Performance studies and requirements on the calorimeters for a FCC-hh experiment

C. Neubüser[1] on behalf of the FCC-hh detector working group

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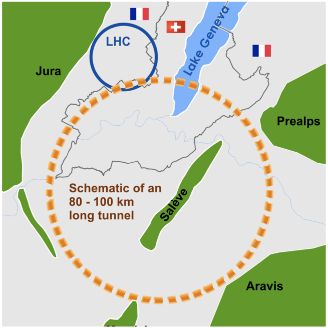
[1] coralie.neubuser@cern.ch

Contents

The Future Circular Collider project

International FCC collaboration (111 institutes, 32 countries)

- 100 TeV p-p collider (**FCC-hh**): main emphasis, defining infrastructure requirements
- 90-400 GeV e^+e^- collider (**FCC-ee**): as potential first step
- $\sim$100 km tunnel infrastructure in Geneva area, site specific
- p-e (**FCC-he**) option studied

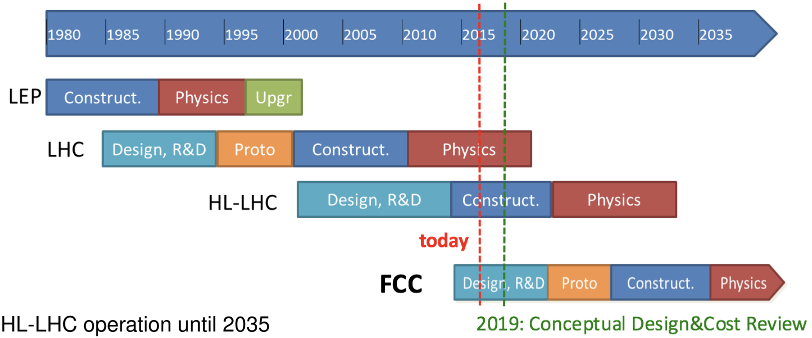


Upgrades for HL-LHC with FCC-hh technology

Goal: CDR for European Strategy Update 2019

similar project studied/to be hosted in China,
50-100 TeV Super proton proton Collider (SppC)

Timescale of FCC-hh project



HL-LHC operation until 2035
$\sim$ 30 years from design to data taking
Development of FCC collider and detector needed NOW to be ready after HL-LHC $\sim$2036

FCC collaboration

- vital community: Theory, Accelerator, Physics and Detector R&D
- close collaboration with LHC experiments (FCC-hh) & ILC/CLIC (FCC-ee)

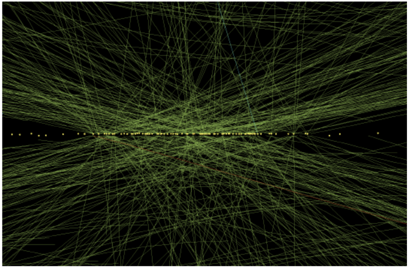
Upcoming: Annual FCC Week 2017 in Berlin, Germany

29th May to 2nd June, 491 registered participants

`https://indico.cern.ch/event/556692/`

The FCC-hh experiment and detector environment

- **Record collision energy 100TeV**
  –> Higher average and maximum pT objects
- **Record peak luminosity**
  baseline: $5 \times 10^{34}\,\mathrm{cm}^{-2}s^{-1}$
  ultimate: $\geq 30 \times 10^{34}\,\mathrm{cm}^{-2}s^{-1}$
  –> huge particle rates, pile-up $\langle\mu\rangle \approx 1000$ for ultimate scenario
  –> huge data rates, strong requirements on trigger and event reconstruction
  –> timing information from the detectors for pile-up rejection
- **Record integrated luminosity**
  $O(30\mathrm{ab}^{-1})$ over 25 years of operation
  –> strong requirements on radiation hardness



High Luminosity LHC, 78 vertices

FCC-hh detector

baseline FCC week Berlin May 2017

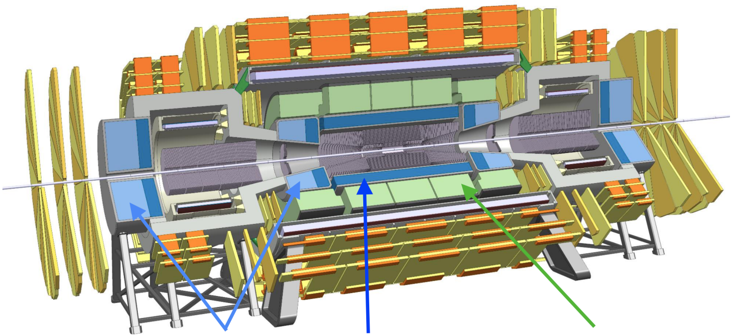
total length ~47 m, height ~18 m

Magnet

3 solenoids
not fully shielded
4 T, 2.5 and 5 m radius

Tracker

1.5 m radius
$\sigma p_T/p_T \sim 10\,\%$ (10 TeV)



Forward calorimeter & tracker

up to η=6

HCAL EC+HFCAL

LAr with Cu/W absorber
$\sigma_E/E \sim 50/100\%/\sqrt{E} \oplus 3/5\%$

ECAL B+EC+FCAL

LAr with Pb absorber
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$

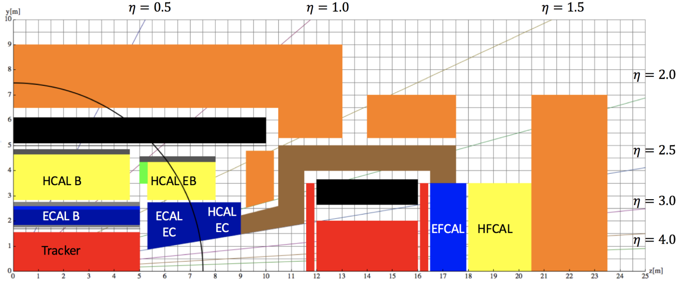
HCAL B+EB

Sci-Steel with SiPM readout
$\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$

FCC-hh detector

baseline FCC week Berlin May 2017

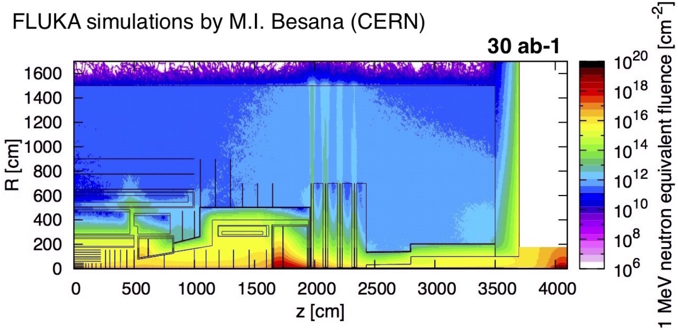
total length ∼47 m, height ∼18 m



NAME	Technology	η coverage	# long.layers	Δη x Δφ	# channels (x10^6)
ECAL B	LAr / Pb	< 1.7	8	0.01 x 0.012	1.3
ECAL EC	LAr / Pb	1.5 – 2.5	6	0.01 x 0.012	0.6
HCAL EC	LAr / Cu	1.7 – 2.5	6	0.025 x 0.025	0.1
EFCAL	LAr / Pb	2.3 – 6.0	6	0.025 x 0.025	0.5
HFCAL	LAr / Cu	2.3 – 6.0	6	0.05 x 0.05	0.1
HCAL B	Scint. Tiles / Stain. Steel	< 1.3	10	0.025 x 0.025	0.2
HCAL EB	Scint. Tiles / Stain. Steel	1.0 – 1.8	8	0.025 x 0.025	0.07
Total	LAr / Pb				**2.3**
	LAr / Cu				**0.2**
	Scint. Tiles / Stain. Steel				**0.3**

Requirement on radiation hardness

FLUKA simulations by M.I. Besana (CERN)



	eq. fluence [n/cm^{-2}]	Dose [MGy]
ECAL B	$\leq 3 \times 10^{15}$	
ECAL EC	$\leq 3 \times 10^{16}$	$\sim$1
HCAL EC	$\leq 1 \times 10^{16}$	$\sim$1
FCAL	$\leq 8 \times 10^{18}$	$\leq 5 \times 10^{3}$
HCAL B	$\leq 3 \times 10^{14}$	≤ 0.006
HCAL EB	$\leq 3 \times 10^{14}$	≤ 0.008
1rst IB	5-6$\times 10^{17}$	

- Liquid Argon extreme radiation hard
  –> E+HCAL up to $\eta = 6$
- Radiation in HCAL B+EB within tolerances for Scintillator and Silicon Photomultipliers (SiPMs)
  2015 J. Phys.: Conf. Ser. 645 012019
  NIM A 824 (2016) 111-114

FCC-hh EM calorimeter – physics requirements

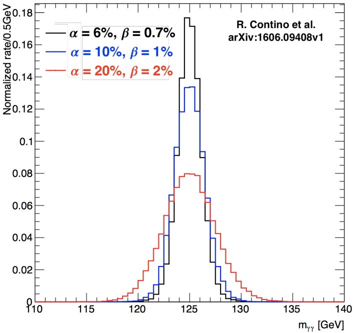
requirements: heavy resonances
($Z' \rightarrow e^+e^-$, $W' \rightarrow e\nu$, $X \rightarrow \gamma\gamma$, $X \rightarrow jj$)

$$\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \qquad (1)$$

1. Significance of mass peaks
   - high energy resolution
   - high angular resolution for p_T
2. Measurement of invariant masses
   - good Linearity of calorimeter response

   e.g. linearity of calorimeter is dominant systematics for ATLAS Higgs-mass measurement.

–> constant term <1 % essential!



FCC-hh EM calorimeter – LiquidArgon-Lead

1. Current baseline for FCC-hh

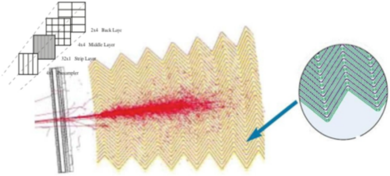
ATLAS type, LAr - Lead
in ECAL Barrel, EC & Forward

changes for FCC-hh:

- simplified absorber/electrode geometry to increase segmentation
  –> needed for pointing, pile-up rejection, γ/π^0 separation, boosted objects
- Pb/LAr ratio: 2mm/3-5.6mm
- goal: decreased cryostat material
- 4 times better granularity:
  $\Delta\phi \times \Delta\eta = 0.01 \times 0.01$

–> one order of magnitude large #channels
(200,000 –> 2,000,000)

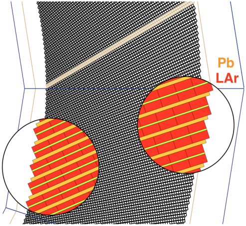
LAr - Copper/Tungsten for HCAL EC and HFCAL –> not yet further studied



Accordion geometry of ATLAS LAr ECAL

ATLAS LAr ECal, electron resolution

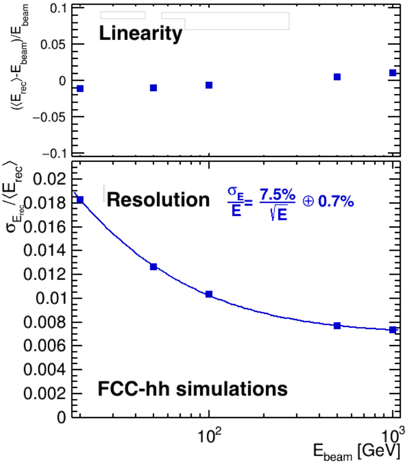
$\sigma_E/E = 10\,\%/\sqrt{E} \oplus 0.7\%$



FCC-hh ECAL Barrel geometry

FCC-hh LAr-Lead ECAL – electron reconstruction

B=4 T, ∼10,000 e^- events per energy, FTFP_BERT, $\eta = 0$



- calibrated to EM scale
- correction for upstream material (Cryostat) applied
- constant term $< 1\%$
- non-linearities always smaller than 2 %

–> EM Calorimeter already meet the requirements on electron resolution (without noise, pile-up)

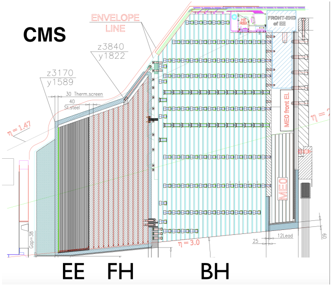
FCC-hh EM calorimeter – Silicon-Lead/Steel

2. High Granularity (HGCAL) option

CALICE type, Silicon - Lead

- Phase II upgrade of CMS Endcaps
  talks by F. Pitters, F. Romeo yesterday
- radiation hard up to 10^{16} neq for 100-300 μm thick Si
- 0.25 and 1 cm^2 cells

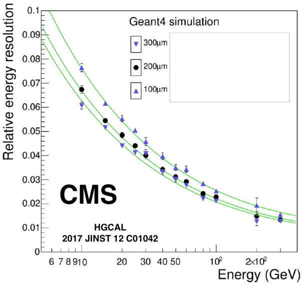
–> worse stochastic term compared to LAr ECAL due to very small em sampling fraction
–> however granularity can be the key to deal with pile-up at FCC



HGCAL layout, EE and FH in Si-Pb

$$\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \qquad (2)$$

	Si thickn.	α	β
$\vert\eta\vert < 1.75$	300 μm	19.9%	0.6%
$1.75 < \vert\eta\vert < 2.15$	200 μm	21.4%	0.7%
$\vert\eta\vert > 2.15$	100 μm	24.3%	0.8%



FCC-hh EM calorimeter – Silicon-Tungsten

3. Digital option

CALICE / ALICE FoCal type, Silicon - Tungsten

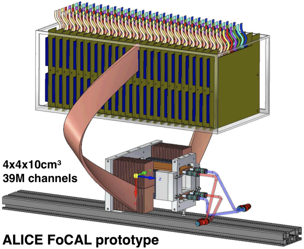
- CMOS Monolithic Active Pixel Sensors (MAPS) with digital readout
- Counts the number of particles in a shower rather than energy deposited
- radiation hardness under development

First tests in FoCAL prototype
talks by H. Wang, Y. Kawamura yesterday

- combined with $1 \times 1\,\mathrm{cm}^2$ Si pads
- shower separation to few mm

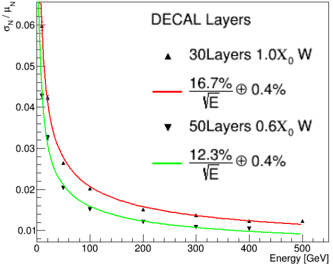
Studies for FCC-hh ongoing at U. Birmingham
talk by T. Price at FCC week 2017

- $50 \times 50\,\mu$m pitch, 2.1 mm W/layer
- 18 μm Epi layers



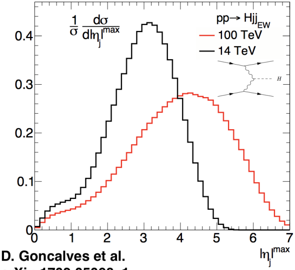
ALICE FoCAL prototype

FCC-hh simulation

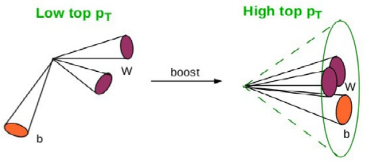


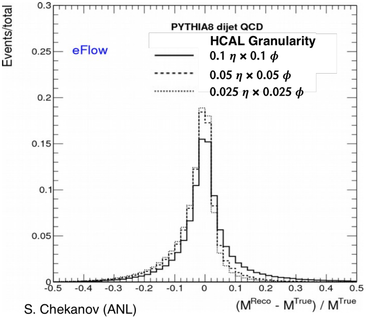
–> Have to be studied in full-detector simulations

FCC-hh hadron calorimeter – physics requirements



D. Goncalves et al.
arXiv:1702.05098v1





S. Chekanov (ANL)

- Jet rapidity of WBF
  –> η coverage up to 6
- Highly collimated final states (boosted decay products of heavy objects)
  –> High granularity to resolve jet sub-structure and background rejection (e.g. pile-up jets, π^0)
- High p_T jets at $\eta = 0$
  –> containment $\geq$ 11 λ

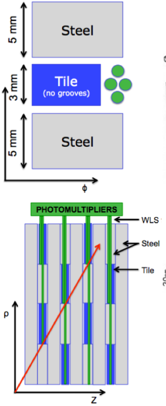
FCC-hh hadronic calorimeter – Scintillator-Steel I

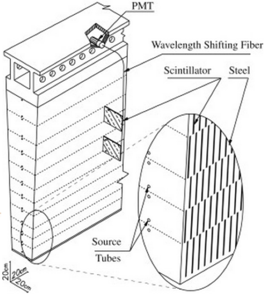
1. Current baseline for FCC-hh

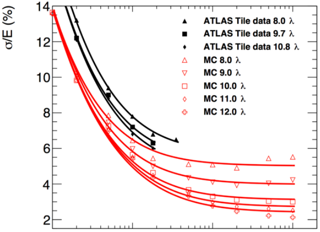
ATLAS type, Scintillator tile - Steel

changes for FCC-hh:

- 4 times higher granularity $\Delta\phi \times \Delta\eta = 0.025 \times 0.025$
- 10 instead of 3 longitudinal layers
- Steel –> stainless Steel absorber (Calos in magnetic field)
- SiPM readout –> faster, less noise, less space







T. Carli et al.
JINST 11 (2016) no.09

Resolution for single pions in 11 λ HCAL:

$\sigma E/E = 43\,\%/\sqrt{E} \oplus 2.7\%$

Good containment achievable with $\sim 11\lambda$ calorimeter system (ECAL+HCAL) at $\eta = 0$

FCC-hh hadronic calorimeter – Scintillator-Steel II

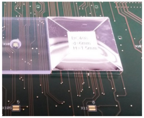
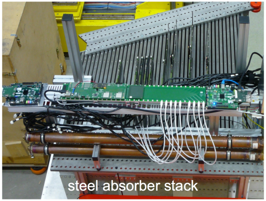
2. High Granularity (HGCAL) option

CALICE type, Scintillator tile - Steel/Brass for the Barrel + EB

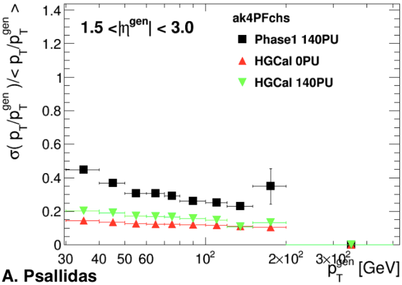
- Phase II upgrade of CMS Endcaps
- $3 \times 3\,\text{cm}^2$ Sci tiles
- integrated SiPM readout
- active prototyping within CALICE collaboration
  talk by Y. Liu yesterday

Plans for FCC-hh:

- combined with high-granularity ECAL (Silicon-Lead/Tungsten)
- granularity used for pile-up rejection

Wrapped Sci Tile of CALICE AHCAL
Testbeam setup in ILD stack



A. Psallidas

HGCAL simulations, jet p_T resolution w/wo pile-up

–> Have to be studied in full-detector simulations

FCC-hh full detector simulations

new Software framework set-up **FCCSW**

Detector geometries described in DD4hep, simulations based on Geant4

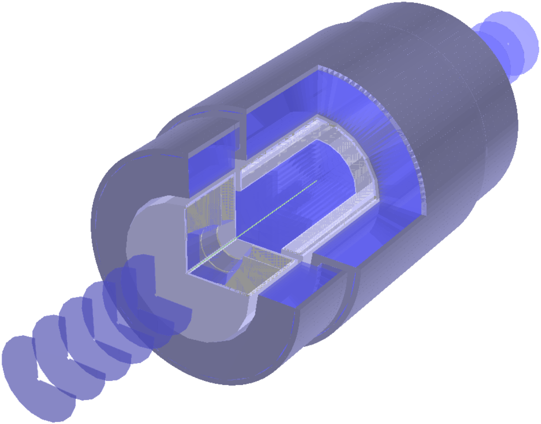
Documentation: `http://fccsw.web.cern.ch/fccsw/`

Software on github: `https://github.com/HEP-FCC/FCCSW`

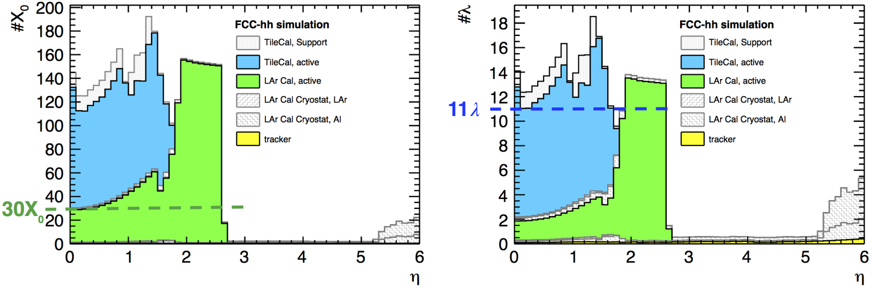
Status:

- Tracker layout (***talk by Z. Drasal at FCC week 2017***)
- ECAL Barrel + Endcaps
- HCAL central + extended Barrel

(Only) baseline technologies implemented yet: LAr/Pb/Cu + Sci/Steel



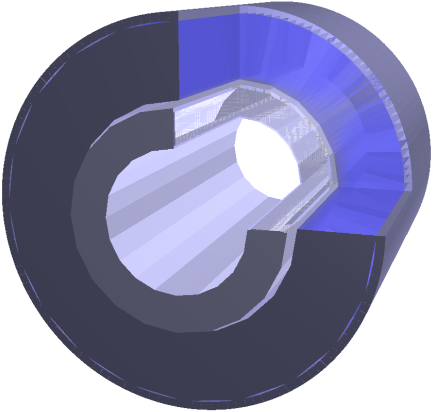
Material scans of FCC-hh **full Barrel+Endcaps**



- ECAL thickness: 30 $\#X_0$
- E+HCAL thickness: 11 $\#\lambda$
- passive calorimeter supports in light grey
- approx. 1.5 $\#X_0$ in front of ECal
- approx. 2 $\#\lambda$ in front of HCal
- good η coverage, dip in $\#\lambda$ at $\eta = 1.7$ requires optimisation

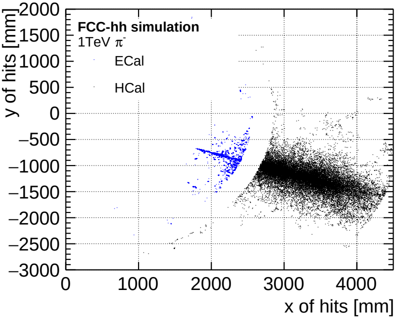
LAr ECal + TileCal

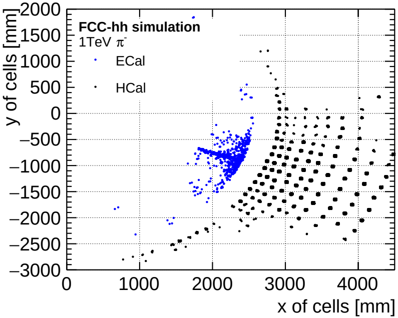
first look into combined single particle reconstruction



LAr ECal + TileCal simulations

from Geant4 depositions (hits) to energy in Calorimeter cells





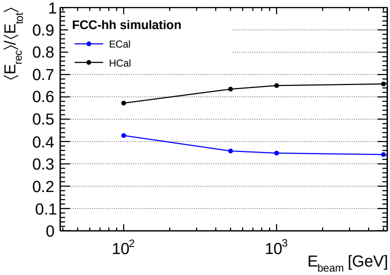
EM showers are contained in ECAL (30 $\# X_0$)

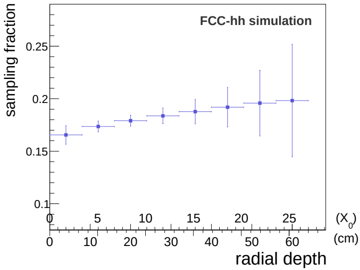
Not included in the simulation yet:

- electronics noise
- pile-up noise

E+HCal Response & Energy Reconstruction

10,000 π^- events per energy, FTFP_BERT, $\eta = 0.36$





Pion showers of >100 GeV deposit less than 40 % of energy in ECAL

$$E_{tot} = E_{rec}(ECal) + E_{rec}(HCal) \quad (3)$$

$$E_{tot} = \sum_{i=1}^{hitsECal} E_i/b + \sum_{j=1}^{hitsHCal} E_j/c \quad (4)$$

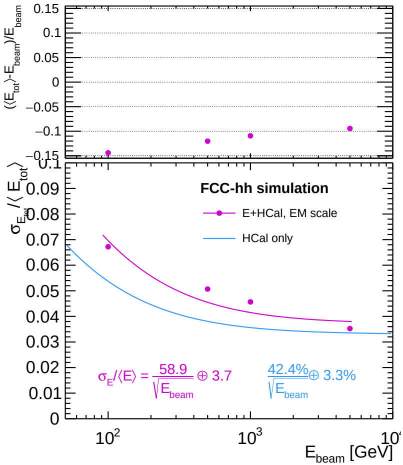
Calibration to EM scale with extracted sampling fractions:

- $b = (16.8 - 21.5)\,\%$
- $c = 3.2\%$

LAr gap size changes with radius

E+HCal Resolution and Linearity

10,000 π^- events per energy, FTFP_BERT, $\eta = 0.36$



- degraded resolution compared to HCAL only: impact different sampling, EM scale ($e/h \neq 1$)
- 0.25 $\#\lambda$ / 1.5 $\#X_0$ passive material between E and HCal
- comparable to ATLAS results: $\alpha = 52.1 \pm 5.5\%$, $\beta = 1.9 \pm 0.3\%$

Next steps:
–> Correction for lost energy needed, constant term expected to improve
–> Clustering algorithm for jet reconstruction

Additional optimisation studies for E and HCAL ongoing! ***talks by J. Faltova, C. Neubüser at FCC week 2017***

Summary & Outlook

New energy frontier reached by FCC-hh requires new calorimeter designs to

- resolve 1,000 pile-up events
- survive harsh radiation environment
- perform precise jet reconstruction of high-energetic particle showers

First (baseline) calorimeter system tested in simulations

- necessary EM resolution achieved
- HCAL alone shows good performance, the combined hadron reconstruction needs re-calibrations (just starting)

Next steps

- implementation of other calorimeter options in FCCSW
- tests including pile-up
- jet reconstruction with particle flow algorithms

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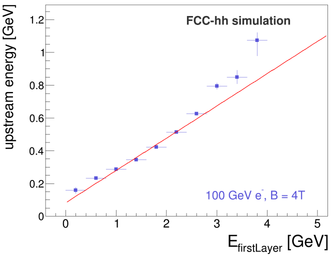
Thank You!

Backup!

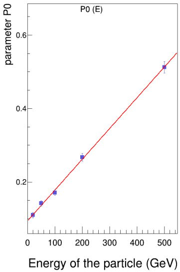
Energy correction in **ECAL only** for material in front

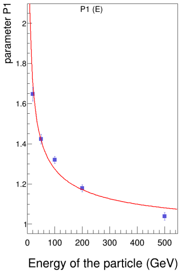


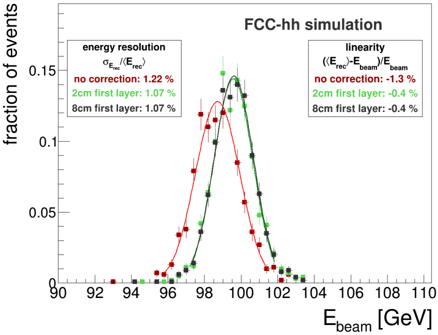
$$E_{ECal} = E_{upstream} + E_{rec} \qquad (5)$$

- $E_{upstream} = p_0 + p_1 \cdot E_{1stLayer}$
- improvement in energy resolution from 1.26 to 0.98 %

–> correction over full energy range, using parameterisation of p_0 and p_1







Key Parameters for Sampling Calorimeters

Energy resolution for sampling calorimeters

$$\frac{\sigma E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \qquad (6)$$

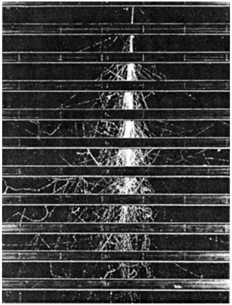
α (stochastic term) dominated by:

- sampling fluctuations, effected by sampling fraction $f_{sampling} = \frac{E_{vis}(e)}{E_{true}(e)}$ and sampling frequency
- non-compensation $e/h \neq 1$

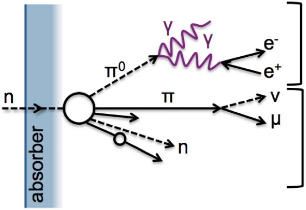
β (constant term) dominated by:

- $e/h \neq 1$
- calibration in-accuracies

–> homogenous Calos have $e/h > 1$ due to E_{inv} in hadron showers
–> sampling Calos can be designed for Compensation



EM shower in cloud chamber



Hadron shower schematic

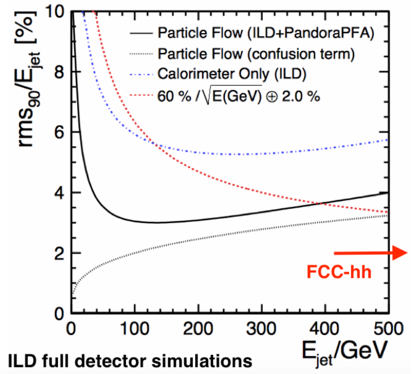
Calorimeters designed for Particle Flow Algorithms

focus on full detector performance
–> Calorimeters are not optimised for the best single particle energy resolution
BUT for the performance in event reconstruction algorithms

PFAs optimise jet energy reconstruction by measuring each jet particle with sub-detector of highest resolution

- Charged hadrons and leptons ($\sim$ 60%) measured by Tracker
- Photons ($\sim$ 30%) measured by Electromagnetic Calorimeter –> $\sigma E/E \approx 10\%/\sqrt{E}$
- Neutral hadrons ($\sim$ 10%) measured by Hadronic calorimeter –> $\sigma E/E \approx 50\%/\sqrt{E}$

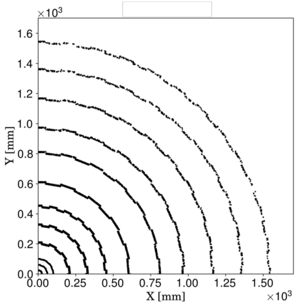
$$\frac{rms_{90}}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus c \cdot E \oplus d \left(\frac{E}{100}\right)^{e} \% \quad (7)$$

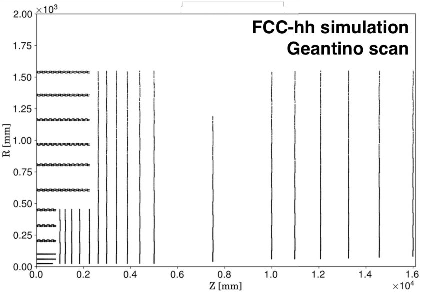


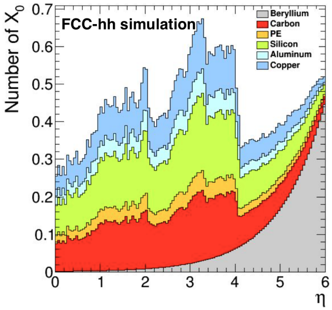
- a: calorimeter resolution
- b: tracking inefficiencies
- c: leakage
- d: confusion

100 TeV pp collider expects high p_T jets:
–> PFA is dominated by confusion
–> small constant term crucial
–> strongly depends on containment

FCC-hh tracker layout





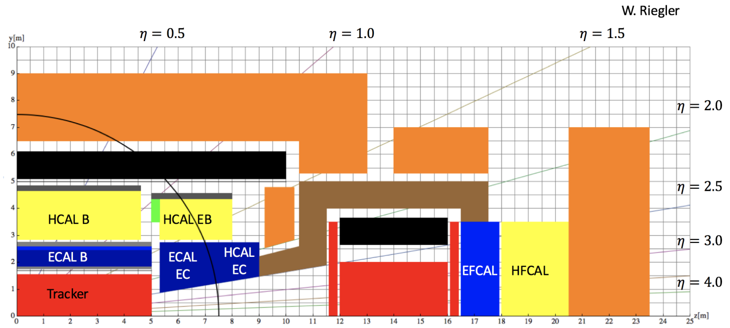


- $< 0.3\,X_0$ at $\eta = 0$
- $< 2.5\%\,X_0$ per layer

FCC-hh detector

baseline FCC week Berlin May 2017

total length ~47 m, height ~18 m



$|\eta| < 1.5$
Central/Extended Barrel

$1.5 < |\eta| < 2.5$
Endcaps

$|\eta| > 2.5$
Forward

–> Goal: precision measurements up to $|\eta| = 4$