O(1ns) Timing with LArTPC neutrino experiments

Path to Dark Sector discoveries workshop @ CSU

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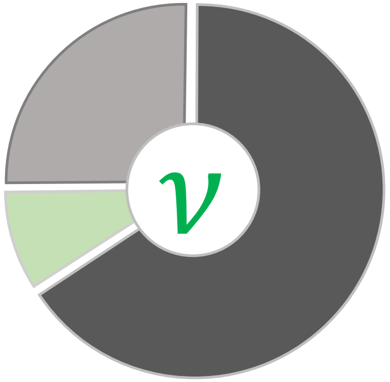
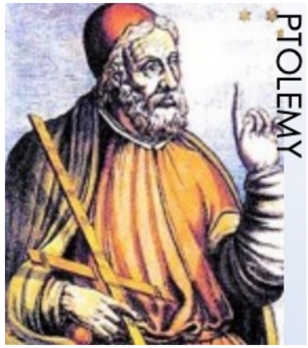
University of California Santa Barbara



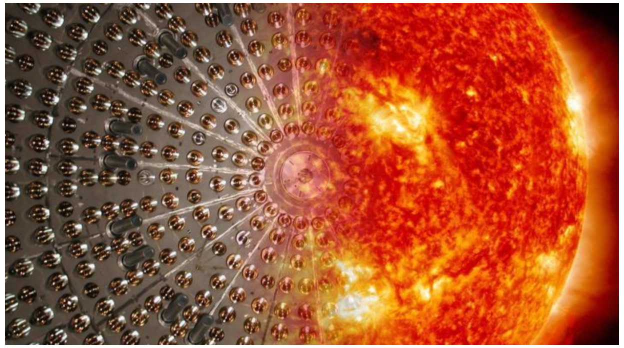
The Unknown Unknowns

PTOLEMY



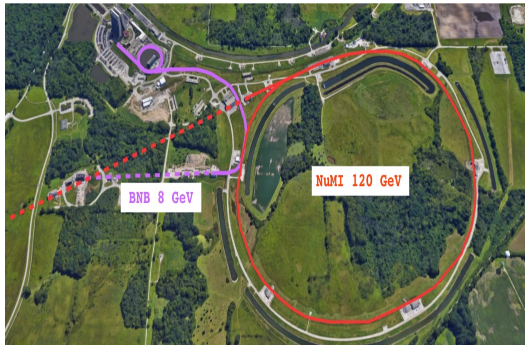
Relic neutrino
Neutrino mass
Majorana or Dirac?
Dark matter

Solar ν



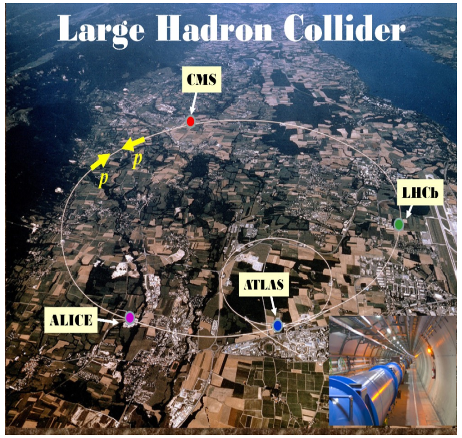
Solar model
Sterile neutrinos
Neutrino oscillation

Accelerator ν



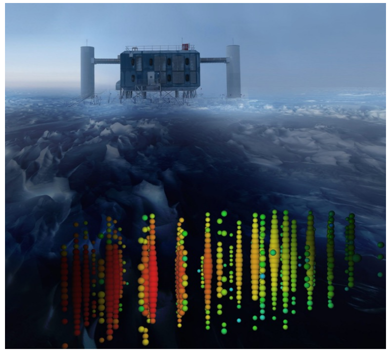
Heavy Neutral Leptons
Long lived Particle
ν portal to dark sector
Axion Like Particle
Millicharged particles
Lorentz invariance
CPT symmetry
eV sterile neutrino

Collider



Heavy Neutral Leptons
Long lived Particle
Dark Matter
Millicharged particles
SUSY

ICECUBE

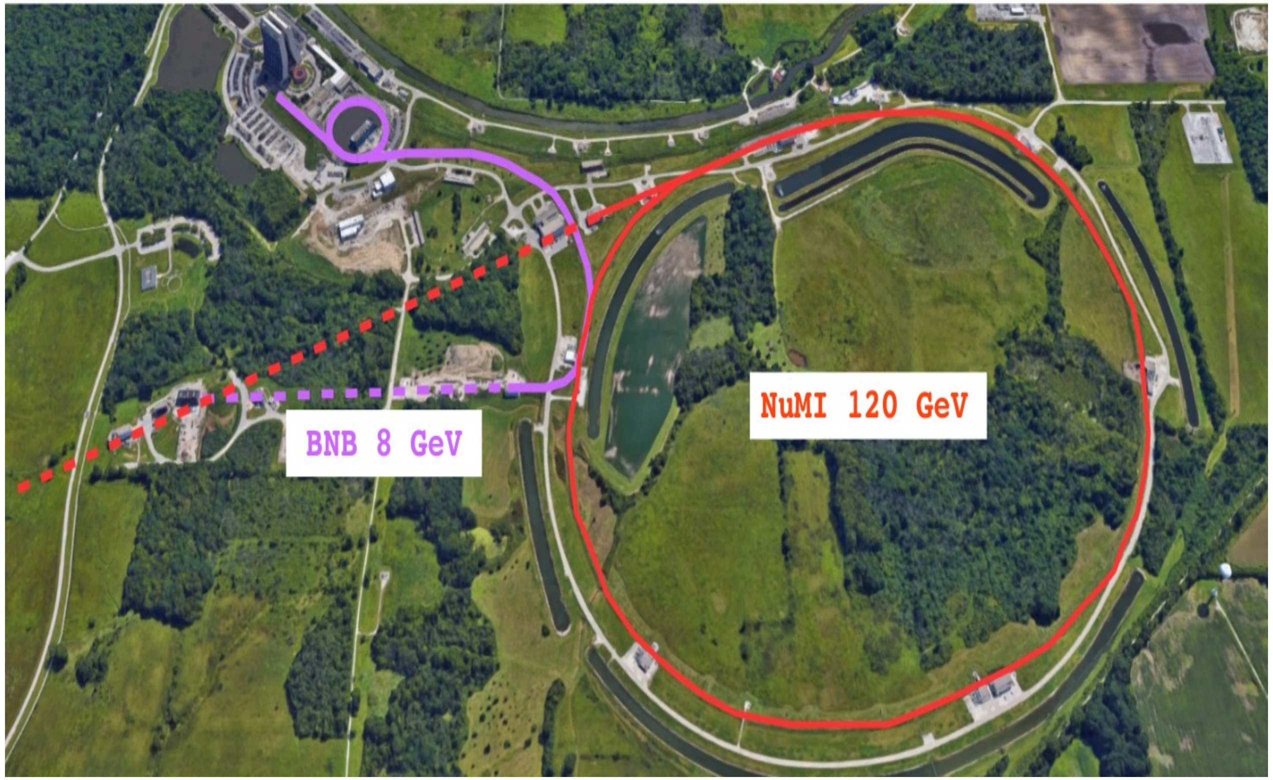


Sterile neutrinos
Mass ordering
Dark Matter
Astrophysics, e.g. Supernovae
Neutrino NSI
CPT symmetry

...meV → eV → keV → MeV → GeV → TeV → PeV ...

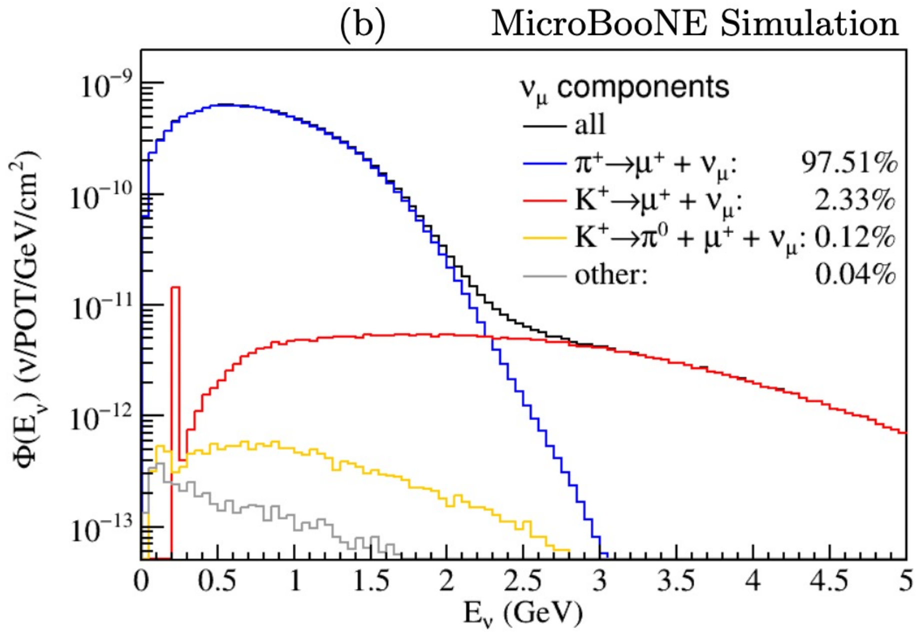
Energy Scale of experiments are probing

MeV – GeV BSM physics



Neutrino beamlines at Fermilab accelerator complex

- BNB produce ~800 MeV neutrinos
- NuMI produce ~2GeV neutrinos



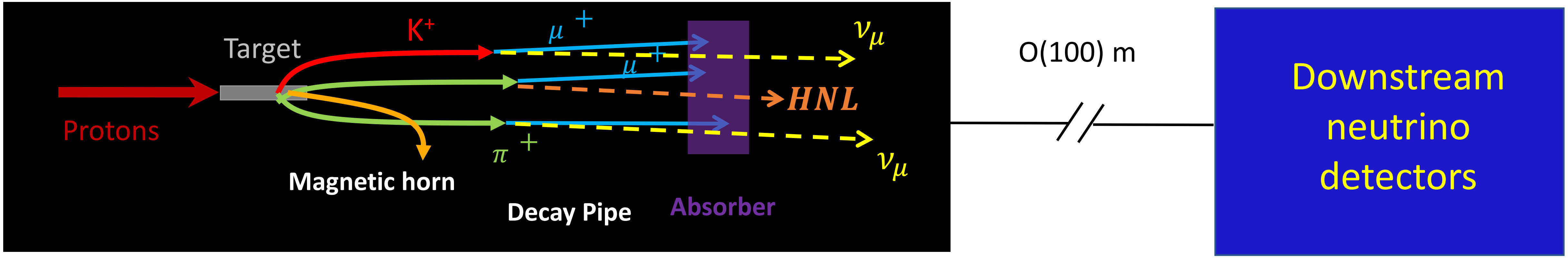
BSM models

Heavy Neutral Leptons
Long lived Particle
Higgs portal scalar
Axion Like Particle
Millicharged particles
Lorentz invariance
eV sterile neutrino ....

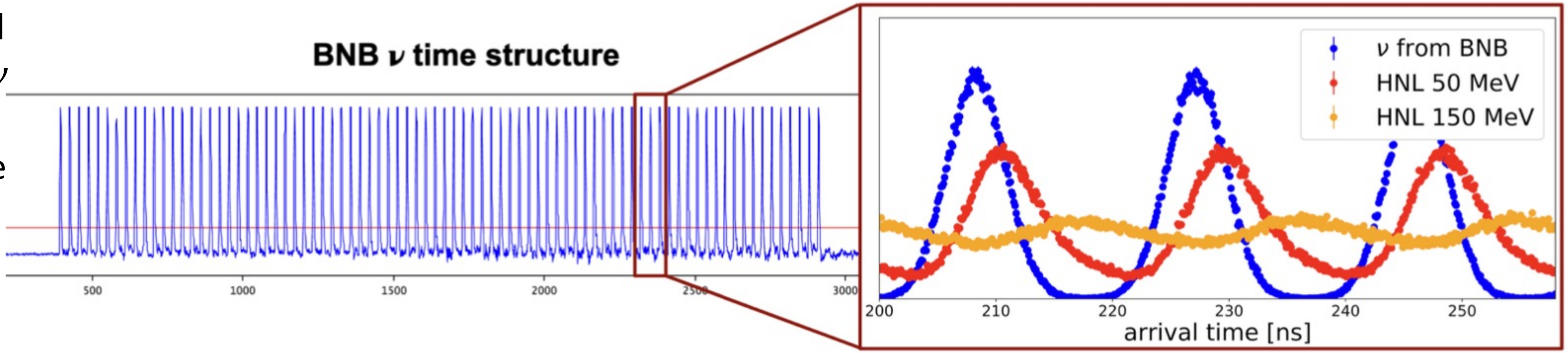
Precision Timing can be leveraged to search for any massive Long lived particle produced in the neutrino beamline

BSM searches in bunched neutrino beam

Massive Long-lived-Particles may be produced near beam target ..... and decay in the ν detector



The bunched structure of ν beamlines offers unique opportunity for BSM



Heavier BSM particles arrived at detector later than ν

ToF is a **model independent** handle for discovering Long-Lived-Particles, e.g. HNL, QCD axion, Higgs Portal Scaler, Dark scalar...

Time-of-Flight is simple idea

O(1) ns timing resolution also doesn’t seem to be too difficult for particle detector

However... Nanosecond neutrino bunches have never been measured by any LArTPC experiment before

Until now...

Analysis overview O(1ns) ToF measurement

First demonstration of O(1 ns) timing resolution in the MicroBooNE liquid argon time projection chamber
arxiv.2304.02076

The dataset used in this analysis is an inclusive selection of ν_μCC interaction candidates from MicroBooNE's BNB

Step 1: More accurate beam signal – initial time of ToF

Step 2: Timing measured from light signals – final time of ToF

Step 3: Calibrating out travel time of neutrinos in the TPC

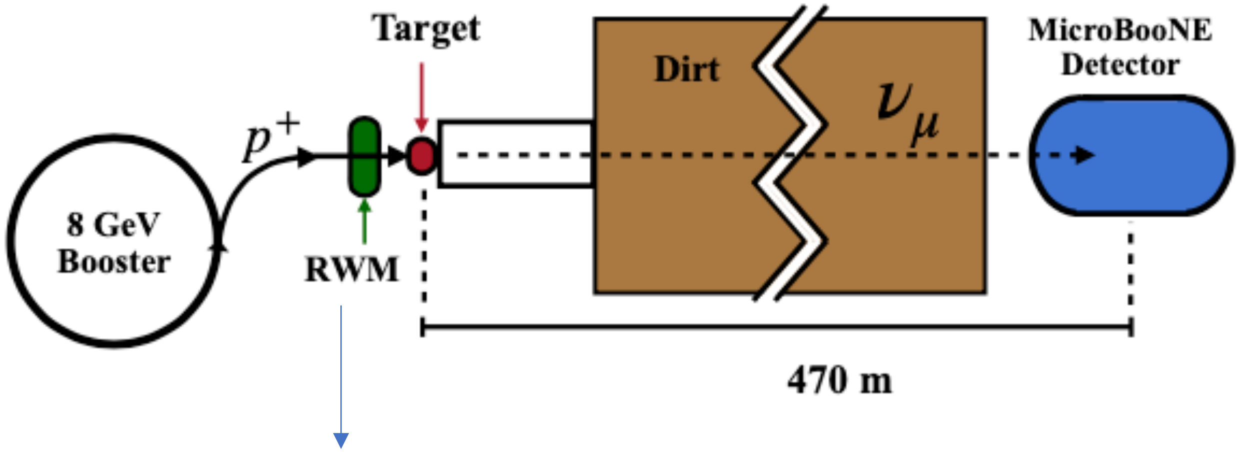
Step 4: Calibrating out travel time of secondary particles from interaction.

Step 5: Calibrating out the travel time of scintillation photons from particle trajectory to light detection system

Step 6: Empirical calibration to reduce residual smearing due to non-uniformity

Beam signal – Booster Neutrino Beamline

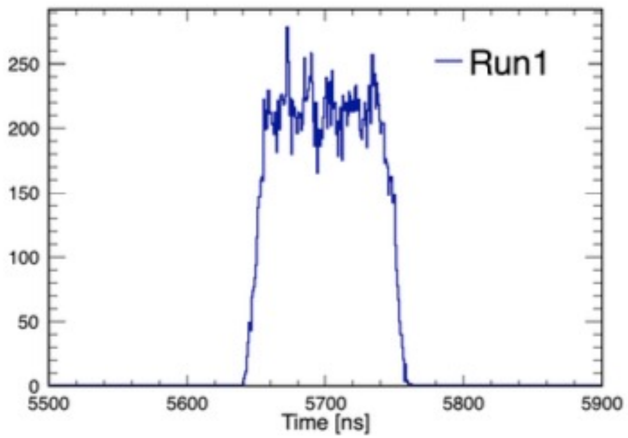
Step 1



The beam signal triggers experiment's readout electronics to record the event.

It also defines T0 for the neutrino ToF

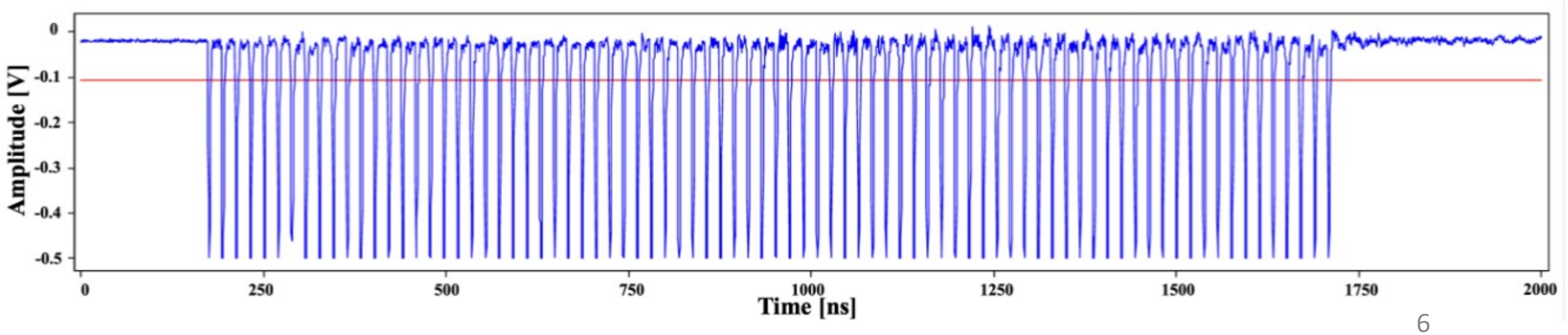
The Old beam trigger has O(100) ns jitter



Resistive Wall current Monitor (RWM) signal measures the proton pulse with O(10) ns precision, which is used to replace the old beam signal as T0

- 1.6 µs beam gate
- 81 bunches
- <2ns wide bunches
- ~18 ns gap

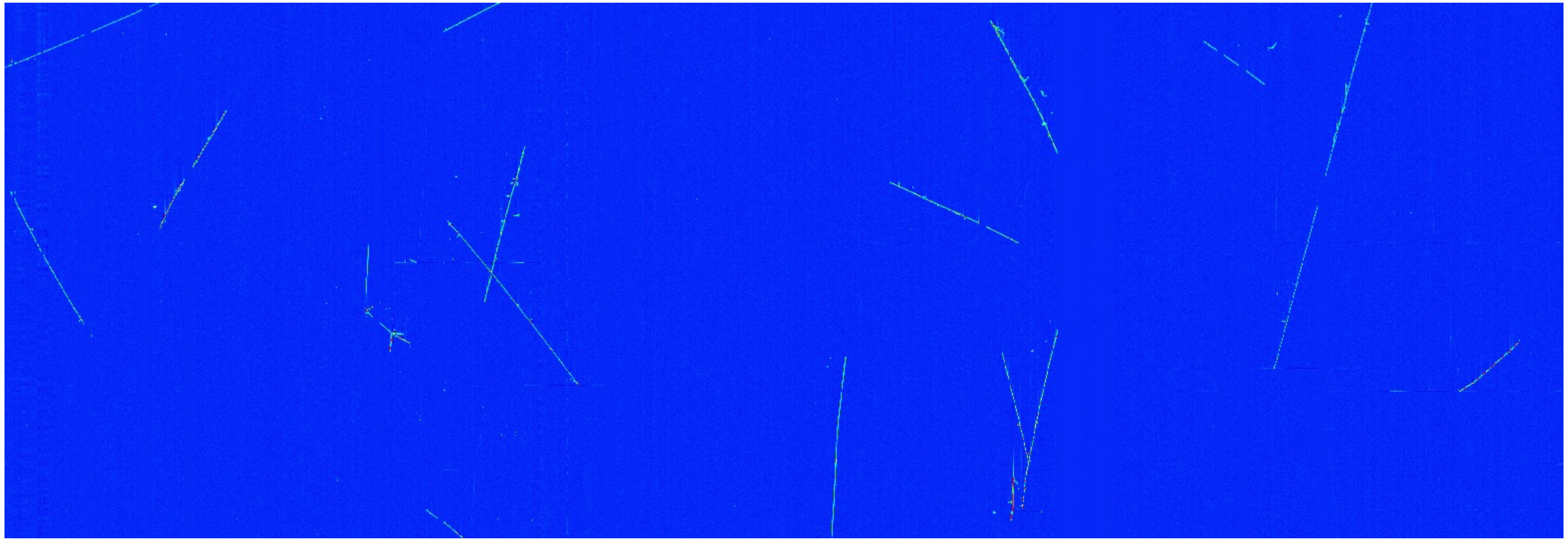
BNB neutrino bunch structure



Neutrino detectors -- LArTPC

- Good for final states particle identification
- Too slow (ms) for timing measurements: long exposure images, surface detector with all the cosmics
- Accompanied by Photon detection system (e.g. PMT) to provide timing of the interactions in the TPC

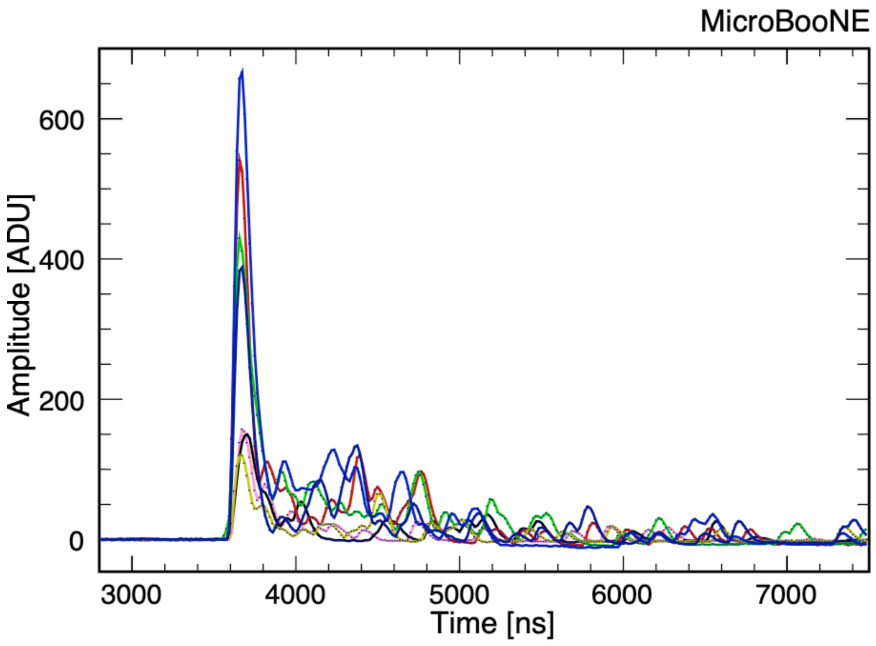
TPC

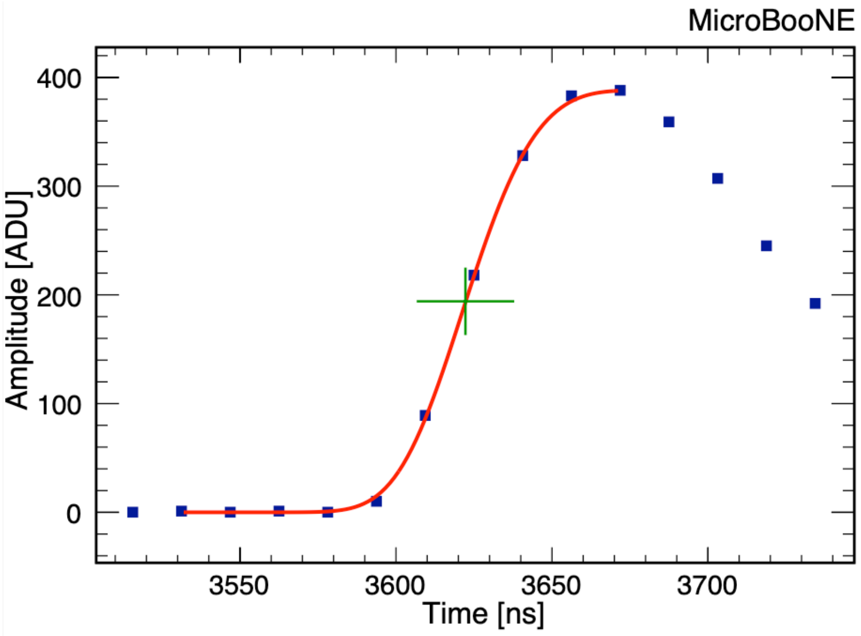


Photon Detection System (PDS)

Photon Detection System (PDS)

- MicroBooNE PDS includes 32 PMTs, readout 23 μs time window triggered by BNB beam signal.
- Rising edge fit gives the PMT's signal timing.
  - **0.2 ns** smearing.
- The median of the PMT's timings is used to assign the event time.
  - Only waveforms with maximum amplitude larger than 2 photons are considered





Fit function:

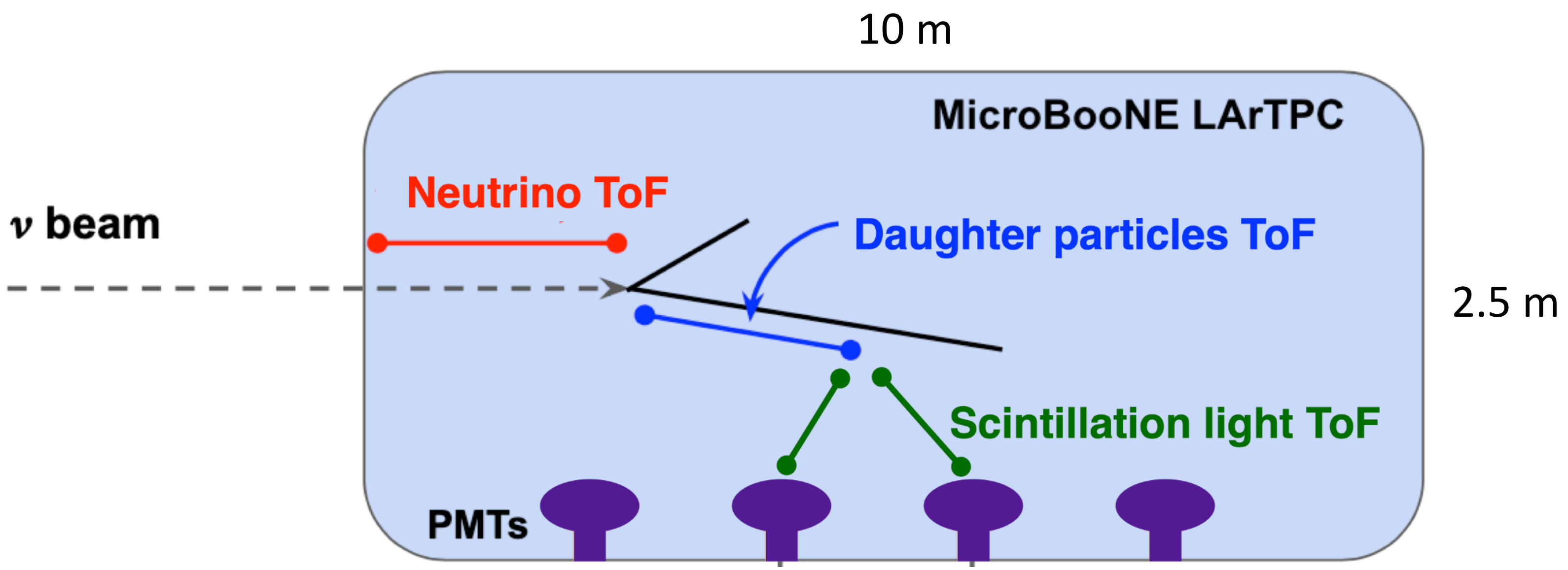
$$f(t) = A \cdot \exp\left(-\frac{(t-t_M)^4}{B}\right)$$

Time at half maximum in the leading edge is considered as measured PMT time

Key step: TPC + PDS

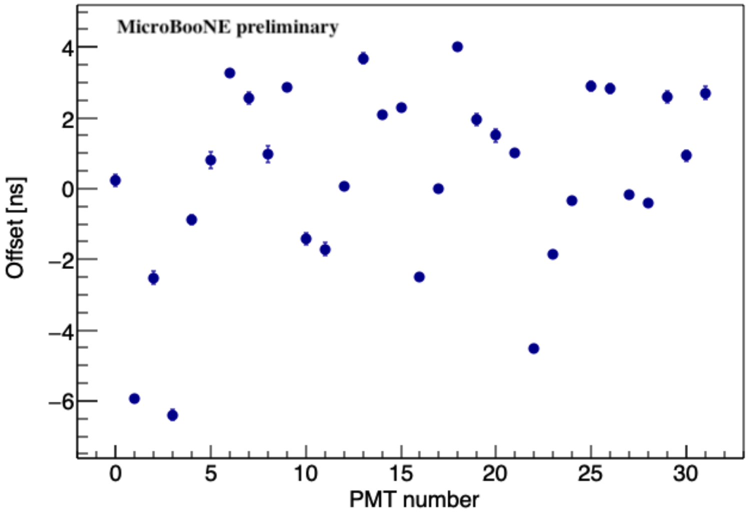
Three processes impact the observed neutrino interaction time – the final time of ToF. Leverage the neutrino interaction vertex and the 3D tracks geometry provided by the **TPC reconstruction**

- **Neutrino ToF inside the TPC:** Distance from **ν**-vertex to TPC front wall / speed of light. (few – 10s ns)
- **Daughter particles ToF:** Distance from **ν**-vertex to daughter space-points / speed of light. (few-10s ns)
  - Speed of light is an approximation, particle type dependent
- **Scintillation light ToF:** Distance from the space-point to PMT / speed of light in liquid Argon (~10 ns).
  - Light in argon travels with 12cm/ns



Empirical calibration

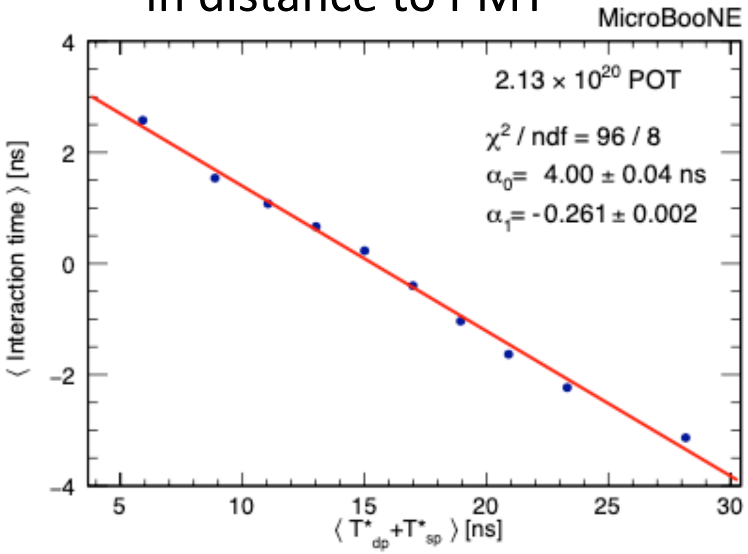
PMT by PMT offset



Source: cable length...

~10 ns smearing

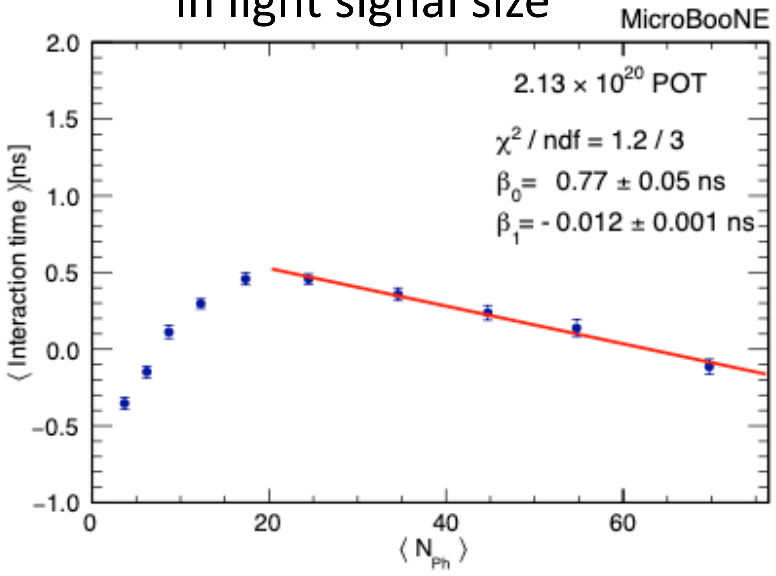
Residual non-uniformity in distance to PMT



Source: Daughter particle travel speed is PID dependent

~5 ns smearing

Residual non-uniformity in light signal size



Source: PMT pulse fit + light absorption

Close to PMT: 10 photons / MeV

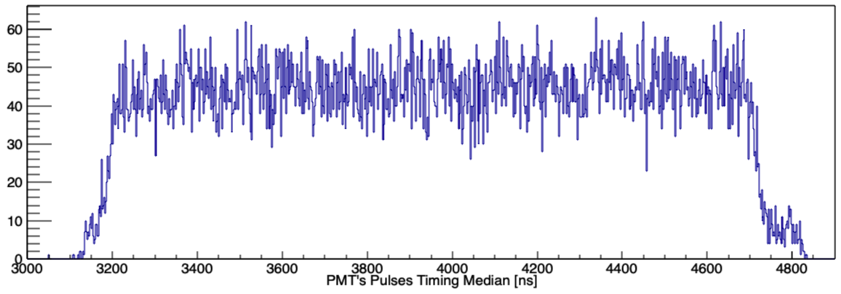
Far to PMT: 0.1-1ph / MeV

~1 ns smearing

Evolution of measured ToF of BNB neutrinos

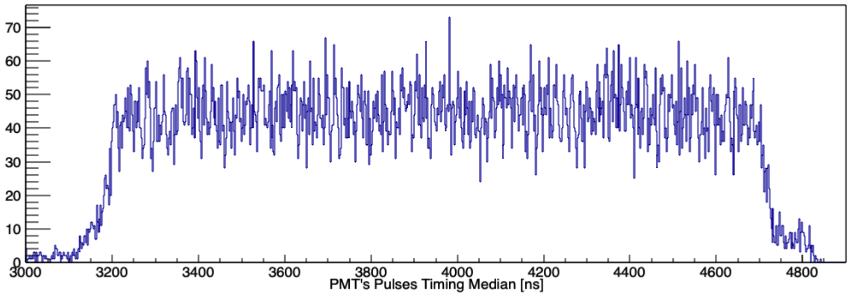
Step 1

Median PMT



Step 2

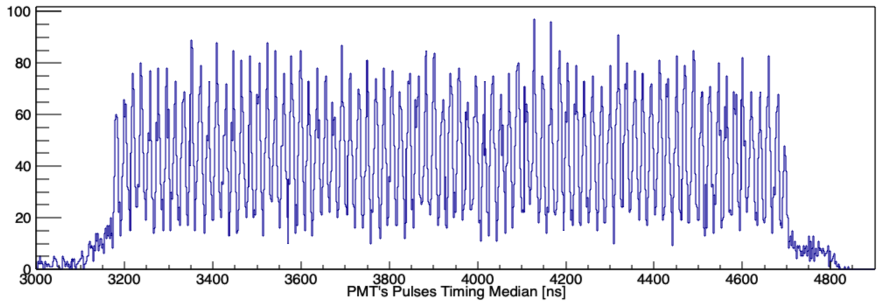
RWM New T0



Step 3

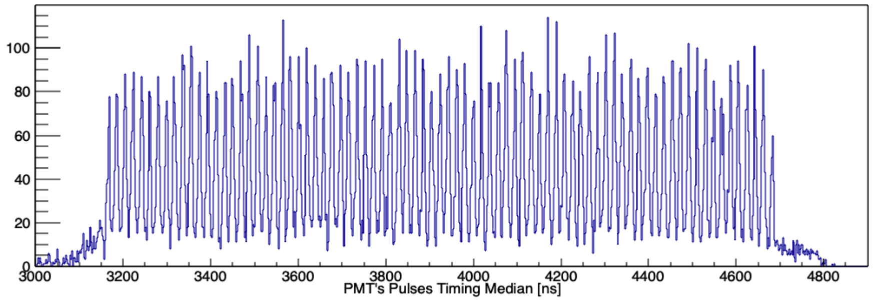
Calibrate out ν flight in TPC

σ ~ 4.7 ns



Step 4

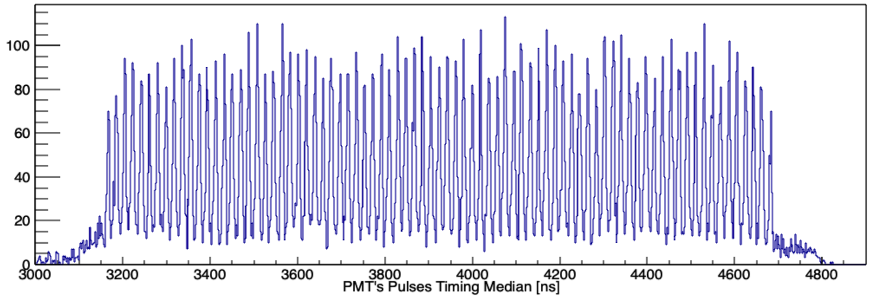
Calibrate out particle propagation



Step 5

Calibrate out light propagation

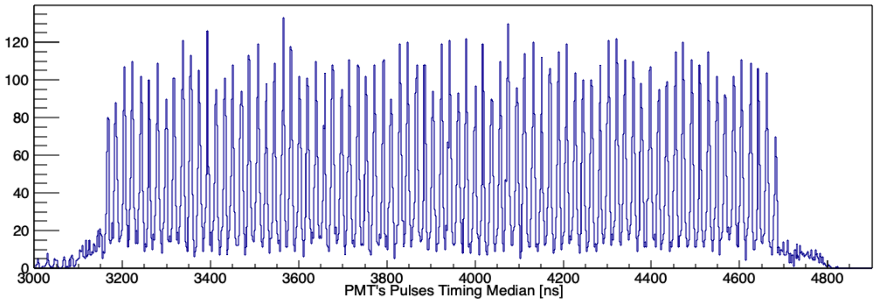
σ ~ 3.1 ns



Step 6

Empirical calibration

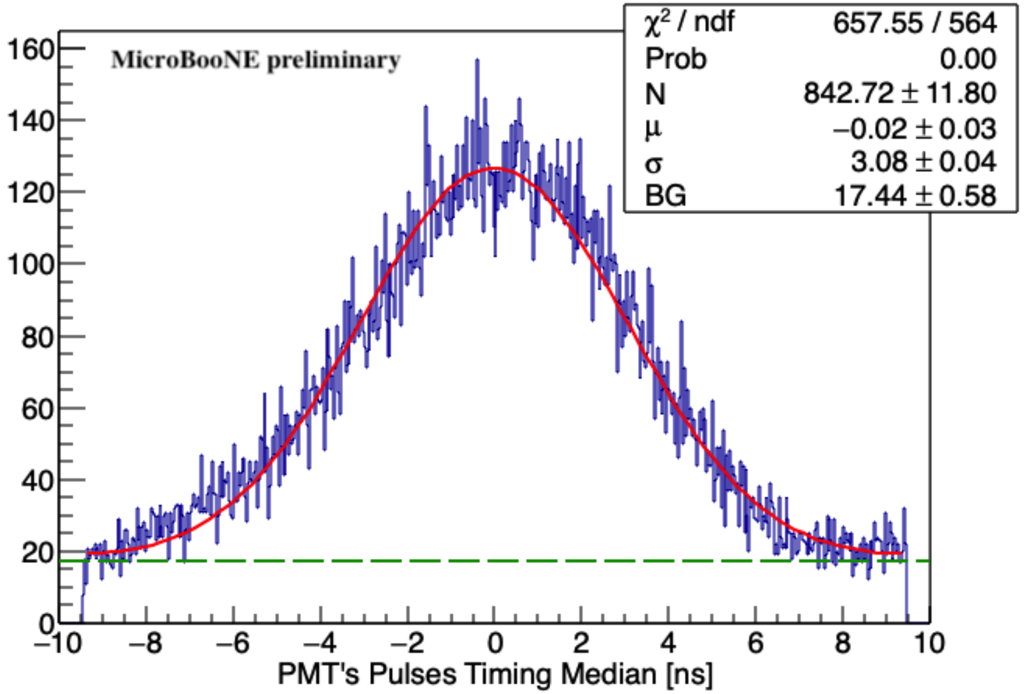
σ ~ 2.5 ns



BNB bunches measured in LArTPC

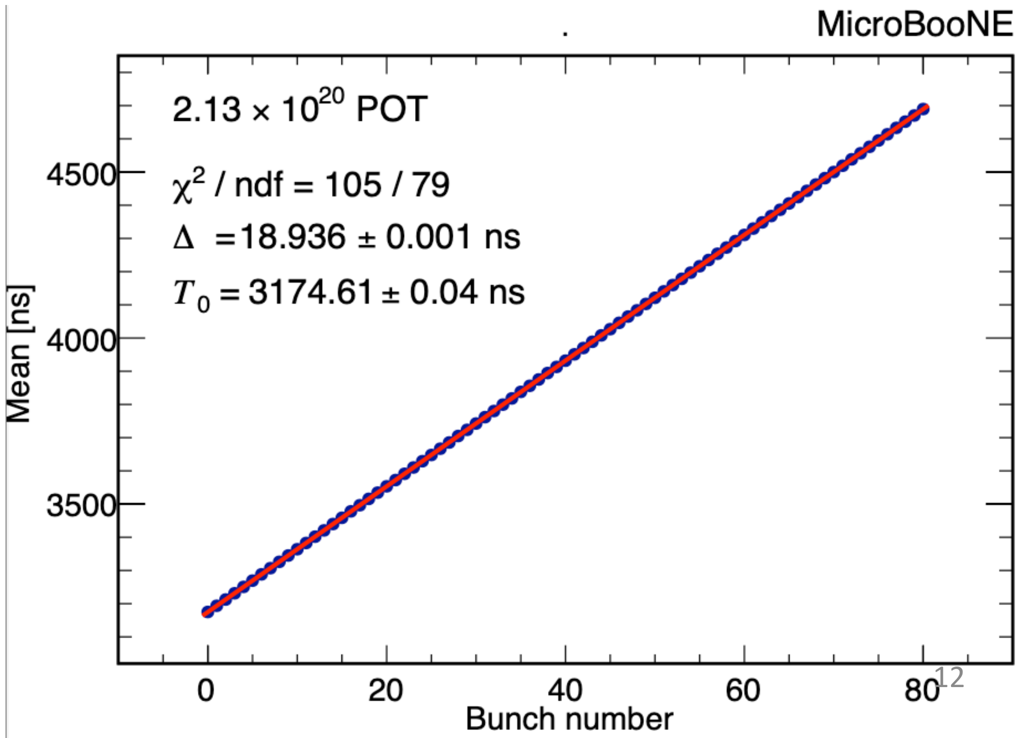
Benchmark the timing resolution

- The 81 peaks are merged in a single one
- Gaussian + Constant term fit.
- Pulse width is given by σ

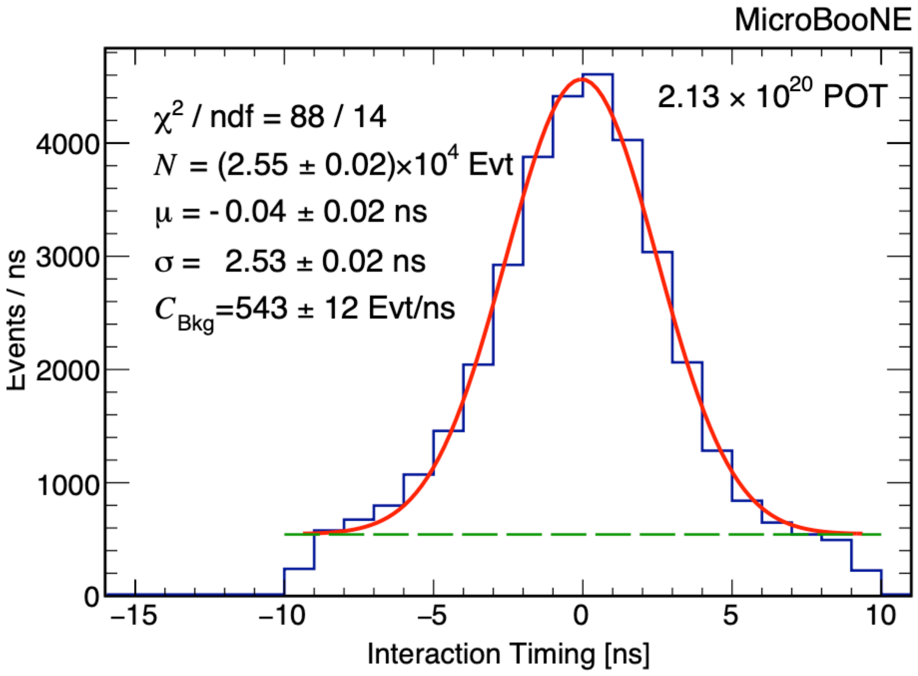


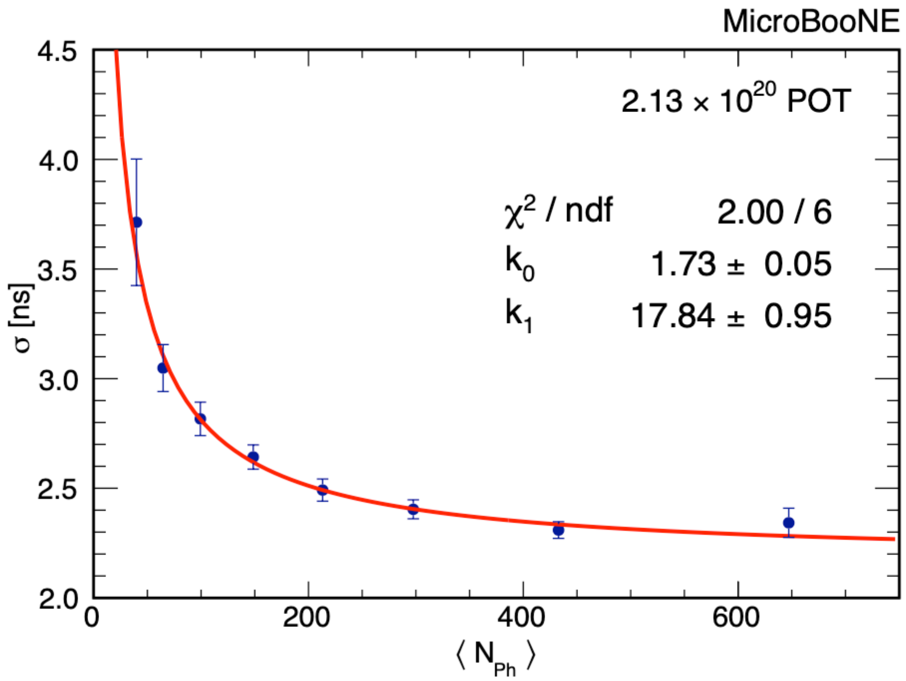
Measured ToF recovered proton beam time structure for the first time:

- Gaussian fit of the 81 bunches
- Bunch mean vs. bunch number linear fit
- Buch separation: Δ = 18.936 ± 0.001 ns



O(1) ns resolution achieved





Timing resolution of BNB neutrinos:

- Gaussian fit gives σ = 2.53 ± 0.02 ns
- The intrinsic beam spread is σ_B = 1.308 ns
- Overall resolution: **2.16 ± 0.02 ns.**

Timing Resolution Vs. number of photons:

- Smaller light signal is poorer resolution
- Using standard resolution fit function

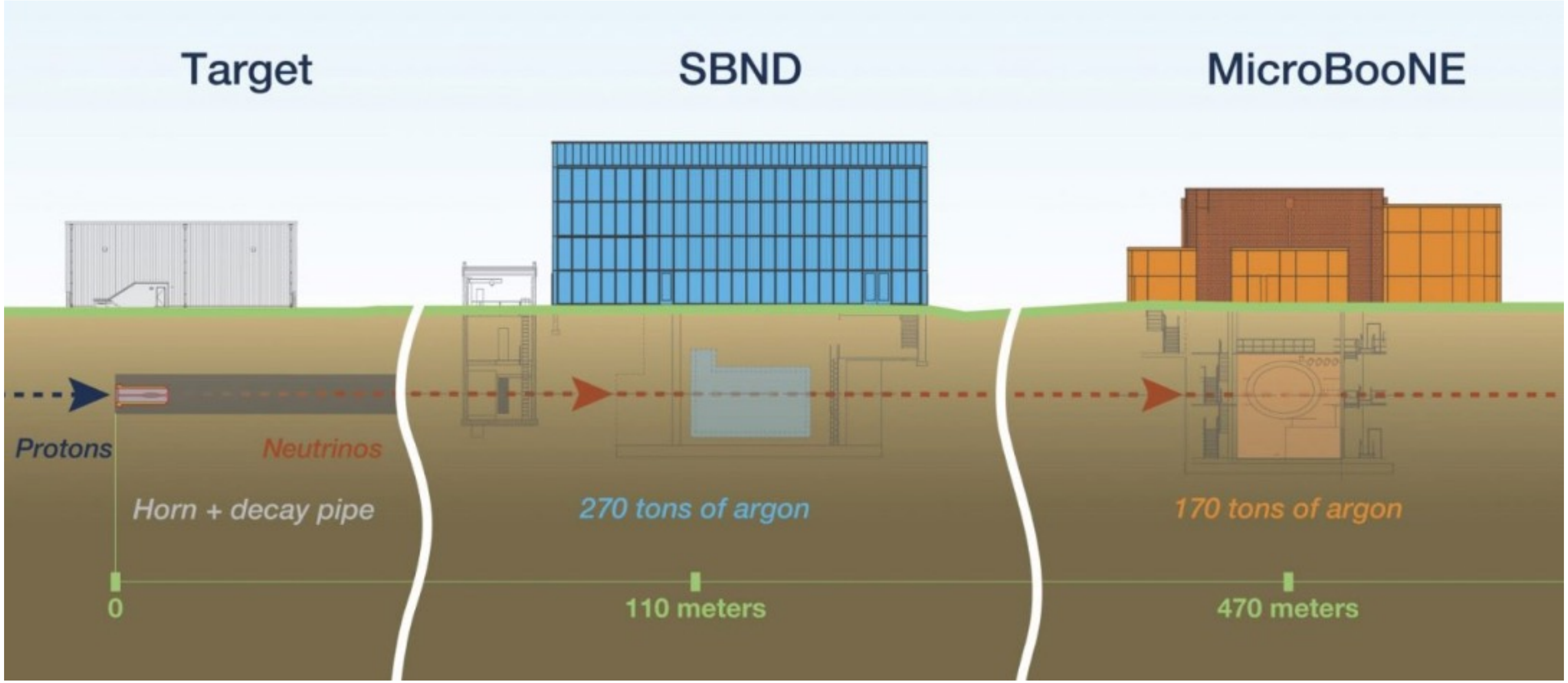
$$\sigma\left(\langle N_{Ph}\rangle\right) = \sqrt{\langle\sigma_{BNB}\rangle^2 + k_0^2 + \left(\frac{k_1}{\sqrt{\langle N_{Ph}\rangle}}\right)^2}$$

- Intrinsic resolution is **k_0 = 1.73 ± 0.05 ns**

O(1) ns in SBN -- MicroBooNE Vs SBND

MicroBooNE has longer baseline than SBND
Different baseline → Different time of flight → broader BSM parameter coverage

SBND has more powerful PDS than MicroBooNE

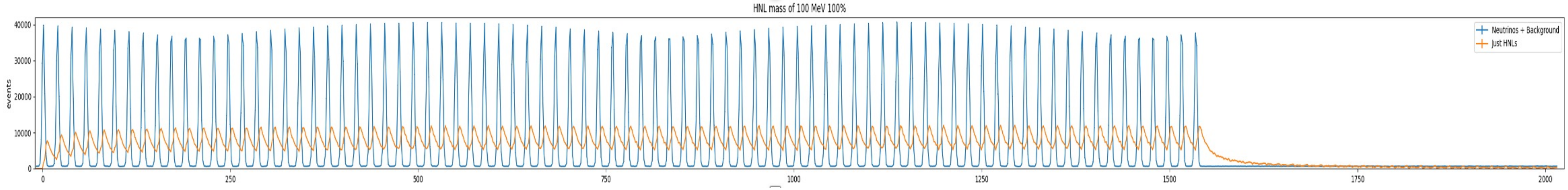


O(1ns) Timing for BSM search - Fast MC

Model-independent search for massive Long-Lived-Particles

Parameters:

- BNB neutrino timing spectrum: ~2ns bunch width, ~18ns gap
- Flat cosmic background: data driven rate with gaussian fluctuation
- LLP mass: O(10 - 1000) MeV
- LLP events rate: percentage to neutrinos
- LLP energy: BNB neutrino beam energy ~ GeV



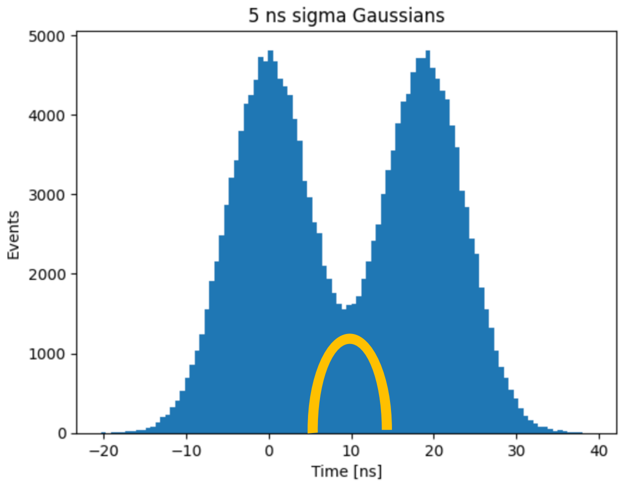
Fast MC – neutrino & cosmic background

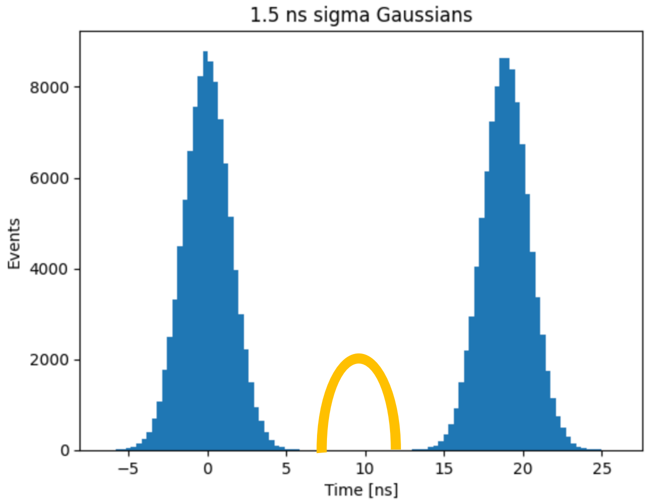
Simulating BNB Neutrino bunch

- 81 Gaussian
- σ is timing resolution achieved
- Better timing resolution -> increased search region and decreased background

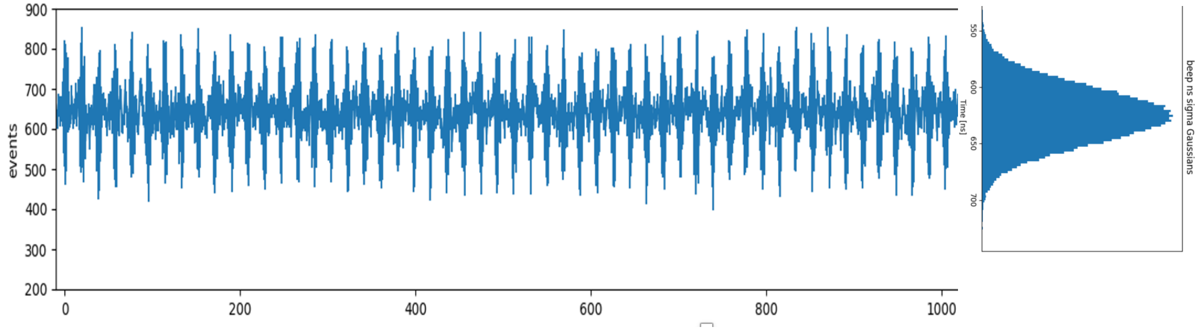
Simulating Cosmic ray

- Constant background
- Central value is data driven
- Gaussian fluctuation





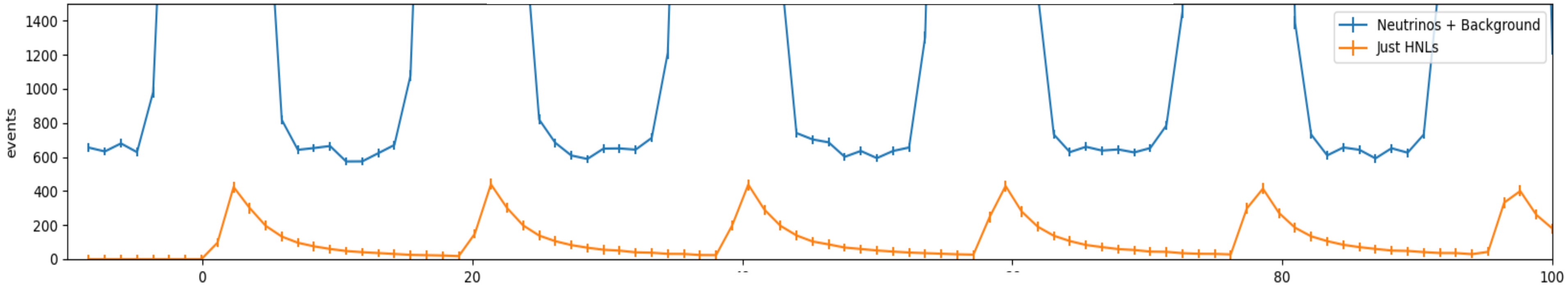
Cosmics– flat background



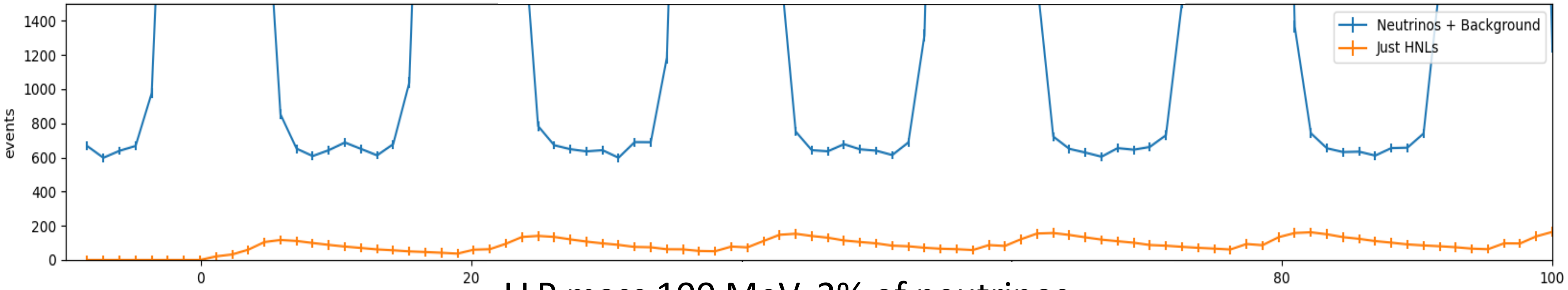
Different masses of LLP

Blue - Large Neutrino Gaussians
Orange – LLP Peaks

LLP mass 50 MeV, 2% of neutrinos



LLP mass 100 MeV, 2% of neutrinos



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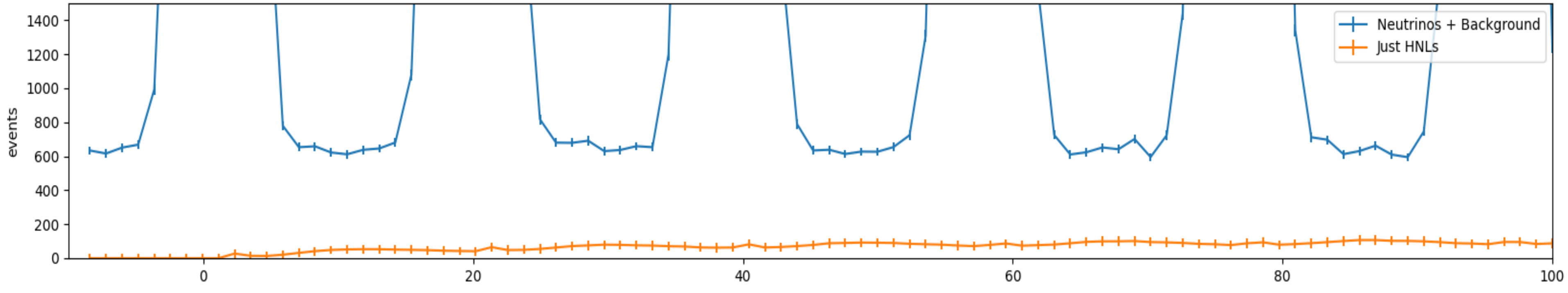
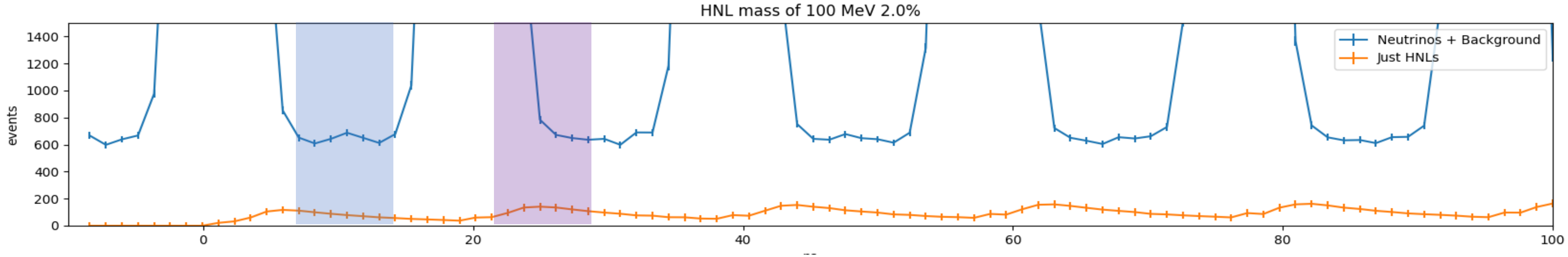


LLP mass and energy impact arrival time and bump shape

Optimal discovery potential arises at the gap between neutrinos bunch

Search window and sensitivity



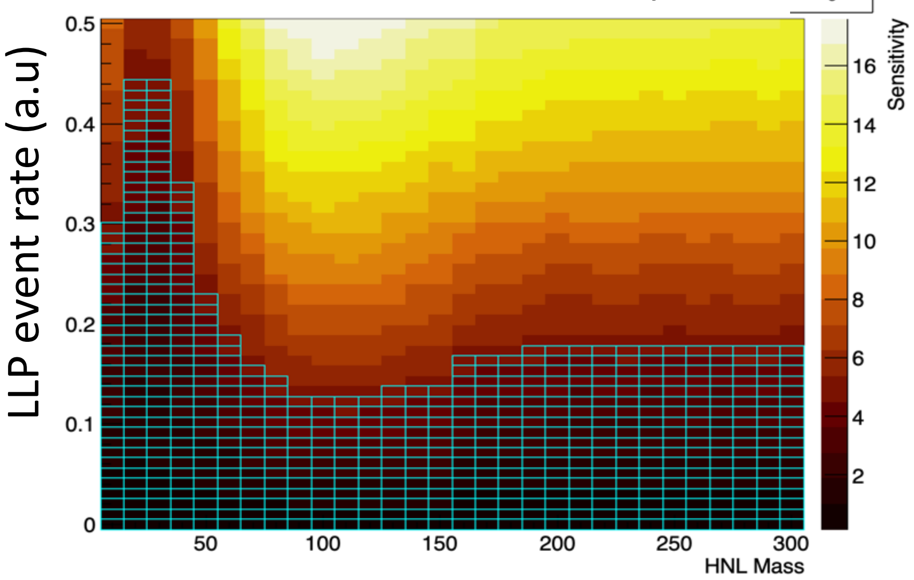
Search window

- Method 1: Search the entire beam gate
- Method 2: Fixed window in between neutrino bunch
- Method 3: Varying window S/B> threshold targeting different LLP masses/energy

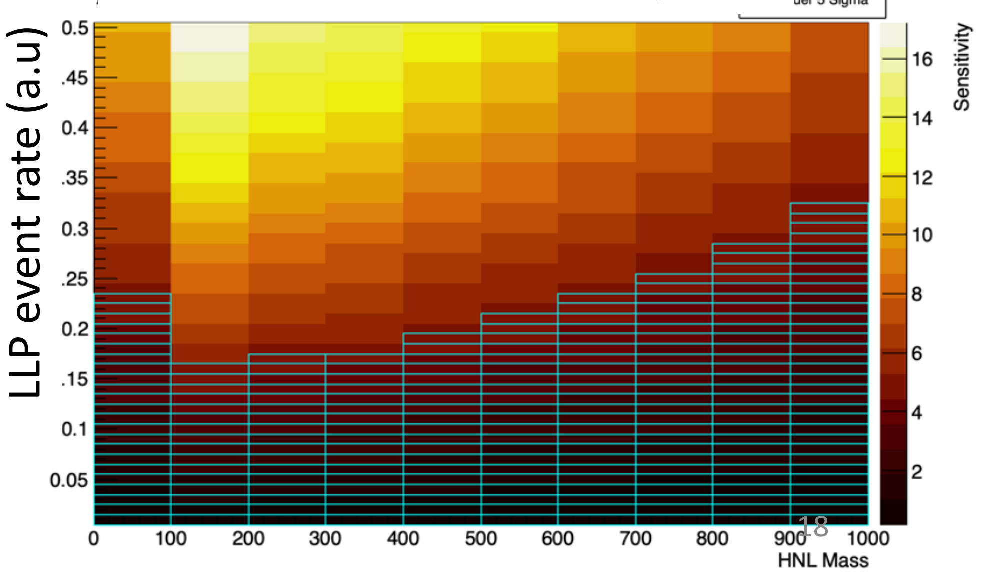
Sensitivity

For each time bin in the search window, count Signal and Background, add all the bins. Benchmark sensitivity using 1-bin Asimov sigma

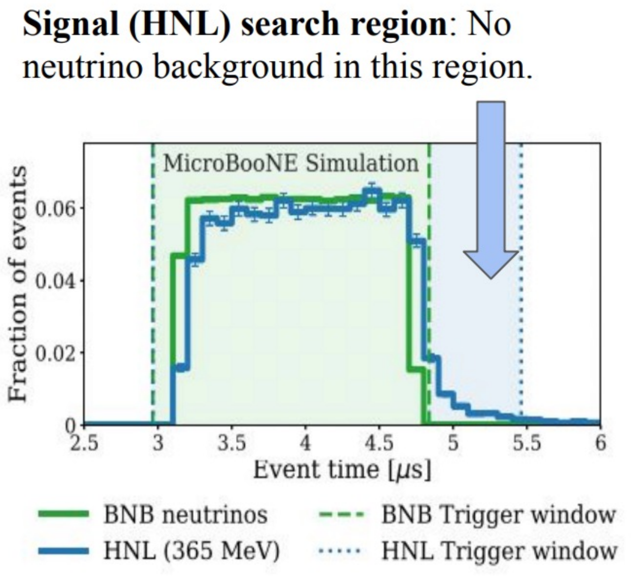
MicroBooNE sensitivity

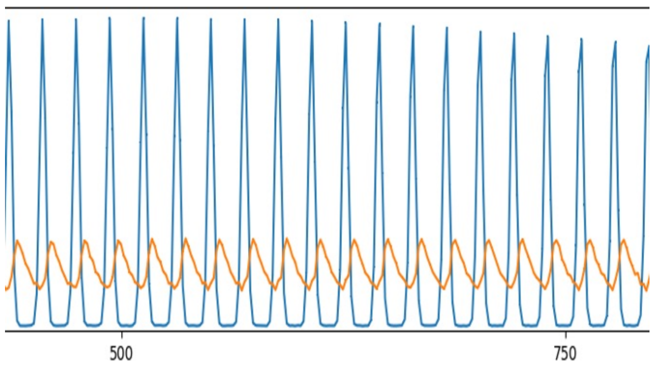


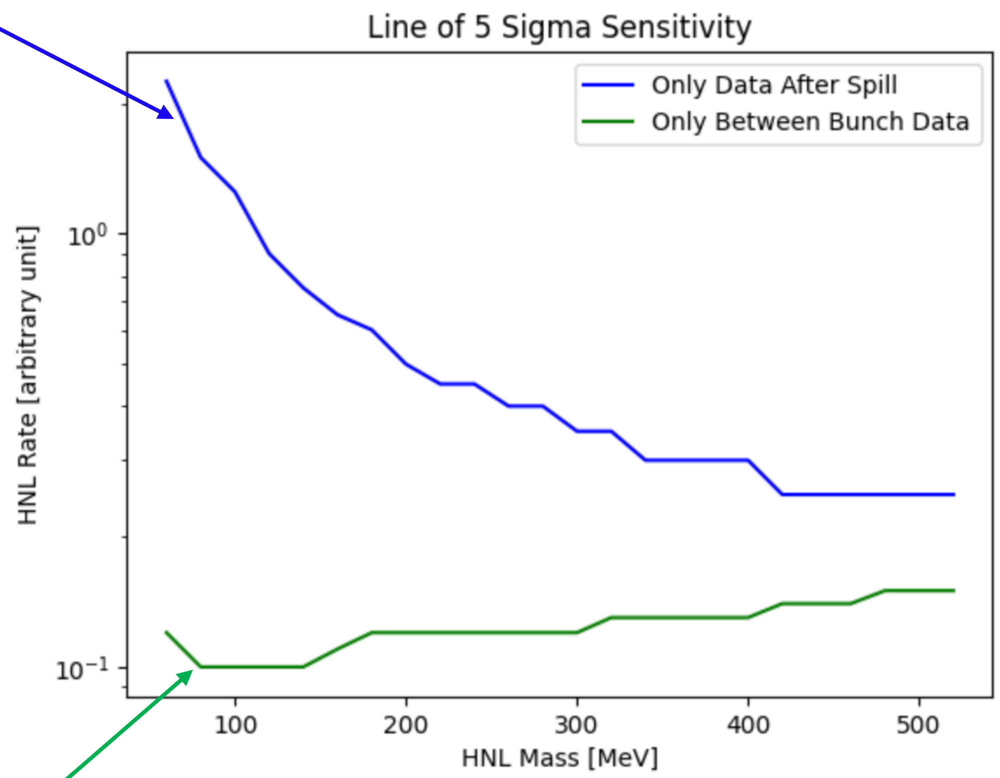
MicroBooNE sensitivity



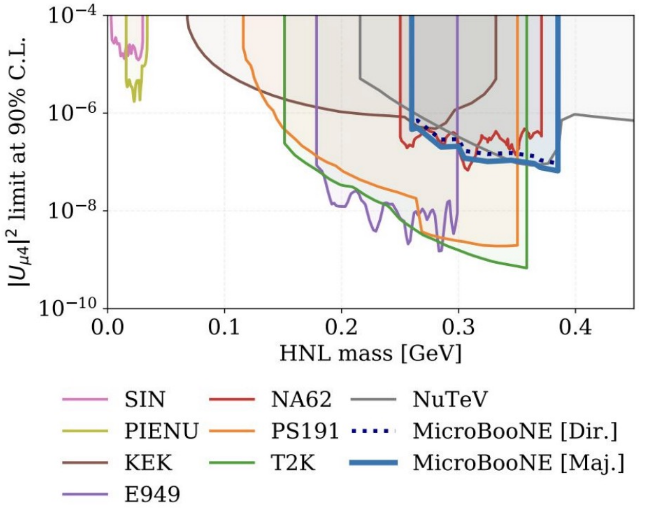
Significant improvement comparing to delayed window







Phys. Rev. D 101, 052001 (2020)



Leverage

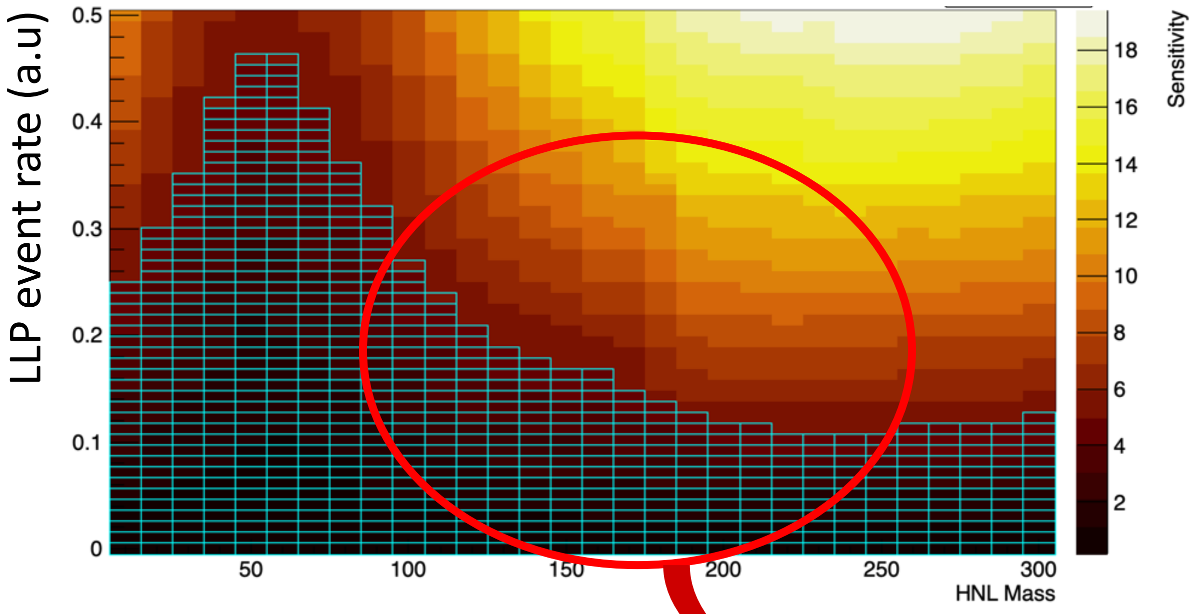
- Bunched ν beam
- O(1) ns timing

offers x10 sensitivity boost at ~100 MeV

Different Search Methods

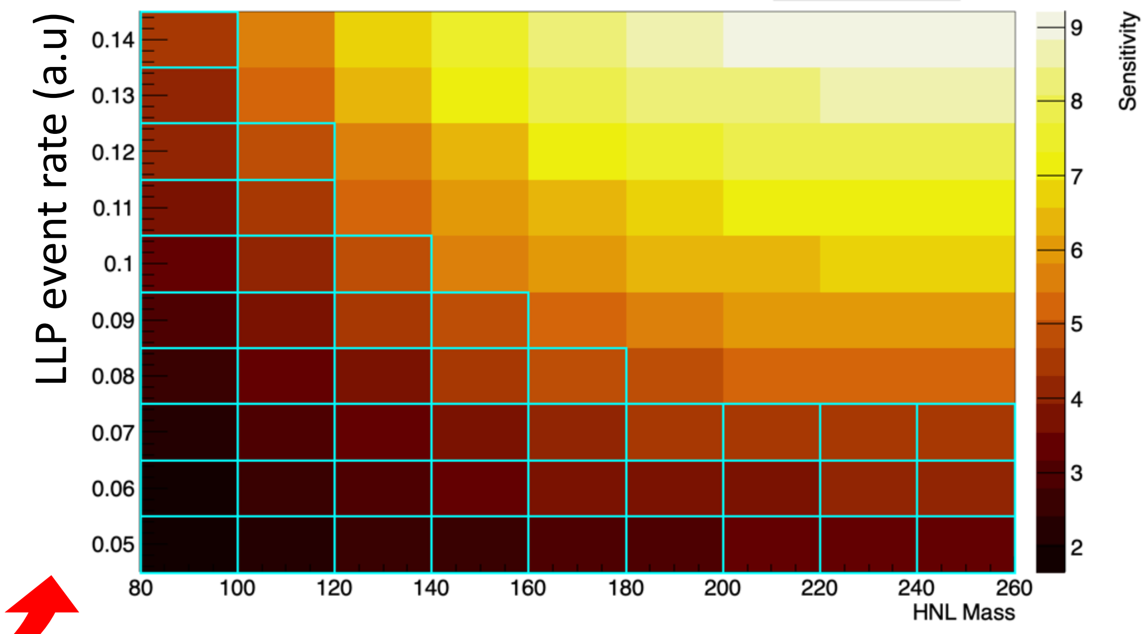
Method 1: entire beam gate as search window

MicroBooNE sensitivity



Method 3: varying search window (S/B > threshold) for different LLP mass

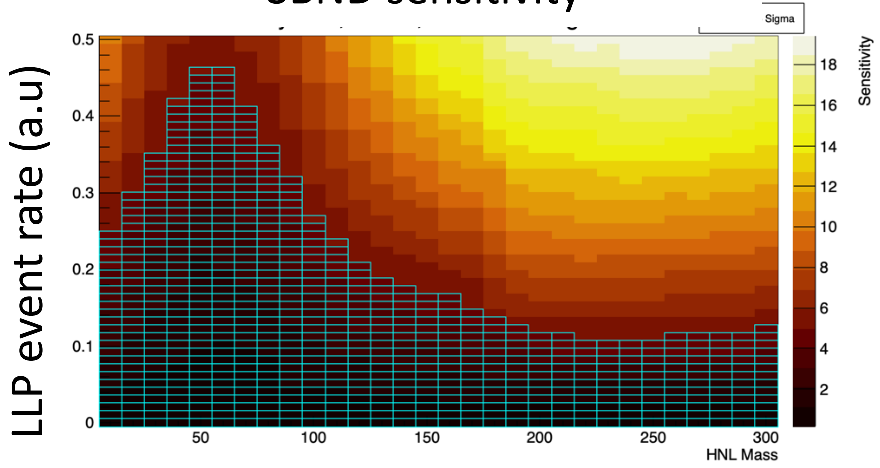
MicroBooNE sensitivity



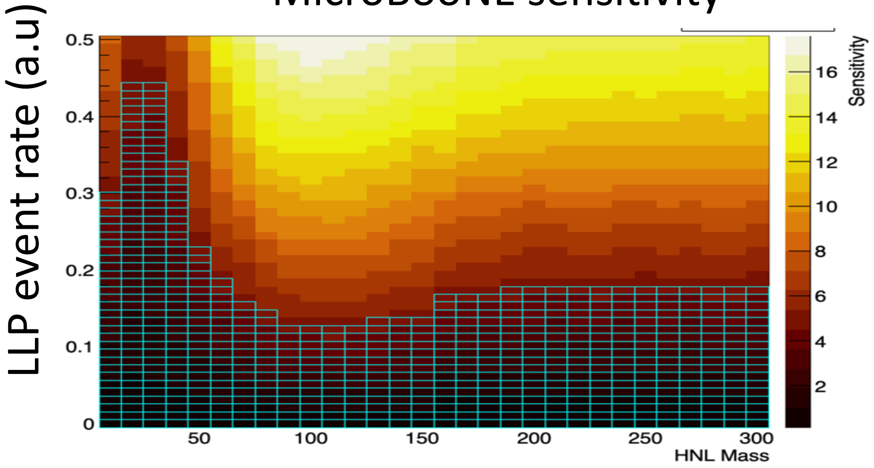
> Factor of 2 improvement

MicroBooNE Vs SBND

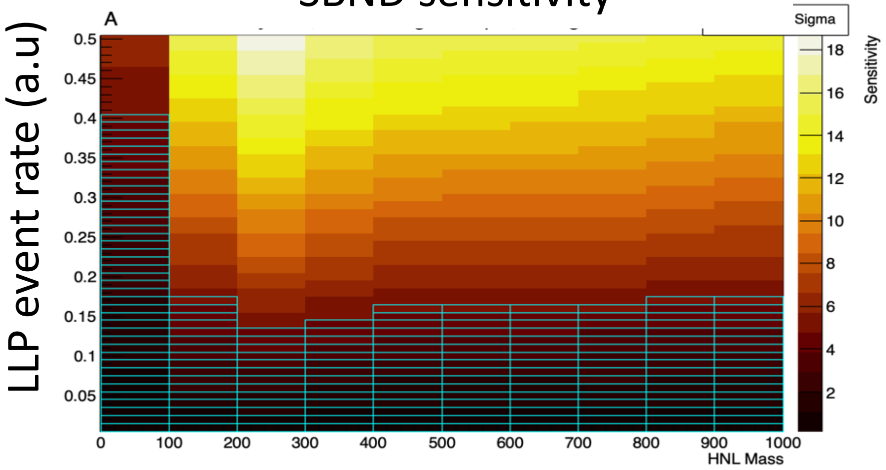
SBND sensitivity



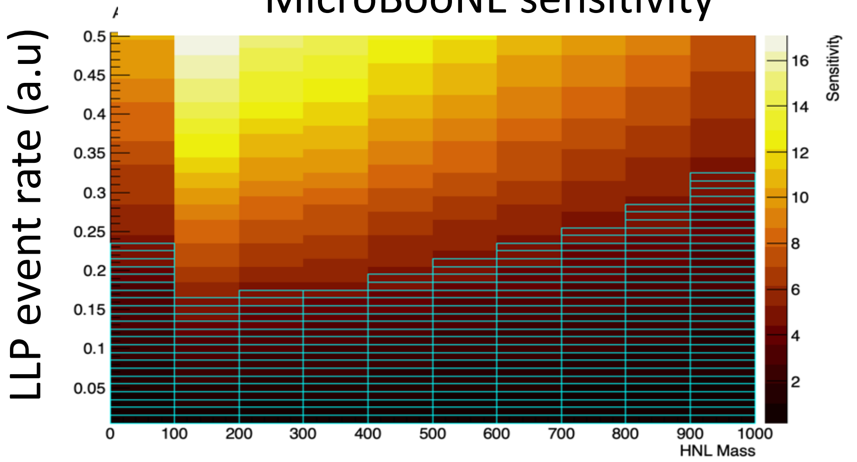
MicroBooNE sensitivity



SBND sensitivity



MicroBooNE sensitivity

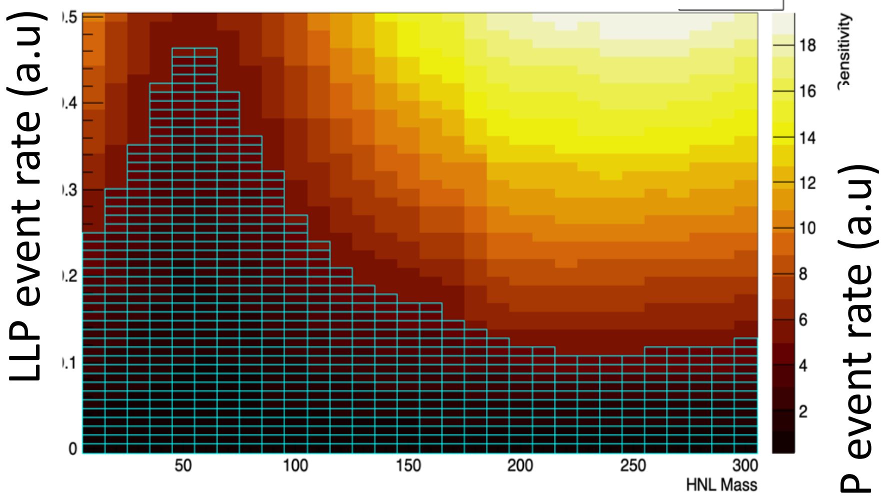


Optimal sensitivity occurs around 210-250 MeV for SBND and 90-120 MeV for MicroBooNE

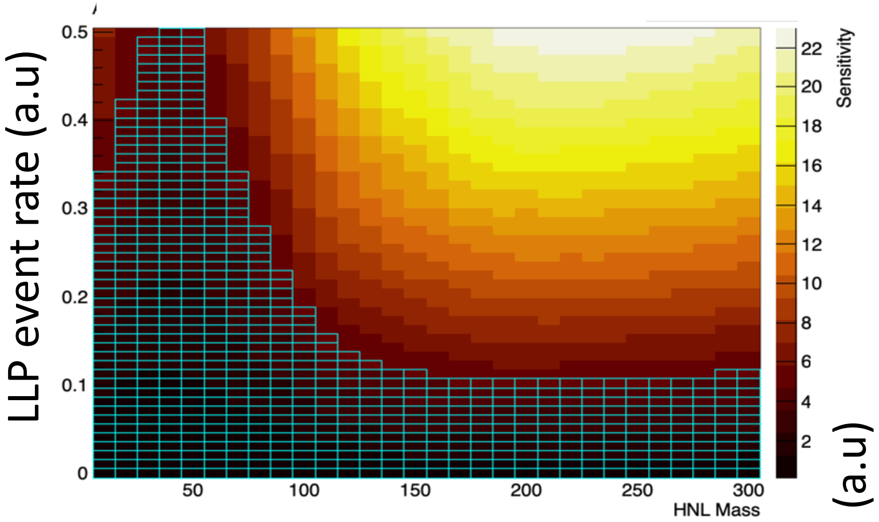
In case of excess in one experiment, combining results in different experiments in the SBN program can pin point the LLP masses and lifetime

Improvements for future experiments

SBND with 1.5 ns resolution

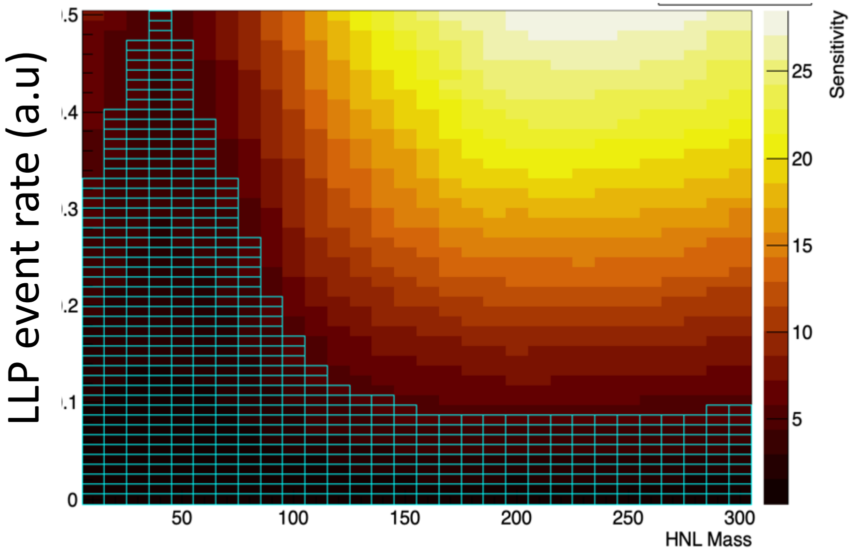


1 ns resolution



DUNE near detector is ~100 m underground Cosmic background will be significantly reduced.

Factor 2 cosmic rejection



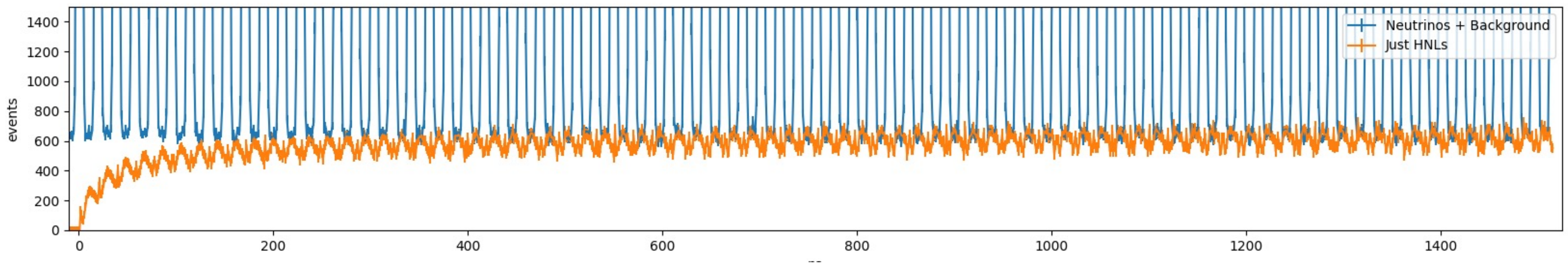
How to improve sensitivity?

- Dedicated search window
- multi – detector combined search
- Better timing resolution
- Less cosmic background

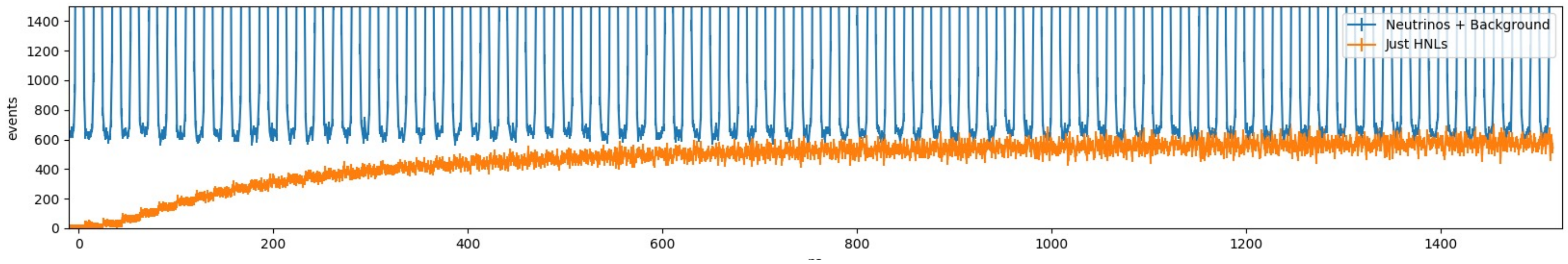
SBND has better Photon detection system Promising to achieve better timing resolution than MicroBooNE

Heavy LLP signature Rising ”floor”?

LLP mass of 150 MeV



LLP mass of 400 MeV



- Heavy LLP is more smeared in time. Long decay could bleed into later neutrino bunch. Signal adds up over time appeared as rising floor
- Can develop optimized algorithm to fit this behavior to characterize LLP mass
- Pre-condition is cosmic background is low

Summary

- O(1) ns timing resolution is achieved for the first time at LArTPC based neutrino experiment (MicroBooNE data)
- The bunch structure of GeV neutrino beamline + O(1) ns resolution offers a golden **model-independent** handle for MeV-GeV Long-lived-Particles.
- Quantitative sensitivity boost is demonstrated with fast MC
- Will apply this technology in BSM searches in SBN and DUNE