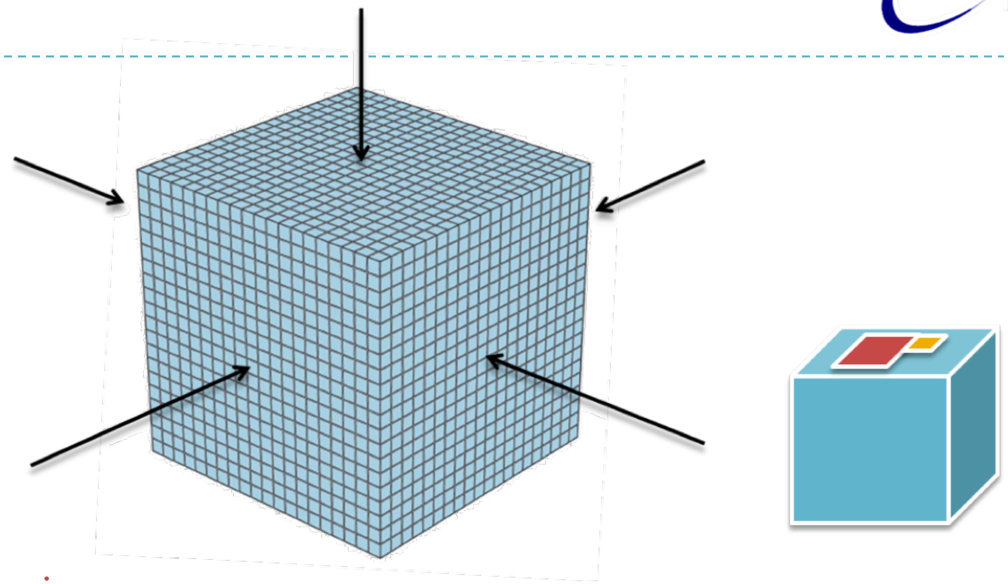
Latest results from CaloCube beam-test
&
Alternative crystals' readout approach

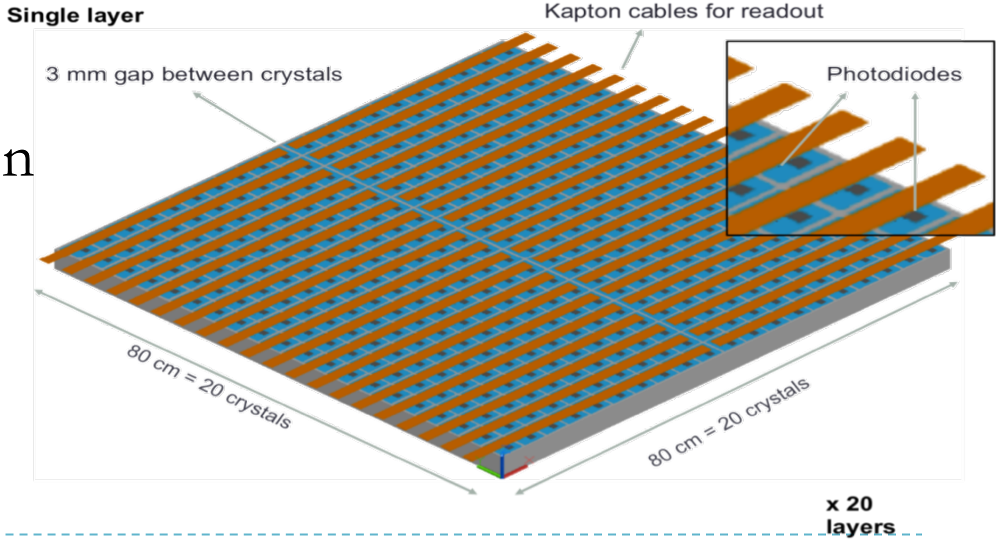
O.Adriani (INFN Florence)
On behalf of the Calocube collaboration

CaloCube

- The concept
  - Large acceptance
    - **Cubic geometry**, 5-facet detection
  - Good energy resolution
    - **Active absorber**
  - Shower imaging
    - **3D segmentation** → isotropic response

- The prototype implementation
  - Scintillating crystals (CsI(Tl))
  - Two-PD readout

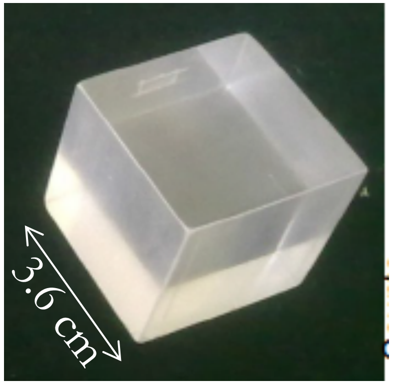




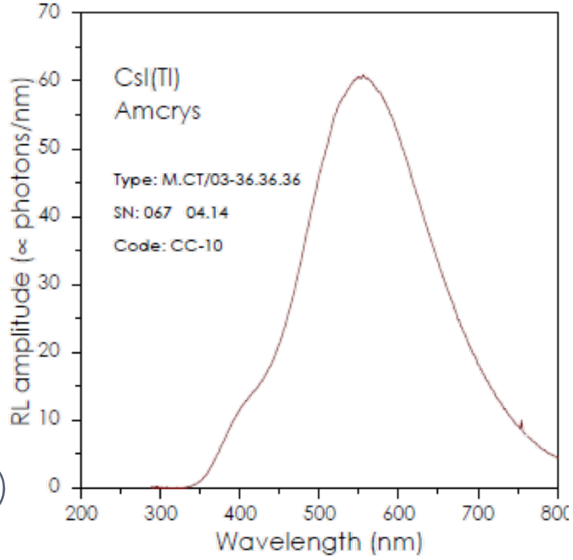
Scintillating material

- **CsI(Tl)** crystals

Density	**4.51 g/cm^3**
Wavelength @max	**550 nm**
Light output	**54 ph/keV** (45 % of NaI(Tl))
Primary decay time	**1 ms**



  - Produced by **Amcrys**
  - **3.6 cm** side (~ 1 Molière radius)

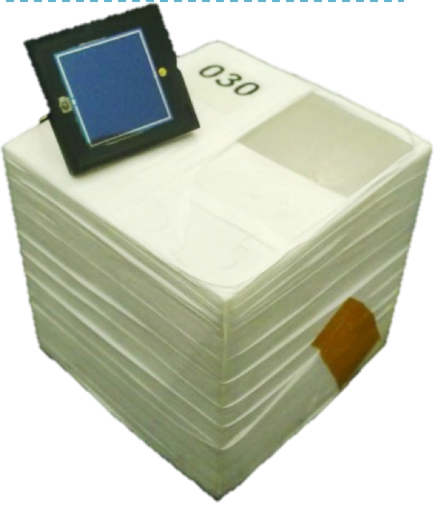


- Expected optical signal
  - 1MIP → ~ 20 MeV ~ 10^6 ph/facet
  - (assuming 80% collection efficiency on one facet from ray-tracing simulation with diffusive surface)

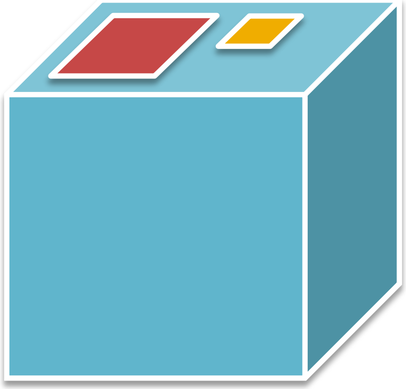
Sensors

- Detector requirements:
  - Sensible to MIPs
  - Shower reconstruction capabilities up to 1PeV
    - From MC, up to 10% of incident energy deposited on a single crystal

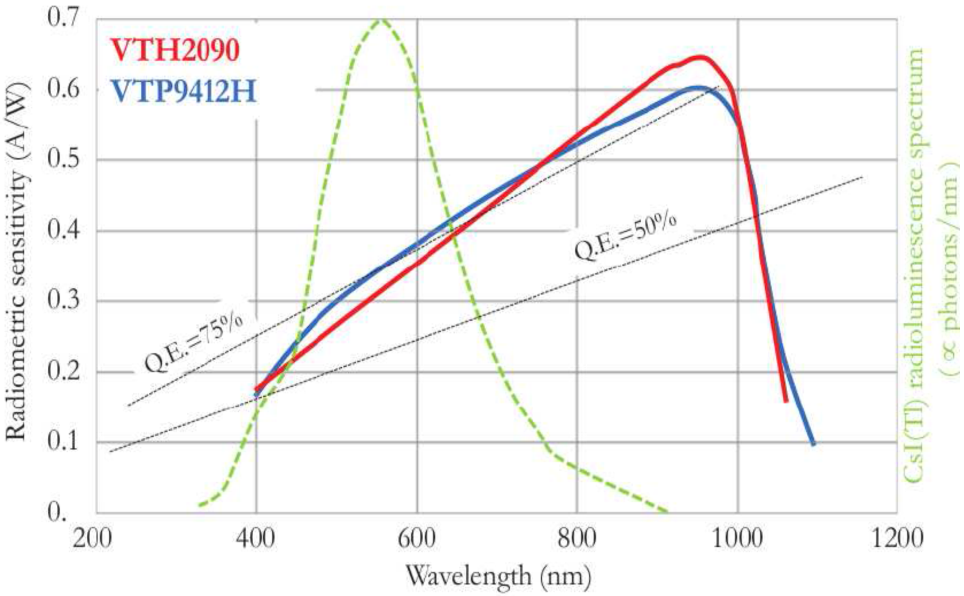
→ Dynamic range ($0.5 \div 5 \cdot 10^6$ MIP) ~ **10^7 MIP**



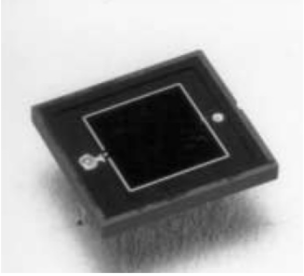
- At least 2 Photo-Diodes necessary for each crystal
  - Large-area PD for small signals
    - VTH2090 (Excelitas)
    - Expected electrical signal
      - ☐ 1MIP ~ $4 \cdot 10^4$ e^- ~ 7 fC
      - ☐ Max signal ~ $2 \cdot 10^{11}$ e^- ~ 30nC
  - Small-area PD for large signals
    - T.b.d. (VTP9412H, VTP3310H,…)
    - With GF ~ 600 times lower → Max.signal ~ 50pC

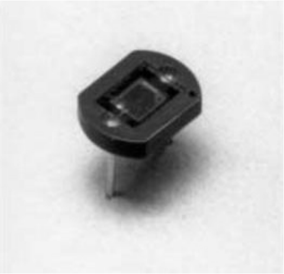


Two-sensor readout



- Relative gain studied with signal induced by atmospheric muons
- Setup:
  - Single cube coupled to both PDs
  - Readout by low-noise CSA and DPA modules (Amptek)
- Measured ratio ~ 55 (expected ~ 49)



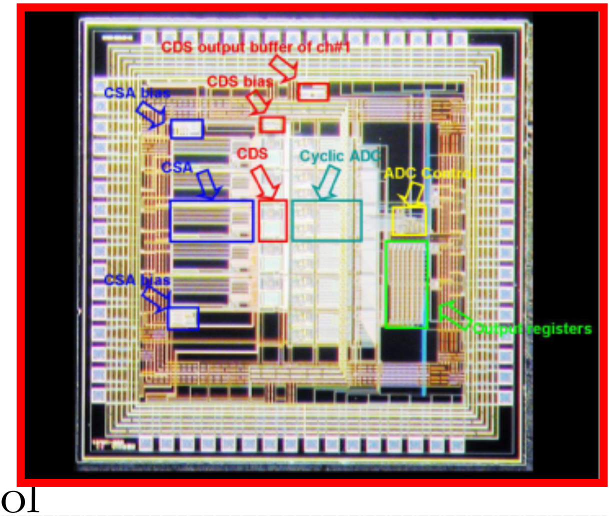


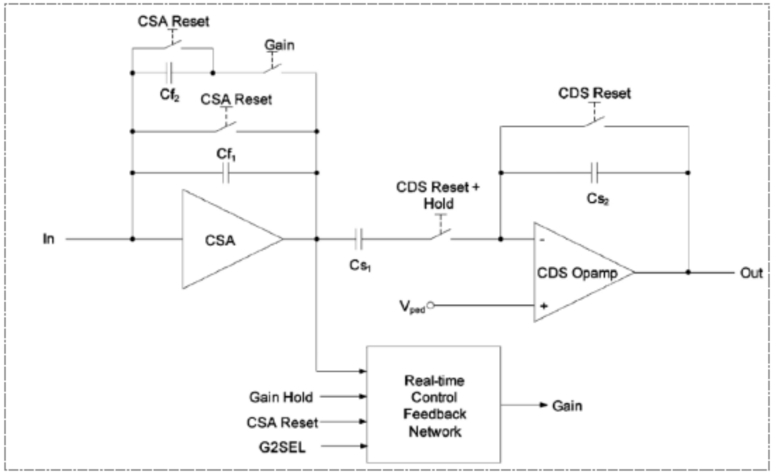
	VTH2090	VTP9412H
Active area (mm^2)	84.6	1.6
Sp.response range/peak (nm)	400÷1100 / 960	400÷1150 / 925
C_J(pF)	70 @30V	6 @15V

Front-end electronics

- CASIS/HIDRA chip
  - R&D project by INFN
  - Designed for Si-calorimetry in space
  - 28 independent analog channels
    - CSA
    - Correlated double sampling system
    - Double gain (1:20) with automatic gain control
  - Characteristics:
    - Dynamic range ~ 52.2 pC
    - ENC ~ 2280e^- + 7.6e^-/pF
    - 2.8 mW/ch

- FE electronics: INFN Trieste



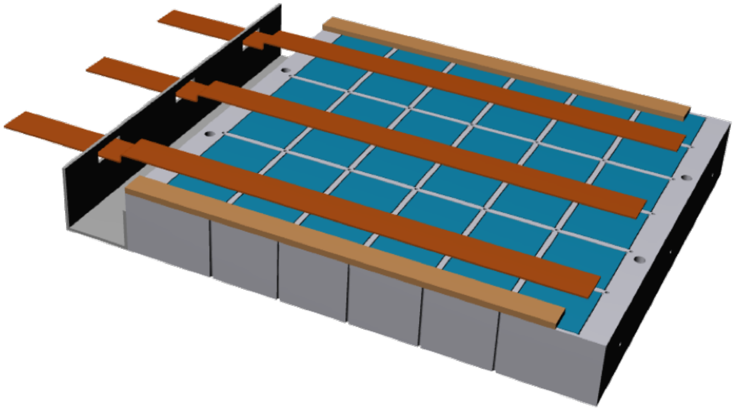


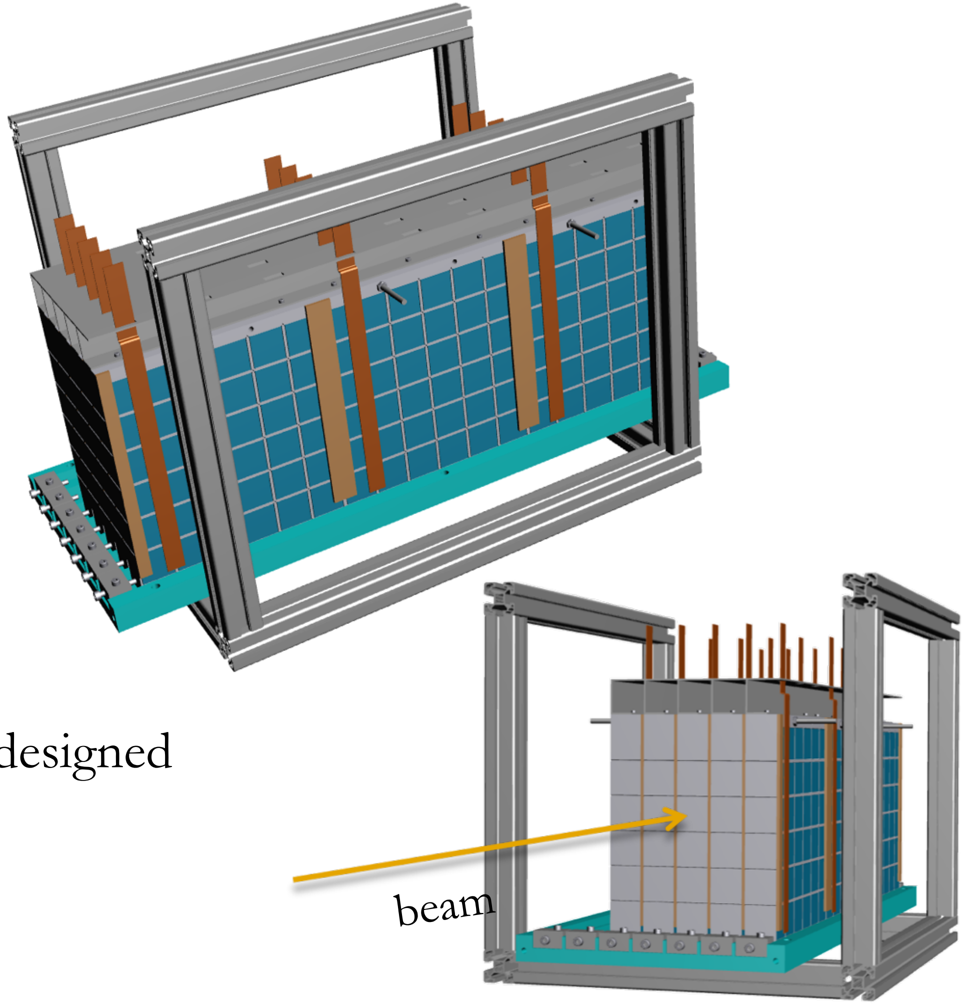
New HIDRA2 chip (just submitted)

- Number of channels: 16
- Automatic double-gain pulse reset Charge Sensitive Amplifier (CSA), calibration circuitry (registers and capacitors), Correlated double sampling, **Self-triggering circuitry**, and output multiplexer
- Power consumption: 3.75 mW/ch
- Dynamic range:
  - High gain: ≈ 2.7 pC (560 MIP on 380 μm Si sensors)
  - Low gain: ≈ 52.6 pC (11000 MIP on 380 μm Si sensors)
- Linearity
  - High gain: ± 0.3 %
  - Low gain: ± 0.6 %
- Equivalent noise charge: 2280 e- + 7.5 e-/pF RMS (CDS time constant of 10 us)
- **Self-trigger gain: ×10**
- **Self-trigger threshold: set by an external resistor, 2 adjustment bits (≈ ×1, ×1.5, ×2, and ×2.5)**
- **Self-trigger comparator hysteresis: 16 mV ± 2.3 mV r.m.s.**
- **Self-trigger response time: ≤ 500 ns for signals 10 mV larger than the effective threshold**

1: Latest results from Calocube test beams

Prototype upgrade (v2)

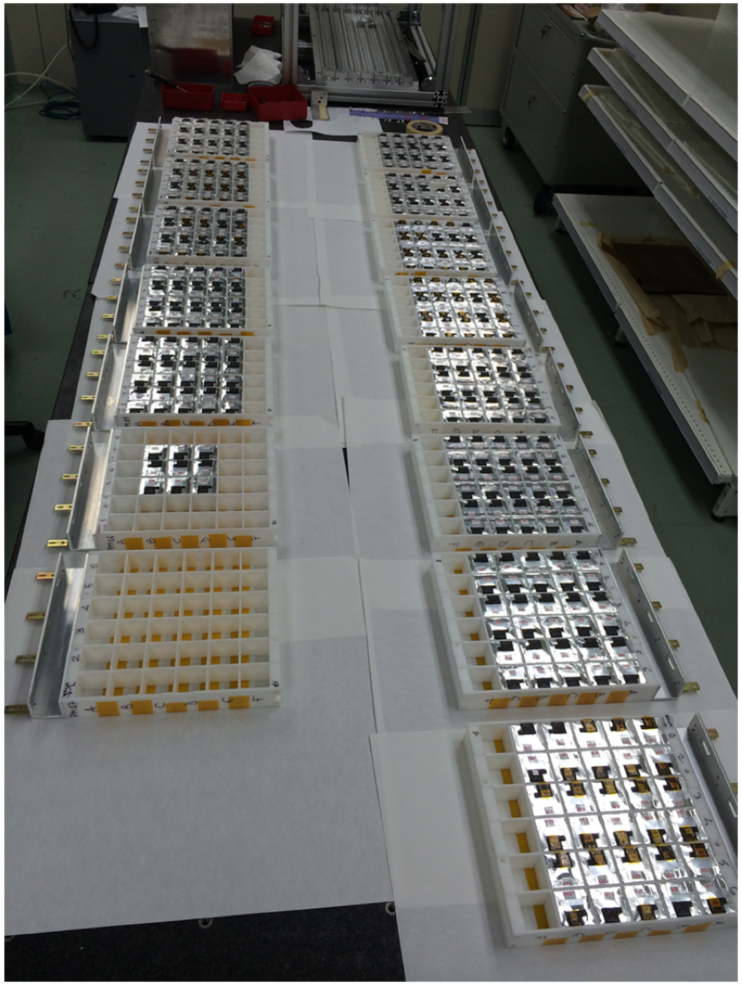


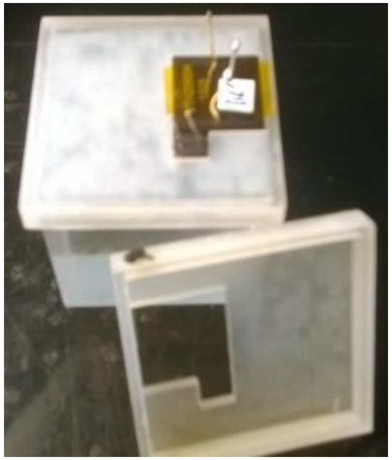


- Prototype mechanics completely redesigned
  - Sensor placed sideways!
  - Up to 18 trays × 36 crystals each
  - active depth **35.0 X_0 → 1.6 λ_I**

- Mechanics: INFN Pisa

Prototype upgrade (v2)





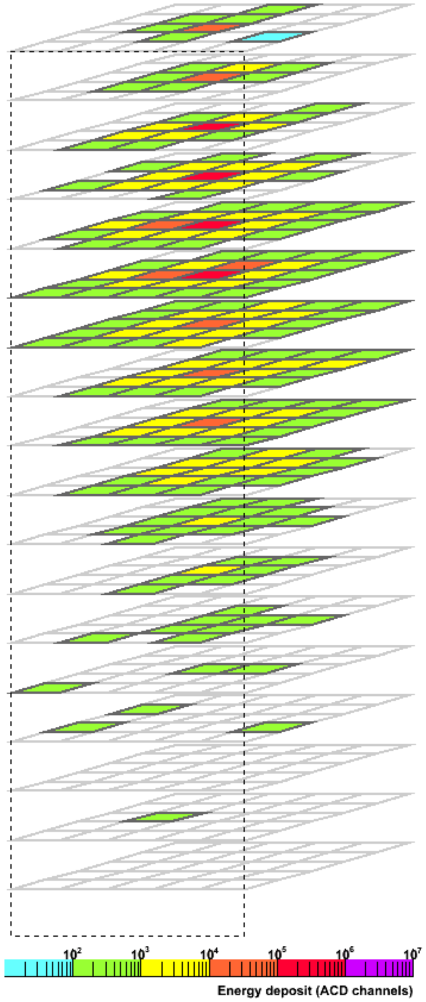
- First version of HIDRA chip (28 channels)
- Two-PD redout
- V2.0 → 5×5×18 instrumented elements

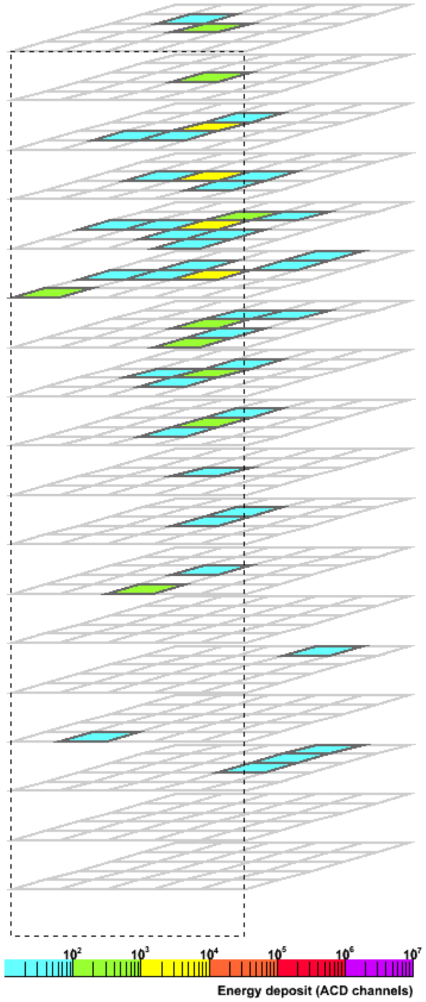
Sep 2016	v2.0	μ,π,e 50÷200 GeV
Oct 2016	v2.0	(3÷40000) e 300MeV
Aug 2017	v2.1	μ,π,e 50÷279 GeV
Nov 2017	v2.1	Ions (Xe+CH2) 300-360 GeV

- Data analysis: INFN Florence+Pisa, CIEMATMadrid

e^- 50 GeV

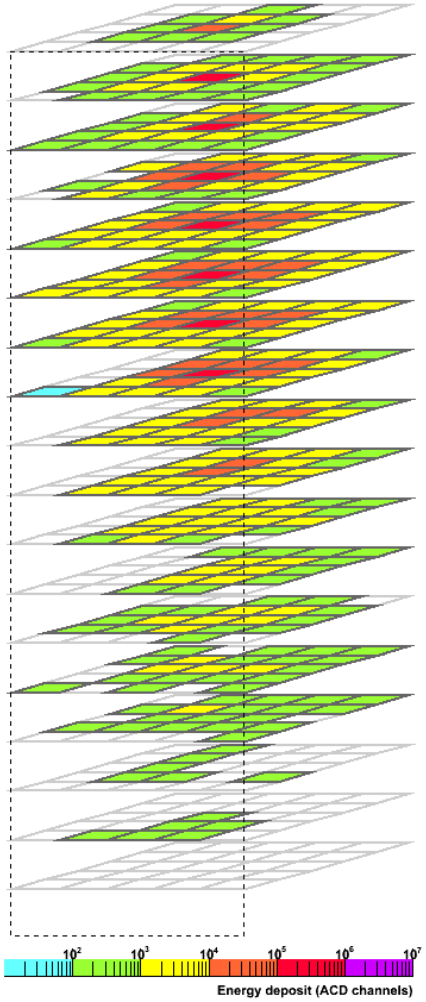
Large PDs



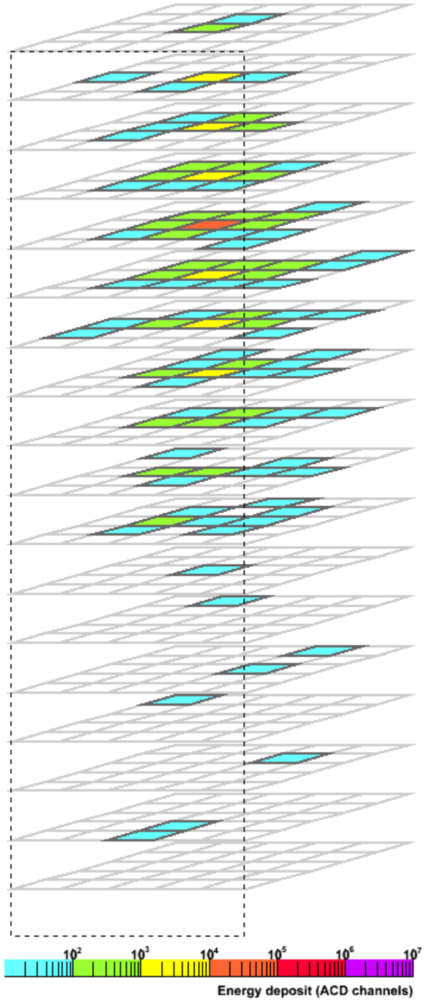


Small PDs

e^- 200 GeV

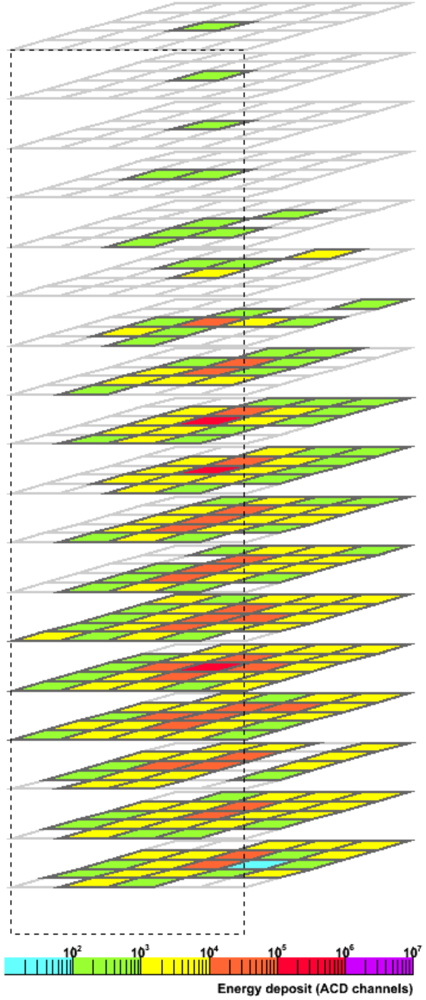


Large PDs

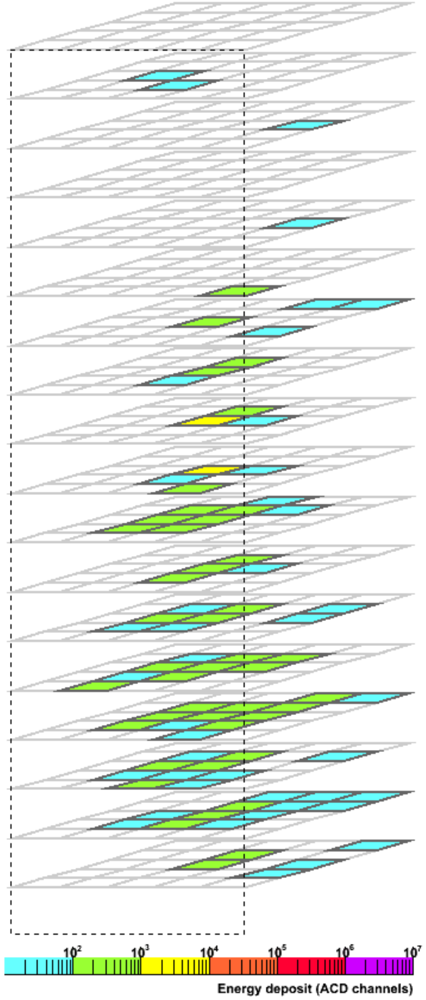


Small PDs

π^- 150 GeV



Large PDs



Small PDs

Single-crystal performances

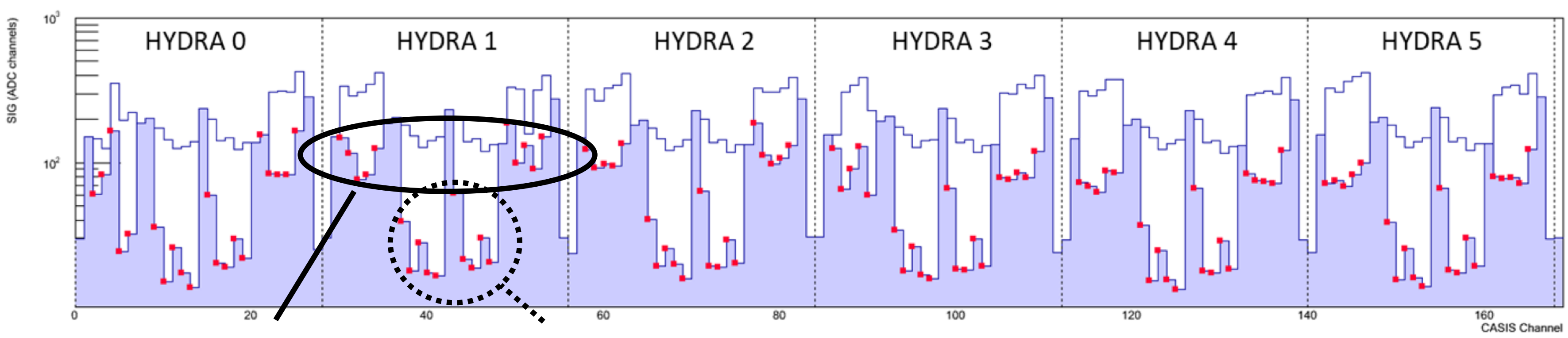
- Prototype v2 affected by larger noise than v1
  - Large common mode component
  - Effective noise reduction by subtracting event-by-event the common level (CN)

Small PD (S)

Lare PD (L)

$RMS(ADC - PED)_i$

$RMS(ADC - PED - CN)_i$



Large PDs

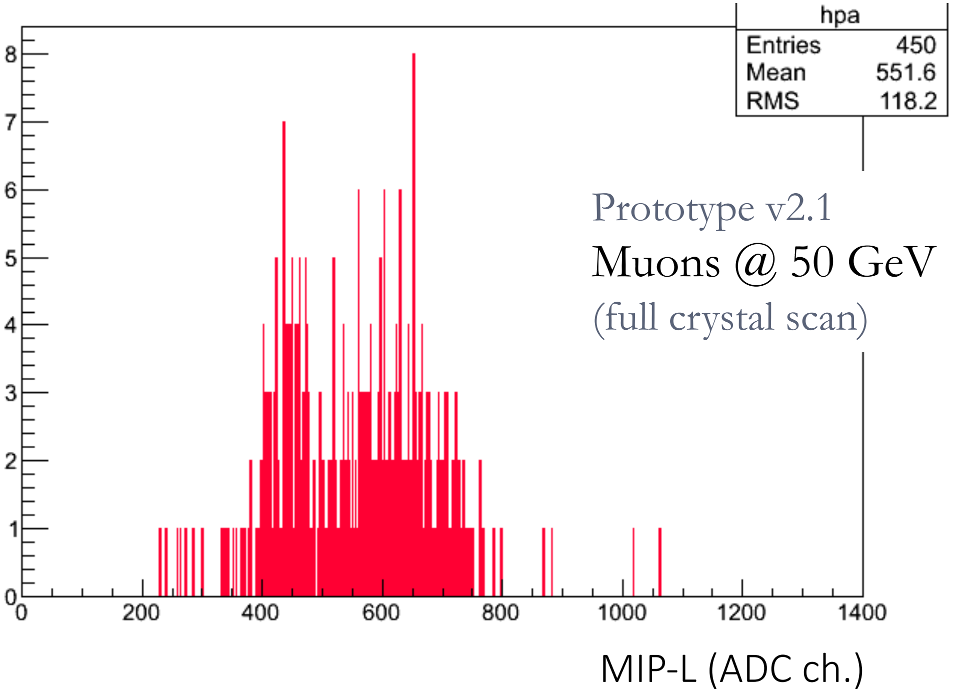
Small PDs

Single-crystal calibration (L-PD)

- Signal induced by MIPs used to equalize crystal L-PD responses
  - V2 setup:
    - ☐ Gain dispersion ~19%
    - ☐ $\langle S/N \rangle_{1MIP} \sim 4 \div 11$

Small PD (S)

Lare PD (L)



Prototype v2.1

Muons @ 50 GeV

(full crystal scan)

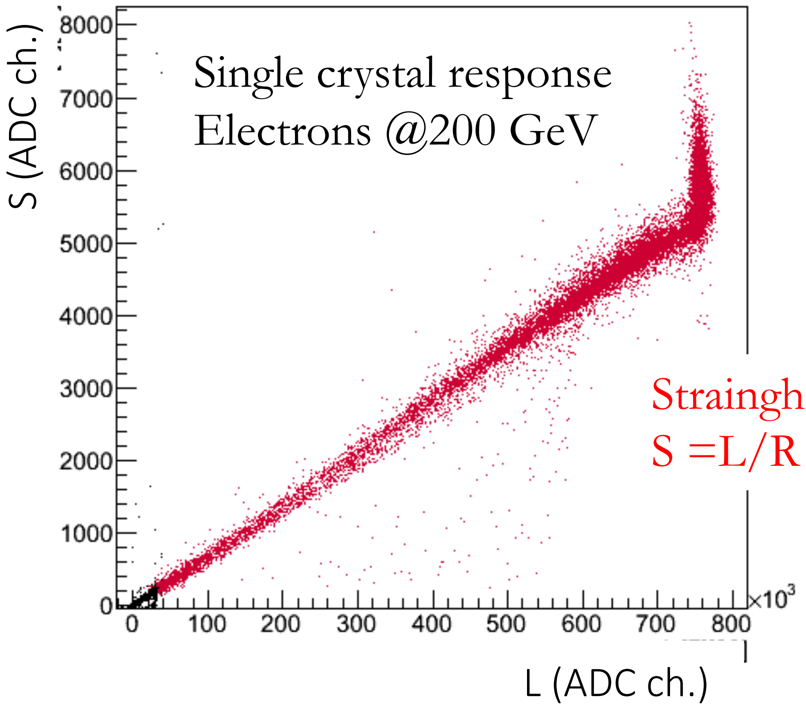
MIP-L (ADC ch.)

Single-crystal calibration (S-PD)

- Signal induced by e.m. showers used to equalize relative sensor responses R=L/S
  - $\langle L/S \rangle \sim 98$

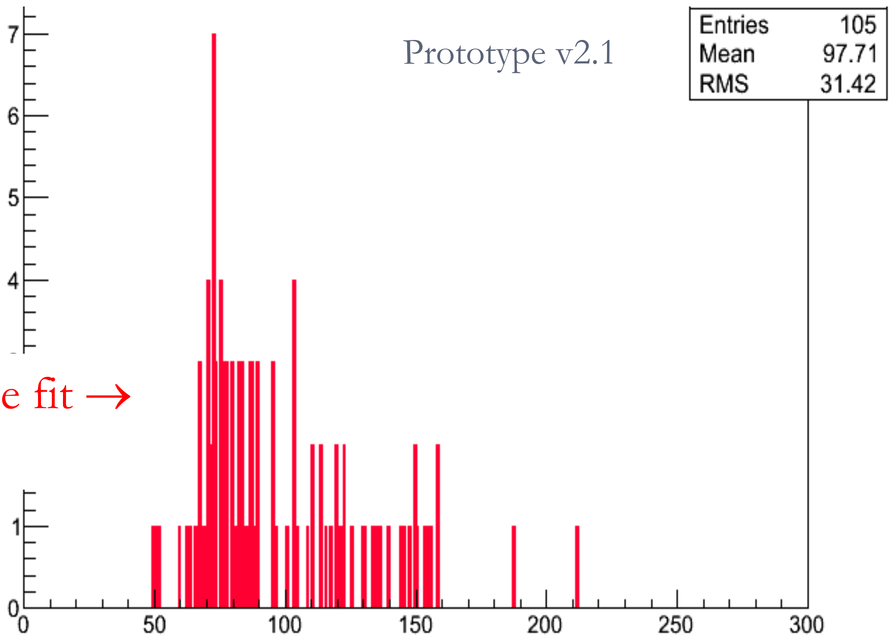
Small PD (S)

Lare PD (L)



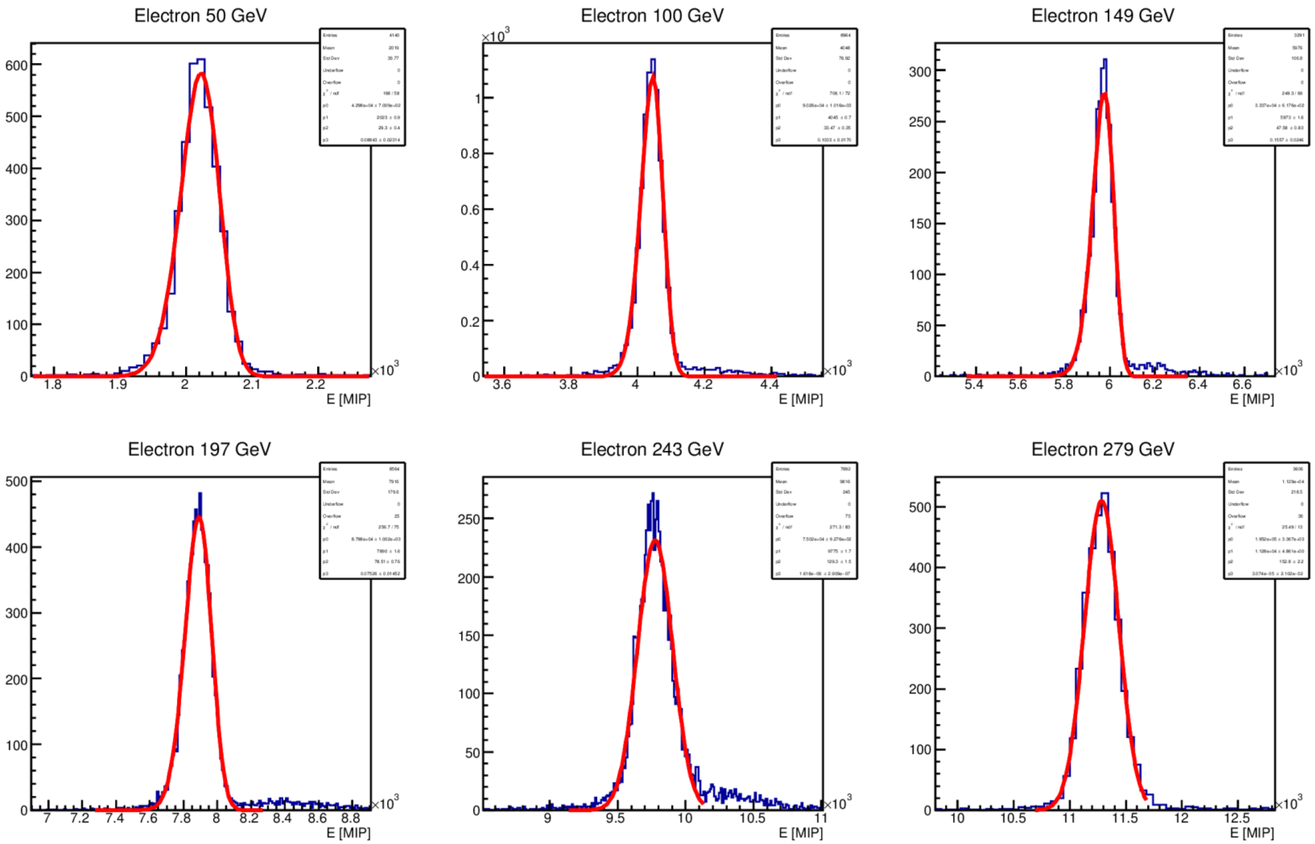
Single crystal response
Electrons @200 GeV

Strainght-line fit →
S =L/R



Prototype v2.1

Energy resolution – e.m. showers



Large+Small PDs

Combined to recover saturation effects

Prototype v2.1
SPS Aug-2017

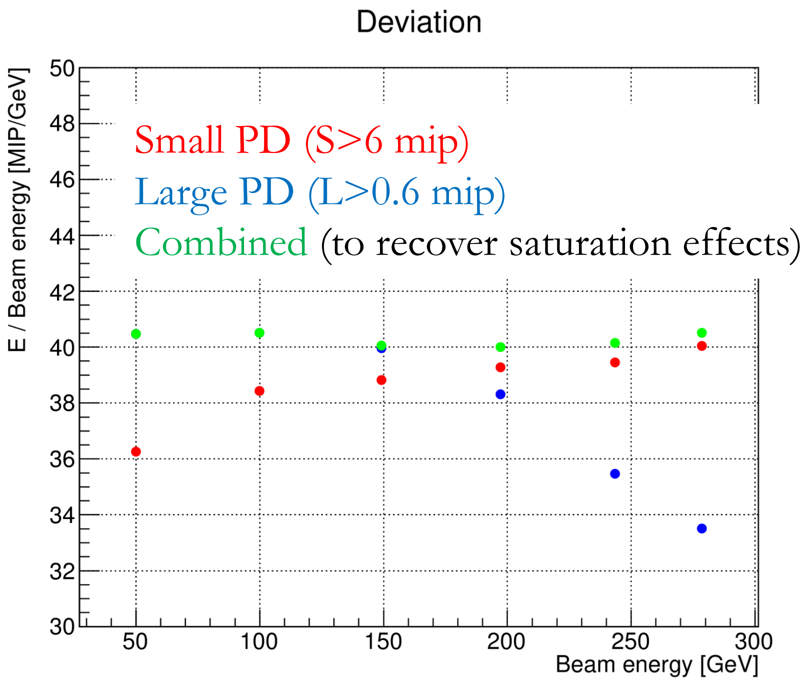
Preliminary results:

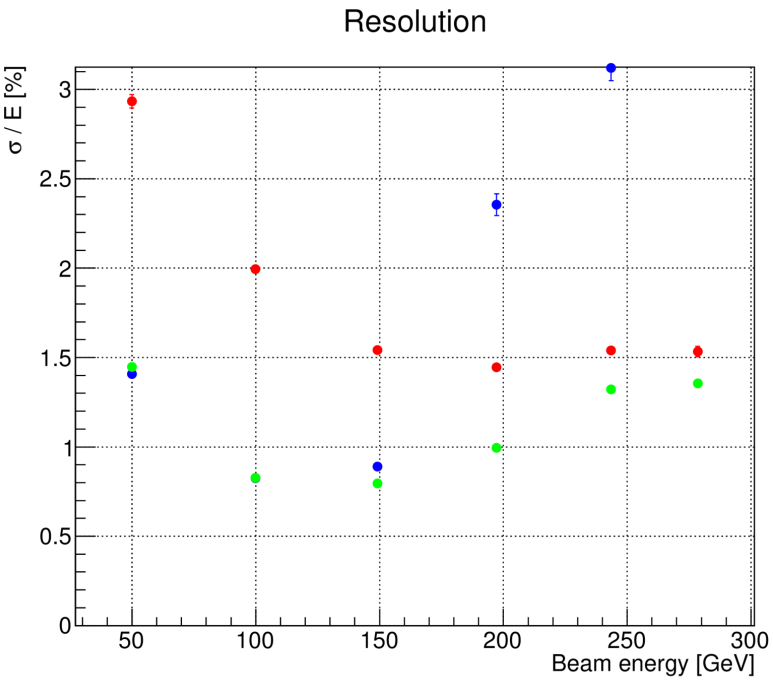
- Full detector calibration
- Particle hitting the detector center

Energy resolution – e.m. showers

Preliminary

SPS 2017 (v2.1)





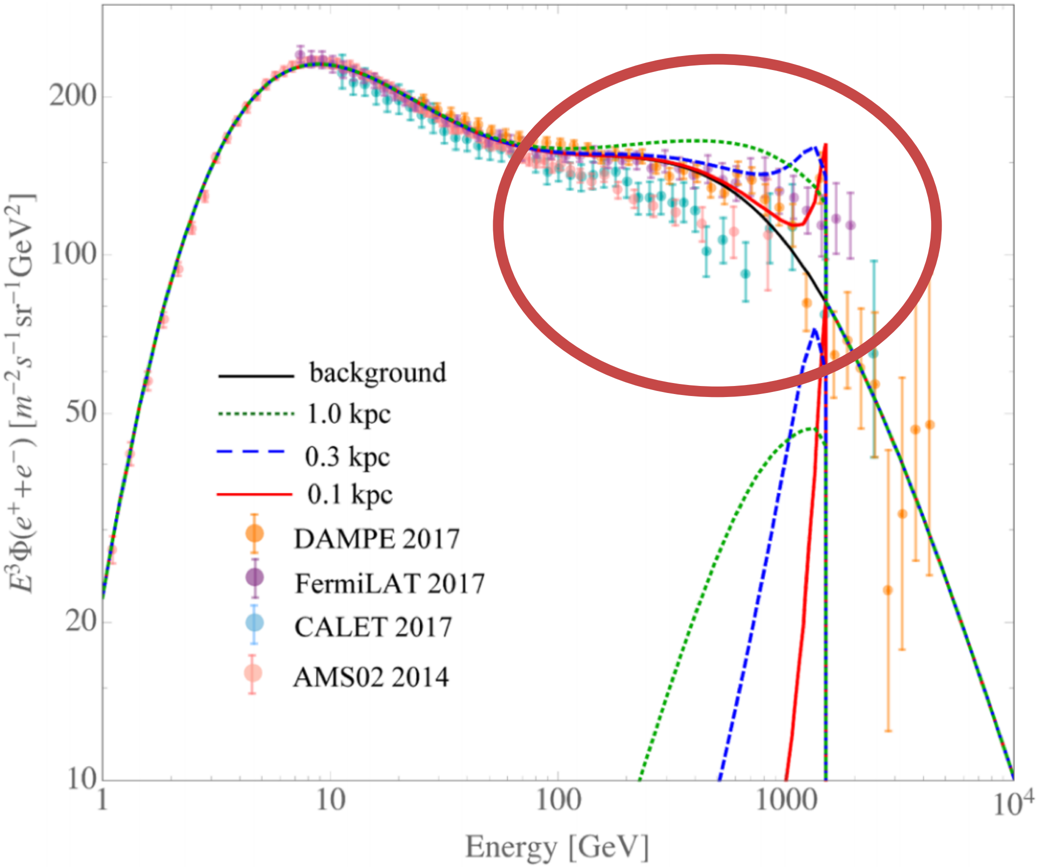
Energy resolution for em showers:

- **0.8%** in the range 100÷150 GeV Better than **1.5%** in the range 50÷300 GeV
- Small-PD performances better Large-PD above 150 GeV
- **Linearity within ~1.25%**

2: Alternative crystals’ readout approach

Main ideas and motivations

- The success of a 'calorimetric only' space experiment relies on the best possible control of the systematics



The electron spectrum measured by different experiments above ~100 GeV is certainly dominated by systematics

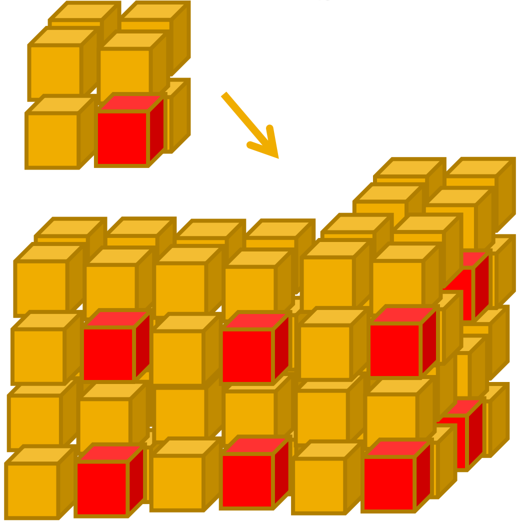
The 'around knee' region for nuclei is really a challenge since the hadronic models are very poorly known

Main source of systematics in HERD

- Absolute energy calibration of the calorimetric part
  - Maximum test beam energies ~ 300 GeV
  - Very large extrapolation
  - Critical mainly for hadron spectra (but ~30% energy resolution)
    - Hadronic high energy models very poorly known
  - Less important for e.m. spectra (but ~1% energy resolution)
- Not stability in time of the calorimetric response
  - Possible deterioration of the response of the fiber readout system
  - Radiation damage
  - Change of the IsCMOS system after few years of operation
- Transition region between the low and high gain operation
- Efficiency estimations based on simulation only

Our proposal

- Readout with Photodiodes ('a la Calocube') a subsample of LYSO crystals
- 1 cube / n cubes, with n to be optimized
  - n too small:
    - Larger power consumption
    - Complexity of the system
  - n too big:
    - Poor energy resolution
    - Not effective in case of huge problems with standard readout
- $n=2x2=2^2=4$
- $n=2x2x2=2^3=8$
- $n=3x3x3=3^3=27$



Advantages of this proposal

- Cross calibration of light measurement with IsCMOS fibers technology for a subset of crystals
  - Many crystals will be readout at the same time with 2 different systems
- Monitor the stability in time of the overall calorimeter
- Alternative (almost, but not completely, independent) particle energy measurement with reduced performance
- Cross calibration of different systems in the energy regions where there is a gain change

The alternative system is used to readout a not homogeneous ('sampling') calorimeter

Redundancy

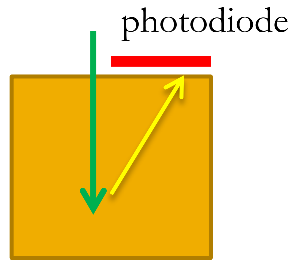
- Redundancy is certainly a great bonus for a space experiment
  - Redundancy in energy measurement
  - Redundancy in the readout system
  - Redundancy in the trigger system (new HIDRA2 chip)
  - Eventually a ‘cold redundancy’ system can be adopted

Simulation studies for the n=2^3 option

Fluka-based MC simulation

- Scintillating crystals de/dx->Scintillation Light collection efficiency and PD quantum efficiency.
- support structure (filling the gaps between crystals)
- 5 mm gaps btw crystals

calocube concept



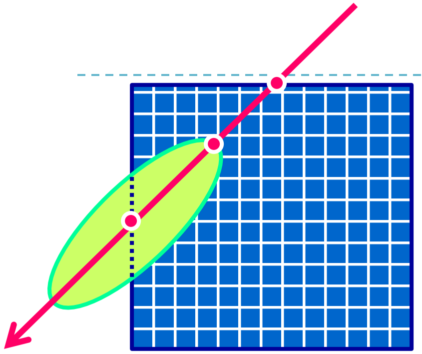
LYSO crystal

Reconstruction tools

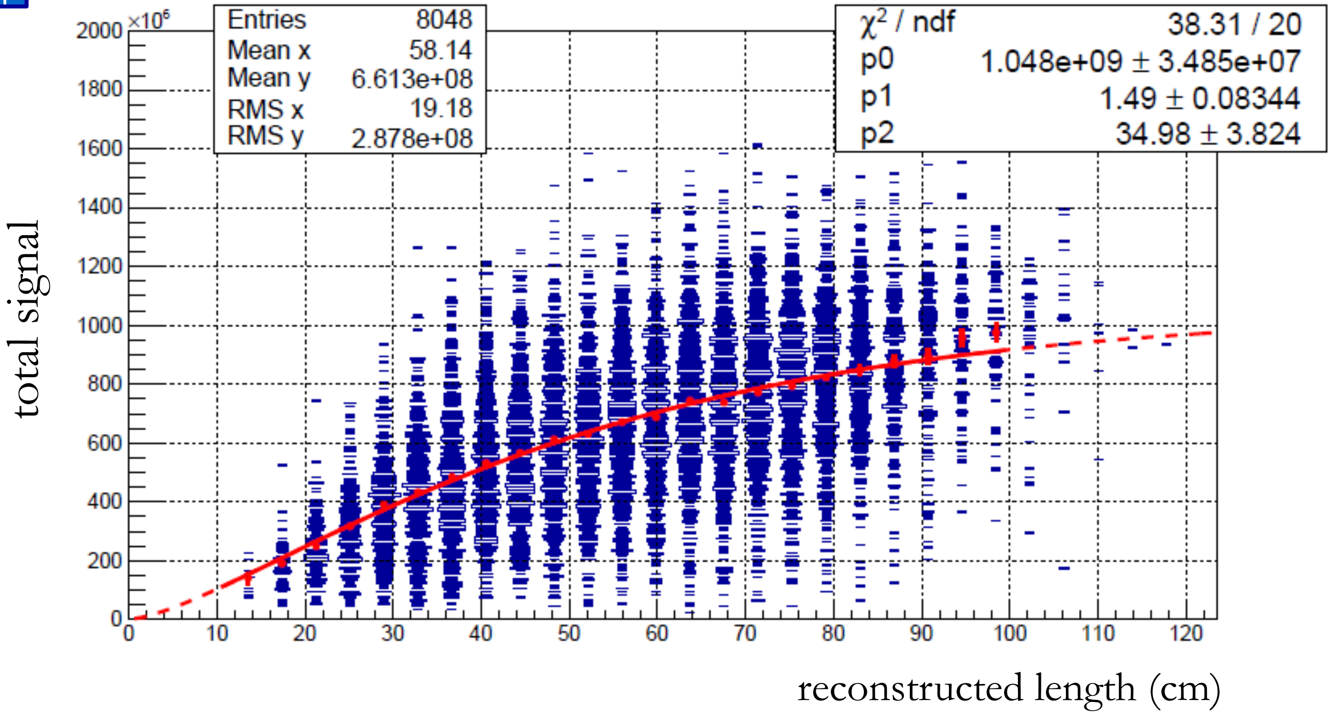
- Shower axis reconstructed by fit
- Lateral and longitudinal profiles respect to axis
- Point of first interaction along axis
- Length from first interaction to end of calorimeter
- noise

No MC truth is needed in the analysys

Protons/Nuclei analysis



Leakage is always important for Hadrons !
The Signal/Energy depends on the **shower length** inside the CALORIMETER (from the first interaction point to the end)

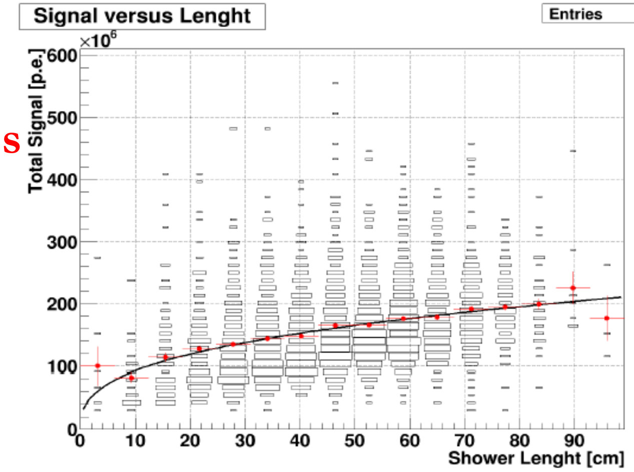


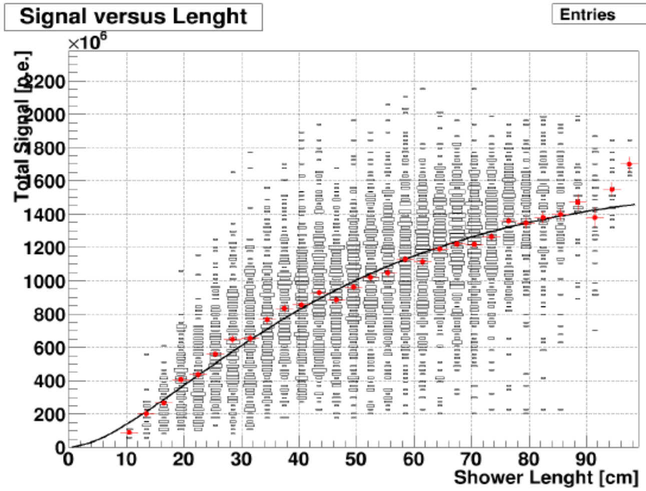
Reconstructed Shower length can be used for energy corrections and cuts
The standard ICCD readout will contribute

1 TeV proton energy reconstruction

Proton 1 TeV - Signal versus lenght

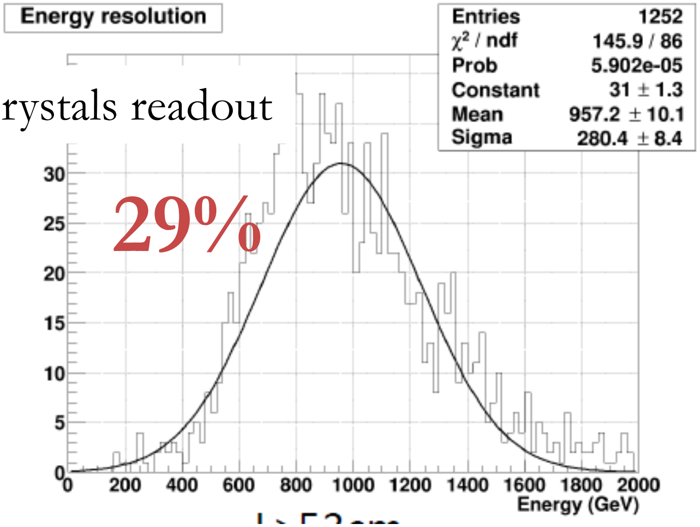
21x21x21 LYSO cubes - **5mm gaps**





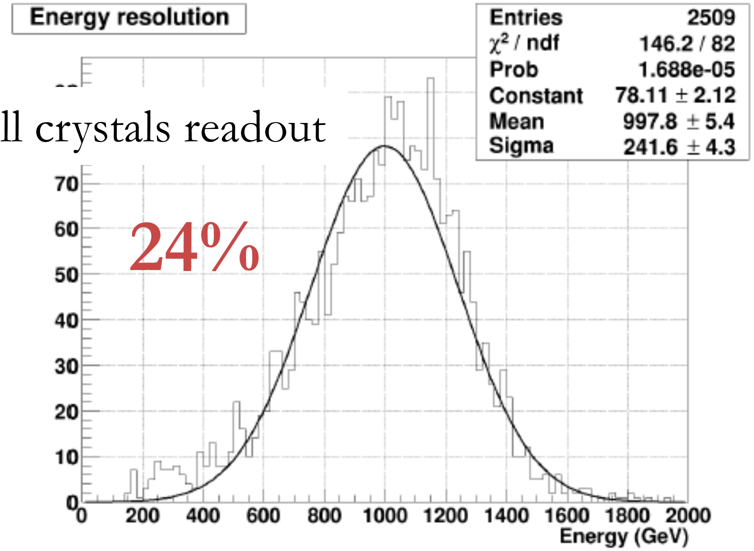
1 crystal in 8

All crystals read



1/8 crystals readout

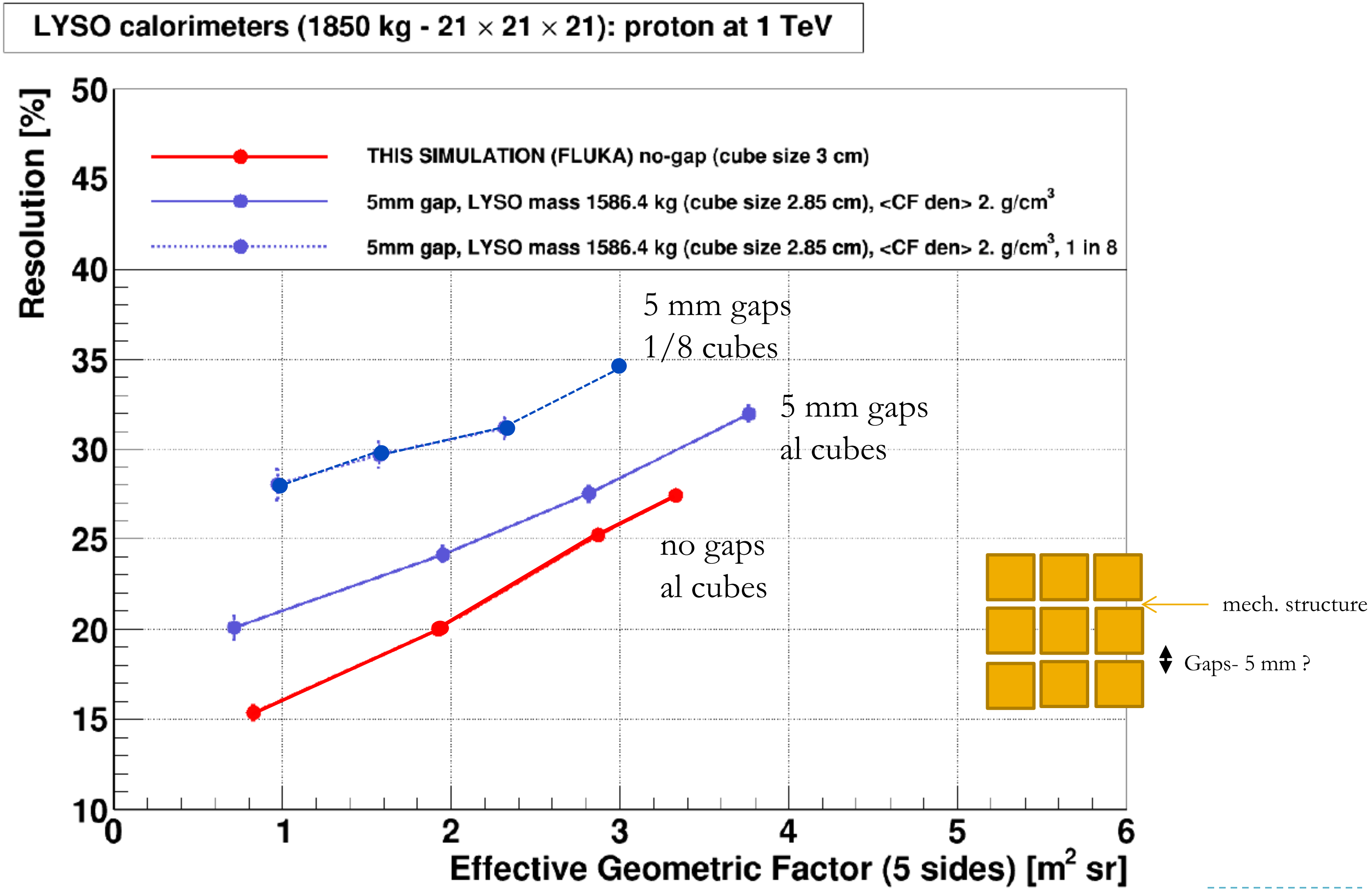
29%



All crystals readout

24%

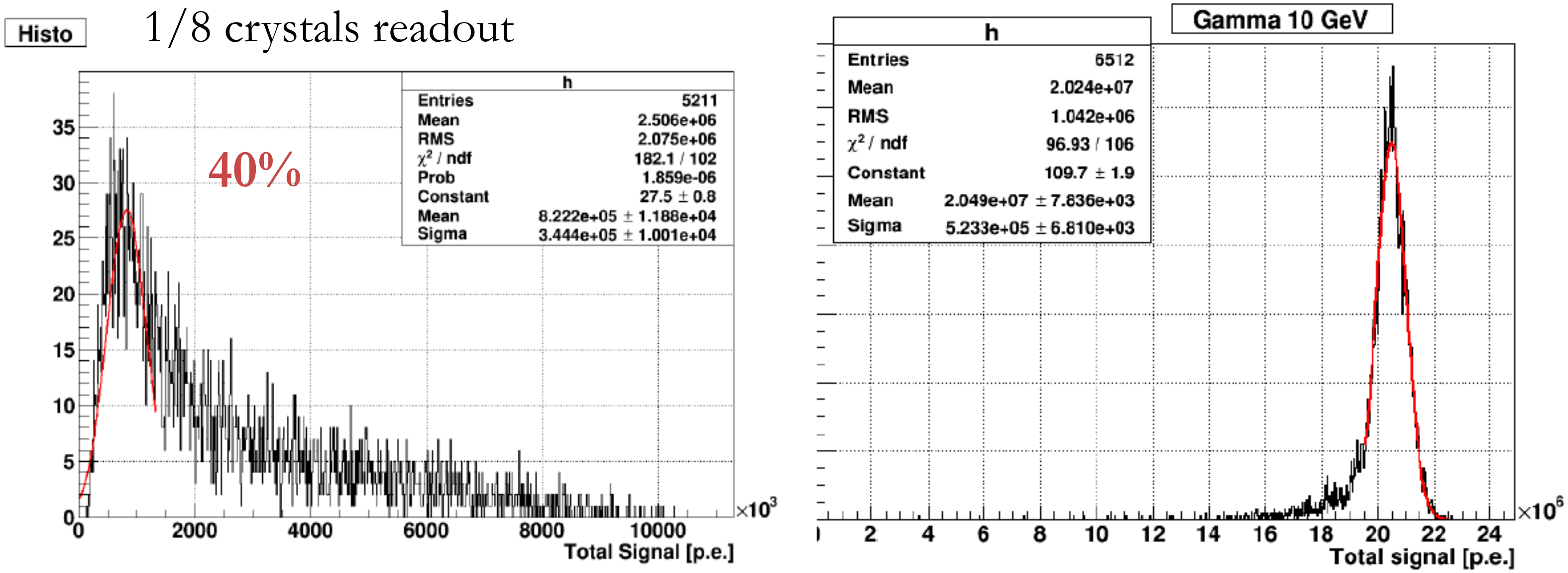
Protons' energy resolution



Please note: the important message is the relative change of resolution from n=1 to n=8

Photons' energy resolution

Gamma 10 GeV – Total signal distribution



1/8 crystals readout

40%

1 crystal in 8

All crystals read

e.m. showers are much more compact and can not be well sampled with 1/8 ratio

Some technical details

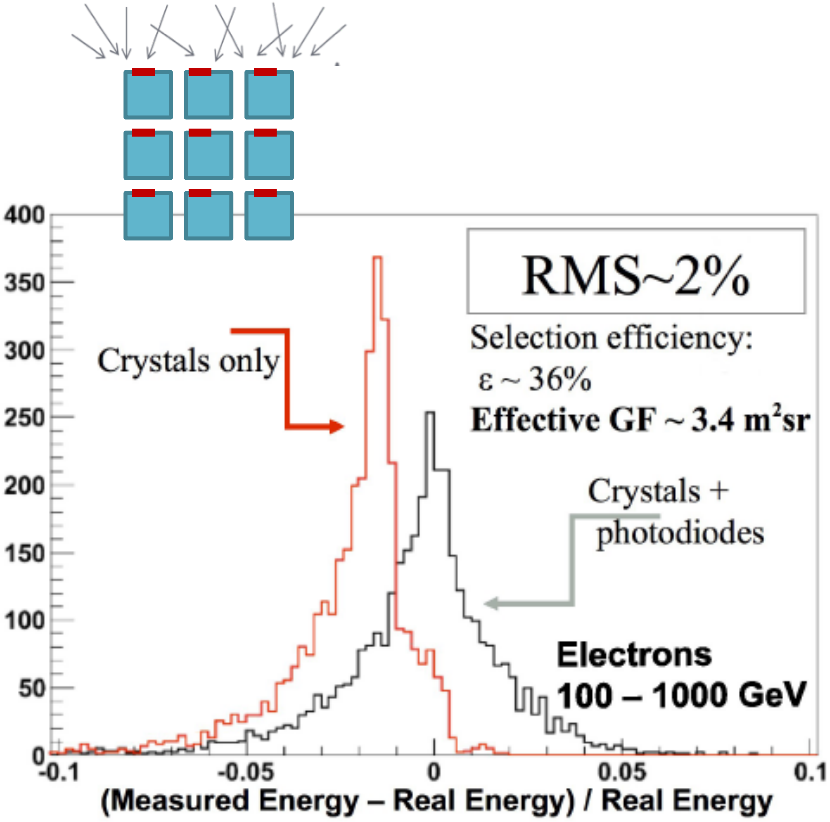
- Power consumption
  - Assume n=8
  - Total crystals ~7500, number of PD readout crystals ~ 900
  - Number of channels: 1800 (2 PD/crystal)
  - Additional power consumption ~ 3mW*1800= 5 W for Front End only
- Mechanical and assembly complexity
  - A simplified flat kapton cable should be realized to bring outside the PD signals
  - Interference with the fibers should be studied but it could be feasible
  - We can provide to Chinese colleagues all the necessary parts (PD, Kapton cables, glue, assembly procedures, electronic board, etc.)
- A full redundant 'cold system' can eventually be studied
  - Instrument all the cubes with PD
  - Assemble the full electronics to readout all the system
  - Switch on only a subset of the electronics, leaving the possibility to switch on the full system in case of major problems or for cross calibration periods

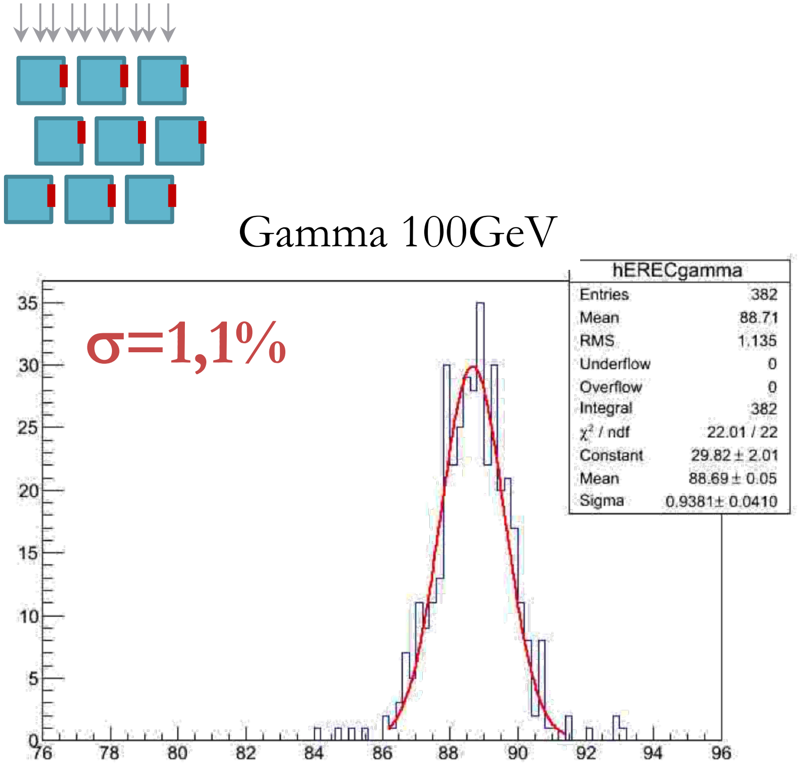
Conclusion

- As a proof-test of the CaloCube concept, a **prototype** made of CsI(Tl) and readout by PDs has been constructed and tested, in several versions, with particle beams.
  - Better than 40% energy resolution for **ions** up to 30 GeV/n (with 3×3×15 detector matrix)
  - Better than 1.5% energy resolution for **electrons** up to 300 GeV
  - Two-sensor readout successfully tested
- We are proposing to readout 1/n crystals with PhotoDiodes
  - Better control of the systematics
  - Cross check of the energy calibrations
  - Monitor the light reduction of the IsCMOS as function of time
  - Redundancy
  - Almost independent energy measurement
  - n and the readout pattern should be optimized as a s compromise btw effectivness, simplicity, performances and power consumption

Spares

Expected CaloCube performances for e.m.-showers

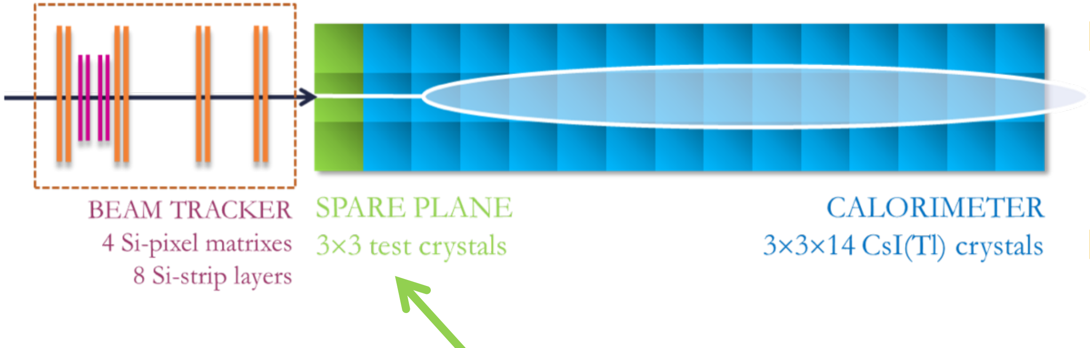




- CaloCube baseline design (CsI 20×20×20)
- Isotropic flux of electrons 100GeV÷1TeV (CR-like)

- CaloCube design optimized for gamma detection

Comparative study of scintillating crystals

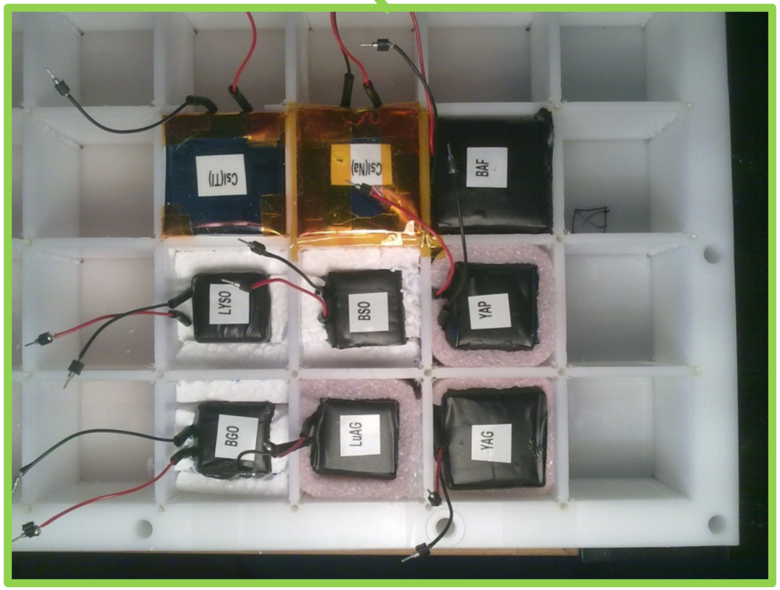


BEAM TRACKER
4 Si-pixel matrixes
8 Si-strip layers

SPARE PLANE
3×3 test crystals

CALORIMETER
3×3×14 CsI(Tl) crystals

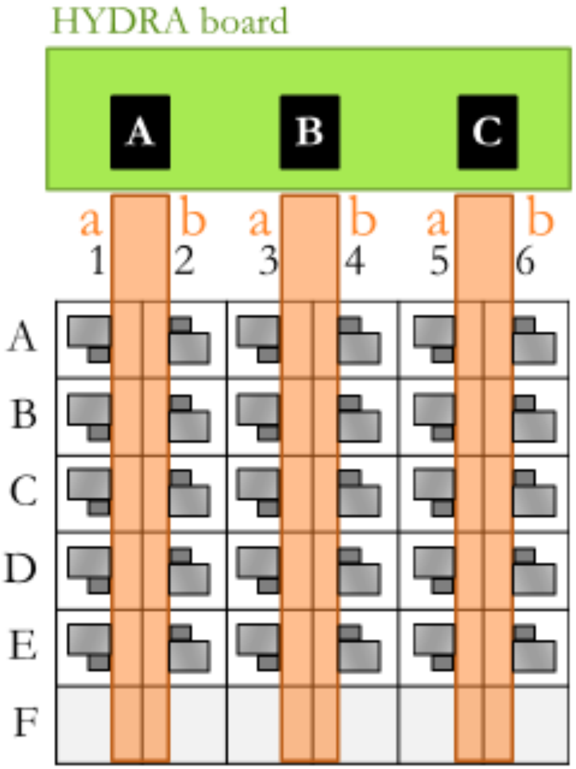
- Samples exposed to ion beams (Z=1÷18) of 19 GeV/n (Feb-2015 @CERN-SPS)
- Characterization of the response to signals induced by ionizing nuclei

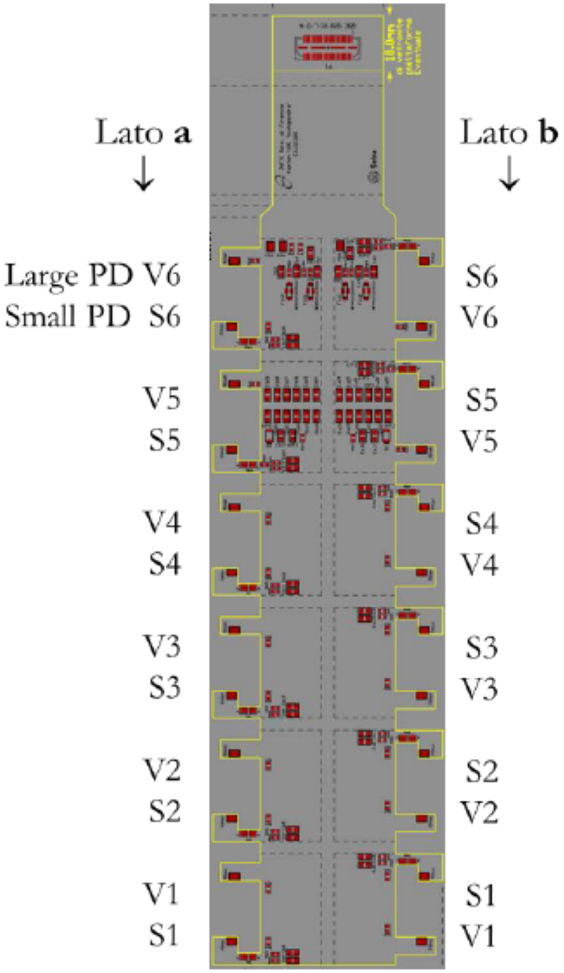


- Wrapping: Teflon+Vkuiti+Tedlar
- Sensor: VTH2090 PD placed laterally

		Z=2 measured	
	Size (cm)	ADC counts	err
CsI Tl	3,6	2427	3,4
LYSO	2	724	2,4
BGO	2	309	1,3
CsI Na	3,6	1376	2,5
LuAG	2,1	710	1,1
BaF2	3,1	77	0,38
YAP	2,2	295	1,5
YAG	2,5	615	1,5

Readout scheme

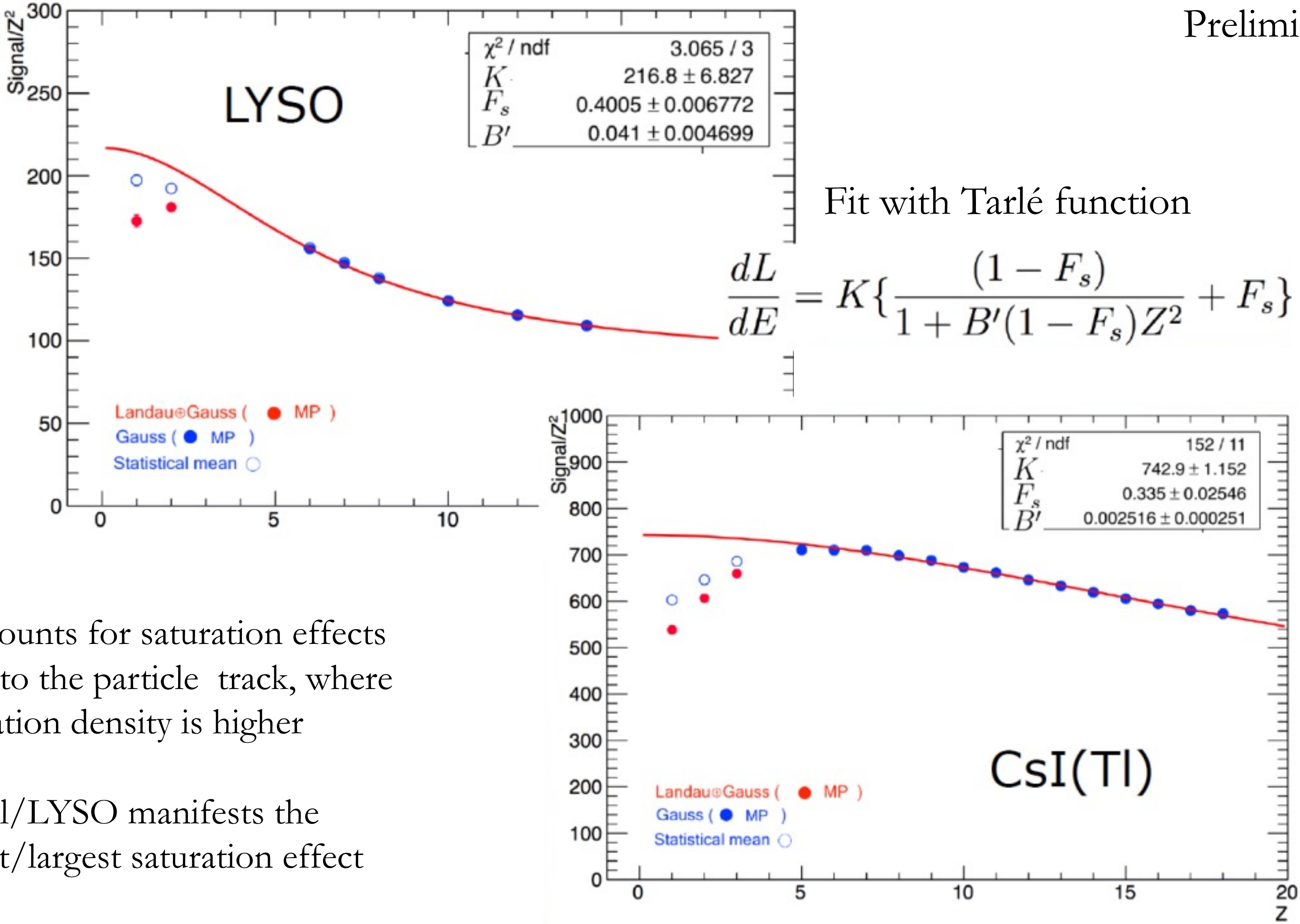




HYDRA Channel	**PD**
1	-
2	CNa
3	V6a
4	V5a
5	V4a
6	V3a
7	V2a
8	V1a
9	S1a
10	S2a
11	S3a
12	S4a
13	S5a
14	S6a
15	S1b
16	S2b
17	S3b
18	S4b
19	S5b
20	S6b
21	CNb
22	V6b
23	V5b
24	V4b
25	V3b
26	V2b
27	V1b
28	-

Scintillation-signal linearity

Preliminary



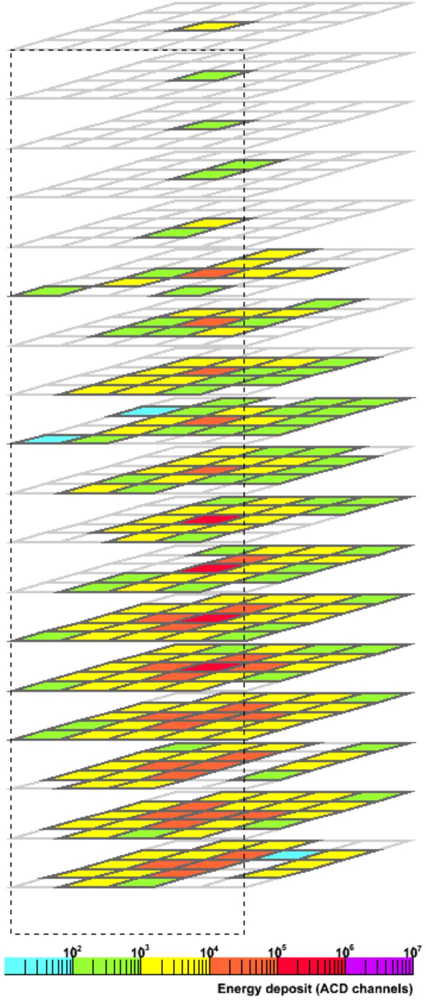
Fit with Tarlé function

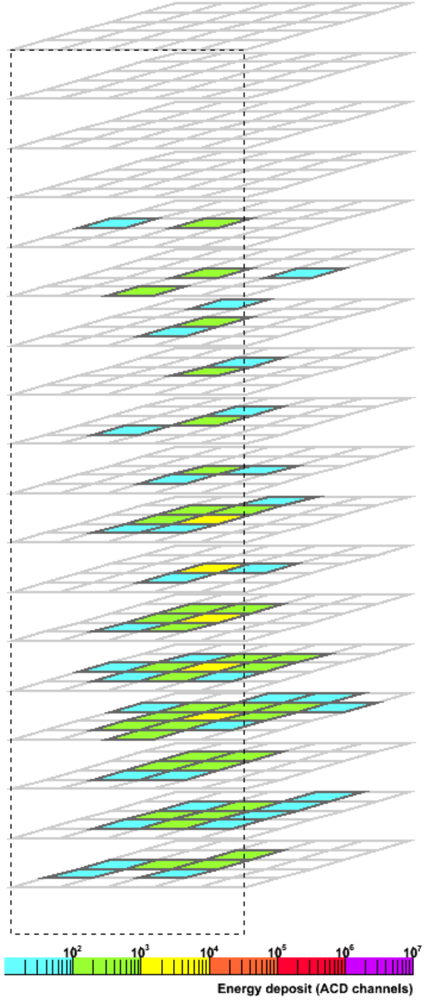
$$\frac{dL}{dE} = K\{\frac{(1-F_s)}{1+B'(1-F_s)Z^2} + F_s\}$$

It accounts for saturation effects close to the particle track, where ionization density is higher

CsI:Tl/LYSO manifests the lowest/largest saturation effect

π^- 150 GeV


10^2
10^3
10^4
10^5
10^6
10^7
Energy deposit (ACD channels)


10^2
10^3
10^4
10^5
10^6
10^7
Energy deposit (ACD channels)

Common-noise model

HYDRA Channel	PD
1	-
2	CNa
3	V6a
4	V5a
5	V4a
6	V3a
7	V2a
8	V1a
9	S1a
10	S2a
11	S3a
12	S4a
13	S5a
14	S6a
15	S1b
16	S2b
17	S3b
18	S4b
19	S5b
20	S6b
21	CNb
22	V6b
23	V5b
24	V4b
25	V3b
26	V2b
27	V1b
28	-

$CN_a = (ADC - PED)_a$

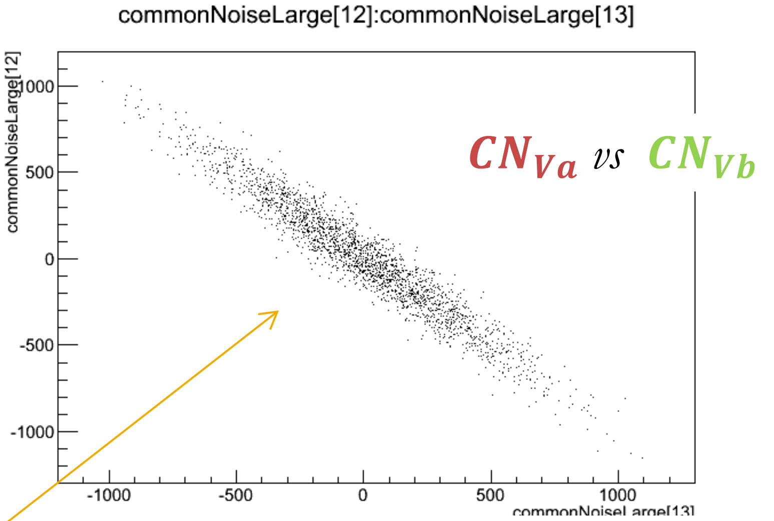
$\boldsymbol{CN_{Va} = \langle ADC - PED \rangle_{Va}}$

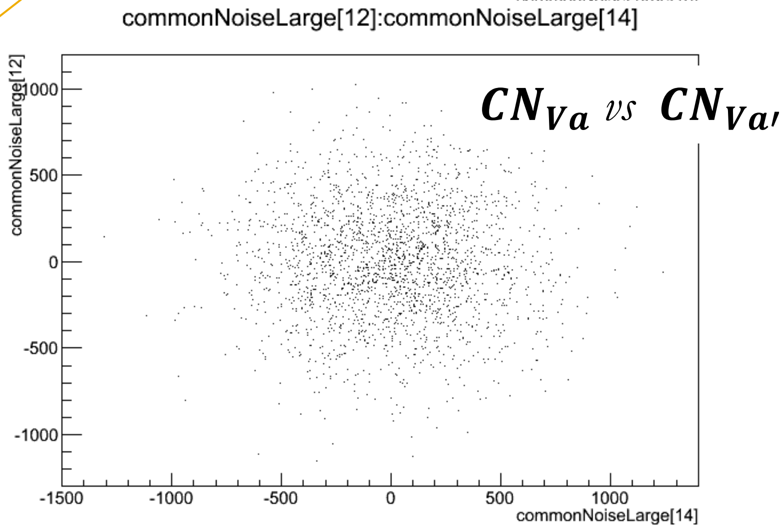
$CN_{Sa} = \langle ADC - PED \rangle_{Sa}$

$CN_{Sb} = \langle ADC - PED \rangle_{Sb}$

$CN_b = (ADC - PED)_b$

$\boldsymbol{CN_{Vb} = \langle ADC - PED \rangle_{Vb}}$





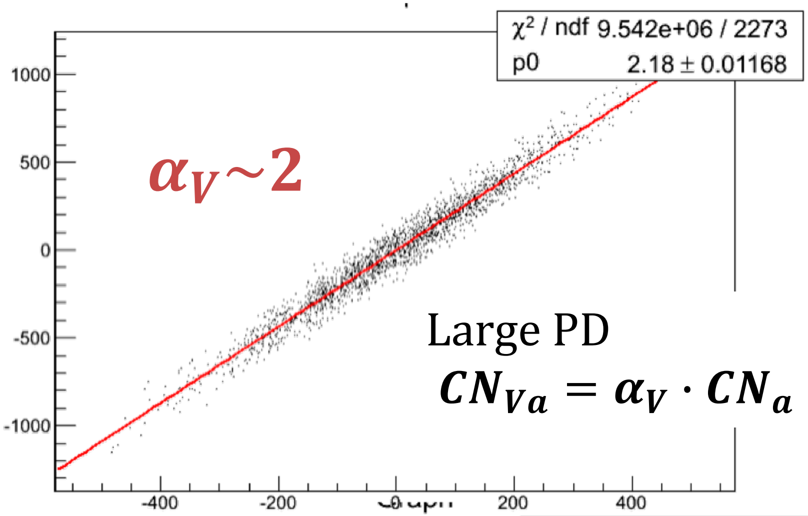
Common-noise model

HYDRA Channel	PD
1	-
2	CNa
3	V6a
4	V5a
5	V4a
6	V3a
7	V2a
8	V1a
9	S1a
10	S2a
11	S3a
12	S4a
13	S5a
14	S6a
15	S1b
16	S2b
17	S3b
18	S4b
19	S5b
20	S6b
21	CNb
22	V6b
23	V5b
24	V4b
25	V3b
26	V2b
27	V1b
28	-

$CN_a = (ADC - PED)_a$

$\boldsymbol{CN_{Va} = \langle ADC - PED \rangle_{Va}}$

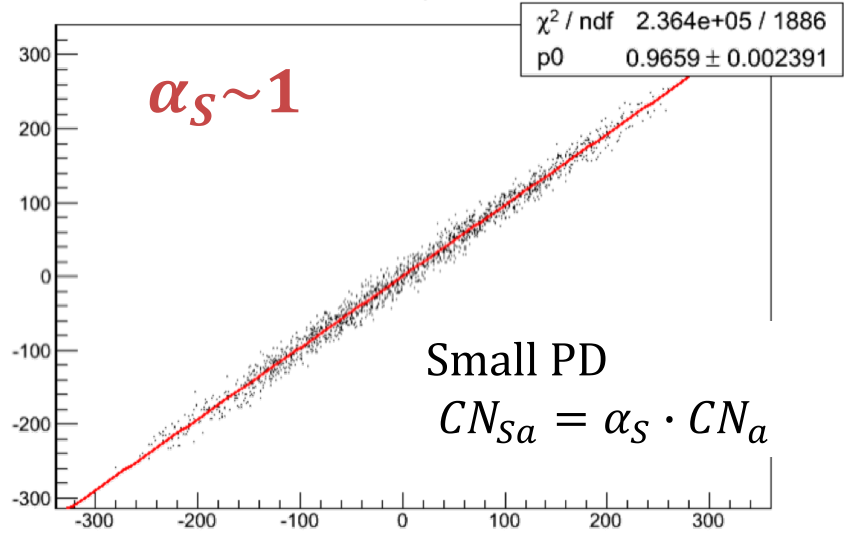
$CN_{Sa} = \langle ADC - PED \rangle_{Sa}$



$\boldsymbol{\alpha_V \sim 2}$

Large PD

$\boldsymbol{CN_{Va} = \alpha_V \cdot CN_a}$



$\boldsymbol{\alpha_S \sim 1}$

Small PD

$CN_{Sa} = \alpha_S \cdot CN_a$