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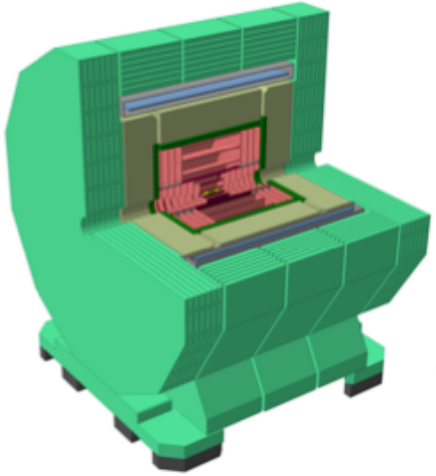
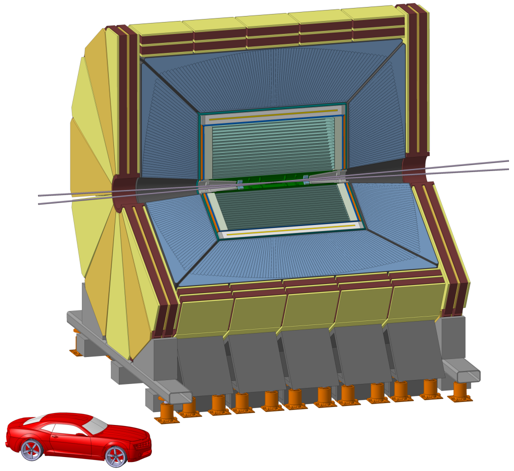
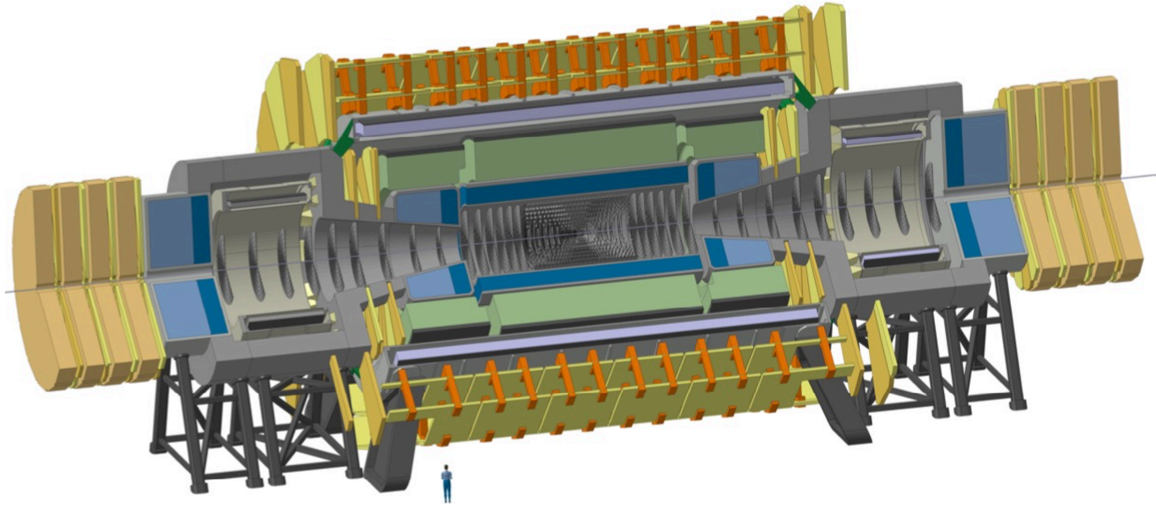
FCC - Experimental Challenges

Mogens Dam
on behalf of the FCC Detector Groups

1st Nordic FCC Day
zoom, 22 March, 2021



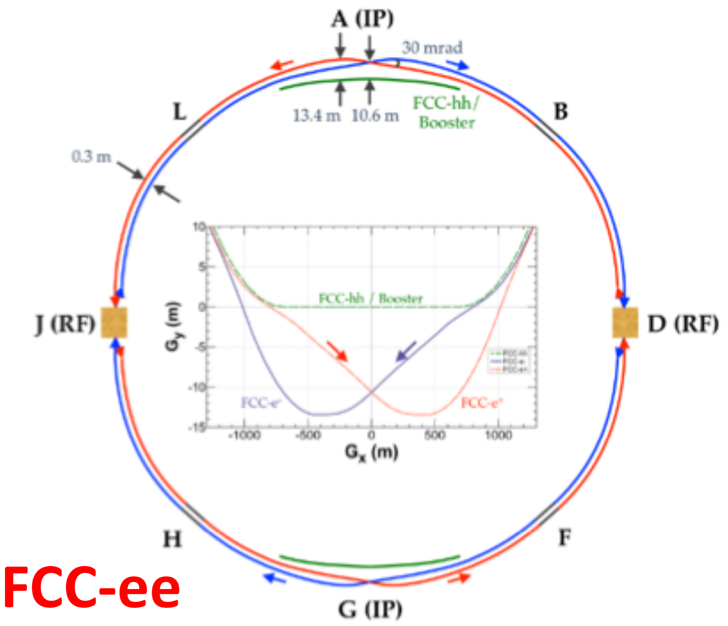




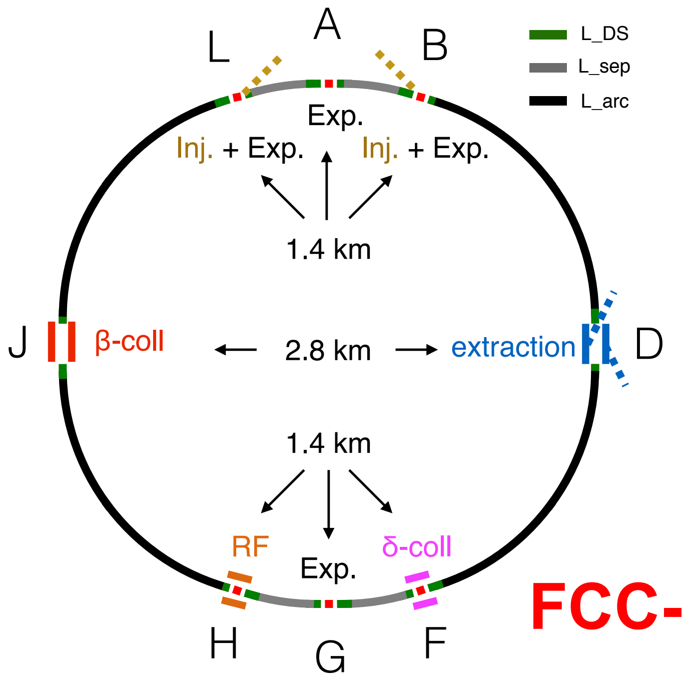
FCC Integraded Program

Comprehensive cost-effective program maximizing physics opportunities

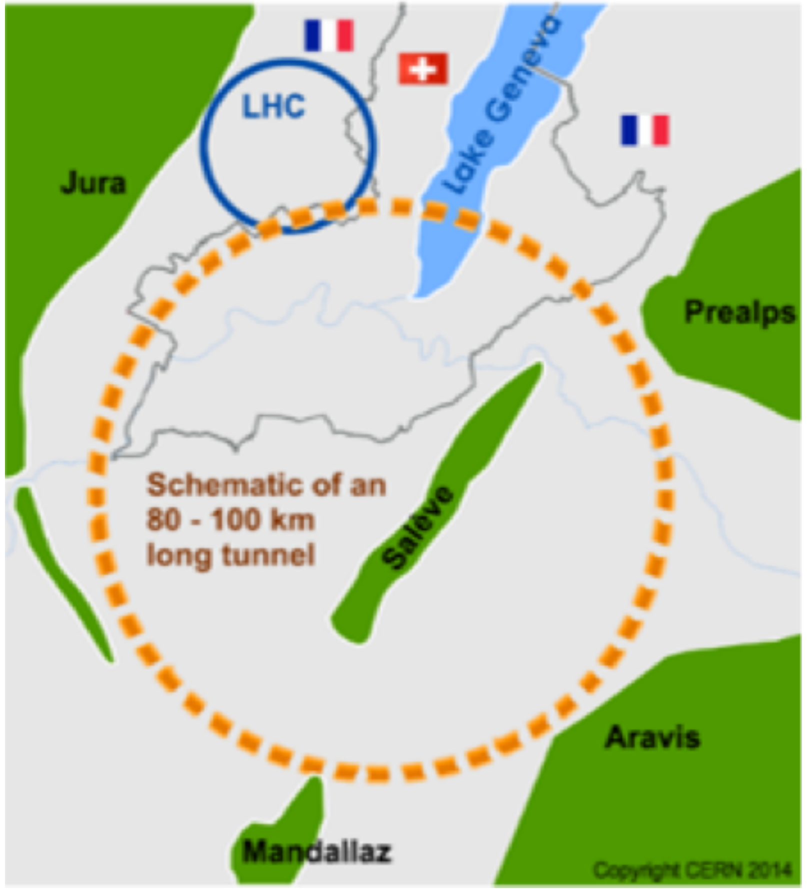
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC



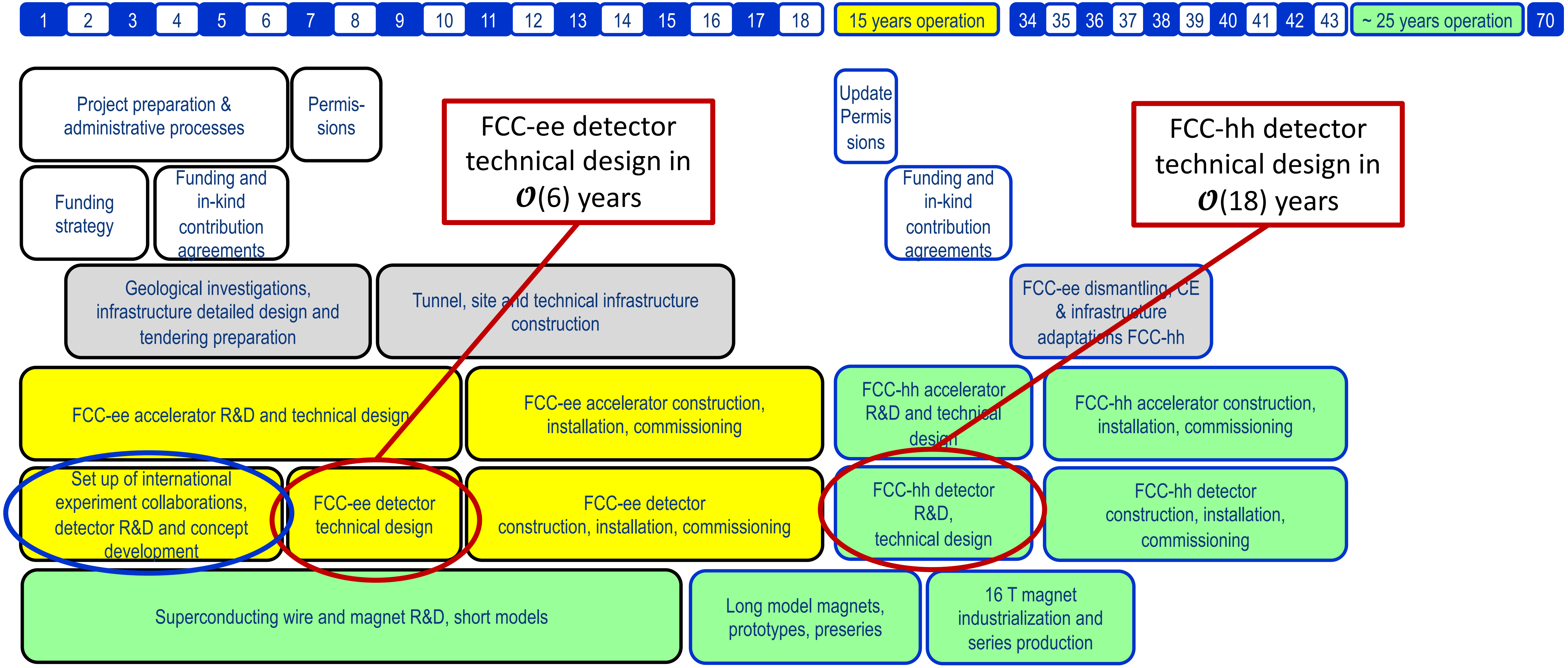
FCC-ee



FCC-hh



FCC Integraded Project Schedule



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

Project preparation & administrative processes

Permis-sions

Funding strategy

Funding and in-kind contribution agreements

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

Superconducting wire and magnet R&D, short models

Long model magnets, prototypes, preseries

16 T magnet industrialization and series production

Update Permis sions

Funding and in-kind contribution agreements

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

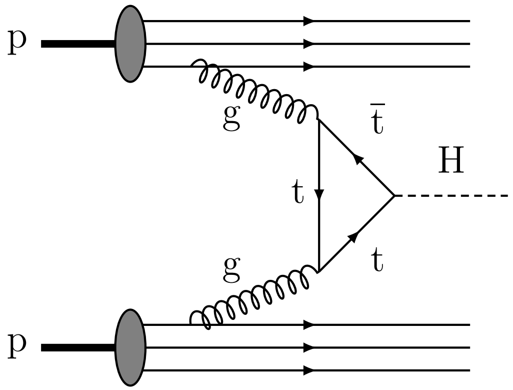
FCC-hh detector R&D, technical design

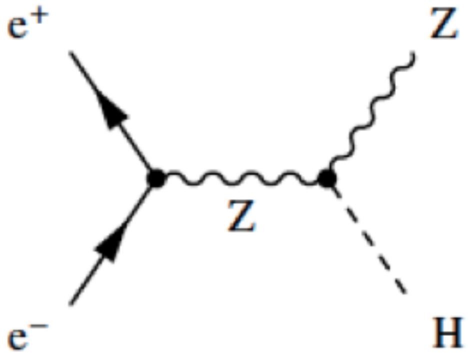
FCC-hh detector construction, installation, commissioning

FCC-ee detector technical design in $\mathcal{O}(6)$ years

FCC-hh detector technical design in $\mathcal{O}(18)$ years

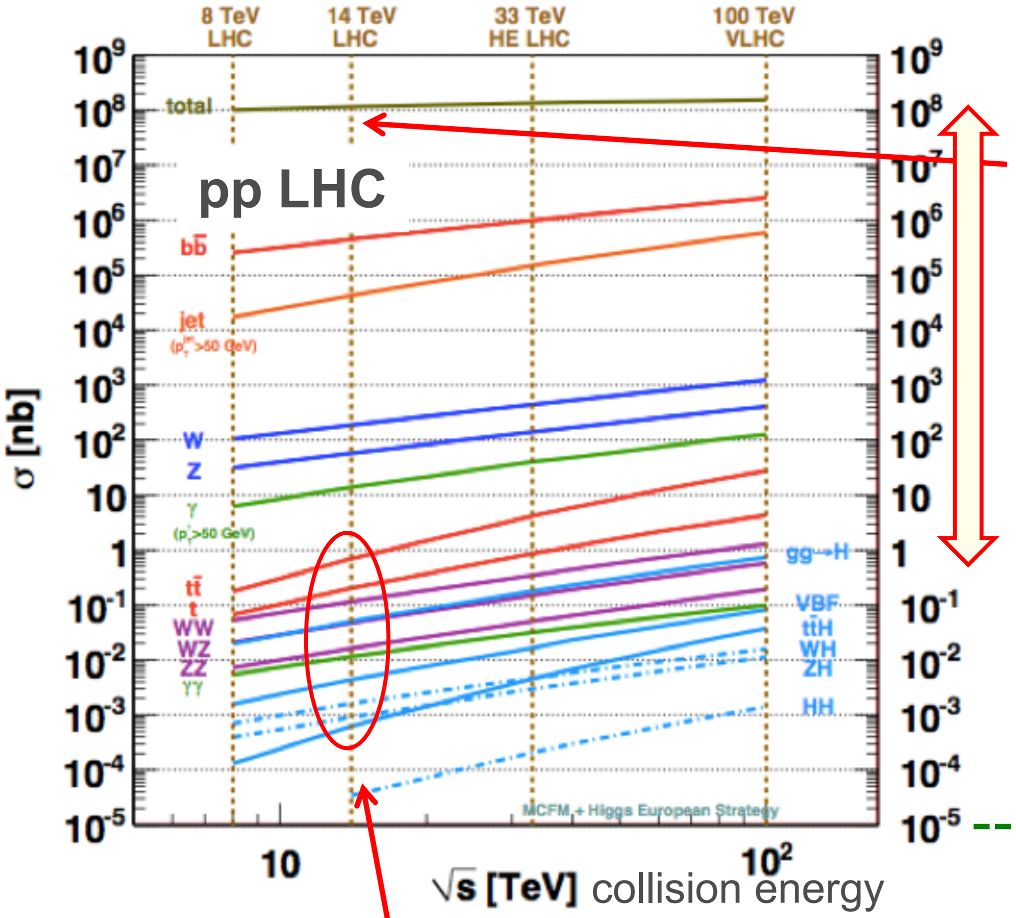
Prelude: pp collisions vs. e^+e^- collisions (i)





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

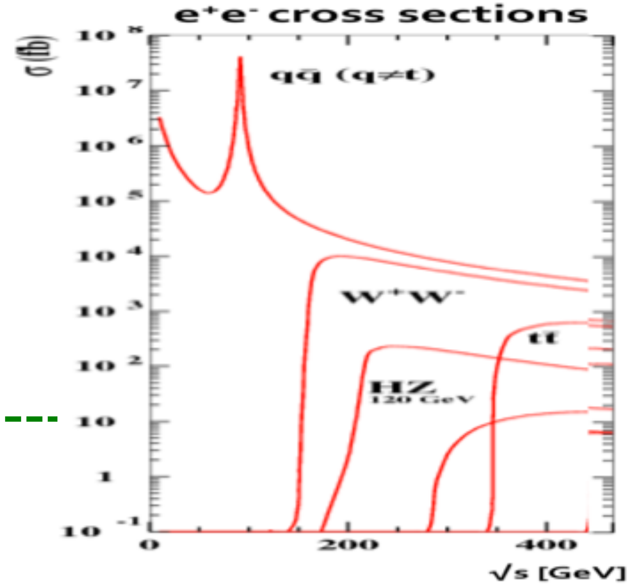
Prelude: pp collisions vs. e^+e^- collisions (ii)



LHC total cross section factor > 100 million !!

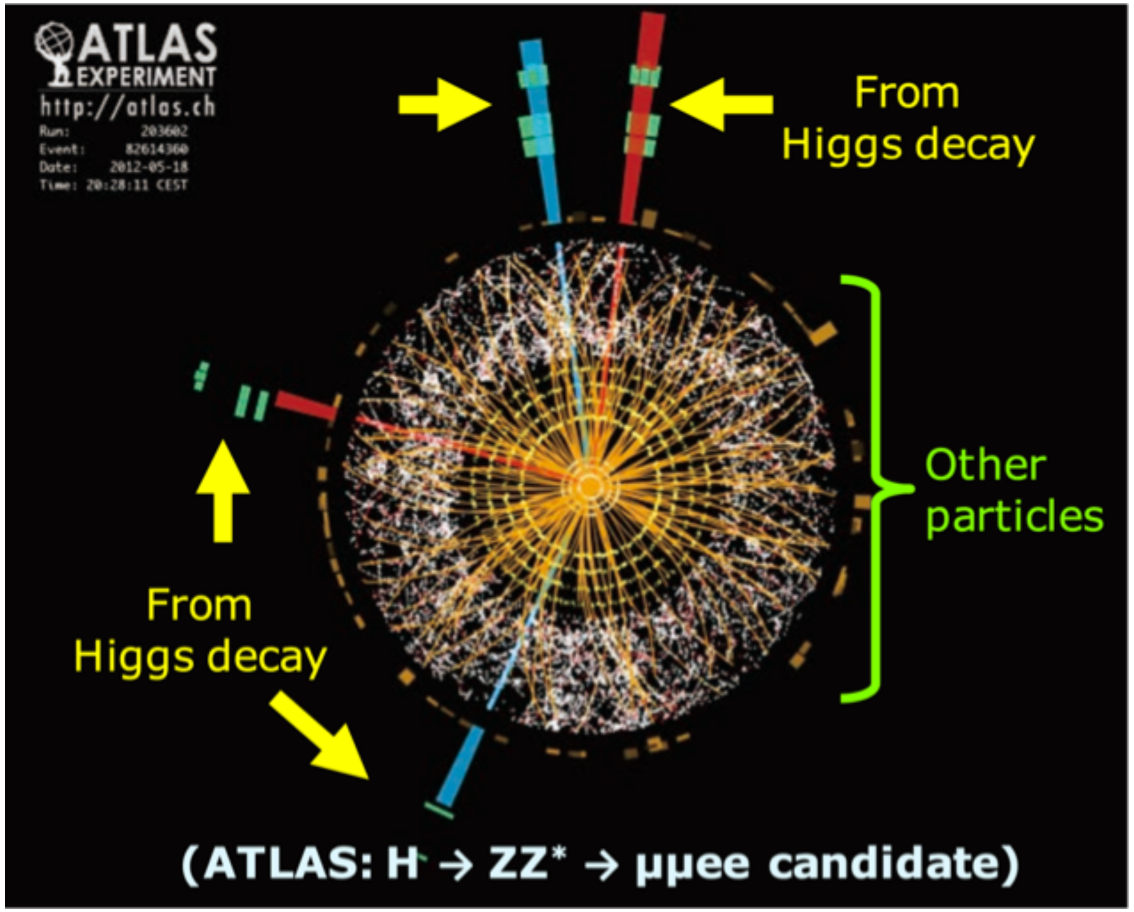
At LHC, much of the interesting physics needs to be found among a huge number of collisions

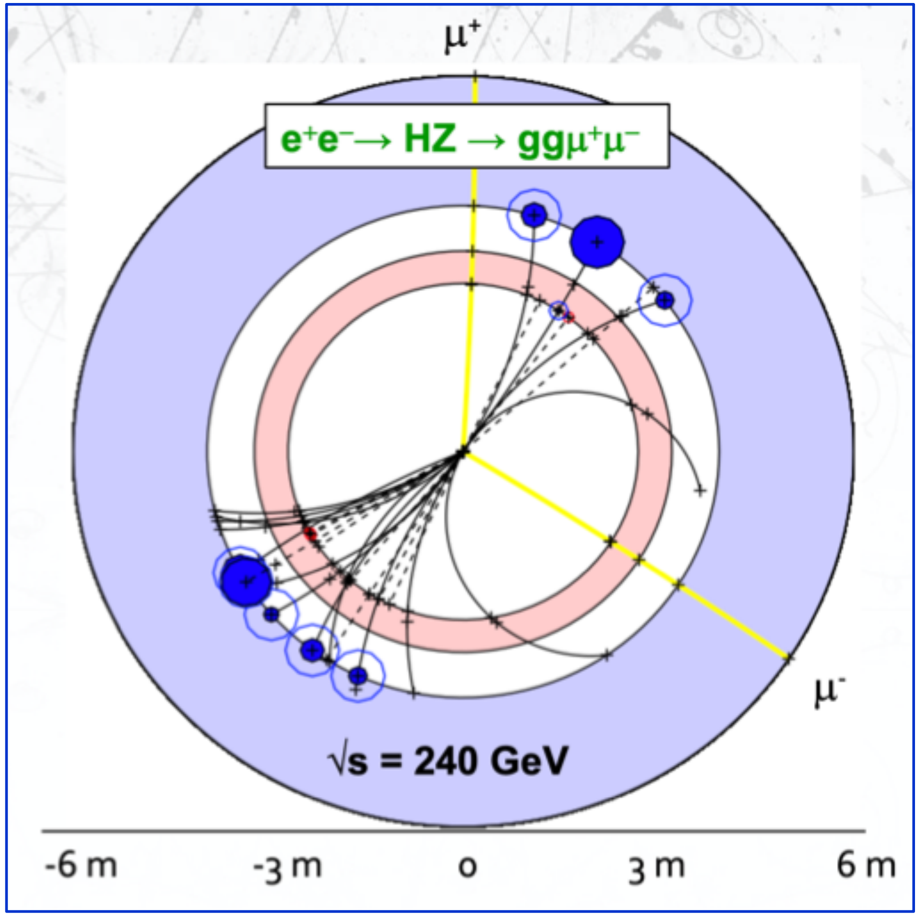
In e^+e^- collisions the total cross section equals the electroweak cross section.



e^+e^- events are "clean"

Example: Higgs event in pp and e$^+$e$^-$

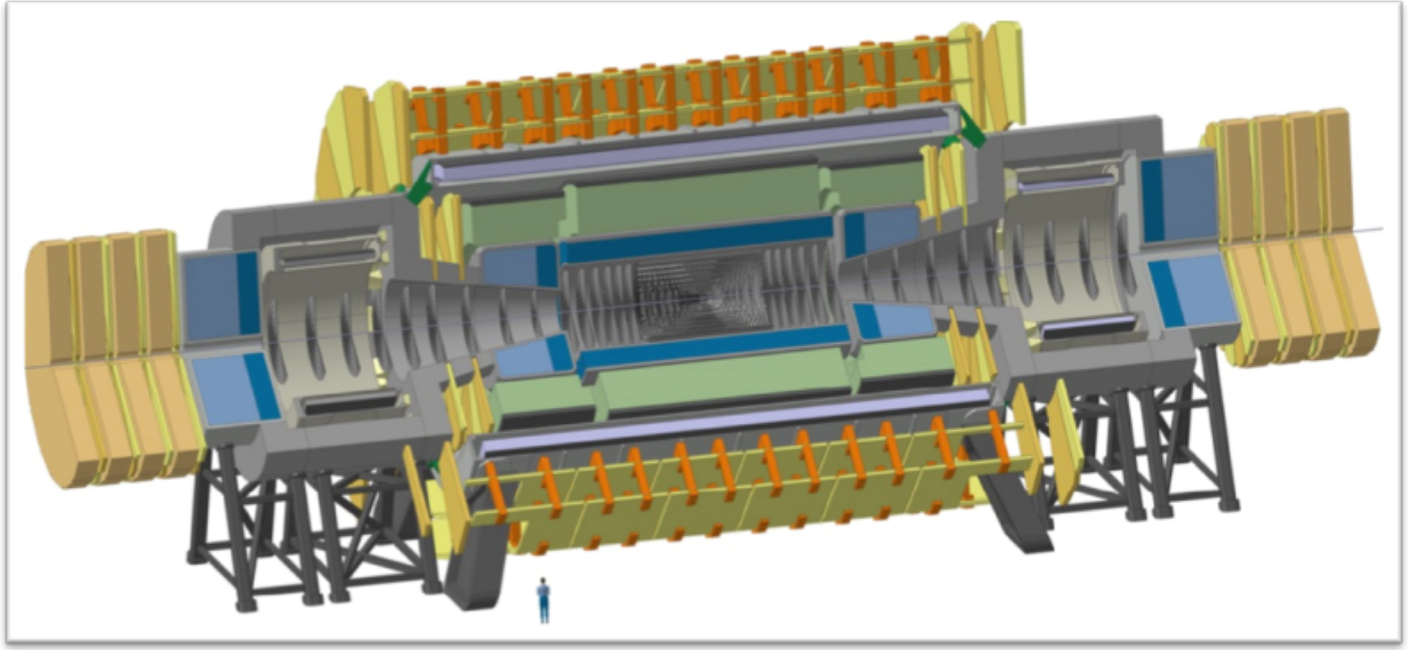




Proton-proton: look for striking signal in large background; high energy reach

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

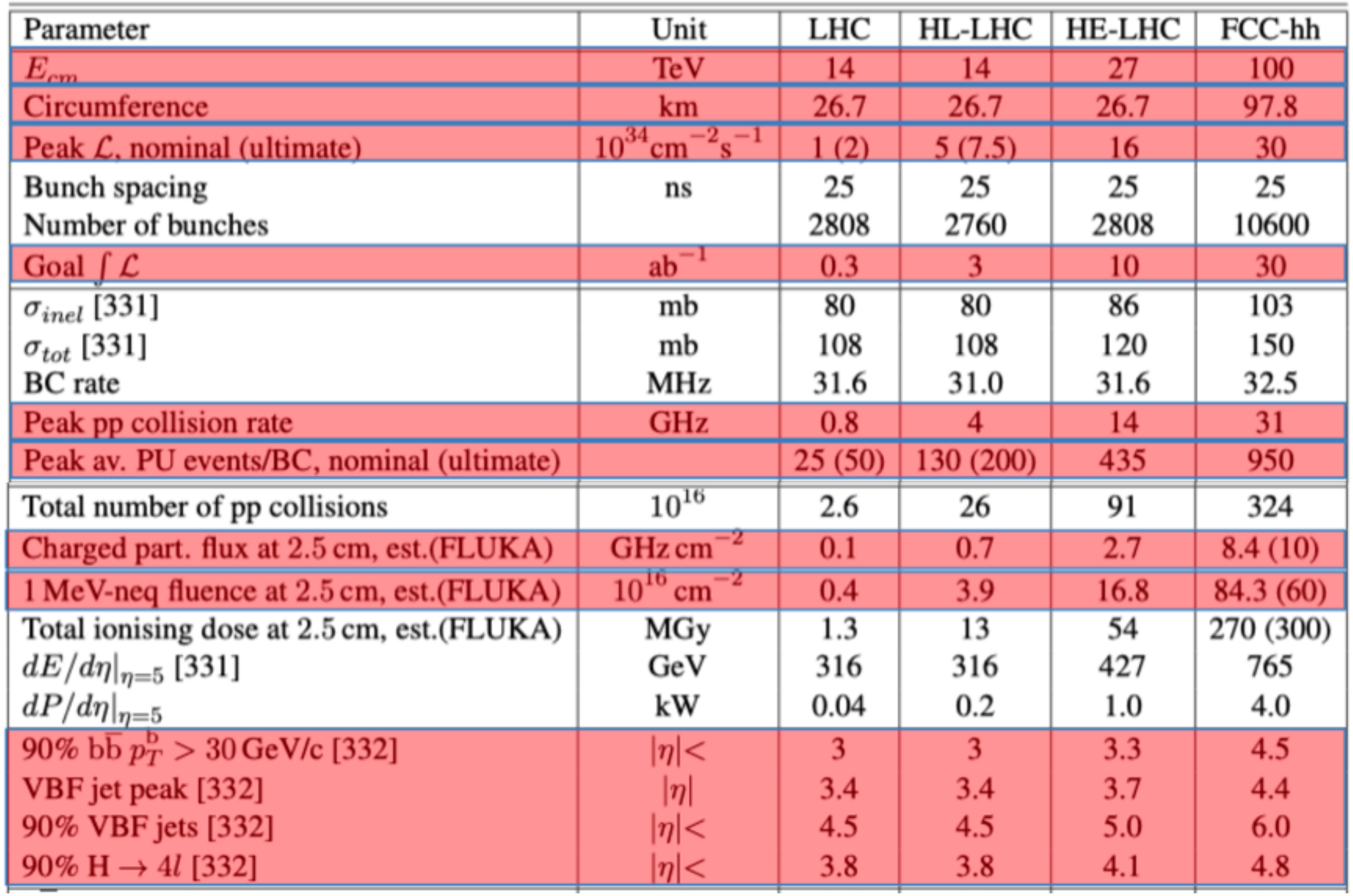
FCC-hh



Thank you to Martin Aleksa for inputs

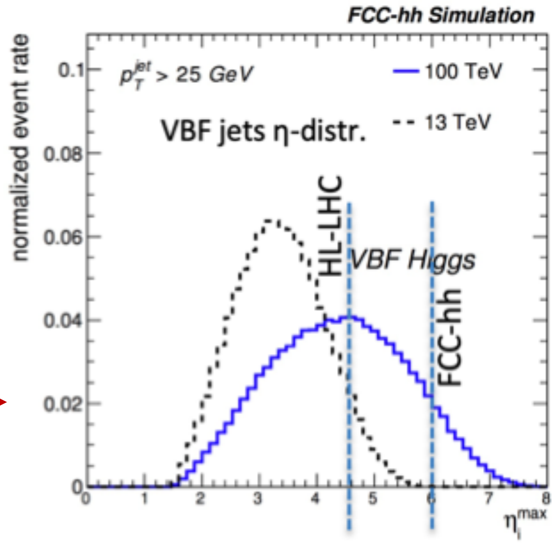
FCC-hh Parameter Table

Table 7.1: Key numbers relating the detector challenges at the different accelerators.



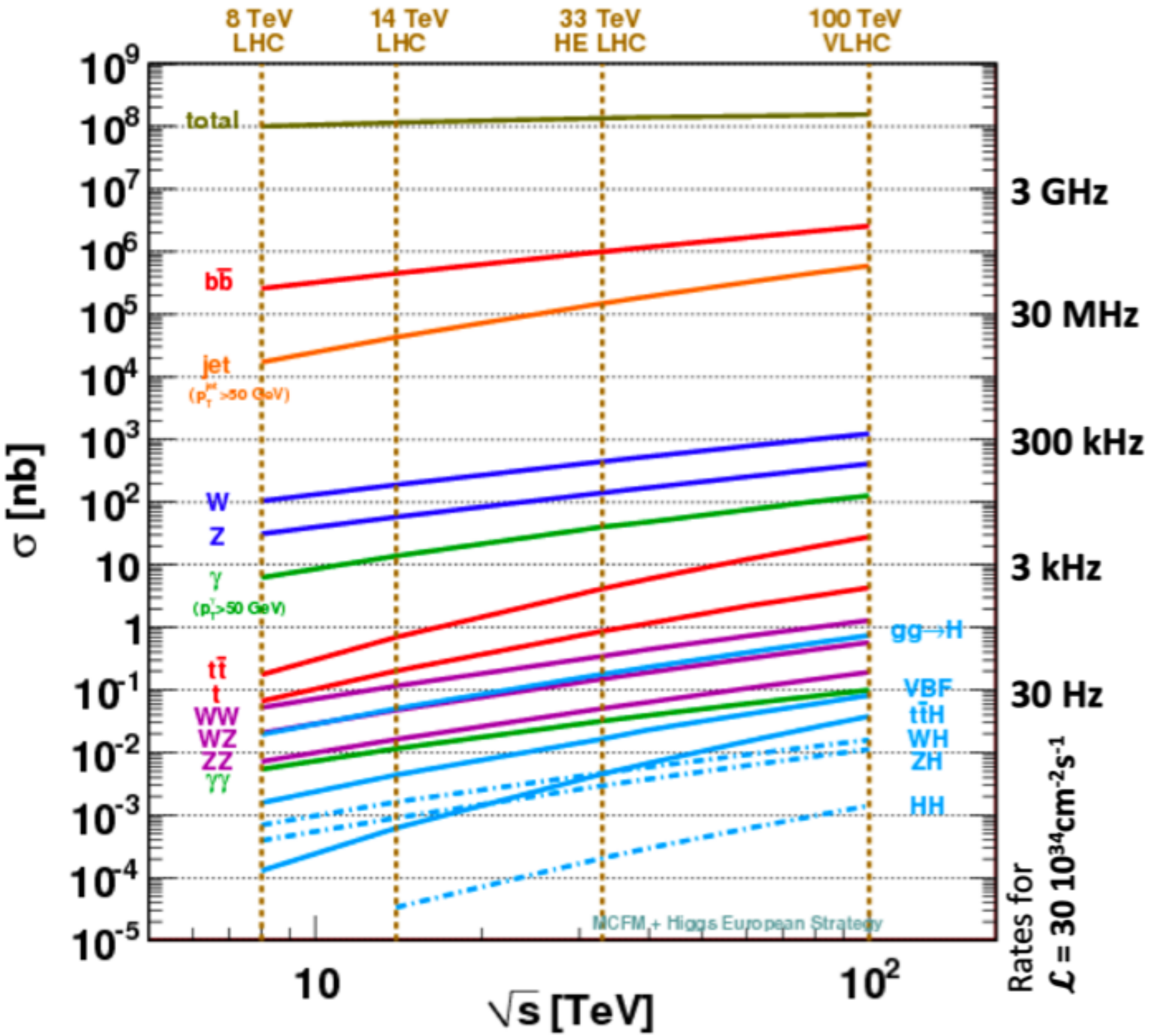
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \rightarrow 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8

- E_{cm} = 1oo TeV
- $\mathcal{L} = 30 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- $\int \mathcal{L} = 30\ \mathrm{ab}^{-1}$
- 31 GHz pp collisions
- Pile-up <μ> ≈ 1000
- 4 THz of charged tracks



- ”Light” particles produced with increasing forward boost

Cross Sections for Key Processes



- Total cross-section and Minimum Bias Multiplicity show only a modest increase from LHC to FCC-hh

- The cross-section for interesting processes increases, however, significantly
  - e.g. factor 50 increase for HH !

- Higher luminosityy to increase statistics
  - Pile-up of 140 at HL-LHC to 1000 at FCC-hh
  - Challenge for triggering and reconstruction

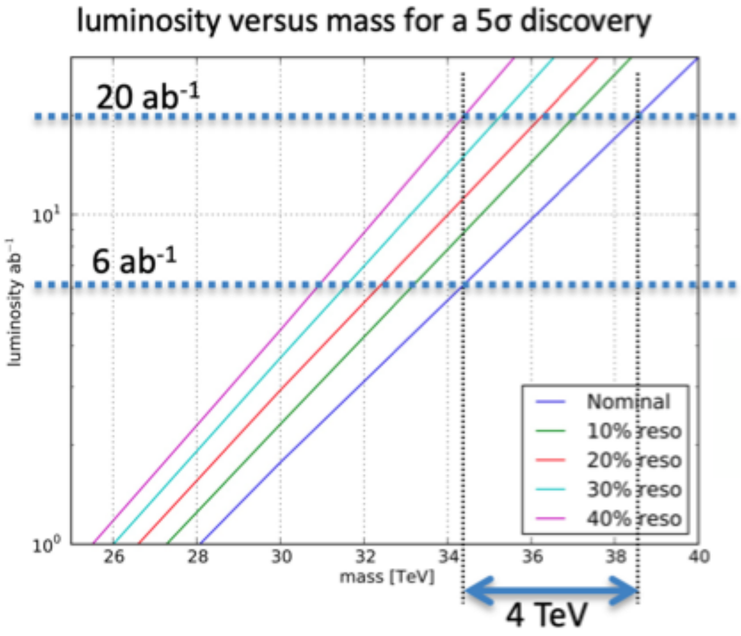
- $\mathcal{L} = 30 \times 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$:
  - 100 MHz of jets $p_T > 50$ GeV
  - 400 kHz of Ws
  - 120 kHz of Zs
  - 11 kHz of ttbars
  - 200 Hz of gg → H

Physics Benchmarks – Detector Requirements

Physics at the $\mathcal{L}\sigma$-limit

Exploration potential through higher energy, increased statistics, increased precision

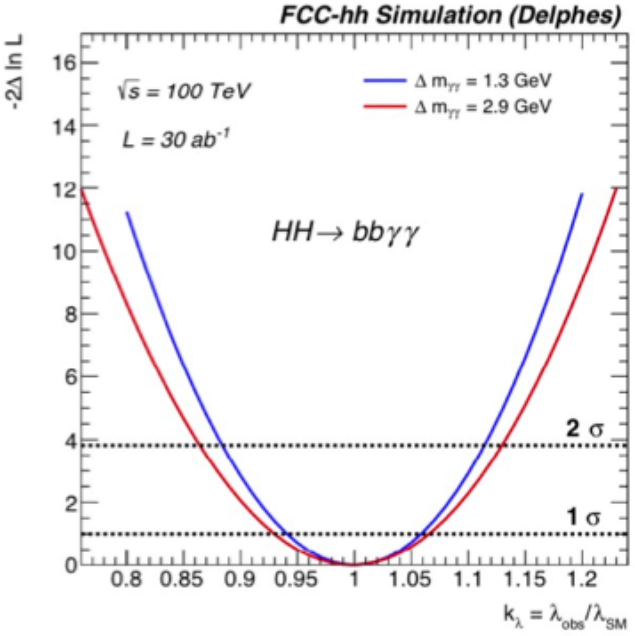
Example: Z’$_{SSM}$ discovery

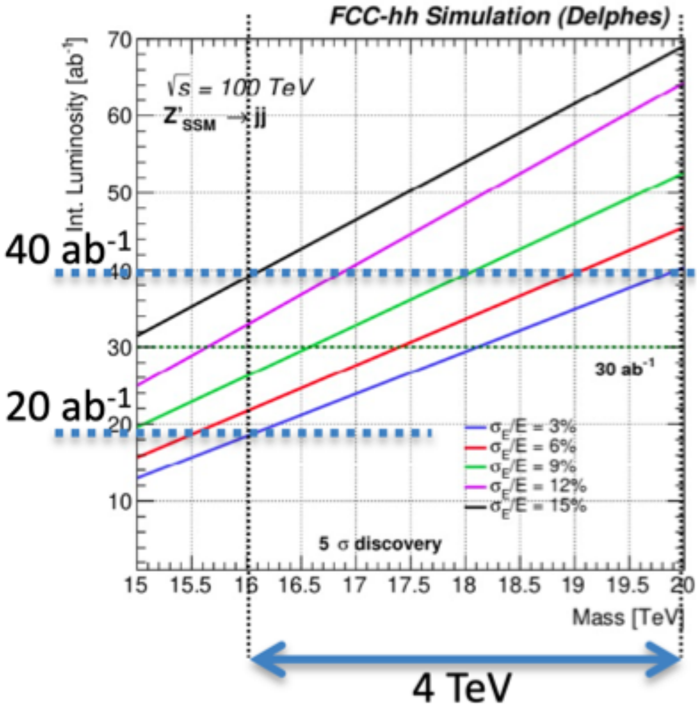


$$\frac{\Delta p}{p} \propto \frac{p}{BL^2}$$

Muon momentum resolution:

- **O(5%) at 10TeV.**
- **Compare to 10% at 1TeV spec. at LHC**





$$\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Higgs self-coupling δλ/λ = 7% for Δ$m_{\gamma\gamma}$ < 3GeV

- → **EM-calorimeter resolution**

  sampl. term *a ≈ 10%* and noise term *b < 1.5 GeV* (including pile-up)!

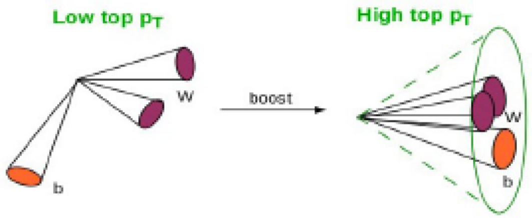
Di-jet resonances: HCAL constant term of *c* = 3% instead of 15%: extend discovery potential by 4 TeV (or same disc. pot. for 50% lumi)

- → **full shower containment is mandatory !**
- → Large **HCAL depth (~ 12 λ_{int})!**

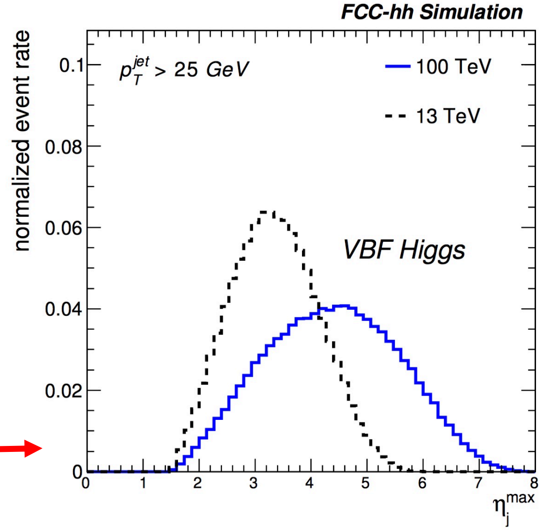
Requirements for FCC-hh Detector

Used in Delphes physics simulations

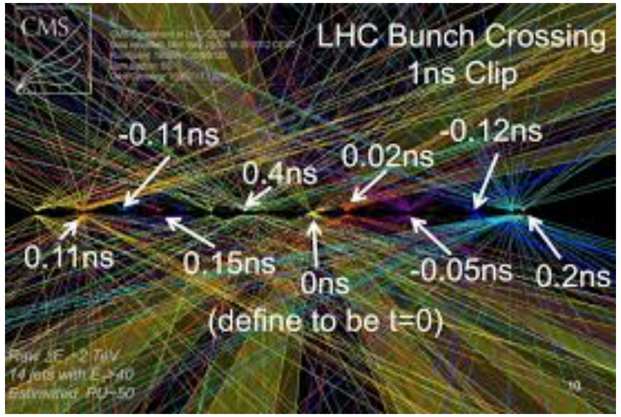
- **ID tracking target**: achieve σ_{p_T} / p_T = 10-20% @ 10 TeV
- **Muon target**: σ_{p_T} / p_T = 5% @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency vertex reconstruction, b-tagging, τ-tagging, particle ID**!
  - Pile-up of $\langle\mu\rangle$=1000 → 120µm mean vertex separation
- **High granularity** in tracker and calos (boosted obj.)



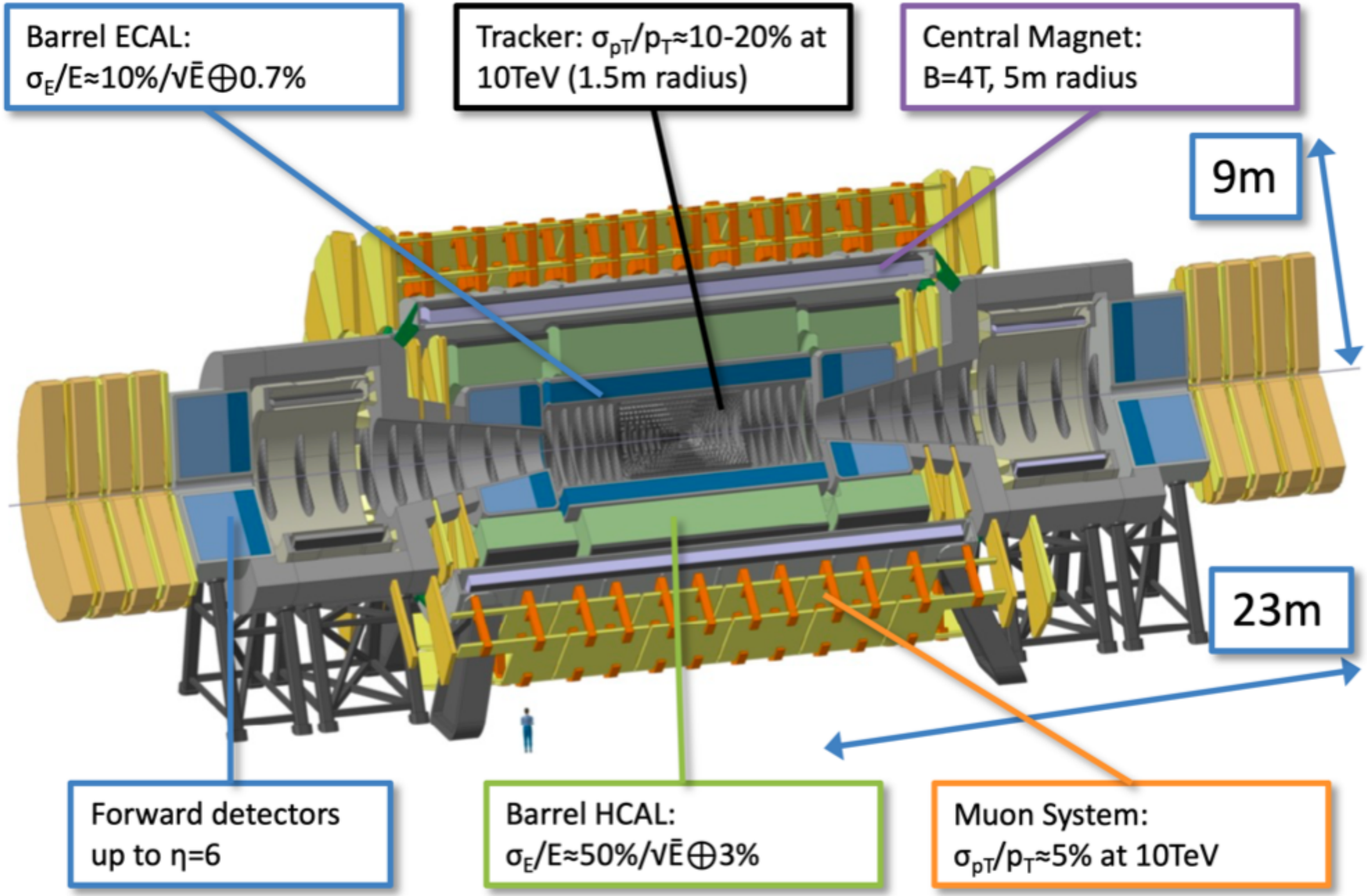
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6



- → **Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**



A Possible FCC-hh Detector – Reference Design for CDR



Barrel ECAL:
$\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Tracker: $\sigma_{p_T}/p_T \approx 10\text{-}20\%$ at 10TeV (1.5m radius)

Central Magnet:
B=4T, 5m radius

Forward detectors
up to $\eta=6$

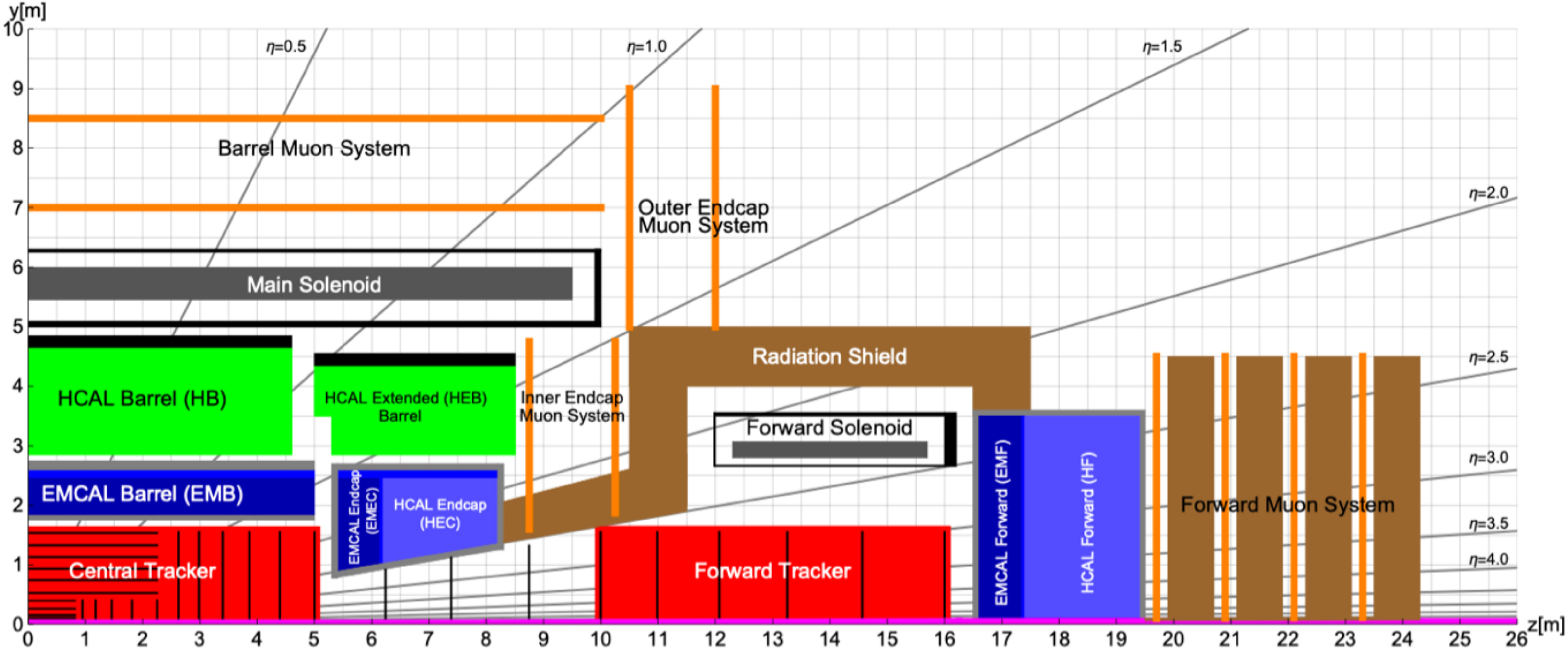
Barrel HCAL:
$\sigma_E/E \approx 50\%/\sqrt{E} \oplus 3\%$

Muon System:
$\sigma_{p_T}/p_T \approx 5\%$ at 10TeV

- **Reference design for an FCC-hh experiment for <u>FCC CDR</u>**
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
  - **Input for Delphes physics simulations**
  - **Radiation simulations**

- However, this is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**

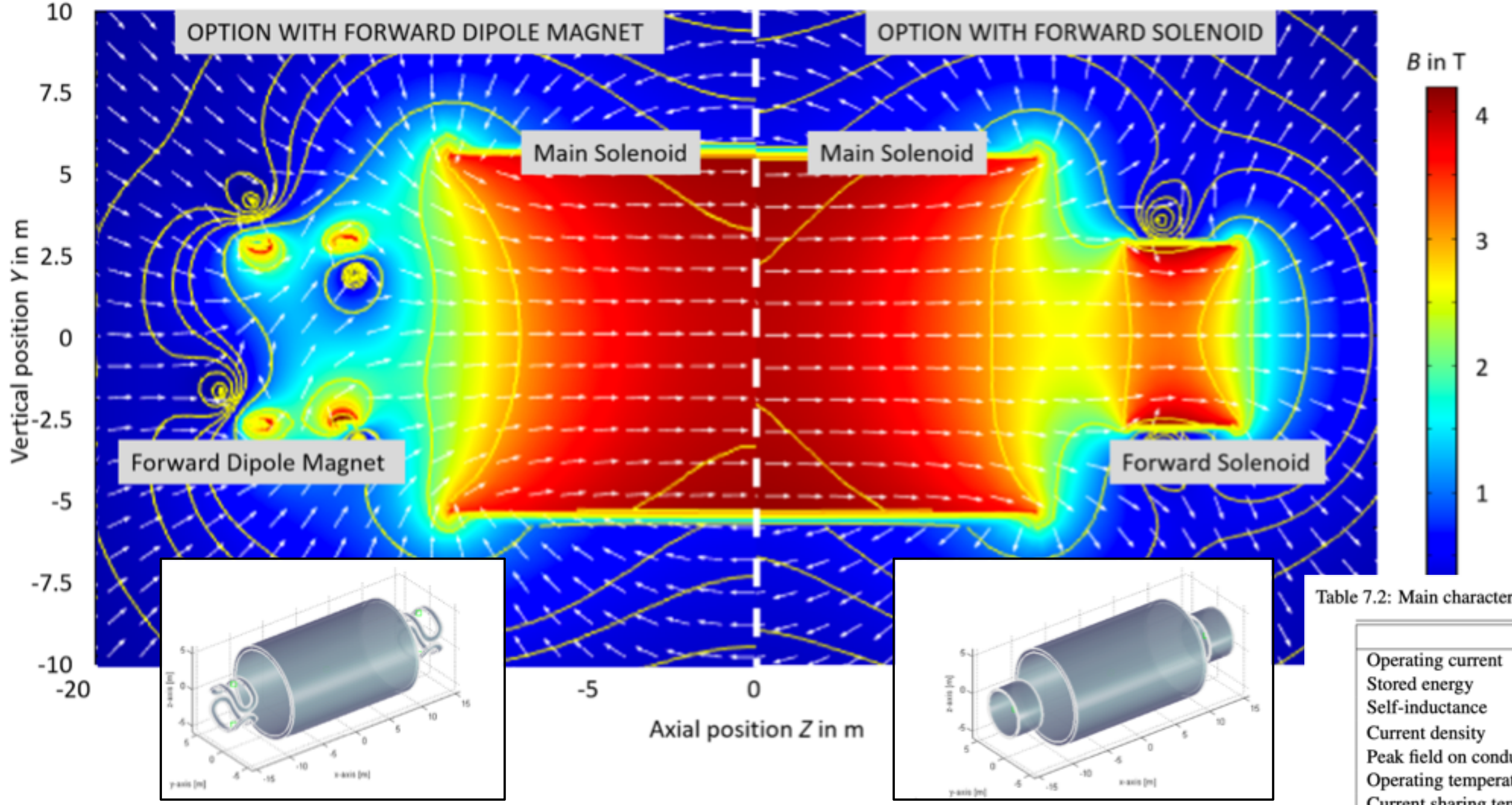
Reference Design for CDR



Forward solenoid adds about 1 unit of η with full lever-arm

Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter

FCC-hh Magnet System



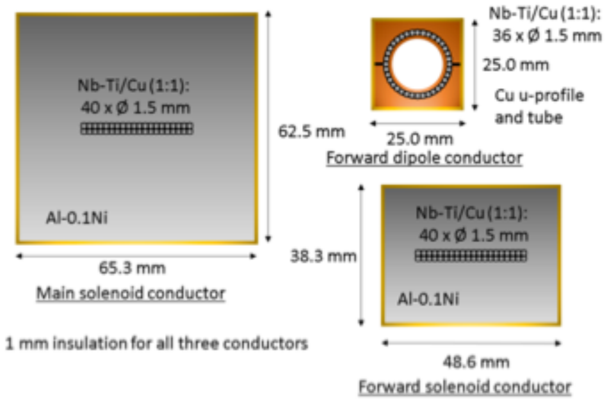
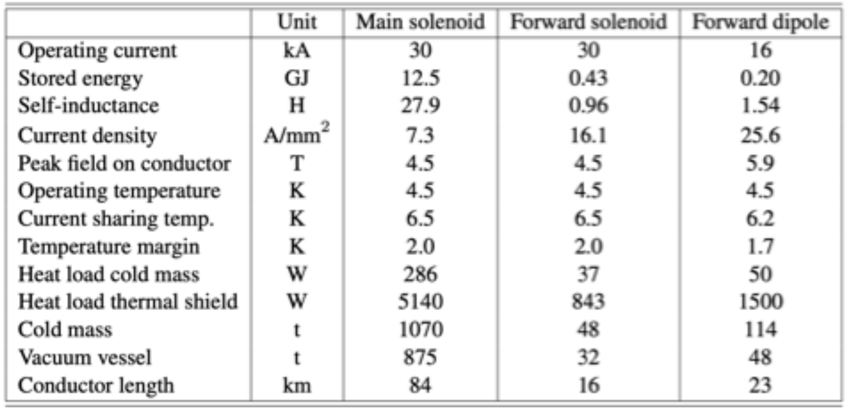


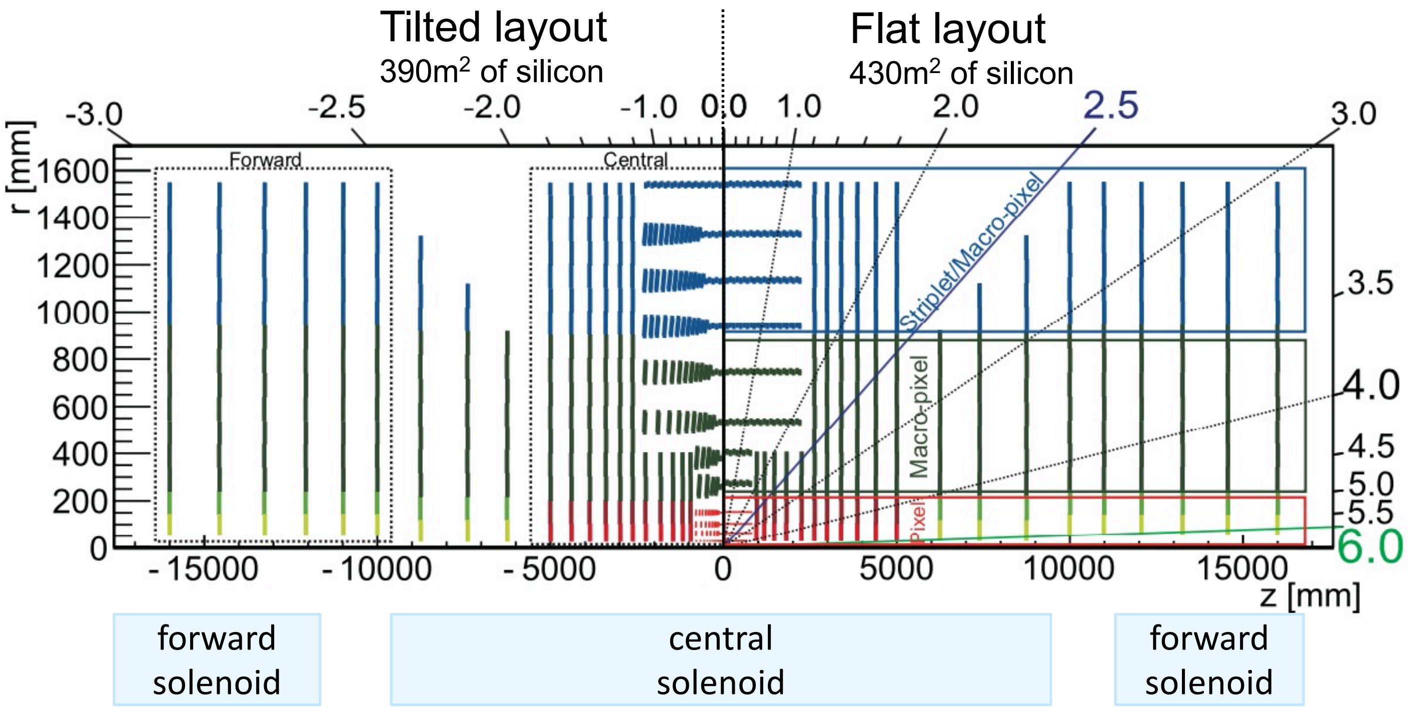
Table 7.2: Main characteristics of the central solenoid, a forward solenoid and a forward dipole magnet.

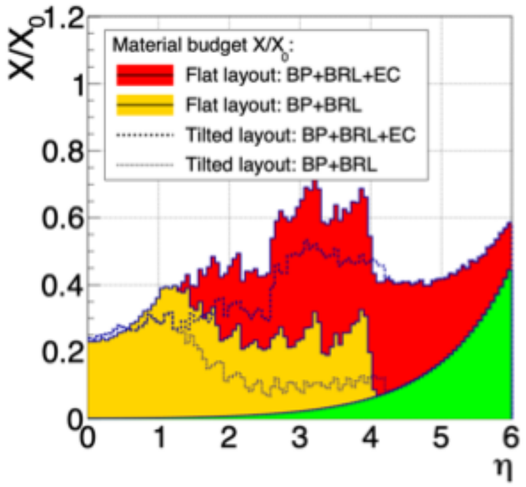


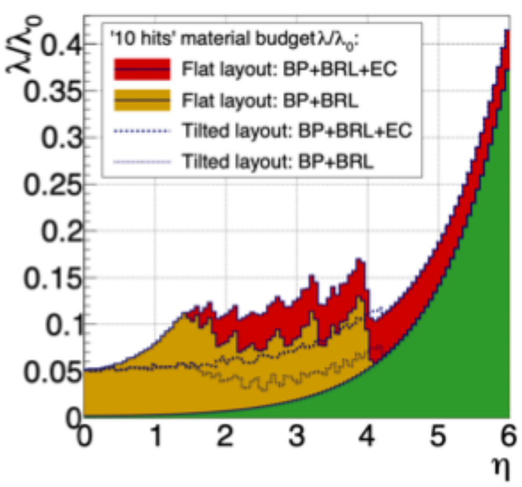
	Unit	Main solenoid	Forward solenoid	Forward dipole
Operating current	kA	30	30	16
Stored energy	GJ	12.5	0.43	0.20
Self-inductance	H	27.9	0.96	1.54
Current density	A/mm^2	7.3	16.1	25.6
Peak field on conductor	T	4.5	4.5	5.9
Operating temperature	K	4.5	4.5	4.5
Current sharing temp.	K	6.5	6.5	6.2
Temperature margin	K	2.0	2.0	1.7
Heat load cold mass	W	286	37	50
Heat load thermal shield	W	5140	843	1500
Cold mass	t	1070	48	114
Vacuum vessel	t	875	32	48
Conductor length	km	84	16	23

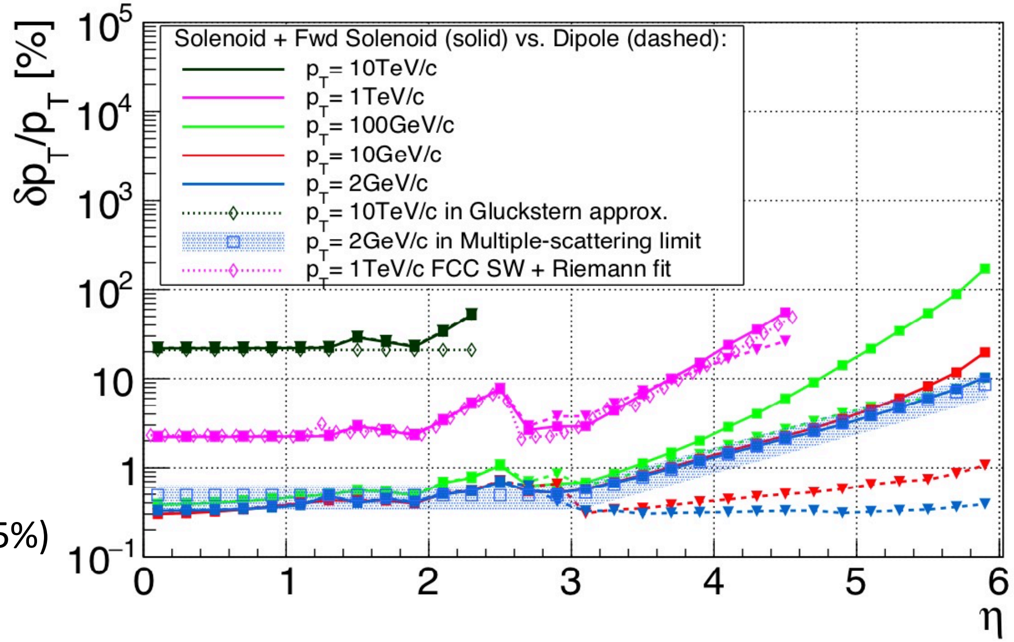
ATLAS Magnet System 2.7 GJ
CMS Magnet System 1.6 GJ
FCC-hh: ~13 GJ, cold mass + cryostat around 2000 tons.
Possible alternative solutions: Ultra-thin solenoid positioned inside the calorimeter (difficulty: muon measurement!)

FCC-hh Tracker









Tilted layout:

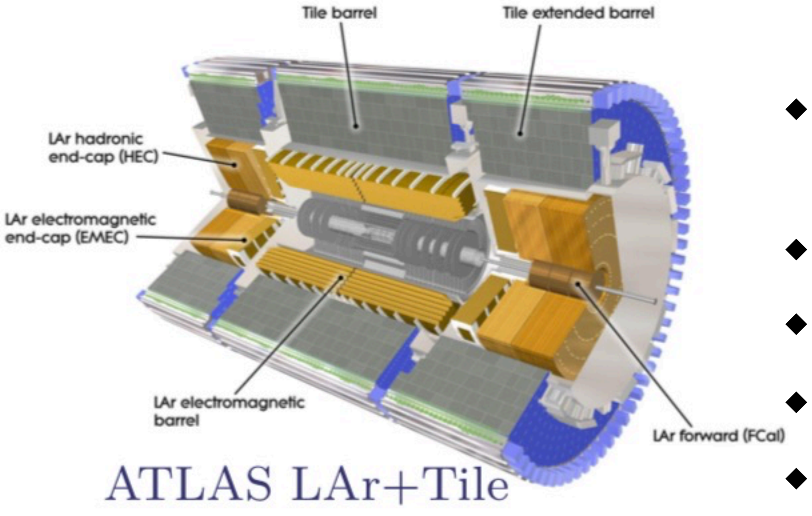
$25 \times 50\,\mu\mathrm{m}^2$ (1–4th BRL)	$33.3 \times 400\,\mu\mathrm{m}^2$	$33.3\,\mu\mathrm{m} \times 1.75\,\mathrm{mm}$ (BRL)
$25 \times 50\,\mu\mathrm{m}^2$ (1st EC ring)		$33.3\,\mu\mathrm{m} \times 1.75\,\mathrm{mm}$ (EC)
$33.3 \times 100\,\mu\mathrm{m}^2$ (2nd EC ring)		$33.3\,\mu\mathrm{m} \times 50\,\mathrm{mm}$ (12th BRL layer)
$33.3 \times 400\,\mu\mathrm{m}^2$ (3–4th EC ring)		

Assuming an r-phi resolution of 7.5-9.5µm per detector layer
$\delta p_T/p_T \leq 10\%$ for

- ≤ 10 GeV/c and $\eta \leq 5.8$
- ≤ 1 TeV/c and $\eta \leq 4.0$

$\delta p_T/p_T = 20\%$ for 10 TeV/c in the central region
Momentum resolution dominated by **multiple scattering** up to 250GeV (limit at $\delta p_T/p_T = 0.5\%$)
→ **low material tracker**!!

FCC-hh Calorimetry



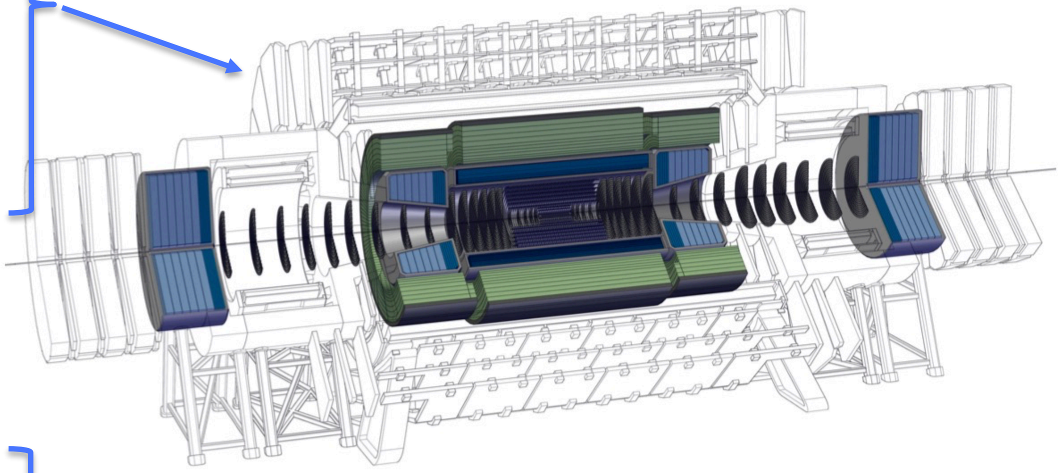
ATLAS LAr+Tile

arXiv:1305.4551

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

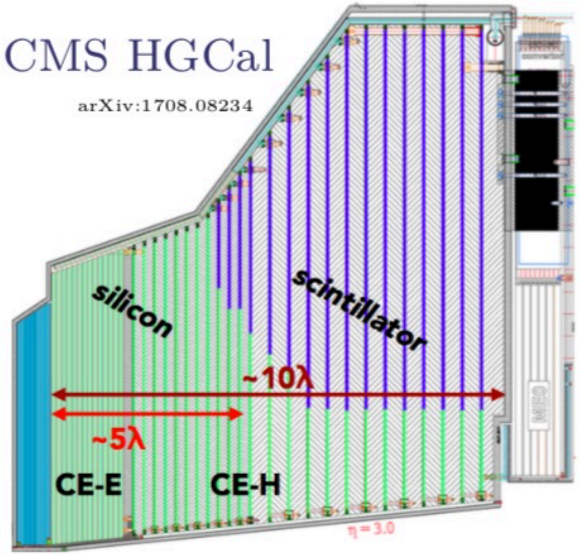
FCC-hh Calorimetry

„conventional calorimetry“
optimized for particle flow



CMS HGCal

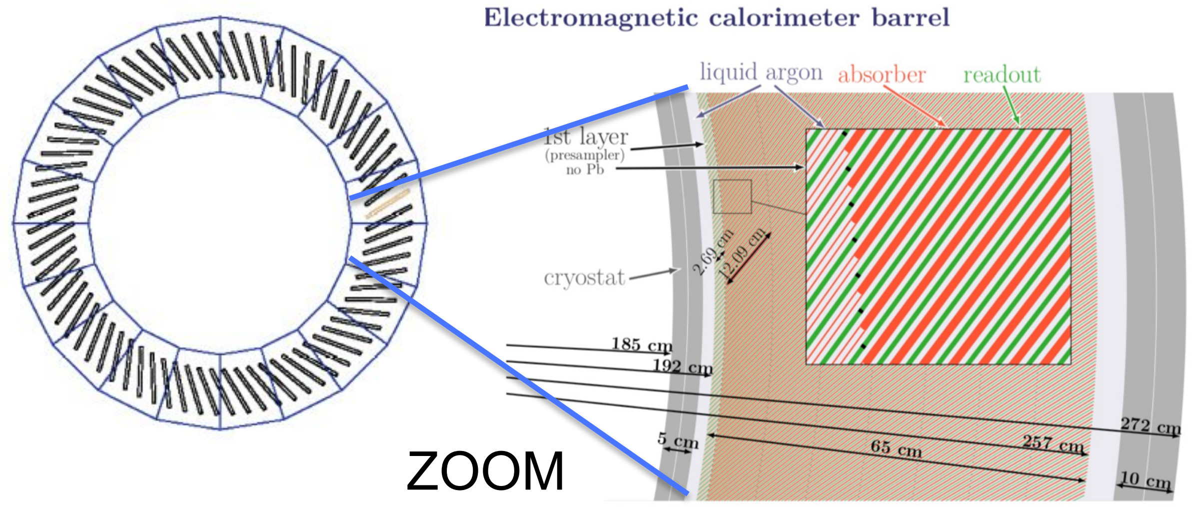
arXiv:1708.08234



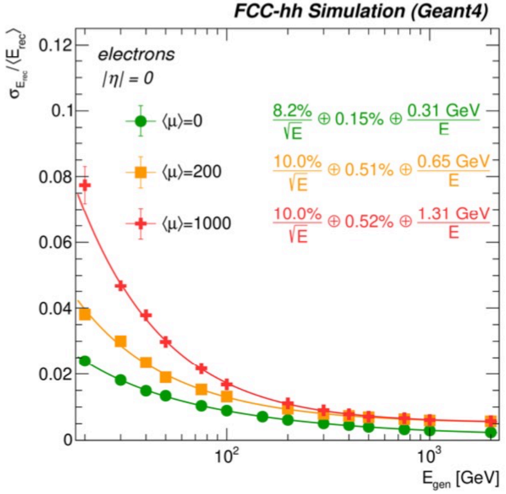
- High granularity
  - ⇒ Pile-up rejection
  - ⇒ Particle flow
  - ⇒ 3D/4D/5D imaging

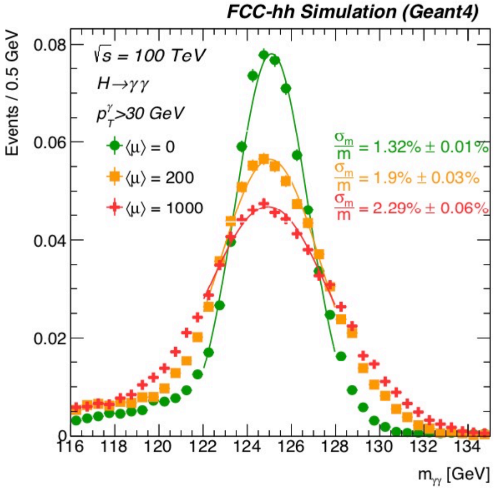
FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

Electromagnetic Calorimeter (ECAL)

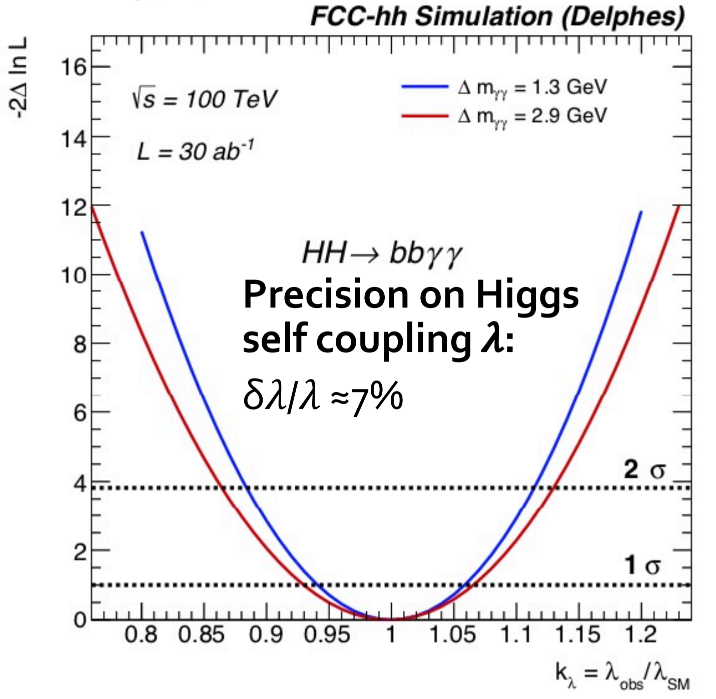


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta$ x $\Delta\phi$ = 0.01 x 0.01, first layer $\Delta\eta$=0.0025),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√Ē, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (no in-time pile-up suppression)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)



Precision on Higgs self coupling λ:

$\delta\lambda/\lambda \approx 7\%$

Hadronic Calorimeter (HCAL)

Barrel HCAL:

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

Combined pion resolution (w/o tracker!):

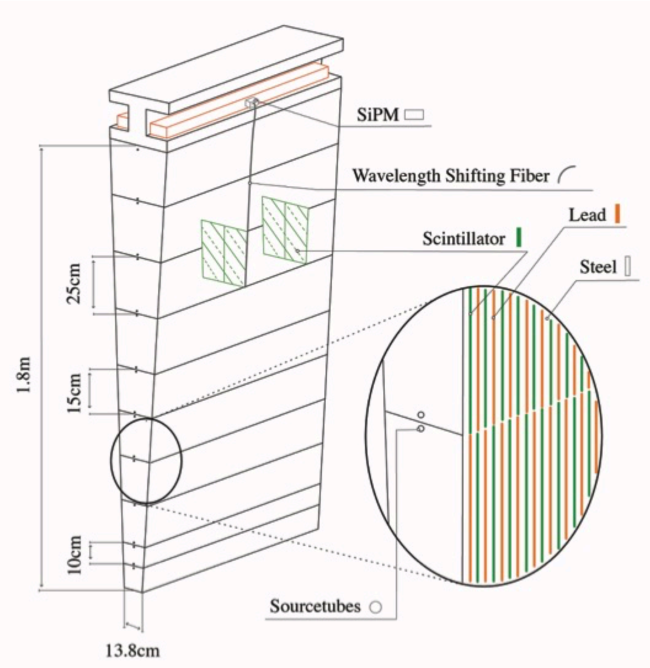
- Simple calibration: 44%/√E to 48%/√E
- Calibration using neural network (calo only):
  - Sampling term of 37%/√E

Jet resolution:

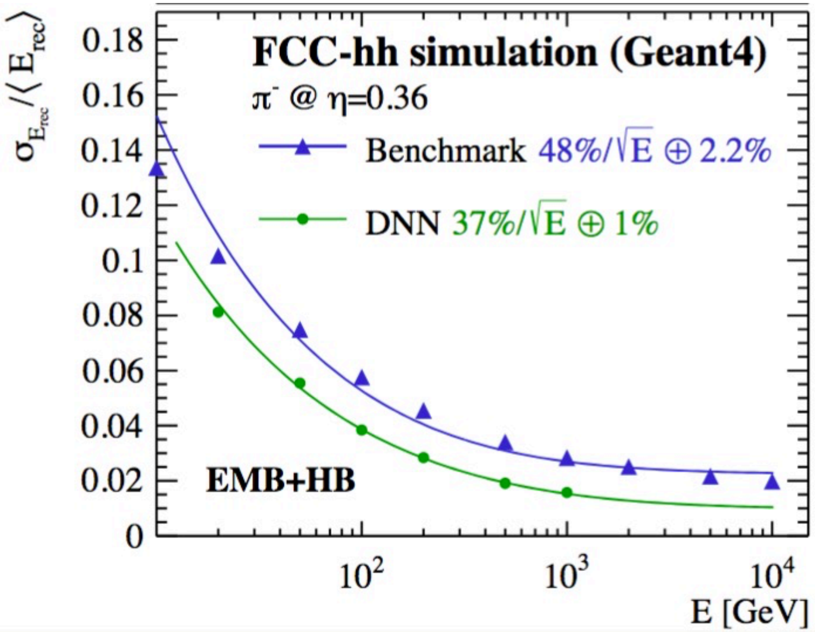
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

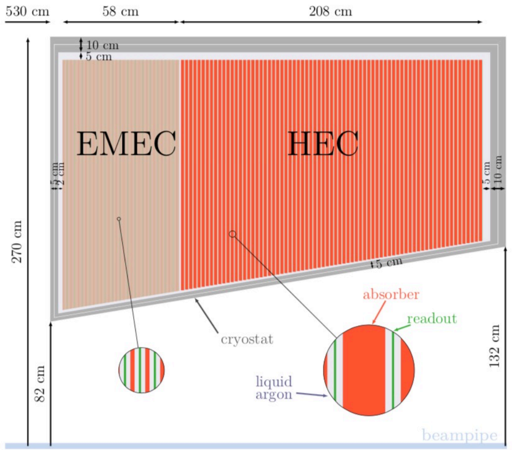
Endcap HCAL and forward calorimeter:

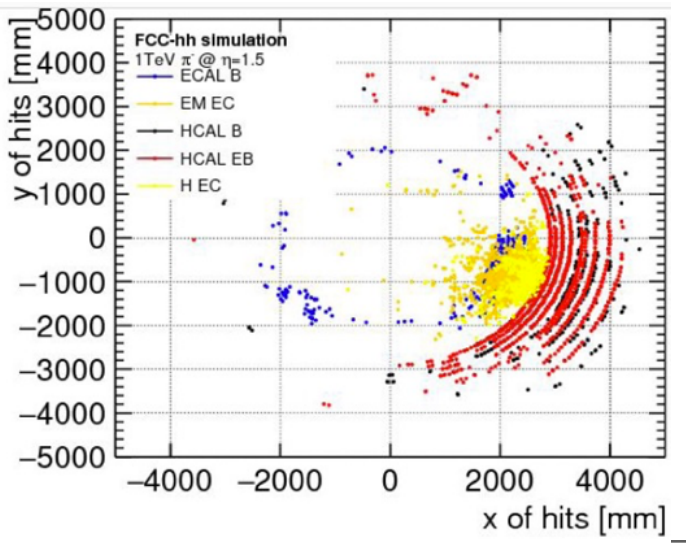
- Radiation hardness!
- LAr/Cu, LAr/W



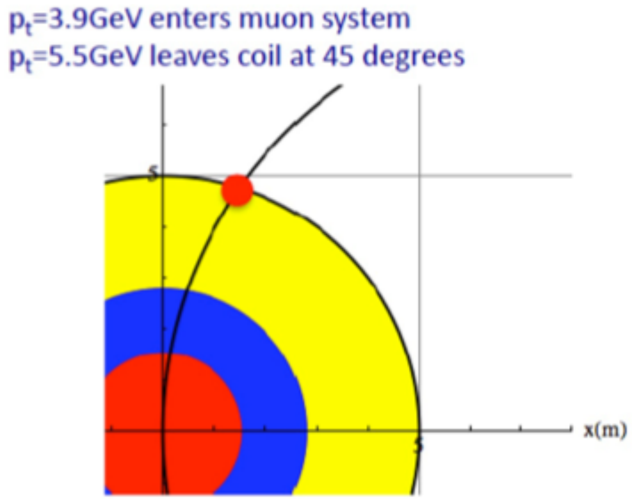
TileCal: e/h ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)

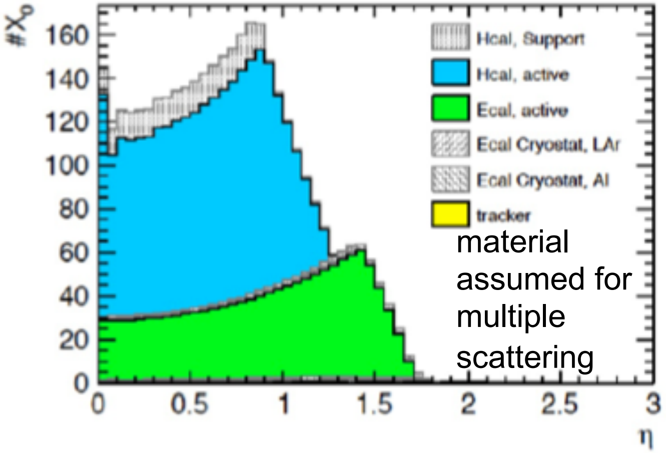


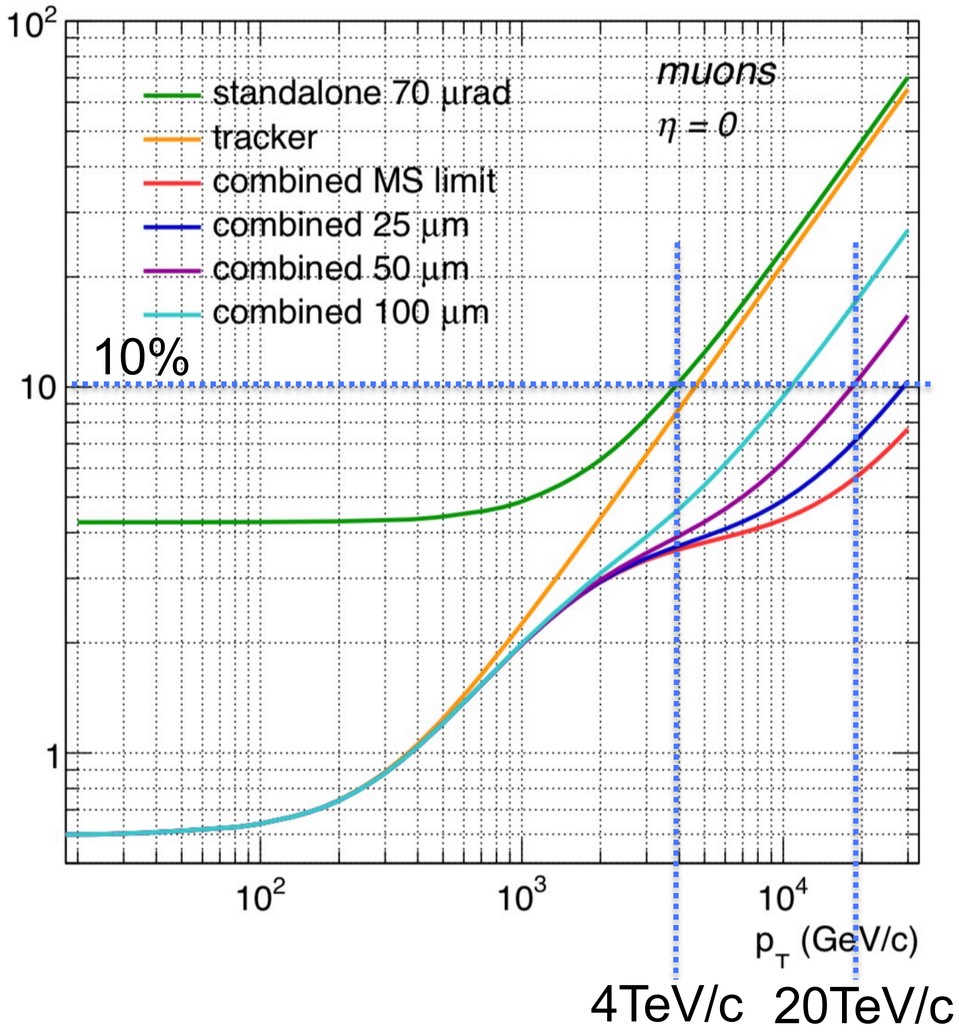




FCC-hh Muon System





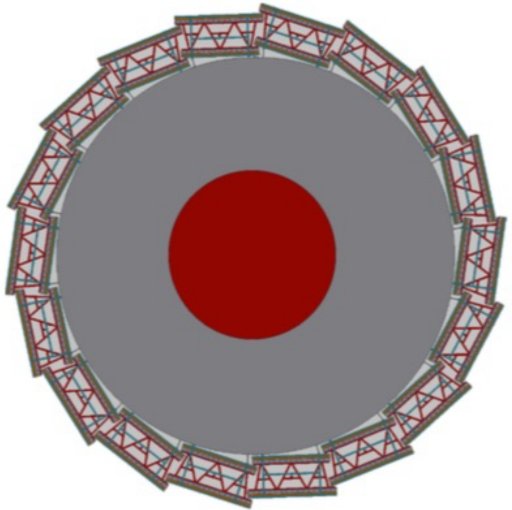


With 50μm position resolution and 70μrad angular resolution we find (η=0):

- ≤10% standalone momentum resolution up to 4TeV/c
- ≤10% combined momentum resolution up to 20TeV/c

Standalone muon performance not relevant, the task of muon system is **triggering and muon identification!**

Muon rate dominated by c and b decays → isolation is crucial for triggering W, Z, t!



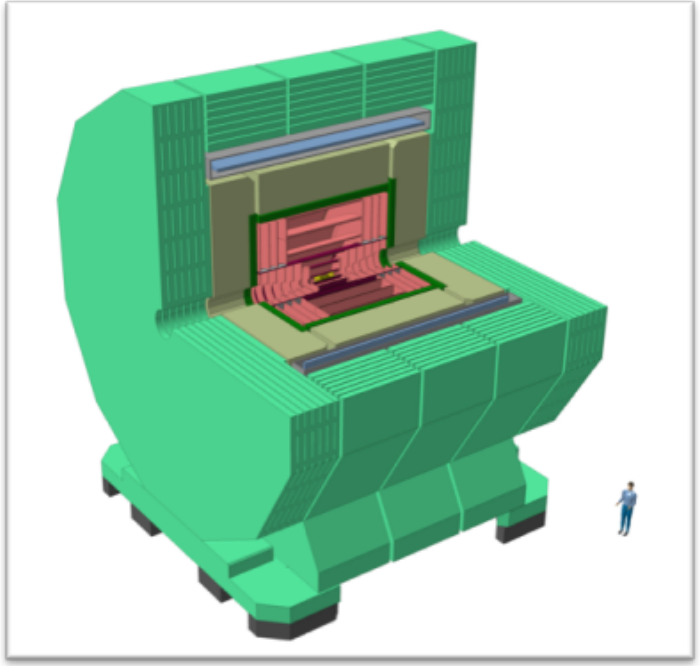
Muon barrel: Rates of up to ~500Hz/cm^2 expected

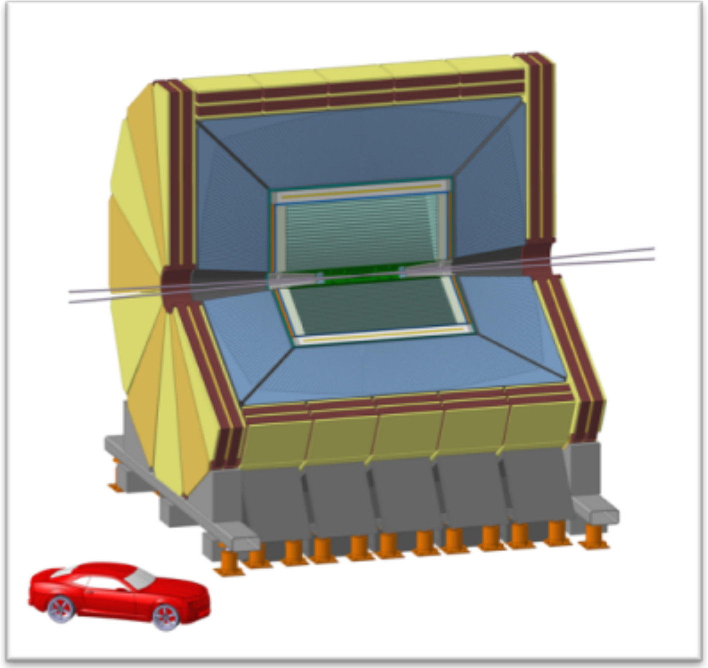
Muon detection in forward region:

Excpected rates up to 500kHz for r > 1m

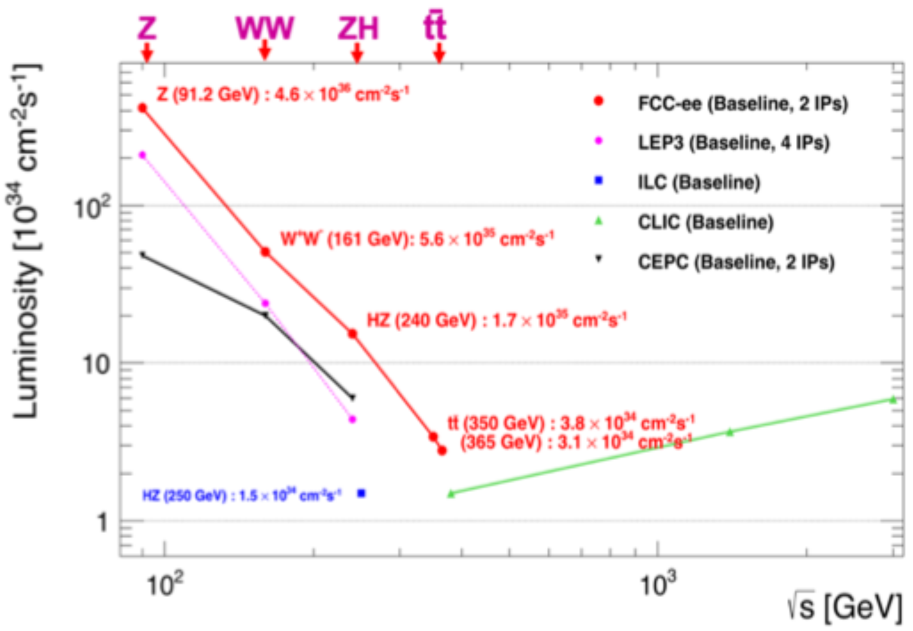
→ HL-LHC muon system gas detector technology will work for most of the FCC detector area

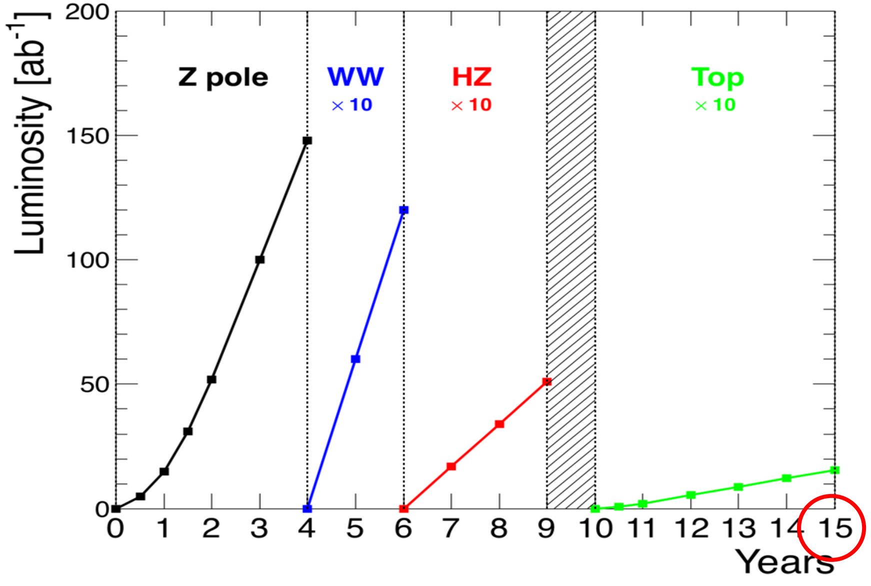
FCC-ee





FCC-ee Luminosity, Operation Model and Conditions





Largest luminosities in the 88 – 365 GeV energy range

Event statistics	√s precision
5×10^{12} $e^+e^- \to Z$	100 keV
10^8 $e^+e^- \to W^+W^-$	300 keV
10^6 $e^+e^- \to HZ$	1 MeV
10^6 $e^+e^- \to tt$	2 MeV

~1 ppm via resonant depolarisation

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	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

- Statistics
  - Very high, 70 kHz of visible Z decays, at Z pole
  - Beam-induced background mild (compared to linear colliders), but not negligible
- Pile-up parameter very small (but not negligible for high precision measts)
  - Aim at 10^{-4} **absolute normalization** from small angle Bhabha scattering
  - Pile-up parameter ~20 times higher at Z-peak

FCC-ee Physics Landscape (ii)

"Higgs Factory" Programme

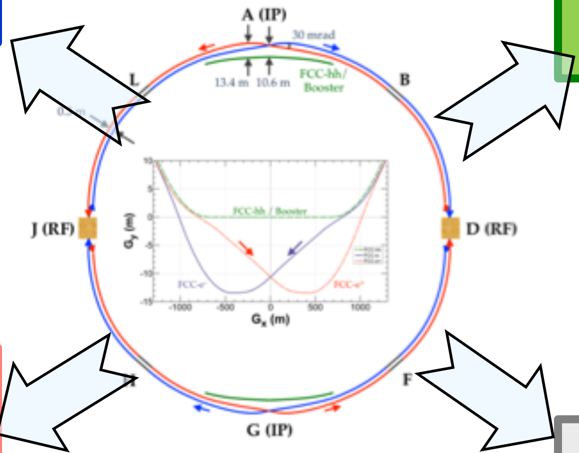
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme

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

- $5\text{x}10^{12}$ 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

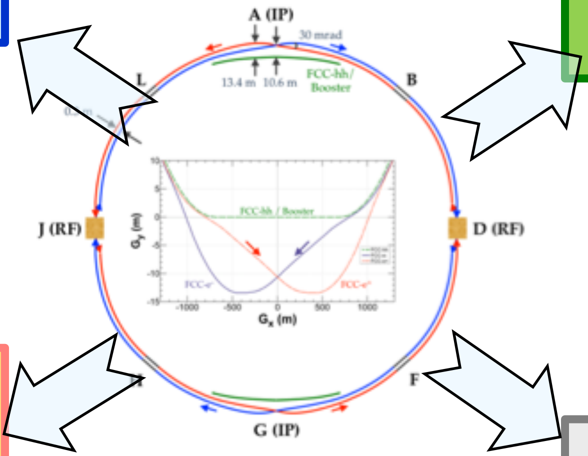
Detector Requirements in Brief

”Higgs Factory” Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/$\sqrt{E}$ 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 $\sqrt{s}$ meast.



Heavy Flavour Programme

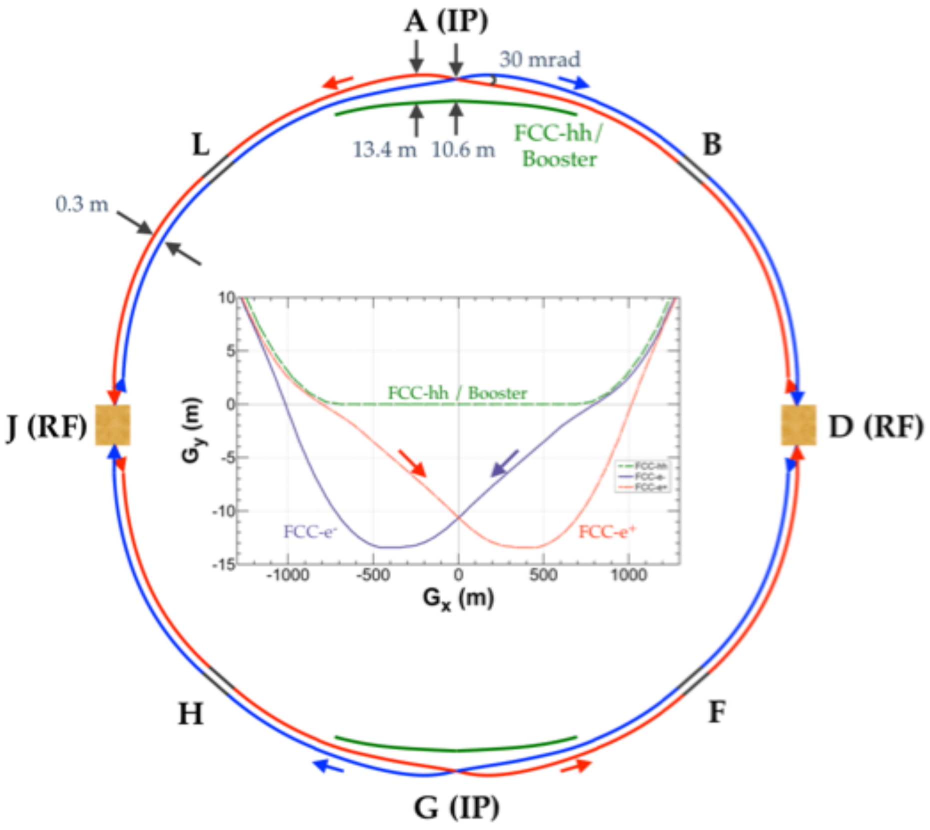
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ $\sqrt{E}$ level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range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

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

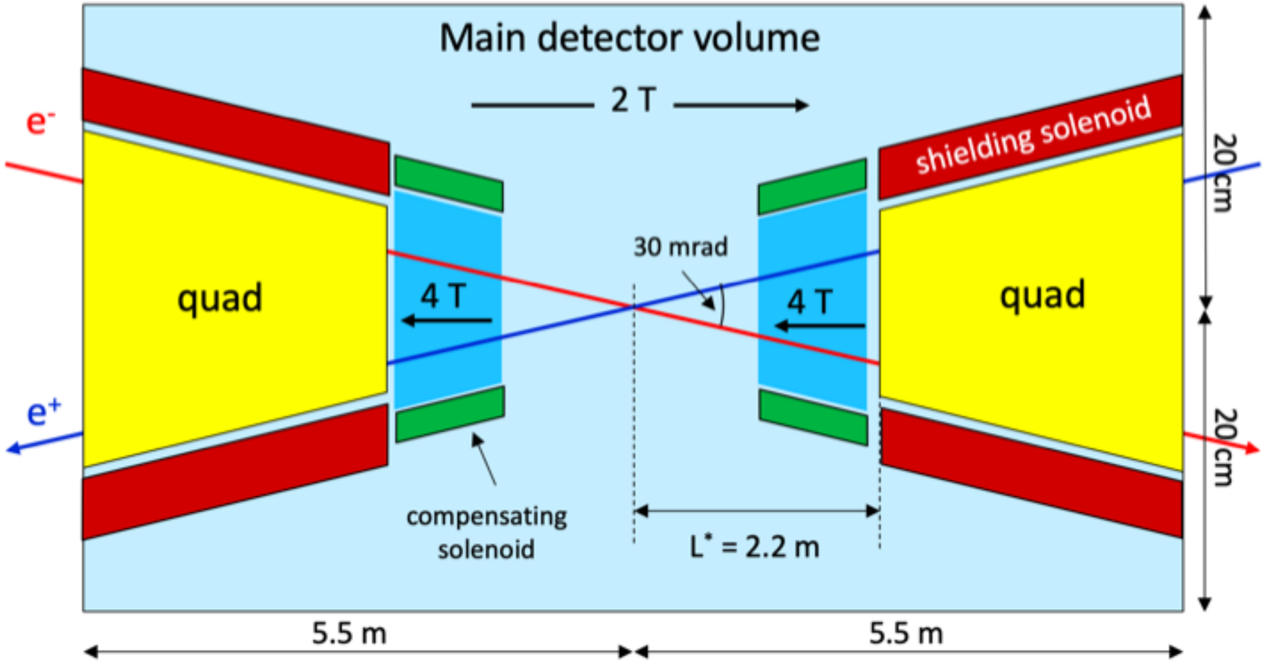
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

FCC-ee Machine Detector Interface



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

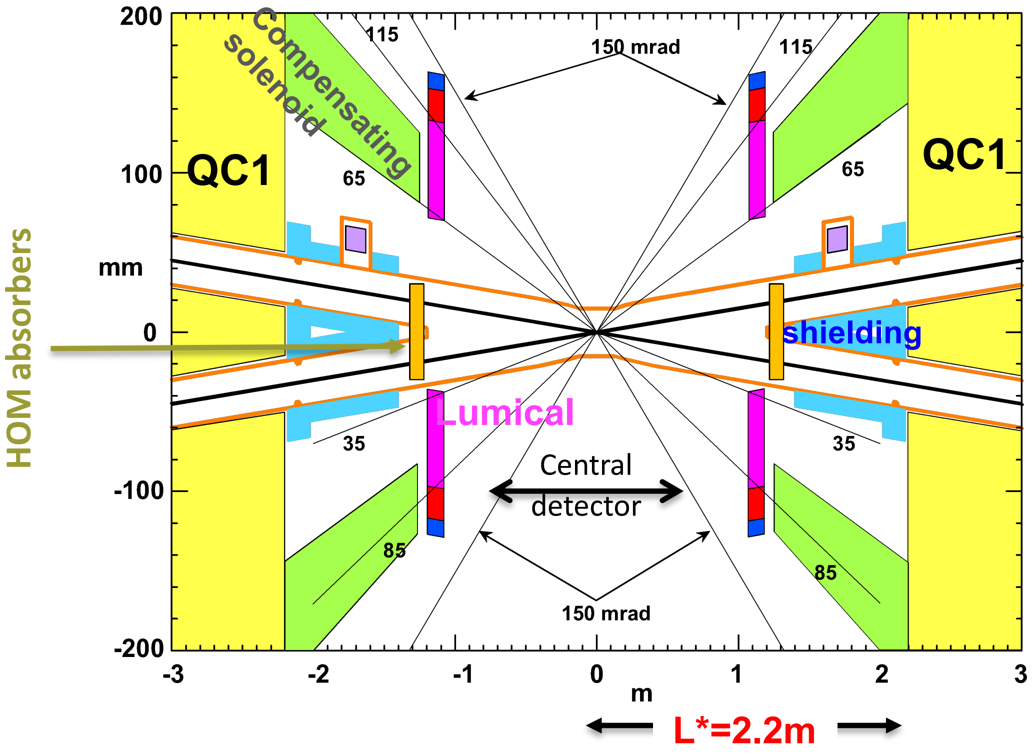
Central part of detector volume – top view



- 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 ε_y blow-up
  - Limits detector field to B = 2 Tesla

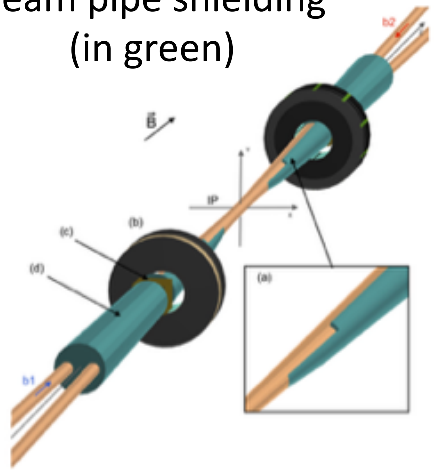
FCC-ee Interaction Region Layout

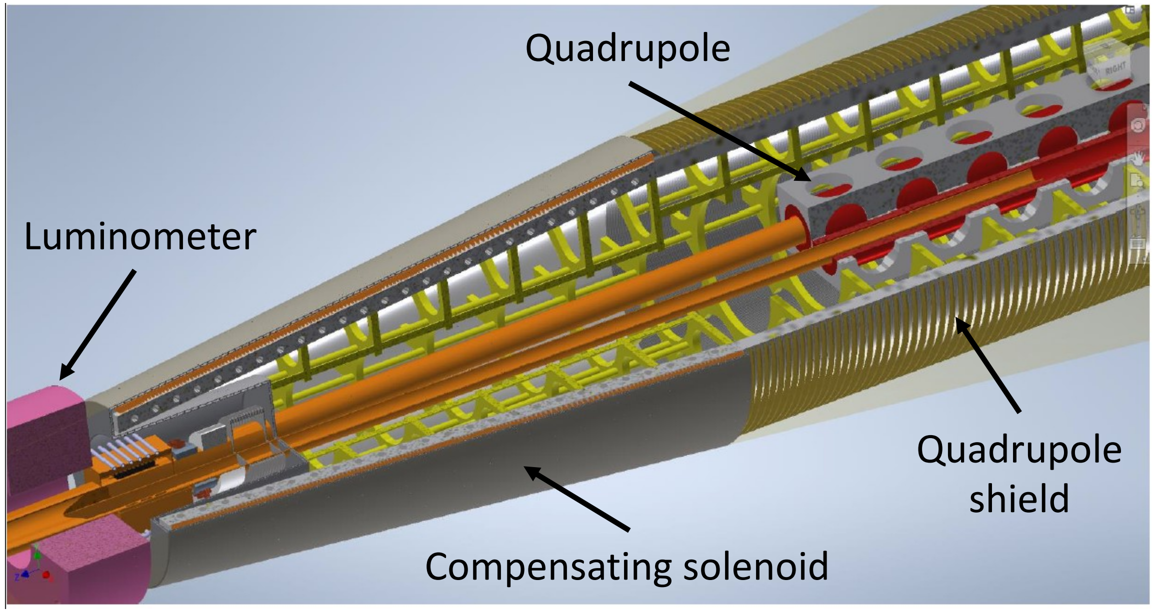
2D-top view with expanded x-coordinate



- Unique and flexible design at all energies
  - Acceptance: 100 (150) mrad
  - Quadrupole shielding
  - Solenoid compensation scheme
  - Beam pipe
    - Warm, liquid cooled
    - Be in central region, then Cu
    - R = 15 mm in central region
      - investigating 10 mm
    - SR masks, W shielding

Beam pipe shielding
(in green)

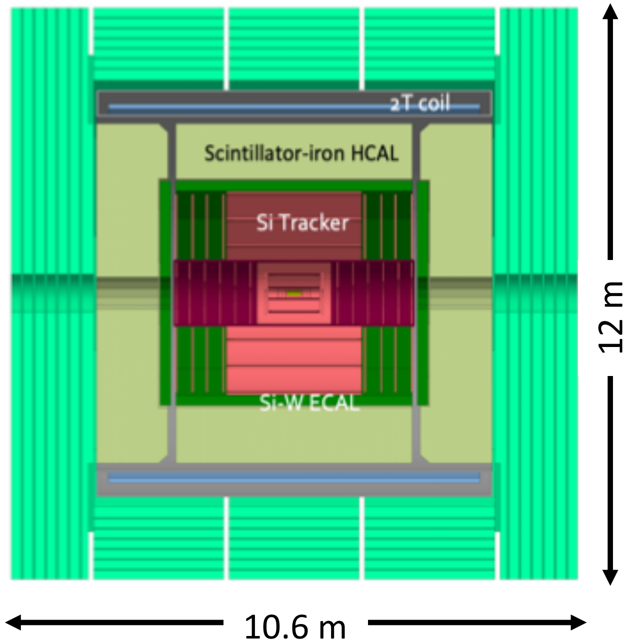




CDR: Two Complementary FCC-ee Detector Concepts

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

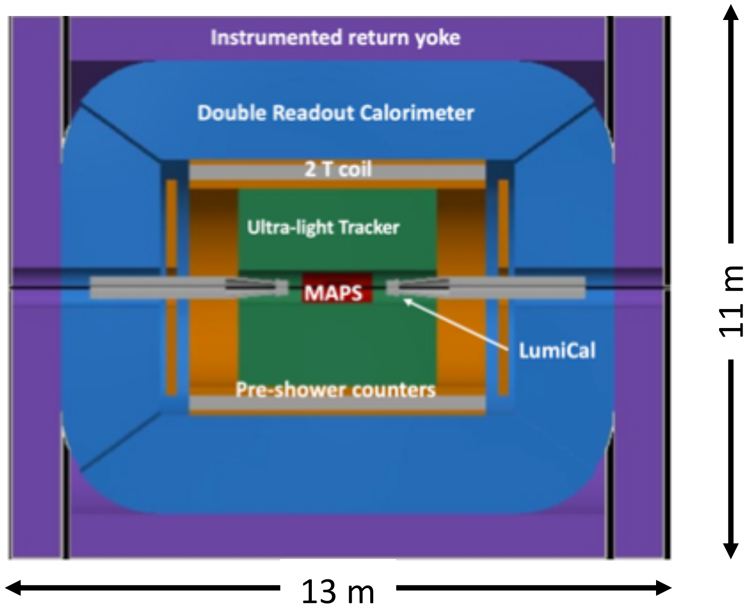
CLD



- Based on CLIC detector design; profits from technology developments carried out for LCs
  - ❑ 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

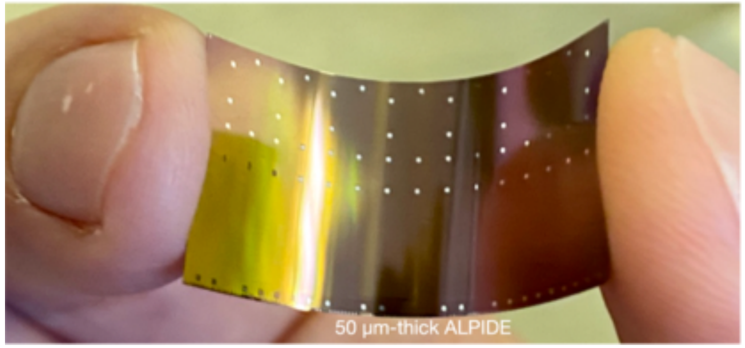


- New, innovative, possibly more cost-effective concept
  - ❑ Silicon vertex detector
  - ❑ Short-drift, ultra-light wire chamber
  - ❑ Dual-readout calorimeter
  - ❑ Thin and light solenoid coil *inside* calorimeter system

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

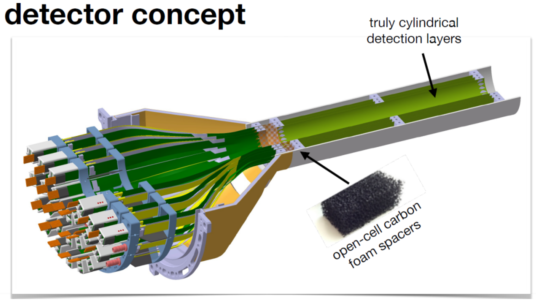
FCC-ee Vertex Detector

- Beam pipe radius:
  - 15 mm base line → 10 mm
- Beam backgrounds are in general negligible, thanks to collimators and effective beam-pipe shielding,
  - Example: max rate of 10^{-5} hits / mm^2 / BX @ $\sqrt{s}$ = 91.2 GeV
- Following ongoing rapid technological development, in particular ALICE ITS
  - Lighter, more precise, closer, less power
  - Cylindrical detection layers situated inside the beampipe



Courtesy of Magnus Mager, CERN

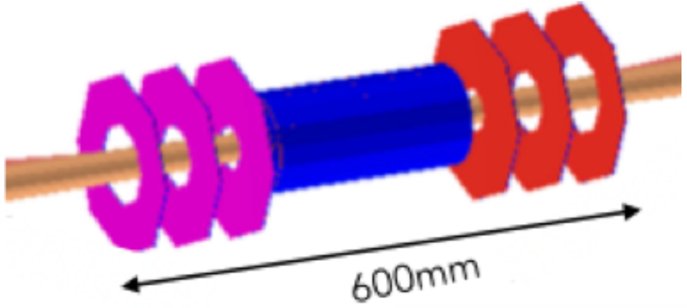
ITS3
detector concept

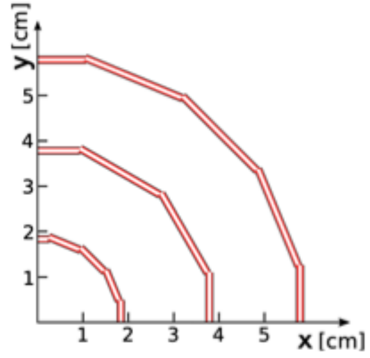


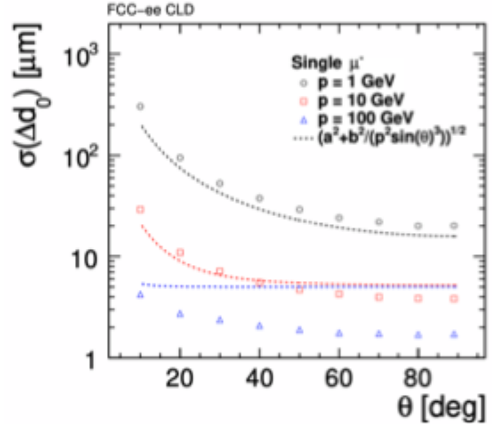
- Extreme alignment-precision needs for life-time measurements
  - Ex.: τ lifetime to $\lesssim 10^{-4}$ relative precision ⇒ $\lesssim$ 0.2 µm on flight distance

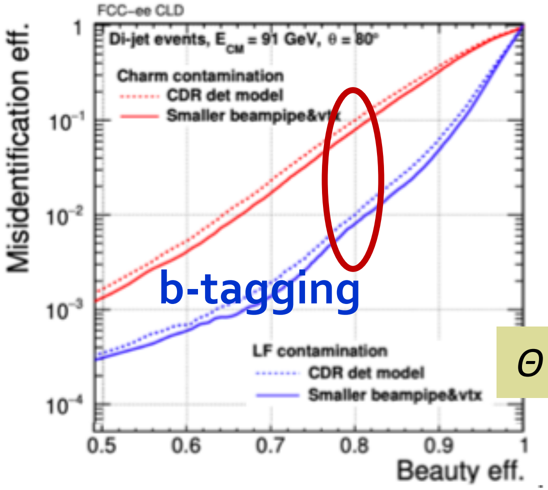
CLD full simulation studies

arXiv:1911.12230

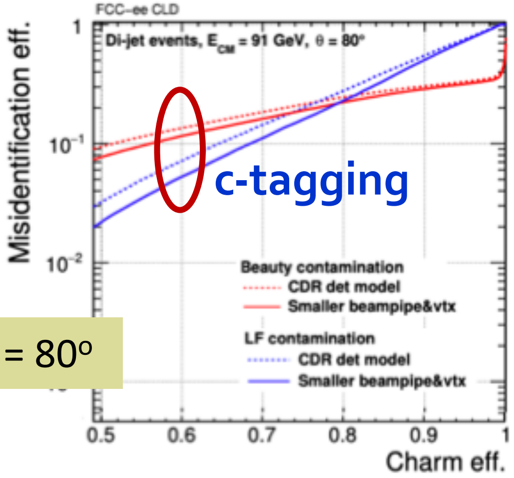








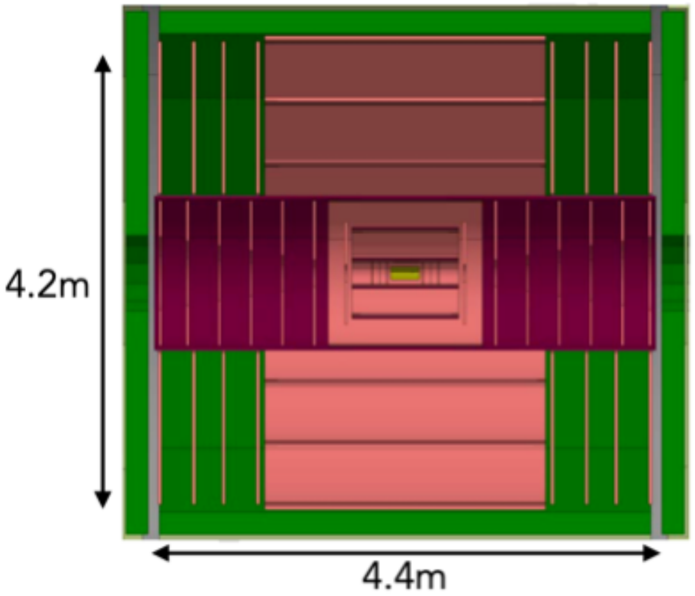
Θ = 80°

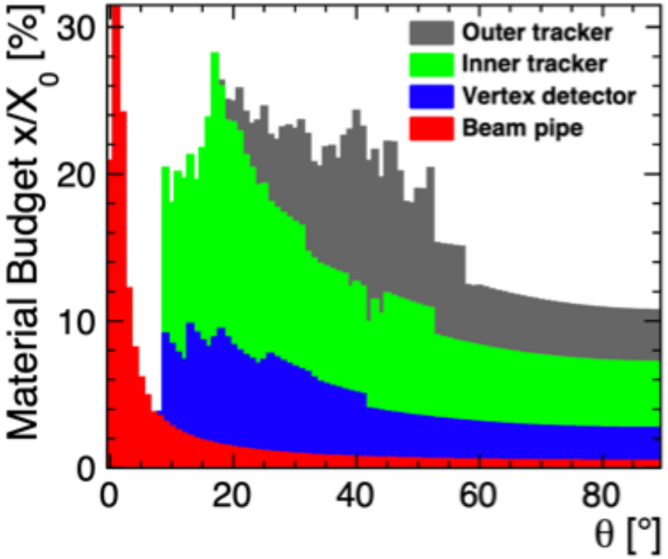


FCC-ee Tracking

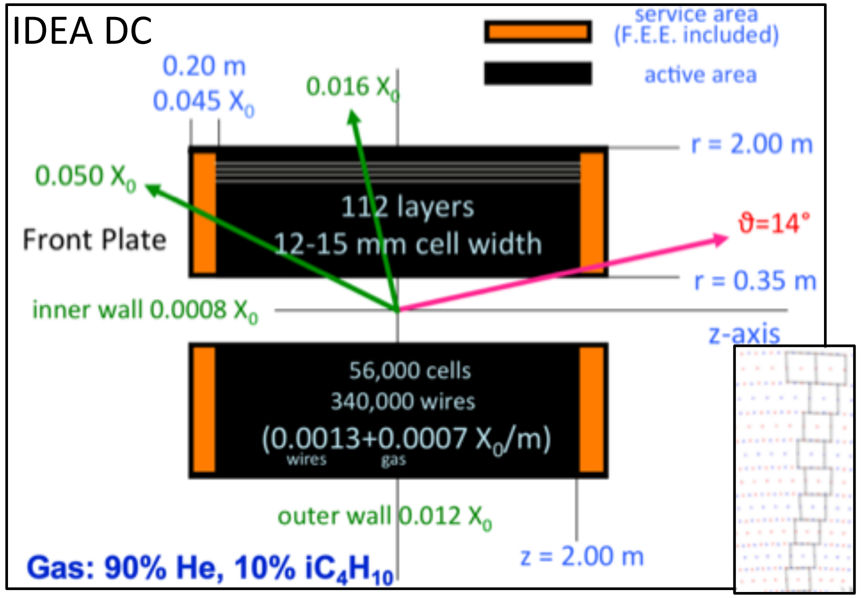
Two solutions under study

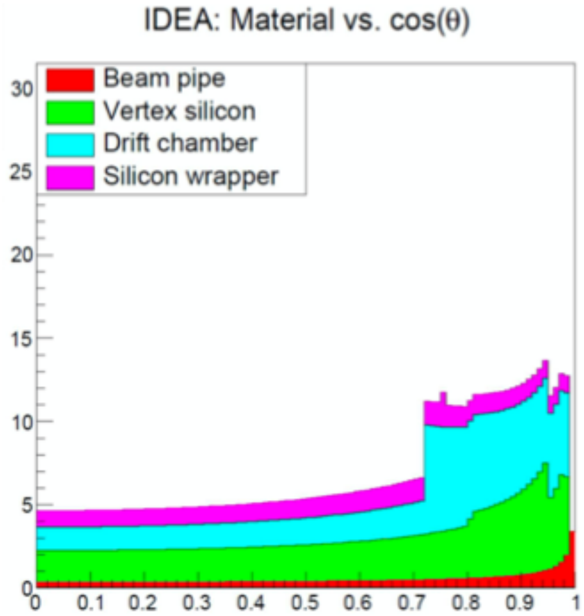
- CLD: All silicon pixel (innermost) + strips
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube (2.5% X_0)





- 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"





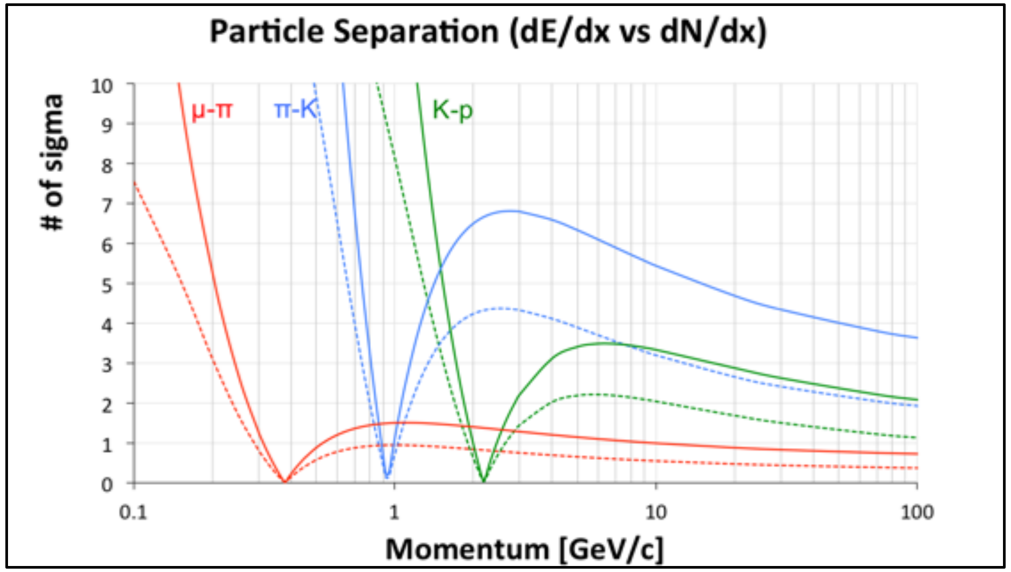
What about a TPC?

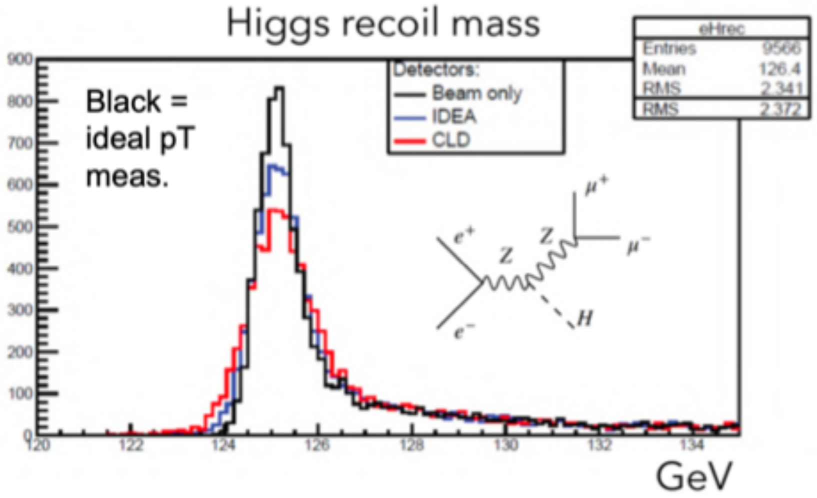
- Very high physics rate (70 kHz)
- B field limited to 2 Tesla
- Considered for CEPC, but having difficulties…

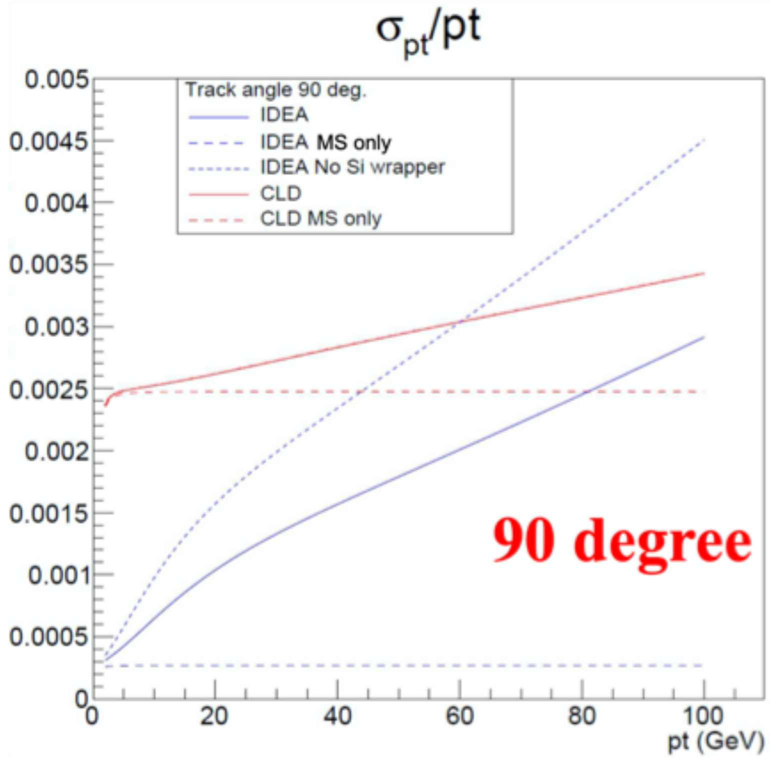
Drift Chamber

- 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







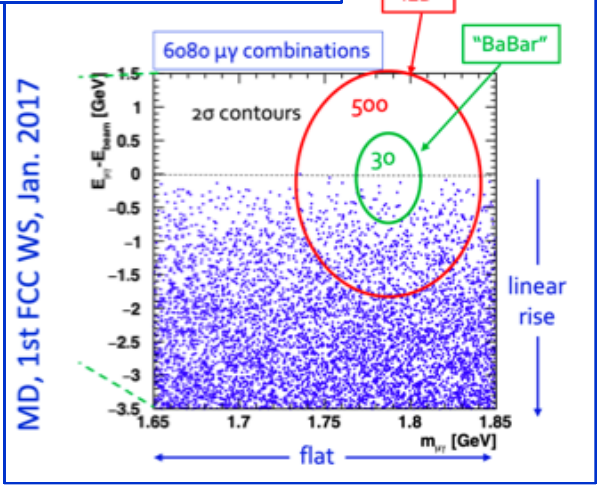
FCC-ee Calorimetry

- Several technologies being considered

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

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

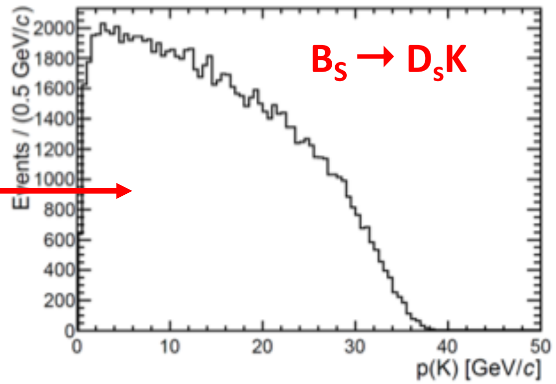
Example: τ →μγ search



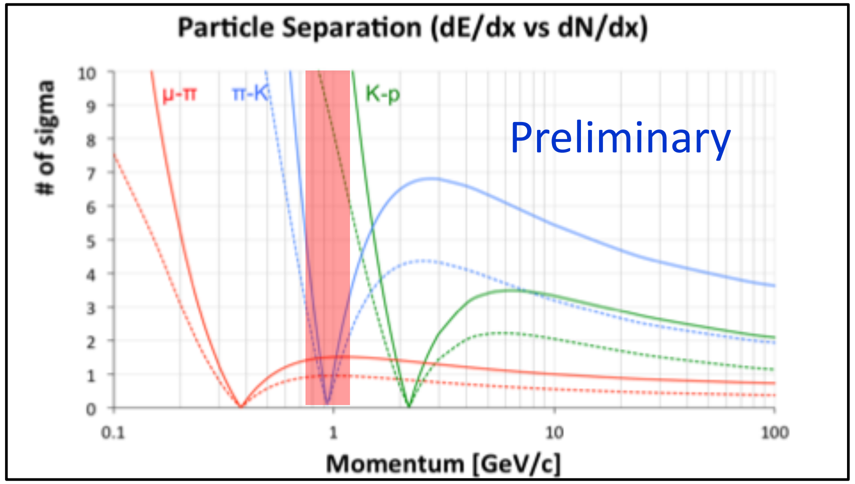
FCC-ee Particle Identification

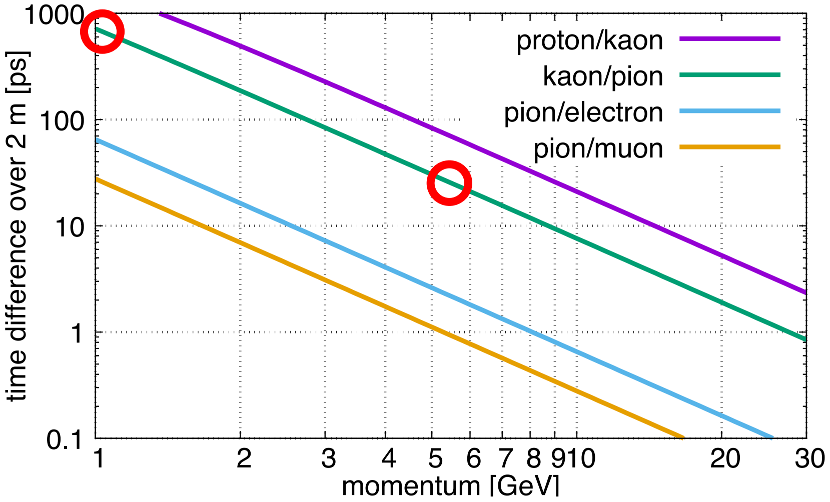
PID capabilities across a wide momentum range is essential for flavour studies and will enhance overall physics reach

- ❑ 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 $B^0_s \to D^\pm_s \pi^\mp$

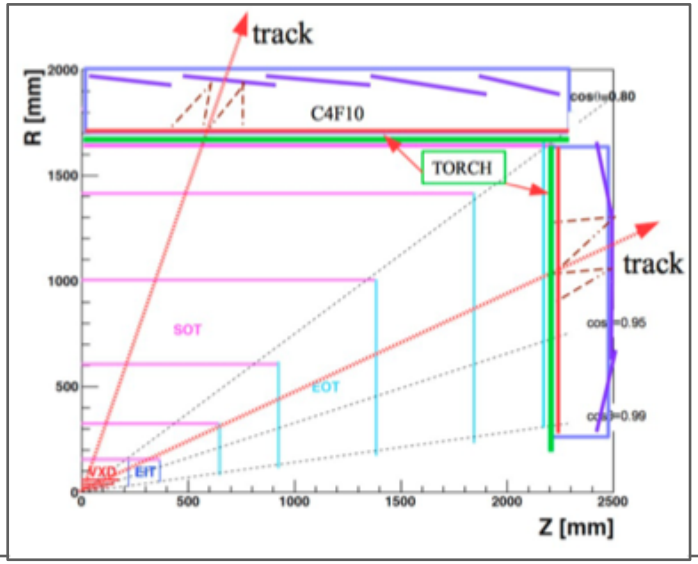


- ◆ IDEA drift chamber promises >3σ π/K separation all the way up to 100 GeV
  - ❑ Experimental validation needed of dN/dx method in relativistic rise region
  - ❑ Cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of δT ≲ 0.5 ns
- ◆ TOF *alone* δT of ∼10 ps over 2 m (LGAD, 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





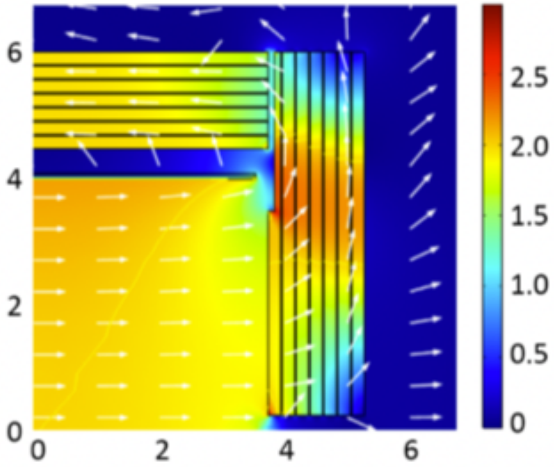
CEPC detector study



FCC-ee 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

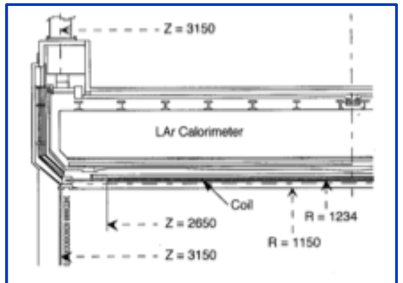
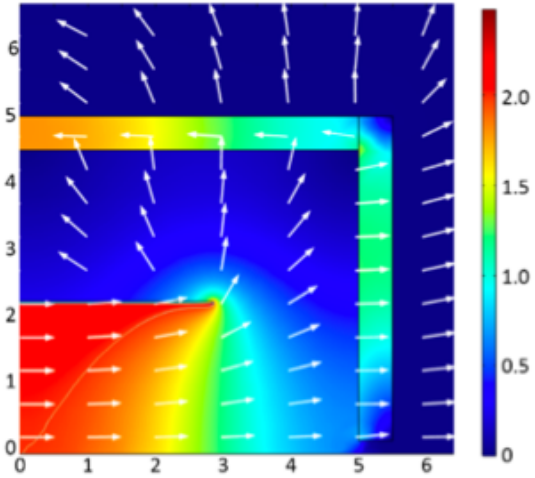


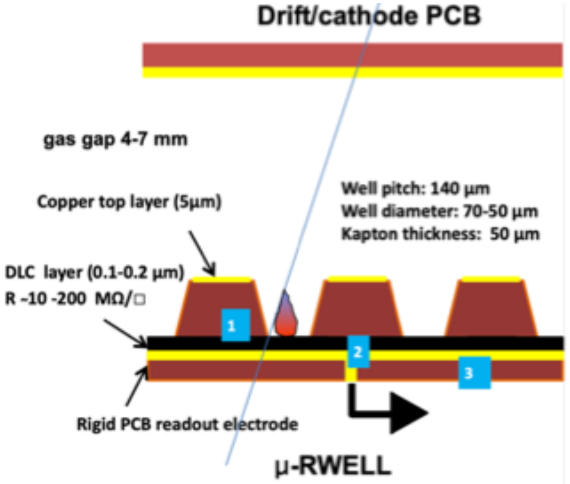
Fig. 2. Cross section of the coil, LAr calorimeter, and the common cryostat.

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)



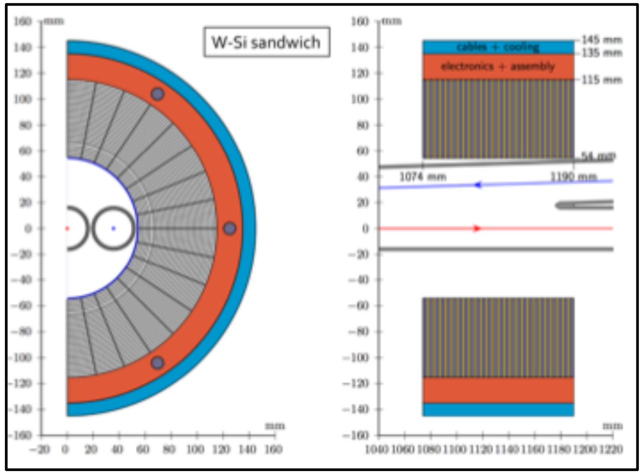
G. Bencivenni et al., 2015_JINST_10_P02008

FCC-ee 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

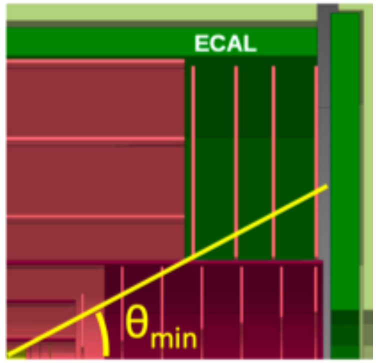
Complementary lumi process: large angle $e^+e^- \rightarrow \gamma\gamma$

- ❑ $10^{-4} \Rightarrow$ 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



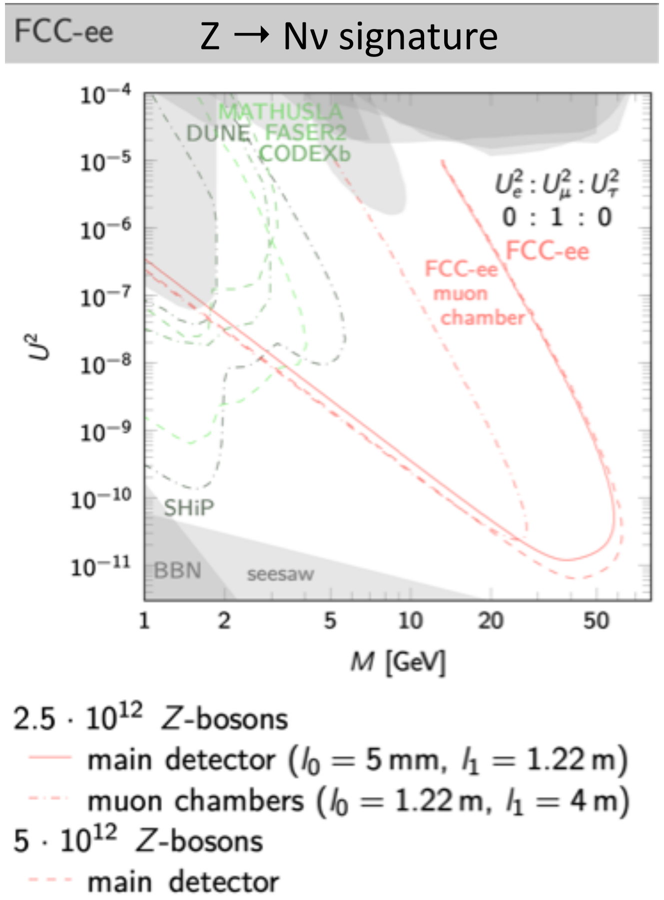
FCC-ee Readout, DAQ, Data Handling

- In particular at Z-peak, challenging conditions
  - 50 MHz BX rate
  - 70 kHz Z rate + ~100 kHz LumiCal rate
  - Absolute normalisation goal 10^{-4}
- 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: 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

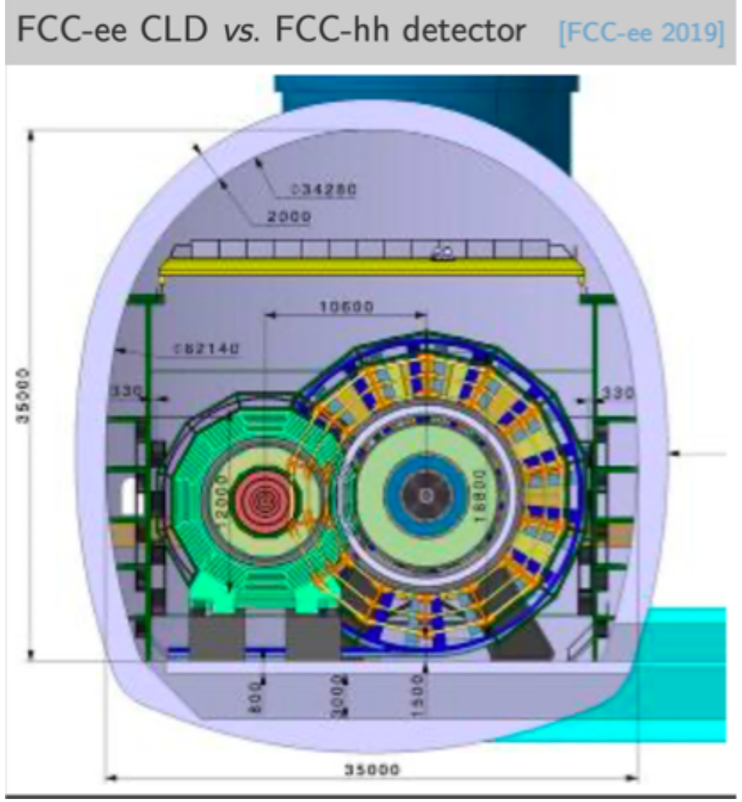
-LHCb DAQ upgrade
-Detectors at EIC

FCC-ee Possibility: Very Large Tracking Volume for LLPs

FCC-ee ”standard” detector

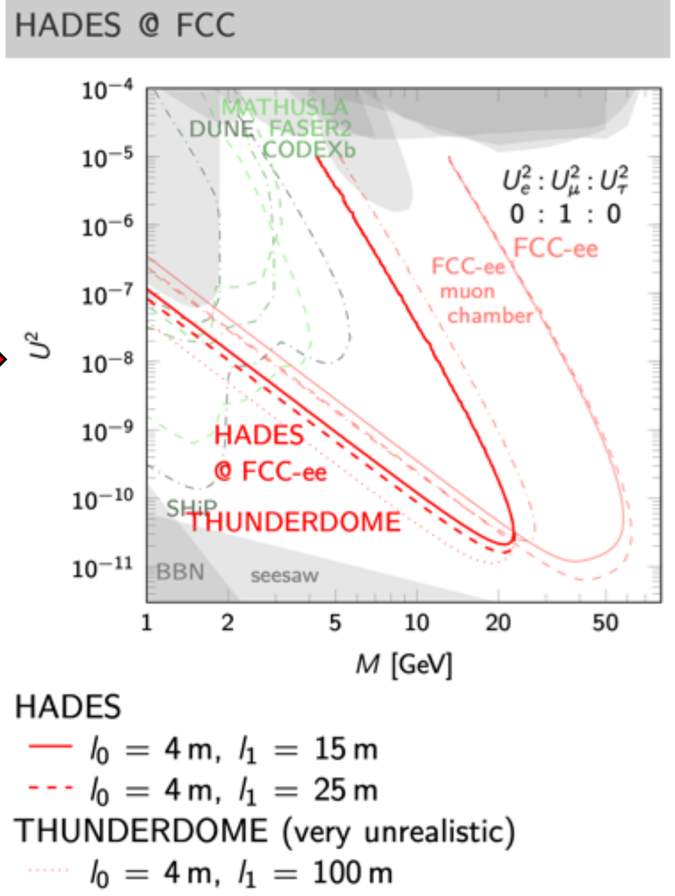


Instrument cavern as huge decay volume



Scintillators
RPCs
…

Half a magnitude sensitivity gain in U^2

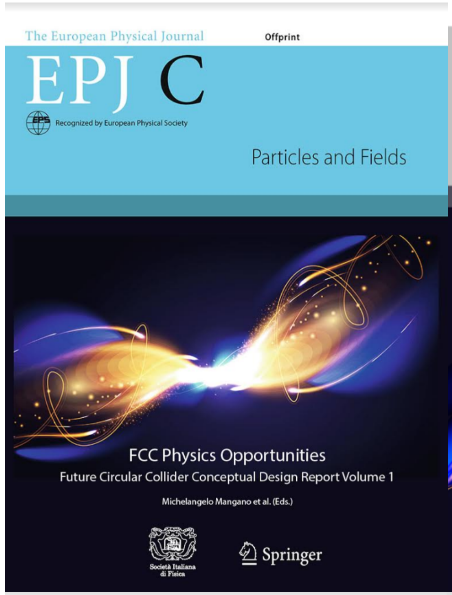


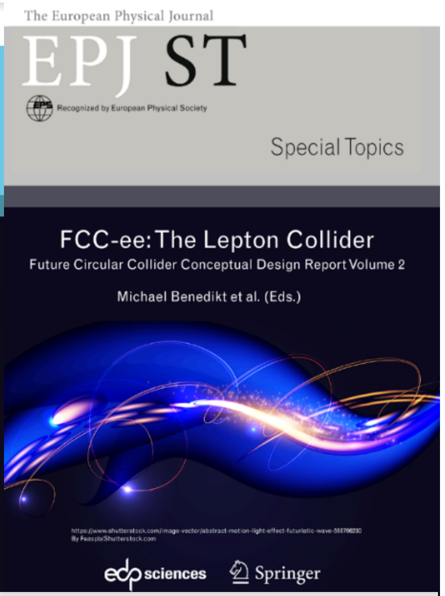
J. Hajer,
4th FCC Physics and Experiments workshop, Nov. 2020

Outlook

- Work presented above is largely based on FCC CDR
- For next Stragety Update, aim at submitting a ”CDR+” for FCC-ee Detector Design
  - ❑ Accelerator and infrastructure will submit TDR
- Currently in the process of finalising/refining *physics requirements* taking into account the wide FCC-ee physics programme
  - ❑ Higgs, precision EW, top, high statistics flavour physics, feebly interacting particle searches, …
- Develop detector concepts and demonstrate that these are compatible with physics requirements
  - ❑ May see development of dedicated experiments (a la LHCb)
- Detailed simulation studies of at least one ”strawman” detector concept for defined list of benchmark processes
- A number of proto-collaborations may/will form
  - ❑ submission of Expressions-of-Interest for next Strategy Update

- Exciting research work - Good chance to contribute !


The European Physical Journal
Offprint
EPJ C
Recognized by European Physical Society
Particles and Fields
FCC Physics Opportunities
Future Circular Collider Conceptual Design Report Volume 1
Michelangelo Mangano et al. (Eds.)
Società Italiana di Fisica
Springer


The European Physical Journal
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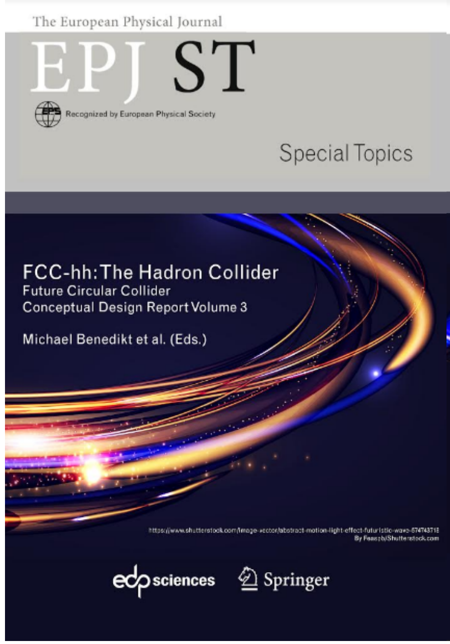
Special Topics
FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
Michael Benedikt et al. (Eds.)
edp sciences
Springer


The European Physical Journal
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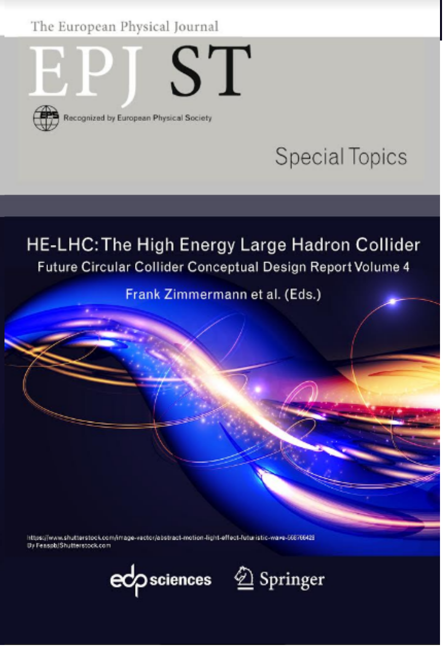
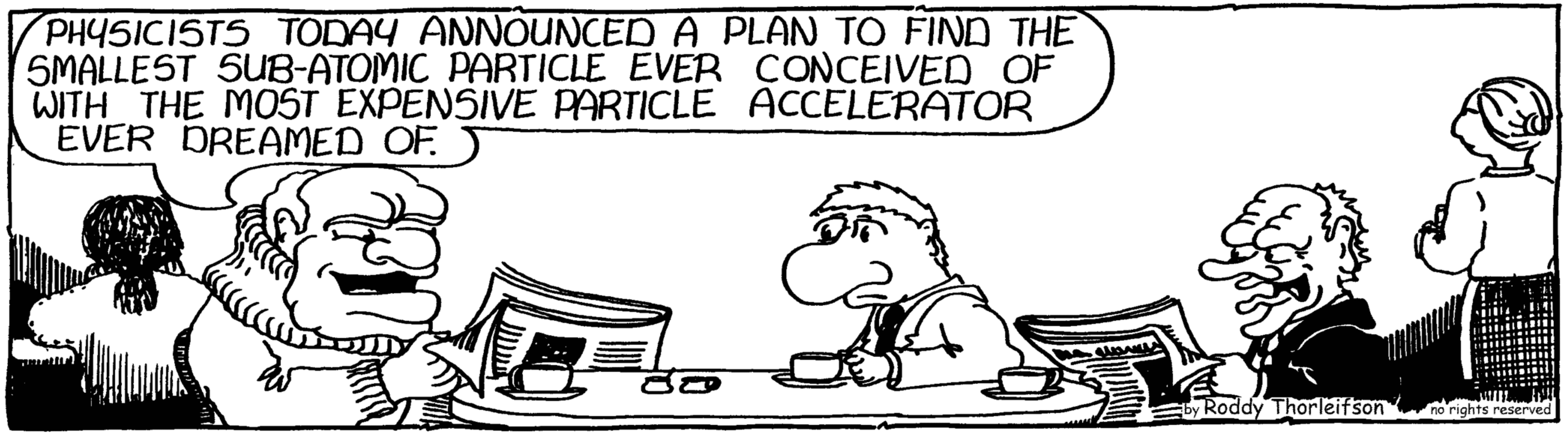
Special Topics
FCC-hh: The Hadron Collider
Future Circular Collider
Conceptual Design Report Volume 3
Michael Benedikt et al. (Eds.)
edp sciences
Springer


The European Physical Journal
EPJ ST
Recognized by European Physical Society
Special Topics
HE-LHC: The High Energy Large Hadron Collider
Future Circular Collider Conceptual Design Report Volume 4
Frank Zimmermann et al. (Eds.)
edp sciences
Springer



"*No doubt that future high energy colliders are extremely challenging projects.*

However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable."

Fabiola Gianotti, DG CERN

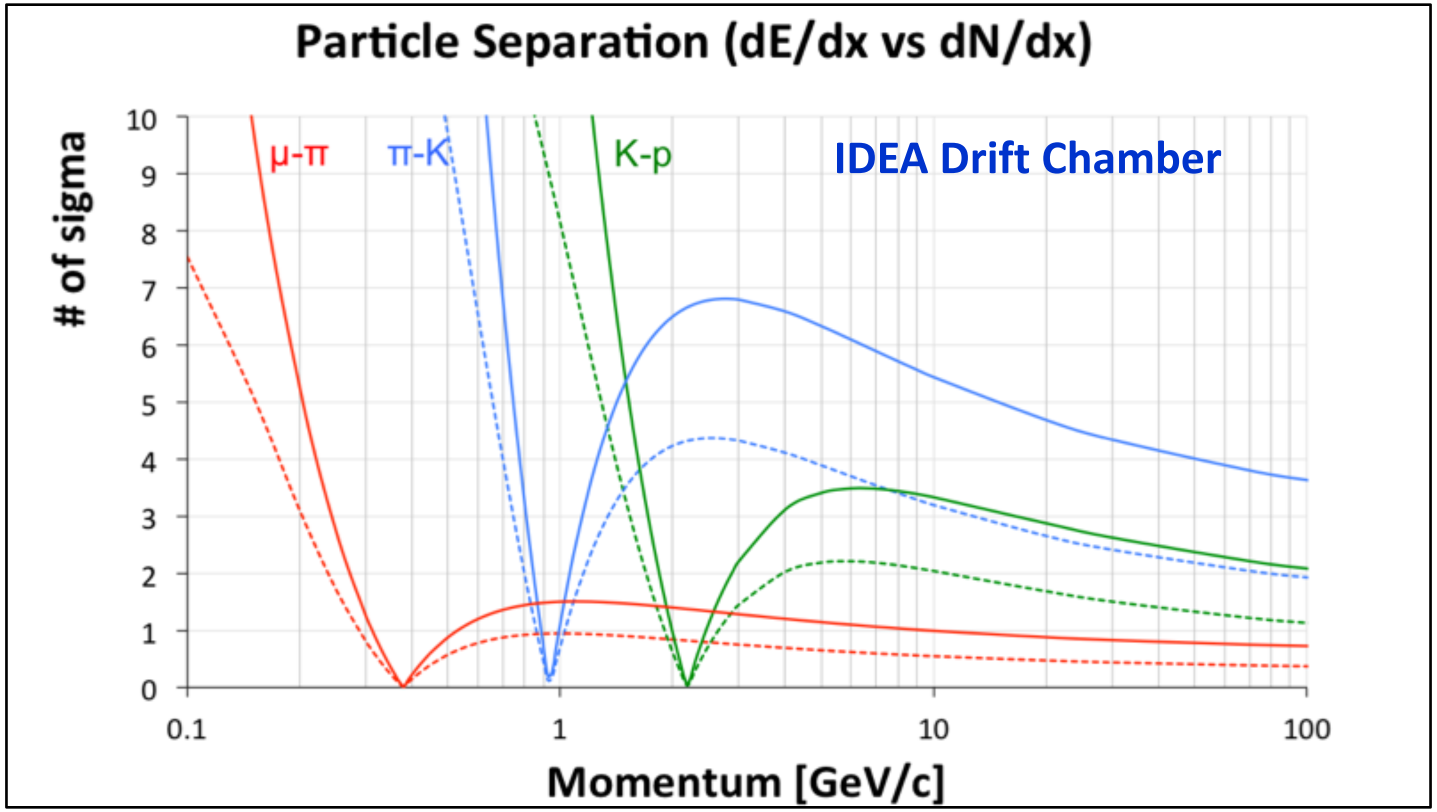
Extra slides

FUTURE CIRCULAR COLLIDER

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)

Epilogue - The Importance of Redundancy



- To beat down uncertainties on ”calorimetric” identifications (e/π, e/μ, π/μ) it is essential to have available a perpendicular, independent, nondestructive identification tool
  - This is exactly what a powerful dE/dx measurement provides you!

Example of precision challenge: Universality of Fermi constant

The Fermi constant is measured in μ decays and defined by

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

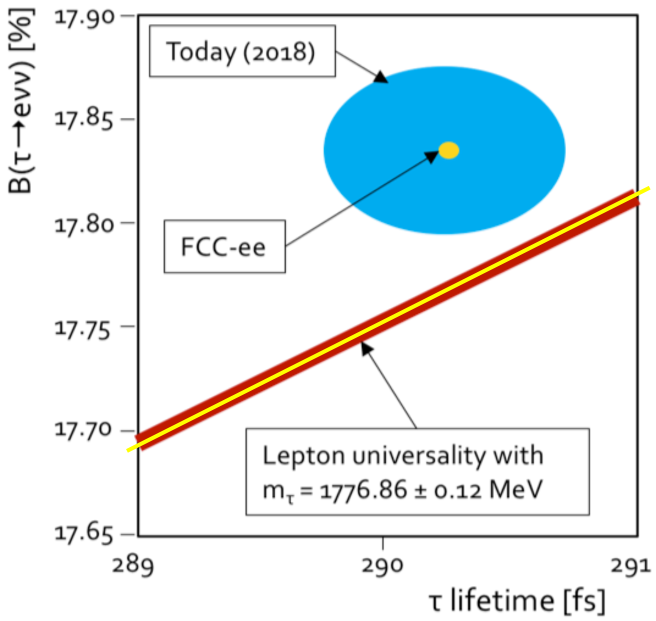
(known to 0.5 ppm)

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

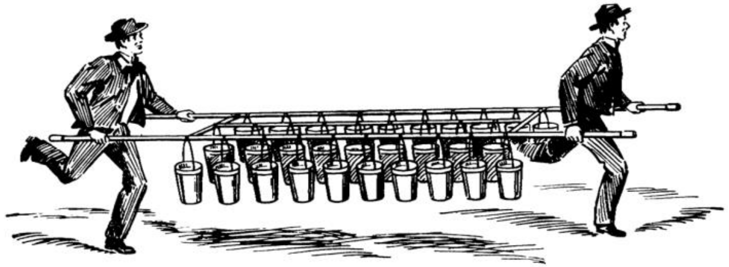
1700 ppm
LEP

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

To trigger or to stream

- Traditional triggered readout:
  - Data is digitized into buffers and a trigger, per event, starts readout
  - Parts of events are transported through the DAQ to an event builder where they are assembled into events
  - At each stage the flow of data is controlled by “back pressure”
  - Data is organized sequentially by event
- Streaming readout:
  - Data is read continuously from all channels
  - Validation checks at source reject noise and suppress empty channels
  - Data flows unimpeded in parallel channels to storage or local compute resource
  - Data flow is controlled at source
  - Data is organized in multiple dimensions by channel and time
  - Requires robust and accurate time stamp generation and distribution
    - Simpler task than an online trigger
- Examples of streaming readout:
  - LHCb DAQ upgrade
  - Detectors at Brookhaven Electron Ion Collider



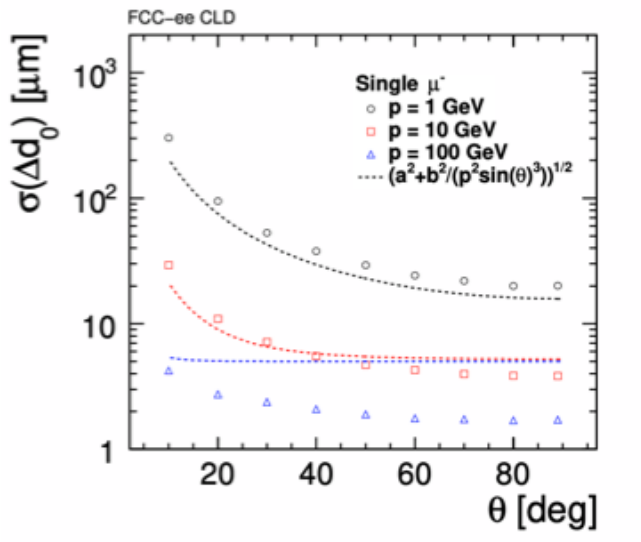
Experimental challenge: impact parameter resolution

Design goal…

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

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

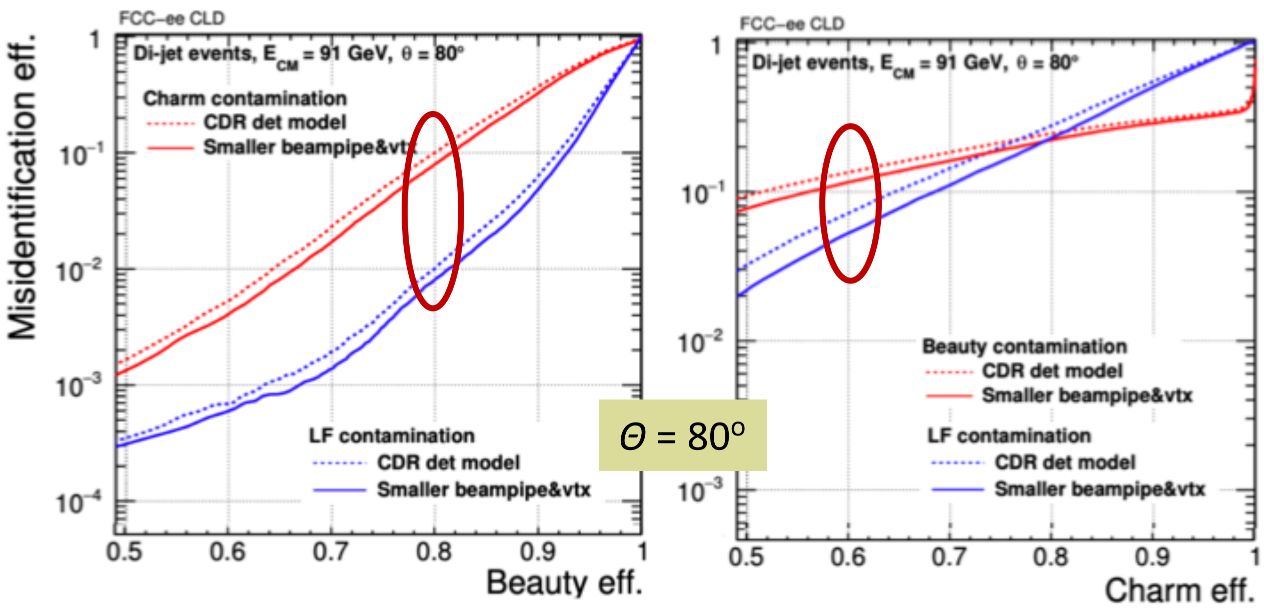
…satisfied in CLD full simulation study



arXiv:1911.12230

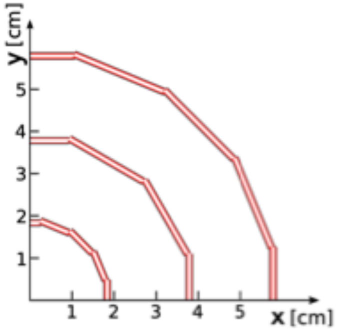
CLD flavour tagging

b-tagging **c-tagging**



Θ = 80°

- ❑ Single point accuracy of 3 μm
- ❑ Three very thin double sensor layers (50 μm Si) at radii 18, 37, 57 mm
  - ❖ 0.6% of X_0 for each double layer
- ❑ Beryllium, water cooled beam pipe at r=15 mm
  - ❖ 0.5% of X_0



Strong development:

- Lighter, more precise, closer
- 10 mm beam pipe under investigation

Accelerator	a (μm)	b ($\mu m \cdot GeV/c$)
LEP	25	70
SLC	8	33
LHC	12	70
RHIC-II	13	19
ILD	< 5	< 10

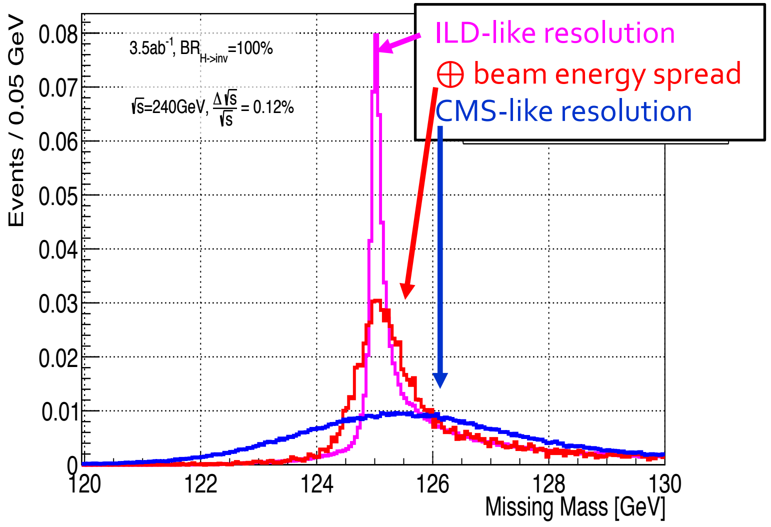
Experimental challenge: Momentum resolution (i)

Often, the "canonical" requirement is expressed as

$$\boxed{\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\ \mathrm{GeV}^{-1}}$$

⇒ Mass reconstruction from lepton pairs in Higgs production

Reconstructed recoil mass in HZ with Z $\rightarrow \ell^+\ell^-$



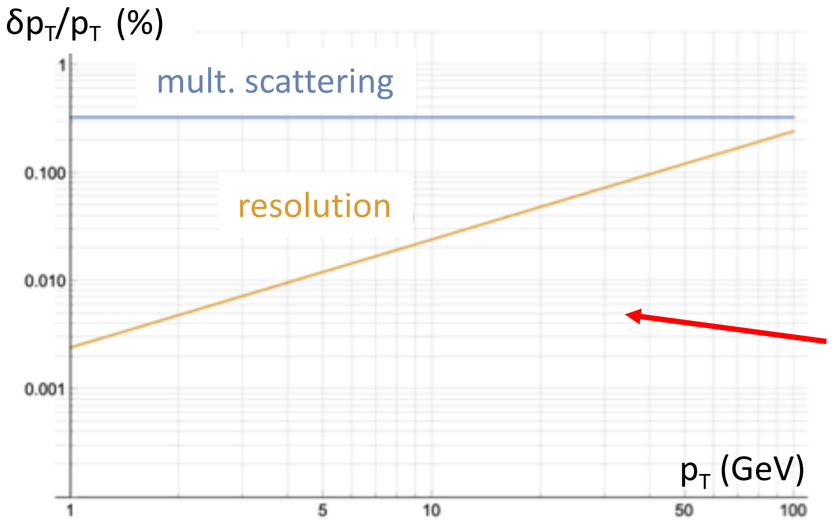
Eur.Phys.J. C77 (2017) no.2, 116

For FCC-ee, this matches well the beam energy spread of $\delta E/E \simeq$ 1-2 × 10^{-3}

In reality, there is of course a resolution term (*a*) and a multiple scattering term (*b*)

$$\boxed{\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = a \oplus \frac{b}{p\sin\theta}}$$

For "standard" ultra-light detectors (e.g. full Si), multiple scattering dominates up to p_T of ~100 GeV



Here illustrated for the CLD detector at 90° : Total material budget = 11% of X_0

From analytic expressions for track parameter resolutions.

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

$$\frac{\Delta p_T}{p_T}\bigg|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

$$\frac{\Delta p_T}{p_T}\bigg|_{res.} \approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

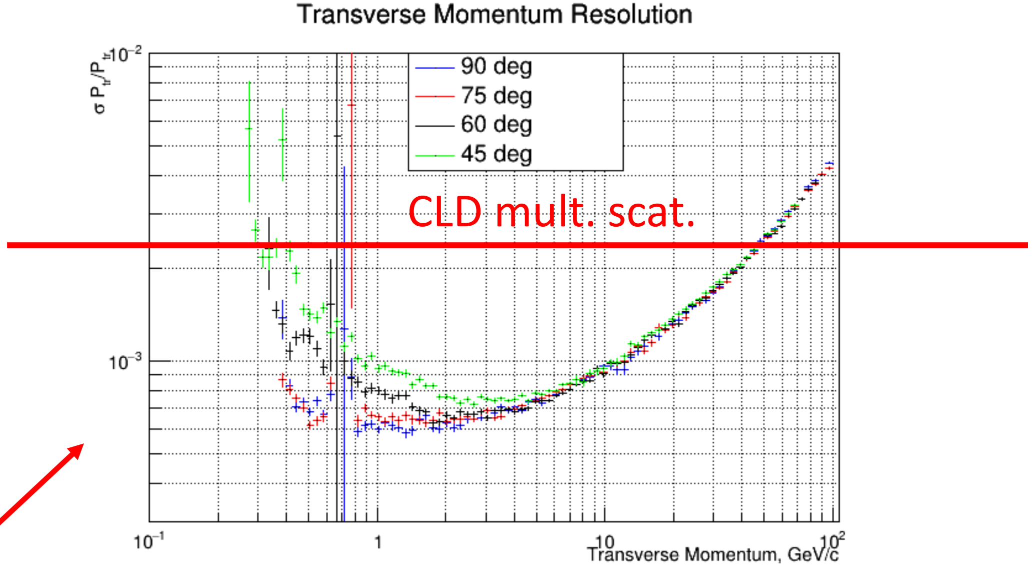
Momentum Resolution (ii)

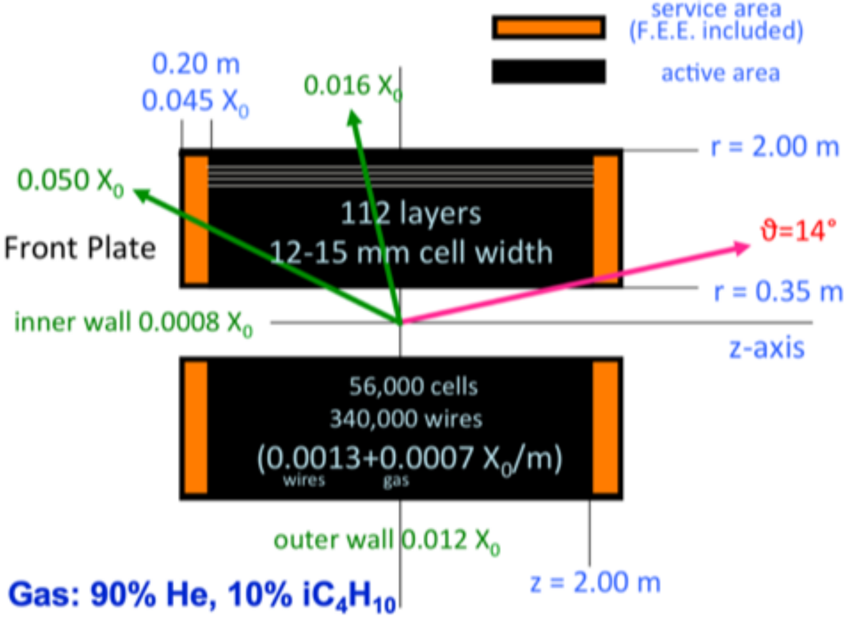
At FCC-ee, very few tracks with $p_T > 100$ GeV. Momentum measurements will be multiple scattering limited

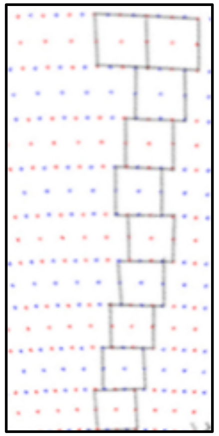
- Possible to reduce multiple scattering contribution?

IDEA Drift Chamber

- GAS: 90% He – 10% iC_4H_{10}
- Radius 0.35 – 2.00 m
- Total thickness: 1.6% (!) of X_0 at 90^o
  - Tungsten wires dominant contribution to material
- Full tracker system includes Si VTX and Si "wrapper"







Further important benefit from reduced material:

- Minimize secondary interactions in material

For full Si tracker option, further thinning of Si sensors not very promising due to the √-behaviour

$$\frac{\Delta p_T}{p_T}\bigg|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Calorimetry – Jet Energy Resolution

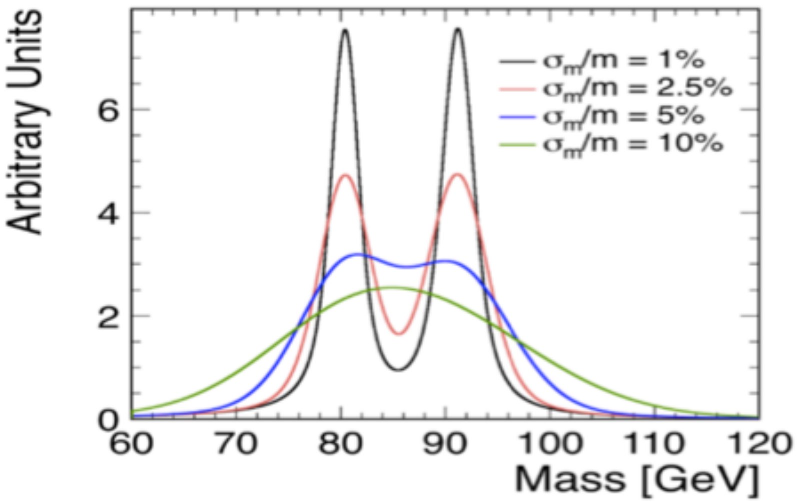
Energy coverage < 300 GeV : $22\ X_0,\ 7\lambda$

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

⇒ **Mass reconstruction from jet pairs**

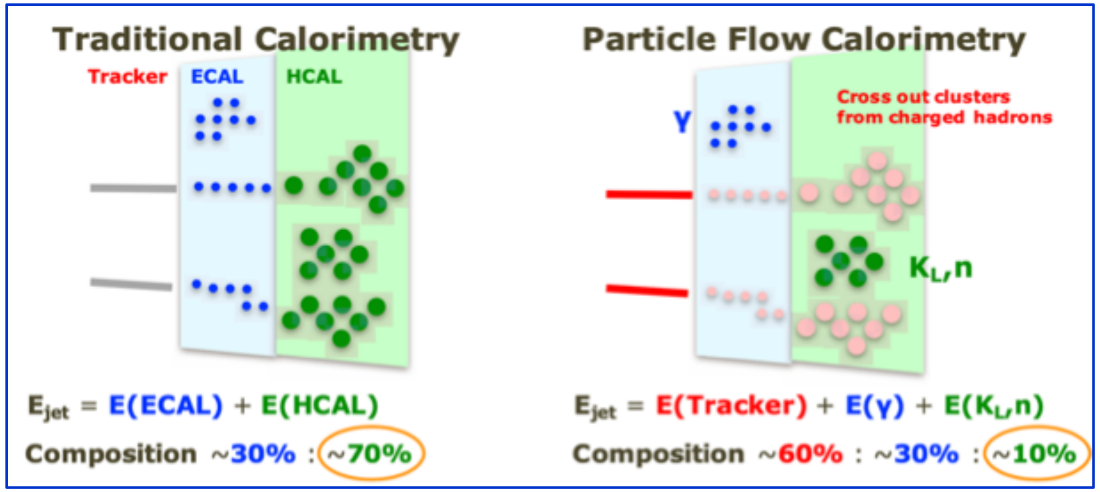
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to $\nu\nu H$
- HZ → 4 jets, $t\bar{t}$ events (6 jets), etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons



To reach jet energy resolutions of ~3%, detectors employ

- **highly granular calorimeters**
- **Particle Flow Analysis techniques**



Technologies being pursued

a) **CALICE** like (ILC, CLIC, CLD)
  - ECAL: W/Si or W/scint+SiPM
  - HCAL: steel/scint+SiPM or steel/glass RPC

b) Parallel fiber **dual readout** calorimeter (IDEA)
  - Fine transverse, but no (weak) longitudinal segmentation

c) **Liquid Argon** ECAL + **Scintillating Tile** HCAL (ATLAS like)
  - Very fine segmentation, $\delta E_{EM}/E_{EM} \lesssim$ 8-9%

Calorimetry – ECAL Performance

ECAL energy resolutiuon parametrised as

$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$

with typically

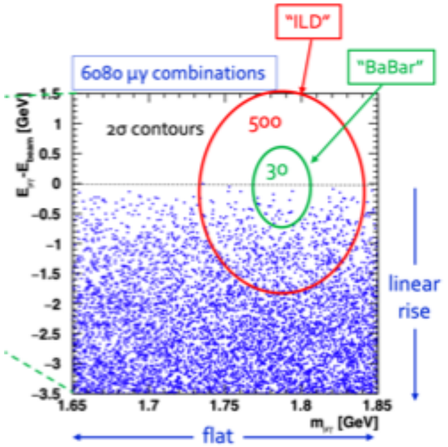
technology	*a*	*b*	*c*
CALICE	15%	-	1%
Fiber DR	10%	-	1%
Lar	9%	-	-
Crystal	3-5%	-	0.5%

- CALICE-like resolution regarded sufficient at linear colliders with main emphasis on physics at 250-500 GeV
- An improved resolution may be advantageous for the 90-160 GeV FCC-ee programme

Finely segmented ECAL (transverse and longitudinal) is important for the precise identification of γ's and π^0's in dense topologies, e.g. τ and other heavy flavour physics

Examples:

a) Much improved search limits for rare decays involving γ's.
- Here LFV decay τ → μγ

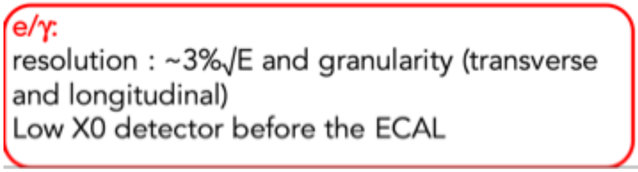


MD, 1st FCC WS, Jan. 2017

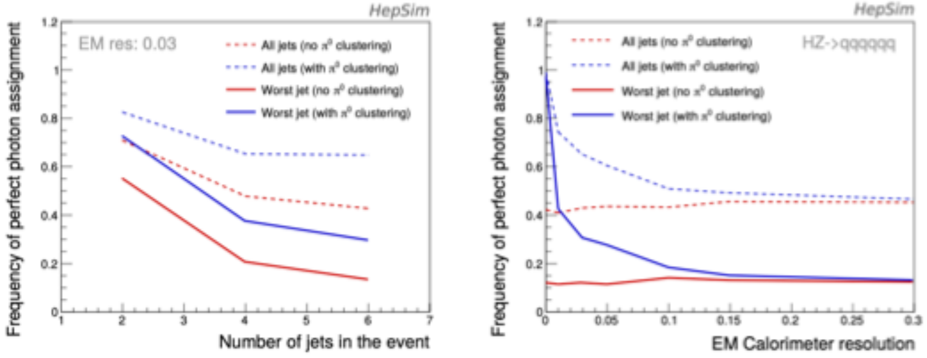
b) Much improved b-physics reach by making accesible exclusive channels with π^0's

Talk by R. Aleksan tomorrow

From M-H. Schune's wish list, 3rd FCC WS, Jan. 2020


e/γ:
resolution : ~3%/√E and granularity (transverse and longitudinal)
Low X0 detector before the ECAL

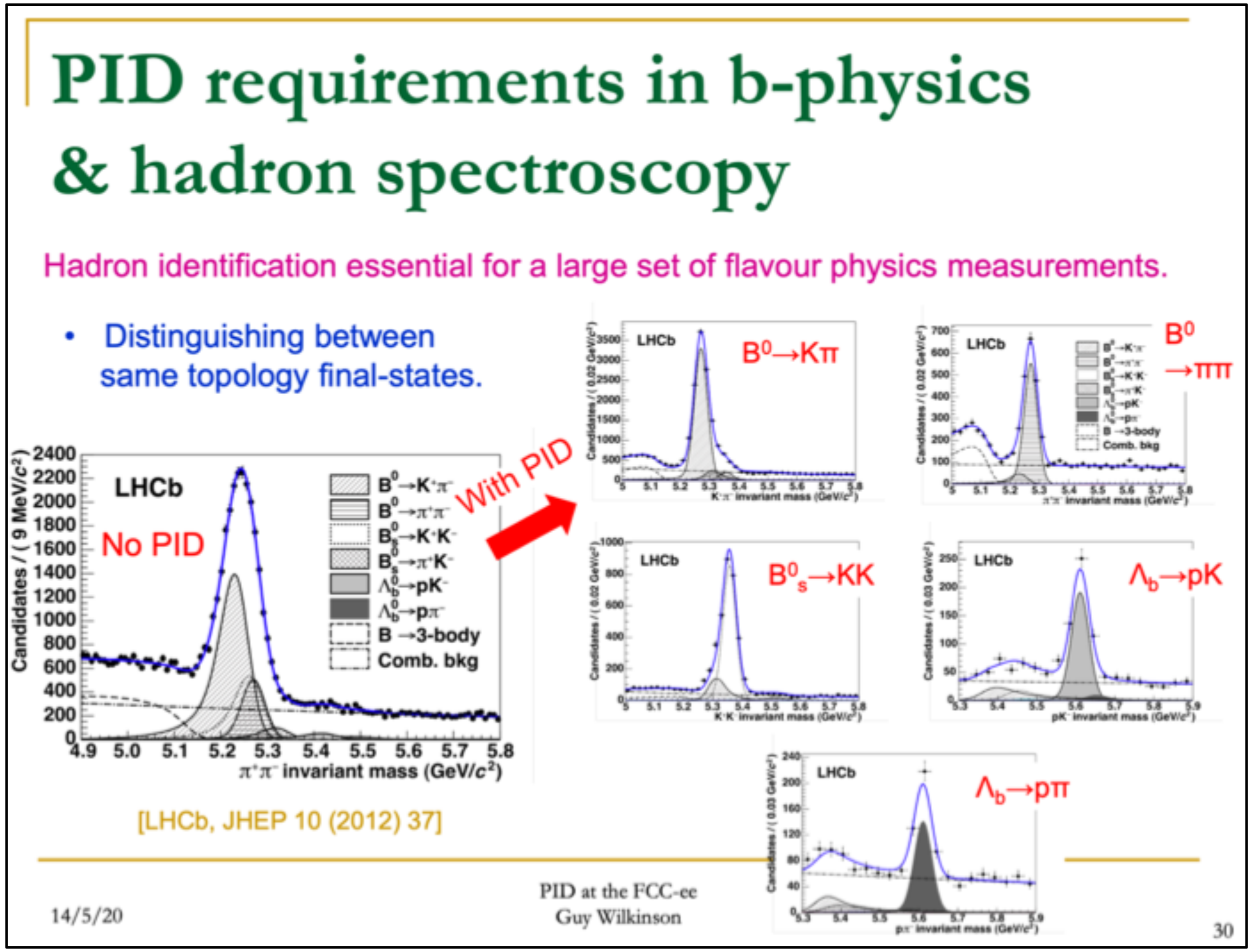
c) More precise jet definition in multijet events



2008.00338

Figure 10. Frequency of events where photons are perfectly assigned to the corresponding jet as a function of the number of jets in the event, assuming a calorimeter resolution of $3\%/\sqrt{E}$ (left), and as a function of calorimeter EM resolution in the case of the $HZ \to q\bar{q}q\bar{q}q\bar{q}$ sample (right).

Experimental Challenge: Particle Identification



PID requirements in b-physics & hadron spectroscopy

Hadron identification essential for a large set of flavour physics measurements.

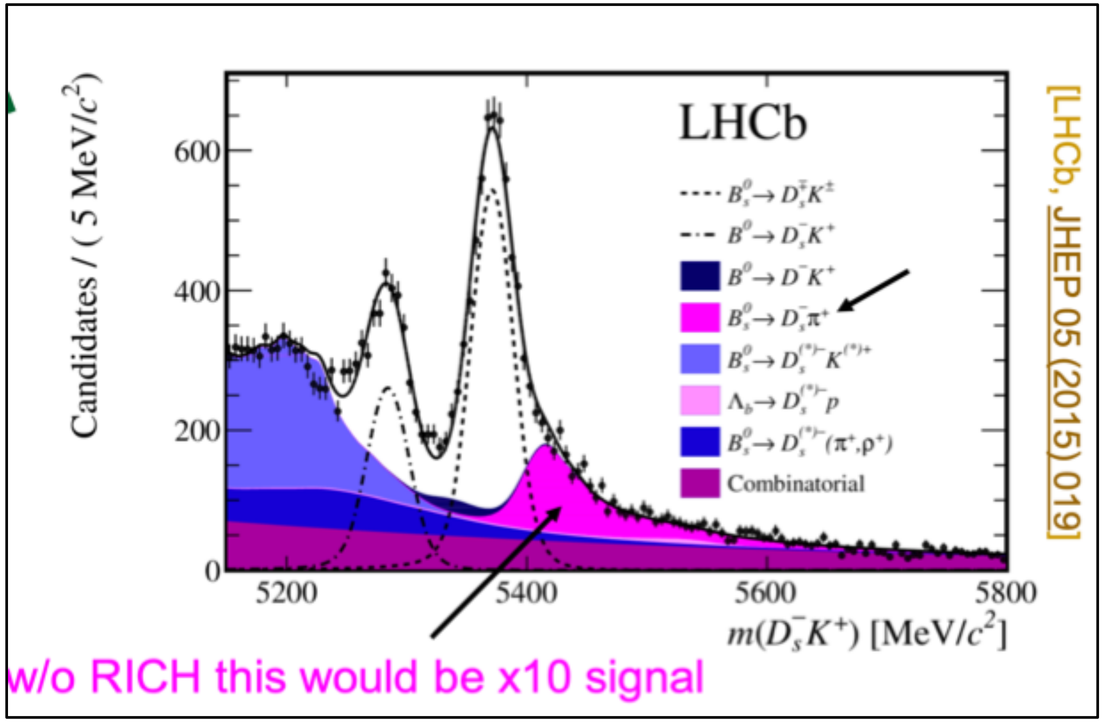
- Distinguishing between same topology final-states.

[LHCb, JHEP 10 (2012) 37]

14/5/20

PID at the FCC-ee
Guy Wilkinson

30



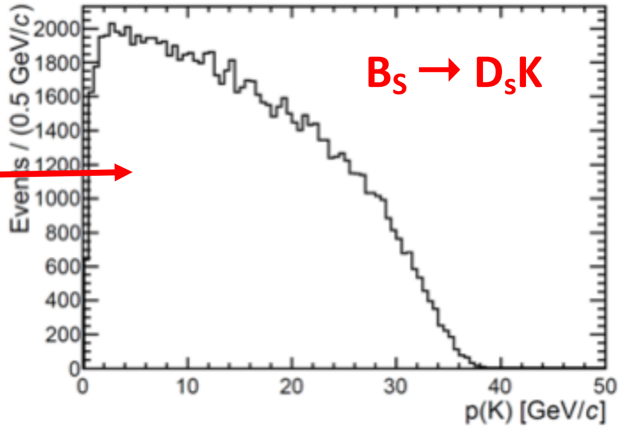
[LHCb, JHEP 05 (2015) 019]

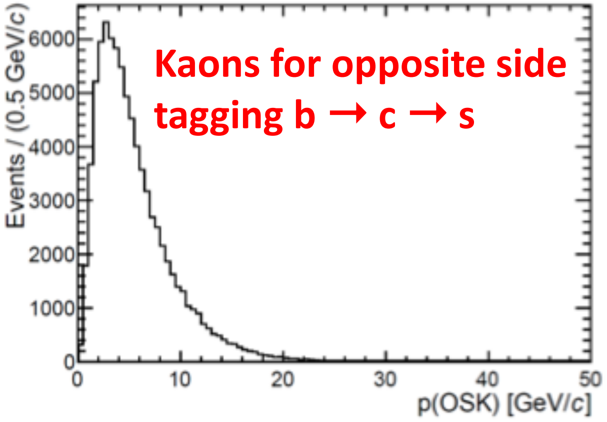
w/o RICH this would be x10 signal

- For b physics, almost full momentum range interesting
- For separation of tau decay modes

$\tau \to \pi\nu$ vs. $K\nu$; $\tau \to \rho\nu$ vs. $K^*\nu$

full momentum range of interest

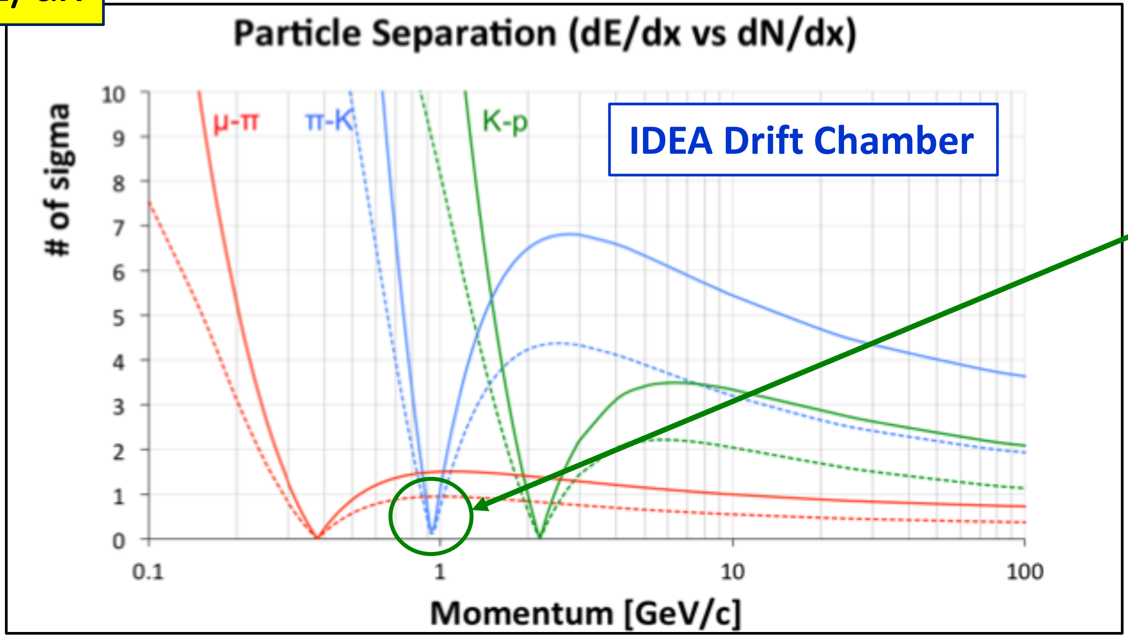




PID possibilities

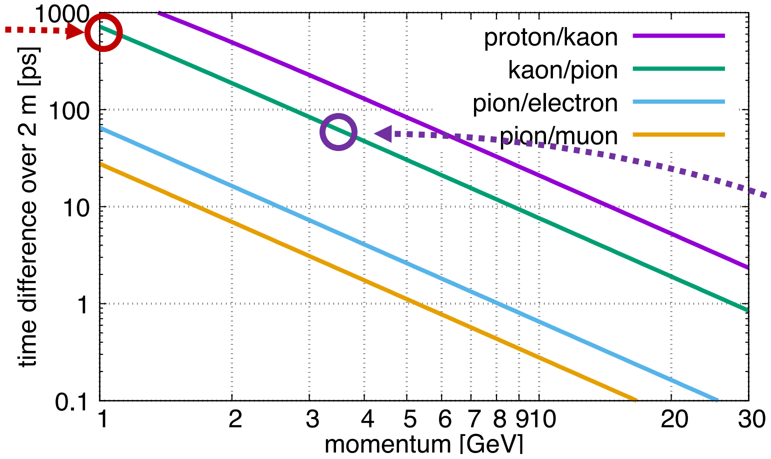
- The IDEA Drift Chamber provides very powerful PID. Improved considerably by the use of *cluster counting*
  - ❑ Standard truncated mean dE/dx : **σ ≃ 4.2%**
  - ❑ Cluster counting : **σ ≃ 2.5%**

dE/dx



- ❑ >3σ π/K separation all the way up to 100 GeV
  - ❖ Except for cross-over window at ~1 GeV.

TOF

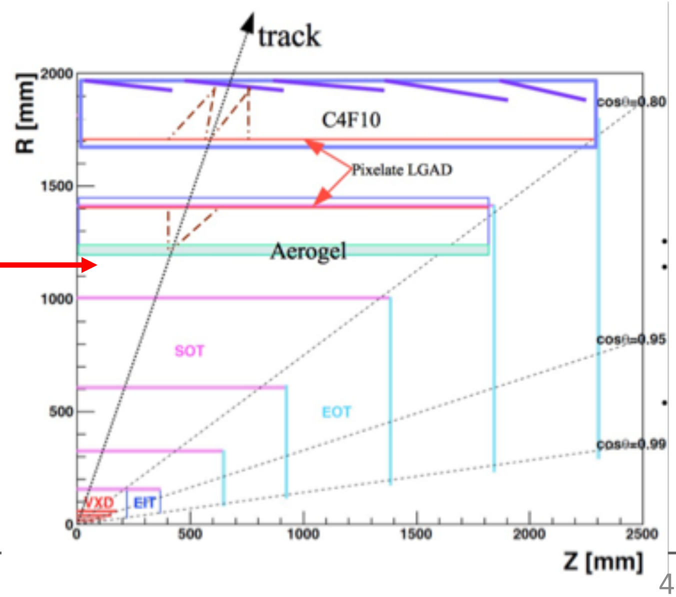


- ❑ Narrow dE/dx cross-over window at ~1 GeV, can be alleviated by unchallenging TOF measurement at r=2m of δT ≲ 0.5 ns
- ❑ TOF *alone* could give 3σ π/K separation up to a 3.5 GeV if measurement precision would be δT ~ 20 ps (LGAD, TORCH)

Cherenkov

Study of RICH counter for CEPC Full Silicon Detector

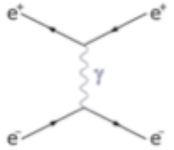
Also TORCH (LHCb) and TOP (BelleII): Essentially precise TOF devices: ~20 ps.



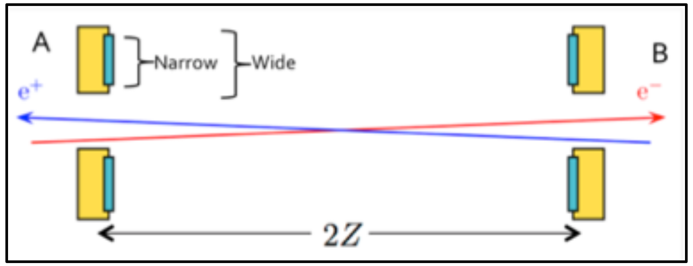
Luminosity Measurement

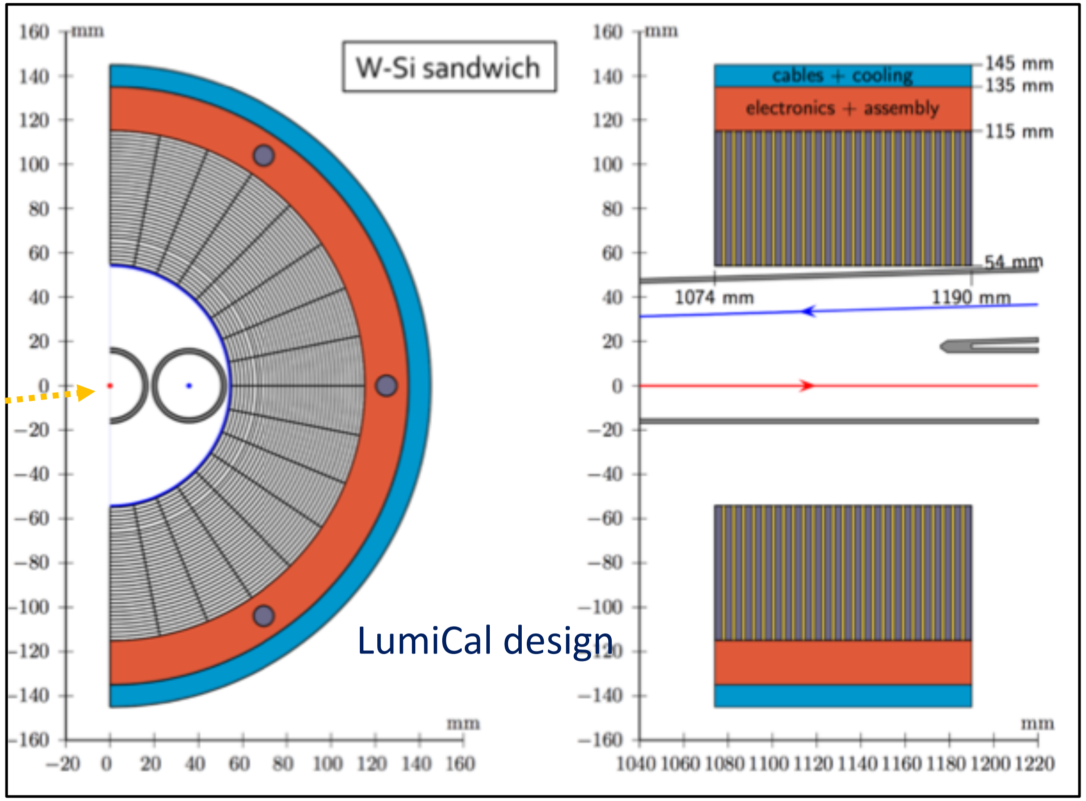
Ambitious goal:
- Absolute to 10^{-4}
- Relative (energy-to-energy point) to 10^{-5}

Small angle Bhabha scattering.
Very strongly forward peaked



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



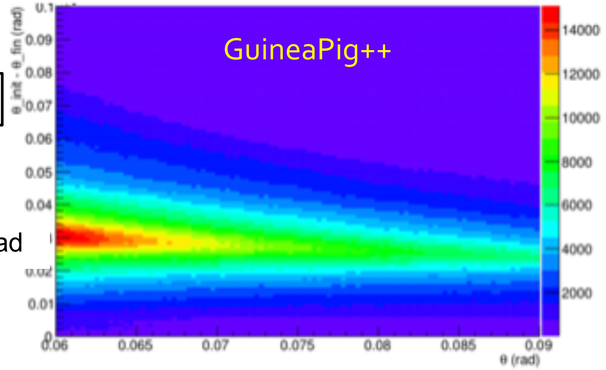


LumiCal design

- **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 top energies
- **Electromagnetic focussing of Bhabhas** (similar to "pinch effect")
  - Controllable effect [https://doi.org/10.1007/JHEP10(2019)225]

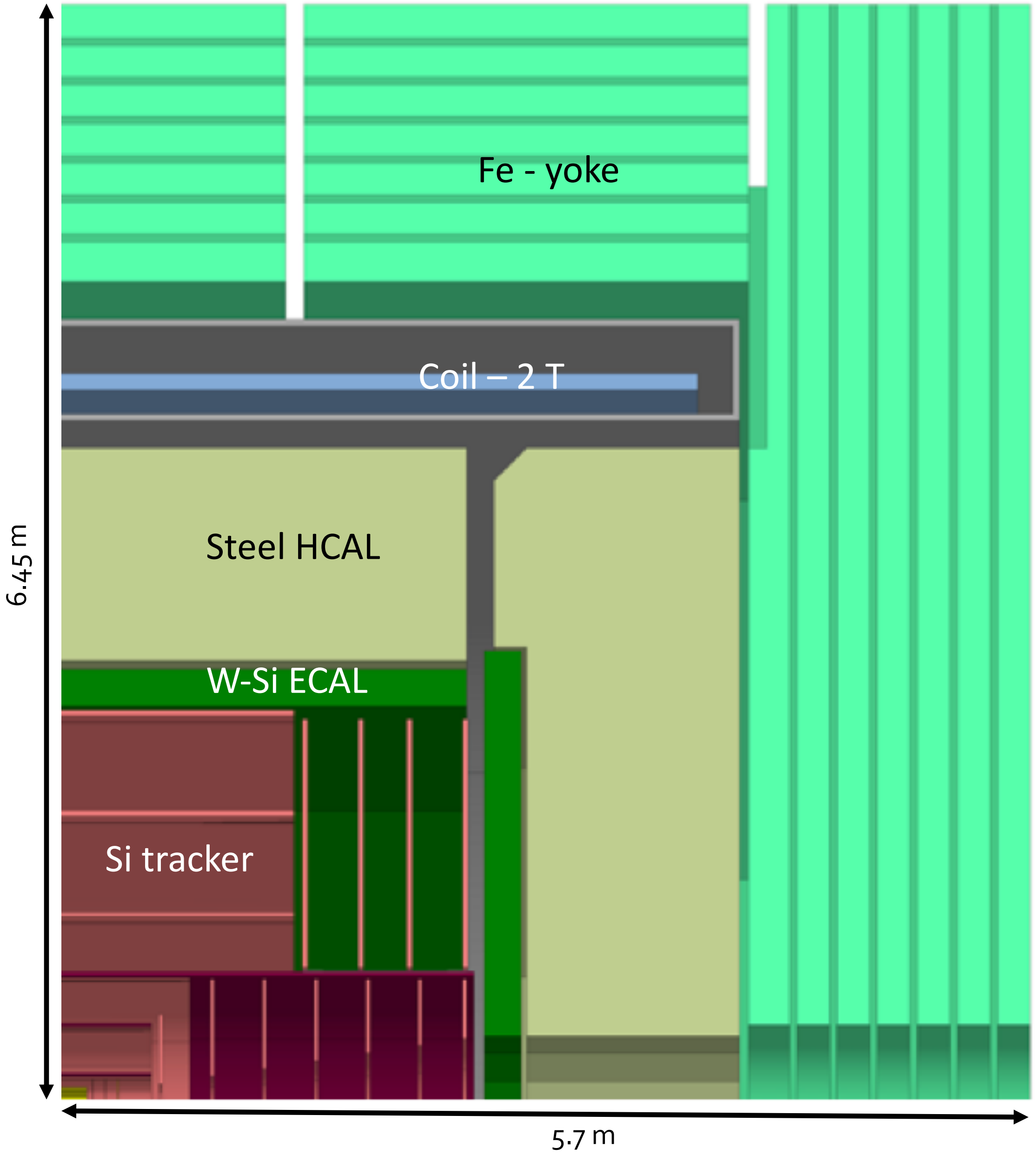
arXiv:1812.01004]

30 µrad

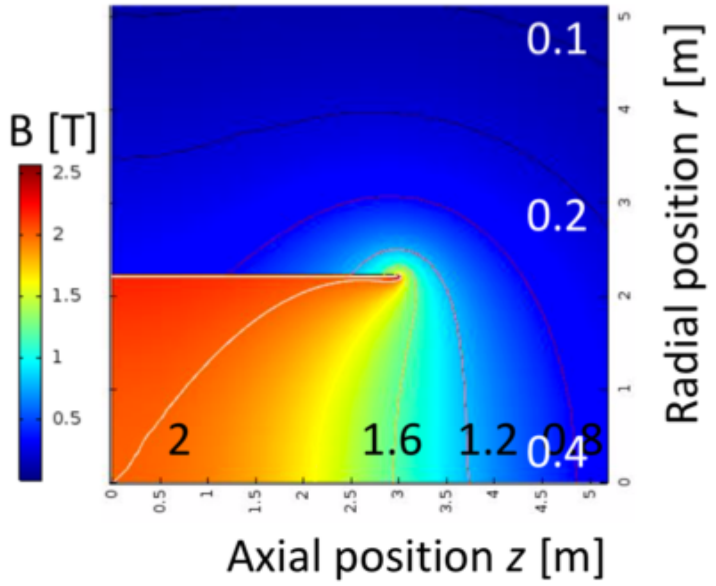


CLD Detector Layout

- 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



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

reinforced

corrugated

honeycomb-like