Understanding the design choices of the e^+e^- Future Circular Collider vertex detector and the interaction region

Fabrizio Palla

INFN Pisa

On behalf of the
FCC-ee Physics, Detector and Experiment group
FCC-ee Accelerator group

Rutherford Lab, Didcot, UK
5 November 2025

Disclaimer and context

- This seminar is intended to give the status of the vertex detector studies and their integration inside the interaction region of FCC-ee, and address some of the points that Chris Damerell alluded to in his seminar of the 15 of October 2025 (https://indico.stfc.ac.uk/event/1651/)

- The presentation is a compilation of the work done by a lot of people and documented in EPJ Techn Instrum (2025) 12:4, "Status of the FCC-ee interaction region design" https://doi.org/10.1140/epjti/s40485-025-00117-3 and the Feasibility Status report Vol. 1 https://doi.org/10.17181/CERN.9DKX.TDH9

For those interested to join FCC-ee PED activities:
https://indico.cern.ch/category/5251/
and more in detail the MDI activities:
indico: https://indico.cern.ch/category/5665/
E-group: fcc-ee-MDI@cern.ch

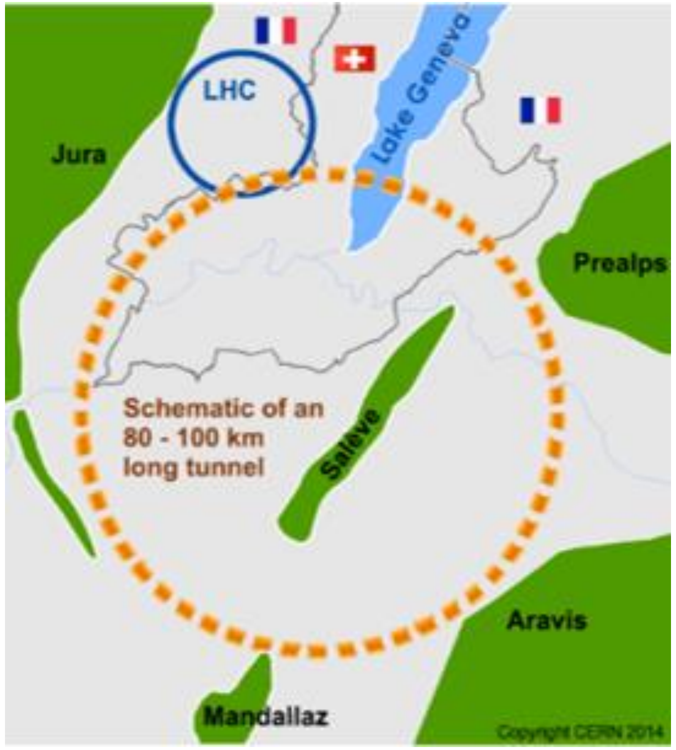
Main points addressed in C. Damerell seminar which I will discuss and show they do not stand

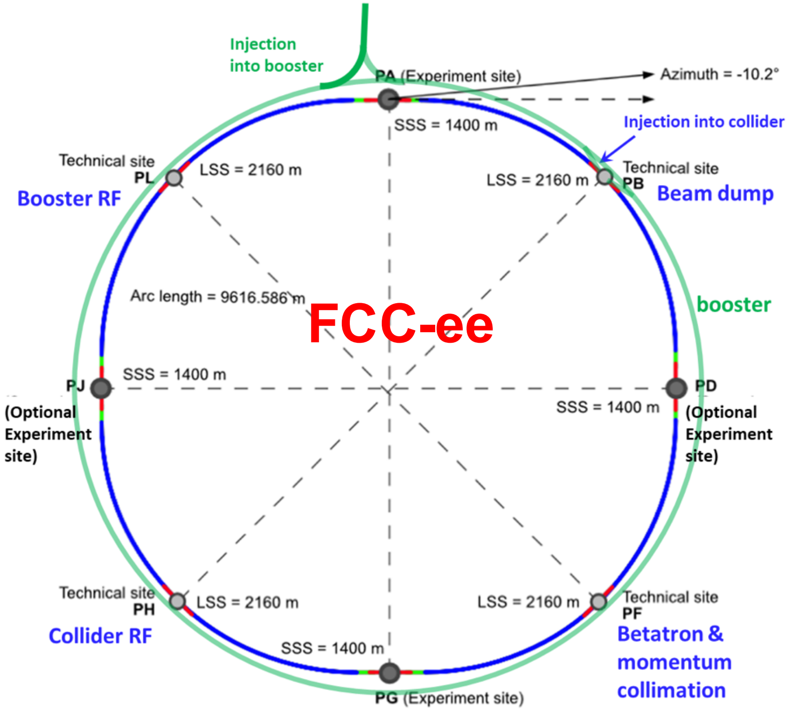
1. "Reading the FCC-ee Feasibility Report of 31 March 2025, I was concerned to find that the background we encountered in the SLD Vertex Detector was not mentioned. Since I believe that this background will probably scale with luminosity, and hence return with increased intensity at FCC-ee (Z), I embarked on a reminder of our experiences"
"They dream of reading out in 1 ms, so would see 6000x50 = 300,000 hits. Occupancy would still be 'only' ~1.5%, but I'd ask the detector people about all this, including claiming air-cooling, before asserting 'feasibility'. "
   - **Backgrounds depend on the current, but also on the crossing angle, detector field and the integration time of the vertex detector, that play a significant role.**
     - SLC and FCC-ee have completely different optics. B-field of 0.6 T (SLD) vs 2 T (FCC-ee), and the FCC-ee vertex det. integration time is thousand times faster than SLD.
     - **The assertion that our occupancy is 1.5% is simply wrong.**
     - **We are demonstrating air-cooling can be done.**
   - **A simplistic comparison is wrong and may bring to completely wrong conclusions**
2. "[Positron annihilation can be switched on or off in GEANT4++]"
   - **In FCC-ee studies positron annihilation has never been switched off in GEANT**
3. "In summary, I'd say that the study of backgrounds at FCC-ee is in its infancy."
   - **In FCC-ee studies of backgrounds are well advanced**
4. "However, this requires a welcoming open minded investigation."
   - **The FCC-ee community is open to anyone who wishes to contribute**

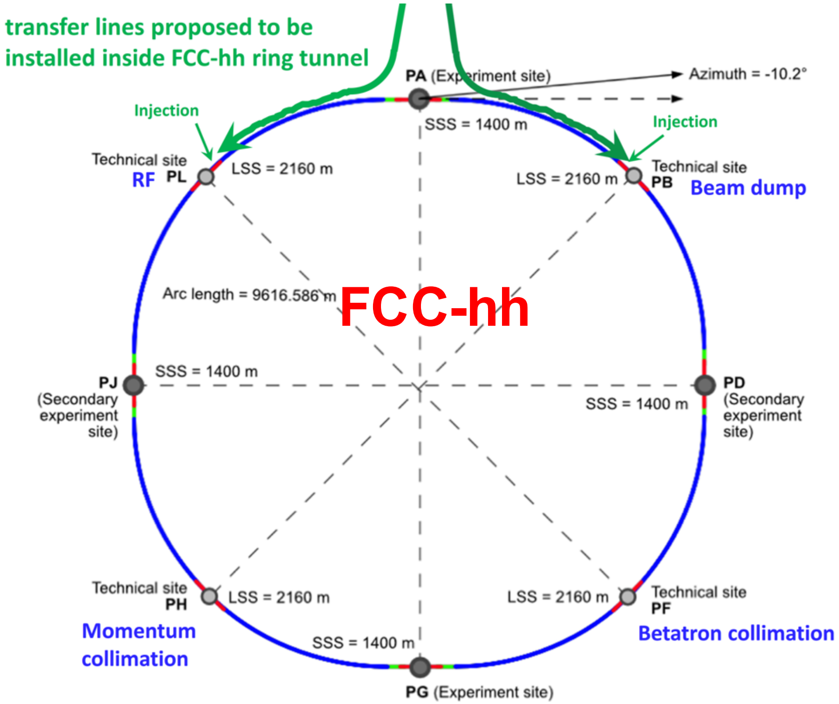
FCC Integrated Program

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC

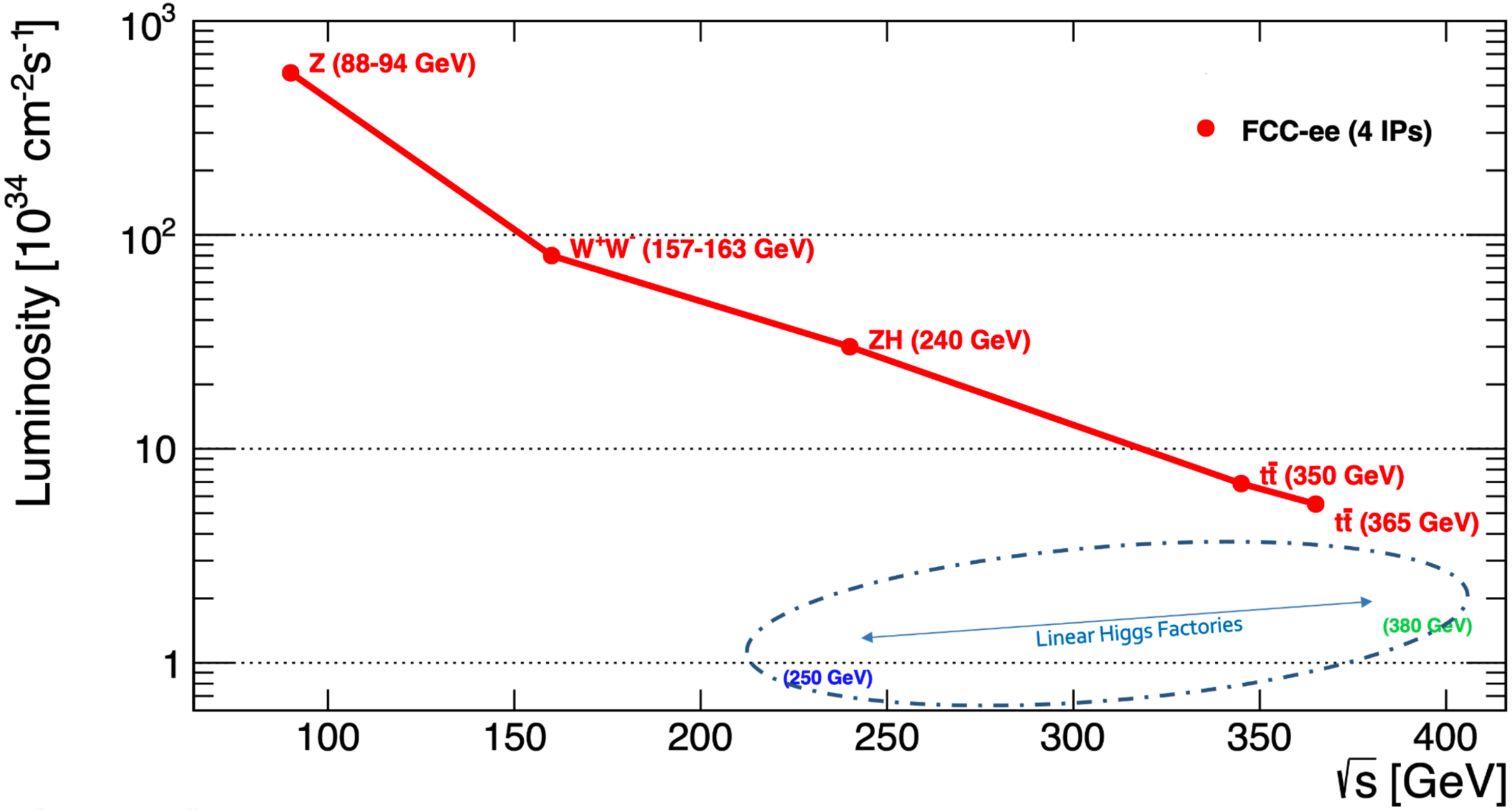


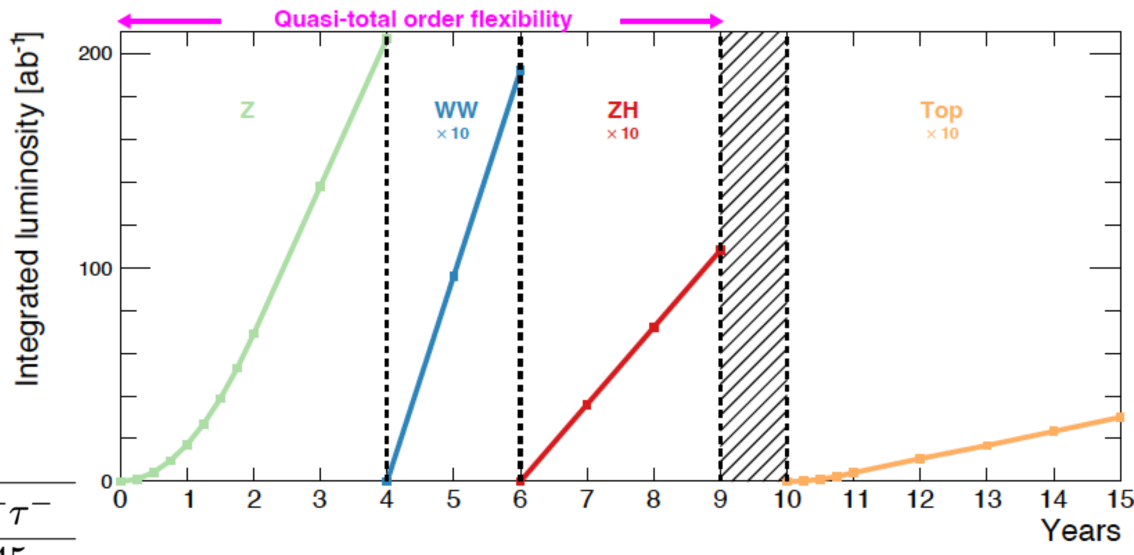




FCC-ee in a nutshell

LEP1 statistics in a few minutes





FCC-ee

- Tera-Z run

  Seamless operation between Z, W and H
  - Huge number of B-hadrons and τ leptons

Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B^0_s/\overline{B}^0_s$	B^+_c/B^-_c	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

- 500 Million W bosons
- 4 Million top quarks
- 2 Million Higgs bosons
- 4 experimental apparata
  - Systematics ~$1/\sqrt{N_{exp}}$
  - Redundancy (cross-checks)

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\rightarrow$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

Main IR parameters

	Z	W^+W^-	ZH	$t\bar{t}$
Beam energy (GeV)	45.6	80	120	182.5
Luminosity / IP (10^{34} cm^{-2}s^{-1})	145	20	7.5	1.41
Beam current (mA)	1 294	135	26.8	5.1
Bunch number / beam	11 200	1 852	300	64
Bunch spacing (ns)	27	163	1 008	4 725
σ_x^* (μm)	9.5	21.8	12.6	36.9
σ_y^* (nm)	40.1	44.7	31.6	43.6
σ_z (mm) SR / BS	4.7 / 14.6	3.46 / 5.28	3.26 / 5.59	1.91 / 2.33
σ_δ (%) SR / BS	0.039 / 0.121	0.069 / 0.105	0.102 / 0.176	0.151 / 0.184

SR/BS=Non-colliding/colliding beams

- Beam crossing angle of 30 mrad in x-z and crab waist optics
  - Allows to reach high luminosity
  - Determines the luminous region size in x and z
- Beam power limited by design to 50 MW (due to synchrotron radiation)
  - determines maximum beam current per each c.o.m. energy and therefore limits the available instantaneous luminosity
  - In turn determines the no. of bunches → interaction frequency
  - Also determines the size of the beam in z together with the beamstrahlung
- Final focus superconducting quadrupoles inside the detector (L*=2.2 m)
  - Determines the luminosity and the beam size in y
- Maximum detector B-field at 2 T at the Z not to decrease luminosity

FCC-ee Interaction Region rationale: crab-waist

Crab-waist scheme, based on two ingredients:

- concept of **nano-beam scheme:**
  - vertical squeeze of the beam at IP and large horizontal crossing angle
  - large ratio σ_z/σ_x reducing the instantanous overlap area, allowing for a lower β_y^*
- concept of **crab-waist sextupoles:**
  - placed at a proper phase advance they suppress the hourglass effect by inducing a constant β_y along the larger coordinate of the beams overlap.

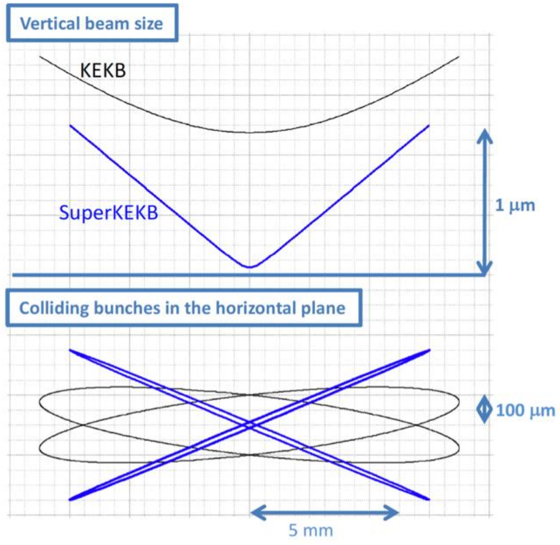
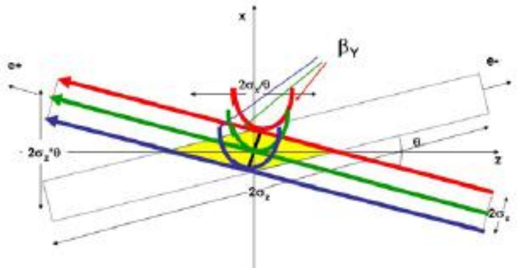
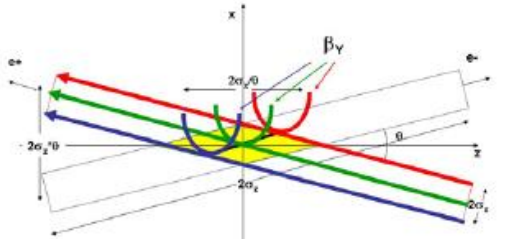


Figure 2: Schematic view of the nanobeam collision scheme.

SuperKEKB https://arxiv.org/pdf/1809.01958.pdf

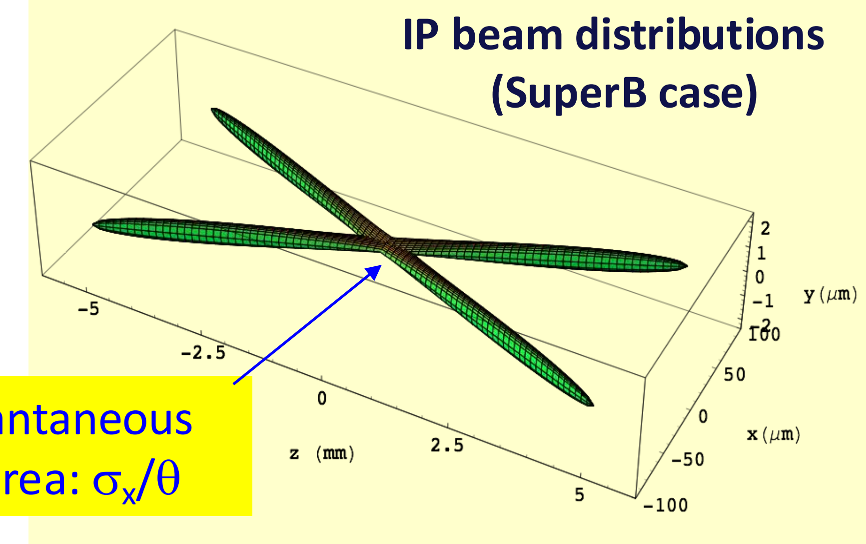


crab sextupoles off



crab sextupoles on

DAFNE, PRL 104, 174801 (2010)



Small instantaneous collision area: σ_x/θ

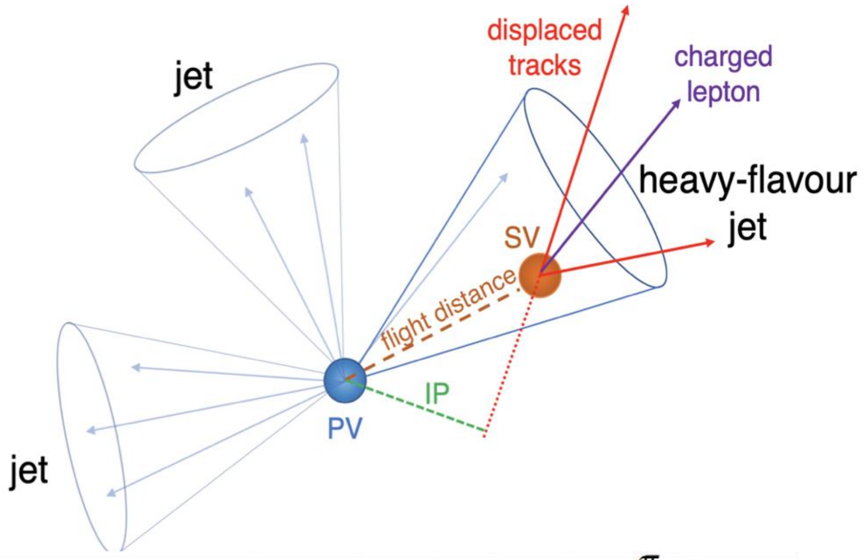
Main drive for vertex detectors: Higgs and B physics

Higgs decays: $H \rightarrow \bar{b}b$; $H \rightarrow \bar{c}c$

- Needs charm and bottom quark tagging
  - Displaced vertices (tertiary for B and secondary for C)
  - Large track multiplicity (~5 charged tracks on average)
  - Non-isolated leptons (BR 10%-20% for C and B, resp)

B Physics

- Secondary and tertiary vertices precisely reconstructed

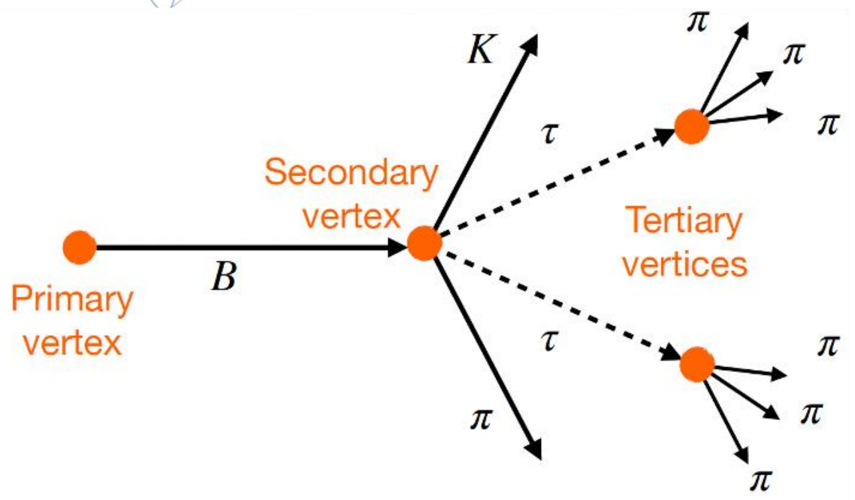


Implies excellent spatial resolution and high efficiency

- $\sigma(d_0) = a(\text{point resolution}) \oplus b(\text{multiple scattering})/(p \sin^{3/2}\theta)$
- Power of tagger ~ N tracks

Low mass and high granularity vertex detectors

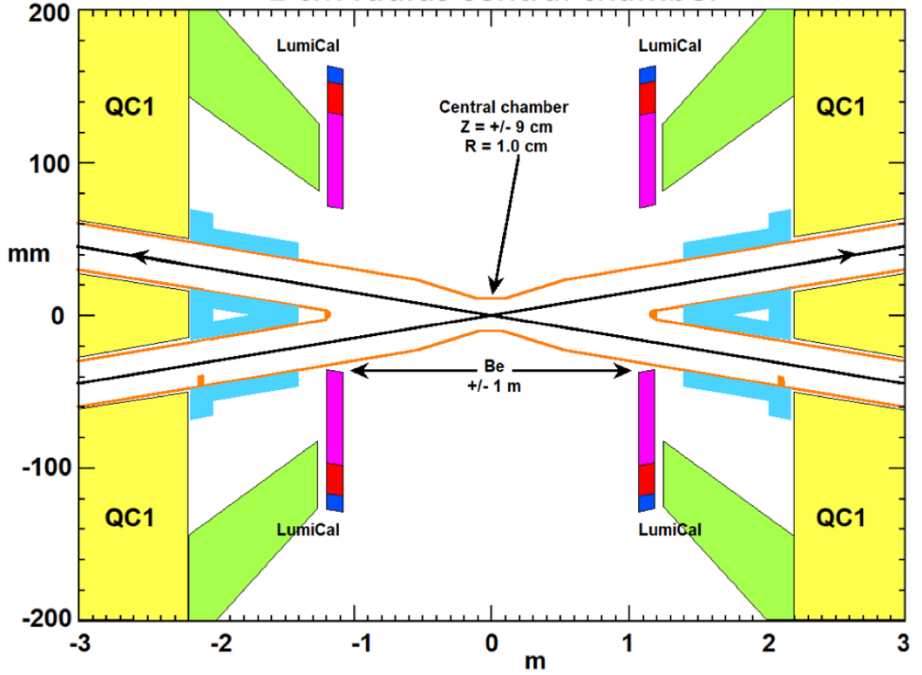
- High hit efficiency: >99.5%
- Large angular coverage $|cos(\theta)| < 0.99$
- Point resolution: ~3 µm
- Material budget (per layer) <0.2% X_0



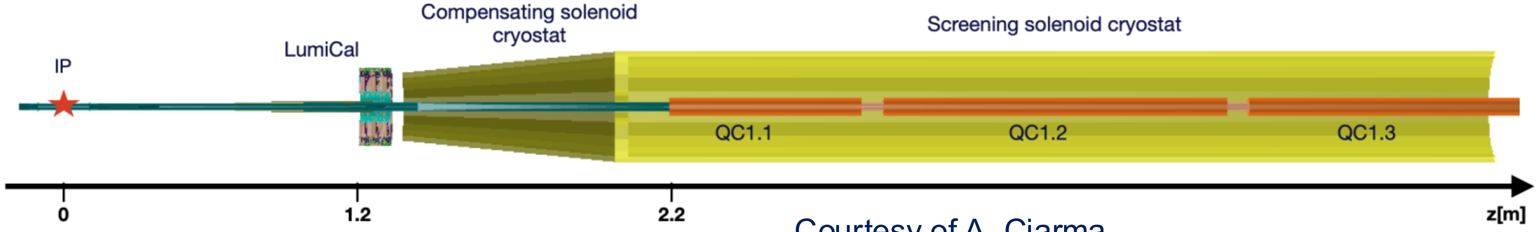
FCC-ee IR requirements

- **Crab-waist scheme** based on **nano-beams and large (30 mrad) crossing** angle to reach extremely high luminosity O(10^{36} $cm^{-2}s^{-1}$) at Z-pole.
- **Solenoid compensation** achieved via two anti-solenoids inside the detector.
- Shielding for beam induced **backgrounds (BIB)**
- **Luminosity monitor**: absolute measurement to 10^{-4} with low angle Bhabha's
  - ➢ Strict alignment tolerances and **low material budget** in front
- **Vertex detector:** largest acceptance and low material budget (<0.2%X_0 per layer)
  - ➢ MAPS with **air-cooling**
- **Calorimeter**: highest possible hermeticity for total energy measurement
- **Beam pipe**: smallest material as possible

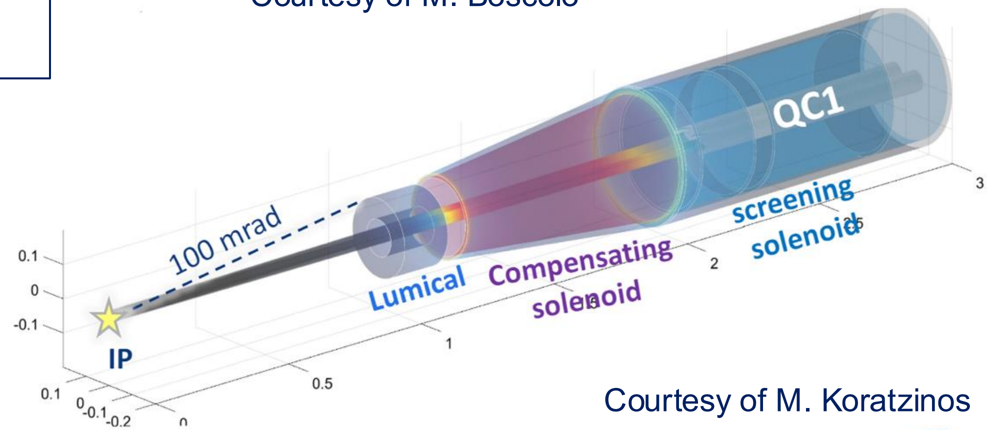
present low impedance beam pipe
1 cm radius central chamber



Courtesy of M. Boscolo

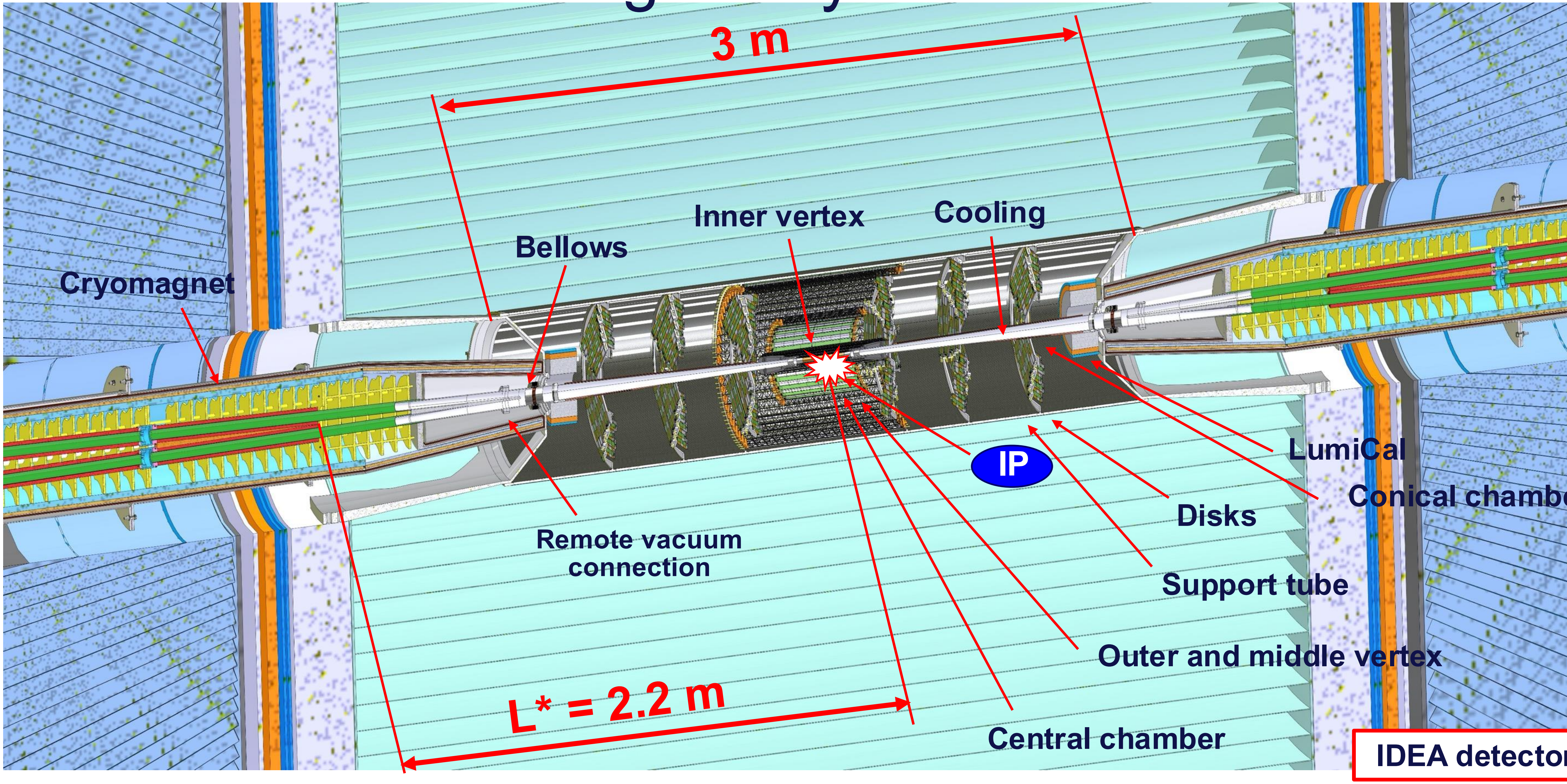


Courtesy of A. Ciarma



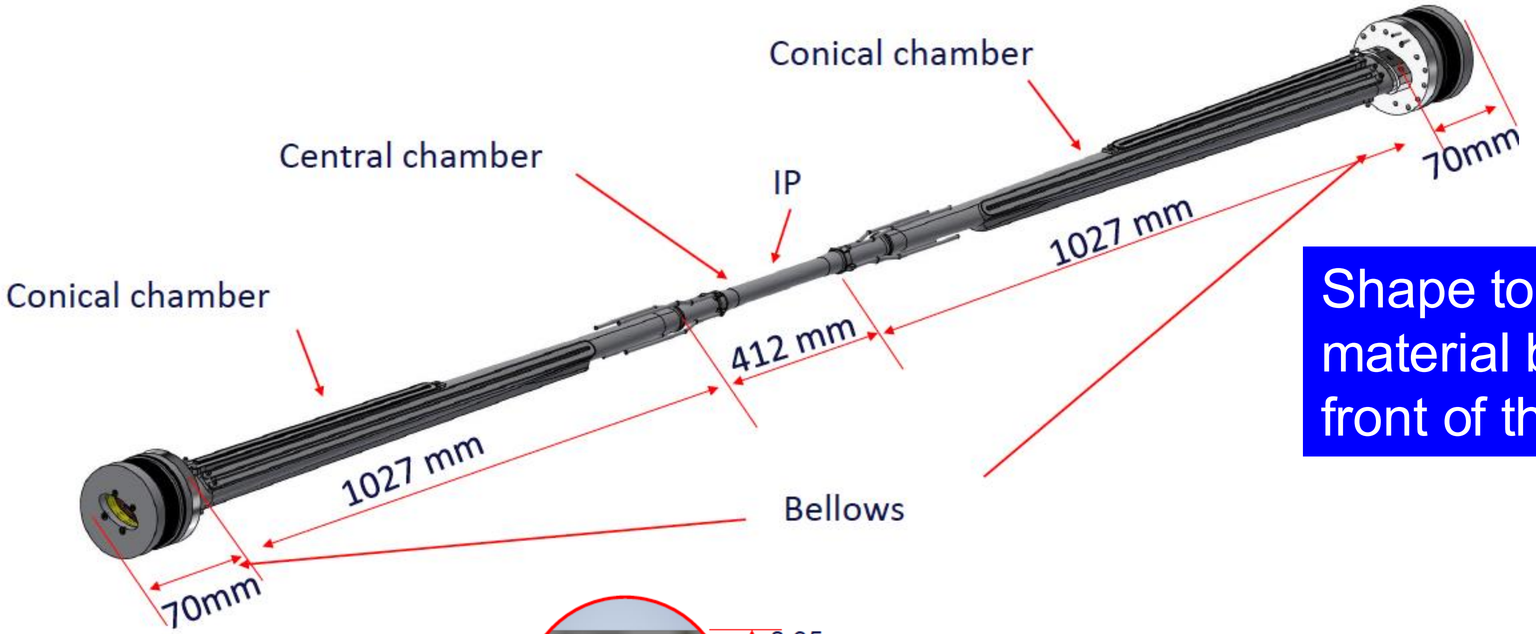
Courtesy of M. Koratzinos

FCC-ee interaction region layout



Beam pipe

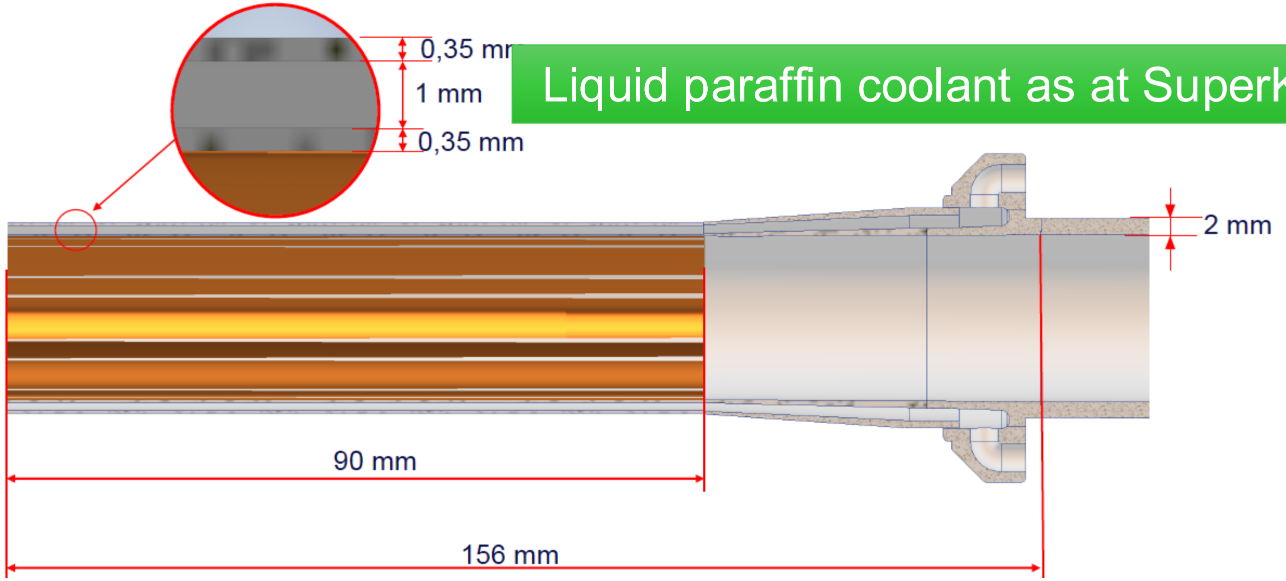
2 cm diameter at the IP
18 cm long
350 μm thick
AlBeMet (38% Al 62% Be)



Shape to minimise material budget in front of the LumiCal

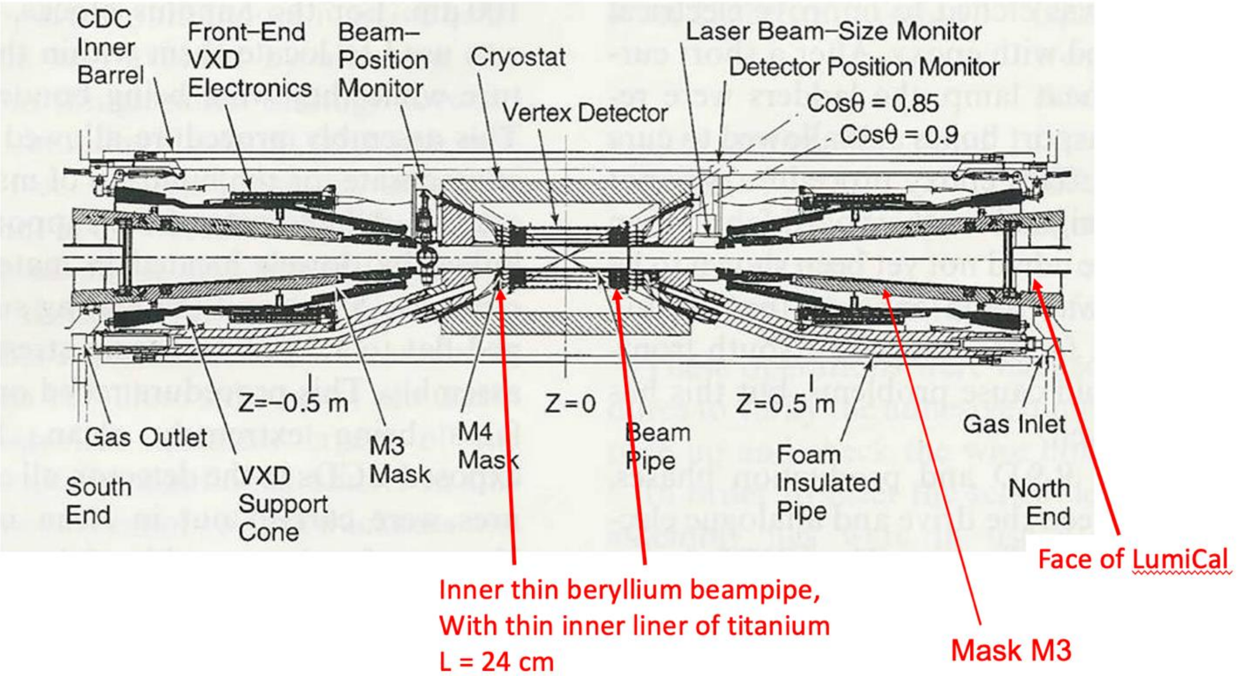
Internal 5 μm gold coating

Liquid paraffin coolant as at SuperKEKB

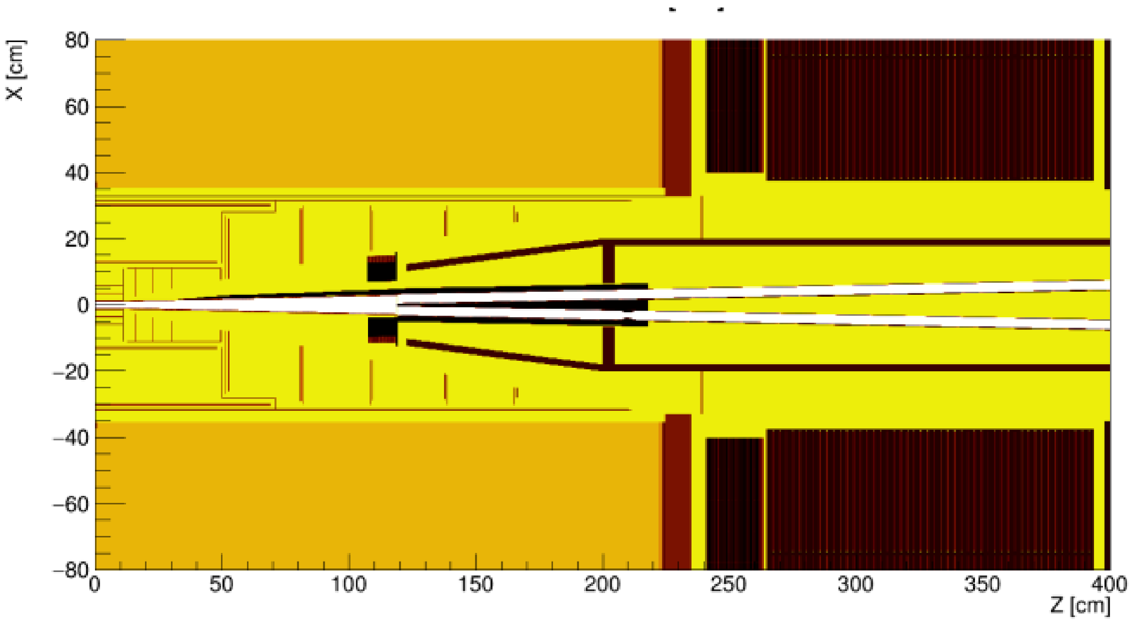


Compare FCC-ee with SLD IR

Notice more bulky material closer to the vertex detector for SLD wrt FCC-ee

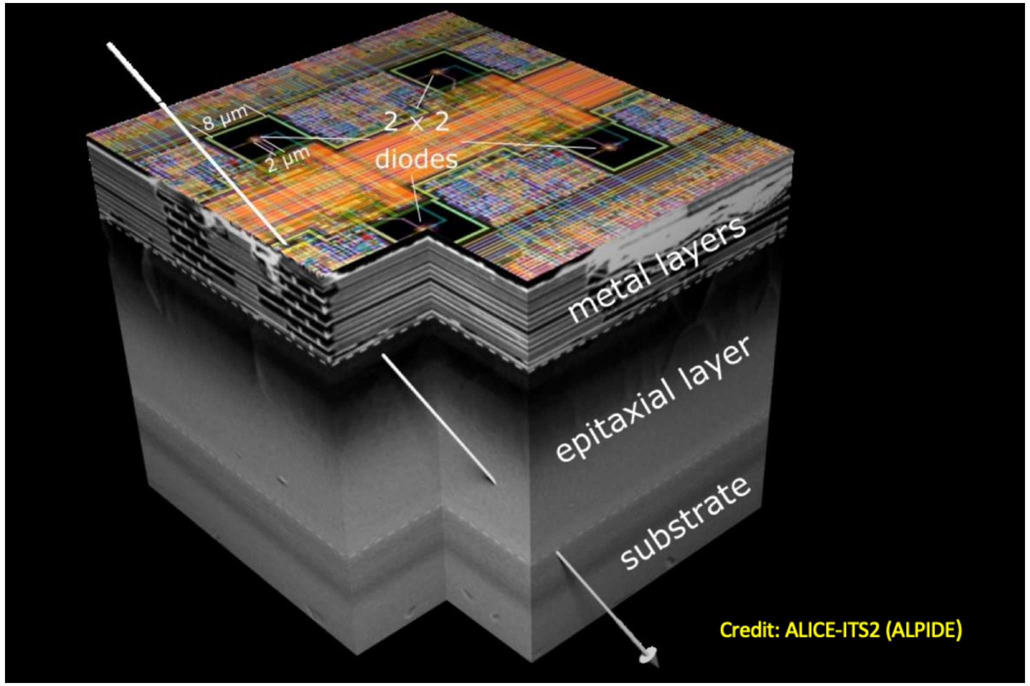


SLD: head-on collisions.
25 mm radius beam pipe
0.6 T solenoid field.



FCC-ee: 30 mrad crossing collisions – crab waist
10 mm radius beam pipe
2 T solenoid field at the Z. 3 T for other energies

Technologies for Vertex detectors



Monolithic Active Pixel Silicon Detectors (MAPS)

- CMOS sensors and electronics fully integrated
- Can reach 30 µm thickness (0.032% X_0)
- Very low power (<50 mW/cm^2)
- Sensors stitching up to 12” or ‘abuttable’

Several CMOS sensors in use or development

- Dependence on CMOS process (foundry) characteristics
  - 3 prominent ones: LFoundry, TJsc, TPSCo
  - ECFA-DRD3 WG1 addresses the R&D

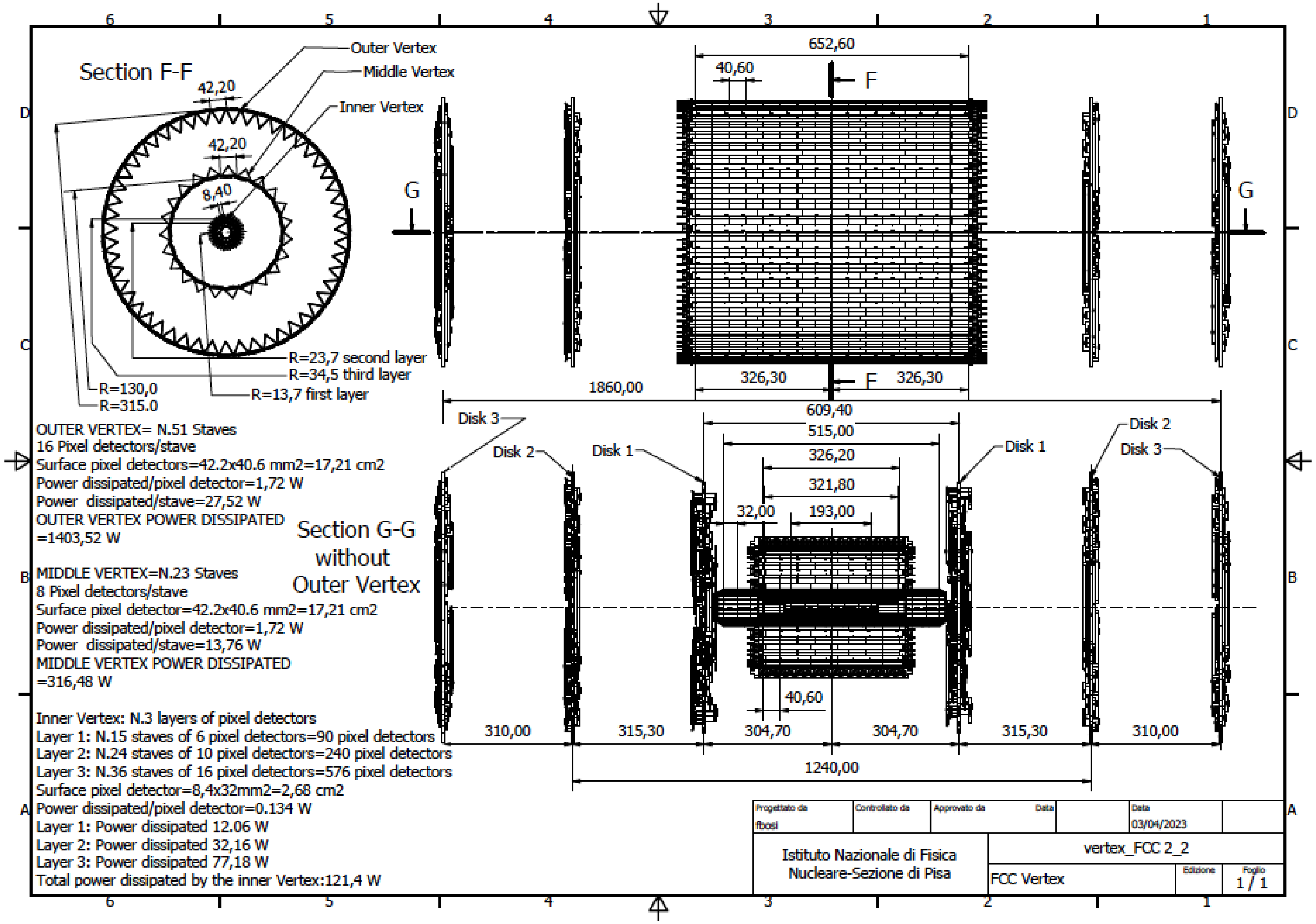
New trends and opportunities

- 3D integration: possibility to have a more complex readout (and Silicon Photonics) tier bonded to a sensor one

Optimisation

- Spatial resolution vs timing vs power vs radiation tolerance

Baseline IDEA vertex detector



Inner Vertex detector:
ARCADIA based

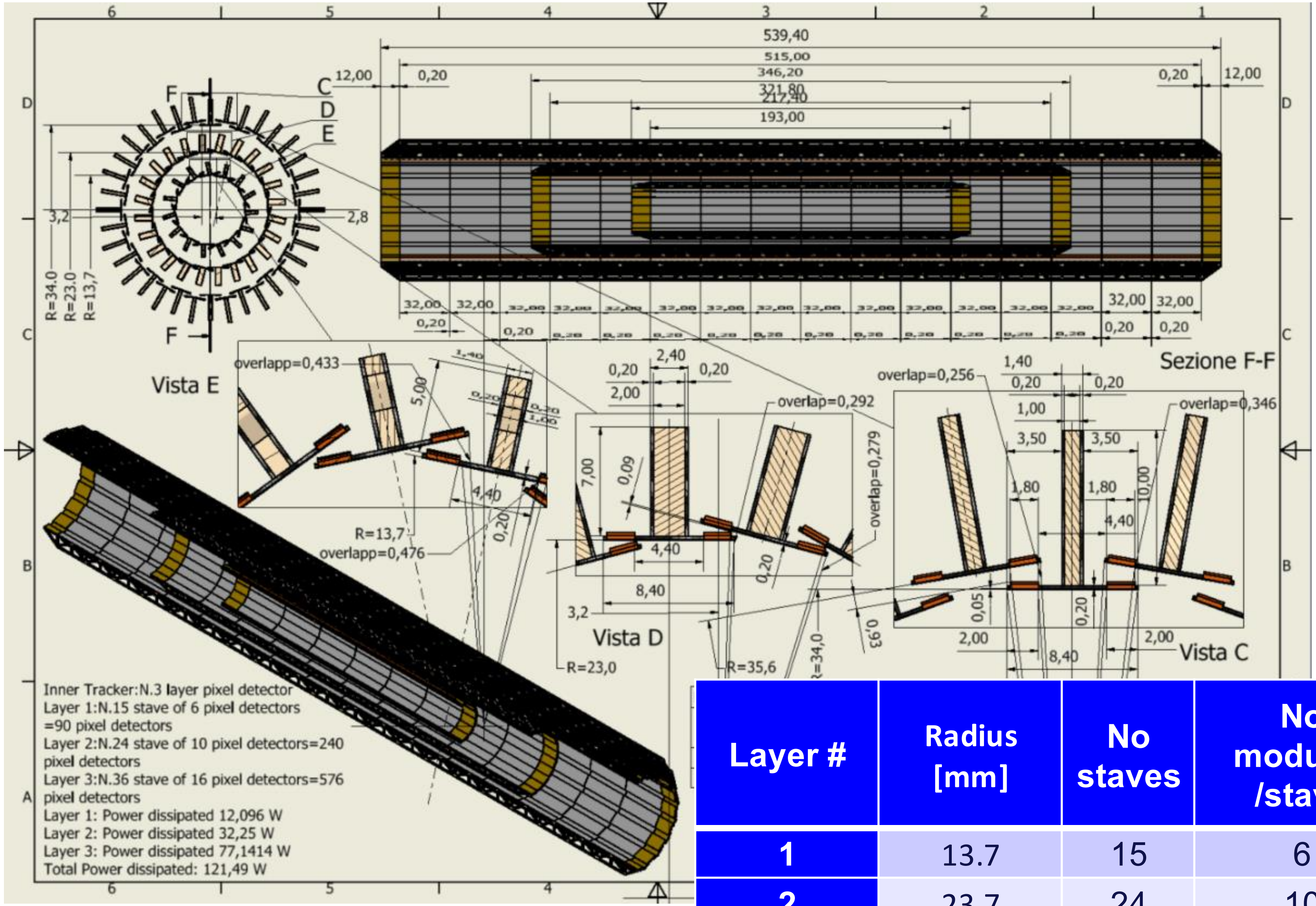
Modules of $25 \times 25\ \mu m^2$ pixel size

3 barrel layers at
- 13.7, 23.7 and 34/35.6 mm radius

Outer vertex tracker:
ATLASPix3 based

Modules of $50 \times 150\ \mu m^2$ pixel size
- Intermediate barrel at 13 cm radius
- Outer barrel at 34.5 cm radius
- 3 disks per side

Vertex detector Layout



Total thickness per layer 0.25% X/X0

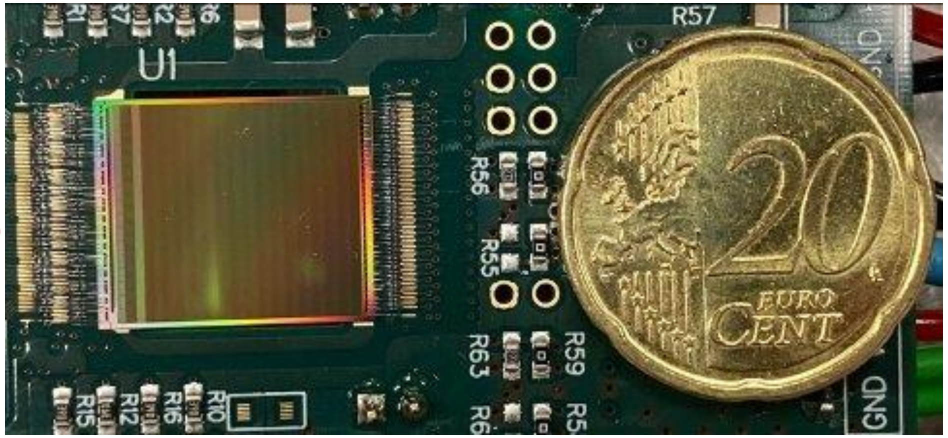
Carbon Fibre ~60 %

Silicon: ~20%

Power and readout bus: ~20%

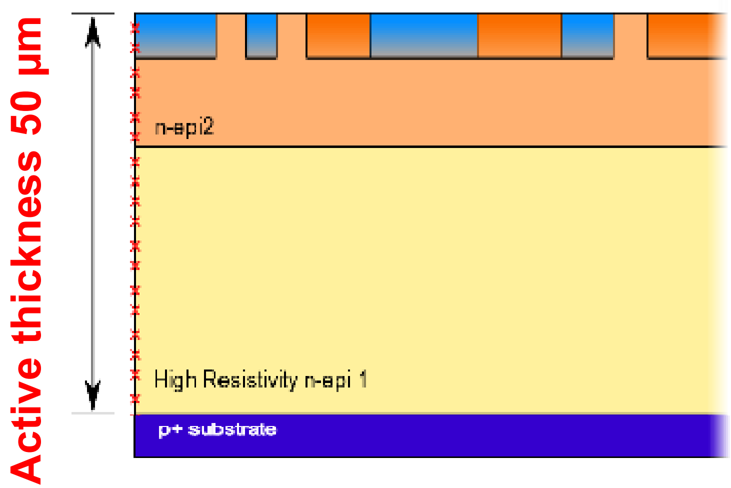
Layer #	Radius [mm]	No staves	No modules /stave	Total Length [mm]	Active Area [cm²]	Power [W]
1	13.7	15	6	217.40	241.92	12
2	23.7	24	10	346.20	645.12	32
3	34 & 35.60	36	16	539.40	1548.29	77

Vertex sensors technology and dimensions



- **Simulated IDEA Inner Vertex (inspired from ARCADIA)**
  - LFoundry 110 nm process
  - p^{+}-type starting substrate
  - **n-type fully depleted layer of 50 μm**
  - Pixel dimensions 25 μm x 25 μm
  - Module dimensions : $8.4\text{mm} \times 32\text{ mm}$
  - Assumed power density 50 mW/cm^2 (core 20 mW/cm^2)
  - Digital readout and data-push architecture
    - Allow for data rates up to 100 MHz/cm^2 by design

p+ wafers - double epi



Not to scale

For TPSCo 65 nm the active epitaxial layer is about 10 µm

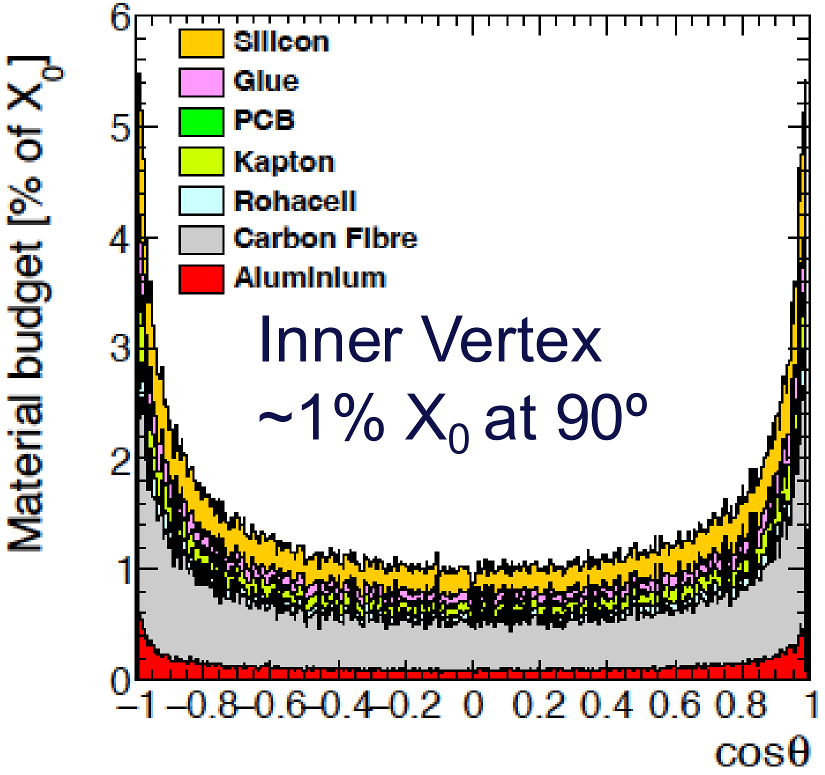
Vertex integration time and BX structure

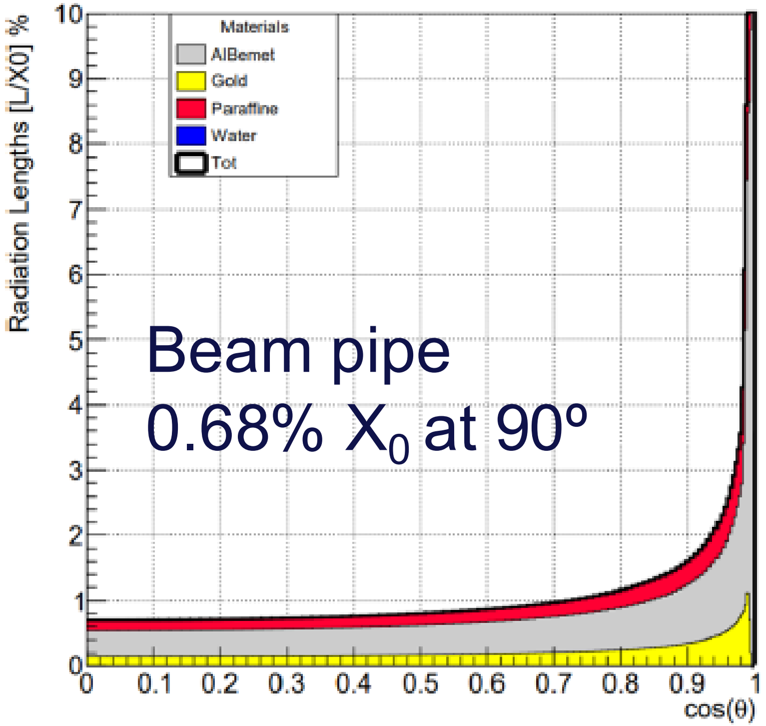
Despite the BX rate is much different between SLC and FCC-ee: 120 Hz vs 40 MHz, the **vertex integration time** is much different as well:

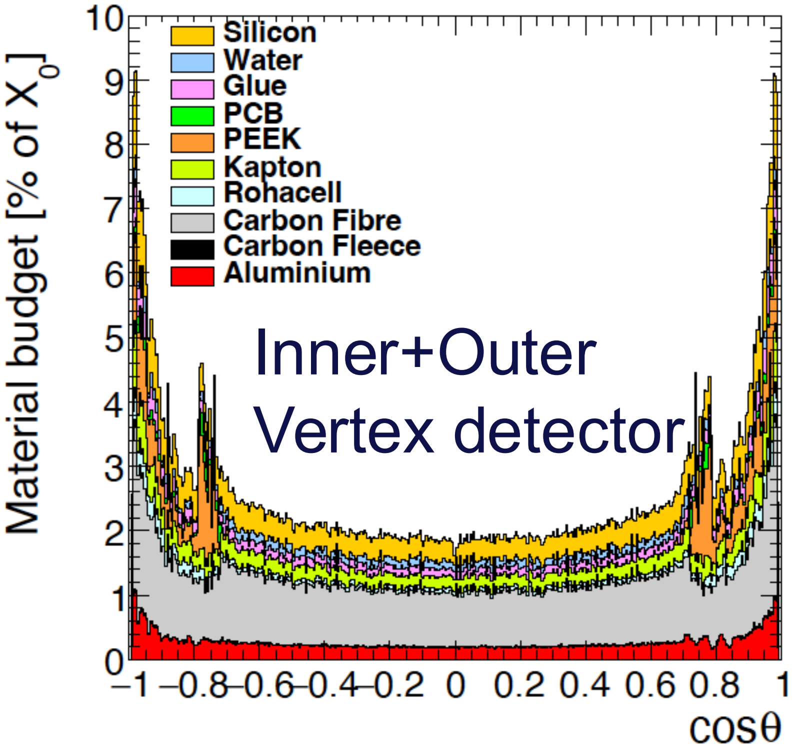
- At SLD was 215 ms, thus corresponding to about 26 BX.
- At FCC-ee will be 1 μs (the current ALICE Mosaix chip is 2 μs), thus corresponding to 50 BX.

Simulated material budget

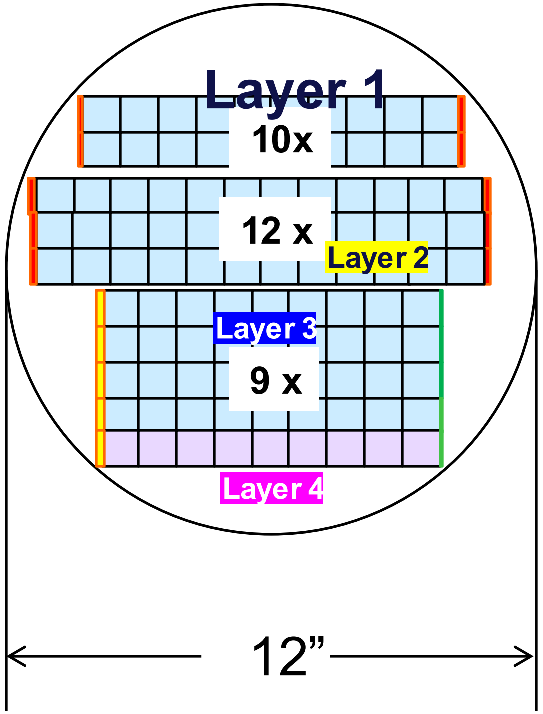
Smaller X/X_0 wrt IDEA CDR estimates even including power and readout cables in the sensitive region
Silicon only ~15% of the total
Impact parameter resolution limited by beam pipe material



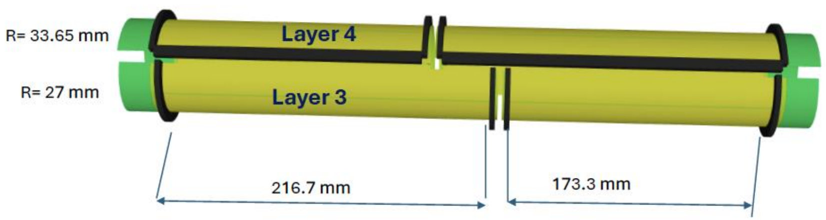


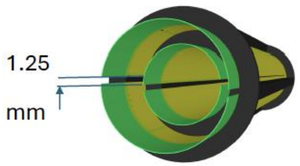


Lowering the material budget

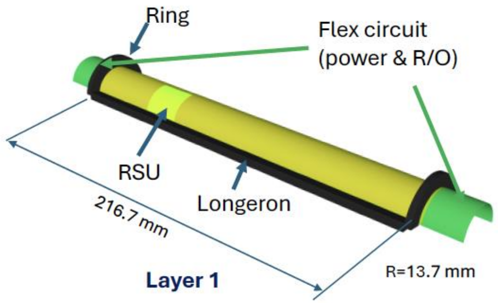


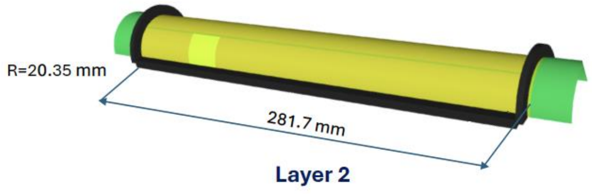
- **Stitching of thin (<50 µm) sensors a la ALICE ITS3:**
  - One row of sensors ~30 cm long; R/O and powered on sides
  - Can be ‘folded’ (curved): self-sustained mechanics: no piping and no cabling in the sensitive areas
- **Problems**
  - Currently internal and periphery circuitry ~5% inefficiency
  - May not be fully hermetic; R&D on overlapping two layers
  - Stitching rules may prevent optimal pitch size

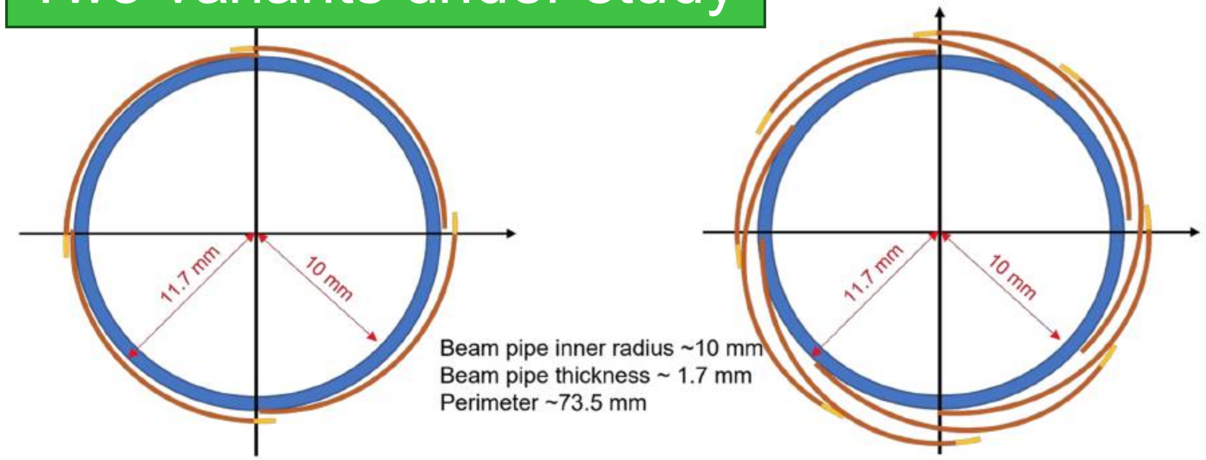




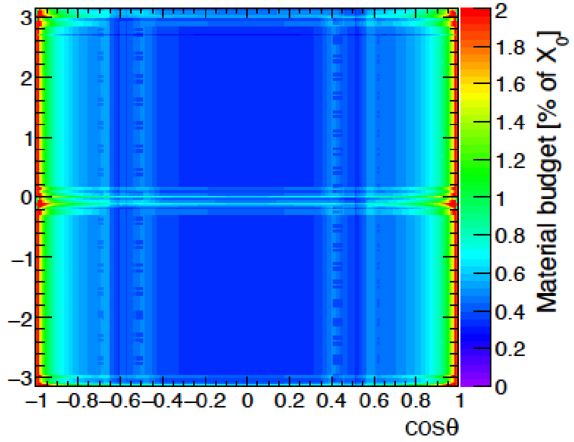
Two variants under study



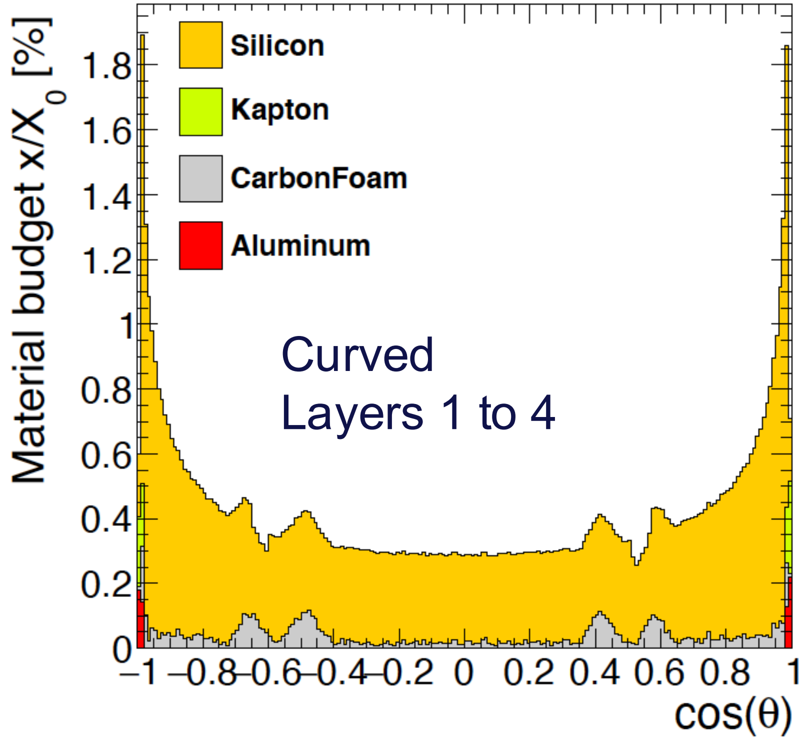


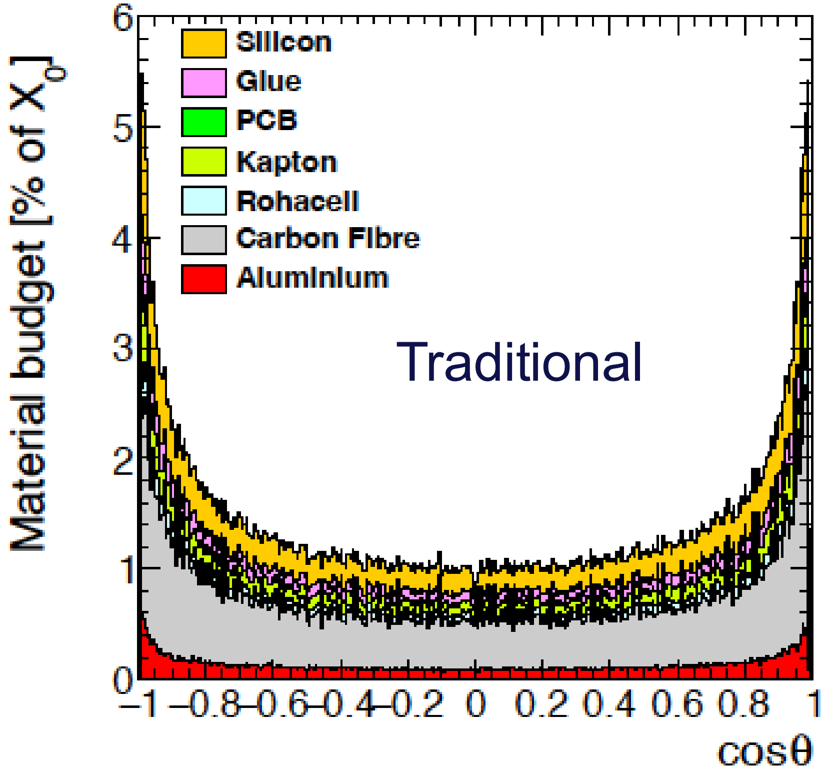


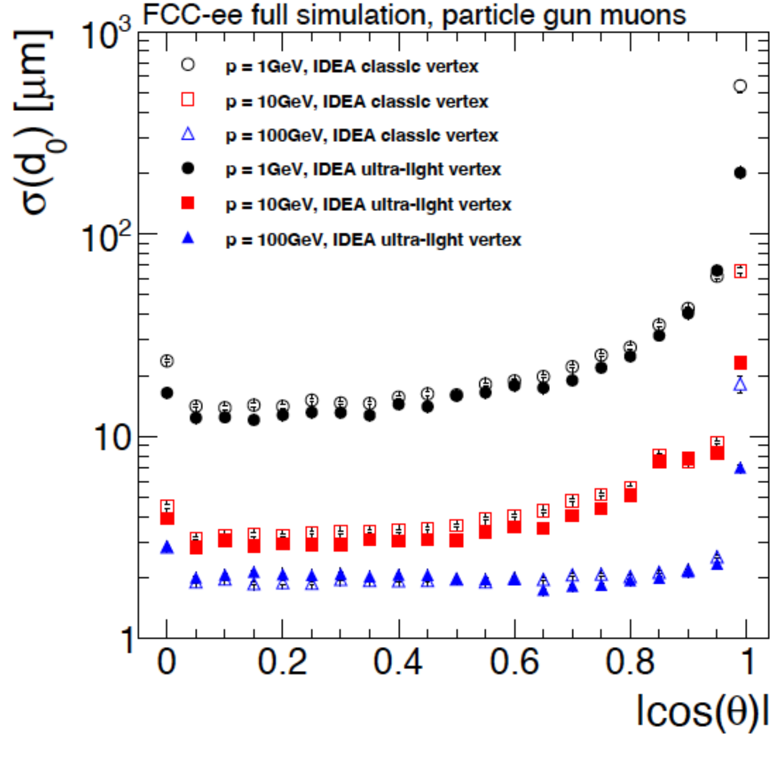
Material budget reduction and impact on resolution



- Factor of ~3 smaller material budget compared to flat
  - More uniform in ϕ and 4 layers instead of 3
- Improved impact parameter resolution especially at lower momentum

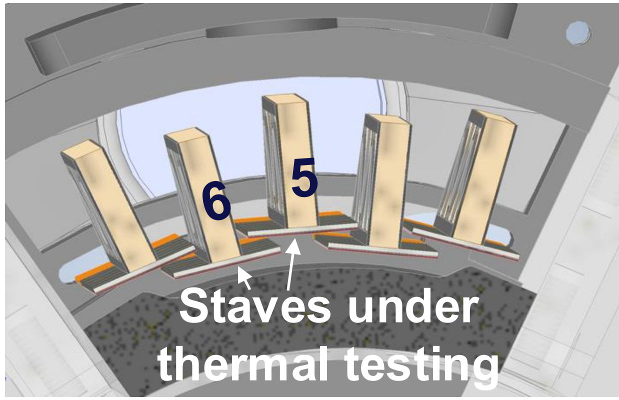


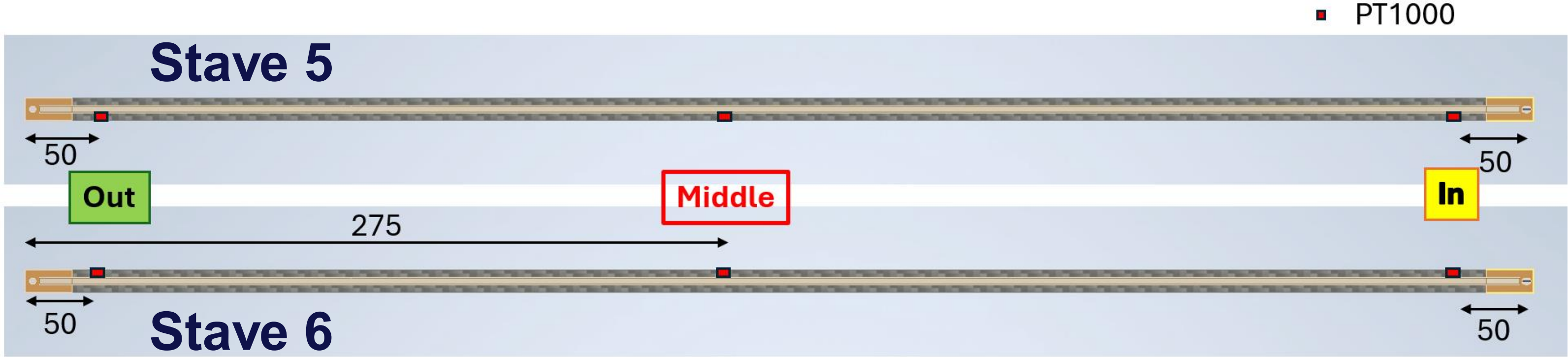


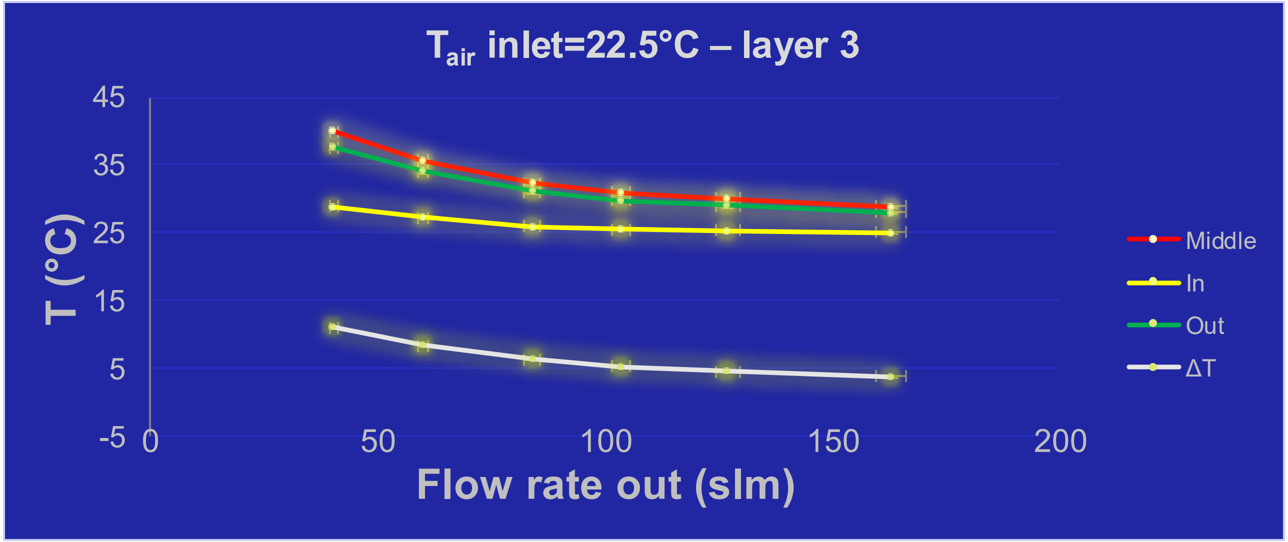


Air cooling tests: towards demonstration

A first study has been performed in Pisa to validate the air-cooling performance



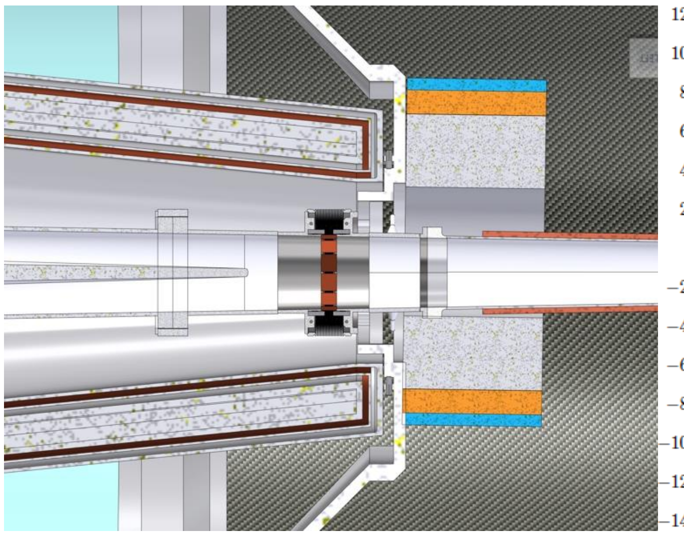
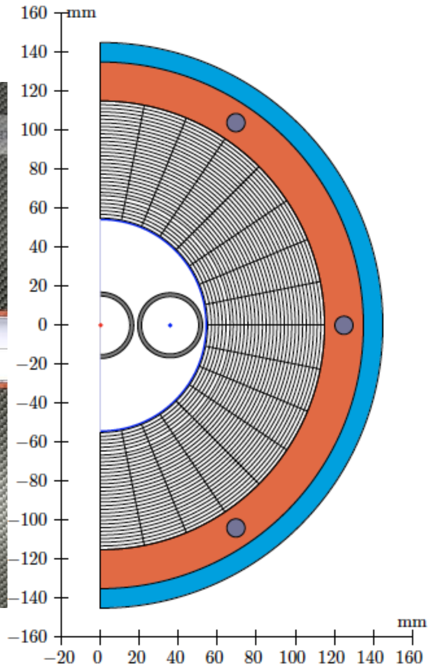


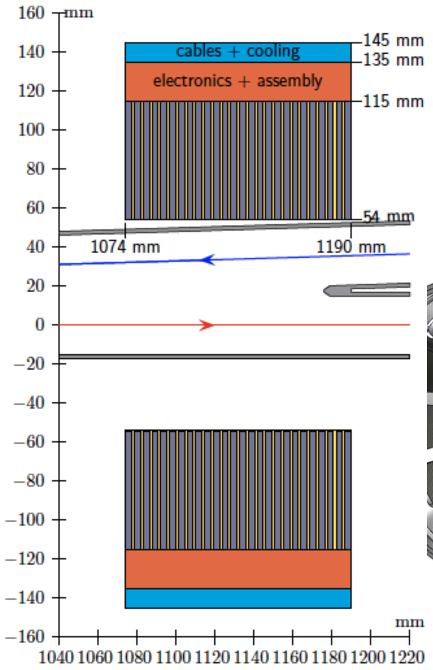


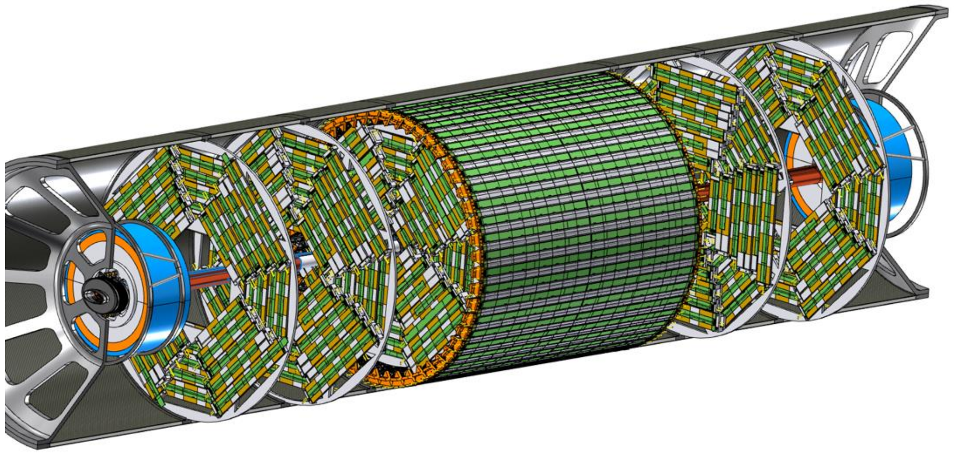
50 mW/cm^2 power density
ΔT~ 6 – 7 °C
Air velocity inlet ~ 20 m/s
Air velocity middle ~ 2 m/s
Expected vibrations from simulation <1.5 μm will be tested experimentally

Luminosity monitor integration

- Luminosity measurement with low angle Bhabha scattering $64 < \theta[mrad] < 88$; Silicon (active) + Tungsten (passive) sampling calorimeter
- Positioned about 1 meter away from the IP
- Centered around outgoing beampipe





Beam-induced Backgrounds (BIB)

Luminosity backgrounds

Synchronous with the interaction, can be discriminated at trigger level

Beamstrahlung: photons and spent beam

- Incoherent e^+e^- Pair Creation (**IPC**) ← **dominant – Use GuineaPig**
- Coherent e^+e^- Pair Creation
- $\gamma\gamma$ to hadrons

Radiative Bhabha - $e^+e^- \rightarrow e^+e^-\gamma$. Use BBBrem (benchmarked with LEP data)

Single Beam effects

- Synchrotron Radiation
- Beam-gas
- Thermal photons
- Touschek
- Injection backgrounds
- Beam halo losses

Mostly can be mitigated with collimators & shielding, except for those produced just in the IR.

A collimation insertion intercepts most the beam losses. Tertiary collimators upstream MDI area protect the experiments. Residual losses produce BIB and need to be tracked into detectors for occupancy and data rates.

FCC-ee beam-induced background sources

Simulation code Xsuite-BDSIM (GEANT4 based) – Currently **the focus is on the Z mode**

Beam losses have been studied from:

- **Generic beam halo**
- **Interactions with residual gas**
- **Beam-beam interactions**
- **Fast instabilities**
- **Top-up injection**
- **Touschek scattering**

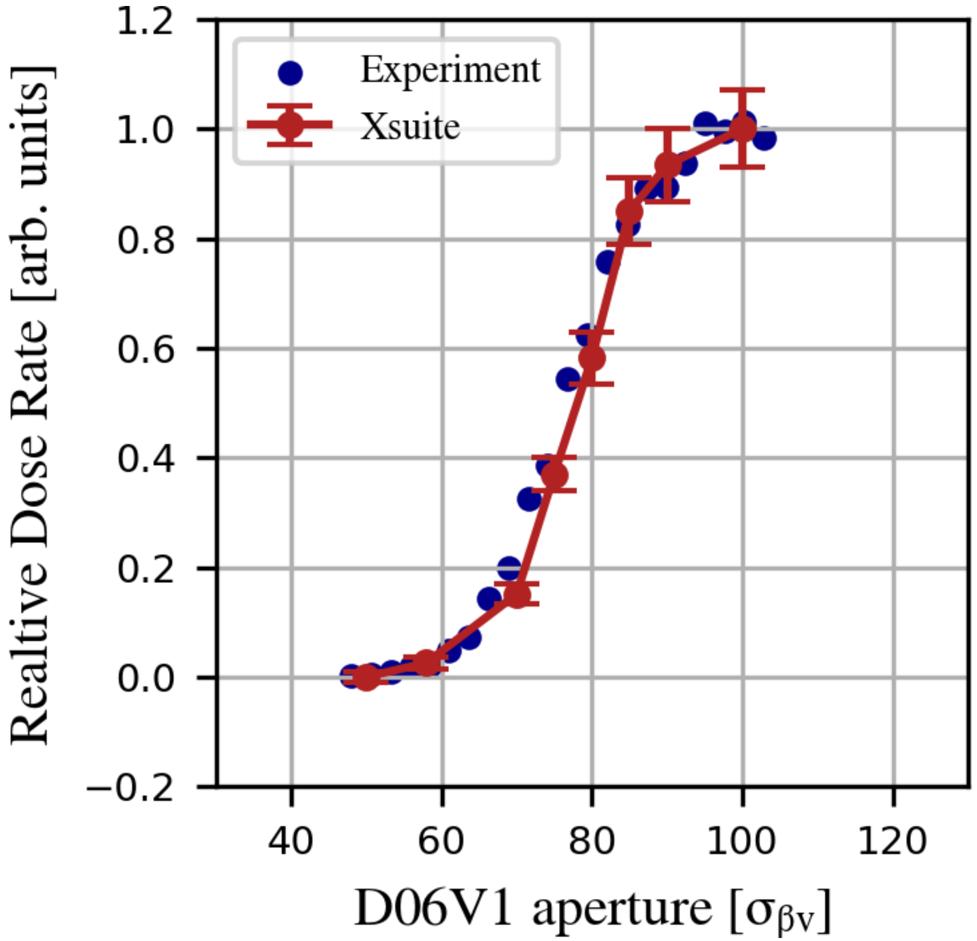
} **First iteration at tracking level done**

- Synchrotron radiation
- SuperKEKB-like sudden beam loss events
- Injection failure

} **Work in progress**

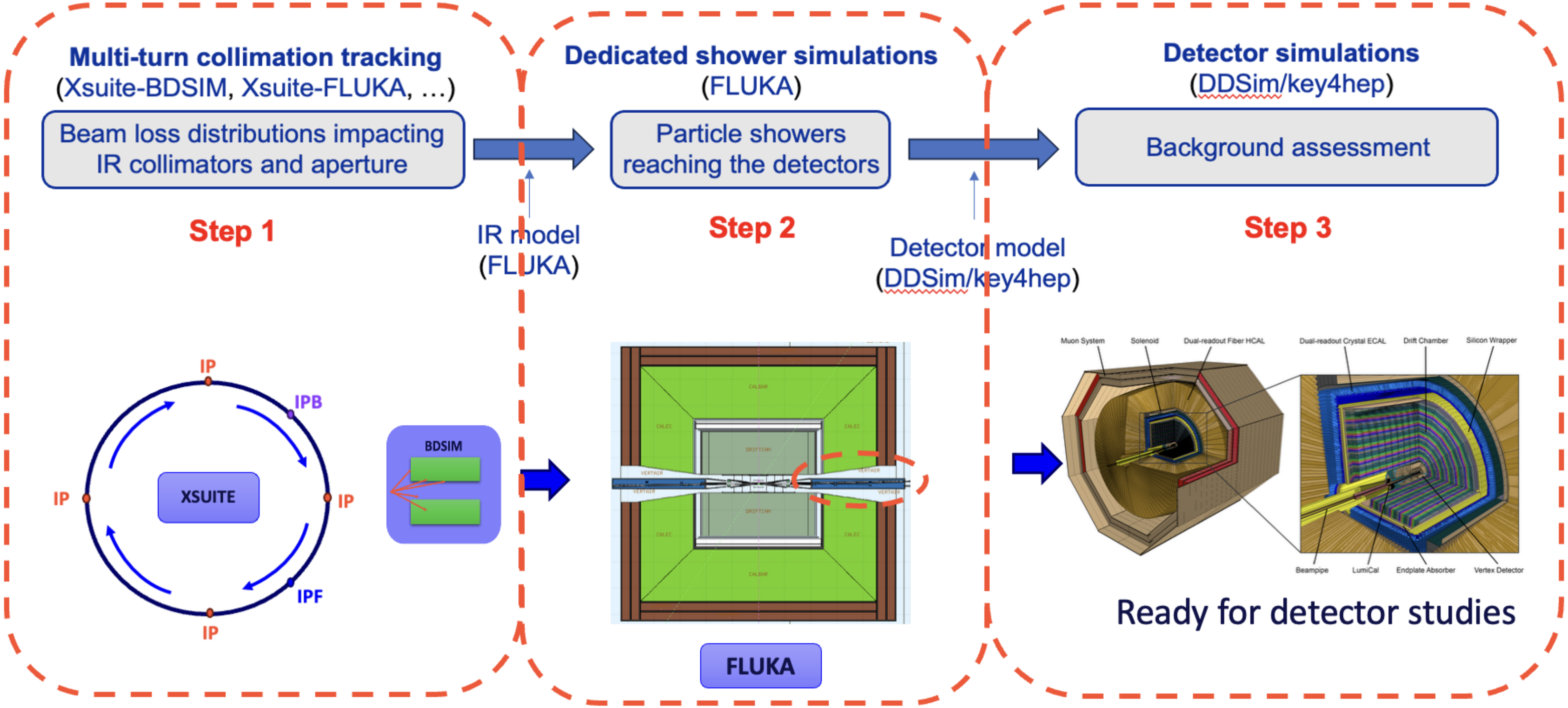
- Interactions with thermal photons
- Extraction failure
- Other failures: power supplies, RF, missing beam-beam, feedback

} **Not started**



Xsuite-BDSIM benchmarked with beam-induced SuperKEKB data (Touschek and beam-gas)

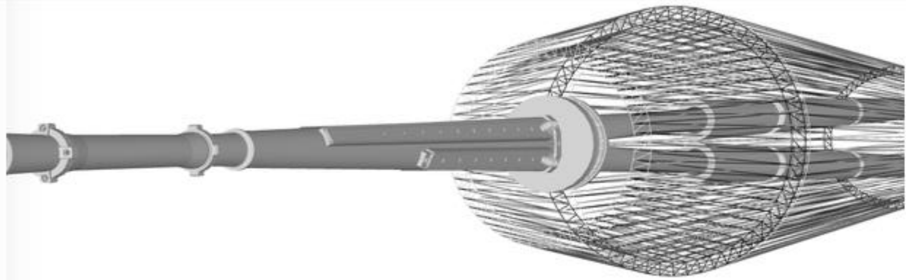
Background simulation workflow



Fluka tracks particles up to the interface plane, defined as:

- the internal beam pipe for losses inside the detector
- external boundary of detector for showers coming from outside the detector

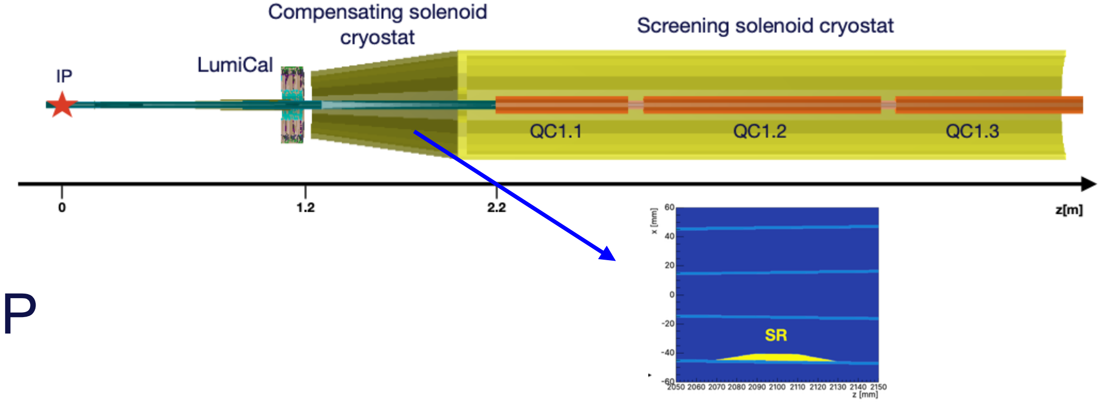
MDI modelisation in FCC-ee



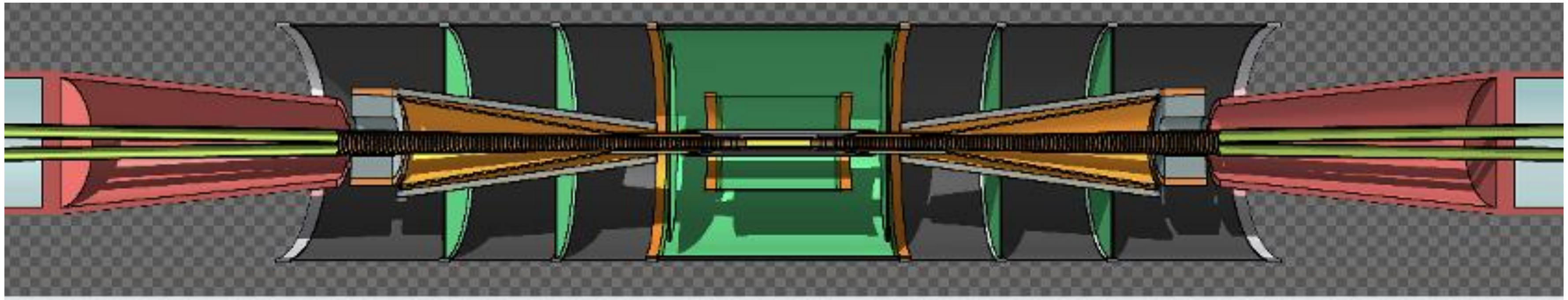
Very relevant for the detector BIB simulations
- **CAD-based model: real beam pipe profile**

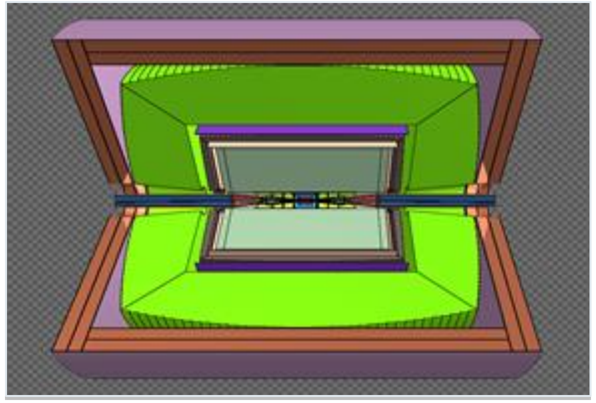
Key4hep – fully GEANT4 based

Engineered CAD model imported in Key4hep:
- IR beam pipe
- IR magnets simple equivalent material model
- Cryostat simple guess, equivalent material
- Synchrotron radiation (SR) mask at 2.1 m from IP



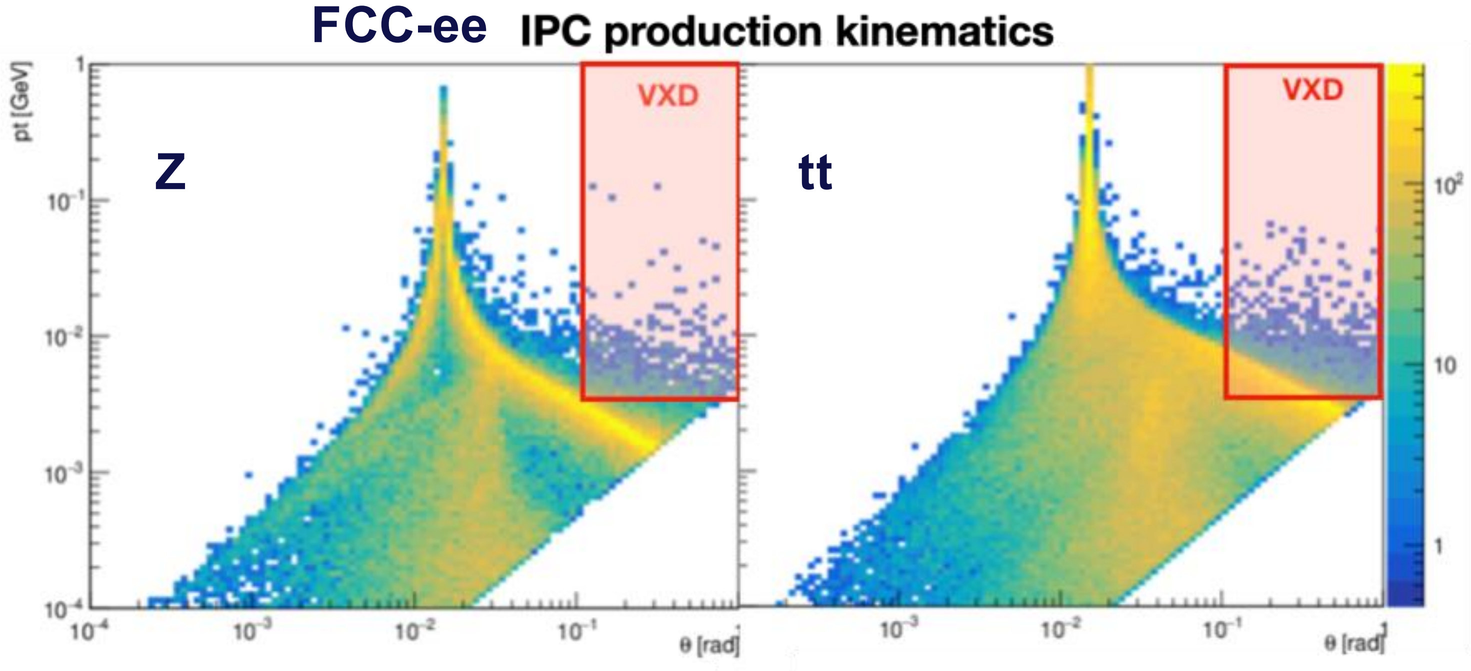
Fluka model

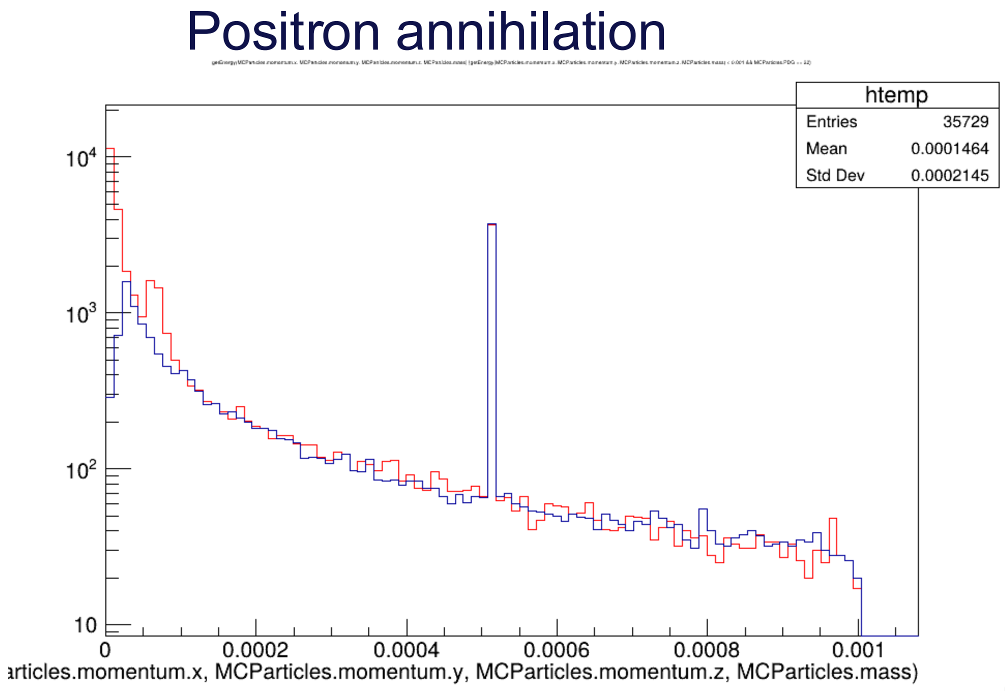




Beamstrahlung in FCC-ee

- IPC: Incoherent pair creation (real or virtual photon scattering e+ e-) dominant background
  - Use GuineaPig as generator
  - Lot of low p_T (few MeV) particles hitting the detectors directly or backscattering
  - Forward direction thanks to 30 mrad crossing, differently from SLC that had head-on collisions
  - Positrons annihilate in a few ns and some photons bounce back to vertex detector
  - 2T at interaction region keeps most of them inside the beampipe





Difference between SLD and FCC-ee

Different currents, and different beam profiles and crossing angles

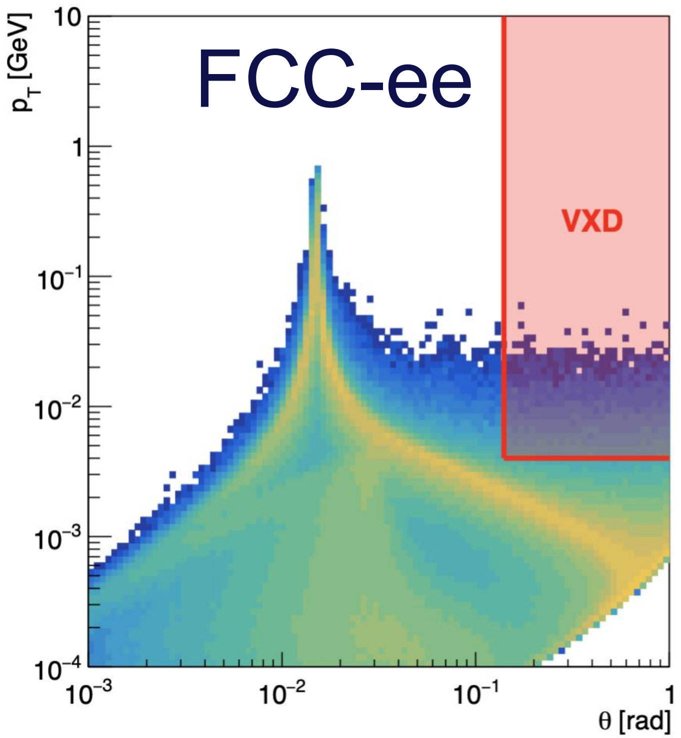
SLC had **<u>head-on collisions</u>, smaller current and different beam sizes**
FCC-ee **30 mrad collision angle**

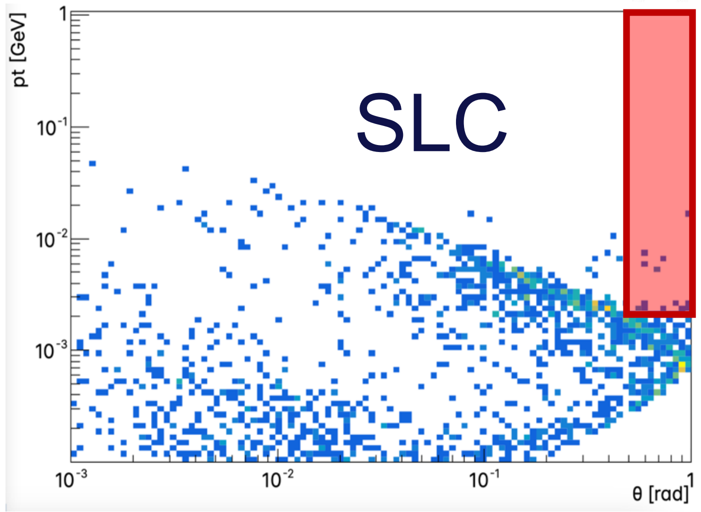
We ran GuineaPig with SLC parameters: **Obtained 1700 particles/BX**

FCC-ee: **1350 particles/BX, but completely different shape because of 30 mrad crossing angle**

Number of particles in the vertex detector acceptance (also different magnetic field, 0.6 T for SLD and 2 T for FCC-ee): **<u>in SLD 0.9%→ 16/BX, while in FCC-ee 0.7%→ 10/BX</u>**

- run SLC with the same current of FCC-ee (x5) we get: ~50,000 particles (a factor 30 more!)
- run SLC with the same crossing angle of FCC-ee (30 mrad) we get: 40 particles (a factor 40 less!)





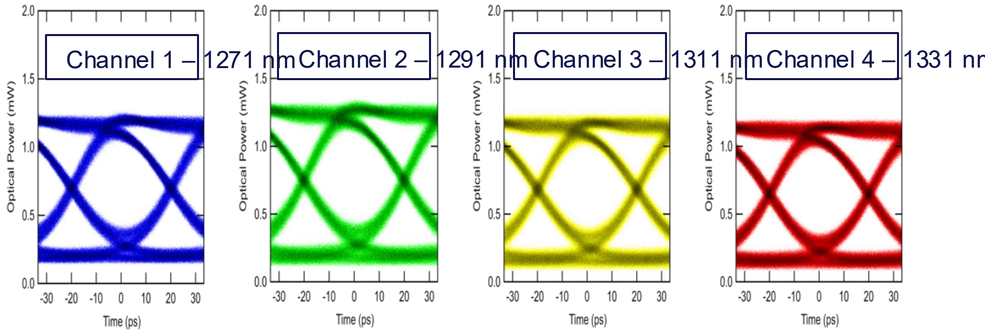
IPC in the FCC-ee Vertex Detector

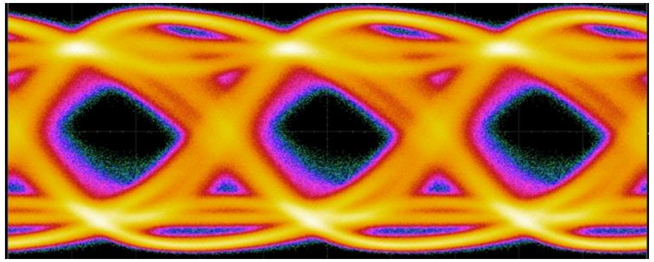
- **Occupancy for the vertex innermost layer** (r=13.7 mm)
  - Assume cluster size of 5
  - **Safety factor of 3**
  - Cut at 500 e- (~1.8 keV)

Hit rates ~200 MHz/cm² (occupancy of $\sim 5 \times 10^{-5}$)

Challenging for readout **~100 Gb/s per ladder,** but …
a single silicon photonics WDM link could accommodate that (see this and that at DRD7 workshop) today … maybe more in 2048!

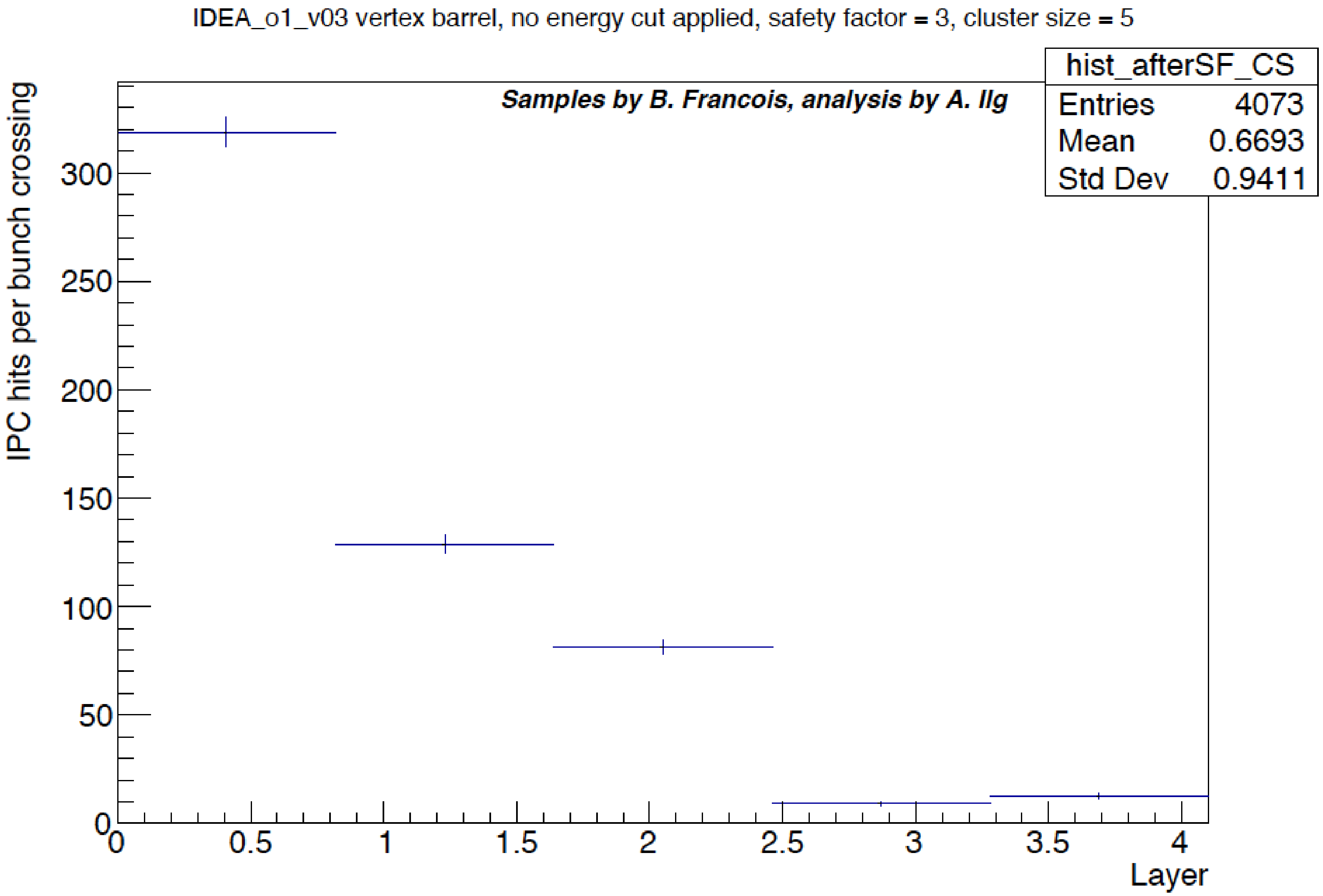
WDM 4x@25 Gb/s





Single lane @56 Gb/s

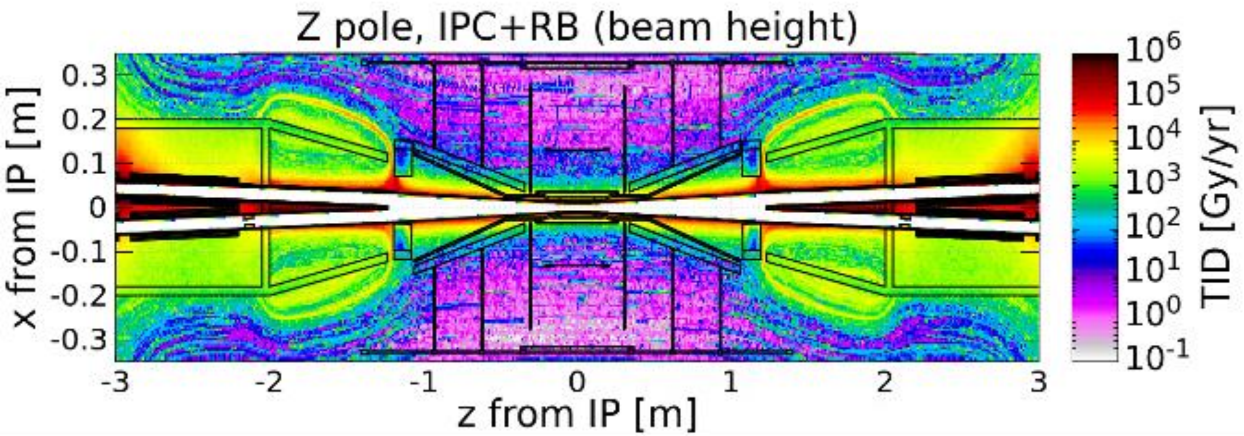
IPC backgrounds as a function of layer

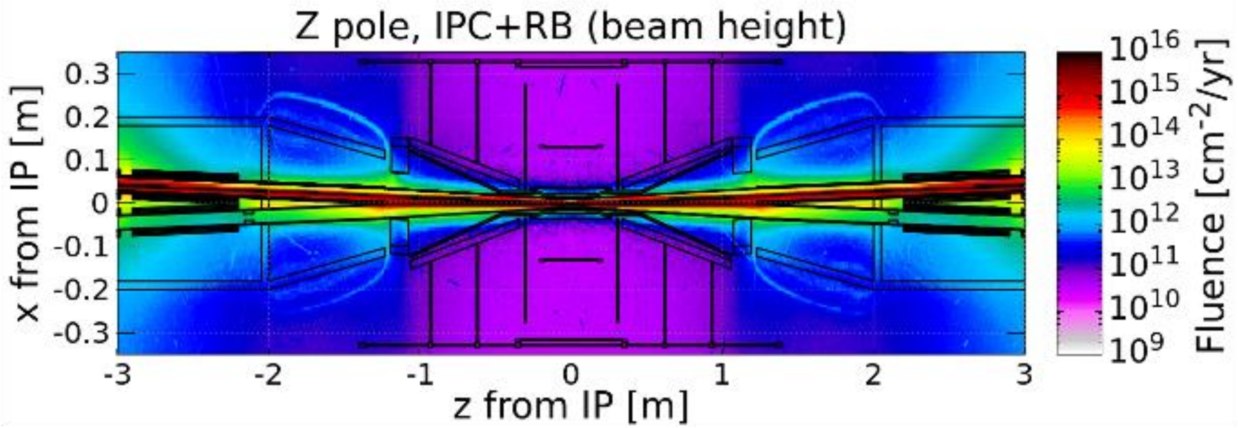


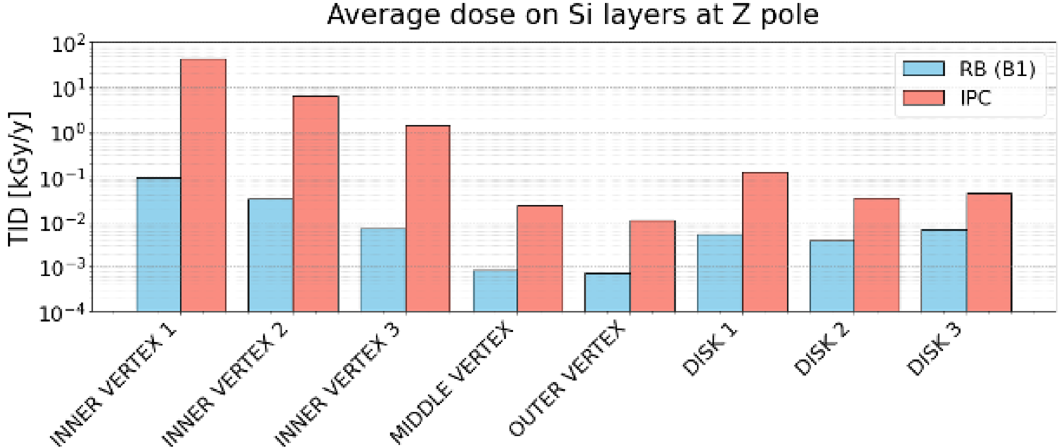
Vertex detector radiation levels – FLUKA based simulation

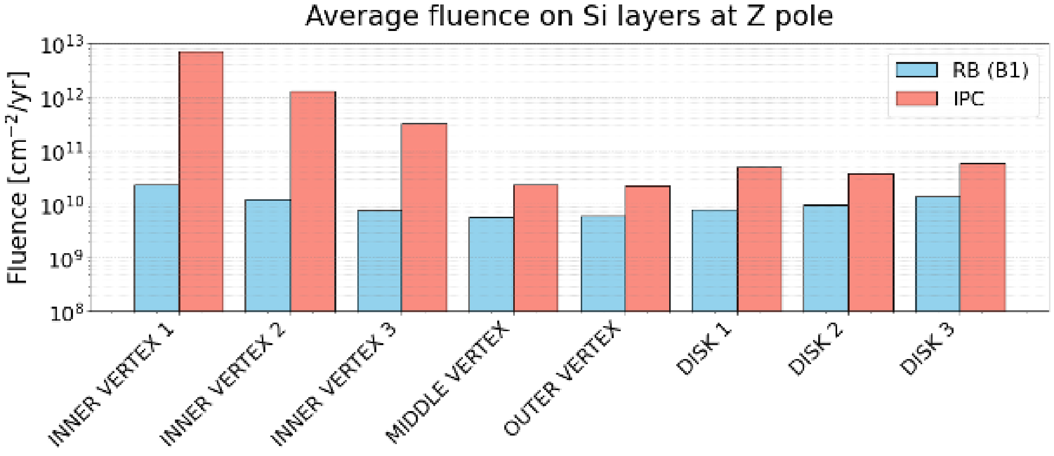
IPC + radiative Bhabha events

- Innermost layer (at ~1.3 cm) TID and fluence are one order of magnitude higher than second layer.
- Current MAPS technologies are OK
  - At 15 cm distance, dose and fluence are about 3 orders of magnitude smaller than innermost layer









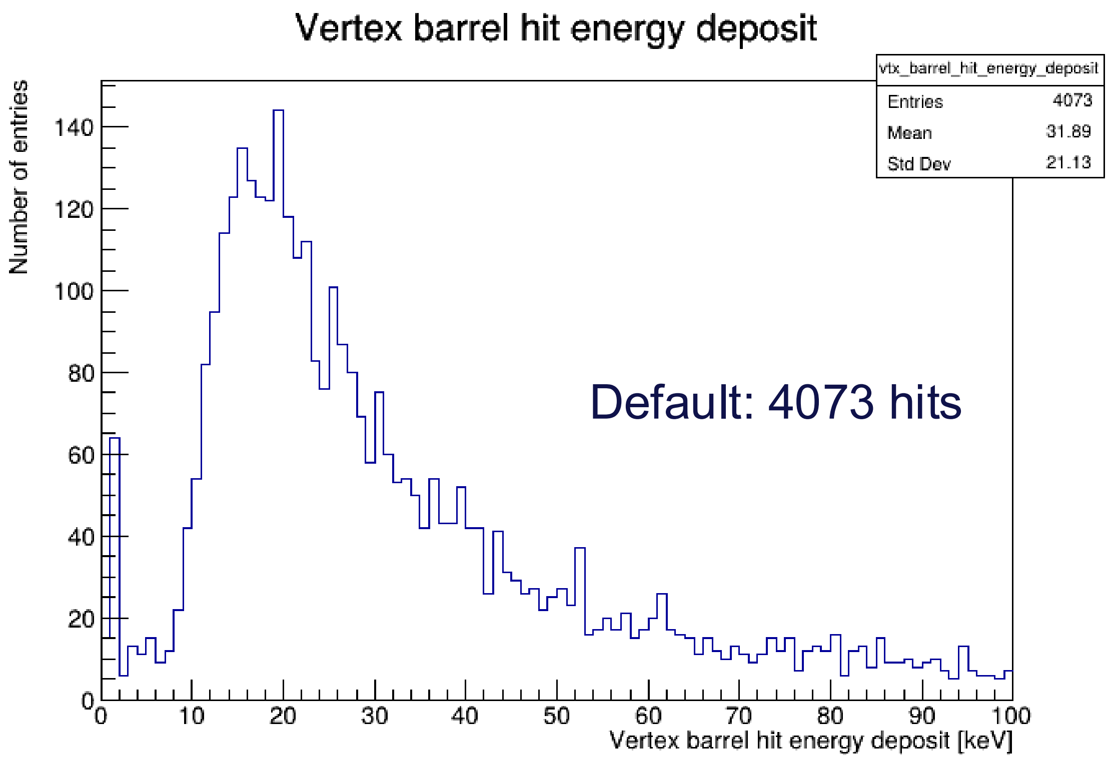
Improvements in the simulation wrt Feasibility Study Report (FSR)

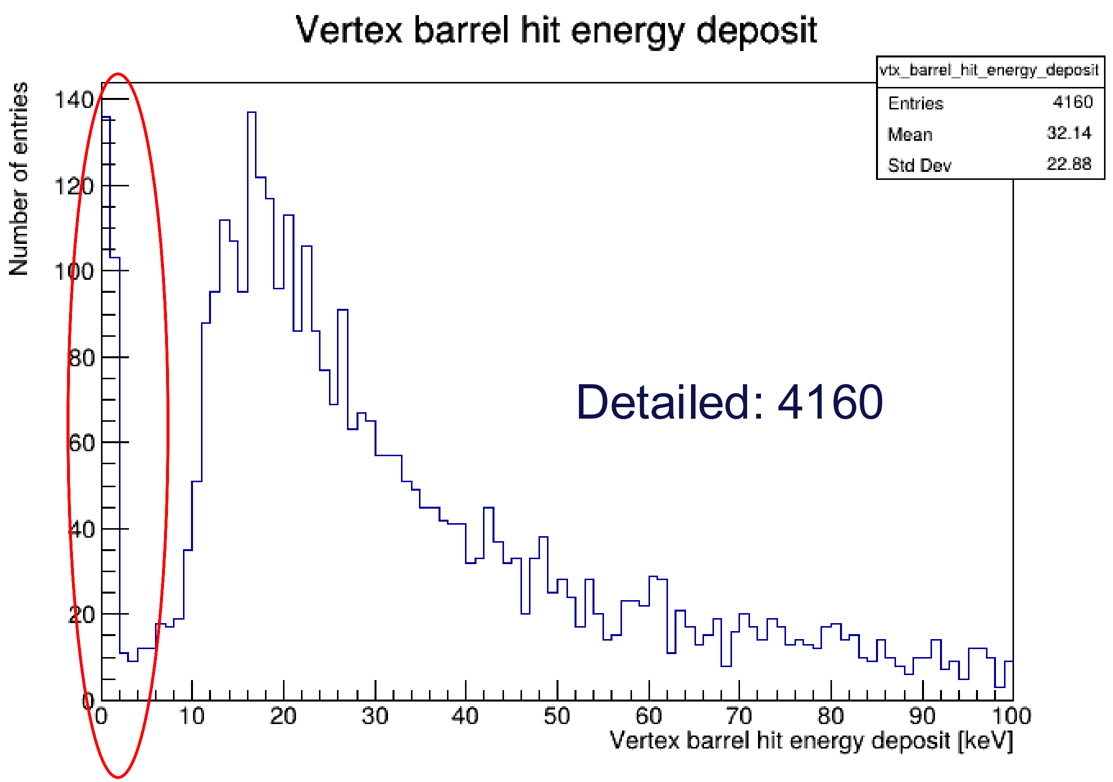
- At the time of writing the FSR the effect of some processes (Auger and fluorescence) have not been switched on by default in GEANT4, as well as the thresholds for tracking were at 1keV (thresholds of ~300 e-).

- Once switched on, and lowered to 0 keV the thresholds**, the effect is of the order of an increase of less than 10%** in the number of hits in the VTX for low energy release (at around 1 keV)

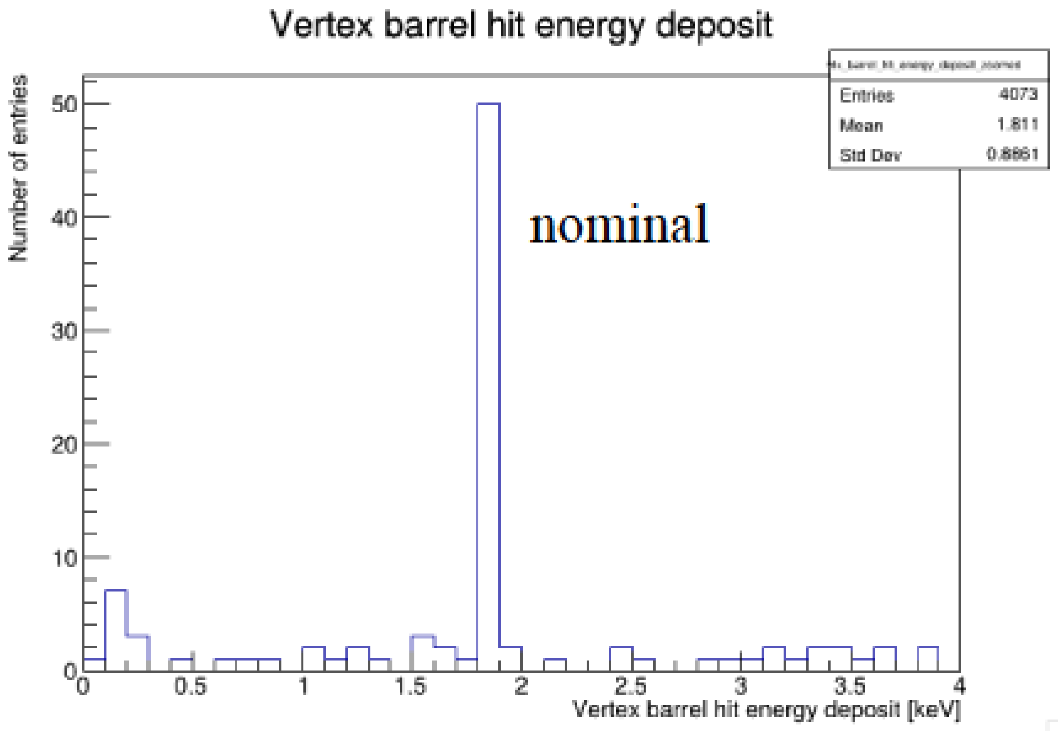
Effects of fluorescence and Auger electrons

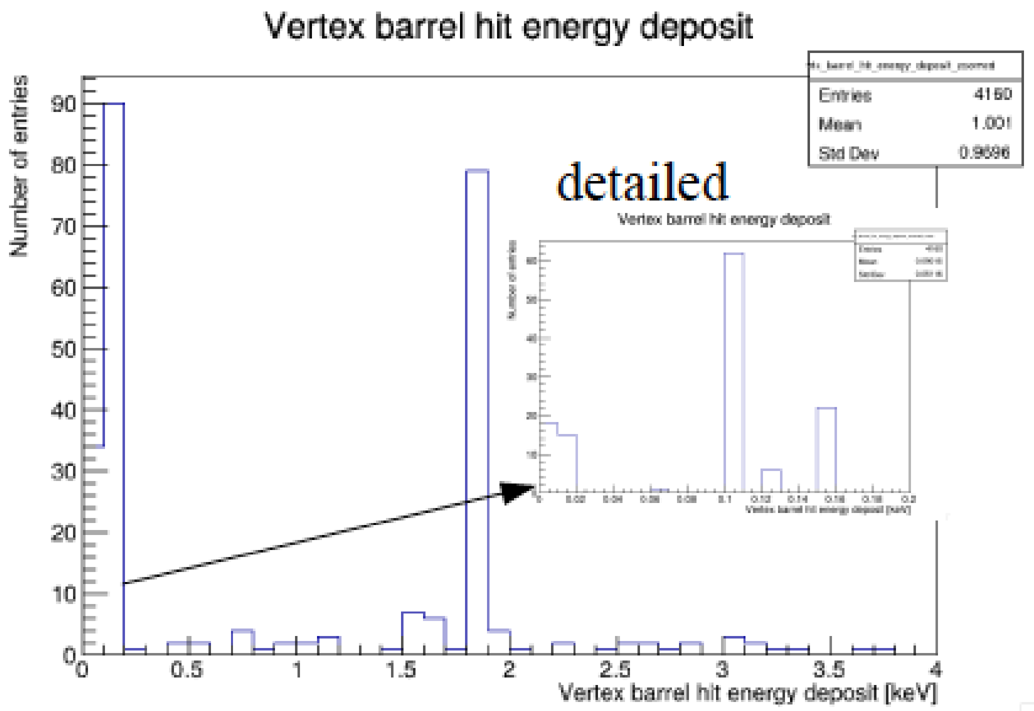
Switching on the fluorescent processes and Auger electrons, and lowering the thresholds of the simhits to ~0 eV, we get a peak below 1 keV





Zoomed energy deposit



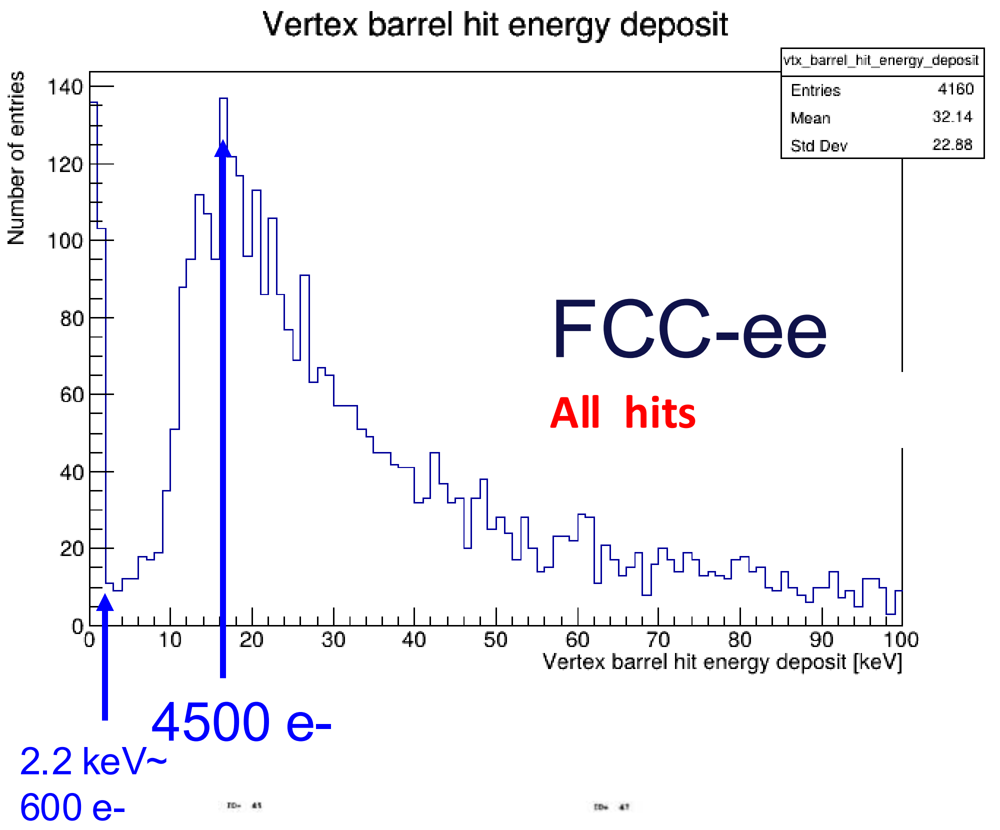


The 1.8 keV peak is the Silicon K-edge
The fluorescence contribution is below 0.2 keV (~56 e-)

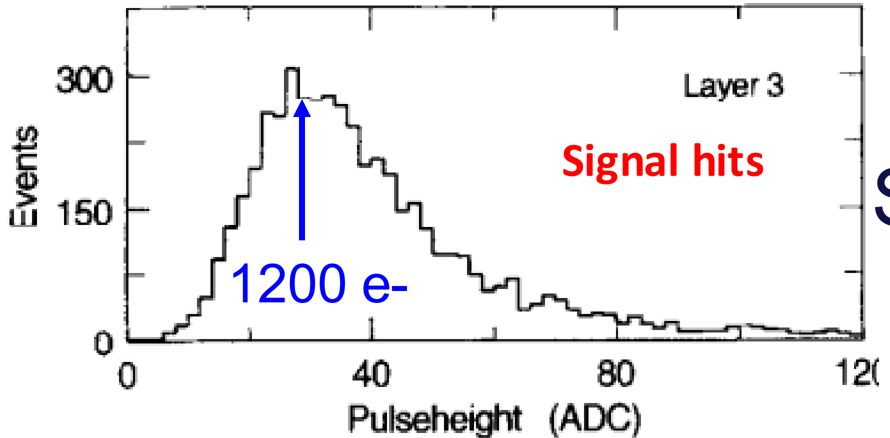
Pulse height and thresholds difference

- The most probable MIP signal in SLD was 1200 electrons,
- FCC-ee simulation assumes 50 μm fully depleted sensors, so the most probable signal is around 18 keV (4500 electrons), **almost a factor 4 larger wrt SLD**

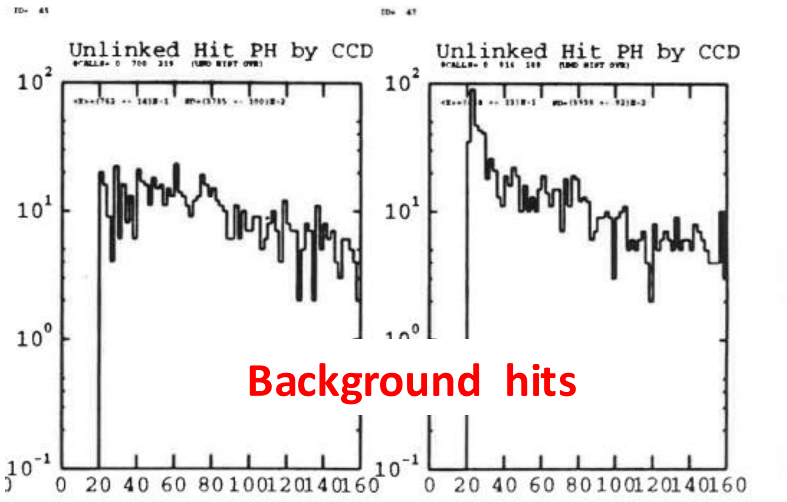
- At SLD data showed a peak close to the thresholds of 800 e-, and a broad spectrum of hits up to 23 keV. Do not know exact origin of it. (maybe SR?)
- The energy released in FCC-ee by the low energy fluorescent x-ray backgrounds is rather small (below 2 keV or so), corresponding to less than 600 electrons and can be easily be rejected w/o losing efficiency, thanks to higher signal in FCC-ee for 50 μm thick sensors



ADC counts
1 count=40 e-

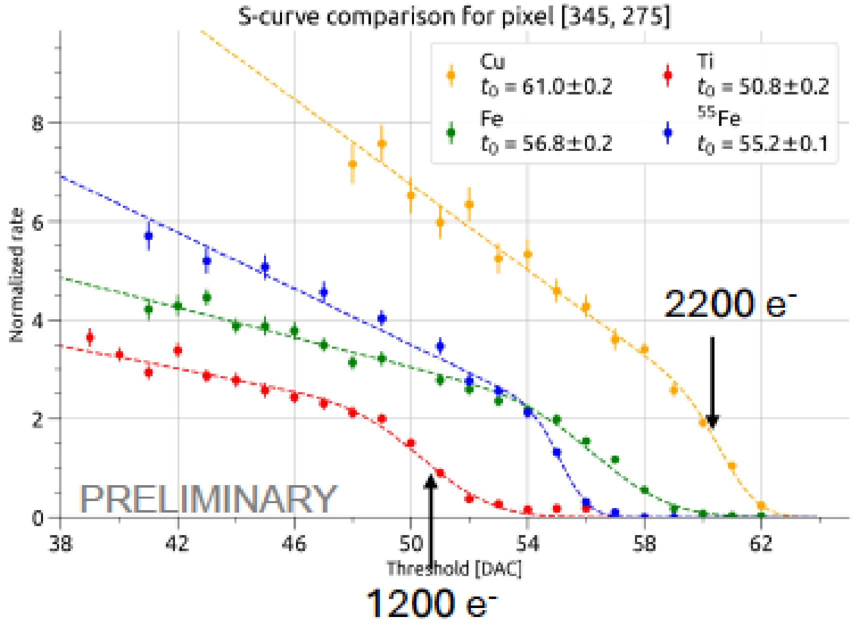


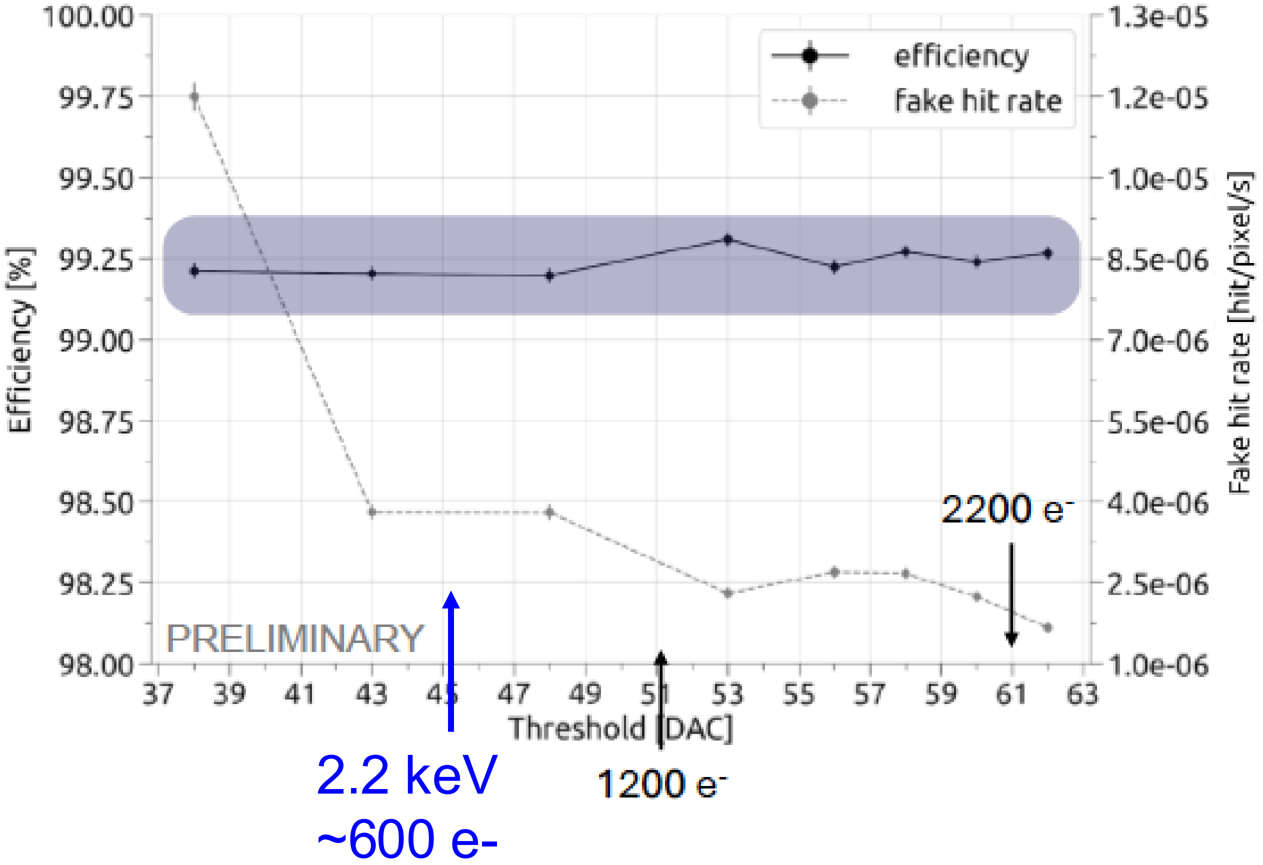
SLD



MD3 test beam: efficiency and fake hit rate

Thresholds for ARCADIA

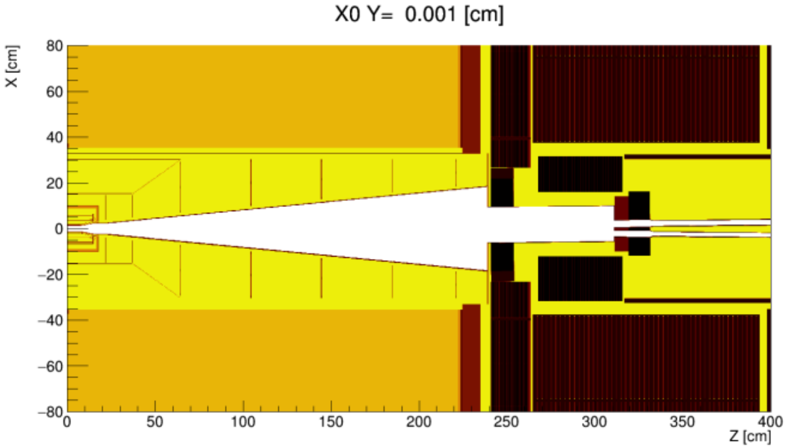


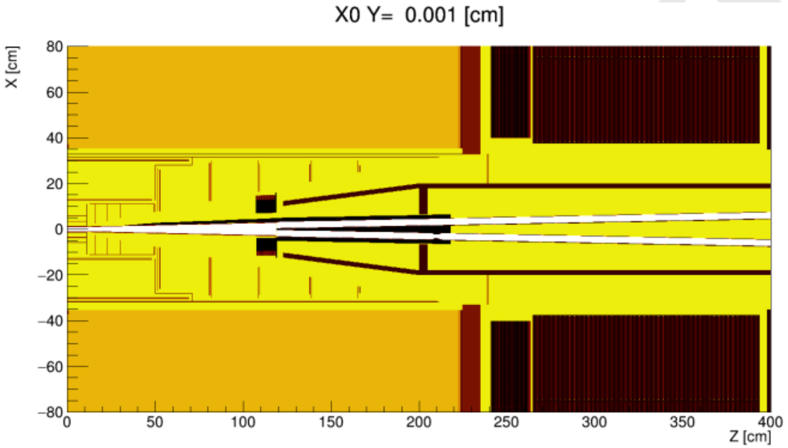


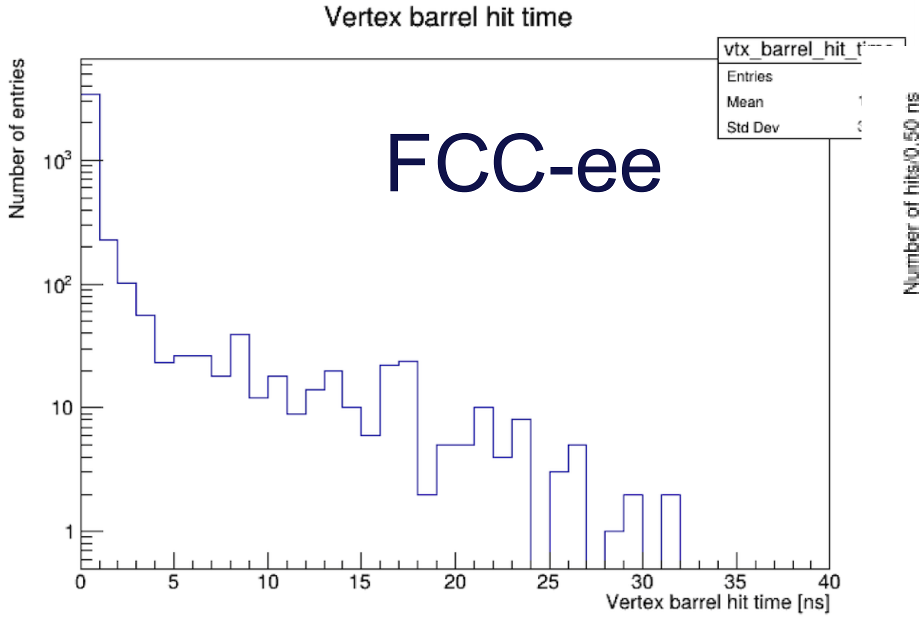
Maximum threshold value corresponds roughly to **2200 electrons** (calibrated via fluorescence measurements).
In 200-µm thickness, a MIP releases ~ 16000 e- → the highest available threshold corresponds to a much lower charge released.

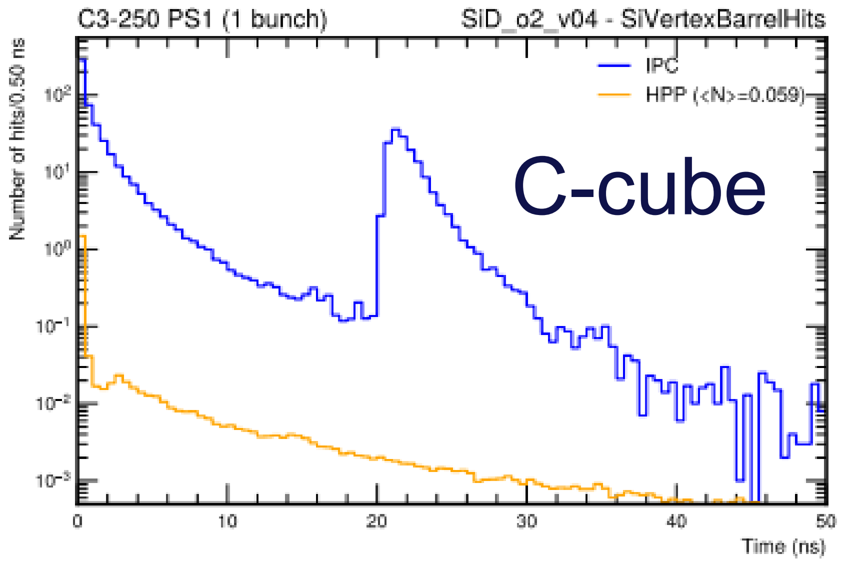
Time structure reflects contribution from the backsplashes

- At FCC-ee the time of arrival of the hits in the vertex shows a broad distribution, albeit much reduced wrt the bulk… produced by the secondary interactions about few ns (the LumiCal is at ~1 meters, so 8 ns once bounced back).
- In the case of linear colliders the distance is ~3 m (20 ns). That's why we did not see the same peak at 20 ns.







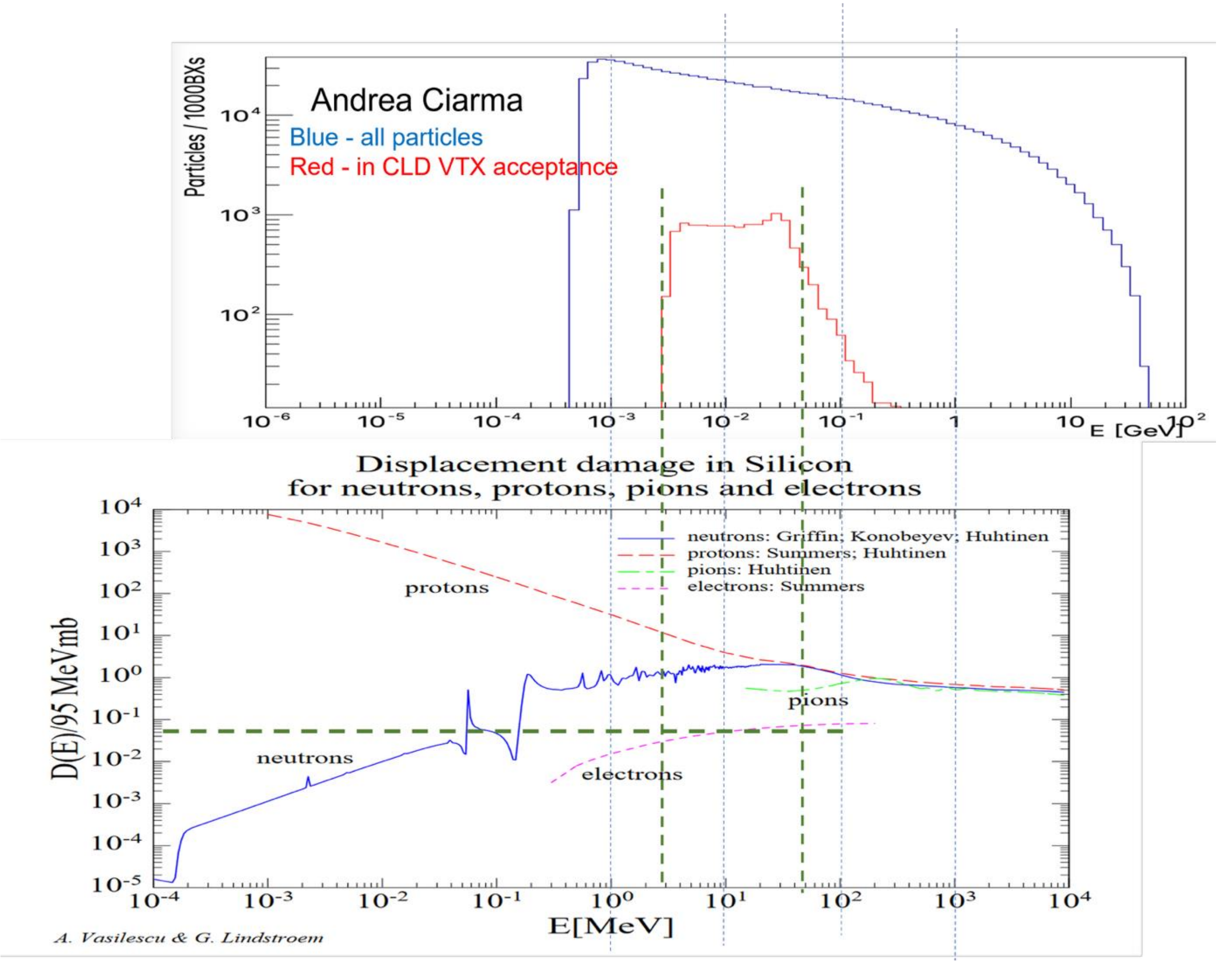


What about FLUKA for FCC-ee?

Completely different setup, starting from the same geometry.

1 MeV neutron equivalent fluence computed for the innermost layer of the vertex detector is ~7 10^{12}/cm^2/year (1 year =10^7 s).

assuming the only source are e+e- from IPC the scaling factor is ~0.05, meaning that one gets an equivalent flux of electrons of 20 times higher (14 MHz/cm^2) and multiplying for a cluster size of 5 and a factor 3 for safety, we reach ~200 MHz/cm^2 , (in agreement with GEANT estimate!)



Difference in luminosity calorimeters

SLAC-PUB-5694

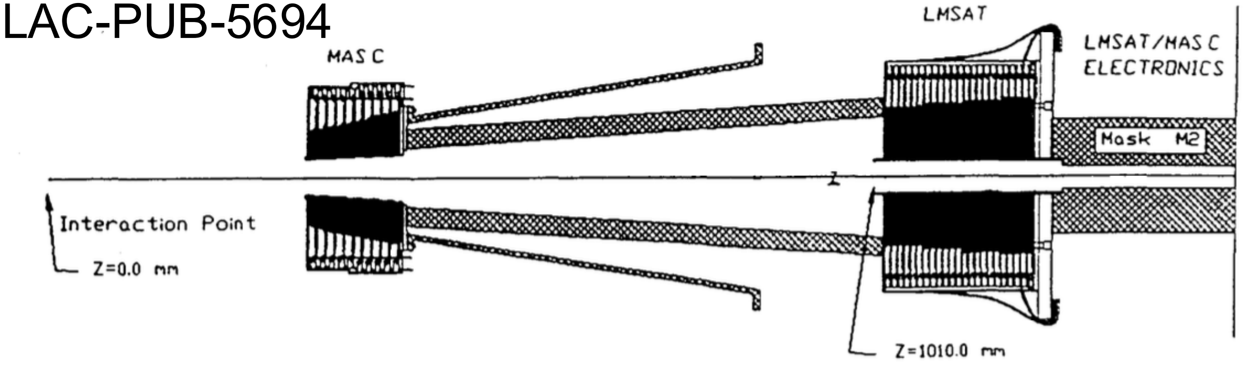
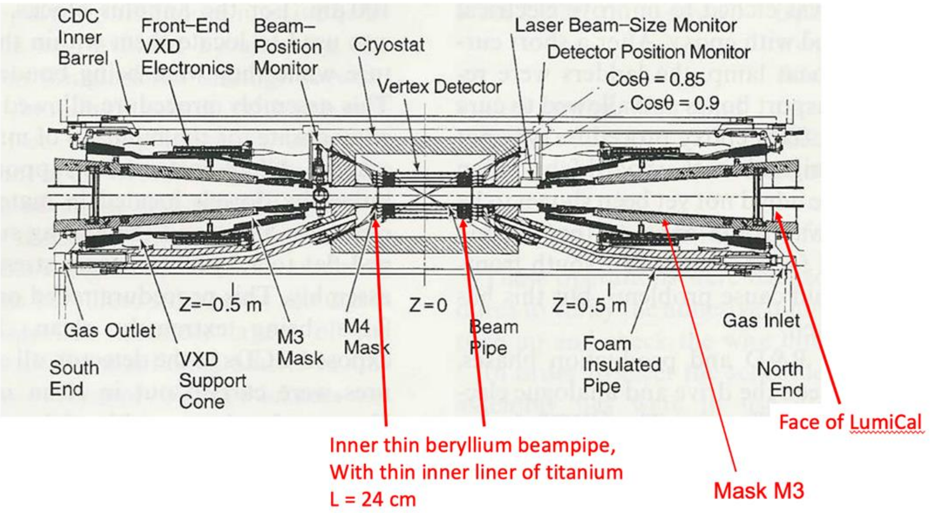


Figure 3. Side view showing LMSAT and MASC positions with respect to the IP.



The SLD luminosity monitor (LMSAT) was a W-Si sandwich with the face 100 cm from IP, rather similar to FCC-ee. LMSAT covers the 23-68 mrad region.

Another W-Si sandwich, MASiC, placed with its face at only 31 cm from the IP overs 68-190 mrad.
The innermost radius of these device is about 30 mm from the detector z-axis, which is similar to LumiCal(at least on the negative x), which is the relevant axis since the IPC spiralize around it.
However, the MASiC is only ~20 cm away in z from the vertex, whereas FCC-ee LumiCal is about 1 meter, and that matters for backsplashes.

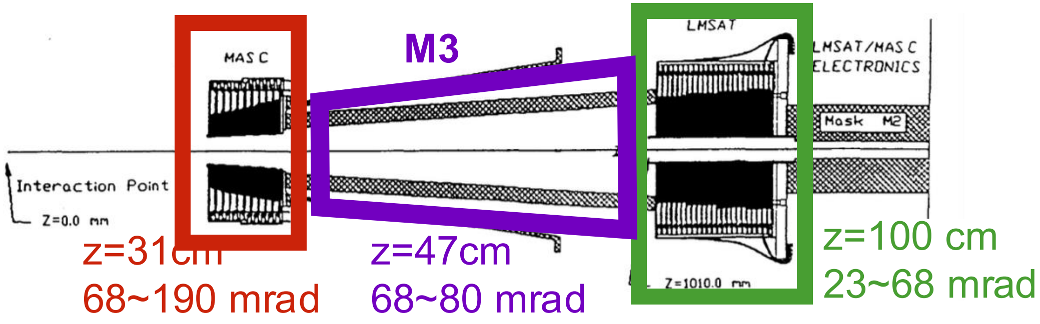
The MASiC was removed in 1995 with the installation of VXD3, but was present for VXD2

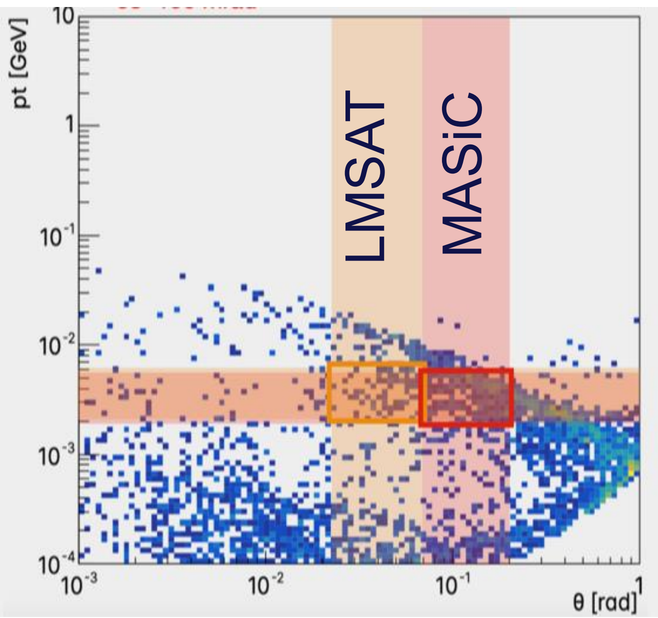
Particles hitting the luminosity calorimeters/masks

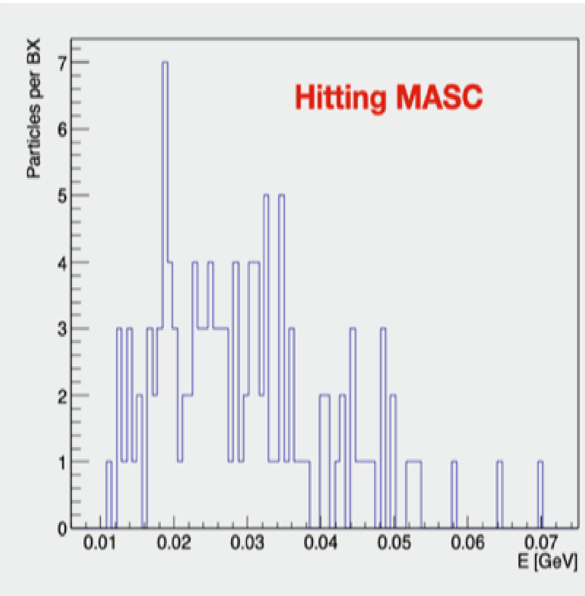
Assume that the number of backscattered particles (photons or electrons) hitting the VTX is proportional to the e+e- pairs hitting the closest bulky structure to VTX

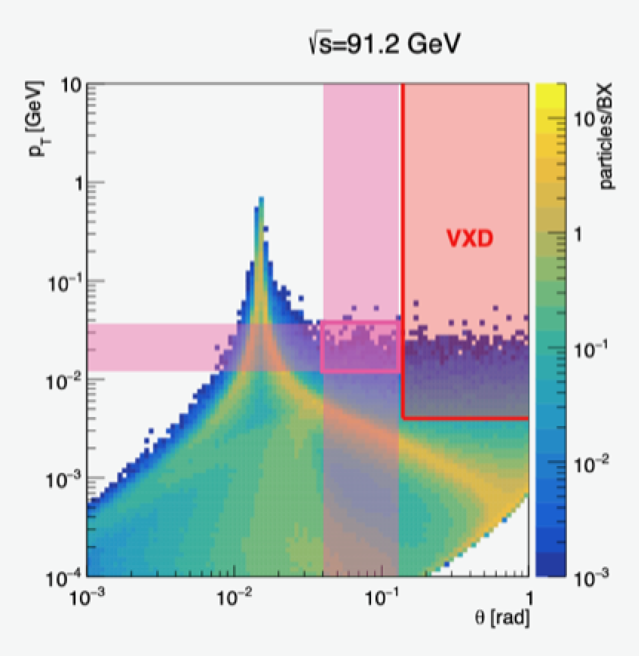
SLD:
- 7% hit MASiC → **120 particles/BX**
- 2.2% of the particles hit LMSAT → **38 particles/BX**
- Those hitting Mask3 are **about 1.5 particles/BX**

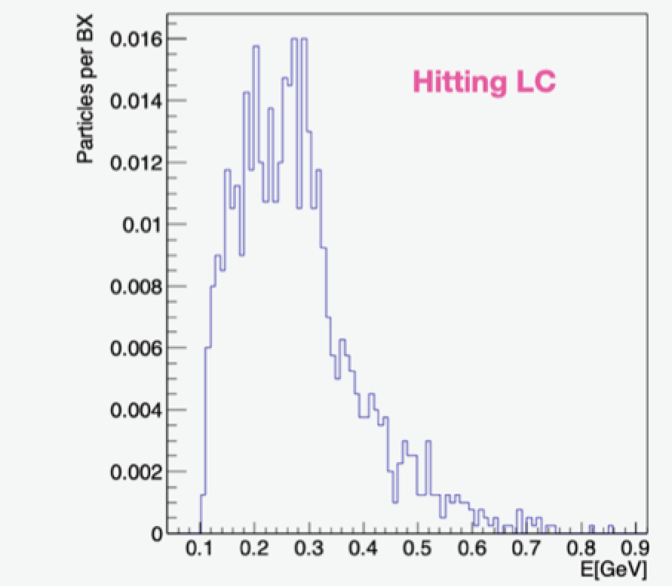
FCC-ee:
- 0.03% hit LumiCal → **0.4 particles/BX**











Comparing IPC at SLC vs FCC-ee

NB. Do not use these numbers to compute absolute occupancies, which can only be estimated by full simulation.

	SLC VXD3	SLC MASiC	SLC LMSAT	SLC M3	FCC-ee Vertex @Z	FCC-ee LUMICAL @Z
Particles/BX from IPC	~1700				~1350	
Particles/BX hitting	16	~120	~40	~1.5	10	~0.4
BX rate	120 Hz				50 MHz	
Particles/s hitting	1’900	14’000	4’500	180	$500\ 10^6$	$20\ 10^6$
Vertex Integration Time	215 ms (~26 BX)				1 µs (50 BX)	
Particles hitting in one Integration Time	~400	~2’000	~1’000	~40	~500	20

The relative proportion of hits in the vertex from direct and backsplashes is inverted between SLD and FCC-ee

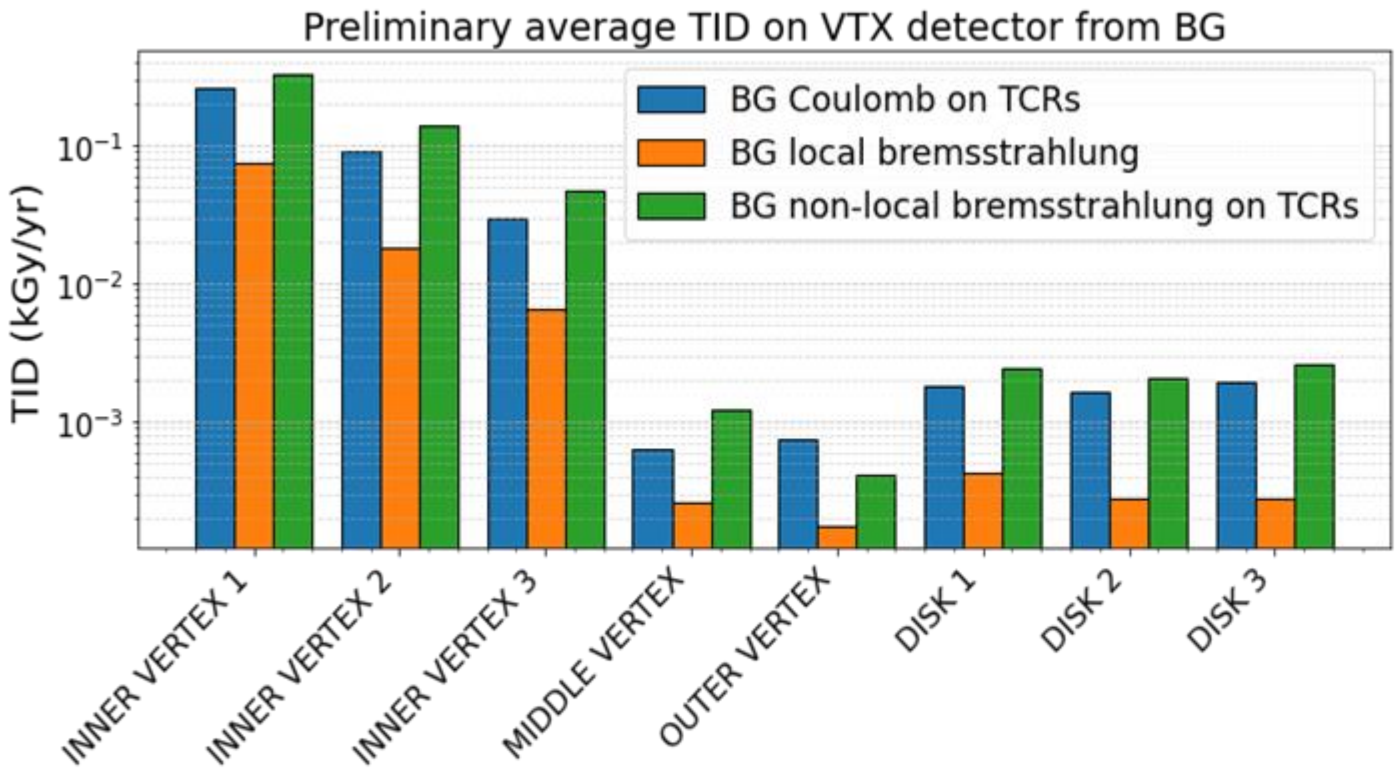
Other background sources

Beam-gas interaction contribution to detector

local: upstream the MDI, single pass
non-local: generated far from IP and multiturn

Beam-gas bremsstrahlung

Beam-gas Coulomb scattering

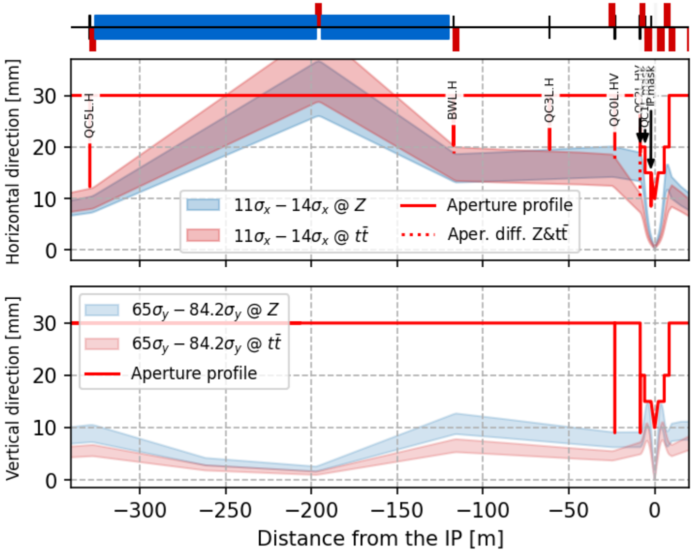


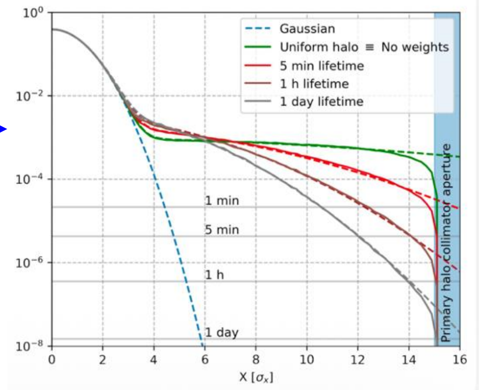
Doses are proportional to backgrounds, subleading wrt IPC

Synchrotron Radiation (SR) backgrounds

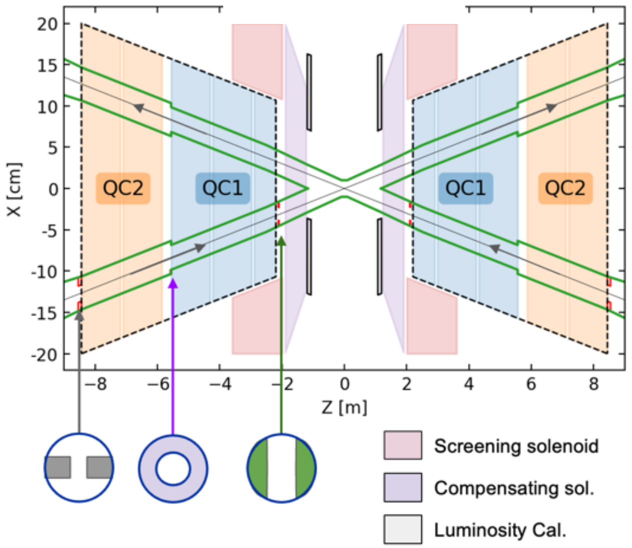
- Simulations with BDSIM (GEANT4 toolkit)
- SR evaluated for
  - **beam core** with non-zero closed orbits for considering optics imperfections
  - **transverse beam tails,** pessimistic weighted halo model used:

bulk of SR produced upstream the IR is stopped by collimators



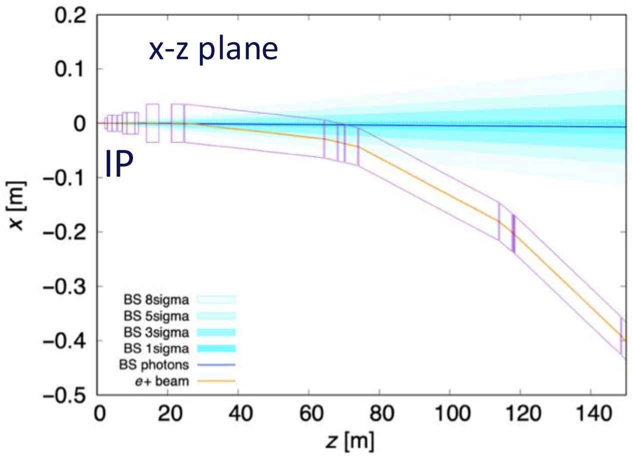


- **SR produced in the IR** by **IR quads and solenoids:**
  - bulk of SR is collinear with the beam and will hit the beam pipe at the first dipole after the IP → no direct hits in the detectors
  - Transverse tails in the fringing field of the final quads produce SR that may hit the detector: **masks at the exit of QC1 and QC2**
    - Optimisation and effects on detectors under way

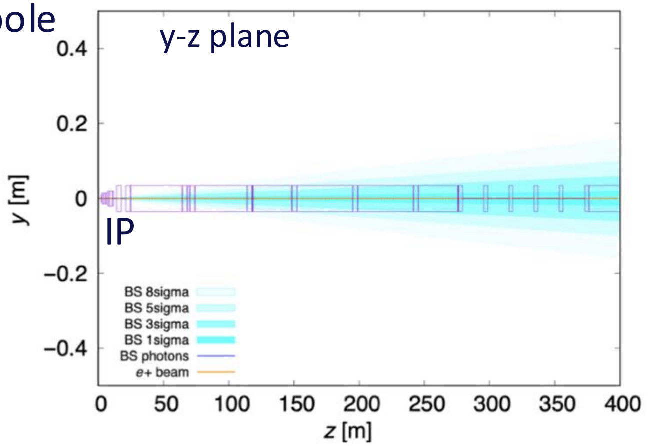


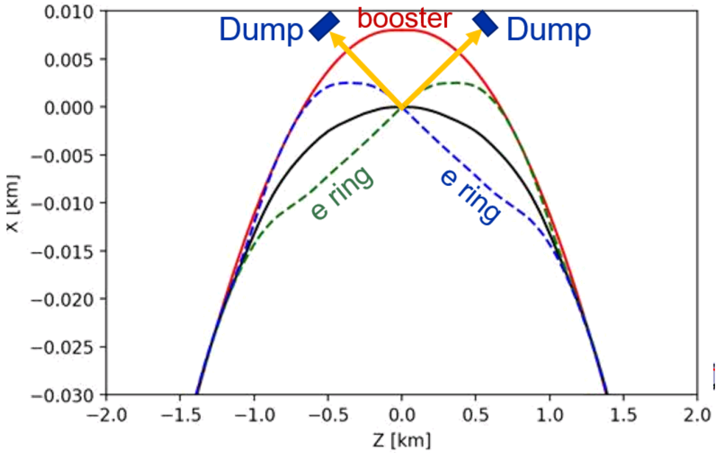
BS and SR radiation produced at IR

Radiation from the colliding beams is very intense 400 kW at Z



Z-pole





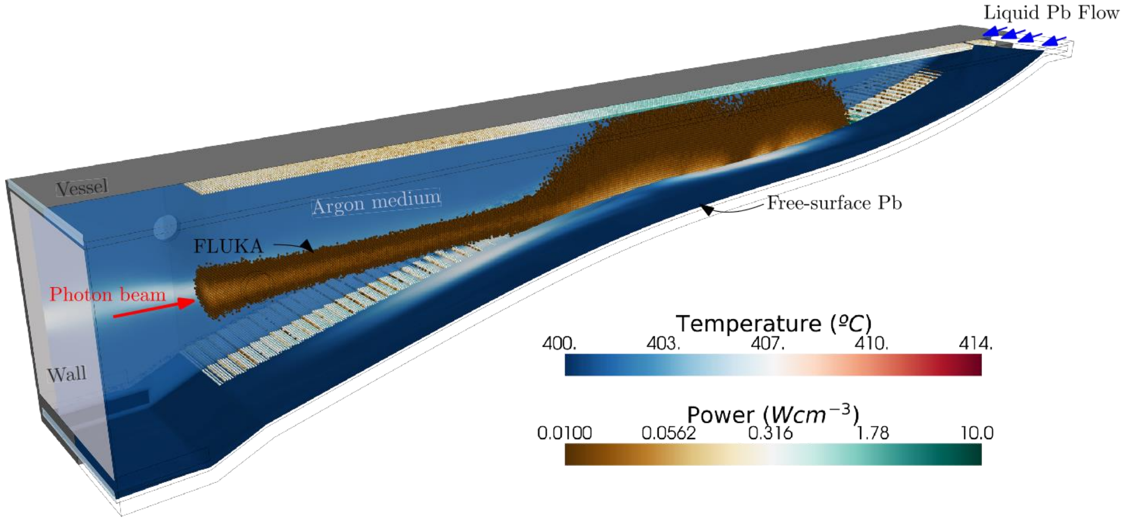
Dump placed 500 m from IP in order to have enough separation from booster / collider (space for shielding)

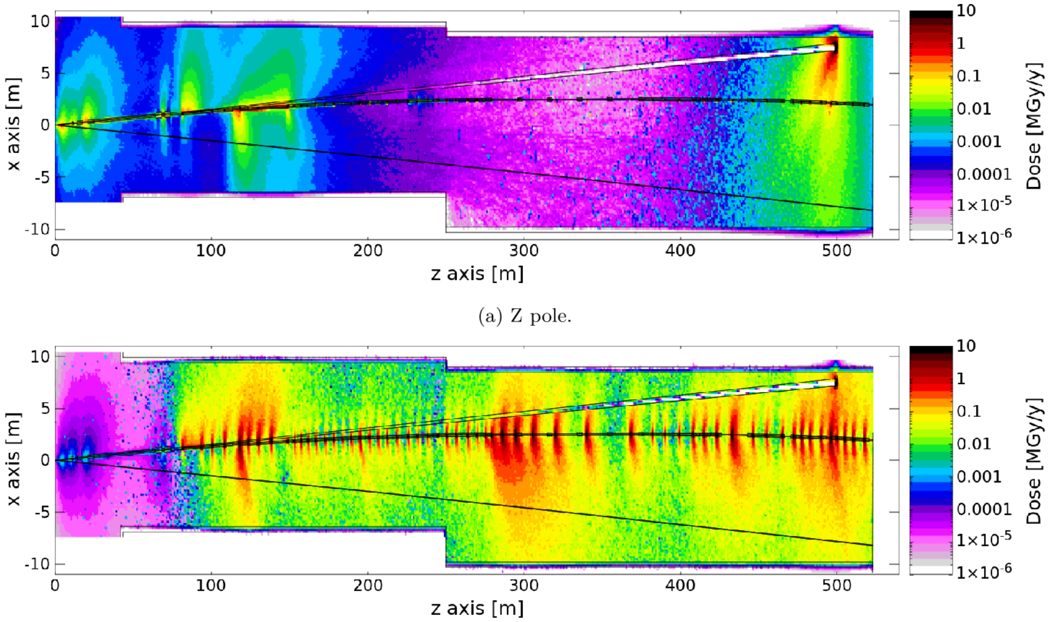
M. Boscolo and A. Ciarma, "Characterisation of the Beamstrahlung radiation at FCC-ee", PRAB 26, 111002 (2023), link

High-power beam dump needed to dispose of these BS photons **+ all the radiation from IR**: FLUKA simulation ongoing

- Different targets as dump absorber material are under investigation (liquid lead at the moment)
- Shielding needed for equipment and personnel protection for radiation environment

Beamstrahlung and SR dump

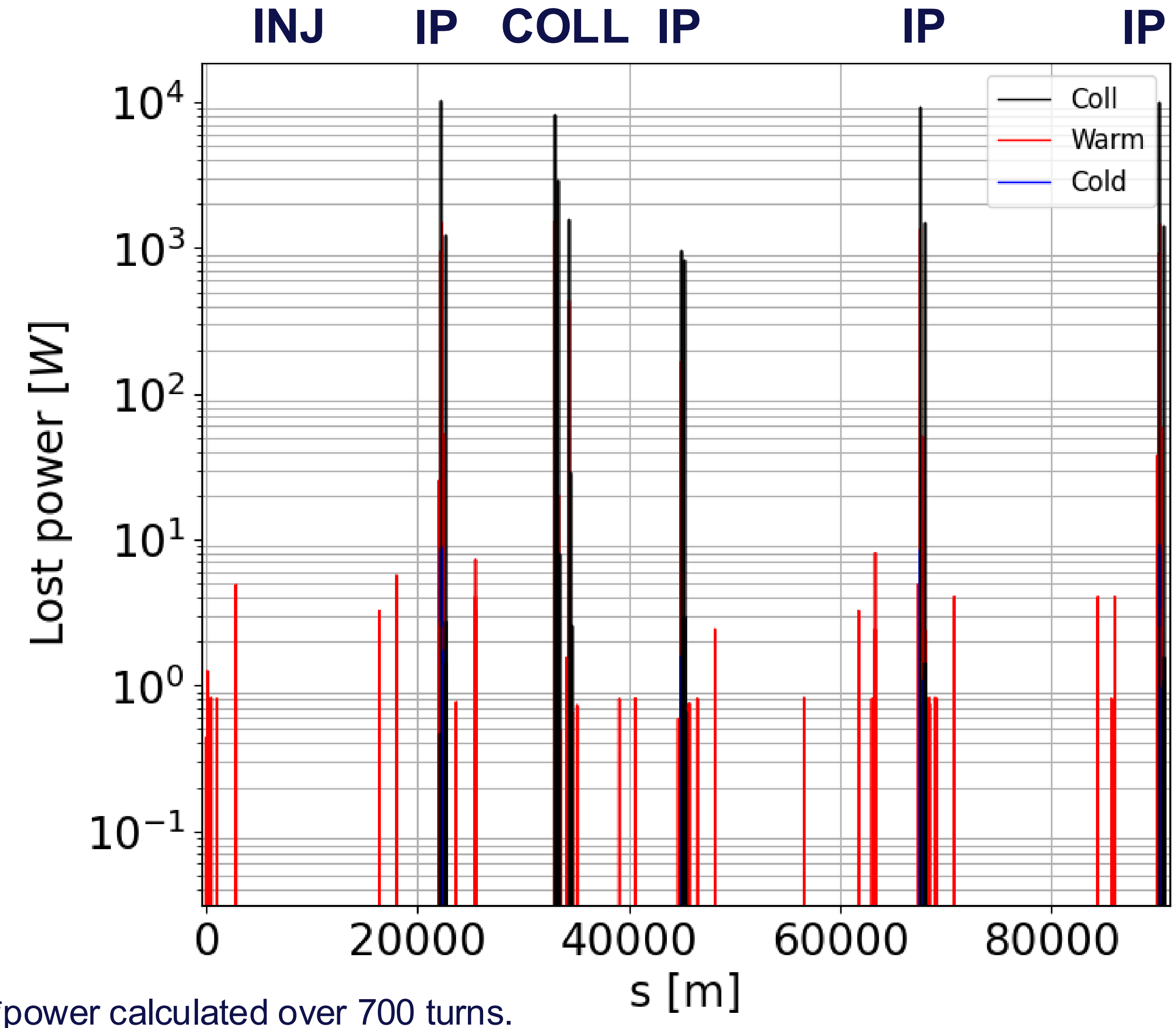




(a) Z pole.

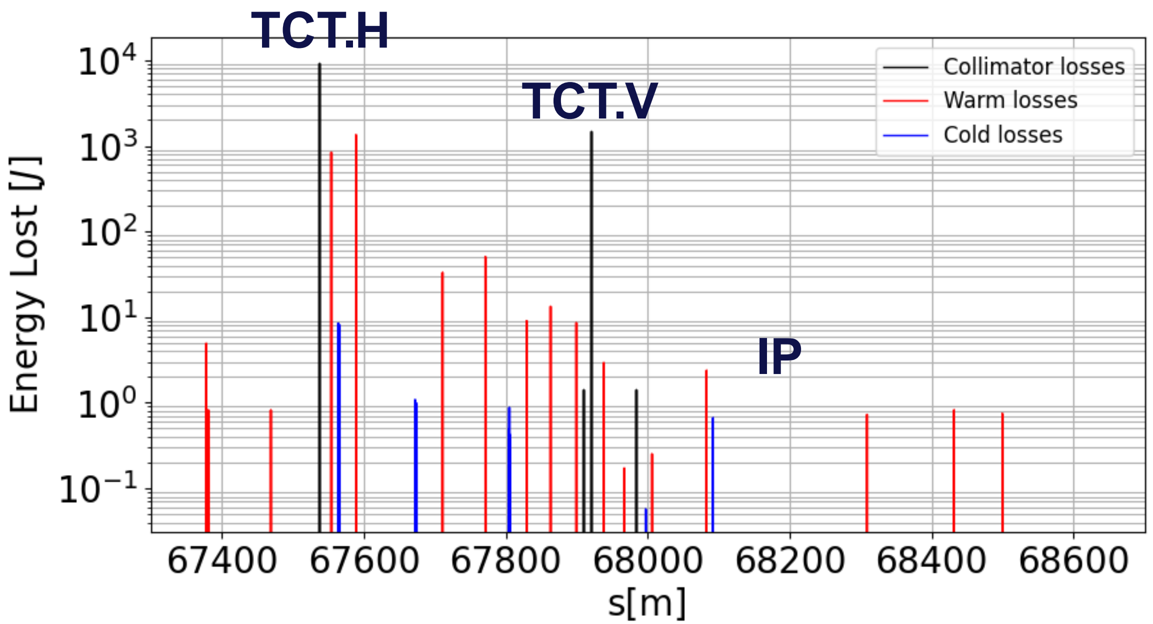
(b) $t\bar{t}$.

Injection losses

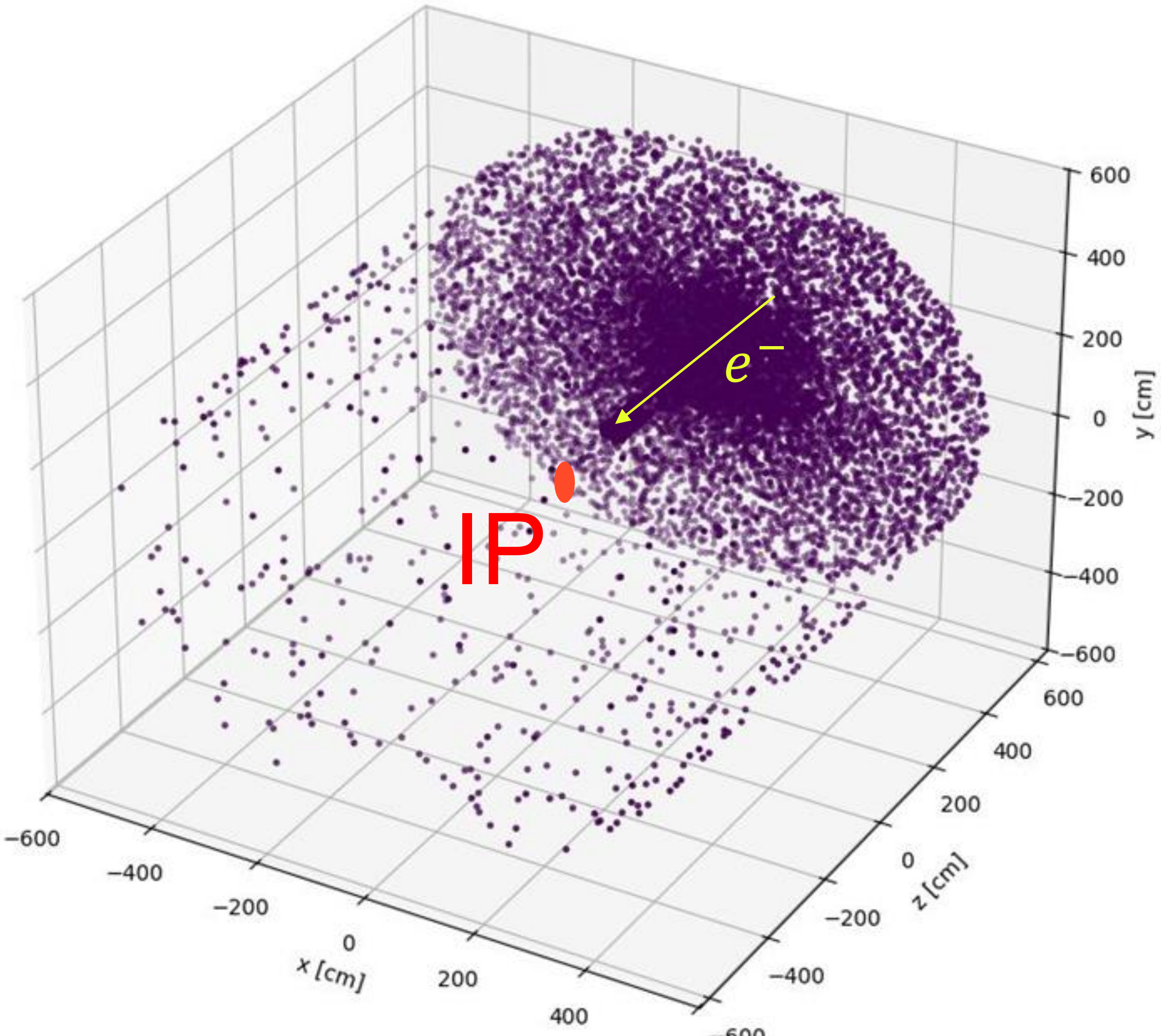


*power calculated over 700 turns.

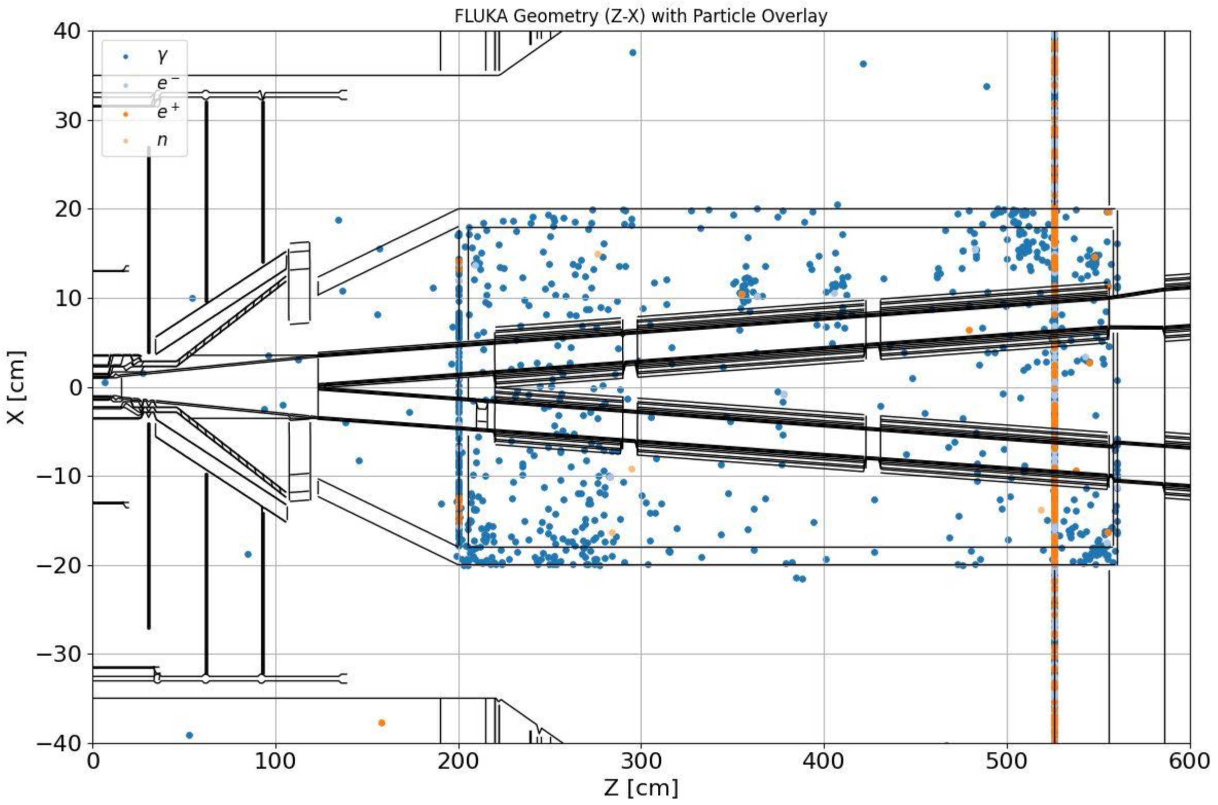
- Losses are focused on the collimation insertion and around the IPs.
- The IP just after the collimation insertion is better protected.
- A weighted average across the IPs will take this into account.
- **Background to the experiment comes from the EM showers at the TCTs.**



Injection losses spatial distribution at MDI



- **Most of the particles reach the external part the detector.**
- Few of them reach the central beam pipe.



Backgrounds from these sources in FCC-ee IR

Number of particles at interface surface per bunch crossing (BX) in 25 ns window

	Beam-gas	Injected beam
Average number of particles lost at surface/BX in 25 ns window	~0.2	~7
Maximum number of particles lost at surface/BX in 25 ns window		~30

Conclusions

The FCC-ee vertex detector design is progressing together with that of the interaction region

- Developments in the layout to minimise the effects of the material budget, however limited by the beam pipe material

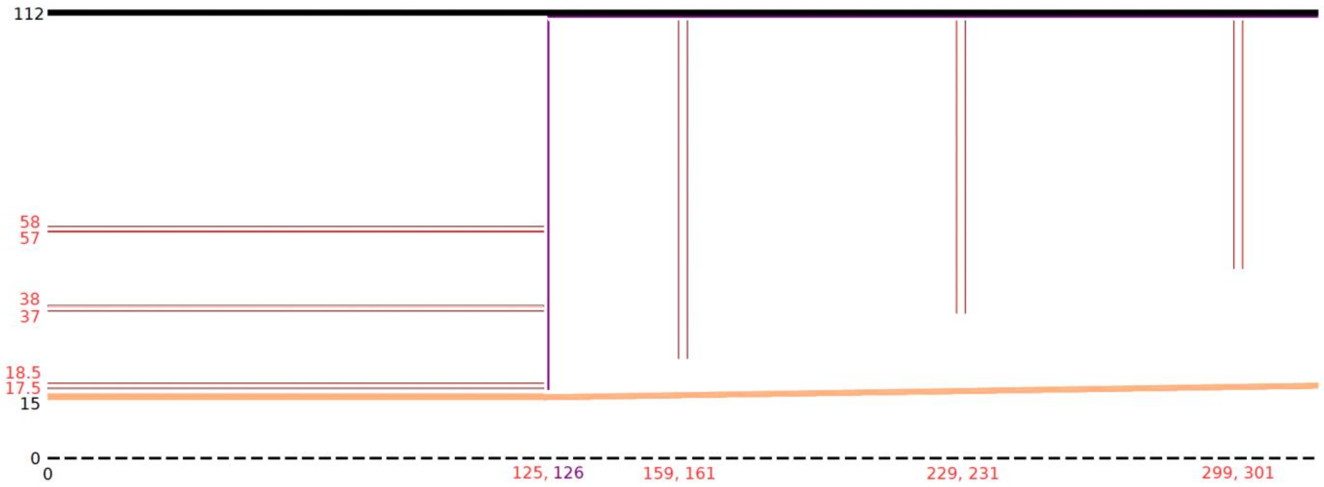
- Background estimates are being carried out in GEANT, with realistic machine conditions, including non-Gaussian tails and injection backgrounds.
  - IPC is confirmed to be the dominant effect (so far)
  - Studies for synchrotron radiation are progressing and optimal mitigations are being implemented

- **We have compared FCC-ee to SLD and were able to reproduce the main features of its backgrounds**

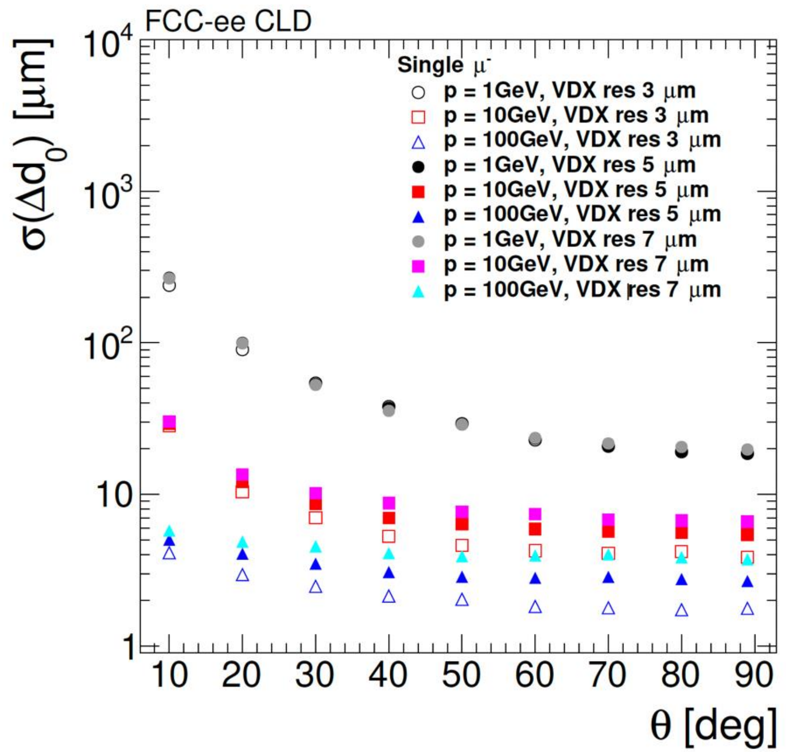
- **Big advantage of FCC-ee compared to SLD:**
  - Beam structure (crossing angle helps)
  - Sensors technologies (less integration time, more charge, lower thresholds)
  - Solenoid magnetic field (2 Tesla at FCC-ee instead of 0.5 at SLD) keep IPC confined
  - Luminosity calorimeters geometry less influences on the backgrounds
  - The relative contributions from direct IPC in the vertex and from backsplashes at SLD and FCC-ee are inverted.

Backup

CLD rescaled from the CLICDet vertex detector



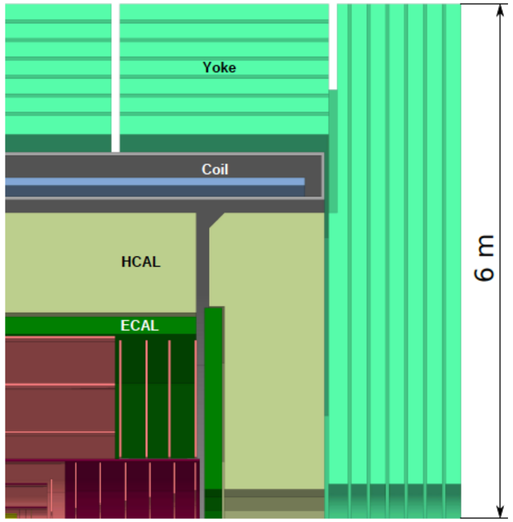
CLD vertex detector layout



- $r_{min} = 13\ mm$
- Three double-sensors barrel layers and disks 0.6% X0 per double layer
- No engineering studies since CLICDet studies
- No specific sensor technology chosen ion

Detector concepts for FCC-ee

CLD

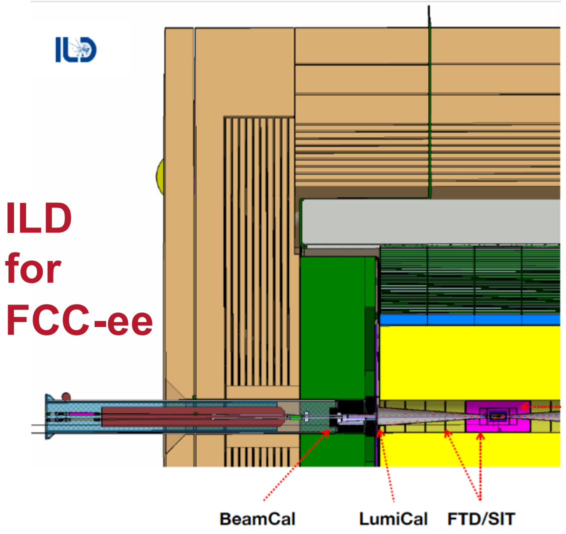


- VTX MAPS
- Main Tracker: Silicon
- Very high granularity (CALICE) inside the Solenoid
  - ECAL Si+W
  - HCAL Fe+scintillator
- PID: RICH and TOF
- Muons ID with RPC

ALLEGRO

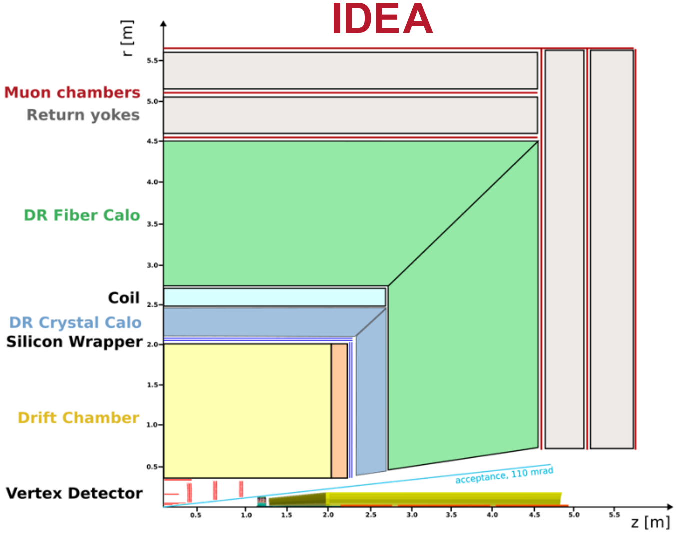
- VTX MAPS
- Main Tracker:
  - Drift Chamber/Straw/Si
- Si/LGAD wrapper (TOF)
- ECAL: Pb+L-Ar/W-L-Kr
- HCAL: Fe+scintillator outside the Solenoid
- PID: RICH (in case of Silicon main tracker)
- Muons with RPC

ILD for FCC-ee

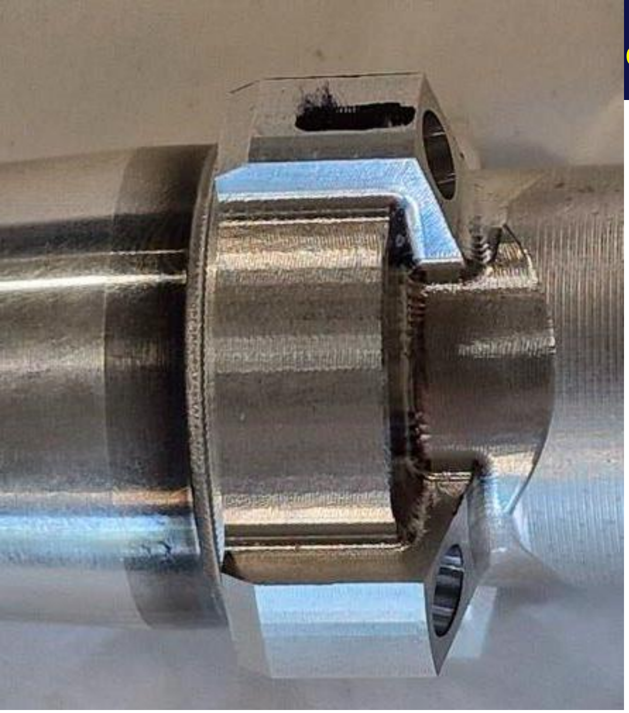


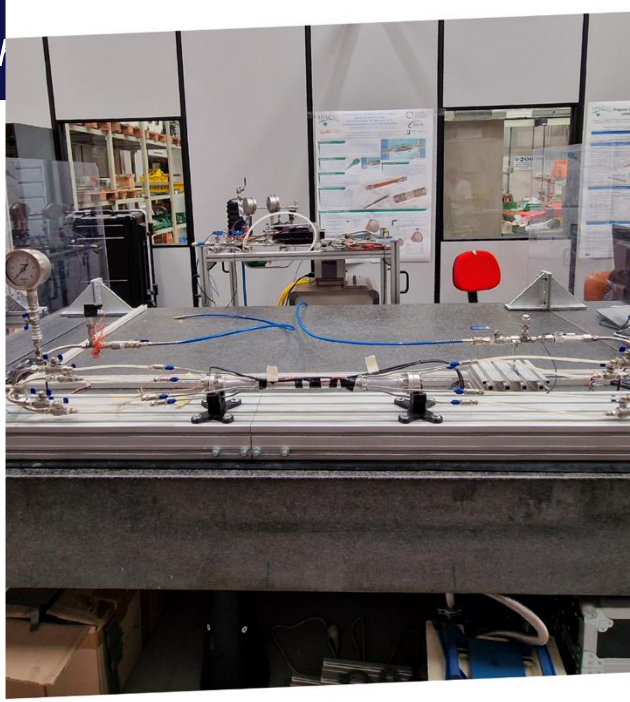
- VTX MAPS
- Main Tracker: TPC
- Very high granularity (CALICE) inside the Solenoid
  - HCAL Fe+scintillator
  - ECAL Si-W
- Muons with scintillator

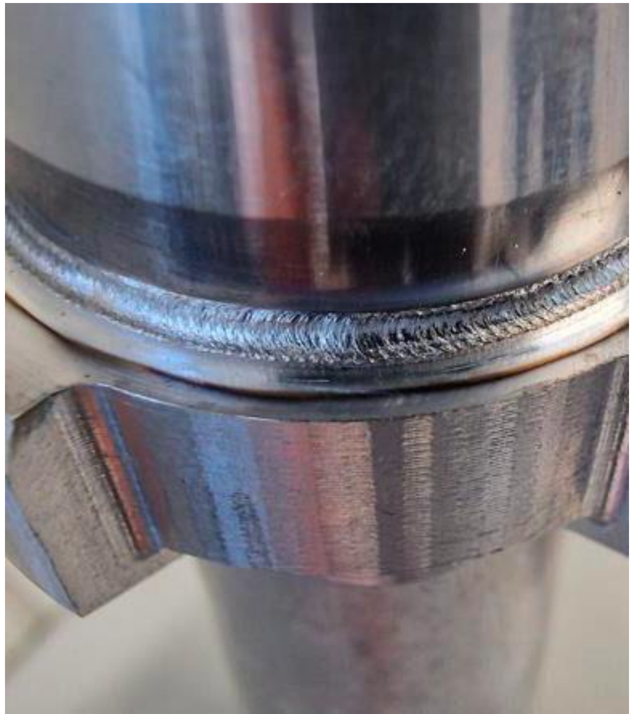
IDEA



- VTX MAPS
- Main Tracker:
  - He+Isob drift chamber
- Si/LGAD wrapper (TOF)
- DR calorimetry (fibres):
  - ECAL: Crystals
  - HCAL: Iron **outside** the Solenoid
- HTS Solenoid (up to 3T)
- Muon ID: μ-RWELL



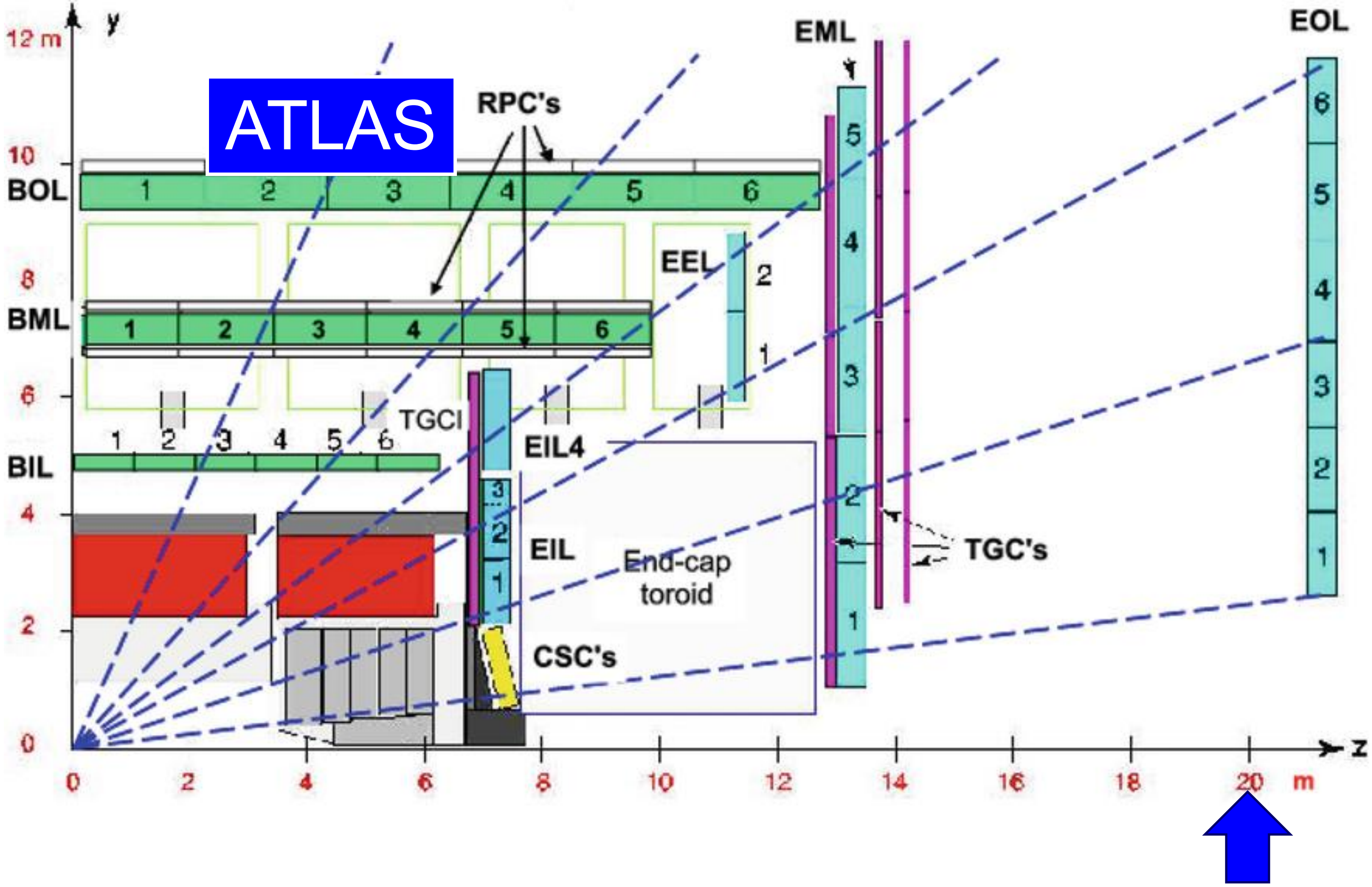





FCC-ee interaction region mockup (INFN Frascati)

- Thin Al beampipes (2 cm diameter and 450 μm thick)
- Liquid paraffin (central) and water (lateral) cooled
- Manufactured at Comeb s.r.l. (IT)
- Electron-beam welded at Ravenscourt Eng. Ltd (UK)
- Next steps:
  - bellows and CF composite support tube fabrication
  - Integration of LumiCal and Vertex detectors mockup
  - Integration of hardware alignment system

Comparison between LHC and FCC-ee MDI

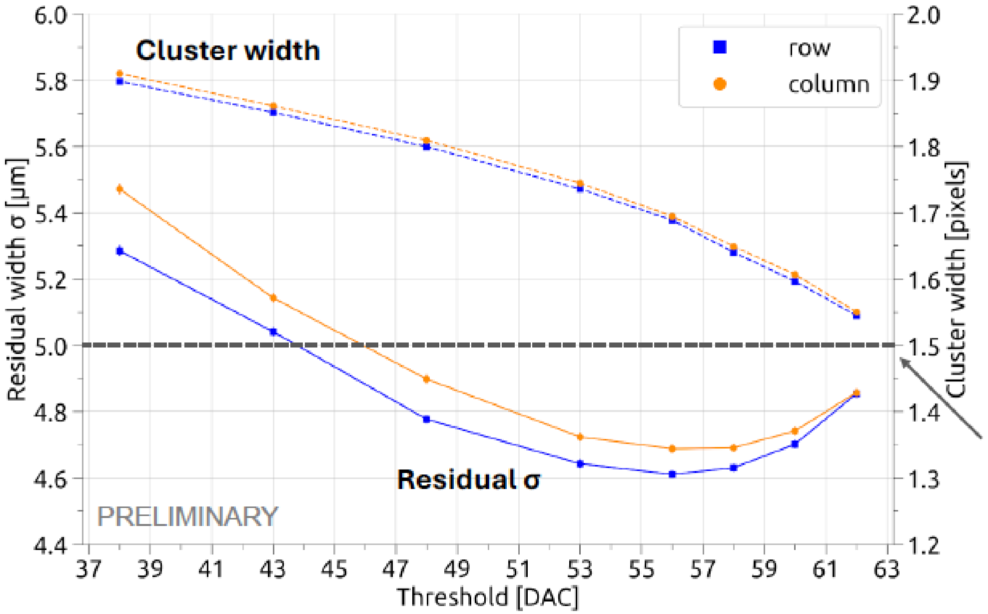


Last accel. element 2.2 m

Last accel. element 20 m

Measured resolution from prototypes

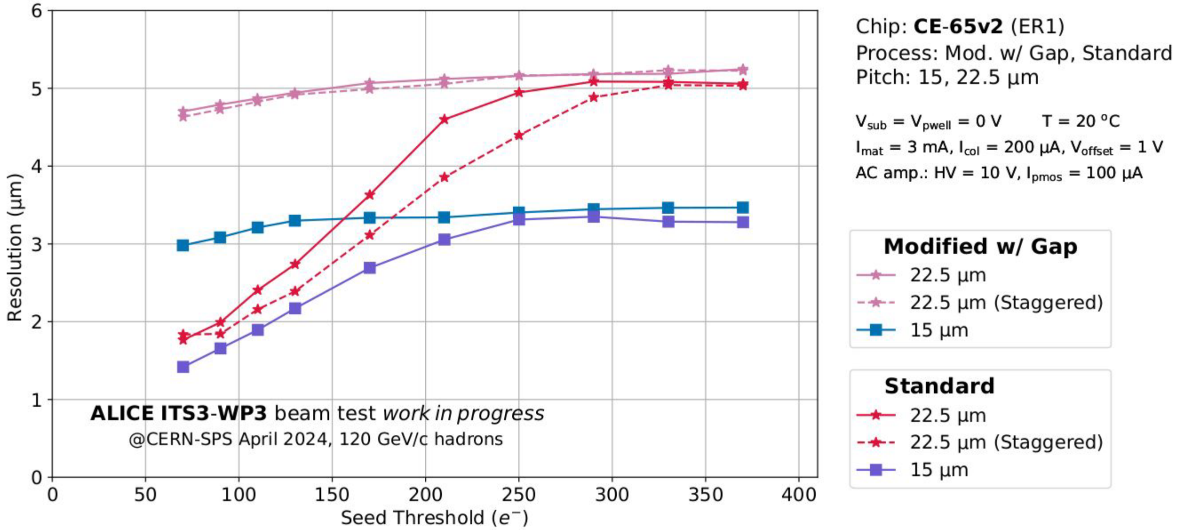
ARCADIA 200 µm thick sensors
120 GeV proton beam at FNAL



Cluster width always greater than 1.5 pixels

Residual width always below the **binary resolution (7.2 µm)**

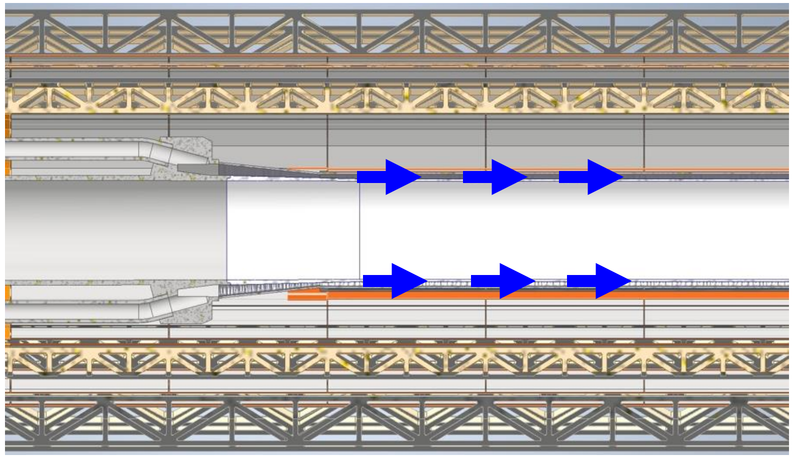
ALICE ITS3 sensors
120 GeV proton beam at CERN

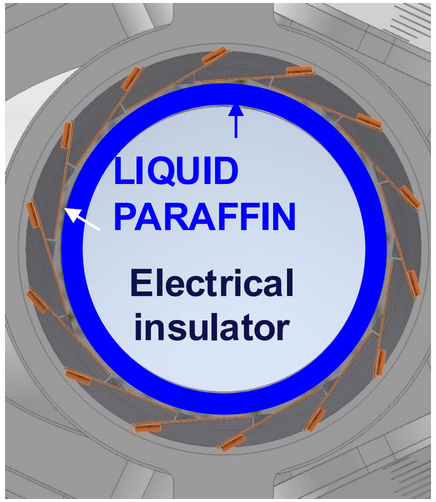


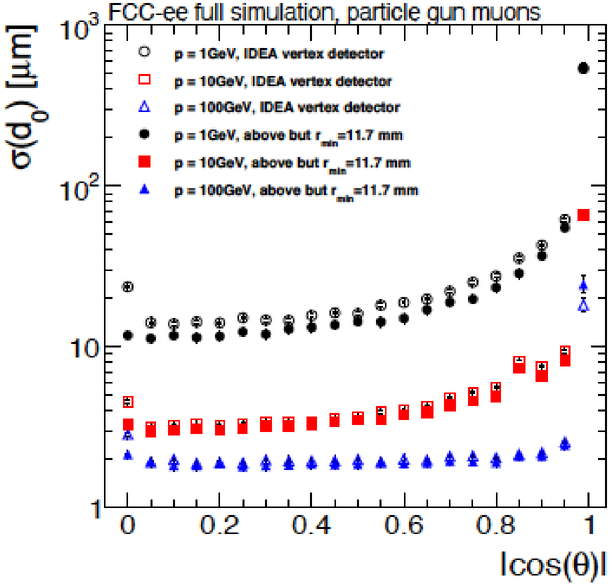
Going closer to the beam pipe and lowering material

Use the beam pipe coolant to cool as well the first vertex detector layer

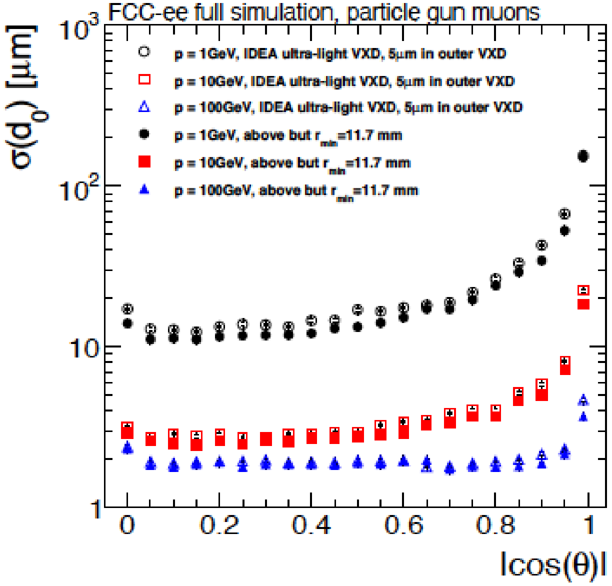
- Can go closer to the beam pipe by ~2 mm
- Reduce the material budget of the stave stiffner
- Reduce the interference with the beam pipe cooling manifolds
- Better i.p. resolution wrt curved layout at nominal radius







IDEA classic



IDEA ultra-light