Application of

SIPMs in Particle Physics Experiments

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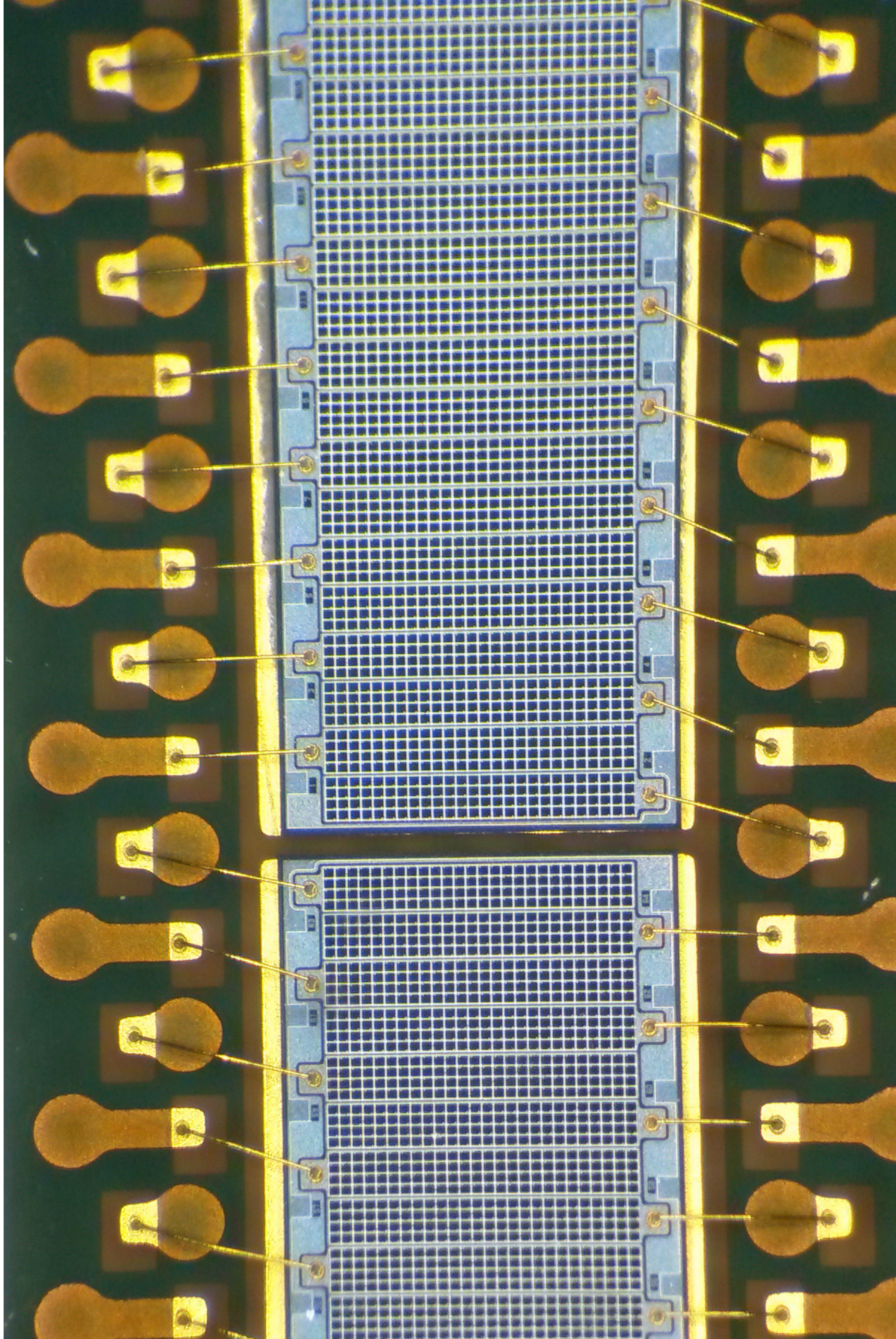

SIPMs used for LHCb Fibre Tracker

SiPM Properties

High gain	[10^5 to 10^7
Compactness	[1 mm^2 and larger
Insensitive to magnetic fields	[up to few T
Low operation voltage	[20 - 70 V
Large PDE	[up to 65% (peak @ 400 nm)
Dynamic Range	[N_{pxl} = O(1000)
Dark-rate	[30 to few 100 kHz/mm^2
Cross-talk, after-pulsing	[1 - 35%
Temperature sensitivity	[20-50 mV/K
Radiation Hardness	[< few × 10^{13}

Overview

Type	Experiment	Relevant Features
Time-of-Flight	Mu3e (Tile), Mu3e (Fibre), Belle2 (TOP), MEG2 (Timing Counter), Panda (ToF), SHIP (Timing Detector) …	Compactness, large PDE, fast response, B insensitivity …
Tracking	LHCb (Fibre Tracker), Belle2 (K_L & Muon Endcap Detector), …	Compactness, high gain, large PDE, radiation tolerance …
PID, Cherenkov	Belle 2 (A-RICH), Panda (DIRC), …	Compactness, single photon detection, radiation tolerance …
Calorimetry	CALICE (AHCAL), CMS (outerHCAL), CMS (HGCAL), sPHENIX (HCAL), GlueX (BCAL), Dune (NearDet), …	Compactness, large dynamic range, B insensitivity, …

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CALICE
Analogue HCAL

The CALICE Analog Hadron Calorimeter

Particle Flow Paradigm:

e^+e^- precision physics
requires W/Z mass splitting …
i.e. 3-4% jet energy resolution @ ~ 50 GeV

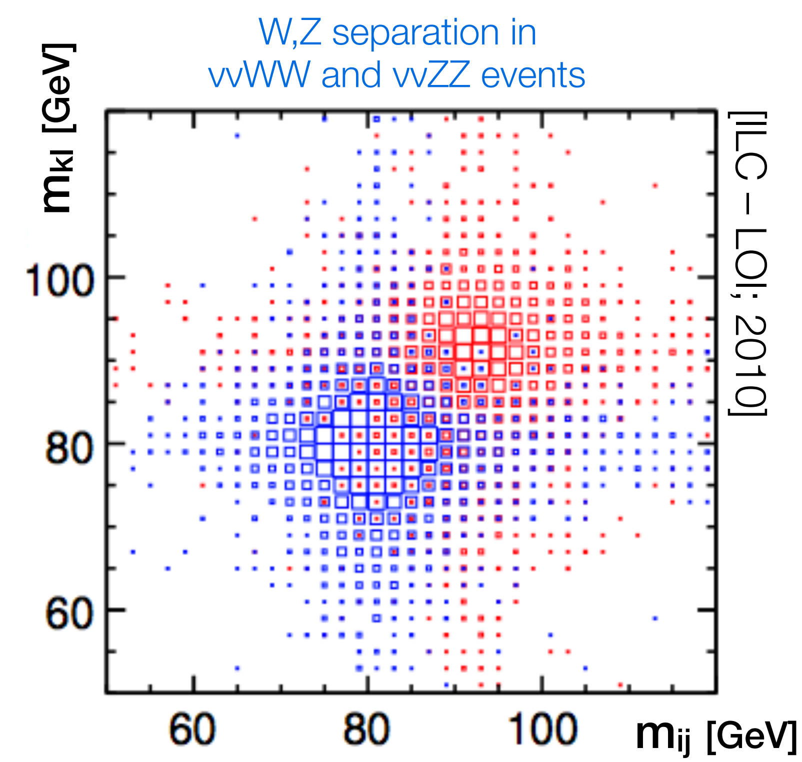
Jet energy reconstruction
by individual particle energies …
requires shower imaging capability

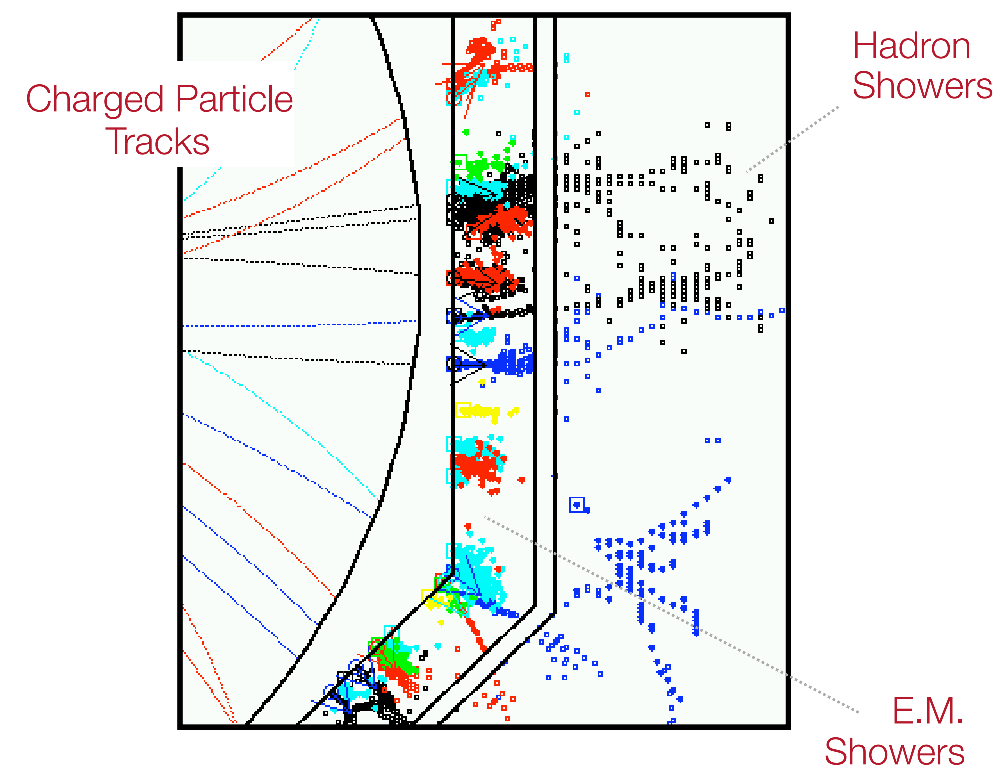
Detector requirements:

Excellent Tracking
[for charged particle reconstruction]

High calorimeter granularity
[for detailed shower reconstruction]

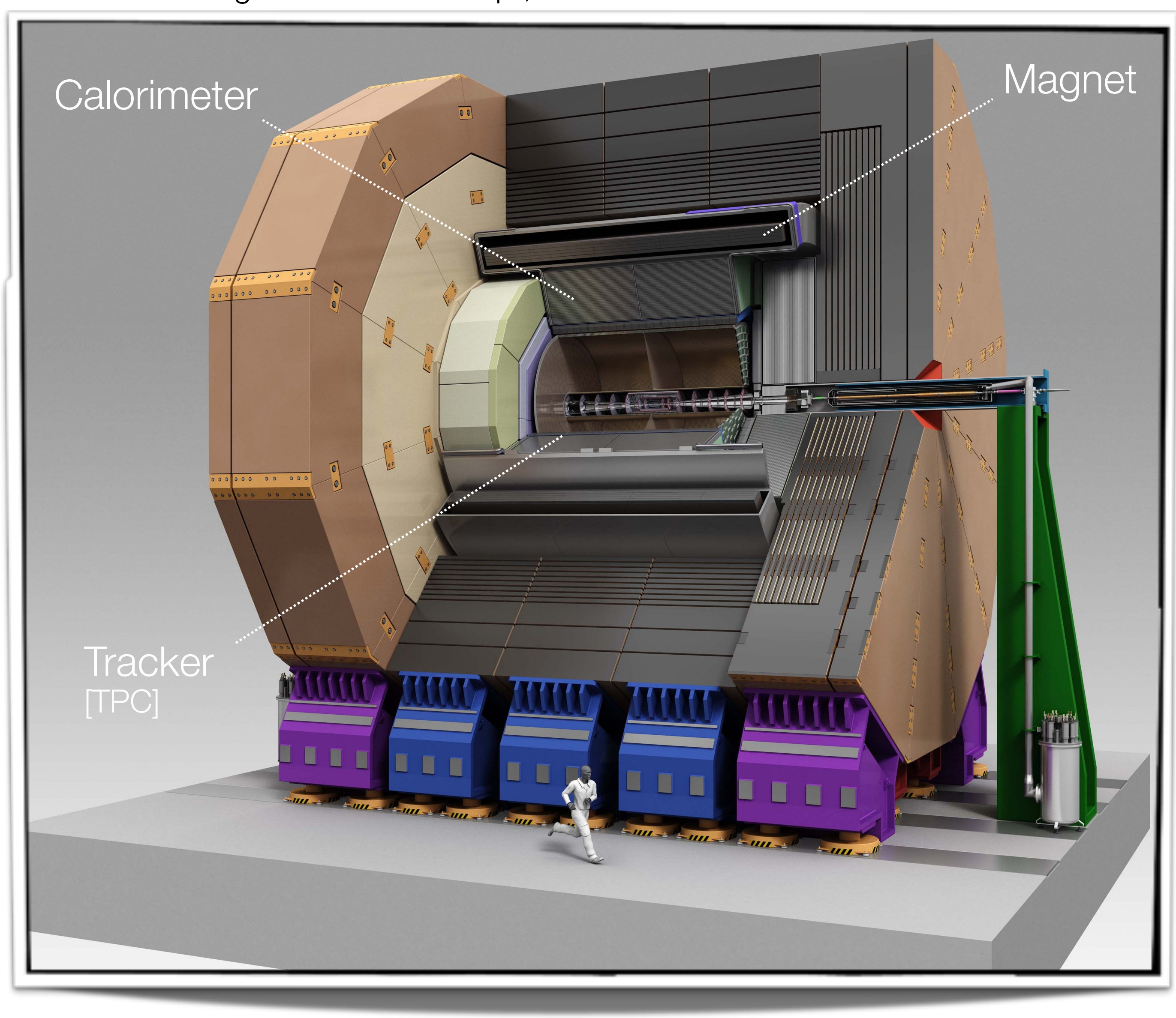
Good calorimeter resolution
[for measuring neutrals]

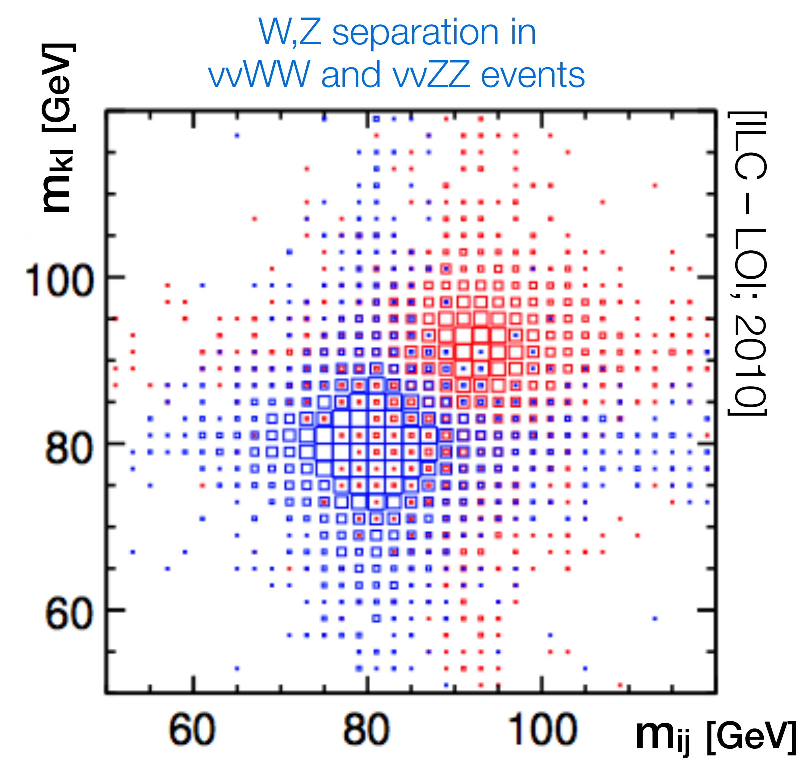


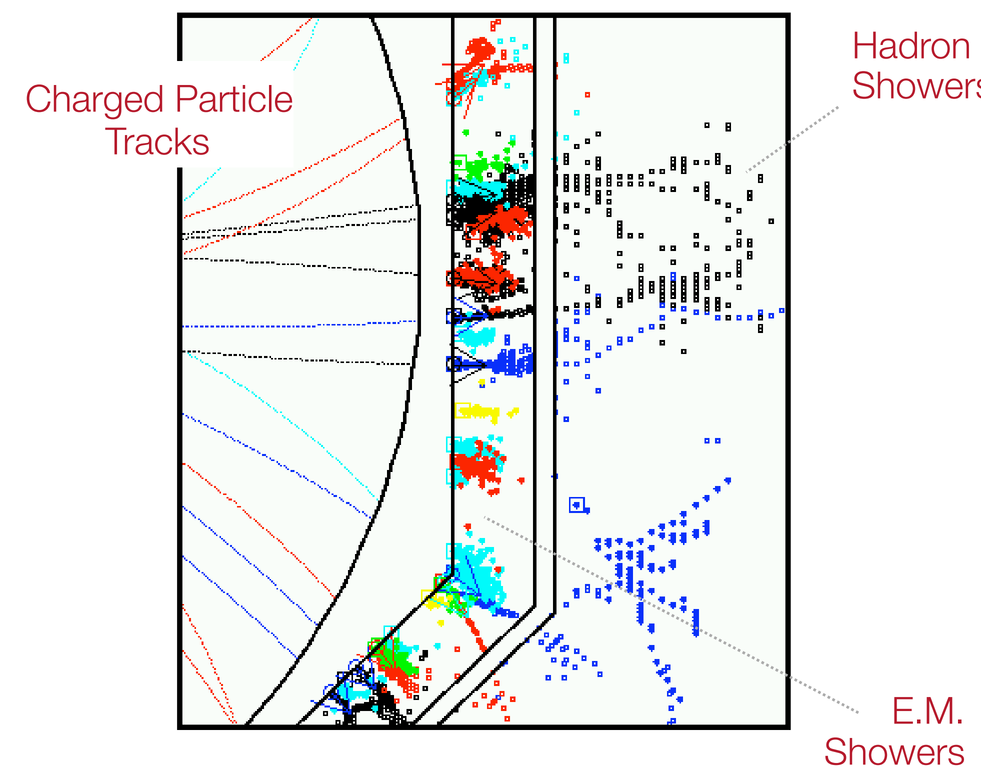


The CALICE Analog Hadron Calorimeter

International Large Detector Concept, ILD

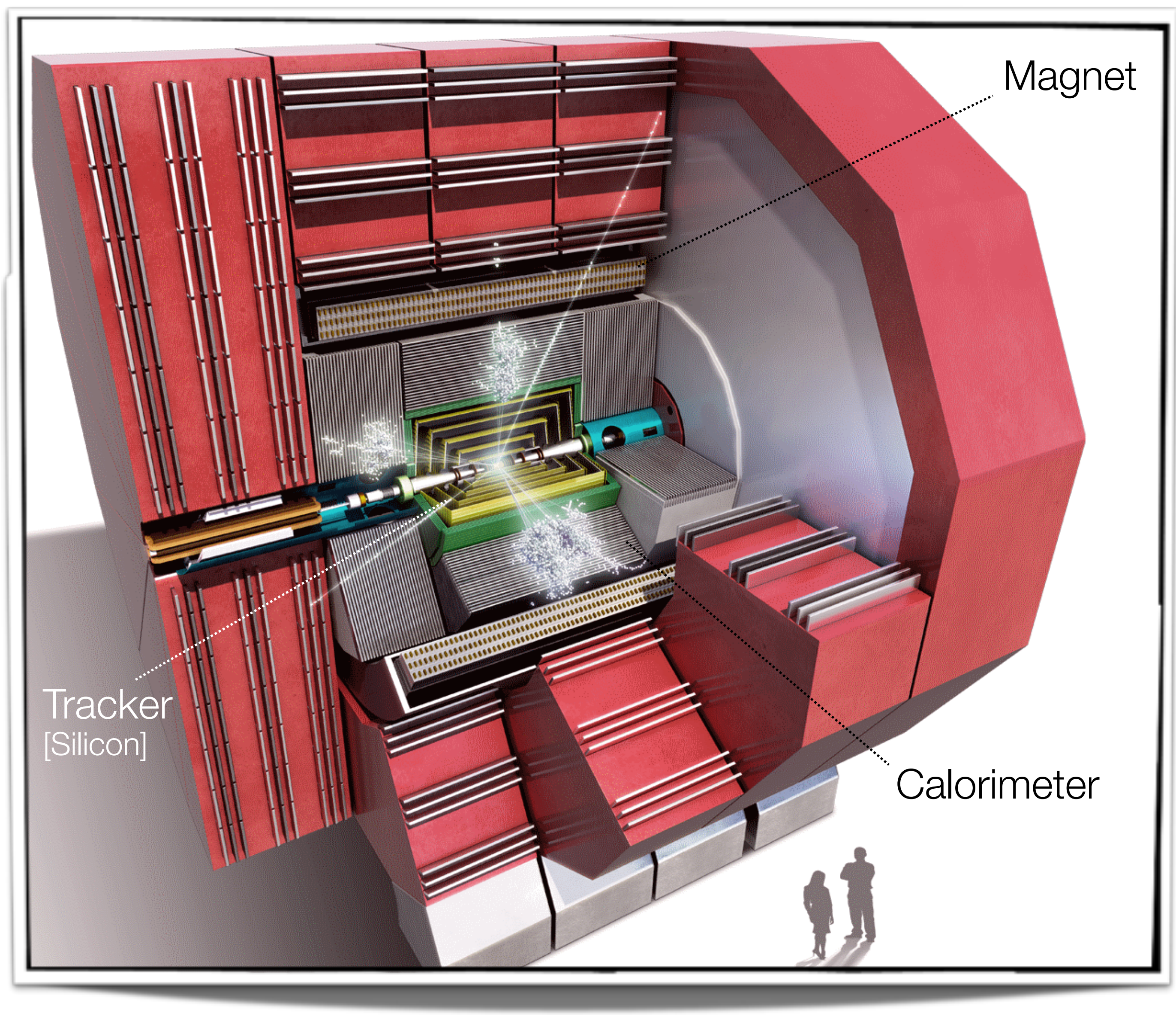


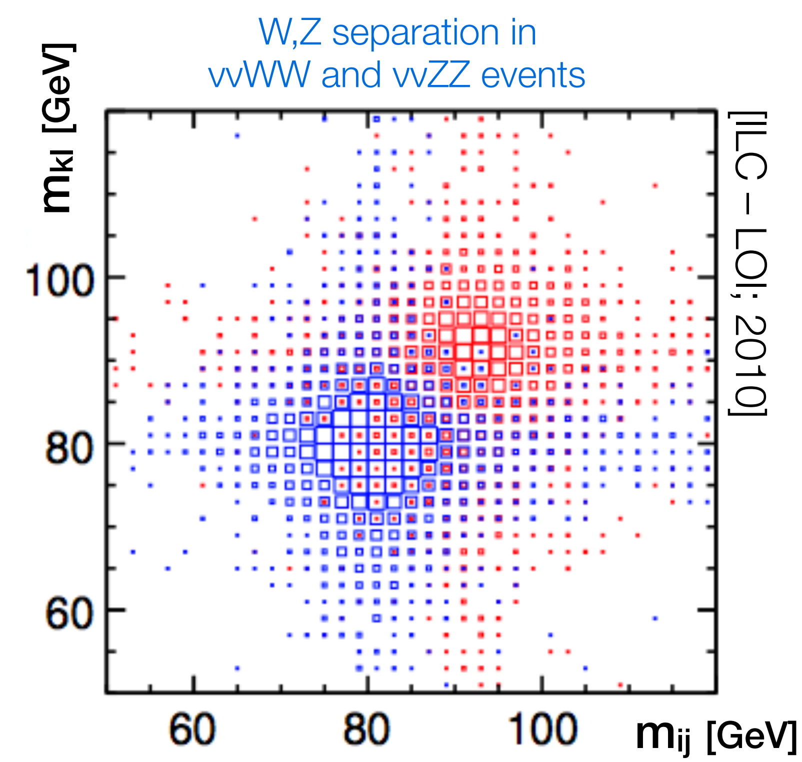


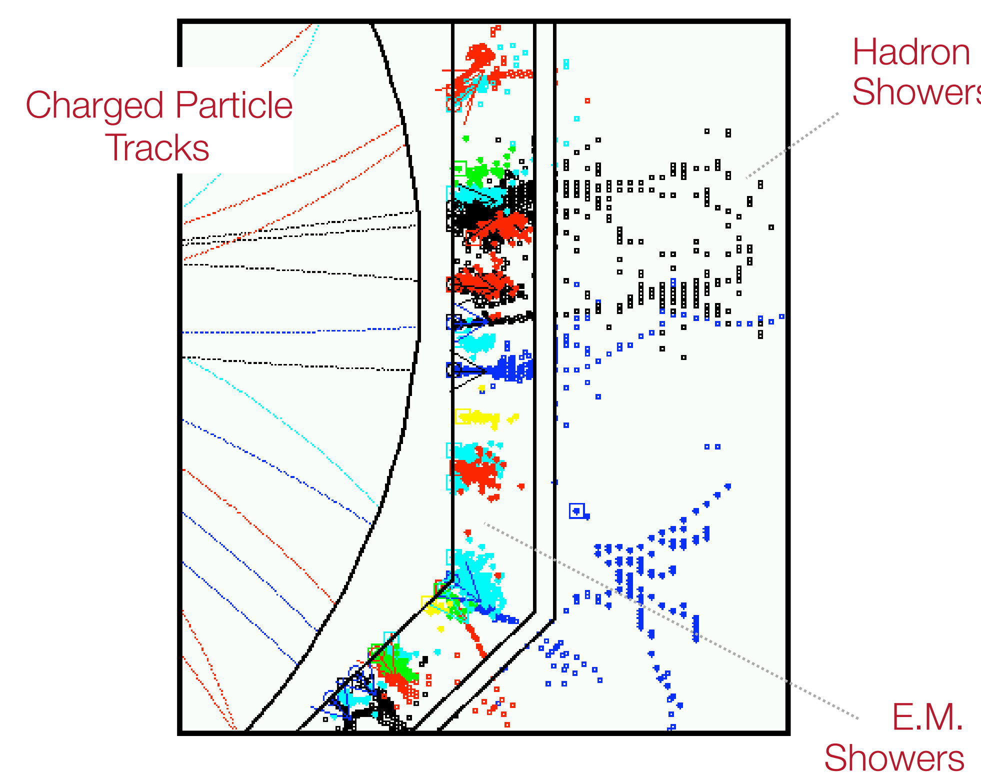


The CALICE Analog Hadron Calorimeter

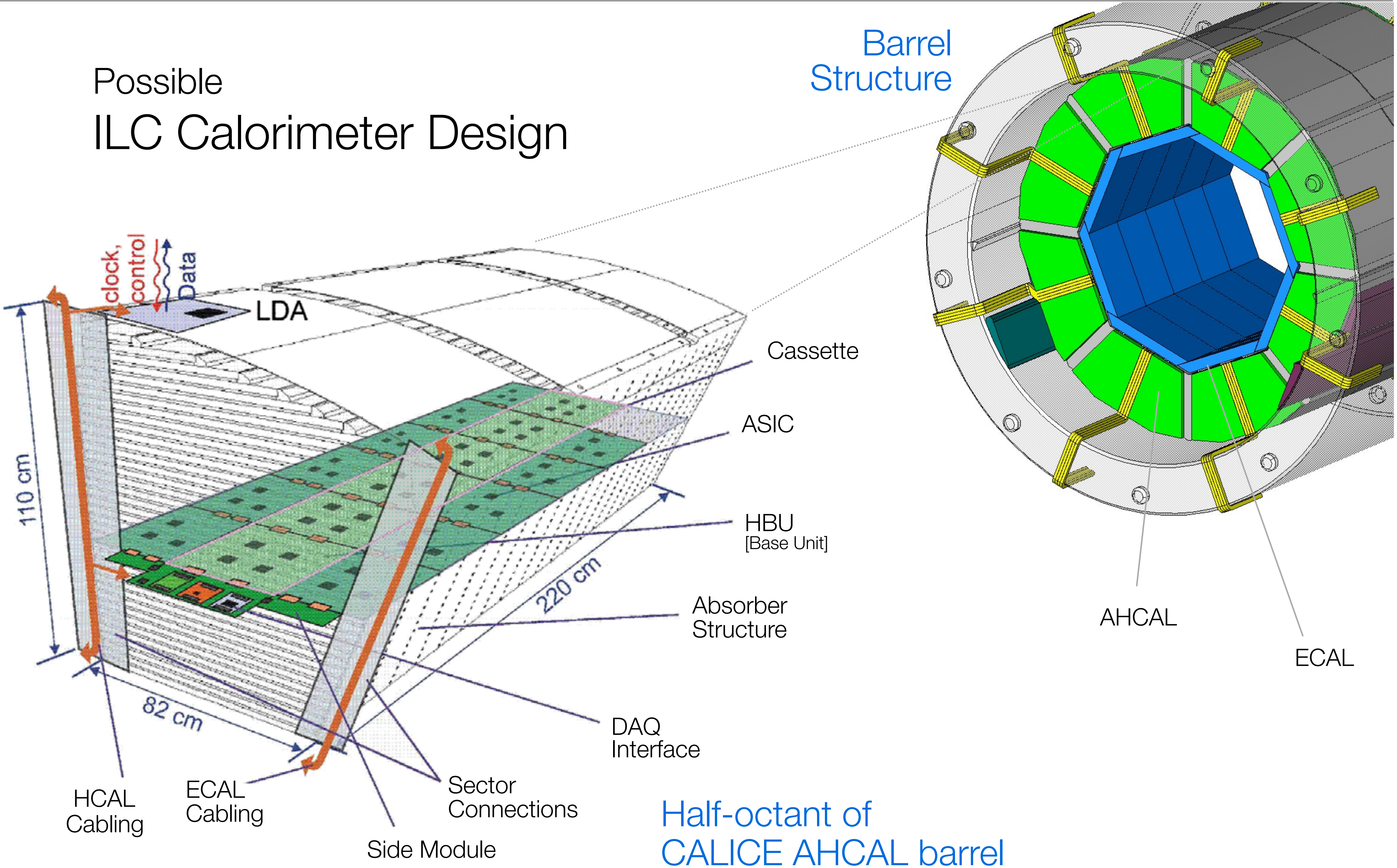
CLIC Detector Concept







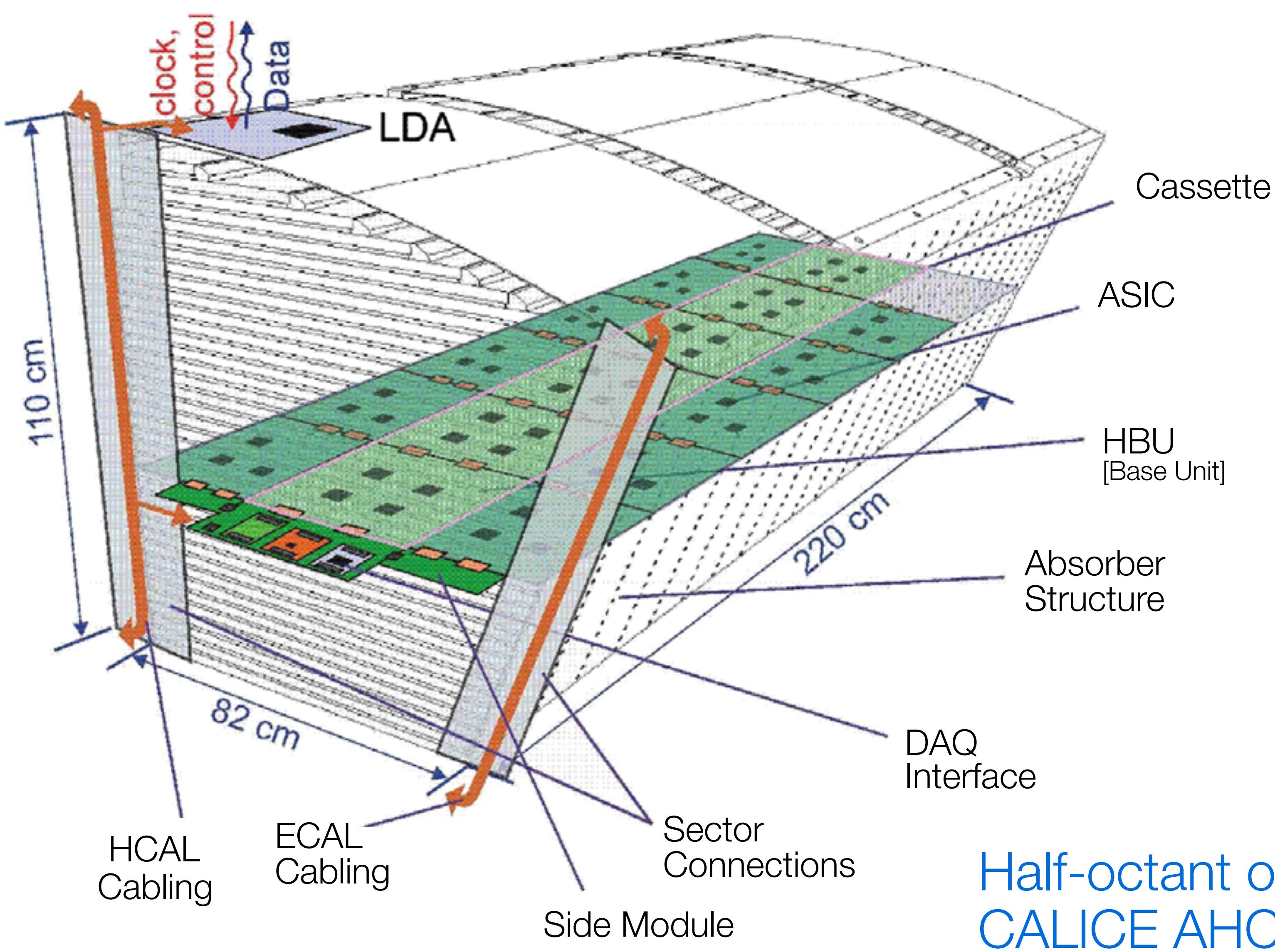
The CALICE Analog Hadron Calorimeter



The CALICE Analog Hadron Calorimeter

Possible

ILC Calorimeter Design



Half-octant of
CALICE AHCAL barrel

Sandwich calorimeter
based on Scintillator Tiles & SiPMs

Highly integrated electronics
with ultra low-power ASICs

8 Million Channels
requires high data concentration

SiPM requirements:

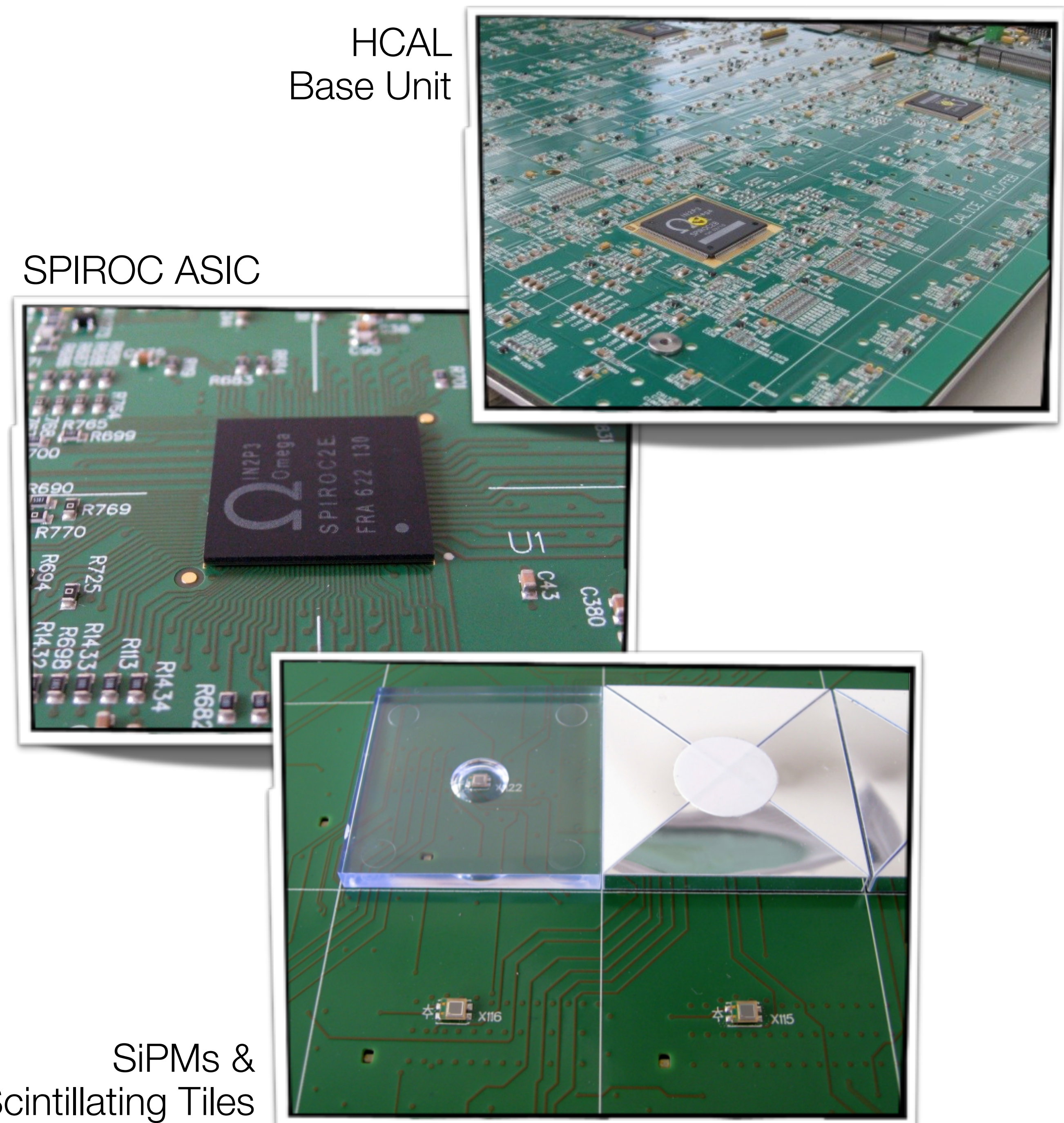
- SMD Technology
- Large Dynamic Range
- Blue sensitivity [25%@420 nm]
- DCR < 500 kHz
- Cross Talk < 3%
- V_{bd} spread < 200 mV
- …

The CALICE Analog Hadron Calorimeter

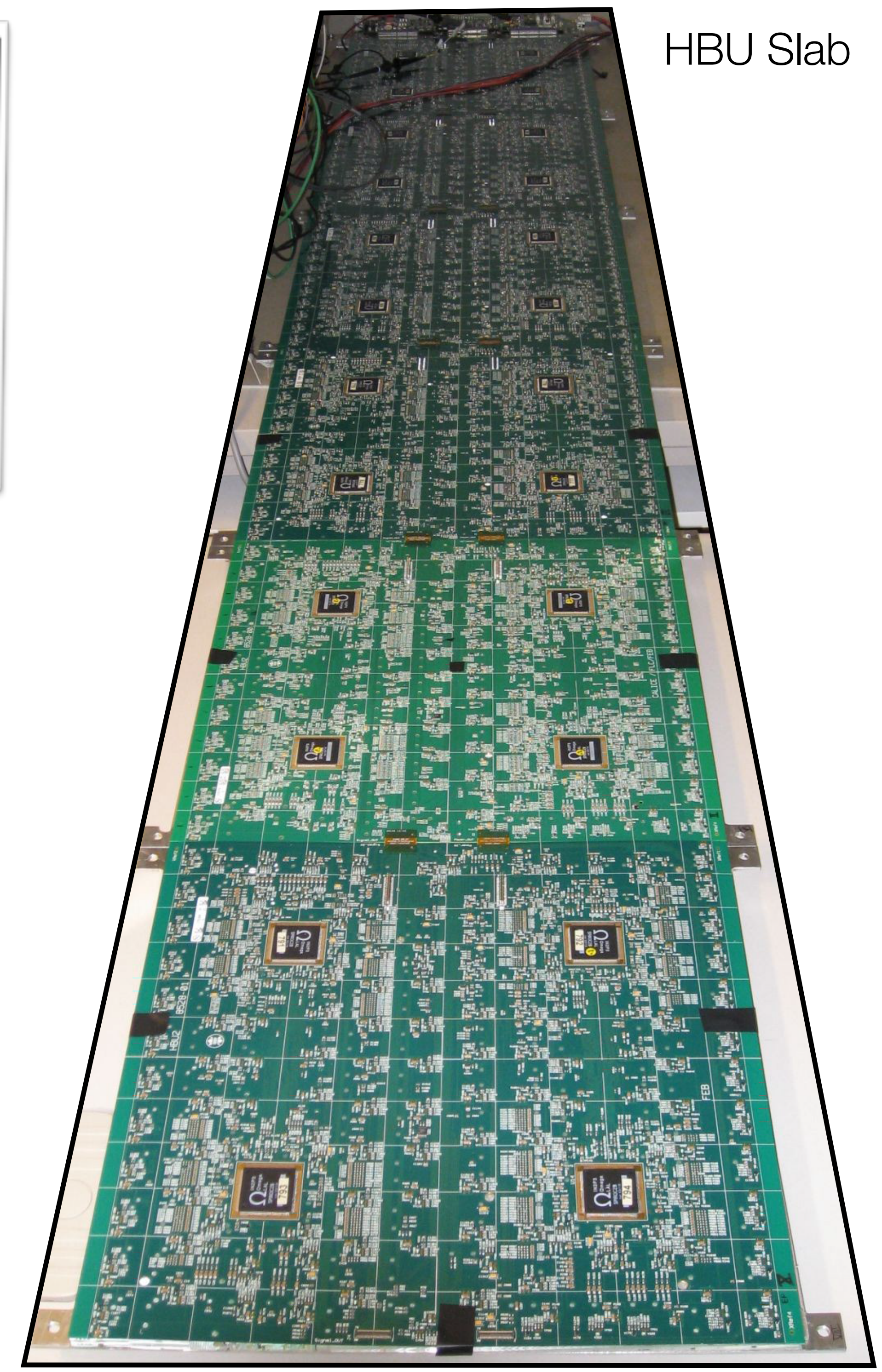
HCAL
Base Unit

SPIROC ASIC

SiPMs &
Scintillating Tiles



HBU Slab



The CALICE Analog Hadron Calorimeter

Dynamic Range Requirement

Gain-Calibr.: Singe Pixel Spectra

MIP-Signal: Typical 20 p.e./MIP

Physics:

Fe-AHCAL: up to 200-300 MIPs/hit

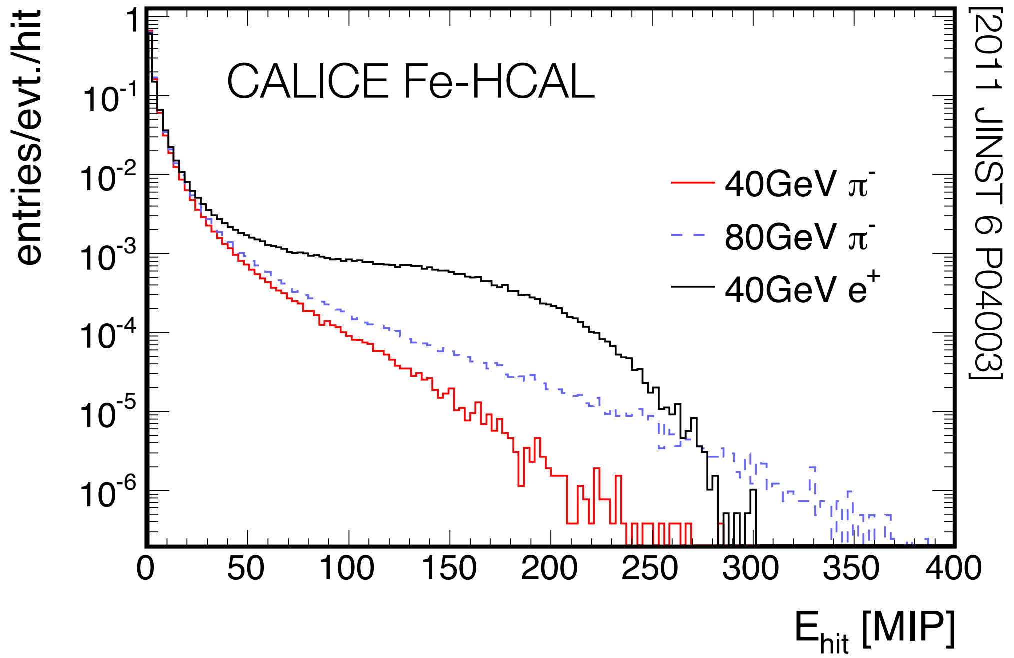
W-AHCAL: up to 300-450 MIPs/hit

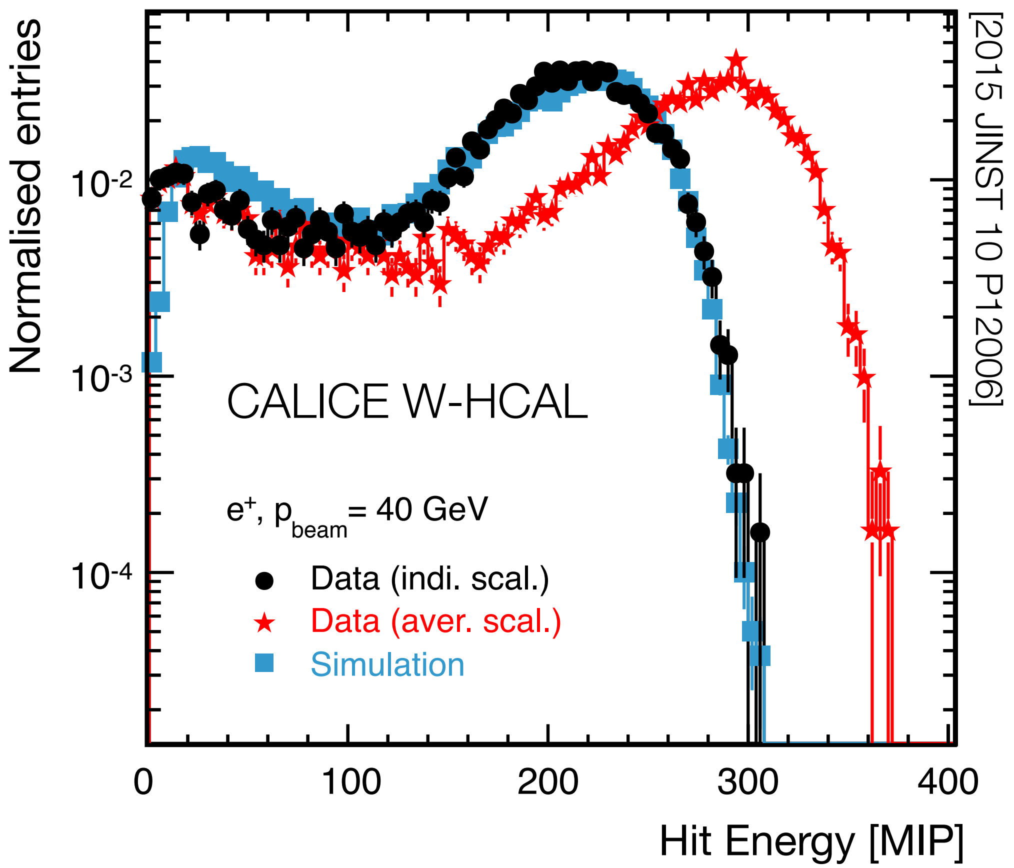
DR limitations:

Finite number of SiPM pixels [1500-3000]

Scintillator light yield [15-20 p.e./MIP]

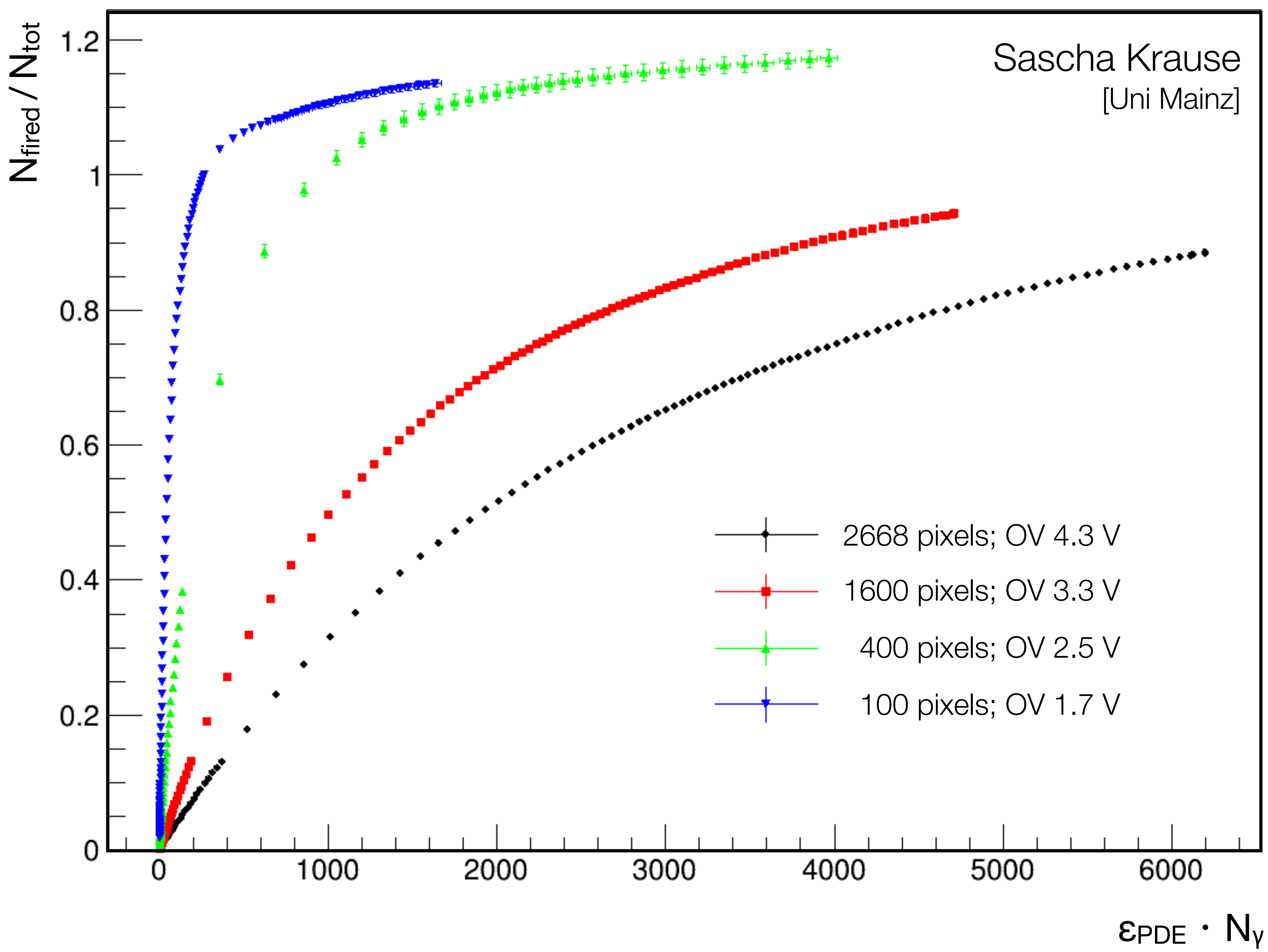
Readout electronics [0.1 – 150 pC]





The CALICE Analog Hadron Calorimeter

Saturation and SiPM Dynamic Range



Saturation:

$$N_{\rm fired} = N_{\rm tot}\left[1 - e^{\frac{-\epsilon_{\rm PDE} N_{\gamma}}{N_{\rm tot}}}\right]$$

Practical limit of correction for $\varepsilon_{PDE} N_{\gamma} \approx 2 N_{tot}$ …

For AHCAL:

#MIPs = 300, 20 p.e./MIP

➛ $\varepsilon_{PDE} N_{\gamma} = 6000$

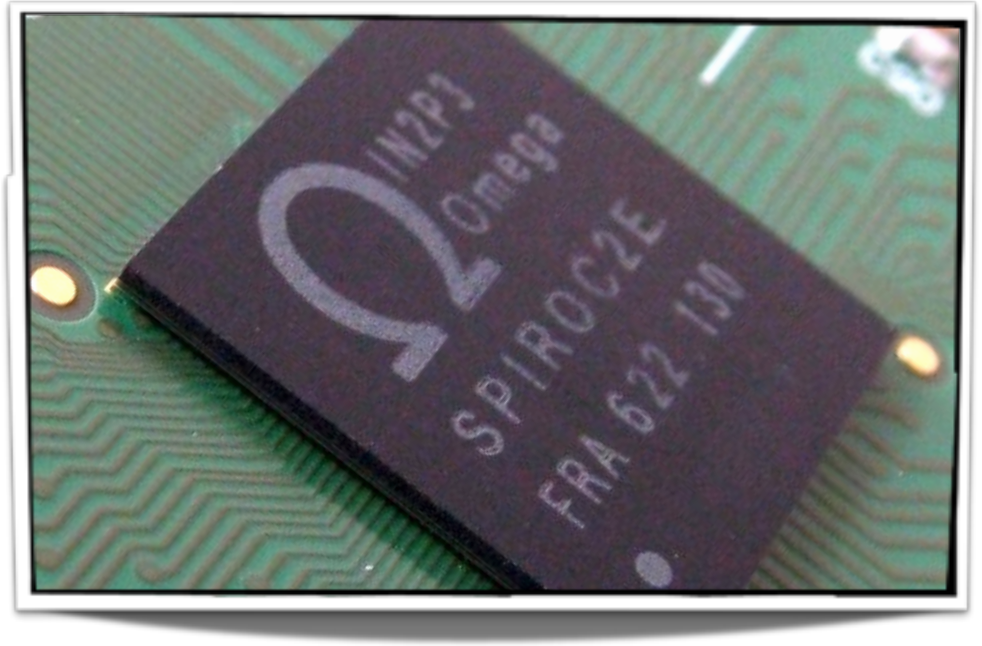
➧ $N_{tot} > 2000$

i.e. use S13360-1325PE

S13360-1325PE	2668 pixels
S12571-25P	1600 pixels
S12571-50P	400 pixels
S12571-100P	100 pixels

The CALICE Analog Hadron Calorimeter

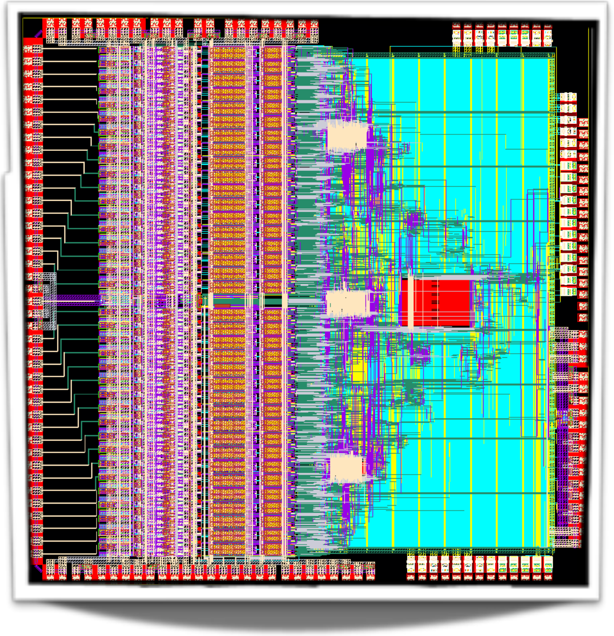
SIPM Readout Electronics

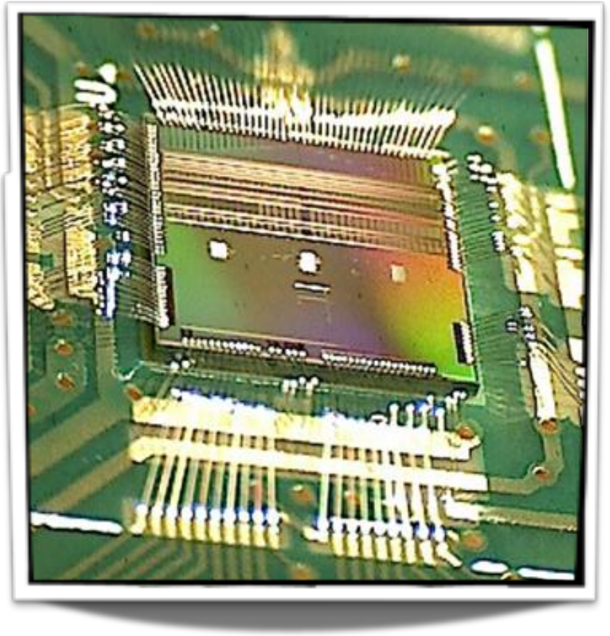


Requirements:

High precision charge measurement ...
High signal-to-noise (SNR) ratio ...
Large dynamic range ...
Auto-Trigger mode ...

SiPM bias adjustment ...
Low power consumption ...
[utilize power pulsing; pp]





Spiroc2e:

Current AHCAL prototype r/o solution …
36 readout channels …
Shared ADC + TAC …

KLauS 5:

Optimised for low gain SiPMs ...
36 readout channels …
Channel-wise ADC …

The CALICE Analog Hadron Calorimeter

SIPM Readout Electronics

Dynamic Range:

Spiroc2e : < 8 fC to 240 pC
KLauS5 : 4 fC to 140 pC

Timing Jitter:

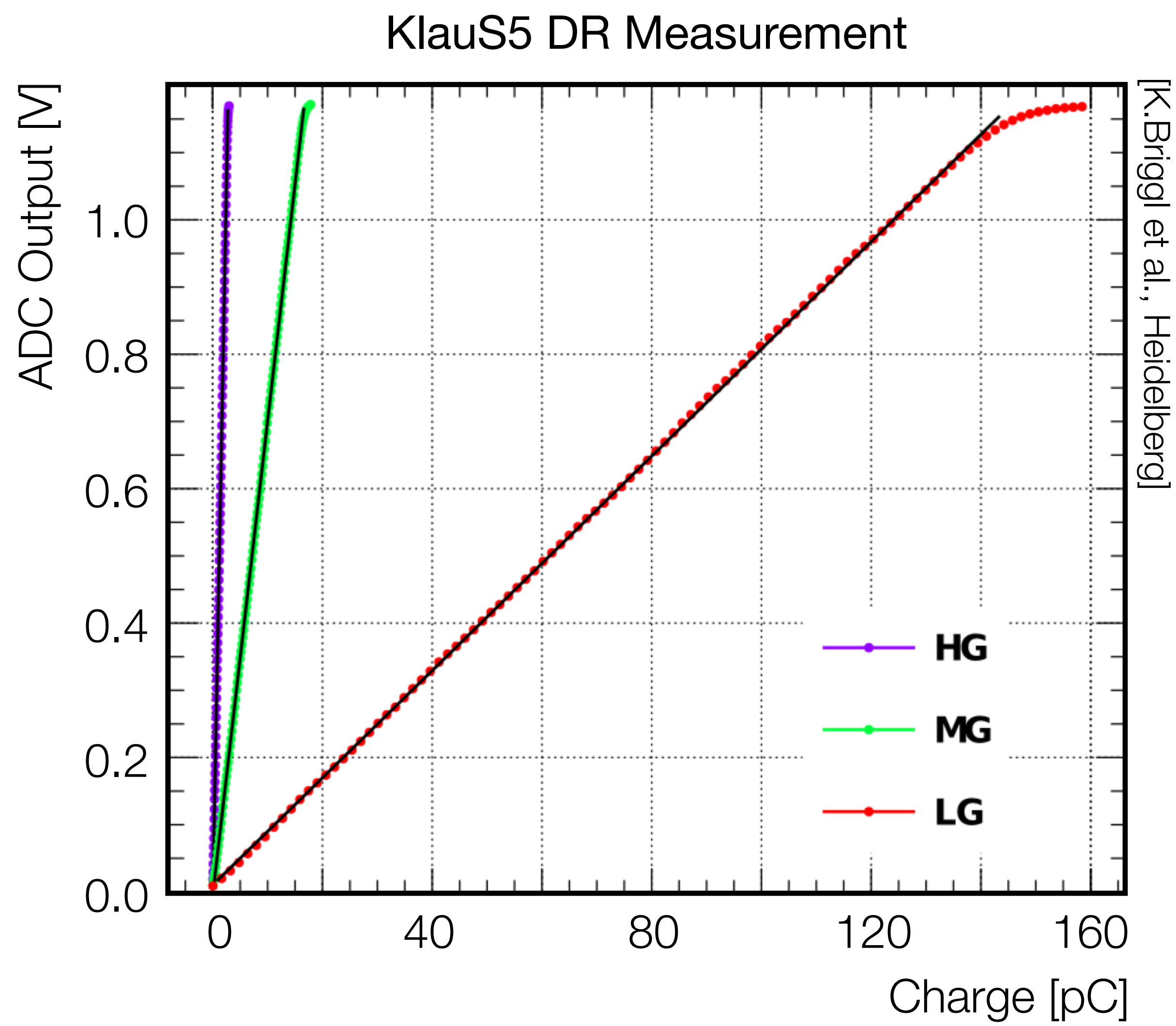
Spiroc2e : 300 ps [for MIP signal]
KLauS5 : 50 ps [for MIP signal]

Signal-to-Noise Ratio:

Spiroc2e : < 20 @ 160 fC
KLauS5 : 10 @ 40 fC

Power Pulsing:

Spiroc2e : < 250 μs [switch-on-time]
KLauS5 : 10 μs [switch-on-time]



The CALICE Analog Hadron Calorimeter

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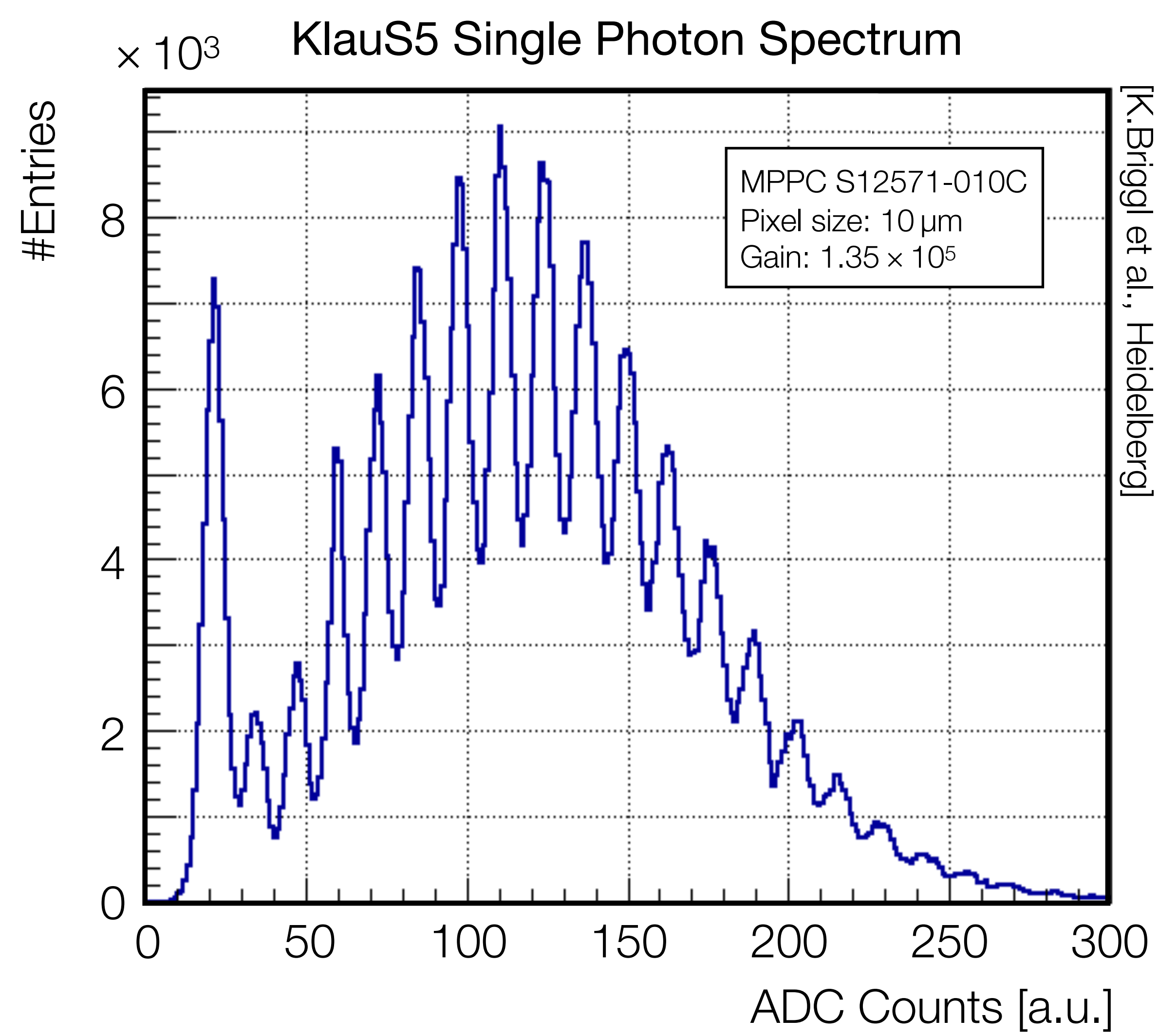

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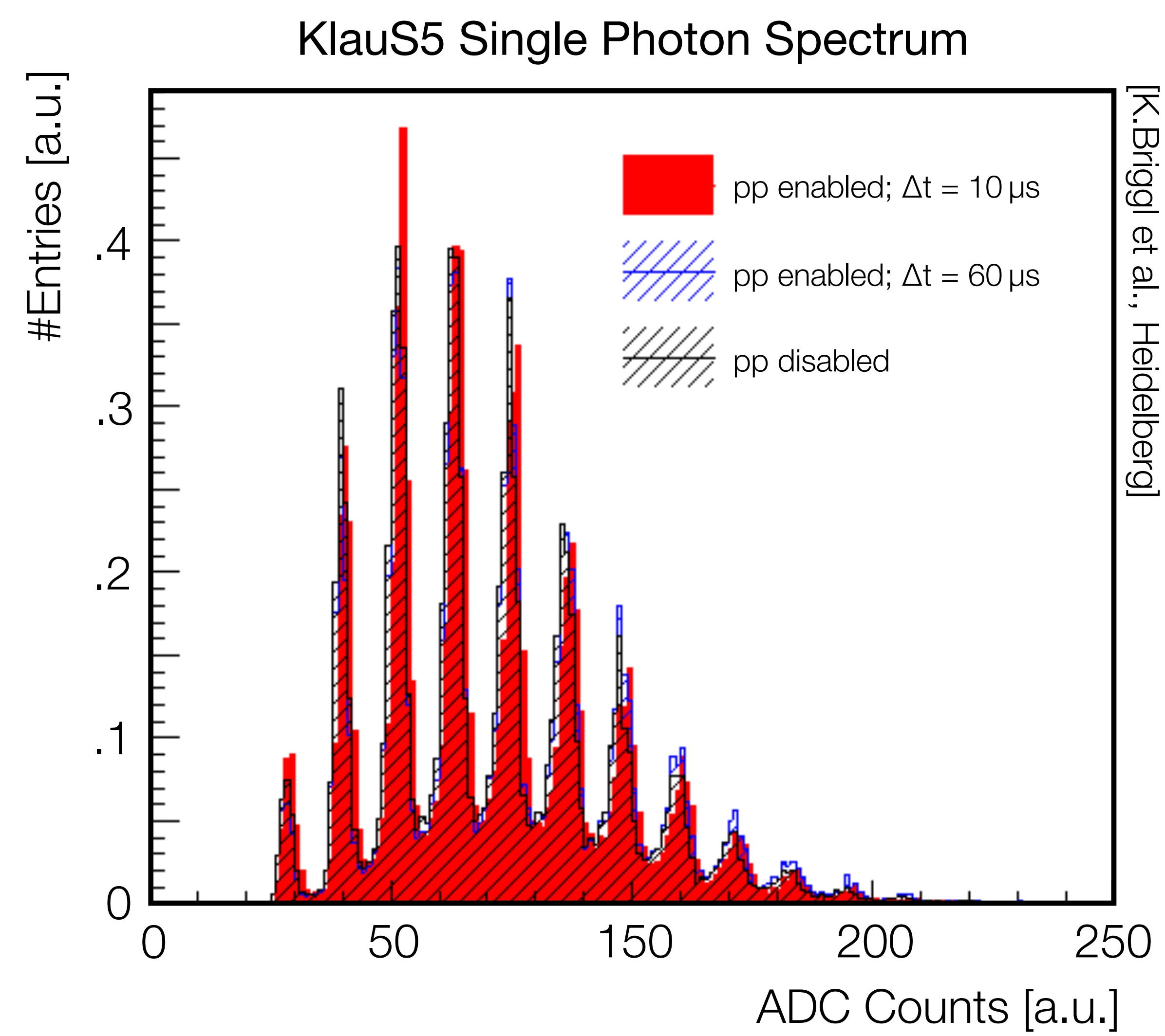

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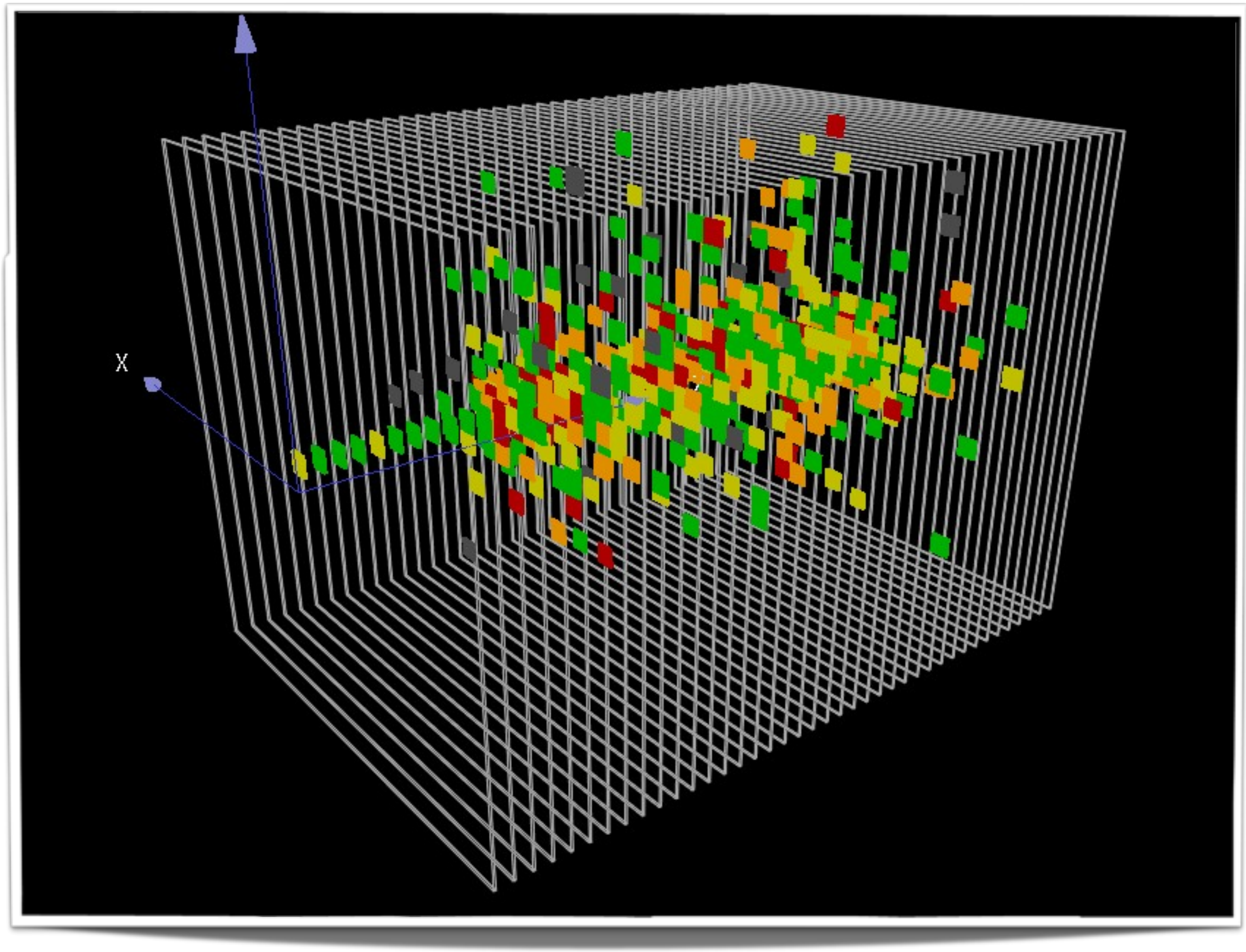
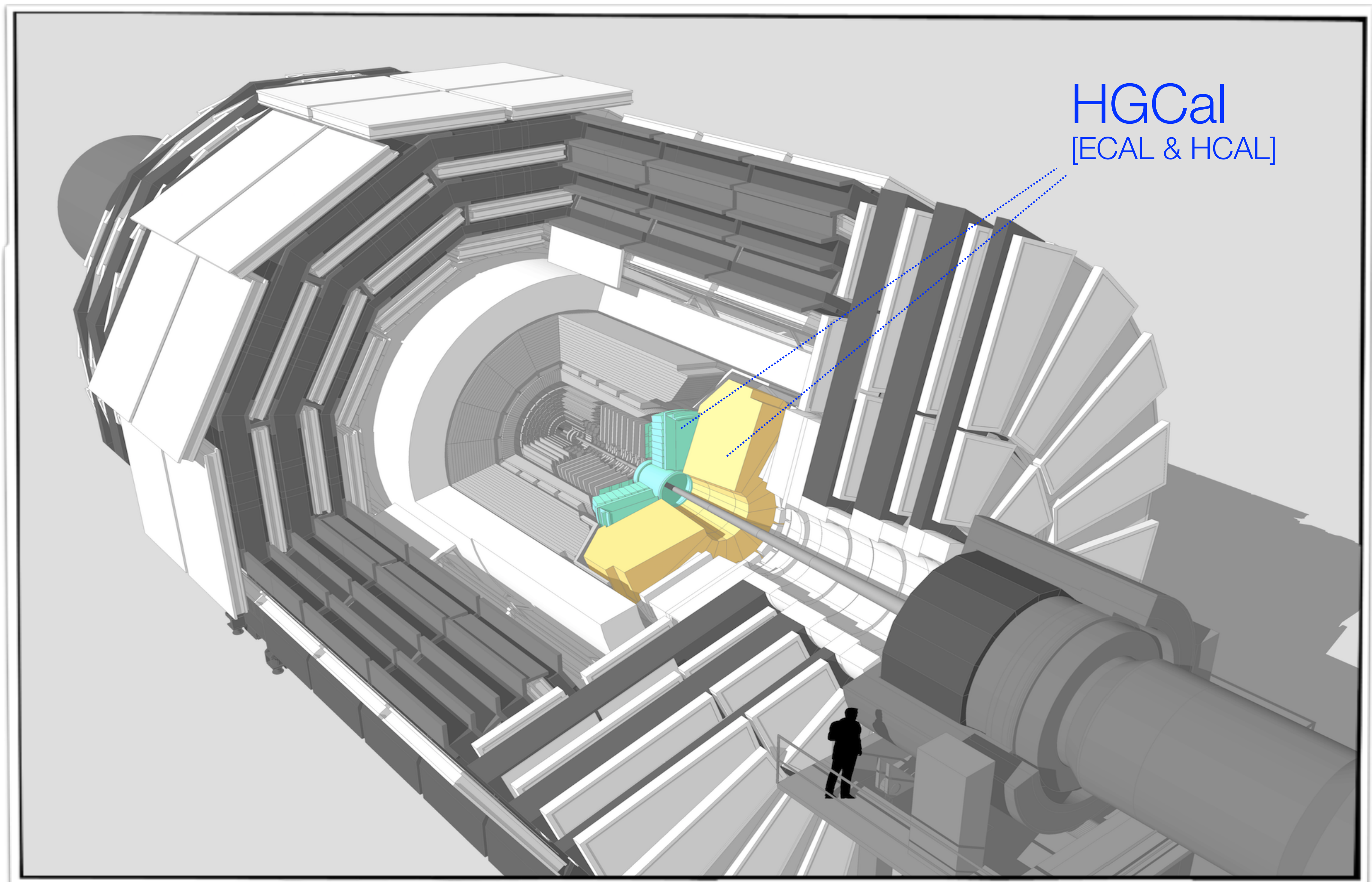


May 2018
SPS Test beam
Hadron shower

CMS
HGCAL

High Granularity Calorimeter @ CMS



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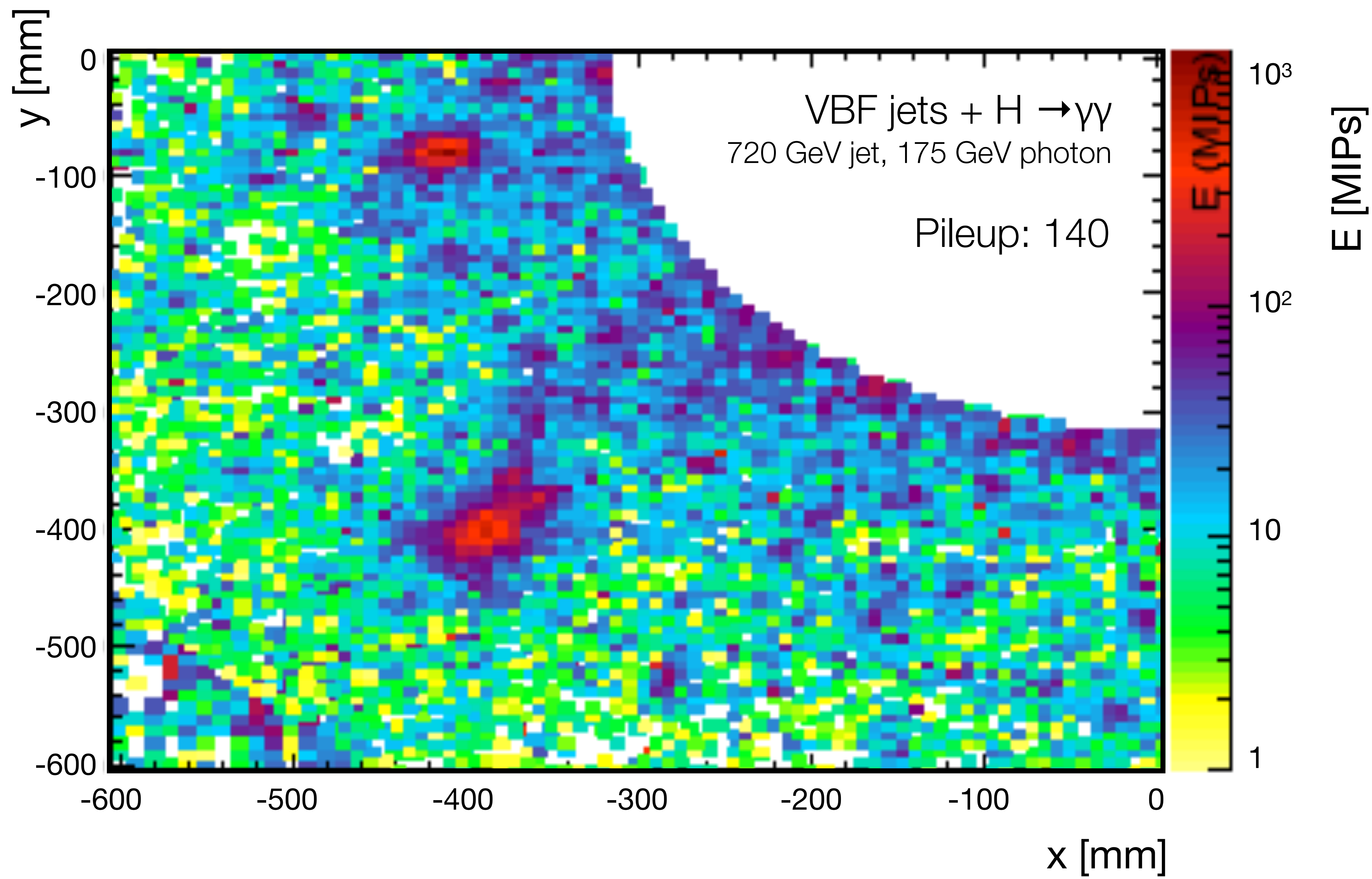
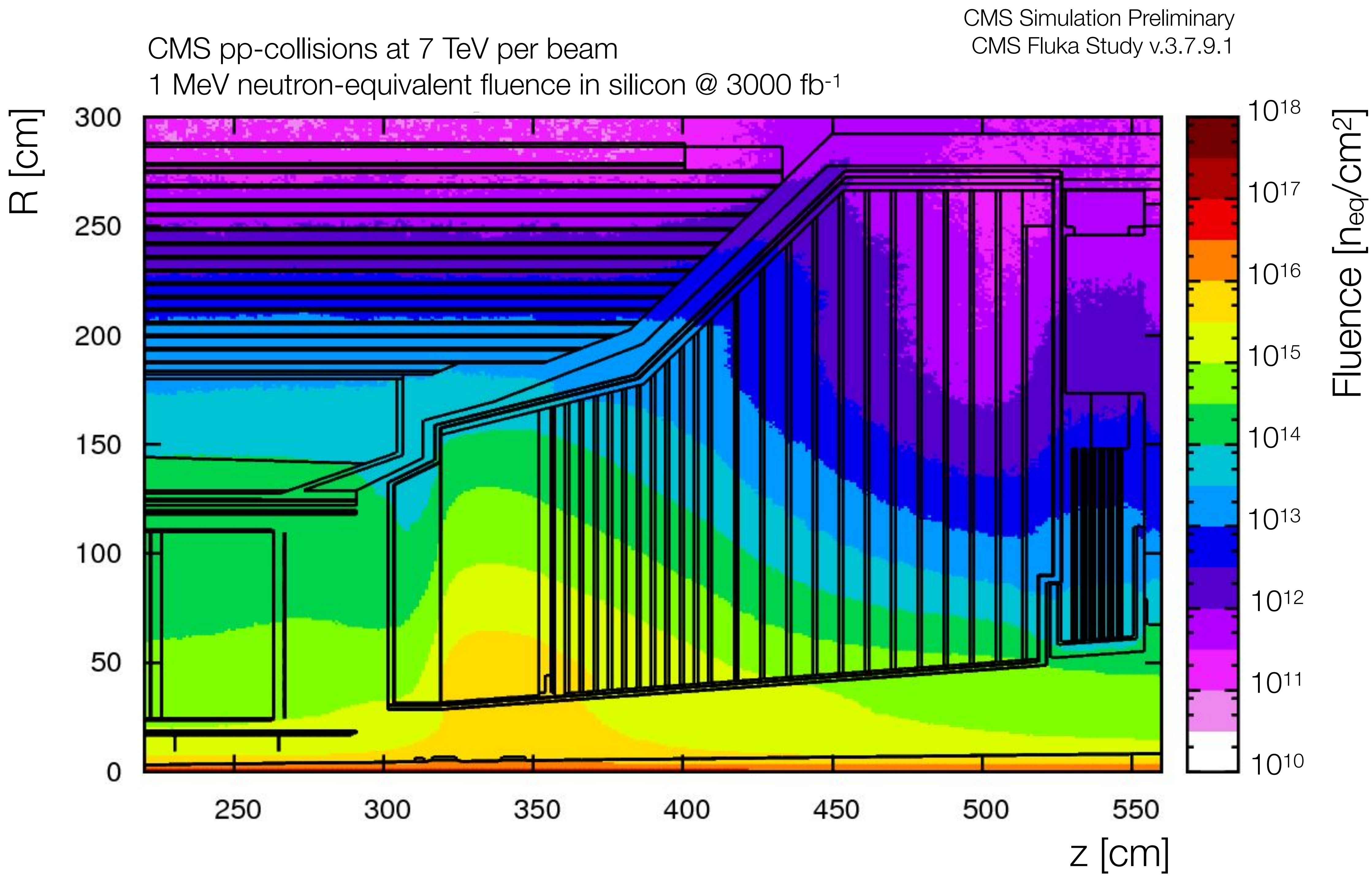


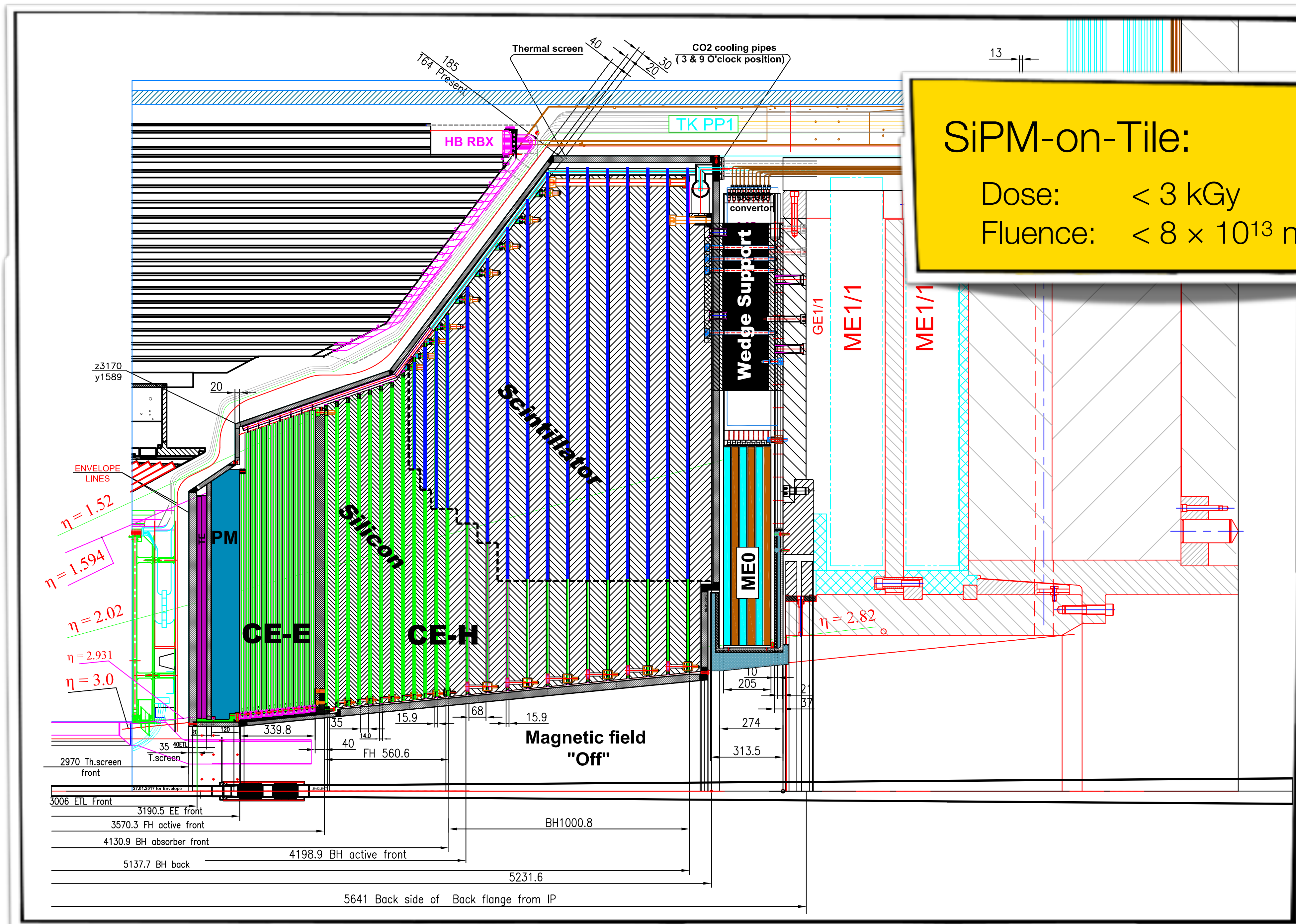
High Granularity Calorimeter @ CMS

[CMS-TDR-17-007]



High Granularity Calorimeter @ CMS

[CMS-TDR-17-007]



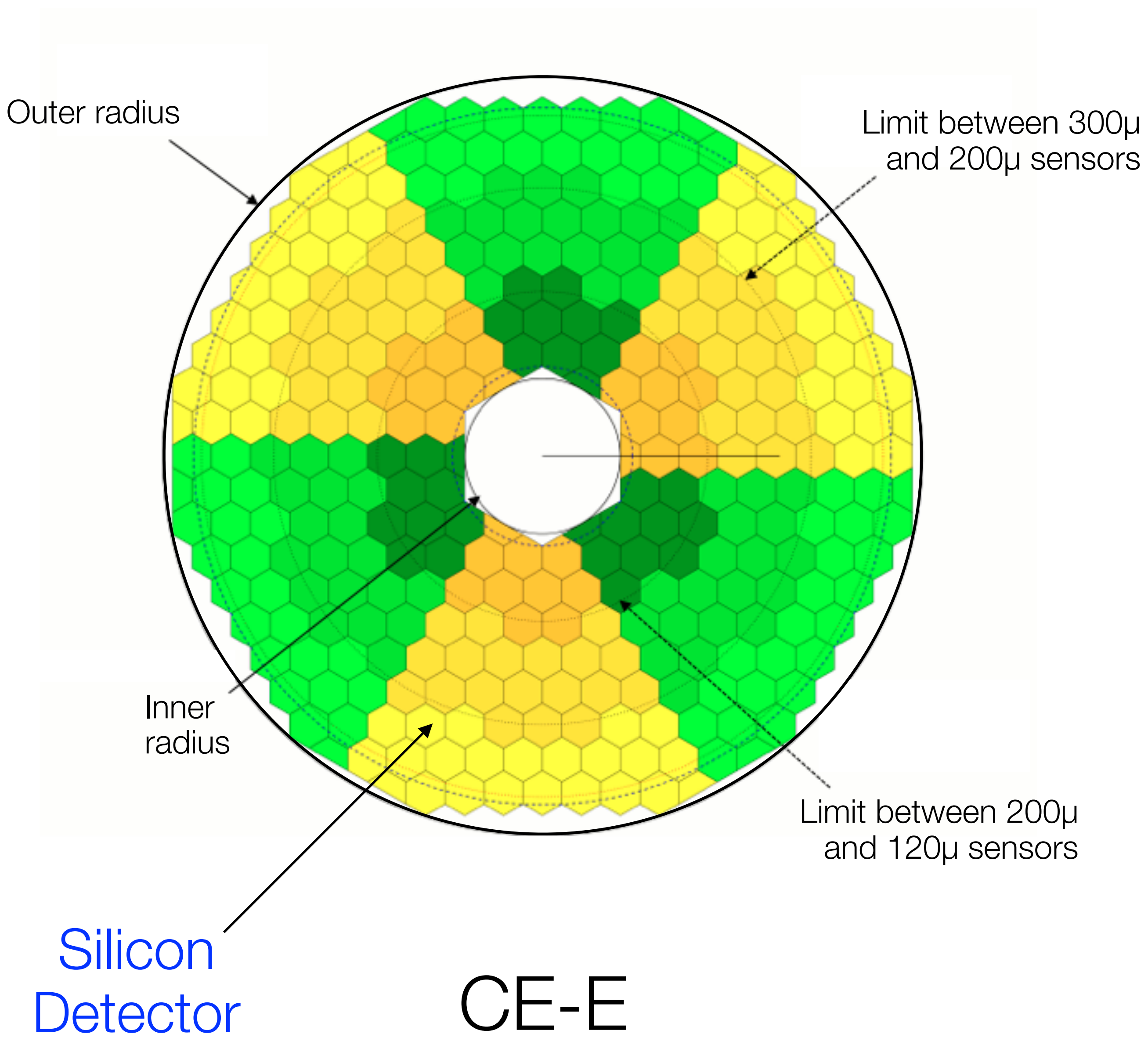
SiPM-on-Tile:

Dose: < 3 kGy

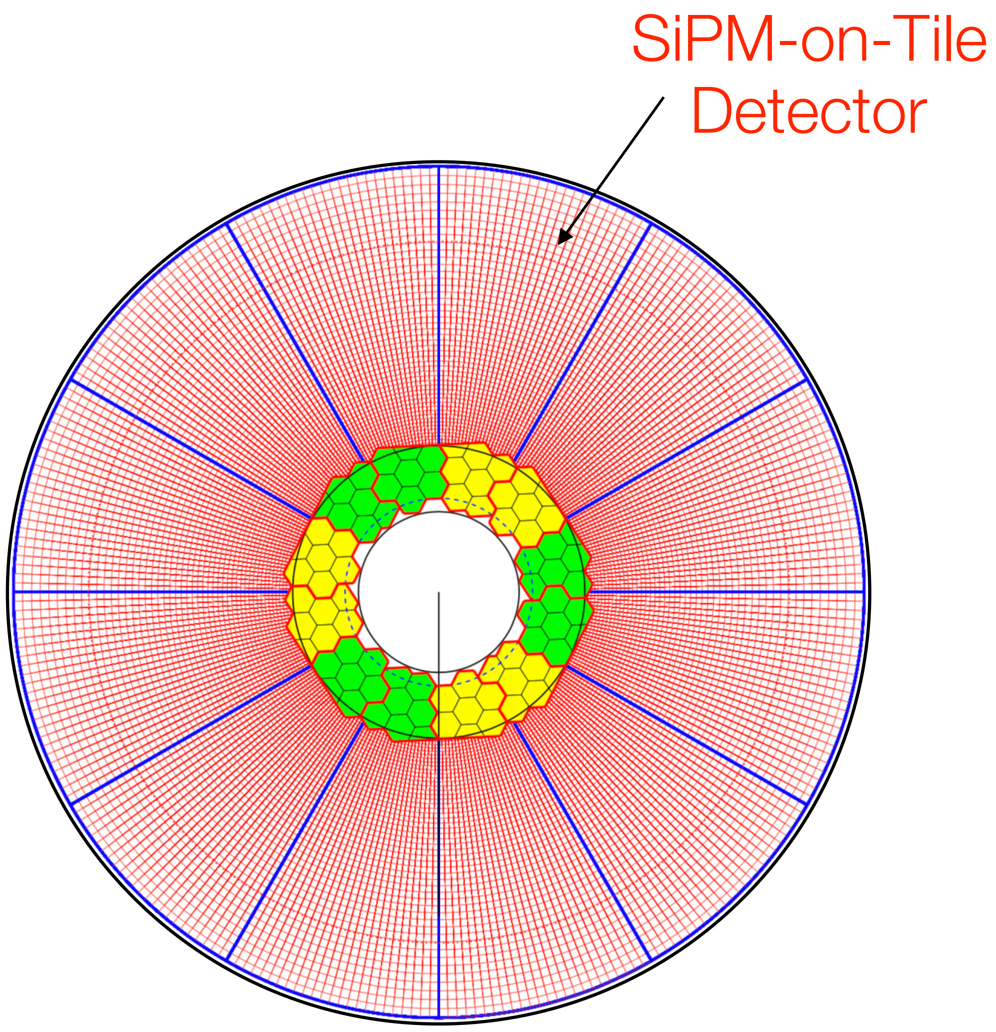
Fluence: < 8 × 10^{13} n_{eq}/cm^2

High Granularity Calorimeter @ CMS

[CMS-TDR-17-007]



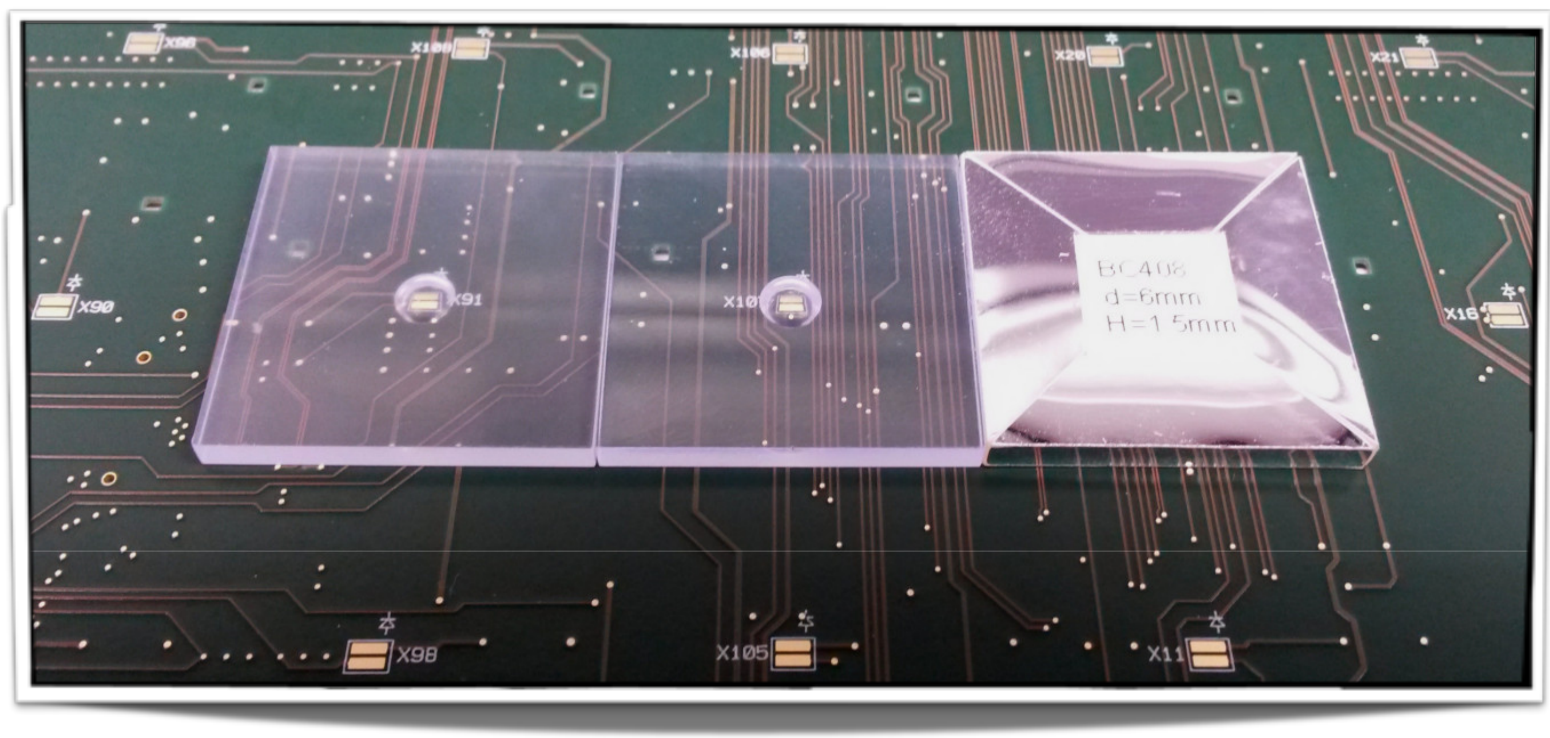
CE-E
9th layer

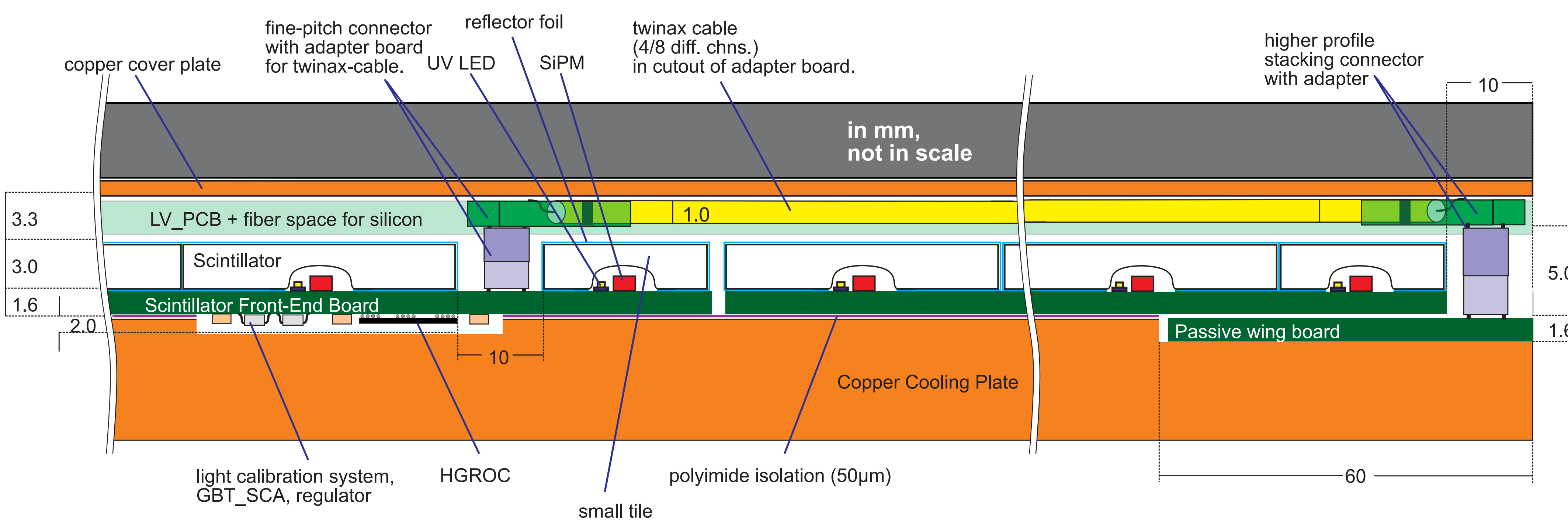


CE-H
22nd layer

High Granularity Calorimeter @ CMS

[CMS-TDR-17-007]





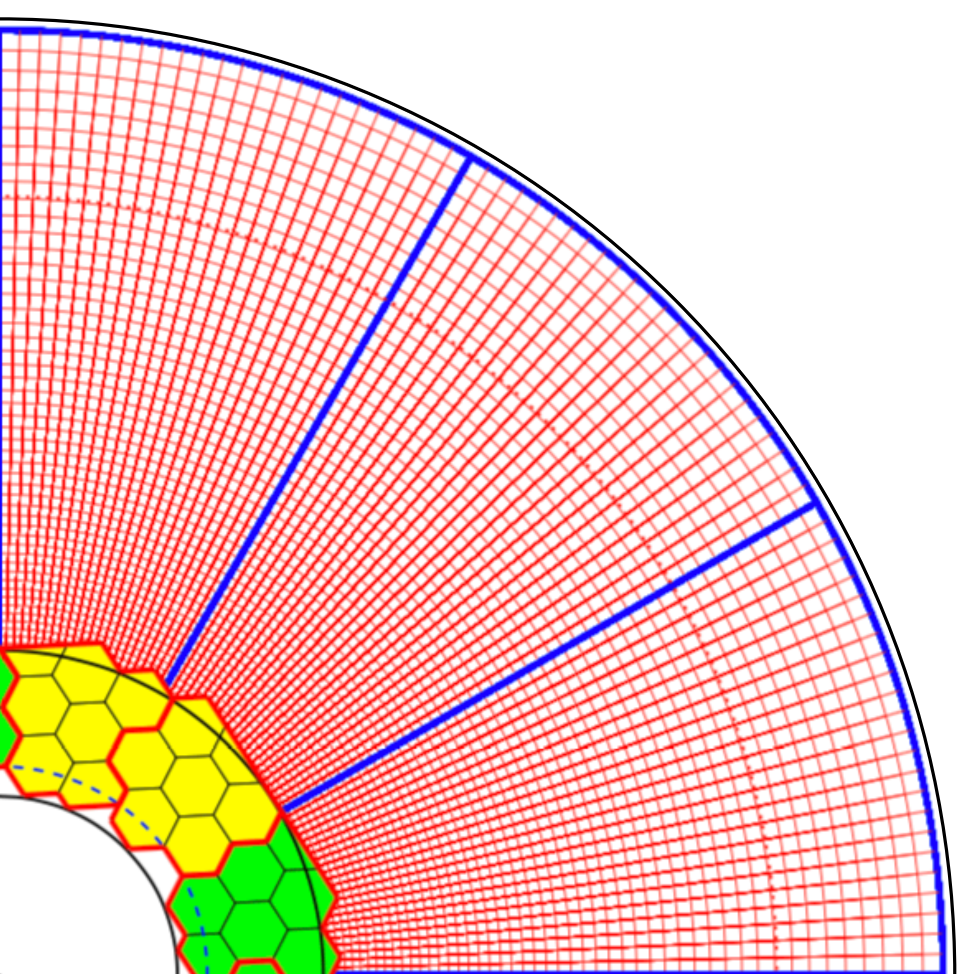
High Granularity Calorimeter @ CMS

[CMS-TDR-17-007]

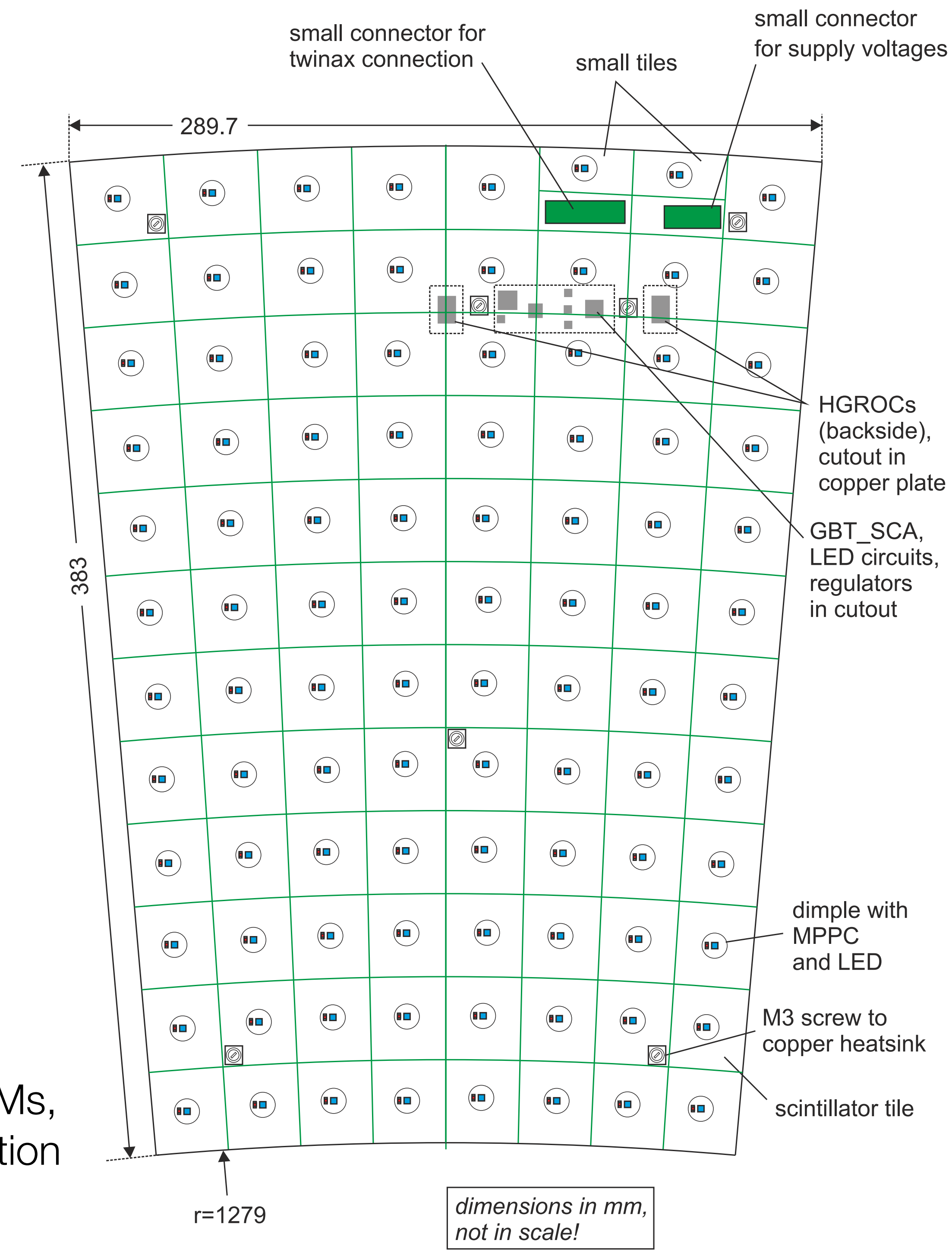
Tile Segmentation:

Small tiles ➛ more signal
Larger SIPMs ➛ better S/N

Inner tiles: 4 cm^2
Outer tiles: 32 cm^2



Tile-Board with scintillator tiles, SiPMs, readout and calibration electronics …



High Granularity Calorimeter @ CMS

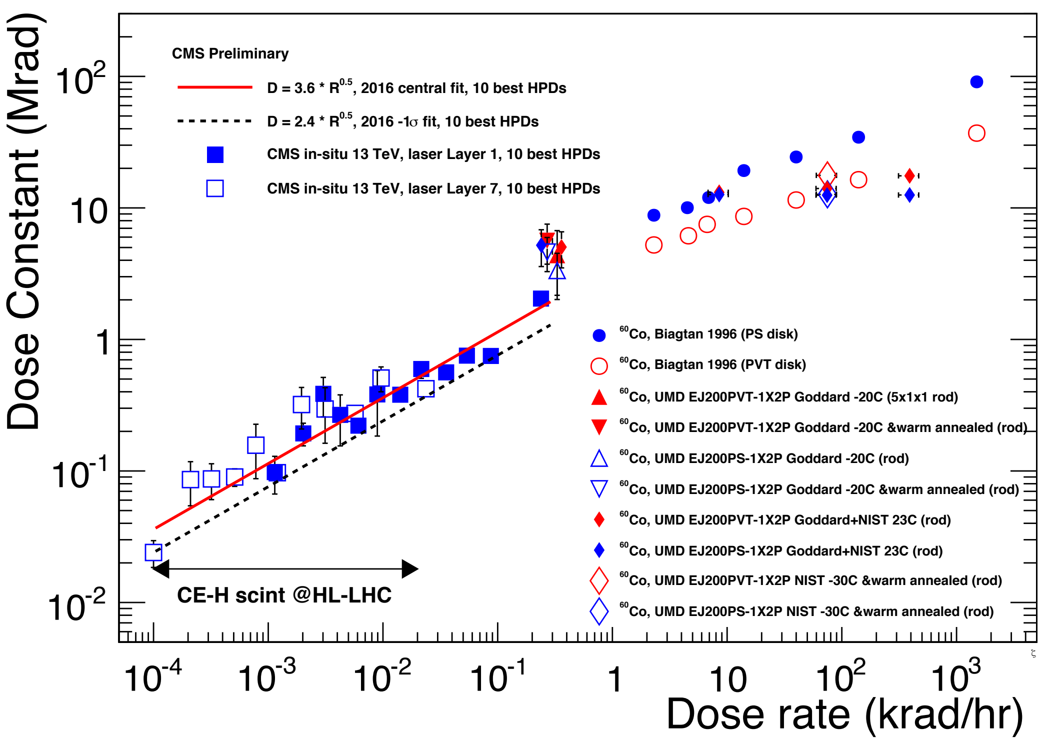
[CMS-TDR-17-007]

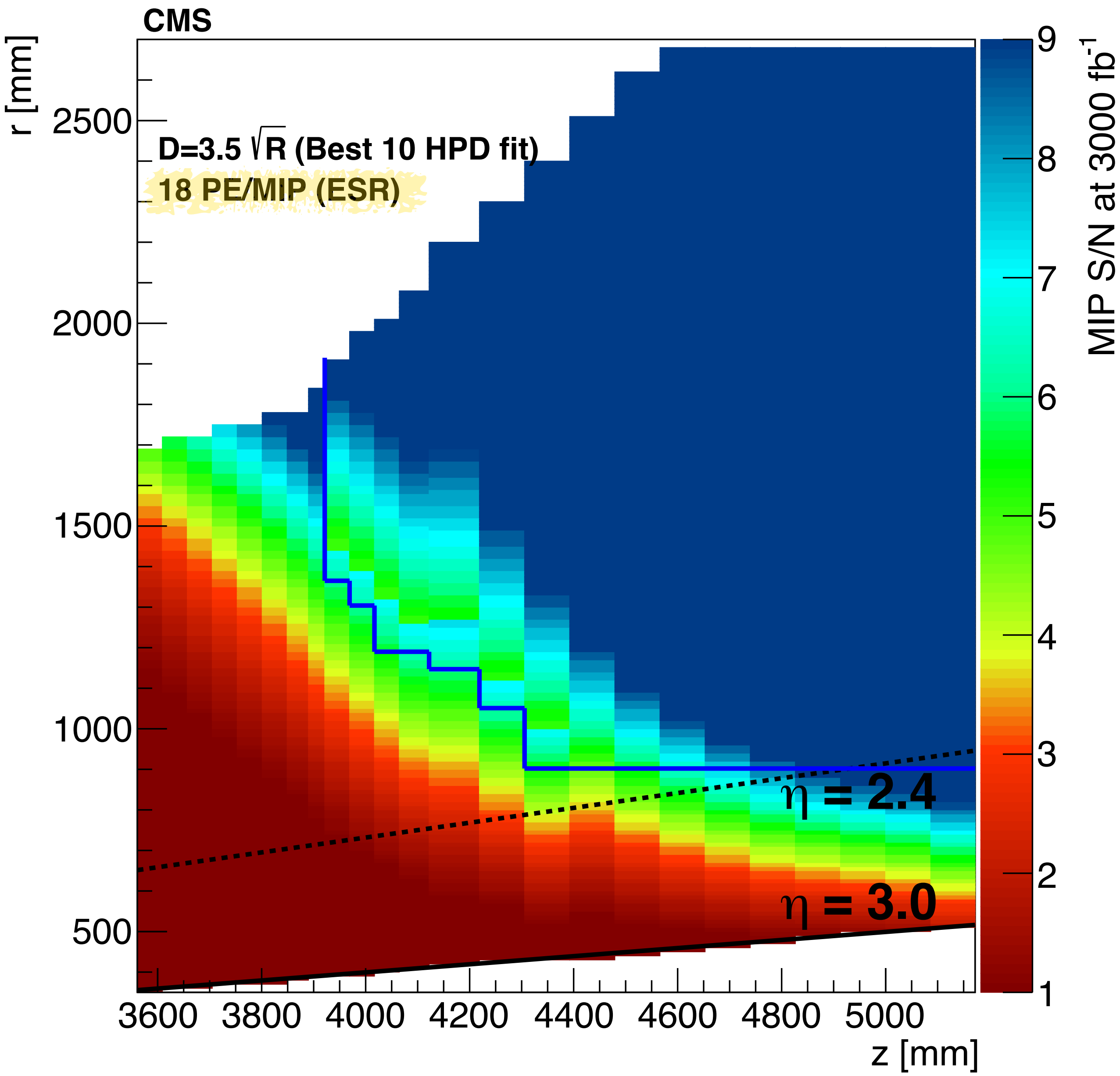
Tile Radiation Tolerance

Measurements based on existing detector [HCAL endcap]

Dose constant: $D_c = 3.6\,\mathrm{MRad}\sqrt{\frac{R}{1\,\mathrm{krad/h}}}$

$$\mathrm{LY} = \mathrm{LY}_0 \cdot \exp\left(-d/D_c\right)$$





S/N > 5

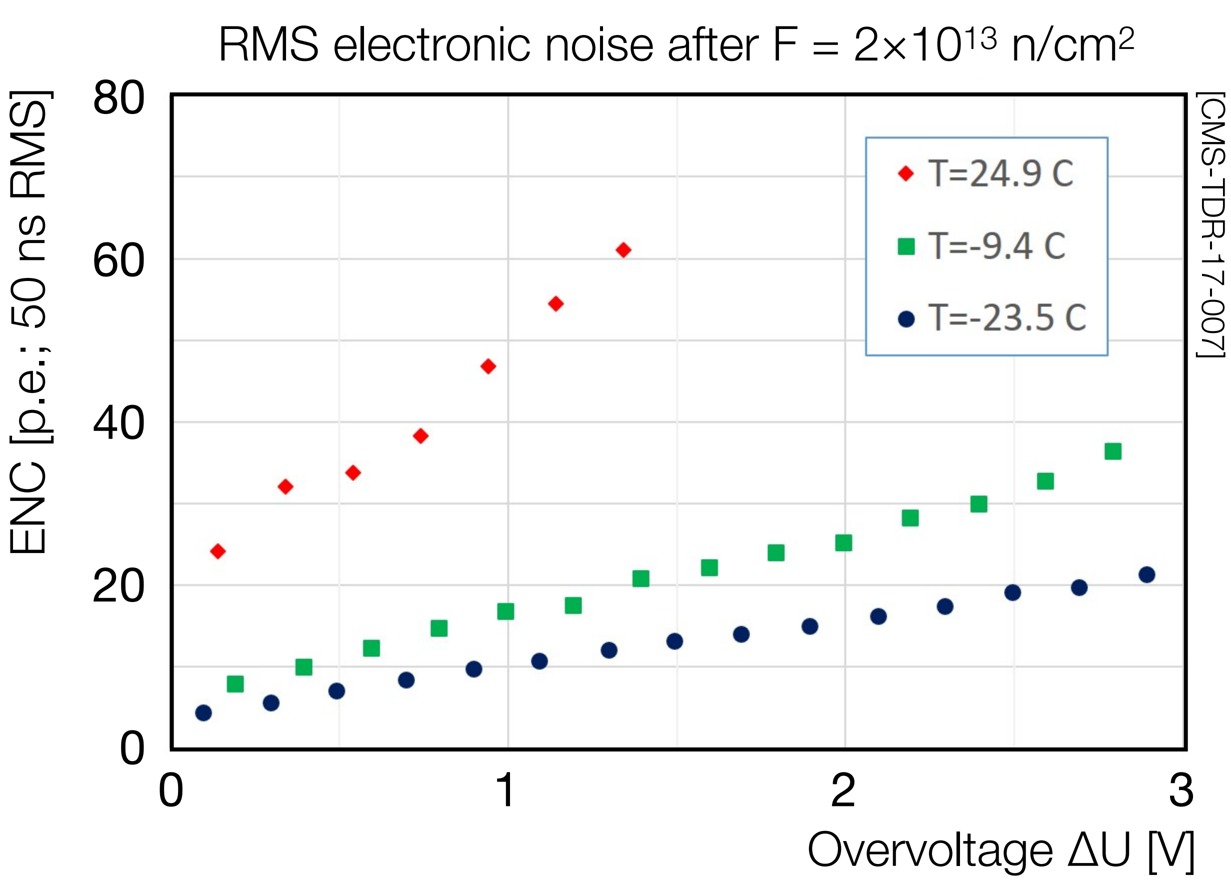
for SiPM-on-Tile Part

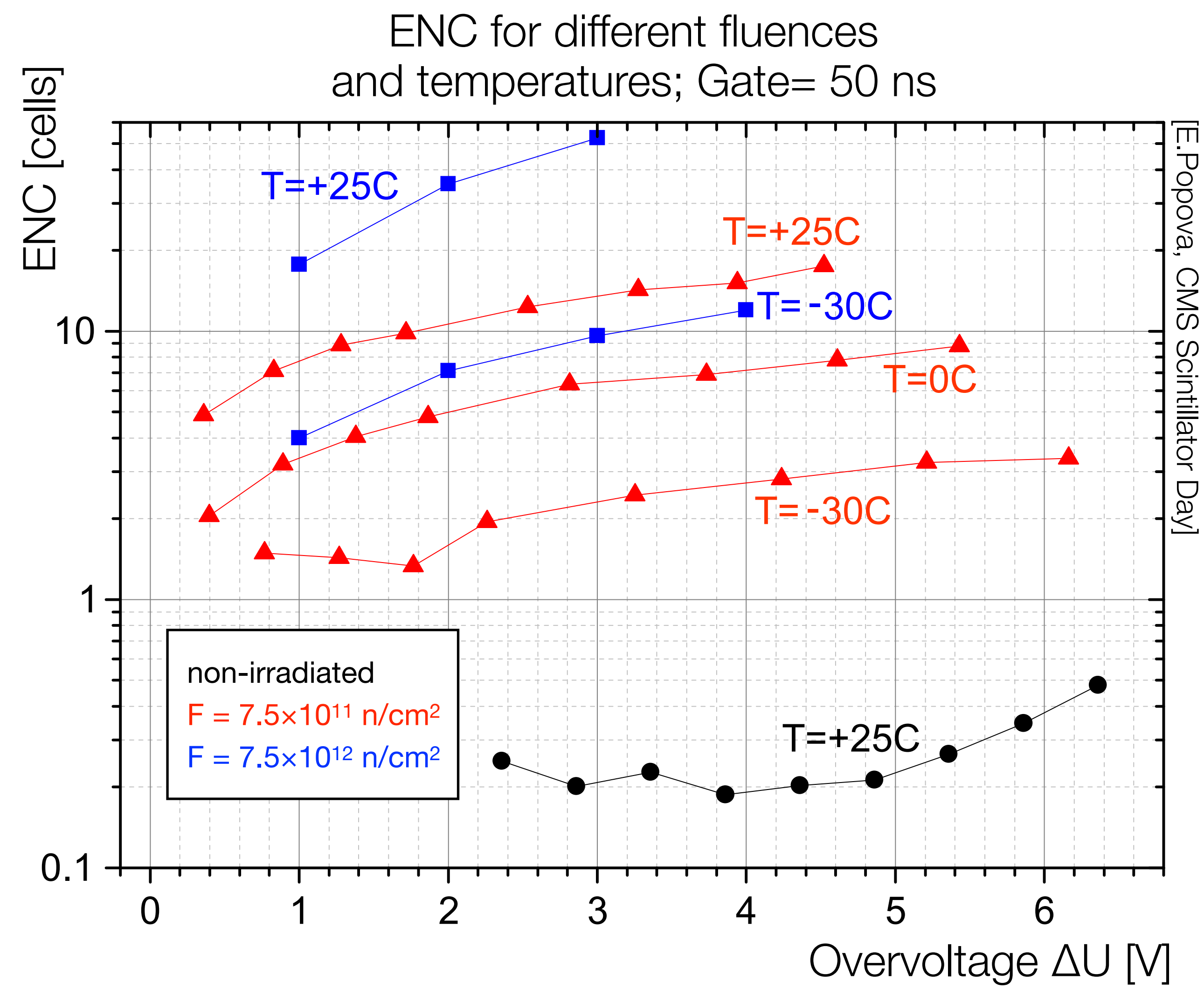
High Granularity Calorimeter @ CMS

SiPM Radiation Tolerance

Dark current increase
by up to a factor O(1000) …

Measured for
MPPC S10943-4732
[A = 6.15 mm²]



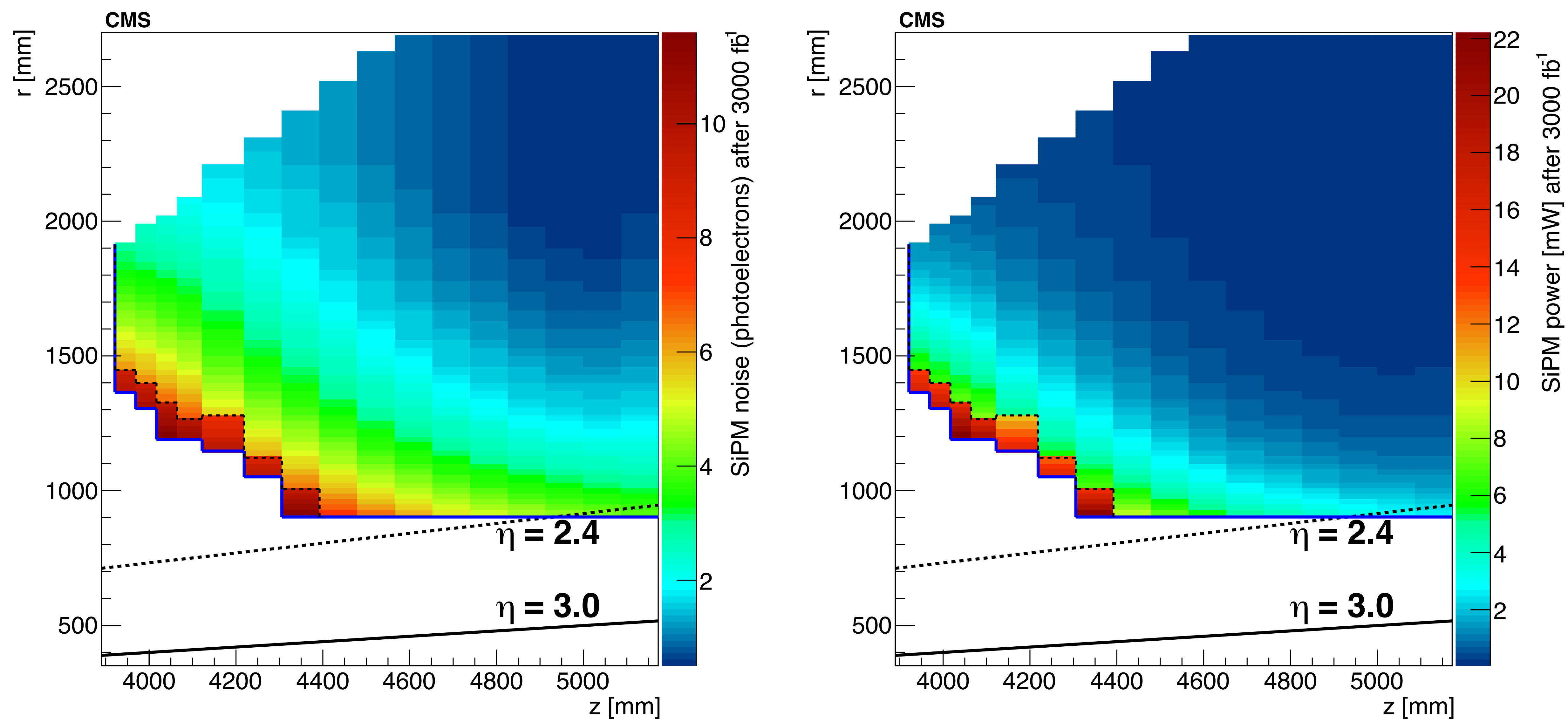


Measurements used
for S/N estimates

High Granularity Calorimeter @ CMS

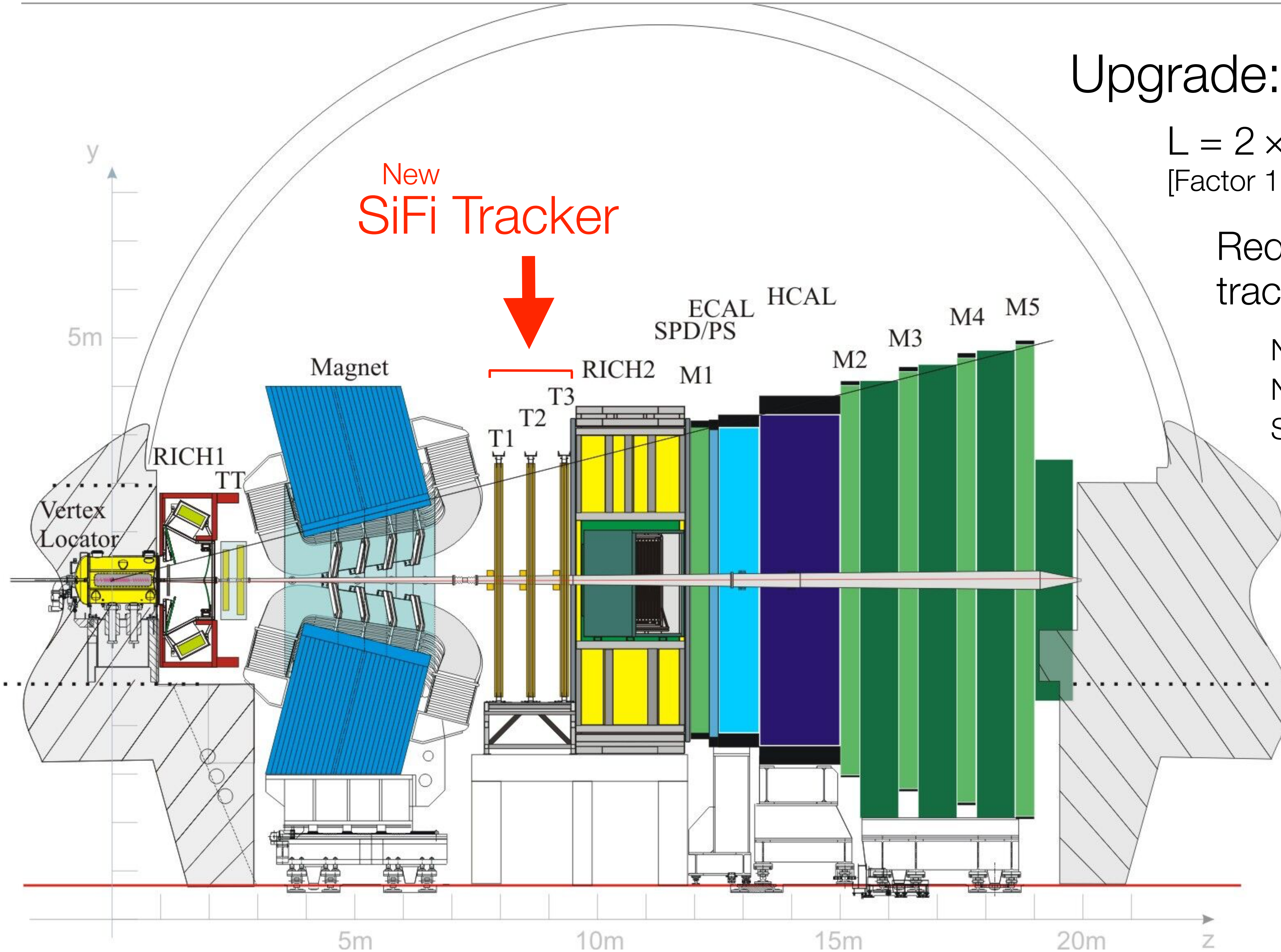
[CMS-TDR-17-007]

Projected SiPM noise level and leakage current power after taking 3000 fb^{-1}



LHCb Fibre Tracker

Scintillating Fibre Tracker @ LHCb



Upgrade:

$L = 2 \times 10^{33}\ cm^{-2}s^{-1}$

[Factor 10 rate increase]

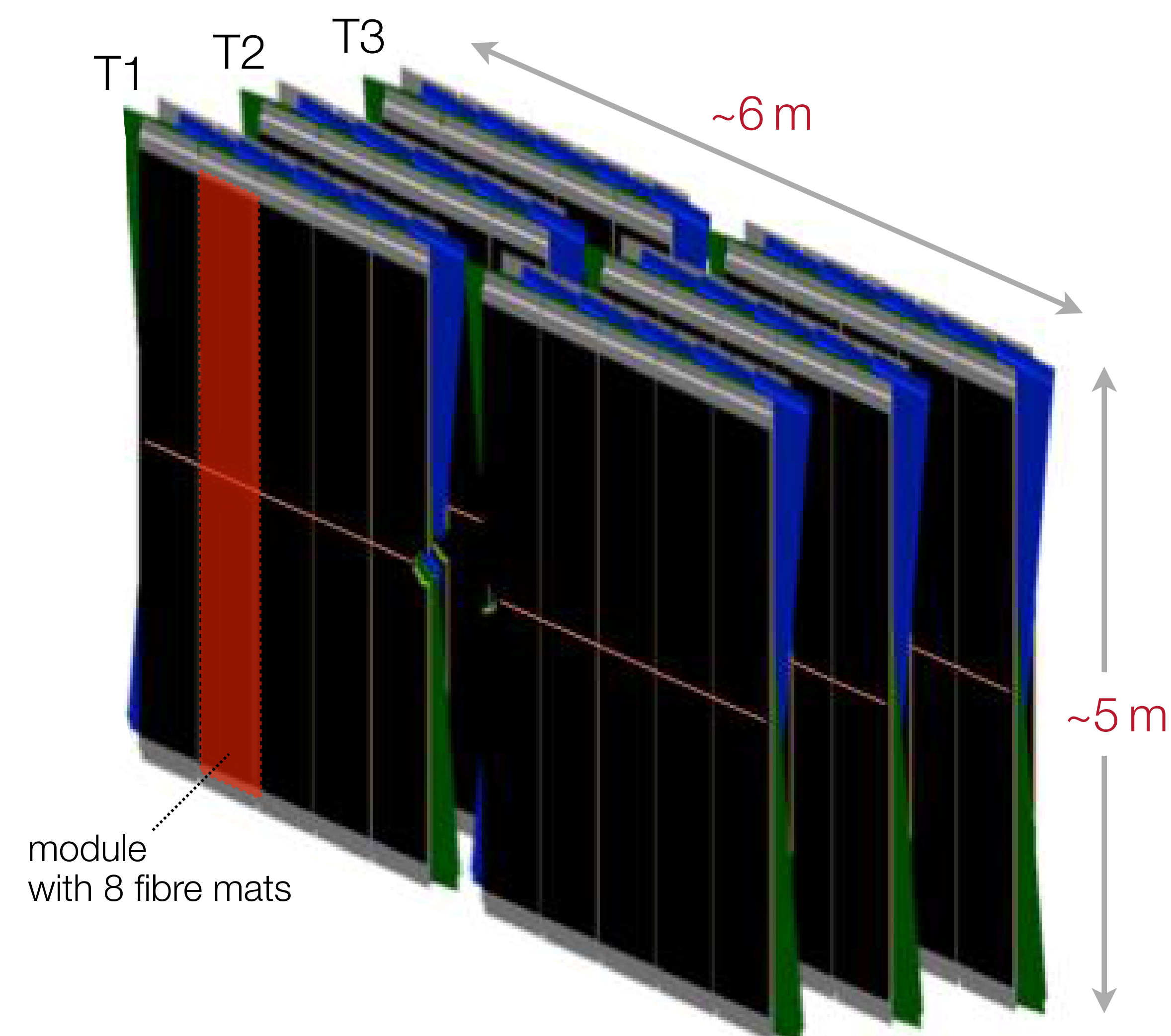
Requires new tracking system …

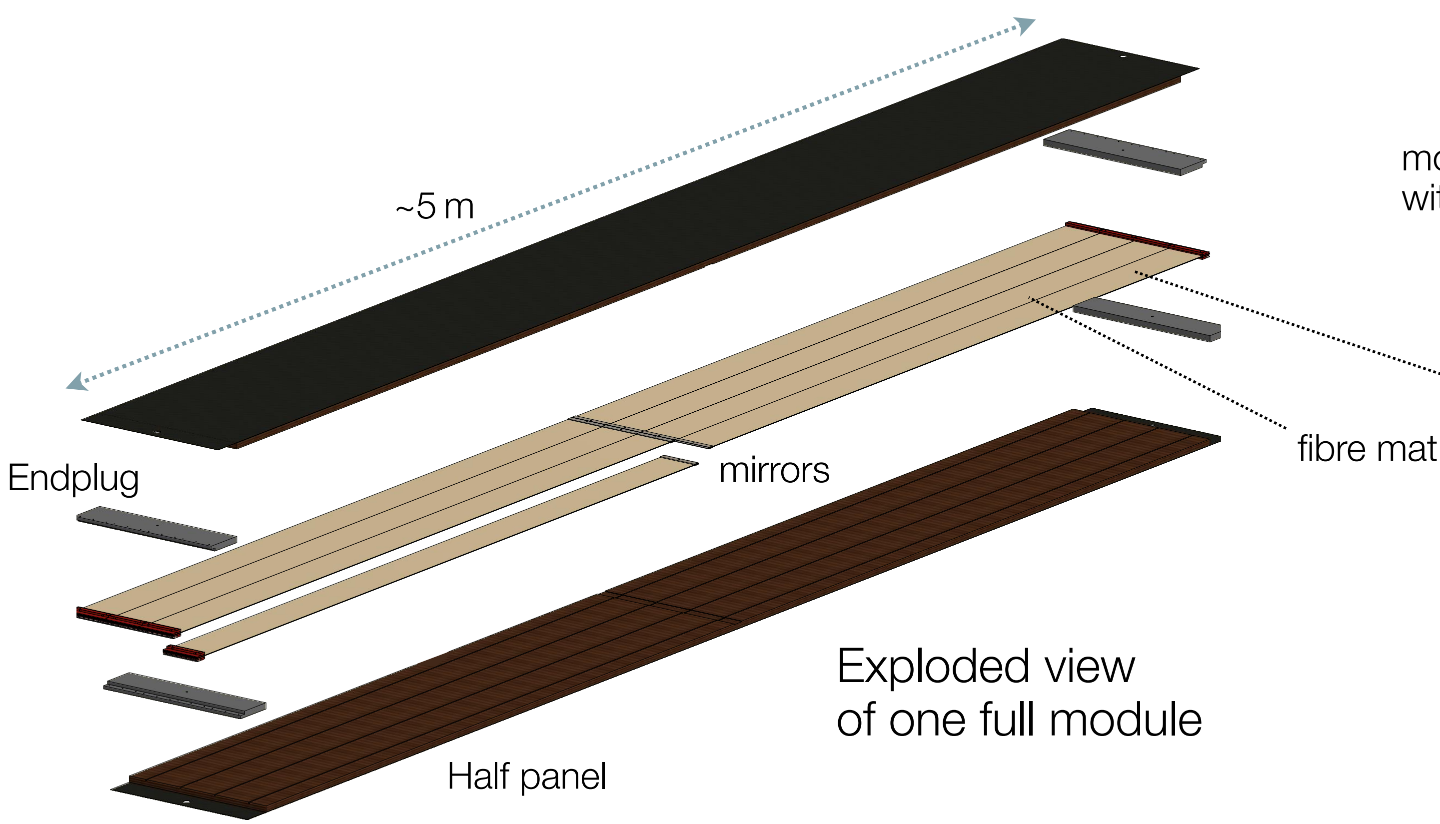
New vertex detector
New Si-strip detector
Scintillating fibre tracker

Scintillating Fibre Tracker @ LHCb

SiFi requirements:

High granularity	[250μm]
High spatial resolution	[$\Delta x < 100\mu m$]
Fast, high efficiency	[$\varepsilon \sim 99\%$]
Radiation tolerant	[up to 35 kGy]
Low material budget	[$< 1\%\ X_0$/layer]
Large area coverage	[$6 \times 5\ mm^2$]





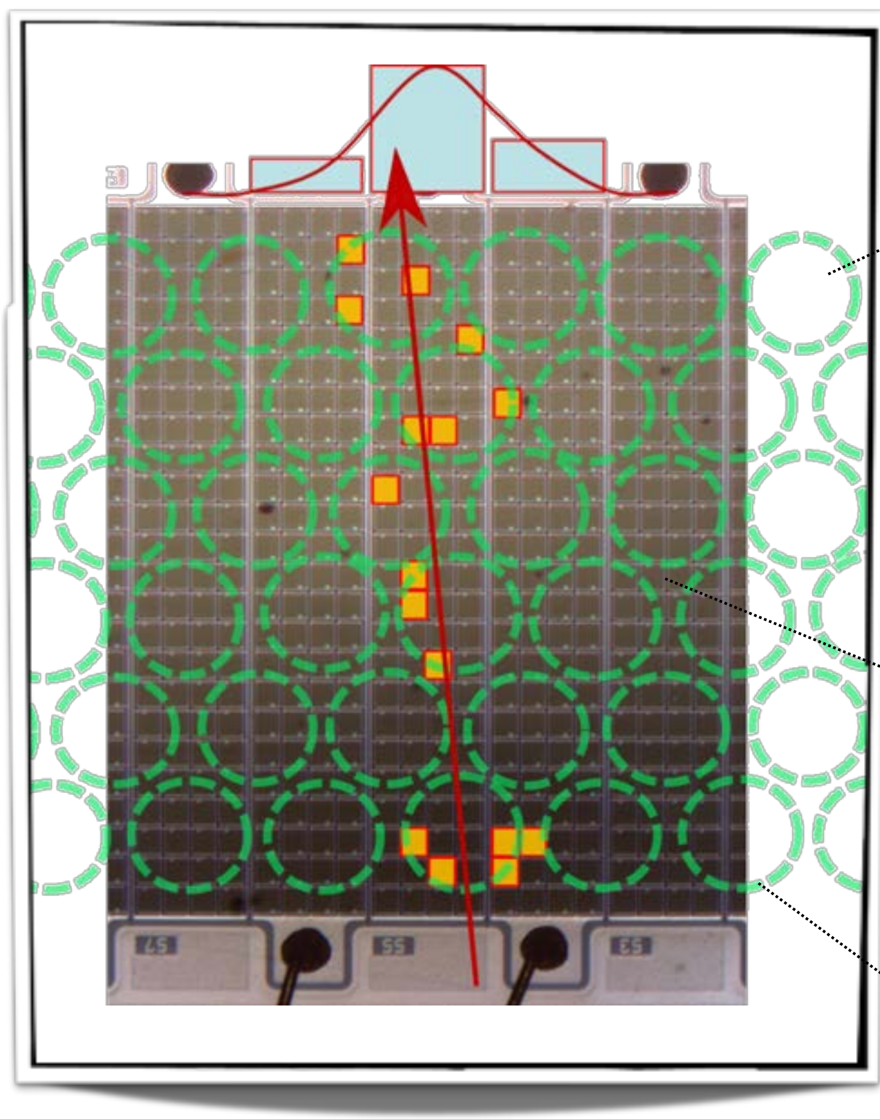
Exploded view
of one full module

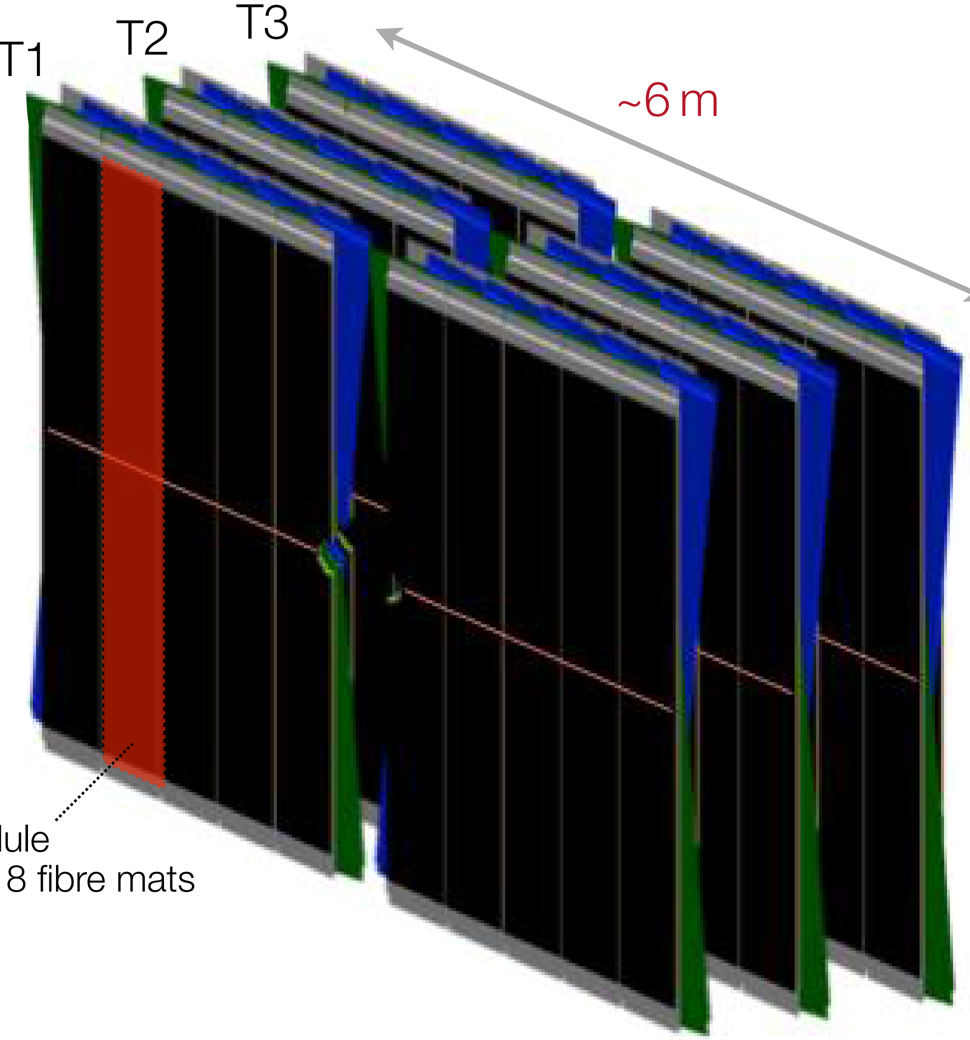
Cross Section
of fibre mat
[d_f = 250 μm]

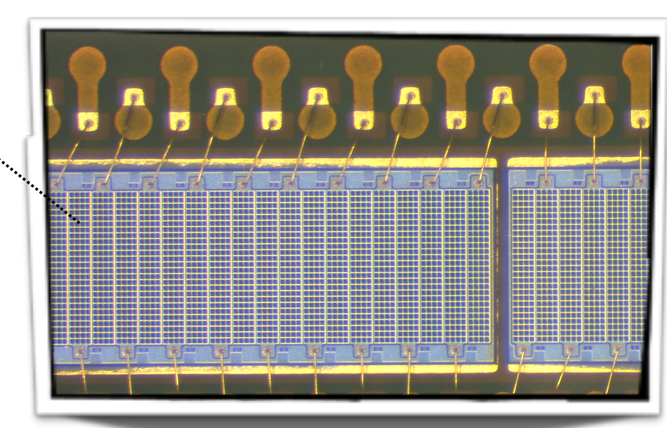
Scintillating Fibre Tracker @ LHCb

Light readout by SiPMs …

Light yield: 16-20 p.e. [6 layers]
Hit position from pulse height spectrum







SiPM multi-channel array
MPPC S13552-H2017

128 channels
104 pixels/channel

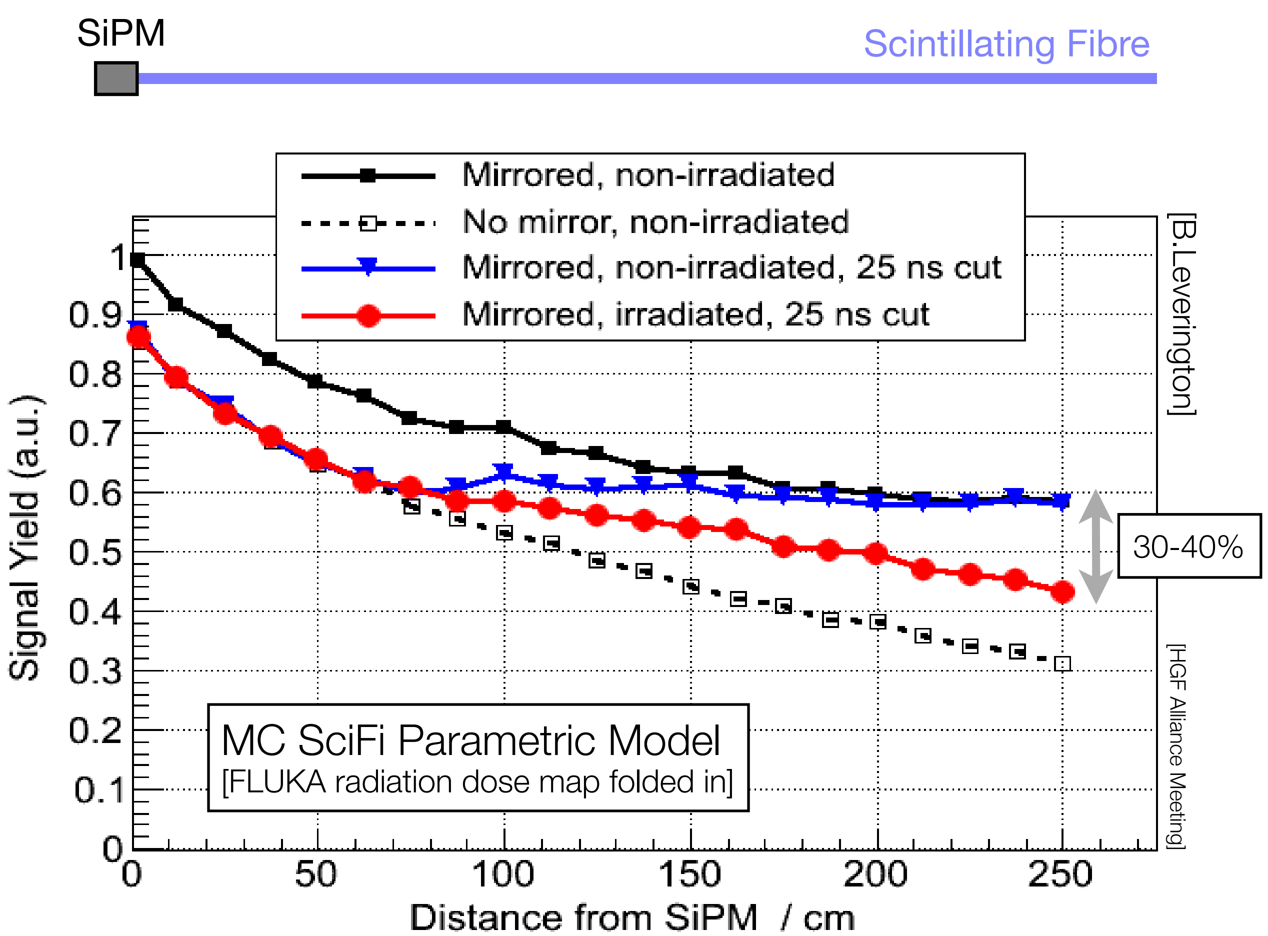
pixel size: 57 × 62 μm²
channel size: 0.25 × 1.62 mm²

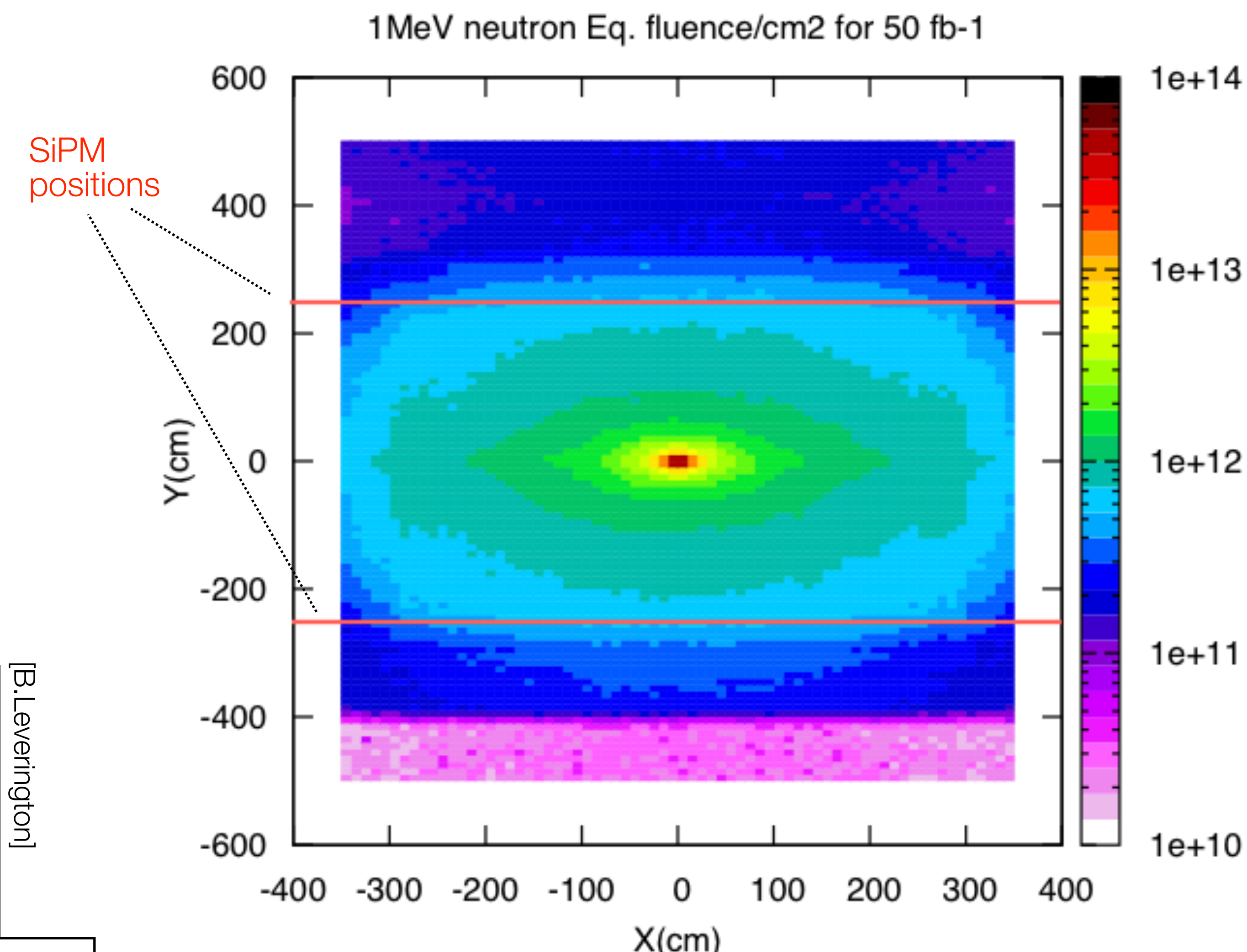
Scintillating Fibre Tracker @ LHCb

Fibre irradiation:

Expect dose up to 35 kGy
at end of lifetime i.e. @ 50 fb^{-1}

Expected light yield reduction: 40%





Test beam result:

[non-irradiated mat w/ mirror]

x = 60 cm: LY = 20 p.e.
x = 200 cm: LY = 16 p.e. ➧ LY ≈ 10 p.e. after irr.

[CERN-LHCb-PUB-2015-025 , p.29]

Scintillating Fibre Tracker @ LHCb

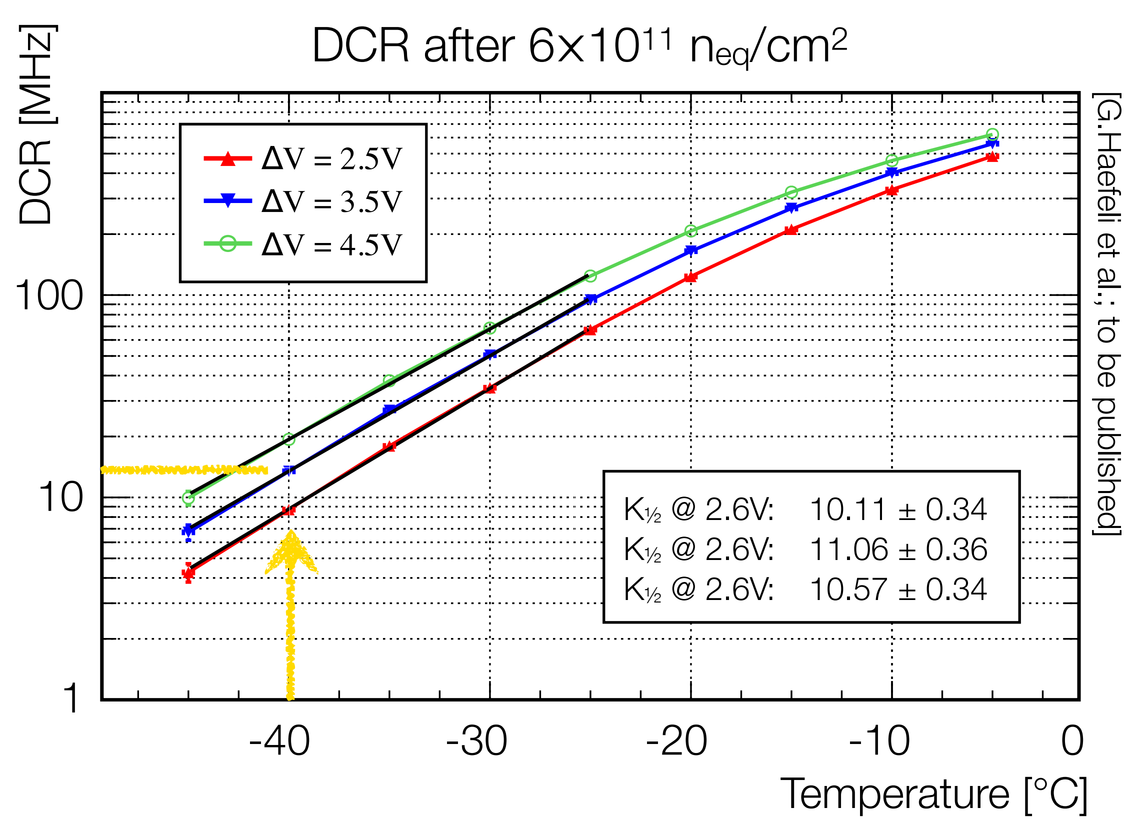
SiPM irradiation:

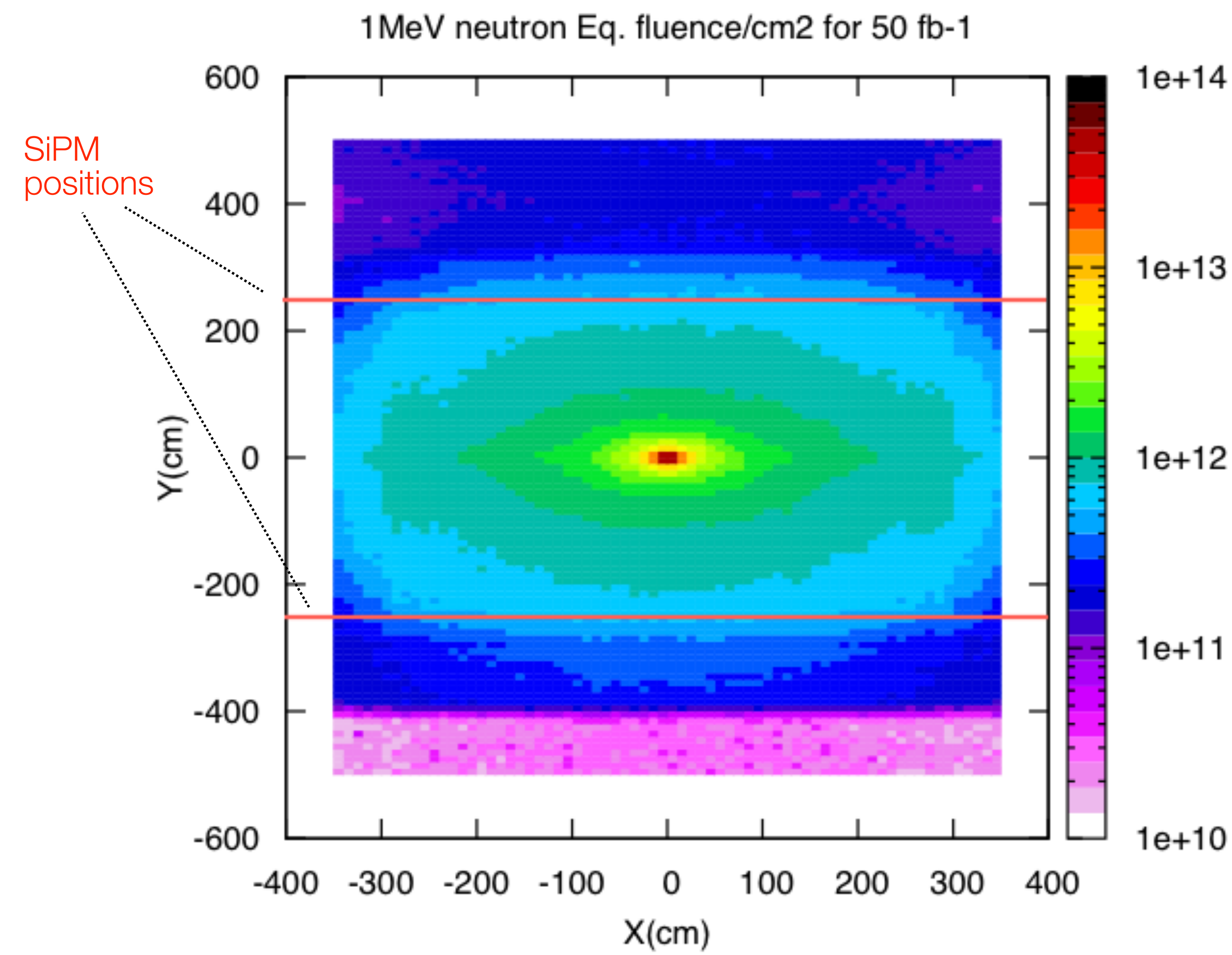
Expect 6 x 10^{11} n_{eq}/cm^2
at end of lifetime i.e. @ 50 fb^{-1}

Yields massive DCR increase …

Other observations:

Less than 5% PDE change
Less than 10% change in gain
No change in cross-talk





SiPM operation @ -40 °C
Signal detection still possible @ 6×10^{11} n_{eq}/cm^2

DCR reduced by factor 2 every 10°C
DCR @ 12 MHz/channel, i.e. 30 MHz/mm

Scintillating Fibre Tracker @ LHCb

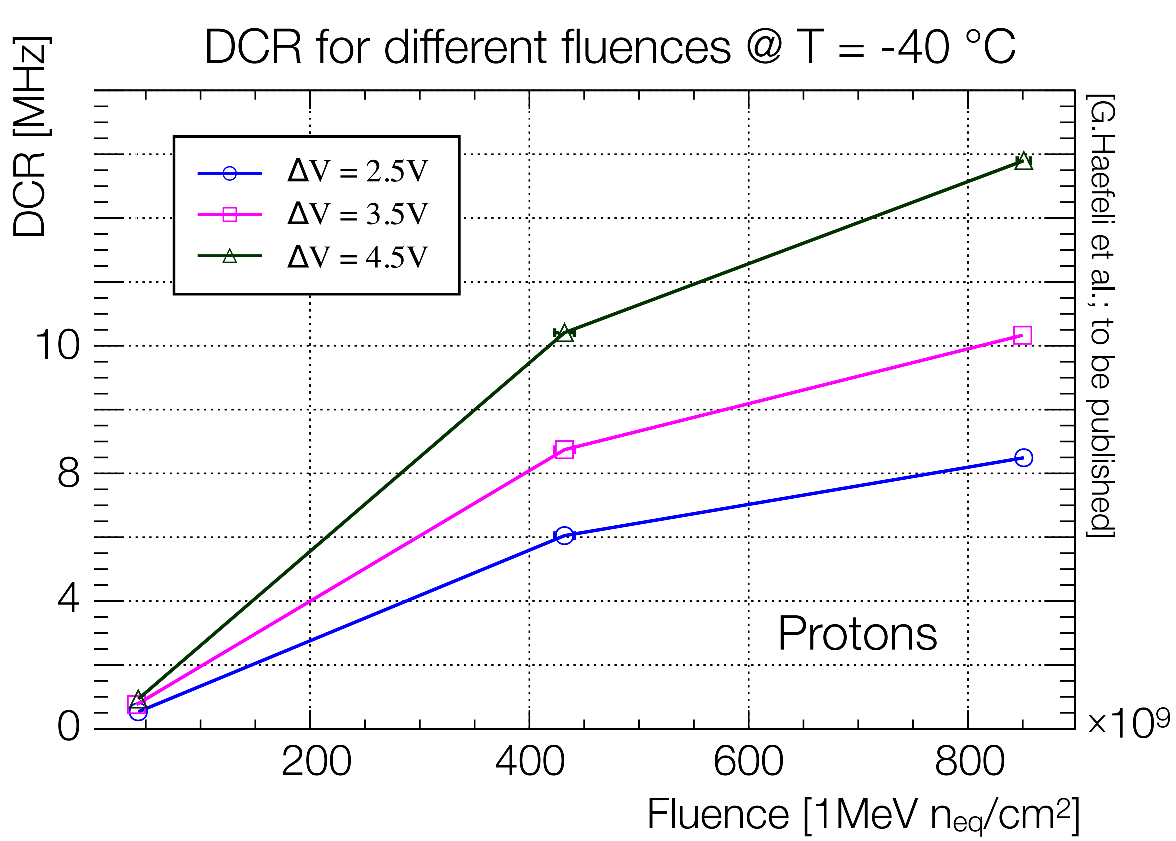
SiPM irradiation:

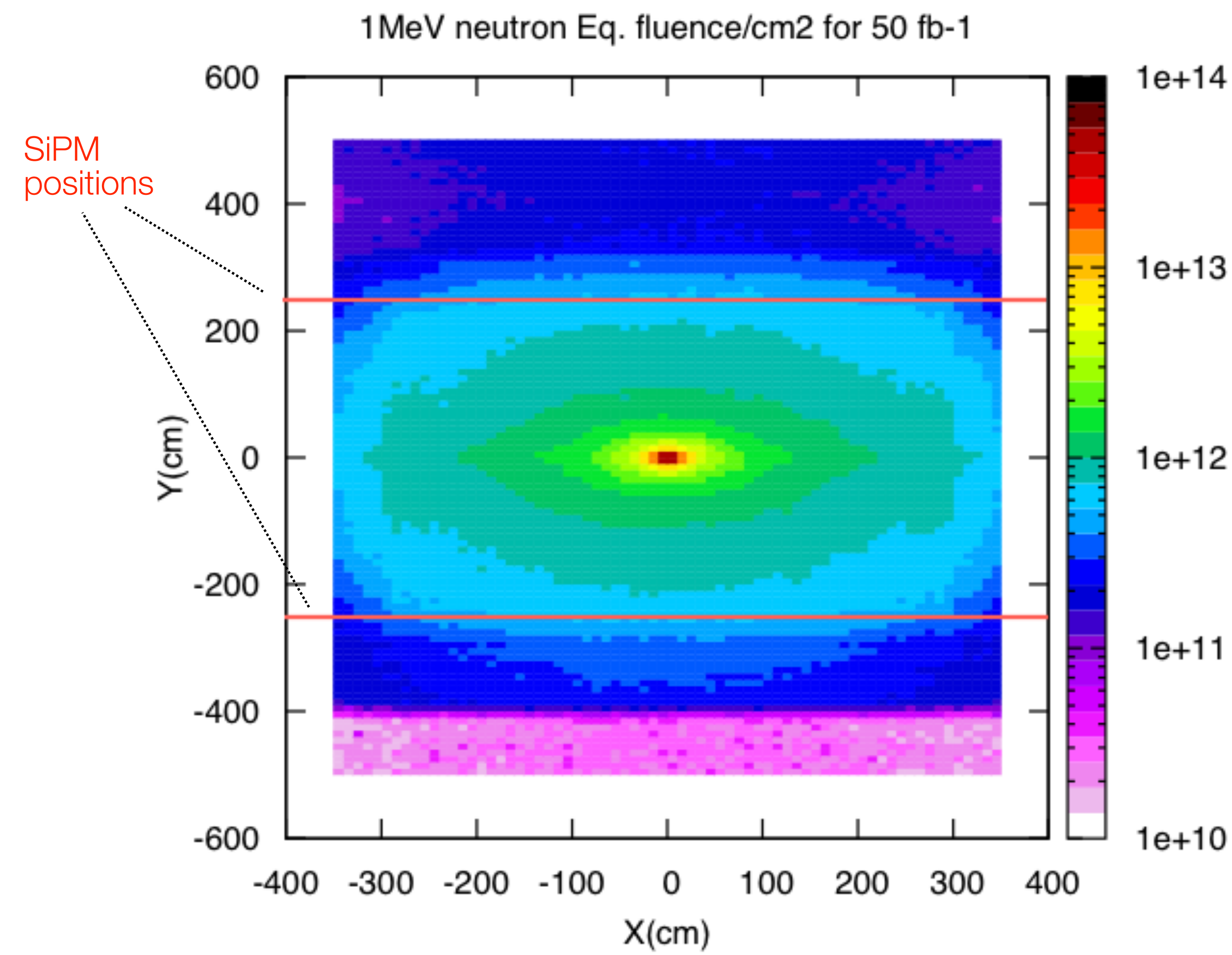
Expect 6×10^{11} n_{eq}/cm^2
at end of lifetime i.e. @ 50 fb^{-1}

Yields massive DCR increase …

Other observations:

Less than 5% PDE change
Less than 10% change in gain
No change in cross-talk





SiPM operation @ -40 °C
Signal detection still possible @ 6×10^{11} n_{eq}/cm^2

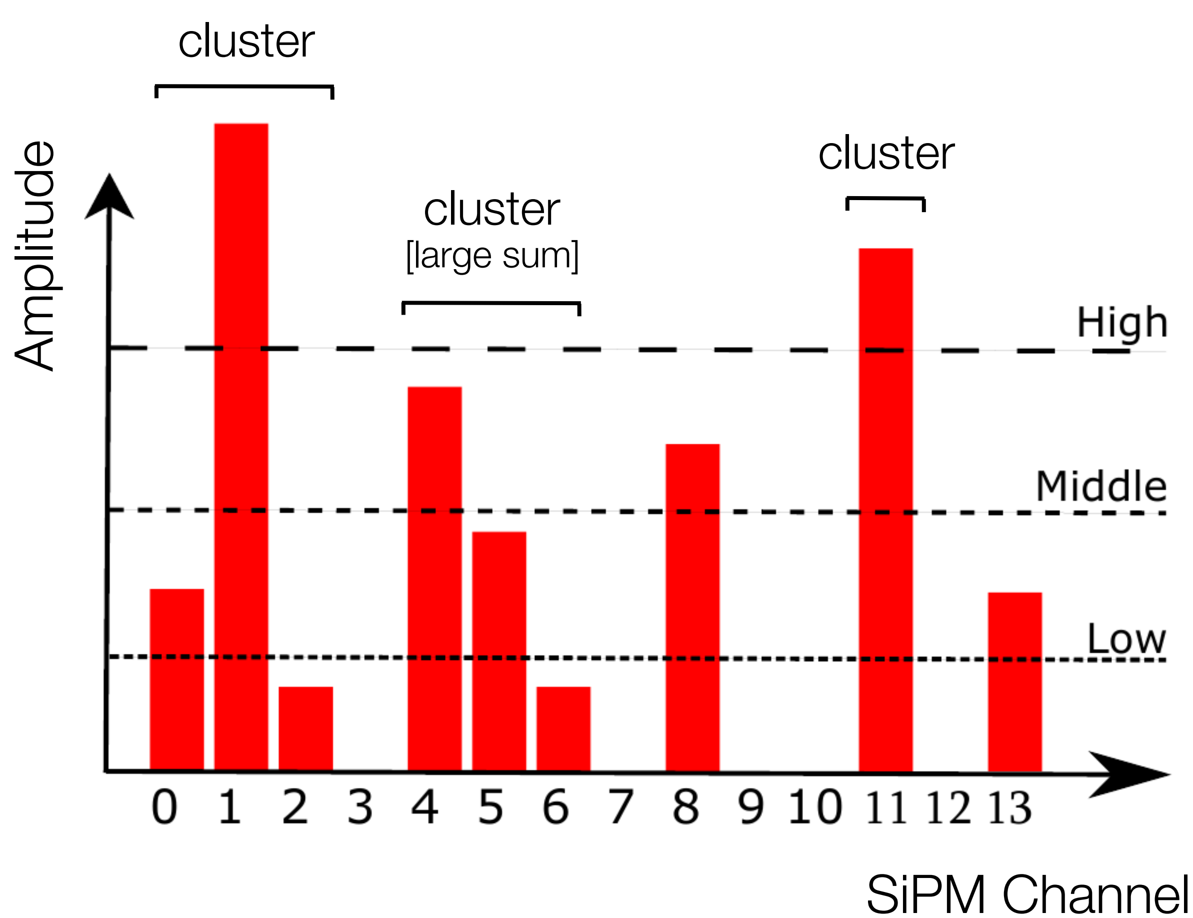
DCR reduced by factor 2 every 10°C
DCR @ 12 MHz/channel, i.e. 30 MHz/mm

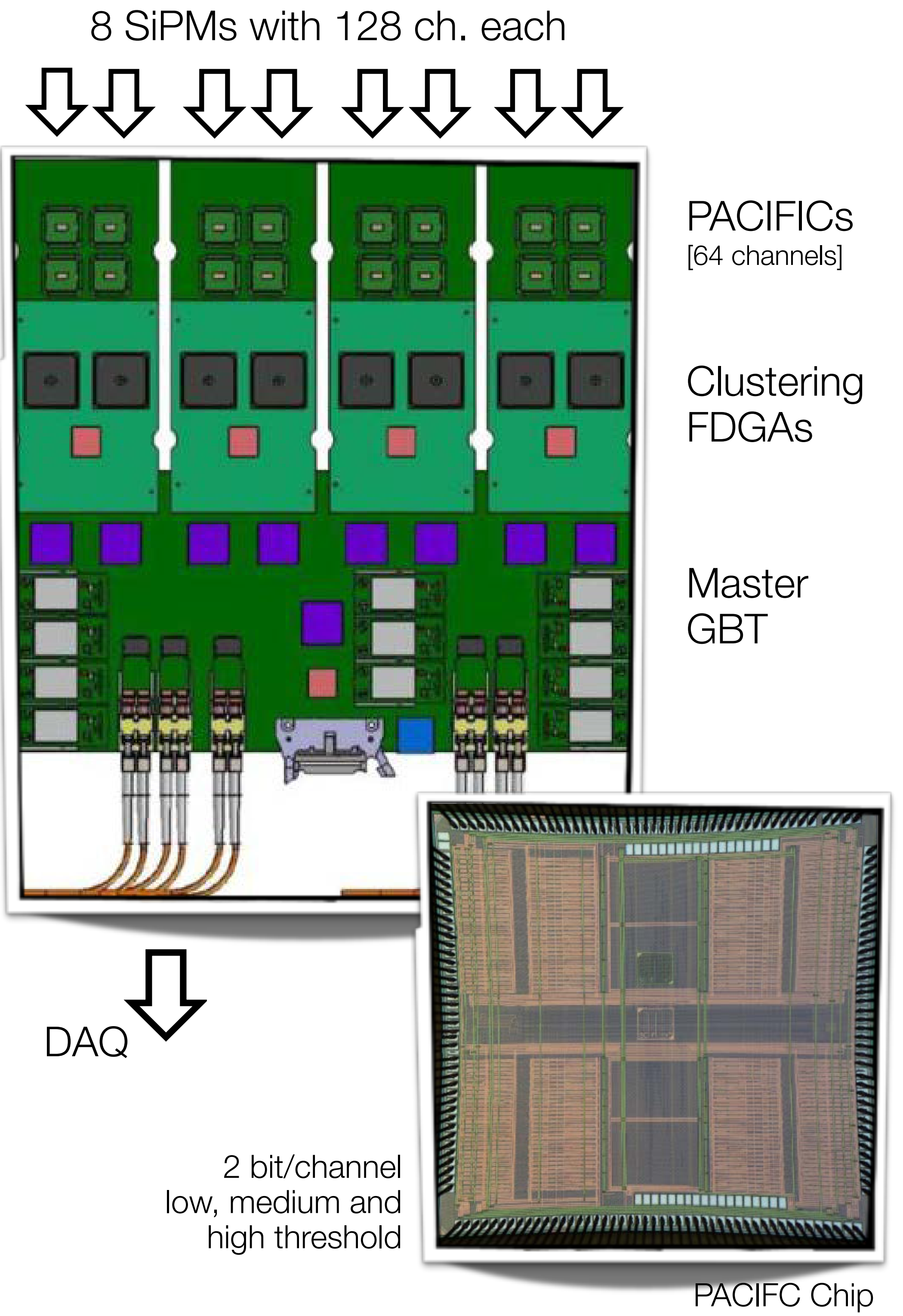
Scintillating Fibre Tracker @ LHCb

SiPM readout & clustering

Clustering is key
to noise/data reduction …

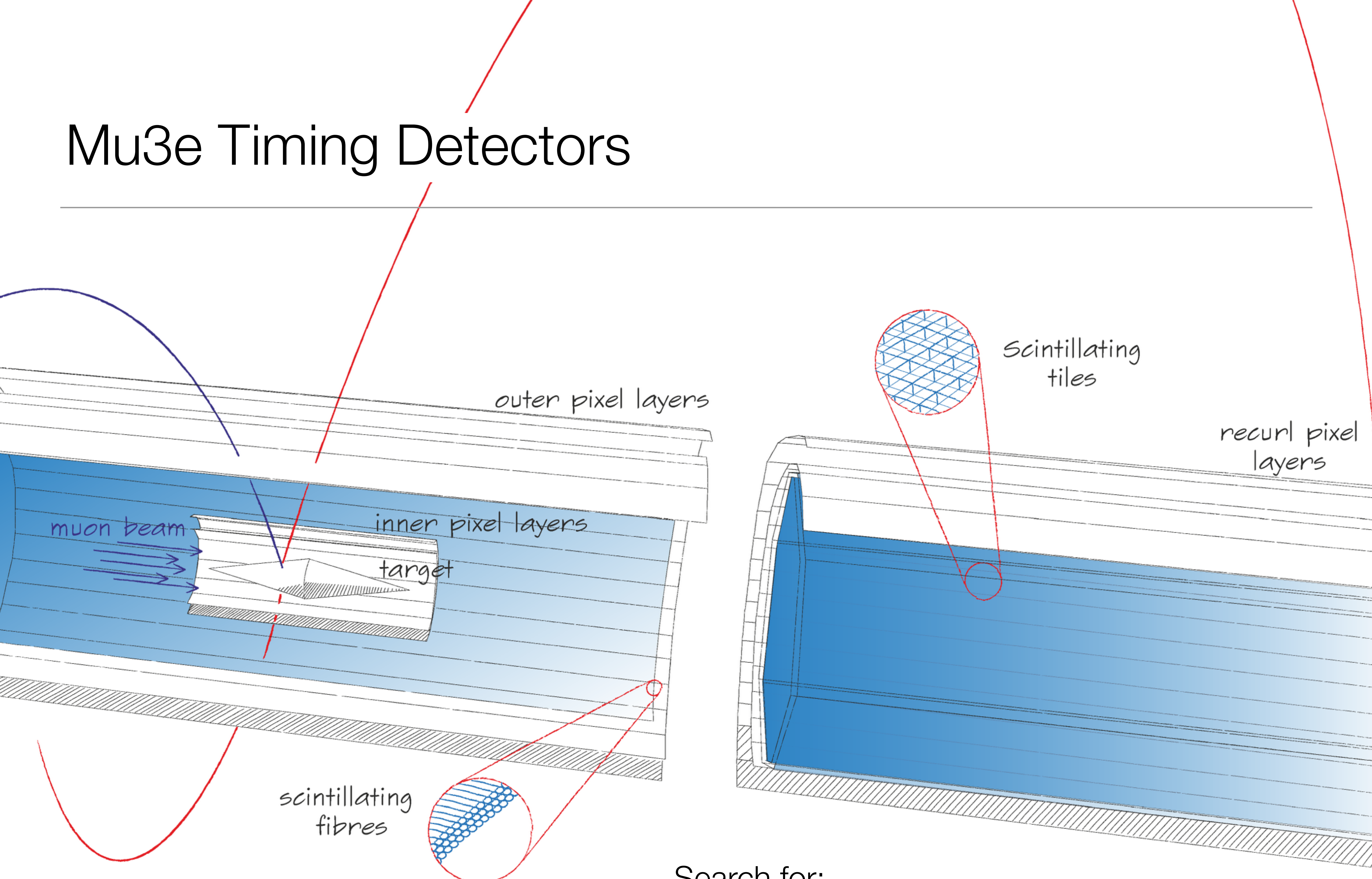
Reduces noise from DCR of 12 MHz/ch to
a cluster noise rate 0.8 MHz/128 channels





Mu3e
Timing Detectors

Mu3e Timing Detectors



Search for:

$$\mu^+ \rightarrow e^+ e^- e^+$$

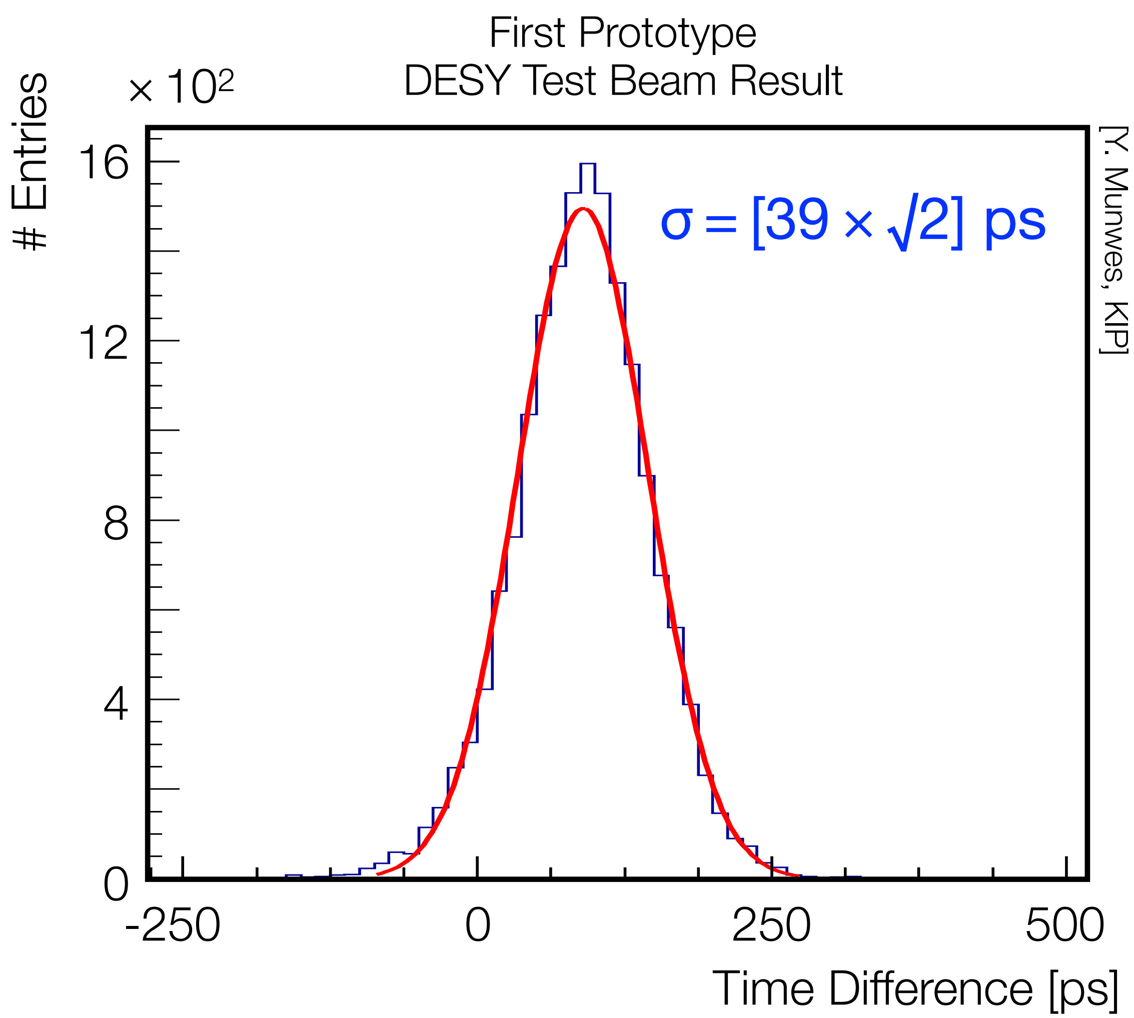
r/o ASIC:
STiC 2.0

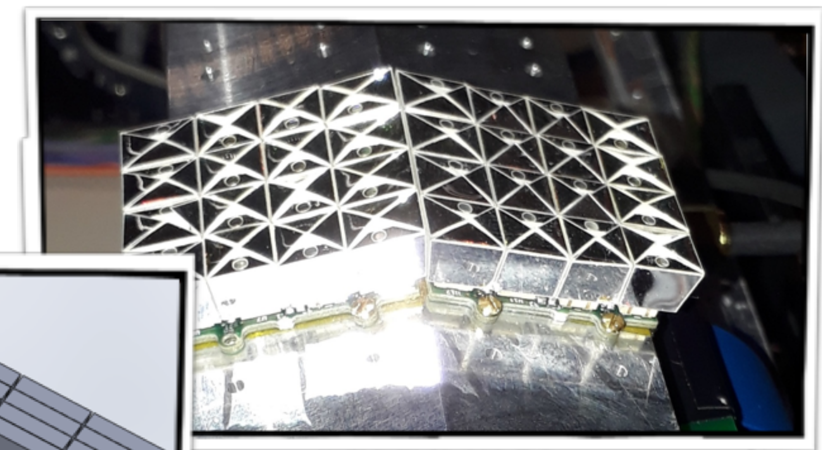
Mu3e Timing Detectors

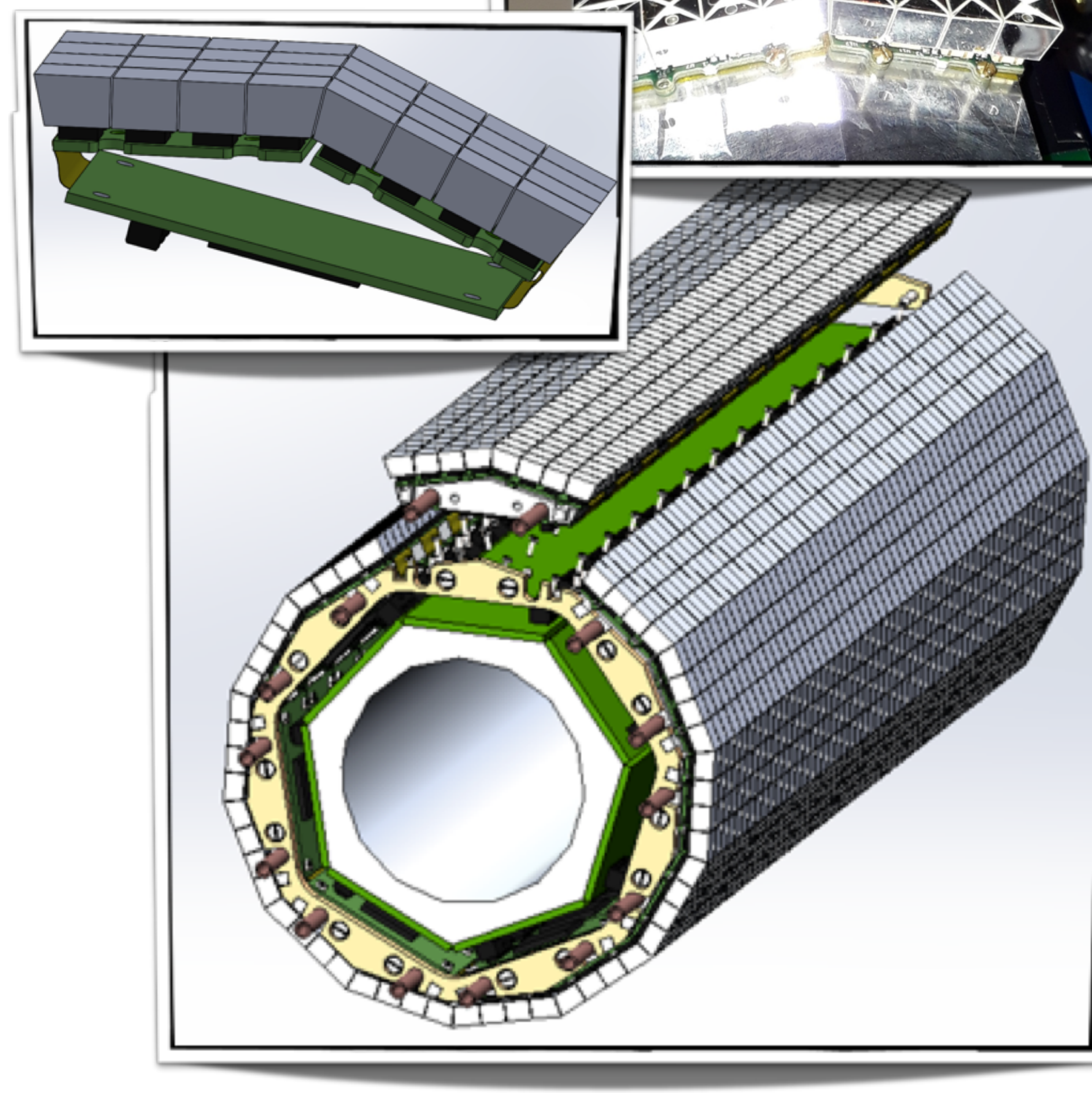
Tile Detector

Tiles per station: 3136 [56 x 56]
Tile size: ~ 6.5 x 6.5 x 5.0 mm³
Time resolution: < 100 ps

Exp. LY: O(2k) p.e.





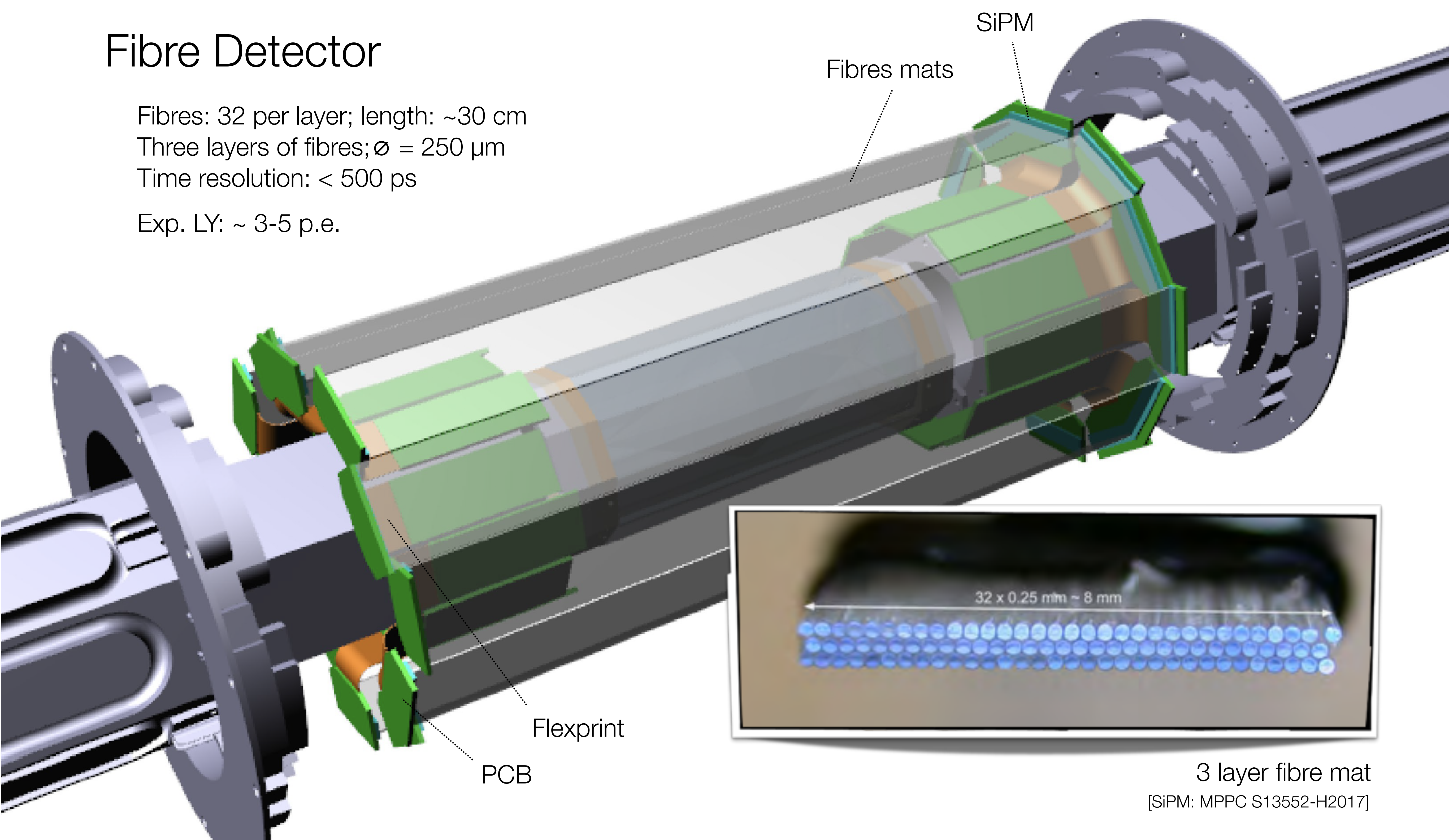


Mu3e Timing Detectors

Fibre Detector

Fibres: 32 per layer; length: ~30 cm
Three layers of fibres; ⌀ = 250 μm
Time resolution: < 500 ps

Exp. LY: ~ 3-5 p.e.



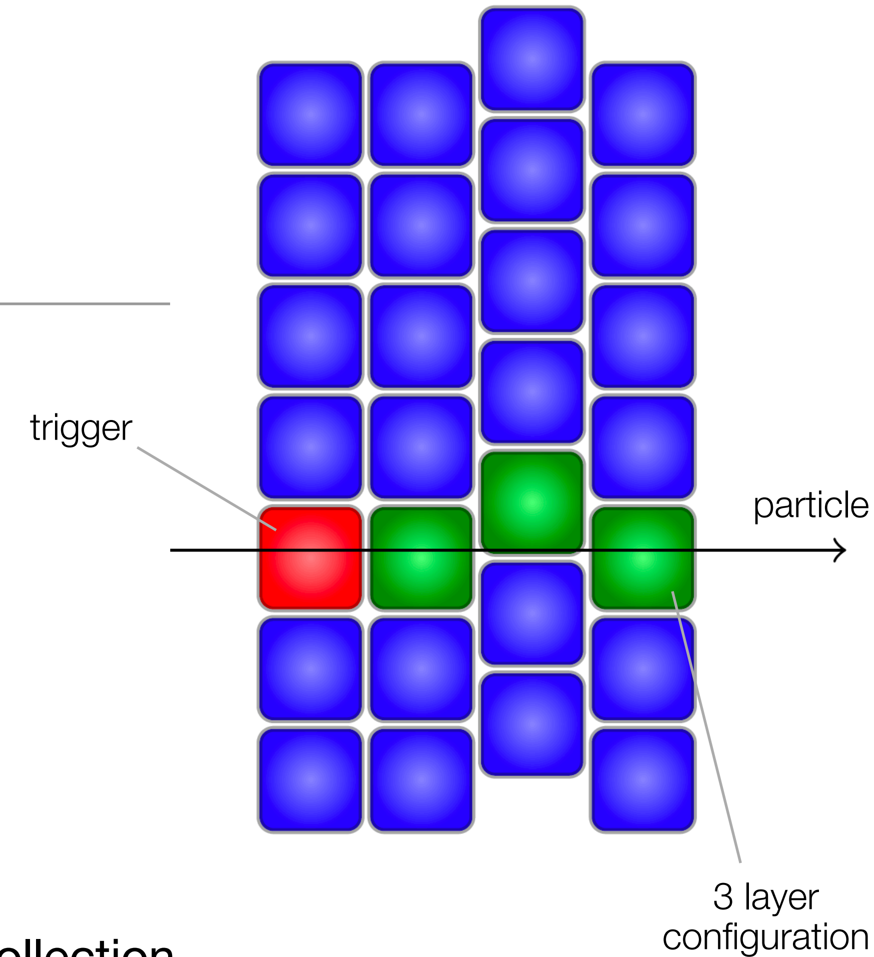
3 layer fibre mat
[SiPM: MPPC S13552-H2017]

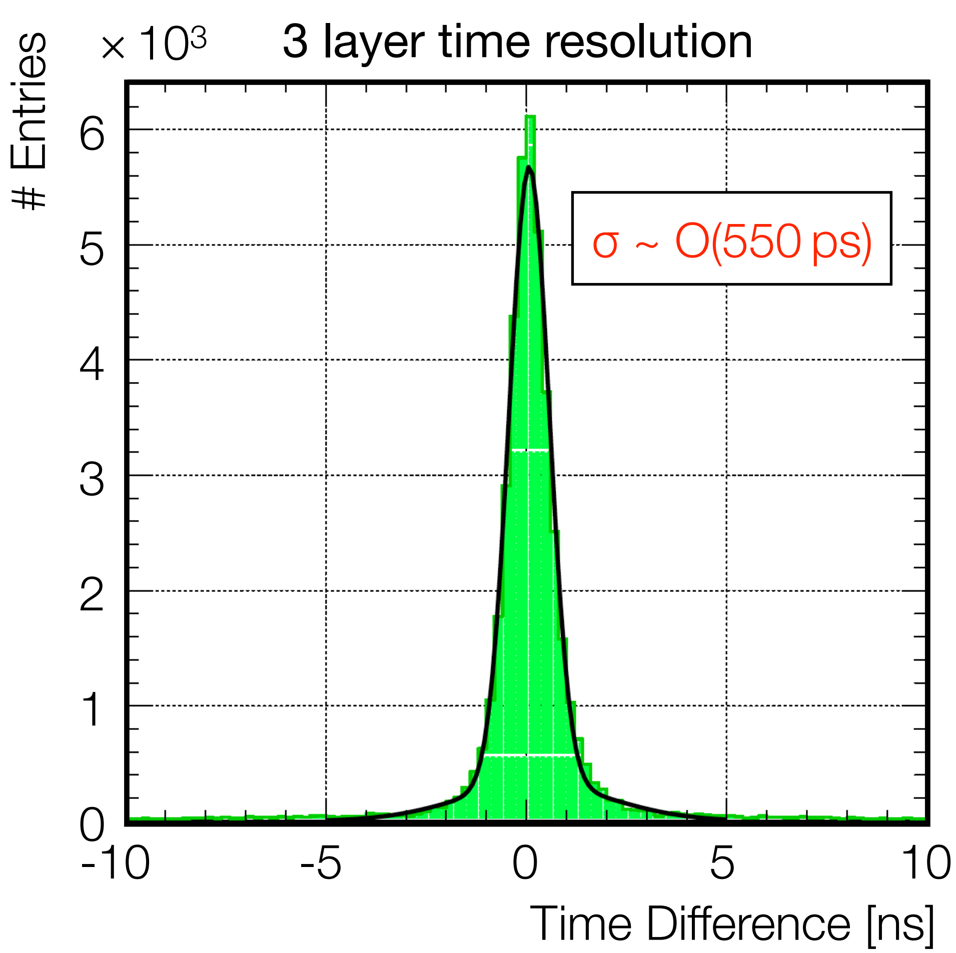
Mu3e Timing Detectors

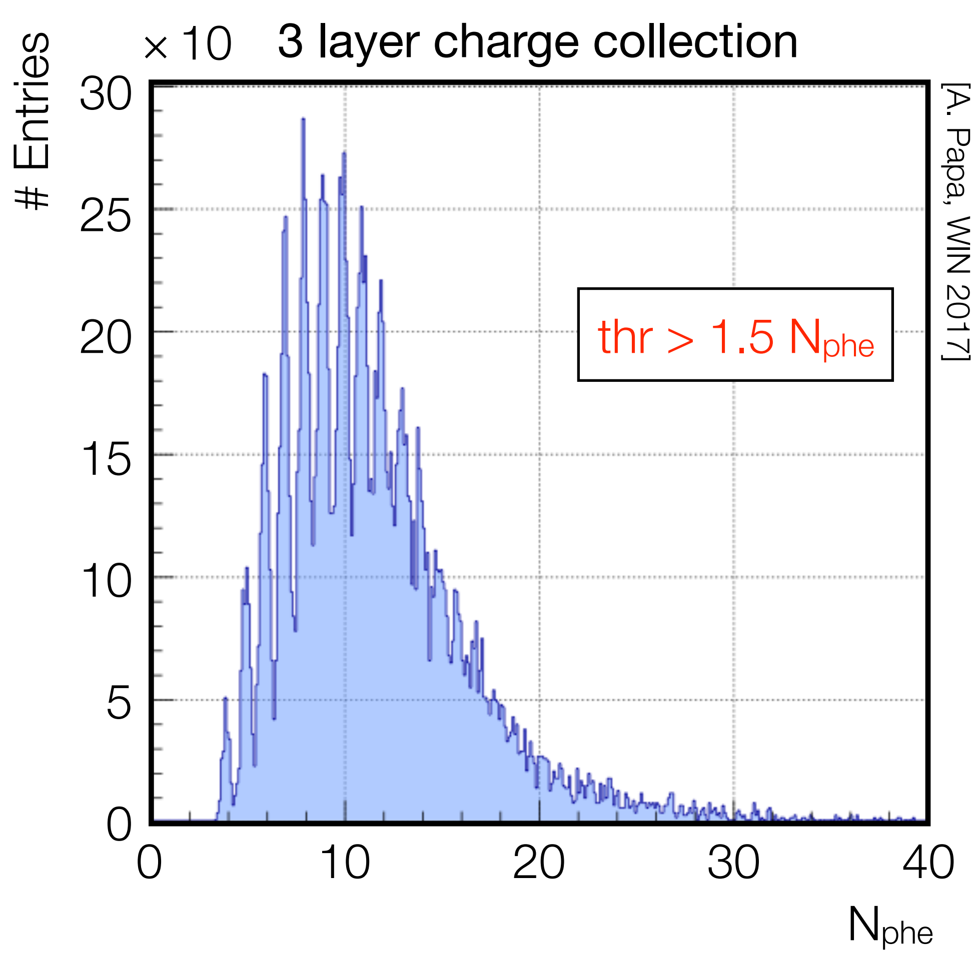
Fibre Detector

First prototype results with multi-layer configuration …

Detection efficiency > 96 % @ 0.5 thr in N_{phe} …
Performances for square and round fibres …
Readout with standalone and prototyping (STiC) DAQ …

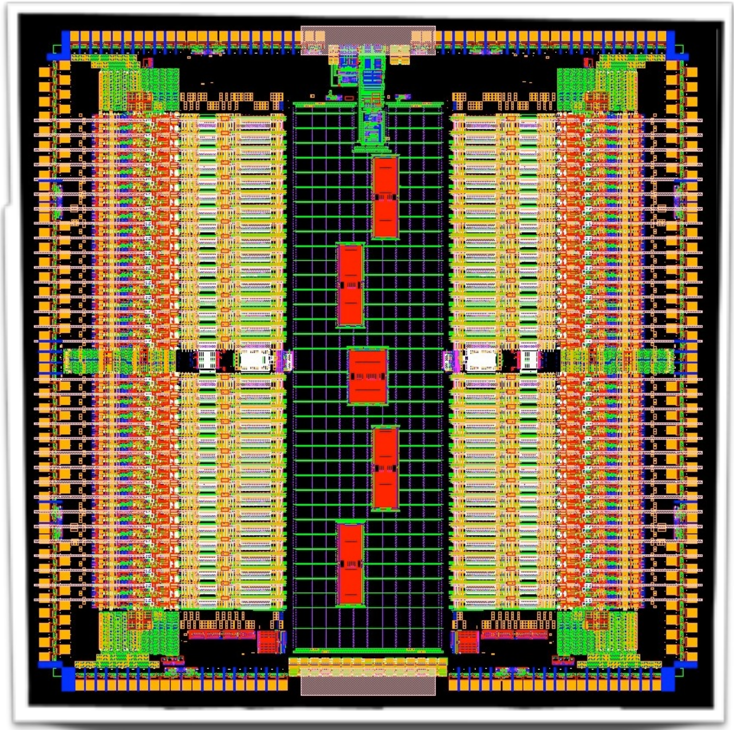




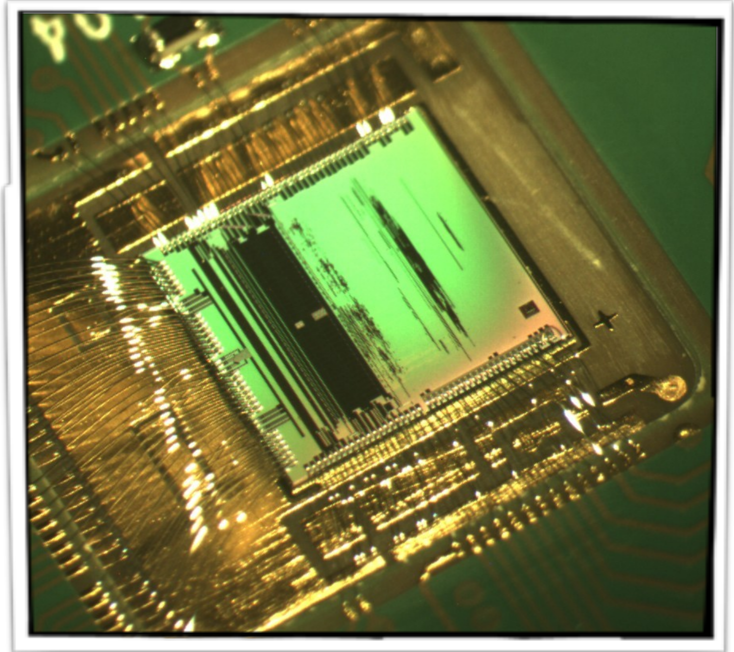


Mu3e Timing Detectors

[W. Shen et al., IEEE TNS Vol. 65 No. 5 (2018) 1196]



STiC 3.0
[Chip layout]



MuTriG
[Mounted chip]

Features:

STiC 3.0 : 64 channels
MuTriG : 32 channels

Differential and
single-ended readout …

Integrated TDC [ZITI, Fischer et al.]
and digital data processing …

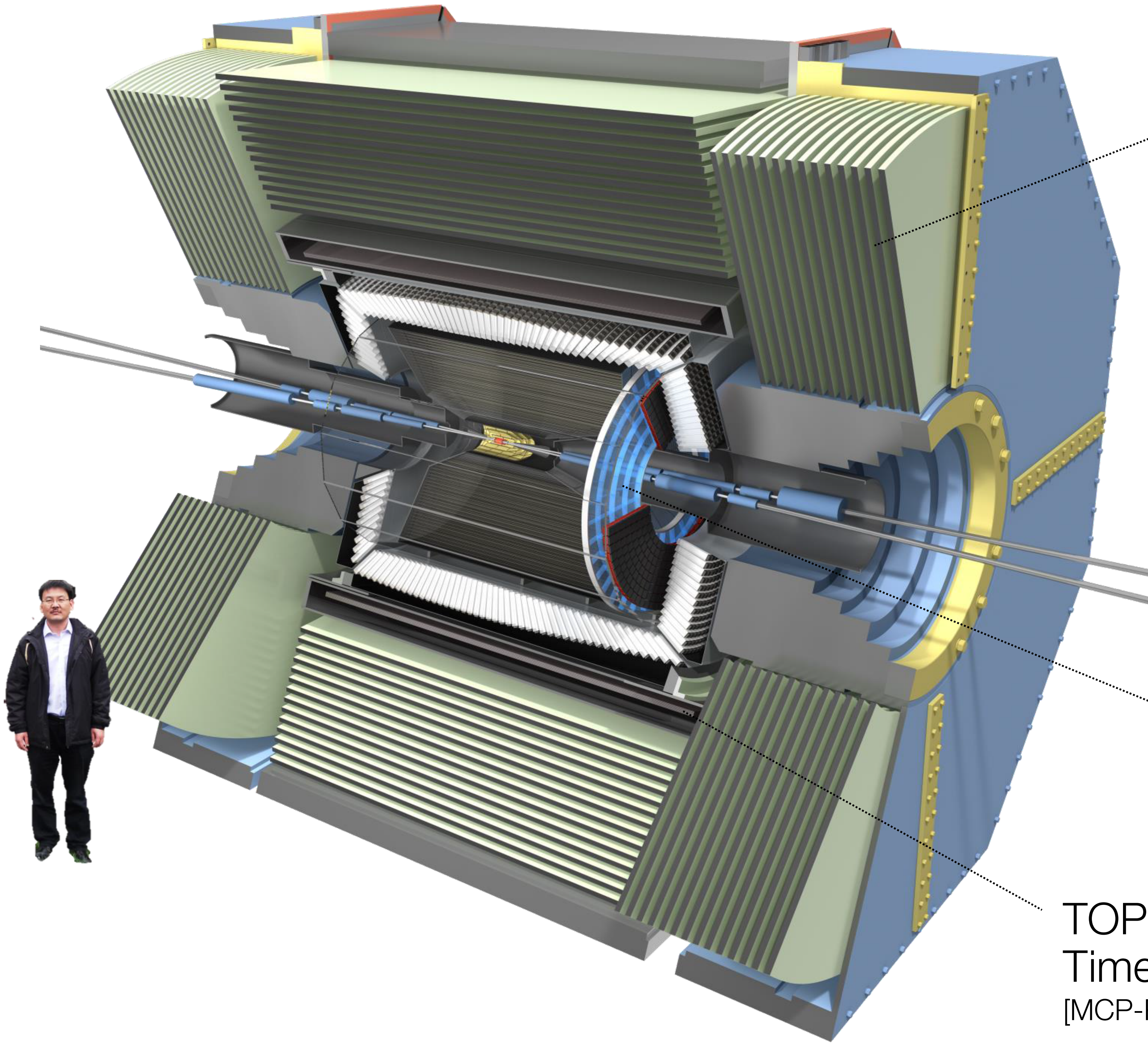
Timing and ToT-based
linearised energy measurement …
[SPTR:180 ps; MPPC S10362-11-100]

SiPM bias tuning …
[Tuning range: ~ 800 mV]

Serial interface for data
transmission and configuration …
[MuTrig: up to 1.25 Gbps]

Belle2
Aerogel RICH

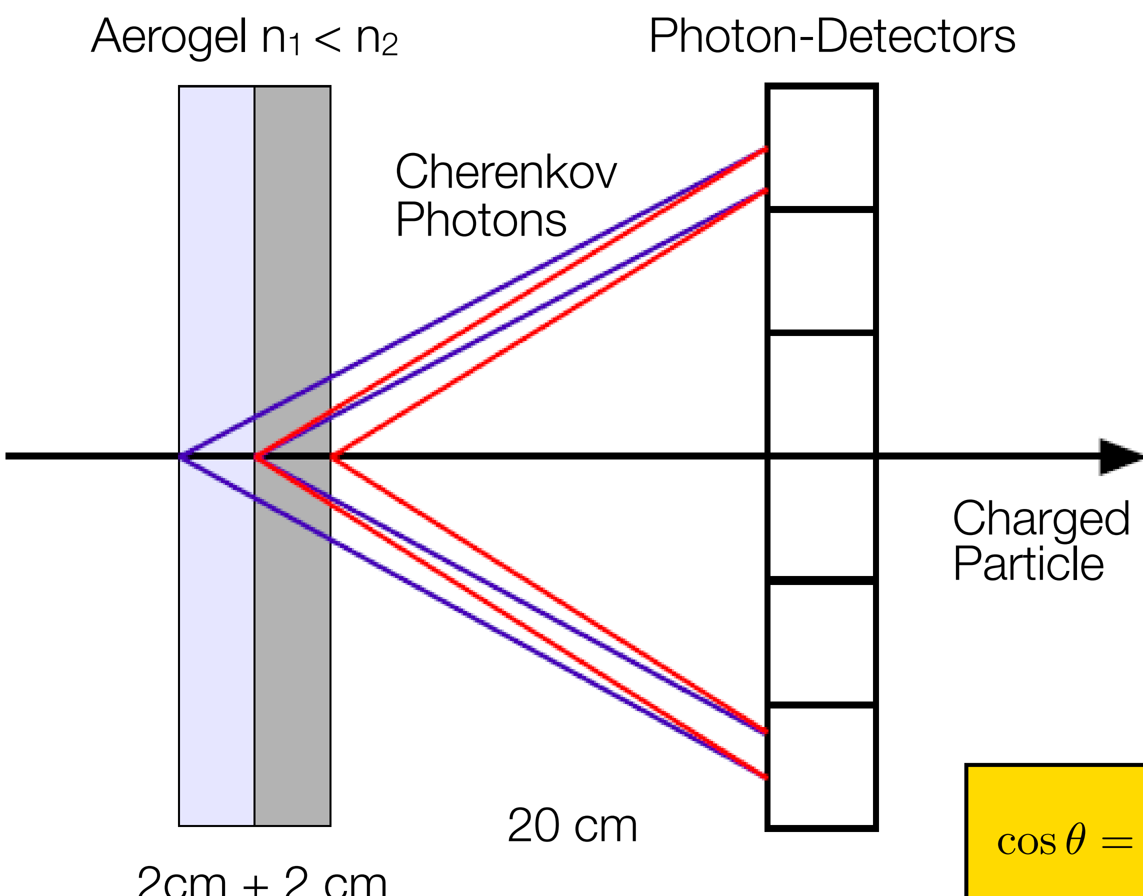
Belle 2 – K_L Counter, TOP and Aerogel RICH



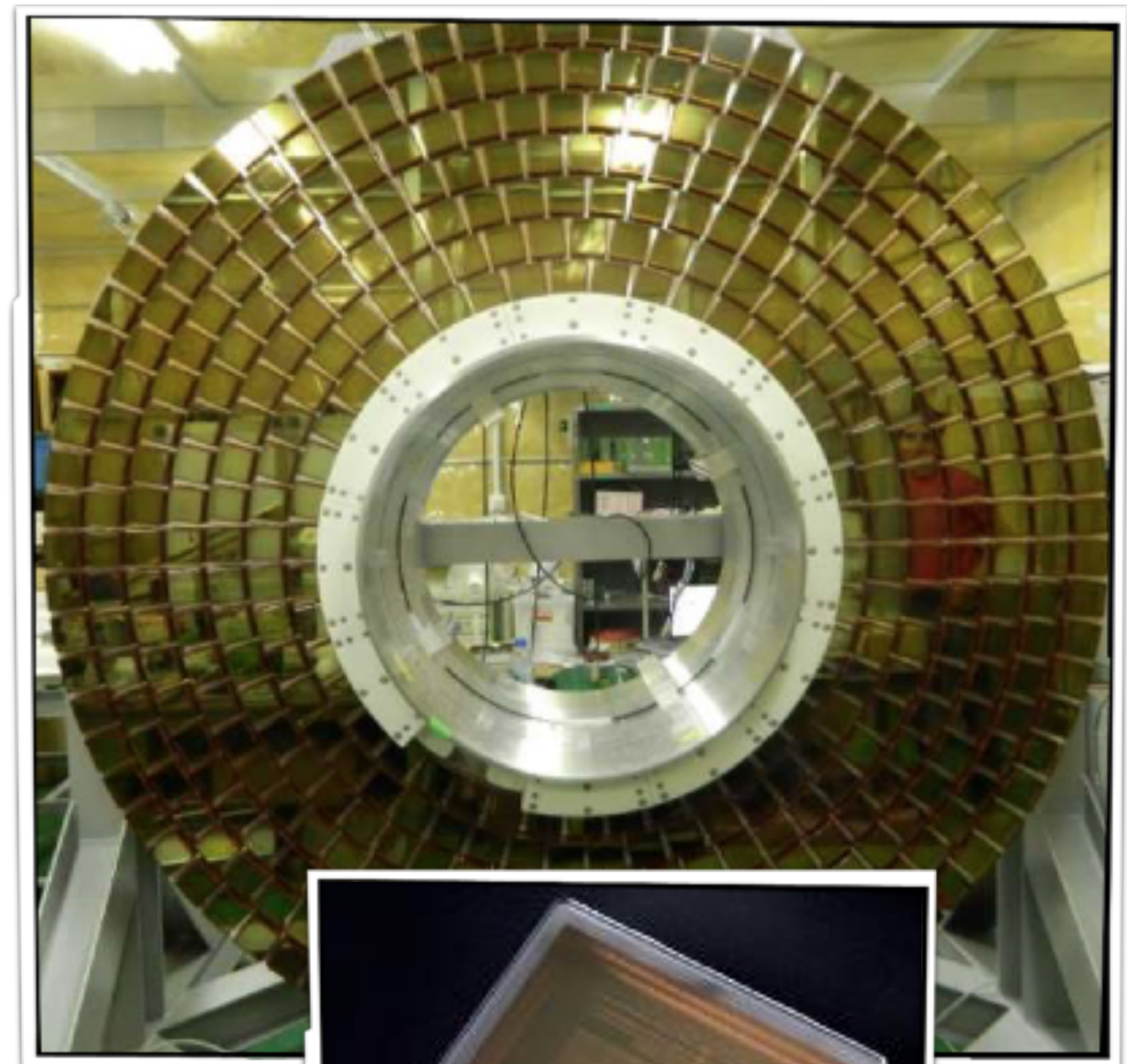
Belle 2 – Aerogel RICH

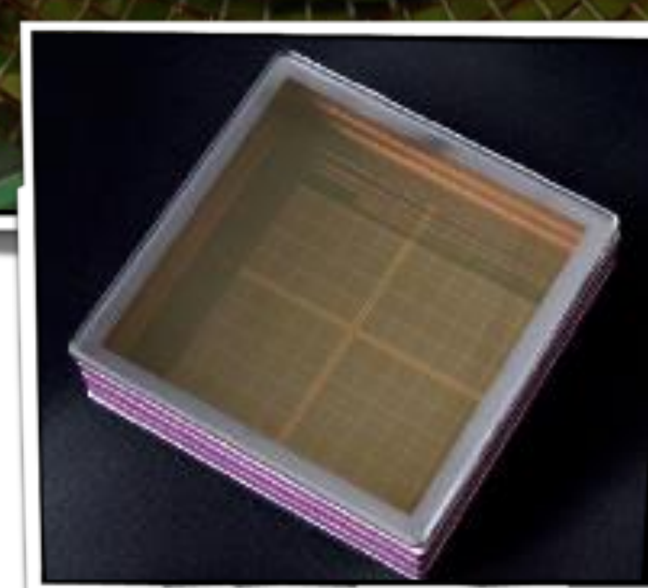
Proximity focusing aerogel RICH …

Requires: single photon detection, sufficient spatial resolution, high efficiency …



$$\cos\theta = \frac{1}{n\beta}$$

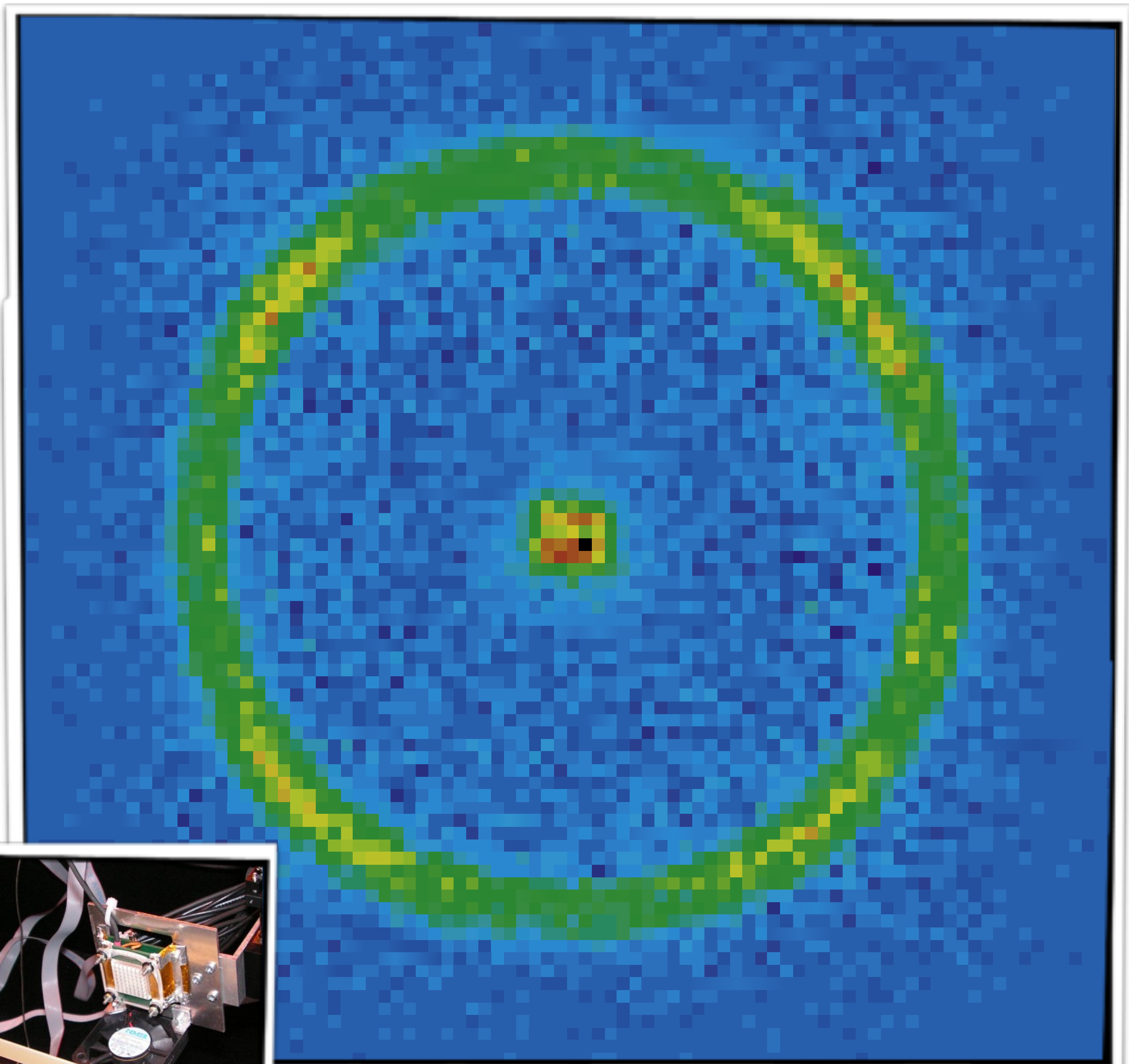


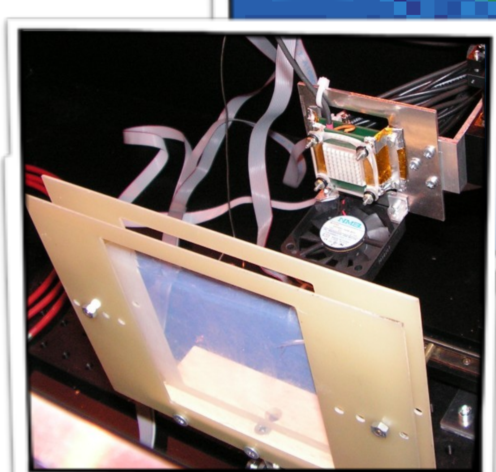


HPD
[Hamatsu]

Belle 2 – Aerogel RICH with SiPMs

[S.Korpar et al., NIM A 613 (2010) 195]

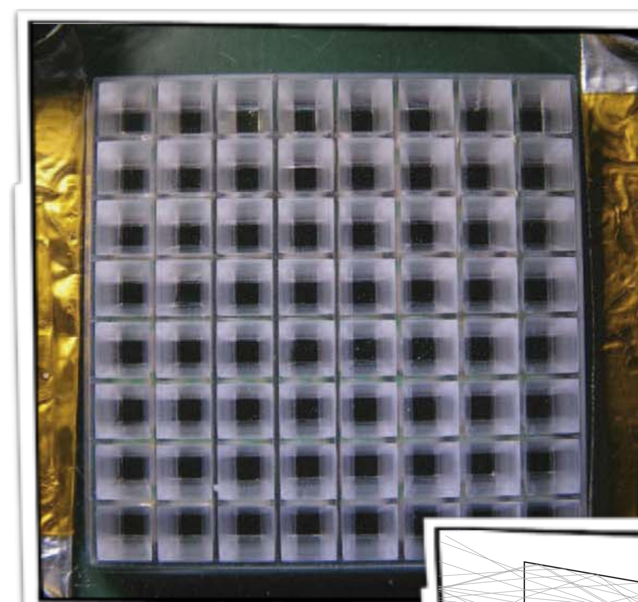


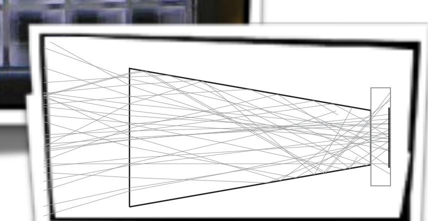


Full ring in pion beam

Detector module

[64 SiPMs]



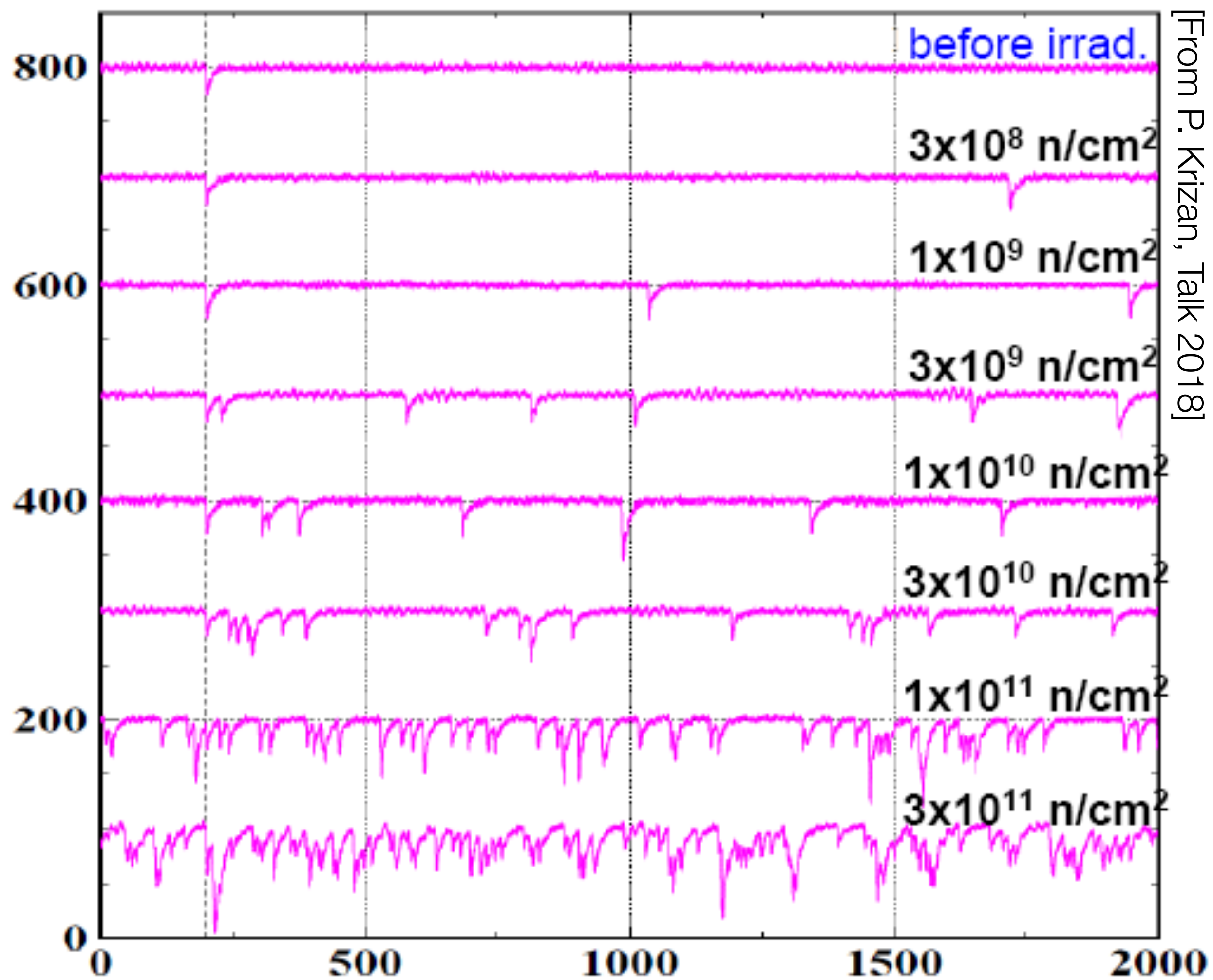


Detector module

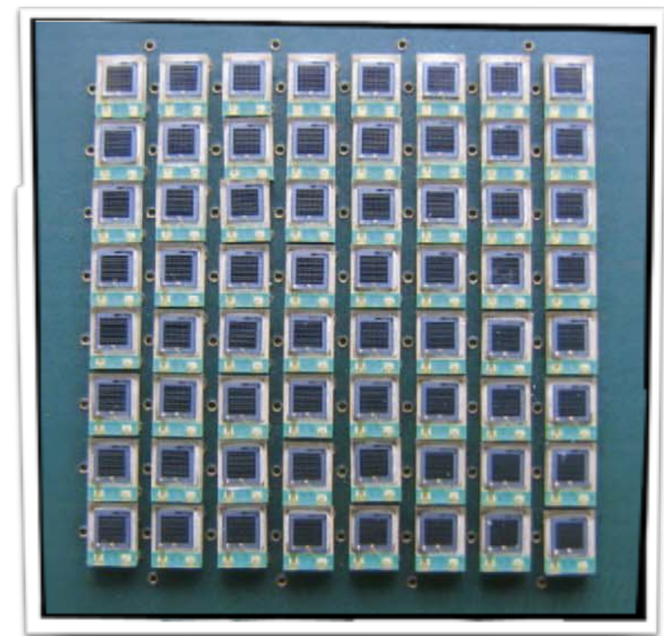
with light guides

Belle 2 – Aerogel RICH with SiPMs

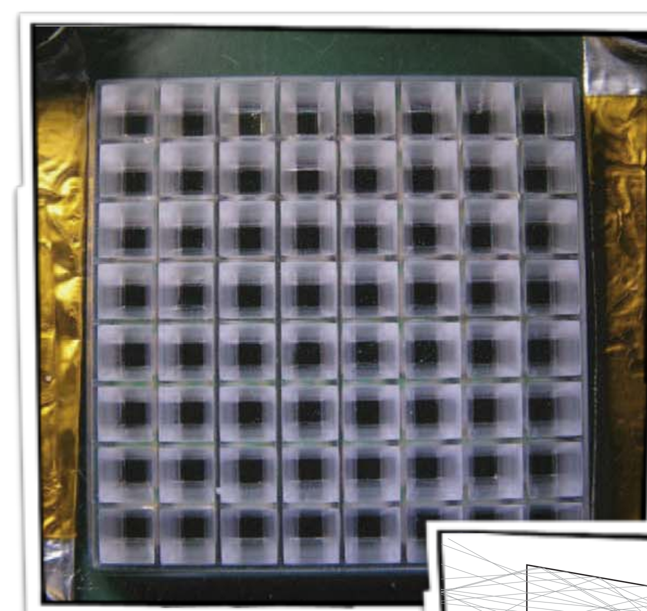
I.Nakamura, JPS Meeting, Sep. 2008

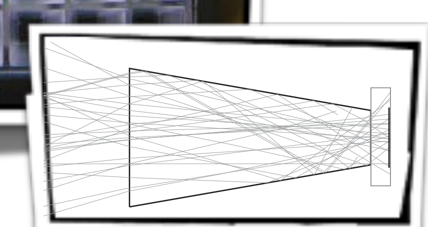


[From P. Krizan, Talk 2018]



Detector module
[64 SiPMs]





Detector module
with light guides

Expected Fluence @ Belle: 2-20 × 10^{11} @ 50 ab^{-1}

➧ Hard to use present SiPMs for Belle 2 RICH …

[or in general as single photon detectors in harsh rad environments]

Concluding Remarks

Growing SiPM applications in particle physics

Important requirements:

Compactness, insensitivity to B-fields, dynamic range, large PDE, fast response, radiation tolerance …

With ongoing developments on SiPMs more to be expected …