Using FeeBL to Study Monochromatization at ILC, FCC-ee

Collision-energy spectra, beam backgrounds and a comparison with HALHF

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DESY / FTX

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Based on B. Madison, *Beam-beam effects on measurements at electron-positron colliders: LEP neutrino counting and Higgs factories* [1].

Why develop a new beam-beam code?

A luminosity measurement depends on what happens inside a bunch crossing. Beam fields change the collision energy and spin, produce pairs and deflect outgoing charged particles.

- Strong fields and SFQED/NPQED
- Crab crossing, crab waists and IP dispersion
- Fine meshes and large particle samples
- Frame resolved field and particle diagnostics

From GUINEA-PIG to FeeBL

1990s and 2000s D. Schulte's GUINEA-PIG and the C++ implementation; spin tracking in GUINEA-PIG++ [2, 3].

2024, v0.0 First experiments adding GPU and multithreaded execution to GUINEA-PIG++.

20 April 2026, v0.1 Fork of version 1.2.2 with byte-identical output on the comparison cards.

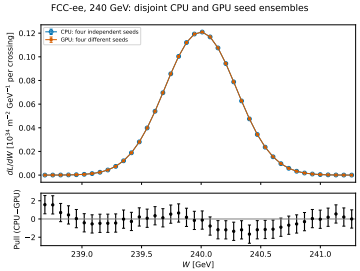
v0.7.0 Public release with CPU and CUDA backends, new IP optics and a beam viewer.

What FeeBL adds to GUINEA-PIG++ 1.2.2

	GUINEA-PIG++ 1.2.2	FeeBL v0.7.0
Execution	Serial CPU	CPU worker pools, OpenMP, CUDA (one GPU), sparse cells and FFTW3
Geometry	Crossing angle	Crab crossing, RF bunch tilt and a local crab waist
IP optics	Undispersed inputs	Horizontal dispersion and re-slicing of transformed particles
Spin	Precession and spin flips	Corrected spin transport and luminosity-weighted polarization by energy and frame
Pairs	Equivalent photon appx.	Finite-mass photon fluxes, Born pair amplitudes, fixes existing errors/bugs
Deflection	Imported events	Track $e^{\pm}$ and $\mu^{\pm}$ by event and particle ID; record $\Delta\theta$ and $\Delta\phi$
Analysis	Text files	Browser viewer, 111 examples and checkpoints



How much faster is a simulation?



FCC-ee at 240 GeV, 10^6 macroparticles per beam. Independent CPU and GPU seeds give a largest bin pull of 1.66 [1].

Wall time on Maxwell in seconds, mean ± SEM across repeats.

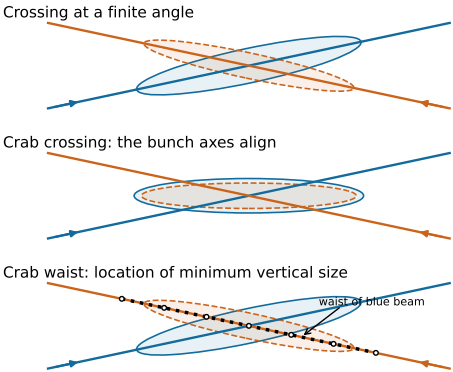
ILC at 250 GeV	200k/beam	800k/beam
GUINEA-PIG++ with FFTW	227.18 ± 0.68	314.69 ± 0.20
FeeBL serial	156.25 ± 0.41	253.99 ± 0.93
FeeBL, ten CPU workers	52.65 ± 0.34	135.95 ± 0.73
FeeBL, one V100	23.46 ± 0.03	104.51 ± 0.28

Three repeats at 200k and two at 800k. FCC-ee at left: 16 cores, 118.46 ± 0.67 s; one V100, 65.11 ± 0.07 s.

Isolating the sparse field solver

On HPC 32 CPU + A100 GPU $\approx 10\times$ faster, with adaptive sparse cells on $\approx 4\times$ faster.

Dedicated crab-crossing and crab-waist collisions



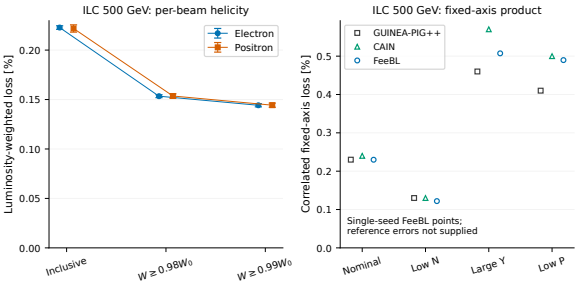
- **new** symplectic incoming maps per beam, at the IP, before the crossing rotation
- Crab: $x \mapsto x + t\zeta$, $\delta \mapsto \delta - t\,p_x$ (ideal tilt) or a two-harmonic RF map [1]
- Crab waist: vertical waist follows the opposing beam [4]

30 mrad numerical test	$\mathcal{L}$ / head-on
Crossing, no crab	5.0%
Crab, $n_z = 16$ slices	68.4%
Crab, $n_z \geq 53$	**92 to 100%**

Top view at the IP. Circles on the opposing path mark the blue beam's vertical waist.

This test increased the ILC crossing angle from 14 to 30 mrad to measure the recovery of luminosity.

Polarization: spin tracking and luminosity weighted depolarization

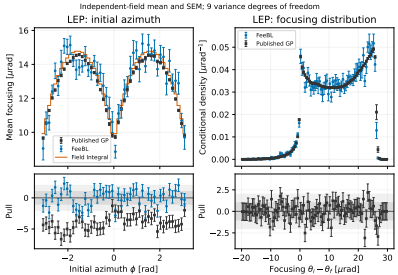


Historical ILC results only. HALHF depolarization coverage pending.

- BMT precession + spin-dependent beamstrahlung (CAIN model) [5, 3]
- **new** three inherited defects fixed (radiation basis, kick direction, χ after recoil)
- **new** luminosity weighted longitudinal polarization for each beam, frame and energy window
- 2009 ILC nominal optics: 0.230% vs 0.23 / 0.24% (GUINEA-PIG++ / CAIN)
- Electron loss, $\beta_x^* = 21$ mm: 0.223% inclusive, 0.153% for $W \geq 0.98W_0$

The nominal ILC loss is similar to GUINEA-PIG++ and CAIN.

LEP Bhabha focusing and the neutrino count



Boundary	Field integral	Published GP	FeeBL
31.3 mrad	13.09	12.81 ± 0.09	13.12 ± 0.08
51.6 mrad	11.49	11.19 ± 0.10	11.49 ± 0.06

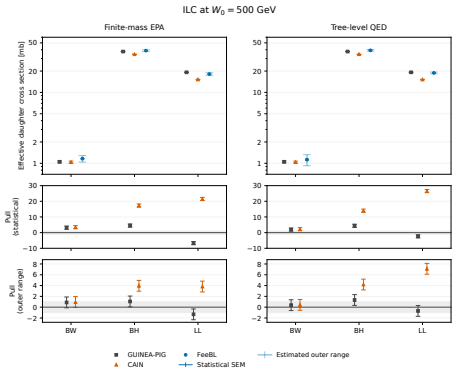
Mean inward electron deflection [μrad] [6].

The two boundary means give a luminosity bias of -0.10671% in FeeBL and -0.10425% using published GP angles.

Effect on N_ν

Published: 2.9963 ± 0.0074 [7]. Extending the focusing shift to all four experiments gives about 2.9965.

Incoherent pair production at the 500 GeV ILC

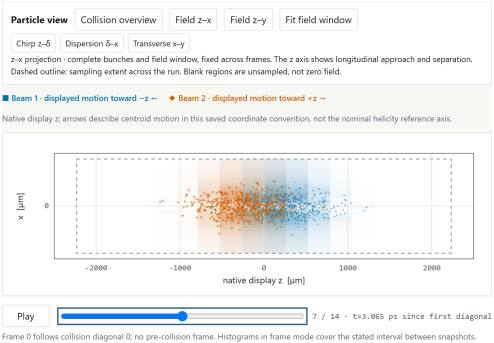


Each channel counts produced daughters per unit e^+e^- luminosity. Twelve independent collisions enter each FeeBL result.

Total effective cross section	mb
Published GP / CAIN	57.95 / 50.74
FeeBL, finite-mass EPA	58.20 ± 1.95
FeeBL, Born matrix elements	59.15 ± 1.73

The quoted ranges include statistical and assessed model and numerical uncertainties [8, 1]. The reference codes use different virtual-photon cutoffs. This can change the Bethe-Heitler and Landau-Lifshitz yields.

Beam viewer: watch the collision, frame by frame



- **new** browser application: finish a run, finalize it, open it in any browser
- One slider sets the frame for all panels.
- Views: overview, z-x, z-y, chirp z-δ, dispersion δ-x, x-y
- Field layers on a fixed GV/m scale
- Points are a display sample; all numbers come from native accumulators

```
feebl --make_gui_files <acc> <par> <out>
python tools/finalize_gui_dataset.py runs/YourRunsHere
python tools/serve_viewer.py --run runs/YourRunsHere
```

▸ Frame diagnostics ▸ Field layers

Any finished run → synchronized bunch, field and spectrum views in a browser.

Reading the numbers in one collision frame

Interval L (integrated)	9.17826e+32 m⁻² / crossing
Fraction of total L	0.06635
L below / above W bins	0.000 / 0.000
Beam 1 ⟨E⟩L	123.891139 GeV
Beam 2 ⟨E⟩L	123.829249 GeV
Configured P_1 / P_2 [1]	0.800000 / 0.300000
Bunch P_1 / P_2 [1], snapshot 31	0.797534 / 0.299094
Interval $\langle P_1 \rangle_L$ / $\langle P_2 \rangle_L$ [1]	0.798210 / 0.299330
Polarization L weight	9.17826e+32 m⁻² / crossing
Peak selection	W ≥ 244.99400 GeV (98% design Wnom)
Peak L weight	7.80941e+32 m⁻² / crossing
Peak $\langle E_1 \rangle_L$ [GeV]	124.567595
Peak $\langle E_2 \rangle_L$ [GeV]	124.554428
Peak $\langle P_1 \rangle_L$ / $\langle P_2 \rangle_L$ [1]	0.798258 / 0.299351
Selected-peak RMS σW [GeV]	1.271941
Beta-Gaussian core σ [GeV]	0.180388
Core-width ratio to input [1]	0.979982

Polarized ILC at 250 GeV, frame 31 of 63.

The peak selection takes collisions with $W \geq 0.98 W_0$ in this frame.

	Inclusive	Peak
$\mathcal{L}$ [10^{32} m^{-2}/BX]	9.178	7.809
$\langle E_1 \rangle_{\mathcal{L}}$ [GeV]	123.891	124.568
$\langle E_2 \rangle_{\mathcal{L}}$ [GeV]	123.829	124.554
$\langle P_1 \rangle_{\mathcal{L}}$	0.798210	0.798258
$\langle P_2 \rangle_{\mathcal{L}}$	0.299330	0.299351

The input polarizations are 0.800 and 0.300. The bunch averages at this frame are 0.797534 and 0.299094.



Monochromatization at the interaction point

How much luminosity can we put into a narrow collision energy window?

Two different measurements

250 GeV: compare ILC optics at the Higgsstrahlung energy. Measure the luminosity in the peak and the pairs from the same collision.

125 GeV: compare ILC/LCF, HALHF and FCC-ee for direct resonant Higgs production.

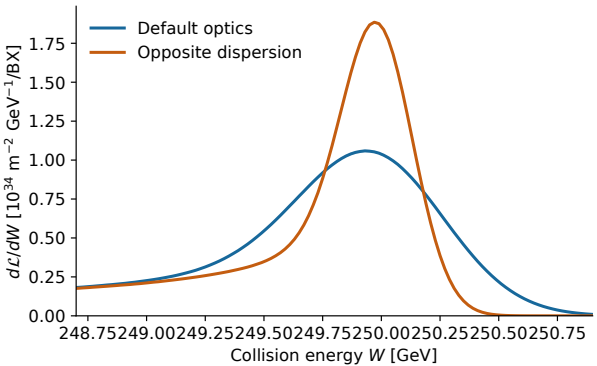
How opposite horizontal dispersions narrow the peak

Dispersion ties a particle's horizontal position to its fractional energy deviation δ,

$$x = x_\beta + D\delta.$$

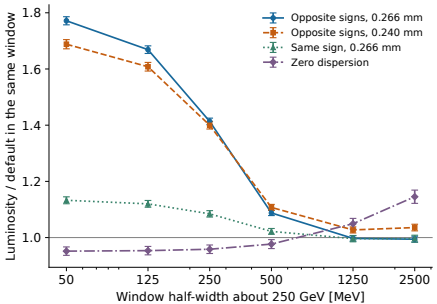
With opposite signs of D, a higher-energy electron overlaps preferentially with a lower-energy positron. Their energy deviations partly cancel in W.

Stronger horizontal focusing can restore the overlap lost to dispersion [9, 1].



Absolute luminosity density at 250 GeV. The bands show the seed SEM for five runs per setting in 20 MeV bins.

ILC at 250 GeV: the luminosity gain depends on the energy cut



All curves use $\beta_x^* = 3$ mm. At 0.266 mm both beam variances sum to the default value. At 0.240 mm only the electron beam recovers its default width.

For $\beta_x^* : 13 \to 3$ mm and opposite $D = \pm 0.266$ mm, the observed FWHM falls from 823.3 ± 1.3 to 395.3 ± 0.3 MeV.

Selection	$\mathcal{L}_{\text{matched}}/\mathcal{L}_0$
All collisions	0.994 ± 0.017
$W \geq 0.98 W_0$	0.994 ± 0.012
$W \geq 0.99 W_0$	0.994 ± 0.011
$\lvert W - W_0 \rvert \leq 250$ MeV	1.413 ± 0.012
$\lvert W - W_0 \rvert \leq 50$ MeV	$\mathbf{1.772 \pm 0.014}$

Dispersion redistributes luminosity within the upper 1% of the spectrum.

ILC at 250 GeV: changing the dispersion sign at fixed focus

Both beams have the same β_x^* in each run. The luminosity ratio uses the default optics in the same window, $|W - 250\,\mathrm{GeV}| \leq 50\,\mathrm{MeV}$.

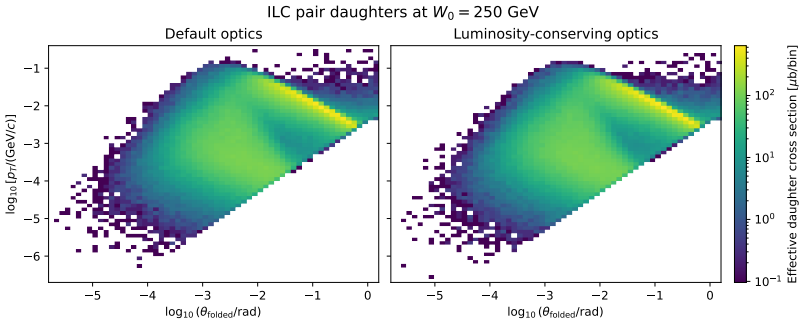
Optics	β_x^* [mm]	(D_{e^-}, D_{e^+}) [mm]	Peak FWHM [MeV]	$\mathcal{L}_{50}/\mathcal{L}_{50,0}$
Default	13	$(0, 0)$	823.3 ± 1.3	1
Focus only	3	$(0, 0)$	901.6 ± 1.4	0.952 ± 0.015
Same signs	3	$(+0.266, +0.266)$	689.4 ± 2.5	1.133 ± 0.012
Opposite signs	3	$(+0.266, -0.266)$	395.3 ± 0.3	$\mathbf{1.772 \pm 0.014}$

The errors are standard errors across seeds, with three runs for focus only and five for each other setting.

At fixed focus, reversing one sign gains $(56.4 \pm 1.4)\%$ in the ± 50 MeV window.

Two 500 GeV linear-collider designs studied a 3 mm horizontal focus [10, 11]. Delivering it with opposite dispersion at ILC250 still requires lattice tracking. ▸ Final-focus studies

Do luminosity-conserving optics change the pair background at 250 GeV?

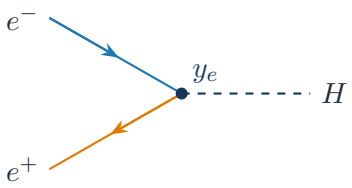


Collision-frame θ is measured from the nearer beam axis. The maps include transported e^- and e^+ with production energy at least 5 MeV.

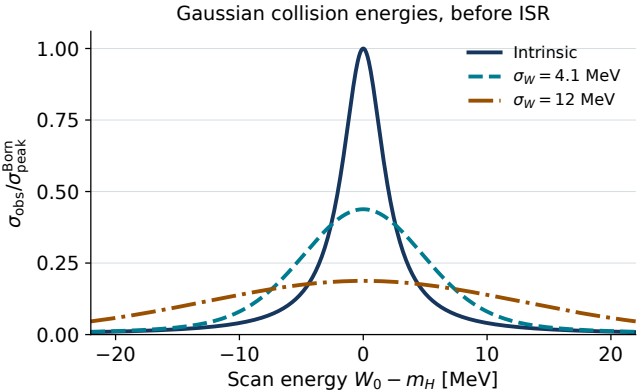
	Effective daughter cross section [mb]	Peak FWHM [MeV]	$\mathcal{L}/\mathcal{L}_{\mathrm{default}}$
Default	55.43 ± 0.19	824.0 ± 1.1	1
Opposite dispersion	56.10 ± 0.11	395.2 ± 0.3	0.997 ± 0.008

The luminosity-normalized daughter yield changes by $(+1.22 \pm 0.31)\%$ across six matched seed pairs.

Direct Higgs production at 125 GeV

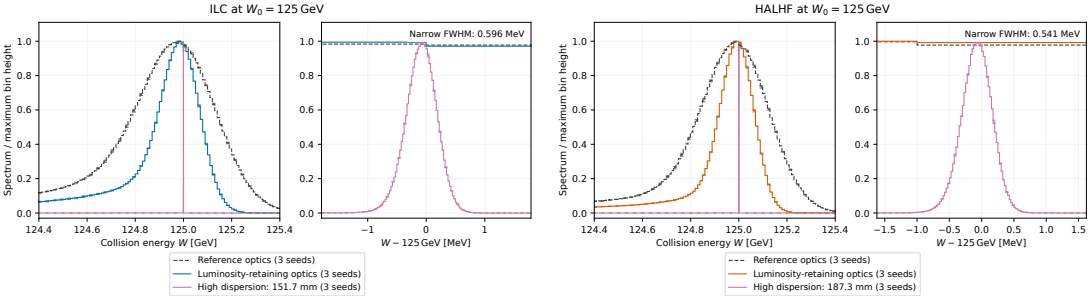


An electron and a positron can form a Higgs boson through the electron Yukawa coupling y_e. The Higgs width is only 4.1 MeV, so optics that concentrate luminosity near m_H enhance the rate [12, 13].



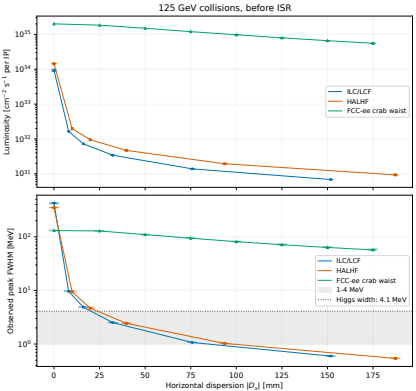
At the same integrated luminosity, a narrower collision energy spread puts more collisions on resonance.

ILC/LCF and HALHF peak spectra at 125 GeV



- Narrowest observed FWHM: 0.596 MeV at ILC/LCF and 0.541 MeV at HALHF.
- The narrowest widths are read directly from the simulated histograms.
- Each spectrum is scaled to unit maximum. The dispersion scan shows absolute luminosity.

How narrow does the simulated peak get at 125 GeV?



At the largest simulated dispersion in each scan:

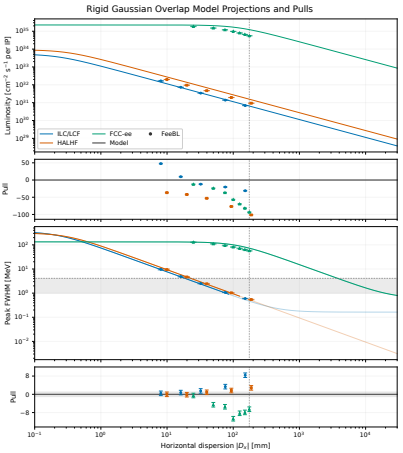
	$\lvert D\rvert$ [mm]	Observed FWHM [MeV]	$\mathcal{L}/\mathcal{L}_0$
ILC/LCF	151.7	0.5964 ± 0.0017	0.073%
HALHF	187.3	0.5405 ± 0.0060	0.064%
FCC-ee	175.0	56.985 ± 0.028	28%

FCC-ee retains its 30 mrad crossing and local crab waist. The bunch length projected across the crossing increases the horizontal overlap size.

Width errors are SEMs over three seeds. Each ratio uses the corresponding zero-dispersion control.

ILC/LCF and HALHF reach sub-MeV FWHM at less than 0.1% of baseline luminosity.

Rigid Gaussian overlap model and simulated peaks



The model holds each Gaussian bunch fixed as it crosses. It omits beamstrahlung, disruption, hourglass and crab-waist weighting.

At maximum $\lvert D\rvert$	ILC	HALHF	FCC-ee
$\Delta\mathcal{L}/\mathcal{L}_{\text{model}}$	-8.4%	-36.3%	-54.9%
$\Delta w/w_{\text{model}}$	$+13.4\%$	$+8.1\%$	-21.9%
Width pull	$+8.4$	$+2.8$	-6.5

w is the observed FWHM in simulation and the first-order Gaussian FWHM in the model. The extrapolation beyond 175 mm for FCC-ee assumes fixed incoming optics.

The FCC-ee model reaches 4, 2 and 1 MeV at 3.86, 8.03 and 19.47 m, respectively. Simulation ends at 0.175 m.

References I

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References II

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How close have final-focus designs come to $\beta_x^* = 3\,\text{mm}$?

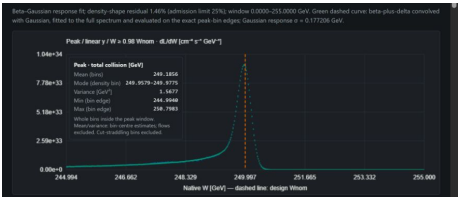
- **500 GeV e^+e^- linear collider.** A DESY and Darmstadt design used $\beta_x^* = 3\,\text{mm}$. Additional sextupoles gave the ideal lattice a momentum bandwidth of at least $\pm 0.8\%$. The authors left alignment tolerances and practical correction for later work [10].
- **CLIC at 500 GeV.** Tracking at fixed incoming emittance reached $\beta_x^* = 3\,\text{mm}$ and $\beta_y^* = 50\,\mu\text{m}$. The beams at the IP developed non-Gaussian tails [11].
- **ILC photon-collider optics.** Telnov estimated a minimum horizontal beta of 3.7 mm for a normalized horizontal emittance of $5\,\mu$m, and 2.2 mm for $2.5\,\mu$m [16]. The first emittance matches the FEEBL input.

An ILC250 lattice study would need to deliver $\beta_x^* = 3\,\text{mm}$ and $D_{e^\mp} = \pm 0.266\,\text{mm}$ together at 125 GeV per beam.

back

Backup: more viewer panels





Quantity	Current frame	Total
Spectra	contributions in the interval	all contributions
$\langle E \rangle_{\mathcal{L}}$, $\langle P \rangle_{\mathcal{L}}$	accepted pairs in the interval	whole collision
Beam moments	stored primary state	pooled weighted moments
Imported particles	change since admission	final state

back