FCC-ee Detector Requirements and Benchmarks

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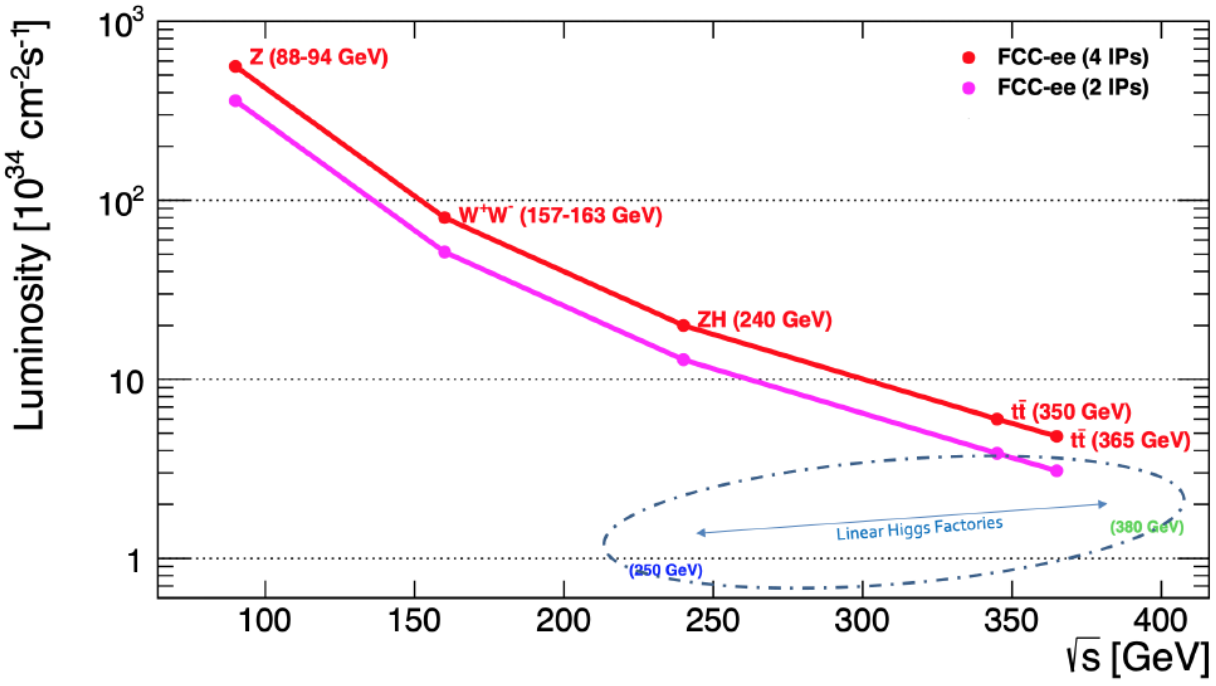
June 10, 2024

FCC-ee physics program



FCC-ee:

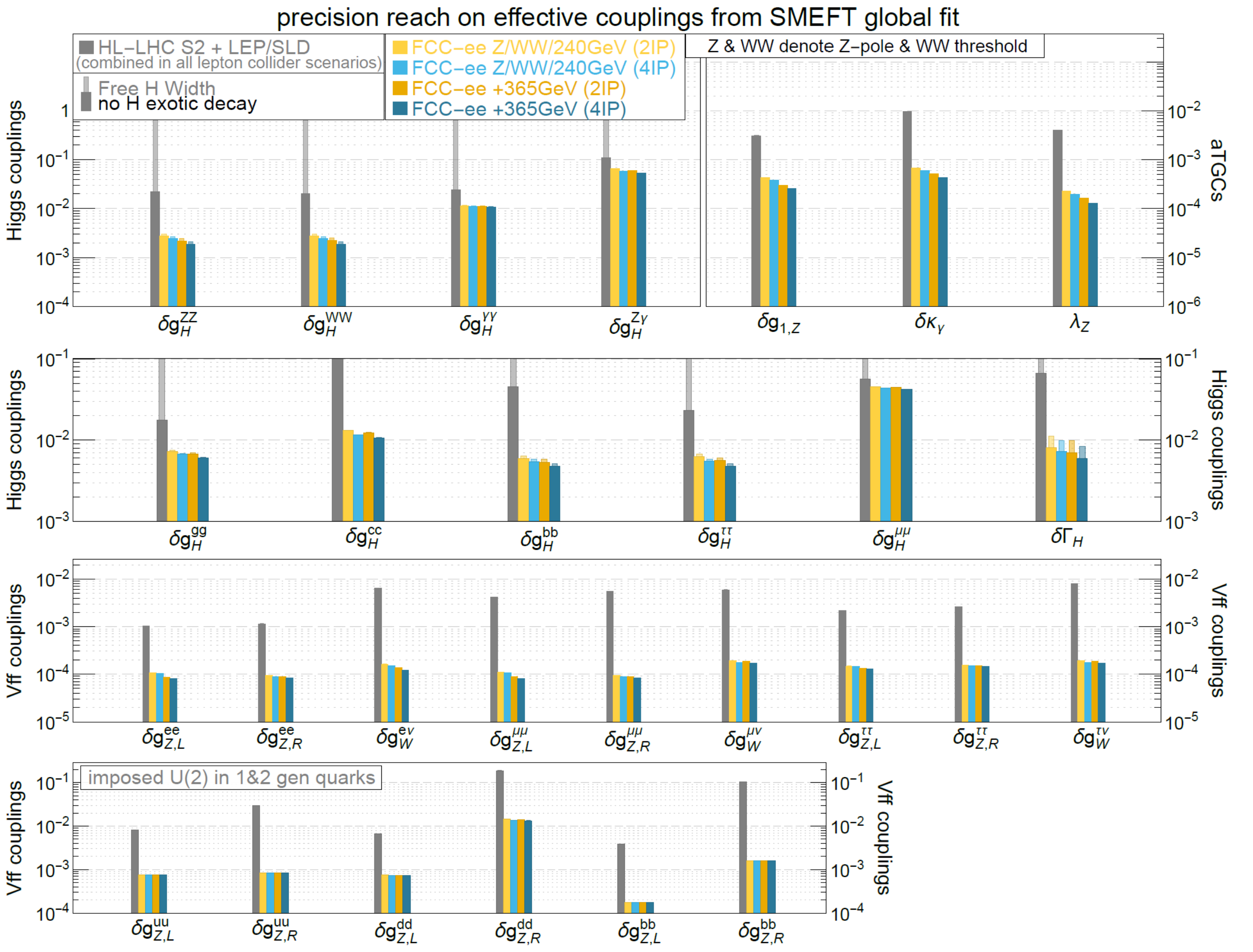
- ~100,000 Z / second
  - ~1 Z / second at LEP
- ~10,000 WW / hour
  - 20,000 WW in 5 years at LEP
- ~1,500 Higgs / day
  - O(10) times more than ILC
- ~1,500 top quarks / day

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

LEP×10^5 **LEP×10^3**

Precision electroweak and Higgs physics

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^{b}, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run



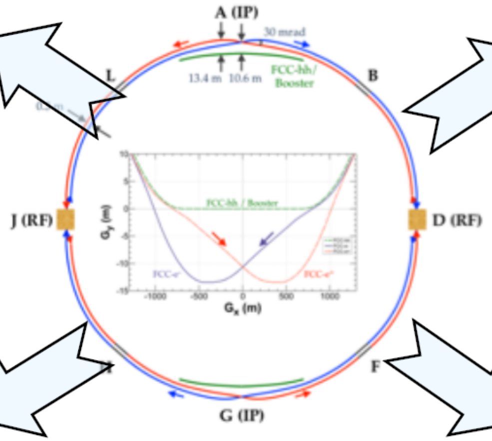
General detector requirements

"Higgs Factory" Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with 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

From Mogens Dam

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- Able to withstand a large dynamic range:
  - in luminosity ($L = 10^{34} - 10^{36}$ cm^2/s)
  - in energy (measure particles from O(100) MeV to O(100) GeV)
- Most requirements are imposed by the Z pole run:
  - Bunch space down to 20 ns with continuous beams
  - Large event rates ~ 100 kHz
  - Beamsstrahlung
- Stable operation (control systematics to 10^{-5}-10^{-6} level)

- Materials from the FCC-ee feasibility study mid-term report, only a few examples are shown here
- Two sessions about detector requirements (Wednesday and Thursday mornings)

Heav

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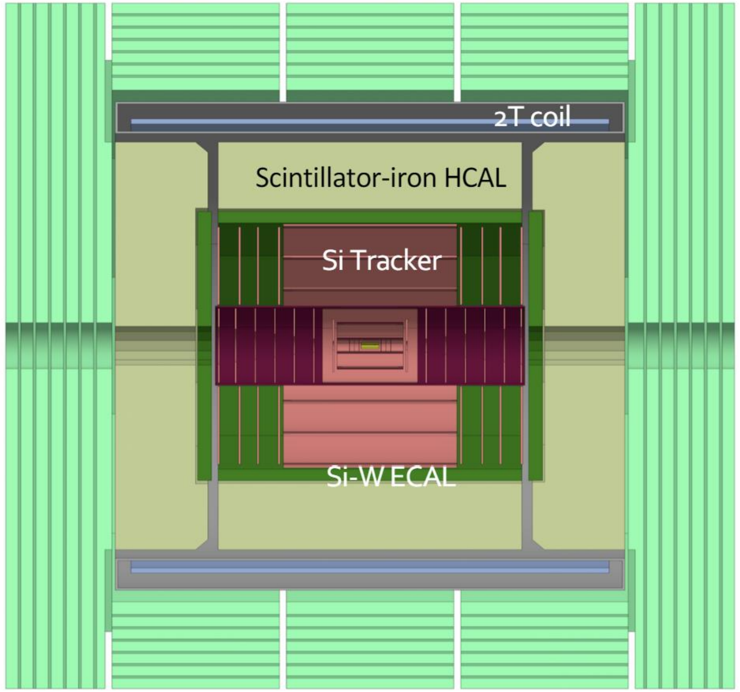
From Mogens Dam

Four detectors considered for FCC-ee

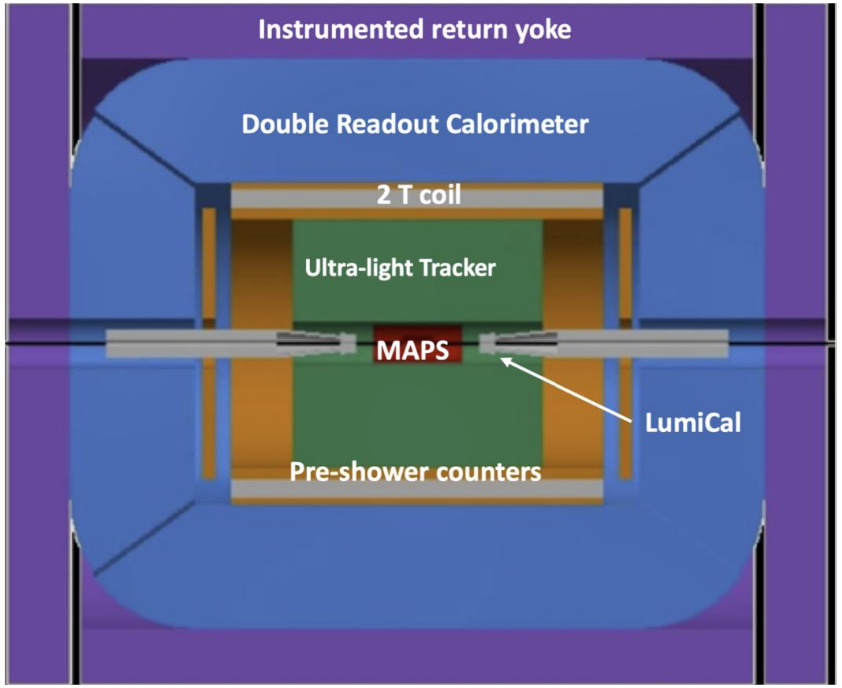
Detector benchmarks

CLD



- Full silicon vertex + strip tracker
- CALICE-like 3D-imaging high-granular calorimetry with Si-W for ECAL and Sci-iron for HCAL
- Muon system with RPCs
- Coil outside of calorimeters

IDEA



- Silicon vertex + ultra-light tracker
- Monolithic dual readout calorimeter with Cu-fibers (possibly augmented by dual-readout crystal ECAL)
- Muon system with μ-RWELL
- Coil inside calorimeters

ALLEGRO

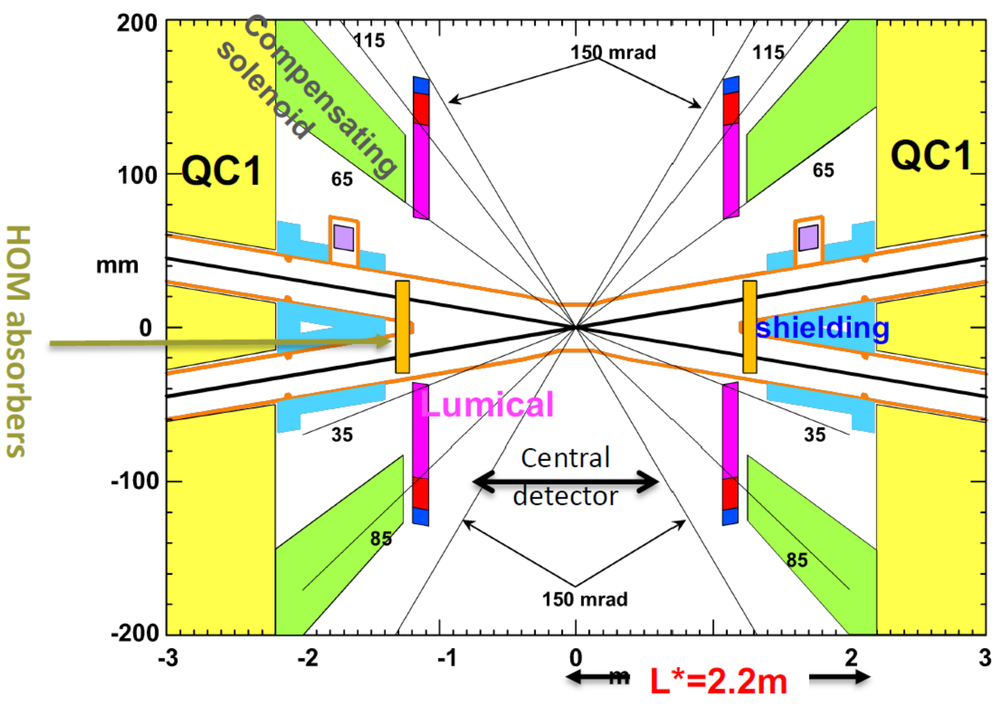
- Silicon vertex + ultra-light tracker
- High granularity noble liquid ECAL (LAr or LKr with Pb or W absorbers)
- CALICE-like or TileCal-like HCAL
- Muon system
- Coil outside of ECAL

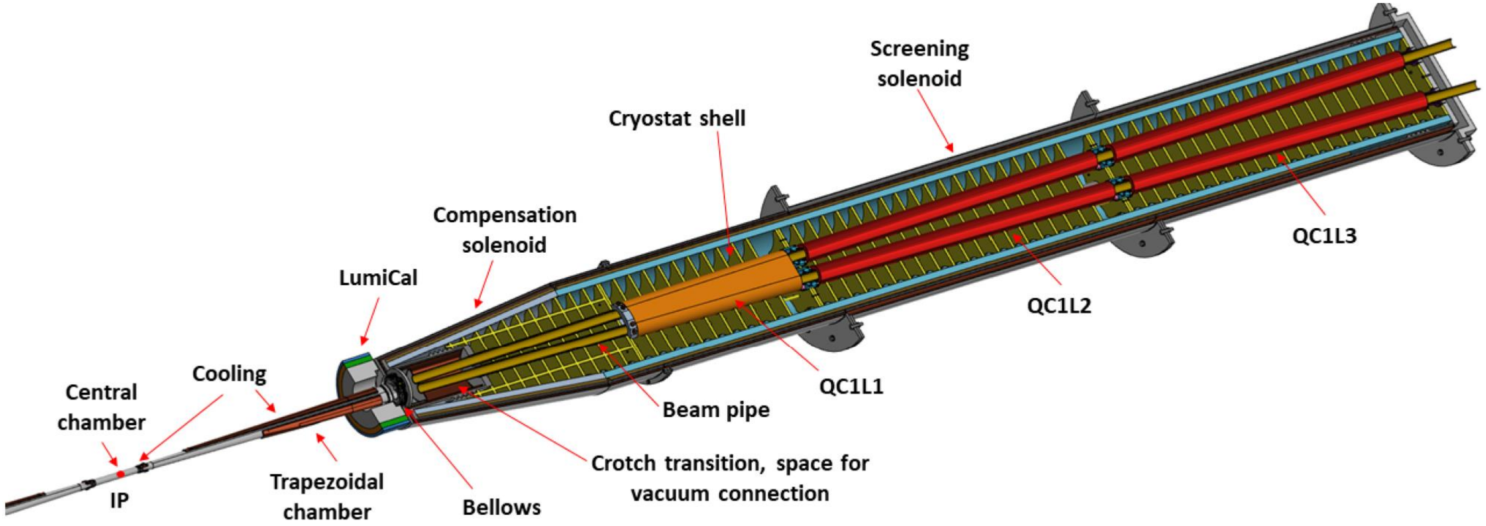
Four detector benchmark sessions on Tuesday and Thursday afternoons

Machine Detector Interface

- Need to have flexible IR optics to allow a common IR layout at all energies
  - Large beam crossing angle 30 mrad
  - Beams entering/exiting with separate beam pipes at about 1.2 m from the IP
  - Focusing quadrupoles protrude into the detector volume
    - QC1 down to a distance of 2.2 m
    - Necessary to shield quads from detector field
- Beams cross detector field at a 15 mrad crossing angle
  - Compensate for detector field
  - Limits detector field to B = 2 Tesla
- Two MDI sessions: Wednesday afternoon and Thursday morning

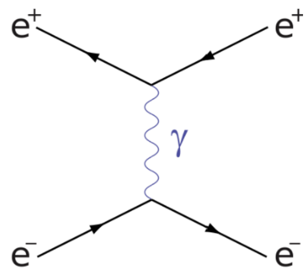
2D-top view with expanded x-coordinate

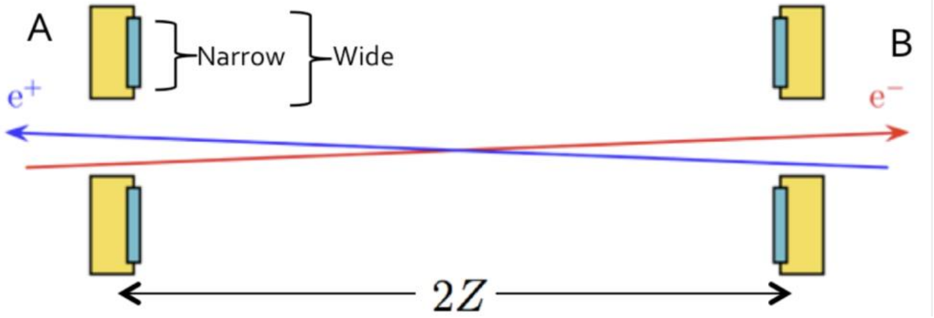




Luminosity measurement

- Ambitious goal:
  - Absolute normalization to 10^{-4} ($O(10^{-2})$ for LHC)
  - Relative (energy scan points) to 10^{-5}
- Small-angle Bhabha scattering is very strongly forward peaked
- Monitors centered around outgoing beam lines:
  - $\delta R_{min} \sim O(1\ \mu m)$, $\delta z \sim O(100\ \mu m)$
- Current theoretical uncertainty: 3.8×10^{-4}, major efforts also needed from the theoretical community

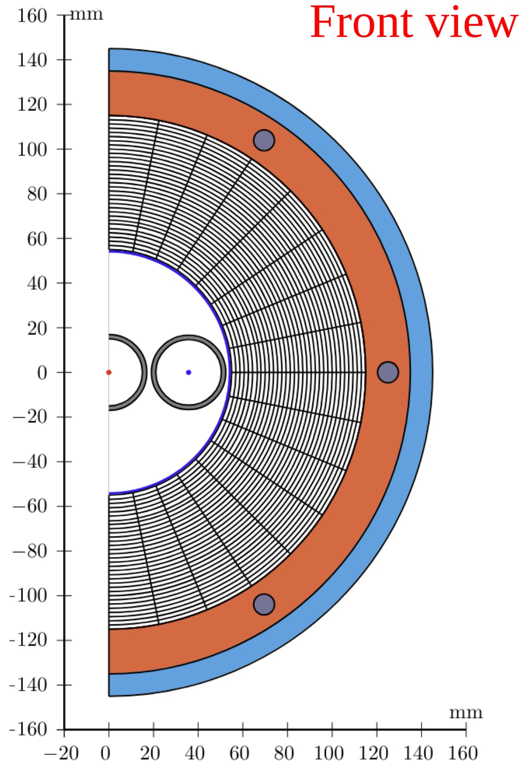




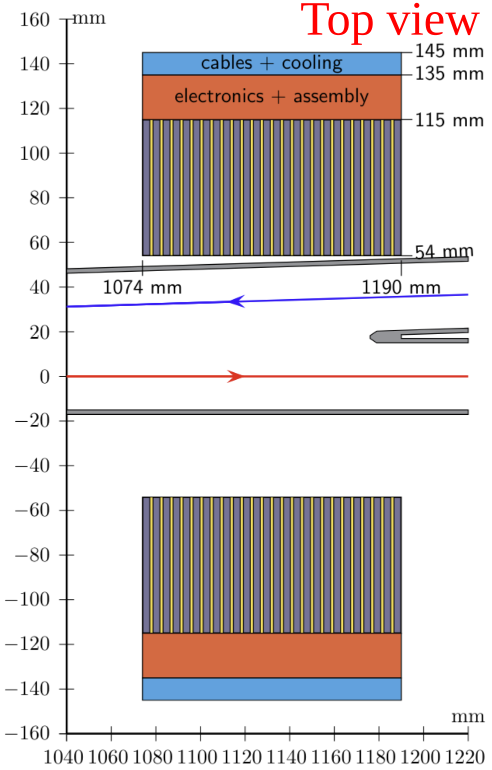
Average of two counting rates:
sideA = NarrowA + WideB
sideB = NarrowB + WideA

$$\frac{\delta\sigma^{acc}}{\sigma^{acc}} \simeq \frac{2\delta\theta_{min}}{\theta_{min}} = 2\left(\frac{\delta R_{min}}{R_{min}} \oplus \frac{\delta z}{z}\right)$$

Front view



Top view



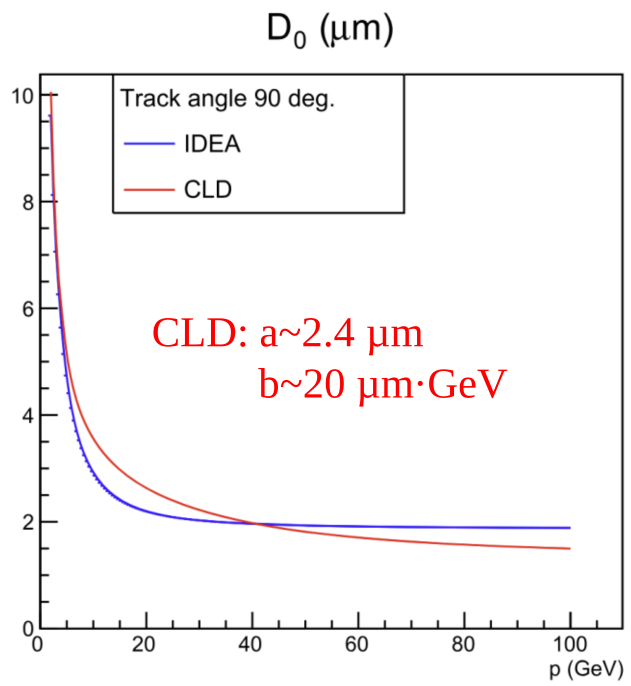
- 25 layers W+Si sandwich: 3.5-mm W plates with Si-sensor plates in 1 mm gaps
- Cylindrical detector dimensions:
  - Radius: 54 < r < 145 mm
  - Along outgoing beam line: 1074 < z < 1190 mm
- Angular coverage:
  - Wide acceptance: 53-98 mrad
  - Narrow acceptance: 55-96 mrad

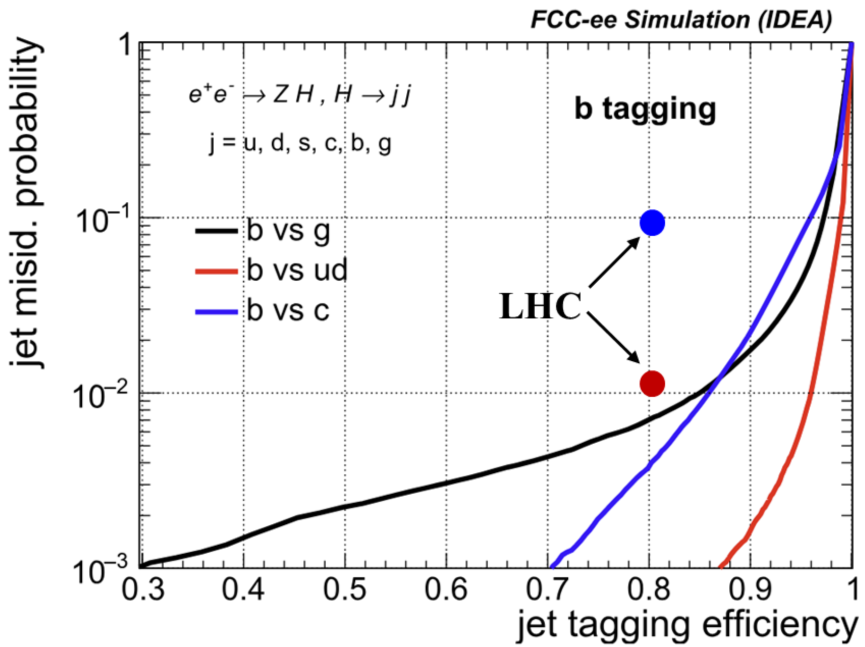
Requirements on the Vertex detector

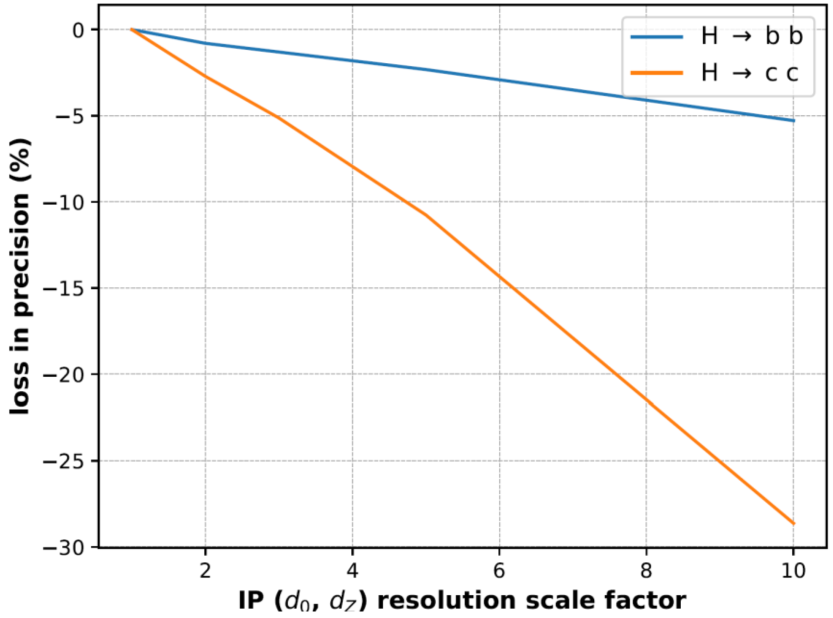
$$\sigma(d_0) = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

a ~ 5 µm, b ~ 15 µm·GeV (FCC-ee)
a ~ 25 µm, b ~ 70 µm·GeV (LEP)
a ~ 12 µm, b ~ 70 µm·GeV (LHC)

- Measurement of impact parameters, reconstruction of primary/secondary vertices, flavor tagging, lifetime measurements
- Cover an angle range of about |cosθ|<0.99
- High resolution (~3 µm single point resolution), light material for vertex and beam pipe (MAPS, 0.3-0.5% X_0 per layer), radial distance of the first layer of the vertex detector (1.2~1.5 cm from the IP)



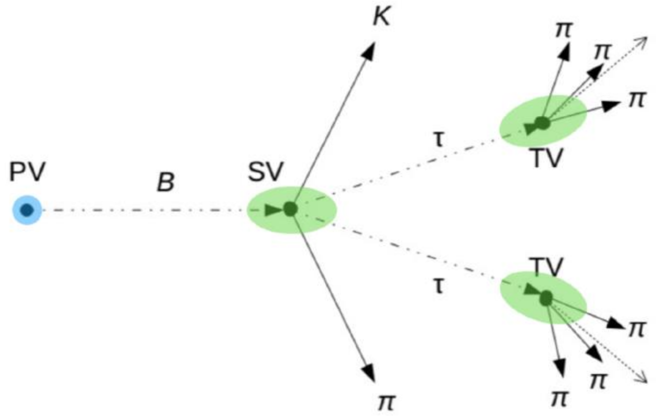


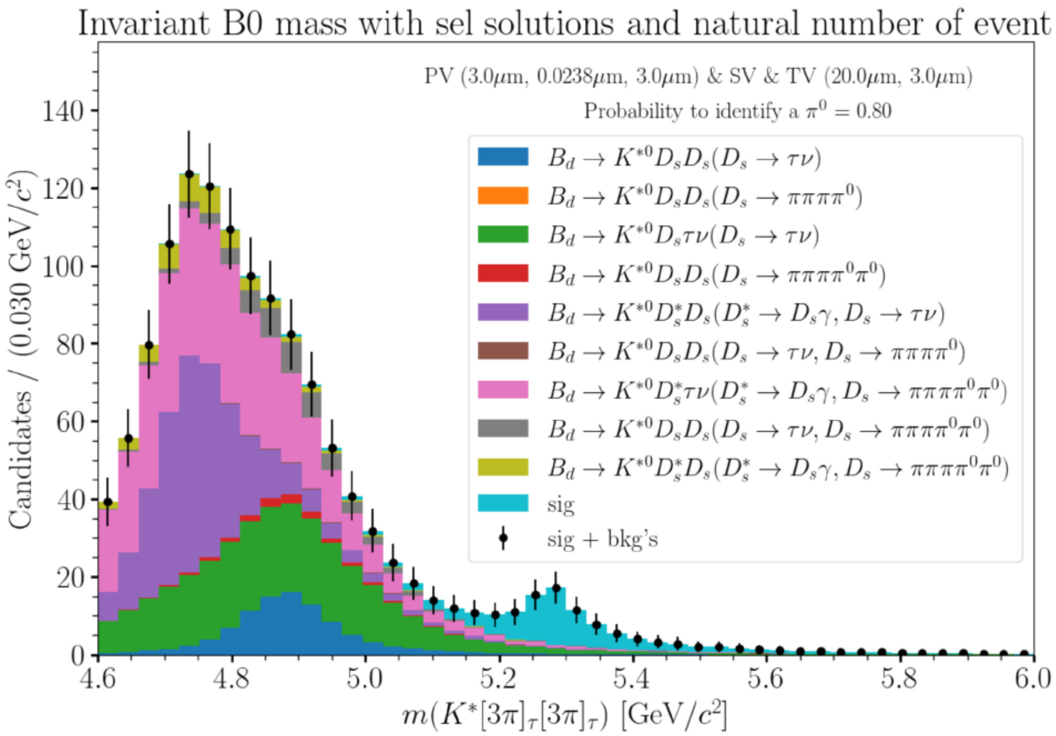


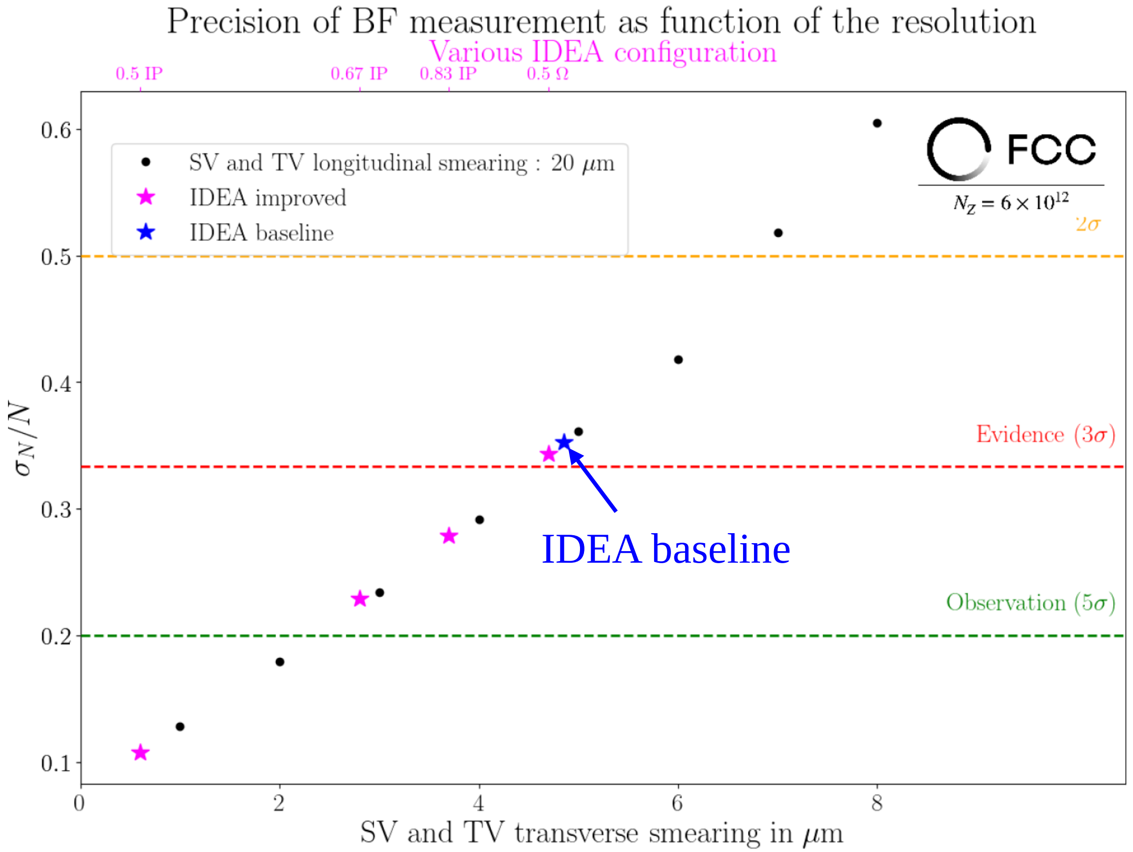
Relative loss of precision on H→bb and H→cc couplings when the IP resolution is degraded by a factor shown on the x axis

Requirements on the Vertex detector

- Resolution on the 3D distance between the primary and displaced vertex is ~10-80 µm, sufficient for most time-dependent CP violation measurements
- The measurement of Br(B→K*ττ)~10^{-7} has been chosen to further explore the IP requirements, kinematics is over-constrained with the precise determination of the SV and TV (backgrounds with additional neutrinos and neutral pions)
- τ lifetime measurement sets the requirement that the systematic uncertainty due to the vertex detector misalignment should be below 10 ppm







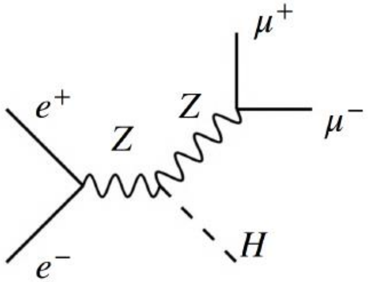
assumed 3 µm (20 µm) in the transverse (longitudinal) direction

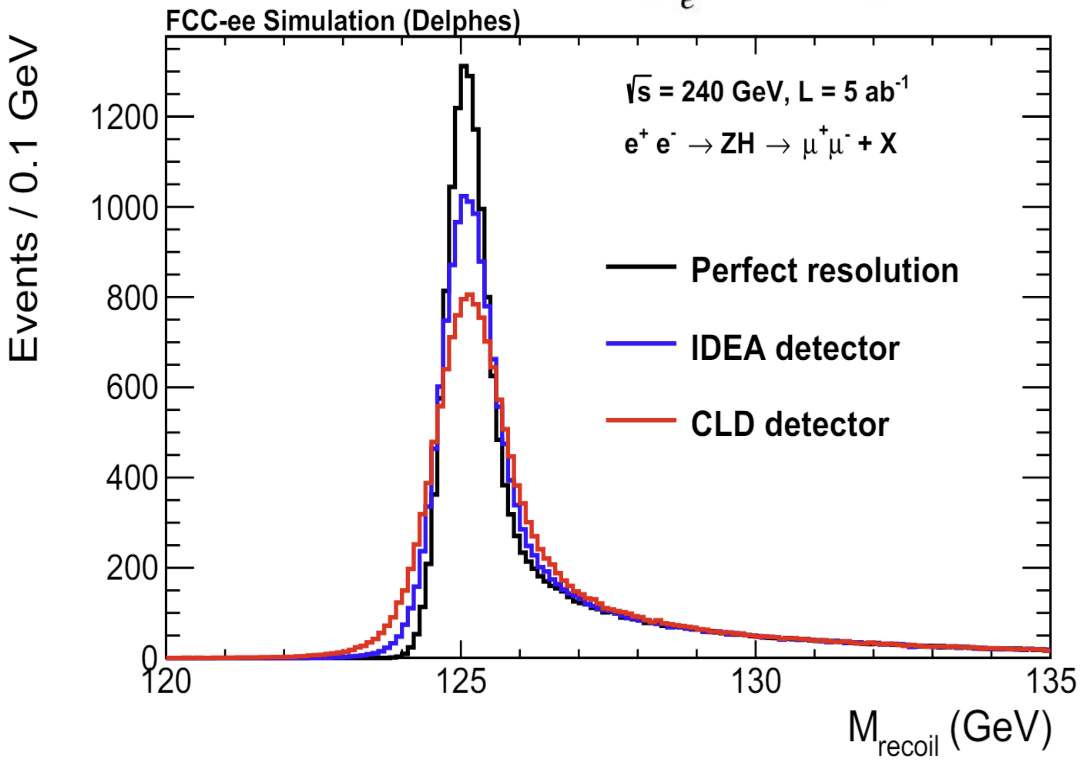
Requirements on the inner tracker momentum resolution

- Important to reconstruct the recoil mass distribution for the Higgs mass measurement (Δm_H~4 MeV)

$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

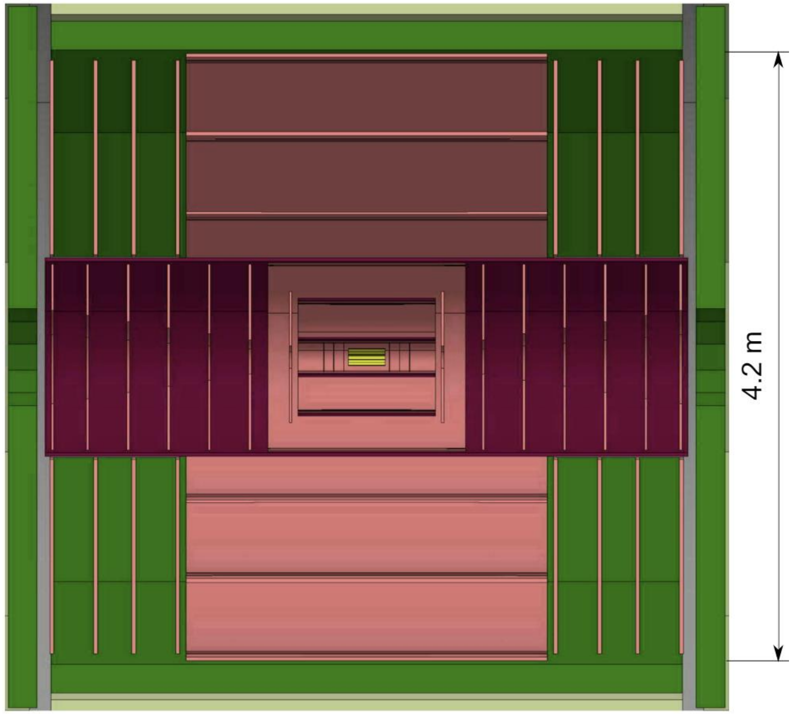
- Sensitivity dominated by the Z→μμ channel
- Require the track momentum resolution should not be worse than the beam energy spread (~0.16% at 240 GeV)
  - $\sigma(p_T)/p_T$ ~ 0.2% at 45 GeV
  - a factor of 5~10 better than the current ATLAS and CMS inner tracker momentum resolution
  - Need to reduce multiple scattering effects
  - Transparent (low material) tracker is the key





CLD and IDEA vertex and inner tracker

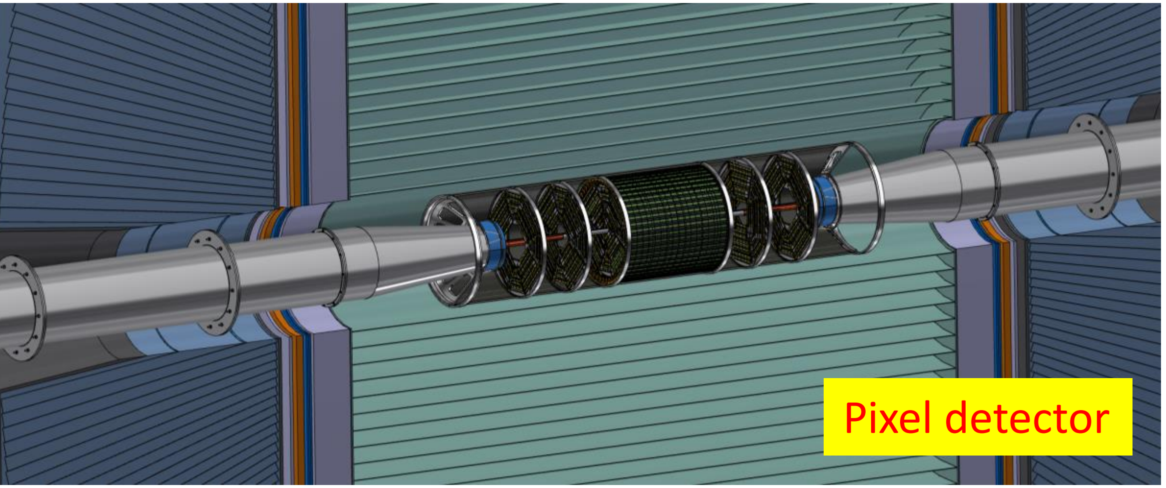
CLD

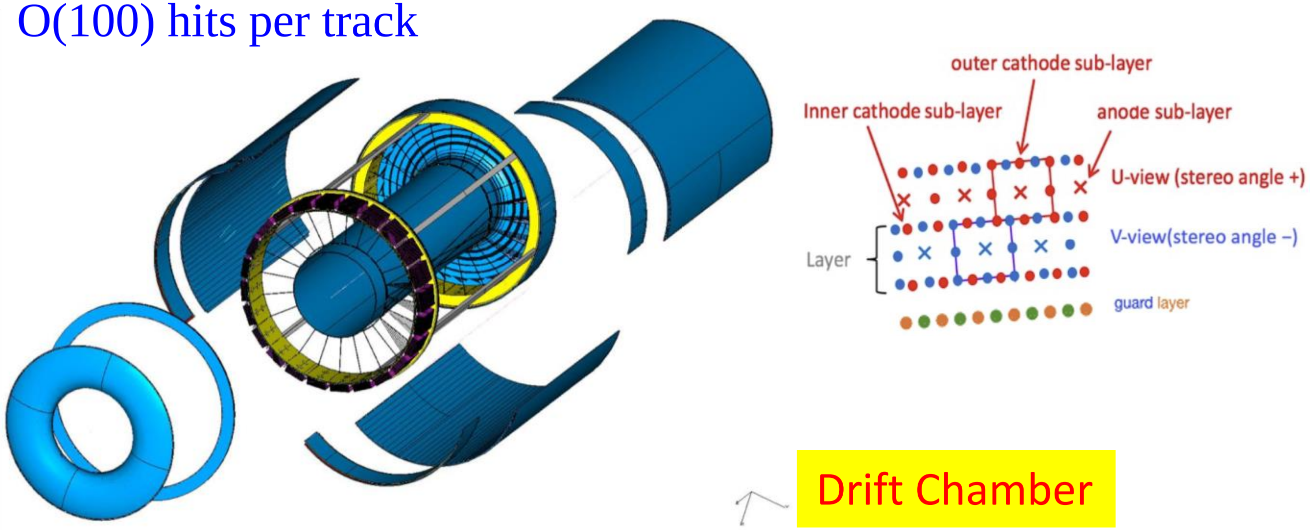


Vertex: 3 double layers for barrel and endcaps, 25 µm pitch pixels
Inner tracker: 3 short and 3 long barrel layers
7 inner and 4 outer endcap disks per side
Pixels for the first inner tracker disk, elsewhere 50 µm pitch strips
12-18 hits per track

IDEA

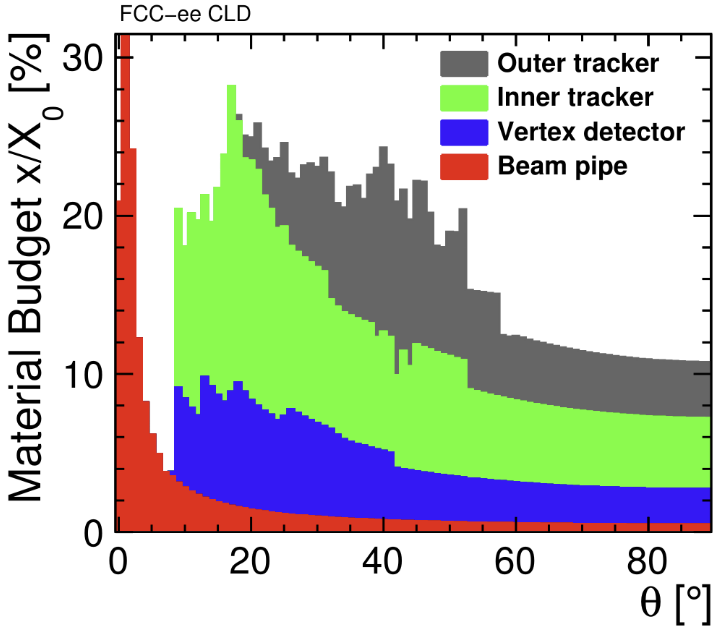
Vertex: 3 inner barrel layers, 25 µm pitch pixels
2 outer barrel layers, 50 µm pitch pixels
3 endcap disks per side
DCH: 112 layers of square-cell drift chambers 12×12 mm^2 square cell from R=0.35 m to R=2m
Outer silicon wrapper at 2 m
O(100) hits per track



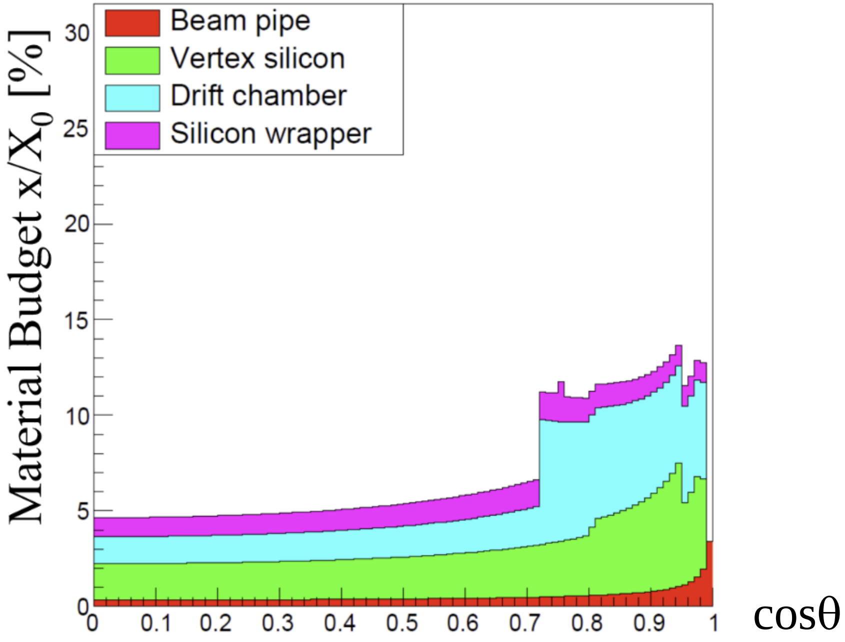


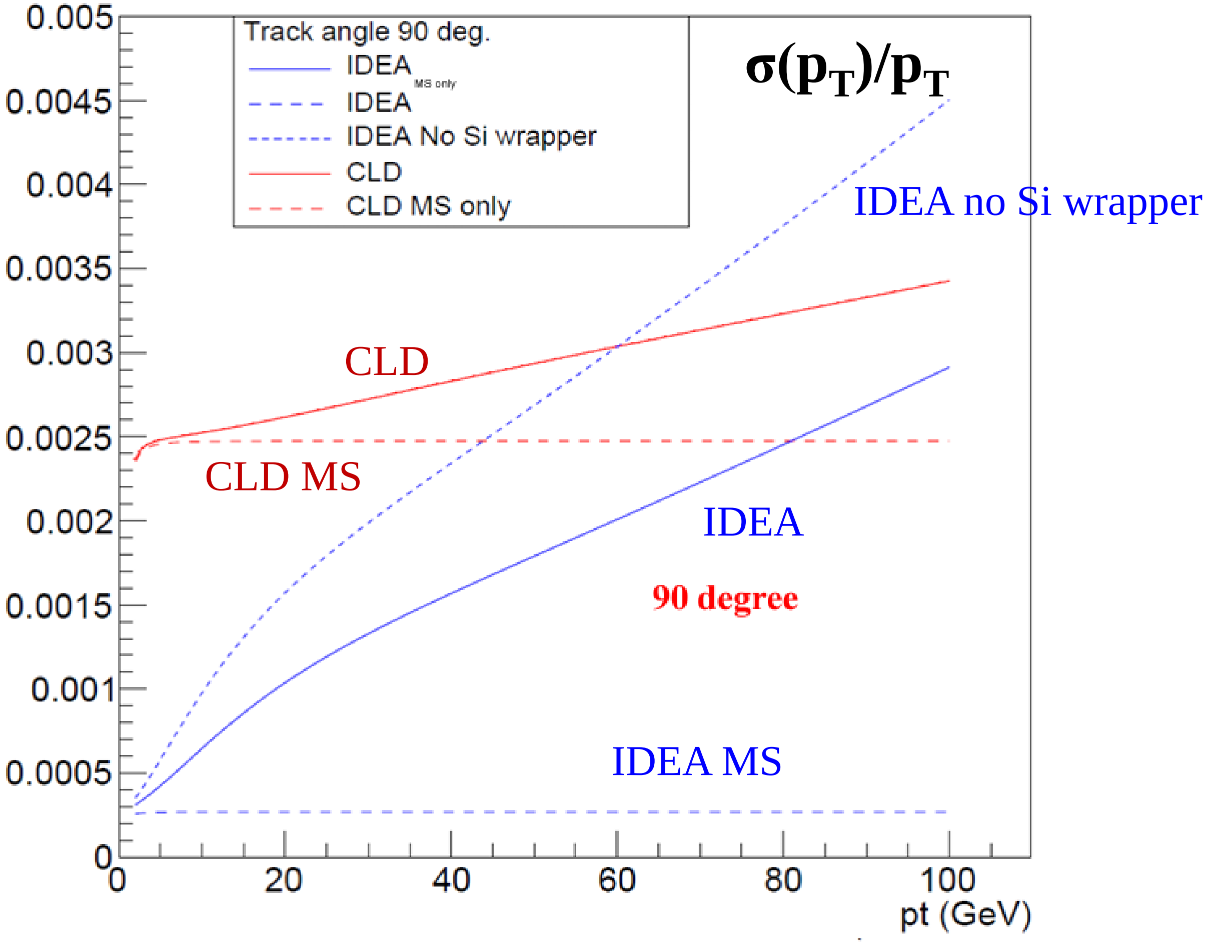
CLD and IDEA vertex and inner tracker material and resolution

CLD



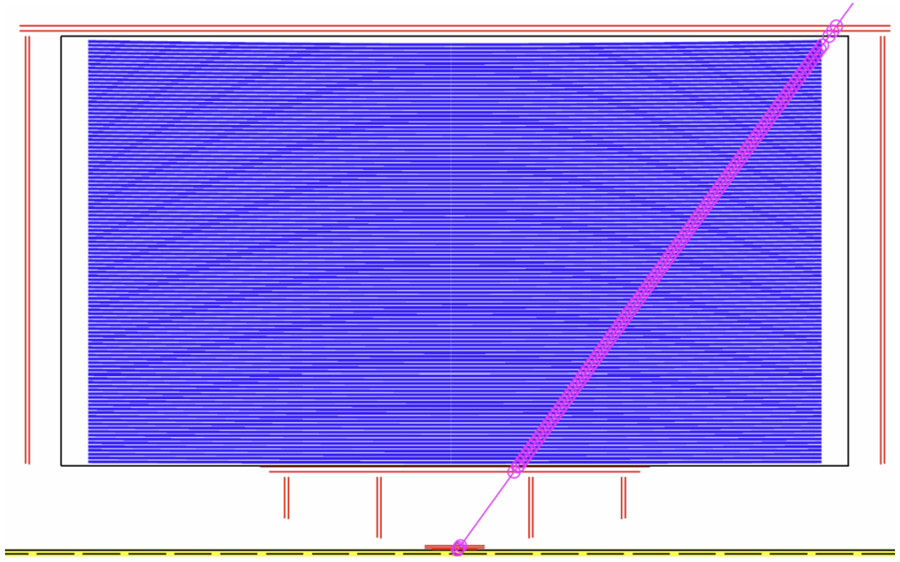
IDEA



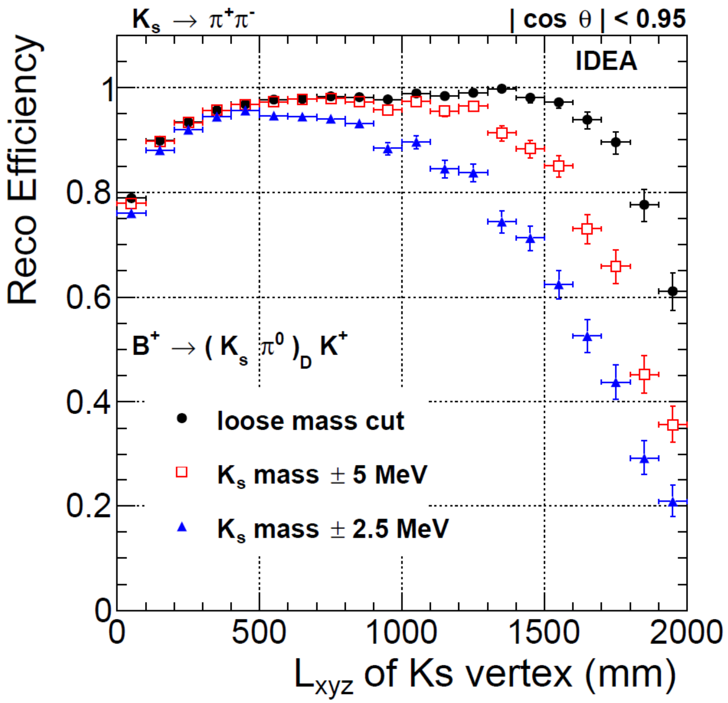


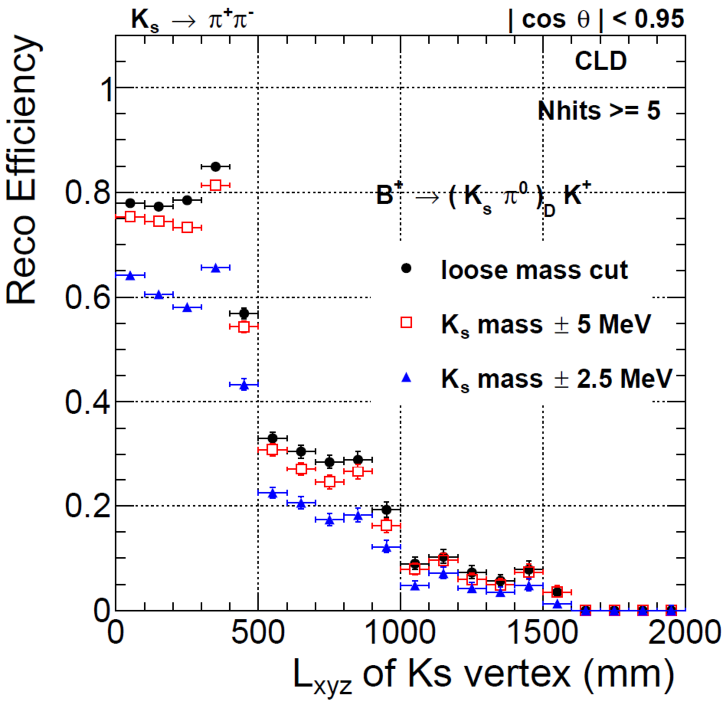
Inner tracker with a gaseous detector

- A gaseous tracker is crucial for low material, pattern recognition, LLP searches, and PID capability
- $Ks \rightarrow \pi^+\pi^-$ reconstruction in the decay of B^+ meson:



IDEA event display with an outdated vertex geometry

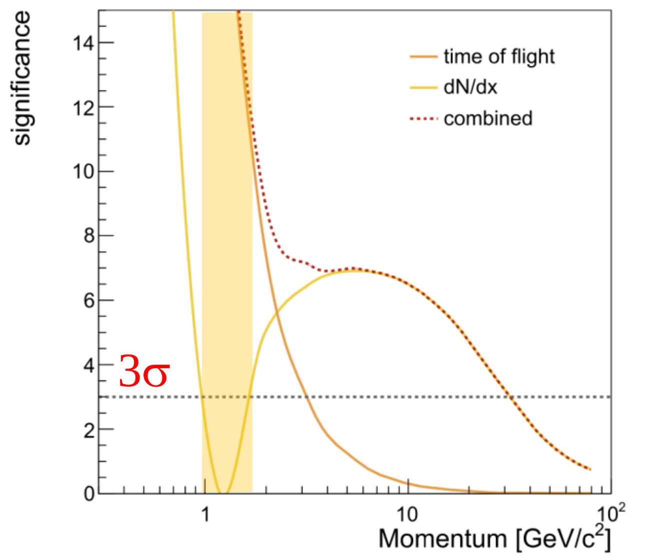


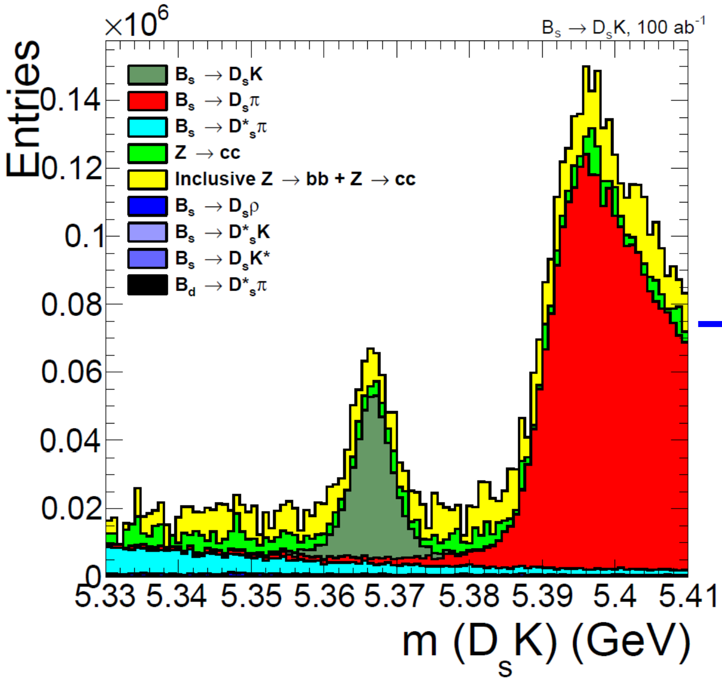


- A silicon+TPC tracker is under consideration for CLD
- A straw tracker could also be a good option for a gaseous tracker

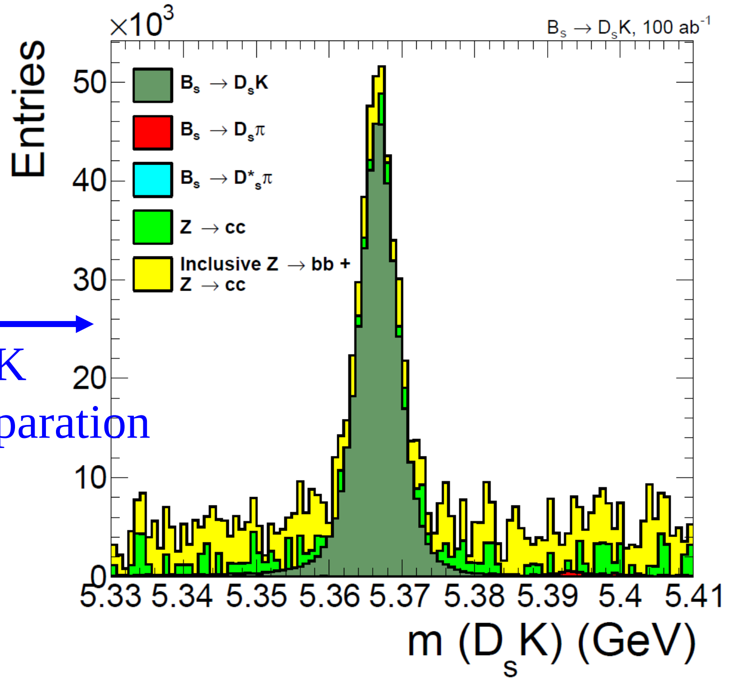
Requirements on particle ID capability

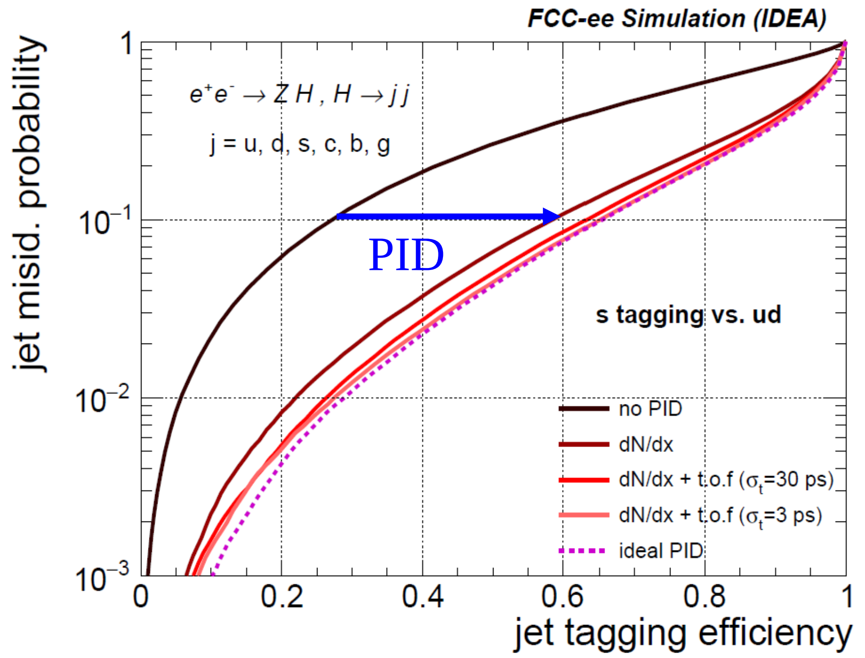
- Essential for flavor physics and bring significant benefits for other areas
  - Flavor physics measurements: $B^0_s \to D^\pm_s K^\mp$, $B \to K^* \nu\nu$, $B_s \to \phi\nu\nu$, …
  - s-quark jet identification → kaon identification ($H \to ss$, V_{ts}, V_{bs}, $H \to bs$, FCNCs, …)
- Challenges: have good PID for the whole momentum range (O(100) MeV to O(100) GeV)
- Toolbox:
  - High momentum: dE/dx (dN/dx) from drift chambers, Cherenkov detector (RICH)
  - Low momentum: time of flight





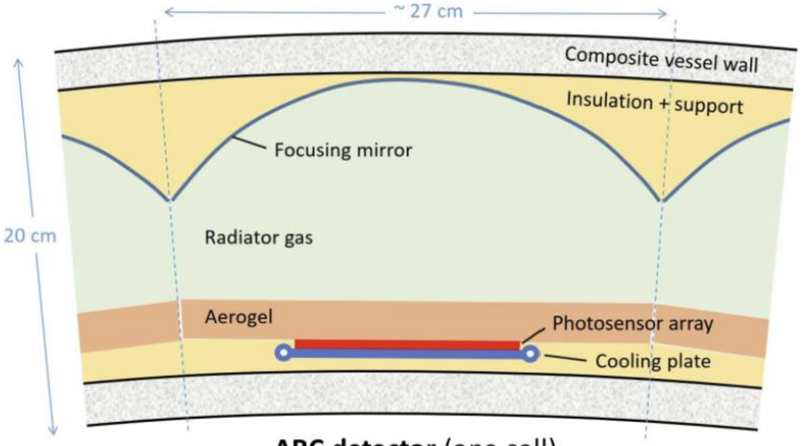
π/K separation



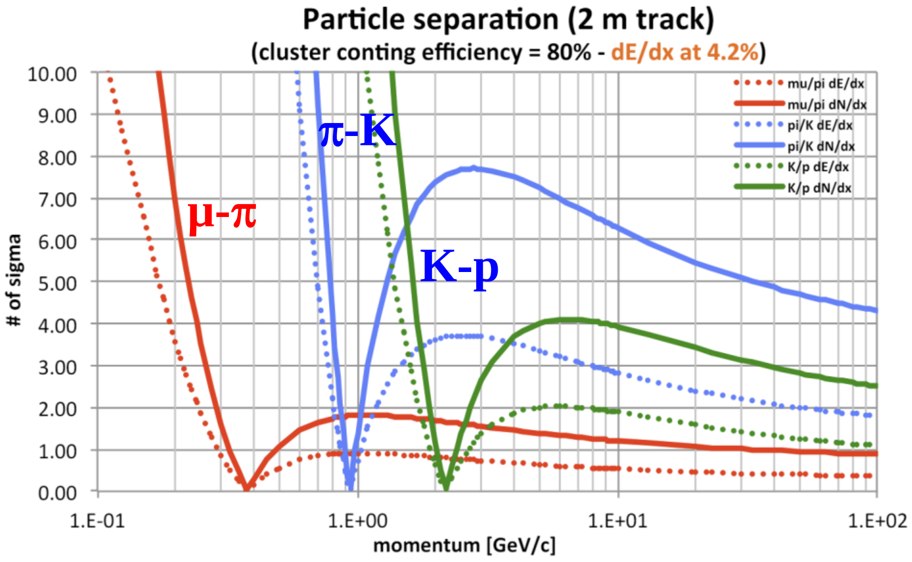


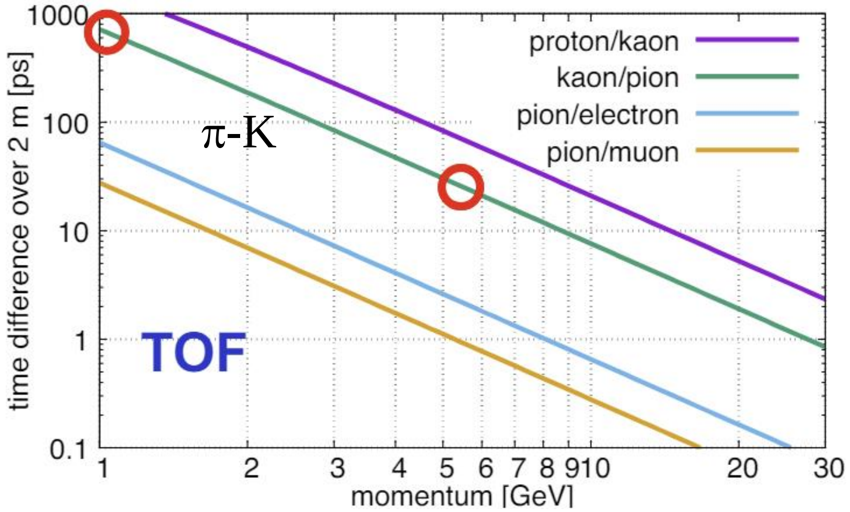
Particle ID capability

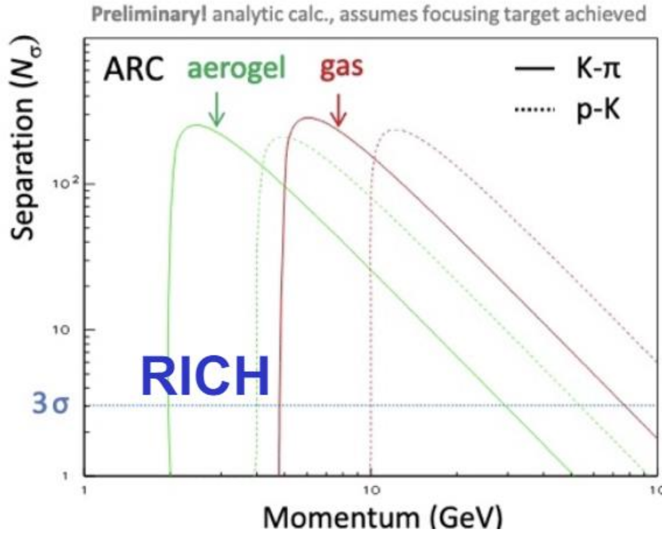
- **IDEA drift chamber** promises >3σ π/K separation up to 50-100 GeV
  - dN/dx is a factor of ~2 better than dE/dx
  - Can be alleviated by TOF measurement of δT ≲ 500 ps for the region around 1 GeV
- **Time of flight (TOF) alone** over 2 m (for example, LGAD)
  - Could give 3σ π/K separation up to ~3 (5) GeV with the 30 (10) ps resolution
- **Alternative approaches**, in particular compact gaseous RICH counters are also investigated (e.g. Array of RICH Cells – ARC)
  - Give 3σ π/K separation from 5 GeV to ~80 GeV



ARC detector (one cell)



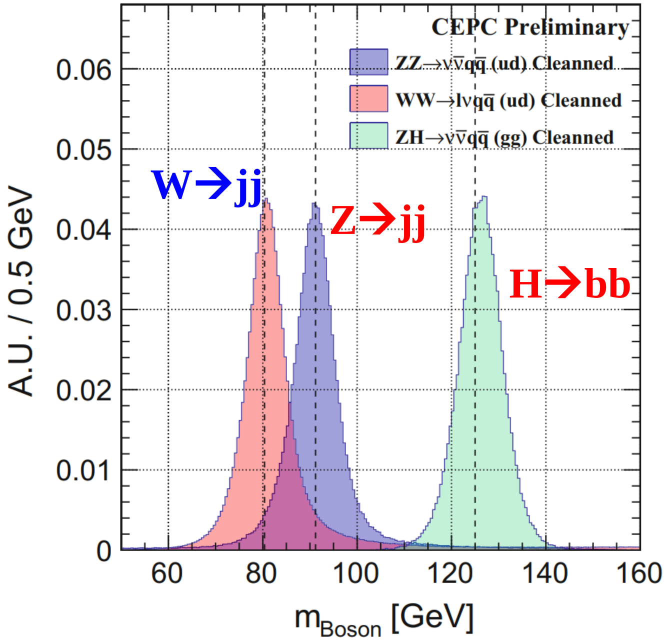


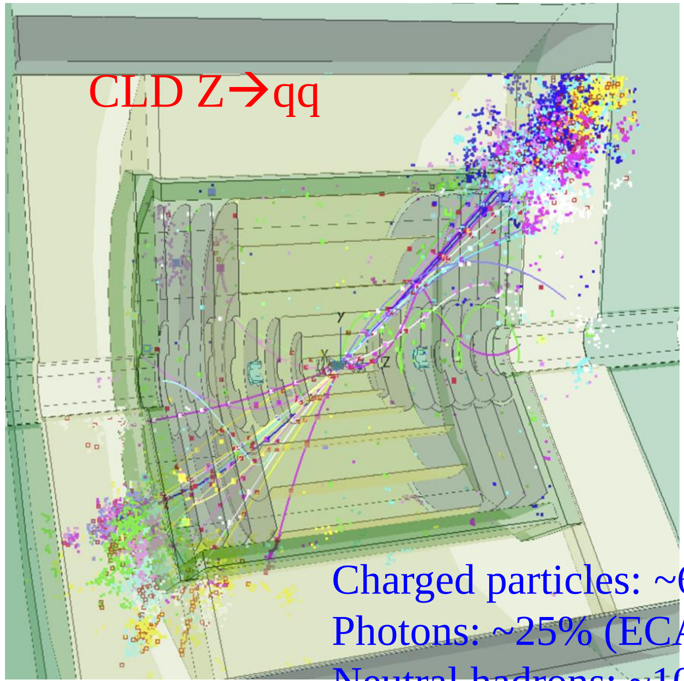


Calorimetry

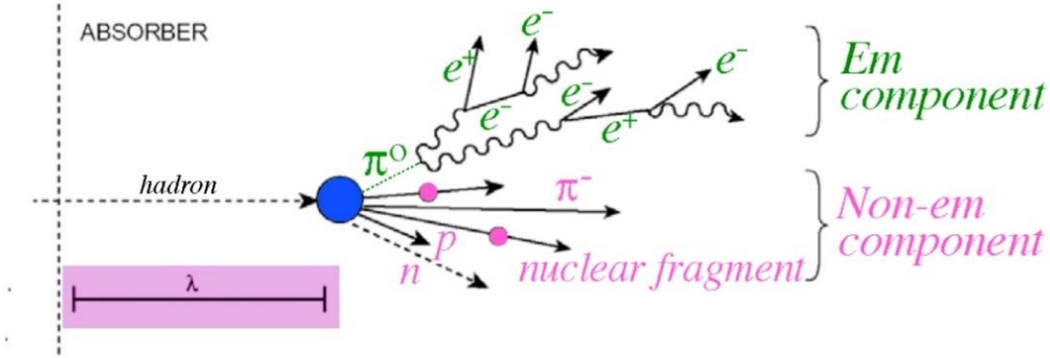
EPJC (2018) 78:426

- Jet energy resolution is a key benchmark of the e$^+$e$^-$ detector performance
- Important to build calorimeters that can achieve ΔE/E ~ 3-4% for jets at 100 GeV to separate hadronically-decayed W and Z bosons
- Very hard to achieve this with a traditional approach to calorimetry
  - Limited by a typical HCAL resolution of >50%/√E
- Two different but complementary approaches considered:
  - High granularity calorimeter – Particle flow algorithm
  - Dual Readout (DRO) calorimeter





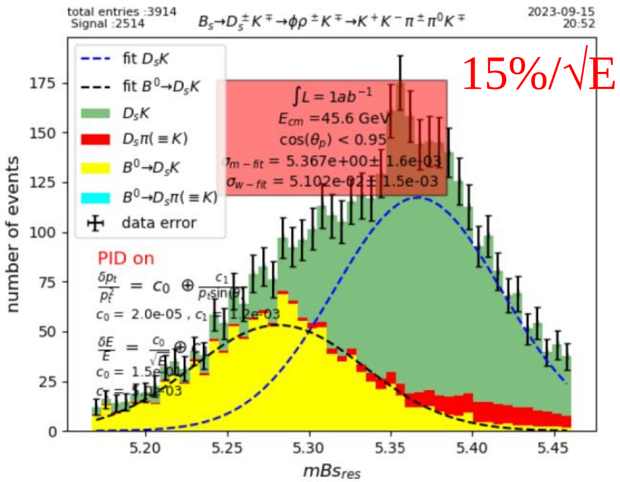
Charged particles: ~65% (Tracker)
Photons: ~25% (ECAL)
Neutral hadrons: ~10% (ECAL+HCAL)



Compensate event-by-event fluctuations through two independent shower-detection processes: scintillation and Cherenkov light production

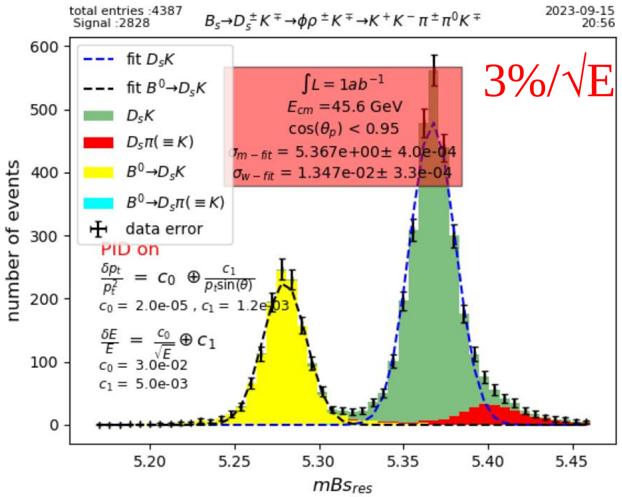
Requirements on ECAL

- EM calorimeter with a resolution of 10-15% /√E for photons (~25% of jet energies) sufficient for jet energy resolution
- Many flavor physics benchmarks (e.g. $B_s \rightarrow D_s K$, $B_0 \rightarrow \pi^0\pi^0$, $B_s \rightarrow K^*\tau\tau$), Higgs, new physics searches (e.g. $Z \rightarrow \mu e$, $\tau \rightarrow \mu\gamma$, $e^+e^- \rightarrow a\gamma \rightarrow \gamma\gamma\gamma$), bremsstrahlung recovery, tau polarization (separate $\tau^\pm \rightarrow \rho^\pm\nu \rightarrow \pi^\pm\pi^0\nu$ and $\tau^\pm \rightarrow \pi^\pm\nu$) put stringent requirements on ECAL resolution and granularity (low energy photon reconstruction, π^0 identification etc)

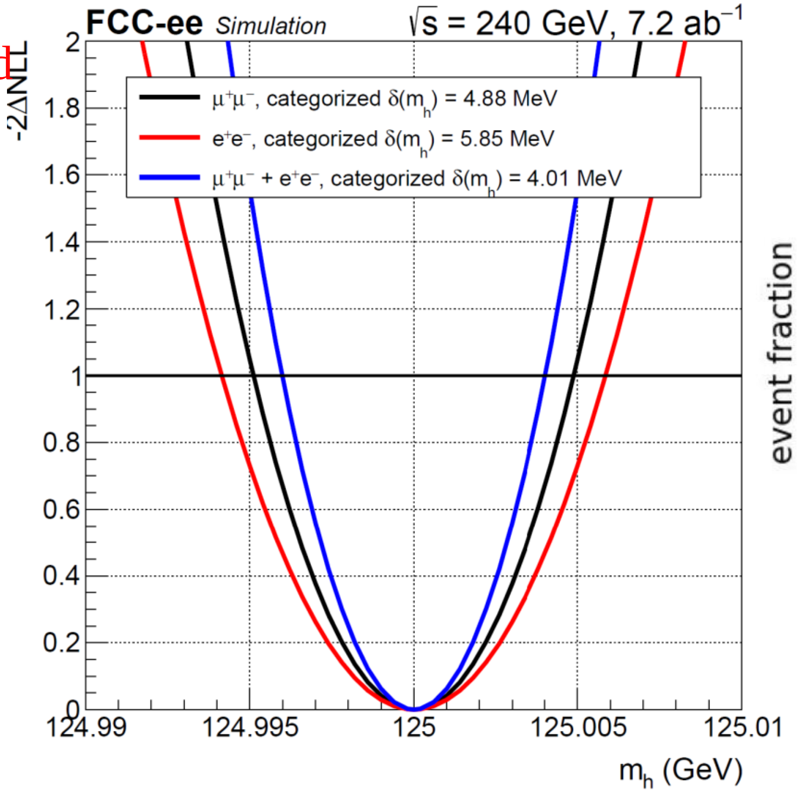


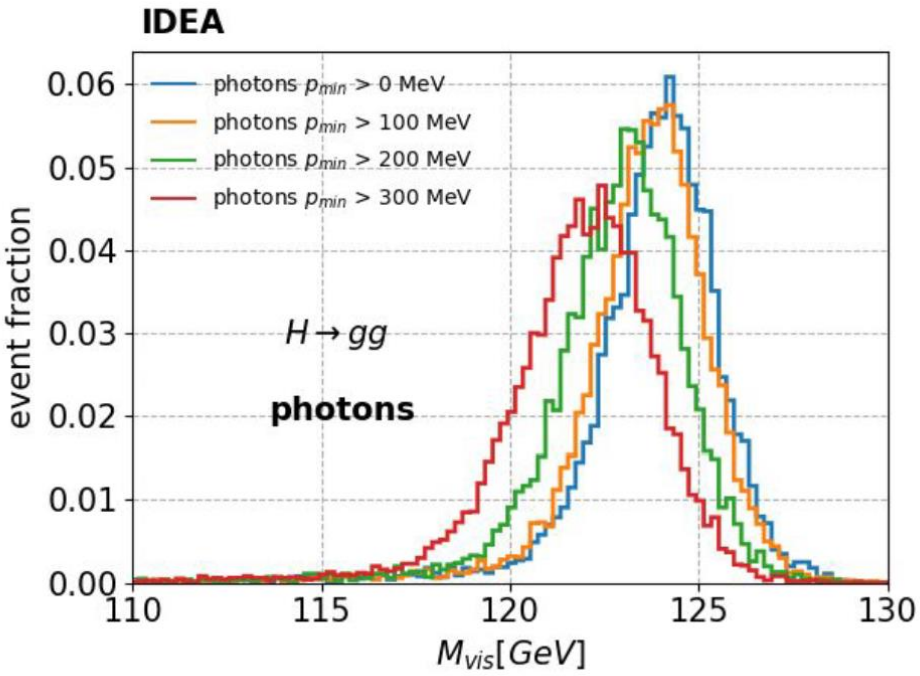
15%/√E assumed

π^0 reconstruction in $B_s \rightarrow D_s^\pm K^\mp \rightarrow K^+K^-\pi^\pm\pi^0K^\mp$



3%/√E assumed

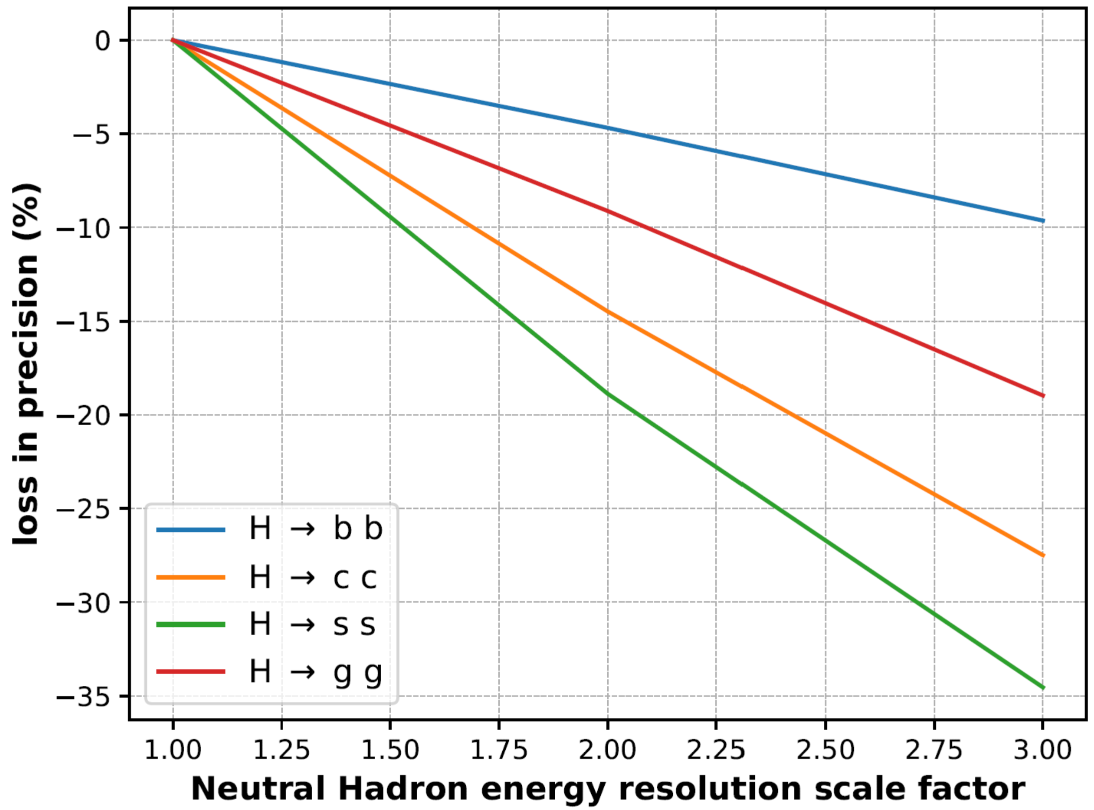




- Add energies of bremsstrahlung photons back to the momentum of the electron track
- 3%/√E EM resolution improves m_h by 22%
- Separation of radiated photons from the electron cluster

- Important to reconstruct low-energy photons (contribute to ~30% of hadronic jet energy)

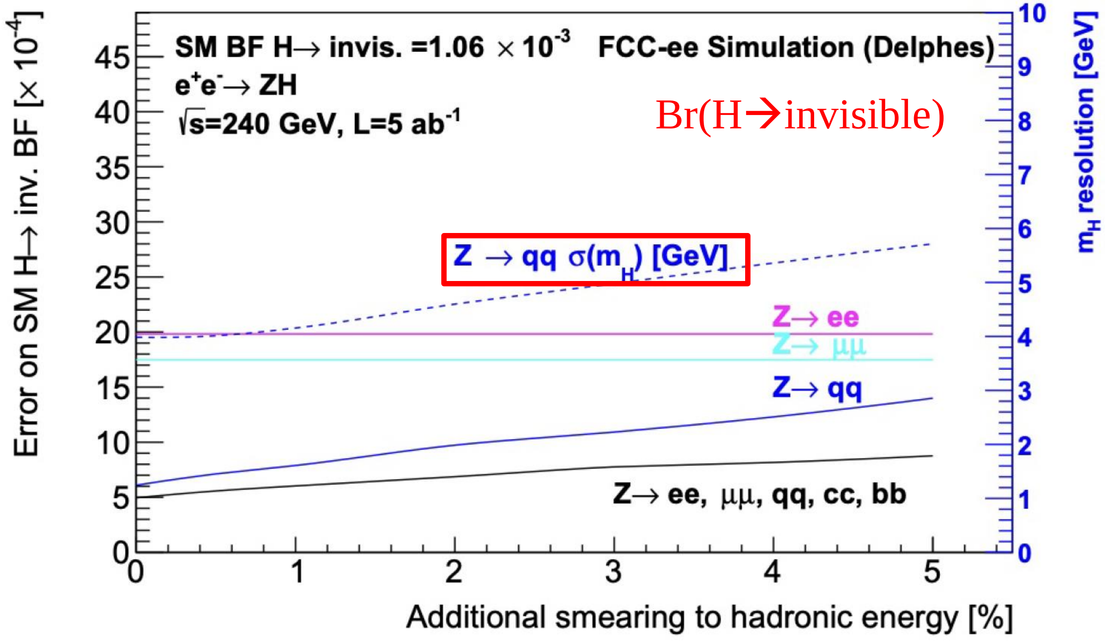
Requirements on HCAL

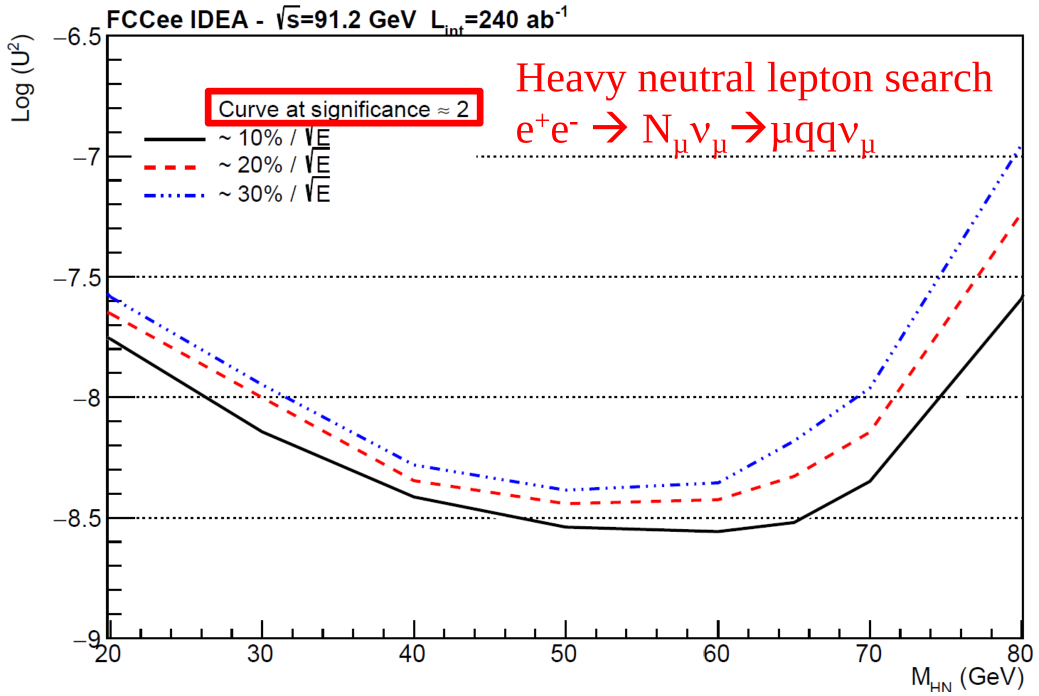


Degradation on Br(H→jj) measurements due to worse neutral hadrons energy resolution

SF=1: IDEA dual-readout calorimeter

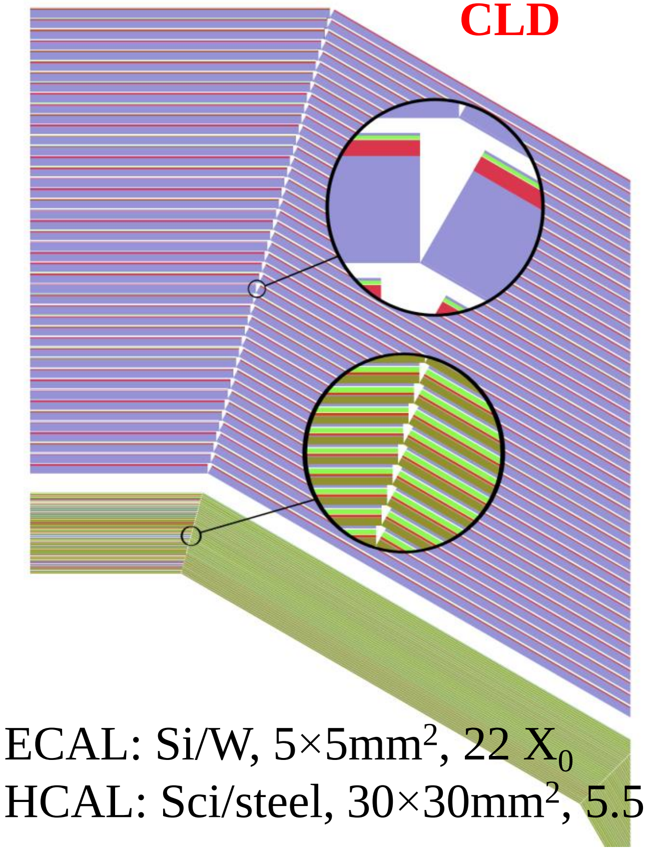
SF~2: ATLAS SF~3: CMS



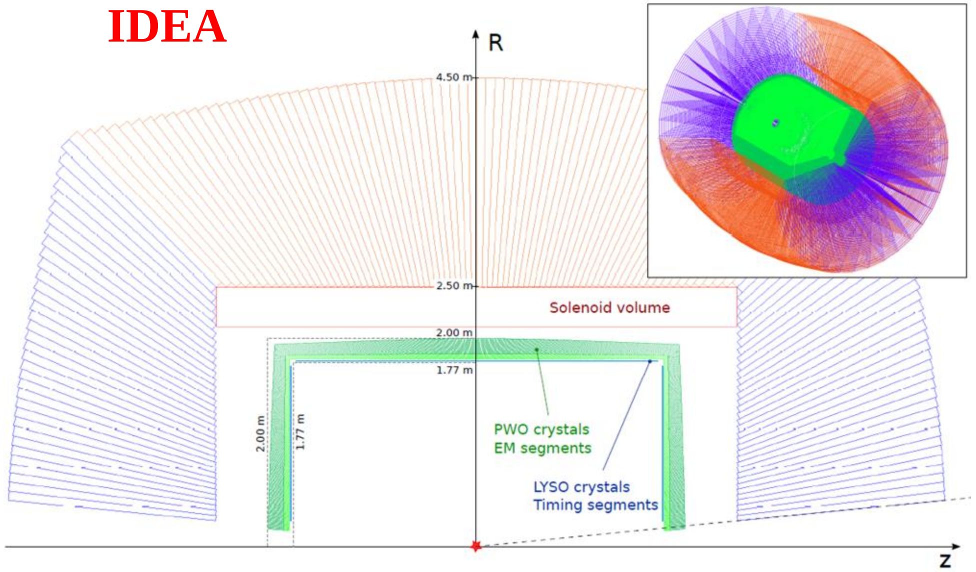


Calorimetry options

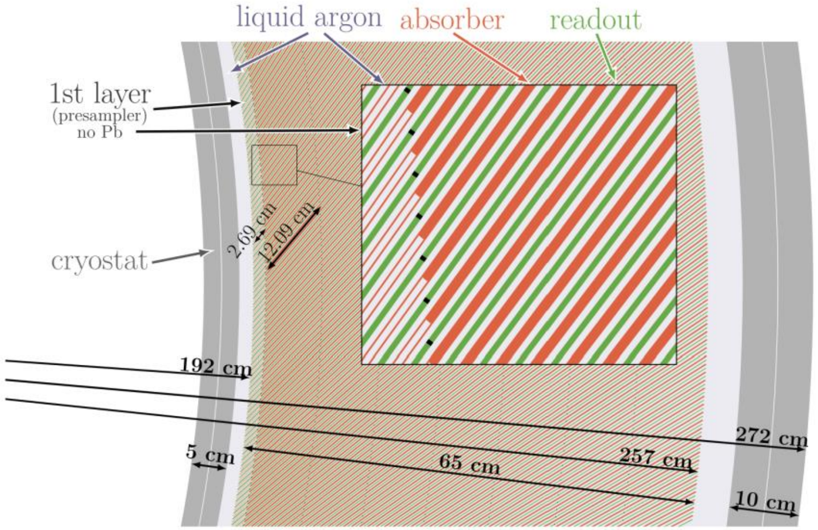
CLD



IDEA



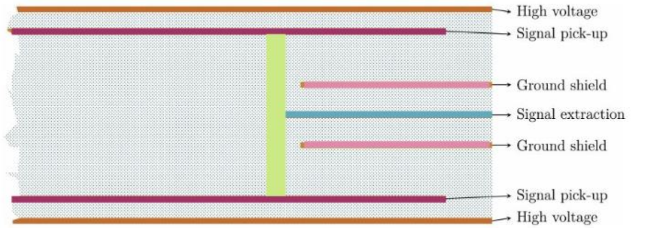
ALLEGRO



ECAL: Si/W, 5×5mm^2, 22 X_0
HCAL: Sci/steel, 30×30mm^2, 5.5 λ

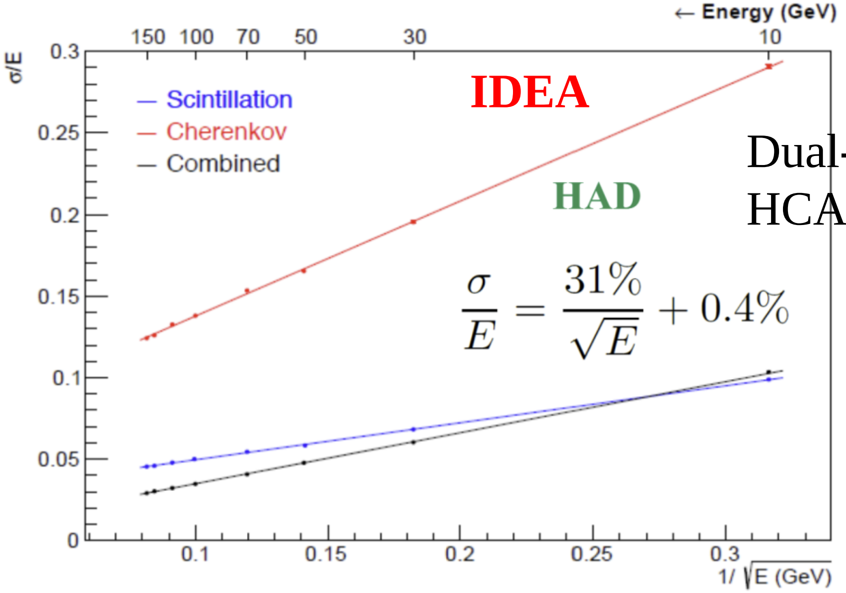
Copper with S/C fiber for both ECAL and HCAL
With the possibility of a dual-readout crystal ECAL

LAr/LKr with Pb or W absorbers for ECAL
CALICE- or TileCal-like HCAL

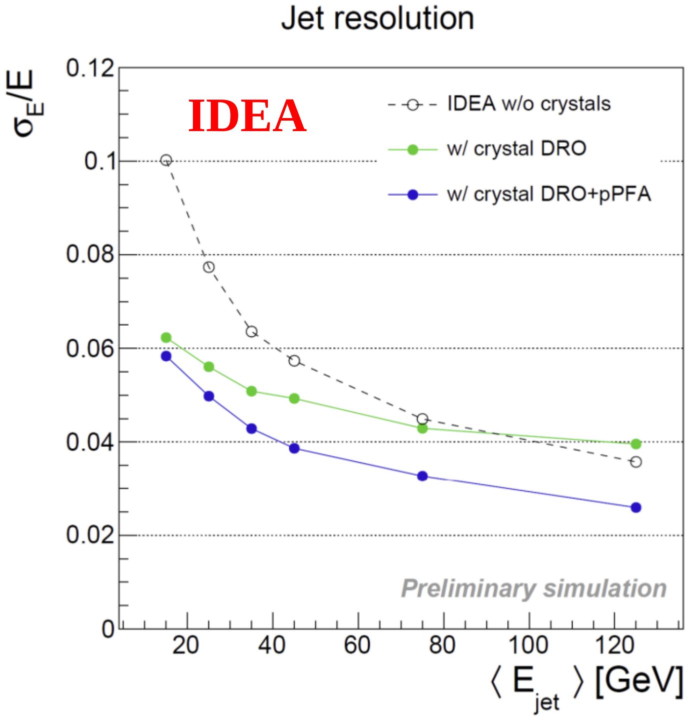


Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [20,45]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8–10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3–4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4–5 % [49]	3–4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5–6 % [30,50]	3–4 % [50]

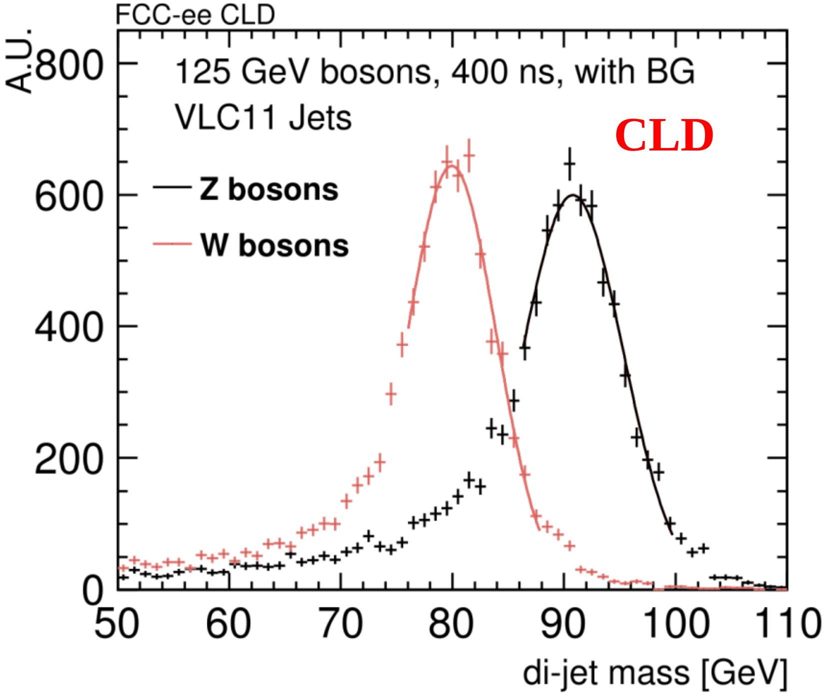
Calorimeter resolutions

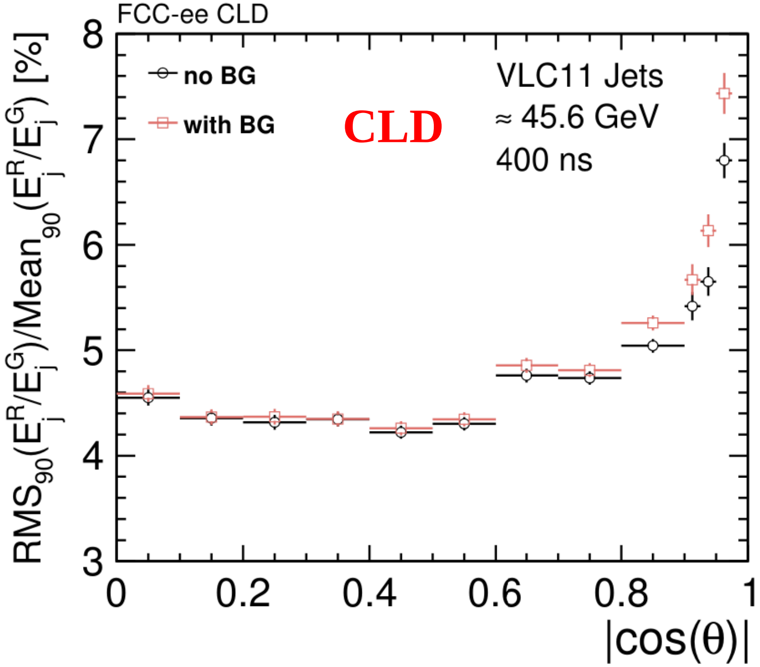


Dual-readout HCAL



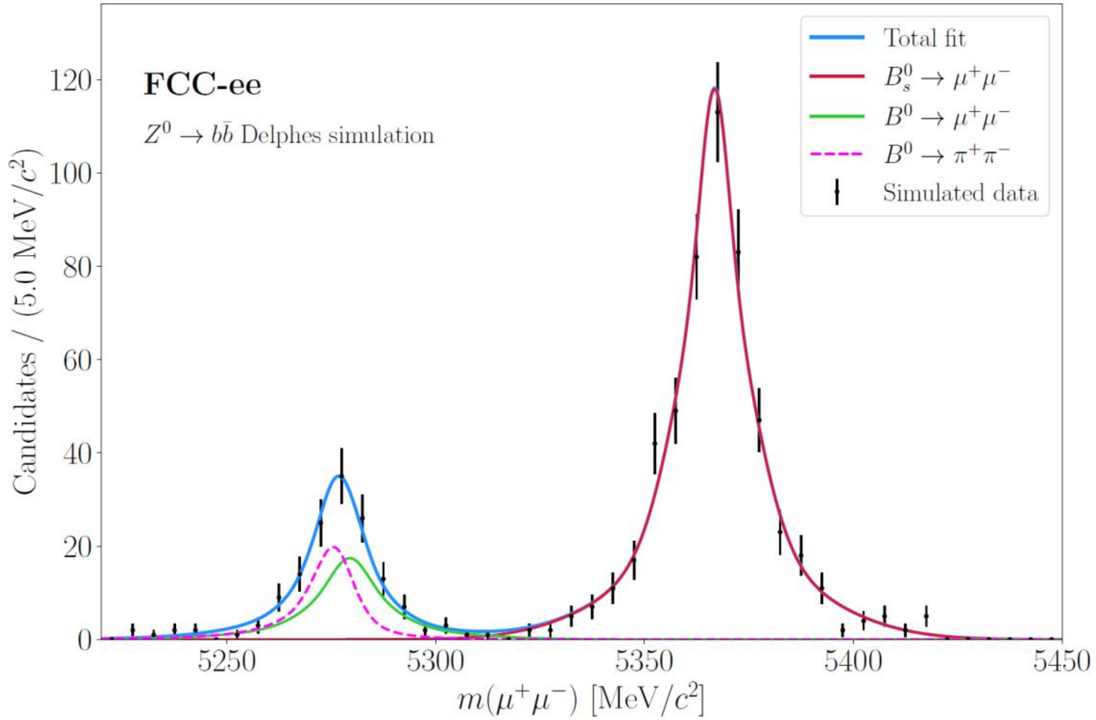
w/ dual-readout crystal ECAL and PFA





Requirements on the muon system

- Identify muons with high efficiency and serve as "tail-catcher" for the hadron showers that may not be fully contained in the calorimeter
- Important for long-lived particles that decay outside the tracker/calorimeter volume
- Technologies considered: RPC, μ-RWELL, scintillator bars, …
- The requirements on the standalone momentum resolution and position resolution need to be quantified (work in progress)



$B^0 \to \mu^+\mu^-$ with an assumption of a $\pi \to \mu$ misidentification rate of 2×10^{-5}

Summary

- Very broad ranges of interesting physics to study at the FCC-ee
- Physics goals we want to achieve put strong constraints on detector design and performances
- Momentum resolution: **$\sigma(p_T)/p_T^2 \sim 3\text{-}4\times10^{-5}$** to match the beam energy spread
- Jet energy resolution: **$\sigma_E/E \sim 30\%/\sqrt{E}$** to separate W and Z hadronic decays
- Electron/photon energy resolution: **$\sigma_E/E < 15\%/\sqrt{E}$** enough for jet resolution and m_h measurement, better resolution needed for low-energy photon and π^0 reconstruction
- Impact parameter resolution:

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

a ~ 5 μm, b ~ 15 μm·GeV (FCC-ee)

- Particle identification: **μ-π, π-K, K-p separation, e/γ/μ/π^0 identification for a wide momentum range**
- Magnetic field: **≤ 2 Tesla**
- Absolute luminosity measurement: **10^{-4}**, and relative measurement between energy scan points: **10^{-5}**, set strong constraints on the design and mechanical assembly of the LumiCal detector
- Track angular resolution: **<0.1 mrad**
- Stability of the magnetic field: **$<10^{-6}$**
- Fine granularity for ECAL and HCAL
- Large detector acceptances for the tracker, ECAL, HCAL, and muon systems
- …
- More discussions about requirements and the three detector benchmarks can be found in the FCC-ee feasibility study mid-term report
- Continuing work to better understand physics requirements on detector performance and to optimize detector designs