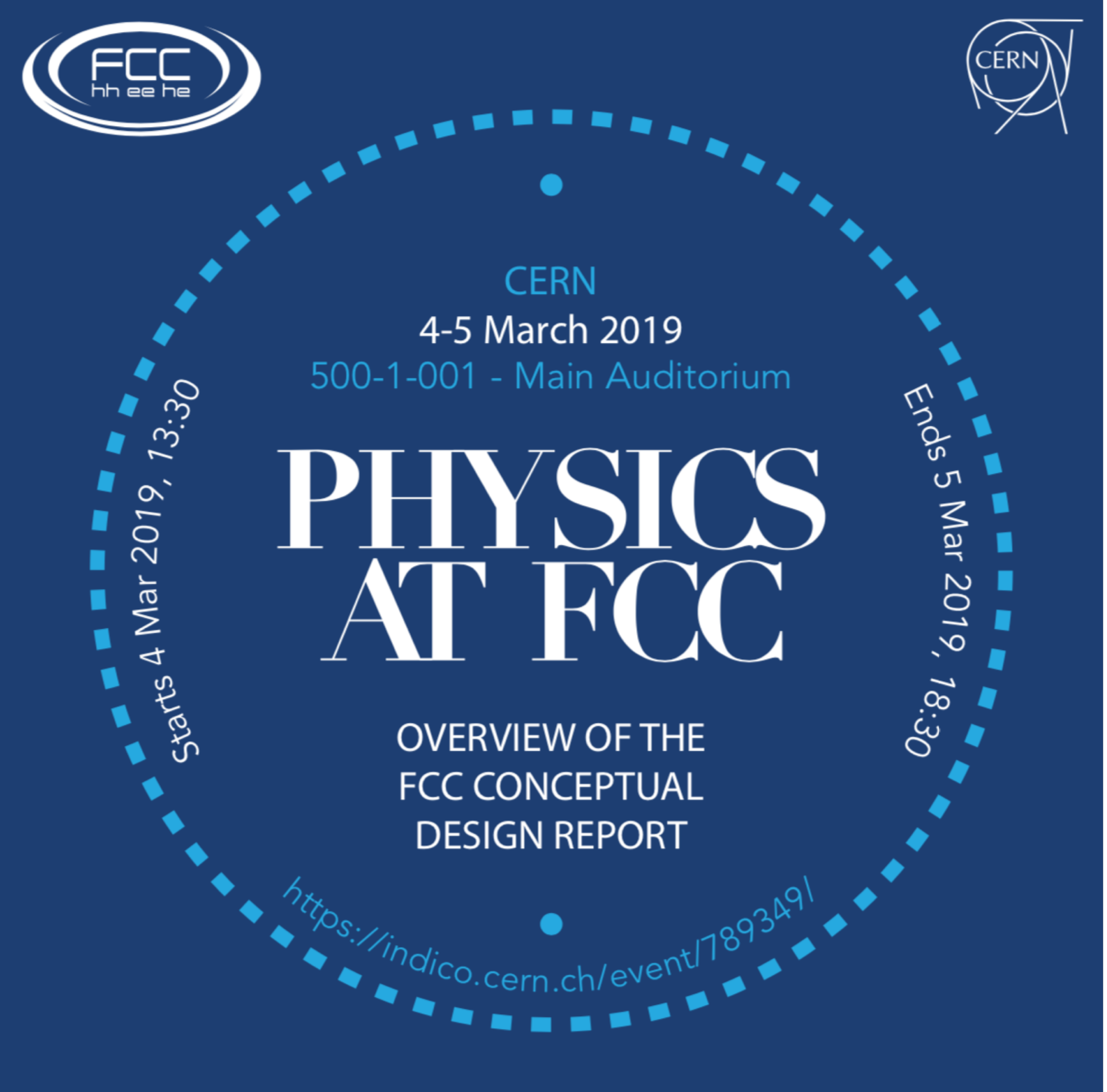


NIELS BOHR INSTITUTE
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# FCC-ee Detector Designs

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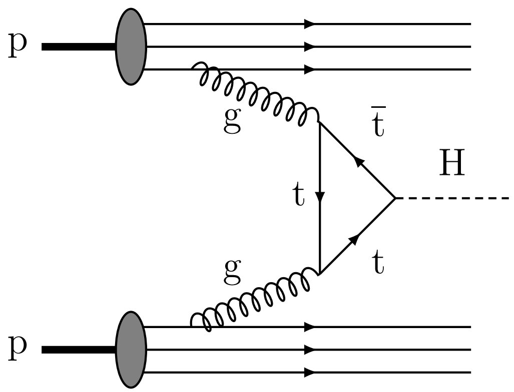
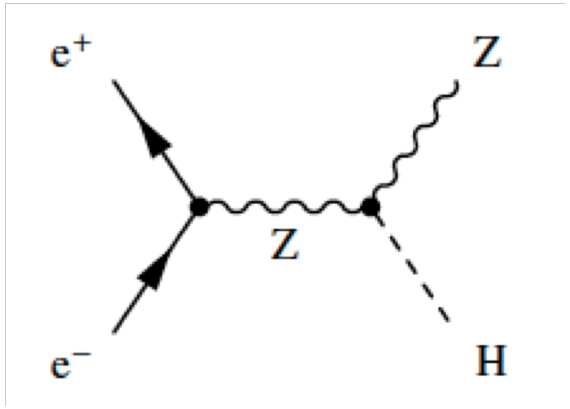
# Outline

- Prelude: pp vs. $e^+e^-$ collisions
- FCC-ee conditions
- Detector Requirements
- Detector Designs
  - CLD Detector Concept
  - IDEA Detector Concept
- Summary

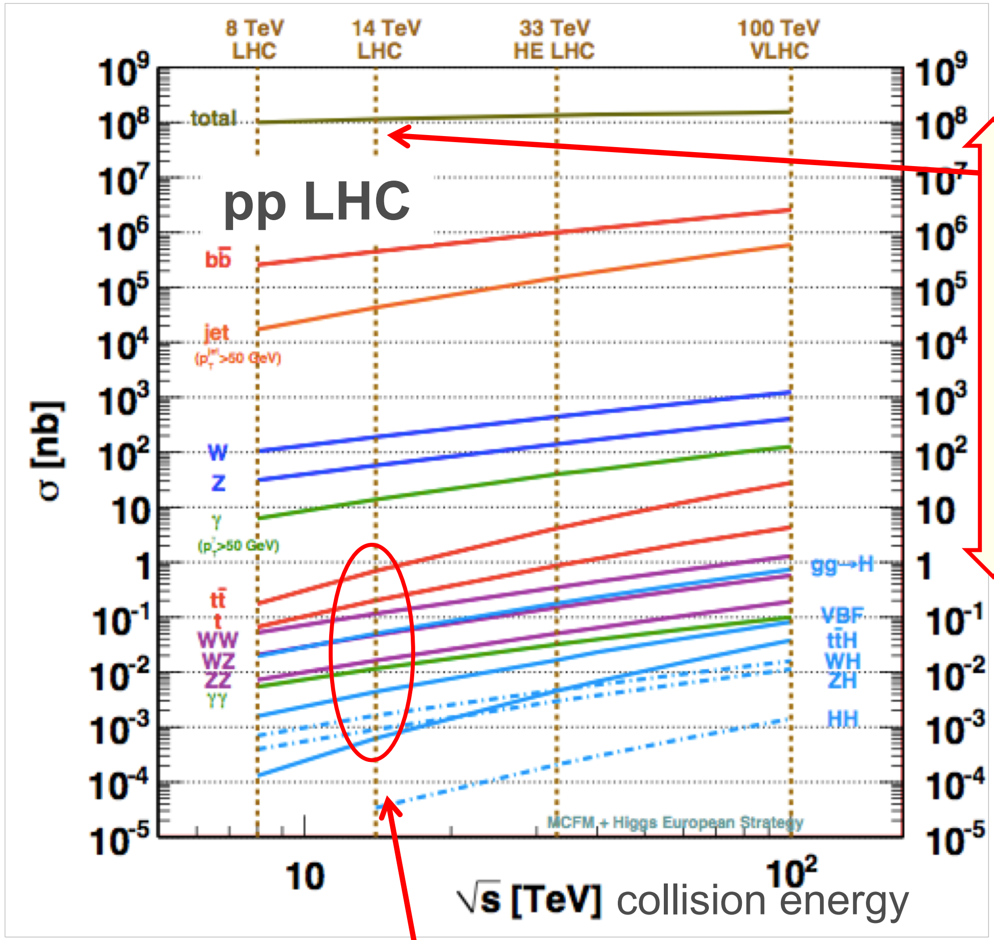
# Prelude: pp collisions vs. $e^+e^-$ collisions (1)




| p-p collisions | $e^+e^-$ collisions |
|---|---|
| **Proton is compound object**<br>→ Initial state not known event-by-event<br>→ Limits achievable precision | **$e^+/e^-$ are point-like**<br>→ Initial state well defined ($E$, $\boldsymbol{p}$)<br>→ High-precision measurements |
| **High rates of QCD backgrounds**<br>→ Complex triggering schemes<br>→ High levels of radiation | **Clean experimental environment**<br>→ Trigger-less readout<br>→ Low radiation levels |
| High cross-sections for **colored-states** | Superior sensitivity for **electro-weak states** |

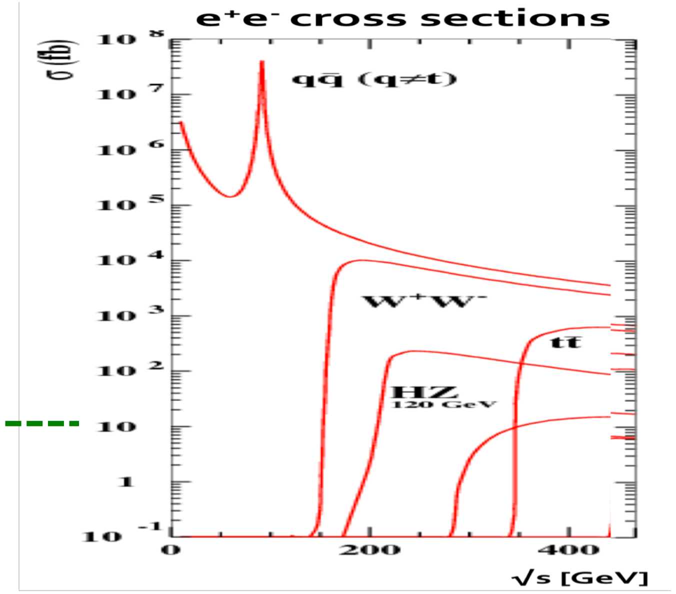
# Prelude: pp collisions vs. $e^+e^-$ collisions (2)




LHC total cross section factor > 100 million !!

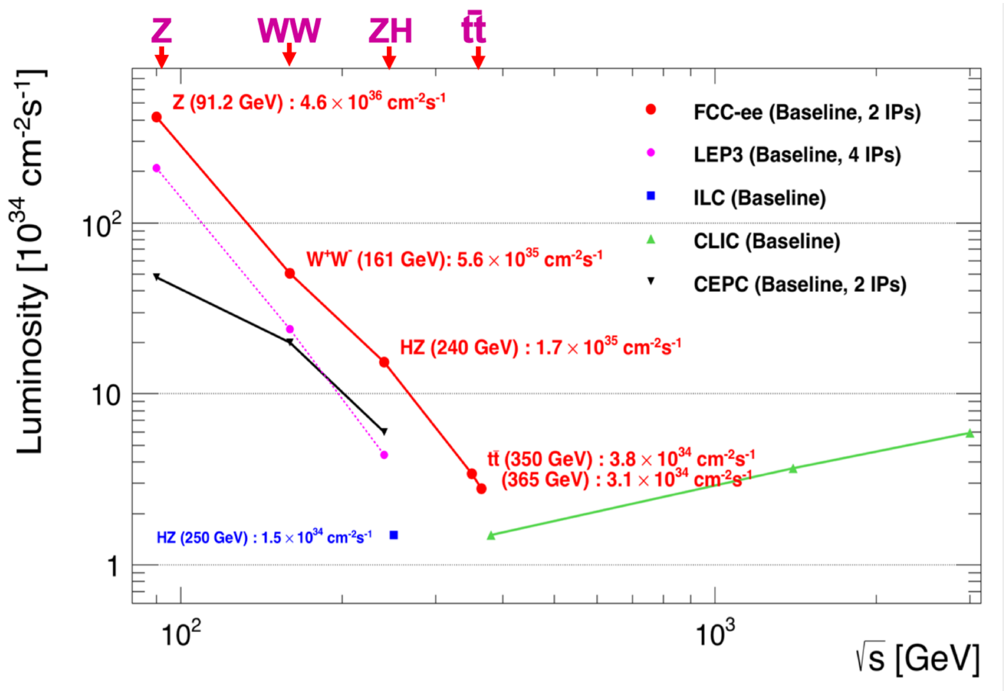
At LHC, much of the interesting physics needs to be found among a huge number of collisions

In $e^+e^-$ collisions the total cross section equals the electroweak cross section.

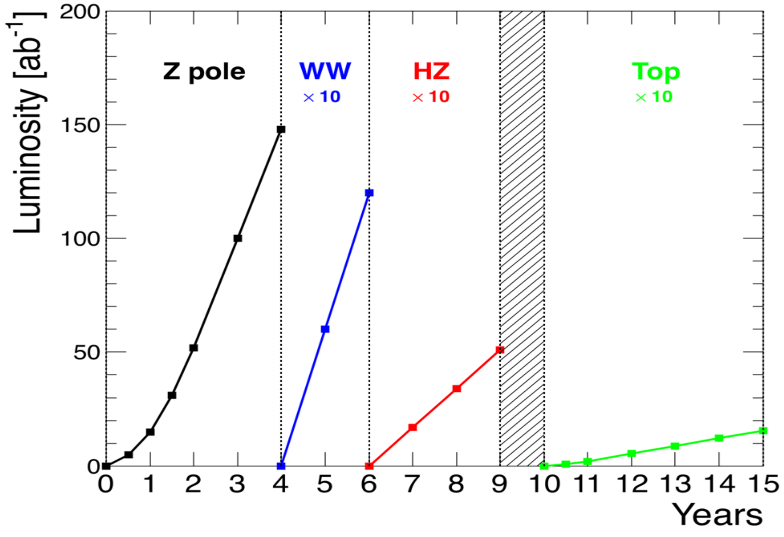



**$e^+e^-$ events are "clean"**

# FCC-ee Conditions




| FCC-ee parameters | | Z | W+W- | ZH | ttbar |
|---|---|---|---|---|---|
| √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 | 40,000 | 10 | 0.2 | 0.5 |
| Total cross section (Z) | pb | 40,000 | 30 | 10 | 8 |
| Event rate | Hz | **92,000** | 8,400 | 1 | 0.1 |
| "Pile up" parameter [$\mu$] | **$10^{-6}$** | 1,800 | 1 | 1 | 1 |



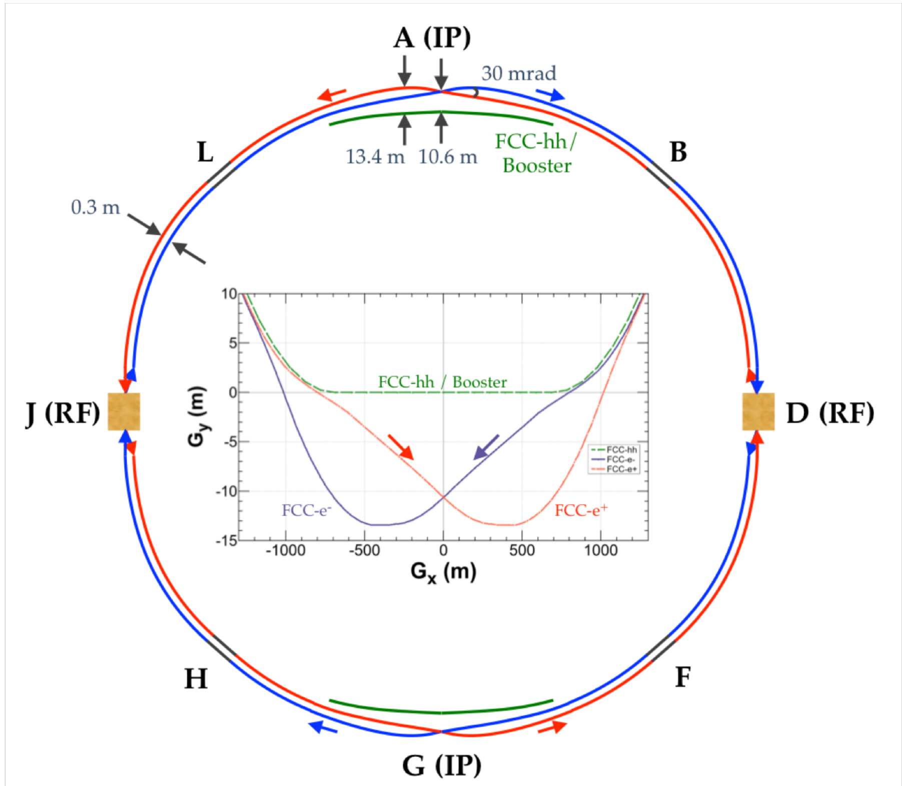

## Event statistics

**$5\times10^{12}$ $e^+e^- \rightarrow Z$**
**$10^8$ $e^+e^- \rightarrow W^+W^-$**
**$10^6$ $e^+e^- \rightarrow HZ$**
**$10^6$ $e^+e^- \rightarrow tt$**

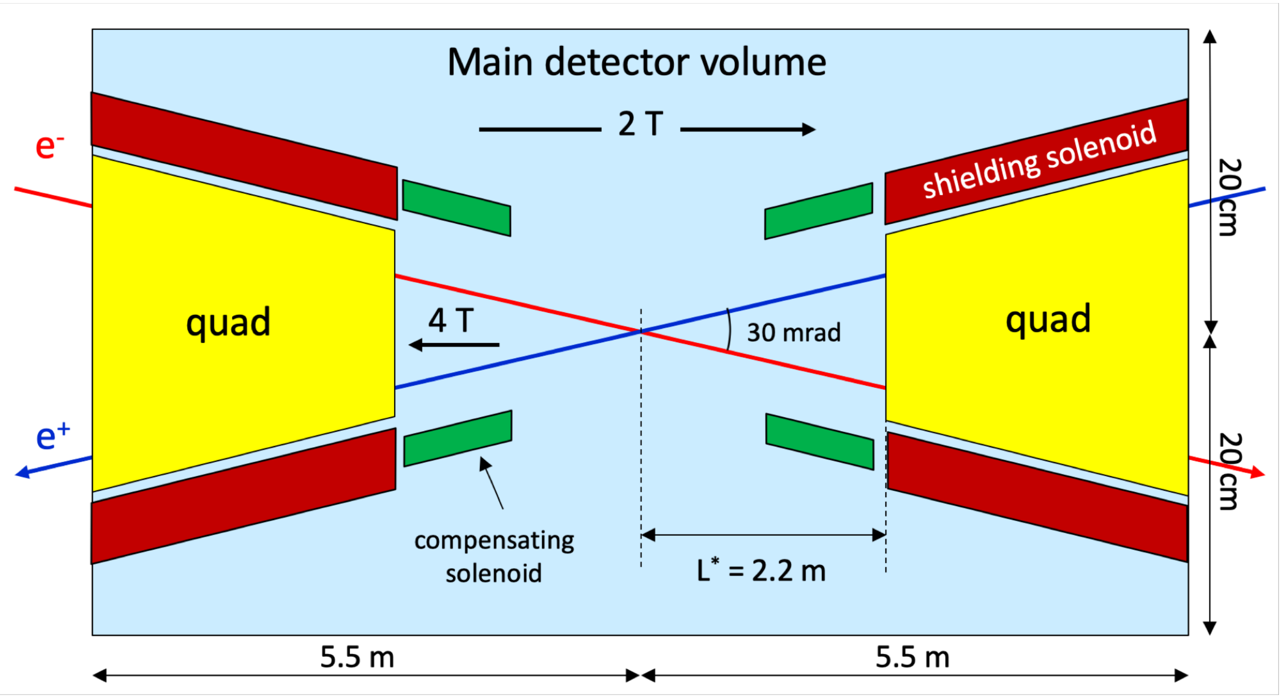
## Need detectors to match conditions

- Extremely large statistics / statistical precision
  - ...need small systematics to match
- Physics event rates up to 100 kHz
- Bunch spacing down to 20 ns
  - Continous beams, no power pulsing
- No pileup, no underlying event, ...

# Machine Detector Interface




## Central part of detector volume – top view

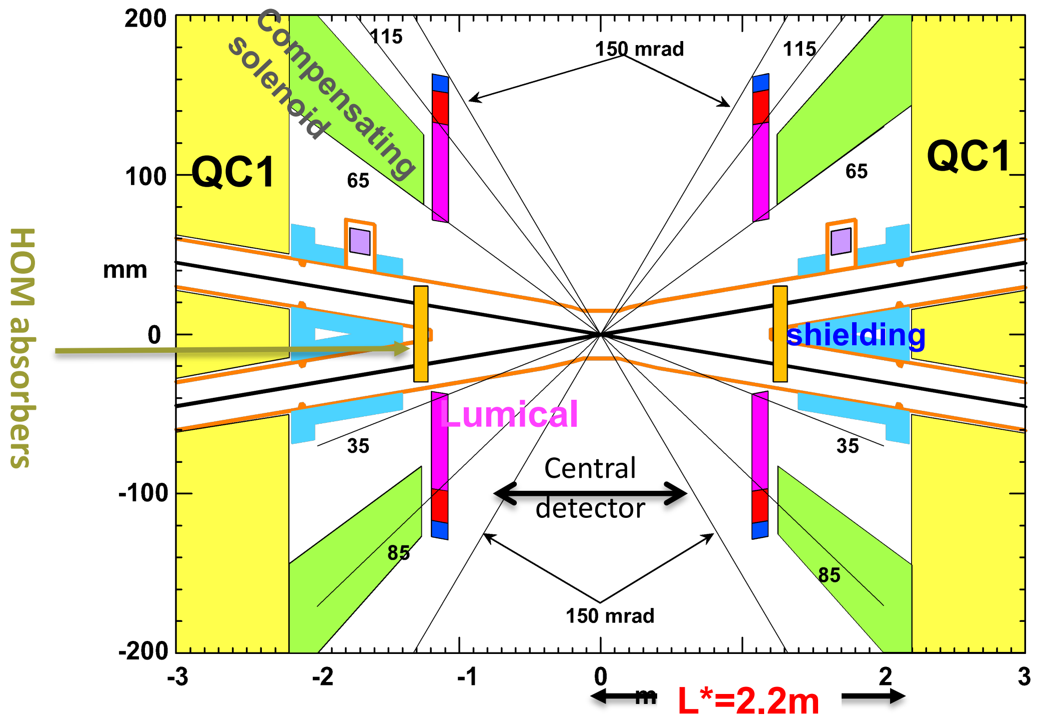



- Large horizontal crossing angle 30 mrad
- Beams only mildly bent before IP to minimize synchrotron radiation into detector volumes
  - Bend beams after IP

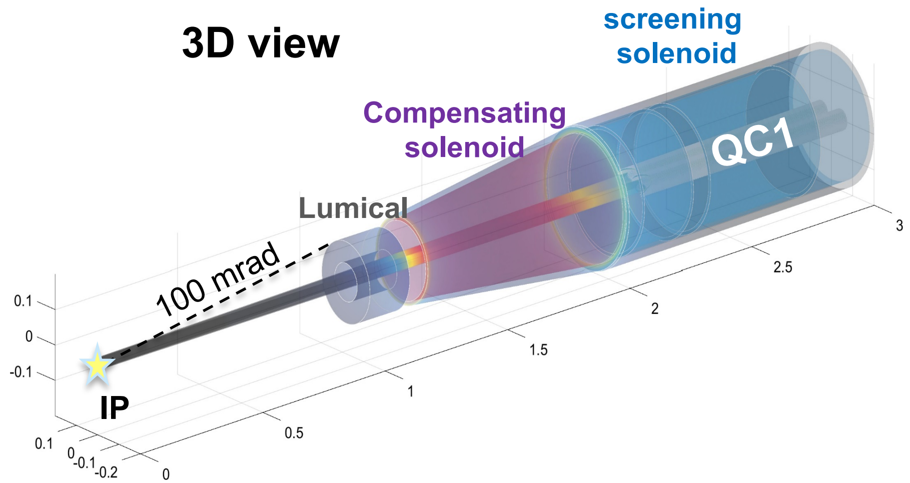
- Focussing quadrupoles protrude into detector volume
  - QC1 down to distance $L^*$ = 2.2 m
  - Necessary to shield quads from detector field
- Beams cross detector field at a 15 mrad crossing angle
  - Compensate for detector field to avoid $\varepsilon_y$ blow-up
  - Limits detector field to B = 2 Tesla

# Interaction Region Layout

2D-top view with expanded x-coordinate




- Unique and flexible design at all energies
  - Acceptance: 100 mrad
  - Solenoid compensation scheme
  - Quadrupole shielding
  - Beam pipe
    - Warm, liquid cooled
    - Be in central region, then Cu
    - R = 15 mm in central region
      - 1st vertex detector layer 17 mm from IP
    - SR masks, W shielding
  - Mechanical design and assembly concept under study

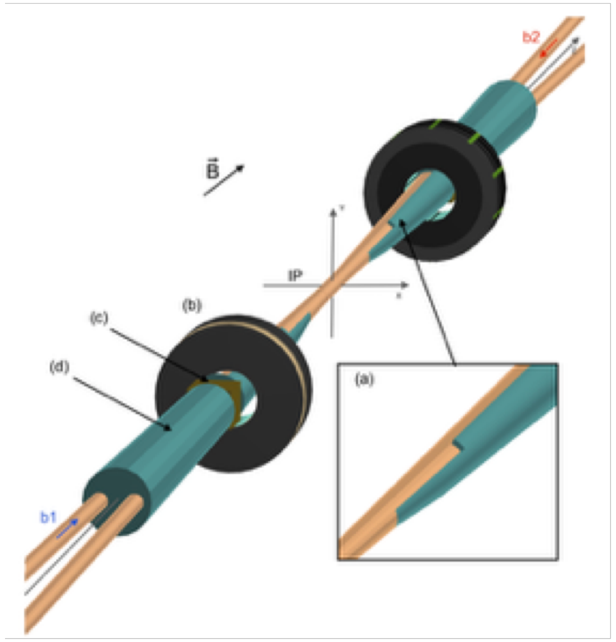


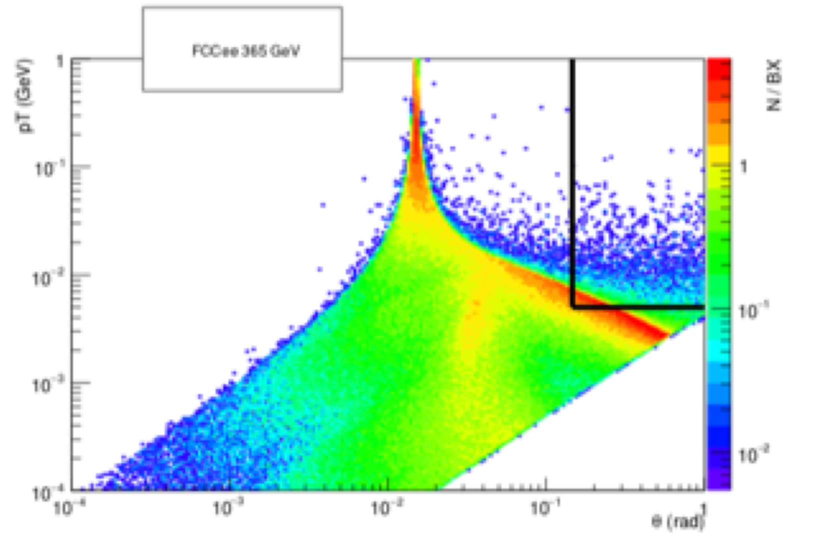
# Vertex Detector Beam Backgrounds

Main beam backgrounds: synchrotron radiation, incoherent γγ → $e^+e^-$ pairs, γγ → hadrons

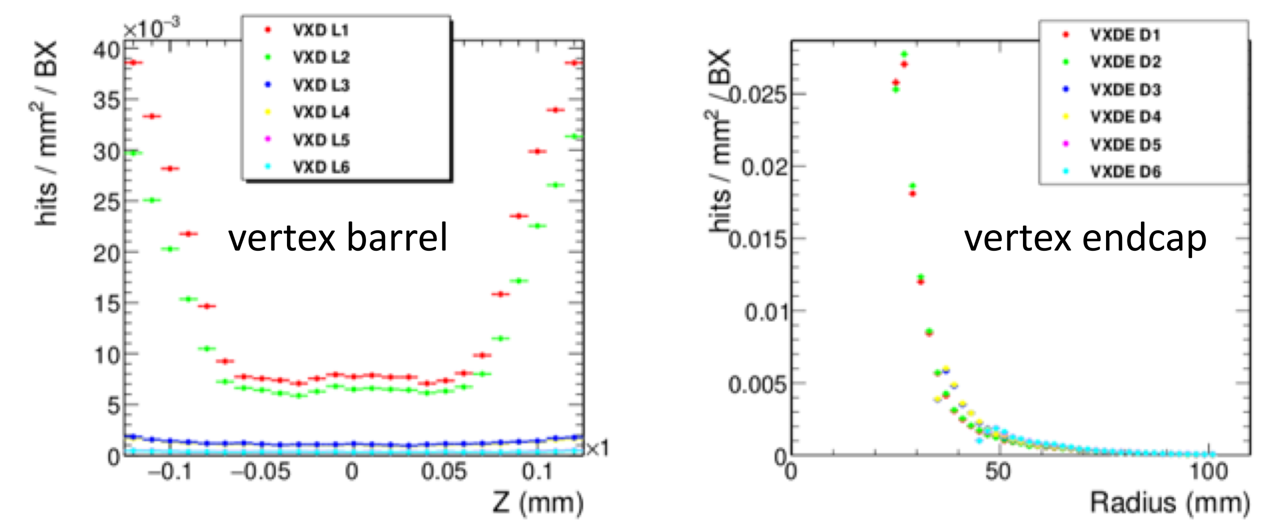
Backgrounds negligible everywhere except at √s = 365 GeV:

- ⇒ synchrotron radiation (SR)
  - ⇒ $7{\times}10^4$ hits / BX in the vertex detector
  - ⇒ reduced to 350 hits / BX with beam pipe shielding
- ⇒ incoherent pair creation (IPC)
  - ⇒ 1100 hits / BX in the vertex detector
- ⇒ γγ → hadrons
  - ⇒ negligible




$e^+e^-$ produced with E>5 MeV




@91 GeV: max $10^{-5} \times 50$BX < $10^{-3}$

Studies for CLD detector
Expect similar results for IDEA

# FCC-ee Detector Requirements

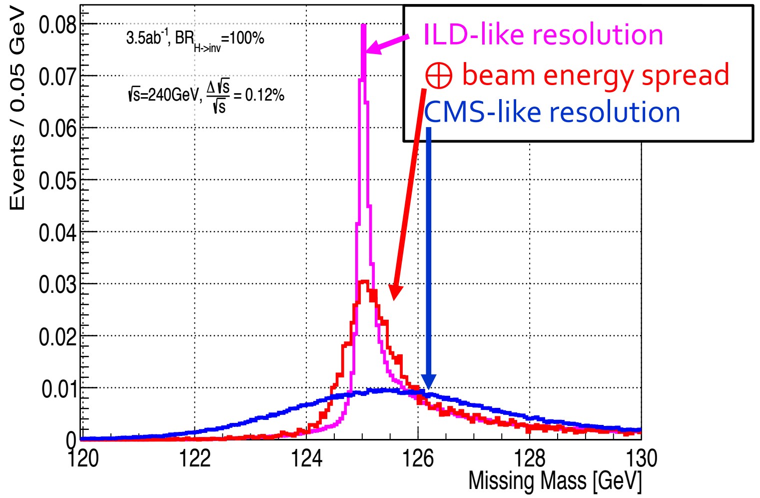
## Momentum resolution

$\sigma_{p_T}/p_T^2 \simeq 3 - 4 \times 10^{-5}$

matching beam energy spread of $\delta E/E \simeq 1\text{-}2 \times 10^{-3}$

⇒ **Mass reconstruction from lepton pairs**

Reconstructed mass of lepton pair in HZ with $Z \to \ell^+\ell^-$




Eur.Phys.J. C77 (2017) no.2, 116

⇒ **Endpoint of $Z \to \ell^+\ell^-$ momentum spectrum**

- Probe to $10^{-9}$ level lepton flavour violation in $Z \to \tau e$, $Z \to \tau\mu$

⇒ **…**

## Jet energy

$\delta E/E \simeq 30\% / \sqrt{E}$ [GeV]

⇒ **Mass reconstruction from jet pairs**

Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- $HZ \to 4$ jets, $t\bar{t}$ events, etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is *comparable* to natural widths of W and Z bosons

## e/γ energy

$\delta E/E \lesssim 15\% / \sqrt{E}$ [GeV]

⇒ **Invariant masses**

- $H \to \gamma\gamma$
- $\pi^0$ identification and measurement for $\tau$ polarisation measurement, etc.
- But also for searches of the kind $\tau \to \mu\gamma$

# FCC-ee Detector Requirements

## Impact parameter

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\text{m}; \quad b \simeq 15\,\mu\text{m GeV}$$

⇒ **Heavy flavour tagging, b/c**

- Precise Z and H branching fraction measurements
- $\mathcal{O}$(1%) measurement of BF for H → bb, cc, gg

| $M_H$ = 126 GeV | SM Br |
|---|---|
| bb | 56.1% |
| WW* | 23.1% |
| gg | 8.48% |
| ττ | 6.16% |
| ZZ* | 2.89% |
| cc | 2.83% |
| γγ | 0.228% |
| Zγ | 0.162% |
| μμ | 0.0214% |

⇒ **Lifetime measurements, b-hadrons, $\tau$-lepton**

## Particle identification

⇒ **Need excellent lepton and photon id**

- **$e/\pi$, $\mu/\pi$, $\gamma/\pi^0$**

⇒ **Also in collimated topologies**

- High granularity calorimetry
- Good two-track separation
- For example, $\tau$ polarisation measurement
  - Separation of decay channels
  - Measurement of charged vs. neutral energy in $\tau^- \to \rho^- \to \pi^- \pi^0$

⇒ **π/K, K/p separation via dedicated PID**

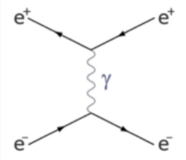
- Full exploitation of large events samples for heavy flavour physics studies

## Extremely good acceptance definition

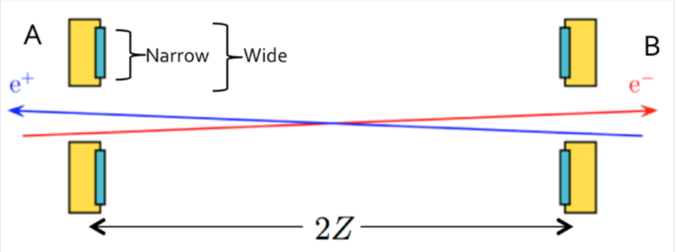
⇒ **In general, allow normalisation to $10^{-5}$ level**

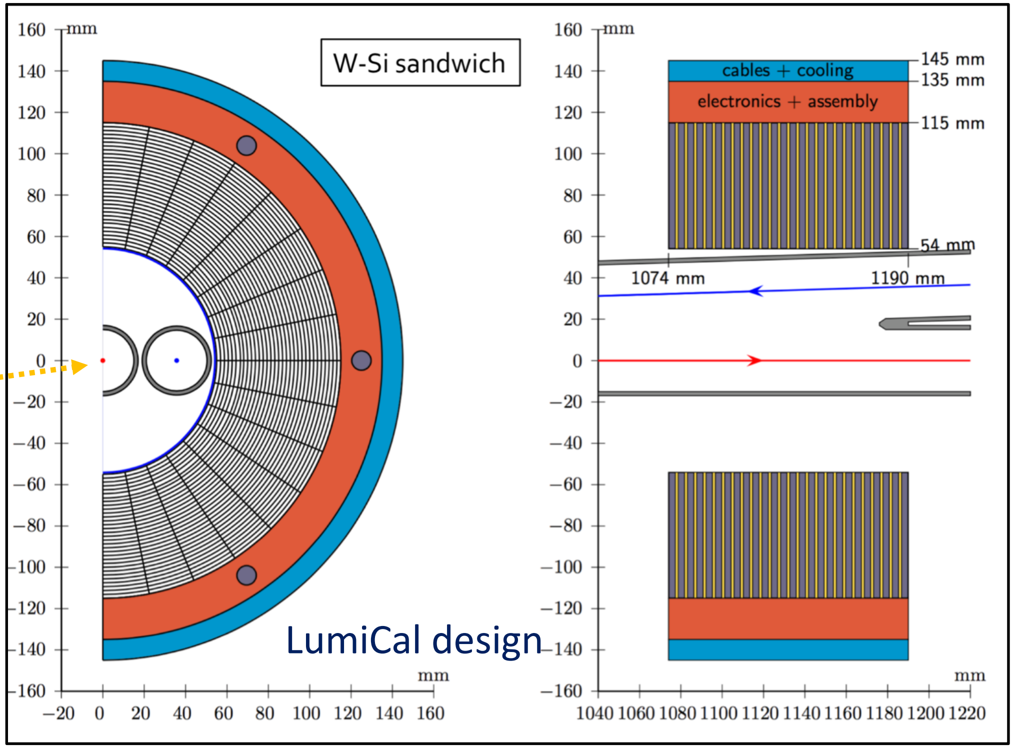
Ambitious goal:
- Absolute to $10^{-4}$
- Relative (energy-to-energy point) to $10^{-5}$

Small angle Bhabha scattering.
Very strongly forward peaked




Monitors centered around outgoing beam lines
-- micron level precision needed on monitor dimensions (inner radius)

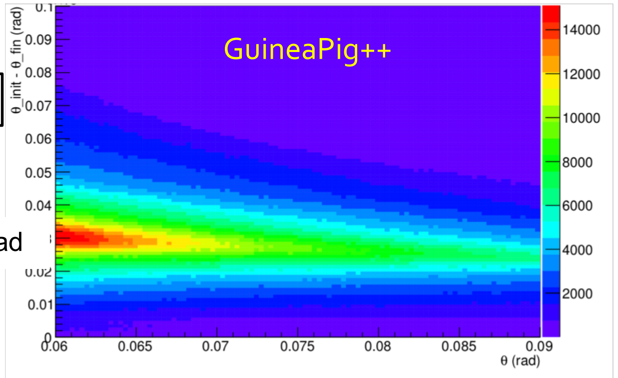


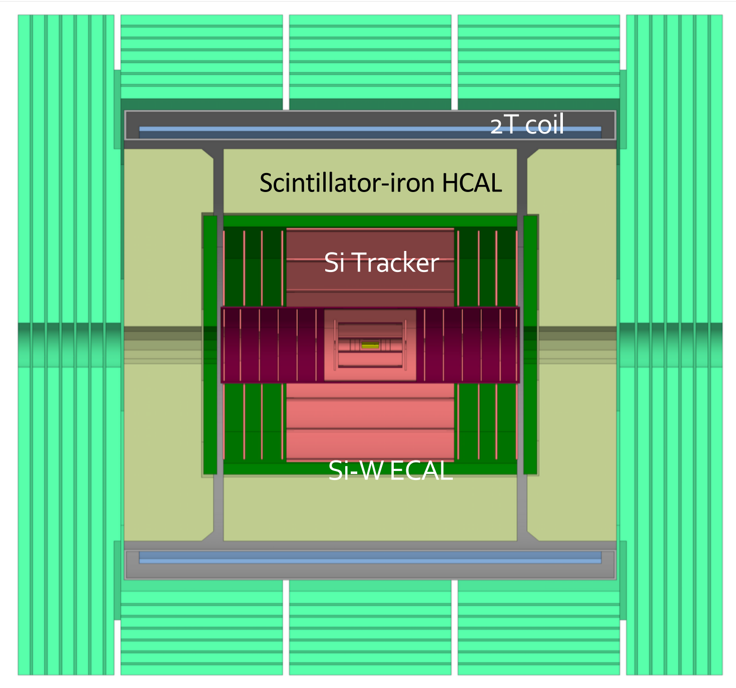

- **Theory**: Now at 3.8 × $10^{-4}$; theory friends foresees that 1 × $10^{-4}$ will happen
- **Backgrounds:** have been studied and seem to be under control
  - Only "incoherent pair production" starts to pop up at ttbar energies
- **Electromagnetic focussing of Bhabhas** (similar to "pinch effect")
  - under study…

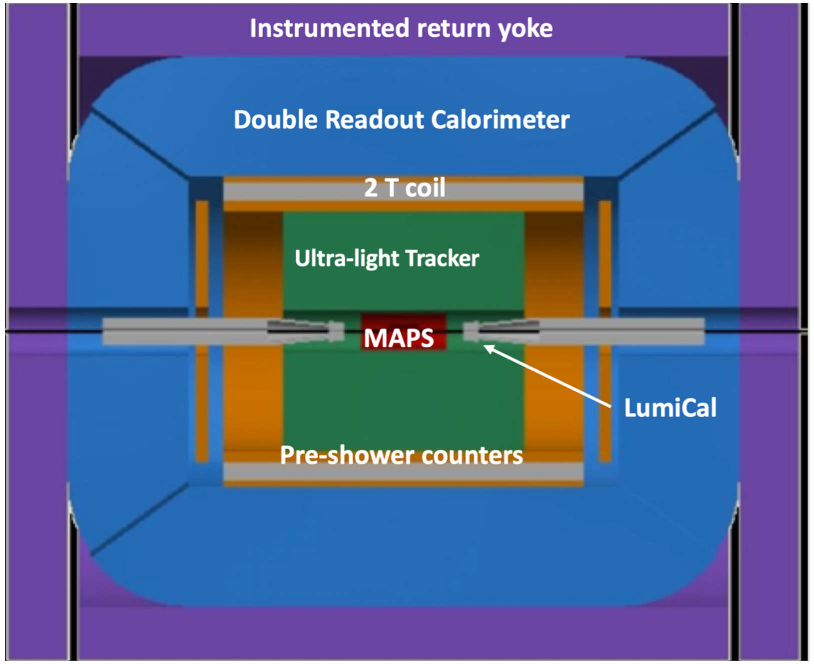
arXiv:1812.01004]

30 μrad



# Two Complementary Detector Designs




## CLD

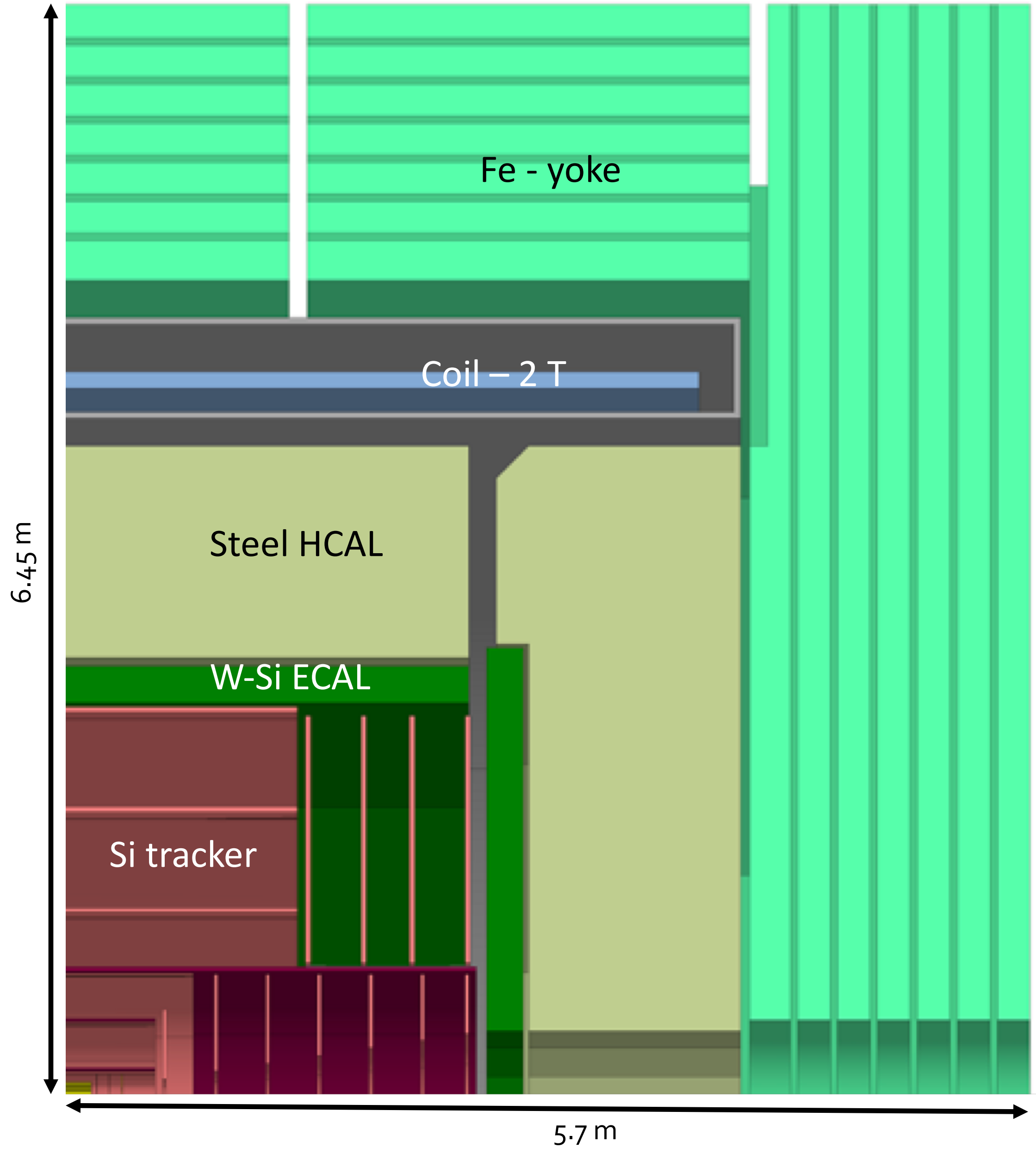
- Consolidated option based on the detector design developed for CLIC
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil outside calorimeter system
- Proven concept, understood performance

## IDEA

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

# CLD Detector Layout

- Full silicon tracking system
  - ≥ 12 hits per track
- Fine-grained ECAL and HCAL optimized for particle flow reconstruction
- Superconducting solenoid outside calorimeter system
- Steel return yoke instrumented with muon chambers
- Forward detector region region reserved for Machine Detector Interface
  - Tracking system >150 mrad, accommodating LumiCal
  - Calorimeter system > 100 mrad
- Support structures, cables and services already included in simulation model



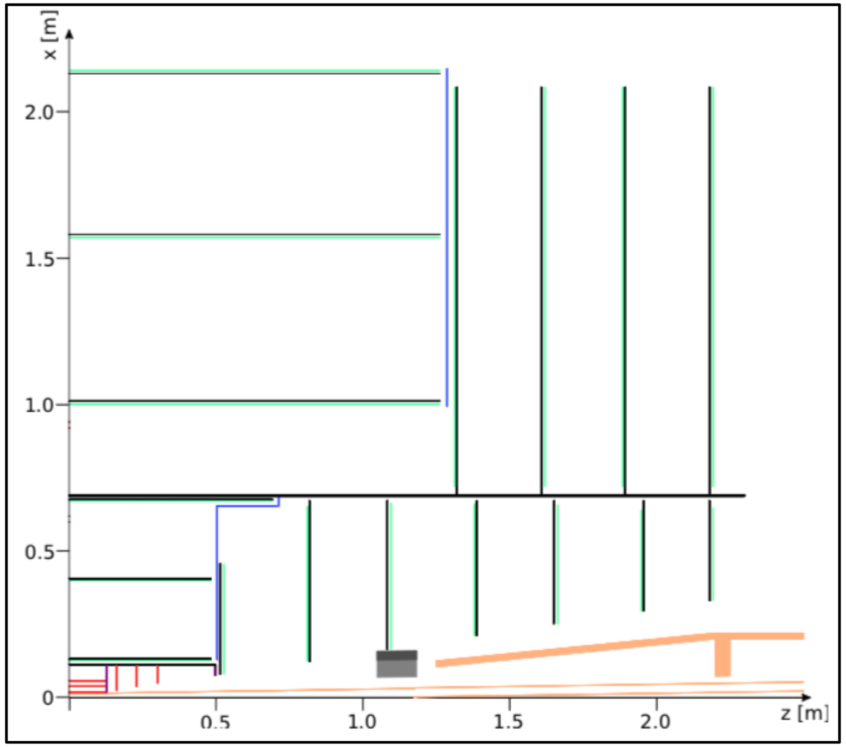
# CLD Tracking System

## Vertex detector

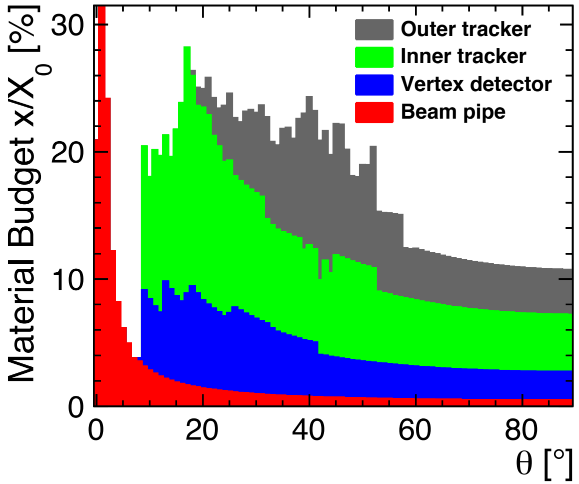
- Silicon pixels 25×25 $\mu m^2$
- Single point resolution: 3 μm
- 3 double layers at r = 17, 37, 57 mm
- 3 double endcap disks per side at z = 160, 230, 300 mm
- Material budget: 0.4% $X_0$ per double layer
  + extra 0.2% $X_0$ per double layer (additional cooling)

## Tracker

- Silicon pixel and microstrips
- Inner Tracker:
  ⇒ 3 barrel layers, 7 disks per side
- Outer Tracker:
  ⇒ 3 barrel layers, 4 disks per side
- Single point resolution:
  ⇒ 1st IT disks: 5×5 $\mu m^2$
  ⇒ rest: 7×90 $\mu m^2$
- Material budget: 1.1 - 1.6% $X_0$ per layer




Overall very lightweight tracking system



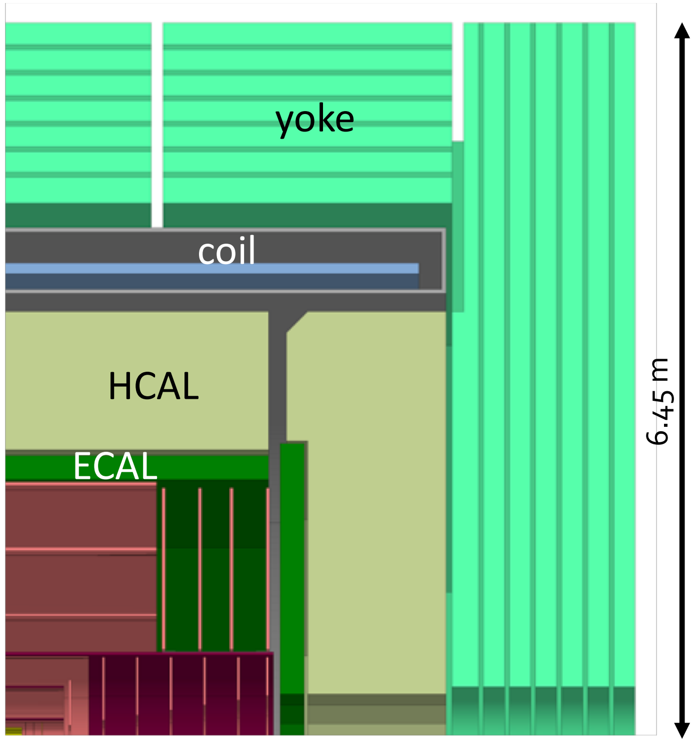
# CLD Calorimeter System

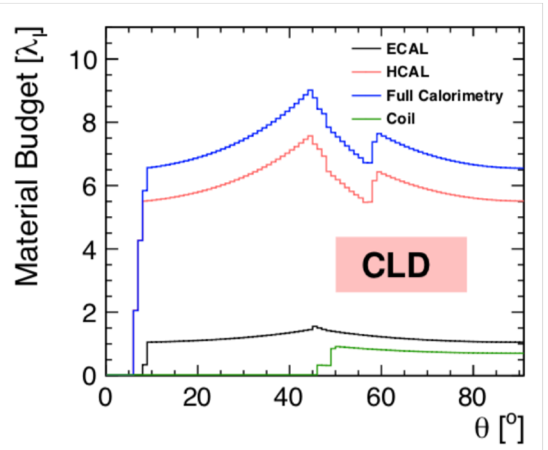
Electromagnetic Calorimeter

- Si-W sampling calorimeter
- Cell size 5×5 $mm^2$
- 40 layers (1.9 mm thick W plates)
- Depth: 22 $X_0$, 1 $\lambda_I$, 20 cm

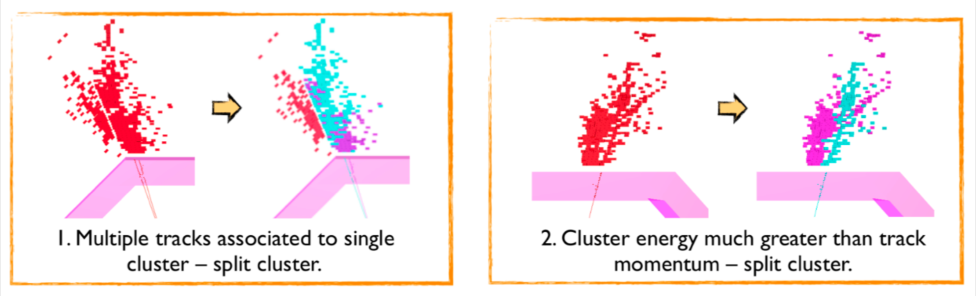
Hadronic Calorimeter

- Scintillator-steel sampling calorimeter
- Cell size 30×30 $mm^2$
- 44 layers (19 mm thick steel plates)
- Depth: 6 $\lambda_I$, 117 cm




Fine grained calorimeter segmentation optimized for optimal performance of **particle flow** identification and energy resolution (PandoraPFA)



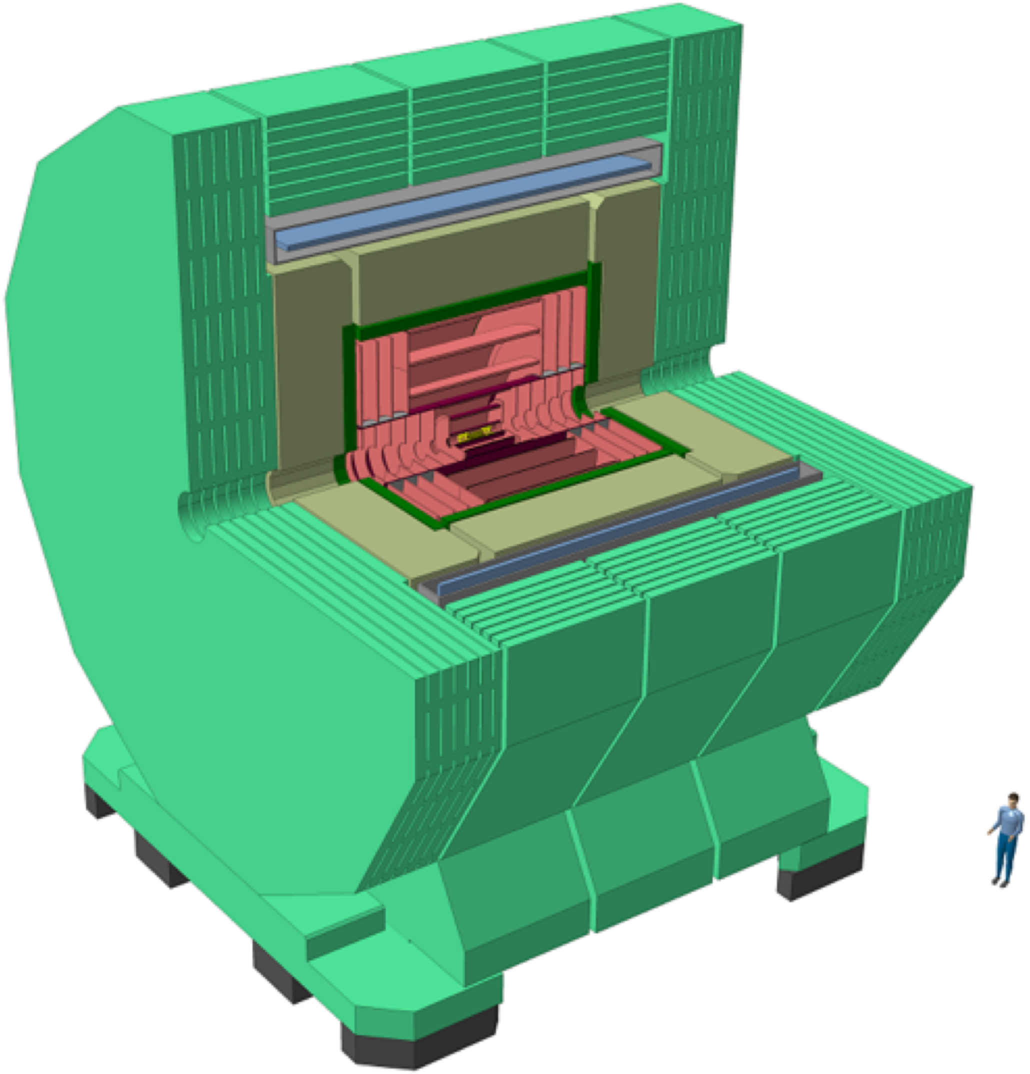
# CLD magnet and muon system

Magnet system

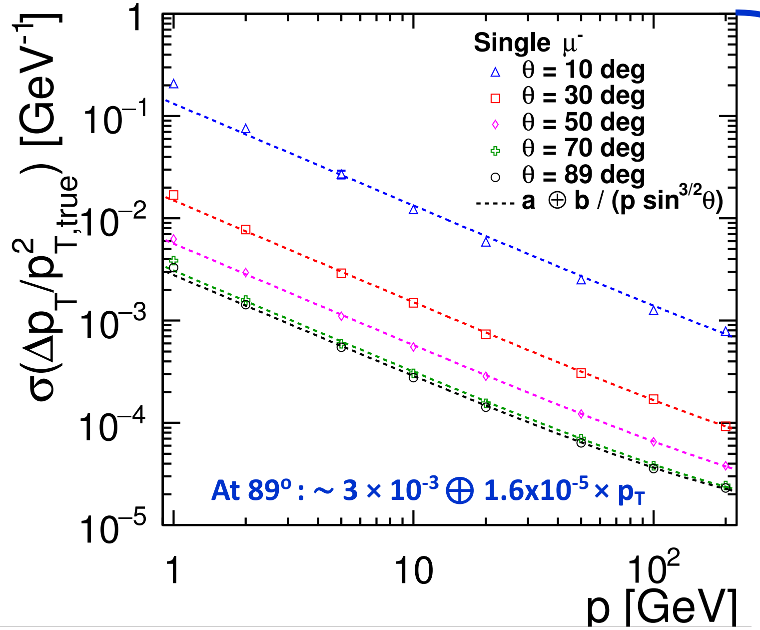
- Superconducting coil outside calorimeter system
  - 90 mm thick aluminum coil
  - 2 T field in the tracker volume
- Return yoke, 1.5 m thick steel

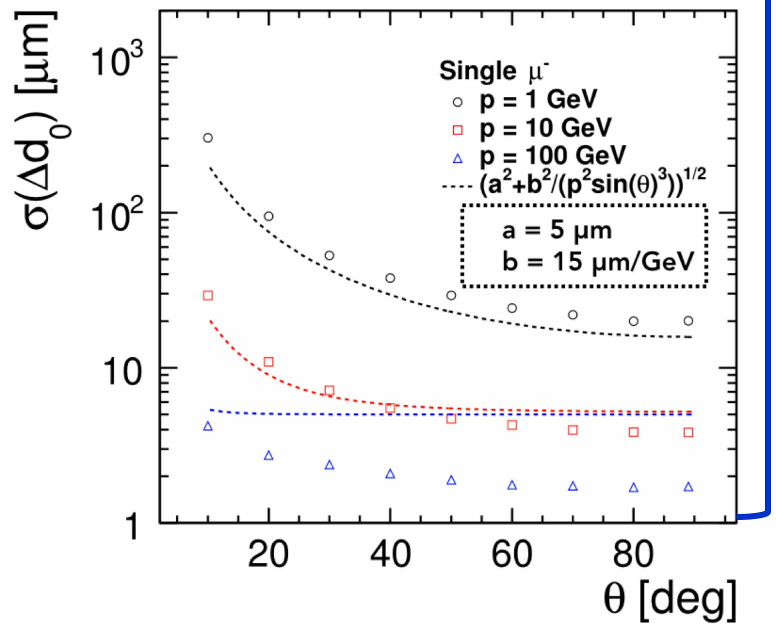
Muon system

- 6 layers of RPC muon chambers inside yoke
  - Cell size: 30 × 30 $mm^2$



# CLD Tracking performance




## Resolutions

Momentum measurement:

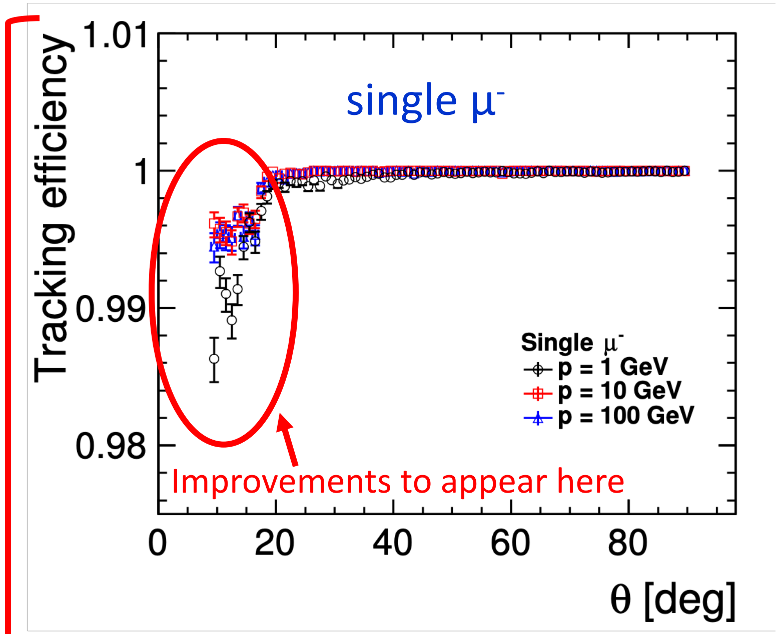
- Excellent point resolution: smaller than mult.scat. term below p = 180 GeV

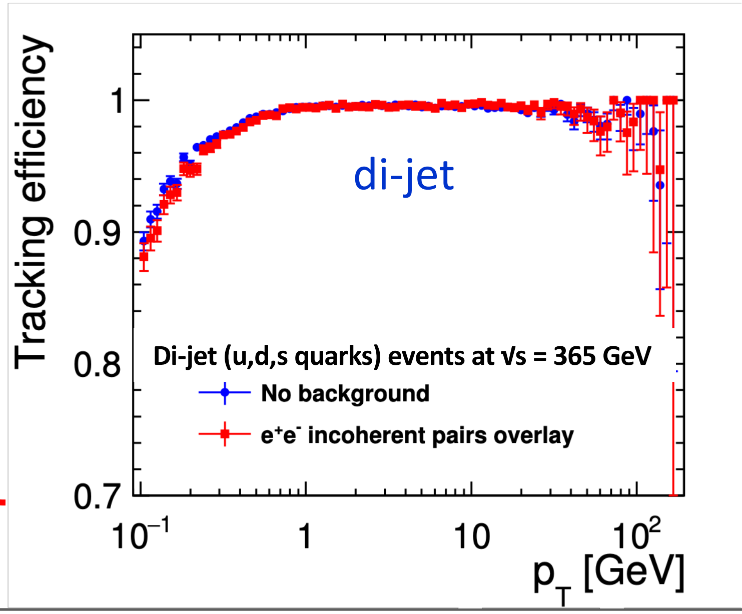
Impact parameter:

- Better than requirements for p ≳ 10 GeV

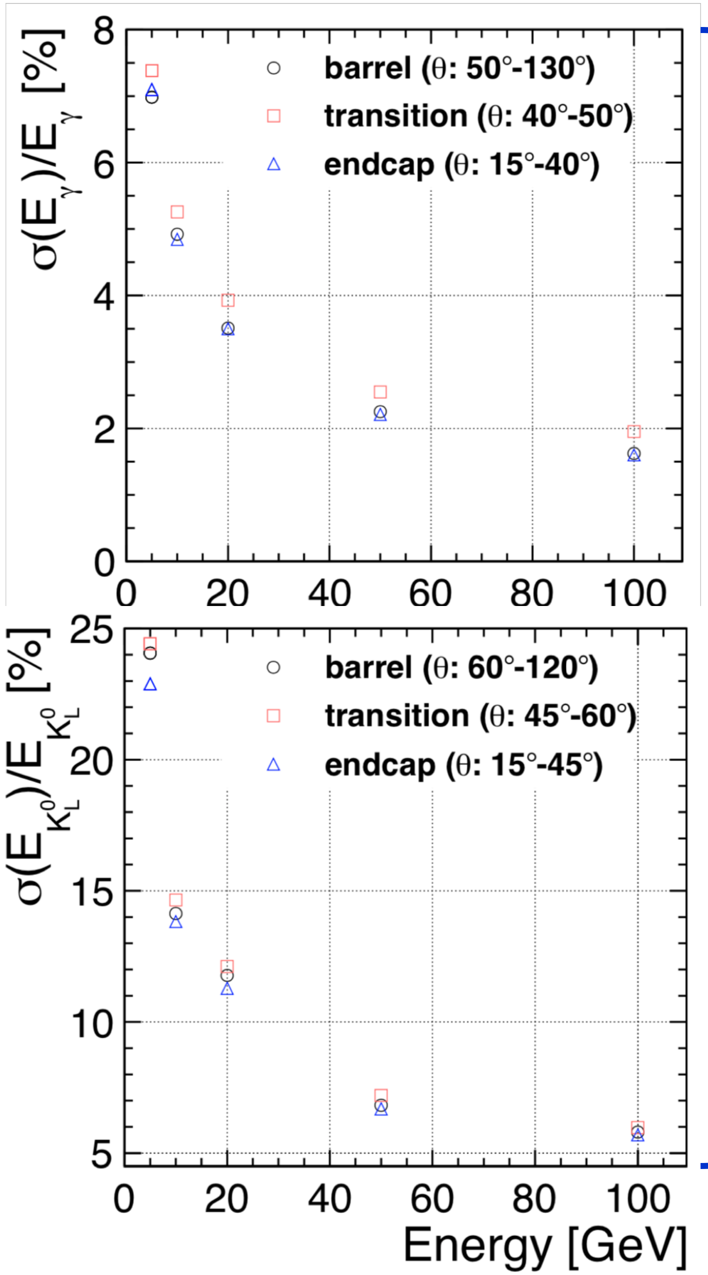
## Tracking efficiencies

- Very high (~100%) for single μs above 20°
- Excellent also in complex events



# CLD Calorimeter Resolutions




## Photons and neutral hadrons

Resolution for 100 GeV particles better than

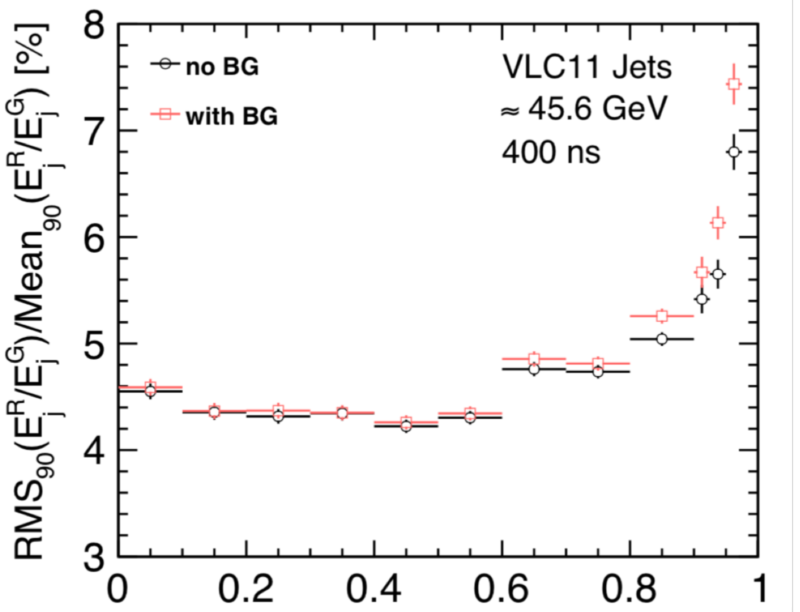
- ECAL (photons): 2%
- HCAL ($K^0_L$s): 5%

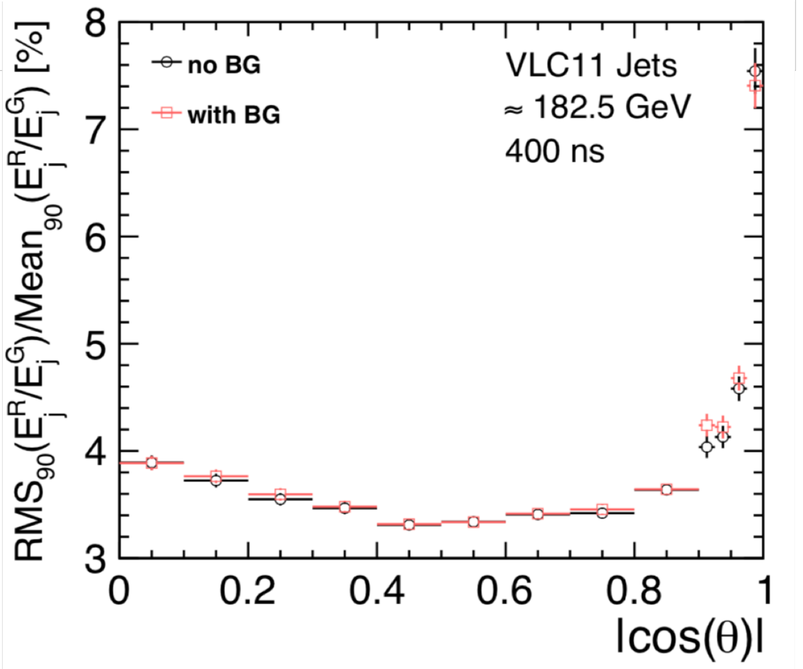
## Jets (u, d, s quarks)

Resolution using Valencia clustering algorithm with $\Delta R$=1.1

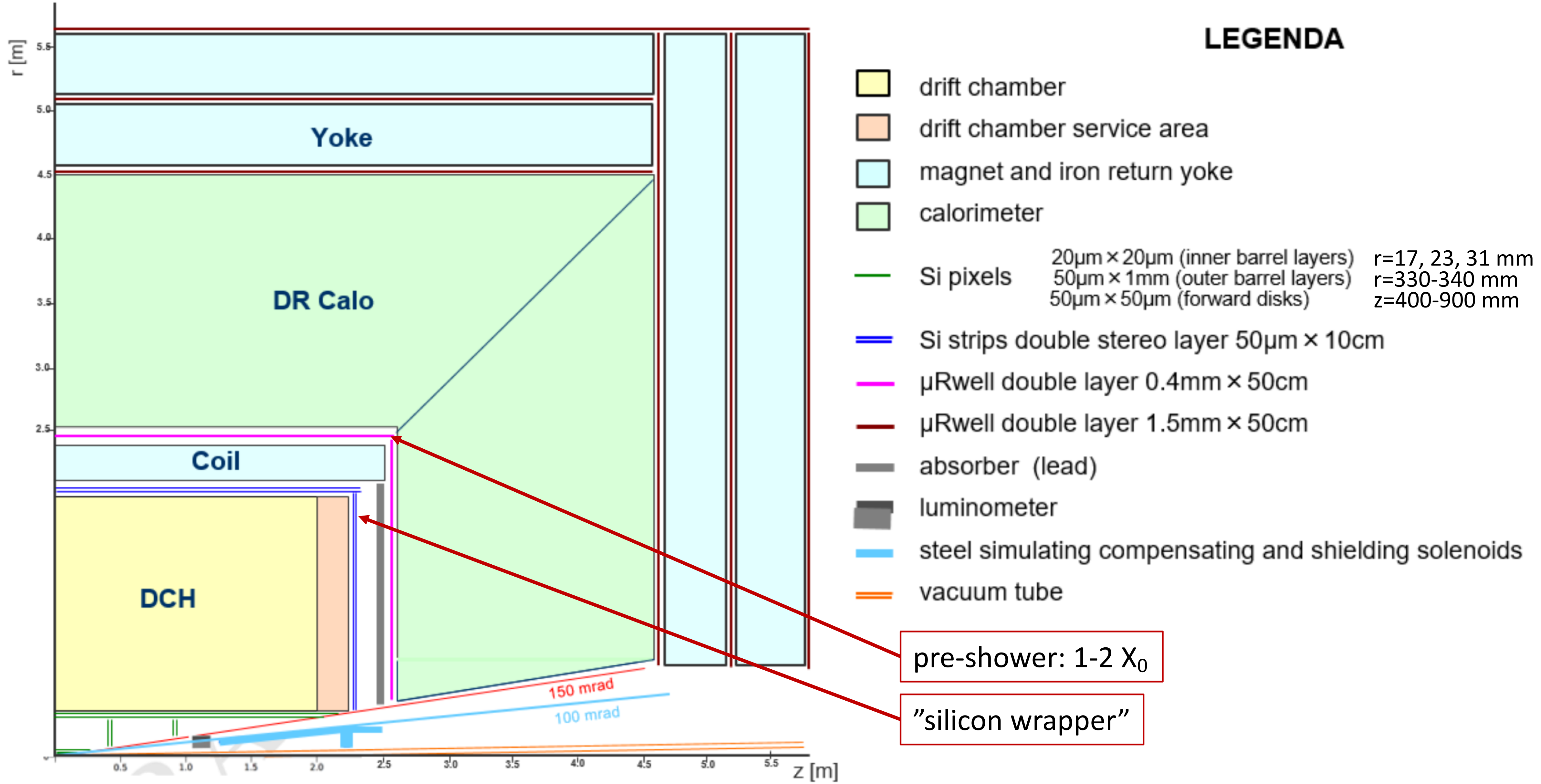
- 4-5% for 45.6 GeV jets
- 3-4% for 182.5 GeV jets

Only small dependence on background (incoherent pair production)



# IDEA Detector Concept Layout

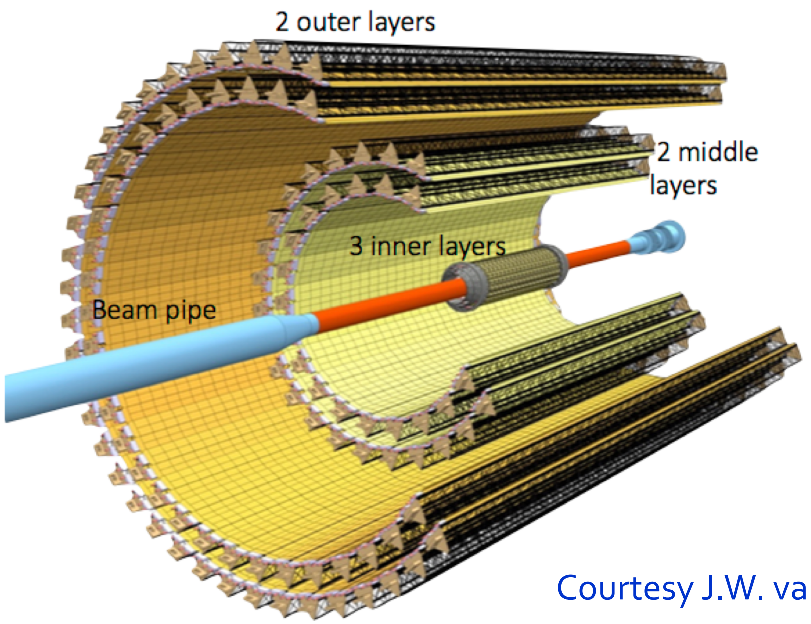


# IDEA Vertex Detector

Inspired by ALICE ITS based on MAPS technology

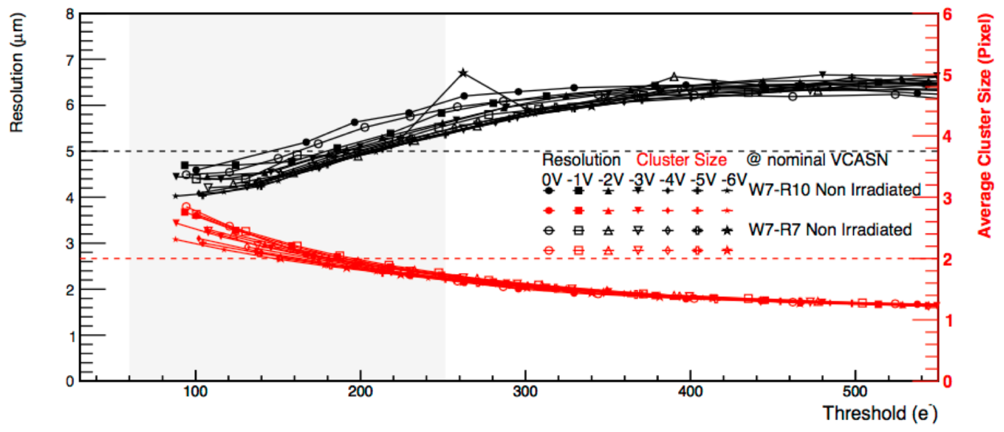
- Pixels 30 × 30 μm$^2$

- Light
  - Inner layers: 0.3% of $X_0$ / layer
  - Outer layers: 1% of $X_0$ / layer
- Performance:
  - Point resolution of 5 μm (or better)
  - Efficiency of ~100%
  - Extremely low fake rate hit rate

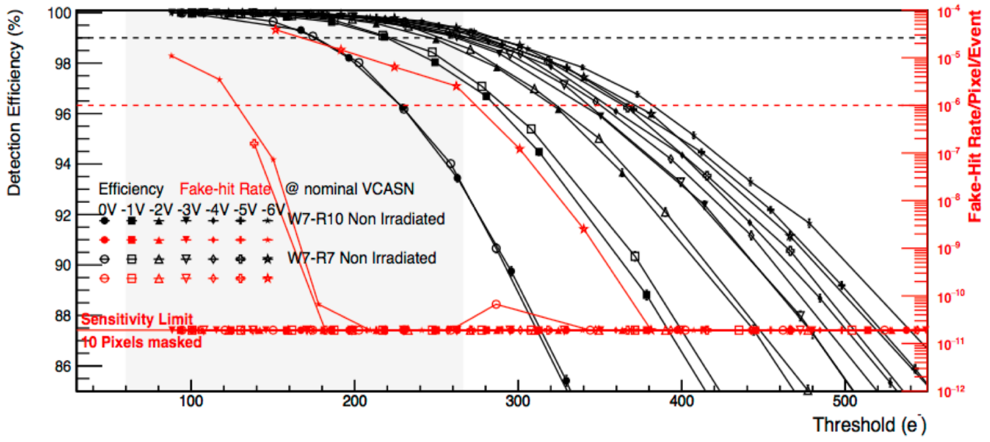



Courtesy J.W. van Hoorne

Position resolution and cluster size




Detection efficiency and fake-hit rate



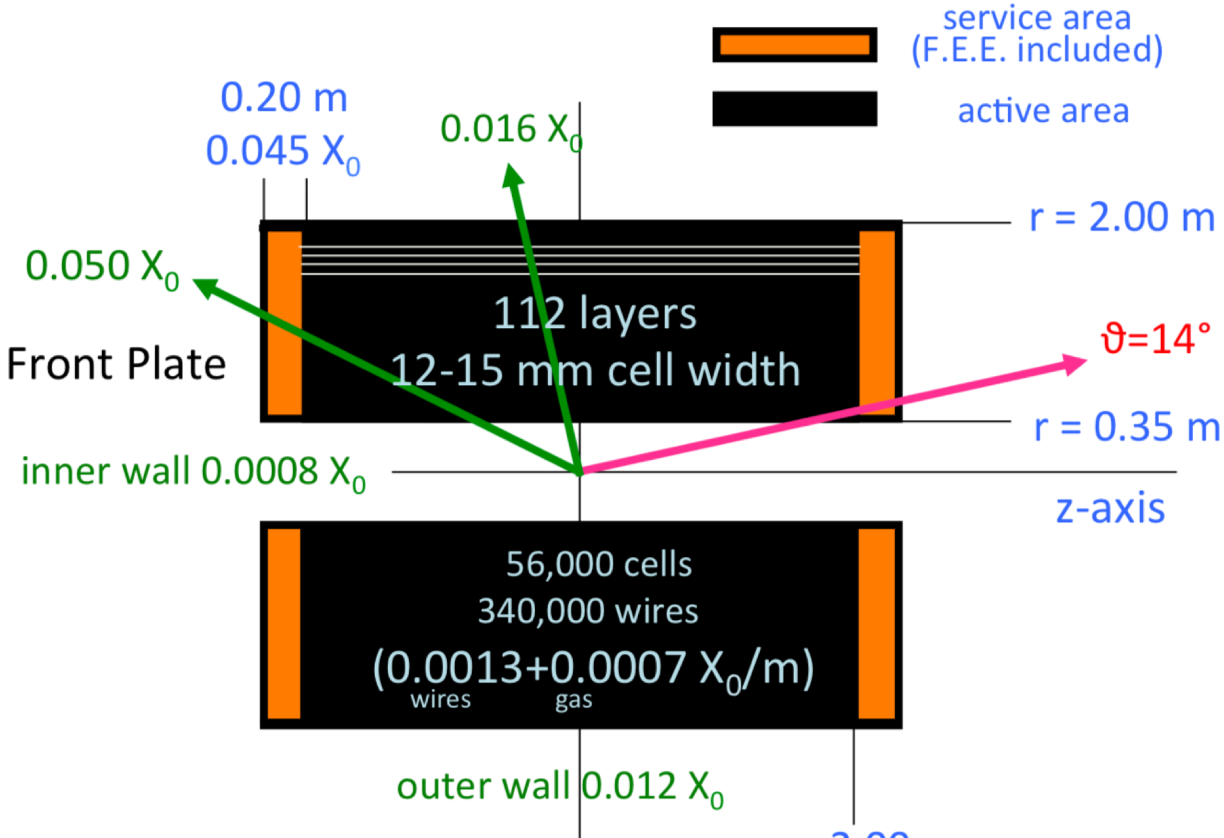
# IDEA ultra-light Drift Chamber

Ancestor:
- KLOE Drift Chamber

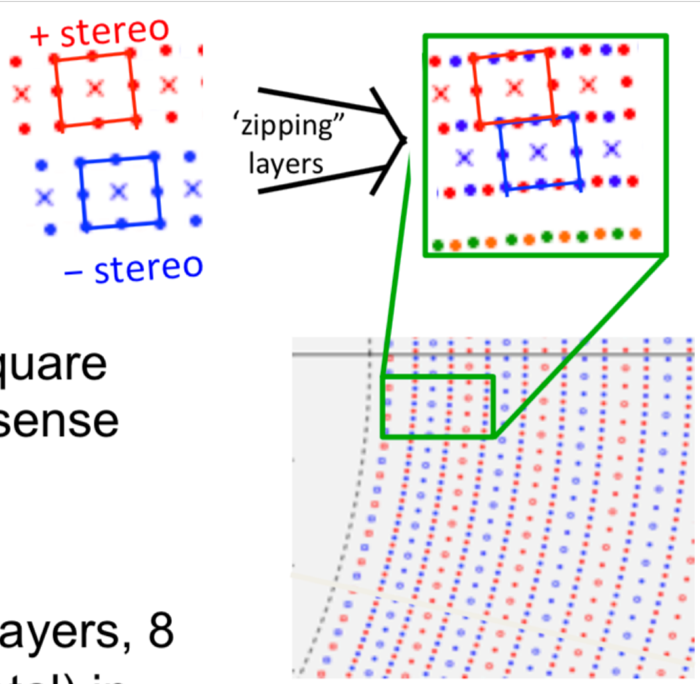
Under construction:
- MEG2 Drift Chamber

tracking efficiency ε ≈ 1 for ϑ > 14° (260 mrad)
97% solid angle

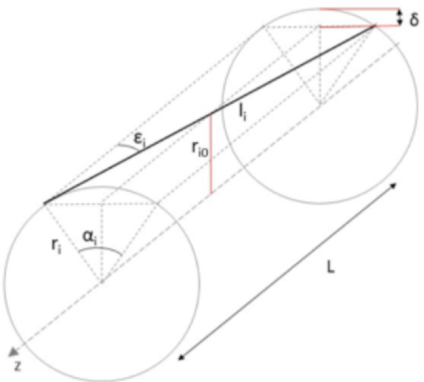
$0.016\ X_0$ to barrel calorimeter
$0.050\ X_0$ to end-cap calorimeter



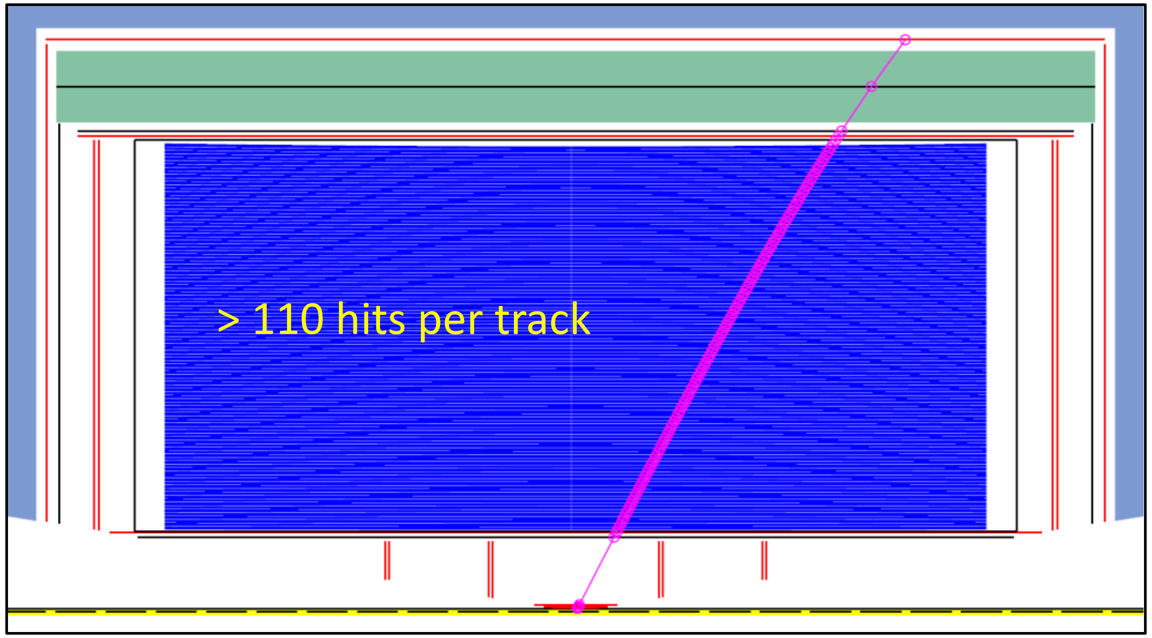

**Gas: 90% He, 10% $iC_4H_{10}$**

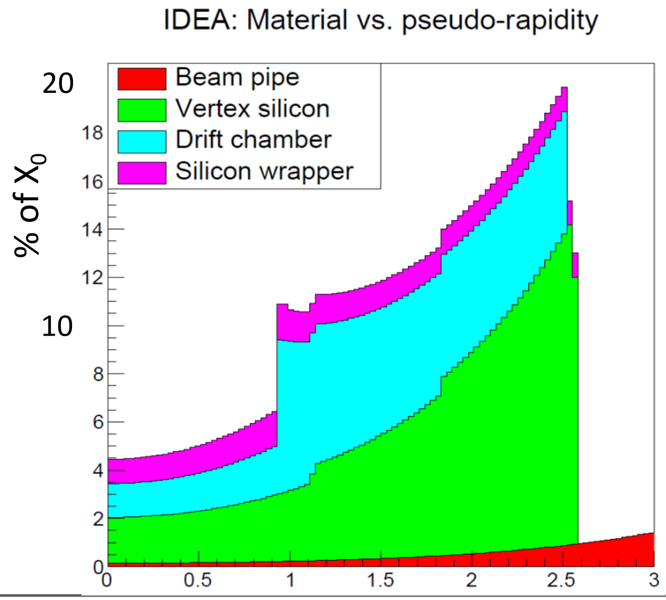



- 12÷15 mm wide square cells 5 : 1 field to sense wires ratio
- 56,448 cells
- 14 co-axial super-layers, 8 layers each (112 total) in 24 equal azimuthal (15°) sectors ($N_i = 192 + (i - 1) \times 48$)
- alternating sign stereo angles ranging from 50 to 250 mrad

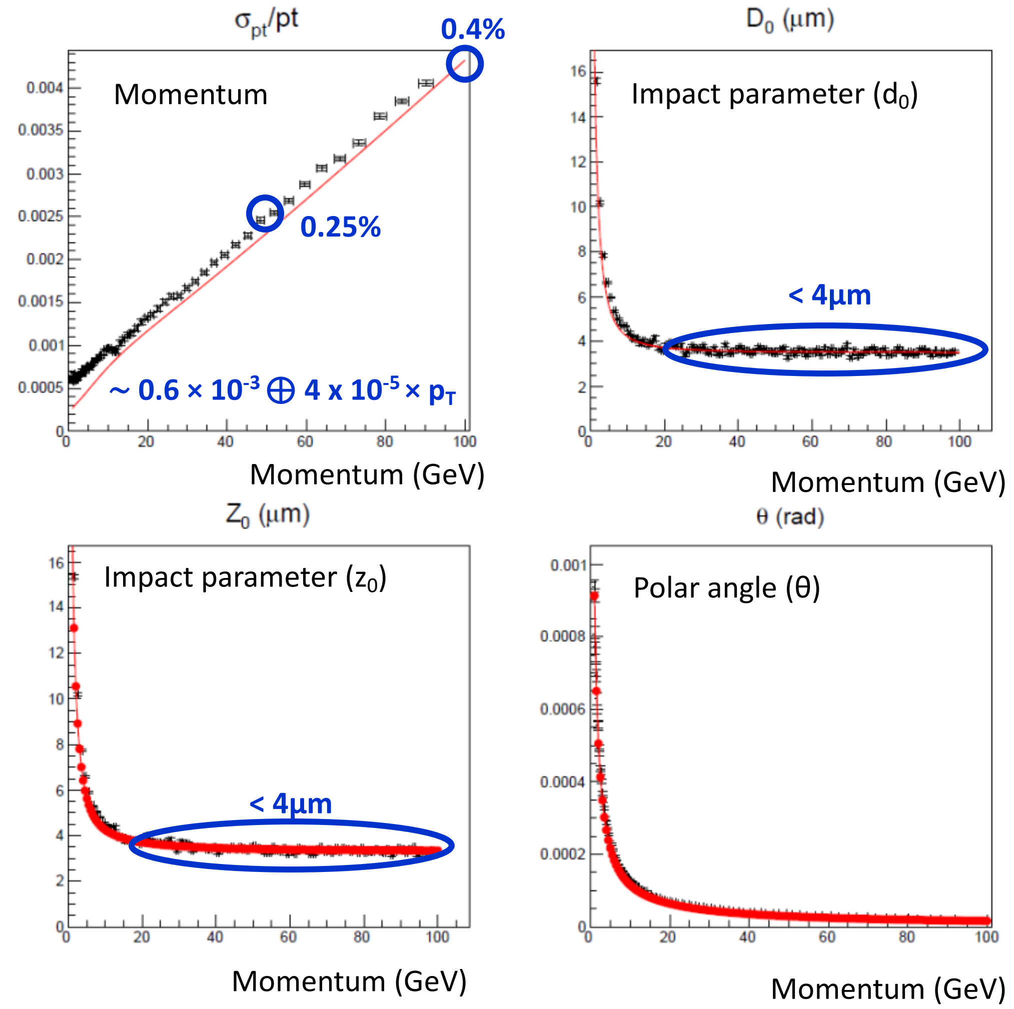


# IDEA Tracker Layout and Resolutions



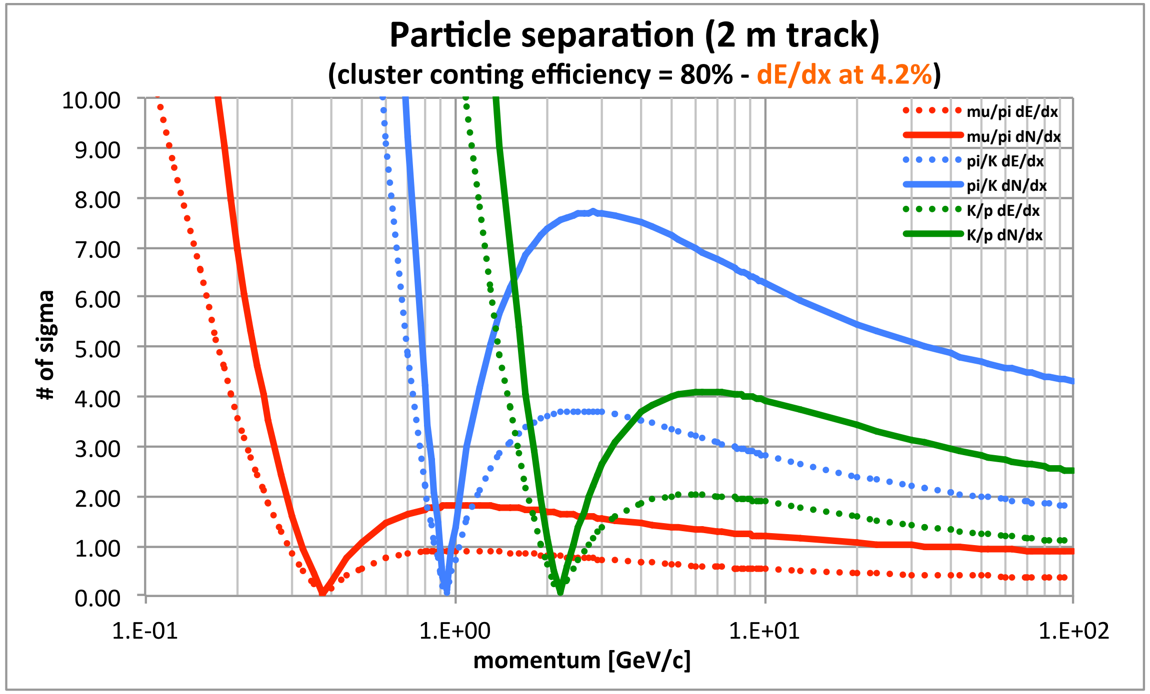

## Resolutions - barrel region

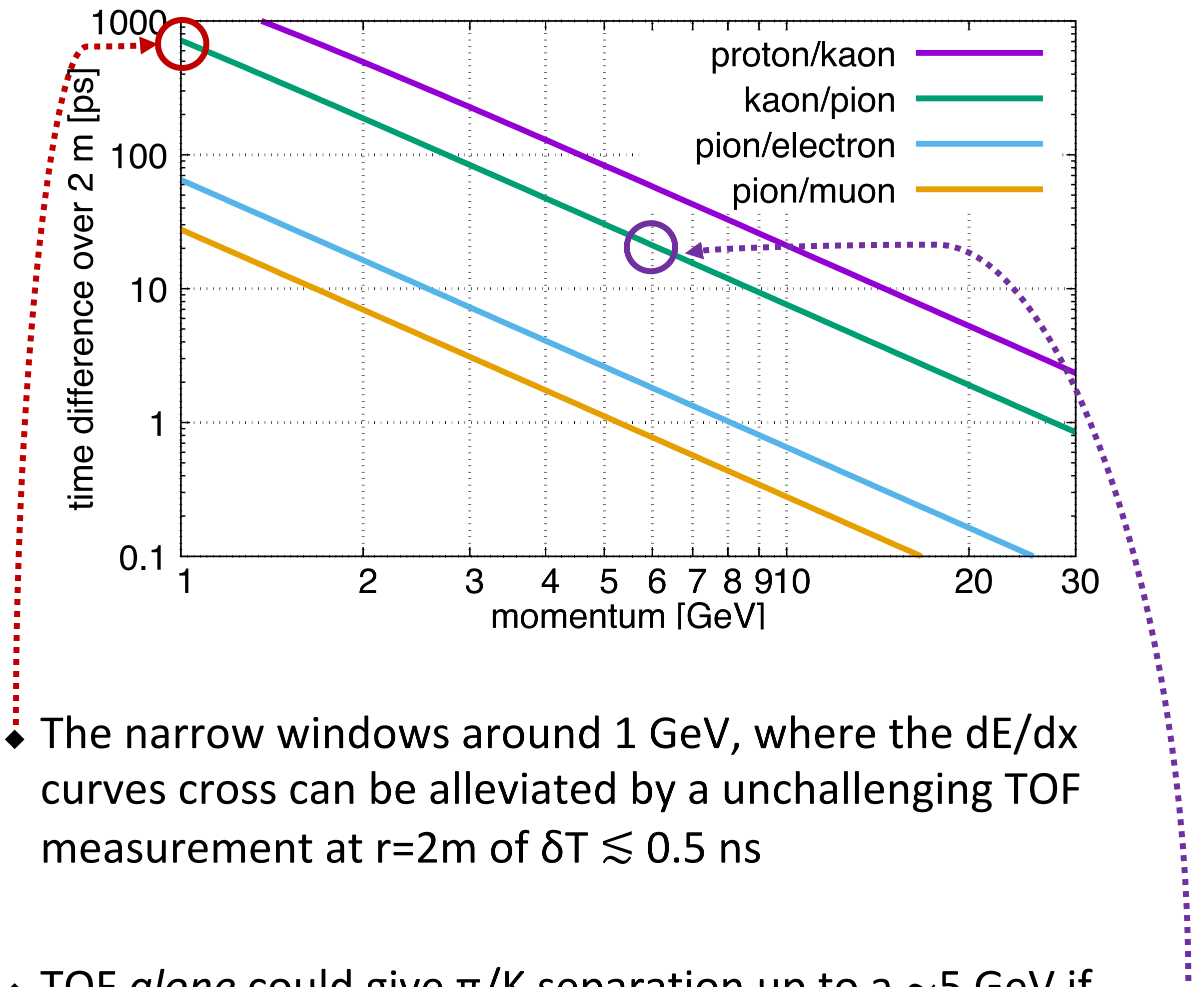



Here, using conservative Si resolution numbers (1/√12), work in progress...

# IDEA Drift Chamber PID

- To fully exploit the enormous statistics of FCC-ee particle ID will be a big asset
- IDEA Drift Chamber PID resolution can be considerable improved using cluster counting:
  - Standard truncated mean dE/dx : **σ ≃ 2.5%**
  - Cluster counting : **σ ≃ 4.2%**

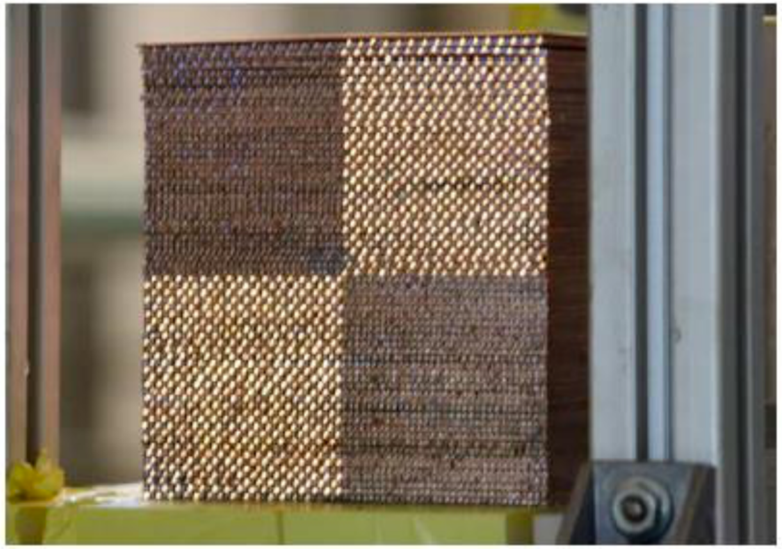


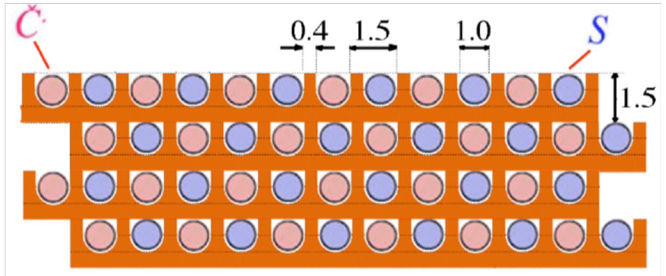




- The narrow windows around 1 GeV, where the dE/dx curves cross can be alleviated by a unchallenging TOF measurement at r=2m of δT ≲ 0.5 ns
- TOF *alone* could give π/K separation up to a ~5 GeV if measurement precision would be δT ~ 20 ps
  - LGADs, …

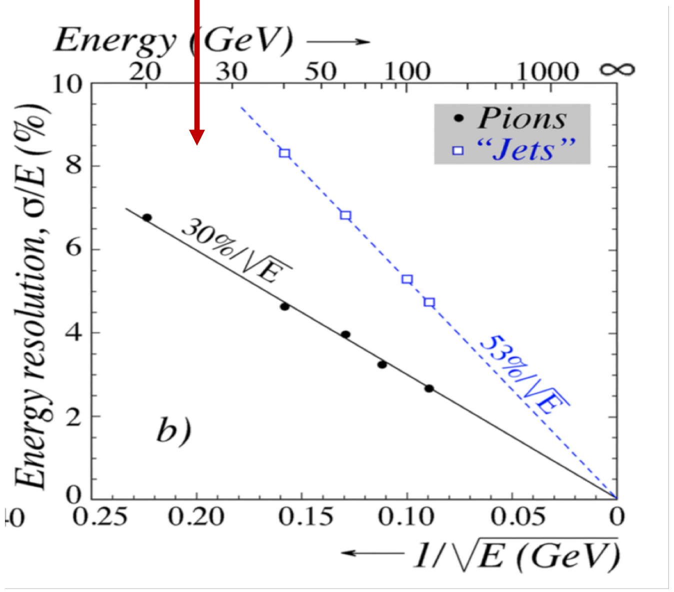
# IDEA Dual Readout Calorimeter

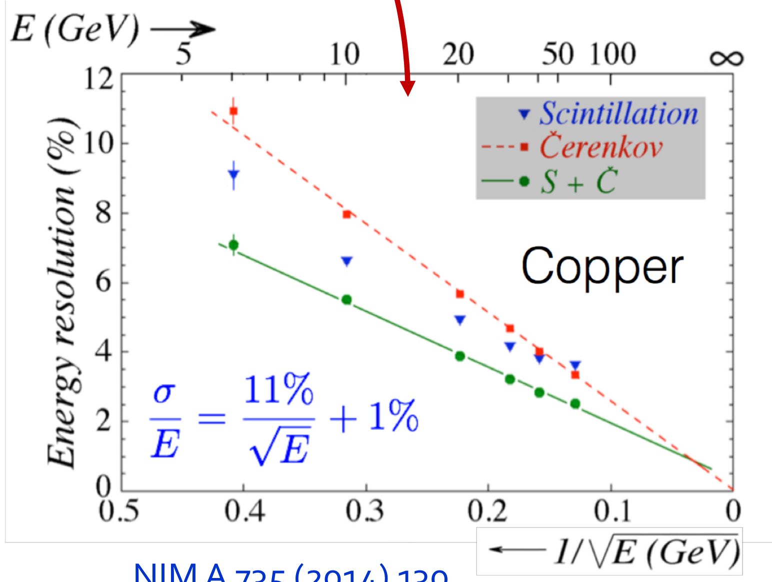
- Alternate clear and scintillating fibers in metal matrix (lead, copper, …)
  - Scintillating fibers sensitive to all charged particles (S)
  - Clear fibers sense only Cherenkov light (C)
    - Mostly electrons and positrons
- Large sampling fraction for good resolution
- Event by event correction for EM fluctuations in hadronic showers
- Particle ID capabilities: shower width, C/S ratio, …
- Test beam:
  - Very good electromagnetic resolution
  - Excellent resolution for (isolated) hadrons






Courtesy of DREAM/RD52

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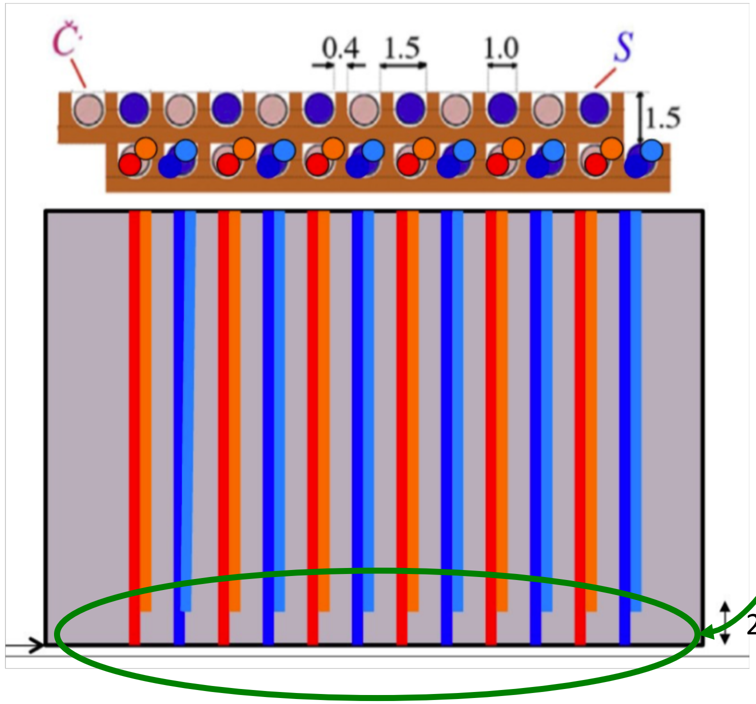
# Towards a full scale dual readout calorimeter

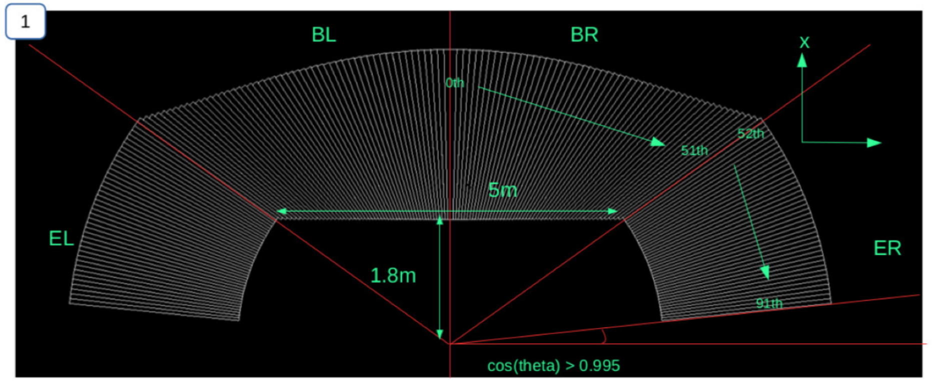
## Longitudinal segmentation study

- For particle ID in multi-particle environment, need information on longitudinal shower development.
- Ongoing studies in test beam and simulation of possibility to let (staggered) fibers start in different depth
  - ECAL compartment is defined as the difference of signals in long and short fibers




## 4π detector design study

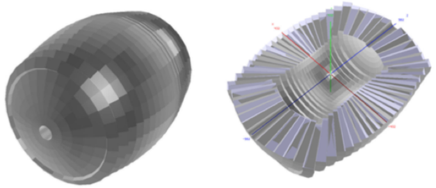
### Projective layout: "wedge" geometry

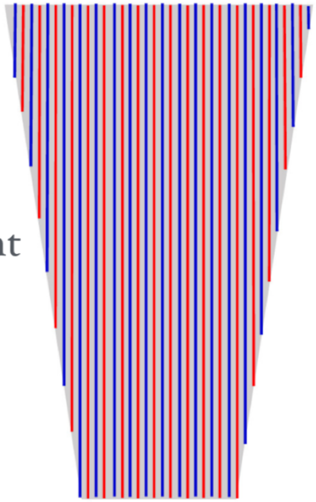



It covers the full volume up to $|\cos(\theta)| = 0.995$, with **92** different types of towers (wedge)

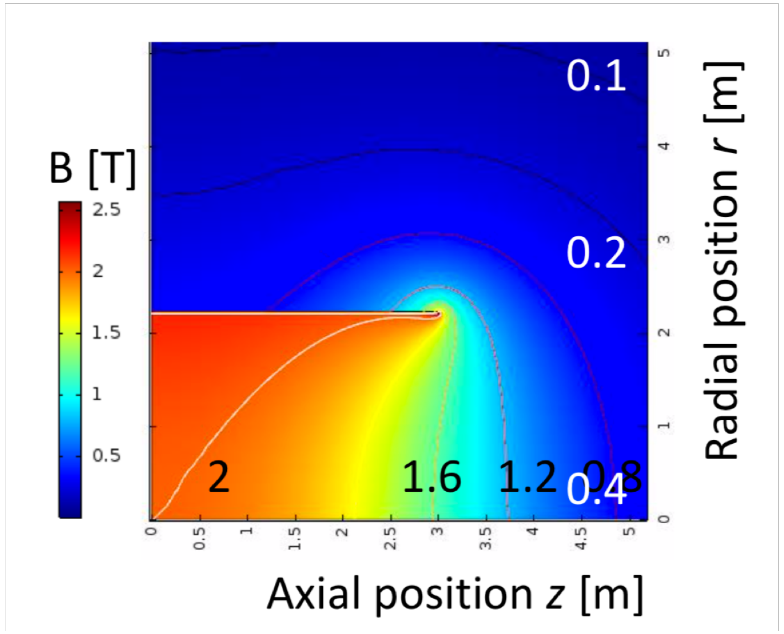
A typical one in the barrel:

- $\Delta\theta \times \Delta\phi = 1.27^\circ \times 1.27^\circ$
- length of 250 cm (~ 10 λ)
- about **4000 fibres** (starting @ different depths to keep constant the sampling fraction)





# 2 T "light and thin" Solenoid inside Calorimeter




| Property | Value |
|---|---|
| **Magnetic field in center [T]** | **2** |
| Free bore diameter [m] | 4 |
| **Stored energy [MJ]** | **170** |
| Cold mass [t] | 8 |
| Cold mass inner radius [m] | 2.2 |
| Cold mass thickness [m] | 0.03 |
| Cold mass length [m] | 6 |

H. Ten Kate et al.

- **Objectives**
  - **Light**: certainly less than 1 $X_0$
  - **Thin**: As thin as possible for optimal tracker-to-calorimeter matching
- Self-supporting single layer coil
  - High yield strength conductor fully bonded
  - Thin Al support cylinder
- Coil composition
  - Aluminum (77 vol.%)
  - NbTi (5 vol.%) / copper (5 vol.%)
  - Glass-resin-dielectric films (13 vol.%)
- Radiation thickness (preliminary studies)
  - Cold mass: $X_0 \approx 0.46$
  - Cryostat (25 mm Al): $X_0 \approx 0.28$
  - Total $X_0 \approx 0.75$ achievable
  - Total radial envelope less than 30 cm
- Prospects for even lighter and thinner outer shell



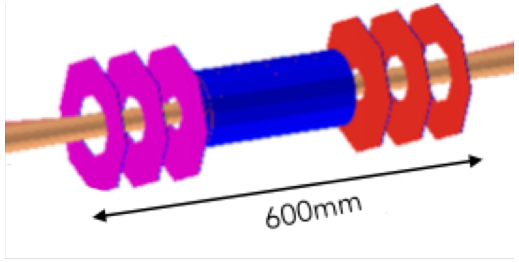
# Summary

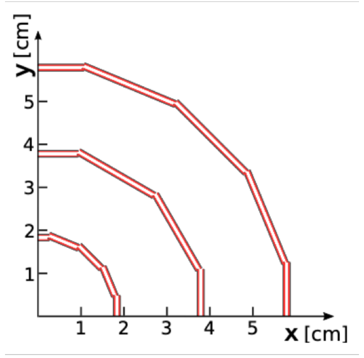
- FCC-ee delivers enormous event samples in a clean environment at its four running points: Z, WW, ZH, and ttbar
- The extreme luminosity comes at the price of a complicated interaction region with final-focus quads to $L^* = 2.2$ m
  - Interaction region design with shielding/compensation of quads and beam from 2 T detector field
  - Limited machine background levels into detectors via effective masks and shielding
  - Very compact LumiCal design with face at 107 cm from IP. Ambitious goal of absolute normalisation to $10^{-4}$
- FCC-ee physics programme calls for detectors with excellent accuracy for high precision measurements
  - Momentum resolution, energy resolution, direction resolution, angular separation, flavour tagging, particle identification
- Two complimentary detector designs have been developed matching the two IPs foreseen at the CDR stage
  - CLD: a consolidated design based on the detector design developed for CLIC
  - IDEA: a new, innovative, possibly more cost-effective design
- CLD Detector Concept
  - All silicon tracker; 3D-imaging highly-granular calorimeter system; 2 T coil outside calorimeter system; instrumented return yoke
  - Proven concept, well understood performance via full simulation studies. Optimisation of design ongoing
- IDEA Detector Concept
  - Silicon vertex detector; ultra-light, short-drift wire chamber (with excellent PID); silicon wrapper; pre-shower; dual-readout calorimeter; 2 T coil inside calorimeter system; instrumented return yoke
  - State-of-the-art technologies. Applicability of chosen solutions and their interplay to be demonstrated for FCC-ee environment via full simulation studies: coil inside calorimeters, longitudinal segmentation of calorimeters, etc.
- Emerging
  - Detector concept based on liquid argon calorimetry (FCC-hh inspired)

# Extras

# CLD - All Silicon Tracking

## Vertex Detector

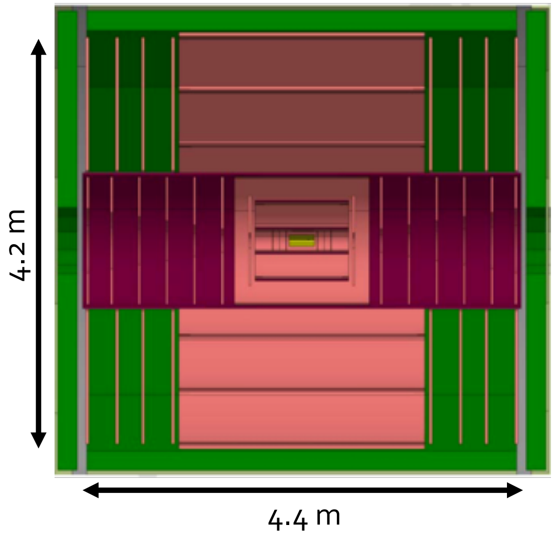


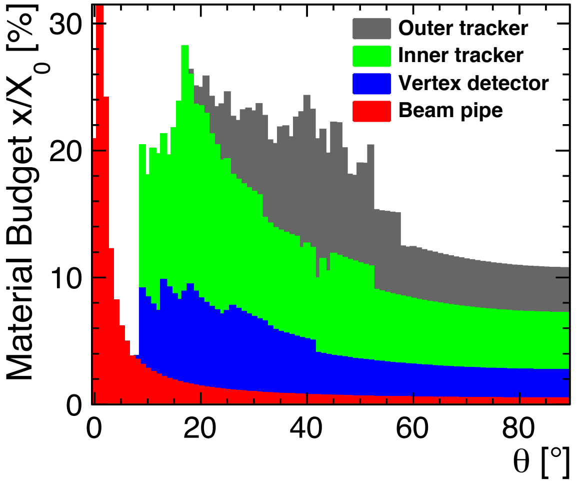

- 3 double barrel layers + 3 double layer disks per side
  - Sensor thickness = 50 µm
  - 0.4% $X_0$ per double layer
    + 0.2% $X_0$ per double layer (additional cooling)
  - Pixel size 25 × 25 µm$^2$
  - Total sensitive area = 0.35 m$^2$

## Main Tracker

- Inner tracker: 3 barrel layers + 7 forward disks per side
- Outer Tracker: 3 barrel layers + 4 forward disks per side
  - Microstrip: 50 µm × 1-10 mm
    - Pixelated 1st inner tracker disk like vertex detector
  - Sensor thickness = 200 µm
  - 1% $X_0$ per layer (sensor + liquid cooling + connectivity) + 2.5% $X_0$ main support, cooling pipes, cabling routes
  - Total sensitive area = 195.6 m$^2$



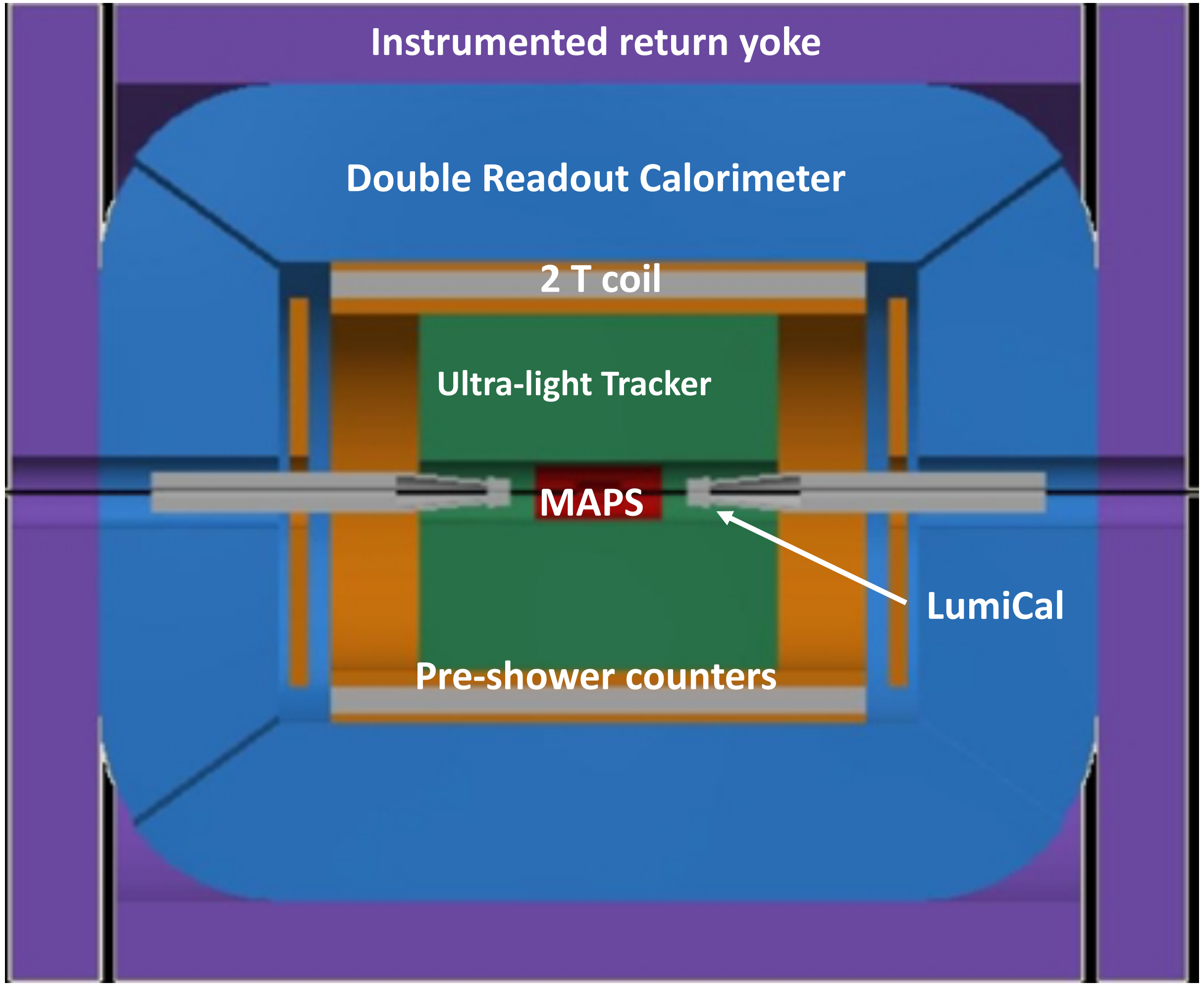

Overall very lightweight tracking system



# IDEA Detector Concept

**Based on present state-of-the-art technologies:**

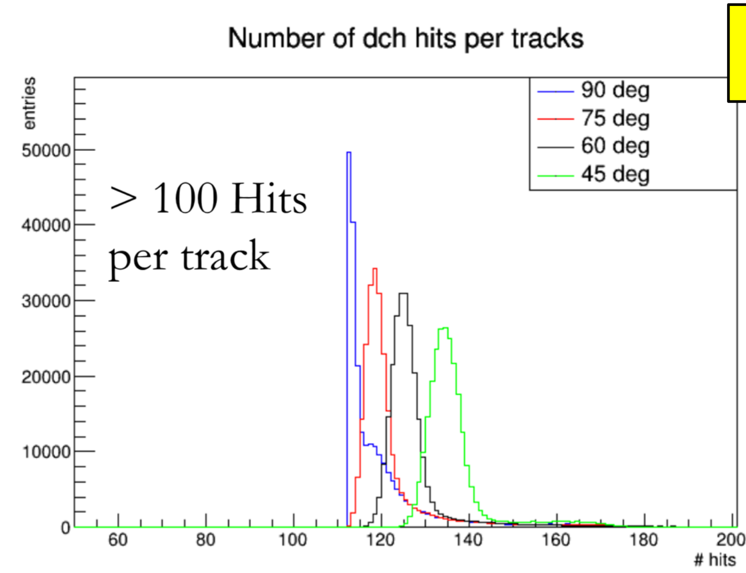
- Vertex detector, 4-7 MAPS layers
- Ultra-light drift chamber with PID capabilities
  - 400 cm long, 30-200 cm radius
- Outer Silicon layer
- Thin and light superconducting coil
  - 2 T, R $\simeq$ 210 cm
- Pre-shower counters, 1-2 $X_0$
- Dual read-out calorimetry, 2 m depth, 7 $\lambda_{int}$
- Return yoke instrumented with µRwell chambers



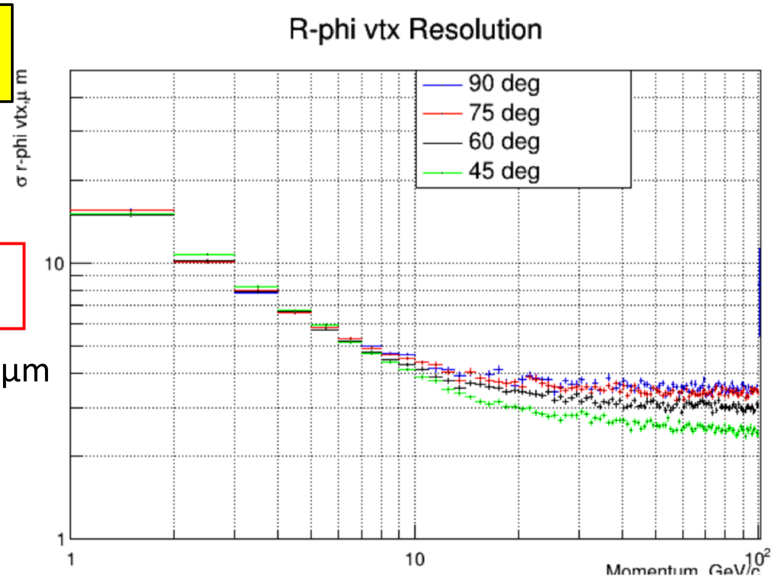
# IDEA Tracking Performance

**Full simulation results**

N hits fitted (DCH)

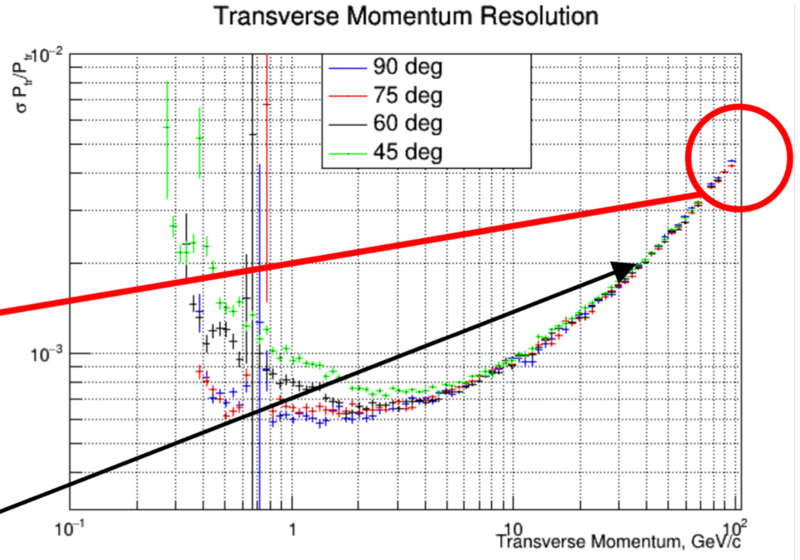



impact parameter




4 μm

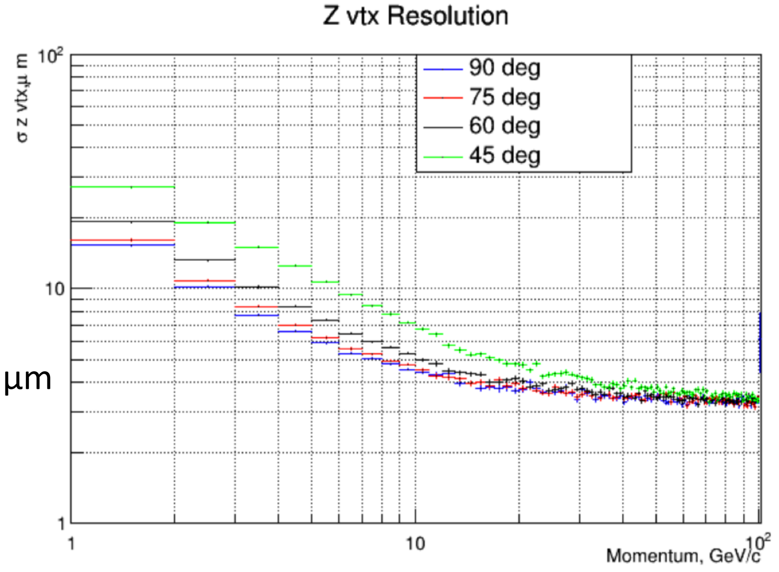
$p_t$




$$\frac{\sigma_{p_t}}{p_t^2} = 4 \bullet 10^{-5}$$

$$\frac{\sigma_{p_t}}{p_t^2} = 5 \bullet 10^{-5}$$

Z



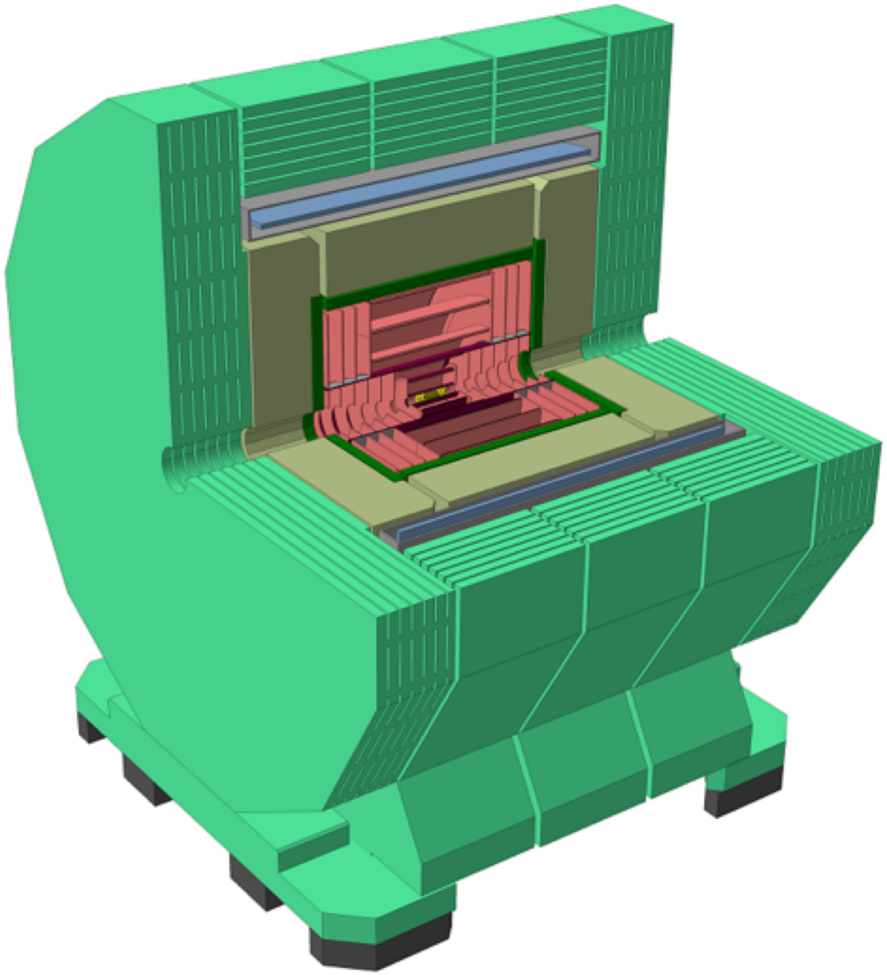

4 μm

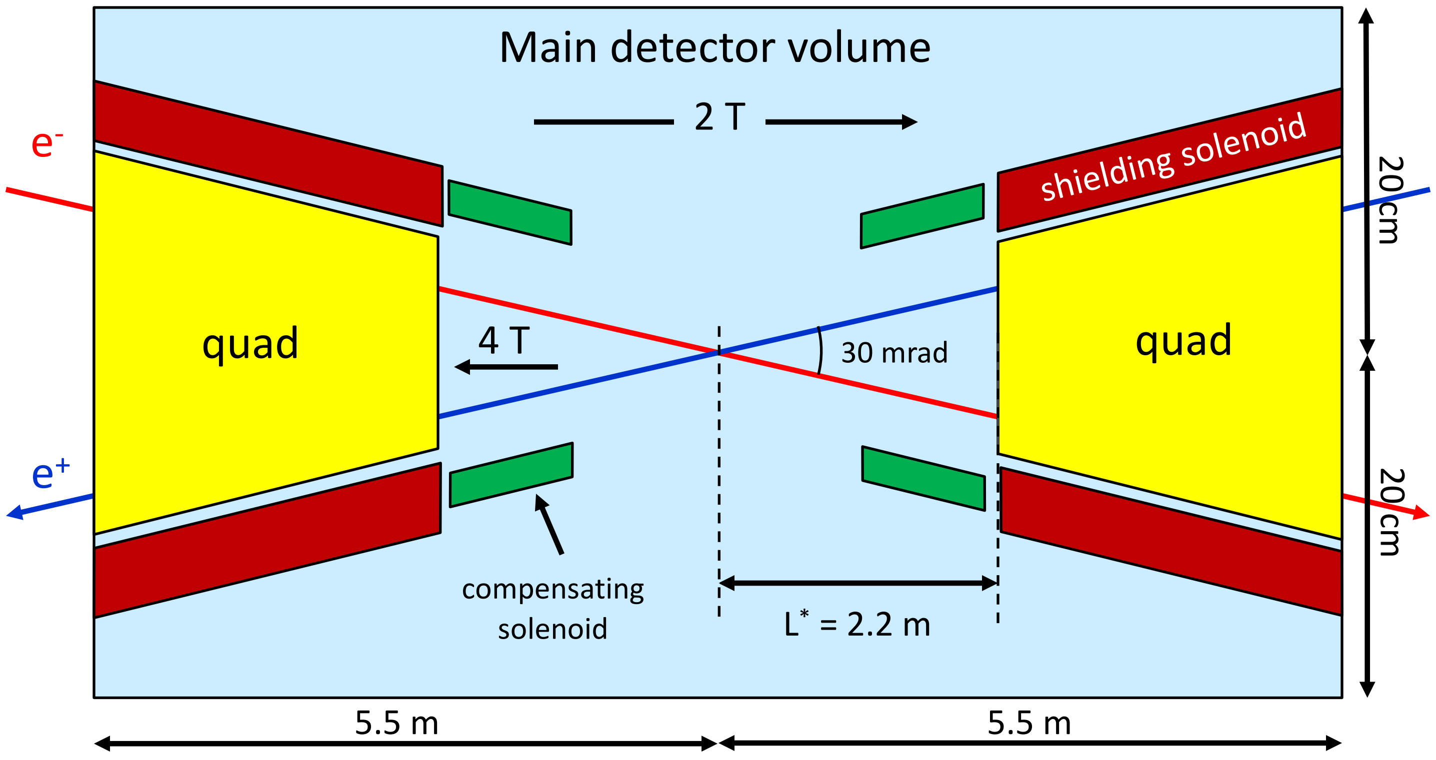
Here, using conservative Si resolution numbers (1/√12), work in progress...

# CLD Detector Concept

- CLD (CLIC-Like Detector) design originates from CLICdet
- Extensive work over two years for adapting the design to FCC-ee and studying its performance
  - Smaller radius beam pipe radius = 15 mm
  - 30 mrad crossing angle, 2 T field
  - Larger tracker outer radius / Thinner HCAL obserber
  - 150 mrad tracker cone reserved for MDI elements; calorimetry to 100 mrad
  - Continous mode – no power pulsing.
    - Cooling issues to be studies

| Concept | CLICdet | CLD |
|---|---|---|
| Vertex inner radius [mm] | 31 | 17 |
| Tracker half length [m] | 2.2 | 2.2 |
| Tracker outer radius [m] | 1.5 | 2.1 |
| ECAL absorber | W | W |
| ECAL $X_0$ | 22 | 22 |
| HCAL absorber | Fe | Fe |
| HCAL $\lambda_I$ | 7.5 | 5.5 |
| Solenoid field [T] | 4 | 2 |
| Overall height [m] | 12.9 | 12.0 |
| Overall length [m] | 11.4 | 10.6 |




Main detector volume
2 T
e-
e+
shielding solenoid
20 cm
20 cm
quad
quad
4 T
30 mrad
compensating
solenoid
L* = 2.2 m
5.5 m
5.5 m