EPS-HEP 2021

The ESS Neutrino Super-Beam Near Detector

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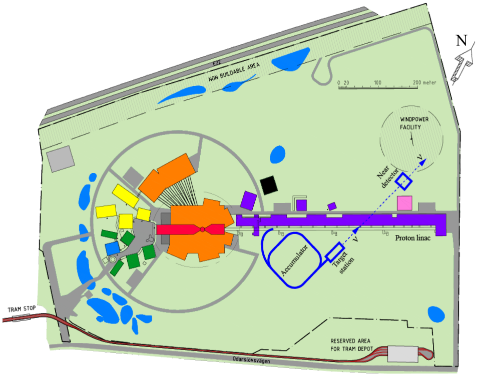
ESS NEUTRINO SUPER BEAM

ESSnuSB

The ESS Neutrino Super-Beam

Objective

- ▷ Measure leptonic δ_{CP} at 2^{nd} oscillation max.



Producing the neutrino beam

- ↪ ESS linac upgrade for dedicated p-beam
  - ▷ 5 MW, 2.5 GeV E_{kin}, 14 Hz repetition
- ↪ Compress pulses to 1.1 μs
- ↪ Produce $\pi^{\pm}$ with p-beam on four Ti-targets
  - ▷ Sign-select with magnetic focusing horn
- ↪ Produce ν-beam in 50 m decay tunnel
- ↪ Unoscillated beam at near detector ($\sim$ 250 m)
- ↪ Oscillated beam at far detector (360 km or 540 km)

The Collaboration

$\sim$ 50 active researchers

$>$ 10 countries

ESSnuSB Near Detector

Near Detector

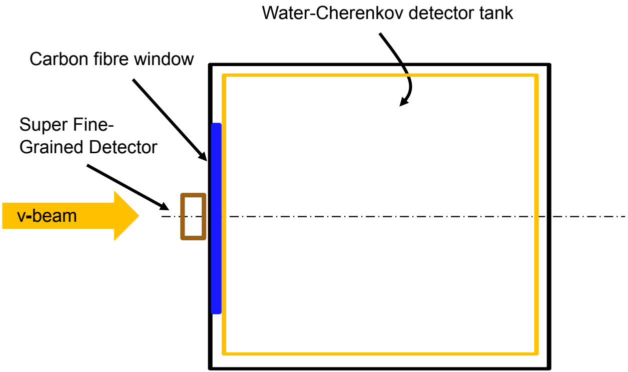
SFGD

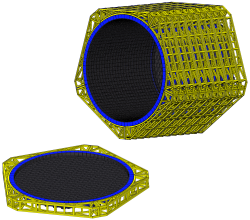
- $1.4 \times 1.4 \times 0.5\,\mathrm{m}^3$
- $\sim 10^6$ plastic scintillator cubes
  - $1 \times 1 \times 1\,\mathrm{cm}^3$

Similar to Hyper-K SuperFGD

WC

- 11 m length
- 4.7 m radius
- 30 % PMT coverage
- 3.5 inch PMTs





Two-fold objective:

- Measure ν_μ-flux: $\sim 10^7$ events per run-year (200 d, 2.16×10^{23} p.o.t.)
- Measure $\sigma_{\nu_e N}$: ν_e-fraction $< 0.5\,\%$
  - → requires selection scheme

Electron-Neutrino Event Selection

1. Separating $e^{\pm}$ from $\mu^{\pm}$
2. Separating ν_e from ν_μ

Separating $e^{\pm}$ from $\mu^{\pm}$

1. Simulate charged lepton samples in detector tank with **WCSim***
   - isotropic, homogeneous, uniform over $E_{kin} < 1\,\text{GeV}$
2. Reconstruct using **fiTQun***
3. Develop selection criteria to address charged-lepton identification

Sub-Cherenkov cut
Reject muons below Cherenkov threshold posing as electrons

Vertex-reco. discrepancy cut
Reject events with a large difference in vertex pos. & dir. between e and μ reco.

Reco. quality cut
Reject low-brightness and close-to-wall events for reco. quality

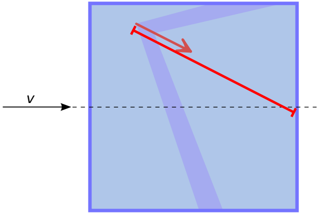
Cherenkov-ring resolution cut
Reject events too close to tank wall in propagation direction

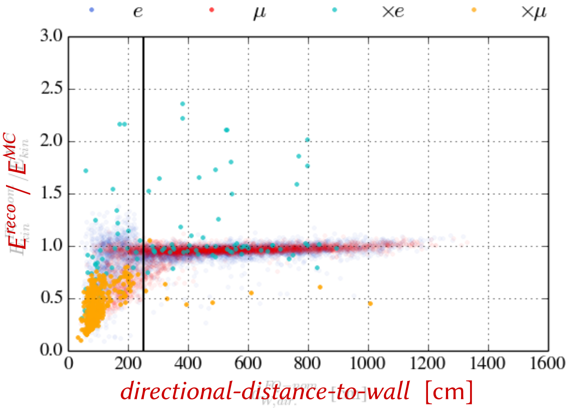
* Thank you to Hyper-Kamiokande members:
Cristovao Vilela, *Erin O'Sullivan*, *Hirohisa Tanaka*, *Benjamin Quilain*, *Michael Wilking*

Separating $e^{\pm}$ from $\mu^{\pm}$

Cherenkov-ring resolution cut

Reject events too close to tank wall in propagation direction

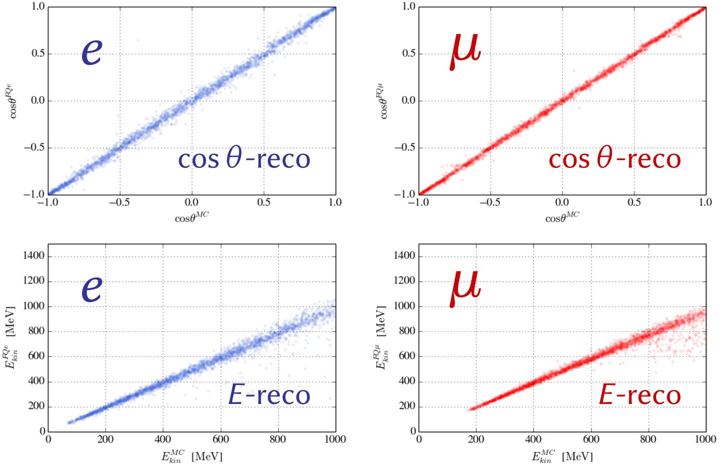




Separating $e^{\pm}$ from $\mu^{\pm}$

Selection acceptance

e	46.3 %
μ	43.3 %



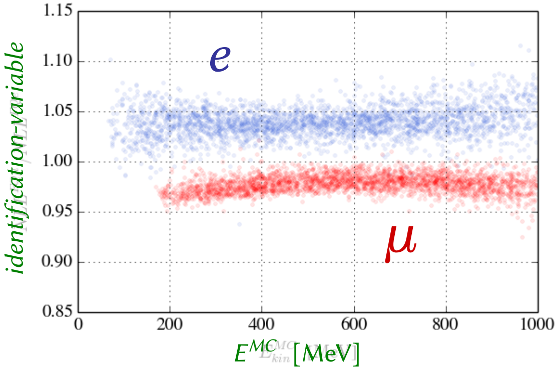
Separating $e^{\pm}$ from $\mu^{\pm}$

Selection acceptance

e	46.3 %
μ	43.3 %

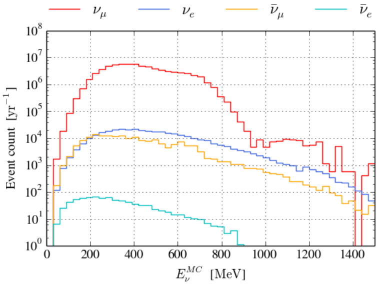
Reco. performance

e	corr-ID	98.4 %
	mis-ID	1.58 %
μ	corr-ID	99.7 %
	mis-ID	0.27 %



Separating ν_e from ν_μ

0. Simulate neutrino interaction vertices according to neutrino spectrum at ND with **GENIE**
1. Insert vertices into WCSim for detector response
2. Reconstruct using fiTQun
3. Apply charged-lepton criteria
4. Develop additional selection criteria to address “real” vertex differences



Pion-like cut

Reject events identified as electrons, but more likely to be (neutral) pions

Multi-subevent cut

Reject events with multiple subevents

Event rate per 200 d running-year

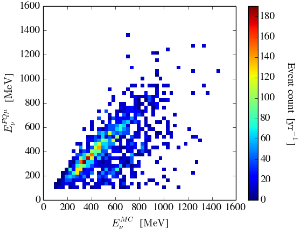
Positive polarity (ν-select)

	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
Tot. interactions	7.25×10^7	3.57×10^5	1.89×10^5	8.33×10^2
Trigger	3.81×10^7	5.61×10^4	9.09×10^4	9.35×10^1

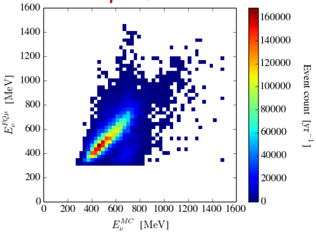
Negative polarity ($\bar{\nu}$-select)

	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
Tot. interactions	6.88×10^5	4.74×10^3	1.39×10^7	4.12×10^4
Trigger	3.48×10^5	6.45×10^2	6.84×10^6	5.04×10^3

ν_e E_ν-reco



ν_μ E_ν-reco



Near detector objective:

- ▷ Measure ν_μ-flux
  - → Count + measure energy

$$E_\nu = \frac{m_f^2 - m_b^2 - m_l^2 + 2 m_b E_l}{2(m_b - E_l + p_l \cos\theta_l)}$$

Event rate per 200 d running-year

Positive polarity (ν-select)

	e-ID ν_μ	e-ID ν_e	e-ID $\bar{\nu}_\mu$	e-ID $\bar{\nu}_e$
Trigger	1.09×10^7	5.26×10^4	2.66×10^4	8.82×10^1
Charged-lepton cuts	5.72×10^5	2.29×10^4	1.43×10^3	3.58×10^1
Neutrino cuts	1.50×10^4	1.10×10^4	4.11×10^1	3.27×10^1

$$S(\nu_e + \bar{\nu}_e)/B(\nu_\mu + \bar{\nu}_\mu) = 0.73$$

Negative polarity ($\bar{\nu}$-select)

	e-ID ν_μ	e-ID ν_e	e-ID $\bar{\nu}_\mu$	e-ID $\bar{\nu}_e$
Trigger	1.08×10^5	6.05×10^2	1.87×10^6	4.74×10^3
Charged-lepton cuts	6.72×10^3	2.59×10^2	5.12×10^4	2.12×10^3
Neutrino cuts	1.23×10^2	1.23×10^2	1.93×10^3	1.86×10^3

$$S(\nu_e + \bar{\nu}_e)/B(\nu_\mu + \bar{\nu}_\mu) = 0.97$$

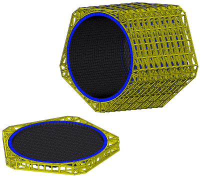
Near detector objective:

- Measure $\sigma_{\nu_e N}$
  - → Substantial increase in $\nu_e(\bar{\nu}_e)$-contribution

Summary

ESSnuSB Near Detector

- Super Fine-Grained Detector ($\sim 1\,\mathrm{m}^3$)
- Water-Cherenkov Detector ($\sim 1\,\mathrm{kt}$)



Objectives

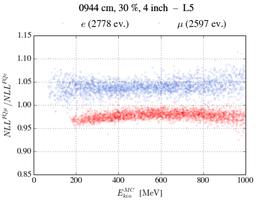
- Measure ν_μ-flux
- Measure $\sigma_{\nu_e N}$

Measuring $\nu_e N$ cross-section

- Requires ν_e selection scheme

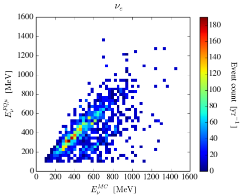
Charged-lepton separation

- 4-fold selection



Neutrino separation

- 2-fold selection scheme



Pos. pol. $S(\nu_e + \bar{\nu}_e)/B(\nu_\mu + \bar{\nu}_\mu) = 0.73$

Neg. pol. $S(\nu_e + \bar{\nu}_e)/B(\nu_\mu + \bar{\nu}_\mu) = 0.97$

Thank you

Backups

Backup 1.1 — Super Fine-Grained Detector

Similar to Hyper-K SuperFGD

- $1.4 \times 1.4 \times 0.5\,\mathrm{m}^3$
- $\sim 10^6$ plastic scintillator cubes
  - $1 \times 1 \times 1\,\mathrm{cm}^3$

Mass 1030 kg

C_8H_8 1014.55 kg

$C_{18}H_{14}$ 15.45 kg

Positive horn polarity (selecting ν)

	Time	Molecule	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
CC	200 days	C8H8	57 334.5	309.178	120.694	0.557
		C18H14	828.734	4.46	1.644	0.007
		Total	58 163.3	313.638	122.339	0.565
NC	200 days	C8H8	39 471	167.746	117.034	0.4649
		C18H14	560.937	2.383	1.768	0.0066
		Total	40 031.9	170.129	118.802	0.4715

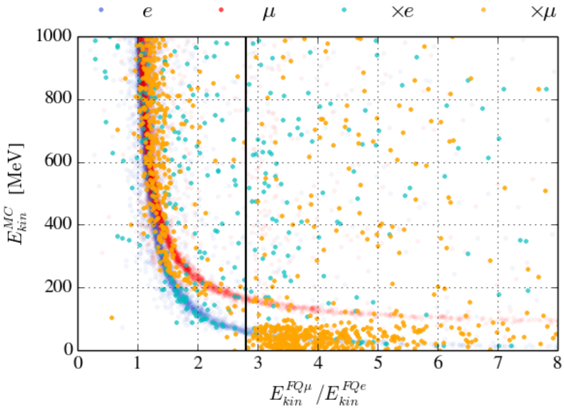
Negative horn polarity (selecting $\bar{\nu}$)

	Time	Molecule	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
CC	200 days	C8H8	524.282	3.874	8 888.4	28.709
		C18H14	7.574	0.056	120.994	0.391
		Total	531.856	3.929	9 009.34	29.101
NC	200 days	C8H8	391.182	2.432	8 336.22	22.447
		C18H14	5.553	0.034	117.87	0.317
		Total	396.736	2.467	8 454.09	22.764

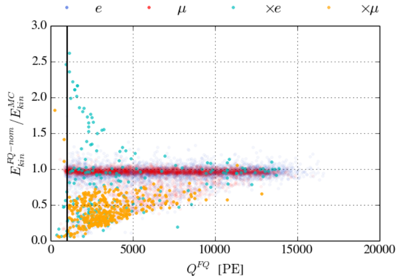
Backup 2.1 — Separating $e^{\pm}$ from $\mu^{\pm}$

Sub-Cherenkov cut

Reject muons below Cherenkov threshold posing as electrons

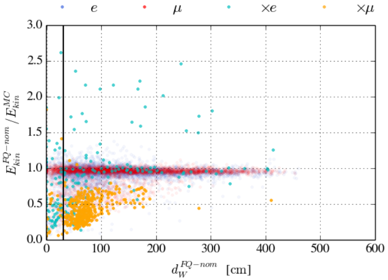


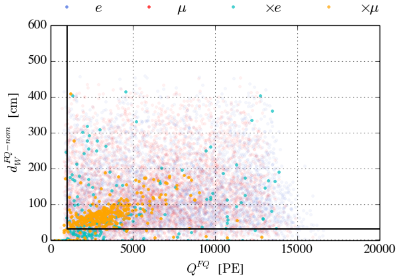
Backup 2.2 — Separating $e^{\pm}$ from $\mu^{\pm}$



Reco. quality cut

Reject low-brightness and close-to-wall events for reco. quality

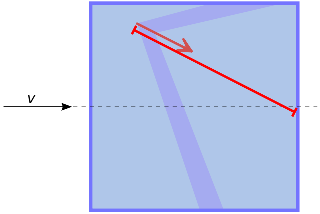


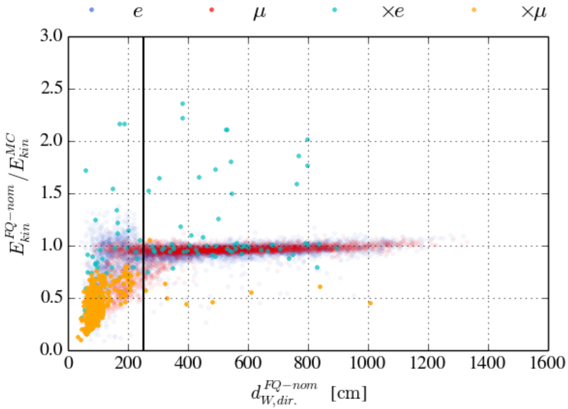


Backup 2.3 — Separating $e^{\pm}$ from $\mu^{\pm}$

Cherenkov-ring resolution cut

Reject events too close to tank wall in propagation direction

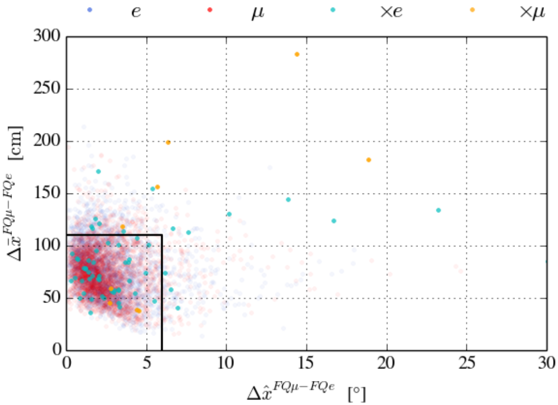




Backup 2.4 — Separating $e^{\pm}$ from $\mu^{\pm}$

Vertex-reco. discrepancy cut

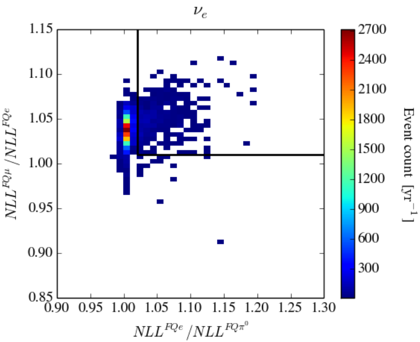
Reject events with a large difference in vertex pos. & dir. between e and μ reco.

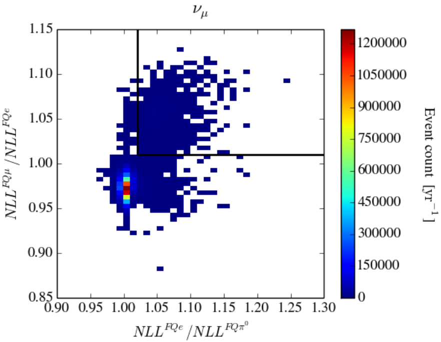


Backup 3.1 — Separating ν_e from ν_μ

Pion-like cut

Reject events identified as electrons,
but more likely to be (neutral) pions





Backup 3.2 — Separating ν_e from ν_μ

Multi-subevent cut

Reject events with multiple subevents