Status in Lund and plans: Migration matrices for the water Cherenkov near detector

Joochun (Jason) Park, Peter Christiansen, Joakim Cederkäll

Lund University

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Introduction

CP violation discovery sensitivity

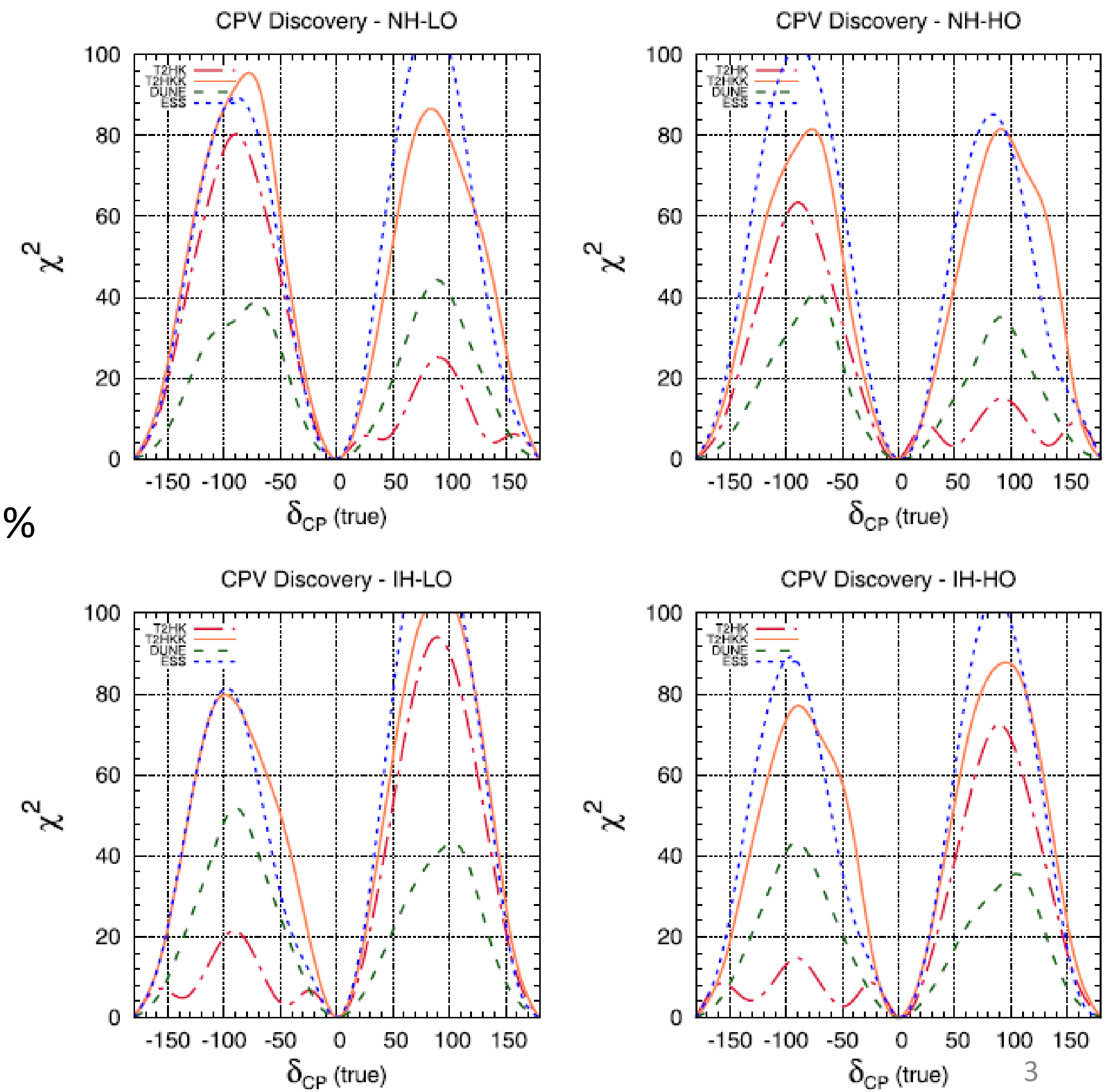
Discovery potential comparisons

- Hyper-K (Japan/Korea)
- DUNE
- ESSνSB: optimized for δ_{CP}, most sensitive

ESSνSB near detector to reduce systematic uncertainties below 5% (5% signal, 10% background normalization error assumed)

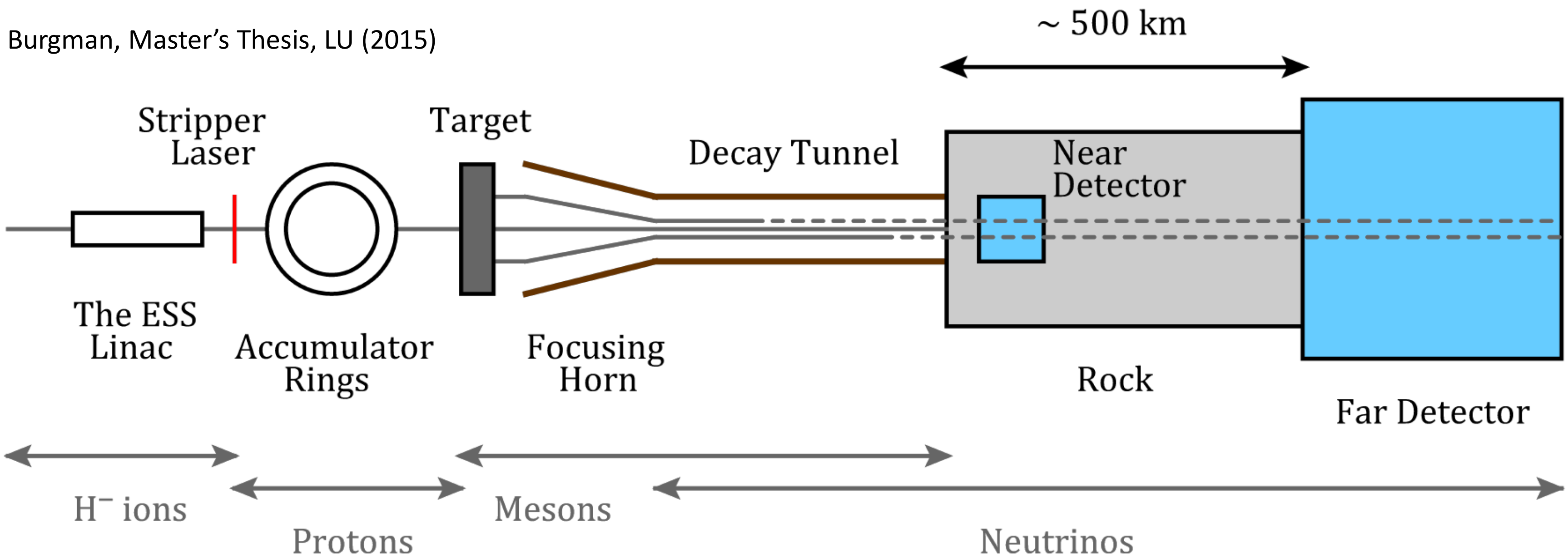
NH/IH – hierarchy
LO/HO – octant for θ_{23} ~ 45°

K. Chakraborty et al. / Nuclear Physics B 937 (2018) 303–332



ESSνSB neutrino production and experiment

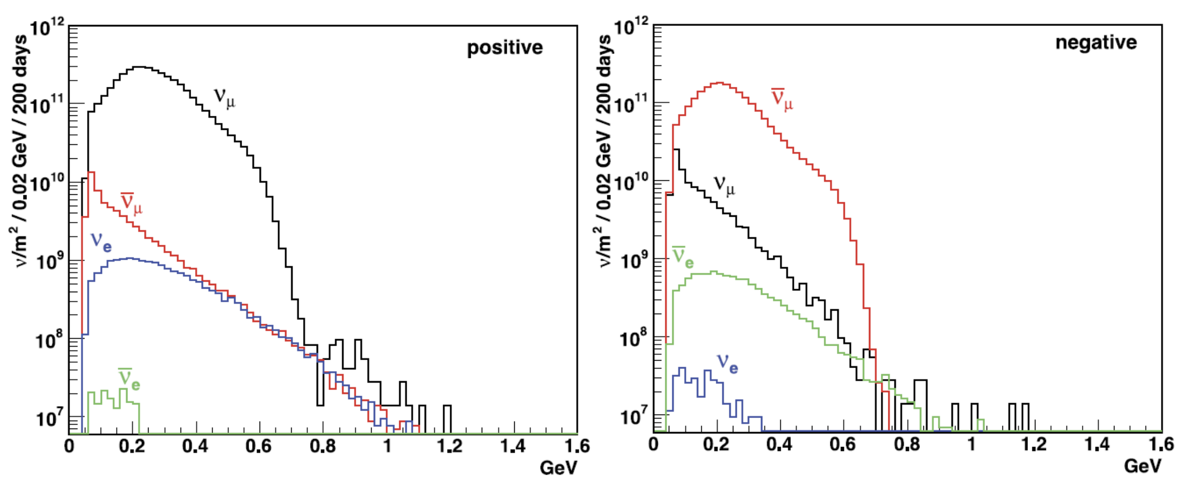
A. Burgman, Master's Thesis, LU (2015)



E. Baussan et al. / Nuclear Physics B 885 (2014) 127–149

Neutrino beam from ESS

5 MW 2-GeV proton beam,
< 1-GeV neutrino beam
→ slow charged leptons



Neutrino fluence, L = 100 km

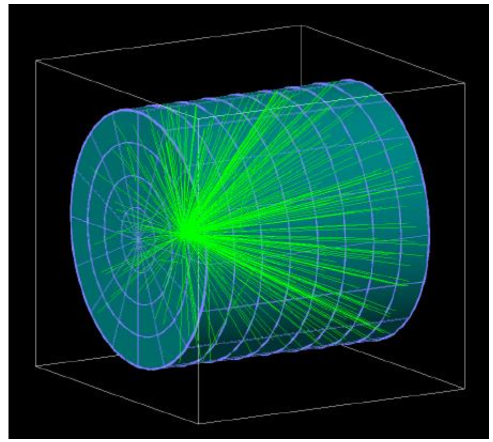
Previous Master’s thesis work (A. Burgman) at Lund University

Near detector simulations

FLUKA 2011.xx/Geant3.21
for ν production (N. Vassilopoulos)

GENIE 2.8.4 for neutrino interactions
with matter; *gxspl-NuMIbig* (in GENIE)
interaction cross section

Geant4 geometry/charged lepton
interaction simulations

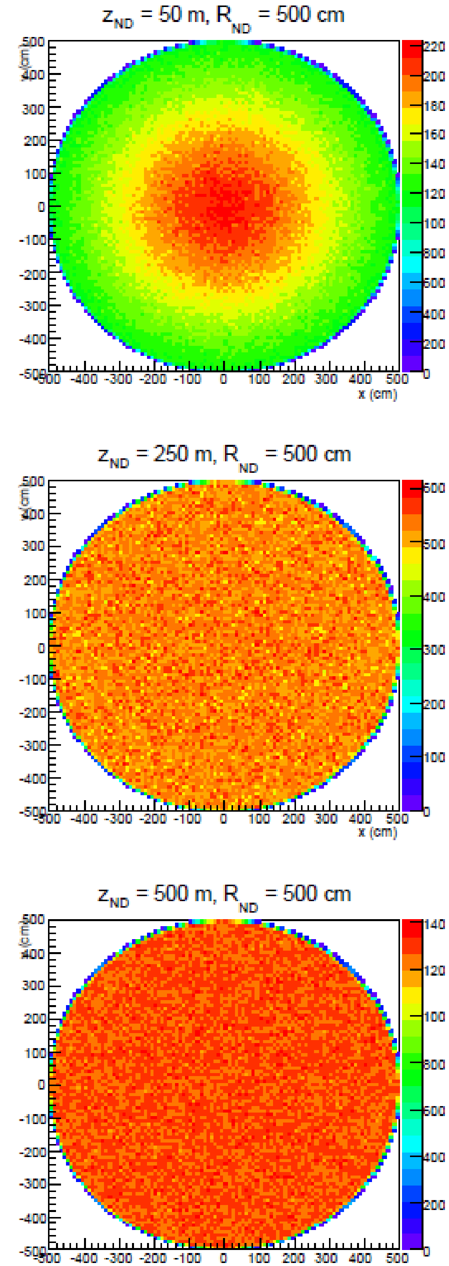


Cylindrical kiloton water Cherenkov detector.

At a distance $z_{ND} \sim 50$ m – 500 m from source.

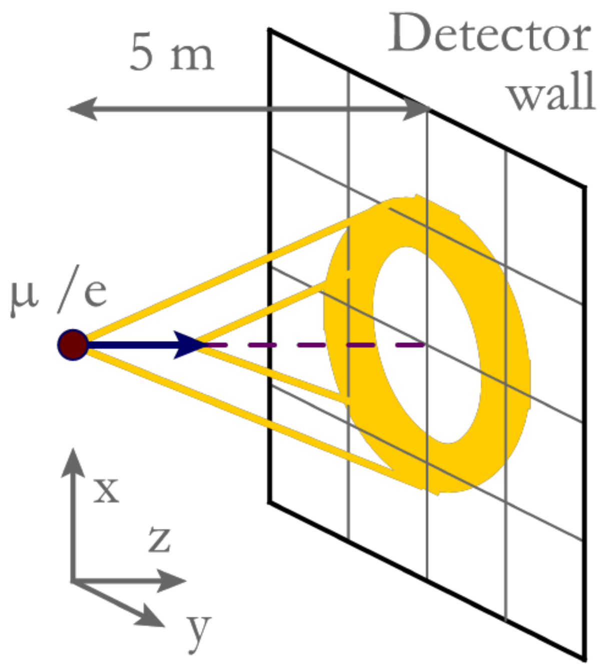
Radius $R_{ND} \sim 5$ m.
Length $L_{ND} \sim 10$ m.

Used to characterise the beam near the production point.



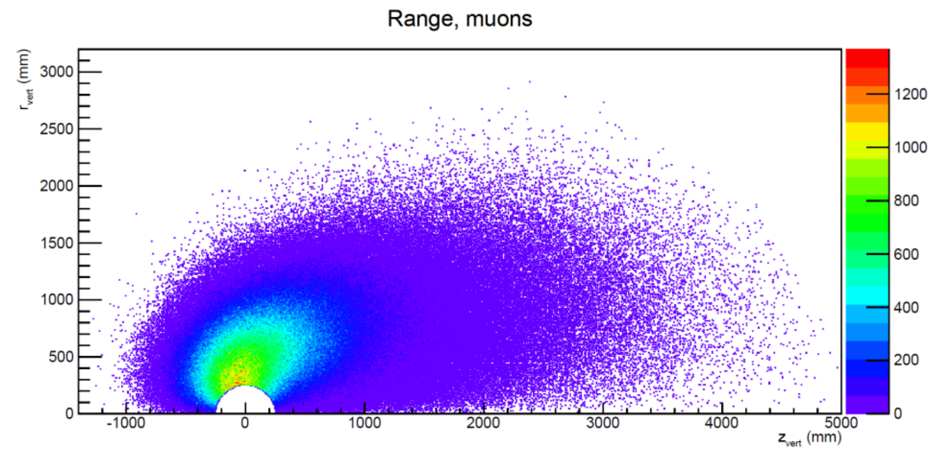
ν beam spatial profile

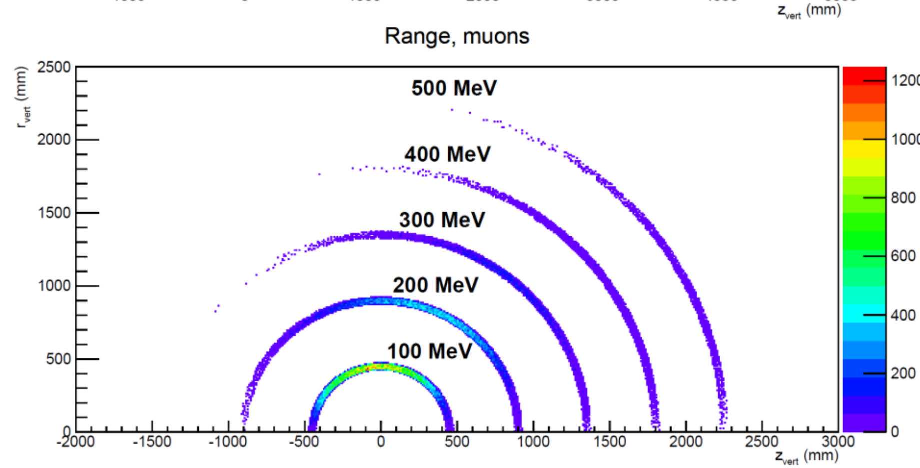
BestCase event simulation



Flavours used: μ^-, μ^+, e^-, e^+
Kinetic energies used (MeV):
100, 200, 300, 400, 500

Lepton direction fixed perpendicular to detector wall, true position at origin

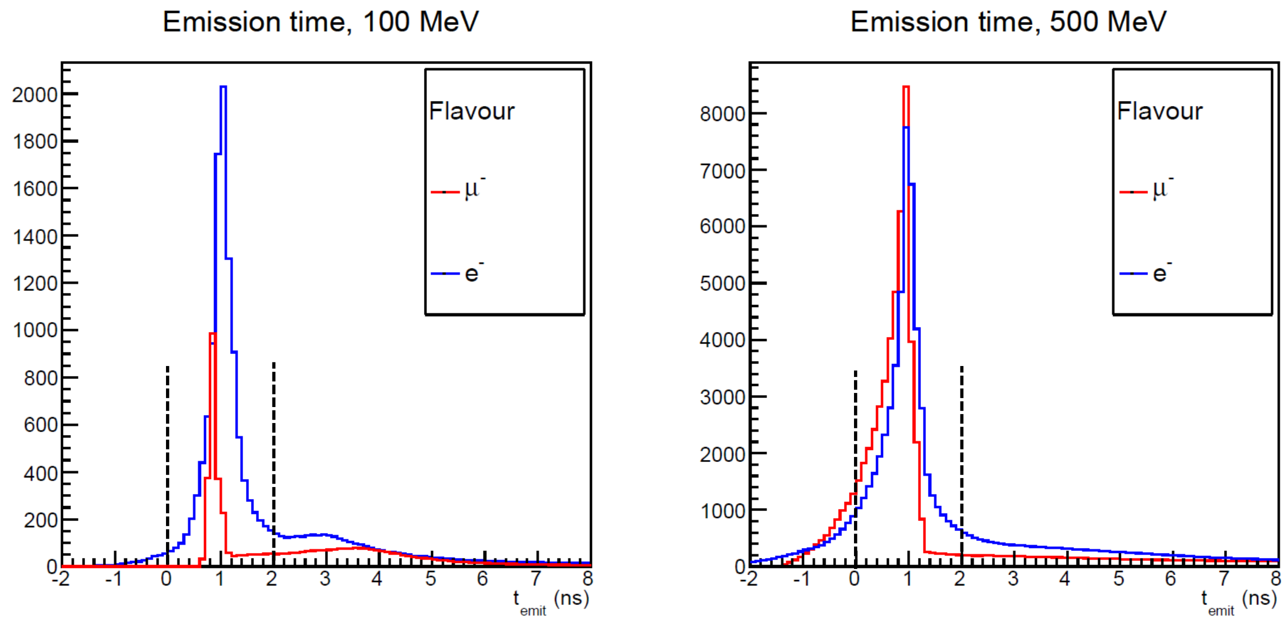




Position distribution of stopped muons (E_μ = 0)

Vertex reconstruction

FindVertex algorithm

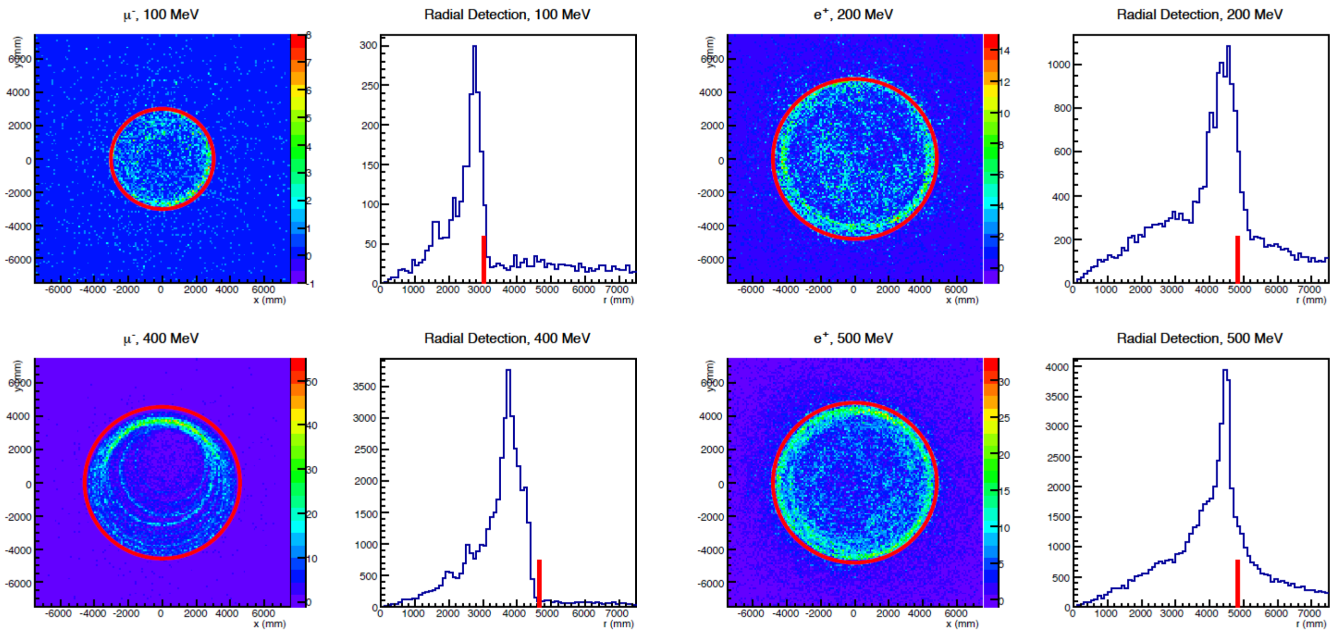


Time measured from single point, t < 0 possible
Find coordinates with maximum N_γ within 0-2 ns time window
→ 2-ns most likely time window for arbitrary emission points

Charged leptons travel ~60 cm in 2 ns, σ ~ 17 cm
Better resolution with higher lepton energies, diminished return for electrons
Resulting δT requirement: 10-100 ps

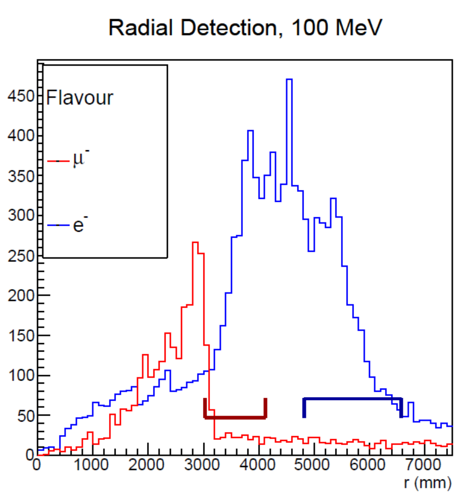
Ring & PID identification

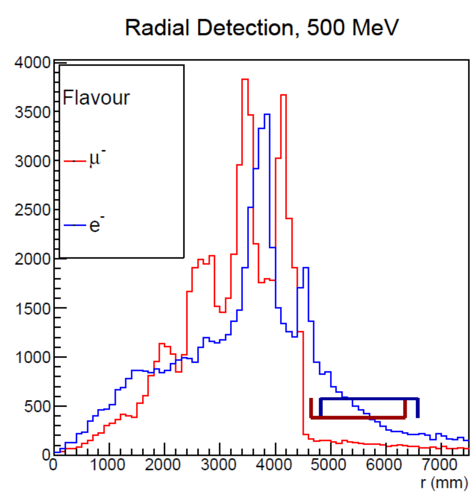
InsideCircle Cherenkov ring finder, *TripleCheck* PID algorithms



1. *RatioInOut*: N_{out}/N_{in} – higher for electrons

2. *DensityIn*: N_{in}/A, lower for muon rings on electron events

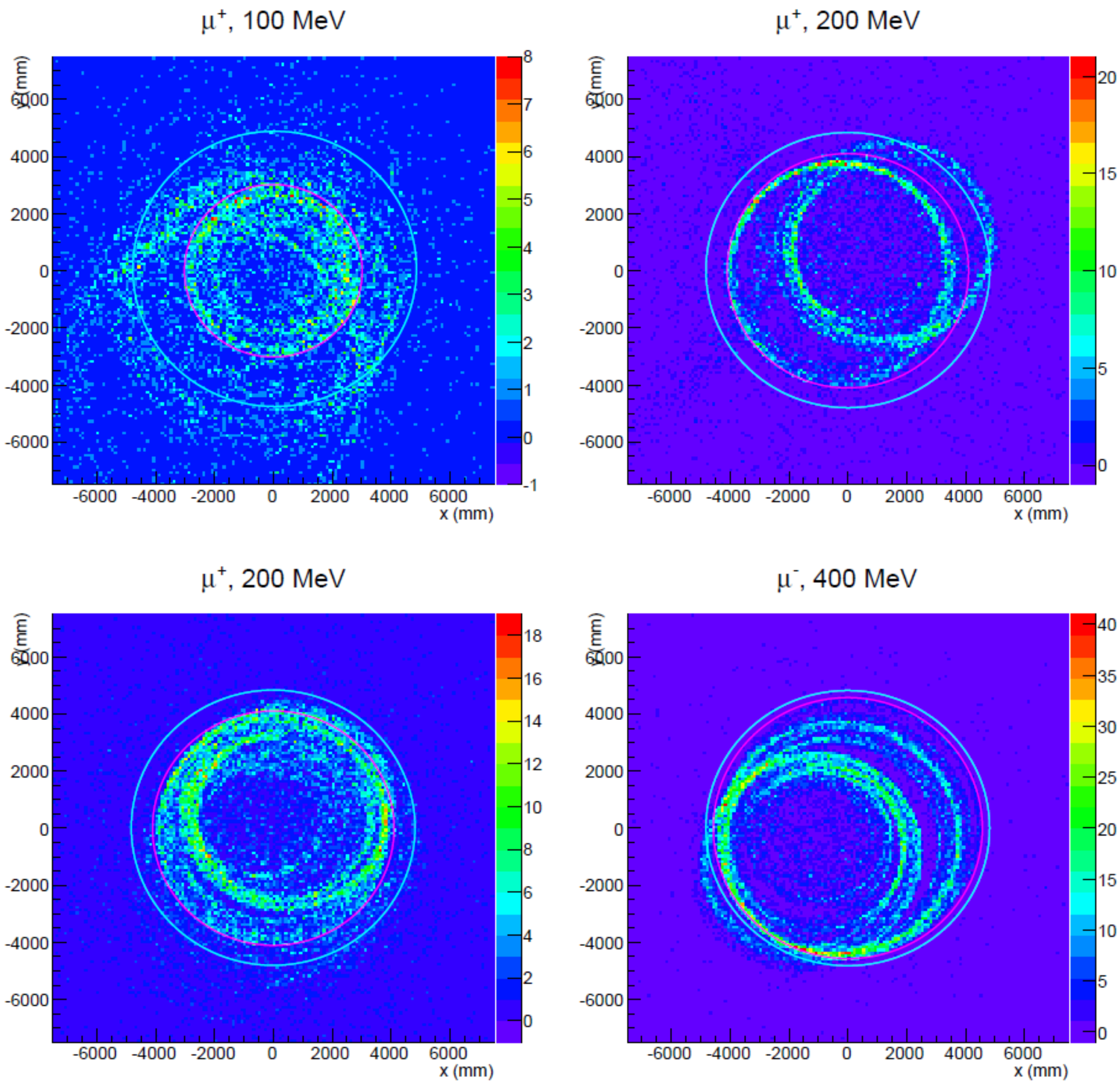




3. *SlopeOut*: dN/dr comparisons
Red interval: 1.1-1.5 × $R_{Ch,\mu}$
Blue interval: 1.1-1.5 × $R_{Ch,e}$

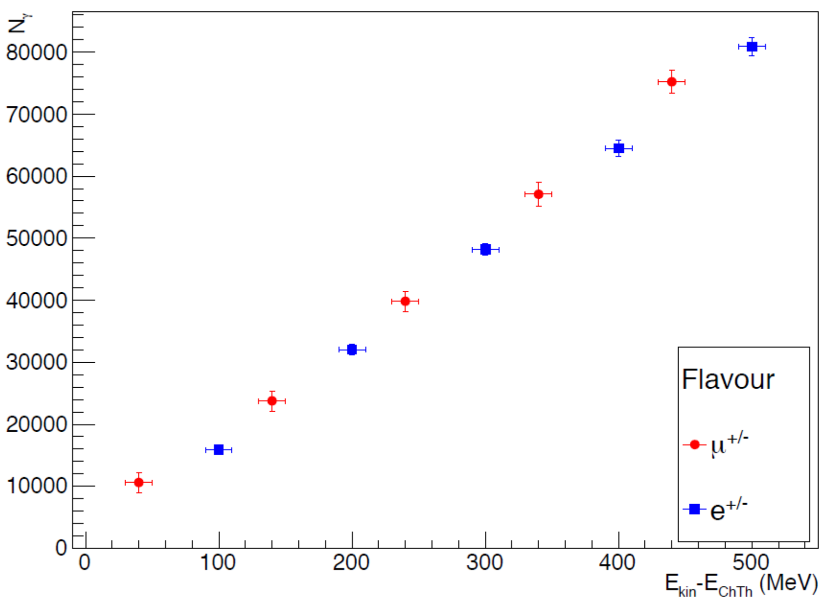
Lepton misidentification

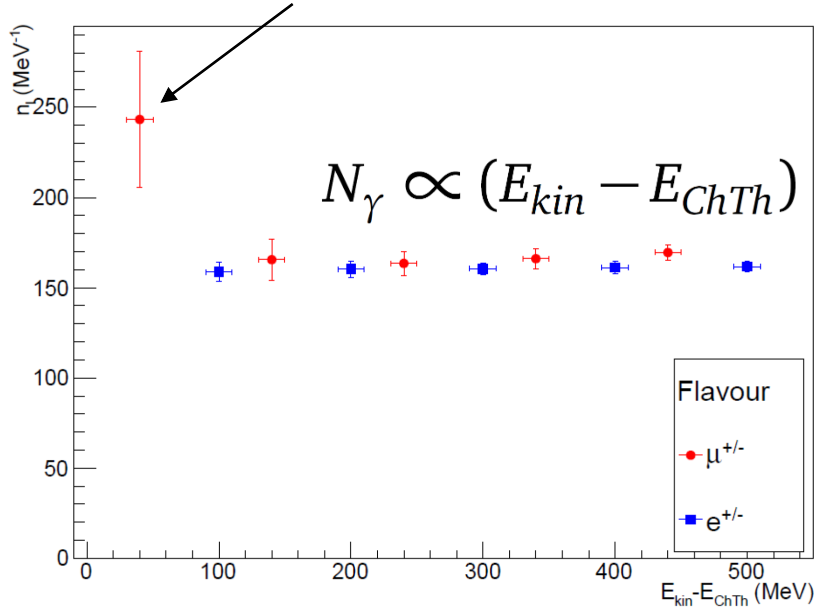
~0.3% misidentification rate, all of them being misidentified as electron events (fuzziness)



Lepton E_k reconstruction

Contribution from scintillation where $E_{kin} < E_{ChTh}$





Accurate knowledge of lepton flavor needed, as $E_{ChTh}(\mu) \neq E_{ChTh}(e)$

Must be generalized into migration matrices!

ESSvSB near detector specifications

From charged lepton kinematics and neutrino beam profile:

For homogeneous spatial distribution

- The length of the near detector: $L_{ND} \gg 3$ m.
- The radius of the near detector: $R_{ND} \gg 2$ m, $R_{ND} \leq \frac{z_{ND}}{50}$.
- The distance between the neutrino beam production and the near detector: $z_{ND} \geq 200$ m.

Considering the effectiveness of the ring identification and PID:

- The detector must have a space resolution smaller than 10 cm.

To identify events with vertices as downstream as ~1 m away from the end wall,

$$w_{pixel} \leq 0.1 \times \Delta l$$

For accurate vertex reconstruction:

- The detector must have a time resolution shorter than 100 ps.

LAAPD: ~ 64 ps resolution (acceptable)
PMT > 170 ps (challenging)

Action plan

Available resources

Reconstruction algorithms

I. A. Burgman's simulations - adapt from *BestCase* scenario

1. *FindVertex*: point with maximum N_γ within 2 ns for possible vertex, ~30 cm accuracy
2. *InsideCircle*: ring identification – N_γ inside $1.1 * R_{ch}$ (accounting for fuzziness)
3. *TripleCheck*: PID algorithm employing 3 metrics: N_{in}/N_{out}, density of N_γ inside ring, dN_γ/dr

II. MEMPHYS simulations:

- Vertex position by determining t_m with

$$G_p = \frac{1}{N}\sum_{i=1}^{n} \exp\left(-\frac{(t_i - t_m)^2}{2(1.5\sigma)^2}\right)$$

- Particle direction determined by maximizing the weighted charge distribution as a function of θ from the vertex
- Lepton flavor identification via ring fuzziness and ring counting; background (π^0, etc) rejection
- Momentum determination by N_γ detected at different PMTs
- Energy of the neutrino via

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + P_l \cos\theta_l}$$

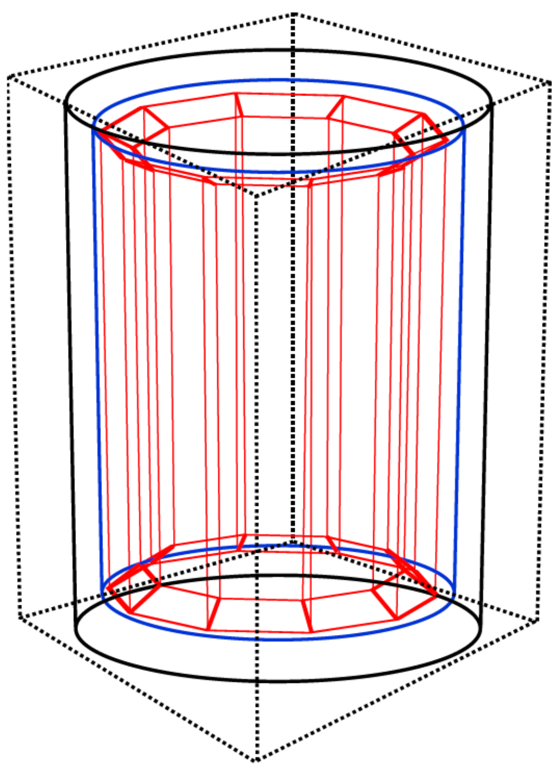
L. Agostino et al., Phys. Rev. STAB 16, 061001 (2013)

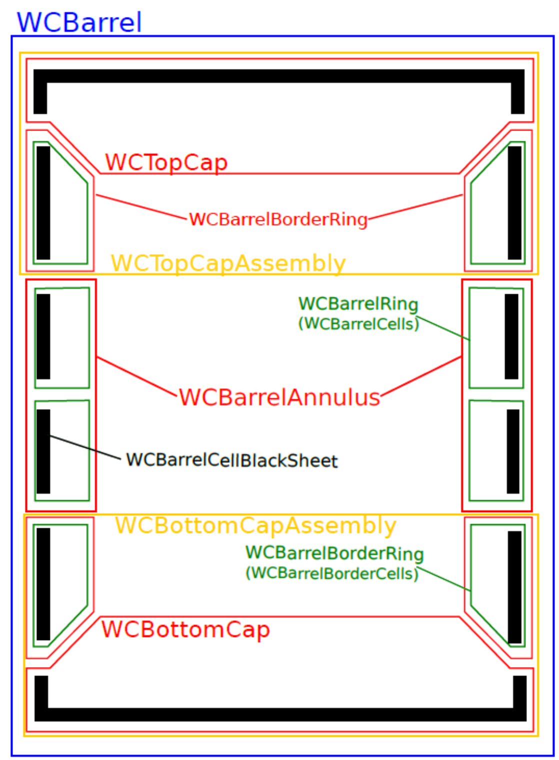
Additional resources

III. Open-source simulation by E. O'Sullivan, IceCube, Hyper-K (Stockholm U.)

https://github.com/WCSim/WCSim

Reconstruction algorithms may be open source in the future; in discussion





Top and side PMTs Simulated

Detector geometry can be modified easily

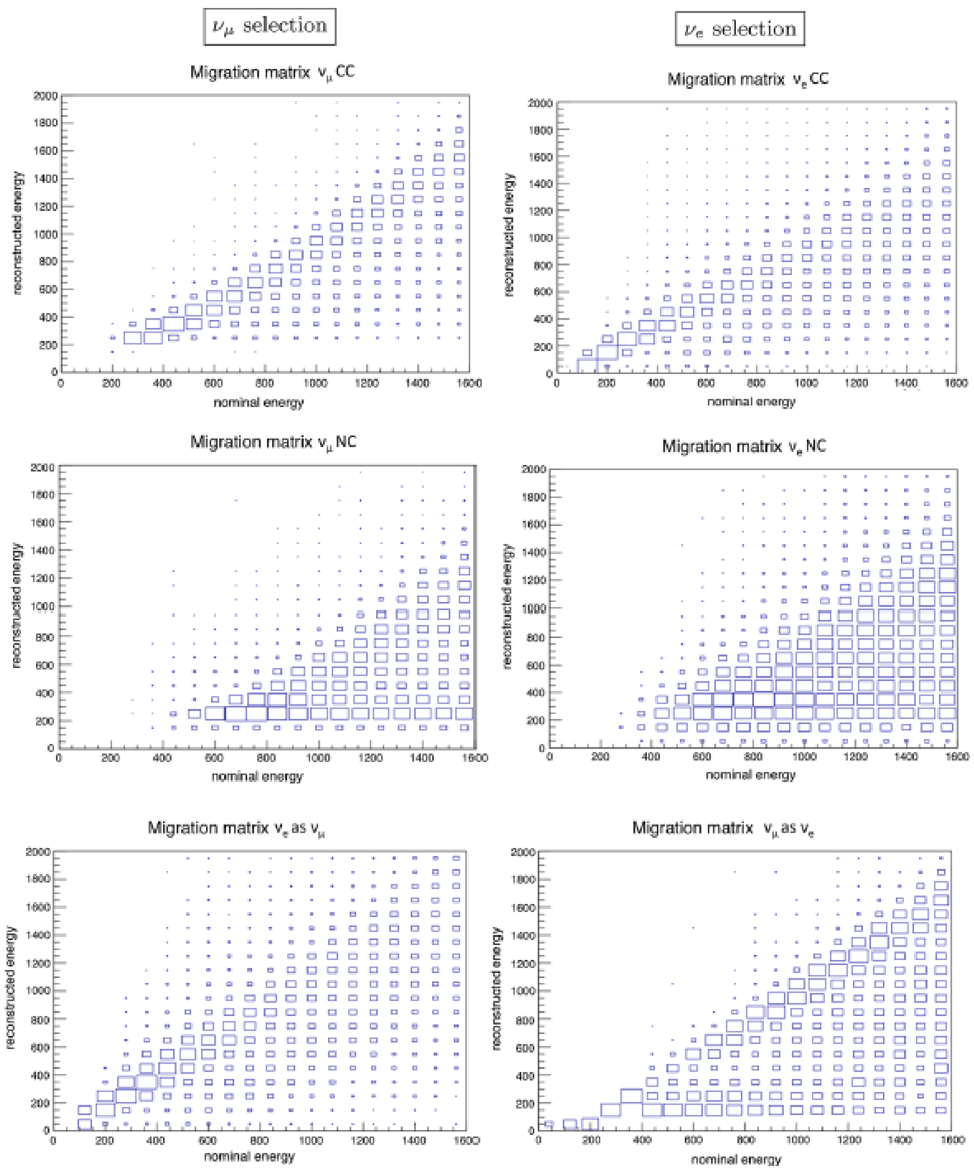
Need to provide input lepton beams

ROOT output files

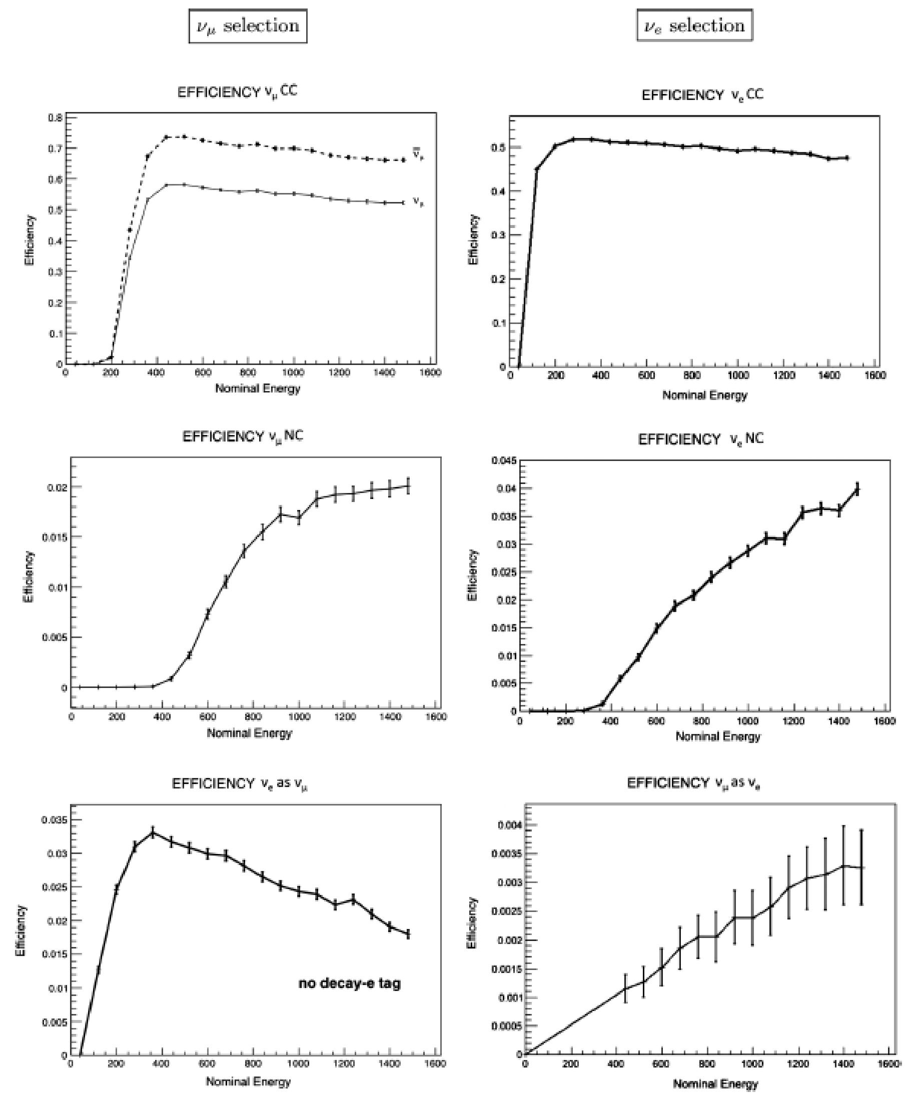
T. Dealtry, A. Himmel, J. Hoppenau, J. Lozier, WCSim document (2016)

Migration matrices

L. AGOSTINO *et al.* Phys. Rev. ST Accel. Beams **16,** 061001 (2013)

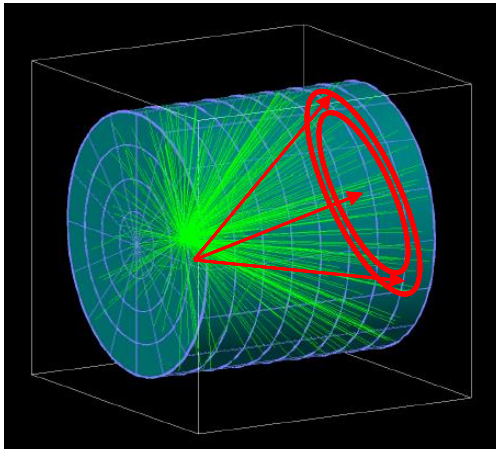


From MEMPHYS detector design



Energies in MeV

Task list



Tasks

- *BestCase* events → arbitrary Cherenkov cone direction on curved surfaces
- Benchmark and compare different reconstruction algorithms as a function of ND simulation parameters (size, dimensions, granularity, etc)
- Energy reconstruction → Migration matrices for each type of ν interaction
- Investigate potential to exploit timing information with slow leptons
- Background event simulation: π^0, cosmic neutrinos, etc