Beam Backgrounds

FCC-ee design parameters

Summary of design parameters for FCC-ee

- Still being optimized – different lattices available (v22/23/24)
- Note the bunch spacings at the different energies
-

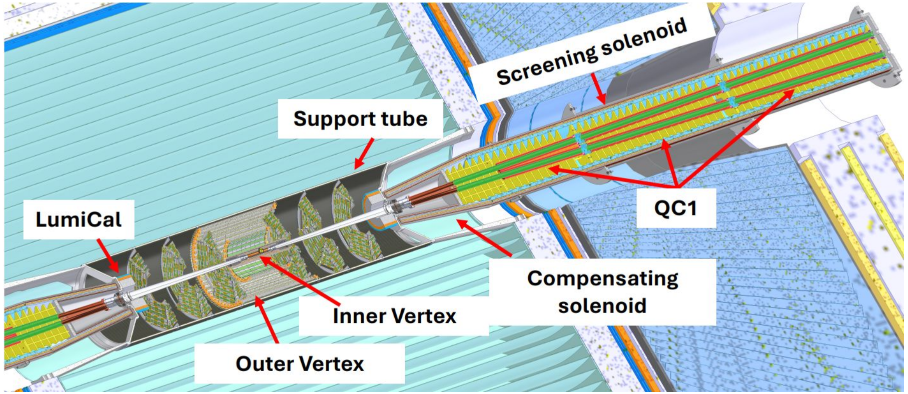
	Z	W^+W^-	ZH	$t\bar{t}$
Beam energy (GeV)	45.6	80	120	182.5
Luminosity / IP (10^{34} cm^{-2}s^{-1})	144	20	7.5	1.45
Beam current (mA)	1 292	135	26.8	5.0
Colliding bunches / beam	11 200	1 852	300	60
→ Bunch spacing (ns)	27	163	1 008	4 725
σ_x^* (μm)	8.84	21.8	12.6	36.9
σ_y^* (nm)	38.1	44.7	31.6	43.0
σ_z (mm) SR / BS	5.15 / 15.2	3.46 / 5.28	3.26 / 5.59	1.91 / 2.34
σ_δ (%) SR / BS	0.039 / 0.115	0.069 / 0.105	0.102 / 0.176	0.152 / 0.186

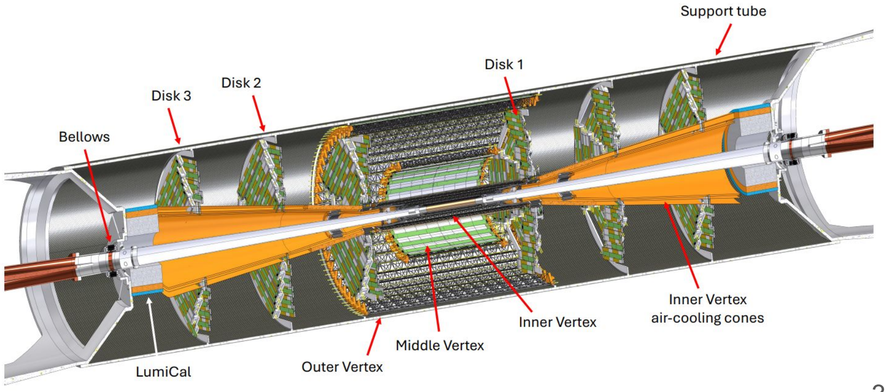
Machine Detector Interface (MDI)

MDI note released last week, info taken from there (https://repository.cern/records/p44x1-18z28)

Complex MDI at FCC-ee because the MDI equipment is partially in the detector volume

1. Final Focusing magnets (FFQ – QC1 in picture)
2. Compensating solenoid of (–5 T) to compensate for detector magnetic field (2 T)
3. Beam pipe split/merge at 1.1 m
4. LumiCal in forward region just before beams split/merge





Sources of beam induced backgrounds

Single beam induced (e+ or e–)

- Synchrotron Radiation (SR)
  - From last bending magnet (~ 100 m away) → collimators to reduce
  - From detector + compensating magnets inside detector volume
  - Samples are produced to get the SR photon flux, but still being validated
- Beam gas scattering – interactions near SR collimators might rise to showers (not yet studied)
- Beam halo losses
- Others (injection backgrounds, backgrounds related to beam instabilities, …)

Luminosity backgrounds – processes due to beam-beam interactions (e+e–)

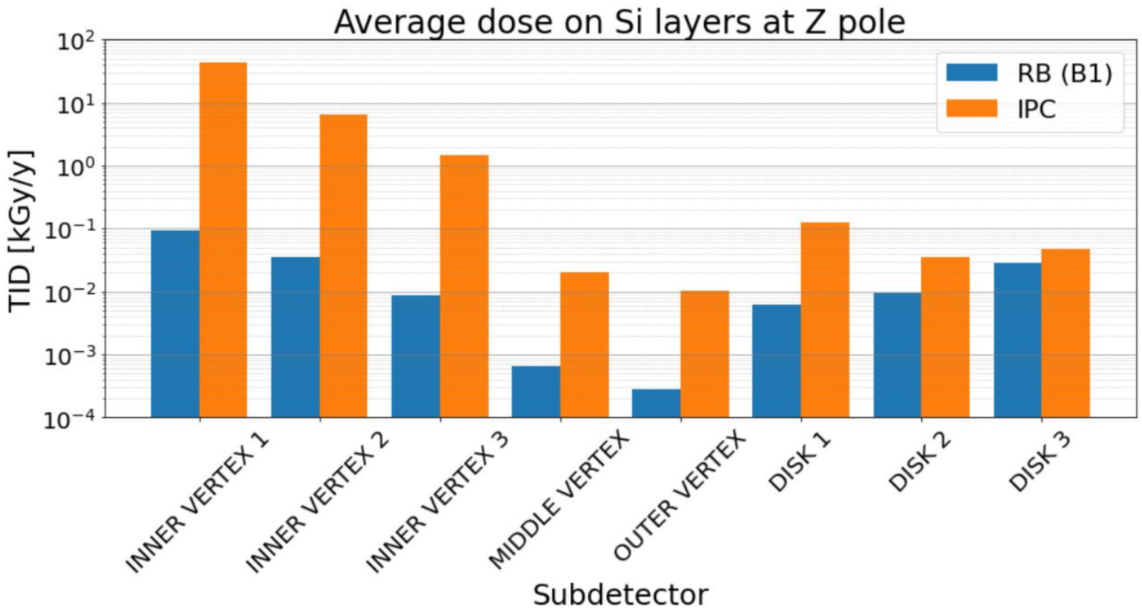
- Incoherent Pair Creation (IPC)
- Radiative Bhabha (RB) – forward e+ e– can cause showers in focusing quadrupoles
- Beamstrahlung (BS) – synchrotron radiation due to EM field of the opposing beam
- Two-photon backgrounds (muons, hadrons) – less impact on detector occupancy

Z pole most severe due to highest luminosity for all sources

Beam induced backgrounds

Generally considered that IPCs and radiative Bhabha contributes the most to beam-induced backgrounds for the detectors

- Dose calculations on inner vertex layer show highest contribution from IPCs
- RB becomes more important in forward region



Incoherent Pair Creation

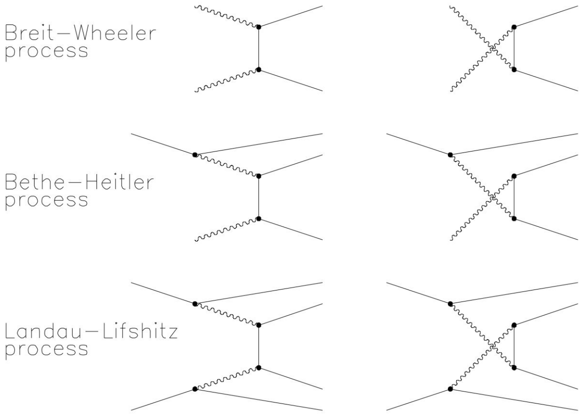
IPCs calculated with Guinea Pig

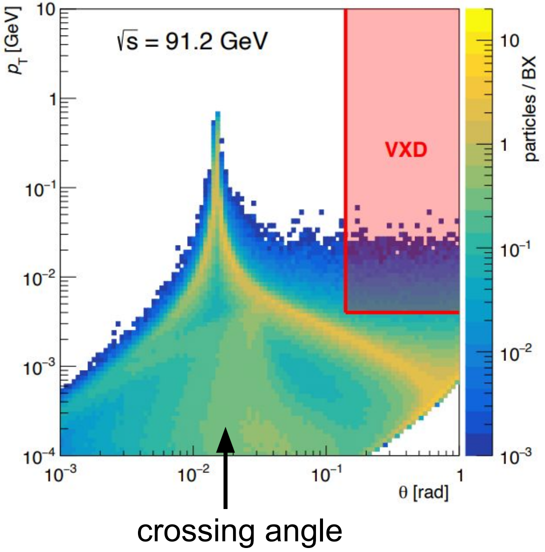
- Pairs are tracked in the EM fields of the beams by GP (slow!)
  - Detector magnetic field not taken into account (may have an impact on local occupancy – implementing atm.)
- Occupancy order of 100-200 MHz/cm2 at first VTX
- More severe for drift chamber with large integration time (400 ns) and space (similarly for LAr calorimetry)
- Cuts on energy deposits or topology can reduce the background “on-the-chip”
  - To be studied for VTX to suppress background contamination

IPC particles created 1300 at Z 3300 at tt per BX

- But majority outside of VTX acceptance

Parameter	Units	Z	WW	ZH	$t\bar{t}$
beam energy	GeV	45.6	80.0	120.0	182.5
IPC per Bunch Crossing		1300	1800	2700	3300
Bunch Spacing	ns	30	345	1225	7598





Radiative Bhabha (RB)

RB calculated using BBBrem

- Calculates precisely the e+e– cross-section produces events
- Only t-channel implemented, dominates the forward region
- No cut on polar angle of outgoing leptons, but cut on minimum energy transfer
- Effects of beam sizes taken into account

Cross-sections depend heavily on cuts applied

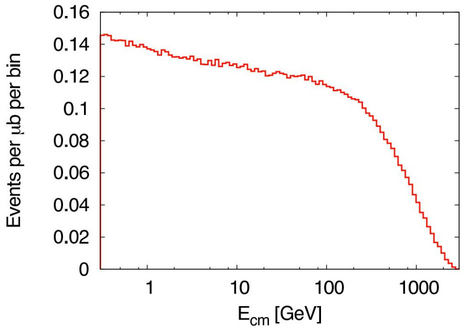
- 100 mbarn means ~ 5000 such RB processes per BX at Z-pole (mostly going forward)
- Backscattering effect via quadrupoles being studied (??)

				σ_{RB} [mbarn]		Luminosity/IP	
$E_0[GeV]$	Lattice	Cutoff		$\delta > 3\%$	$\delta > 50\%$	$[cm^{-2}s^{-1}]$	$[ab^{-1}yr^{-1}]$
45.6 (Z)	v530 (V22)	—	—	226.4	32.9	1.82×10^{36}	20.9
		$1\sigma_y$	33.7 nm	112.1	18.2		
182.5 (T)	v530 (V22)	—	—	251.3	37.0	1.24×10^{34}	0.14
		$1\sigma_y$	69.0 nm	118.5	19.2		

Two-photon background

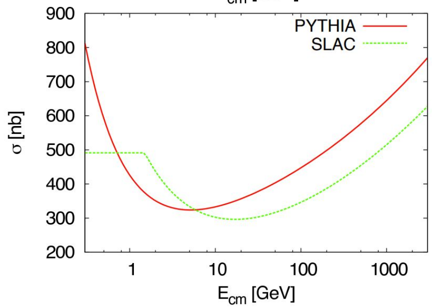
IPCs mainly focus on e+e– pair creation due to potential effects on detector occupancy and machine components

- Also muon pair creation possible with similar processes, having similar cross-section as IPCs
- Not considered to impact detector occupancies
- But might affect physics (modeling, differential distributions)



Similarly for e+e– → e+e–$\gamma\gamma$ → e+e– + hadrons

- Difficult to model → challenging for physics
- Cross-section parameterized (in Pythia and also in GP)
- Typical cross-section order of 500 nb (6 orders of magnitude lower than RB)
- Guinea pig produces the photon spectrum
  - Can also produce the hadronization and fragmentation (Jetset)
  - Or interfaced to another MC program (e.g. Whizard) by reading the photon spectra
- Producing some test samples right now



$$\sigma_H = 211\,\mathrm{nb}\cdot\left(\frac{s}{\mathrm{GeV}^2}\right)^{0.0808} + 297\,\mathrm{nb}\cdot\left(\frac{s}{\mathrm{GeV}^2}\right)^{-0.4525}$$

Hit occupancy from IPCs

From Guinea Pig, we calculate a background of ~ 200 MHz/cm2 on the first layer

- This should be verified independently

How does the background rate affect the single-cell pixels with a given readout time?

- Suppose we have pixels of 25x25um (target), with a readout time of 1us (large? conservative?)
- The probability to have a background event in a single pixel is 1.25e-3 = 0.125%
- This number is very small, therefore the (large) readout time is not critical for background occupancy (given the small cell size)
    - The occupancy still can be high w.r.t. to the readout of all cells from the entire layer

Does the same picture hold with trigger-less design?

Overview of samples + software

Analysis repository: https://github.com/jeyserma/FCCPhysics/tree/main/beam_backgrounds/vtx

- Changed code a bit (using ROOT histograms only, no BOOST due to incompatibility)
- Will push the code to generate the samples (at CERN)

Samples produced (focus on CLD Vertex detector with layout CLD_o2_v05)

- guineaPig_andrea_June2024_v23 → official samples
- guineaPig_andrea_June2024_v23_vtx000 → official samples (but IPCs placed at IP)
- FCCee_Z_4IP_04may23_FCCee_Z → re-generation of official samples, as a cross-check
- FCCee_Z_4IP_04may23_FCCee_Z_n128 → reduced lattice parameter from 256 to 128 cells (drastic speed up)

The 4 above samples have been validated and give the same physical results

Samples under production/validation

- Z→hadrons physics sample (today/tomorrow)
- With detector magnetic field (this week)
- Radiative Bhabha (this week) – only direct effect, no propagation yet to the quadrupoles)
- Synchrotron Radiation (this week)
- Two-photon backgrounds with muons and hadrons

TODO for students

1. Event display for IPCs: plot the phi-z 2D distribution for 1 event
2. Make comparison of the 4 samples above (energy deposit, hitmaps, occupancy)
3. For the baseline samples, calculate again the occupancy and convert it to a hit rate Hz/cm2 (should match the order or 100-200 MHz/cm2 as in the MDI note)
4. Detailed comparison of default and n128

BACKUP MAPS detectors

Achieving simultaneously $\sigma \approx 3$ µm, < 0.1 % $X0$ / layer, < 50 mW/cm², $\Delta t \approx O(100)$ ns within a single sensor seems unlikely with currently available CMOS technologies

Guidance from devices constructed or under advanced devt.

- **STAR-PXL**: 2 layers (1600 cm²), 0.37 % X_0/layer, 170 mW/cm² (~300 W), air cooled (10 m/s), < 4 µm

  Not adapted to FCCee: **~ 200 µs, bulky services (no end-caps);** *wind mill geom. (?)*
- **ALICE-ITS2**: 7 layers (> 10 m²), 0.35 % X_0/layer, < 50 mW/cm² (~500 W), air + water cooled, 5 µm

  Not adapted to FCCee: **~ 5-10 µs ?, mild hermiticity (end-cap) constraints;** *wind mill geom. (?)*
- **MU3E**: 4 layers (~ 1.1 m²), 0.12 % X_0/layer, < 250-350 mW/cm² (< 4 kW), He cooled, < 20 ns

  Not adapted to FCCee: **pixels of 80x80 µm² → < 30 µm, bulky services (no end-caps)**
- **CBM-MVD**: 4 2-sided stations (2000 cm²), < 100 mW/cm² (< 200 W), cooled mecha. support (TPG),

  Not directly adapted to FCCee: 5-6 µm**,** 0.5 % X_0/2-layer**, bulky services (no end-caps),** 5 µs (< 0.5 µs possible)
- **ALICE-ITS3**: 3 layers (1200 cm²), < 0.1 % X_0/layer, ~ 50 mW/cm² (~60 W), air cooled (8 m/s),~ 5 µm, ~ 2 MHz/cm²

  Not directly adapted to FCCee: **~ 2-10 µs, somewhat bulky services (mild constraints from end-caps)**

- **ATLAS-ITk**: 5 barrel layers + end-cap rings (13 m²), 3D & planar hybrid pixels (25x100 µm² & 50x50 µm²)

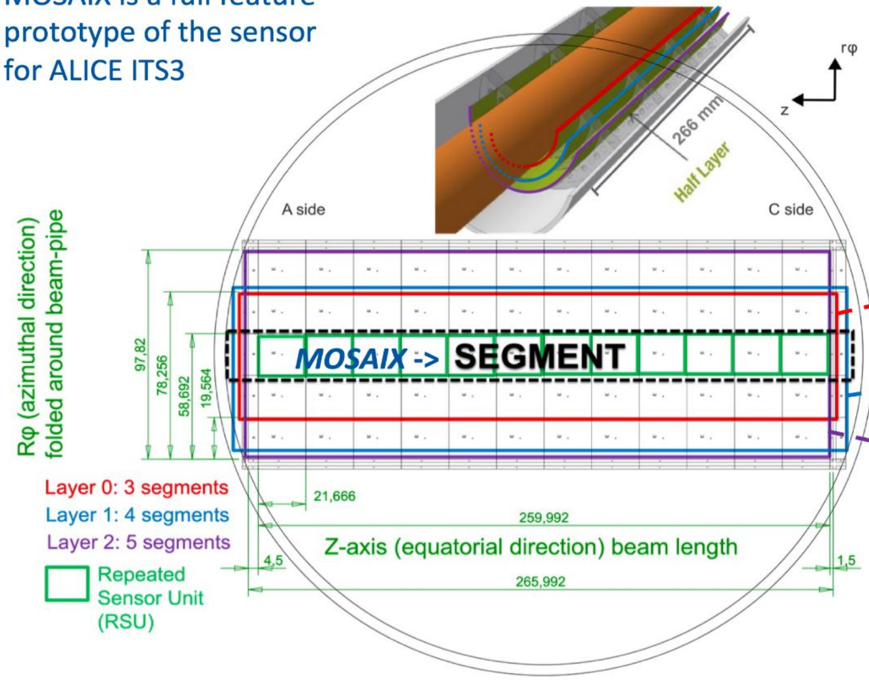
  ***Not adapted to FCCee*: ~ 10 µm, > 1% X_0/layer, O(1) W/cm², active cooling, cold operation,** *etc.*

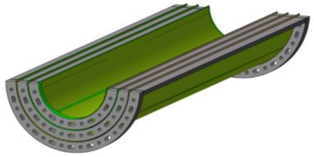
Numerous CMOS Sensors in Use or Development (illustrative/partial sub-sample)

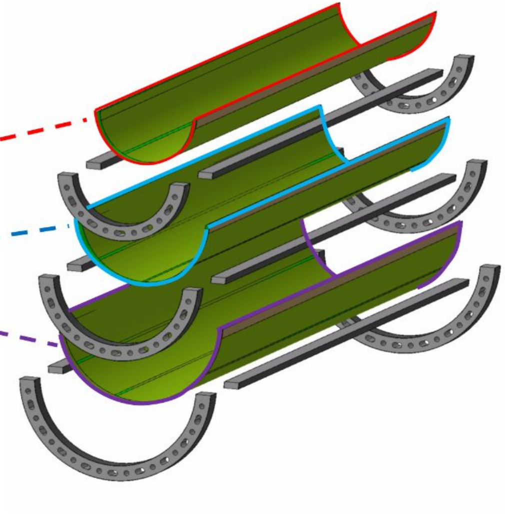
Name	Expt	Sub-syst	Area	Δ Pos., Time	Power (fid.)	Technology	Comment
ALPIDE	ALICE-ITS2	Vx & In. Trkr	10 m²	5 µm, ≤ 10 µs	≤ 50 mW/cm²	TJsc 180 nm EPI	In operation
MOSAIX	ALICE-ITS3	Vx only	0.12 m²	5 µm, 2-10 µs	≤ 40 mW/cm² ?	TPSco 65 nm EPI	Wafer scale CPS
FASTPIX	→ HL-LHC	Demonstr.		≥ 1 µm, ≤ 100 ps	+++	TJsc 180 nm EPI	Timing & Rad. Tol.
MonoPix	→ ATLAS	ITk	few m²	< 10 µm, ≤ 20 ns	> 0.5 W/cm²	TJsc 180 nm EPI	Not retained
CACTUS	FCC, eIC, …	Timing det.	few m²	< 100 ps	< 300 mW/cm²	LF 150 nm	Proto., 1 mm² pixels
MALTA	HL-LHC, …	Fast det.	few m²	36x40 µm², 25 ns	> 100 mW/cm²	TJsc 180 nm EPI	512x512 pixels
MIMOSIS	CBM/FAIR	Vx & In. Trkr	0.16 m²	5 µm, 5 µs	< 100 mW/cm²	TJsc 180 nm EPI	Fixed target HI expt
TaichuPix	CEPC	Vx & In. Trkr		≤ 5 µm	90-160 mW/cm²	TJsc 180 nm EPI	8x8 µm² n-well
NAPA	SiD/C3	Trkr, (calo.)		7µm pitch, O(ns)	20 mW/cm²	TPSCo 65 nm EPI	Target values
ARCADIA	IDEA/FCCee	Vx & In. Trkr		10-50 µm		LF 110 nm	Working horse
CLICpix	CLICdp	Vx & In. Trkr		25 µm pitch, 10 ns		TPSCo 65 nm EPI	Follows TimePix
OBELIX	Belle-II	Vx (7 layers)	O(1) m²	≤ 10 µm, ≤ 100 ns	≈ 200 mW/cm²	TJsc 180 nm EPI	Follows MonoPix
MuPix	Mu3e expt	Vx & Trkr		≤ 30 µm, ≤ 20 ns	≤ 350 mW/cm²	HV TJsc 180 nm	Fixed target expt

ALICE ITS3 and MOSAIX

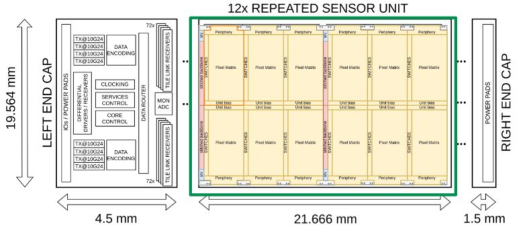
MOSAIX is a full feature prototype of the sensor for ALICE ITS3



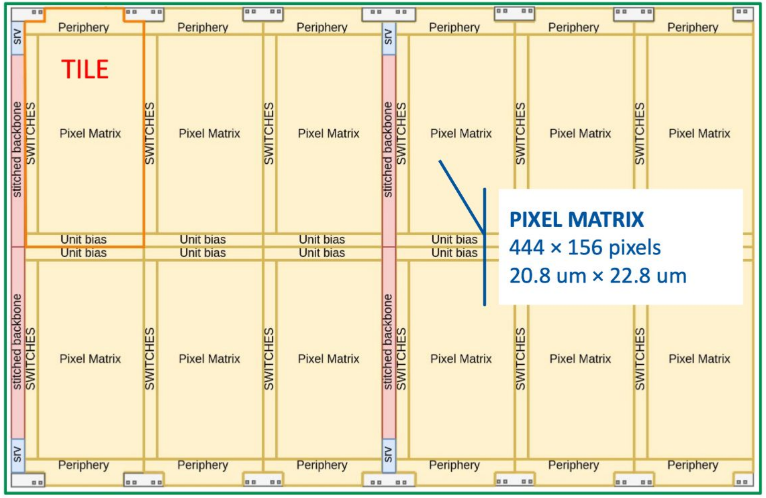




RSU Architecture



RSU



12 RSU per segment, 12 TILEs per RSU

144 TILEs can be switched on, biased and read out independently

- Programmable Switches
- One TILE is 1/864=0.116% of L0 acceptance

Table 2: Main parameters of the ultra-light inner vertex detector.

Layer	Sensors	Radius [mm]	RSUs in ϕ	RSUs in z	Length [mm]	Coverage
1	2	13.7	2	10	108.3	$\lvert\cos(\theta)\rvert < 0.992$
2	2	20.35	3	13	140.8	$\lvert\cos(\theta)\rvert < 0.990$
3	4	27	4	$8\ (-z)/10\ (+z)$	199.5	$\lvert\cos(\theta)\rvert < 0.990$
4	4	33.65	5	$10\ (-z)/\ 8\ (+z)$	199.5	$\lvert\cos(\theta)\rvert < 0.986$

IDEA https://arxiv.org/abs/2502.21223