Summary of FCC-hh Experiment and Detector (3), Common Software (1), Common Technology (1)

FCC week, April 11-15, 2016, Rome

W. Riegler

Martin Aleksa, Ilaria Besana, Sergei Chekanov, Dmitri Denisov, Zbynek Drasal, Benedikt Hegner, Clement Helsens, Julia Hrdinka, AshutoshKotwal, Matthias Mentink, Dave Newbold, Estel Perez, Walter Snoeys, Ian Shipsey, Hans Kristian Soltveit, Herman Ten Kate, Marianna Testa, Georg Viehhauser, Anna Zaborowska,

Baseline Parameters for the FCC-hh Machine

5 year long operation periods

- 3.5 years operation periods with
- 1.5 year shutdown

2 periods at baseline parameters (10 yrs) Phase1

- Peak luminosity $5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 25ns, pileup 170
- Total of $2.5\mathrm{ab}^{-1}$ (per detector)

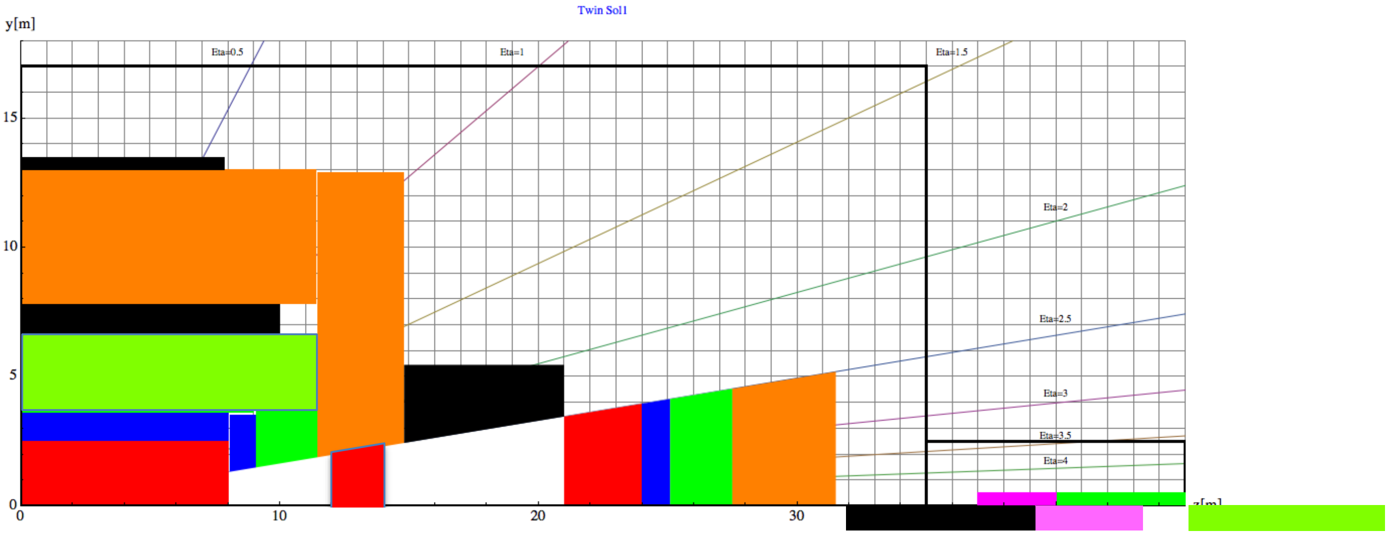
3 periods at ultimate parameters (15 yrs) Phase 2

- Peak luminosity $<=30\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, **25(5)ns, pileup 1020(204)**
- $5\mathrm{ab}^{-1}$ per period total of $15\mathrm{ab}^{-1}$

→ **Although some of us are confident about prospects of being able to deal with high pileup, the 5ns option should be considered 'at least with equal priority' as 25ns.**

→ **The transition from Phase1 to Phase2 luminosity is not related to major hardware changes in the accelerator, so it may be continuous. Important aspect for experiment strategy.**

Baseline Geometry used up to now , Twin Solenoid, 6T, 12m bore, 10Tm dipole



Barrel:

Tracker available space:
R=2.1cm to R=2.5m, L=8m

EMCAL available space:
R=2.5m to R= 3.6m → dR= 1.1m

HCAL available space:
R= 3.6m to R=6.0m → dR=2.4m

Coil+Cryostat:
R= 6m to R= 7.825 → dR = 1.575m, L=10.1m

Muon available space:
R= 7.825m to R= 13m → dR = 5.175m
Revision of outer radius is ongoing.

Coil2:
R=13m to R=13.47m → dR=0.475m, L=7.6m

Endcap:

EMCAL available space:
z=8m to z= 9.1m → dz= 1.1m

HCAL available space:
z= 9.1m to z=11.5m → dz=2.4m

Muon available space:
z= 11.5m to z= 14.8m → dz = 3.3m

Forward:

Dipole:
z= 14.8m to z= 21m → dz=6.2m

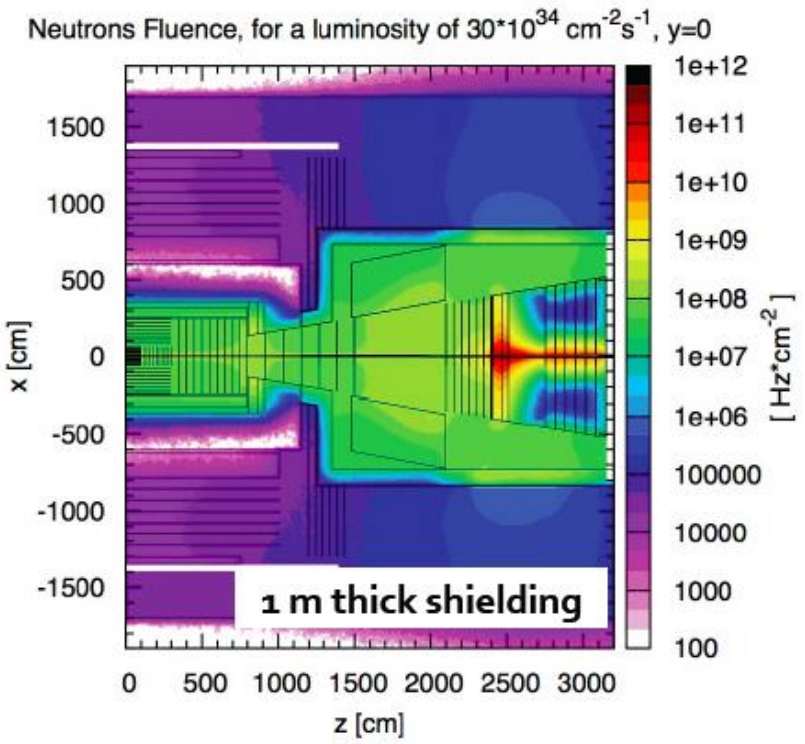
FTracker available space:
z=21m to R=24m, L=3m

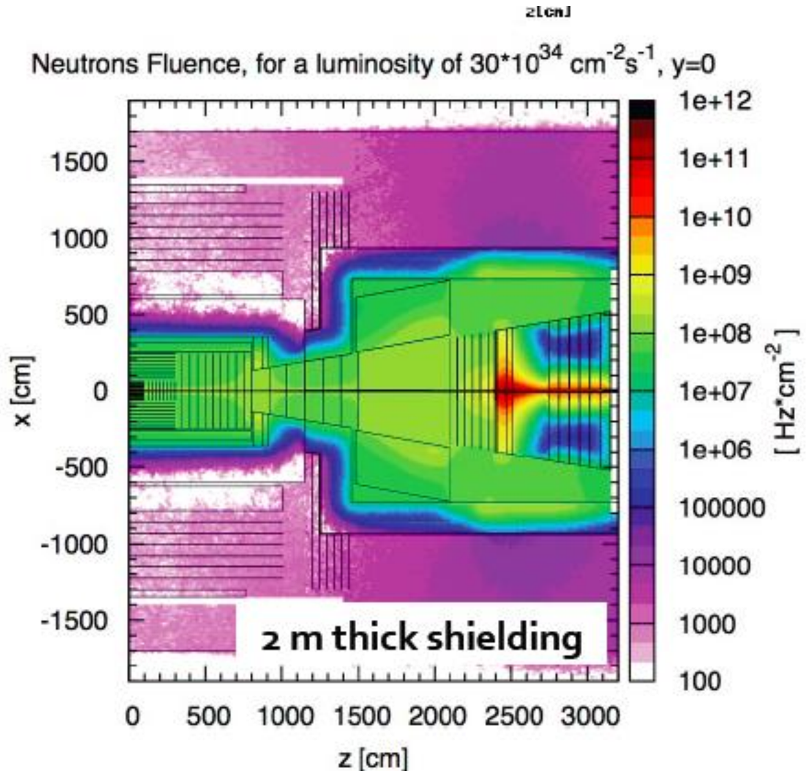
FEMCAL available space:
Z=24m to z= 25.1m → dz= 1.1m

FHCAL available space:
z= 25.1m to z=27.5m → dz=2.4m

FMuon available space:
z= 27.5m to z=31.5m → dz=4m

Radiation Calculations





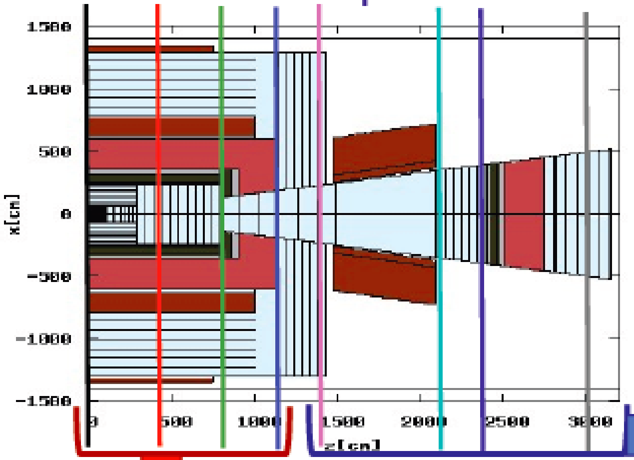
In the central tracker, close to the beampipe, the radiation is dominated by the primary hadrons.

In the forward tracker there is in addition a significant neutron flux from the calorimeter.

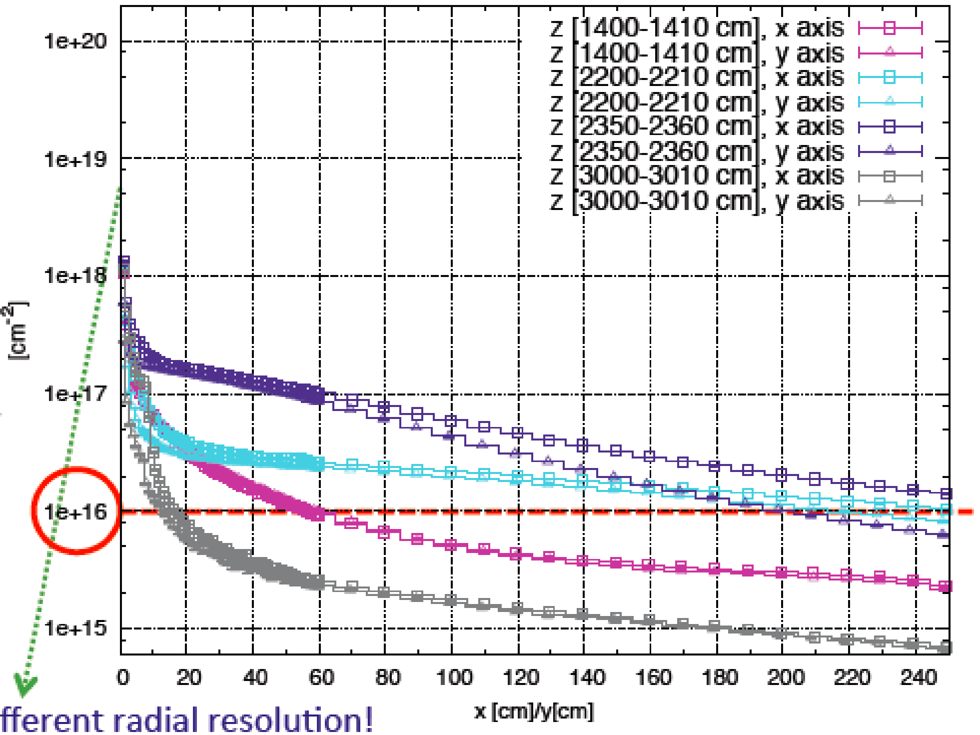
Ilaria Besana

Radiation Calculations

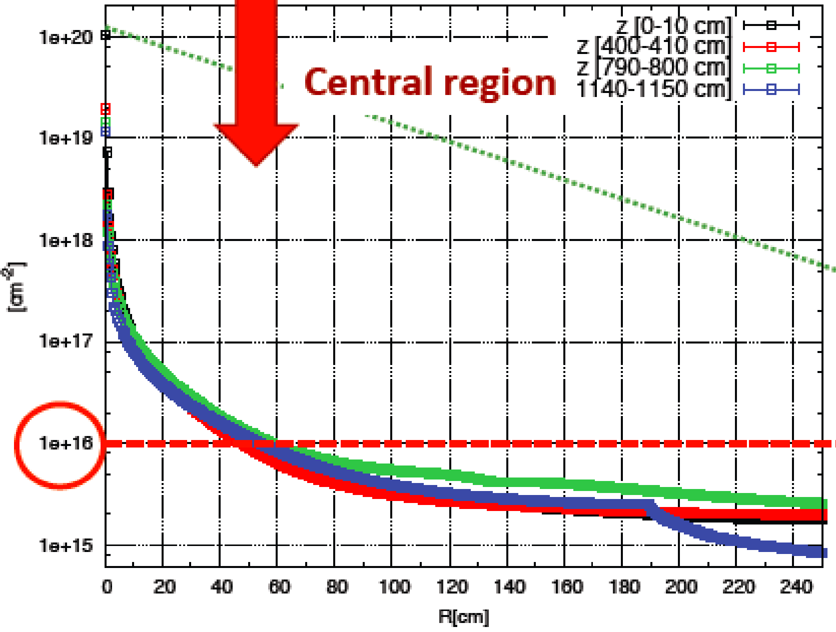
1 MeV neutron equivalent fluence vs R at different z positions **in the tracker:**



Forward region



Central region



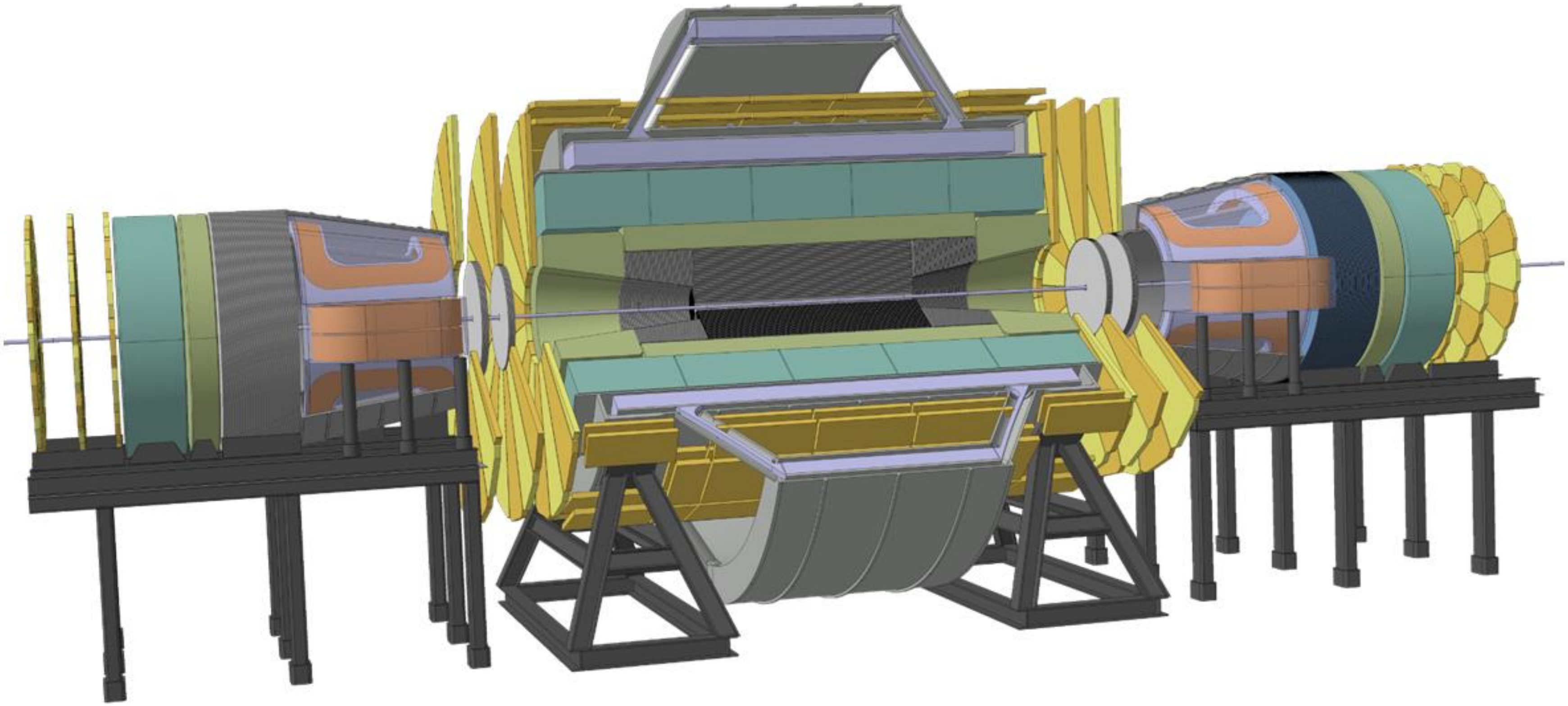
Different radial resolution!

For radii < 50 cm the fluence exceed the value expected at HL-LHC (10^{16} cm^{-2}) by up to 2 orders of magnitude → Technology challenge!

Fluence is even higher close to forward calorimeter: at z= 23.5 m the fluence vs x > 10^{16} cm^{-2} for x<2.5 m

Ilaria Besana

Twin Solenoid 6T, 12m bore, Dipoles 10Tm



Herman Ten Kate, Matthias Mentink

Development of ‘Detector Baseline’

Considering that the experiment cost should be a reasonable fraction of the accelerator cost one could naively assume a very large budget for the detectors.

The magnet group studied the 6T, 12m bore, 10Tm dipole as engineering challenge.

This geometry allows comfortably a 2.4m tracker cavity, 2.4m HCAL for 12 lambda.

Considering that such a magnet system costs on the order of 0.7-0.9 BEuros, and that for a reasonable balance the magnet system should represent between 20-30% of the detector cost, we are talking about a multi Billion cost for such a detector.

Scaling down the magnet system to 4T/10m and 4Tm dipoles reduces the cost by about a factor 2 to 0.35 to 0.45 BEuros, which brings the detector cost closer towards the ‘one Billion’ range.

We should therefore think about a more realistic baseline for the 2018 report.

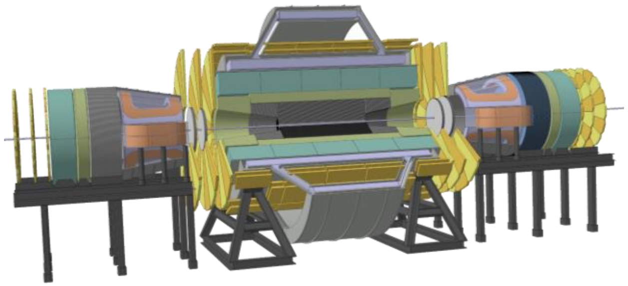
Development of ‘Detector Baseline’

100 TeV Collider

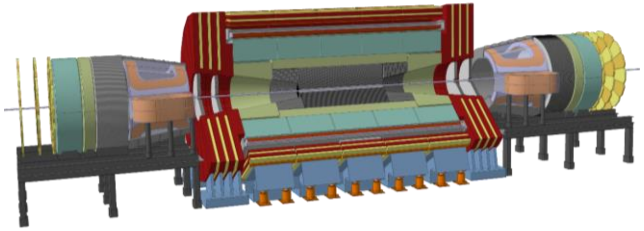
100km Tunnel

10m Bore Solenoid

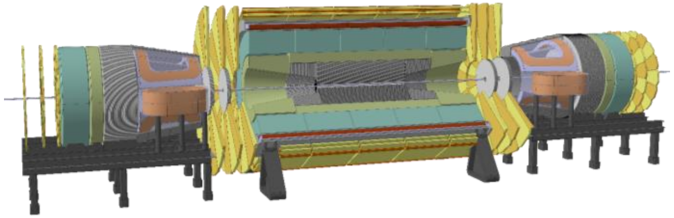
Magnet systems under consideration



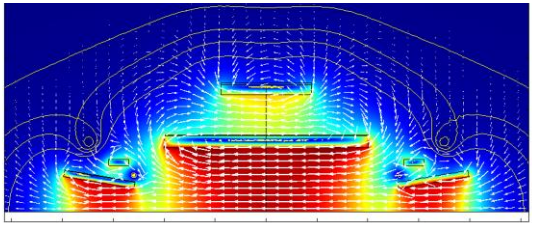
Twin solenoid with dipoles
(min. shaft diameter 27.5m)



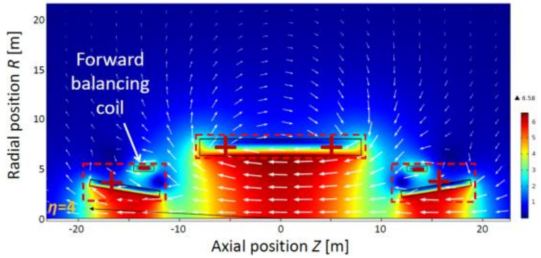
Partially shielded solenoid with dipoles



Unshielded solenoid with dipoles
(min. shaft diameter 16.3m, if rotated under ground)



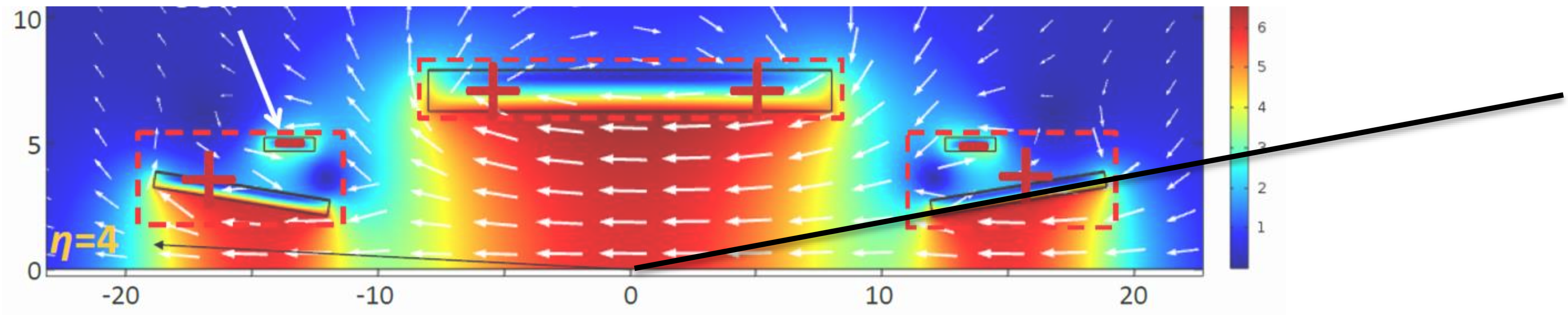
Twin solenoid with balanced conical solenoid

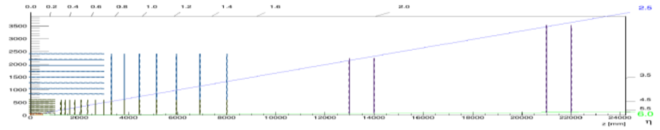


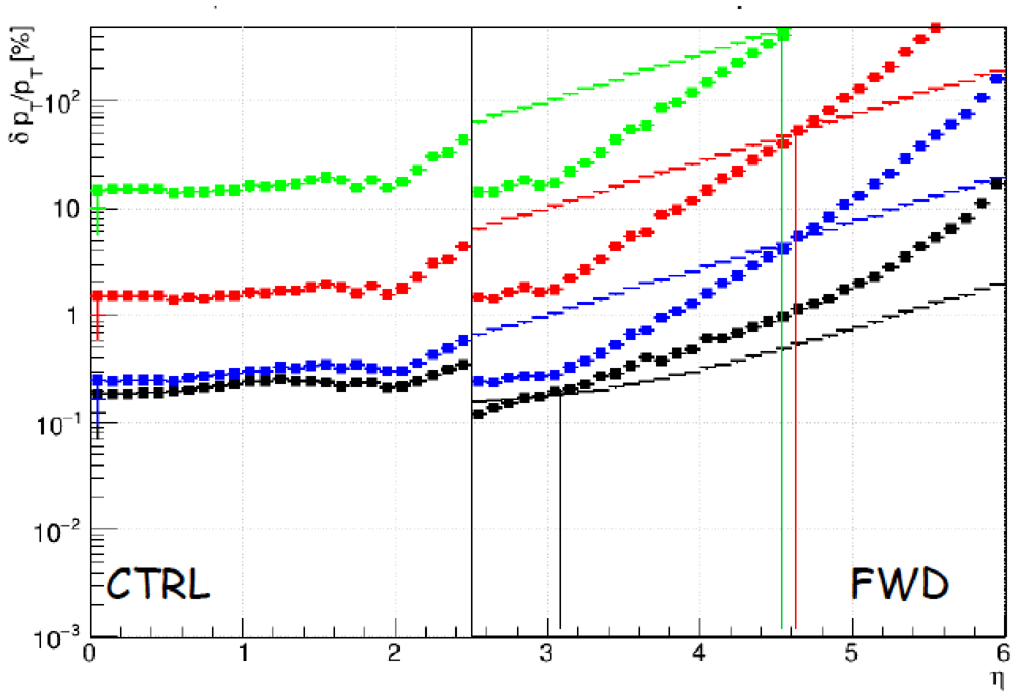
Unshielded solenoid with balanced conical solenoid

Herman Ten Kate, Matthias Mentink

Tracking Resolution for Dipole and Solenoid







Simulated p_T:

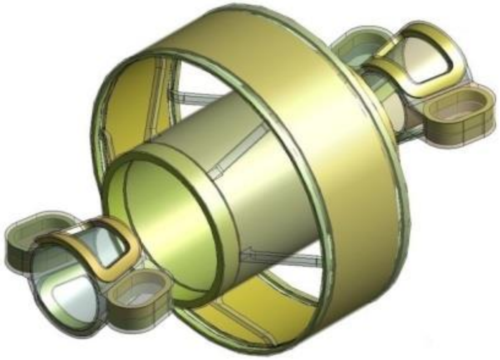
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV

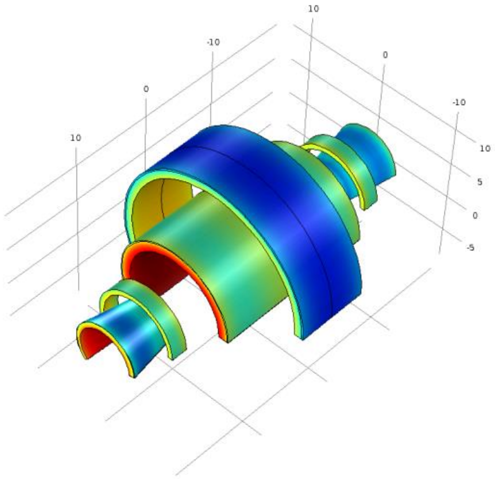
■ solenoid

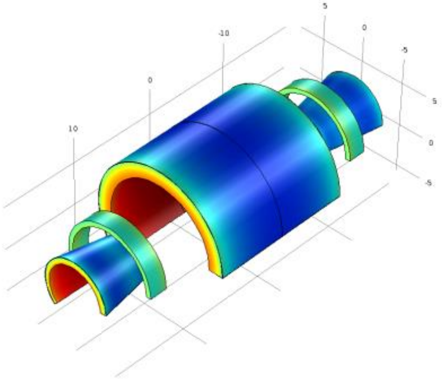
– dipole

Zbynek Drasal

Advantages of a Forward Solenoid







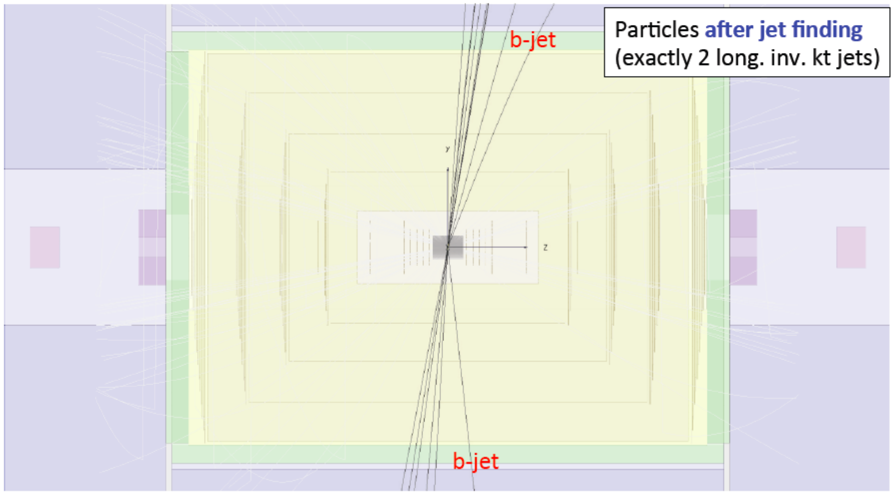
- → Construction is easier
- → No need for compensation in the machine
- → Keeping the rotational symmetry is a big advantage (Missing E_T etc.)

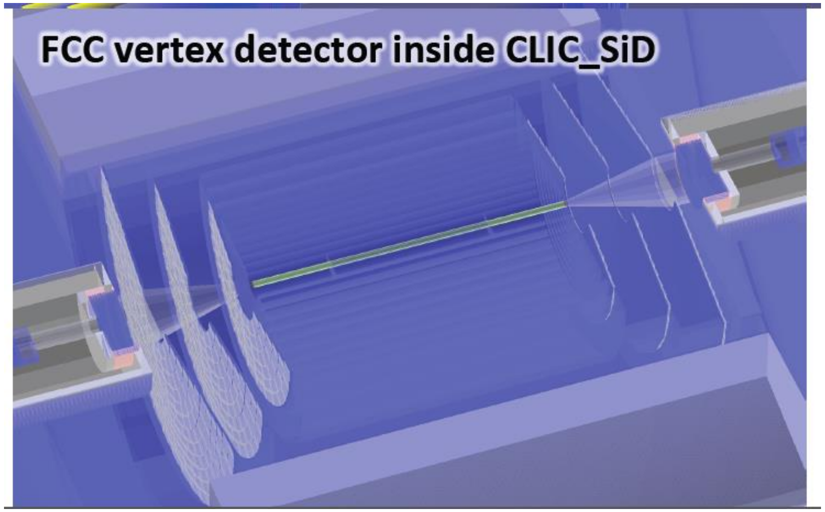
Some more performance parameters have to be understood before deciding on the ‘reference design’.

Herman Ten Kate, Matthias Mentink

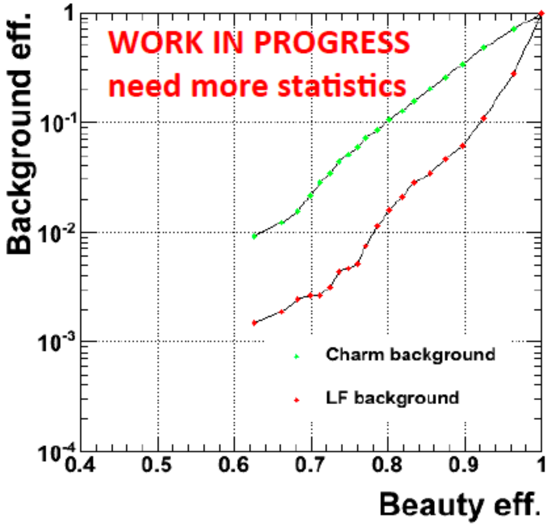
B-tagging studies

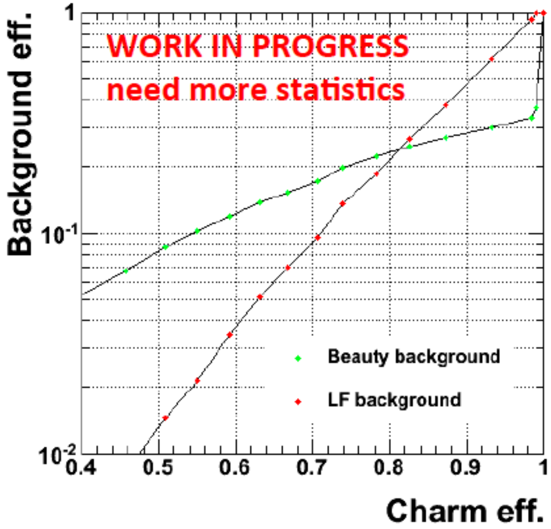
$pp \longrightarrow b\bar{b}$ collision at $\sqrt{s}$=100 TeV reconstructed in the CLIC detector





FCC vertex detector inside CLIC_SiD



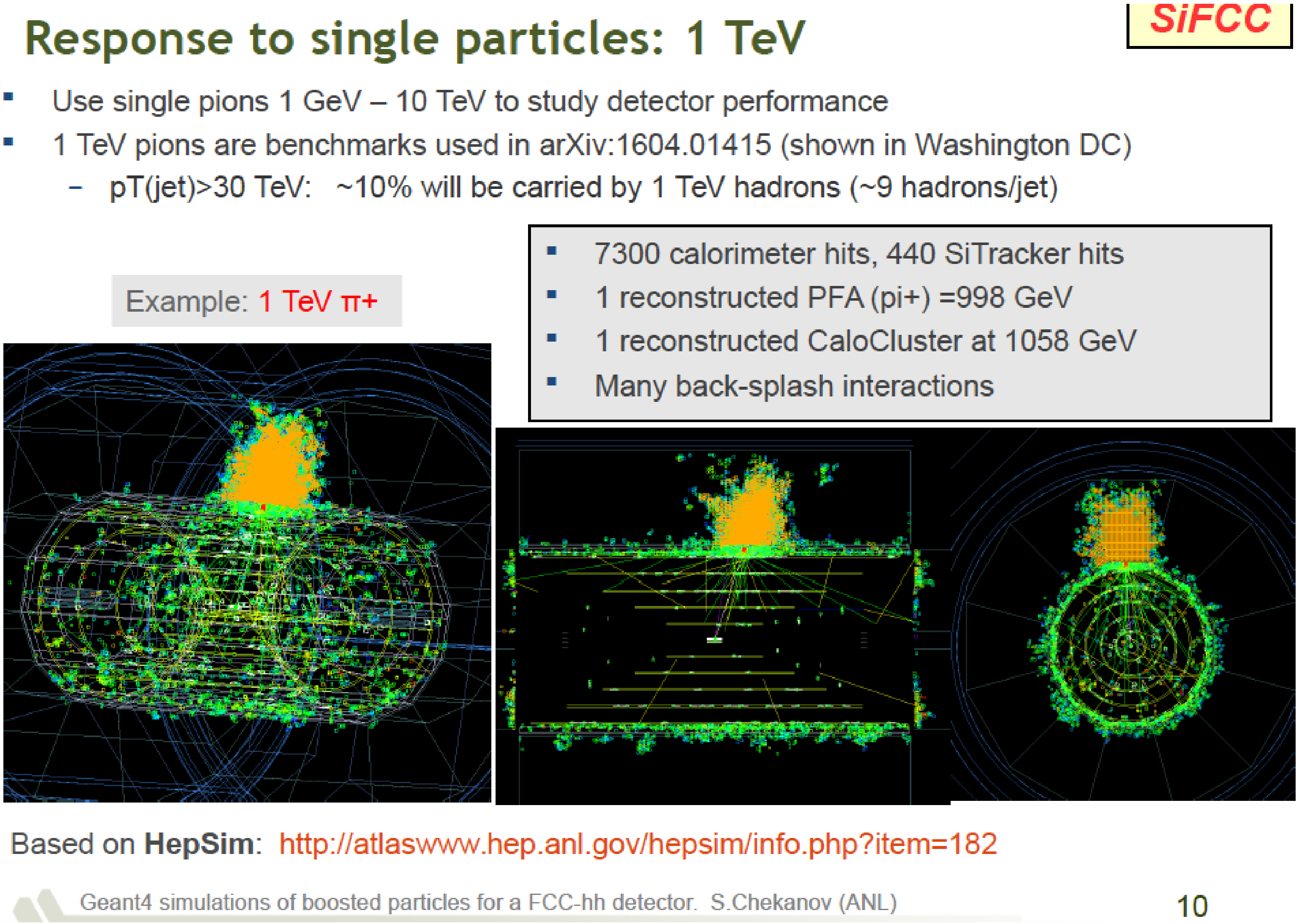


Collaboration with the CLIC detector group:

B-tagging studies for the FCC tracker geometry in the CLIC simulation framework.

Estel Perez

Calorimeter Studies



SiFCC

Response to single particles: 1 TeV

- Use single pions 1 GeV – 10 TeV to study detector performance
- 1 TeV pions are benchmarks used in arXiv:1604.01415 (shown in Washington DC)
  - pT(jet)>30 TeV: ~10% will be carried by 1 TeV hadrons (~9 hadrons/jet)

Example: 1 TeV π+

- 7300 calorimeter hits, 440 SiTracker hits
- 1 reconstructed PFA (pi+) =998 GeV
- 1 reconstructed CaloCluster at 1058 GeV
- Many back-splash interactions

Based on **HepSim**: http://atlaswww.hep.anl.gov/hepsim/info.php?item=182

Geant4 simulations of boosted particles for a FCC-hh detector. S.Chekanov (ANL) 10

HCAL studies using the SiD detector software.

Sergei Chekanov

Energy Deposition vs Integration Time for t_{abs}

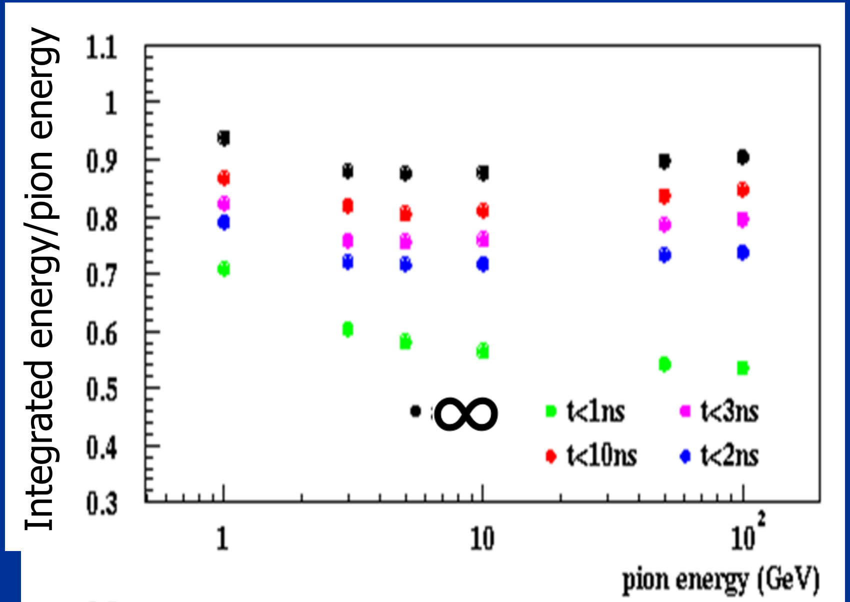
- **Question we address in this study**

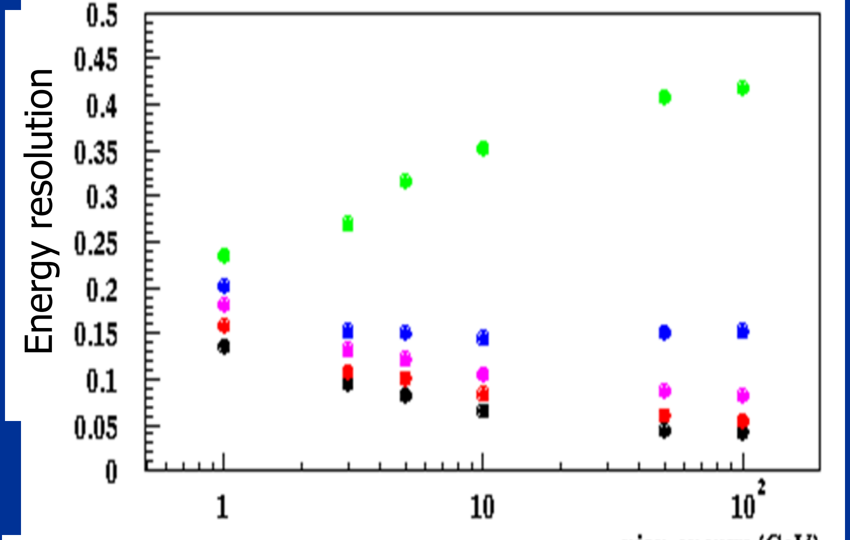
  How narrow could be the signal integration window in a hadron calorimeter in order to preserve energy resolution?

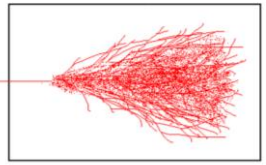
- **Energy integration window starts when the pion hits the absorber and ends at the time specified on the plots**

- **For short integration windows only small initial part of the shower development is integrated**
  - **Even for infinite integration window there is "undetected" energy due to nuclear fragments and escaping neutrons/neutrinos**

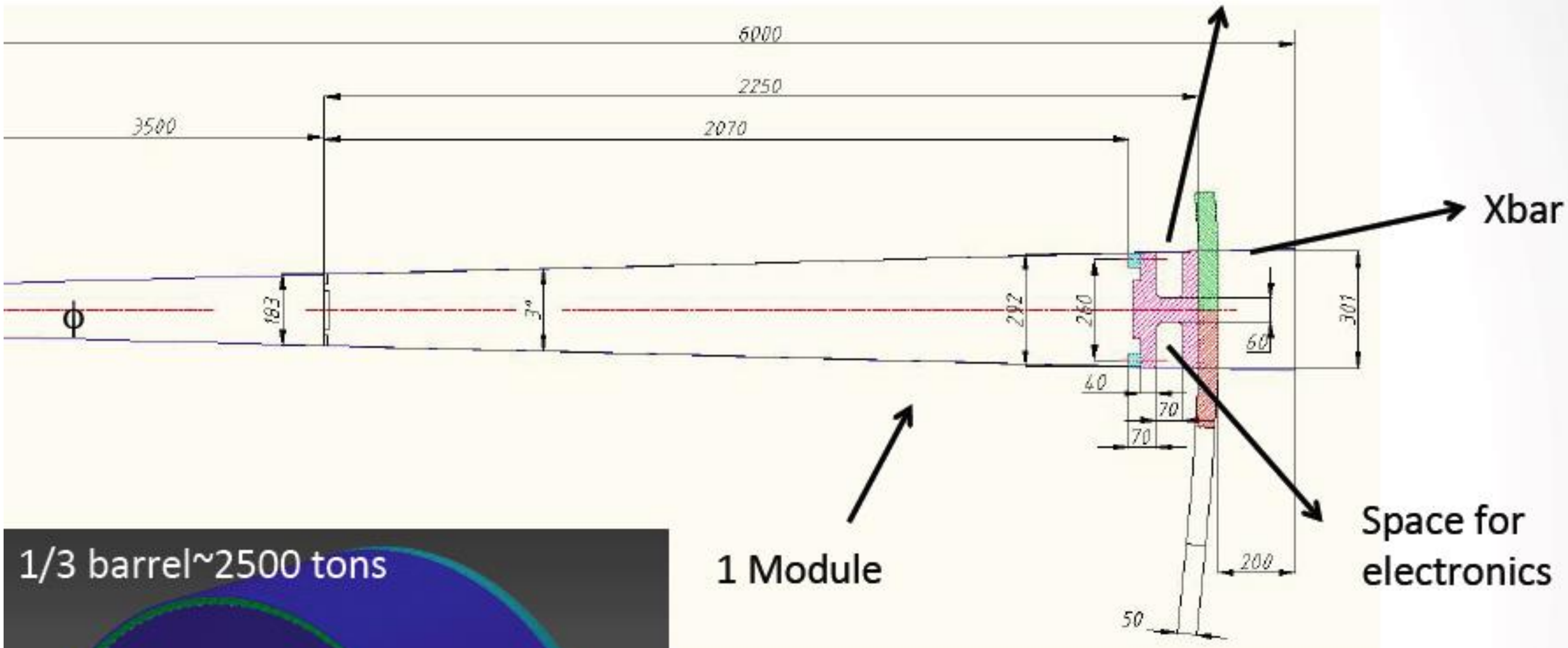
- **For the integration times below 3 ns energy resolution defined as RMS of the integrated energy over the pion initial energy deteriorates significantly**
  - **For the integration times of ~5 ns and above the energy resolution is comparable to the ideal**

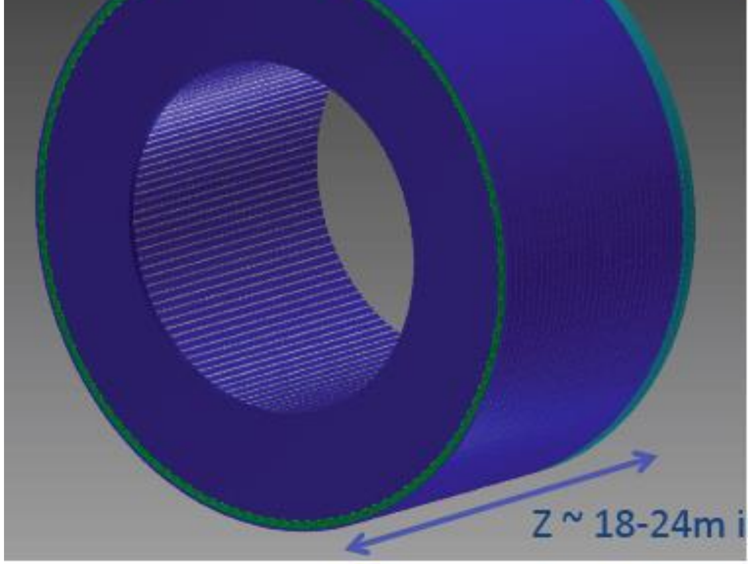






HCAL Studies

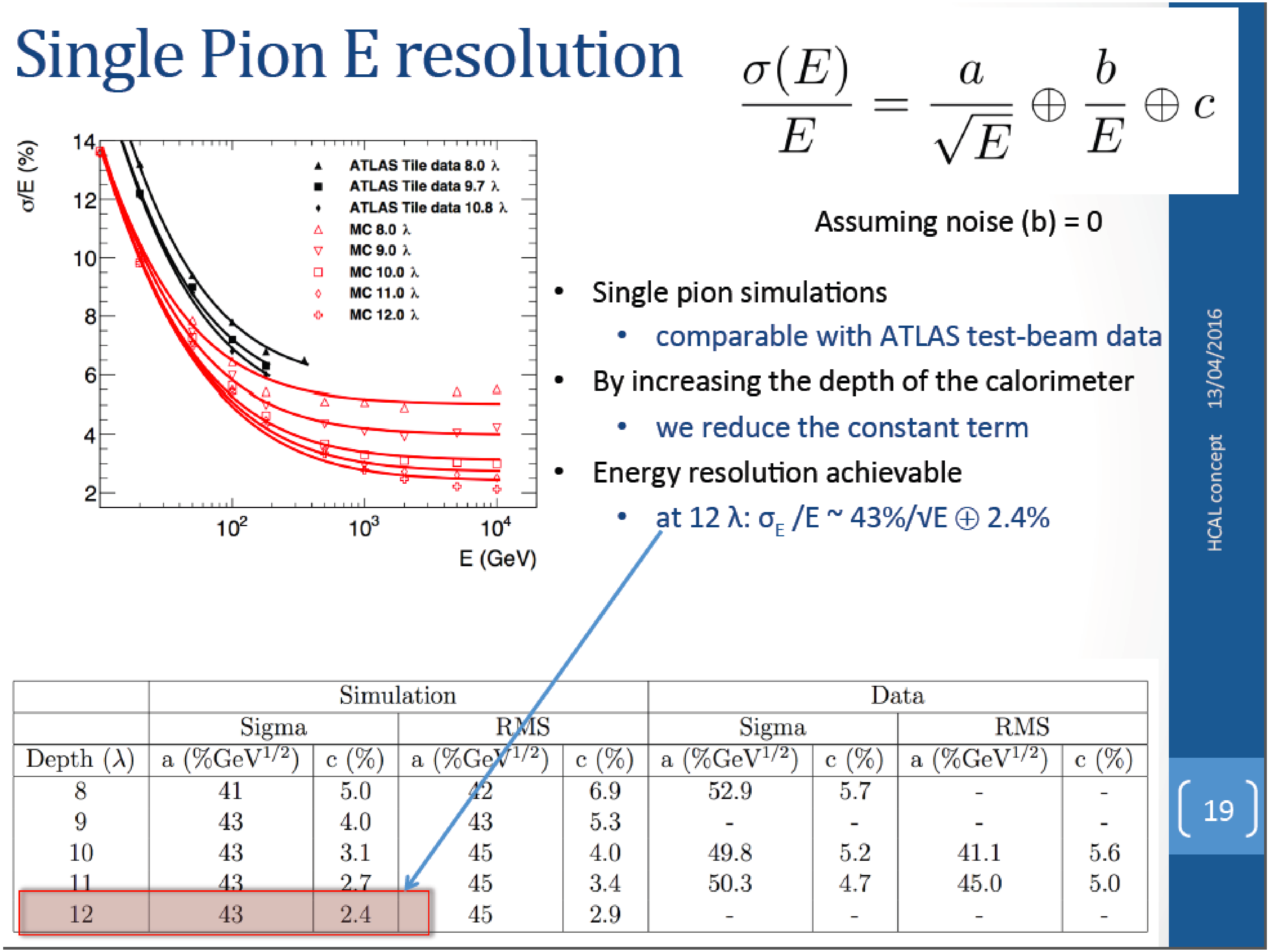




- 120 modules in ϕ,
  ~2 times better than ATLAS
- Depth active cells
  ~10λ -> ~2m (+29% than ATLAS)

Clement Helsens

Calorimeter Studies



Single Pion E resolution

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Assuming noise (b) = 0

- Single pion simulations
  - comparable with ATLAS test-beam data
- By increasing the depth of the calorimeter
  - we reduce the constant term
- Energy resolution achievable
  - at 12 λ: σ_E /E ~ 43%/√E ⊕ 2.4%

	Simulation				Data			
	Sigma		RMS		Sigma		RMS	
Depth (λ)	a (%GeV$^{1/2}$)	c (%)	a (%GeV$^{1/2}$)	c (%)	a (%GeV$^{1/2}$)	c (%)	a (%GeV$^{1/2}$)	c (%)
8	41	5.0	42	6.9	52.9	5.7	-	-
9	43	4.0	43	5.3	-	-	-	-
10	43	3.1	45	4.0	49.8	5.2	41.1	5.6
11	43	2.7	45	3.4	50.3	4.7	45.0	5.0
12	43	2.4	45	2.9	-	-	-	-

Clement Helsens

Requirements for EM Calorimeters

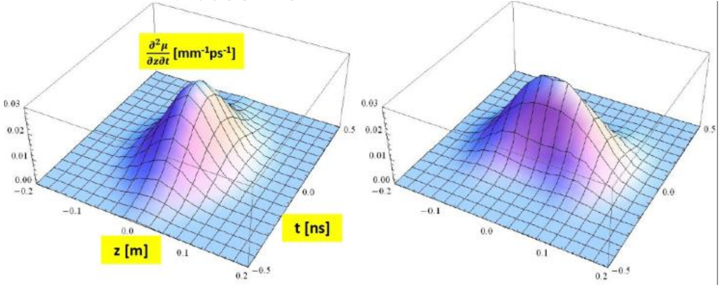
Timing information – additional information for pile-up rejection

Vertices distributed in z-position and time

- For pile-up μ ≥ 200 vertex density ≥ 1 vertex / mm (depending on bunch crossing concept, e.g. crab-crossing, crab-kissing, …)
  - → **Vertex merging**
  - → **Timing information could be used for vertex determination**

S. Fartoukh, <μ> ≈ 140

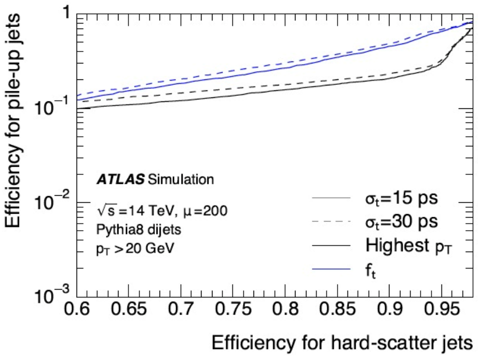
HL-LHC baseline



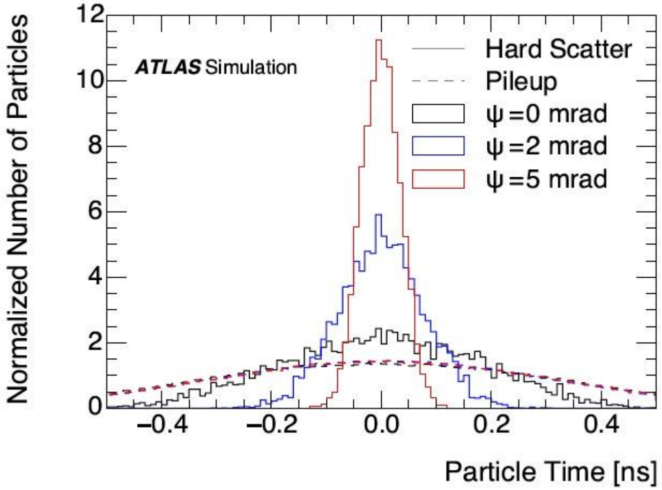
crab-crossing crab-kissing

Timing information can be used to help pile-up rejection in the calorimeters

- **Ideas in CMS and ATLAS for HL-LHC**
  - → If primary vertex is known, timing can be used to reject energy deposits from pile-up vertices
  - → Depends on bunch-crossing concept, first studies for HL-LHC

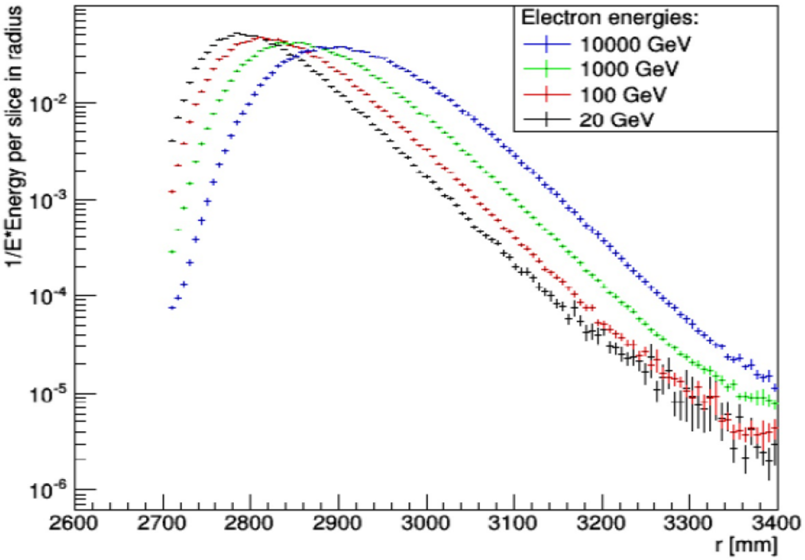


Performance with crab-kissing

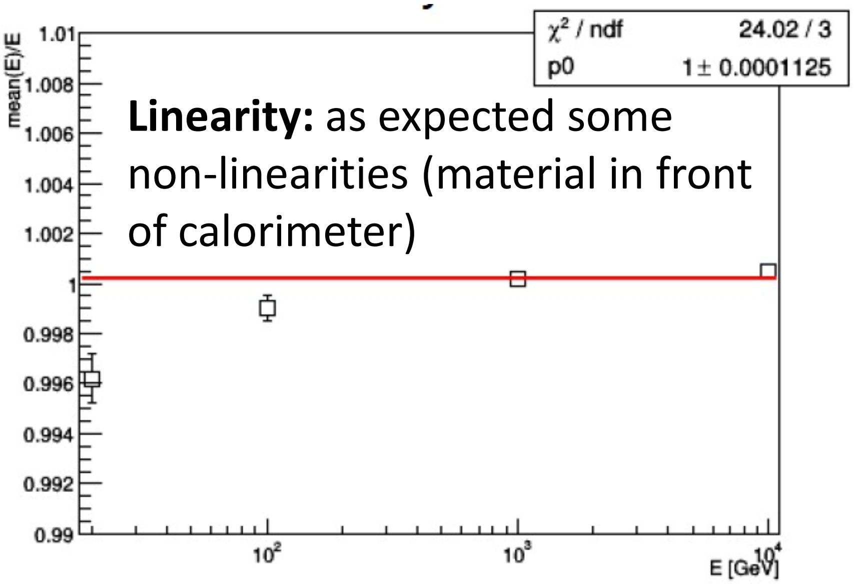


Martin Aleksa

First Tests of EM Calo in FCC SW

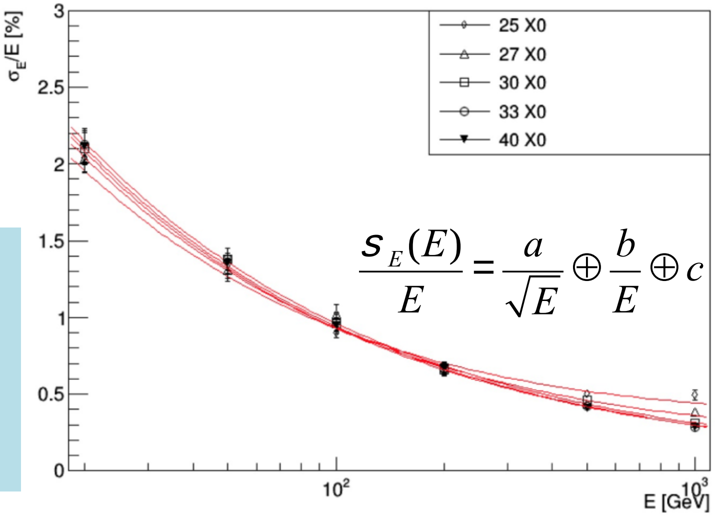


Longitudinal energy profiles of single electrons (η=0.25)



Linearity: as expected some non-linearities (material in front of calorimeter)

J. Faltova: see talk in last FCC-hh detector meeting



$$\frac{s_E(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Energy resolution

E-resolution e⁻ without magnetic field

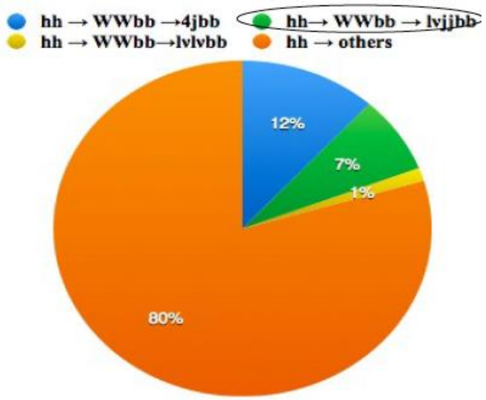
- sampling term *a*=9.2%
- perfect geometry, no noise
- expect *b*=0,
- *c* very small (only leakage), here 0 to 0.4% depending on depth

Encouraging first results with simple test-geometry in FCC SW

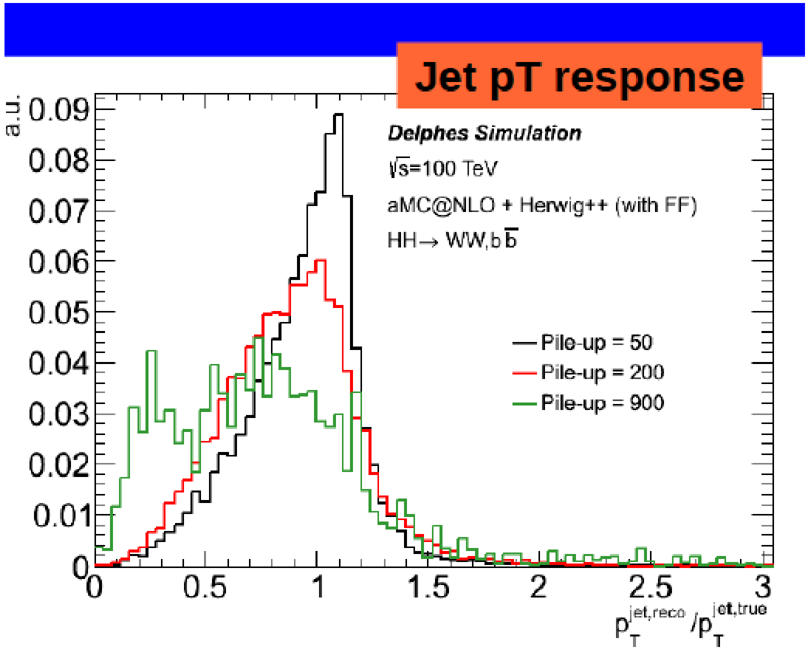
- Studies can now start!

Martin Aleksa

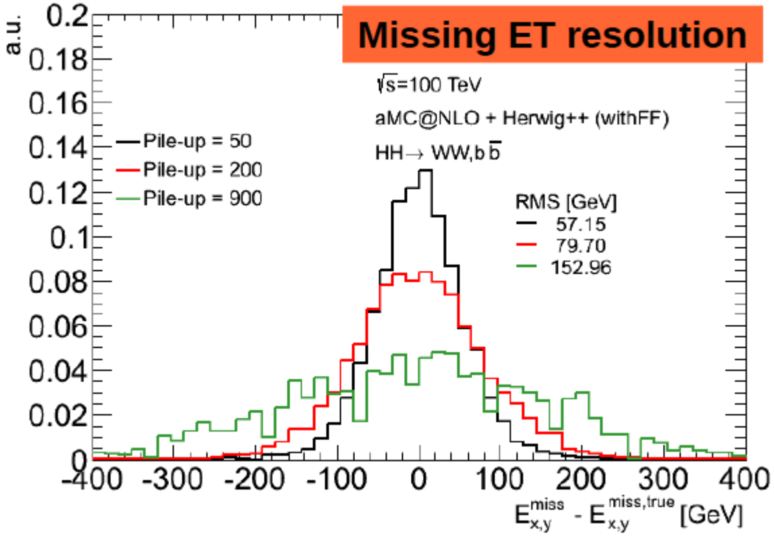
Study of hh production in the WWbb channel at the FCC-hh



Jet pT response



Missing ET resolution



Marianna Testa

Common Software

Status of the Software Project

- Aim of the Software Project is to **support all of hh/ee/eh studies**
  - Need to support multiple detectors in simulation and reconstruction
  - Need to support simulation in different levels of details
- Since FCC Week 2015 plenty of work finished
  - Most of the progress up to our highly motivated students!
- Simulation
  - **Delphes** integrated and **ready to use**
  - Technical infrastructure for combined **fast/full simulation with Geant4** in place
- Reconstruction
  - Joint project with ATLAS to apply their track reconstruction software (**ACTS**)
  - **PAPAS** for fast simulation and particle-flow reconstruction
- Analysis
  - Standalone reader for FCC data model
  - **Heppy** as python-based analysis framework
  - Both can be installed on your laptop!
- **For details see other presentations in this session**

FCC Software in the HEP SW Landscape

- We do not have resources to do everything by ourselves
  - Whenever there is something (almost) ready to use ⇒ take advantage of the work others do!
- Our software is based on the following external software
  - **Gaudi** as underlying framework
  - **Delphes** for parameterized simulation
  - **Geant4** for simulation
  - **DD4hep** for detector description
- Collaborating with
  - ATLAS on tracking
  - CMS on analysis interface
  - LHCb on simulation framework and infrastructure
  - CLIC on grid processing (planned)
  - **Surprisingly successful cooperation within HEP SW community**
- We are as well contributing to the HEP Software with our additions
  - **Heppy and PAPAS** as integrated Python-solution
  - **PODIO** for data models

Benedikt Hegner

FCC Tracking

FCC should profit from already existing software – well tested and used in running experiments

=> using the ACTS - A(TLAS) Common Tracking Software package for tracking

https://gitlab.cern.ch/acts/a-common-tracking-sw

- Encapsulation of the ATLAS tracking software Code
  - updated to new coding standards
  - prepared for concurrent use (GaudiHive)

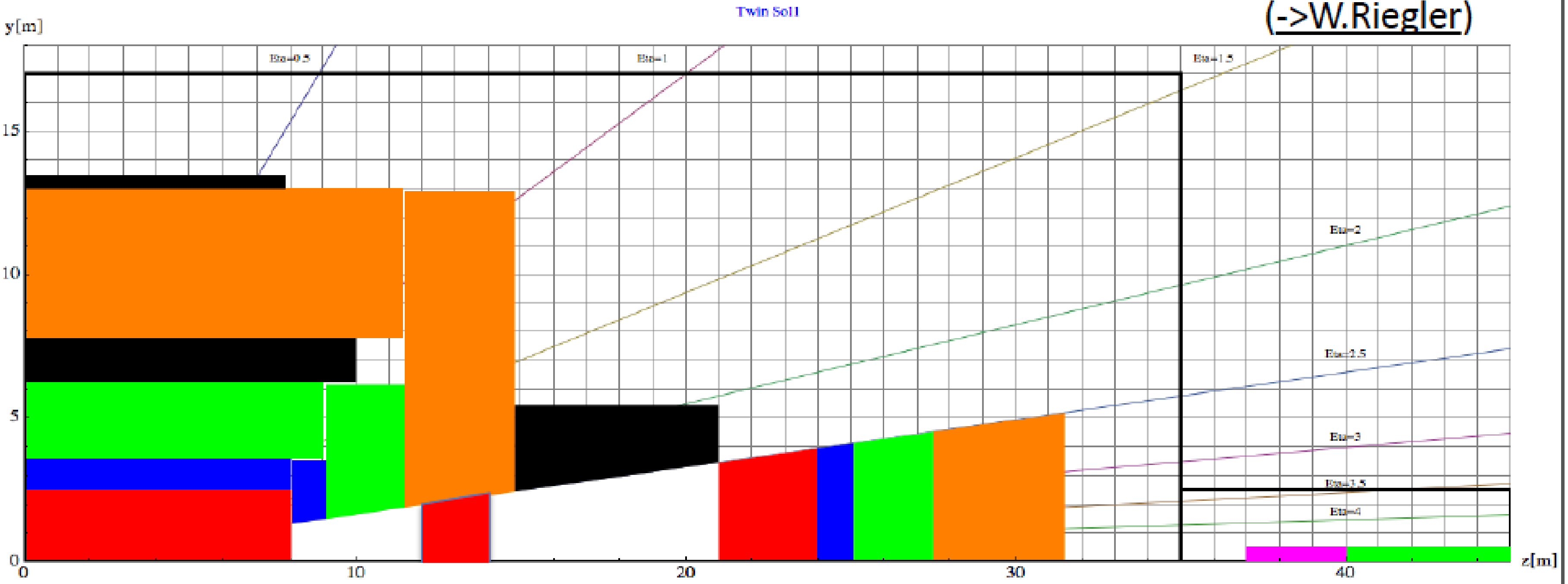
- Common tracking software toolkit useable in various applications
  - ATLAS Run3
  - FCC
  - Machine Learning Challenge 2016

Julia Hrdinka

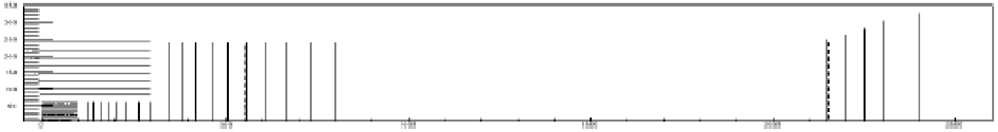
FCC-hh Detector Design

with forward detectors

(->W.Riegler)



DD4hep



ACTS – Fast simulation

GEANT4
FULL AND FAST
SIMULATION FRAMEWORK

What can you do now...

- run Geant4 full simulation in the common software framework FCCSW
- create geometry (and sensitive detectors) in DD4hep
- run fast simulation in tracker using simple resolutions or resolutions obtained with tkLayout
- mix fast & full simulation

Currently validating...

- fast simulation for calorimeters (GFlash)

Future

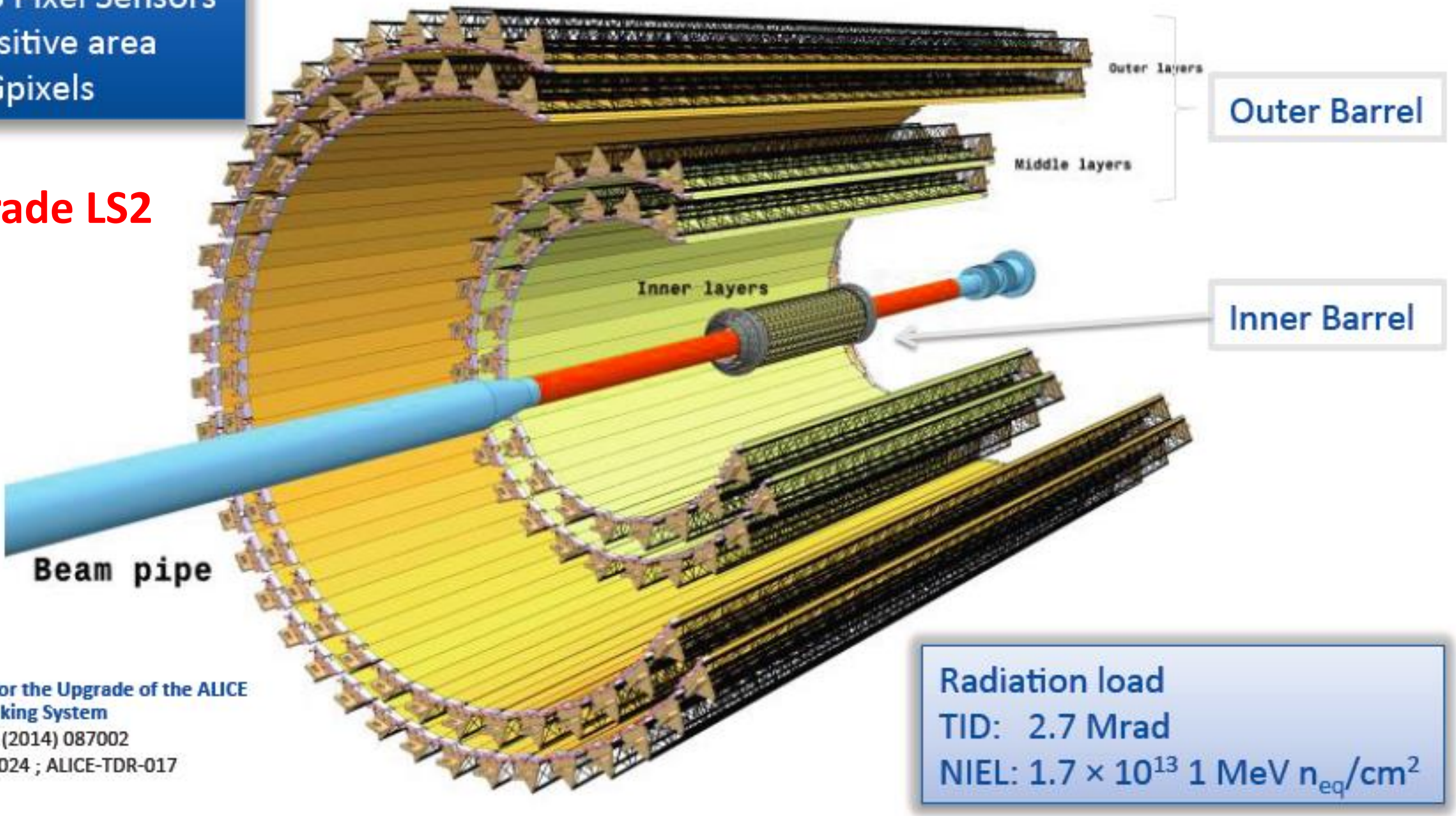
- fast simulation in tracker using resolutions obtained from full simulation
- frozen showers
- use the output tracks and calorimeter hits in the higher-level reconstruction algorithms, e.g. particle flow, jet clustering, b tagging

Common Detector Technologies

Monolithic Active Pixel Sensors (MAPS)

~24000 CMOS Pixel Sensors
10 m^2 sensitive area
12.5 Gpixels

ALICE upgrade LS2



Technical Design Report for the Upgrade of the ALICE Inner Tracking System
J. Phys. G 41 (2014) 087002
CERN-LHCC-2013-024 ; ALICE-TDR-017

Radiation load
TID: 2.7 Mrad
NIEL: 1.7×10^{13} 1 MeV n_{eq}/cm^2

Barrel geometry

3 Inner Barrel layers (IB) 0.3% X_0
4 Outer Barrel layers (OB) 1% X_0

Coverage

23 mm < r < 400 mm, $|\eta| < 1.22$
Layers z-lengths: 27 - 150 cm

Comments on Future of MAPS

Readout circuits are already fabricated in CMOS commercial technologies, but CMOS now offers high volume, low cost production capability also for the sensor, including wafer scale integration, ideally integrating both readout and sensor.

HL-LHC 3ab^{-1} and FCC 3ab^{-1} comparable and more or less compatible with existing radiation tolerance results, FCC 30ab^{-1} still far out:

- Transistor radiation tolerance is quite good for large transistors, but technology and bias dependent effects in transistors close to minimum size require extensive verification and measurement campaigns
- Sensor radiation tolerance requires thin sensitive layers and further optimization of the sensor capacitance for low analog power. For monolithic sensors the challenge is to combine low capacitance with depletion of the sensitive layer and a large drift field to collect the signal fast. We are not yet there but several developments are ongoing and significant progress is being made.

walter.snoeys@cern.ch

Comments on Future of MAPS

Optimization of power consumption will be essential to profit from single point resolutions of 5 µm or even better, which can be achieved even on thin sensitive layers:

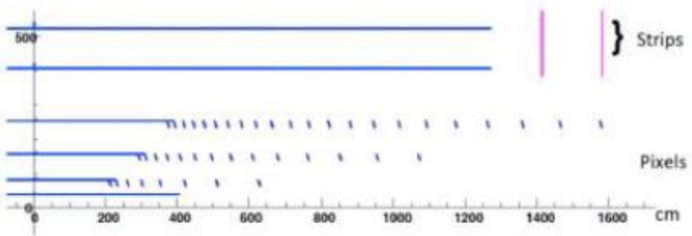
- Thin layers to contain sensor leakage
- Low C to reduce or eliminate analog power (C < 1fF ?)
- No clock distribution and special hit-driven architectures for low digital power
- Efficient data transmission

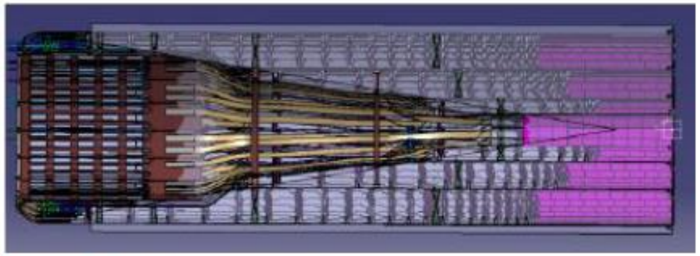
Monolithic CMOS detectors (or advanced hybrid) offering low mass, high granularity, low cost wafer-scale integration, are an excellent candidate for FCC.

Making significant progress on this in advanced CMOS technologies requires sufficient funding for submissions in the R&D phase.

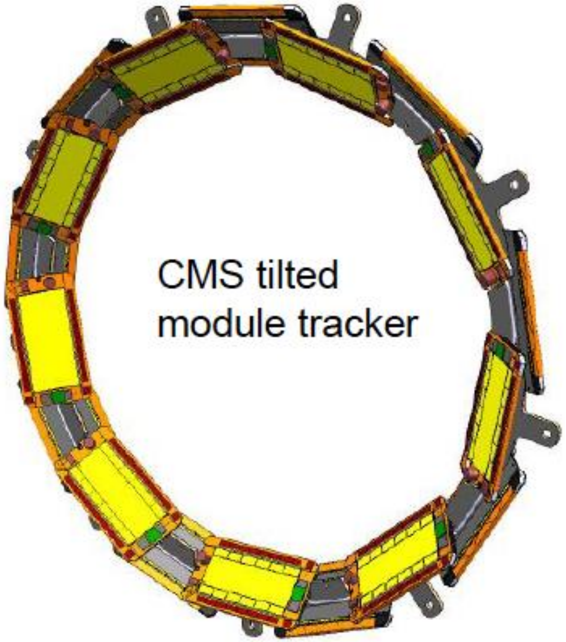
Did not mention many developments, like LGAD, DEPFET, etc

Tracker Mechanics



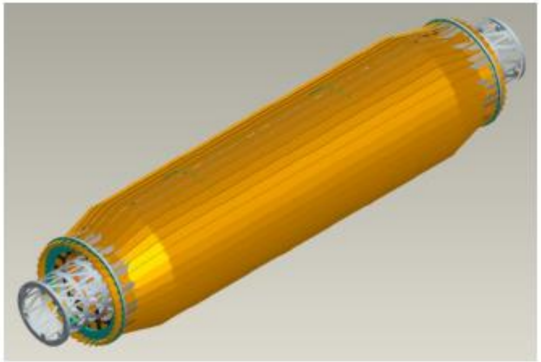


ATLAS Alpine pixels



CMS tilted module tracker

15



ATLAS I-beams with tilted ends

We should study alternatives to the traditional tracker layouts.

Georg Viehhauser

Q: 'Can we build an FCC-hh GPD with triggerless readout?'

- A: 'No'
  - Recording the full data stream is inconceivable even in 203x
  - But 'trigger' may mean something different to today

- First rough estimates (within factor of two)
  - Tracking and calo *each* have raw data rates of ~2000TB/s
  - Using 10Gb/s modularity links, this is 4M optical fibres
    - Also implies an event-building network of 40Pb/s capacity

- For comparison:
  - 'Entire internet WAN' today is ~500Tb/s; largest Google data centre is ~1Pb/s

- A very scary number, even for 2035, but perhaps not impossible

Dave Newbold

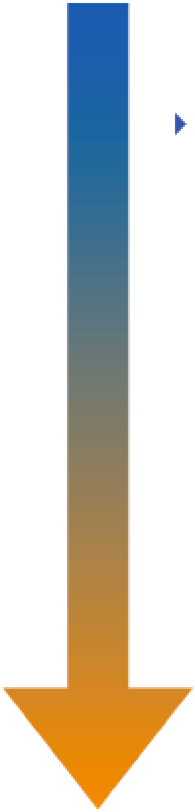
Technology Issues

- How much power do rad-hard data links take?
  - 'Best in class' *today* seems to be lpGBT at ~500mW for 5Gb/s (plus laser)
    - If no progress on this, indicates a power budget of 2MW for links alone – infeasible
  - There are no commercial applications for these links, so no COTS
  - Technology will improve, but there are some fundamental limits
    - New ideas for power saving are coming forward, but may not be applicable for us
- What are the limits?
  - Electrical signalling places a fundamental limit of ~10mW per link
    - But Shannon's limit also mandates a move to PAM / FEC → more tx and rx power
    - ~10mW for 5Gb/s in lab with 'fancy technology' (high mass, expensive, not rad hard)
  - Reducing to this level would require substantial investment in R&D
    - Not clear when / if we will have access to the required technology nodes
  - The real limit is likely to be cost
    - Also bearing in mind that COTS rx ports are ~$100, and not decreasing
    - This implies aggregation onto fast (100Gb/s+) fibres from lower speed local links
- Cost & power budget of on-detector electronics is *the* problem

Dave Newbold

Possible Approaches

- ‘Conventional trigger’
  - Extreme processor performance
  - On-detector primitives logic
  - On-detector front end buffers
  - Emphasis on on-detector processing



- ‘Sequential readout’
  - Stage out event to multi-level trigger
  - Successive levels of details with time
  - All data through event-builder network
  - Trigger implemented in software
  - Implement large ‘bulk memory’ in low radiation zone of detector
  - Emphasis on on-detector buffer

- ‘Triggerless’
  - Massive bandwidth
  - Little on-detector logic
  - Small front end buffers
  - Emphasis on data transmission

Dave Newbold

Wireless readout

MULTI-GIGABIT WIRELESS DATA TRANSFER USING THE 60 GHZ BAND

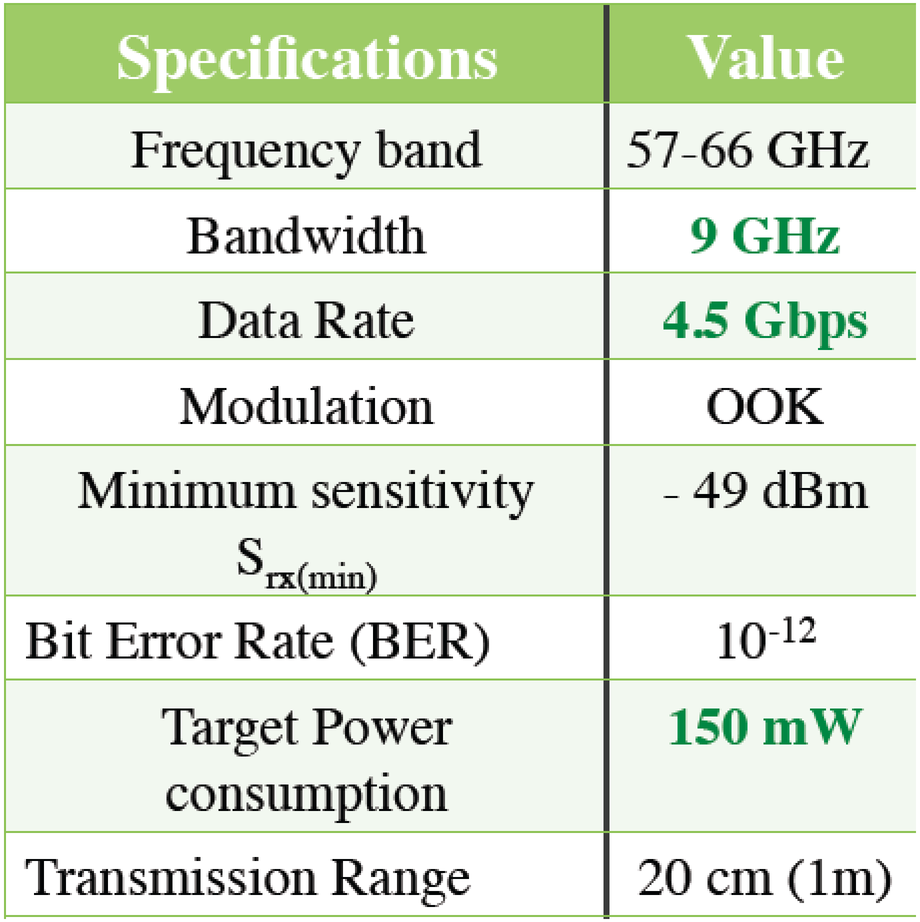
Hans Kristian Soltveit

On behave of the WADAPT Working Group

Wireless Allowing Data And Power Transmission

FCC-Week Rome 14-04-2016

Wireless Data Transmission



Specifications	Value
Frequency band	57-66 GHz
Bandwidth	**9 GHz**
Data Rate	**4.5 Gbps**
Modulation	OOK
Minimum sensitivity $S_{rx(min)}$	- 49 dBm
Bit Error Rate (BER)	10^{-12}
Target Power consumption	**150 mW**
Transmission Range	20 cm (1m)

Power consumption less than GBT, still similar order of magnitude.

Many practical implementation issues to be overcome.

Very promising.

Hans Kristian Soltveit

Concluding Remarks

A lot of of progress since the last FCC week.

A few reality checks required rescaling of some ‘dimensions’.

The FCC hadron detector studies can heavily draw from the LHC experiments and their upgrade plans.

It is very important to plant the thinking about pp physics at 100TeV into the heads of people who work on the 14TeV physics analysis.

The FCC hadron detectors require significant R&D on detectors and electronics. Once the LHC Phase II R&D is finished, which is soon, we must install dedicated R&D programs.

Access to state of the art electronics processes for readout electronics and sensor (e.g. MAPS) is very expensive, so this R&D will require significant funding.

The FCC project is an excellent environment to transfer the vast amount of knowledge and experience in the field to the young generation.