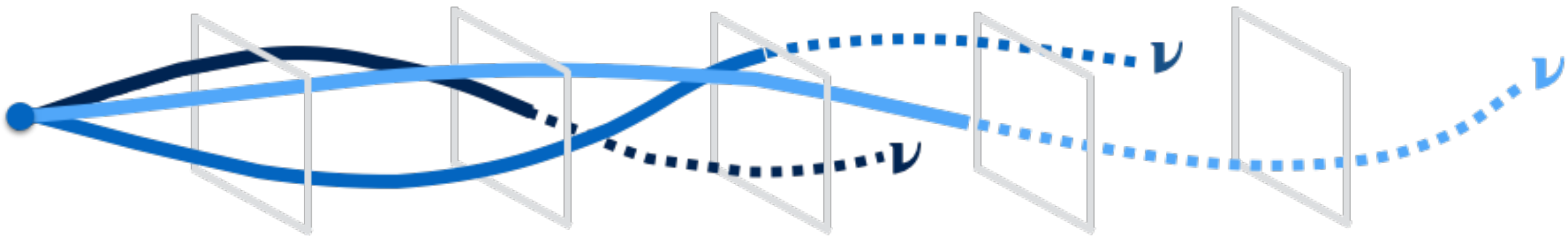



# Physics with Precision Time Structure in On-Axis Neutrino Beams

Nov 2019

Evan Angelico, Jonathan Eisch, Andrey Elagin, Henry Frisch, Sergei Nagaitsev, Matt Wetstein

Fermilab

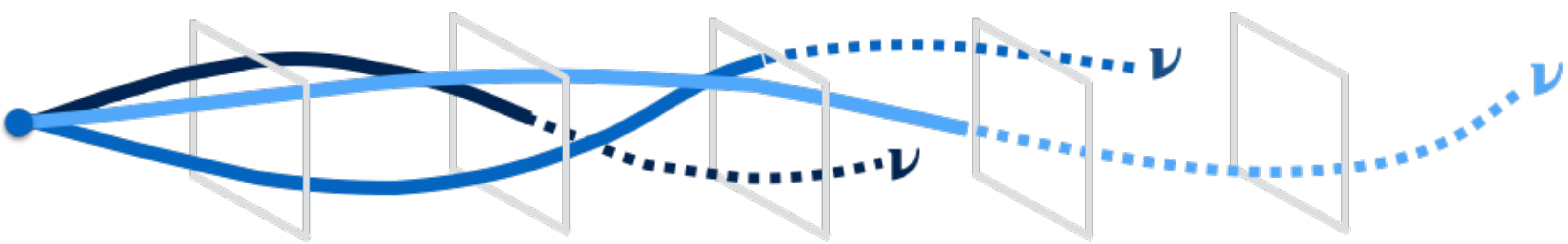
STATE

THE UNIVERSITY OF CHICAGO 1890

## Workshop on Precision Time Structure in On-Axis Neutrino Beams

**Fermilab November 2-3**

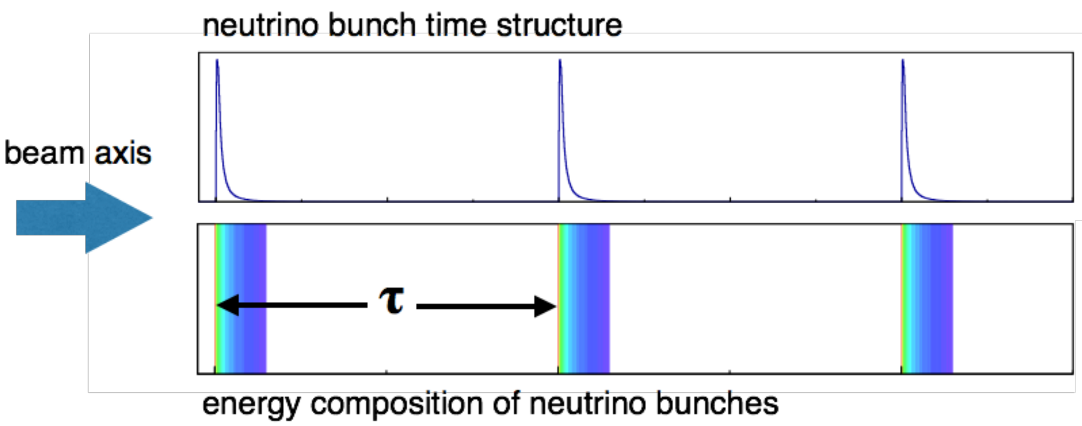
https://indico.fnal.gov/event/21409/

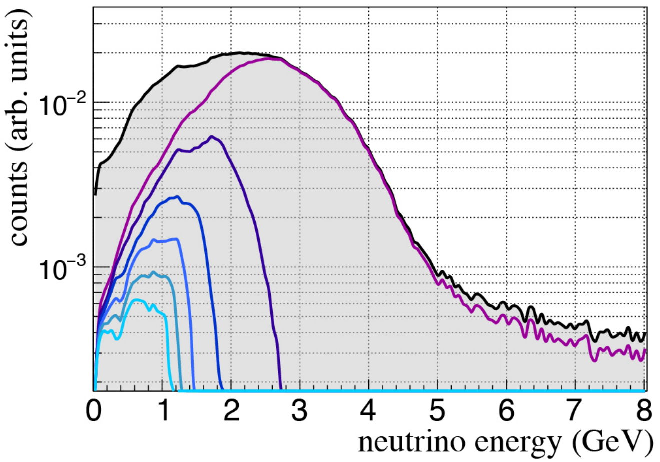



PHYS REV D 100, 032008 (2019) https://arxiv.org/abs/1904.01611

# Introduction

- Neutrinos beams have an intrinsic time structure imprinted on them by the accelerators used to produce them
- The relative arrival time of neutrino with respect to the bunch correlates with the neutrino energy, parent hadron, and flavor
- Timing in neutrino beams could therefore provide a strong experimental handle to help understand and reduce beam systematic uncertainties on flux, cross section, and energy reconstruction in DUNE
- It may also provide a new handle in searching for new physics



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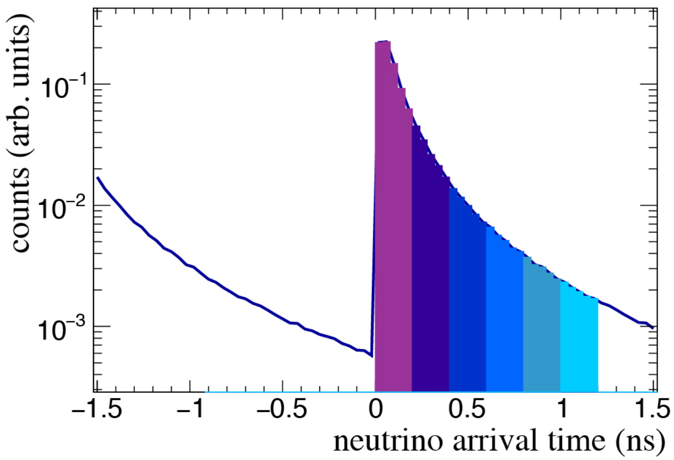
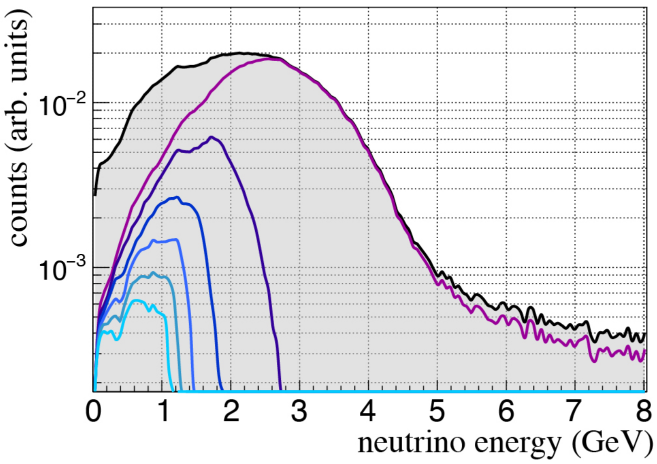
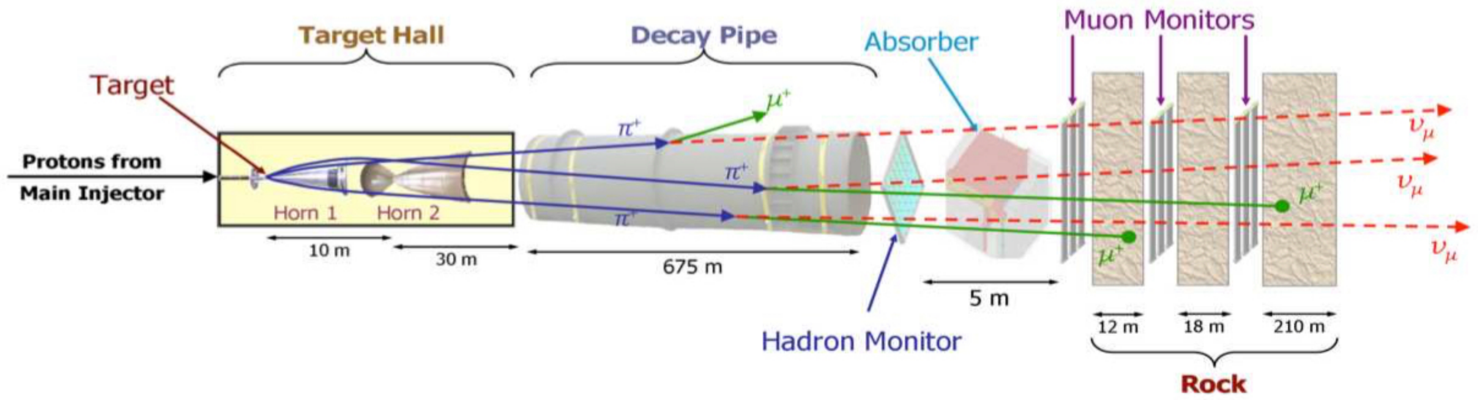


# Kinematics of the Neutrino Timing

The arrival time difference between neutrinos from relativistic hadrons and neutrino from hadron of energy E:

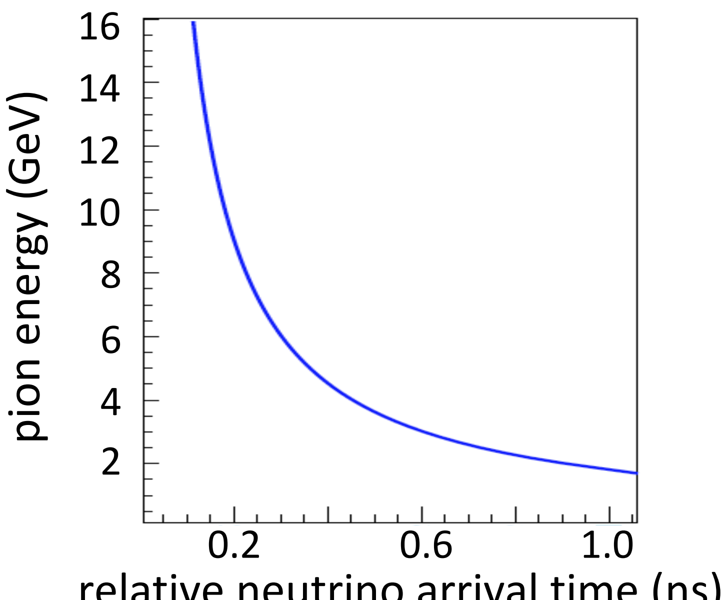



$$\Delta t(E) = \tau(E)[1-\beta(E)]$$

$$\Delta t(E) = (\gamma\tau_0)[1-\sqrt{(1-1/\gamma^2)}]$$

$$\Delta t(E) \rightarrow \tau_0 \quad \text{as} \quad \gamma \rightarrow 1$$

$$\Delta t(E) \rightarrow \tau_0/2\gamma \quad \text{for} \quad \gamma >> 1$$



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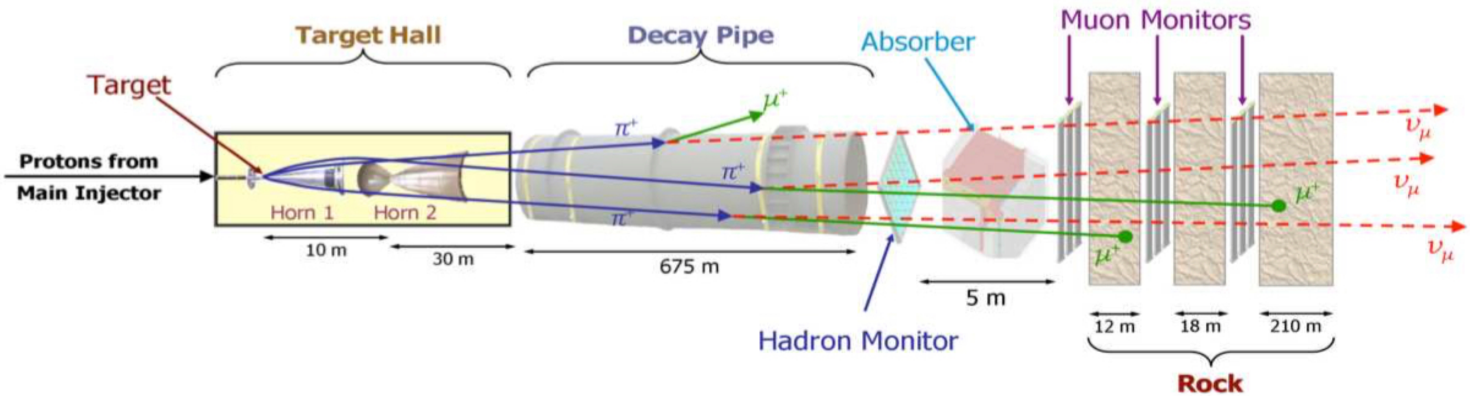


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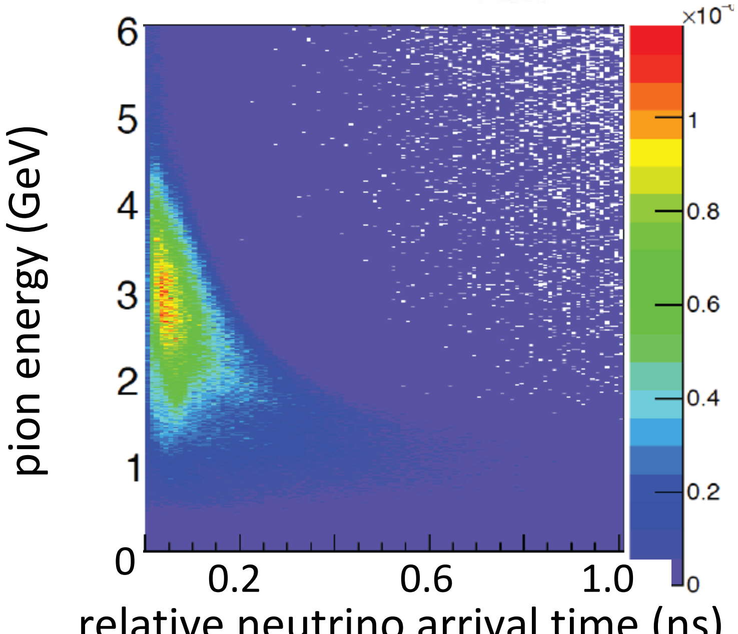
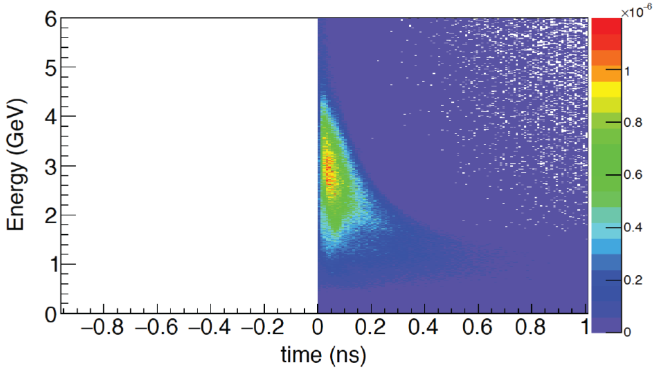


# Characteristic Timescales/Limiting Factors

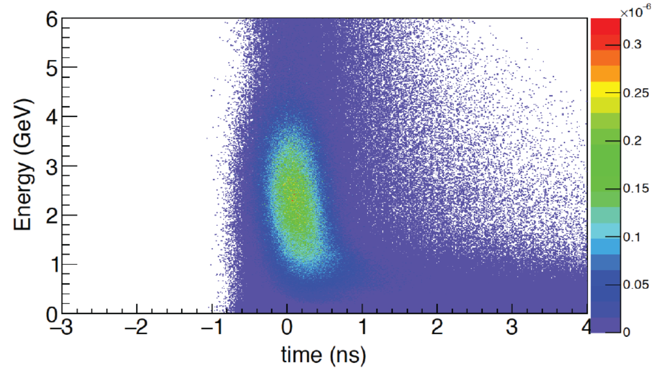
Stroboscopic techniques require sufficiently short bunch sizes

- If all hadrons are produced at the same time, the different neutrino energies will stratify over roughly ~1 nsec
- This effect starts to wash out if the proton beam width or detector resolutions exceed a nsec
- The current Fermilab RF structure is not designed to deliver proton bunches much shorter than 1 nsec.

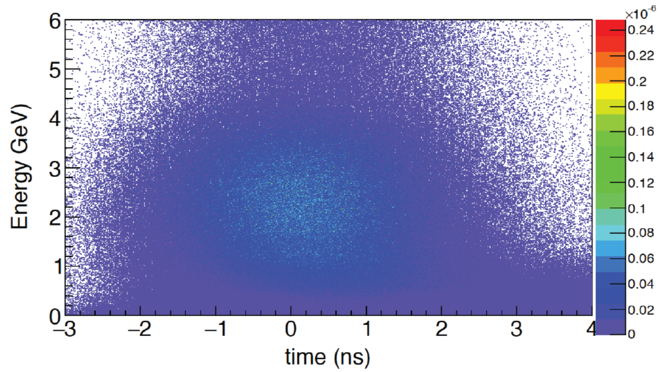
infinitesimal proton bunch




200 psec smearing




1 nsec smearing

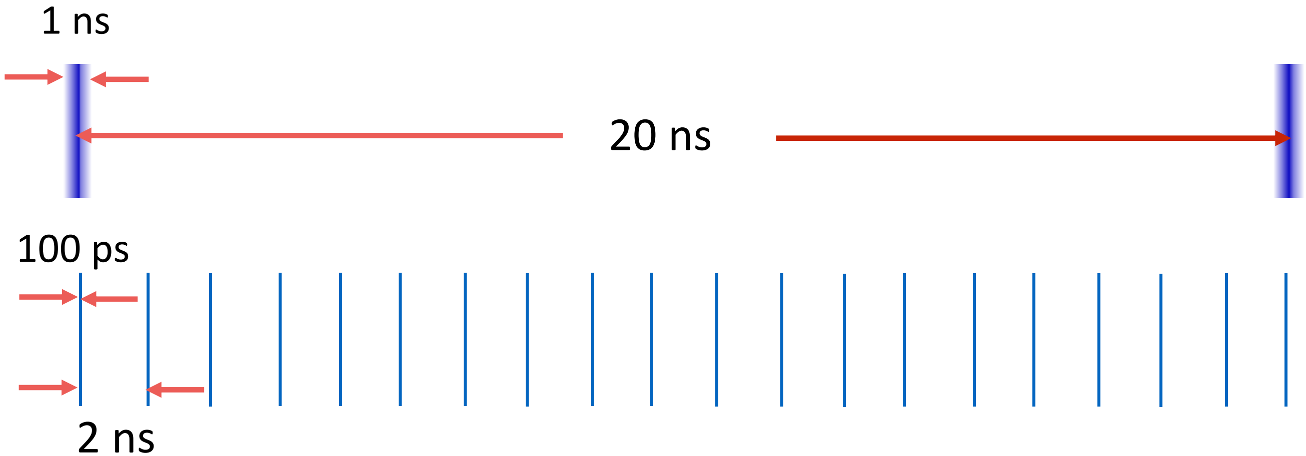


# Rebunching the Beam

- Compressing the existing proton bunches in time in not feasible
- However, imposing a higher frequency harmonic on top of the bunch structure would be compatible with FNAL accelerator operation.
- The 10x harmonic, going from 53.1 MHz to 531 MHz, has a particularly advantageous relationship between bunch size and spacing
- The total number of protons is preserved, just "reorganized"

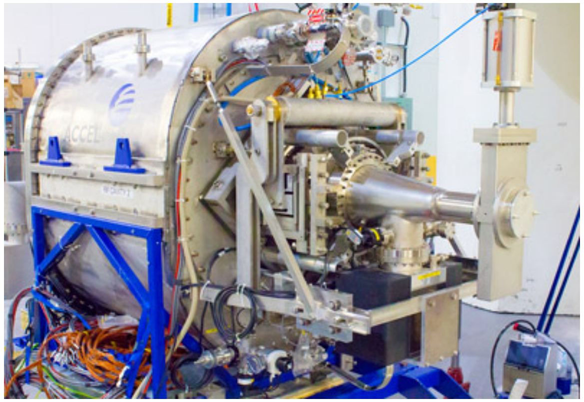
53.1 MHz → 531 MHz

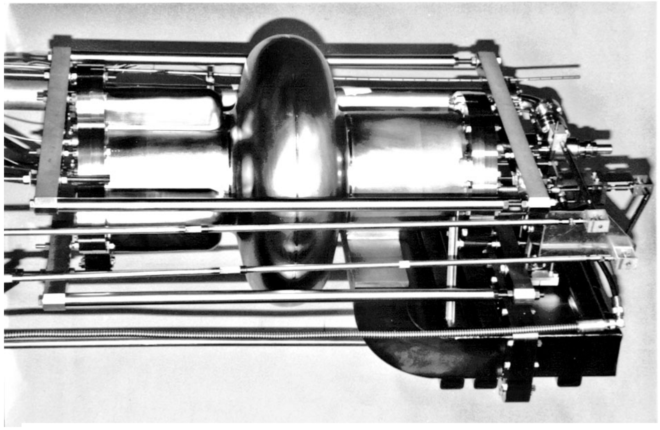
O(1) ns bucket every 20 ns → O(100) ps bucket every 2 ns

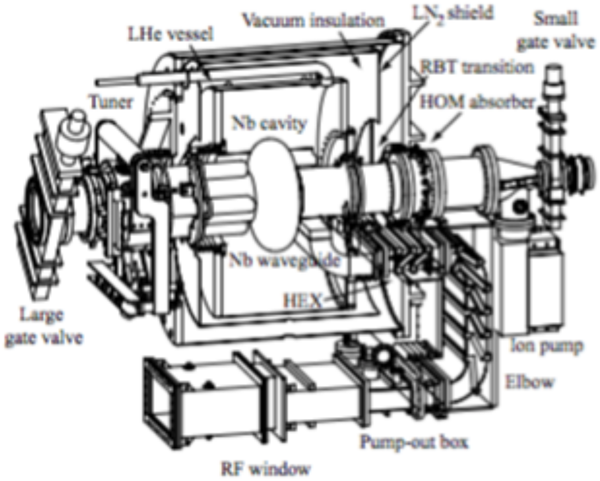


# Adding a Superconducting RF Cavity

- Rebunching could be achieved with the addition of just 1 or 2 superconducting RF (SRF) cavities
- There is a commercially available SRF cavity that closely matches our needed expectations: The Cornell B Cavity:
  - 500 MHz (versus 531 MHz)
  - Well tested in the field
  - Large aperture
- Feasible to implement, would be first MI cryomodule



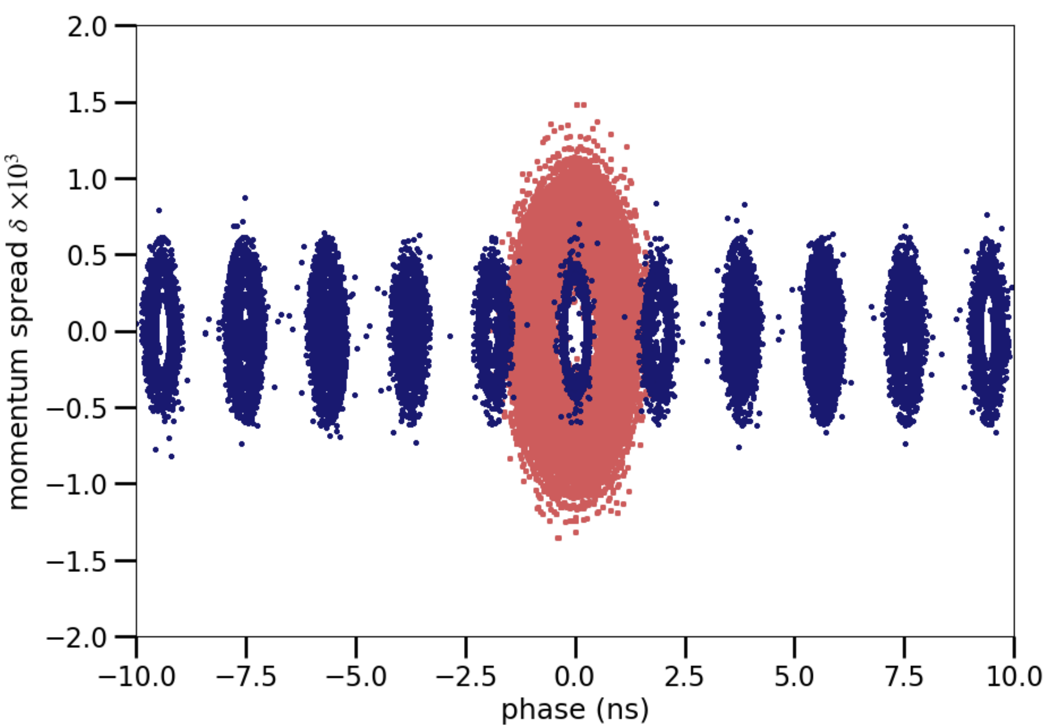




# RF Simulation

A realistic, multi-particle simulation was performed to study the following properties of the rebunching procedure:

- ramp-down/ramp-up functions for rebunching at a higher frequency
- the final time structure/RMS time widths of the 531 MHz bunches



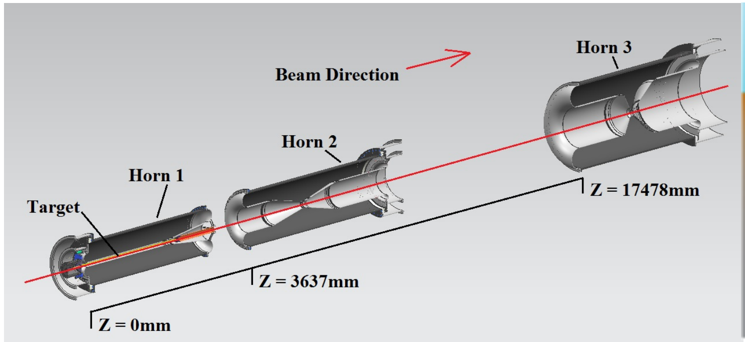

- The resulting rebunched structure is promising
- Typical 531 MHz bunches have an RMS of around 200 ps
- These bunches have sharp edges and substructure, which could be measured by RF monitors and exploited for better extracting time information

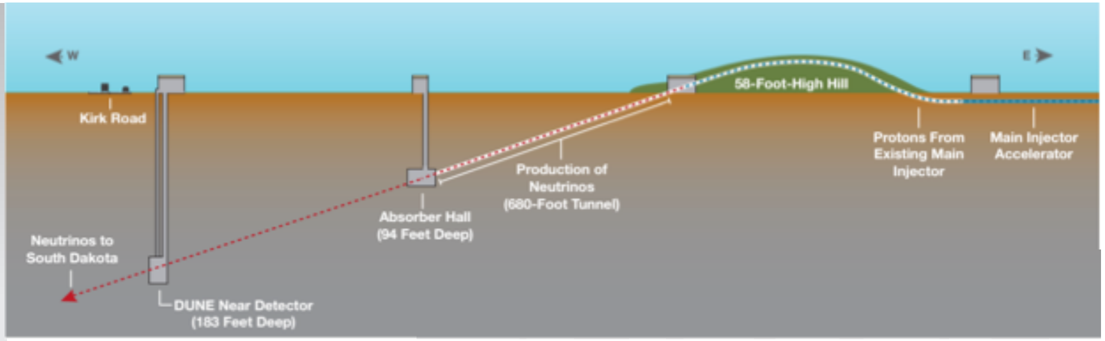
Evan Angelico, Sergei Nagaitsev

# Realistic Flux Simulation

https://home.fnal.gov/~ljf26/DUNEFluxes/

- Optimized 3-Horn Design presented at the October 2017 Beam Optimization Review (used in the DUNE TDR)
- Timing information is included in the ntuples
- All simulated protons hit the target at the same time




- We convoluted the proton hit times with the timing of the emergent bunch structure from the accelerator simulations
- We also added 100 psec Gaussian smearing to account for plausible, albeit ambitious detector capabilities
- We also added in the effects of pileup from the previous bunches

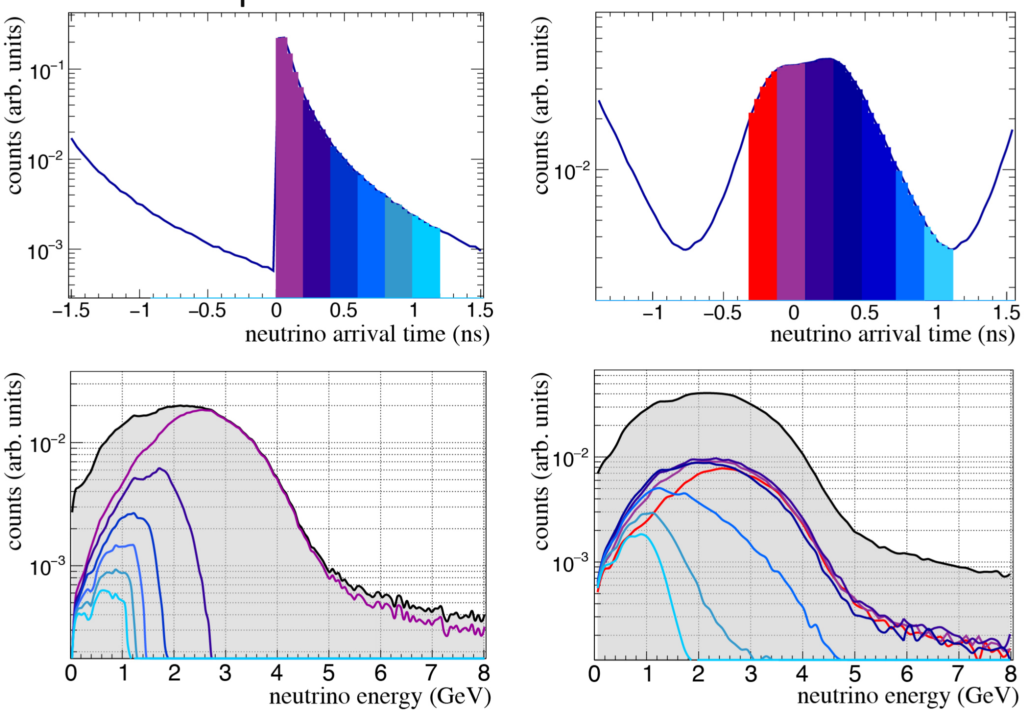
# Time slicing in a more realistic scenario

Even with
- a realistic simulation of the 531 MHz rebunched time structure
- an additional 100 ps Gausian to account for detector affects
- the effects of pileup between the bunches

it is still possible to select isolated, lower energy flux bins

Inifinitesimal proton bunches

"realistic scenario"

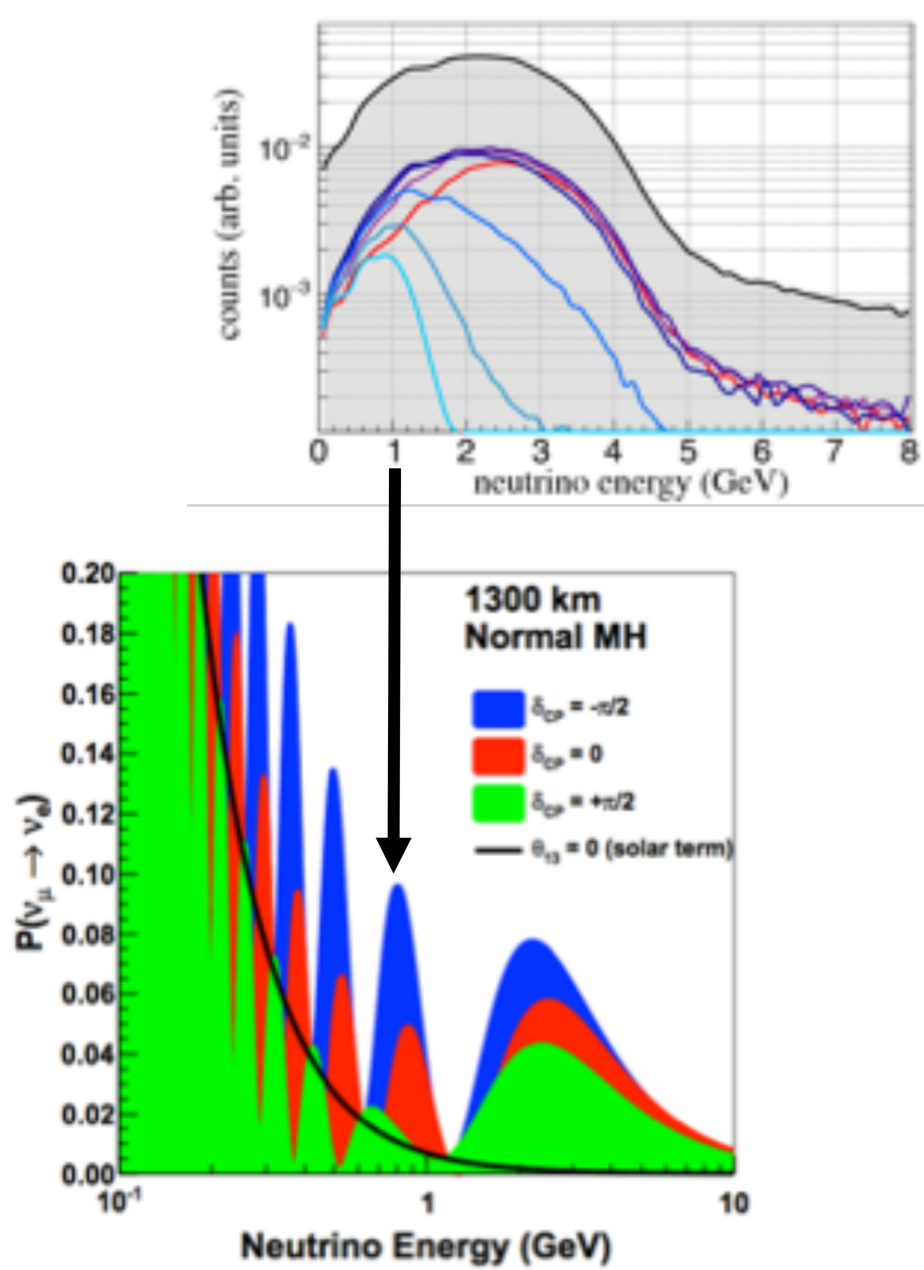


# The second maximum

Time slicing in the far detector
is particularly advantageous as it can

- select a more pure sample of neutrinos from the second maximum
- suppress "feed down" from higher energy backgrounds
    - Resonant pion production
    - Deep Inelastic Scattering
- Suppress downward migration of reconstructed energy from higher energy interactions

Being able to fit both maxima would place strong constraints on oscillation parameters



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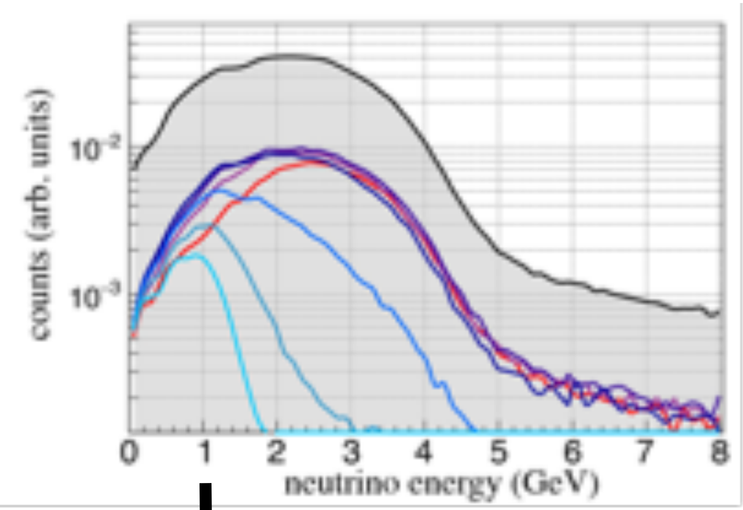
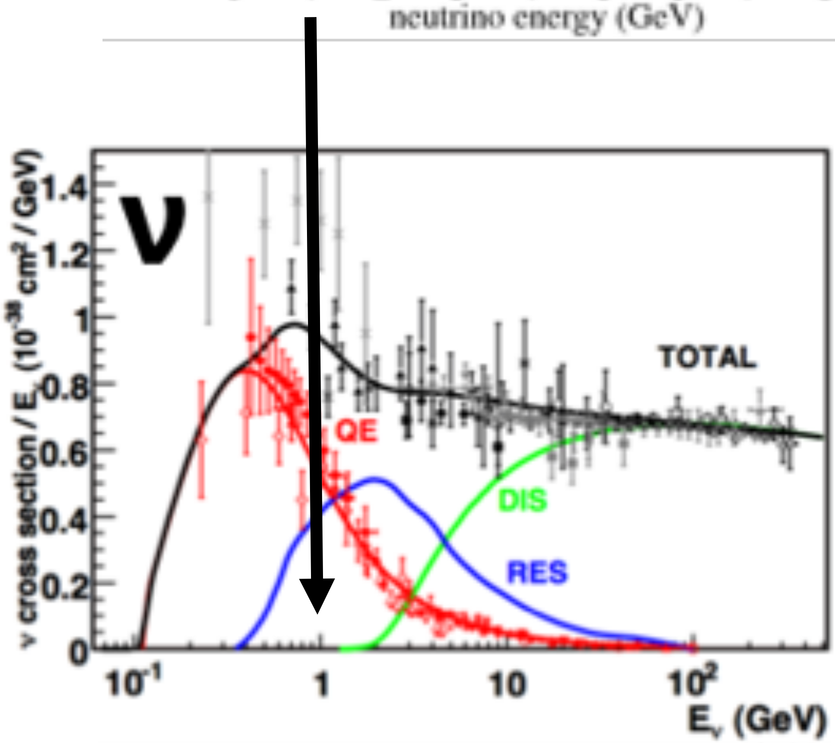
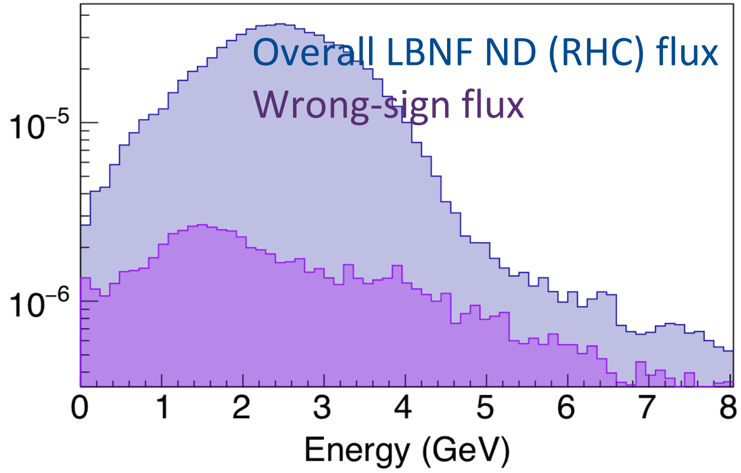


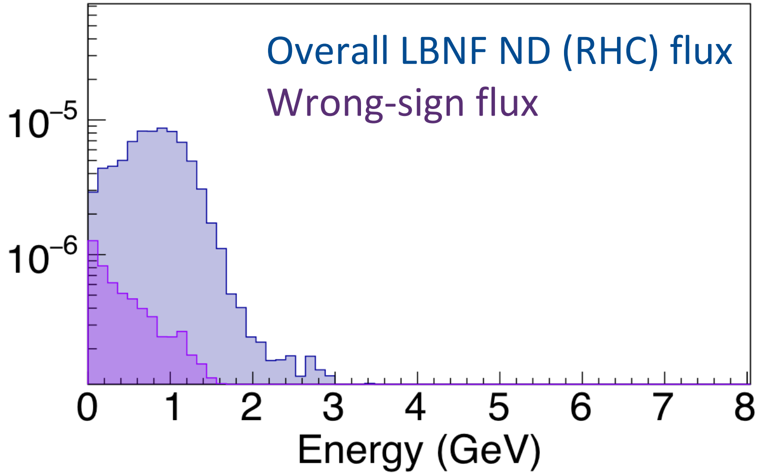
# Separating different components of the beam

- The relative normalization and ***shape*** of the different components of the neutrino flux (wrong-sign, intrinsic $\nu_e$ , K/π) evolve differently and in deterministic ways with respect to the timing cuts
- Fitting in multiple time slices greatly constrains the fit to the overall flux

time slice from -0.3 to –0.1 ns




time slice from 0.9 to 1.1 ns



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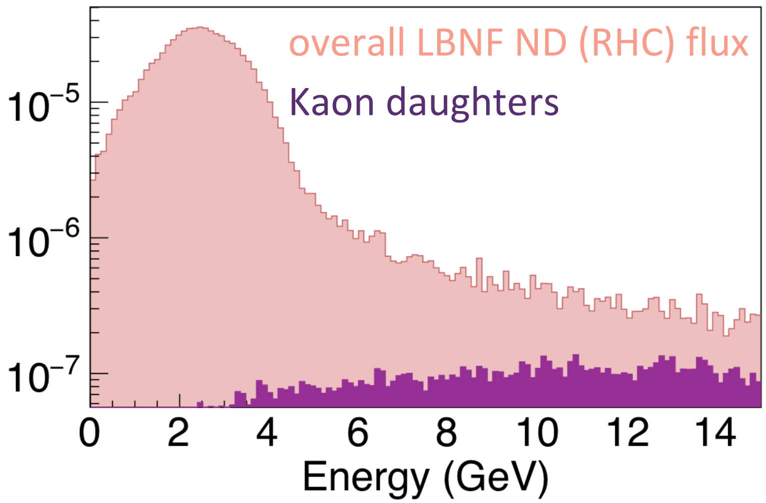


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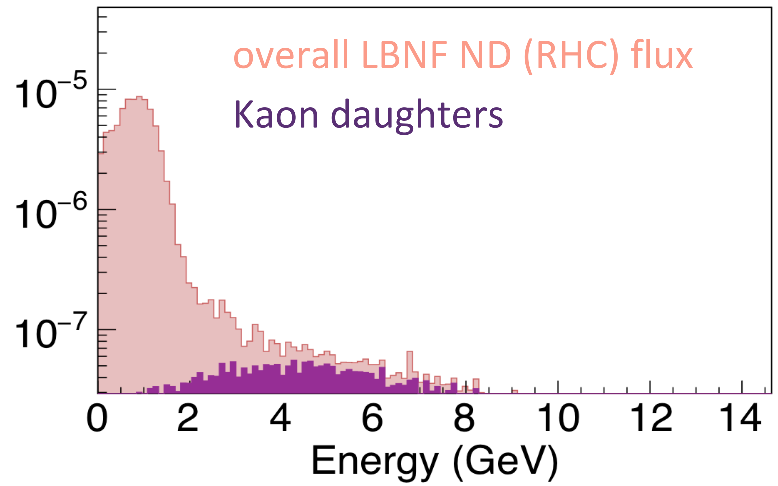

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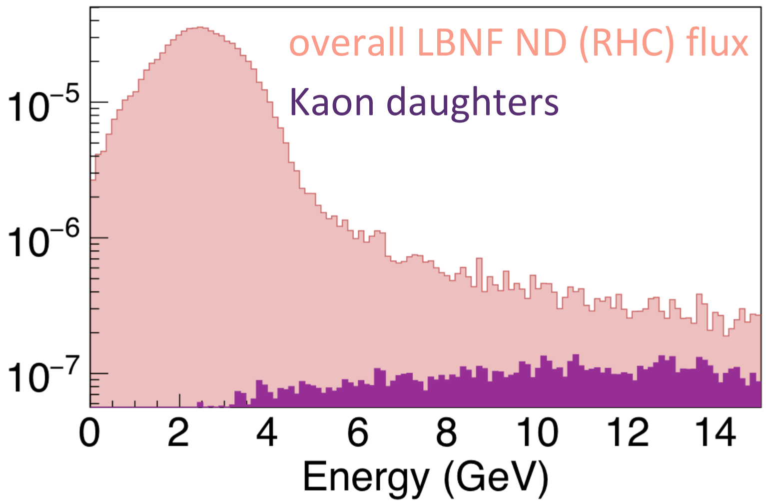


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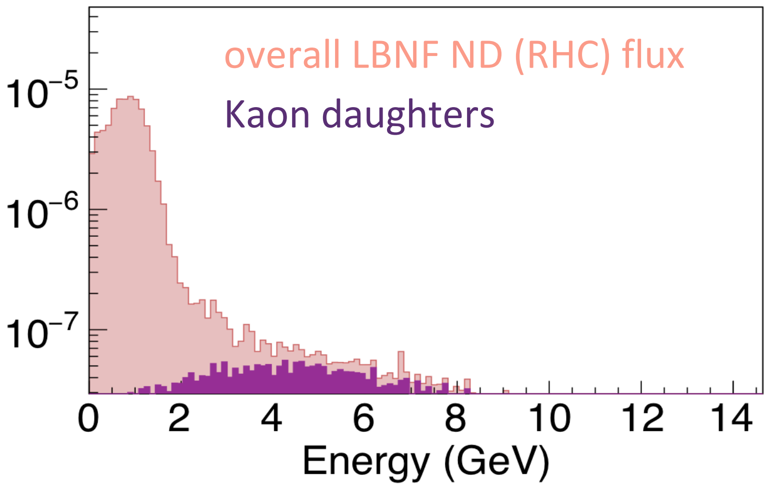
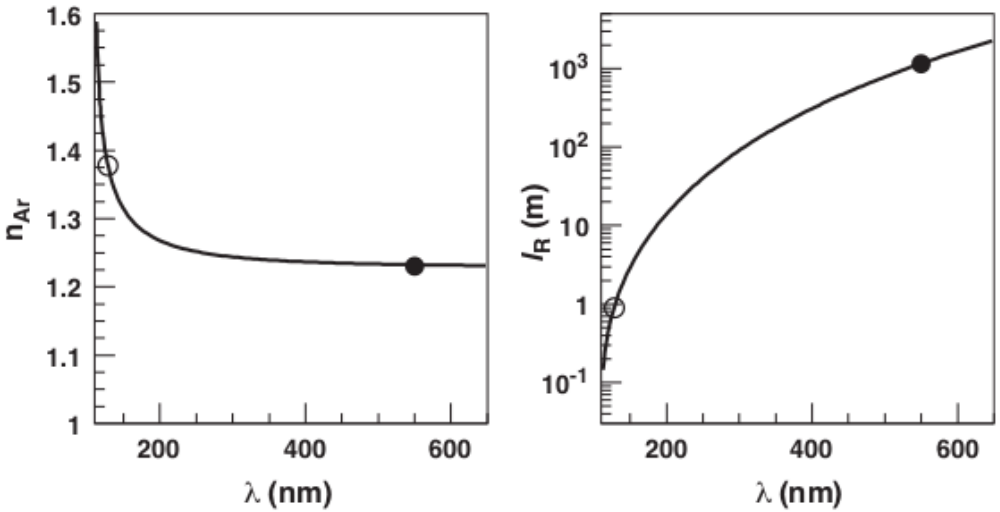



- Imagine having to fit the flux model to a 2-d grid of spectra binned in off-axis angle *and* time slice!

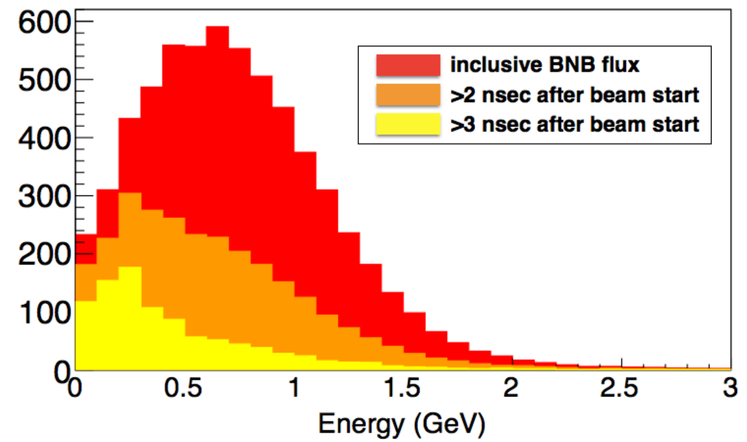
# Feasibility of precision timing in LAr

https://arxiv.org/abs/2004.00580

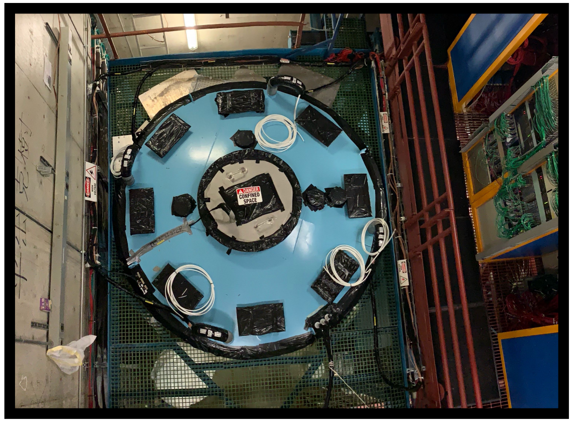
- Cherenkov light could be used to establish a precision T0 for LAr-TPCs. The characteristics of liquid Argon are good for direct detection of optical wavelengths
- Since the other parameters of the track are well known, measuring T0 requires only a sampling of light at a few different points. Not a lot of coverage would be necessary.



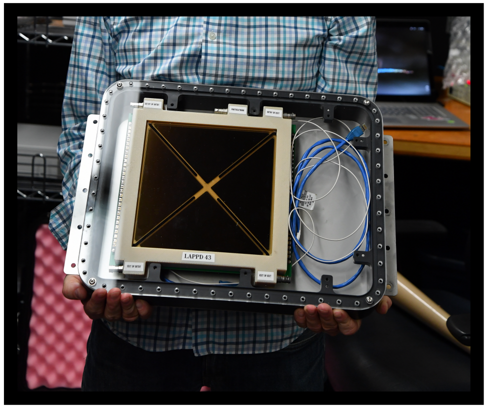
# ANNIE/Testbeam




- ANNIE is capable of providing a first demonstration of this technique on neutrinos from the BNB
- The ANNIE detector will have the time resolution
- Because the energy of the BNB spectrum skews towards the low end, there is a broader tail of low-energy neutrinos
- Detecting the time-slicing effect should be possible, even with 1 ns bunches



- A testbeam time-of-flight system, under development by Evan Angelico with Henry Frisch provides an excellent context and controlled for working on issues like clock synchronization with beam RF.



# Conclusions

- Precision timing could be used to select different beam fluxes based on neutrino arrival time, due to the correlation between the energy of the beam neutrinos and the velocities of the parent hadrons.
- The ability to select different fluxes is a powerful capability for constraining complicated and correlated systematic uncertainties on flux, cross sections, and neutrino energy. This is important for guarding against unknown unknowns and in searching for new physics
- This technique has some interesting and complementary aspects to off-axis techniques, like those of DUNE Prism and would thus strengthen the DUNE program
- The rebunching technology in delivering beam is potentially compatible with exsiting accelerator plans for DUNE
- Timing in the Near Detector may be achievable within the framework of the current design.
- **Theia is naturally suited for precision timing in a far detector.**
- New technological capabilities often bring new physics reach in areas that weren't originally planned. Continued thinking about precision timing is worthwhile
- This idea is new and there is much work ahead to establish it's feasibility and cost-benefit.
- We welcome feedback from the community in establing the feasibility and cost-benefits of this technique and look forward to the discussions!

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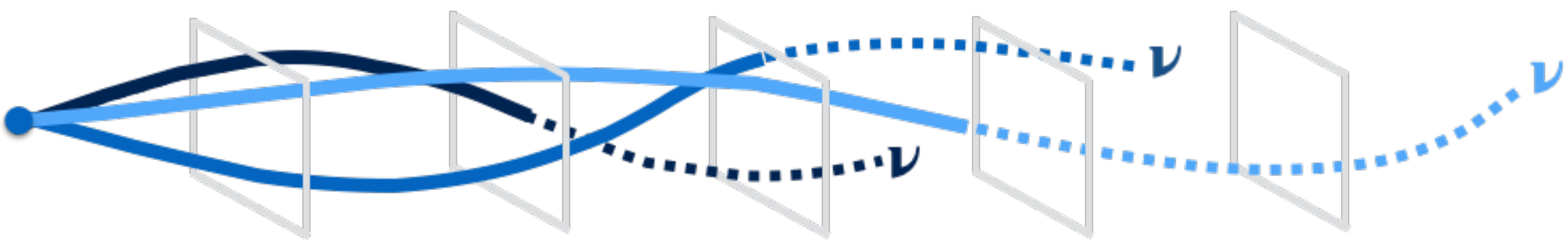
## Fermilab November 2-3

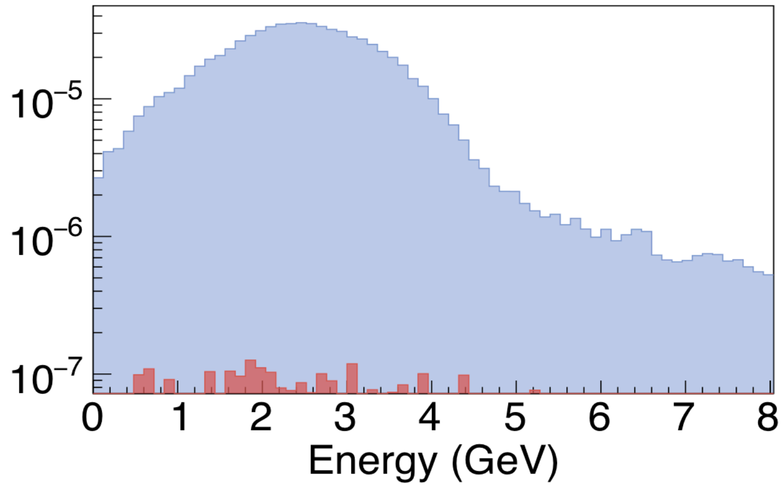
https://indico.fnal.gov/event/21409/



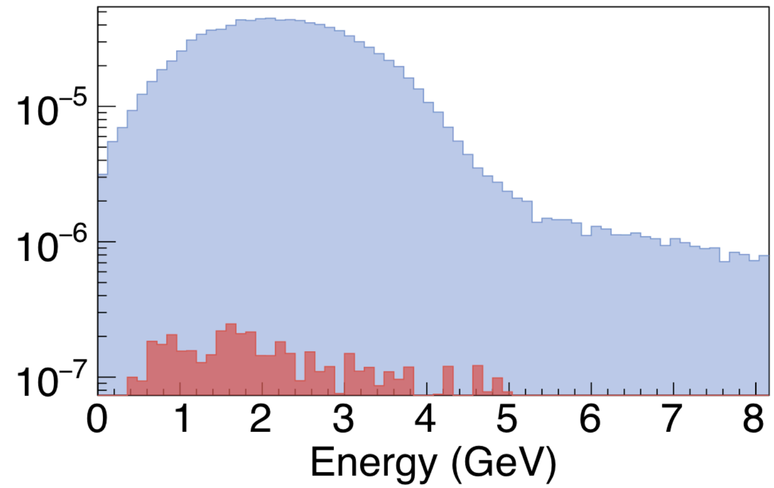

PHYS REV D 100, 032008 (2019) https://arxiv.org/abs/1904.01611

# Intrinsic Nuebar Contamination (RHC)

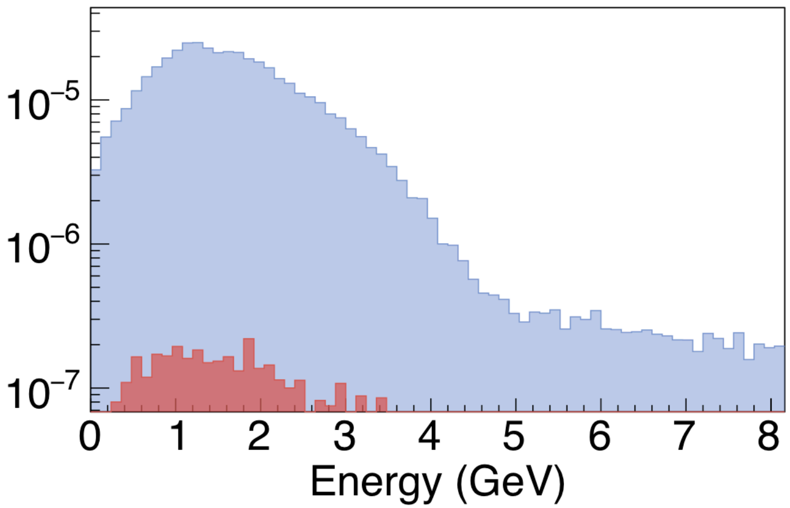
Slice 0: -0.3 to –0.1 ns



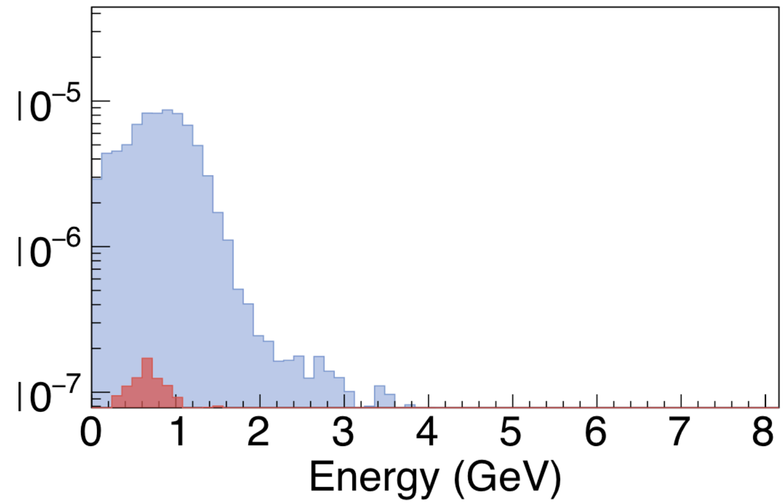

Slice 2: 0.1 to 0.3 ns




Slice 4: 0.5 to 0.7 ns

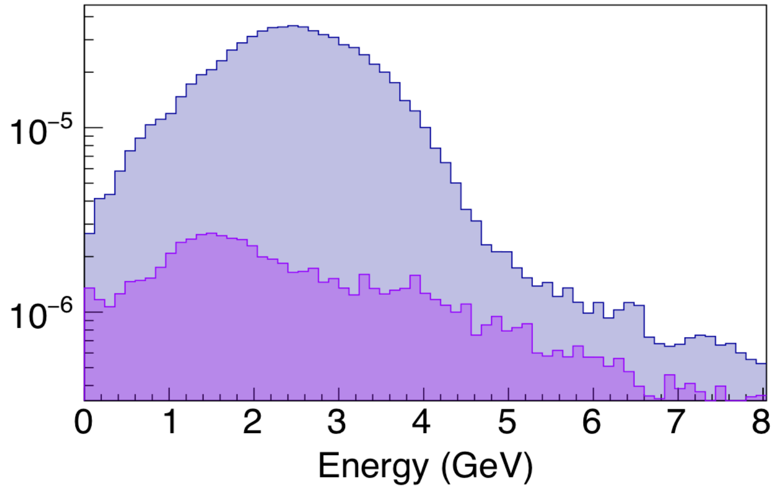



Slice 6: 0.9 to 1.1 ns

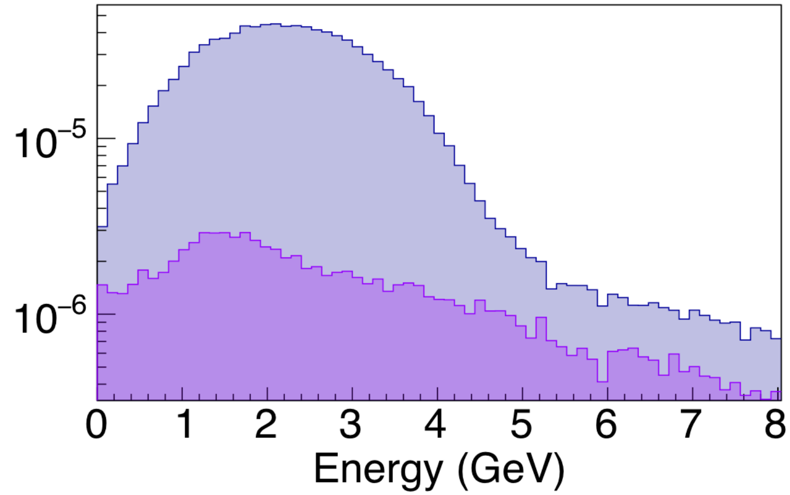


# Wrong Sign Contamination (RHC)

Slice 0: -0.3 to –0.1 ns




Slice 2: 0.1 to 0.3 ns

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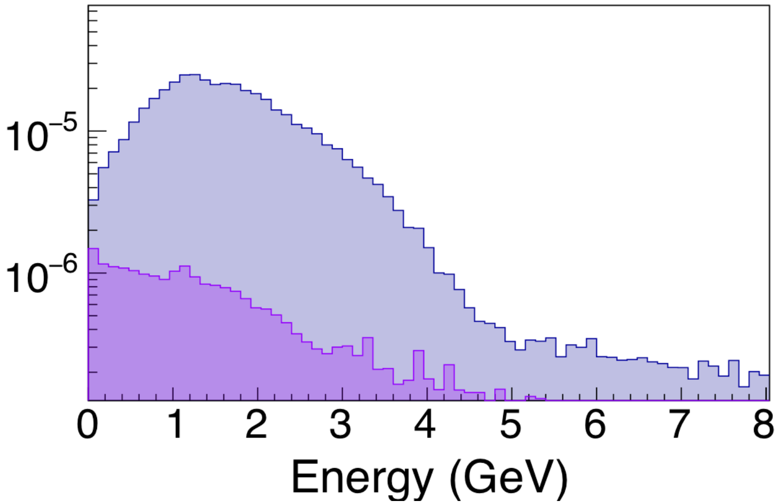


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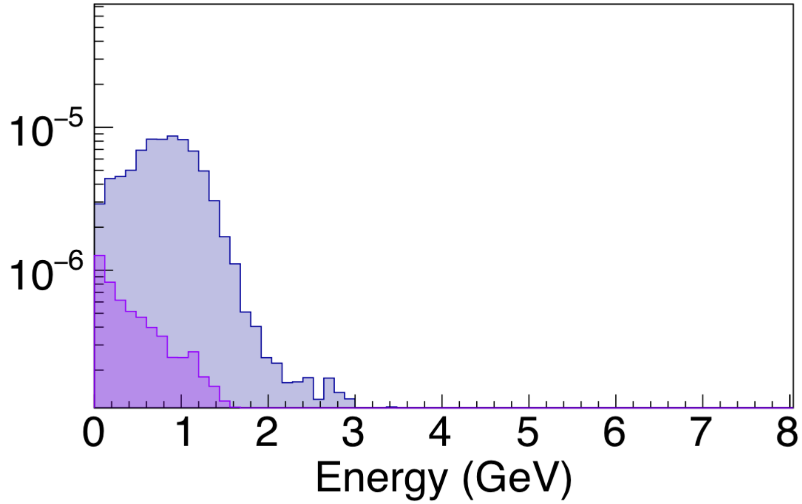
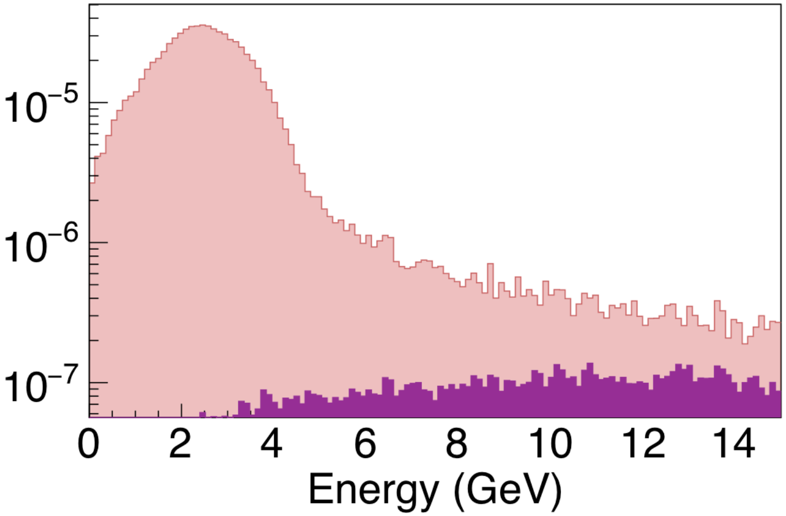
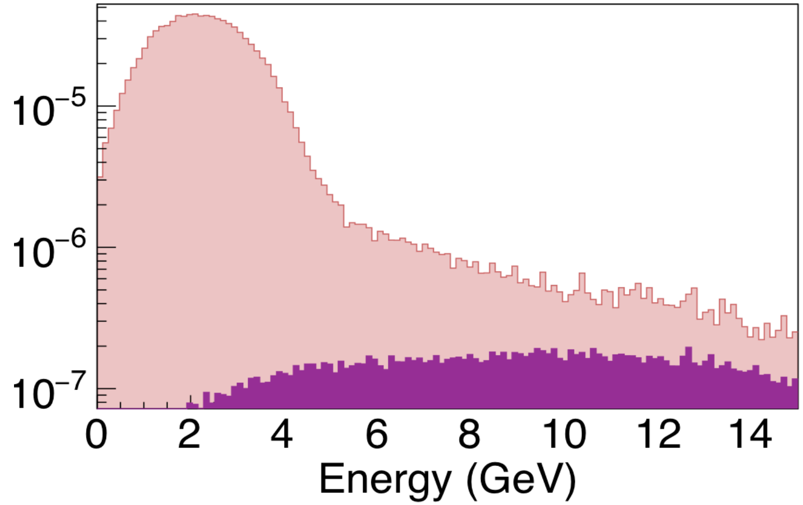


# K- component(RHC)

Slice 0: -0.3 to –0.1 ns




Slice 2: 0.1 to 0.3 ns

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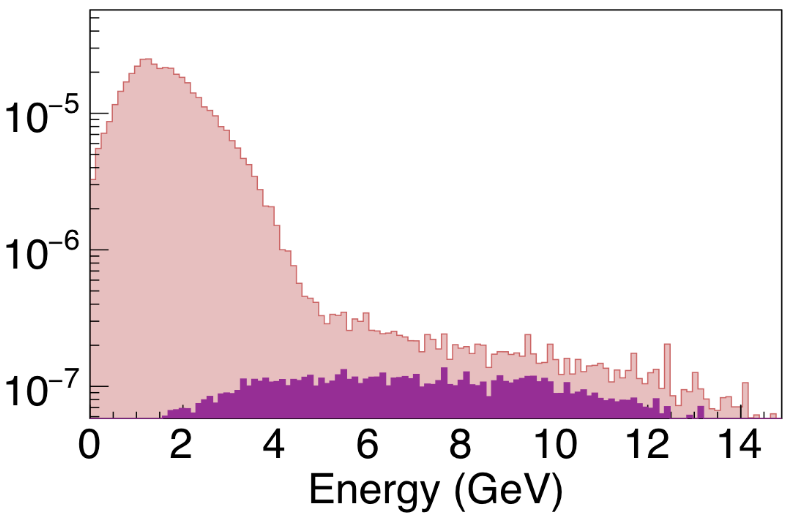


Slice 6: 0.9 to 1.1 ns