Benchmarking WarpX against Guinea-Pig for incoherent pair creation backgrounds at FCC-ee

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Incoherent Pair Creation at the FCC: why and how?

- The Future Circular Collider (FCC) has expected luminosity of 10^{36} cm^{-2} s^{-1} at the Z pole
- The FCC would like to keep everything, with a near triggerless detector readout
- High luminosity produces massive amounts of beam backgrounds which dominant detector occupancy and therefore drive detector design
- We must study Incoherent Pair Creation (IPC), a potential dominant beam background source
- We compare two generators, Guinea-Pig and WarpX

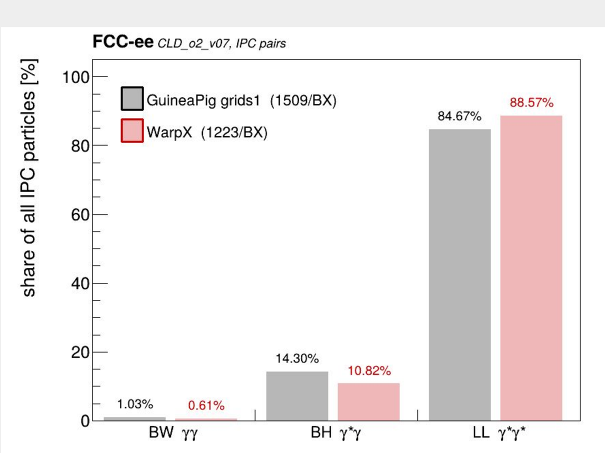
GUINEA-PIG

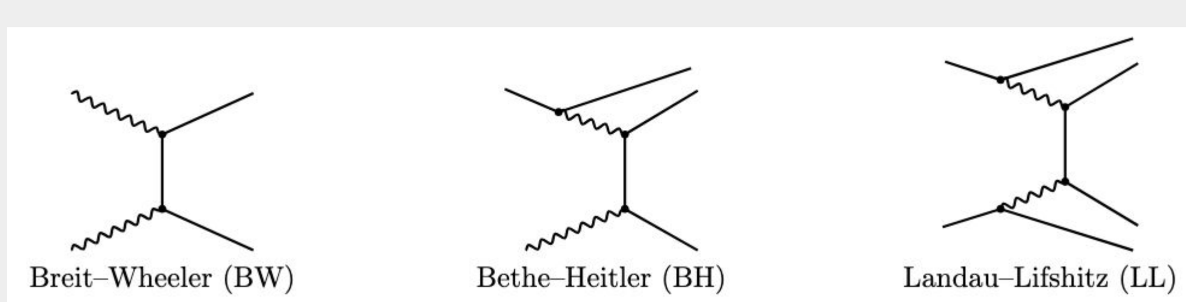
- Purpose-built beam-beam code for collider IPs; the field is solved, the pairs are a by-product
- Bunches are cut into longitudinal slices that are stepped through one another; at each step the transverse charge density of a slice pair is deposited on a 2D grid and Poisson-solved by FFT
- Several grids share the same cell count (ex. 128 × 128) but each covers a progressively larger area
  - Fine cells where the beam core is, coarse cells out in the tails
  - Grid1 = innermost grid only; Grid5 = five nested layers

WARPX

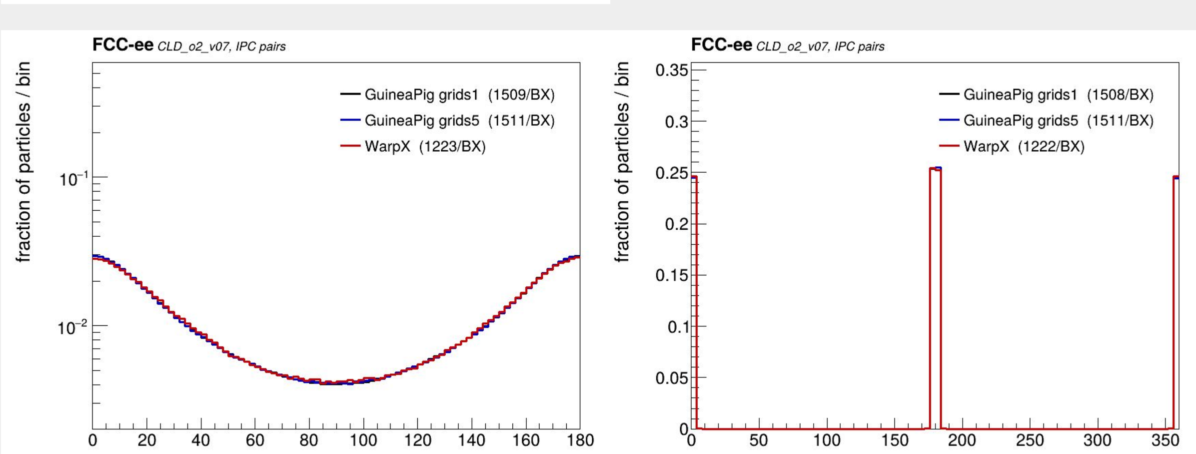
- General-purpose particle-in-cell code (AMReX), GPU-native and massively parallel
- One uniform 3D Cartesian grid; beams are macroparticles pushed through it with a relativistic electrostatic solver, open boundaries, FFT Poisson on 2D transverse slices
- The grid is the simulation domain, i.e. particles leaving it are absorbed, so the box must be large enough to contain the whole bunch
- Here: 256 × 1024 × 512 cells chosen to match GP's cell sizes (7.44 µm × 26.0 nm × 475 µm), 2 T solenoid

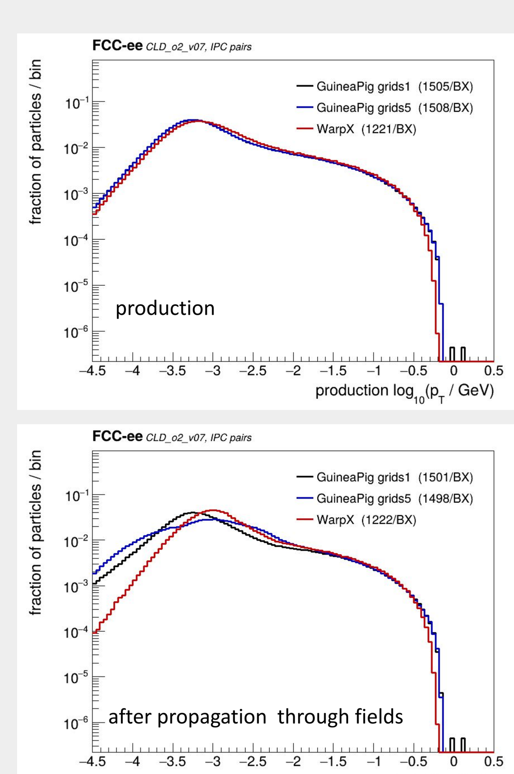
Results on production kinematics





The results for the processes are roughly similar, with WarpX notably producing less BW and BH, and more LL.





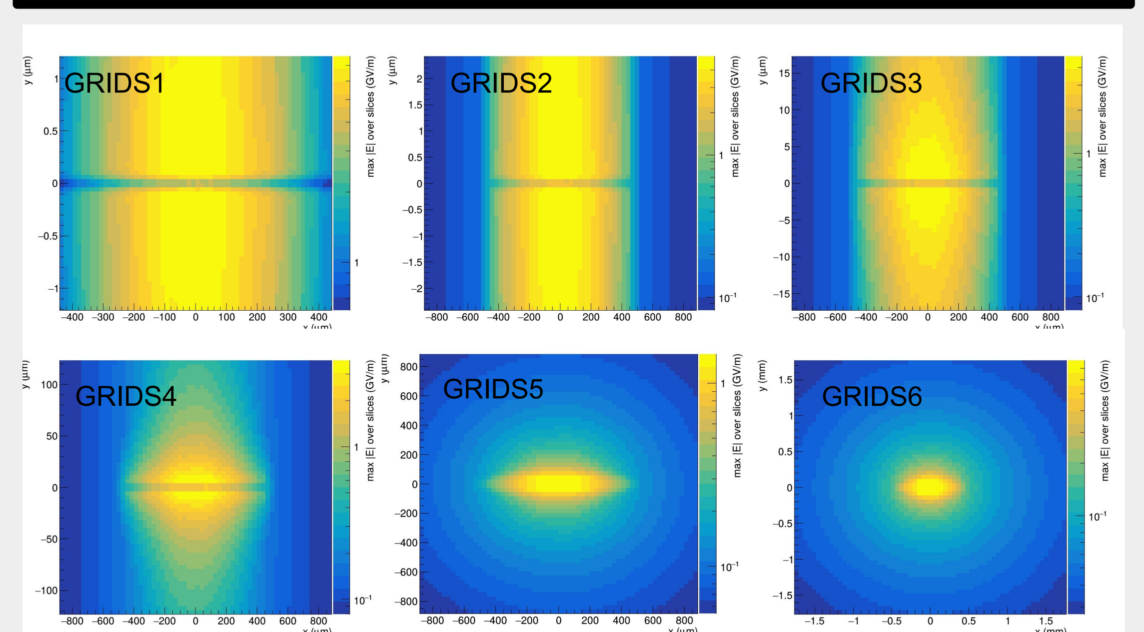
- Production kinematics agree nicely.
- After propagation through the beam fields, we see the IPCs have picked up different amounts of energy from the fields, with WarpX's spectra concentrated slightly more with higher pT pairs

Convergence

GUINEA-PIG Convergence

- In order to properly compare WarpX and Guinea-Pig, we must ensure that all meaningful measureables are first properly converged
- This includes luminosity → number of pairs created as well as the fields
- We need to make sure the grid is large enough so that the IPCs can travel through the beam fields and gain energy

FIELD CONVERGENCE:



- The beam fields themselves, along with the IPCs, stop gaining energy at around 1 mm in radius
- Our final configuration uses Grid5

LUMINOSITY CONVERGENCE:

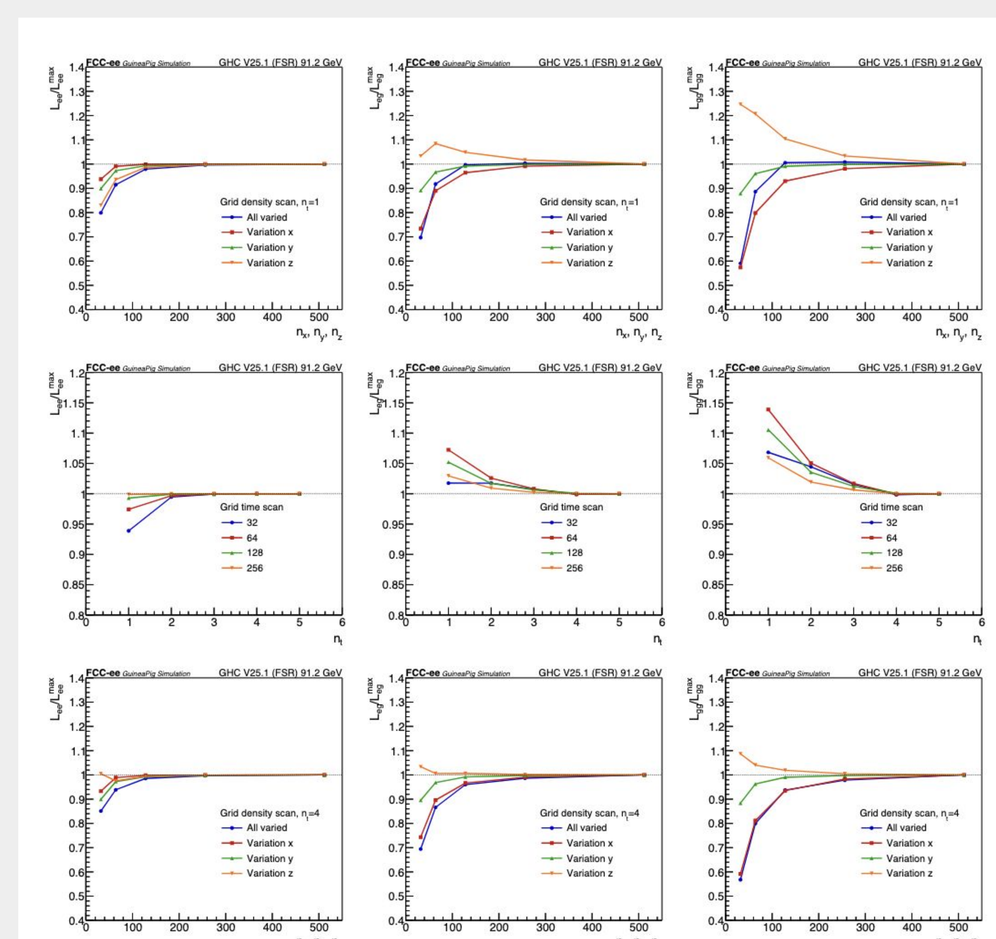
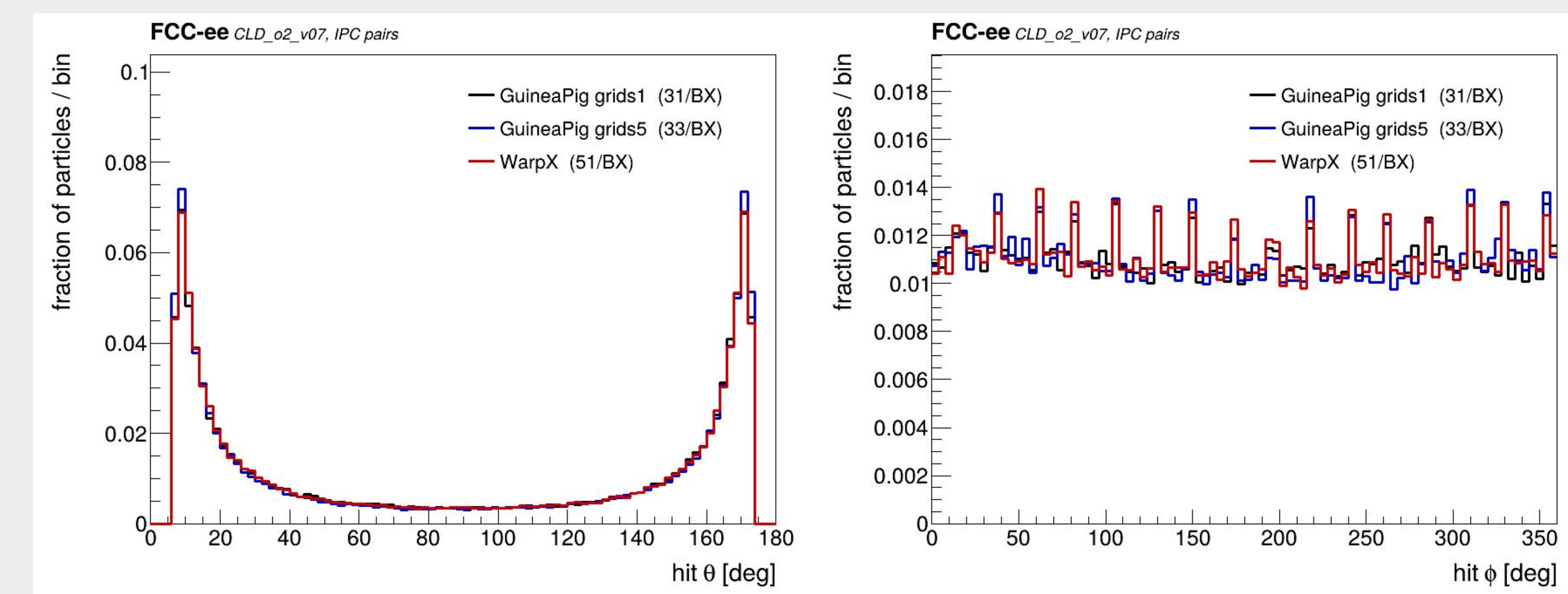


Figure 5: Convergence of the luminosity components $\mathcal{L}_{ee}$ (left column), $\mathcal{L}_{e\gamma}$ (middle column) and $\mathcal{L}_{\gamma\gamma}$ (right column) with respect to the primary-grid parameters, for the FCC-ee Z running point (GHC V25.1). Top row: scan of the number of cells n_x, n_y, n_z (simultaneously and independently, with the respective other dimensions fixed to 256) at fixed grid extent, with a single integration sub-step per slice crossing ($n_t = 1$). Middle row: scan of the number of sub-steps n_t for fixed grid densities. Bottom row: cell scan repeated at the converged $n_t = 4$. All curves are normalized to their finest configuration.

- Luminosity converges with proper nx ny nz nt
- Our final configuration uses nx = ny = nz = 128 and nt = 4

Detector comparison of Guinea-Pig and WarpX

- **From HDF5 to EDM4hep:** WarpX writes its particles as openPMD HDF5, which ddsim cannot read. The converter turns those files into the same ROOT format GuineaPig produces, so both generators feed the detector simulation through an identical path.
- **Un-weighting:** WarpX pairs carry fractional statistical weights, and Geant4 cannot track a fraction of an electron. Each macroparticle is kept with probability equal to its weight, which turns the weighted cloud back into whole particles. No weight exceeds one, so nothing is ever duplicated.



When normalized to unit area, the hitmaps on CLD barrel layer are nicely in agreement!

- Need proper luminosity convergence to compare absolute distributions
- Grid1 and the WarpX configuration lie on top of each other
- Slight difference in Grid5 is visible in the forward region
  - Due to the IPCs gaining energy in the beam fields

We see this slight shape difference due to the simulation grid in WarpX being too small

- But, like we saw in Guinea-Pig convergence studies, we must ensure that the simulation (especially at the interaction point) is fine enough and properly converged

region	n_x	n_y	n_z	cells
WarpX today	256	256	256	1.7×10⁷
±0.5 mm	281	153,850	256	1.1×10¹⁰
±1 mm	561	307,700	256	4.4×10¹⁰

Not feasible!

We must be able to increase the grid size in WarpX while maintaining proper convergence and resolution at the interaction point

- Possible solutions:
  - Layered FFT such as Guinea-Pig
  - Dirichlet solver

Conclusions

- Guinea-Pig and WarpX show promising first results in the agreement of their detector hits
- We must focus on WarpX convergence studies and increasing the simulation volume while maintaining granularity