CALOR 2020 – 19th International Conference on Calorimetry in Particle Physics
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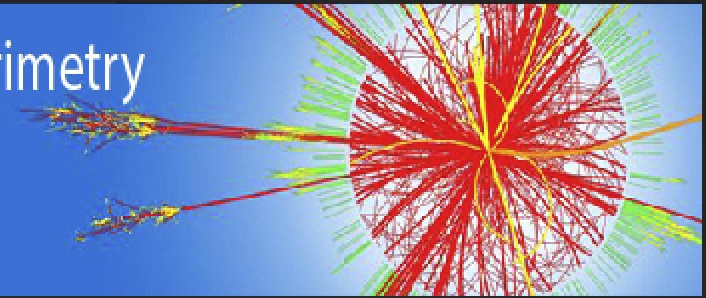

The impact of crystal light yield non-proportionality on a typical calorimetric space experiment.

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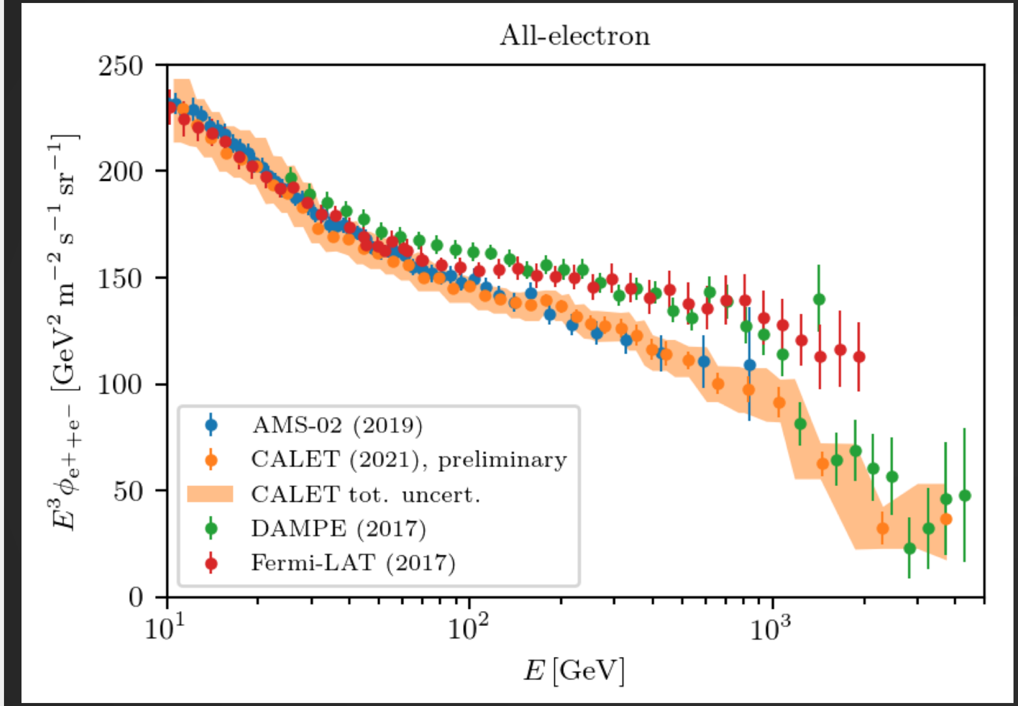
A paper including the details of this work was recently submitted on JINST.

Space detetor for cosmic rays (CR).

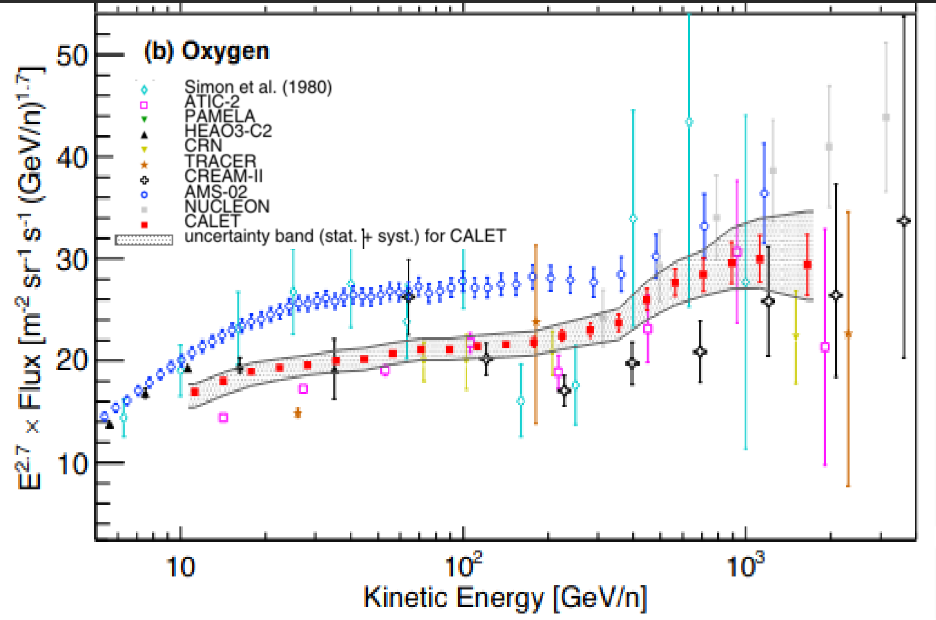
- Direct CR detection in the multi-TeV region is relevant for:
  - dark matter models (electron, positron…),
  - CR sources nearby the Earth (electron, positron…),
  - acceleration, propagation models (protons, nuclei…).
  - …
- Spectrometers (AMS-02, PAMELA, …):
  - Limited acceptance and M.D.R. → particle energy < ~TeV
- Recent calorimetric experiment:
  - Large acceptance → high energy region
  - Current experiment: DAMPE, CALET, Fermi-LAT…
  - Future experiment: HERD (2027).

Disagreement among experiments.

Electron+positron flux



Oxygen flux



Understand the reason of the discrepancies for a correct interpretation of the data and for designing future experiments.

Main idea of this work.

- Calorimeters are typically made with inorganic scintillating crystals.

Experiment	Material	Electromagnetic depth (X_0)	Hadronic depth (λ_I)	Launch year
CALET	PWO	27	1.2	2015
DAMPE	BGO	32	1.6	2015
FERMI	CsI(Tl)	8.6	0.4	2008
HERD	LYSO	55	3.0	2027 (expected)

- Possible systematic effect is due to the non proportional light response of the crystals.
- The scintillation light yield depends on dE/dx.
- Minimalist approach: two phenomena are considered.

Minimalist approach: “Birks” (1).

- At high excitation density the quenching (or Birks) effect is dominant.
- Assuming a division of the energy deposition into cylindrical "core" and "halo" regions surrounding the particle trajectory
- G. Tarle,The Astrophysical Journal, 230:607–620, June 1979.

$$L'_B = \frac{1-\eta_H}{1+B(1-\eta_H)\times\frac{dE}{dx}} + \eta_H$$

Birks parameter

Fraction of carries escaped to the halo region

Minimalist approach: “Onsager” (2).

- At low excitation density another phenomenon can be dominant. A fraction of initial electrons and holes that do not form excitons can combine if they are closer than the Onsager radius can combine to form excitons
- Stephen A., IEEE Transactions on Nuclear Science, 56(6):2506–2512, 2009.

$$L_O = 1 - \eta_{e/h} \exp\left(- \frac{(dE/dx)}{(dE/dx)_O} \right)$$

Fraction of initial electrons and holes that do not form excitons.

Strength of the Onsager term.

Minimalist approach and MC simulation.

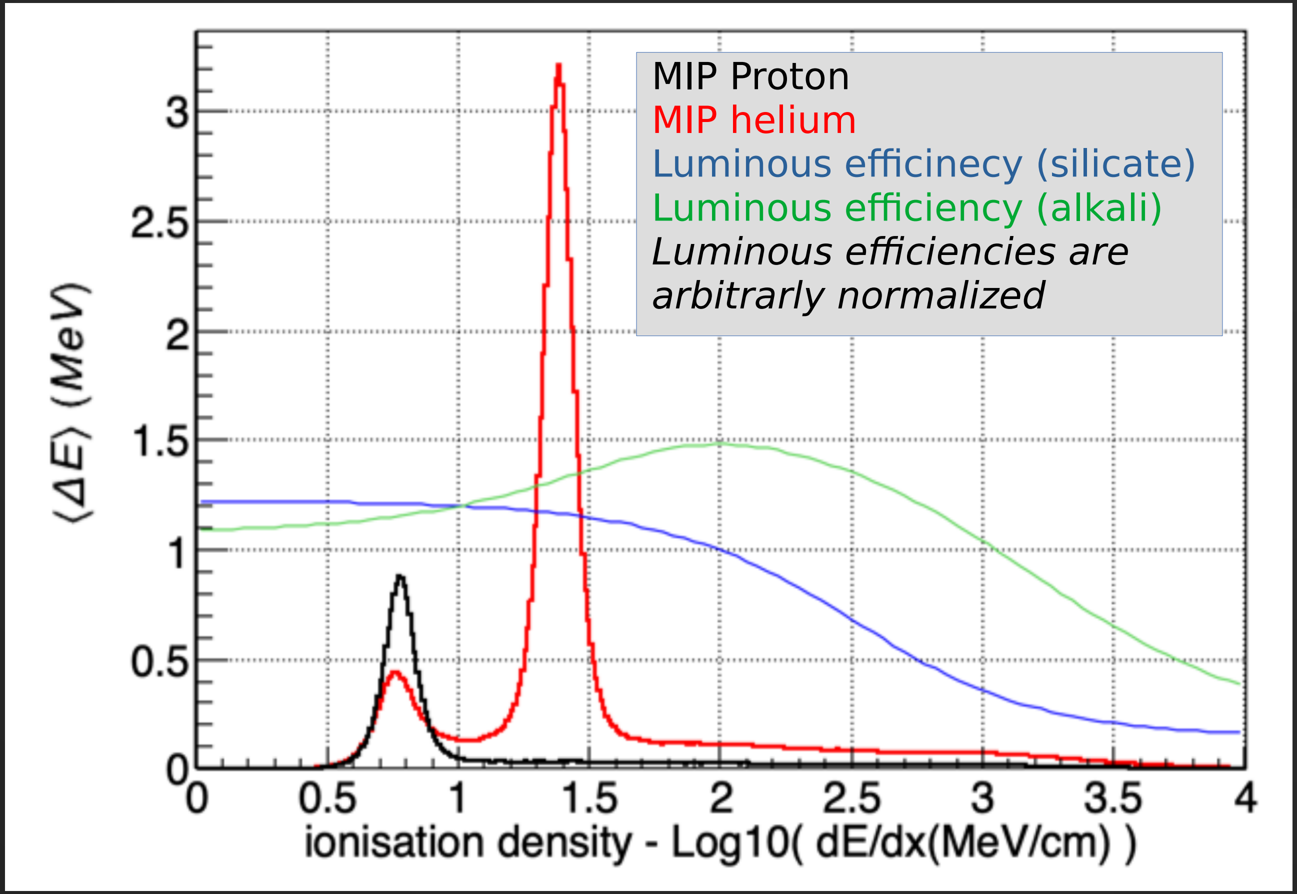
- Combining the modified Birks and Onsager mechanisms the relative luminosity efficiency is:

$$L = \left[1 - \eta_{e/h} \exp\left(- \frac{(dE/dx)}{(dE/dx)_O} \right) \right] \times \left[\frac{1 - \eta_H}{1 + B(1 - \eta_H) \times \frac{dE}{dx}} + \eta_H \right].$$

- To study the dE/dx in different materials, FLUKA simulation of particle showers is employed.
- Minimum energy threshold: 1 keV for electrons and 100 eV for photons.
- All the physical processes that can contribute to the amount of ionisation are activated.

MIP energy deposit density.

- For every bin of ionisation density, the amount of the energy released is provided by the simulation.

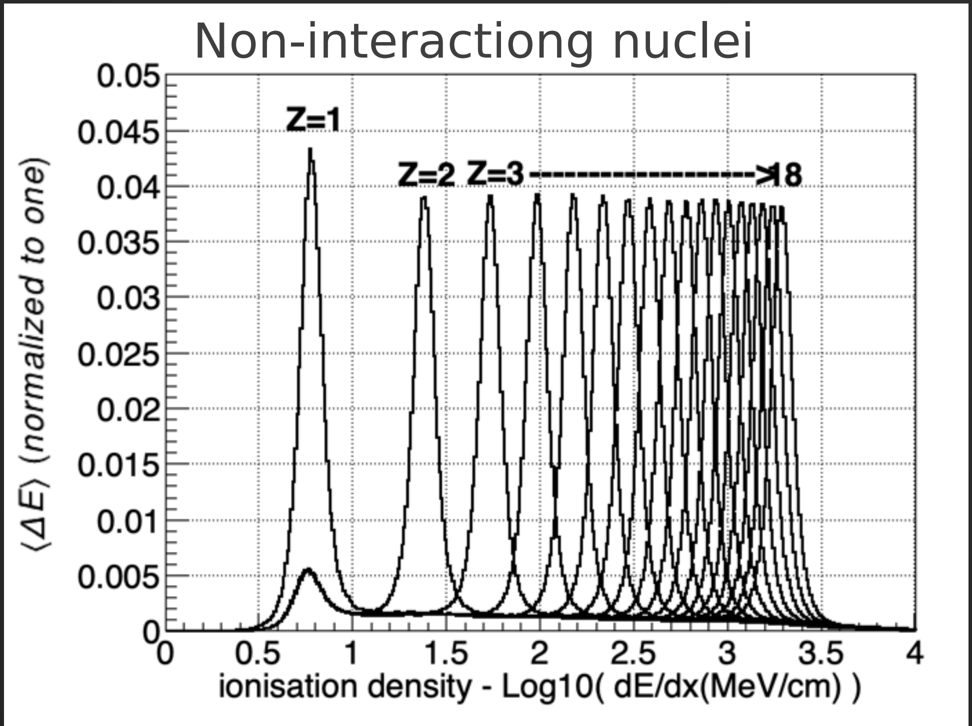


Helium/proton light singal ratio is different from 4.

It will be less or greater than 4 for silicate or alkali scintillator respectively.

Material characterization with nuclei

- The usual ways to study the scintillator non proportionality are Compton electrons, photon response.
- Here the ionization produced by high energy nuclei is used:
  - Technique already exploited by: FERMI, DAMPE, ...



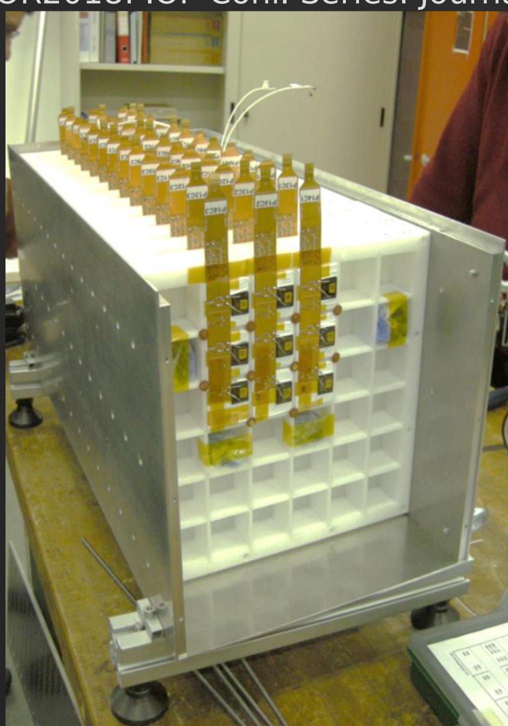
Results of FLUKA simulation for LYSO crystals

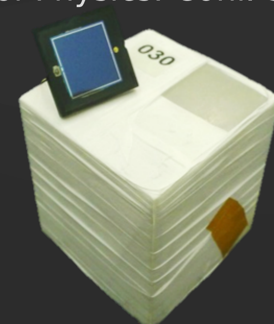
Ionization range:
5 MeV/cm – 2 GeV/cm

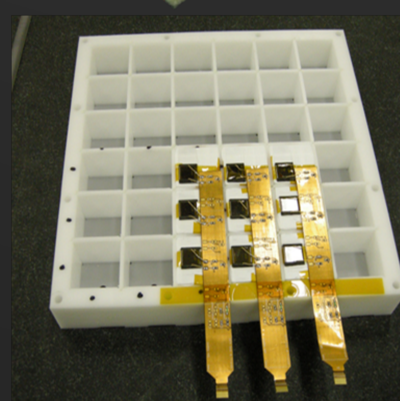
CaloCube project and prototype.

- CaloCube was a 4 years R&D activity aiming to optimize the design of a wide-acceptance, 3-D imaging calorimeter to be operated in space
- Main application of CaloCube idea → HERD (2027)

CALOR2018: IOP Conf. Series: Journal of Physics: Conf. Series 1162 (2019) 012042,doi:10.1088/1742-6596/1162/1/012042







2015: prototype made of CsI(Tl) crystals read-out with photo-diodes tested with nuclei at CERN (SPS)

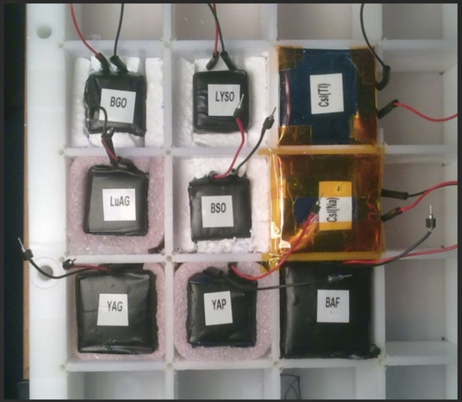
PDs: VTH2090.

Electronics: CASIS chip.

Different crystals tested with nuclei.

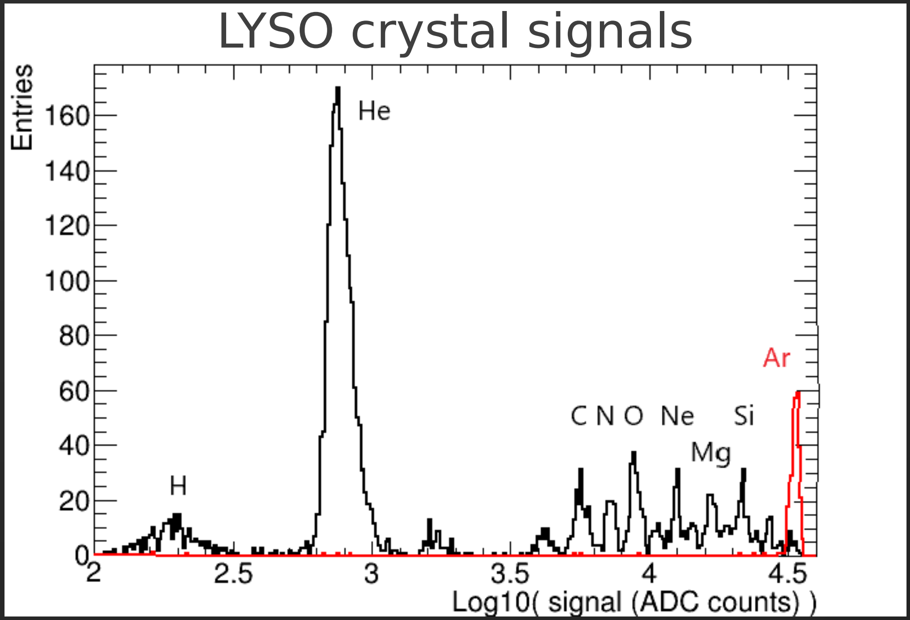
- A tray was loaded with cubic crystals made of different scintillator materials.

Material	Size (cm)	ρ (g/cm^3)	λ_I (cm)	X_0 (cm)	λ_{max} (nm)	τ_{decay} (ns)
BGO	2.0	7.1	23	1.1	480	300
CsI(Tl)	3.6	4.5	40	1.9	550	1220
LYSO	2.0	7.4	21	1.1	420	40
YAP	2.2	5.5	22	2.7	370	27
YAG	2.5	4.6	25	3.5	550	70
BaF_2	3.1	4.9	31	2.0	300	650



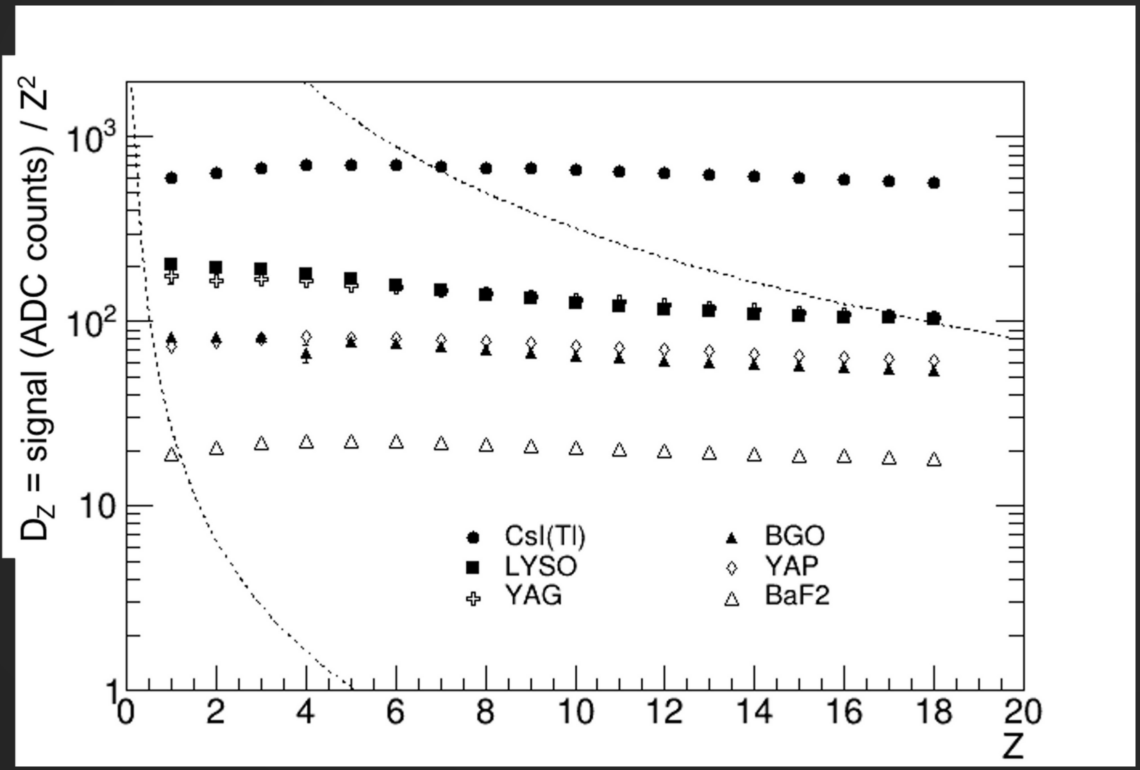
Silicon tracker upstream the prototype: it provides the particle impact position and nuclei charge.

With CSI(Tl) crystals, ions that traversed the test crystal without starting a shower are selected.

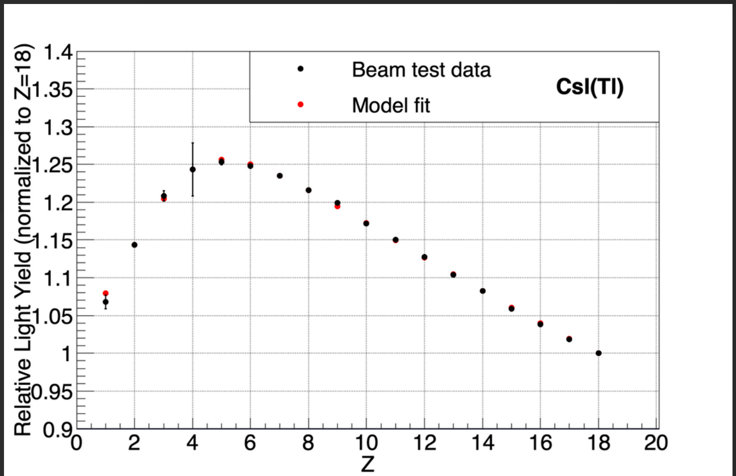


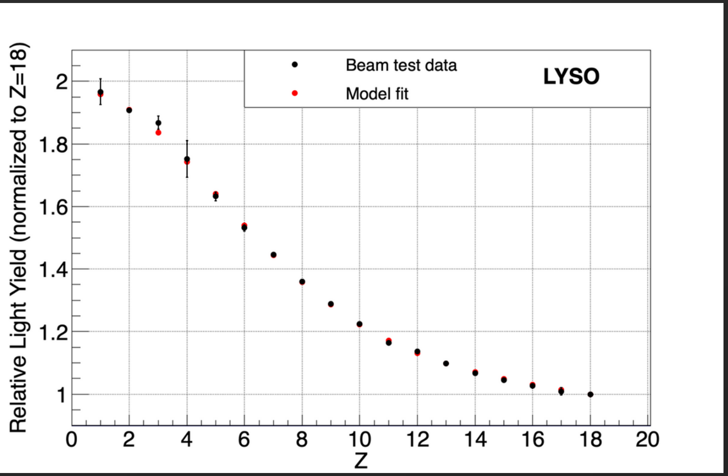
Nuclei measurement results

Mean value of the signals divided by Z^2



Relative luminosity efficiency

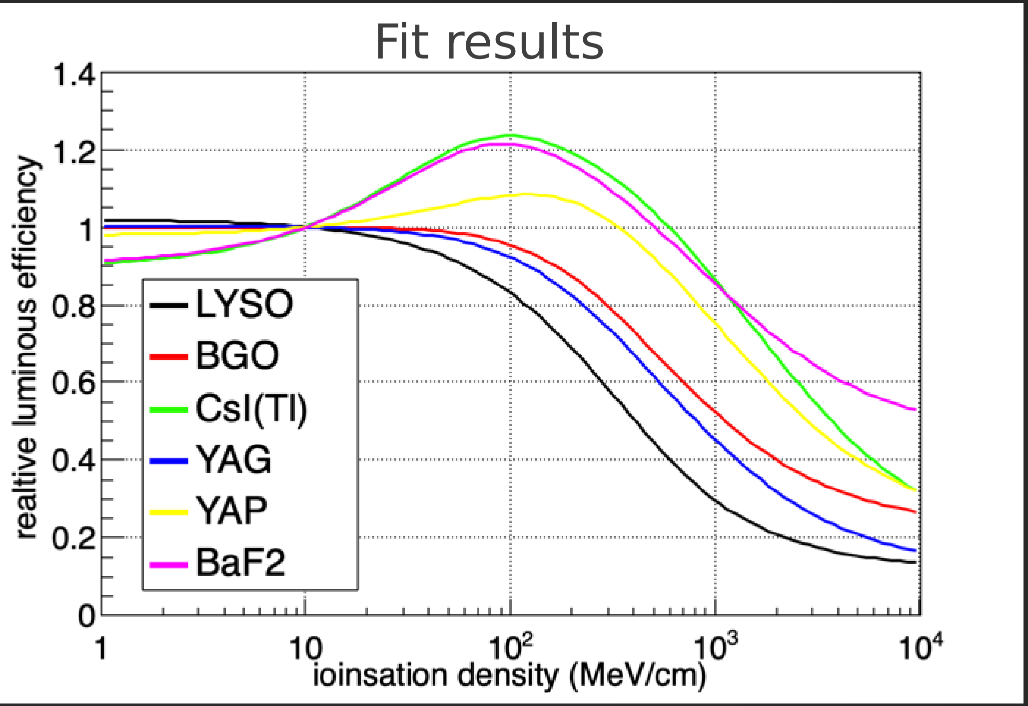




“Minimalist approach” fit.

The output of the simulation and the luminosity data are used to fit the minimalist model.

This is able to reproduce the experimental trends:
χ^2_{red} from 0.64 to 1.64.



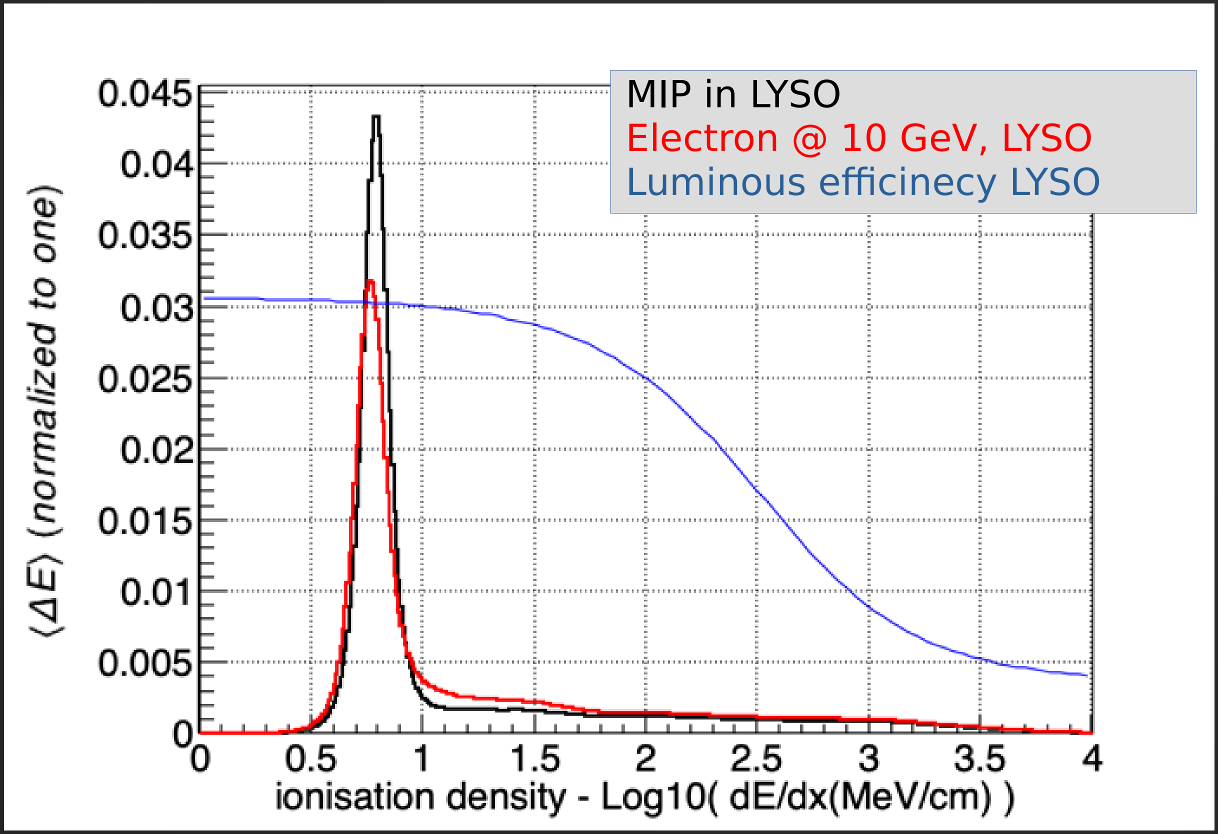
Material	$\eta_{e/h}$	$(dE/dx)_O$ MeV/cm	η_H	$(1/B)$ MeV/cm	χ^2_{red}
BGO	0.159 ± 0.033	98 ± 45	0.1884 ± 0.0039	364 ± 42	1.64
CsI(Tl)	0.326 ± 0.010	34.1 ± 2.8	0.121 ± 0.012	1338 ± 64	0.81
LYSO	0.758 ± 0.045	164.7 ± 8.4	0.0274 ± 0.0048	45.1 ± 9.1	0.64
YAP	0.2212 ± 0.0085	90 ± 11	0.174 ± 0.012	873 ± 70	1.24
YAG	0.0912 ± 0.015	73 ± 29	0.1052 ± 0.0055	462 ± 31	1.23
BaF_2	0.322 ± 0.024	35.8 ± 6.2	0.3440 ± 0.0071	546 ± 36	1.11

Typical space calorimeter simulation.

- Possible systematic effects on space calorimeter energy measurements, simulation:
  - homogeneous cube of 1 m^3 LYSO, BGO, CsI.
  - high energy electron and proton shower.
- For a real experiment the effect will depend on:
  - crystal manufacturer,
  - specific geometry and calibration,
  - acquisition system (e.g. integration time)
  - ...
- Here we show the possible existence of systematic effects due to non-proportionality and we can not determine quantitatively these effects for running experiments

MIP vs electron showers.

- Calorimeter calibrated with non-interacting particle on-orbit.
- Different ionization density profile between MIP and shower.



We assume:

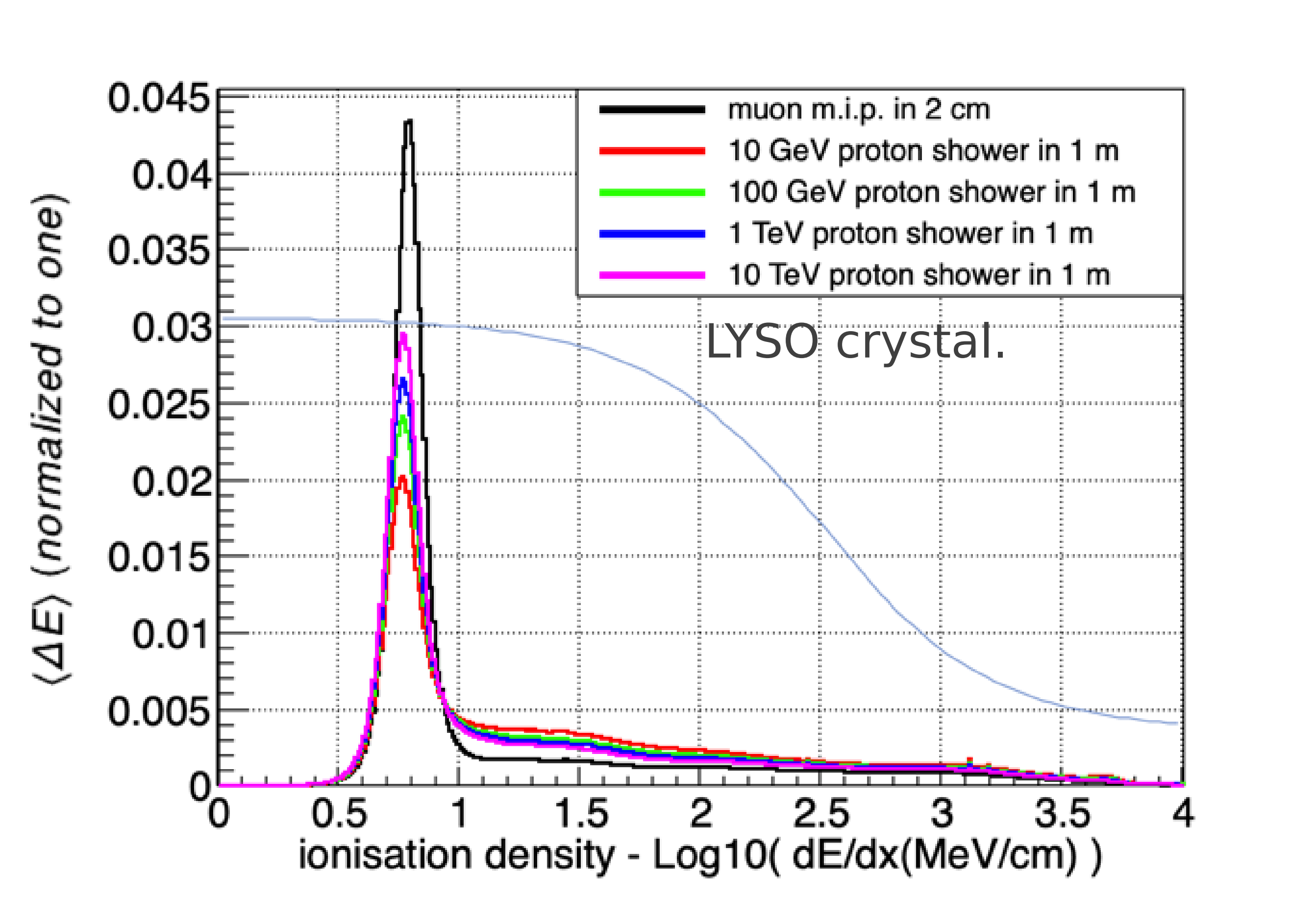
calibration with MIP.

Systematic shift of the measured total shower energy with LYSO ~ -2.3%.

Constant with electron energy from 10 GeV to 1 TeV

Systematic error on proton showers.

- The ionization density profile is not constant with proton energy, thus the systematic error does depend on energy

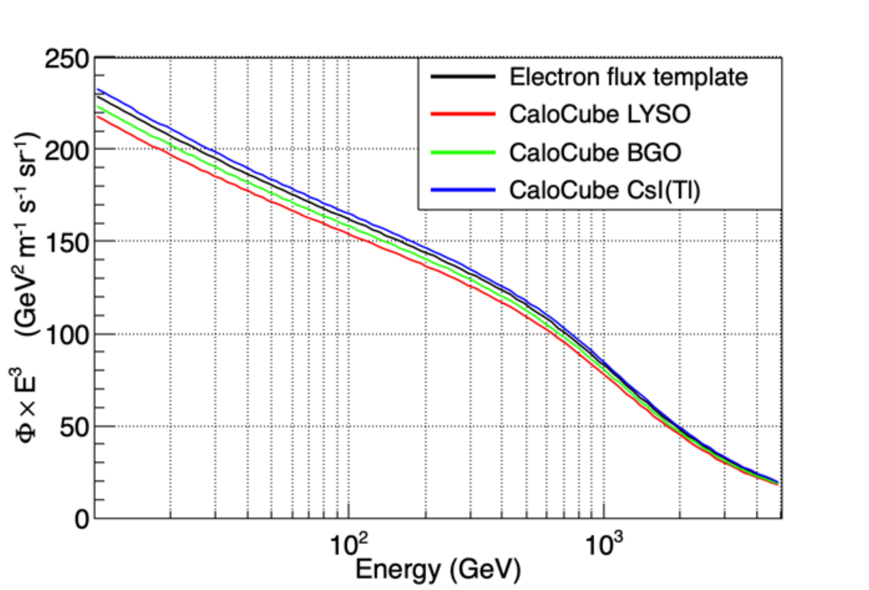


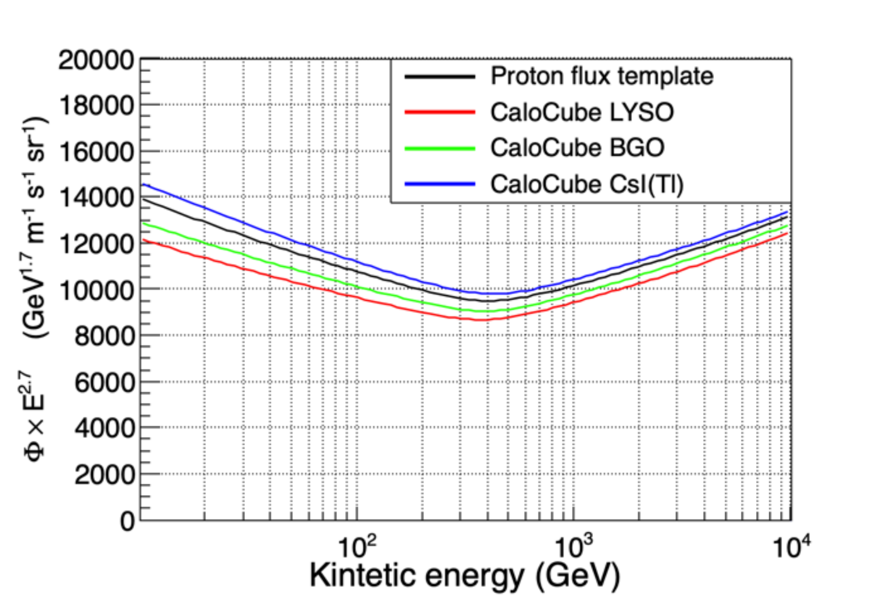
Impact on electron and proton fluxes.

- Systematic shift of energy measurement

Material	electrons $\geq$10 GeV	protons 10 GeV	protons 100 GeV	protons 1 TeV	protons 10 TeV
LYSO	-2.3%	-7.1%	-5.6%	-4.6%	-3.4%
BGO	-1.1%	-4.3%	-3.0%	-2.3%	-1.8%
CsI(Tl)	+0.82%	+2.9%	+2.0%	+1.5%	+1.2%

- Fluxes affected by the systematic error.





Conclusion

- CaloCube data and minimalist approach are employed to characterize the non proportionality of scintillators.
- **If the calorimeter response is calibrated with MIP, a effect on the energy measurement of few percents exists.**
- For future experiment, we suggest:
  - to characterize the scintillator material with the flight readout system (e.g. by using high energy nuclei),
  - To estimate the impact of non-proportionality and eventually to implement the effect inside shower simulation.
- About the results published by running experiments, it is not clear if this effect is already included in detector simulation, since it is not mentioned in papers.