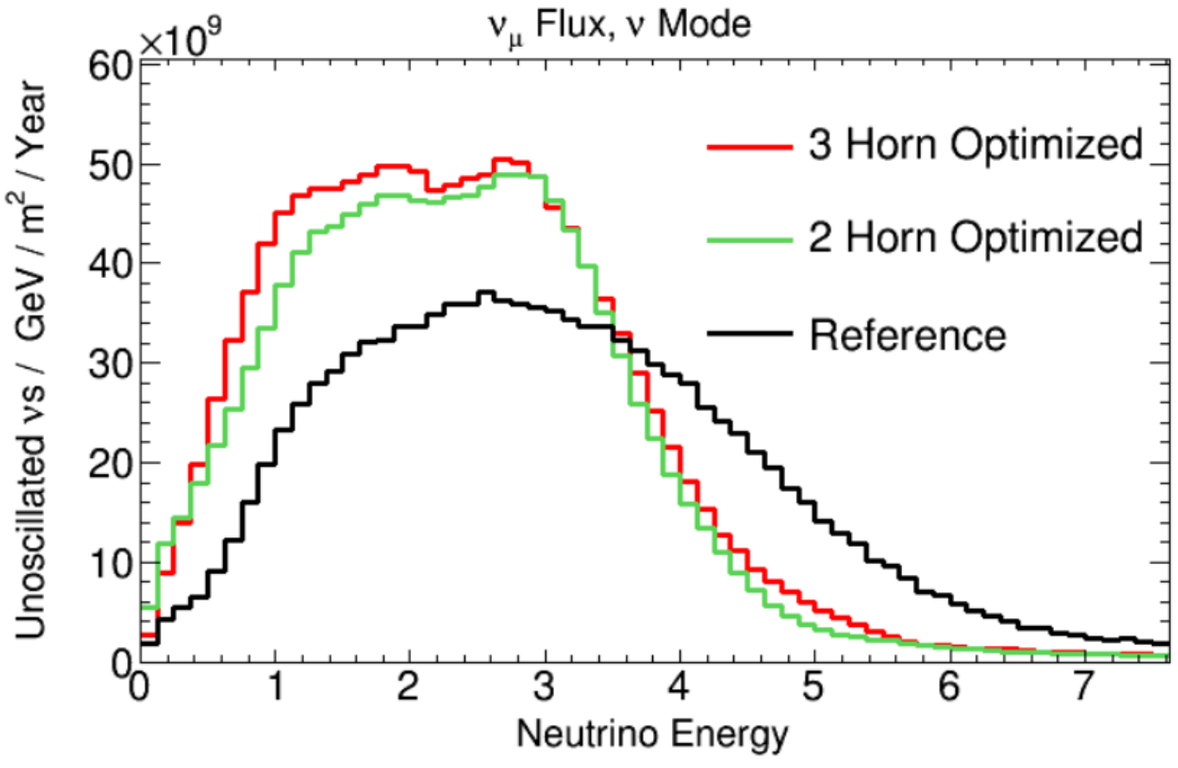


See talk by Jim Hylen and Rowan Zaki



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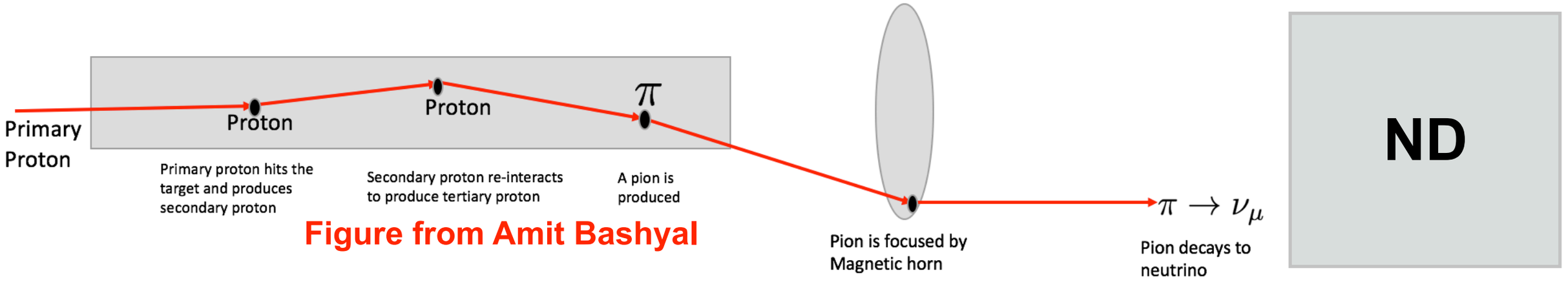

Figure from Amit Bashyal

- Flux uncertainty comes from hadron production and beam focusing.

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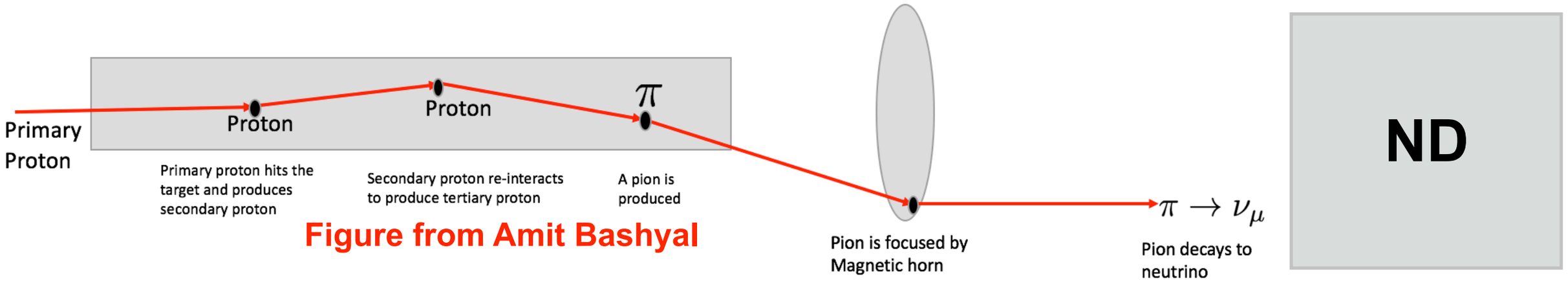


Figure from Amit Bashyal

- Flux uncertainty comes from hadron production and beam focusing.
- External hadron production data constraint.
- Talk on Monday by Amit Bashyal: PPFX for DUNE.

Flux Measurement for DUNE

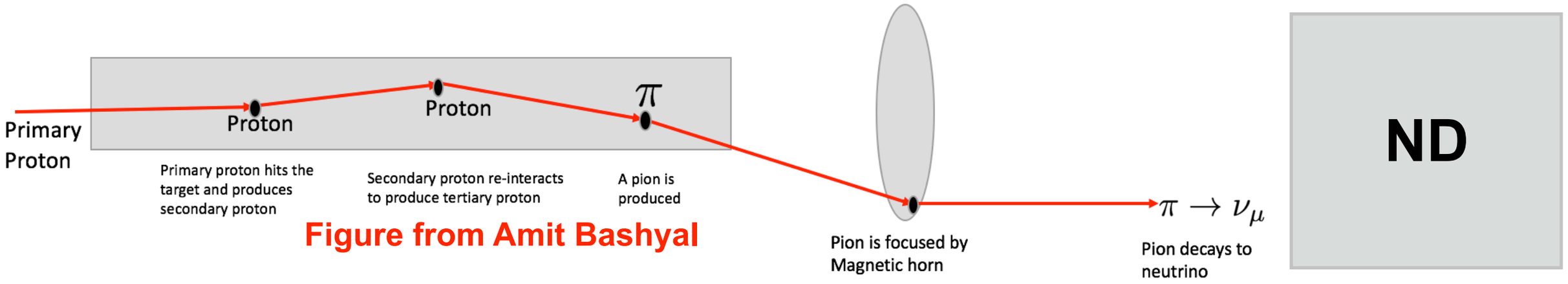
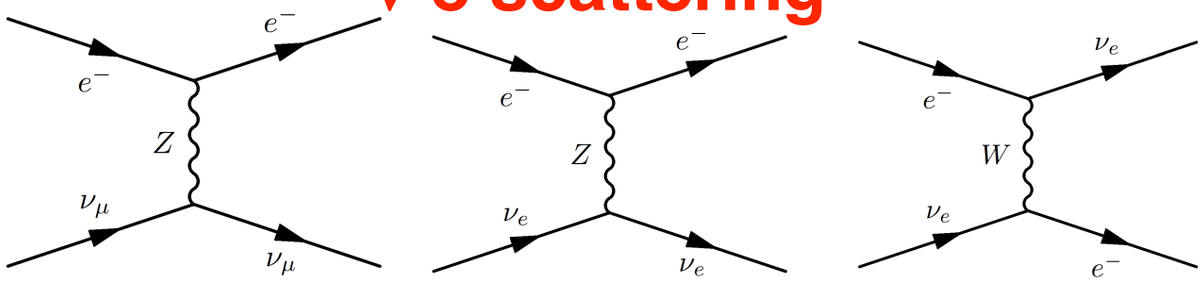


Figure from Amit Bashyal

- Flux uncertainty comes from hadron production and beam focusing.
- External hadron production data constraint.
  - Talk on Monday by Amit Bashyal: PPFX for DUNE.
- In situ measurement at ND: the focus of this talk.
  - Generally speaking neutrino interaction cross-sections have large uncertainty
  - We need some neutrino interaction channels known well enough in some aspect to measure flux:
    - Neutrino-electron scattering for absolute flux.
    - Low-ν sample for flux shape.
    - Coherent pions for $\bar{\nu}/\nu$ ratio and beam divergence.

Neutrino-Electron Scattering

ν-e scattering



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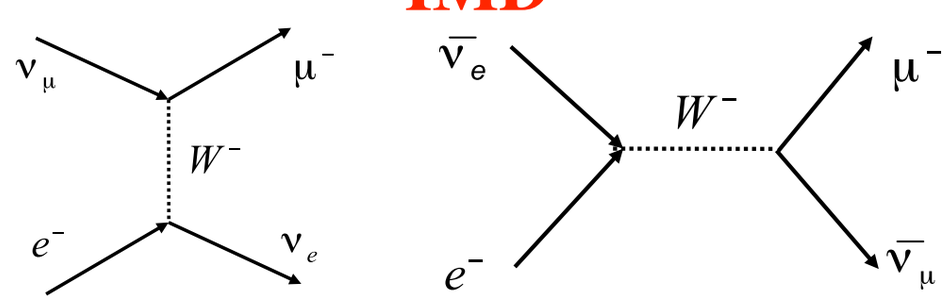
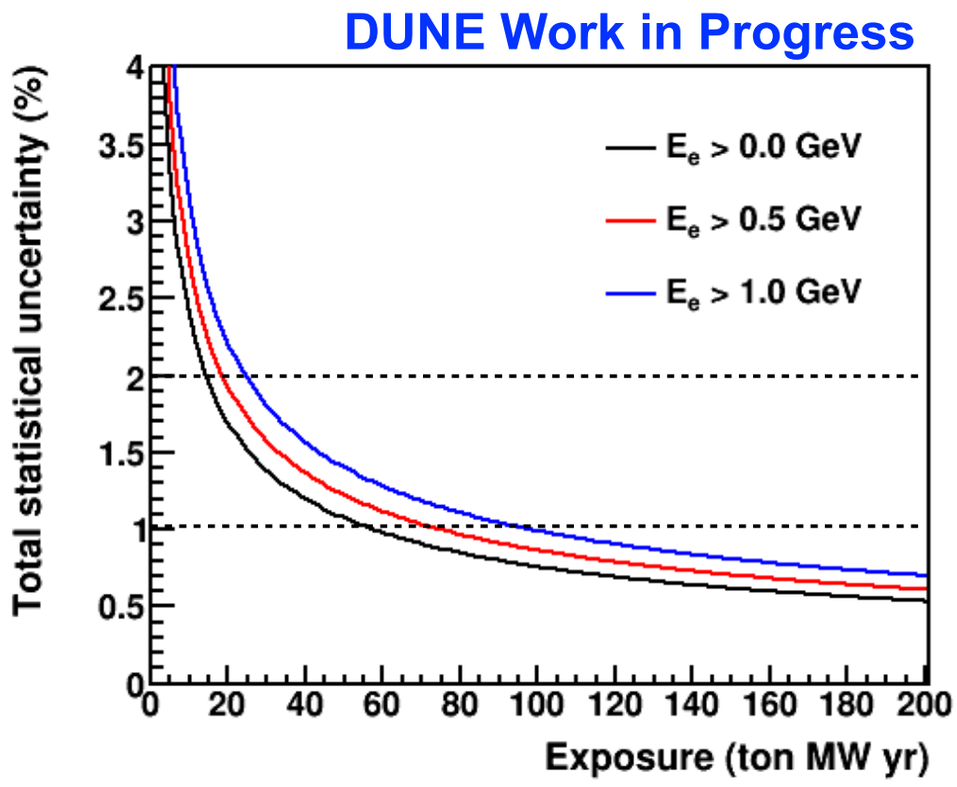


- Pure electroweak process with small, but very well known cross section: Good for measurement of absolute flux.
- Very forward-going electron/muon (small $E_e\theta^2$) in final state with no other particles.
- Uncertainty will be dominated by statistics: need enough detector mass.



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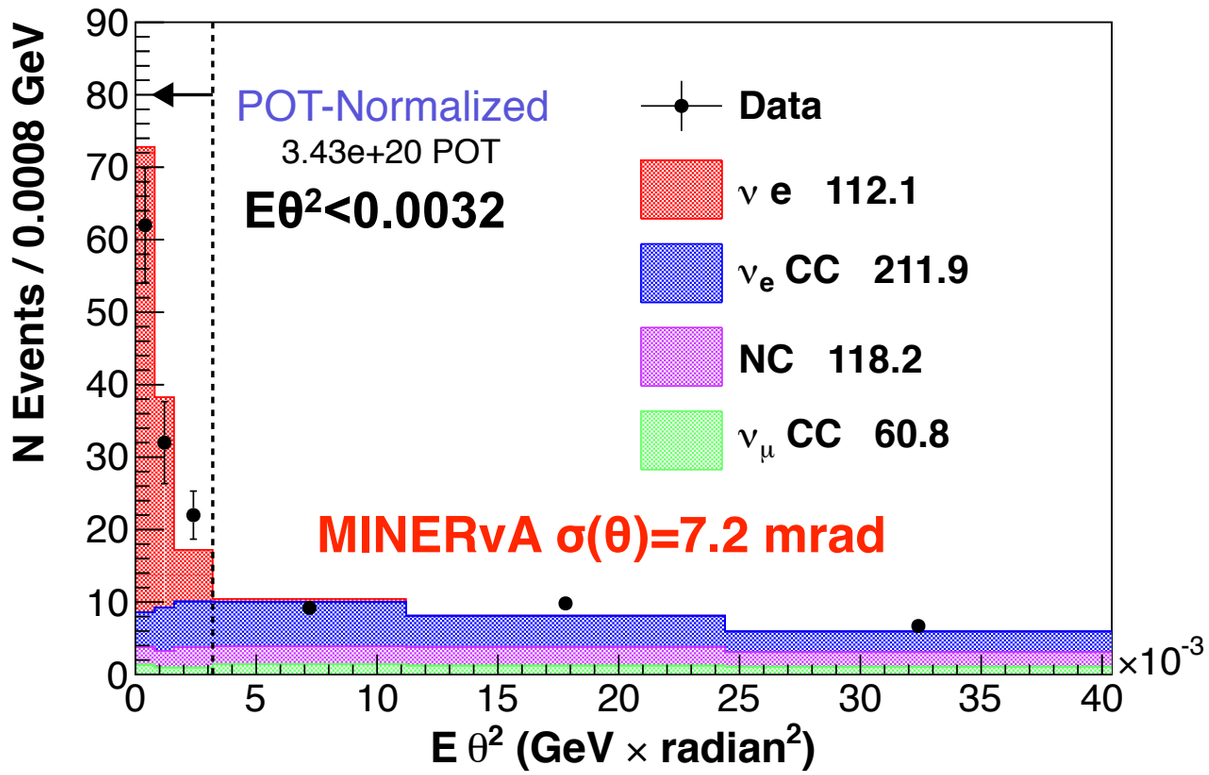

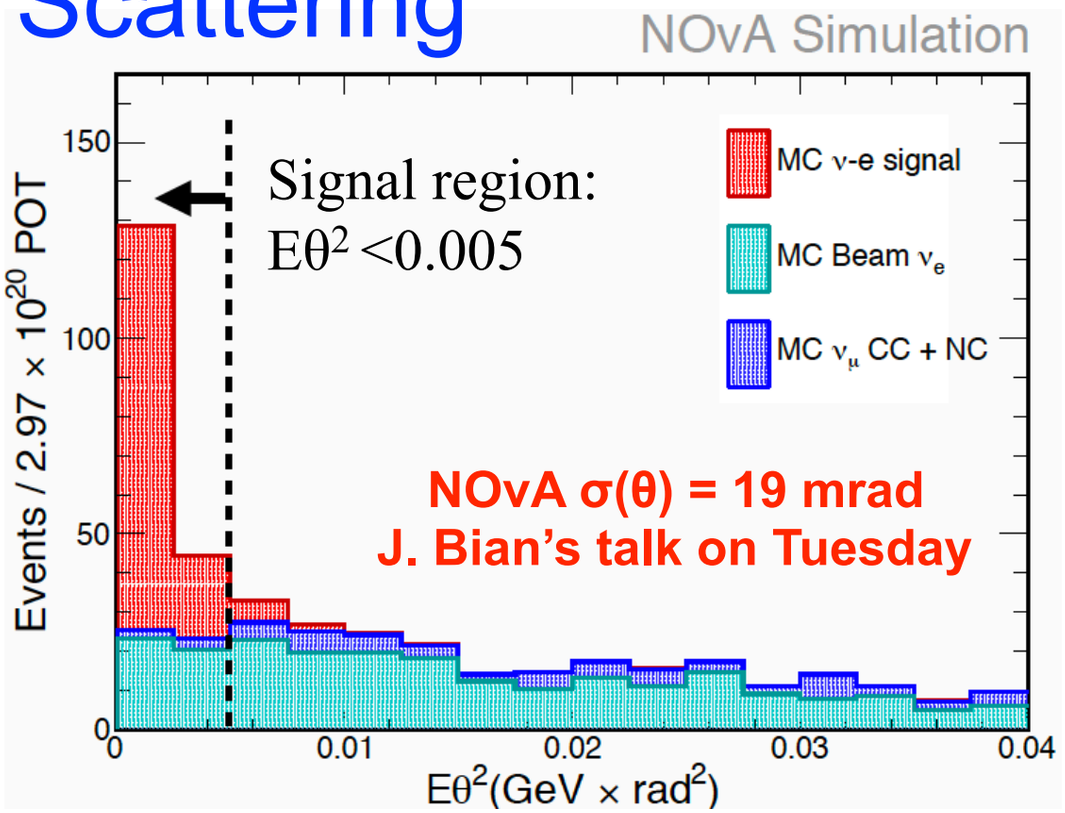

- $E_e\theta^2 = 2m_e(1-y) < 2m_e$.
- Good angular resolution is critical to reduce background.

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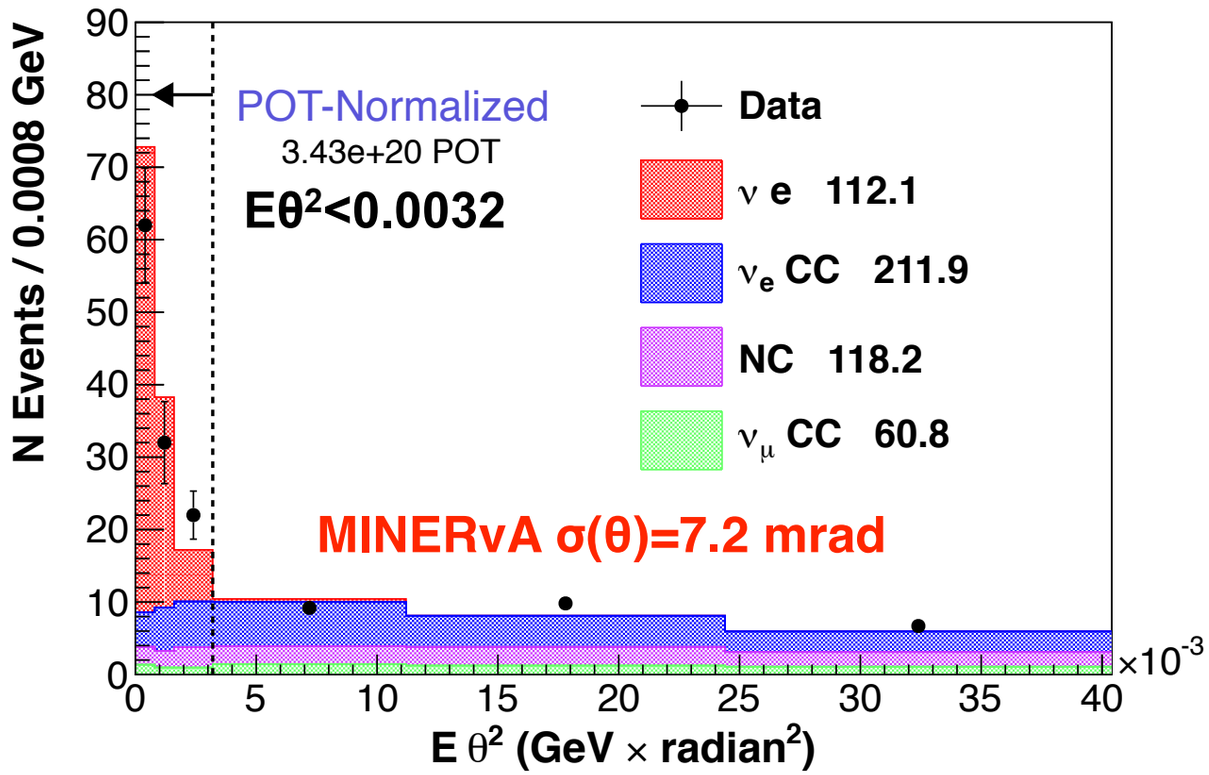

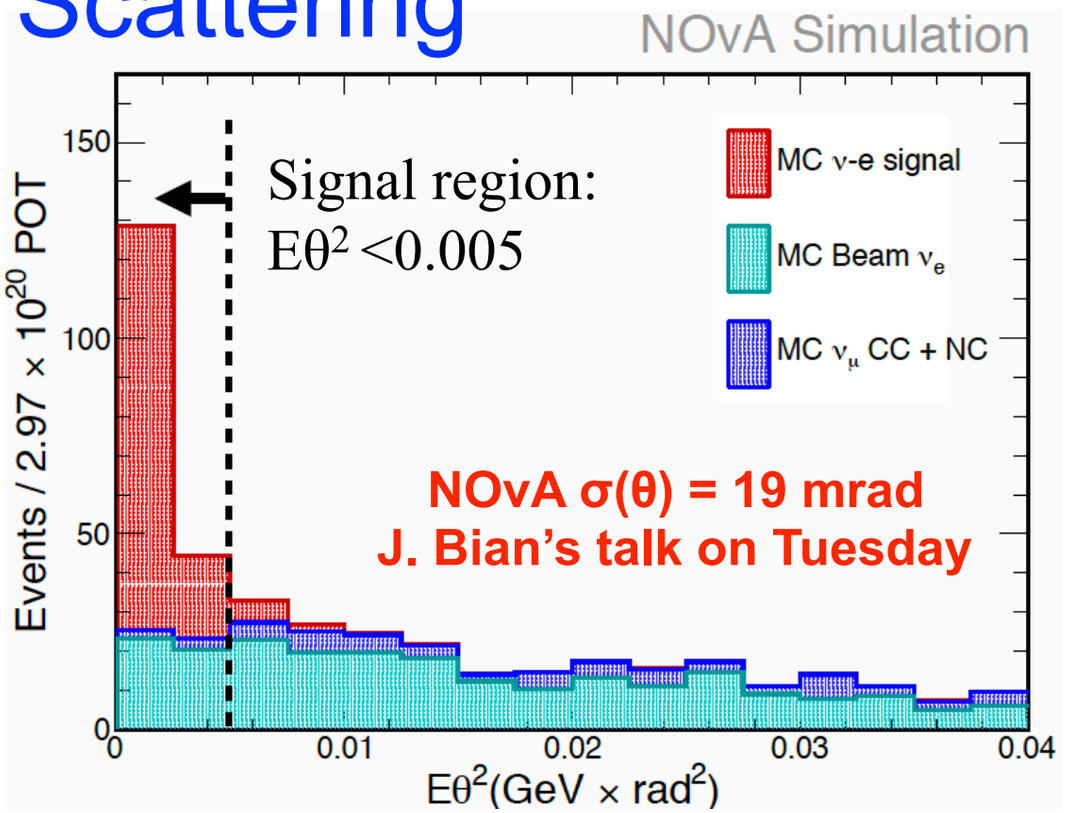

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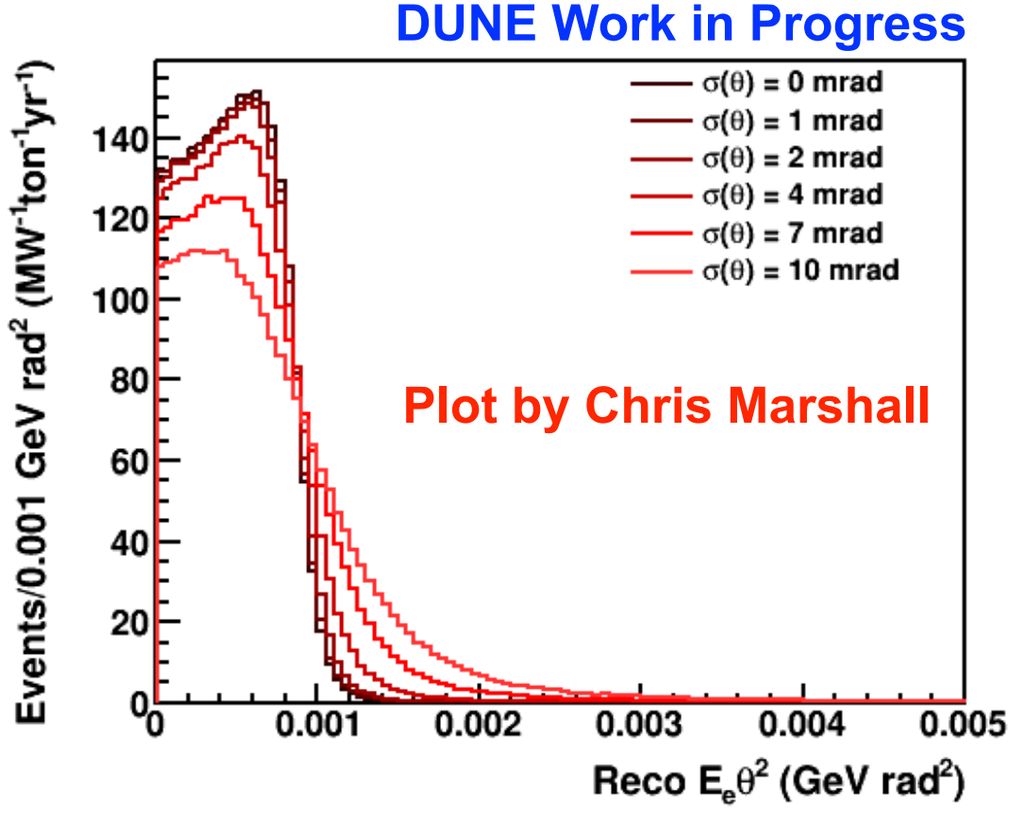
- Assuming 2 mrad angular resolution, 6% background is expected.



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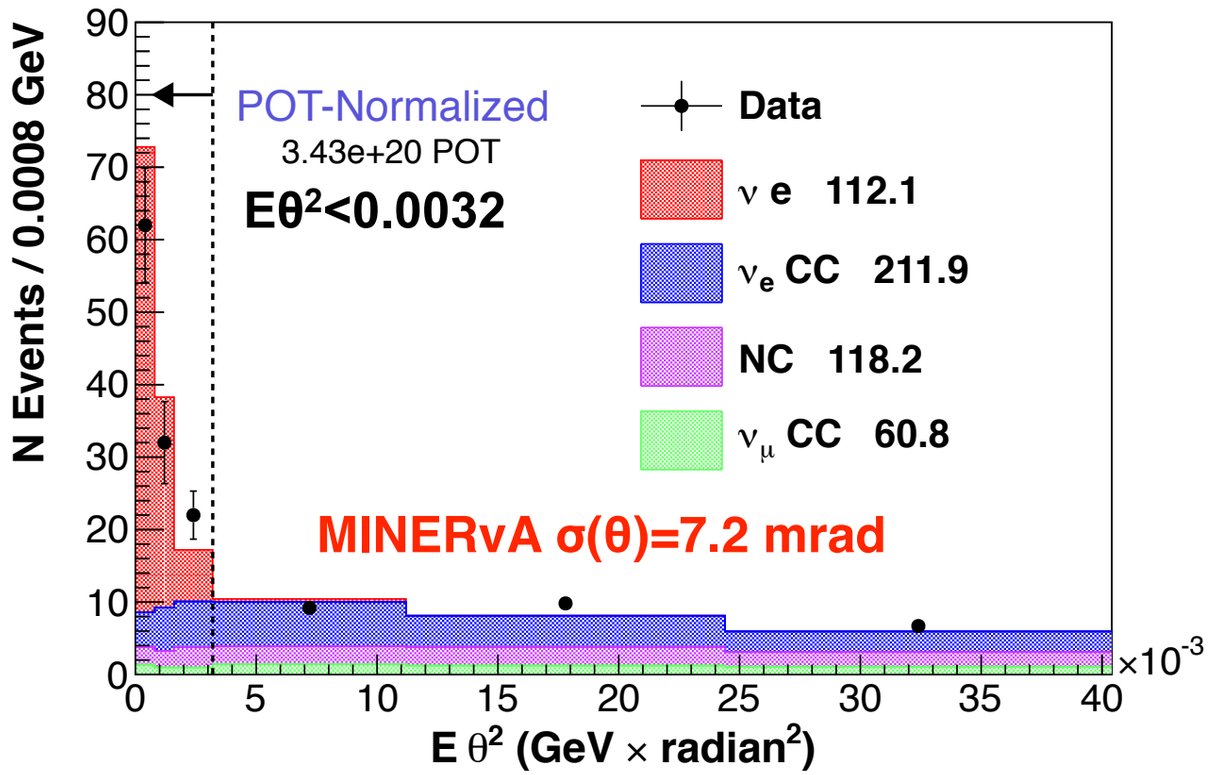

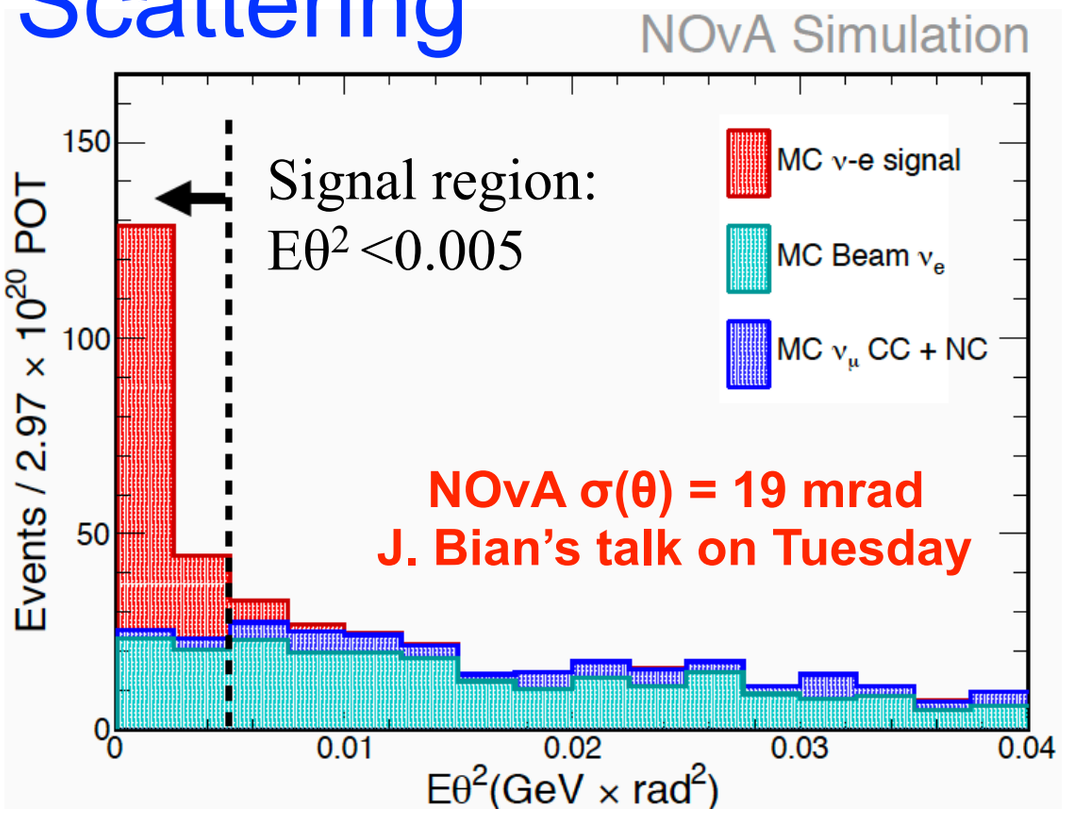

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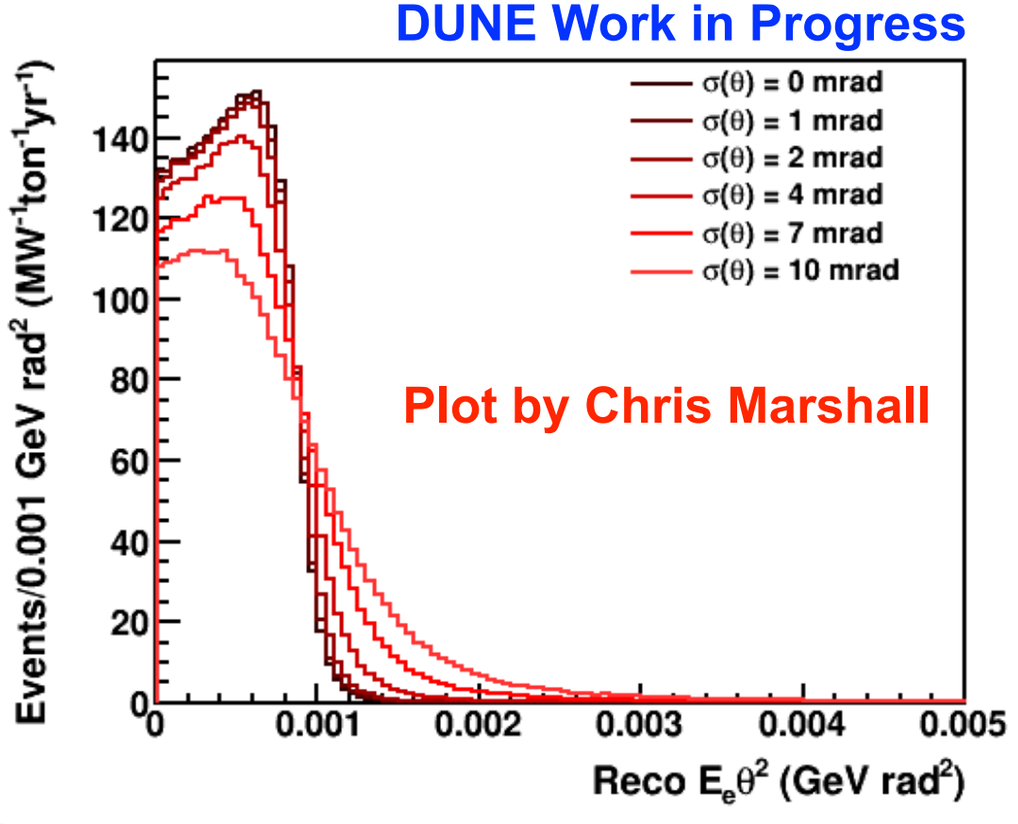
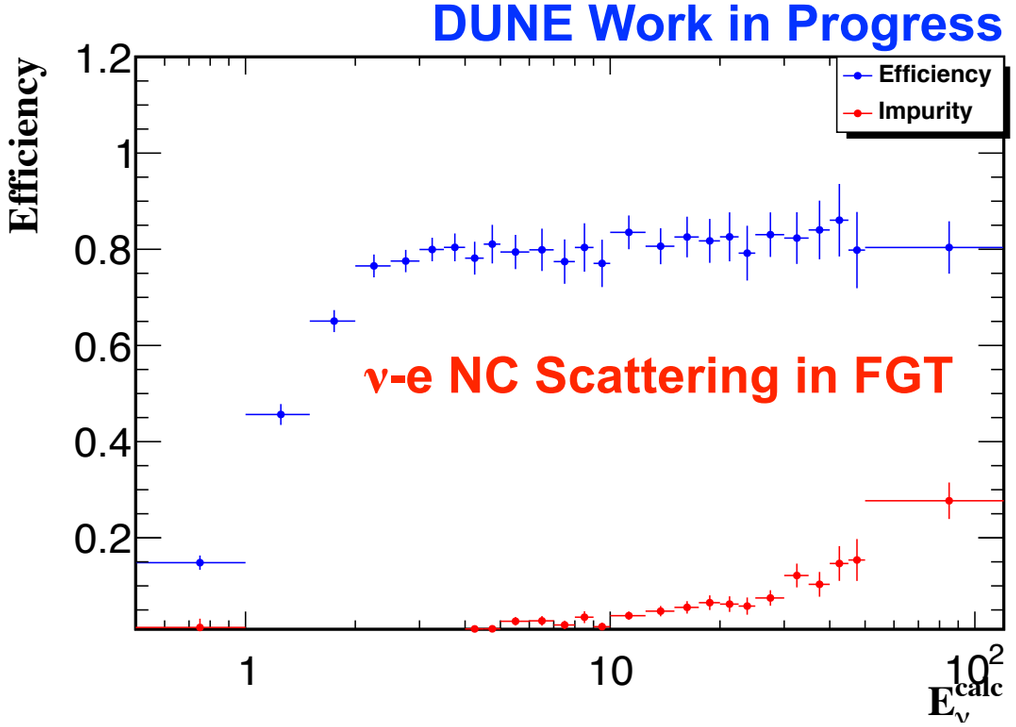
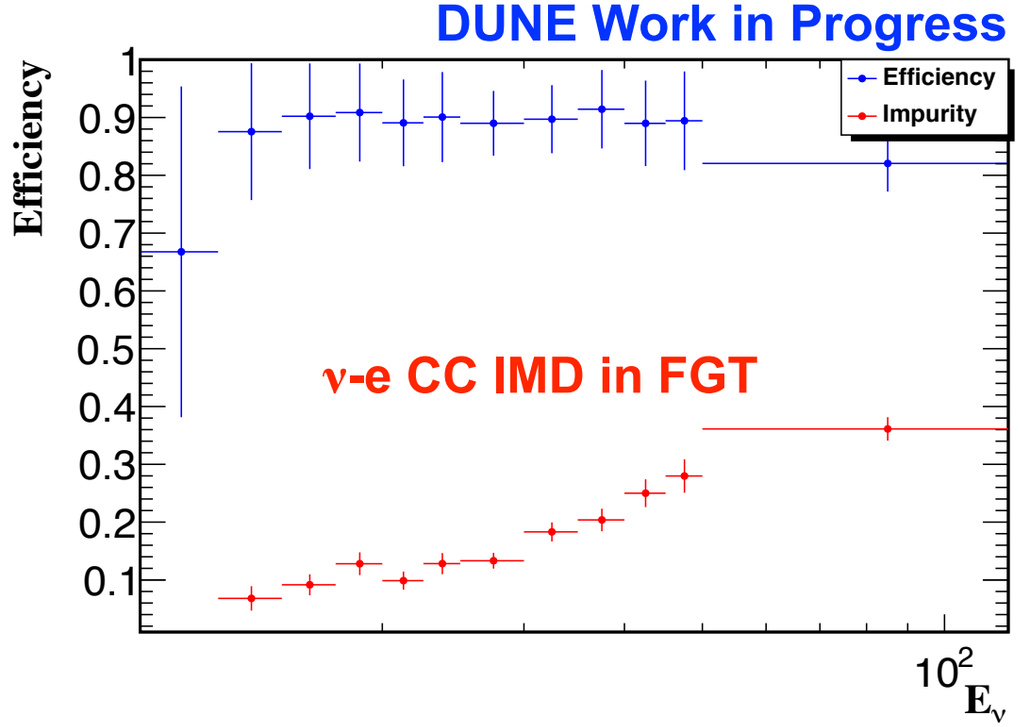
- Good angular resolution is critical to reduce background.
- Assuming 2 mrad angular resolution, 6% background is expected.
- Background comes from π^0 and ν_e-CC (QE) events:
  - e^+ sample to control π^0 bkg: need e^+/e^- ID.
  - 2-track ν_e-CC QE-like events to constrain ν_e-CC QE background (50% efficiency in FGT).



Neutrino-Electron Scattering

- Assuming 1.2 MW beam power, 5 tons ND fiducial mass, 3 years neutrino running we expect:
  - **~7.8k** $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$: **~2%** precision in 2.5~10 GeV.
  - **~4k** $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$: **~2.5%** precision in 11~50 GeV.
- Given known neutrino direction and good detector resolution it is also possible to measure flux shape (work in progress).





Low-ν method

- At very low $\nu = E_\nu - E_l$, the cross section is independent from E_ν:

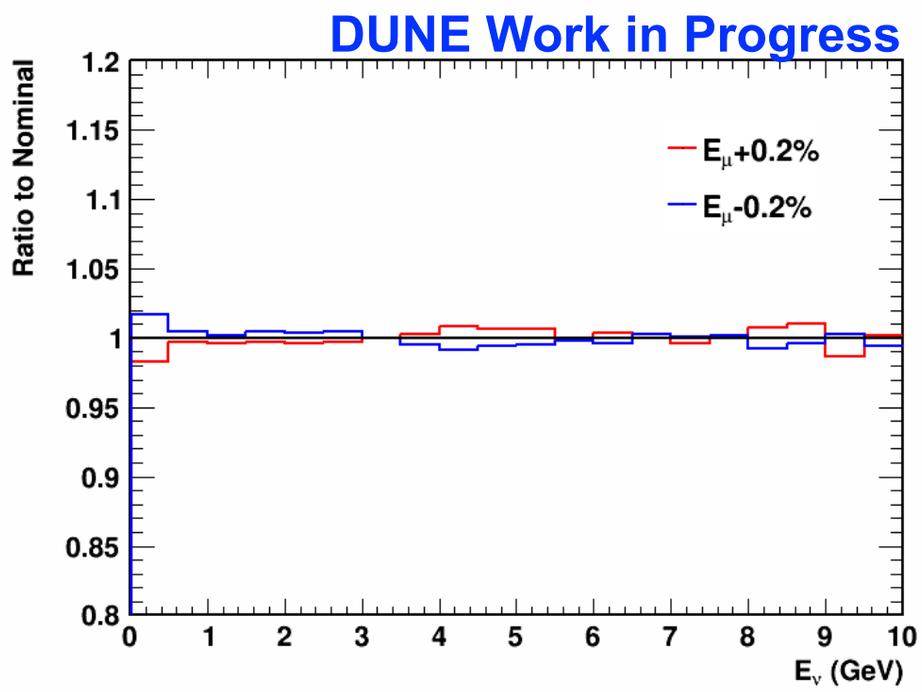
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

(A, B and C are parameters formed by nuclear structure functions.)

- the measurement of low ν spectrum is approximately a measurement of flux shape.
- The effect of non-zero ν cut is account for by a theoretical correction:

$$S(E) = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E)^{\nu\to 0}} = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E\to\infty)^{\nu<\nu_0}}$$

- Systematic uncertainty dominant:
  - Muon energy
  - Hadronic energy (ν)
  - Theoretical correction
- See Lu Ren's talk on Tuesday for MINERvA's Low-ν flux measurement

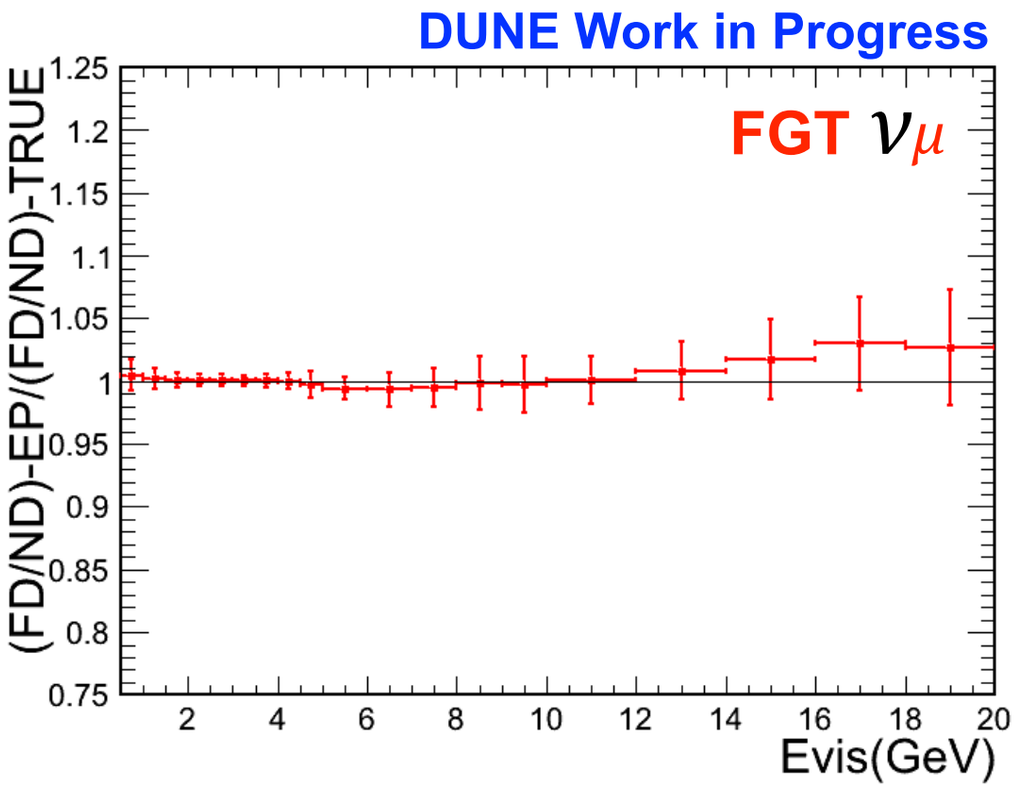


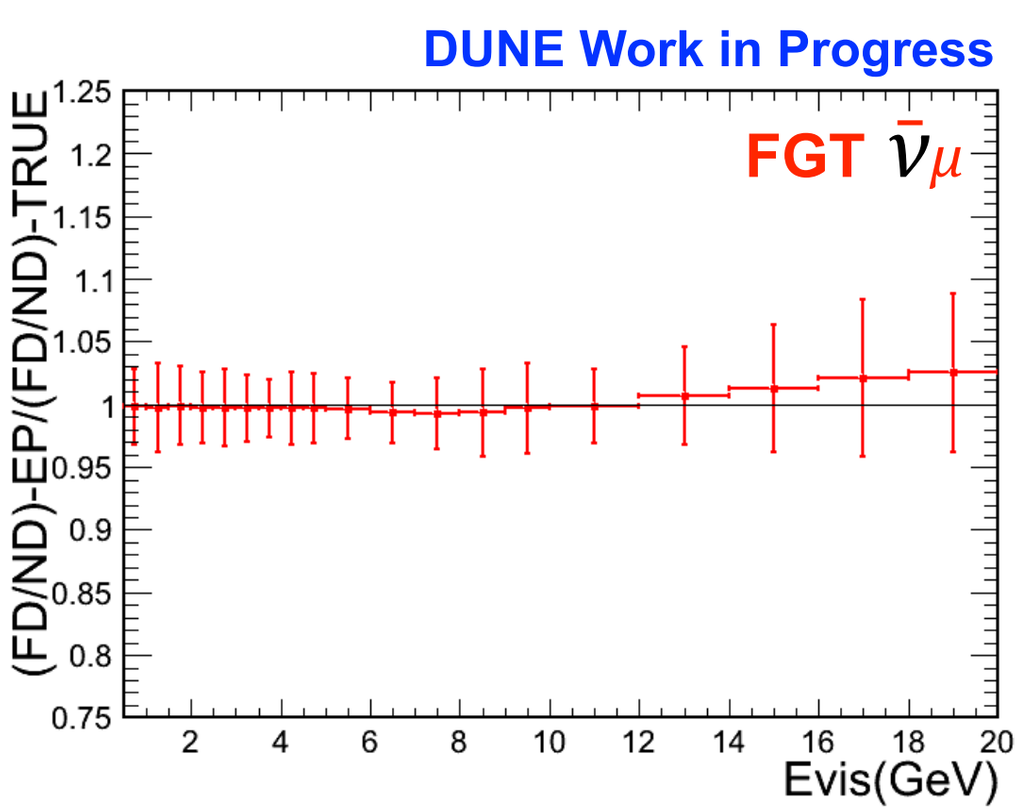
Low-ν method

- Beam hadron production can be parametrized using empirical functions:

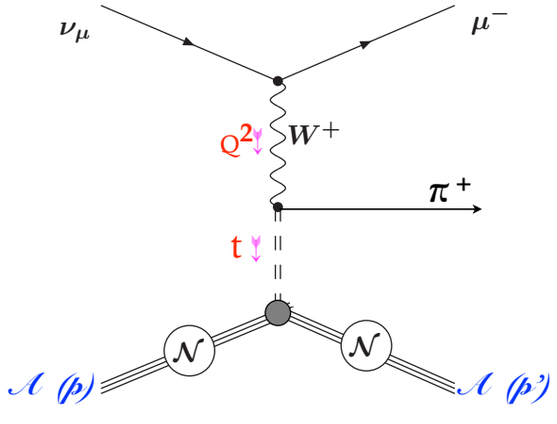
$$\left(E \times \frac{d^3\sigma}{dp^3}\right) = A\,(1-x_R)^{\alpha}\,(1+Bx_R)x_R^{-\beta} \times \left(1 + a'(x_R)p_T + b'(x_R)p_T^2\right) e^{-a'(x_R)p_T}$$

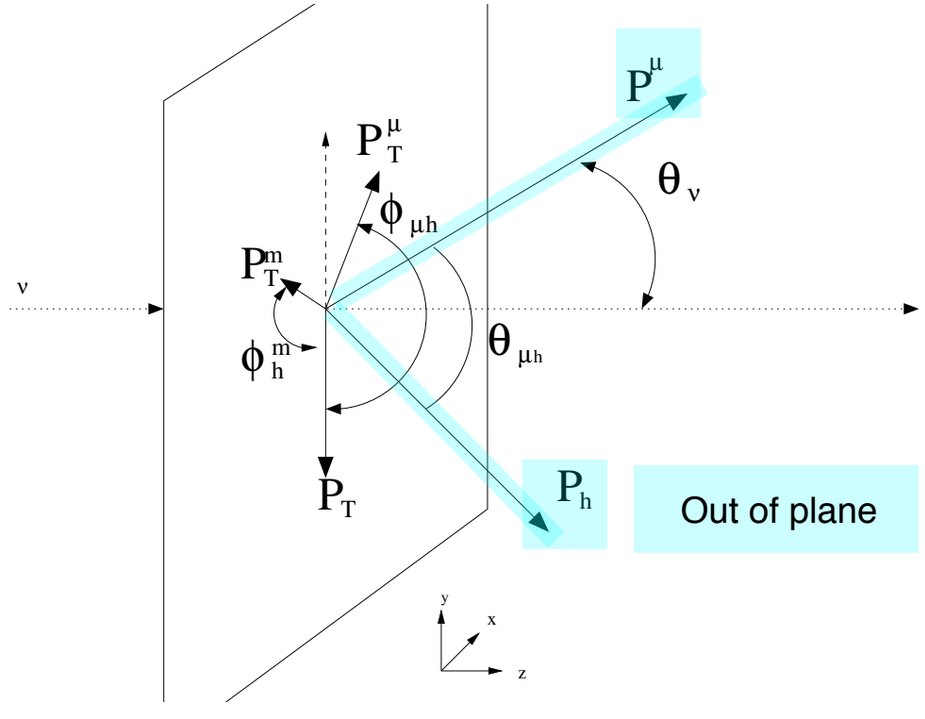
- Use ND low-ν neutrino and antineutrino data to constrain beam hadron productions.
- Given good muon/hadron energy resolution, expect an FD/ND ratio at **1~2%** precision in 0.5~50 GeV.

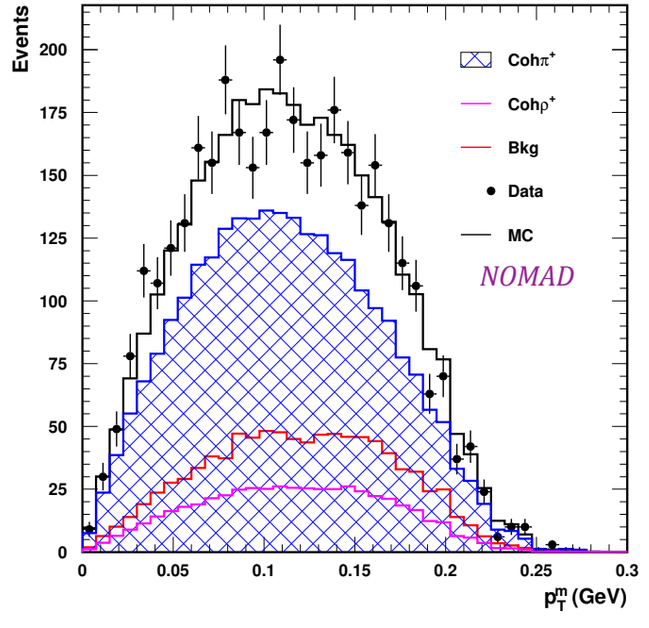




Coherent Pion







- Identical topology between neutrino and antineutrino to the first order: constraint on $\bar{\nu}/\nu$.
- Final state muon and pion collinear with incident neutrino with little nuclear effect: constraint on beam divergence
- Combined with neutrino-electron scattering study it might be possible to constrain flux shape $\phi(E)$.
- Requires good momentum resolution for muon and pion.
- Work in progress.

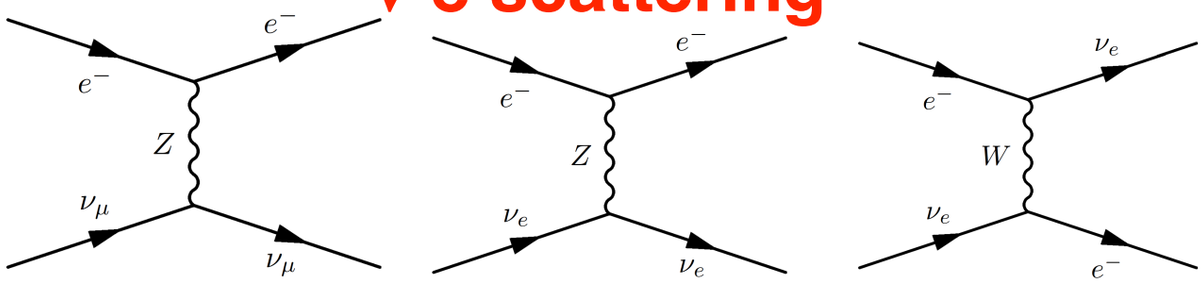
Summary

- A capable ND is important to constrain the systematic uncertainty for oscillation analysis, including neutrino flux uncertainty.
- A lot of work going on to develop flux measurement methods.
  - Neutrino-electron scattering for absolute flux.
  - Low-ν method for relative flux.
  - Coherent pions for $\bar{\nu}/\nu$ ratio and beam divergence.
- Combined with external data we aim at a precise flux prediction for DUNE.

Back up slides

Neutrino-Electron Scattering

ν-e scattering



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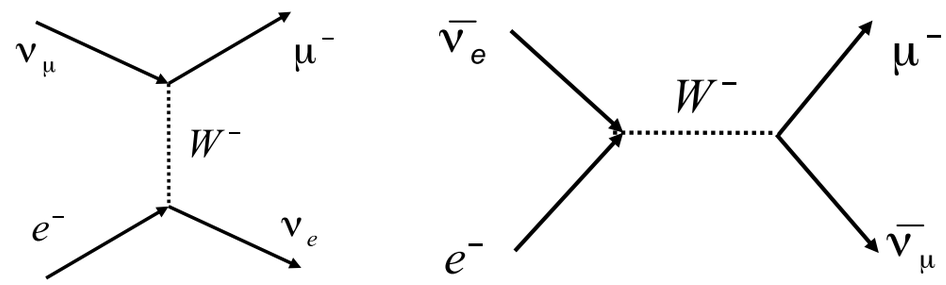

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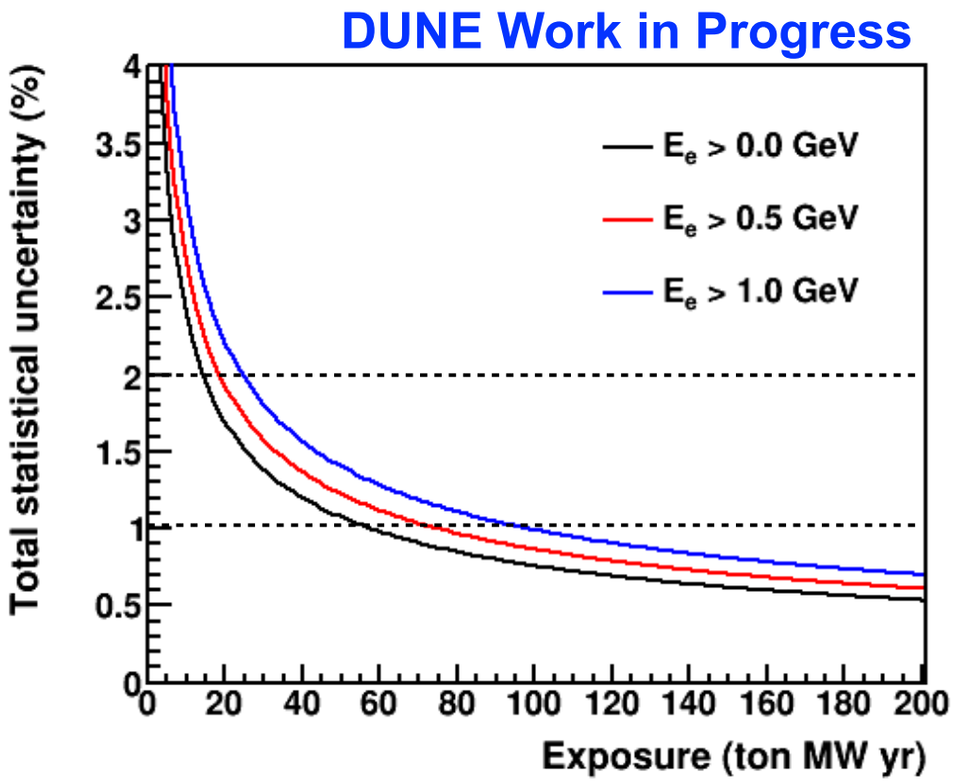

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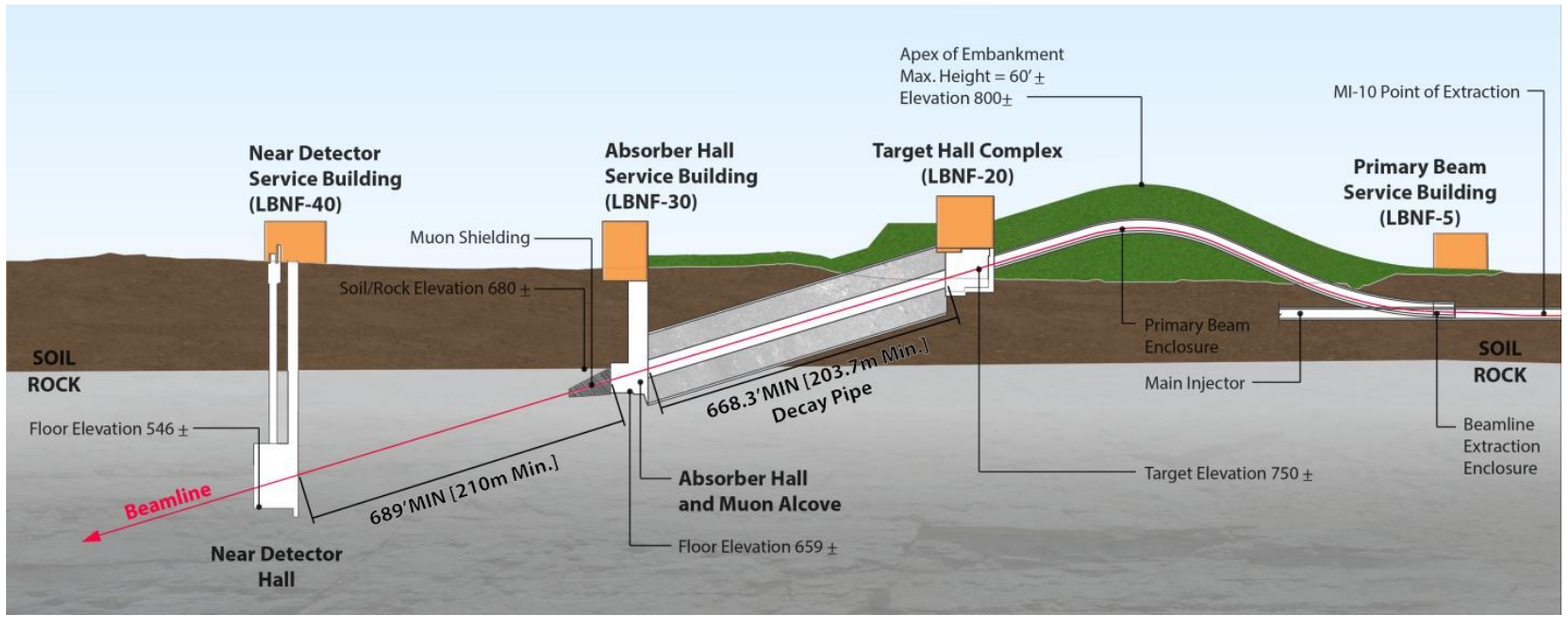

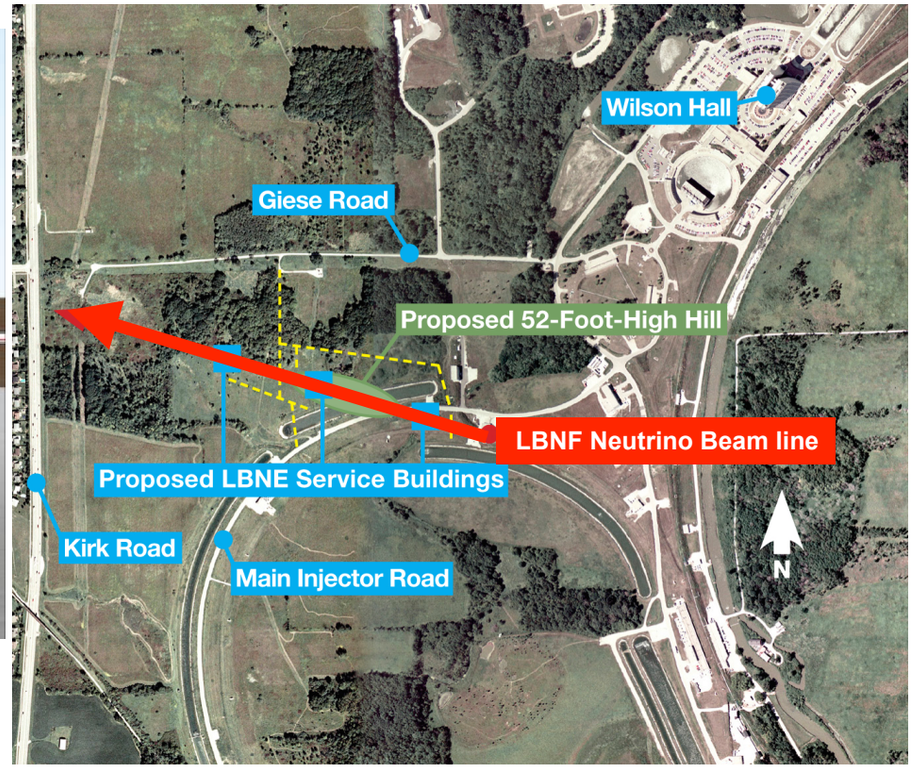

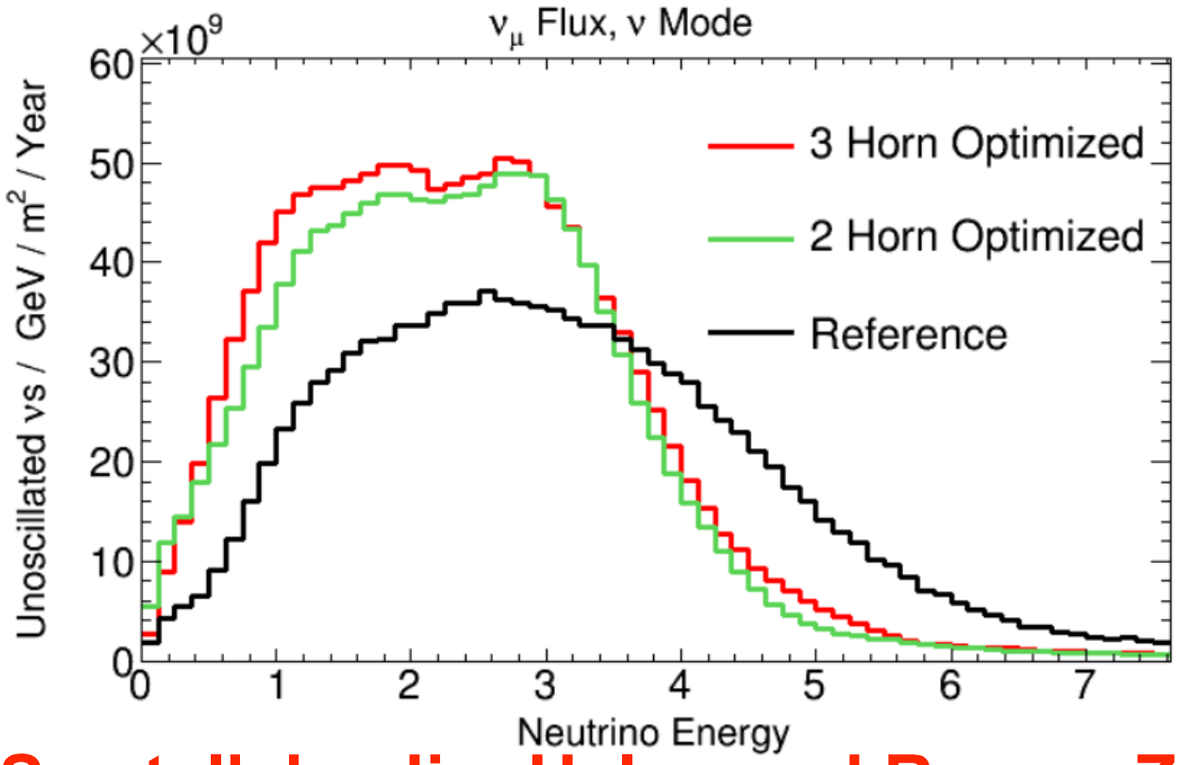

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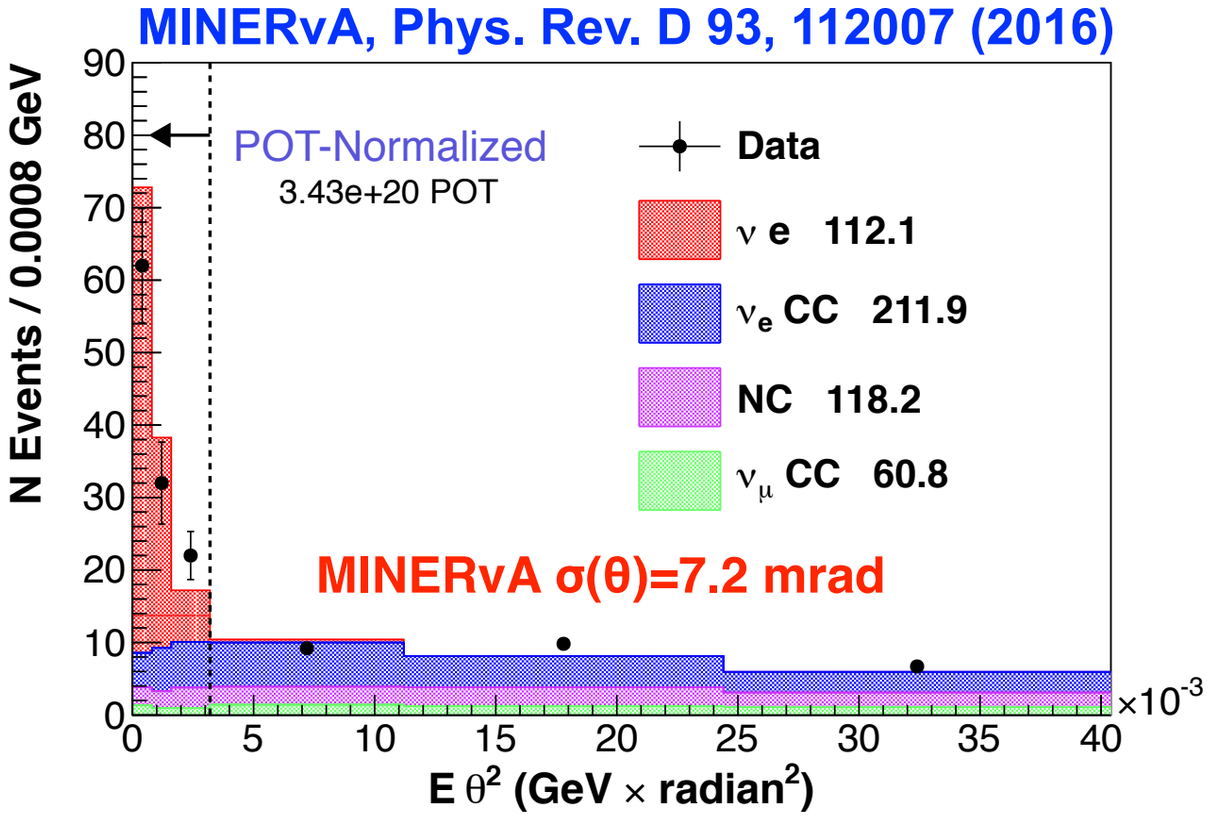
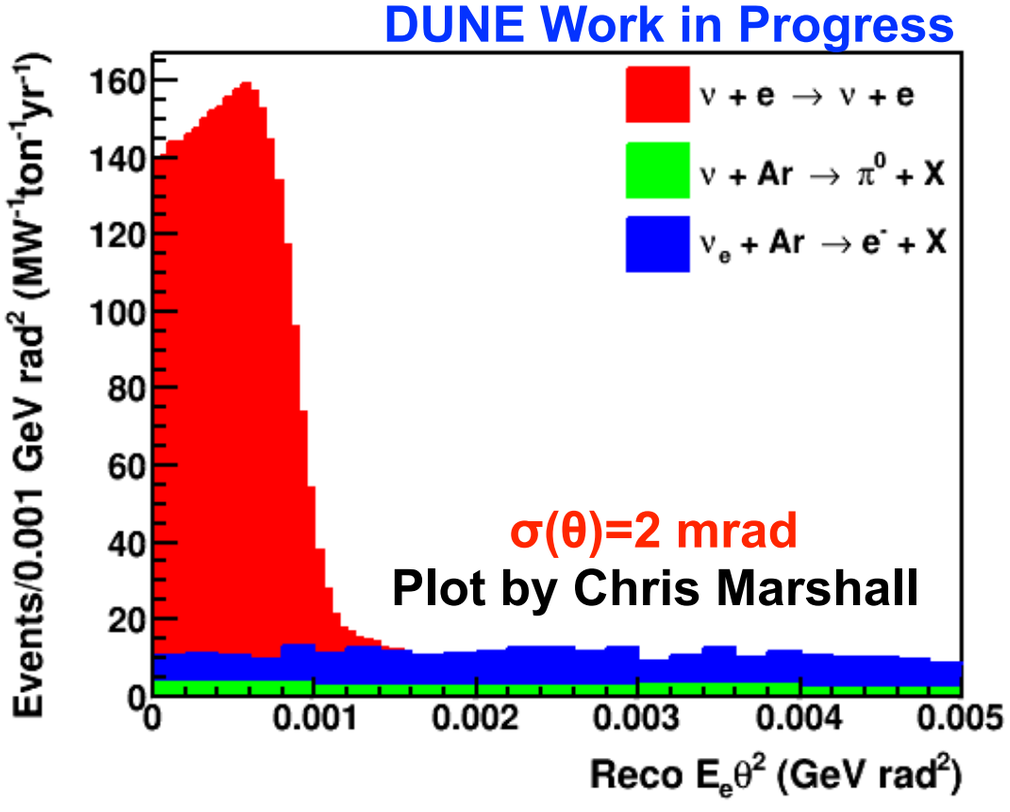
Neutrino-Electron Scattering





- $E_e\theta^2 = 2m_e(1-y) < 2m_e$.
- Good angular resolution is critical to reduce background.
- Assuming 2 mrad angular resolution, 6% background is expected.
- Background comes from π^0 and ν_e-CC (QE) events:
  - e^+ sample to control π^0 background: need e^+/e^- ID.
  - 2-track ν_e-CC QE-like events to constrain ν_e-CC QE background (50% efficiency in FGT).