The experimental challenge for flavour physics at the FCC-ee

Flavour for New Physics at Present and Future Colliders, MITP

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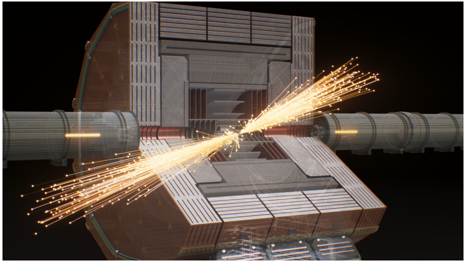
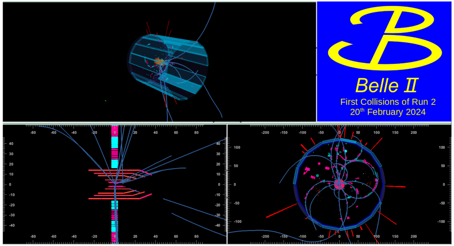
17.06.2025



Let's look closer at most prominent* experiments dedicated to flavour physics

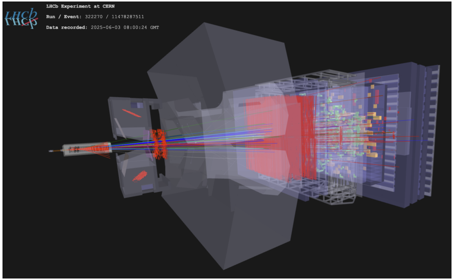
Belle II

- Asymmetric e^+e^- collisions (Lorentz boost of 0.28), at $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58\,\text{GeV}$)
- High inst. luminosity of $> 5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, target $6 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$ in the future [1]
- Target final luminosity of $50\,\text{ab}^{-1}$



LHCb

- At the LHC, precisely measure forward physics
- Up to $1.5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
- Target final luminosity of $> 300\,\text{fb}^{-1}$



How to get the best of both worlds?

*Don't forget CMS/ATLAS and Co.!

Flavour physics wish list

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Collider mode	$\Upsilon(4S)$	pp
All hadron species		✓
High boost		✓
Enormous production cross section		✓
Negligible trigger losses	✓	
Low backgrounds	✓	
Initial energy constraint	✓	
Flavour-tagging power	✓	(✓)
4π acceptance	✓	

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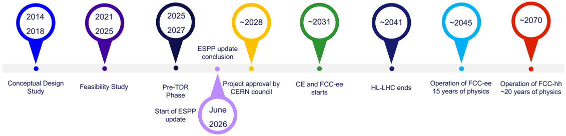
Circular collider with 90.7 km circumference machine to serve HEP for the rest of the century

The Future Circular Collider (FCC) integrated programme

Circular collider with 90.7 km circumference machine to serve HEP for the rest of the century



FCC-hh: *hh* collisions at $\sqrt{s} \geq 84\,\text{TeV} \rightarrow$ *energy frontier*

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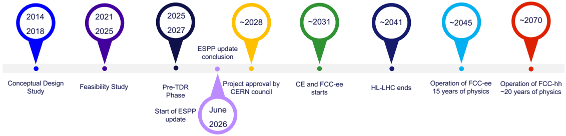
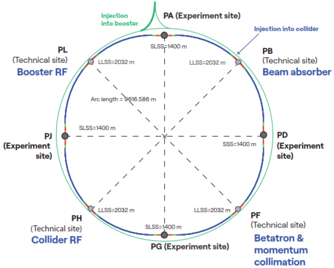
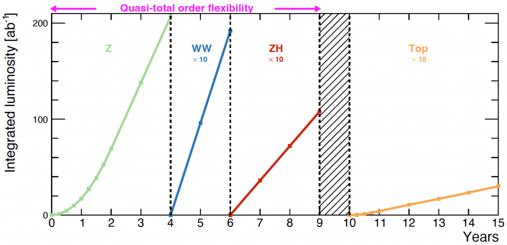


FCC-hh: *hh* collisions at $\sqrt{s} \geq 84$ TeV $\rightarrow$ *energy frontier*

FCC-ee: e^+e^- collisions at highest luminosities $\rightarrow$ *intensity frontier* $\leftarrow$ **Focus on this!**





Baseline operation model for FCC-ee [2]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z
H: $1.78 \cdot 10^6$ HZ, 125k WW $\rightarrow$ H
Top: $1.9 \cdot 10^6$ $t\bar{t}$

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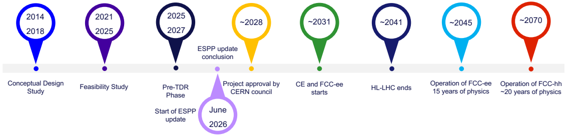

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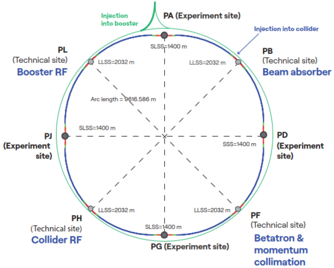

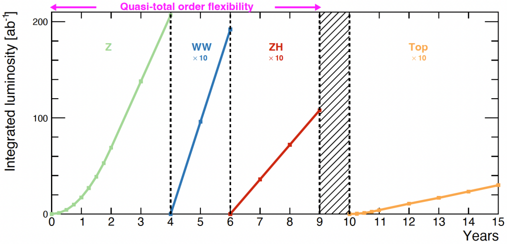

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Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$!

FCC-ee – a flavour factory

Particle species	B^0	B^+	B_s^0	λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield at Belle II ($\times 10^9$ [3])	27.5	27.5	n/a	n/a	n/a	65	45
Yield at FCC-ee ($\times 10^9$, FCC FS [2])	370	370	90	80	2	720	200

$\rightarrow$ ≥ 10 more $b\bar{b}$ and $c\bar{c}$ pairs than Belle II, B_s^0, B_c, and Λ_b accessible

- Boosted b's and τ's $\rightarrow$ Higher reconstruction efficiencies for modes with missing energy

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The Z pole is not all!

- Access to flavour parameters from W decays
- Flavour-violating decays of Z and H (rare!)
- V_{ts} from $t \rightarrow Ws$

In the early days of LEP3 and FCC, flavour physics was mostly an afterthought. This has changed. Flavour as key component of FCC(-ee) physics case

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I'll discuss the experimental challenges (and opportunities) of flavour physics at the FCC-ee!

Focus on what the experiments need to deliver for you guys to enjoy

FCC-ee to make precise measurements of rare and elusive flavour processes

Precision, precision, precision

- Precise measurement of particle properties
  - Vertices and decay history
  - Momentum
  - Identity
  - Energy
- All the time
  - Alignment, stability, redundancy, efficiency
- Everywhere
  - Hermeticity

Experimental requirements for flavour physics at the FCC-ee

FCC-ee to make precise measurements of rare and elusive flavour processes
Precision, precision, precision

- Precise measurement of particle properties
  - Vertices and decay history $\rightarrow$ Vertex detector
  - Momentum $\rightarrow$ Tracker
  - Identity $\rightarrow$ Particle identification
  - Energy $\rightarrow$ Calorimeter
- All the time
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Vertex detector

For anything that has secondary and tertiary vertices!

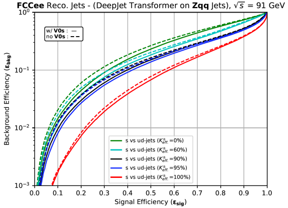
- b and c hadrons, taus, V0s, ...
- Reconstruct complex decay chains
- Particle lifetime measurements (τ, oscillations)
- Efficient flavour tagging (b/c/g/**s**)

Stringent requirements on vertex detector to limit syst. uncertainties:

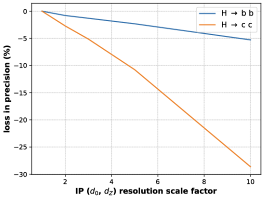
→ Coverage down to $|\cos(\theta)| \lesssim 0.99$ and high reco. efficiency

→ $\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$ with $a \approx 3\,\mu\mathrm{m}$, $b \approx 15\,\mu\mathrm{mGeV}$

- a given by sensor resolution → Small single-hit resolution, pixels
- b given by *multiple scattering* → Minimise material budget (number of radiation lengths X_0) in vertex and beam pipe



Secondary vertices for *s*-tagging [4]

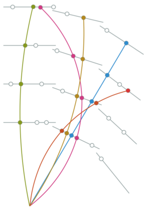


Impact of IP resolution on Yukawa coupling measurement (L. Gouskous)

University of Zurich[UZH]

Reconstruction of the charged particle trajectories

- Large radius due to lower momenta and B field limited to 2 T (up to 3 T may be possible except for Z pole run)
- Precise angle determination in di-muons, $< 100\,\mu\text{rad}$
- Need for exquisite momentum resolution of $\sigma(1/p_\mathrm{T}) \approx a \oplus b/p_\mathrm{T}$, with $a \approx 3 \times 10^{-5}\,\mathrm{GeV}^{-1}$, $b \approx 0.6 \cdot 10^{-3}$
  - Again minimise the material budget
- Either some precise hits (silicon tracking) or many less precise hits (gaseous tracking)
  - Gaseous tracking benefitial for continuous tracking (e.g. for long-lived particle searches)
- Precise tracks are crucial ingredient to *particle flow reconstruction* and thus jet energy resolution



Visualisation of tracking [5].

Particle identification: Distinguishing K, μ, π, e, γ

- Kaon ID for flavour tagging (s jets contain more kaons) and flavour physics
- γ/neutral hadron separation for particle flow reconstruction
- Background suppression in flavour physics (e.g $B_s^0 \to D_s K$ from $B_s^0 \to D_s \pi$)

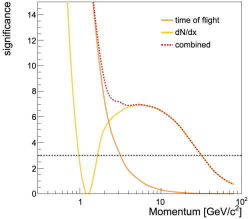
Drift chamber as tracker

- dE/dx and/or cluster counting (dN/dx)

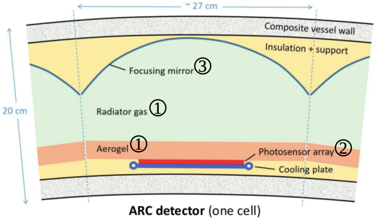
Timing measurement for time-of-flight

- $O(30)$ ps to get PID at low momenta (LGADs, MAPS, etc.). $O(100)\mathrm{m}^2$ of sensors needed

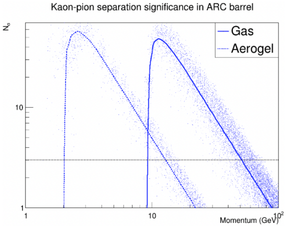
Ring imaging Cherenkov (RICH) detectors



Kaon-pion separation using drift chamber and TOF (F. Bedeschi [6])



Cell of ARC detector for FCC-ee (R. Forty)



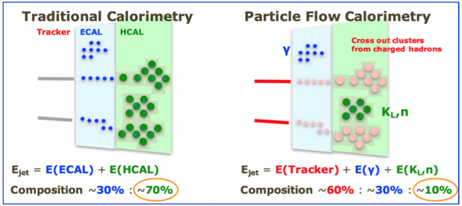
Kaon-pion seperation in ARC (M. Tat)

EM calorimeter

- Supreme energy resolution for
  - some flavour physics processes (more soon)
  - Resolution on Higgs mass in $e^+e^- \to Z(\to e^+e^-)H$ almost as good as in $\mu^+\mu^-$ with $3\%/\sqrt{E}$ (M.T. Lucchino et al. [7])
  - $Z\nu_e\bar{\nu}_e$ coupling

Particle-flow reconstruction

- Optimise jet energy resolution by individually reconstructing each particle and using the best measurement for each (tracker, ECAL, HCAL)
- Needs transverse and longitudinal granularity



Particle flow calorimetry (M. Dam)

Hadronic calorimeter

- Sensitivity down to few 100 MeV
- Single hadron resolution of 25–50%$/\sqrt{E}$
- Particle Flow $\to$ Enough for jet resolution of $\sim$ 3–4 %

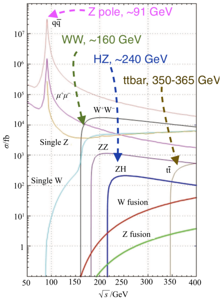
Experimental environment at the FCC-ee (Z pole)

University of Zurich[UZH]

☺: e^+e^- collisions are *clean* - there's no QCD in the initial state

☹: Very high inst. luminosity of $140 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ thanks to 50 MHz bunch collision rate ($t_{\text{BC}} = 20\,\text{ns}$ currently)

- Very high rate of interesting events (100 kHz of Z, 30 kHz of $\gamma\gamma \rightarrow$ hadrons, 50 kHz of bhabha pairs) that need to be read out and saved (and simulated!)



e^+e^- annihilation cross section [8]

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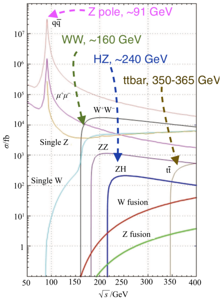
  - $\rightarrow$ Integrate over of a couple of bunch crossings?
  - $\rightarrow$ But need to check impact on uncertainties
  - Timing of $\mathcal{O}(\text{few ns} - 1\,\mu\text{s})$ in vertex detector



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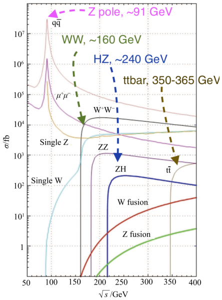
- Considerable beam backgrounds, mainly from incoherent pairs
  - High hit rate innermost vertex layers, occupancy challenges in gaseous tracker and ECAL
  - → Challenge also for readout
  - $\mathcal{O}(1 \times 10^{13}\ 1\,\mathrm{MeV}\ \mathrm{n_{eq}cm^{-2}})$ and few tens of kGy per year



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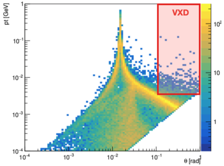

Incoherent pairs at Z pole [9]

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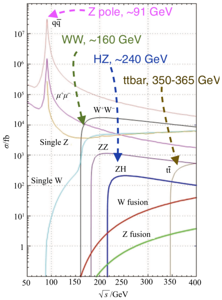
- Unclear if hardware trigger is needed or not



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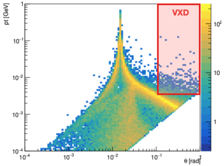

Incoherent pairs at Z pole [9]

FCC-ee detector *concepts* (modulo some variations)

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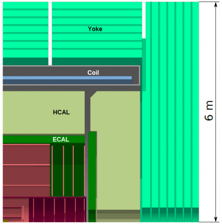
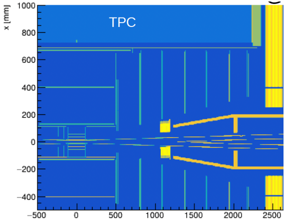
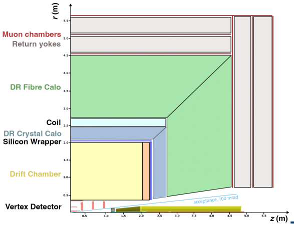


CLD [10, 11]



ILD [12, 13]



IDEA [14]

ALLEGRO [15]

- Light silicon vertex detector using monolithic active pixel sensors (MAPS)

CLD
- Si tracker
- dE/dx + ARC (?)
- CALICE-like highly-granular ECAL/HCAL
- Solenoid coil outside calorimeter system

ILD
- Si tracker + time projection chamber
- Si or ECAL with T.O.F
- CALICE-like highly-granular ECAL/HCAL
- Solenoid coil outside calorimeter system

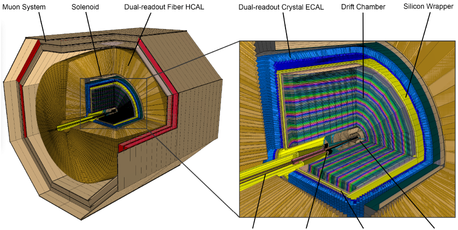
IDEA
- Ultra-light drift chamber with d$N_{\text{ion.}}$/dx
- Si layer with T.O.F
- Dual-readout crystal ECAL
- Light solenoid up to 3 T
- DR fibre HCAL

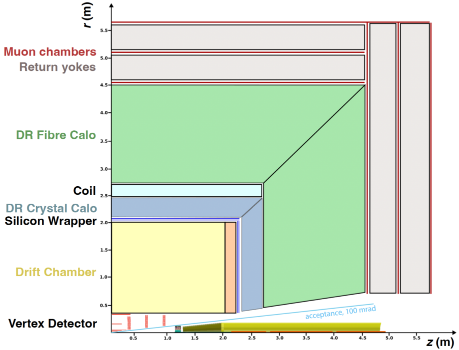
ALLEGRO
- DC/SciFi/Straw tubes
- Si layer with T.O.F
- Noble liquid ECAL, Pb/W+LAr or W+LKr
- Solenoid in same cryostat as ECAL
- TileCal HCAL

- Muon system in return yoke, pretty much det. concept independent (e.g. μ-RWELL in IDEA)

The IDEA detector concept

- **Vertex detector** with light layers of monolithic active pixel sensors (MAPS)
  - → Integrated into MDI, together with two lumicals in the forward region
- Ultra-light **drift chamber** providing up to 112 hits per track ($\sigma_{xy} \approx 100\,\mu\text{m}$) and $\mathrm{d}N_{\text{ion.}}/\mathrm{d}x$ for PID
- Silicon wrapper for momentum resolution and time-of-flight ($\mathcal{O}(100\,\text{ps})$) for PID
- Dual readout crystal ECAL for energy resolution
  - *Dual readout*: Measure both relativistic ($\approx$ EM) and non-relativistic shower ($\approx$ hadr.) components
  - → Inside a high-temperature superconducting solenoid with up to 3 T
- Dual readout fibre HCAL complementing ECAL
- ≥ 3 layers of μ-RWELL muon detectors





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How to concretisise the detector designs?

University of Zurich[UZH]

A lot of work done for the feasibility study, but many points still under investigation

- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- Can novel detector technologies can benefit the physics program? New detector concepts?

Fast simulation (DELPHES), parametrised simulation of detector response

- Idealised, fast, simple
- **Explore** how detectors could look like and what measurements can be done

$\rightarrow$ Over the years with more R&D we can mostly achieve or even surpass these estimates

Full simulation:

- Realistic, detailed, complex
- Needed to guide **development** of detector layouts, actual sensor prototypes

$\rightarrow$ A bit pessimistic in hindsight

Feedback-loop

Sensor perf. $\xrightarrow[\text{sim.}]{\text{detector}}$ Subdetector perf. $\xrightarrow[\text{analysis}]{\text{sample}}$ physics perf. $\xrightarrow[\text{input}]{\text{theory}}$ sensor specification

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- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- Can novel detector technologies can benefit the physics program? New detector concepts?

Fast simulation (DELPHES), parametrised simulation of detector response

- Idealised, fast, simple
- **Exp**

→ Ove … nates

Most studies presented in the following were done using fast simulation.
~~Expected sensitivity and limits~~ → Required exp./theo. developments

Full simulation:

- Realistic, detailed, complex
- Needed to guide **development** of detector layouts, actual sensor prototypes

→ A bit pessimistic in hindsight

Feedback-loop

Sensor perf. $\xrightarrow[\text{sim.}]{\text{detector}}$ Subdetector perf. $\xrightarrow[\text{analysis}]{\text{sample}}$ physics perf. $\xrightarrow[\text{input}]{\text{theory}}$ sensor specification

Flavour physics case studies: $B_s \to D_s K$

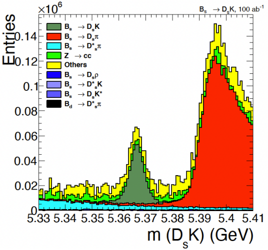
University of Zurich[UZH]

Measurement of time-dependent CP asymmetry $\to \gamma$ angle of V_{CKM}

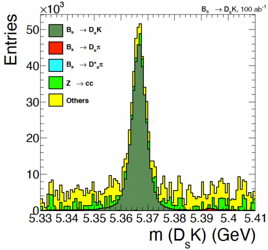
- Use $D_s \to \phi(KK)\pi$ channel
- ϕ resonance, no neutral particles in final state $\to$ Easy to reconstruct
- Many backgrounds considered (inclusive $Z \to b\bar{b}/c\bar{c}$ added for FS report)
- Reconstruct ϕ candidates then D_s candidate without PID, build B_s candidates by fitting D_s with another track
- PID ($\mathrm{d}N/\mathrm{d}x$ and 30 ps TOF) on last track to reject $Z \to b\bar{b}$ backgrounds
- ECAL performance of $5\,\%/\sqrt{E}$ necessary to distinguish peaks

FCC-ee able to measure γ down to few tens of a degree (LHCb 300 fb^{-1} similar, ± 4 deg currently, LHCb)

$\to$ Can be further improved by adding other decay modes



Before PID [2]



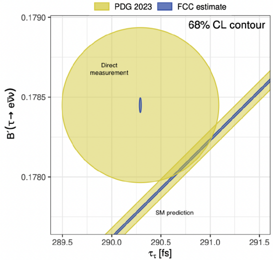
After PID [2]

Flavour physics case studies: The τ lepton

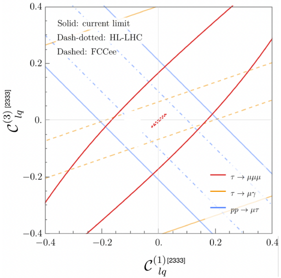
Extrapolation from DELPHI 2004 τ_τ using three-prong tau pair decays

- Benefit from tiny statistical uncertainty
- Need to keep luminosity systematic under control
- Mind vertex detector alignment and length scale

Comparison to Belle II: Benefit from better momentum, vertex resolution, and PID at Z pole than Belle II thanks to larger momenta and light detectors



	DELPHI 2004 [fs]	DELPHI 2004 [ppm]	FCC-ee(Z) $6{\cdot}10^{12}$ Z [ppm]
statistical uncertainty	5.2	18000	15.0
luminosity-dependent systematics	1.3	4500	3.9
- background	0.2		
- reconstruction bias	0.8		
- vertex detector alignment	1.0		
luminosity-independent systematics			
- detector length scale	-	100	5.0
- average tau energy	-	-	1.0
- radiative energy loss	0.1	350	11.5
- tau mass	-	68	10.0
total systematics			15.9
total uncertainty			22.3

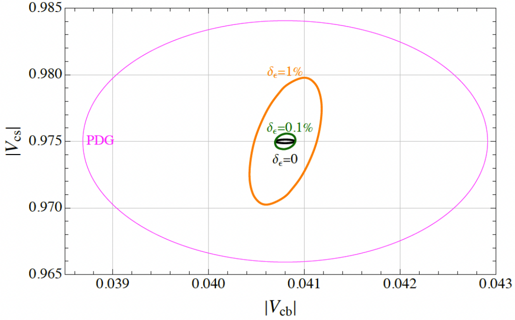


University of Zurich[UZH]

Example for flavour at FCC-ee beyond Z pole: World-best limits of $|V_{cs}|$ and $|V_{cb}|$!

- V_{cb} is normally measured in tree-level semi-leptonic B decays, tensions in inclusive vs. exclusive decays
- At FCC-ee can instead directly look at 2.4×10^8 on-shell WW pair decays
  - Independent measurement, independent from lattice QCD

- Focused on V_{cb} and V_{cs} $\rightarrow$ Good tagging and large statistics
- $|V_{cb}|$ statistically limited for reasonable systematic uncertainties
  - $\rightarrow$ Need good light jet rejection
- $|V_{cs}|$ limited by systematic uncertainty on tagging efficiency
  - $\rightarrow$ Need good s-tagger performance (= good Kaon/Pion discrimination and vertexing)



68% CL contours in $(|V_{cb}, V_{cs}|)$ plane for different syst. uncertainties on tagging efficiencies [16]

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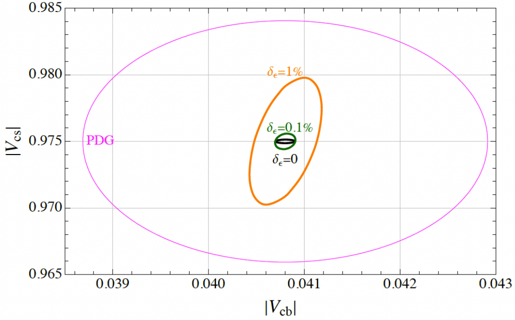


68% CL contours in ($|V_{cb}, V_{cs}|$) plane for different syst. uncertainties on tagging efficiencies [16]

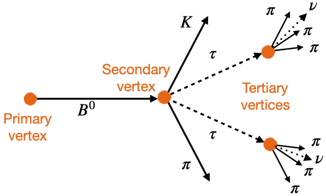
Importance of **jet flavour tagging**

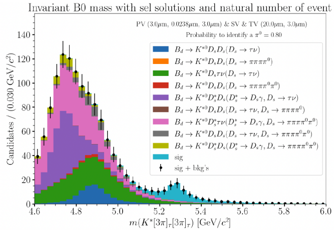
Flavour physics case studies: $b \to s\tau^+\tau^-$ (1/3)

- $B^0 \to K^{*0} + \tau^+ + \tau^-$ not observed yet, limit of BR $< \mathcal{O}(10^{-3}$–$10^{-4})$
  $\to$ but SM value at 10^{-7}, strongly enhanced in many beyond SM theories!

$\to$ Three-prong τ decays allow reconstruction of event kinematics and B^0 mass

$\to$ Precise vertex reconstruction crucial!





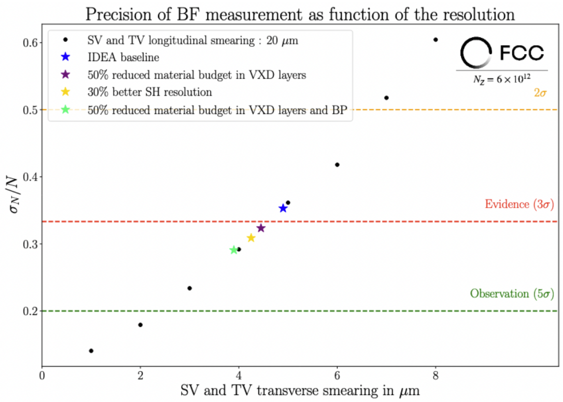
- Close to evidence (3σ) using current IDEA baseline in Delphes fast simulation study (T. Miralles et al. at FCC Physics Workshop 2024, [17])

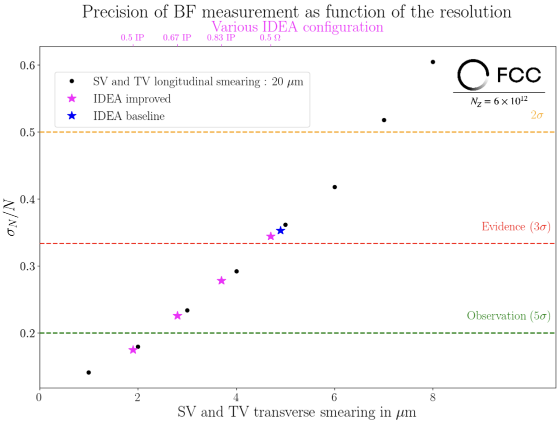
Assumptions:

- 80% vertexing efficiency
- 80% π^0 detection rate to reduce this background

Again importance of Kaon-Pion distinction

Flavour physics case studies: $b \to s\tau^+\tau^-$ (2/3)

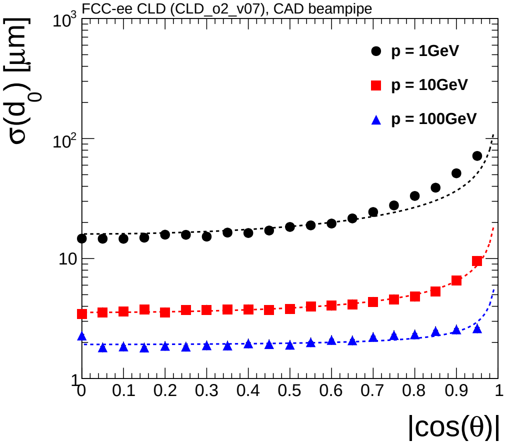




Need to improve impact parameter resolutions by $\approx 40\%$ to have chance at discovery (down to the SM expected value)$\rightarrow$ Improve single-hit resolution and **material budget**!

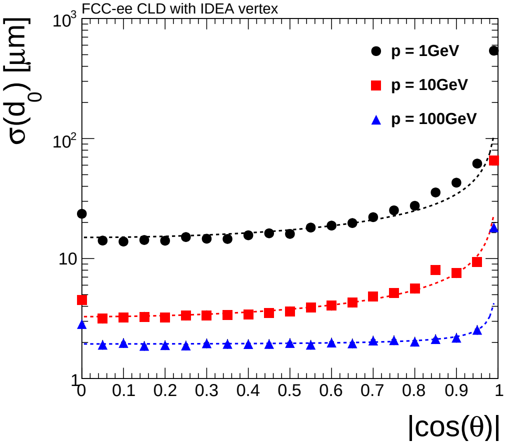
Flavour physics case studies: $b \to s\tau^+\tau^-$ (3/3)

University of Zurich[UZH]

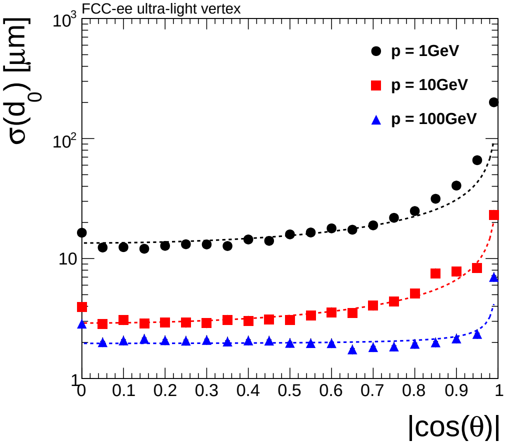


- CLD vertex detector already gives decent impact parameter resolution

Flavour physics case studies: $b \to s\tau^+\tau^-$ (3/3)



- CLD vertex detector already gives decent impact parameter resolution
- IDEA vertex has lighter, single-hit layers
  - No hit in first layer at $\cos\theta = 0$



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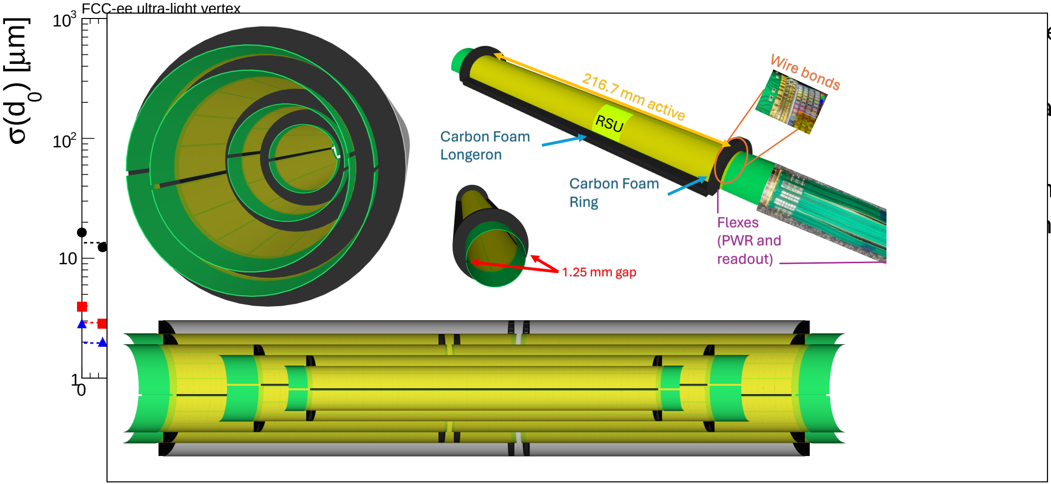

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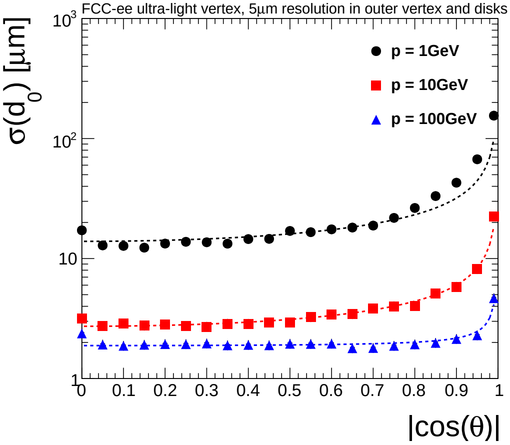

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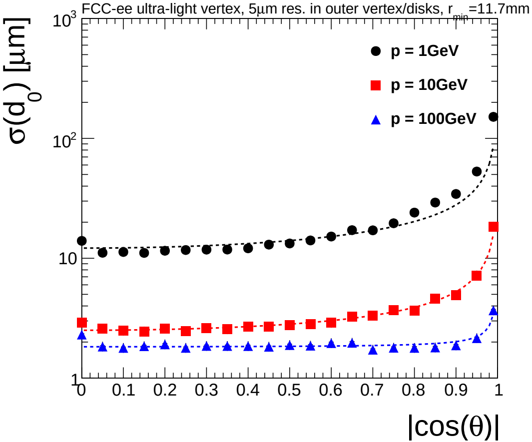

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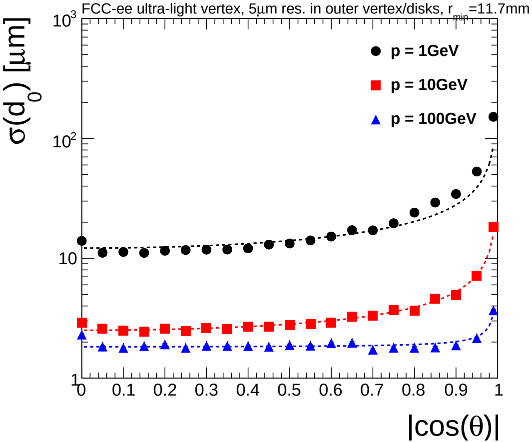

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- Impact parameter resolution in transverse direction of $\sigma_{d_0} \approx 1.8 \bigoplus \frac{12\,\mu\text{m GeV}}{p \sin^{3/2}\theta}$ reachable
  - Similar numbers in σ_{z_0}

Probably not quite enough yet. Will do a full simulation study and see what is actually needed

A dedicated flavour physics experiment at FCC-ee?

Currently there are four detector concepts for FCC-ee

- Detector concepts $\neq$ experimental collaborations
- Currently, all detector concepts aim to run at all $\sqrt{s}$ stages (ILD@FCC TPC yet to demonstrate Z pole capabilities)
  - → First discussions on potential upgrades/differences between $\sqrt{s}$ stages
  - → Experimentally, the Z pole run is the most challenging
    - n.b: Flexibility to change between Z/WW/HZ run very quickly thanks to shared RF system

How would the perfect detector concept focusing on flavour physics look like?

- Amazing vertex detector
  - Ultra-light, spatial resolution $\leq 3\,\mu$m
  - Inside beam pipe ?!? Different machine-detector interface design?
- Efficient, prudent particle identification
  - More than two PID systems (ARC, T.O.F, dN/dx, ...) for redundancy and performance?
- High-resolution ECAL

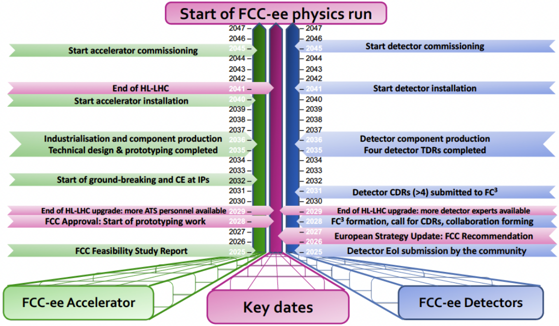
→ Where would a flavour-focused experiment be willing to compromise?

- HCAL? Muon system?

Next steps towards the FCC-ee

pre-TDR phase until end of 2027

- Further develop FCC-ee (flavour) physics case
- Defines detector requirements
- Towards experimental collaboration formation



FCC community building

- It's the early career experimentalists/theorists/phenomenologists/engineers/accelerator physicists of today that will lead the field of tomorrow

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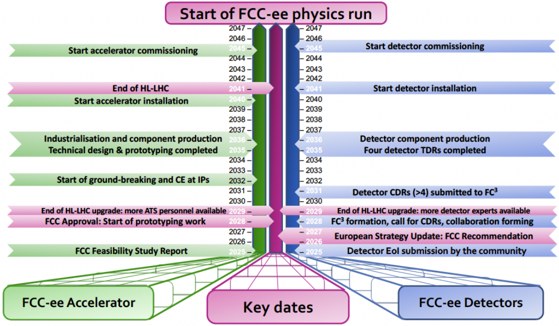

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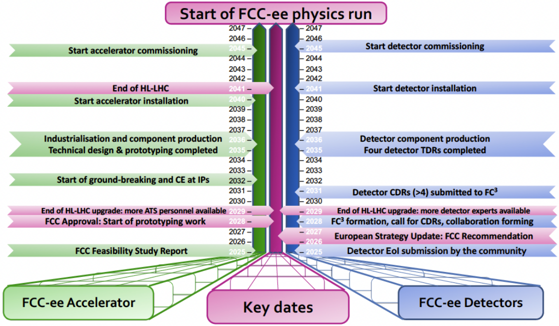
Next steps towards the FCC-ee



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- Exchange among all crucial to realise the Future Circular Collider
- FCC: Friends, Co-workers, Colleagues (EP-FCC's idea ☺)

Thanks!

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https://cds.cern.ch/record/2890181.
Co-project Manager: Magnus Mager, magnus.mager@cern.chds.

Summary of requirements (see arXiv:2502.04071 for details)

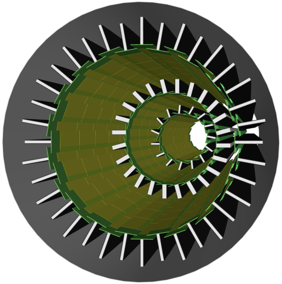
University of Zurich[UZH]

Physics challenges	Requirement
Coverage down to $\lvert\cos(\theta)\rvert \lesssim 0.99$	Long barrel, forward disks
High reconstruction efficiency	Hermetic layers, small peripheries, $> 99\%$ hit eff., more layers?
Asymptotic resolution of $a \approx 3\,\mu\text{m}$	$3\,\mu\text{m}$ single-hit resolution, small r_{min}
Multiple scattering: $b \approx 15\,\mu\text{m GeV}$	• light beam pipe • $\leq 0.3\%\ X_0$/layer $\rightarrow$ thin sensors, air-cooling, light support

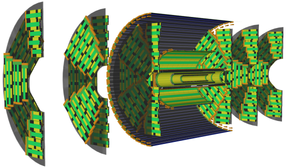
Collision environment challenges	Requirement
High luminosity	• Save events at $\gtrsim 200 kHz$ • With trigger or without
Avoid pile-up of Z's	Integration time $\lesssim 1\,\mu\text{s}$
Beam backgrounds	Hit rate capability up to $\mathcal{O}(100\,\text{MHz/cm}^2)$
Radiation environment	Few 1×10^{13} 1 MeV $n_{\text{eq}}\text{cm}^{-2}$ and $\mathcal{O}$(few tens of 10 kGy) per year

Advanced challenges	Requirement
≈ 2 reduction of σ_{d_0}	Smaller spatial resolution and r_{min}, lighter vertex and beam pipe
Bunch tagging/inner T.O.F reference	$\mathcal{O}(20\,\text{ns})$ time resolution/$\mathcal{O}$(10's of ps)

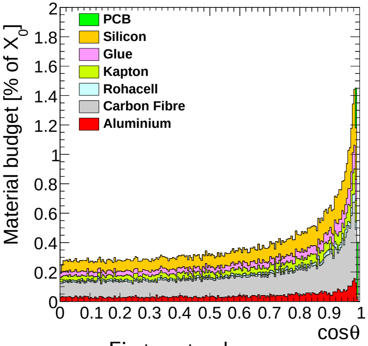
IDEA vertex detector full simulation model



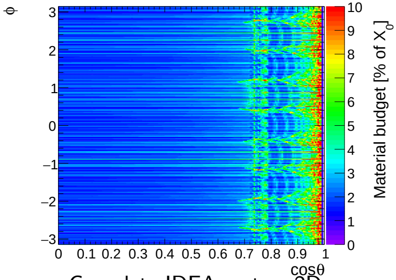
Inner vertex barrel in DD4hep



Complete vertex in DD4hep



First vertex layer



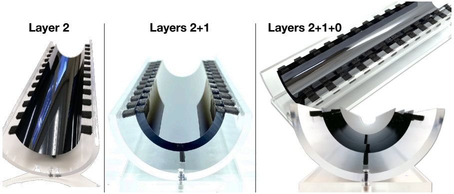
Complete IDEA vertex, 2D

Sensor-only vertex detector

University of Zurich[UZH]

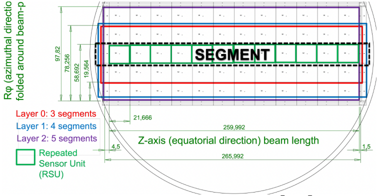
DMAPS in 65 nm TPSCo process

- More logic per cm^2 $\rightarrow$ More functionality/smaller pixels
- Low power consumption $\rightarrow$ Helps air cooling
- Enables 12" wafers $\rightarrow$ Large, bent sensors!



Layer assembly concept for ALICE ITS3 [18]

	ALICE ITS3	FCC-ee
r_{min} [mm]	19	~ 13.7
$\lvert\cos(\theta)\rvert$ coverage until	0.97–0.99	0.99
Single-hit resolution [μm]	5	3
Part. hit density at r_{min} [MHz/cm^2]	8.5	?



MOSAIX wafer layout [19]

- First layer at smaller radius $\rightarrow$ Use just two segments
- Forward-backward asymmetries measurements $\rightarrow$ Read and power from both sides
- Forward coverage $\rightarrow$ Multiple sensors in a row at larger r
- Tight hermiticity requirement at FCC-ee, but have $\sim 5\%$ insensitive periphery in sensor and difficult to overlap sensors
  $\rightarrow$ Four layers ensures ≥ 3 hits in vertex, minimise periphery

The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis

- Event data model: EDM4hep for exchange among framework components
  - Podio as underlying tool, for different collision environments
  - Including truth information
- Data processing framework: Gaudi
- Geometry description: DD4hep, ability to include CAD files
- Package manager: Spack: `source /cvmfs/sw.hsf.org/Key4hep/setup.sh`