Application of Precision Time Structure in On-Axis Neutrino Beams

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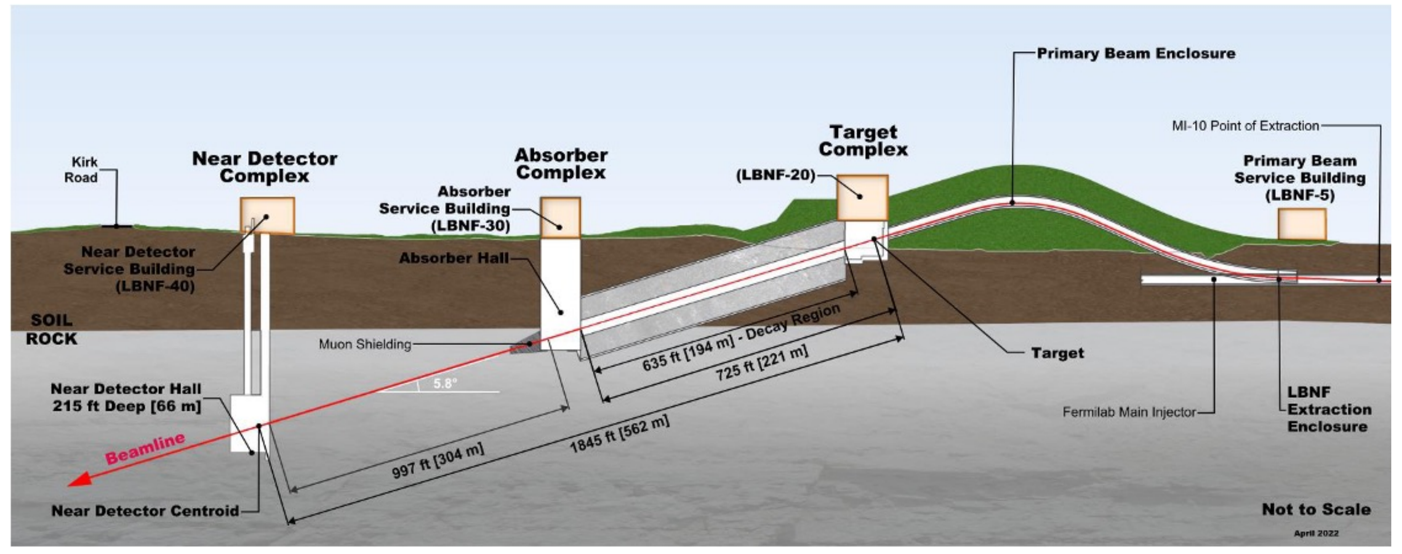
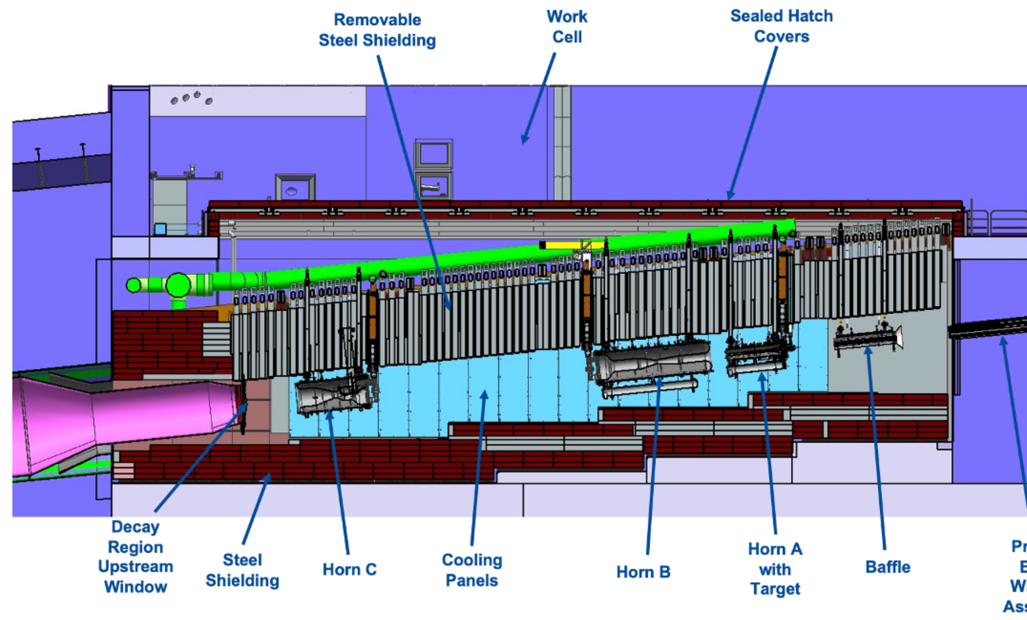
LBNF Beamline



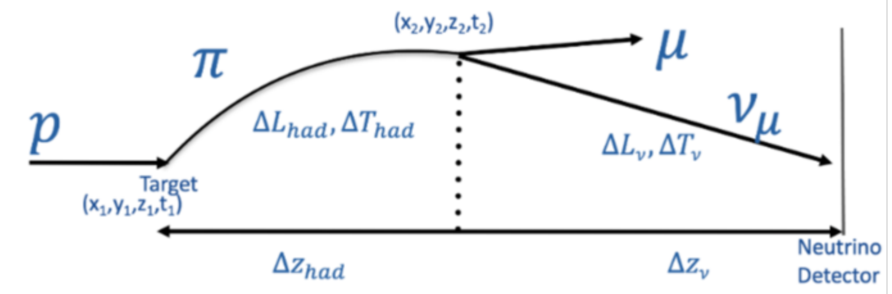
- Proton beam extracted from Fermilab's Main Injector in the range of 60 – 120 GeV every 0.7 – 1.2 sec with pulse duration of 10 μs
- Protons per cycle:
  - -1.2 MW era: 7.5×10^{13}
  - -2.4 MW era: $(1.5\text{-}2.0)\times10^{14}$

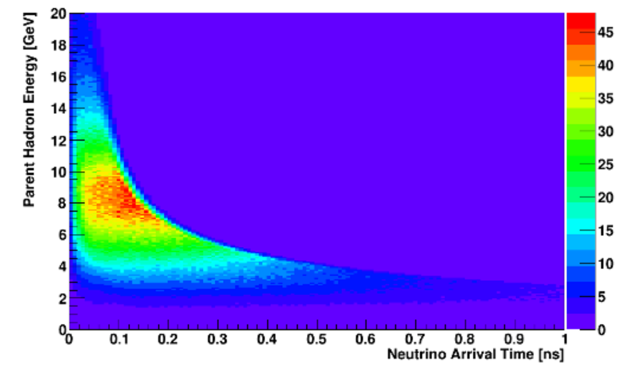
Target Hall Shield Pile Layout - Optimized Design

- Proton beams collide with a target, producing pions and kaons
- These hadrons selected by sign and momentum and focused by a series of magnetic horns
- The hadrons decay into muons and ν_μs with a strongly forward directionality



Neutrino Beam Timing





Arrival time difference between neutrinos from relativistic hadrons and neutrino from hadron of energy E

$$T_A = \Delta T_{had} + \Delta T_\nu = (t_2 - t_1) + \Delta L_\nu/c$$

$$T_A^{prompt} = \Delta z/c = (\Delta z_{had} + \Delta z_\nu)/c$$

$$\Delta T_{had} = t_2 - t_1$$

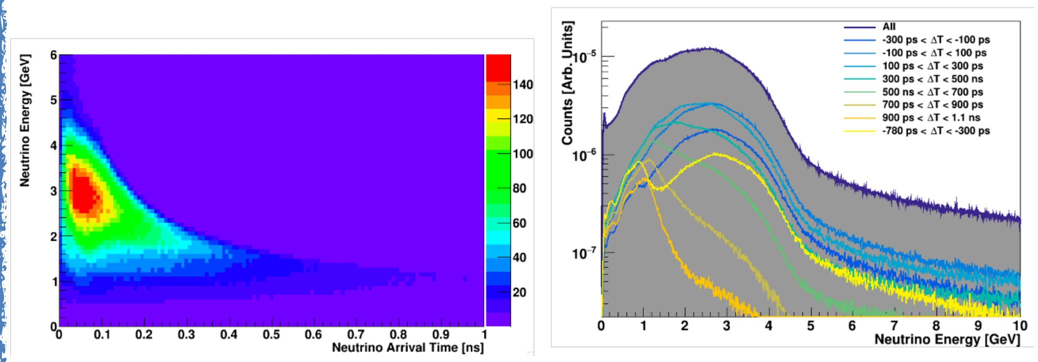
$$\Delta T_\nu = \Delta L_\nu/c$$

Eqn1: $\Delta T = T_A - T_A^{prompt} = \Delta T_{had} + \Delta L_\nu/c - (\Delta z_{had} + \Delta z_\nu)/c$

For $\Delta L_\nu \approx \Delta z_\nu$

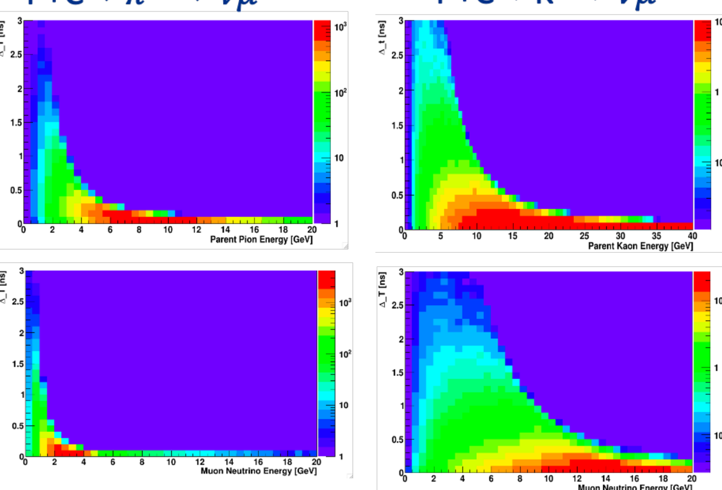
Eqn2: $\Delta T \approx \Delta T_{had} - \Delta z_{had}/c$

Neutrinos at Near Detector

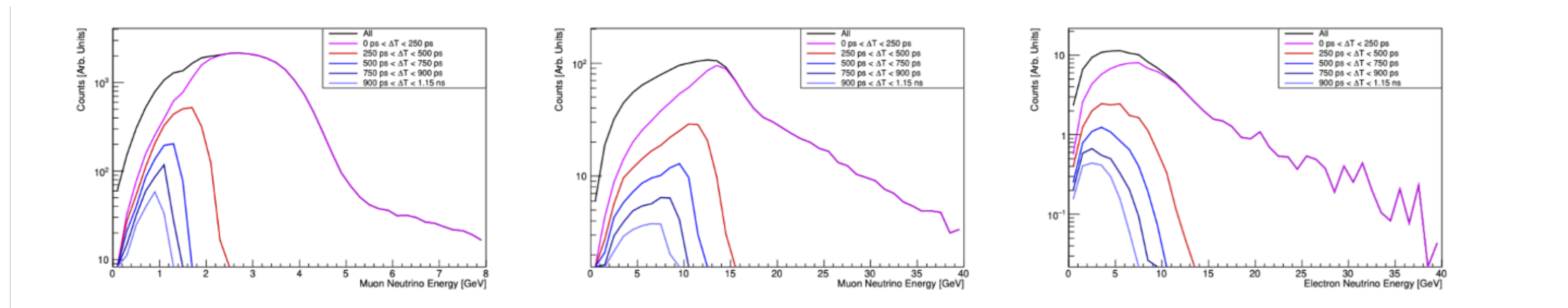


P+C→ π^+→ $\nu\mu$

P+C→ K^+→ $\nu\mu$

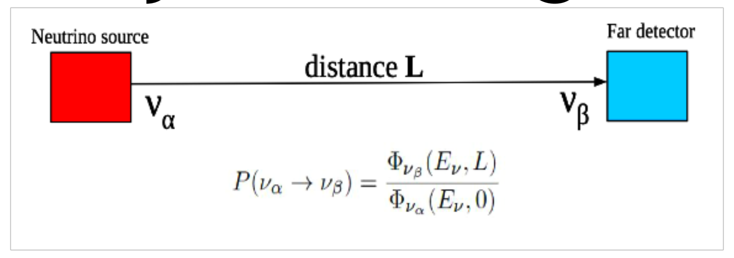


Simulation of neutrino energy distribution (outer dark blue envelope), overlaid with fluxes corresponding to increasingly later binned time cuts, assumes 250 ps bunch width, 100 ps detector timing in 200 ps bins at Near Detector



Parent hadron: pion only — Parent hadron: kaon only — Parent hadron: kaon only

Why is Timing Useful?



$$P(\nu_\alpha \to \nu_\beta) = \frac{\Phi_{\nu_\beta}(E_\nu, L)}{\Phi_{\nu_\alpha}(E_\nu, 0)}$$

Number of Near Detector events = Flux · Cross section · Detector effects

Number of Far Detector events = Flux · Oscillation probability · Cross section · Detector effects

- Want to measure oscillation probability
- Instead measure neutrino interaction rate N
- N depends on flux, cross-section, detector acceptance
- Need to deconvolve initial neutrino flux & reaction cross sections, detector effects – each energy dependent
- Neutrino energy spectra different at Near & Far Detectors, fluxes different due to oscillation
- Cross sections highly uncertain due to strong energy dependence
- N sensitive to nuclear effects – FSI, missing energy
- E_{rec} ➜ E_{true} depends on poorly understood neutrino interaction models
- Even if ND & FD were literally identical, flux differences mean no cancellation b/w ND & FD

- With stroboscopic approach, PRISM Near Detector program can be further enhanced with a fast Near Detector
- Also opens possibility of using PRISM's default program by providing Far Detector oscillated time slices
- With tools developed for time synchronization, precision timing can be applied to future oscillation experiments with fast detectors - there is an excellent opportunity here to think about fast timing for LAr-TPCs

For BSM:

- DUNE ND is expected to have neutral lepton sensitivities that are competitive with other experiments & will be enhanced by application of stroboscopic techniques
- Improved timing at Far Detector can distinguish inelastic interactions of cosmogenic inelastic Boosted Dark Matter (iBDM)
- Fast timing could be used in large liquid argon detectors to detect nuclear de-excitations of 40Ar following a baryon number violating process in order to increase efficiency and reduce background in search for proton decay

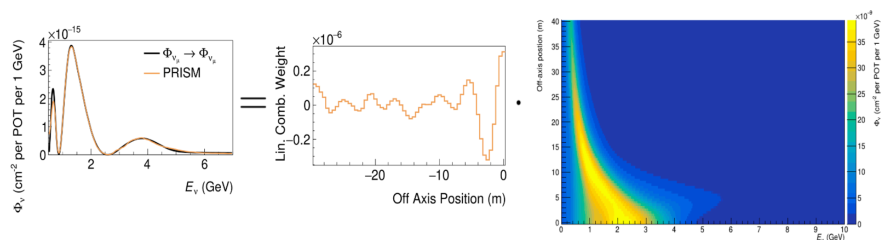
PRISM Complementarity of Stroboscopic Approach

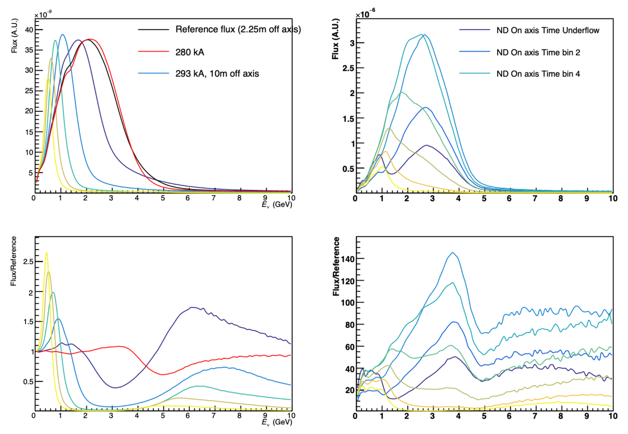
DUNE PRISM:

-application limited to ND

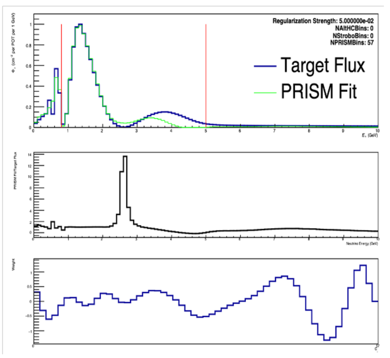
- measure oscillated flux at the near detector

$$\vec{\Phi}^{\nu}_{Far} \cdot P^{H}_{Osc} = \vec{C} \cdot \vec{\Phi}^{\nu}_{Near}$$

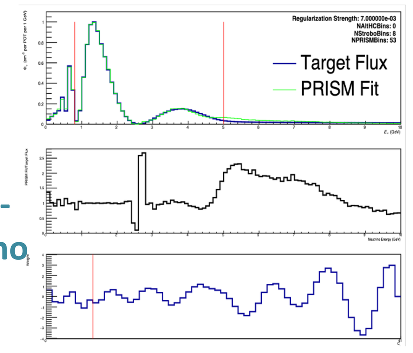


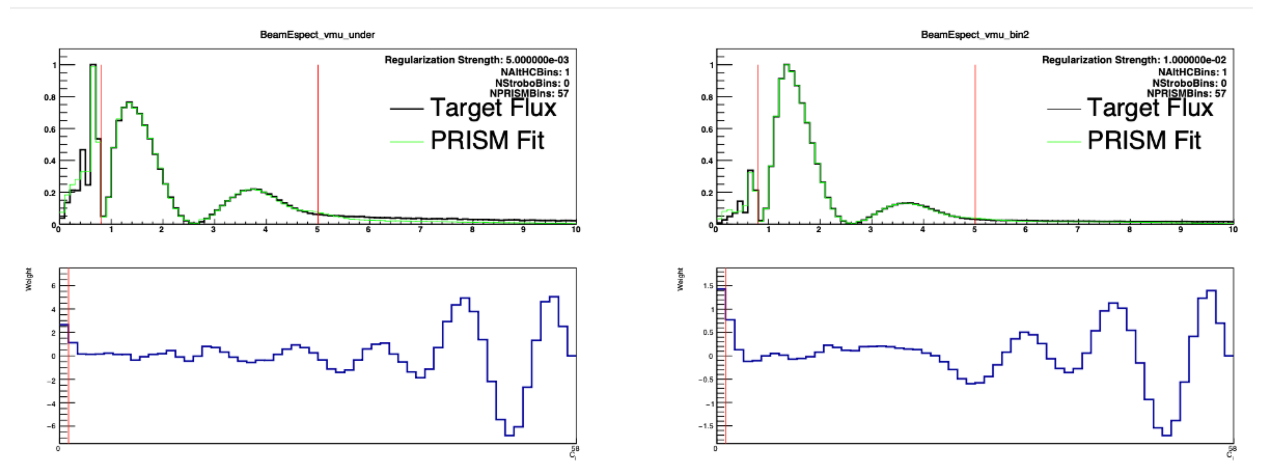


PRISM fit with PRISM on and off-axis fluxes only, no altHC flux



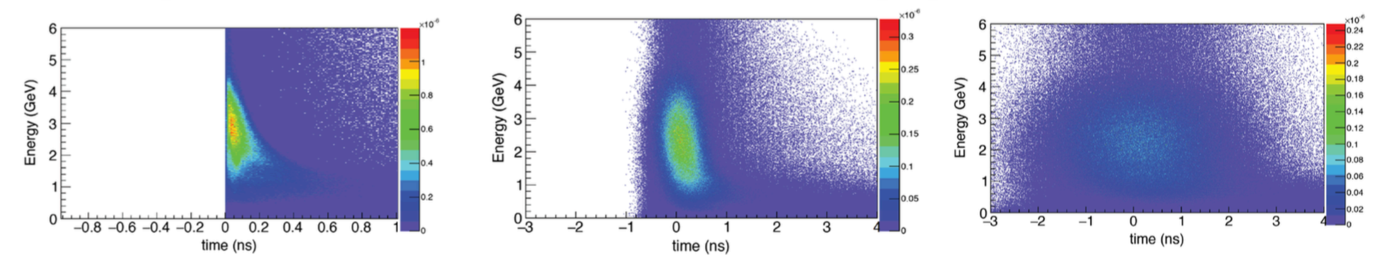
PRISM fit with PRISM off-axis fluxes only, stroboscopic on-axis fluxes and no altHC flux



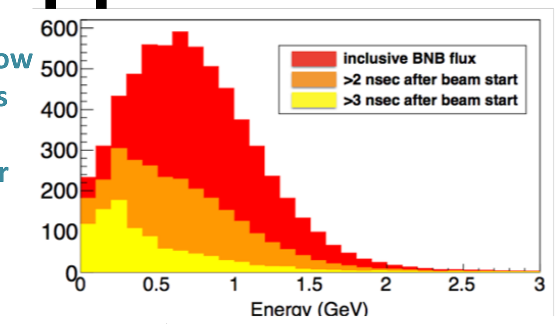


PRISM fits to oscillated Far Detector time bins

Required Efforts in Application of Stroboscopic Approach



- Energy of BNB spectrum skews towards low end, a broader tail of low-energy neutrinos
- Detecting time-slicing effect should be possible, even with 1 ns bunches, a smaller bunch length is better

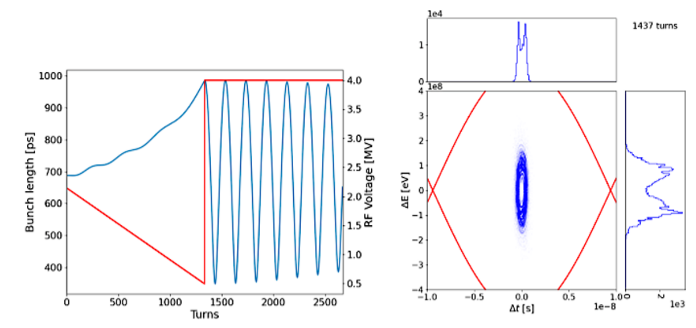


Energy and time correlation of neutrinos becomes smeared when proton bunch has a non-zero time-width

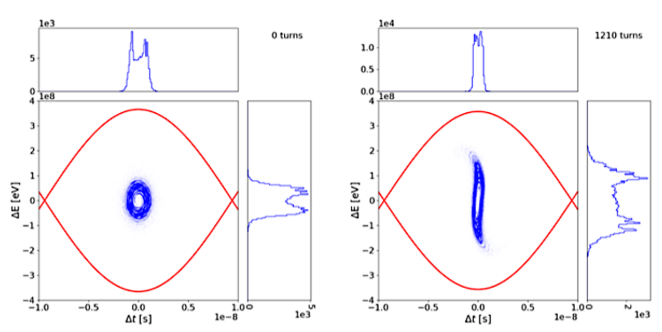
Creation of short (O(100 ps)) proton bunch length

Detectors with fast timing to get equivalent time resolution

Synchronization b/w time at detector & time of bunch-by-bunch proton

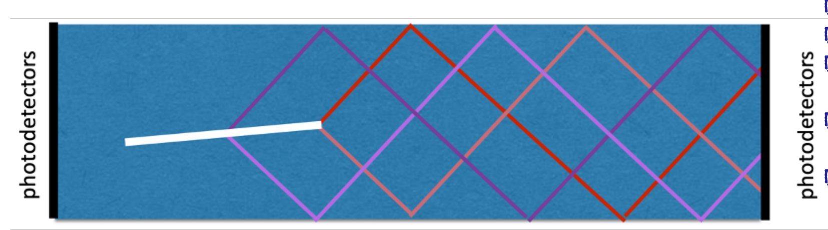


Snap Bunch Rotation in MI



Adiabatic excitation of longitudinal bunch shape oscillation in MI

Proposed method: https://arxiv.org/abs/2004.00580



- From electron TPC data, liquid Argon-based detectors can precisely re-construct each event in space
- Use reconstructed track from electron drift to simulate detected time and position of Cherenkov photons
- Only one parameter, neutrino event time needs to be fitted for, in comparison of 4D-coordinates of simulated photons and measured photons
- For 50-100 ps precision timing in liquid Argon, prompt light must be detected precisely, and Cherenkov light at visible wavelengths has properties required
- Mirror top, bottom, sides, and place photodetectors on end cap

Conclusion

- Neutrino beams will play a crucial role in future neutrino experiments.
- Using stroboscopic approach neutrino beams can be exploited to their fullest potential

Reference - https://arxiv.org/pdf/1904.01611.pdf https://indico.fnal.gov/event/58470/

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