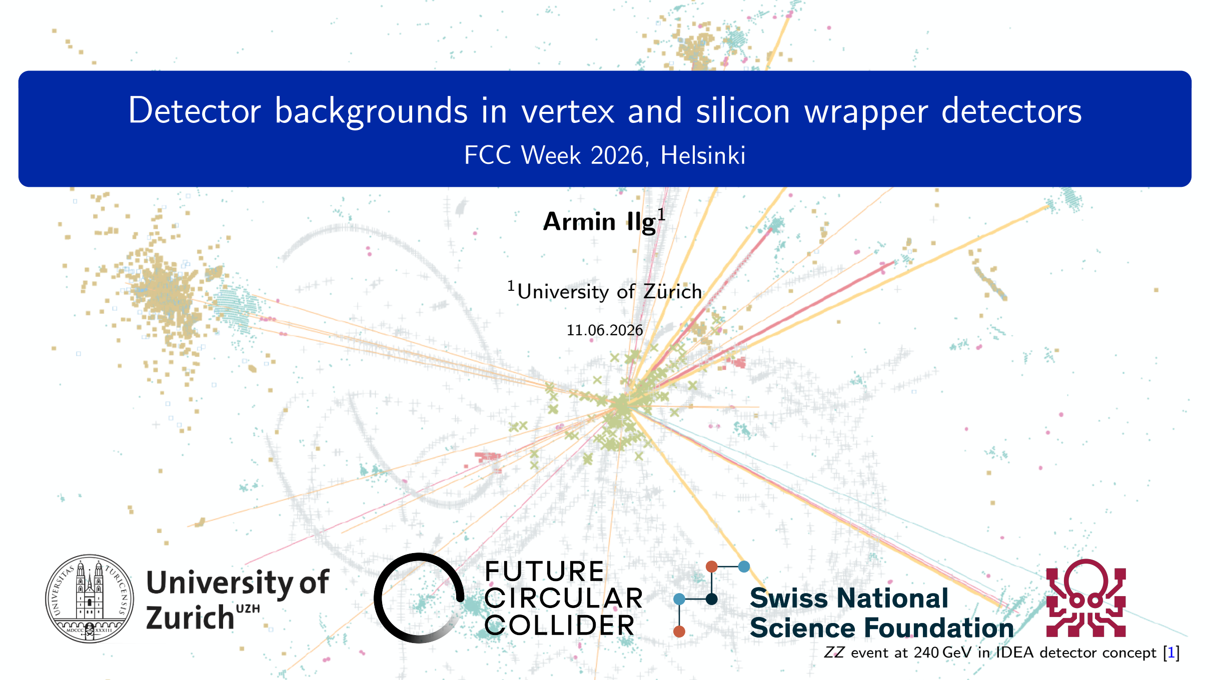
Detector backgrounds in vertex and silicon wrapper detectors

FCC Week 2026, Helsinki

Armin Ilg[1]

[1]University of Zürich

11.06.2026



ZZ event at 240 GeV in IDEA detector concept [1]

University of Zurich UZH

FUTURE CIRCULAR COLLIDER

Swiss National Science Foundation

Setup and studies to be presented

Beam background evaluation

- Using BIB samples from `/eos/project/f/fcc-ee-mdi/BIB/` as input for ddsim
- Central det. samples: `/eos/experiment/fcc/ee/simulation/key4hep_2026_04_08/91GeV/`
- Following recipe and using scripts from bib-studies repo
- Assumed bunch crossing rate of 37.04 MHz for LCCv106 lattice (newest) samples
- Z pole, incoherent pair creation (IPC) and synchrotron radiation (SR) background
- Safety factor of 3, cluster size of 5 (2) for IPC (SR) background

Machine-detector interface

- mdi_v2 branch from A. Ciarma. Details: https://hep-fcc.github.io/FCCSW/mdi/

Vertex detector variants

- Default: IDEA/ALLEGRO stave-based vertex detector with $r_{\text{min}} = 13.7\,\text{mm}$. Threshold: $500e^-$
- Alternative: Stave-based vertex detector at $r_{\text{min}} = 11.8\,\text{mm}$. Threshold: $500e^-$
- Alternative: Ultra-light inner vertex detector at 13.7 mm. Threshold: $100e^-$
- Alternative: Ultra-light inner vertex detector at 11.8 mm. Threshold: $100e^-$

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- Z po
- Safe

→ Updated BIB samples and MDI region compared to my Physics Workshop presentation from January. More details about general methodology there.
Disclaimer: Fresh off the press, every plot is new compared to January. First results ∼ 1.5 weeks ago.

Machine

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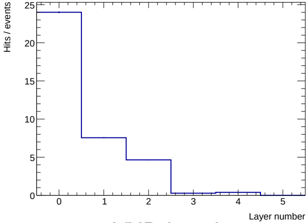
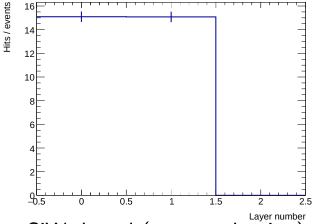
Incoherent pair production

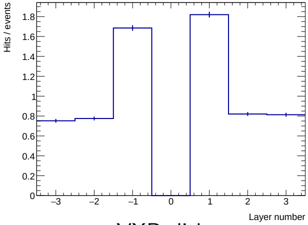
IPC (central samples): SIM hits



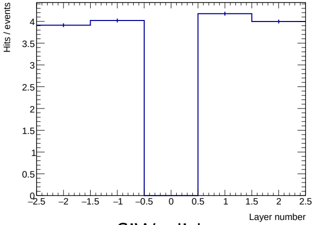
VXD barrel



SiWr barrel (own production)



VXD disks

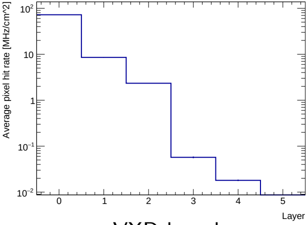


SiWr disks

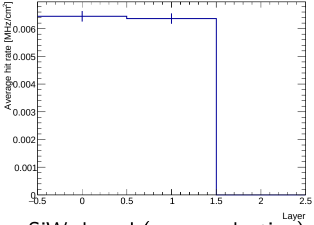
- v106.2 LCC lattice (latest), 15 mrad crossing angle boost applied, 2129 bunch crossings (out of 20501) used
- Much less SIM hits then in old samples (v23 GHC lattice) for VXD disks and SiWr

IPC (central samples): Average pixel hit rates

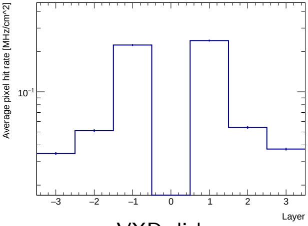
Pixel hit rate (not particle hit rate)



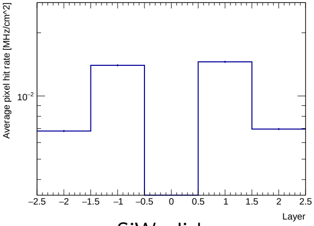
VXD barrel



SiWr barrel (own production)



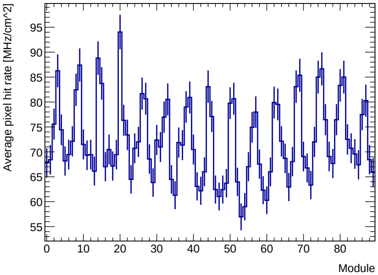
VXD disks



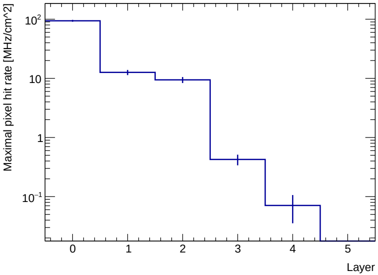
SiWr disks

- First VXD barrel hit rate reduced from 140 to $70\,\mathrm{MHz\,cm^{-2}}$
- VXD disks show factor ≥ 10 smaller rates (also when looking at raw sim hits)
- Same observed for SiWr barrel and disks

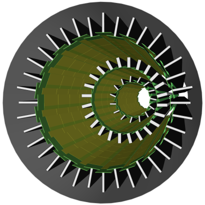
IPC (central samples): Module hit rates



VXD barrel first layer

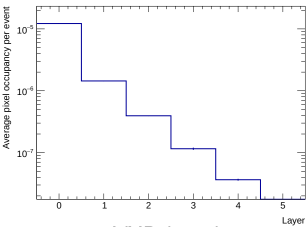


VXD barrel

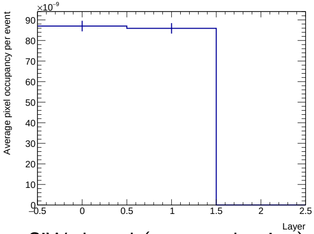


IDEA/ALLEGRO inner vertex detector in DD4hep

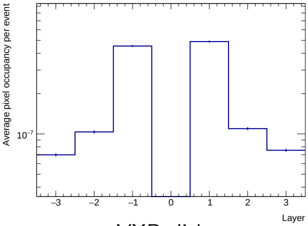
- VXD barrel from 170 to 100 $\mathrm{MHz\,cm^{-2}}$ for first layer
- For other subdetectors: Need to fix some bib-studies bugs to see per-module hit rate



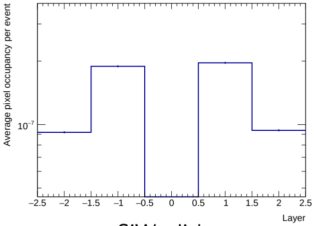
VXD barrel



SiWr barrel (own production)



VXD disks

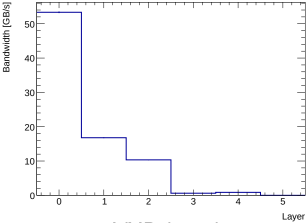


SiWr disks

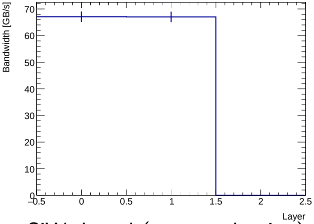
→ Corresponding much lower pixel occupancies in VXD disks and SiWr

- Assuming $t_{\text{int}} < t_{\text{BC}}$. Otherwise scale by $t_{\text{int}}/t_{\text{BC}}$.
- $25 \times 25\,\mu\text{m}^2$ (VXD barrel), $50 \times 150\,\mu\text{m}^2$ (VXD disks), $50 \times 1000\,\mu\text{m}^2$ (SiWr) pixel pitches
- Not taking into account sensor noise.

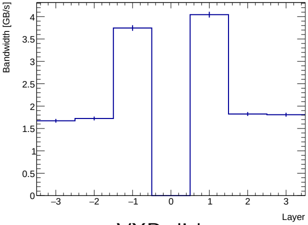
IPC (central samples): Bandwidths



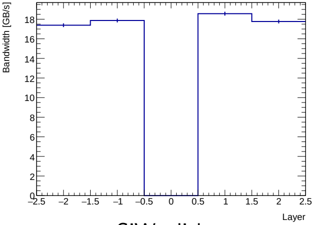
VXD barrel



SiWr barrel (own production)



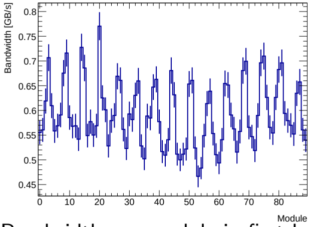
VXD disks



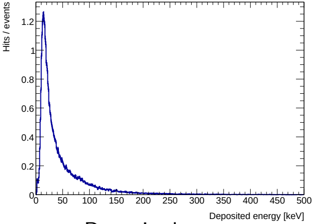
SiWr disks

- 32 bits per VXD pixel hit, 64 hits per SiWr pixel hit, no overhead or sensor noise accounted for
- Corresponding much lower bandwidths in VXD disks and SiWr

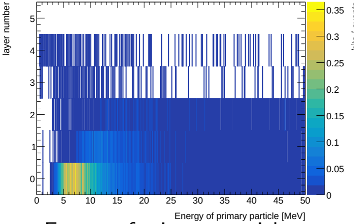
IPCs in VXD barrel: More details



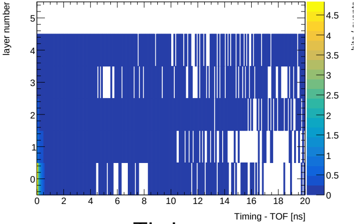
Bandwidth per module in first layer



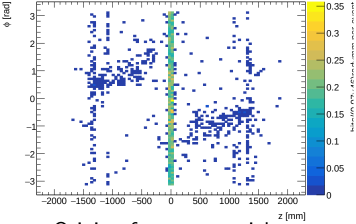
Deposited energy



Energy of primary particle



Timing



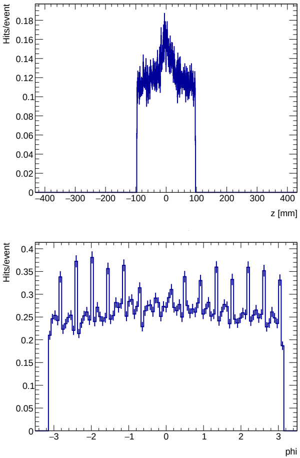
Origin of parent particle

As in past study: $\sim$ one 10 Gb/s fibre link per module. Timing not helping much to reject IPCs.

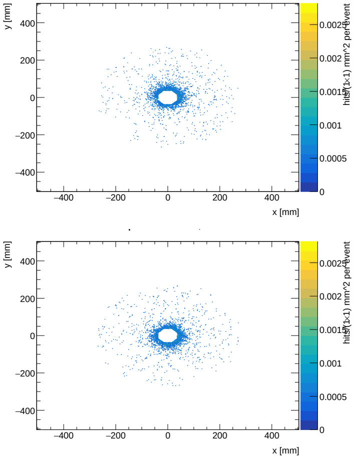
IPCs in VXD: Maps

University of Zurich[UZH]

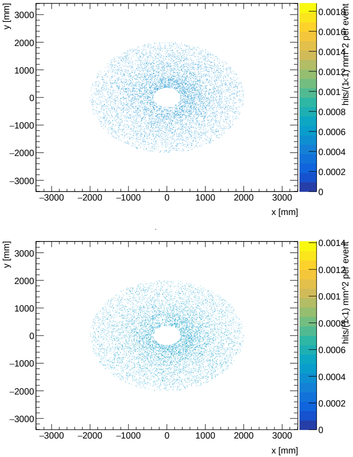
VXD barrel first layer



VXD disks -1 and +1

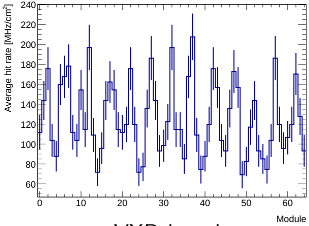


SiWr disks -1 and +1

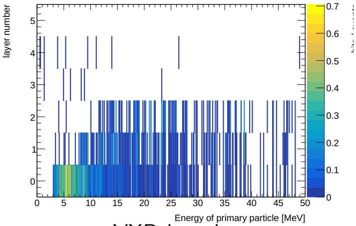


VXD barrel similar to previous studies, VXD disks don't have 'hot spots' anymore

Outer beam pipe radius of 11.7 mm, then 100 µm of Kapton. Reduced number of modules and staves.



VXD barrel



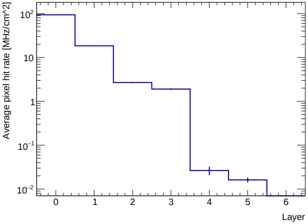
VXD barrel

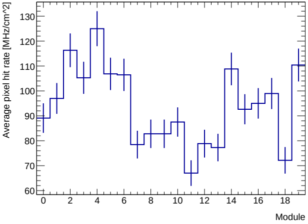
- Increased hit rate of 125 $\mathrm{MHz\,cm^{-2}}$ (average), max. hit rate of up to 200 $\mathrm{MHz\,cm^{-2}}$ in some modules
- Also lower-p_{T} particles will reach first layer

$\rightarrow$ More then from geometrical effect only ($13.7/11.8 = 1.16$)

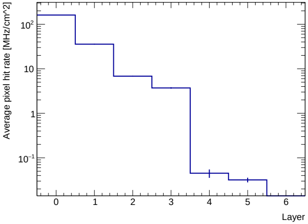
$\rightarrow$ Not crazy to think about going this close to the beam pipe in terms of IPC hit rates

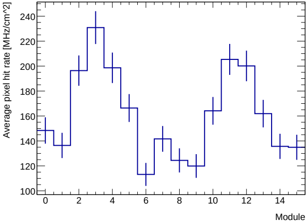
$r_{\text{min}} = 13.7\,\text{mm}$

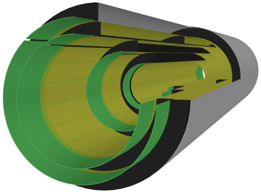




$r_{\text{min}} = 11.8\,\text{mm}$







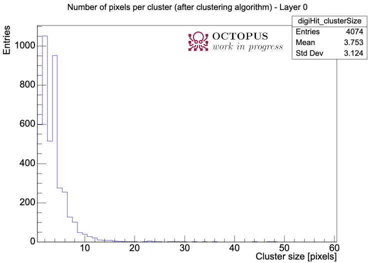
Ultra-light inner VXD in DD4hep

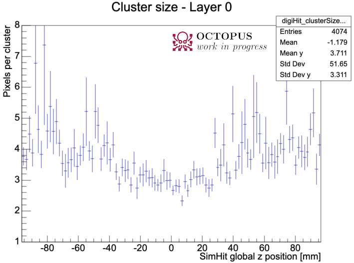
- Hit rates bit larger than in the stave-based design
- Lower average $r \rightarrow$ Higher hit density
- Especially modules around $z = 0$ get quite high rates (4th and 5th module in each half barrel for $r_{\text{min}} = 11.8\,\text{mm}$)

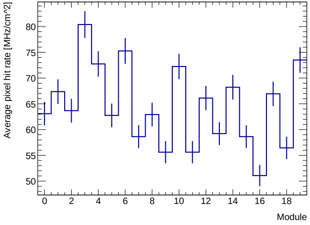
IPC in VXD barrel with realistic sensor charge sharing (1/2)

University of Zurich[UZH]

- Using look-up table (LUT) based digitiser (see talk from J. Dilg right now). LUTs from DRD3 OCTOPUS project in TCAD+Allpix2 simulation, interfaced to Key4hep. −1.2 V bias voltage, 2 T magnetic field
- 65 nm TPSCo process (also used in ALICE ITS3) → Apply to ultra-light inner vertex detector, $r_{\mathrm{min}} = 13.7$ mm
- In simulation: 38 μm insensitive silicon, then 12 μm sensitive silicon
- Threshold of $100e^-$ (realistic), 'standard layout' featuring lots of charge sharing



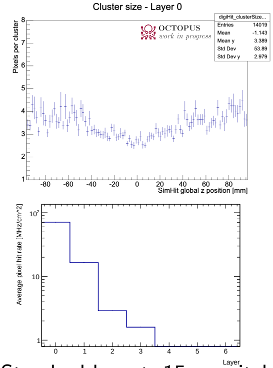




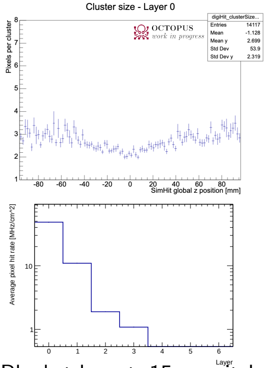
→ Even this LUT, with lots of charge sharing, features an average cluster size < 5

→ Cluster size higher in forward region, where there are less IPC pairs → Balancing out hit rate a bit (averge 70 compared to 100 MHz cm^{-2} in first layer)

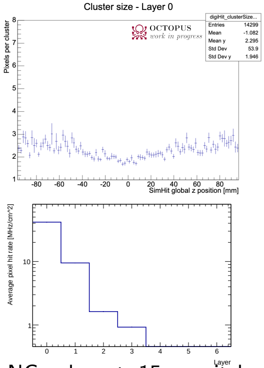
Allows to compare cluster sizes (and later also sensor resolution!) among different processes, bias voltages, pitches, etc.



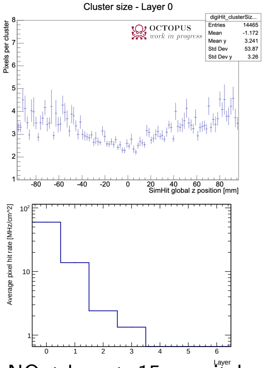
Standard layout, 15 µm pitch



Blanket layout, 15 µm pitch



NGap layout, 15 µm pitch



NOpt layout, 15 µm pitch

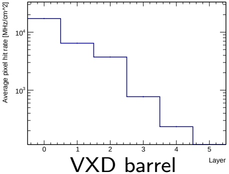
TDAQ requirements (bandwidth), sensor requirements (hit rate), and physics performance (more charge sharing = better resolution) all intertwined

Synchrotron radiation

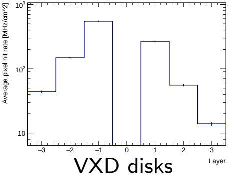
SR hit rates (central samples), 50 µm sensitive silicon

University of Zurich[UZH]

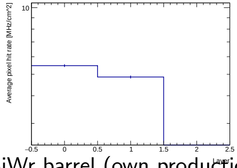
Halo (outermost 1% of bunch, 5 min τ_B): 21641 files totalling to a weight of 0.47 (used 2339)



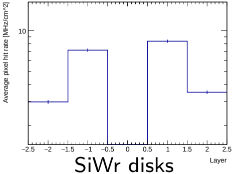
VXD barrel



VXD disks

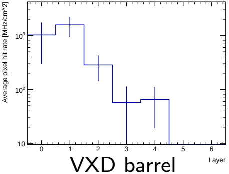


SiWr barrel (own production, 1680 evts)

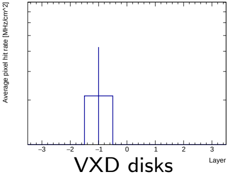


SiWr disks

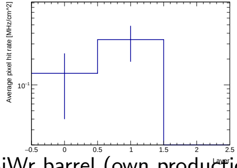
Core (other 99% of bunch): 65184 files totalling to a weight of 15.34 (used 7276)



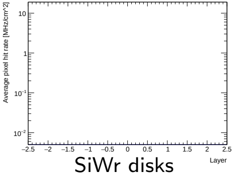
VXD barrel



VXD disks



SiWr barrel (own production, 2506 evts)

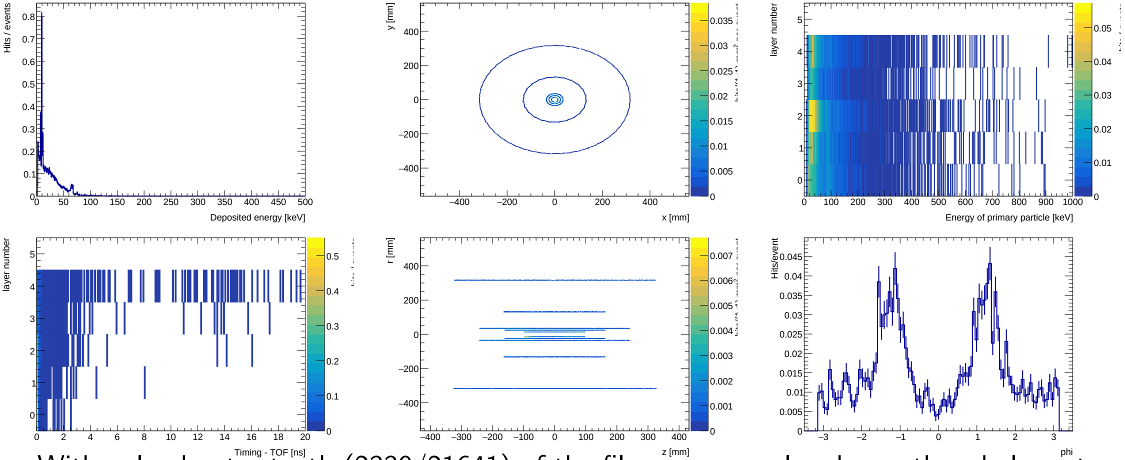


SiWr disks

$> 10\,\mathrm{GHz\,cm^{-2}}$ for beam halo in VXD barrel. This is not good! Especially in the vertex barrel, some SR photons survive flying through the beam pipe and hit the sensors, producing a large-enough energy deposit to be above threshold. Esp. beam halo looks scary (look at low stat. errors)

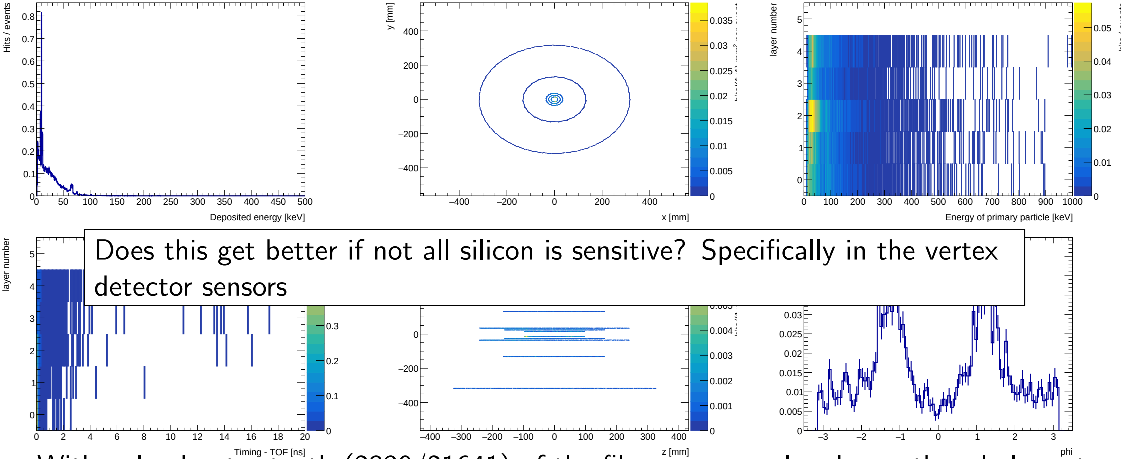
More details on SR halo in VXD barrel

University of Zurich[UZH]



- With only about a tenth (2339/21641) of the files, one can already see the whole vertex barrel light up...
- Higher threshold would not really help

More details on SR halo in VXD barrel

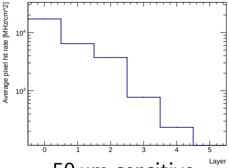


Does this get better if not all silicon is sensitive? Specifically in the vertex detector sensors

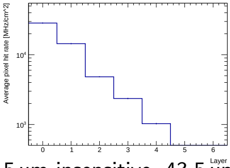
- With only about a tenth (2339/21641) of the files, one can already see the whole vertex barrel light up...
- Higher threshold would not really help

SR for different VXD sensor assumptions

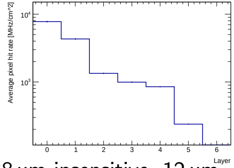
Halo



50 μm sensitive

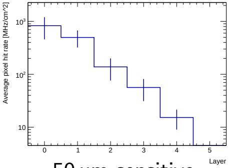


6.5 μm insensitive, 43.5 μm sensitive (ARCADIA)

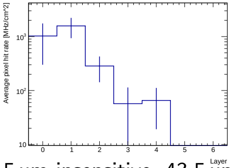


38 μm insensitive, 12 μm sensitive (ultra-light, TPSCo 65 nm)

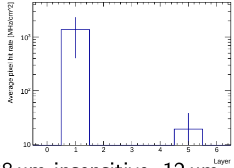
Core



50 μm sensitive



6.5 μm insensitive, 43.5 μm sensitive (ARCADIA)

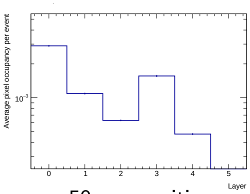


38 μm insensitive, 12 μm sensitive (ultra-light, TPSCo 65 nm)

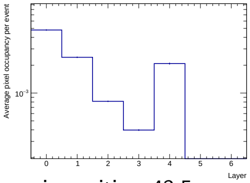
→ Does not solve the SR issue, but having a sensor with some insensitive thickness before the sensitive thickness reduces the hit rates by factor 3 (halo), need to run over more samples to properly evaluate impact on SR core

Assuming $t_{\text{int}} < t_{\text{BC}}$. Otherwise scale by $t_{\text{int}}/t_{\text{BC}}$. Not taking into account sensor noise.

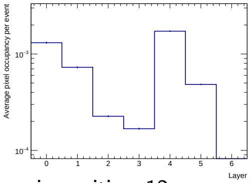
Halo



50 µm sensitive

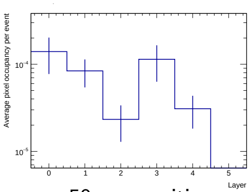


6.5 µm insensitive, 43.5 µm sensitive (ARCADIA)

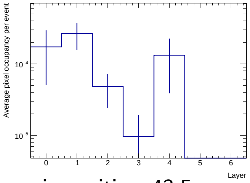


38 µm insensitive, 12 µm sensitive (ultra-light, TPSCo 65 nm)

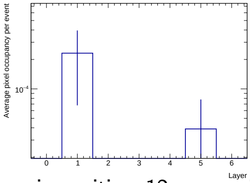
Core



50 µm sensitive



6.5 µm insensitive, 43.5 µm sensitive (ARCADIA)



38 µm insensitive, 12 µm sensitive (ultra-light, TPSCo 65 nm)

Pixel occupancies of $\sim 3 \times 10^{-3}$, reduced to $\mathcal{O}(10^{-3})$ with TPSCo 65 nm-like sensors.

Bandwidths equally bad (see backup)

Conclusions and discussion

University of Zurich[UZH]

Knowledge of hit rates in the VXD important for sensor R&D and TDAQ. VXD barrel first layer could define whether streaming readout is possible

- IPC background in VXD first layer reduced compared to previous study (old v23 lattice) $\rightarrow$ $< 100\,\mathrm{MHz\,cm^{-2}}$ (even lower with realistic digitiser)
- First layer closer to beam pipe increases hit rate by ~ 2
- IPC greatly reduced in VXD disks and SiWr

Larger SR samples for the first time allow to properly evaluate this background

- SR background looks very scary in both VXD and SiWr, esp. SR halo in VXD barrel

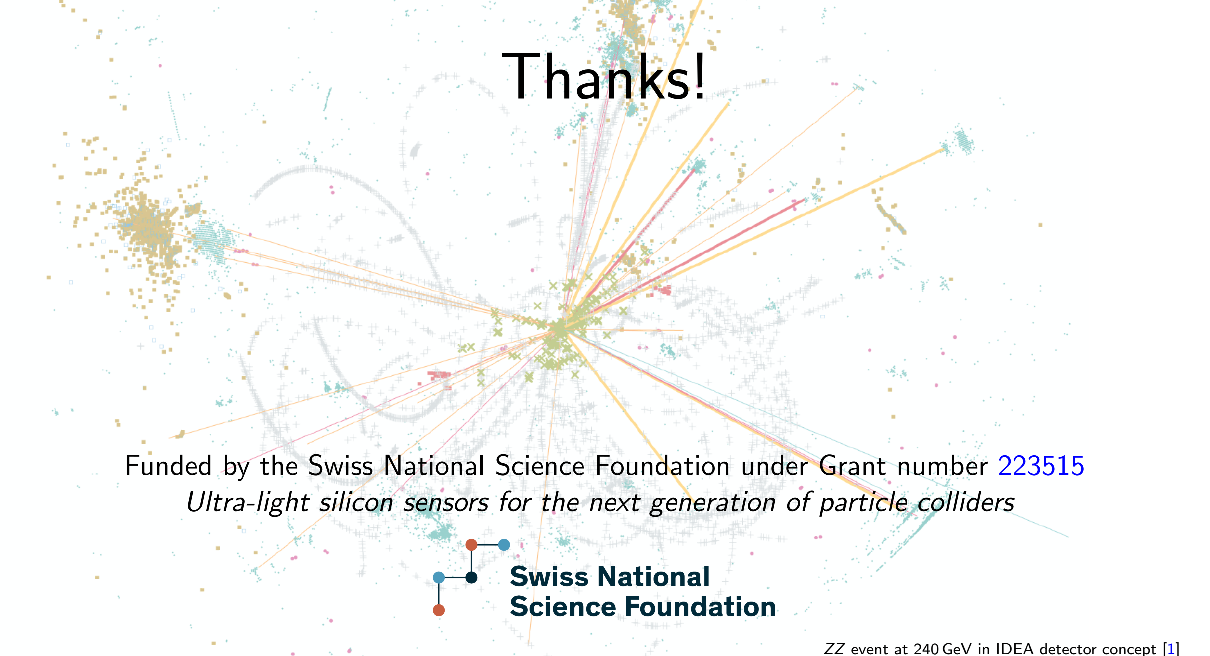
$\rightarrow$ Need to revisit lattice and MDI design. Unclear if older lattice designs had same magnitude of SR issue $\rightarrow$ to be checked

- Difference of ~ 3 between different VXD sensor assumptions. Relevant but not game changer

Next steps:

- Run over more SR samples to reduce stat. errors
- Evaluate BIBs in FCC-SEED vertex detector $\rightarrow$ No reason this should be very different to the ultra-light design, but should be checked
- How well does a thicker beam pipe Au coating help? How much is needed to suppress SR enough?
- Look at SR cluster size with LUT-based digitiser

Thanks!



Funded by the Swiss National Science Foundation under Grant number 223515

Ultra-light silicon sensors for the next generation of particle colliders

Swiss National Science Foundation

ZZ event at 240 GeV in IDEA detector concept [1]

University of Zurich[UZH]

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

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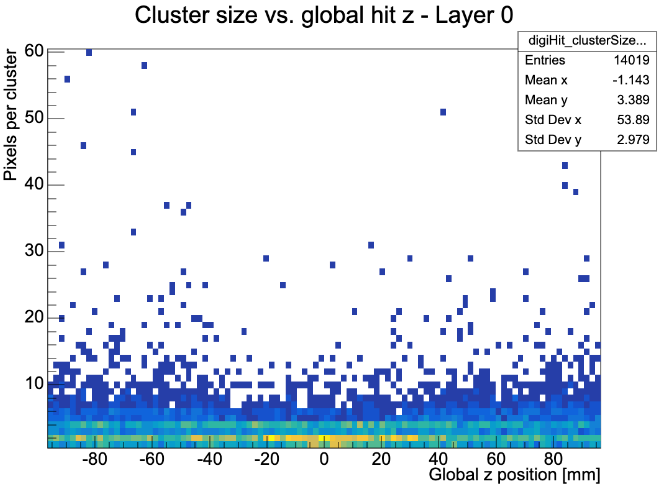
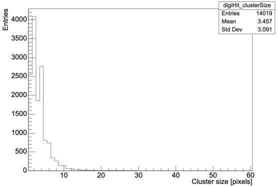
Cluster size vs. z in 2D



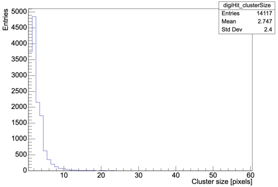
Standard layout, 15 µm pitch

Cluster size for different LUTs

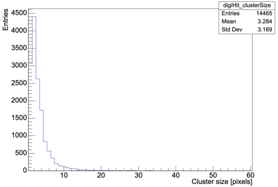
University of Zurich[UZH]



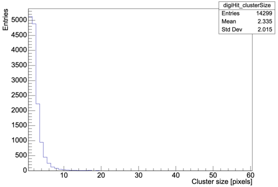
Standard layout, 15 μm pitch



Blanket layout, 15 μm pitch

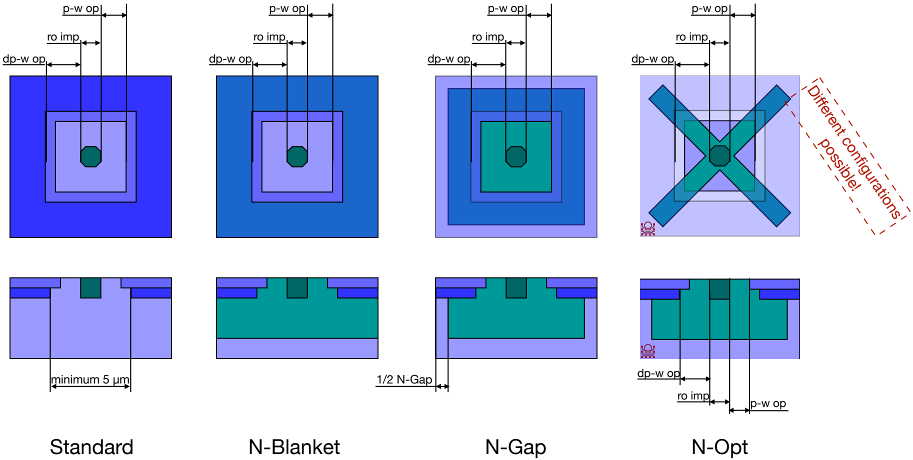


NOpt layout, 15 μm pitch



NGap layout, 15 μm pitch

Sensor Layouts



5

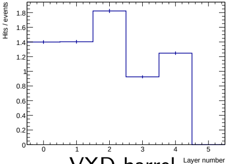
A.Velyka | 4th DRD3 Week | 13.11.2025

Sensor layouts in OCTOPUS (A. Velyka @ 4th DRD3 workshop)

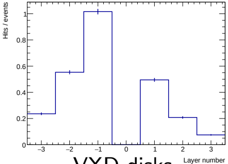
SR SIM hits (central samples), 50 μm sensitive silicon

University of Zurich[UZH]

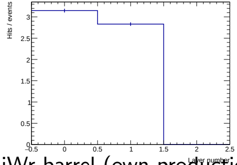
Halo (outermost 1% of bunch, 5 min τ_B): 21641 files totalling to a weight of 0.47 (used 2339)



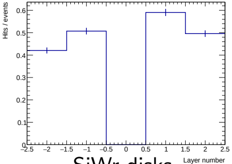
VXD barrel



VXD disks

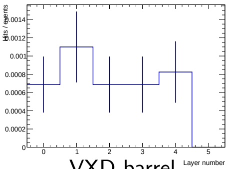


SiWr barrel (own production, 1680 evts)

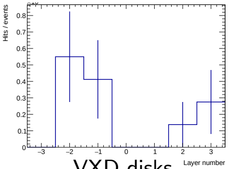


SiWr disks

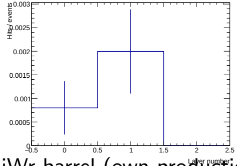
Core (other 99% of bunch): 65184 files totalling to a weight of 15.34 (used 7276)



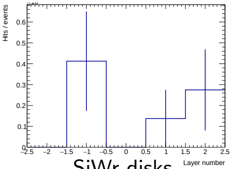
VXD barrel



VXD disks



SiWr barrel (own production, 2506 evts)



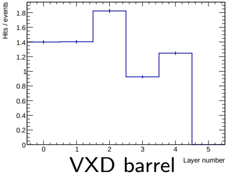
SiWr disks

!!! SIM hits per event (file). But actually, they all together only describe 1/0.47 or 1/15.34 of a BC !!!

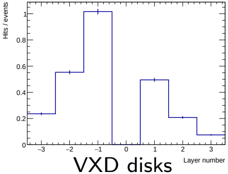
SR SIM hits (central samples), 50 µm sensitive silicon

University of Zurich[UZH]

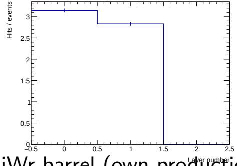
Halo (outermost 1% of bunch, 5 min τ_B): 21641 files totalling to a weight of 0.47 (used 2339)



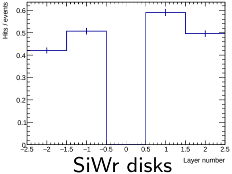
VXD barrel



VXD disks



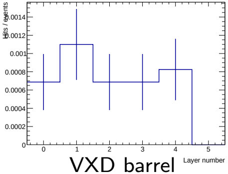
SiWr barrel (own production, 1680 evts)



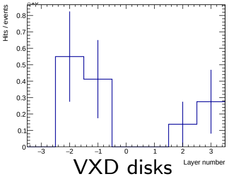
SiWr disks

Core (oth

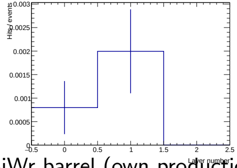
To get to actual rate, need to scale by * #files * weight * #filesTotal/#files



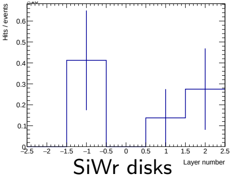
VXD barrel



VXD disks



SiWr barrel (own production, 2506 evts)

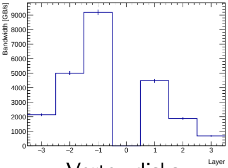


SiWr disks

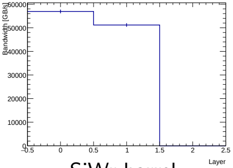
!!! SIM hits per event (file). But actually, they all together only describe 1/0.47 or 1/15.34 of a BC !!!

All assuming 50 μm sensitive silicon

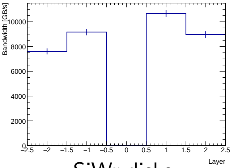
Halo



Vertex disks

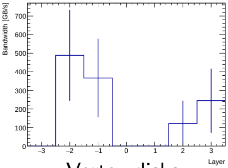


SiWr barrel

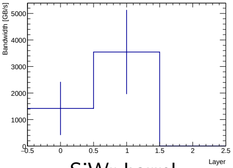


SiWr disks

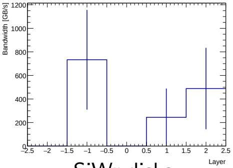
Core



Vertex disks



SiWr barrel



SiWr disks

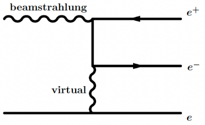
Correspondingly, also the SR bandwidths are bad...

IPCs are considered to be the dominant background for the vertex detector at FCC-ee

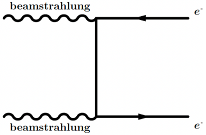
→ Last study (see backup): 90 MHz cm^{-2} in 1st vertex barrel layer

Today's study:

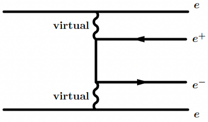
- 3994 bunch crossings in GuineaPig (v23 lattice, samples by A. Ciarma)
- IDEA/ALLEGRO vertex detector with CAD beam pipe, GuineaPig particles set to (0.0,0) (good approximation)
- Detector simulation with ddsim/Key4hep (samples by S. Franchellucci) with IDEA steering file, modified
  - `SIM.physicsList = "FTFP_BERT_EMZ"`
  - `SIM.filter.tracker = "edep0"`
  - `SIM.ui.commandsConfigure = ["/cuts/setLowEdge 50 eV", "/process/em/lowestElectronEnergy 1 eV", "/process/em/auger true" , "/process/em/deexcitationIgnoreCut true"]`



(a) *Bethe-Heitler*



(b) *Breit-Wheeler*



(c) *Landau-Lifschitz*

IPC diagrams at LO [2]

Even earlier IPC estimations

- IPC simulated in GuineaPig MC generator and interfaced with Key4hep
- SIM hit to REC hit conversion: Assume cluster size of 5 (conservative), safety factor of 3, $25 \times 25\,\mu m^2$ pixels

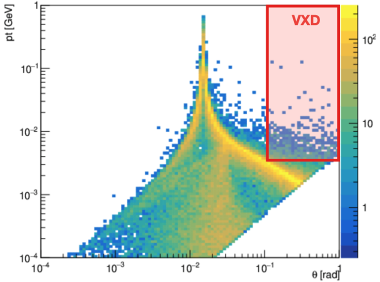
Occupancy and hit rates:

- 2022, old lattice with 30 ns bunch spacing, CLD vertex detector, 70×10^{-6} per BC $\widehat{=}$ 373 MHz cm^{-2} [3]
- 2024, V23 lattice, IDEA vertex detector: 20×10^{-6} per BC $\widehat{=}$ 170 MHz cm^{-2}, 19.2 ns bunch spacing
- 2024, V23 lattice, ultra-light vertex detector: 30×10^{-6} per BC $\widehat{=}$ 250 MHz cm^{-2}, 19.2 ns bunch spacing
- 2025, V23 lattice, IDEA vertex detector with CAD beam pipe, GuineaPig particles set to (0,0,0), *SIM.filter.tracker = "edep0"*: 11×10^{-6} per BC $\widehat{=}$ 90 MHz cm^{-2}, but bug in CAD beampipe (Air inside), 19.2 ns bunch spacing, samples by B. Francois

University of Zurich[UZH]

Unique vertex detector properties:

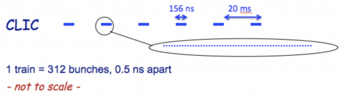
- Fully integrated into machine-detector interface (MDI) region (beam pipe, lumical) → Defining r_{min}, z_{max}, ...
- Most affected by beam backgrounds and beam properties → Driving hit rates and timing requirements
  - Circular colliders: Bunch collisions at $\mathcal{O}(40\,\text{MHz})$
  - Linear colliders: Bunch trains → Power pulsing → Lower power consumption → Simpler/less cooling



Incoherent pairs at FCC-ee Z pole [3]

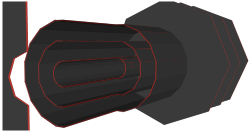
Performance requirements

- $\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$ with $a \approx 3\,\mu\text{m}$, $b \approx 15\,\mu\text{mGeV}$ (FCC-ee)
  - *a* by sensor resolution → Small single-hit resolution, pixels
  - *b* by *multiple scattering* → Minimise material budget (number of radiation lengths X_0) in vertex and beam pipe
- → A bit relaxed at higher $\sqrt{s}$ machines



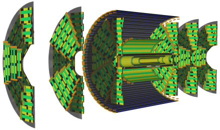
Bunch structure at CLIC [4]

CLD VXD
(CLD/ILD), [5]



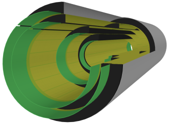
- Adapted from CLIC design
- $r_{\text{min}} = 13\,\text{mm}$
- Three double-layer barrel layers and disks, 0.6–0.7% X_0 per double layer
- No specific sensor chosen, assume 3 μm resolution

Classic IDEA VXD
(IDEA/ALLEGRO), [6]



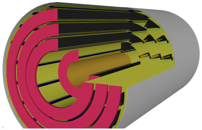
- $r_{\text{min}} = 13.7\,\text{mm}$
- 3 inner barrel (0.25% X_0), 2 outer barrel layers, 3 disks
- Engineered design (Pisa) integrated into MDI (LNF [7])
- IDEA baseline: ARCADIA [8] (inner barrel) and ATLASPix3 [9] (outer barrel and disks)

Ultra-light inner VXD
(IDEA/ALLEGRO), [10]



- Curved, 2D-stitched MAPS (ALICE ITS3-like [11])
- Four layers 0.075% X_0 per layer
- Sensitive sensor fraction of ≈ 95%
- Powering via metal layers, readout in silicon

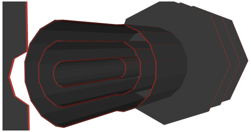
FCC-SEED VXD
(being added to ILD)



- Curved, 1D-stitched MAPS
- Five layers, ≈ 0.1% X_0 per layer
- Overlapping curved sensors to avoid gaps
- Powering and readout via long flex cables

Vertex detector designs at FCC-ee

CLD VXD
(CLD/ILD), [5]



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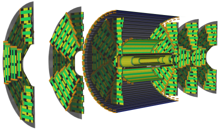

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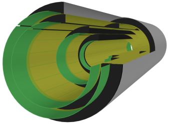

- Curved, 2D stitched ... ITS3-like [11])
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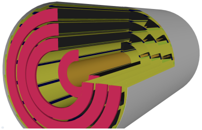

- Curved, 1D stitched
- Five layers, $\approx 0.1\%$ X_0 per layer
- Overlapping curved sensors to avoid gaps
- Powering and readout via long flex cables

Compromise between material budget and hermeticity, resolution

Technologies for vertex detectors @ e^+e^- colliders

Light, low-power, small pixels, reasonable timing? $\rightarrow$ Monolithic active pixel sensors (MAPS)!

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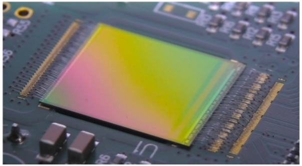
Let's look at three examples of MAPS developments!

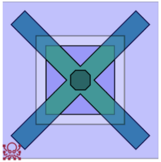
Technologies for vertex detectors @ e^+e^- colliders

Light, low-power, small pixels, reasonable timing? → Monolithic active pixel sensors (MAPS)!

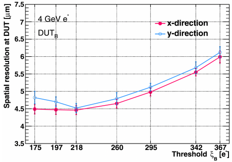
	ARCADIA [12]	**OCTOPUS [13]**	**TaichuPix [14]**
Process	110 nm LFoundry	65 nm TPSCo	TJ 180 nm
Pitch [μm²]	25×25	$\mathcal{O}(20 \times 20)$	25×25
σ_{xy}[μm]	Down to 4.6 [15]	Goal: 3	Down to 4.5 [16]
Timing	$\mathcal{O}$(ns) to $\mathcal{O}$(10's of ps)	5 ns time tag with ToT	∼ 100 ns time dispersion
Size [cm²]	1.28×1.28, side-abuttable	$\approx 2 \times 3$	2.56×1.28
Thickness [μm]	< 50 to 500	50	150
Power [mW cm^{-2}]	< 30	≤ 500 (first prototype), ≤ 50 (goal)	< 200
Pixel hit rate [MHz cm^{-2}]	Up to 100	100, matrix readout with Asynchronous Priority Arbiter	Spec: 36 [17]
Project status	Full-scale proto.: MD3	Design phase	Full-scale proto.: TaichuPix3



ARCADIA MD3 chip [12]



N-opt sensor variation in OCTOPUS (A. Velyka @ 4th DRD3 week)



TaichuPix3 spatial resolution [14]

Light, low-power, small pixels, reasonable timing? → Monolithic active pixel sensors (MAPS)!

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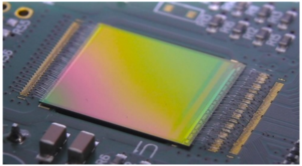
Power [mW cm...			
Pixel hit rate [MHz cm^{-2}]	Up to 100	100, matrix readout with Asynchronous Priority Arbiter	Spec: 36 [17]
Project status	Full-scale proto.: MD3	Design phase	Full-scale proto.: TaichuPix3

The challenge: Meeting all vertex requirements simultaneously while keeping power consumption low



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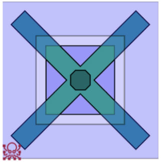

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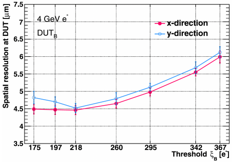


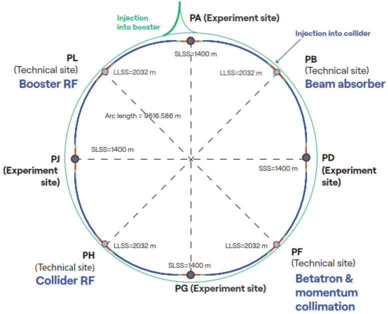
TaichuPix3 spatial resolution [14]

The Future Circular Collider (FCC) integrated programme

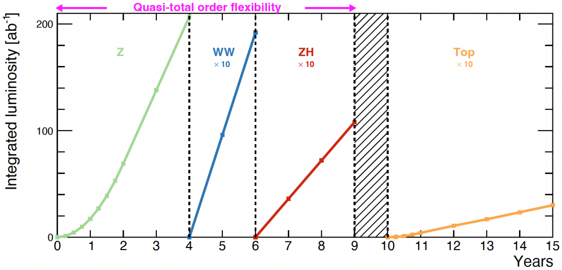
Circular collider with 90.7 km circumference machine to serve HEP for the rest of the century

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

Paving the way towards a **hadron collider** reusing the tunnel and much of the infrastructure $\rightarrow$ Direct discovery reach beyond 10 TeV energy scale



FCC-ee layout with four collision points and four technical insertions [18]



Baseline operation model for FCC-ee [19]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z
H: $1.78 \cdot 10^6$ HZ, 125k WW $\rightarrow$ H
Top: $1.9 \cdot 10^6$ $t\bar{t}$
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$!

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

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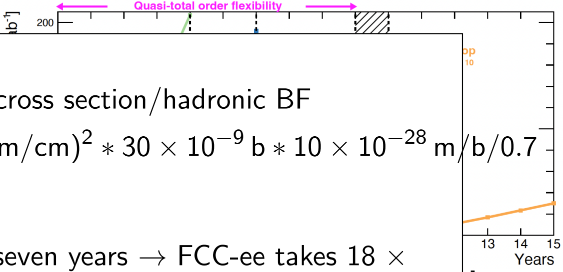
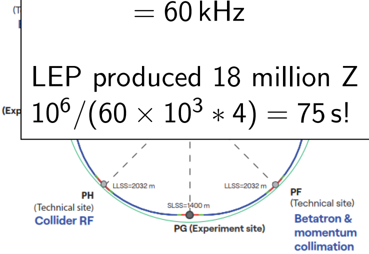
Paving the way towards a **hadron collider** reusing the tunne… discovery…



$$f_{Z\ \text{per IP}} = \text{inst. luminosity} * \text{hadronic cross section}/\text{hadronic BF}$$
$$= 140 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}/(0.01\,\text{m}/\text{cm})^2 * 30 \times 10^{-9}\,\text{b} * 10 \times 10^{-28}\,\text{m}/\text{b}/0.7$$
$$= 60\,\text{kHz}$$

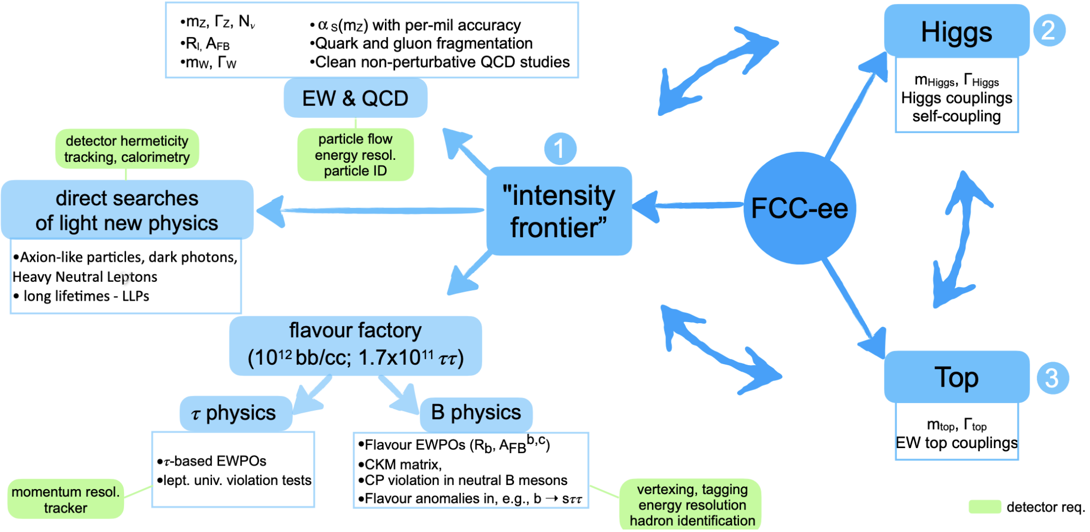
LEP produced 18 million Z bosons in seven years $\rightarrow$ FCC-ee takes $18 \times 10^6/(60 \times 10^3 * 4) = 75\,\text{s}$!



FCC-ee layout with four collision points and four technical insertions [18]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z
H: $1.78 \cdot 10^6$ HZ, 125k WW $\rightarrow$ H
Top: $1.9 \cdot 10^6$ $t\bar{t}$
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$!

Overview of FCC-ee physics case

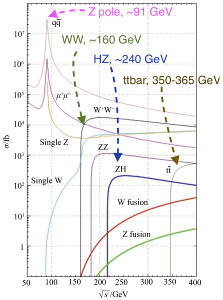


C. Grojean

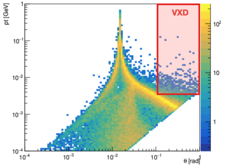
☺: e^+e^- collisions are *clean* - there's no QCD in the initial state

☹: Very high inst. luminosity of $140 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ thanks to 40 MHz bunch collision rate ($t_{BC} = 25$ ns currently)

- Very high rate of interesting events (60 kHz of Z, 18 kHz of $\gamma\gamma \rightarrow$ hadrons, 30 kHz of bhabha pairs) that need to be read out and saved (and simulated!)
- "Pile-up" Z bosons of $\sim 50\,\text{kHz}/50\,\text{MHz} = 0.00162$
  - $\rightarrow$ Integrate over of a couple of bunch crossings?
  - $\rightarrow$ But need to check impact on uncertainties
- Considerable beam backgrounds, mainly from incoherent pairs
  - High hit rate innermost vertex layers, occupancy challenges in gaseous tracker and ECAL
  - $\rightarrow$ Challenge also for readout
  - Few 10^{13} 1 MeV $\text{n}_{\text{eq}}\text{cm}^{-2}$ and few tens of kGy per year in vertex detector
- Unclear if hardware trigger is needed or not

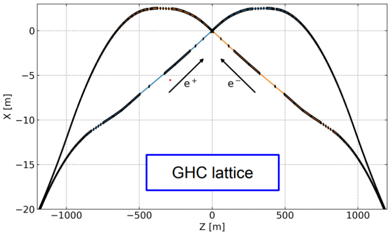


e^+e^- annihilation cross section [20]



Incoherent pairs at Z pole [3]

Synchrotron radiation

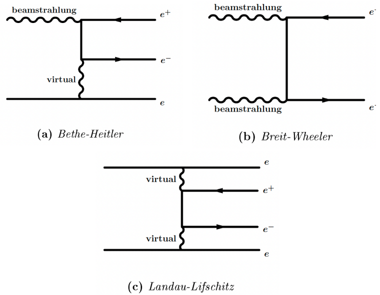


γ's emitted tangentially by charged particles when following curved trajectory, $\Delta E = \frac{e^2}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho}$ per cycle [21]

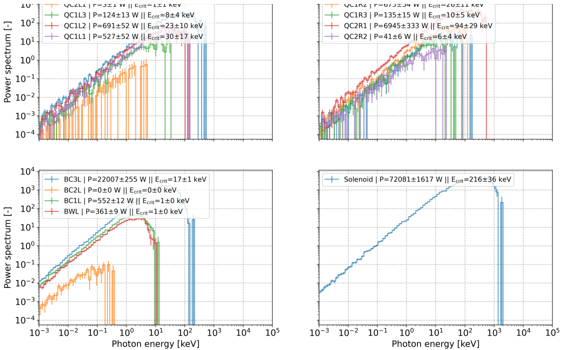
→ Design MDI region to avoid SR hitting the detector directly and add SR masks

Incoherent pair creation

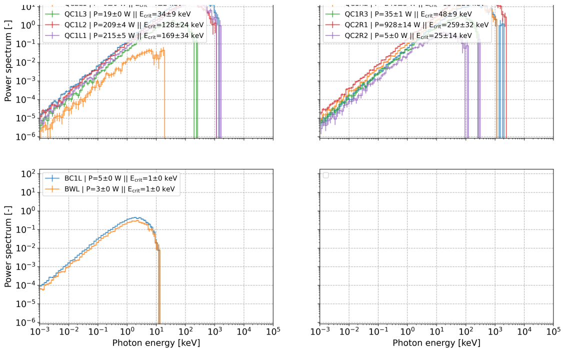
Beamstrahlung photons (synchrotron radiation emitted during collision in the EM field of the opposing beam) and beam particles make IPC background



IPC diagrams at LO [2]



Energy spectrum core



Energy spectrum halo

GHC V25.4, 5 min beam lifetime, 45 GeV beam energy

Vertexing at FCC-ee

For anything that has secondary and tertiary vertices!

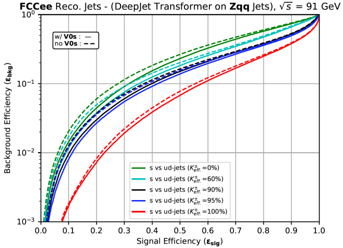
- b and c hadrons, taus, V0s, ...
- Reconstruct complex decay chains
- Particle lifetime measurements (τ, oscillations)
- Efficient flavour tagging (b/c/g/**s**)

Stringent requirements on vertexing to limit syst. uncertainties:

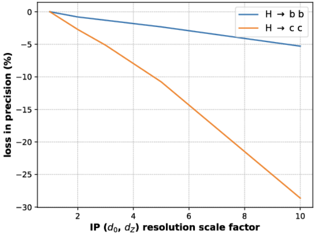
→ Coverage down to $|\cos(\theta)| \lesssim 0.99$ and high reco. efficiency

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

- *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 [22]



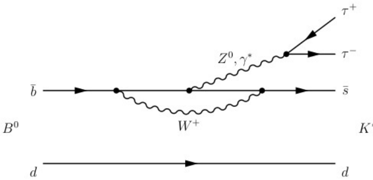
Impact of IP resolution on Yukawa coupling measurement (L. Gouskous)

The golden vertexing channel at FCC-ee: $B^0 \to K^{*0}\tau^+\tau^-$

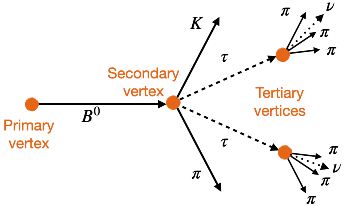
- $B^0 \to K^{*0} + \tau^+ + \tau^-$ not observed yet, limit of BR $< \mathcal{O}(10^{-3}\text{–}10^{-4})$
  $\to$ but SM value at 10^{-7}, strongly enhanced in many beyond SM theories!

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

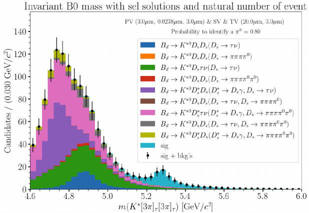
$\to$ Precise vertex reconstruction crucial!



Feynamn diagram [23]



Two three prong decays



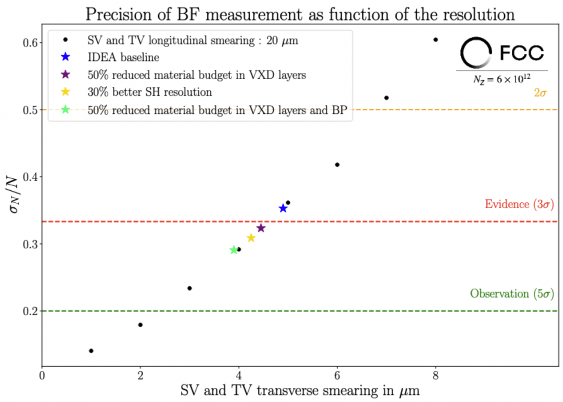
Reconstructed B^0 mass [24]

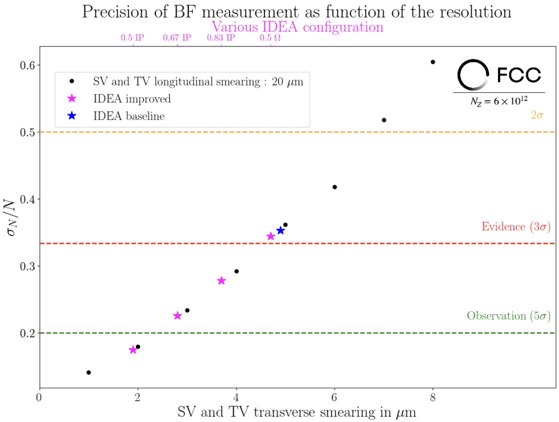
Close to evidence using current IDEA baseline in Delphes fast simulation study [24]

Assumptions:

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

Further improving $B^0 \to K^{*0}\tau^+\tau^-$ sensitivity





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**!

FCC-ee detector requirements in a nutshell

University of Zurich[UZH]

Beam pipe and vertexing

Example: $B^0 \to K^{*0}\tau^+\tau^-$, BR improvement from $\mathcal{O}(10^{-3})$ down to SM value of 10^{-7} [24]

- Material budget of beam pipe $< 0.5\%\ X_0$
- Material budget of vertex $< 1\%$

$\to \quad \sigma_{d_0} = 3 \oplus 15/(p \sin^{3/2}\theta)\mu\text{m}$

Light and precise vertex detector

Tracking and particle identification (PID)

Example: δM_{H} down to 4 MeV, $\delta\Gamma_{\text{Z}}$ down to 15 keV (study)

$\to \quad \sigma_p/p < 0.1\,\%$ for $\mathcal{O}(50)$GeV tracks

Example: $H \to s\bar{s}$ [25], $b \to s\nu\bar{\nu}$

$\to \quad 3\sigma\ K/\pi$ separation for $p < 40$ GeV

Superb momentum resolution

Strong particle identification capabilities

Electromagnetic calorimeter

Example: $Z \to \nu_e\bar{\nu}_e$ coupling [26], $B_s \to D_s K$

$\to \quad \sigma_E/E = 3\,\%/\sqrt{E}$

Example: τ polarisation [27]

$\to \quad \Delta x \times \Delta y = 2 \times 2\,\text{mm}^2$

Hadronic calorimeter

Example: $H \to s\bar{s}/c\bar{c}$ [28]

$\to \quad \sigma_E/E = 30\,\%/\sqrt{E}$

$\to \quad \Delta x \times \Delta y = 2 \times 2\,\text{mm}^2$

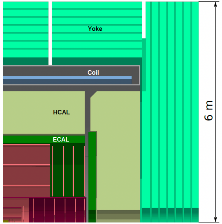
High granularity, good hadronic resolution

FCC-ee detector requirements in a nutshell

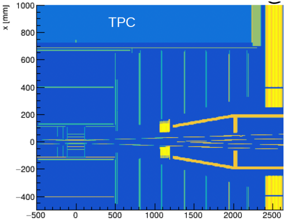
	Aggressive	Conservative	Comments
Beampipe	$X/X_0 < 0.5\%$	$X/X_0 < 1\%$	$\mathrm{B} \to \mathrm{K}^*\tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15\,/\,(p \sin^{3/2}\theta)\ \mu\mathrm{m}$ $X/X_0 < 1\%$	–	$\mathrm{B} \to \mathrm{K}^*\tau\tau$ R_c
	$\delta L = 5\,\mathrm{ppm}$	–	$\delta\tau_\tau < 10\,\mathrm{ppm}$
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\sigma_p/p < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_\mathrm{H} = 4\,\mathrm{MeV}$ $\delta\Gamma_\mathrm{Z} = 15\,\mathrm{keV}$ $\mathrm{Z} \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1\,\mathrm{mrad}$	$\delta\Gamma_\mathrm{Z}(\mathrm{BES}) < 10\,\mathrm{keV}$
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$\sigma_E/E = 10\%/\sqrt{E}$	$\mathrm{Z} \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y =$ $2 \times 2\,\mathrm{mm}^2$	$\Delta x \times \Delta y =$ $5 \times 5\,\mathrm{mm}^2$	τ polarisation boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100\,\mu\mathrm{m}$, $\delta R_{\mathrm{min}} = 10\,\mu\mathrm{m}\ (\theta = 20°)$	In-situ constraint with dilepton/diphoton events	alignment tolerance for $\delta\mathcal{L} = 10^{-5}$ with $\gamma\gamma$ events
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$\sigma_E/E = 50\%/\sqrt{E}$	$\mathrm{H} \to s\bar{s}, c\bar{c}, gg$, invisible HNLs
	$\Delta x \times \Delta y =$ $2 \times 2\,\mathrm{mm}^2$	$\Delta x \times \Delta y =$ $20 \times 20\,\mathrm{mm}^2$	$\mathrm{H} \to s\bar{s}, c\bar{c}, gg$
Muons	low momentum ($p < 1\,\mathrm{GeV}$) ID	–	$\mathrm{B_s} \to \nu\bar{\nu}$
Particle ID	$3\,\sigma$ K/π $p < 40\,\mathrm{GeV}$	$3\,\sigma$ K/π $p < 30\,\mathrm{GeV}$	$\mathrm{H} \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100\,\mu\mathrm{m}$, $\delta R_{\mathrm{min}} = 1\,\mu\mathrm{m}$ acceptance 50–100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$e^+e^- \to \gamma\gamma$ $e^+e^- \to e^+e^-\tau^+\tau^-(c\bar{c})$

FCC-ee detector requirements [19]

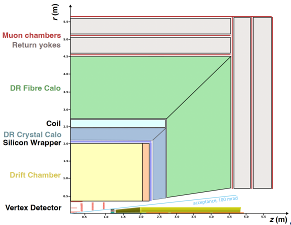
FCC-ee detector *concepts* (modulo some variations)



CLD [5, 29]



ILD [30, 31]



IDEA [1]

ALLEGRO [32]

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

CLD
- Si tracker
- $\mathrm{d}E/\mathrm{d}x$ + 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 $\mathrm{d}N_{\mathrm{ion.}}/\mathrm{d}x$
- 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)

FCC-ee accelerator design parameters

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658509			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0387	0.369	1.86	9.93
SR power / beam	[MW]	50			
Beam current	[mA]	1292	135	26.8	5.0
Colliding bunches / beam		11200	1856	300	60
Colliding bunch population	$[10^{11}]$	2.18	1.38	1.69	1.58
Hor. emittance at collision ε_x	[nm]	0.71	2.16	0.66	1.65
Ver. emittance at collision ε_y	[pm]	2.1	2.0	1.0	1.32
Lattice v. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.87	1.20	0.57	0.82
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	$[10^{-6}]$	28.52	28.67	7.52	7.57
Arc sext families		73		144	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		218.168 / 222.200	218.185 / 222.220	398.150 / 398.220	394.148 / 390.218
Chromaticities $Q'_{x/y}$		+5 / +5	0 / +5	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.115	0.069 / 0.105	0.102 / 0.176	0.152 / 0.186
Bunch length (SR/BS) σ_z	[mm]	5.15 / 15.2	3.46 / 5.28	3.26 / 5.59	1.91 / 2.34
RF voltage 400/800 MHz	[GV]	0.0885 / 0	1.00 / 0	2.09 / 0	2.10 / 9.20
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.788026			
Synchrotron tune Q_s		0.0310	0.0809	0.0334	0.0892
Long. damping time	[turns]	1179	218	65.4	19.4
RF acceptance	[%]	1.21	3.32	2.06	3.07
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.9	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	60	55	50	40
Beam-beam ξ_x/ξ_y[2]		0.0023 / 0.098	0.013 / 0.129	0.0108 / 0.130	0.066 / 0.144
Piwinski ang. $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		25.8	3.6	6.6	0.91
Lifetime (q + BS + lattice)	[sec]	5200	4500	6000	6300
Lifetime (lum)[3]	[sec]	1330	960	600	640
Luminosity / IP / 10^{34}	$[/\mathrm{cm}^2\mathrm{s}]$	144	20	7.5	1.45

FCC-ee design parameters [18]

Summary of vertex detector requirements (arXiv:2502.04071)

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 $a \approx 3\,\mu m$	$3\,\mu m$ single-hit resolution, small r_{min}
Multiple scattering: $b \approx 15\,\mu m\,GeV$	• 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 $\lesssim 1\,\mu s$
Beam backgrounds	Hit rate capability up to $\mathcal{O}(100\,MHz/cm^2)$
Radiation environment	Few 10^{13} 1 MeV $n_{eq}cm^{-2}$ 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	$\mathcal{O}(20\,ns)$ time resolution/$\mathcal{O}$(10's of ps)