First detection of neutrinos in water-based liquid scintillator at ANNIE

annie

DPG Frühjahrstagung Göttingen
3. April 2025
Johann Martyn

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

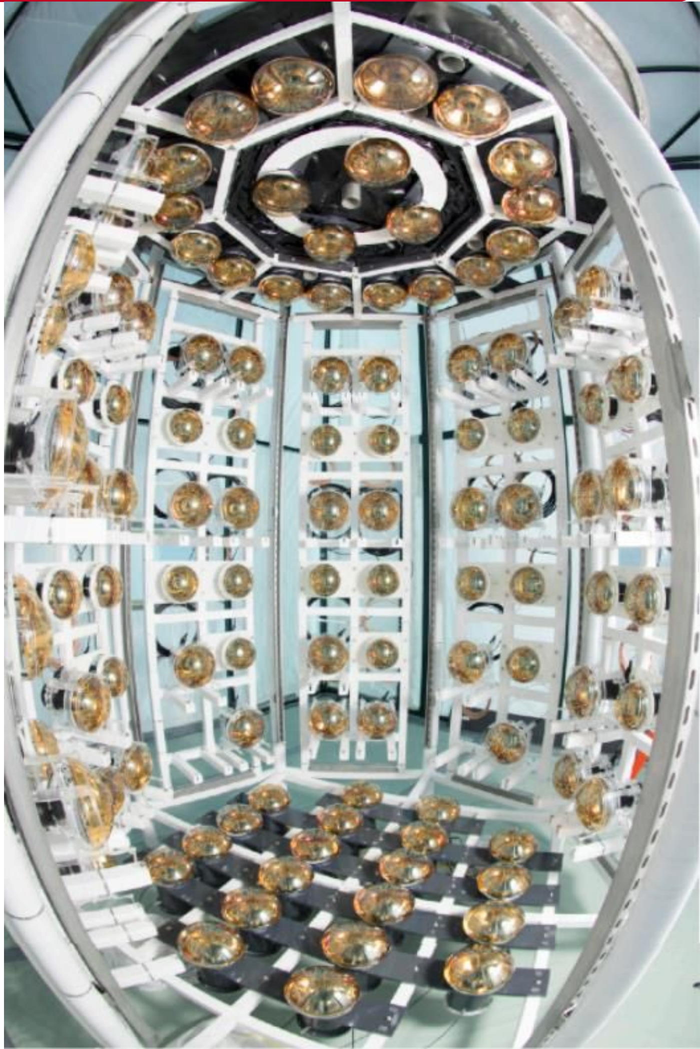
ANNIE is an international collaboration of 45+ collaborators from 17 institutions in 6 countries.

ANNIE

- The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment
- Located at the Fermilab, 100 m downstream of the Booster Neutrino Beam (BNB)
- 26 ton Gadolinium loaded Water Cherenkov detector
- ~120 **P**hoto**M**ultiplier **t**ubes (PMTs) and some **L**arge **A**rea **P**icosecond **P**hotodetectors (LAPPDs)

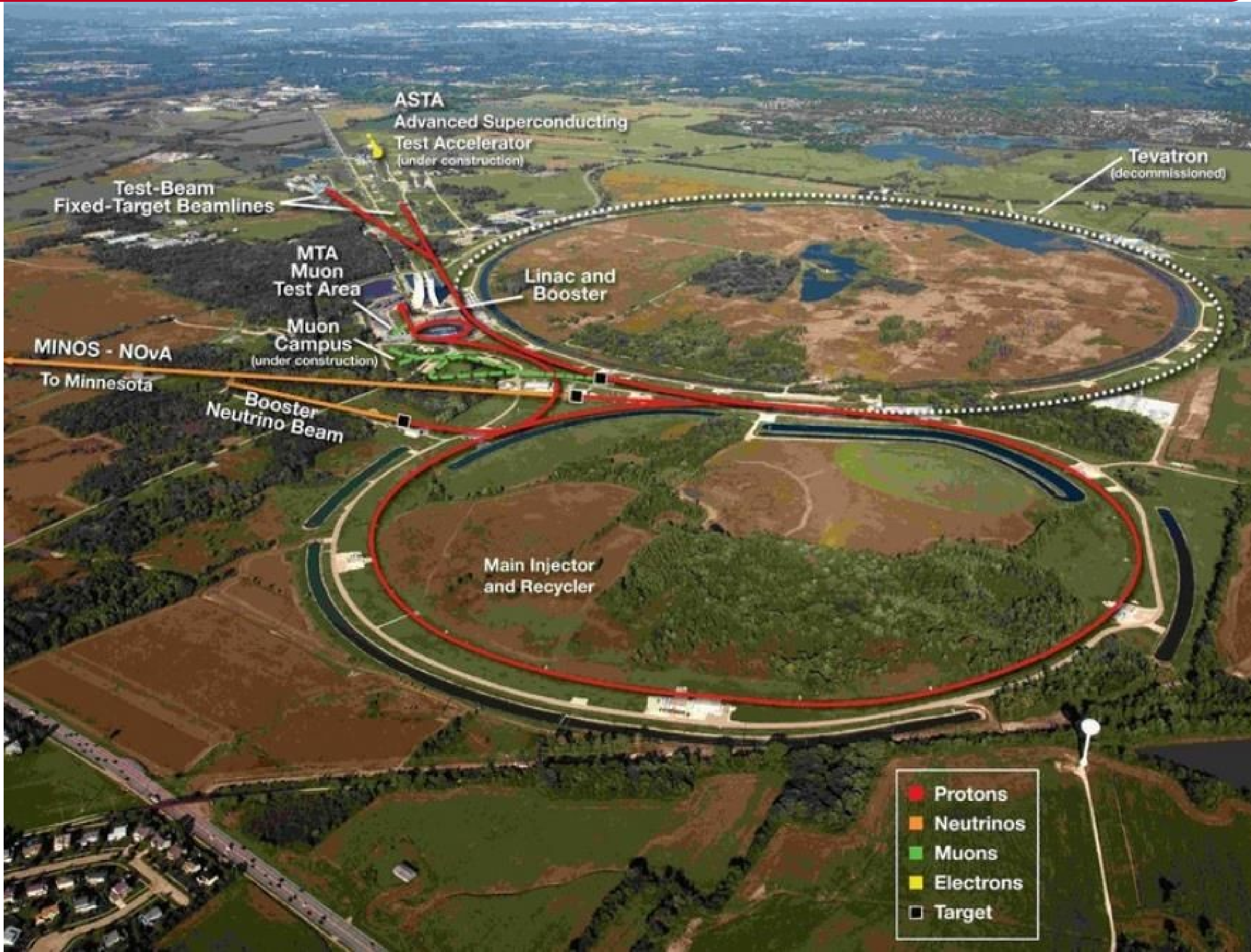
Main goals:

- Measurement of neutrino cross section
- Measurement of neutron multiplicity from neutrino – nucleus interactions in water
- Demonstration and investigation of new detector technologies:
  - Gadolinium doped water for neutron detection
  - LAPPDs
  - **W**ater **b**ased **L**iquid **S**cintillator (**WbLS**)

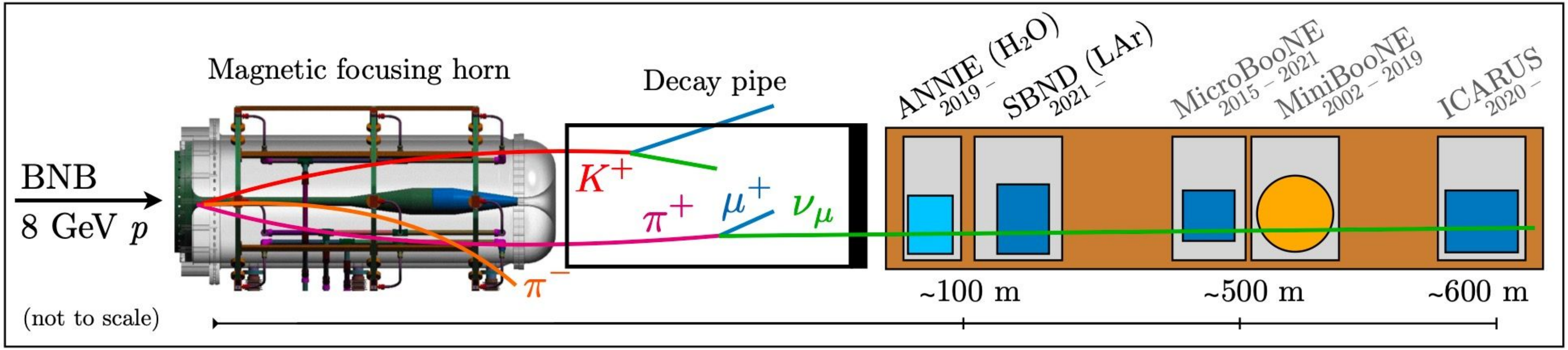


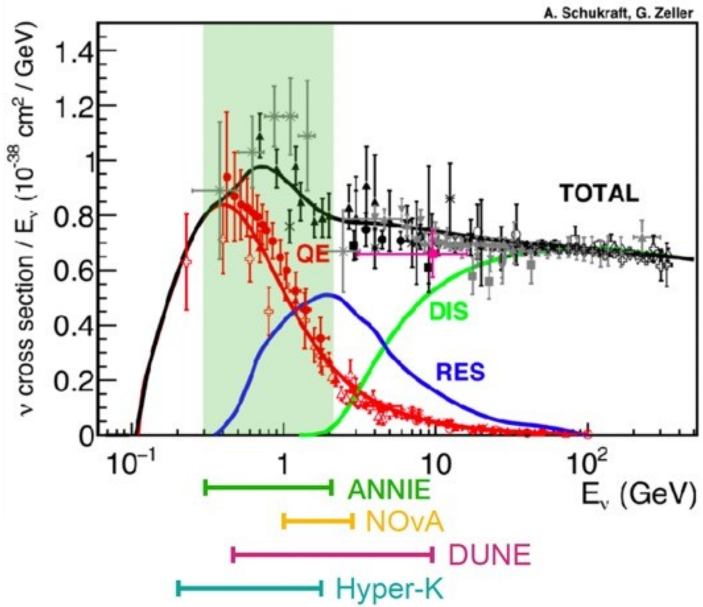
Fermilab Accelerator Complex

- Accellerator provides $E_{kin} = 8\,\mathrm{GeV}$ protons to BNB
- 84 bunches (2 ns) of protons in a beam spill of $\Delta t = 1.6\,\mu s$
- Muon neutrinos $\sim$ 93%, muon anti-neutrinos $\sim$ 6%, electron (anti) neutrinos <1%
- Mean neutrino energy ~800 MeV



ANNIE: Measurement of neutrino cross section





- ANNIE shares the BNB with several LAr experiments
=> Comparison of oxygen & argon cross sections

- ANNIE is near the target of a neutrino beam
=> High statistics: O(10^4) neutrino events per year

- Neutral current quasi-elastic interactions (νNCQE) on oxygen is dominant background for Diffuse Supernova Neutrino Background (DSNB)

ANNIE: Measurement of neutron multiplicity

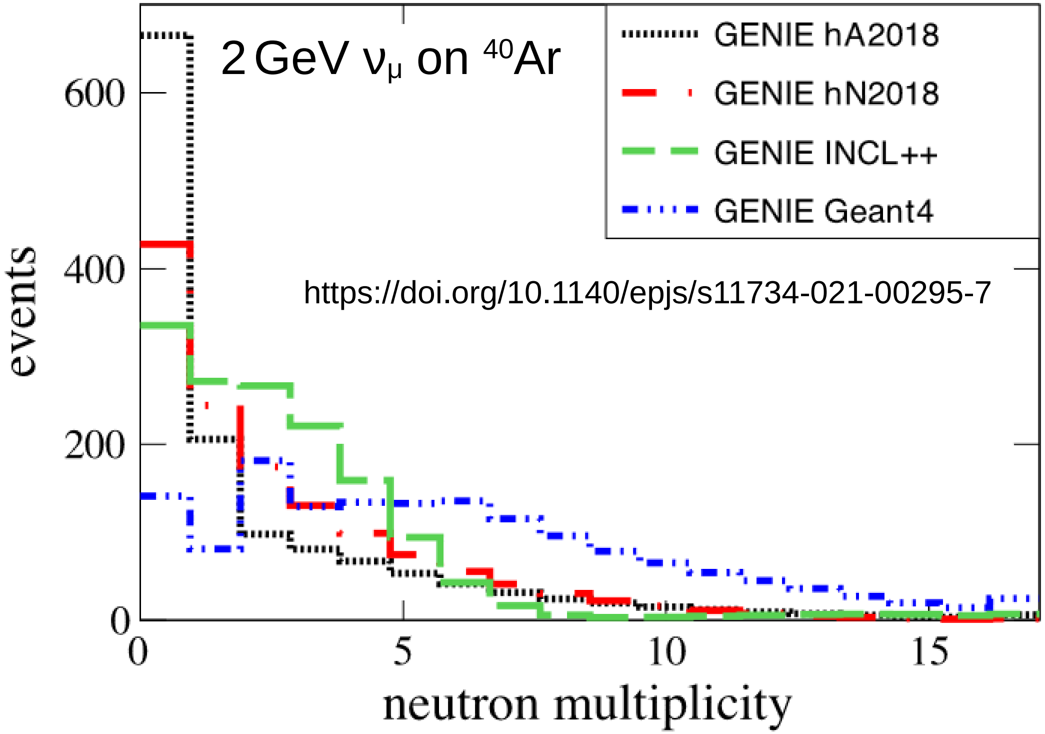
- Neutrino experiments: want precise measurement of the neutrino energies

- After neutrino-nucleon interaction hadronic component may undergo further interactions

- Outgoing neutrons can carry away energy if they are not detected

- Precise knowledge of neutron multiplicity reduces energy reconstruction uncertainty

- Simulating nuclear effects is hard
=> models show significant variations



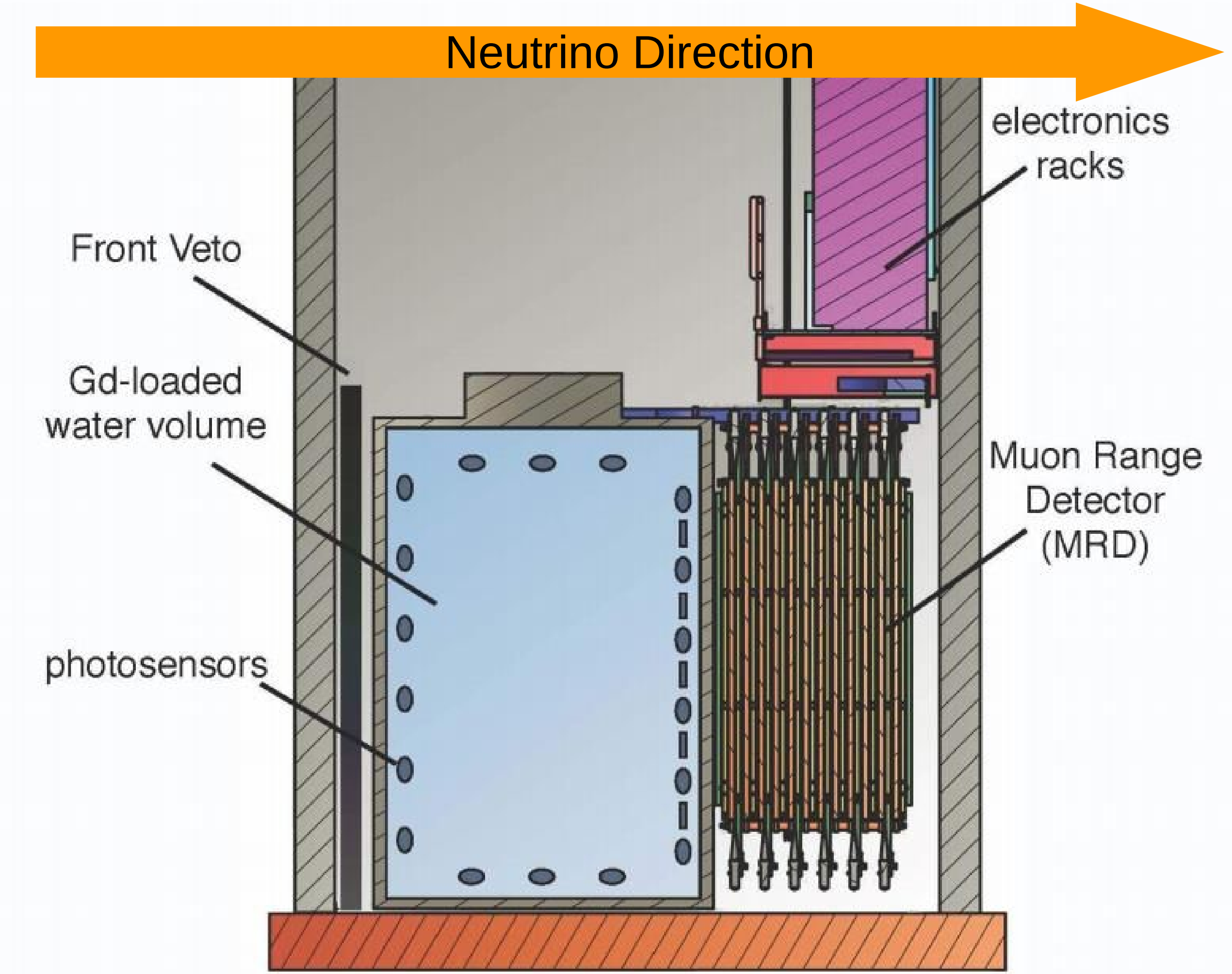
https://doi.org/10.1140/epjs/s11734-021-00295-7

ANNIE Detector

- Front Muon Veto (FMV):
  26 scintillator paddles to reject upstream dirt muons
- Water Tank:
  ~3 m x 4 m volume filled with 26 t water with 0.2% $Gd_2(SO_4)_3$

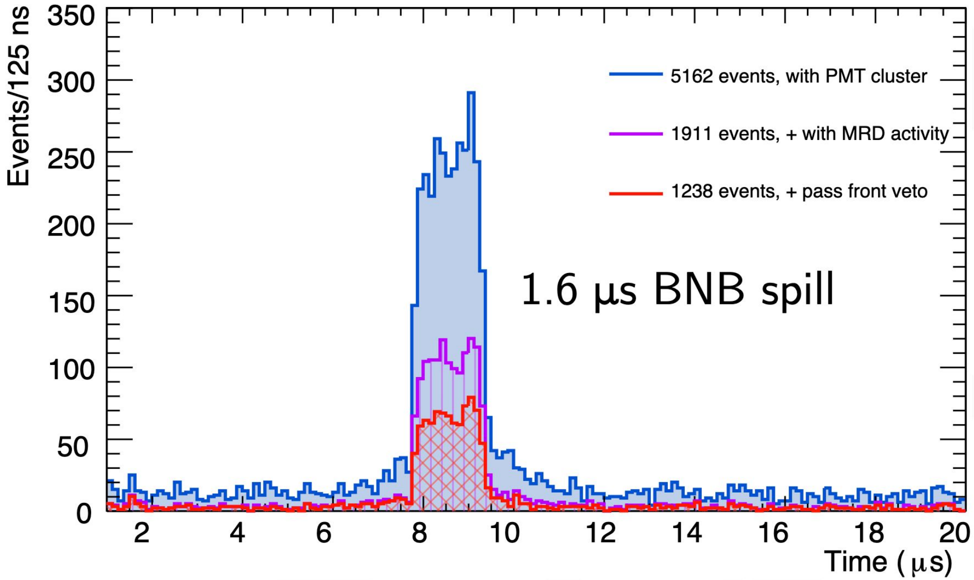
=> Neutron capture on H: 2.2 MeV
Neutron capture on Gd: ~8 MeV

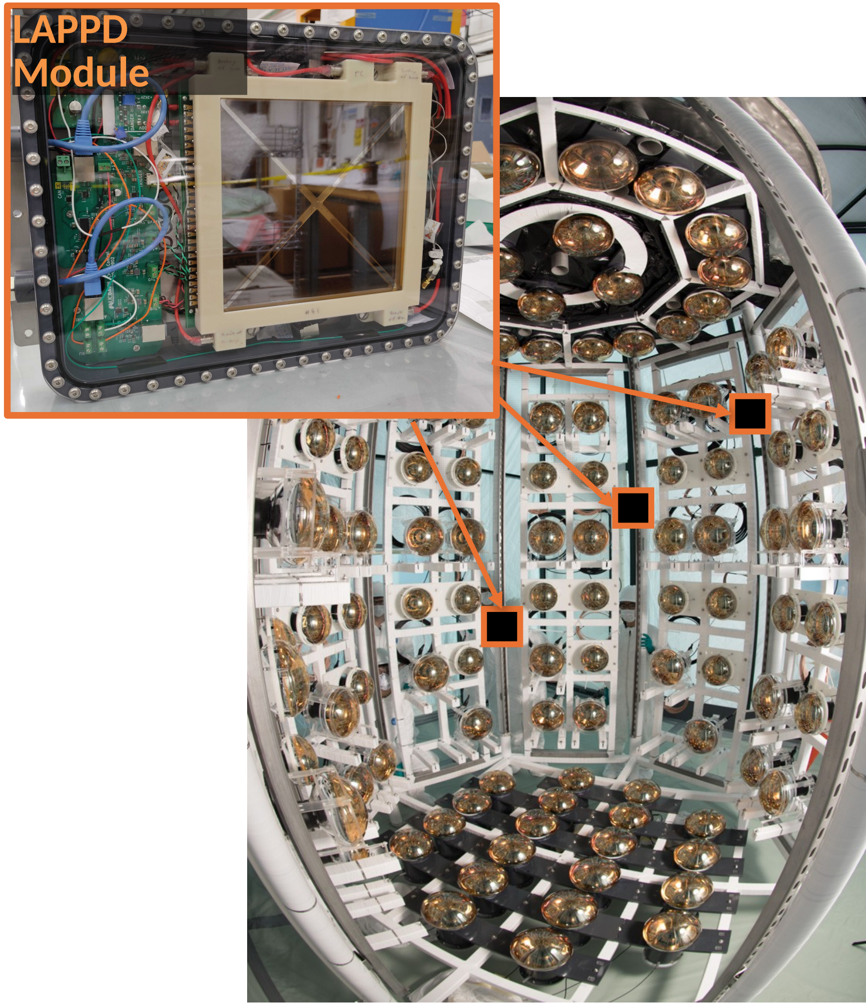
- Photosensors:
  ~120 PMTs, up to 5 LAPPDs for light collection and event reco.
- Electronics rack:
  Data acquisition (DAQ) system
- Muon Range Detector (MRD)
  310 scintillator paddles
  Used for muon reco.



LAPPDs: Large Area Picosecond Photodetectors

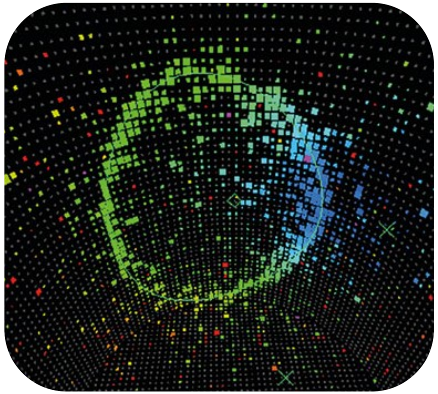
- LAPPDs: photosensors using micro channel plates
- Large detectin area: 20 cm x 20 cm
- Timing resolution < 100 ps, ~ 1 cm spatial resolution
- Inclusion of LAPPDs will improve vertex reco
for ANNIE from ~30cm to < 10 cm with 5 LAPPDs
- ANNIE: first to detect beam neutrinos using LAPPDs!



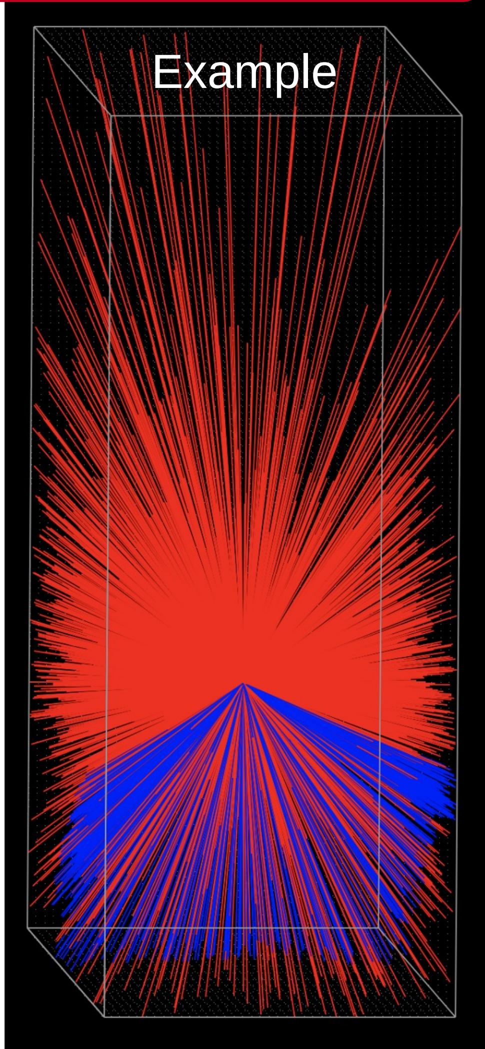


Hybrid Event Detection

- Water Cherenkov detectors are great for detecting leptons but no signal for low energy hadrons
- Cherenkov directionality and ring counting allows for powerful discrimination of event topologies
- Scintillation has no energy threshold
  => detection of sub-Cherenkov particles
- Hybrid event detection:
  Combine Cherenkov and scintillation signals

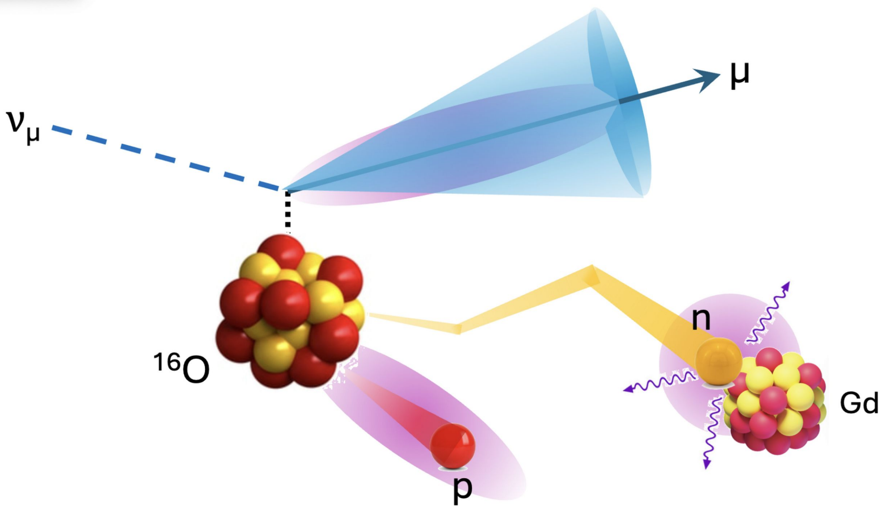


Super-Kamiokande



Hybrid Event Detection

- Hybrid event detection: Combine Cherenkov and scintillation signals
- Better particle identification and discrimination of event topologies
- Improved energy reconstruction through higher light yield and through detection of missing hadrons
- Improved neutron signal and detection efficiency



Hybrid event detection demands disentanglement of Cherenkov and scintillation light

Hybrid Event Detection

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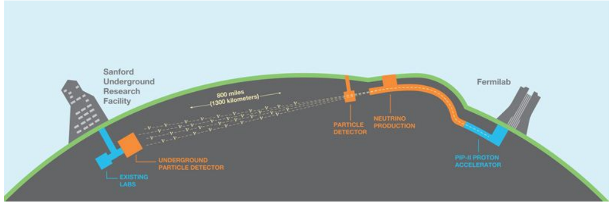
“Eierlegende Wollmilchsau”

A pig that bears merino wool and furthermore lays eggs, too

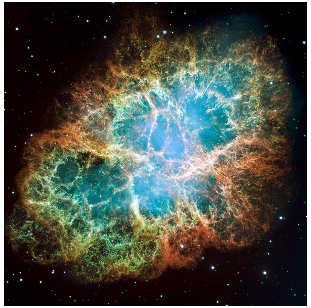
Hybrid Event Detection

Hybrid signal allows (potentially) for broad physics program:
(Potentially) Unprecedented levels of background rejection, with low energy threshold

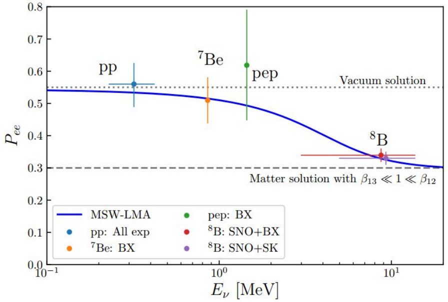
Long baseline oscillations



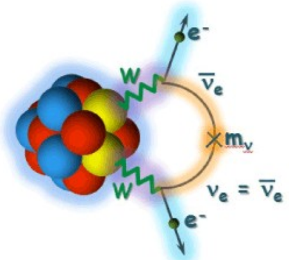
Supernova burst neutrinos & DSNB



Solar neutrinos

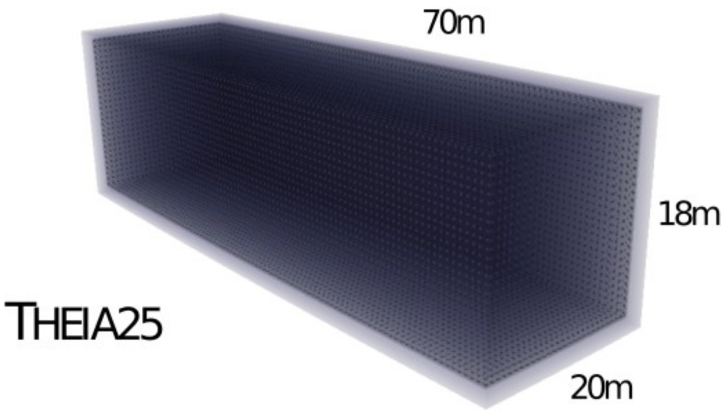


0νββ-decay



Neutrinoless
double beta decay

THEIA
hybrid detector proposal
(arXiv:1911.03501)



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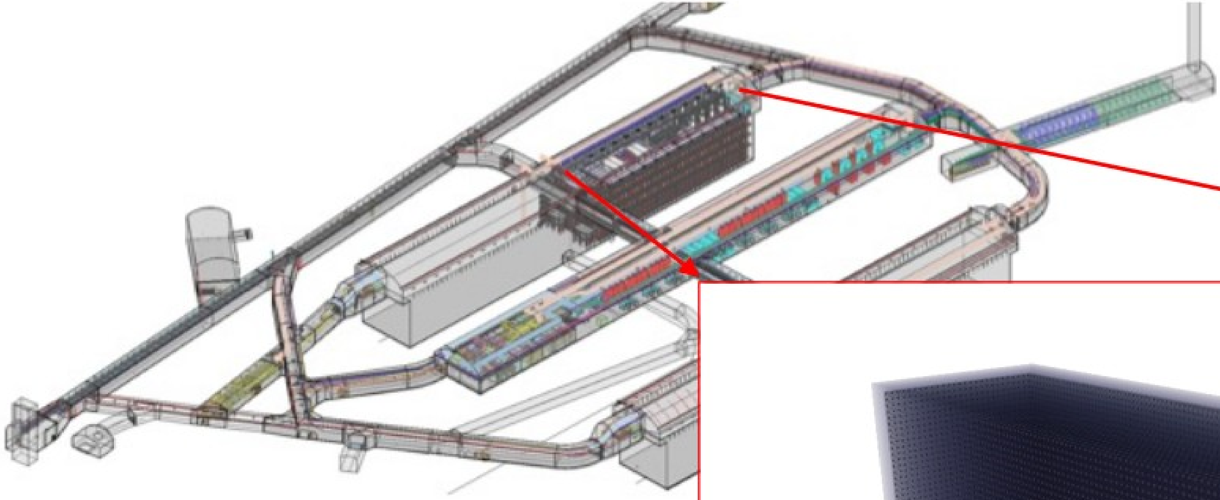
(Potentially) Unprecedented levels of background rejection, with low energy threshold



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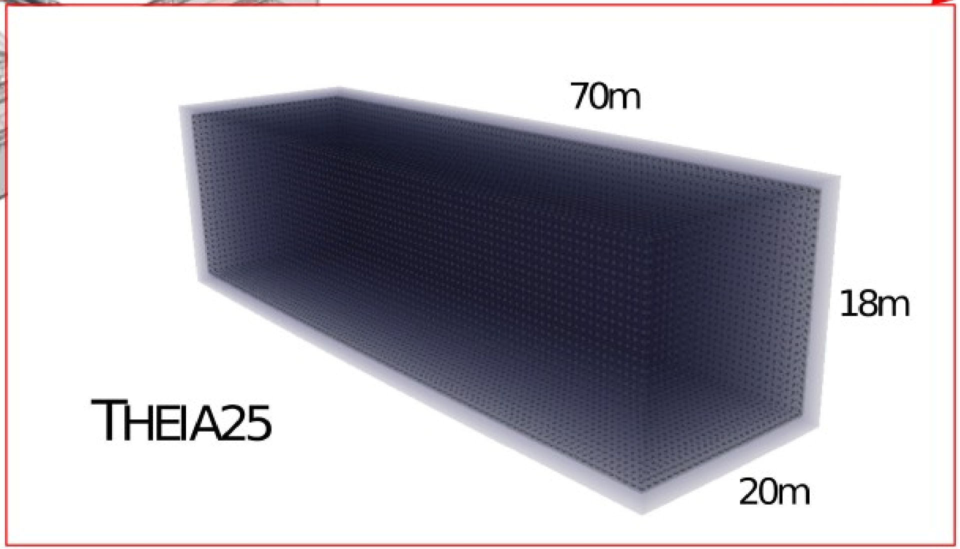
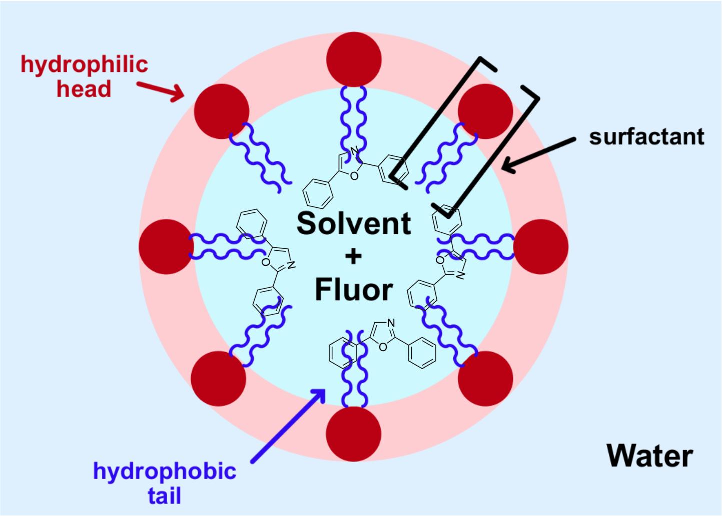
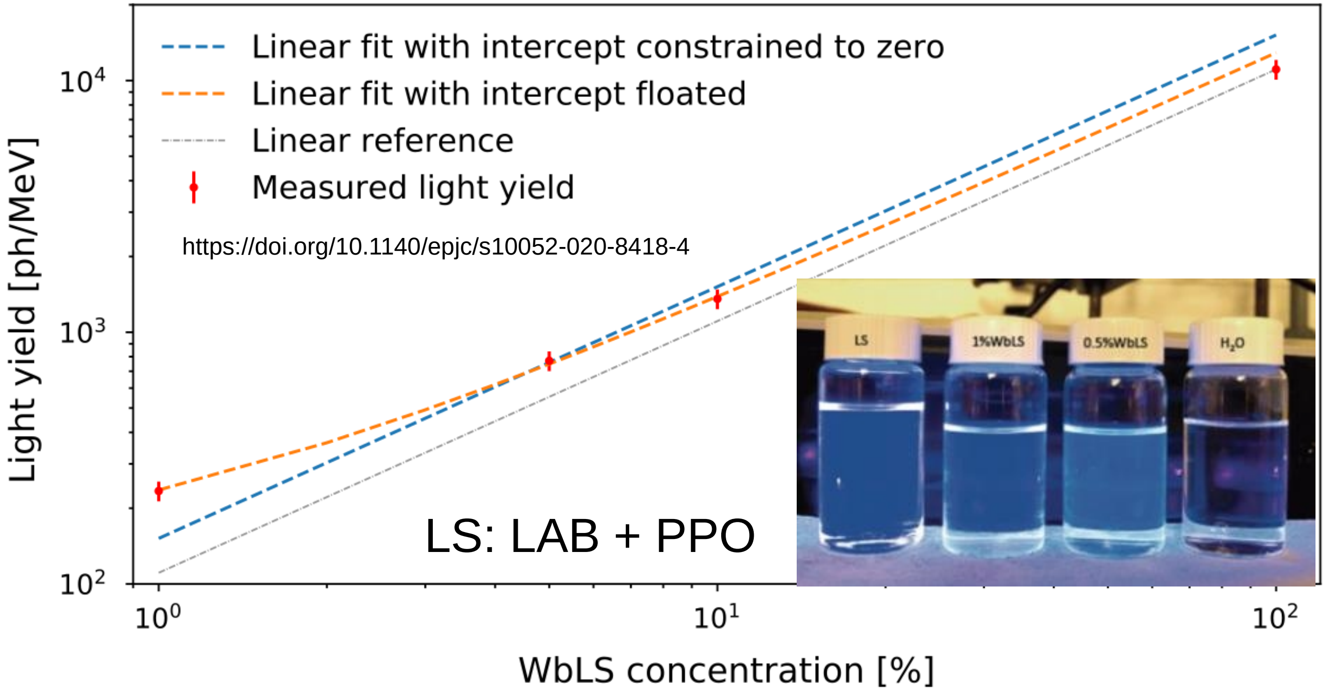
In the DUNE caverns



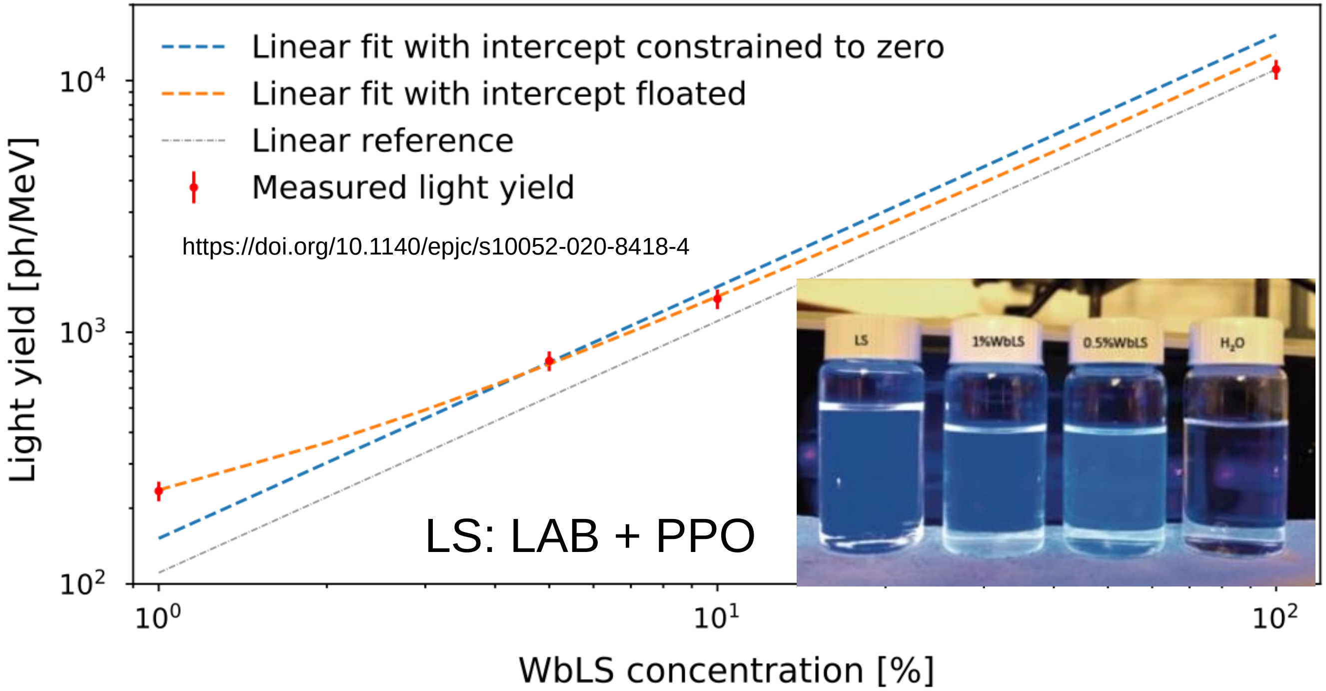
Water-based Liquid Scintillator





- Combination of pure water with liquid scintillator in micelles
- Directionality & kinematic reconstruction (Cherenkov)
- High(er) light yield & improved energy reconstruction (scintillation)

Water-based Liquid Scintillator



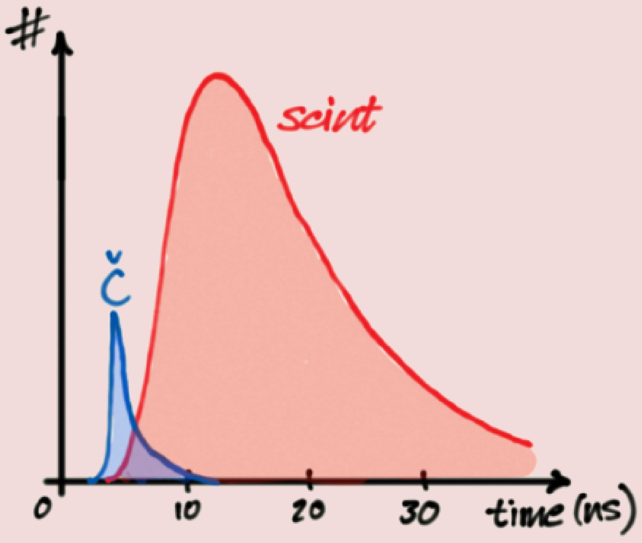
- Combination of pure water with liquid scintillator in micelles
- Directionality & kinematic reconstruction (Cherenkov)
- High(er) light yield & improved energy reconstruction (scintillation)

Combines the advantages of water and liquid scintillator
=> Potential for reconstruction of event topologies and unprecedented background rejection

Water-based Liquid Scintillator

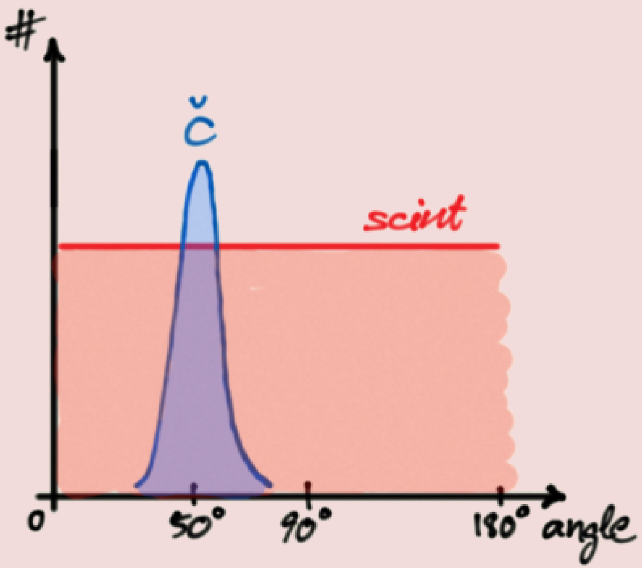
Timing

“instantaneous” Cherenkov vs. delayed scintillation light
→ ns resolution or better



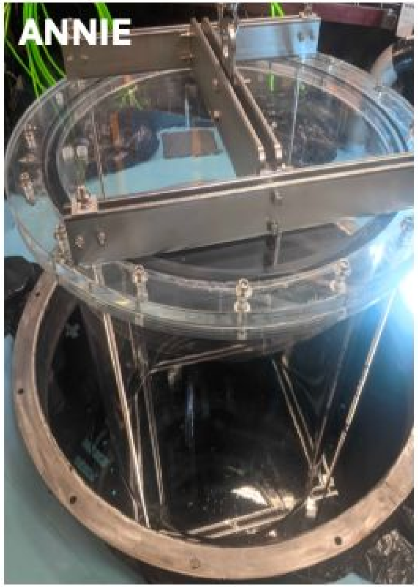
Angular distribution

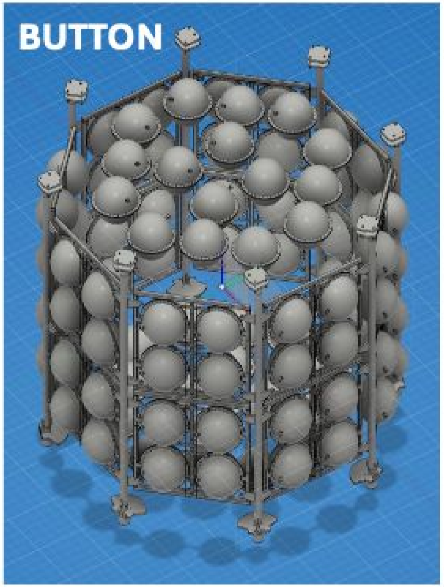
increased PMT hit density under Cherenkov angle
→ sufficient granularity

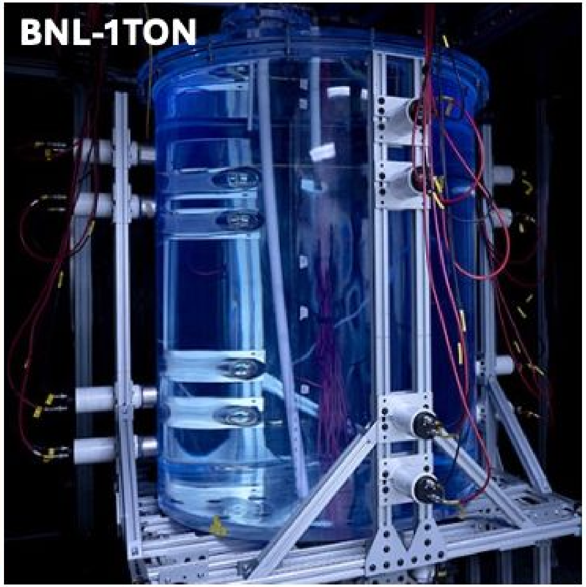


- Low scintillator concentration: Cherenkov signal still visible
- Scintillation: slow compared to Cherenkov light
- Scintillation: isotropic
  Cherenkov: directional
- Is ANNIE detector capable of hybrid event detection, using WbLS?

International WbLS Effort







- EOS (USA, 20-ton)
- Brookhaven 1-ton and 30-ton (USA)
- BUTTON (UK, 20-ton)

SANDI

- 90 cm x 72 cm acrylic vessel filled with WbLS, ~366 L submerged in ANNIE
- WbLS produced in Brookhaven 1% organics, Gd-compatible
- Deployment: 2 months in 2023

Goals:

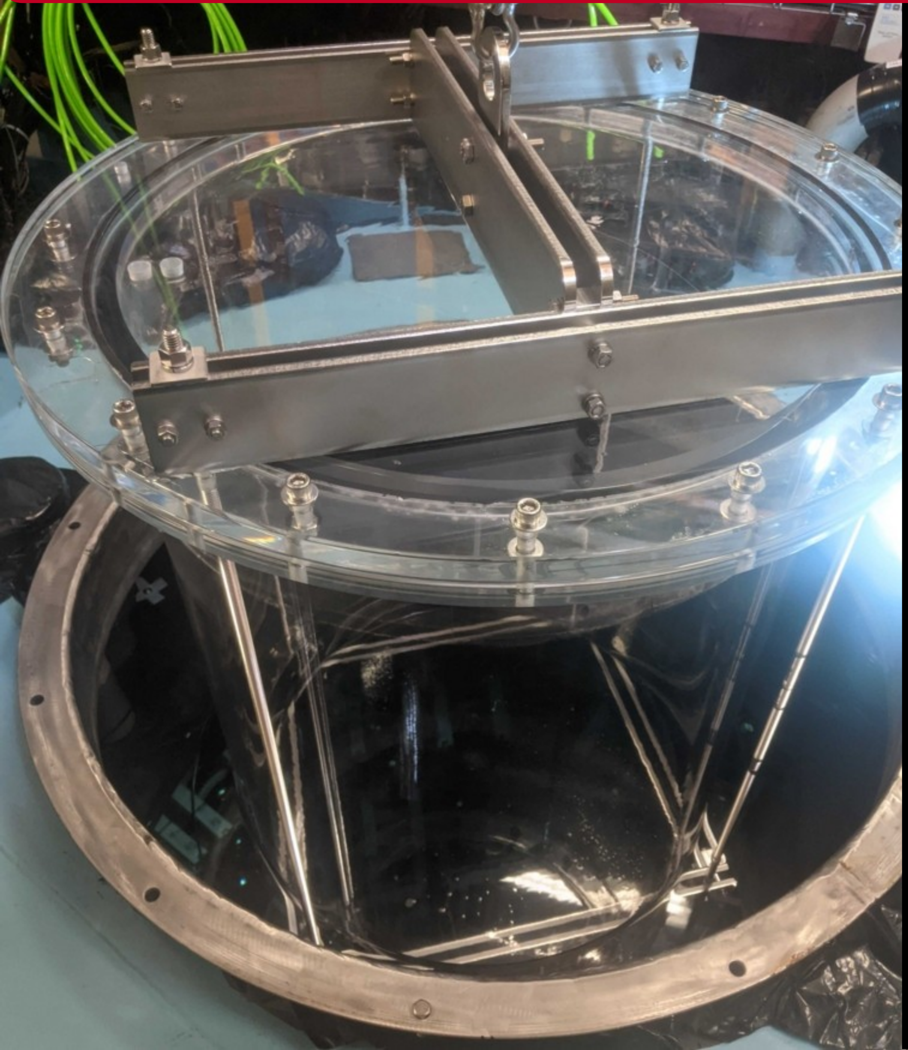
- Proof-of-principle for hybrid event detection
  => Done! JINST 19 P05070 (2024)

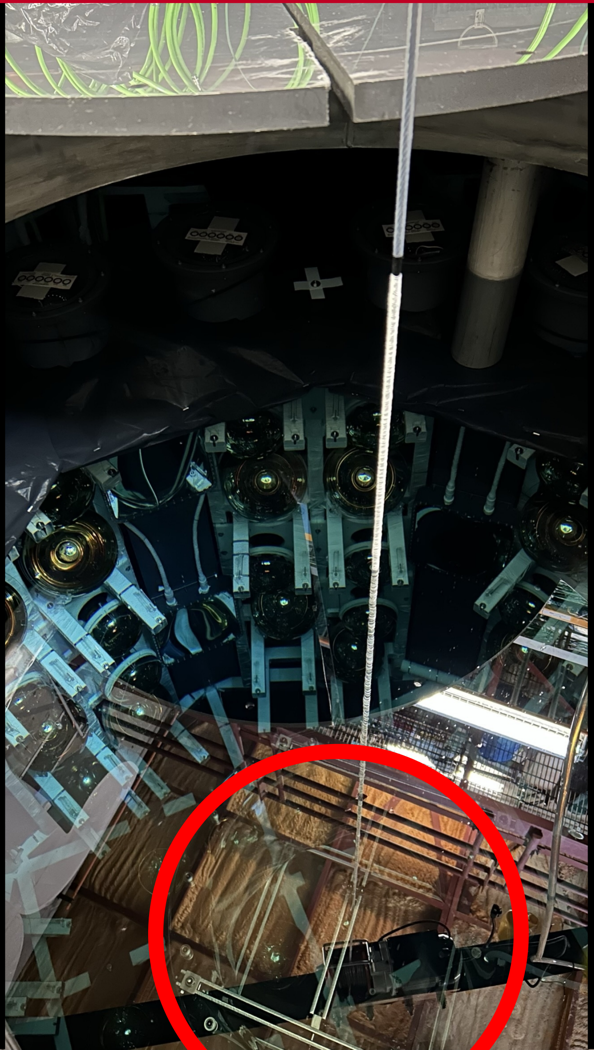
Work to be done:

- Measure the WbLS light yield
- LAPPD Che/scint time separation
- Search for hadronic component
- Improved energy/vertex reco.
- Search for NC events

Scintillator for **A**NNIE **N**eutrino **D**etection **I**mprovement

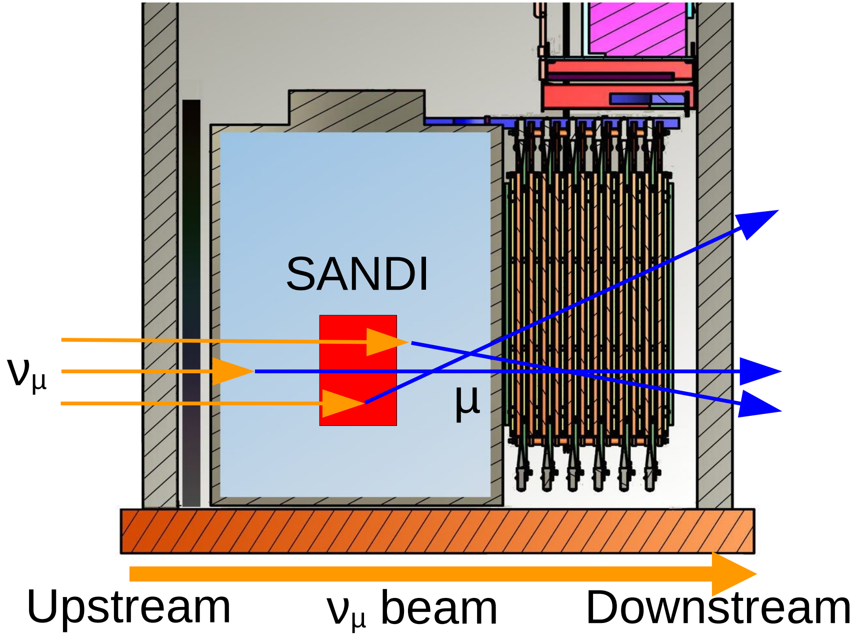
Pictures of SANDI Deployment

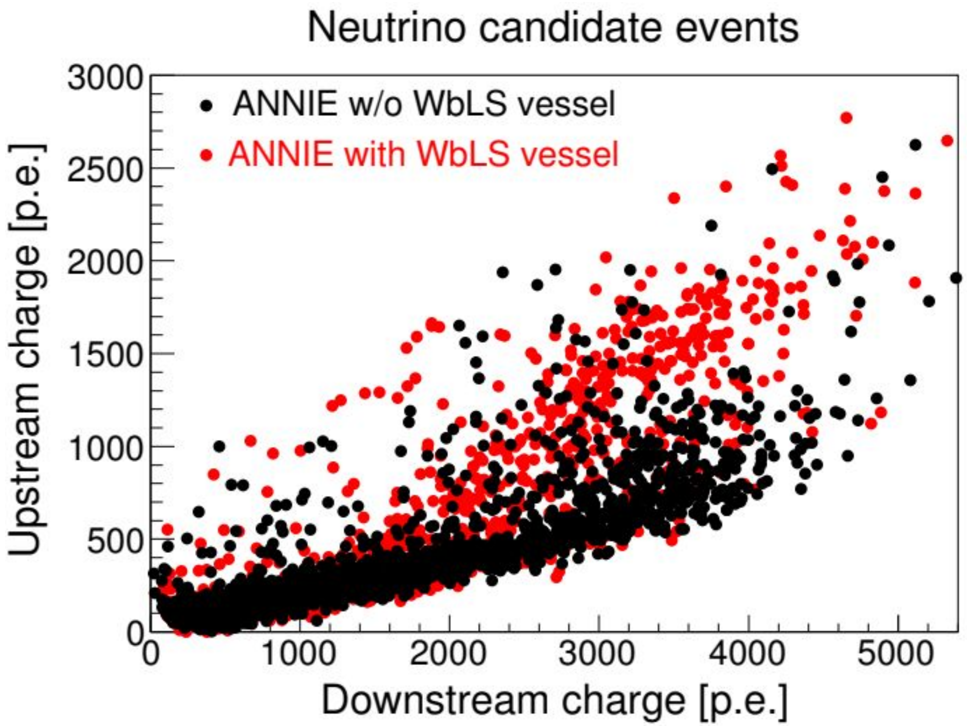




Neutrino Candidates

No FMV trigger: neutrino candidates



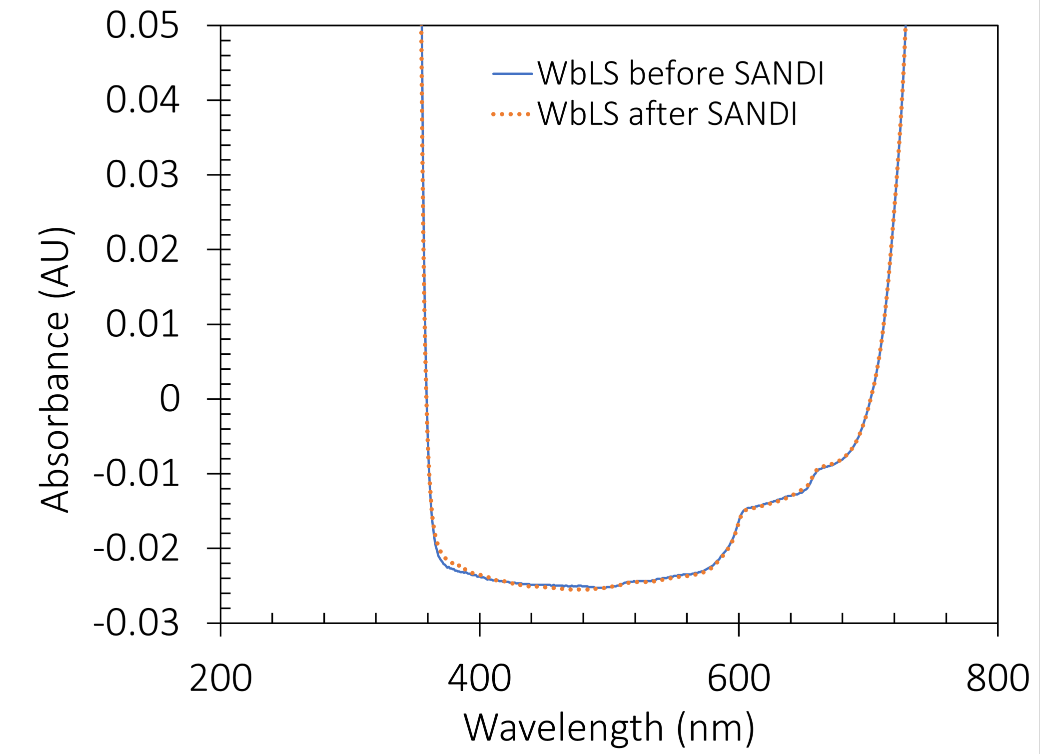


- ANNIE with SANDI for 2 months: Two event populations
    1) Similar events as ANNIE without SANDI due to MRD mis-reconstruction
    2) Muons with actual scintillation contribution
- Starting around 2000 downstream p.e.: muons can pass SANDI
- Scintillation: Stronger linear dependency between downstream / upstream charge

Summary

- ANNIE has already achieved significant milestones
- First detection of beam neutrinos in Gd-loaded water
- First detection of beam neutrinos using LAPPDs

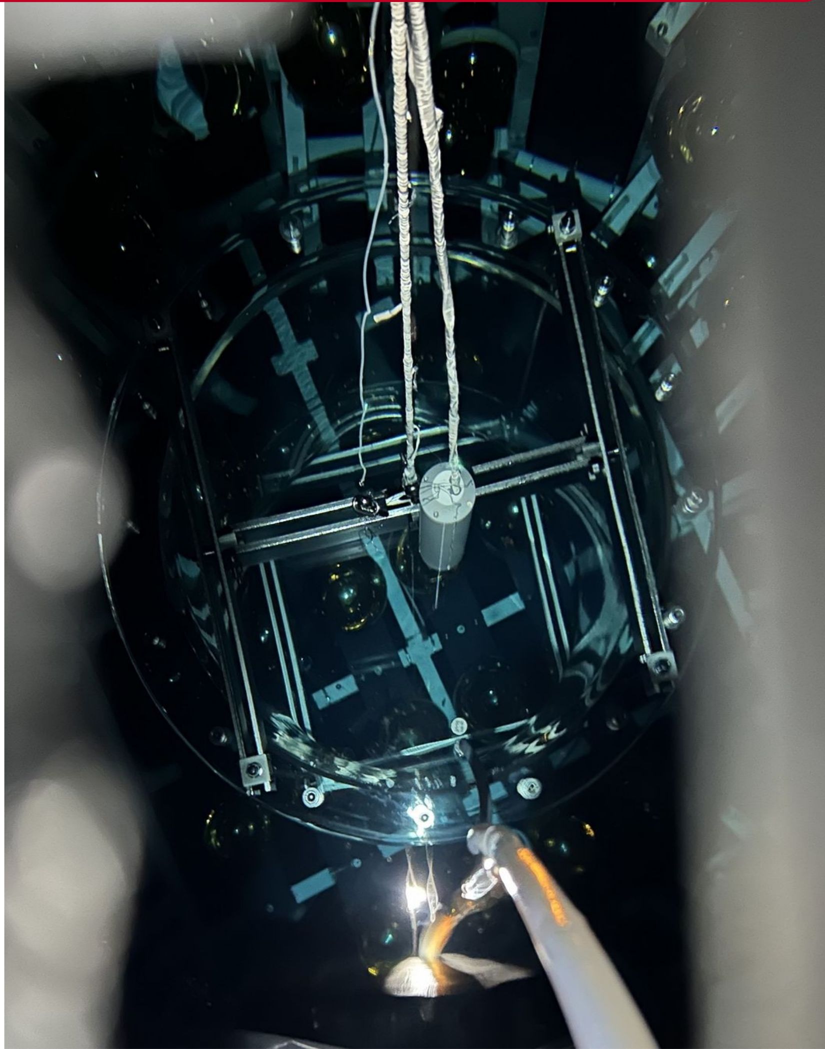
- SANDI-1 deployment:
  Proof-of-principle of hybrid event detection of beam neutrinos in WbLS
  => Done! JINST 19 P05070 (2024)
- Production, shipment, deployment, measurement, draining: ~9 months
  => WbLS shows good stability!
- Cherenkov+scintillation light has been detected for different event topologies



- One main goal of ANNIE is the investigation of the hybrid event detection concept, using WbLS
  => We are on a good path

Outlook: More WbLS Hybrid Event Detection

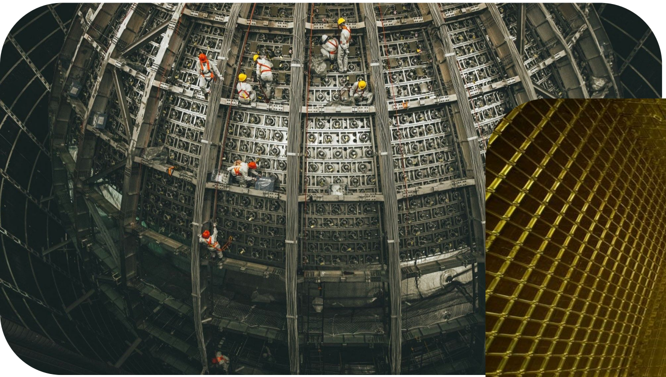
- Second 2 month SANDI deployment until Feb. 2025:
    - Gd-loaded WbLS => enhanced neutron detection
    - We have doubled our WbLS statistics!
    - Deployment of AmBe neutron source
- More exciting work:
    - Measure intrinsic WbLS light yield (possible)
    - LAPPD Che/scint time separation (**low stat.**)
    - Search for hadronic component (**low stat.**)
    - Search for neutral current events (**low stat.**)
    - Enhanced Neutron sensitivity (AmBe source)
      Mon, 17:45, T17.5 — Amala Augusthy
    - Improved energy/vertex reconstruction
      Wed, 17:15, T59.5 — Daniel Bick



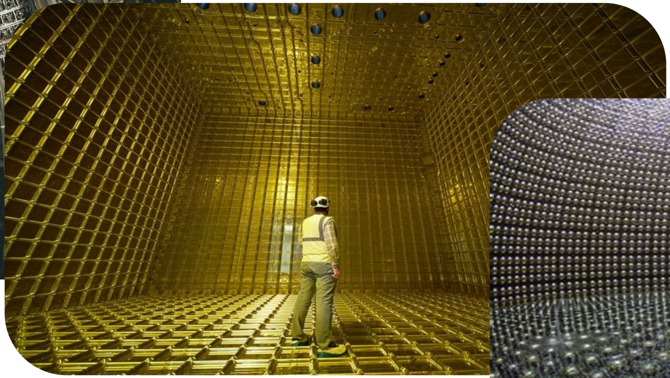
Outlook: BIGGER WbLS Hybrid Event Detection

- Super-Kamiokande: 50 kt water
- Jiangmen Underground Neutrino Observatory (JUNO): 20 kt liquid scintillator
- IceCube Neutrino Observatory: 1 km³ frozen water
- Deep Underground Neutrino Experiment (DUNE): 70 kt liquid argon

- 366 l WbLS~ 0.0004 kt WbLS is a bit small for a neutrino experiment!

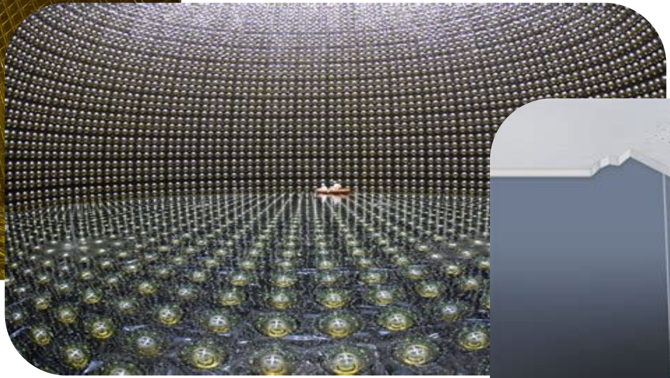


JUNO

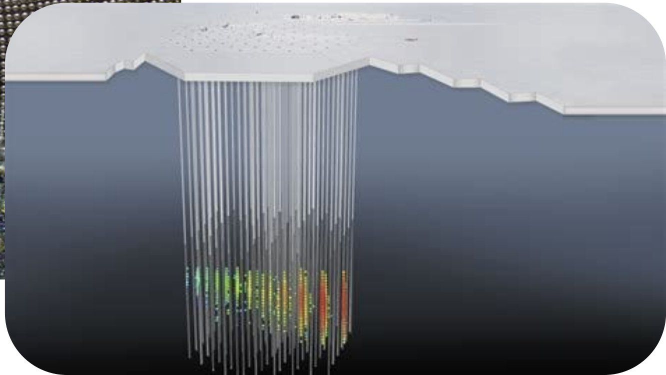


DUNE

Super-K



IceCube



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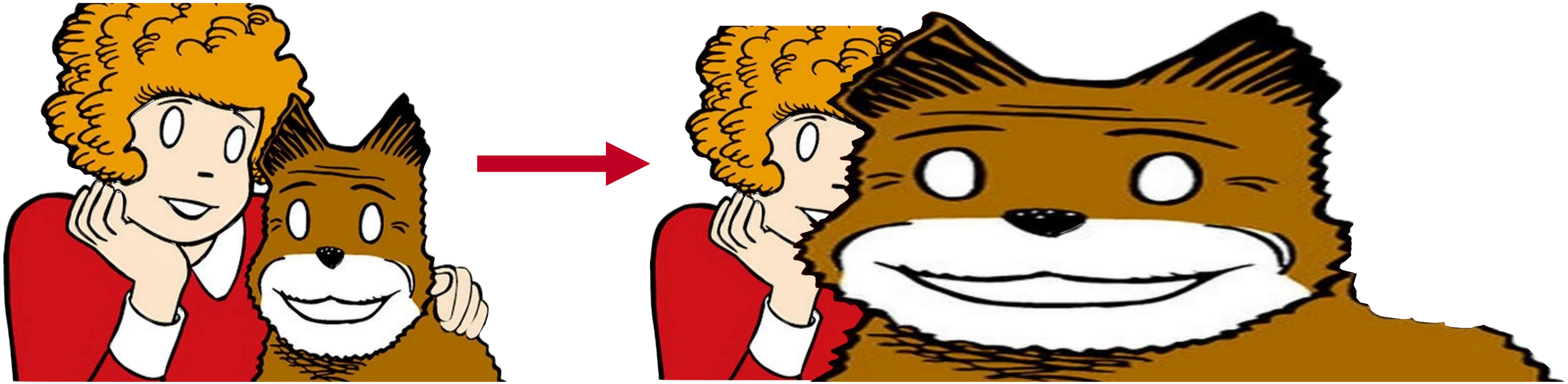
=> Make Big-SANDI

Thu, 17:45,T81.7 — Philipp Kern



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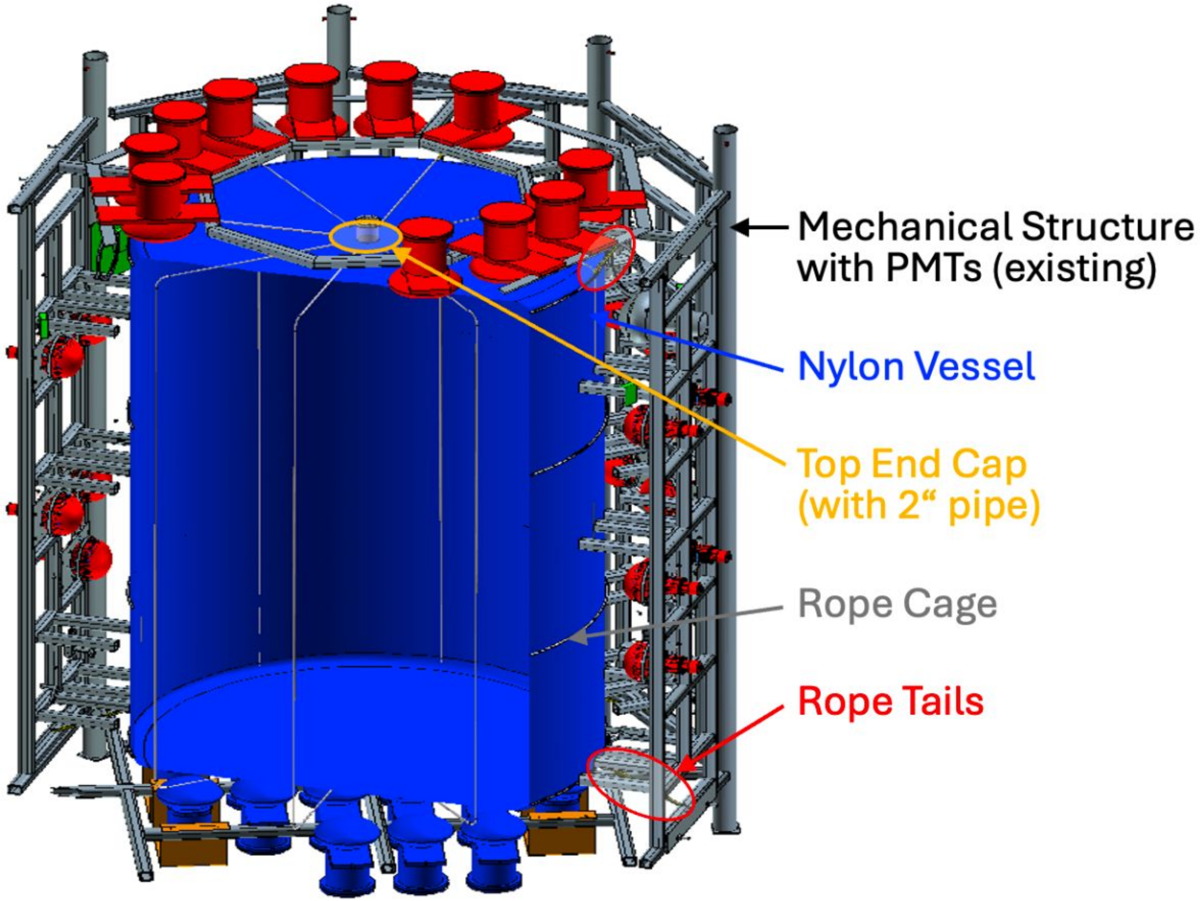
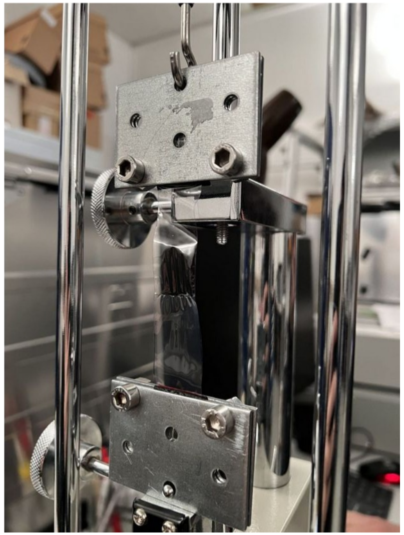


Soaking tests
(chemical stability)



Breaking tests
(mechanical stability)

Thank you for your attention!

Supplementary slides
||
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V

ANNIE Collaboration

ERCİYES ÜNİVERSİTESİ 1978 Araştırma Üniversitesi

THE UNIVERSITY of EDINBURGH

SOUTH DAKOTA MINES
An engineering, science and technology university

UCI

UH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

University of Sheffield

FLORIDA STATE UNIVERSITY

IOWA STATE UNIVERSITY

UCDAVIS

WARWICK
THE UNIVERSITY OF WARWICK

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

भारतीय प्रौद्योगिकी संस्थान कानपुर
Indian Institute of Technology Kanpur

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

DEMOKRITOS

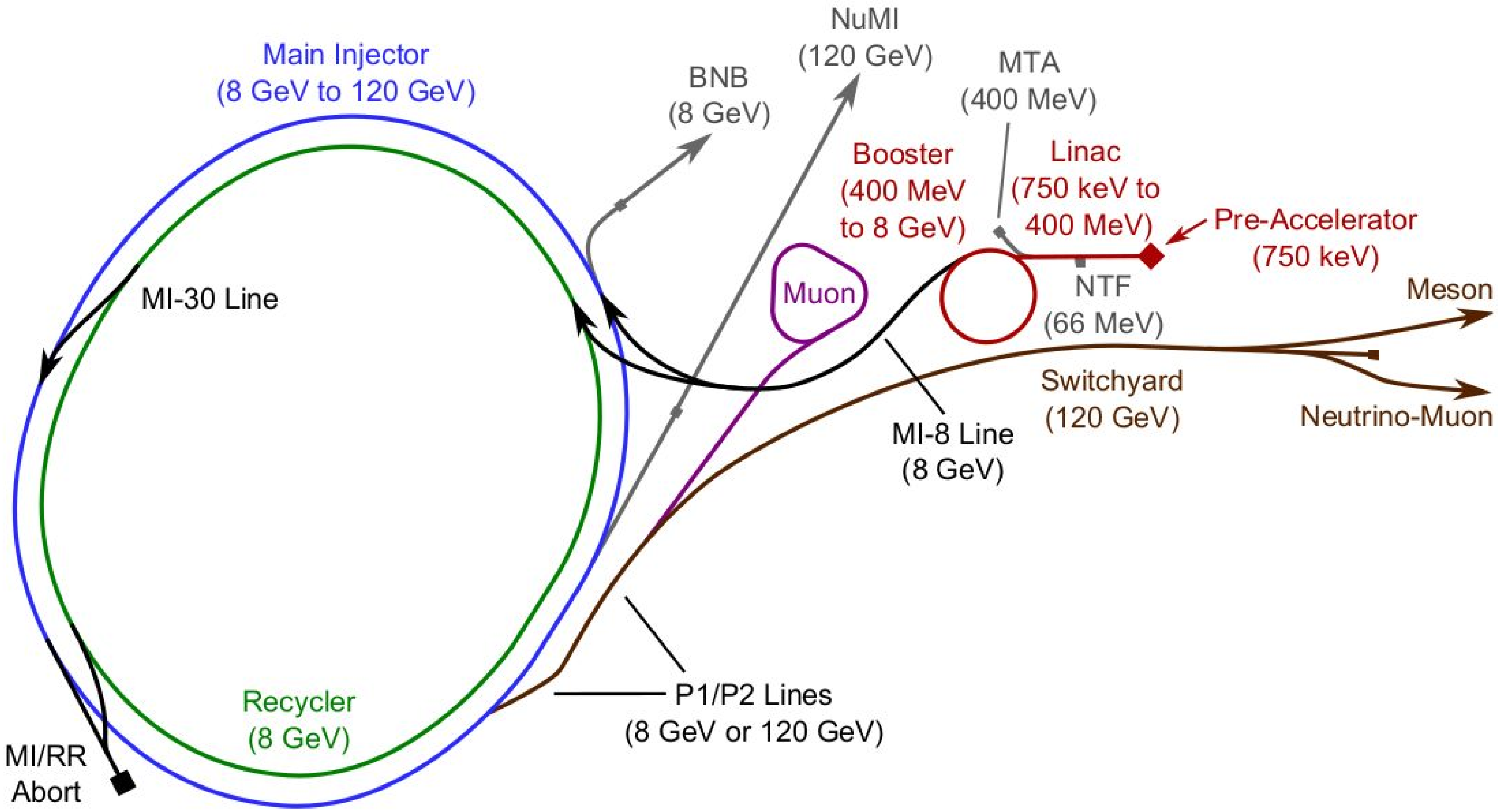
THE OHIO STATE UNIVE

THE UNIVERSITY OF CHICAGO

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

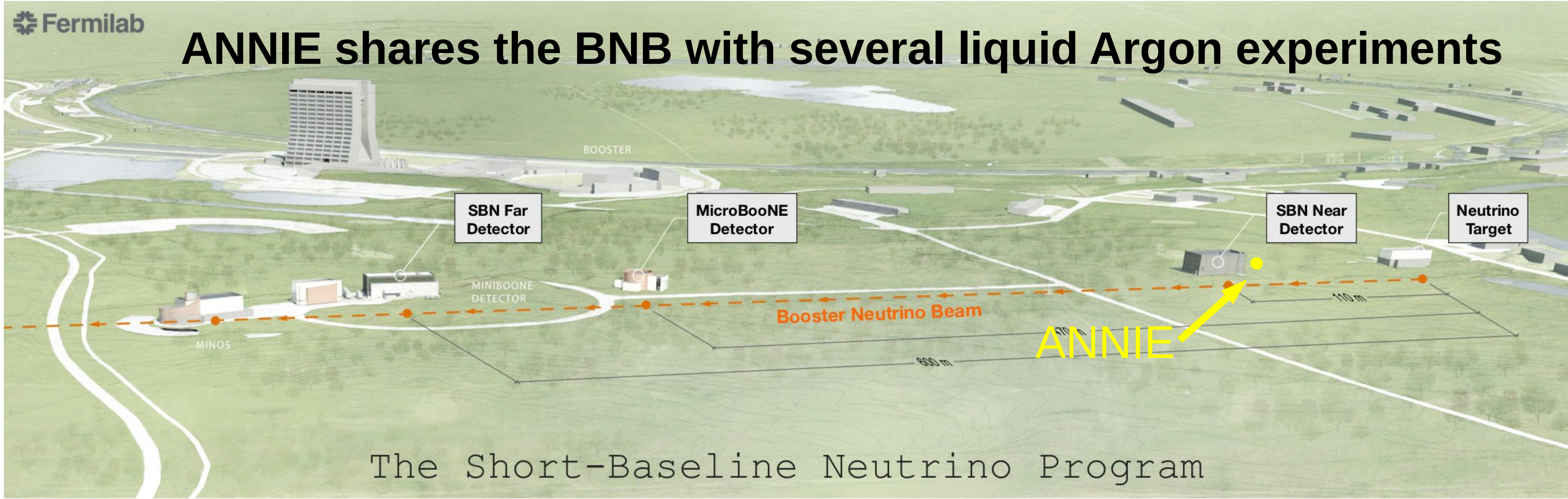
Lawrence Livermore National Laboratory

Fermilab Accelerator Complex



Fermilab Accelerator Complex

- Accellerator provides $E_{kin} = 8\,GeV$ protons to BNB
- Maximum average repetition rate for BNB is 5 Hz
- 84 bunches of protons in a beam spill of $\mathbf{\Delta t = 1.6\,\mu s}$
- We know when the protons are coming (**clock signal**)
- We know how many protons are coming (**beam monitoring**)

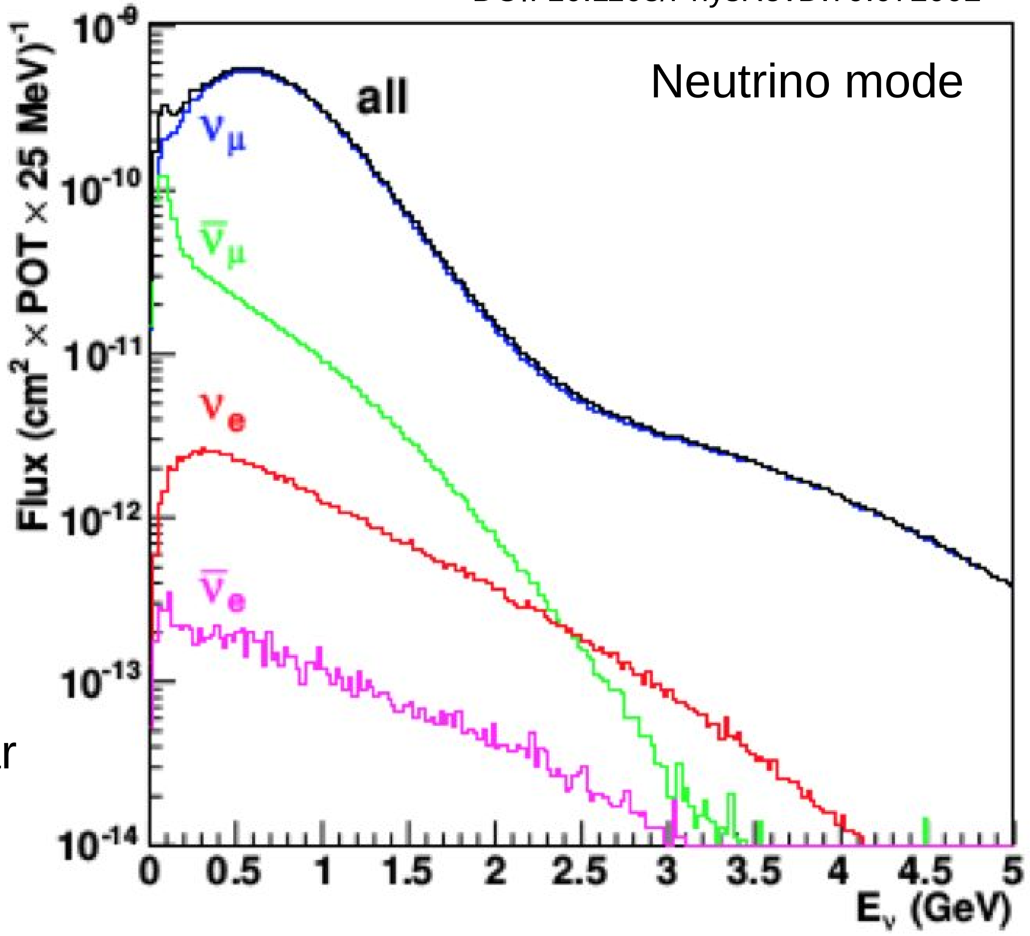


Neutrino Flux Predictions

DOI: 10.1103/PhysRevD.79.072002

- Neutrinos are produced at Beryllium target
- MiniBooNE collaboration simulated neutrino flux predictions
- Muon neutrinos ~ 93%, muon anti-neutrinos ~ 6%, electron (anti) neutrinos <1%
- Mean neutrino energy ~700 MeV

=> Close proximity to beam target: high neutrino flux of ~10 000 CC/ton/year



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- Electronics rack:
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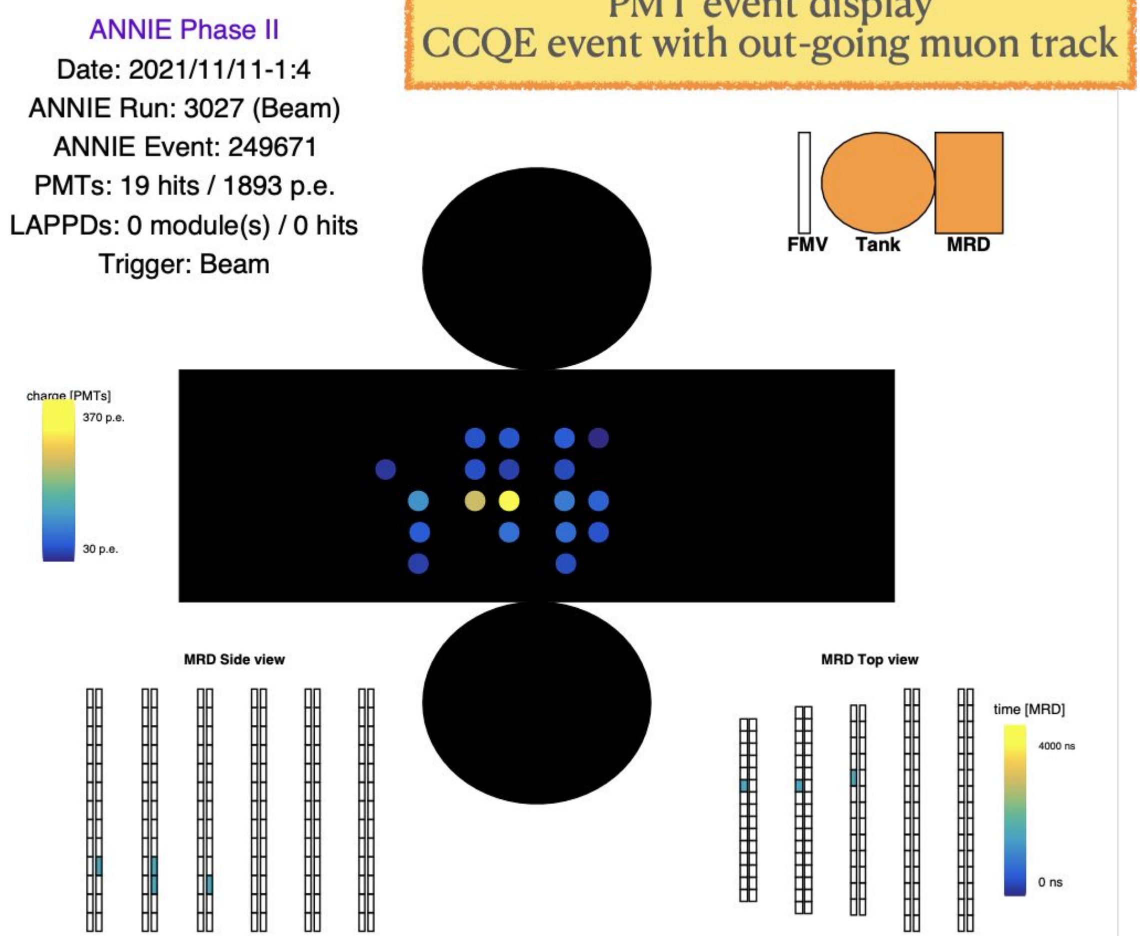
PMT event display
CCQE event with out-going muon track

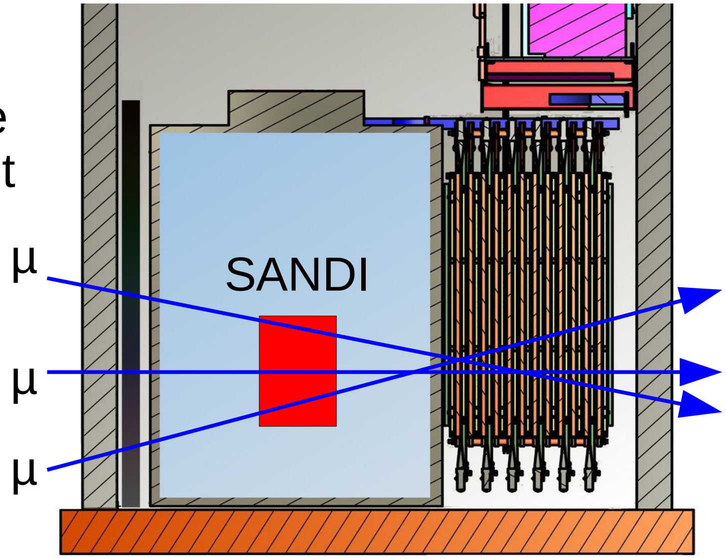


Event Selection

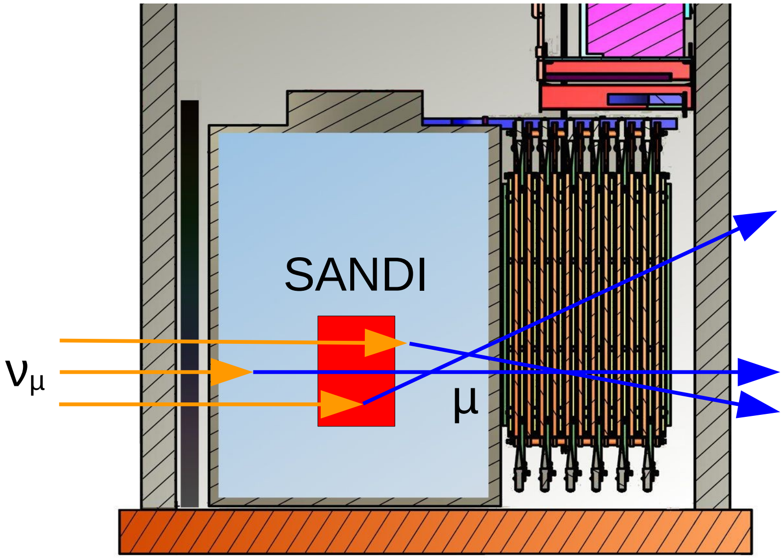
Full MC not ready:
Simple proof-of-principle with selection of different event topologies

a) Troughgoing muons
b) Neutrino candidates

FMV trigger: throughgoing muons



No FMV trigger: neutrino candidates

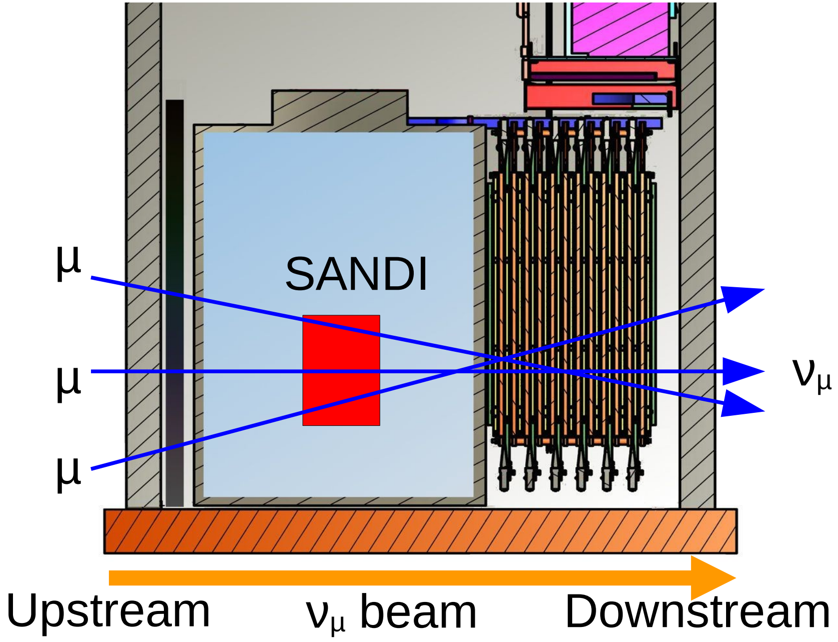


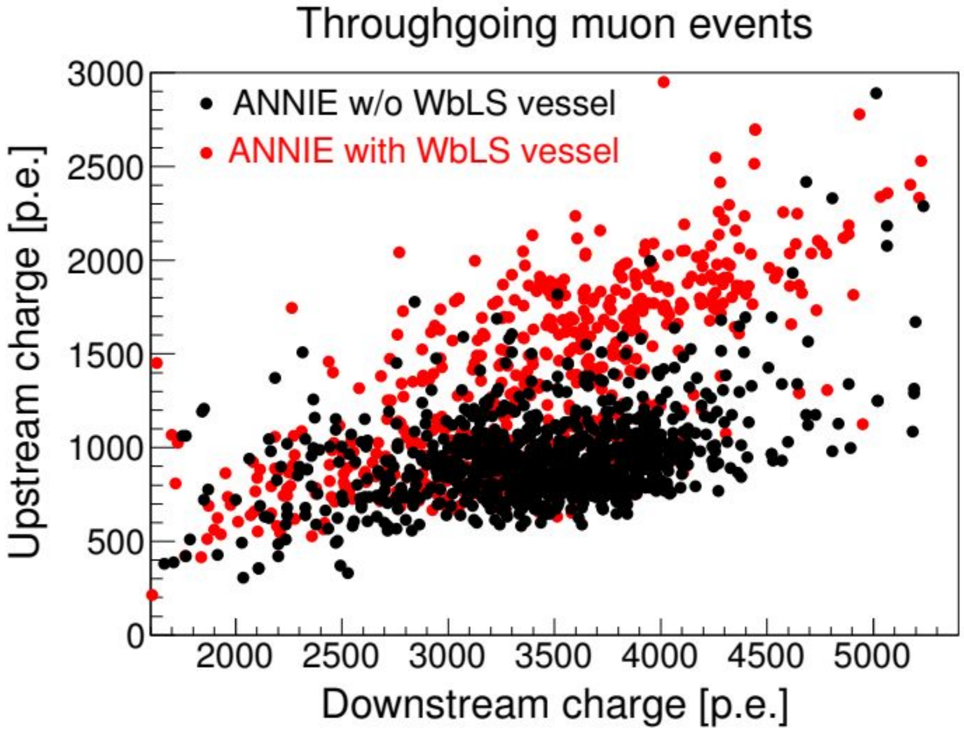
Selection of events for troughgoing muons and neutrino candidates:

ANNIE w/o WbLS: December 2022 – March 2023
ANNIE with WbLS: March 2023 – May 2023
Coincidence between Beam, Tank and MRD
Select events with MRD reco. track through SANDI

Throughgoing Muon Events

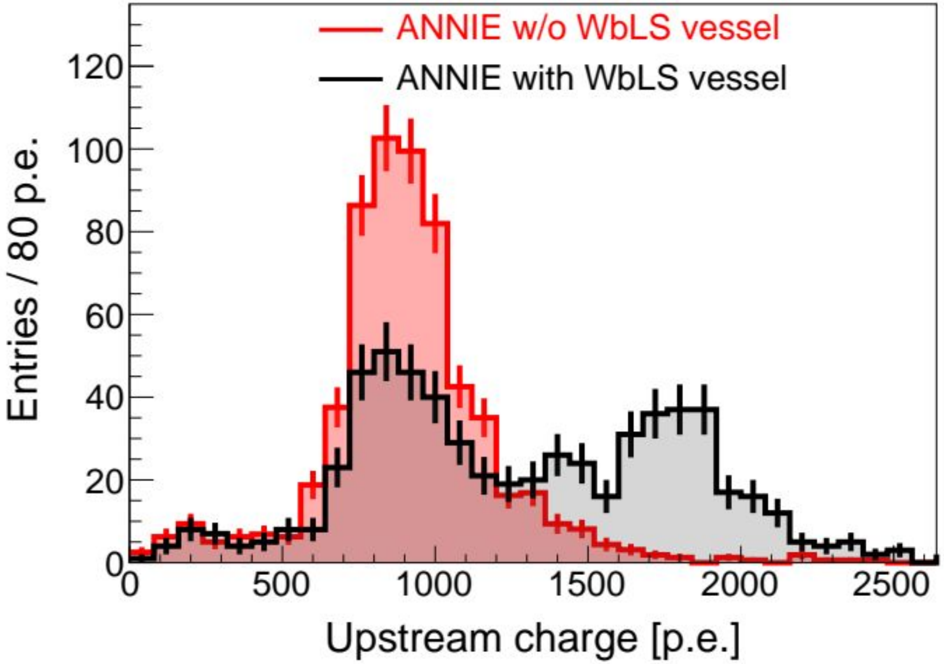
FMV trigger: throughgoing muons

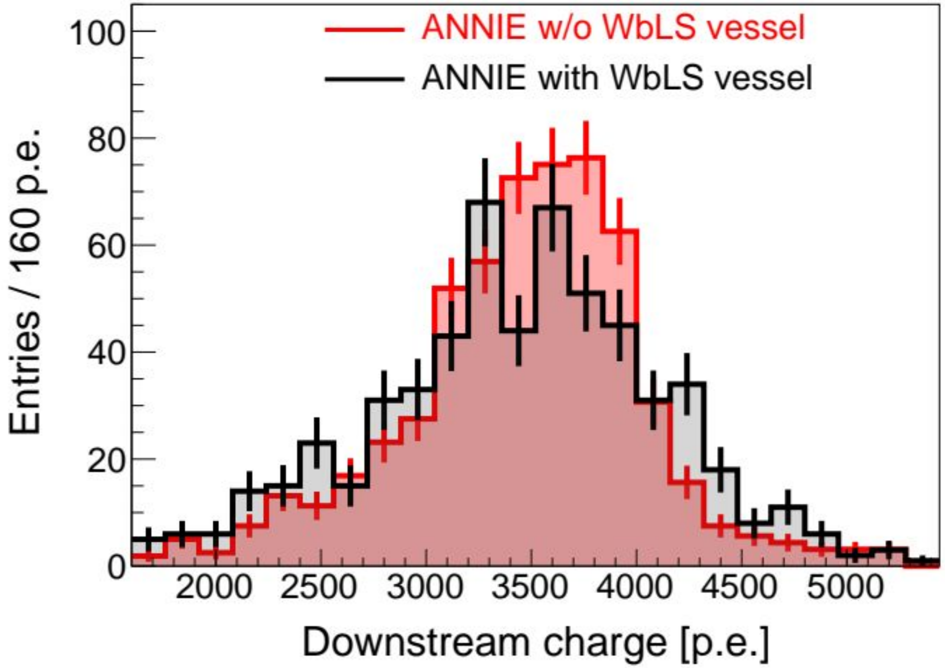




- ANNIE without SANDI: only Cherenkov light + reflection
- ANNIE with SANDI: Two event populations
  1) Similar events as ANNIE without SANDI due to MRD mis-reconstruction
  2) Muons with actual scintillation contribution
- Scintillation: Stronger linear dependency between downstream / upstream charge

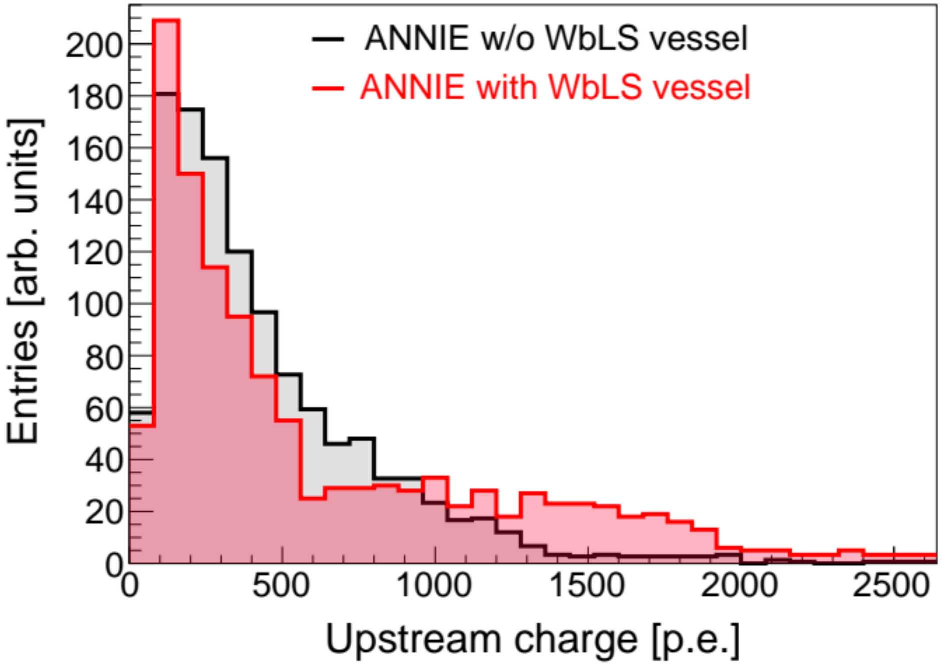
Throughgoing Muon Events

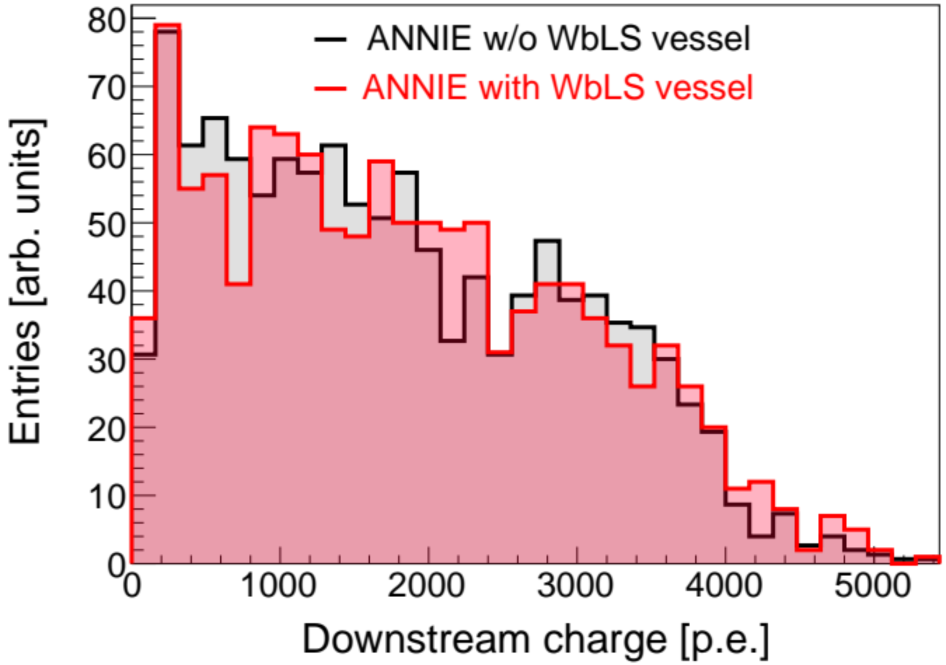




- Upstream with SANDI: Small contribution of reflected Cherenkov + scintillation
- Downstream with SANDI:
  Dominated by direct Cherenkov hits + scintillation.
  Absorption of Cherenkov light due to acrylic vessel and WbLS visible due to broadening of charge distribution.

Neutrino Candidates





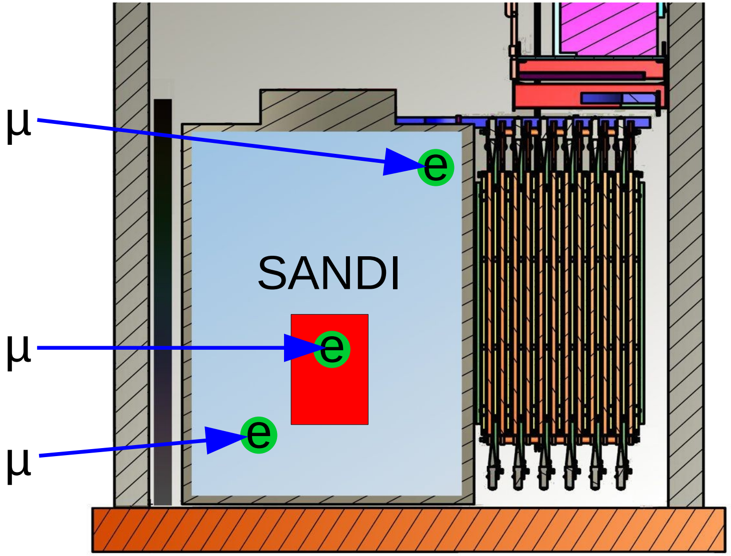
- Upstream with SANDI: Small contribution of reflected Cherenkov + scintillation
  Two event populations visible => Neutrino events with Cherenkov+scintillation!
- Downstream with SANDI:
  Dominated by direct Cherenkov hits + scintillation

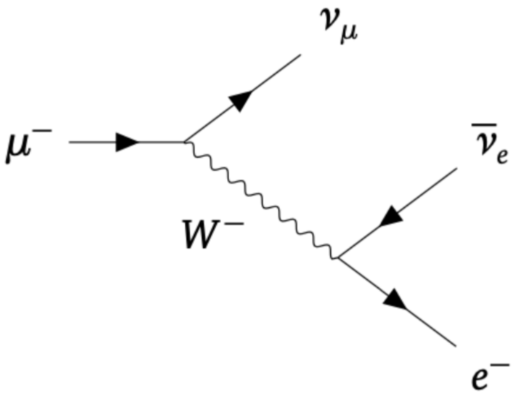
Event Selection: Michel Electrons

FMV signal, no MRD trigger, event coincidence:
Michel electrons

Full MC not ready:
Simple proof-of-principle with selection of different event topologies

c) Michel electrons





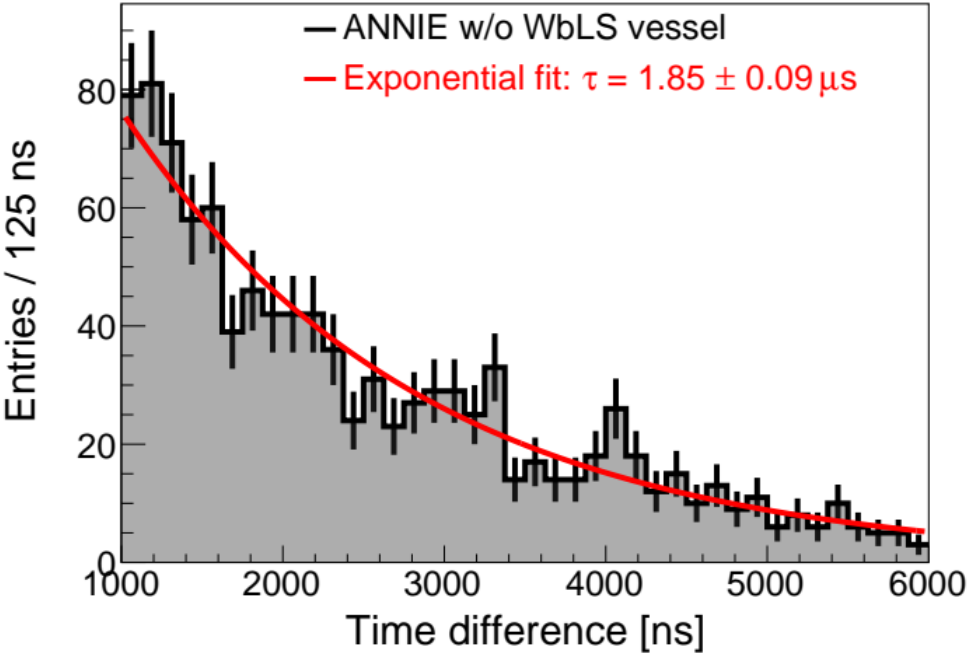
$$N(E) = 3\left(\frac{E}{E_{\max}}\right)^2 - 2\left(\frac{E}{E_{\max}}\right)^3$$

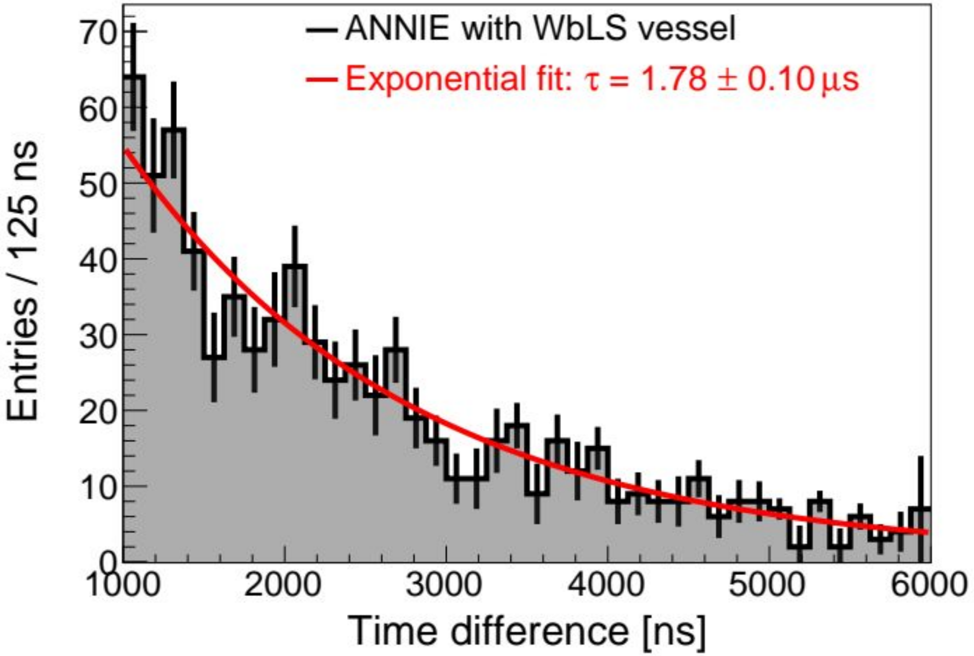
$E_{max} \sim 53$ MeV

Michel electrons have well known energy distribution:
Ideal candidates for scintillator investigation and calibration

Select time coincidence between muon and electron candidates
Muon: FMV signal, no MRD trigger, charge cut [1000, 4000] p.e.
Electron: Event time difference $\Delta t < 6000$ ns

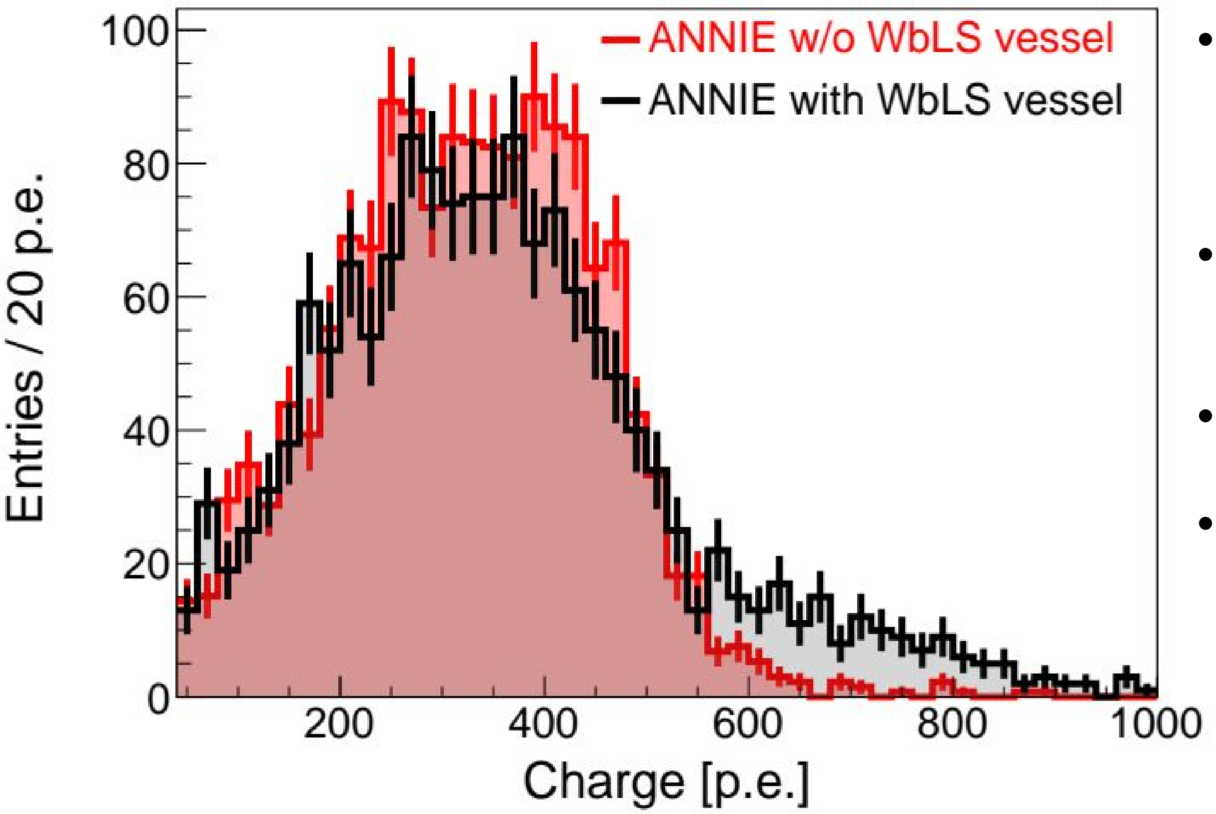
Event Selection: Michel Electrons





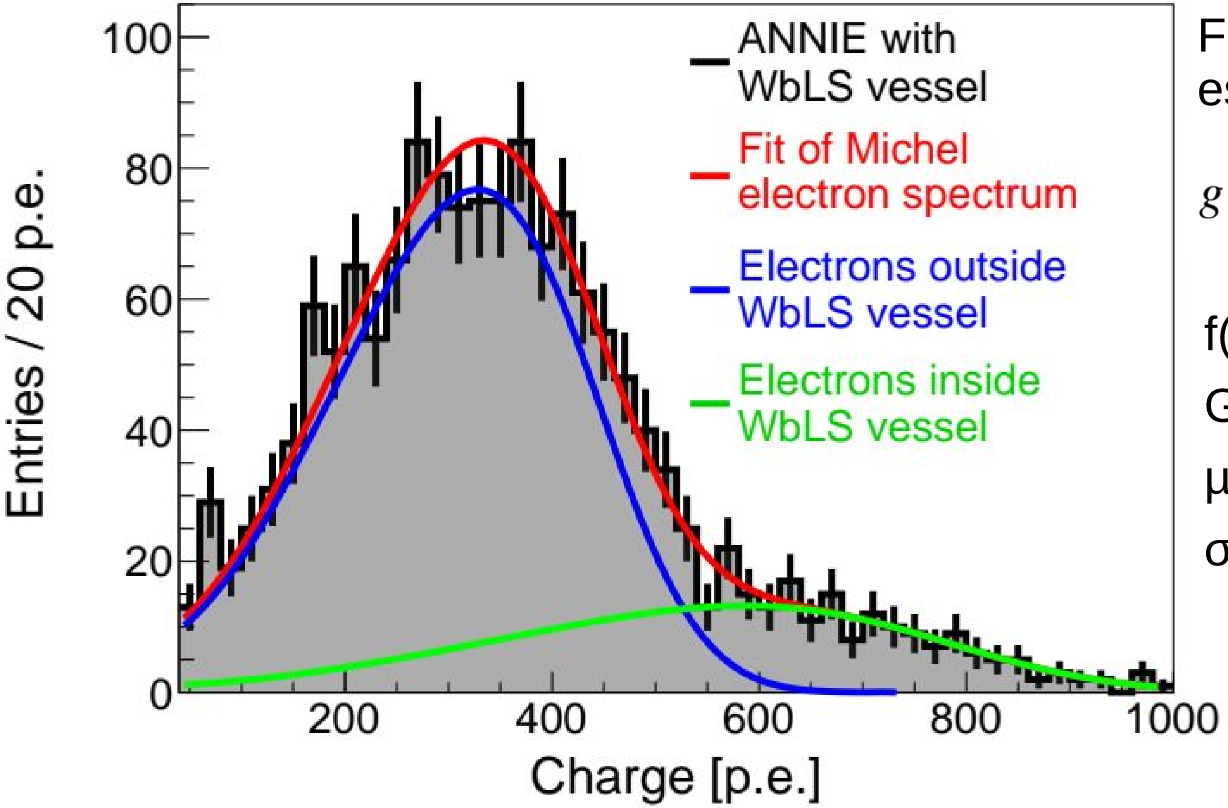
Look at electron candidate Δt distribution for validation of selection
Expected lifetime of muons in water + gadolinium: (1.788 ± 0.002) μs
Selection of electron events looks correct

Michel Electron Charge Spectrum



- Michel electrons have well known energy distribution, smeared by detector response
- Comparison of charge distribution shows existence of scintillation
- Two event populations for SANDI
- Larger relative number of events above ~550 p.e.:
  => Electrons confined within SANDI

Michel Electron Charge Spectrum



Fitting Michel spectrum allows to estimate increase effective light yield:

$$g(Q) = \int_0^{E_m} A \cdot f(E) \cdot G\left(Q, \mu(E), \sigma\right) dE$$

f(e): Michel spectrum

G(Q, μ(E), σ): Gaussian function

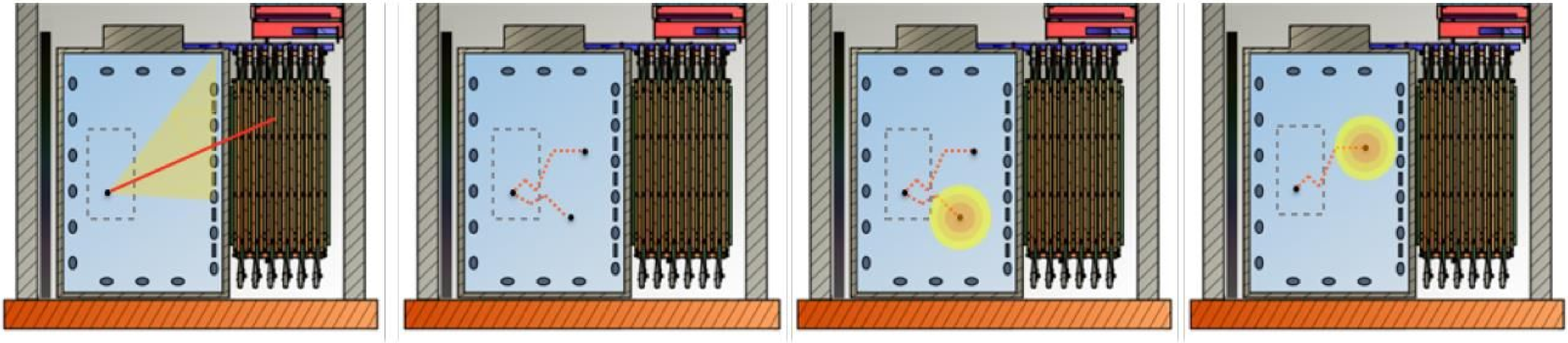
μ(E) = k·E: mean number of p.e. per MeV

σ(E): Detector response, (poissonian) smearing

k_{SANDI} = 14.44 ± 0.87 p.e./MeV, k_{Water} = 8.17 ± 0.14 p.e./MeV => k_{SANDI} / k_{Water} = 1.77 ± 0.08

Effective increase in detected number of photo-electrons is +77% due to scintillation

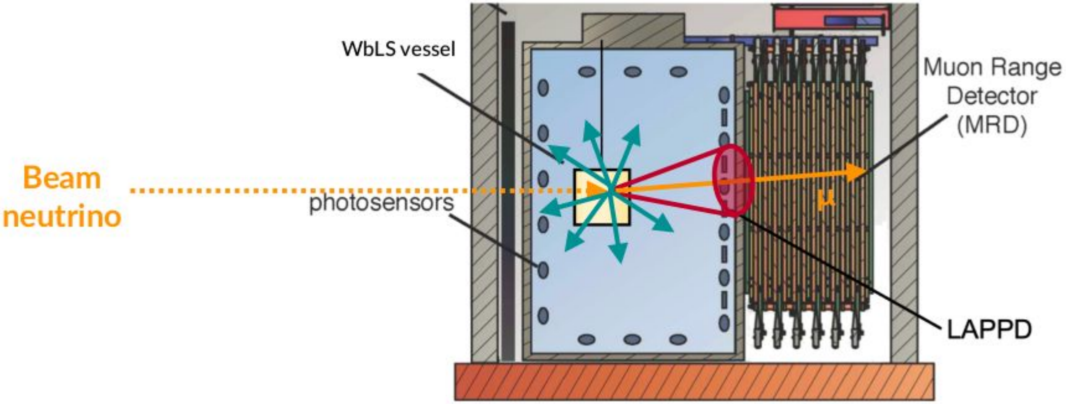
Neutron Detection Principle



- CC interaction in the tank (fiducial volume): Prompt event in 2µs window around beam trigger
- Muon is produced and may be reconstructed (direction, energy)
- Neutrons thermalize in the water volume
- Neutron capture on Gd detected by the PMTs: Second window of 68µs to catch all neutrons
  - Gadolinium has the best neutron capture cross section
  - 50 000 barn, 30µs capture time, compared to 0.3 for protons or ~250µs
  - Gd produces on average 4-5 gammas, 8 MeV total energy (proton: 2.2 MeV)

WbLS Energy Reconstruction

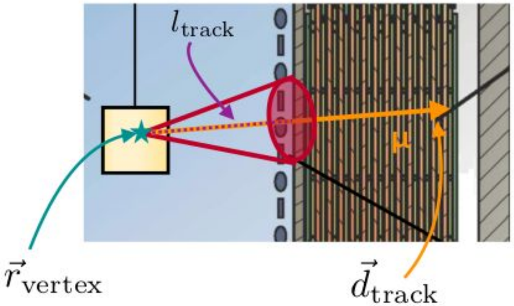
- First MC simulations done by Michael Nieslony
- Neutrino energy reco based on muon track reco.



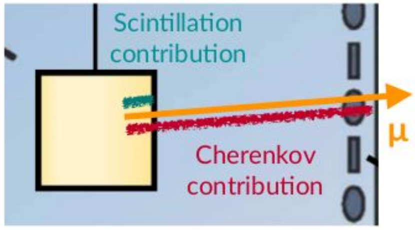
$$E_\nu = E_\nu(\mathrm{CCQE}) + f_{\mathrm{corr}} \cdot Q_{\mathrm{non-muon}}$$

- Preliminary studies seem promising
- Needs more work to actually implement it in the analysis.

I) Reconstruct track (vertex, dir)
(assume a given reconstruction uncertainty for initial study)

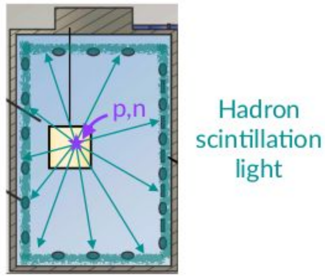


II) Calculate muon signal
based on fitted track parameters



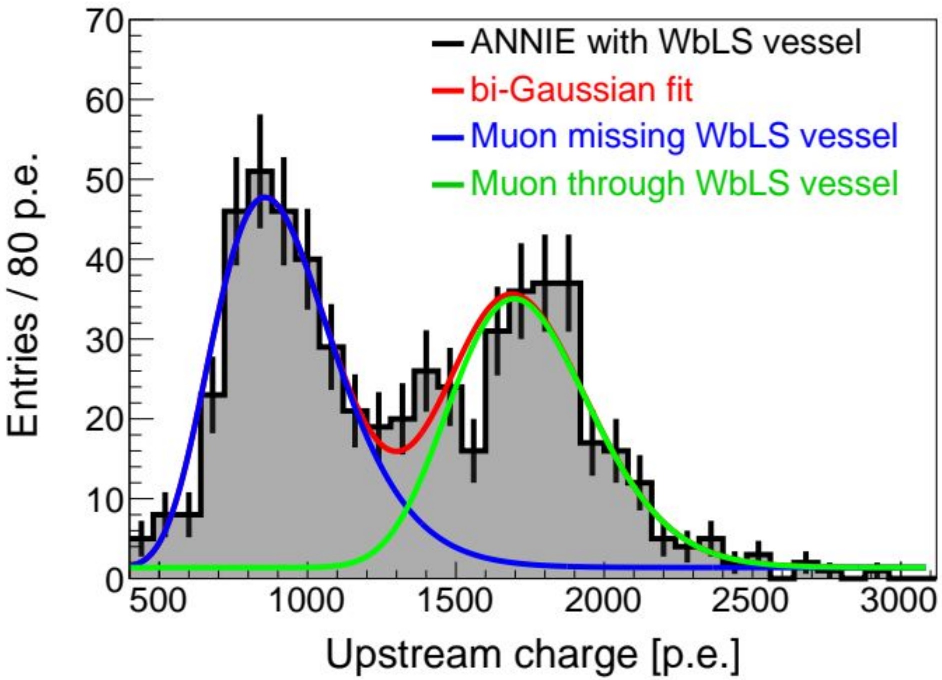
propagate estimated muon light contribution to PMTs & LAPPDs

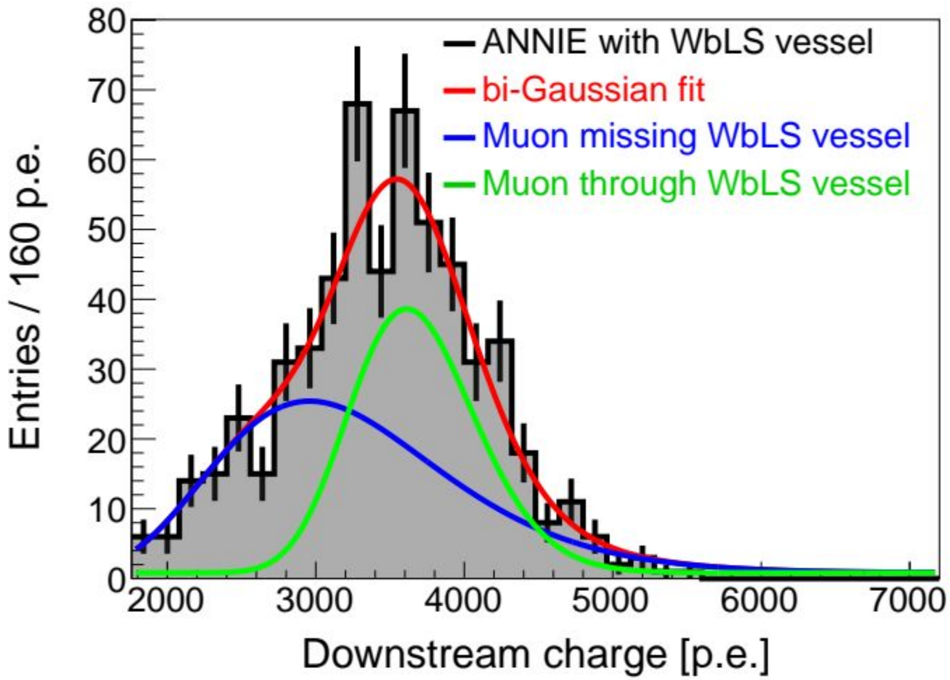
III) Calculate amount of hadron scintillation light



Remaining hits should correspond to hadron scintillation contribution

Throughgoing Muons





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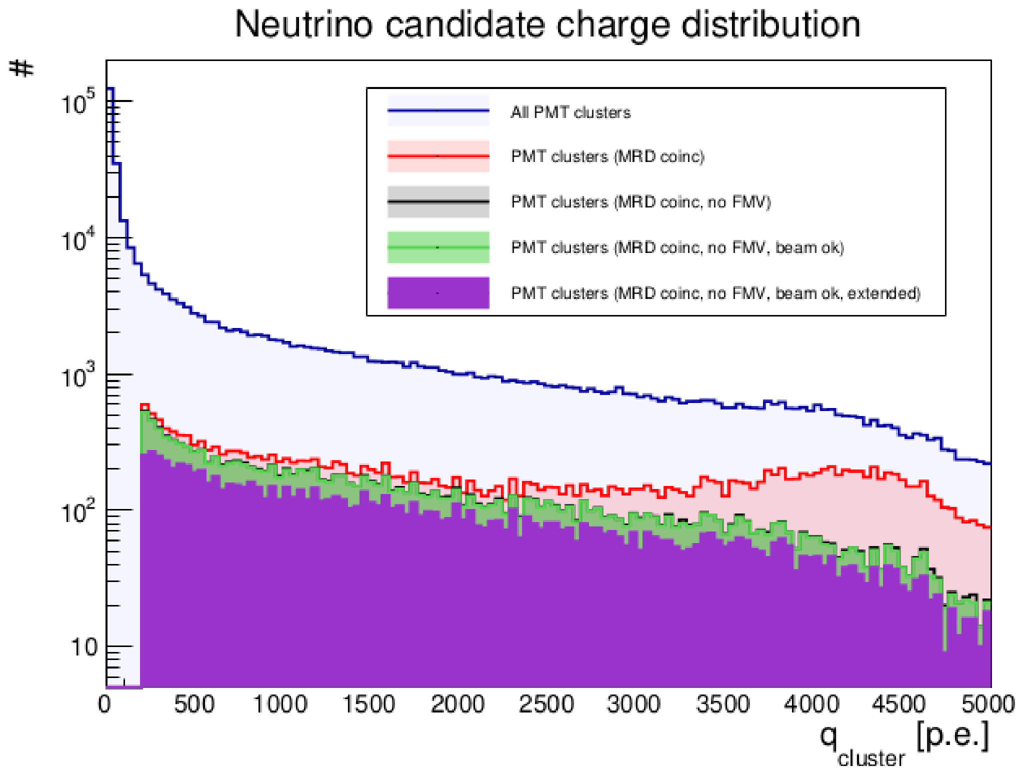
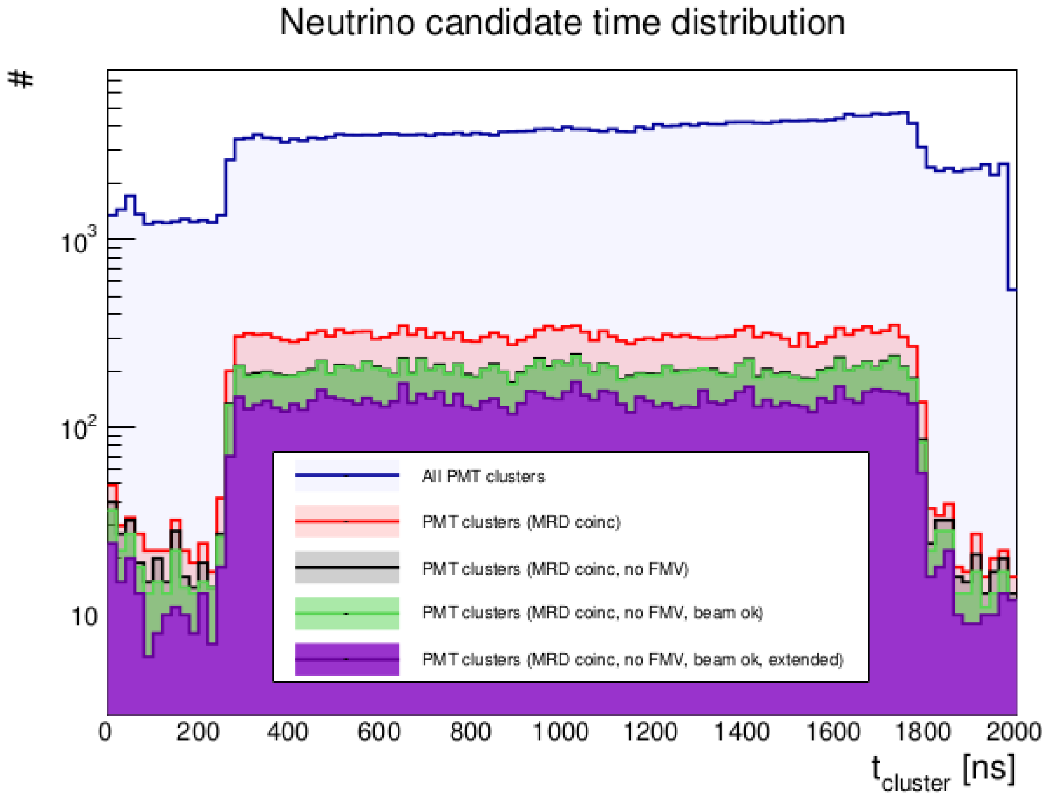
Exemplary Selection Cuts

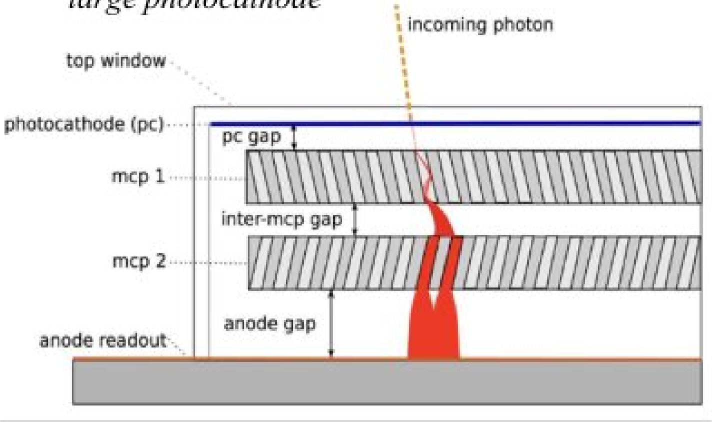




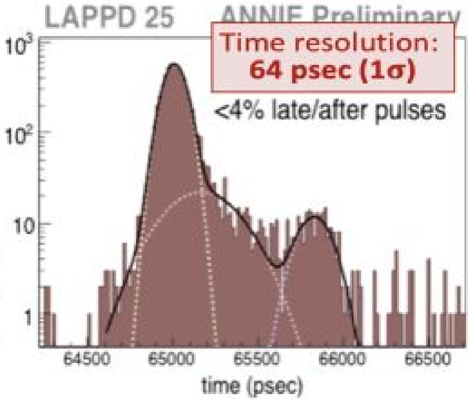
Sub-nanosecond timing with LAPPDs

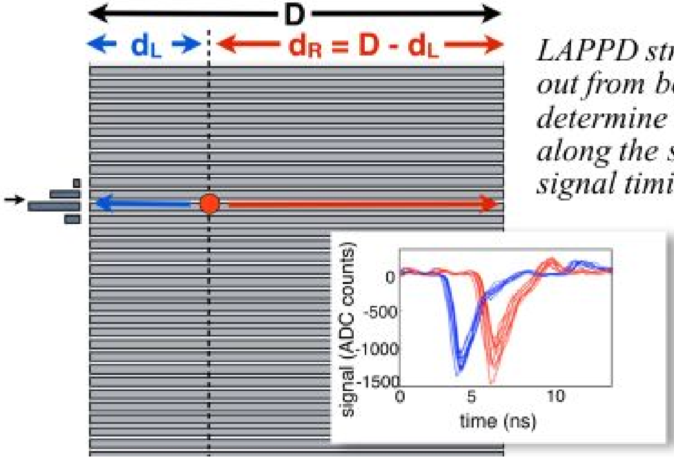
- Electron amplification in flat geometry
  → excellent timing for Cherenkov cone
  → demonstrate enhanced vertex reco
- Incom's Gen-I LAPPDs feature
  - Large detection area (8" x 8")
  - Timing: - in-situ ~ 50ps
    - absolute ~ 100ps
  - Anode structured in strips,
    28 strips with double-sided readout
    → spatial resolution better ~1cm

LAPPDs use two layers of multi-channel plates to enable electron amplification in a very uniform geometry for a large photocathode



LAPPD timing (without electronics effects) can reach down to 50ps.



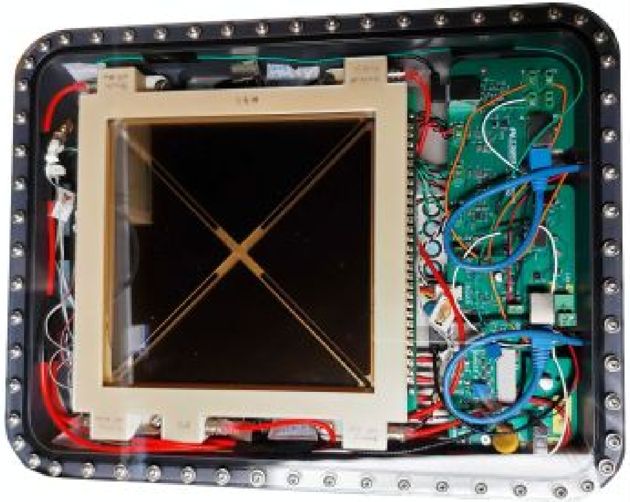


LAPPD strips are read out from both ends to determine hit positions along the strip by relative signal timing.

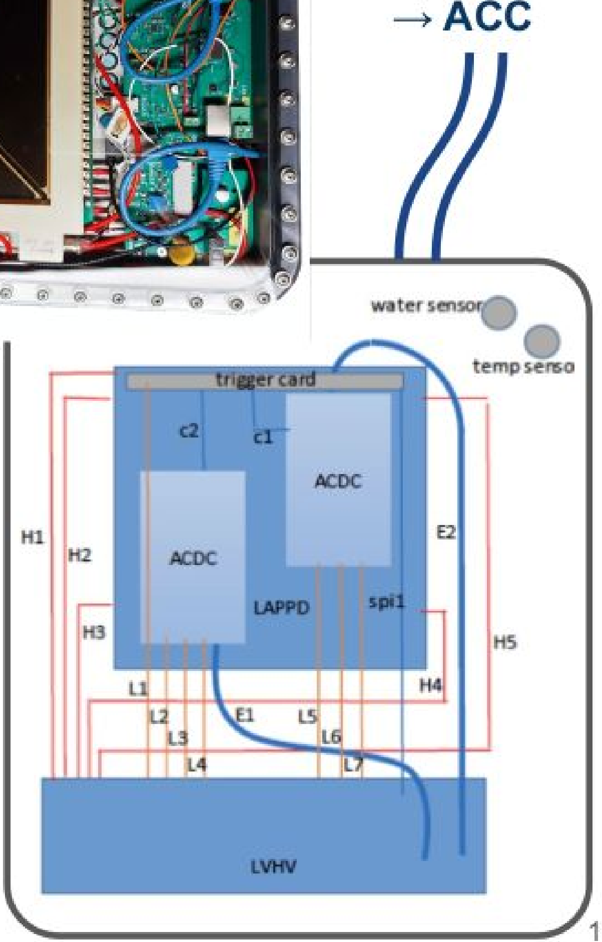
ANNIE LAPPD module

- Overall, 5+1 LAPPDs available
- To maintain sub-nanosec resolution, signals have to be digitized directly at the LAPPDs → underwater electronics
- 28 anode strips are read out at both ends with PSEC4 ADCs
  → sampling rate 10GS/s, 25ns window
  → 2 ACDC cards per LAPPD
- Waterproof housing contains as well HV for LAPPD MCPs and on-board trigger

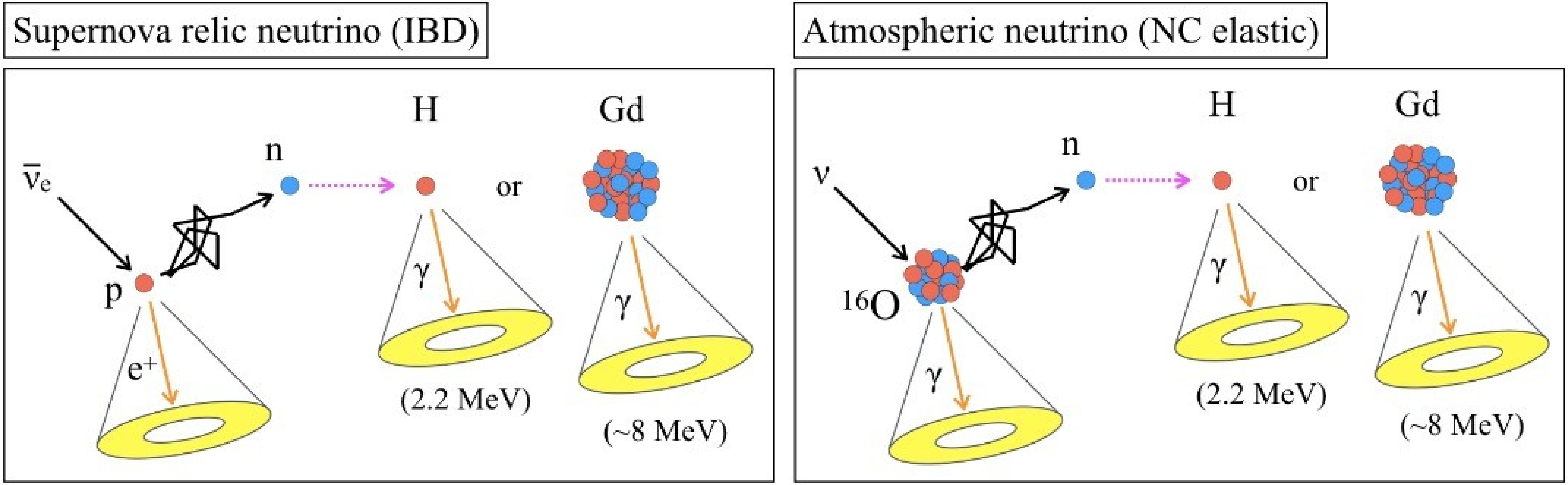
→ successful integration of LAPPDs in a module suitable for neutrino detectors



Water-proof housing contains LAPPD, two digitizer cards (ACDCs), trigger card, low/high-voltage supply (LVHV), environmental sensors

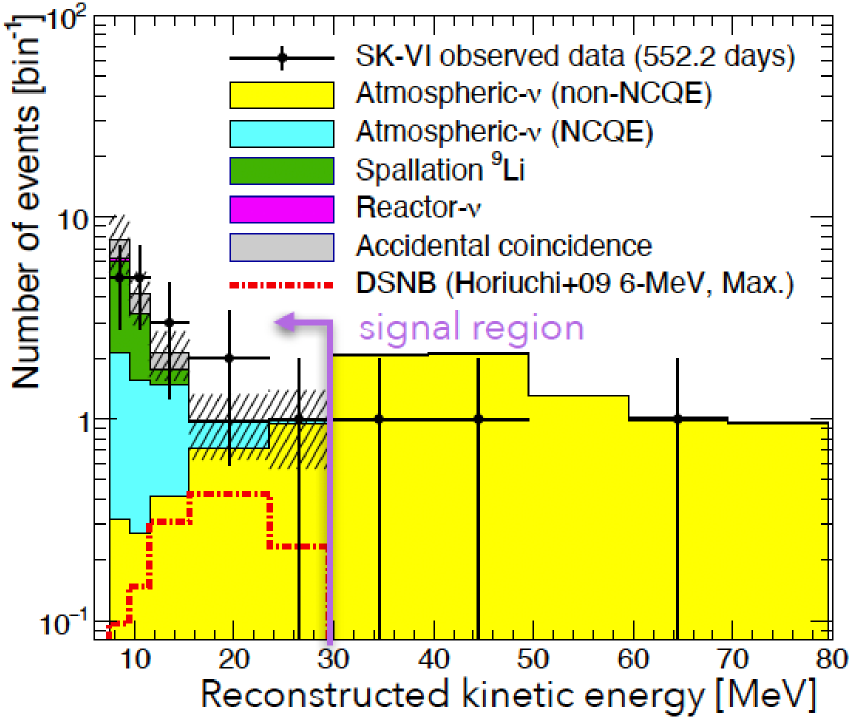


DSNB Primary Background



"Present uncertainty on [νNCQE] interactions induces a large error on atmospheric neutrino backgrounds, limiting the sensitivity at low energies where the [DSNB] flux is predicted to be large." – T2K collaboration

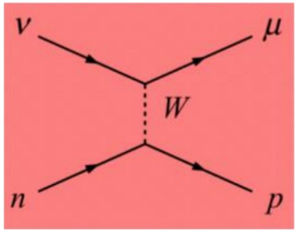
DSNB Primary Background



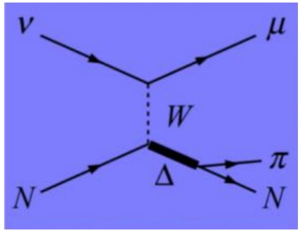
"Present uncertainty on [νNCQE] interactions induces a large error on atmospheric neutrino backgrounds, limiting the sensitivity at low energies where the [DSNB] flux is predicted to be large." – T2K collaboration

GeV-scale CC Neutrino Interactions

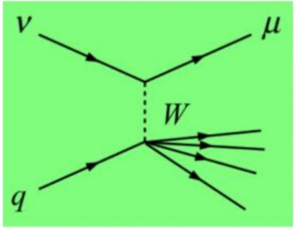
Quasielastic (QE):
Neutron (proton) is converted into a proton (neutron)

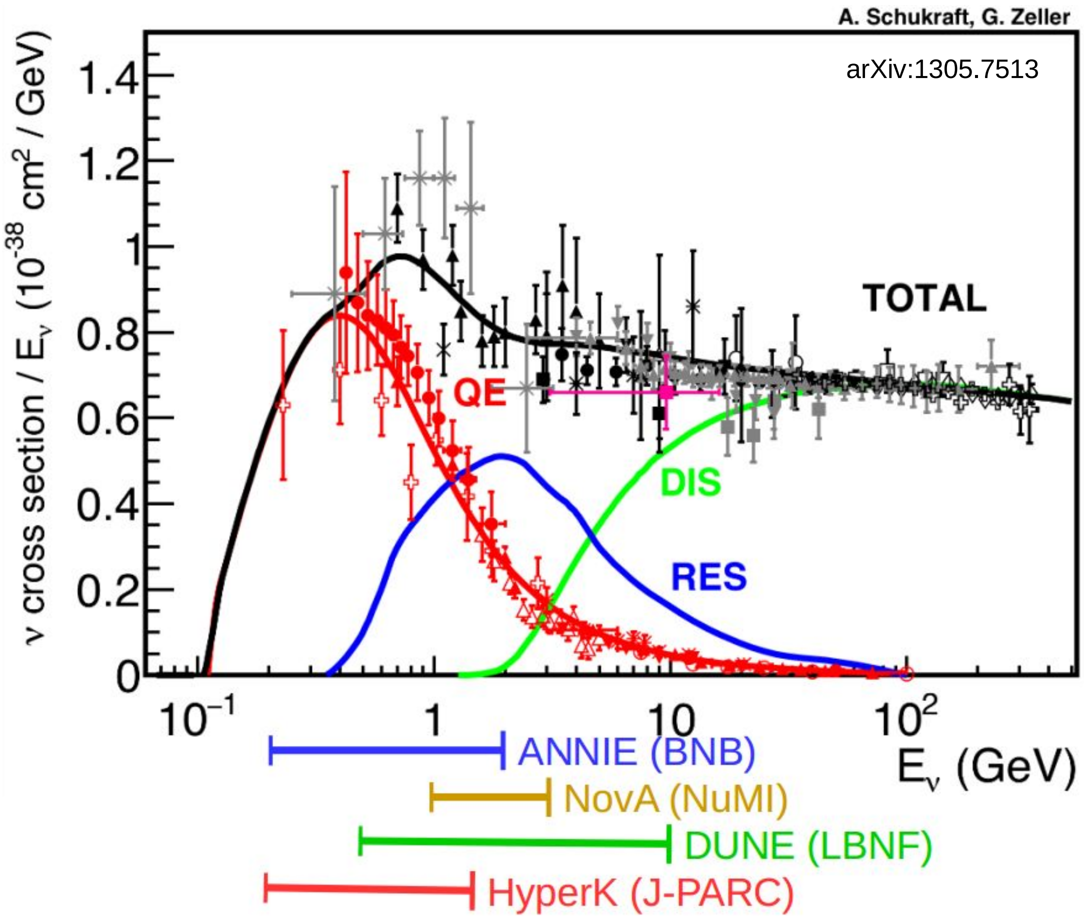


Resonant production (RES):
Δ-resonance decays into pion

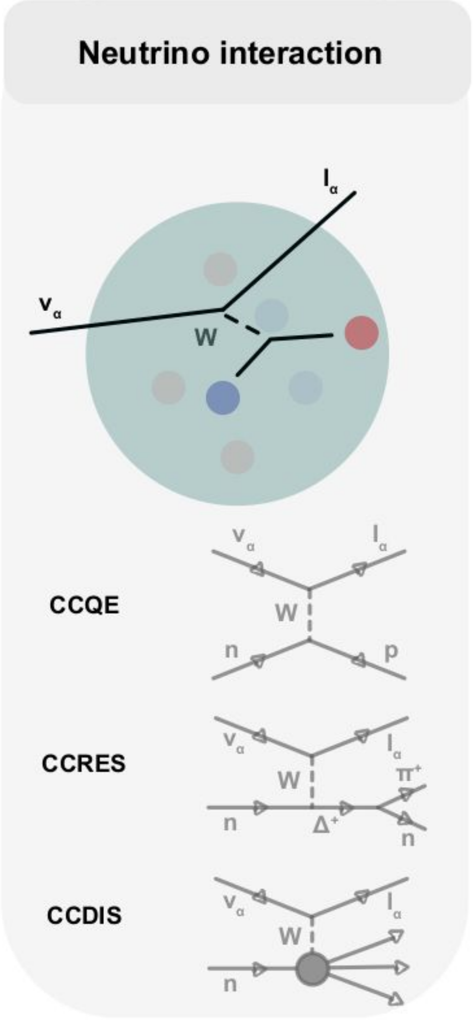


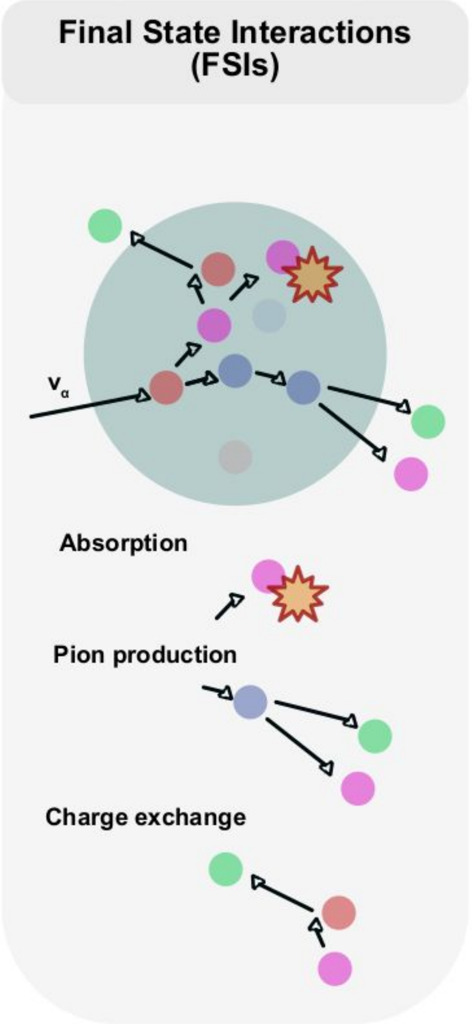
Deep Inelastic Scattering (DIS):
Scattering off individual quarks within the nucleon





GeV-scale CC Neutrino Interactions





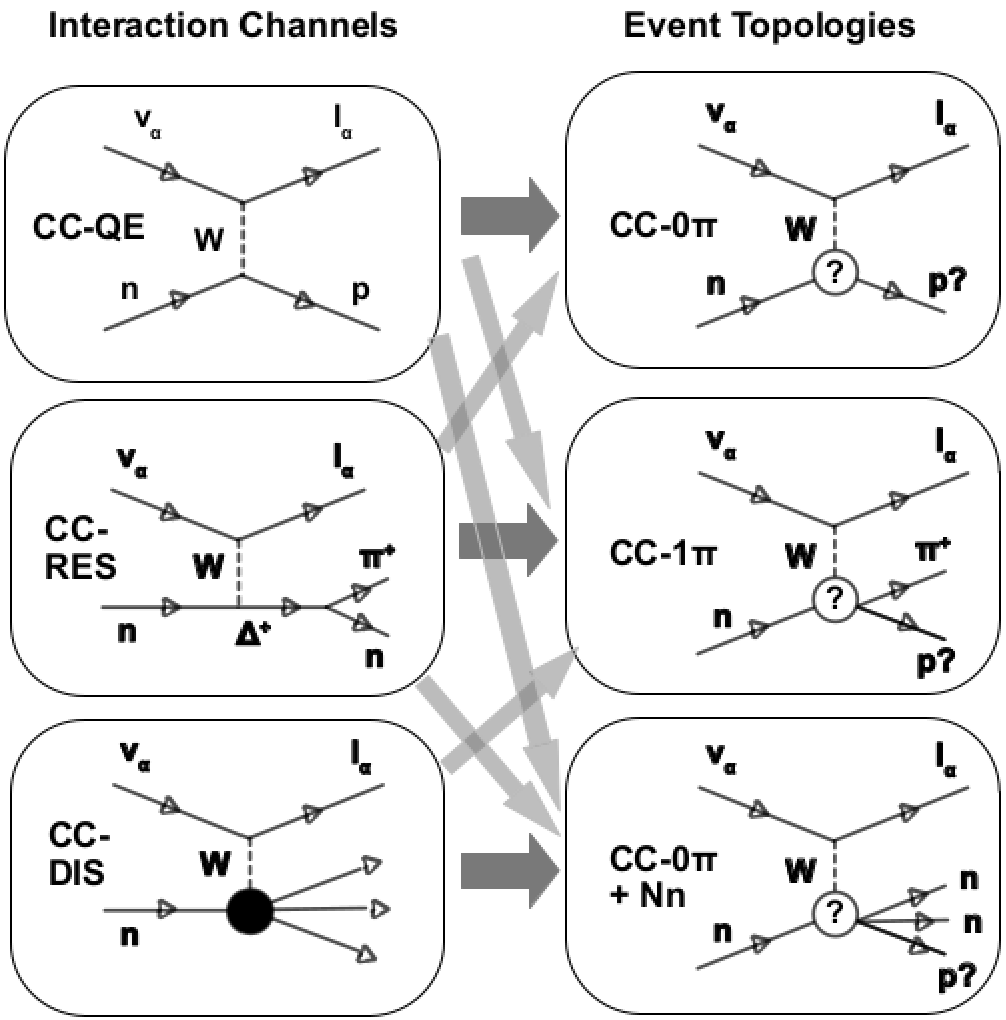
Final State Interactions:

- After neutrino-nucleon interaction hadronic component may undergo further interactions.
- Has significant influence on the set of observed particles

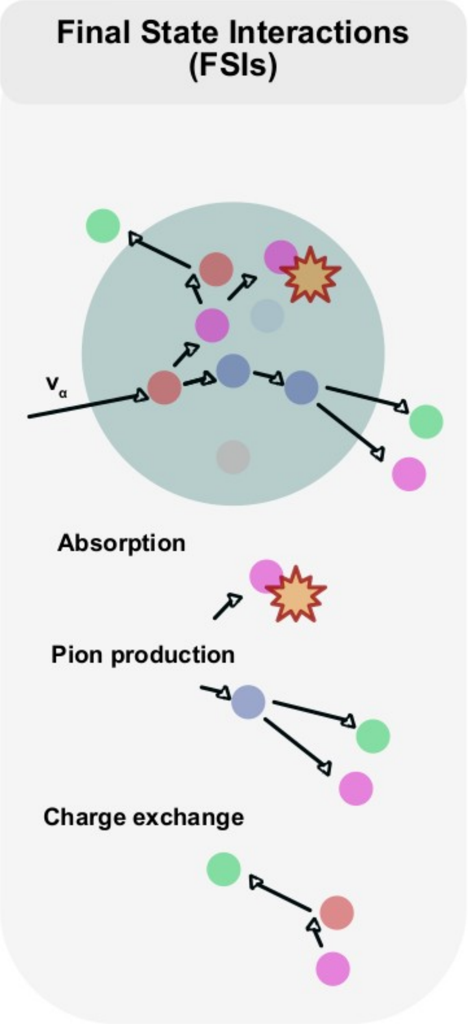
Global neutrino physics:

- Knowledge of neutrino-nucleus scattering cross sections is important
- Experiments must measure neutrino energies precisely
- Number of neutrons produced in neutrino interactions is a powerful discriminator between event topologies

Impact of Neutron Multiplicity

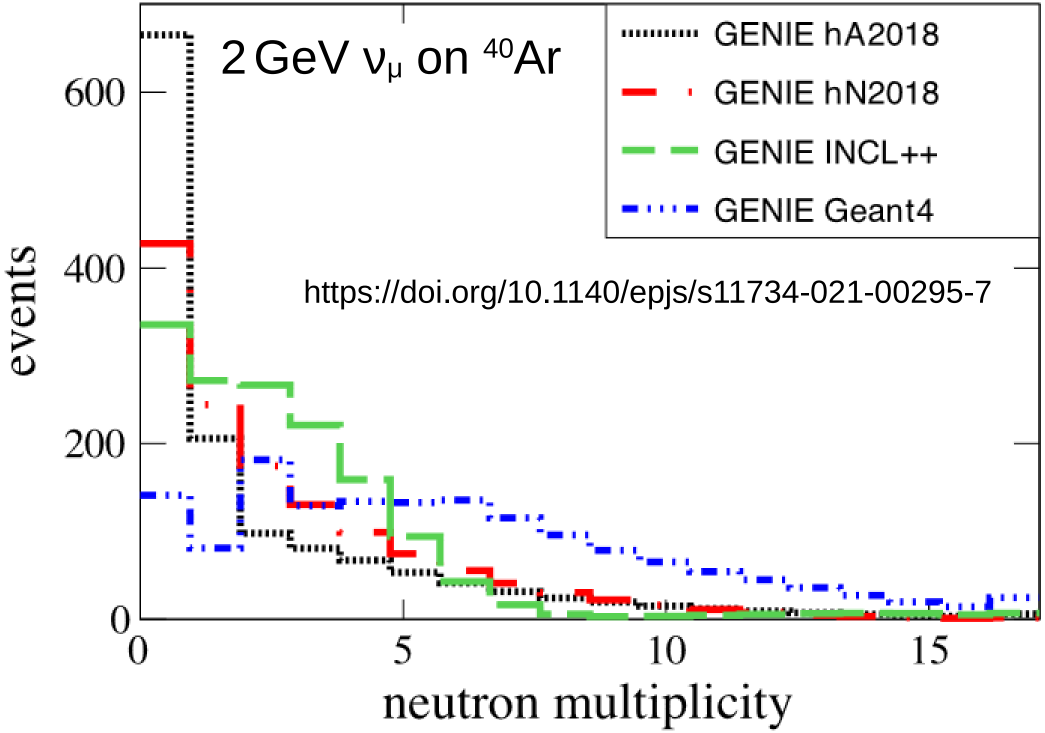


Neutron Multiplicity



- Neutrino Generators important to interpret neutrino data
- Final state interaction (FSI) models important part of the code
- FSI mask evidence of principal neutrino interaction, as hadrons propagate through the residual nucleus

- Simulating nuclear effects is hard => models show significant variations
- ANNIE can improve neutrino generators



https://doi.org/10.1140/epjs/s11734-021-00295-7

Impact of Neutron Multiplicity

- Bias in reconstructed energy affects precise measurement of neutrino oscillation parameters.

- Precise knowledge of neutron multiplicity reduces energy reconstruction uncertainty

=> ANNIE! ANNIE! ANNIE!

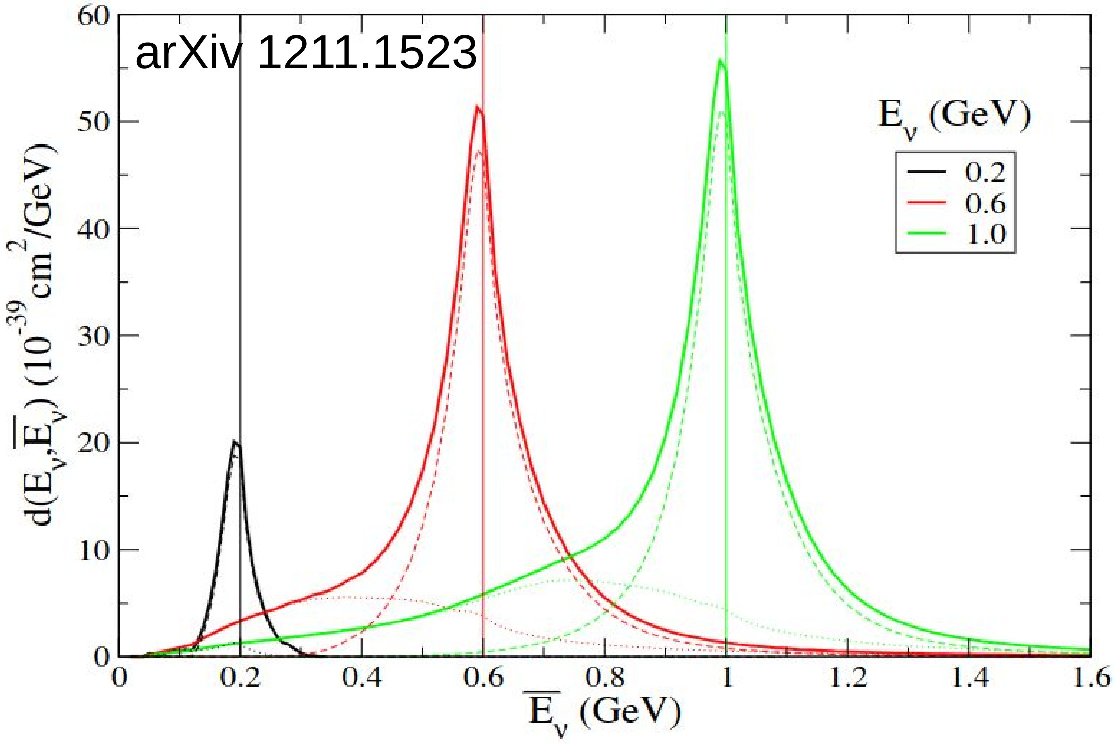


FIG. 1: (Color online) The spreading function $d(E_\nu, \overline{E_\nu})$ of Eq. (4) per neutron of ^{12}C in the case of electrons evaluated for three E_ν values. The genuine quasielastic (dashed lines) and the multinucleon (dotted lines) contributions are also shown separately.

Search for Rare Physics

Some interesting physics signals have 0 or 1 neutrons.

- Potential proton decay channels: $p \rightarrow e^+ + \pi^0$ / $p \rightarrow K^+ + \nu$
- Diffuse Spernova Neutrino Background (DSNB) has large atmospheric neutrino background (Neutral Currents!)
- Current models for the neutron multiplicity in atmospheric background events have large uncertainties.
- Accellerator neutrinos are better understood than atmospheric neutrinos