Institute of High Energy Physics
Chinese Academy of Sciences

HGCAL module beam tests

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Outline

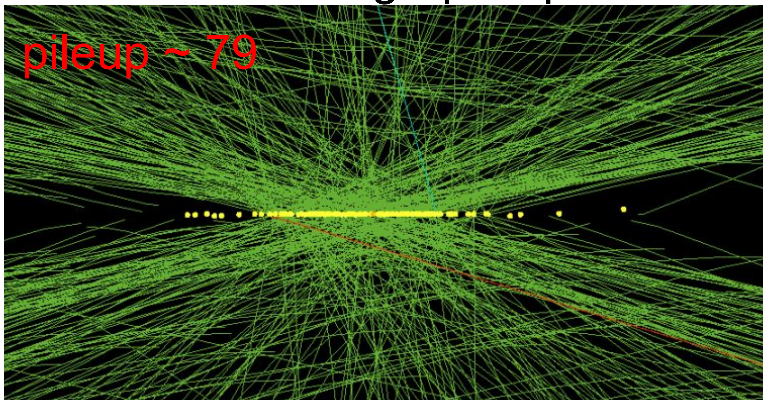
- Introduction
- Characterization of silicon sensors, PCB, ASICs, & module prototypes in lab @CERN
- Module test beam results

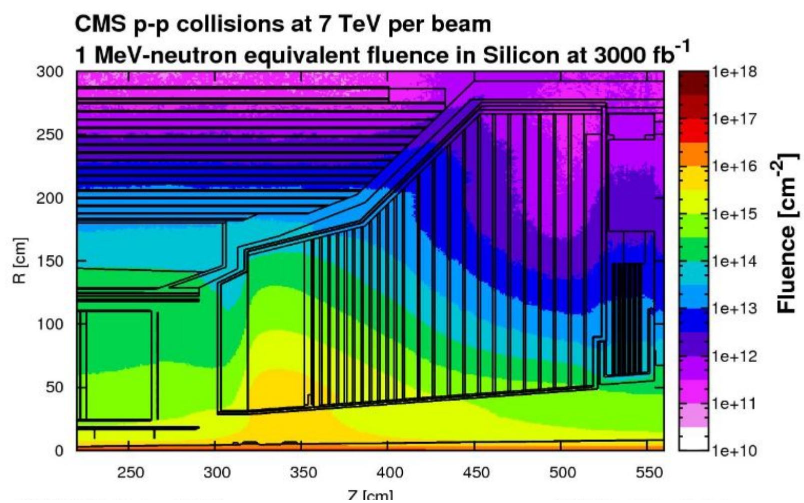
Opportunity and challenges of the CMS @HL-LHC

- 3× increase of luminosity wrt Run 2-3
  - 3000 fb^{-1} in ~ 10 years of operation → the legacy of the LHC

- 140-200 simultaneous interactions per bunch crossing (pileup or PU)
  - <PU> ~ 50 in CMS Phase 1

A reconstructed CMS Run 2 event in a high-pileup run





- Need for detectors with high radiation tolerance
  - Forward region most severely affected!!

➢ New CMS endcap calorimeter based on silicon sensors

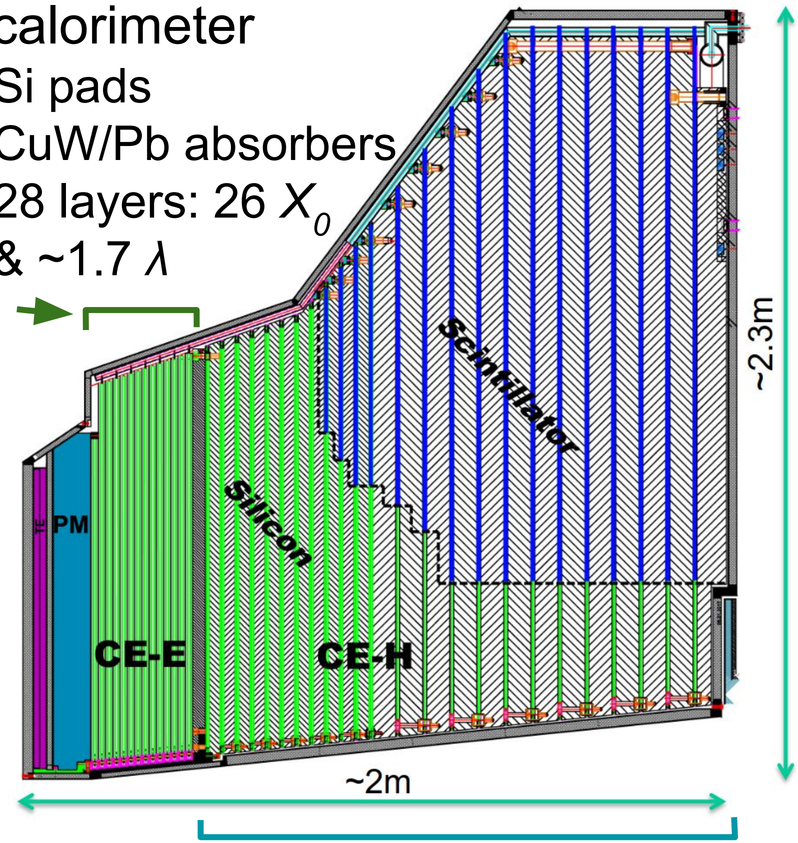
The CMS high-granularity calorimeter (HGCAL)

focus of this presentation

- 6M Si pads of 0.6-1.2 cm^2
  - total area of ~1.5 fields
- 420k scint. tiles of 4-30 cm^2
  - total area ~0.9 fields
- 5D reconstruction: *x*, *y*, *z*, *time*, *energy*
  - Used in trigger to mitigate PU
  - Fully exploited to maximize particle reco and ID eff.

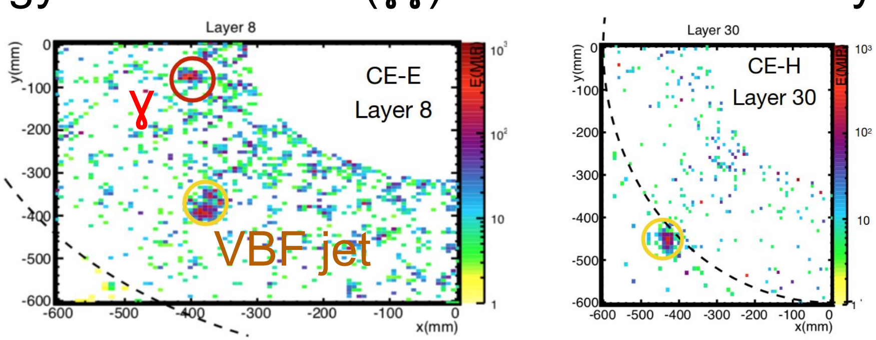
Longitudinal XS of one HGCAL upper half

EM calorimeter
- Si pads
- CuW/Pb absorbers
- 28 layers: 26 X_0 & ~1.7 λ



Hadronic calorimeter
- Si pads or scintillator+SiPM
- Steel absorbers
- 24 layers: ~9.0 λ

Energy from a VBF H(γγ) MC event in two layers



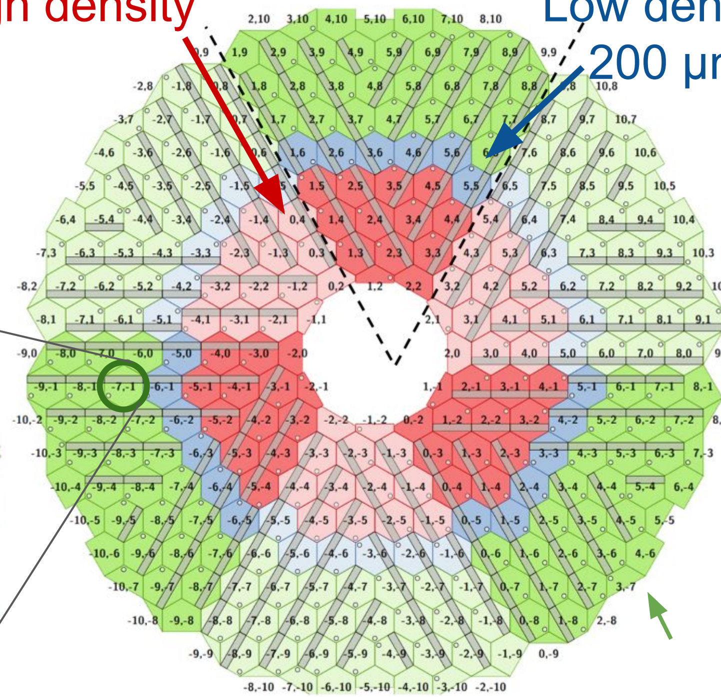
Layout of the Si pads modules - hexagon is the key

- Hexagonal modules of 8‘’
  - “low density” with ~200 cells and 200 or 300 µm Si sensor
  - “high density” with ~360 cells and 120 µm Si sensor

Transverse XS of HGCAL layer 8

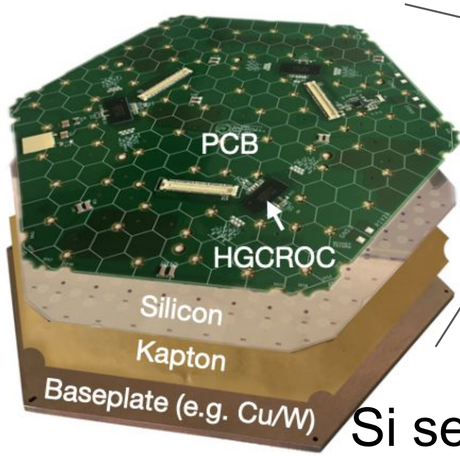
High density

Low density 200 µm



Low density 300 µm

“hexaboard” PCB
- Si cells↔”HGCROC” frontend ASICs
- module↔motherboard



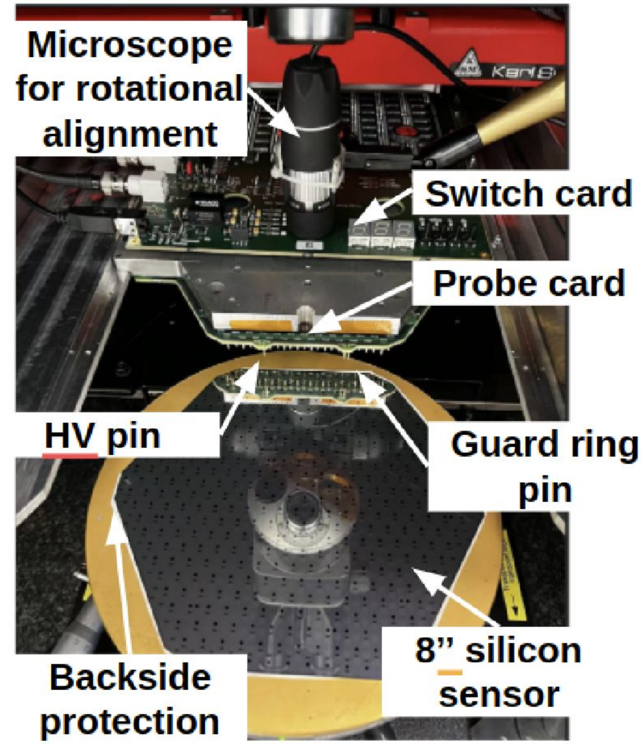
Metalized kapton layer
- Power Si backplate
- Insulation from Cu/W

Si sensor with hexagonal cells (channels)

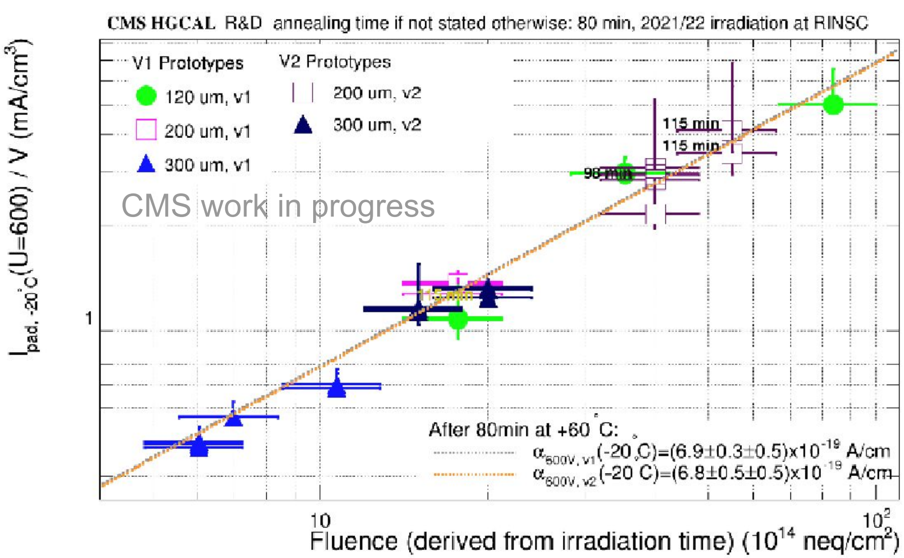
➢ IHEP contribution to work ongoing @CERN
  - Characterization of Si sensors, PCB, ASICs, & module prototypes in lab + module tests w/ beam + DAQ developments

Characterization of the silicon sensors at CERN

- Test first batches of pre-series low and high density sensors
  - Level and uniformity of leakage current, depletion voltage & thickness
  - Excellent quality and good agreement with producer measurements



Leakage current vs fluence

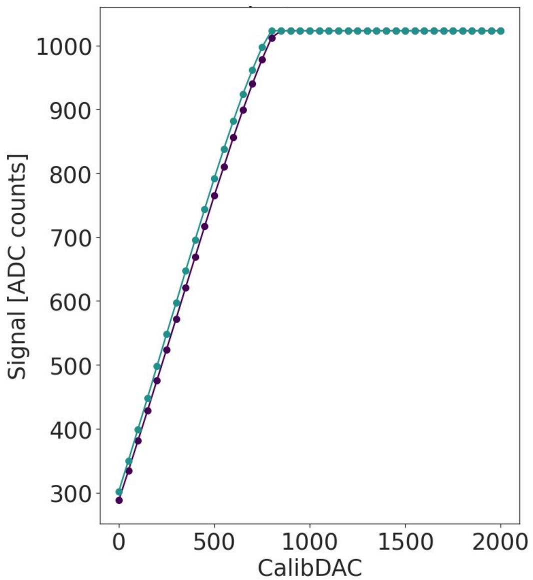


- Sensor irradiation tests completed up to 1.5x nominal fluence
  - All effects consistent with expectations

Tests of ASICs and PCBs

- Throughout 2021 test batches of HGCROCs
    - input/output, ch noise and response to charge injection
    - “bad” chips < 4%
    - Chip features understood and fixed in new version
- Some good chips mounted on hexaboards and tested
- Latest chip versions tested by LLR team in Paris with dedicated robot
    - [Collaboration to develop a new fast & flexible python-based software for DAQ&analysis]()

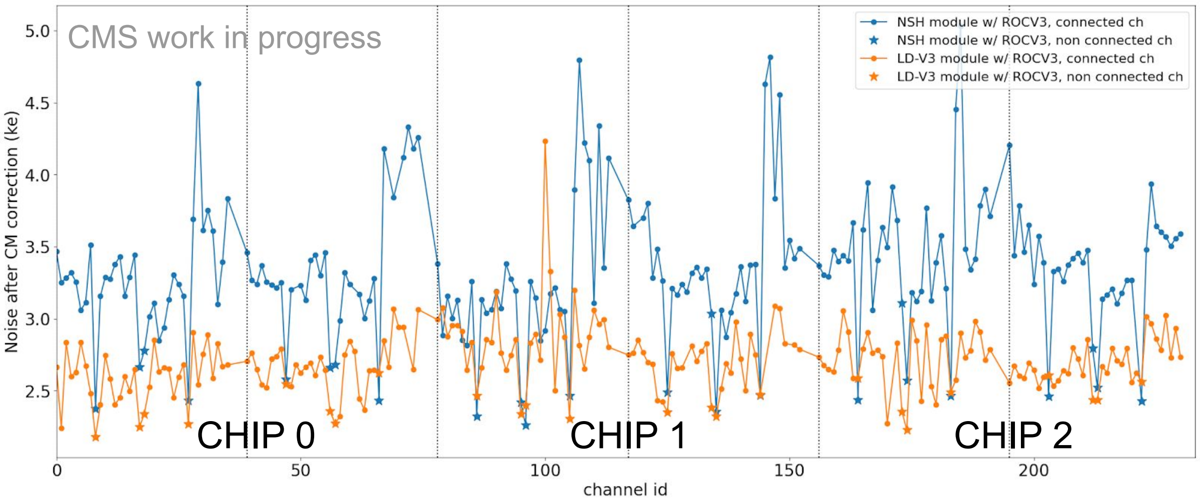
ADC vs injected charge in two hexaboard ch’s



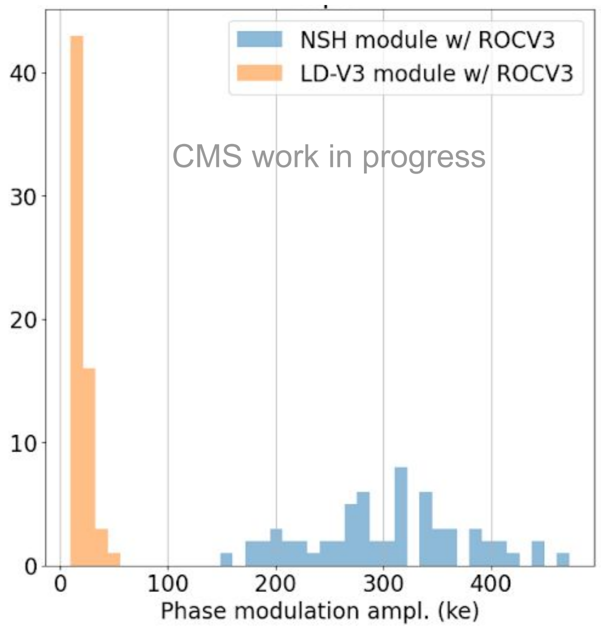
Module prototype performance

- First test of new low density 300 µm module (LD-V3)
- Many lessons learned with previous PCB version (NSH)
    - 40 MHz modulation of ADC pedestal understood and fixed

Noise vs channel ID



Amplitude of pedestal modulation for ch's of chip 2



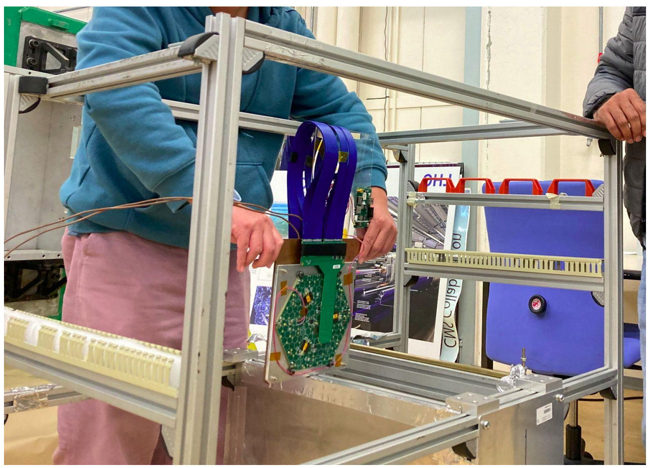
➢ Noise close to design performance

➢ Encouraging results with new high density PCB prototype

October 5th - 12th test beam @CERN

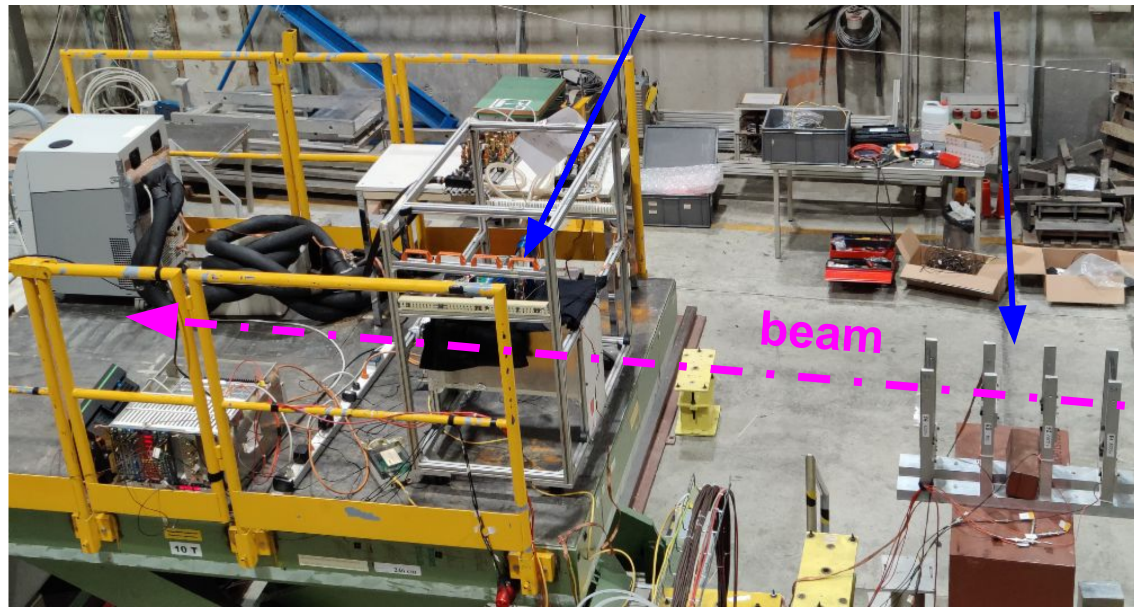
- Test low density 300 μm module prototype (LD-V3)
  - Si and ASIC chip close to final version

Preliminary test of the setup in the lab



Module inside aluminum frame

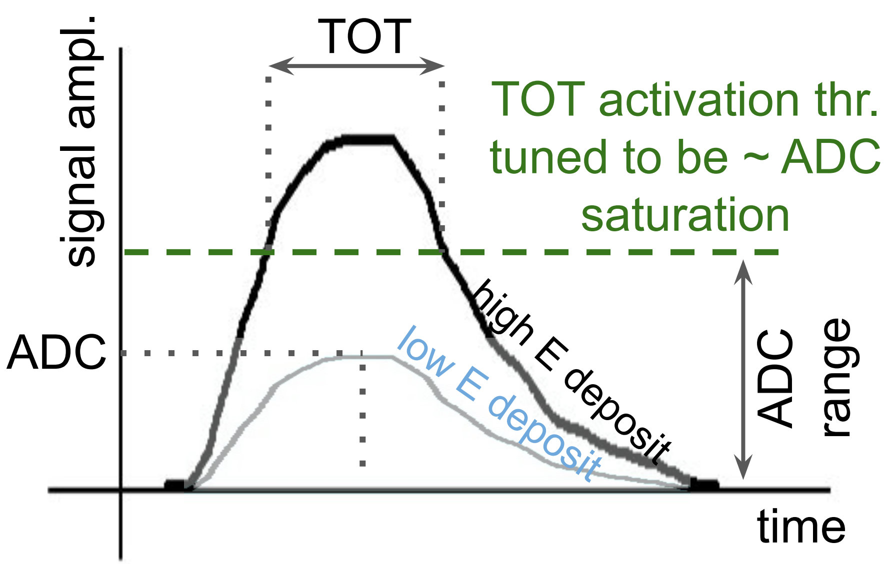
PMTs to provide external trigger



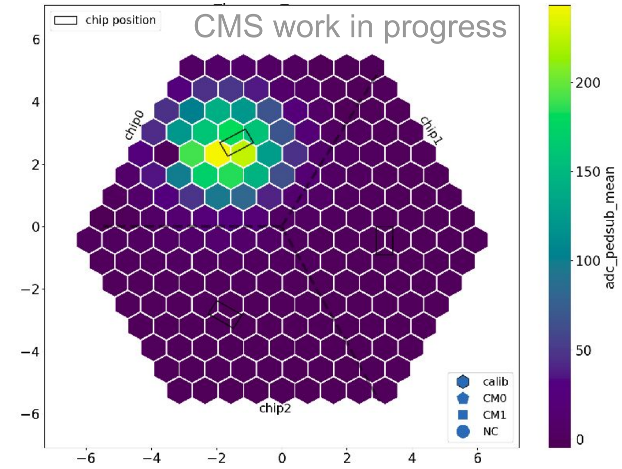
➢ 150 GeV muons or pions w/o absorber, and 20-200 GeV electrons with Pb absorber
  - Response to em showers: test time-over-threshold & time-of-arrival
  - Response to MIP: signal/noise, ch. response uniformity

time-over-threshold (TOT) response to em showers

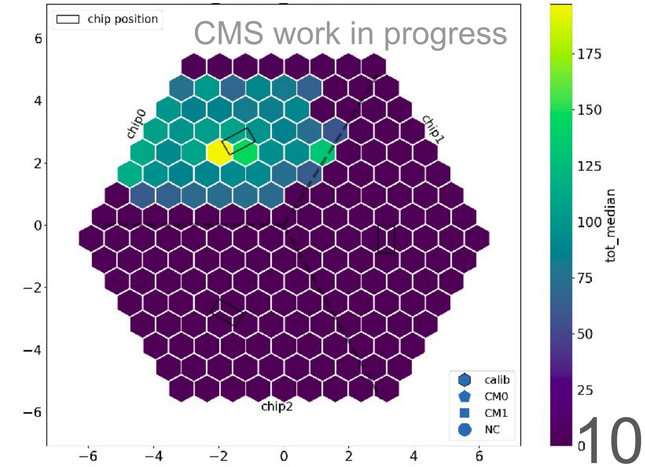
- charge/energy measurement via ADC `xor` TOT



median of ADC in module ch's in a run with electron beam



median of TOT in module ch's in a run with electron beam



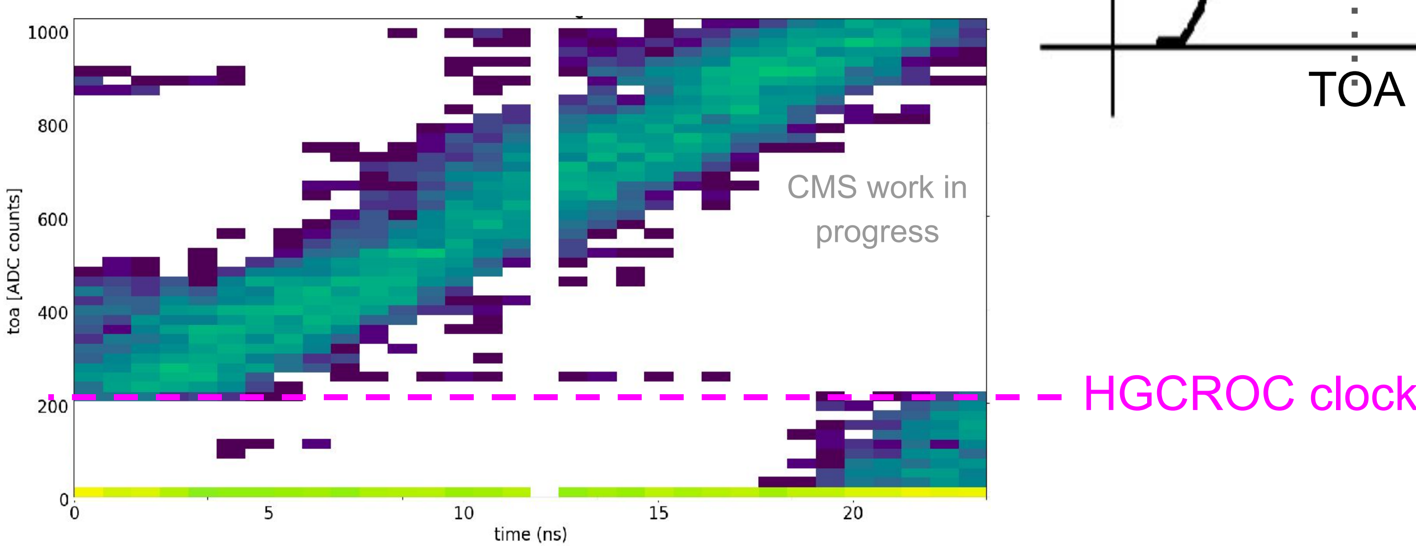
First demonstration of TOT in 8" Si modules w/ beam

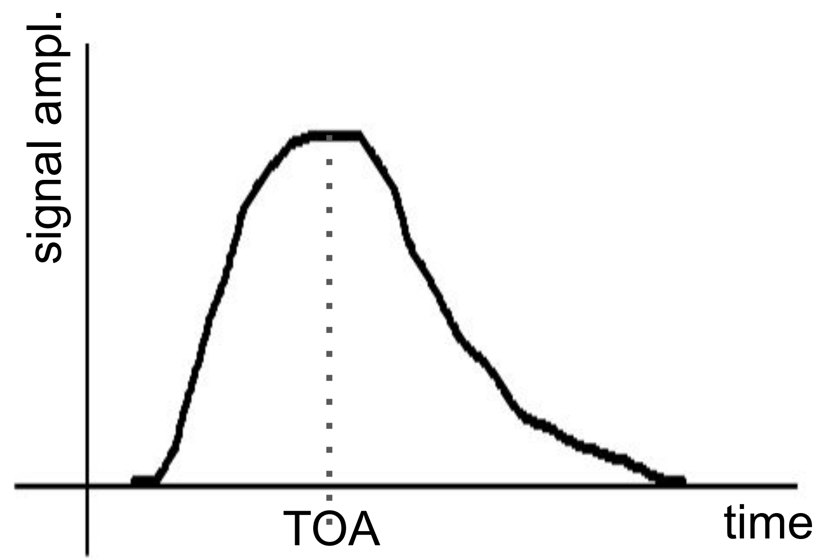
- Work ongoing to calibrate TOT and estimate performance

time-of-arrival (TOA) response to em showers

- By design, TOA resolution ~25 ps for signals ≳ 10 MIPs
- 10 bits over 25 ns

TOA vs external trigger time for a ch at the center of the em shower



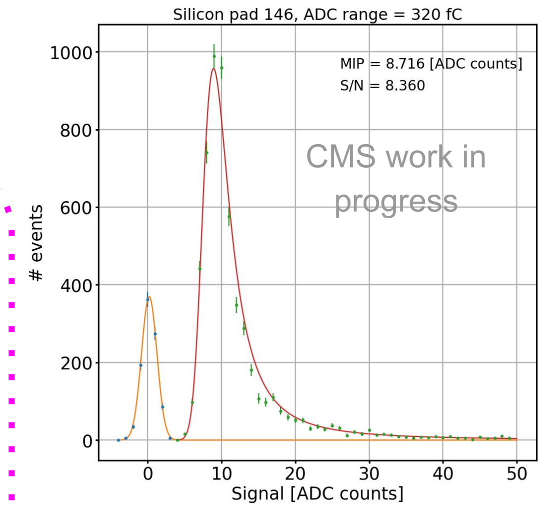


➢ First demonstration of TOA in 8” Si modules w/ beam
  - Refined analysis ongoing to estimate time resolution

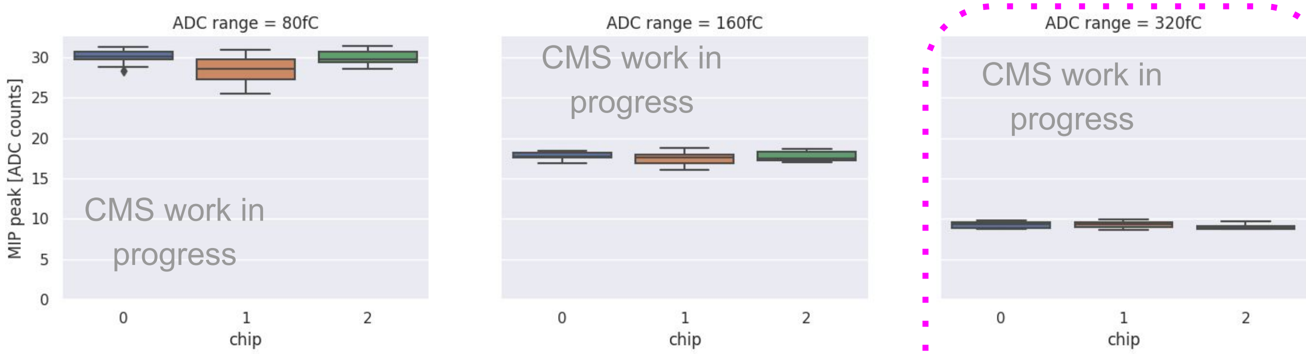
Module response to MIPs

- 40 cells scanned with pion beam
  - 3 preamplifier gains tested

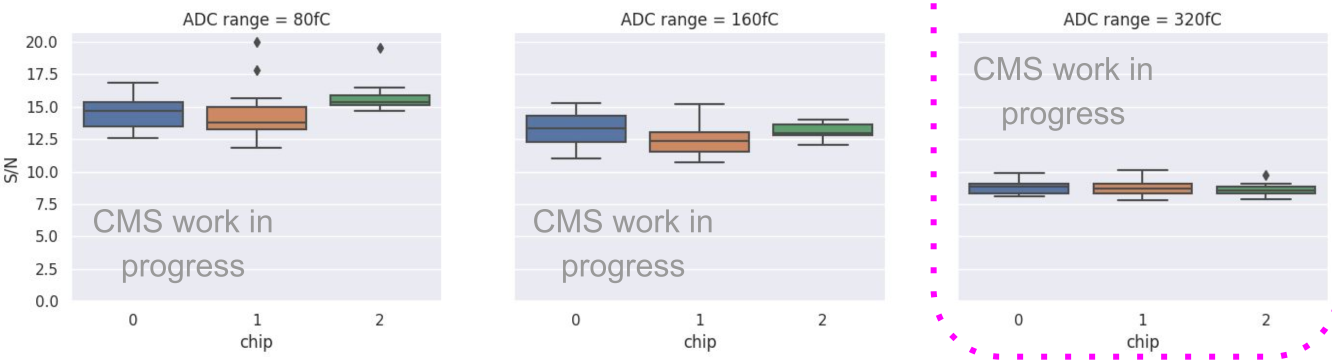
Fit of MIP signal + noise model to data in one cell



MIP peak position vs chip ID for the three preamp. gains



S/N vs chip ID for the three preamp. gains



Standard gain for LD 300 µm module

- ➢ Good uniformity across different chips & cells of module
- ➢ S/N ~ 8.5 close to design performance

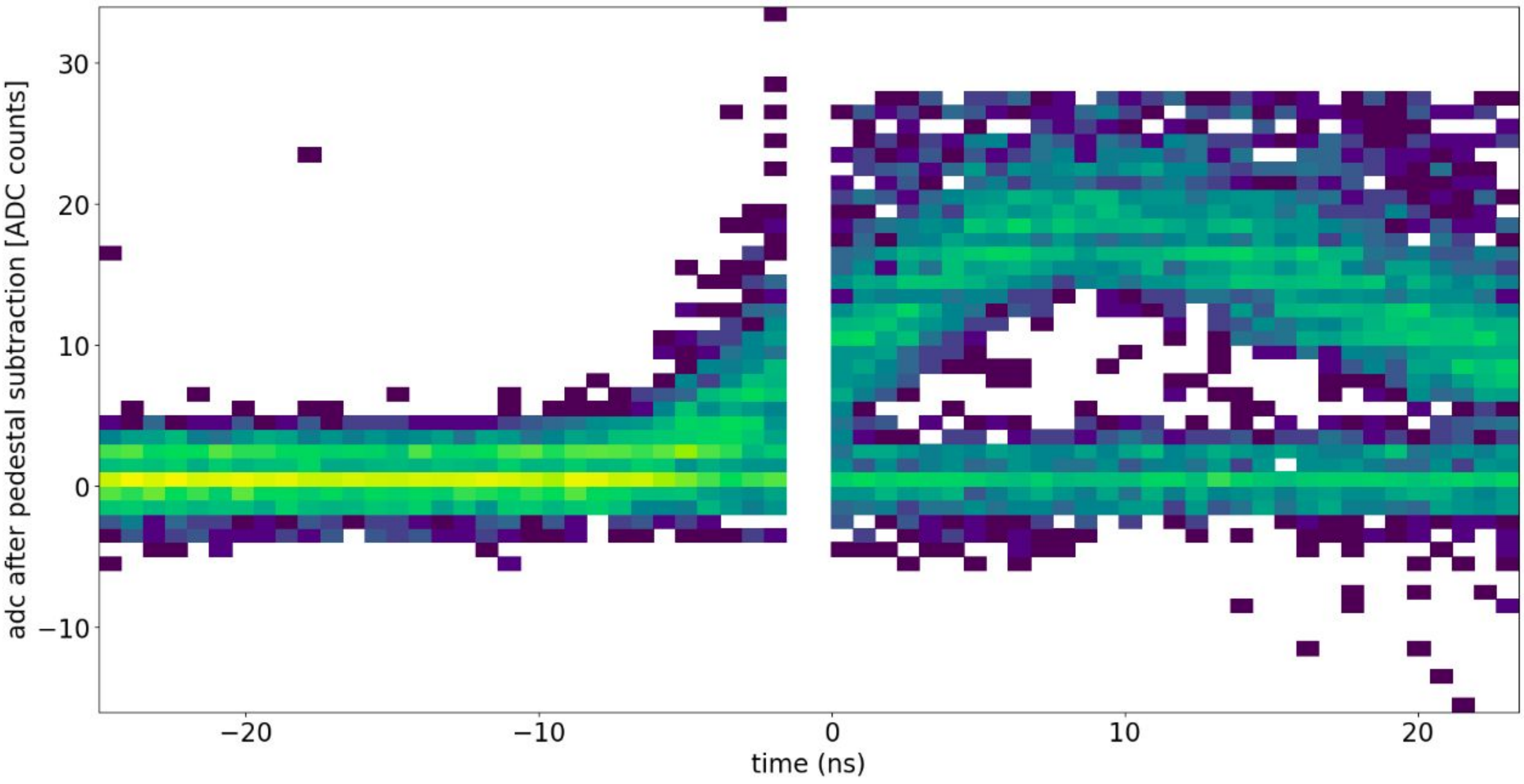
Summary

- Innovative silicon-based high-granularity calorimeter for CMS HL-LHC
  - Radiation tolerance and 5D reconstruction to mitigate pileup
- Significant IHEP contribution in characterization of Si sensors, ASICs, PCB and modules prototypes @CERN
- Encouraging results with new almost-final Si modules prototypes tested in the lab and with beam
  - S/N ~ 8.5 for a MIP → close to design performance

BACKUP

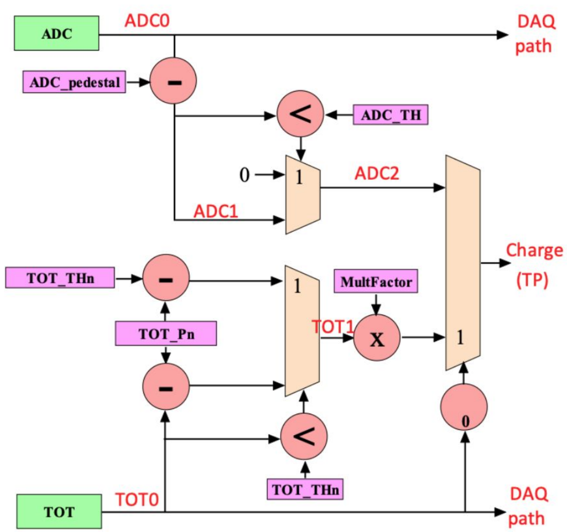
Pulse shape for MIPs

Reconstruction of the pulse shape for pion beam

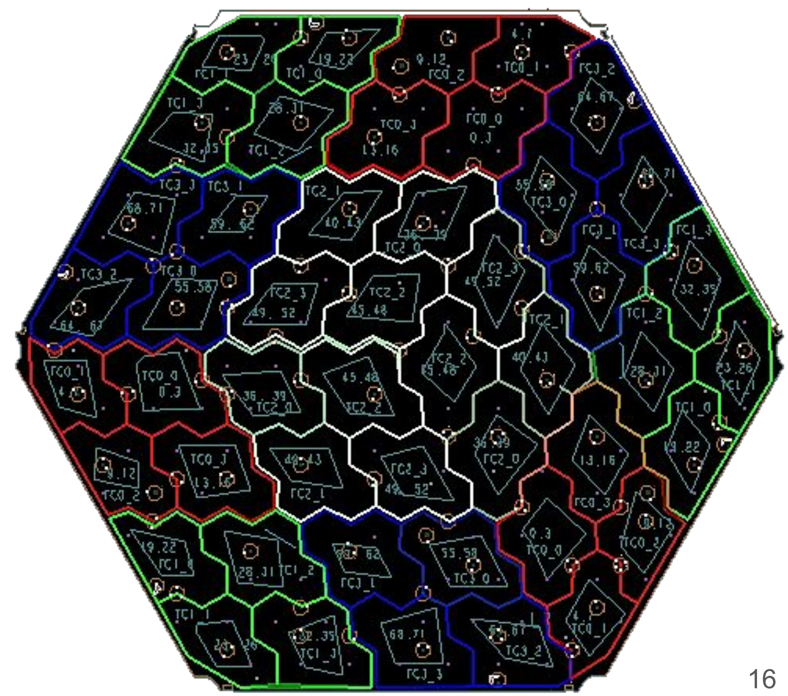


Trigger output from Si module

- LD hexaboard trigger primitive (TP) = sum of charge linearized over adc/tot range in four adjacent cells
  - 7 bit floating point w/ 4 bits exponent + 3 bits mantissa
- HGCROC parameters controlling TP calculation
  - Channel adc pedestal subtraction
  - Channel adc threshold
  - Similar for tot
  - tot2charge conversion coefficients



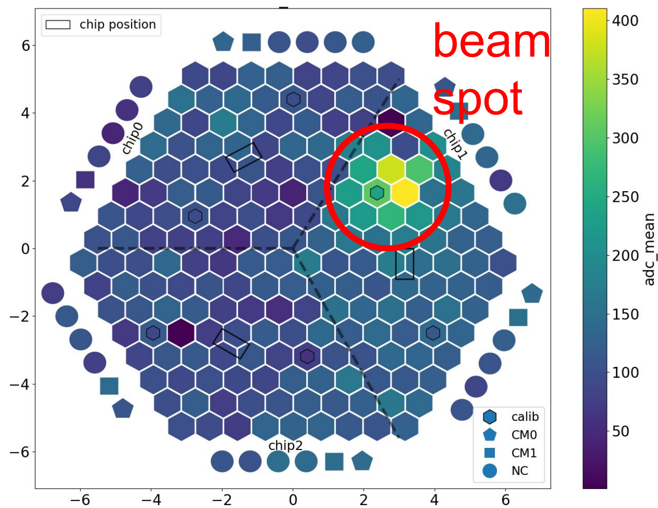
Trigger links (colors) and TPs



TP response to em showers

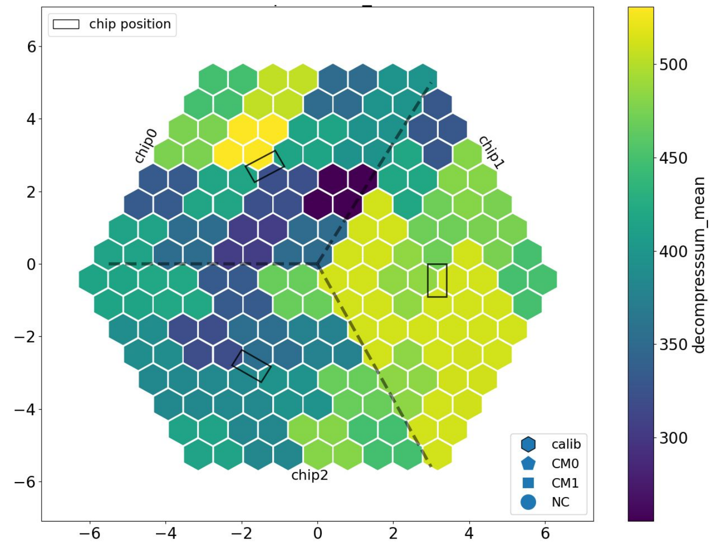
- 80 GeV electron beam with 6 Pb absorber slabs in front
    - Preliminary run before TP parameter configuration

adc mean

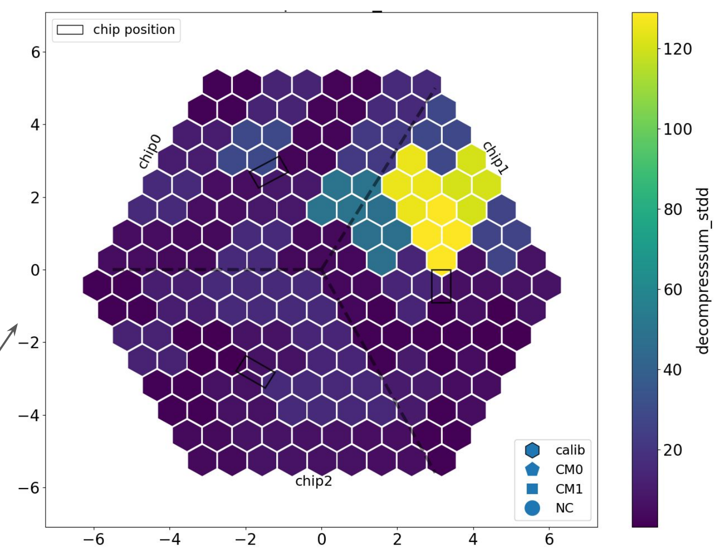


- TP mean determined by channels pedestals
- TP rms pattern matches beam spot region

TP mean

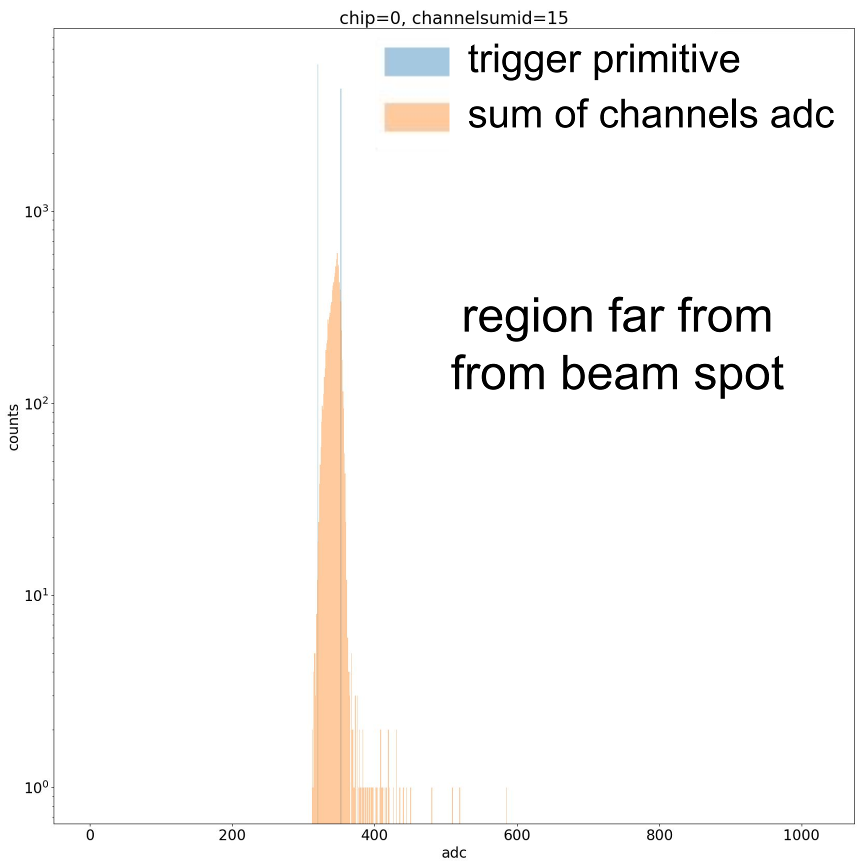


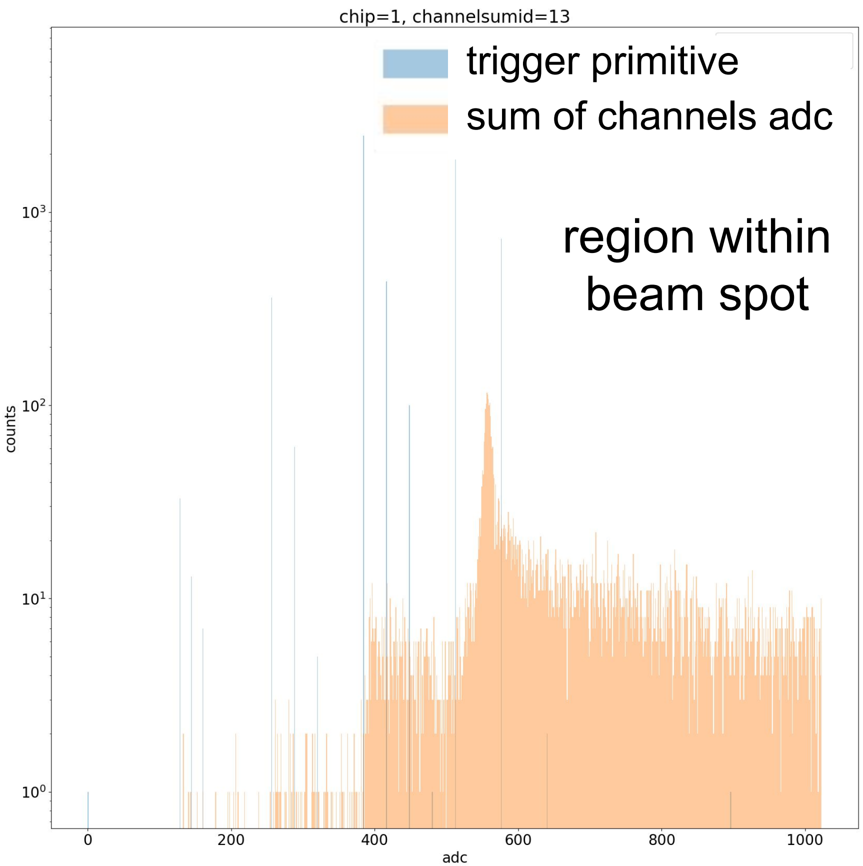
TP rms



Event-by-event TP response to em showers

- 80 GeV electron beam with 6 Pb absorber slabs in front
  - Preliminary run before TP parameter configuration





- adc granularity of TPs driven by floating point precision
  - Moving closer to one w/ ped. subtraction should improve this