Organic scintillator sampling calorimetry for the central Hadron Calorimeter FCC-hh detector ($\eta \lesssim 1.5$)

A. Henriques/CERN

Many thanks for feedback or informal discussions with: T. Carli, P. de Barbaro, S. Chekanov, C. Doglioni, H. Hakopian, A. Heering, C. Helsens, H. Jivan, C. Young, B. Mellado, D. Miller, I. Minashvili, S. Nemecek, J. Proudfoot, P. Rumerio, C. Solans, O. Solovyanov, A. Solin, P. Starovoitov, J.Starchenko, N. Topiline, T. Tabarelli, G. Usai, I. Vichou, and apologize to all that I may have forgotten to mention …

Outline

- Requirements for the FCC-hh central HCAL (η~<1.5) (see C. Helsens talk)
- Organic scintillator calorimeter technologies being used in HEP with some potential for the FCC-hh central Hadron Calorimeter:
  - "SPACAL" in dual readout mode (discussed in N.Akchurin talk)
  - "CMS-HCAL"
  - "CALICE for CLIC/ILC/FCC-ee "
  - "ATLAS-TILECAL"
  - ….
- Experience from ATLAS, CMS in LHC

- Advantages of an organic scintillator calorimeter for the central HCAL of FCC-hh detector (η ~<1.5) using:
  - The optics/mechanics concept inspired on ATLAS-Tilecal and
  - Si-PMTs readout inspired in CMS upgraded HCAL and CALICE

- Needed R&D-next steps for FCC-hh in a small and big detector scenario

Requirements for the FCC-hh central HCAL (η~<1.5) FCC-hh

(details in C. Helsens talk)

- Good jet resolution at high-TeV and medium-GeV pT
  - ~50-60%/$\sqrt{E}$ (di-Higgs production, …)
  - + ~3% (di-jet resonances (Z', q*, ….)=> keep single hadron long. leakage ~98% (as in ATLAS), e/h<->calibration)
- Good Etmiss resolution
  - minimize cracks , good containment
- Fast response and time resolution (for pile-up rejection)
- High transverse and longitudinal granularity (highly boosted objects, jet substructure)=> Better than ATLAS/CMS, by how much (x2, 4, 20…), as good as CALICE for ILC/CLIC?

- Radiation resistance
  - $\propto$ to Luminosity , ~1/R^2 detector (advantage for a bigger detector radius)
  - Dose at FCC-hh ~ 2X HL LHC for same Luminosity $5x10^{34}cm^{-2}s^{-1}$ BUT should add safety factors for probable increase in Luminosity, unknowns…..

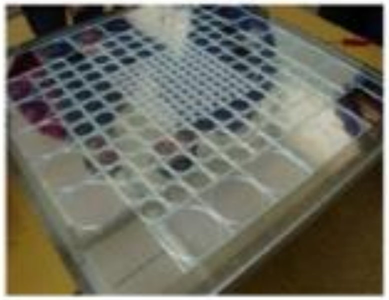
More info:

http://indico.cern.ch/event/304759/contribution/19/material/slides/0.pdf

Particle Flow in Segmented Calorimeters – CALICE Experiment

Being proposed for ILC/CLIC/….

Analogue HCAL: physics prototype



- based on scintillator tiles with WLS fibers, read out by SiPMs
  - $3*3\ \mathrm{cm}^2$ - $12*12\ \mathrm{cm}^2$ tiles
  - analogue readout: 12 bit
- $1\mathrm{m}^3$ prototype in beam tests 2006-2012 → 1M channels
  - steel absorber
  - tungsten absorber

=>~10 M channels at CLIC

	CLIC 3 TeV
Technology	Tungsten / scint.
# longitud. readout segments	75
Readout segment size [cm^3] (longitudinal × 'tilesize')	1.7 x 3.0 x 3.0
Interaction length [λ_I]	7.5 (+1 for ECAL)

		CLIC 3 TeV
Intrinsic energy resolution $\sigma_E / E = a / \sqrt{E} \oplus b$		a = ~60% b = ~2.5%
Jet energy σ_E / E	p = 45 GeV p = 0.5 TeV	5% 3.5%

Useful links:
http://arxiv.org/abs/1202.5940
https://indico.cern.ch/event/210720/material/slides/1.pdf

CMS HCAL: Barrel, Endcaps and Outer

P. De Barbaro

Barrel (HB): $|\eta|<1.3$, 36 wedges (18 HB+, 18 HB-)

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

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

Endcaps (HE): $1.3<|\eta|<3.0$, 36 petals per endcap

17 layers of brass → ~10 λ

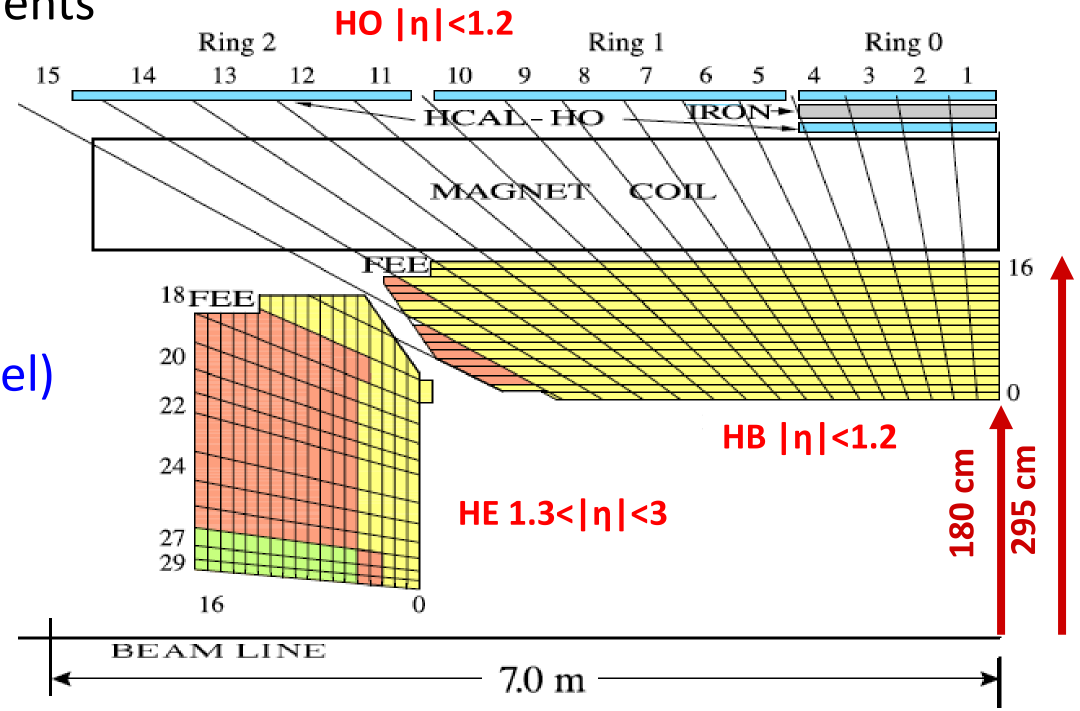
17 scintillator layers; 12 η and 1 or 2 ϕ divisions per wedge

2 or 3 (high η) longitudinal segments

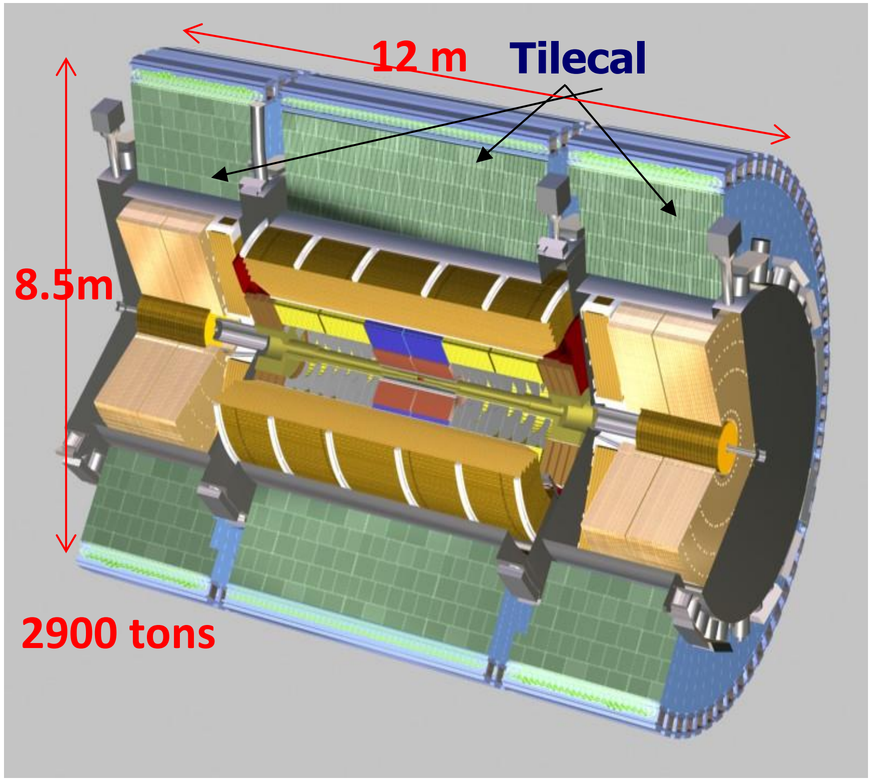
channels total= 7344

Pion resolution (2007 test beam):

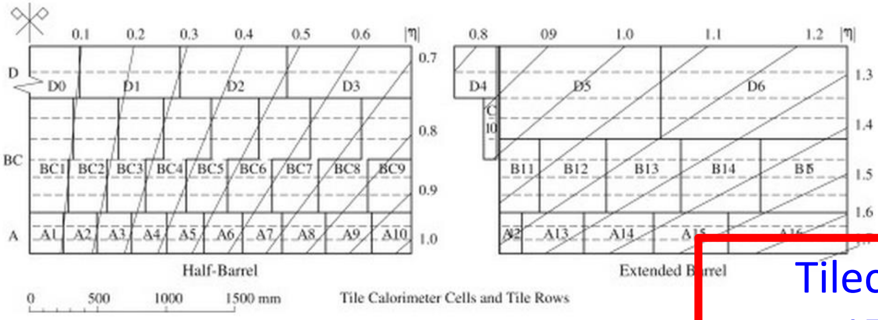
$\sigma_E/E \sim 113\%/\sqrt{E} \oplus 3$ % Endcap, Barrel)



ATLAS Tile hadron calorimeter ($|\eta|<1.7$)



- Scint. Tiles; fibres ∥ to incoming particles at $\eta=0$
- Steel/Tiles: = 4.7 : 1 (λ = 20.7 cm)
- Active cells volume: ~ 372m3
- ~ 620k fibres ; 40k Tiles
- 10 k channels
- 7.7 λ at $|\eta|=0$; (9.7 λ with the em LAr calo)
- Transversal granularity $\Delta\eta x \Delta\phi=0.1x0.1$
- Longitudinal segmentation: 3 layers
- e/h = 1.33
- Pion resolution (test beam):
  - $\sigma_E/E \sim 52\%/\sqrt{E} \oplus 5.7\ \%$ (7.9 λ)
  - $\sigma_E/E \sim 45\%/\sqrt{E} \oplus 2\ \%$ (9.2 λ)
- target (with e.m. LAR) at ATLAS/LHC:
  - Jet $\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\%$
  - 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

Needs for scintillator HCAL upgrades in ATLAS/CMS for HL LHC

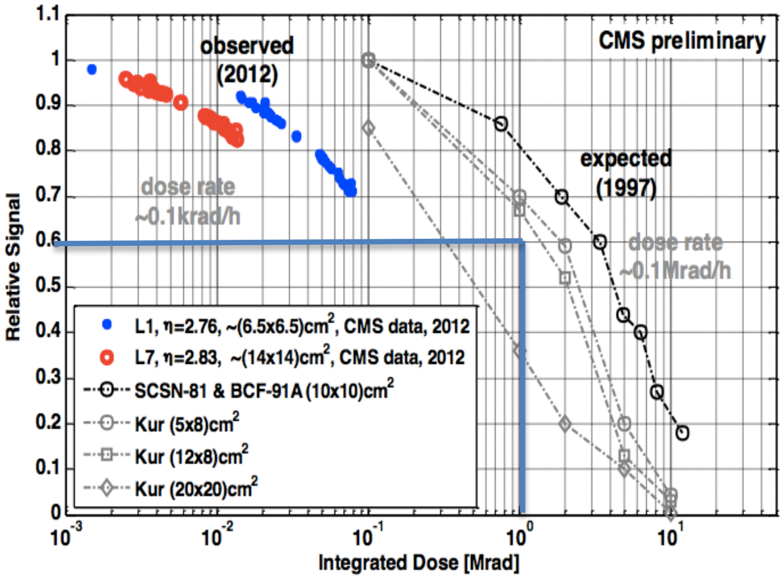
CMS:

- 2014/LS1: HPDs→SiPMs in outer layer (better S/N; better perf. in B field)
- 2018 phase 1: new photo-detectors and electronics (improve long. Segmentation +trigger capabilities)
- 2022 phase2: Endcap calorimeter replacement (radiation damage). The upgrades in phase 1 will mitigate partially the performance degradation due to rad. damage in 2018-2022

ATLAS:

- optics unchanged (reduced radiation damage)
- replace electronics to cope with 40 MHZ digital trigger

Effects of radiation in ATLAS/CMS **optics** at run1 and consequences for HL-LHC



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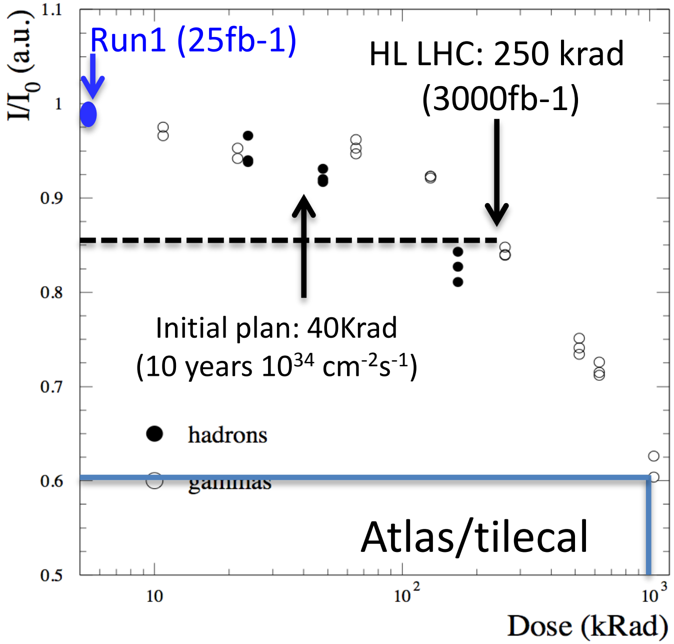

Run1 (25fb-1)

HL LHC: 250 krad
(3000fb-1)

Initial plan: 40Krad
(10 years 10^{34} $cm^{-2}s^{-1}$)

Atlas/tilecal

- CMS/ATLAS 1997 data w/ similar results <u>(1 Mrad-> -40%)</u>
- In LHC CMS x 100 dose than ATLAS because:
  - CMS R_{min}= 0.4 m in endcap |η|<2.8
  - ATLAS R_{min}=2.2m ; |η|<1.7
- In run1 (25 fb^{-1}) maximum damage:
  - ATLAS: -2% for 2.2Krad within expectations (in few inner cells w/ shorter em calo in front at η~1.3)
  - CMS end-cap: -30% for 0.2Mrad (losses 2-3 larger than expected, dose rate effects?).
  - CMS barrel: -5% for 3Krad
- Expectations at HL-LHC (3000 fb^{-1}):
  - ATLAS: 0.3 Mrad max.=> -15% in few inner cells at η~1.3 => no impact in jet performance
  - CMS: 25 Mrad max=> replace end-caps in phase 2, get longitudinal segmentation in phase 1

Important to get enough safety factors in planning new detectors for future FCC-hh

The advantages of an organic scintillator HCAL for the central FCC-hh detector (η ~<1.5) using:

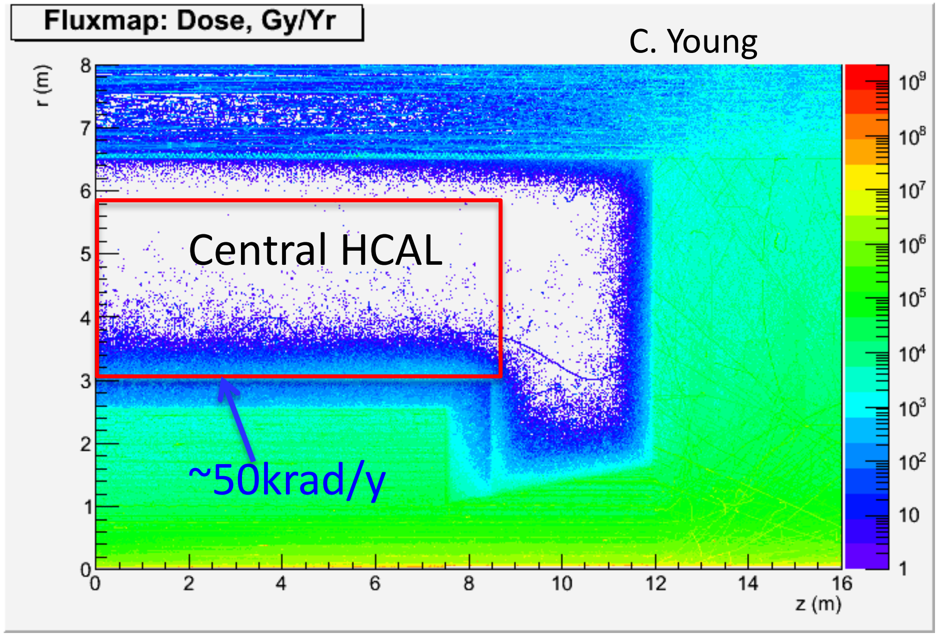
- The optics/mechanics concept inspired on ATLAS-Tilecal

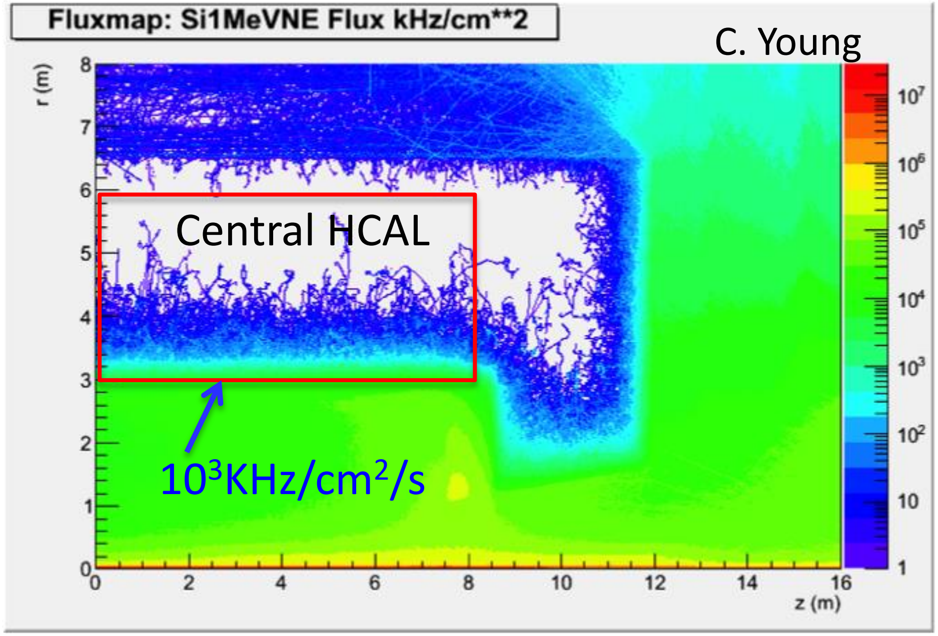
and

- Si-PMTs readout inspired in CMS upgraded HCAL and CALICE

Doses in FCC-hh for L=10^{36}cm^{2}s^{-1} (x 20 today nominal FCC-hh L=5x10^{34}cm^{-2}s^{-1}) C. Young talk

(assuming radial dimensions: tracker=2.5m ; 2.5m<ECAL <3m ; 3m<HCAL<6m and Zbarrel=+-8.5m)

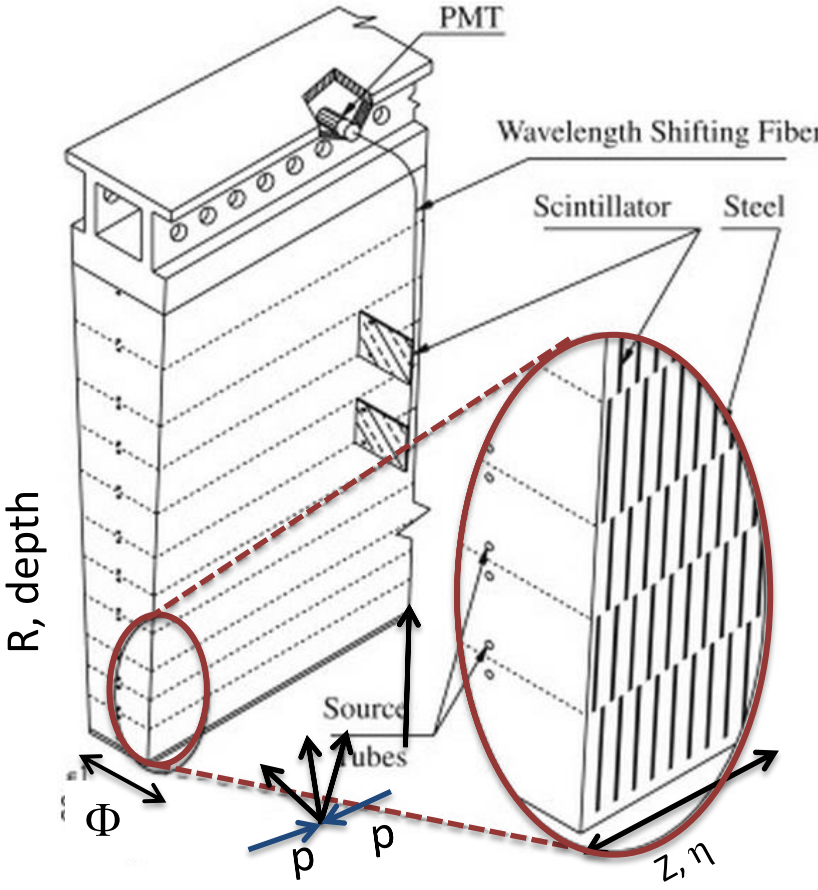


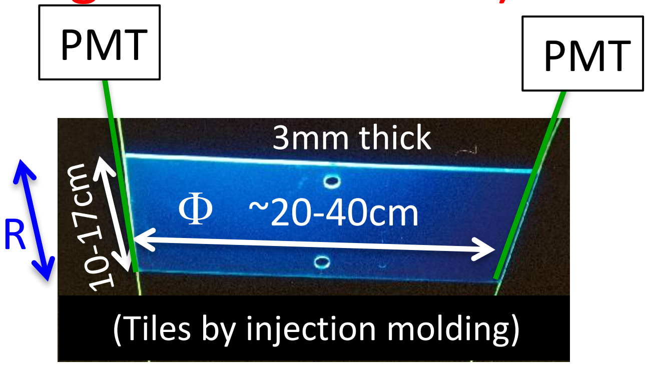


- In central HCAL Dose ~ constant vs. Z/eta ; shielded by ECAL ; lower for bigger radius
- Max. annual dose in central HCAL at L= 10^{36}cm^{-2}s^{-1} :
  - ~5x10^2Gy/y = 50krad/y max. **=>**
  - **=> 0.5 Mrad after 10 years at L=10^{36}cm^{2}s^{-1} (=> -15% total based on atlas-tilecal scintillators)**
  - 10^3KHz/cm^2/s (1 MeV n eq.) => 10^{13} n/cm^2/year. In the electronics/outer radius flux much smaller)

- Today's commercial scintillators (BC408 ; EJ 200) ~ 1.5-2 more radiation resistance than the scintillators used in ATLAS-Tilecal (B. Mellado, A. Jivan)
- Active R&D on-going on radiation hard scintillators (CMS calo upgrades, …)
- **The use of organic scintillators in the central HCAL ($\eta \lesssim 1.5$) seems to be a safe option.**

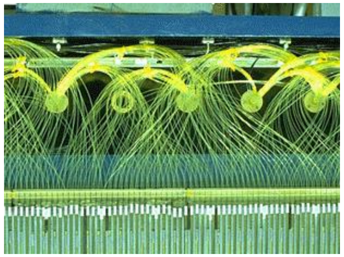
Today's ATLAS Tilecal optics granularity (but merged at readout…)

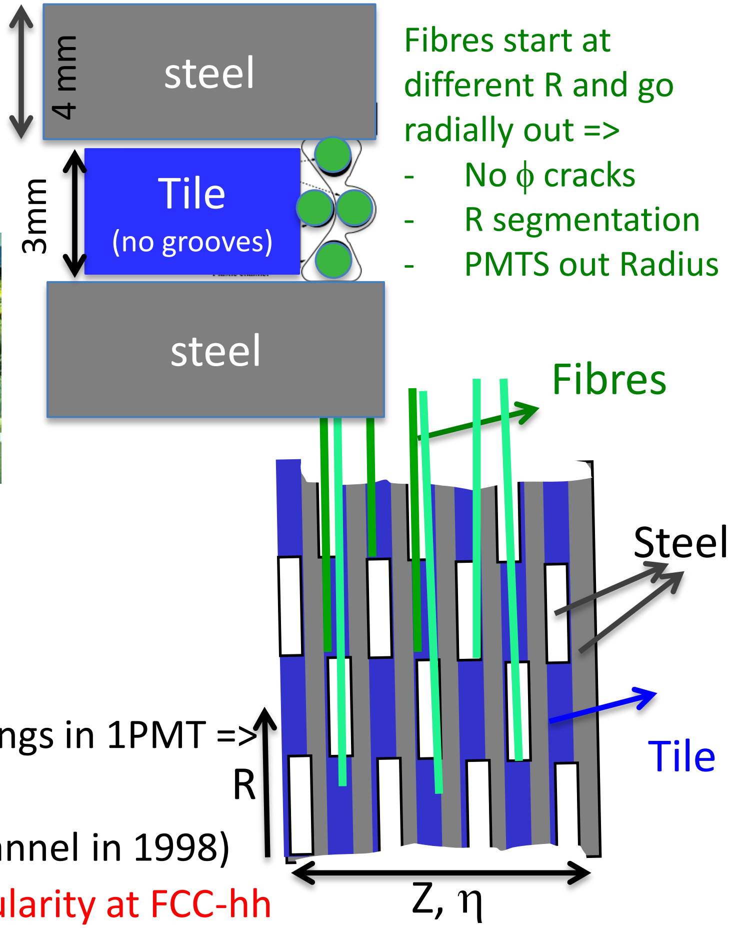




(Tiles by injection molding)

Fibre bundles (at outer radius)





Fibres start at different R and go radially out =>

- No ϕ cracks
- R segmentation
- PMTS out Radius

$\Delta\eta$: 3mm tiles every 9-18mm in Z->$0.0007<\Delta\eta<0.008$

ΔR: 11 tiles and 8 fibres in R -> 8-11 layers with $1\lambda<\Delta R<0.5\ \lambda$

$\Delta\Phi$: 20 cm tiles-> $\Delta\phi=0.1$ (with dual fibre readout)

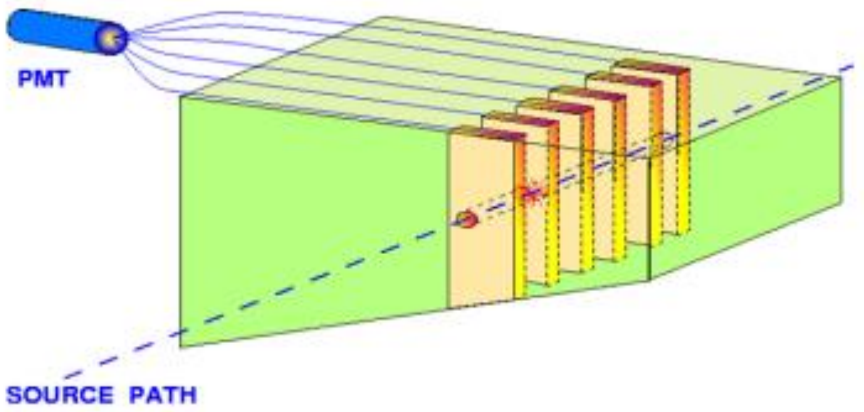
In total ~ 620k fibres and 40k tiles ; but ~80-300 Tile-fibres couplings in 1PMT =>

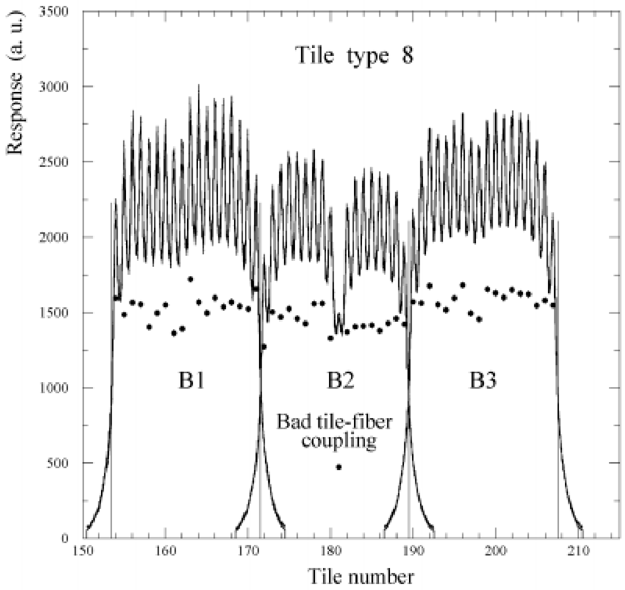
10 k channels ; $\Delta\eta \times \Delta\phi=0.1\times0.1$; 3 longitudinal layers in LHC

Cost/performance compromise in electronics costs (~730CHF/channel in 1998)

Minimal changes needed in optics/mechanics to exploit full granularity at FCC-hh

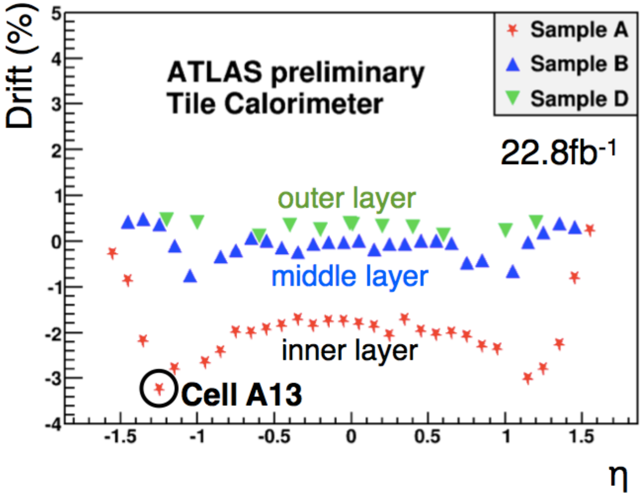
ATLAS-Tile cesium calibration system





- 137 Cs ~ 1/month monitor optics + electronics (~ 0.3% precision in 10 000 channels)
- Laser ~ 2-3/week monitor PMTS gain (the main source of cells drifts)

- Cs constants: average of all Tile/fibre peaks in a cell
- => same system well adapted to a Tilecal concept with bigger/full readout granularity for FCC-hh

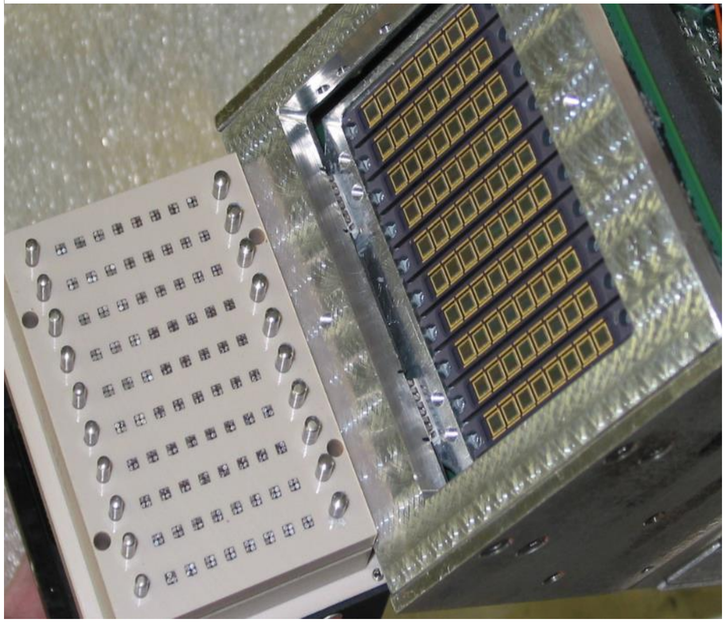


Main R&D/improvements needed for an “ATLAS-Tile layout using Si-PMTS” in the central HCAL FCC-hh detector ($\eta \lesssim 1.5$)

- Electronics:
  - Si-PMTs very promising in performance and cost. Used for CMS upgrades, CALICE,….(details T. Tabarelli talk and back-up slides):
    - Allows to increase lateral and longitudinal readout granularity, profiting from the existing/or better optics granularity.
    - Insensitive to magnetic field
    - Faster time response than PMTs
    - Read single 1mm fibres or grouped fibres
    - Better quantum efficiency than PMTS (QE ~ 35% in CMS, still improving)
    - Dynamic range ~ 10^5 adequate (smaller cells).
    - Radiation resistance to ~ 10^{12}n/cm^2/y (Si-PMTS at outer radius like in CMS). R&D on-going to improve with reduced pixel size (15μm-> 5μm).
    - Cost per readout channel is promising (~ 50CHF/ for CMS upgrades) . But still (too much ?) if we wanted to exploit the full potential of ATLAS-Tile concept in eta and depth....
  - Readout electronics/cooling: developments for upgraded CMS calorimeters (and others experiments) very useful and with potential synergies.
  - …..

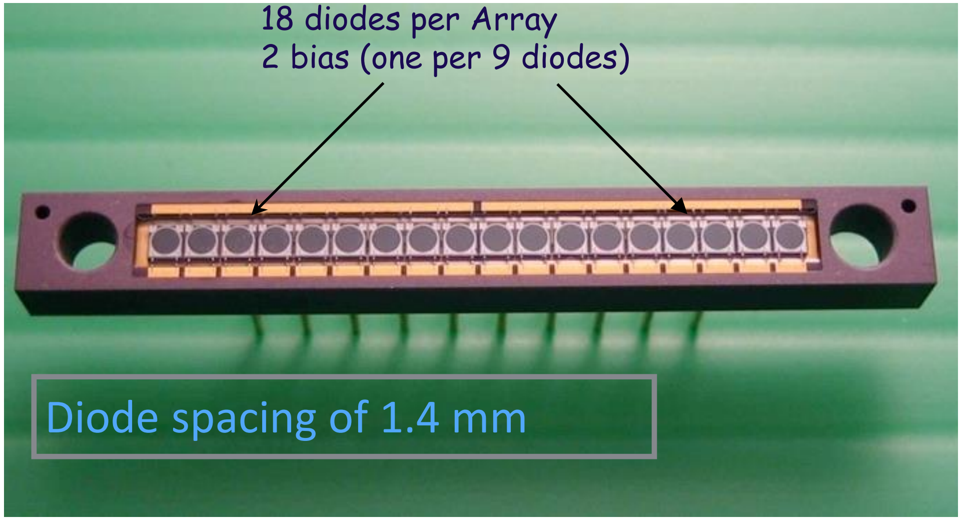
Si-PMTS under study for CMS calorimeter upgrades

8 ch Array package w/ 4 fiber/ch readout



P. De Barbaro; P. Rumerio; A. Heering, T. Tabarelli

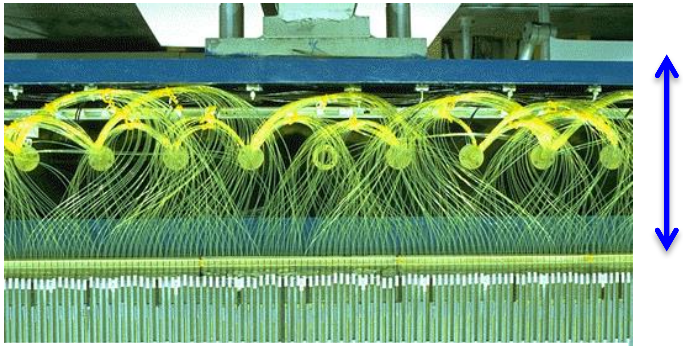
18 ch Array package for single fiber readout



18 diodes per Array
2 bias (one per 9 diodes)

Diode spacing of 1.4 mm

Si-PMts insensitivity to B field and more granular readout should minimize space at outer radius for fibre bundles (if any) and electronics



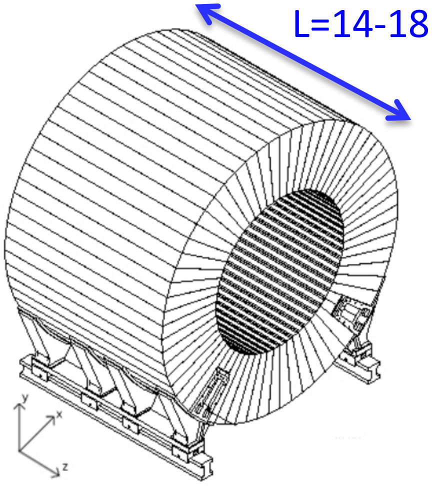
~ 30cm (~ 1.5 λ)

Fibre bundles in ATLAS Tilecal

Main R&D/improvements needed for an "ATLAS-Tile layout using si-PMTS" in the central HCAL FCC-hh detector (η~<1.5) (cont.)

Mechanics :

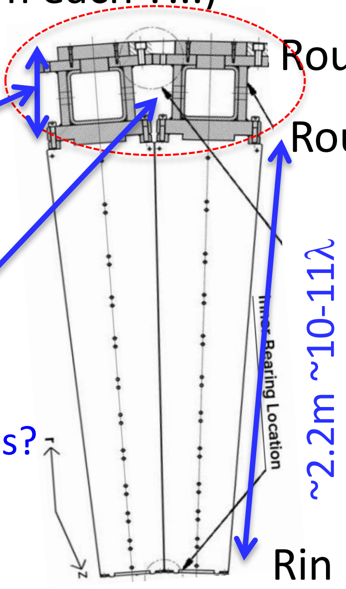
- Optimize choice of absorber (non-magnetic for solenoid options) .
  - Steel, brass, Cu, W… Steel: cheapest and best performance (shower speed, μ tails,….
  - Increase active cells thickness to 10-11λ (2-2.2m) ($\lambda_{Tilecal}$=20.7cm). Could reduce λ_{eff} using part of absorber plates (spacers) with W, see impact in performance…)
  - Redesign outer radius girder to reduce "dead" calo thickness (ATLAS ~30 cm; 1.5λ):
    - Optimize fibres to Si-Pmts coupling (need little/absent fibre bundles)
    - Optimize electronics location/space (no need to shield Si-PMT)
- Minimize cracks in the Z at η=0 if barrel made in 2 halfs of ~7-9 m each ?...)
- Optimize supports with ~ x2 volume/weight than ATLAS
- …..



L=14-18m in 2 half?

Redesign support,
(Reduced Rout'-Rout)

New place for electronics?



Main R&D/improvements needed for an “ATLAS-Tile layout using si-PMTS” in the central HCAL FCC-hh detector (η~<1.5) (cont.)

Optics:

- R&D on more radiation hard scintillators/fibres (> safety factors)
- Improve ϕ granularity. Possible cumulative actions

  Example $\Delta\phi$ =0.1-> 0.025:
  - Move outer radius; R_{min} =2.2 m (ATLAS-tilecal) -> 3.0m => $\Delta\phi$ =0.1 -> 0.07 (64 ->87 modules in cylinder).
  - Half trapezoidal tiles read by fibres in 1 side ($\Delta\phi$ =0.07-> 0.035) ; 87 modules; loose light and uniformity
  - Modules/tiles with smaller ϕ dimensions ($\Delta\phi$ =0.035 -> 0.025 (87 -> 122 modules/cylinder)
- Optimize depth granularity with the best match tiles-fibres and Tile depth dimensions (depends on real needs)
- ….

Main remarks

- Organic scintillator calorimetry is promising for the central HCAL FCC-hh detector,($\eta \lesssim 1.5$). Excellent performance-cost effective
- Annual max. doses in central HCAL ~50Krad/y at L=10^{36}cm^{-2}s^{-1} ; R_{min}=3m) =>

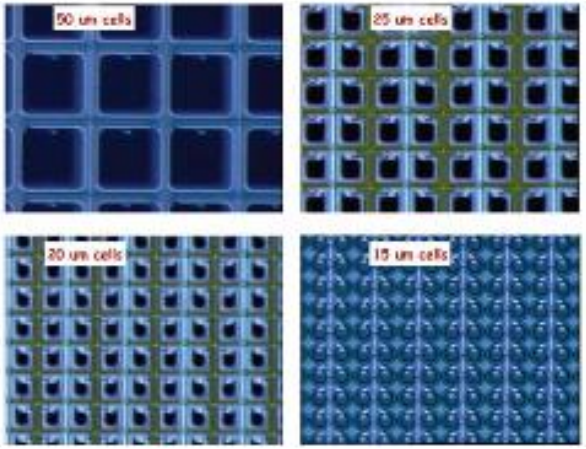
  confortable even w/ current scintillators. Need to quantify dose increase in a scenario of a smaller detector. More radiation hard scintillators are obviously desirable.
- From LHC experience would not recommend organic scintillators in ECAL and HCAL behind $\eta > \sim 1.5$ (small radius…) .
- Using Tiles&fibres ǁ to incoming particles at $\eta=0$ (ATLAS-Tilecal inspired) => , easy and cost effective to get good long./lateral granularity (>> x10 vs LHC), without
- Using Si-PMTs inspired on CALICE, CMS upgrades (placed at outer radius) allows to profit from optics granularity, improve performance.
- Other optics/mechanics calorimeter layouts (CALICE-Particle flow based) can provide even finer granularity, in depth in particular. The complexity and costs involved in the optics/electronics are higher compared to Tilecal design (grooved tiles w/ fibres inside, Si-PMTs at tiles exit, electronics access/cooling,...).
- Detailed studies on the required performance, in particular in granularity, are needed to progress further on more detailed designs/options.
- Today’s discussions may trigger ideas in view of the March Washington FCC week and establish working group towards the longer term goals of defining R&D for FCC-hh detector

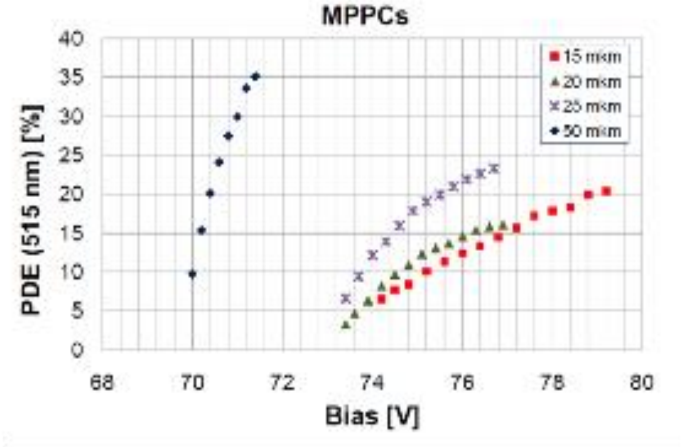
Back-up

Slides on CMS HCAL SiPMs (provided by P. De Barbaro; A. Heering)

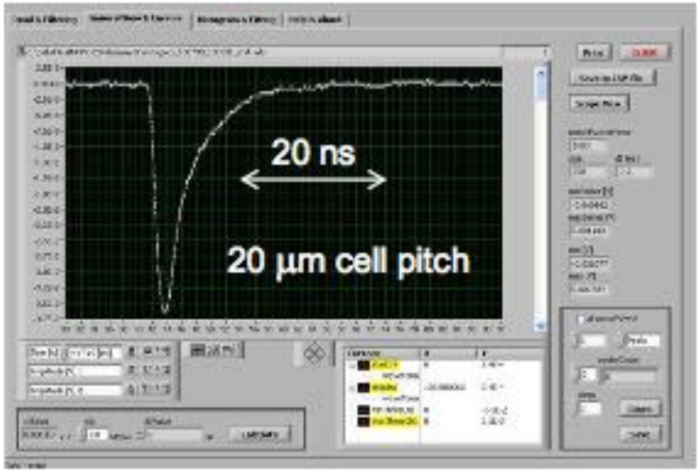
P. De Barbaro; A. Heering

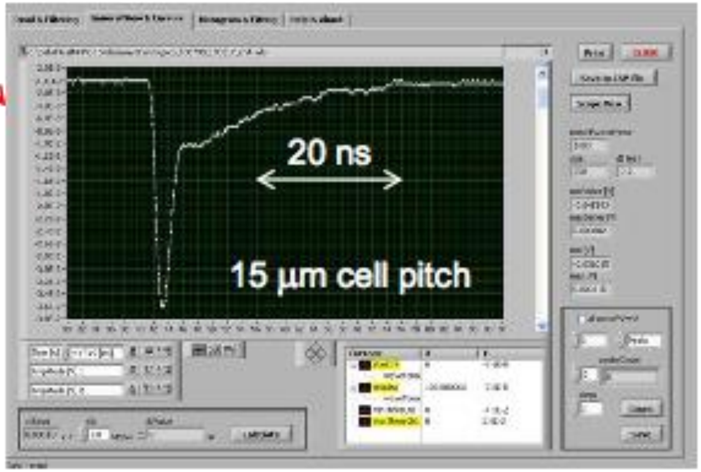
SiPM Pulse shape vs cell size





MPPC responses to a fast (35 psec FWHM) laser pulse





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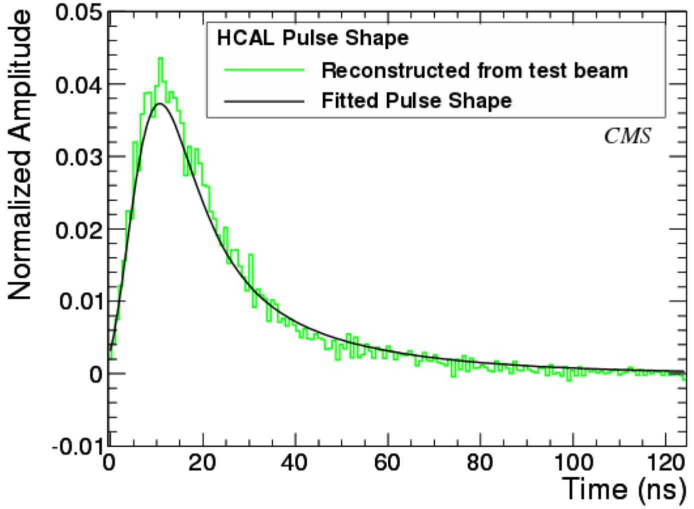
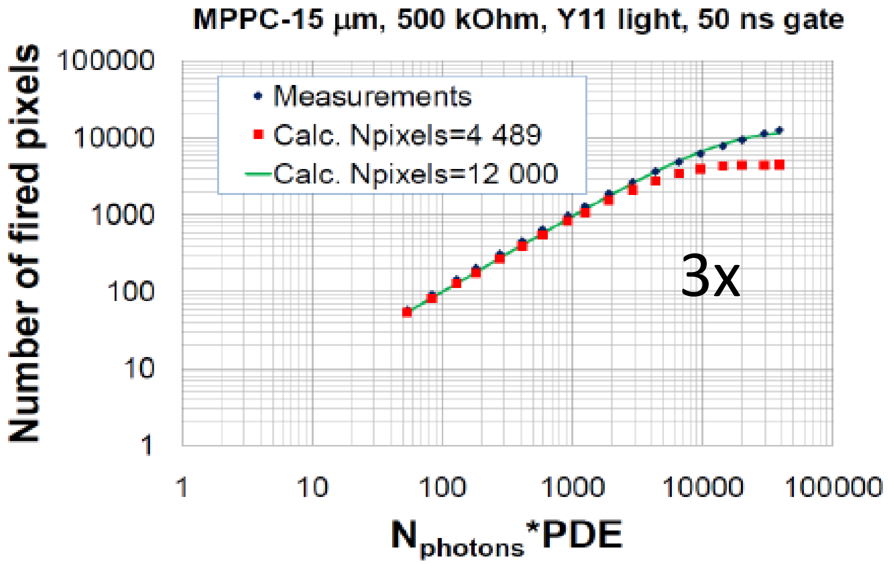
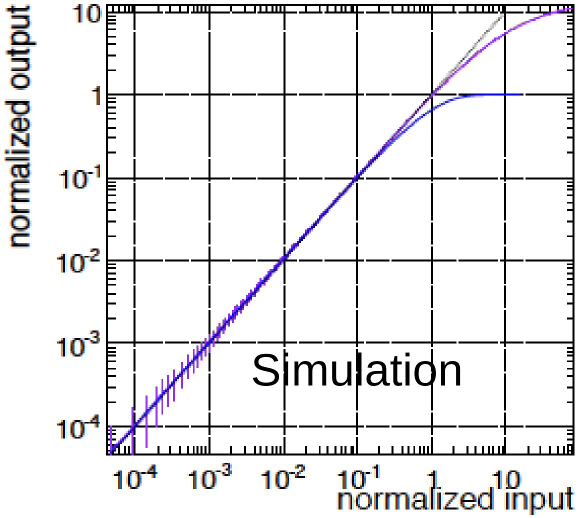
Recovery Time vs Linear range (State of the Art)

- Because of the long Y-11 pulse shape, a very fast SiPM (able to reset its pixels within a few ns) can fire multiple times within the pulse: effective increase in dynamic range
- Validated in simulation and on the bench with real SiPMs
- State of the Art of even smaller SiPMs with smaller 10 and 5 micron can give **>> 100 k cells/mm2** effective pixels







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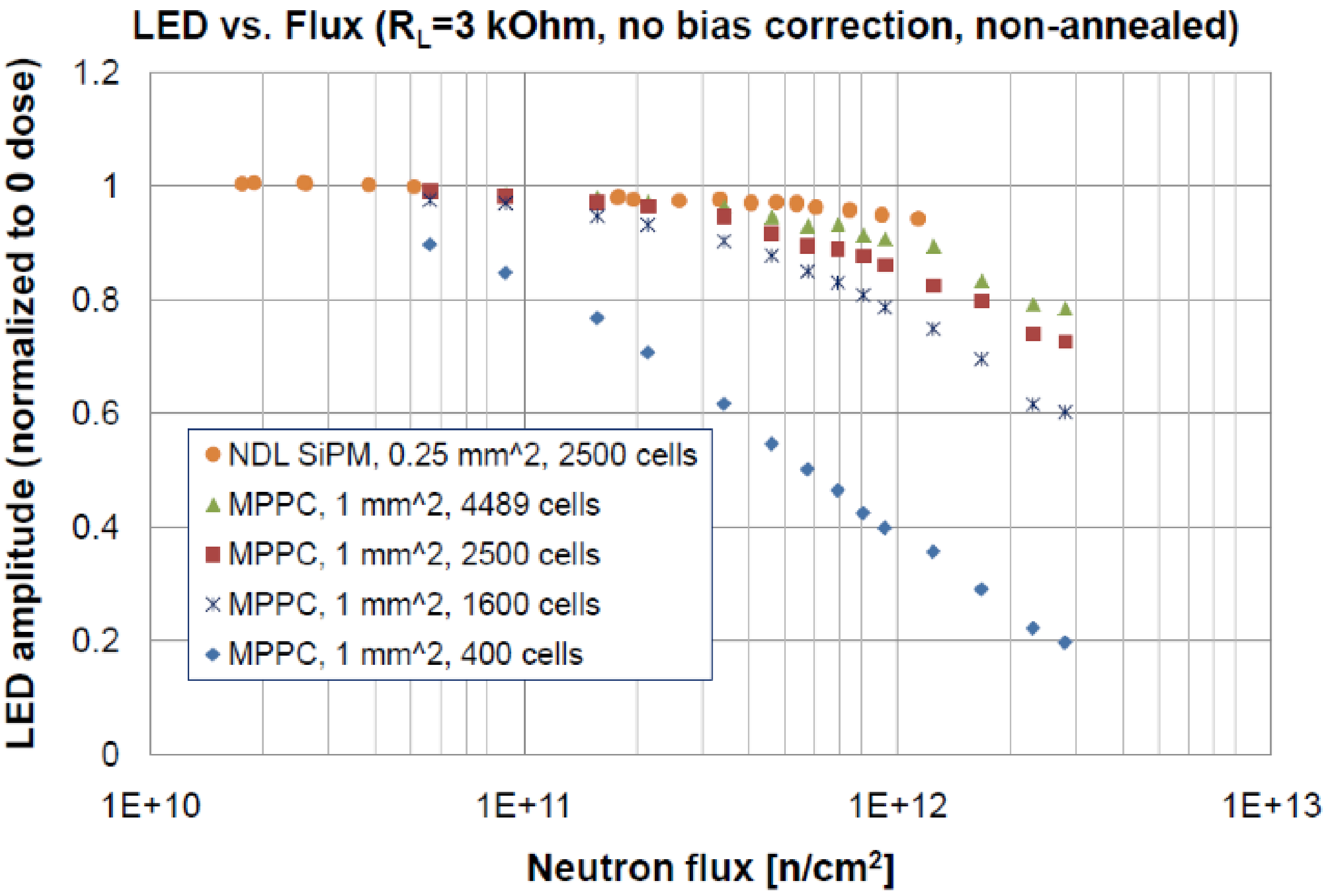
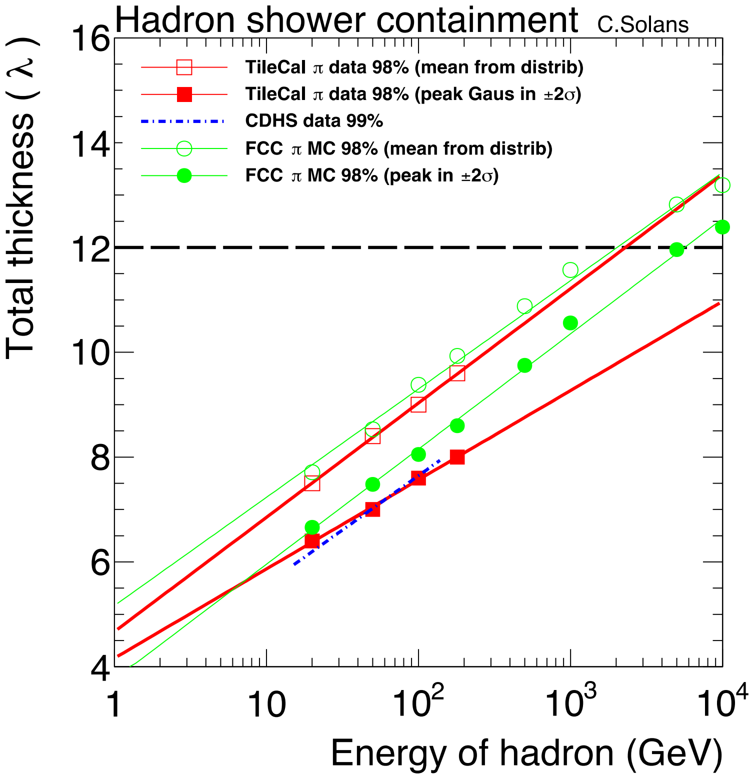
SiPM Cell size vs Radiation Damage

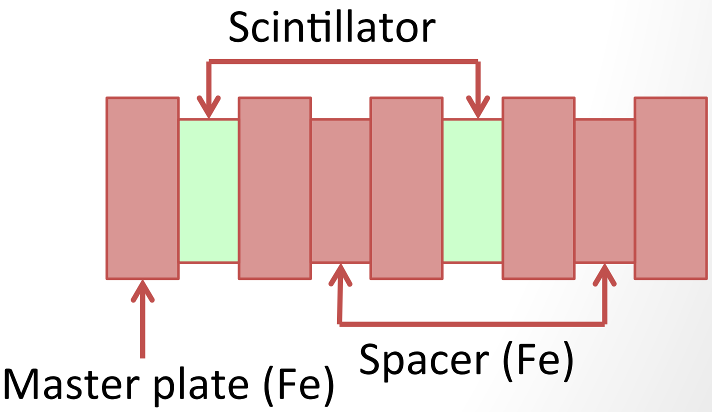


Ana, Carlos, Clement

Longitudinal containment

- Propose a calorimeter depth based on simulation of single pions and multi TeV jets
  - Self contained study
  - Guided by calorimeter technology choice
- Using a pure Geant4 simulation of a sampling calorimeter (a la TileCal)
  - Easy implementation, large user community
  - Shortcut to obtain results
- Event simulation
  - Geant4 particle gun for pions
  - HepSim dijet / pythia samples for jets





Wedge Δφ = 2π / 128
Tile height: 10 cm
Scintillator and spacer width (Δz): 4 mm
Master plate width (Δz): 5 mm

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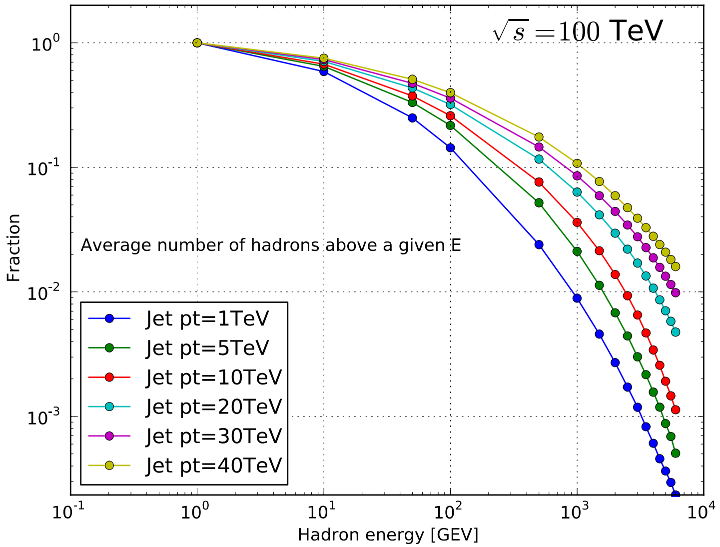
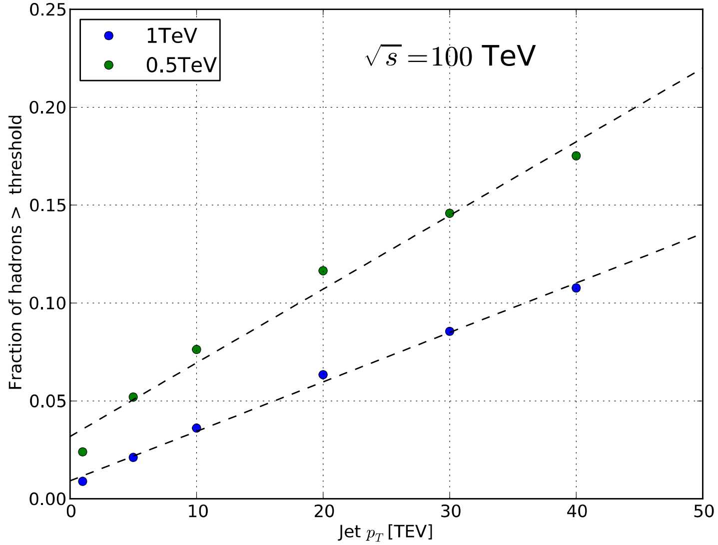
Hadronic Calorimetry

- Leading particle in a jet can carry significant fraction (~10%) of jet energy
- eg In a 30 TeV jet, 8% of hadrons have energy > 1 TeV, and on average ~1 of ≥5TeV)
- Need more detailed studies in full simulation
- Good case for test beams with p/π/μ/e energies up to a few TeV

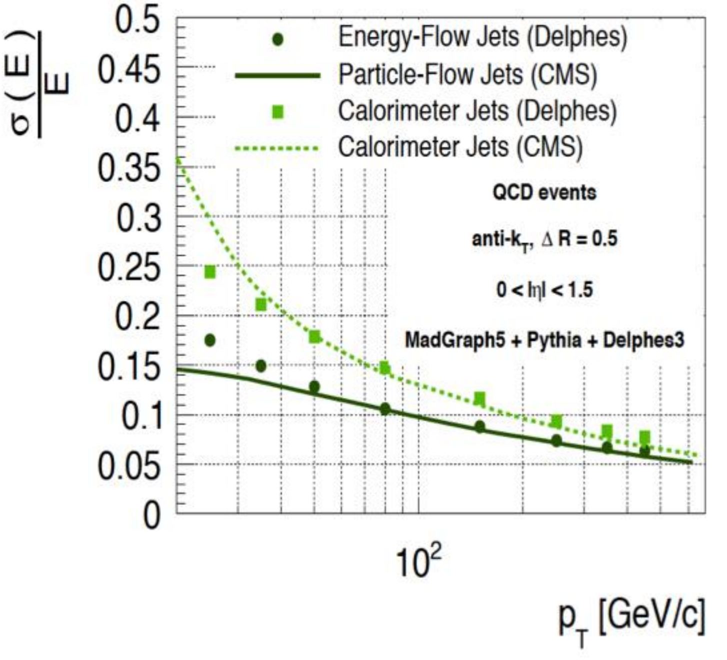


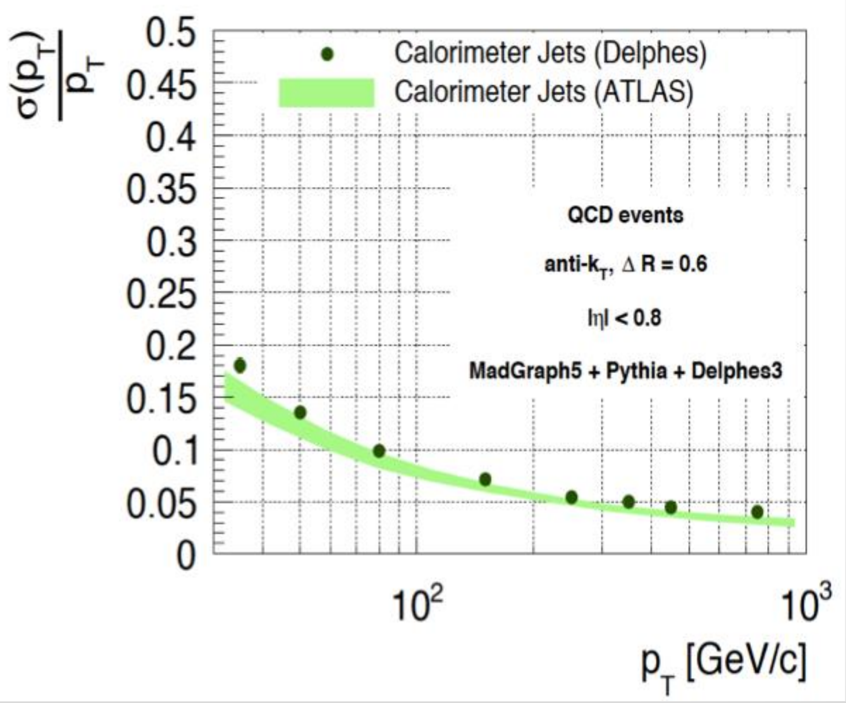
C. Helsens



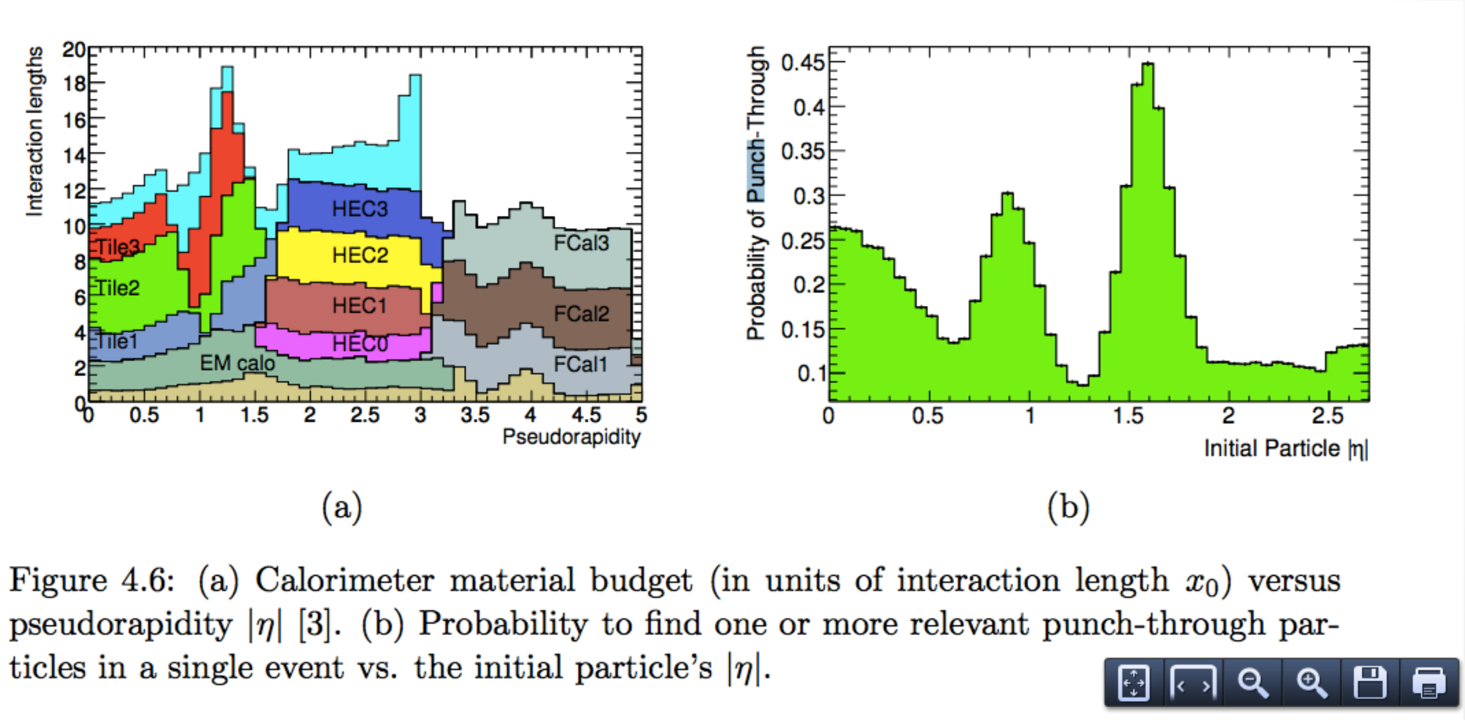
Jet resolution (LHC detectors)

- At high p_T calorimeter and particle flow jets are very close in CMS
- With a larger tracker and stronger magnetic field this will improve but will also look at much high PT regime.
- Longitudinal leakage and calibration determine the high PT resolution (constant term)





ATLAS%depth%and%punchR through%probability%



(a) (b)

Figure 4.6: (a) Calorimeter material budget (in units of interaction length x_0) versus pseudorapidity $|\eta|$ [3]. (b) Probability to find one or more relevant punch-through particles in a single event vs. the initial particle's $|\eta|$.

ATLAS Tile calorimeter characteristics

Characteristics	ATLAS $|\eta|<1.7$
Absorber	Steel
Absorber/scintillator ratio	4.7:1
Geometry	Tiles & fibres $\perp$ to pp beam axis
Tiles-Fe periodicity in Z	18 mm (3mm Tiles+14mm Fe)
Tiles characteristics:	Polystyrene+1.5%PTP+0.04%POPOP by injection molding, no grooves ; ~ 70 tons
- Tile dimensions (ηxϕxR):	11 trapezoidal sizes in depth/R ; ~ 40105 tiles
- Inner radius	3 mm x ~22 cm x ~10 cm ;
- Outer radius	3 mm x ~35 cm x ~19 cm
- WLS Fibres	Kurary Y11 ; 1mm diameter ; ~1062 Km ; ~620 000 fibres
3 cylinders (Barrel+2 Ext B):	
Length in Z	12m
Outer radius(w/supports+elect.)	4.2 m
Outer active radius	3.9 m
Inner active radius	2.3 m
Active depth ΔR at η=0	1.6m; 7.7 λ
Volume (inner-outer active R)	372m3
Weight	2900 T
Longitudinal Segmentation	3 layers
Transversal granularity ($\Delta\eta$x$\Delta\phi$)	0.1x0.1 inner and middle layers ; 0.2x0.1 outer layer
# channels/PMTs	10 000 channels
Gain-dynamic range	10^5 ; 2 gain 10 bits ADCs
Xo ; λ_p ; Moliere Radius	22.4 mm ; 20.7 cm ; 20.5 mm

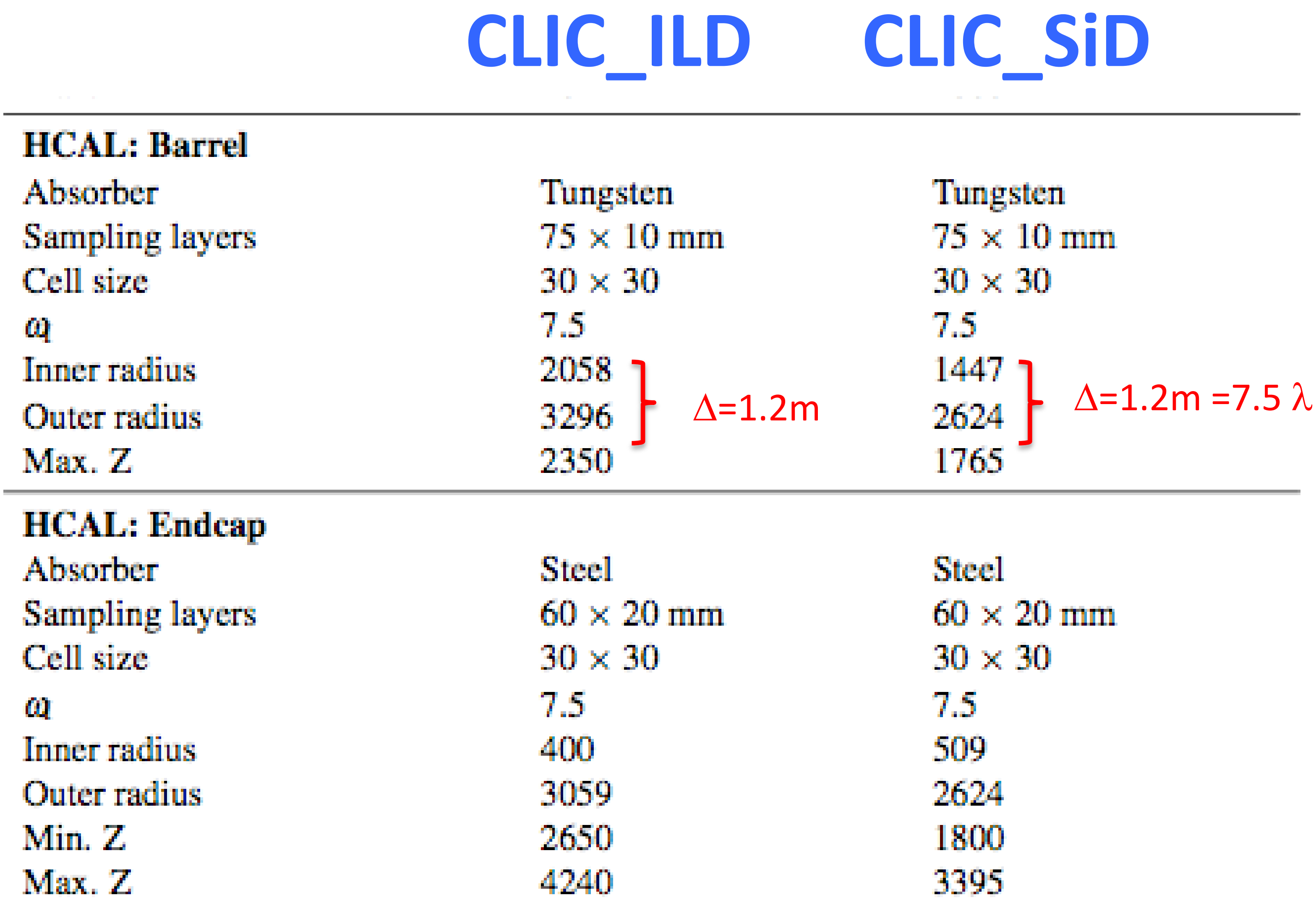
ATLAS Tile calorimeter Performance

Characteristics	**ATLAS $\|\eta\|<1.7$**
Light yield	70 phe/GeV
σ_E/E (tbeam standalone)	52%/√E+ 5.7% (7.7 λ) 45%/√E+2 % (if 9.2 λ)
Jet resolution target	~50-60%/VE $\oplus$ 3%
e/h	1.33
em sampling fraction	3%
Max dose at HL LHC (3000 fb-1)	0.2Mard
Max light reduction due to irradiation in run1	-2%
Max. light reduction expected at HL LHC	-15%

CMS scintillator HCAL characteristics

P. De Barbaro

Characteristics	**CMS |η|<3.0**
Absorber Absorber/scintillator ratio Geometry Tiles-Fe periodicity in Z	Brass (70% Cu, 30% Zn) Tiles & fibres ⊥ to particles at η=0 n/a
Tiles characteristics: WLS Fibres diameter	3.7mm thick Kuraray SCSN-81 (9 mm thick Bicron BC408 for the 1st sampling layer) scintillator tiles machined and grooved to house WLS fibers 0.94mm di, multi-clad Kuraray Y11 fibers
3 cylinders (Barrel+2 Ext B): Length in Z Outer radius(w/suports+elect.) Outer active radius Inner active radius Active depth ΔR at η=0 Volume (inner-outer active R) Weight	Two half-barrels + two endcaps 3.9 m (4.3 m) half-Barrel at inner (outer) radius Barrel Outer radius: 2.95 m Barrel Inner radius: 1.8 m 1.15 m ; 6 λ Barrel : 2x 500t; Endcap: 2x 300 t
Longitudinal Segmentation	One readout depth in Barrel, 2-3 readout depth in Endcap
Transversal granularity ($\Delta\eta$x$\Delta\phi$)	0.087 x 0.087 (ϕ x η)
# channels/PMTs	7344 channels (readout by HPDs)
Gain-dynamic range	4-range, 5bit non-linear bit ADC, full range 10^4
Xo λ_p	1.49 cm (brass) 16.4 cm (brass)



	CLIC_ILD	CLIC_SiD
HCAL: Barrel		
Absorber	Tungsten	Tungsten
Sampling layers	75 × 10 mm	75 × 10 mm
Cell size	30 × 30	30 × 30
ω	7.5	7.5
Inner radius	2058	1447
Outer radius	3296	2624
Max. Z	2350	1765
HCAL: Endcap		
Absorber	Steel	Steel
Sampling layers	60 × 20 mm	60 × 20 mm
Cell size	30 × 30	30 × 30
ω	7.5	7.5
Inner radius	400	509
Outer radius	3059	2624
Min. Z	2650	1800
Max. Z	4240	3395

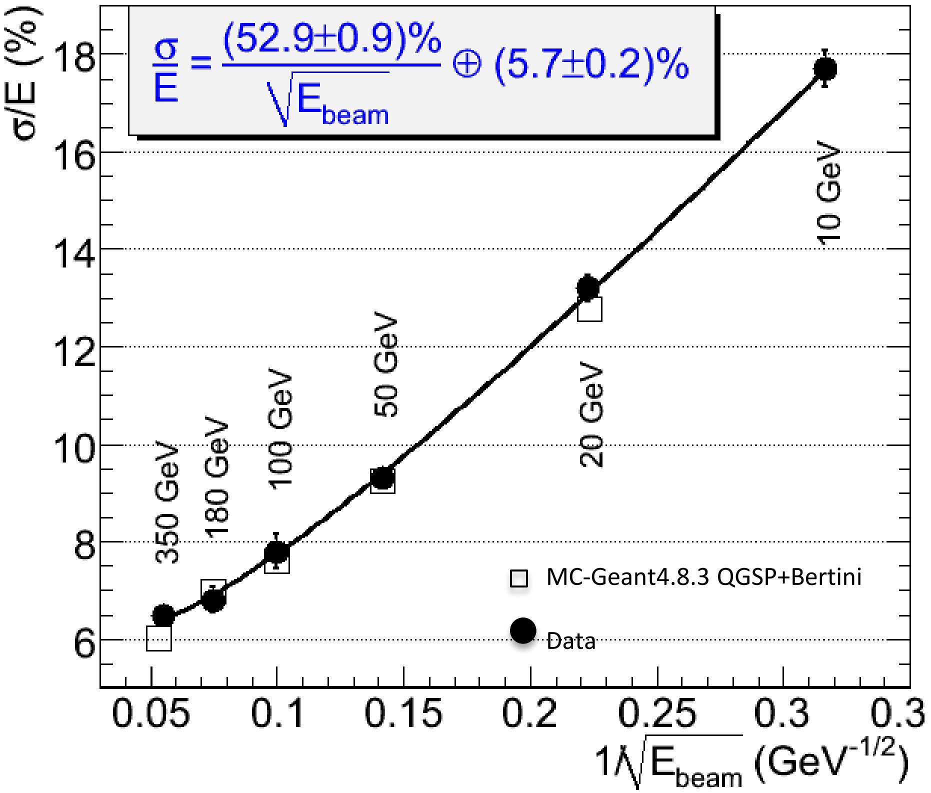
Δ=1.2m

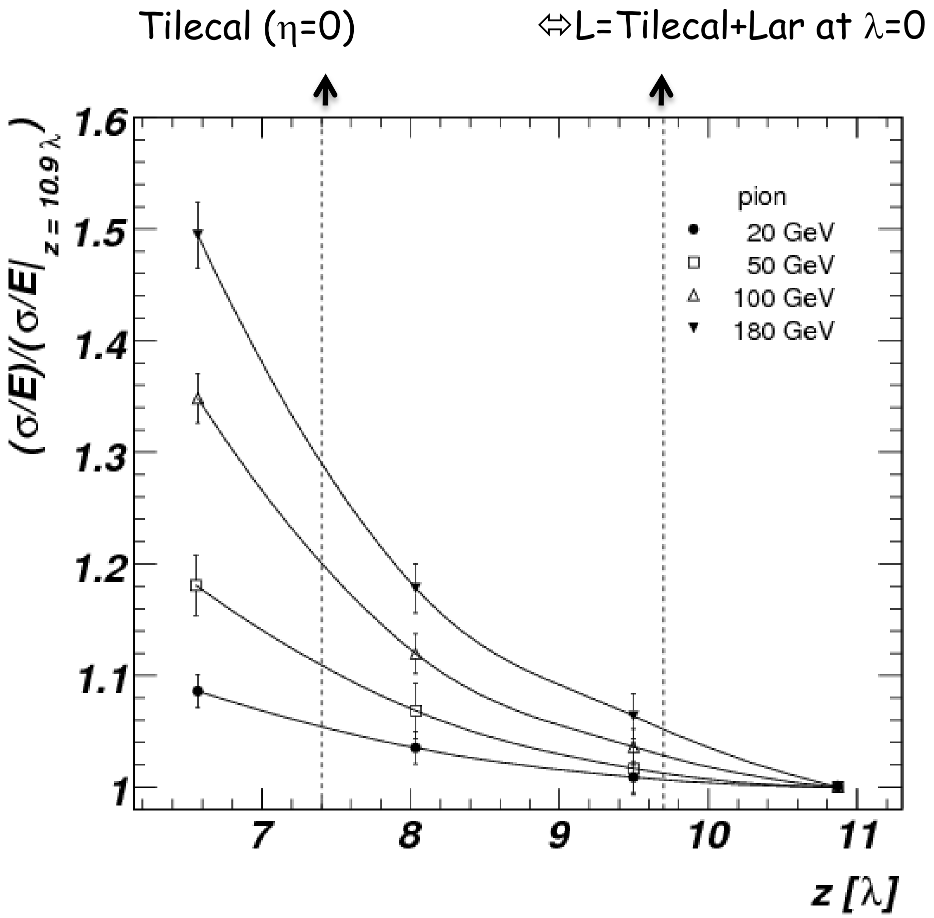
Δ=1.2m =7.5 λ

π resolution (ATLAS tilecal standalone in tbeam)

(NIM A 606 (2009) 362-394)

|η|=0.35 (⇔ depth=7.9λ)





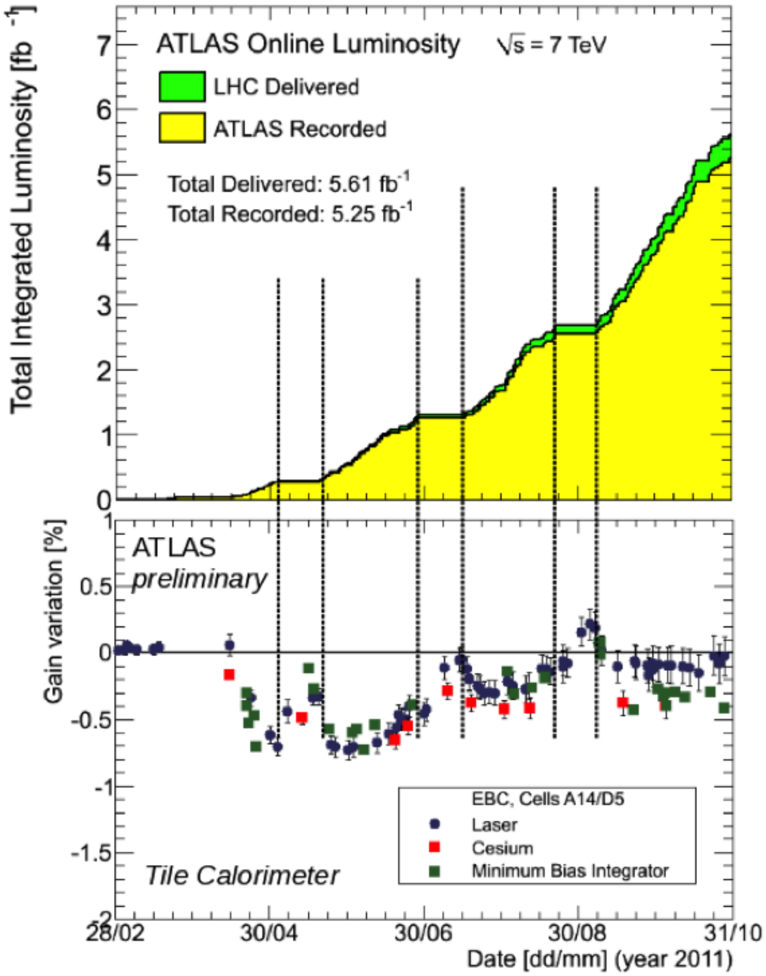
- 5.7% constant term affected by long. leakage. If tilecal longer and ⇔ ATLAS, constant term ~ 2.5% (from longer tilecal longer prototypes and 90° data)

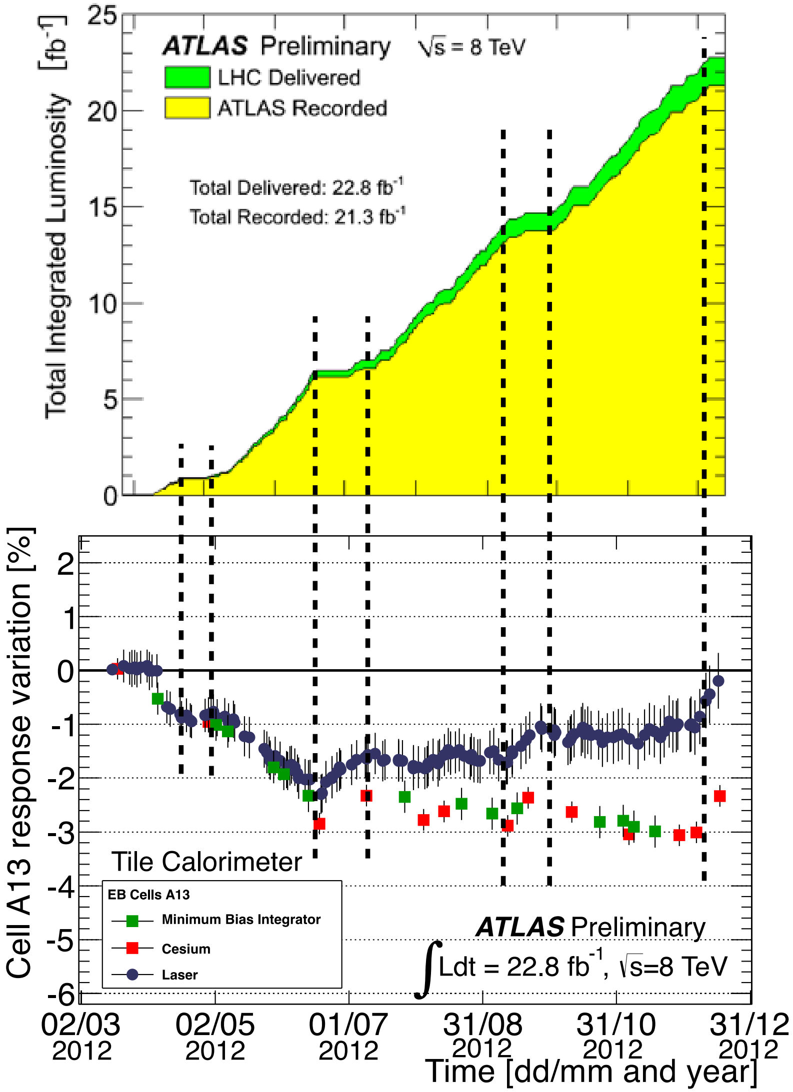
- The expected constant term for jet energy resolution in ATLAS: Tilecal+LAr (depth=9.7 at λ=0) is ~ 2.6%

ATLAS Tile most exposed cells A14/A13 in 2011 and 2012

https://twiki.cern.ch/twiki/pub/AtlasPublic/ApprovedPlotsTile/TileCalLumi.eps

https://twiki.cern.ch/twiki/pub/AtlasPublic/ApprovedPlotsTileCalibration/A13 lumi.pdf





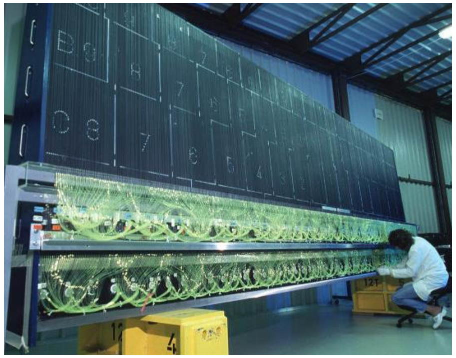
Main effect is PMT gain drift (see with laser)

Scintillator irradiation is difference cs-laser. No irradiation see in 2011, ~-2% max in 2012

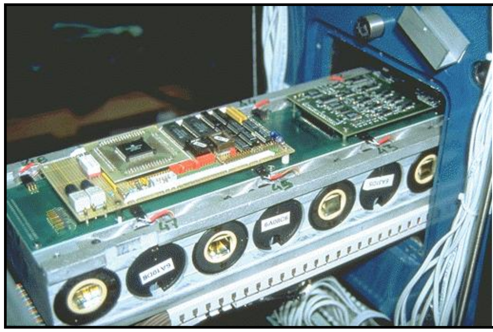
A bit of history of ATLAS Tilecal

1993-1995 R&D

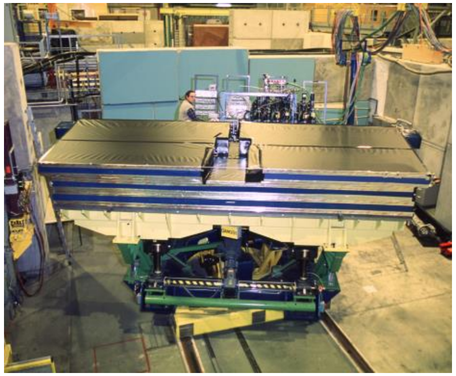
1996-2002:construction)



1999-2002 Instrumentation

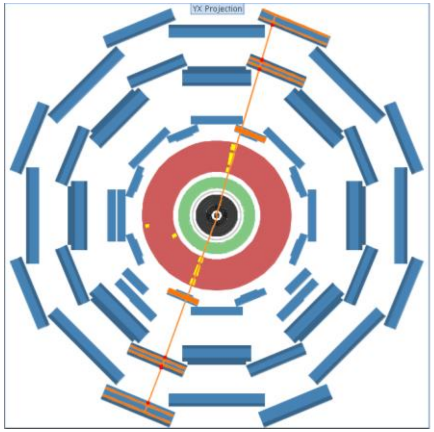


1999-2004: Electronics



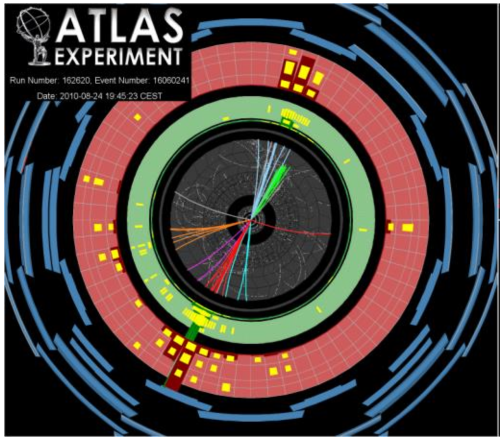
2002-2004: calibrations

2004-2006 Installation



2007-2009 commissioning

(Mostly with cosmics)



2009--→: LHC data taking

(Highest dijet M_{jj} ~ 3.1 TeV)

A long way to arrive to the excellent performance of Tilecal in ATLAS/LHC

ATLAS TILECAL refs

- Optics instrumentation :
- http://iopscience.iop.org/1748-0221/8/01/P01005/

- Mechanics/assembly:
- http://iopscience.iop.org/1748-0221/8/11/T11001/

- Readiness for collisions:
- http://www.springerlink.com/content/l355548m7h9x6gh3

- Perf.:
- http://dx.doi.org/10.1016/j.nima.2009.04.009
- http://dx.doi.org/10.1016/j.nima.2010.01.037