Estimate of the cosmic ray-induced background to ν_e interactions for LBNE 10 kton surface-level far detector

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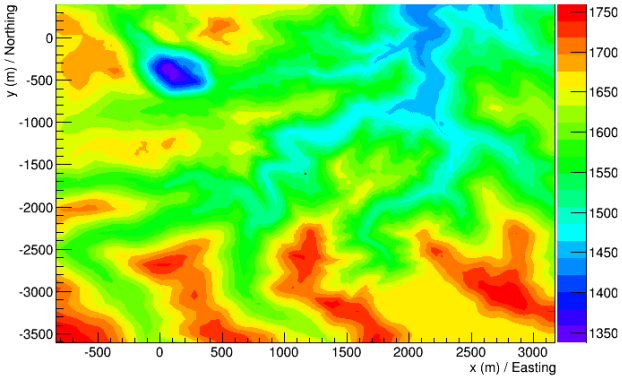
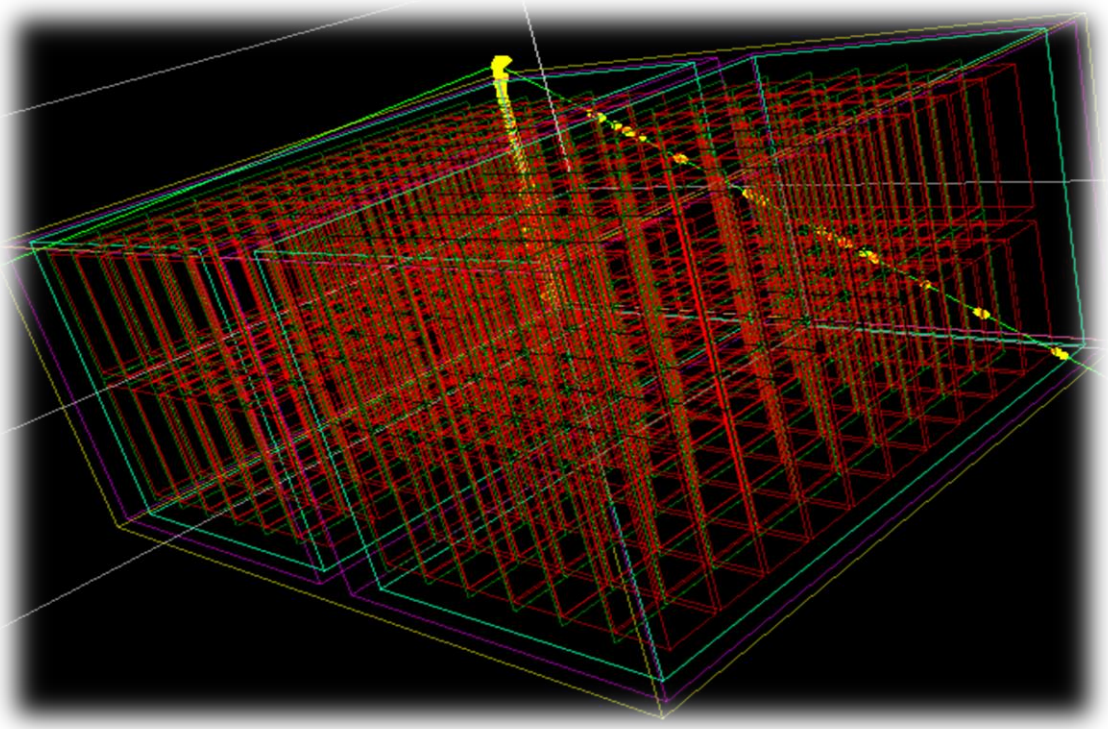
- ν_e interaction indicated by EM shower; incoming cosmic ray particles cause background EM showers.

- Showers have been counted by recording just 1st γ in shower (ie. the '1st-generation γ').

- Detector geometry includes individual TPC cells surrounded by dead regions of LAr, as well as shielding from 0.5 m concrete + 0.8 m polyurethane on both cryostats, and a 3 m rock overburden.

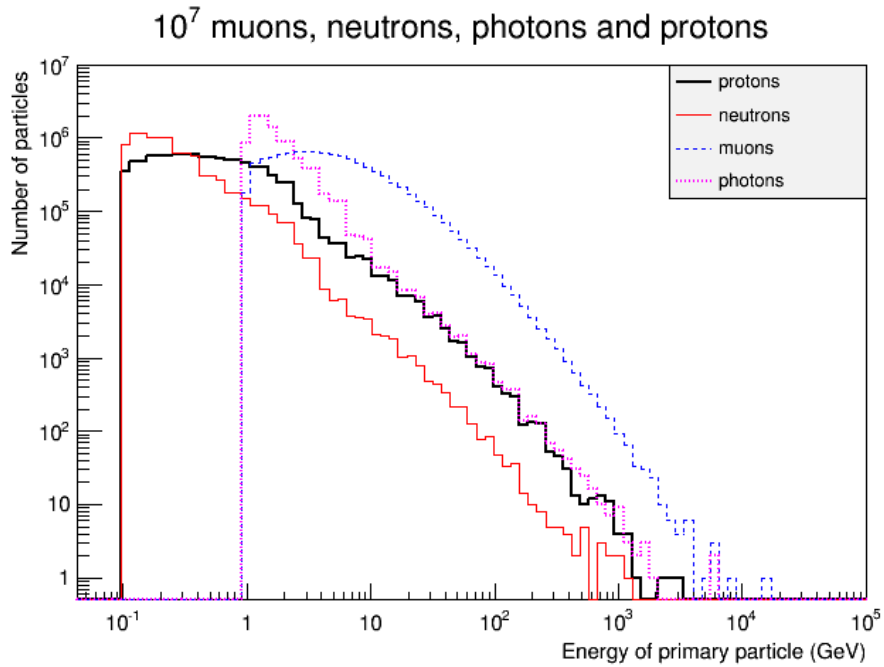
- Accurate surface profile used.

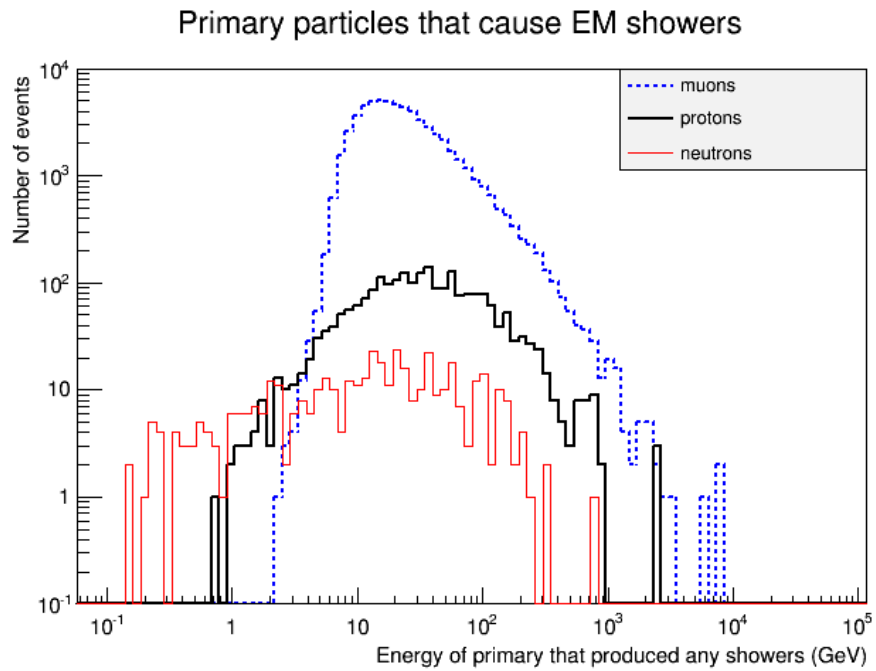




- Large number of background EM showers seen (**>10^8 yr $^{-1}$**) but cuts reject most of it….

- Primary particles used to generate events in Geant4: **μ, γ, neutrons, protons**





- Left plot shows energy of primary particles randomly selected and passed to Geant4. Right plot shows energy of primary particles which cause 1 or more EM showers in 2×10^7 events.

- Statistics improved / computation time reduced by only generating events using primary particles above the following energy thresholds:

  μ : 19.6% with $E_\mu > 10$ GeV cause 92.3% of showers
  p : 0.8% with $E_p > 10$ GeV cause 92.8% of showers
  n : 6.0% with $E_n > 1$ GeV cause 95.6% of showers

- Backround rates are scaled up to correct for this missing 7.7%, 7.2% and 4.6% respectively.

Corrections:

- **CRY used to generate fluxes of p, n, γ but CRY does not include contribution from heavier nuclei cosmic rays**
  → Underestimates fluxes by 70% so background rates are increased by factor of 1.7.

- **Particle fluxes generated for different altitudes than detector's elevation**
  → Detector elevation 1534 m.
  → μ flux generated for sea level, other fluxes generated for sea level + 2100 m.
  → Scaling factor applied to annual background rate:

μ :	*1.4000*
p :	*0.5784*
n :	*0.6418*
γ :	*0.5476*

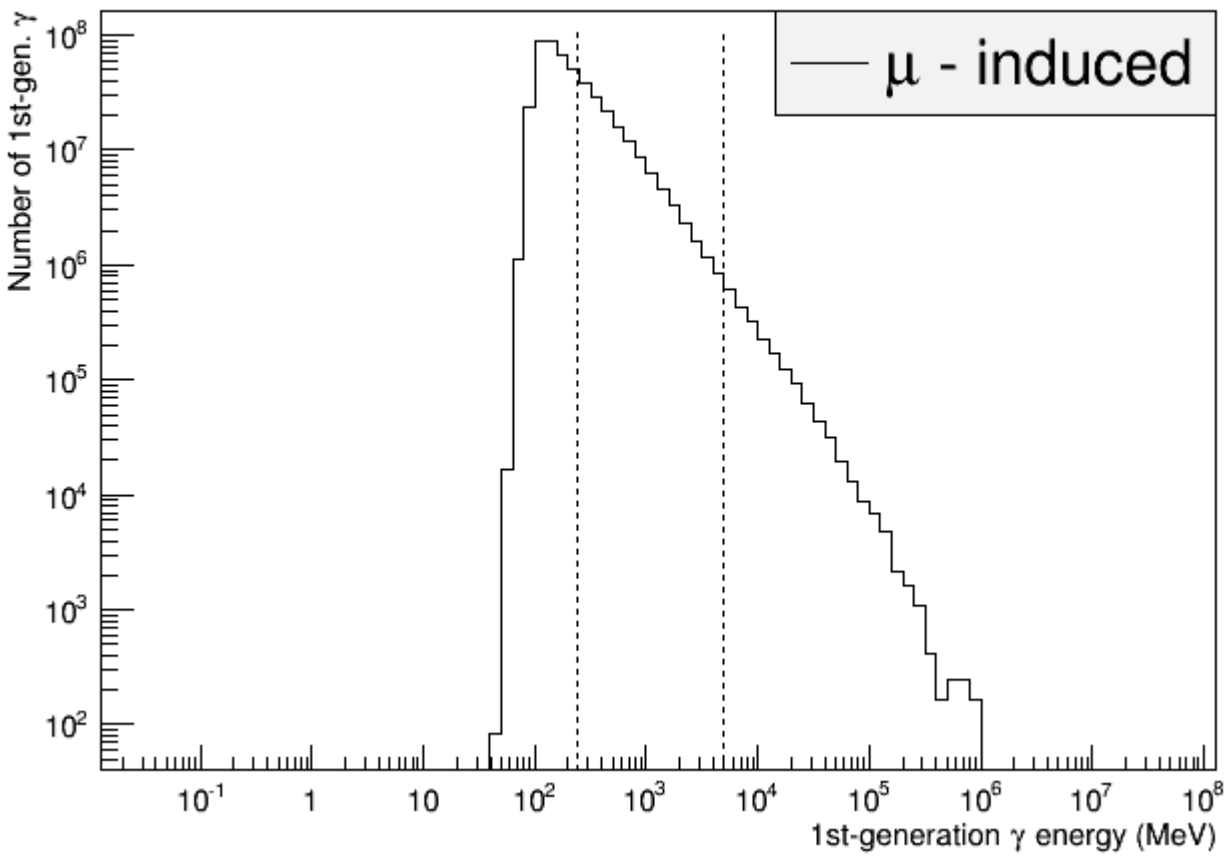
- **CRY fluxes generated on 100x100 m^2 plane**
  → Injection area can be reduced to one appropriate for detector size (50x50 m^2).
  → Increases effective time per event by factor (100x100) / (50x50).

Cuts applied

- **Energy of 1st – generation γ** - Must be within **0.25 GeV < E_γ < 5.00 GeV** (appropriate for ν beam).

- Plot shows energy of all 1st – generation γ from μ - induced events (normalized to 1 year) .

- Only 1st – generation γ between the dashed lines are potential background candidates.

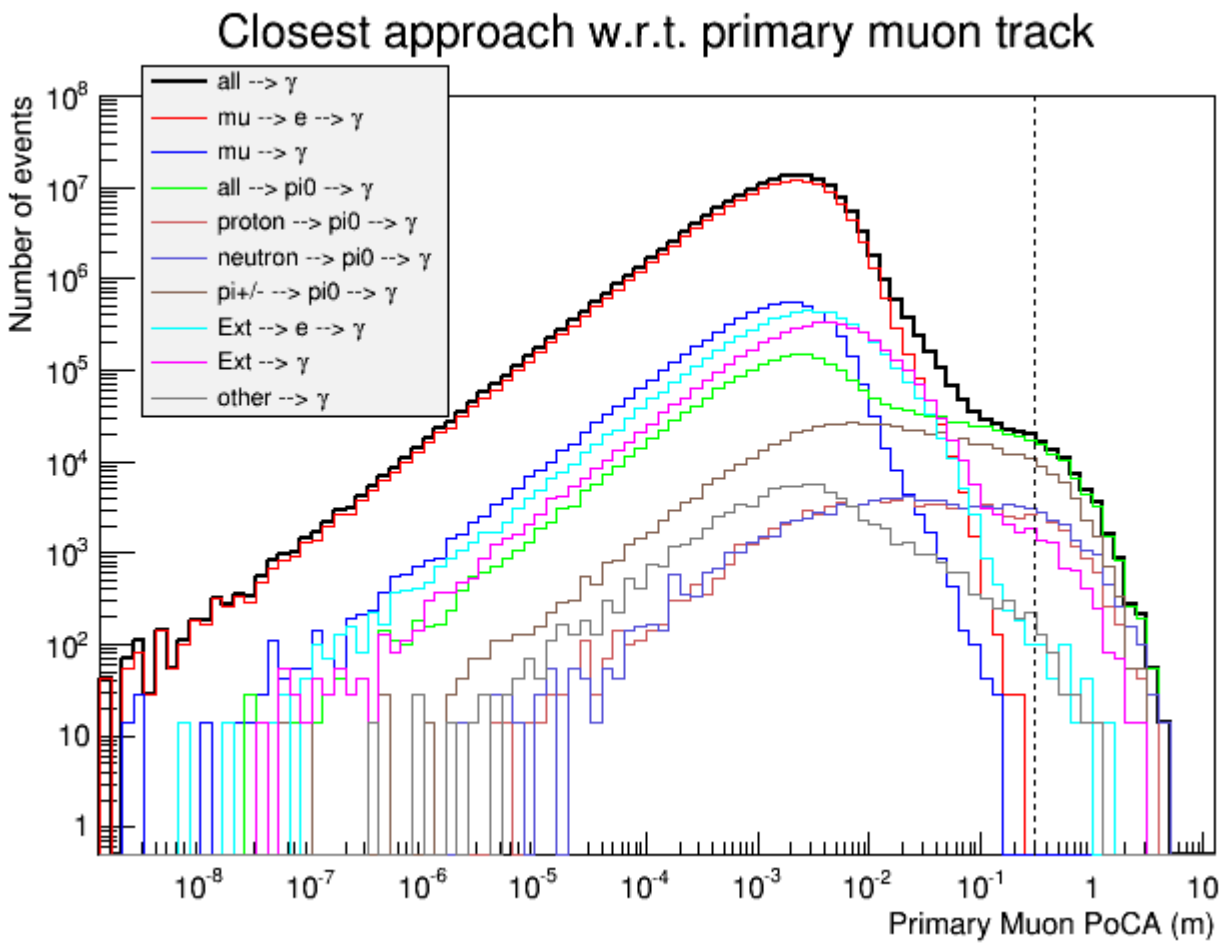


Cuts applied

- **Point of Closest Approach (PoCA)** – extrapolate direction of the γ and each segment of a track left by a charged particle.

→If minimum separation of these lines is below a certain threshold, reject shower.

→Cuts of PoCA > 30 cm w.r.t. primary muon track and > 10 cm w.r.t. any other track used.



- Plot shows distribution in PoCA w.r.t. primary muon track.

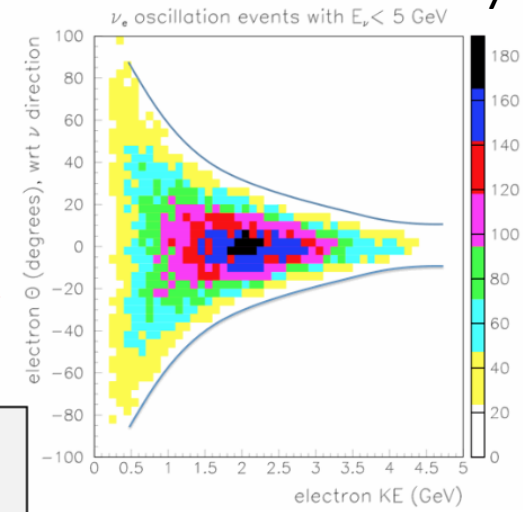
- Only γ to the right of the dashed line are potential background candidates.

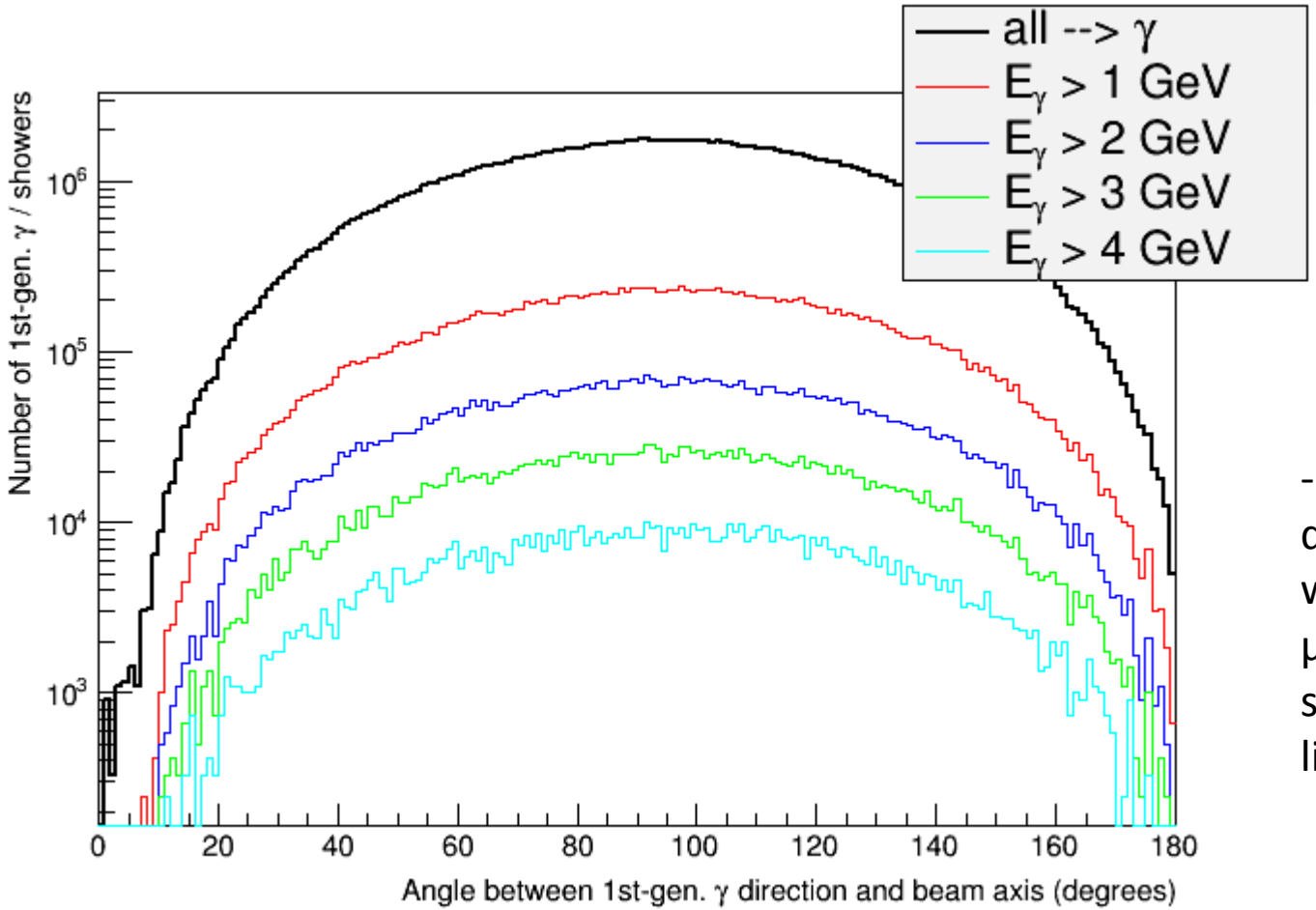
Cuts applied

- **Beam angle (θ_{beam})** – The angle between γ and beam axis.

  → If angle is too great, shower can be rejected.

  → An energy dependent cut, based on another study which recorded EM showers from actual ν_e interactions.





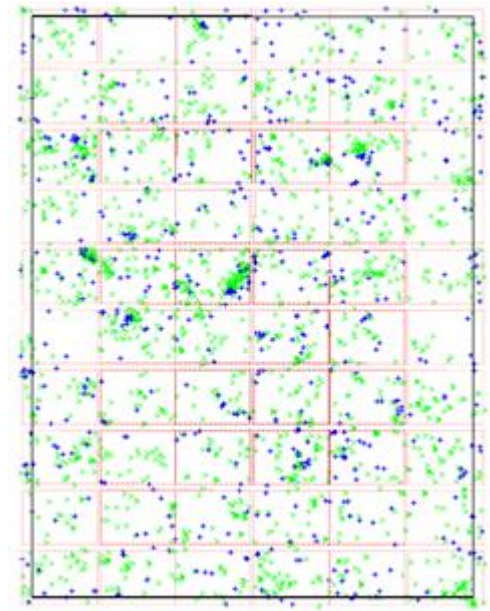
- This plot shows distribution in angle w.r.t. beam axis of γ in μ-induced events, as successive energy limits are applied.

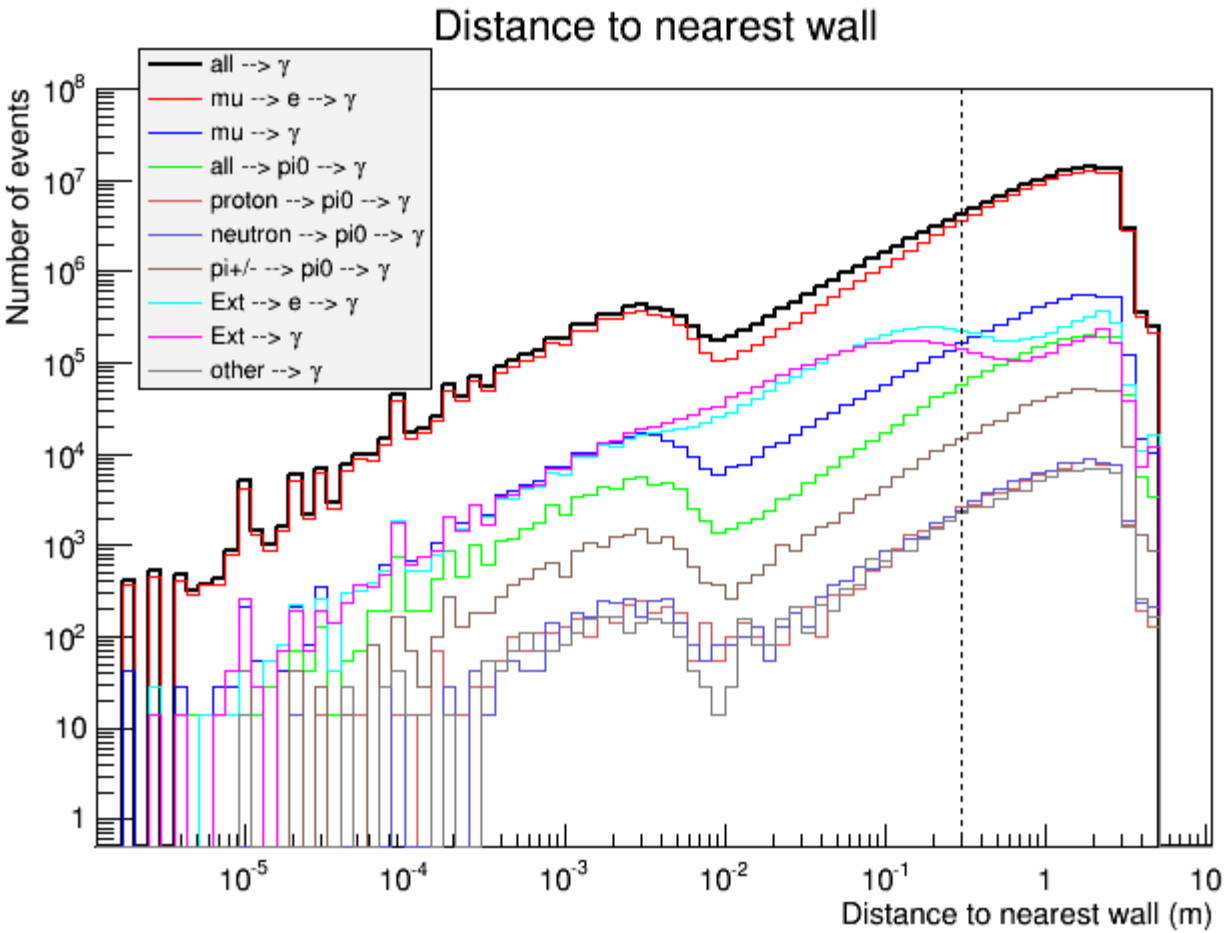
Cuts applied

- **Distance to nearest wall (D)** – Distance from a shower's first γ → $e^+ e^-$ vertex to nearest outward-facing face of TPC active volume.

  → A cut of D > 30 cm used.

- Upper plot shows D cut region (black line) in bird's eye view of 1 cryostat (TPC cell edges denoted by red lines).





- Lower plot shows distribution in D for γ from μ-induced events.

- The γ to the right of dashed line are rejected.

Further reductions:

- **e-γ separation** – Distinguish between showers starting with 1 vs. 2 electrons.
  → Failure rate of 10% (ie. reduction factor 1/10) used although should be energy-dependent.

- **Photon detection system** – Rapid detection of scintillation light reduces event window from 1.4 ms (ie. drift time) to 10 μs (duration of beam pulse).
  → reduction factor of 1/140 used.

- **The number of showers in an event** – If an event contains too many distinct EM showers, it may be impossible to discern a shower from a genuine ν_e interaction among them.
  → events with a threshold of at least 10 showers / 1st gen. γ are rejected.

- **Reject many γ based on their ancestry** – Any γ whose parent is an e^-/e^+ which has crossed into an active volume from outside (although any γ who have themselves crossed inside are not rejected).

  Any γ whose parent is e^-/e^+ and grandparent is μ^-/μ^+ is also rejected (shower is connected to primary μ, which is >99% of total background).
  → PoCA cut removes these completely anyway.

Normalization calculation

- Shower rates are normalized to 1 year and have certain correction factors applied.

- Example: Proton-induced rate:

Real (mean) time elapsed per primary proton:	9.93×10^{-6} s
Correction for primary particle energy threshold:	131.579
Correction factor for primary particle injection area:	4.00
Corrected real time elapsed per primary proton:	5.23×10^{-3} s
Number of proton-induced events simulated:	1.00×10^{7}
→ **Real time simulated:**	**52261.79 s**

Seconds of detector operation in 1 year:	2×10^{7} s
TPC cell drift time:	1.4 ms
Beam pulse duration:	10 µs
Repetition time:	1.3 s
→ **Live detector time in 1 calendar year:**	**21053 s**
→ **Years' statistics gathered:**	**2.482 yr**

Example of calculation of background rate – proton-induced background

→Tables show number of first-generation γ as successive cuts are applied.

raw numbers

	E	±	D	±	thetaBeam	±	PoCA__all	±	e - gamma	±	photon det.	±
total --> gamma	3.62E+04	190	2.47E+04	157	8136	90	748	27	74.80	2.73	0.534	0.020
pi0 --> gamma	2.76E+04	166	2.17E+04	147	7254	85	697	26	69.70	2.64	0.498	0.019
Ext --> gamma	7306	85	2010	45	654	26	51	7	5.10	0.71	0.036	0.005
other --> gamma	1228	35	993	32	228	15	0	0	0.00	0.00	0.000	0.000

Protons simulated: 10^7

normalized to 1 year

	E	±	D	±	thetaBeam	±	PoCA__all	±	e - gamma	±	photon det.	±
total --> gamma	1.46E+04	77	9960	63	3277	36	301	11	30.13	1.10	0.215	0.008
pi0 --> gamma	1.11E+04	67	8750	59	2922	34	281	11	28.08	1.06	0.201	0.008
Ext --> gamma	2943	34	810	18	263	10	21	3	2.05	0.29	0.015	0.002
other --> gamma	495	14	400	13	92	6	0	0	0.00	0.00	0.000	0.000

Years simulated: 2.482

corrected for altitude

	E	±	D	±	thetaBeam	±	PoCA__all	±	e - gamma	±	photon det.	±
total --> gamma	8430	44	5761	37	1896	21	174	6	17.43	0.64	0.124	0.005
pi0 --> gamma	6442	39	5061	34	1690	20	162	6	16.24	0.62	0.116	0.004
Ext --> gamma	1702	20	468	10	152	6	12	2	1.19	0.17	0.008	0.001
other --> gamma	286	8	231	7	53	4	0	0	0.00	0.00	0.000	0.000

Correction factor: 0.5784

corrected for CRY underestimate

	E	±	D	±	thetaBeam	±	PoCA__all	±	e - gamma	±	photon det.	±
total --> gamma	1.43E+04	75	9793	62	3223	36	296	11	29.63	1.08	0.212	0.008
pi0 --> gamma	1.10E+04	66	8604	58	2873	34	276	10	27.61	1.05	0.197	0.007
Ext --> gamma	2894	34	796	18	259	10	20	3	2.02	0.28	0.014	0.002
other --> gamma	486	14	393	12	90	6	0	0	0.00	0.00	0.000	0.000

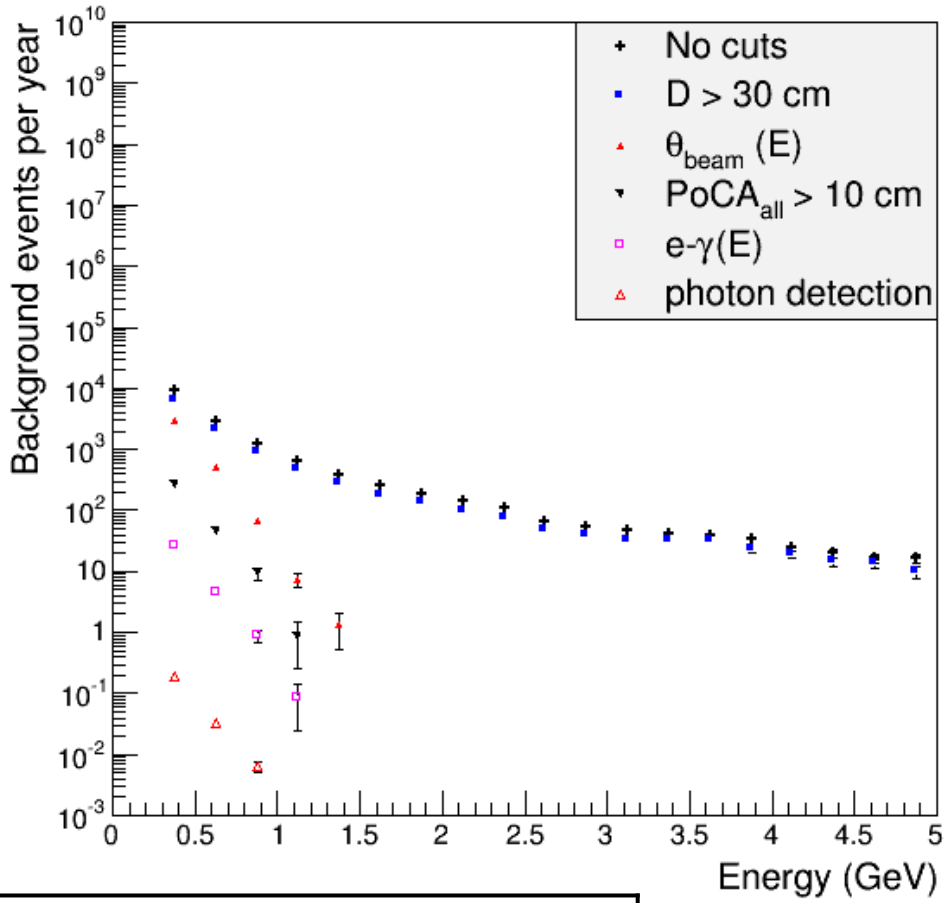
Correction factor: 1.7

corrected for primary energy threshold underestimate

	E	±	D	±	thetaBeam	±	PoCA__all	±	e - gamma	±	photon det.	±
total --> gamma	1.55E+04	81	1.06E+04	67	3475	39	319	12	31.95	1.17	0.228	0.008
pi0 --> gamma	1.18E+04	71	9277	63	3098	36	298	11	29.77	1.13	0.213	0.008
Ext --> gamma	3120	37	858	19	279	11	22	3	2.18	0.31	0.016	0.002
other --> gamma	524	15	424	13	97	6	0	0	0.00	0.00	0.000	0.000

Correction factor: 1.078

Primary particle: protons



The energy distribution of every 1st-generation γ (annual rate).

Each series is with successive cuts applied.

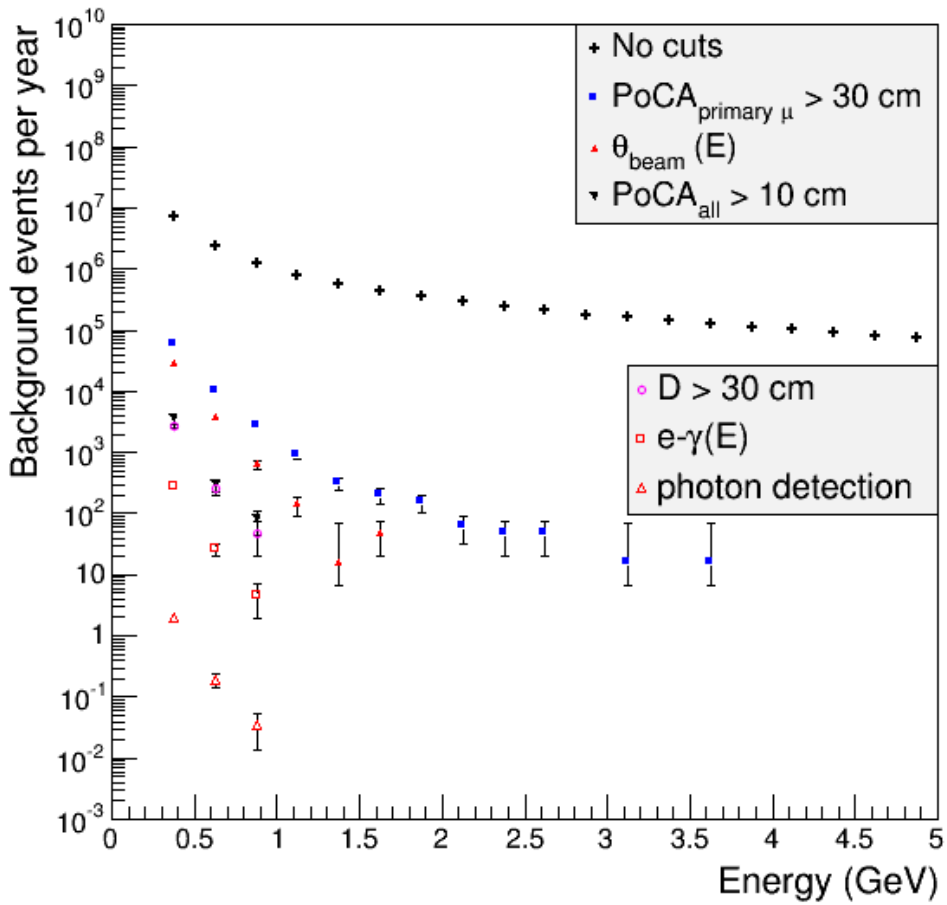
10^7 protons simulated (2.482 years' statistics)

normalized and fully corrected

	E	+/-	D	+/-	thetaBeam	+/-	PoCA__all	+/-	e-gamma	+/-	photonDet +/-	0
total --> gamma	1.55E+04	81	1.06E+04	67	3475	39	319	12	31.95	1.17	0.228	0.008
pi0 --> gamma	1.18E+04	71	9277	63	3098	36	298	11	29.77	1.13	0.213	0.008
Ext --> gamma	3120	37	858	19	279	11	22	3	2.18	0.31	0.016	0.002
other --> gamma	524	15	424	13	97	6	0	0	0.00	0.00	0.000	0.000

Background EM shower rate is **1.55×10^4 yr $^{-1}$** before cuts and **0.23 ± 0.01 yr $^{-1}$** afterwards.

Primary particle: muons which strike an active volume



The energy distribution of every 1st-generation γ (annual rate).

Each series is with successive cuts applied.

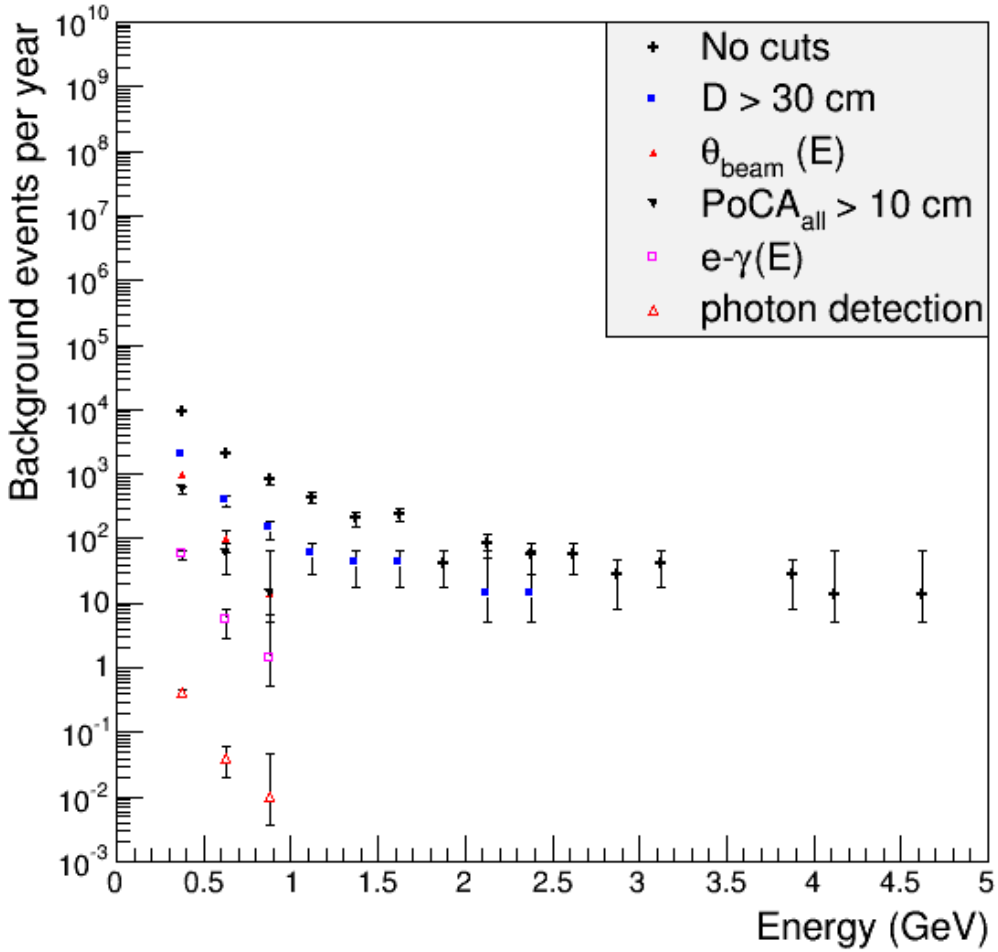
2.00×10^8 muons simulated (0.100 years' statistics)

fully normalized and corrected

	E	±	PoCA_mu	±	7	±	PoCA__all	±	D	±	E-gamma	±	photon det.	±
total --> gamma	1.48E+07	15144	71260	1053	32039	706	3917	247	2984.73	215.4	298.473	21.540	2.132	0.154
pi0 --> gamma	2.51E+06	6249	65011	1005	29210	674	3482	233	2891.46	212.0	289.146	21.201	2.065	0.151
Ext --> gamma	5.02E+06	8837	5876	302	2720	206	435	82	93.27	38.08	9.327	3.808	0.067	0.027
mu --> gamma	7.13E+06	10527	0	0	0	0	0	0	0.00	0.00	0.000	0.000	0.000	0.000
other --> gamma	88205	1171	373	76	109	41	0	0	0.00	0.00	0.000	0.000	0.000	0.000

Background EM shower rate is **1.48×10^7 yr $^{-1}$** before cuts and **2.13 ± 0.15 yr $^{-1}$** afterwards.

Primary particle: muons which miss all active volumes



The energy distribution of every 1st-generation γ (annual rate).

Each series is with successive cuts applied.

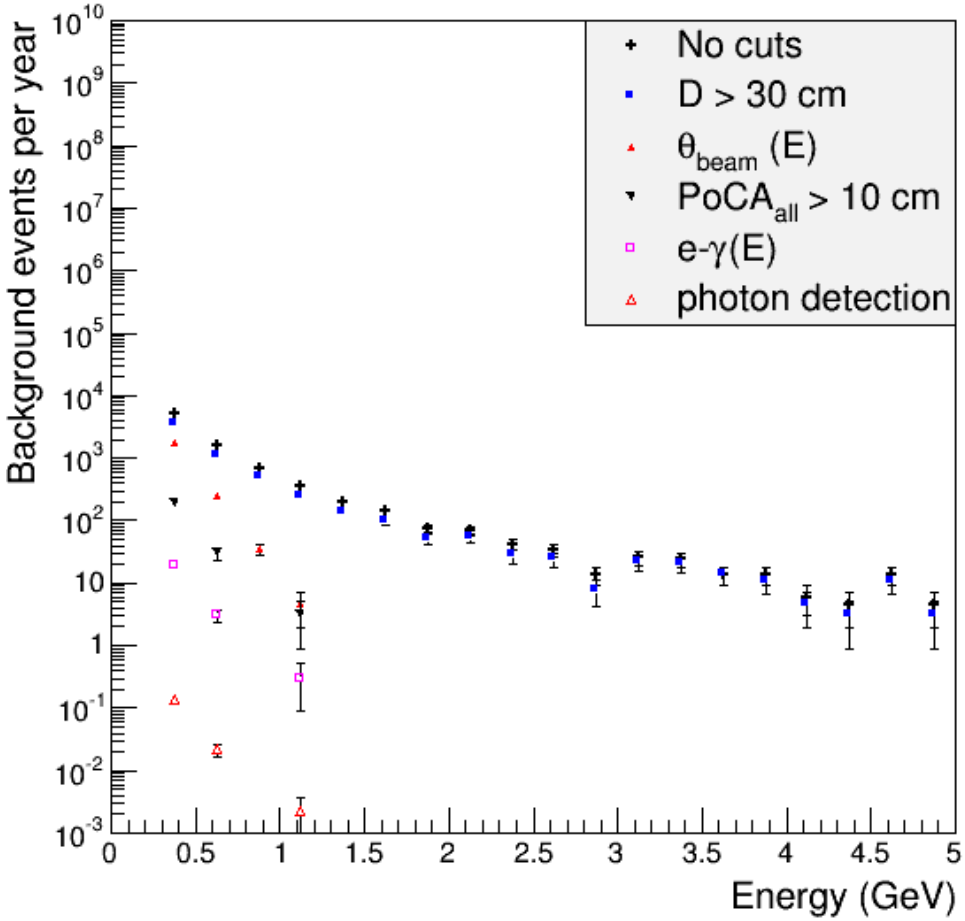
2.00×10^8 muons simulated (0.100 years' statistics)

normalized and fully corrected

	E		D		thetaBeam		PoCA__all		e-gamma		photonDet	0
total --> gamma	1.33E+04	431	2679	193	1088	123	642	95	64.18	9.46	0.458	0.068
pi0 --> gamma	2330	180	795	105	377	72	84	34	8.37	3.42	0.060	0.024
Ext --> gamma	1.10E+04	392	1870	162	698	99	558	88	55.81	8.82	0.399	0.063
other --> gamma	14	14	14	14	14	14	0	0	0.00	0.00	0.000	0.000

Background EM shower rate is **1.33×10^4 yr $^{-1}$** before cuts and **0.46 ± 0.07 yr $^{-1}$** afterwards.

Primary particle: neutrons



The energy distribution of every 1st-generation γ (annual rate).

Each series is with successive cuts applied.

1.10×10^8 neutrons simulated (0.757 years' statistics)

normalized and fully corrected

	E		D		thetaBeam		PoCA__all		e-gamma		photonDet	0
total --> gamma	8403	113	5695	93	1949	54	225	18	22.46	1.84	0.160	0.013
pi0 --> gamma	6397	98	5050	87	1744	51	194	17	19.44	1.71	0.139	0.012
Ext --> gamma	1796	52	470	27	169	16	30	7	3.01	0.67	0.022	0.005
other --> gamma	209	18	175	16	36	7	0	0	0.00	0.00	0.000	0.000

Background EM shower rate is **8403 yr $^{-1}$** before cuts and **0.16 ± 0.01 yr $^{-1}$** afterwards.

Primary particle: photons

8.0×10^7 photons simulated
(2.317 years' statistics)

normalized and fully corrected

	E	+/-	D	+/-	thetaBeam	+/-	PoCA__all	+/-	e-gamma	+/-	photonDet +/-	0
total --> gamma	35	4	34	4	0	0	0	0	0.00	0.00	0.000	0.000
pi0 --> gamma	34	4	34	4	0	0	0	0	0.00	0.00	0.000	0.000
Ext --> gamma	0	0	0	0	0	0	0	0	0.00	0.00	0.000	0.000
other --> gamma	0	0	0	0	0	0	0	0	0.00	0.00	0.000	0.000

Background EM shower rate is **35 yr $^{-1}$** before cuts and **<< 1 yr $^{-1}$** afterwards.

Summary of results

primary particle responsible	annual EM shower rate
μ	2.59 ± 0.17
p	0.23 ± 0.01
n	0.16 ± 0.01
γ	<< 1
total	**2.98 ± 0.17**