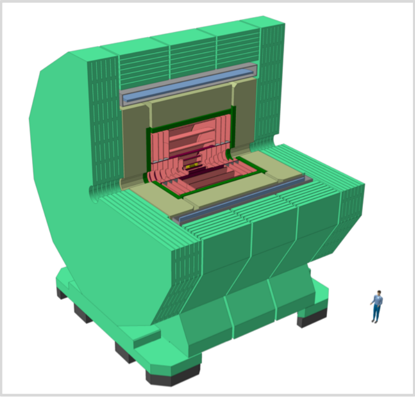
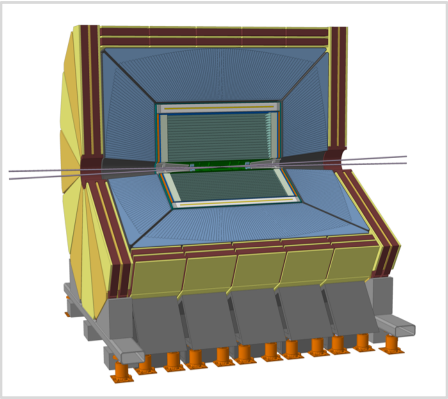
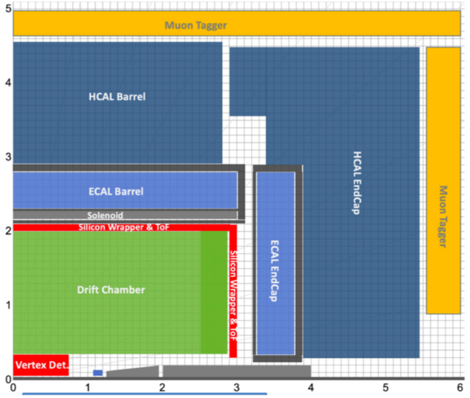
Detector Concepts Overview

Detector Concepts working group

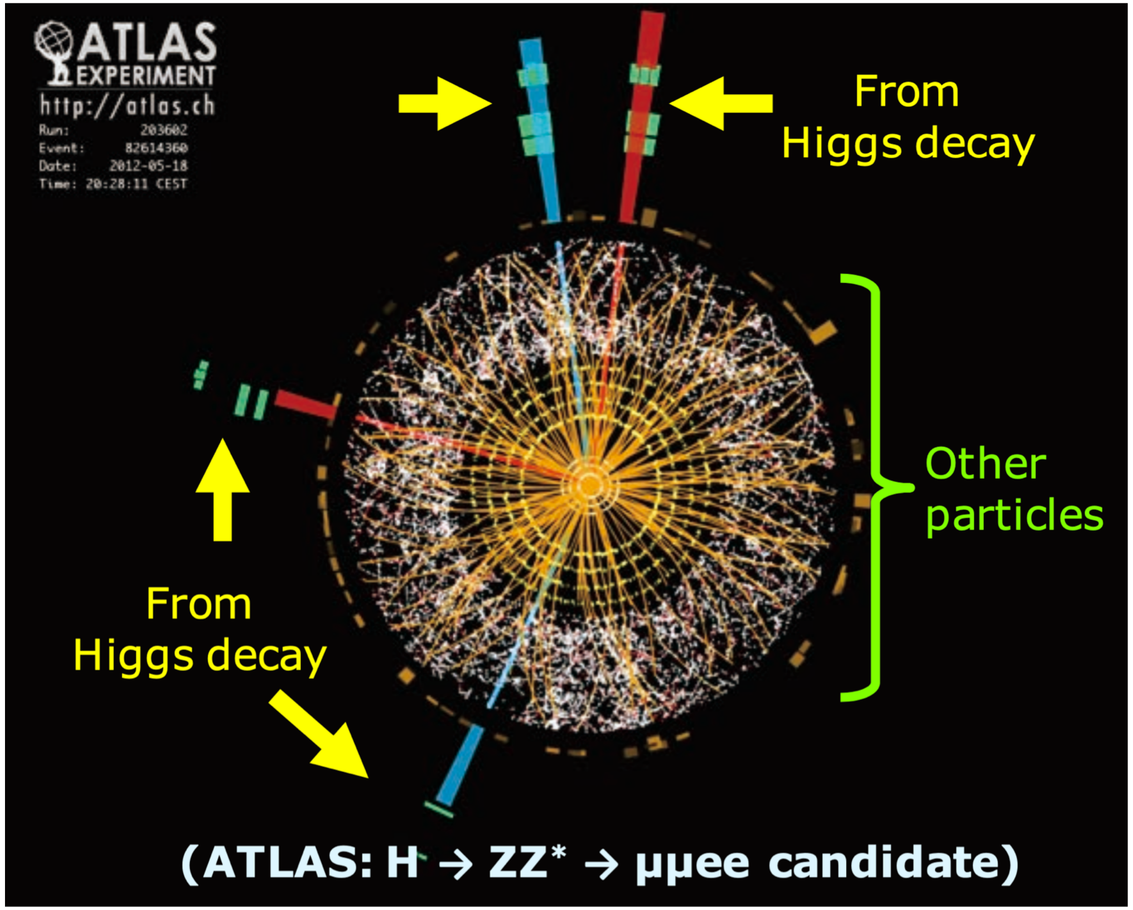
Mogens Dam, Philipp Roloff, Felix Sefkow

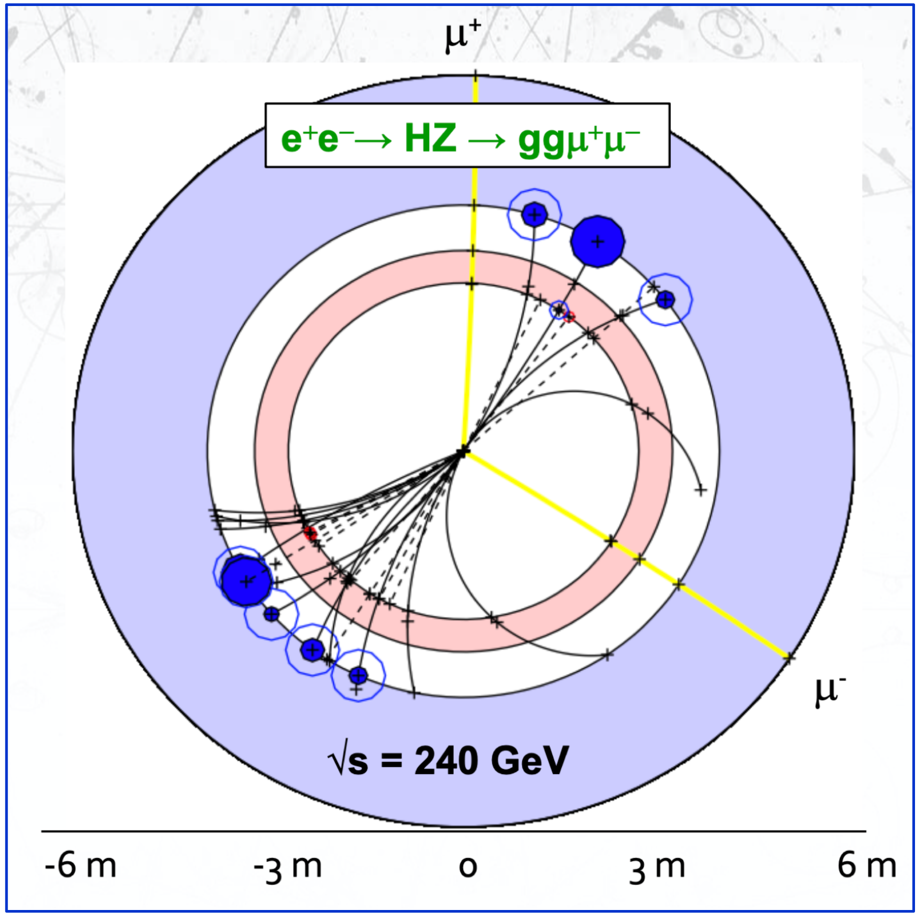






Reminder: Higgs event in pp and e^+e^-

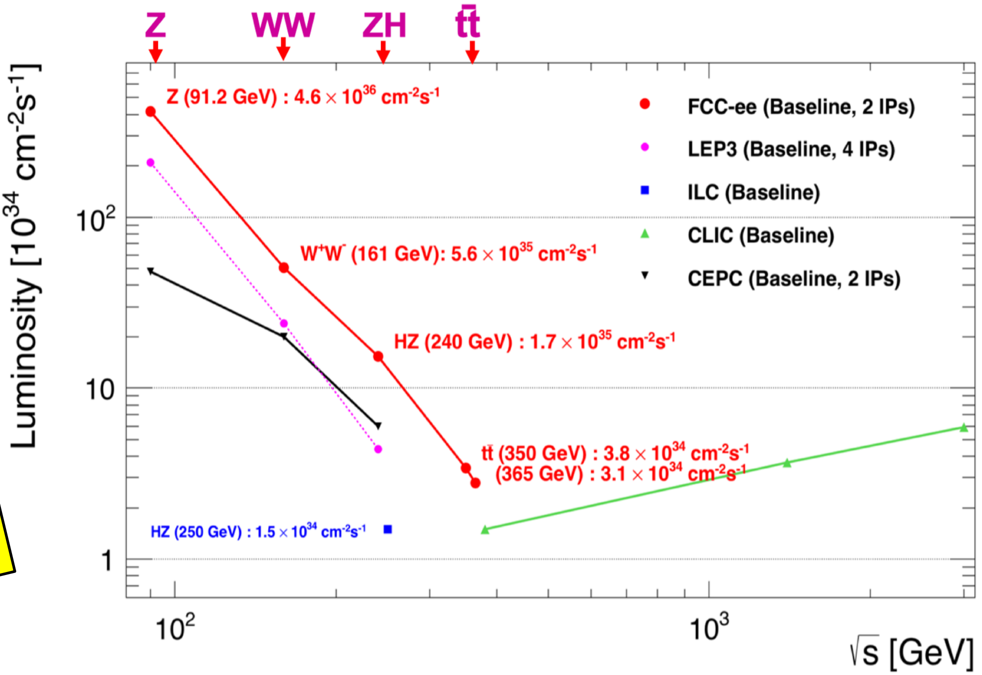




Proton-proton: look for striking signal in large background

$e+e^-$: detect everything; measure precisely

FCC-ee Conditions



Numbers to be updated for newest FCC-ee parameters

Event statistics

$5×10^{12}$ e$^+$e$^-$ → Z
10^8 e$^+$e$^-$ → W$^+$W$^-$
10^6 e$^+$e$^-$ → HZ
10^6 e$^+$e$^-$ → tt

FCC-ee parameters		Z	W$^+$W$^-$	ZH	ttbar
$\sqrt{s}$	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	230	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	92,000	8.4	1	0.1
"Pile up" parameter [μ]	10^{-6}	1,800	1	1	1

Experimentally, Z pole most challenging

- Extremely large statistics
- Physics event rates up to 100 kHz
- Bunch spacing at 20 ns
  - "Continuous" beams, no bunch trains, no power pulsing
- No pileup, no underlying event …
  - …well, pileup of 2 x 10^{-3} at Z pole

FCC-ee Physics Landscape

"Higgs Factory" Programme

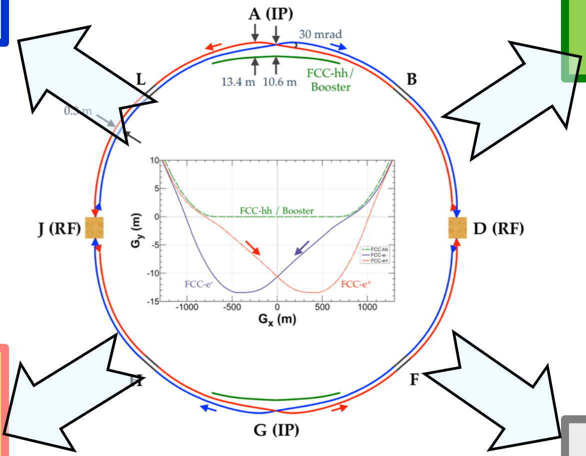
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- $5\text{x}10^{12}$ Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; $1.7\text{x}10^{11}$ ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays

- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs

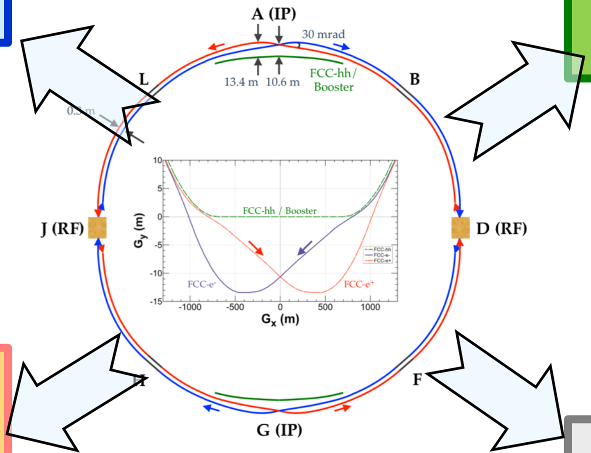
Detector Requirements in Brief

”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 & QCD

- 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

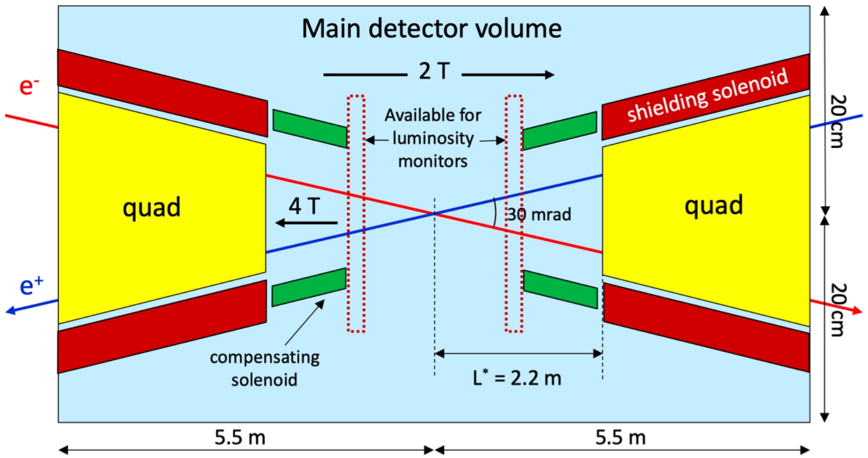
Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

Experimental challenges

- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla at Z-peak operation
  - Very complex and tightly packed MDI (Machine Detector Interface)
- ”Continuous” beams (no bunch trains); bunch spacing down to 20 ns
  - Power management and cooling (no power pulsing)
- Extremely high luminosities
  - High statistical precision – control of systematics down to 10^{-5} level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics: ”Big Data”
- Physics events at up to 100 kHz
  - Fast detector response ($\lesssim 1\ \mu s$) to minimise dead-time and event overlaps (pile-up)
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - At the same time, keep low material budget: minimise mass of electronics, cables, cooling, …

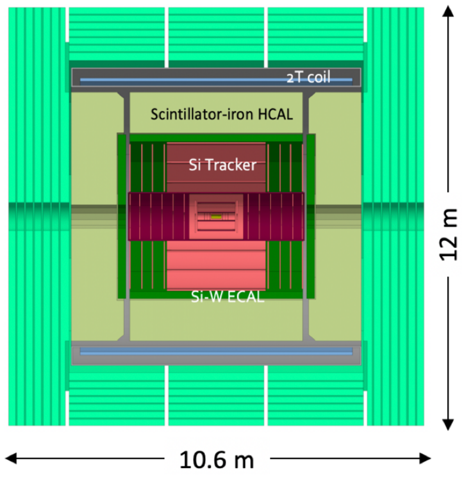
Central part of detector volume – top view



- More physics challenges
  - Luminosity measurement to 10^{-4} – luminometer acceptance (radius) to $\mathcal{O}(1\ \mu m)$
  - Detector acceptance to ~10^{-5} – acceptance definition to few × 10 μm, hermeticity (no cracks!)
  - Stability of momentum measurement – stability of magnetic field wrt E_{cm} (10^{-6})
  - Impact parameters, detached vertices – Higgs physics (b/c/g jets); heavy flavour physics, life-time measurements
  - Particle identification (π/K/p) without ruining detector hermeticity – heavy flavour physics (and rare processes)

Detector Concepts Fast Overview

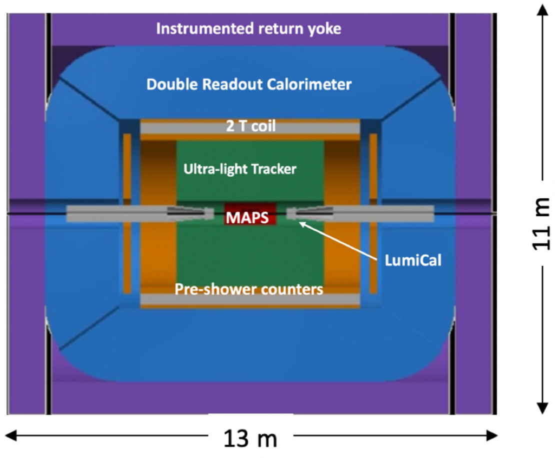
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Engineering needed to make able to operate with continous beam (no pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations?
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

- Robust software stack
  - Now ported (wrapped) to FCCSW

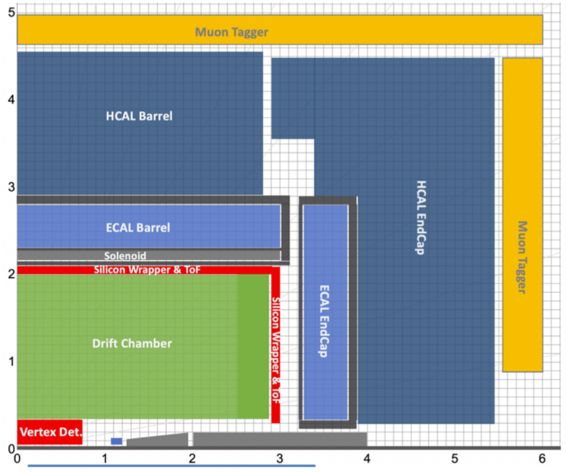
IDEA



- Less established design
  - But still ~15y history: 4th Concept
- Developed by very active community
  - Prototype construction / test beam compains
  - Italy, Korea,…
- Is IDEA really two concepts? Or will it be?
  - w, w/o crystals

- Software under active development
  - Being ported to FCCSW

Noble Liquid ECAL based



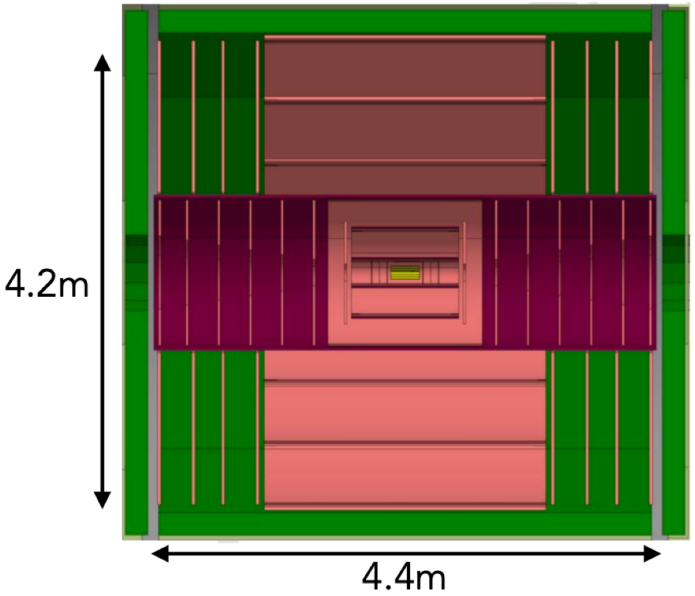
- A design in its infancy
- High granul Noble Liquid ECAL is the core
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

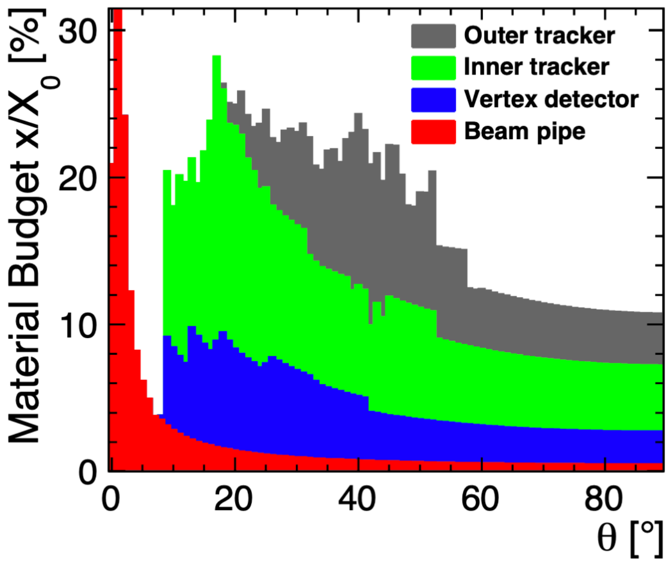
- Full simulation of ECAL available in FCCSW

Tracking

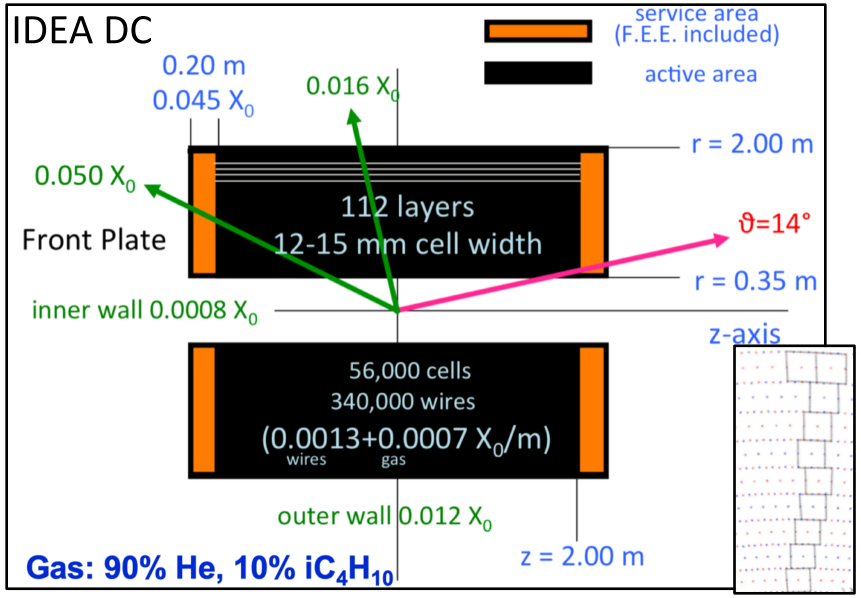
Two solutions under study

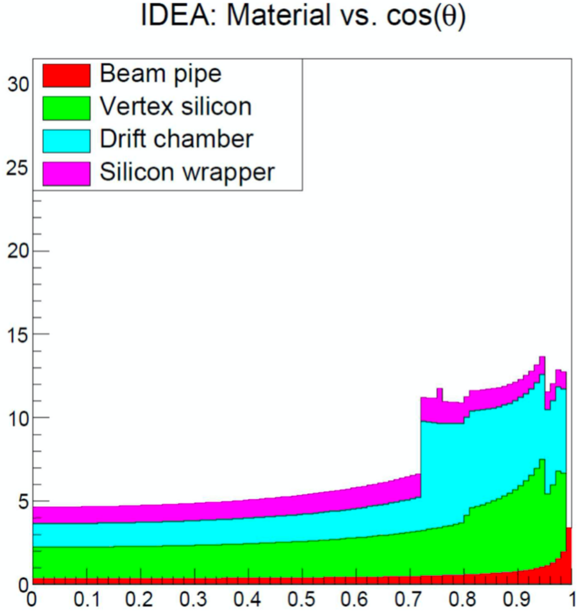
- CLD: All silicon pixel (innermost) + strips
  - ❑ Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - ❑ Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - ❑ Separated by support tube (2.5% X_0)





- IDEA: Extremely transparent Drift Chamber
  - ❑ GAS: 90% He – 10% iC_4H_{10}
  - ❑ Radius 0.35 – 2.00 m
  - ❑ Total thickness: 1.6% of X_0 at 90°
    - ❖ Tungsten wires dominant contribution
  - ❑ Full system includes Si VXT and Si "wrapper"





What about a TPC?

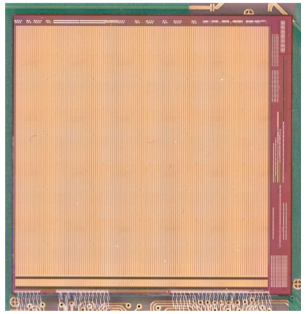
- Very high physics rate (70 kHz)
- B field limited to 2 Tesla
- Considered for CEPC, but having difficulties…

Si Tracker R&D

A. Andreazza - DMAPS for large area FCC trackers

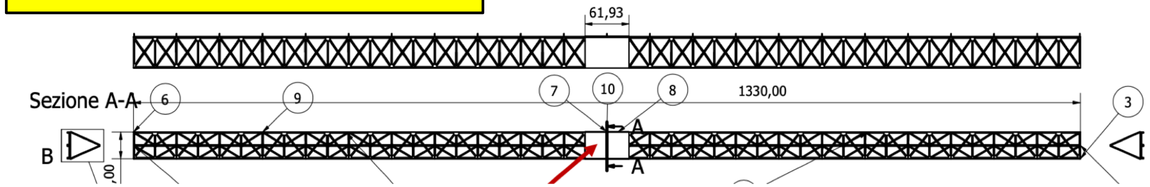
- Similar approaches for ILC, CLIC, FCCee, CepC:
  - High resolution **pixel vertex detector** O(few m²)
  - Either **full silicon tracker** or **central gas chamber** **+ Si wrapper** O(100 m²)

- **Depleted Monolithic Active Pixels Sensors**
  - CMOS process allows to produce **large areas**, **fast** and **cheap**
  - **no hybridization** (bump-bonding) needed
  - **single detection layer**, can be **thinned** keeping high signal efficiency and low noise rate



ATLASPIX3
(estimation at ATLAS TDR)
150 mW/cm^2
400-500 kCHF/m^2

R&D on support structures…

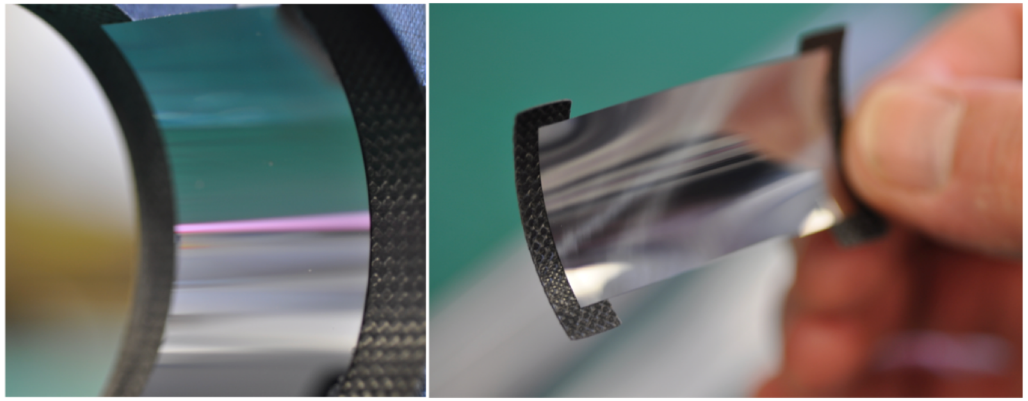


… and cooling

Liverpool slide

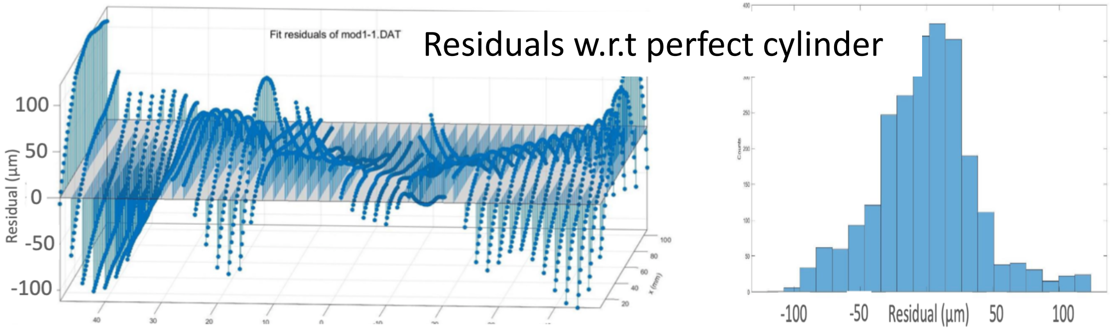
Large area curved silicon modules for future trackers
Adrian Bevan, Feb 2021

Queen Mary University of London



- Radius of curvature shown: 25mm
- Able to bend silicon to radii of 13mm

c.f. 10 mm beam pipe radius



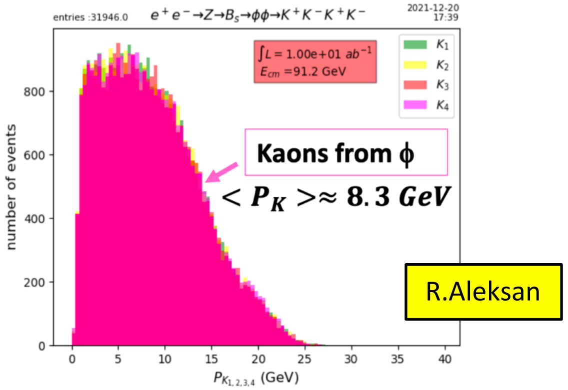
Residuals w.r.t perfect cylinder

Today @ 14:20: A. Besson, Silicon vertexing and tracking R&D

Particle Identification

Liverpool slide

K/π separation asked for over large momentum range



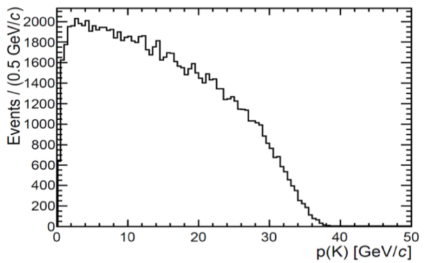
Kaons from ϕ

$< P_K > \approx 8.3\ GeV$

R.Aleksan

Flavour physics

$B_s \to D_sK$ simulation in Z events



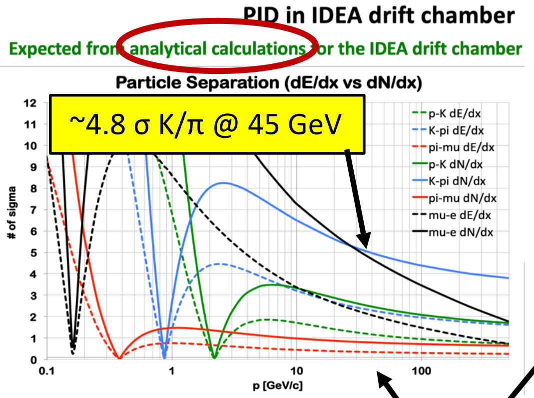
$Z \to \tau\tau$; $\tau \to \pi\nu$ vs $\tau \to K\nu$

π/K separation from 0 to 45.6 GeV

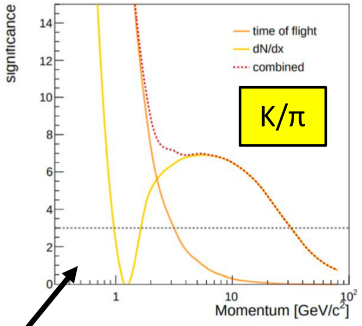
Higgs physics

- Derive sensitivity to **Higgs strange Yukawa coupling**
- Develop a **strange tagger** and apply the tagger to a direct ***SM $h \to s\bar{s}$*** or ***BSM $H \to cs$*** analysis

IDEA Drift Chamber exploiting cluster counting



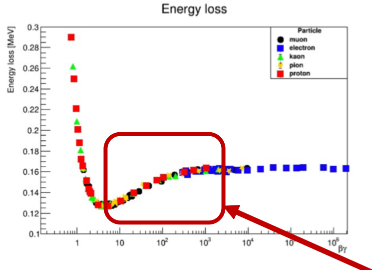
~4.8 σ K/π @ 45 GeV

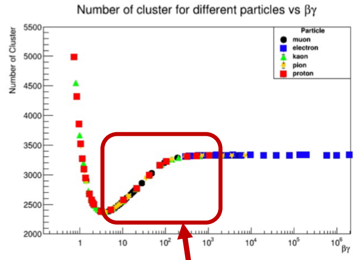


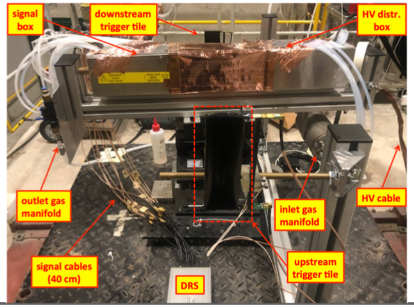
K/π

3-sigma separation for tracks with **p < 30GeV**

Geant4: Relativistic plateau earlier for dN/dx





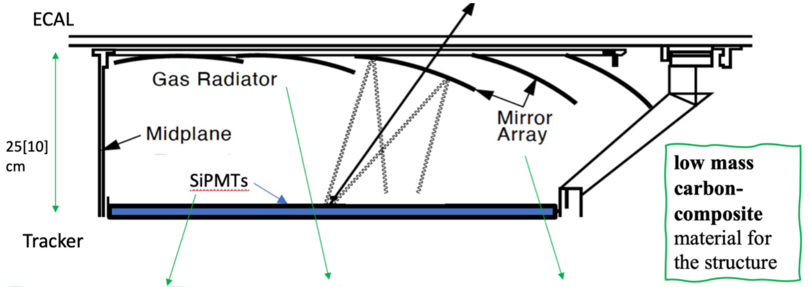


Test beam campain summer 2022: investigate relativistic rise region

Two initiatives on compact RICH

Valentina Maria Martina Cairo (CERN)

Compact Gaseous RICH with SiPMTs



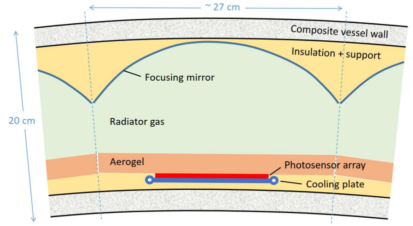
low mass carbon-composite material for the structure

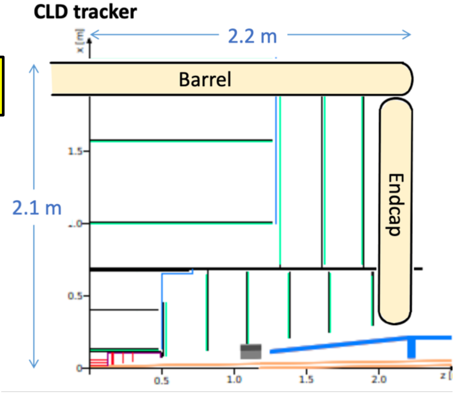
Fast timing device (<100 ps) to provide ToF covering the lower p range and complementing the RICH

Pure C_4F_{10} at 1 bar (boiling point -1.9 C at 1 bar, good refraction index)

Beryllium with reflective coating

R.Forty, FCC Week, 1 July, 2021

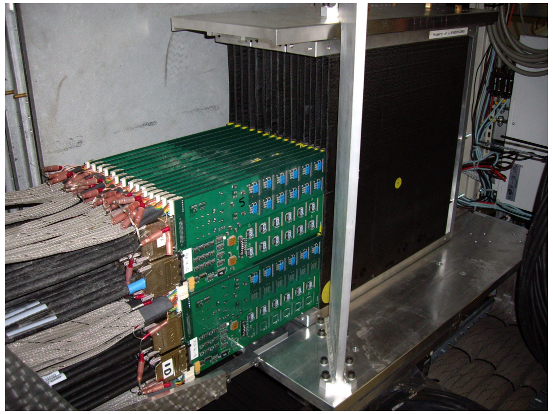


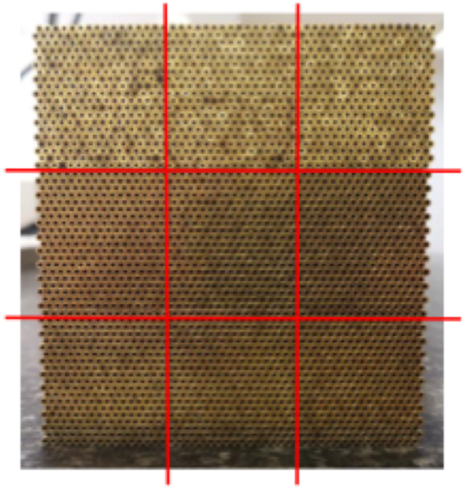


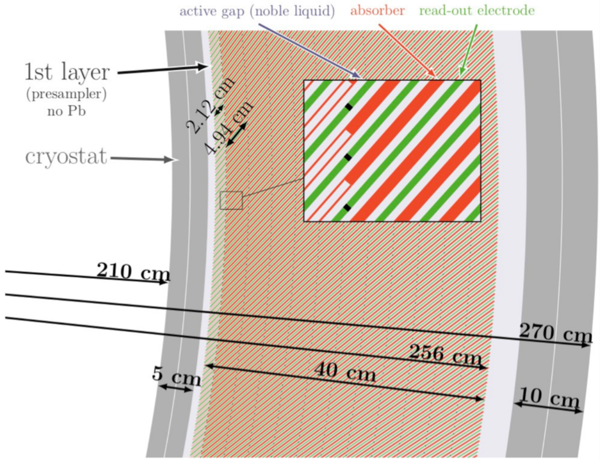
Calorimetry

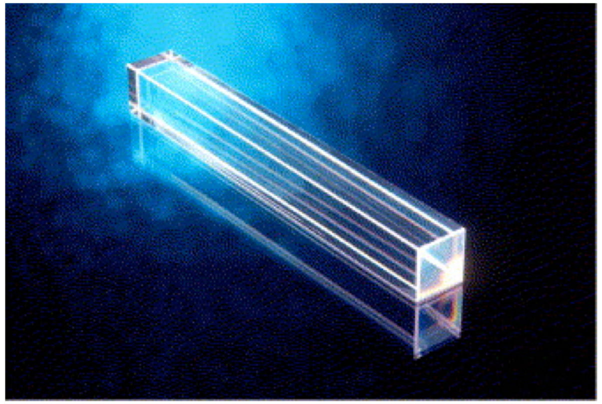
- Several technologies being considered

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 / Pb [W/LCr]	CALICE-like ?
IDEA w Crystals	Finely segmented crystals (possibly DR)	Dual Readout fiber









Liverpool slide

Vincent Boudry

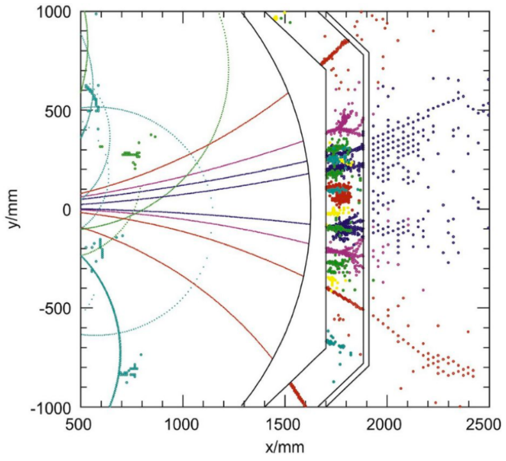
CALICE Calorimetry

I.Laktineh

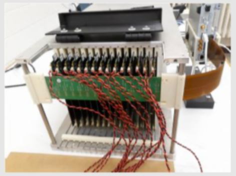
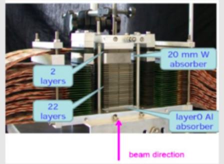
➡ Highly Granular Imaging Calorimetry

ECAL+HCAL

Optimised for Particle Flow



4,5 prototypes, 15⁺ years of R&D, all [to be] tested

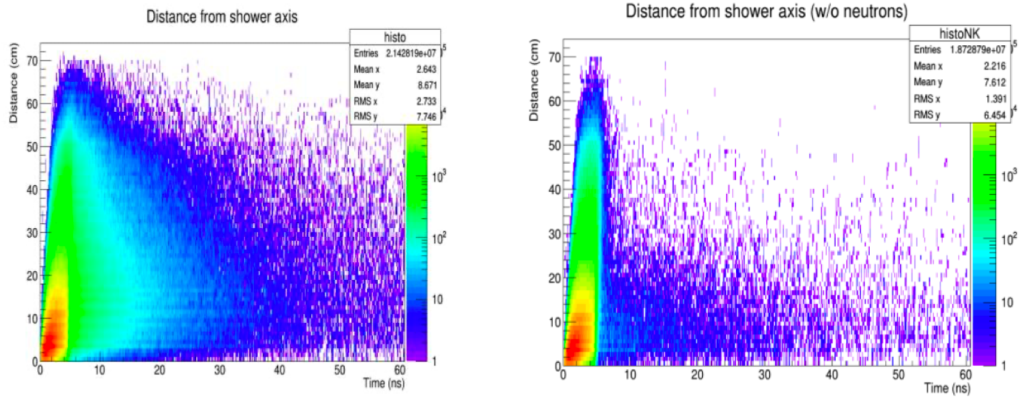
Si-W ECAL	(ALICE FoCAL)	[Scint-W ECAL]	AHCAL	SDHCAL
				
0,5×0,5 cm² ×15 (⟶30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS

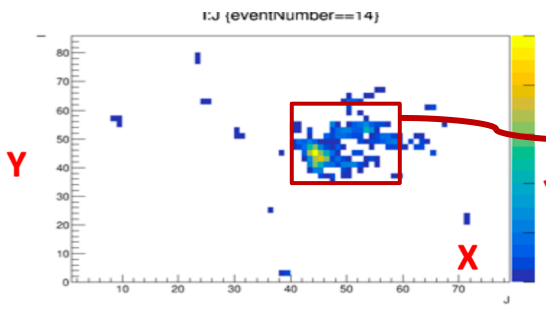
FCC-ee :

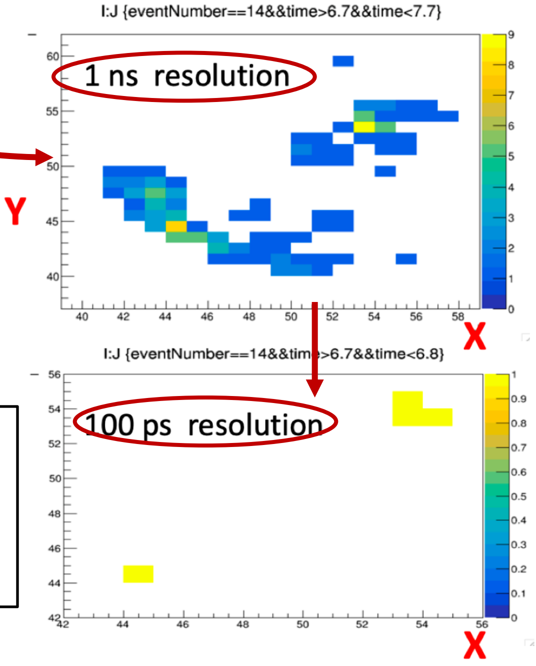
- Need to fix parameters & detector philosophy for a large range of conditions → Think large / complementary
  - Technology ↔ Performances : Trigger/DAQ ↔ noise, noise ↔ detection efficiency, cooling ↔ granularity, …
- … but ~ **+5y for R&D for FCC-ee…**
  Time for new technologies: Timing, ML optimisation, other sensors (Crystal, MGRP, ℓAr, DR, …), μ-cooling, projective readout, Digital sensors (dSiPM)

Bringing precise timing into calorimetry

Timing is an important factor to identify delayed neutrons and **better reconstruct their energy**







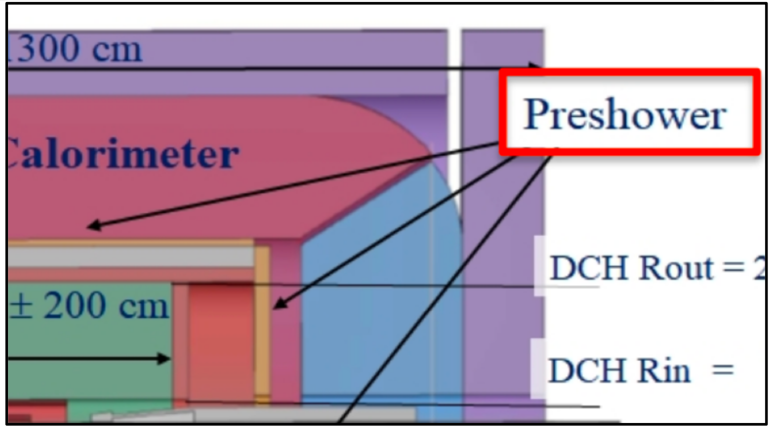
Interesting - but also a challenge
- Readout, data volume ?
- On-detector building of showers?

Marco Lucchini

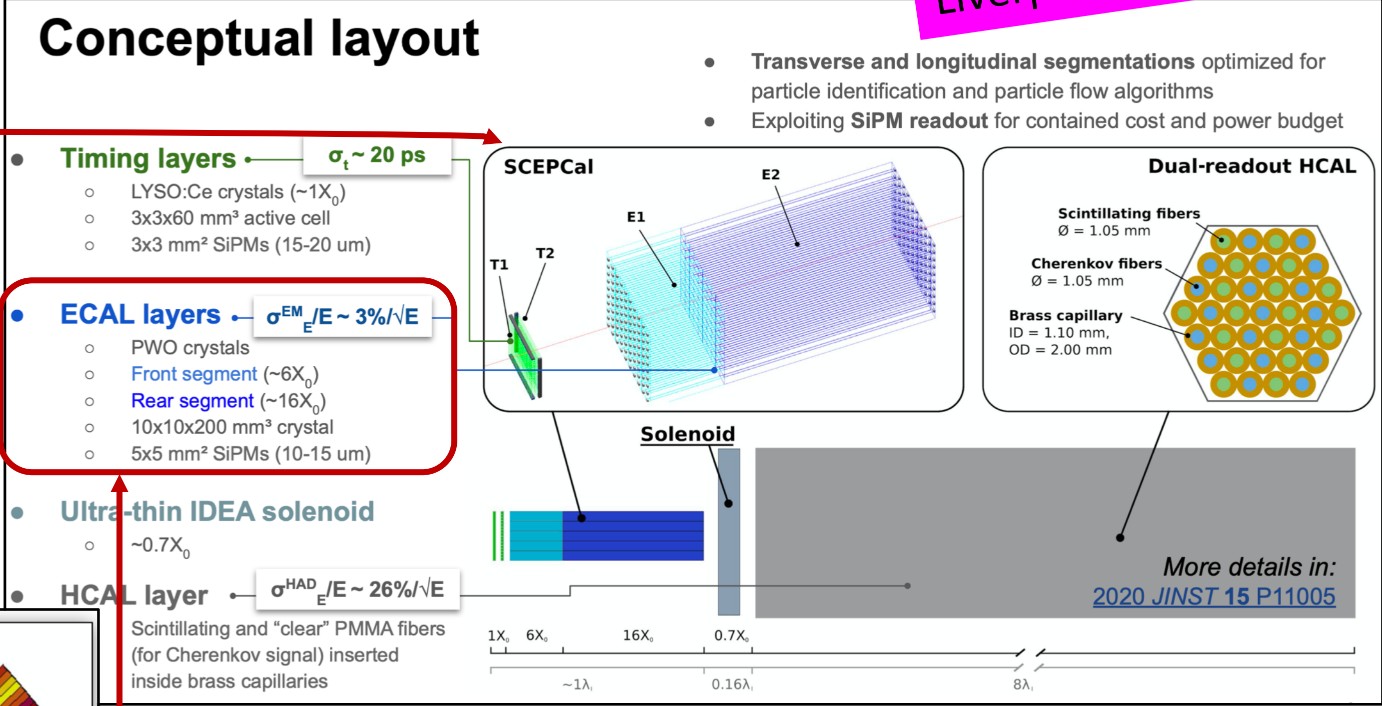
Crystals meet Spaghetti

Liverpool slide

IDEA Concept:
Monolitic calorimeter + preshower



Add crystals



Conceptual layout

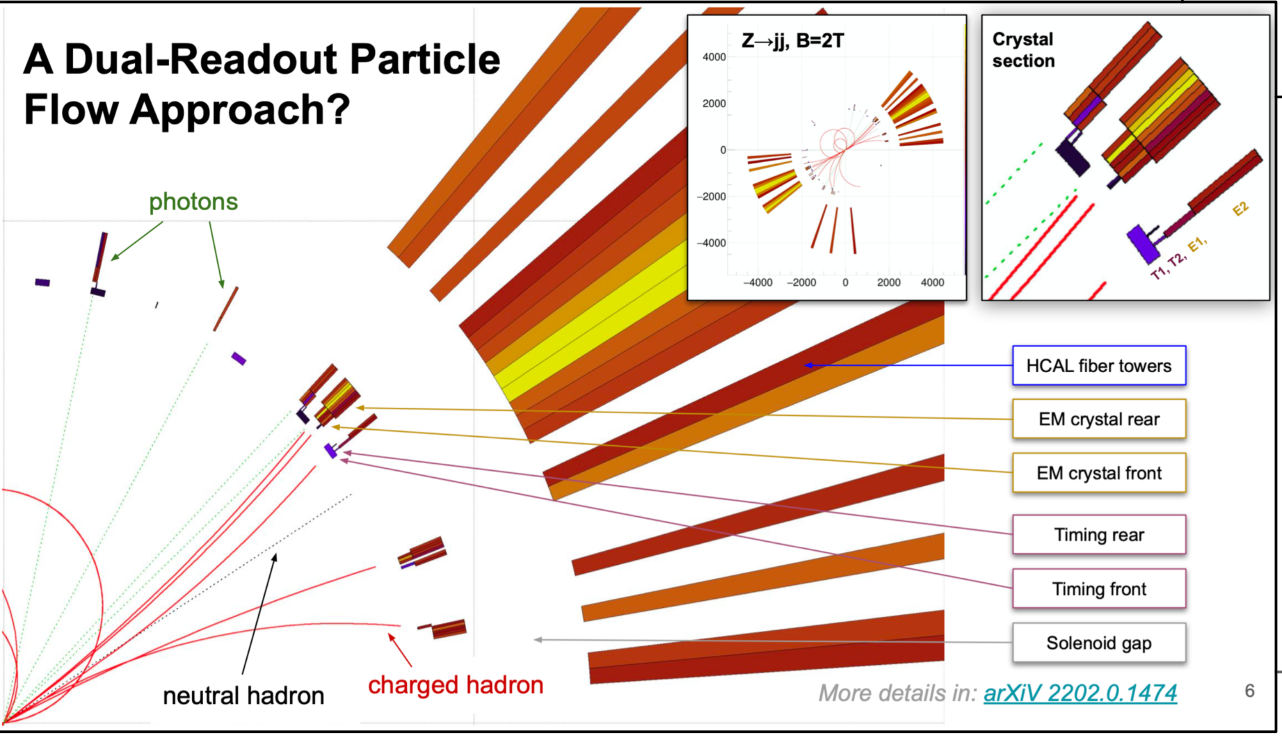
- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~1X_0)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~6X_0)
  - Rear segment (~16X_0)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~0.7X_0
- **HCAL layer** $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$

  Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries

More details in:
2020 *JINST* **15** P11005

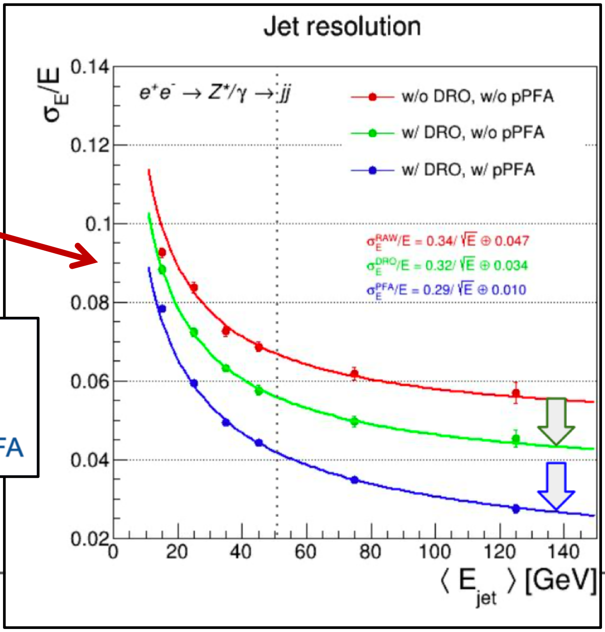
Excellent energy resolution for
- EM
- Jet via DR and pPFA algo



A Dual-Readout Particle Flow Approach?

More details in: arXiV 2202.0.1474

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA



Jet resolution

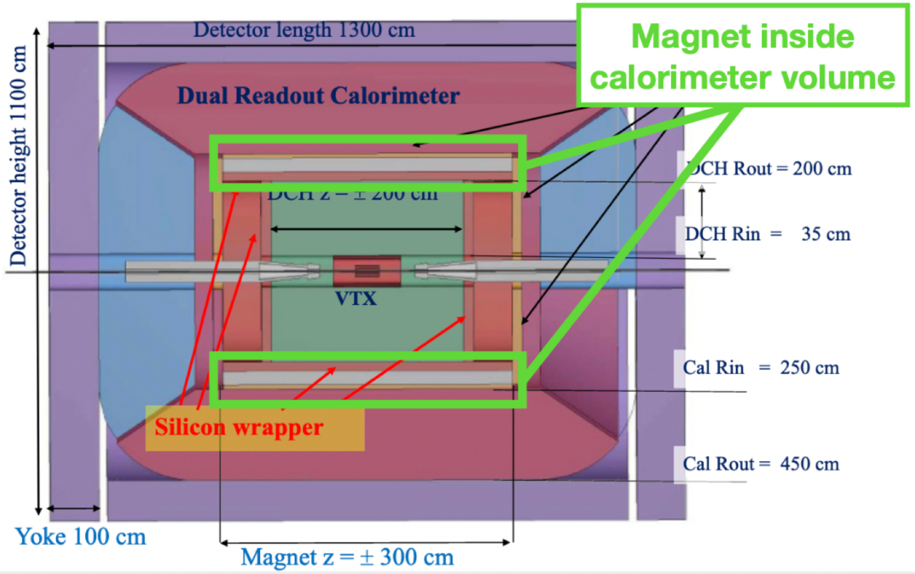
1 Jun, 2022

Liverpool slide

Solenoid Magnet

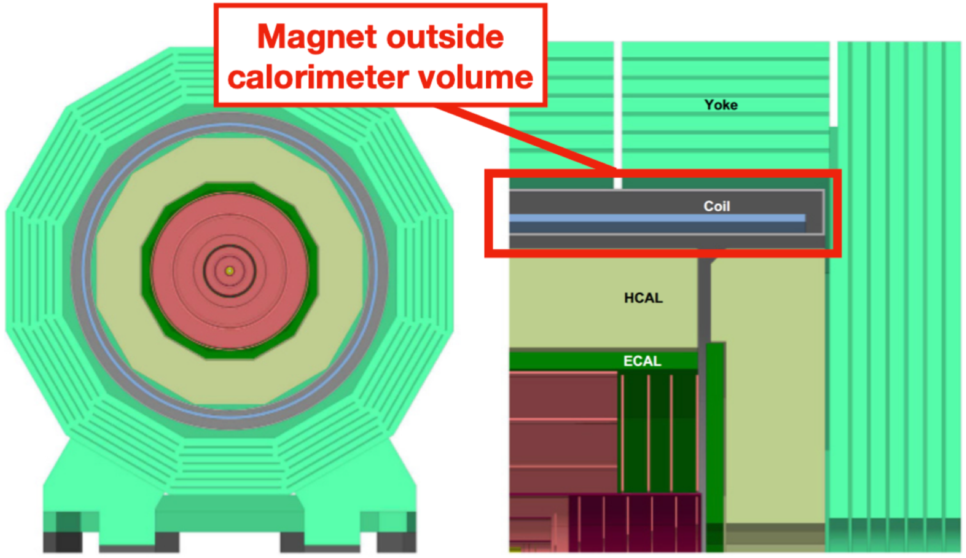
Nikkie Deelen,

International Detector for Electron-positron Accelerators

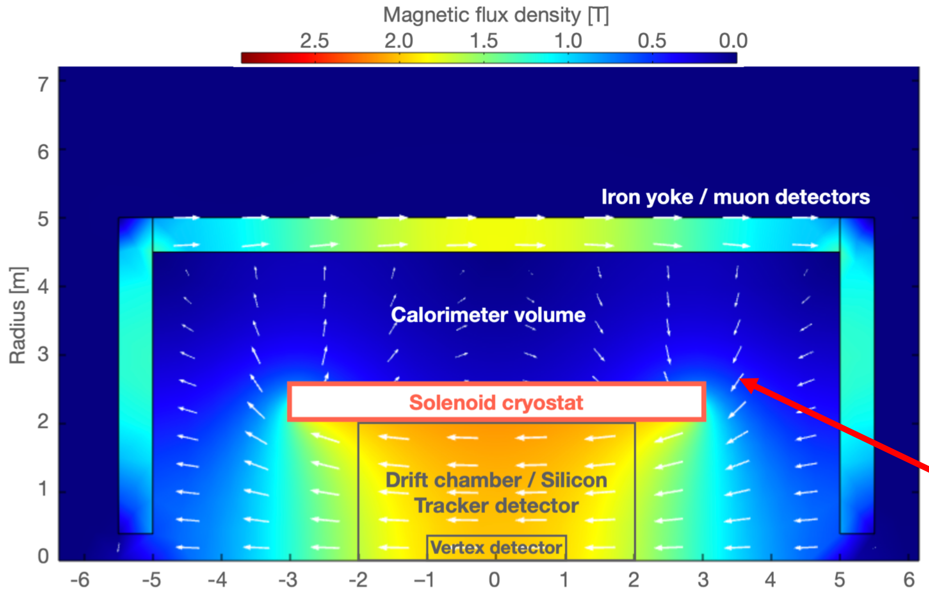


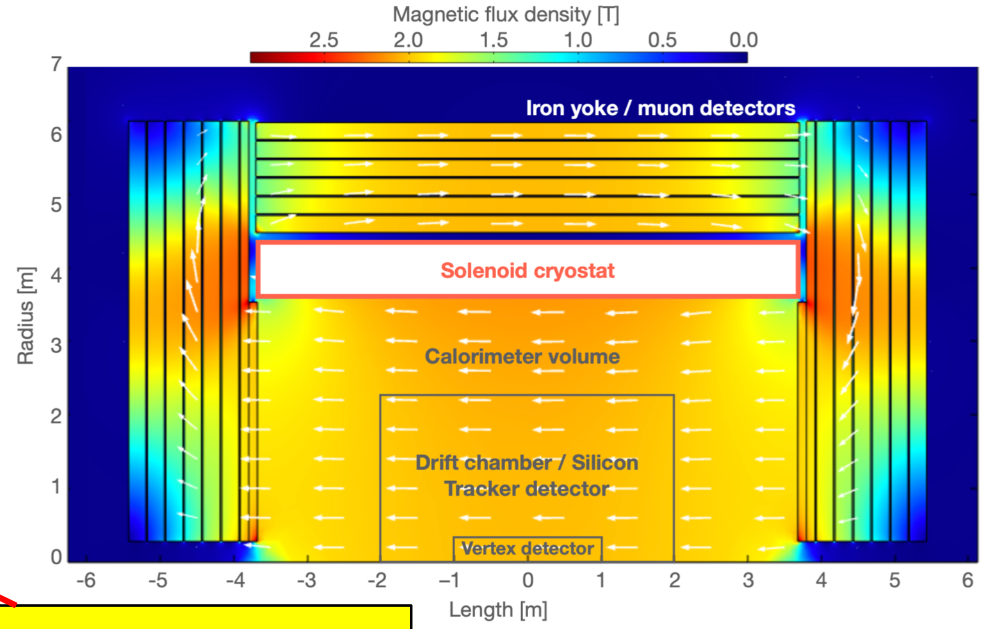
Magnet inside calorimeter volume

CLIC-Like Detector



Magnet outside calorimeter volume





Transparency of the cold mass: 0.76 X_0
Energy density: ~14 kJ/kg [2]

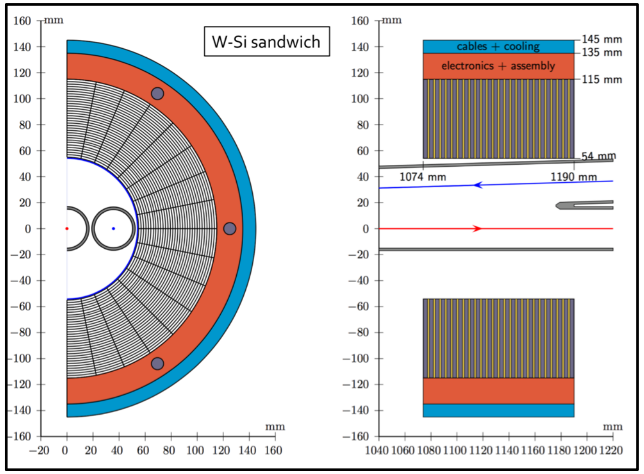
For crystal IDEA:
- Hybrid solution; coil between ECAL and HCAL

Normalisation Issues

Ambitious goals:

- Absolute luminosity measurement to $\lesssim 10^{-4}$
- Relative luminosity (energy-to-energy point) to $\lesssim 10^{-5}$
- Inter-channel normalisation (e.g. μμ/multi-hadronic) to $\lesssim 10^{-5}$

Luminosity Monitors (low angle Bhabha)



- Many R&D/engineering challenges
  - Precision on acceptance boundaries to $\mathcal{O}(1\ \mu m)$!
  - Mechanical assembly, metrology, alignment
  - Physics rate of $\mathcal{O}(100\ kHz)$
  - Readout at 50 MHz BX rate ?
  - Power management / cooling
  - Support / integration in crowded and complex MDI area

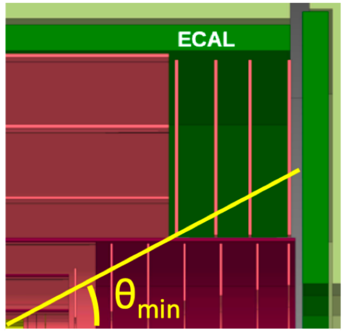
Dedicated presentation in MDI session tomorrow

Complementary lumi process: large angle $e^+e^- \rightarrow \gamma\gamma$

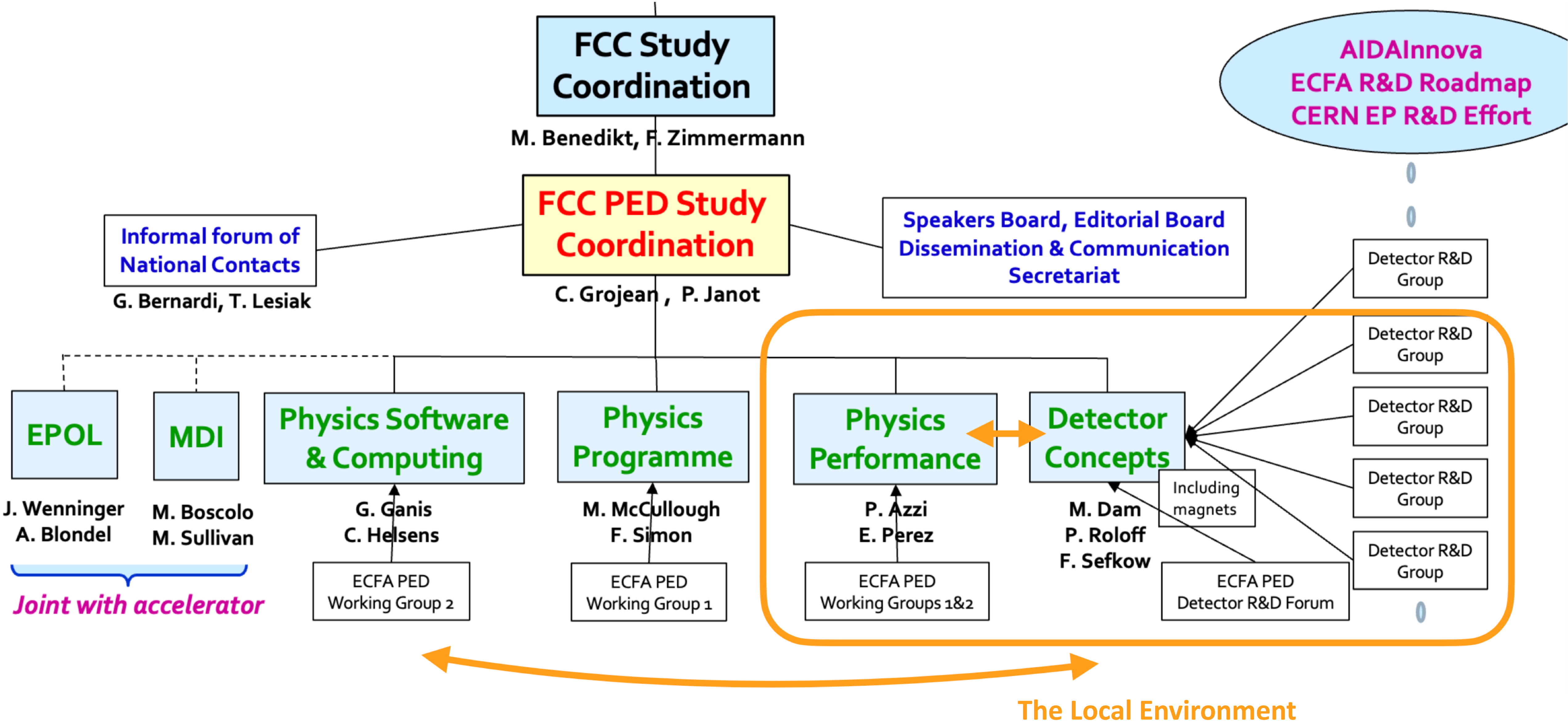
- $10^{-4} \Rightarrow$ control of acceptance boundary $\delta\theta_{min}$ to **$\mathcal{O}$(50 μrad)**
- Possible bckg: $Z \rightarrow \pi^0\gamma \Rightarrow$ need to control $\mathcal{B}(Z\rightarrow\pi^0\gamma)$ to 10^{-7}

Acceptance of $Z \rightarrow \ell\ell$ to 10^{-5}

- Control of acceptance boundary $\delta\theta_{min}$ to **$\mathcal{O}$(50 μrad)**
- No holes or cracks
- Possible implementation: Precisely machined pre-shower device in front of forward calorimeter
  - Note 1: IDEA concept already includes pre-shower + Si wrapper
  - Note 2: CM and detector systems differ by a β=0.015 transverse boost



Detector Concepts in the PED effort



FCC Study Coordination

M. Benedikt, F. Zimmermann

FCC PED Study Coordination

C. Grojean , P. Janot

Informal forum of National Contacts

G. Bernardi, T. Lesiak

Speakers Board, Editorial Board
Dissemination & Communication
Secretariat

AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort

EPOL

J. Wenninger
A. Blondel

MDI

M. Boscolo
M. Sullivan

Joint with accelerator

Physics Software & Computing

G. Ganis
C. Helsens

ECFA PED
Working Group 2

Physics Programme

M. McCullough
F. Simon

ECFA PED
Working Group 1

Physics Performance

P. Azzi
E. Perez

ECFA PED
Working Groups 1&2

Detector Concepts

M. Dam
P. Roloff
F. Sefkow

Including magnets

ECFA PED
Detector R&D Forum

Detector R&D Group

Detector R&D Group

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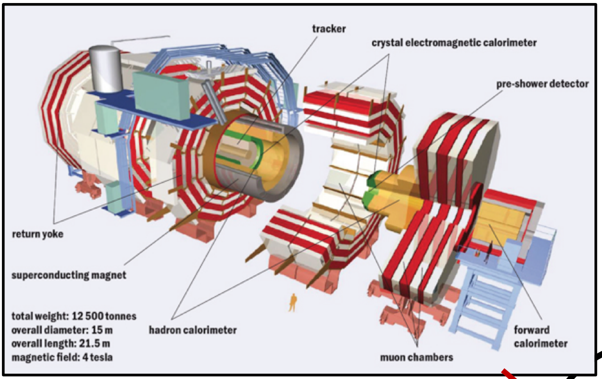
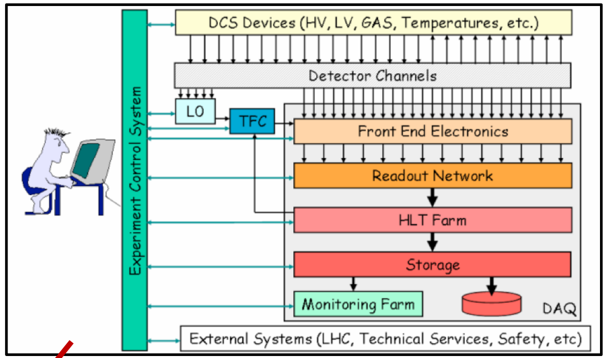
Detector R&D Group

The Local Environment

Detector Concept

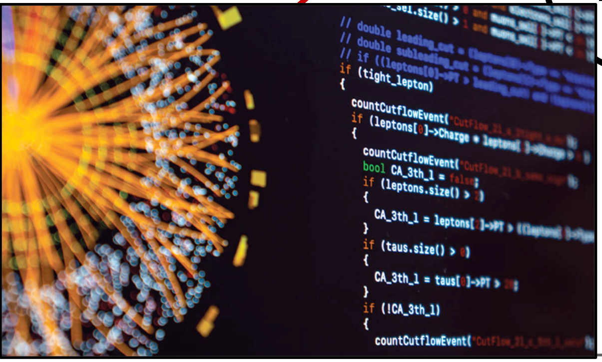


From mandate document



A Detector Concept eventually includes

- Assembly of sub-detectors including magnet system
- Systems for data acquisition, processing, powering and cooling based on estimate of data rates and size
- Software implementation of detector allowing performance evaluation
- Overview of services, consumables, power consumption, and ecological impact
- Evaluation of construction and operating costs



Detector Concept Working Group Goals

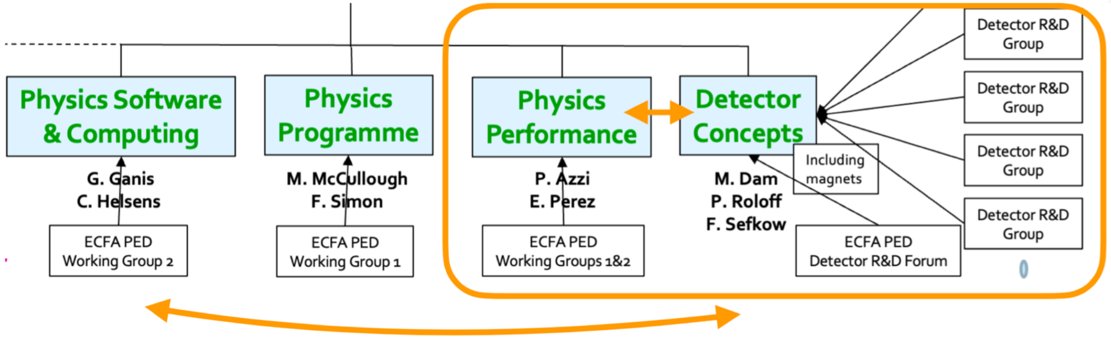
From mandate document

- Demonstrate that detectors can be built to fully exploit the FCC physics opportunities
  - ❑ Optimize the compatibility of the detector concepts with operation at the FCC-ee, with the MDI layout, and with the timing and background conditions
  - ❑ Show that performance requirements can be met with existing or emerging technologies and realistic integration concepts
- Provide guidance for coherent detector R&D efforts to address FCC detector requirements
  - ❑ And to support their funding requests
- Function as a forum, where progress, ideas, and results from individual R&D efforts and test-beam activities are presented, discussed and reviewed in view of the FCC-ee detector requirements and physics; in particular, follow technological developments that could lead to new physics opportunities.

Kick-off Workshop on Detector Optimisation and Benchmarking

Kick-off workshop at CERN, 22-23 June

- Jointly prepared by DetCon, PhysPerf and Software.



Physics Software & Computing
G. Ganis
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ECFA PED Working Group 2

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Including magnets
ECFA PED Detector R&D Forum

Detector R&D Group
Detector R&D Group
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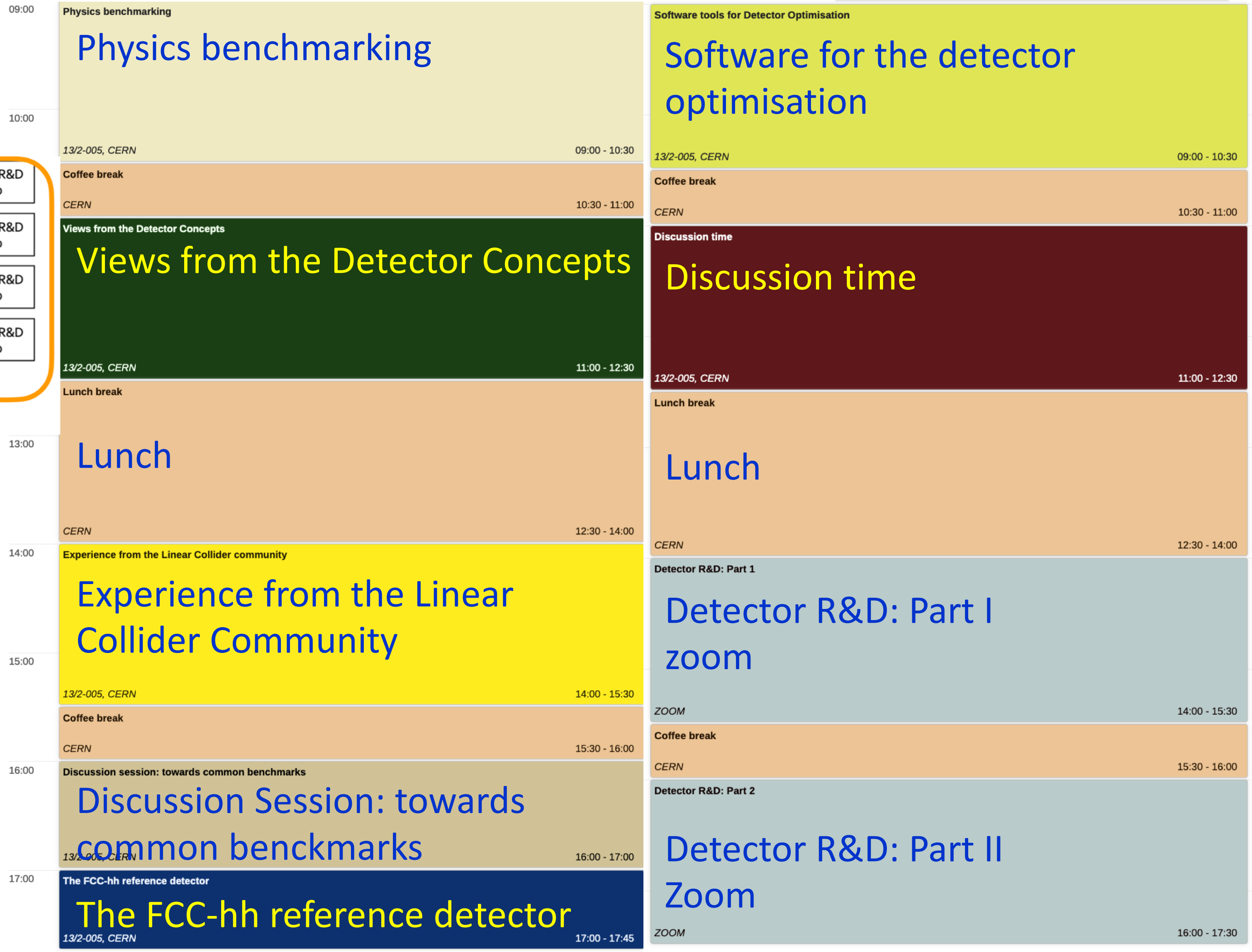
Detector R&D Group

- Agenda and registration at
  - https://indico.cern.ch/event/1165167/

- Foresee other future workshops with different focus, e.g. background and MDI.

Wednesday 22

Thursdays 22



Wednesday 22:

09:00 Physics benchmarking — **Physics benchmarking** — 13/2-005, CERN — 09:00 - 10:30

Coffee break — CERN — 10:30 - 11:00

Views from the Detector Concepts — **Views from the Detector Concepts** — 13/2-005, CERN — 11:00 - 12:30

Lunch break — **Lunch** — CERN — 12:30 - 14:00

Experience from the Linear Collider community — **Experience from the Linear Collider Community** — 13/2-005, CERN — 14:00 - 15:30

Coffee break — CERN — 15:30 - 16:00

Discussion session: towards common benchmarks — **Discussion Session: towards common benckmarks** — 13/2-005, CERN — 16:00 - 17:00

The FCC-hh reference detector — **The FCC-hh reference detector** — 13/2-005, CERN — 17:00 - 17:45

Thursdays 22:

Software tools for Detector Optimisation — **Software for the detector optimisation** — 13/2-005, CERN — 09:00 - 10:30

Coffee break — CERN — 10:30 - 11:00

Discussion time — **Discussion time** — 13/2-005, CERN — 11:00 - 12:30

Lunch break — **Lunch** — CERN — 12:30 - 14:00

Detector R&D: Part 1 — **Detector R&D: Part I zoom** — ZOOM — 14:00 - 15:30

Coffee break — CERN — 15:30 - 16:00

Detector R&D: Part 2 — **Detector R&D: Part II Zoom** — ZOOM — 16:00 - 17:30

Beer & Pizza!

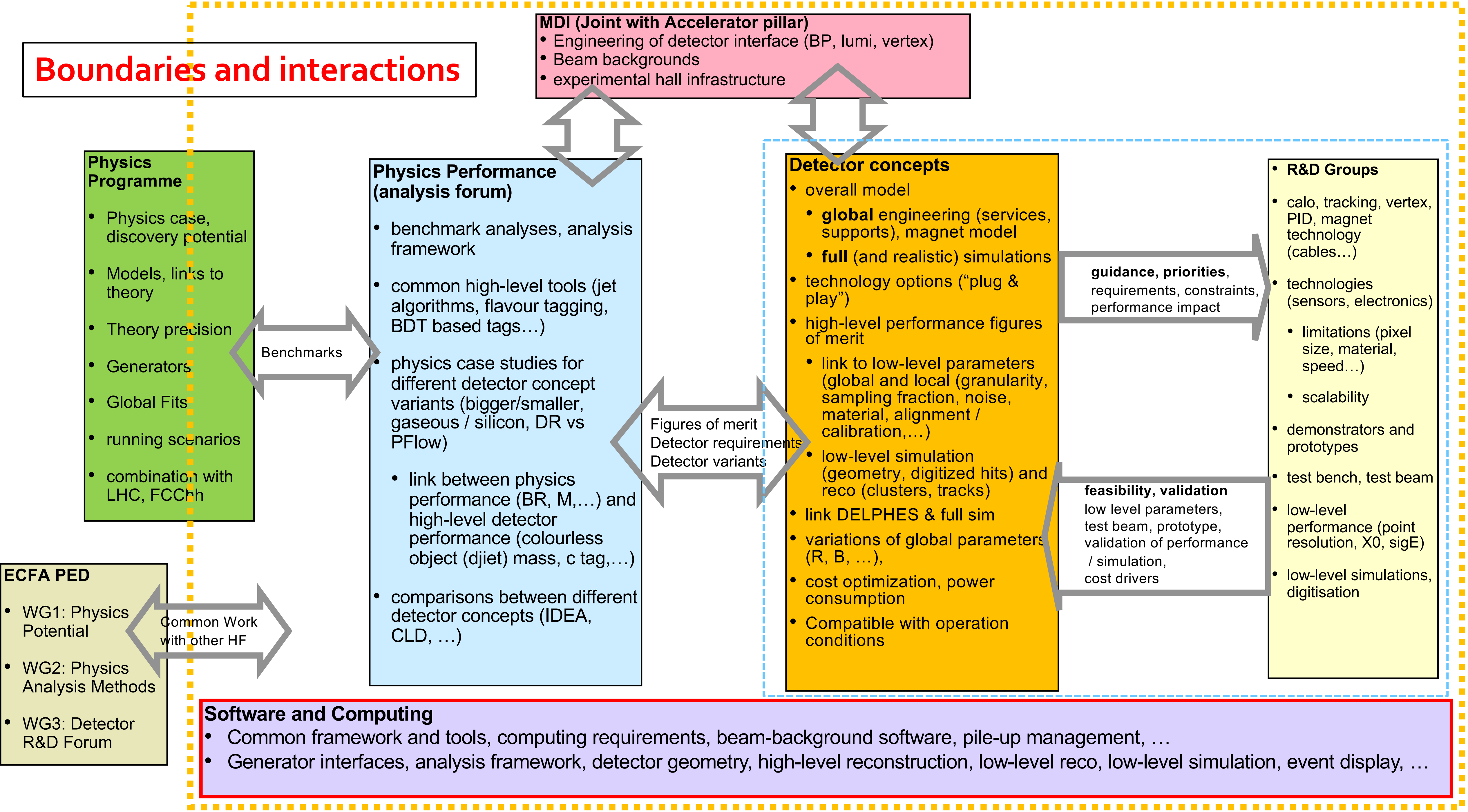
Outlook

- FCC-ee has an enormous physics potential
  - Unprecedented factory for Z, W and Higgs bosons; for top, beauty, and charm quarks; and for tau leptons
  - Possibly also factory for BSM particles !!
- Instrumentation to fully exploit the physics potential is challenging and exciting
  - FCC-ee can host (up to) four experimental collaborations
  - Full exploitation of physics potential via N ”general purpose” experiments, possibly complemented by M dedicated experiments
    - e.g. heavy flavour
- For next ESUPP, need to demonstrate that experimental challenge can be met by several (N+M ≤ 4) Detector Concepts
- Detector Concepts working group formed early this year
  - Provide guidance for coherent detector R&D efforts to address FCC detector requirements
  - Establish forum, where progress, ideas, and results from individual R&D efforts and test-beam activities are presented, discussed and reviewed
  - Work as interface to MDI and accelerator groups
- Monthly meetings, first held in April https://indico.cern.ch/event/1137809/
- Dedicated ”kick off” workshop in at CERN June 22-23 https://indico.cern.ch/event/1165167/
- e-group: *FCC-PED-DetectorConcepts*

Please don't hesitate to join!

Extras

Boundaries and interactions



MDI (Joint with Accelerator pillar)
- Engineering of detector interface (BP, lumi, vertex)
- Beam backgrounds
- experimental hall infrastructure

Physics Programme
- Physics case, discovery potential
- Models, links to theory
- Theory precision
- Generators
- Global Fits
- running scenarios
- combination with LHC, FCChh

Benchmarks

ECFA PED
- WG1: Physics Potential
- WG2: Physics Analysis Methods
- WG3: Detector R&D Forum

Common Work with other HF

Physics Performance (analysis forum)
- benchmark analyses, analysis framework
- common high-level tools (jet algorithms, flavour tagging, BDT based tags…)
- physics case studies for different detector concept variants (bigger/smaller, gaseous / silicon, DR vs PFlow)
  - link between physics performance (BR, M,…) and high-level detector performance (colourless object (djiet) mass, c tag,…)
- comparisons between different detector concepts (IDEA, CLD, …)

Figures of merit
Detector requirements
Detector variants

Detector concepts
- overall model
  - **global** engineering (services, supports), magnet model
  - **full** (and realistic) simulations
- technology options (“plug & play”)
- high-level performance figures of merit
  - link to low-level parameters (global and local (granularity, sampling fraction, noise, material, alignment / calibration,…)
  - low-level simulation (geometry, digitized hits) and reco (clusters, tracks)
- link DELPHES & full sim
- variations of global parameters (R, B, …),
- cost optimization, power consumption
- Compatible with operation conditions

guidance, priorities, requirements, constraints, performance impact

feasibility, validation
low level parameters,
test beam, prototype,
validation of performance / simulation,
cost drivers

- **R&D Groups**
- calo, tracking, vertex, PID, magnet technology (cables…)
- technologies (sensors, electronics)
  - limitations (pixel size, material, speed…)
  - scalability
- demonstrators and prototypes
- test bench, test beam
- low-level performance (point resolution, X0, sigE)
- low-level simulations, digitisation

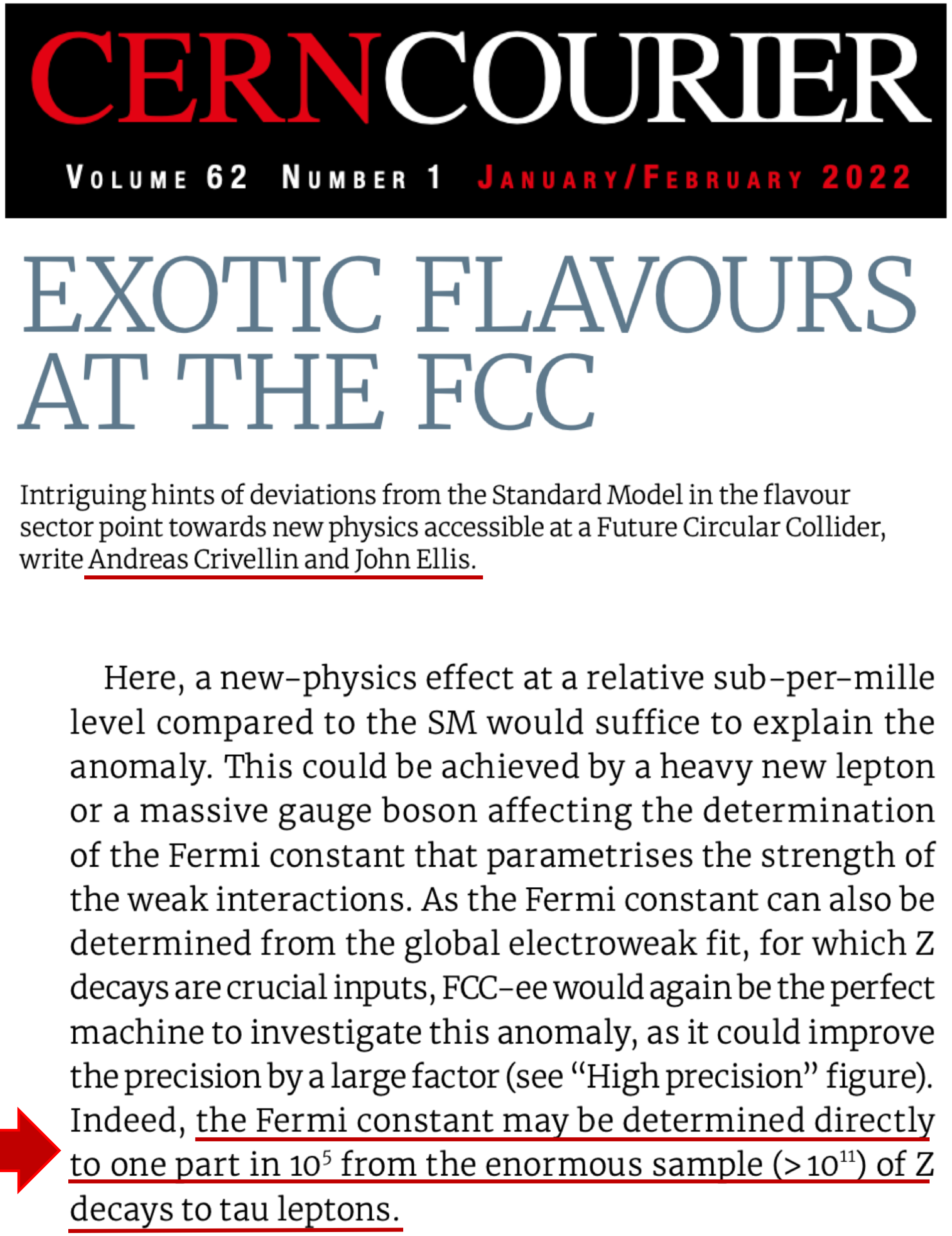
Software and Computing
- Common framework and tools, computing requirements, beam-background software, pile-up management, …
- Generator interfaces, analysis framework, detector geometry, high-level reconstruction, low-level reco, low-level simulation, event display, …

Readout, DAQ, Data Handling

- In particular at Z-peak, challenging conditions
  - 50 MHz BX rate
  - 70 kHz Z rate + ~100 kHz LumiCal rate
  - Absolute normalisation goal 10^{-4}
    - In comparison, ”pileup” parameter for LumiCal is ~$2x10^{-3}$
- Different sub-detectors tend to prefer different integration times
  - Silicon VTX/tracker sensors: $\mathcal{O}$(μs) [also to save power]
    - Time-stamping probably needed
  - LumiCal: Probably preferential at ~BX frequency (20 ns)
    - Avoid additional event pileup
- How to organize readout?
  - Need a ”hardware” trigger with latency buffering a la LHC
    - Which detector elements provide the trigger ?
  - Free streaming of self-triggering sub-detectors, event building based on precise timing information
    - Need careful treatment of relative normalisation of sub-detectors

- Need to consider DAQ issues (trigger vs. streaming) when designing detectors and their readout
- Off-line handling of $\mathcal{O}(10^{13})$ events for precision physics
  - … and Monte Carlo

Example of precision challenge: Universality of Fermi constant (i)



CERNCOURIER
VOLUME 62 NUMBER 1 JANUARY/FEBRUARY 2022

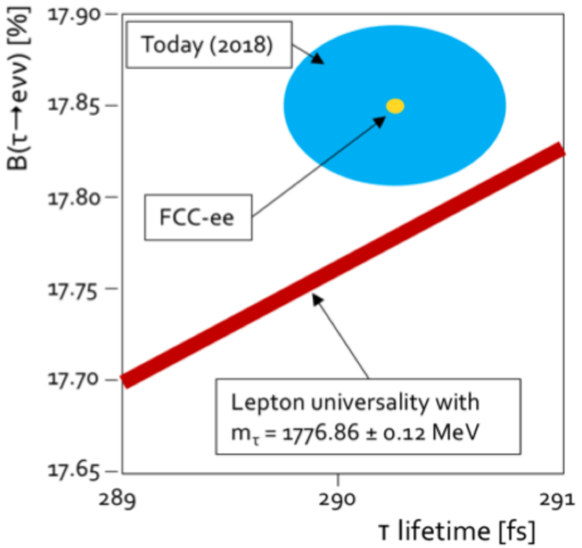
EXOTIC FLAVOURS AT THE FCC

Intriguing hints of deviations from the Standard Model in the flavour sector point towards new physics accessible at a Future Circular Collider, write Andreas Crivellin and John Ellis.

Here, a new-physics effect at a relative sub-per-mille level compared to the SM would suffice to explain the anomaly. This could be achieved by a heavy new lepton or a massive gauge boson affecting the determination of the Fermi constant that parametrises the strength of the weak interactions. As the Fermi constant can also be determined from the global electroweak fit, for which Z decays are crucial inputs, FCC-ee would again be the perfect machine to investigate this anomaly, as it could improve the precision by a large factor (see "High precision" figure). Indeed, the Fermi constant may be determined directly to one part in 10^5 from the enormous sample ($>10^{11}$) of Z decays to tau leptons.

Kamenik

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04



M. Dam, SciPostPhys.Proc.1,041(2019)

Example of precision challenge: Universality of Fermi constant (ii)

The Fermi constant is measured in μ decays and defined by

$$\left(G_F^\mu\right)^2 = 192\pi^3 \frac{\tau_\mu}{m_\mu^5}$$

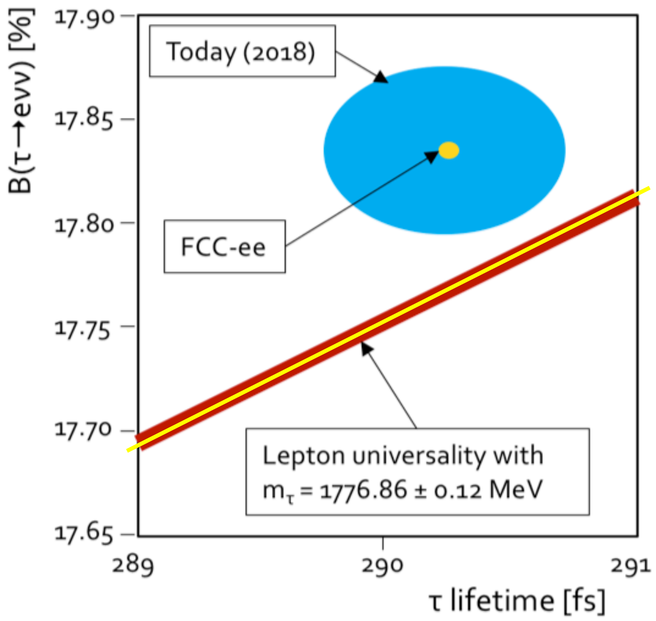
(known to 0.5 ppm)

Similarly can define Fermi constant measured in τ decays by

$$\left(G_F^\tau\right)^2 = 192\pi^3 \frac{\tau_\tau}{m_\tau^5} \cdot \frac{1}{\mathscr{B}(\tau \to e\nu\nu)}$$

(known to 1700 ppm)

Universality supported by current data
- 1σ error ellipse (blue) consistent with mass (red)



Shown in yellow: first guestimates on FCC-ee precisions

$$\frac{\delta G_F^\tau}{G_F^\tau} = \frac{5}{2}\frac{\delta m_\tau}{m_\tau} \oplus \frac{1}{2}\frac{\delta \tau_\tau}{\tau_\tau} \oplus \frac{1}{2}\frac{\delta \mathscr{B}}{\mathscr{B}}$$

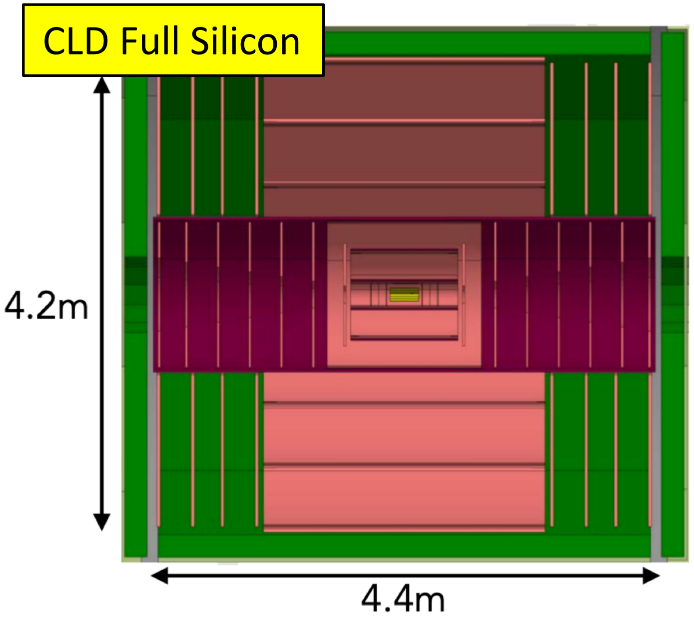
Today:	67 ppm BES	1700 ppm Belle	1700 ppm LEP

FCC-ee: Will see 3x10^{11} τ decays
Statistical uncertainties at the 10 ppm level
How well can we control systematics?

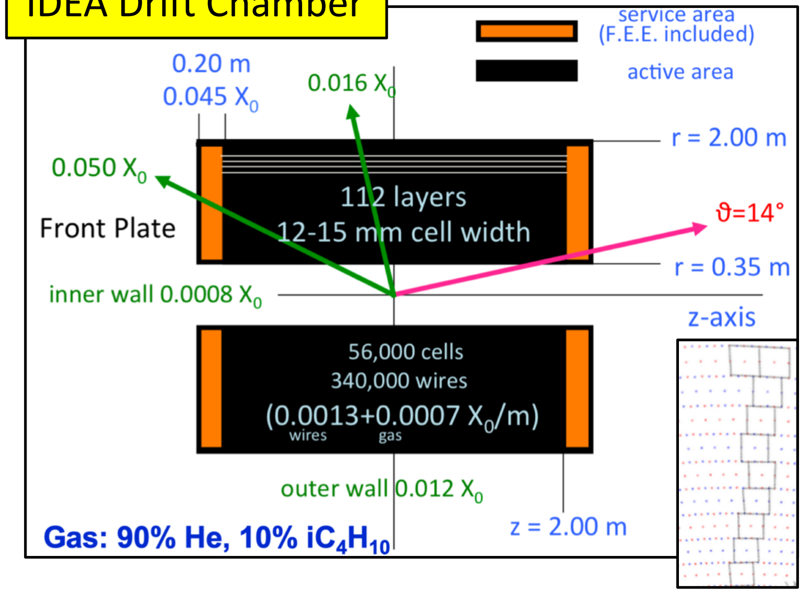
m_τ	Use J/ψ mass as reference (known to 2 ppm)	tracking
τ_τ	Laboratory flight distance of 2.2 mm ⇒ 10 ppm corresponds to 22 nm (!!)	vertex detector
$\mathscr{B}$	No improvement since LEP (statistics limited) Depends primarily e$^-$/π$^-$ (& e$^-$/ρ$^-$) separation	ECAL dE/dx

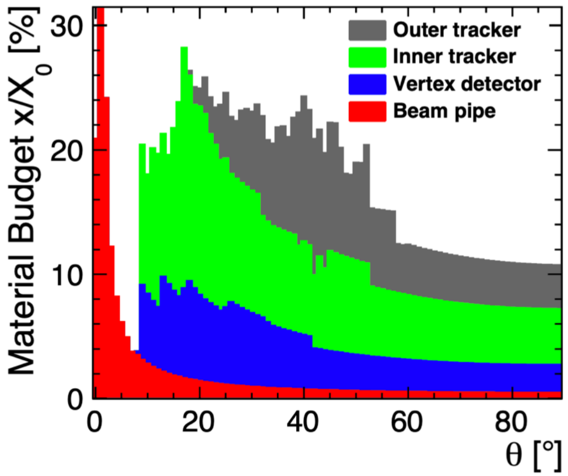
Trackers

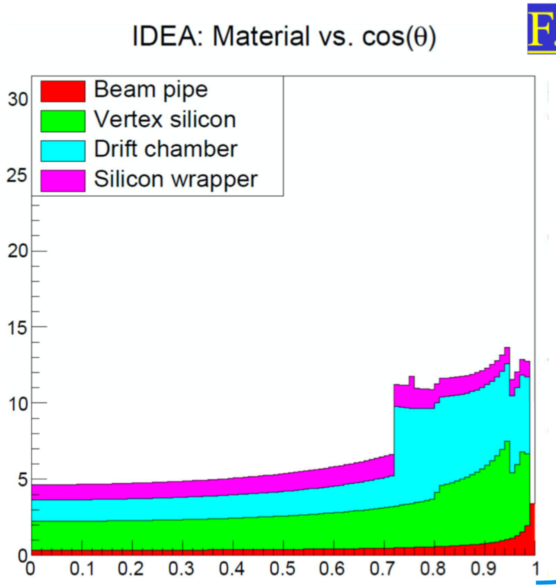
CLD Full Silicon



IDEA Drift Chamber



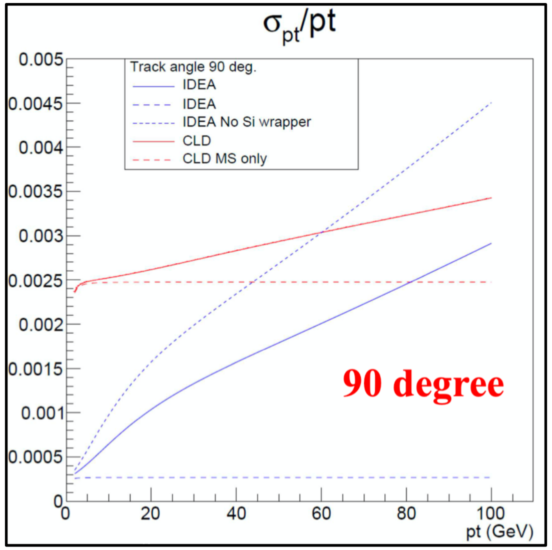




F. Bedeschi

IDEA He-based Drift Chamber considerably lighter than CLD full silicon tracker

For FCC-ee momenta, momentum resolution highly affected by multiple scattering



However, even if one goes for Drift Chamber, still need for large area Si sensors:

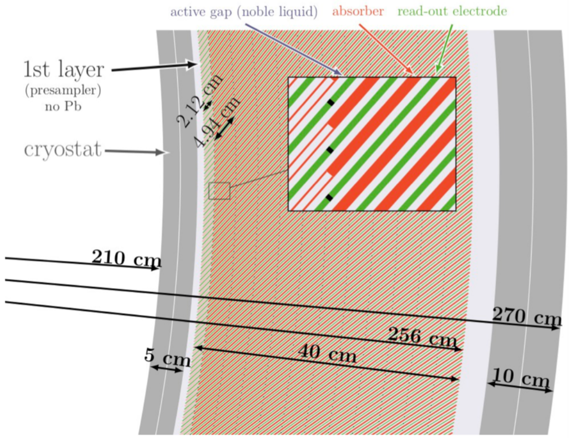
- Precise Vertex Detector
- Large area Si Wrapper

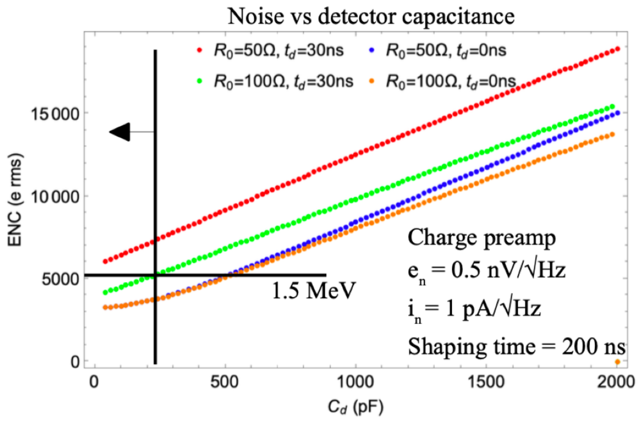
What about a TPC?

- Very high physics rate (70 kHz)
- B field limited to 2 Tesla
- Considered for CEPC, but having difficulties…

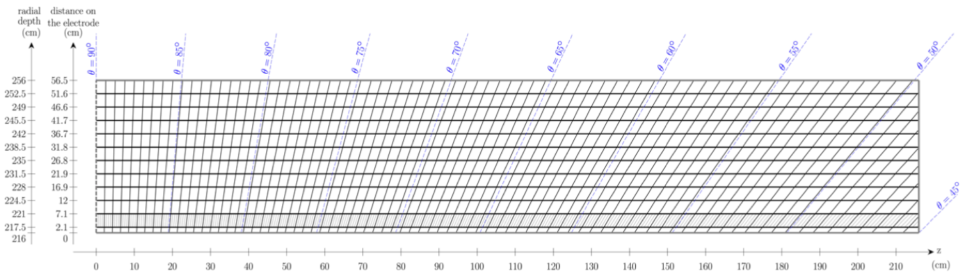
NEW!! Detector Concept with LAr ECAL taking shape

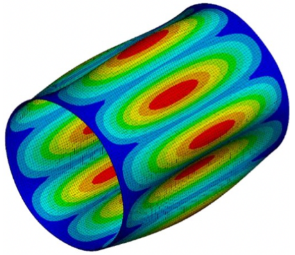
Brieuc François





MIP signal over noise > 5, per cell, can be achieved!



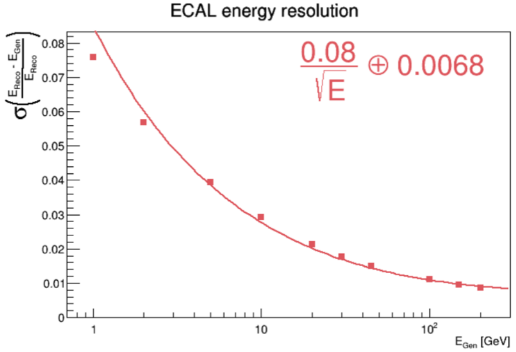


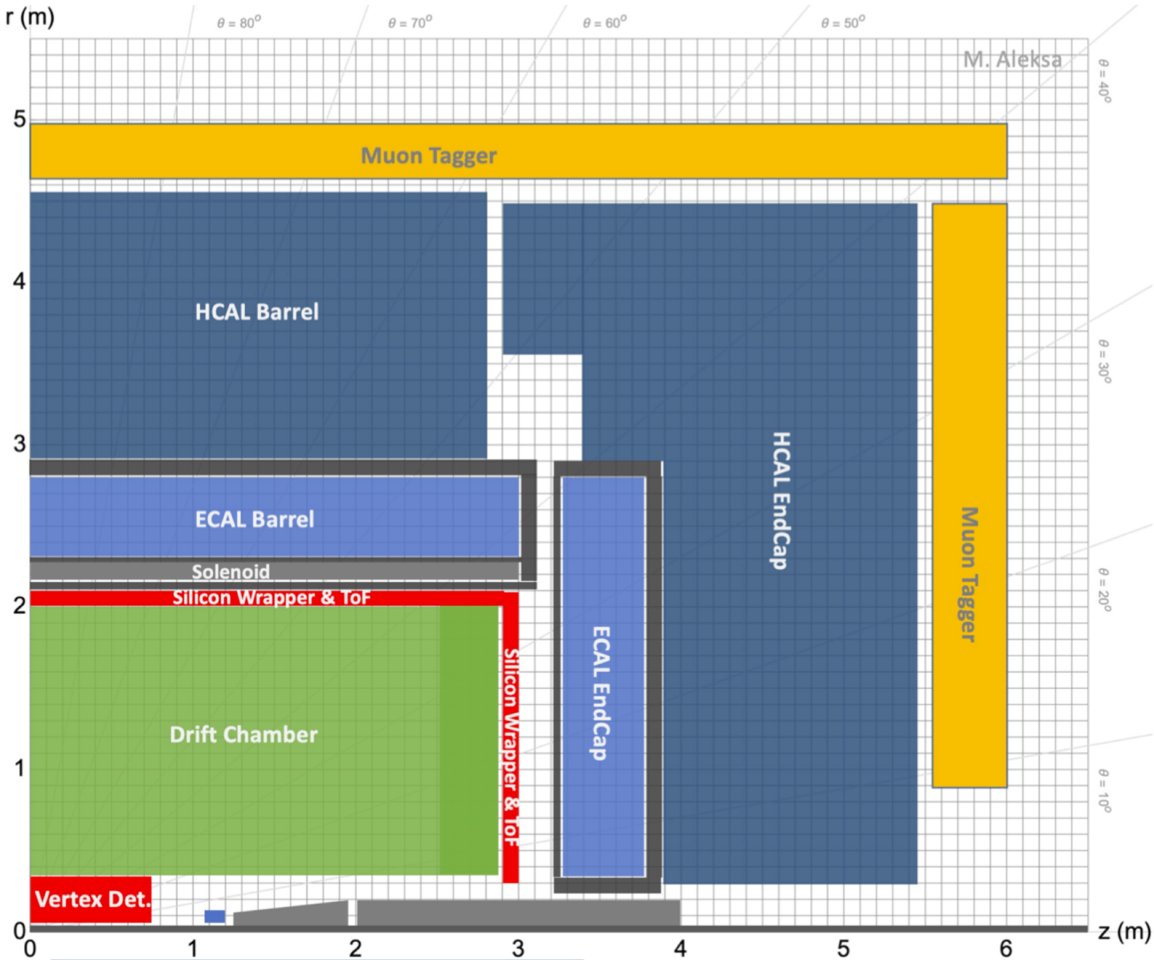
Lightweight cryostat

Tau identification migration matrix

Recon → Gen ↓	$\pi^\pm\,\nu$	$\pi^\pm\,\pi^0\,\nu$	$\pi^\pm\,2\pi^0\nu$	$\pi^\pm\,3\pi^0\nu$	$\pi^\pm\,4\pi^0\nu$
$\pi^\pm\,\nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm\,\pi^0\,\nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm\,2\pi^0\nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm\,3\pi^0\nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

Full simulation. Cut based analysis;
Simplified geometry (2x2x4 cm^3 cells)





Detector Concept

- Vertex Detector:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- Drift Chamber (±2.5m active?) – TPC?
- Silicon Wrapper + ToF:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- Solenoid B=2T, sharing cryostat with ECAL
- High Granularity ECAL:
  - Noble liquid + Pb or W
- High Granularity HCAL / Iron Yoke:
  - Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
- Muon Tagger:
  - Drift chambers, RPC, MicroMegas