Benchtop scintillator measurements at Berkeley

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Introduction

Context of these slides is R&D for "large optical neutrino detectors"

- Fully contained events (calorimetry)
- $\sim 4\pi$ holographic coverage (directionality)
- Think SNO/+, Super-/Hyper-K, Borexino, Juno, ...

We all dream of a hybrid detector...

- Distinguish between Cherenkov / scintillation photons to leverage advanced reconstruction to address a variety of physics topics
- Next-gen reconstruction to improve physics reach
- Solars, supernovae, $\bar{\nu}$, δ_{CP}, $0\nu\beta\beta$, ...

This talk: R&D measurements to support getting there

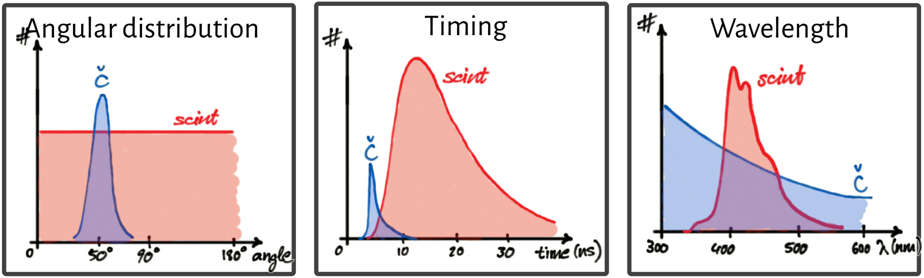
- Mostly WbLS based on LAB + PPO mixtures - plus gadolineum!
- German DIN-infused slow scintillator

R&D for hybrid optical detectors

Remember: we have to reconstruct the neutrino interaction from "hits"

- Energy, position resolution improves with # of hits
- Direction resolution improves with *significance of Cherenkov hits*

Cartoons from Michi Wurm



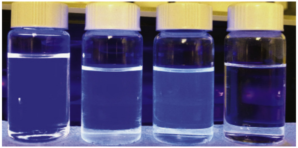
R&D for hybrid optical detectors at Berkeley

Local campaign making use of:

- Modern chemical synthesis techniques
- State-of-the-art photodetectors
- Novel spectral sorting technology

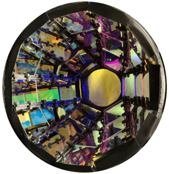
...to characterize and, hopefully, achieve high-purity Cherenkov selection

WbLS



LAPPDs

Dichroicons



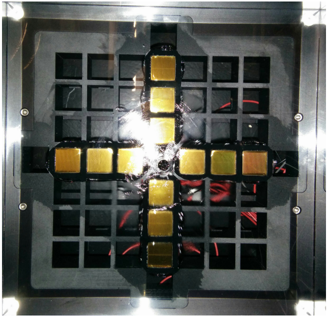
CHESS of yesterday

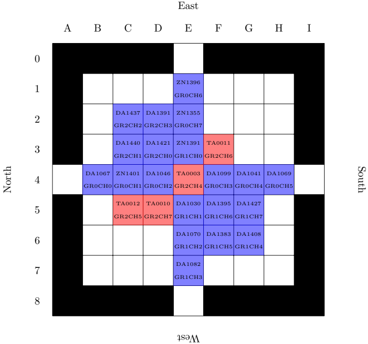
CHESS proper was an apparatus to demonstrate

* **Ch**erenkov and **S**cintillation **S**eparation *

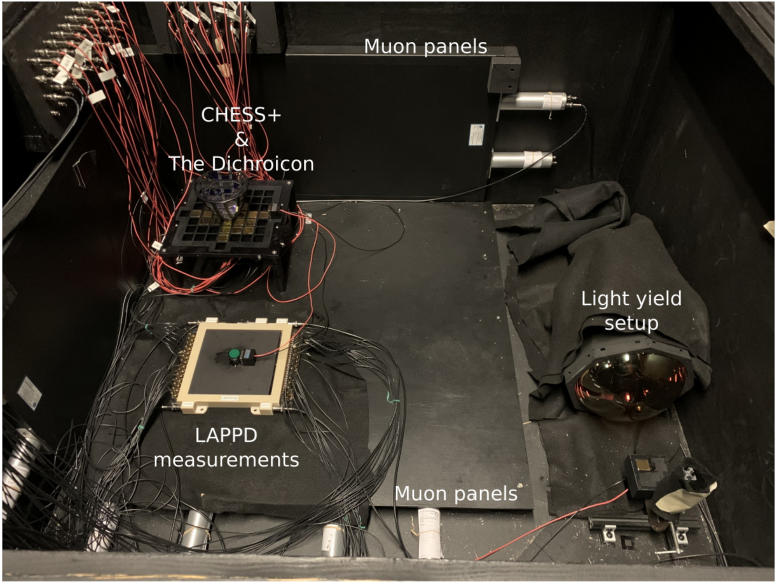
Originally consisted of 12+2 H11934s, 1 R7081, and 6 veto PMTs

- CAEN V1742s, V1730s
- Have since upgraded with additional 12+1 H11934s

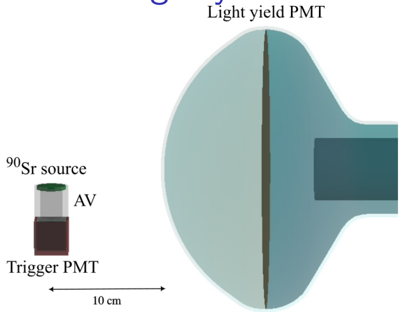


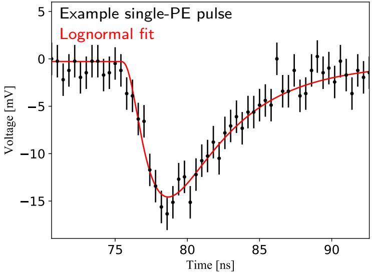


CHESS of today



Scintillator light yields





Birks says mean photon production along a trajectory is $\frac{dN}{dx} = \frac{S}{1+kB\frac{dE}{dx}}$

- For contained events, integrate over E down to 0
- ^{90}Y: β^-; Q-value of 2.3 MeV, ^{210}Po: α, energy of 5.3 MeV

We measure charge collected "$\propto$" # of photons collected

- Need to correct for Q.E. (known), geometric efficiency

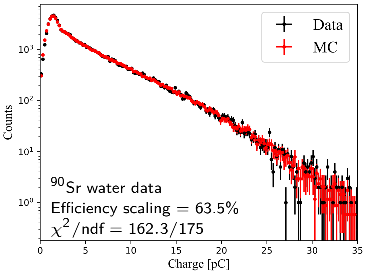
Simulation tuning

Model system using RAT-PAC Monte Carlo

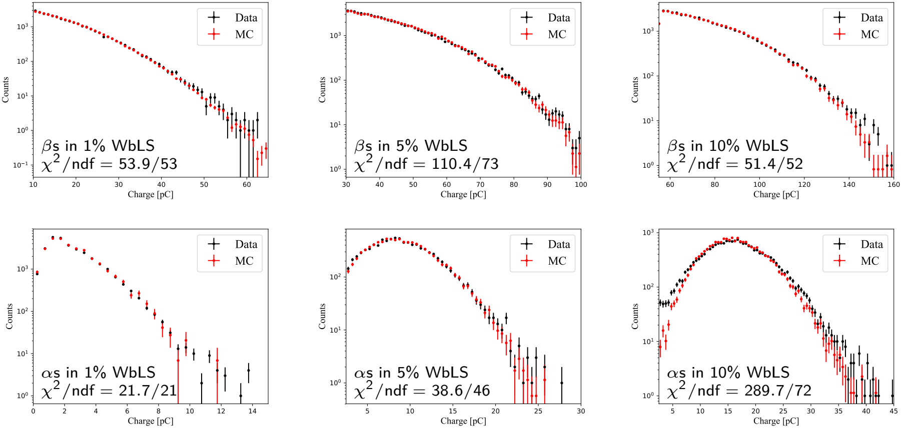
- Prediction of Cherenkov production rates
- Easily include wavelength-dependencies
- To some extent, "edge effects"

Reducing to 1D problems, parameters can be inferred via χ^2 scans

- Water data (βs): efficiency fudge-factor
- With fixed k_B, α/β scintillation efficiency (S)



Best-fit charge spectra

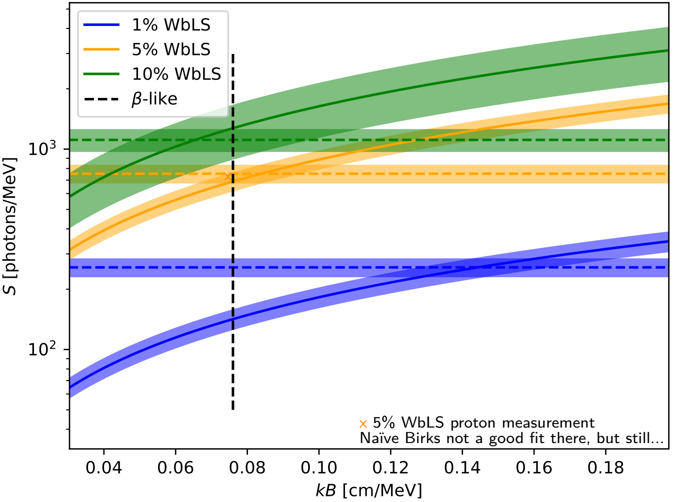


Best-fit model parameters

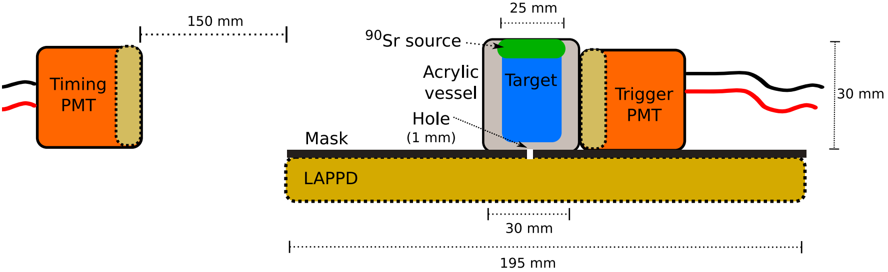
Material	S_β [photons/MeV]	$\langle N \rangle_\alpha$ [photons]
1% WbLS	$257 \pm 4 \pm^{25}_{24}$	$58 \pm 2 \pm 6$
5% WbLS	$754 \pm 10 \pm^{73}_{70}$	$281 \pm 3 \pm 28$
10% WbLS	$1380 \pm 14 \pm^{134}_{128}$	$516 \pm 8 \pm 153$
LAB + 2 g/L PPO	~ 12200	

β results assume same k_B of LAB + 2 g/L PPO

Assessing Birks' quenching



Scintillator time profiles



Birks further says that $\frac{dN}{dt} = \sum_i A_i \frac{e^{-t/\tau_i} - e^{-t/\tau_R}}{\tau_i - \tau_R}$

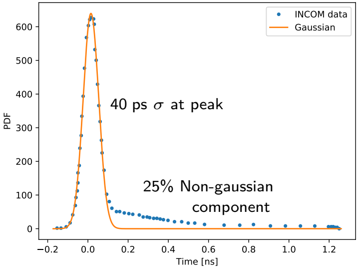
- Time measured since an energy deposition
- Energy transfers non-radiatively from matrix to visible fluor
- Various visible decay modes

From there, can include Cherenkov component and system response

The LAPPD

Large Area Picosecond Photodetectors extend micro-channel plate technology to sensitive areas $> 10\times$

- Timing resolution < 100 ps ("σ")
- $\sim 400\ \text{cm}^2$ sensitive area
- 32% peak quantum efficiency
- Various anode options (pixels, strips, ...)



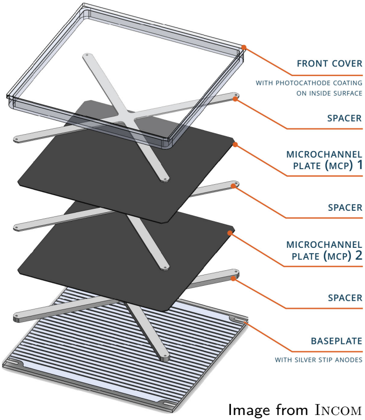


Image from INCOM

Model implementation and analysis strategy - βs

Joint LAPPD-PMT single-PE measurement

- LAPPD demonstrates C/S separation, sensitive to risetime
- PMT constrains long decay times (lower noise rate)

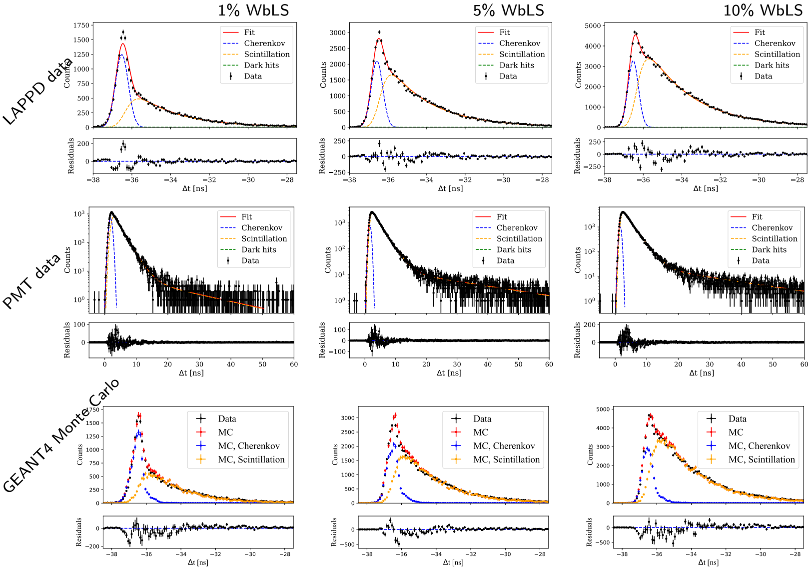
At high trigger occupancy (high charge) system response is approximately Gaussian

- Gaussian approximation allows for analytic model evaluation
- Efficiently fit for underlying time profile parameters

GEANT4-based RAT-PAC simulation improves on modeling of system response

- Improvements in modeling of C/S transition region
- Accurate measurement of Cherenkov purity

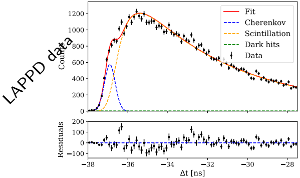
Visual WbLS results - βs



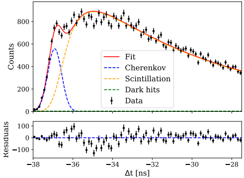
EPJC **82** 169 (2022) `arXiv:2110.13222`

Visual LAB+PPO results - βs

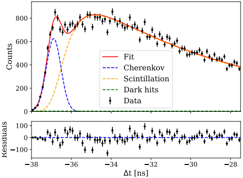
2.0 g/L



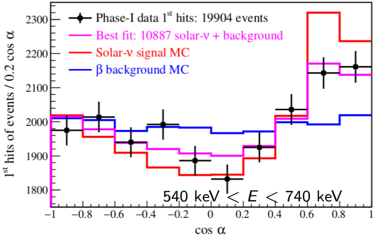
Sampled from SNO+ detector
1.1 g/L



Sampled from SNO+ detector
0.61 g/L

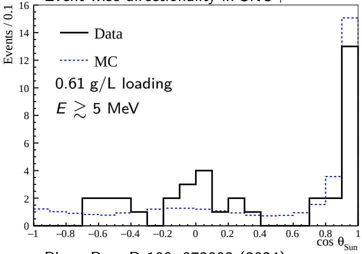


Statistical directionality in Borexino



Phys. Rev. Lett. 128, 0981803 (2022).

Event-wise directionality in SNO+



Phys. Rev. D 109, 072002 (2024).

Quantitative results - βs

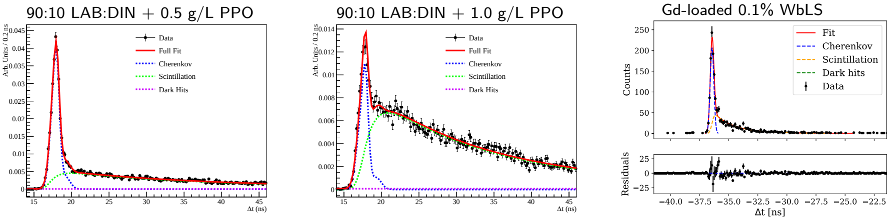
$$S(t) = \sum_{i=0}^{n} A_i \left(\frac{e^{-t/\tau_i} - e^{-t/\tau_R}}{\tau_i - \tau_R} \right)$$

$$F(t) = (1 - f_D)\, G(t - t_0; \sigma) \otimes (f_C \delta(t) + (1 - f_C)\, S(t)) + \frac{f_D}{T}$$

Increasing scintillator fraction $\rightarrow$

	1% WbLS	5% WbLS	10% WbLS	2 g/L LS
τ_R [ps]	270^{+26}_{-20}	209^{+10}_{-11}	276^{+7}_{-7}	594^{+22}_{-15}
τ_1 [ns]	$2.22^{+0.02}_{-0.02}$	$2.25^{+0.01}_{-0.01}$	$2.36^{+0.01}_{-0.01}$	$4.64^{+0.06}_{-0.06}$
τ_2 [ns]	$17.7^{+1.3}_{-1.1}$	$23.5^{+1.0}_{-0.9}$	$22.8^{+0.7}_{-0.7}$	$18.1^{+0.6}_{-0.6}$
A_1 [%]	$95.6^{+0.3}_{-0.3}$	$94.8^{+0.1}_{-0.1}$	$94.9^{+0.1}_{-0.1}$	$78.9^{+0.8}_{-0.9}$
χ^2/ndf	2967.6/2388	3031.1/2388	3373.2/2388	2706.0/2388
Purity in MC [%]	80.4	68.6	64.3	-

Bonus samples



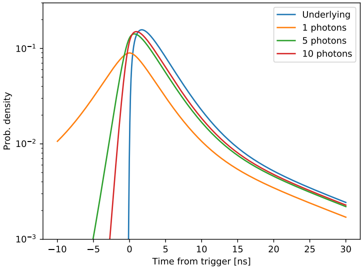
	Slower German	Slow German	0.1% GdWbLS
Light yield [ph./MeV]	6679 ± 268	9345 ± 375	$\lesssim 100$
τ_R [ps]	140 ± 40	120 ± 43	0.5 ± 19
τ_1 [ns]	11.7 ± 3.2	13.0 ± 3.4	1.74 ± 0.03
τ_2 [ns]	29.1 ± 3.5	26.3 ± 4.6	11.1 ± 0.8
A_1 [%]	21.0 ± 6	44.0 ± 7	91.6 ± 1.6
χ^2/ndf			2618.3/2388
Purity in MC [%]	90.1	80.3	-

Model implementation and analysis strategy - αs

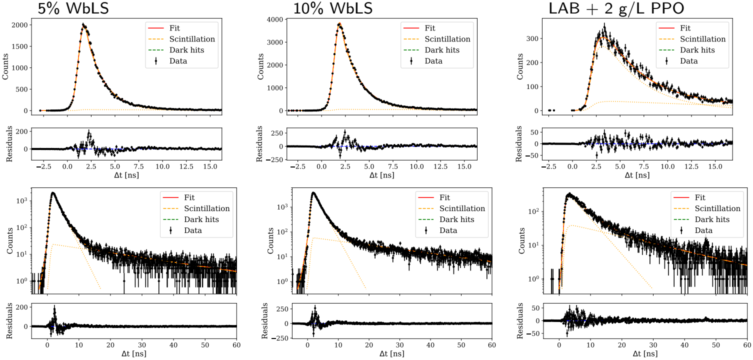
PMT-only measurement

Trigger occupancy is naturally low

- Explicitly model compound asymmetric system response
- Too many details, ask if interested



Results - αs



	5% WbLS	10% WbLS	LAB + 2 g/L PPO
τ_R [ps]	169^{+15}_{-15}	129^{+13}_{-13}	709^{+49}_{-49}
τ_1 [ns]	$1.82^{+0.01}_{-0.01}$	$1.92^{+0.01}_{-0.01}$	$4.13^{+0.13}_{-0.13}$
τ_2 [ns]	$24.7^{+0.8}_{-0.8}$	$26.1^{+0.5}_{-0.5}$	$20.3^{+0.8}_{-0.8}$
A_1 [%]	$89.7^{+0.2}_{-0.2}$	$86.6^{+0.1}_{-0.1}$	$64.7^{+1.3}_{-1.3}$
χ^2/ndf	1430 / 1194	1685 / 1194	1316 / 1194

α/β discrimination

Given two different time profiles for αs and βs, we define the likelihood-ratio

$$F(t) = \log\left(P_\alpha(t) / P_\beta(t)\right)$$

and for a finite # (n) of hits at times $\{t_i\}$ compute a normalized "test-statistic," "classifier value," or "PID value"

$$Q_n(\{t_i\}) = \frac{1}{n}\sum_i F(t_i)$$

This is the average of an r.v., and so asymptotically Gaussian

α/β discrimination - benchmark detectors

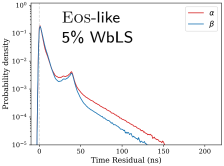
Size matters: wavelength-dependent attenuation and dispersion distort the observed time profile in a real detector

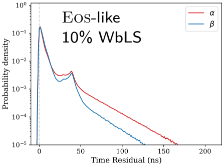
Quantify PID performance for central events in three simulated detectors

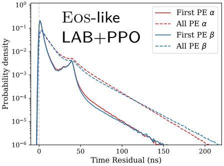
- Right-cylindrical geometry
- Generally Hamamatsu R14688-100-like PMTs
- Match photoproduction: ^{210}Po vs 400-500 keV βs

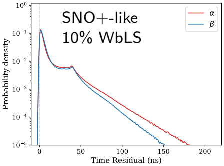
	Dimension [m]	H_2O-equiv. mass [t]	Photocoverage [%]
Eos-like		4	40
SNO+-like	5.4	10^3	54
Theia-like	25.2	10^5	85

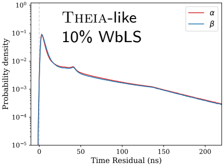
α/β discrimination - benchmark time profiles



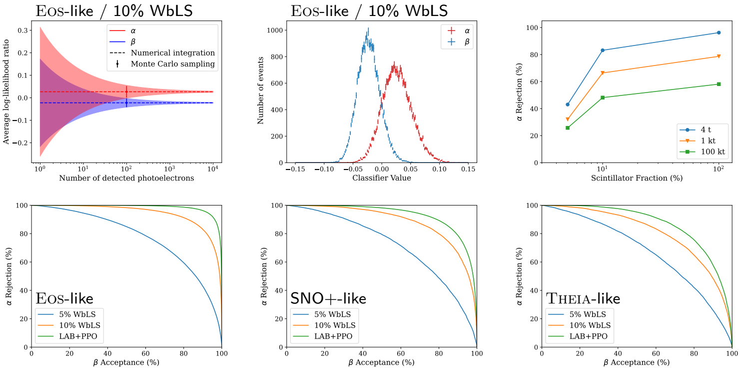








α/β discrimination - performance



Summary

Resources at Berkeley for scintillator characterization

- Simulation-free / -backed light yield and timing measurements

Part of a wider campaign

- Dichroicon deployments
- Proton light yield measurements (collabs. w. 88-Inch, Mainz)

General takeaways:

- LAPPDs work, but: we had high noise and 2 cathode failures
- In favorable scenarios, can see Cher. light in plain LAB+PPO
- WbLS is fast, but fast photodetectors can still distinguish Cher.
- W.r.t. PID, dominant factor is occupancy

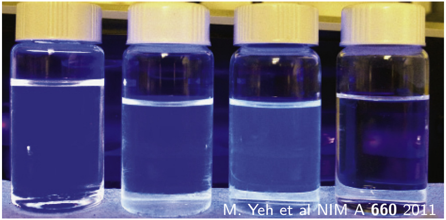
Water-based liquid scintillator

Hybrid reconstruction has been utilized by e.g. LSND and MiniBooNE
But energy range was much higher (more favorable C/S ratio), and there are hurdles to scalability:

- Scintillator is relatively costly
- Optical effects play a larger role

To go larger, go WbLS: start with water, mix in scintillator as needed

- But need to know optical properties, timing, light yield...



M. Yeh et al NIM A **660** 2011

5% WbLS in 2019

Proton light yield measurement - Motivation

Variety of motivations

- Background rejection for inverse beta decay (IBD)
- Probe quenching mechanisms
- Supernova studies via νp-scattering

Focus is fast neutrons: in LS, can see n-p scatter(s) before capturing

- Background to IBD
- Typically below Cherenkov threshold

Proton light yield measurement - Methodology

"Double time-of-flight" method: Pulsed deuteron beam on Be target + PID-capable secondary detectors
Collaboration with Bay Area Neutron Group (BANG — UCB/LBNL)

- Brown et al, Jour. Appl. Phys. 124, 045101 (2018)

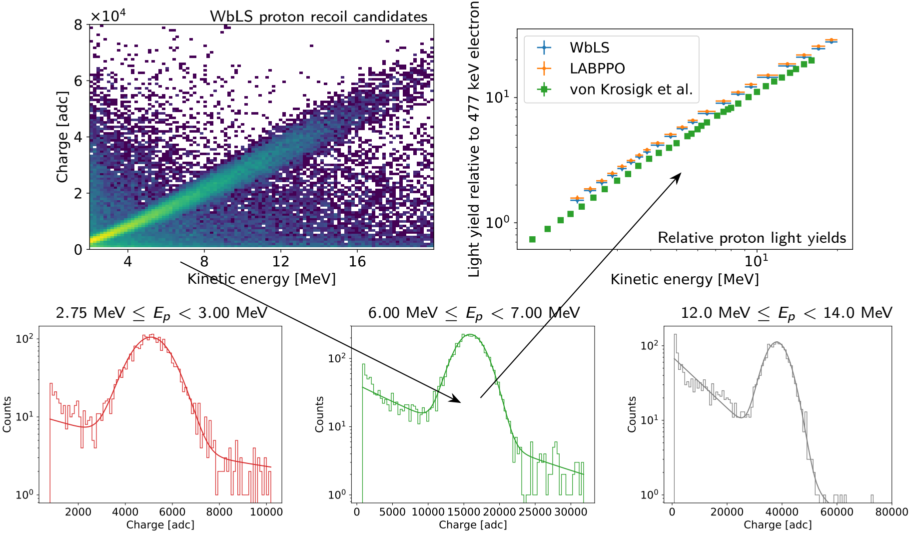
Protons excited via n-p elastic scattering internal to measurement sample
Two kinematic measures of neutron energy (before/after scattering)

- Three measures of proton energy (under single-scatter hypothesis)
- Enforce consistency with beam-neutron hypothesis

Charge collected in photomultiplier tube (PMT) used as proxy for light
Measure two samples: 5% WbLS and LAB + 2 g/L PPO (from Yeh et al, BNL)

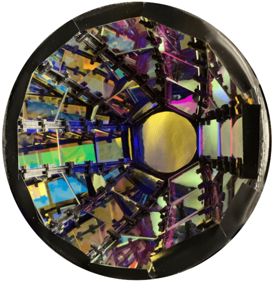
- Existing LABPPO measurement: von Krosig et al, EPJC **73**, 2390 (2013)

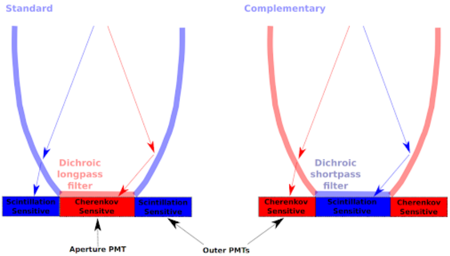
Proton light yield measurements - Results



The Dichroicon

A different approach (from UPenn):
Instead of using timing information to change the C/S proportions, use dichroic filters to manually affect cuts on wavelength



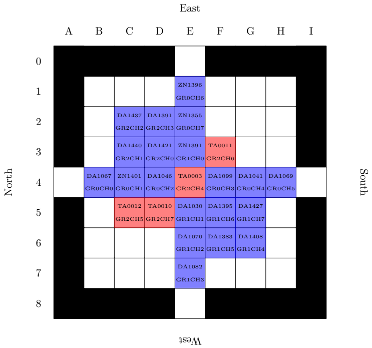


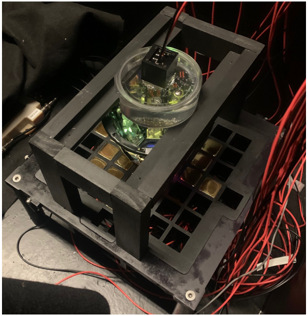
Kaptanoglu et al. Phys. Rev. D **101** 072002 (2020)

Dichroicons in CHESS

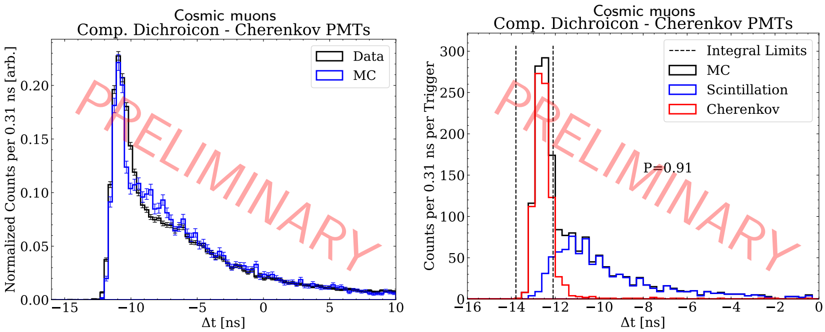
Upgrade CHESS array with 8 additional “blue-sensitive” PMTs, and 4 “red-sensitive” PMTs

Use α, β, γ sources, as well as cosmic muons, to demonstrate different C/S proportions with different filter choices





Dichroicons in CHESS



Figures courtesy of S. Naugle