Status of LENA and Developments in Large Liquid Scintillator Detectors

Next Generation Nucleon Decay and Neutrino Detectors – NNN12

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Motivation

What do we gain from a next-generation neutrino detector?

- better understanding of astrophysical an terrestrial ν sources
- investigation of neutrino properties
- target for neutrino beam
- search for proton decay

- KamLAND and Borexino show the outstanding physics potential of liquid scintillator detectors.
- Increase detection sensitivity and precision $\rightarrow$ higher target masses.
- A large LS detector addresses a large range of NNN physics!

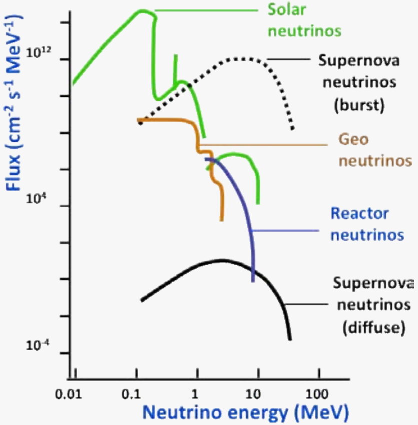
Physics with Liquid Scintillator

Neutrino Physics

- Galactic supernova neutrinos
- Diffuse supernova ν background
- Solar neutrinos
- Geoneutrinos
- Reactor neutrinos
- Neutrino oscillometry
- Neutrino beams
- Atmospheric neutrinos
- π decay @ rest beam

Also

- Indirect dark matter search
- Proton decay



Low Energy Neutrino Detection

Detection channels

ν: elastic scattering $\nu + e^- \to \nu + e^-$
proton recoil $\nu + p \to p + \nu$
reactions on ^{12}C (NC and CC)

$\bar{\nu}_e$: inverse β-decay $\bar{\nu}_e + p \to e^+ + n$

Advantages of LS

- very low energy threshold ($\approx$ 200 keV)
- good energy resolution ($\approx$ 7% @ 1 MeV)
- proven purification techniques for high radiopurity

Background rejection

- pulse shape analysis
- coincidence signals

LENA Detector

LENA Detector Design

Egg shaped cavern

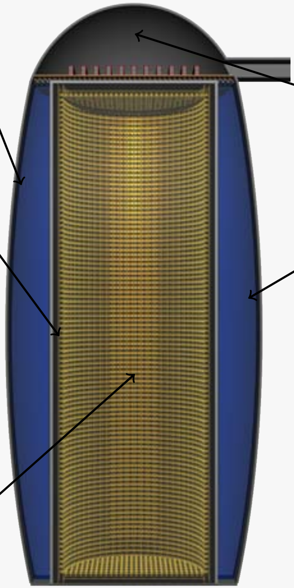
- $\updownarrow$ 120 m
- $\varnothing > 36$ m

Detector Tank

- concrete wall
- cylindrical – $\updownarrow = 100$ m $\varnothing = 32$ m
- $\sim$ 30000 12" PMTs

Target

- 50 kt scintillator



Electronics hall

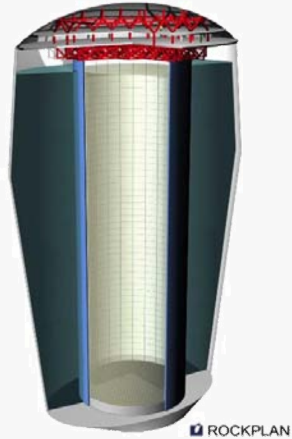
- 15 m high
- top muon veto

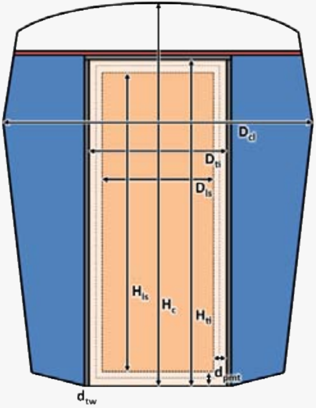
Water-filled cavern

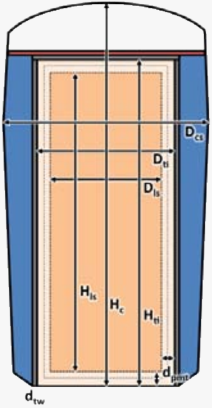
- $\sim$ 2000 12" PMTs
- veto for inclined muon tracks
- shielding for fast neutrons

Cavern Design

Egg shaped cavern







Height: 120 m, maximum diamter: 71.2 m

Tank Design

Hollow-Core Concrete Tank

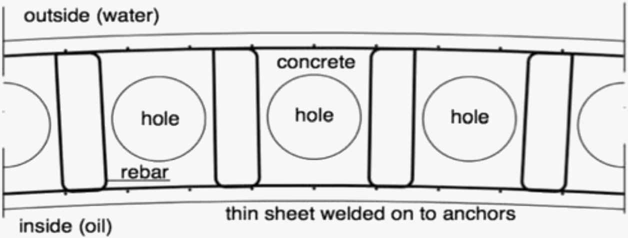
- 600 mm wide concrete layer
- covered on both sides by thin steel sheets

→ compatibility with the scintillator

- Cylindrical cavities of 300 mm diameter and 500 mm interspacing

→ reduce the needed amount of material

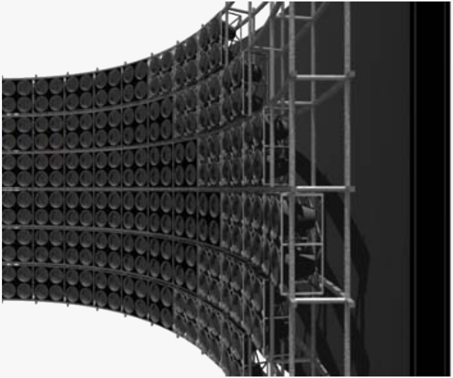
→ space for installations (e.g. cooling or active leak proving)

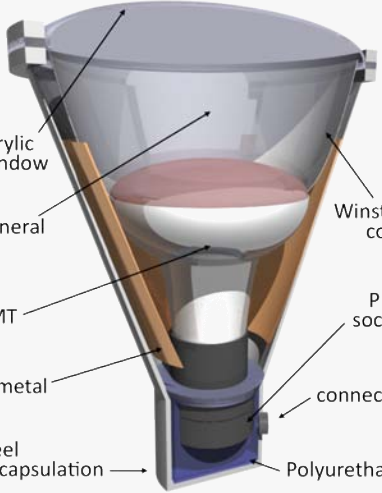


PMT Support Structure

- scaffolding 2 m from tank wall
- optical separation of inner volume by non-reflective plastic sheets

⇒ reduces impact of γ activity from concrete tank wall





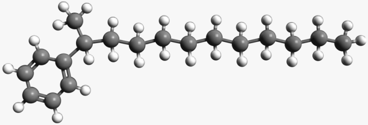
- Winston cones for light concentration
- $\sim$ 30000 12" PMTs
- 30% optical coverage
- pressure encapsulation
- non-scintillating buffer volume included in front of the PMT
- total weight: 40 kg
- contained within PSS

LENA Scintillator

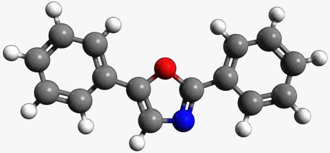
- linear-alkyl-benzene as solvent
- high flashpoint 140°C
- PPO + bisMSB as wavelength shifters
- emission @ 430 nm
- time response: 5.2 ns
- high light yield $\sim 10^4$ γ per MeV
- high transparency $\sim$ 20 m
- low cost ($<$ 1.30 €/ℓ)

Altogether 80300 m^3 (69.1 kt) needed.

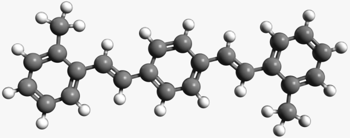
LAB ($C_{18}H_{30}$)



+3 g/ℓ PPO ($C_{15}H_{11}NO$)



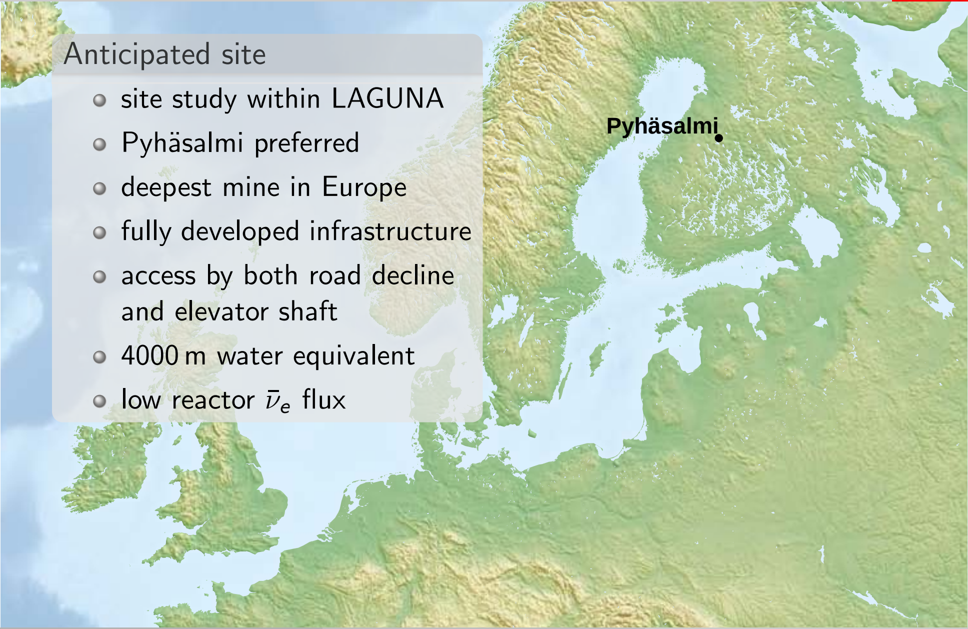
+20 mg/ℓ bisMSB ($C_{24}H_{22}$)



LENA Site

Anticipated site

- site study within LAGUNA
- Pyhäsalmi preferred
- deepest mine in Europe
- fully developed infrastructure
- access by both road decline and elevator shaft
- 4000 m water equivalent
- low reactor $\bar{\nu}_e$ flux



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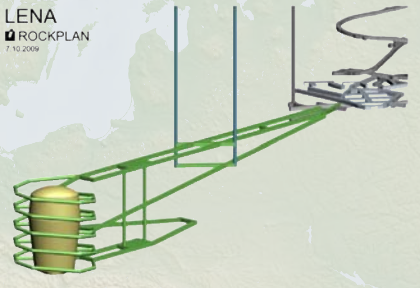
LENA @ Pyhäsalmi



Galactic Supernova Neutrinos

Multi-channel signatures

- core collapse supernova produces (ν_e) neutrino burst
- $\nu\bar{\nu}$-pairs during cooling phase

$\rightarrow$ individual, time dependent spectra for different neutrinos

- 15000 ν interactions expected for SN in galactic center
- different detection channels for individual neutrino flavors
  - main channels:inverse β-decay ($> 10^4$ events)
  - $\nu p \rightarrow p\nu$ (few 1000 events depending on average ν energy)
- energy and flavor resolved real-time analysis

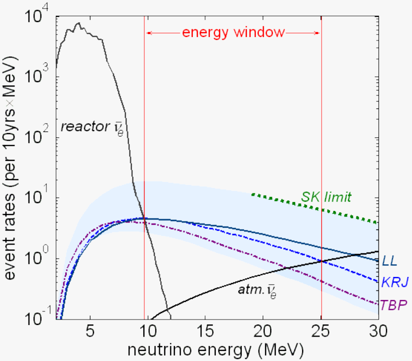
$\Rightarrow$ follow different stages of core collapse

$\Rightarrow$ oscillations of SNνs sensitive to mass hierarchy

- SNEWS

Diffuse Supernova Neutrino Background

- only 1–3 galactic supernovae per century
- isotropic neutrino background from SN on cosmic scales
- information on average neutrino spectrum
- redshifted by cosmic expansion
- expected flux: 100 $\nu/\mathrm{s}/\mathrm{cm}^2$
- not yet observed
- LENA: 2 – 20 events per year
- inverse β-decay: background free



Solar Neutrinos

Spectral measurements

- high statistics energy dependent flux measurements
- $\sim 10^4$ events per day
- ~ 200 CNO neutrinos
- fiducial mass: $\sim 30\,\text{kt}$ to reduce γ background

Oscillation physics

- test transition region of MSW effect

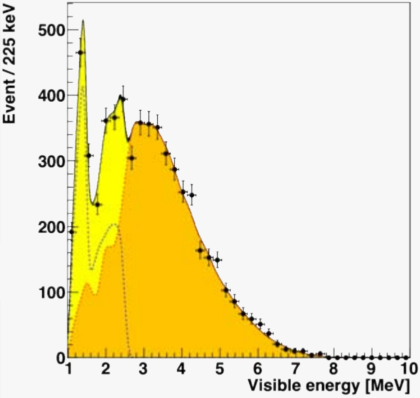
Investigation of the Sun

- metallicity
- precise determination of SSM neutrino rates
- search for time variations in ^{7}Be flux on a 10^{-3} level
- helioseismic g-modes

LENA will detect $\mathcal{O}(10^3)$ events from terrestrial $\bar{\nu}_e$ per year

Geoneutrinos

- direct messengers $\rightarrow$ abundances and distribution of radioactive elements in Earth
- test radiogenic contribution to Earth heat flux: 1% precision
- 10 years LENA: 5% precision of U/TH flux ratio



Reactor Neutrinos

- background for geo-ν and DSNB
- high statistics study of oscillation parameters

- monoenergetic ν_e source
- ν_e disappearance can be detected within the length of the detector
- reactor antineutrino anomaly $\Rightarrow$ sterile neutrinos?

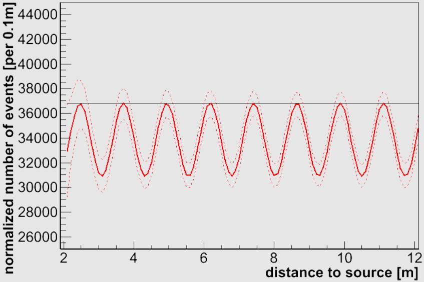
$\rightarrow$ several oscillations within the first 10 m

- test between 3+1 and 3+2 models

EC Sources

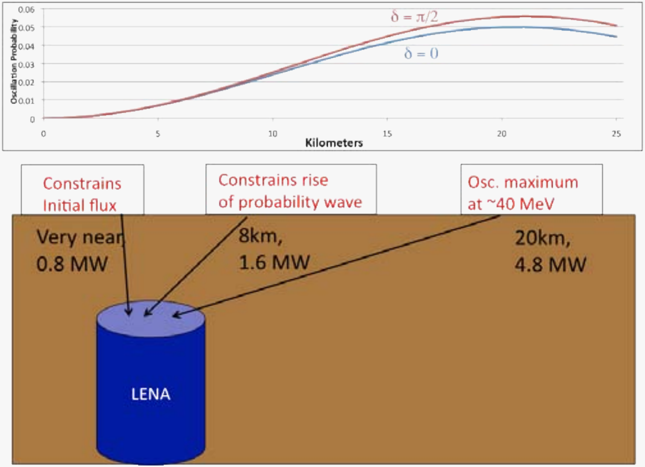
Type	Element	Energy
ν_e	^{51}Cr	747 keV
ν_e	^{37}Ar	811 keV
$\bar{\nu}_e$	^{90}Sr	1.8–2.3 MeV

55 days – 5 MCi ^{51}Cr source



Pion Decay at Rest

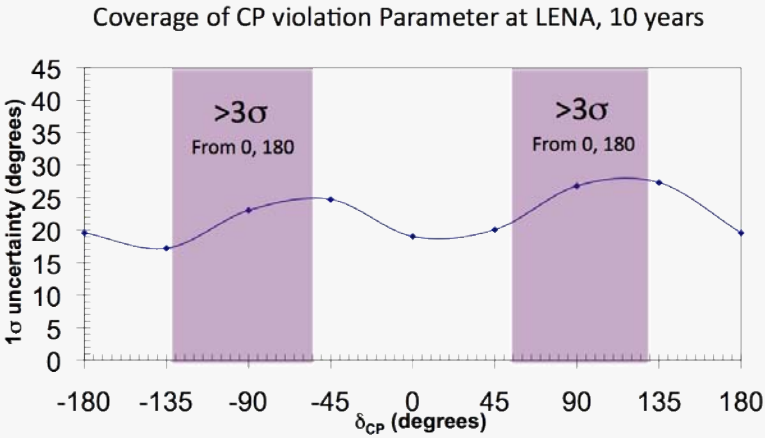
Daeδalus for LENA – look for $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance



LENA has excellent detection efficiency for inverse β-decay.

$\sim$ 100 IBD per year for each baseline.

Sensitivity to δ_{cp}



Predicted coverage for δ_{cp} at 3σ: 42% after 10 years.

LAGUNA – LAGUNA-LBNO

Large Apparatus for Grand Unification and Neutrino Astrophysics

LAGUNA design study

- 2008–2011
- 3 detector types

GLACIER	100 kt LAr TPC
MEMPHYS	440 kt water
LENA	50 kt liquid scintillator

- physics potential
- 7 locations in Europe
- cavern design

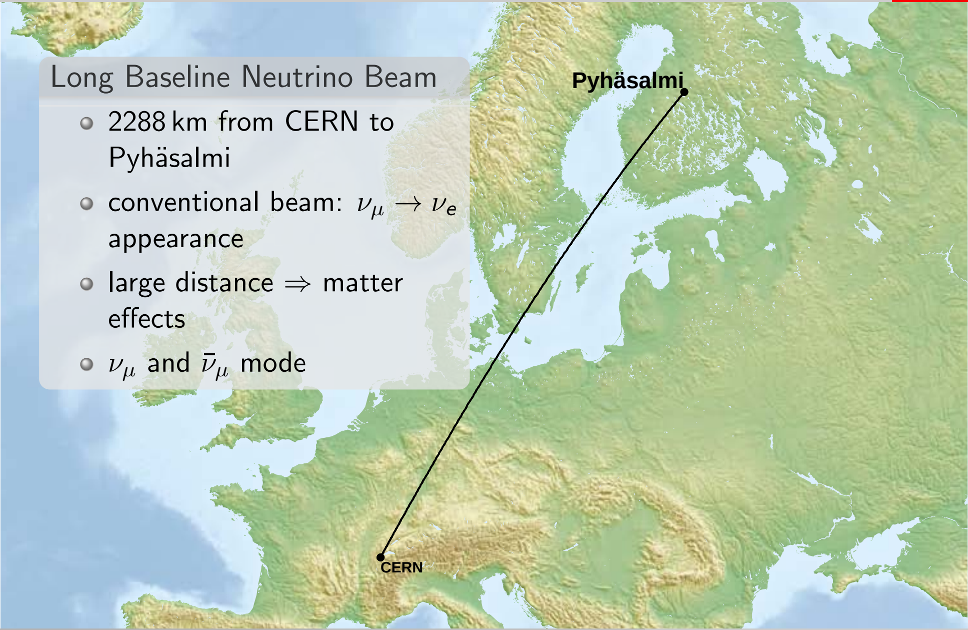
LAGUNA-LBNO

- follow up study (2011–2014)
- Long Baseline Neutrino Oscillations
- possible beam @ CERN
- detector tank
- instrumentation

Possible Beam from CERN

Long Baseline Neutrino Beam

- 2288 km from CERN to Pyhäsalmi
- conventional beam: $\nu_\mu \rightarrow \nu_e$ appearance
- large distance $\Rightarrow$ matter effects
- ν_μ and $\bar{\nu}_\mu$ mode



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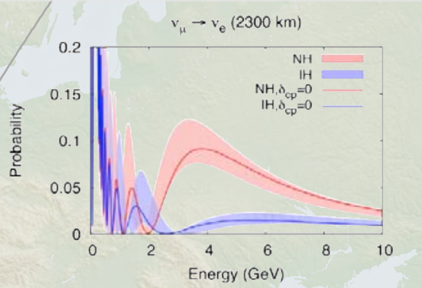
Pyhäsalmi

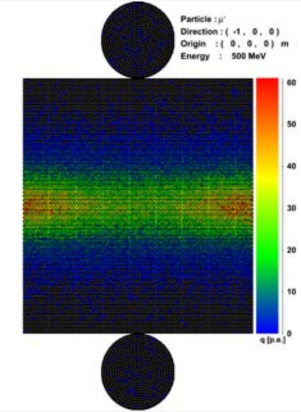
CERN

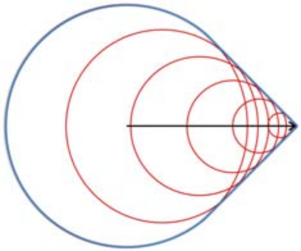
Strong signature for MH



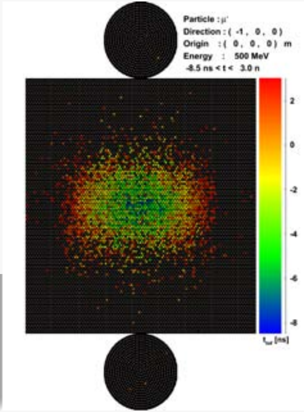
Tracking

Charge distribution



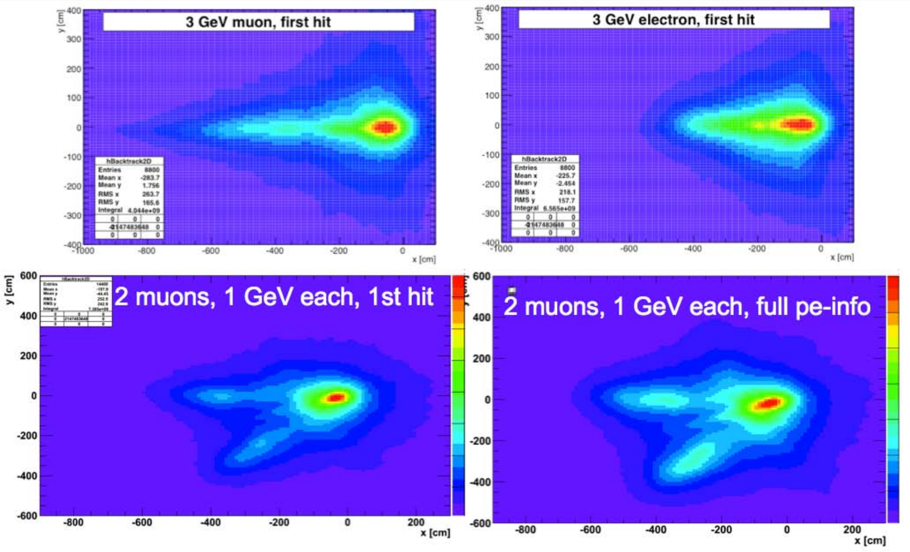


Arrival times



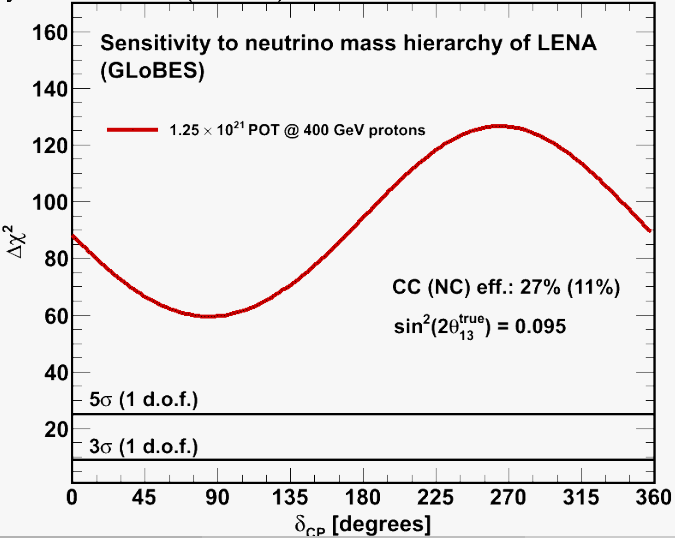
Use patterns of first photon arrival times and integrated charge per PMT

Event Reconstruction



Mass Hierarchy

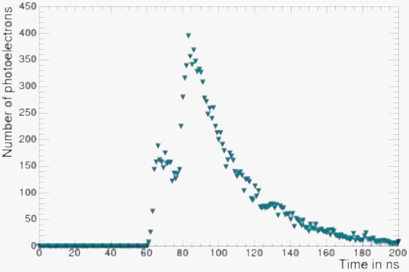
- Sensitivity plots created using GLoBES.
- 10 years of beam (5ν, $5\bar{\nu}$).

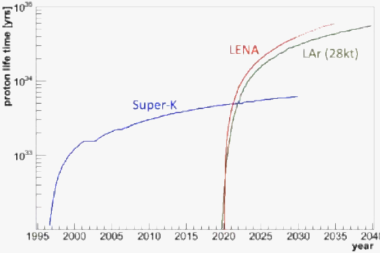


LENA can set a limit of
$\tau_p > 4 \times 10^{34}$ years in the channel

$$p \rightarrow K^+ + \bar{\nu}$$

- distinct pulse shape
- signal generated by kinetic energy deposition of kaon
- special for LS – cherenkov threshold not reached in water
- prompt signal followed by signals from decay products
- background free for 10 years





Conclusions

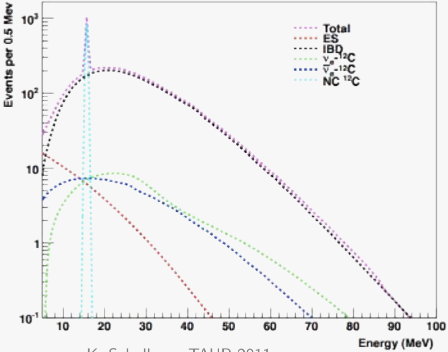
- Liquid scintillator is optimal for neutrino detection in the MeV range.
- Rich physics program includes SN neutrinos, solar neutrinos, geo neutrinos, reactor neutrinos, neutrino oscillometry ...
- Significant progress has been achieved with tracking in the GeV Range.
- LENA as a far detector for a neutrino beam from CERN has the potential of determining the mass hierarchy at $> 7\sigma$
- Sensitive to $\tau_p > 4 \times 10^{34}$ years in the channel $p \rightarrow K^+ + \bar{\nu}$.

5 Additional Slides

- SN Rates
- DSNB NC Background
- Mass Hierarchy and CP Violation
- Beam NC Background
- π^0
- Tracking

Galactic Supernova Rates

Reaction	Type	$\langle E_\nu \rangle = 14\,\mathrm{MeV}$
$\bar{\nu}_e\, p \rightarrow n\, e^+$	CC	$1.3\times\ 10^4$
$\nu\, p \rightarrow p\, \nu$	NC	2.6×10^3
$\nu\, e \rightarrow e\, \nu$	NC	6.2×10^2
$\nu\, {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^*\, \nu$ ${}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C}\, \gamma$	NC	1.0×10^3
$\bar{\nu}_e\, {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B}\, e^+$ ${}^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C}\, e^-\, \bar{\nu}_e$	CC	2.9×10^2
$\nu_e\, {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}\, e^-$ ${}^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C}\, e^+\, \nu_e$	CC	3.4×10^2



K. Scholberg, TAUP 2011

DSNB Background Rejection

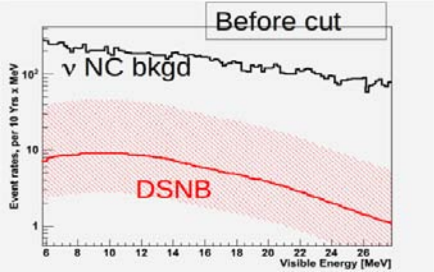
Atmospheric neutrino NC reaction neutron production

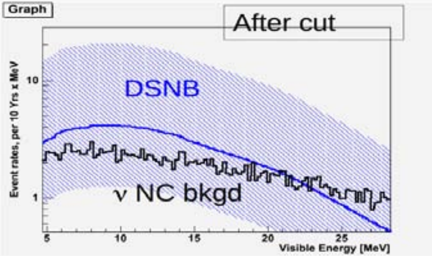
$$\nu + {}^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{C}^{*} + n$$

- tag β^+ from ^{11}C decay
- $^{11}\mathrm{C}^*$: deexcitation via emission of p,n, or α

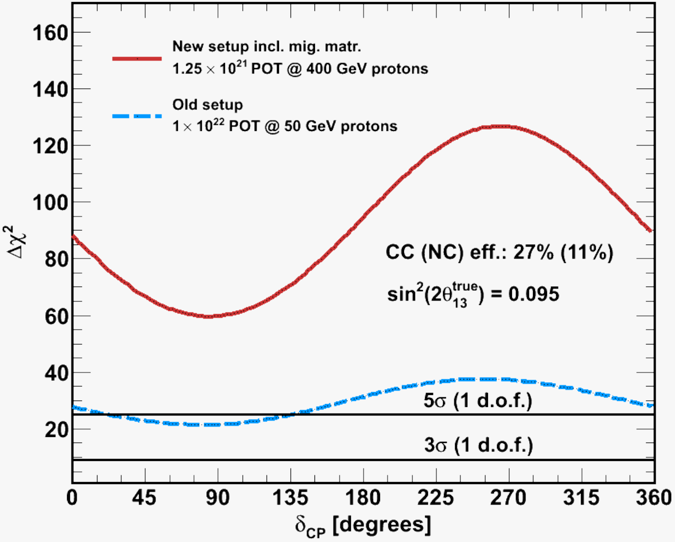
$\rightarrow$ pulse shape analysis

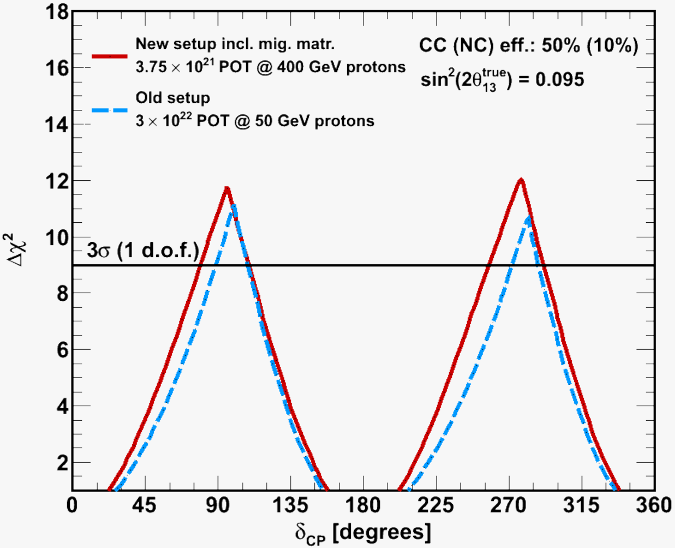
Preliminary results: Monte-Carlo simulation based on recent results of PSD parameter on LAB scintillators





Improved Calculations for Mass Hierarchy




New setup incl. mig. matr.
3.75 × 10^21 POT @ 400 GeV protons
Old setup
3 × 10^22 POT @ 50 GeV protons
CC (NC) eff.: 50% (10%)
sin²(2θ13^true) = 0.095
3σ (1 d.o.f.)
Δχ²
δCP [degrees]
0
45
90
135
180
225
270
315
360
2
4
6
8
10
12
14
16
18

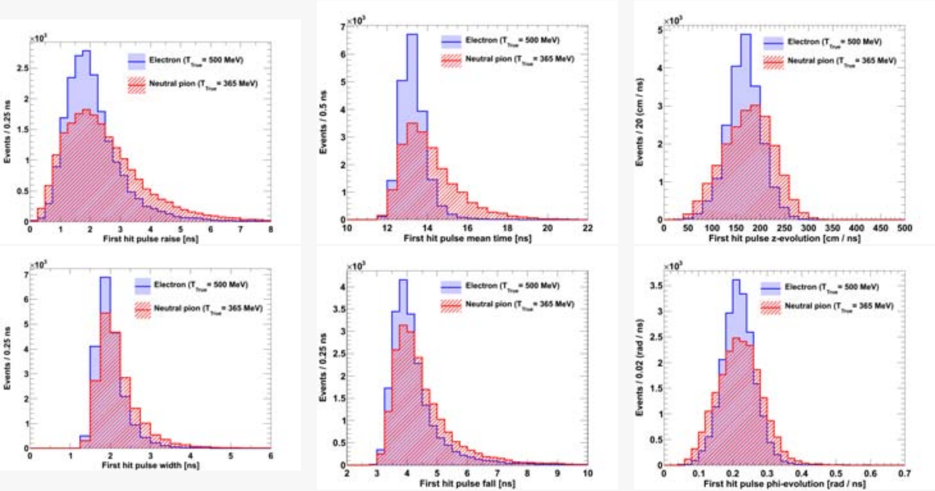
Background from NC Beam Events

$$\nu + X \rightarrow \nu + X^* + \text{other particles}$$

- 44% $\pi^+ \rightarrow$ tagging of μ^+ (86% efficiency)
- 32% π^0, no $\pi^+ \rightarrow$ multivariate analysis
- 1.7% $e^\pm$, γ, $K^{0,\pm}$
- 7% Pure $\pi^- \rightarrow$ pulse shape
- 15% p, $n \rightarrow$ pulse shape

Conservative estimates:
27% of all CC are reconstructed
11% of all NC events are misidentified as CC events

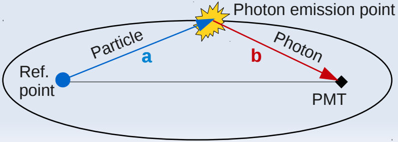
π^0-Discrimination - Multivariant Analysis



Tracking algorithm

General idea of the tracking algorithm:

1) Construct spatial point the event is located on for a given point in time
2) Use the constructed point as reference for all signal times;
   signal time = particle tof + photon tof (different speeds!)
3) Construct surfaces containing the corresponding photon emission points (drop-like shape)
4) Smear out surface boundaries by including timing effects e.g. PMT resolution, scintillator decay etc.
5) Superimpose all drop-like shapes on spatial binning of the detector
6) Keep bins containing significant overlap of „drops“
   → reflection of the events spatial topology



$ct = |\mathbf{a}| + |\mathbf{b}|$ (ellipse)

$ct = |\mathbf{a}| + n^*|\mathbf{b}|$ („drop“)

n : refractive index

Preliminary Results