CAPHRI(Calo Precise High Resolution Intensity detector) : monitoring muon stopping rate in the DS

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CAPHRI: Adding LYSO or LABR to EMC

The question is: Can the calorimeter perform a precise measurement of the muon capture rate looking at 1.8 MeV photon peak? And at the same time measure also the Proton Intensity Variation ?

- Basic idea: adding 2 or 4 HPC (High Precision Crystal, LYSO/LaBr) inside the calorimeter
- Useful on Disk-0 since it has good acceptance for photons coming from the stopping target
- Better if these HPCs are placed at high radius to reduce mixed-background contamination
- **Dimension limited to 34x34 mm^2 ➔ for today used 30x30 mm^2**
- Maximum length available: 20 cm (LYSO) , 3" i.e. 7.5 cm for LABR
- No coupling with grease to sensors (keep same quality used for CsI crystals)

What has been done:

➔ Experimental test of prototypes for energy resolution

➔ Studied MC to evaluate MIXED-background on selected disk position

➔ Determined Muon Capture monitoring capability looking at the 1.8 MeV line with MIXED-background in overlap

➔ Determined monitoring of POT intensity looking with the same data stream at integral variables in the calorimeter

➔ Calculated the data-throughput needed to save this in a dedicated "data-stream"D

CAPHRI: how many and where?

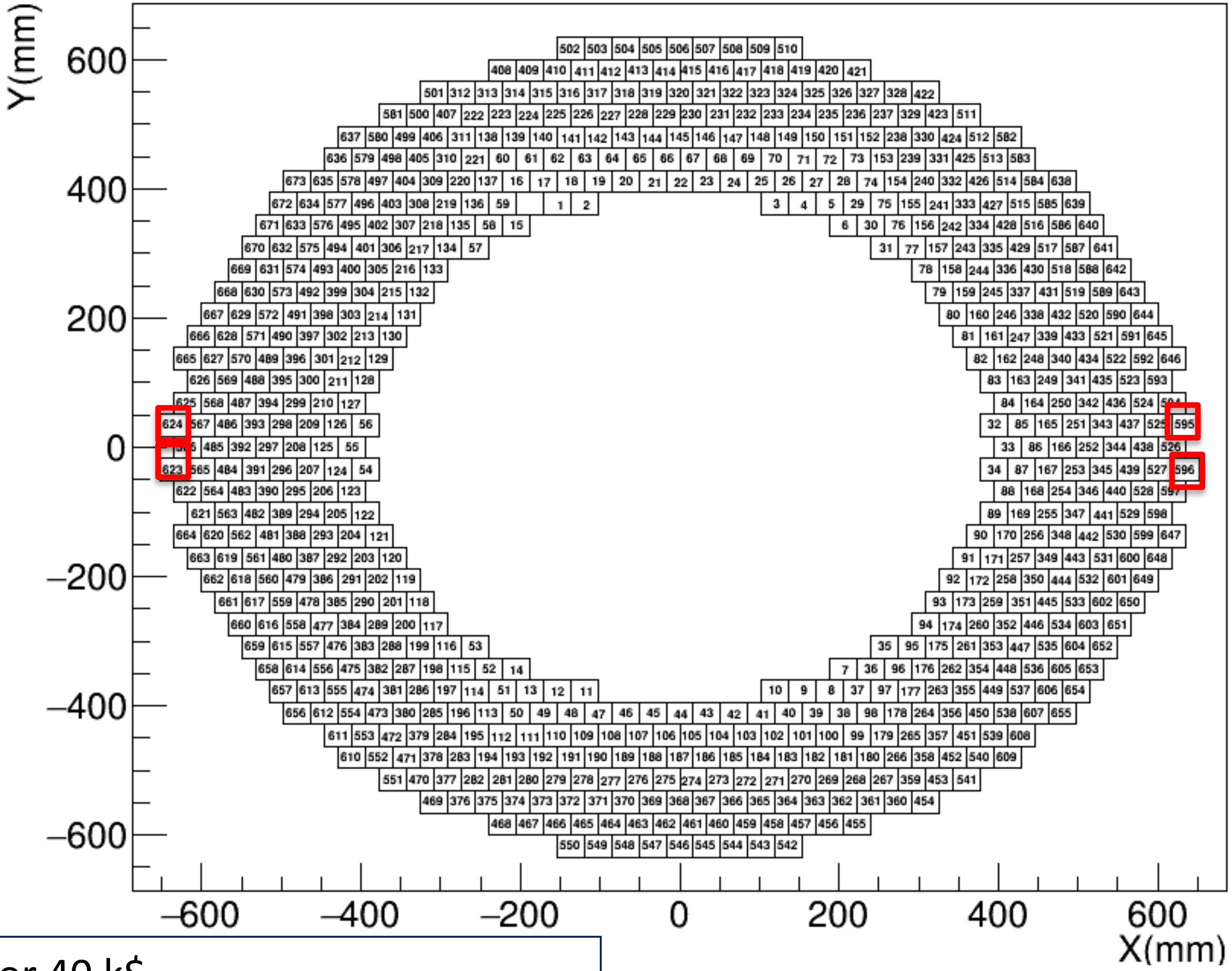
Cryid=623,624
Cryid=595,596

- Very external Crystals
- Symmetric in X
- Symmetric in Y

☐ *Negligible interference with clustering and cables*

☐ *poor calibration with cosmics*

☐ *They can be reduced to 2 if needed for saving Data-througput*

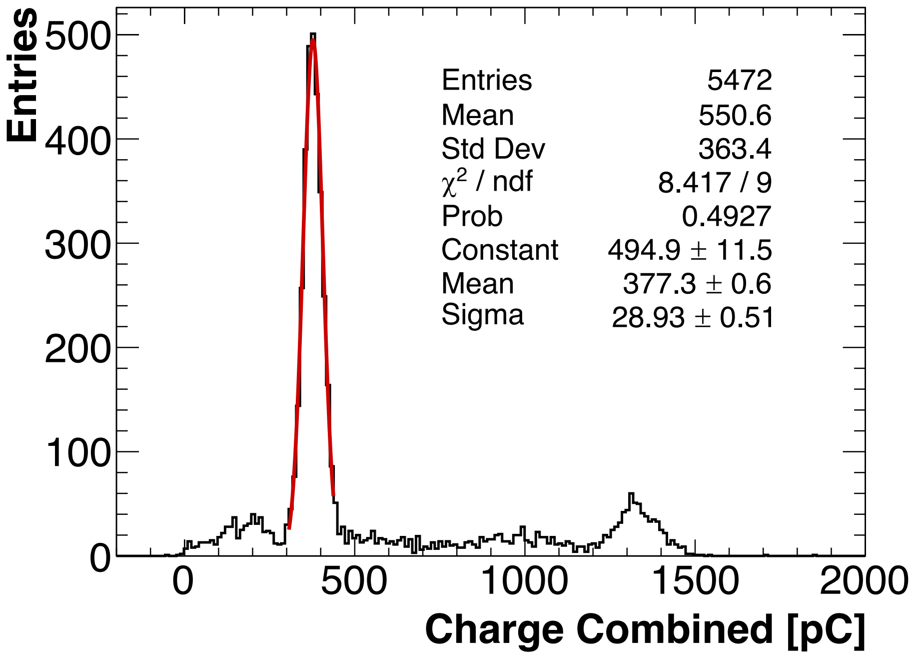


10 k$ each crystal → 20 or 40 k$
Asked 16 kEuro to INFN, discussion with Ron in progress

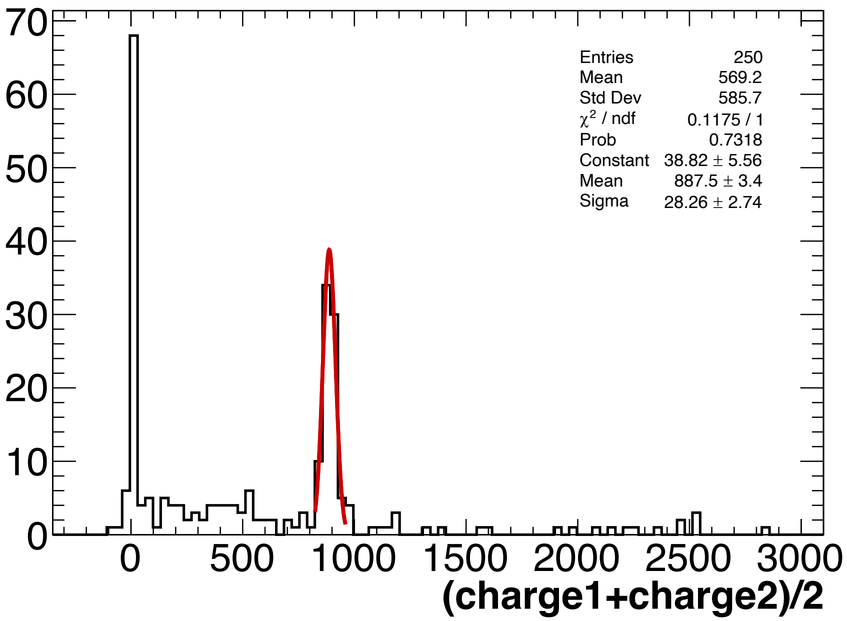
Other positions up-down under test

CAPHRI: Energy res HPC+SiPMs (docdb # 25302)

LYSO+MU2E SIPMS



LABR+MU2E SIPMS



6.7% at 511 keV

3.2% at 511 keV

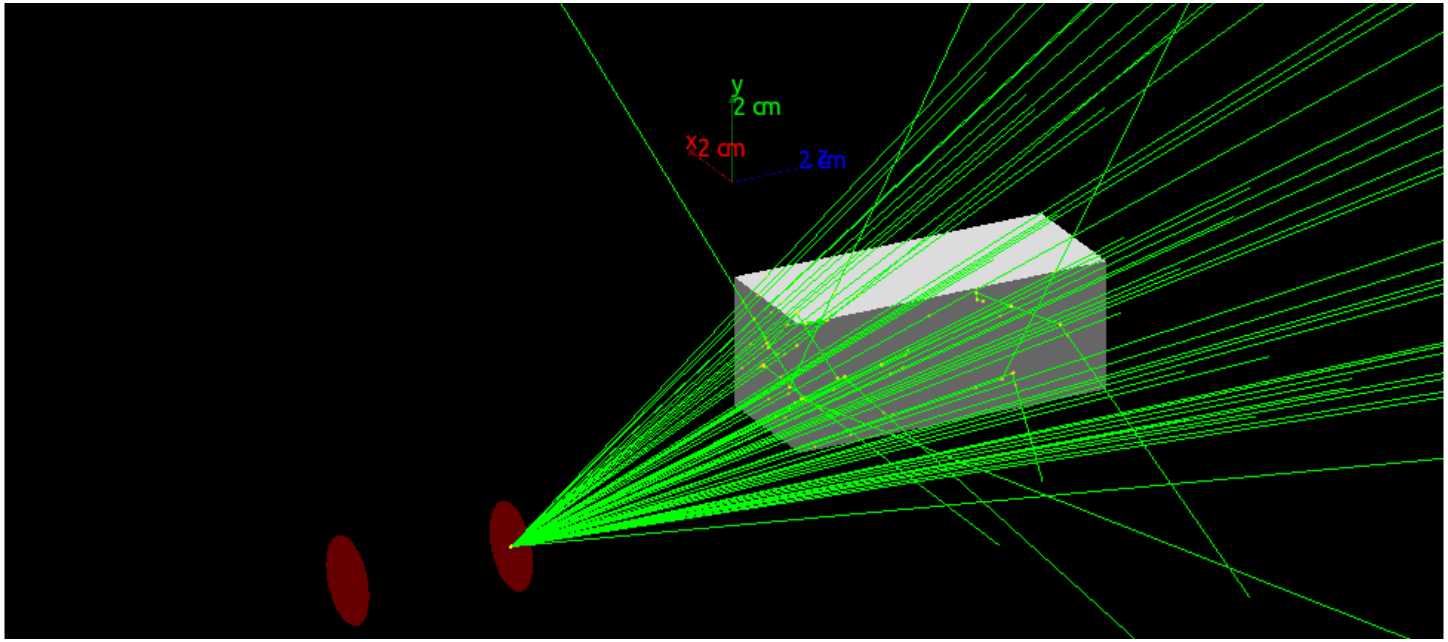
Extrapolated with sqrt(E) to 1.7% (LABR), 3.6% (LYSO) at 1.8 MeV

i.e. a line resolution of 30 keV, 60 keV in the two cases

SIGNAL NORMALIZATION: Labr

Docdb# 24220
By S. Huang & D.Koltick

⇒ $9\ E^6$ photons at 1.8 MeV generated in 1 degree cone

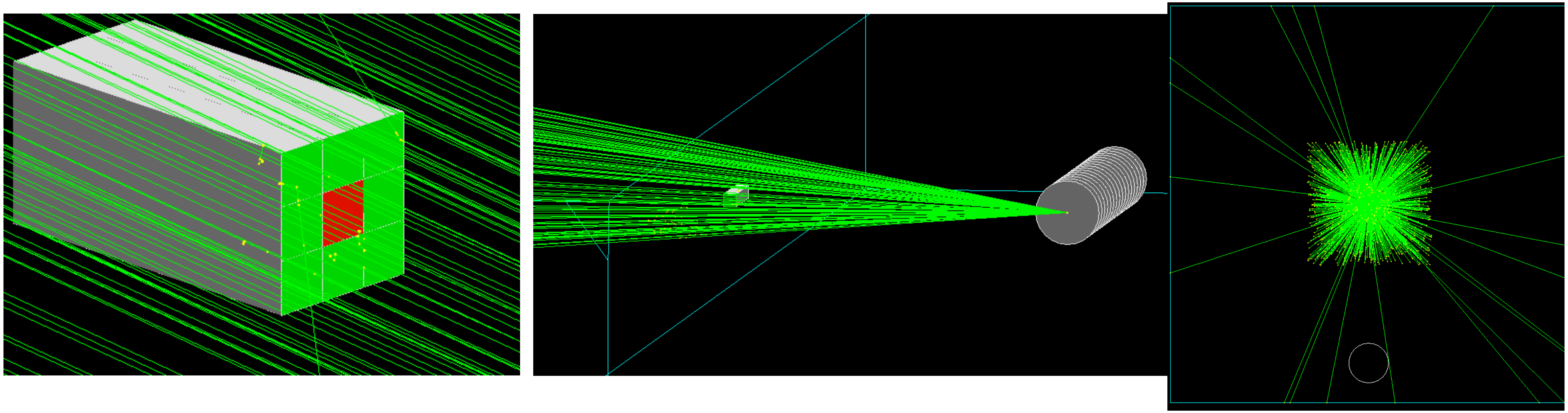


Target (mm)	3D-Dist (mm)	Npeak	Npeak/9E6	E(1deg)/E(3x3)	E(peak)	E(3x3)	E(tot)
5471	6387	37439	4.15xE-3	43.83	18.2%	1,75 E-6	3.20 E-7
6271	5620	48265	5.40xE-3	33.93	18.3%	2,27 E-6	4.16 E-7
Average	**6003**				18.3%	2,01E-6	**3.7 E-7**

Ng/Ngen= e(3x3)/e(1-degree) x e(photopeak) ➔ E(photopeak) = Ng/Ngen *E(1deg)/E(3x3)

ε(tot) = ε(3x3)x ε(photopeak) → Average = 3.7E-7. **With absorber reduction of ~ 3%**

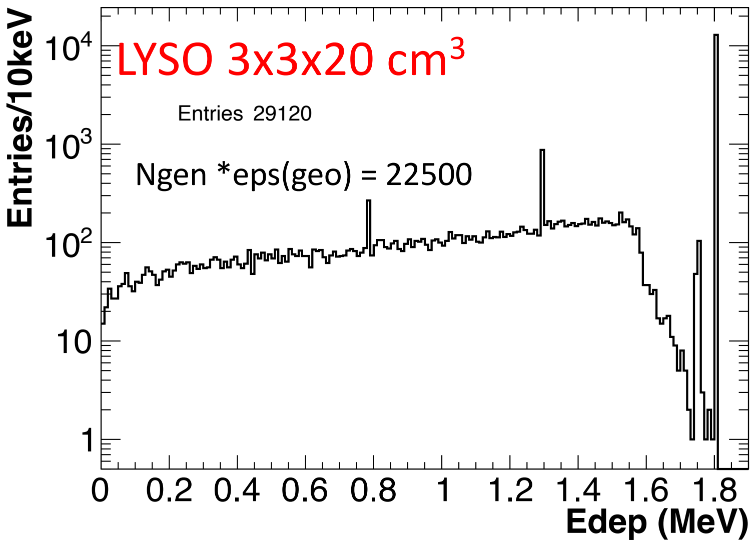
SIGNAL NORMALIZATION: CAPHRI

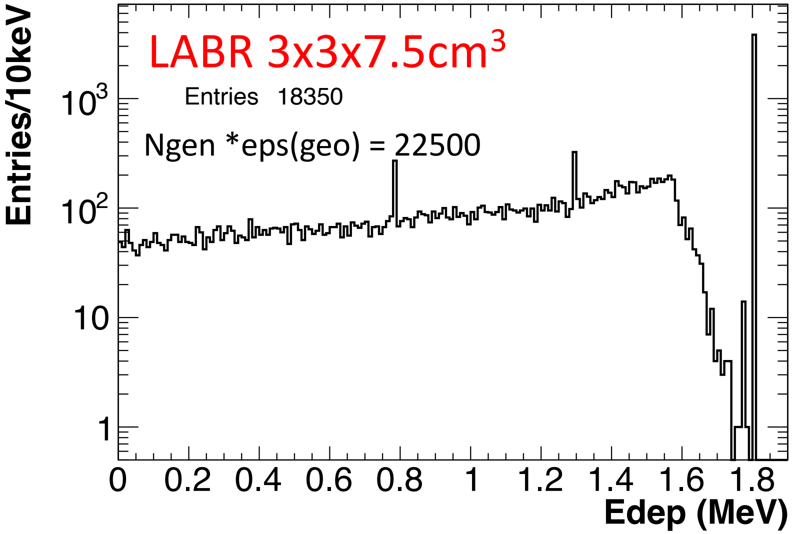


- A more detailed simulation with Geant-4 is in progress to understand changes on acceptance depending upon configurations:

1. LaBR detector 30x30x75 mm^3 or LYSO detector 30x30x200 mm^3 in empty space;
2. a 3x3 matrix with the central crystal either LaBr or LYSO inside a CsI matrix
3. the beam impacting normally on the surface
4. the beam impacting with the right average angle on the surface
5. spreading uniformly the origin on the targets

SIGNAL NORMALIZATION: CAPHRI vs LABR





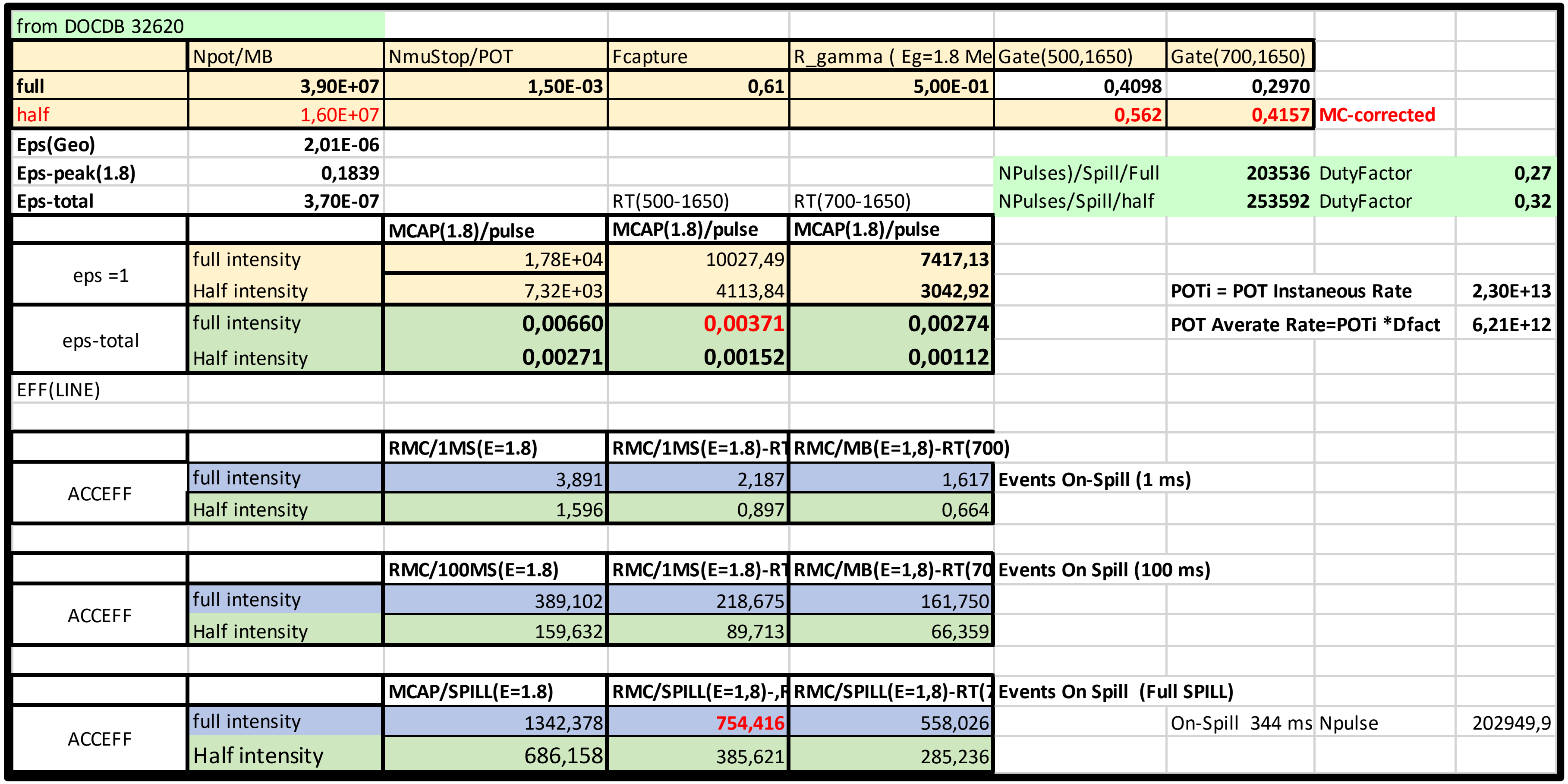
10^6 events produced from different targets fired uniformly in a 20 cm square centered around 1 CAPHRI crystal. **# of events producing a photopeak as total number and in percentage to the expected ones**

Origin	CAPHRI POS	DOC #24220	LABR only	LYSO only	LYSO +CSI
Near Target	High (60 cm)	5408	3961 (20.7%)	14857(44.3%)	11434
Far target	High (60 cm)	4159	3832 (20.7 %)	14126(44.2%)	11253

- ➔ Comparison between our LABR simulation and DOC #24220 +13%
- ➔ Photopeak efficiency for LYSO looks much higher (x 2.1) due to density.
- ➔ Effect of surrounding CsI seems to be important . Counts decrease of 25%
- ➔ Length of crystal also changes acceptance

CAPHRI absolute rate for 1.8 MeV

- **Since the comparison between LYSO and LABR still needs some time to mature we have provided the following estimates based only on LABR of absolute acceptance (photopeak) of 3.7 E-7**
  - ➔ it does not include the eventual x2 increase due to longer and denser LYSO crystals
  - ➔ it does not include any eventual relative reduction/increase due to neighbouring crystals
  - ➔ it assumes a perfect gaussian shape from the measured resolutions @ 511 keV
  - ➔ it does not include the response spectrum and the dark rates from the detectors



from DOCDB 32620								
	Npot/MB	NmuStop/POT	Fcapture	R_gamma (Eg=1.8 Me	Gate(500,1650)	Gate(700,1650)		
full	**3,90E+07**	**1,50E-03**	**0,61**	**5,00E-01**	**0,4098**	**0,2970**		
half	1,60E+07				**0,562**	**0,4157**	**MC-corrected**	
Eps(Geo)	**2,01E-06**							
Eps-peak(1.8)	**0,1839**				NPulses)/Spill/Full	**203536**	DutyFactor	**0,27**
Eps-total	**3,70E-07**		RT(500-1650)	RT(700-1650)	NPulses/Spill/half	**253592**	DutyFactor	**0,32**
		MCAP(1.8)/pulse	**MCAP(1.8)/pulse**	**MCAP(1.8)/pulse**				
eps =1	full intensity	1,78E+04	10027,49	**7417,13**				
	Half intensity	7,32E+03	4113,84	**3042,92**		**POTi = POT Instaneous Rate**		**2,30E+13**
eps-total	full intensity	**0,00660**	**0,00371**	**0,00274**		**POT Averate Rate=POTi *Dfact**		**6,21E+12**
	Half intensity	**0,00271**	**0,00152**	**0,00112**				
EFF(LINE)								
		RMC/1MS(E=1.8)	**RMC/1MS(E=1.8)-RT**	**RMC/MB(E=1,8)-RT(700)**				
ACCEFF	full intensity	3,891	2,187	1,617	**Events On-Spill (1 ms)**			
	Half intensity	1,596	0,897	0,664				
		RMC/100MS(E=1.8)	**RMC/1MS(E=1.8)-RT**	**RMC/MB(E=1,8)-RT(70**	**Events On Spill (100 ms)**			
ACCEFF	full intensity	389,102	218,675	161,750				
	Half intensity	159,632	89,713	66,359				
		MCAP/SPILL(E=1.8)	**RMC/SPILL(E=1,8)-,F**	**RMC/SPILL(E=1,8)-RT(7**	**Events On Spill (Full SPILL)**			
ACCEFF	full intensity	1342,378	**754,416**	558,026		On-Spill 344 ms	Npulse	202949,9
	Half intensity	686,158	385,621	285,236				

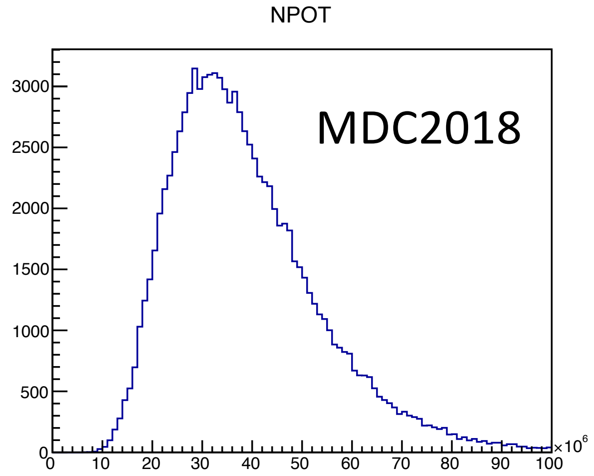
CAPHRI: Background Normalization

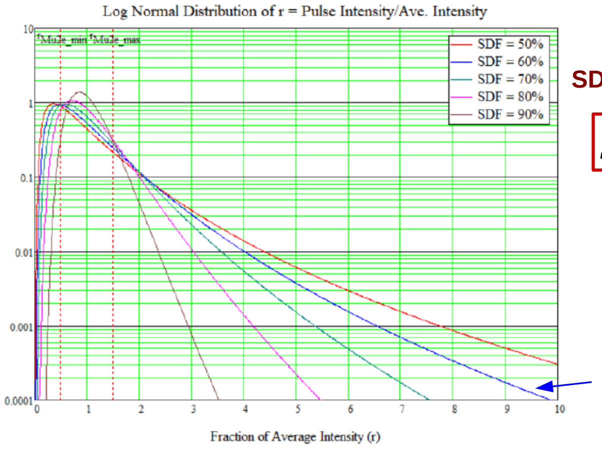
- Used 500000 events from MDC2018 No-primary-mix dataset
- Selected events with hits in 2 “Caphri” (cryid=623,625) E>1 MeV, T>500 ns
- Fit with simple exponential law around signal region in (1.5-2.1) MeV
- **Normalization done with “Full-intensity” MDC-2018 profile ➔ Npulses/spill = 203536.**
- Assumed to have 4 detectors i.e. divide by 2 the number of simulated spill
- **Simulation presented as “MDC2018” is equivalent to 1.25 SPILL**

To check detector behaviour for: higher intensity/pulse or (equivalently) for higher number of spills “scale-bkground” with a Toy MC ➔

use fixed-fitted slope in “MDC2018” making random generation of events for SCALE-times

the MDC2018 background



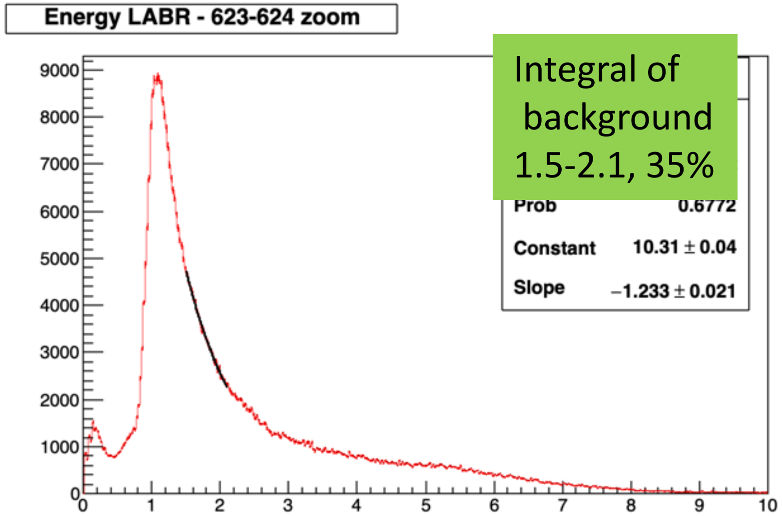


SDF: Spill Duty Factor

$$\boxed{SDF = e^{-\sigma^2}}$$

SDF = 60%
is the current
design value

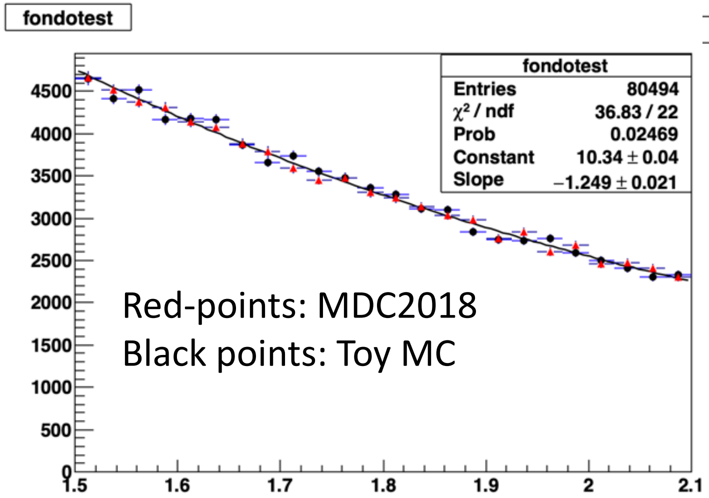
CAPHRI: Background for MDC2018 and TOY MC



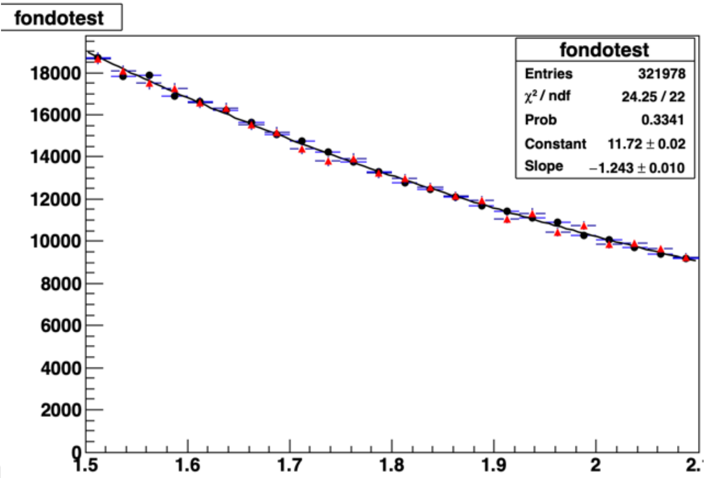
Integral of background 1.5-2.1, 35%

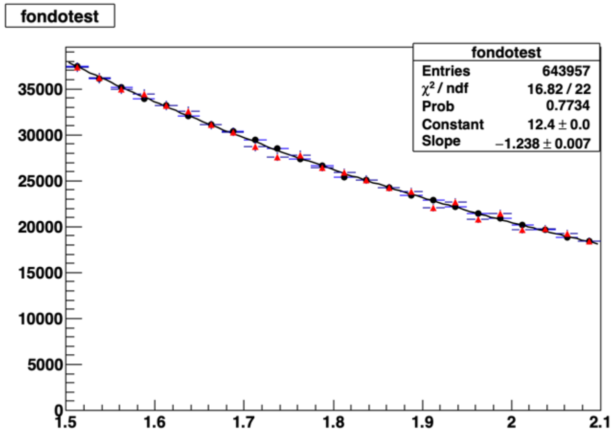
Caphri Integral of background with 4 channels has at least 1 hit with T>500 ns and Ehit in 1.5-2.1 MeV around 35%/events

	Intensity x1.25	Intensity x5	Intensity x 10
NINTEG	80510 (283)	321978 (567)	643957 (802)
NFIT(bkg only)	80495 (1353)	321969(2677)	643966(3799)

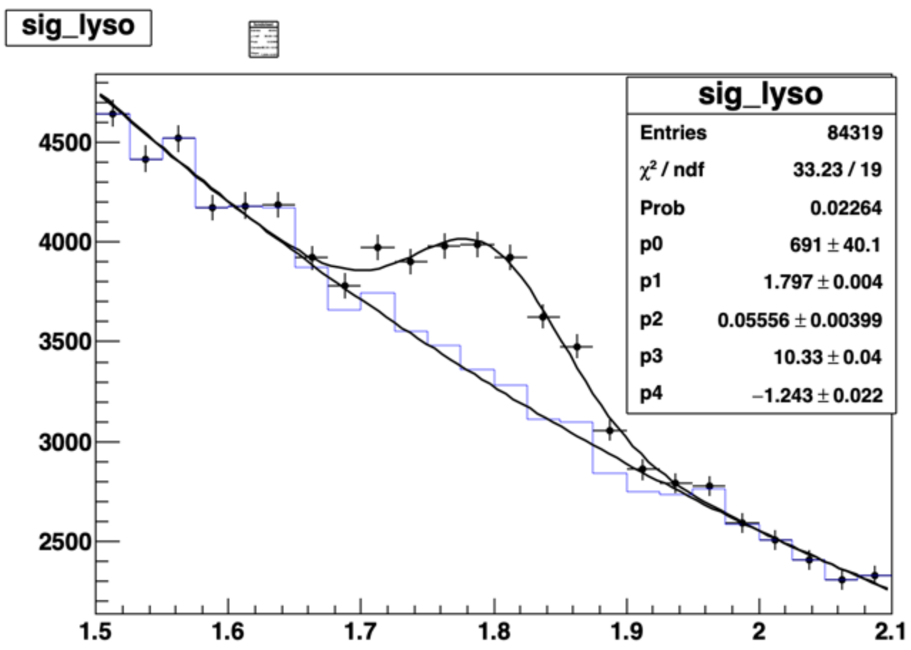


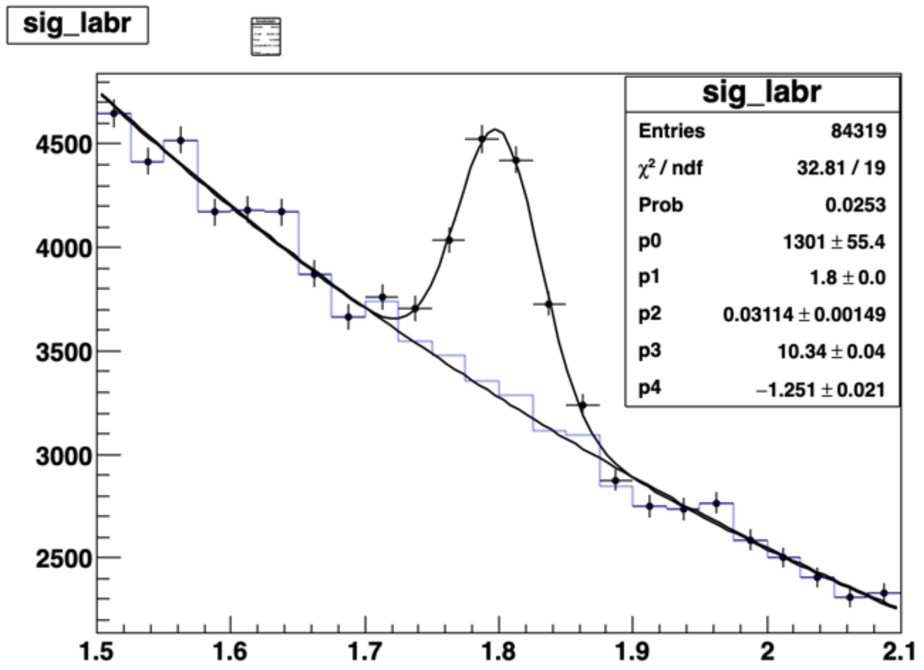
Red-points: MDC2018
Black points: Toy MC





CAPHRI: S/B for 1.25 spills, MDC2018 intensity

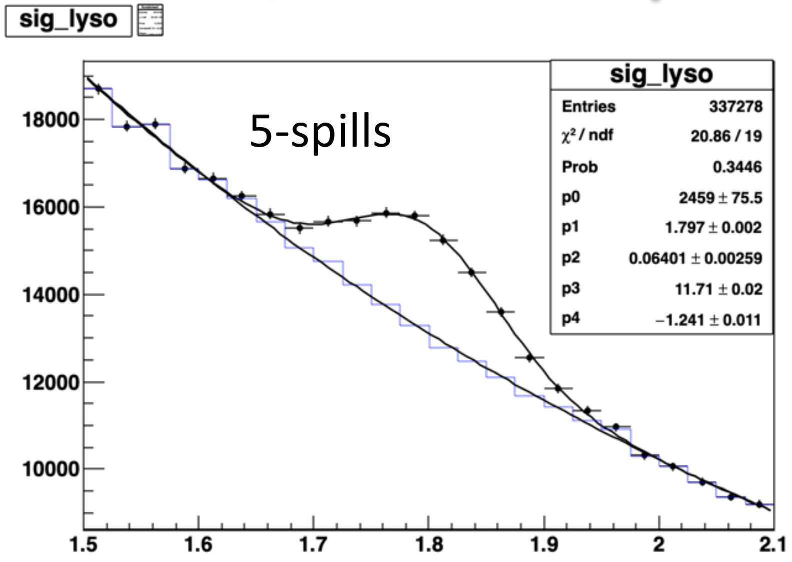


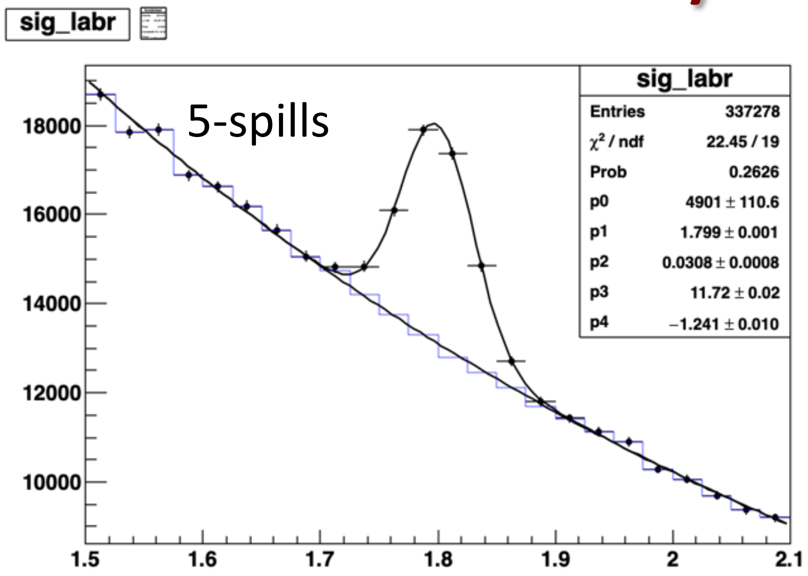


Intensity x1.25	LYSO-only	LYSO+BKG	LABR-only	LABR+BKG
Ninteg	3825(61)	3825(61)	3825(61)	3825(61)
NFit	3804(84)	3850(355)	3818 (88)	4060(260)
P1	641	691	1248	3825(61)
Mean(keV)	1.800	1.798	1.800	1/800
Sigma(keV)	59.2	55.5	30.5	31.1

In ~ 1 spill , 9% resolution on muon capture/spill (LYSO), 5% with LABR

CAPHRI: S/B for 5 spills, MDC2018 intensity





Intensity x 5 spill	LYSO-only	LYSO+BKG	LABR-only	LABR+BKG
Ninteg	15300(124)	15300(124)	15300(124)	15300(124)
NFit	15288(175)	15788(802)	15289(175)	15134(511)
Intensity x 10 spill	LYSO-only	LYSO+BKG	LABR-only	LABR+BKG
Ninteg	30600(174)	30600(174)	30600(174)	30600(174)
NFit	30584(248)	31370(1091)	30593(249)	30209(735)

- ❑ In 15 seconds assuming average intensity of 3.9E7 POT/pulse ➔ counting precision goes to 3% for LYSO, 2 % for Labr. Fit value in agreement of better than 2% with simulated value
- ❑ Error dominated by sqrt(B). Higher intensity /pulse improves Signal/B determination
- ❑ Using 2 instead of 4 channels will reduce the counting precision only of sqrt(2)
- ❑ **For 1 " subrun-length we can make a great monitor also as a function of intensity variation/pulse**

CAPHRI data-flow (1)

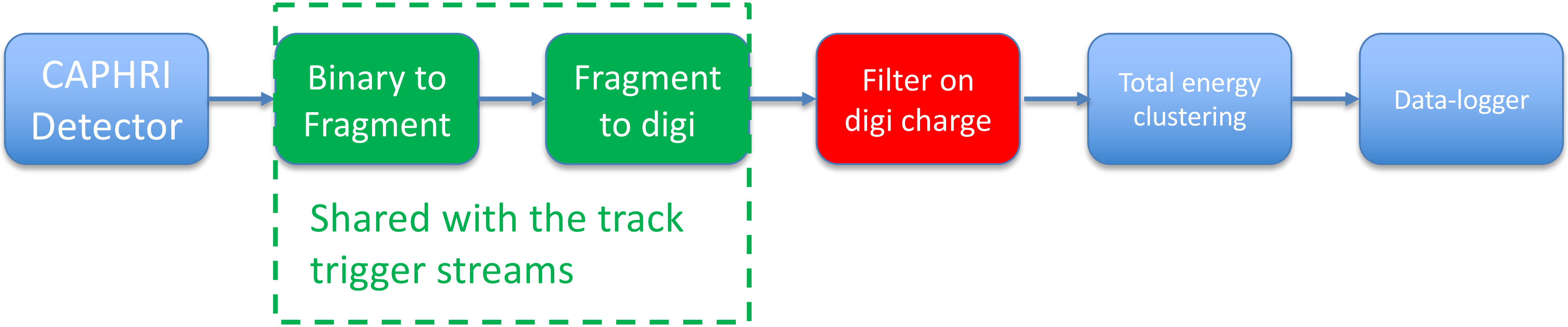
- We can set up an independent data-stream for the CAPHRI data:
  1. Data-fragment to digi ➔ **create an independent digi collection for the 4 channels**

  2. **Filter data** with a charge selection on the waveform pulses
     i.e. Epeak > 1.5 -2.1 MeV (Fraction with Mix-BKG ➔ 35%/pulses)

  3. **Create calo-clusters** integrating all the crystal hits in a time gate (dt>100 ns)
     ➔ E500, E600, E700 …. E1700 (decide if disk-0 or disk0+disk1)
     ➔ N500 … N1700
     ➔ Total of 12 x 2 info, around 24 x 2 Bytes up to 50 Bytes/event

  4. Data is sent to the data logger for being saved in an **independent output file**

- The info of the total energy reconstructed in the calorimeter allows us to correlate the number of μ-stopped with the beam intensity **in the same data-stream**



CAPHRI data-flow (2)

Save only the data where there the hits have Epeak> 1.5 – 2.2 MeV

1. w.o. losing any information CAPHRI has an event size of at least 1 hit in 35% of the cases for the FULL-INTENSITY RUNNING! Roughly half of that in startup phase.

   Storing all wave is 60 sampling x 2 bytes , around 120 bytes

   ➔ Rate of ~ 70000 events/spill on disk means 8.4 MB/spill, 8.4/1.4 sec → **6 MB/sec**

   ➔ Additional overhead of Clusters word for beam intensity of around 50 bytes will increase of +40% this size ➔ **8 MB/sec**

2. Assuming a Trigger reduction of ~ 300 and an average Calo size of ~ 11 GB/s, the corresponding calorimeter raw-data writing on disk after trigger is of ~ 36 MB/sec In this respect, **Caphri will be around 15% (5 %) of the Calorimeter (MU2E) data throughput on disk af full intensity.**

3. **Reduction of data through-put better than a factor of 3 can be easily achieved by:**
   - → Reducing from 4 to 2 the channels in CAPHRI (favorite and easy option)
   - → Reducing the calo-cluster info from each 100 ns to each 200 ns or using only inclusive calo-cluster data (E>500, E>700 ns). (Easy to add save 30%)
   - → play with EBuilder and save only a shorter part of the wave or the peak directly (complicated to do now, it can be done if /when needed)

4. **The addition load in the processing time is expected to be small**
5. Maximum size on disk in 1 year (assuming 2E7 seconds) → **8x 2E7 MB = 160 Tbytes (0.15 pB)**
6. Skimming easy to save on DST's only the Q /T info ➔ a factor of 30 reduction → **5 TB/year**

Next steps and systematics check

1. **Select btw LYSO and LABR**

   → both due to detector length, cost and easy to use we believe LYSO to be the right choice for this first running period. It will leave us time to develop a "better" detector for phase-2

2. **Complete study of Acceptance.**

   We are now using the most conservative results done by S.Huang in docdb# 24220. Ivano has now completed the study of acceptance in calorimeter rings but we have not yet updated the result.

3. **Quantify more precisely muon-capture and counting capability for different POT intensity**

   We could improve the Toy-MC using the shape of the pulses provided by S.Werkema and repeat the exercise in a similar way to the one done by R. Kutschke lately.

   CAPHRI statistical precision improves at higher intensity both on:

   → the muon capture rate

   → the determination of POT/pulse

4. **Study variation of counting as a function of detector resolution (easy)**

5. **Compare Geant-4 with source measurements scanning across neighbouring crystals**

6. **Check if there is any muon-capture process of OOT muons stopping on surrounding aluminum**

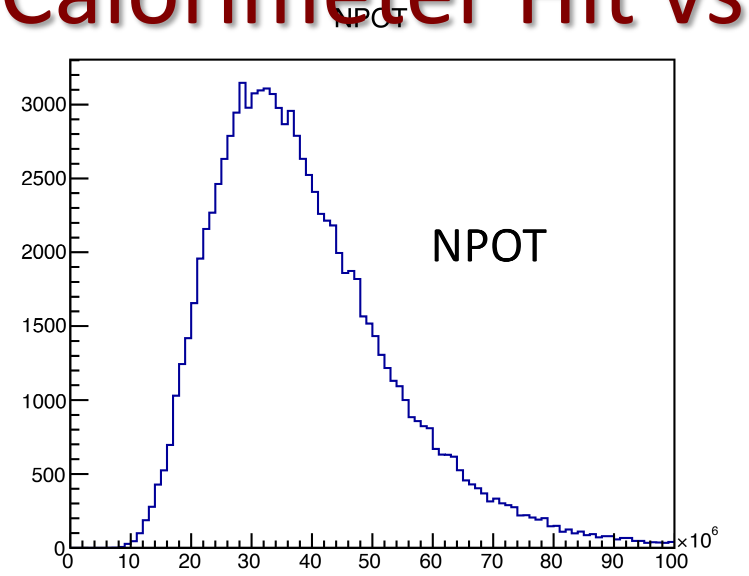
   Done .. No contamination

7. **Decide how to stream the events (and how much to store) for the special CAPHRI path**

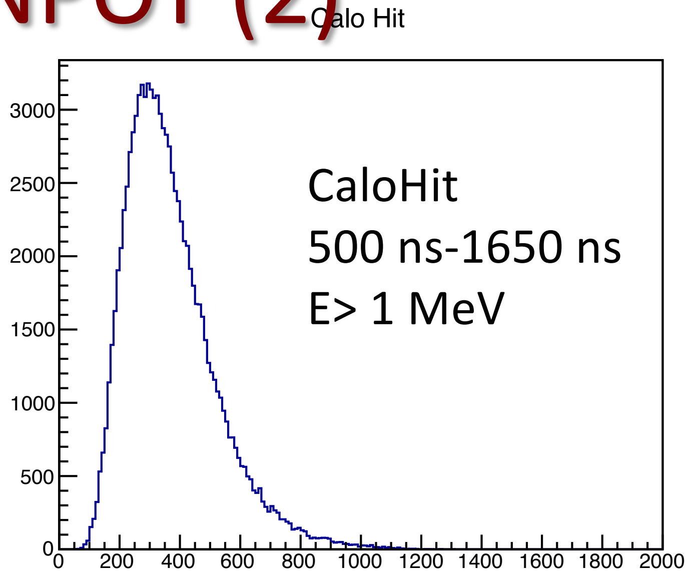
Additional Information

Calorimeter Hit vs NPOT (2)

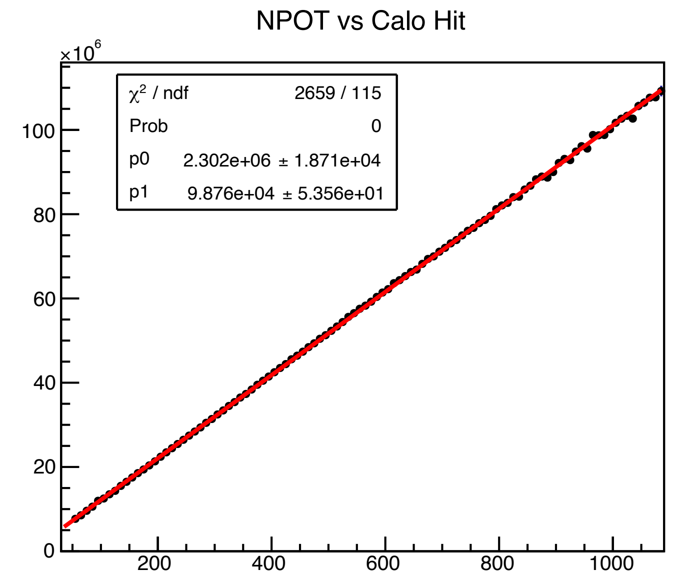
MDC2018



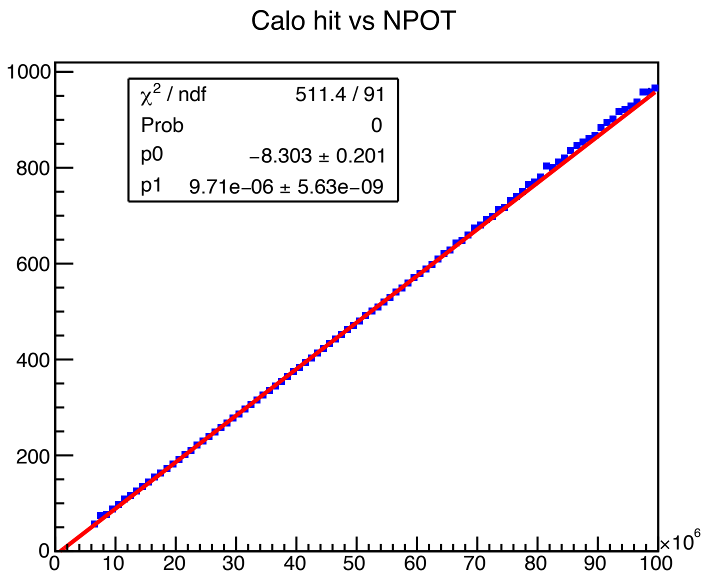
NPOT



CaloHit
500 ns-1650 ns
E> 1 MeV

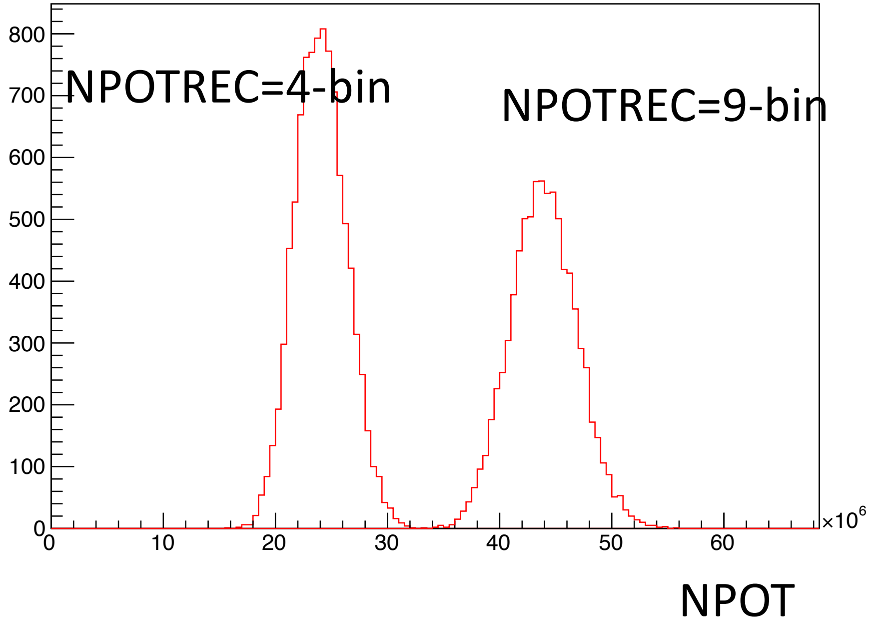


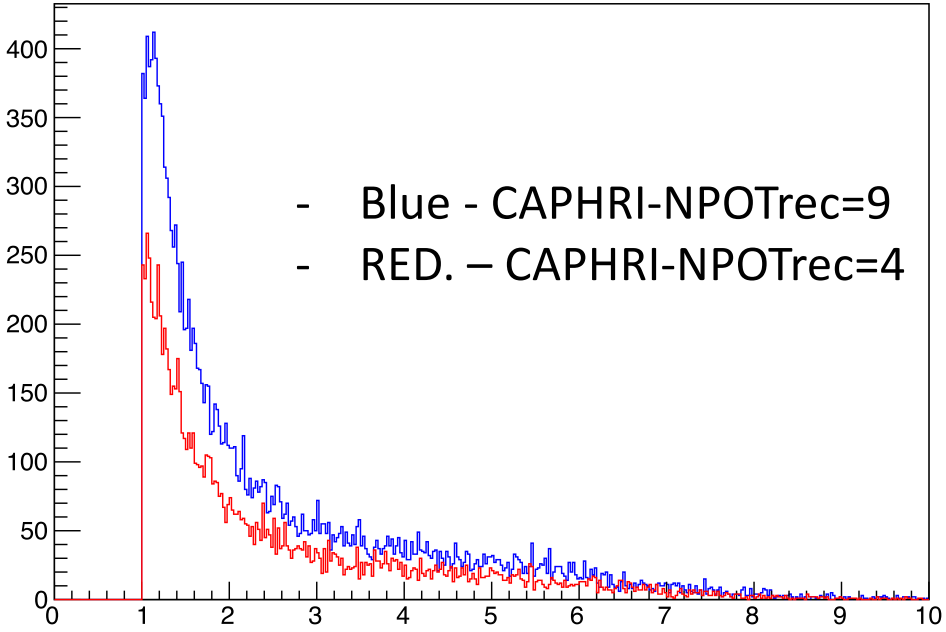
NPOT = 2.3 E6+ 9.9E4 * CaloHit



CaloHit = 9.7 *(NPOT/E6 -8)

Hit-scaling by "NPOTREC"





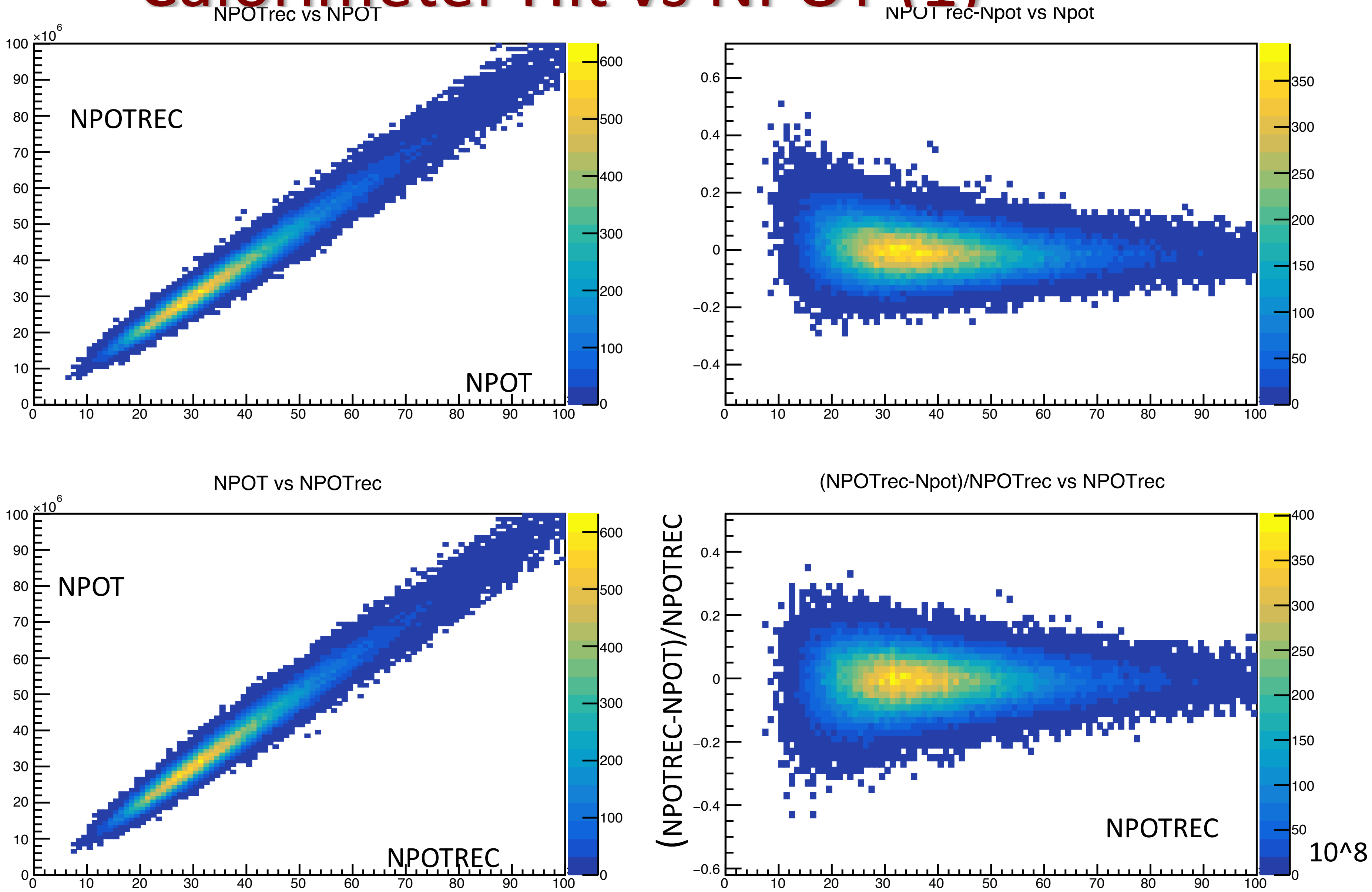
- Blue - CAPHRI-NPOTrec=9
- RED. – CAPHRI-NPOTrec=4

Mean NPOT for Npotrec=4 → 2.4E7
Mean NPOT for Npotrec=9 → 4.4E7
Number of POT4 = <NPOT4> x NeV4 = 2.3 E11
Number of POT9 = <NPOT9> x Nev9 = 3.6E11
Ratio = 1.59

CAPHRI integran for NPOTREC=4 → 10662
CAPHRI Integral for NPOTREC=9 → 17467

Ratio = 1.63

Calorimeter Hit vs NPOT (1)



- Npot and Npotrec from Calo are very well correlated and can be inverted easily
- **Resolution/pulse on NPOT from NPOTREC is 6-7% at 3.9E7 and 3% at 1E8**

LYSO

- Bkg is low for the external crystals: low contamination and the possibility to measure the **1809 keV γ-ray** from the reaction 27Al(μ−, νnγ)26Mg in the Mu2e acquisition window

→ **We are far away from the LYSO self emission endpoint (1 MeV).**

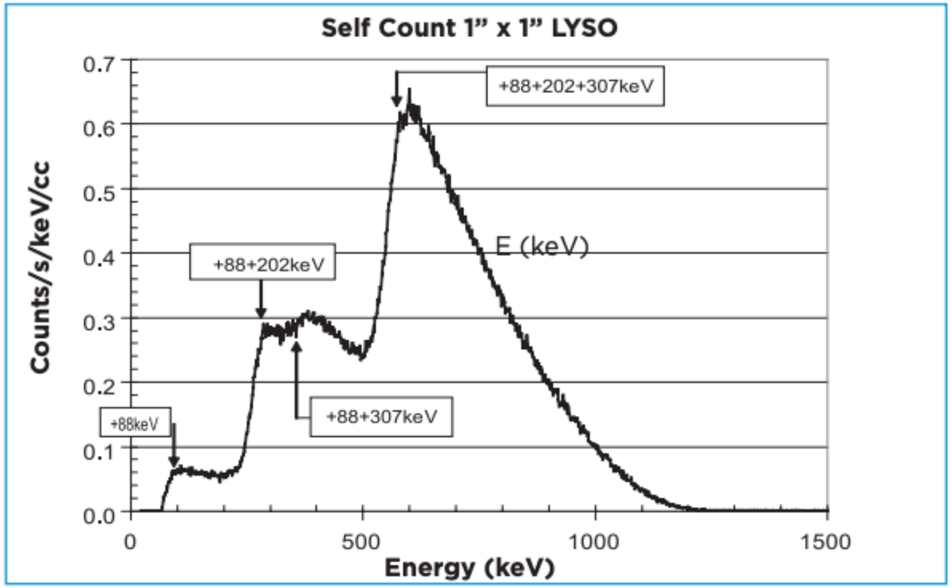


Figure 3. LYSO is a Lutetium-based scintillator which contains a naturally occurring radioactive isotope 176Lu, a beta emitter. The decay results in a 3 gamma ray cascade of 307, 202 and 88 keV, where self-absorption of these photons results in the above spectra in a 1"x1" cube. Total rate for this activity is 39 cps/g.

LaBr specifications (enhanced)

- Decay time 25 ns, Emission light 380 nm
- 73.000 photons /MeV, Index refraction 2.0

→ 2 x2 cm 2 vs 1x1 = ¼ area reduction

→ Match it to 1 cm^2 SiPM UV extended 25% qe

→ With Tyvek wrapping and in air coupling assume ¼ (1/2x1/2)

Rough calculation:

→ Area*Eq* Collection = $(¼)^3$ loss =1.5 %

→ LY (pe/MeV) = 1.5 E-2 x 73 E3/MeV = 730x1.5 = 1095

LY at 1.8 MeV = 2000 pe → 2.2% eres

2000 pe for signals also OK with our own SiPM pixel size 50um.

We can one/two of our SiPMs and Sum them up with our electronics. It will look as a 66 MeV signal

LaBr specifications: Pro and Contra

- 1) Very good for linearity
- 2) resolution as 1/SQRT(Npe)

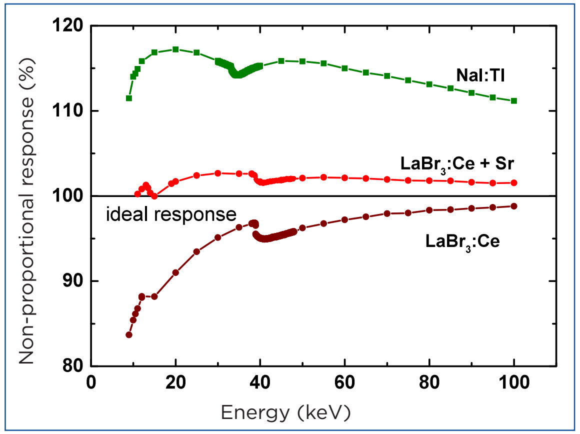


Figure 1. Non-proportionality of Lanthanum Bromide & Enhanced Lanthanum Bromide compared to NaI(Tl)

- 1) **Hygroscopic. Encapsulated**
- 2) its own Rad Background
- 3) good Alfa/Gamma separation

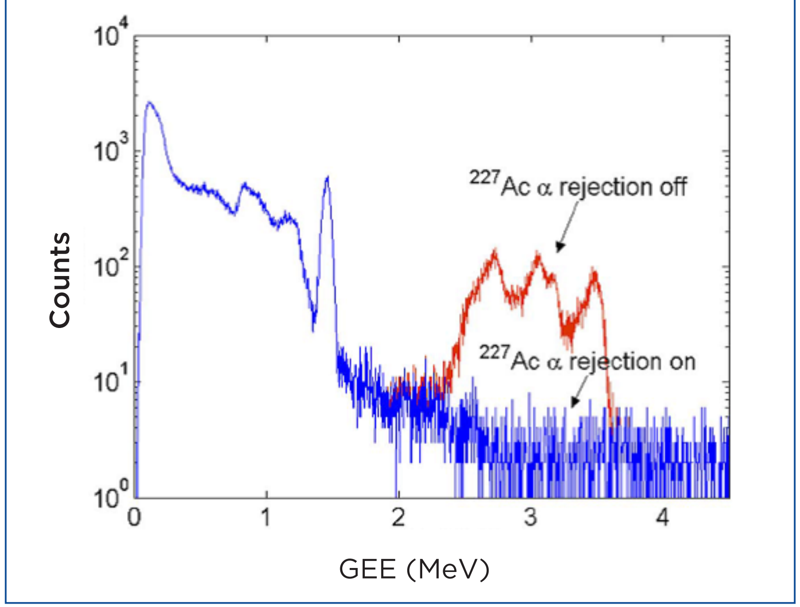


Figure 4. Radiation background spectrum of LaBr3:Ce, Sr with and without α rejection.