European Strategy for Particle Physics

PARALLEL 6 / **DETECTOR TECHNOLOGIES**

Welcome to the parallel session on "Detector Instrumentation"

- Technologies for Accelerator-based experiments

Coffee Break

- Beyond accelerators and emerging technologies
- Electronics, TDAQ and the ecosystem for instrumentation

23-27 JUNE 2025 Lido di Venezia

European Strategy for Particle Physics

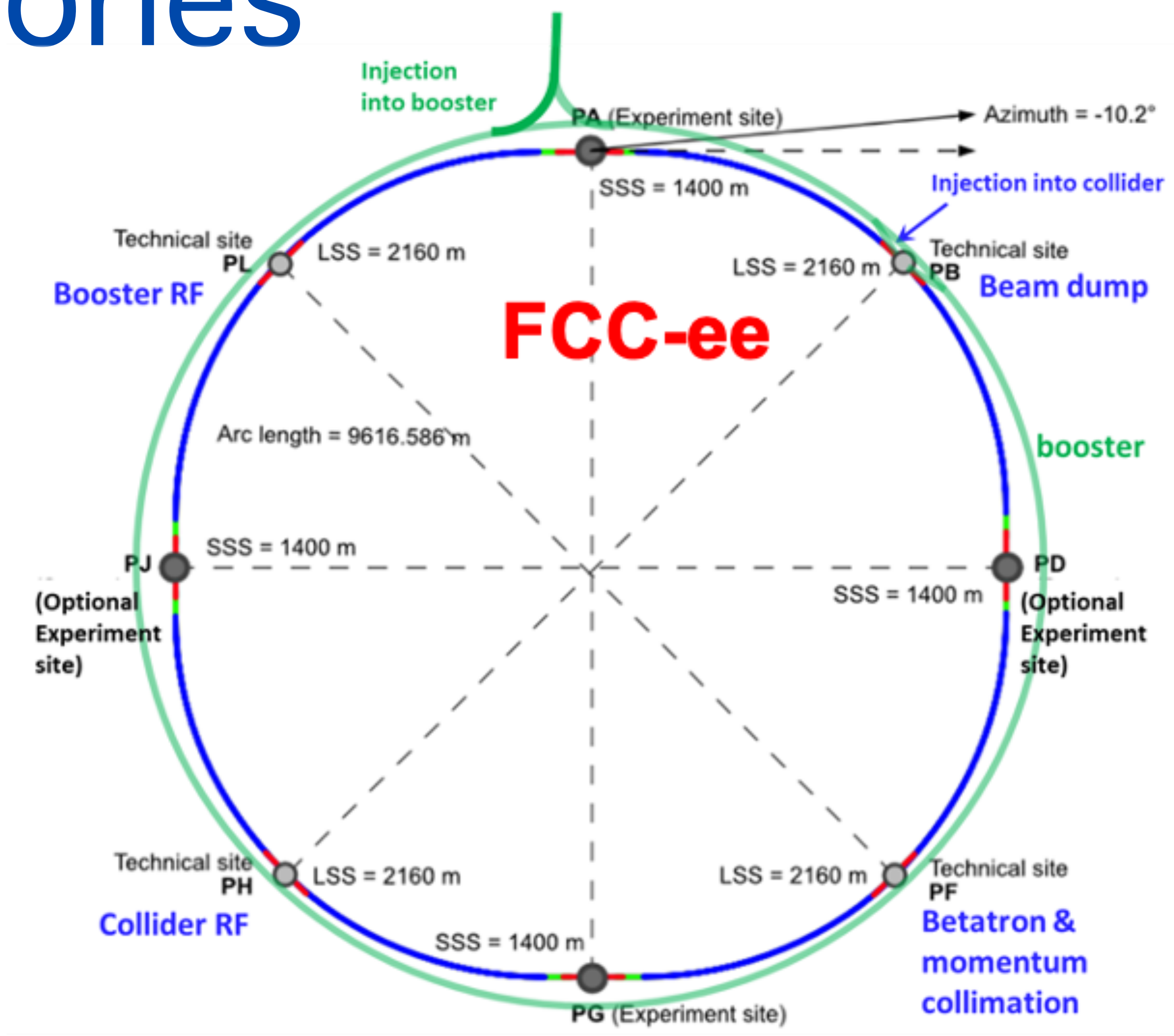
PARALLEL 6 / **DETECTOR TECHNOLOGIES**

Detector concepts for future Higgs, Electroweak and Top factories

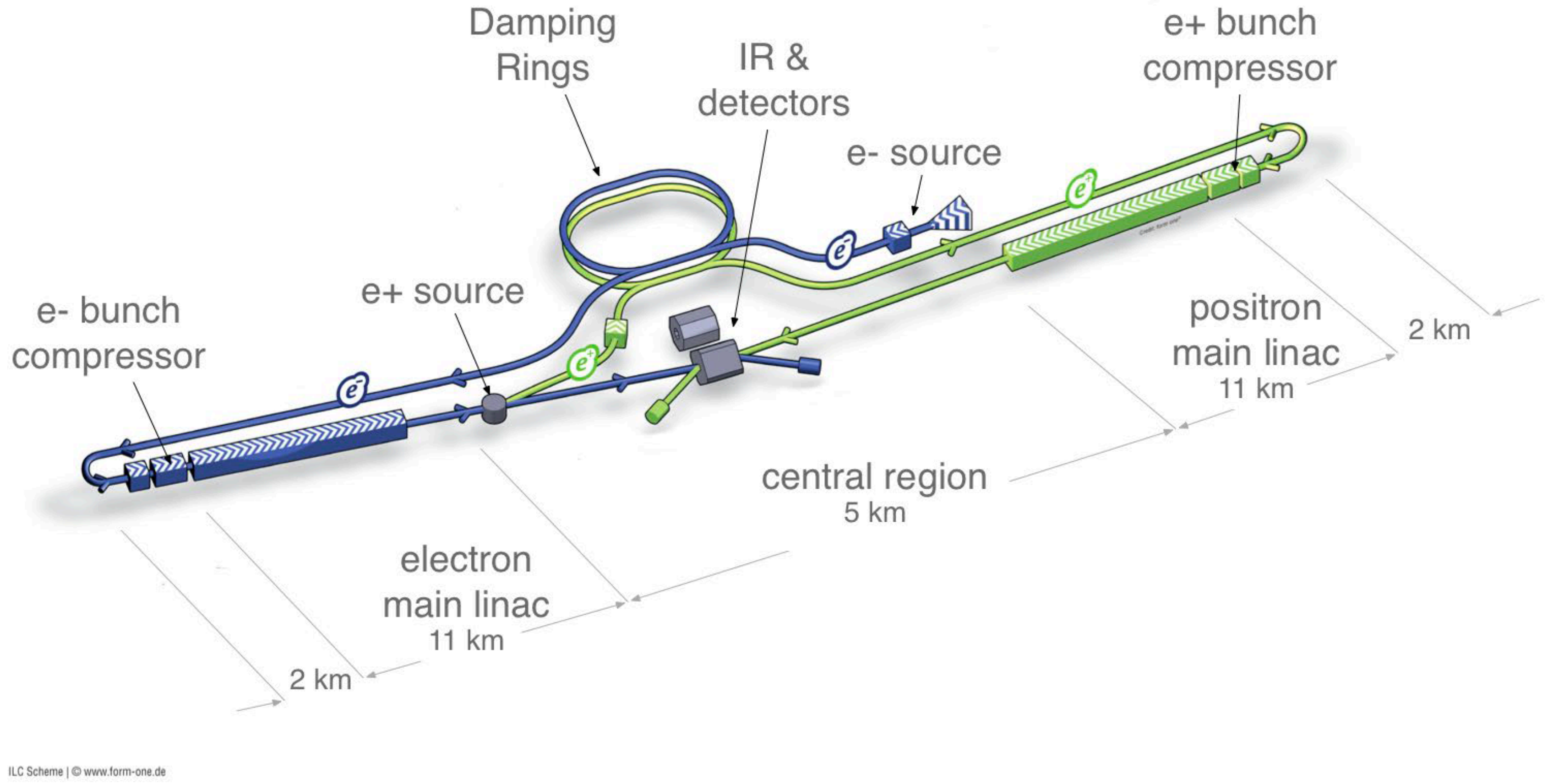
Fabrizio Palla (INFN Pisa)

Higgs, EW and Top factories

- Circular (FCC-ee/CepC)
  - Highest luminosity at Z/WW/ZH and t-tbar
  - 4 (2) experimental points for FCC-ee (CepC)



- Linear (ILC/CLIC)
  - Can reach higher c.o.m energies (TeV) but c.o.m. energy spread
  - Up to 2 experimental points



Higgs, EW and Top factories

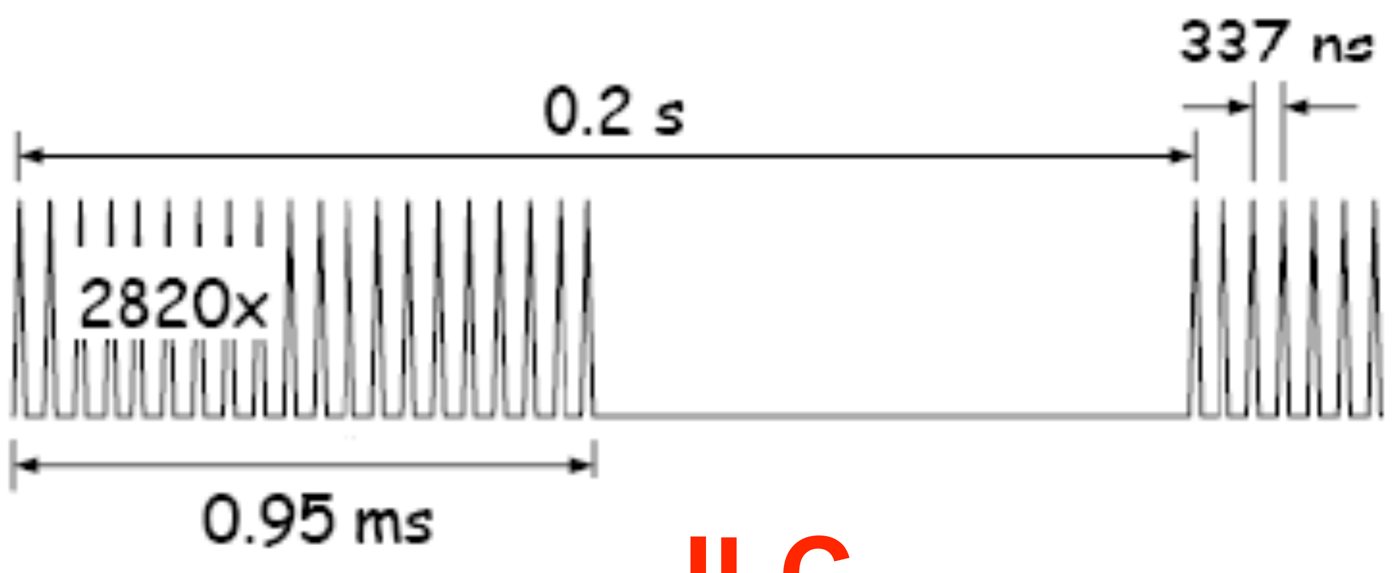
Circular (FCC-ee/CepC)

- Highest luminosity at Z/WW/ZH and t-tbar
- 4 (2) experimental points at FCC-ee (CepC)
- Continuous injection and 40 MHz collision rate (Z)
  - Continuous powering of electronics

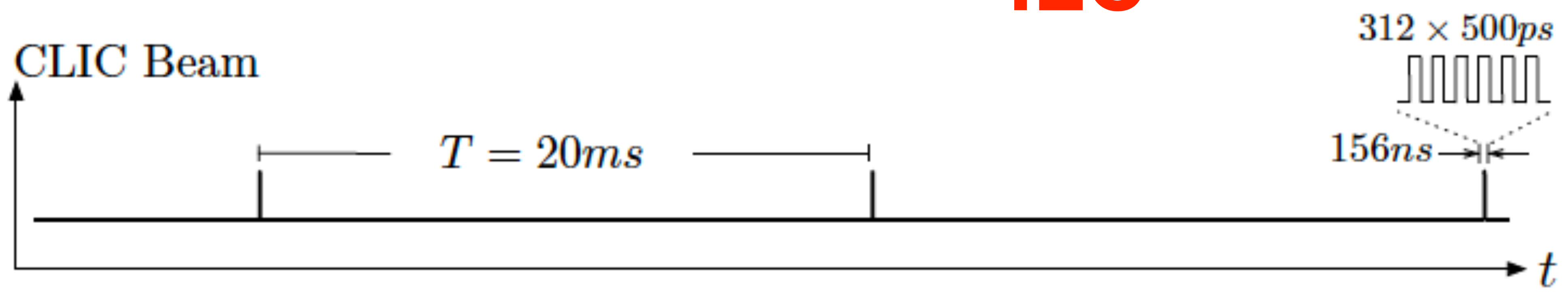
$\sqrt{(s)}$ (GeV)	91.2	160	240	365
Bunch separation (ns)	25	170	680	5000
σ_x (μm)	9	21	13	40

Linear (ILC/CLIC)

- Can reach higher c.o.m energies (TeV) but c.o.m. energy spread
  - Up to 2 experimental points
- Collisions in bunch trains (~0.5% duty cycle)
  - Power pulsing allows saving of power and material
    - CLIC inter-bunch 0.5 ns drives detector timing requirements



ILC



CLIC

(Main) Detector requirements

Higgs physics

- Momentum resolution
  - $\sigma(p_T)/p_T \approx 2 \cdot 10^{-5} \cdot p_T(GeV) \oplus 0.2\,\%$
- Jet energy resolution ~3% in multi jet events for Z/W/H separation
  - Particle flow (high granularity calorimeters)
- Precise impact parameter resolution for b- and c- quark tagging
- Hadron ID for s-quark tagging for $H \to s\bar{s}$

Electroweak and QCD

- Absolute luminosity determination $\sim 10^{-4}$
- Acceptance definition ~10 μm
- Track angular resolution <0.1 μrad
- B field stability and mapping up to 10^{-6}

Heavy flavours

- Superior impact parameter resolution
  - ~3 μm hit resolution and <0.1% X_0 material budget per layer
- Beam pipe thickness <~0.35 mm @FCC-ee
  - Limiting ultimate material buget
- π^0/γ separation
  - High granularity ECAL $\sigma(E)/E \approx \%/\sqrt{(E)}$,
- PID: π/K separation between 1-30 GeV and μ-ID

BSM

- Detached vertices for long lived particles
  - Reconstruction of tracks up to meters
- Precise timing (~tens of ps)
- Detector hermeticity

Detector concepts features

- Integrated designs leveraging on detector R&D (ECFA DRD) to address the technical feasibility to match the requirements of physics goals
  - Full simulation model for sub-detector and system performance on specific physics benchmarks
- Several solutions being investigated
  - Different detector concepts built around different calorimeter and detector solenoid choices
    - Other subsystems mostly interchangeable (vertex, tracking and muon systems)
- Accelerator backgrounds dominate detector occupancies
  - Challenge for both detector readout and trigger strategy
    - Integration between detector and accelerator experts needed to best design both systems
- Detector integration/installation/maintenance and system interdependence
  - Cooling, power distribution and readout architectures impact material budget, detector acceptance and ultimate resolutions
  - Detector maintenance in the cavern impacts detector availability

Sub-detector features - I

- Active detector cooling (also of the beam pipe) necessary for circular colliders
  - Air cooling for vertex detectors is a common feature
- Vertex detectors (DRD3, DRD7 and DRD8)
  - MAPS technology to allow for few μm single-hit resolution and low material budget (~0.1% X0 per layer), as close as possible to IP
    - ALICE ITS3/ALICE3, Belle-II upgrade and ePIC will pioneer these technologies
- Different technologies for the main tracker (DRD1, DRD3 and DRD8)
    - Small #points 3D with high precision (~10 μm) silicon detectors layers
    - Large #cells 3D/2D of moderate precision (~100 μm) gaseous drift chambers (including TPC) or straw-tubes or scintillating fibres (coarser resolution in z)
    - Complemented by a precise (time & space) wrapper
- Particle identification (DRD4)
  - Gaseous detectors (cluster counting or dE/dx) PID capability but need ToF for p~1 GeV
  - Dedicated RICH for full-silicon trackers

Sub-detector features - II

- Different solutions for the calorimeters (DRD6)
  - Compact very high granularity sampling calorimeters from the CALICE experience
    - Instrumental input will come from HL-LHC (CMS HGCAL, ALICE FoCal), ePIC, LUXE, SHIP experience
  - Dual readout technology exploiting disentangling electromagnetic/hadronic contributions
    - LHCb upgrade II (PicoCal) will be instrumental
  - Fine grained noble liquid based (LAr+Pb or LKr+W)
    - Dedicated cryogenic electronics and integrated cryogenics with superconducting detector solenoids
- Large area muon detectors (DRD1 and DRD4)
  - Self-triggering and standalone reconstruction for exotica (LLP, etc)
  - Minimisation of the costs and eco-friendly gas mixtures
- Trigger and data acquisition (DRD7)
  - Trigger-less vs triggered impacts front-end electronics (buffers/data rates), hence material budget, but also calibration, data processing and offline data storage needs
  - Controlling trigger efficiency for Tera-Z factories may become limiting factor in precision

Detectors for FCC-ee

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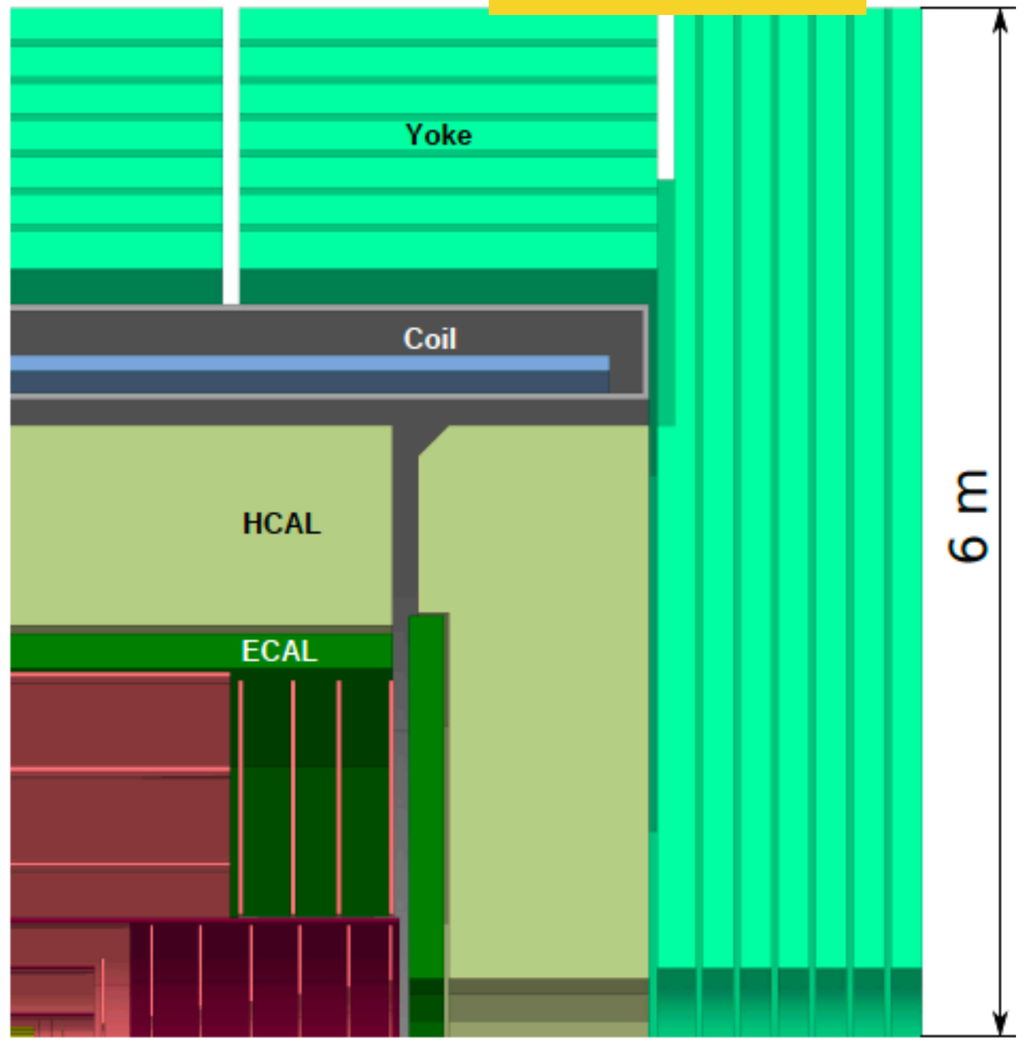
CLD (ID#95)

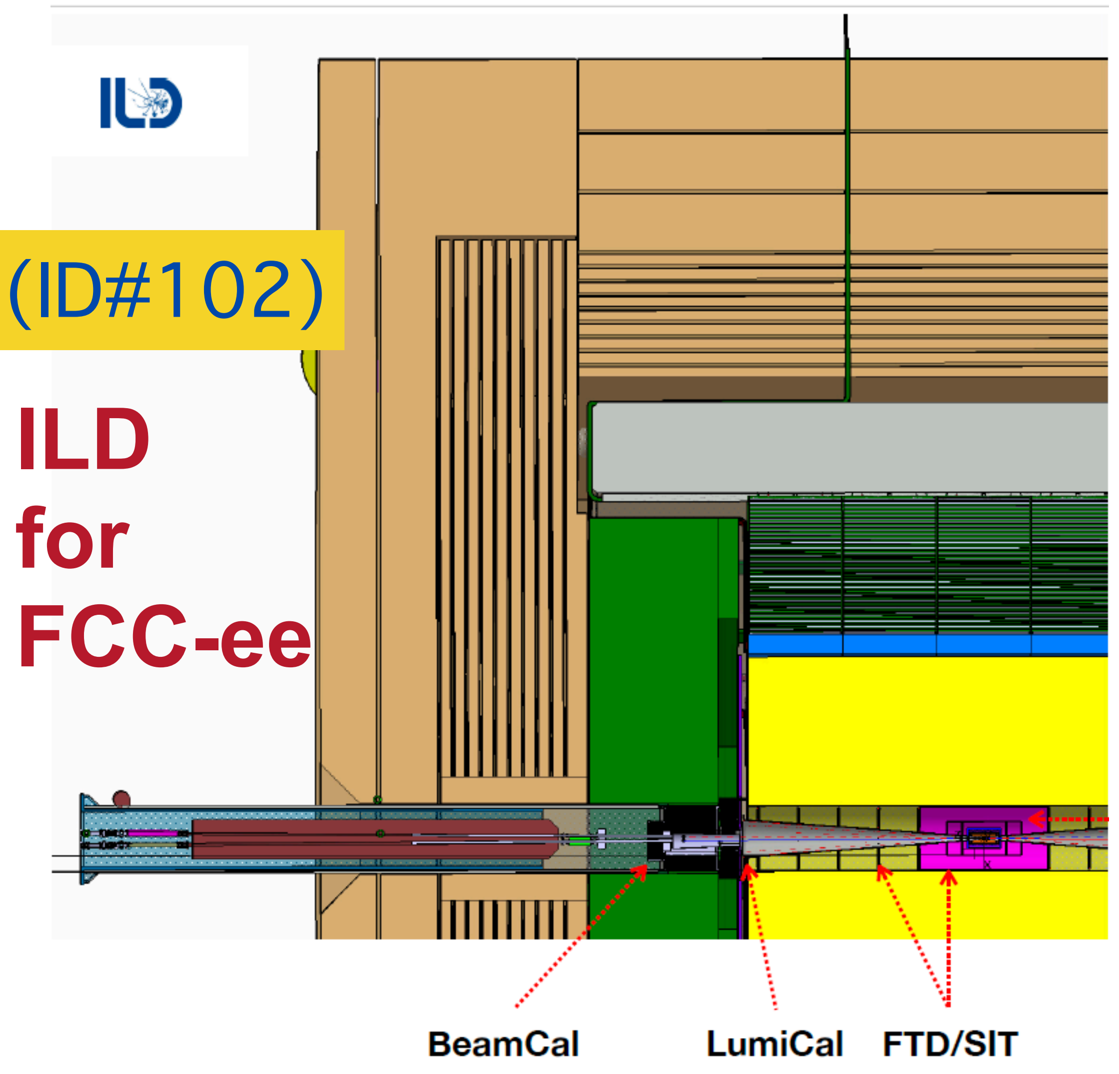


- VTX MAPS
- Main Tracker: Silicon
- Very high granularity (CALICE) inside the Solenoid
  - ECAL Si+W
  - HCAL Fe+scintillator
- PID: RICH and TOF
- Muons ID with RPC

(ID#211) ALLEGRO

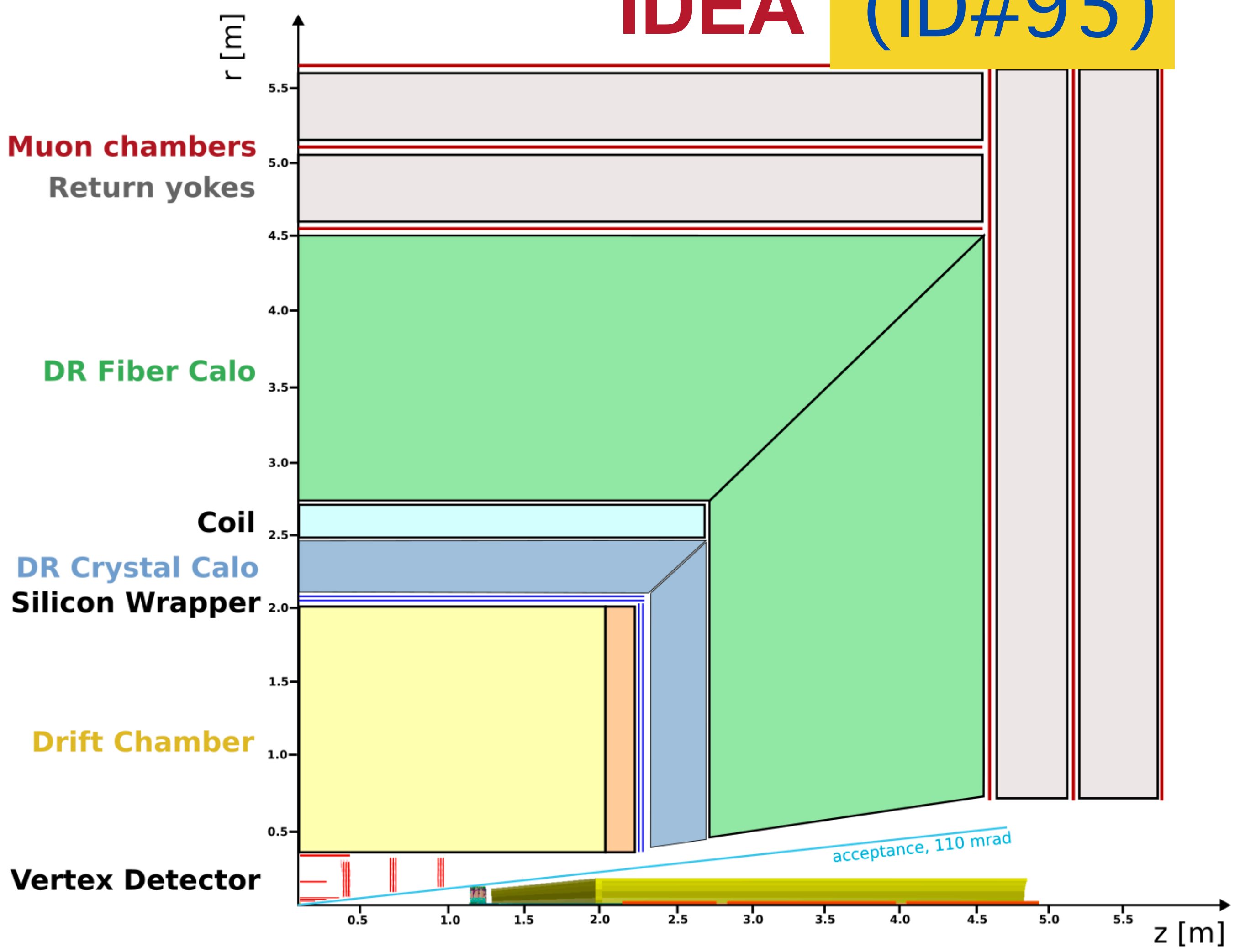
- VTX MAPS
- Main Tracker:
  - Drift Chamber/Straw/Si
- Si/LGAD wrapper (TOF)
- ECAL: Pb+L-Ar/W-L-Kr
- HCAL: Fe+scintillator outside the Solenoid
- PID: RICH (in case of Silicon main tracker)
- Muons with RPC

(ID#102) 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

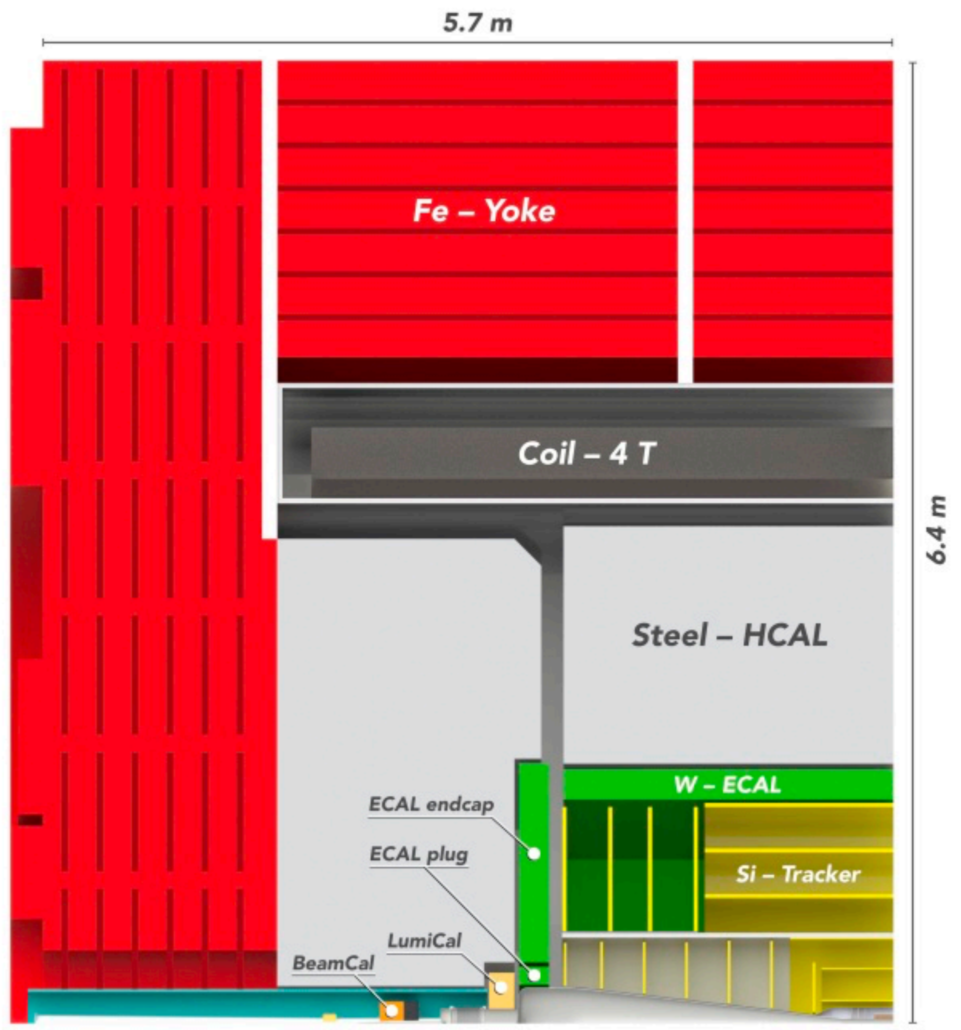
IDEA (ID#95)



- 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

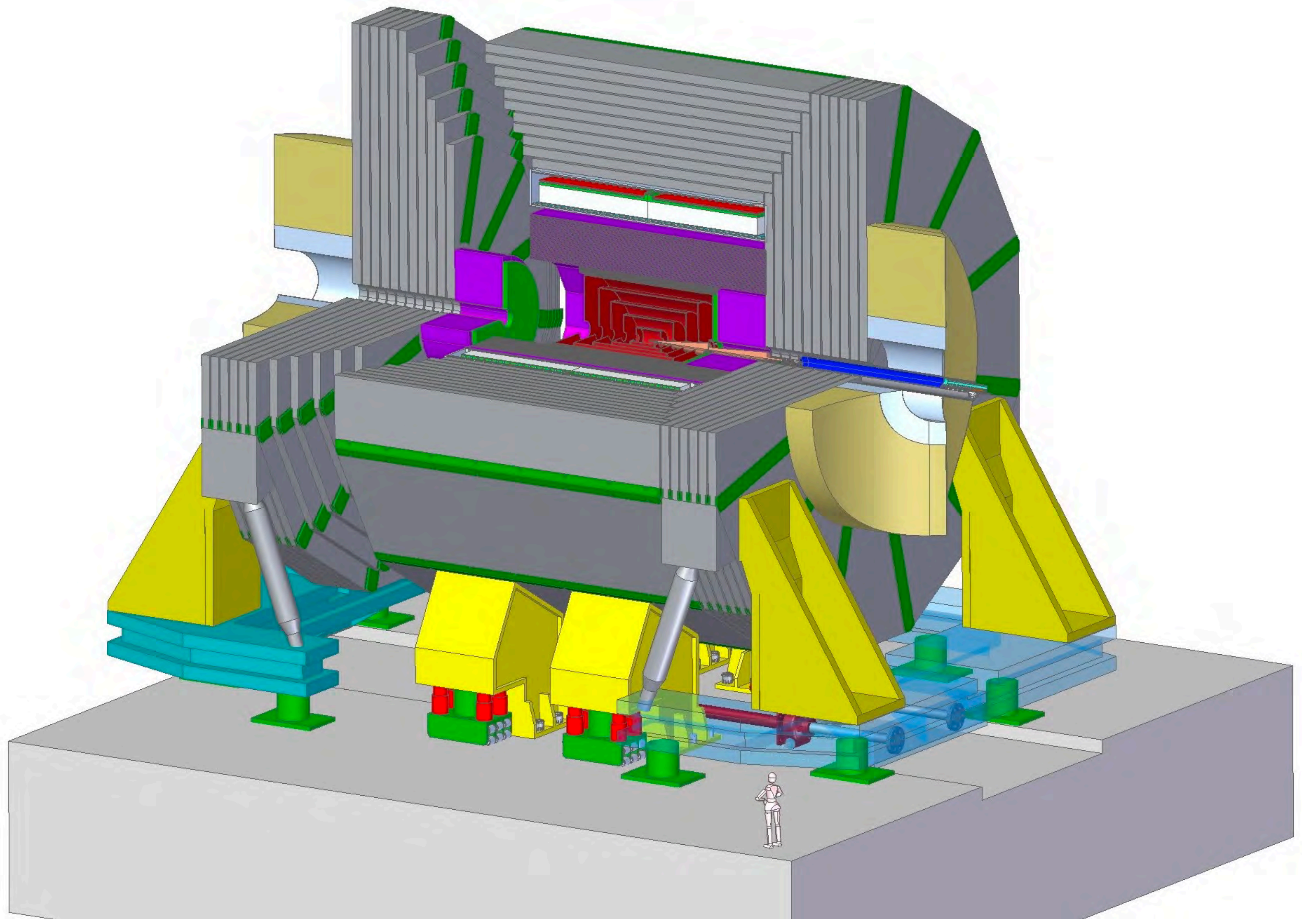
Detectors for Linear Colliders

CLICdet



- 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

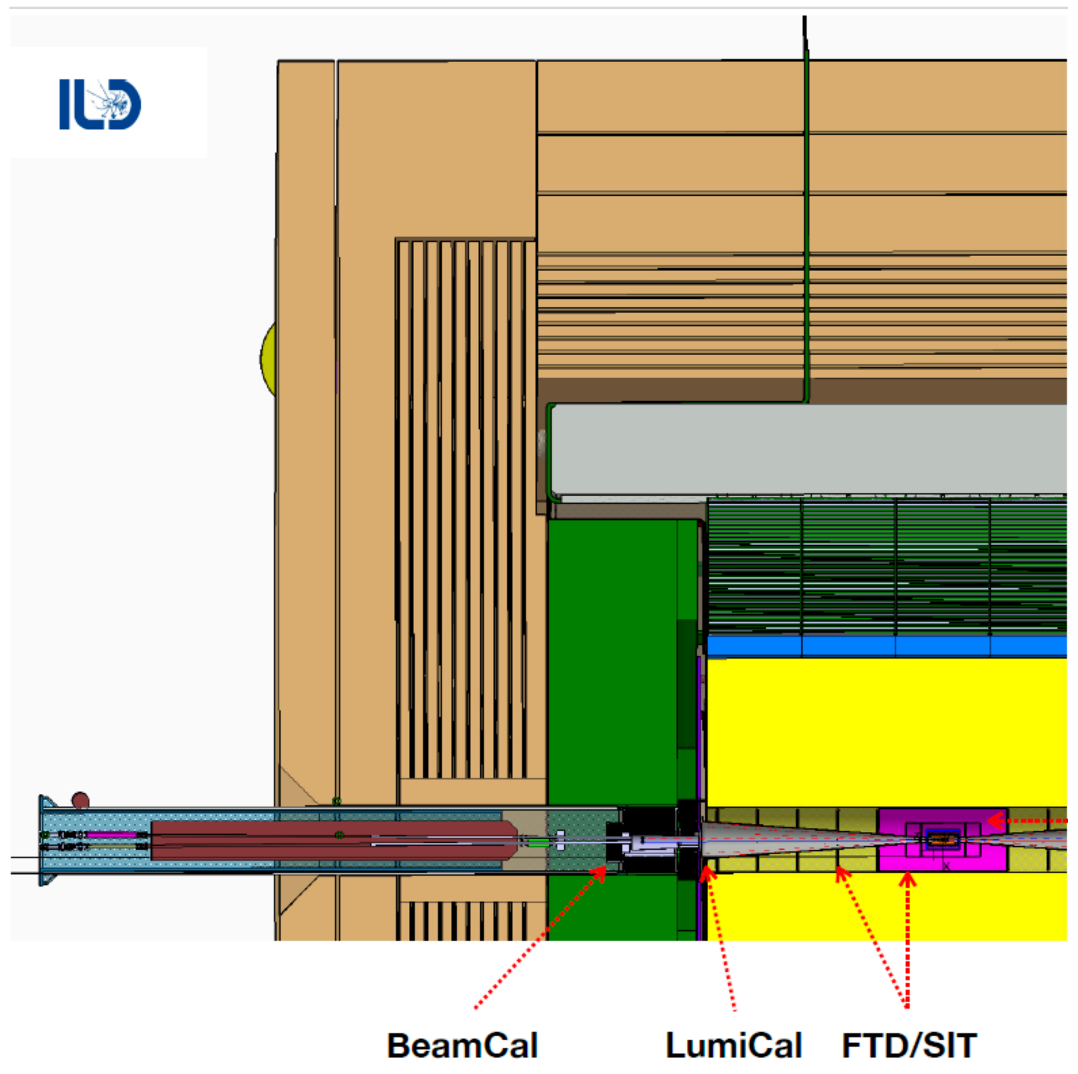
ID#78



SiD

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

ID#94



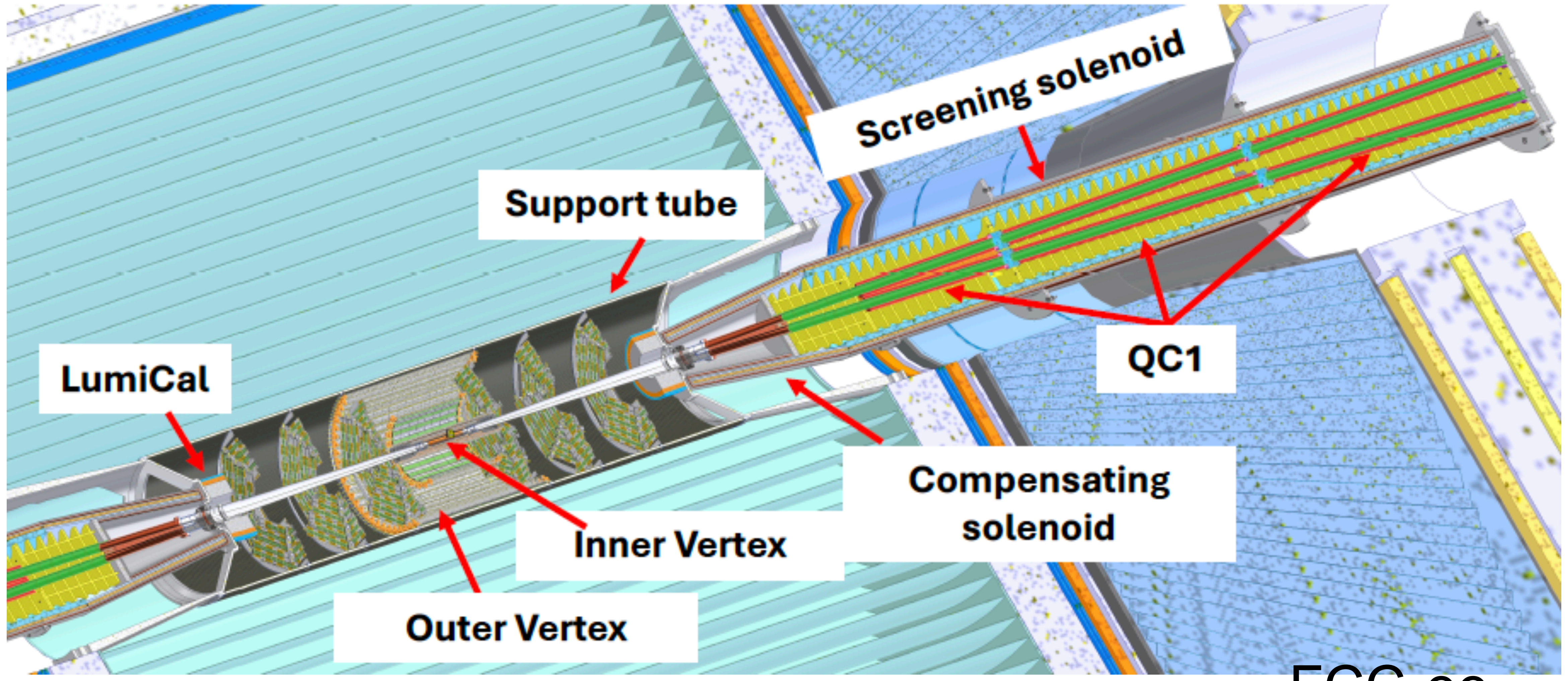
ILD

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

ID#102

Machine-detector integration

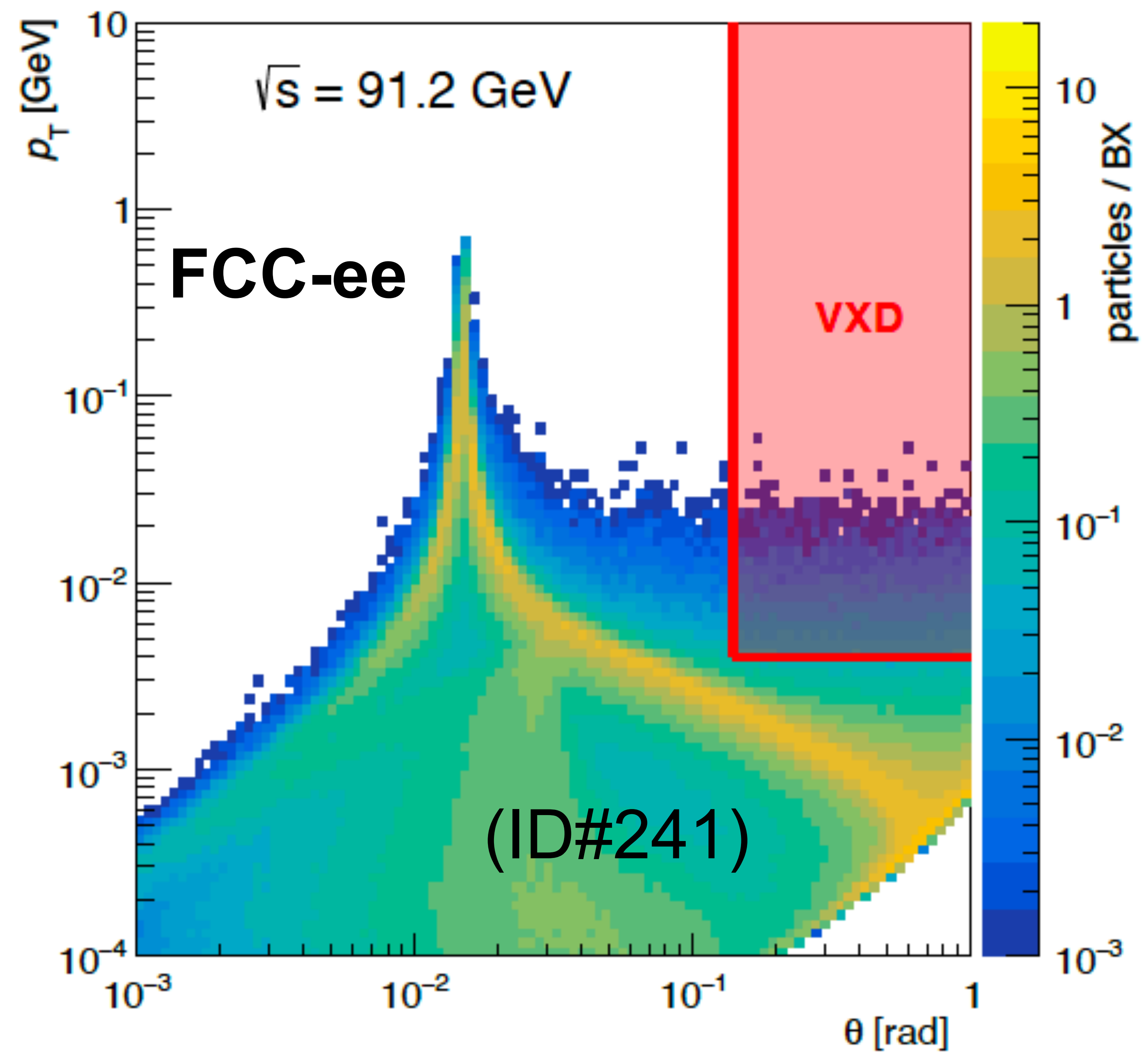
- Vertex performance constrained by machine and services
  - Innermost layer radius limited by beam pipe
    - FCC-ee: 1 cm
    - ILC: 1.3 cm
    - CLIC: 2.96 cm
- Luminosity detectors acceptance
  - Limited by first quadrupole distance (L*)
    - In FCC-ee at 2.2 m (inside the detectors)
    - At linear colliders is outside the detector (ILC 4.1 m, CLIC 6 m)
- Detector solenoids
  - Circular colliders limitation at 2 Tesla at the Z-pole not to increase emittance

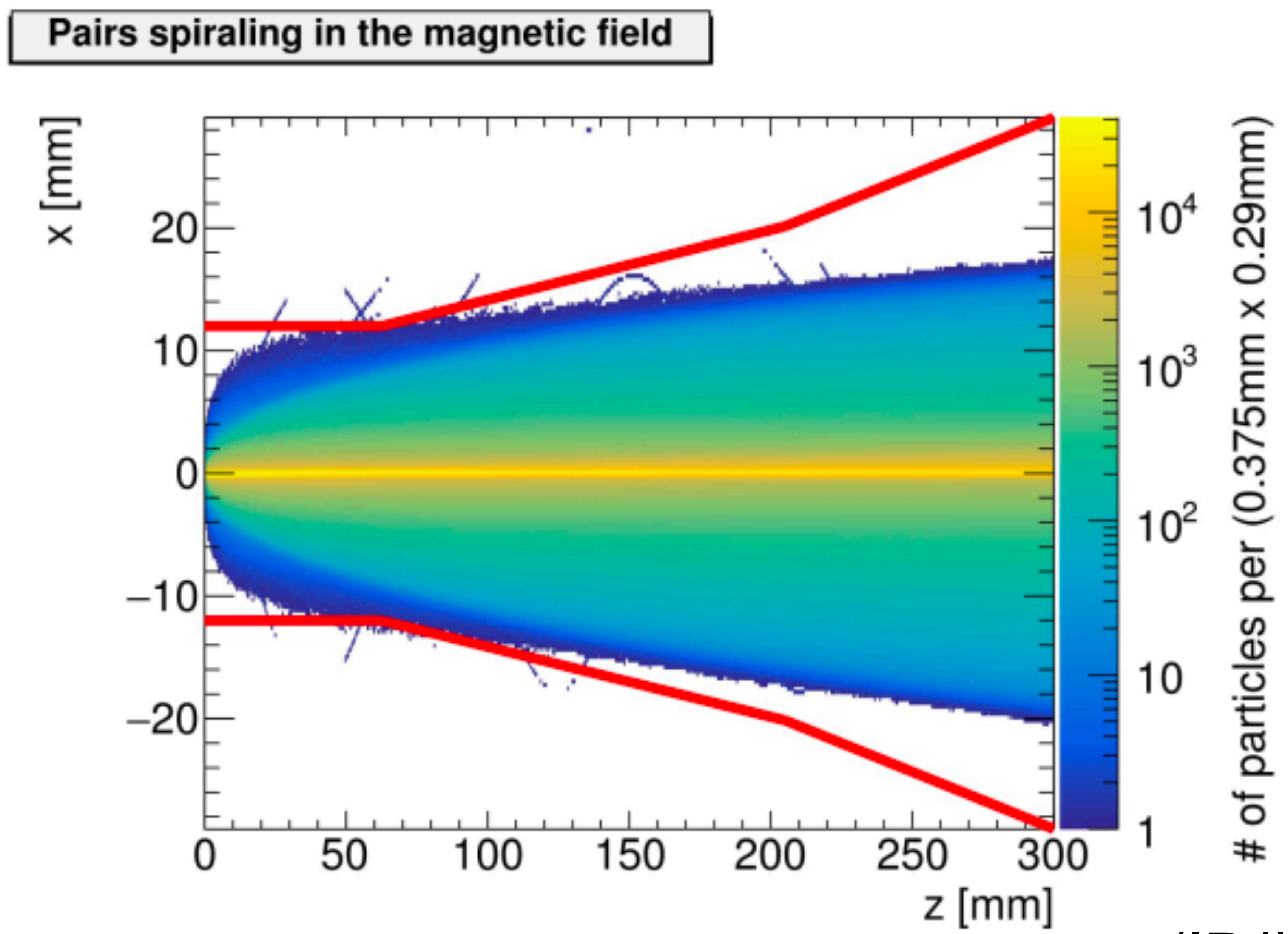


FCC-ee (ID#241)

Beam-induced backgrounds

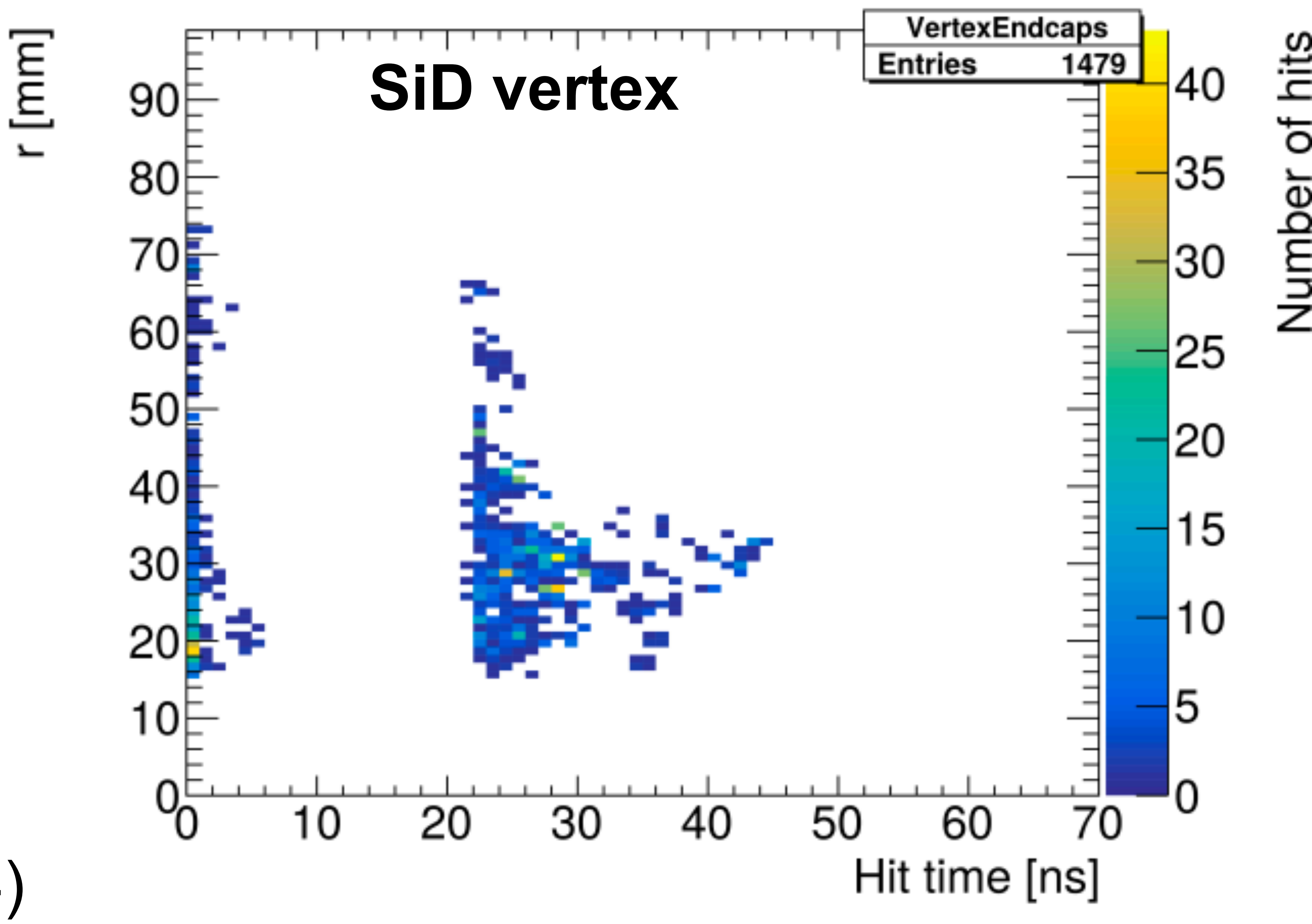
- **Beamstrahlung limits the beam pipe size and determines occupancy in vertex detector**
  - Final focus of linear colliders is more intense than at FCC-ee: larger beamstrahlung at ILC hence higher beam pipes
  - IPC: Incoherent pair creation (real or virtual photon scattering e+ e-) dominant
    - Lot of low p_T (few MeV) particles hitting the detectors directly or backscattering
    - Hit rates of up to 200 MHz/cm^2 for the innermost layer: challenging for readout (~100 Gb/s per ladder) (DRD7)
      - Time structure may be exploited to suppress backgrounds
    - TPC is particularly affected by large #ions produced, with distortions up to 1 cm at FCC-ee





(b) *ILC250 set (A)*

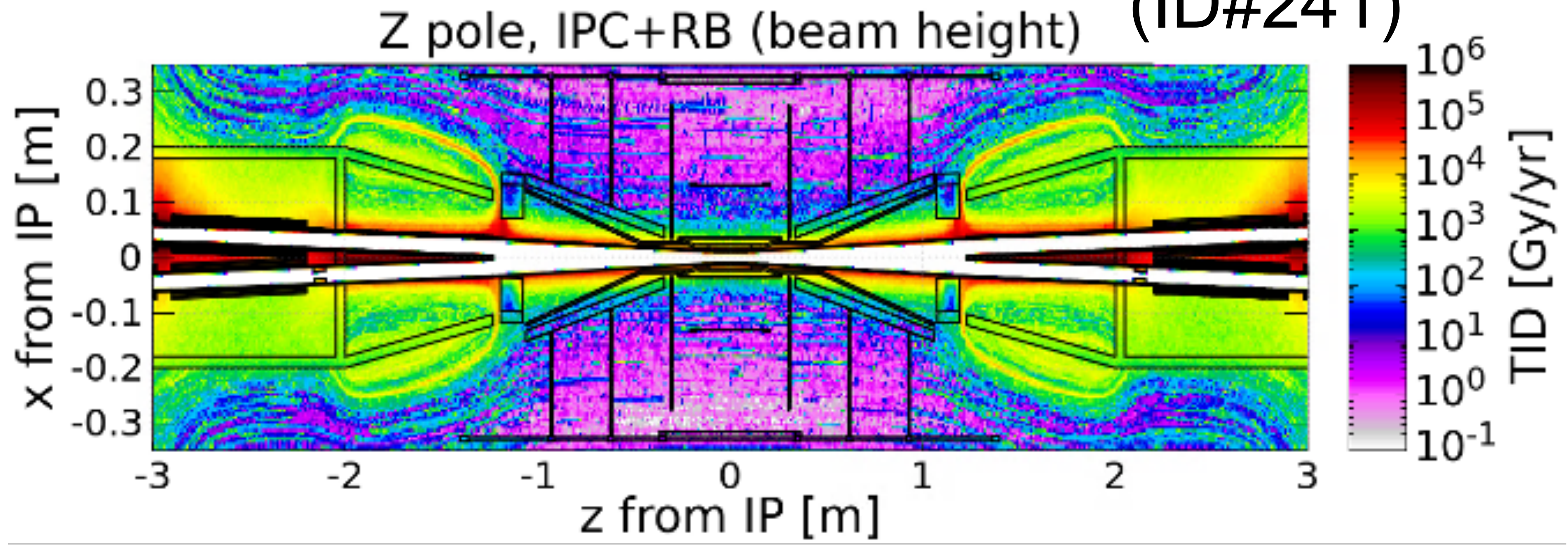
(ID#94)

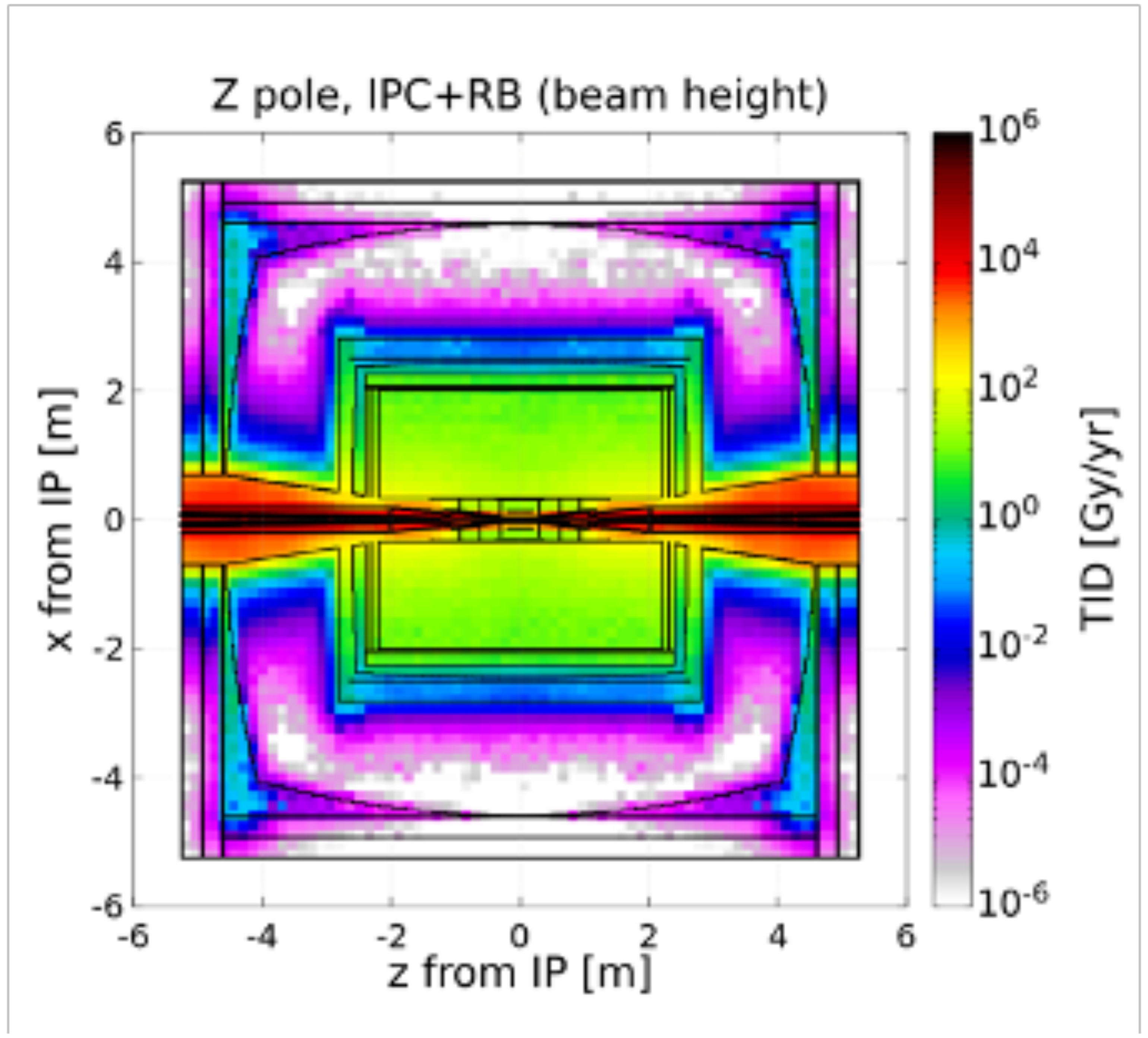


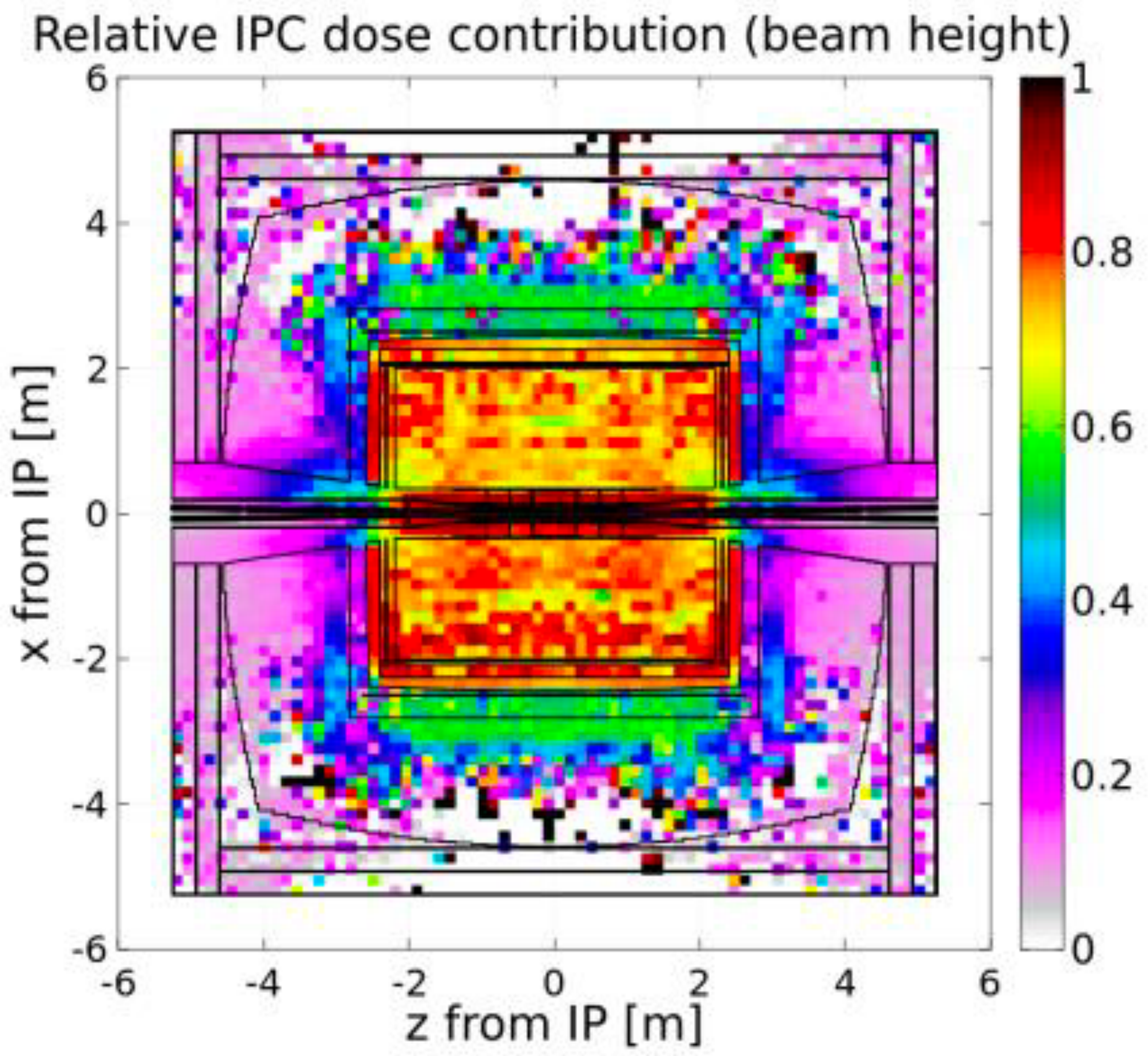
Detector radiation levels

- **FCC-ee smaller radiation environment than LHC**
  - IPC dominant up to the drift chamber, centrally, whereas radiative Bhabha's ($e^+e^- \rightarrow e^+e^-\gamma$) in forward direction (HCAL endcaps) and muon chambers
  - Intense synchrotron radiation (SR) in the forward direction, outside of the detector. SR from the last dipole (~100 m from IP) is suitably shielded before the experiments
  - Injection backgrounds (important at SuperKEKB) under study

(ID#241)

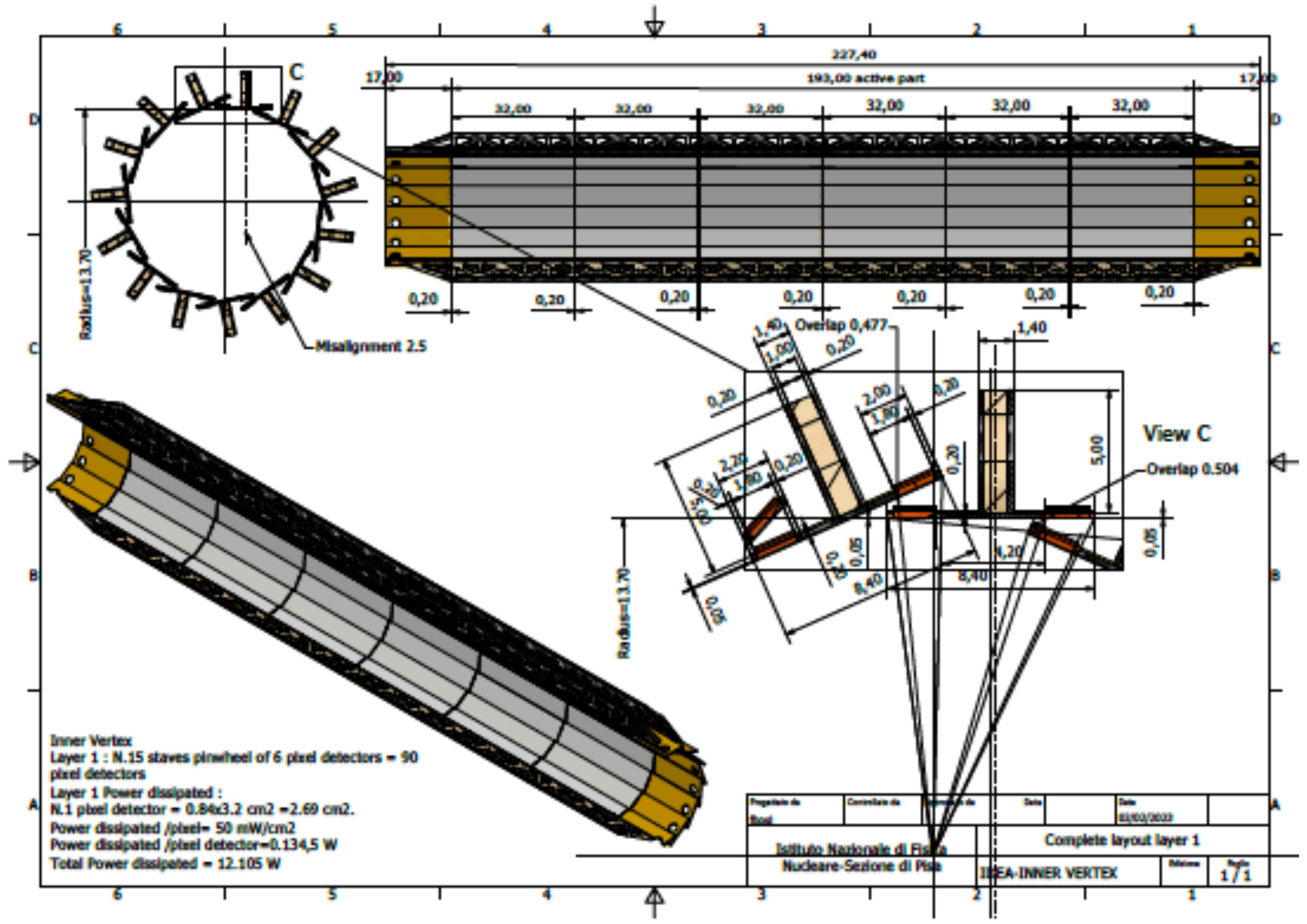




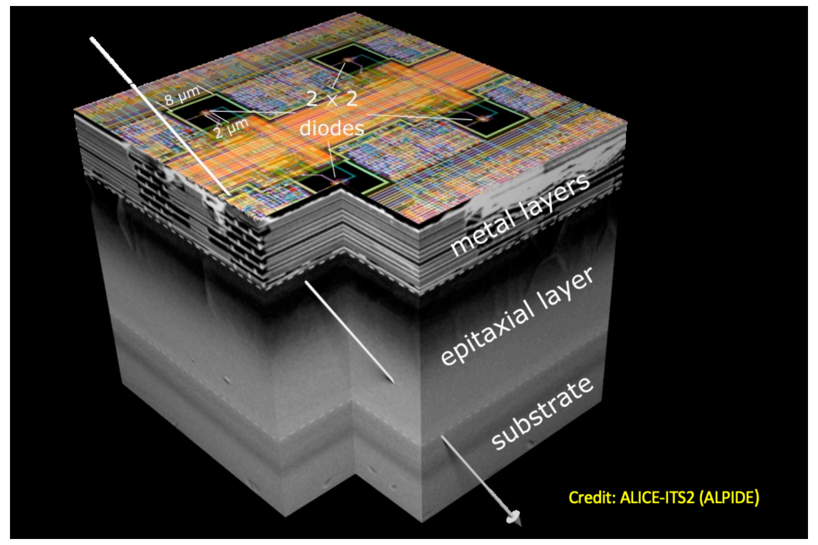


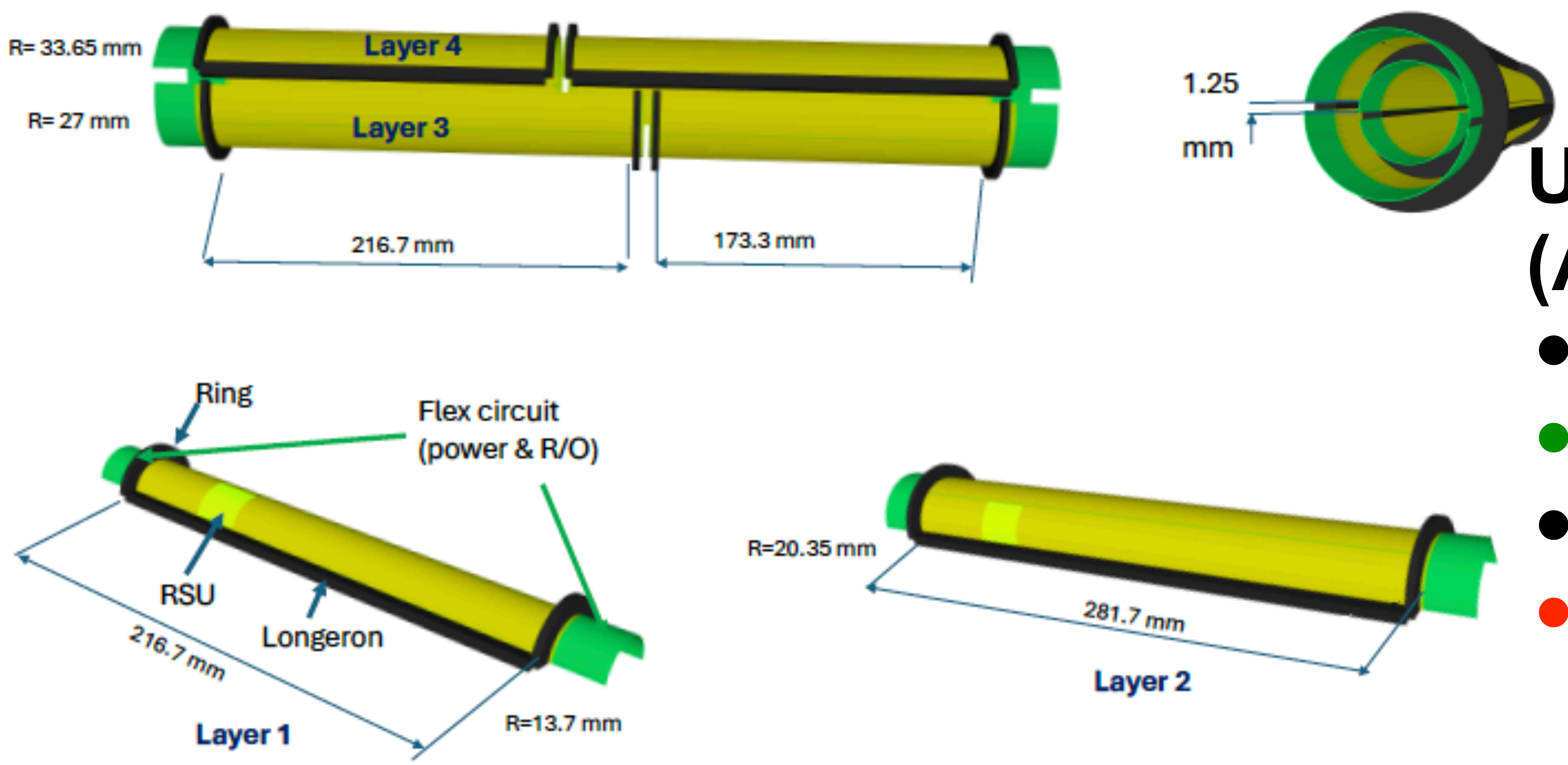
	TID [Gy/yr]	**Fluence** [cm^{-2}/yr]
Vertex	~40k	~10^{13}
Drift	~10	~10^{11}
ECAL	~1	~10^{10}
HCAL	<1	<10^{10}
Lumical	~10k	~5 10^{12}

FCC-ee vertex detector designs

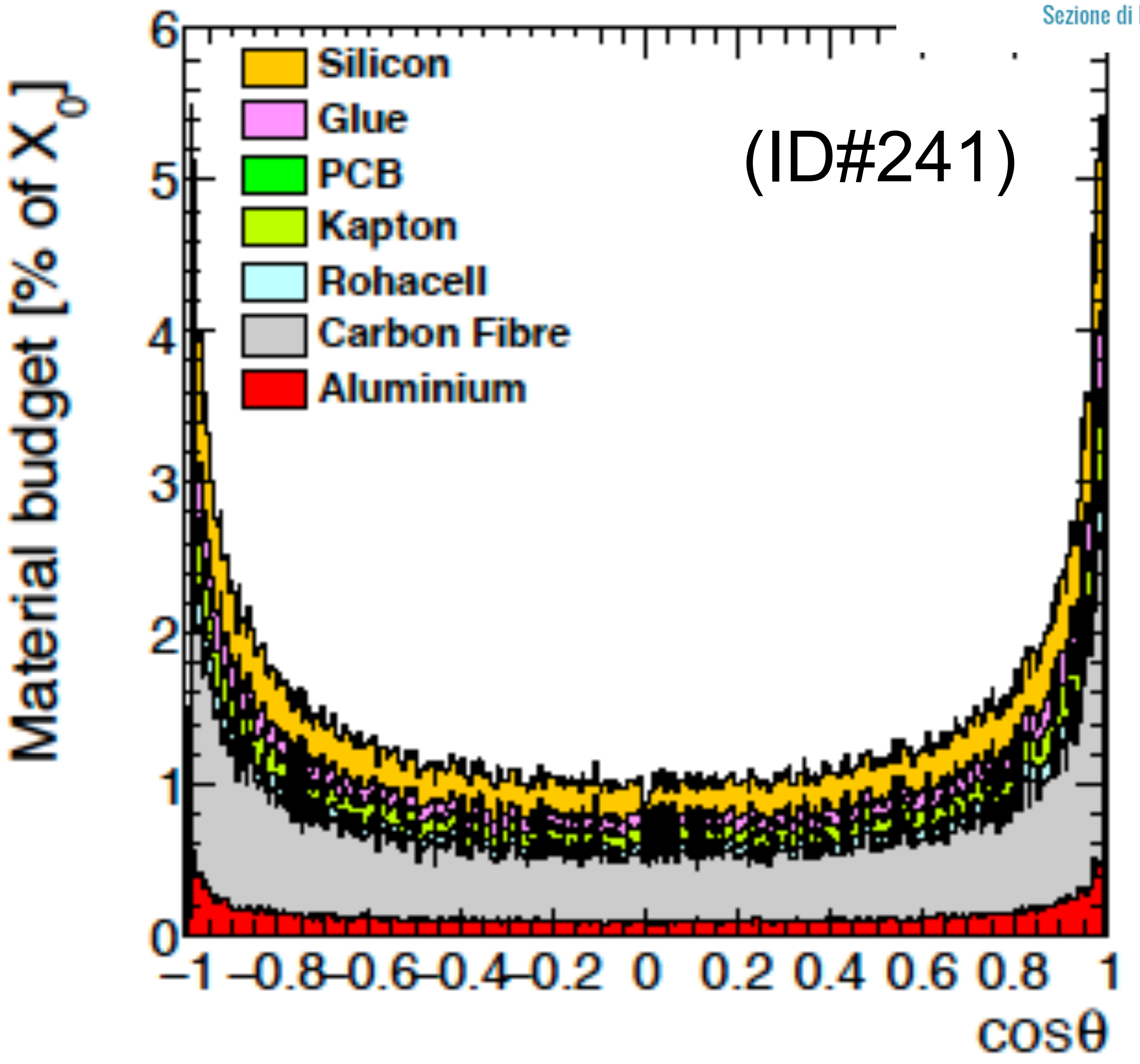


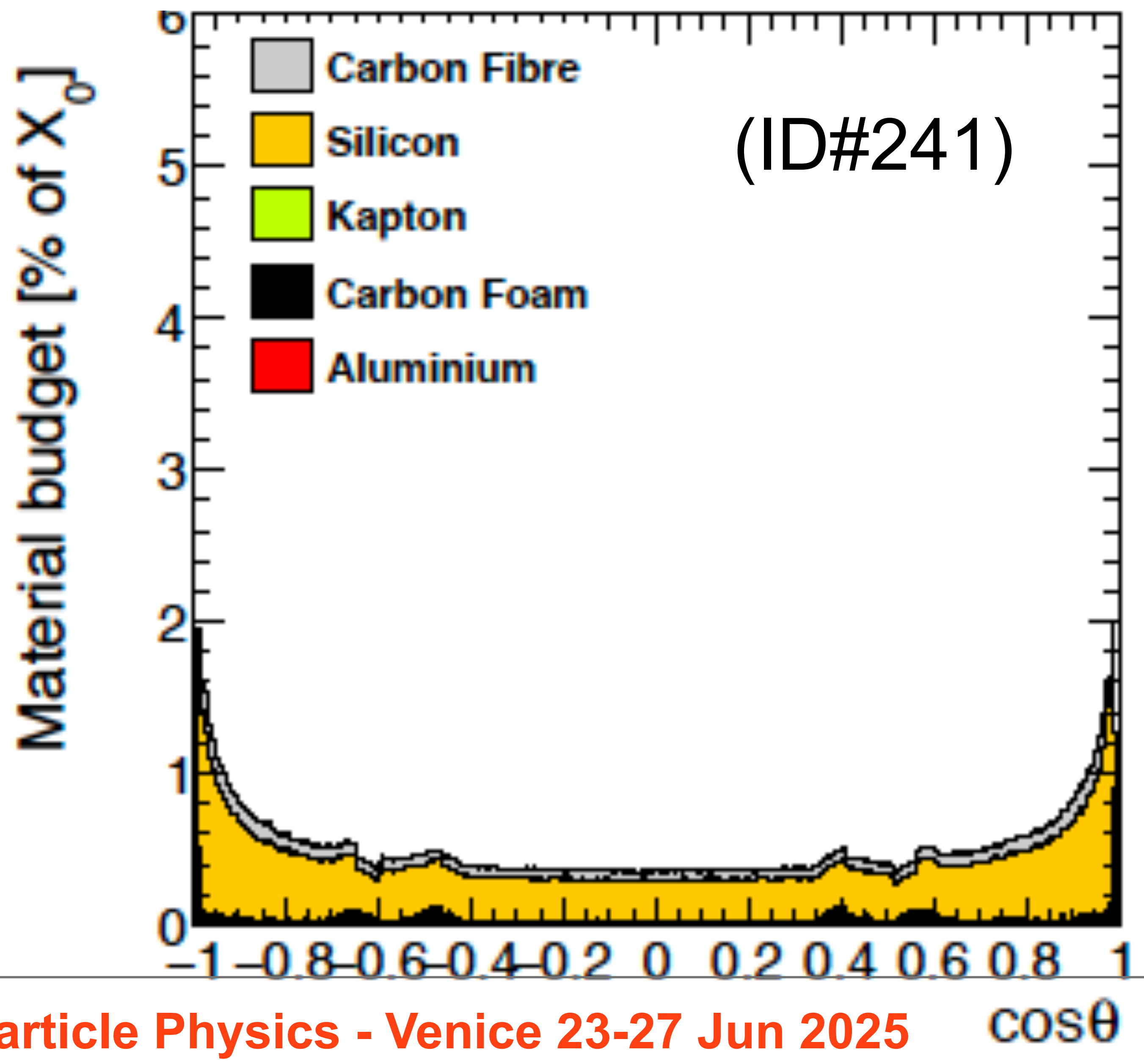
Carbon fibre supported
- Fully engineered
- 3 layers MAPS
- Air cooled
- ~0.25% X_0 per layer





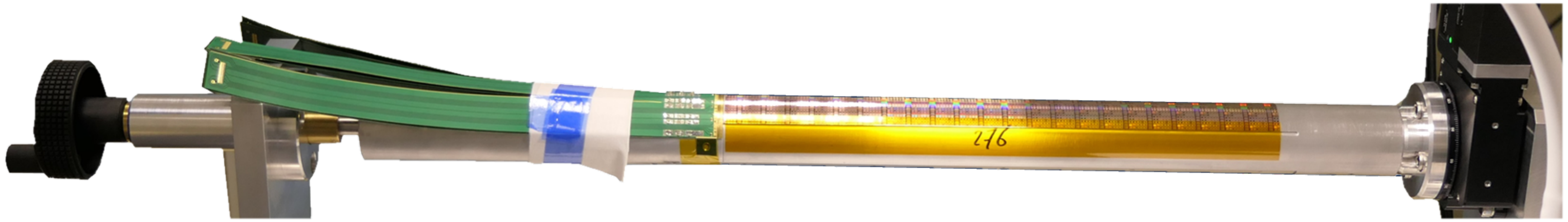
Ultra-light curved geometry (ALICE ITS3 inspired)
- Conceptual design
- 4 layers MAPS
- Air cooled
- ~0.075% X_0 per layer



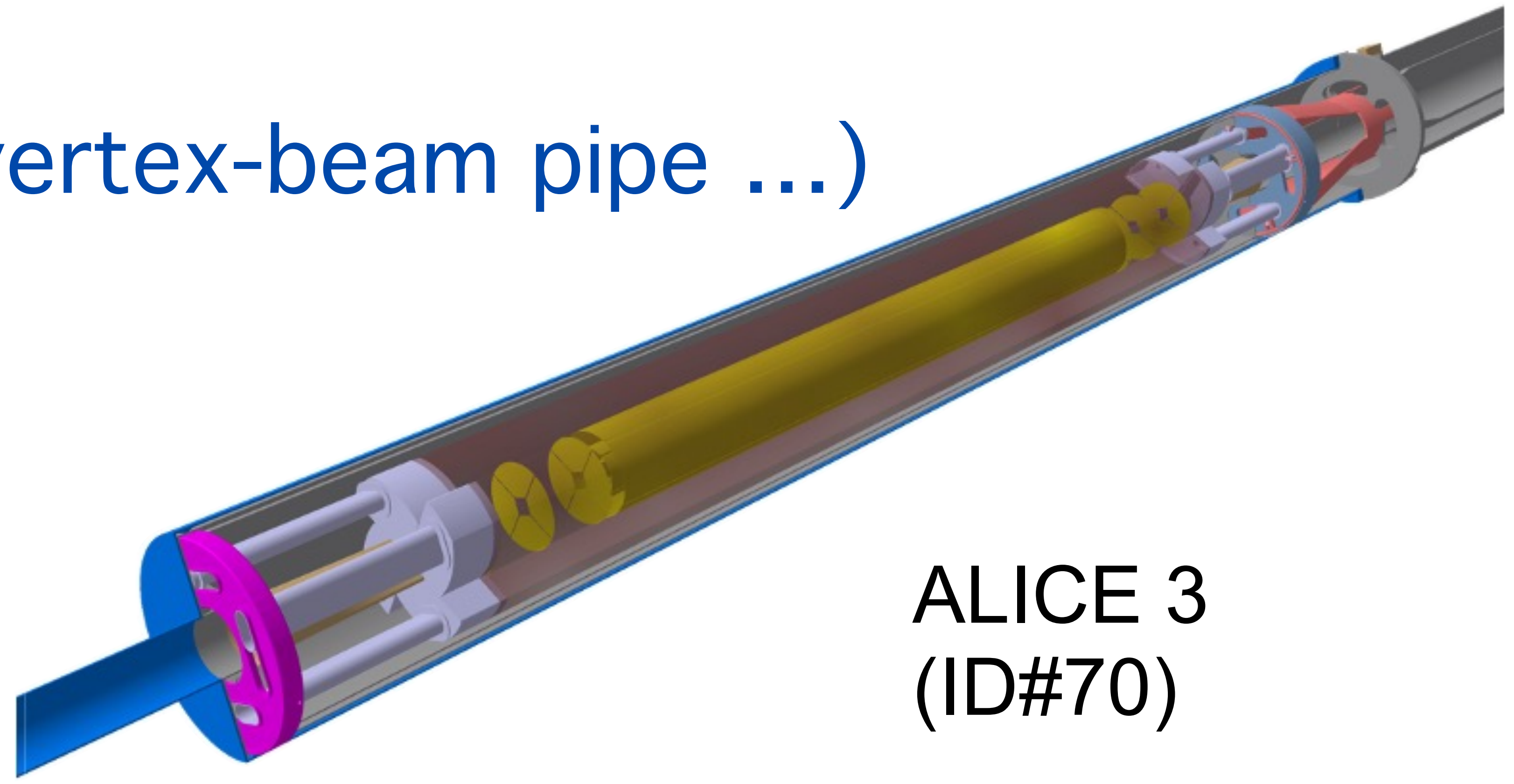


Vertex integration issues

- Use of air cooling to cool down the vertex detectors
  - Pixel matrix is already ~15-30 mW/cm^2
  - Most of the power at chip periphery (up to 700 mW/cm^2)
    - Non uniform heat dissipation
      - Similar problems studied for ALICE ITS3 and ePIC VDET
  - Air induced vibrations must stay < ~1 μm not to spoil 3 μm hit resolution
- Further decreasing material budget (DRD7 and DRD8)
  - Thinner beam pipes
  - Low mass flex PCB
  - Low mass alignment system
  - Vertex & beam pipe co-design (Retractable detectors, integrated vertex-beam pipe ...)



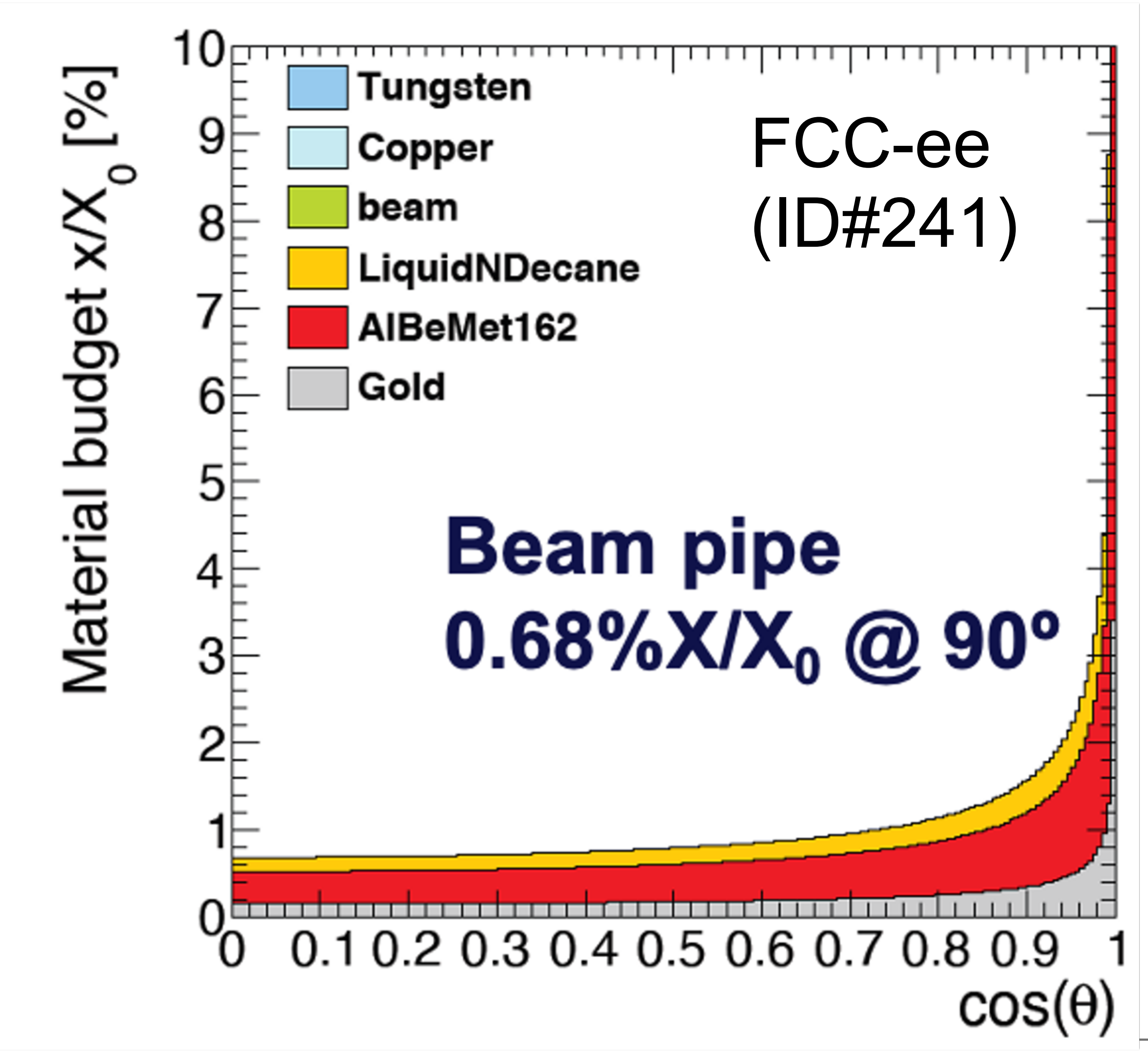
ALICE ITS3

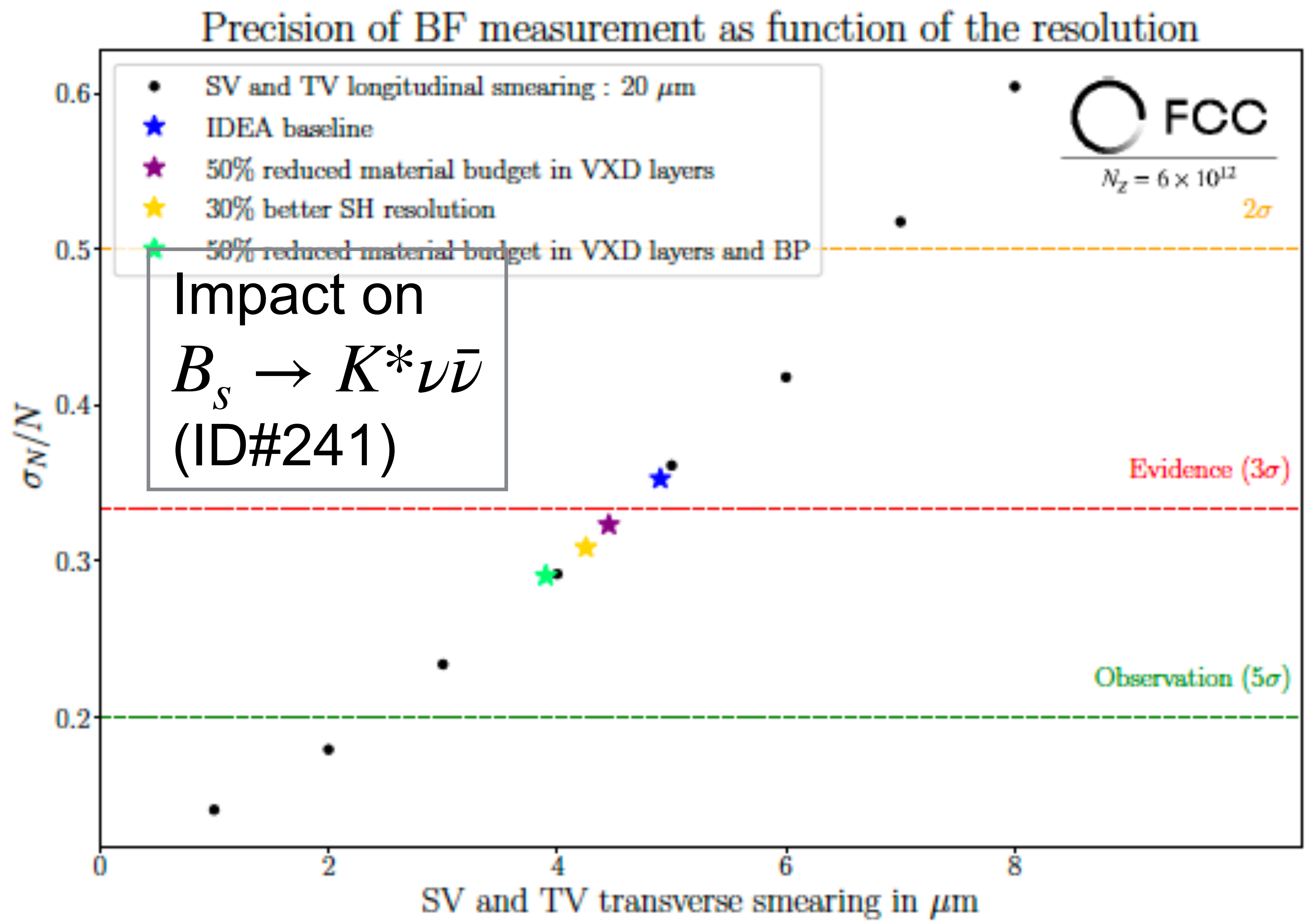


ALICE 3 (ID#70)

Beam pipe material impact on physics

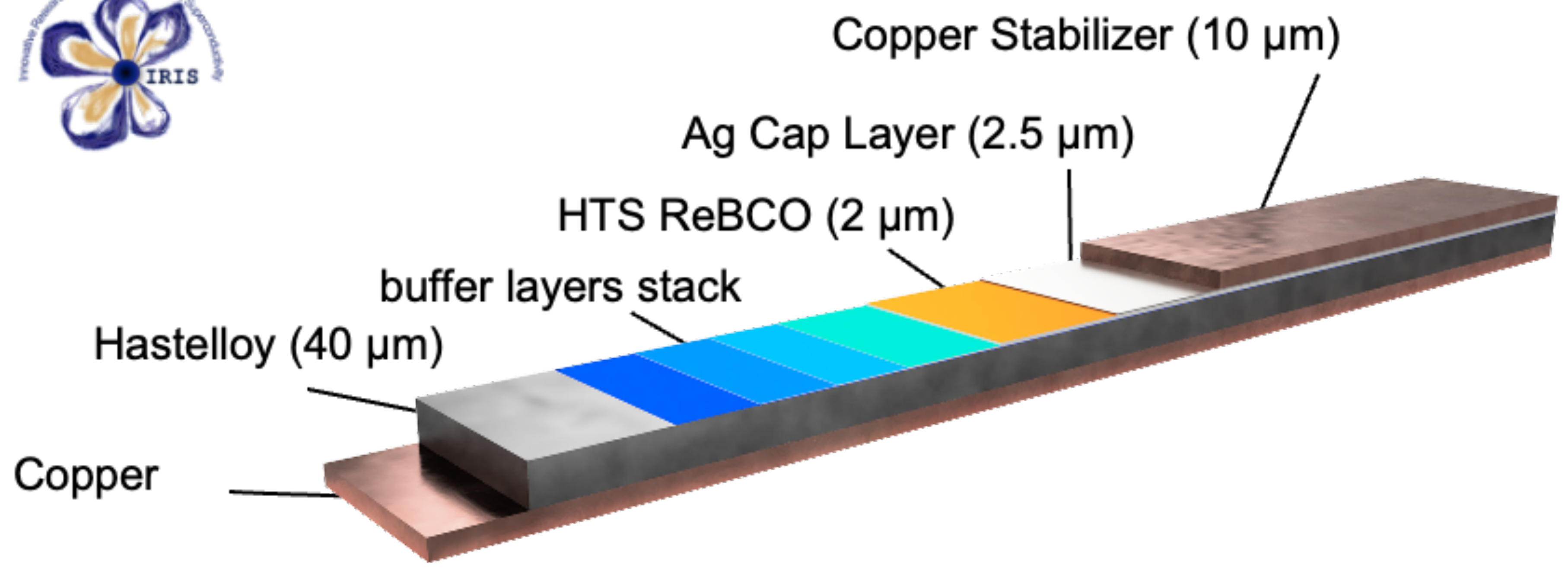
- FCC-ee IR-beam pipe needs active cooling
  - Power deposited from wake fields ~60 W (central beam pipe) at the Z
  - Additional power from synchrotron radiation (depends on SR shielding effectiveness and beam tails)
    - ~5 μm gold layer inside the beam pipe
  - Liquid paraffin based cooling, inspired by SuperKEKB, but with smaller wall thickness and diameter
    - Material budget ~0.7% X_0 might jeopardise excellent vertex resolution
  - R&D ongoing in DRD8 for alternative (lighter) solutions



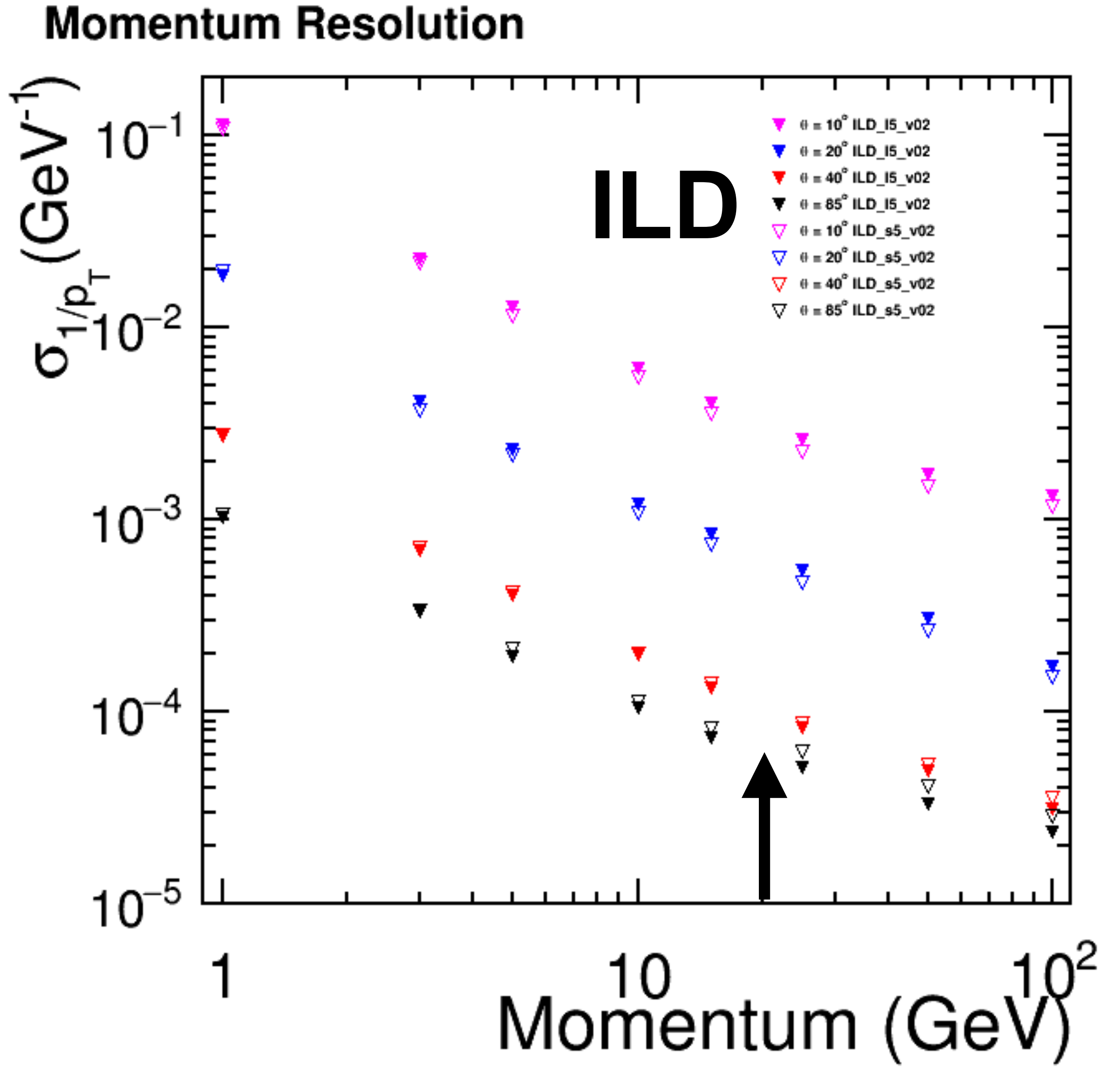


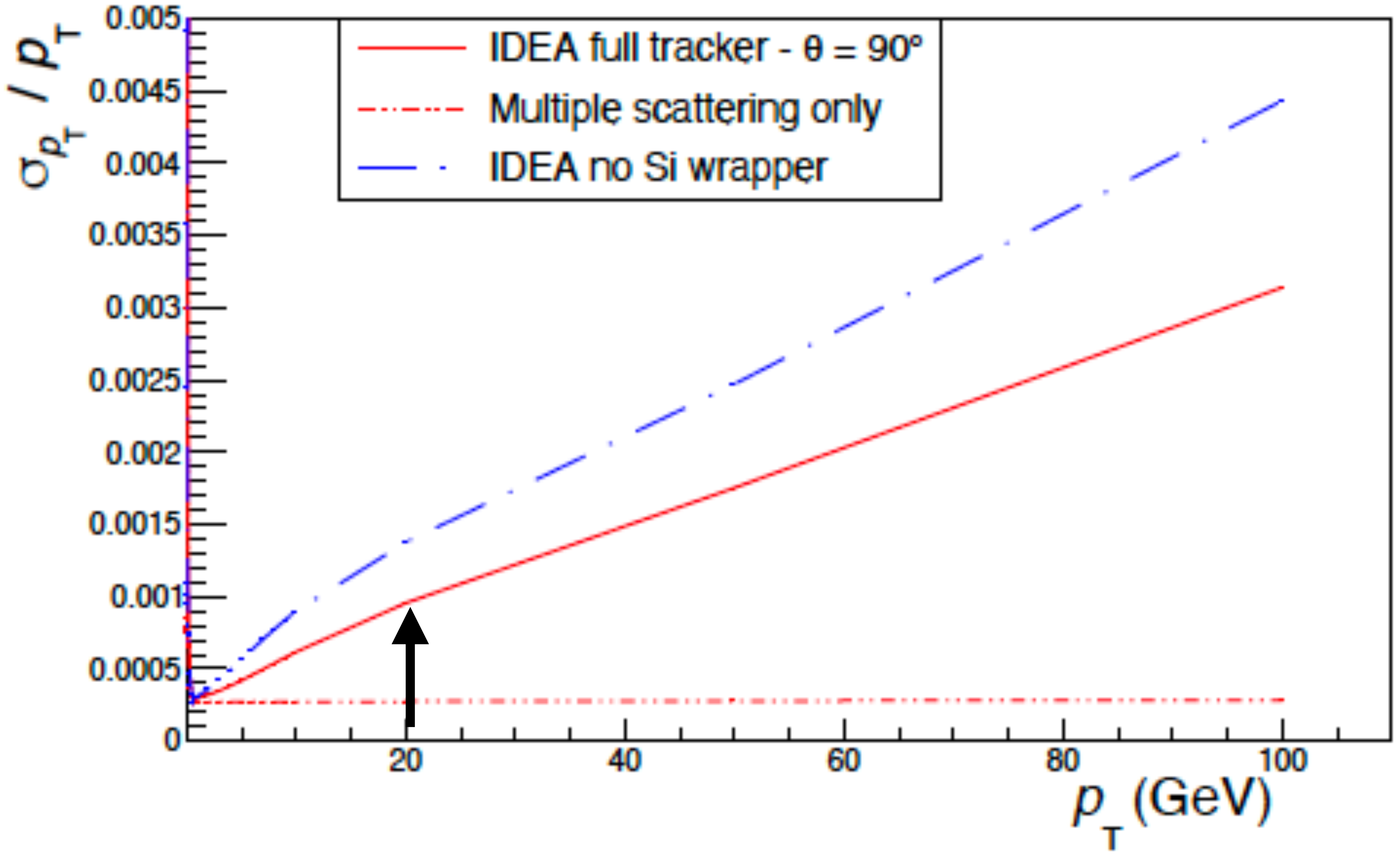
Detector magnets

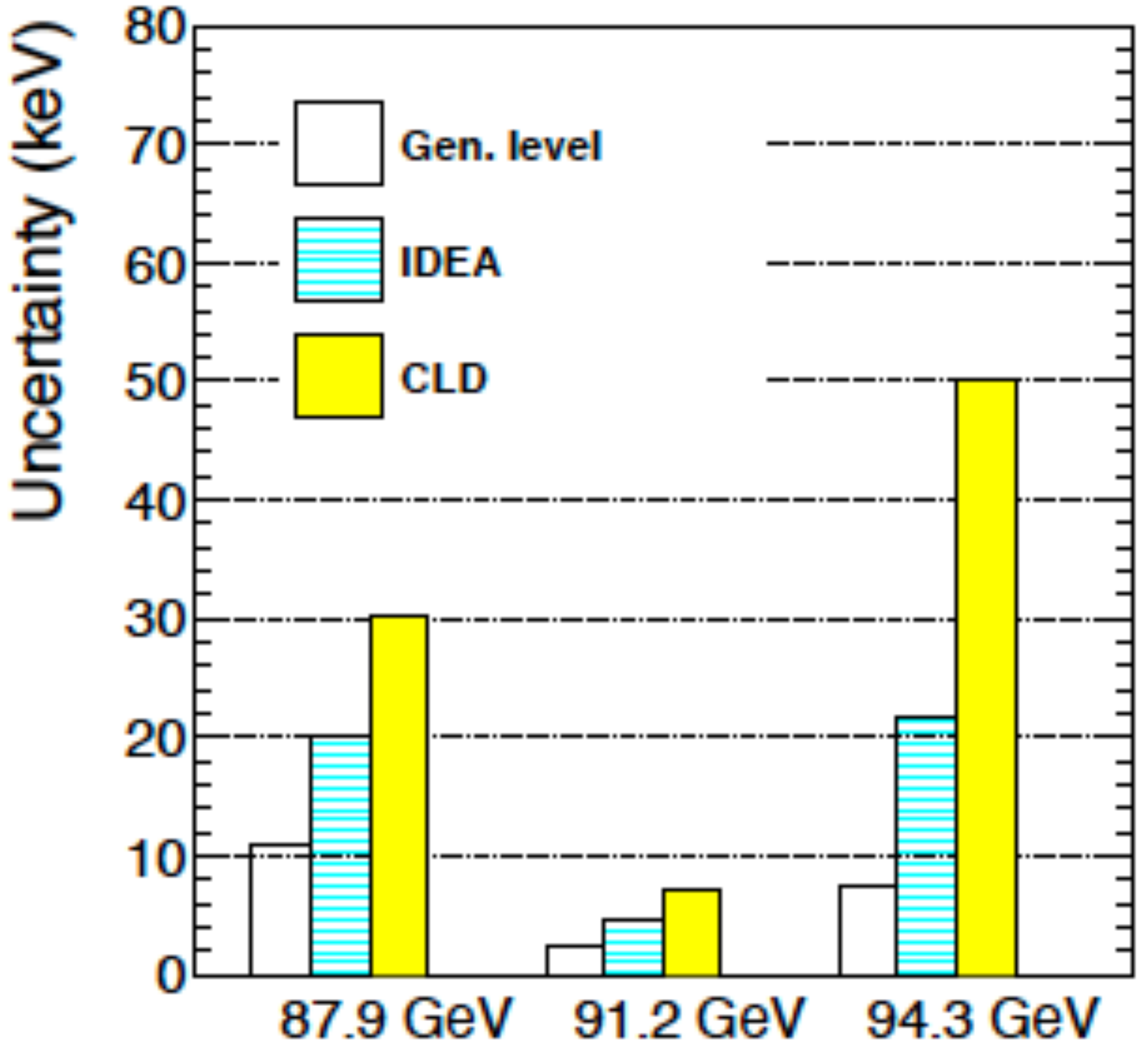
- High energy density (stored energy/ cold mass weight) similar to CMS
  - High mechanical stress in the conductors
    - Determines conductor technology
- Reinforced Al stabilised Nb-Ti conductor technology
  - In the last 10 years production stopped
    - CERN Joint Committee for Experimental Magnets established 2023
    - Contacts established with industries
  - Targeting ALICE3 (solenoid) and iAXO (toroid) magnets
- High Temperature Superconducting (HTS)
  - REBCO conductors @20K reducing operating costs
  - Price of HTS decreasing with time (even if now > LTS)
  - To be studied: quench protection system and mechanics
  - IDEA R&D for 3 Tesla solenoid (ID#96)
- Long term challenge should be planned ahead
  - ATLAS and CMS magnets took15 years from CDR to completion of commissioning
  - Strong support from multiple institutes (9 ATLAS, 7 CMS) working with industry



Detector performance: Tracker





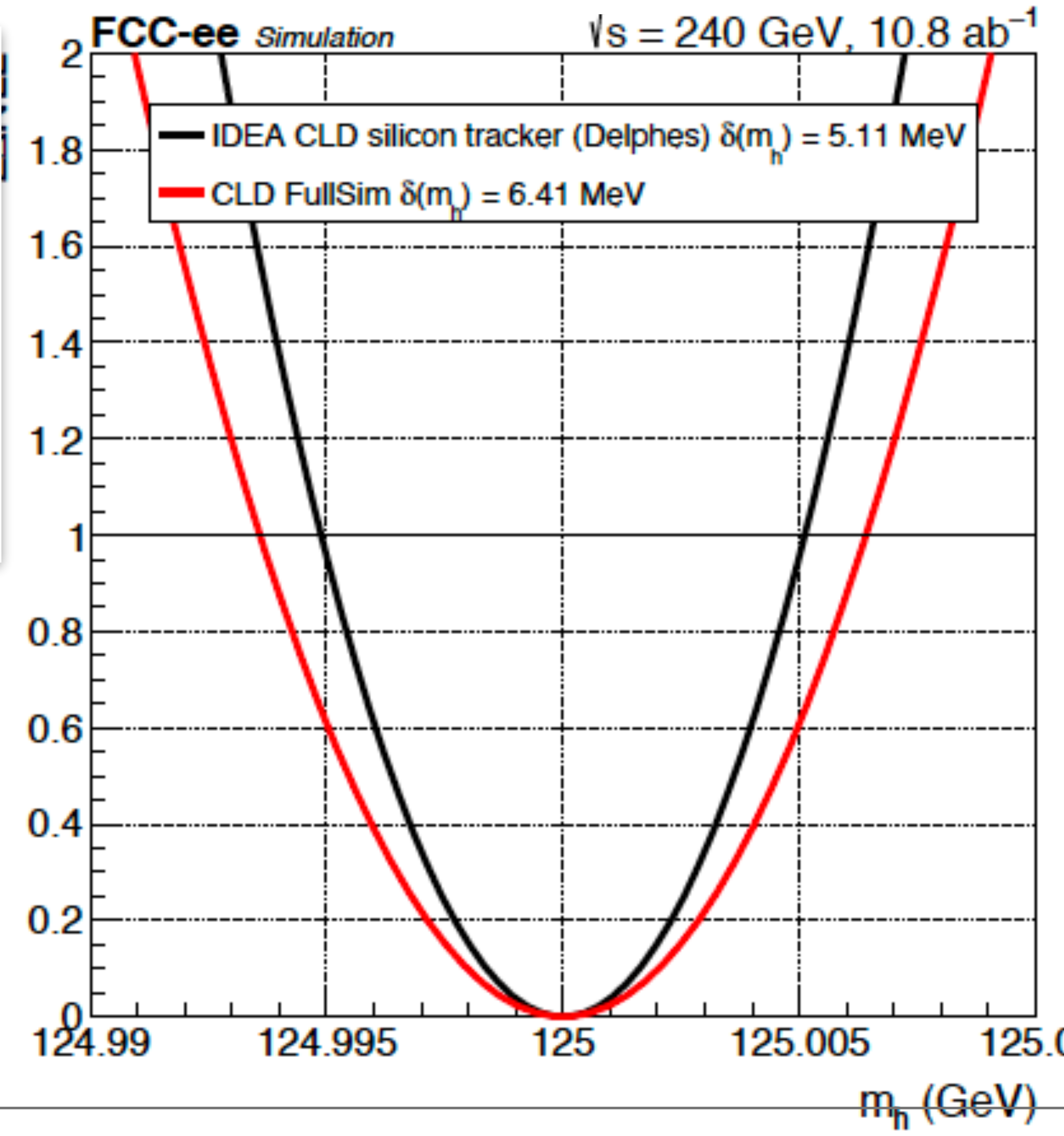


Low material budget and extended points with Silicon Wrapper

ILD: TPC @10 GeV: $\sigma_{p_T}/p_T = 0.2\,\%$

IDEA Drift chamber + Si-Wrapper@10 GeV: $\sigma_{p_T}/p_T = 0.1\,\%$

CLD: Si-Tracker @10 GeV: $\sigma_{p_T}/p_T = 0.4\,\%$ (higher material budget)



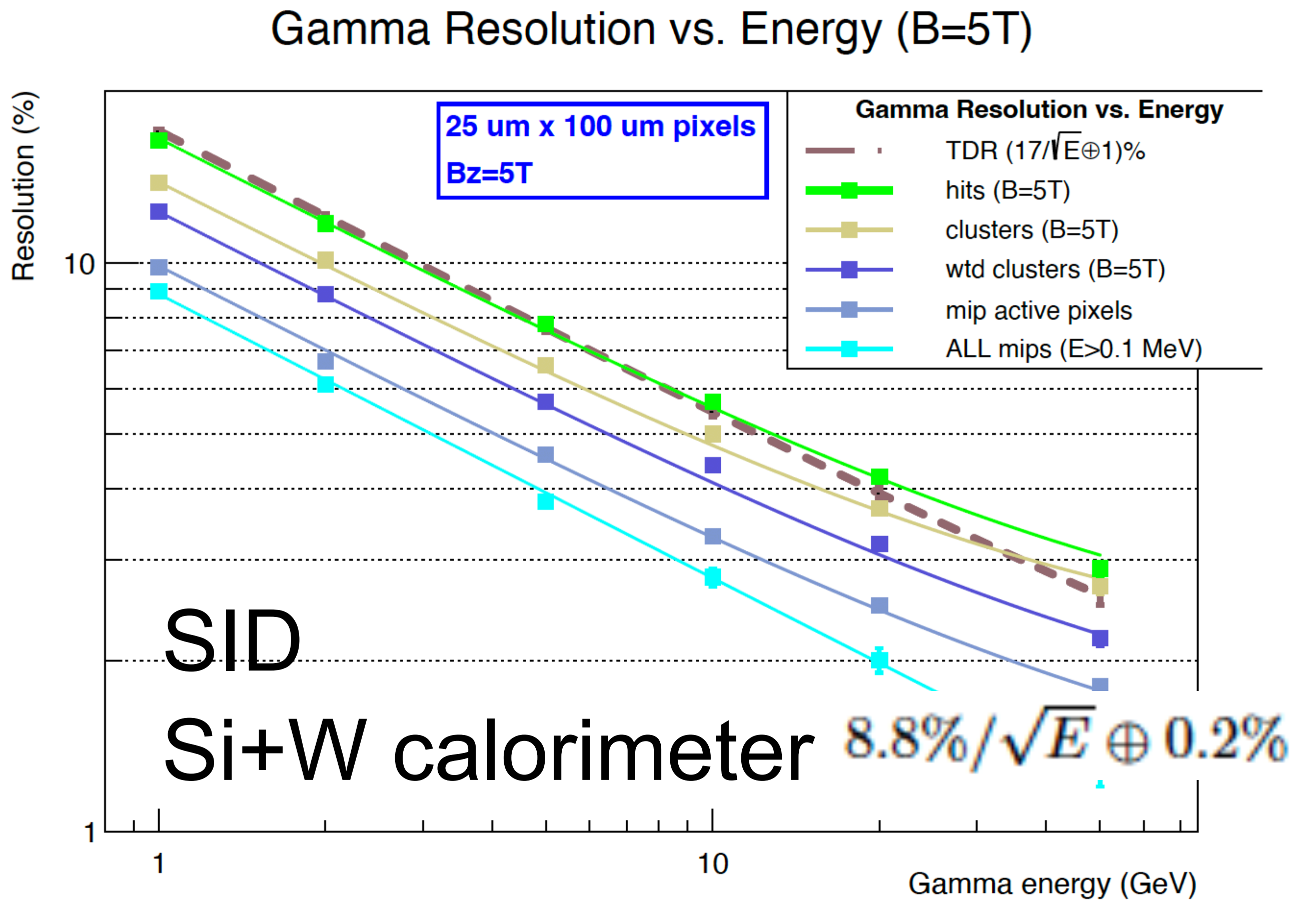
$\mu^+\mu^-$ peak position resolution

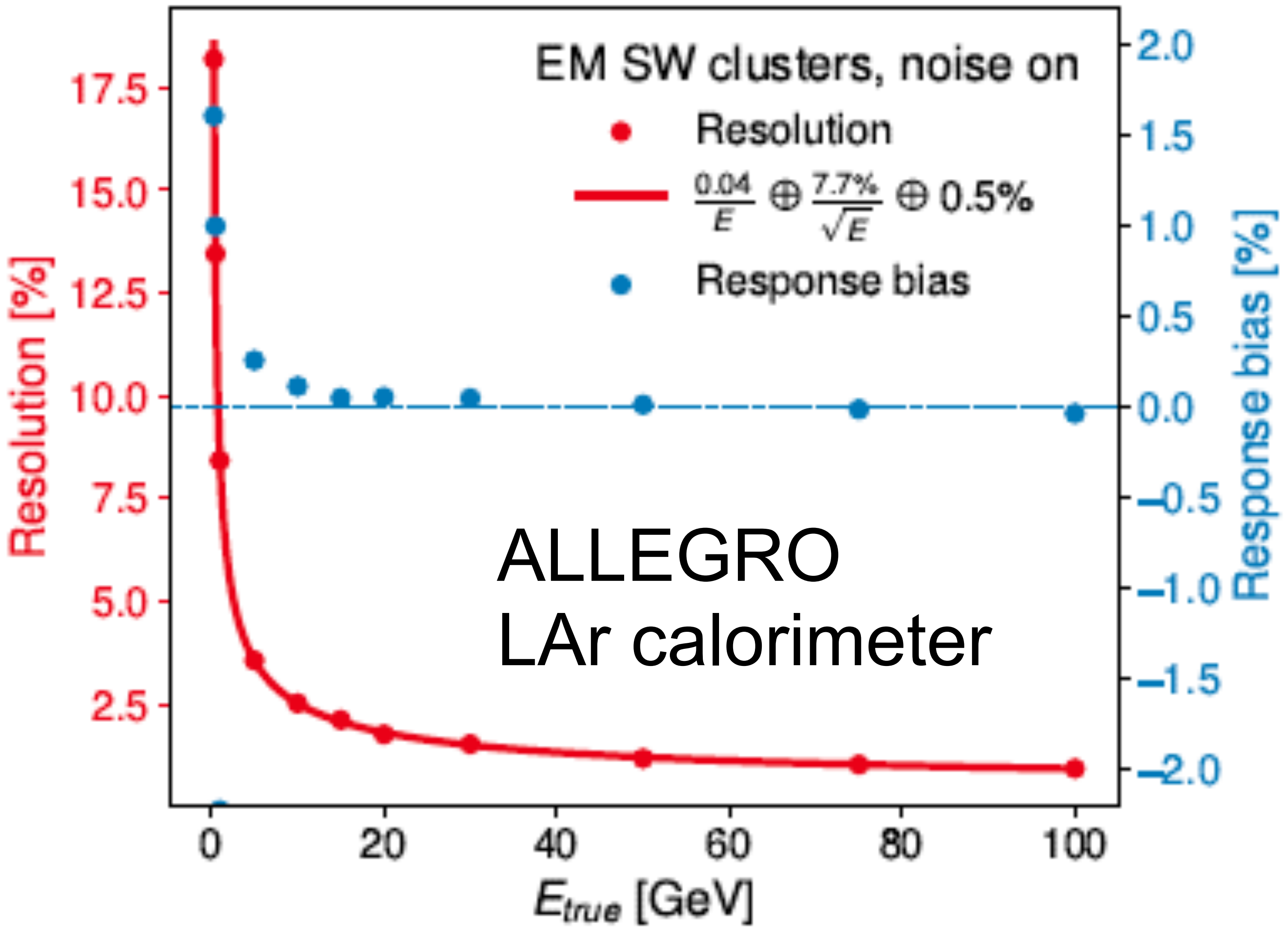
Uncertainty on Γ_Z from line shape

IDEA: 11 keV
CLD: 22 keV

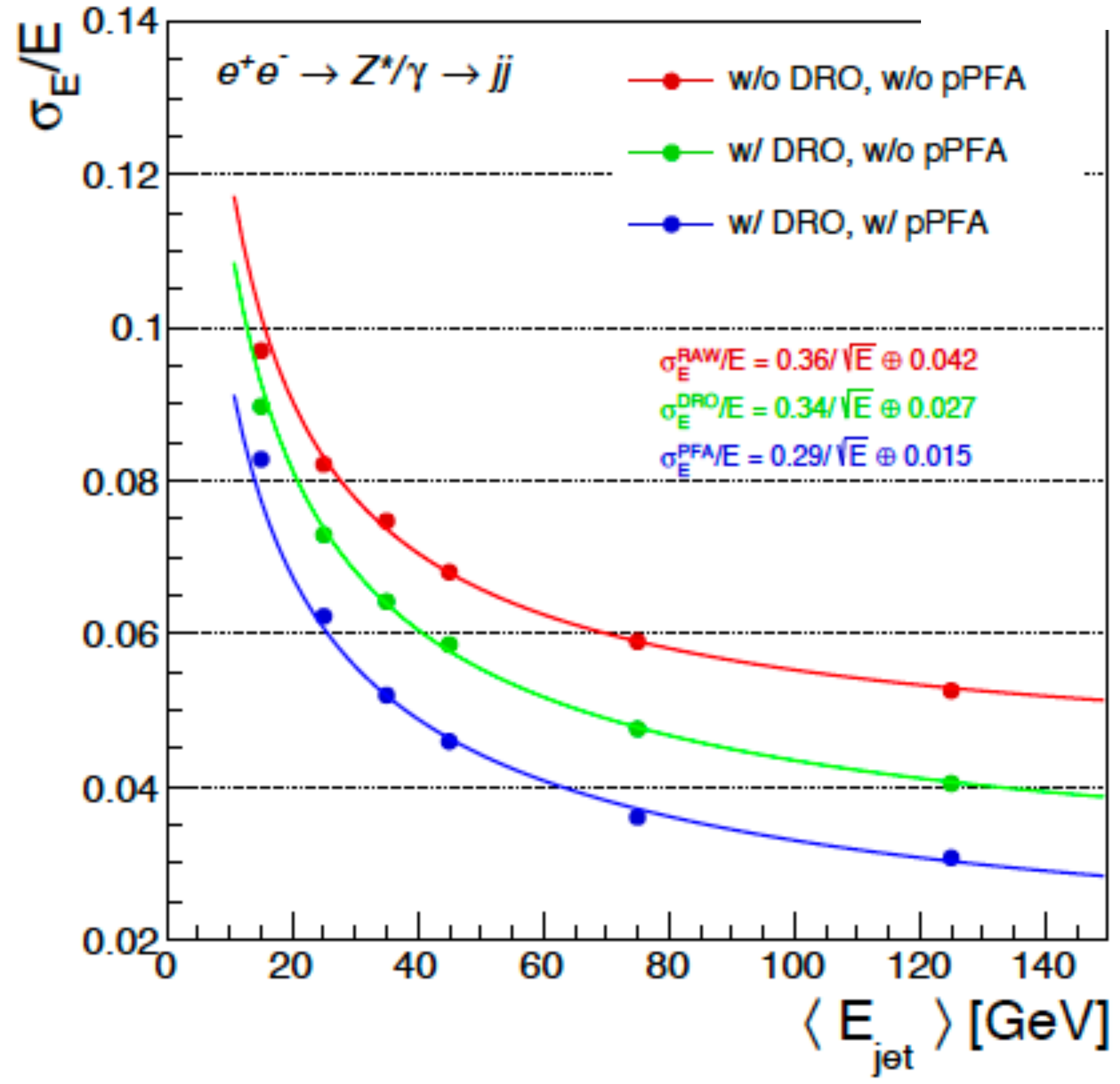
Impact on Higgs mass resolution using recoil method $Z(\to \mu^+\mu^-)\ H$

Detector performance - Calorimeters

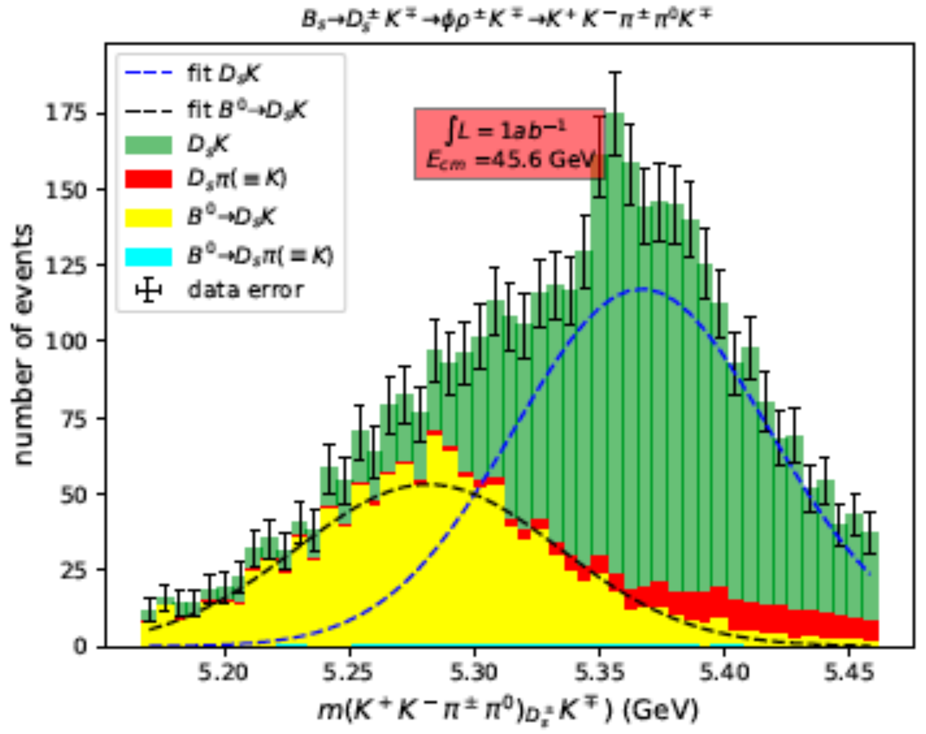




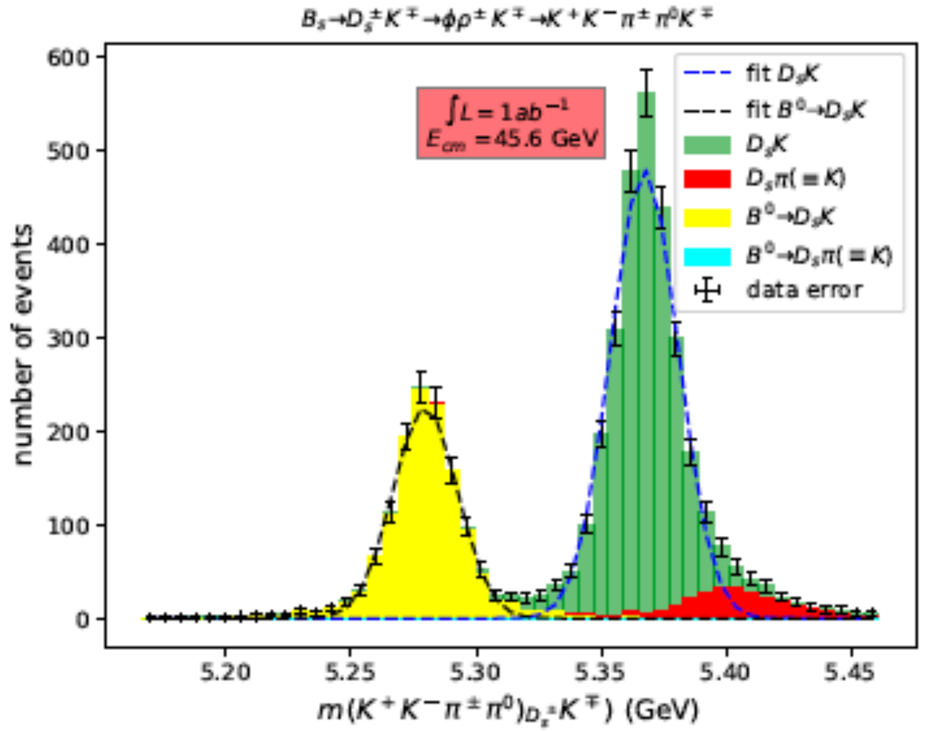
Jet energy resolution

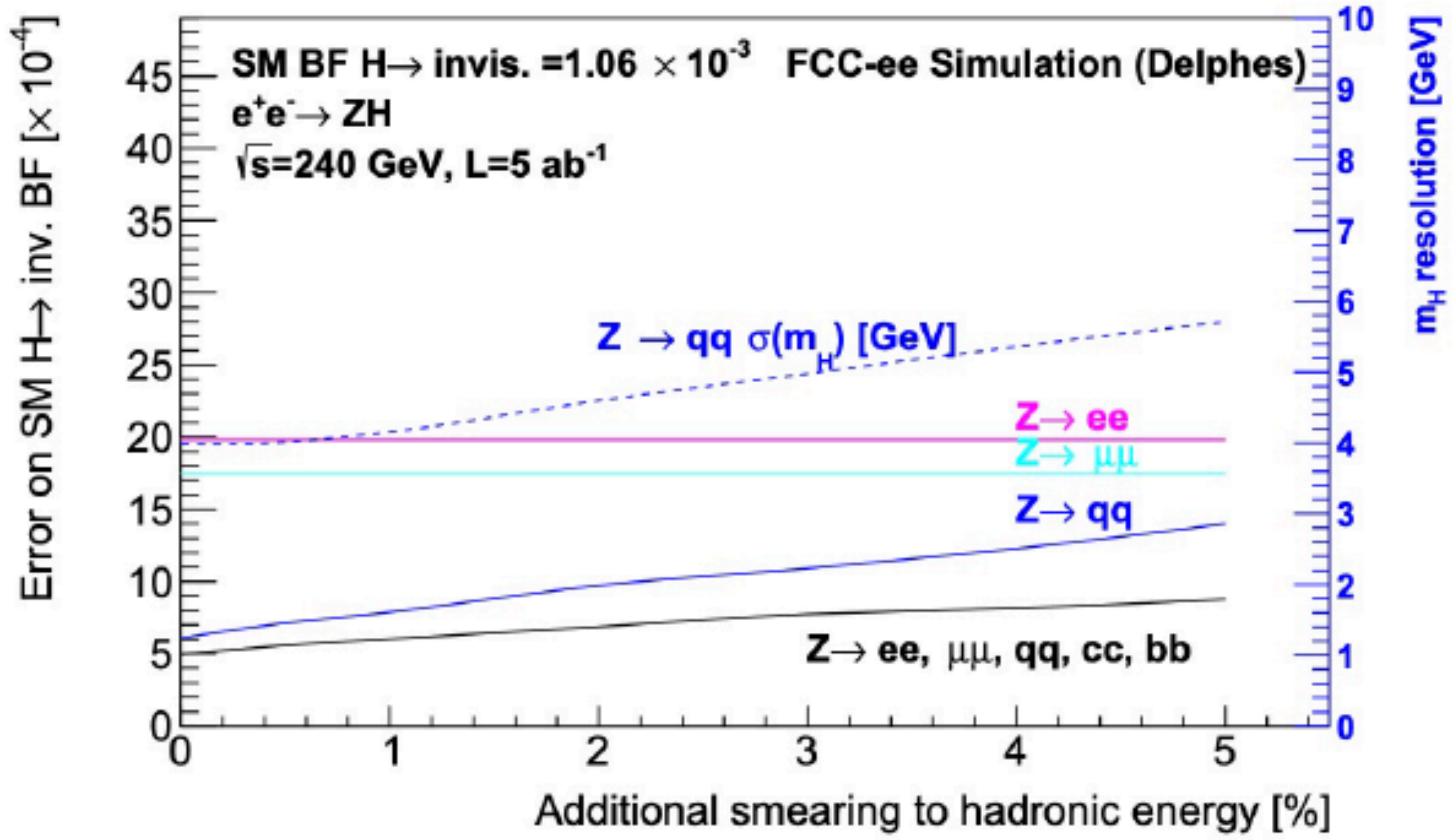


$\sigma_E/E = 15\,\%/\sqrt{E} \oplus 0.005$



$\sigma_E/E = 3\,\%/\sqrt{E} \oplus 0.005$

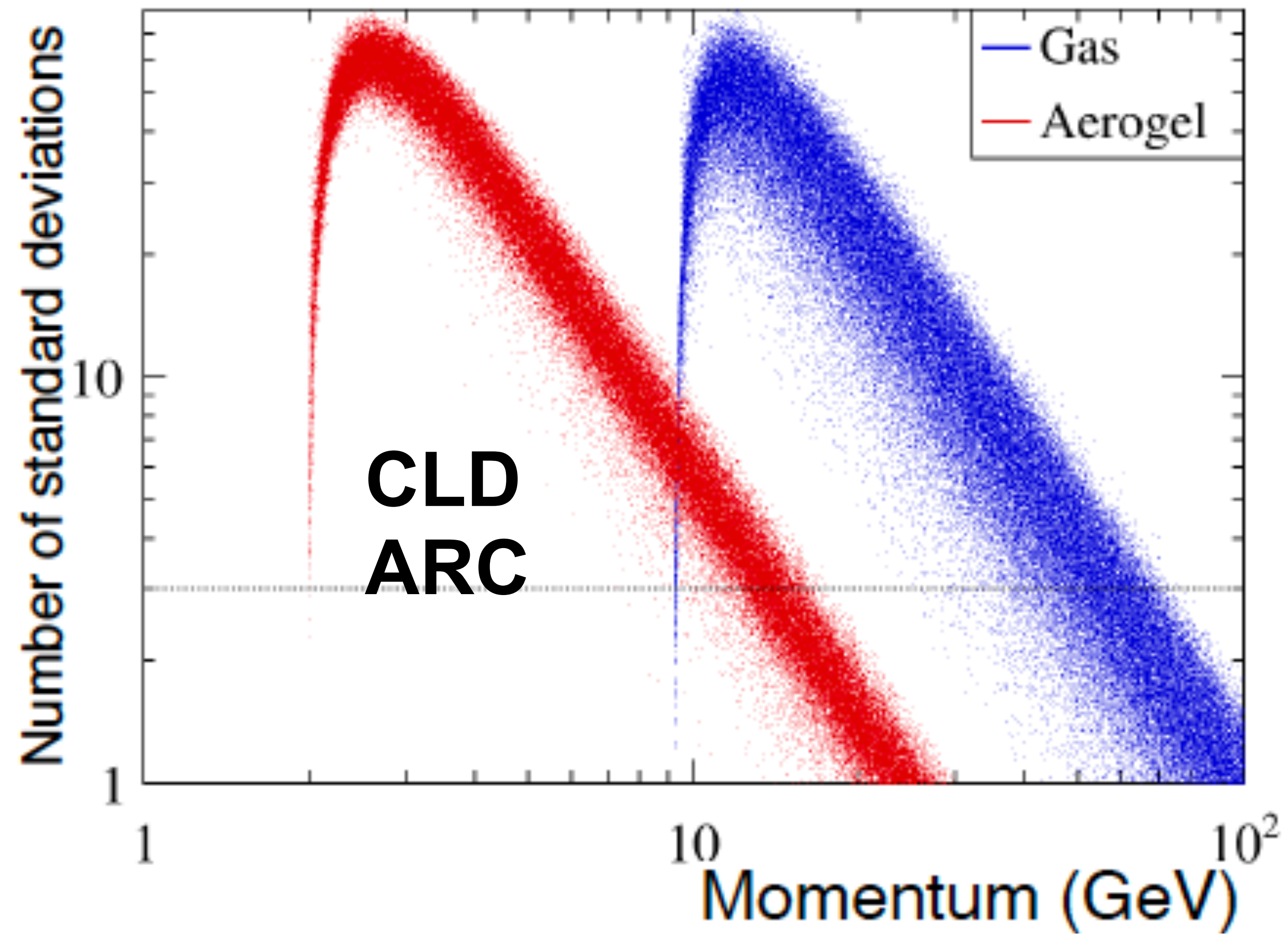


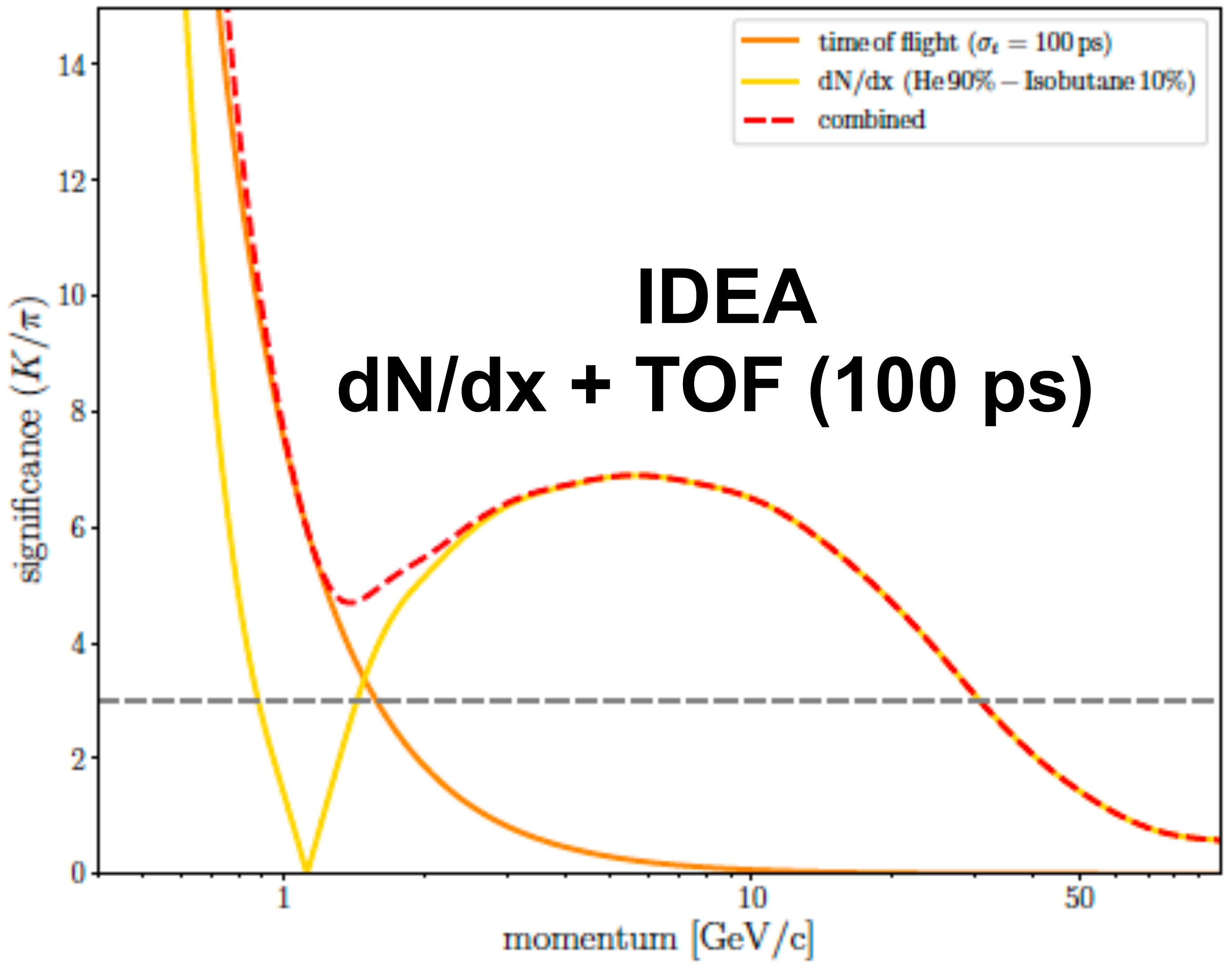


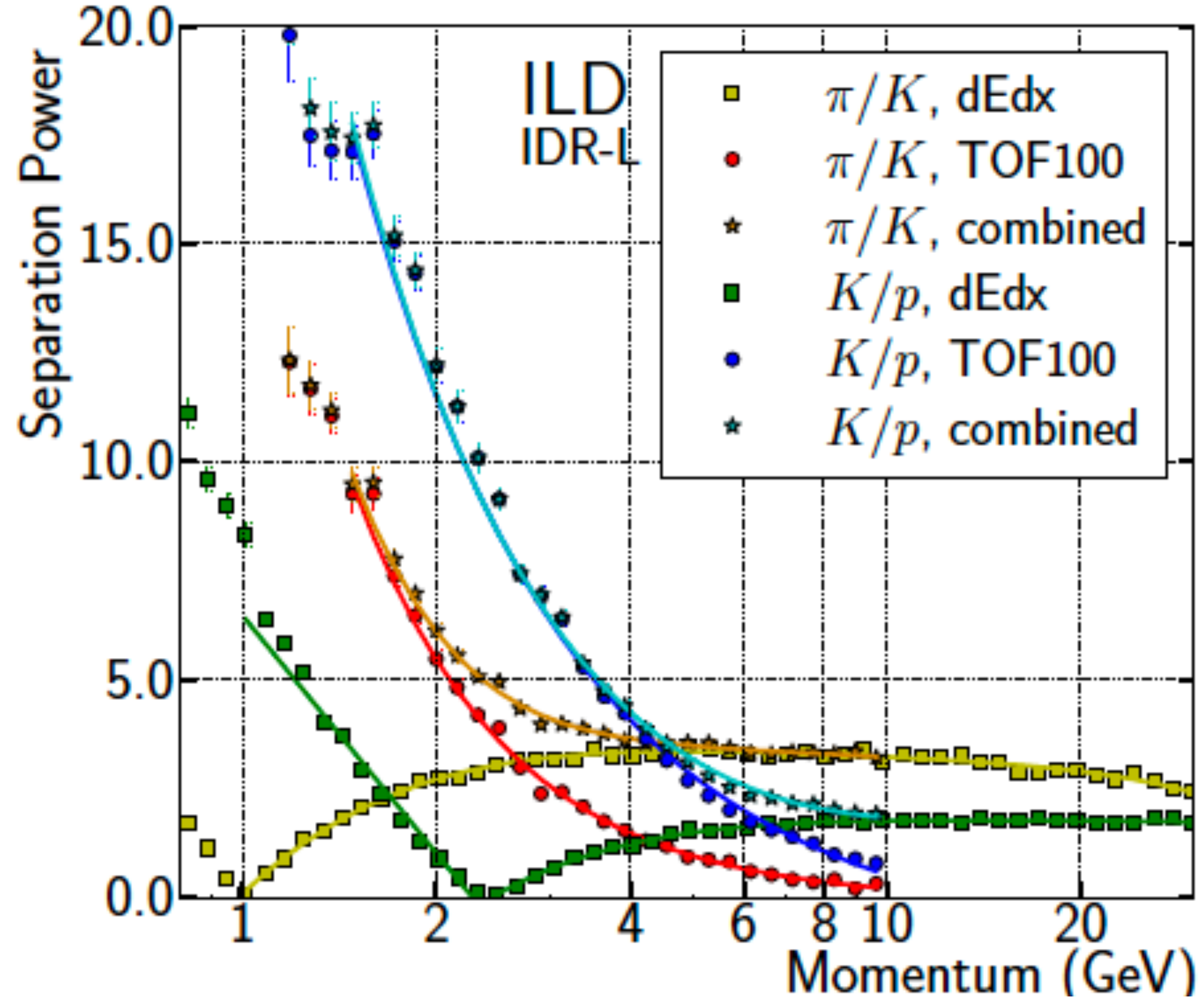
Impact of ECAL resolution on $B_s \to D_s^+(K^+K^-\pi^+\pi^0)\ K^-$

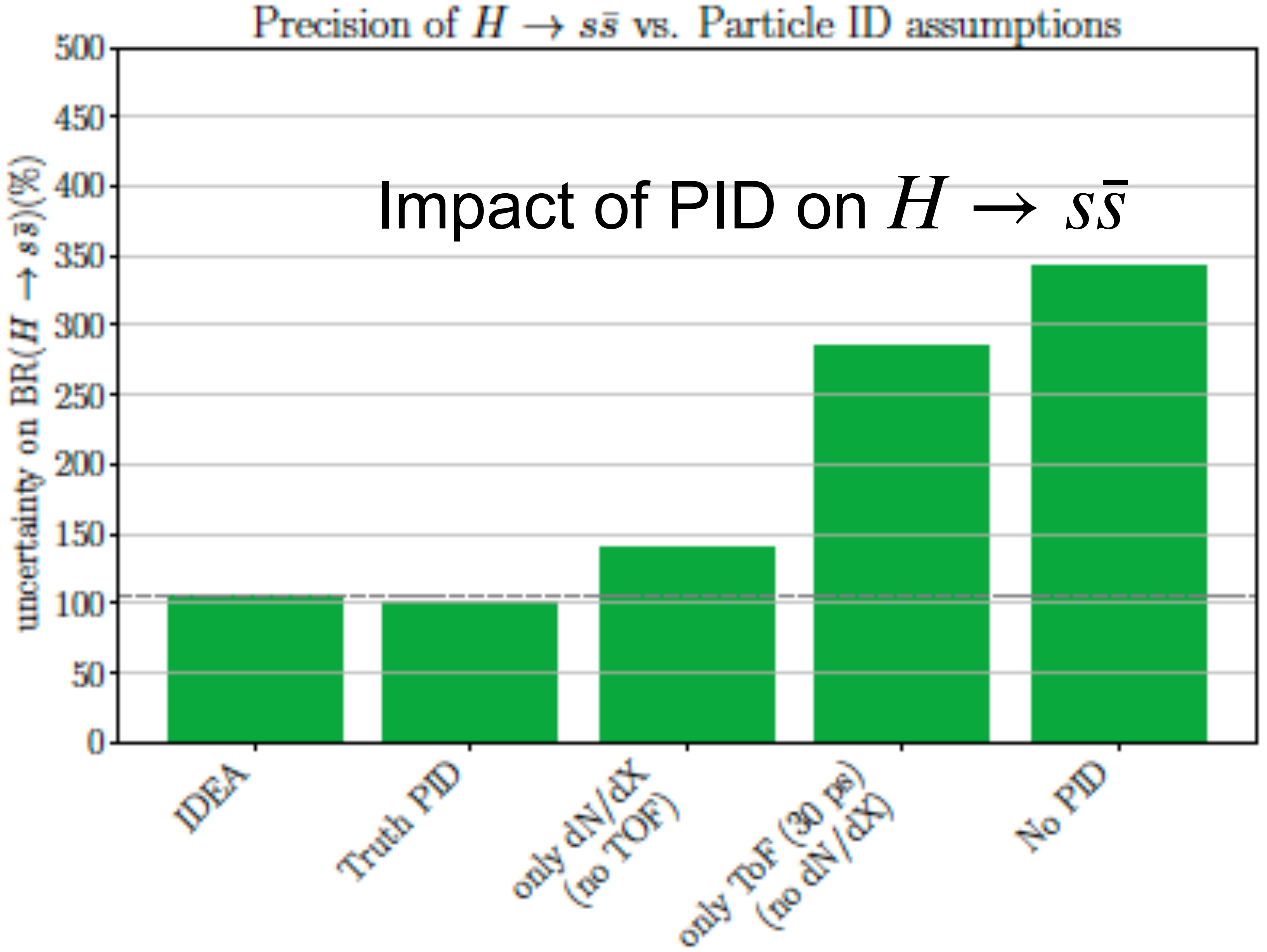
Impact of HCAL resolution on $H \to \nu\bar{\nu}\nu\bar{\nu}$ and Higgs mass

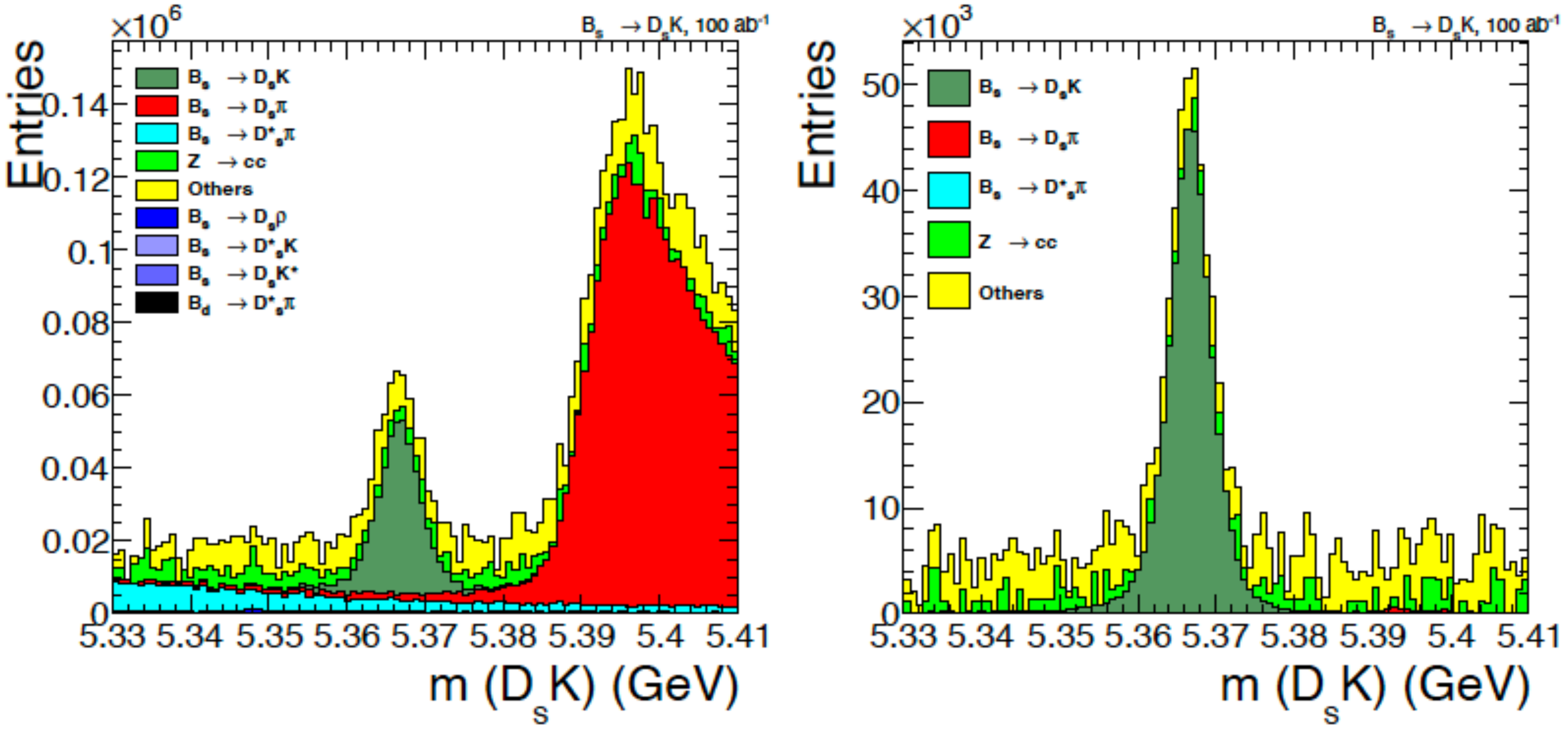
Detector performance - Particle ID











Impact of PID on $B_s \to D_s^+ K^- \to \phi(K^+K^-)\pi^+K^-$

Conclusions and perspectives

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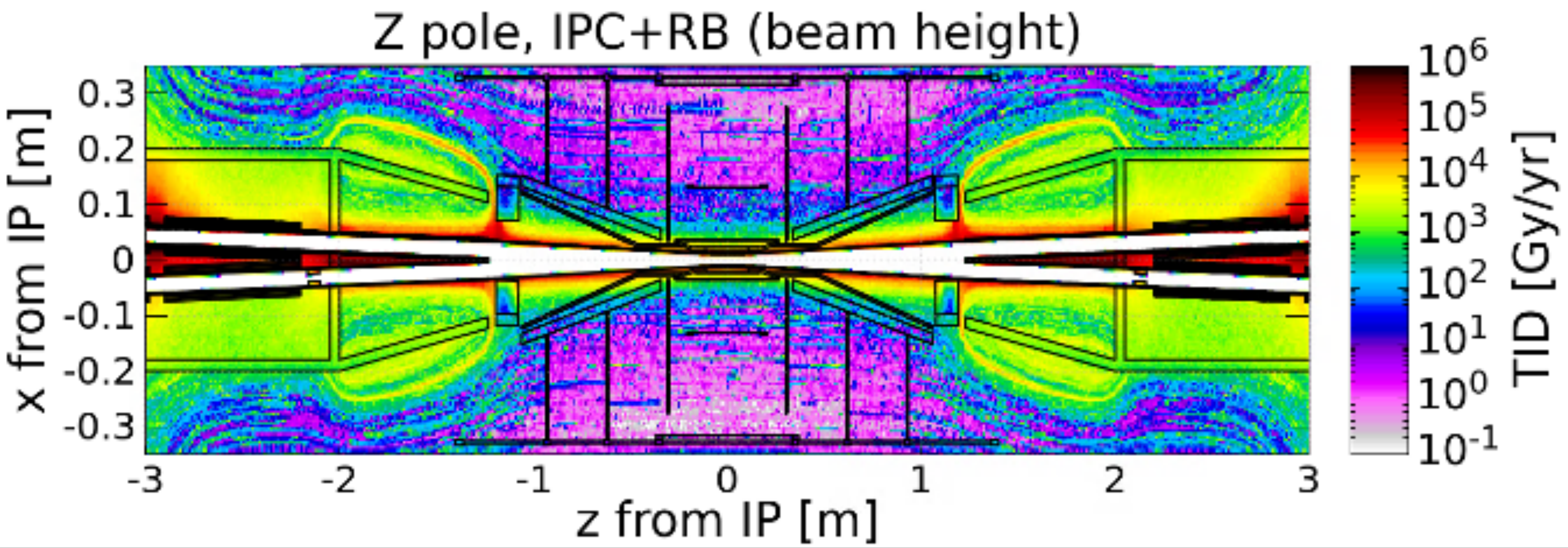
Sezione di Pisa

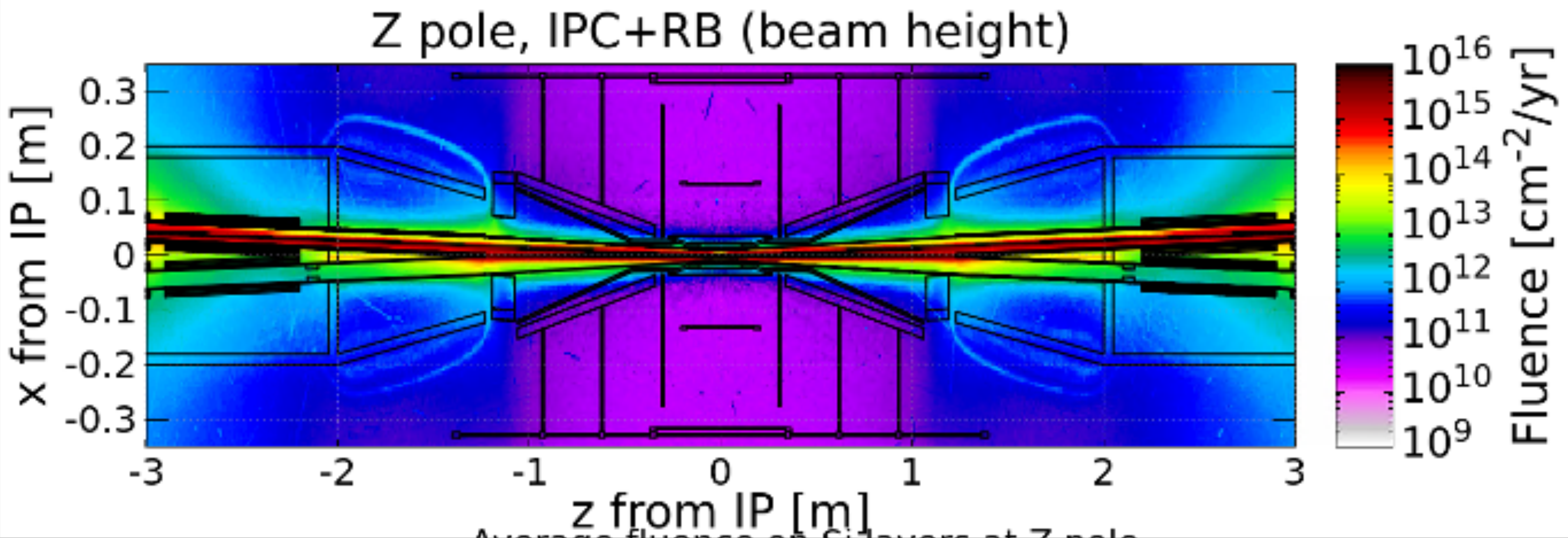
- Physics performance for future Higgs, Electroweak and Top factories impose stringent requirements on detectors
  - Individual sub-detectors R&D addressed in ECFA DRD and elsewhere (e.g. CPAD in US, ITDC in Japan)
- High luminosity and beamstrahlung lead to constraints to the detector systems
  - Machine-Detector Integration becomes of vital importance for full apparatus design
- Detector concepts address these challenges using different technologies
  - Big phase space of integrated detector technologies to satisfy physics requirements allow to study optimisation, robustness and limitations of the designs
  - Predicted performance matches the requirements, but systematics due to calibration and alignment need to be studied in detail
- Integration of different sub-detectors must be studied accurately
  - Services (cabling, cooling etc) need to be carefully designed, accounting also those of the machine
  - Ultimate accuracy on physics measurements may be coming from systematics on detector resolution, calibration and alignment

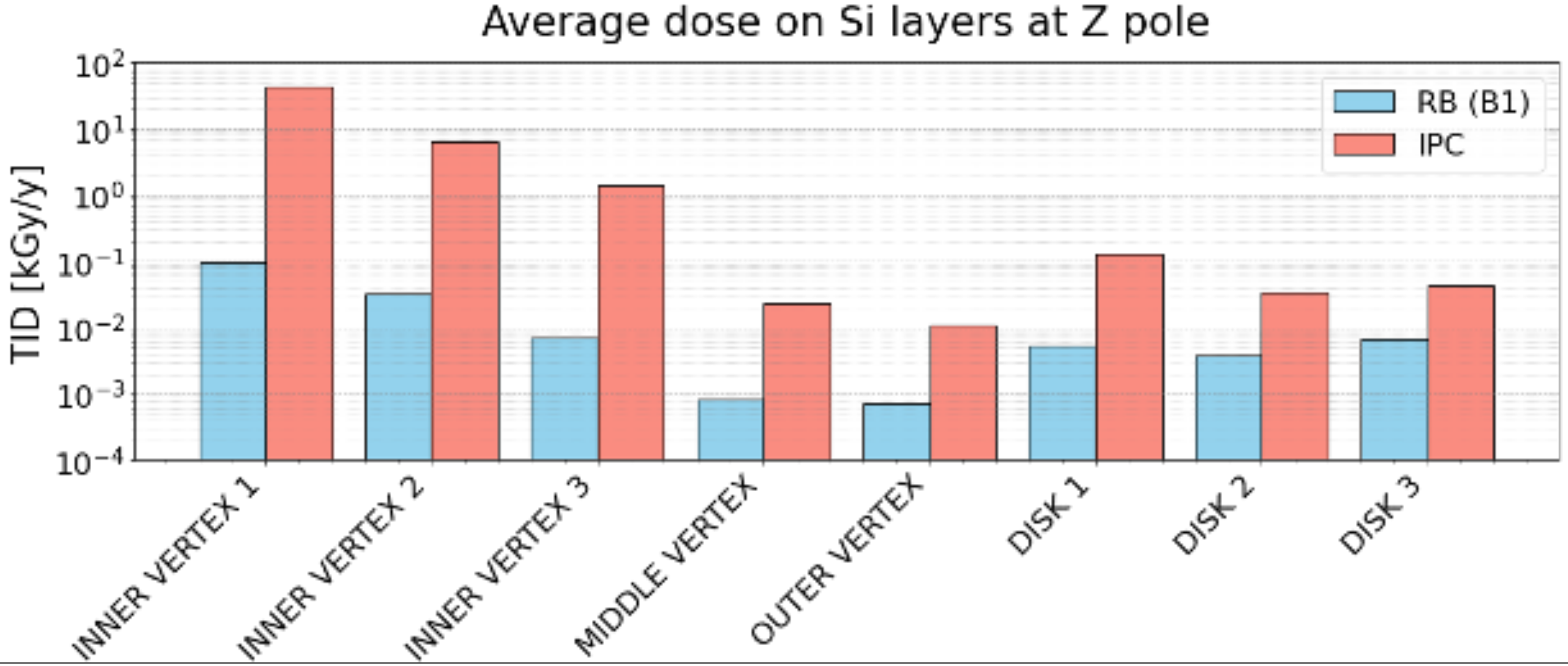
Backup

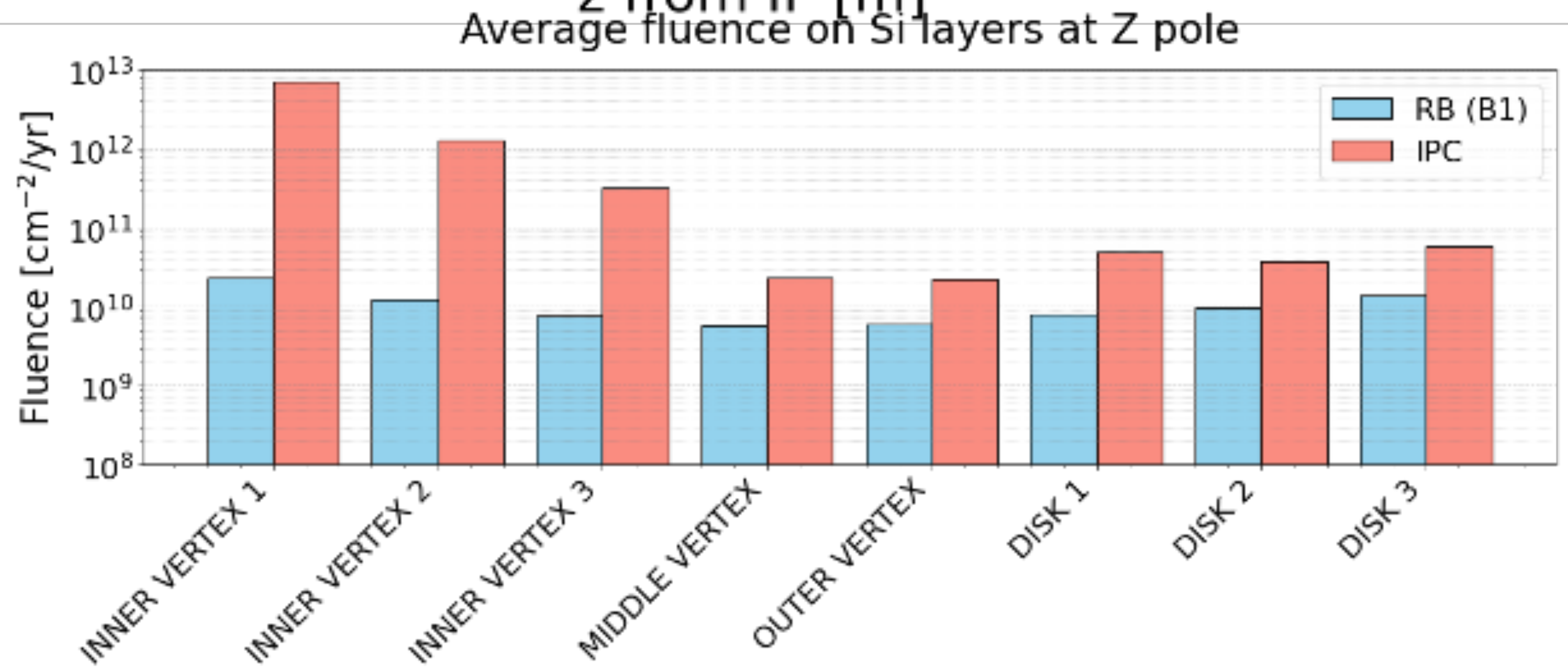
Vertex detector radiation levels

- IPC dominant source
  - 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









Detector assembly and accessibility

- Detector assembly and maintenance design important for efficiency
  - Impacts on repair faulty sub-detector systems and detector uptime (integrated luminosity)
- Example:
  - Transversal shift to a garage position and full longitudinal opening
    - FFQ may stay inside detector in FCC-ee
    - At linear colliders 2nd experiment can shift-in
    - Needs sufficient (lateral) space in cavern
    - Needs realignment of FFQ and detector