LENA: tracking detector?
Applications for GeV neutrinos

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Work done in
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High energy physics with LENA

- Performance of LENA at high energies not known too well
- Earlier studies up < 1 GeV
  - Proton decay and studies for beta beams (Teresa)
- Some studies being made for HanoHano
  - Learned (Hawaii)
- For Borexino muon studies
  - echidna,...
Simulate high-energy measurement

• A simple Java app “Scinderella.java”
• Initial brute-force simulations to get the feeling
  • Not designed to be a full analysis program
• Uses a simplified internal event generator
• Uses a simplified model for the detector
  • Reduced number of photosensors, no deficiencies
  • Scintillator decay time and pmt time jitter modelled
• Records observation times of photons in photocounters
  • Selectable data loss by errors, smoothing etc
• Compare the light signals of “true event” to “test event”
  • “true event” Monte Carlo
  • “test event” analytic
DETECTOR
Volume = 21206 m³
Photosensor coverage = 6 %
PDE of photosensors = 100 %

ORIGINAL EVENT QE with neutrino energy 2000.0 MeV
Depositable energy 1679.60 MeV Measurable energy 1984.00 MeV
muon:1592.13 MeV and 8.00 m.
proton:287.47 MeV and 0.554 m. vertexEnergy = 0.00 MeV

MEASUREMENT
measured 320332 photons of 20.56 M (1.56 %)

FIT (done fit for selected event)
ln(L) = 1097186 s=0.00
Vertex at (0.54, 0.42, 14.05)64.60 MeV t0 = 67.73 ns.
Deposit energy 1945.02 MeV Measured energy 2049.42 MeV
Inferred neutrino energy 2068.07 MeV with uncertainty 16.65 MeV
Neutrino energy from lepton angle: 2081.33 MeV [GES]
[0] muon:1542 MeV and 8.24 m.
[1] proton:238 MeV and 0.405 m.
[2] -0 MeV and 0.000 m.
[3] -0 MeV and 0.000 m.
Predict 319721 photons of 20.49 M emitted. (1.56 %)
best fit original, with measured E= 1984.00, Chi = 922337203885477580

COMMAND: Fit selected event
event generated
VIEW: top
LAYER: photons
Mean = 508.46 and variance = 307.20

FINAL VERDICT
Error in measured energy 65.42 MeV = 3.30 %
Error in lepton energy 50.16 MeV = 3.15 %
Error in lepton track 0.24 m = 3 %, vertex: 0.11 m.
Error angle L 0.01 rad = 0 deg (p 0.49 rad = 28 deg)

PMT[1:12]@([3.706.10,17.86])
1326 photons 1320 photons
Duration 87.89 ns Duration 107.00 ns
Time 3.97 ns Time 4.27 ns
Mean time 8.65 ns Mean time 9.20 ns
Decay signal = 18 Decay signal 570.54
+18 +18.00
ln(L)-4140.40
Volume = 21206 m³
Photosensor coverage = 6 %
PDE of photosensors = 100 %

**ORIGINAL EVENT DIS with neutrino energy 4000.0 MeV**
Depositable energy 3460.80 MeV Measurable energy 3984.00 MeV
muon:2033.87 MeV and 10.05 m.
proton:141.28 MeV and 0.166 m. vertexEnergy =1.08 MeV

**MEASUREMENT**
measured 600405 photons of 37.36 M. (1.59 %)

**FIT (done fit for selected event)**
ln(L) = 2173201 s=0.00
Vertex at (-6.07, 0.14, 15.89) 37.72 MeV t0 = 46.03 ns.
Deposit energy 3606.53 MeV Measured energy 4129.73 MeV
Inferred neutrino energy 4387.96 MeV with uncertainty 258.23 MeV
Neutrino energy from lepton angle: 5311.41 MeV [DIS]

[0] muon:2137 MeV and 10.52 m.
[2] pion:87 MeV and 0.256 m. 73.71 ns.
[3] pion:194 MeV and 0.796 m. 38.80 ns.

Predict 598310 photons of 37.86 M emitted. (1.58 %)
bestfit original, with measured E= 3982.70, Chi = 922337203685477580
**DETECTOR**
Volume = 21206 m³
Photosensor coverage = 6 %
PDE of photosensors = 100 %

**ORIGINAL EVENT SPP with neutrino energy 4000.0 MeV**
Depositable energy 3845.19 MeV Measurable energy 3984.00 MeV
electron: 2004.02 MeV and 5.78 m.
proton: 1835.67 MeV and 8.26 m. vertexEnergy = 0.00 MeV
pion: 5 MeV (157 ns)

**MEASUREMENT**
masured 675485 photons of 41.90 M. (1.61 %)

**FIT (cone fit for selected event)**
ln(L) = 2302.063 s = 0.00
Vertex at (0.89, 0.15, 14.71) t0 = 63.82 ns.
Deposited energy 3861.59 MeV Measured energy 4000.40 MeV
Inferred neutrino energy 4026.32 MeV with uncertainty 25.92 MeV
Neutrino energy from lepton angle: 3675.42 MeV [SPP]
[0] electron: 1978 MeV and 5.76 m.
[1] proton: 1878 MeV and 8.50 m.
[2] pion: 5 MeV and 0.003 m. 157.00 ns.
Predict 811213 photons of 43.18 MeV emitted. (1.88 %)
best fit original, with measured E= 3984.00, Chi = 922337203085477580

**FINAL VERDICT**
Error in measured energy 16.40 MeV = 0.41 %
Error in lepton energy -25.80 MeV = -1.28 %
Error in lepton track 0.02 m = 0 %, vertex: 0.06 m.
Error angle L 0.03 rad = 2 deg (p 0.00 rad = 0 deg)

**COMMAND:** Fit selected event
event generated

**VIEW:** top

**LAYER:** chi

**932 photons**
Duration 130.39 ns Duration 95.00 ns
Time 13.93 ns Time 13.59 ns
Mean time 10.35 ns Mean time 9.75 ns
Decay signal = 7 Decay signal = 0.00
+7 +2.59
ln(L) = -3615.83
Results so far

- Very good fit to simple events
  - Almost absolute flavor recognition (even without muon decay signal)
  - Positional accuracy a few cm
  - Angular accuracy few degrees
    - Neutrino angle limited by unseen nuclear recoils
- Good fit to more complicated events, too
  - Three tracks can be fitted if well separated
  - More tracks very challenging
  - Muon track always fittable (if exists)
- So far no flavor misidentifications for any topology
  - Only unconsidered major fluctuations or rare rescatterings
Energy resolution

• In simple events all tracks fitted better than 1 % accuracy
• In complicated events
  • Single tracks fitted less accurately
  • Total light output is fitted at few % accuracy
• Typically the accuracy of the routine better than 1 %
• Larger uncertainties:
  • Nuclear physics: Carbon binding energy, nuclear spillouts etc: uncertainty of 20-40 MeV
  • Misrecognized hadrons: quenching factor significant
  • Neutrons so far lost energy – to be studied more
• May assume 5 % accuracy, sufficient for neutrino beams
Recognizing antineutrinos and neutrinos?

- Recognize prompt nucleon?
  - Neutron can be recognized by absorption signal (95 %)
  - Neutron track may be followed
  - Proton track distinguishable if energy > 100 MeV
  - But: nucleon interchange within nucleus (20-30 %) or charged pions may complicate the analysis

- Muon charge can be measured with magnetic field?
  - Bending in a moderate magnetic field 0.1 T or less clearly observable
  - Fluctuations in trajectory (Coulombian scat.) limiting factor
  - Magnetized liquid scintillator needs different photosensor technology
Bending in magnetic field

**DETECTOR**
Volume = 21206 m^3  \( B = 0.05 \) T
Photosensor coverage = 6 %  \( \text{FDE of photosensor} = 100 \% \)

**ORIGINAL EVENT**
QE with neutrino energy 3000.0 MeV
Deposable energy 2858.80 MeV  \( \text{Measurable energy} = 2963.00 \) MeV
muon: 2664.15 MeV and 12.87 m, vertexEnergy = 0.00 MeV
proton: 194.45 MeV and 0.290 m.

**MEASUREMENT**
measured 307529 photons of 31.16 M. (0.99 %)

**FIT (studied charge)**
\[ \ln(L) = 1109822 s=0.00 \]
Vertex at (-3.41, 0.02, 0.13) 0.00 MeV  \( t_0 = 60.79 \) ns.
Deposited energy 2862.65 MeV  \( \text{Measured energy} = 2967.95 \) MeV
Inferred neutrino energy 3101.45 MeV with uncertainty 134.39 MeV
Neutrino energy from lepton angle: 2949.58 MeV [QE]
N0 muon(-1) 2643 MeV and 12.78 m.
[1] proton: 220 MeV and 0.360 m.
Predict 307745 photons of 2.28 M emitted. (13.51 %)
best fit original, with measured E = 2963.00, \( \text{Chi} = 922337203685477580 \)

**FINAL VERDICT**

- 177 photons
- Duration 82.34 ns
- Time 60.88 ns
- Mean time 6.41 ns
- Decay signal = 1
- +1
- PMT quality perfect
- 171 photons
- Duration 60.00 ns
- Time 61.13 ns
- Mean time 6.16 ns
- Decay signal 0.76
- +0.76
- \( \text{In(L) 0.14} \)

**COMMAND:**
Check charge

**VIEW:**
top

**LAYER:**
photons
Considerations for detector design

- **Important**
  - Fast scintillator (< 5 ns)
  - Small scattering of light in liquid
  - Very good photosensors & electronics:
    - Total photon count & start time for each PMT very important
    - Recording individual photon times would be nice but not mandatory
- **Less relevant**
  - Light yield & light attenuation
  - Noise
- The buffer and the shield can be used to extend the fiducial volume
Atmospheric neutrinos

• Vertical direction optimal – upward going neutrinos best
• Three interesting ranges
  • 10-20 GeV: upward-going neutrinos, satisfactory energy resolution and good angular resolution
  • Around 3 GeV – matter resonance: ability to differentiate neutrinos from antineutrinos very valuable
  • Near 100 MeV: study solar neutrino parameters. A small window for LENA?
• A task to be done
Neutrino beams

- **Conventional wide band beam: 1-6 GeV (< 100 M€)**
  - Baseline > 1000 km preferred
  - Vertical alignment not a burden if wide enough
  - Good for $\sin^2(2\theta) > 10^{-2}$

- **Beta beam: 300 MeV – 5 GeV (1 G€)**
  - LENA very good with a high-energy beta beam
  - May study $\sin^2(2\theta) > 10^{-3}$ or less, depending on beam power and detector size
  - Larger detectors preferable, with horizontal alignment

- **Neutrino factory 3 GeV – 50 GeV (>2 G€)**
  - Requires a magnetic detector (B > 0.1 T)
  - For $E > 5$ GeV detector to be aligned parallel to the beam
  - Good for $\sin^2(2\theta) \approx 10^{-3} ... 10^{-4}$
Conclusions

- Large volume liquid scintillation detector serves as a good tracking detector for high-energy events (> 1 GeV)
  - Flavor recognition very good
  - Energy resolution typically better than 5 %
  - Capacity mostly limited by physics
- Very good detector for neutrino beams
  - Wide band beam
  - High-energy beta beam
  - Low-energy neutrino factory: Magnetized liquid scintillator
- Interesting for atmospheric neutrinos
- Challenges for the design of the detector
  - Light sensors, electronics, data acquisition
WBB with LENA @2300 km
Some comparisons

**Left Panel:**
- Title: Required fiducial mass of the detector to measure non-zero theta_13
- Plot: Color gradient from yellow to purple, indicating mass in units of kg/kt.
- Axes:
  - Y-axis: log(sin(\theta/2))
  - X-axis: log(sin(\theta/2))

**Right Panel:**
- Title: Theta reach: theta_13 and baseline for 50 kt
- Plot: Color gradient from yellow to purple, indicating energy resolution.
- Axes:
  - Y-axis: log(sin(\theta/2))
  - X-axis: log(sin(\theta/2))

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**Legend:**
- Color bar for left panel: 0 to 300 kg/kt
- Color bar for right panel: 0 to 10 units