Status of beam-induced background simulation at FCC-ee

Jan Eysermans
Fourth US FCC meeting
September 9, 2026

FCC-ee design parameters

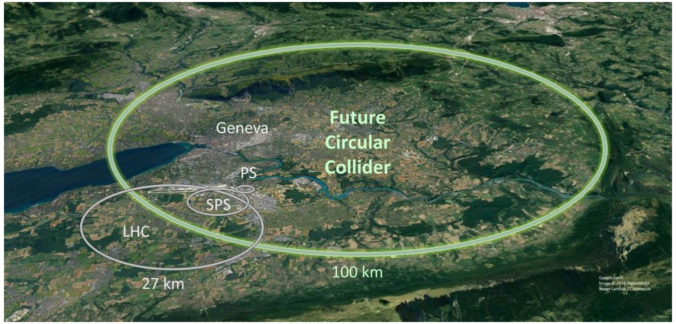
Key aspects of the FCC-ee accelerator

- Crab Waist collision scheme to push the luminosity to ~ 144x10^{34} $cm^{-2}s^{-1}$ at the Z pole
- Crossing angle of 30 mrad
- Excellent squeezing of beams from final-focus quadrupoles inside detectors (reaching very small β^*_y)
- Top-up injection from the booster ring: up to 1 % of full beam intensity is injected every 6 s per beam
- 27 ns bunch spacing at the Z pole, increase with energy

FCC-ee accelerator design still being optimized

- Currently using the LCC lattice for further studies

	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)

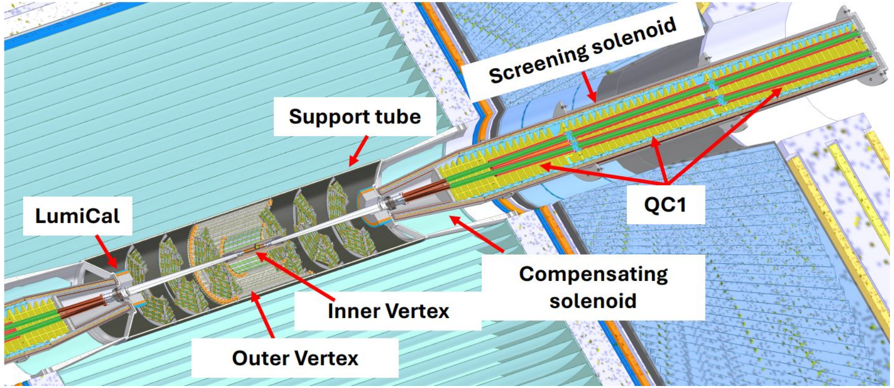
MDI note for the FSR:
https://repository.cern/records/p44x1-18z28

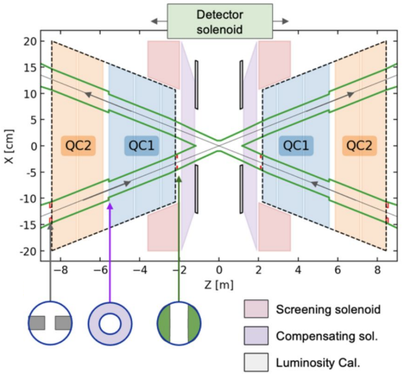
Complex MDI at FCC-ee because the MDI equipment is partially in the detector volume

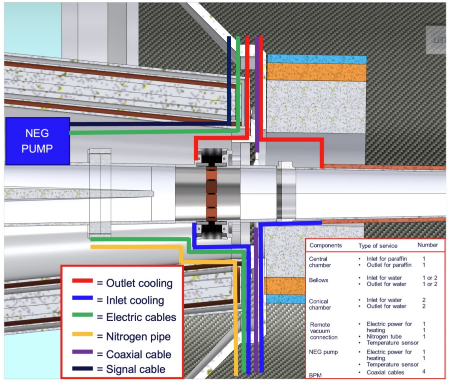
- Final-focusing magnets inside the detector volume → *give rise to localized synchrotron radiation*
- Beam pipes split and merge at ~1.1 m from the IP → *hot spot for backscattering of forward particles*
- Compensating solenoid system to cancel integrated detector magnetic field → *fringe fields give rise to synchrotron radiation*
- LumiCal integrated in the forward MDI region, services of vertex/lumical to be routed, cooling → *material budget*

High-intensity beams and material in front of detector will induce beam backgrounds

- These backgrounds need to be understood, quantified and taken into account in the detector design
- The MDI plays a central role in reducing beam-induced backgrounds before they reach the detector



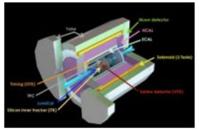
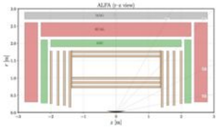
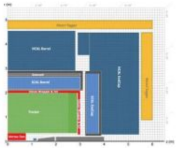
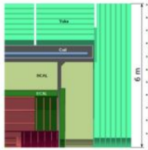
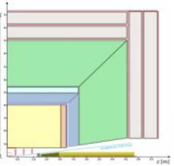
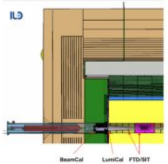




Detector concepts

Several detector concepts under study

- Different geometries and technologies used → response to beam backgrounds can be very different
- Integration with MDI: specific aspects to be studied, beam-background impacts must be assessed for all concepts
    - Ideally, utilize the same MDI design elements as much as possible
- Digitization and readout is important for realistic occupancy studies, data-rate estimates, readout architectures
- Magnetic field: solenoid baseline 2 T, efforts in going to 3 T (allowing for more compact tracking volumes)
- Requires close involvement of detector and sub-detector experts

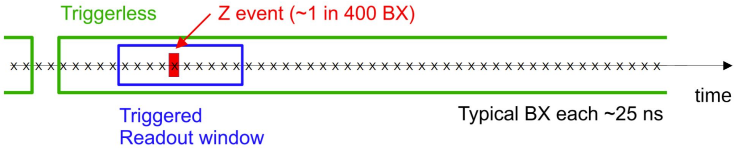
	AGORA	ALFA	ALLEGRO	CLD	IDEA	ILD
Vertex	MAPS	MAPS	MAPS	MAPS	MAPS	MAPS
Tracker	Si+TPC	MAPS	DCH/Straw/SciFi	Silicon	DCH	Si+TPC
ECAL	Crystals	Grainita	LAr	Si+W	DR-Crystals	Si+W
HCAL	Fe+Scint	DR Fibre	Fe+Scint	Fe+Scint	DR Fibre+Fe	Fe+Scint
Muon	Scint	TBD	RPC	RPC	µRWell	Scint

Why study beam backgrounds?

Impact on detector design and MDI

- Detectors have to cope with large fluxes of beam-backgrounds
- Optimization of the MDI layout, shielding, segmentation, detector solenoid
- Power deposition on these elements for design and cooling, collimators, masks (including dose and radiation levels)

Impact on detector readout and trigger strategy



- Dominant beam backgrounds happen every bunch crossing ~ 40 MHz
- Physics events only happen 1 in 400 BX
- Need to estimate the size and nature of these “empty” events → trigger, continuous readout or streaming?
- Occupancy in detectors drives the readout segmentation
- On-chip suppression of beam backgrounds

Impact on physics

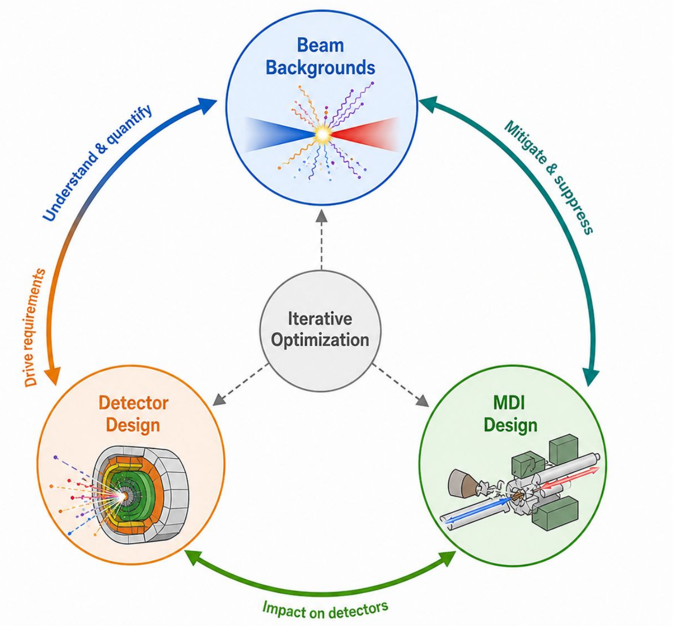
- Beam backgrounds manifest (mostly) as low energy particles, hits in detector elements, reconstruction possible?
- Enhancement of fake rates and hit overlap, degrading potentially detector performance (suppression techniques necessary)
- Need to properly overlay most important beam backgrounds and estimate the effect on the physics

How to tackle these questions for FCC-ee?

Reference Design Phase (2028): establish a viable MDI concept and demonstrate detector compatibility

The work spans several domains

- Characterize the source and reduce beam-induced backgrounds
  → accelerator/lattice dependent
- Optimize the interaction region and MDI to suppress backgrounds
- Quantify the impact on detectors, occupancies and data readout



This is inherently an iterative process with a tight schedule

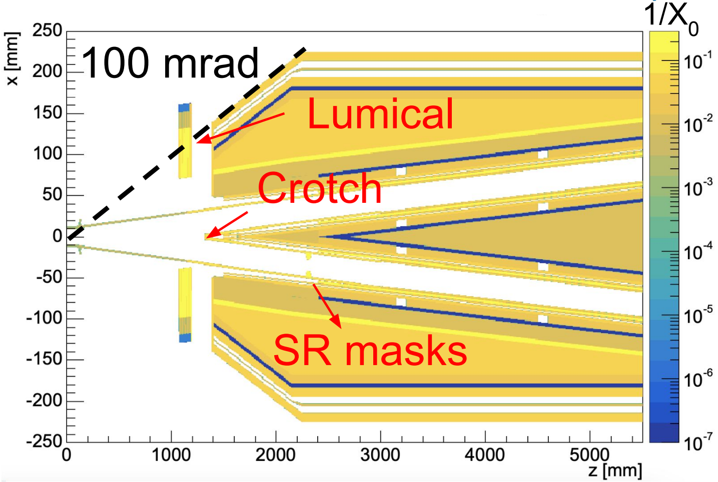
- Beam backgrounds ↔ MDI ↔ detector performance are tightly coupled
- Fast turnaround and validation workflows are essential
- *Requires close collaboration between accelerator, MDI and detector experts*

Simulation of the MDI region

Contributions from J.Seeman/S.Gessner (SLAC)

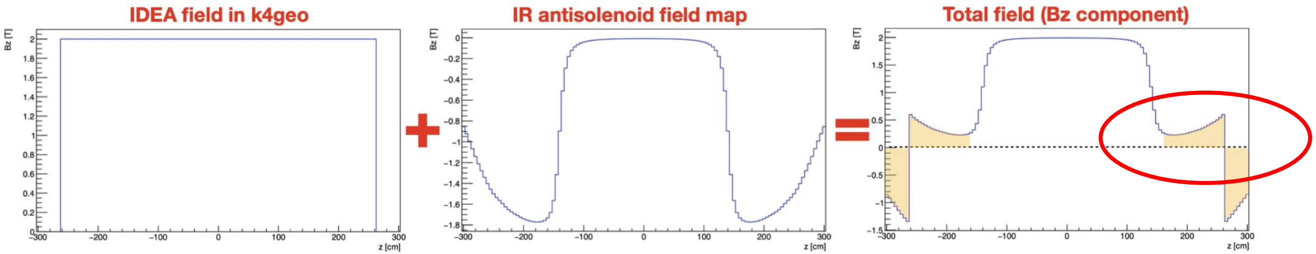
Detailed modeling of the important MDI elements in Geant4

- Central beam pipe and conical evolution towards 2 beam pipes + crotch
- Materials: shielding, collimators, masks, services, mechanics
- Cryostat for compensating and screening solenoids, magnetic fields
- Custom steering file for detailed processes and accuracies



Current status of the simulation

- Full CAD-based model in place
  - Cryostat model consistent with the 100 mrad acceptance
  - Quadrupoles and two SR masks implemented for L* = 2.4 m
  - Anti-solenoid optimization still ongoing + detector dependency → crucial for propagation of low-energy forward particles
- Towards shape-based design: more flexibility, faster can CAD model (modeling of special conical shapes, crotch and masks challenging in Geant4)



Brett Parker (BNL)

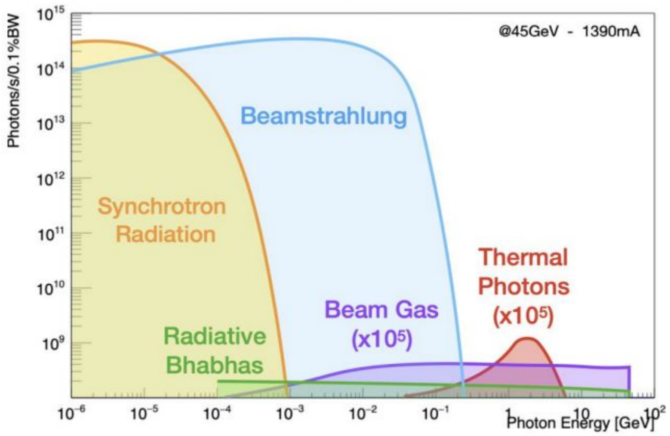
Sources of beam induced backgrounds

Beam induced backgrounds can be classified as follows

- Single beam induced: from the electron and positron beams
- Luminosity backgrounds: processes due to beam-beam interactions

Largest backgrounds expected at the Z pole

- Highest luminosity and tightest bunch spacing
- TTbar also to be studied, mostly for higher expected synchrotron radiation
- Other energies (WW, ZH) will be bound by the Z and TTbar results



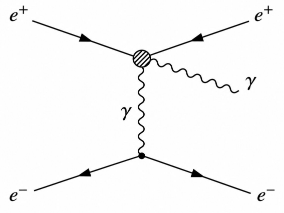
Ideally, reduce all sources of backgrounds to the “irreducible” luminosity background levels

- Single beam induced can mostly be mitigated with collimators and shielding, except for those produced just in the IR
- Appropriate design of the MDI, materials, beam pipe, shielding

Typically considered beam equilibrium parameters for their estimation, but should not restrict to that

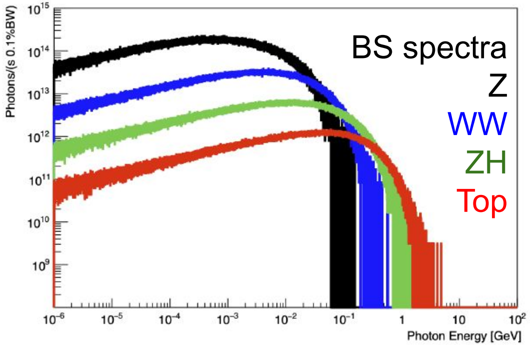
- Also need to study non-equilibrium (multi-turn effects)
- Injection backgrounds (top-up): losses and failures
- Misalignment scenarios giving asymmetric impacts on the detector
- Beam instabilities

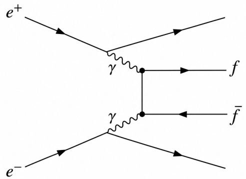
Luminosity backgrounds



Several processes considered

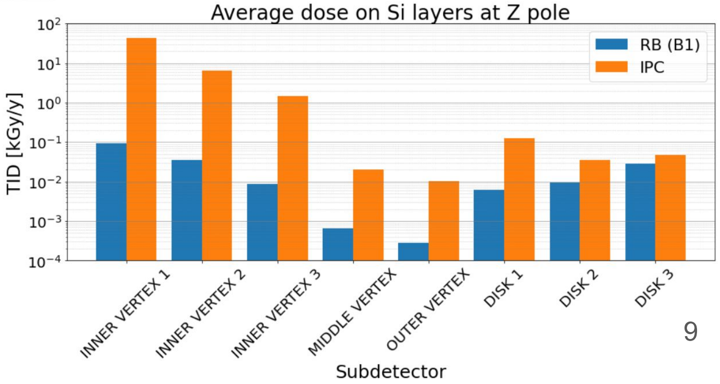
- Incoherent Pair Creation (IPC) – next slides
- Radiative Bhabha (RB): forward e^+e^- can cause forward showers (BBBREM+GuineaPig)
- Beamstrahlung (BS) (GuineaPig)
    - Synchrotron radiation due to EM field of the opposing beam
    - Mostly collinear with beams, limited impact at IR
    - But O(100 kW) to be evacuated in dedicated BS dum
- Two-photon backgrounds (hadrons, muons)
    - Less impact on detector occupancy
    - More impact as background for physics





Studies consistently indicate that IPC is the dominant beam-induced background in the central detector

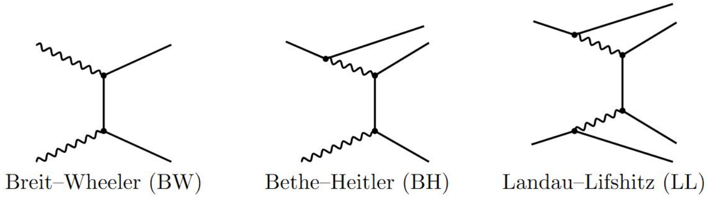
- Dose calculations on inner vertex layer show highest contribution from IPCs compared to RB
- RB becomes more important in forward region
- Nevertheless *all* processes should be studied



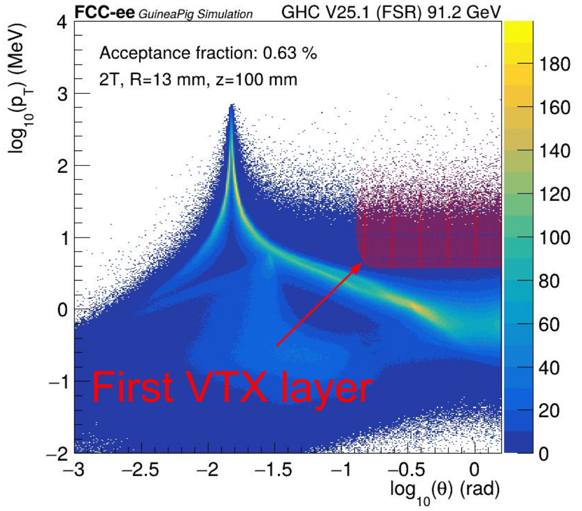
Incoherent Pair Creation (IPC)

IPCs are a dominant background in the luminous region

- 3 main production processes depending on photon virtuality
  - Real-real, real-virtual or virtual-virtual
  - Virtual-virtual (LL) most dominant at FCC-ee
- Cross-section ~20 mbarn (!)
- Manifest as low p_T electrons and positrons, penetrating the beam pipe to the detector
- Source of high occupancies in the vertex detector



1% 15% 84%



Available generators and tools for IPC simulation

- CAIN (80's): not maintained anymore
- Guinea-Pig (90's): commonly known and considered state-of-the-art
- WarpX (> 20's): new modern tool, fast (GPU) → the future
- ML-based tools (Deeffusion) to generate events from known samples → faster

GuineaPig generator and recent implementations

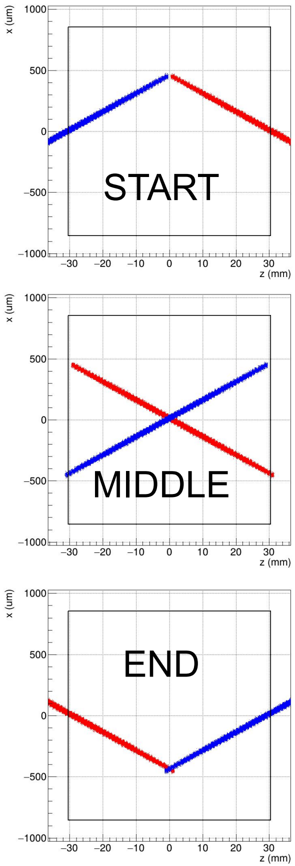
Discrete simulation of beam-beam interaction

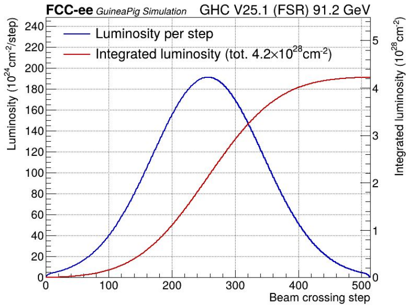
- Important and validated that Guinea-Pig is able to reproduce tabulated luminosities within 5-10%

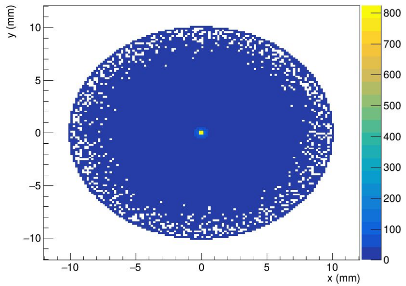
Originally developed for linear colliders, adapted to FCC-ee environment

- Stop IPC transport at the inner beam-pipe radius → clean handoff to Geant4
- Detector-solenoid field included during IPC propagation
- Particle creation and arrival-time information retained
- EDM4hep ROOT output + metadata (replacing the legacy *.pairs* format)
- Scaling of IPC production per run, storing several events in the ROOT format

Porting GuineaPig to GPU? – GuineaPigX see poster D. Ntounis (SLAC)







WarpX as generator for beam-induced backgrounds

Modern parallel particle-in-cell (PIC) simulation framework optimized for CPU and GPU architectures

- More than two order-of-magnitude reduction in runtime compared to GuineaPig (single core)
- GPU acceleration enables large-scale parameter scans and background studies

FCC-ee beam-beam capabilities implemented in WarpX

- Crossing-angle geometry and Lorentz transformations
- Crab-waist collision scheme
- Processes: incoherent pair creation (IPC), radiative and elastic Bhabha scattering

More and future features

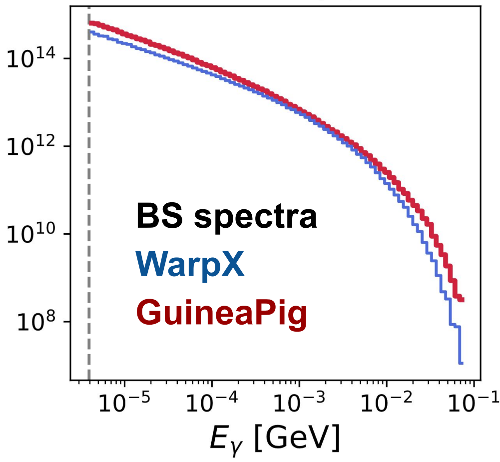
- Coupling to XSuite and multi-turn tracking
    - In this context, study the impact of machine dynamics on beam backgrounds
- Extended Bhabha simulation capabilities
    - Beam lifetime studies
    - Beam-loss and background studies
    - Luminosity monitoring and calibration
- Interface with Geant4 for secondary particle propagation and IR/detector design

See tutorial sessions on Tuesday to explore WarpX capabilities (link)

WarpX benchmarking and performance

Continuous extensive benchmarking against GuineaPig

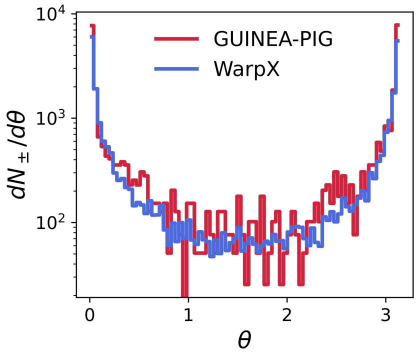
- Beamstrahlung photon spectra reproduced
- IPC kinematics and dynamics validated for all three processes (LL, BH, BW)
- Good agreement observed across key observables

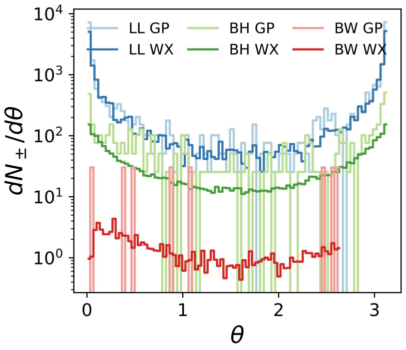


Detector-level performance benchmarking shows good agreement w.r.t. GuineaPig

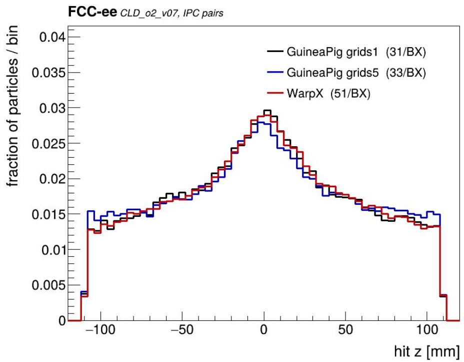
See poster sessions for detailed comparisons:

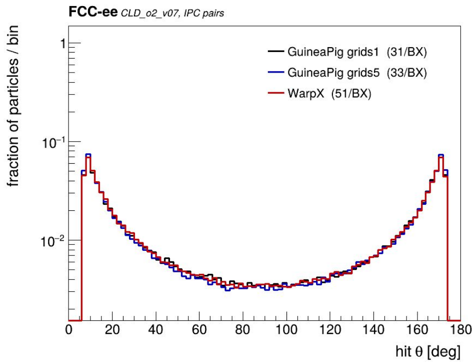
- Anna Kinderman (SLAC) and Katie Kudela (MIT)





Particle level



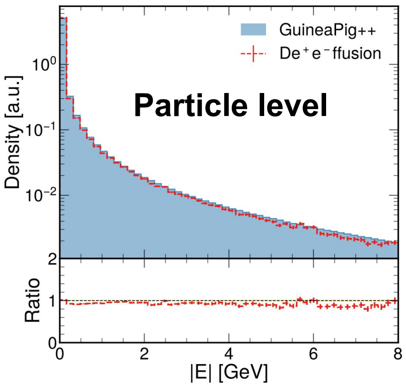


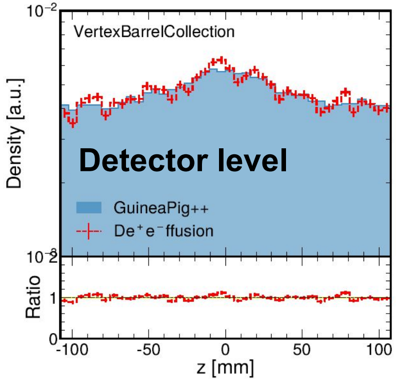
Detector level

Deeffusion: ML surrogate for fast IPC generation

Developed a fast ML surrogate for IPC event generation

- Trained on FSR lattice based on 50k GP events
- Fixed lattice, will be extended to first-order lattice perturbations
- IPC processes taken into account due to different kinematics
- Preserve the detector-relevant physics and correlations



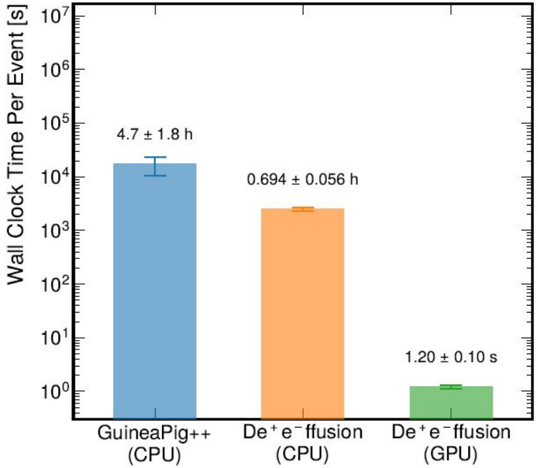


Extensive validation at particle and detector level

- Particle level: kinematics and IPC processes reproduced consistently
- Detector level: Full Geant4 simulation of generated events
- General agreement at the % level

Performance

- Order of magnitude improvement w.r.t. Guinea Pig on CPU
- 4 orders of magnitude faster when running on GPU
- Allows for large and fast generation of beam background samples

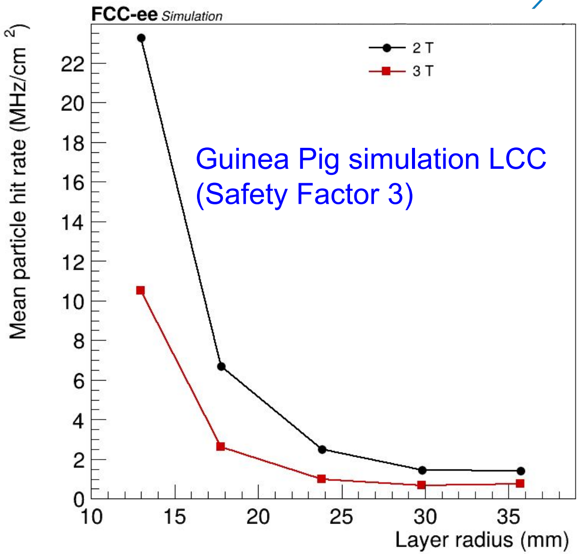


https://arxiv.org/pdf/2607.18512
[SLAC, MIT, Stanford University, FNAL, Brown University, Imperial College]

Particle hit rates from IPCs

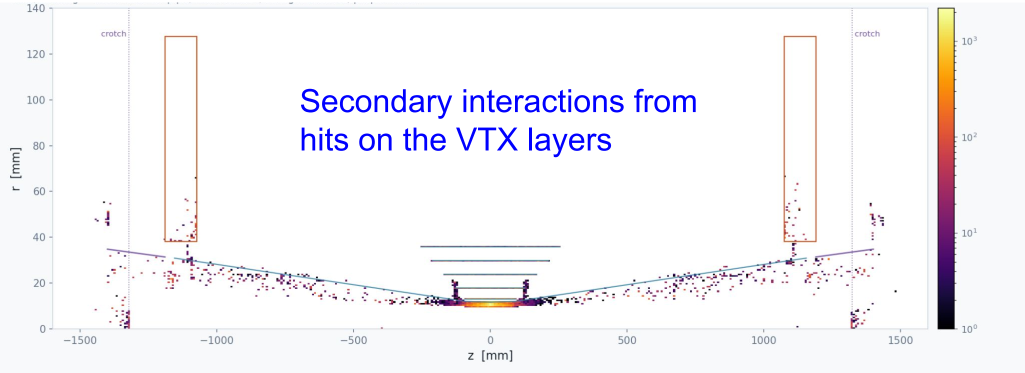
Estimated particle hit rates from IPC on the vertex detector

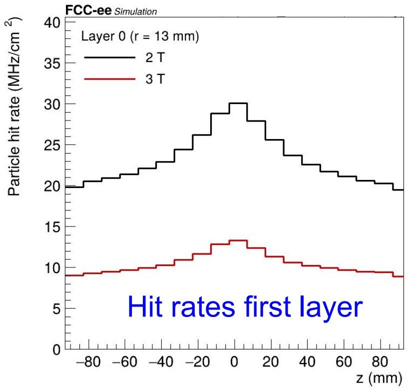
- Count particles crossing idealized 50 μm Si cylindrical layers
- Compare 2 T and 3 T detector magnetic fields
- Apply a safety factor of 3



Innermost vertex layer (r = 13 mm): 20 MHz/cm^2 (affordable!)

- Mostly induced by loopers, particles hitting the same layer multiple times
- Increasing the field from 2 T to 3 T reduces the rate by about a factor of 2
- Most vertex hits directly from the IP, with particles traversing the beam pipe
- Forward/endcap disks have significantly lower hit rates





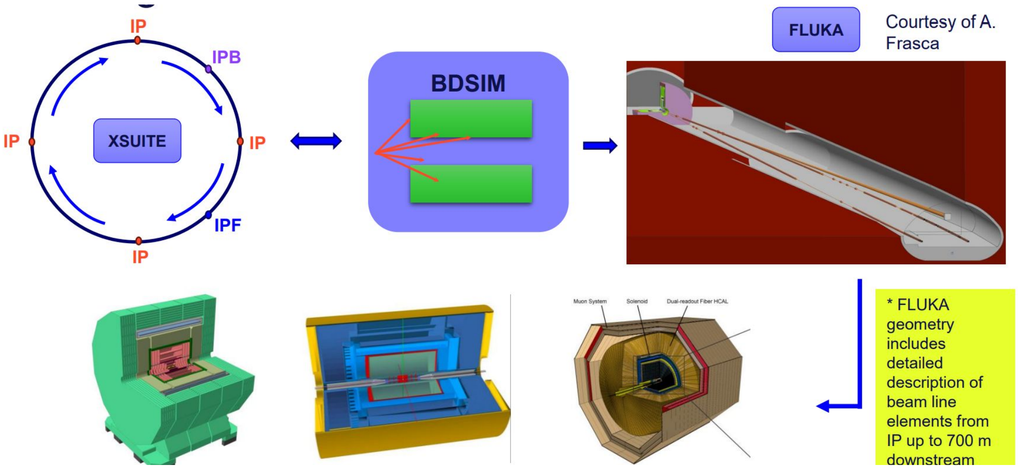
Single beam induced backgrounds

Processes

- Synchrotron Radiation
- Collimation backgrounds – interactions near SR collimators may give rise to secondary showers
- Beam gas scattering, beam halo losses
- Injection backgrounds
- Beam instabilities

Simulation workflow

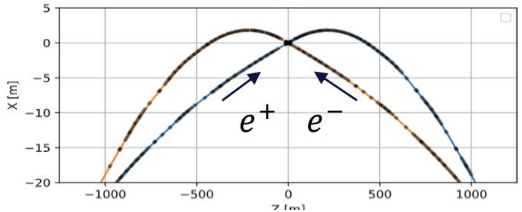
- XSUITE: accelerator simulation (multi-turn)
- BDSIM: particle-matter interaction (Geant4 based)
- FLUKA: particle transport and depositions
- Detector simulation (Geant4 based)



Many of these particle sources affect directly machine elements

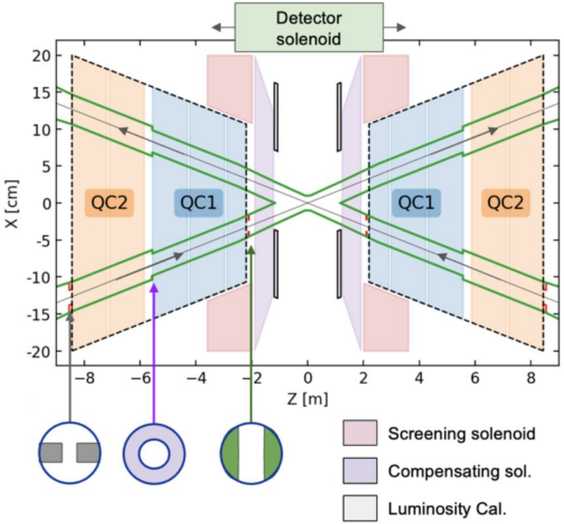
- Studies ongoing to quantify effects and power depositions
- At IR, can be mostly mitigated with collimators and shielding
- Except for those produced just in the IR, which can give rise to backgrounds in the detector

Synchrotron Radiation

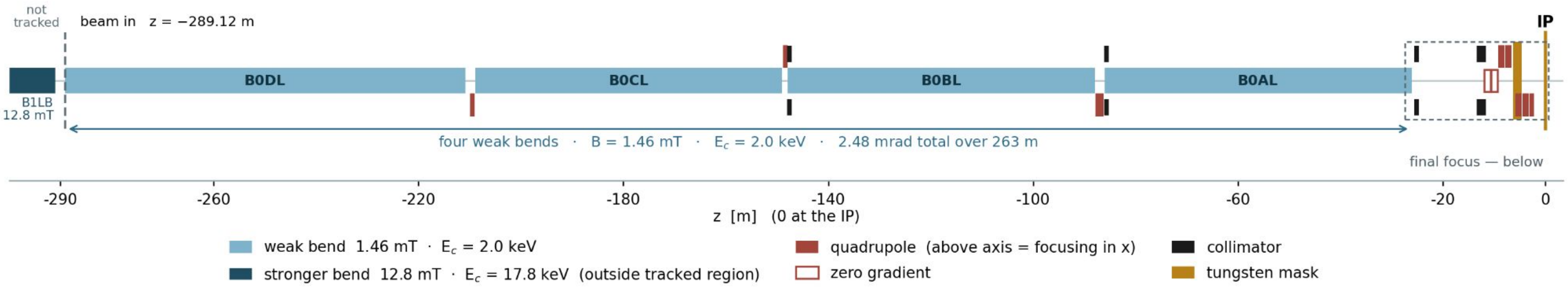


SR produced in the IR by quadrupoles and solenoids

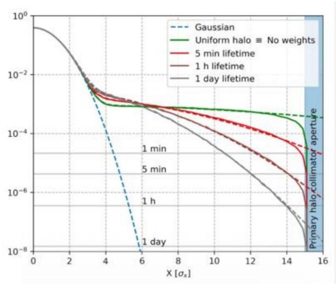
- Incoming beam trajectory is kept essentially straight for more than 100 m before the IP (closest bending magnet is more than 100 m from the IP)
- Bulk of SR is collinear with the beam, will hit the beam pipe at the first dipole after the IP → no direct hits in the detectors; residual SR can be intercepted by masks and collimators
- Transverse tails in the fringing field of focusing magnets (QC) *inside the detector* produce SR that may hit the detector



SR backgrounds depend critically on beam parameters, magnet configurations, geometry of beam pipe and materials used

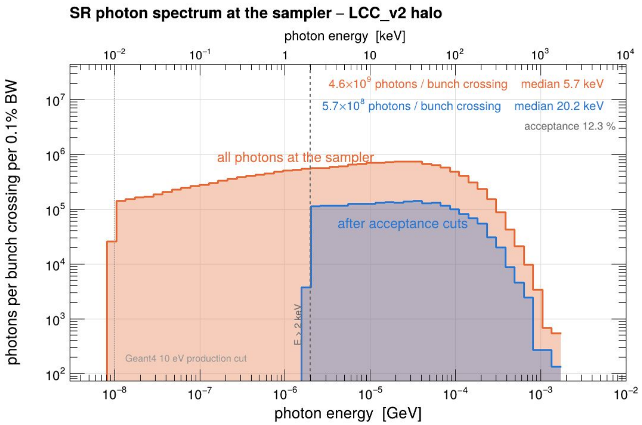


Simulation of Synchrotron Radiation



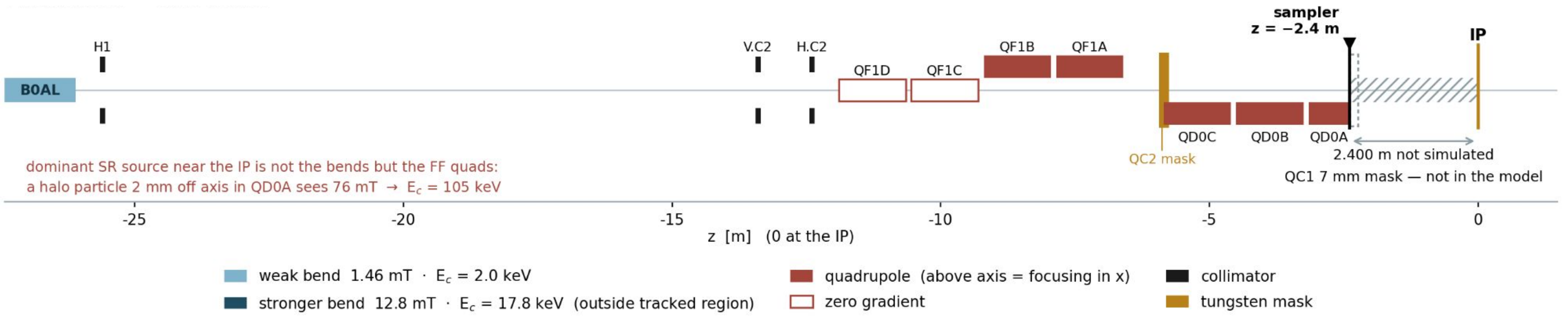
Simulation with BDSIM (Geant4-based toolkit)

- Track single positron beam from first strong dipoles upstream (~300m) towards the IP
- Implementation of lattice elements (weak dipoles, collimators, masks, FFQs)
- Sampling of SR photons at L* = 2.4 m (exit of the last FFQ)
- Hand off photons to detector simulation to estimate occupancies



Simulated beam core (Gaussian) and halo/tails (exponential)

- Acceptance cuts to remove collinear and soft photons
- $O(10^8)$ photons produced within acceptance
- Dominated by relatively soft photons in the keV–MeV range



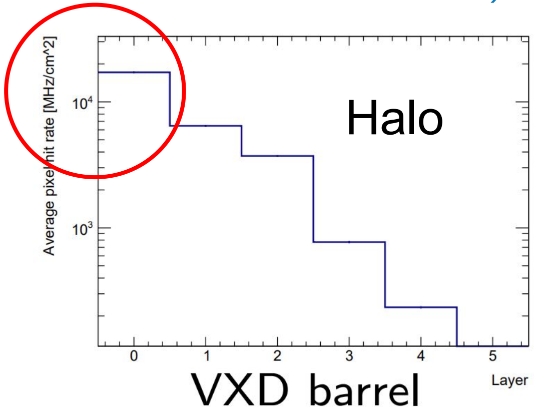
Impact on vertex detectors

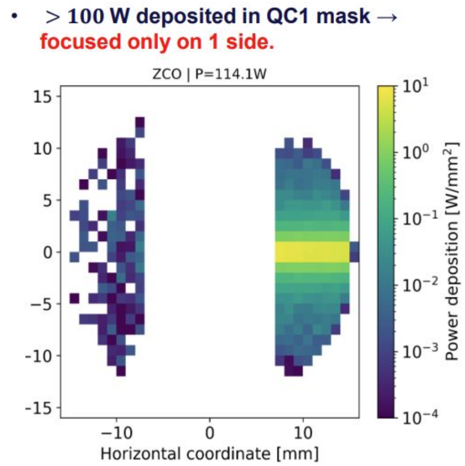
SR photons propagated through the detector simulation

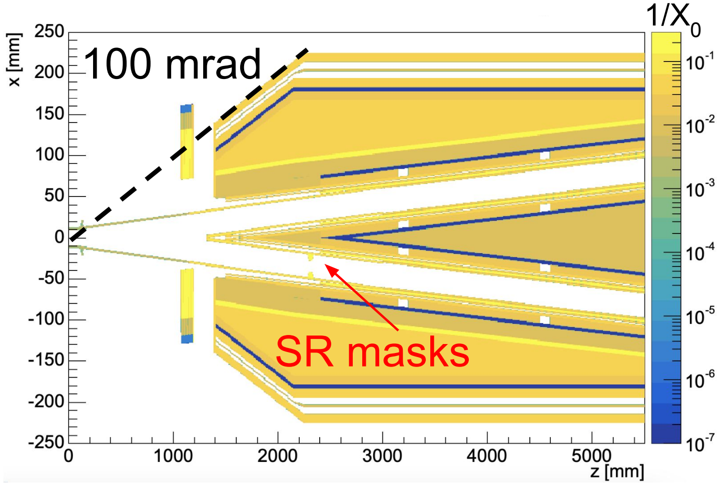
- Two SR masks in place, gold coating on inner beam pipe
- Preliminary estimates O(GHz/cm2) on first vertex layer

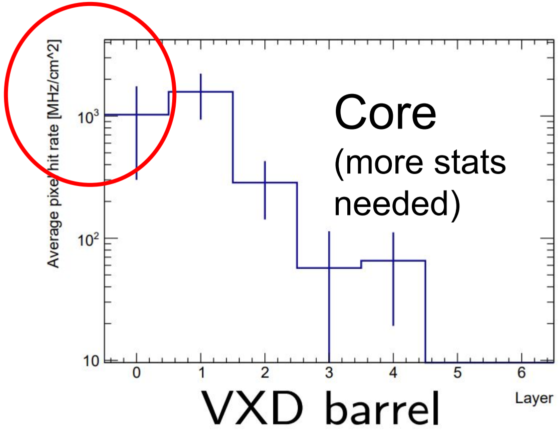
Work ongoing to further suppress the SR radiation using dedicated masks

- Two additional SR masks closer to the IP for further SR suppression
- Need to verify beam impedances, total power deposition on the masks
- For original masks, more than 100 W deposited!





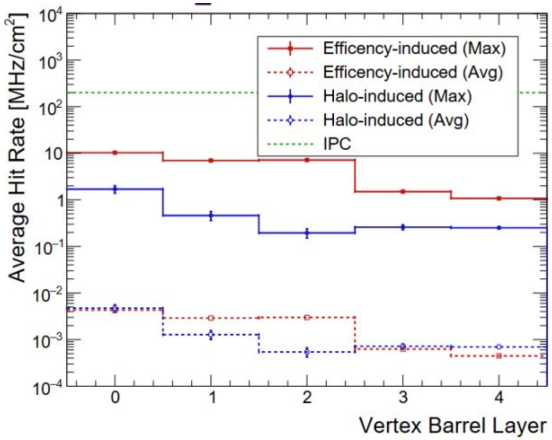




Other single beam backgrounds

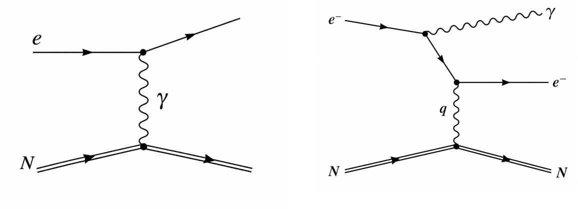
Top-up injection for FCC-ee

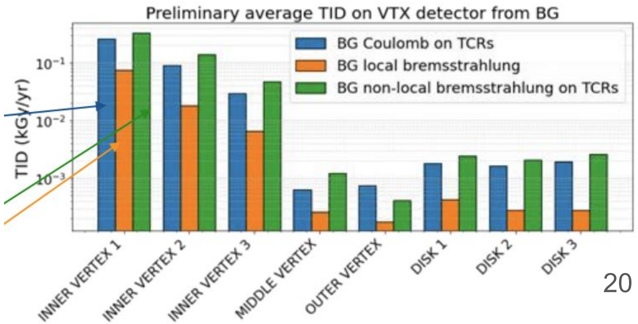
- Injection efficiency ~ 88%, remaining particles are lost during injection
- About 50% of the injected beam halo is scraped near the injection point
- Residual losses are distributed around the ring and can potentially reach IR
- Studied with Xsuite + BDSIM: track particles from injection losses to the IR to estimate detector hit rates
- Expected hit rates in the vertex detector are well below those from IPC



Beam-gas interactions (beam losses)

- Elastic (Coulomb) and inelastic (Bremsstrahlung) scattering
- Simulated with Xsuite + BDSIM, assuming conservative vacuum conditions
- Most scattered particles are intercepted by the collimation system; losses remain within acceptable limits
- Near IR, strongly focusing beam optics (β_y) amplify tiny angular kicks, making Coulomb scattering an important source of local beam losses
    - Impact evaluated through dose calculations in the vertex detector
    - Beam–gas contribution found subleading compared with IPC





Centrally produced background samples (LCC lattice)

Building and improving workflows to evaluate the impact of beam backgrounds on detector

- Requires expertise across accelerator, MDI, detector and computing domains
- Central productions available with sufficient statistics for the main beam-induced backgrounds
  - IPC, synchrotron radiation and collimation backgrounds
  - Additional background sources will follow
- Latest MDI model implemented throughout the production chain
- Generator samples centrally available
- Detector simulation available for the four main detector concepts

Samples and recipes documented
https://hep-fcc.github.io/FCCSW/mdi/

Subscribe to e-group
FCC-PED-SoftwareAndComputing-MDI@cern.ch

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Detector and physics groups are encouraged to use these samples and contribute to the ongoing studies

Background	#BX simulated	# files	Generator size (GB)	Detector sim size (GB)
IPC	20k	20k	10	70
SR halo	2	20k	200	100
SR core	0.067	60k	26	15
Collimation	1	10	1	1

Summary

Overview of beam-background and MDI simulation studies

- Beam-background studies require an **integrated simulation chain**: MDI geometry, background generation, particle transport and detector response, using multiple tools (Geant4, BDSIM, Xsuite, GuineaPig, …)
- **MDI optimization is an iterative process**, with close interplay between machine design and detector performance
- **Incoherent pair creation (IPC)** is the dominant luminosity-related background; several complementary generators and simulation approaches are available
- Ongoing work focuses on **mitigating synchrotron-radiation backgrounds**, in particular through optics, masking and MDI optimization
- Other **sub-dominant beam backgrounds** are being evaluated
- A **central repository of simulated samples and usage recipes** is available to support common studies