

ANNIE:

The Accelerator Neutrino Neutron Interaction Experiment

NuInt 2024

Instituto Principia, São Paulo

April 18, 2024



Andy Mastbaum

Rutgers University

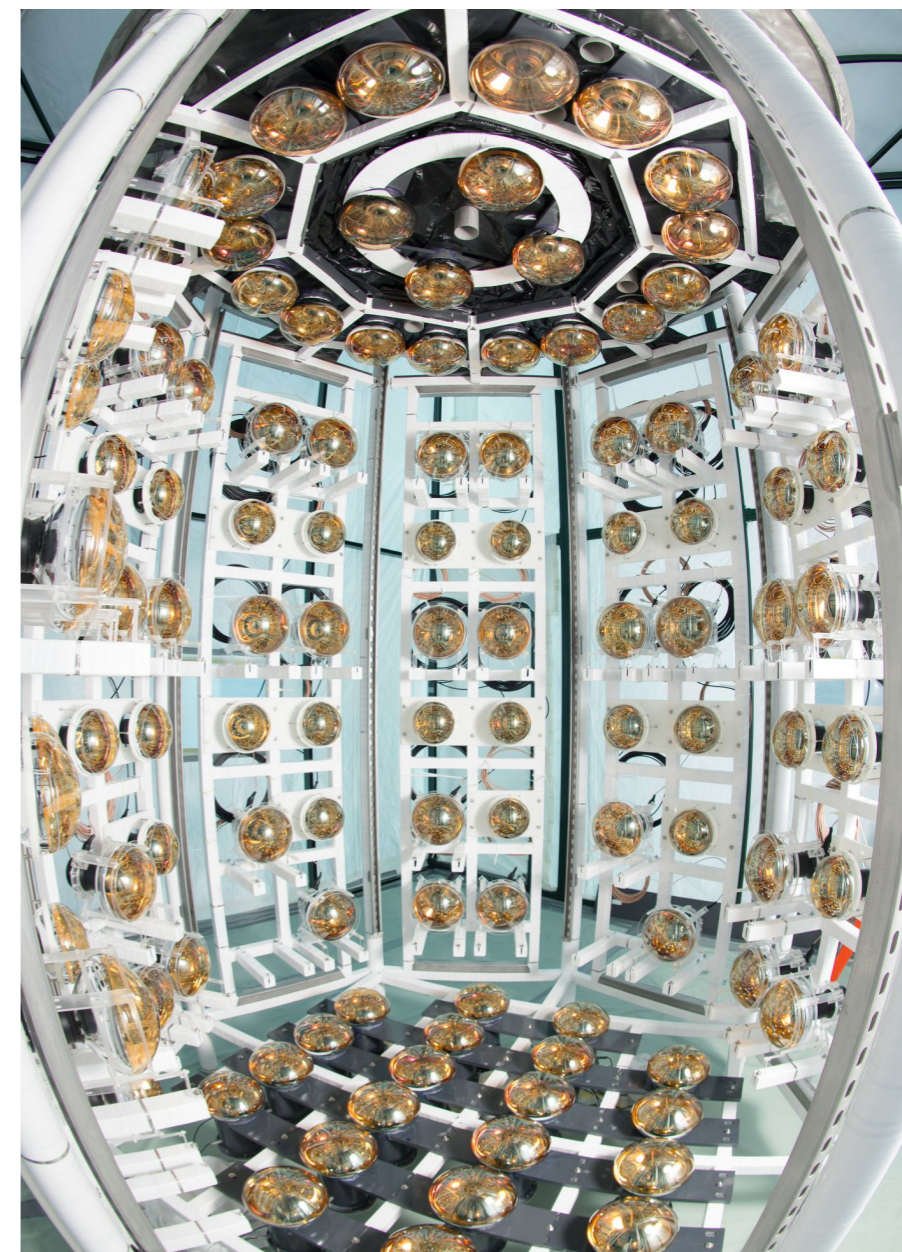
mastbaum@physics.rutgers.edu

on behalf of the ANNIE collaboration





- Introduction to ANNIE
 - Goals & capabilities
 - The ANNIE detector
- Physics program
 - Neutrino interactions
 - Neutrino-induced neutrons
- Neutrino detector R&D
 - Novel targets, fast timing
- Status & Prospects



ANNIE Collaboration

March 2024 at
Florida State University



Small collaboration, 17 institutions, 6 countries



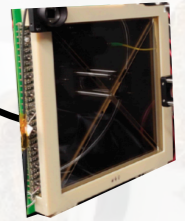
ANNIE Goals

PHYSICS

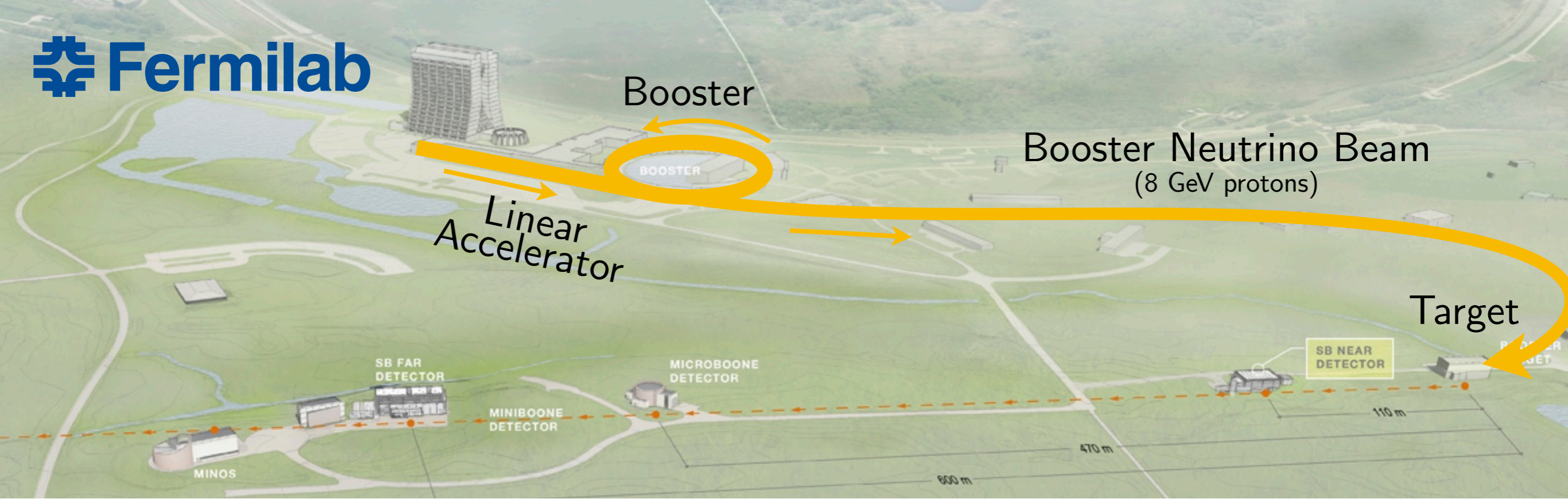


- **Neutrino-nucleus interactions**
 - GeV ν_μ + H₂O target
 - High flux near fixed target
- **Neutrino-induced neutron multiplicity, vs. Q^2**
 - Probe an important source of systematic uncertainty for oscillation measurements
 - Gd-loaded H₂O target
- **Multi-target cross sections**
 - Same neutrino beam as SBN LArTPCs, strongly correlated flux

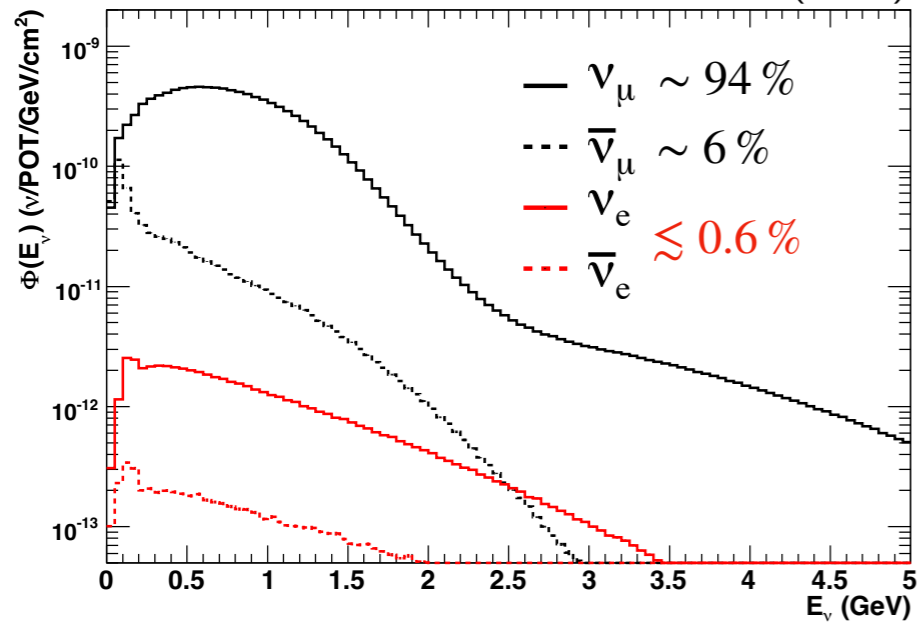
R&D

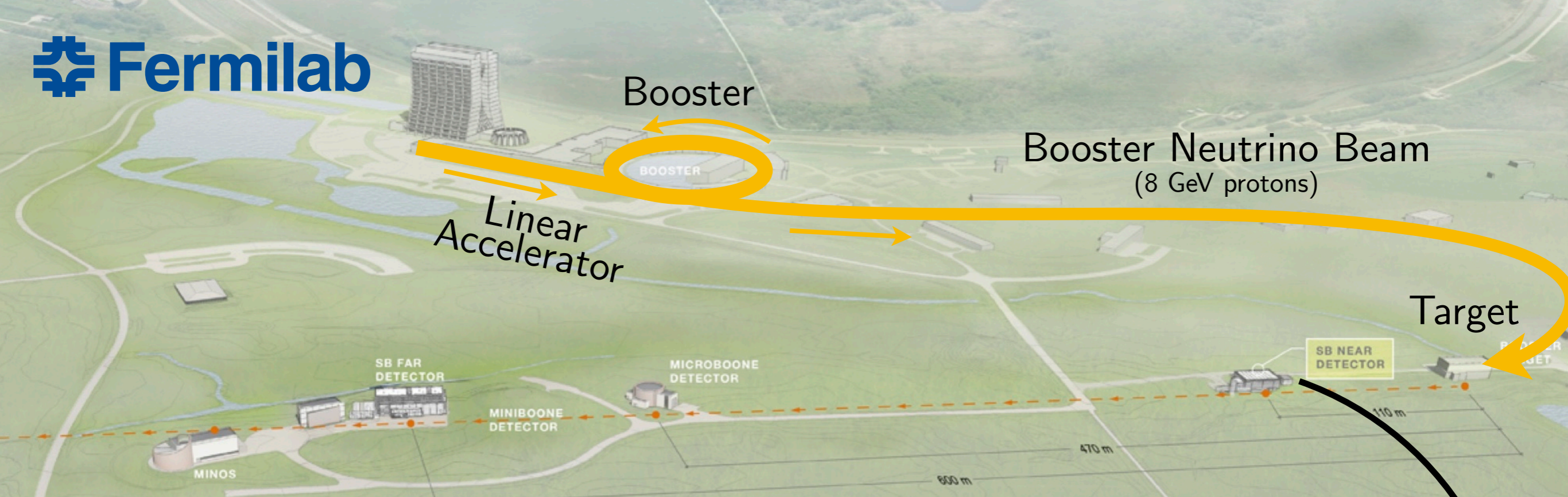


- **Flexible testbed to develop next-generation neutrino detector technologies**
- **Gd-loaded water target**
 - High-efficiency neutron tagging
- **Fast timing**
 - Large-Area Picosecond Photodetectors (LAPPDs)
- **Novel target media**
 - Deployable volume of Water-based Liquid Scintillator (WbLS) with Cherenkov + scintillation signals

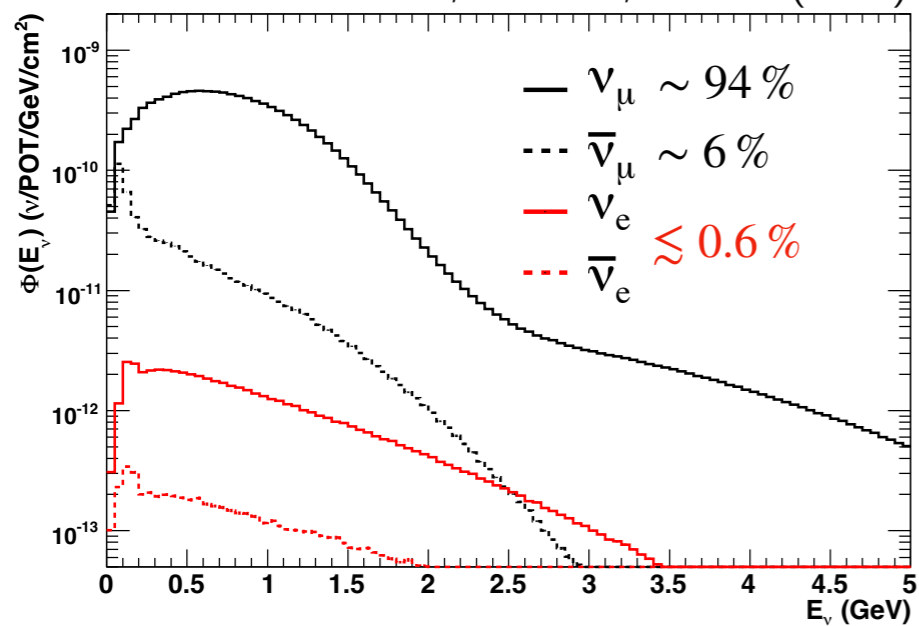


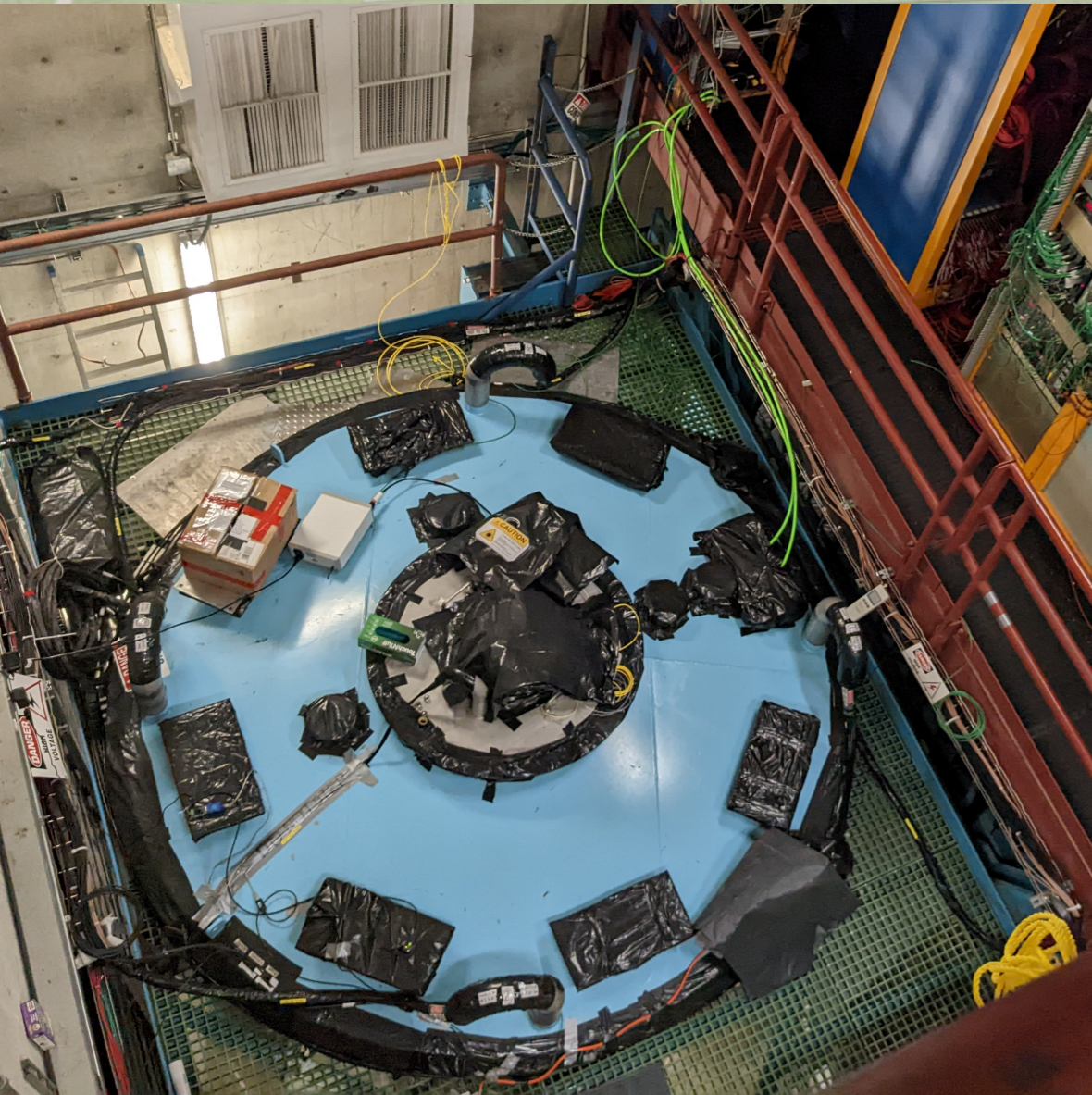
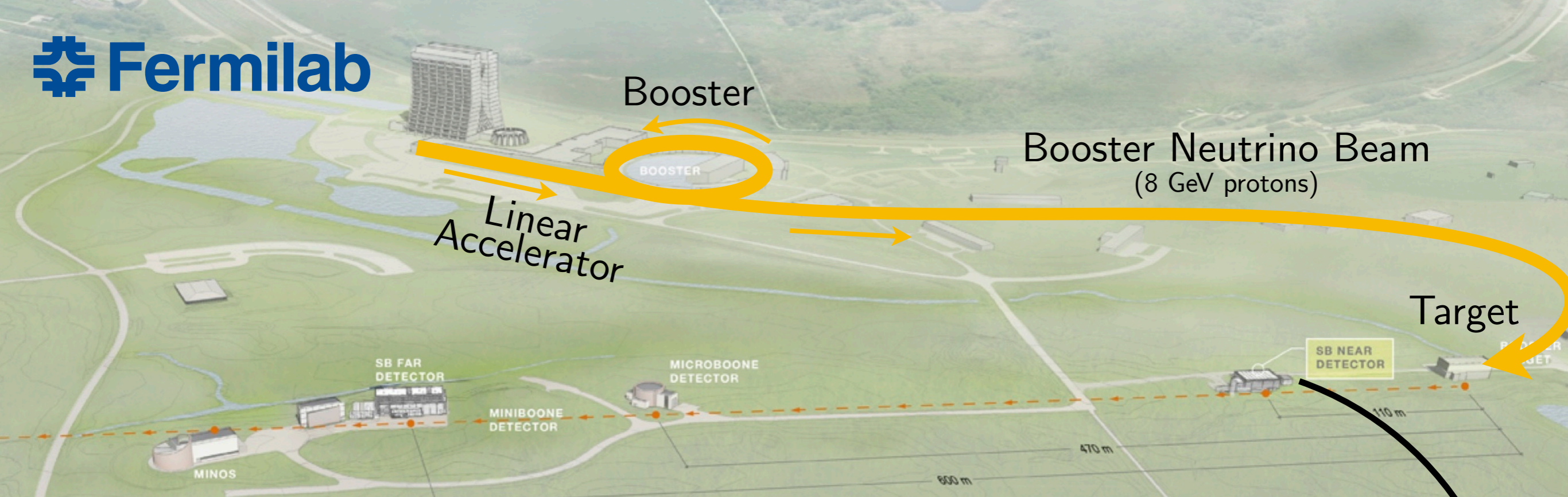
MiniBooNE, PRD **79**, 072002 (2009)



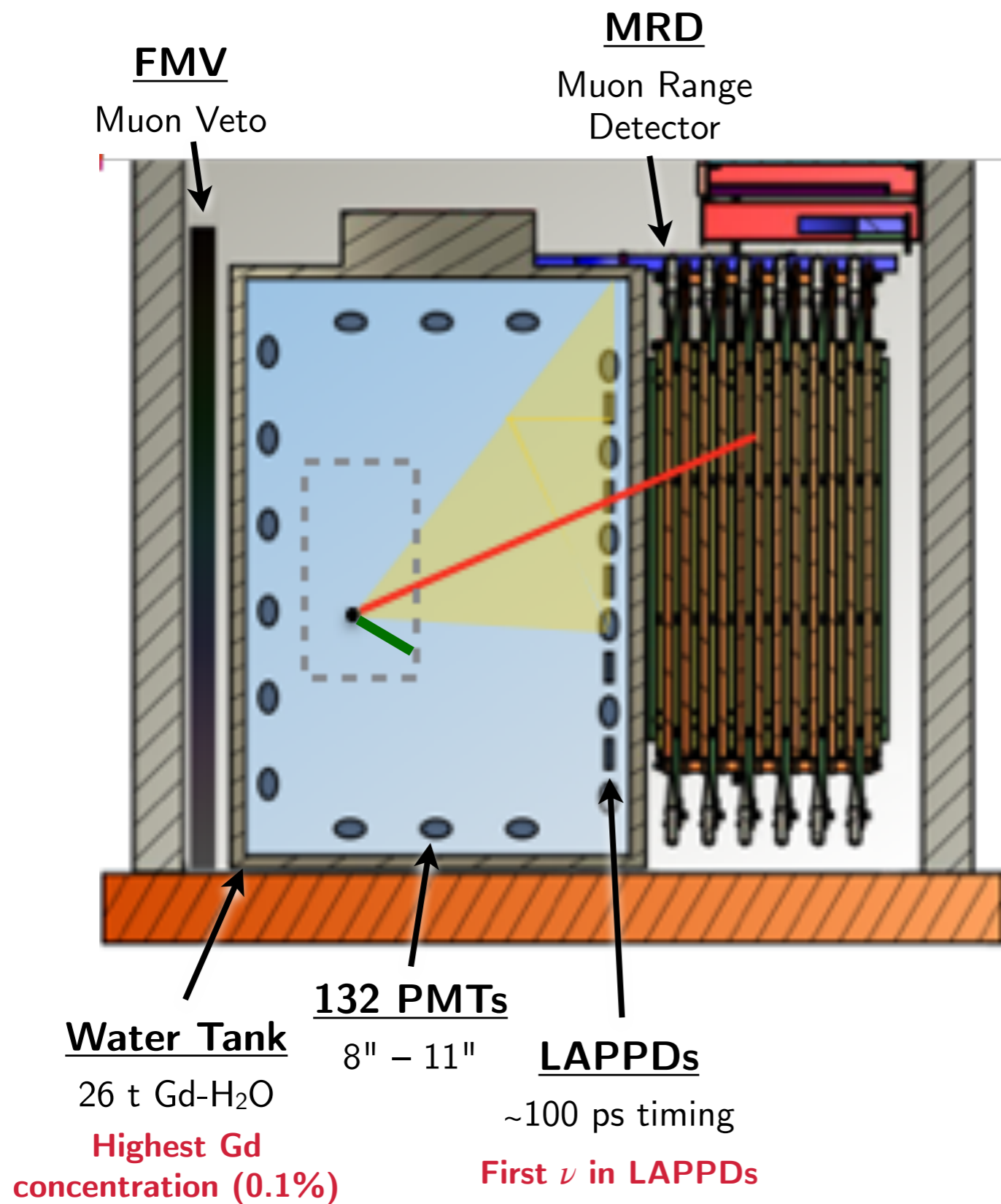


MiniBooNE, PRD **79**, 072002 (2009)

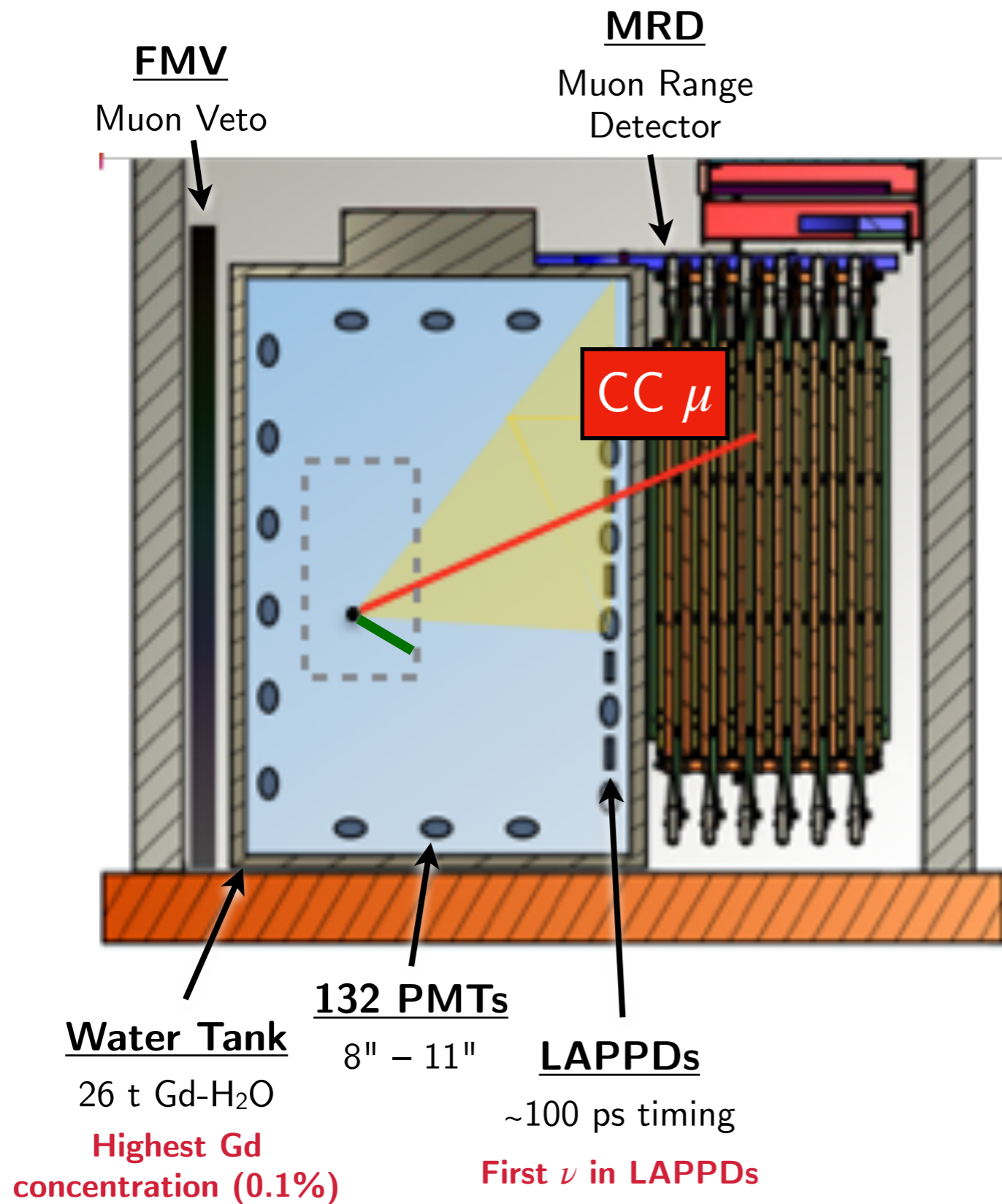




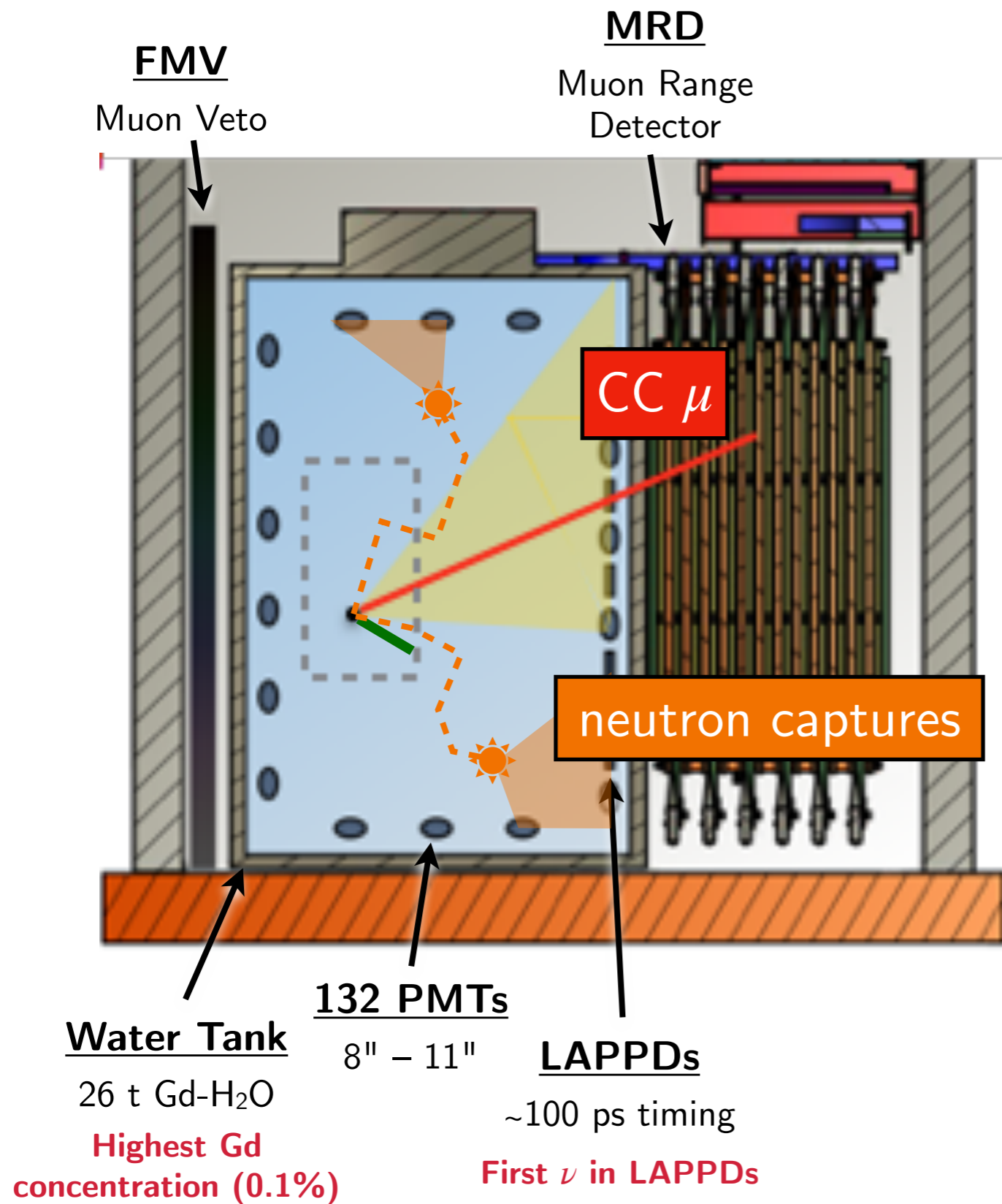
ANNIE Detector



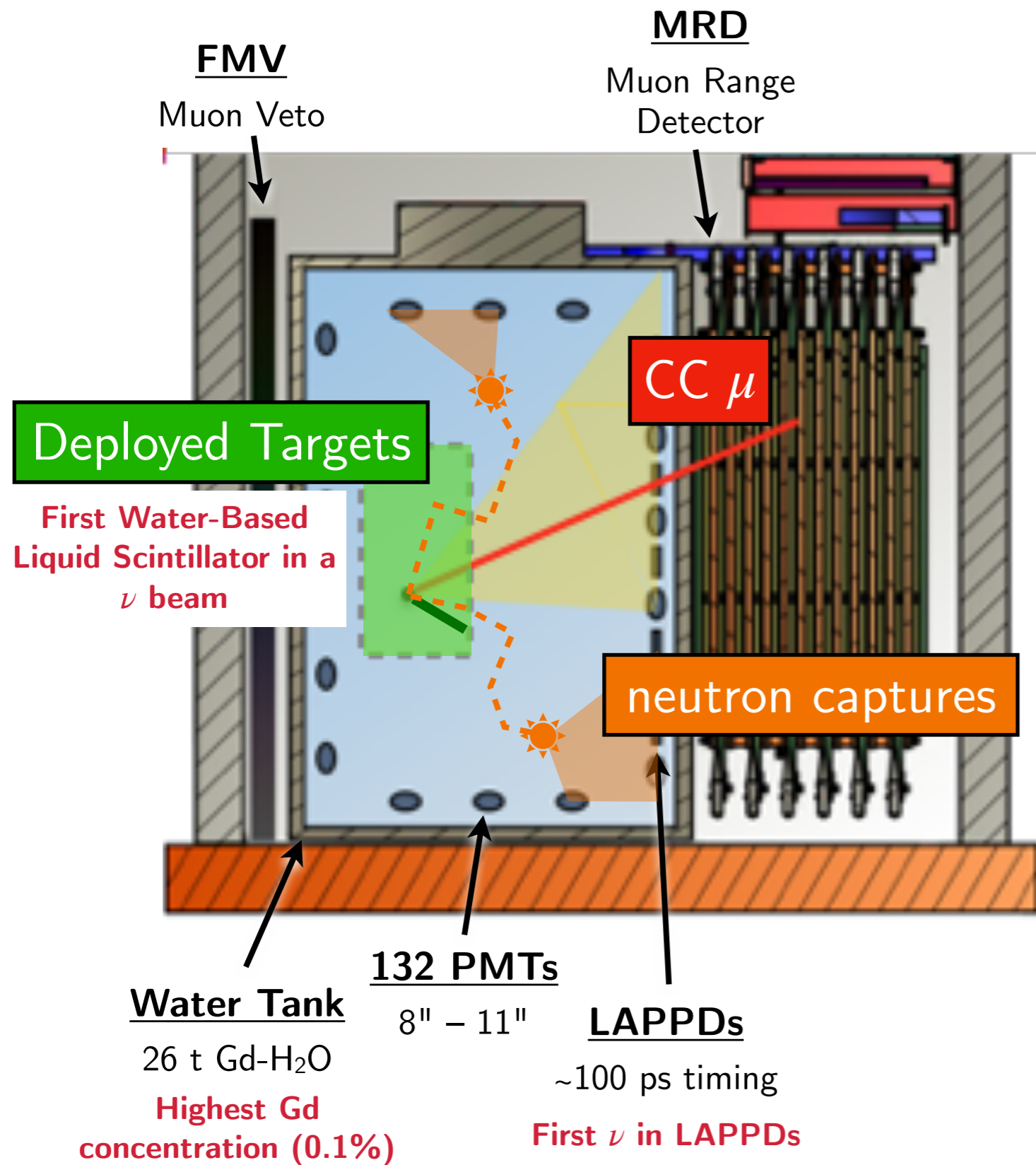
ANNIE Detector



ANNIE Detector



ANNIE Detector



ANNIE Detector

FMV
Muon Veto

MRD
Muon Range
Detector

Deployed Targets

First Water-Based
Liquid Scintillator in a
 ν beam

CC μ

neutron captures

Water Tank
26 t Gd-H₂O

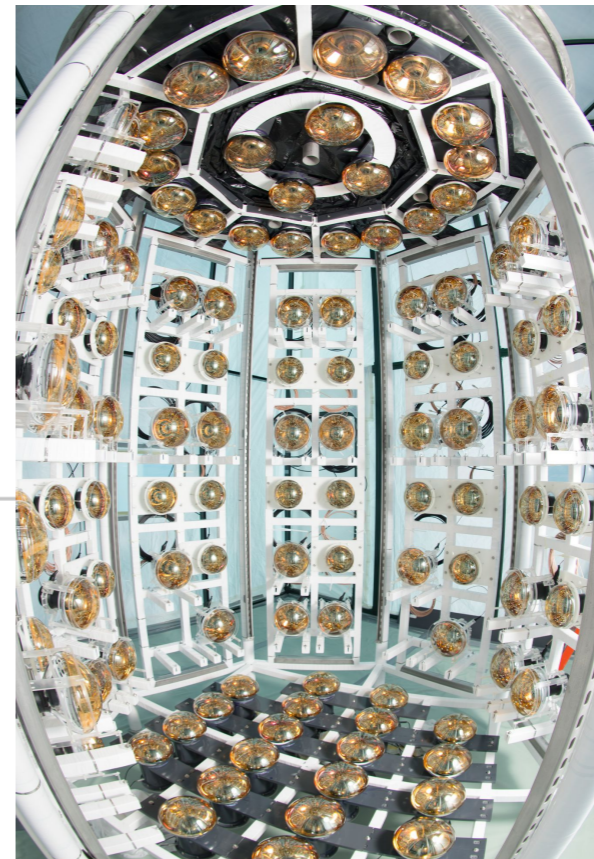
132 PMTs
8" - 11"

LAPPDs

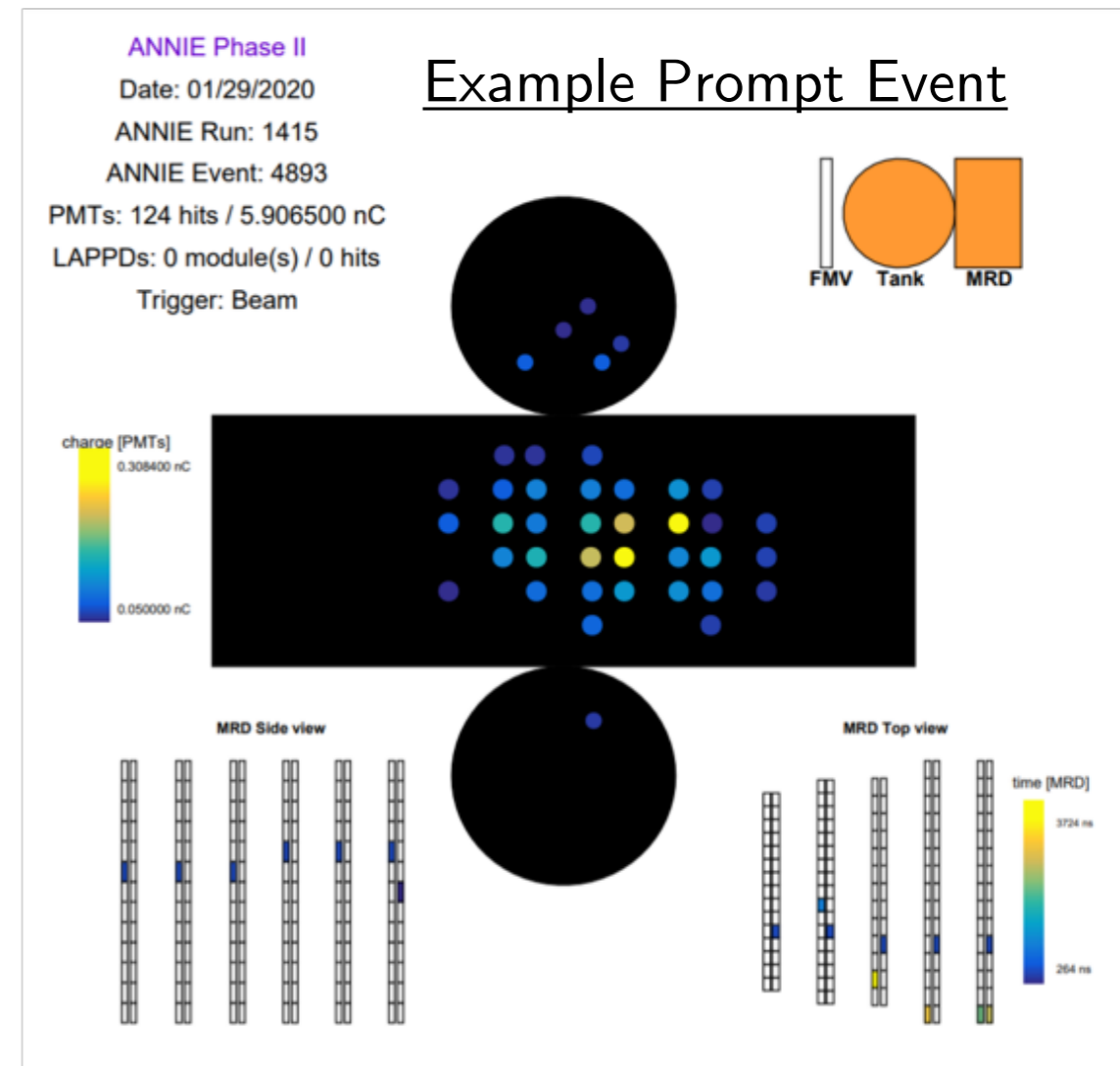
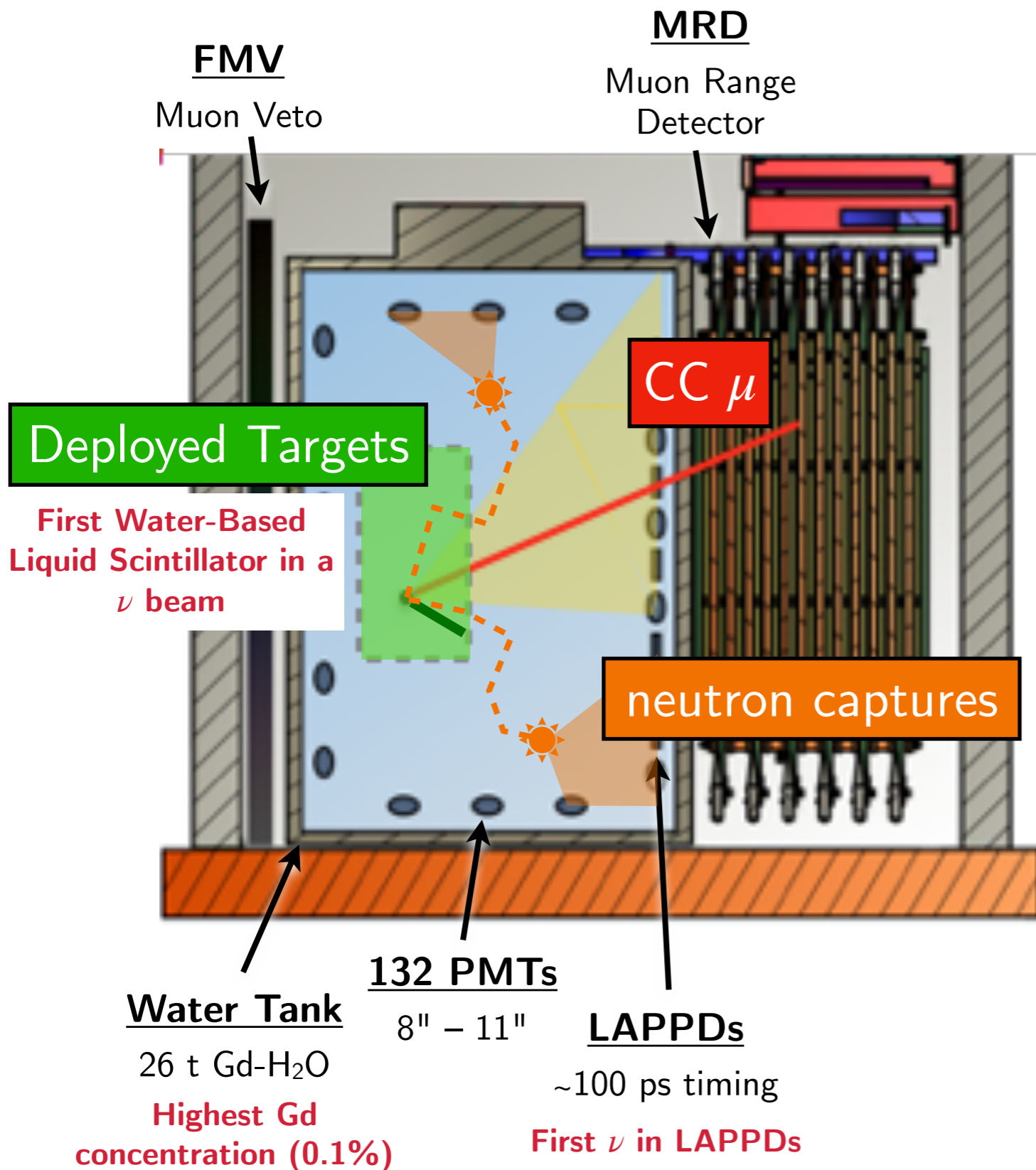
~100 ps timing

Highest Gd
concentration (0.1%)

First ν in LAPPDs



ANNIE Detector

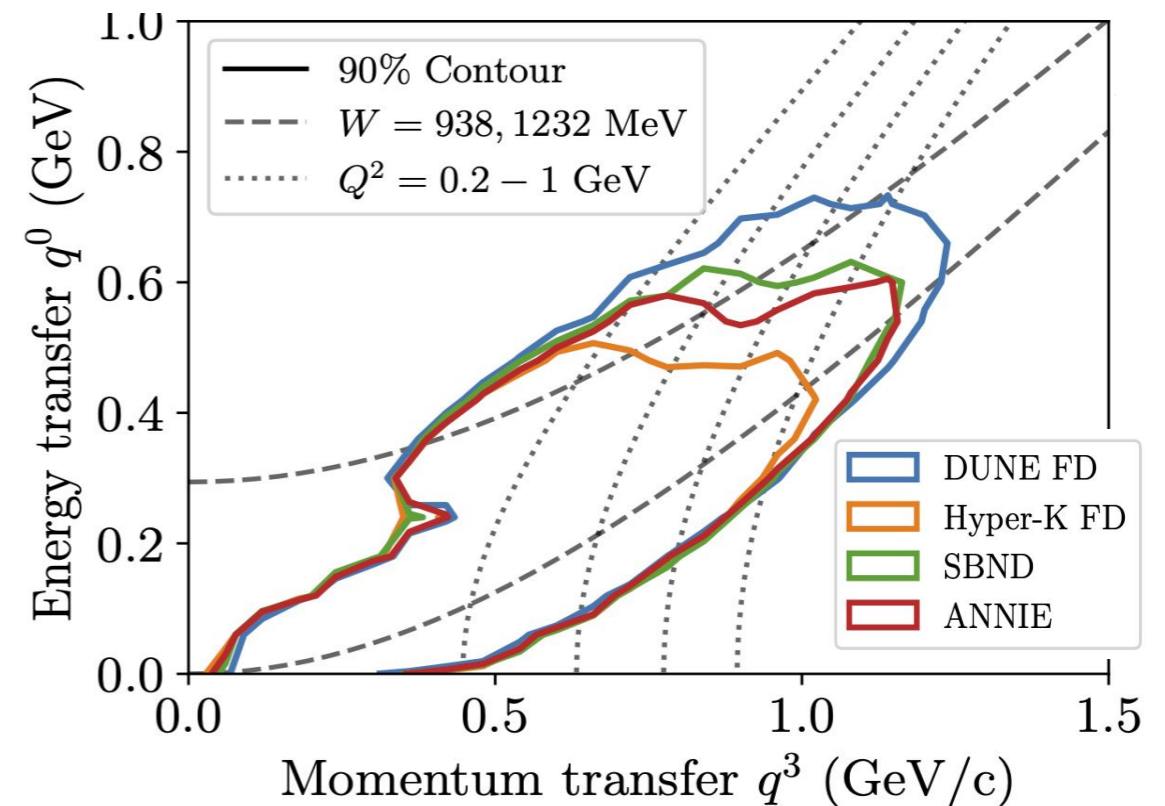
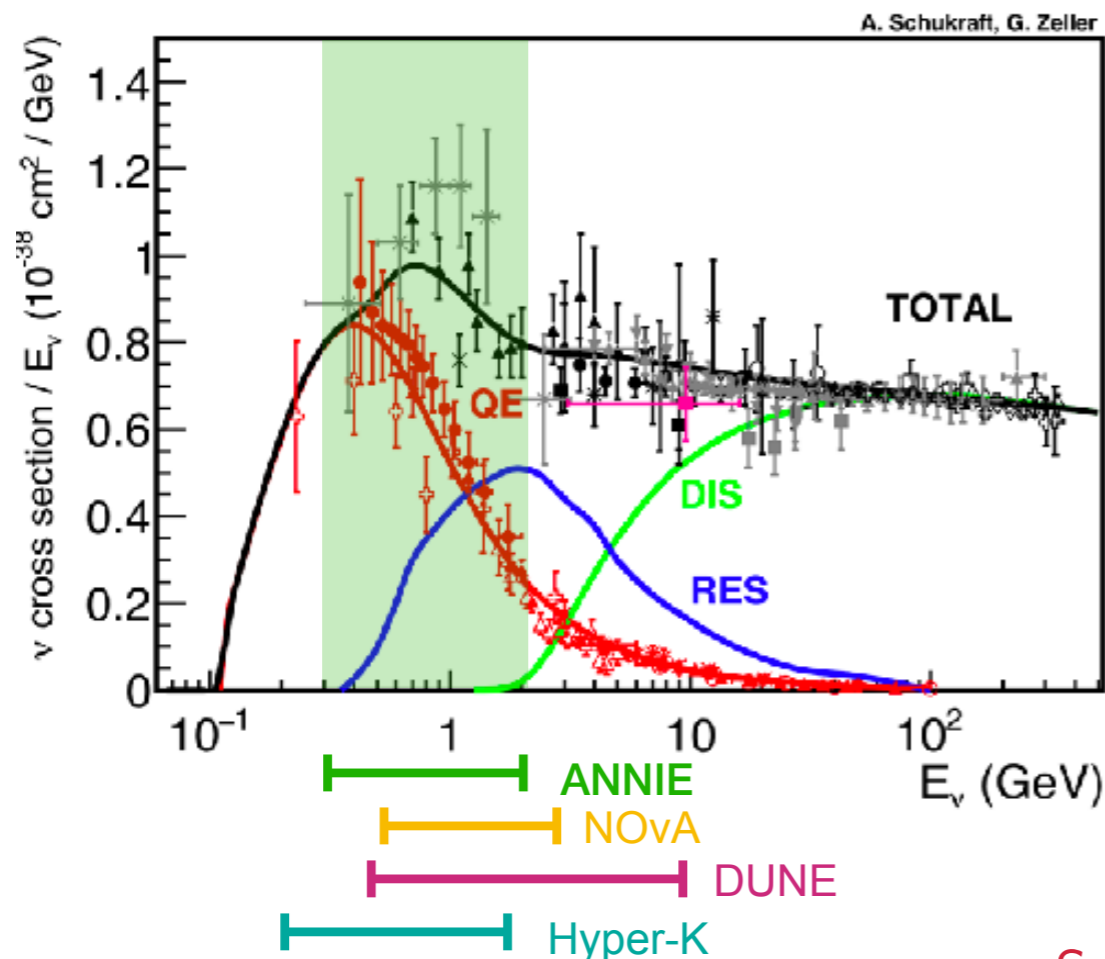


Prompt μ Cherenkov + MRD track
Delayed Gd neutron capture γ
Front veto rejects upstream μ
Deployable target volumes

ANNIE Physics Program

Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target \rightarrow high flux, overlap with T2K/LBNF
 - Spans the neutrino energy range where DUNE & HK overlap
 - Currently taking data, analyzing existing \sim 2 year dataset

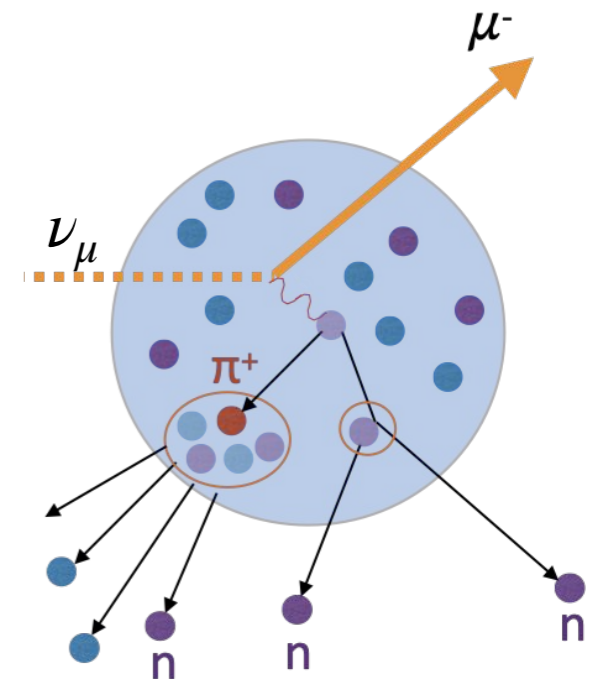
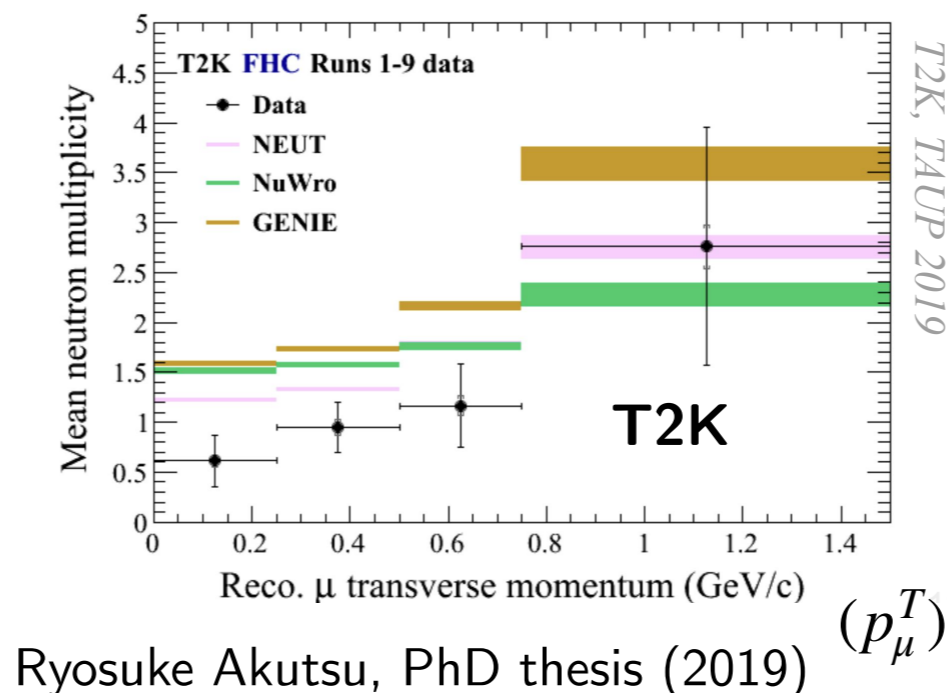
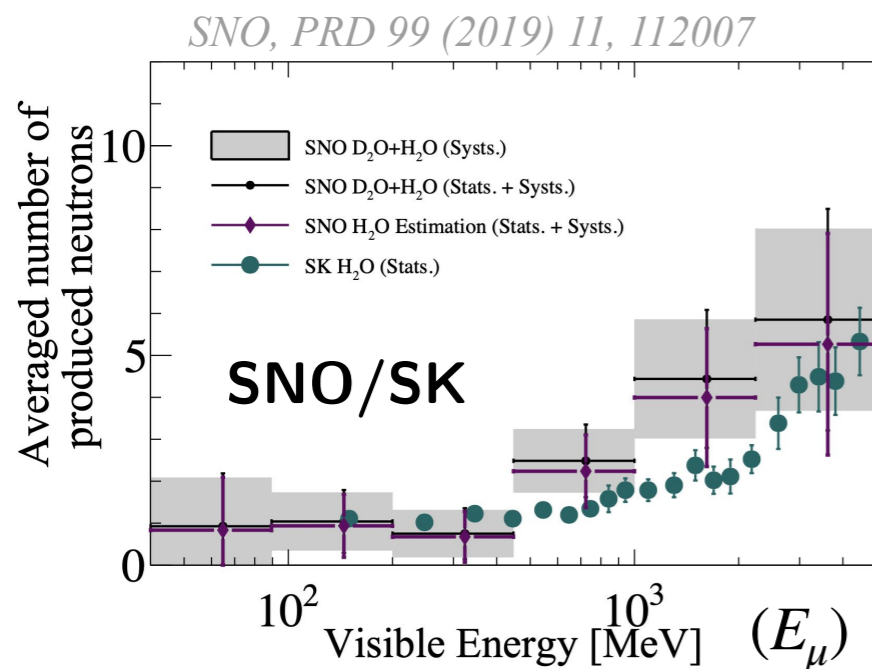


See also: Mun Jung Jung's SBND talk (April 17)

ANNIE Physics Program

Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target → high flux, overlap with T2K/LBNF
- ν_μ CC interactions with oxygen, final state neutrons
 - Differential cross sections, *high-statistics* n multiplicity vs. Q^2
 - Improved modeling of FS neutral production, input to generators
 - Constrain systematics for E_ν reconstruction in oscillation experiments

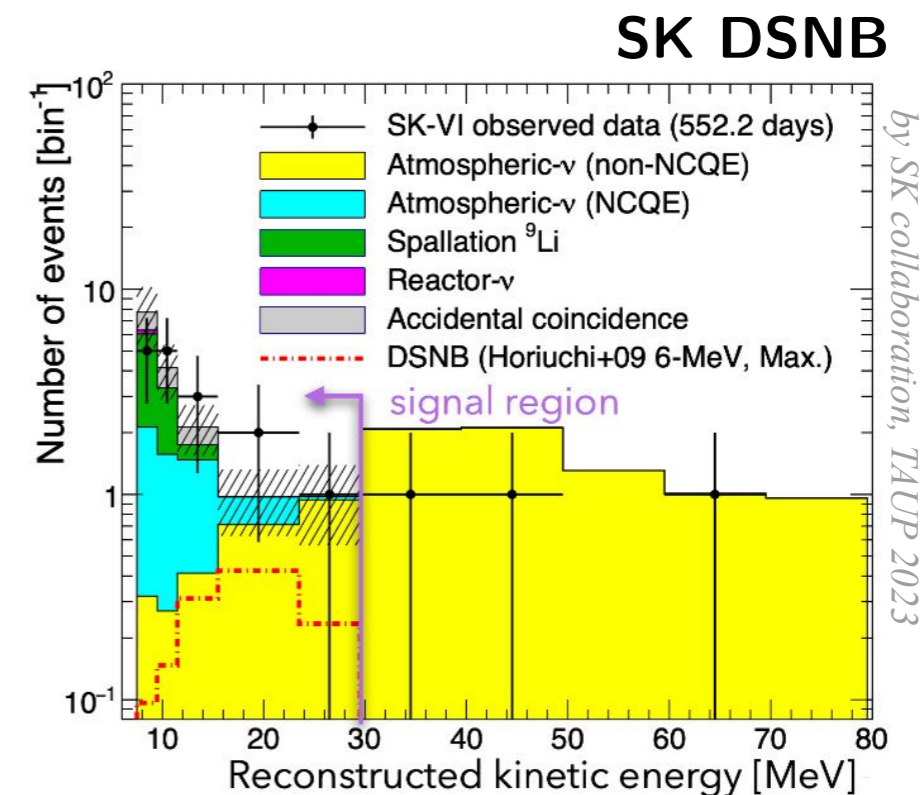
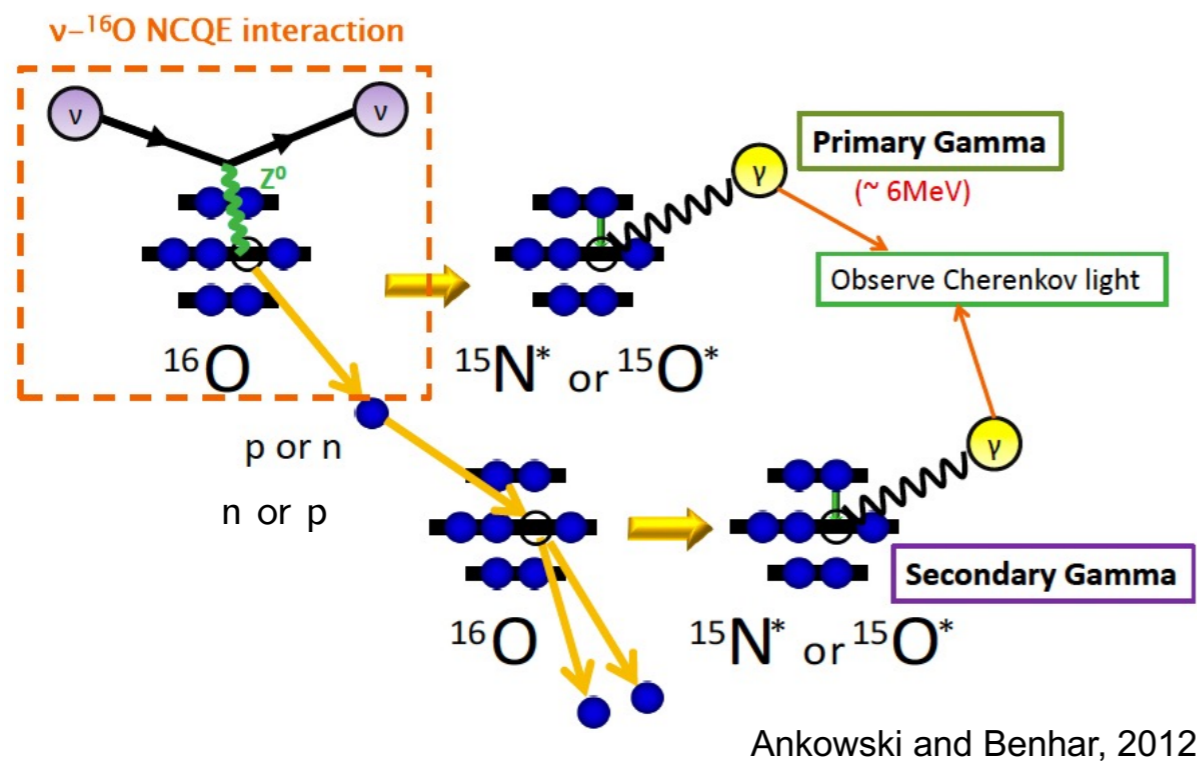


Ryosuke Akutsu, PhD thesis (2019)

ANNIE Physics Program

Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target \rightarrow high flux, overlap with T2K/LBNF
- ν_{μ} CC interactions with oxygen, final state neutrons
- ν NC interactions (γ cascade and neutrons)
 - Constrain backgrounds for LBL & p decay, DSNB searches
 - ~ 10 k fiducial NC events/beam year, $\sim 50\%$ of which are NCQE

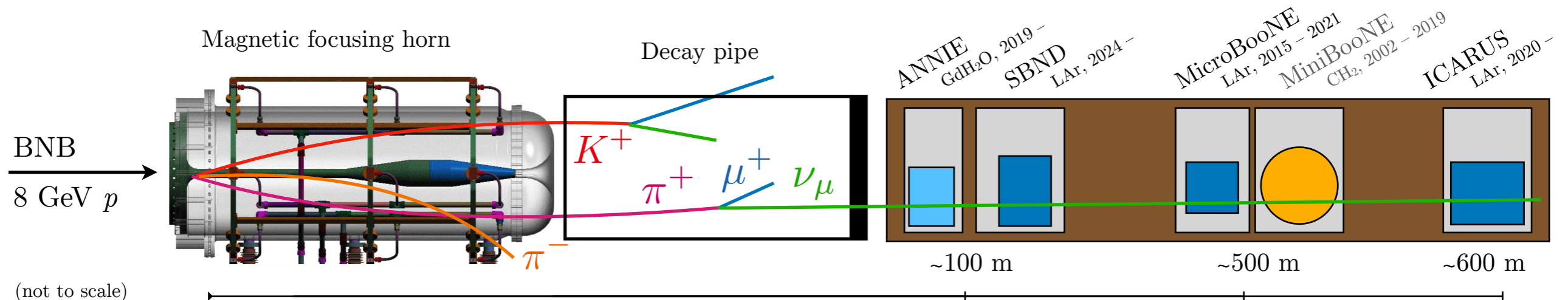
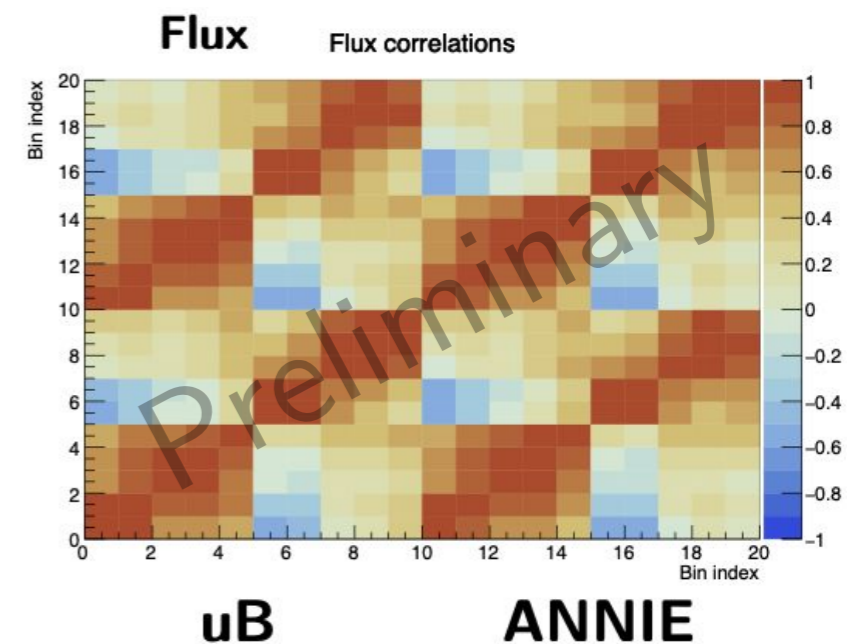


See also: Jie Cheng, Atm. NC (April 15); Anna Ershova, de-ex in p FSI (April 15)

ANNIE Physics Program

Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target \rightarrow high flux, overlap with T2K/LBNF
- ν_{μ} CC interactions with oxygen, final state neutrons
- ν NC interactions (γ cascade and neutrons)
- Same neutrino beam as SBN LArTPCs
 - Precision $^{40}\text{Ar}/\text{H}_2\text{O}$ σ comparisons
 - Probe A scaling, simultaneous tuning
 - Correlations in hadron production (n/p)

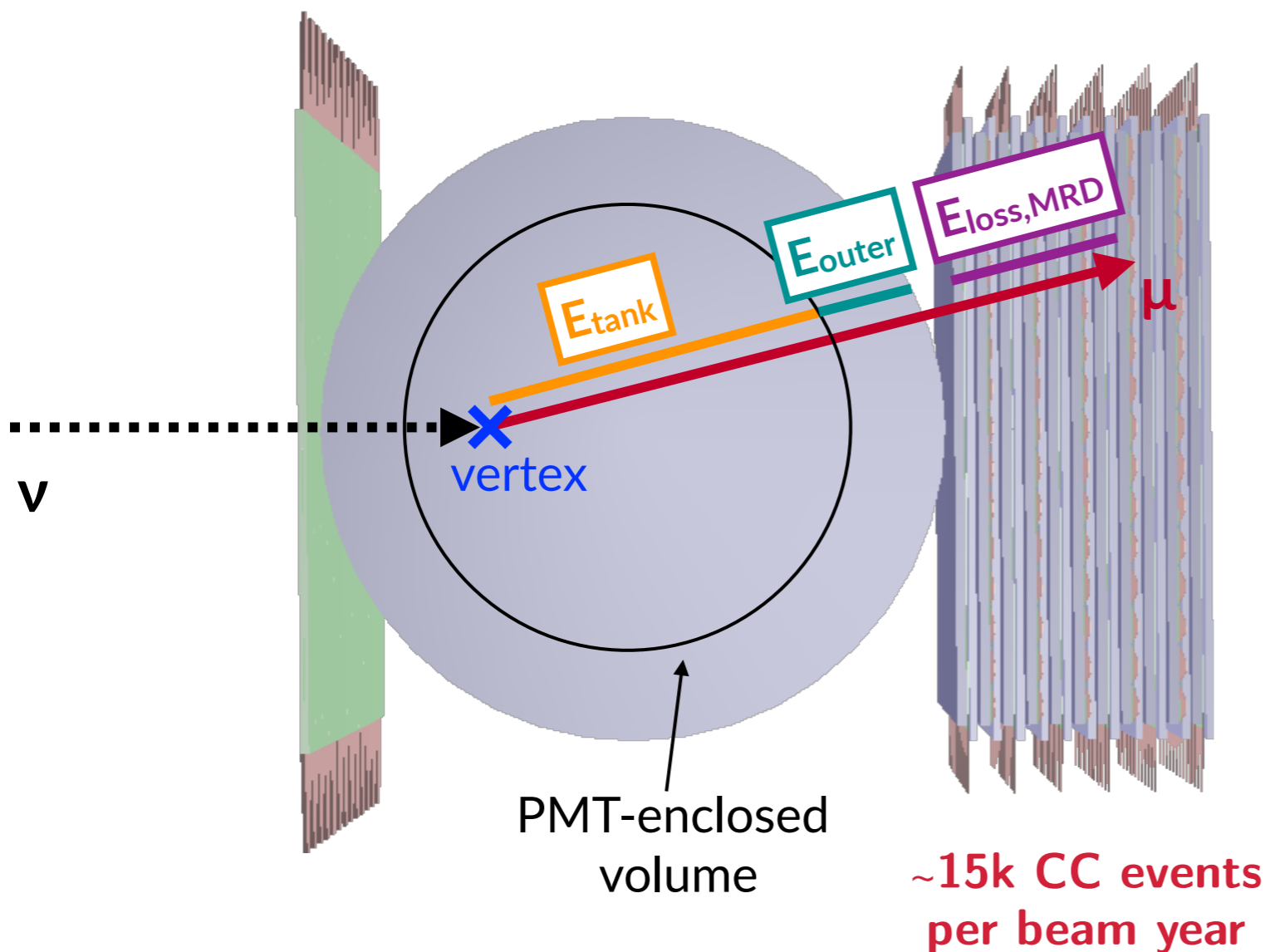


See also: Steven Gardiner, Andy Furmanski, μ BooNE CC0 π Np (April 17)

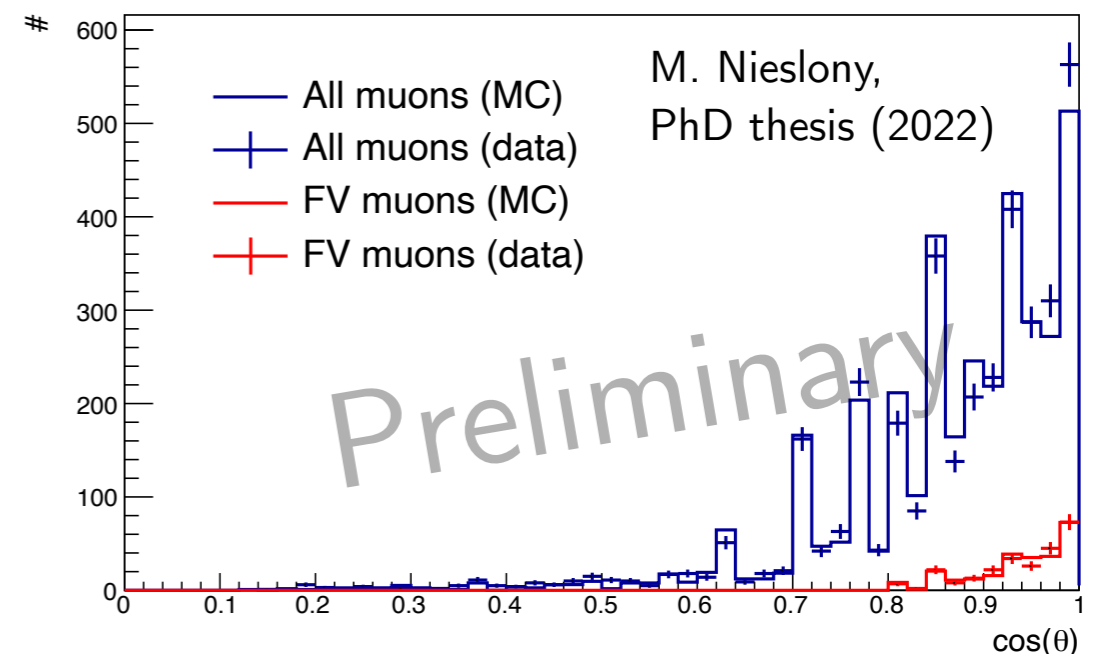
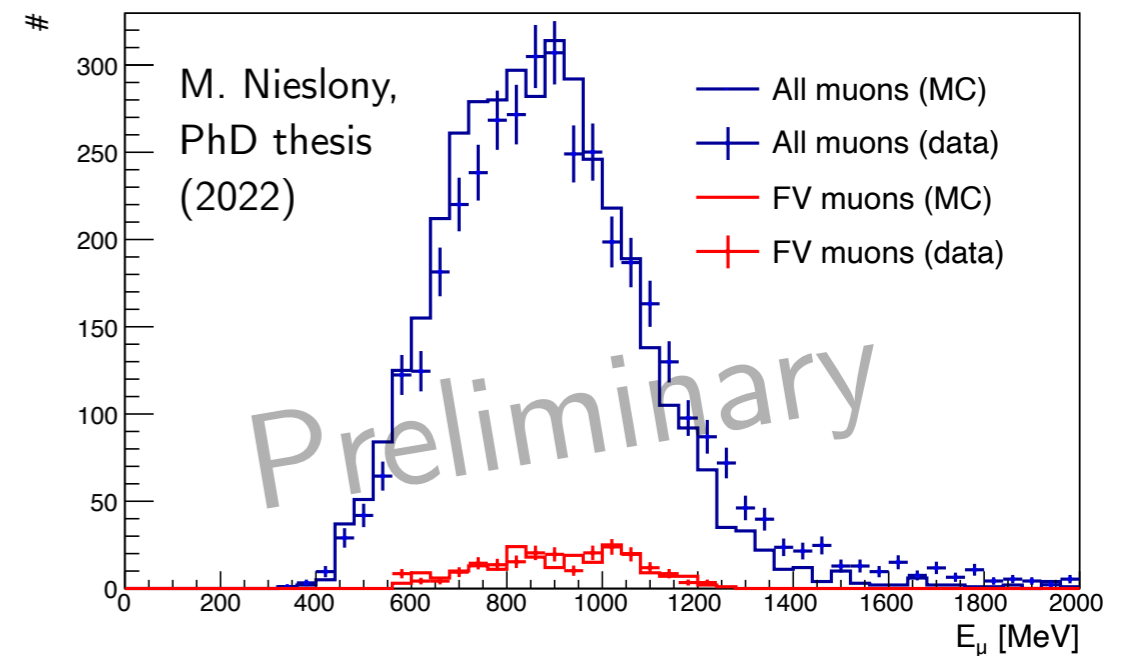
Interactions

Prompt Scattering Events

Prompt: Final state muon energy and angle reconstruction using tank PMTs + MRD tracking



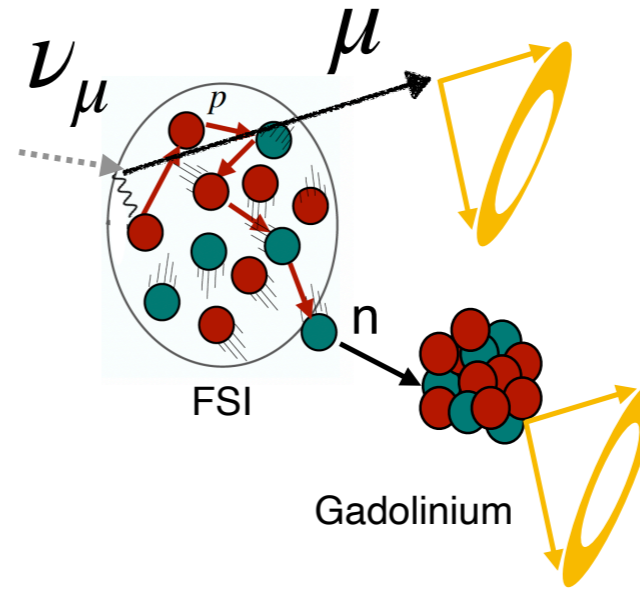
- MRD requirement restricts μ momentum and angle coverage
- $0.4 \lesssim E_\mu \lesssim 1.2 \text{ GeV}$, $\theta_\mu \gtrsim 60^\circ$
- Tank-only ring reconstruction (under development) enables wide coverage for CC kinematics



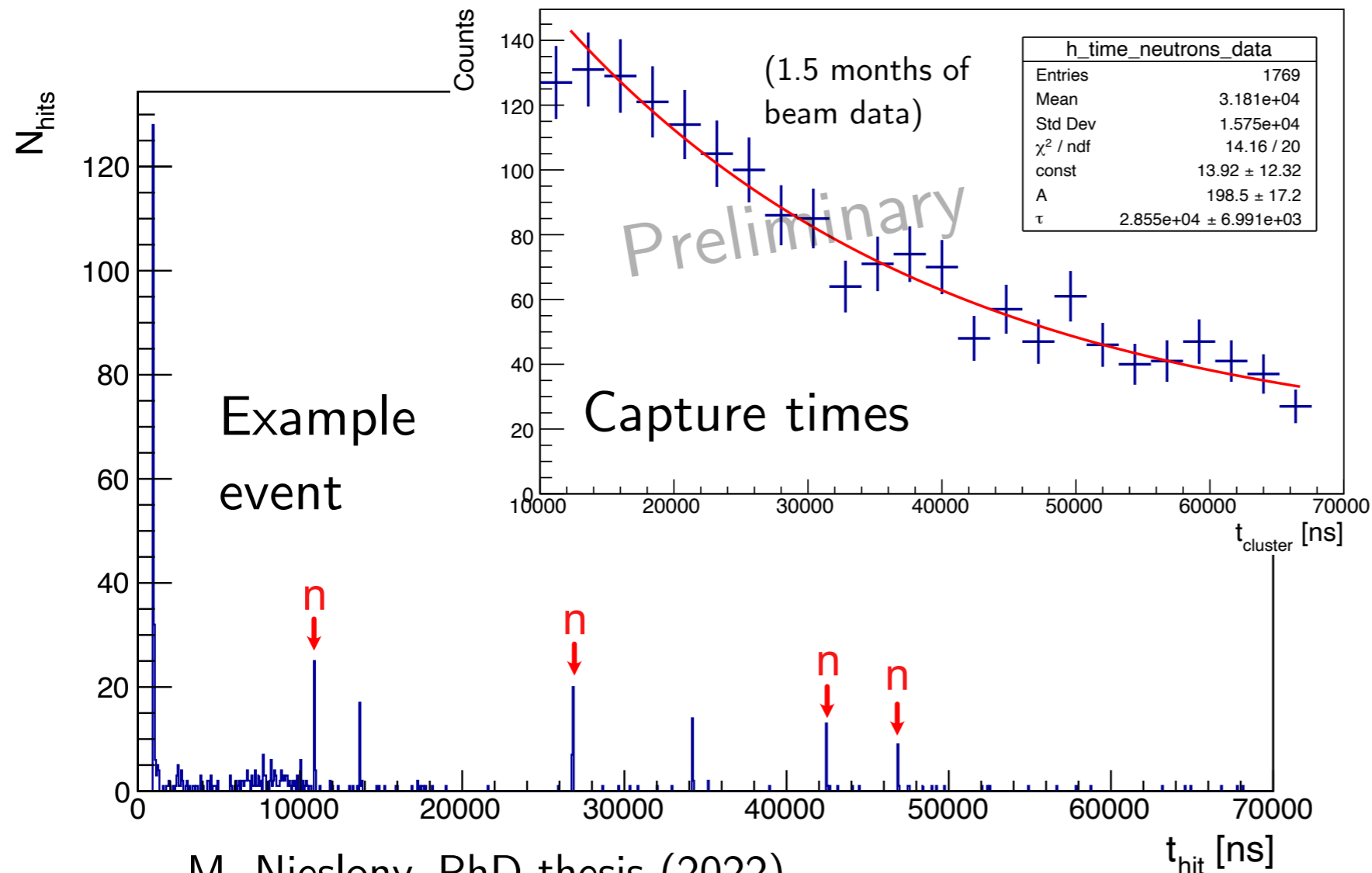
Interactions

Delayed Neutron Events

Delayed: 8 MeV γ signal from neutron captures on gadolinium



	H	Gd
σ	0.33 bn	49000 bn
τ	300 μs	30 μs
E_γ	2.2 MeV	8 MeV

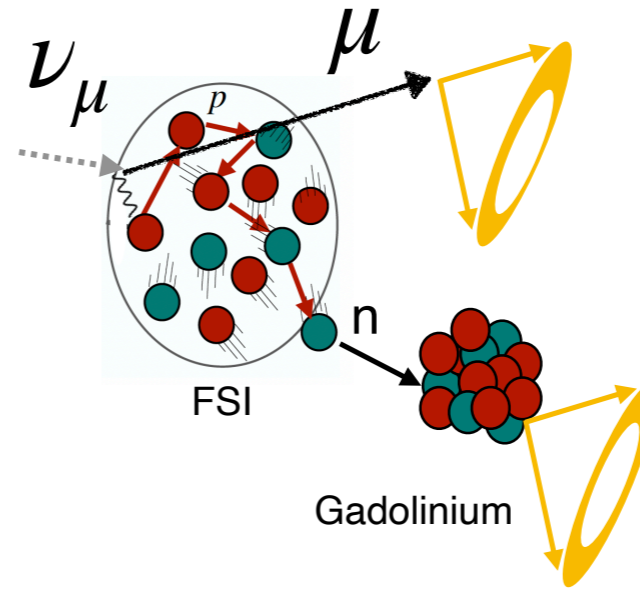


M. Nieslony, PhD thesis (2022)

Interactions

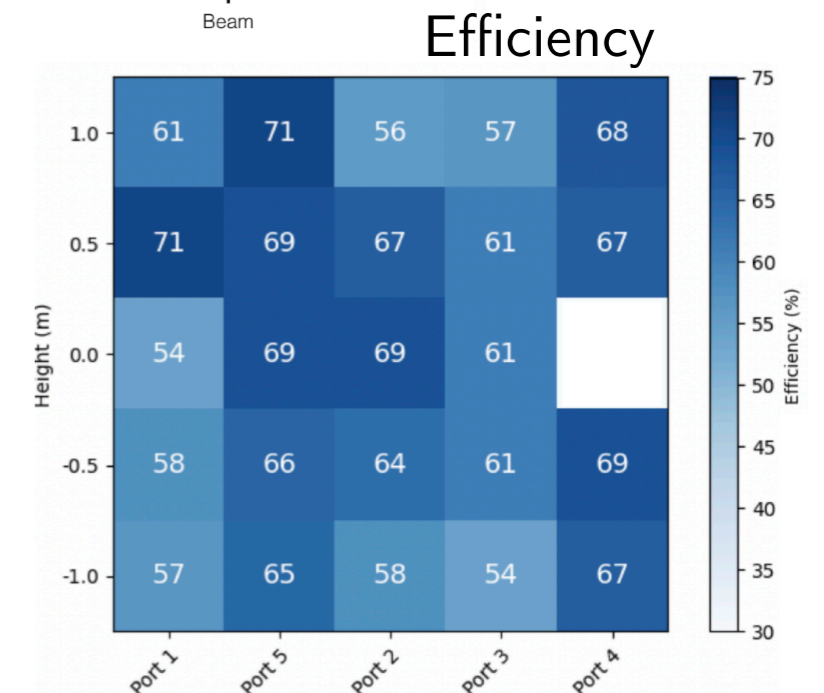
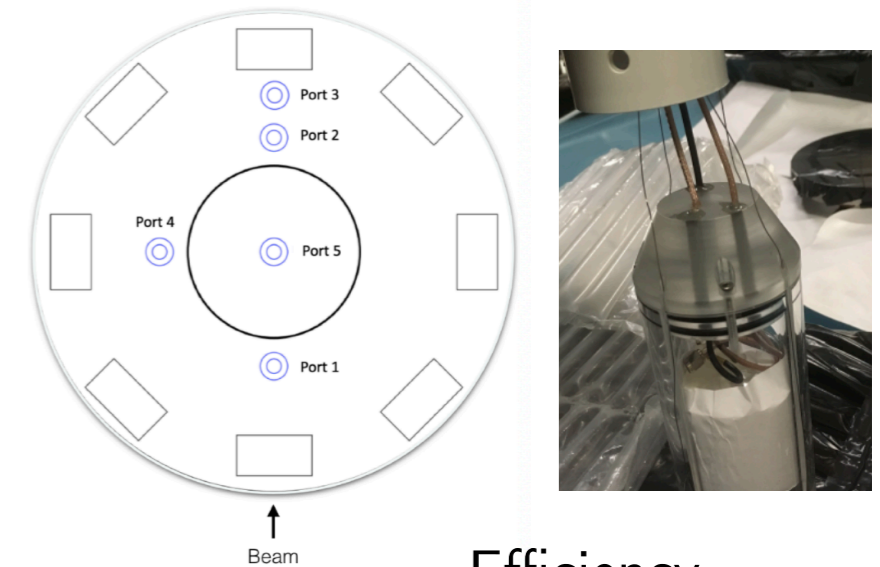
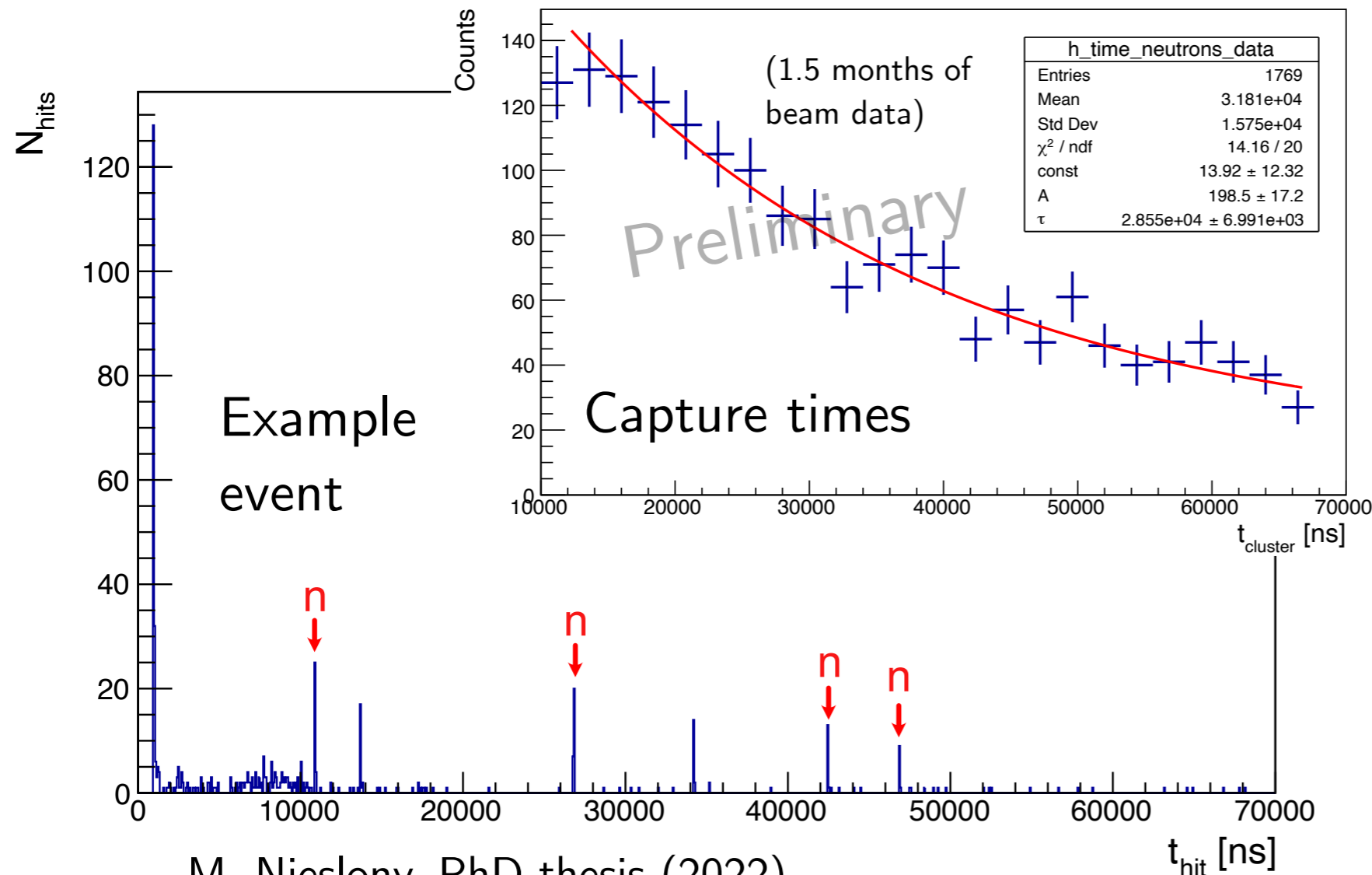
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AmBe source calibrations

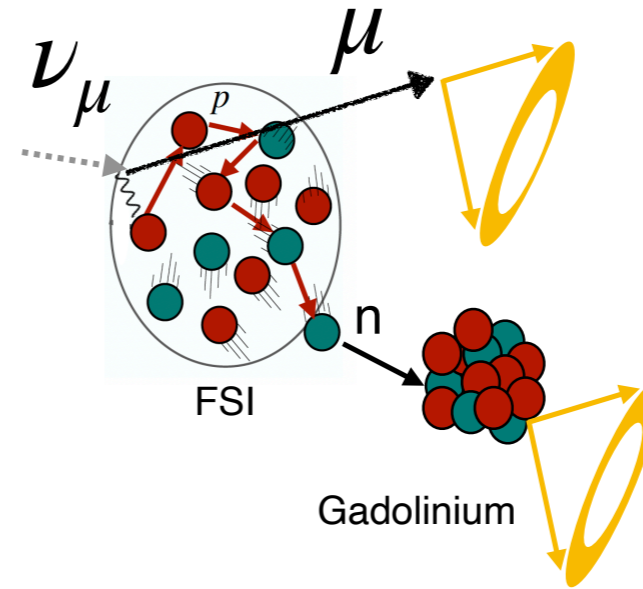


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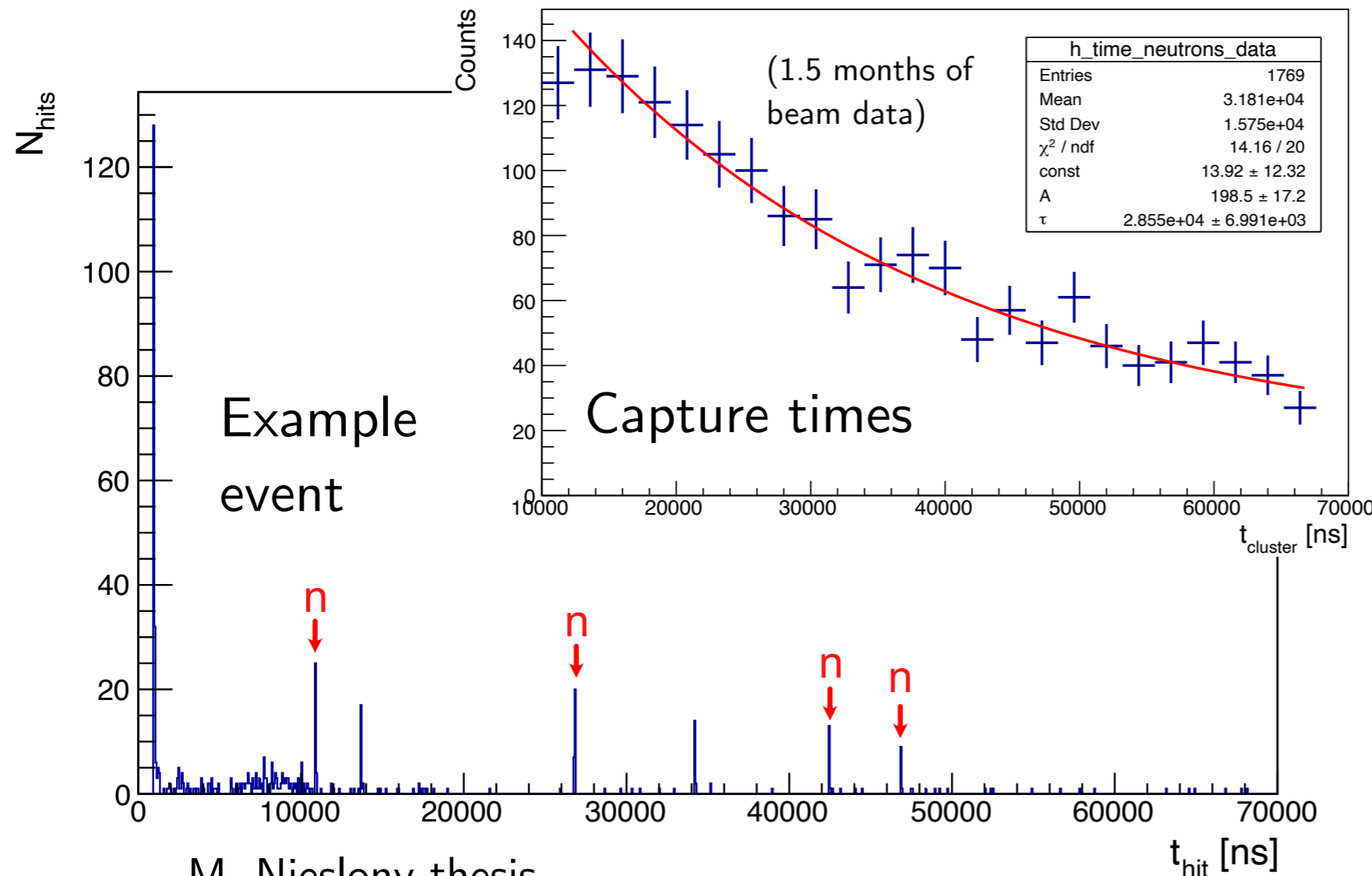
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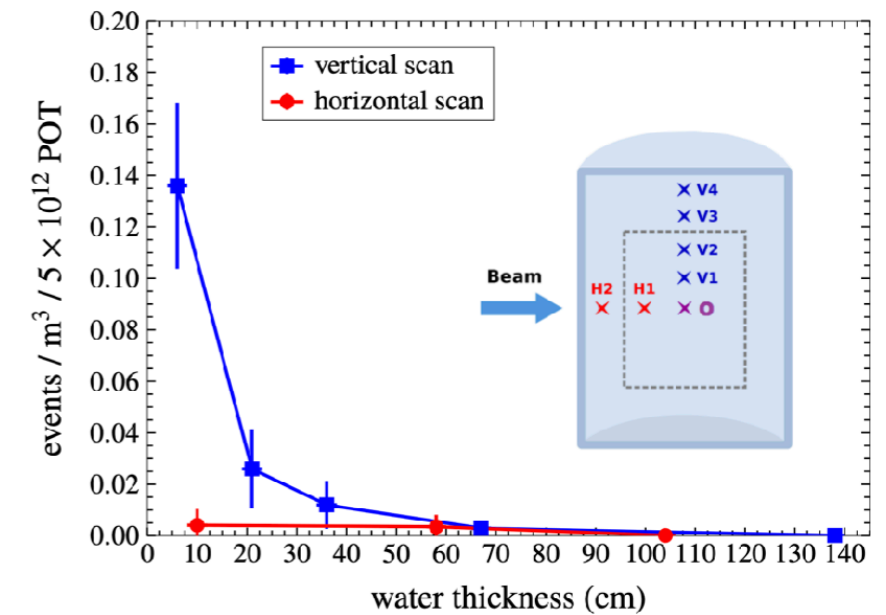


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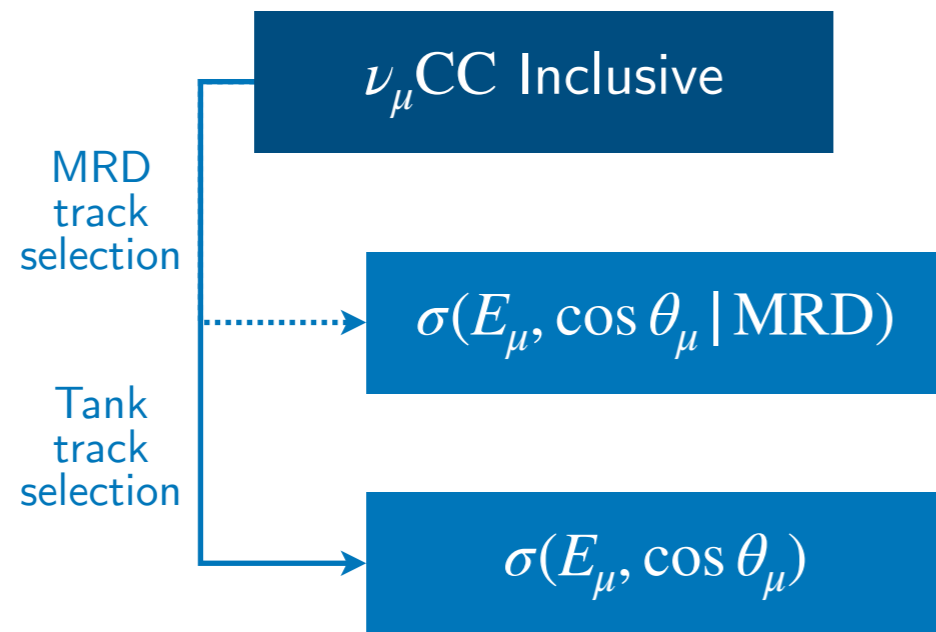
Phase I: Beam-correlated neutron background characterization



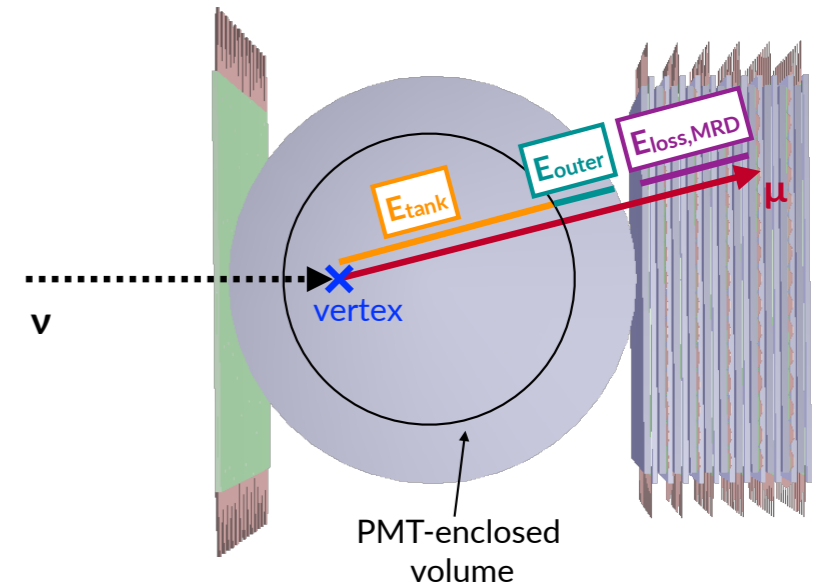
Position-dependent in situ measurements of neutron capture rates

JINST 15, P03011 (2020)

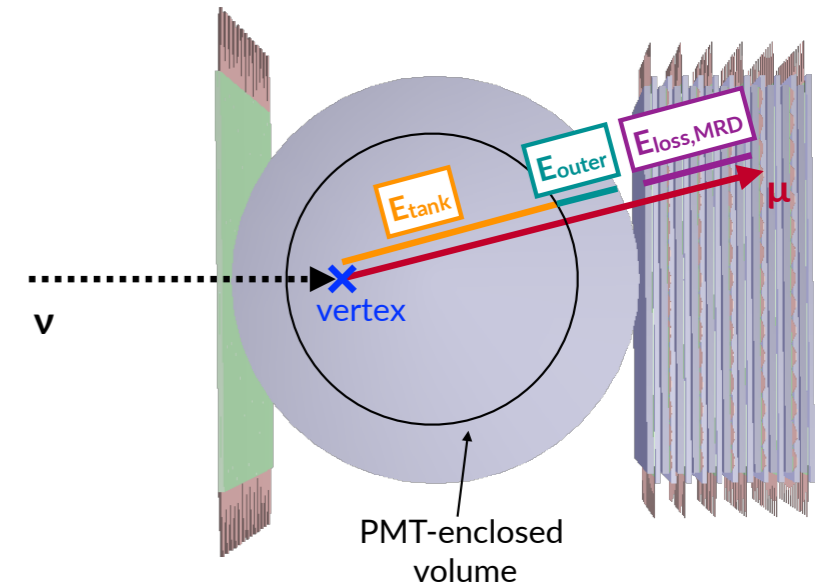
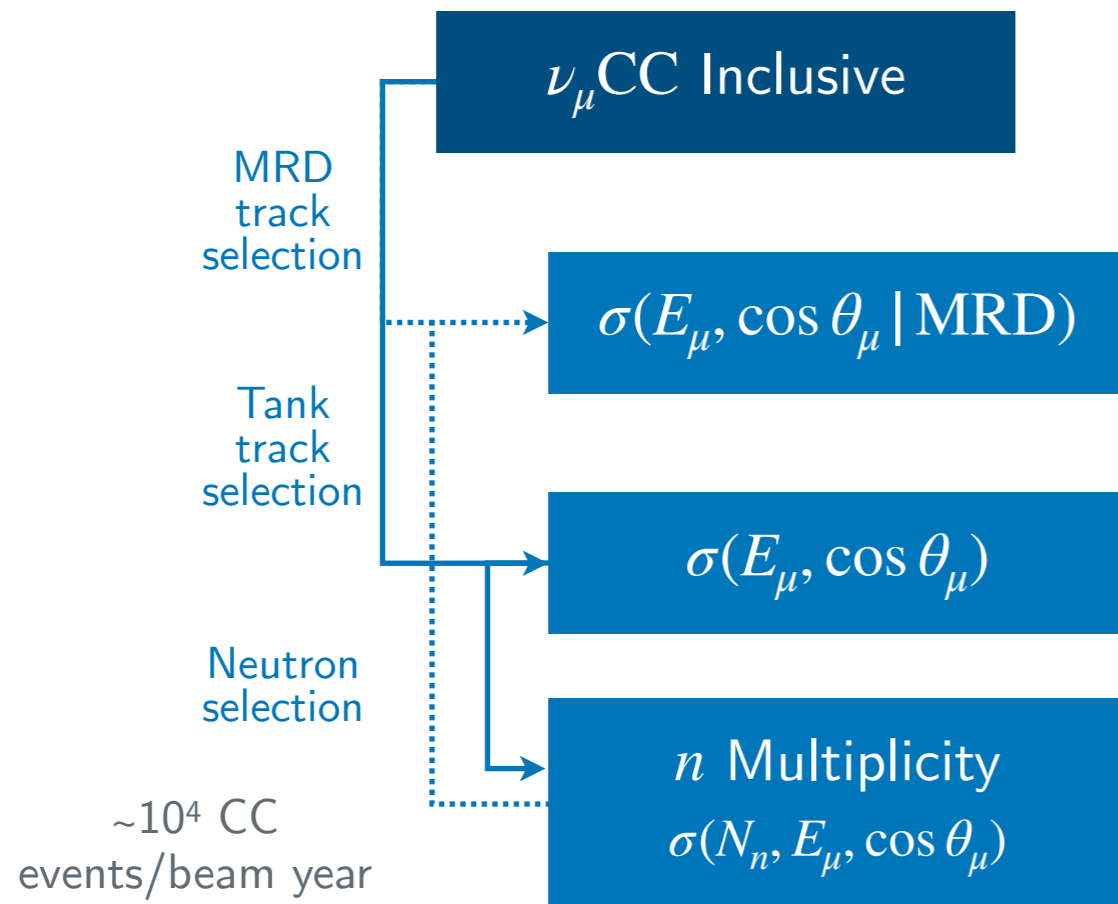
CC Program With Neutron Captures



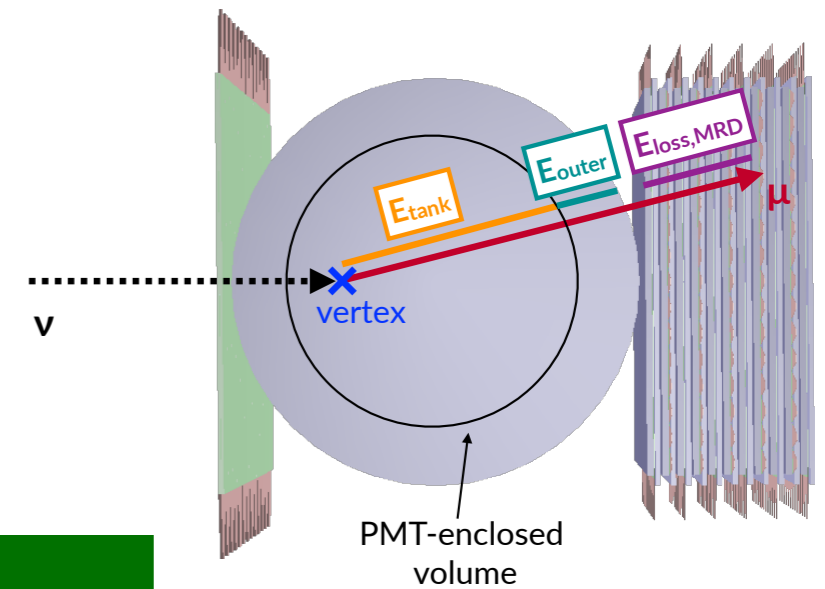
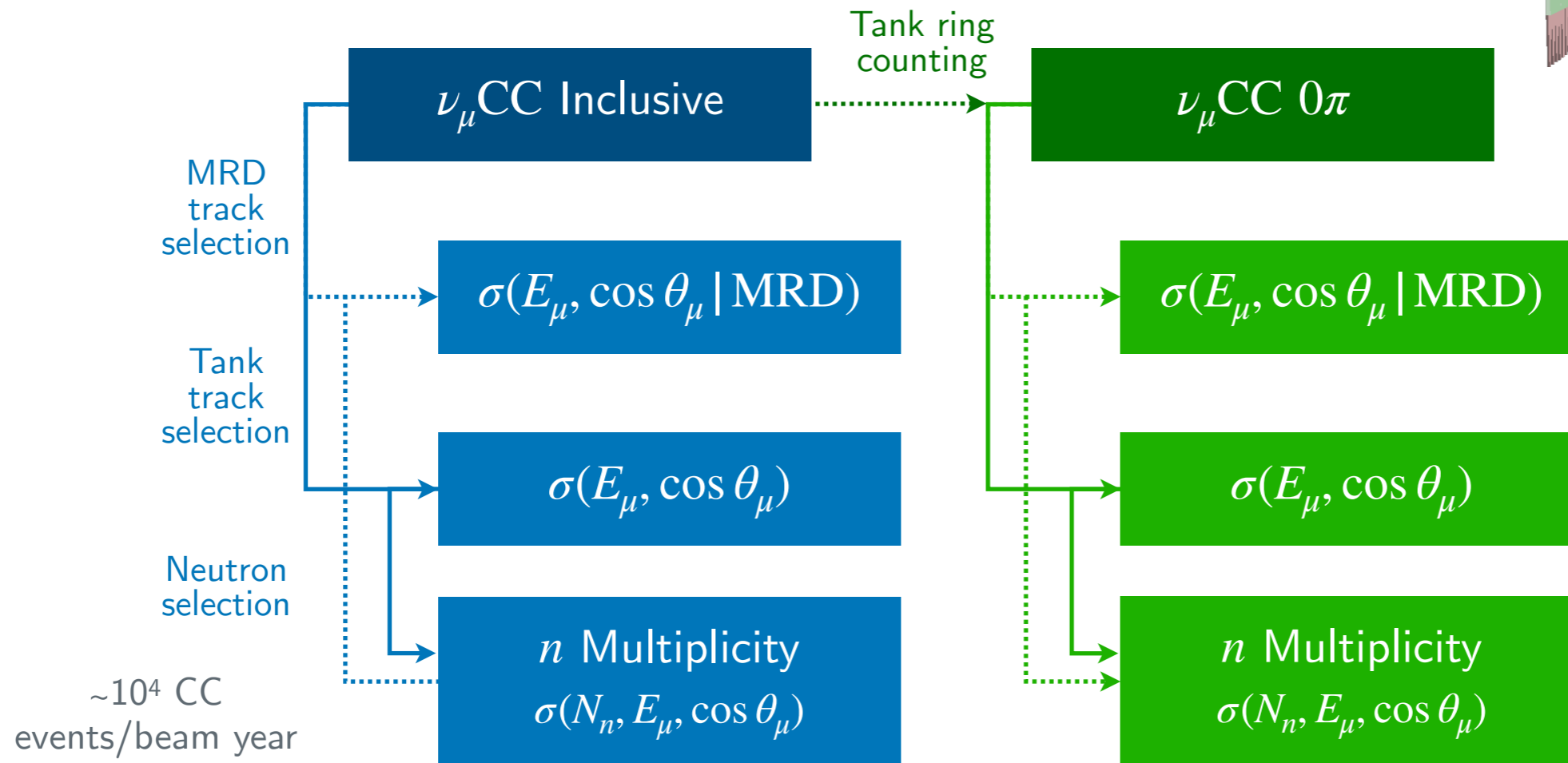
$\sim 10^4$ CC
events/beam year



CC Program With Neutron Captures

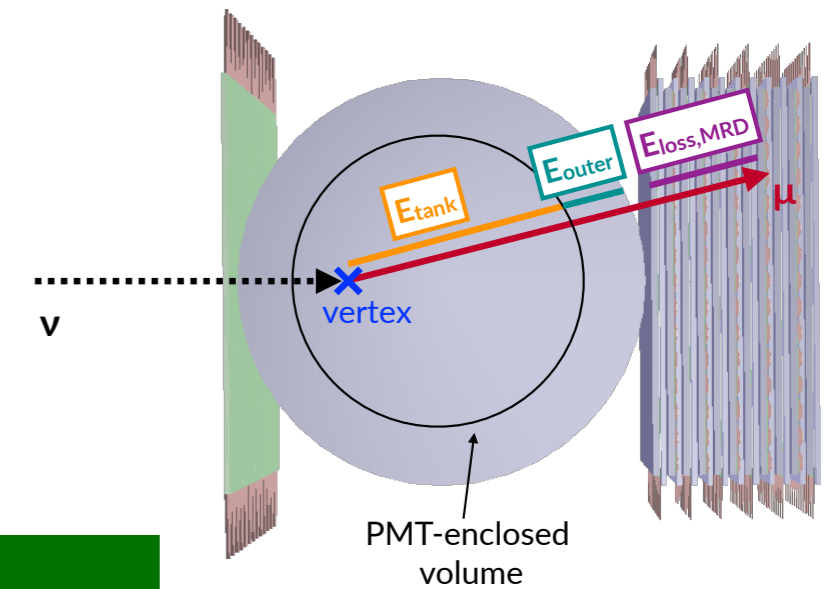
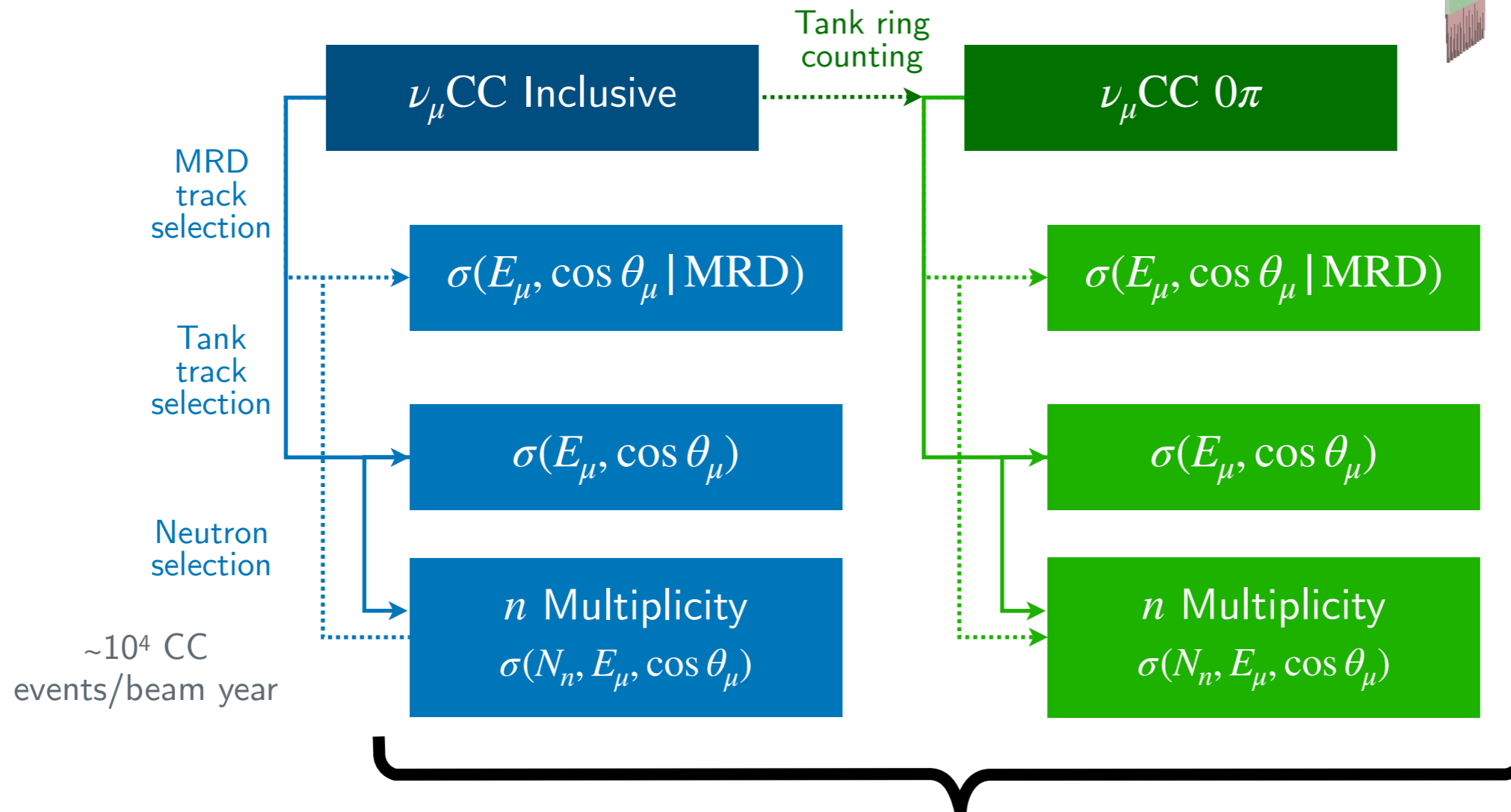


CC Program With Neutron Captures



CC Program

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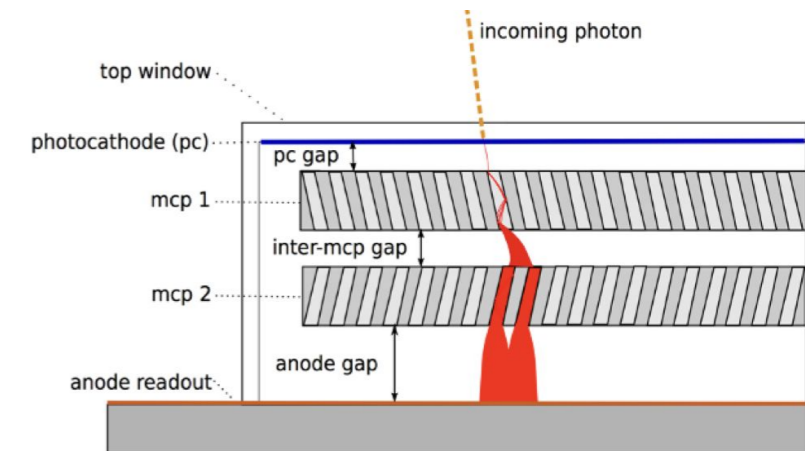
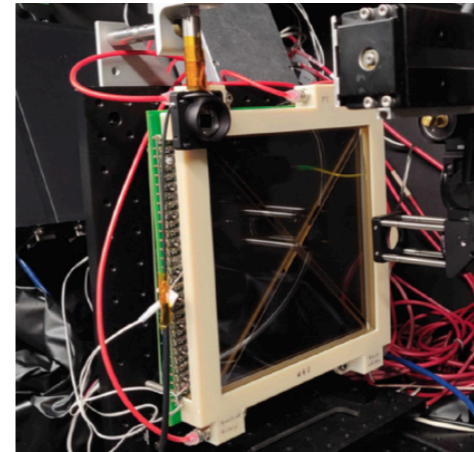


- Improved measurements of neutrino-induced neutron production
- New constraints for neutral energy losses in neutrino energy reconstruction
- Correlated measurements with BNB LArTPCs (low-threshold protons)

LAPPDs

First Results & Prospects

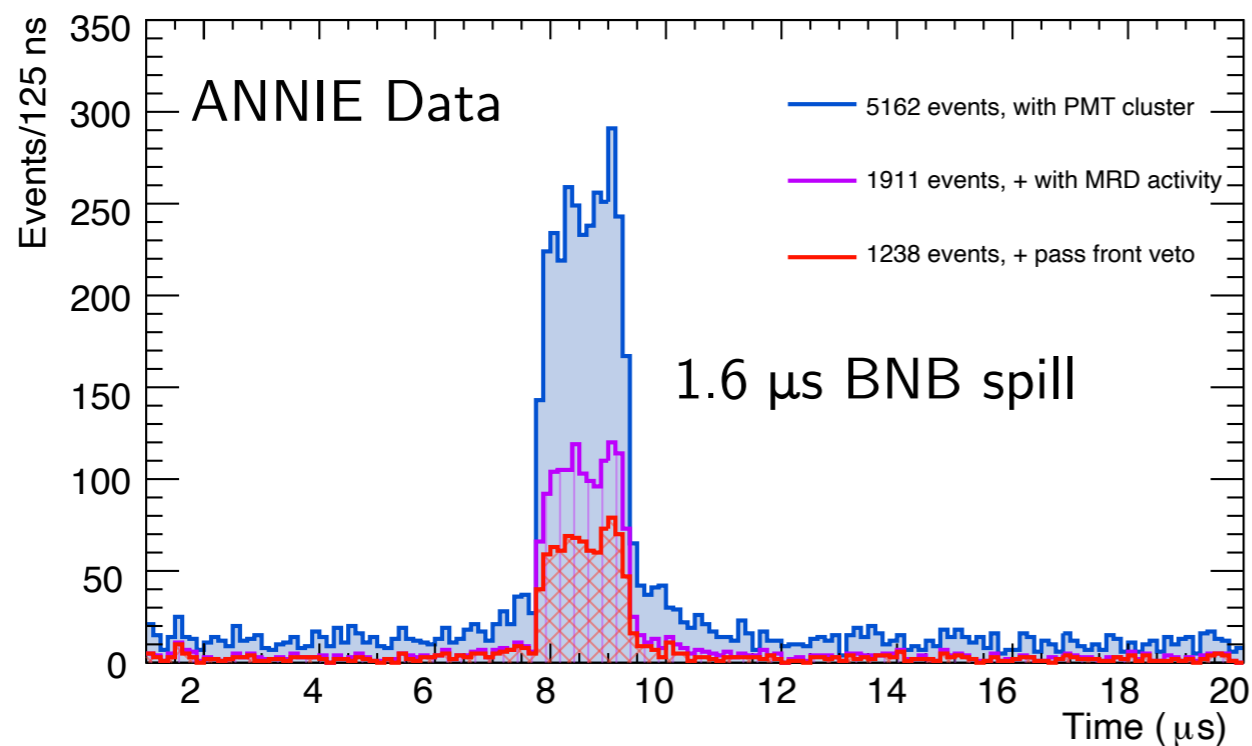
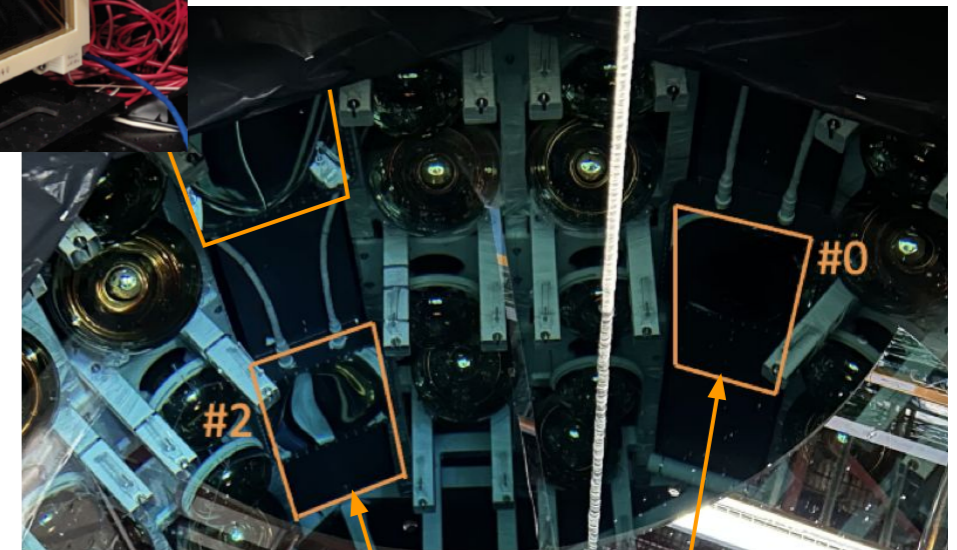
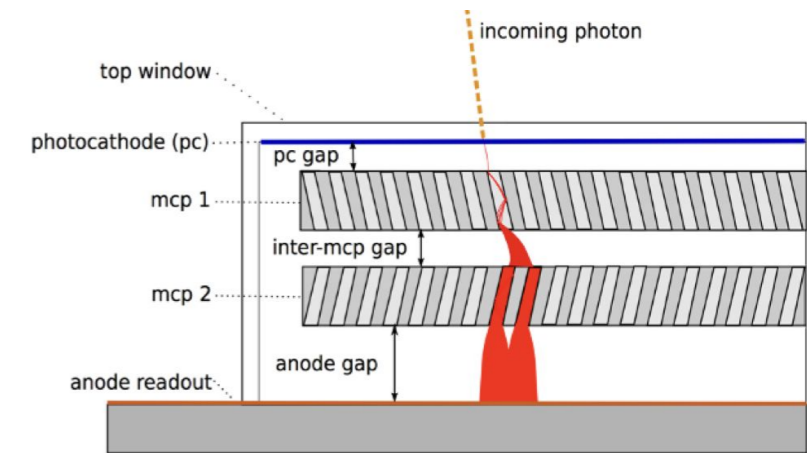
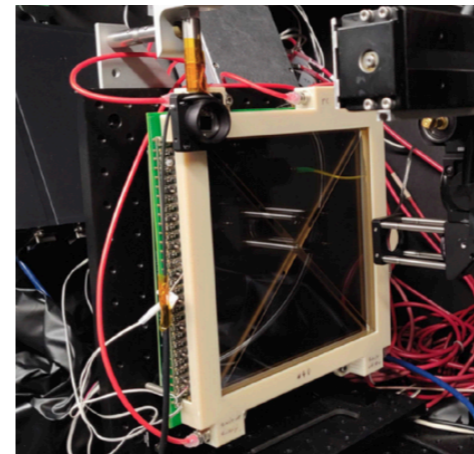
- Large-Area Picosecond Photodetectors
 - 8" × 8" MCP-based photodetector
 - Absolute 1 pe timing ~100 ps
 - Spatial resolution ~1 cm
 - Multi "pixel" imaging detectors



LAPPDs

First Results & Prospects

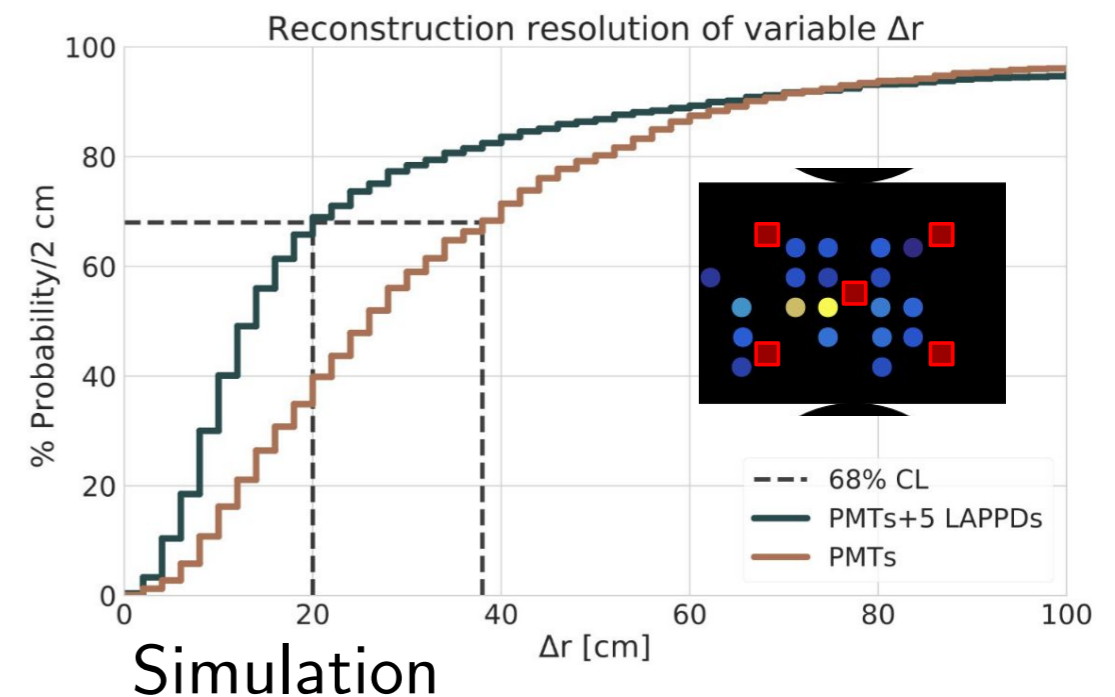
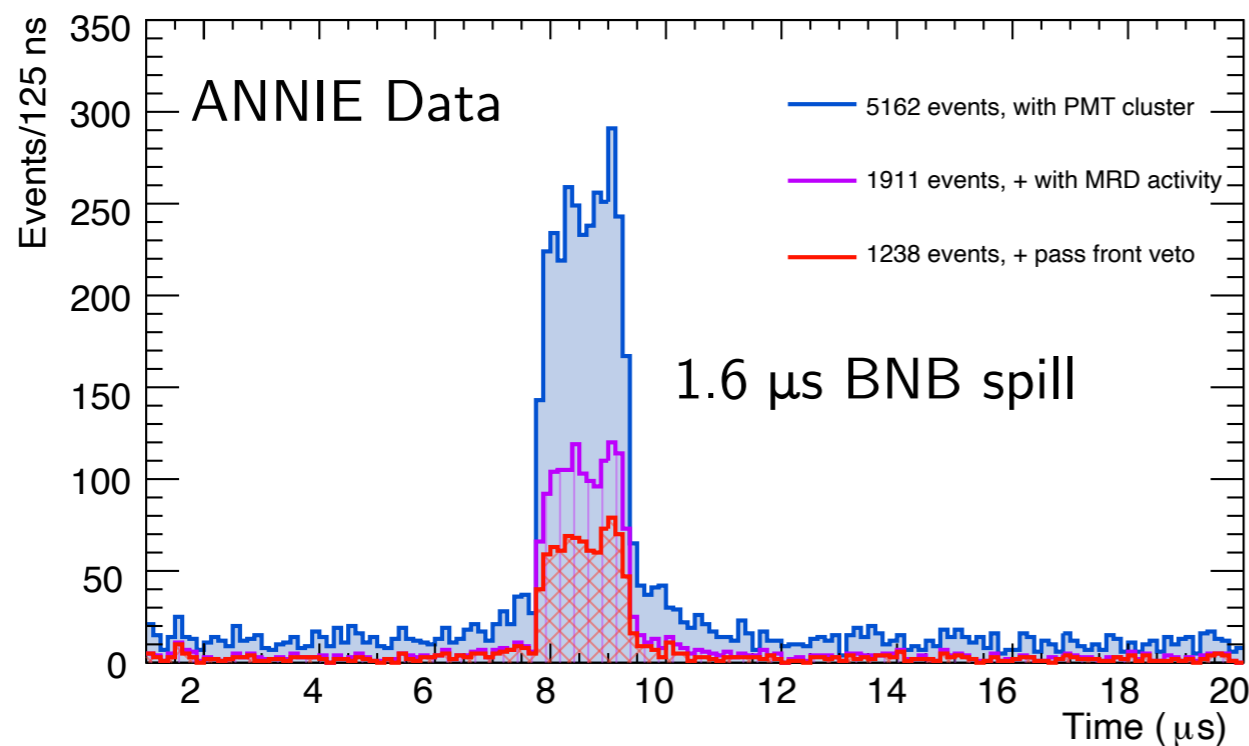
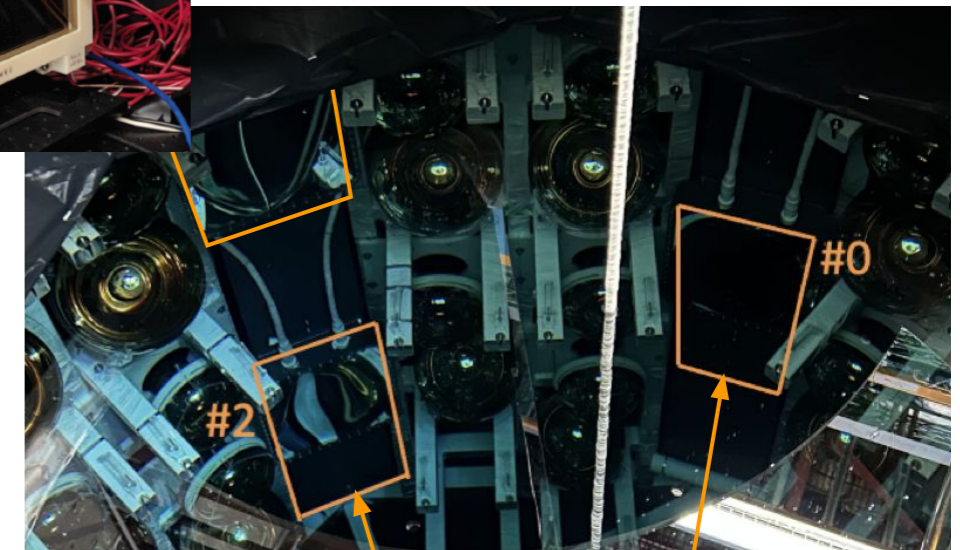
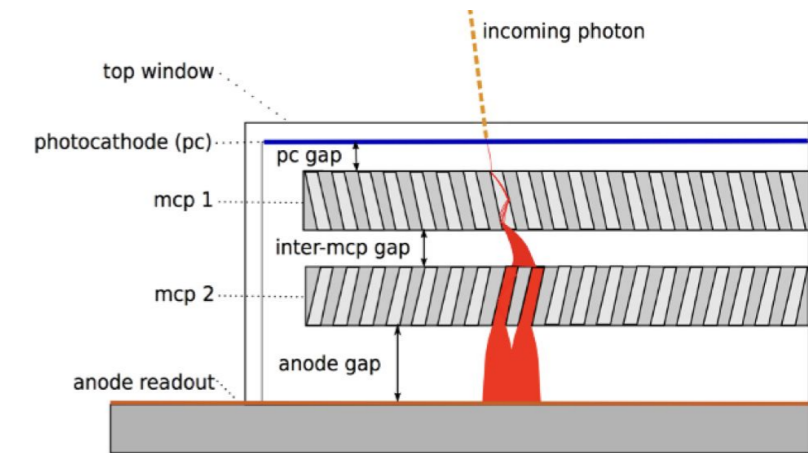
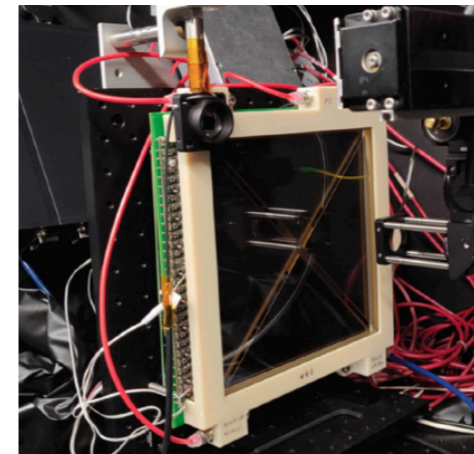
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 - 8" × 8" MCP-based photodetector
 - Absolute 1 pe timing ~100 ps
 - Spatial resolution ~1 cm
 - Multi "pixel" imaging detectors
- Deployed 1–3 LAPPDs since May '22
 - First neutrinos seen by LAPPDs:



LAPPDs

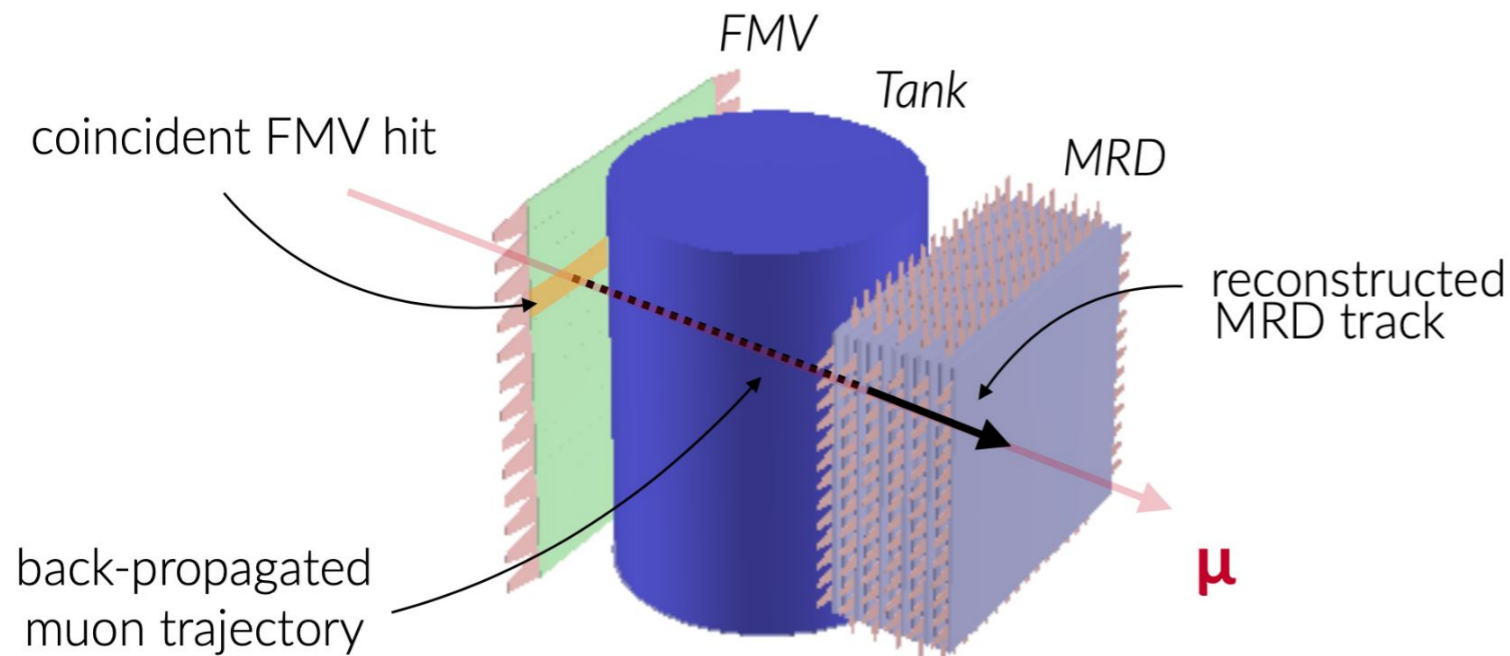
First Results & Prospects

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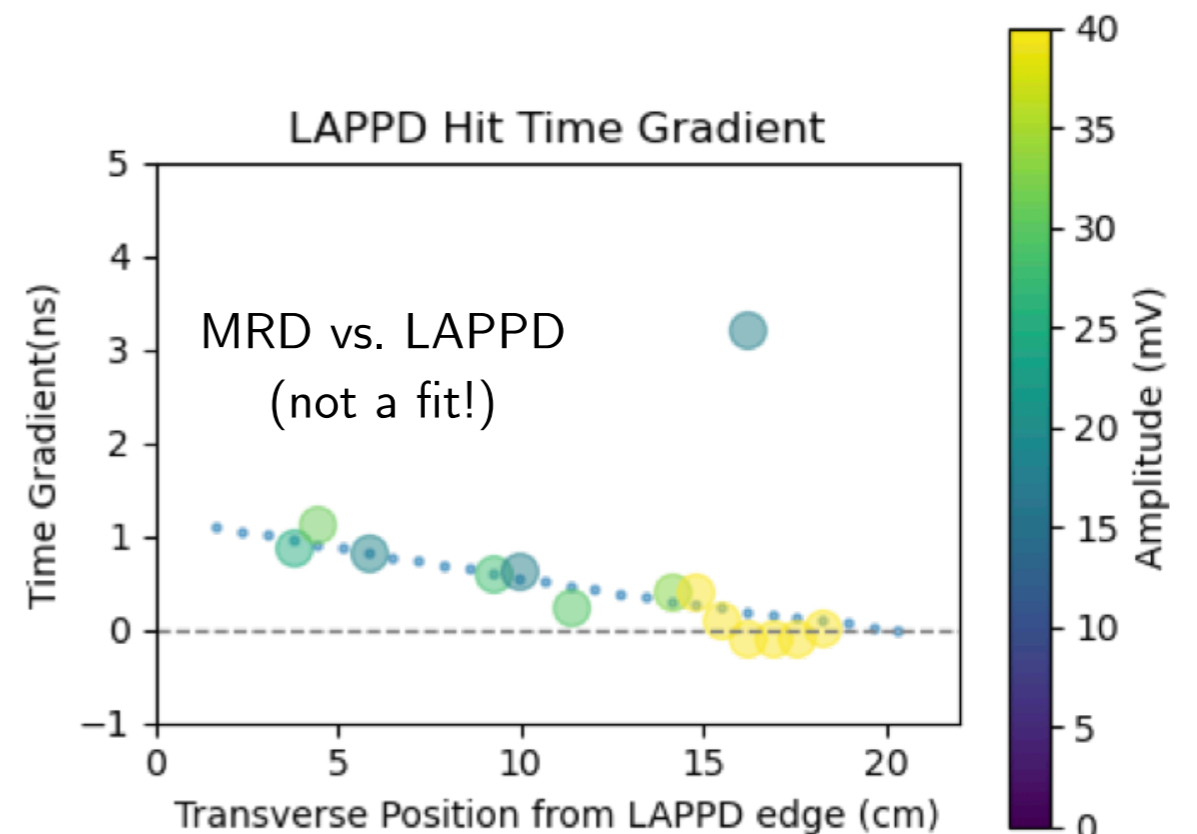
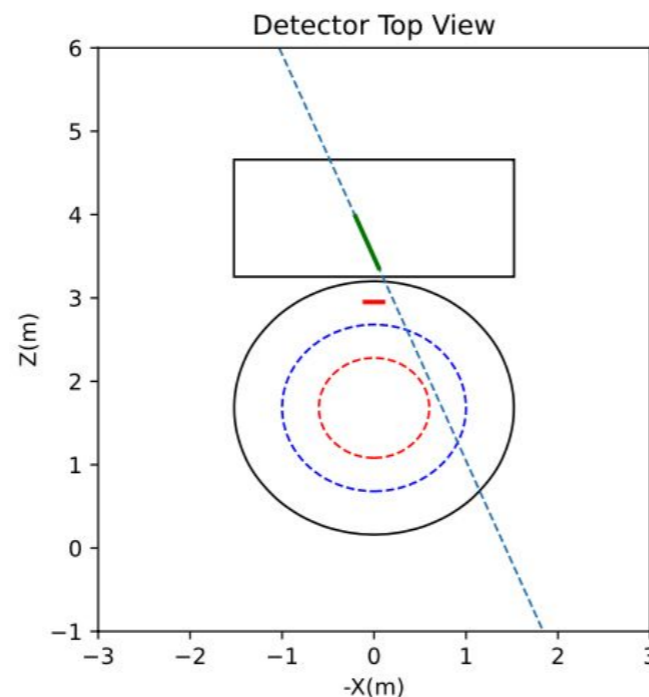
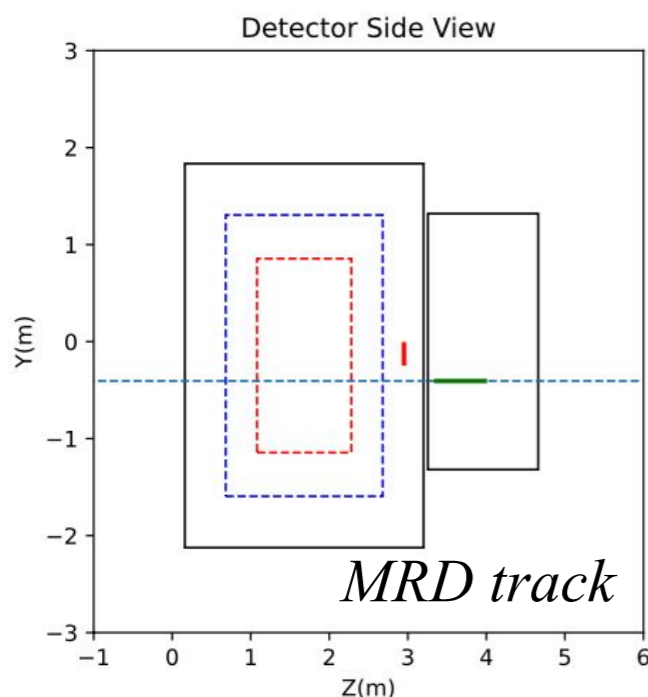


LAPPDs

First Results & Prospects



- Time evolution of the Cherenkov ring across *a single LAPPD* can reconstruct track direction
- Currently planning to deploy 5 LAPPDs in ANNIE during the current Phase II



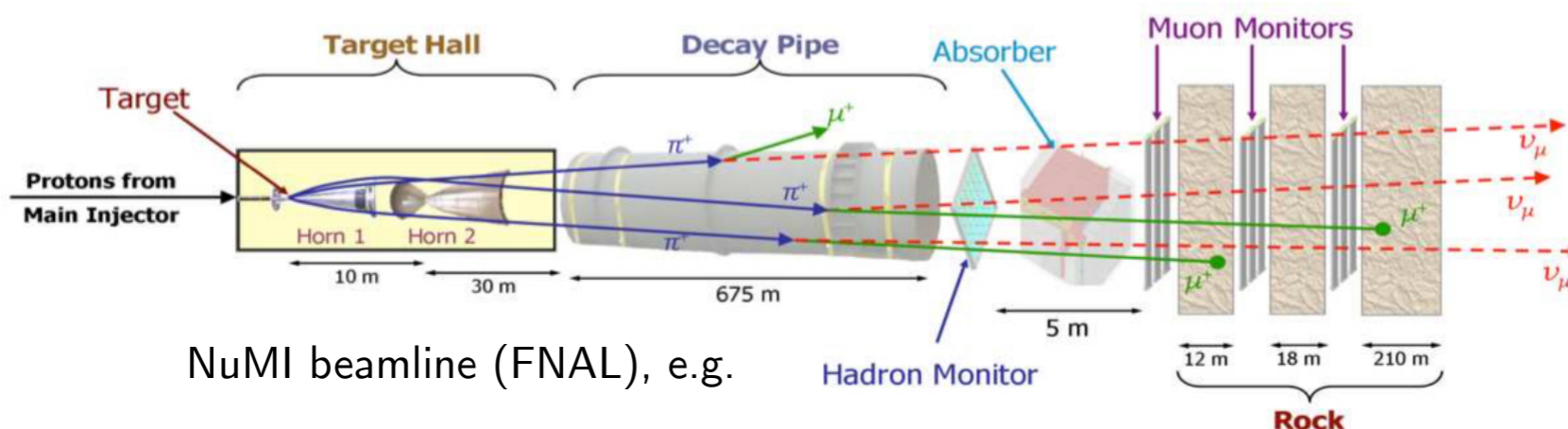
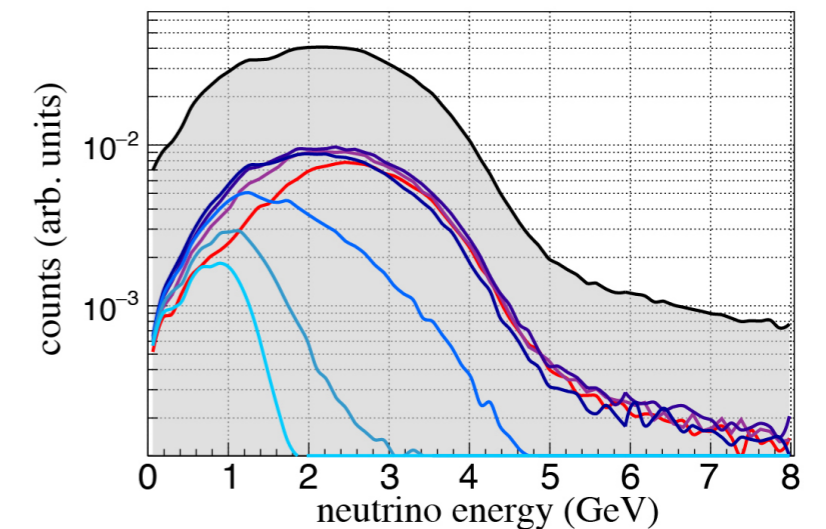
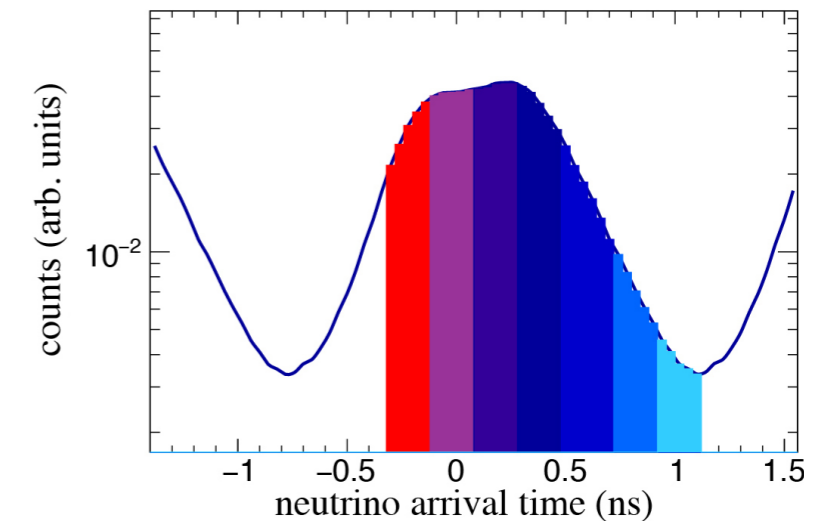
LAPPDs

Stroboscopic Approaches

- Fast timing (detector and beam) could enable a new handle on neutrino flux complementary to off-axis "prism" approaches
 - Lower-E hadrons \rightarrow lower $\beta \rightarrow$ later ν
 - (Note: ≈ 250 ps bunches for the LBNF beam (at right) would require high-frequency RF proton beam rebunching to preserve intensity)

E. Angelico et al., PRD **100**, 032008 (2019)

250 ps bunches, 100 ps detector



NuMI beamline (FNAL), e.g.

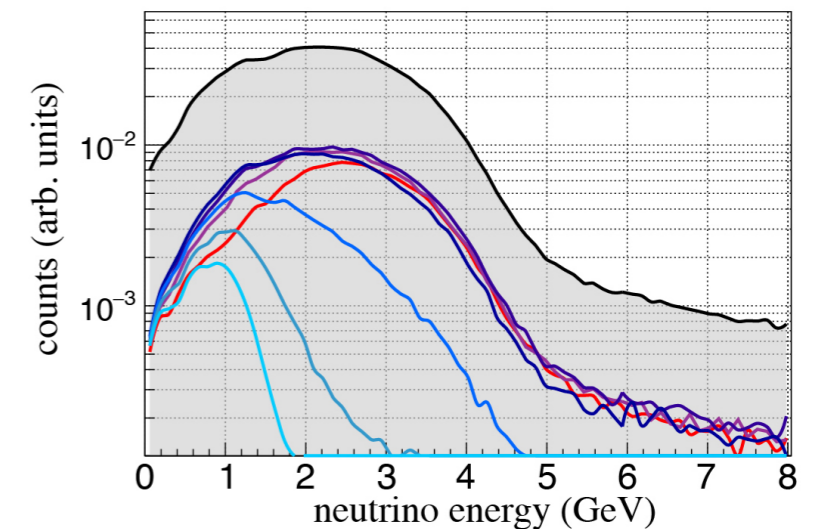
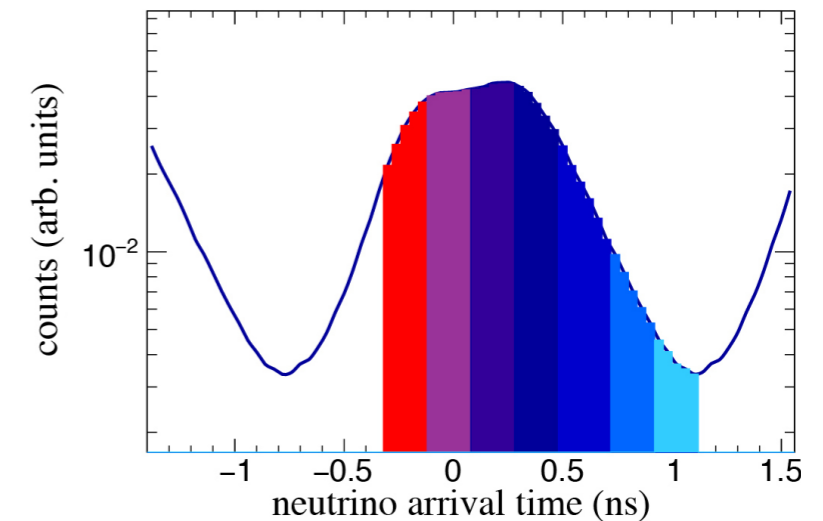
LAPPDs

Stroboscopic Approaches

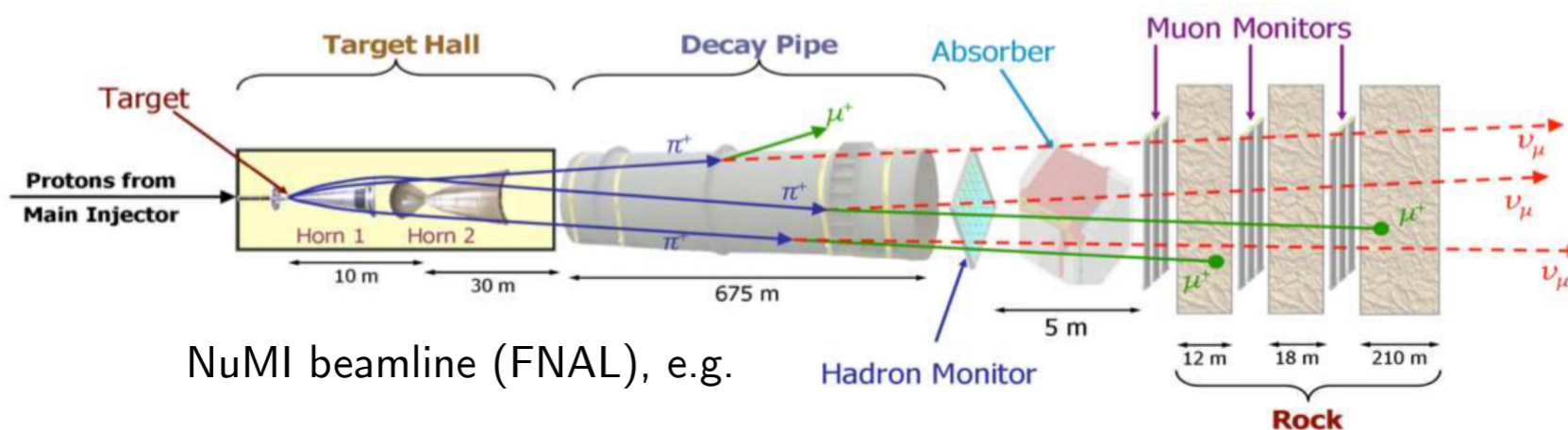
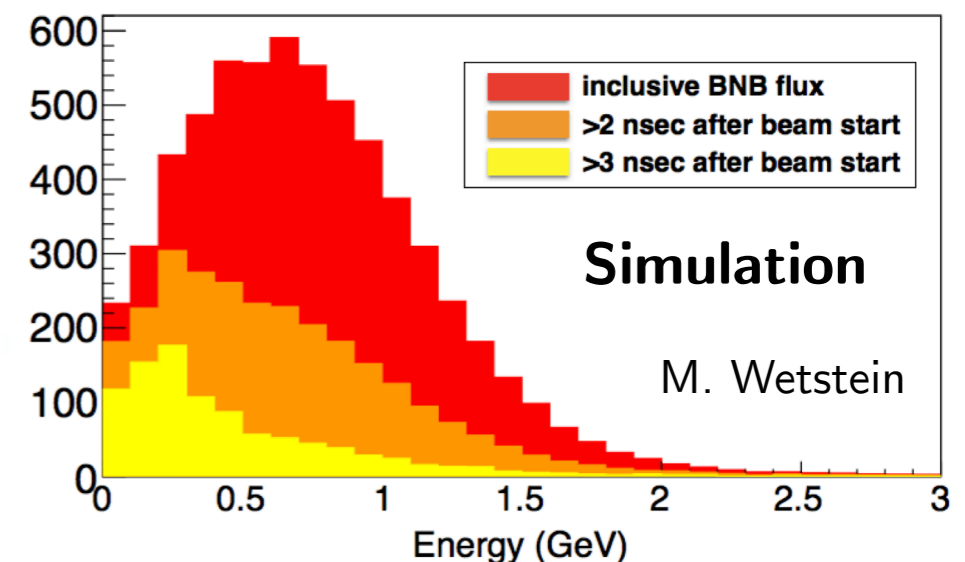
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 - Lower-E hadrons \rightarrow lower $\beta \rightarrow$ later ν
 - (Note: ≈ 250 ps bunches for the LBNF beam (at right) would require high-frequency RF proton beam rebunching to preserve intensity)
- ANNIE with LAPPDs could demonstrate this technique using coarse ns-scale binning (and the relatively lower-energy BNB beam)

E. Angelico et al., PRD **100**, 032008 (2019)

250 ps bunches, 100 ps detector

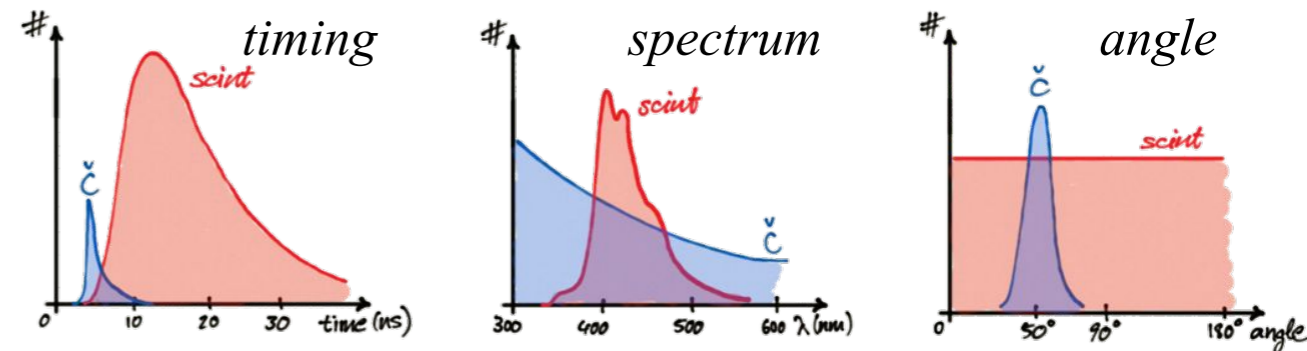


BNB, 1 ns bunches at ANNIE

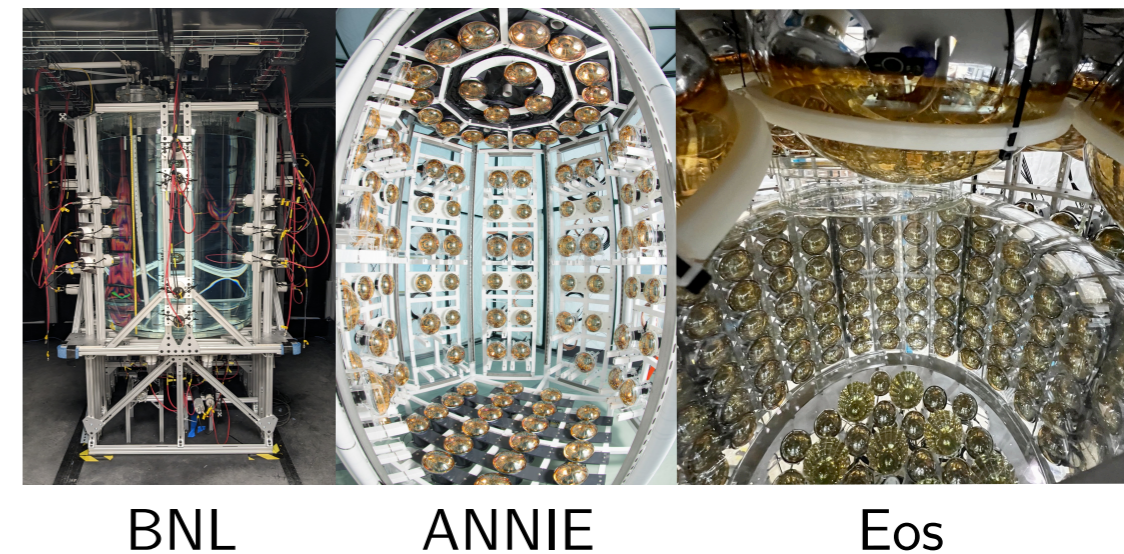
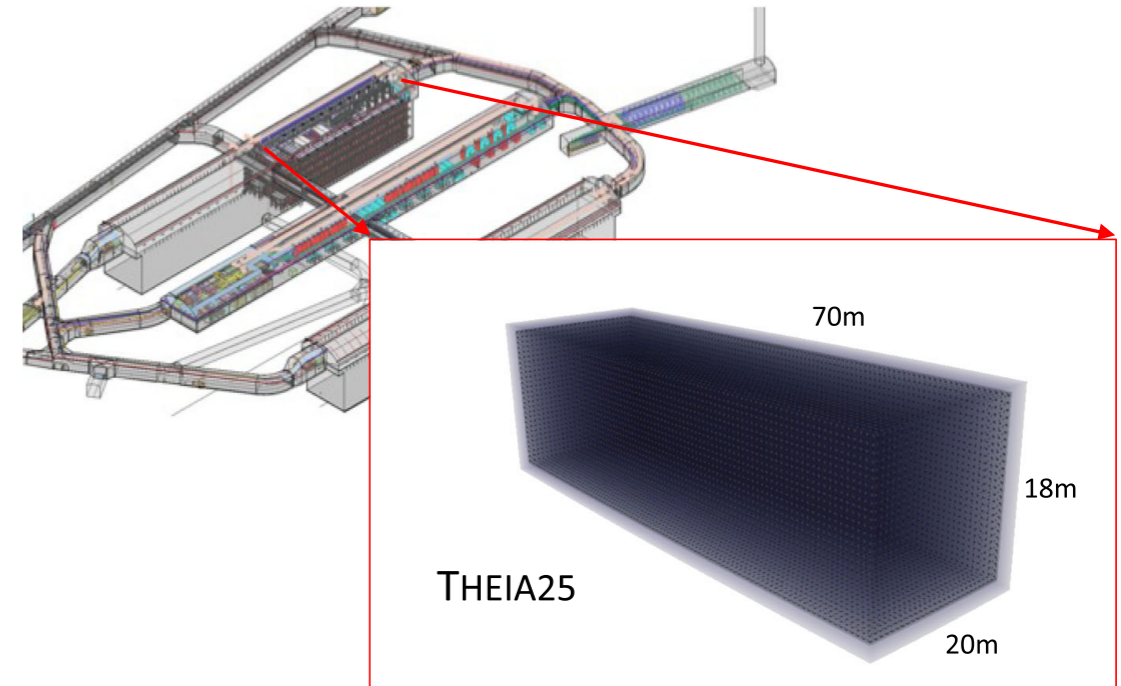


Water-Based LS

First Results & Prospects



- Water-based Liquid Scintillator (WbLS) is a novel target medium
 - Cherenkov & scintillation, tunable ratio
 - Calorimetric reconstruction of low-energy hadrons in WC-like detectors
 - Improved particle ID using C/S ratio
 - C+S improves vertex & energy reco
- Ton-scale prototypes: Eos, BNL 1t/30t, BUTTON, ANNIE
- WbLS Theia is a DUNE FD4 option, offering a complementary FD target



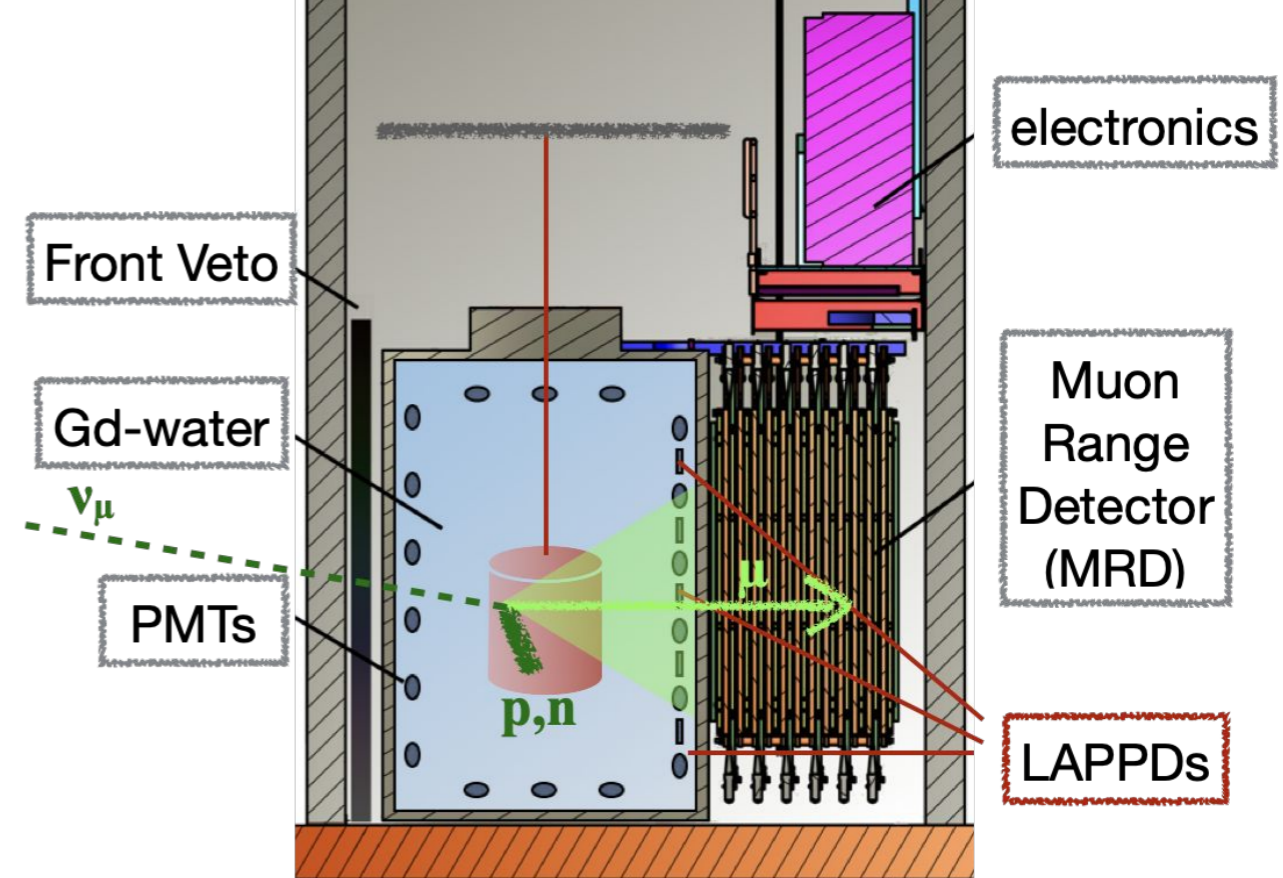
3.1.4 – Future Opportunities: DUNE FD4, the Module of Opportunity

A range of alternative targets, including low radioactivity argon, xenon-doped argon, and novel organic or **water-based liquid scintillators**, should be considered to maximize the science reach, particularly in the low-energy regime.

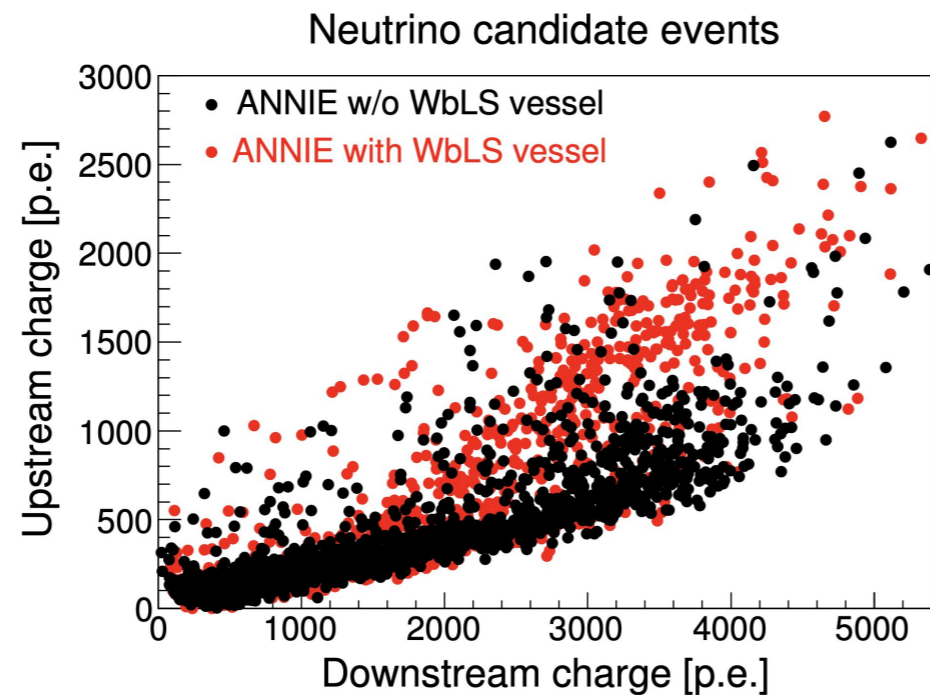
Water-Based LS

ANNIE Deployment

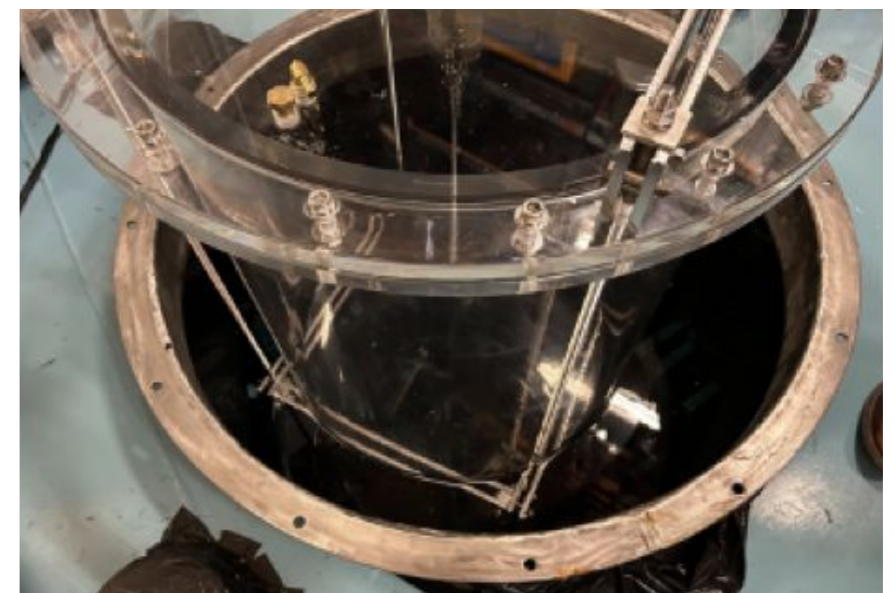
- "SANDI" deployed March 2023
 - First WbLS in a neutrino beam
 - 2 months, few thousand events
- 365 kg of 0.5%LS WbLS
- Planning future deployments, SANDI+LAPPDs, and potentially a future WbLS-filled phase



Measured the upstream/downstream asymmetry from isotropic scintillation, full MC/reco is now in progress



arxiv:2312:09335, accepted to JINST



Outlook

First Results & Prospects



- **Phase I** completed: detector characterization, measurements of beam-induced neutron backgrounds.
- Now in **Phase II**: next-generation detector R&D and collecting physics data for our initial cross section results:
- **Physics program** and data taking are underway now:
 - Differential ν_{μ} CC cross sections on ^{16}O , inclusive and 0π
 - Neutron multiplicities, vs. differential μ kinematics
 - Correlated σ , hadron production with LArTPC ^{40}Ar
- Novel **detector R&D** relevant to neutrino interactions
 - Gd- H_2O \rightarrow High-efficiency neutron reconstruction
 - LAPPDs deployed \rightarrow Event reco, stroboscopic ν flux
 - Water-based LS deployed \rightarrow Water Cherenkov + calorimetry & hadrons

