Tracking with LENA

Dominikus Hellgartner

Technische Universität München
Physik Department, E15

522. Wilhelm and Else Heraeus-Seminar

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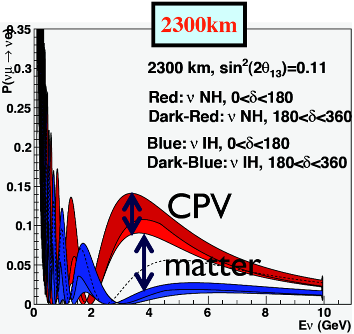
Contents

Long baseline neutrino oscillations

Physics goals

- Determination of the mass hierarchy
- Measurement of the CP-violating phase δ_{CP}



Detector requirements

- Good energy resolution
- Large target mass and cheap target material
- Capability to discriminate between ν_μ-CC, ν_e-CC and ν_x-NC interactions

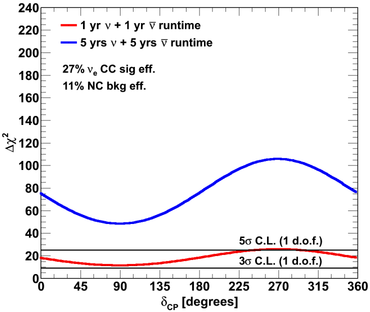
Current situation for LENA

NC background discrimination

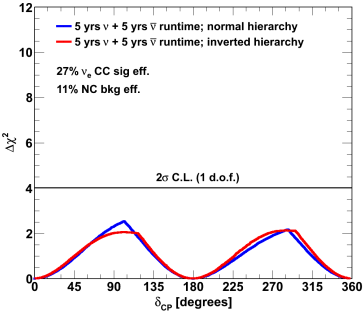
- Based on multivariate analysis (boosted decision trees)
- Input parameters from overall photon pulse shape
- Only first photon time and total charge on each PMT used
- Time of flight correction w.r.t. charge barycenter

Sensitivity (2300 km, 10^{20} *POT* / *a*)

Mass Hierarchy

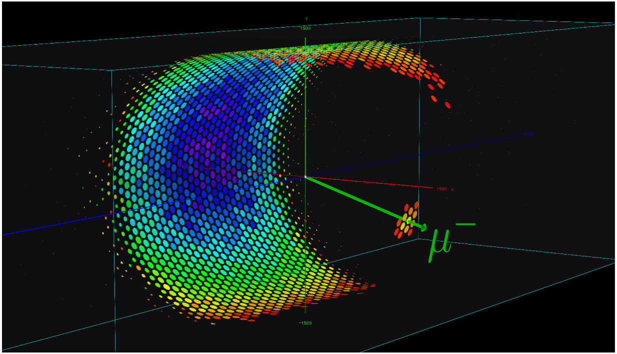


δ_{CP}



GLoBES plots by Sebastian Lorenz, Universität Hamburg

How to improve the situation



- The arrival times of the photons on the individual PMTs contains important information

⇒ Go beyond the overall pulse shape

⇒ Use the hit pattern to reconstruct general event structure

⇒ Additional input parameters for multivariate analysis

Basic considerations for LSc detectors

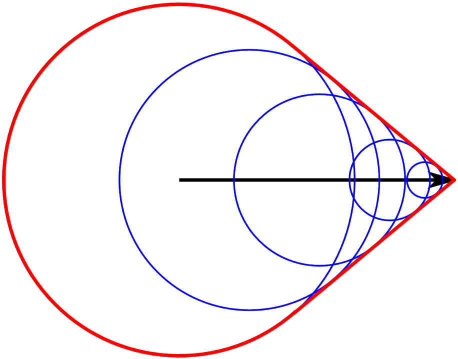
Problem: Scintillation photons are emitted isotropically

⇒ 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



Contents

Basics

Requirements

- Obtain bubble chamber like images
- Do not require any input knowledge

⇒ Goal: Get basic picture of an event

General idea

- Use only PMTs with a high charge
  - ⇒ The first detected photon on each PMT is emitted instantly
  - ⇒ The first detected photon on each PMT is not scattered

⇒ Time resolution dominated by PMTs

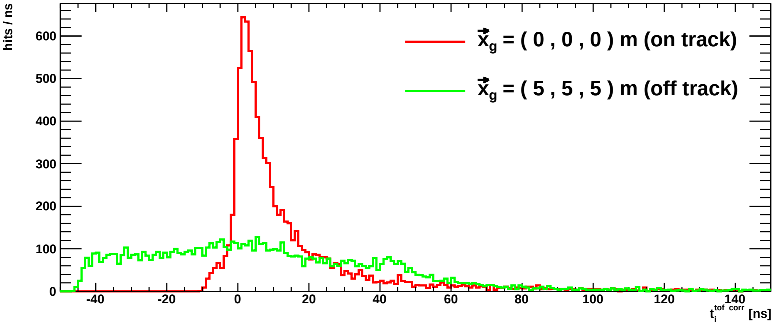
- Photons from a point source in the detector cluster in time after taking the photon TOF into account

This algorithm is currently developed by Kai Loo (University of Jyväskylä)

Algorithm I

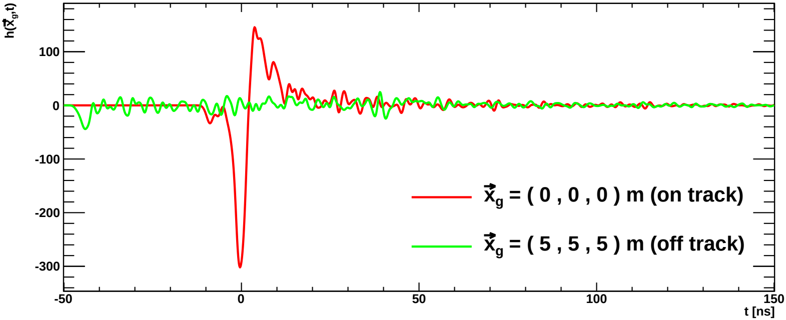
1. Choose a point to qualify whether a track was there: $\boldsymbol{x}_g$
2. Create a vector with the TOF-corrected hit times w.r.t. $\boldsymbol{x}_g$:

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



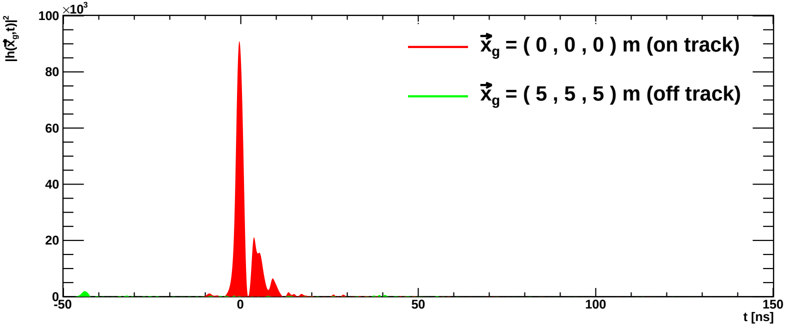
3. Calculate:

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



Algorithm III

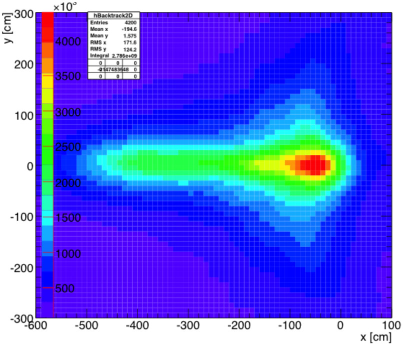
4. Calculate: $\left|h(\boldsymbol{x}_g, t)\right|^2$

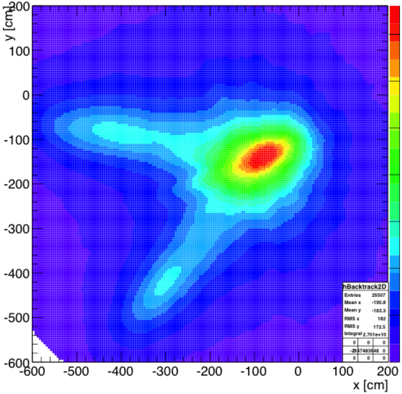


5. The figure of merit is:

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

Capabilities





- μ^-
  - 1 GeV
  - Origin (0,0,0)
  - Direction (-1,0,0)
- Only first hit information used

- 2 μ^-
  - 1 GeV each
  - Origin (0,0,0)
  - Enclosed angle 45°
- Multi-hit information used

Contents

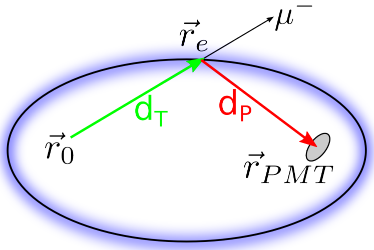
Basics

Assumption

- One reference point on/near track known $(\boldsymbol{r}_0, t_0)$.

Allowed photon emission points

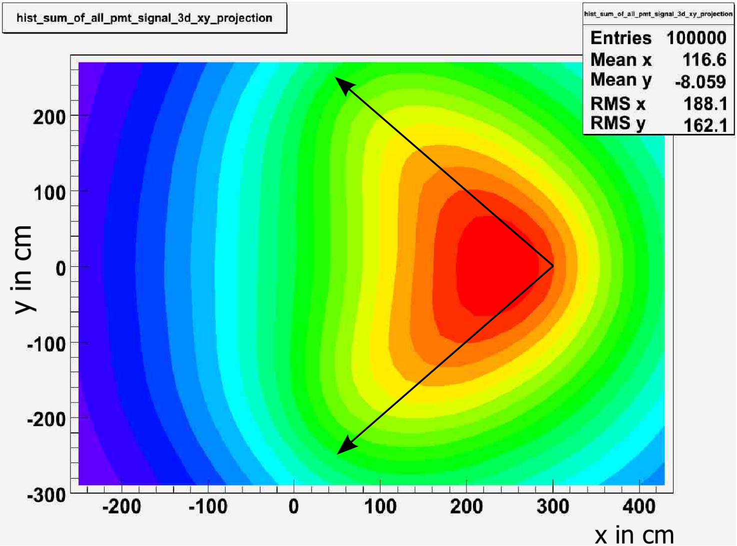
- $(t - t_0)c = d_T + n \cdot d_P$
- All allowed photon emission points $\boldsymbol{r}_e$ are
  - on an ellipsoid $(n = 1)$
  - on a drop-like surface $(n \neq 1)$
- Drop surfaces are smeared due to PMT-resolution and scintillator decay time
- Superimposing all smeared drop surfaces reveals the track



Invented and developed by Björn Wonsak (Universität Hamburg)

Results for LENA

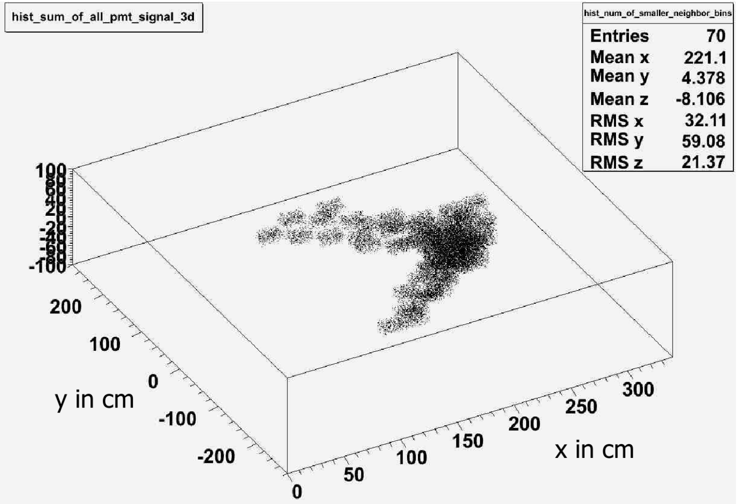
- 2 μ^-, 750 MeV each, enclosed angle 90°.
- Full hit information used



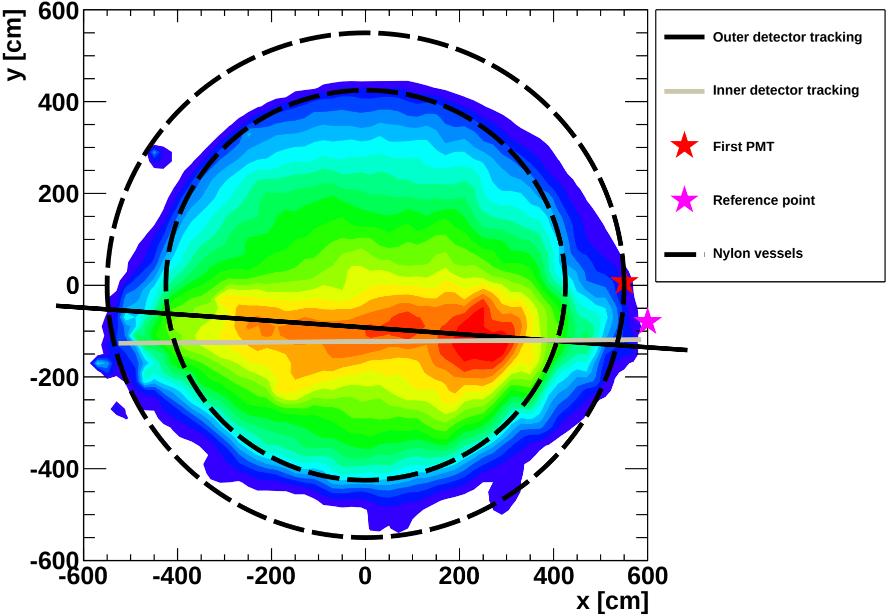
Ridge line analysis

- Tracks should show up as a ridge

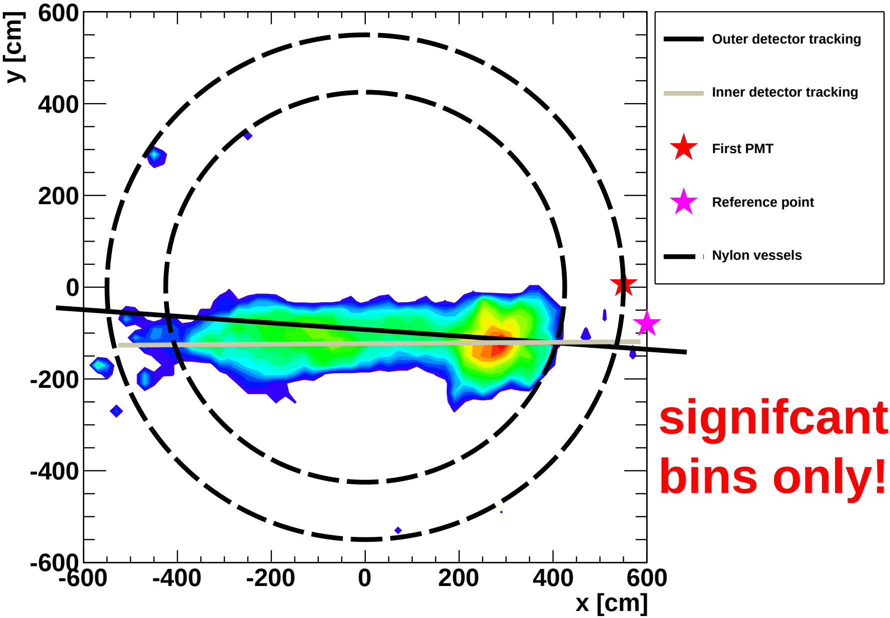
⇒ Take only bins with more than 17 smaller neighbors



Application to CNGS-μ^- in Borexino



Application to CNGS-μ^- in Borexino



signifcant bins only!

Contents

Basics

Assumption

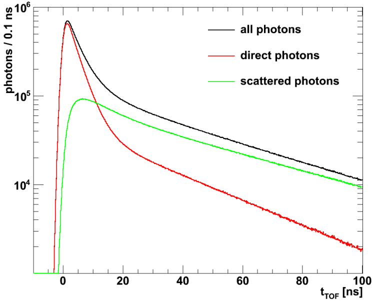
- There is at least one model for the event (1 track, 2 tracks, particle types ...)

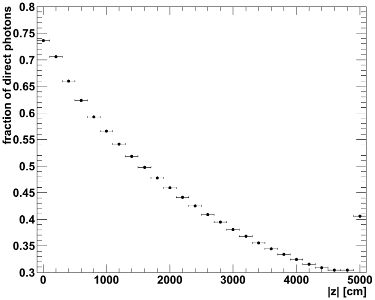
Likelihood fitting

- Determine free parameters of model: $\boldsymbol{x}$.
- Obtain a set of seed parameters for the fit ($\rightarrow$ Input from other tracking mechanisms)
- Calculate PDF for photon arrival times and charge: $P(\boldsymbol{t}, \boldsymbol{q}|\boldsymbol{x})$
- Maximize likelihood $L(\boldsymbol{x}|\boldsymbol{t}, \boldsymbol{q}) = P(\boldsymbol{t}, \boldsymbol{q}|\boldsymbol{x})$ w.r.t. $\boldsymbol{x} \Rightarrow \hat{\boldsymbol{x}}$.
- Distinguish different models by taking the model with the highest $L(\hat{\boldsymbol{x}}|\boldsymbol{t})$.

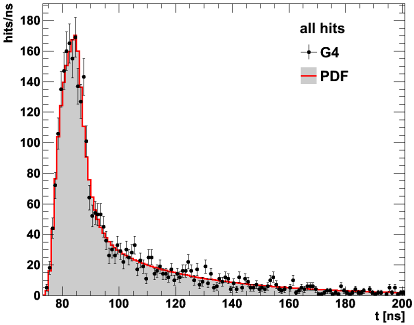
Considerations for calculating the PDF

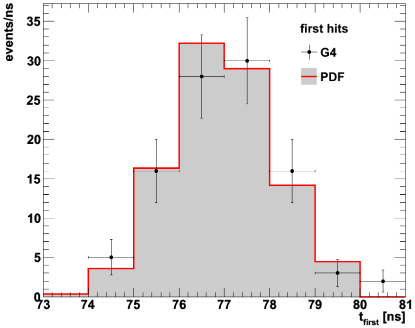
- Mean number of photons emitted per unit track length
- Particle/shower propagation in time
- Time resolution of the PMTs
- Finite dimensions of the PMTs
- Winston Cone acceptance function
- Decay time distribution of the scintillator
- Absorption/scattering of photons in the scintillator (changes both the number of detected photons as well as their arrival times, have to use MC input)





Comparison of calculated time PDF with Geant4





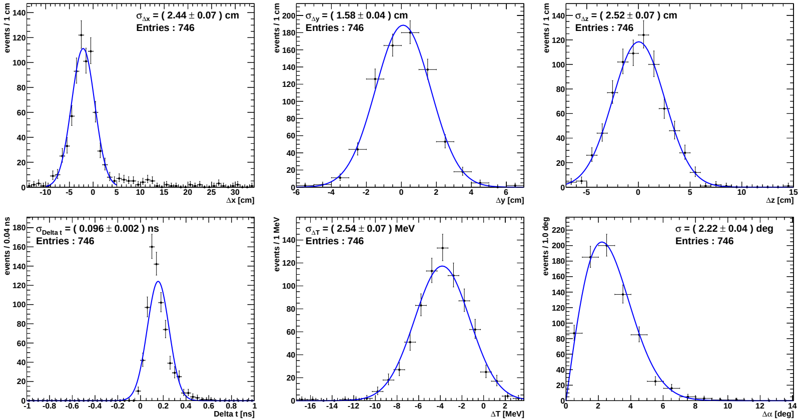
- Good agreement for total spectrum as well as for first-hit spectrum
- Agreement gets worse for lower energies as tracks deviate from straight line.

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

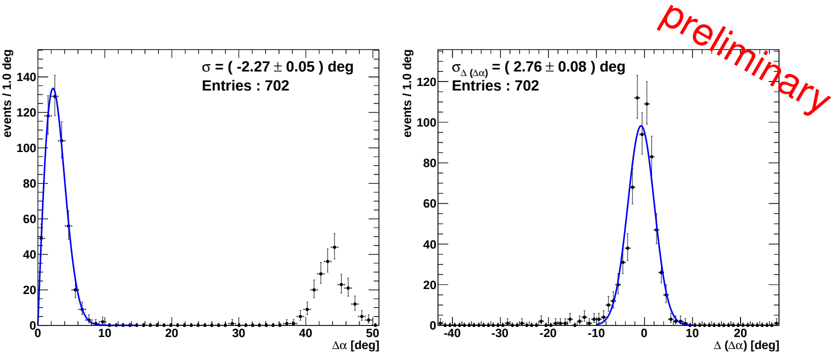
Results



Multi track fitting

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

- Currently uses MC-truth as seed.
- Vertex resolution (in 1 direction) $\approx$ 4 cm
- Energy resolution of each track $\approx$ 4%
  - Charge no longer strongly constrains energy
  - Energy of track determined from its length



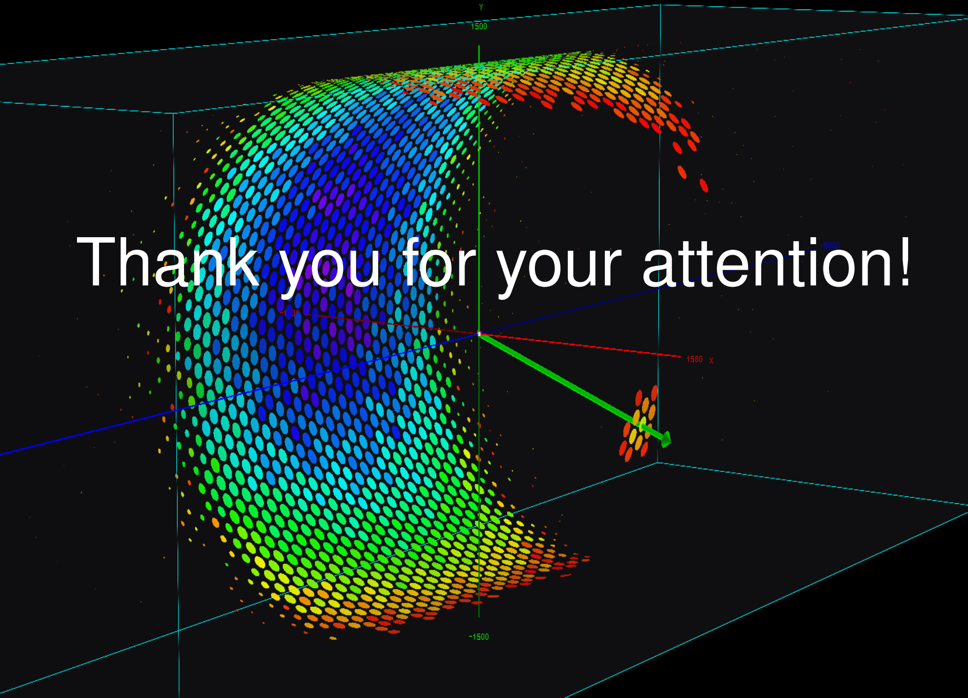
Conclusion

Current status

- Three approaches to reconstruct spatially extended events in LENA
- All algorithms work on muon events
- Two algorithms are currently tested on muons in Borexino.

Outlook

- Connect the algorithms: Use the result of one algorithm as input to the next algorithm.
- Extend the algorithms to be applied to full neutrino events
- Use the gathered information to improve the LENA beam performance



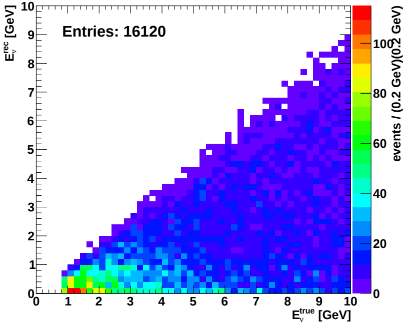
Thank you for your attention!

LENA Migration matrices

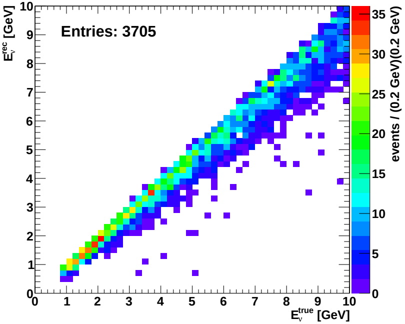
Simulation

- Neutrino events created with GENIE
- Detector simulation using GEANT4
- Simplified set-up with $\sim$ 10 000 PMTs
- Analysis uses only total charge and position of barycenter

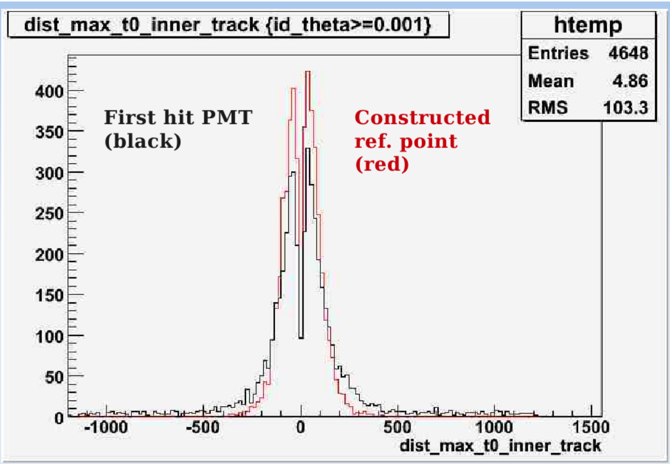
NC



ν_e-CC



Resolution Start Point Wonsack's tracking



Distributions for distance of reference point to the track

- Mean distance of constructed reference point to the track: $\sim$ 60 cm

Application CNGS-μ^- in Borexino

Complications

- No flash ADCs $\Rightarrow$ Only first hit information
- PMTs/Electronics in saturation $\Rightarrow$ No charge information

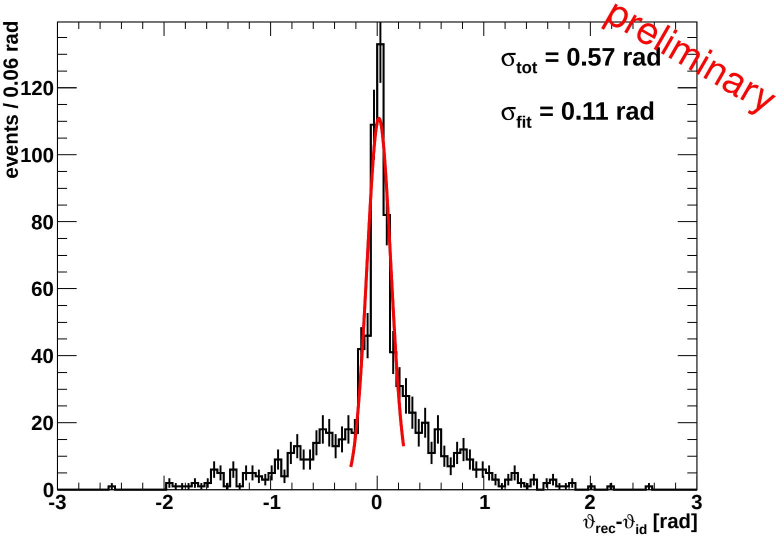
$\Rightarrow$ No charge barycenter available

$\Rightarrow$ Getting reference point challenging

Strategy

- Construct reference point
  1. For each spatial point, calculate required time correction
  2. Histogram time corrections
  3. Take point with overall highest bin
- Construct last point on reconstructed track
- Use this point to track backwards in time
- Use the first point on the backwards track as reference point for final fit

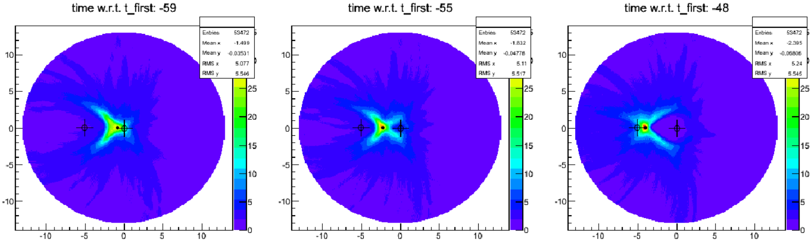
Resolution w.r.t. Borexino tracking

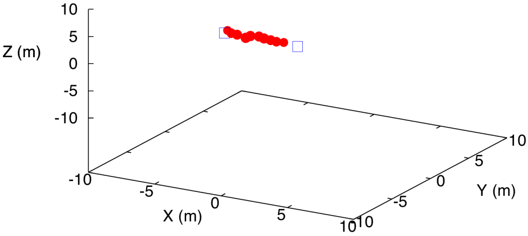


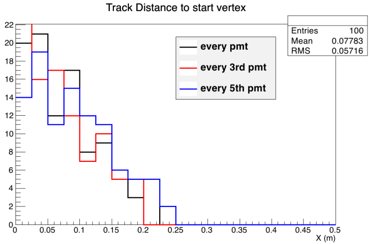
Note: Resolution of Borexino tracking $\approx$ 0.09 rad

Single muon tracking

- Divide event in time snapshots and propagate the PMT pulses backwards to this time.
- Follow maximum







Beam performance input parameters

Sebastian Lorenz, Universität Hamburg

General setup

- GLoBES simulation
- 50 kt LAB LSc detector
  - X-secs simulated with GENIE for carbon and hydrogen
- 5% systematic error for signal and background
- Migration matrices for ν_e CC, ν_μ CC and NC events
- ν_τ CC events not included
  → migration matrices in preparation
- 90% efficiency for ν_μ CC + efficiency decreases linearly between 3 and 7 GeV

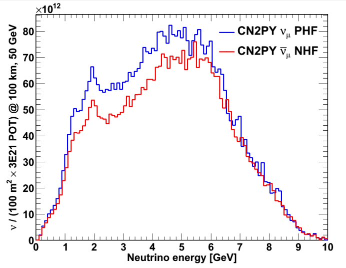
Oscillation parameters and priors

Parameter	Value	Error
θ_{12}	33.8°	5%
θ_{13}	9.1°	7%
θ_{23}	45°	10%
Δm^2_{12} [eV^2]	7.5×10^{-5}	3%
Δm^2_{23} [eV^2]	2.5×10^{-3}	5%
δ_{CP}	changed	free
ρ_{mass}	PREM	5%

Neutrino beams

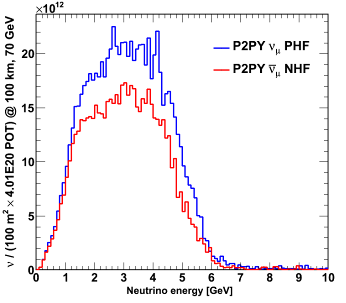
CERN to Pyhäsalmi (CN2PY)

- Based on LBNO EOI
- 400 GeV protons
- $1x10^{20}$ POT / yr (shared mode)
- Baseline: 2288 km
- Used „official“ 50 GeV spectrum and rescaled



Protvino to Pyhäsalmi (P2PY)

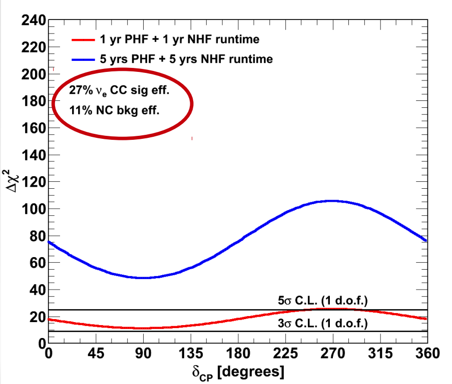
- 70 GeV protons
- $4.01x10^{20}$ POT / yr → 450 kW
- Baseline: 1160 km



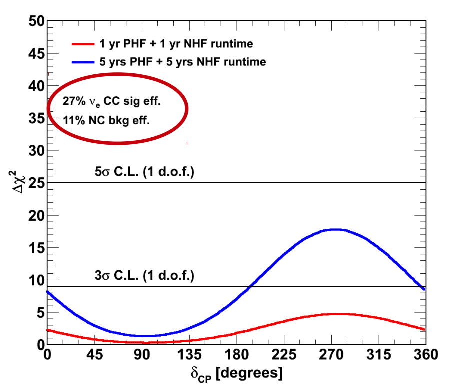
Neutrino mass hierarchy I

Simulated: normal mass hierarchy
Fitted: inverted mass hierarchy

CERN to Pyhäsalmi (CN2PY)



Protvino to Pyhäsalmi (P2PY)

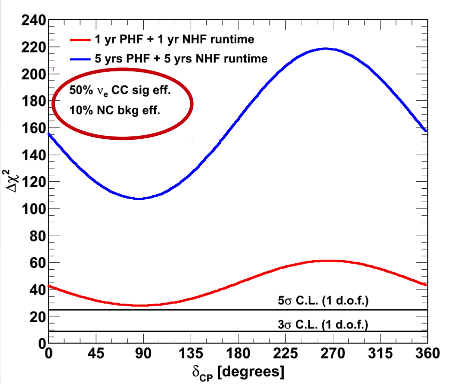


Different scales!

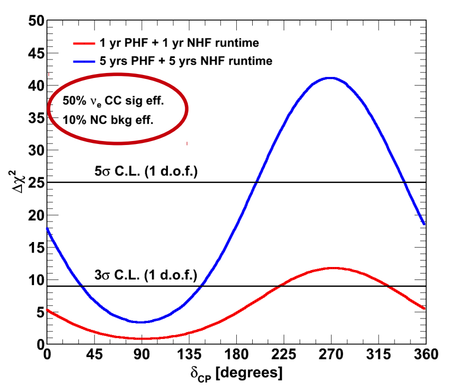
Neutrino mass hierarchy II

Simulated: normal mass hierarchy
Fitted: inverted mass hierarchy

CERN to Pyhäsalmi (CN2PY)



Protvino to Pyhäsalmi (P2PY)

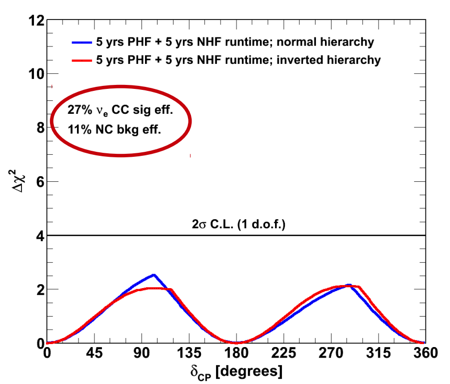


Different scales!

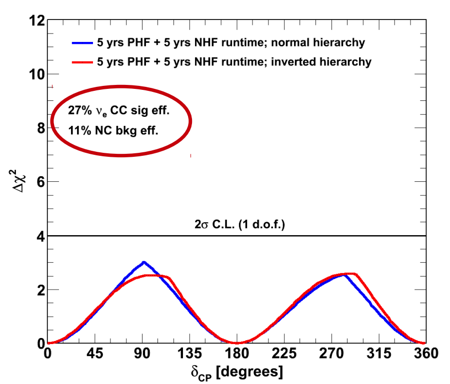
CP phase I

Simulated: different true values of δ_{CP}
Fitted: $\delta_{CP} = 0°$ and $\delta_{CP} = 180°$

CERN to Pyhäsalmi (CN2PY)



Protvino to Pyhäsalmi (P2PY)

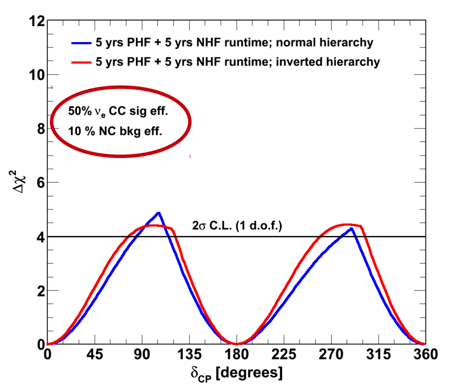


CP phase II

Simulated: different true values of δ_{CP}

Fitted: $\delta_{CP} = 0°$ and $\delta_{CP} = 180°$

CERN to Pyhäsalmi (CN2PY)



Protvino to Pyhäsalmi (P2PY)