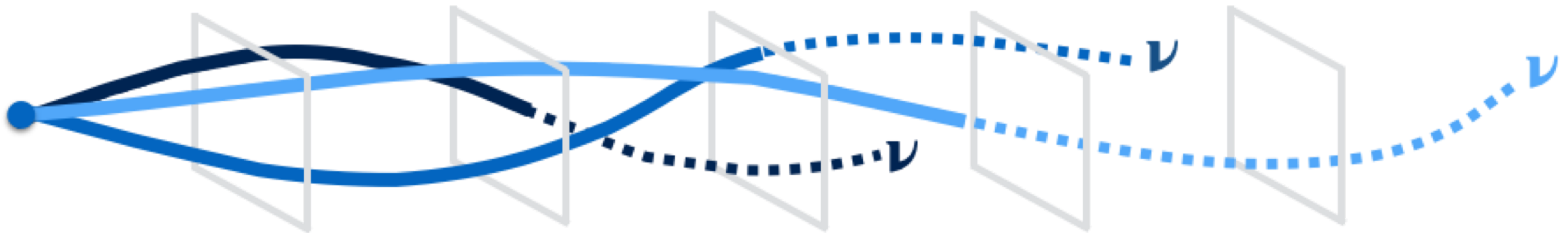
Physics with Precision Time Structure in On Axis Neutrino Beams



E. Angelico,[1] J. Eisch,[2] A. Elagin,[1] H. J. Frisch,[1] S. Nagaitsev,[3] and M. Wetstein[2]

[1] *Enrico Fermi Institute, University of Chicago, Chicago IL 60637*
[2] *Iowa State University, Ames IA 50011*
[3] *Fermi National Accelerator Laboratory, Batavia IL 60510*

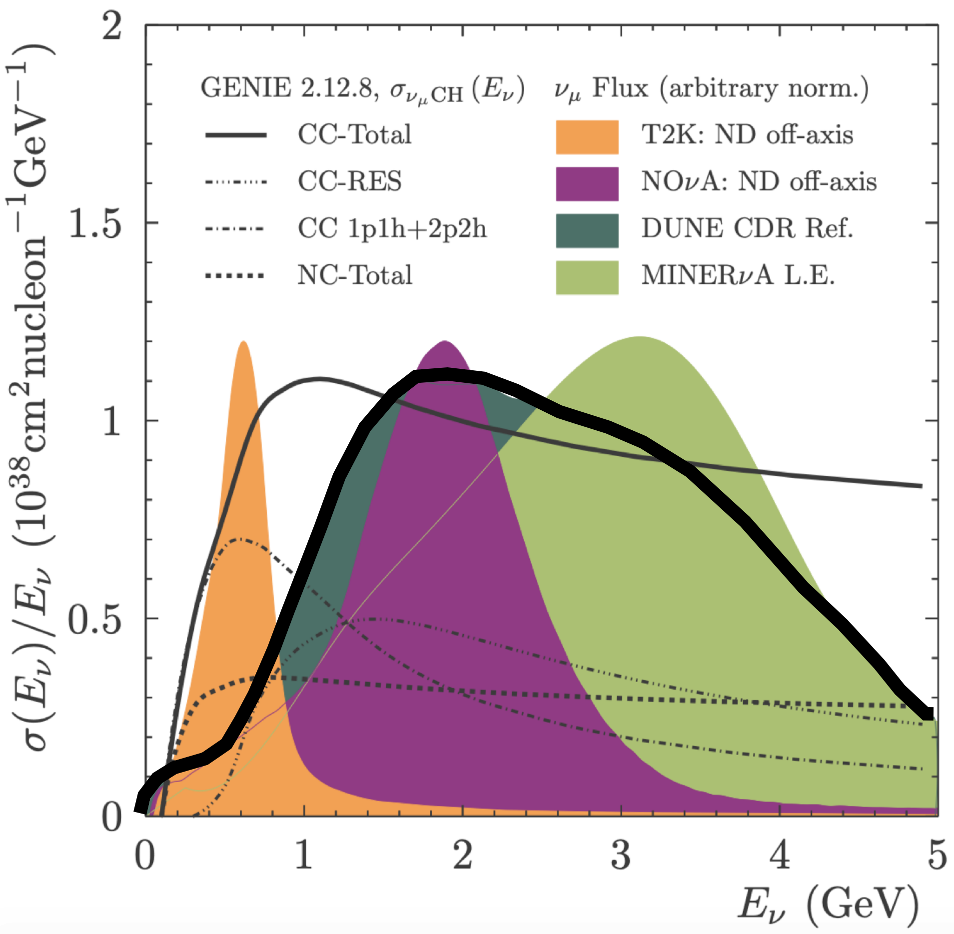
Phys. Rev. D 100, 032008. 26 August 2019. https://doi.org/10.1103/PhysRevD.100.032008

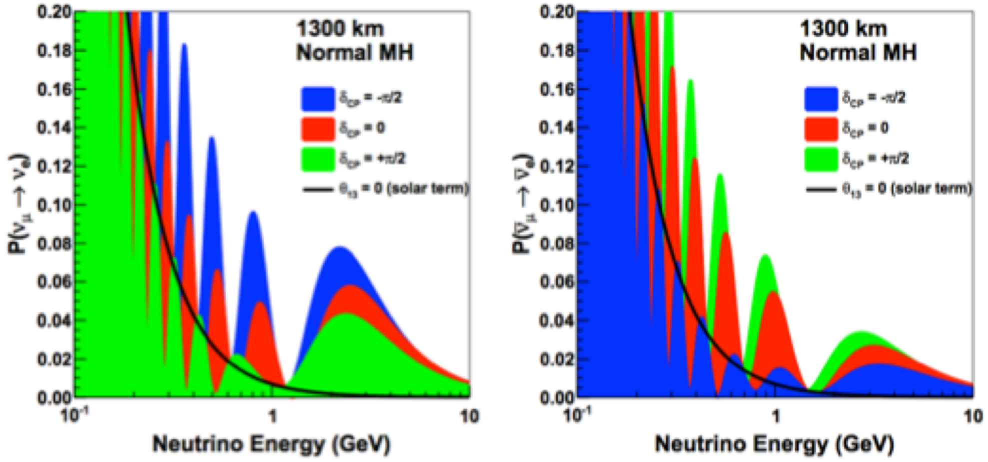
Accelerator neutrino physics

- Fermilab Main Injector (MI) sources LBNF/DUNE neutrino beam

- Broad energy-band for exploring wide range of physics

Kendall Mahn et. al. arXiv: 1803.08848v1





DUNE CDR volume 2 fig 3.1

Major challenges deconvolving observables

For a given set of kinematic variables **k**, the event rate R(**k**) is given by

$$R(\mathbf{k}) = \sum_{i}^{process} \sum_{j}^{target} \int_{E_{min}}^{E_{max}} \phi(E_\nu) \times \sigma_i(E_\nu, \mathbf{k}) \times \epsilon(\mathbf{k}) \times N_j \times P_{\nu_a \to \nu_b}(E_\nu)$$

what is detected

flux

cross sections

detector effects (efficiency / number of targets)

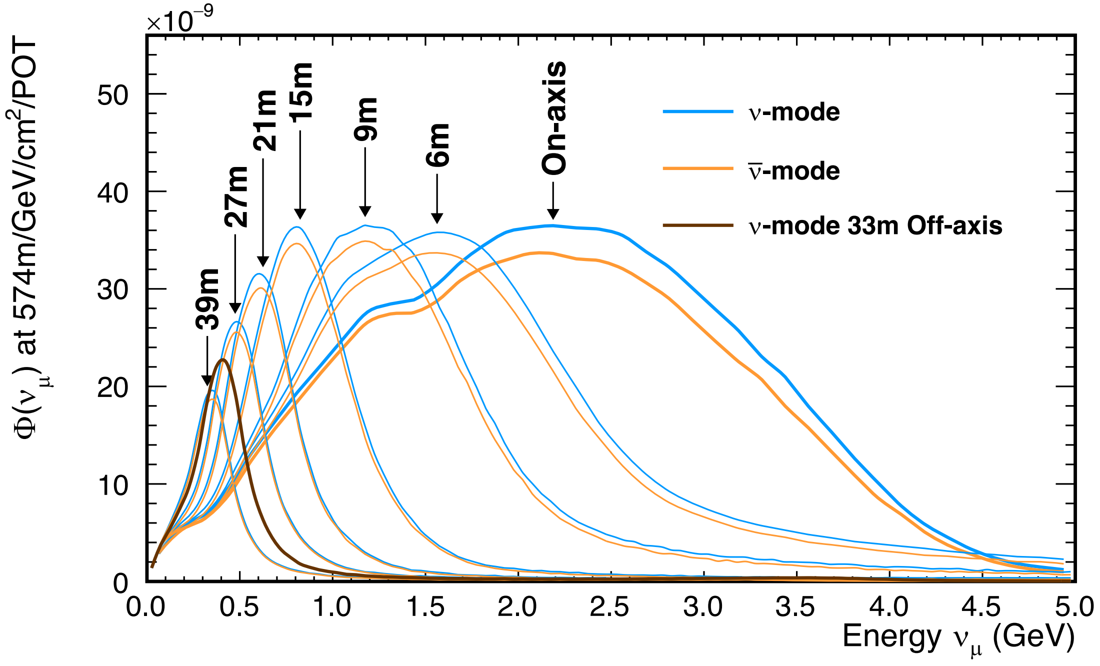
what we want to measure

Need a near detector, want independent measurements of each component of this integral. Constrain cross-sections and fluxes

Constrain cross-section and flux-energy uncertainties

DUNE-PRISM

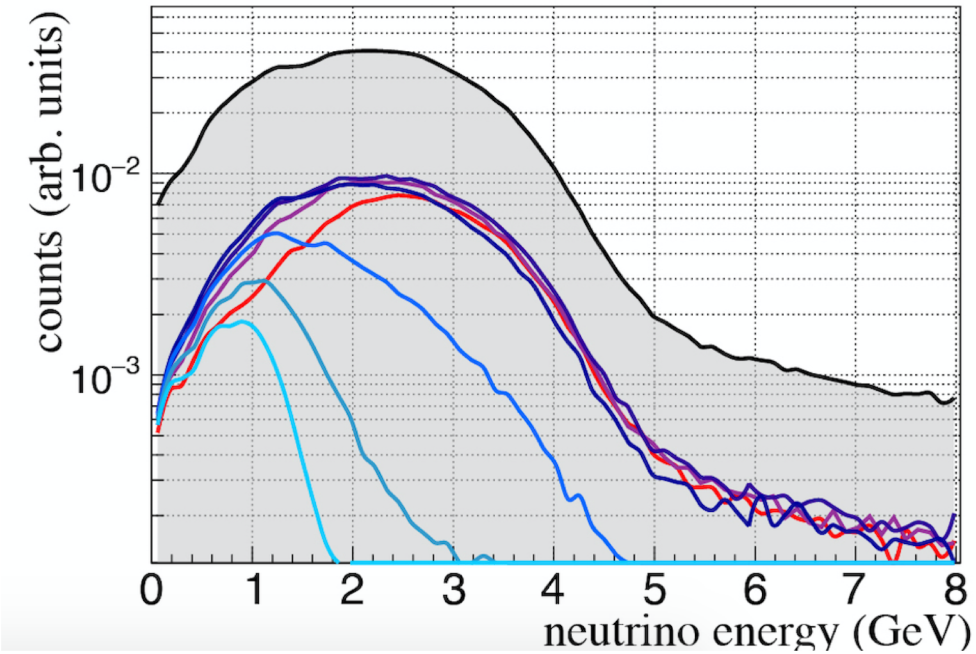
Near detector moves relative to beam axis
(plot courtesy of Michael Wilking and DUNE TDR)



utilizes **angular** kinematics of hadrons to select different spectra

Stroboscopic

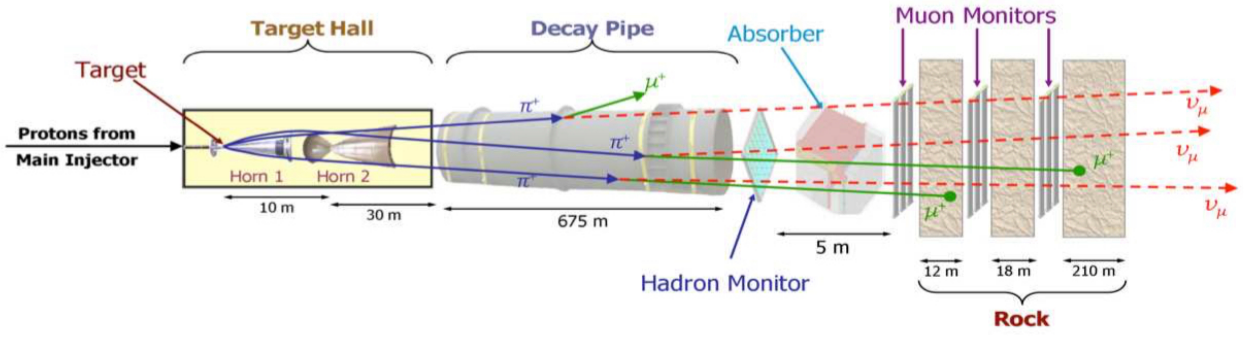
Measure time-of-arrival relative to proton bunch



utilizes **timing** kinematics of hadrons to select different spectra

Two hadrons with different energies decay at different times

Neutrinos arrive at different times



$$\Delta t = \tau_0[(1-\beta_2)\gamma_2 - (1-\beta_1)\gamma_1]$$

$\beta_1 \to 1$ (compare highly relativistic hadron to lower energy hadron)

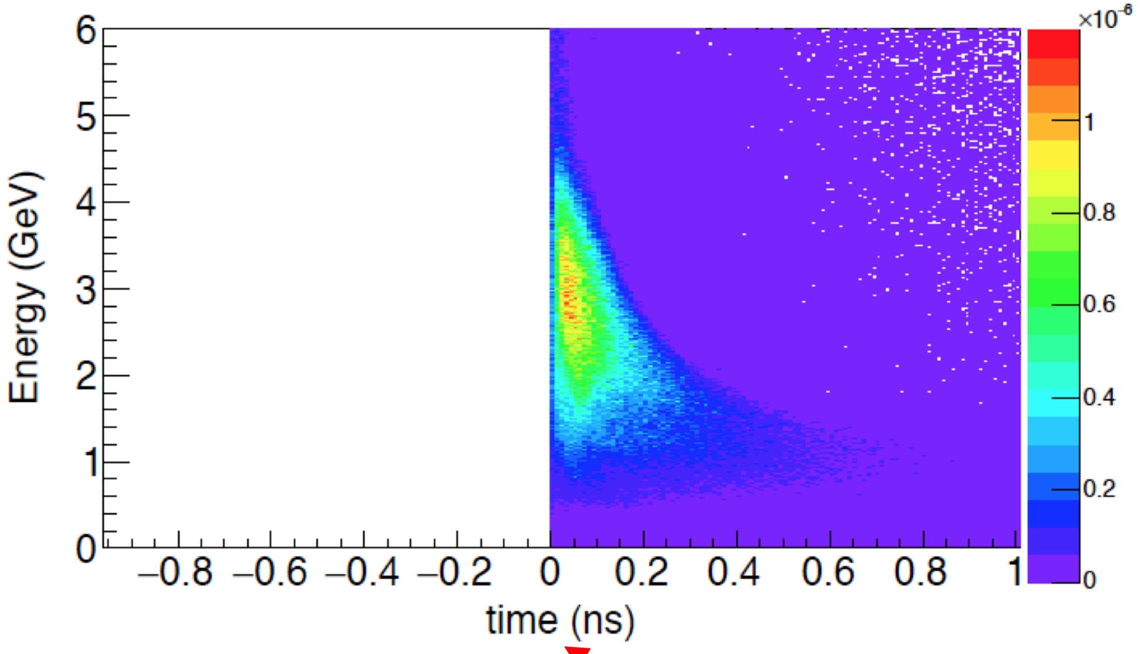
$$\Delta t = (\gamma_2\tau_0)(1-\sqrt{1-1/\gamma_2^2})$$

Some limiting cases

$\gamma_2 \to \infty$ $\quad \Delta t = (\gamma_2\tau_0)(\frac{1}{2\gamma_2^2})$

$\gamma_2 \to 1$ $\quad \Delta t = \tau_0$

Hadron and neutrino timing relative to 0-width proton bunch



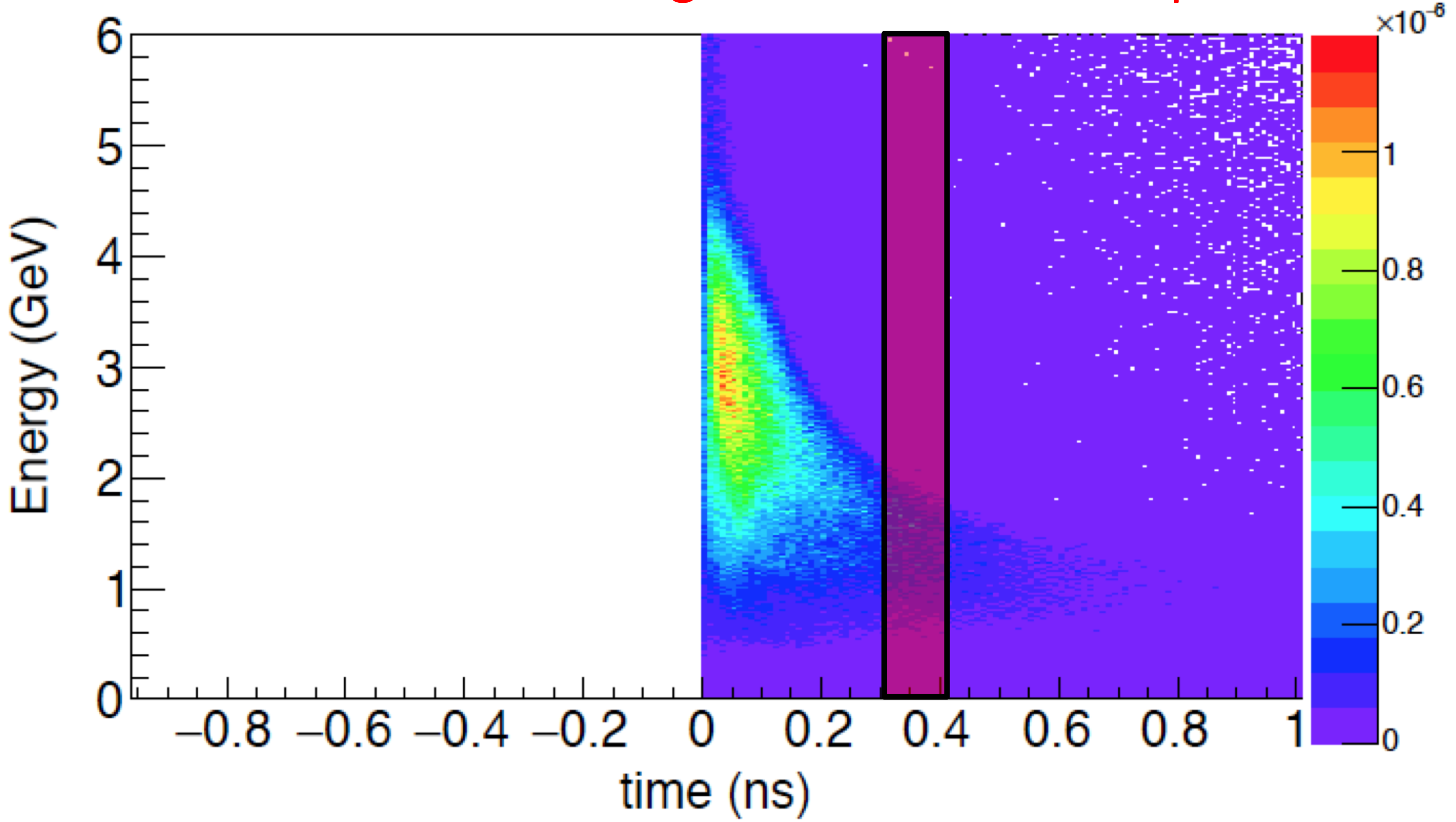
Simulation code from:

T. e. a. Alion (DUNE), Experiment Simulation Configurations Used in DUNE CDR , FERMILAB-FN-1020-ND, (2016), arXiv:1606.09550 [physics.ins-det].

Simulations by Matthew Wetstein

Introduction to the stroboscopic energy selection

Hadron and neutrino timing relative to 0-width proton bunch

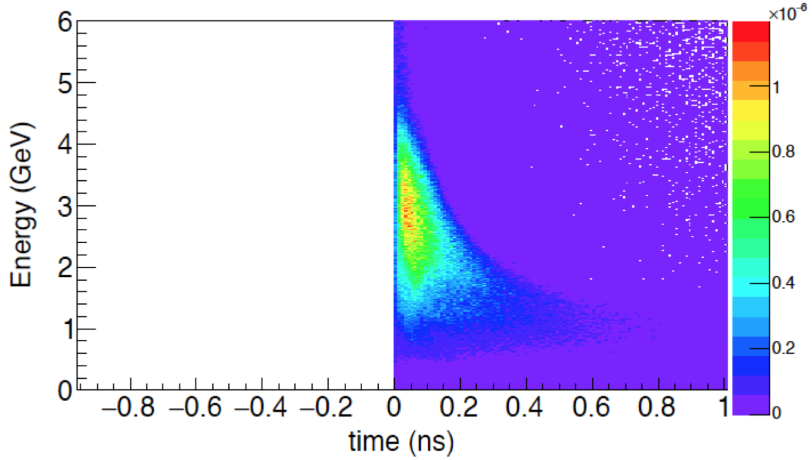


Selection of energy using timing relative to proton bunch

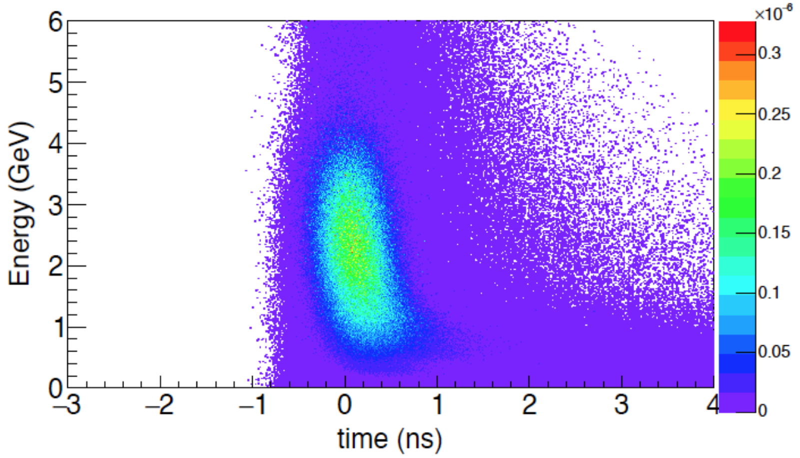
<u>What is needed to perform this selection?</u>

- Measurement of the time when hadrons are born
- Measurement of the time of arrival of the neutrino at a detector (~100 ps level)
- A thin distribution of hadron birth times (thin proton bunch)

Proton bunch width

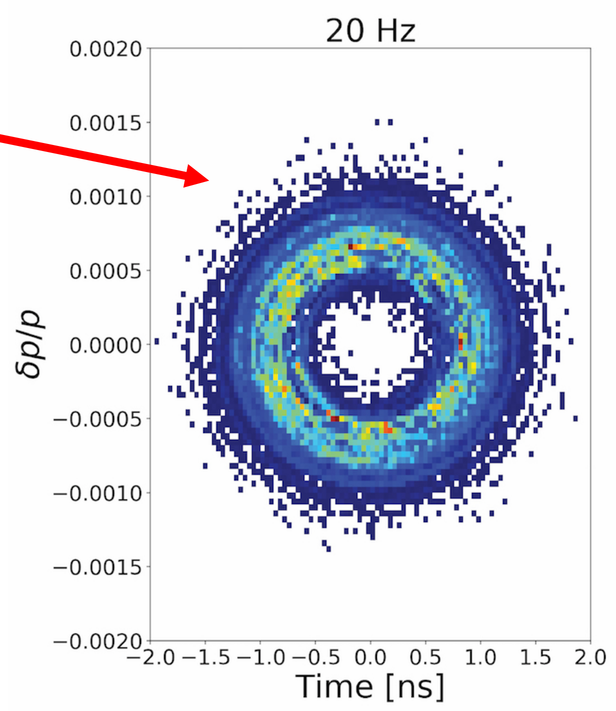


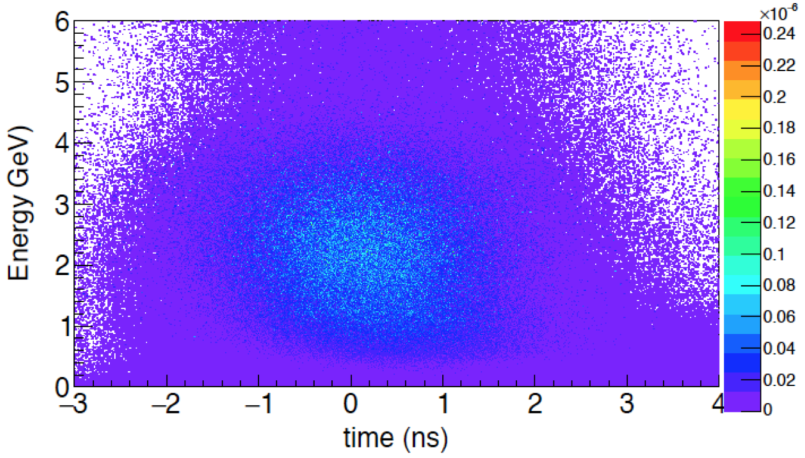
0 ps bunch width



250 ps bunch width

Current simulated MI distribution LBNF/DUNE





1000 ps bunch width (current Fermilab MI)

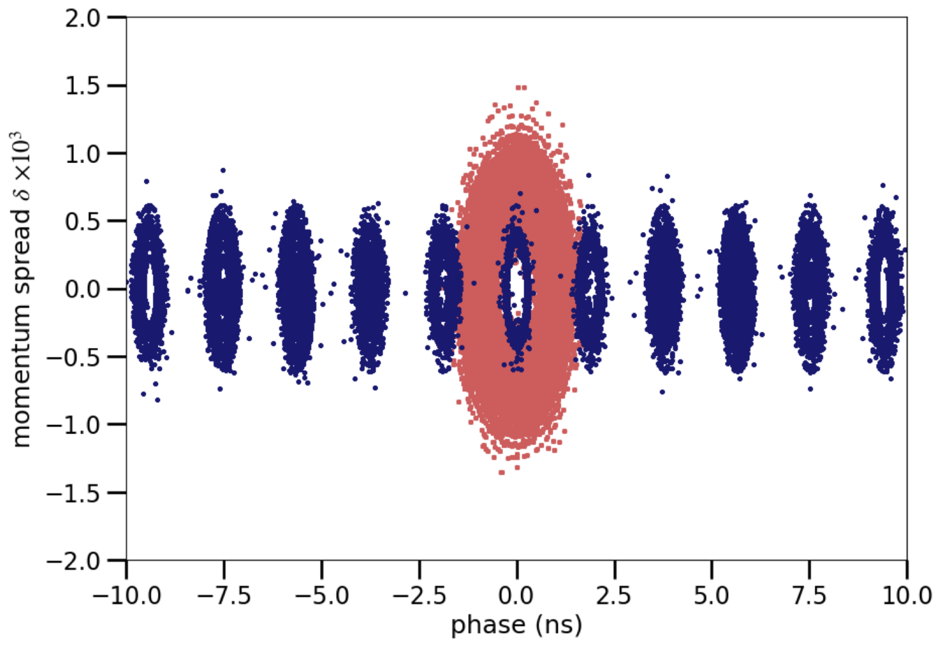
Need an accelerator modification to form ~200 ps wide bunches

One possible method for thin bunches at Main Injector

Initial simulations performed by Evan Angelico and Sergei Nagaitsev, confirmed by Paul Derwent at Stroboscopic workshop

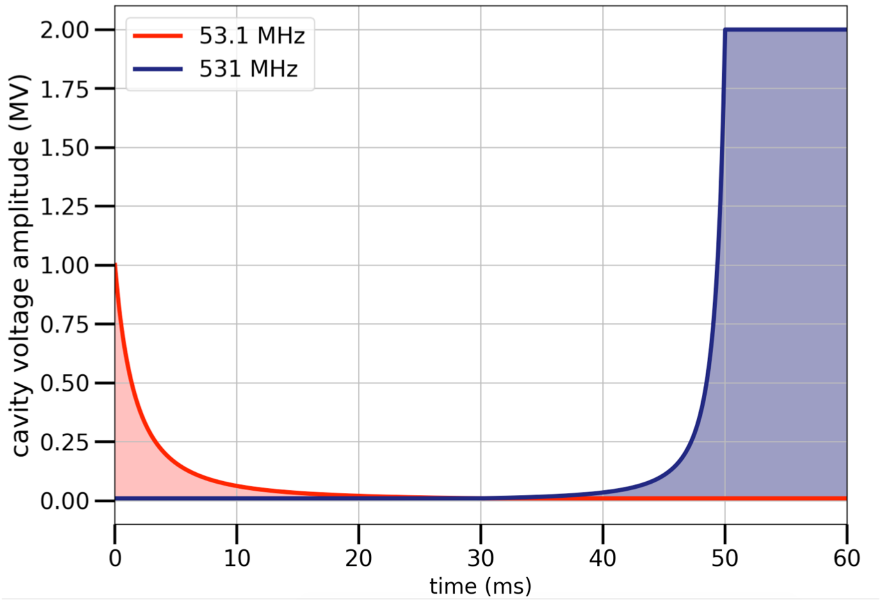
Red: main injector protons after acceleration

Blue: main injector protons after rebunching



Red: 51.3 MHz cavity voltage

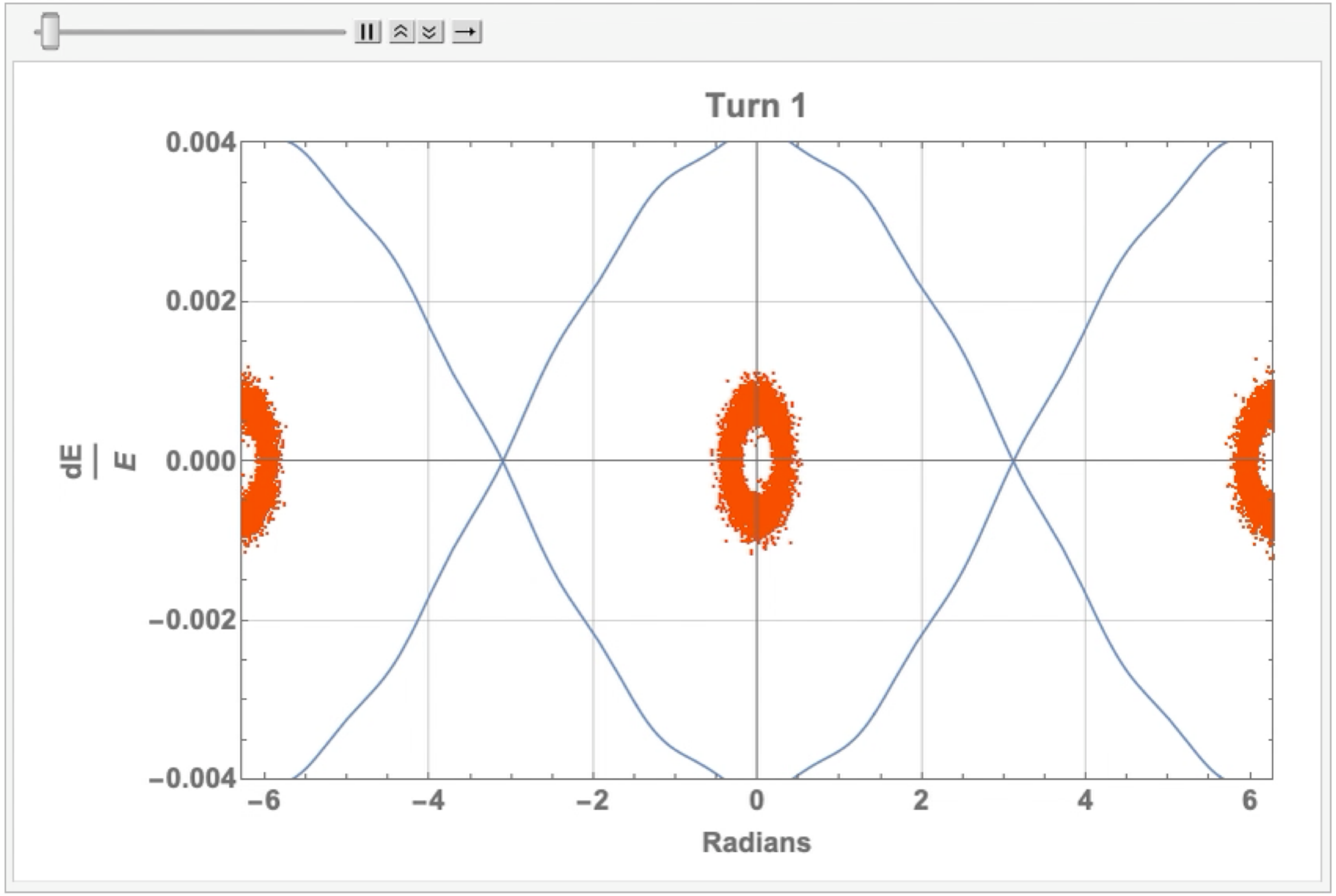
Blue: 531 MHz cavity voltage



Rebunching from 53.1 MHz @ 4.6 MV to 531 MHz @ 4 MV produces reasonable bunch widths

1 ns bunches spaced at 20 ns goes to ~150 ps bunch spaced at 2 ns

Re-bunching simulation video



Taken from Paul Derwent, AD/RF Department Fermilab, “Main Injector Scenarios”, Precision Time Structure Workshop

Candidate RF cavity

Investigated by Sergei Nagaitsev and Sergey Belomestnykh

1. Cavity considerations
   a. Rebunch after acceleration – at ‘flat-top’

   b. MI is 53.1 MHz. 531 MHz non-superconducting cavity will have a small dynamic aperture. Superconducting will allow for the large dynamic aperture at 531 MHz. Only need one cavity.

   c. Cornell B-Cell Cavity is SC at 500 MHz, commercially produced

2. Rebunching has been done in other settings
   a. Mu2e rebunches Fermilab 53.1 MHz to 2.5 MHz

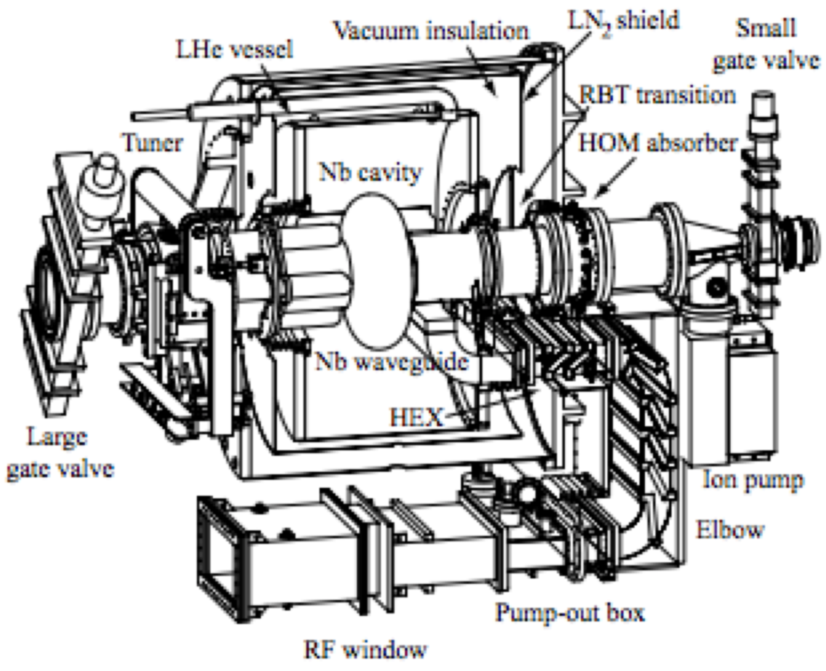


Figure 1. Layout of the B-cell cryomodule.

S. Belomestnykh et. al. Operating experience with superconducting RF at CESR and overview of other SRF related activities at Cornell University

Spectra resulting from simulation using rebunched protons

Realistic Flux Simulation organized by Matthew Wetstein

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

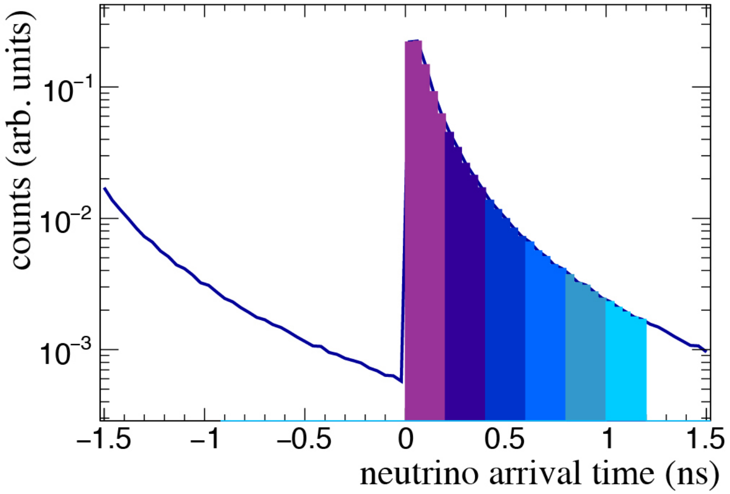
- Optimized 3-Horn Design presented at the October 2017 Beam Optimization Review (used in the DUNE TDR)
- Timing information is included in the ntuples
- All simulated protons hit the target at the same time

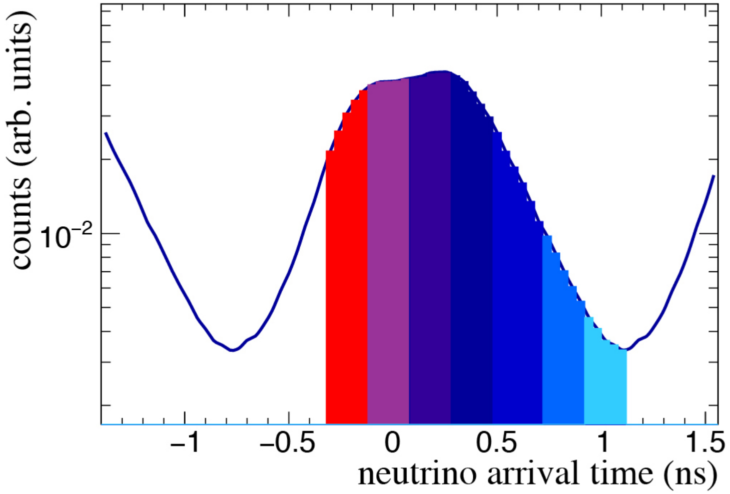
- We convoluted the proton hit times with the timing of the emergent bunch structure from the accelerator simulations
- We also added 100 spec Gaussian smearing to account for plausible, albeit ambitious detector capabilities
- We also added in the effects of pileup from the previous bunches

From Matt Wetsteins talk at Fermilab Wine and Cheese Nov 1st 2019

Spectra resulting from simulation using rebunched protons

Zero-width proton bunches at 2 ns spacing

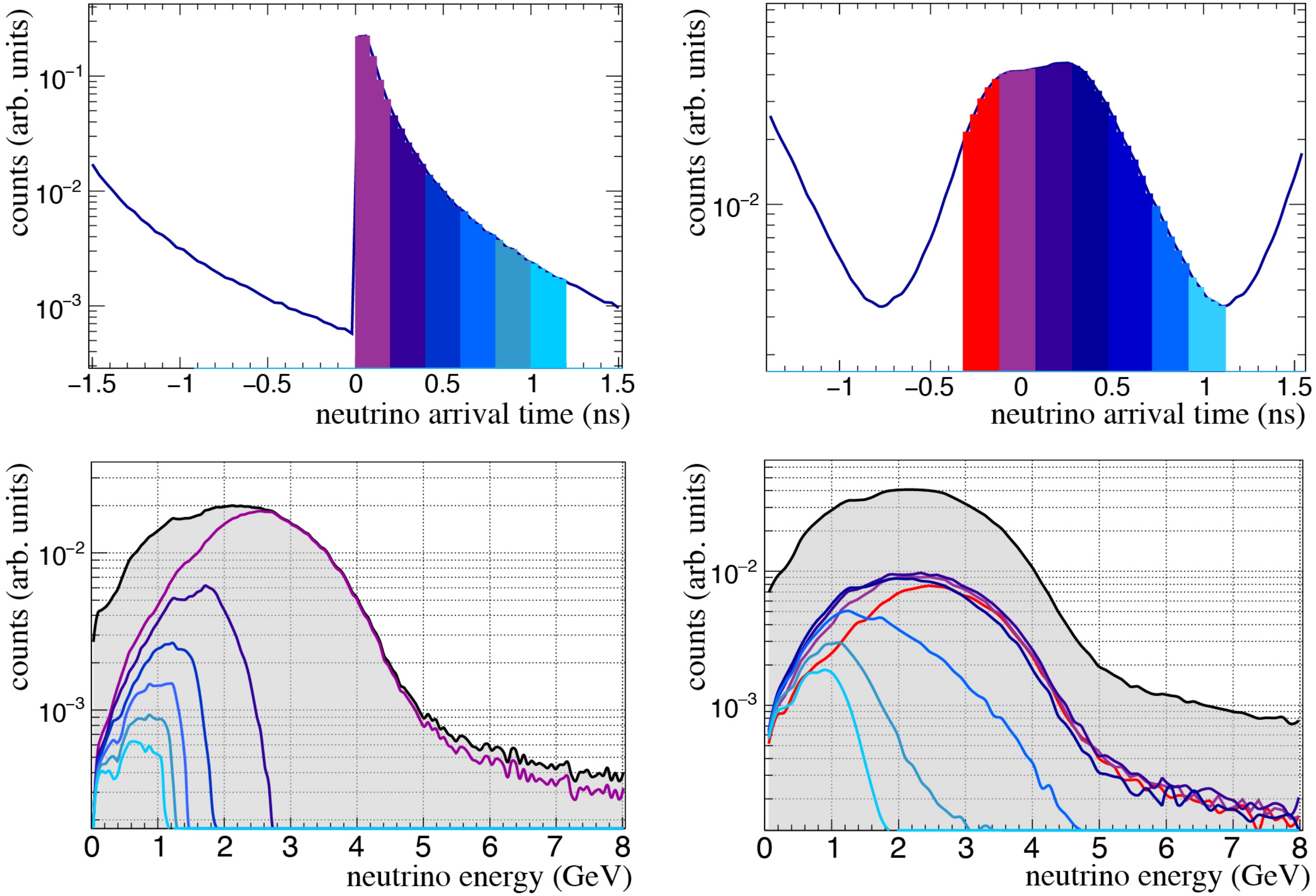




250 ps wide proton bunches from rebunching simulations
+
100 ps detection timing resolution

Spectra resulting from simulation using rebunched protons

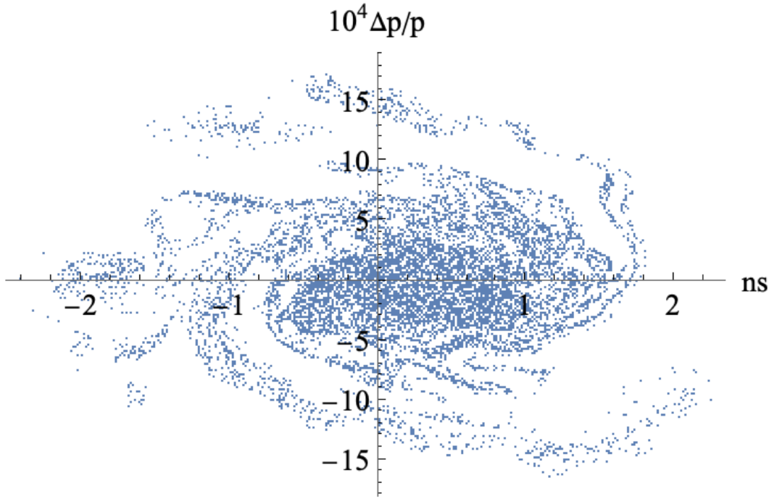
Zero-width proton bunches at 2 ns spacing



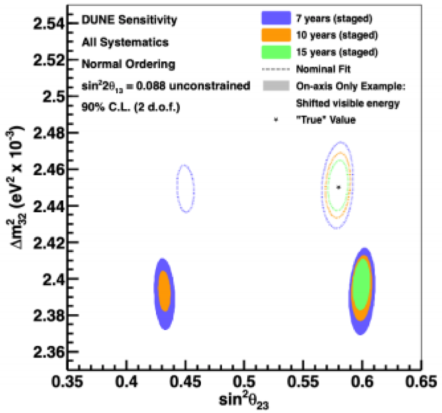
250 ps wide proton bunches from rebunching simulations + 100 ps detection timing resolution

Workshop on Precision Time Structure in On-Axis Neutrino Beams, Nov 2&3 2019

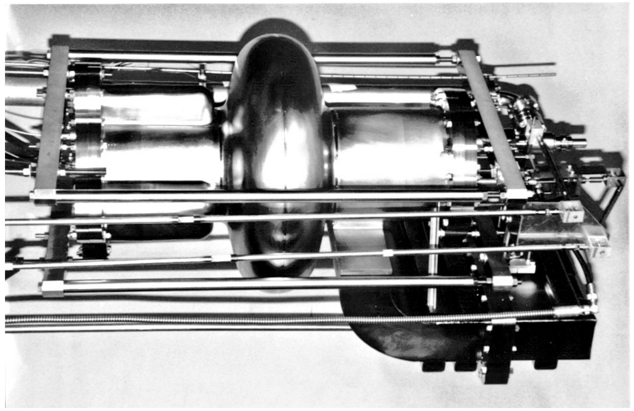
https://indico.fnal.gov/event/21409/



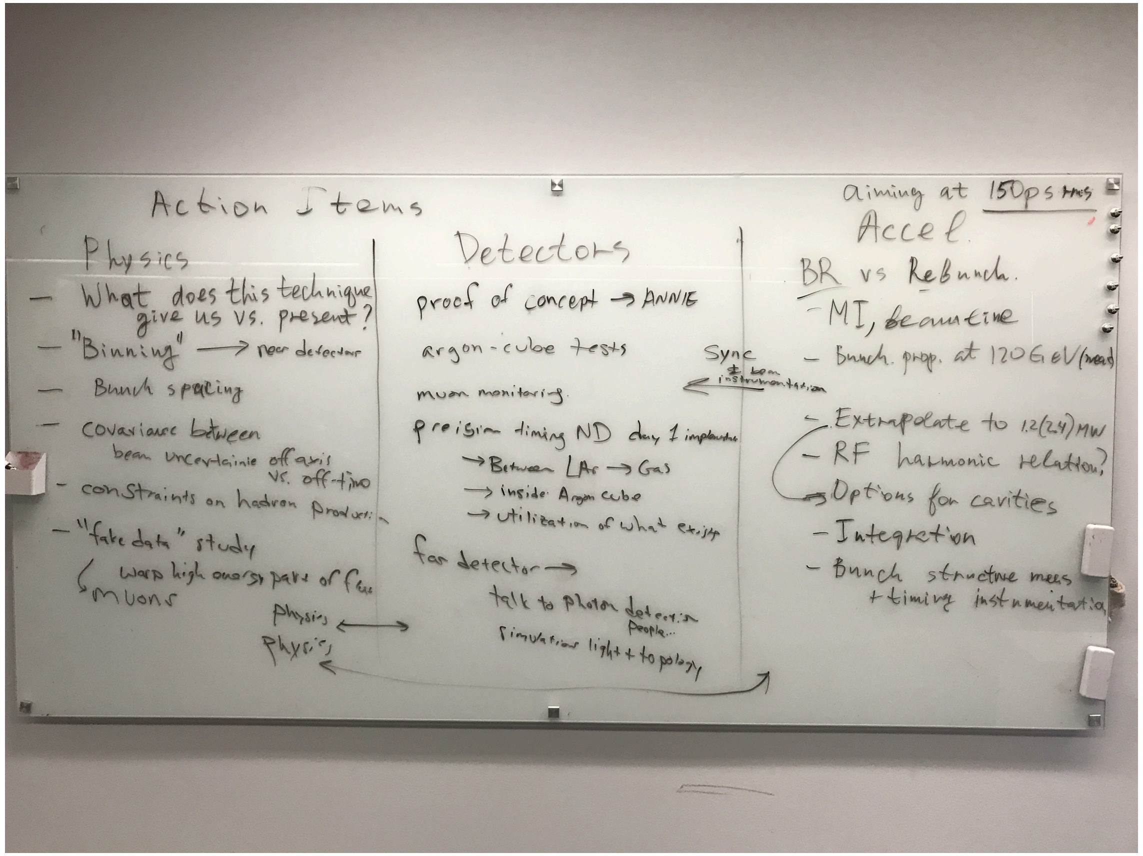
Alexey Burov



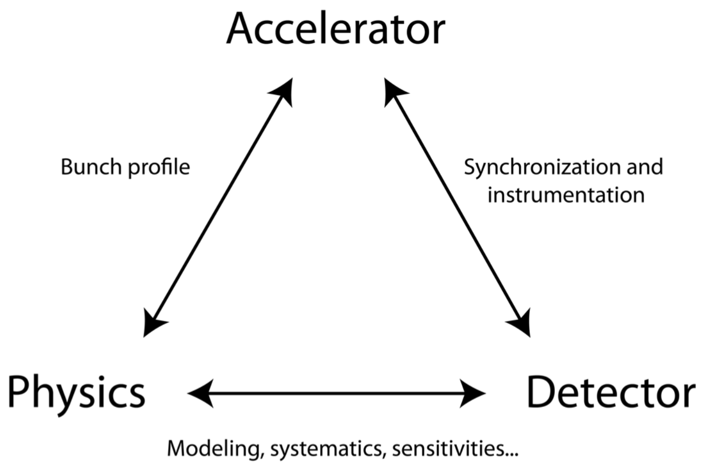
Michael Wilking



Matthew Wetstein



Some items discussed at workshop



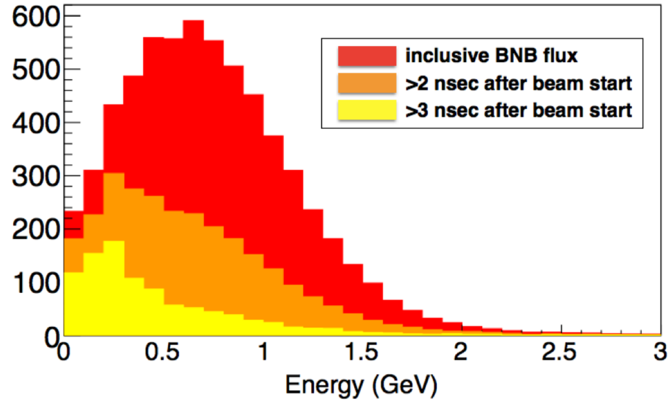
Physics impact

Need to assess the impact that these spectra have on neutrino physics. For example, running analysis with DUNE systematics and warped data; observe the ways in which having the timing information detects issues with systematics

Detector systems

Develop time transfer methods to synchronize proton bunch to detector systems. Simulate fast-timing detection systems, for example the detection of Cherenkov light. Proof of concept with ANNIE detector at Fermilab

ANNIE at Fermilab with no re-bunching



Accelerator systems

Explore possible alternative methods to re-bunching at higher harmonic. Measure main injector longitudinal phase space after acceleration. Characterize cavity impedances, and extrapolate from 1.2 to 2.4 MW scenario

Action items formed for each category

Summary

- Additional handles on neutrino energy combat detector systematics
- A method of using timing to constrain neutrino energies is being explored, idea is documented here: https://doi.org/10.1103/PhysRevD.100.032008
- Stroboscopic approach and DUNE-PRISM approach are complimentary, providing another layer of flux constraints
- A proton re-bunching strategy has been simulated, seems feasible but further exploration of accelerator systems is necessary
- How does having these fluxes affect physics reach?

Thank you

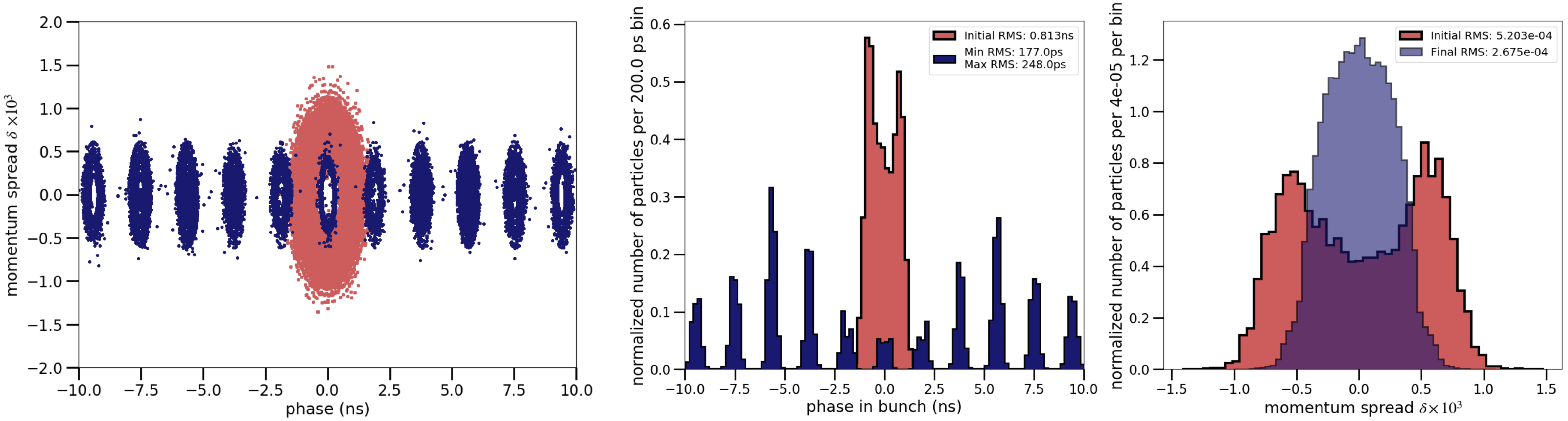
Backup

One possible method for thin bunches at Main Injector

Initial simulations performed by Evan Angelico and Sergei Nagaitsev, confirmed by Paul Derwent at Stroboscopic workshop

Red: main injector protons after acceleration

Blue: main injector protons after rebunching



Rebunching from 53.1 MHz @ 4.6 MV to 531 MHz @ 4 MV produces reasonable bunch widths

1 ns bunches spaced at 20 ns goes to ~150 ps bunch spaced at 2 ns