Directionality in Water-Based-Liquid Scintillator

Theia 2018 workshop

UC Davis

Björn Wonsak

Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

Important Notes about MC

- THEIA detector → cylinder with radius 22 m & 44m high
- 90% coverage → ~100000 PMTs
- Water based liquid scintillator (5%)

  → combination of optical model for water and LAB from SNO

  → realistic optical model including all wavelength dependencies
- Average attenuation length: 30m
- PMT sensitivity similar to JUNO (QE 25 %, λ_{max} =420 nm)

Idea to get Cherenkov-Direction

- **For emitted isotropic light we have:**

$$\langle \vec{D} \rangle = \sum_i \vec{d}_i = \vec{0}$$

- **For emitted Cherenkov light we have:**

$$\langle \vec{D} \rangle = \sum_i \vec{d}_i = N_{Cher} \cdot \cos(\theta) \cdot \vec{P}$$

with:

- $\vec{D}$ = total
- $\vec{d}_i$ = single photon direction (PMT position - vertex)
- $\vec{P}$ = direction of particle
- N_{Cher} = Number of Cherenkov photons

Events I used

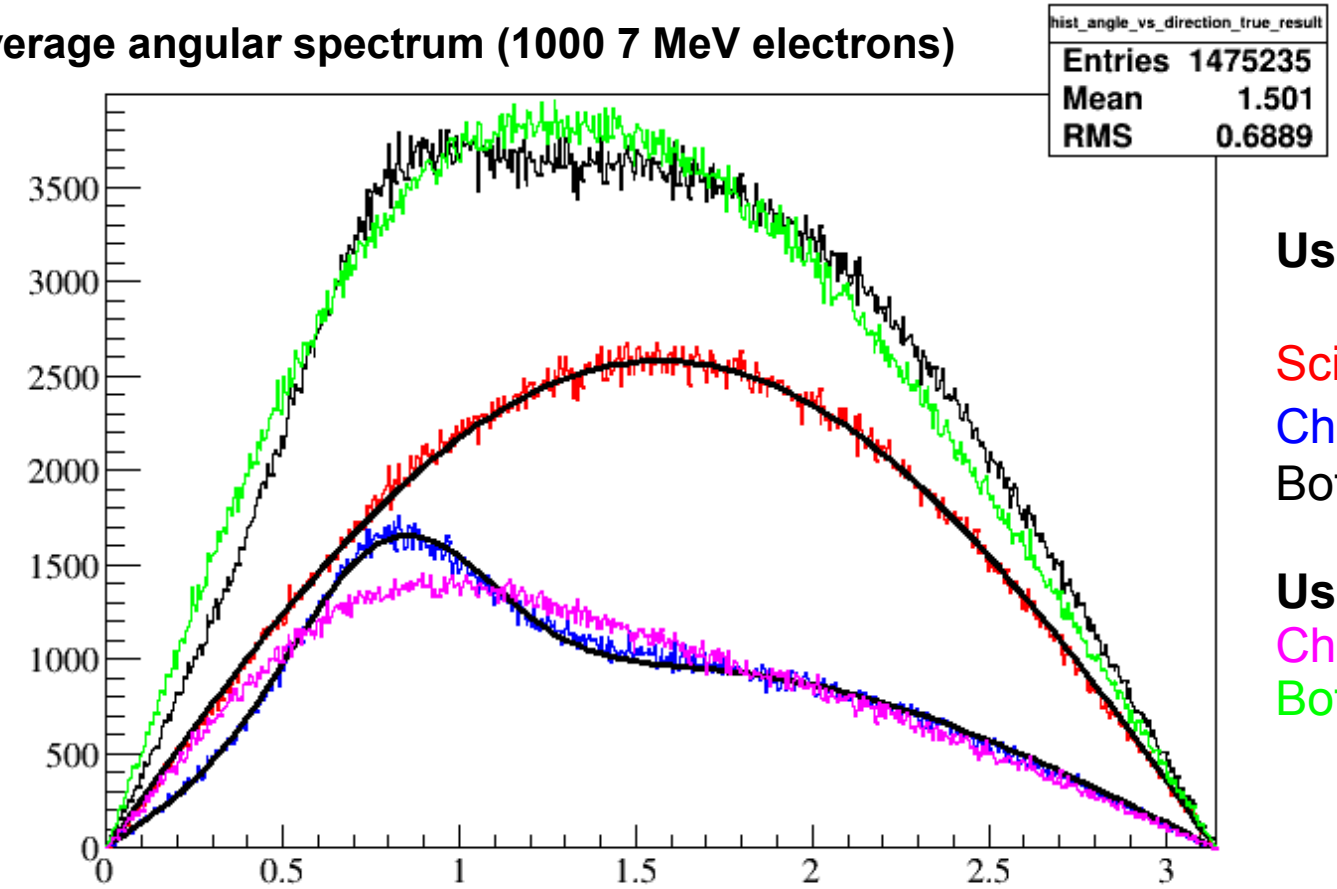
- Vertex position: (0., 18 m, 0.)
- Direction (0.,0.,1.) (also working with random directions)

- 3 MeV electrons → 425 scint & 186 cher
- 7 MeV electrons → 986 scint & 489 cher
- 2 MeV positrons
- 3 MeV gammas
- $0\nu\beta\beta$ Te-130 (nothing to show yet)

JUNO 3 MeV positron at detector center: 3757 scint & 148 cher

The Angular Spectrum

Average angular spectrum (1000 7 MeV electrons)



Use True MC-Direction:

Scintillation ($\sin(\theta)$)

Cherenkov (gaus + $\sin(\theta)$)

Both

Use first-guess direction:

Cherenkov

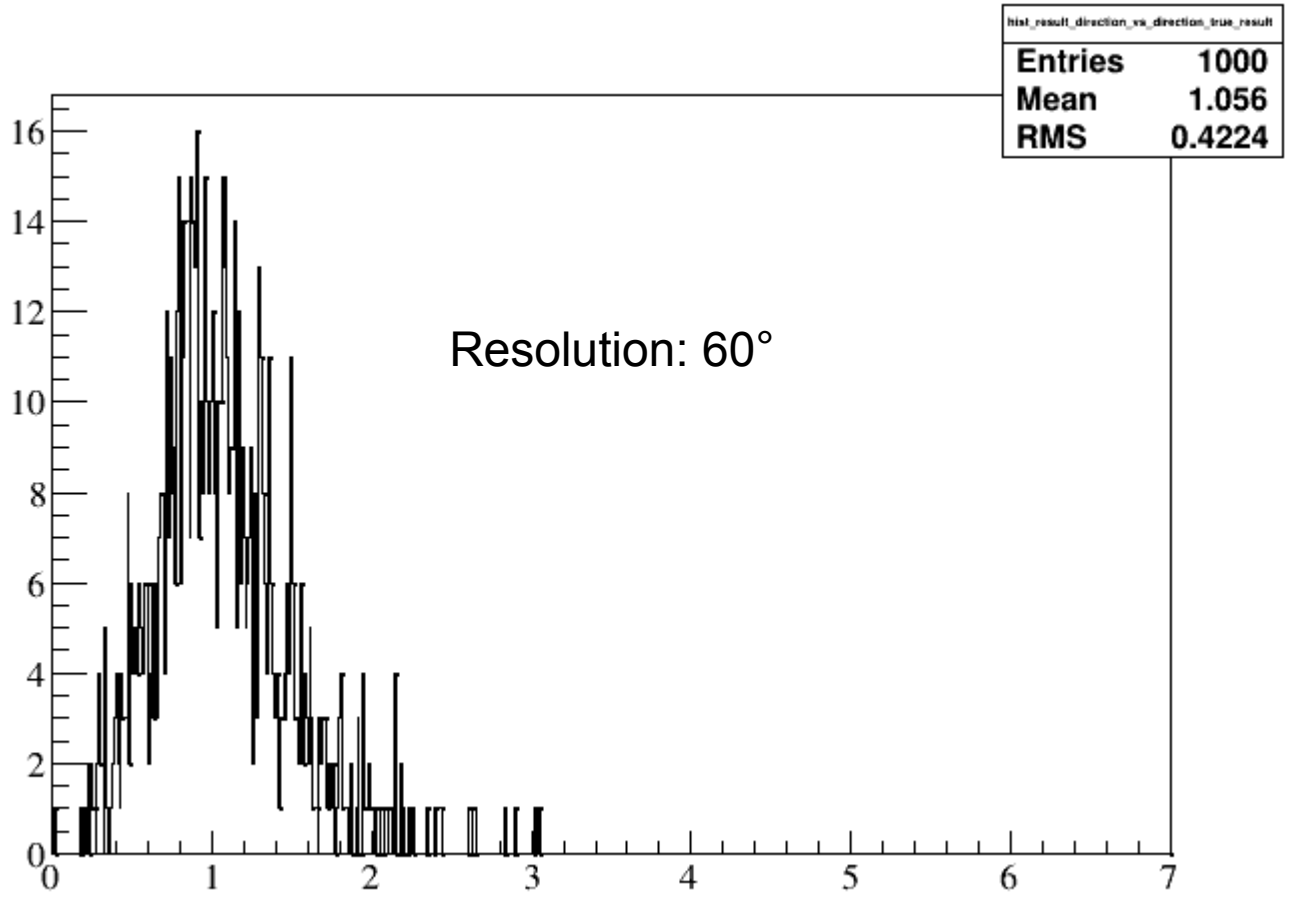
Both

- Scattering leads to almost isotropic component for Cherenkov-light
- Fit: [0]*sin(θ)+[1]*Gaus(θ_{Cher}, σ_{Cher})

Only 1/3 of the Cherenkov-light still retains directional information!

First Result without Correction

- 3 MeV electrons



First Correction

- Expectation value for isotropic light at a given position is affected by attenuation, instrumentation density and scattering

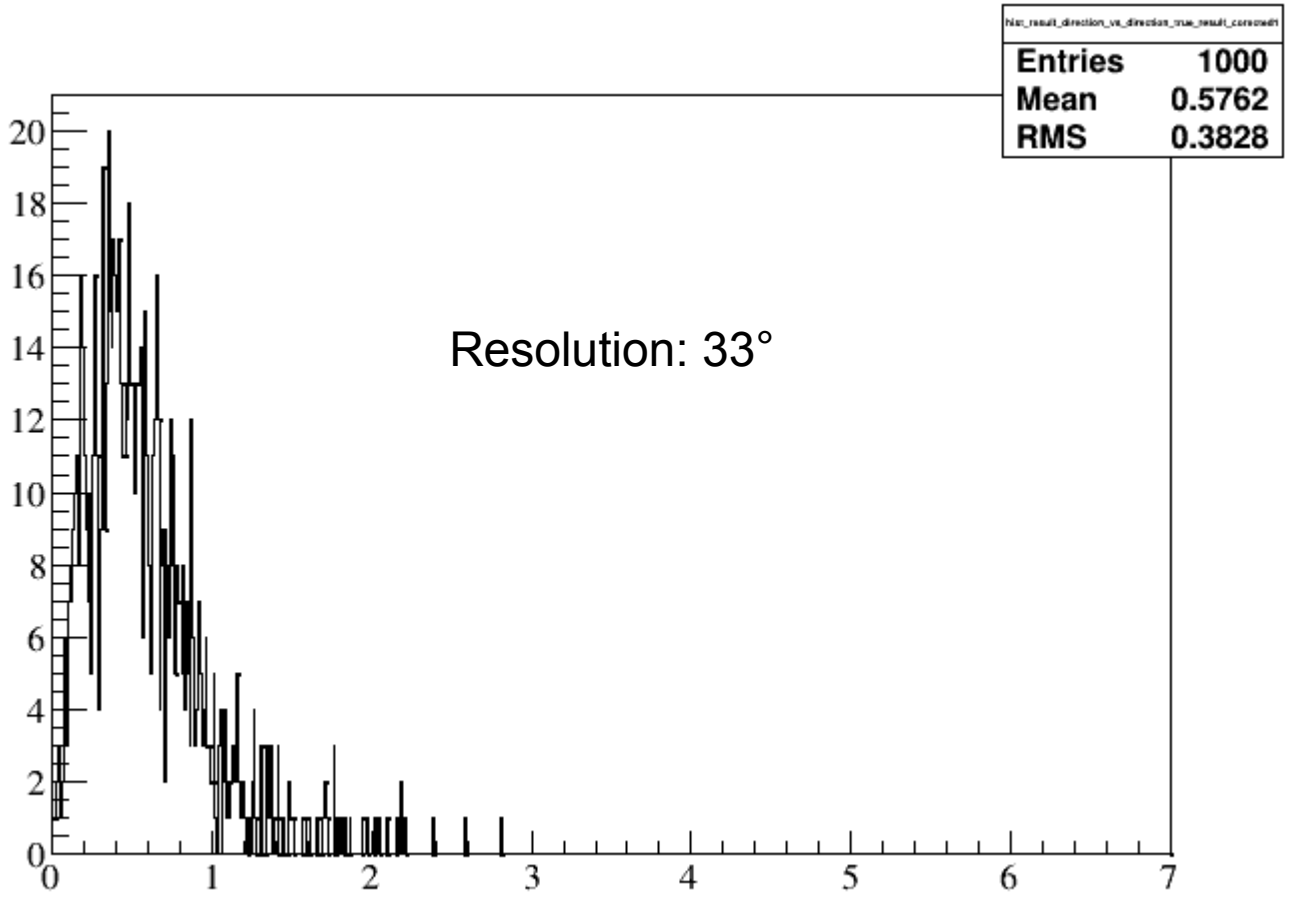
→ Not zero, but tends to be dragged to nearest detector wall

→ Can be corrected with Look-Up-Table (LUT)

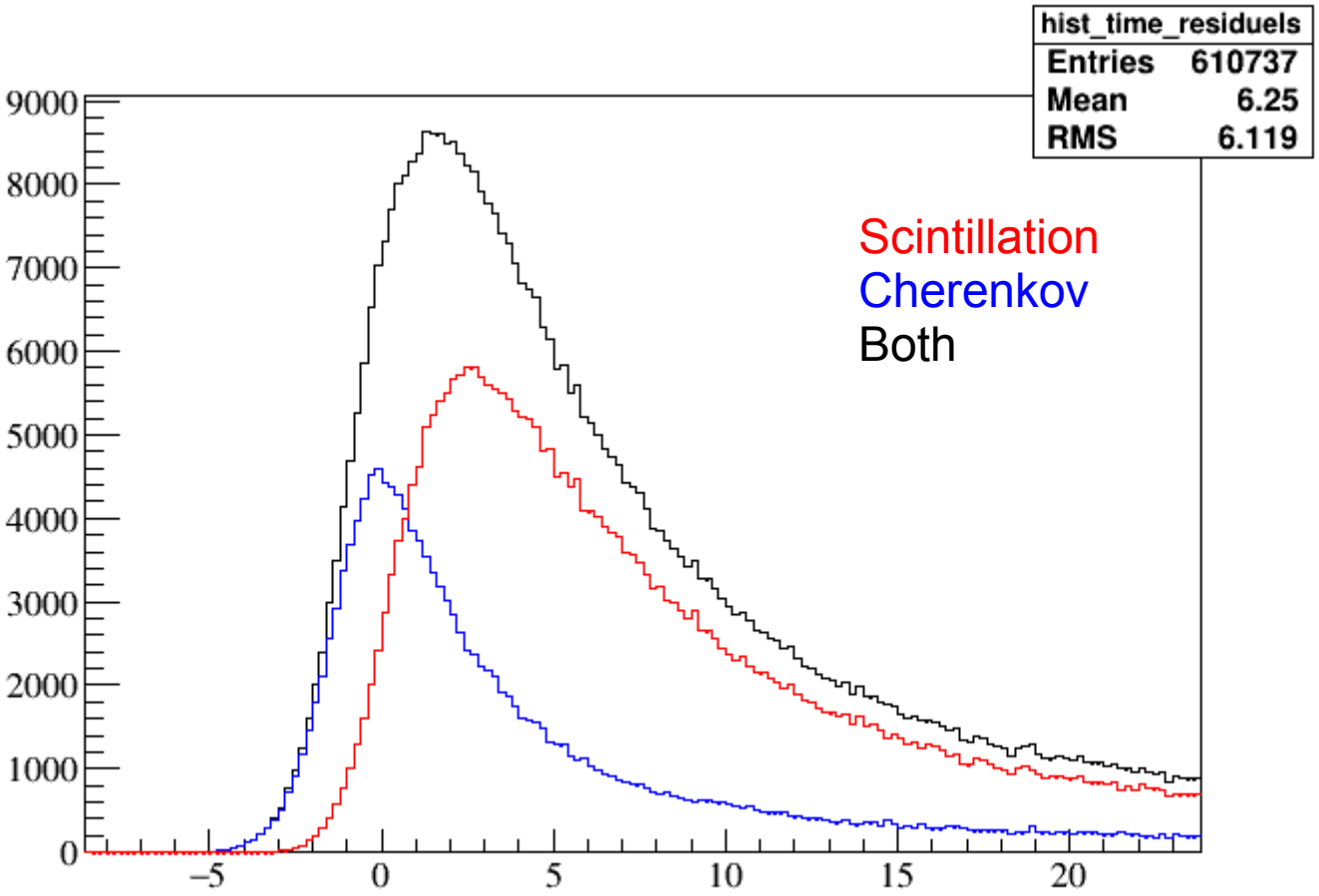
$$\vec{D}_{corrected} = \sum_i \vec{d}_i - \left\langle \vec{D} \right\rangle_{isotropic\ at\ \vec{v}}$$

First Result with Correction

- 3 MeV electrons



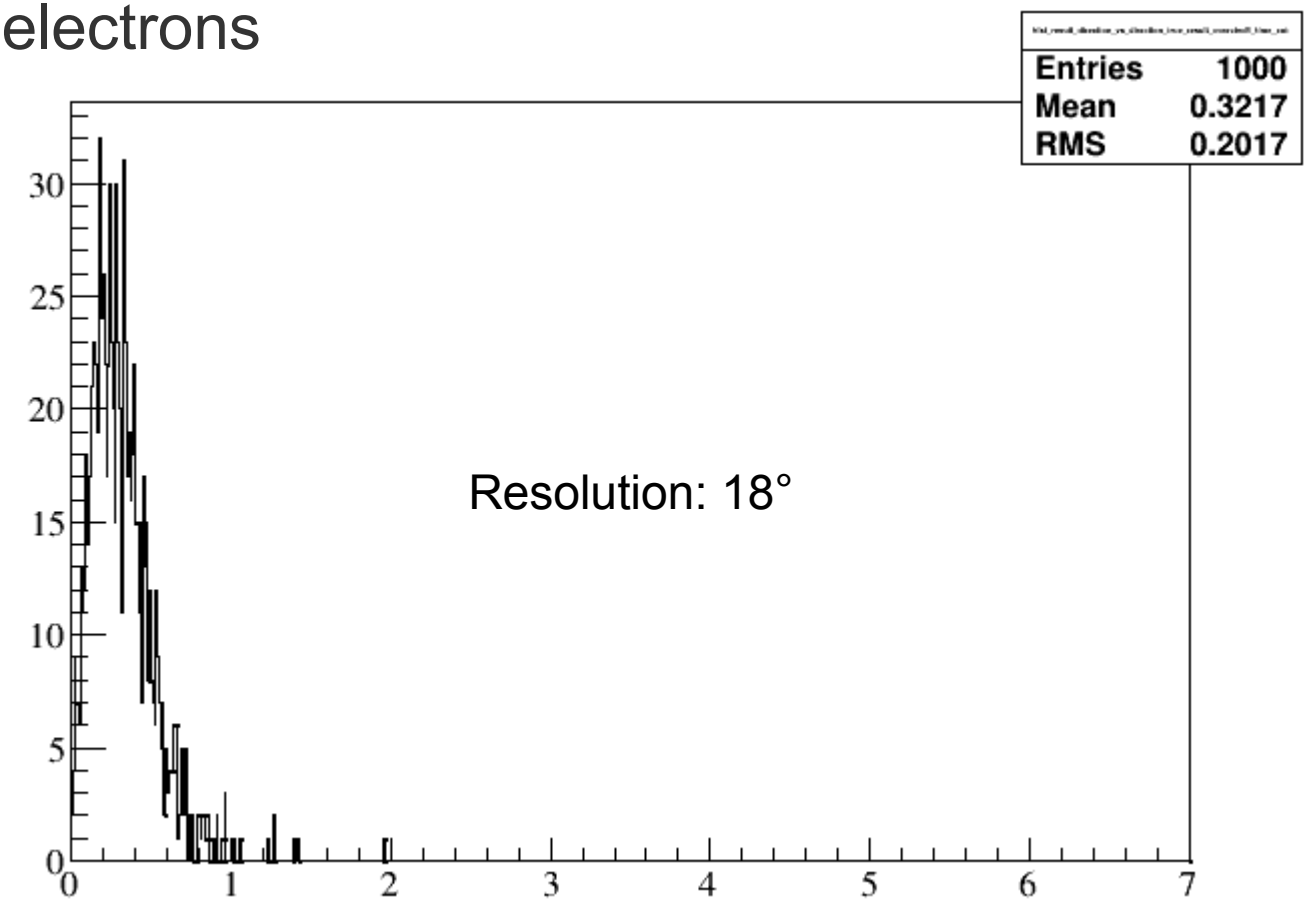
Time Distribution → Time Cut



- Choose to take only light that that is not later than 2ns after expected ToF

First Result with Time Cut

- 3 MeV electrons

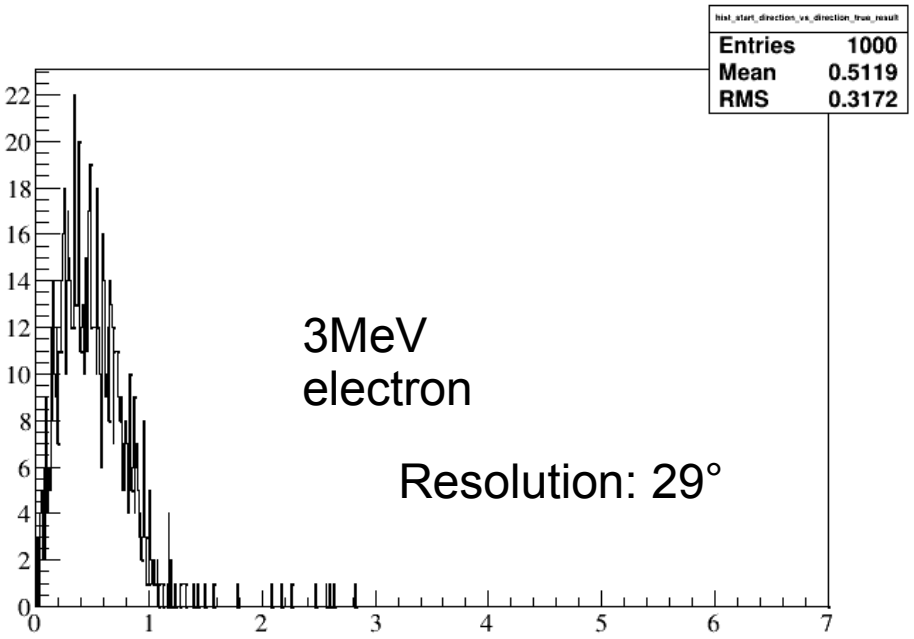


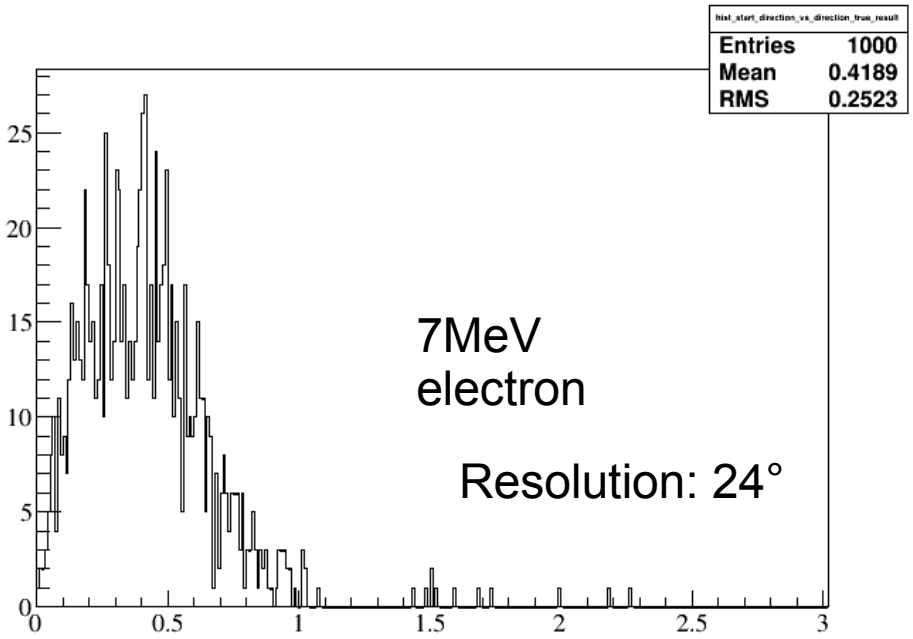
- Correction has to be adapted for time cut
  → dedicated LUT

Angular Resolution Cherenkov-Light

- **Multi-scattering**

  → MeV electron do not propagate straight



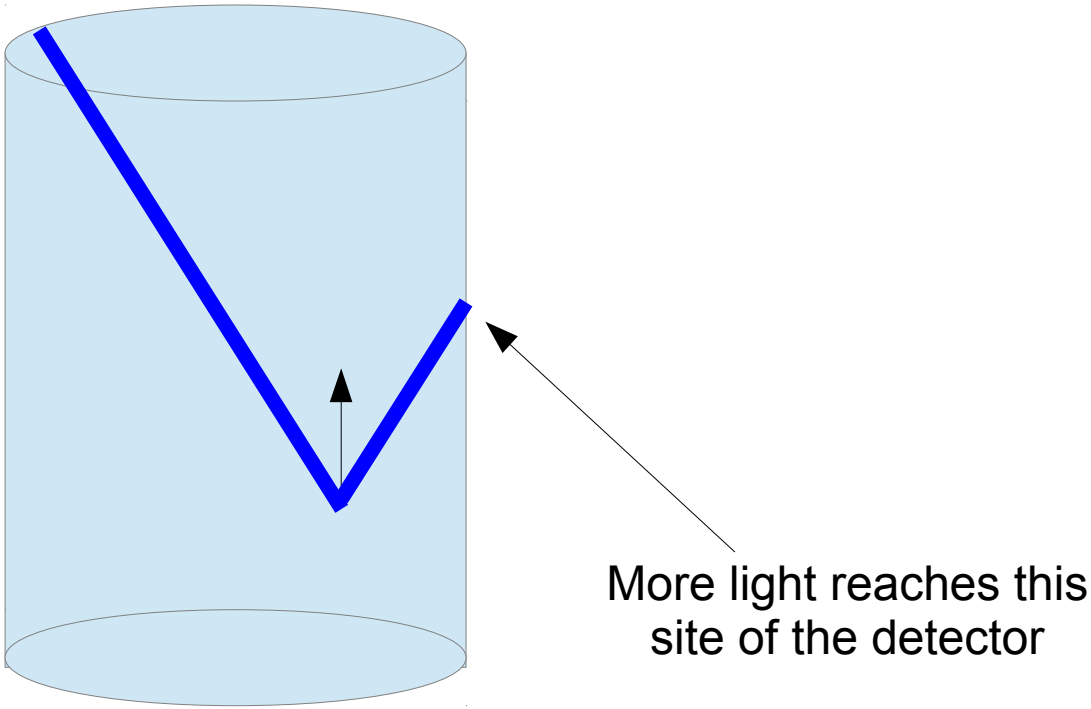


Previous results have been with respect to average electron direction from MC-true!

Correction Due to Cherenkov-Direction

- The expectation value for the directional sum D of Cherenkov-light also depends on position and direction

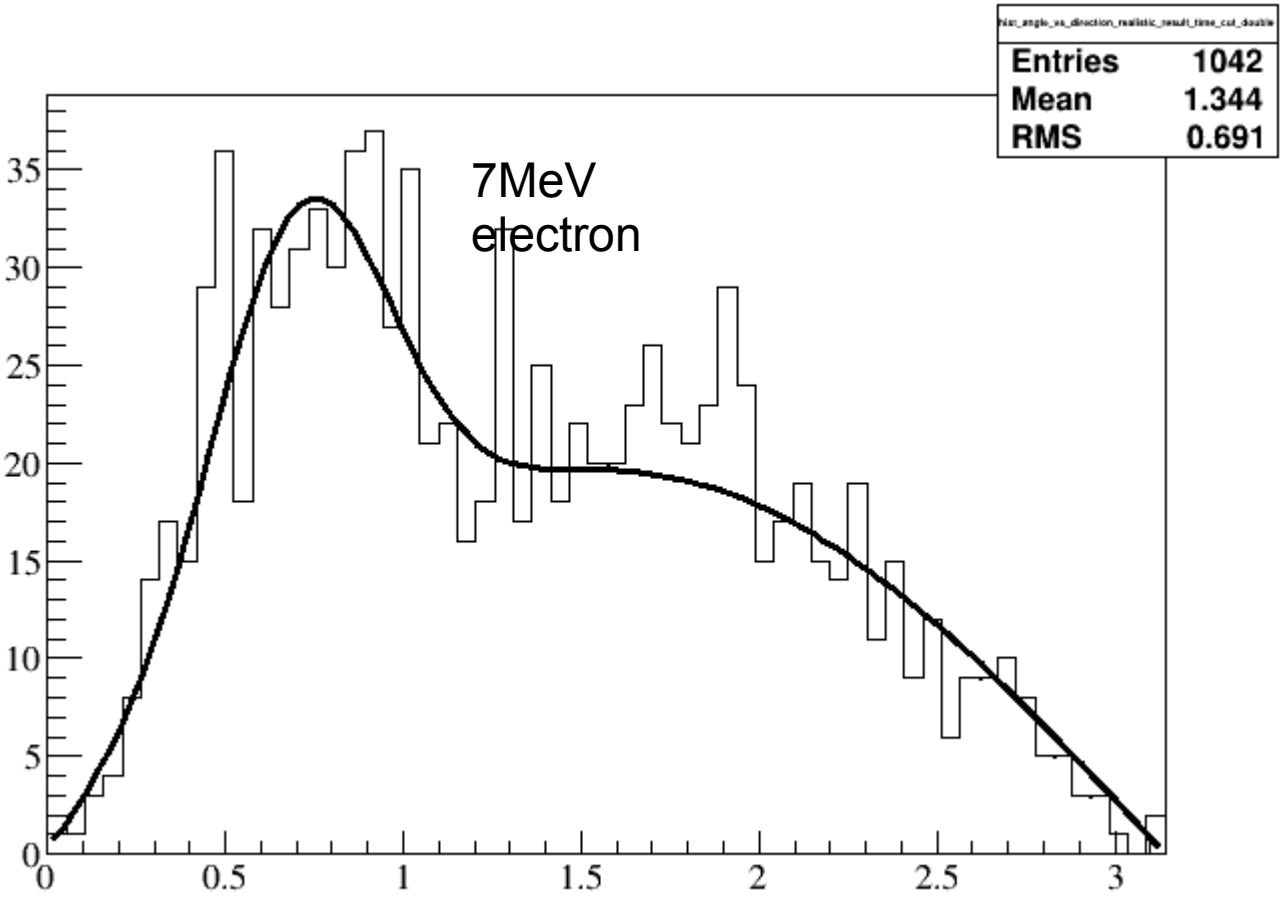
  → Additional correction needed (not done yet)



Remark small Detectors

- Less attenuation → better Cherenkov information
- **Example:** THEIA with old/wrong attenuation length

Angular distribution with respect to reconstructed direction and time cut!



Fit can give me amount of Cherenkov-light, width and maybe also Cherenkov-angle!

Directionality for Positrons

- Two 511keV Gammas
- Less Cherenkov light in forward direction

- But for similar kinetic energy of primary particle I got similar results

- But this does not mean I know the neutrino direction for IBD

- For electrons I have elastic scattering
  → good correlation between electron direction and neutrino!

Remark IBD Directionality

IDB: positron angular distribution

- Inverse beta-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Positron angular resolution given by (Vogel-Beacom 1999)

$$\frac{d\sigma}{d\cos\theta} \approx 1 + velocity_{e^+} a(E_\nu) \cos\theta$$

- θ positron-neutrino angle
- Valid for reactor neutrino energies
- Average <cos θ > :

$$\langle \cos\theta \rangle \approx \frac{velocity_{e^+} a(E_\nu)}{3} \approx -0.03$$

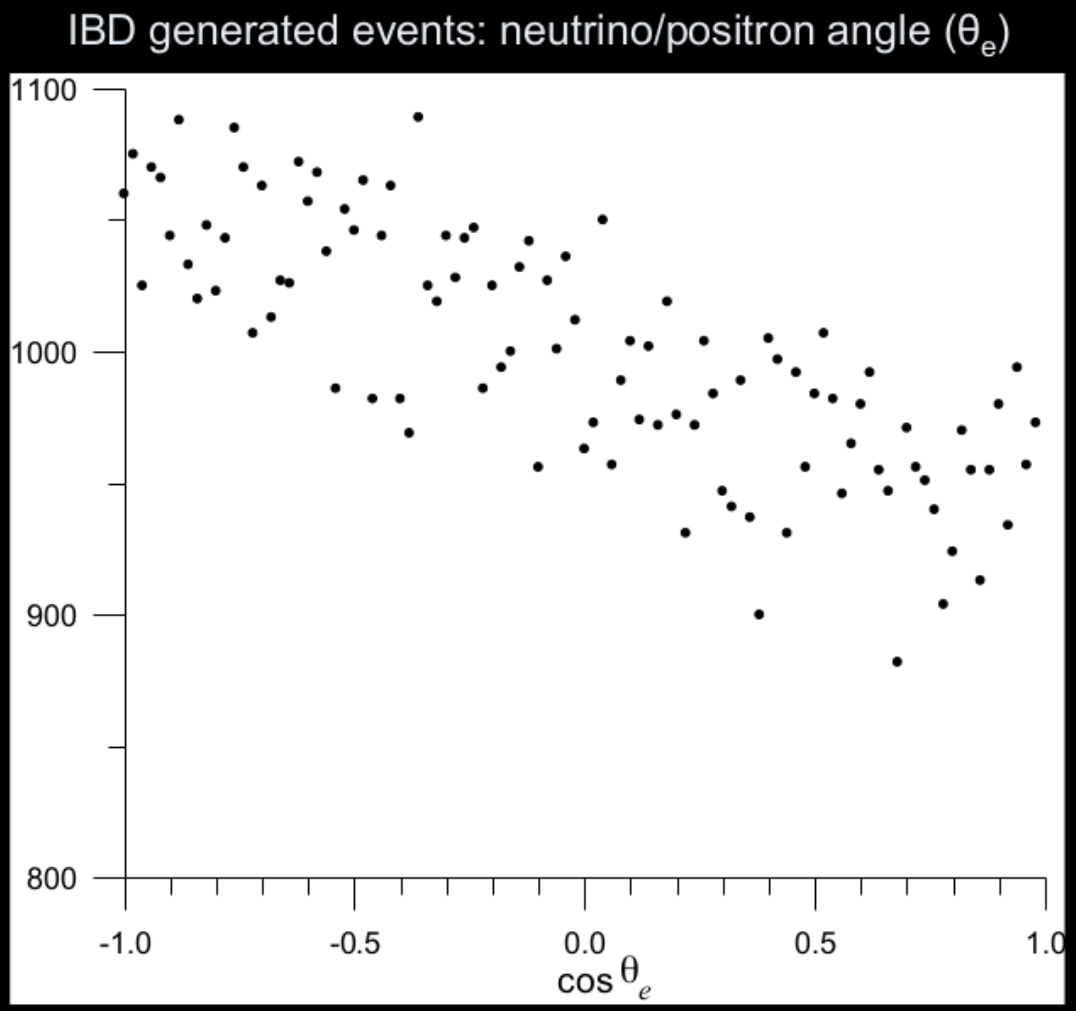
  - velocity = 1 (but near to the threshold)
  - Infinite nucleon mass approximation a(E)=a
  - Fermi/Gamow-Teller transitions competition → a=-0.1

- Angular distribution of the positron is slightly backward
- Rarely accessible…

Thierry Lasserre (Saclay)

Remark IBD Directionality

IDB: positron angular distribution



Thierry Lasserre (Saclay)

Remark IBD Directionality

IDB: neutron angular distribution

- **IDB reaction**
  - Positron emission (no position information): vertex reconstruction
  - First neutron step in the forward direction → directionality information
  - Then neutron thermalization → random walk → loose directionality
  - Finally neutron capture → vertex localization possible

- After vertex reconstruction: (e^+,n) vertex vector reconstructed for all events and statistically studied → 1.5-2 cm displacement in the antineutrino direction

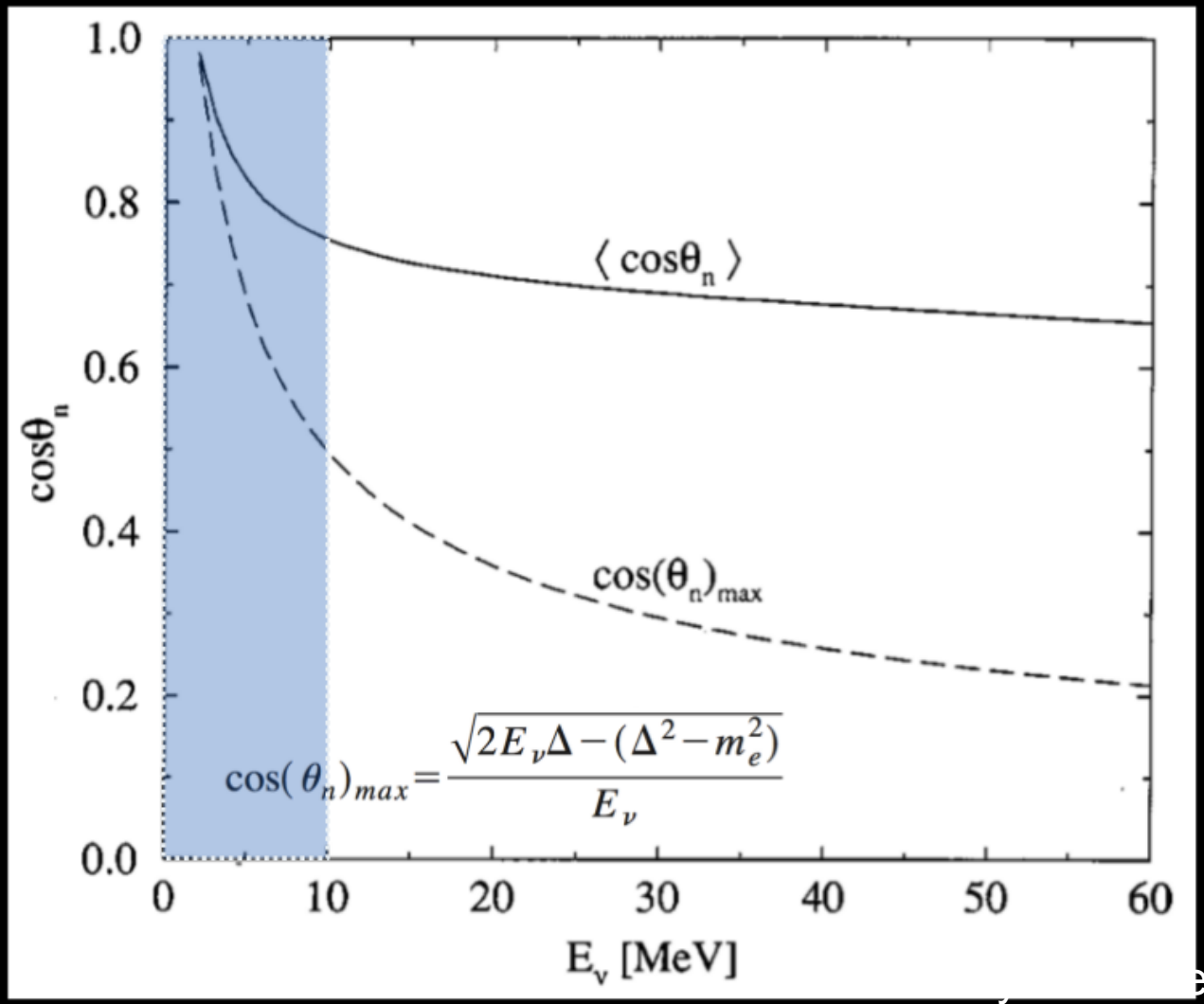
- **Experimentally**
  - Observed in the Goesgen experiment (10 sigmas)
    - Segmented detector
  - Observed in the Bugey-3 experiment
    - Segmented detector
  - Observed in the CHOOZ experiment
    - Unsegmented detector

- **Future Goal: Could directionaly being used for background rejection?**

Thierry Lasserre (Saclay)

Remark IBD Directionality

IDB: neutron angular distribution



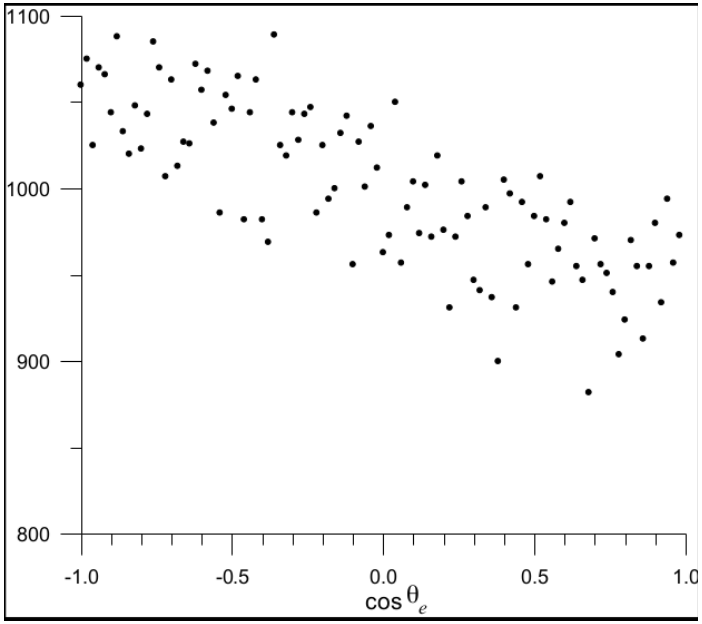
e (Saclay)

Summary IBD Directionality

- Want to find neutrino direction
- In principle full kinematic reconstruction possible, if I know the electron direction and energy and the neutron direction
- However, in reality the error on the neutron direction is too large due to vertex reconstruction resolution & scattering

  → Hopeless on event by event basis

- Others have shown that for a strong source (e.g. SN) neutrons alone can already help
- We could measure angular distribution of positrons to get direction (compare slide 16)



Additional Remark on Potential

- Could always use the same techniques to get a combined expectation value for many events

$$\langle \vec{D}_{combined} \rangle = \sum_{i}^{N_{Events}} \left(\sum_{i} \vec{d}_i \right) = \sum_{i}^{N_{Events}} \left(\langle D_{isotropic}(x, y, z) \rangle \right)_i$$

- This could already be enough to monitor a strong source

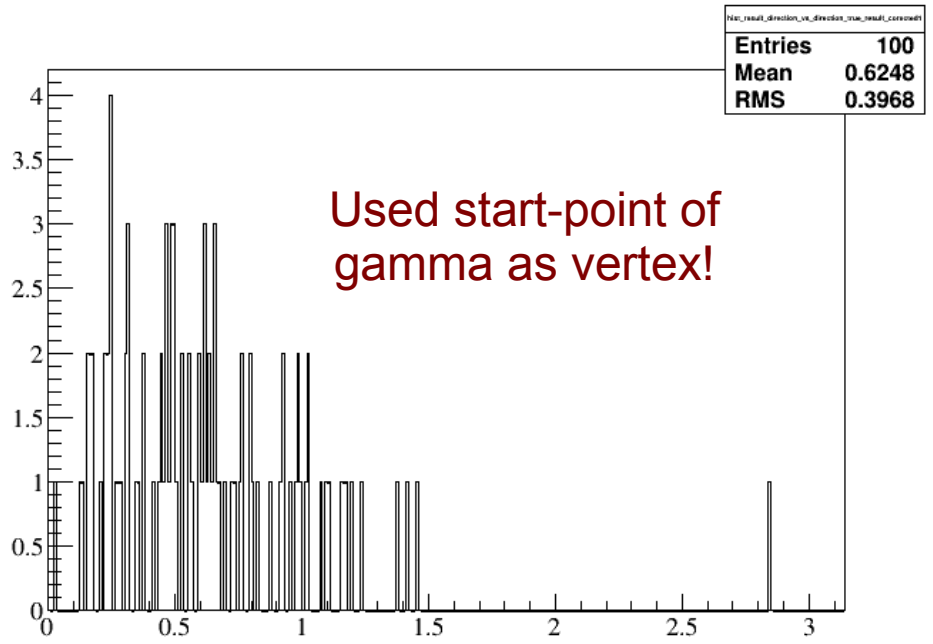
  → The reconstructed direction should remain stable in direction and strength

- If I have a strong source (with fixed position or a reference system following its position) I could use this to estimate energy bins for signal to background ratio

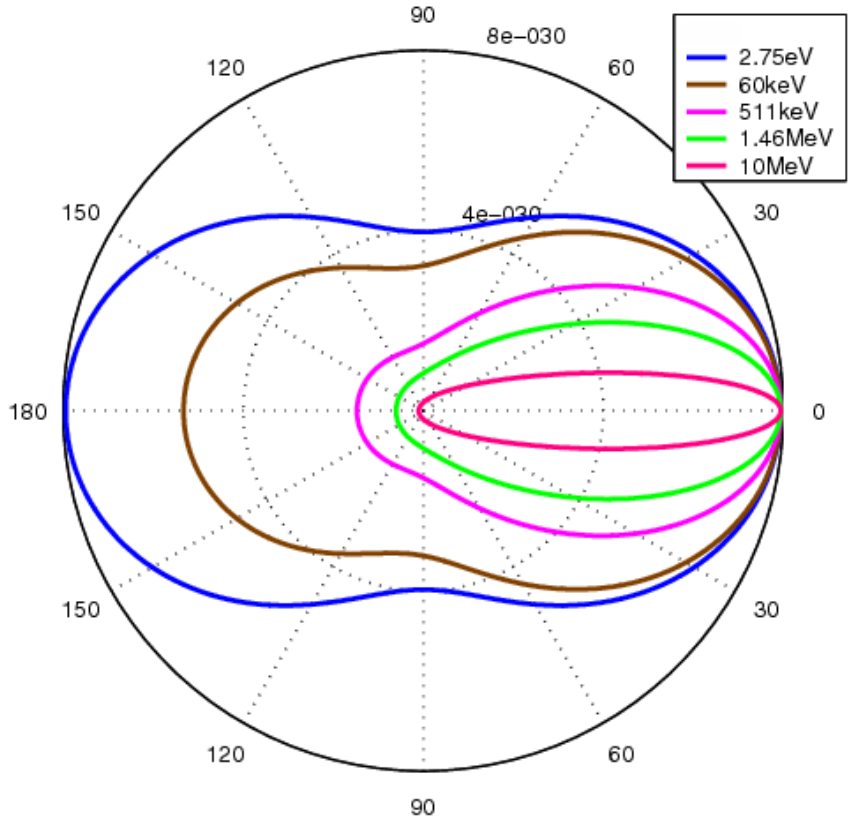
  → Perfect for solar neutrinos

Directionality for Gammas

- **Useful for background analysis**
- **Finding source of background!**



Got similar result using point of first energy deposition as vertex



Particle Discrimination

- **Considering e+, e- and gamma** (with same visible energy)
  - Different total Cherenkov-light
  - Different efficiency of time-matching
  - Different sharpness of cone

- **Two parameters easily acessible:**
  - Magnitude of directional sum |D|
  - Total number of time-cut survivors N_Cut

	|D|	N_Cut
electron	24±10	133+-16
positron	14±8	92+-12

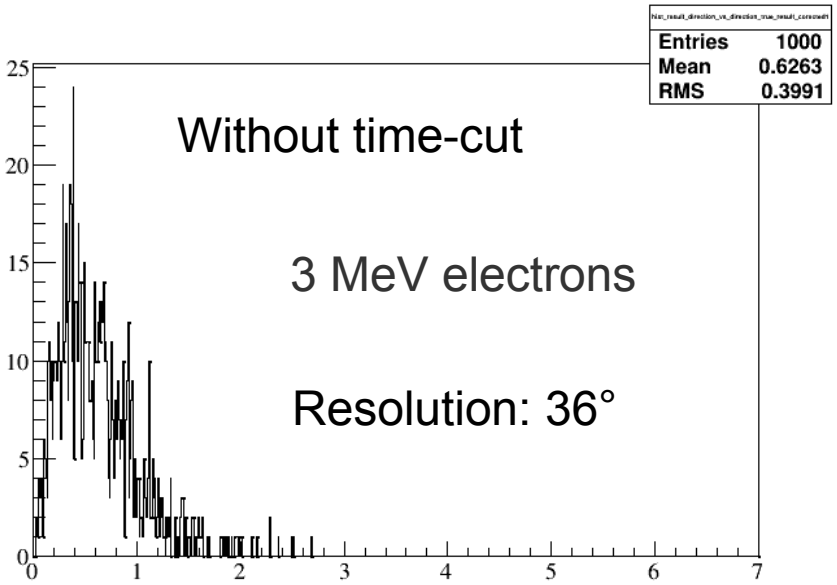
E_Vis = 3MeV
Direction (0,0,1)

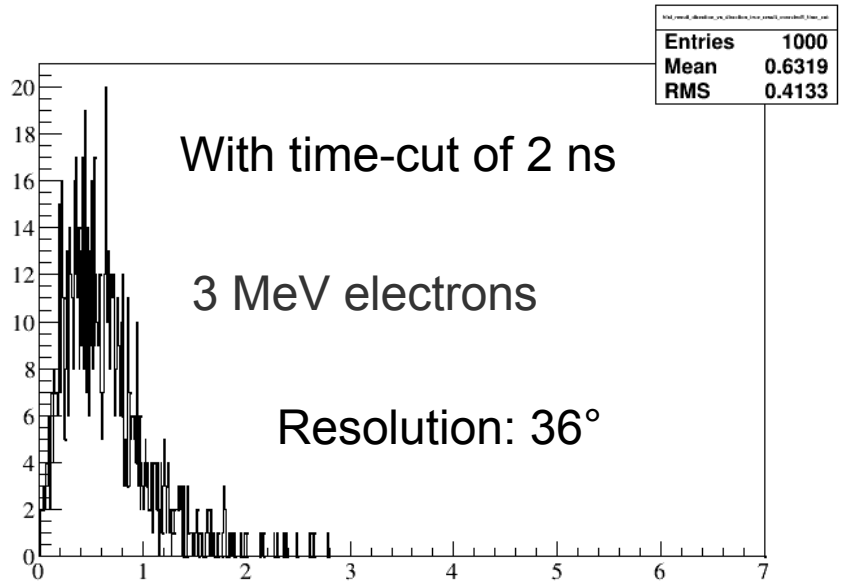
However: |D| and N_Cut are correlated! But not completely!
|D| will be directional dependent due to detector geometry.

Vertex Resolution

- So far I did not include a realistic vertex resolution
- Especially if the Cherenkov-light leads to an systematic error (offset) in the direction of the particle this could be dangerous

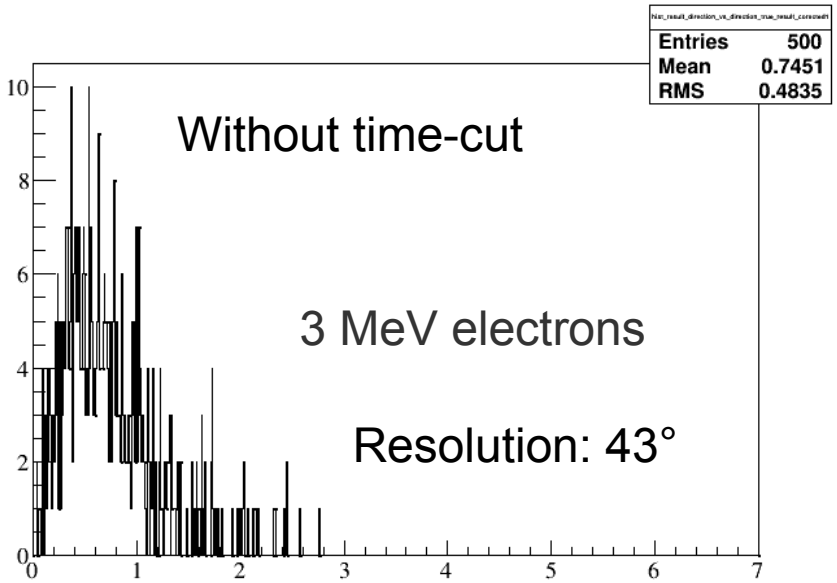
- Using a vertex resolution of 17 cm

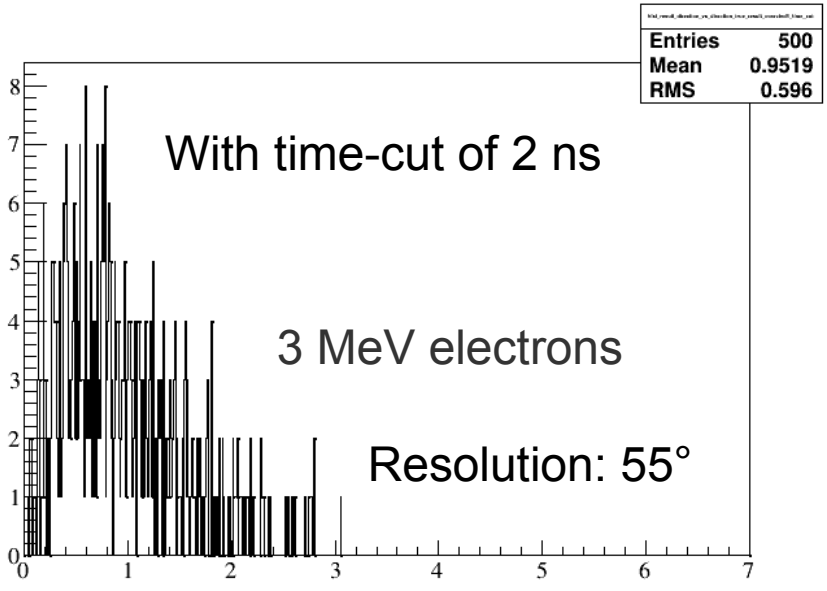




Vertex Resolution

- Using a vertex resolution of 17 cm
- Plus offset in track direction of 16 cm





→ Time-cut makes thinks worse!

Reason: The scintillation photons that get faster times due to the offset come from the backside of the track!

(Maybe I also forget to update the LUT for the time cut correction!)

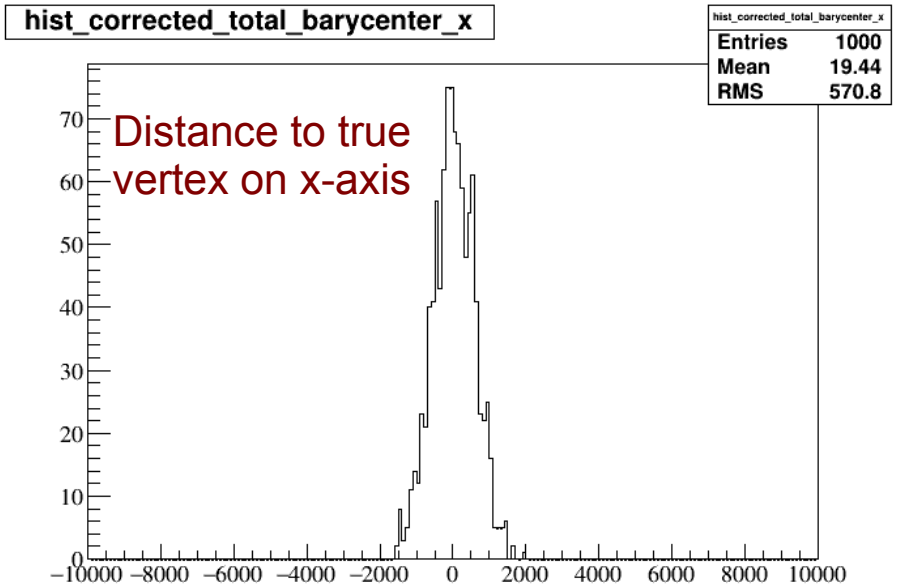
How about the Vertex Offset?

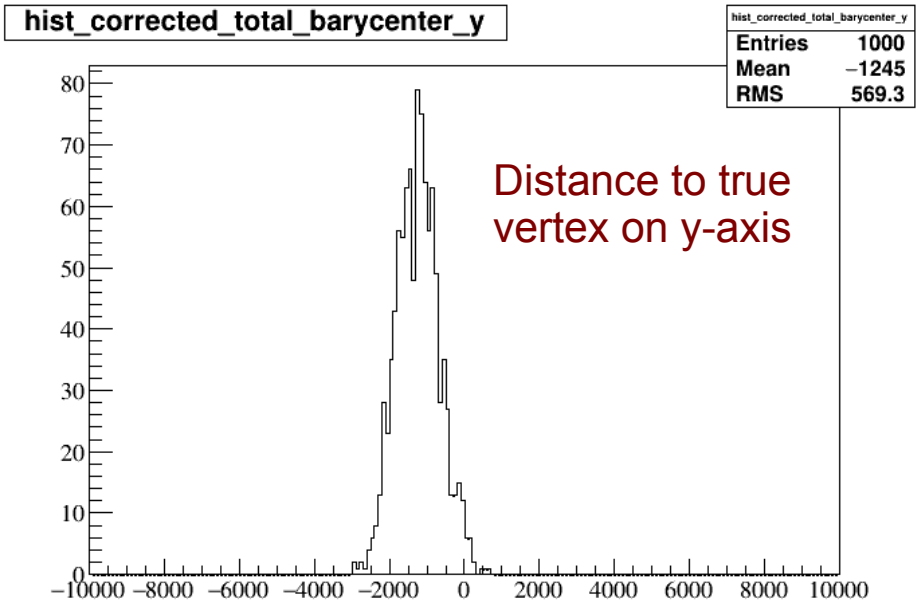
- **Can I use it?**
- **Idea:**
  - Using the charge distribution should be more sensitive than time matching
- **Reason:**
  - Charge needs correct detection efficiencies
  - This needs already information about the direction and amount of Cherenkov-light
- **Ansatz:**
  - Use deviation between vertex from charge and vertex from time

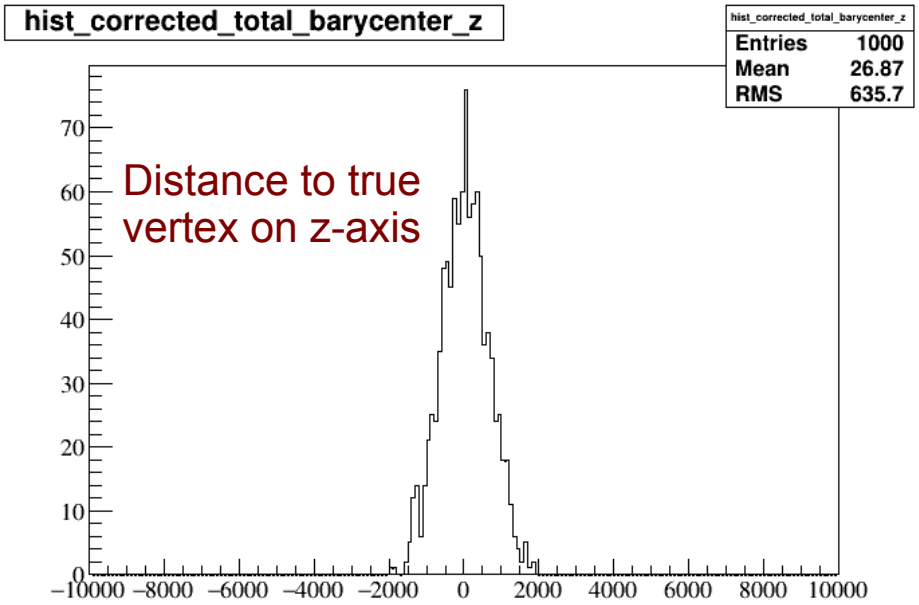
Results: Vertex from Charge

- **Use only barycenter**

- Vertex position: (0., 18 m, 0.)
- Direction (0.,-1.,0.)





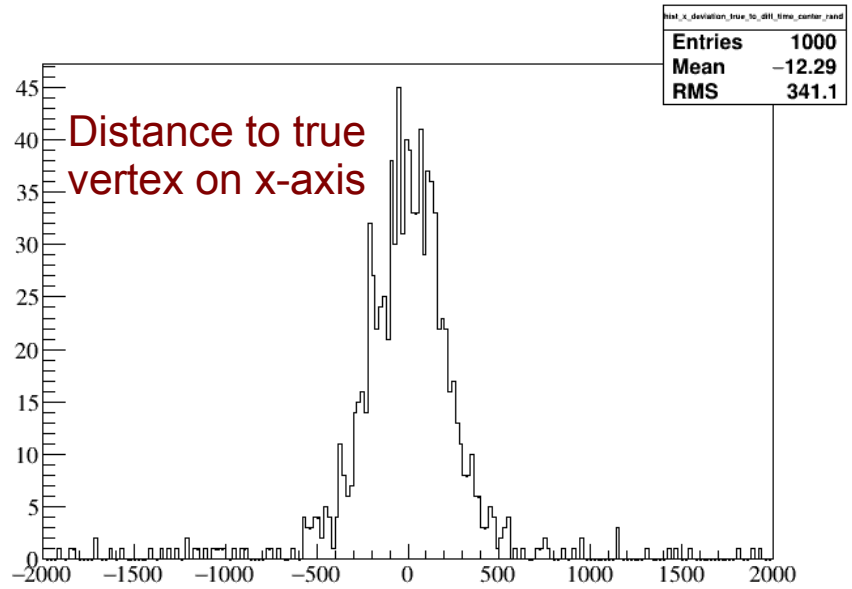


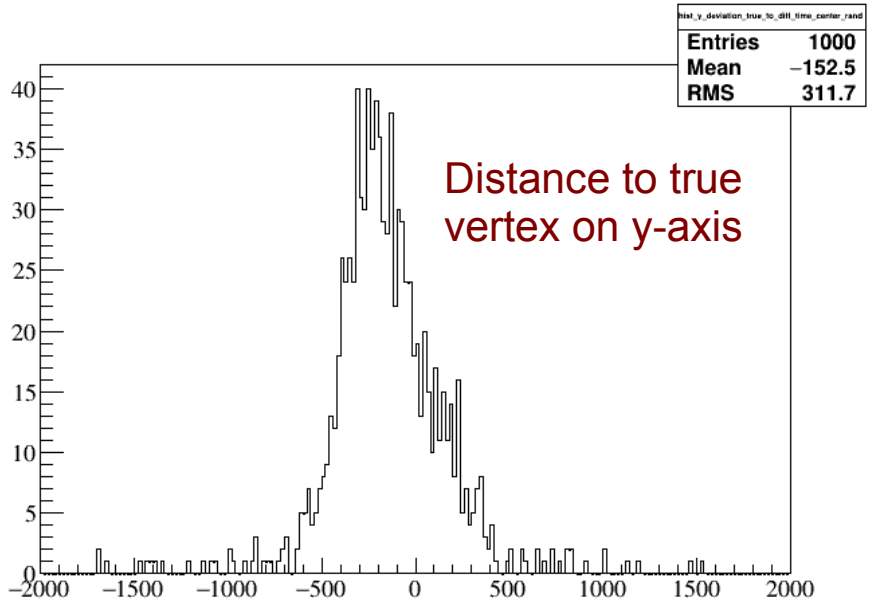
Results: Vertex from Time

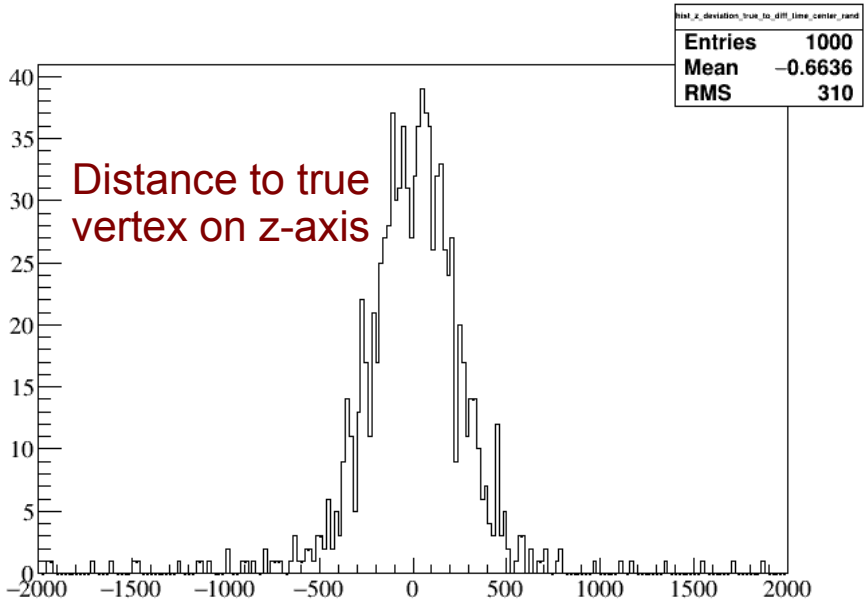
- **Use time-matching**

  (similar to back-tracking)

- Vertex position: (0., 18 m, 0.)
- Direction (0.,-1.,0.)







Result: Vertex from Time + Vertex

- Both vertices are displaced along the track direction
- Barycenter is much more affected
- Distance between both vertices: ~110 cm
- Resolution of barycenter: 60 cm (each dimension)

→ Can already get some directional information

→ Can use this to correct vertex?

Summary

- **Simple & robust method to get track direction**
- **Also working for gammas at a few MeV**
- **Opportunities for particle discrimination**
- **Affected by vertex resolution and offset, but still working**
- **Charge and timing can also reveal direction**
  - → Maybe can correct vertex
  - → A likely-hood fit including the direction and the Cherenkov-light should work
  - Seed from my techniques
- **Question: Will it work in pure LS?**
- **At least integrated analysis of strong sources are possible!**

Still very preliminary!

Need to implement full reconstruction chain to estimate final results!