Cosmic-ray background for beam neutrinos at the surface

D. Barker[1], M. Diwan[2], M. Goodman[3], J. De Jong[4], V. A. Kudryavtsev[5], D.-M. Mei[1], M. Richardson[5], M. Robinson[5], R. Svoboda[6], C. Zhang[1]

[1]Department of Physics, University of South Dakota, Vermillion, SD 57069, USA

[2]Brookhaven National Laboratory, USA

[3]Argonne National Laboratory, USA

[4]Department of Physics, Oxford University, Oxford, UK

[5]Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

[6]Department of Physics, University of California, Davis, USA

Outline

- **Problems with cosmic rays.**
- **Sources of background.**
- **Geometry.**
- **Muon sampling.**
- **Background events with muons crossing the detector.**
- **Background events without muon signal in the detector.**
- **Events caused by neutrons from atmospheric showers.**
- **Uncertainties.**
- **Summary and conclusions.**

Problems with cosmic rays

- **High event rate for DAQ to handle - LHC experiments have demonstrated that modern DAQs are capable of processing events separated by tens of nanoseconds. In fact, only about 1.4 ms of data (or slightly more) are needed to be processed (maximum drift time) every 1.33 s since no physics other than with beam neutrinos is likely to be possible on the surface.**
- **High data rate for processing and analysis - see above.**
- **Track confusion. This may be a problem but does not look as severe as a 'background problem'. As soon as the background problem is better understood and the reconstruction software for specific detector configuration is working, we can consider the 'confusion' problem.**
- **Cosmogenic background. Appears to be the most severe of the aforementioned problems. Here we will consider cosmogenic background induced by muons, neutrons and their secondaries.**
- **Space charge. Considered separately.**

Previous studies and recent improvements

- **D. Barker et al. Muon-induced background for beam neutrinos at the surface. LBNE-doc-6232 (August 2012).**
- **Energy threshold decreased to 0.1 or 0.25 GeV in all simulations.**
- **Point of closest approach (PoCA) has been studied extensively as the most promising technique.**
- **Tracks of electrons have been recorded (not just photons and other neutrals).**
- **Background of neutrons from atmospheric showers determines the required depth.**
- **More details on the recent simulations in LBNE-doc-6476 (October 2012) and references therein.**

Signal versus background events

- We are primarily concerned about events which can mimic electron neutrino interactions.
- These are electromagnetic cascades possibly with some hadronic component.
- The energy of the cascade (event): 0.1 (0.25) - 5 GeV.

Background events - I

- **Electron tracks and e^+e^--pairs produced by muons or other charged particles in cascades.**
- **The vast majority of these events will be associated with knock-on electron and e^+e^--pairs production by muons.**
- **Rejecting this background is relatively easy: cut a cylinder of a few cm diameter around a muon track and any charged secondary track requesting for a candidate neutrino event to start outside such a cylinder. Even better way: to use point of closest approach (PoCA). Loss of fiducial volume <1%.**
- **Removing volumes close to the surface of the detector (charged tracks entering the detector should not be considered as candidate ν_e interactions). Fiducial volume could be as much as 90% of the total volume. Implemented in the design.**
- **Also removing volumes (a few cm thick) close to dead regions. To be done anyway for ν_e interactions to be reconstructed properly.**

Background events - II

- Bremsstrahlung from muons. As we require a photon to have an energy more than 0.1 (0.25) GeV, the probability of emitting such a photon at a large angle from the muon track is quite small. Photons (and induced electromagnetic cascades) travelling close to the original muon can be rejected in the same way as charged tracks (mainly PoCA).
- Neutral hadrons:
  - π^0 giving two photons,
  - K_S^0 decaying into two neutral pions and then 4 photons,
  - Neutrons giving neutral pions and again photons.
  - In all these cases we will have two or more photons in the final state.

Background events - III

- **K_L^0 decay. This is in fact a special case of neutral hadron production and decay which can mimic ν_e interaction. The signature of the decay can be the same as the signature of the signal event: $K_L^0 \rightarrow \pi e \nu_e$.**
- **In most cases K_L^0 will decay at rest (losing energy in hadronic interactions before it decays) and the energy of the electron will be below the minimum energy of interest 0.25 GeV.**
- **There is still a danger that some K_L^0 decays will be indistinguishable from ν_e events.**

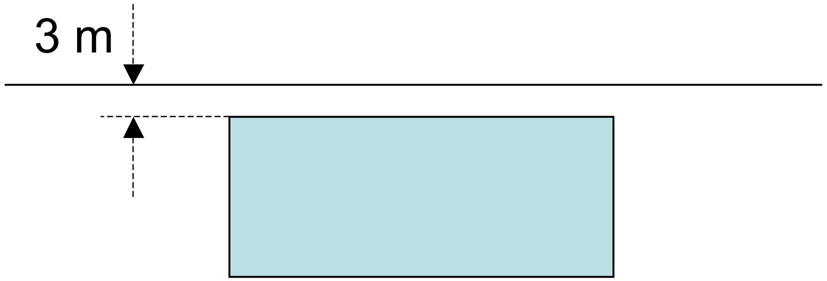
Background for beam neutrinos

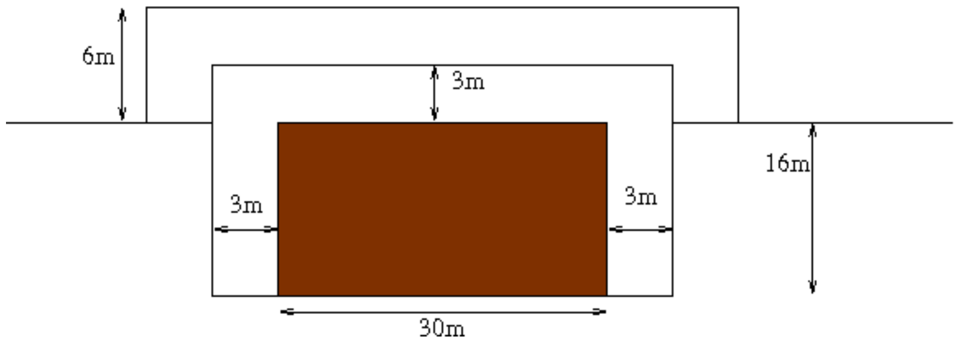
- **Events mimicking signal beam events:**
  - **Electromagnetic cascades initiated by electrons or positrons with energy 0.1 (0.25) - 5 GeV.**
  - **Other (hadronic) energy deposition should be very limited.**
- **Electrons and positrons are most likely to be produced by high-energy photons.**
- **Photons can be produced by other particles but only photons can give electromagnetic cascades.**
- **Additional background rejection factor: only 2% of photon-induced cascades can be misidentified as neutrino-induced cascades.**
- **K_L^0 decay can give an electron and a pion but most likely at rest -> electron energy <0.25 GeV - should be checked more accurately.**

Three main types of events

1. **Background events from muons which cross the detector.**
2. **Background events from muons which do not cross the detector.**
3. **Background events caused by neutrons from atmospheric showers.**

Geometry





- Cuboid of liquid argon: 30 m long, 15 m wide, 16 m high; total mass 10 kt.
- 30 cm fiducial cut (9.1 kt fiducial mass).
- LAr is placed 3 m underground.
- Muons are coming from upper hemisphere although a few of them may scatter and come from below.
- GEANT4.9.5 for muon transport; physics list: Shielding (some simulations with QGSP_BERT).

Muon flux

$$\frac{dI_\mu}{dE_\mu d\Omega}(E_\mu,\theta) = 0.14 \times (E_\mu + \Delta)^{-2.70} \times p_d \times \left(\frac{1}{1+\frac{1.1E_\mu \cos\theta^\star}{115GeV}} + \frac{0.054}{1+\frac{1.1E_\mu \cos\theta^\star}{850GeV}} + R_c \right)$$

- **The total muon flux on the surface of the Earth through a sphere is equal to 170 m^{-2} s^{-1}.**
- **Flux through a horizontal plane is 130 m^{-2} s^{-1}.**
- **Positioning the detector at a depth of 10 m w. e. underground will reduce the flux on the detector by approximately a factor of 2.**
- **If the detector is 3-4 metres below the ground the expected flux through a sphere will be ~100 m^{-2} s^{-1}.**

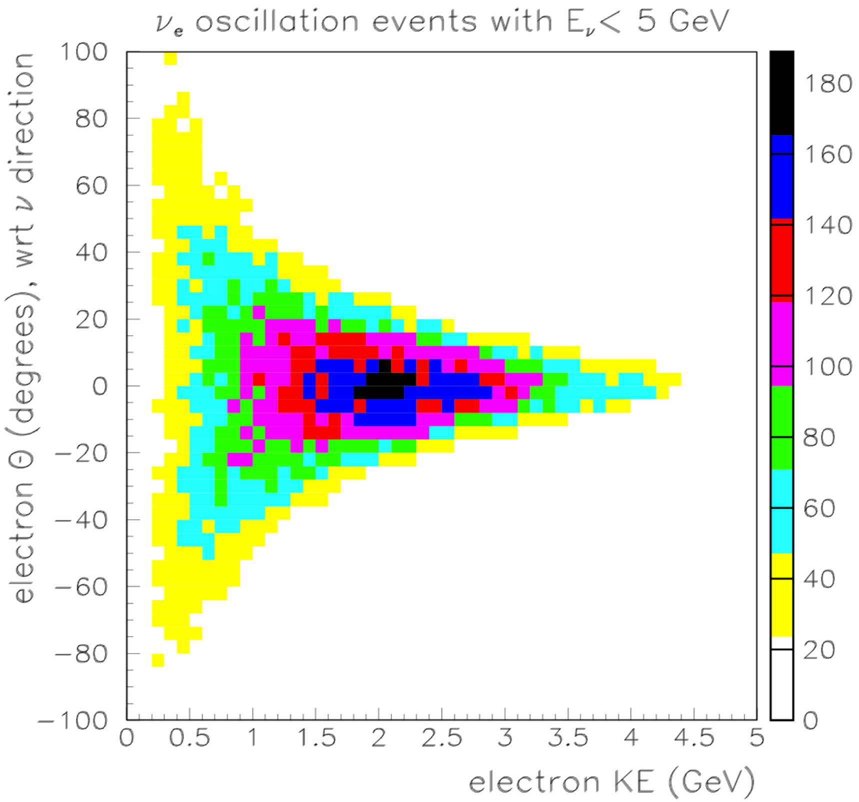
Statistics

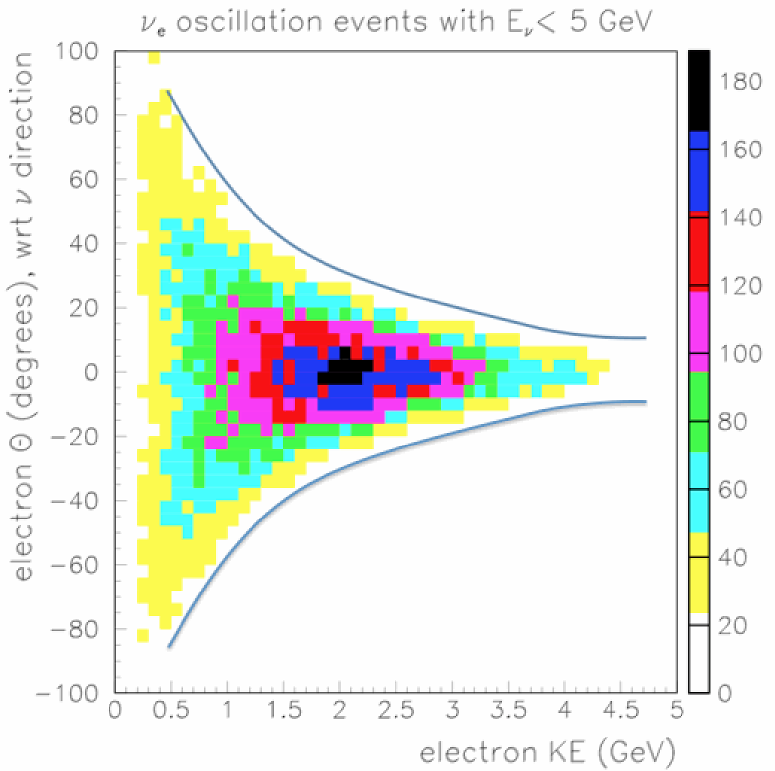
- **Muons sampled on a surface of te Earth, *E* > 1 GeV and *E* > 10 GeV. Simulations with *E* > 1 GeV will be reported here.**
- **Beam running time: 2×10^7 s per year.**
- **Maximum drift time: 1.4 ms, spill duration: 10 μs, spill repetition time: 1.33 s.**
- **Live time (neutrinos on target assuming 1.4 ms window): 2×10^7 s / 1.33 s × 0.0014 s = 21053 s per calendar year.**
- **Live time (neutrinos on target assuming 10 μs window): 2×10^7 s / 1.33 s × 10^{-5} s = 150 s per year.**
- **A factor of 140 difference in background rates.**
- **For most reported results statistics is 0.047 years assuming 1.4 ms time window.**

Parameters studied

- **Event parameters recorded and used for defining the cuts:**
  - **Point of closest approach (PoCA): minimum distance between the two tracks.**
  - **Distance of a photon at the point of conversion into a pair from the muon track (minimum distance) - obsolete, replaced by PoCA.**
  - **Angle of a photon with respect to the beam - θ_b.**
  - **Angle of a photon with respect to the muon - θ_μ (correlated with PoCA).**
- **θ_b is useful if we assume that the electron direction from neutrino interaction is close to the beam direction.**
- **Events without muon track: neutral particles are coming from outside:**
  - **Position with respect to edge of the detector.**
  - **Angle with respect to the beam.**
- **Neutrons from the atmosphere:**
  - **Only angle with respect to the beam.**

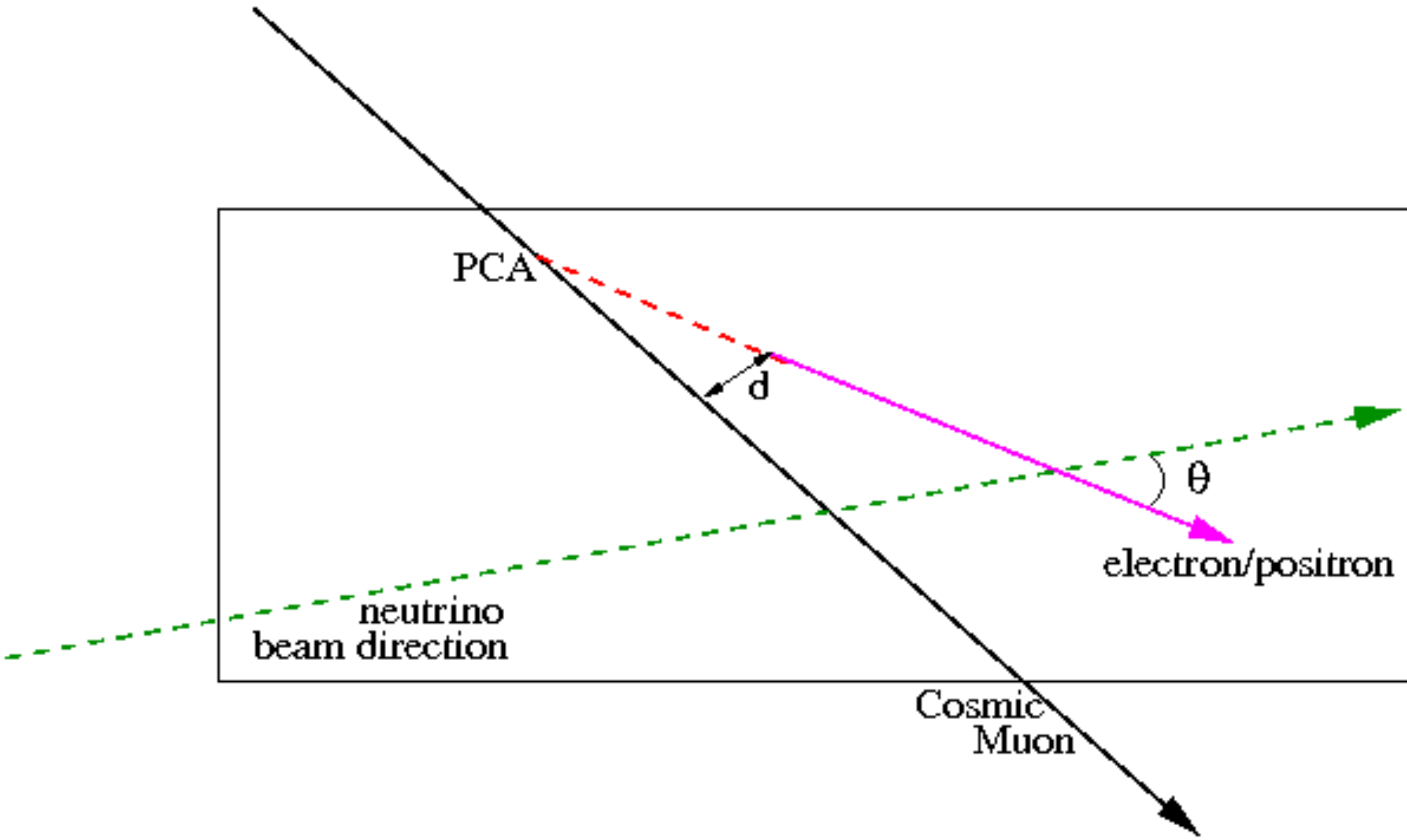
Signal events





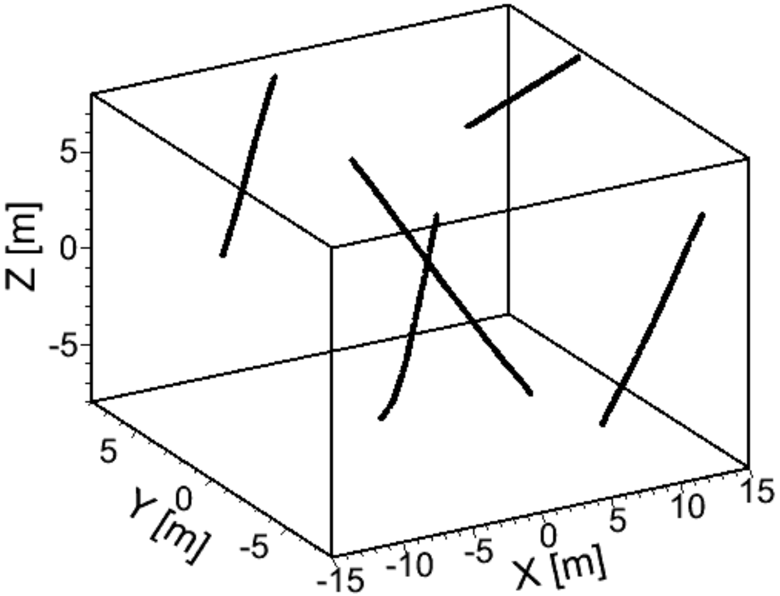
- **Projected electron emission angle as a function of electron energy in electron neutrino induced events.**
- **Almost all events are within 80^0 cone. About half of events below 0.5 GeV are within 40^0 cone.**

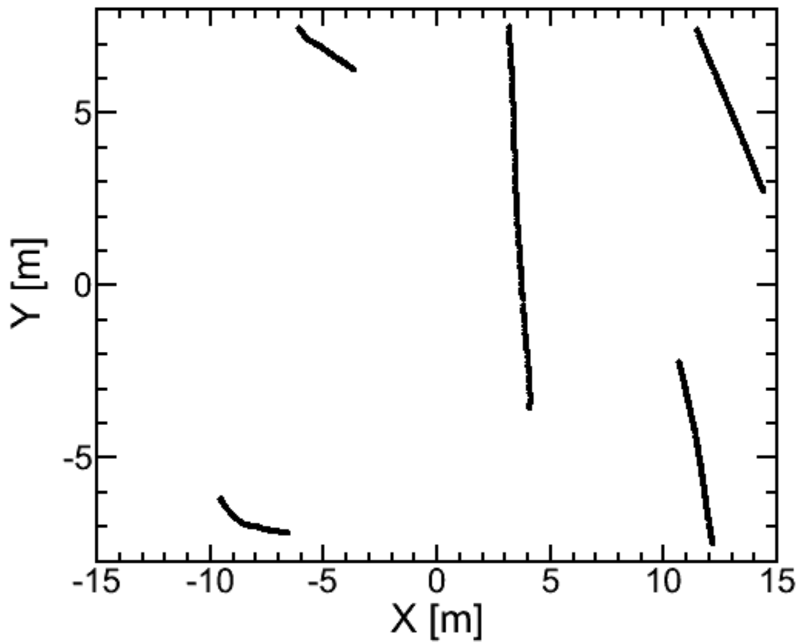
Point of closest approach (PoCA)



- PoCA has been calculated for each e^- or e^+ with E > 0.1 GeV produced by the first photon in a cascade.
- Also for photons.

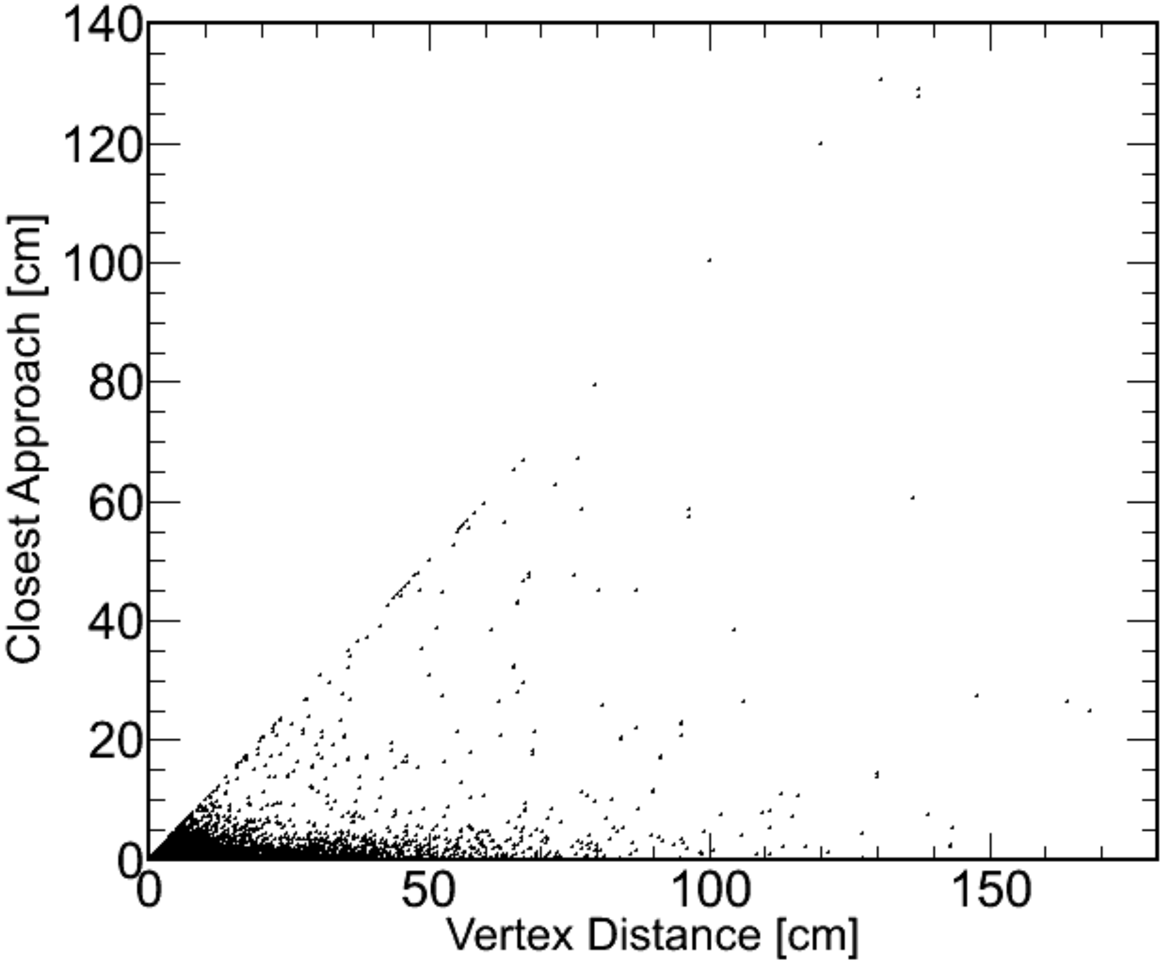
Muon tracks





- **Muon tracks, in particular at low energies and producing high-energy secondaries, are not straight lines.**
- **PoCa has been calculated by tracking an electron back to the parent muon and comparing their positions at all points of the tracks.**

PoCa vs distance



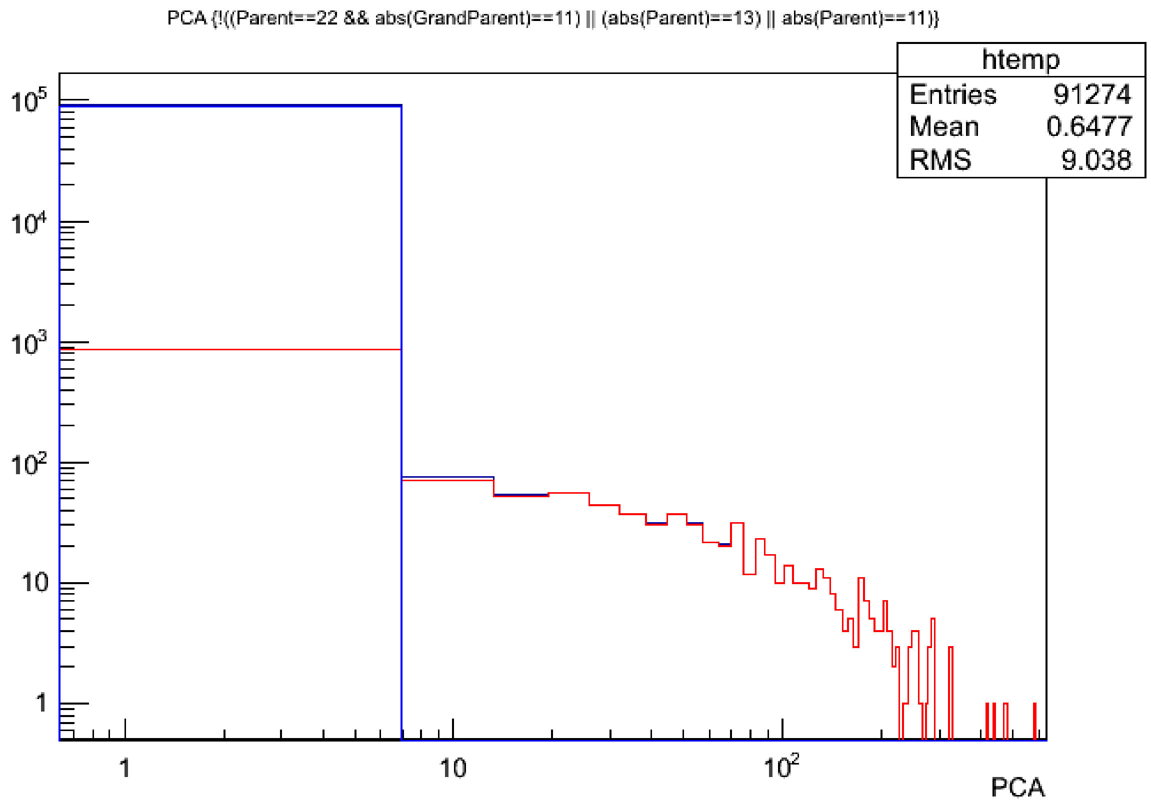
- **PoCA to the muon track is always smaller than the distance from the track as expected.**
- **Hence cutting on PoCA is more efficient and retains a larger fraction of fiducial volume.**

Muons in the detector: summary table

Table 1: Rate of electrons with energy above 0.1 GeV per calendar year from different sources before and after cuts on PoCA (d) and energy. Columns from 2 to 6 shows event rates after specific cuts on PoCA and electron energy: column 2 – electron energy $E > 0.1$ GeV; column 3 – $E > 0.1$ GeV, PoCA $d > 10$ cm; column 4 – $E > 0.25$ GeV, PoCA $d > 10$ cm; column 5 – $E > 0.25$ GeV, PoCA $d > 30$ cm (this column gives an estimate for the expected rate of events since PoCA evaluation has been done for γ's, not electrons). The last column shows additional cut on fiducial volume: events starting within 30 cm from the walls are rejected. The simulated statistics corresponds to 0.047 of the calendar year. The figures in this Table do not account for an efficient (≈98%) $e - \gamma$ separation factor [13] or for a reduction of the time window due to the efficient photon detection system.

	Rate per year				
Source of electrons	$E > 0.1$ GeV	$E > 0.1$ GeV $d > 10$ cm	$E > 0.25$ GeV, $d > 10$ cm	$d > 30$ cm (estimate)	30 cm from the walls
Knock-on electrons and e^+e^- pairs, $\mu \to e^\pm$	1.25×10^8	< 1000	< 100	~ 0	~ 0
Charged particles (not muons) or from outside	3.04×10^6	1.33×10^4	2.68×10^3	~ 0	~ 0
$\pi^0 \to e^\pm$	2.47×10^3	447	170	~ 70	~ 70
$K_L^0 \to e^\pm$	~ 100	< 100	~ 0	~ 0	~ 0
$\mu \to \gamma \to e^\pm$	1.28×10^6	< 100	< 100	~ 0	~ 0
$\pi^0 \to \gamma \to e^\pm$	3.02×10^5	4.47×10^4	2.01×10^4	8.4×10^3	$\sim 8 \times 10^3$
outside $\gamma \to e^\pm$	1.61×10^6	1.93×10^4	4.55×10^3	1.8×10^3	~ 200

PoCA distribution

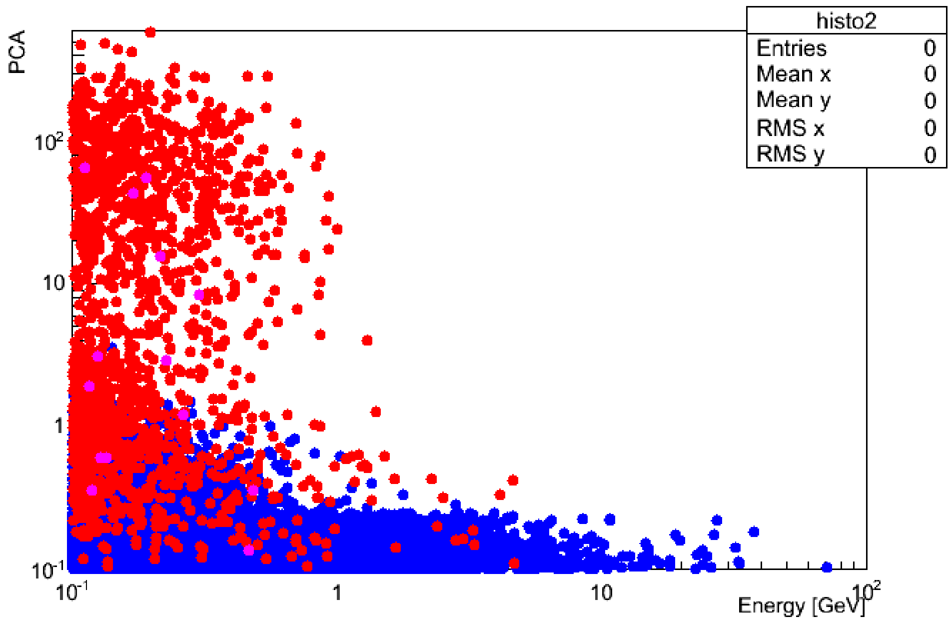


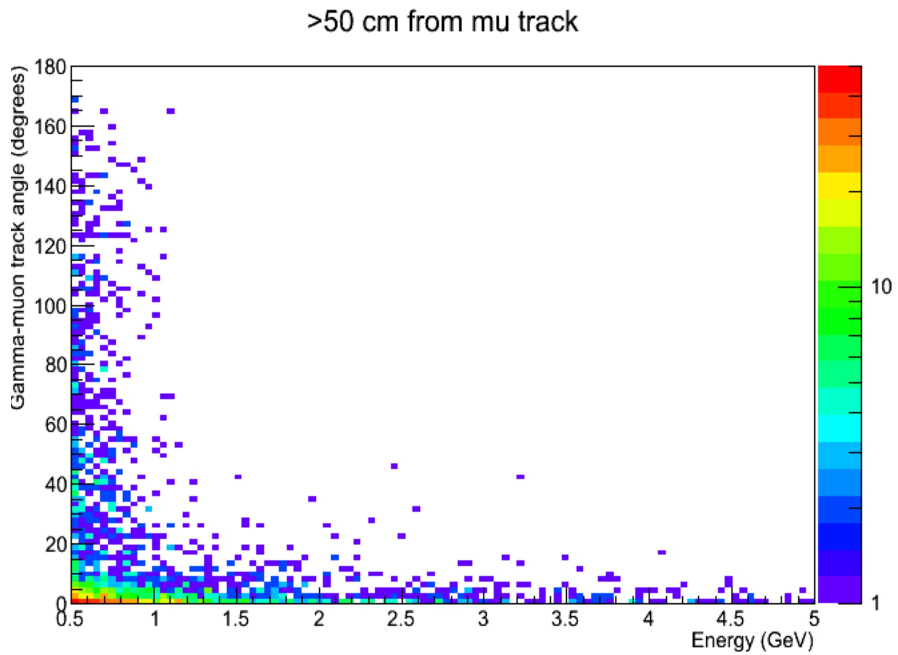
Red: $\pi^0 \rightarrow 2\gamma \rightarrow 2e^{\pm}$.

Blue: bremsstrahlung from muons $\mu \rightarrow \gamma \rightarrow e^-$.

- **This and other figures are based on limited statistics and are shown for illustration purpose only. Yearly rates are given in the table.**
- **Electrons due to bremsstrahlung from muons can be efficiently cut by PoCA (or distance + angle w.r.t. the muon).**

PoCA and angle w.r.t. the muon





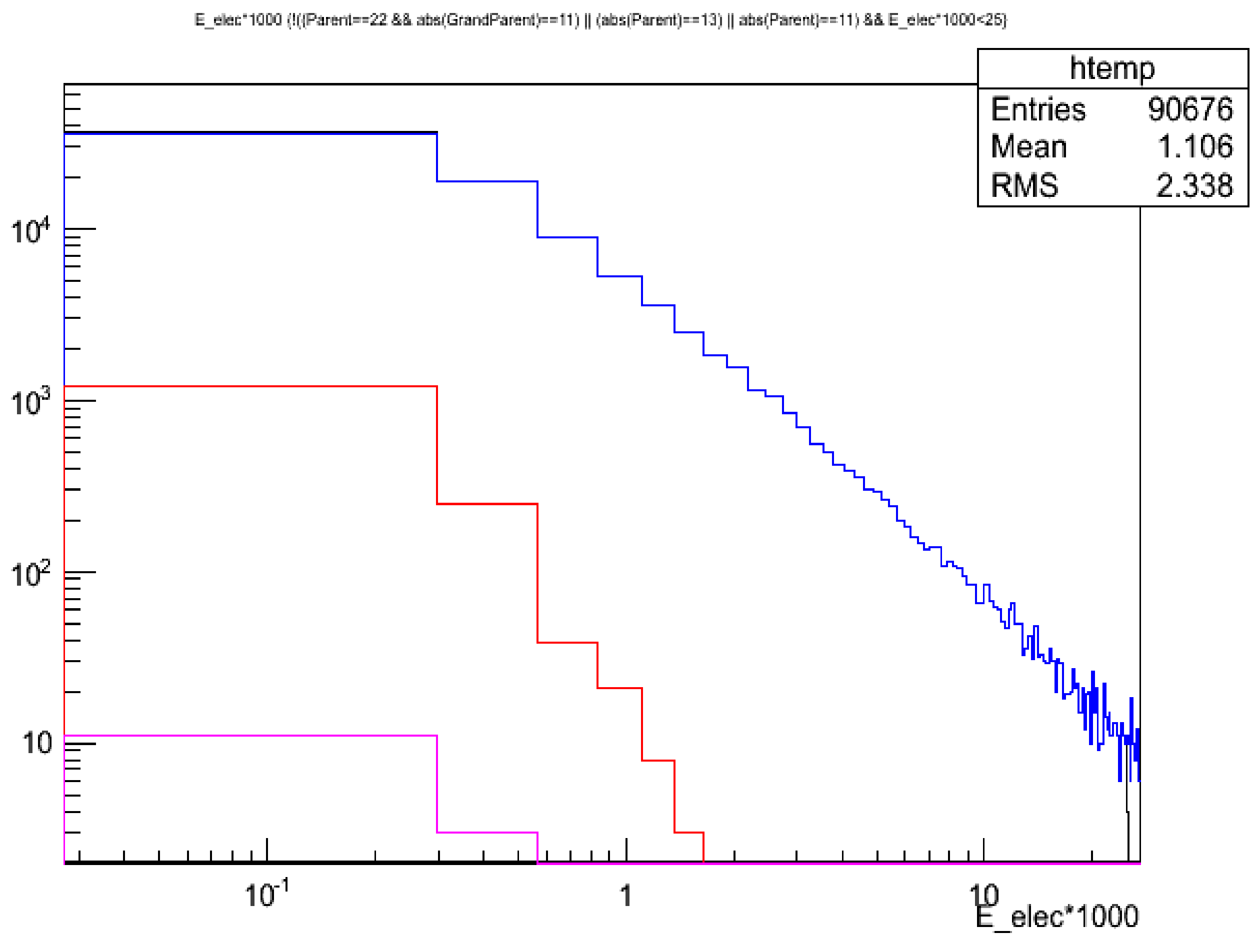
Red: $\pi^0 \rightarrow 2\gamma \rightarrow 2e^{\pm}$.

Blue: bremsstrahlung from muons $\mu \rightarrow \gamma \rightarrow e^-$.

Left: electrons, right: photons.

High-energy photons are near parallel to the muon.

Energy spectra before PoCA cuts



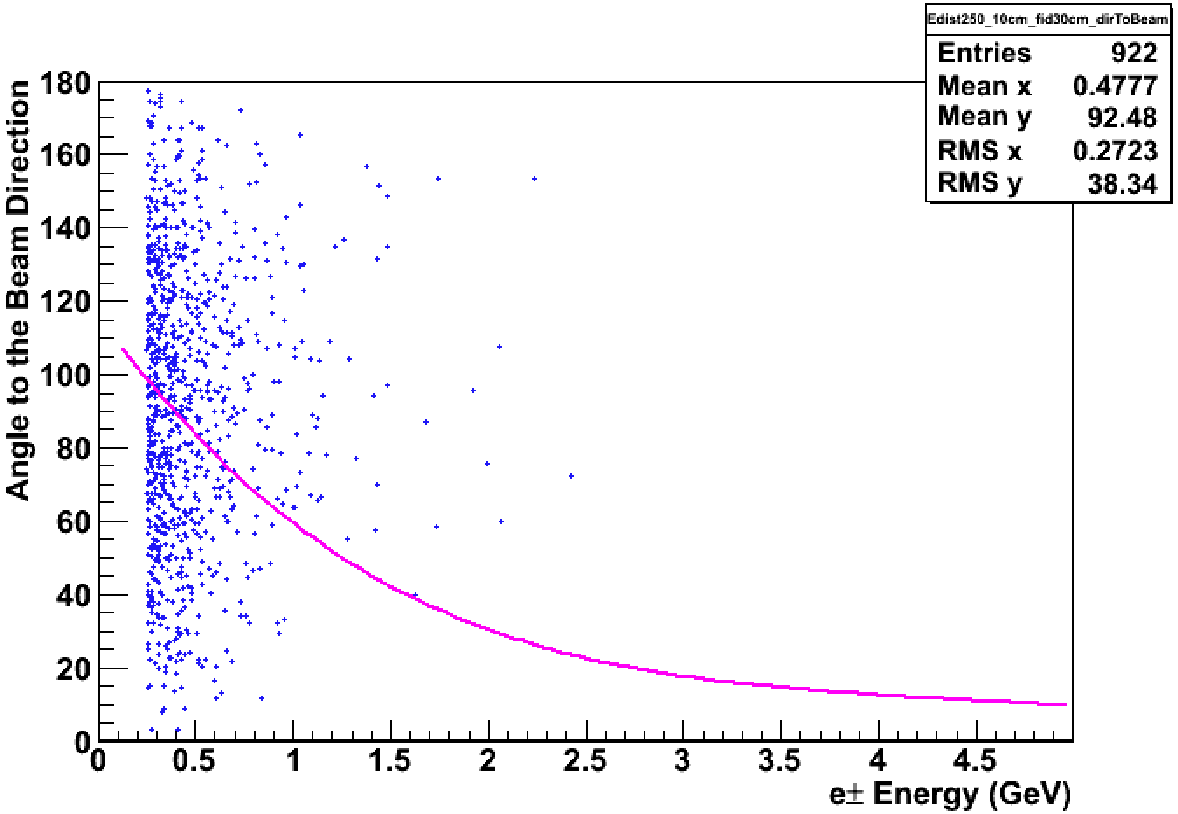
Red: $\pi^0 \rightarrow 2\gamma \rightarrow 2e^{\pm}$.

Blue: bremsstrahlung from muons $\mu \rightarrow \gamma \rightarrow e^-$.

Magenta: $\pi^0 \rightarrow \gamma e^{\pm}$.

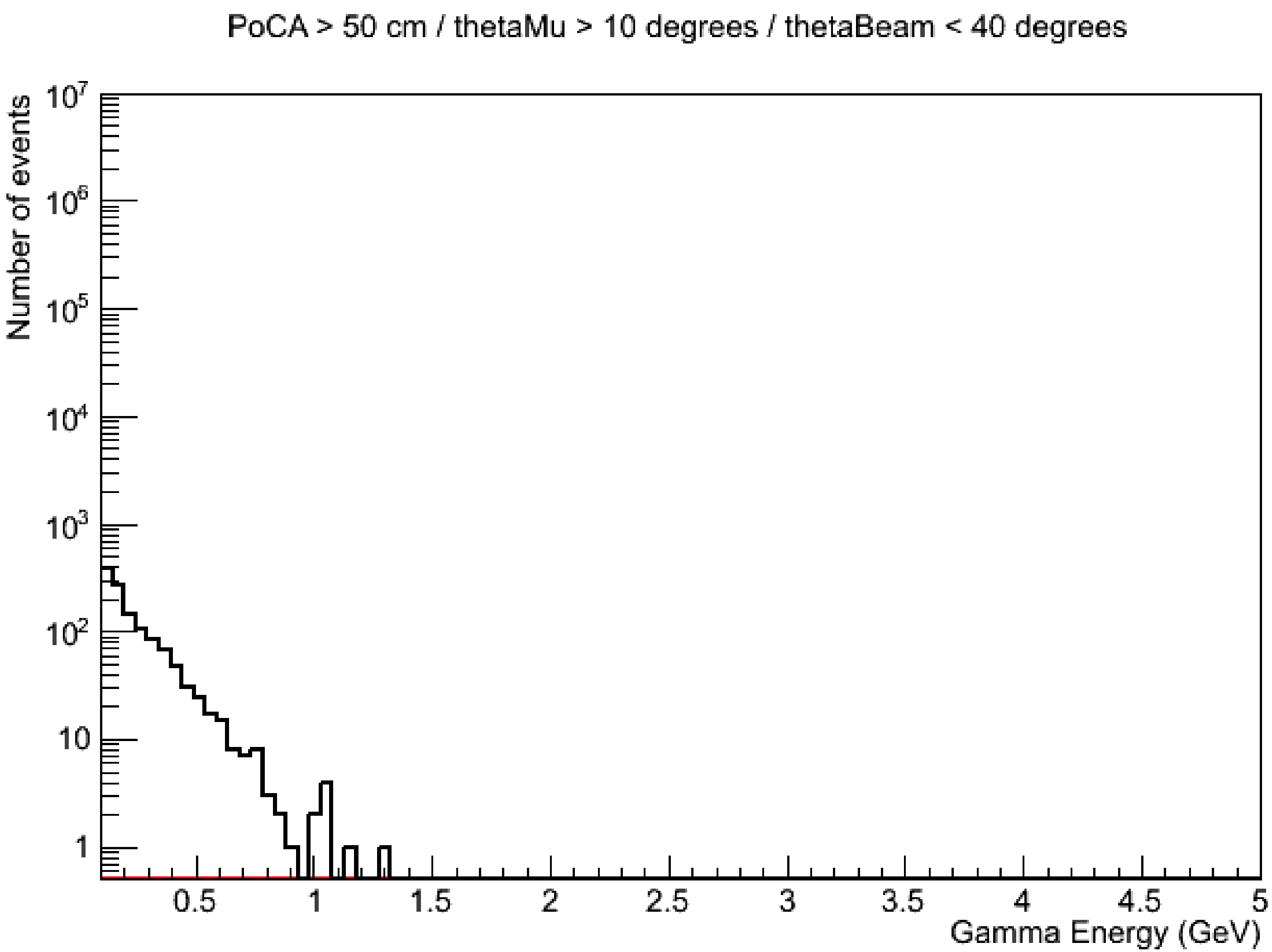
Most events are below 1 GeV.

Angle w.r.t. the beam



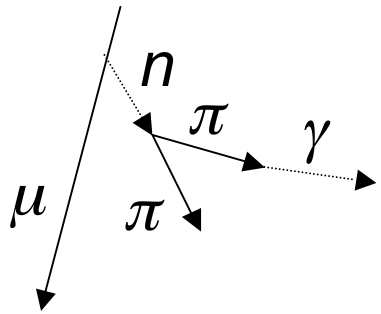
- *E* > 0.25 GeV.
- Cutting on the beam angle will remove 2/3 of events (practically all events above 1 GeV).

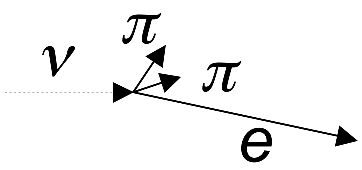
Energy spectrum

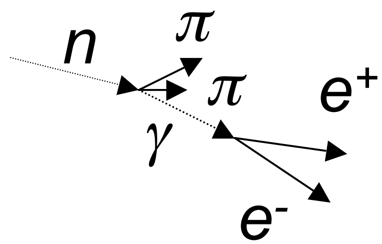


Other background rejection cuts

- PoCA with respect to the charged parent. Efficient, for instance against π^0 produced by charged pions. PoCA w.r.t. the muon may be large but PoCA w.r.t. the parent charged particle may be small.
- Additional features in hadronic events dominated by neutron-induced events. Usually high-energy neutrons are produced in large cascades containing many particles that can be identified.
- Neutron interaction with π^0 production may produce other hadrons too. Then the initial point of these hadrons will be different from the electromagnetic cascade initiated by photons which will still be pointing back to the neutron interaction. Neutrino interactions will have all tracks starting at the same point.







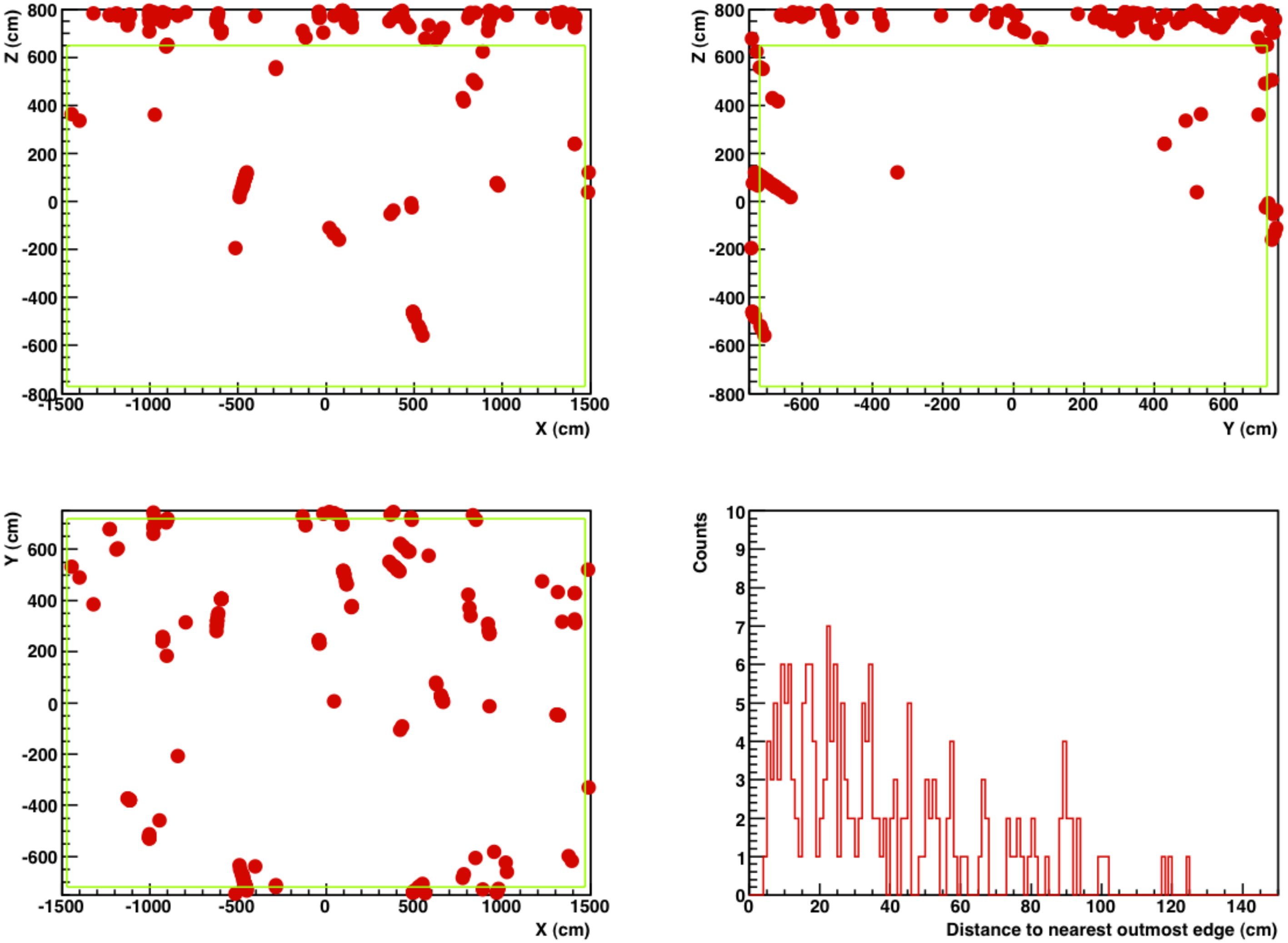
Other background rejection cuts

- **Angle with respect to the muon: correlated with PoCA but may help.**
- **Angle with respect to the beam: cuts 2/3 of events or more. (If a cut of 40^0 cone is applied then neutrino event rate reduces by about a factor of 2 - not recommended at the moment.) 8000 events per year (30 cm PoCA) are reduced to 3200 events per year.**
- **Particle ID: e/γ separation - 98% efficiency, a factor of 50 reduction; 3200 -> 64 events per year or 150 events with PoCA cut of 10 cm.**
- **Efficient photon detection: reduction by a factor of 140 due to the time window; 64-150 -> ~1. Further reduction due to a short scintillation pulse is possible.**

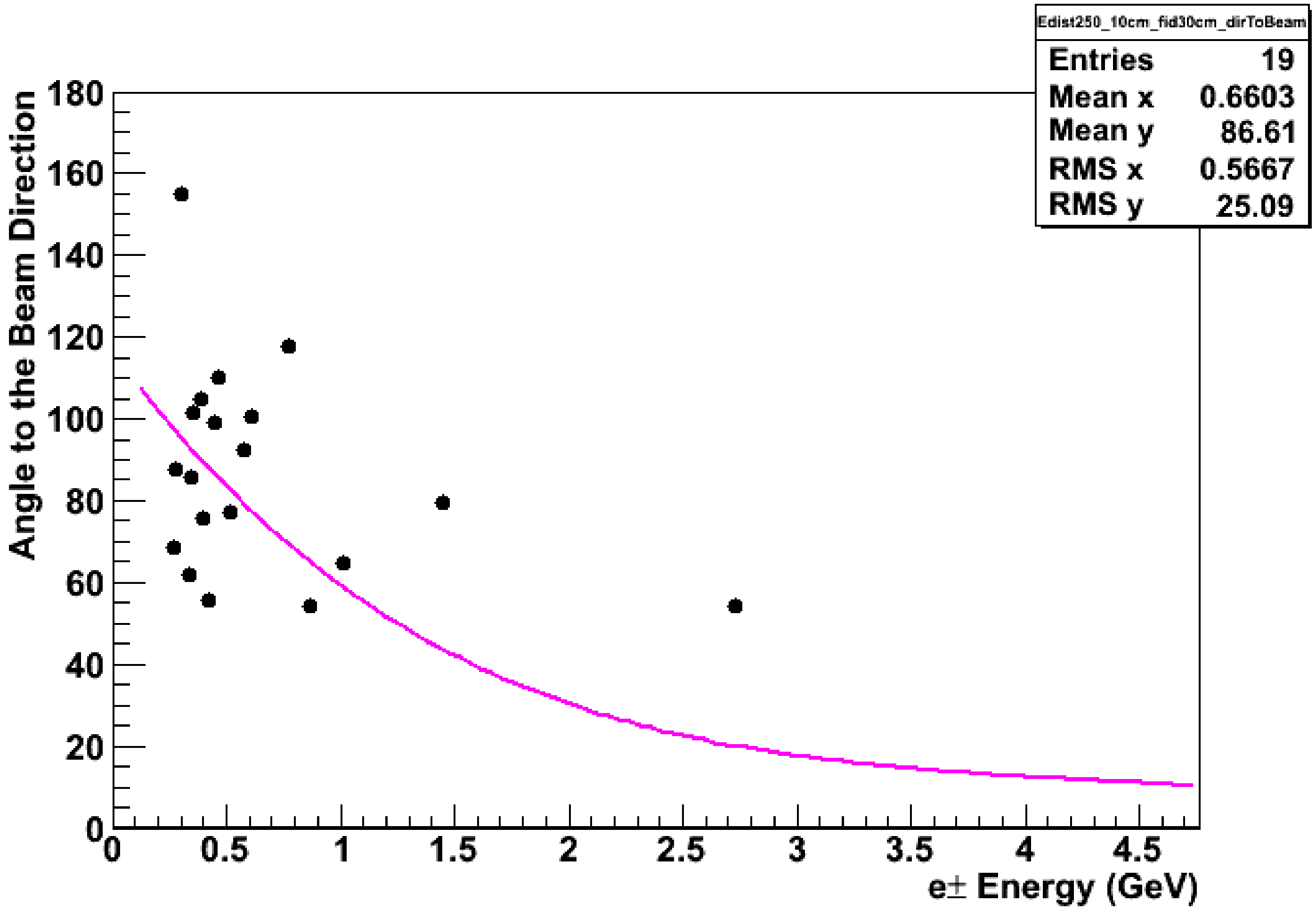
Events without muon track in LAr.

- Statistics 0.057 of a calendar year.
- All electrons/positrons with a kinetic energy >0.1 GeV entering the LAr volume were recorded.
- A fiducial cut was applied to remove particle tracks starting within 30 cm from the detector edges.
- About 20,000 events per year are expected before cuts.
- Half of them are electrons entering LAr - easily rejected by fiducialisation.
- 360 survive stricter energy cut (E > 0.25 GeV) and 30 cm fiducial volume cut.
- Beam direction cut: ~140 events.
- e/γ separation: ~3 events per year.
- Photon detection: << 1 event.

Gammas before fiducial volume cut

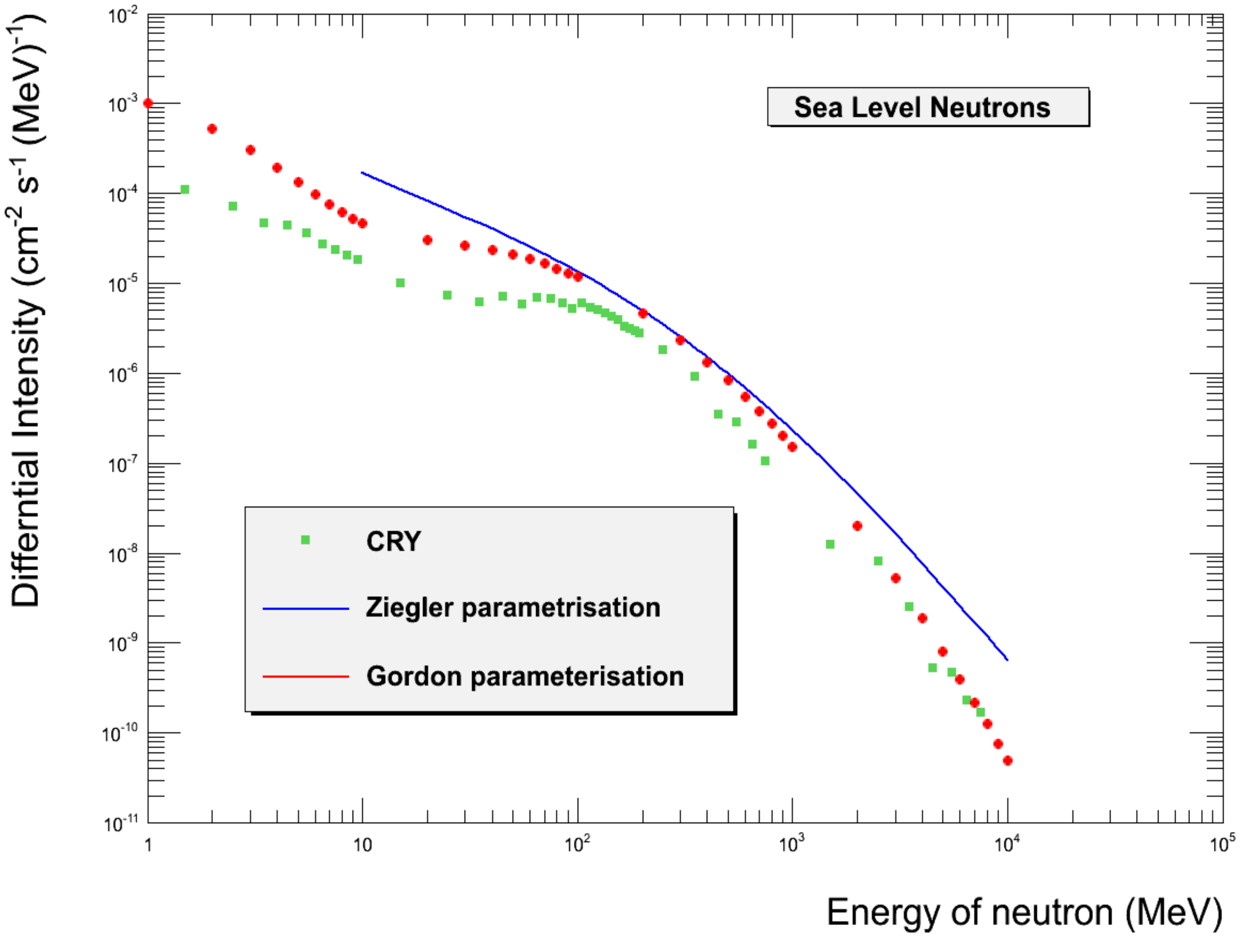


Angle w.r.t. the beam within fiducial voilume



- Practically all events are outside 40^0 cone.

Neutrons from atmospheric showers

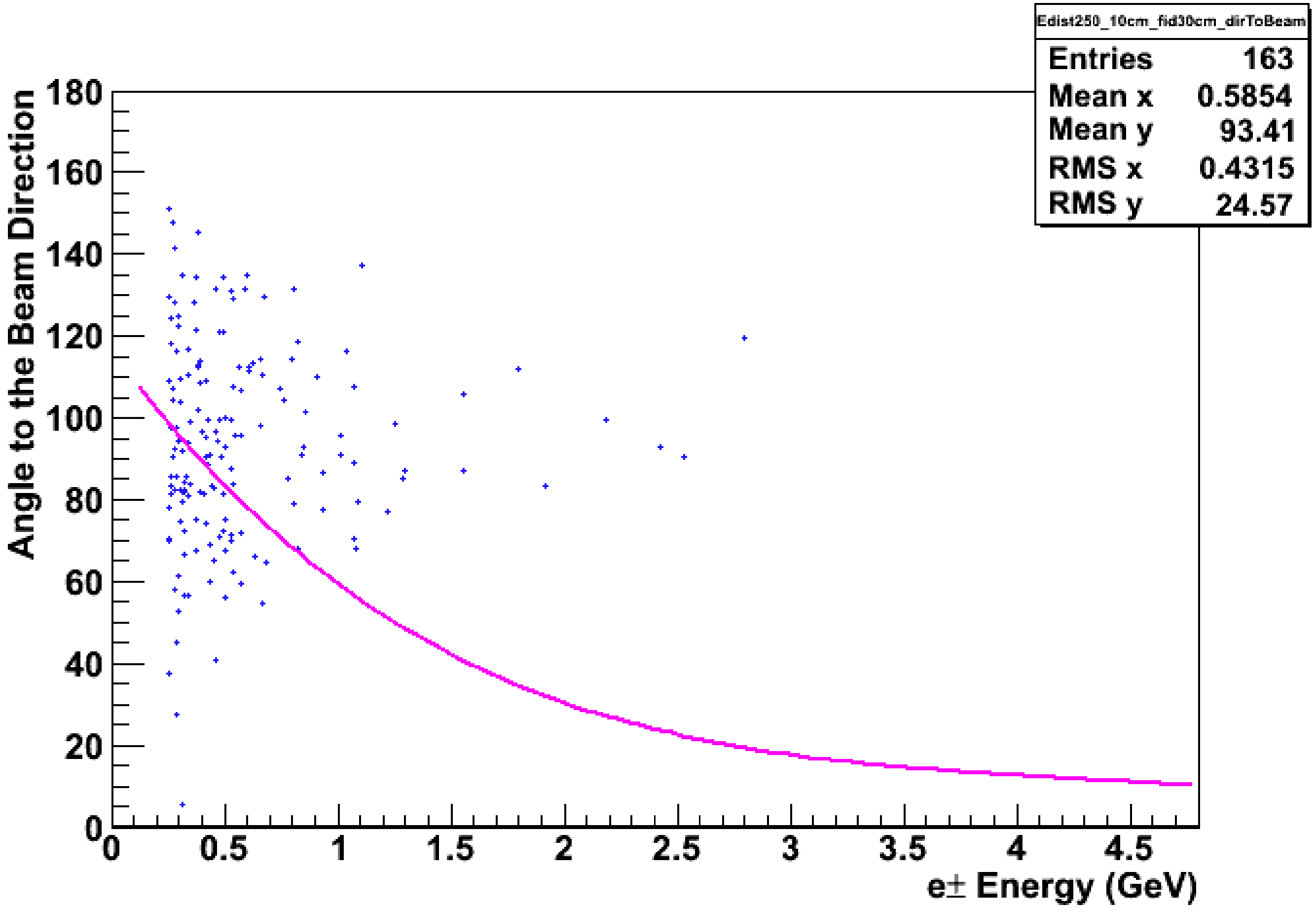


- **Neutron spectra.**
- **CRY was used.**
- **CRY underestimates the flux by ~60% above 100 MeV.**

Cuts and event rates

- 3 m of rock with density 2.71 g/cm^3 giving the column density of 8.13 g/cm^2.
- E > 0.1 GeV.
- ~2000 electrons are entering LAr from outside - rejected by fiducial volume cut.
- ~10,000 per year are from gammas.
- PoCA cannot be applied.
- ~2800 with E > 0.25 GeV after fiducial volume cut - not efficient.
- e/γ separation: 57 events per year.
- Beam angle cut: 20 events.
- Efficient photon detection: << 1 event.

Angle w.r.t. the beam



- **The cut defined by the magenta curves removes 2/3 of events.**
- **Most events are outside 40^0 cone.**

Increasing depth?

- **4 m of rock -> an order of magnitude decrease in the event rate.**
- **5 m of rock -> ~35 events with E > 0.25 GeV after fiducial volume cut; reduced to < 1 after *e*/γ separation.**
- **With efficient photon detector this is not needed.**

Summary: thanks to Mary Bishai

Table 6–7: Cosmic ray backgrounds that produce electromagnetic showers in the detector and the expected event rate/yr after various selection critiria are applied. The initial background event rate is calculated assumning a 1.4 ms drift time per beam pulse, a beam pulse every 1.33 seconds and 2×10^7s of running/yr. The detector is assumed to be on the surface with 3m of rock overburden.

Background	$E_e > 0.25$ GeV	PoCA > 10cm	Fid > 30cm	Beam angle	e/γ PID	Beam timing
Muons in the detector						
$\mu^\pm \to e^\pm$	3.3×10^7	64	0	0	0	0
$\pi^0, K_L^0 \to e^\pm$	940	170	170	68	68	0.5
$\pi^\pm, K^\pm, ... \to e^\pm$	7.4×10^5	2.7×10^3	43	17	17	0.12
$\pi^0 \to \gamma \to e^\pm$	1.6×10^5	2.0×10^4	1.9×10^4	7.5×10^3	150	1.1
$\mu \to \gamma \to e^\pm$	1.3×10^6	8.7×10^4	21	0	0	0
Outer $\gamma \to e^\pm$	4.7×10^5	4.6×10^3	530	210	4	0.03
Muons outside the detector						
Outer $\gamma \to e^\pm$	3.5×10^4	N/A	360	152	3	0.02
$\pi^0 \to \gamma \to e^\pm$	43	N/A	43	18	0.4	0.003
Cosmic neutrons from the surface						
Outer $\gamma \to e^\pm$	1.5×10^3	N/A	230	81	1.6	0.01
$\pi^0 \to \gamma \to e^\pm$	3.4×10^3	N/A	2.4×10^3	890	18	0.13
$n, \eta, \Sigma \to \gamma \to e^\pm$	140	N/A	110	37	0.75	0.05
Total $e^\pm$ background events/yr						
	3.7×10^7	2.2×10^5	2.2×10^4	9.0×10^3	270	2.0

Summary

- **If not enough:**
  - **PoCA 30 cm rather than 10 cm.**
  - **Stricter cut on the angle w.r.t. the beam (but reduced the rate of neutrino events).**
  - **Other features discussed above.**
  - **Bigger depth?**

Uncertainties

- **Known knowns (thanks to Donald Rumsfield):**
  - **Statistics - only about 0.05 of a calendar year.**
  - **OK for the most important background so far: $\pi^0 \rightarrow 2\gamma \rightarrow 2e^{\pm}$.**
  - **Need more statistics for K_L^0 decays (e/γ separation cannot be applied here).**
- **Known unknowns:**
  - **Possible dependence of the results on the model (physics list).**
  - **Simplified approach used to reconstruct the energy and apply some cuts.**
  - **We assumed, for instance that e/γ separation efficiency is energy independent.**
- **Overall probably about a factor of 4.**
- **Unknown unknowns:**
  - **…..**

Summary and conclusions

- **Three types of background have been studies:**
  - **Background events from muons which cross the detector.**
  - **Background events from muons which do not cross the detector.**
  - **Background events caused by neutrons from atmospheric showers.**
- **Ignoring e/γ separation and light detection we may have a few thousand events per year.**
- **Additional factor of 50 (e/γ separation) and 140 (light detection) reduces this to about 1-2 per year.**
- **Other cuts have been identified: still to be studied.**
- **Large uncertainty (about a factor of 4).**
- **Slightly deeper location (5 m of rock) would be better and would secure the absence of the neutron-induced background from atmospheric showers.**

Next steps

- Increase statistics.
- Check K_L^0 decays.
- Check again the dependence on the physics list - results are not always consistent.
- Implement proper geometry as in the design.
- Position the detector beyond the hill - may help in rejecting background.
- Look at the background for muon-neutrino interactions.
- Implement event reconstruction - long term.
- ….