ECFA Detector R&D
TF6
-
Calorimetry

Roberto Ferrari
Tommaso Tabarelli de Fatis

Discussione Roadmap
17 marzo 2021

TF6 Composition

Convenors:

- Roberto Ferrari (INFN Pavia)
- Roman Poeschl (IN2P3-IJCLab)

Expert members:

- Martin Aleksa (CERN)
- Dave Barney (CERN)
- Frank Simon (MPP Munich)
- Tommaso Tabarelli de Fatis (INFN & Univ. MiB)

TF6 Mandate

Calorimetry:

Not technology driven

Must cover system aspects

Short-, Mid-, Long- (Very Long-) term vision

TF6 Symposium

Date:

7 May 2021

Agenda:

https://indico.cern.ch/event/999820/

TF6 Symposium (2)

ECFA Detector R&D Roadmap Symposium of Task Force 6 Calorimetry

Friday 7 May 2021, 09:00 → 18:00 Europe/Zurich

Roberto Ferrari (Universita and INFN (IT)) , Roberto Ferrari (INFN Pavia (IT)) , Roman Poeschl (Université Paris-Saclay (FR))

Description Details about the ECFA Detector R&D Roadmap can be found on: https://indico.cern.ch/e/ECFADetectorRDRoadmap

09:00	→ 09:30	**Introduction** **Speakers**: Roberto Ferrari (INFN Pavia (IT)) , Roman Poeschl (Université Paris-Saclay (FR))	30m
09:30	→ 10:10	**Lessons learned from HL-LHC** **Speaker**: David Barney (CERN)	40m
10:10	→ 10:45	**Si based highly and ultra-highly granular calorimeters** **Speaker**: Vincent Boudry (LLR – CNRS, École polytechnique, Institut Polytechnique de Paris)	35m
10:45	→ 11:00	**Coffee break**	15m
11:00	→ 11:35	**Future Noble Liquid Systems** **Speaker**: Brieuc Francois (CERN)	35m
11:35	→ 11:55	**Gaseous calorimeters** **Speaker**: Maria Fouz Iglesias (Centro de Investigaciones Energéti cas Medioambientales y Tecno)	20m
11:55	→ 12:30	**Tile and strip calorimeters** **Speaker**: Katja Kruger (Deutsches Elektronen-Synchrotron (DE))	35m
12:30	→ 12:45	**Discussion and spillover**	15m
12:45	→ 13:45	**Lunch break**	1h

TF6 Symposium (3)

12:45 → 13:45	**Lunch break**	1h	
13:45 → 14:20	**Crystal calorimetry** **Speaker**: Marco Toliman Lucchini (Princeton University (US))	35m	
14:20 → 14:55	**R&D for Dual-Readout fibre-sampling calorimetry** **Speakers**: Gabriella Gaudio (Dipartimento di Fisica Nucleare e Teorica) , Gabriella Gaudio (INFN-Pavia)	35m	
14:55 → 15:30	**Compact and high performant readout systems** **Speaker**: André David (CERN)	35m	
15:30 → 15:45	**Coffee break**	15m	
15:45 → 16:20	**Precision timing and their applications in calorimetry** **Speaker**: Nural Akchurin (Texas Tech University (US))	35m	
16:20 → 16:45	**Wrap up and the way ahead** **Speakers**: Roberto Ferrari (INFN Pavia (IT)) , Roman Poeschl (Université Paris-Saclay (FR))	25m	

Process

Set of guidelines ready (as in backup slides)

Prepared sharepoint for interacting with speakers

Speakers responsible for collecting information/input from the community, nevertheless verify is happening

Two preparation meetings:

1st (~beginning of April) - check flow of information, spot problems, first pass of coordination

2nd - for each talk, discuss bulleted list of contents, check overlap, uncovered issues, ...

What the target ?

DOE – Basic Research Needs for Detector R&D

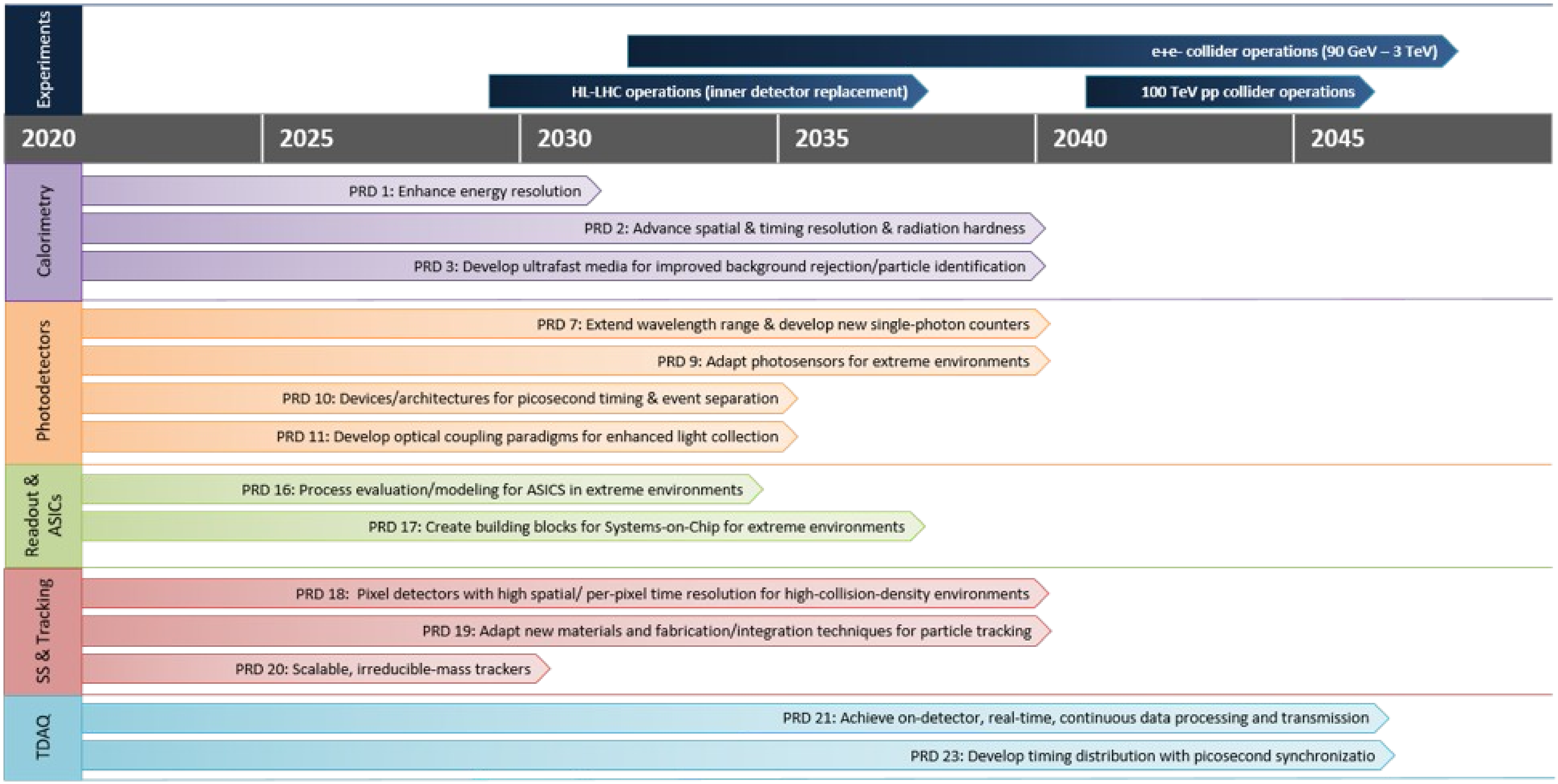


Figure IV: Higgs and Energy Frontier Timeline

Higgs and Energy Frontier Timeline

Few main pillars

Improve:

Energy resolution(s) for precision EWK mass and missing-energy measurements (PRD 1)

$\longrightarrow$ new materials

$\longrightarrow$ PFA and dual-readout

High spatial granularity + timing and radiation hardness for high-rate environments (PRD 2)

Bkg rejection and PID with new ultrafast media (PRD 3)

not so much surprising …

not so much surprising …

you wonna:

not so much surprising …

you wonna:

highly granular
highly precise
highly resistant
high-speed

detectors

Input sessions on future facilities

Input sessions on future facilities

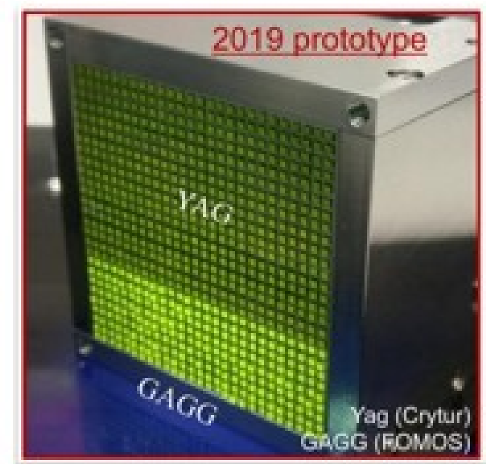
High-resolution timing common issue followed by high granularity and radiation resistance

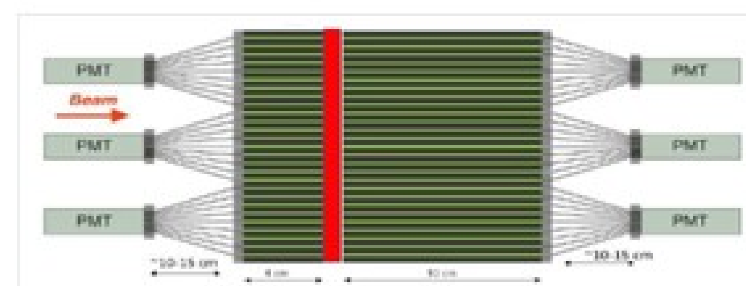
HL-LHC (LHCb)

TF6: Calorimetry

LHCb Upgrade II : Electromagnetic Calorimetry

- Increased interest in ECAL: LFU, electrons, π^0, radiative decays
- Requirements:
  - Radiation regions: 1MGy, 200kGy, < 10kGy
  - Energy Resolution: $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
  - Timing capabilities: O(10)ps for pile-up mitigation
- R&D: SPACAL, Shashlik with timing
  - Crystal Scintillator, Tungsten absorber
  - Polystyrene fibres, Lead absorber
- Timing Layer
  - i-MCP layer for 10-20ps, Si layer ?





Chris Parkes, ECFA R&D Roadmap, February 2021 17

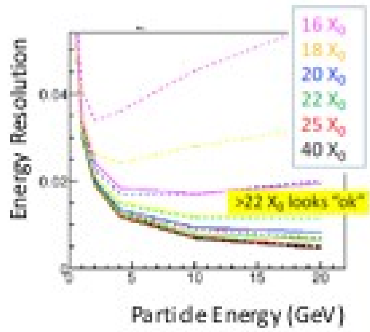
Shashlik technology with doped crystal fibres
Rad-hard materials for fast timing
Fast and rad-hard SiPMs

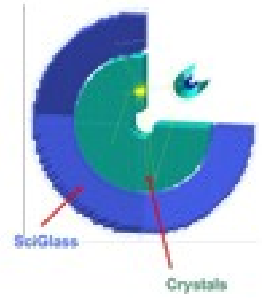
EIC – ECal

Backward arm

High-resolution important in region -4 < η < -2

- Determines electron kinematics
- Physics requires ~2%/ /√ E
- Particle E: ~0.02 – 18 GeV





Outer part alternatives
- Pb/Sc, W/Sc Shashlik
- W poweder/ScFi Sampling

REFERENCE
$PbWO_4$ crystals (inner)
- Compact, radiation hard, luminiscence yield to achieve high energy resolution, including the lowest photon energies

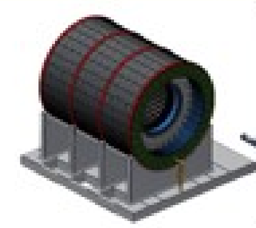
SciGlass (Outer)
- EIC eRD51
- More cost efficient, easier manufacturing
- Potentially better optical properties

Sensor: SiPMs (TBC)

Barrel

Physics requires 10-12%/√ E in region -1 < η < 1
- Particle E: ~0.1 – 35 GeV

REFERENCE
Pb/Sc, W/Sc Shashlik
- Pb, W absorber g high density absorber can provide 8-15%/√ E, energy resolution can be tuned by adjusting sampling fraction and frequency



W poweder/SciFi
- Compact, resolution 12-14%/ √ E

Higher resolution
- $PbWO_4$, SciGlass

Forward arm

Physics requires 10%/√ E in region 1 < η < 4
- Particle E: ~0.5 – 100 GeV • High Q^2/high x

Pb/Shashlik, W/Sc Shashlik
SciGlass

REFERENCE
W poweder/ScFi
- Absorber: tungsten powder matrix with embedded scintillating fibers (0.5mm diameter).
- Modules can be made 2D projective
- Readout with light guides and SiPMs

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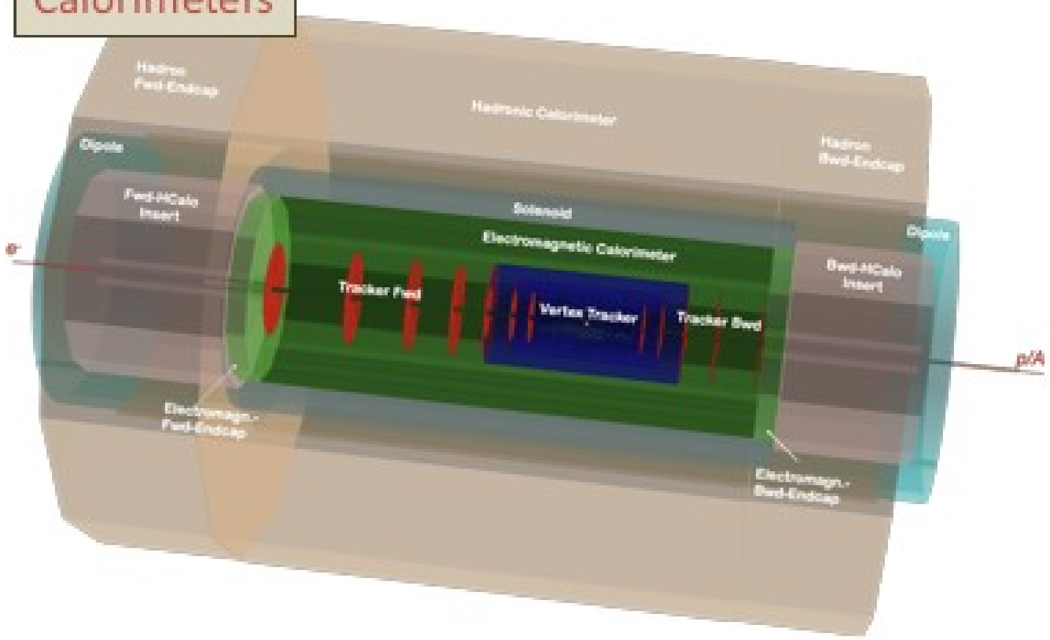
Different options for different regions:
crystals ($PbWO_4$), Pb/scint or W/scint Shashlik

High-res important in backward arm

LHeC

LHeC – The Large Hadron-Electron Collider at the HL-LHC

Calorimeters



- Complete coverage: $-5 < \eta < +5.5$
- Forward Region: dense, high density jets of few TeV
- Backward Region: in DIS only deposit of $E < E_e$
- Calorimeter depth
  - ECAL: 30 X_0 barrel & backward, ~ $50X_0$ forward
  - HCAL: 7.1-9.3 Λ_I barrel & backward; 9.2-9.6 Λ_I forward
- Detector technologies (ala ATLAS):
  - ECal: Pb/LAr with accordeon geometry
  - HCAL: Pb/Scintillating tiles
  - Alternative: ECAL: Pb/Scintillator ⇨ eliminate cryogenics

Barrel Calorimeters

Calo (LHeC)		EMC	HCAL		
		Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber		Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers		38	58	45	50
Integral Absorber Thickness	[cm]	16.7	134.0	119.0	115.5
η_{max}; η_{min}		2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$	[%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0		$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci	[m^2]	1174	1403	3853	1209

Forward/Backward Calorimeters

Calo (LHeC)		FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber		Si,W	Si,W	Si,Pb	Si,Cu
Layers		300	49	49	165
Integral Absorber Thickness	[cm]	156.0	17.0	17.1	137.5
η_{max}; η_{min}		5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$	[%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0		$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si	[m^2]	1354	187	187	745

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CDR-2020 (arXiv:2007:14491), tables 12.3 and 12.4

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Technologies: ECal: Pb/LAr (or Pb/scint) - HCal: Pb/scint

FCC-eh

FCC-eh – The Large Hadron-Electron Collider at the FCC

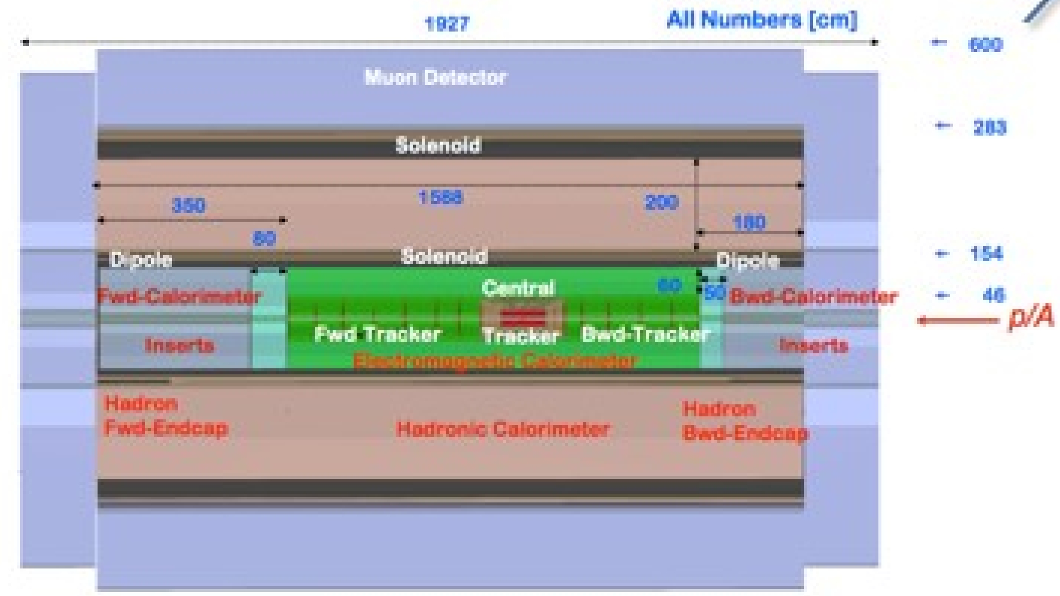
FCC-eh – The Large Hadron-Electron Collider at the FCC

Similar schemes in collision with protons of 7 TeV (LHeC), 13 TeV (HE-LHeC) and 50 TeV (FCC-eh)

Detector scales in size by up to ln (50/7) ~2

Double Solenoid + Dipole

Even larger tracking region to retain 1° performance



R&D Needs for LHeC and FCC-eh

- Current (baseline) proposal based on detecor technologies for HL-LHC and FCC-hh ⇨ no (need for) dedicated R&D
- **Detector performance/cost optimization will benefit singificantly from R&D in several areas:**
  - High-resolution, low-power MAPS for vertex and inner tracking layers (**low radiation envinronment**)
  - Low-power & low(er) cost silicon sensors and module assembly for (large surface) outer tracker
  - Progress on ECal technologies, in particular remove need for cryogenics
  - R&D on thin magnet technologies

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Conclusions on e-h detectors

(Luciano Musa)

High-precision calorimetry

• High-resolution ECal typically requires crystals such as Lead Tungstate ($PbWO_4$)

• Crystals are expensive, few vendors, QA issues, moderate production capacity, raw material shortage

→ R&D on scintillating glasses and other materials

Fixed target experiments

NA61 / CERN

Beam position detectors

NA61/SHINE, as a fixed target experiment, has to monitor the beam's interaction point with the target. This required direct position measurement of each beam particle.

- Detector/detectors should work with beams from p to Pb beams.
- The detector should determine the position of the X and Y hit of each beam particle (probability of pileup should be minimized).
- The accuracy of the position measurement is expected to be better than 250 micrometers.
- The detector should be installed in a vacuum.
- Material on the beamline should be minimized.
- Large active area for low energy beams.

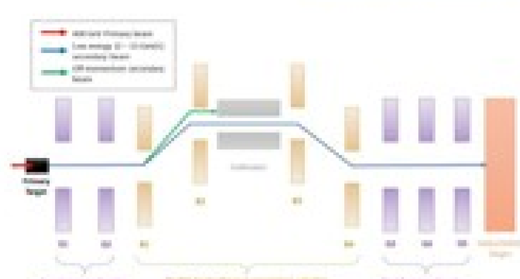
Need for beam detectors with a time resolution better than 40 *ps* for particle mass measurements at low beam momenta

TF3, TF4, TF7

Very Low Energy Beamline

All of the interested physics communities (accelerator-based neutrino, atmospheric neutrino, and spallation source experiments) have strongly requested studying and building a Very Low Energy (VLE) beamline.

- Taking into account the community's request, NA61/SHINE with the strong support of EN-EA experts, will therefore aim to construct the VLE beamline



Future calorimeter

TF4, TF6, TF7

- Recently used calorimeters have to have a hole for ion beams due to limited radiation hardness.
- Hole in the calorimeter acceptance limits acceptance of projectiles and complicated determination of the centrality of the collision.
- Development of radiation hard (Pb beam at 158*A* GeV/c with intensity up to 100 kHz) compensating calorimeters.

Low Energy Ion Beam

Improvement in the ion beams' quality at low momenta (below 40AGeV/c)

- An improvement of the ion emittance from the machine would be necessary, but this seems to require studies from the machine side to understand the possibilities that can be made available for that.
- Beam quality could be improved by the **implementation of Gabor-Lenses** (GL) into the existing beamline. Therefore, experiments are planned to test to what extent the luminosity can be improved using this type of lens. Gabor-Lenses use a static confined electron column for the focusing and manipulation of positively charged particle beams.

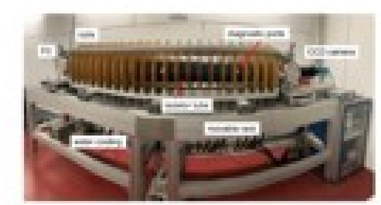


Figure 25: Gabor-lens prototype GL2000 on its test bench at Goethe-University Frankfurt. It is equipped with several diagnostic tools to characterize the properties of the confined electron column.

19.02.2021 R&D | Strong Interaction | Fixed Target | J. Bernhard 21

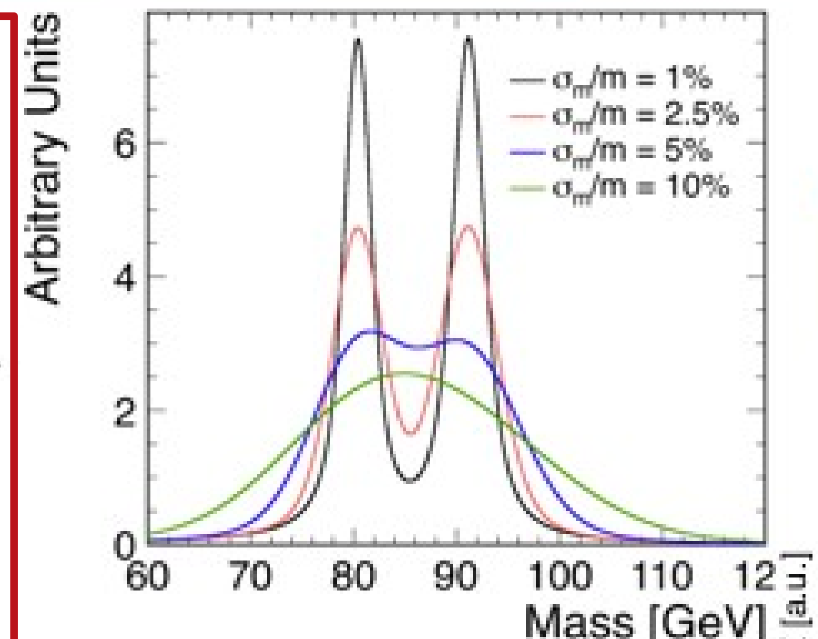
Development of rad-hard compensating calorimeters

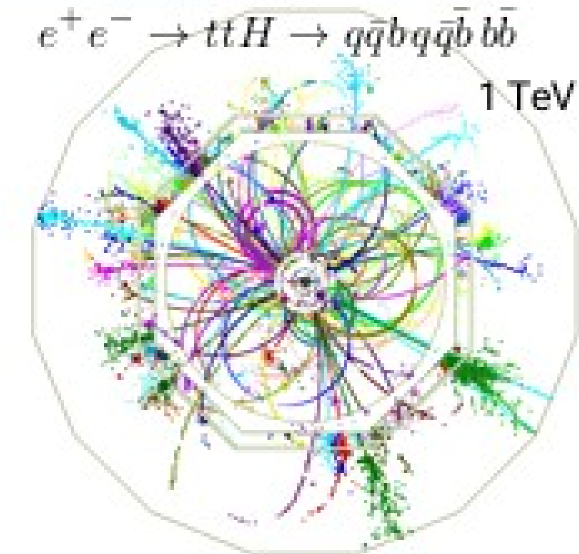
Linear Colliders

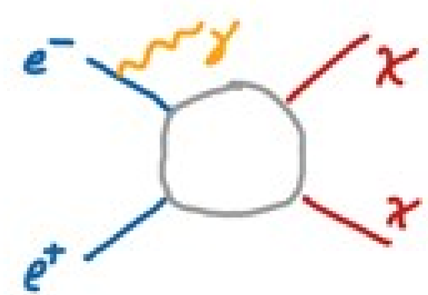
Detector Performance Goals - Jets, Photons, PID

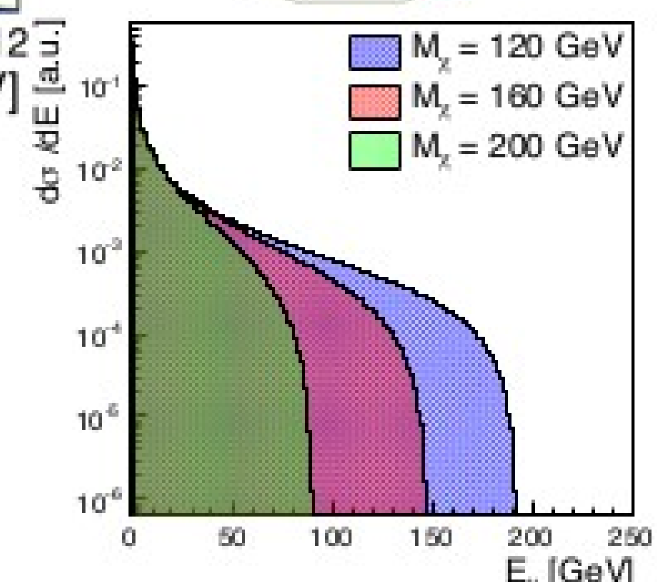
Motivated by key physics signatures

- ***Jet energy resolution***
  Recoil measurements with hadronic Z decays, separation of W, Z, H bosons, …
  $\sigma(E_{jet})$ / E_{jet} ~ 3% - 5% **for E_{jet} > 45 GeV**
  reconstruction of complex multi-jet final states.
- ***Photons***
  Resolution not in the focus: ~ 15 - 20%/√E
  Worth another look ?
  Coverage to 100s of GeV important
- ***Particle ID***
  Clean identification of e, μ up to highest energies
- PID of hadrons to improve tagging, jets,…
- ***Hermetic coverage***
  Dark matter searches in mono-photon events, …
  N.B.: Achievable limits do not depend strongly on $\sigma(E_\gamma)$









Detector R&D for Linear Collider Detectors - *ECFA Detector Roadmap Input, February 2021* Frank Simon (fsimon@mpp.mpg.de) **6**

Hadronic resolution (both stochastic and constant term) with PFA
Technology: Si/scint (RPCs)

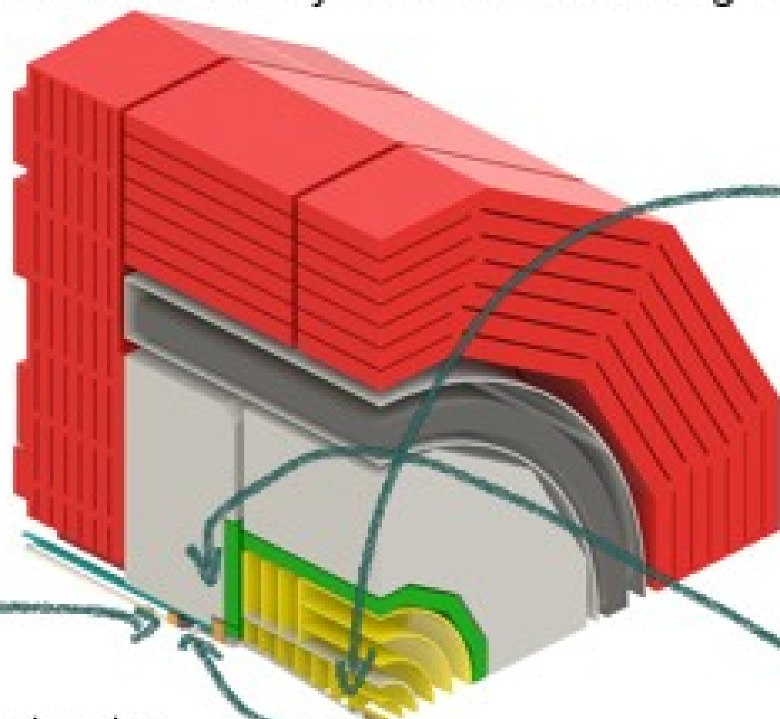
Linear Colliders (2)

Occupancies and Radiation

Higher for CLIC - Put in Focus here

MAX-PLANCK-INSTITUT

- In general the radiation environment and the particle density at Linear Colliders is benign compared to HL-LHC - but not fully free from challenges. The most stringent requirements are imposed by CLIC 3 TeV



Hit rates

Energy stage	380 GeV		3 TeV	
Subdetector	Minimum Hits[1/mm^2/train]	Maximum Hits[1/mm^2/train]	Minimum Hits[1/mm^2/train]	Maximum Hits[1/mm^2/train]
Vertex barrel	0.2	3.2	0.6	8.8
Vertex endcaps	0.1	2.7	0.2	8.8
Tracker barrel	0.0003	0.03	0.002	0.1
Tracker endcaps	0.0004	0.1	0.002	0.6

Background energy

Energy stage	380 GeV		3 TeV	
Subdetector	Incoherent pairs [GeV/train]	$\gamma\gamma \to$ hadrons [GeV/train]	Incoherent pairs [GeV/train]	$\gamma\gamma \to$ hadrons [GeV/train]
ECAL barrel	3.6	2.1	14	52
ECAL endcaps + plugs	11.1	9.4	39	252
HCAL barrel	0.05	0.18	0.22	5.0
HCAL endcaps	2874	7.0	11 790	312
Total ECAL+HCAL	2889	19	11 840	621
LumiCal	68.5	4.5	283	193
BeamCal	54 730	5.6	270 600	540

Radiation levels:

- inner vertex: 6 x 10^{10} n$_{eq}$/cm^2/year; 300 Gy/year
- ECAL endcaps: 2 x 10^{11} n$_{eq}$/cm^2/year; ~ 10 Gy/year
- BeamCal: 1.4 x 10^{14} n$_{eq}$/cm^2/year; ~ 7 MGy/year

Detector R&D for Linear Collider Detectors *- ECFA Detector Roadmap Input, February 2021* Frank Simon (fsimon@mpp.mpg.de) **9**

CLIC at 3 TeV poses moreover rad-hard issues

Linear Colliders (3)

TF6 Calorimetry

A Focus on PFA

- Calorimetry is central to the "philosophy" of Linear Collider detectors optimised for Particle Flow reconstruction - The original motivation for highly granular ("imaging") calorimeter. Key performance demonstrated in test beams.
- Key topics for further development:
  - ***Scalability*** and ***cost-effective*** mass production
    - Silicon, Scintillator / SiPM, Gas detectors
  - ***Performance improvements*** (in particular in areas of clustering and hadronic resolution) with integration of new technical capabilities, such as ***ps-level timing***, ***novel optical materials, dual readout techniques*** **in high granularity**; improved ***electromagnetic resolution*** in highly granular calorimeters
  - Development of CMOS-based ***digital ECAL*** solutions
  - Central for all: ***highest possible integration***: compact active layers, smallest mechanical tolerances, minimum volume for interfaces, smallest possible power consumption to avoid active cooling wherever possible, ...

⇨ Calorimetry drives developments in sensor and electronics areas - "ripple effects" for other TFs

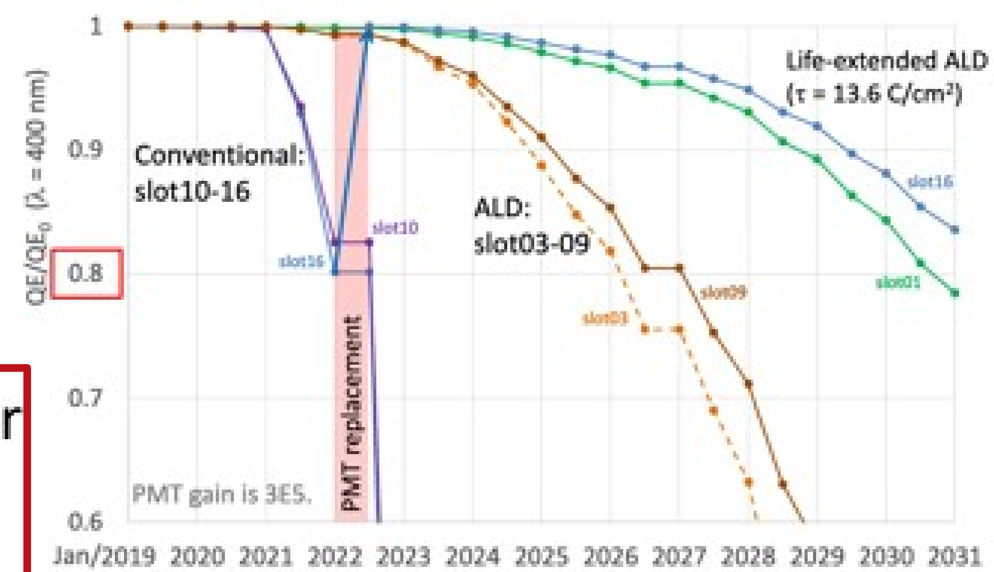
Detector R&D for Linear Collider Detectors *- ECFA Detector Roadmap Input, February 2021* Frank Simon (fsimon@mpp.mpg.de) **18**

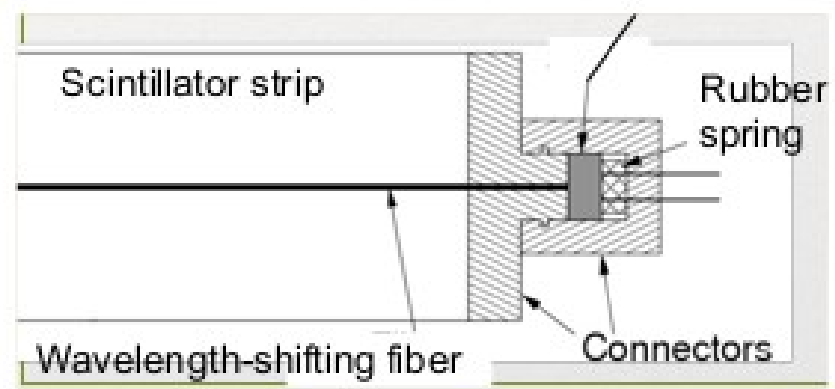
Frank Simon's conclusions

Issues and options for Belle II upgrades for high luminosity II

- Maintain large coverage high efficiency PID system (TF4)
  - Life-extended MCP-PMTs (Latest generation Atomic Layer Deposition)
  - Study of low noise single photon capable SiPMs
- Reduce pileup effects and maintain good calorimeter resolution (TF6)
  - Study of improved photo detector (APD) and/or pure CsI crystals.
  - Possibility of a crystal pre-shower
- Maintain muon efficiency; improve on KLong detection (TF4)
  - Replace aging RPCs with Scintillator+WLS+SiPM (already done for first layers)
  - Study of TOF option for Klong detection (need order of 100 ps resolution)

Projection of QE degradation



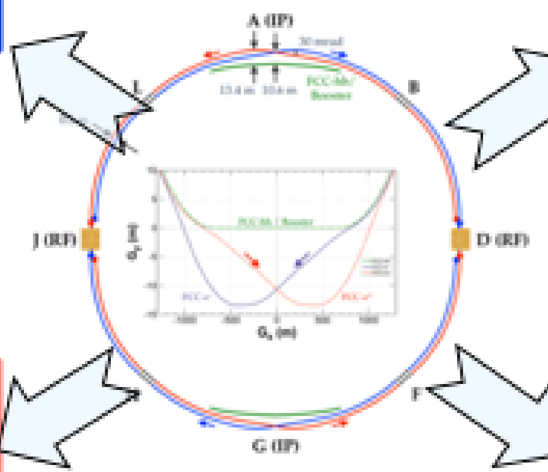


Circular e+e- Colliders (EWK factories)

Detector Requirements in Brief

"Higgs Factory" Programme
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme
- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6}: stability of √s meast.



Heavy Flavour Programme
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs
Benchmark signature: Z → νN, with N decaying late
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

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keys: resolution, granularity

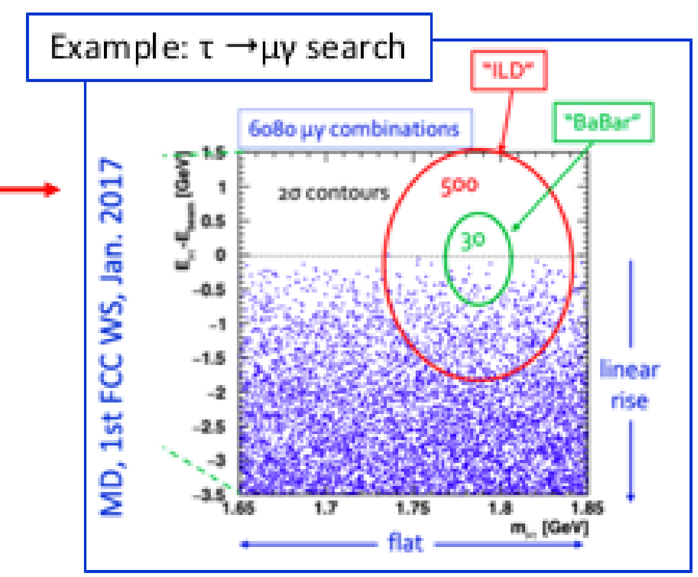
EWK factories (2)

Calorimetry

- Several technologies being considered

Technology	ECAL	HCAL
CLD / CALICE-like	W/Si W/scint + SiPM	Steel/scint + SiPM Steel/glass RPC
IDEA / Dual Readout	Brass (lead, iron) / parallel scint + PMMA (Č) fibres, SiPM	
Noble Liquid	Fine grained LAr (LKr) / Pb (W)	CALICE-like ?
Crystals	Finely segmented crystals (possibly DR)	Dual Readout fiber?

- Jet energy and angular resolutions via Particle Flow algorithm
  - Possibibly augmented via Dual Readout
- Fine segmentation for PF algorithm and powerful γ/π^0 separation and measurement
- In particular for heavy flavour programme, superior ECAL resolution needed
  - 15%/√E → 8%/√E → 3%/√E
- Other concerns
  - Operational stability, cost, …
- Optimisation ongoing for all technologies
  - Choice of materials, segmentation, read-out, …



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technology: all possible solution are in

Circular e+e- Colliders – Mogens' selected issues

Selection of R&D Issues

High duty-cycle detectors [TF7, TF8]

a) Low-power readout electronics and low-mass cooling

Silicon sensors – VTX, tracker, calorimeters [TF3]

b) High spatial resolution (3-5 μm), timing (at least 20 ns for BX assignment), low material budget, low power consumption

Drift chamber [TF1]

c) Prototypes: full length (few cells) to verify wire stability and electronics issues; portions of full-scale end-plate

d) Investigate possibility to save material going from metal wires to metal-coated carbon monofilaments
   - Wire production line need to be engineered

e) Experimental verification of dN/dx method for PID
   - Need test beams, e, μ, π, K, p in range ≳ 100 MeV to 50 GeV

Calorimetry [TF6, TF4, TF7]

f) Optimisation for each technology including choice of materials and segmentation

g) Dual Readout: SiPM/FE electronix, had-shower-size prototype

Coil design/placement [TF8]

h) Quantititive study of impact of "early" coil on phys. perf.

PID (other than specific ionisation) [TF4, TF3]

i) Precise timing, gaseous RICH

Muon system [TF1, TF4]

j) Technology choice for very large area detectors
   - RPC, scintillator, μRWell,...

Readout & DAQ [TF7, TF8]

k) Design of DAQ architecture: triggered or free streaming

l) Sub-detector readout to be designed correspondingly

Normalisation issues [TF6, TF7]

m) LumiCal: micron level mechanical precision; fast, low-power read-out electronics

n) Definition of geometrical acceptance of main detector to 10s of μm precision (dedicated low-angle (pre-shower) device?)

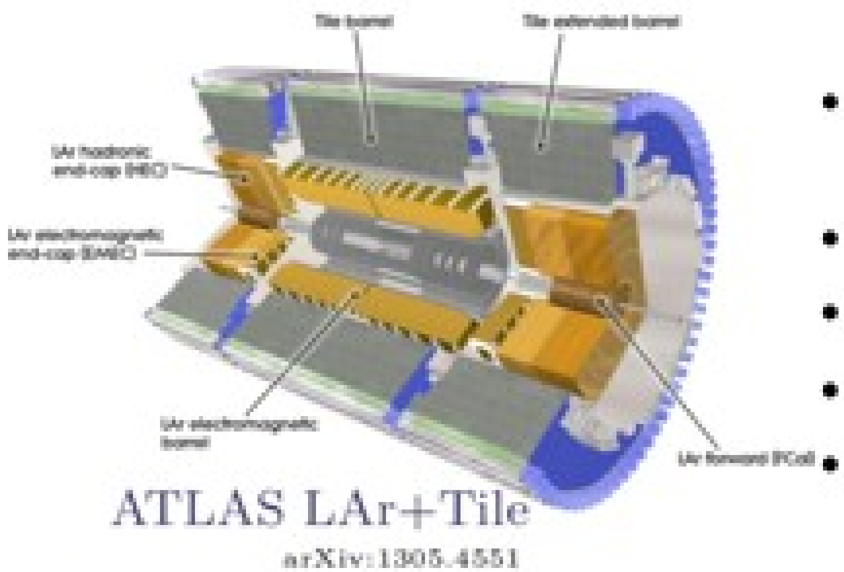
Large detector volume for LLPs [TF1, TF4, TF6]

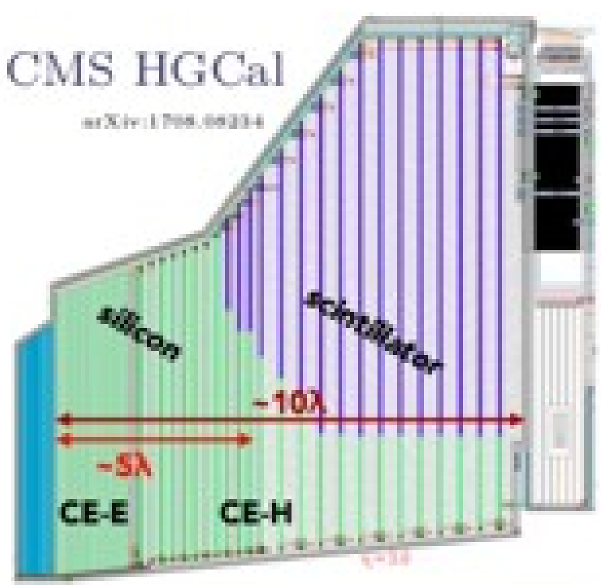
o) Optimization of calorimeter and muon system for late decaying particles

p) Possibility of large instrumented decay volume in surrounding cavern

Mogens Dam / NBI Copenhagen   ECFA Detector R&D Roadmap Input Session   19 Feb, 2021   24

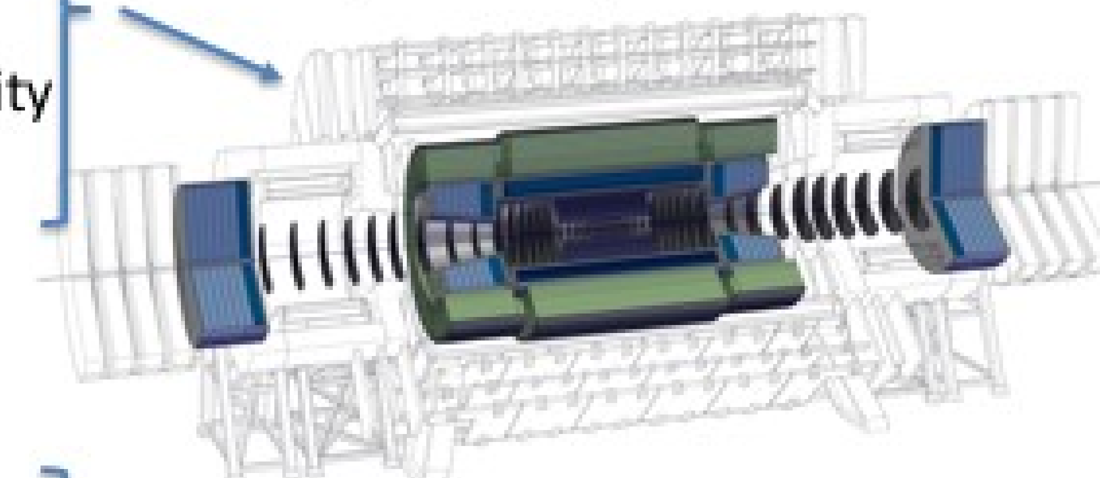
FCC-hh Calorimetry





- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

FCC-hh Calorimetry
„conventional calorimetry“
optimized for particle flow



- High granularity
  → Pile-up rejection
  → Particle flow
  → 3D/4D/5D imaging

FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

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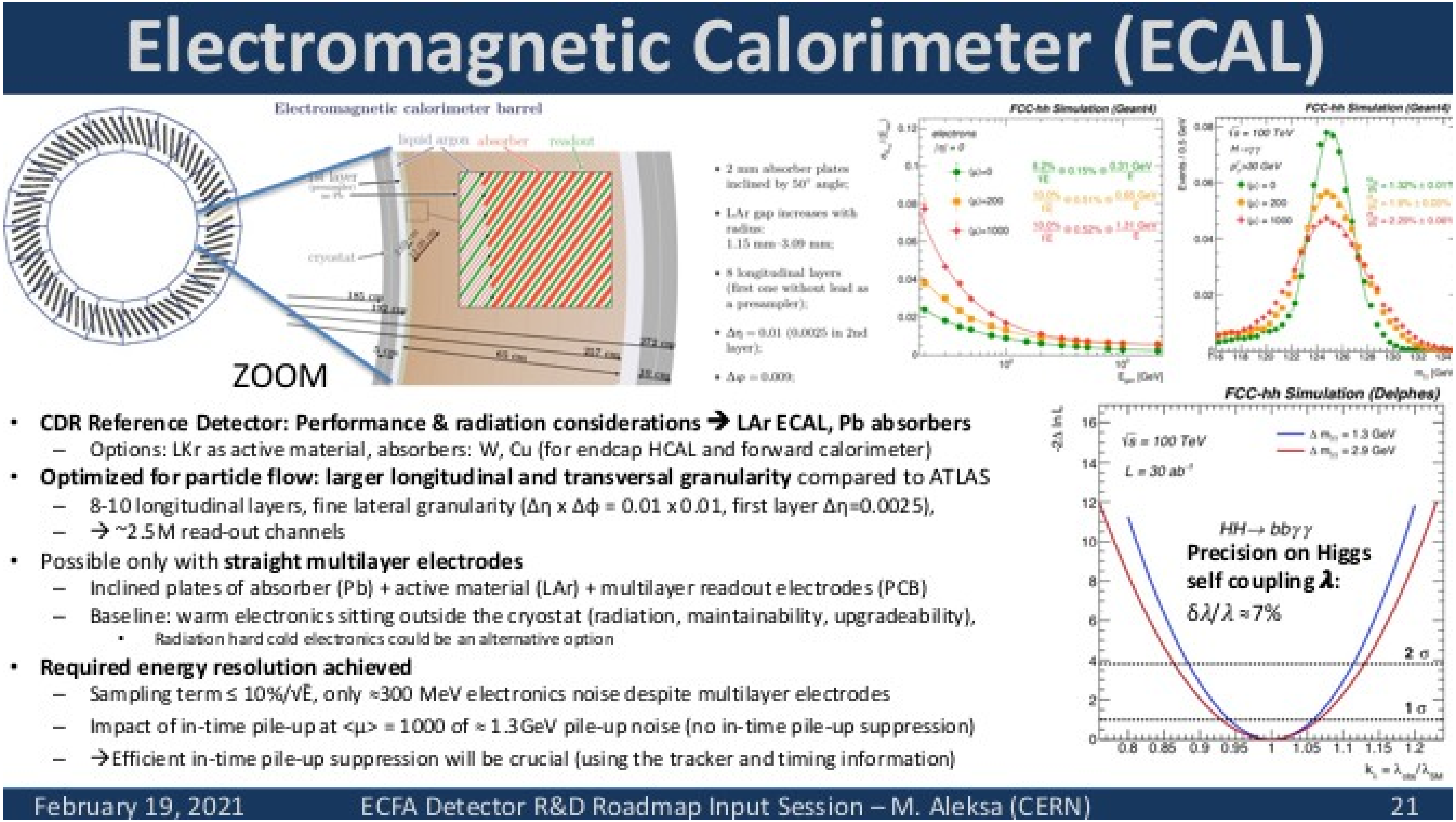
Hadronic resolution (good stochastic term, ALAP constant term), granularity, rad-hardness, pile-up rejection …

FCC-hh (2)



Technology: Pb/LAr (options W, Cu and LKr, but also Si/W)
Mechanics (electrodes), granularity, timing (pile-up soppression)

FCC-hh (3)

Hadronic Calorimeter (HCAL)

Barrel HCAL:

- **ATLAS type TileCal optimized for particle flow**
  - Scintillator tiles – steel,
  - Read-out via wavelength shifting fibres and SiPMs
- **Higher granularity** than ATLAS
  - $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

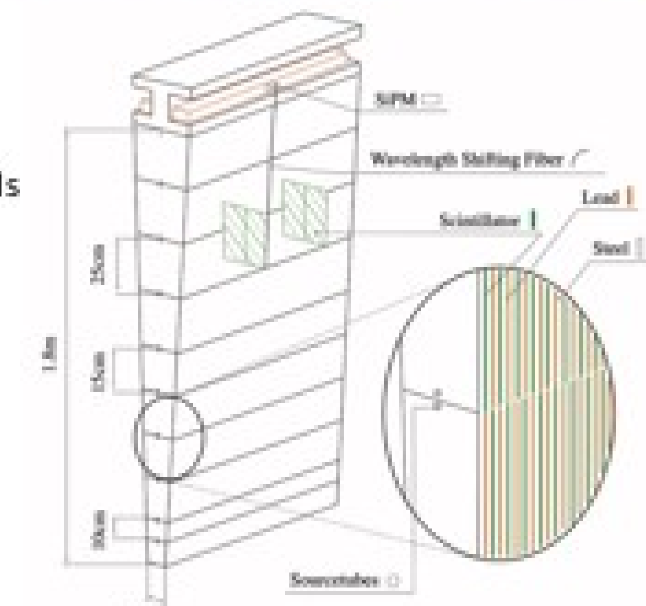
- Simple calibration: 44%/$\sqrt{E}$ to 48%/$\sqrt{E}$
- Calibration using neural network (calo only):
  - Sampling term of 37%/$\sqrt{E}$

Jet resolution:

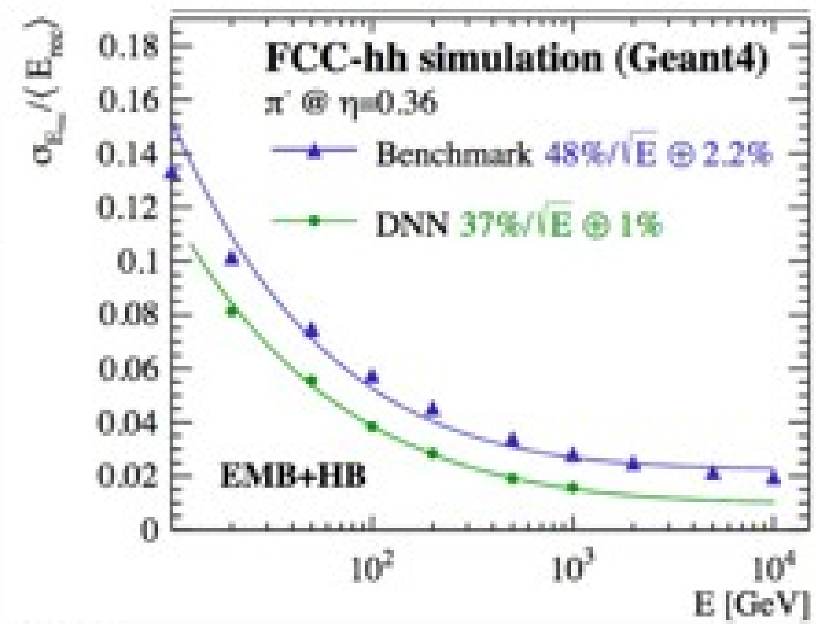
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

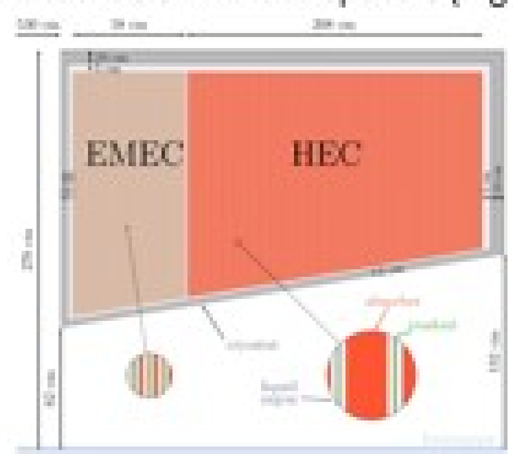
Endcap HCAL and forward calorimeter:

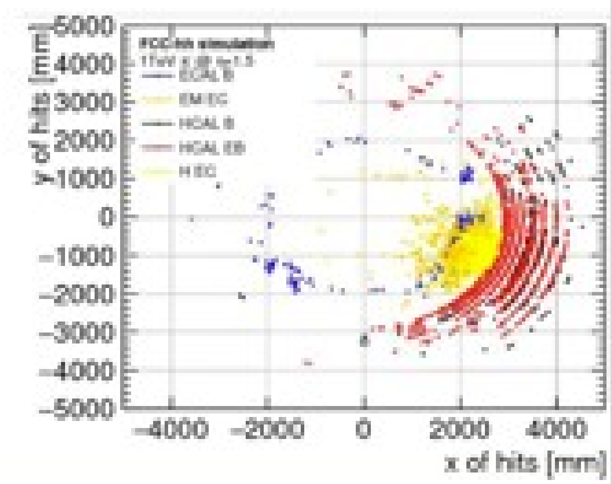
- Radiation hardness!
- LAr/Cu, LAr/W



TileCal: e/h ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)







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Technology: steel+tiles (barrel), LAr/Cu or LAr/W (endcap)

FCC-hh (4)

Challenges for Calorimetry – R&D Needs (TF6)

- **High granularity** (lateral cell sizes of ≤2cm, like for the proposed reference detector LAr calorimeter)
  - Particle flow (measure each particle where it can be best measured)
  - 5D calorimetry (imaging calorimetry, including timing) → use of MVA based reconstruction (Neural Networks, …)
  - Pile-up rejection
    - Efficient combined reconstruction together with the tracker
- **Timing for pile-up rejection, 5D calorimetry:**
  - O(25ps) to reduce pile-up by factor 5 ($<\mu>$ = 1000 → 200) → LGADs, 3D pixel sensors → further R&D on pad sizes and radiation hardness
  - O(5ps) to reduce pile-up by factor 25 ($<\mu>$ = 1000 → 40) → ultra-fast inorganic scintillators, ultra-thin LGADs
- **Data rates – Triggering**
  - Noble-liquid calorimetry + scintillator/Fe HCAL: O(3M) channels 200 – 300TB/s → full read-out at 40MHz (like ATLAS in HL-LHC)
  - Si option: many more channels, zero suppression on-detector necessary
  - → 100Gbps data links, off-detector real-time event processing with advanced hardware (GPUs, FPGAs)
  - → on-detector processing with radiation tolerant processing
- **Crazy ideas for the future:** Possible "maximal information" calorimeter: divided into small detection volumes (voxels) that measure ionization, time, and Cherenkov and scintillation light simultaneously – e.g. noble liquid calorimetry

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Martin's R&D list for calorimetry

General requirements for the detector

- ✓ Track efficiency and momentum resolution – for feasibility and precision of many physics studies e.g. final states with leptons
- ✓ Good ECAL energy and position resolution for e/gamma reconstruction
- ✓ Good jet energy resolution
- ✓ Efficient identification of a secondary vertex for heavy quark tagging
- ✓ Other considerations (Missing Energy/MET, taus, substructure)

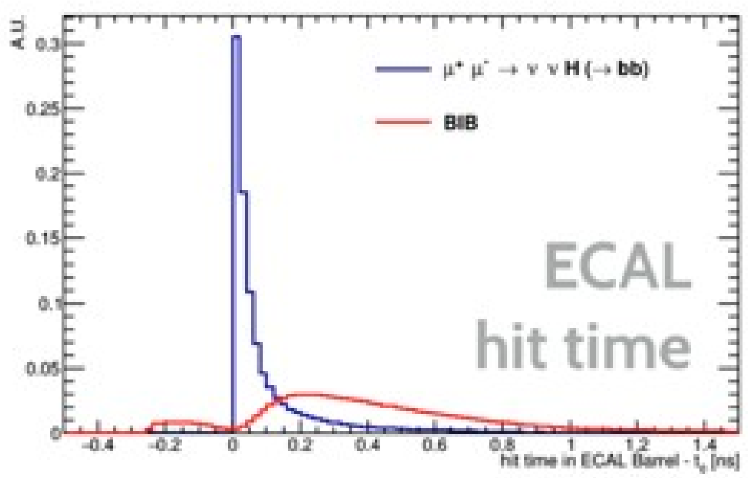
- ✓ Many ILC or CLIC considerations apply to Muon Collider detectors, although beam background conditions are different and much more challenging requiring a dedicated design for Muon Collider experiment: vertex/tracking – calorimetry – triggerless DAQ
- ✓ Detector design considerations should be driven by physics requirements and BIB considerations
- ✓ **Optimal design will very likely be different for different collision energies**

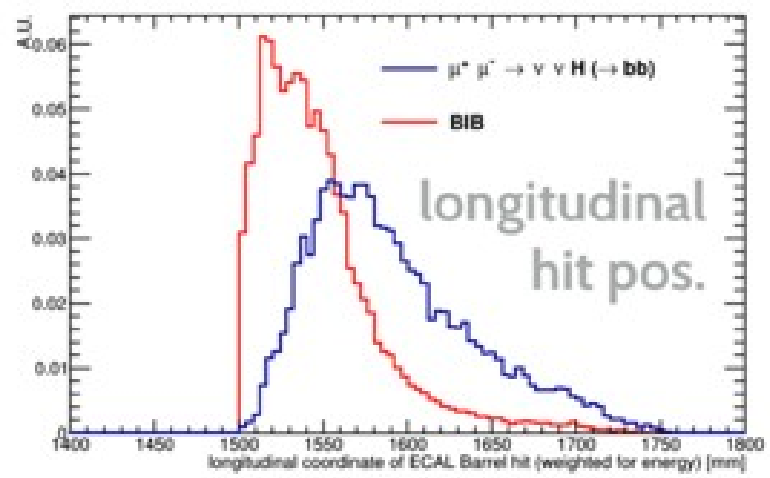
Main issue: Beam-Induced Background (BIB)

Muon Collider (2)

Calorimeter optimization

Timing and longitudinal shower distribution provide a handle on BIB in ECAL





Various BIB mitigation approaches for ECAL can be studied

- possibly adding a preshower for absorbing the initial part of BIB in ECAL
- subtraction of BIB depositions using the hit time+depth information

Hadronic showers have longer development time → timing not critical

- the most straightforward approach: evaluate the average BIB energy deposition and consider only energy deposits above the BIB level

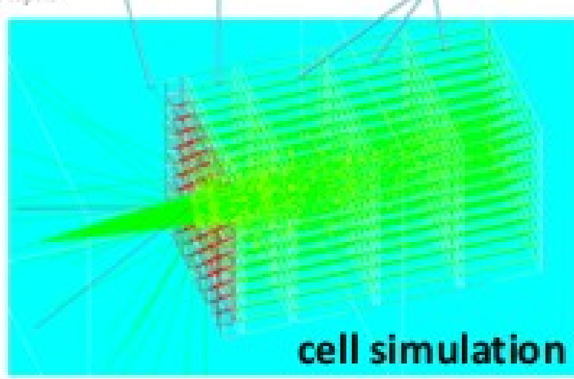
Technology: Si/W (ECal) + Si/iron (HCal) with high granularity

Muon Collider (3)

New materials and technologies

- A first layer of LYSO could be used for time measurement, then PbF_2 layer to absorb the BIB
- PbF_2 has good light yield (3 pe/MeV), fast signal (300 ps for muons 50 ps for pions), radiation hard, relatively cheap

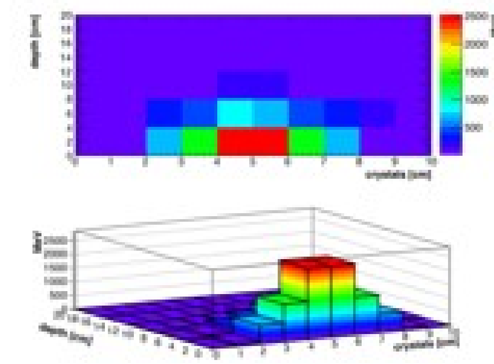
1 cm of LYSO (for timing) + 3 cm of PbF2 (to stop the BIB) + 3x 5 cm of PbF2 + 5x3 mm copper bias layers



cell simulation with Geant

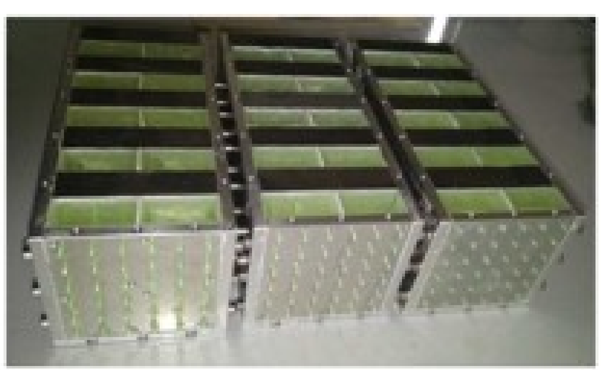
Most of BIB photons are absorbed in the first layer

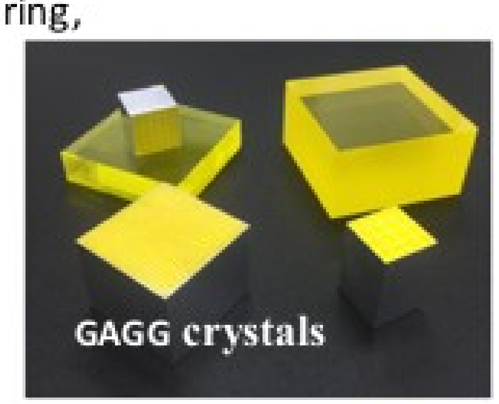
BIB parametrized as 1.7 MeV photons – 300 particles/cm² per event



→ cerium-doped GAGG: fast scintillation light (100 ps and 50 ns of rise and decay time), high light yield (50k photons/MeV)

→ Polysiloxane: lightweight, fast response, reduced cost and ease of manufacturing, although they display reduced light output with respect to inorganic crystals





Polysiloxane calorimeter [*J. Phys.: Conf. Ser.* **1162** 012032] 25

Other options: crystals + SiPMs

R&D on rad-hard fast crystals (synergies with KLEVER + LHCb …)

Muon Collider (4)

Hadronic calorimeter features

- High longitudinal and transversal granularity (~1cm^2)
  - to distinguish the jet constituents from the BIB
  - to solve the substructures that are necessary for the fat jet identification
- High time resolution (few hundred of ps) to measure the time of arrival of particles to remove the BIB. Jet time resolution of the order of tens of picoseconds
- Excellent energy resolution (5%) to properly exploit the jet sub-structure in the fat-jet reconstruction algorithm.
- High radiation hardness
- Development of new HV power supplies with high sampling rate
- Further development of Front-End electronics specific for time and energy measurement

Options considered for active layers:
- plastic scintillator+SiPMs (exploited in the CMS HGCAL),
- RPCs, GEM and Micromegas.

➔R&D of gas-based detector as active layer to a new MPGD detector, optimized for fast timing, and based on the GEM detector concept: Fast Timing MPGD (FTM) (https://arxiv.org/abs/1503.05330) and the related readout electronics.

Gaseous Detectors are naturally rad-hard and can be designed for high rate capability and high spatial resolution

Gaseous Detectors can economically instrument large areas

Can measure Energy & Timing. Can send digital data out of the detector

28

Rad-hard, high energy and timing resolution, high longitudinal and transverse segmentation
Technology: scint + gas detectors optimised for fast timing

Rare decay searches

Kaon exp. @ CERN SPS and J-PARC (KLEVER and KOTO):
- 5D calorimetry and vetoes
  - excellent efficiency and time resolution (~100 ps)
  - good two-cluster separation (time-resolved particle flow)
  - rad hardness for small-angle veto
  - KLEVER calorimetry readout system:
  - free-running, very fast response, 100 MHz readout

Charged lepton flavour violation (Mu3e, COMET, Mu2e-II, TauFV):
- sinergic with LHCb upgrade II
- rad-hard (>100 Mrad), high-rate (~450 MHz) environment
- high time (< 100 ps) and energy resolution
- longitudinal shower sampling
- spatial and pointing resolution
- time-resolved particle flow
  - Possible options (TauFV):
    - 1) W + rad-hard GAGG fibres
    - 2) (YAG or GAGG) Crystals with (optional) longitudinal readout

Low-energy facilities

Speaking of PSI, GSI/FEAR, KEK, ELENA, COSY, ESS

μ-calorimeters based on superconducting Transition Edge Sensors (TES):

- Energy (sigma): 2.5 eV @ 6 keV, 1.0 eV @ 500 eV
  (to be compared to 150 eV @ 6 keV for Ge)

increase active surface (> 104 channels)
improve energy resolution (1 eV @ 5 keV)
improve recovery time to few tens μs
improve time resolution (< 100 ns)

Backup

Guidelines – General remarks

The talks should explicitly cover technical progress we can expect in 20+ years from now
Note that the European Strategy Update[1] expresses itself on projects that start either in 20-40 years from now (FCC, Muon Collider) or, if starting earlier, that will have a very long research program (DUNE, LHC after LS4, ILC)

R&D on calorimeters has always to take system aspects into account !

- This distinguishes a bit the Calorimeter-symposium from the others
    - Calorimeters imply interplay between absorber, sensitive material, electronics and mechanical structures
- Need to find the right balance between being visionary and realistic
- When presenting R&D results or describing future R&D, please keep in mind how to translate testbench results into calorimetric systems
- Where possible/applicable describe test beam plans and the scale of the devices/prototypes that should be tested

Try to identify (potentially) important issues that are not covered by any current plan

How do you consider (to the best of your knowledge) the step from prototypes to full systems?

- Which level of cooperation with industrial partners?
- Which level of "in house" contributions?

[1] https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

Guidelines – State of the art

Describe what exists now as "state of the art"

At which target facilities (if applicable)? (if in running experiment, please mention explicitly)

Specify distinguished features of the target application (high rate, low rate, energies …)
... and feedback on this current state of the art

Please mention the present technological limits

Who are the main players of the developments? (e.g. approved experiments, R&D Collaborations)

Guidelines – What are foreseeable next steps?

Plans of existing collaborations and/or experiments?

Major breakthroughs that are necessary to achieve the proposed goals?

Otherwise said: are there radical steps needed or is it a rather gradual development?

Mention risks and alternatives

- Is there a risk that an experiment will find itself without a validated calorimeter concept? Or, if applicable, a technical problem that requires sizeable redesign?

Is the infrastructure available (in Europe in particular, but also worldwide) sufficient to incorporate quickly new ideas and developments? In terms of:

- Collaborative structures
- Modular prototypes, test benches, technical know-how (it is very important to understand which know-how needs to be preserved or newly acquainted)

In principle this/these slide(s) will yield the prioritisation in the Roadmap. So this is the most important part!

Guidelines – What is not covered in the present & foreseen R&D plans?

Possible further R&D on hardware?
I.e. Detectors, sensors, front-end electronics, data transfer/trigger/DAQ etc.?

Possible further R&D on software/simulation?

Possible further R&D about new analysis architectures/strategies?

Guidelines – Synergies among HEP Projects

Even if target application may call for diverging solutions

- Are there still overlaps to exploit synergies?

Common development teams

- Are there development teams that work for different target applications? e.g.: IN2P3-OMEGA works for both HL-LHC and future e+e- colliders
- Experience and ways to encourage communication within institutes where different developments are carried out

Is too specific funding (i.e. too project-oriented funding) a bottleneck for synergies?

Applications to other HEP-Projects (e.g. Collider experiment ↔ fixed target)

Guidelines – The look over the fence

Developments in neighboring fields (Nuclear Physics, Astroparticle physics)
- E.g. Xtals for EiC, Liquid Scintillators for Neutrino Experiments

Synergies with applications beyond fundamental science
- In the past our developments were useful for medical applications, vulcanology ...
- What will be in the future?
    - Pattern recognition in highly granular calorimeters?
    - High level reconstruction in front end electronics?
    - Your bright idea ...

Societal impact of our work
- Can we contribute to solutions for limiting climate change?
    - Your bright idea ...