10 - 14 June FCC WEEK 2024

New simulation tools for beam-beam collisions at the interaction point

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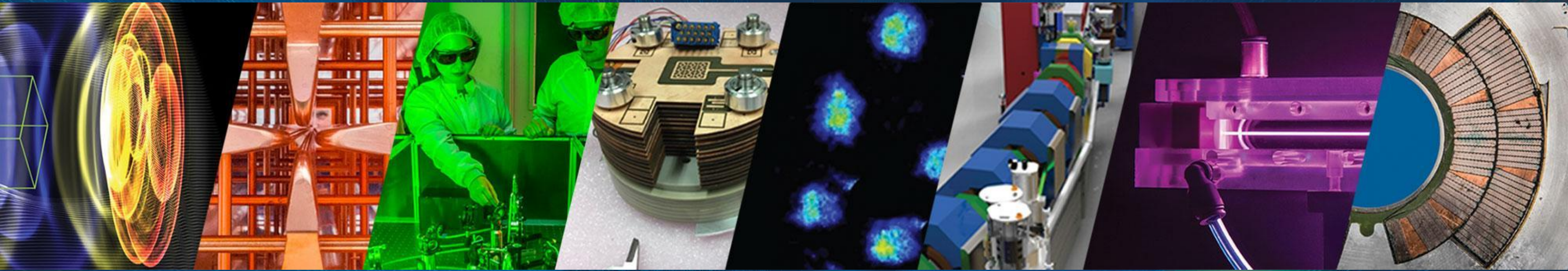

FCC Week 2024
San Francisco, 13th June

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

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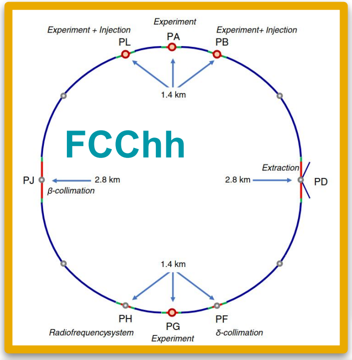
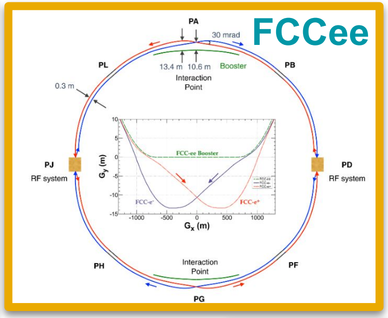
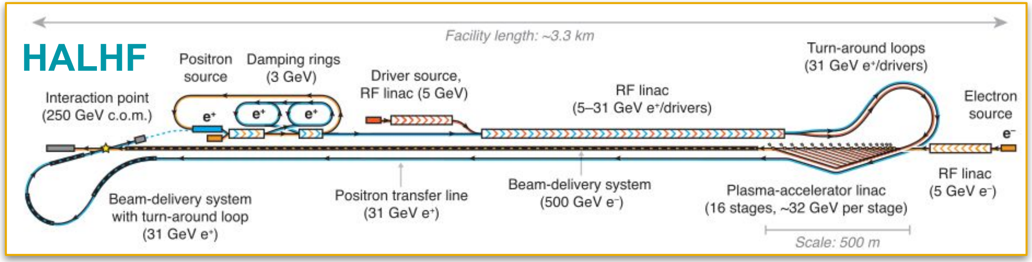
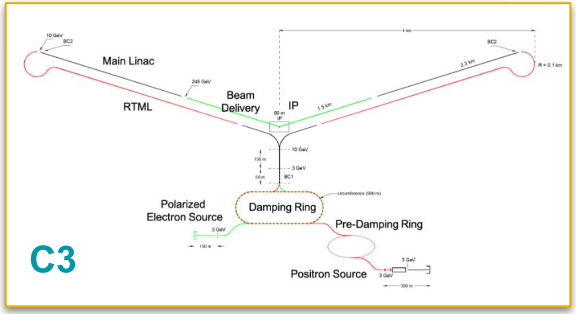
cea

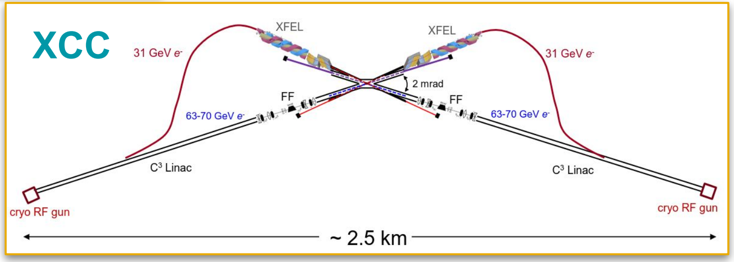
There are many designs & ideas for future Higgs factories and 10 TeV colliders

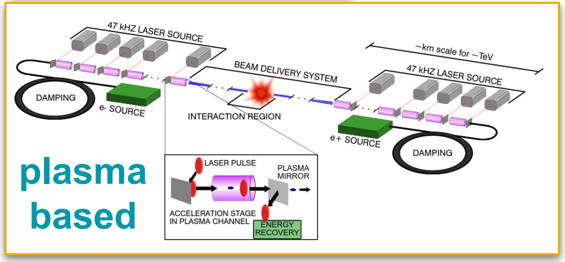


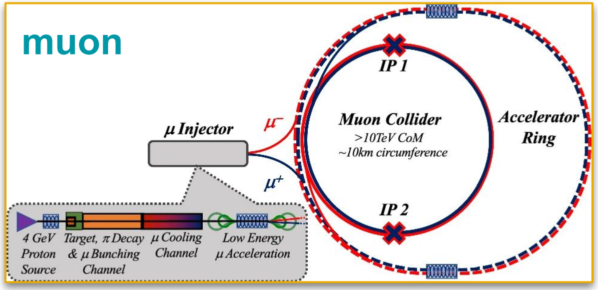


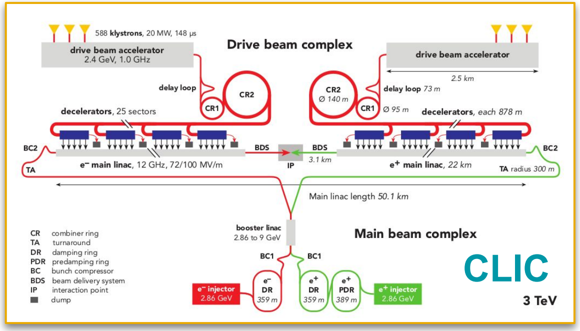


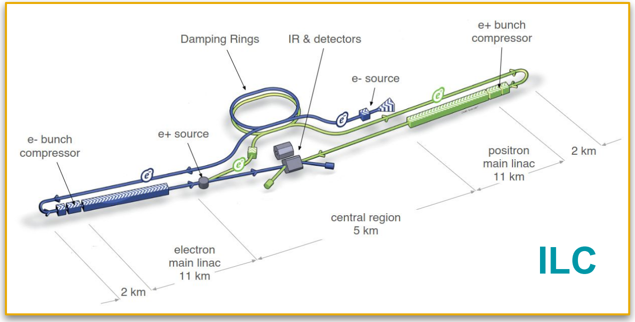




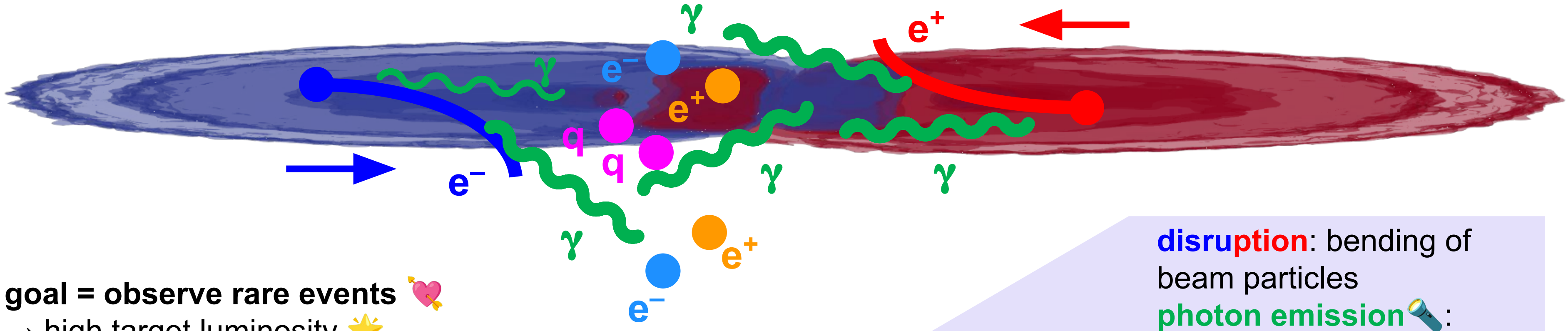




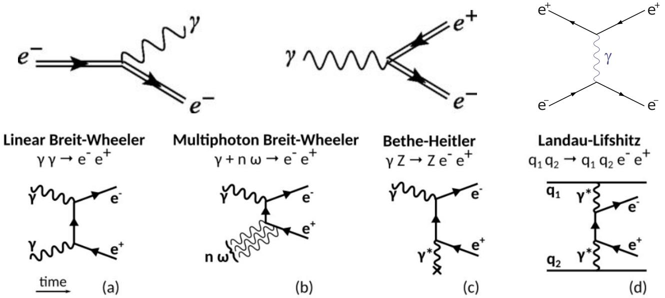




A key challenge is mitigating or embracing beam-beam effects



goal = observe rare events 💘
→ high target luminosity 🌟
→ need to squeeze the beams 🍋
→ very high EM fields 😱
→ **beam-beam effects** 😡**: incoherent & collective**
→ **luminosity different from target value** 😭



💡 accurate modeling to control these effects! 🎯💃

disruption: bending of beam particles

photon emission 🔦:
- beamstrahlung
- bremsstrahlung

pair creation 👯:
- nonlinear Breit-Wheeler
- linear Breit-Wheeler
- Bethe-Heitler
- Landau-Lifshitz

scattering
- Compton
- Bhabha

hadron photoproduction

…

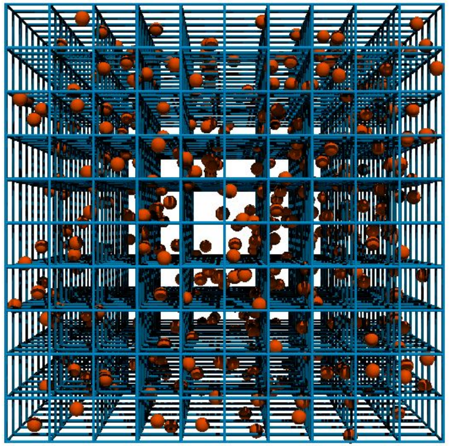
Particle-In-Cell + Monte Carlo simulations are the main modeling tools

ab initio approach

fields on a grid

$$\begin{cases} \nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} = \dfrac{1}{c^2}\dfrac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J} \end{cases}$$

Δt



project current densities on the grid
$\mathbf{x}_p$, $\mathbf{p}_p \rightarrow \mathbf{J}$

interpolate fields at particles' positions
$\mathbf{E}, \mathbf{B} \rightarrow \mathbf{E}_p, \mathbf{B}_p$

QED, ionization, collisions, reactions, …

macroparticles motion

$$\begin{cases} \dfrac{d\mathbf{x}_p}{dt} = \mathbf{v}_p \\ \dfrac{d\mathbf{p}_p}{dt} = q(\mathbf{E}_p + \mathbf{v}_p \times \mathbf{B}_p) \end{cases}$$

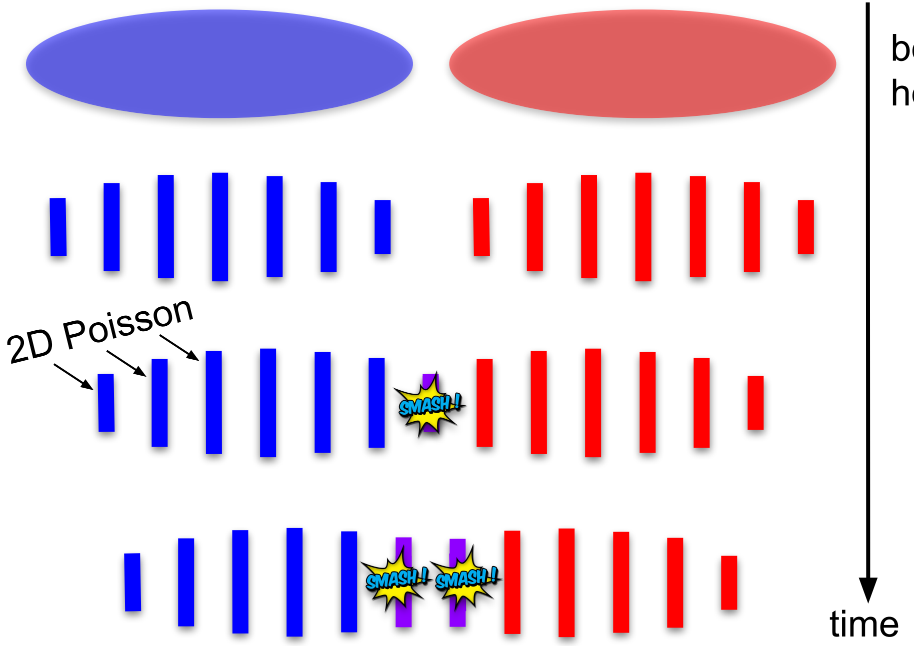
The community needs new tools that can provide long term support and vision

PIC codes specific to strong-strong beam-beam collisions

GUINEA-PIG https://gitlab.cern.ch/clic-software/guinea-pig

CAIN https://github.com/slaclab/CAIN

beams are sliced along z
the slices interact subsequently



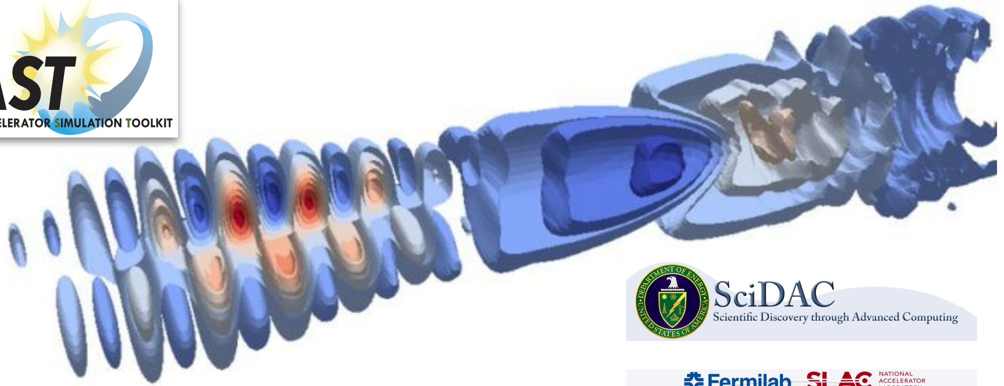
both codes are well-established in the collider community, however:

- serial
- poorly maintained: no active developer
- poorly adaptable: algorithms, initial condition
- limited diagnostics
- **lack of self-consistency** (pair plasmas @ 10 TeV)
- **corrections will be required** (rates of QED at χ>50)

WarpX, part of the BLAST toolkit, is a promising candidate for beam-beam studies

https://ecp-warpx.github.io/

BLAST — BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT



open-source
OS portable: Linux, MacOS, Windows,
GPU portable: NVIDIA, AMD, Intel
multi-platform: multi-CPUs/GPUs
flexible:

- different geometries: 1D, 2D, RZ, 3D
- many algorithms
- many diagnostics
- electromagnetic, electrostatic, magnetostatic

versatile:

- plasma-based accelerators
- RF accelerators
- fusion devices
- laser-plasma interactions
- astrophysics
- …

international, cross-disciplinary & active community!
WELL DOCUMENTED!!!!!!

SciDAC — Scientific Discovery through Advanced Computing

Fermilab · SLAC NATIONAL ACCELERATOR LABORATORY · BERKELEY LAB · CAMPA · UCLA · Argonne NATIONAL LABORATORY · OAK RIDGE National Laboratory

We have a poster about BLAST this evening!

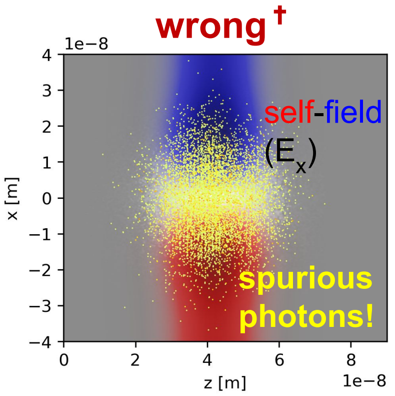
Our main goal: establish WarpX as a next-gen tool in the collider community

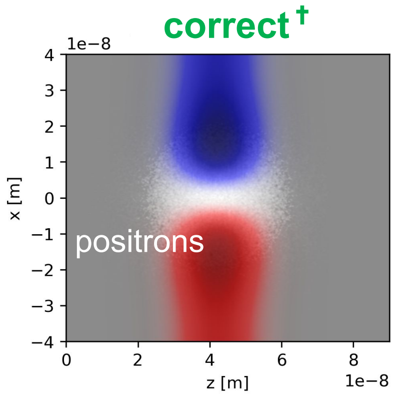
OUTLINE

- numerical challenges ⛰️
- benchmarks ✅
- performances 🏃
- preliminary results
- conclusions & next steps 🏁

The numerical algorithms and resolution matter

single spherical bunch of left-propagating positrons

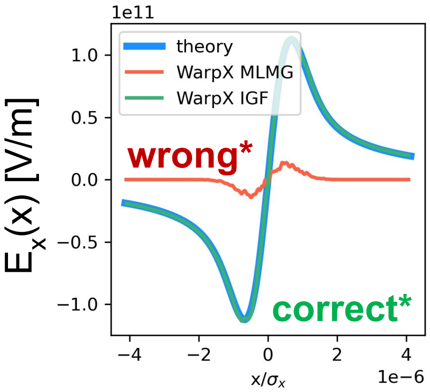


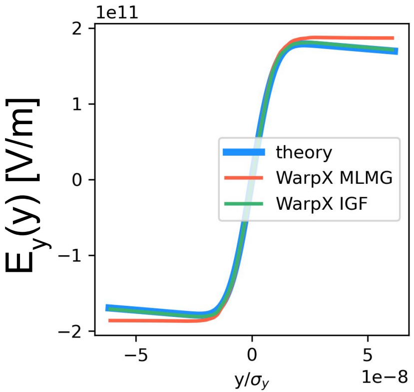


† Yee solver with PEC BCs

† iterative nodal solver with PEC BCs

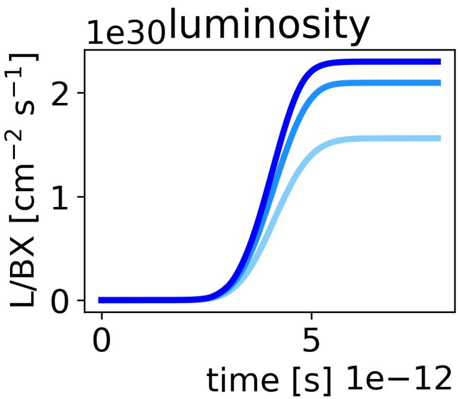
self-field of a flat beam

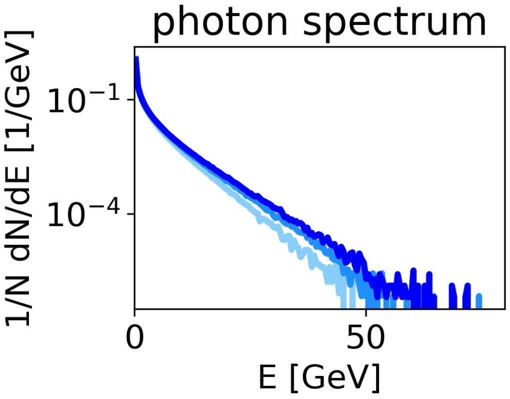




* iterative nodal solver with PEC BCs

* FFT-based solver with open BCs





higher res

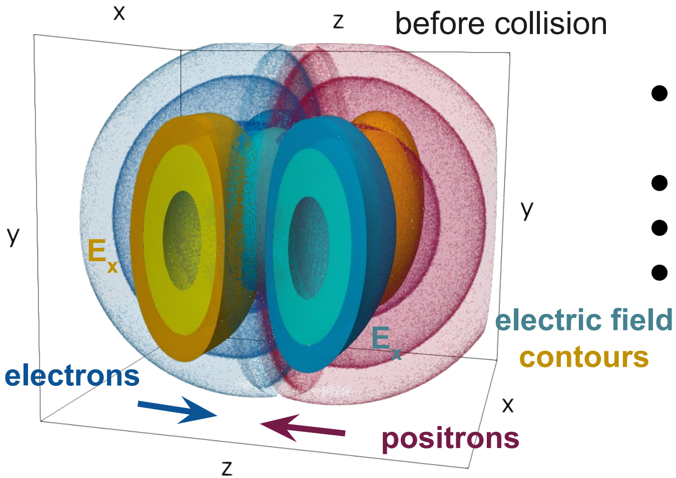
256 x 256 x 512

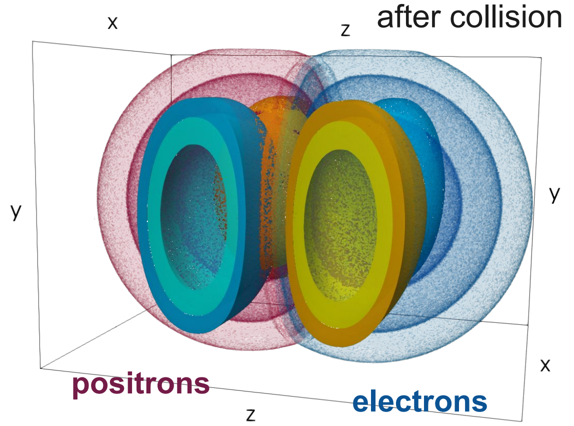
128 x 128 x 256

64 x 64 x 128

lower res

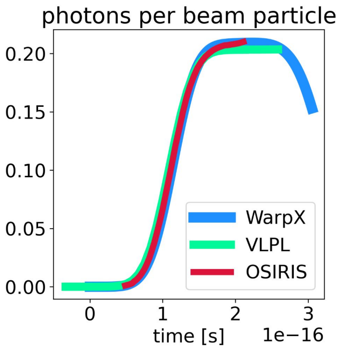
Excellent agreement between several codes with spherical ultra-tight beams

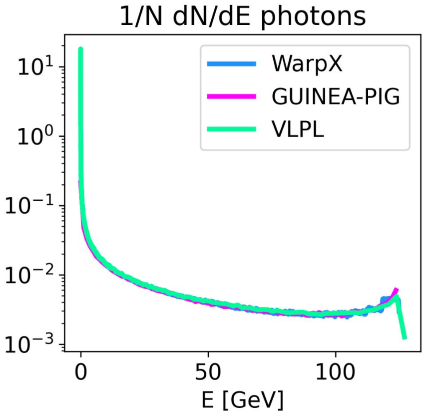


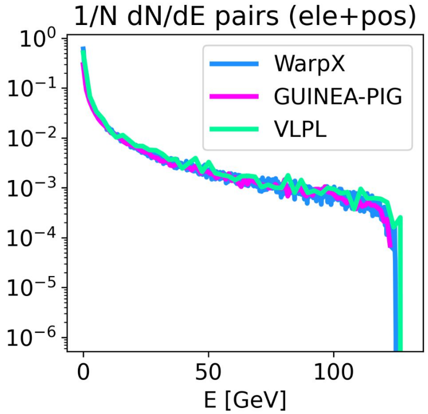


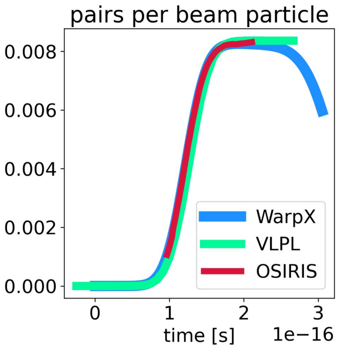
Yakimenko et al. PRL 2019

- main parameters:
  E_{COM} = 250 GeV | N = 8.7 * 10^8 | $\sigma_z = \sigma_x = \sigma_y$ = 10 nm
- significant generation of coherent pairs
- low disruption D = 0.001
- spherical beams → "convenient" for "traditional" PIC simulations since the domain is not stretched (as in flat beams)







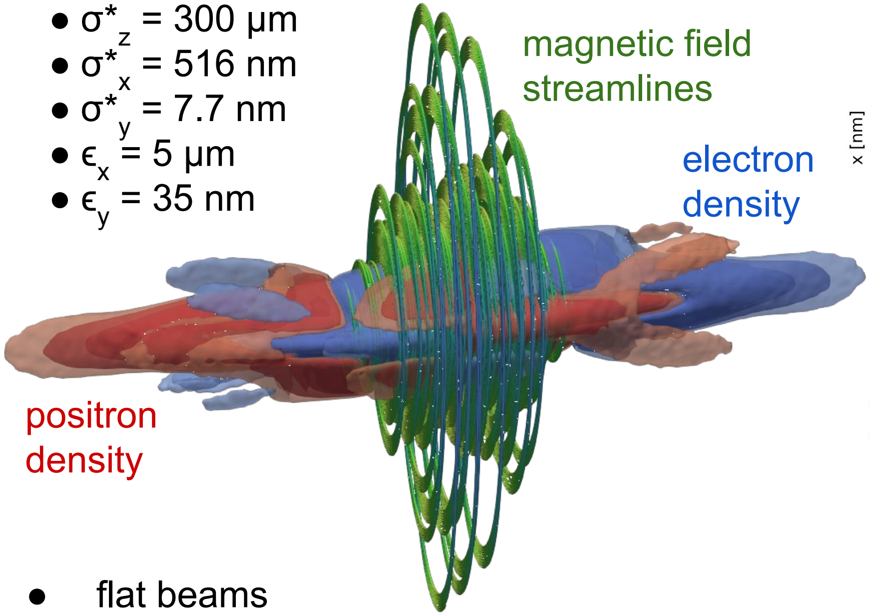


Excellent agreement with flat ILC beams

main parameters

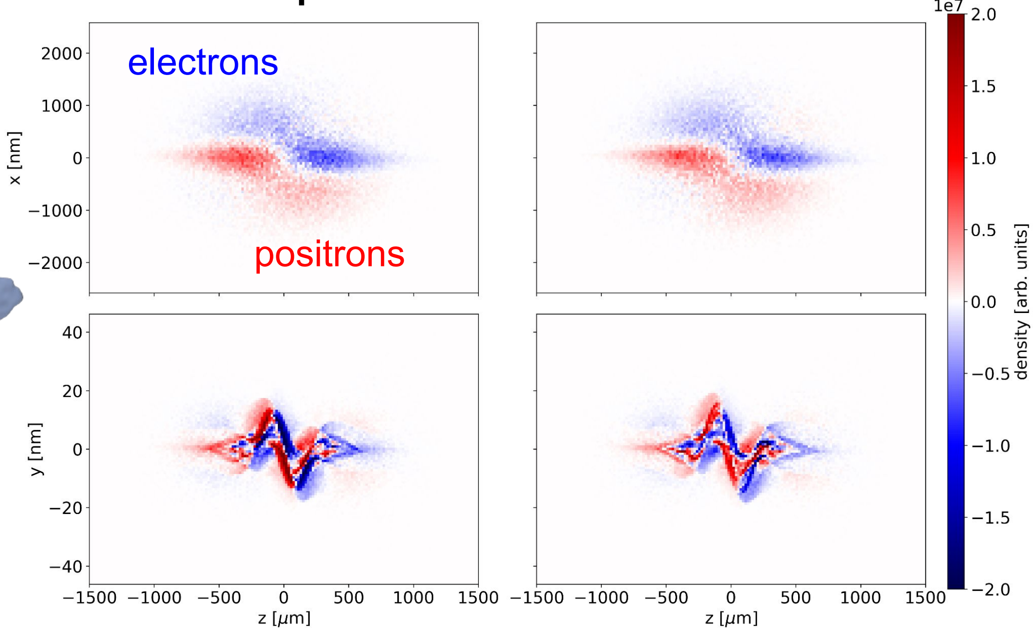
- E_{COM} = 250 GeV
- N = 2 10^{10}
- σ^*_z = 300 μm
- σ^*_x = 516 nm
- σ^*_y = 7.7 nm
- ϵ_x = 5 μm
- ϵ_y = 35 nm

The International Linear Collider: Report to Snowmass 2021



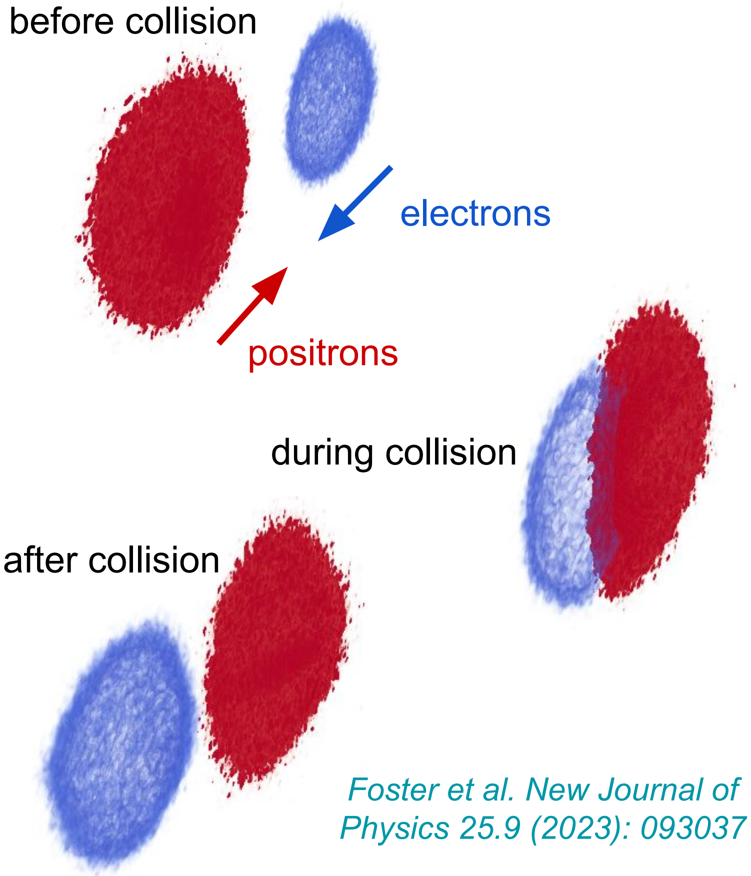
- flat beams
- significant disruption D_x = 0.30, D_y = 24.39
- negligible coherent pairs

snapshot of the beams' ***density integrated along the missing coordinate*** during collision



offsets along x and y ~$\sigma_{x,y}$/10 to induce the kink instability and mitigate stochastic discrepancies

Excellent agreement with flat asymmetric HALHF beams

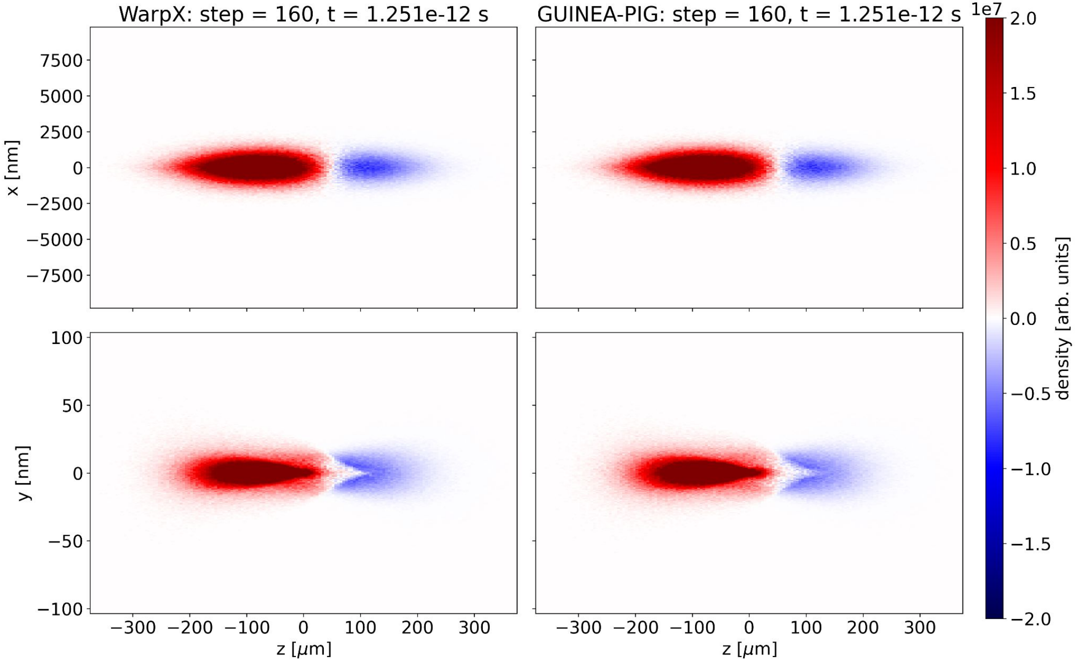


Foster et al. New Journal of Physics 25.9 (2023): 093037

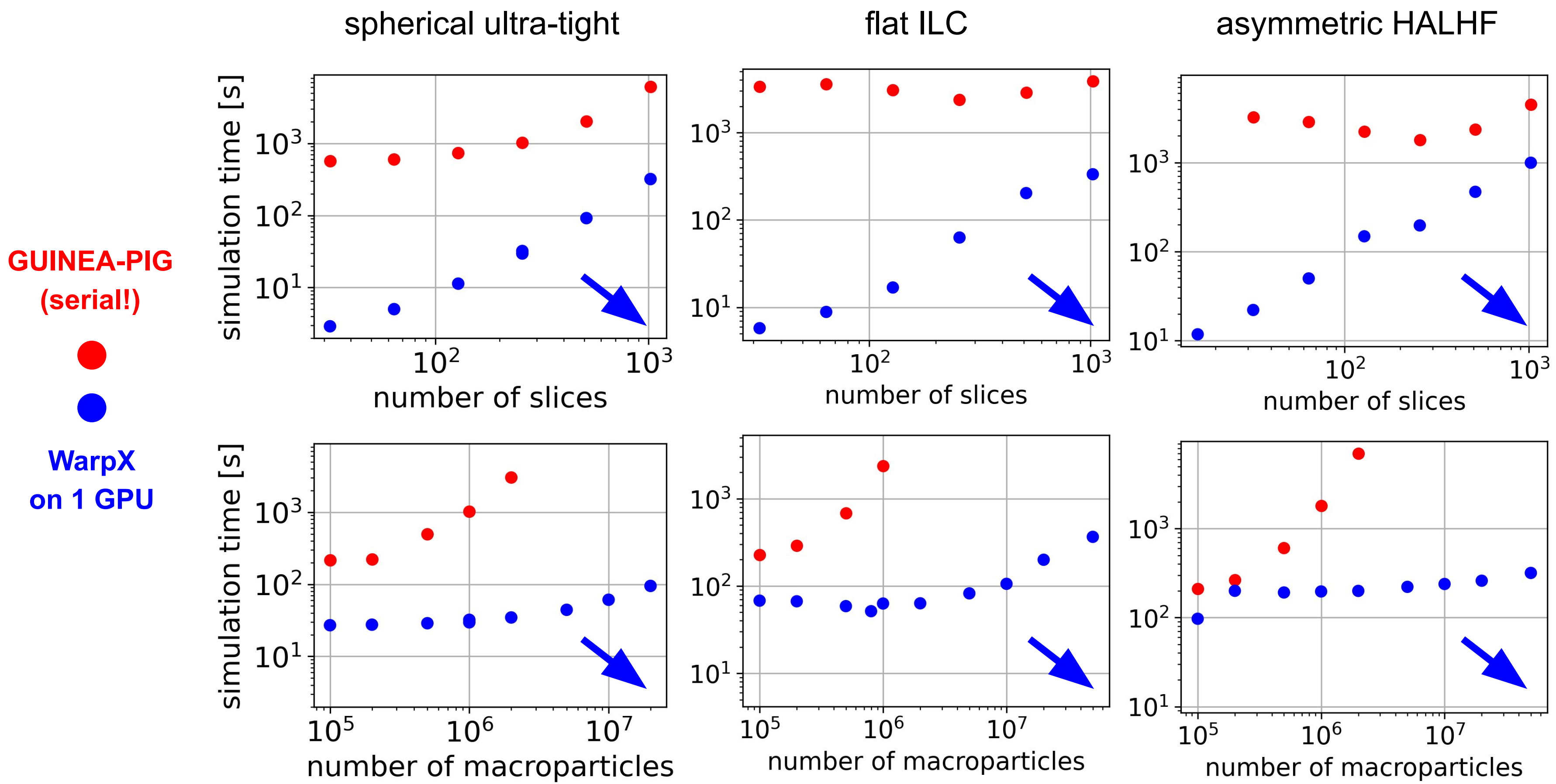
electrons
- E = 500 GeV
- $N = 10^{10}$
- ϵ_x = 160 μm
- ϵ_y = 560 nm

positrons
- E = 31.25 GeV
- $N = 4 \times 10^{10}$
- ϵ_x = 10 μm
- ϵ_y = 35 nm

both
- E_{COM} = 250 GeV
- σ^*_z = 75 μm
- σ^*_x = 729 nm
- σ^*_y = 7.7 nm

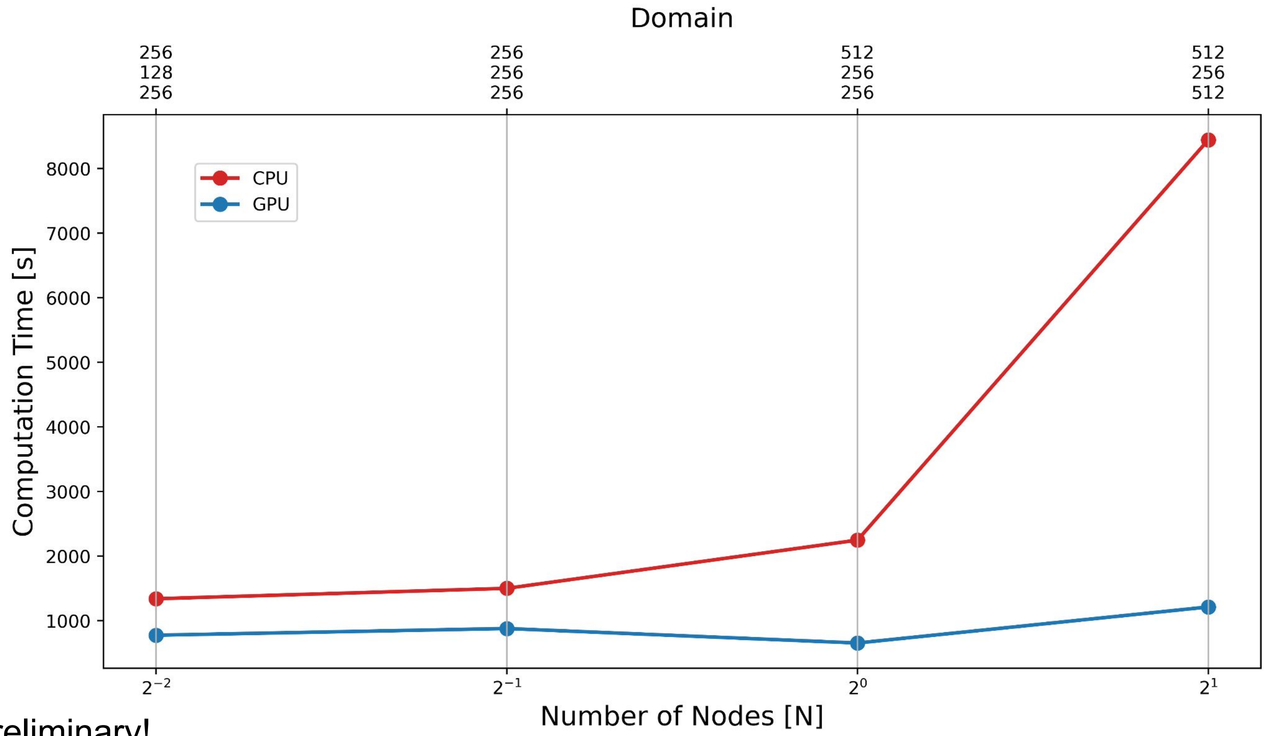


WarpX can be faster and/or go to higher resolution and statistics



We are working to guarantee good performances on multiple GPUs

flat ILC beams on Perlmutter @ NERSC



preliminary!

1 CPU node = 128 cores AMD Milan

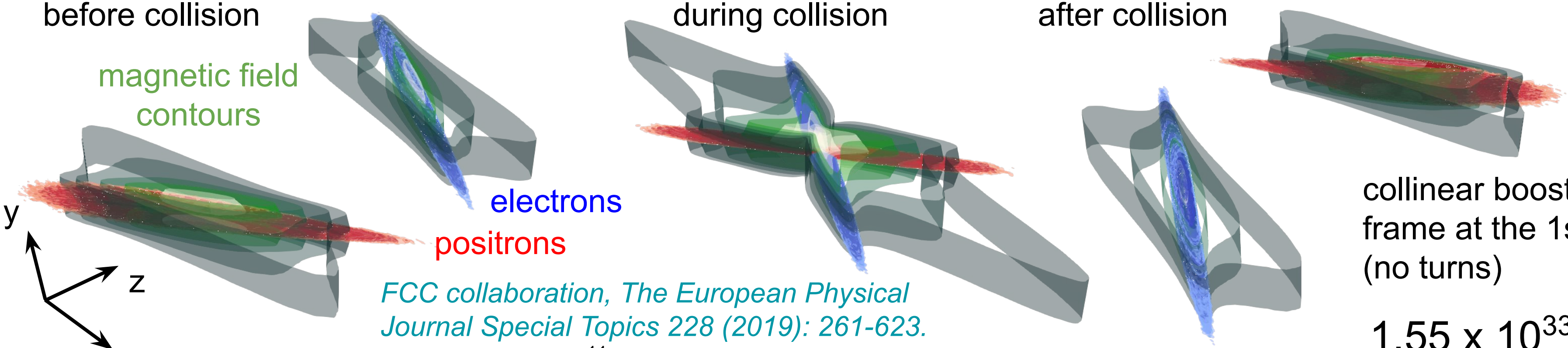
1 GPU node = 4 NVIDIA A100

National Energy Research Scientific Computing Center

heFFTe

Highly Efficient FFTs for Exascale

Preliminary simulations with FCC-ee Z beams & 10 TeV plasma-based beams



FCC collaboration, The European Physical Journal Special Topics 228 (2019): 261-623.

E_{COM} = 45.6 GeV | N = 1.7 * 10^{11} | σ_z = 3.5 mm | σ^*_x = 6.36 μm | σ^*_y = 28.3 nm

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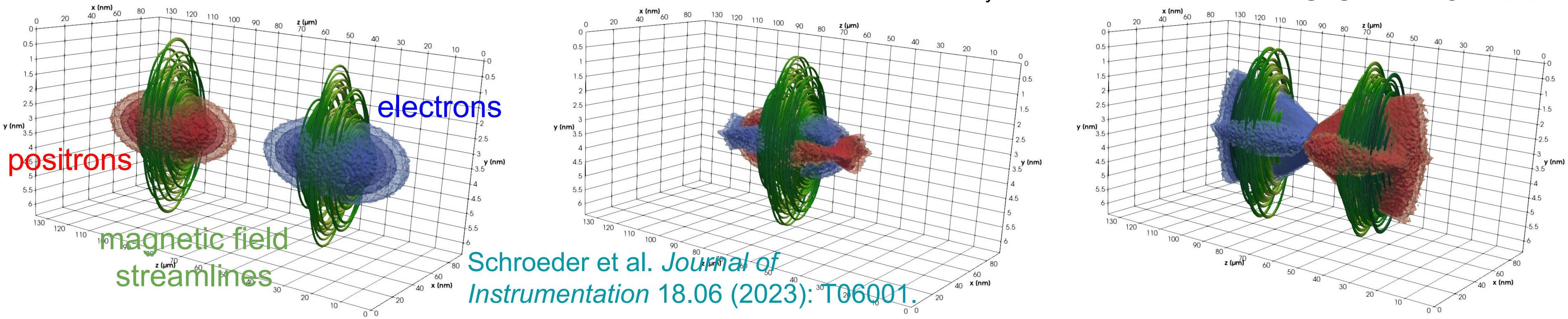
E_{COM} = 10 TeV | N = 1.2 * 10^{9} | σ_z = 8.5 mm | σ^*_x = 6 nm | σ^*_y = 0.4 nm

collinear boosted frame at the 1st IP (no turns)

L/BX

1.55×10^{33} m^{-2}

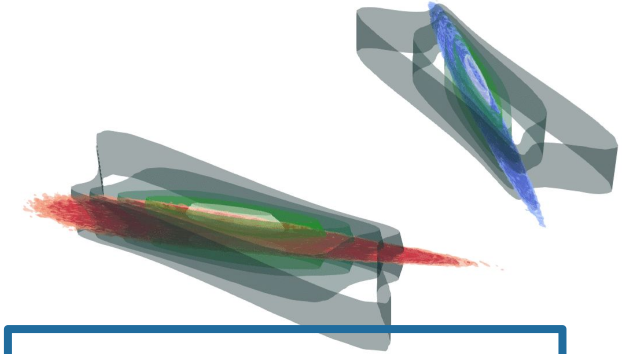
8.84×10^{34} m^{-2}



Schroeder et al. *Journal of Instrumentation* 18.06 (2023): T06001.

Conclusions and next steps

We are working to make WarpX a next-gen code for next-gen colliders



Goal
establish WarpX as a modern high-performance tool in the extended collider community

Outline

- numerical challenges ⛰️
- benchmarks ✅
- performances 🏃
- preliminary results

Two main takeaways 🏁

🎯 WarpX agrees well with GUINEA-PIG under very different parameters

🎯 WarpX can be much faster than GUINEA-PIG

Open discussions 🎤

- what are the modeling needs of the FCC & other communities?
- how can we work synergistically with/on different tools?

Next steps

add missing physics
✅ more benchmarks
🔮🎩do magic

Thank you for your time :)