Neutrino-beam physics in LAGUNA-LBNO

Dominikus Hellgartner

Technische Universität München
Physik Department, E15

Seminar on Dark Matter and Neutrinos

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Contents

Leptonic mixing matrix

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{interference}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

Results of global fit:

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.62 ± 0.19	7.27–8.01	7.12–8.20
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.34 - 2.69$ $-(2.25 - 2.59)$	$2.26 - 2.77$ $-(2.15 - 2.68)$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	0.41–0.62 0.42–0.62	0.39–0.64
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	0.019–0.033 0.020–0.034	0.015–0.036 0.016–0.037
δ	$\left(0.83^{+0.54}_{-0.64}\right)\pi$ 0.07π [a]	$0 - 2\pi$	$0 - 2\pi$

arXiv:1205.4018v2

Missing parameters:

- The sign of Δm^2_{31}
  $\Rightarrow$ Mass hierarchy
- The CP violating phase δ

$\Rightarrow$ Both missing parameters can be determined using neutrino beam experiments

Oscillation probabilities

- Most important channel for long-baseline conventional beams: $\overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_e$
- Oscillation probability for given baseline L:

$$
\begin{aligned}
P_{\mu e} \approx \; & \sin^2(2\vartheta_{13}) \sin^2(\vartheta_{23}) \left(\frac{\Delta_{13}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) \\
& + \cos^2(\vartheta_{23}) \sin^2(2\vartheta_{12}) \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right) \\
& + J \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\mp\delta - \frac{\Delta_{13} L}{2}\right)
\end{aligned}
$$

$$
J = \cos(\vartheta_{13}) \sin(2\vartheta_{12}) \sin(2\vartheta_{23}) \sin(2\vartheta_{13})
$$

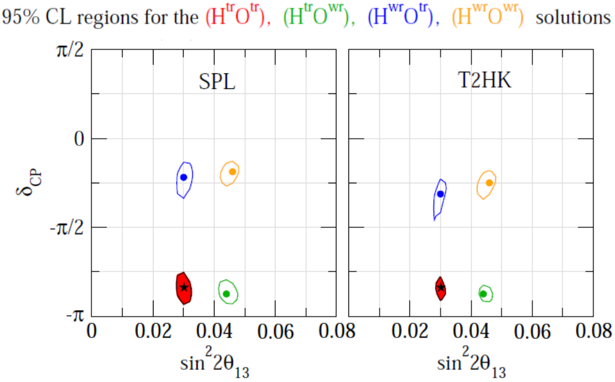
$$
B = |A \mp \Delta_{13}|, \quad A = \sqrt{2} G_f n_e \quad \text{and} \quad \Delta_{ij} = m_{ij}^2/2E
$$

$\Rightarrow$ All parameters can be measured in one experiment

$\Rightarrow$ All parameters are correlated

- Adjust L/E to first oscillation maximum

Degeneracies



J.-E. Campagne, M. Maltoni, M. Mezzetto and T. Schwetz, JHEP 04, 003 (2007), [hep-ph/0603172]

- Intrinsic degeneracy: Two solutions in ϑ_{13}-δ-plane with same oscillation probability (for one energy)
- Sign degeneracy: Sign of Δm^2_{13} unknown
- Octant degeneracy: Octant of ϑ_{23} unknown

$\Rightarrow$ Up to 8 degenerate solutions

Channels

Interactions

- Quasielastic scattering (Qel):
  - CC: $\nu_l + n \rightarrow l^- + p$
  - NC: $\nu_l + x \rightarrow \nu_l + x, \quad \text{with} \;\; x \in \{p, n\}$
- Resonant pion production (Res):
  - CC: $\nu_l + x \rightarrow l^- + x^* \rightarrow l^- + \pi + x', \quad \text{with } x, x' \in \{p, n\}$
  - NC: $\nu_l + x \rightarrow \nu_l + x^* \rightarrow \nu_l + \pi + x', \quad \text{with} \;\; x, x' \in \{p, n\}$
- Deep inelastic scattering (Dis)
  - Interaction with single quarks
  - Following hadronization produces lots of pions

Signal

- ν_e-appearance $\Rightarrow$ CC-reactions with ν_e

$\Rightarrow$ Electromagnetic shower in detector

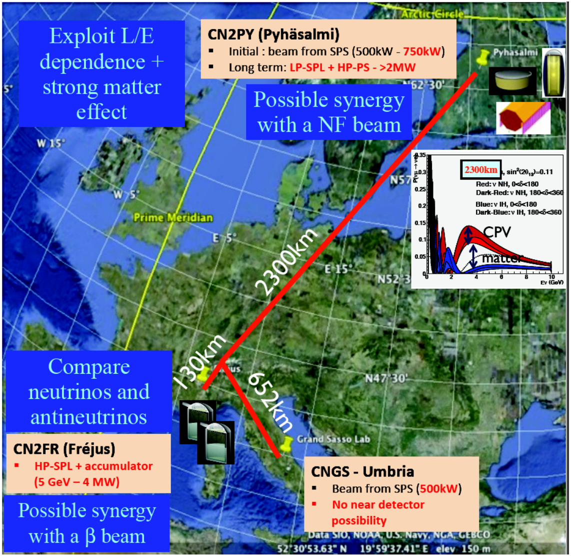
Background

- Everything which fakes an electromagnetic shower
- Main background: π^0 with overlapping gamma showers

LAGUNA-LBNO

Large Apparatus for Grand Unification and Neutrino Astrophysics

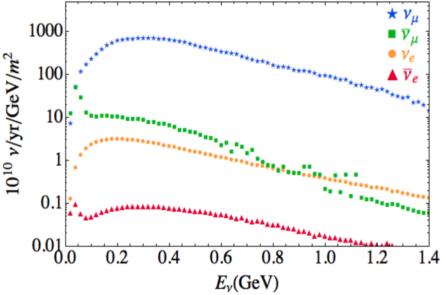
- Feasibility study of megaton scale underground detectors with neutrino beams
- Focus on 3 sites
- Main focus currently on Pyhäsalmi
- Frejus to come
- Umbria as “backup” solution
- Currently considering ∼MW superbeams

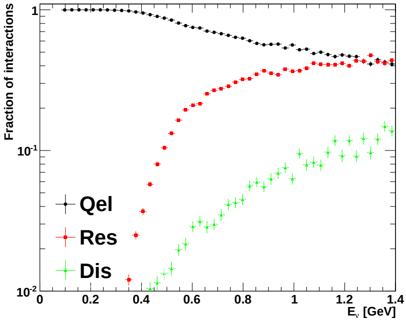


The Frejus beam

- 4 MW superbeam
- Baseline 130 km
- Matter effects negligible
- Wide beam favorable for resolving degeneracies
- Small ν-cross section due to low neutrino energies
  $\Rightarrow \sim$100 kt detectors required
- Qel and Res interactions dominate
  $\Rightarrow$ Simple event geometries

A. Longhin, 1106.1096 [physics.acc-ph]

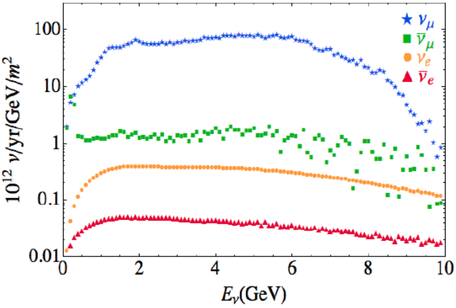


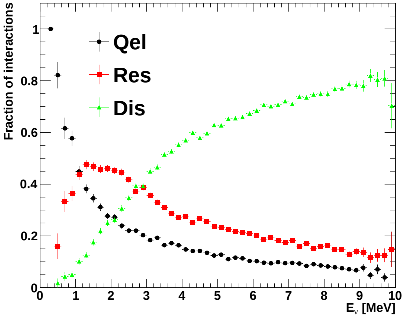


The Pyhäsalmi beam

- 0.8/2.3 MW superbeam
- Baseline 2300 km
- Flux $\propto L^{-2}$
- $\sigma \propto E$ (Dis regime)
- Wide beam to resolve degeneracies + 2nd oscillation maximum
- Strong matter effects
- Dominated by the deep-inelastic regime $\Rightarrow$ Event reconstruction challenging

A. Longhin, PoS ICHEP2010 (2010) 325



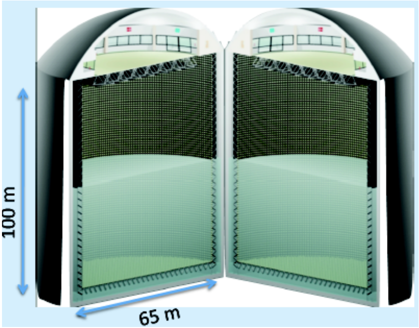


The WC-MEMPHYS

- Huge Water-Cherenkov Detector
- 2 cylindrical modules, 65 m × 100 m

⇒ Total fiducial volume 500 kt

- Size limited due to attenuation length and pressure
- 222 000 PMTs (8”) @ 30%coverage



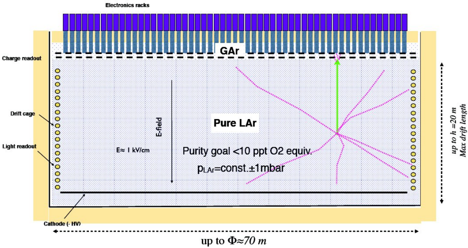
- Reconstruction algorithms adapted from SuperK
- Site: Frejus

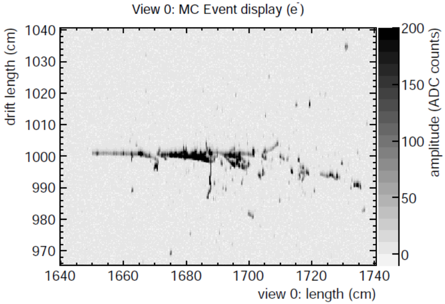
The LAr-GLACIER

- Liquid Argon two-phase TPC
- Scalable design, up to 100 kt
- Very high purity required due to long drift paths
- Up to now only small prototypes built
- Excellent energy and spatial resolution

⇒ Excellent event reconstruction even for complicated event structures

- Supplemented with a magnetized iron detector





The LSc-LENA

Detector Layout

- Cylindrical detector (h = 100 m, r = 16 m)
- Filled with liquid scintillator ∼50 kt
- ∼30% photo-coverage

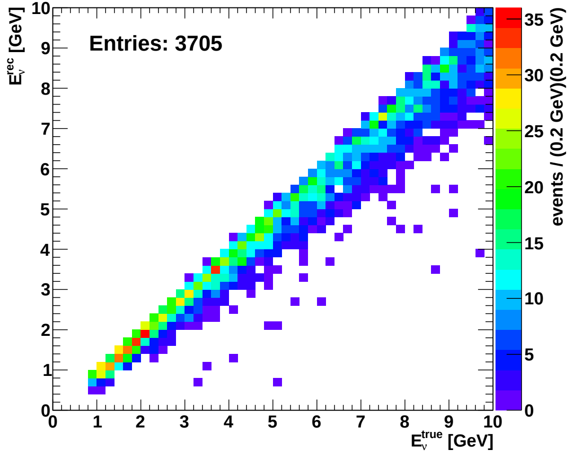
  ⇒ ∼ 30 000 12”-PMTs with light concentrators
- Surrounded by > 2 m water
- Overburden ∼ 4000 mwe
- Additional feature: Very rich low energy physics program

Energy resolution

- For full neutrino events, energy resolution limited by:
  - Nuclear effects
  - Quenching (Light yield is dependent on particle type)

$\Rightarrow$ Overall CC energy resolution $\approx$ 10%

CC-ν_e



Event reconstruction: Basic principle

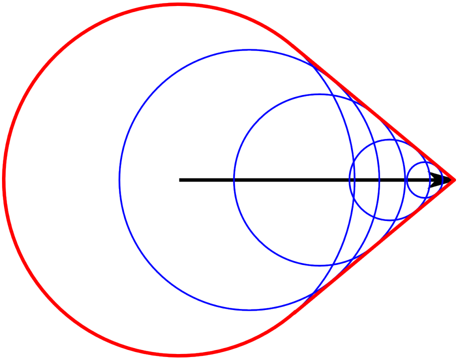
Problem: Scintillation photons are emitted isotropically

⇒ No directional information from the charge distribution

⇒ Use photons' arrival times for track reconstruction

General idea

- Isotropic emission over total track length
- Superposition of spherical "waves" leads to first photon cone
- The shape of the cone contains information about the track direction

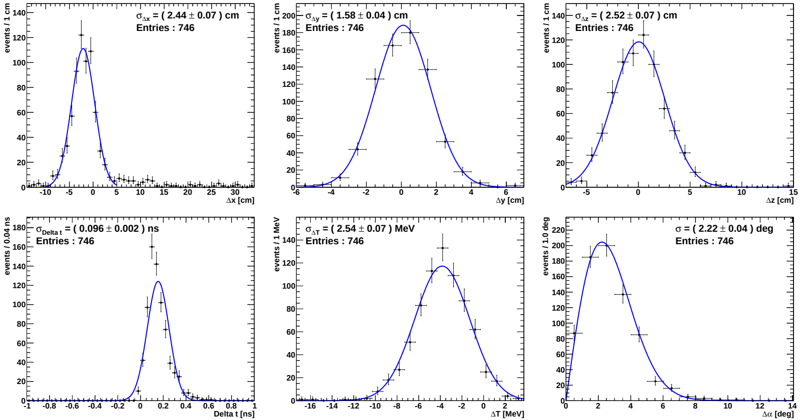


500 MeV Muons

Sample

- Simulation: 1000 μ^- from $(0, 0, 0)$ along negative x-axis
- Require an identified muon decay with decay time > 500 ns

Results



GLoBES input parameters

Detector parameters

Detector	kton	ϵ	NC Bg.	$\sigma(E)$	E_ν (GeV)
LAr	100	90%	$0.5\%^*$	$0.15(\nu_e)$ $0.20E(\nu_\mu)$	$[0.5, 10]$
LSc	50	$90\% - 50\%$	$30\% - 10\%$	$0.05E$	$[0.5, 7]$
WC LE	440	$\sim 70\%$	$< 0.1\%^*$	MigMat	$[0.1, 1]$

$^* \equiv$ Migration Matrices used

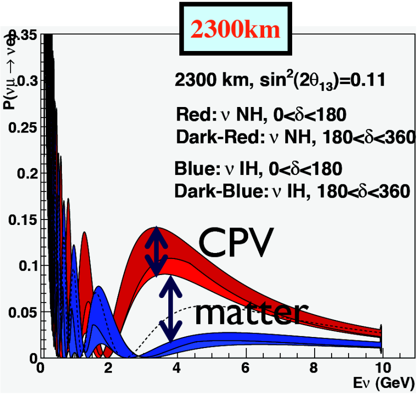
General parameters

- 4%/10% errors on solar/atmospheric parameters
- Normal hierarchy
- Matter density uncertainty 2%
- 130 km beam: $5.6 \cdot 10^{22}$ pot/a (4 MW, $10^7 s/a$), 2+8 a
- 2300 km beam: $3 \cdot 10^{21}$ pot/a (2.4 MW, $10^7 s/a$), 5+5 a

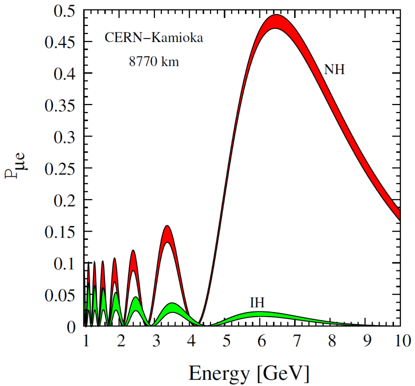
Mass hierarchy: The case for longer baselines

- The longer the baseline, the bigger the matter effect
- Separation of hierarchies improved with longer baselines

2300 km: Pyhäsalmi

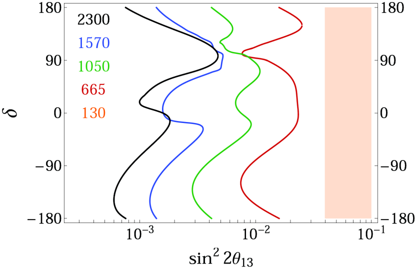


8770 km: SuperK

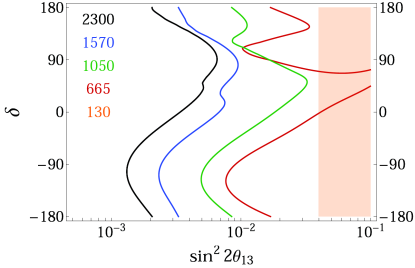


Mass Hierarchy: Expected sensitivity

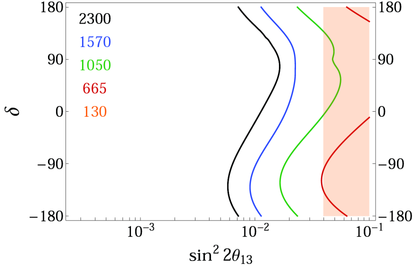
GLACIER

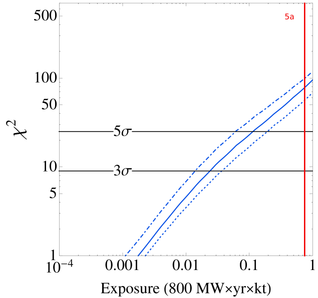


MEMPHYS



LENA

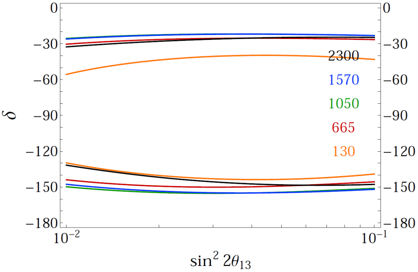




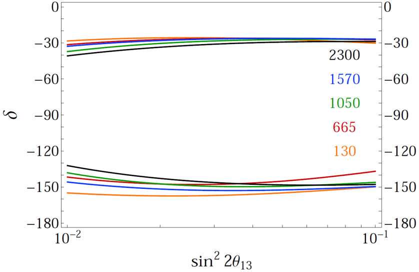
P. Coloma, T. Li, S. Pascoli, arXiv:1206.4038v1

CP-violation: Expected sensitivity

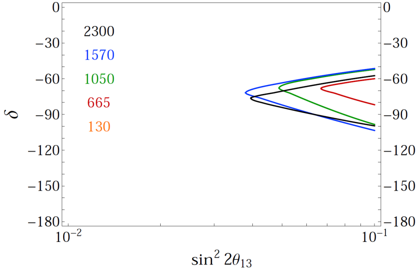
GLACIER

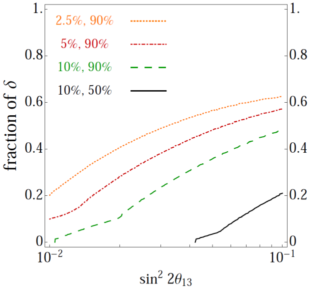


MEMPHYS



LENA

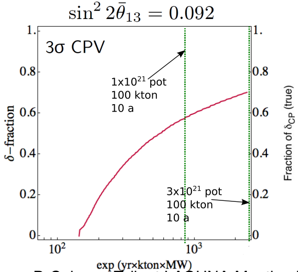




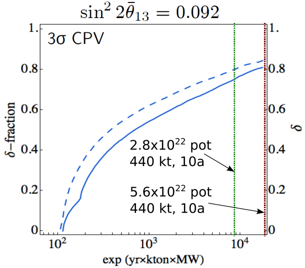
P. Coloma, T. Li, S. Pascoli, arXiv:1206.4038v1

CP-violation: Expected sensitivity II

GLACIER @ 2300 km

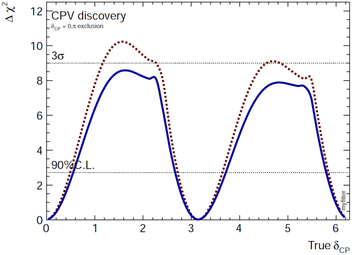


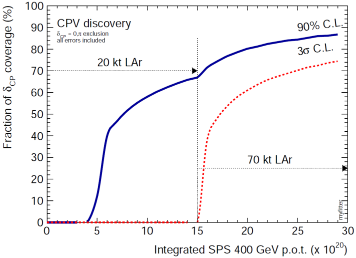
MEMPHYS @ 130 km



P. Coloma, Talk at LAGUNA-Meeting in Paris

20 kt GLACIER @ 2300 km



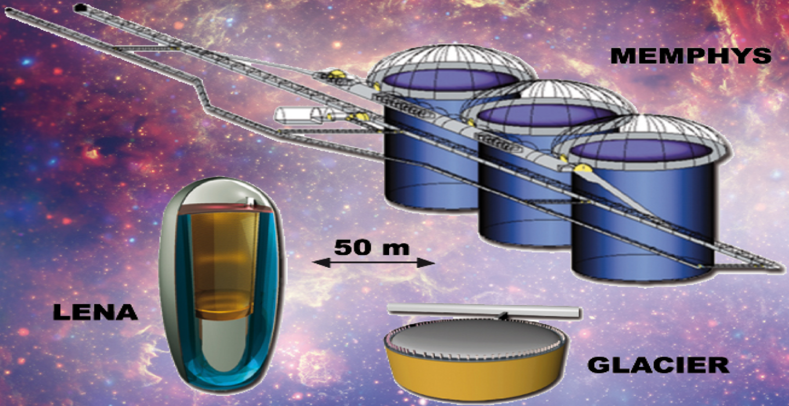


A. Rubbia, Expression of Interest for a very long baseline neutrino oscillation experiment

Conclusion

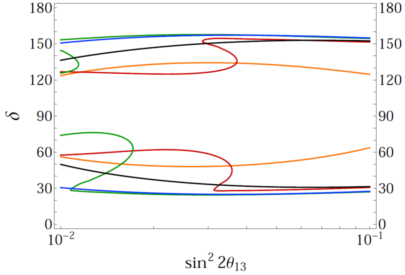
- LAGUNA-LBNO design study ongoing
- Three detector options GLACIER, MEMPHYS and LENA
- Reconstruction of extended events in LENA possible
- The mass hierarchy:
  - Is “easier” to measure due to big $\sin^2(2\vartheta_{13})$
  - Can be measured at 5σ by all three detectors if CN2PY baseline is used
  - Is difficult to measure on short baselines
- The CP-violation
  - Is more challenging to measure
  - Requires higher statistics
  - Is more sensitive to background
- $70 - 80\%$ CP-violation at 3σ possible

Thank you four your attention!

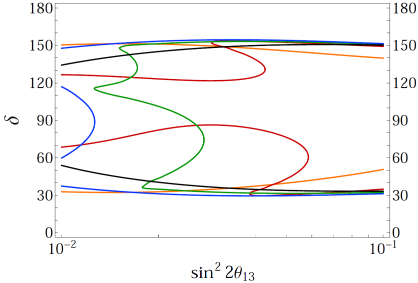


CP-violation: $\delta > 0$

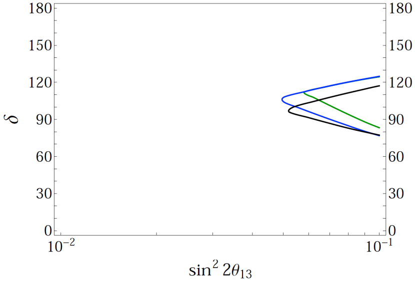
GLACIER

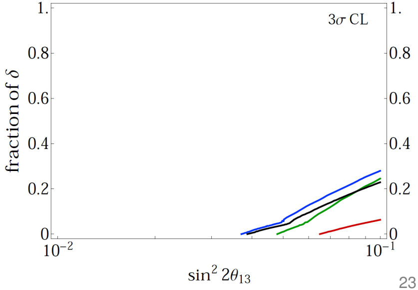


MEMPHYS



LENA

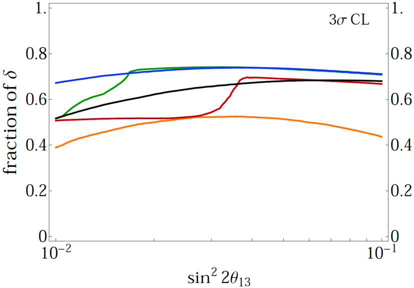


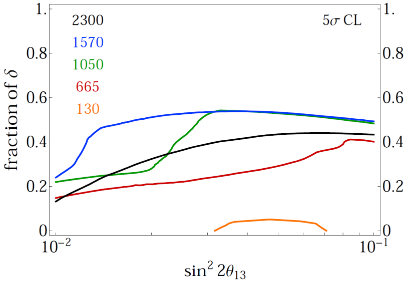


P. Coloma, T. Li, S. Pascoli, arXiv:1206.4038v1

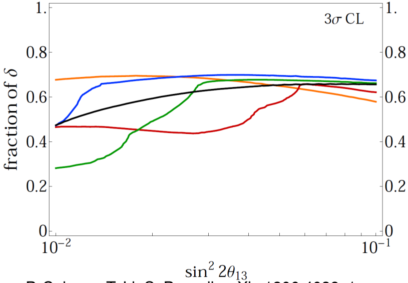
CP-violation: Coverage

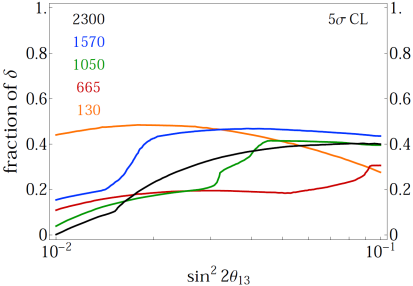
GLACIER





MEMPHYS

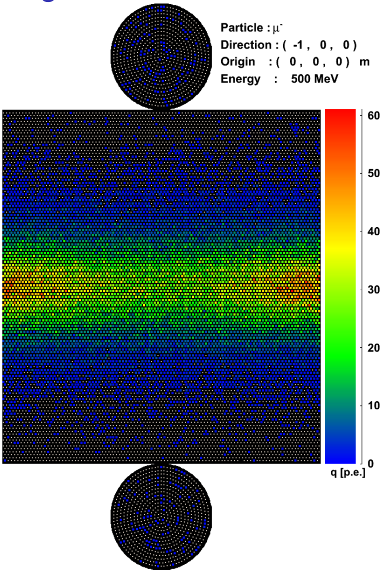




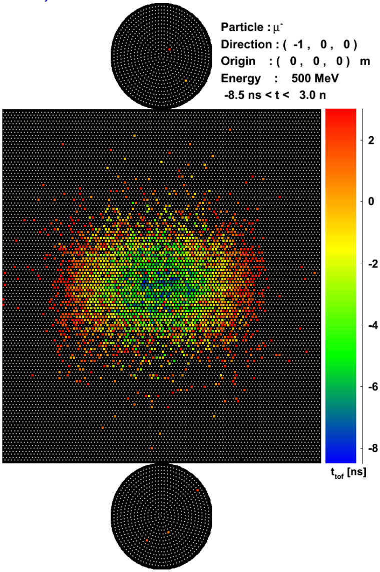
P. Coloma, T. Li, S. Pascoli, arXiv:1206.4038v1

Event signature

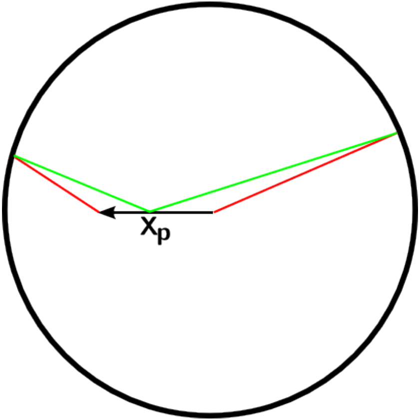
Charge



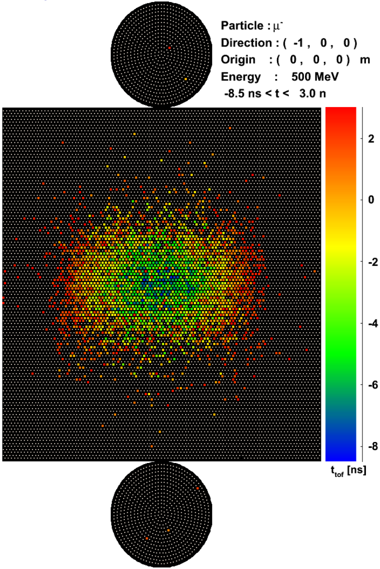
(First) hit-time



Event signature



(First) hit-time



Fit parameters

Assumptions

- Track length fluctuations and multiple scattering of muons negligible
- Muons decay at rest

7 fit parameters: $\boldsymbol{X}$

- Kinetic energy $\rightarrow$ 1 parameter: T
- Coordinates of track start point $\rightarrow$ 3 parameters: $\boldsymbol{x}_s$
- Direction of the track $\rightarrow$ 2 parameters: (ϑ, φ)
- Start time of event $\rightarrow$ 1 parameter: t_s

Parameter estimation

- Use charge $\boldsymbol{q}$ and first hit-time $\boldsymbol{t}$ of each PMT as signal
- Calculate PDF $P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X})$
- Minimize NLL $\mathcal{L}(\boldsymbol{X}|\boldsymbol{q}, \boldsymbol{t}) = -\ln\left[L(\boldsymbol{X}|\boldsymbol{q}, \boldsymbol{t})\right] = -\ln\left[P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X})\right]$

Basic structure of the PDF

- PDF $P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X})$ of very high dimension
- Assume all PMTs to be equal and independent of each other

$$\Rightarrow \; P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X}) = \prod_{i=1}^{N_{\mathrm{PMT}}} P_i(q_i, t_i|\boldsymbol{X}) = \prod_{i=1}^{N_{\mathrm{PMT}}} P(q_i, t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i)$$

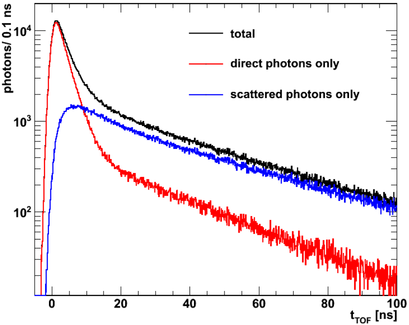
- For PMTs with $q_i = 0$ the PDF is independent of t_i
- For PMTs with $q_i \neq 0$ the PDF can be decomposed: $P(q_i, t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i) = P(q_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i)P(t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i, q_i)$

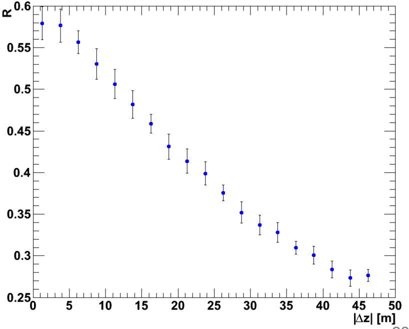
$\Rightarrow$ The overall PDF is of the form:

$$P(\boldsymbol{q}, \boldsymbol{t}|\boldsymbol{X}) = \prod_{i}^{q_i=0} P(q_i = 0|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i) \prod_{i}^{q_i\neq 0} P(q_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i)P(t_i|\boldsymbol{X}, \boldsymbol{r}_i, \boldsymbol{n}_i, q_i)$$

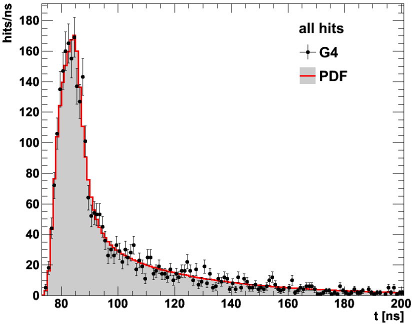
Considerations for calculating the PDF

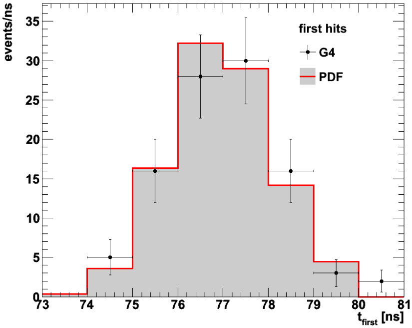
- Mean number of photons emitted per unit track length
- Muon propagation in time
- Time resolution of the PMTs
- Finite dimensions of the PMTs
- Decay time distribution of the scintillator
- Attenuation/scattering in the scintillator (changes both, the number of detected photons as well as their arrival times)
- Expected hit-time of an ideal photon





Comparison of time PDF with Geant4





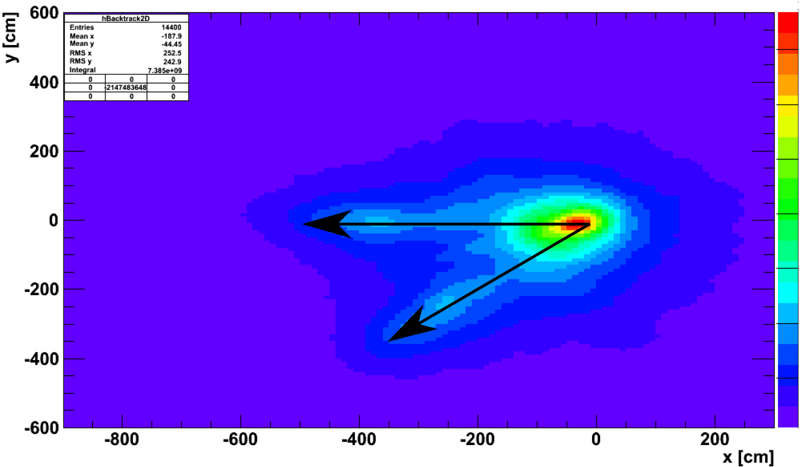
- Good agreement for total spectrum as well as for first hit-time spectrum
- Agreement deteriorates for lower energies as assumptions are no longer valid

Backtracking

- PROBLEM How to estimate start parameters for the tracking

⇒ Need ”bubble chamber“ like imaging without previous input

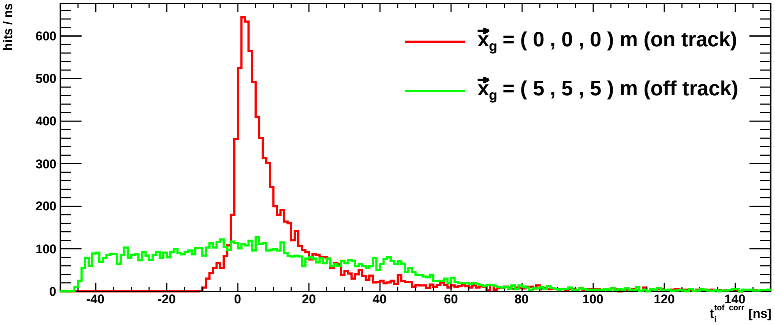
- Can be done using the ”sharpness“ of TOF corrected pulses as parameter



Backtracking

1. Choose a point to qualify whether a track was there: $\boldsymbol{x}_g$
2. Create a vector with the TOF-corrcted hit times w.r.t. $\boldsymbol{x}_g$:

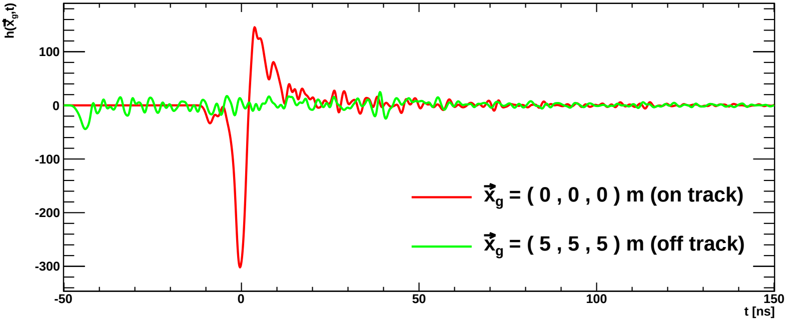
$$\boldsymbol{t}^{\text{TOF}} = \left(t_i^{\text{TOF}} \right) = \left(t_i^{\text{hit}} - \frac{n}{c} \left| \boldsymbol{x}_g - \boldsymbol{x}_i^{\text{PMT}} \right| \right)$$



Backtracking II

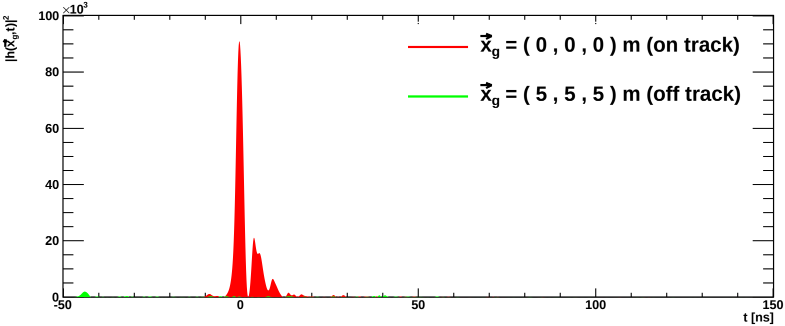
3. Calculate:

$$h(\boldsymbol{x}_g, t) = \sum_{i=1}^{N_{\text{PMT}}} (t - t_i^{\text{tof\_corr}}) \cdot \exp\left[-\frac{(t_i^{\text{tof\_corr}} - t)^2}{2\sigma_{\text{tts}}^2} \right]$$



Backtracking III

4. Calculate: $\left| h(\boldsymbol{x}_g, t) \right|$

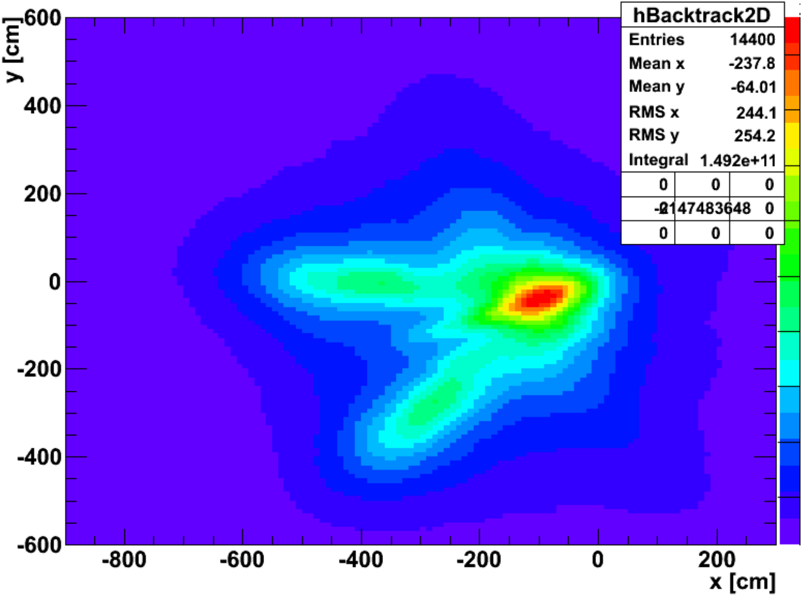


5. The figure of merit is:

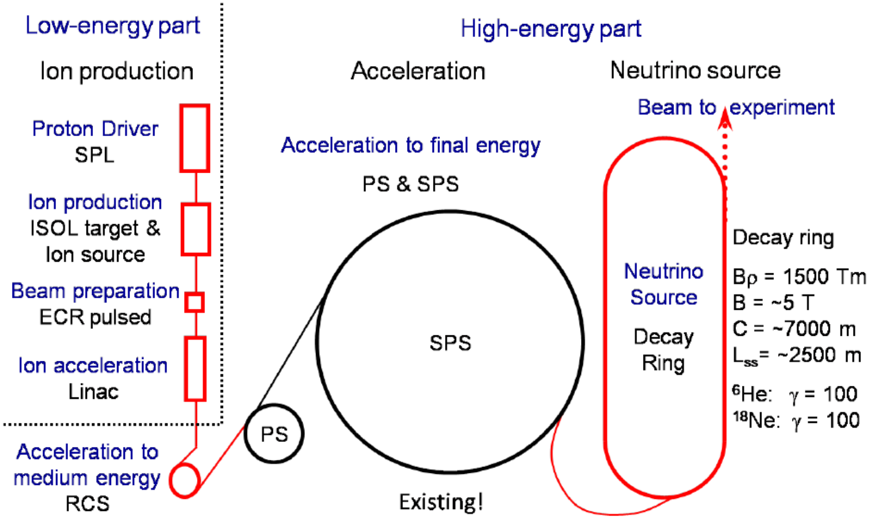
$$f_{\text{FCN}}(\boldsymbol{x}_g) = \int_{-\infty}^{\infty} \left| h(\boldsymbol{x}_g, t) \right|^2 dt$$

Backtracking IV

Two muons with the first 7 hits on each PMT taken into account:



β-beam

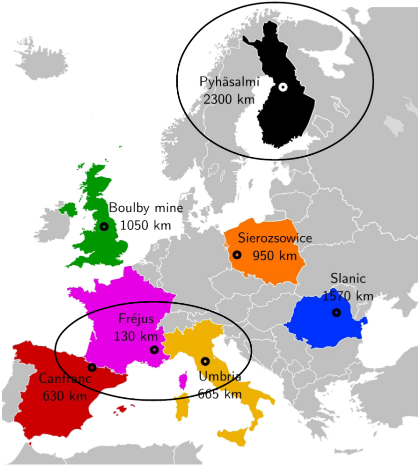


Low-energy part
Ion production
Proton Driver
SPL
Ion production
ISOL target &
Ion source
Beam preparation
ECR pulsed
Ion acceleration
Linac
Acceleration to
medium energy
RCS
High-energy part
Acceleration
Acceleration to final energy
PS & SPS
PS
SPS
Existing!
Neutrino source
Beam to experiment
Neutrino
Source
Decay
Ring
Decay ring
Bρ = 1500 Tm
B = ~5 T
C = ~7000 m
L$_{ss}$= ~2500 m
^{6}He: γ = 100
^{18}Ne: γ = 100

The LAGUNA design study

Large Apparatus for Grand Unification and Neutrino Astrophysics

- European founded FP7 design study:
  Feasibility of megaton scale underground detector
- Investigated 7 different sites
- Continued since 2011 as LAGUNA-LBNO:
  - Additional focus on neutrino beams
  - Focus on detector construction and operation



Multi track fitting

- 2 μ^- with 500 MeV each, enclosed angle 45°