Calorimetry challenges and possible detector technology evolution

F. Lanni
on behalf of the full calorimeter WG.
(see a partial list of contributors in the calorimeter session of: https://indico.cern.ch/event/358198/other-view?view=standard)

- Requirements on calorimeters @ FCC-hh
- Challenges of calorimeter technologies and possible evolution
  - Photon-based
  - MPGD
  - Solid-state
  - Noble Liquids

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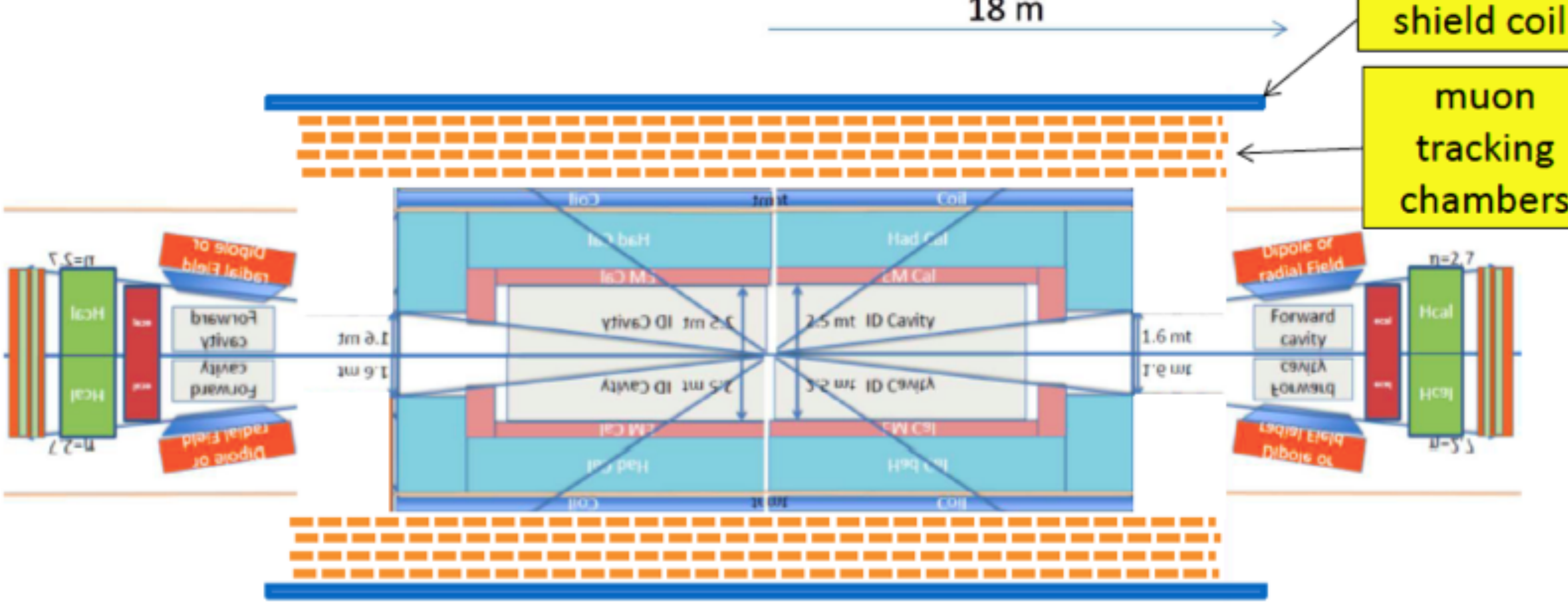
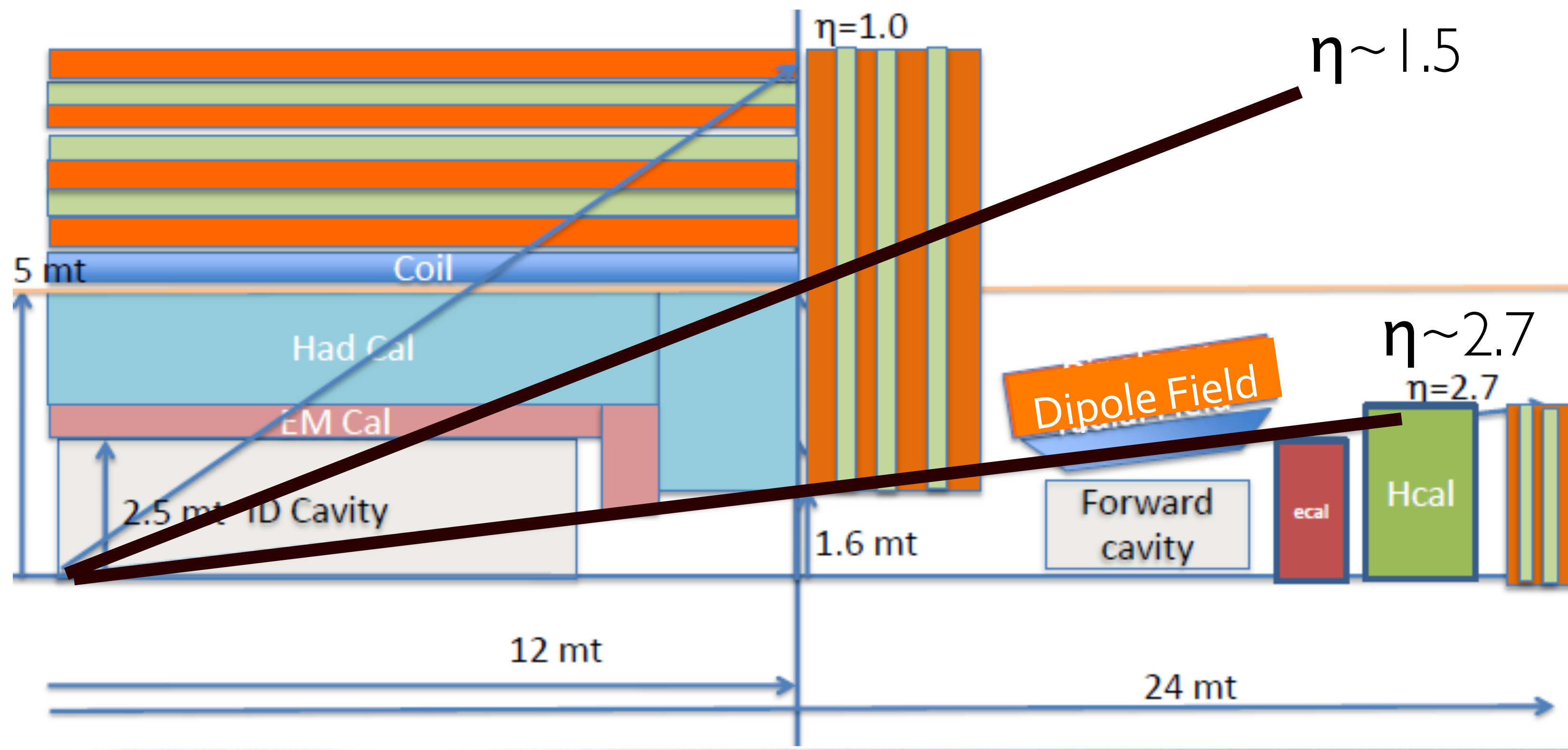


3(4) Regions in η

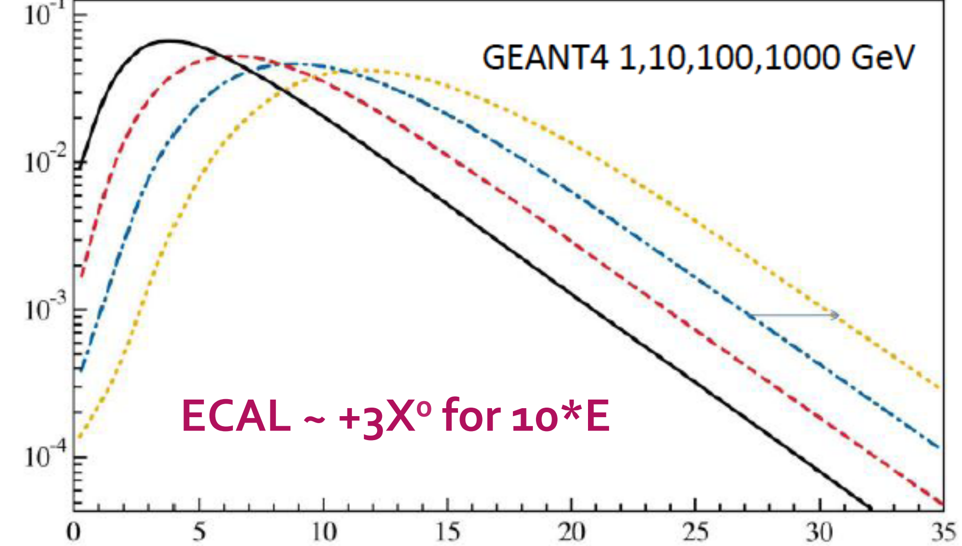


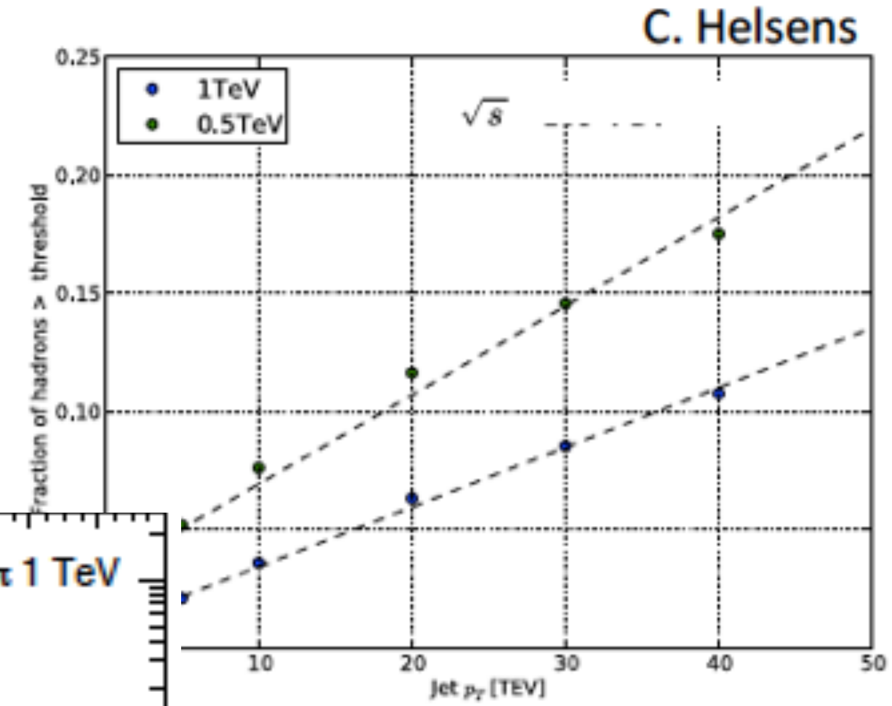
- Barrel: $0<|\eta|<1.5$
- Extended Barrel: $1.5<|\eta|<2.7$
- Endcap: $2.7<|\eta|<4(6)$
- (Forward: $4<|\eta|<6$)

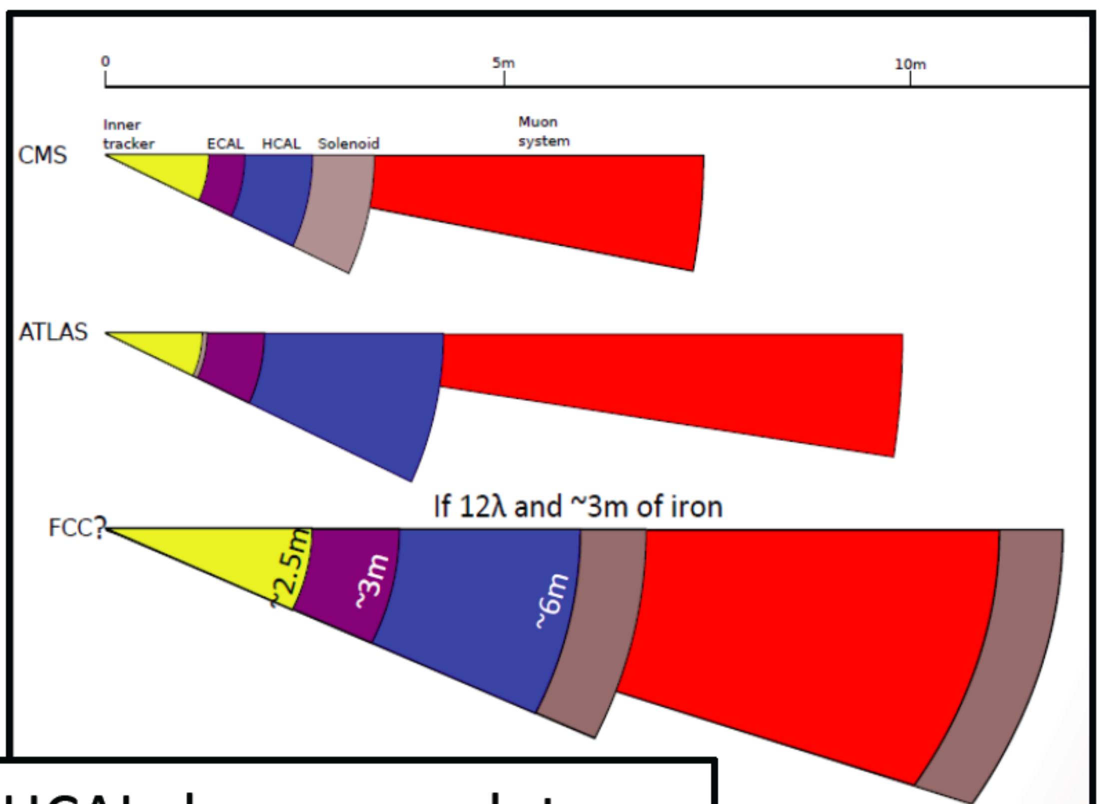
What technology? A single one? Likely each region will need to be optimised separately.

Requirements: Volume

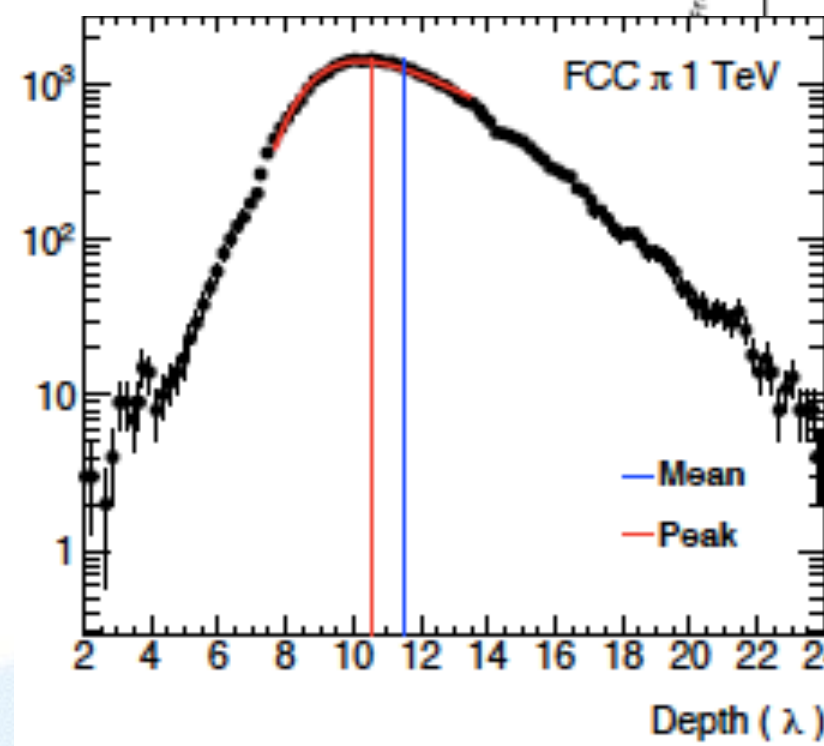
- Inner Radius determined by precision required on charged tracks pT measurements and on the magnets
- ECAL depth only moderately sensitive to $\sqrt{s}$=100 TeV: 30 X_o for ~1 TeV fully contained e/γ.
- Jet containment poses more severe constraints :
  - Leading particle in a jet carry significant fraction (~10%) of jet energy:
  - Example: 30 TeV jets 8% of constituents have E>1 TeV (and in average ~1 with E>5TeV)





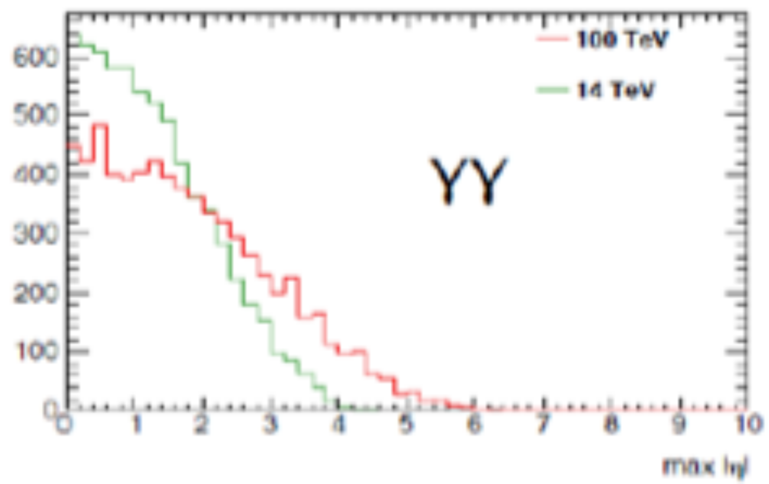


HCAL deep enough to prevent punch-through

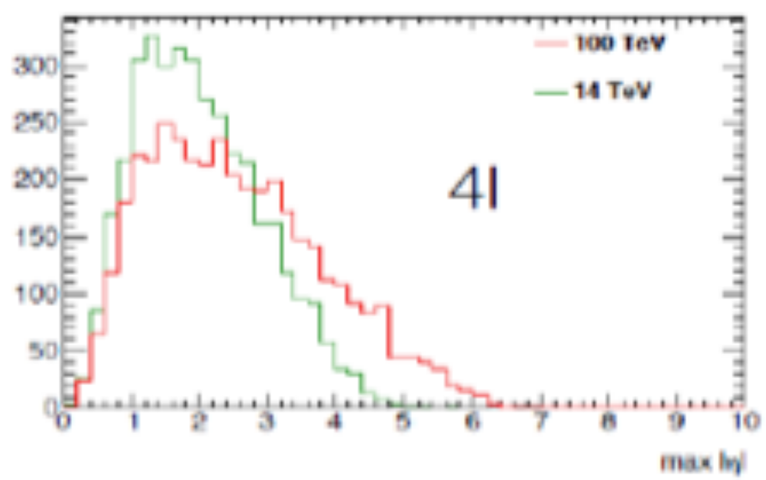


→ 98% containment of 1 TeV hadrons requires ~12λ @ $\sqrt{s}$=100 TeV (10λ @ LHC)

Requirements: Acceptance

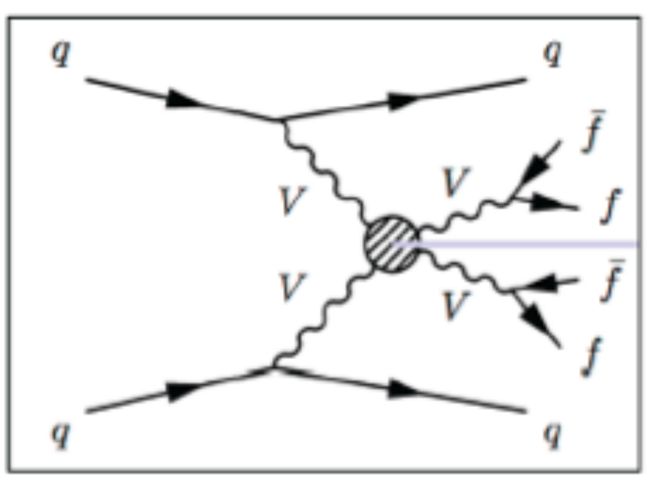


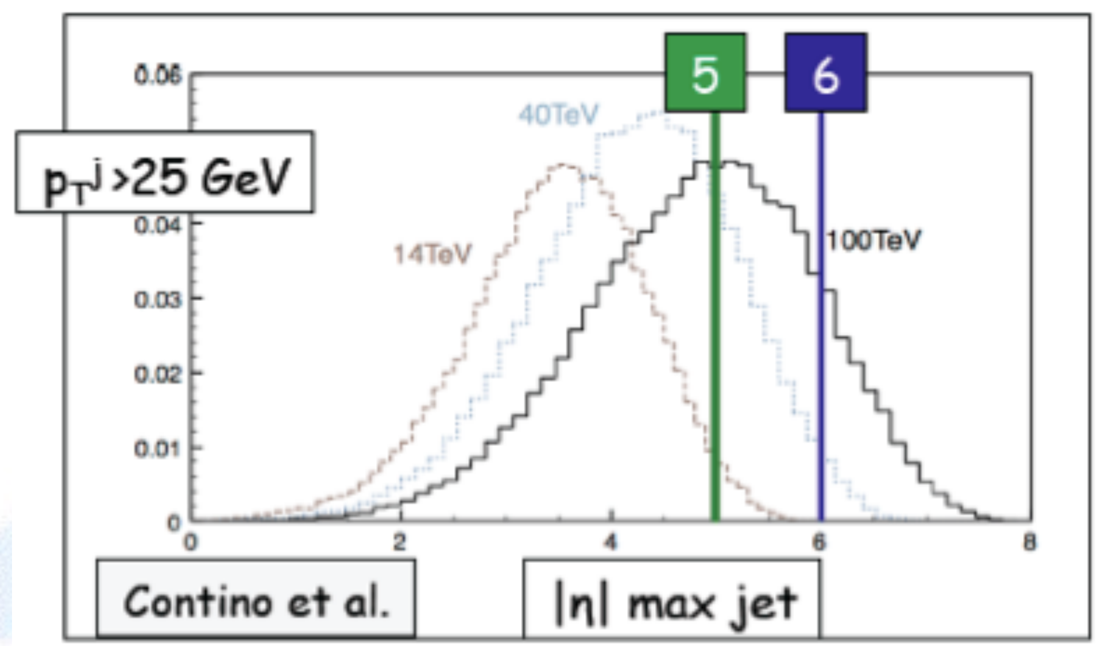
		$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$	$\lvert\eta\rvert < 5$
ll	100 TeV	0.56	0.88	0.97
	14 TeV	0.74	0.99	0.99
YY	100 TeV	0.74	0.95	0.99
	14 TeV	0.90	1	1



4lep

	Inclusive		Higgs p_T > 100 GeV		Higgs p_T > 150 GeV	
	2.5	4	2.5	4	2.5	4
ggF	0.56	0.88	0.64	0.93	0.70	0.95
WH	0.45	0.77	0.53	0.84	0.54	0.87
ZH	0.48	0.81	0.53	0.85	0.58	0.88
ttH	0.56	0.90	0.59	0.92	0.63	0.95
VBF	0.55	0.87	0.61	0.93	0.67	0.95

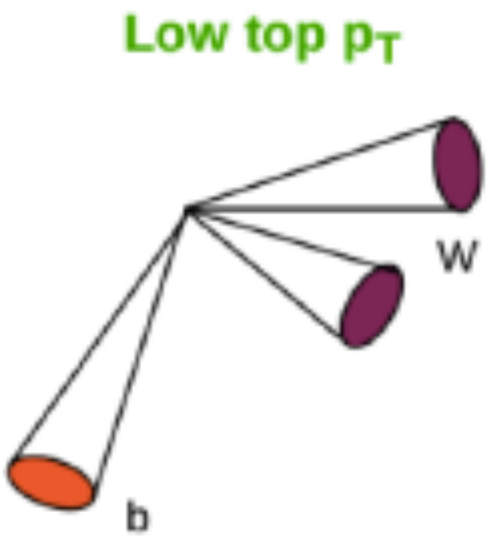


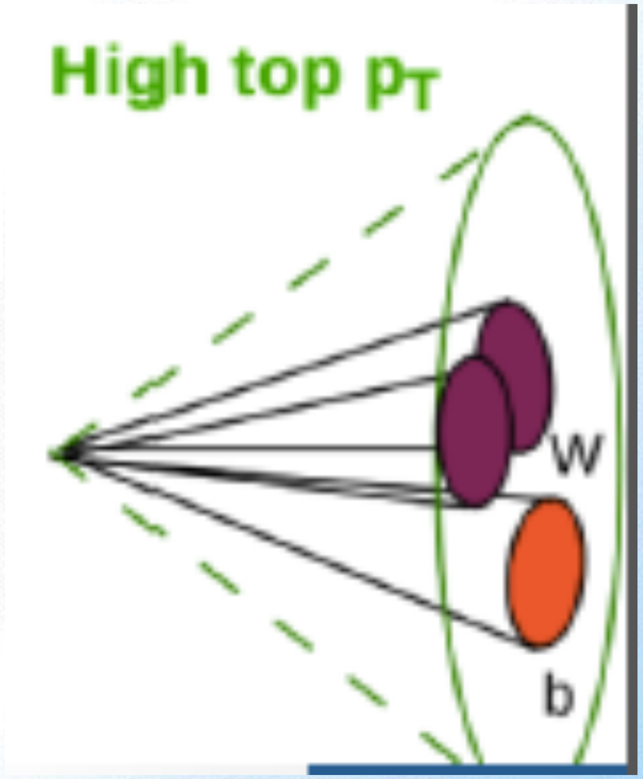


→ ***Calorimeter extension up to η~6***

Requirements: Granularity

- At $\sqrt{s}$=100 TeV super-boosted regime: p_T>5 TeV
- Cone size: R ~ 1/boost
- ***Highly collimated final states***
- Minimal distance to resolve two partons: $\Delta R \sim 2m/p_T$.
- Example for top:
  - p_T = 200 GeV ⇒ R ≃ 2
  - p_T = 1 TeV ⇒ R ≃ 0.4
  - ***p_T = 10 TeV ⇒ R ≃ 0.05***





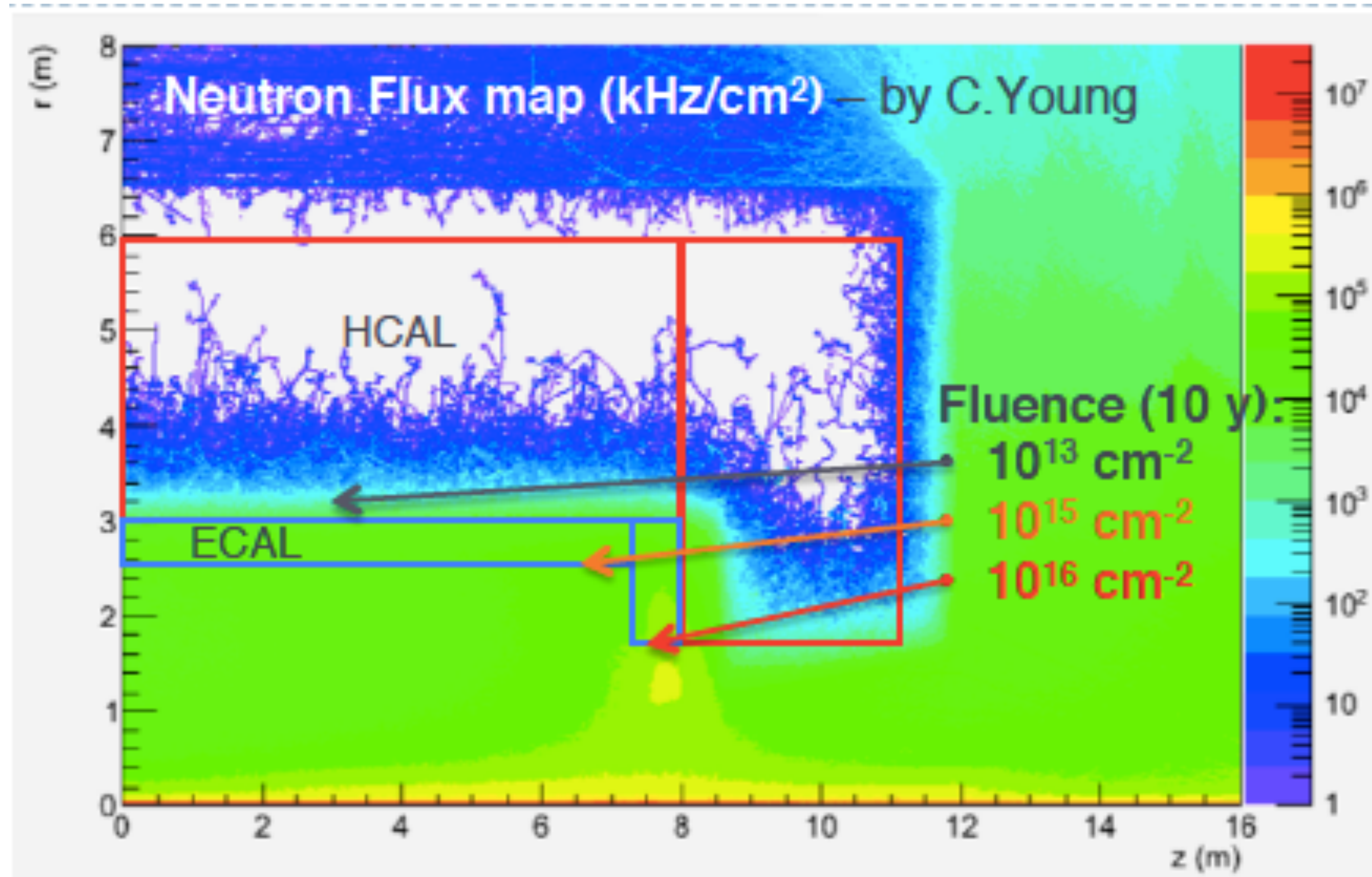
- ***Sub-structure identification will become difficult as the jet cone tend to be very narrow when particles enter the calorimeter (comparable to the Moliere radius)***
- Object overlap will be challenging.

→ ***High granularity is a key factor***

Requirements:

Pileup mitigation

- Pileup conditions can be as much as 900 @ 25 ns (180 @ 5 ns) min-bias events/crossing.
- Calorimeters with excellent timing resolution (10-20ps) may be required to mitigate pileup effects



Radiation Tolerance

- ~20ab-1 integrated luminosity
- In the barrel larger distance of the calorimeters compensates partly (x2 HL-LHC)
- Endcap predictions can not be calculated without a solid understanding of the beam line shielding etc.

"Maximum" in Calorimeters

	More reliable	Depends on position	Very sensitive to beam line shielding etc

ECal

	Barrel	Extended Barrel	Endcap
Dose (Gy/year)	$4\ 10^3$	$6.5\ 10^4$	
Fluence (KHz/cm²)	$6\ 10^4$	$2\ 10^5$	

~ 10x

HCal

	Barrel	Extended Barrel	Endcap
Dose (Gy/year)	$5\ 10^2$	$3\ 10^4$	
Fluence (KHz/cm²)	$7\ 10^3$	$6\ 10^5$	

~ 100x

SLAC

Challenges and possible evolutions of

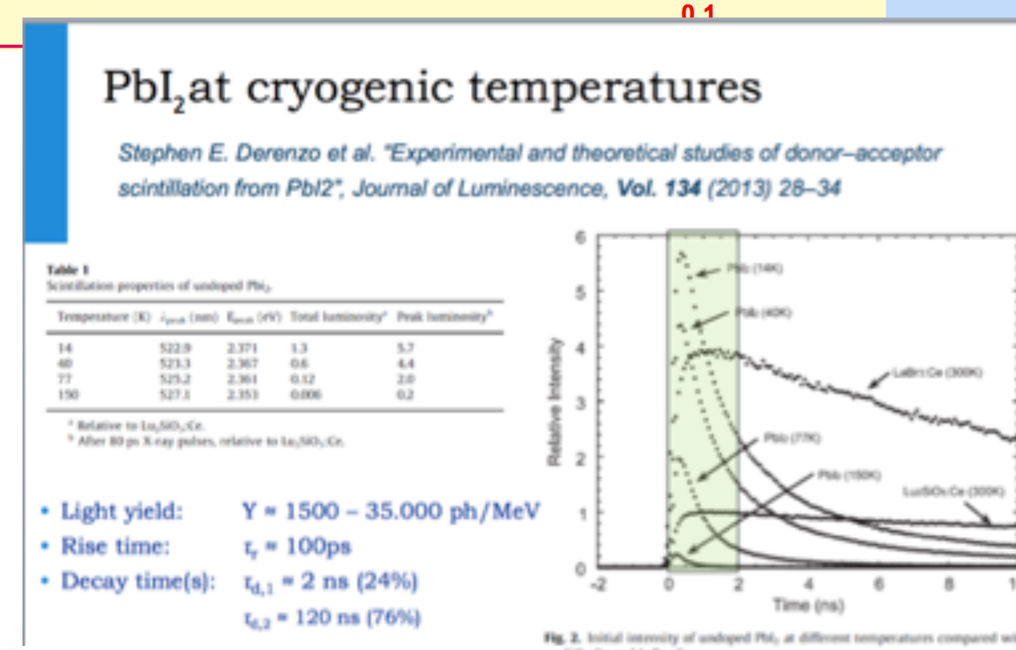
Photon based calorimeters

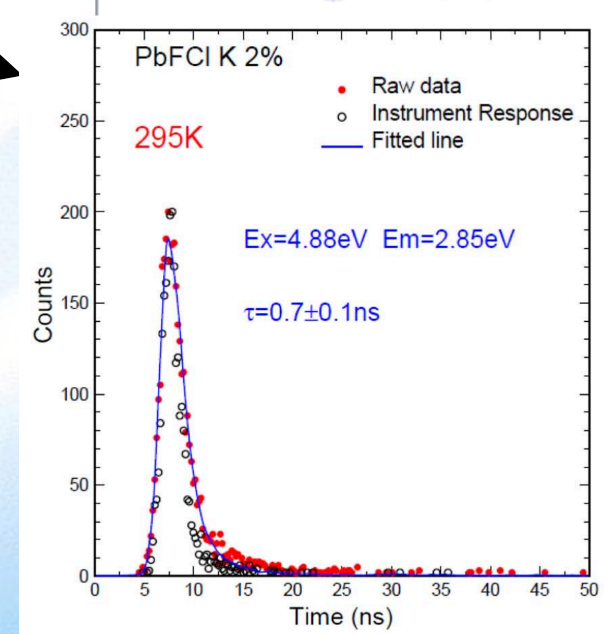
Crystals: ***P. Lecoq,*** https://indico.cern.ch/event/358198/session/2/contribution/1/1/material/slides/1.pdf
Organic Scintillators: ***A. Henriques,*** https://indico.cern.ch/event/358198/session/2/contribution/1/3/material/slides/1.pdf
Dual Readout: ***N. Ackurin***, https://indico.cern.ch/event/358198/session/2/contribution/1/2/material/slides/0.pdf
Photodetectors: ***T. Tabarelli***, https://indico.cern.ch/event/358198/session/2/contribution/1/4/material/slides/0.pdf

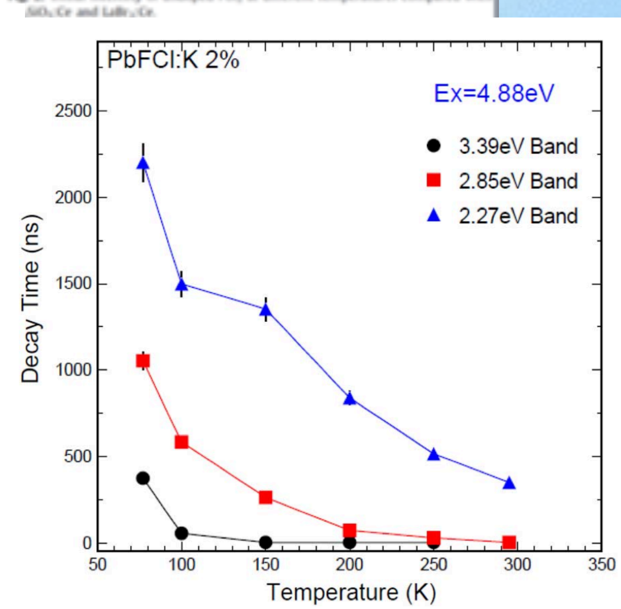
Crystals

- Crystal developments over last 25 years focusing on understanding material properties (light yield, good energy resolution, decay time, radiation tolerance):
  - PWO, Pb halide family, LSO, LYSO, LGSO, LuAP, LuYAP…
  - LYSO is an excellent option, except for cost!!!
- New Pb halide crystals:
  - PbI_2 at cryogenic temperatures (Derenzo 2013)
  - PbFCl:K several emission bands. Some with short decay times
- Focus on Timing performance for many applications (HEP, MI, Homeland security)
  - New production technologies: Micro-pulling-down, transparent ceramics, thin films,

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO
Density (g/cm³)	3.67	4.51	4.51	4.89	7.13	7.40	8.3
Melting Point (ºC)	651	621	621	1280	1050	2050	1123
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20
Hygroscopicity	Yes	Slight	Slight	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	310	300 220	480	402	425 420
Decay Time [b] (ns)	245	1220	26	650 0.9	300	40	30 10
Light Yield [b,c] (%)	100	165	3.7	36 4.1	21	85	0.3 0.1
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5



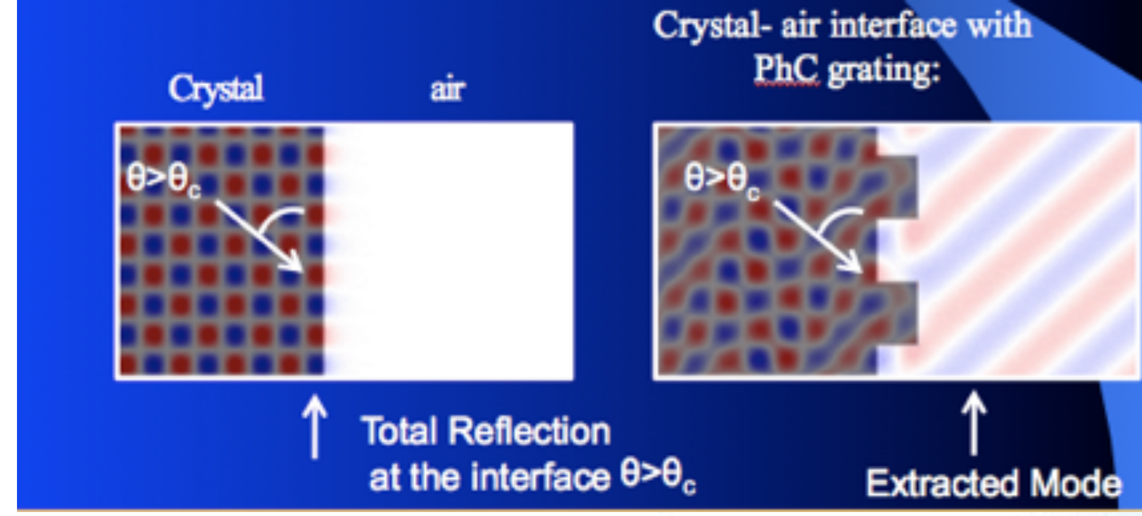




Crystals

Improve Light transport and extraction efficiency:

- Nanostructured interfaces allowing to couple light propagation modes inside and outside the crystal even for ostensibly full internal reflection
- Chiral nanophotonic waveguides to control the flow of light
  - Allows scattering of light by a nanoparticle at the surface of the nanofiber to be redirected in the direction of the fiber toward the photodetector (>50% even at light emitted at large angle)



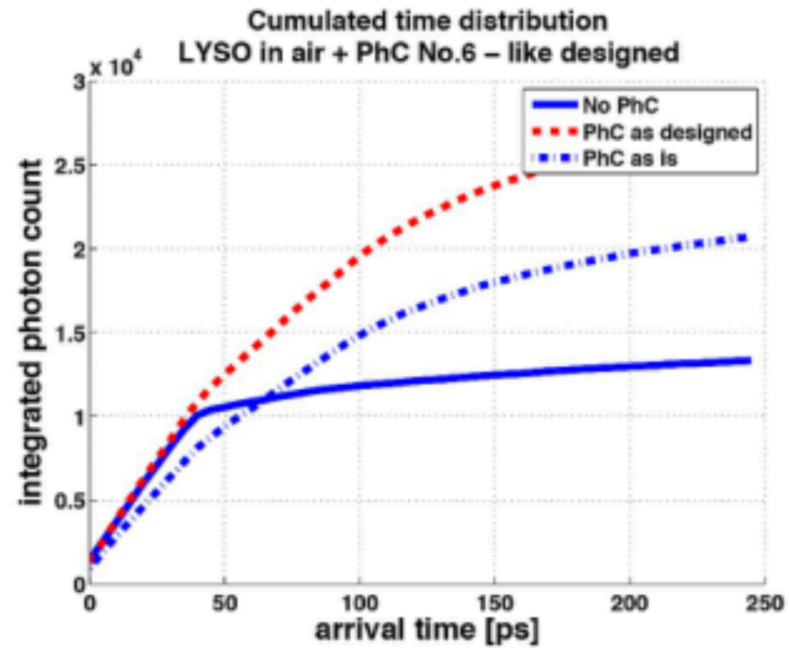
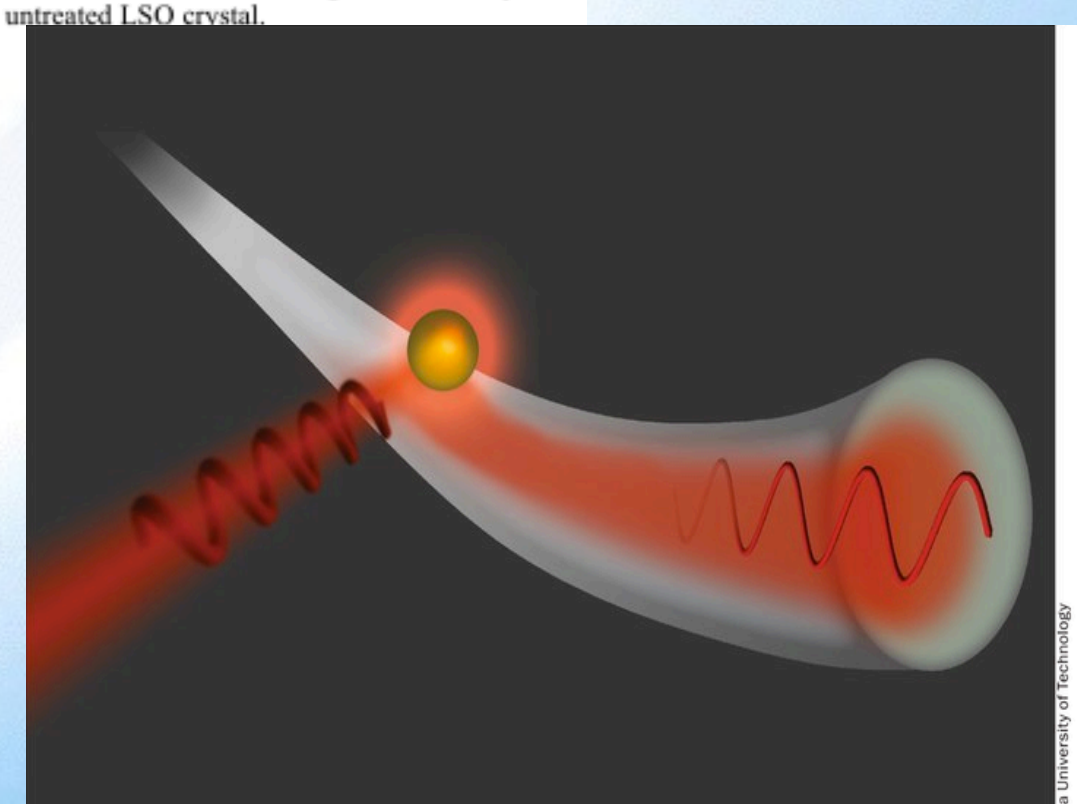


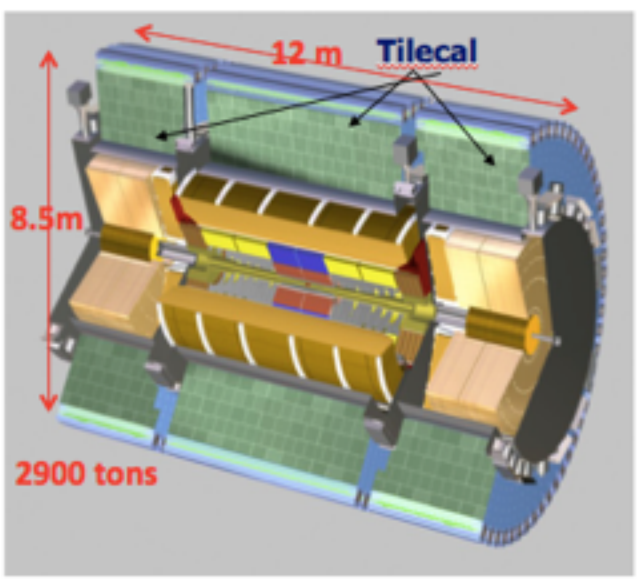
Fig. 4. Integrated photon yield over time for the "as designed" and "as produced" PhC compared with an untreated LSO crystal.

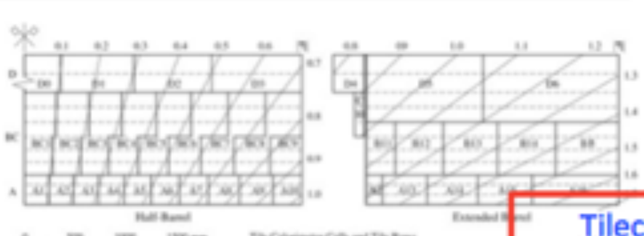


Organic Scintillators

- Organic scintillator calorimetry well established detector technology for hadronic calorimeters @ LHC and for their upgrades.
  - Scintillating tiles and fibers coupled to photodetectors on the outer periphery.
  - Cost effective solution
  - Promising for central HCAL in a FCC-hh experiment where radiation levels are expected to be moderate (50kRad/yr @ 10^{36})

ATLAS Tile hadron calorimeter (|η|<1.7)





- Scint. Tiles; fibres // to incoming particles at h=0
- Steel/Tiles: = 4.7 : 1 (λ = 20.7 cm)
- Active cells volume: ~ 372m3
- ~ 620k fibres ; 40k Tiles
- 10 k channels
- 7.7 λ at |η|=0 ; (9.7 λ with the em LAr calo)
- Transversal granularity ΔηxΔϕ=0.1x0.1
- Longitudinal segmentation: 3 layers
- e/h = 1.33
- Pion resolution (test beam):
  - σ_E/E~52%/☒E ☒ 5.7 % (7.9 λ)
  - σ_E/E~45%/☒E ☒ 2 % (9.2 λ)
- target (with e.m. LAR) at ATLAS/LHC:
  - Jet σ_E/E~50-60%/☒E ☒ 3%
  - Containment ~ 98% TeV hadrons, jets

Tilecal MoU Core Cost (1998):
- 17 MCHF (46% mechanics ; 11% optics ; 43% electronics).
- Readout elect. determine cost: ~730 CHF/channel
- 3.6% cost of the ATLAS detector

CMS HCAL: Barrel, Endcaps and Outer

P. De Barbaro

Barrel (HB): |η|<1.3, 36 wedges (18 HB+, 18 HB-)

14 layers of brass + steel front/back plates → ~ 6 λ in Barrel (90°), 10 λ w/ Outer

16 scintillator layers; 16 η and 4 ϕ divisions per wedge

Endcaps (HE): 1.3<|η|<3.0, 36 petals per endcap

17 layers of brass → ~10 λ

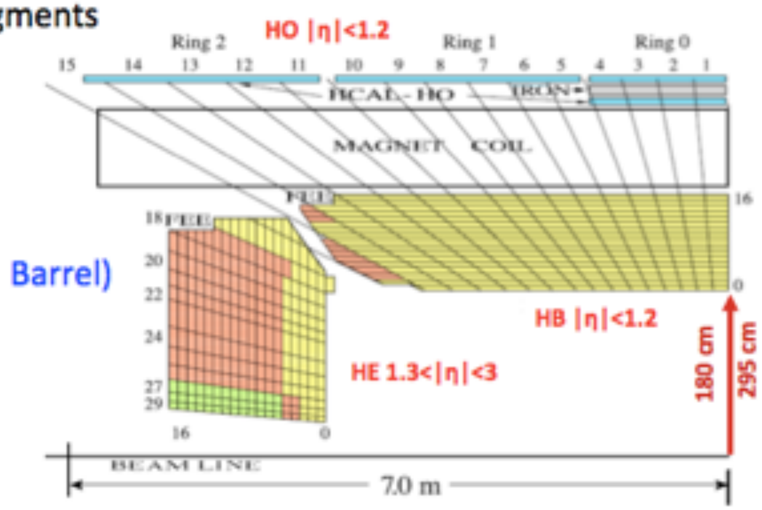
17 scintillator layers; 12 η and 1 or 2 ϕ divisions per wedge

2 or 3 (high η) longitudinal segments

channels total= 7344

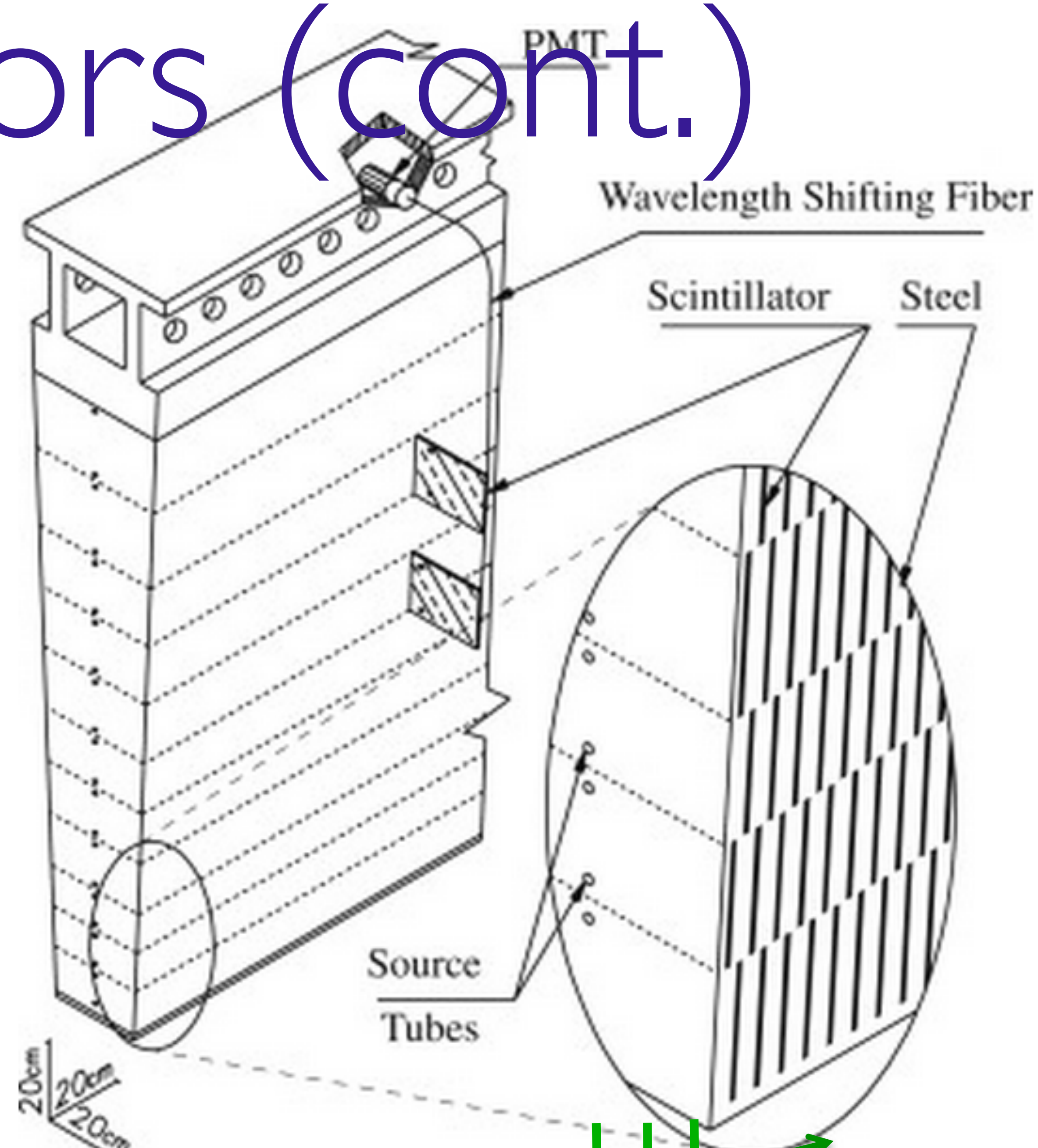
Pion resolution (2007 test beam):

σ_E/E~113%/sqrt(E) + 3 % Endcap, Barrel)

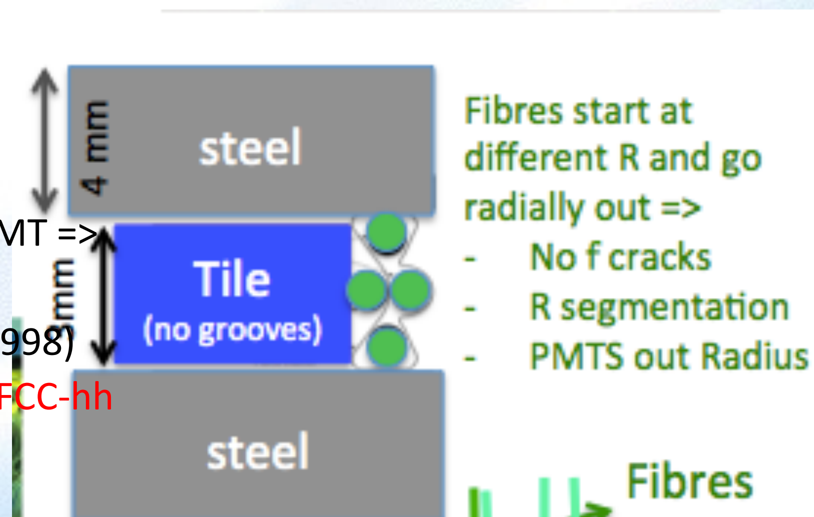


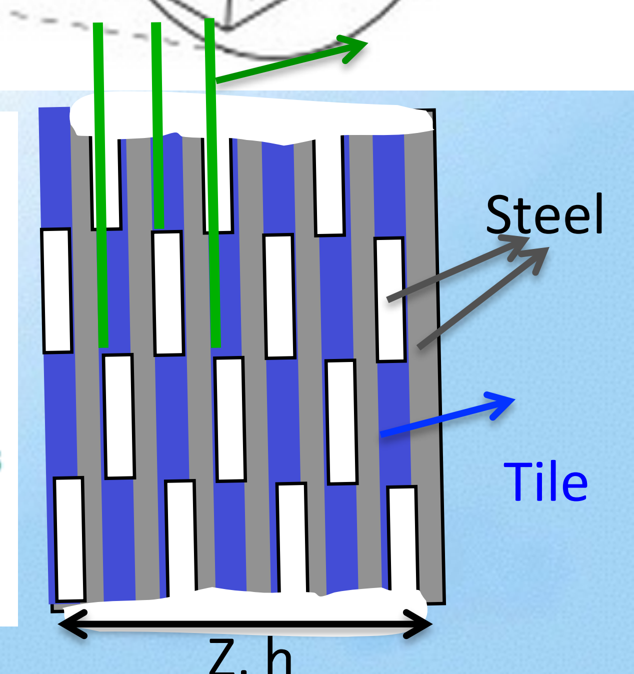
Organic Scintillators (cont.)

- High segmentation achievable by optimised organization of tiles and by the number of fibres coupled to a single photo-detector.
  - Minimal changes needed in optics/mechanics to exploit full granularity @ FCC-hh



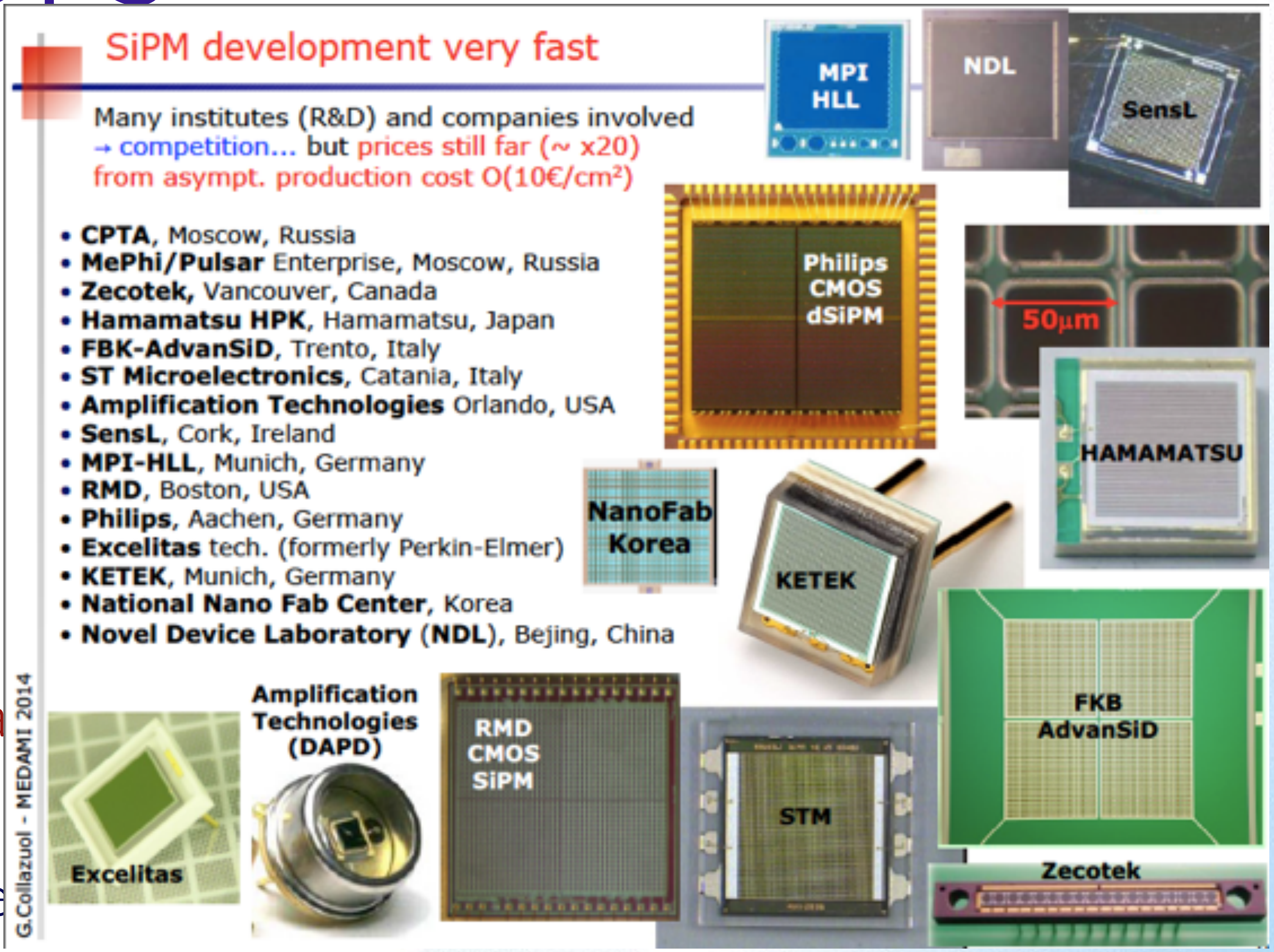
Dh: 3mm tiles every 9-18mm in Z->0.0007<Dh<0.008
DR: 11 tiles and 8 fibres in R -> 8-11 layers with 1l<DR<0.5 l
DF: 20 cm tiles-> Df=0.1 (with dual fibre readout)
In total ~ 620k fibres and 40k tiles ; but ~80-300 Tile-fibres couplings in 1PMT =>
10 k channels ; DhxDf=0.1x0.1 ; 3 longitudinal layers in LHC
Cost/performance compromise in electronics costs (~730CHF/channel in 1998)
Minimal changes needed in optics/mechanics to exploit full granularity at FCC-hh





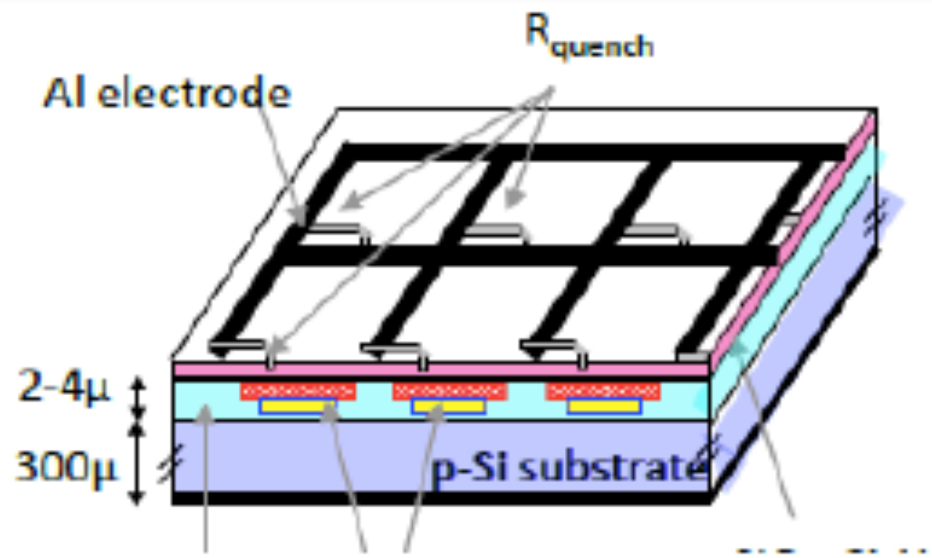
Photodetectors

- General requirements:
  - Rad hardness
  - B-field immunity
  - Time response
  - Dynamic range
  - Integration/channel multiplicity
  - Matching to light emission of scintilla radiators



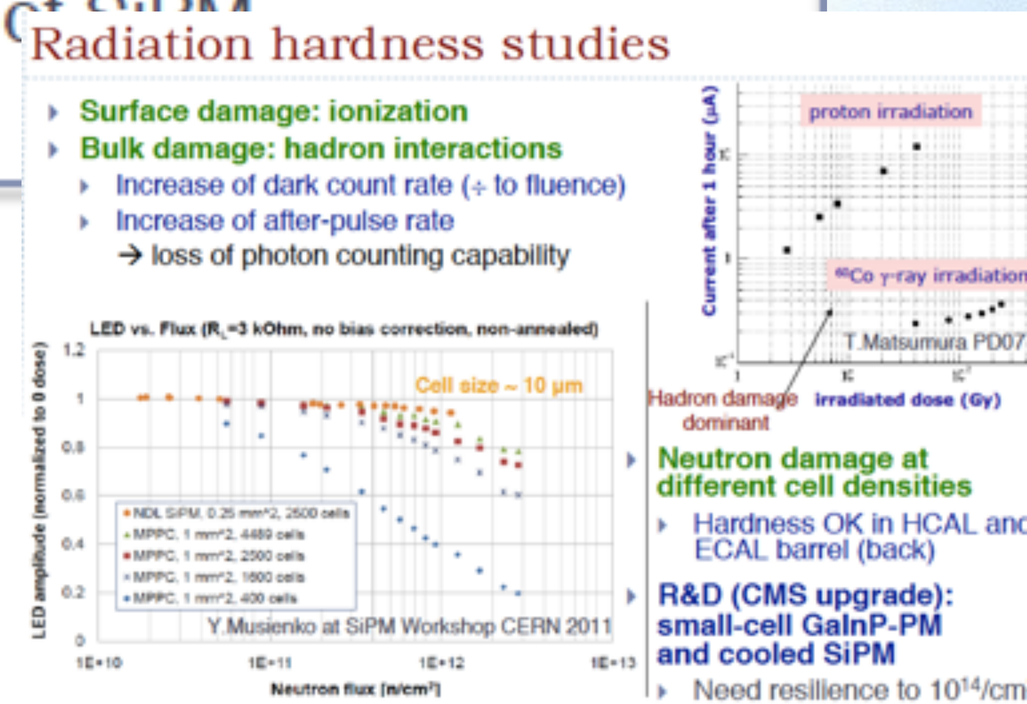
- Existing Technologies under developme
  - **SiPM**
  - **PMT-MCP**
- New technologies:
  - GaInP-PM
  - Tipsy (MEMS based transmission dynode stack on Si pixel CMOS anode)

Photodetectors: SiPM



Typical SiPM size: 5x5 mm²
Typical cell size: 50 μm× 50 μm

- **Arrays of *GM-APDs* with binary output**
  - Analog output = Σ of binary signals ÷ Nb. Incident photons
- **Technology mature, but still in progress**
  - Adopted in experiments (e.g. HCAL at CMS at colliders)
  - Many flavours of SiPM
  - Cost still high



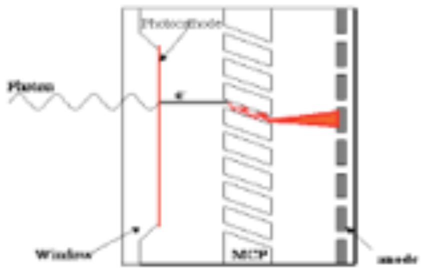
- **Advantages**
  - Immunity to B-field
  - High PDE (~30-50% including fill-factors)
  - Timing can be excellent (<50 ps)
- **Limiting factors**
  - Dynamic range
  - Dark rate
  - Radiation soft

All improve at smaller pixel size
Active R&D towards 5 μm × 5 μm
(Dynamic range >10^6 / cm²)

T.Tabarelli, https://indico.cern.ch/event/358198/session/2/contribution/14/material/slides/0.pdf

Photodetectors: MCP-PMTs

Micro-channel plates (MCP) PMTs



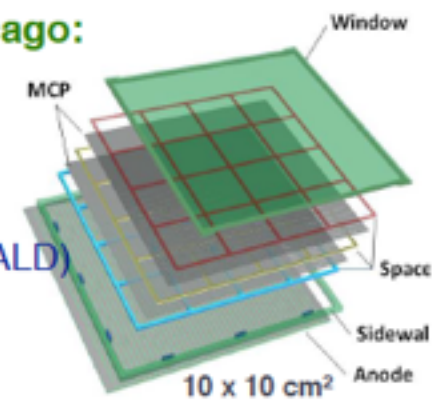
Typical size: a few 1 cm²
Pore size: 10-50 μm

- **Photomultiplier with very compact amplification stage**
  - Micro-channel plates ~ 1 mm thick
- **Well known technology, diverse usage**
  - Time resolution <10 ps → TOF systems
  - High granularity → Image intensifiers
  - Cost for large areas still prohibitive!

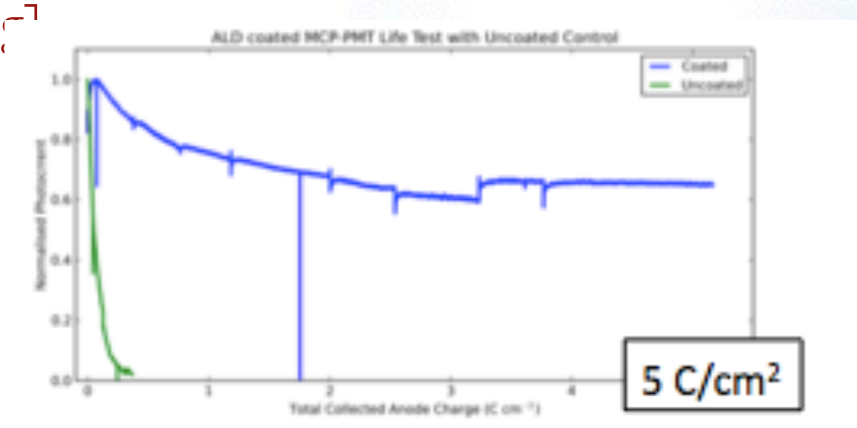
- **Recent R&D development at Argonne / U.Chicago:**
  - LAPPD collaboration → R&D towards mass (and affordable) production of large area MCPs

1. Glass microcapillary array providing pores
2. Resistive coating by Atomic Layer Deposition (ALD)
3. High-emissivity coating ALD

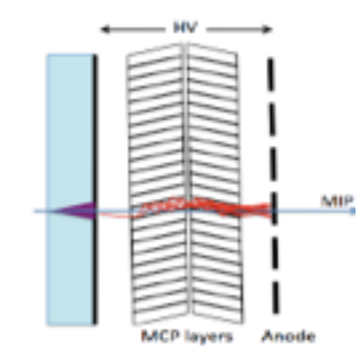
[LAPPD Docs: http://psec.uchicago.edu/]



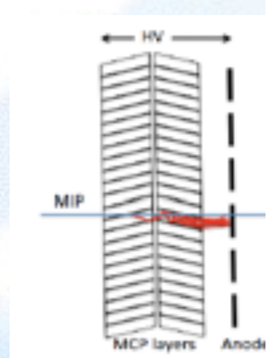
- Limitations:
  - Operations in Magnetic field (tested up to 2T)
  - Need lifetimes above 100 C/cm² [achieved > 5C/cm² in MCPs with ALD (Atomic Layer Deposition) coating - which reduces out-gassing]



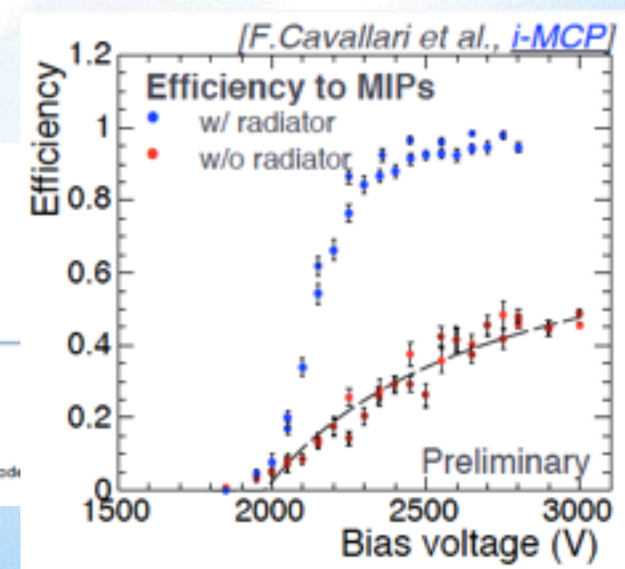
- Alternative use of MCPs
  - Coupled to a Cerenkov radiator

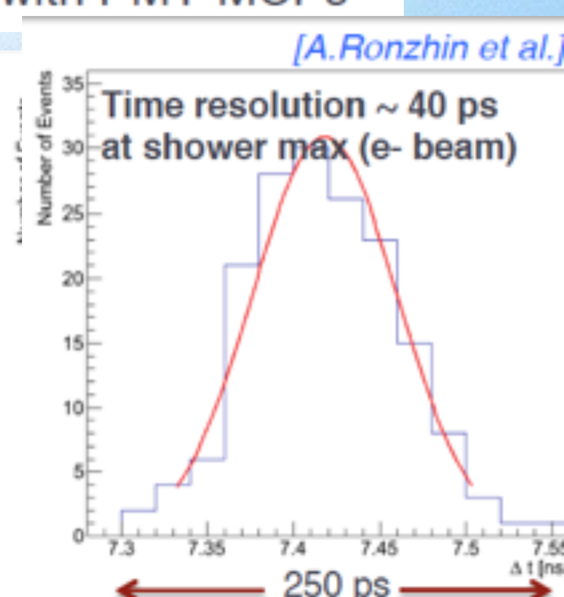


  - As a secondary emission device



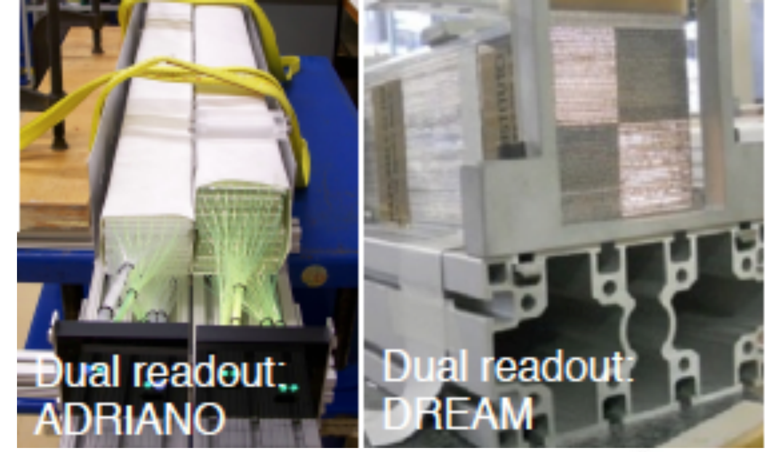
- **20-30 ps in shower detection at beam tests**
  - [A.Ronzhin et al, NIM A 759 (2014) 65]
- Confirms time resolution on MIPs obtained by several groups with PMT-MCPs

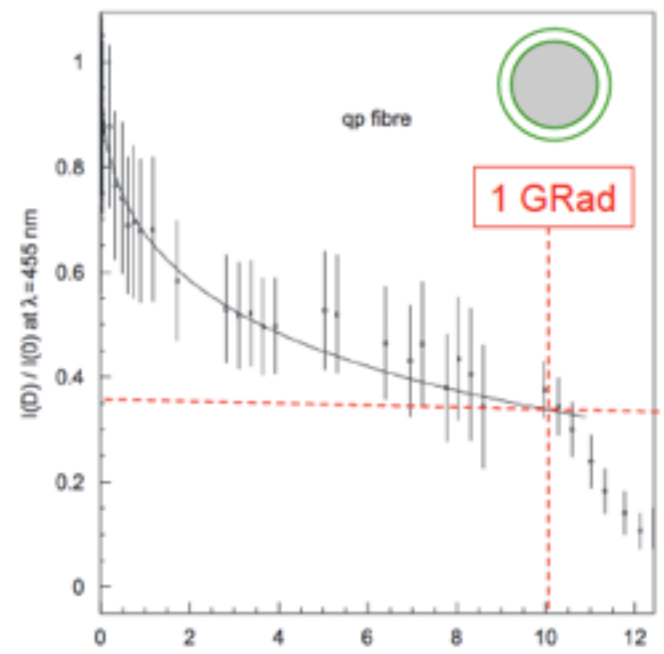


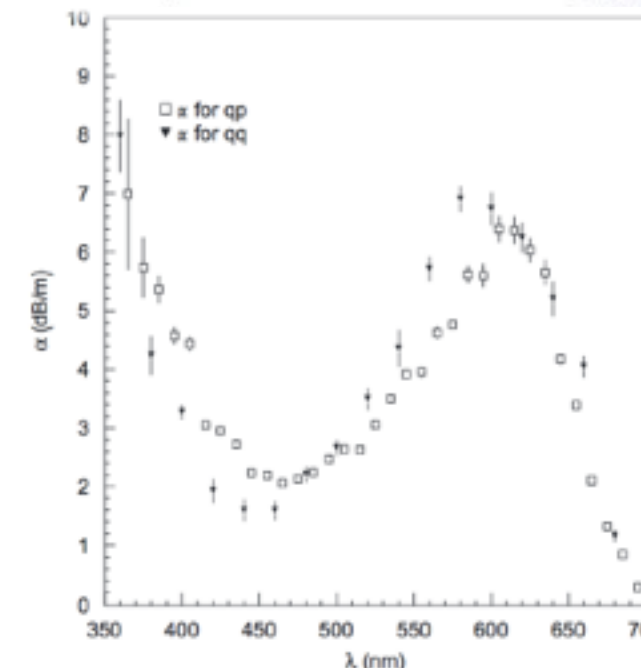


Dual Readout

- Radiation hardness tests on quartz fiber during R&D phase of the CMS FCAL
  - Hard-polymer-clad/high OH-fused-silica core fibres (QP) shows significant radiation hardness and can deployed in forward and end-cap calorimeters
  - PRL 71(1993) 1019, NIM A490(2002) 444, NIM A585(2008) 20
- DREAM and ADRIANO





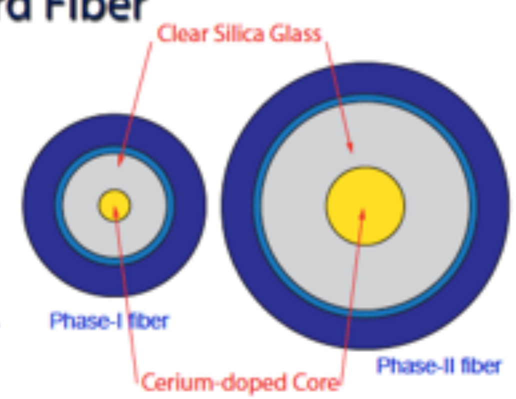


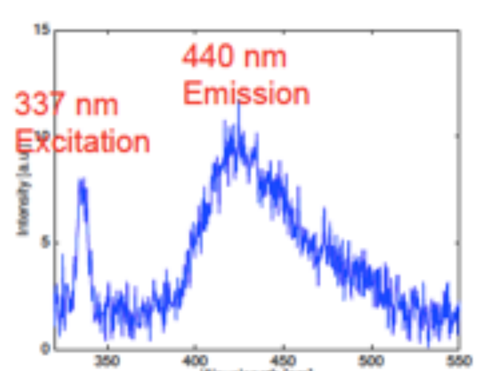
Scintillation/Cherenkov Light in a Single Radiation-hard Fiber

Several R&D projects are underway investigating cerium-doped fused-silica fibers ($SiO_2:Ce^{3+}$) and a number of prototype fibers have been produced

It may be possible to use a single fiber (*e.g.* $SiO_2:Ce^{3+}$) to extract both Cherenkov and scintillation light at the same time reducing the number of readout channels by a factor of 2 in dual-readout

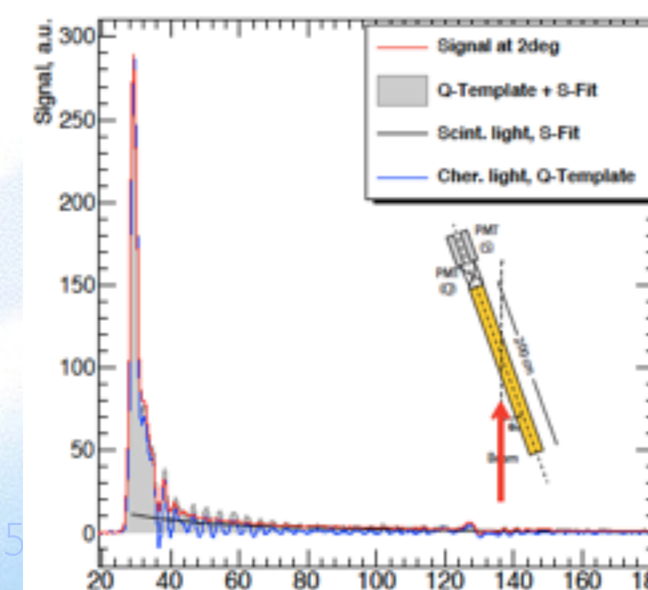
Preliminary results on radiation hardness are encouraging

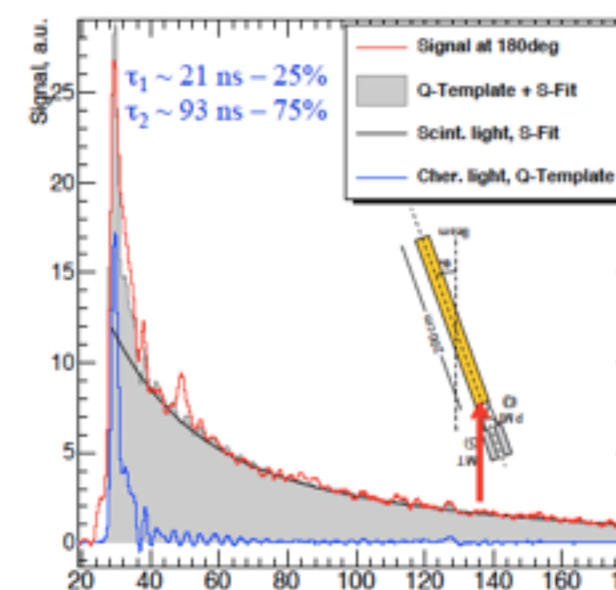




Scintillation/Cherenkov Light in a Single Radiation-hard Fiber - II

The Cherenkov (SiO_2) and scintillation ($SiO_2:Ce^{3+}$) light coexist in a single fiber and the balance between the two types of light can be "tuned" by geometry



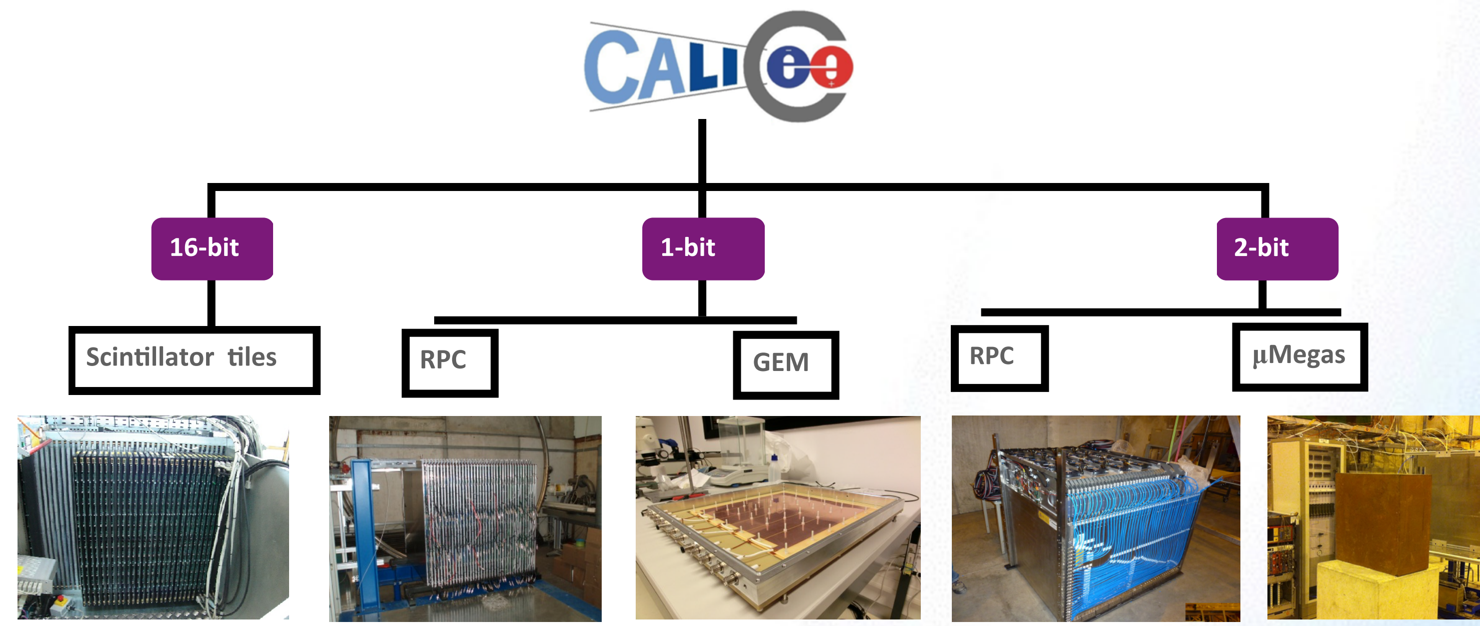


Challenges and possible evolutions of

Gas Micro Pattern Calorimeters

A Sharma, https://indico.cern.ch/event/358198/session/2/contribution/1/0/material/slides/1.pdf
J Repond, https://indico.fnal.gov/getFile.py/access?contribId=24&sessionId=3&resId=0&materialId=slides&confId=7864

- MPGDs may offer a cost-effective means to provide a finely segmented active medium for imaging calorimeters
- Extensive R&D for Imaging Hadronic Calorimeters in the CALICE collaboration
  - Both analog and digital calorimetry
  - RPC, MicroMegas and GEMs as possible active media
- Further R&D required for possible use of MPGD-based calorimeters in high intensity pp colliders



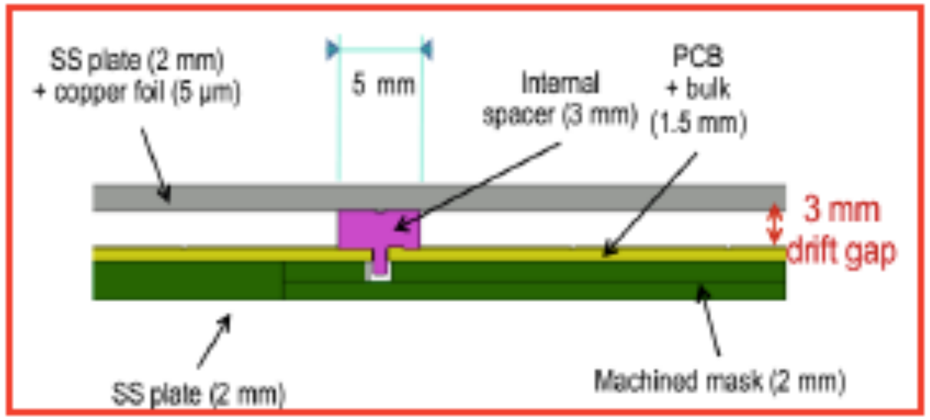
MPGDs	RPCs	MicroMegas	GEMs
Signal charge	Dependent on location of 1st ionization	Proportional to dE	Proportional to dE
MIP detection efficiency	>90%	>90%	>90%
Noise rate	~0.1 Hz/cm^2	0.02 Hz/cm^2 + sparks (10^{-5}/event)	
Rate capability	~0.1 kHz/cm^2	~10 kHz/cm^2	~1 kHz/cm^2
Cost	Cheap	More expensive	Expensive (foils) Cheap (THGEMs)
Robustness	Yes	To be demonstrated	Not so much (foils) Yes (THGEMs)

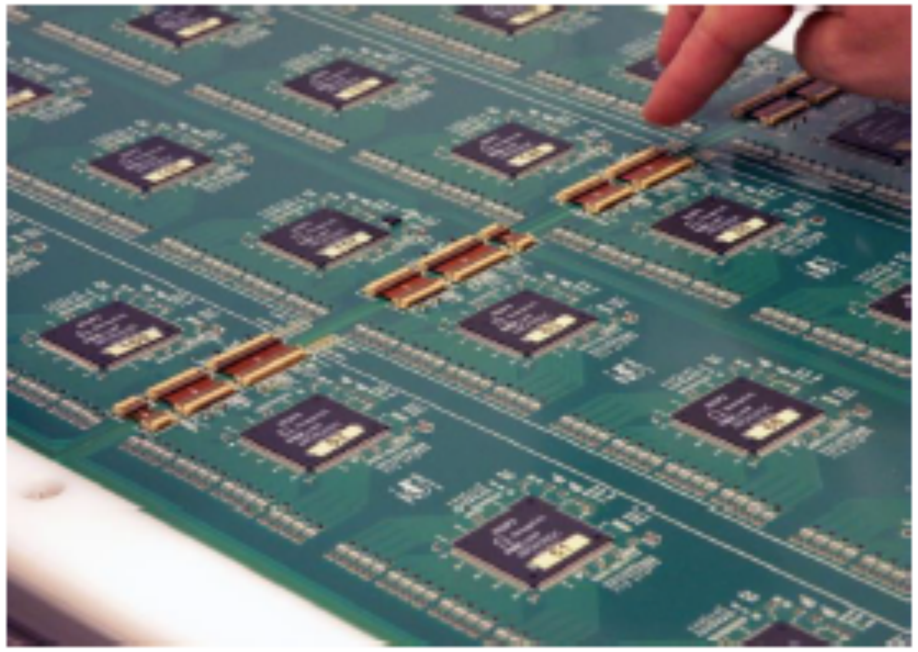
Potential limitations and challenges

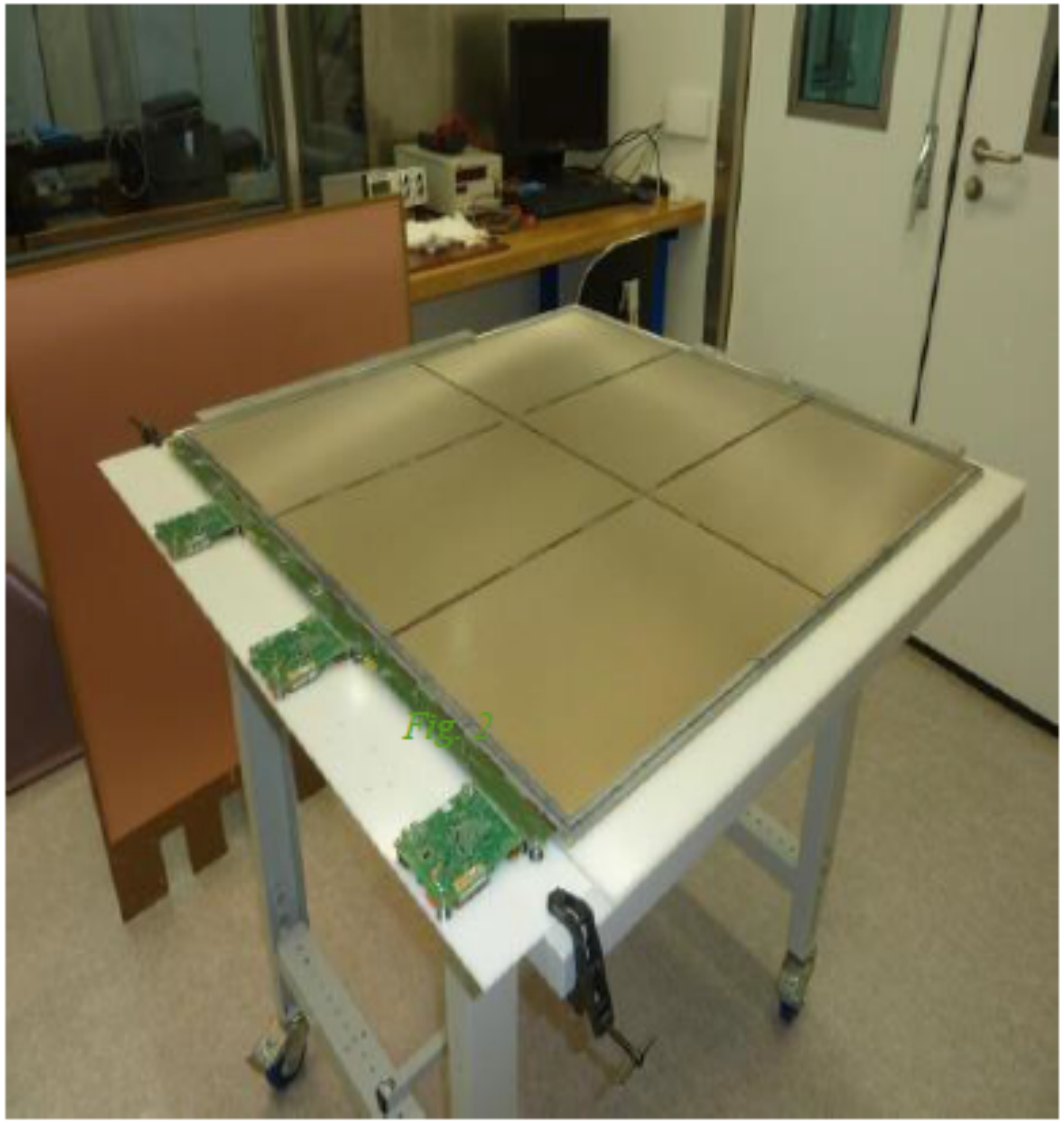
- Rate capabilities
- Linearity of response and saturation at high energies
- Calibration (in particular for digital readout)
- Trigger schemes
- Time resolution achievable
- Aging

Large Area Prototypes DHCAL: Micromegas

Calorimeters will be highly segmented:
(10^6-10^7) channels ~1x1 cm^2 pads)
1x1 m^2 = 6 boards in 1 vessel
Total thickness once chamber closed
~ 1 cm
Published in NIMA, 729 (2013) 90







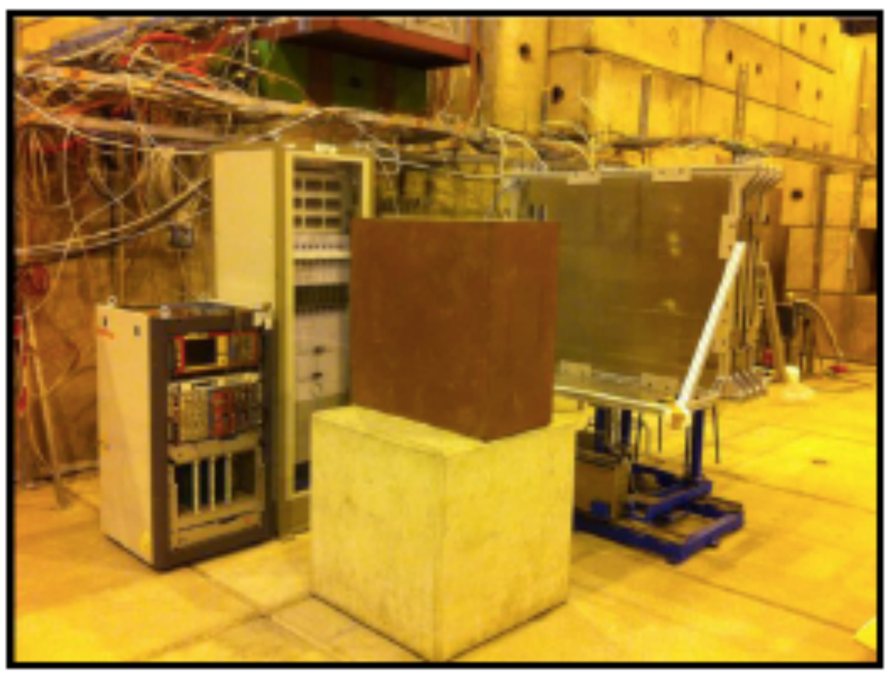
M. Chefdeville et al CALICE
T. Gerialis and M. Titov for CMS

Measured performance (1/2)

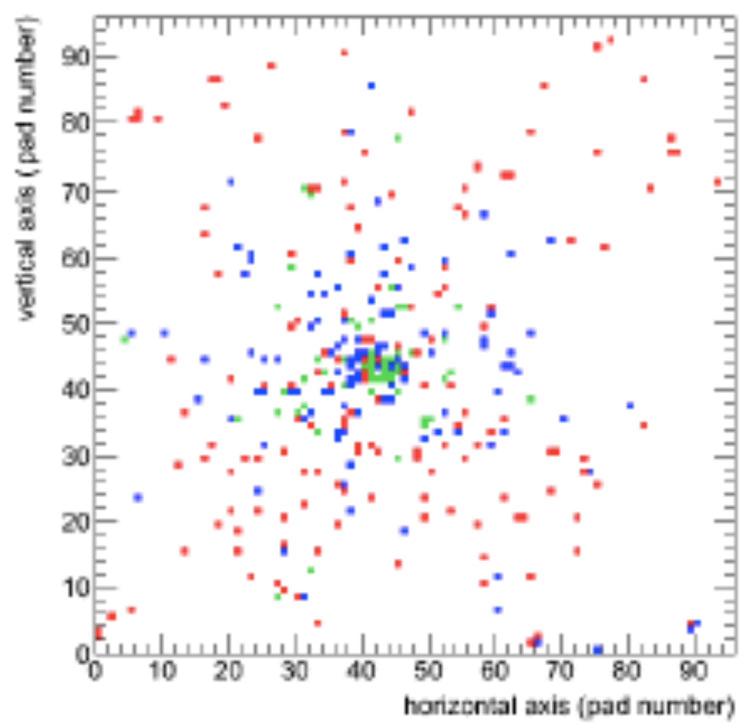
Standalone test of 4 prototypes (SPS H4, Nov. 2012)

- High efficiency (>95%), low hit multiplicity (<1.1), good signal uniformity (~5%)
- Shower response constant from 1-30 kHz pion beam,
- spark probability ~ 10^{-5} / shower
- Published in NIMA, 763 (2014) 221

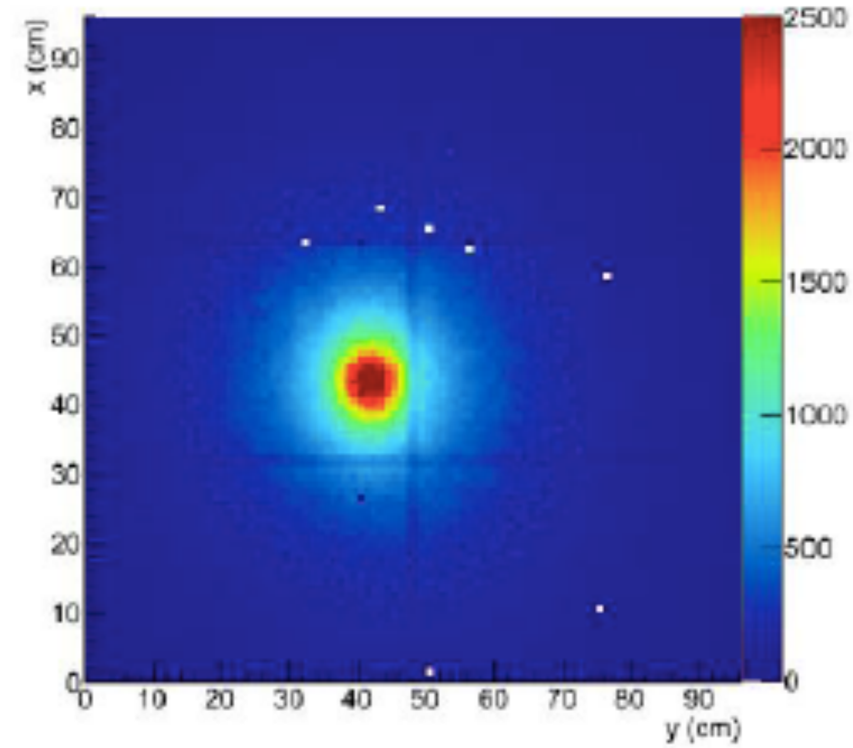
Iron block → shower set-up with 4 layers



1 shower event in first layer



50 k shower events



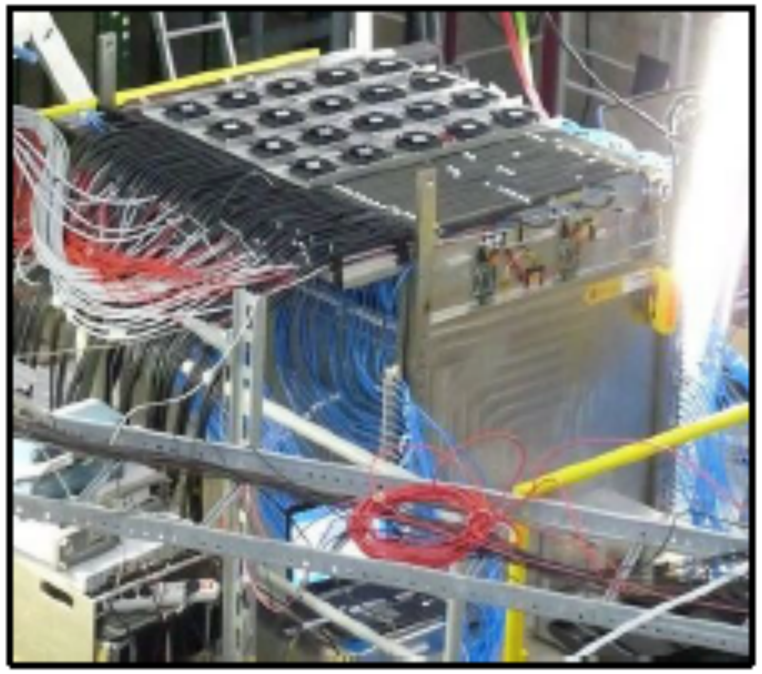
From Max Chefdeville

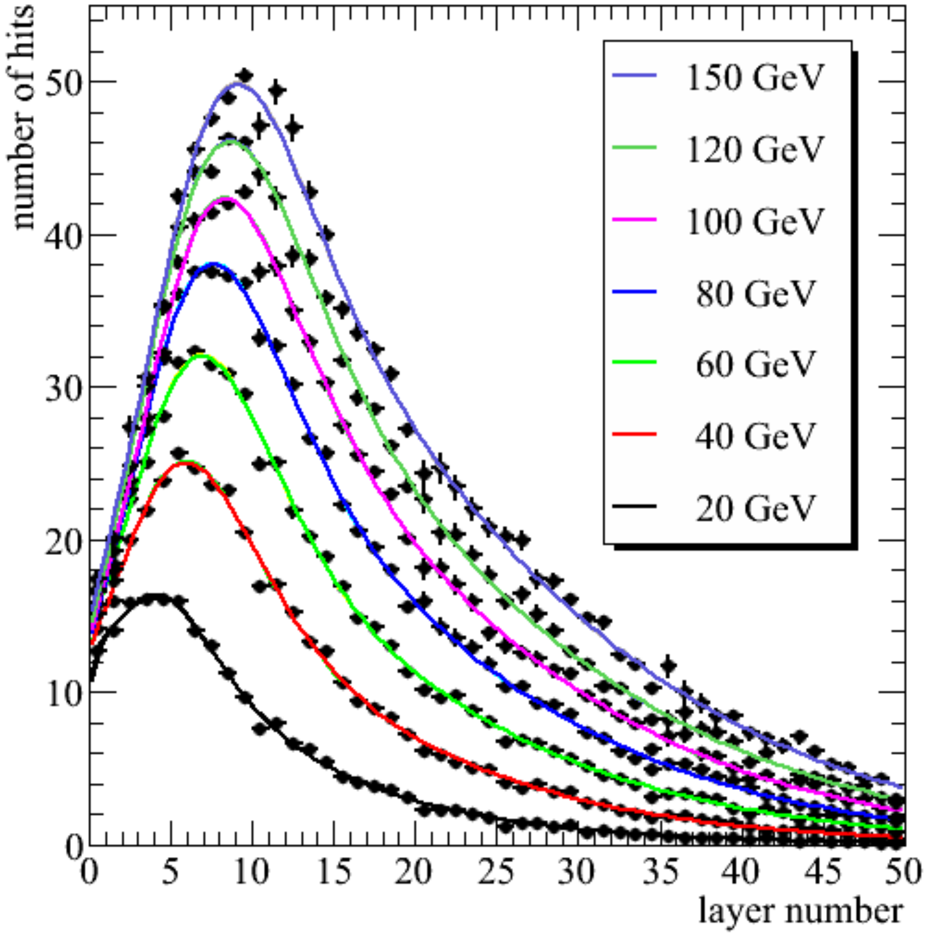
Measured performance (2/2)

Test inside the RPC-SDHCAL (46 RPC+ 4 Micromegas, SPS H2, Nov. 2012)

- Common readout system → tag shower start layer z0
- → N_hits in Micromegas for different z0
- Build longitudinal pion shower profile
- Get response by integration of the profile (test Geant4 models...)

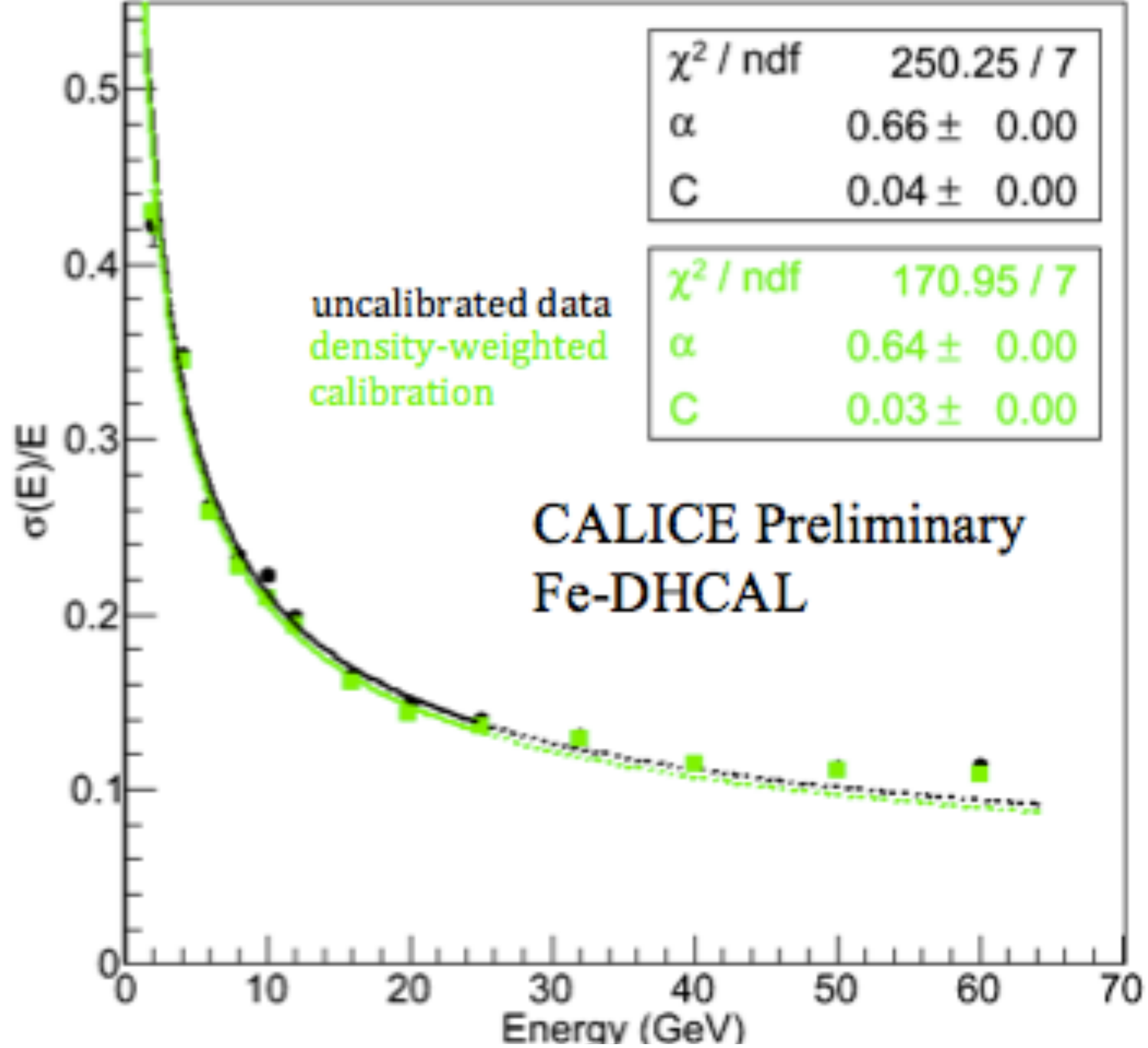
SDHCAL @ SPS

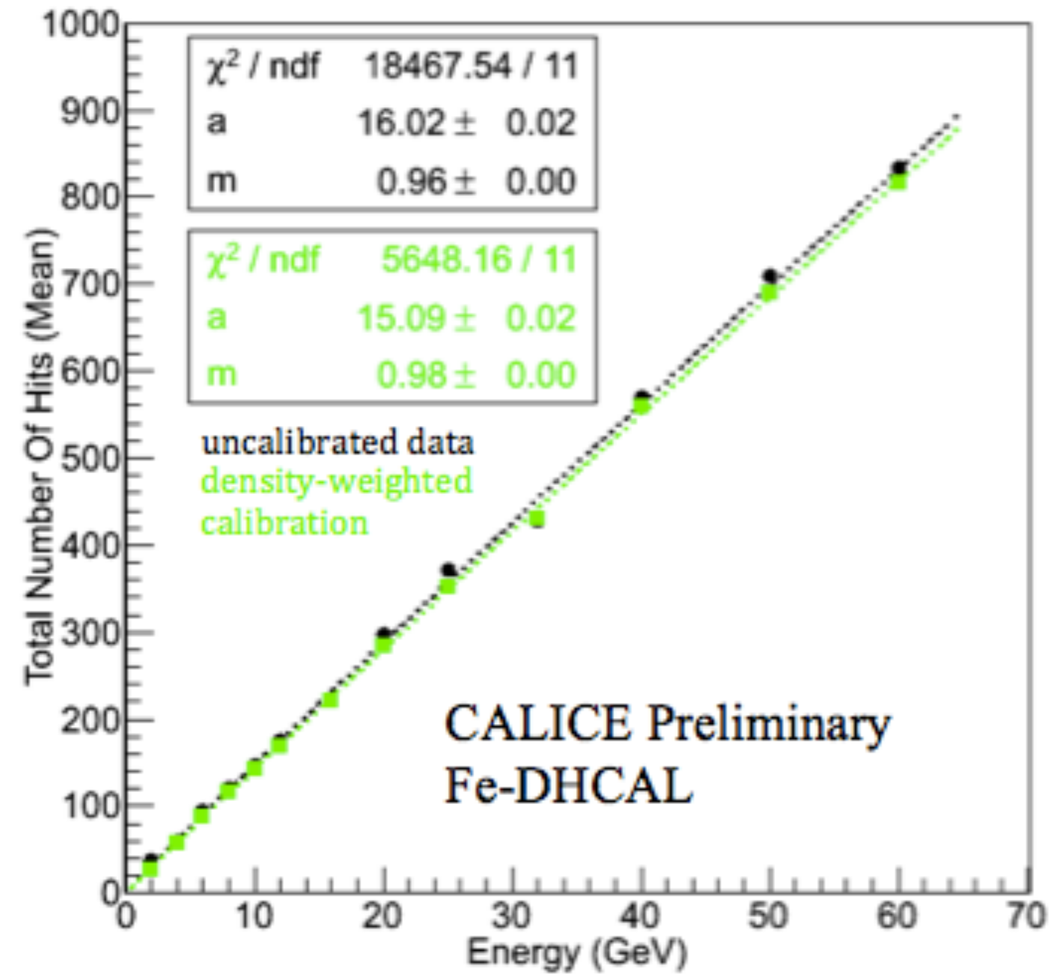




Response

- Example DHCAL with Fe absorber on pion beam
- Close to linear response up to 60 GeV
  - Power law fit to measure saturation at high energies
- Energy resolution stochastic term ~64%/√E (adequate for PFA)



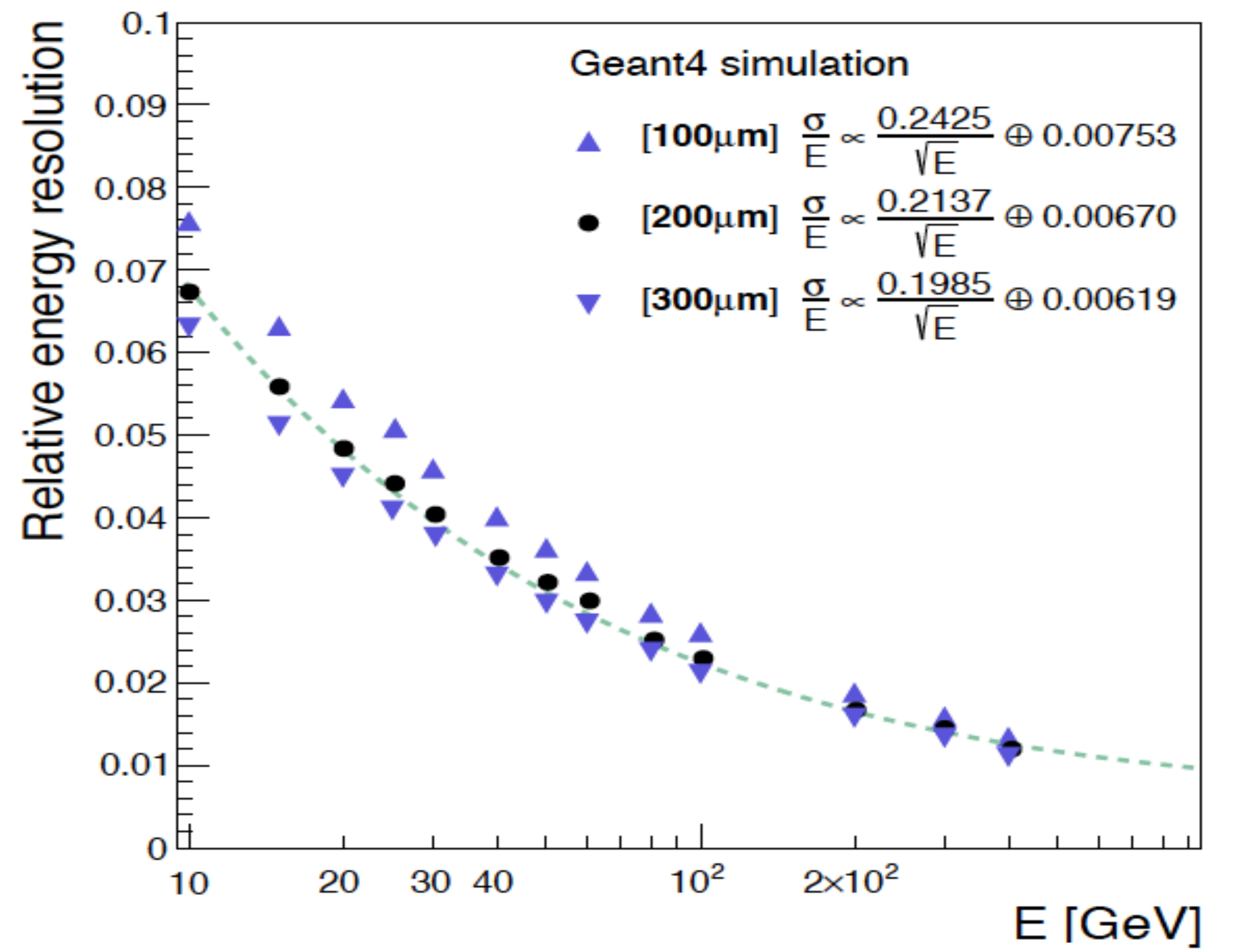


Challenges and possible evolutions of

Silicon-based High Granularity Calorimeters

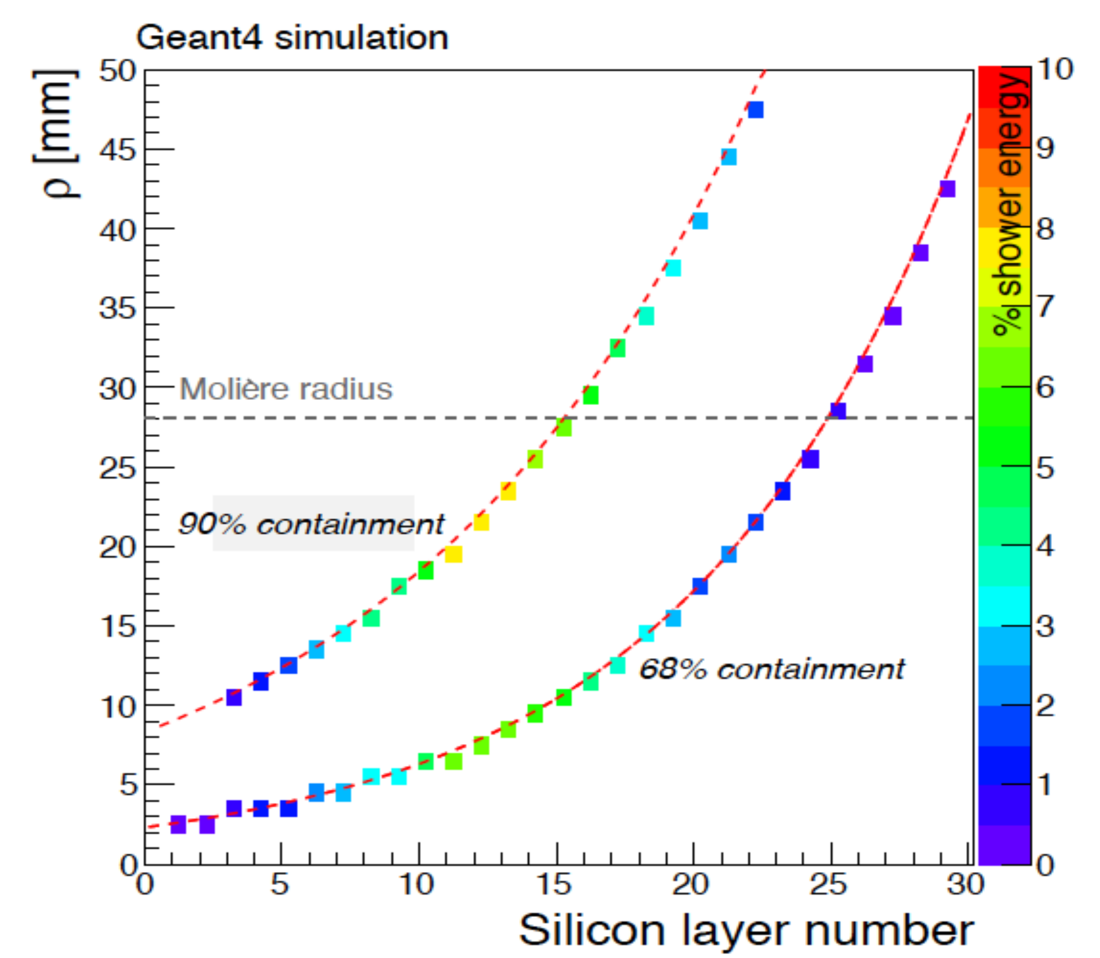
M. Mannelli, https://indico.cern.ch/event/358198/session/2/contribution/1/6/material/slides/0.pptx
J. Incandela, https://indico.fnal.gov/getFile.py/access?contribId=23&sessionId=3&resId=0&materialId=slides&confId=7864

- ***Si-HGC extends Tracking into Calorimeter***
  - Provides good cluster energy resolution
  - Very detailed topological information
  - Excellent space resolving power for nearby clus
- ***Ideally suited for PF reconstruction in 'high-densit energy deposit environment***
  - Baseline choice for ILC/CLIC
  - Option for HL-LHC upgrade of CMS EC-ECAL
- Possible applications for EM calorimeters in the cer region of a FCC-hh experiment



Potential Limitations and/or Challenges

- Size and costs
- Cell size mm2-cm2 and no. of readout channels
- Radiation tolerance of sensors and electronics
  - Thin sensors vs. noise & MIP sensitivity
- Dynamic Range vs. technology
  - MIP to 100-200pC range
  - Complexity, dead-time & pileup sensitivity
- Power and cooling
- Analog vs. Digital readout (UHGC)

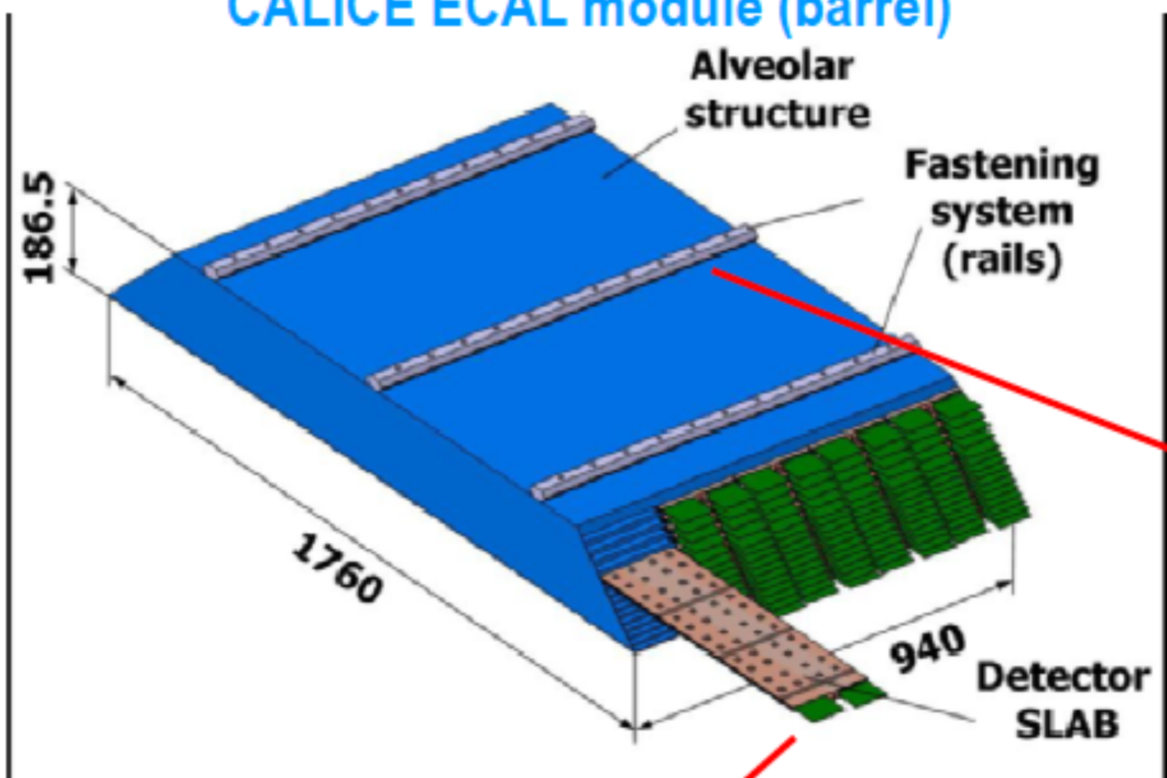


Si-HGC parameters for FCC-hh

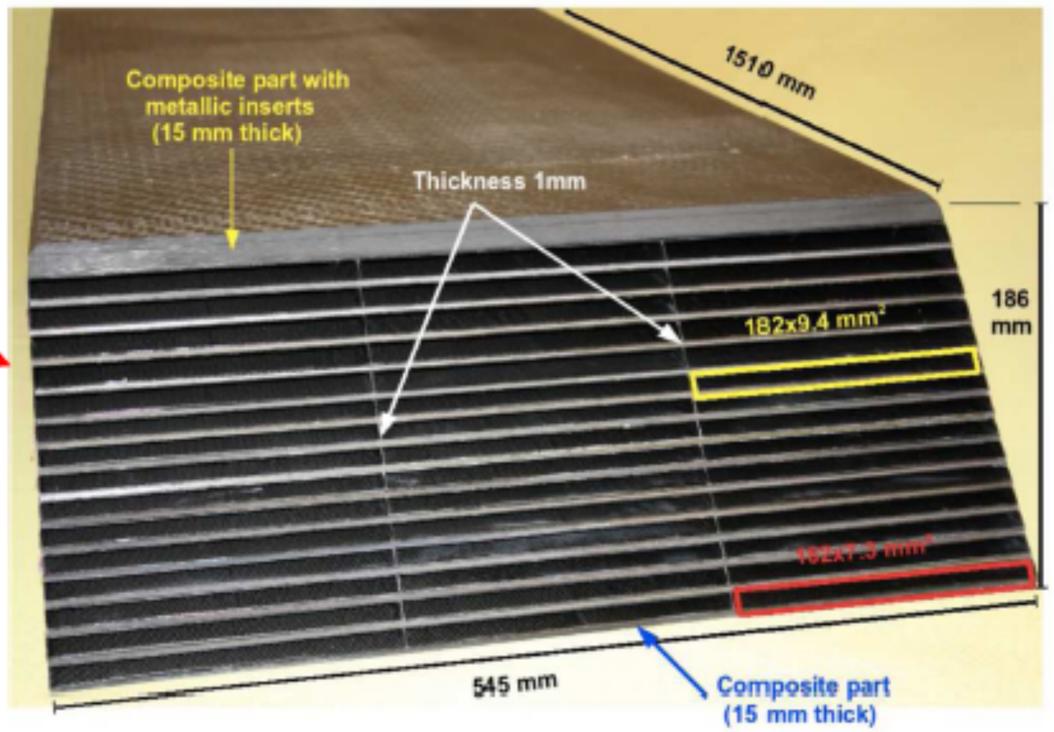
- Electromagnetic 26 ~ 28 X^0 (~ 1 l)
  - 30 sampling layers
    - *Silicon surface (very rough estimate!)*
      - For Large CMS-like Solenoid ~ 3'000m²
      - *For Very Large Double Solenoid ~ 10'000m²*
  - Cell size 0.25 ~ 1cm²
  - Gap between absorber layers ~ 4mm
- Front Hadronic ~ 4 l
  - 12 ~ 20 samples sampling layers, cell size ~ 1cm²
    - *Silicon Surface & Number of Channels (very rough estimate!)*
      - For Large CMS-like Solenoid 3'000 ~ 6'000m²
      - *For Very Large Double Solenoid 7'000 ~ 14'000m²*

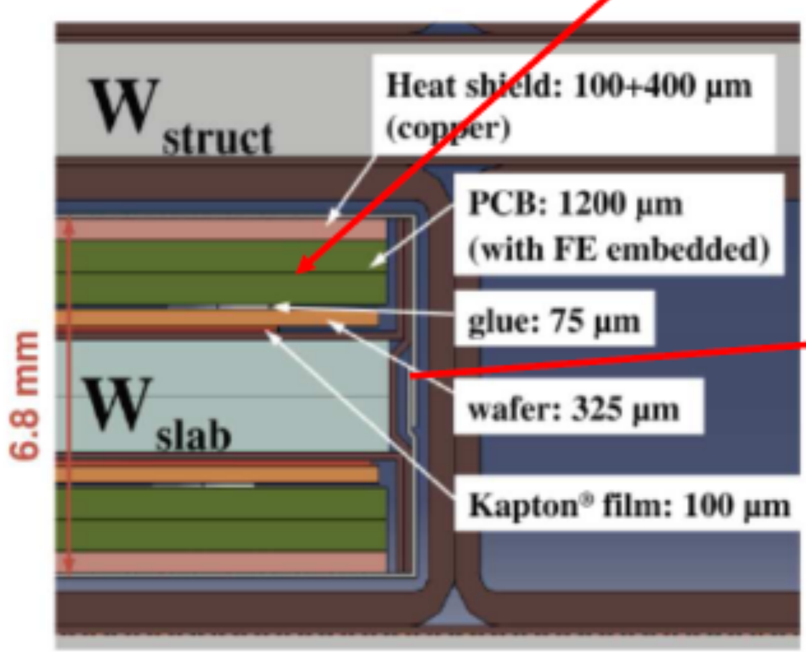
ILC-like structure for FCC-HGC

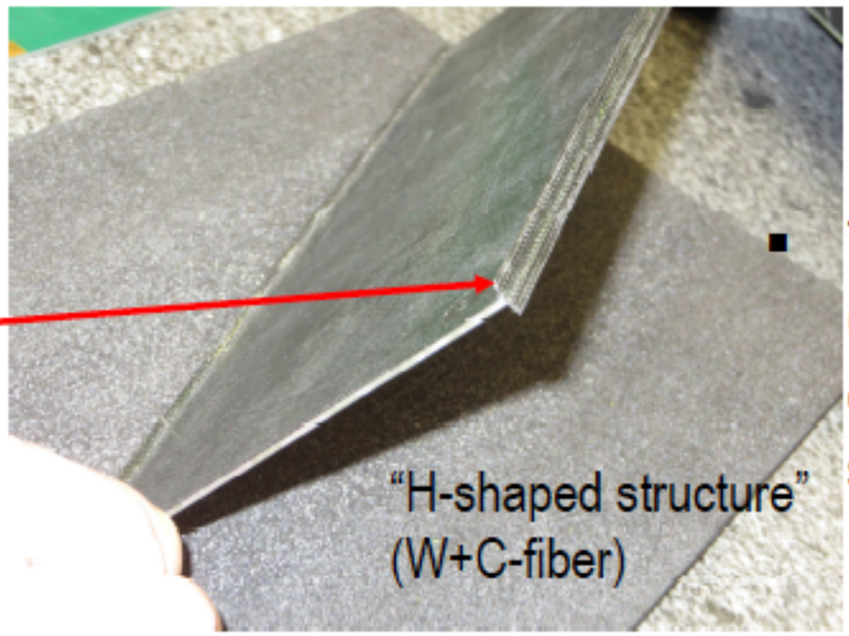
Reminder of the CALICE ECAL concept



- Half of the tungsten plates is incorporated into a self-supporting **alveolar composite structure** (carbon)

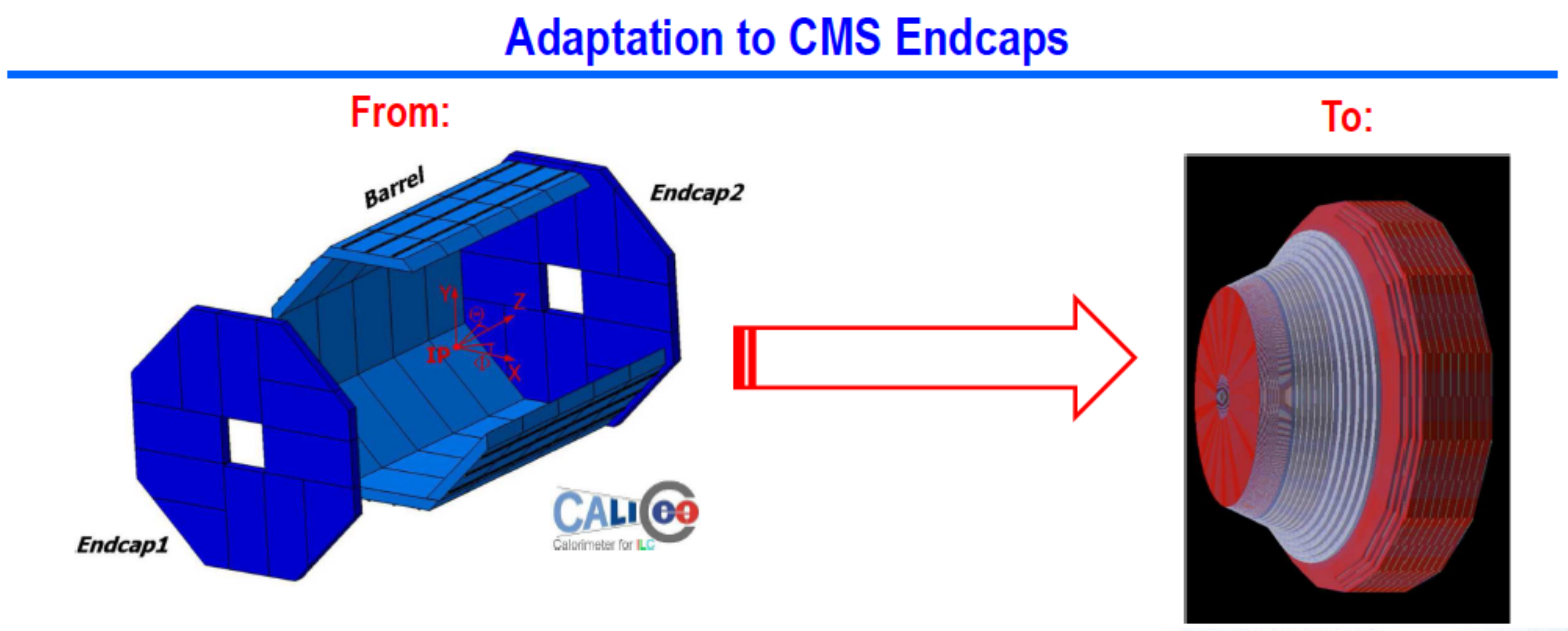






- The other half of the W plates in supports (H-shaped structure) called **detector SLAB (or "drawer")**, slide inside each cell.

ILC-like structure for FCC-HGC

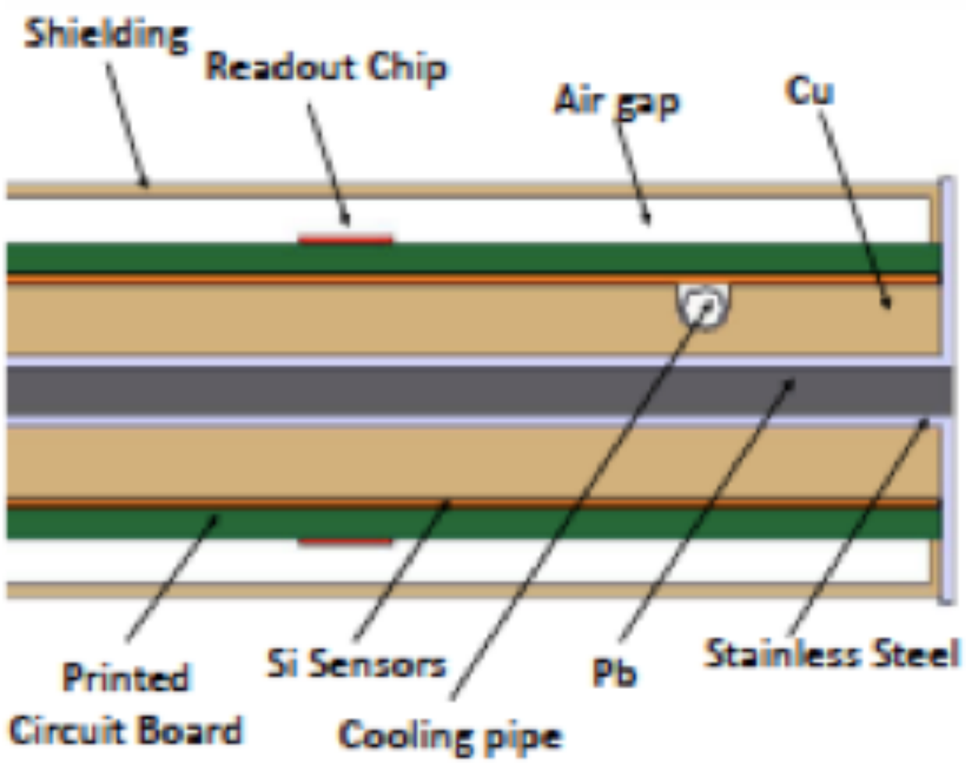


Big Differences include

- Power consumption, cooling, & Data rates
- Radiation and -30^{0}C operating temperature
  - Thermal enclosure & services feed-troughs
- Profit from synergy with Tracker R&D
  - Sensors, cold operation & CO_2 cooling, Power & Read-Out

Power and cooling estimates for the CMS-HGC upgrade

Power consumption, cooling & data rates



Power ranges from ~ 100W/m² in Barrel (300um thick sensors and 1cm² cell size)

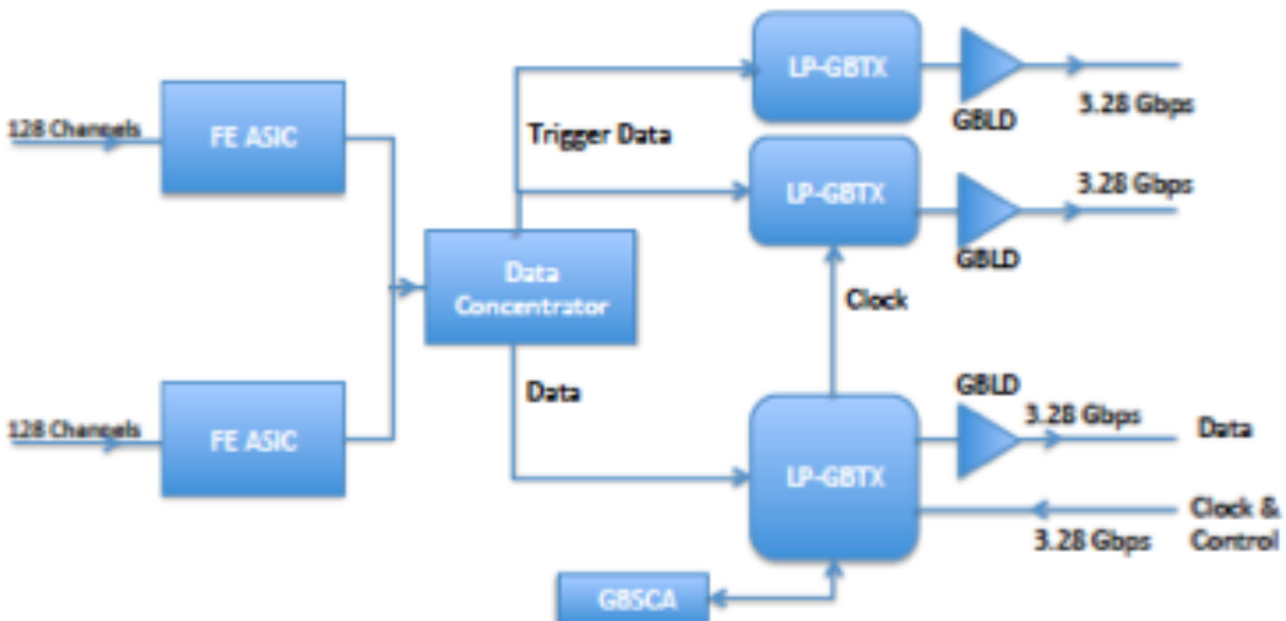
Up to ~ 250W/m² in End-Cap (100um thick sensors and 0.5cm² cell size)

Operate Silicon at -30C⁰ (-35C⁰ if possible)

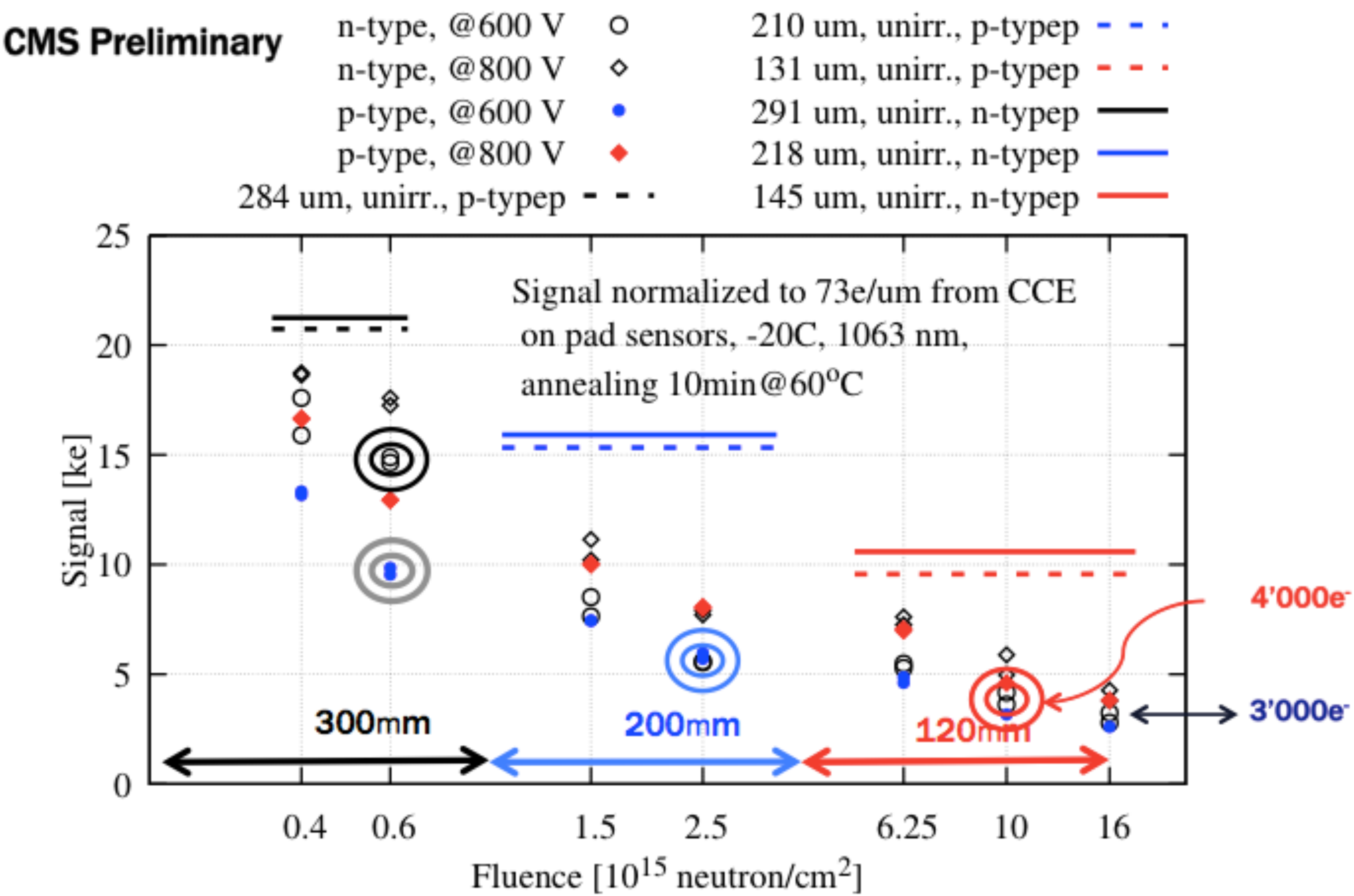
Exploit low cell occupancy and steeply falling energy spectrum, with simple data compression algorithm

CMS: from 1~2Gbps/Module up to ~8Gbps/Module in End-Cap; Dominated by L1 Trigger data

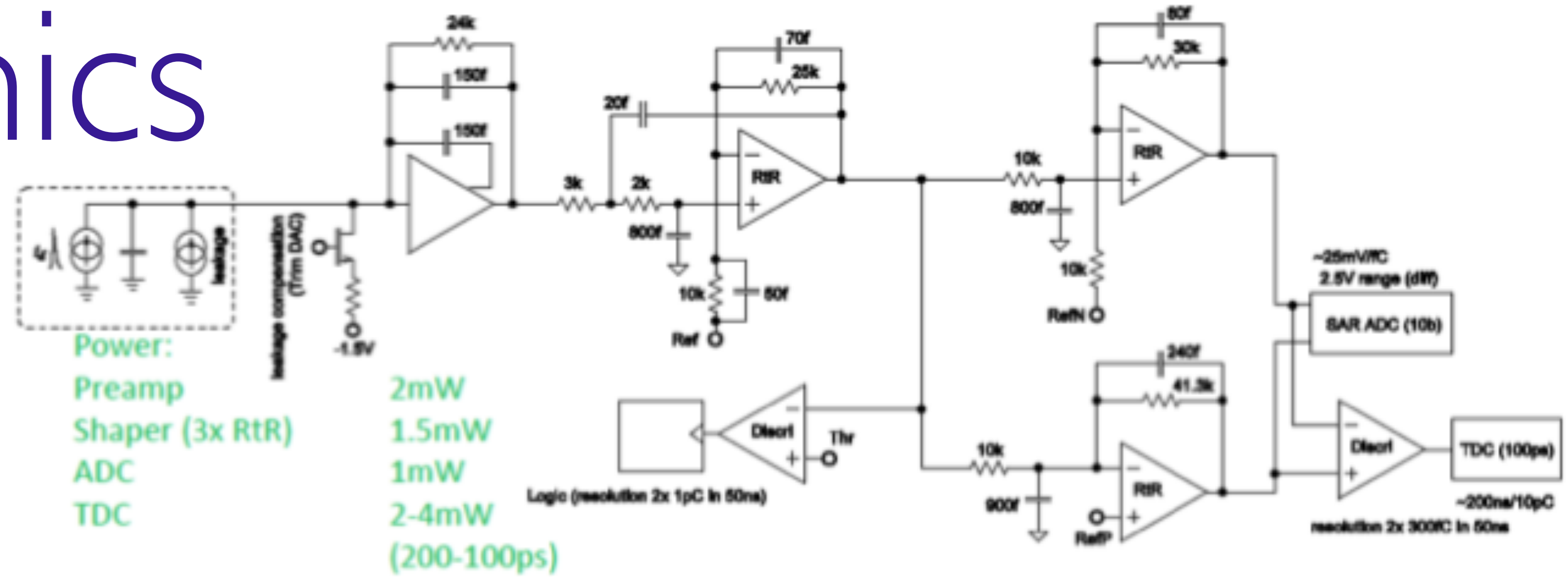
Expect ~ *2 at FCC



Si-HGC radiation resistance



FE Electronics



:Pix (NA62), 320MHz coarse clock, 100ps bin from DLL, 2012 JINST 7 C01065
JST group

Jan Kaplon (CERN)

- Developed HGC FE ASIC design which meets our performance requirements
  - Uses ToT to provide low noise (2'000e-) and cover full dynamic range
    - *Full SPICE simulation of analogue performance*
    - *ADC and TDC based on existing designs*
  - *Potential for ~50ps timing for each cell in core of showers with $E_T > 2 \sim 3$ GeV*
    - *More on this later*
  - Potential issues related to this design being investigated
- Have also simpler back up design
  - Lower gain to avoid issues associated with saturation
    - *Higher noise (11'000e-) => not sensitive to single MIP, requires dedicated channels for MIP calibration*

- Large energy deposits may results in ToT spanning several bunch crossing
  - Dead-time
  - Integration of pileup (noise source) potentially spoiling the energy resolution
- MAPS and digital readout for pixelized detector w. low-occupancy pixels could be an interesting alternative

Challenges and possible evolutions of

Noble Liquid Calorimeters

Well established techniques for large systems:

- High density medium (LAr: 1.4g/cm^3, LKr: 2.4 g/cm^3)
- Purely electronic calibration provides cell energy-scale reconstruction
- Uniformity of response ensured by mechanical precision and electronics calibration resulting in a low constant term of the energy resolution
- Stability of response: O(10^{-3})
- Intrinsically radiation hard
- Intrinsic no detector limitations for high magnetic fields
- Ease for configuration that can be optimised for different applications
    - Segmentation mainly through configuration of the electrodes collecting the ionisation charges and stacking geometries of electrodes w. or wo. absorbers

Potential limitations and challenges

- Inactive material upfront (e.g. cryostat structures), however possible internal compensation in absorber construction (e.g. massless gap option studied for the GEM/SSC LKr detector)
- Cryogenics
- Purity
- Long drift time (450ns in ATLAS EM). Sensitivity to pileup?
- Costs (LKr, LXe)

Resolution

ECAL Energy Resolution:

ATLAS	H1	NA48	GEM/SSC
LAr+Pb (2.0+1.5mm) accordion: [|η|<3.2]: ~175k channels	LAr+Pb (2.4+2.5mm): ~30k channels	quasi-homogeneous LKr: 13k towers of 2x2 cm (1cm drift of LKr)	LKr+Pb prototype (NIM A344 1994) on testbeam: *Constant term not measured in testbeam. 0.7% estimated in GEM TP/TDR*
$\frac{\sigma}{E} \simeq \frac{10\%}{\sqrt{E}} \oplus 0.7\%$	$\frac{\sigma}{E} \simeq \frac{11.2\%}{\sqrt{E}} \oplus \frac{150 MeV}{E} \oplus 0.65\%$	$\frac{\sigma}{E} \simeq \frac{3.2\%}{\sqrt{E}} \oplus \frac{90 MeV}{E} \oplus 0.4\%$	$\frac{\sigma}{E} \simeq \frac{6.7\%}{\sqrt{E}} \oplus \frac{80 MeV}{E}$

HCAL Jet Energy Resolution (e.g. ATLAS):

Hadronic End-cap (HEC): Cu absorbers, electrostatic transformers [1.5<|η|<3.2]: 5.6k channels

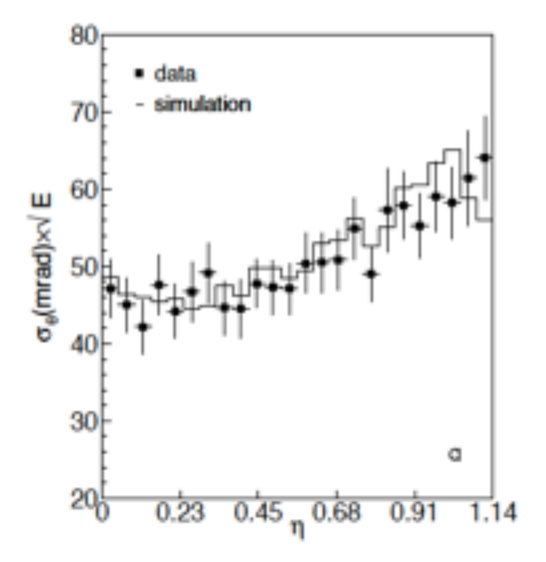
$$\frac{\sigma}{E} \simeq \frac{50\%}{\sqrt{E}} \oplus 3\%$$

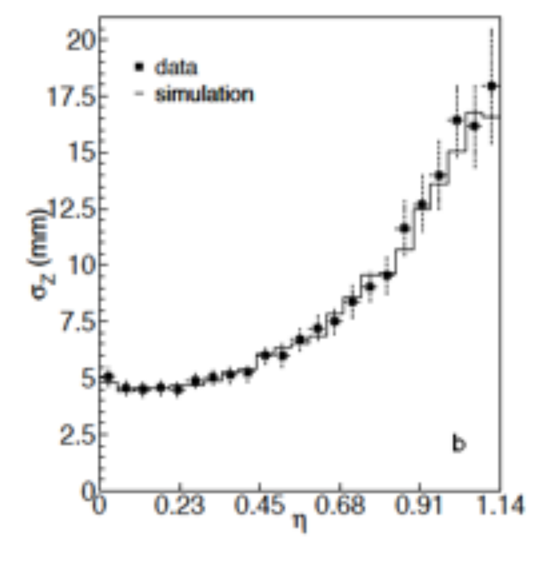
Forward Calorimeter (FCal): narrow gap tubes in Cu (FCAL1 module) / W (FCAL2,3 modules) absorbing structure [3.1<|η|<4.9]: 3.5k channels

$$\frac{\sigma}{E} \simeq \frac{100\%}{\sqrt{E}} \oplus 10\%$$

Pointing Resolution (e.g. ATLAS):

$$\sigma_z \simeq 5mm(@\eta \approx 0)$$



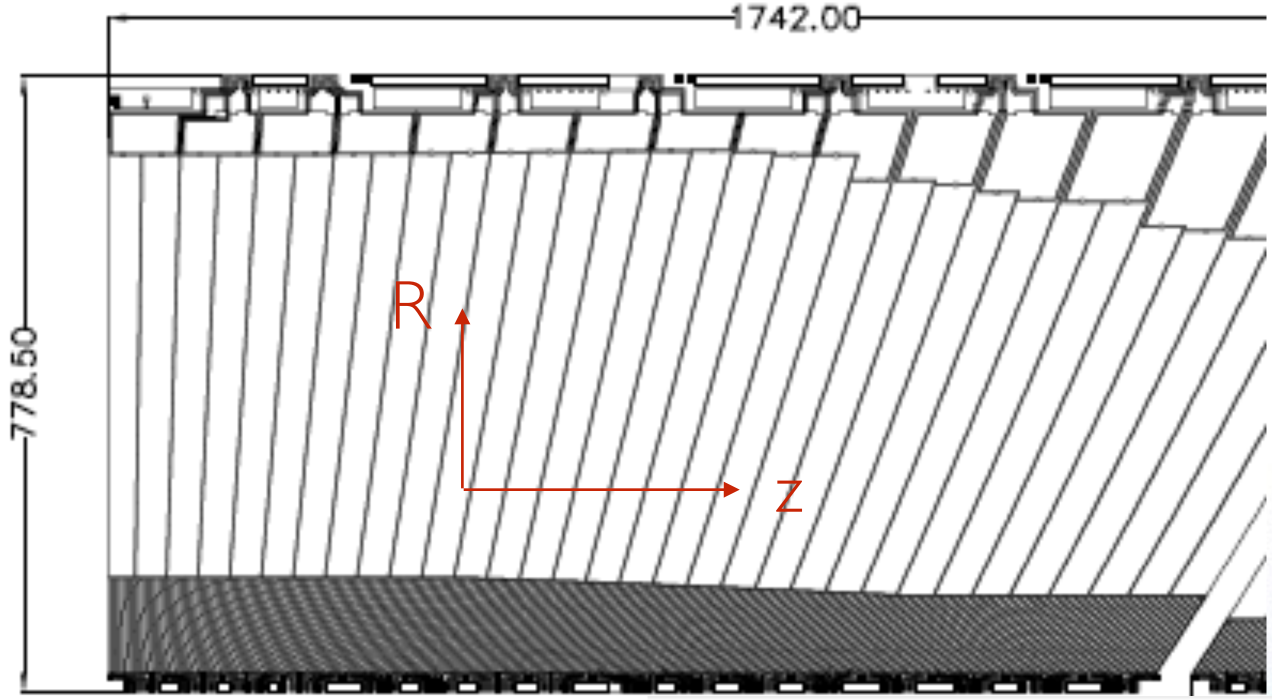


$$\sigma_\vartheta \simeq 40 \times \sqrt{E} mrad(@\eta \approx 0)$$

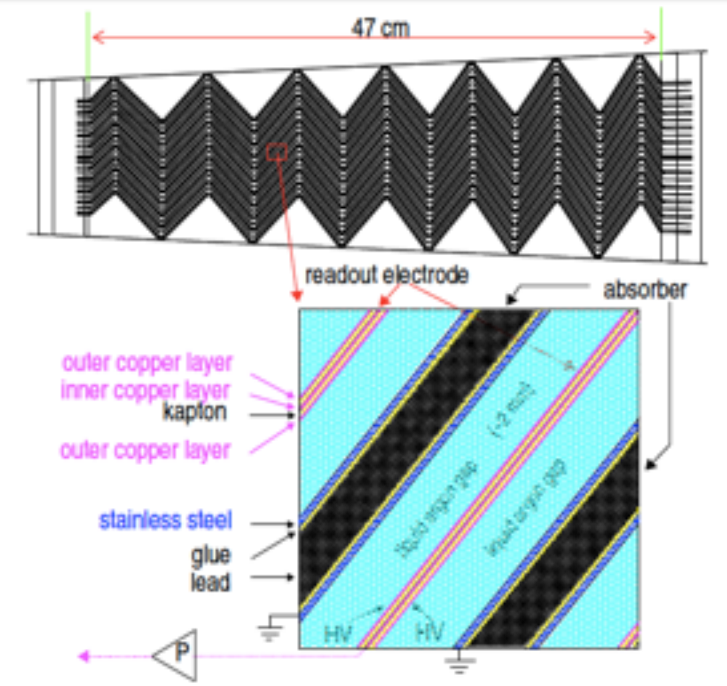
Granularity

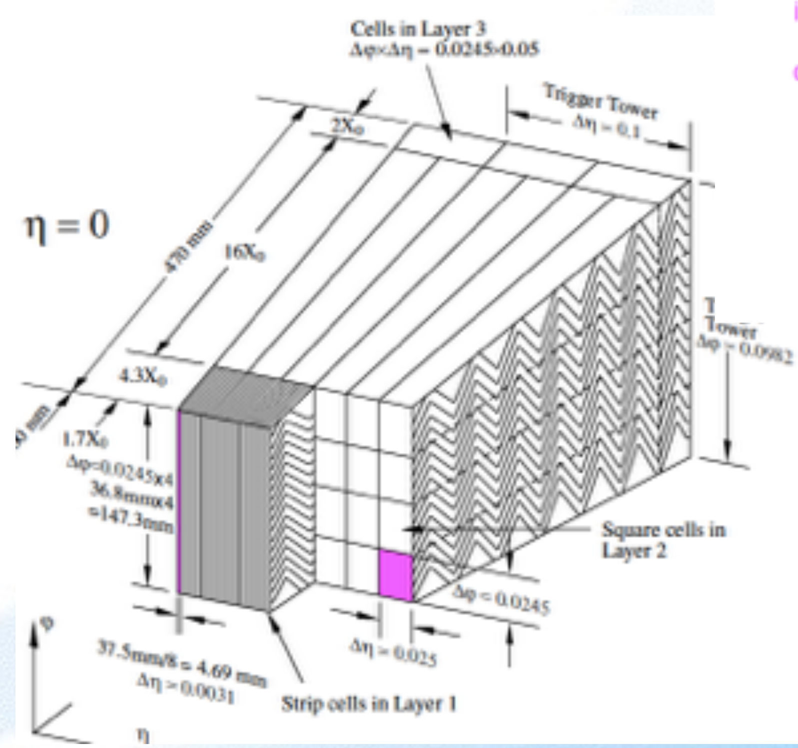
Sampling fraction/frequency, transverse and longitudinal granularity tuned to the application.

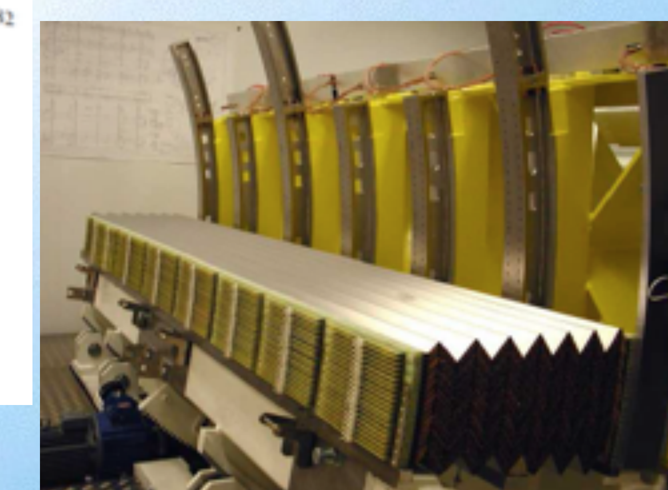
- E.g ATLAS LAr EM barrel calorimeter (http://cds.cern.ch/record/883909/files/phep-2005-034.pdf?version=1)
  - Pointing
  - Transverse segmentation (η) determined by strip-line design in kapton electrodes
  - Granularity in **φ** by ganging electrodes through PC boards installed in front (inner R) and in the back (outer R)
  - 3(4) layers of longitudinal segmentation is achievable by developed techniques (ATLAS). ***More will require substantial R&D on large area multi-layer kapton structures***



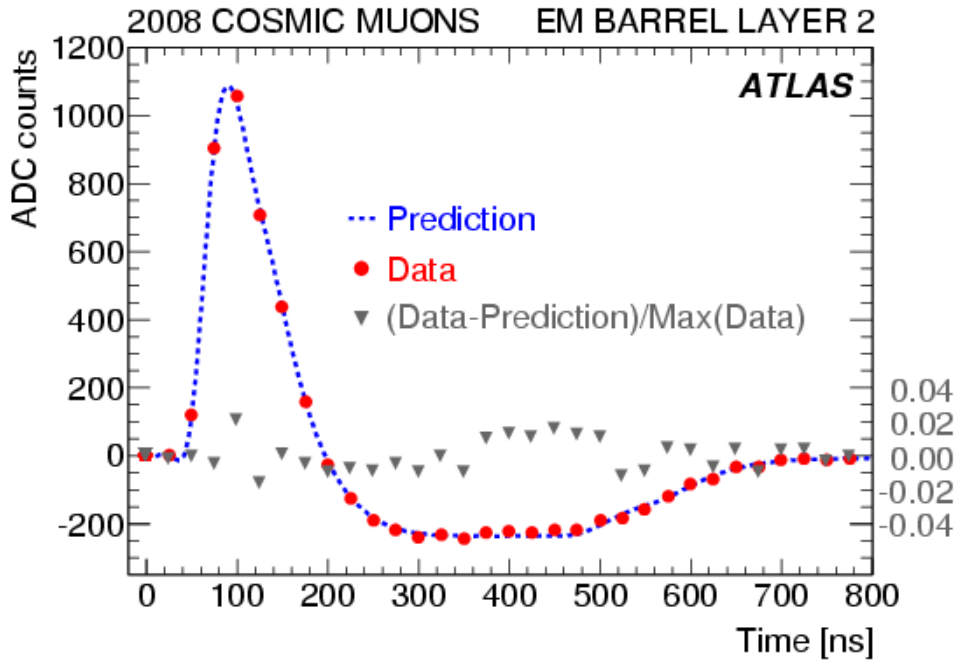
Accordion geometry - Fournier RD3 (1990ca.)







Timing Performance



Multiple sampling and Optimal Filtering reduce noise (main contribution to resolution at low energies)

$$E = \sum_i \alpha_i (S_i - p)$$

$$E\tau = \sum_i \beta_i (S_i - p)$$

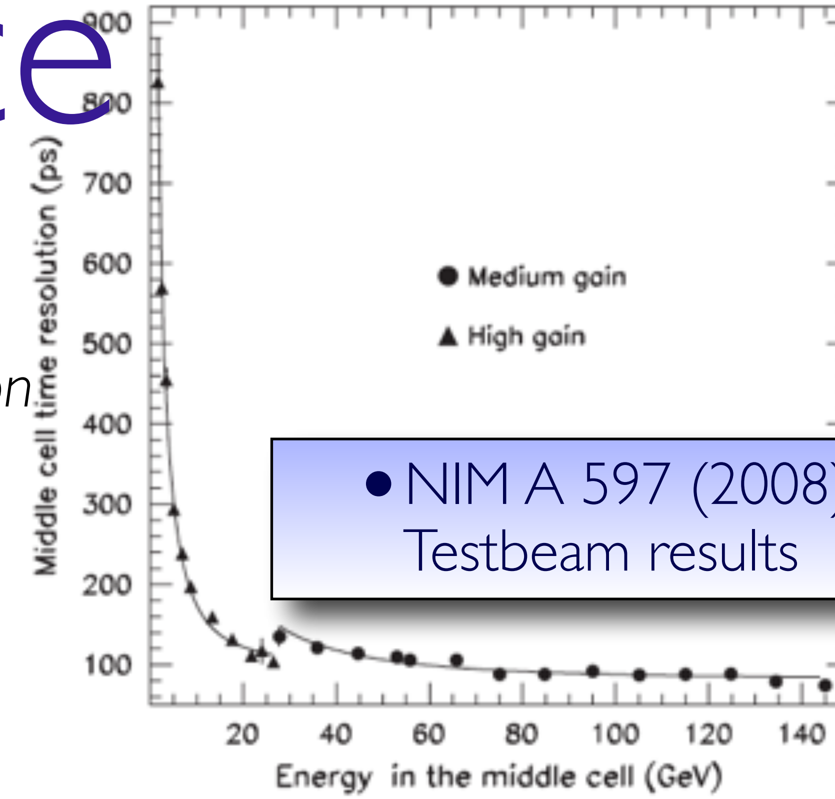
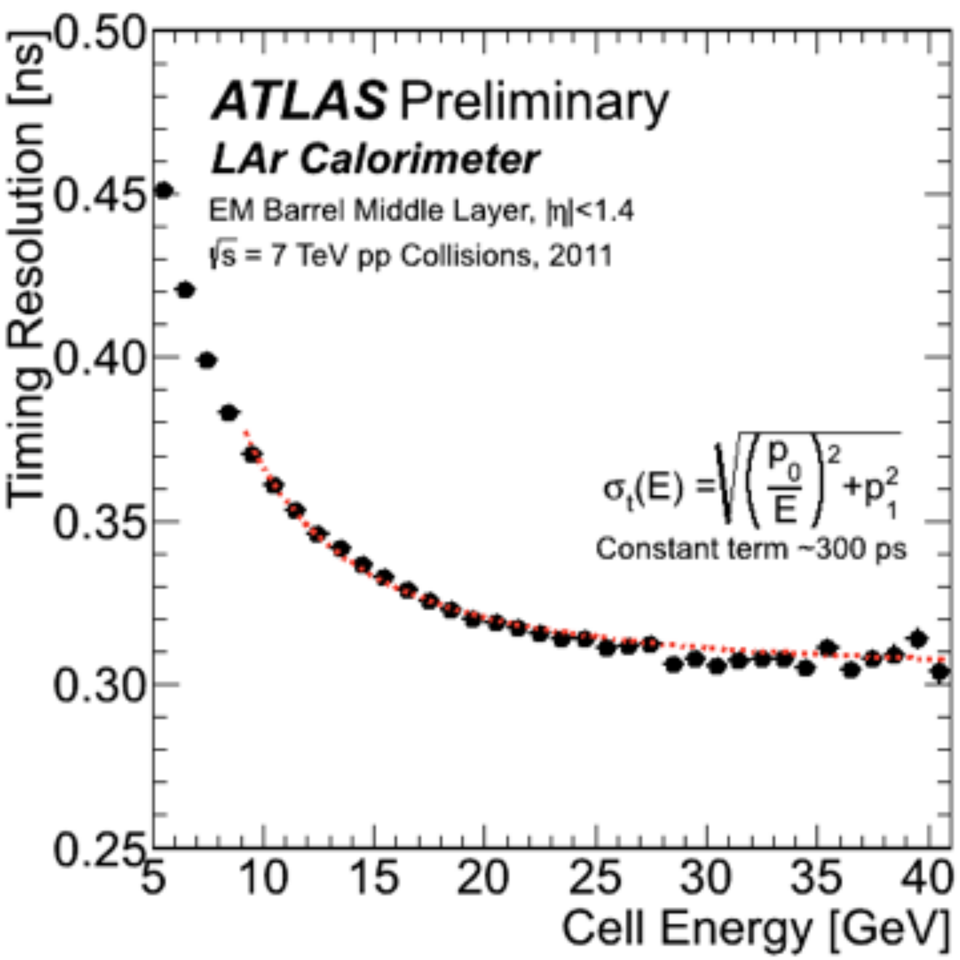


Fig. 12. Time resolution (ps) as a function of the energy deposited in the middle layer cell. Events with beam energy at 10, 20, 50, 100, 150, 180 and 245 GeV beam energy have been used. The resolution of the trigger, as well as that of the TTC system, has been subtracted. The solid line is the result of a fit in the high gain and medium gain.

- NIM A 597 (2008) Testbeam results



- 2011 collisions (https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArCaloPublicResults2010)

Using electrons from $W \to e\nu$ candidate events recorded in ATLAS during the 2011 pp data taking period, various corrections (as a function of the data taking period, front-end board, channel within the front-end board, cell energy and primary vertex position) were studied and applied to calibrate the LAr EM Barrel Calorimeter time measurement and gauge its timing resolution. A timing resolution of $\approx$ 300 ps is achieved for a large energy deposit in a cell of the EM Barrel.

The plot shows the single cell timing resolution energy dependence, for cells reconstructed in HIGH gain, in the Middle layer of the LAr EM Barrel Calorimeter ($|\eta| < 1.4$). A fit with the expected energy dependence, comprising a so-called "noise term" and a "constant term", added in quadrature, is shown superimposed.

By comparing the corrected time of the two electrons in $Z \to ee$ events from the same period, this resolution is understood to include a correlated contribution of $\approx$ 200 ps, expected to be dominated by the spread of the proton bunches along the LHC beamline, and an uncorrelated contribution of $\approx$ 200 ps. The latter component includes the intrinsic timing resolution of the LAr EM Barrel Calorimeter and its readout, as well as residual nonuniformities and imperfections in the calibration procedure.

Even if not as performing as some other technologies, timing resolution should be sufficient to associate efficiently objects to bunch crossing ID even in 5ns beam spacing scenarios

Evolution and long R&D studies

- Higher longitudinal and transversal granularity in accordion or more traditional geometries
- Composite materials for "massless" structures to minimise dead material in front (e.g. inner cold tube structure in a potential noble liquid barrel calorimeter).
- Front-end electronics in cryogenics: reduction of noise (if needed at low energies) can be achieved with the analog front-end operating at LAr temperatures (i.e. installed directly on detector). Long term reliability issues of cryogenic electronics have been addressed and solved by both NA48 and the ATLAS LAr HEC calorimeter (for ~10k channels)
- Integration of readout (and functional blocks) for a cost effective potential solution in an application that require likely a much larger number counts of channels wrt. LHC.
- Limits of operations at very high rates in particular for the forward region
- Potential performance benefit of other (than LAr) liquid nobles (depending also on the experimental layout and material budget in front)

Summary/Conclusions

- Several technologies in consideration
- Each requires a robust program of R&D to satisfy all requirements imposed by an experiment at the FCC
- Guidelines and technology choice will be driven by physics, by environmental constraints/experimental layout and integration aspects
- Benefits from what will be learnt for the HL-LHC upgrades
- Optimization of the detector performance will likely lead to different technologies for the 4 regions considered