Pattern recognition techniques to reduce backgrounds in the search for the ^{136}Xe $\beta\beta0\nu$ with gaseous TPCs

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Outline

- Motivation.
- Simulation of a HPXe TPC.
- Discrimination algorithms based on Graph Theory.
- Background reduction in LD & HDXe.
- Conclusions and prospects.

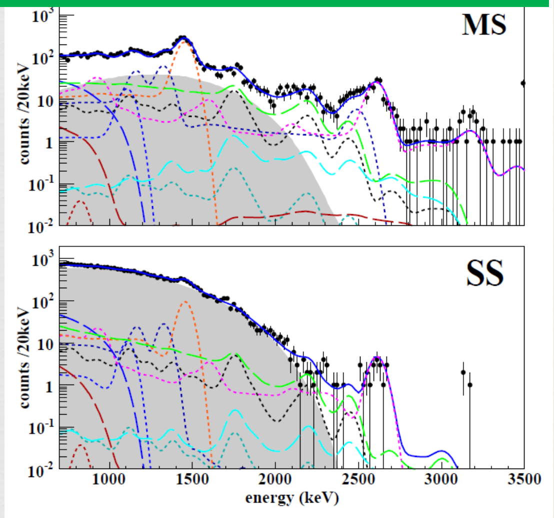
Motivation: Pattern recognition techniques in ββ0ν decay experiments of ^{136}Xe

- ββ0ν decay: neutrino mass & Majorana.
- Many experiments taking data (EXO-200, KAMLAND) & others in near future.
- Calorimeter detection with HP Xenon: natural abundance, nuclear factors, energy resolution and **event's topology**.
- Background reduction techniques have been widely treated in other approaches like pulse shape analysis in Ge detectors.
- In HPXe, Gothard collaboration studied the event's topology and described some discrimination parameters.

Full simulation of the HPXe approach with a 3D event reconstruction & automated discrimination algorithms.

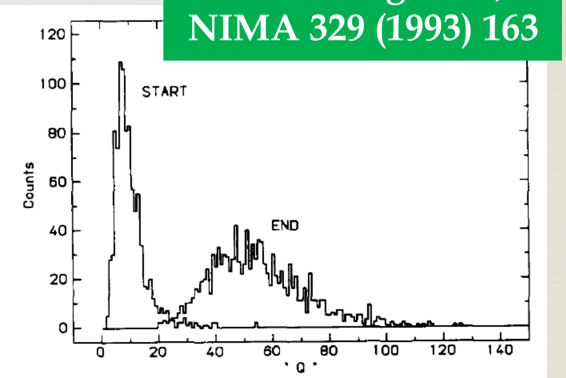
EXO-200: M. Auger et al., Phys. Rev. Lett 109 (2012) 032505

Multisite & singlesite spectra

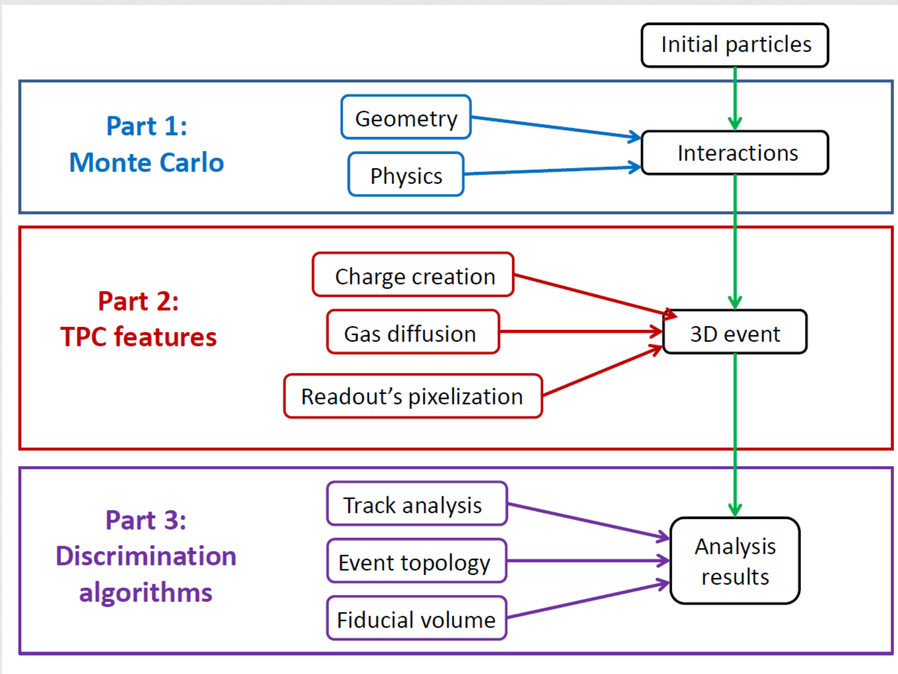


H.T. Wong et al., NIMA 329 (1993) 163

Little blob charge Background



The simulation chain

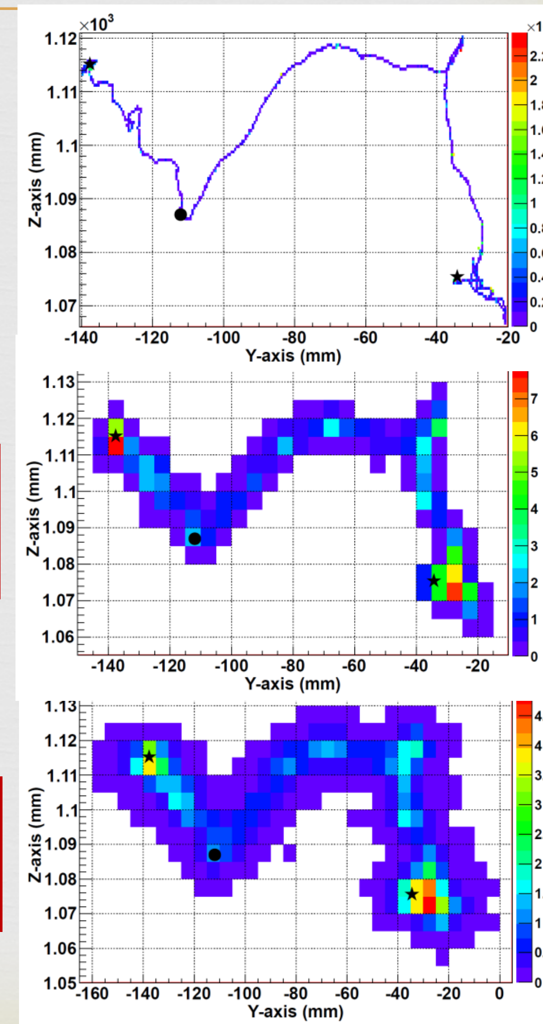


Signal ββ0ν

Geant4

Low Diffusion 0.5 cm

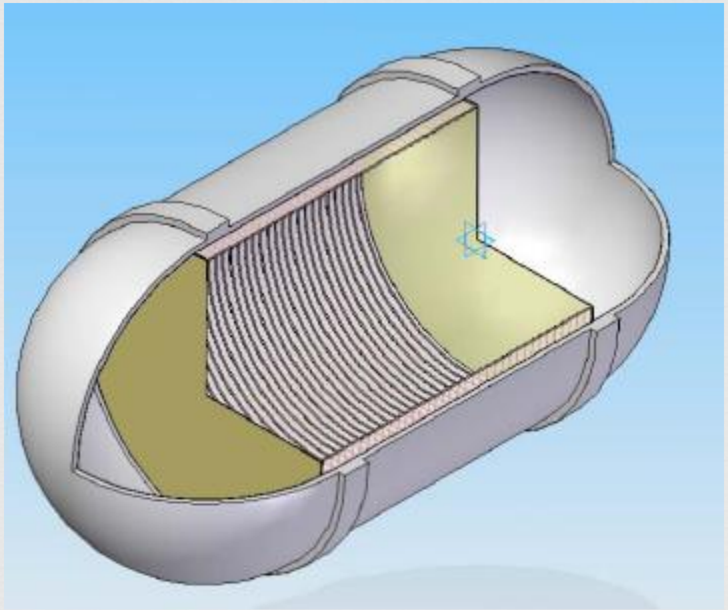
High Diffusion 0.5 cm



- 1st block: Decay4+Geant4.
- 2nd block: TPC features.
- 3rd block: analysis algorithms.

The geometry implemented in Geant4

- Cylindrical TPC:
  - Copper made, 3 cm thickness.
  - Length 1.5 m, diameter 1.6 m
- Field cage & cathode:
  - Teflon as insulator.
  - Copper rings embedded.
  - Copper cathode.
- Readout:
  - Surface contamination.
  - 2D readout (3D pixel size of 1 cm^3).
- Fiducial volume:
  - Length 1.5 m, diameter 1.38 m.
  - Xenon gas at 10 bar. Mass of 124 kg.
  - Low & High Diffusion Xenon cases.



Expected backgrounds in the RoI

- RoI: 2400-2500 keV (1% FWHM at $Q_{\beta\beta}$= 2458 keV).
- Two neutrinos mode: for a 3% FWHM, level < 10^{-6} keV^{-1} kg^{-1} yr^{-1}.
- Internal:
  - ^{232}Th decay chain: ^{208}Tl (γ 2614.5 keV + electrons).
  - ^{238}U decay chain: ^{214}Bi (γ 2447 keV & βs 3272 & 824 keV).
  - ^{60}Co: γs 1173 & 1332 keV & β 318 keV. Easily vetoed.
- External:
  - Gamma flux produces 10^4 keV^{-1} kg^{-1} yr^{-1} in absence of shielding.
  - With 25 cm of lead shielding, < 10^{-4} keV^{-1} kg^{-1} yr^{-1}.
- Neutron activation:
  - ^{137}Xe (67% β 4173 keV & 30% γ 455 keV) but neglectable activity.
- High energy photons by muons:
  - Low contribution (< 10^{-4} keV^{-1} kg^{-1} yr^{-1}) and they can be actively vetoed.

Topology of signals & expected background events in RoI

Expected signal

- Two electrons emitted from the same vertex and sharing a total energy of 2458 keV.

Note that background events have…

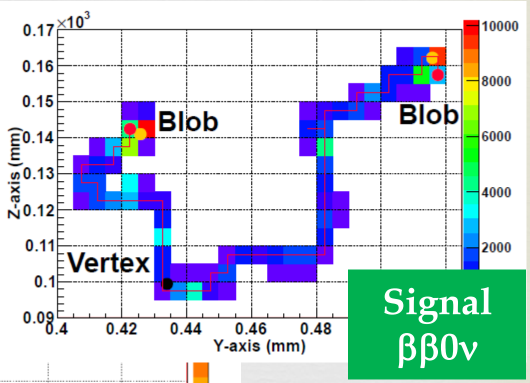
… two or more conexions (or tracks)

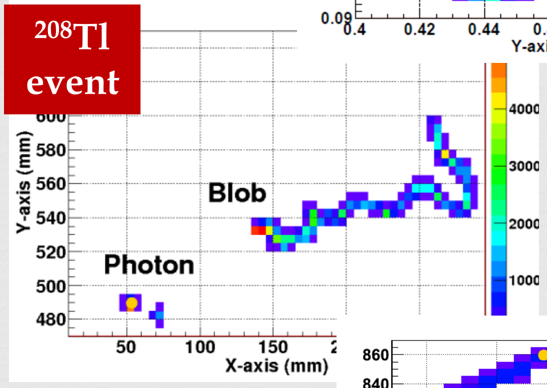
- ^{208}**Tl**: External or multi-Compton (2615 keV)
- ^{214}**Bi**: Compton of high energy gammas.

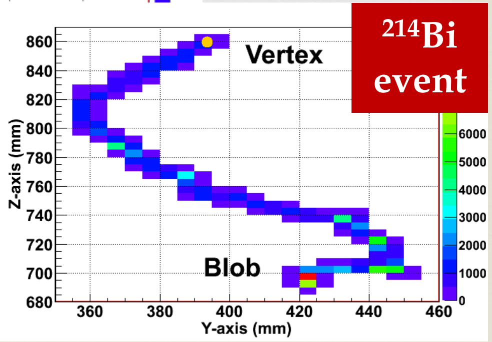
… only one blob at both ends

- ^{208}**Tl**: Photoelectric + bremmstrahlung photons.
- ^{214}**Bi**: Photoelectric of the 2448 keV γ-line.

… deposit energy at the fiducial limits.







Discrimination methods

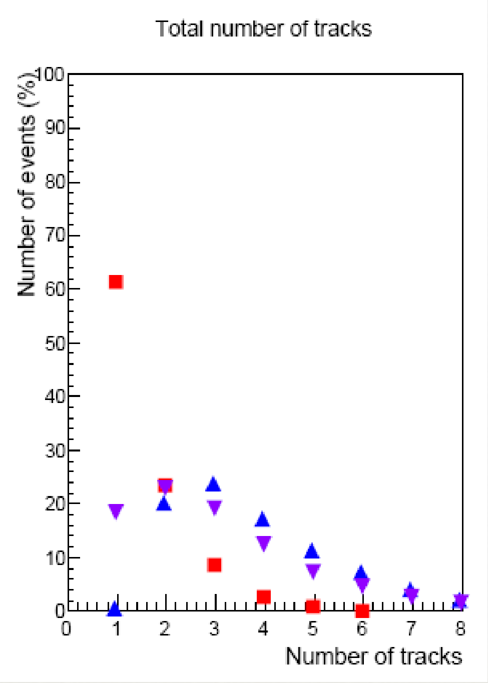
- The absence of energy deposits far from the main conexión/track.
- The existence of two big charge accumulations at both ends.

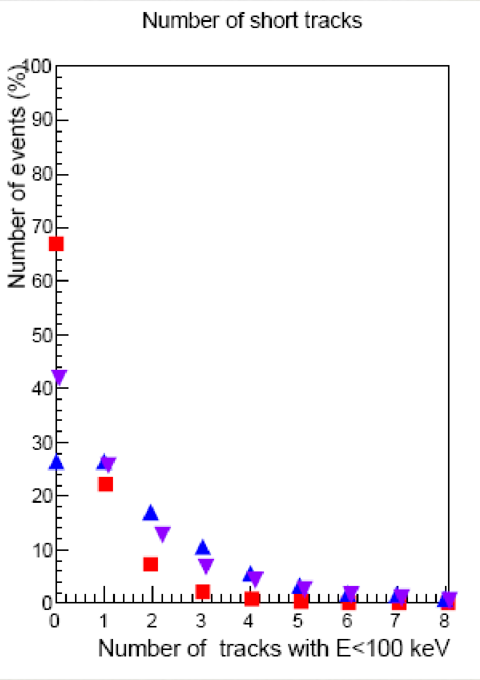
Algorithms based on Graph Theory: conexions search

- Each event is transformed to a graph.
- Pixels are identified with vertex & adjent pixels are linked by a segment.
- A classical method of Graph Theory is used to find tracks (components).

RED: ββ0ν
BLUE: ^{208}Tl, vessel.
VIOLET: ^{214}Bi, vessel.

- A "one-track" condition rejects too many signals (only 62% fullfill it) due to x-ray emissions.
- Events with another low energy track (< 100 keV) also accepted.

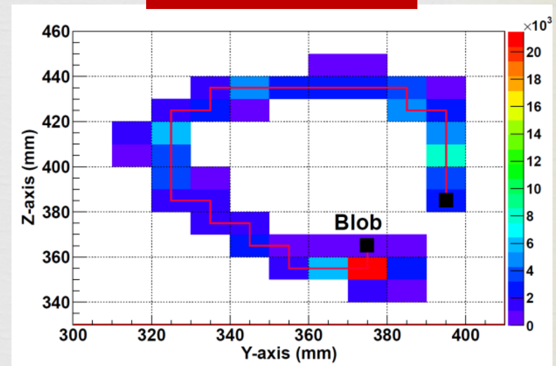




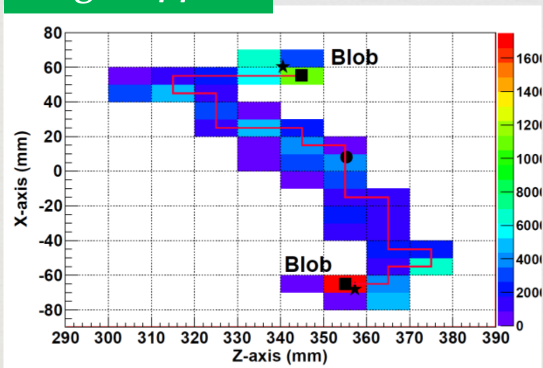
Algorithms based on Graph Theory: blob identification (I)

- Based on the method to find the longest track in a graph.
- The longest track-line calculated between:
  - Two blobs (> 150 keV).
  - One blob and a normal pixel.
- Chosen the 1st track except if the 2nd track is 30% longer. Compromise to recognize:
  - Signals with 2 blobs & unbalanced energy sharing (1 blob).
  - Backgrounds: normally 1 blob but random energy deposits (δ-rays or bremsstrahlung photons) may create a fake blob at the main track.

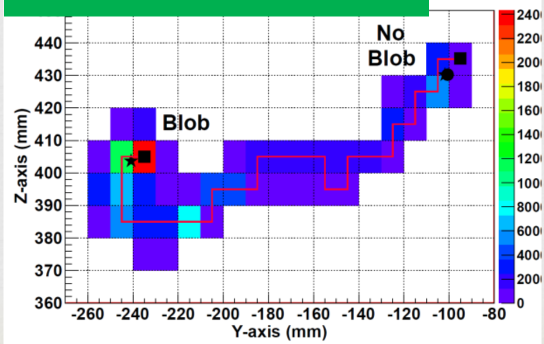
^{208}Tl Vessel

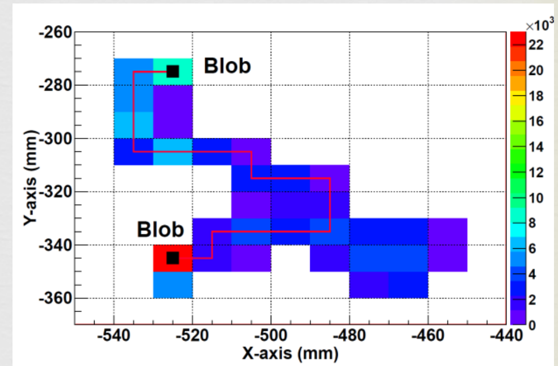


Signal $\beta\beta0\nu$



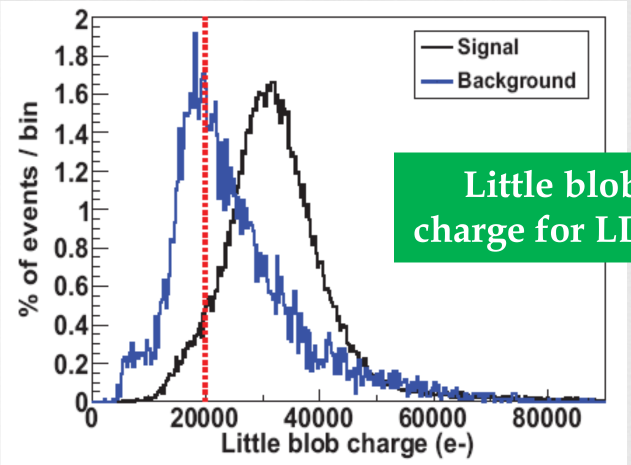
Signal $\beta\beta0\nu$
2.29 MeV & 0.17 MeV

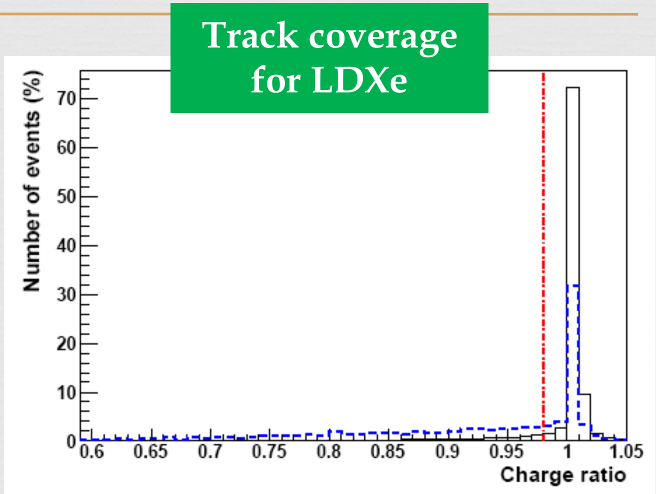




^{214}Bi Vessel
An extra fake blob is present

Algorithms based on Graph Theory: blob identification (II)





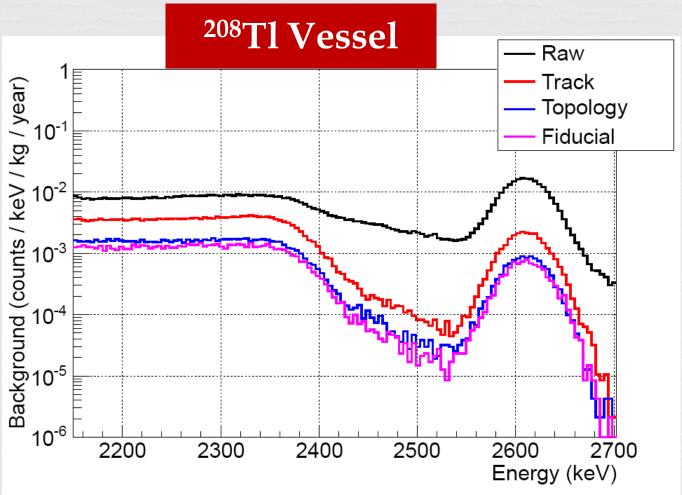
- Distance between calculated and real blobs is < 2 pixel lengths for 80% cases.
- Little blob's charge is a good discrimination parameter, already used by Gothard. A threshold of 470 keV is set.
- Background events may have fake blobs in the middle of the track. In those cases, the generated track-line will not cover the whole event.
- The track coverage (ratio of covered and total charge) can reject these events. A threshold of 98% is set.

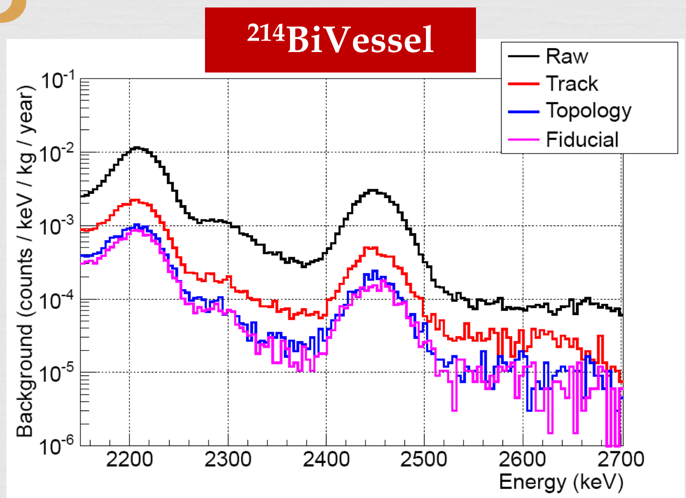
Background reduction in HDXe (I)

Origin	Isotope	AF Track	AF Topology	AF Fiducial vetoes: Lateral	Bottom	Top
Lateral vessel	^{208}Tl	7.0±0.3	41.9±3.8	68.9±8.1	100.0±12.8	98.4±12.6
	^{214}Bi	14.1±0.5	43.1±2.7	82.1±6.4	99.7 ±8.2	99.0 ±8.1
Drift cage	^{208}Tl	4.8±0.1	43.5±2.0	33.9±2.6	97.8 ±9.3	97.7 ±9.4
	^{214}Bi	41.9±0.7	39.4±1.0	12.7±0.8	99.6 ±8.8	98.1 ±8.7
Readout	^{208}Tl	3.2±0.1	40.7±2.6	90.8±7.1	16.8 ±2.5	100.0±19.4
	^{214}Bi	51.6±0.5	36.6±0.6	88.6±1.7	0.4 ±0.0	100.0±32.4
Cathode	^{208}Tl	3.8±0.1	56.9±3.2	80.0±5.3	100.0 ±7.0	19.1 ±2.4
	^{214}Bi	65.7±1.1	34.9±0.4	76.6±1.5	100.0 ±2.0	0.6 ±0.1

- A 40% signal efficiency kept in this study. Note that the geometrical efficiency is already 70% due to deposits near the walls and bremsstrahlung emissions.
- Track criterium is more powerfull for inner ^{208}Tl contaminations than external.
- Track criterium is less effective for ^{214}Bi events (few multicompton events) and less for inner components (β-emission 3272 keV, later rejected by fiducial veto).
- The efficiency of the topology criterium is low (**40%**). See later…
- Fiducial criteria mainly rejects cathode & readout events (better ^{214}Bi than ^{208}Tl).

Background reduction in HDXe (II)





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- The efficiency of the topology criterium is low (**40%**). See later…
- Fiducial criteria mainly rejects cathode & readout events (better ^{214}Bi than ^{208}Tl).

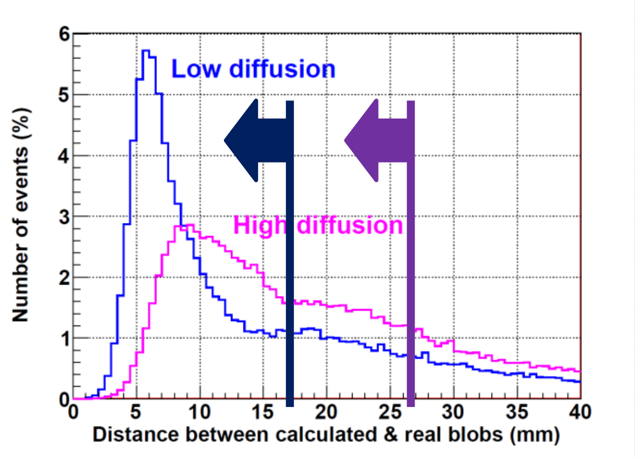
Background reduction in LDXe

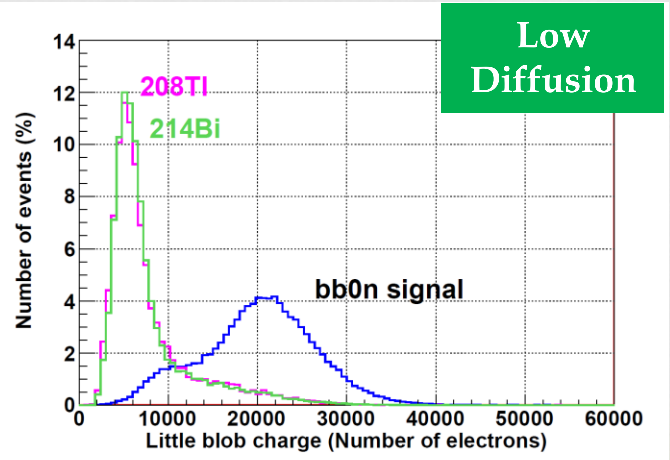
				AF Fiducial vetoes		
Origin	Isotope	AF Track	AF Topology	Lateral	Bottom	Top
Lateral	^{208}Tl	7.1±0.3	11.7±1.6	83.1±16.1	100.0±20.2	98.0±19.9
vessel	^{214}Bi	16.0±0.6	12.6±1.2	93.4±12.2	99.1±13.2	100.0±13.4
Drift	^{208}Tl	4.4 ±0.2	14.7±1.6	64.9±10.7	100.0±18.1	96.7±17.7
cage	^{214}Bi	42.1±0.4	10.6±0.2	19.8± 1.1	99.3 ±6.9	98.5 ±6.9
Readout	^{208}Tl	2.4±0.1	23.9±2.2	92.8±10.8	14.9 ±3.5	100.0±30.9
	^{214}Bi	37.2 ±0.5	30.2±0.8	89.8± 2.9	0.2 ±0.1	100.0±81.6
Cathode	^{208}Tl	4.8±0.1	18.0±1.4	93.6± 9.4	100.0±10.2	24.1 ±4.0
	^{214}Bi	57.4±0.6	26.9±0.5	83.6± 1.9	100.0 ±2.4	0.3 ±0.1

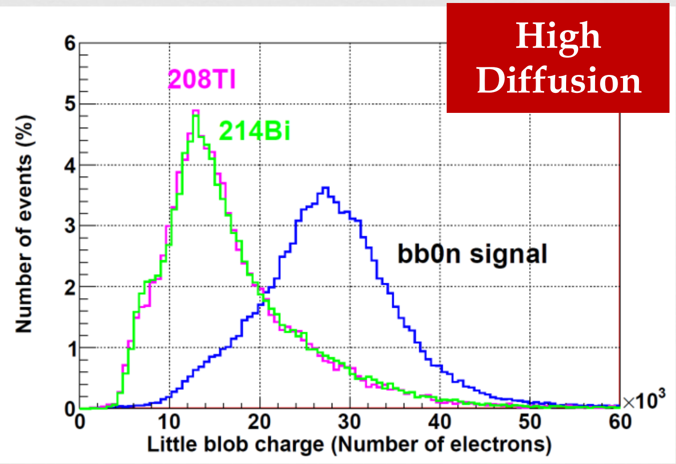
- Topological cut is a factor 3 better than in HDXe. Reason: blobs better determined and a shorter radius must be used to calculate their energy.
- Near the efficiency given by Gothard analysis (**8.6%**). Still space for improvements (see next slide).
- The rest of criteria show the same efficiency as in the HDXe case.

Still space for improvements…

- Current work on a better determination of blobs.
- Several changes made: track length, number of blob candidates, charge determination…
- Preliminary results show a cleaner separation of the distributions of the little blob charge.
- Efficiency better than Gothard (**6.0% vs 8.6%**) if the track criterium is worsen **~20-30%**.
- Still to be fully understood…







Conclusions and prospects

- Complete simulation of a HPXe TPC with a pixelized readout for $\beta\beta0\nu$ made.
- Using the event's topology, two key signatures (a single track & one blob at both ends) have been identified to select signals from backgrounds.
- Two pattern recognition algorithms based on Graph Theory have been created for searching the components & the possible blobs, with good results.

Results

- Fixing a 40% efficiency, track criterium rejects mainly ^{208}Tl events (**4.8 – 7.1%** efficiency), as events in the RoI suffer several physical processes. It rejects maximum 80% of ^{214}Bi events (mainly photoelectric of the 2547 keV γ-line).
- The efficiency of the topology criterium is **12%** in LDXe near the **8.6%** given by Gothard. Still space for further improvements. A factor 3 worse for HDXe.
- Fiducial criteria mainly rejects cathode & readout events.

Prospects

- Current work focused on a better determination of blobs.
- Other TPC features to be studied: pressure, pixel size & 2D pixelized readout.

Back-up

Physical processes suffered by ^{208}Tl to deposit its energy in the RoI

1) Compton at the external volume => γ of less energy that is photoabsorbed or suffers a Compton process at the target.
2) Multi-Compton at the target with energy loss by low energy γs.
3) Photoelectric at the target with the emission of bremsstrahlung photons that escape from the TPC.

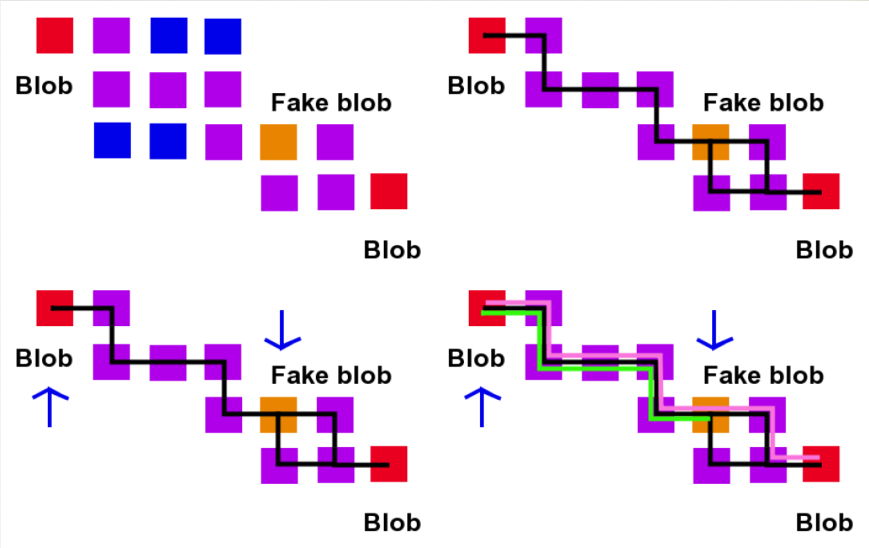
Notes:

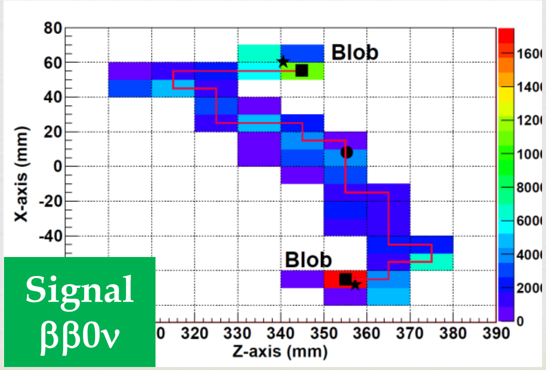
- 1 & 2 are multitrack.
- 3 is single track but only 1 blob.
- 1 & 2 are more probable by emissions near the target.

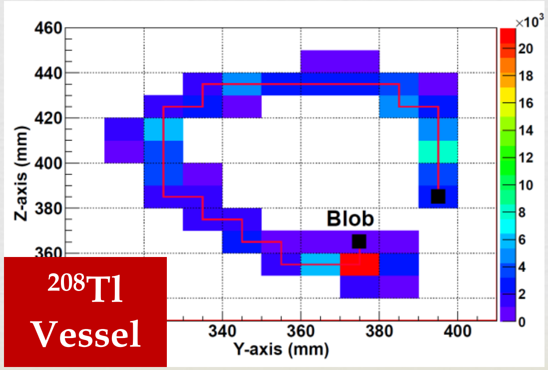
The method to find the two longest track-lines in detail

- Based on the method to find the longest track in a graph.

1) Pixels with little charge are removed.
2) Pixels are linked by segments.
3) Big charge depositions (> 150 keV) are identified as blob candidates.
4) Found the longest track between blob candidates and the longest between one blob candidate & a normal pixel.
5) If 2nd is 30% longer, it is kept. If not, the 1st.





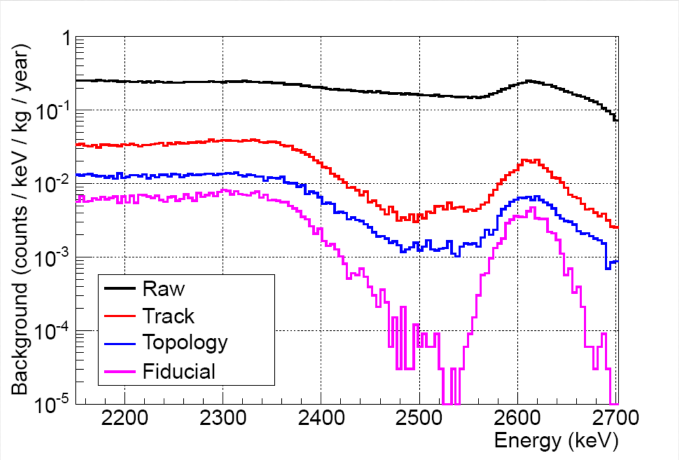


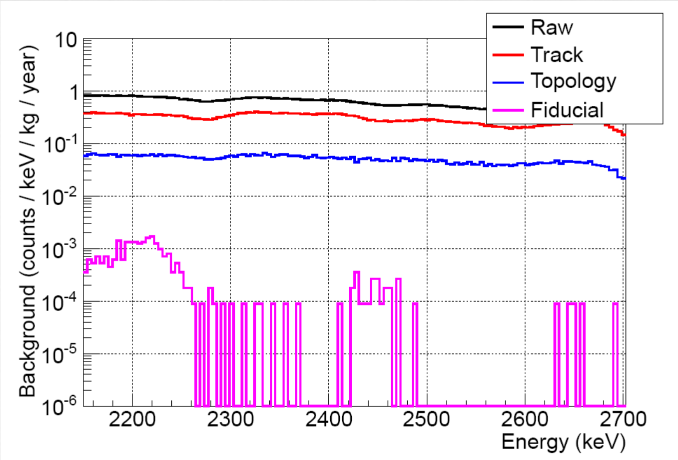
Signal efficiency

Origin	Isotope	Eff. Track	Eff. Topology	Eff. Fiducial vetoes		
				Lateral	Bottom	Top
Target	^{136}Xe	77.5±0.4	85.4±0.5	88.5± 0.5	99.1 ±0.6	98.6±0.6

- Initial efficiency depends on gas pressure & the TPC geometry.
- Final efficiency has been fixed to 40% for comparison.
- Track efficiency is low as low-energy x-rays & Compton near the main track are accepted.
- Little effect of fiducial criteria.

Background reduction for the readout





- ^{208}Tl: little background reduction.
- ^{214}Bi: many alpha events eliminated. Only gamma events are kept!!

Comparison with Gothard analysis

- TPC: Xe-CF4, 5 bar, XY wires (2D readout), 168 channels, 6.8 mm pitch, ε_{geom} = 29.7%.
- γ sources calibration: ^{137}Cs, ^{22}Na, ^{88}Y, ^{232}Th.
- Blobs are located by eye one-by-one.
- Blobs charge is defined using both 2D views of an events.
- Result by calibrations: **1.4%** of efficiency.
- Result by real data: **8.6%** of efficiency.
- Better result presented here (**12%**).
- Even if a 3D readout is used, not so good result as pressure is 10 bar & pitch is 1 cm.

Table 1
Data reduction and inefficiency factors for various cuts in the analysis procedures

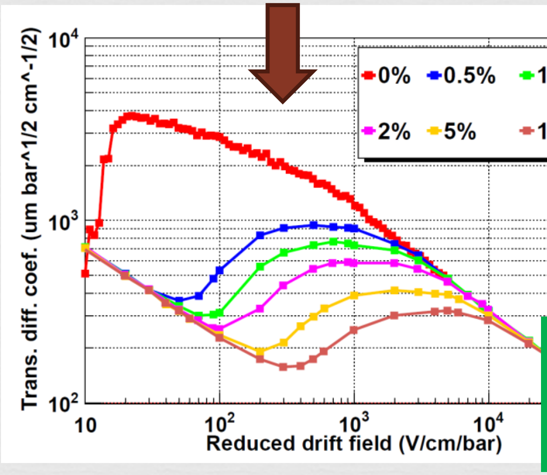
Cuts	Data reduction	Inefficiency ($\bar{\eta}$) MM	Inefficiency ($\bar{\eta}$) RHC
On line analysis			
Hardware veto	0.5	10^{-5}	10^{-5}
Energy > 600 keV	0.22	0	0
Software	0.46	$< 10^{-3}$	$< 10^{-3}$
Net reduction	0.051	–	–
Off-line analysis			
Energy > 1600 keV	0.060	0	0
Delayed coincidence	0.98	0	0
Events not fully contained [a]	0.93	0.0032	0.0032
"Alpha-like" events	0.98	0.0073	0.0073
Blob count	0.88	–	–
Multiple events	0.95	0.0053	0.0053
Single electron	0.20	0.062	0.054
Net reduction	0.009	–	–
Off-line scanning			
Energy > 2000 keV	0.13	0	0
Events not fully contained [a]	0.82	0	0
Isolated charge > 100 keV	0.76	0.072	0.072
One end with $Q < 30$ [b]	0.086		
Energy distribution		0.052	0.202
Detector response		0.067	0.067
Net reduction	0.0070	–	–
Total reduction in data	3.2×10^{-6}	–	–
Net analysis efficiency $= \Pi_i(1-\bar{\eta}_i)$	–	0.76	0.65

[a] Detector efficiency not included.
[b] Same inefficiency factor.

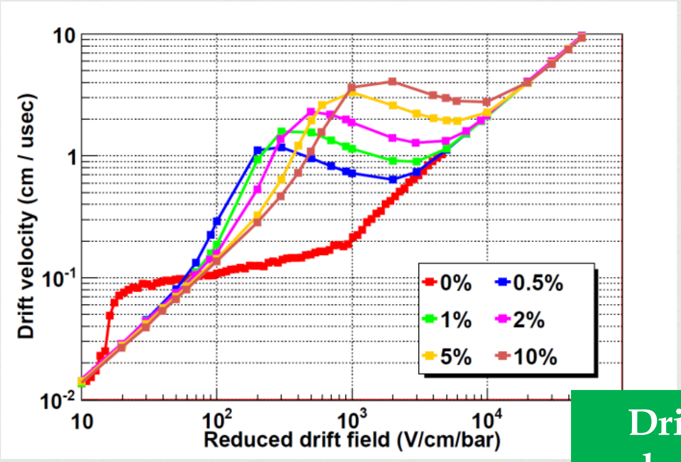
H.T. Wong et al., NIMA 329 (1993) 163

Example of low diffusion mixtures: Xe-TMA

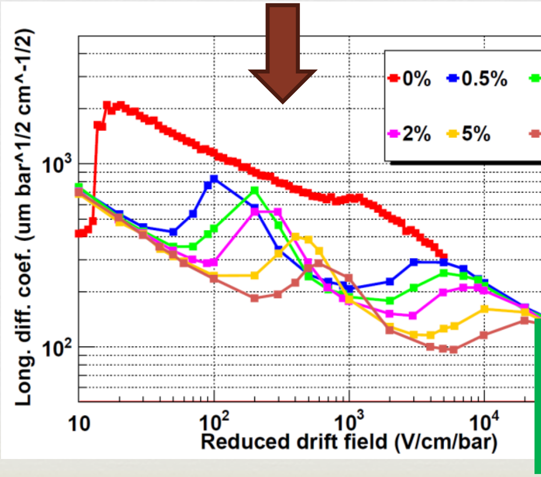
- Drift field: 300 V/cm/bar.
  - Xe: 0.14 cm/μs
  - Xe-2%TMA: 1.36 cm/μs
- HDXe (pure xenon):
  - Transversal: 630 μm/cm$^{0.5}$
  - Longitudinal: 250 μm/cm$^{0.5}$
- LDXe (Xe+2%TMA):
  - Transversal: 140 μm/cm$^{0.5}$
  - Longitudinal: 170 μm/cm$^{0.5}$



Transversal coefficient at 1 bar



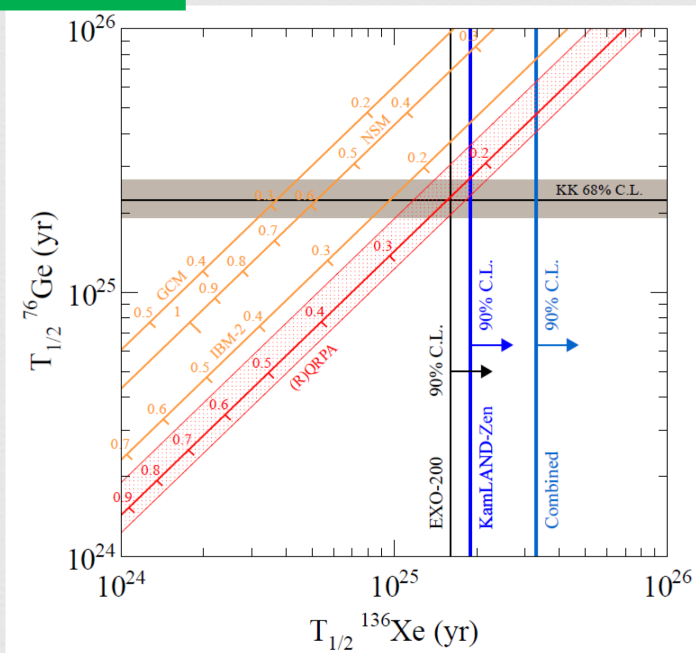
Drift velocity



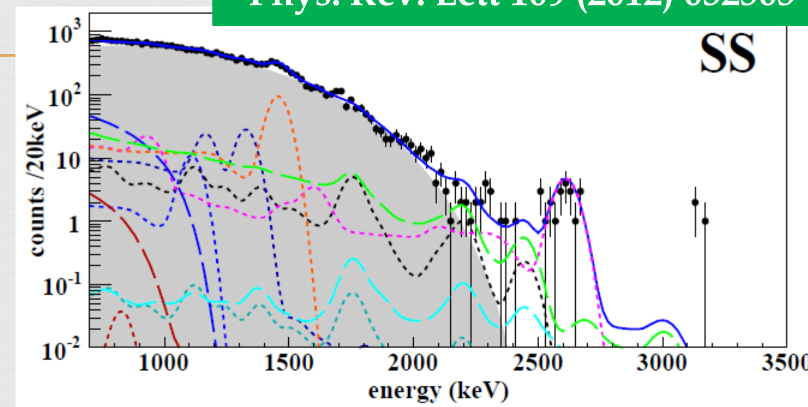
Longitudinal coefficient at 1 bar

Xe TPC experiments taking data

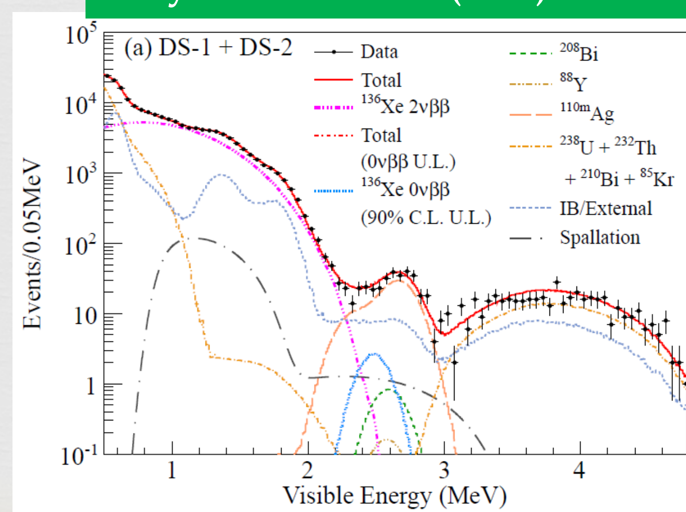
Comparison with KK claim



EXO-200: M. Auger et al., Phys. Rev. Lett 109 (2012) 032505



KamLAND-Zen: A. Gando et al., Phys. Rev. Lett 110 (2013) 062502



- EXO-200 & KamLAND-Zen are taking data.
- Liquid Xenon & light readout.
- ββ2ν measured for 1st time:

$$T_{1/2}=2.11\pm0.04(\text{stat.})\pm0.21(\text{sys.})\times10^{21}\ \text{yr}$$

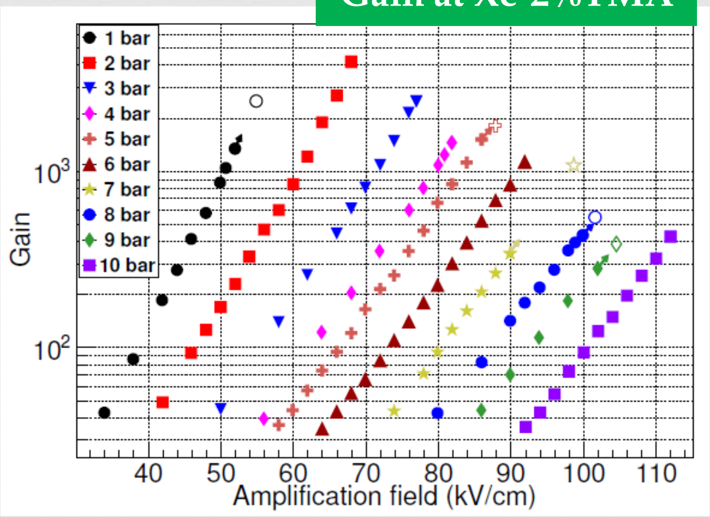
- ββ0ν limit:

$$T^{0\nu}_{1/2} > 3.4\times10^{25}\ \text{yr (90\% C.L.)}$$

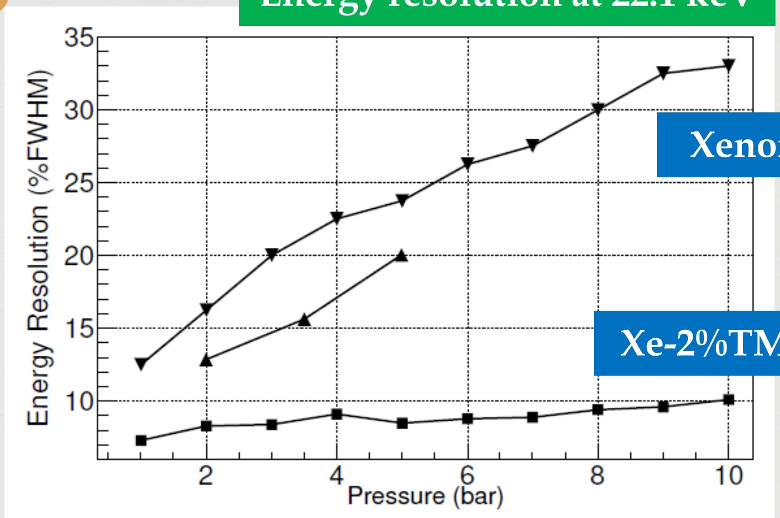
Gain & energy resolution of MM in Xe & Xe-TMA

S. Cebrian, JINST 8 (2013) P01012
D.C. Herrera, arXiv:1303.5790

Gain at Xe-2%TMA



Energy resolution at 22.1 keV



- Study of Xe-TMA mixtures at 1-10 bar for Micromegas detector (charge readout).
- Optimum %TMA between 1.5 & 2.
- The maximum gain improves x3 and the energy resolution a factor x2 (3) at 22 keV at 1 (10) bar, in comparison to pure Xenon.
- Further study for light readout (PMTs) being made by LBNL