LENA: tracking detector?
Applications for GeV neutrinos

Presented by

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Work done in

Excellence Cluster Universe

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In collaboration with

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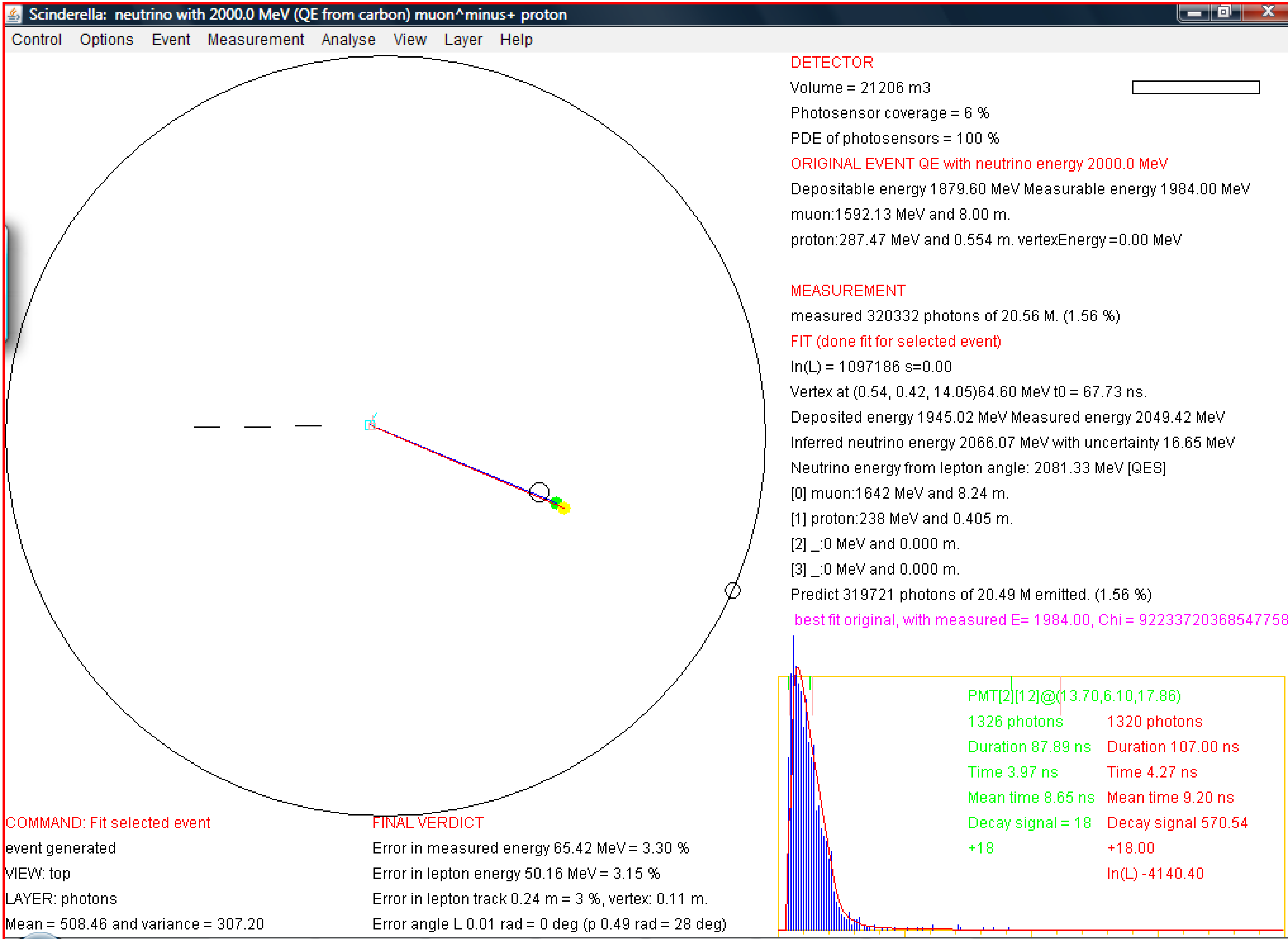
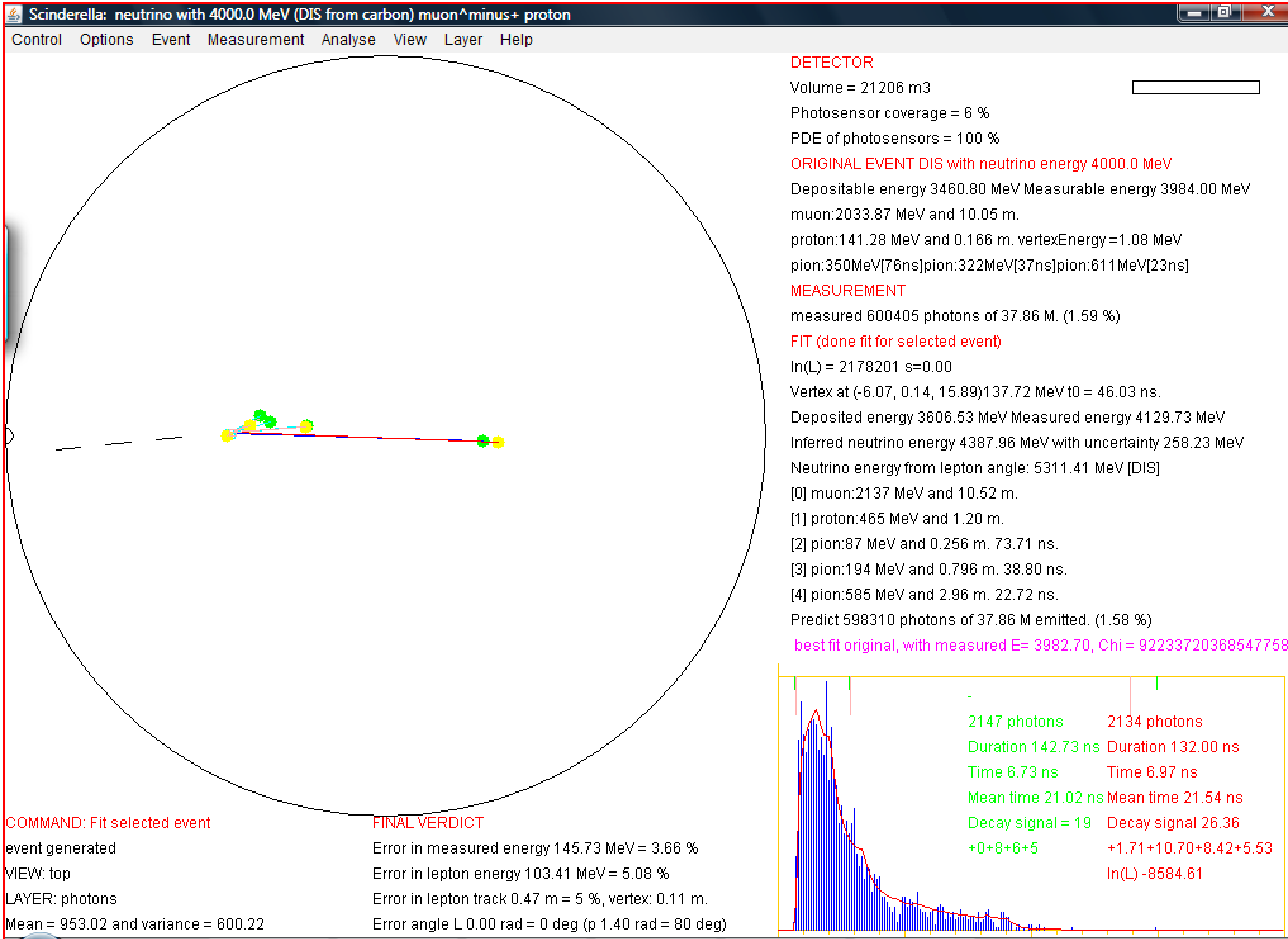
High energy physics with LENA

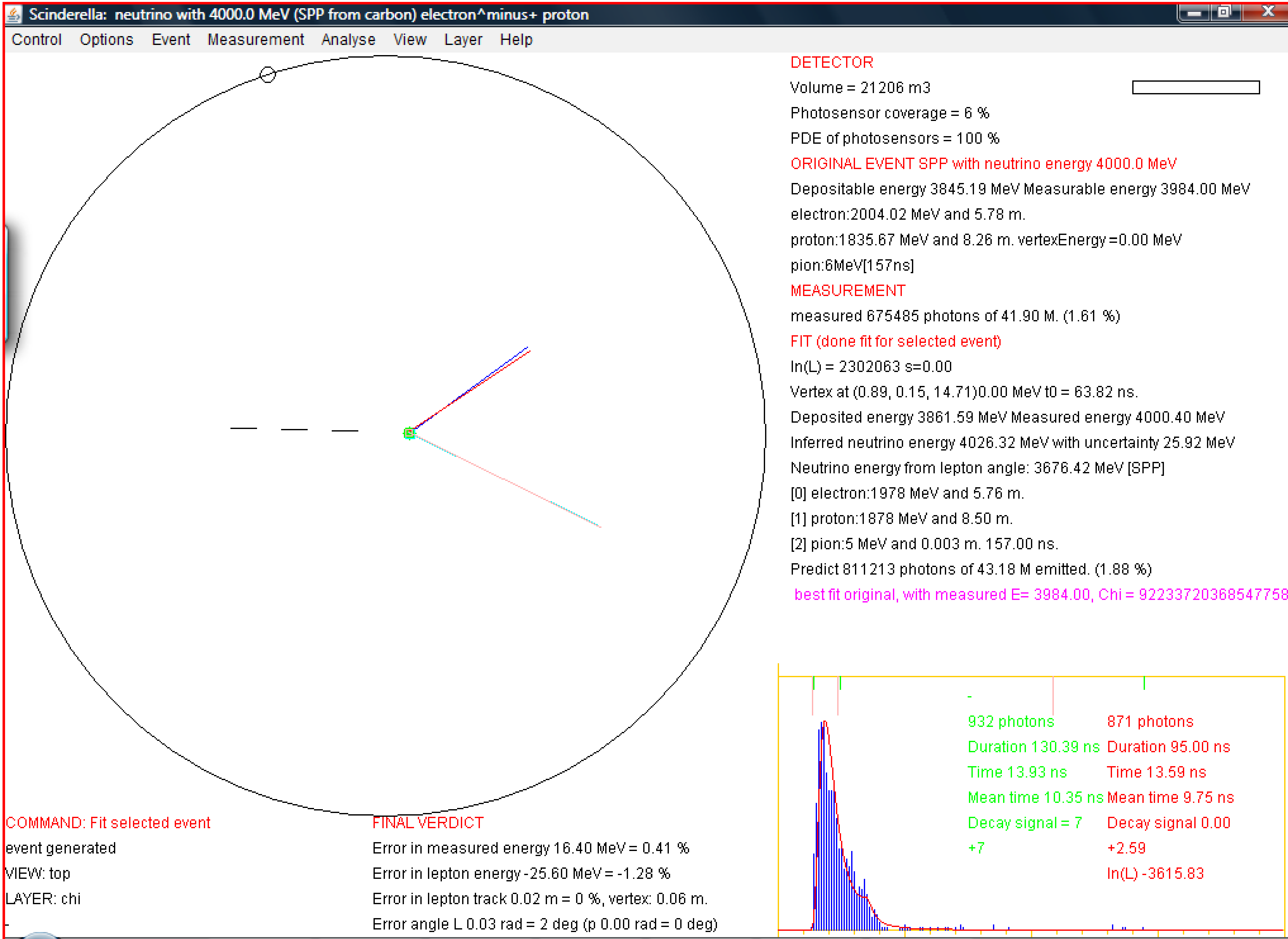
- Performance of LENA at high energies not known too well
- Earlier studies up < 1 GeV
  - Proton decay and studies for beta beams (Teresa)
- Some studies being made for HanoHano
  - Learned (Hawaii)
- For Borexino muon studies
  - echidna,...

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


Scinderella: neutrino with 2000.0 MeV (QE from carbon) muon^minus+ proton
Control Options Event Measurement Analyse View Layer Help
DETECTOR
Volume = 21206 m3
Photosensor coverage = 6 %
PDE of photosensors = 100 %
ORIGINAL EVENT QE with neutrino energy 2000.0 MeV
Depositable energy 1879.60 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.
Deposited energy 1945.02 MeV Measured energy 2049.42 MeV
Inferred neutrino energy 2066.07 MeV with uncertainty 16.65 MeV
Neutrino energy from lepton angle: 2081.33 MeV [QES]
[0] muon:1642 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 = 9223372036854775807
PMT[2][12]@(13.70,6.10,17.86)
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
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)


Scinderella: neutrino with 4000.0 MeV (DIS from carbon) muon^minus+ proton
Control Options Event Measurement Analyse View Layer Help
DETECTOR
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
pion:350MeV[76ns]pion:322MeV[37ns]pion:611MeV[23ns]
MEASUREMENT
measured 600405 photons of 37.86 M. (1.59 %)
FIT (done fit for selected event)
ln(L) = 2178201 s=0.00
Vertex at (-6.07, 0.14, 15.89)137.72 MeV t0 = 46.03 ns.
Deposited 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.
[1] proton:465 MeV and 1.20 m.
[2] pion:87 MeV and 0.256 m. 73.71 ns.
[3] pion:194 MeV and 0.796 m. 38.80 ns.
[4] pion:585 MeV and 2.96 m. 22.72 ns.
Predict 598310 photons of 37.86 M emitted. (1.58 %)
best fit original, with measured E= 3982.70, Chi = 922337203685477580
2147 photons
Duration 142.73 ns
Time 6.73 ns
Mean time 21.02 ns
Decay signal = 19
+0+8+6+5
2134 photons
Duration 132.00 ns
Time 6.97 ns
Mean time 21.54 ns
Decay signal 26.36
+1.71+10.70+8.42+5.53
ln(L) -8584.61
COMMAND: Fit selected event
event generated
VIEW: top
LAYER: photons
Mean = 953.02 and variance = 600.22
FINAL VERDICT
Error in measured energy 145.73 MeV = 3.66 %
Error in lepton energy 103.41 MeV = 5.08 %
Error in lepton track 0.47 m = 5 %, vertex: 0.11 m.
Error angle L 0.00 rad = 0 deg (p 1.40 rad = 80 deg)



Scinderella: neutrino with 4000.0 MeV (SPP from carbon) electron^minus+ proton
Control Options Event Measurement Analyse View Layer Help
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:6MeV[157ns]
MEASUREMENT
measured 675485 photons of 41.90 M. (1.61 %)
FIT (done fit for selected event)
ln(L) = 2302063 s=0.00
Vertex at (0.89, 0.15, 14.71)0.00 MeV 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: 3676.42 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 M emitted. (1.88 %)
best fit original, with measured E= 3984.00, Chi = 922337203685477580
932 photons
Duration 130.39 ns
Time 13.93 ns
Mean time 10.35 ns
Decay signal = 7
+7
871 photons
Duration 95.00 ns
Time 13.59 ns
Mean time 9.75 ns
Decay signal 0.00
+2.59
ln(L) -3615.83
COMMAND: Fit selected event
event generated
VIEW: top
LAYER: chi
FINAL VERDICT
Error in measured energy 16.40 MeV = 0.41 %
Error in lepton energy -25.60 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)

Results so far

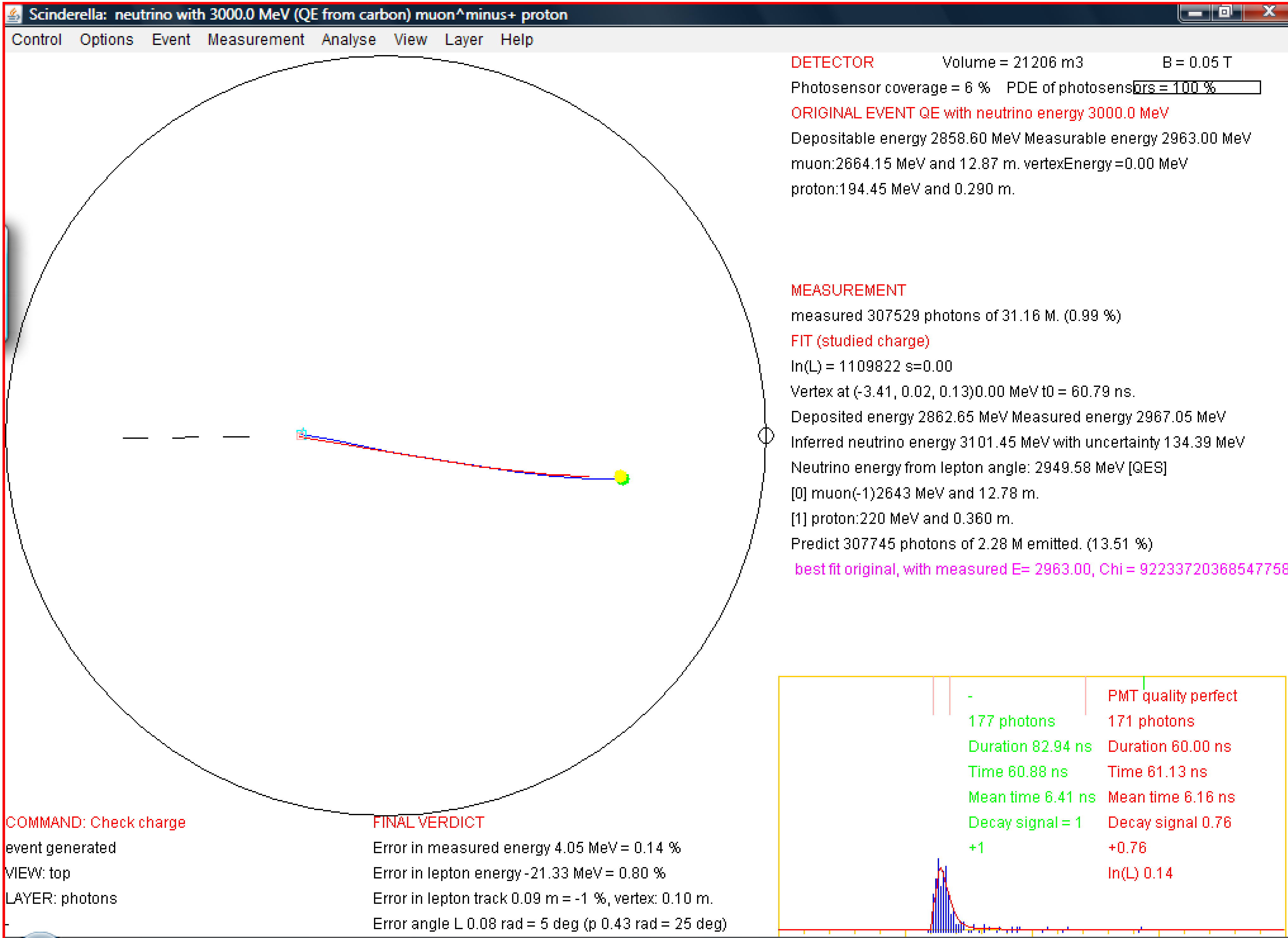
- Very good fit to simple events
  - Almost absolute flavor recognition (even without muon decay signal)
  - Positional accuracy a few cm
  - Angular accuracy few degrees
    - Neutrino angle limited by unseen nuclear recoils
- Good fit to more complicated events, too
  - Three tracks can be fitted if 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

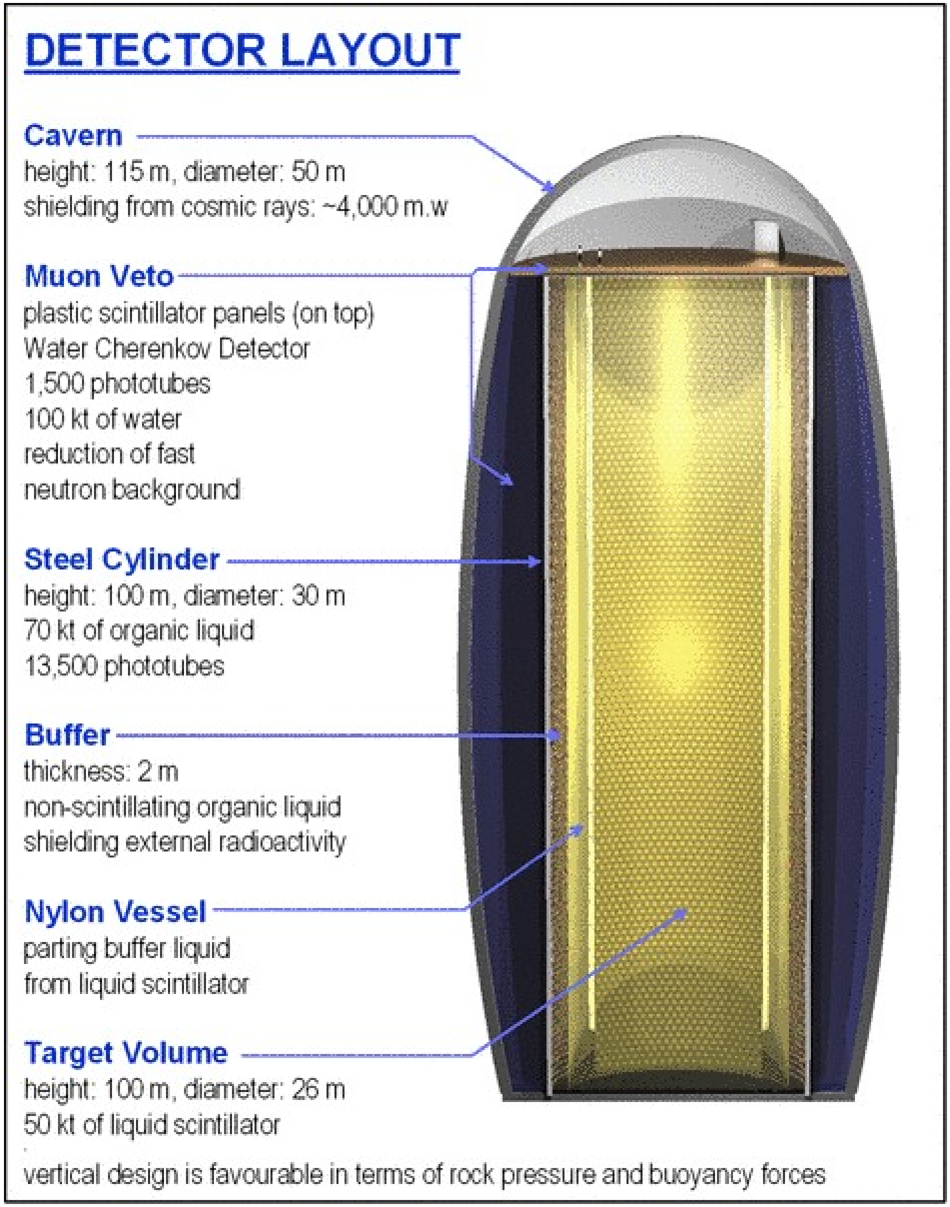
Recognizing antineutrinos and neutrinos?

- 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


Scinderella: neutrino with 3000.0 MeV (QE from carbon) muon^minus+ proton
Control Options Event Measurement Analyse View Layer Help
DETECTOR Volume = 21206 m3 B = 0.05 T
Photosensor coverage = 6 % PDE of photosensors = 100 %
ORIGINAL EVENT QE with neutrino energy 3000.0 MeV
Depositable energy 2858.60 MeV 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 t0 = 60.79 ns.
Deposited energy 2862.65 MeV Measured energy 2967.05 MeV
Inferred neutrino energy 3101.45 MeV with uncertainty 134.39 MeV
Neutrino energy from lepton angle: 2949.58 MeV [QES]
[0] 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, Chi = 922337203685477580
-
177 photons
Duration 82.94 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
ln(L) 0.14
COMMAND: Check charge
event generated
VIEW: top
LAYER: photons
FINAL VERDICT
Error in measured energy 4.05 MeV = 0.14 %
Error in lepton energy -21.33 MeV = 0.80 %
Error in lepton track 0.09 m = -1 %, vertex: 0.10 m.
Error angle L 0.08 rad = 5 deg (p 0.43 rad = 25 deg)

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

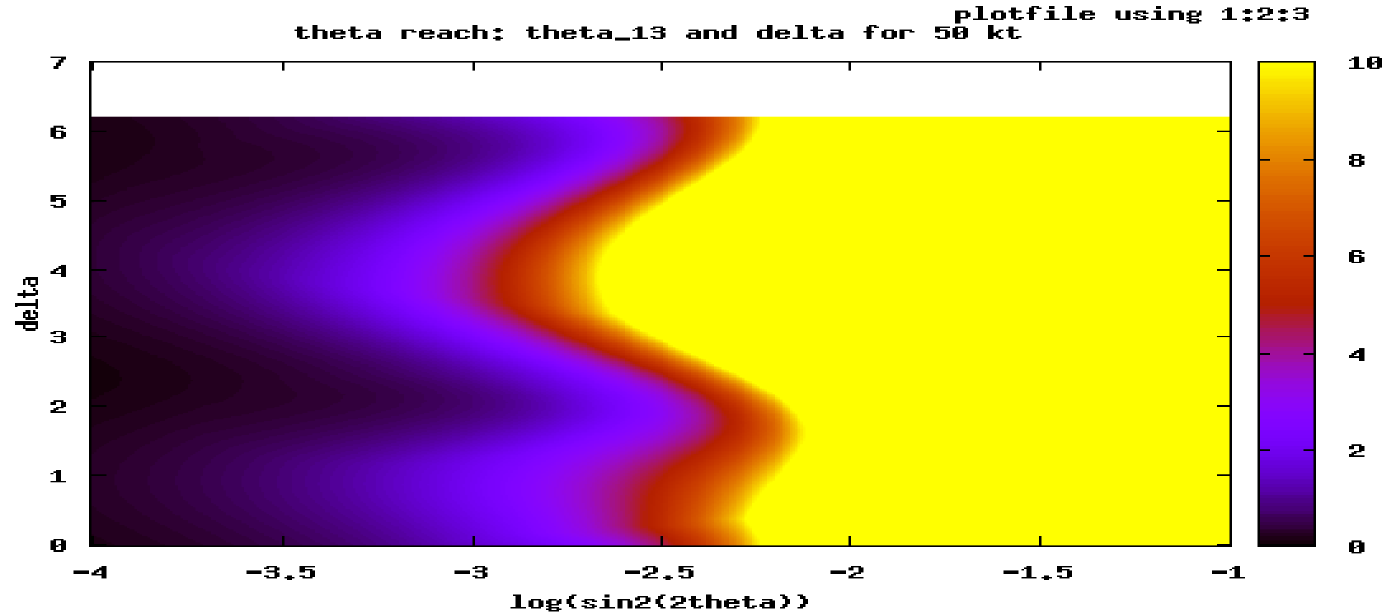
Neutrino beams

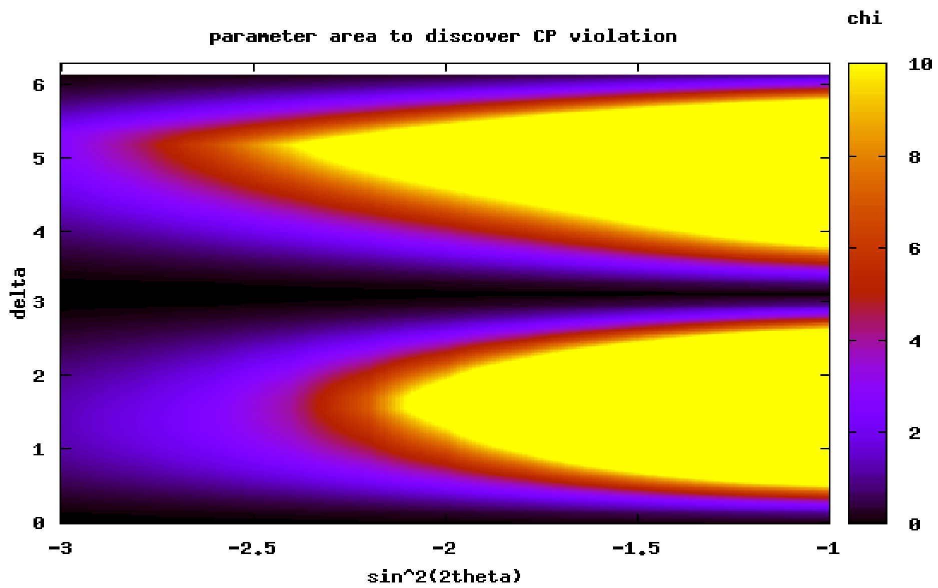
- **Conventional wide band beam: 1-6 GeV** (< 100 M€)
  - Baseline > 1000 km preferred
  - Vertical alignment not a burden if wide enough
  - Good for $\sin^2(2 theta) > 10^{-2}$
- Beta beam: 300 MeV – 5 GeV (1 G€)
  - LENA very good with a high-energy beta beam
  - May study $\sin^2(2 theta) > 10^{-3}$ 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 $\sin^2(2 theta) \approx 10^{-3} \ldots 10^{-4}$

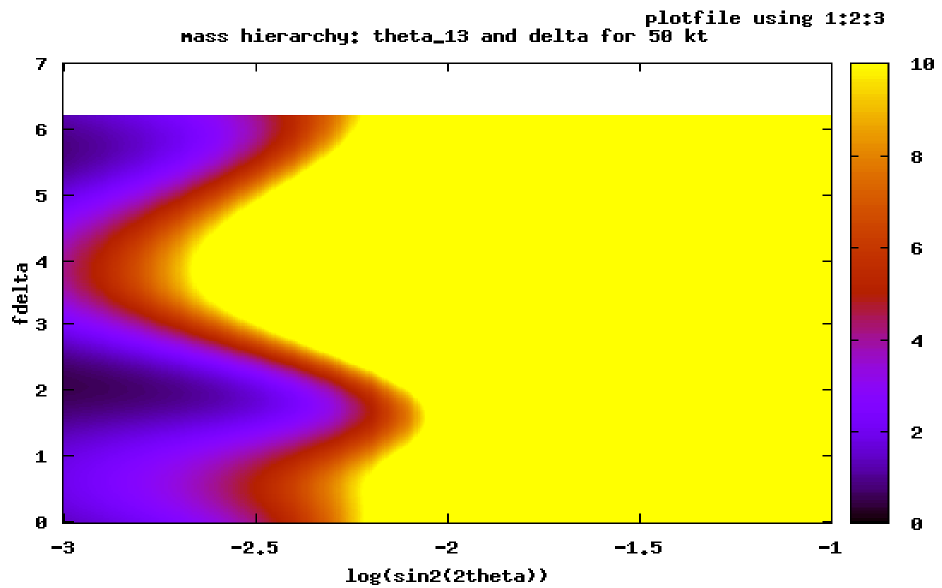
Conclusions

- 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