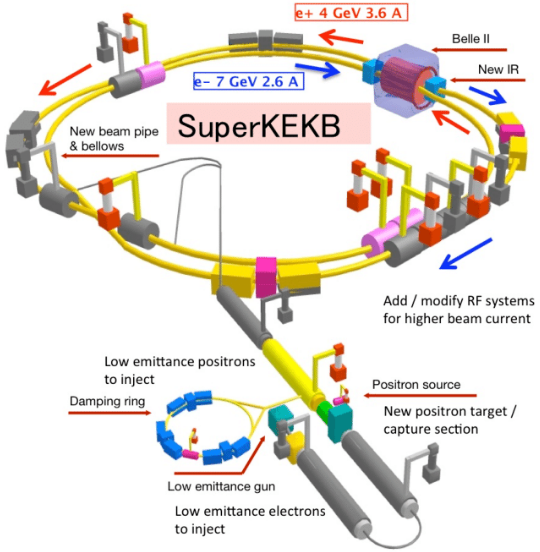
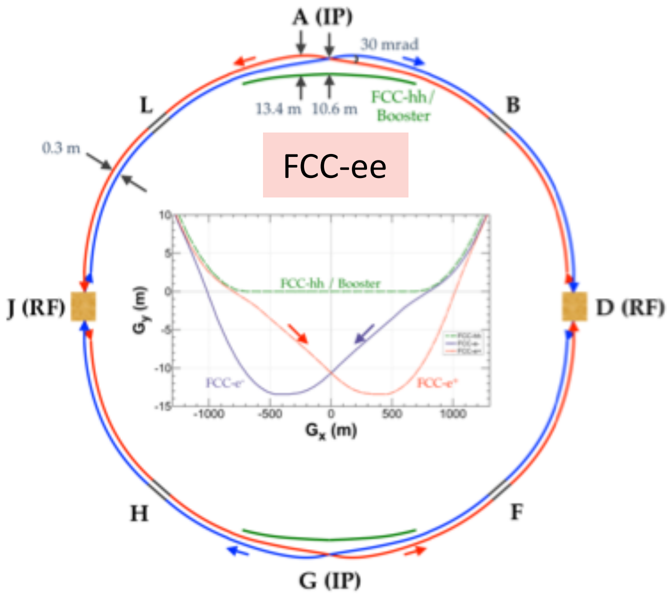
# Detector R&D requirements for future circular high energy $e^+e^-$ machines



Mogens Dam
Niels Bohr Institute,
Copenhagen

ECFA Detector R&D Roadmap
Input from Future Facilities

19th Feb., 2021



# Outline

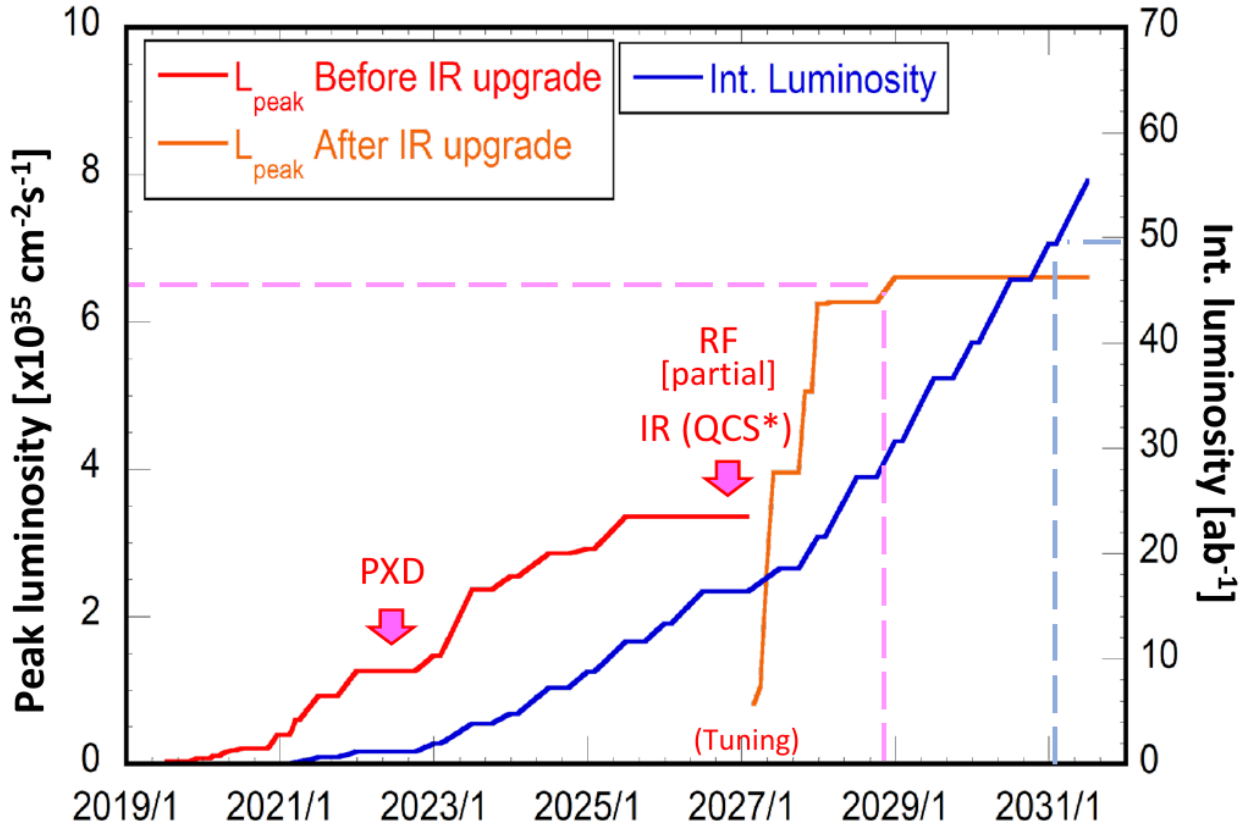
1. Belle II upgrades for high luminosity
2. Instrumentation for FCC-ee

# Belle II Upgrades for High Luminosity *)

*) Slides prepared by Fransesco Forti
Francesco.Forti@pi.infn.it

# Belle II / SuperKEKB upgrade plans

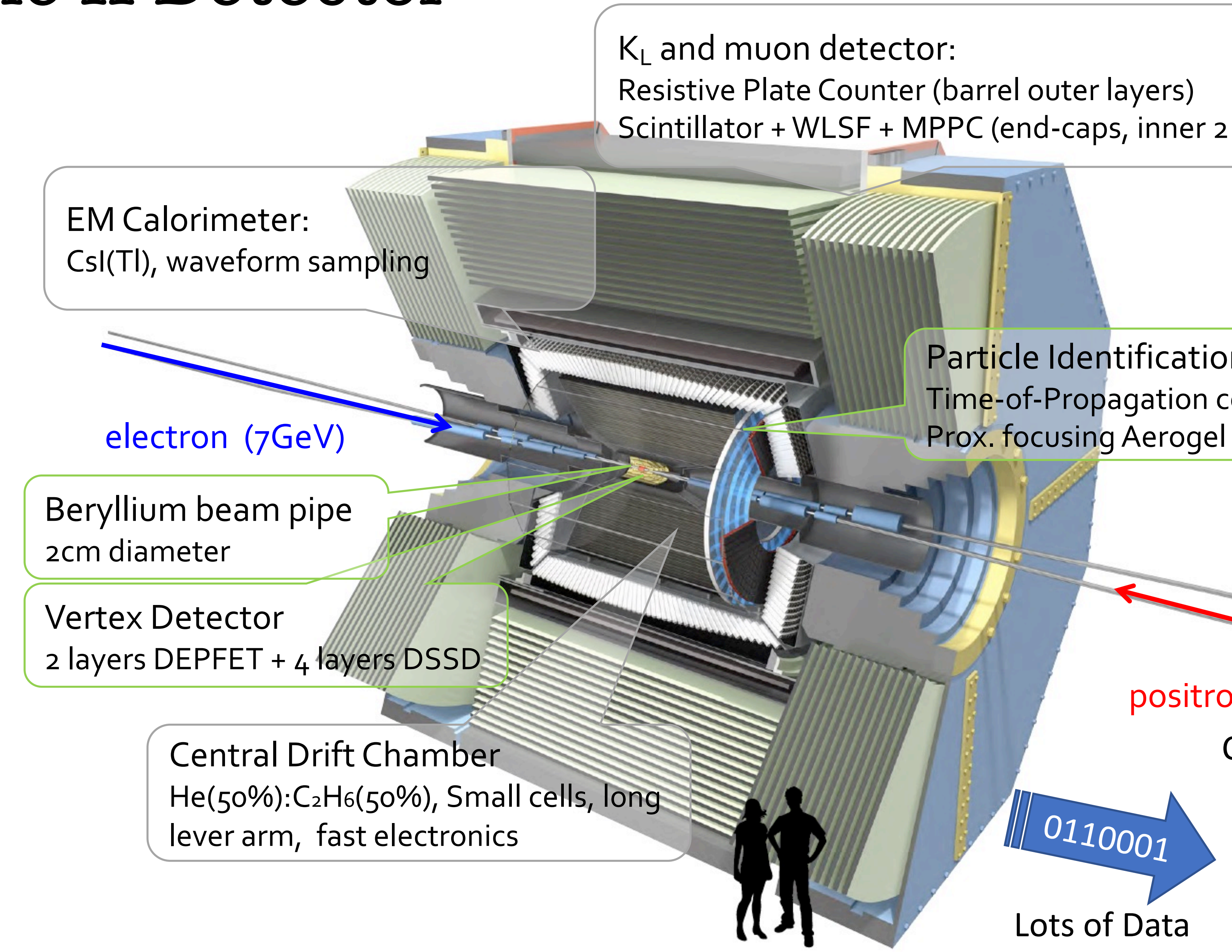
- In 2020 a long term operation plan for the SuperKEKB accelerator has been proposed to MEXT
- Two time scales defined
- 2026: Final focus replacement to obtain full luminosity
- >2030: possible luminosity upgrades and/or polarization
- This defines the scales of the detector technology and R&D
    - Short time scale with small amount of R&D
    - Longer time scale with ultimate performance



https://confluence.desy.de/display/BI/Snowmass+2021

https://docs.belle2.org/record/2137?ln=en

# Belle II Detector



$K_L$ and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

Beryllium beam pipe
2cm diameter

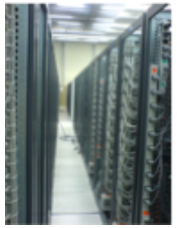
Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):$C_2H_6$(50%), Small cells, long lever arm, fast electronics

positron (4GeV)

Lots of Data

COMPUTING

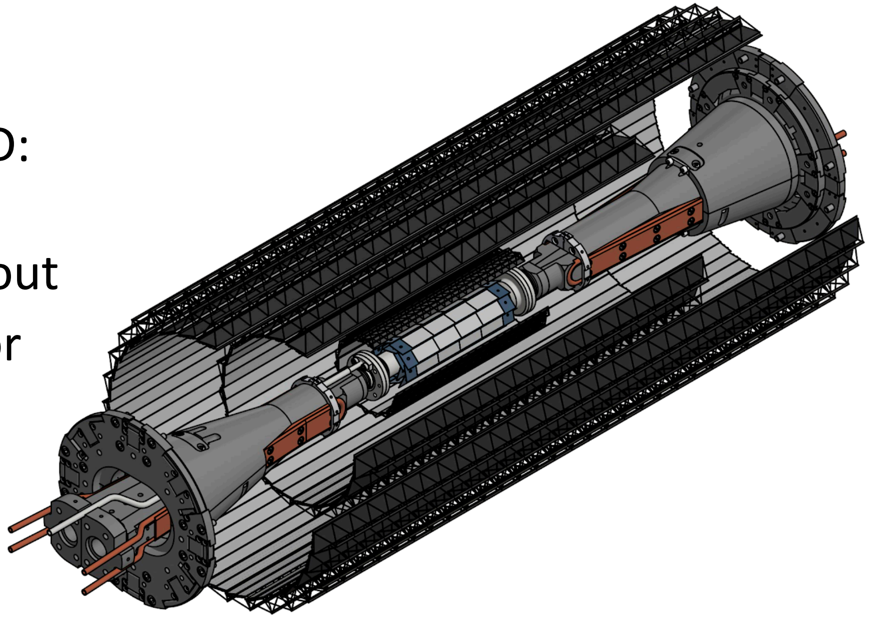


# Issues and options for Belle II upgrades for high luminosity I

- Robustness against machine backgrounds: many different sources (TF8)
  - From interaction region, from tunnel, from Interactions in nearby material
  - Very complex and tight space constraints in interaction region

- Small pixel pitch: 30x30 $\mu m^2$
- Fast chip integration time: 25 ns (100 ns total integration time window)
- Thin material: 0.1% $X_0$ inner, 0.3-0.5% $X_0$ outer
- Low and homogeneous power consumption: < 200 mW/cm$^2$
- Radiation hard: 100 Mrad TID, $10^{14}$ $n_{eq}$ cm$^{-2}$ NIEL

- Very low material tracking; good space and time resolution (TF1, TF3, TF7)
  - Fast, high granularity, low mass replacement for current VXD: study of depleted CMOS MAPS; SOI sensors; thin strips
  - Faster and more radiation tolerant electronics for CDC readout
  - Replacement for drift chamber under study: CMOS MAPS for inner part; study of a TPC option



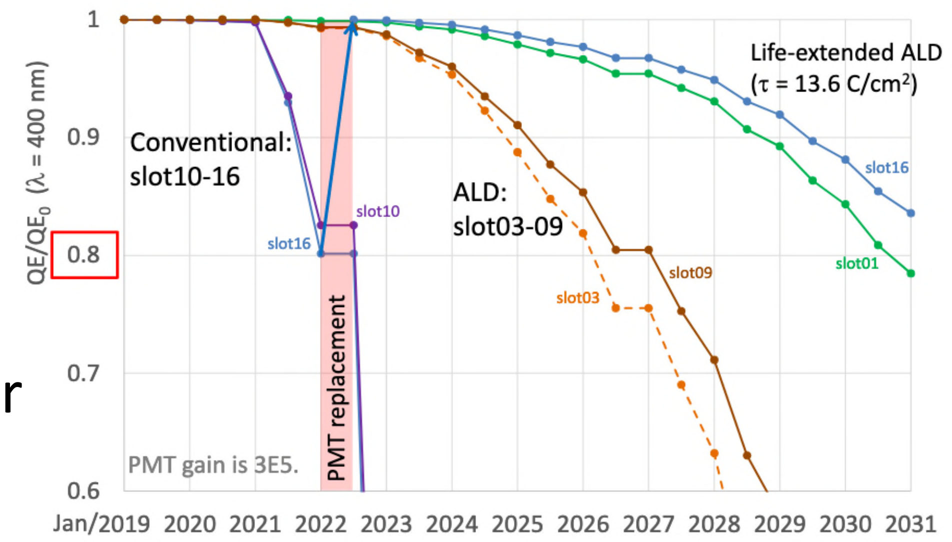
- New ideas: timing layers (TF3, TF7)
  - Possible use as TOF to improve PID performance
  - Provide track trigger in addition to or instead of CDC

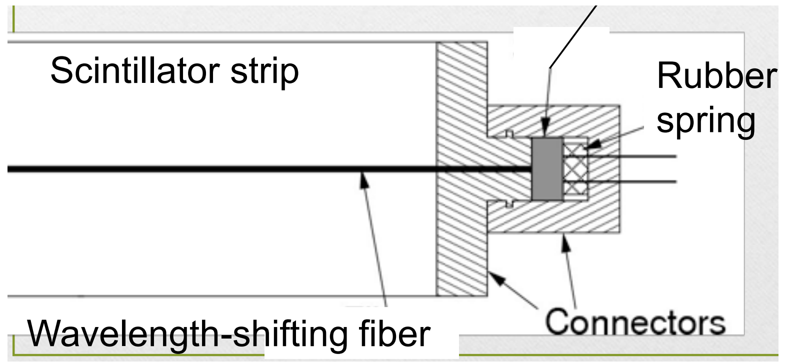
https://indico.cern.ch/event/895924/contributions/3968854/attachments/2102385/3560917/baudot-VXDupgrade-Belle2.pdf

# 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



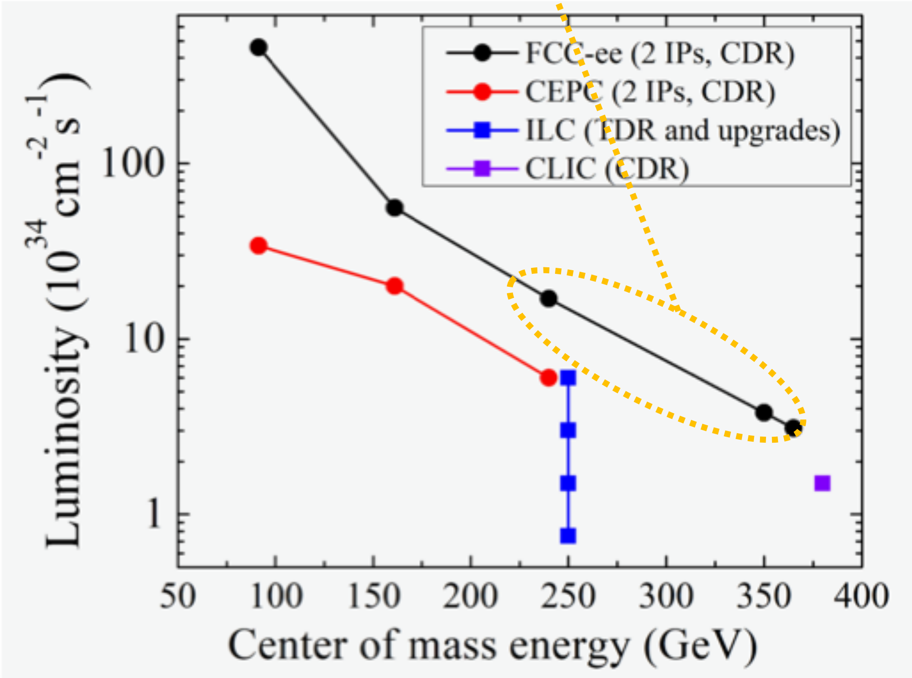


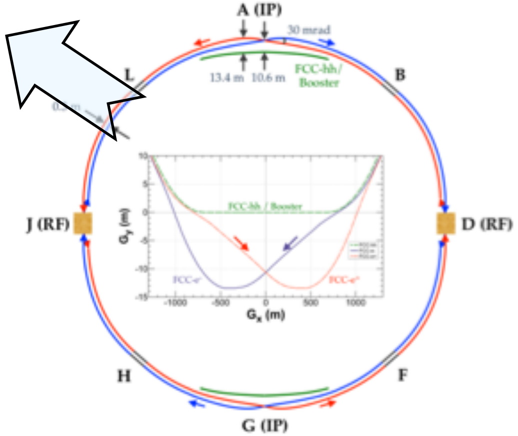
# Instrumentation for FCC-ee

# FCC-ee Physics Landscape (i)

**”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





**FCC-ee reminder**

- 100 km circumference
- Separate $e^+$, $e^-$, and acceleration rings
- 30 mrad crossing angle
- **Two (possibly four) interaction regions**

# FCC-ee Physics Landscape (ii)

## ”Higgs Factory” Programme

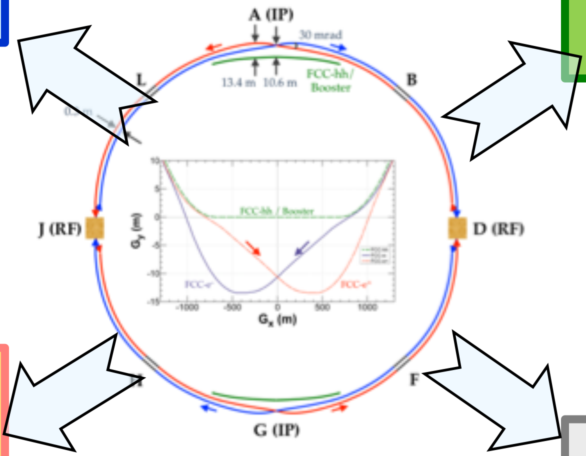
- At two energies, 240 and 365 GeV, collect in total
    - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

## Ultra Precise EW Programme

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

- 5x$10^{12}$ Z and $10^8$ WW
    - $m_Z$, $\Gamma_Z$, $\Gamma_{inv}$, $\sin^2\theta_W^{eff}$, $R^Z_\ell$, $R_b$, $\alpha_s$, $m_W$, $\Gamma_W$,…
- $10^6$ tt
    - $m_{top}$, $\Gamma_{top}$, EW couplings

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



## Heavy Flavour Programme

- Enormous statistics: $10^{12}$ bb, cc; 1.7x$10^{11}$ 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

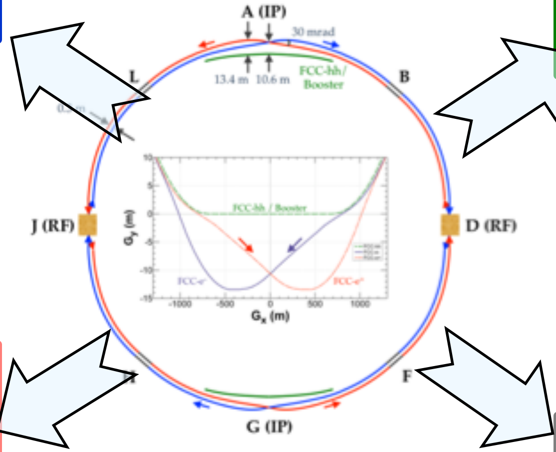
# Detector Requirements in Brief

### ”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

- 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 $\pi^0$s or γs
- Excellent $\pi^0/\gamma$ 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

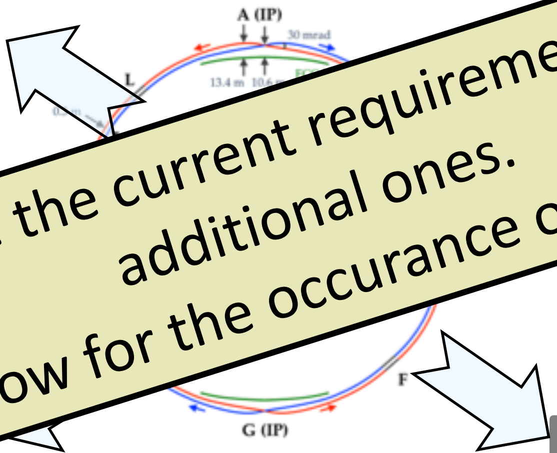
# Detector Requirements in Brief

## ”Higgs Factory” Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$ 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. $\Gamma_{had}/\Gamma$ ) to $10^{-5}$
- Momentum resolution ”a we gan get it”
  - Multiple sc
- Track a ES from μμ)
- s meast.



Work is progress to refine the current requirements and study the need for additional ones.

R&D road-map could allow for the occurance of new challenges and ideas ?

## Hea

- Superior imp ,
  vertices, taggi measts.
- ECAL resolutio level for inv. mass of states w s or γs
- Excellent $\pi^0/\gamma$ separation and measurement for tau physics
- PID: K/π separation up to ~30 GeV (45 GeV) for b (tau) physics

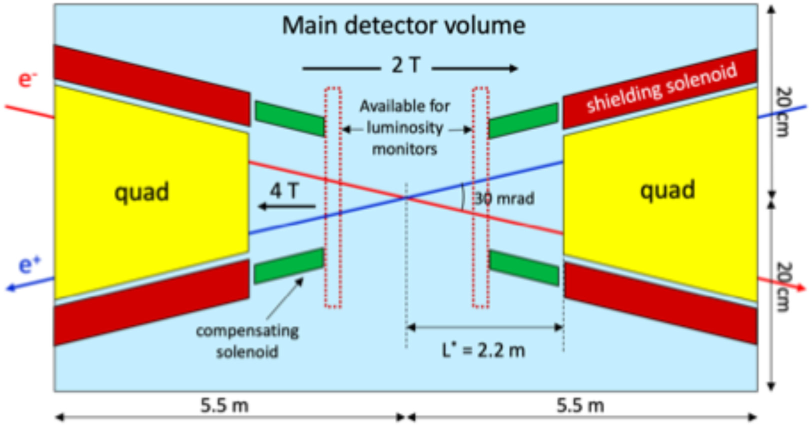
## Feebly Coupled Particles - LLPs

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

# Experimental challenges

**Central part of detector volume – top view**



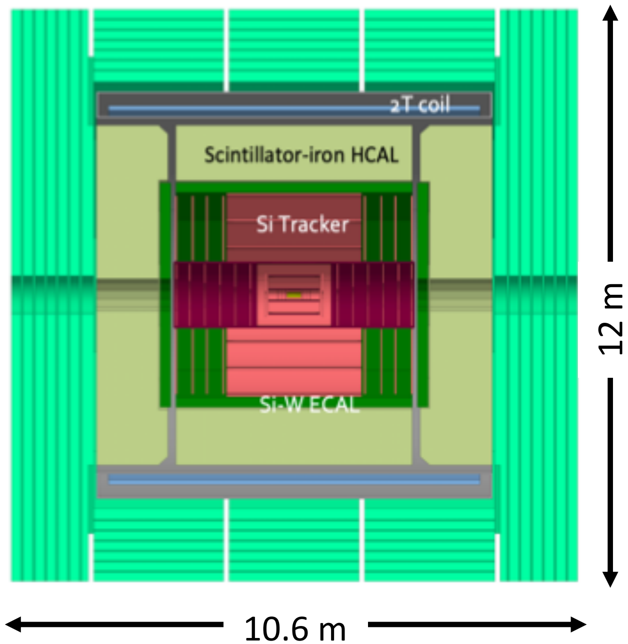
- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla at Z-peak operation
  - Very complex and tightly packed MDI (Machine Detector Interface)
- ”Continuous” beams (no bunch trains); bunch spacing down to 20 ns
  - Power management and cooling (no power pulsing)
- Extremely high luminosities
  - 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 μs) 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, …

- More physics challenges
  - Luminosity measurement to $10^{-4}$ – luminometer acceptance to 1 μm level
  - Detector acceptance to ~$10^{-5}$ – acceptance definition to few 10s of 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); flavour and τ physics, life-time measurements
  - Particle identification (π/K/p) without ruining detector hermeticity – flavour and τ physics (and rare processes)

# CDR: Two Complementary Detector Concepts

”Proof of principle concepts”
- Not necessarily matching (all) detector requirements, which are still being spelled out

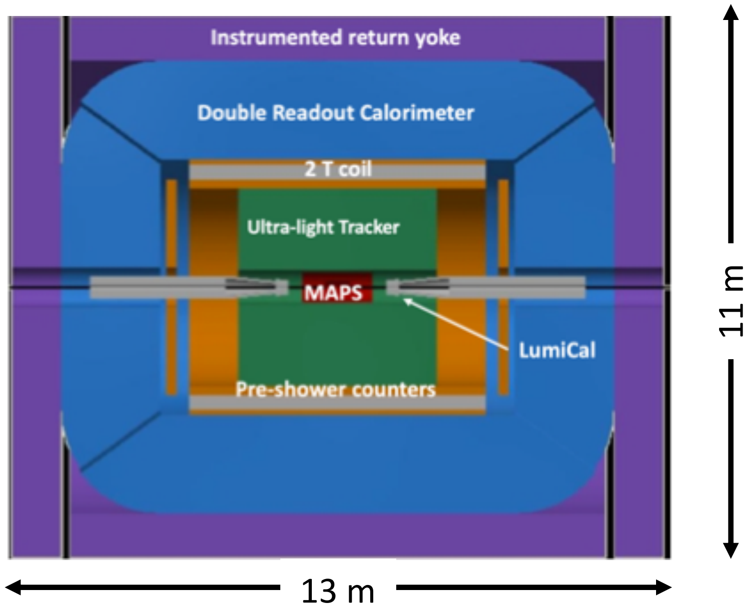
## CLD



- Based on CLIC detector design; profits from technology developments carried out for LCs (c.f. F.Simon’s talk)
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil *outside* calorimeter system

https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520

## IDEA

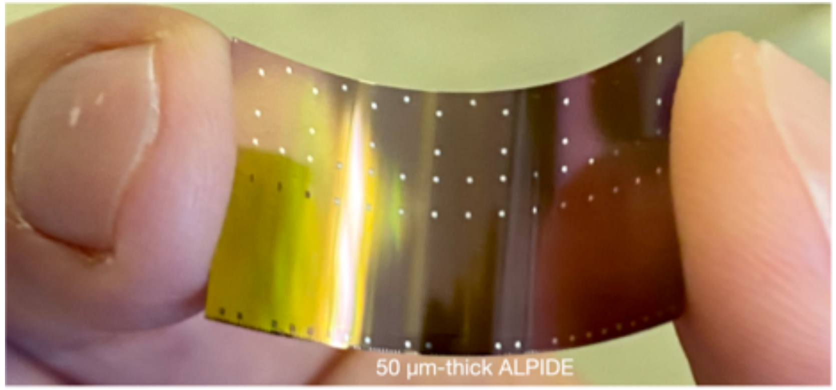


- New, innovative, possibly more cost-effective concept
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil *inside* calorimeter system

https://pos.sissa.it/390/

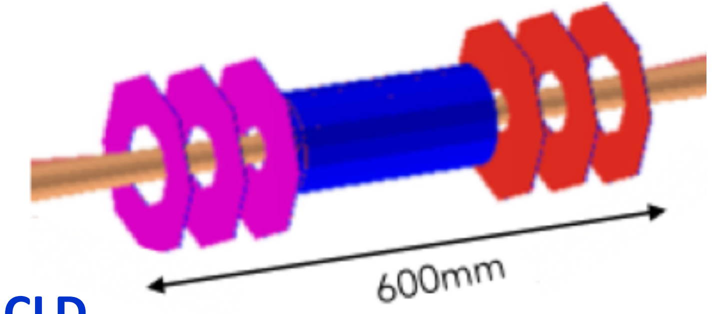
# Vertex Detector

- Beam pipe radius:
  - ❑ 15 mm base line → 10 mm
- Thanks to collimators and effective beam-pipe shielding, beam backgrounds are in general negligible
  - ❑ Example: max rate of $10^{-5}$ hits / mm$^2$ / BX @ √s = 91.2 GeV
  - ❑ This and other simulation results from CLD full simulation
- Following ongoing rapid technological development
  - ❑ Lighter, more precise, closer, less power

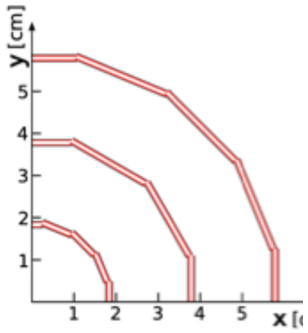


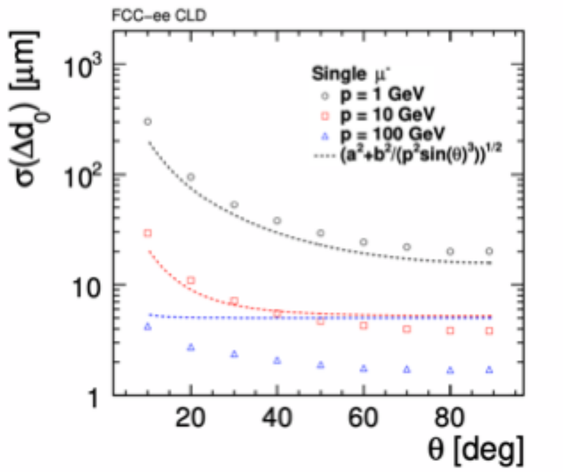
Courtesy of Magnus Mager, CERN

- Extreme alignment-precision needs for life-time measurements
  - ❑ Ex.: τ lifetime to ≲ $10^{-4}$ relative precision ⇒ ≲ 0.2 µm on flight distance

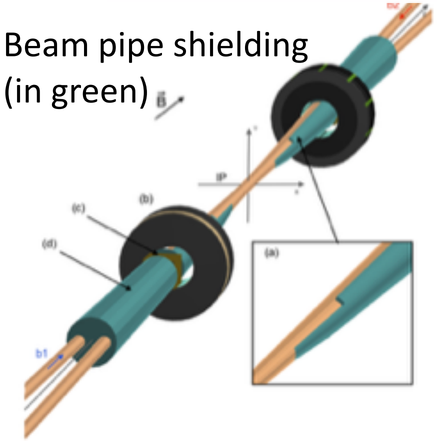


**CLD**





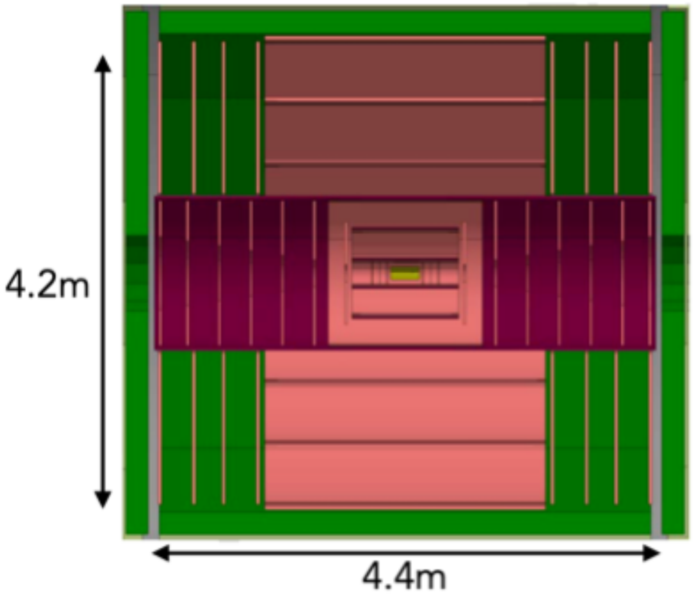
Beam pipe shielding (in green)

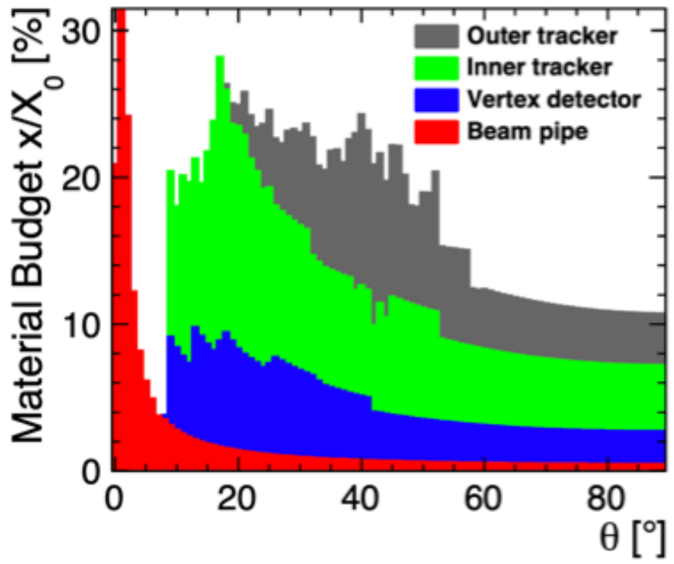


# Tracking

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% $X_0$)

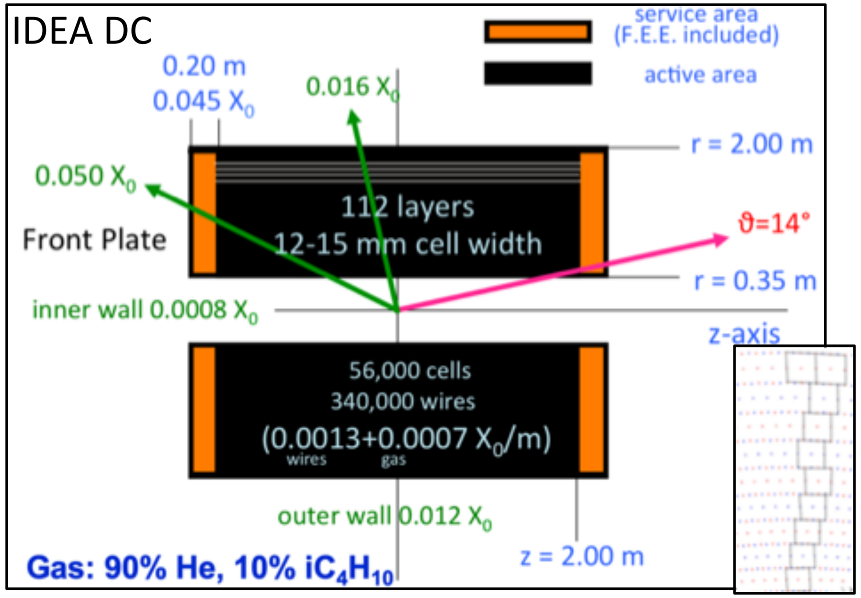


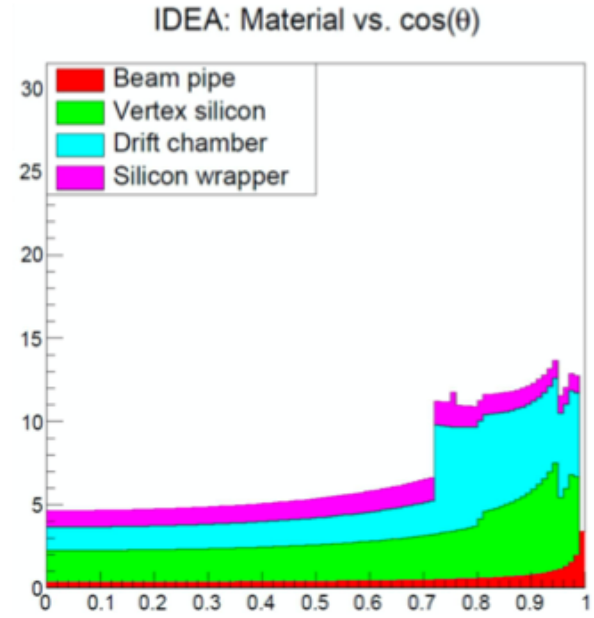


- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% $iC_4H_{10}$
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of $X_0$ at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXTand Si “wrapper”

What about a TPC?

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

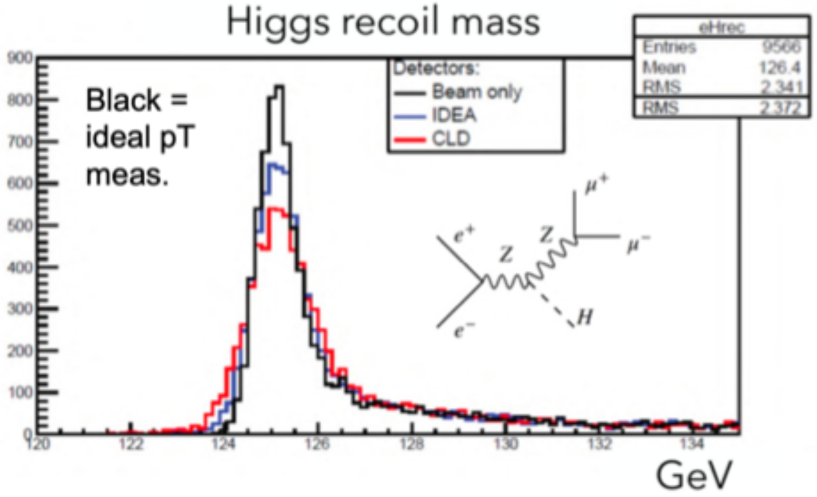


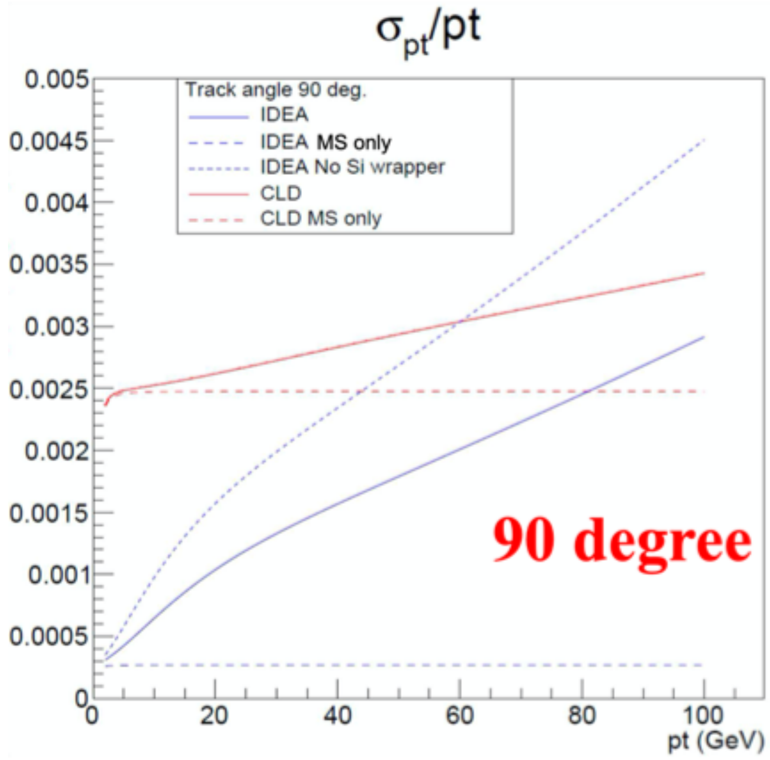


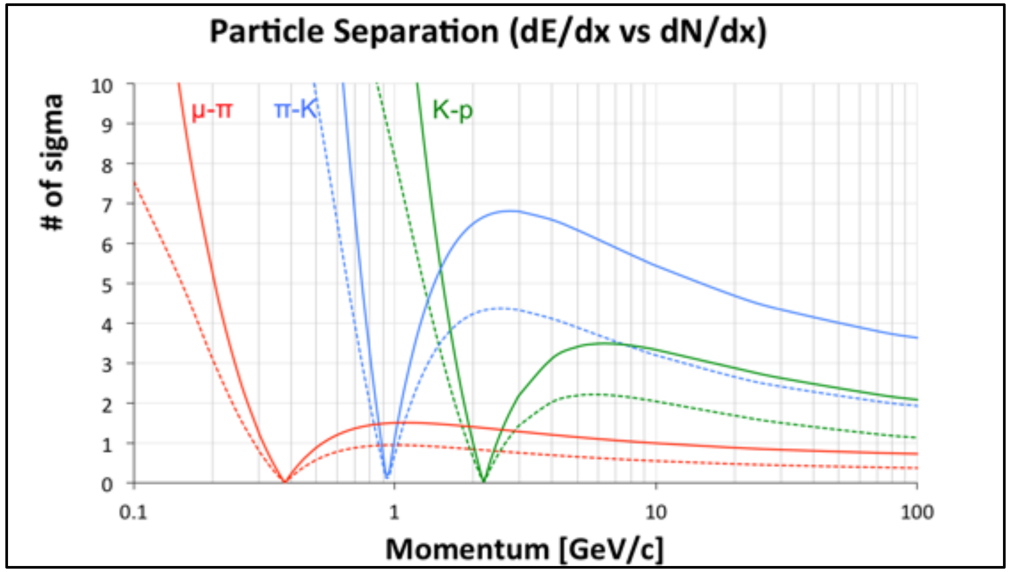
# Drift Chamber

- For Higgs recoil mass analysis, both proposed tracker designs match well resolution from beam energy spread
- However, in general, tracks have rather low momenta ($p_T \lesssim 50$ GeV)
  - ❑ Transparency more relevant than asymptotic resolution

- Drift chamber (gaseous tracker) advantages
  - ❑ Extremely transparent: minimal multiple scattering and secondary interactions
  - ❑ Continous tracking: reconstruction of far-detached vertices ($K^0_S$, Λ, BSM LLPs)
  - ❑ Particle separation via dE/dx or cluster counting (dN/dx)
    - ❖ dE/dx much exploited in LEP analyses







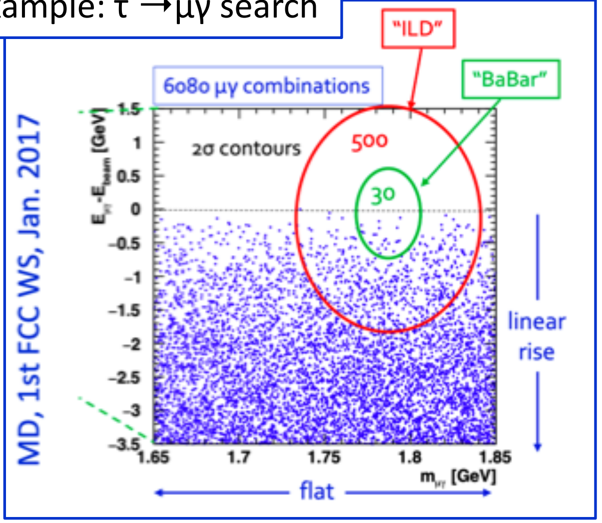
# Calorimetry

- Several technologies being considered

| Technology | ECAL | HCAL |
|---|---|---|
| CLD / CALICE-like | W/Si<br>W/scint + SiPM | Steel/scint + SiPM<br>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 $\gamma/\pi^0$ separation and measurement
- In particular for heavy flavour programme, superior ECAL resolution needed →
  - $15\%/\sqrt{E}$ → $8\%/\sqrt{E}$ → $3\%/\sqrt{E}$
- Other concerns
  - Operational stability, cost, …
- Optimisation ongoing for all technologies
  - Choice of materials, segmentation, read-out, …

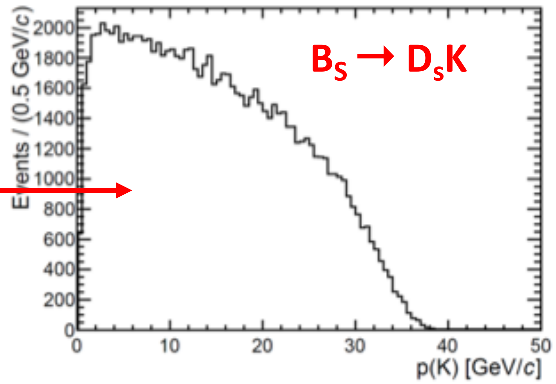
Example: τ →μγ search



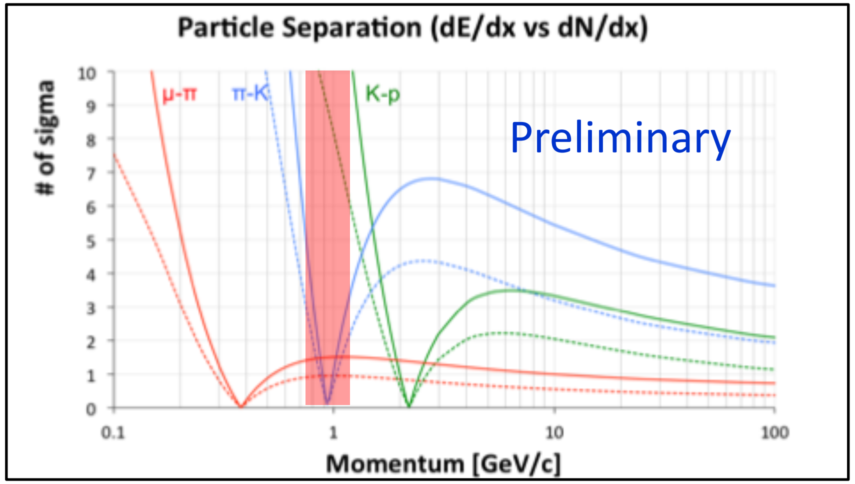
# Particle Identification

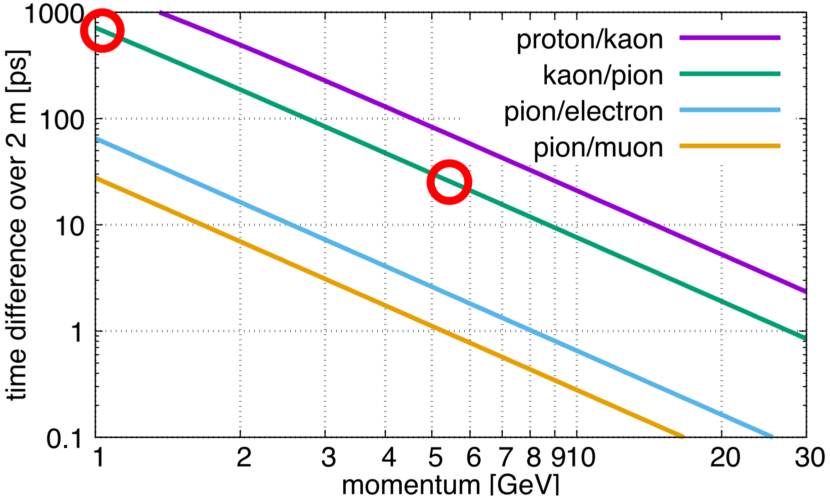
PID capabilities across a wide momentum range is essential for flavour studies and will enhance overall physics reach

- ❑ Example: important mode for CP-violation studies **$B^0_S \to D^\pm_S K^\mp$**
  - ❖ Require K/π separation over wide momentum range to suppress same topology $B^0_S \to D^\pm_S \pi^\mp$

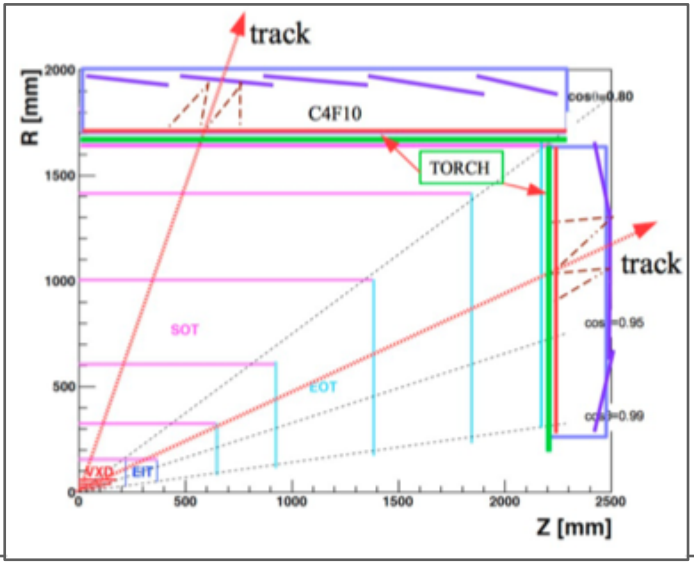


- ◆ IDEA drift chamber promises >3σ π/K separation all the way up to 100 GeV
  - ❑ Experimental validation needed of dN/dx method in relativistic rise region
  - ❑ Cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of δT ≲ 0.5 ns
- ◆ TOF *alone* δT of ∼10 ps over 2 m (LGAD, TORCH) could give 3σ π/K separation up to ~5 GeV
- ◆ Alternative approaches, in particular (gaseous) **RICH** counters to be investigated
  - ❑ R&D needed to develop RICH solution compatible with detector/tracker space requirements





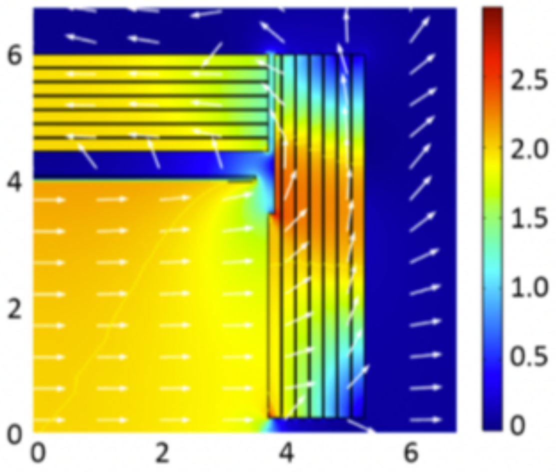
CEPC detector study



# Solenoid Magnet and Muon System

## Large solenoid outside calorimeter system (CLD)

CMS-like dimensions



## Thin solenoid inside calorimeter system (IDEA & LAr)

Must be **thin** and very **transparent**
- R&D ongoing

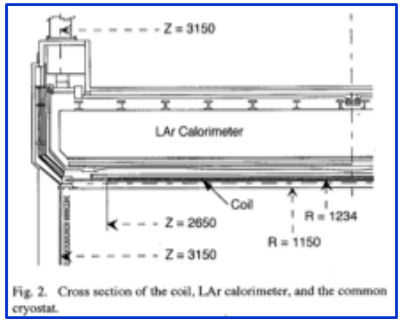
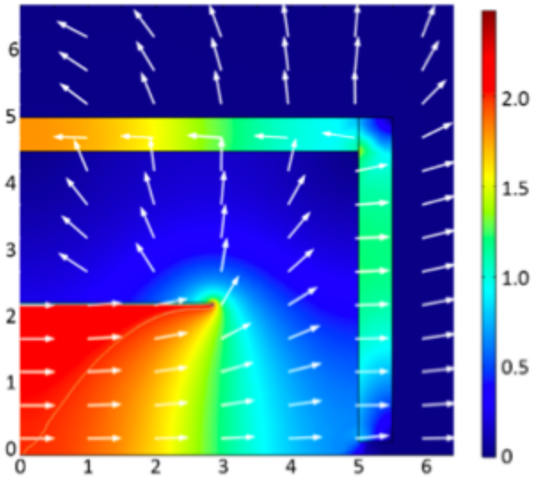


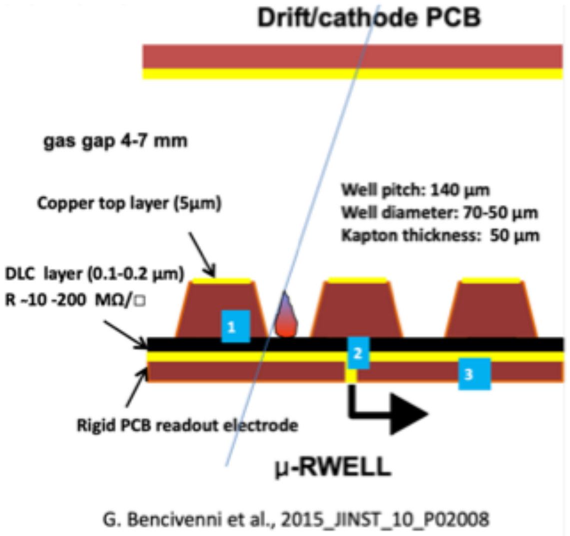
Fig. 2. Cross section of the coil, LAr calorimeter, and the common cryostat.

LAr: Calorimeter and
coil in same cryostat (ATLAS style)



## Muon system in instrumented return yoke

- ❑ 3-7 layers being considered: 3000-6000 m$^2$
- ❑ Proposed technologies
  - ❖ RPC (30 × 30 mm$^2$ cells)
  - ❖ Crossed scintillator bars
  - ❖ µRWell chambers (1.5 × 500 mm$^2$ cells)
    - Also for IDEA pre-shower detector
    - Ongoing R&D work



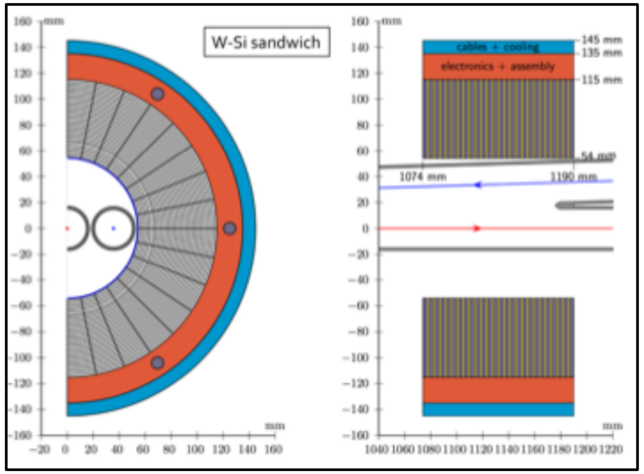
G. Bencivenni et al., 2015_JINST_10_P02008

# 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)

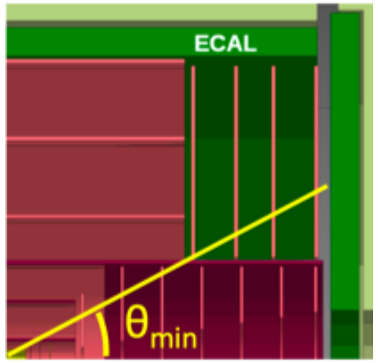


- Many R&D/engineering challenges
  - ❑ Precision on acceptance boundaries to $\mathcal{O}$(1 µm) !
  - ❑ Mechanical assembly, metrology, alignment
  - ❑ Physics rate of $\mathcal{O}$(100 kHz)
  - ❑ Readout at 50 MHz BX rate ?
  - ❑ Power management / cooling
  - ❑ Support / integration in crowded and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

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)**

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 sytems differ by a β=0.015 transverse boost

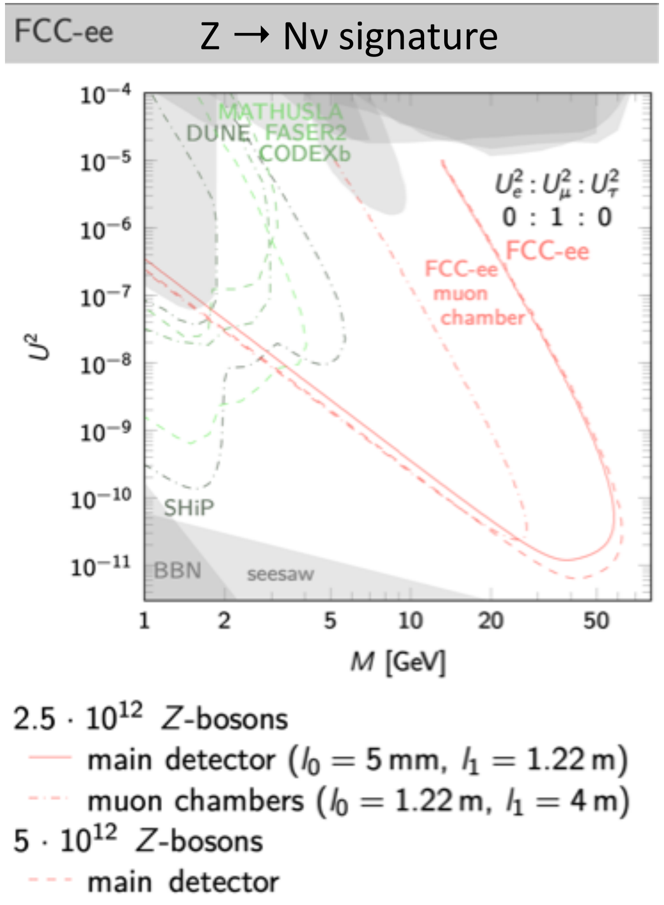


# Readout, DAQ, Data Handling

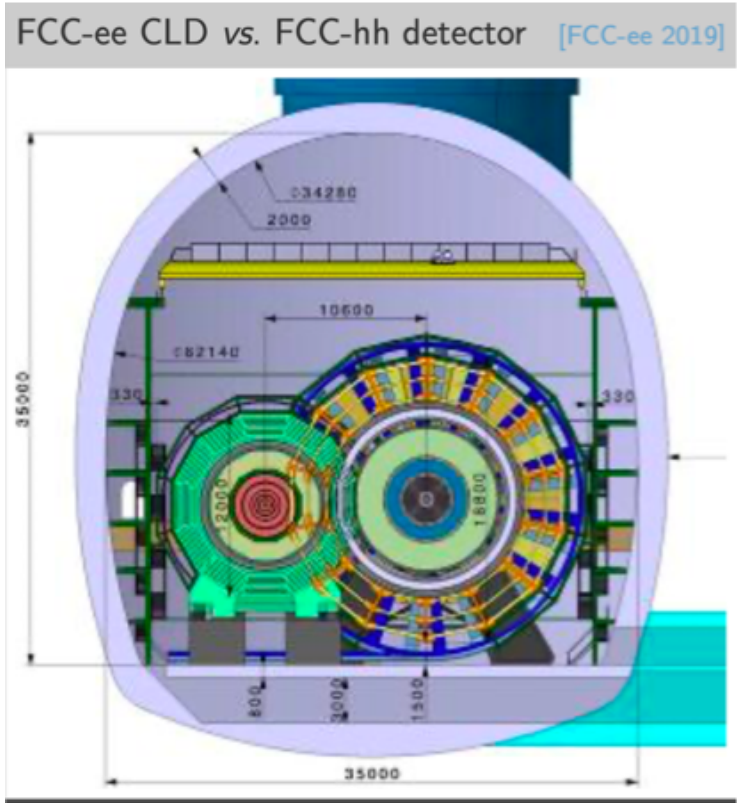
- In particular at Z-peak, challenging conditions
  - 50 MHz BX rate
  - 70 kHz Z rate + ~100 kHz LumiCal rate
  - Absolute normalisation goal $10^{-4}$
    - In comparison, ”pileup” parameter for LumiCal is ~$2\times10^{-3}$
- Different sub-detectors tend to prefer different integration times
  - Silicon VTX/tracker sensors: $\mathcal{O}(\mu s)$ [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 element provides 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

# Possibility: Very Large Tracking Volume for LLPs

FCC-ee ”standard” detector

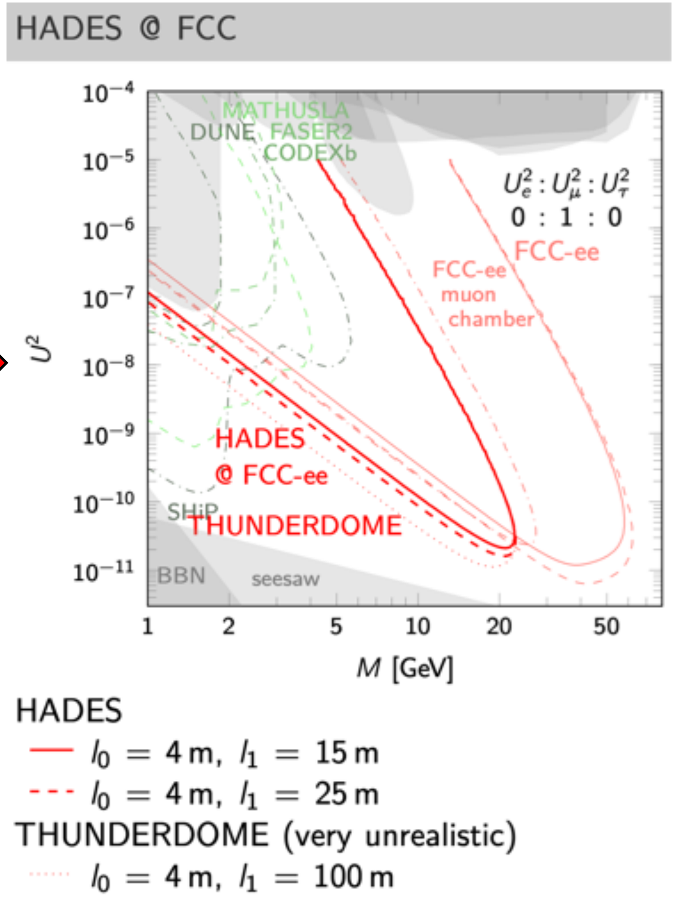


Instrument cavern as huge decay volume



Scintillators
RPCs
…

***Half a magnitude sensitivity gain in $U^2$***



J. Hajer,
4th FCC Physics and Experiments workshop, Nov. 2020

# 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

# References

- *Detector requiremets for FCC-ee*, P. Azzi & E. Perez, Presentation at 4th FCC Physics and Experiments Workshop
- *CLD – A Detector Concept for FCC-ee*, N. Bacchetta et al., [1911.12230]
- *Detector Technologies for CLIC*, A.C. Abusleme Hoffman et al., [1905.02520]
- IDEA General: *A detector concept proposal for a circular $e^+e^-$ collider*, F. Bedeschi, https://pos.sissa.it/390/819/pdf
- IDEA Drift Chamber: *A proposal of a drift chamber for the IDEA experiment for a future $e^+e^-$ collider,* G. Tassielli, https://pos.sissa.it/390/877/ (To be published)