Energy discrimination using precision time structure in on-axis neutrino beams

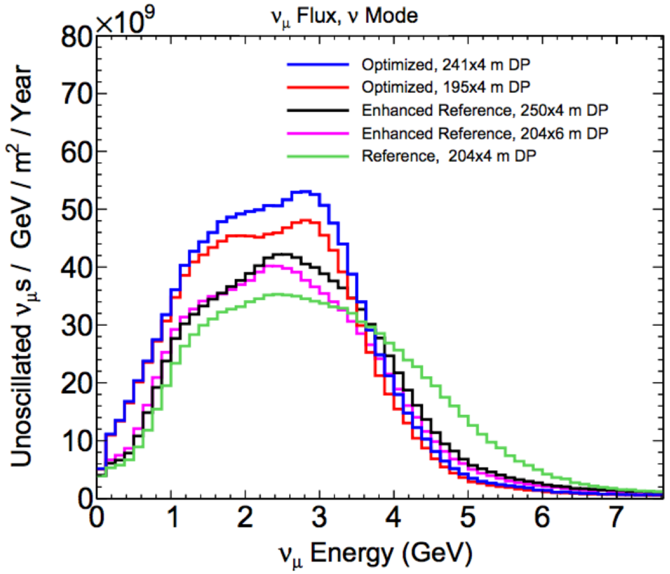
E. Angelico,[1] J. Eisch,[2] A. Elagin,[1] H. J. Frisch,[1] S. Nagaitsev,[3] and M. Wetstein[2]

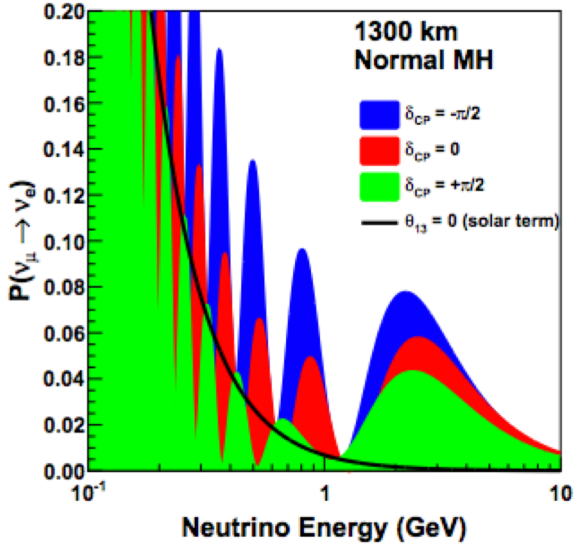
[1] *Enrico Fermi Institute, University of Chicago, Chicago IL 60637*
[2] *Iowa State University, Ames IA 50011*
[3] *Fermi National Accelerator Laboratory, Batavia IL 60510*

arXiv: 1904.01611, Phys Rev D submission in progress

Broadband neutrino sources

- Broadband neutrino sources are useful for a wide variety of measurements, in particular neutrino oscillation physics where one wants to map oscillation probabilities continuously from 500 MeV to 5 GeV+
- Near and far detectors need to be able to reconstruct the energy of neutrino interactions. Calorimeters have finite energy resolution. Energy measurement can be challenging when there are intense numbers of neutrinos of all energies
- Additional methods for energy discrimination, such as prismatic or off-axis detection, provide *independent* handles on the energy of interactions





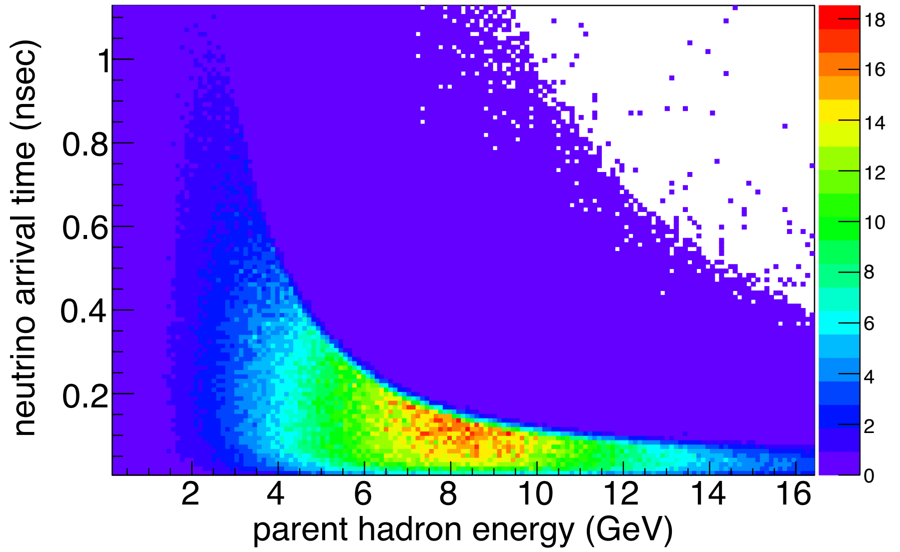
Both plots from the LBNF and DUNE Conceptual Design Report volume 2, Jan 2016

Parent hadrons have an energy spread that can be exploited

Nu beam kinematics plots by Matthew Wetstein, thank you Zarko Pavlovic and Laura Fields for DUNE flux simulations

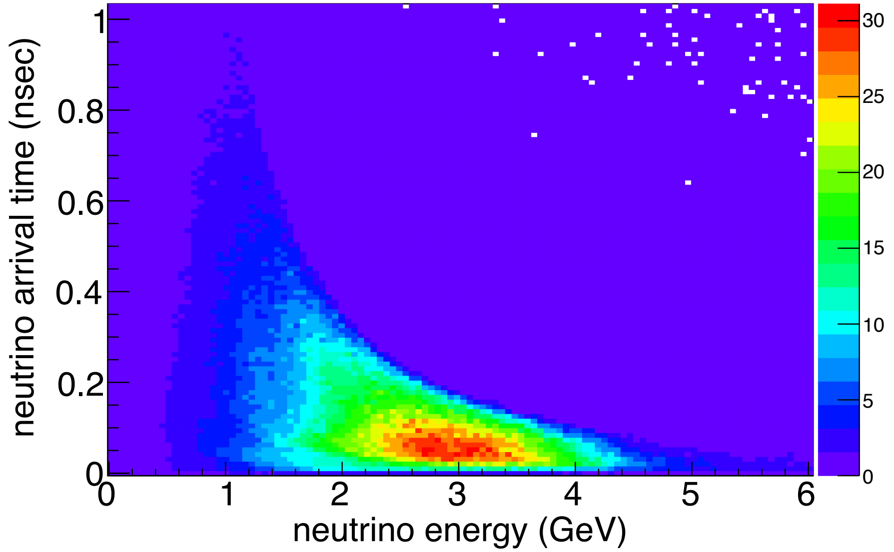
T. e. a. Alion (DUNE), Experiment Simulation Configurations Used in DUNE CDR , FERMILAB-FN-1020-ND, (2016), arXiv:1606.09550 [physics.ins-det].

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



In the limit of the higher energy neutrino being highly relativistic

$$\beta_1 \to 1$$



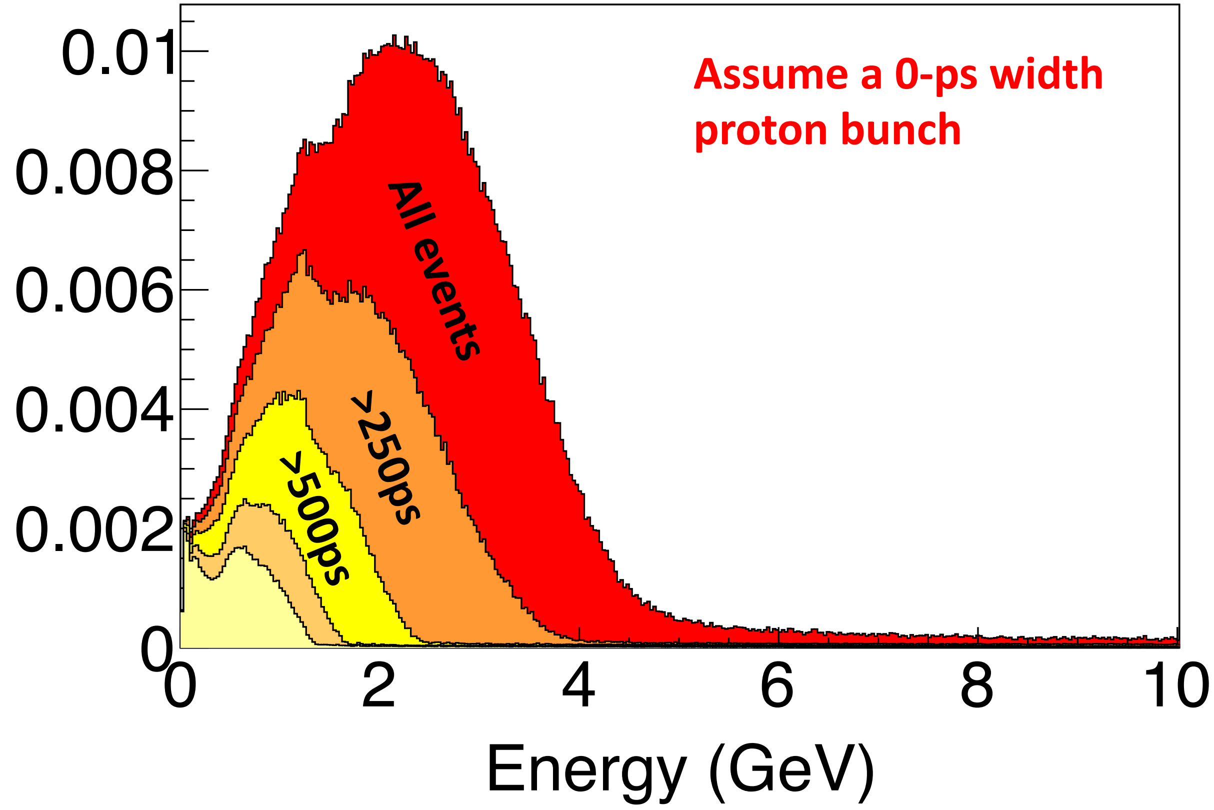
$$\Delta t = (1-\beta_2)\gamma_2\tau_0$$

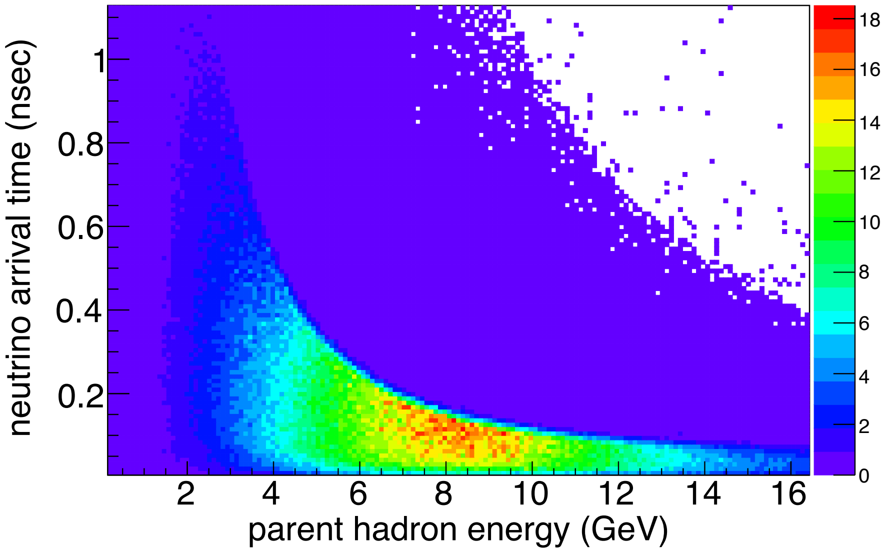
$$= (\gamma_2 - \sqrt{\gamma_2^2 - 1})\tau_0$$

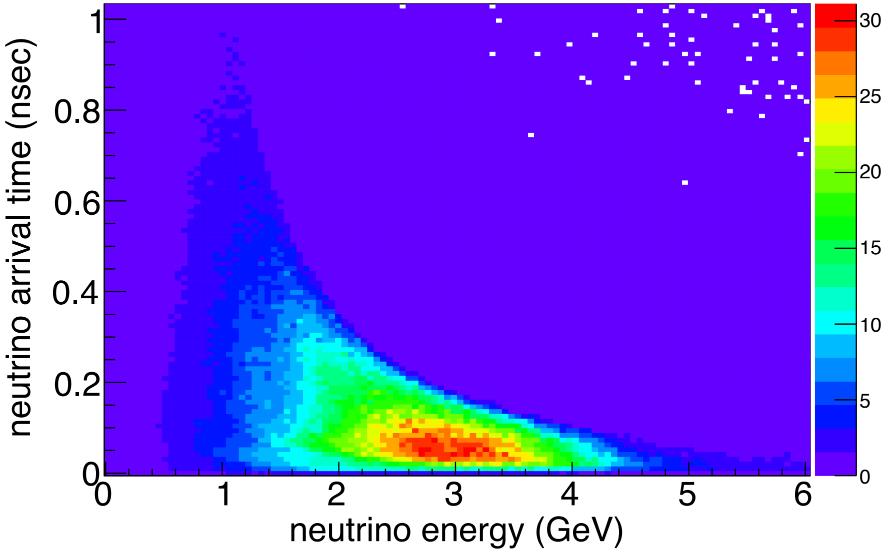
Parent hadrons have an energy spread that can be exploited

Nu beam kinematics plots by Matthew Wetstein

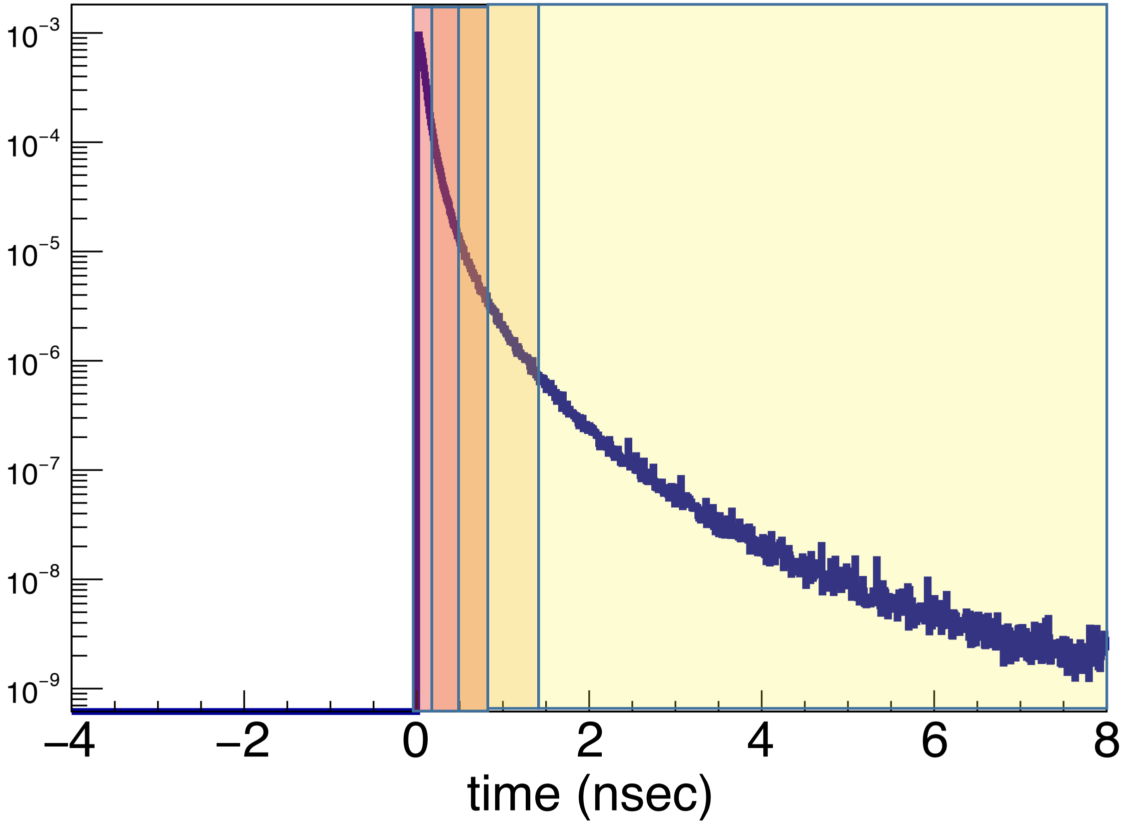
T. e. a. Alion (DUNE), Experiment Simulation Configurations Used in DUNE CDR , FERMILAB-FN-1020-ND, (2016), arXiv:1606.09550 [physics.ins-det].

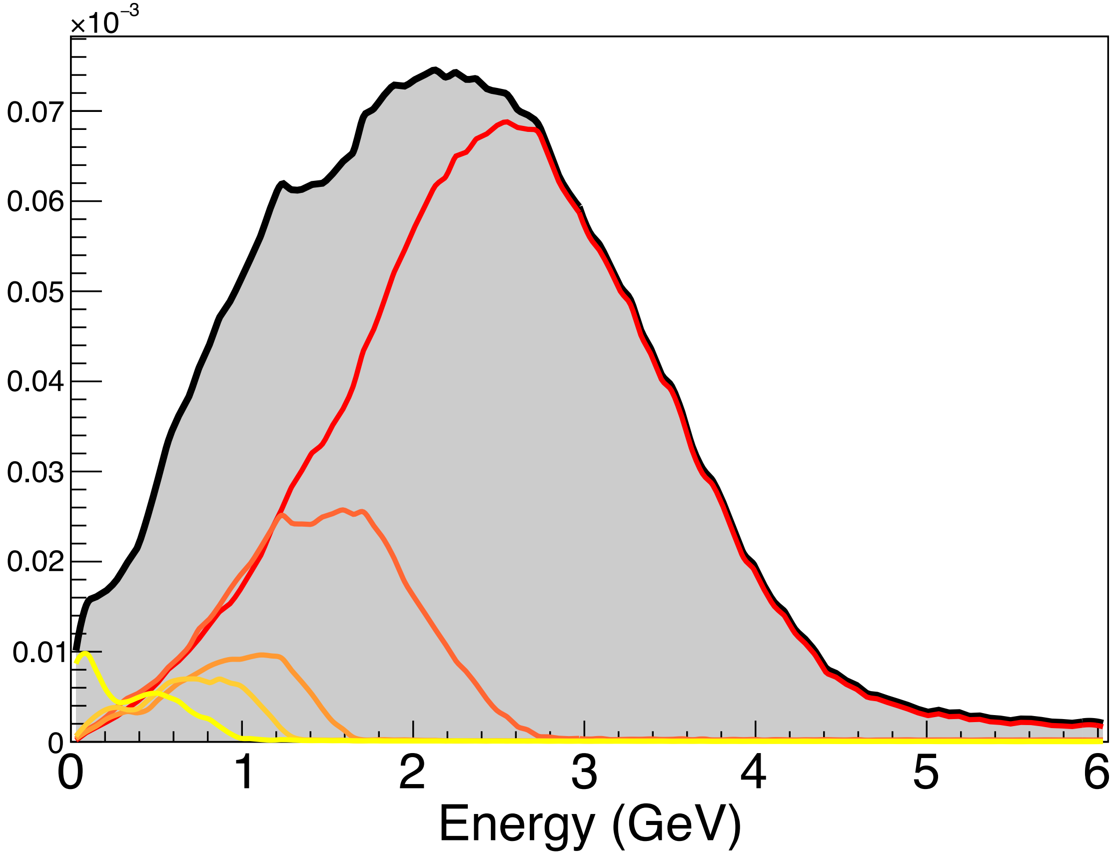






Parent hadrons have an energy spread that can be exploited



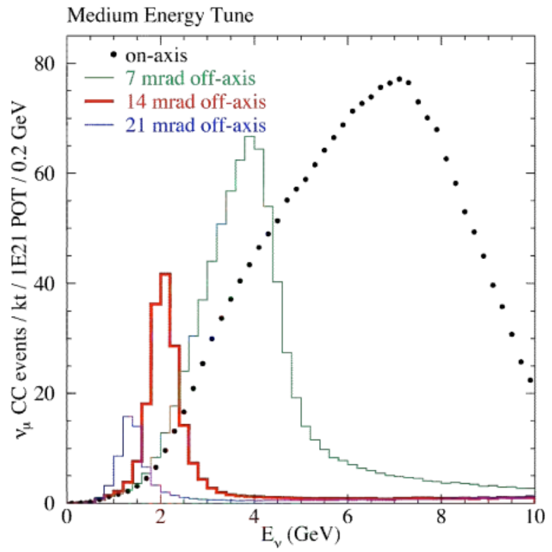


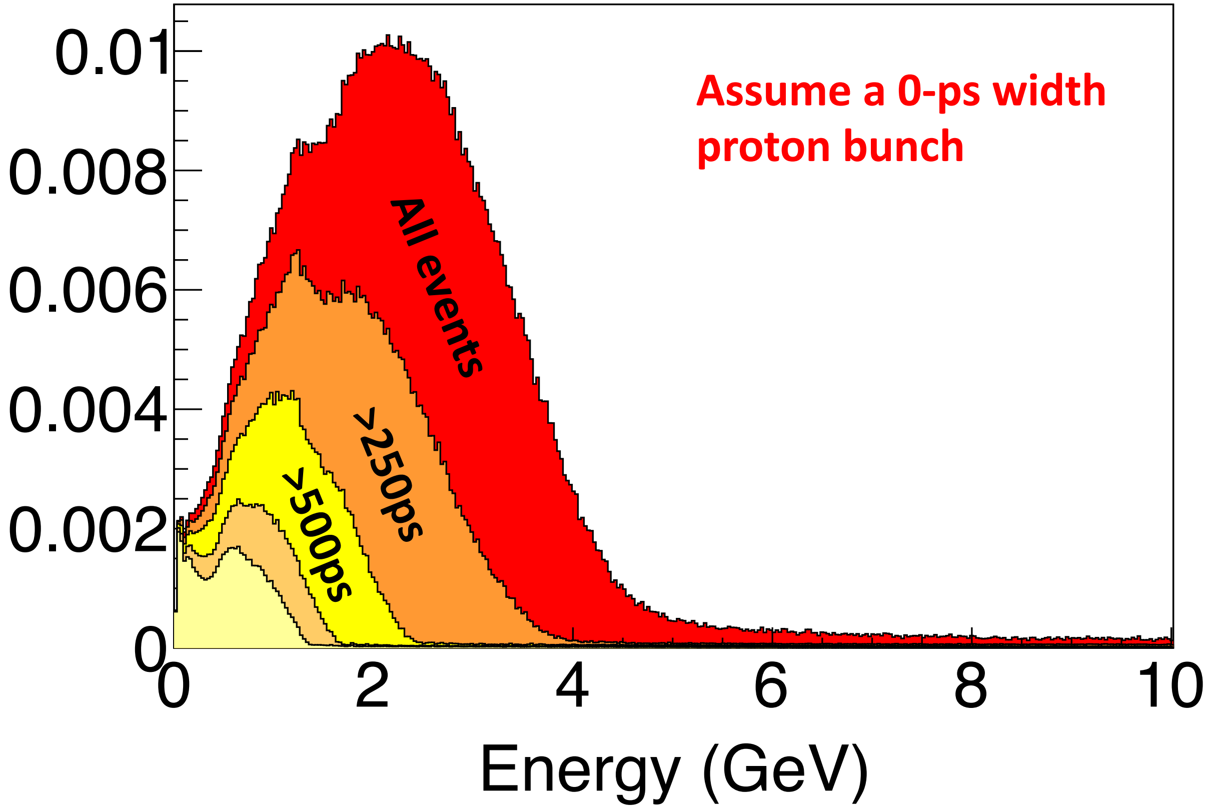
Binned in arrival time: left plot shows time selection bins with colors for the right plot

Practical Considerations

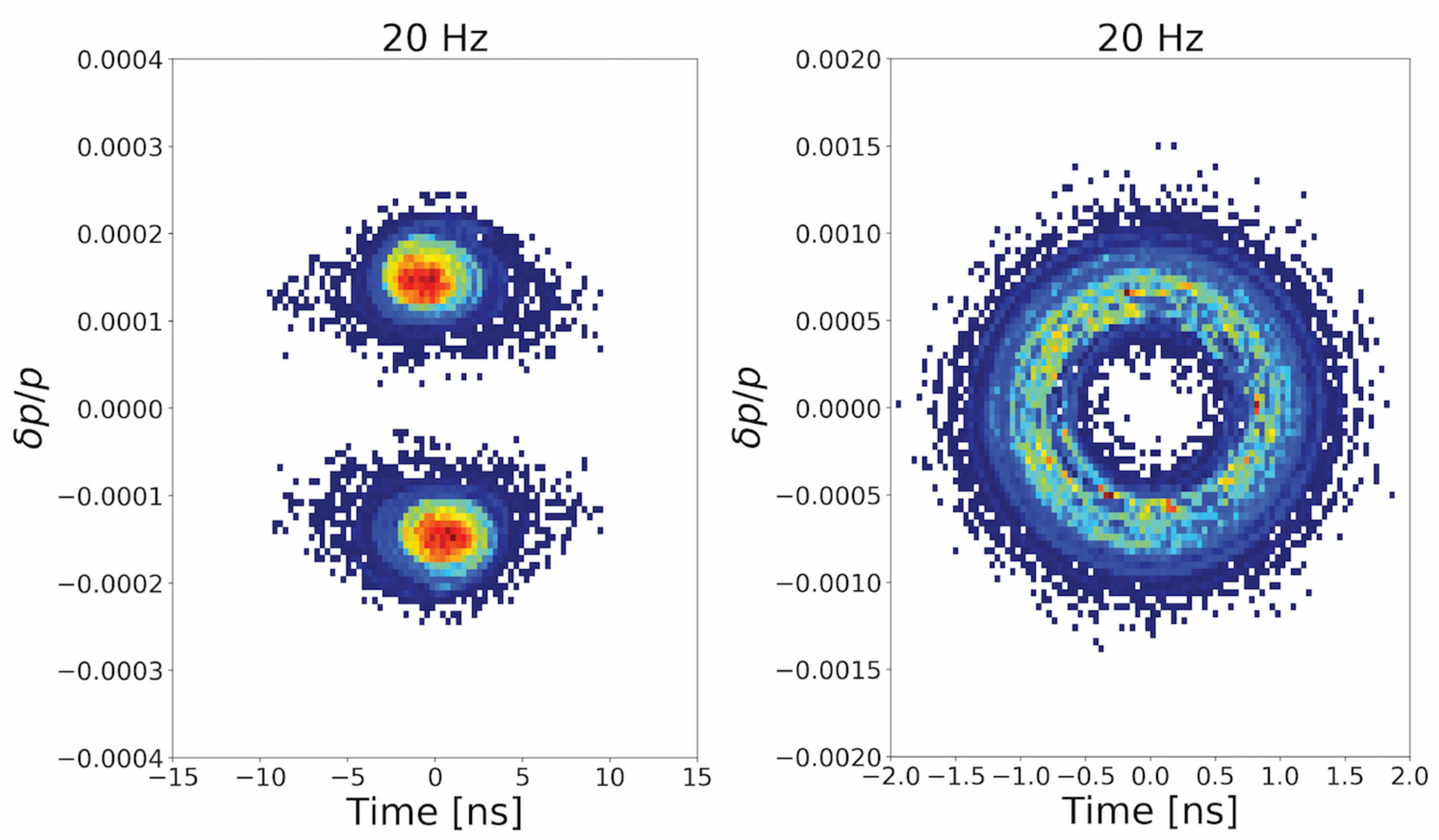
1. Detector timing measurement/resolution on the order of <100 ps
2. Proton bunch widths on the order of 100 ps

NOvA Technical Design Report. Figure 2-1. 2007





Practical considerations of making O(100 ps) proton bunch widths

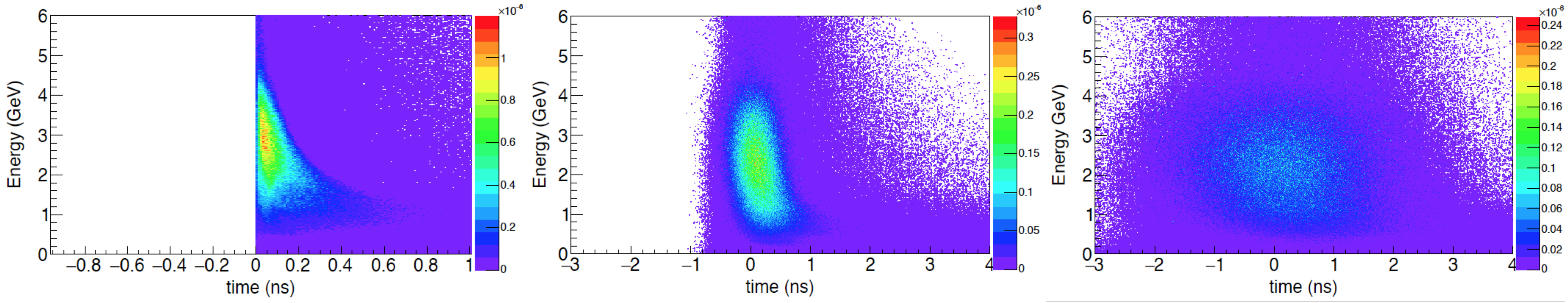


Figures courtesy of Robert Ainsworth and conference proceedings: R. Ainsworth et. al *Transition Crossing in the Main Injector for PIP-II.* IPAC18

The Fermilab Main Injector (MI) as a use-case

Width of proton bunch affects energy/time distribution

Nu beam kinematics plots by Matthew Wetstein



0 ps bunch width **250 ps bunch width** **1000 ps bunch width**

Want the shortest bunch possible as a time reference for parent hadron creation

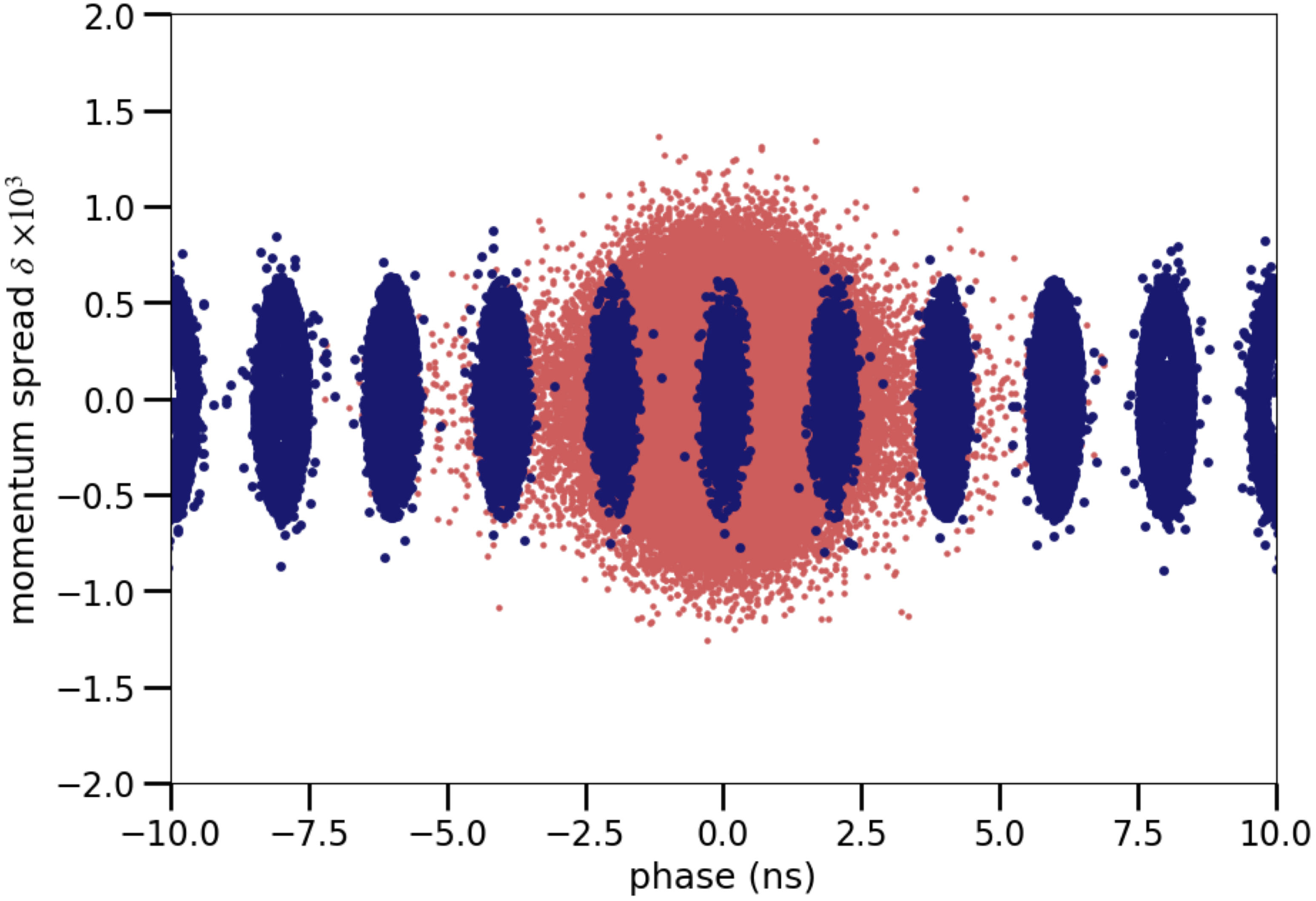
How to make short bunches

Research/simulations by
Sergei Nagaitsev and E. Angelico

Louiville Theorem. This longitudinal phase space area is preserved (under transformations that preserve energy or are adiabatic)

- Do not try to squeeze in the dp/p direction (not enough HV, not enough dynamic aperture)

- Instead superimpose a higher harmonic (10x) RF frequency to make 10 shorter bunches



Rebunch!

This is a reasonable idea:

Credit Sergei Nagaitsev

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

3. First rough-draft simulations have decent results

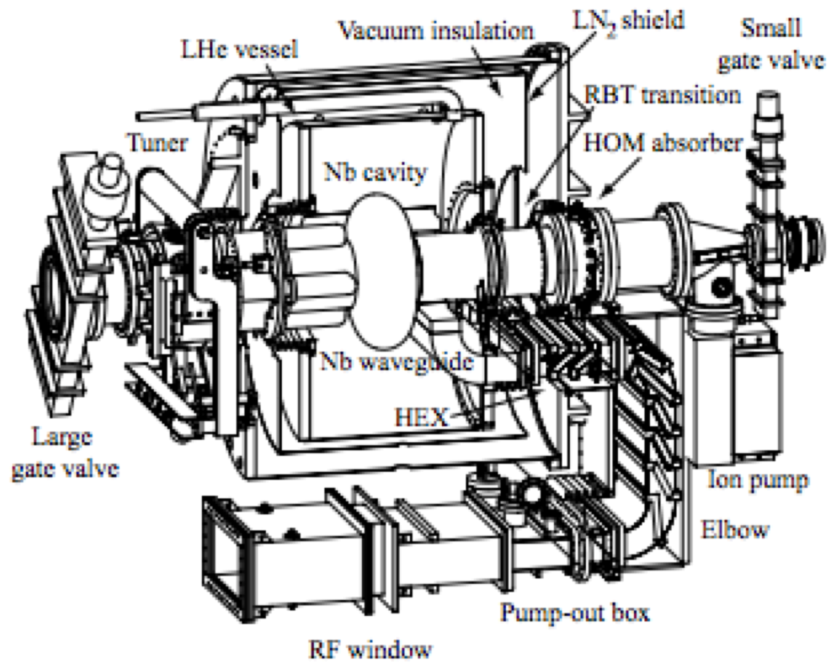
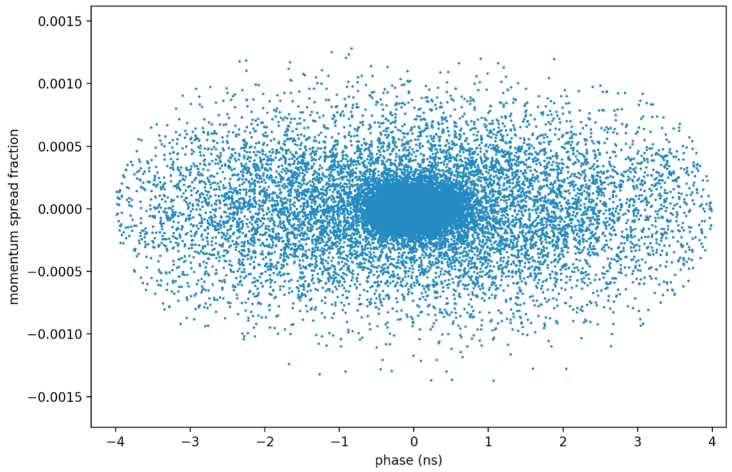


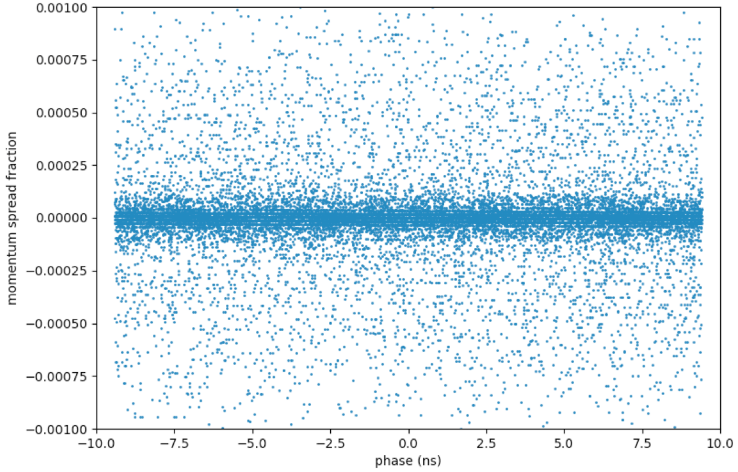
Figure 1. Layout of the B-cell cryomodule.

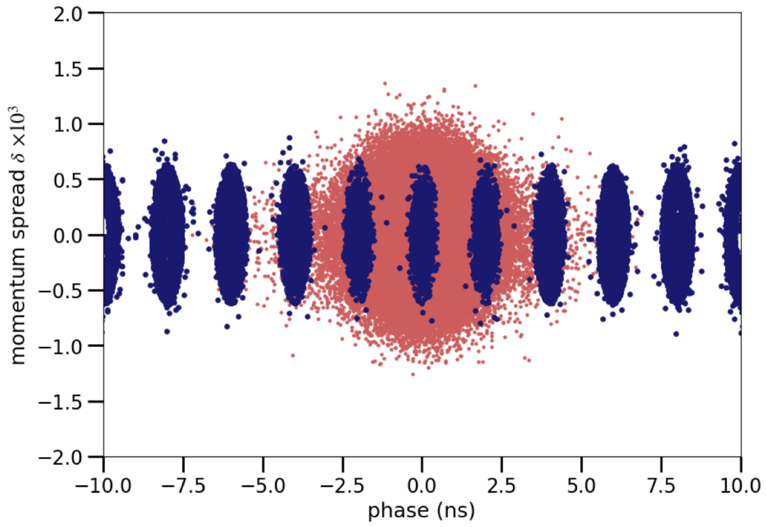
S. Belomestnykh et. al. Operating experience with superconducting RF at CESR and overview of other SRF related activities at Cornell University

Rebunching simulations

Research/simulations by Sergei Nagaitsev and E. Angelico



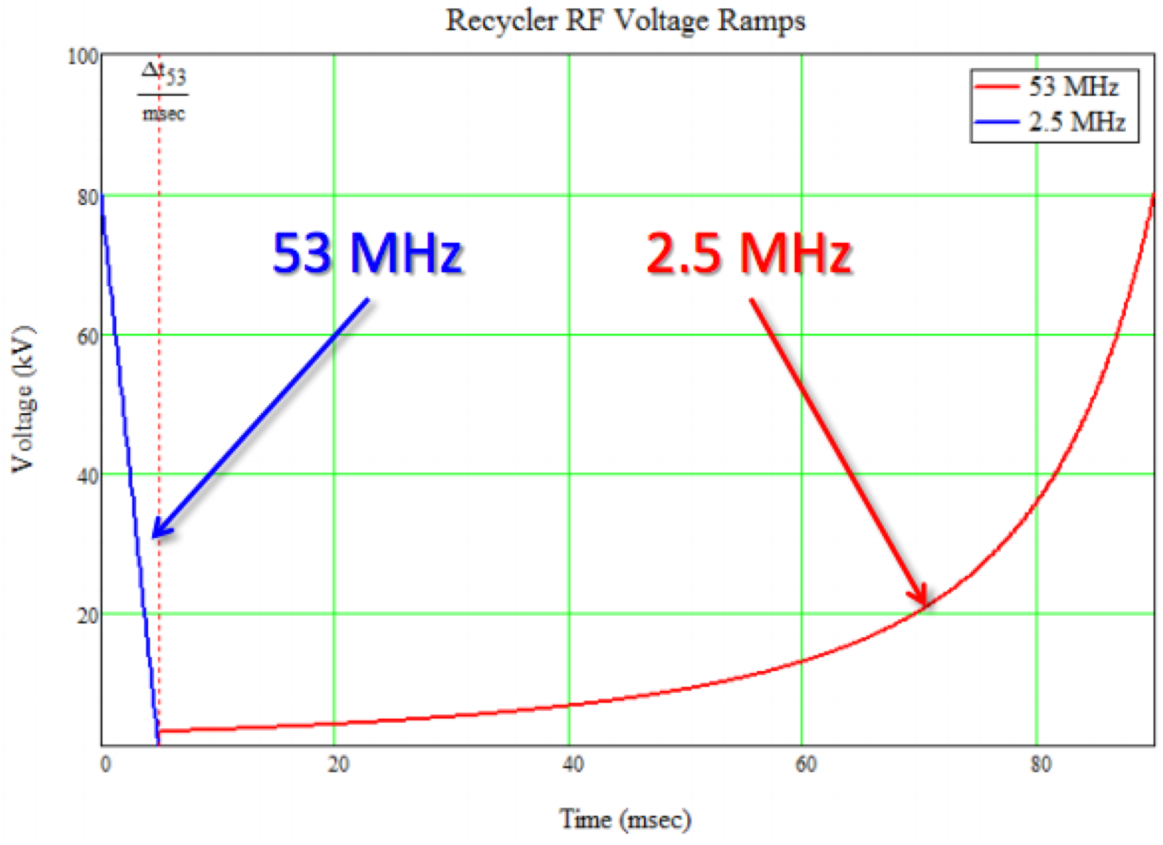


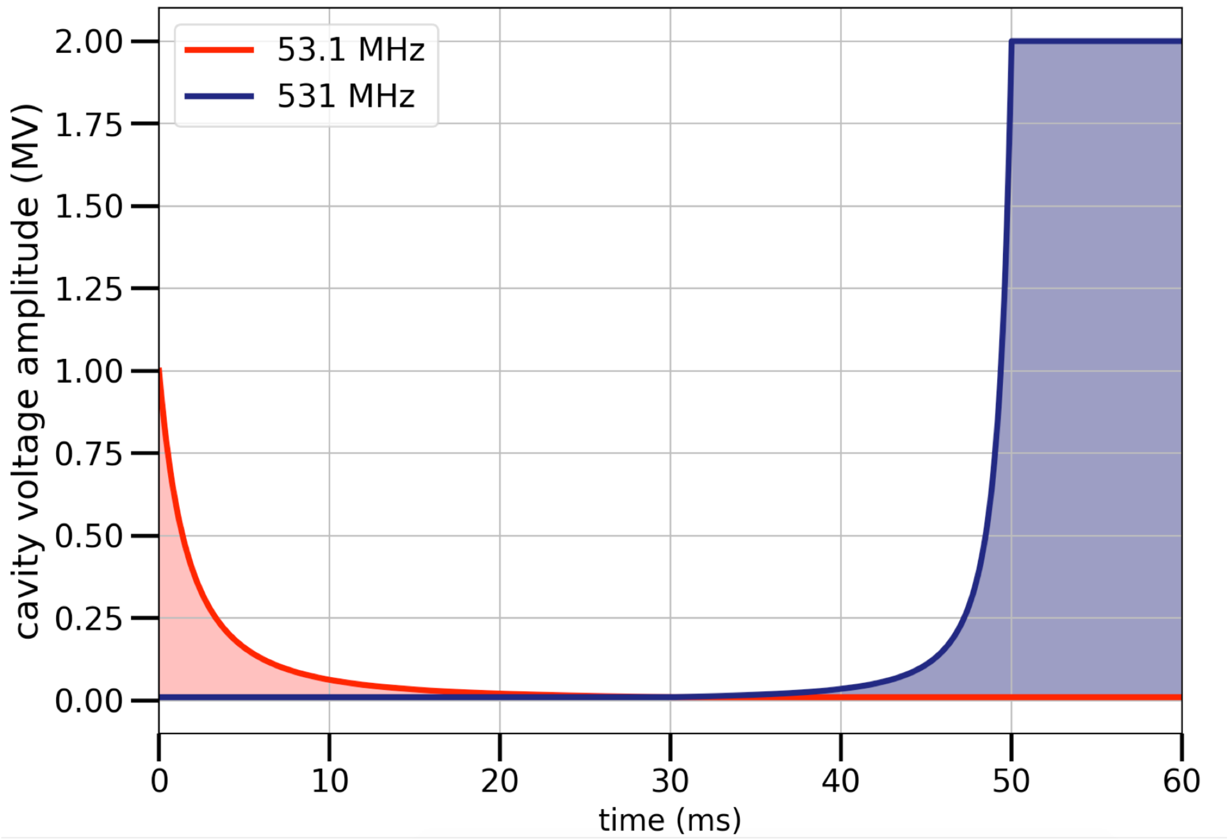


Considerations

- Time-scale set by synchrotron frequency. Adiabatic changes are long compared to synch. freq.
- Entire rebunching cycle takes between 40-80 ms. Can be optimized. **Keep ~5% of 1.2 ms dump rate**

Rebunching simulations





Steve Werkema. "Simulation of Bunch Formation Mu2e Longitudinal Phase Space. Presentation at Mu2e Extinction Technical Review. Nov 2015

Simulations by Sergei Nagaitsev and E. Angelico

Voltage functions from: K. Y. Ng, Adiabatic capture and debunching , FERMILAB-FN-0943-APC, 10.2172/1038543 (2012).

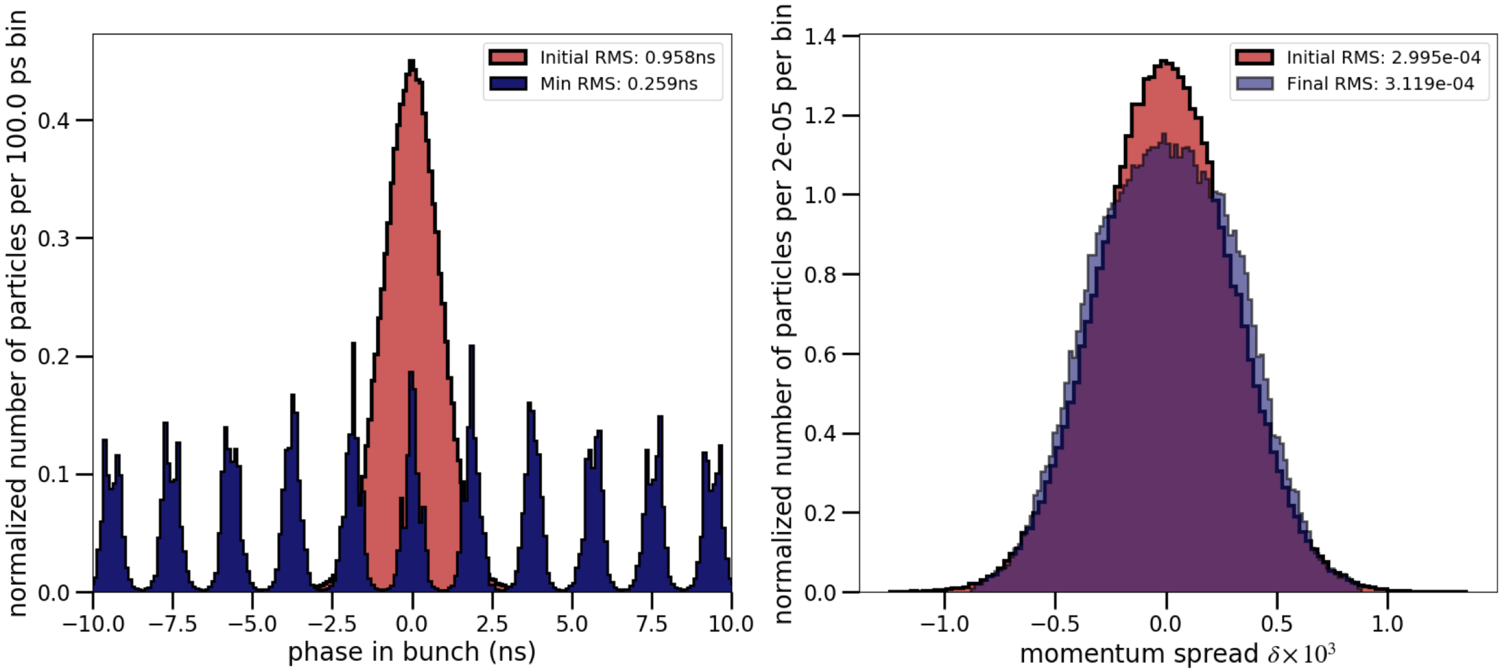
Research/simulations by Sergei Nagaitsev and E. Angelico

Rebunching simulations

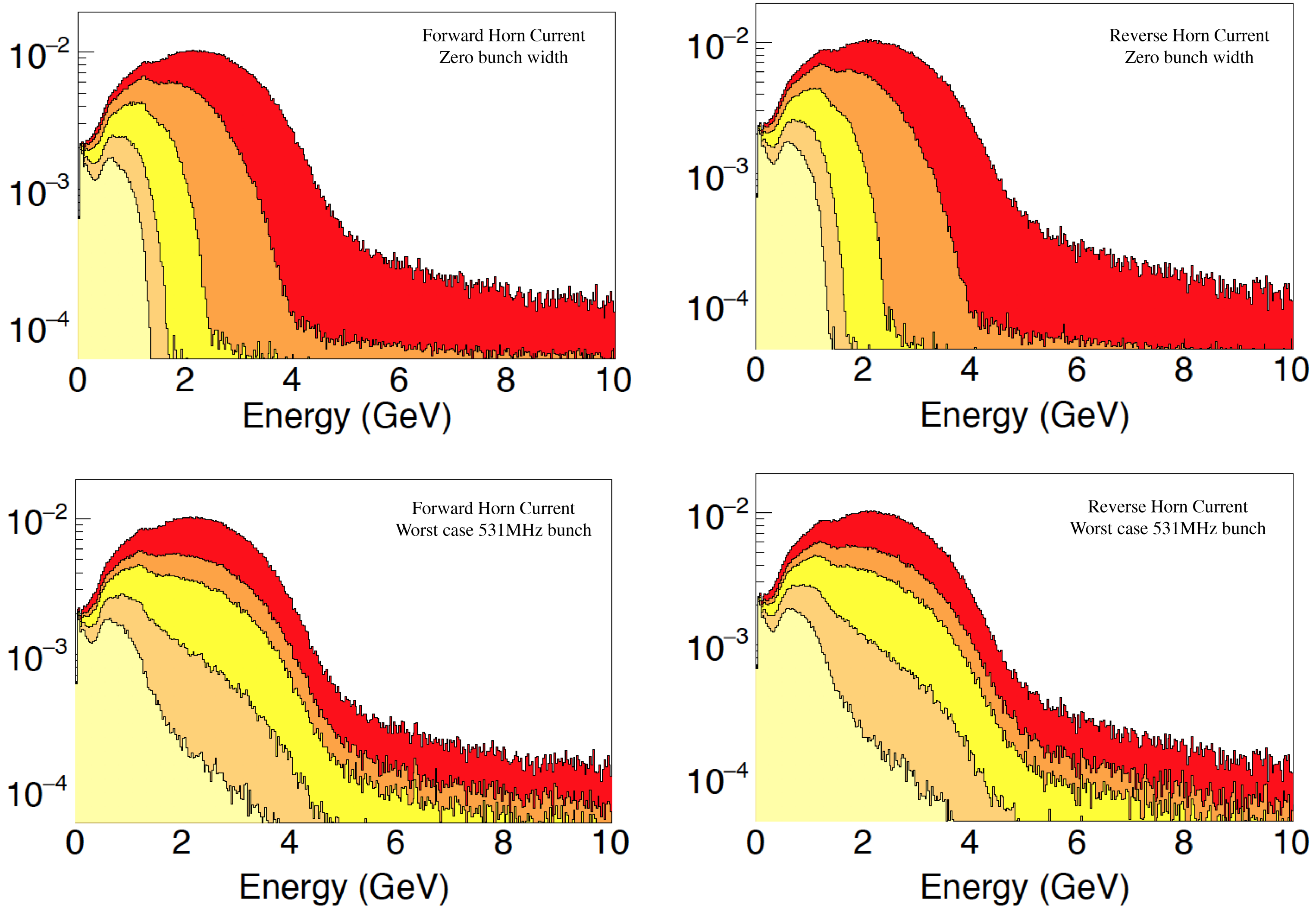
Takeaway: with little optimization, we can achieve 150-250 ps wide proton bunches

Working on now:

- Using real FNAL proton distributions / full scan of time-scales for optimum procedure
- Can't set cavities to 0V. How is rebunching affected
- Beam loading changes during rebunching. Cavity considerations
- Robinson/longitudinal instabilities



Effect of non-zero bunch width on energy discrimination



To do: Clocks and synchronization

- Fermilab would be a great place to develop time distribution systems
  - Europe has a wide landscape of technologies
  - FNAL has fast timing efforts in CMS that could lead
  - FNAL has experiments on-site that would be good test-beds

- Experiments at Fermilab that could be a test-bed
  - ANNIE detector (100 m)
  - LAPPD time-of-flight setup in FTBF (10 – 100 m)

Menlo Systems GmbH

Fermilab as a driving force for timing distribution

To do: Beam monitoring

(may be many methods to monitor, this is one example from T2K)

- Effort from BIWG specifically and Accelerator division/target systems department
- A 10ps level precise input to the clock/synchronization system (prompt-decay muon monitor? Transition radiation monitor?)

What monitoring technology/configuration should be used?

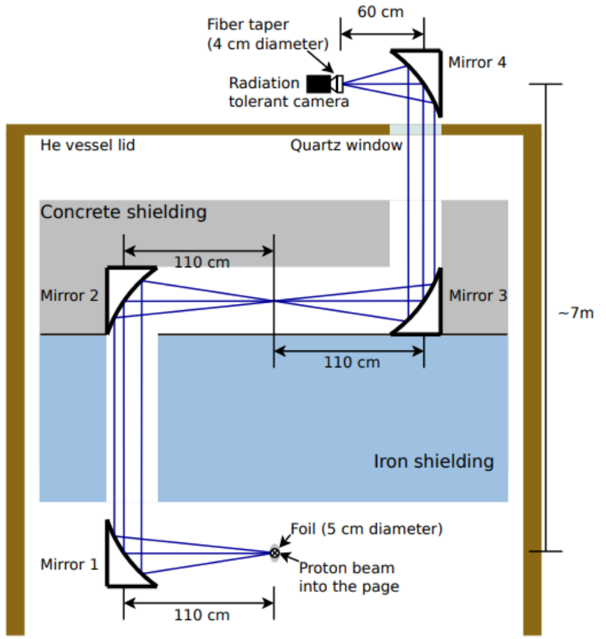


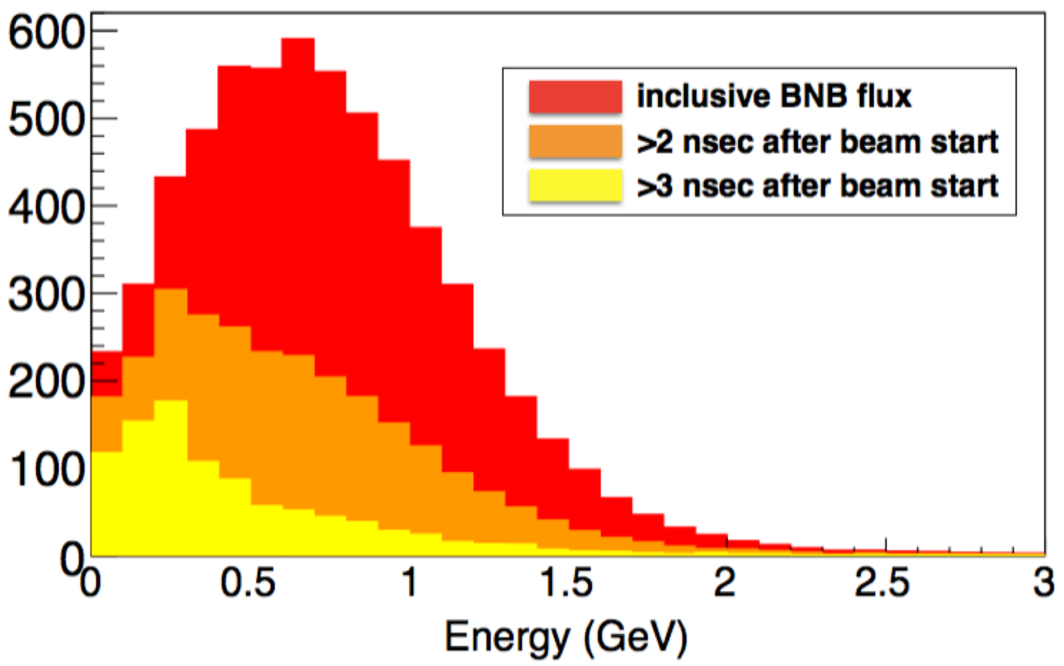
Figure 3: This figure shows a slice through the optical path of the OTR system where the proton beam is going into the page and striking the foil. Three light rays illustrate the focussing properties of the optics.

S. Bhadra et. al. *Optical Transition Radiation Monitor for the T2K Experiment*. arXiv:1201.1922v1 . 2012

To do: First demonstration

- Even with the 1 nsec bunch sizes of the BNB, this stroboscopic technique is demonstrable in ANNIE next year (2019/2020)
- Because the BNB has a lower peak beam energy, a higher fraction of the parent pions fall in the sub-relativistic shoulder → the effect is more pronounced
- ANNIE will have the timing resolution and likely have the beam signals to carry this out.

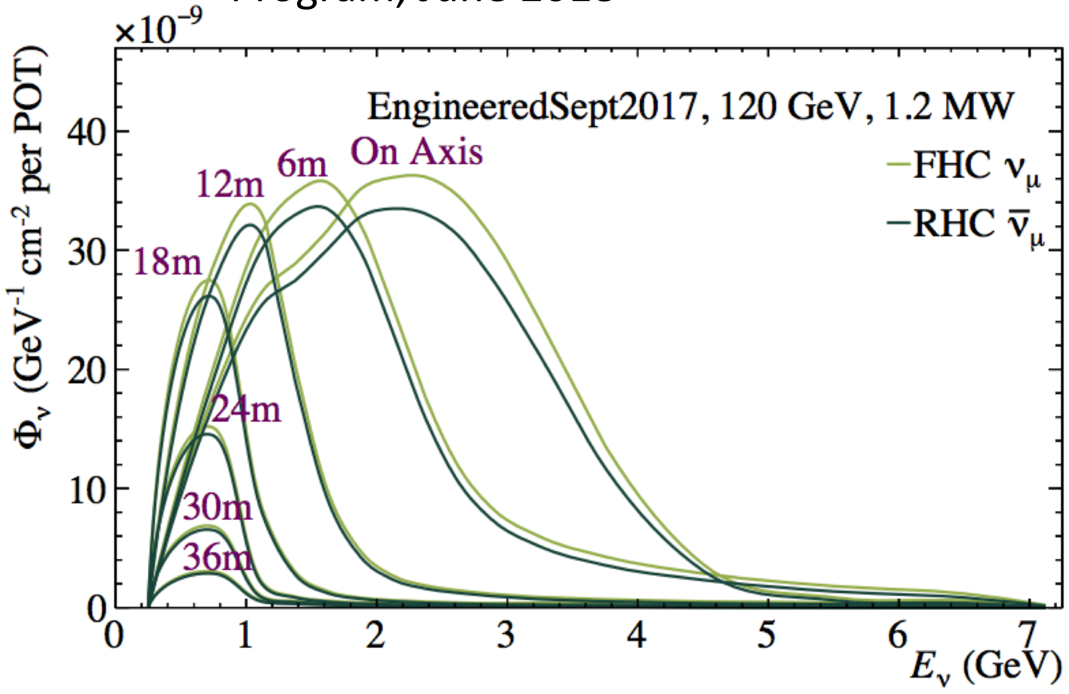
From Neutrino 2018



Bunch rotation (proposed for next year) would wash out the effect. We strongly advocate for some fraction of the BNB operations to include time w/o bunch rotation

To do: Physics impact

T. Cai et. al. The DUNE-PRISM Near Detector Program, June 2018



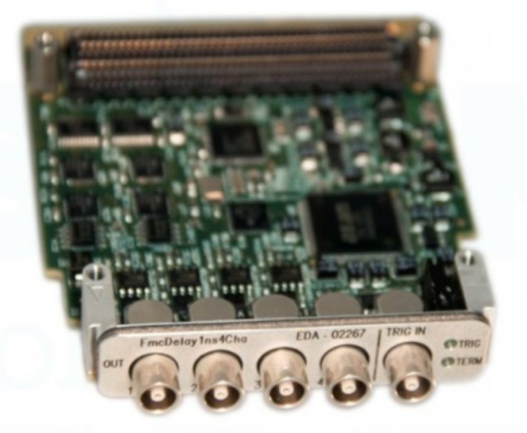
- How to integrate this method with the present Fermilab neutrino program? This gives the far detector an energy filtering method
- How much improvement in physics sensitivity does this provide if used in conjunction/combination with present energy discrimination methods?
- Perform in depth simulations on how this affects background rejection in energy regions around the second oscillation maximum.

How does reconstruction/background rejection improve when this method is used in combination with planned methods such as DUNE-PRISM above?

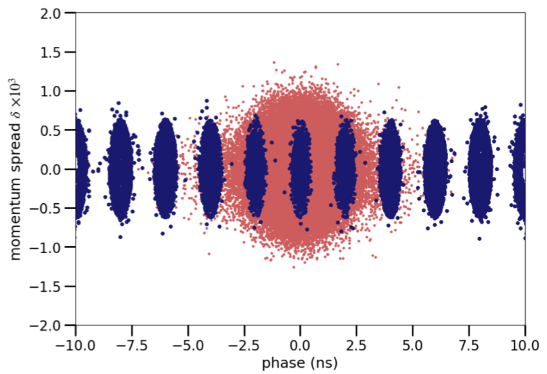
Fermilab has expertise and interest broadband and energy discrimination

Conclusion: Fermilab is the right place drive these efforts

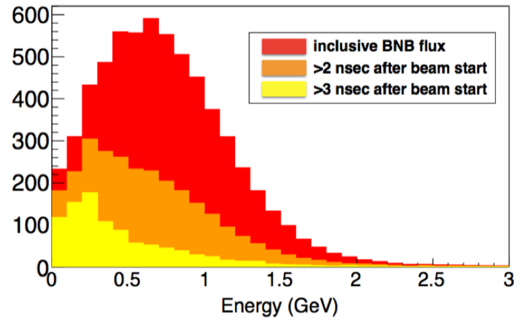
Clocks and Synchronization



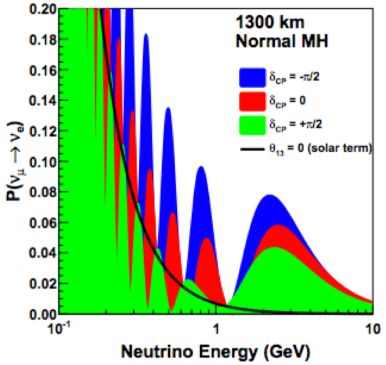
Beam monitoring and rebunching



First demonstration



Physics impact



Backup

Flavor separation attempt

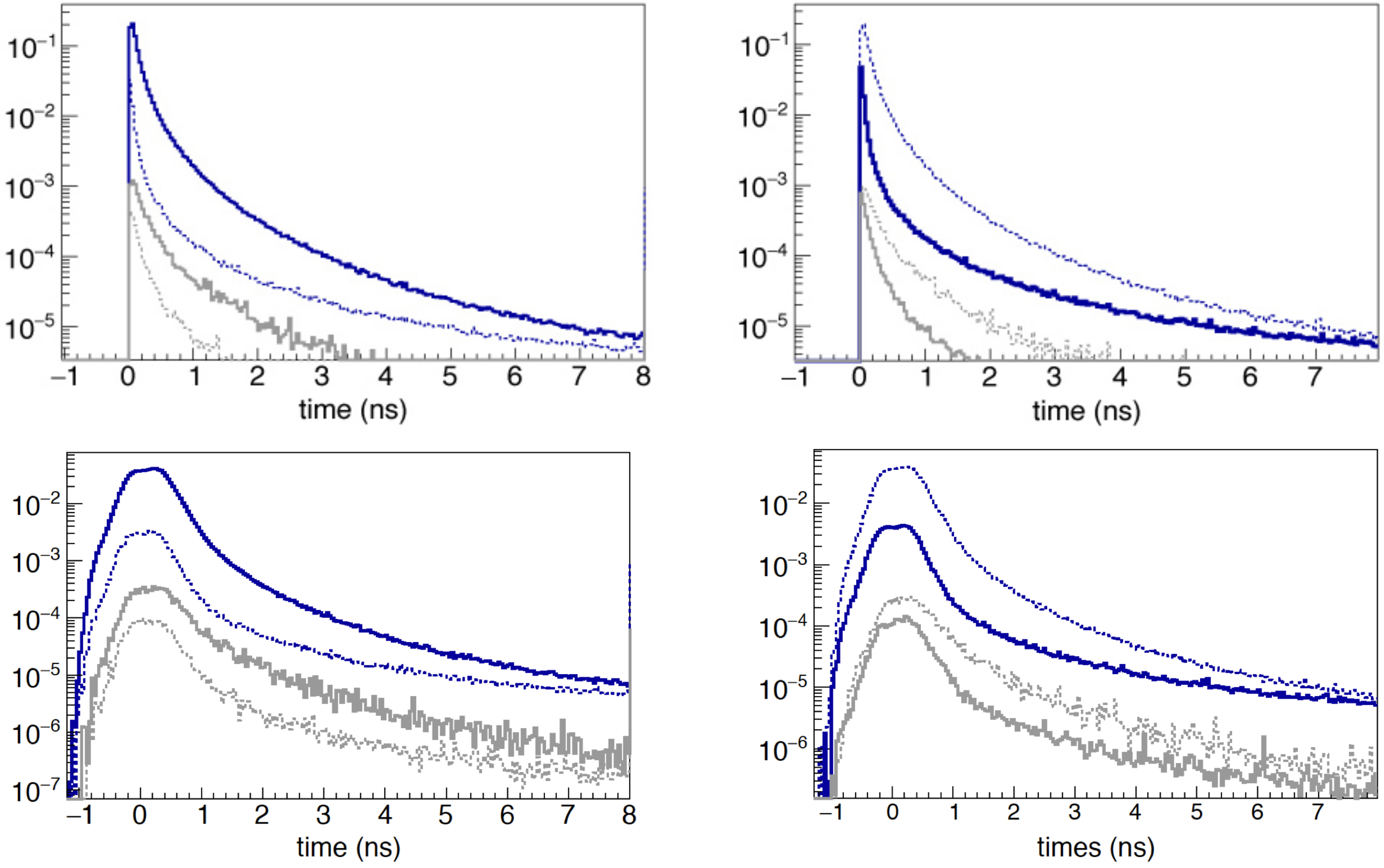


Figure 4: Simulated arrival time distributions for muon neutrinos (solid blue), muon anti-neutrinos (dashed blue), electron neutrinos (solid grey), and electron anti-neutrinos (dashed grey) in Forward Horn Current (LEFT) and Reverse Horn Current configurations of the DUNE beam. This is plotted for the case with all protons on target at the same instant (zero bunch width).

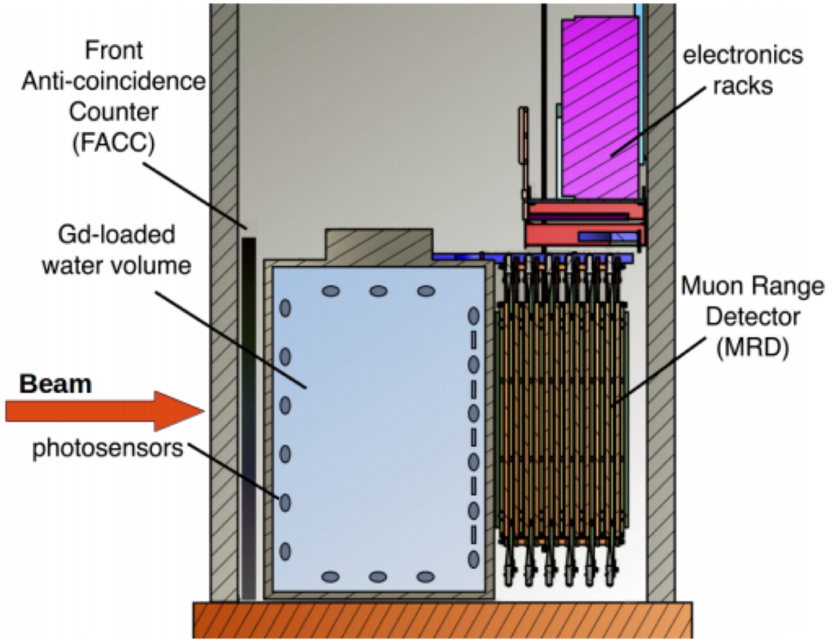
From Vincent Fischer. Lake Louise Winter Institute 2019. University of California, Davis.

UCDAVIS
UNIVERSITY OF CALIFORNIA

The ANNIE detector

annie

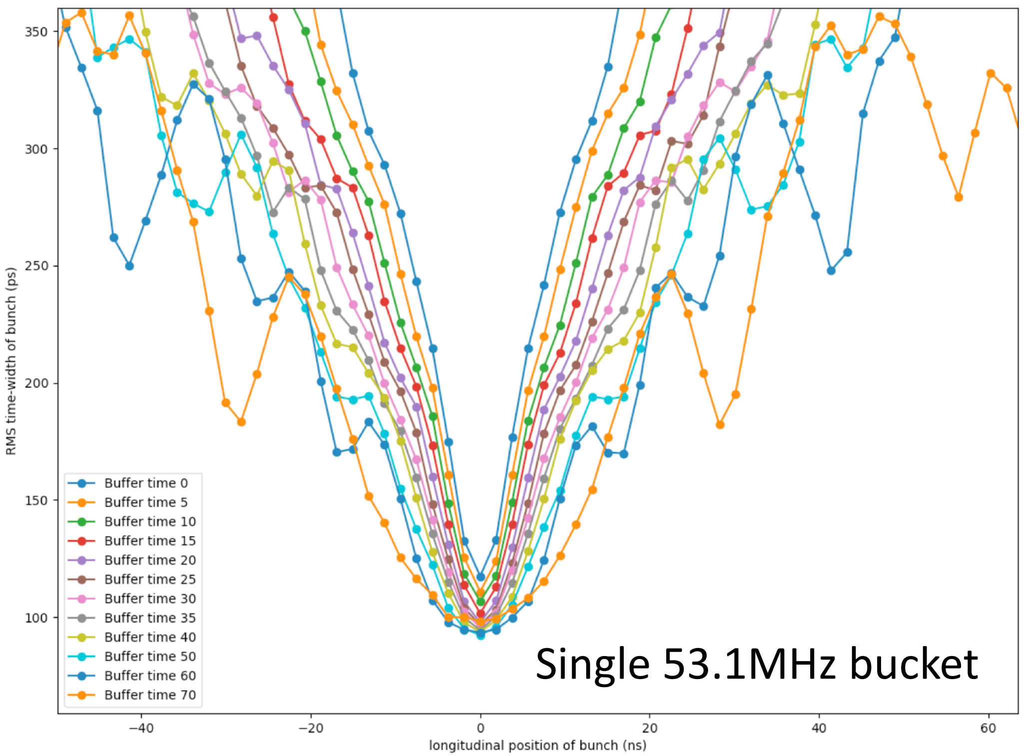
- **Gadolinium-loaded water** volume of 30 tons (0.1% by weight)
- Photosensors: ~**130 PMTs** (8, 10 and 11-inch, ~20% total photocoverage) and more than **5 LAPPDs** distributed in the tank
- **Front veto**: Scintillator paddles **tagging charged particles** originating from the rock upstream
- **Muon Range Detector (MRD)**: Legacy from SciBooNE, steel-scintillator sandwich detector capable of **muon direction and energy reconstruction**
- **~10,000 CC interactions per ton per year** (2×10^{20} POT) expected

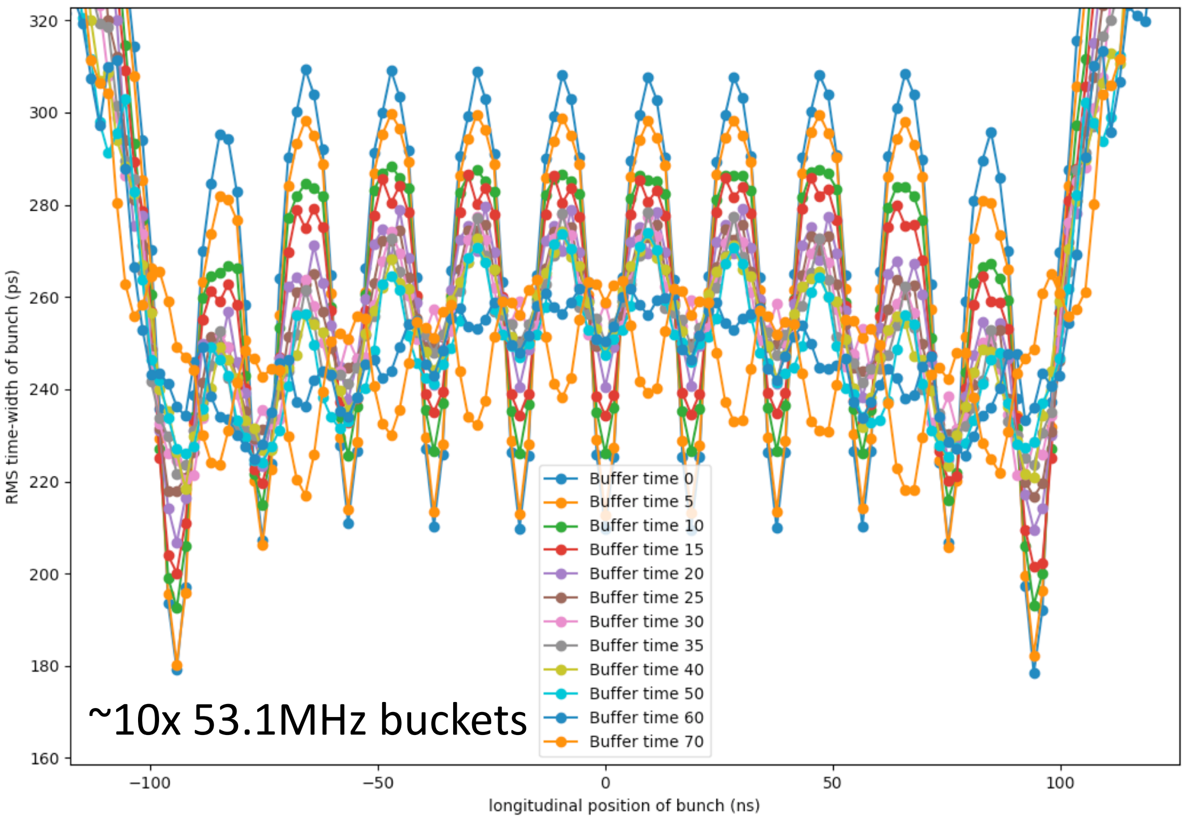


7

Layering of many 53.1 MHz RF buckets

Bunch RMS (ps)





Longitudinal position of the 531 MHz bunches (each point is a bunch center)

Start with 2e-6 dp/p width, uniform distribution

Initial conditions are a uniform, longitudinal line

~50 ps bunch width