Modern simulations of the interaction point in colliders

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cea

We need simulations of the interaction point to answer some questions

💥 what “luminosities” can we achieve depending on the beam parameters?
✨ what wakefield collider would be “best” and in what sense?
🔬 what discoveries can we make?

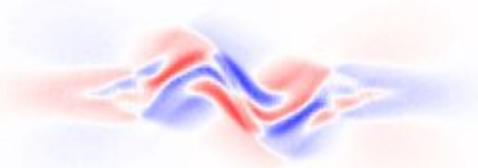
GUINEA-PIG https://gitlab.cern.ch/clic-software/guinea-pig

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

many beam-beam effects:
disruption 💔, photon emission 🔦, pair creation 👯, scattering 🎱, hadron photoproduction 💪,
…
→ **luminosity??? backgrounds???**

nominal beams 😍

disrupted beams 😱



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

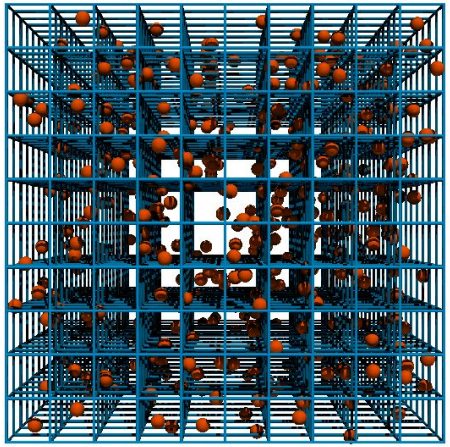
fields* on a grid

$$\begin{cases} \left[\Delta - (\boldsymbol{\beta}\cdot\nabla)^2\right]\phi = -\rho/\epsilon_0 \\ \mathbf{E} = -\nabla\phi + \boldsymbol{\beta}(\boldsymbol{\beta}\cdot\nabla\phi) \\ \mathbf{B} = -\boldsymbol{\beta}/c \times \nabla\phi \end{cases}$$

*space-charge

Δt

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



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

incoherent effects modeled as binary collisions (+ virtual photons)

*including "QED" photons

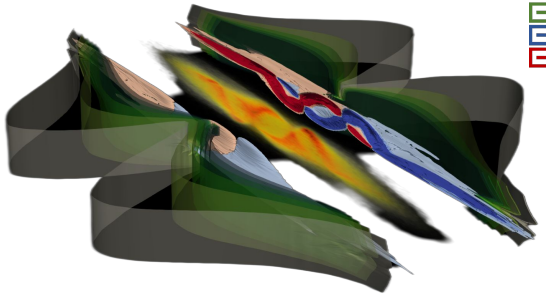
macroparticles* motion

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

WarpX is a particle-in-cell code that can simulate beam-beam effects

https://ecp-warpx.github.io

https://warpx.readthedocs.io



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SciDAC Scientific Discovery through Advanced Computing

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

- different geometries: 1D, 2D, RZ, 3D
- many algorithms
- many diagnostics
- electromagnetic, electrostatic in beam frame
- QED modules

international, cross-disciplinary & ACTIVE community!
(WELL) DOCUMENTED!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

Beam-beam collision

This example shows how to simulate the collision between two ultra-relativistic particle beams. This is representative of what happens at the interaction point of a linear collider. We consider a right-propagating electron bunch colliding against a left-propagating positron bunch.

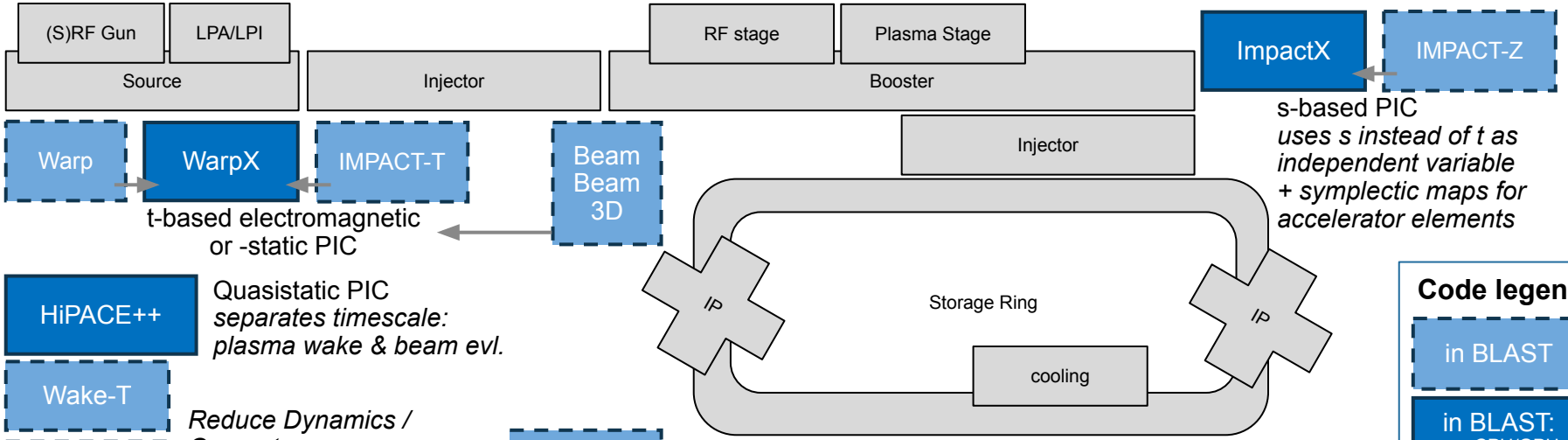
We turn on the Quantum Synchrotron QED module for photon emission (also known as beamstrahlung in the collider community) and the Breit-Wheeler QED module for the generation of electron-positron pairs (also known as coherent pair generation in the collider community).

To solve for the electromagnetic field we use the nodal version of the electrostatic relativistic solver. This solver computes the average velocity of each species, and solves the corresponding relativistic Poisson equation (see the WarpX documentation for *warpx.do_electrostatic = relativistic* for more detail). This solver accurately reproduced the subtle cancellation that occur for some component of the $E + v \times B$ terms which are crucial in simulations of relativistic particles.

This example is based on the following paper Yakimenko *et al.* [9].

EXASCALE COMPUTING PROJECT

WarpX ∈ BLAST, a comprehensive simulation toolkit for accelerator physics



BLAST

BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

Standards

open standard for particle-mesh data files

openPMD

picmi Standard

input files for PIC simulations

Other libraries

LASY

optimas

PICSAR

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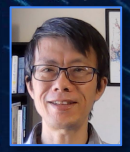
Jean-Luc Vay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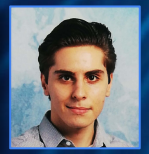
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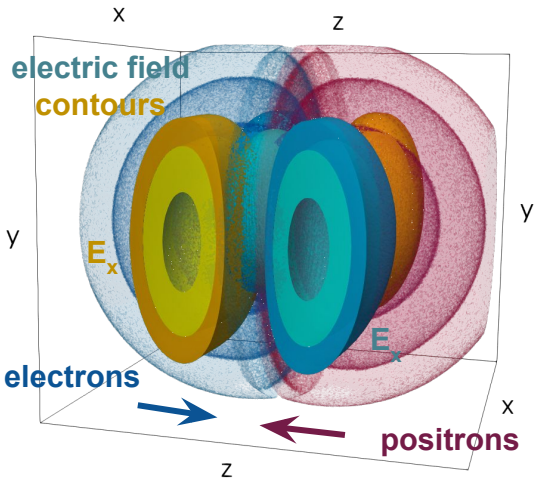
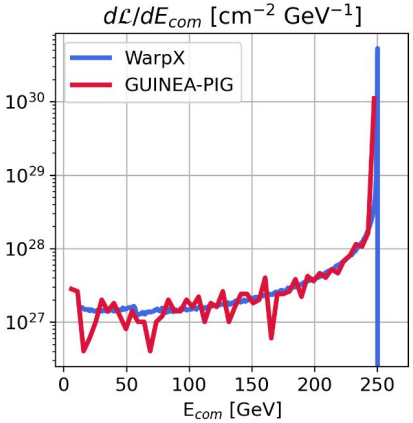
AVALANCHE

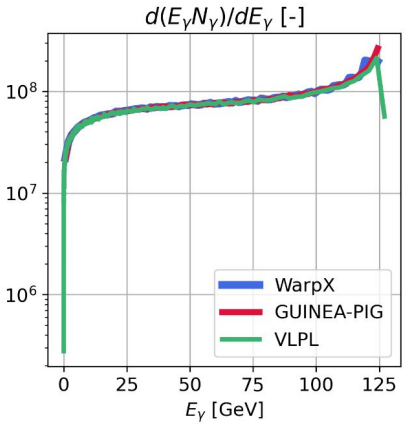
MODERN ELECTRON

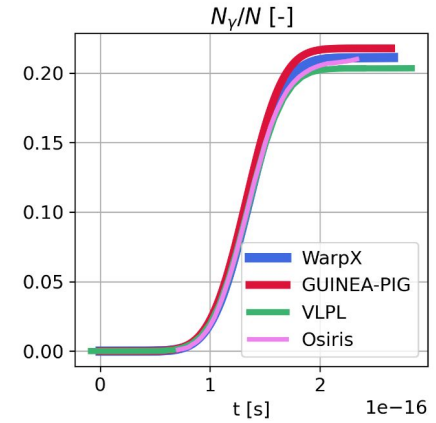
over 80 **contributors,** incl. from the private sector

Excellent agreement between WarpX and other codes with spherical nanobeams



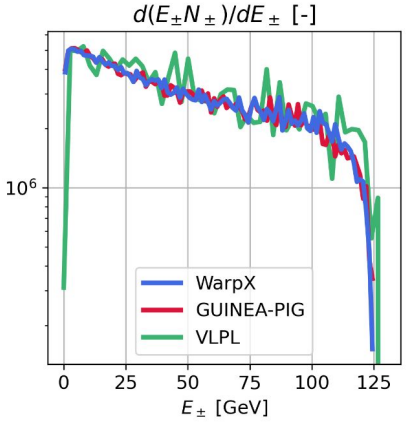


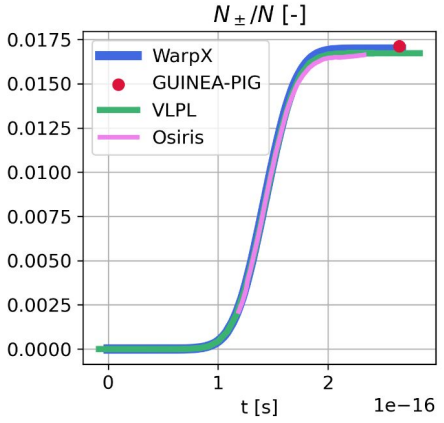




- E_{COM} = 250 GeV
- N = 8.7 * 10^8
- spherical beams: $\sigma_z=\sigma_x=\sigma_y$ = 10 nm
- zero emittance
- low disruption D = 0.001
- max quantum parameter χ = Υ ~ 1700

Yakimenko et al. PRL 2019

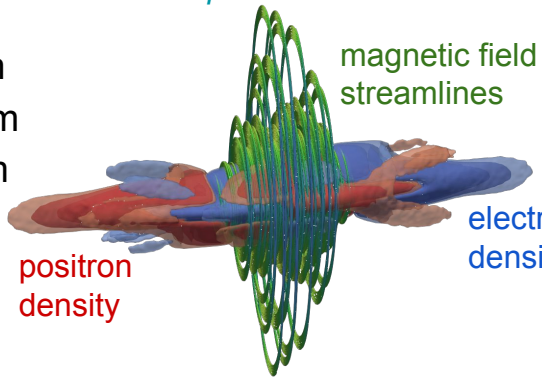




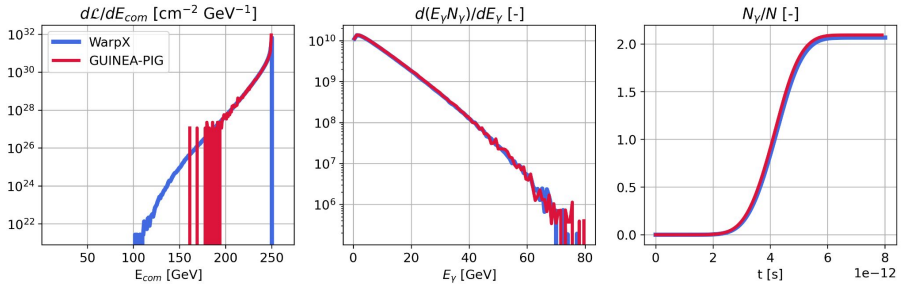
Excellent agreement between WarpX and GUINEA-PIG with flat ILC beams

- E_{COM} = 250 GeV
- N = $2x10^{10}$
- σ_z = 300 μm
- σ^*_x = 516 nm
- σ^*_y = 7.7 nm
- ϵ_x = 5 μm
- ϵ_y = 35 nm

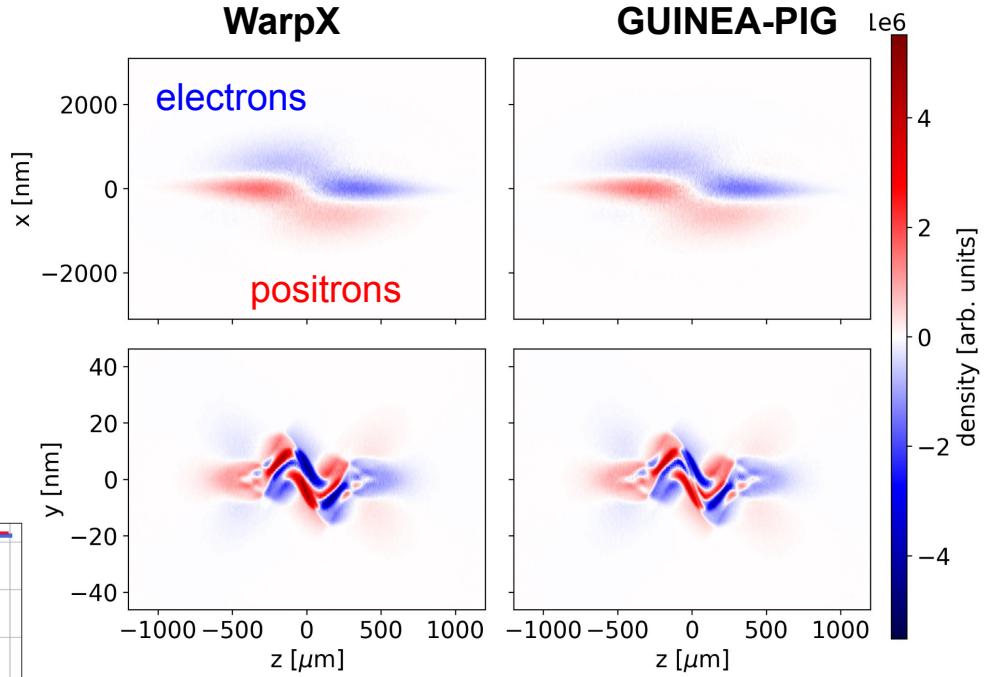
The International Linear Collider: Report to Snowmass 2021



- flat beams
- significant disruption D_x = 0.30, D_y = 24.39
- max quantum parameter $\chi = \Upsilon \sim 0.3$



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

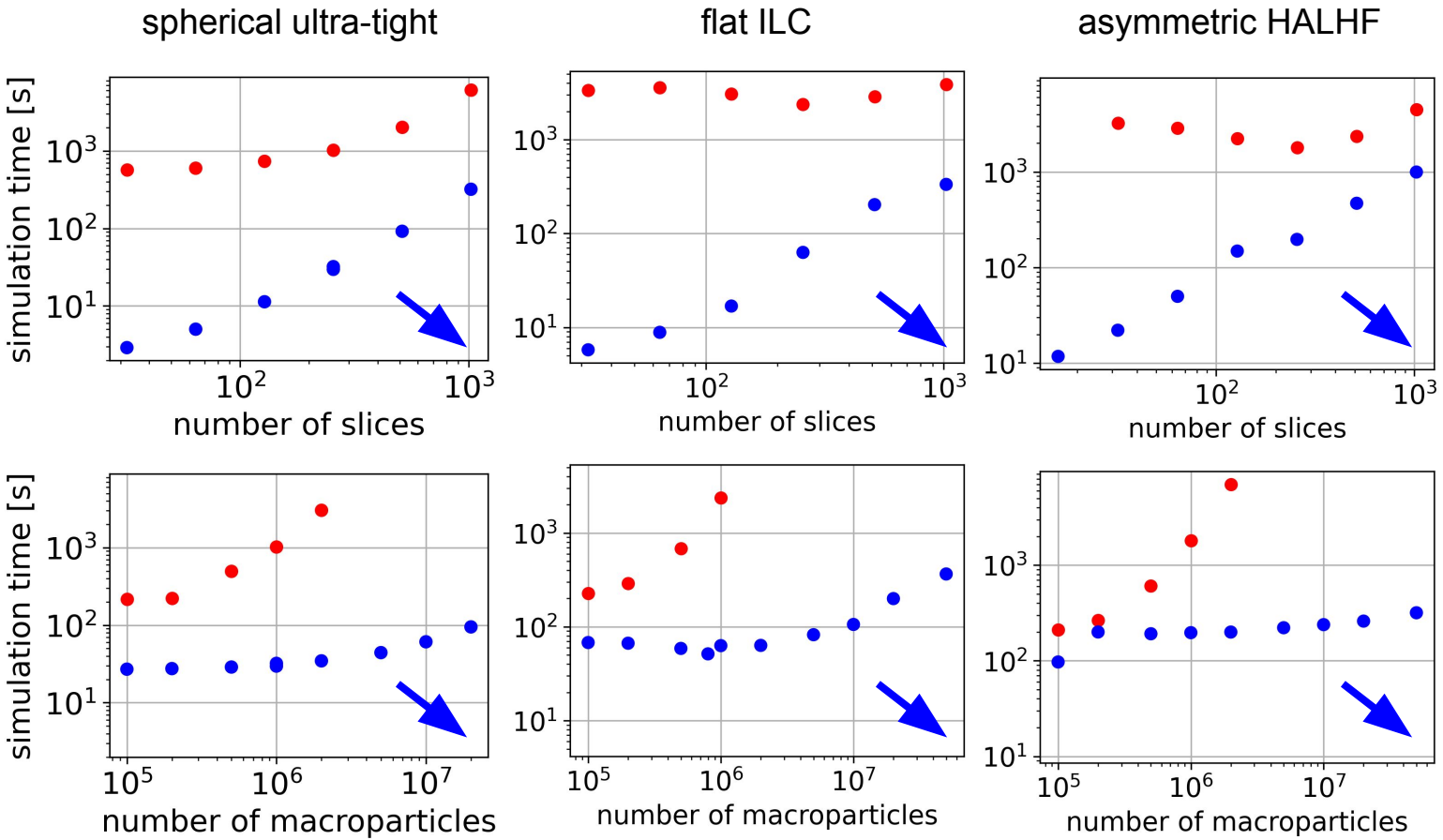


offsets along x and y ~$\sigma_{x,y}$/10 to induce the kink instability and mitigate stochastic discrepancies

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

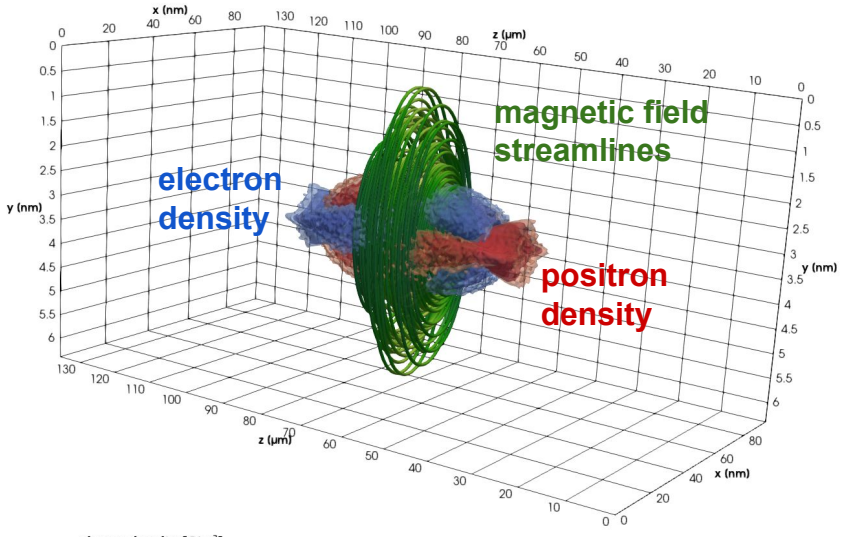
GUINEA-PIG
1 CPU

WarpX
1 GPU



First simulations with wakefield lepton beams at 10 TeV – preliminary!

⚠ SEVERAL CAVEATS EXIST ⚠



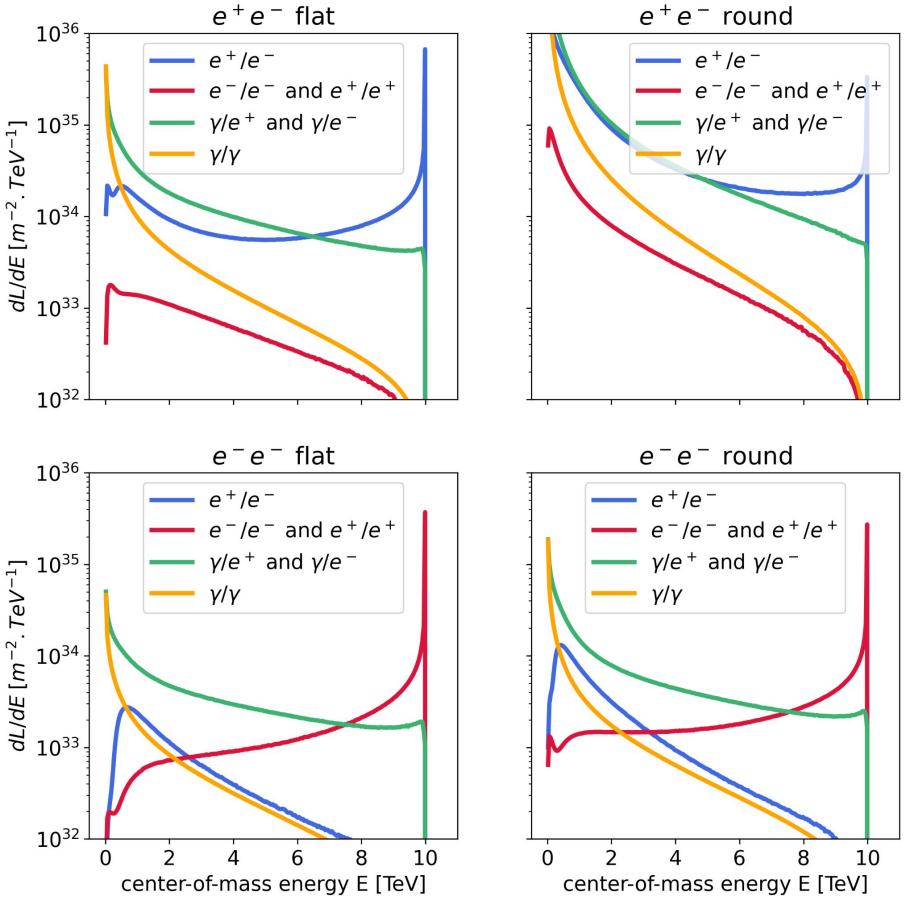
E_{COM} = 10 TeV | N = 1.2 * 10^9 | σ_z = 8.5 um

e^+e^- vs. e^-e^-

round: σ^* = 1.55 nm | D = 1.22 | χ = 970

flat: σ^*_x = 6 nm | σ^*_y = 0.4 nm | D_x = 0.15 | D_y = 2.3 | χ = 470

luminosity spectra



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

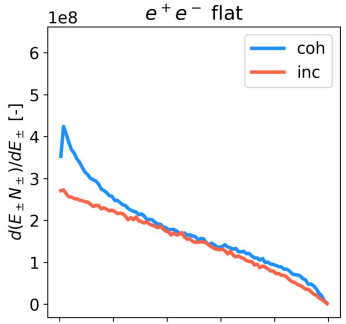
The caveats

Simplifications

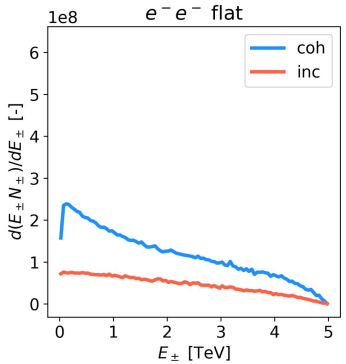
- local constant field approximation (LCFA)
- collinear emission of photons
- only coherent processes (beamstrahlung & nonlinear Breit-Wheeler)

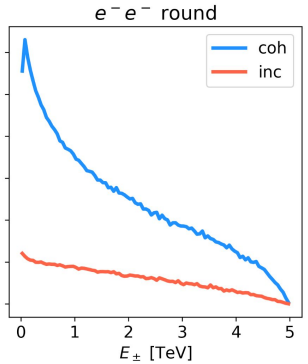
Physics open questions

- transition from incoherent to coherent photon emission
- transition from incoherent to coherent pair generation
- emission rates at very high quantum parameters
- validity of LCFA
- circular colliders: couple with other codes
- other processes for muon colliders?
- ...



this simulation didn't finish, my bad 😬





We are setting up a framework that includes accelerator-physics-detector

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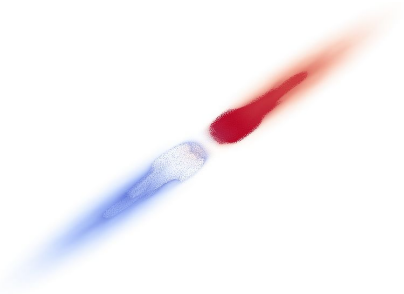
funded through LDRD at LBNL

beam properties from design studies

WarpX



Carl Schroeder
Jens Osterhoff
Stepan Bulanov
Jean-Luc Vay
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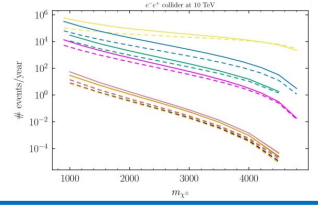
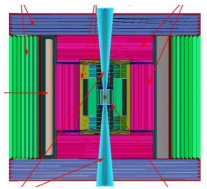
ATAP
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

luminosity distributions

outgoing particles

production rates of new particles, sensitivity to BSM physics





G4 backgrounds, constraints on detector design

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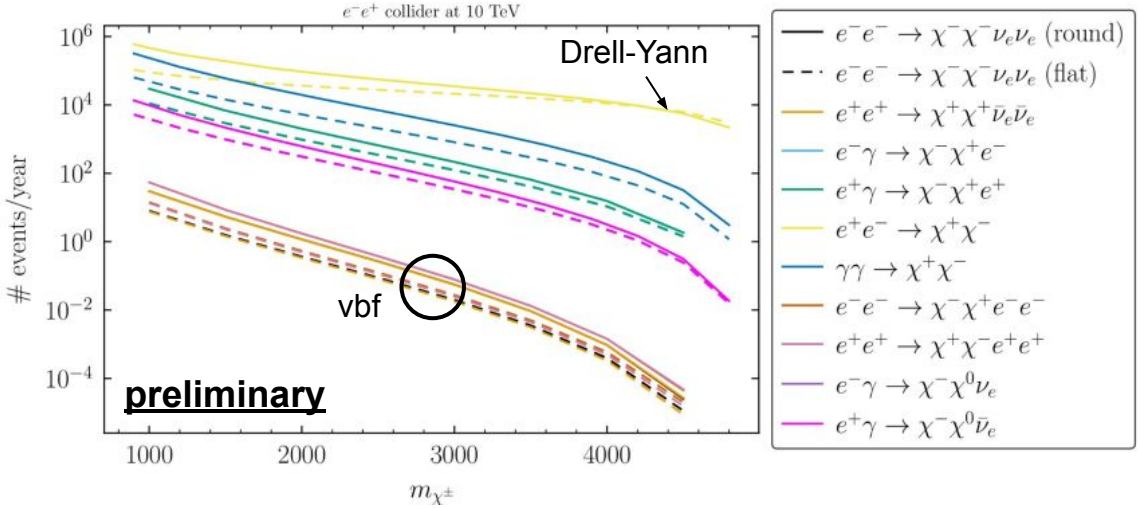
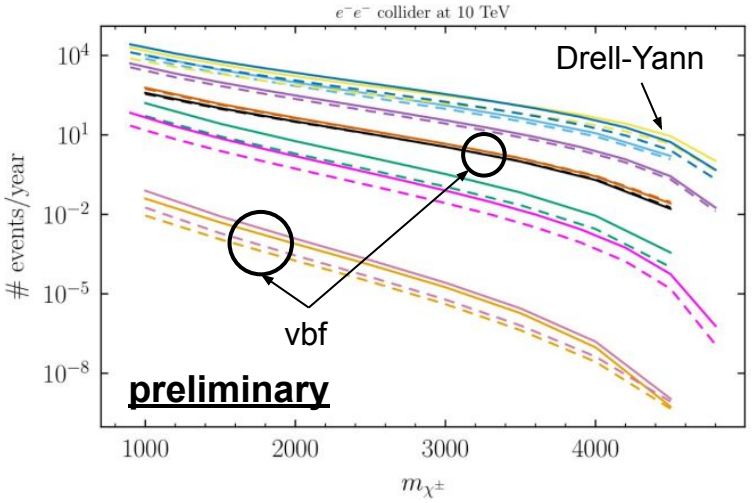
From the luminosity distributions we get the production rate of exotic particles

searching wino-like chargino χ+ as visible charged partner to χ0 (dark matter candidate)

- use MadGraph to generate events for chargino production
- to include luminosity spectra need to run over grid of center of mass energies and fold with luminosity spectrum
- repeat for multiple chargino masses
- (implement decays by hand)

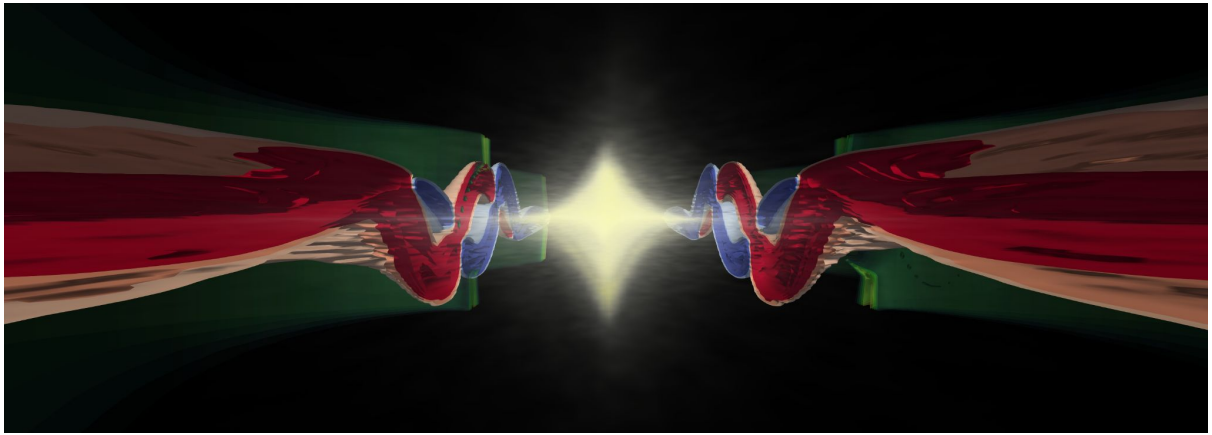




Conclusions

main takeaways 🏁 and next steps ⏭️

🔄 we are continuing to develop WarpX as a next-gen code for IP simulations
🎯 WarpX agrees well with and is much faster than GUINEA-PIG
🚧 we are developing a broader simulation framework to support the design of future colliders in a cross-disciplinary team
🤔 we started and will continue addressing the caveats!



Thank you for your time! 🙏