Simulation of Beam-Related Backgrounds at Higgs Factories

ILC IDT-WG3 Open Meeting

https://agenda.linearcollider.org/event/10257/

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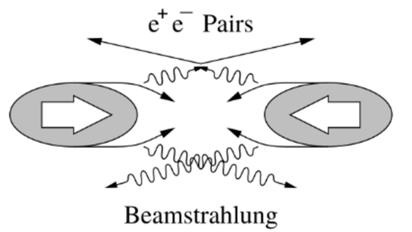
Introduction

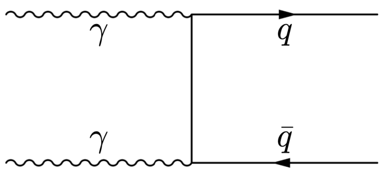
Beam-Beam interactions at e^+e^- colliders

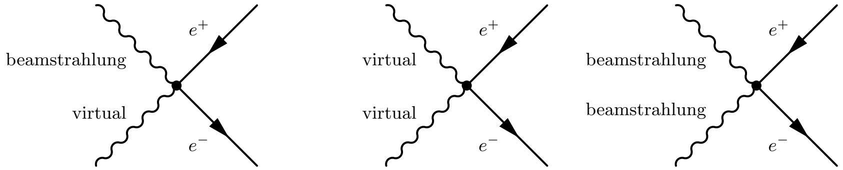
- Nm-sized beams → high charge densities at the IP → interactions of particles from one bunch with the opposite bunch → production of secondary particles, that collectively constitute the **beam-induced background (BIB).**
- BIB particles are by-products of photons radiated when the two bunches intersect at the IP. Those photons are called **Beamstrahlung (BS).**
- Dominant processes for Higgs Factories:
  - Incoherent pair production:

$$\gamma_{BS} e \xrightarrow[\text{(virtual)}]{\gamma} e^+e^-e, \quad ee \xrightarrow[\text{(virtual)}]{\gamma} eee^+e^-, \quad \gamma_{BS}\gamma_{BS} \to e^+e^-$$

  - Hadron photo-production: $\gamma_{BS}\gamma_{BS} \to q\bar{q}$







(a) Bethe-Heitler (b) Landau-Lifshitz (c) Breit-Wheeler

$O(10^5)$ ***pairs per BX***

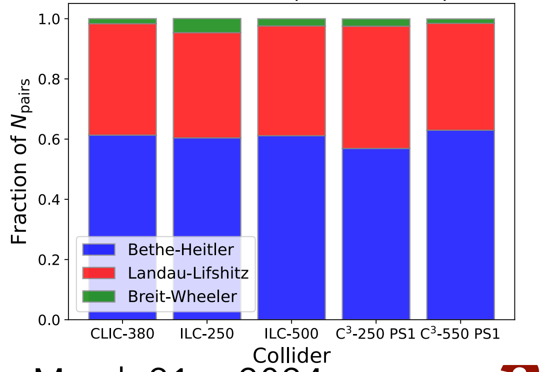
(BX = Bunch Crossing)

$O(1)$ ***hadrons per BX***

(more central)

Incoherent pair production processes

- *Bethe-Heitler (BH)*: interaction of BS photon with a virtual photon
- *Landau-Lifschitz (LL)*: interaction of two virtual photons
- *Breit-Wheeler (BW)*: interaction of two BS photons



Beam-Beam interactions at e⁺e⁻ colliders

- Strength of beam-beam interactions and number of produced BIB particles are expressed through the **Ypsilon parameter $\langle\Upsilon\rangle$.**
- Larger values of $\langle\Upsilon\rangle$ correspond to stronger Beamstrahlung → emission of more BS photons and reduction in the energy of beam particles.

$$\langle\Upsilon\rangle = \frac{5}{6}\frac{N_e r_e^2 \gamma}{\alpha(\sigma_x^* + \sigma_y^*)\sigma_z^*}$$

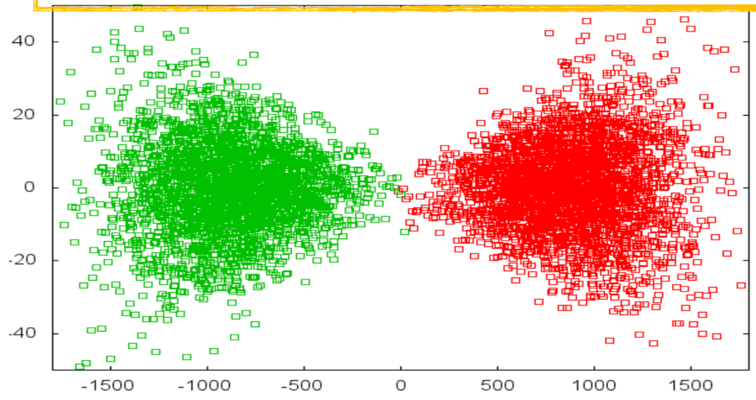
$$n_\gamma = \frac{12}{\pi^{3/2}}\frac{\alpha^2\sigma_z^*}{\gamma r_e}\frac{6\langle\Upsilon\rangle}{5}$$

- Instantaneous Luminosity: $\mathscr{L}_{\text{inst}} = H_D \frac{N_e^2 n_b f_r}{4\pi\sigma_x^*\sigma_y^*} = H_D \mathscr{L}_{\text{geom}}$

Luminosity depends on strength of beam-beam interactions!

- N_e : # of particles per bunch
- n_b : # of bunches per bunch train
- f_r : train repetition rate
- $\sigma_{x,y}^*$:horizontal and vertical RMS beam sizes at the IP.
- σ_z^*: bunch length
- H_D:enhancement factor that accounts for the effects of beam-beam interactions (~1.5-2).

$$\sigma_{x,y}^* = \sqrt{\frac{\epsilon_{x,y}^*\beta_{x,y}^*}{\gamma}}$$



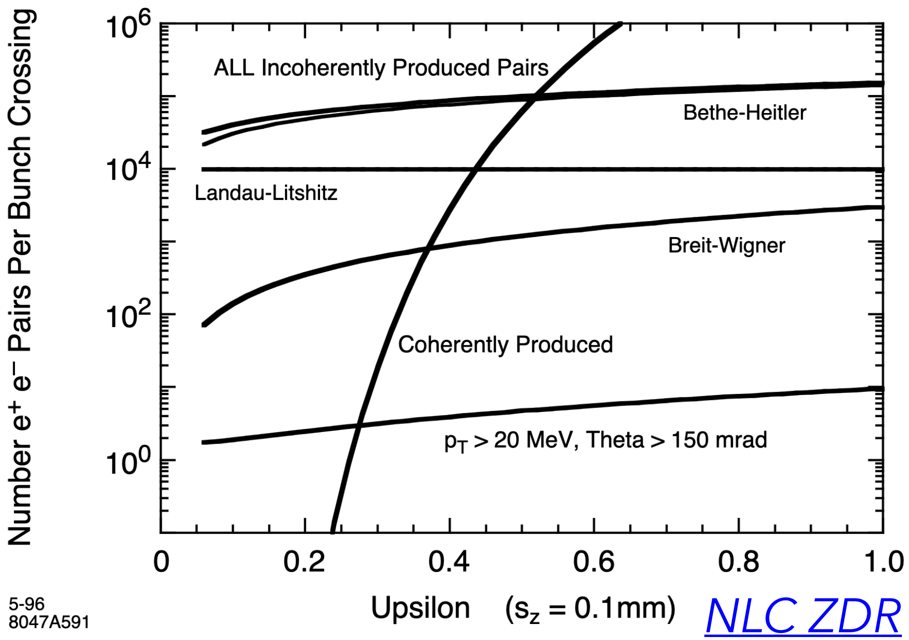
$$\delta_E = \frac{16\sqrt{3}}{5\pi^{3/2}}\frac{r_e\alpha N_e}{\sigma_x^*}\langle\Upsilon\rangle$$

$$\left\langle\frac{E_\gamma}{E_0}\right\rangle = \frac{\delta_E}{n_\gamma}$$

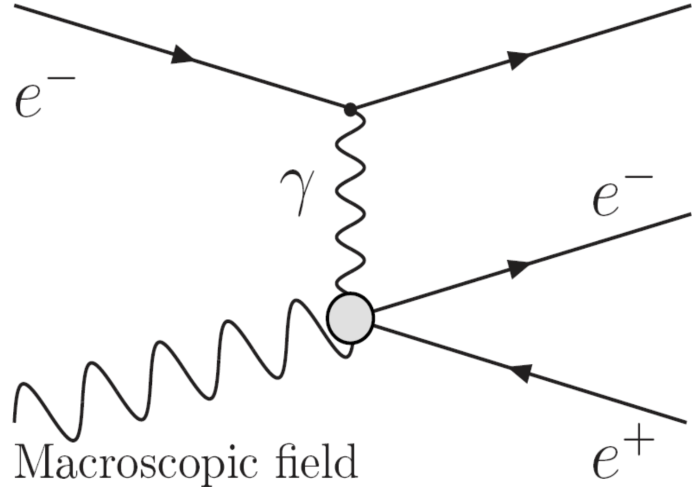
Beam-Beam interactions at e+e- colliders

- In addition to **incoherent pair production**, which stems from interactions of individual, real or virtual, photons, e^+e^- pairs can also be produced through the following mechanisms:
  - **Coherent pair production**: interaction of BS photon with the collective EM field of the beams → exponentially suppressed for $\langle \Upsilon \rangle \lesssim 0.5$
  - **Trident cascade**: interaction of virtual photon with the collective EM field of the beams → non-negligible for $\langle \Upsilon \rangle > 1$

- Those backgrounds are *negligible for HFs*, but *become significant for high Beamstrahlung advanced-accelerator-concept (AAC) colliders*, e.g. WFA-based.



NLC ZDR



Beam-Beam interactions at e^+e^- colliders

- **Typical parameter values for linear colliders**
- For circular machines (FCC-ee, CEPC), the Beamstrahlung parameter is $\mathcal{O}(10^4)$, see e.g. here.

Parameter	Symbol[unit]	CLIC	ILC-250	ILC-500	C^3-250 (PS1)	C^3-550 (PS1)
CM Energy	$\sqrt{s}$[GeV]	380	250	500	250	550
RMS bunch length	σ_z^*[µm]	70	300	300	100	100
Horizontal beta function at IP	β_x^* [mm]	8.2	13	22	12	12
Vertical beta function at IP	β_y^* [mm]	0.1	0.41	0.49	0.12	0.12
Normalized horizontal emittance at IP	ϵ_x^* [nm]	950	5000	5000	900	900
Normalized vertical emittance at IP	ϵ_y^* [nm]	30	35	35	20	20
RMS horizontal beam size at IP	σ_x^* [nm]	149	516	474	210	142
RMS vertical beam size at IP	σ_y^* [nm]	2.9	7.7	5.9	3.1	2.1
Num. Bunches per Train	n_b	352	1312	1312	133	75
Train Rep. Rate	f_r [Hz]	50	5	5	120	120
Bunch Spacing	Δt_b [ns]	0.5	554	554	5.26	3.5
Bunch Charge	Q[nC]	0.83	3.2	3.2	1	1

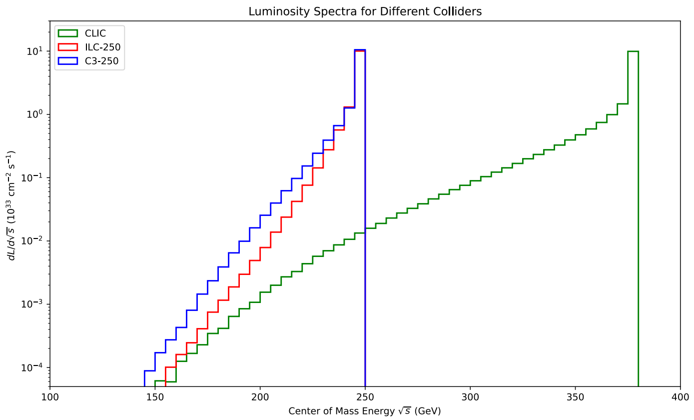
Parameter	Symbol[unit]	CLIC	ILC-250	ILC-500	C^3-250 (PS1)	C^3-550 (PS1)
Horizontal Disruption	D_x	0.26	0.51	0.30	0.32	0.32
Vertical Disruption	D_y	13.1	34.5	24.3	21.5	21.5
Average Beamstrahlung Parameter	$\langle\Upsilon\rangle$	0.17	0.028	0.062	0.065	0.21
Total Luminosity	$\mathscr{L}$ [x10^{34}/cm^2 s]	1.6	1.35	1.8	1.35	1.7
Peak luminosity fraction	$\mathscr{L}_{0.01}/\mathscr{L}$	59%	74%	64%	73%	52%
Enhancement Factor	H_D	1.8	2.6	2.4	1.8	1.8
Average Energy loss	δ_E	6.9 %	3.0 %	4.5 %	3.3 %	9.6 %
Photons per beam particle	n_γ	1.5	2.1	1.9	1.4	1.9
Average Photon Energy fraction	$\langle E_\gamma/E_0\rangle$ [%]	4.6 %	1.4 %	2.3 %	2.5 %	5.1 %
Number of incoherent particles	N_{incoh} [10^4]	6.0	13.3	18.5	4.7	12.6
Total energy of incoh. particles	N_{incoh} [TeV]	187	117	439	58	644

Beam-Beam interactions at linear e^+e^- colliders

- The effects of beam-beam interactions on the experiments can be split in **two categories**:

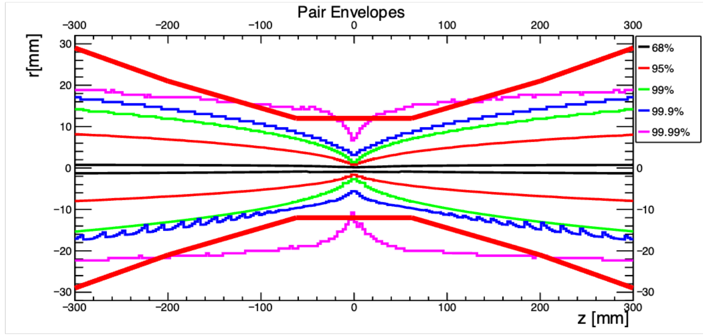
Physics Analyses

- BS widens the luminosity spectrum considerably
- Enables collisions at lower $\sqrt{s}$
- Softens initial state constraints -> important for kinematic fits
- Need to unfold the luminosity spectrum for measurements.
- Photoproduced jets affect clustering performance, JER, JES



Detector Performance

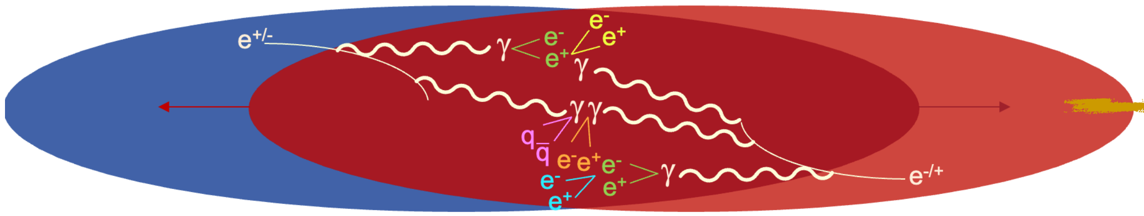
- High flux in vertex barrel and forward sub detectors
- Increase in detector occupancy → might miss interesting Physics (HS) events!
- Impacts detector design decisions, e.g. radius of 1st vertex barrel layer, buffer depth etc.



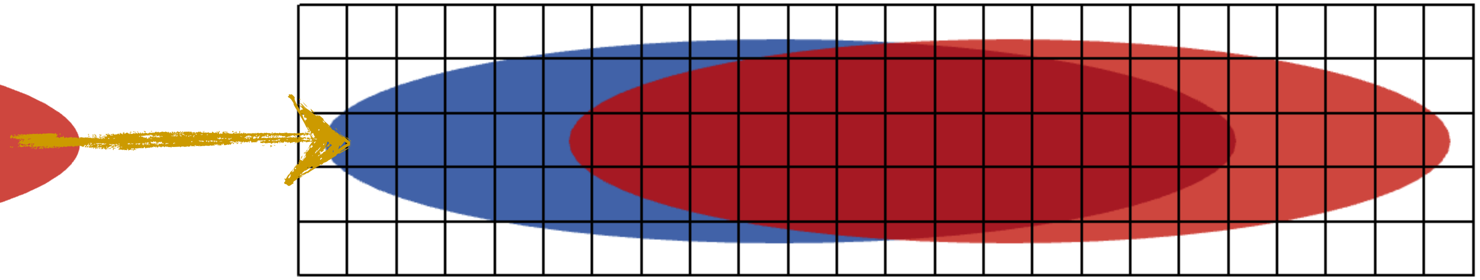
Simulation of Beam-Induced Background

Simulation of Beam-Induced Background

- For the simulation of BIB at e+e- colliders, two simulation tools have traditionally been used, GUINEA-PIG and CAIN.
- Both of them are Particle-In-Cell (PIC) codes that rely on the description of the colliding bunches through an ensemble of macroparticles, distributed on a 3D grid. Poisson solvers are used to update the EM field and charge/current density at each time step.
- QED processes are simulated on top of the EM solvers.
- More modern simulation tools, such as WarpX, are also being adapted to serve the purposes of background simulations for Higgs factories → *see J.L. Vay's talk at the recent C3 workshop*



Jean-Luc Vay



Jean-Luc Vay

Simulation of Beam-Induced Background

GUINEA-PIG++ is used to simulate beam-beam interactions for the C^3 beam configuration at 250 and 550 GeV. Some of the outputs are:

- `.ref` file: contains summary information, including the total instantaneous luminosity (accounting for enhancement factor), the number of background particles produced per BX etc.
- `Pairs.dat` file: contains positions and four-momenta of incoherently produced e^+e^- pairs → used to plot distributions of pair particles and roughly gauge the effect of BIB (and, later on, as input to full detector simulation using dd4hep to quantify effect on detector occupancy – see Lindsey's talk).
- `lumi.ee.out` file: contains four-momenta of colliding particles after Beamstrahlung emission →used to calculate luminosity spectra

Example of how to run GP++

```
./build/bin/guinea --acc_file testing/
acc_lumi_opt.dat "$collider"
Jim_pars_Aug2023 output/"$collider"
_general_optimization/test_"$collider".ref
```

Simulation Parameters

```
$PARAMETERS:: Jim_pars_Aug2023
{n_z=25; n_t=6; n_m=100000; cut_z=3.5*sigma_z.1; n_x=512;
n_y=512;cut_x=20*sigma_x.1; cut_y=20*sigma_y.1; pair_q2=1;
beam_size=1; grids=7; store_beam=1; do_pairs=1;
track_pairs=1; store_pairs=1; do_photons=1;
store_photons=1; do_hadrons=1; do_jets=1; do_coherent=1;
electron_ratio=1; photon_ratio=1; do_eloss=1;
do_espread=1; rndm_seed=978360; rndm_load=0; rndm_save=1;
do_lumi=1; automatic_grid_sizing=0;
bmt_precession=1;pair_ecut=0.;}
```

Simulation of Beam-Induced Background

- The beam parameters that GP++ is used to produce the beams can be modified from the corresponding `.dat` file and include N_e (bunch charge), $\beta^*_{x.y}$ (beta functions at IP), $\epsilon^*_{x,y}$ (transverse emittances at IP), σ^*_z (bunch length). $w_{x,y}$ (transverse waist shifts at the IP), Δx, Δy (beam-beam offsets at the IP), beam polarization, natural energy spread, longitudinal charge distribution, train rep rate f_r and number of bunches per train n_b
- Each one or combinations of these parameters can be changed and GP++ rerun in order to study luminosity and BIB dependence

Example of how to run GP++

```
./build/bin/guinea --acc_file testing/
acc_lumi_opt.dat "$collider"
Jim_pars_Aug2023 output/“$collider”
_general_optimization/test_”$collider”.ref
```

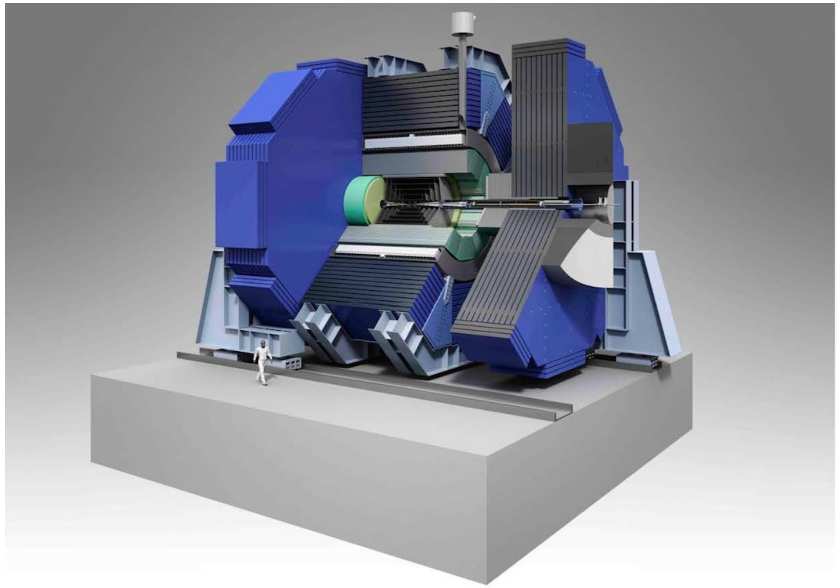
Collider Parameters

```
$ACCELERATOR:: C3_250
{energy=125.0;particles=0.624;charge_sign=-1;
beta_x=12.0;beta_y=0.12;
emitt_x=0.9;emitt_y=0.02;
sigma_z=100.0;
scale_step=1.0;
polar_z.1=-0.8;polar_z.2=0;
espread=0.003;which_espread=3; dist_z=0;
f_rep=120;n_b=133;
offset_y=0.;offset_x=0;
waist_y=0;}
```

Simulation of Beam-Induced Background

For all C³ studies, we use well-established and/or modern software tools, to guarantee modularity, preservation and reusability of our code:

- For the simulation of beam-beam interactions, the tools **GuineaPig++** and **CAIN v2.4.2** have been used and their results cross-validated.
- For full detector simulation with GEANT4, **DD4hep** is used.
- The SiD detector geometry (02_v04) is ported from **k4geo** (lcgeo).



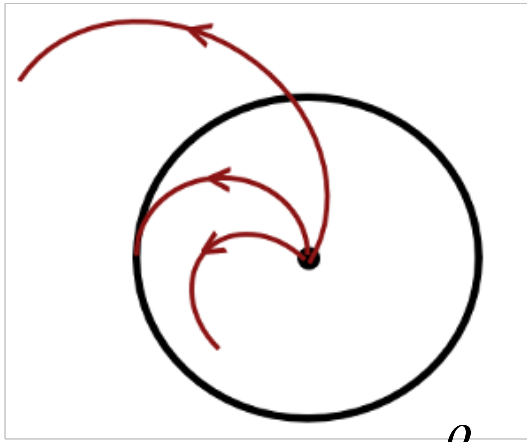
Links

GUINEA-PIG
Key4hep
DD4hep
k4geo

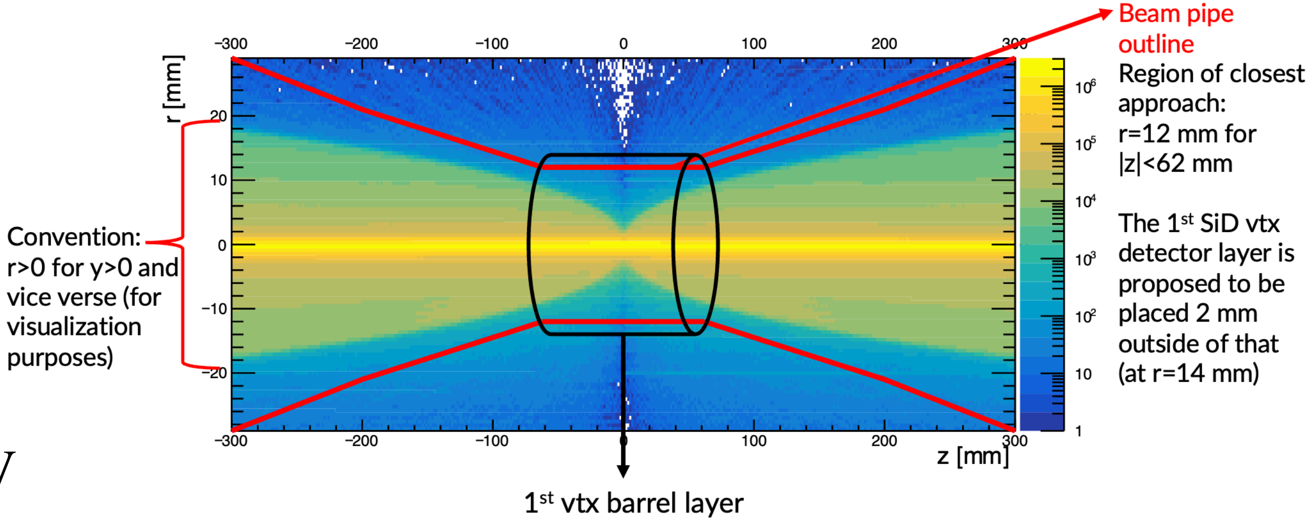
* *Also: efforts with MUCARLO ongoing to simulate the halo muon background*

Pair background at linear e^+e^- colliders

- The produced incoherent pairs are mostly at low p_T and get significantly deflected in the strong magnetic field (~T) of the detector. Thus, most of them are "washed" away from the Interaction Region (IR) within the beam-pipe → **pair background envelope**
- However, those that reach the detector (for C3, $\sim 0.1\ \%$ or ~ 40 particles/BX) can increase its occupancy and impact its performance, compromising the very stringent precision requirements of the experiment.
- The ***vertex barrel detector***, which is the closest to the IP (r=14 mm for the 1st layer of SiD) and is necessary for precise vertexing and tagging, is mostly affected.



$$p_T^{(\mathrm{min})}[\mathrm{MeV}] = 0.3 \cdot B[\mathrm{T}] \cdot \frac{\rho}{2}[\mathrm{mm}] \simeq 10\ \mathrm{MeV}$$

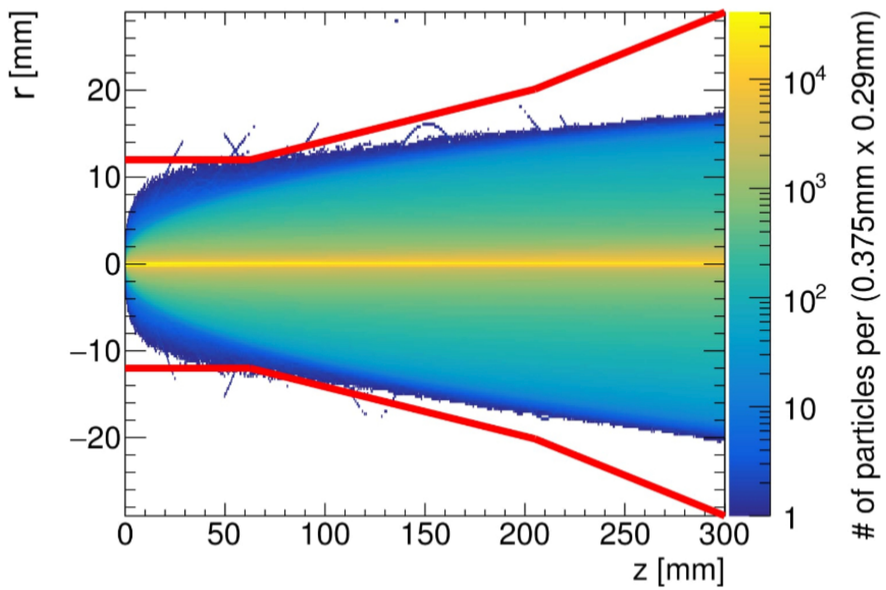


Pair Background Envelopes

Results shown here correspond to $\sqrt{s} = 250$ GeV , $B = 5$ T *(uniform)*

ILC - Previous results

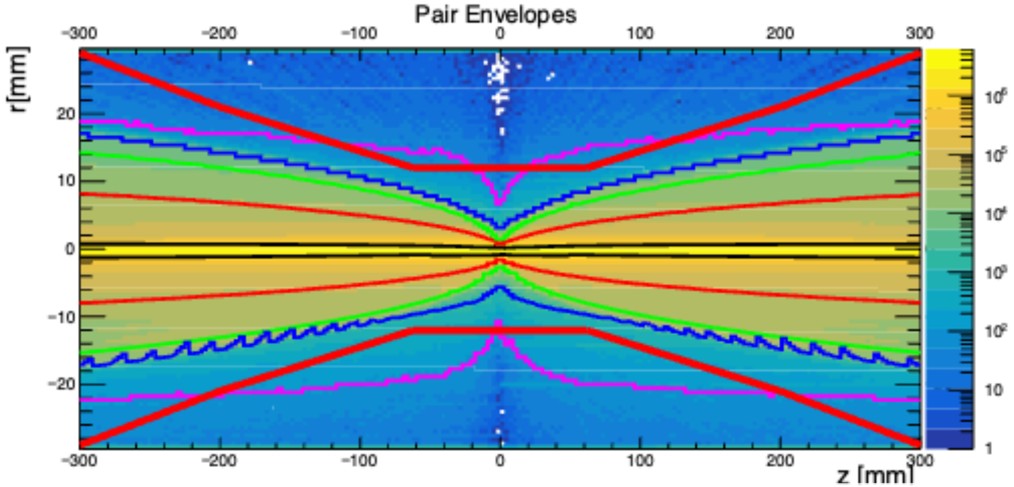
r vs z

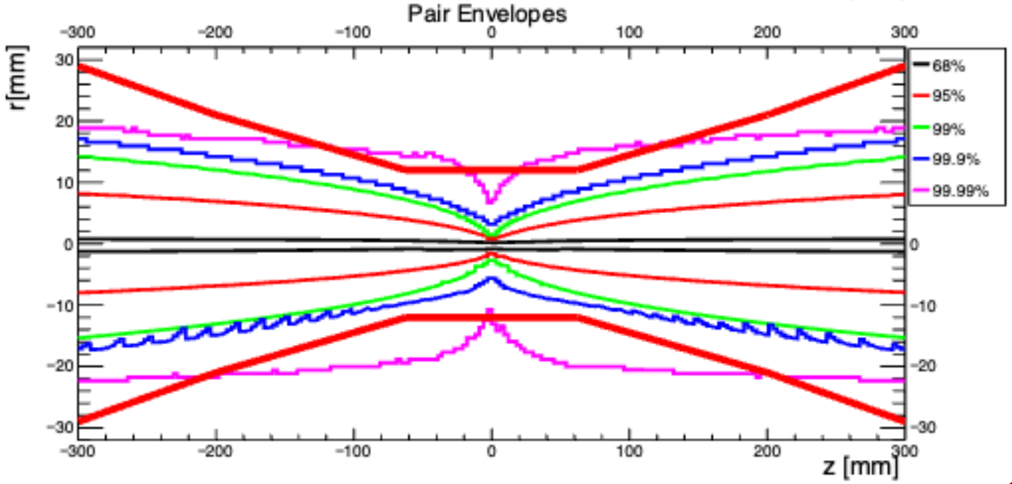


From Anne Schutz's PhD thesis (2018)

C³ - New results

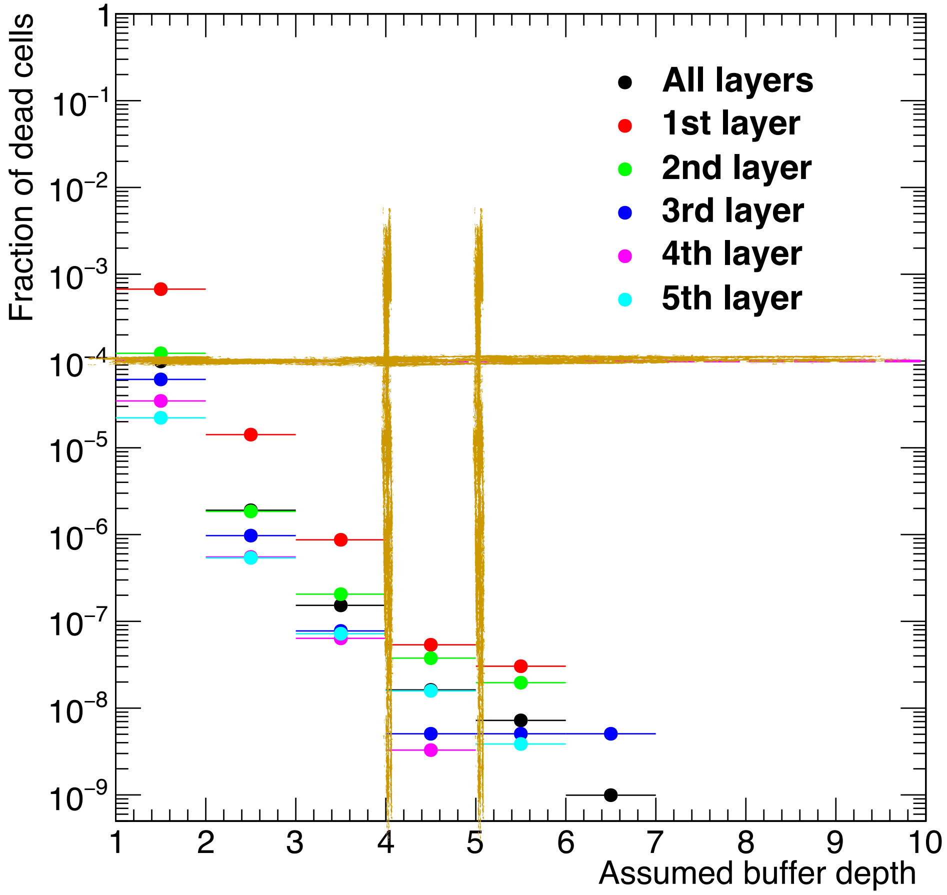
r vs z





Pair background occupancy

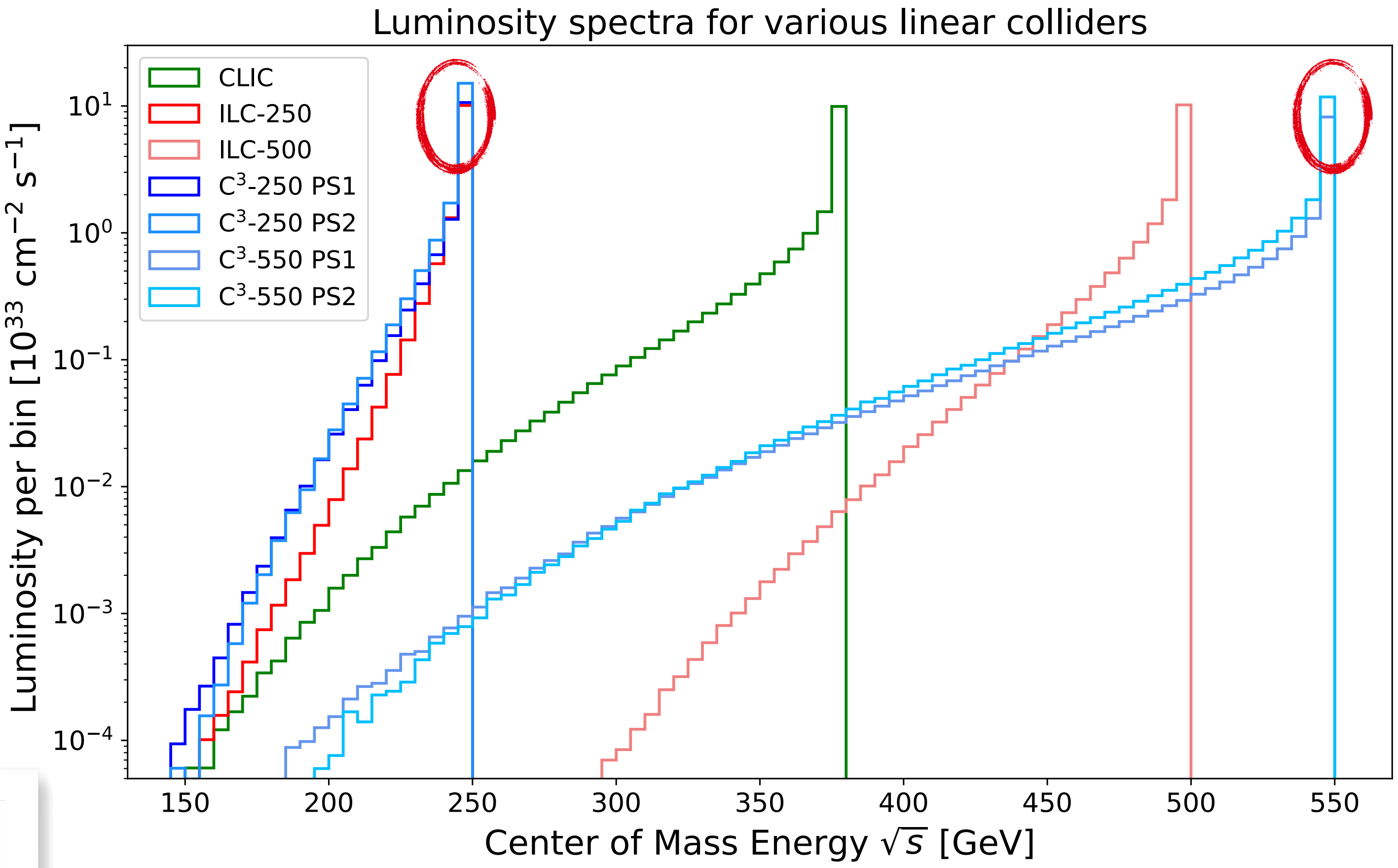
- We define the detector **occupancy** as the fraction of dead cells, i.e. cells with a number of hits $\geq$ the available number of buffers (called **buffer depth**).
- In the current readout schemes, hits will be stored in the buffer system and read out after each bunch train.
- To estimate the occupancy, we run full detector simulations for all pair background particles for a full C^3 bunch train (133 BXs).
- For ILC detectors, an occupancy upper limit of 10^{-4} and buffer depth of 4 has been proposed.
- *The occupancy in the SiD vertex barrel for the C^3 beam structure is well within that limit.*



Occupancy in the vertex barrel as a function of assumed buffer depth for C^3-250.

Luminosity Spectra

- The *luminosity spectrum* broadens when beam-beam interactions are increased, leading to energy losses for the beam particles.
- ***For C³, PS2 leads to luminosity enhancement at the peak, without significant increases in the tails.***
- For C³-550, further optimizations are required in order to reduce the luminosity spread.



Detailed Luminosity Studies: 2403.07093

$$x_{1,2} = \frac{E_{1,2}}{E_{\text{beam}}}, \quad x = \frac{\sqrt{s}}{\sqrt{s_0}} = \sqrt{x_1 x_2}$$

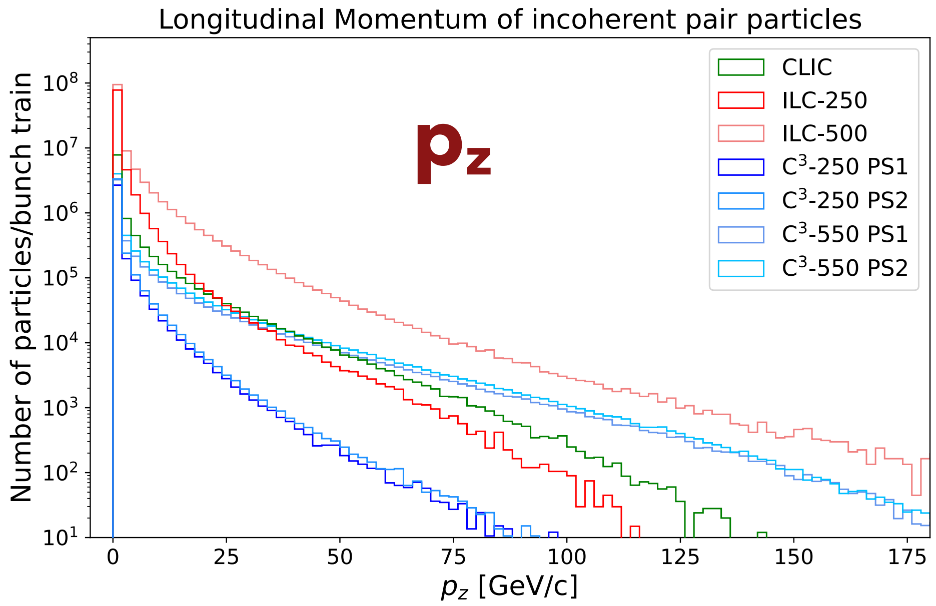
$$\mathscr{L}(x) = \iint_0^{x_{\max}} dx_1 dx_2 \delta(x - \sqrt{x_1 x_2}) \mathscr{L}(x_1, x_2)$$

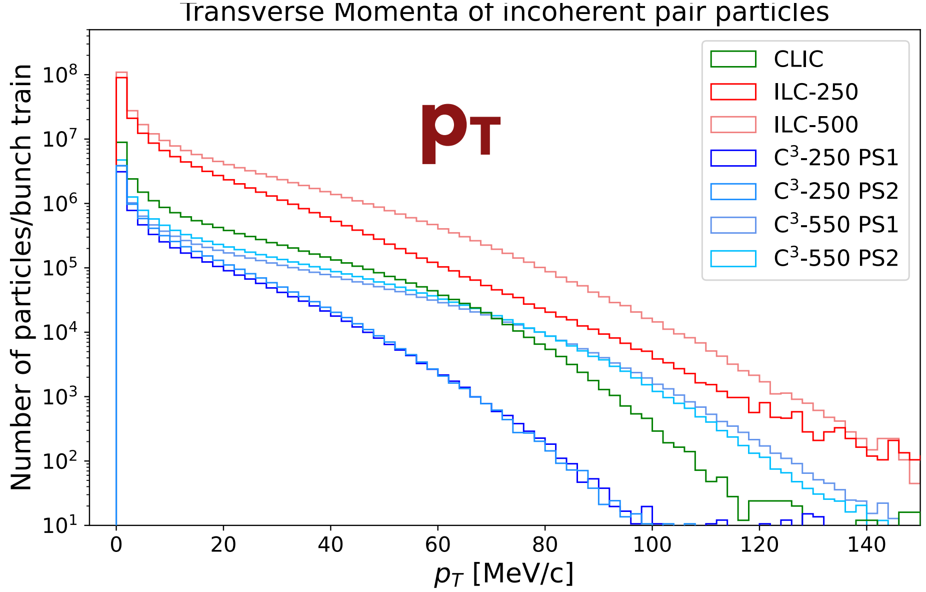
$$\sigma_{\text{eff}} = \int_0^{x_{\max}} dx \mathscr{L}(x) \sigma(x\sqrt{s_0})$$

Comparison with other linear colliders

- Longitudinal and transverse momenta distributions for the incoherently produced background e^+e^- pairs.
- Pair particles are mostly boosted in the forward direction.
- The normalization corresponds to the expected number of pairs produced per bunch train $\langle N_{\text{incoh}} \rangle \cdot n_b$, assuming a common per-bunch-train readout scheme for all colliders.
- ***C³ has a smaller, overall, number of pair particles produced but would have to deal with a much faster readout rate of 120 Hz.***

Detailed Luminosity Studies: [2403.07093](2403.07093)





Simulation of Beam-Induced Background

Hadron Photoproduction

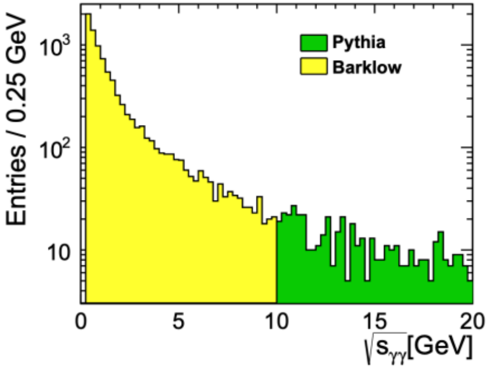


FIG. 1: Energy spectrum of $\gamma\gamma \to$ low p_T hadron events as a function of centre-of-mass energy. The figure shows the energy cutoff of 10 GeV below which the events are generated by the Barklow generator. Above 10 GeV the events are generated by Pythia.

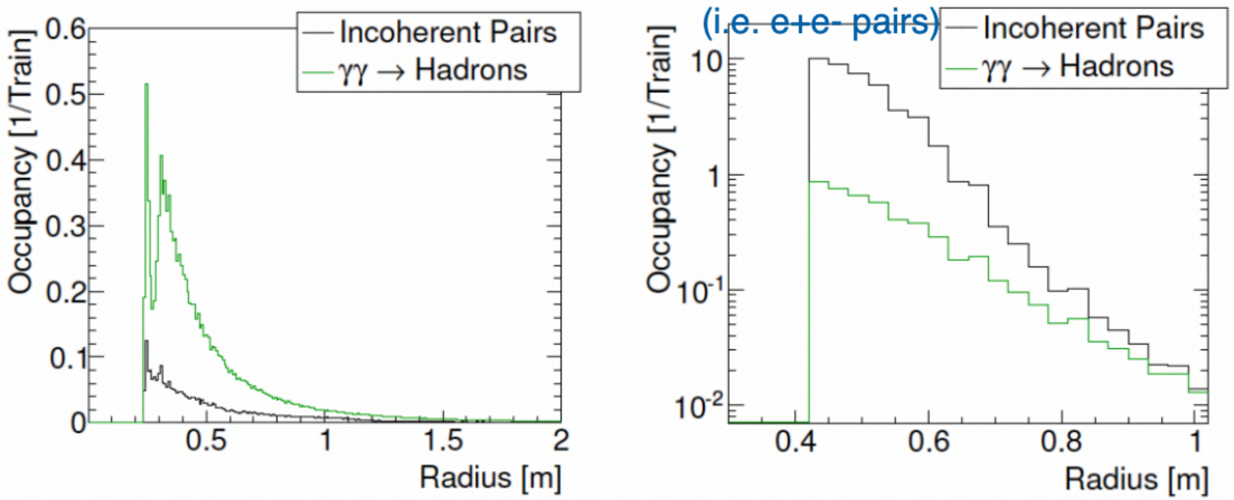


Figure 14. The radial distribution of the train occupancy per pad in ECal (left) and per cell in HCal (right) endcap [10].

Hadron Backgrounds in **Pythia5.7 -> Pythia8**, Latest Whizard and CIRCE

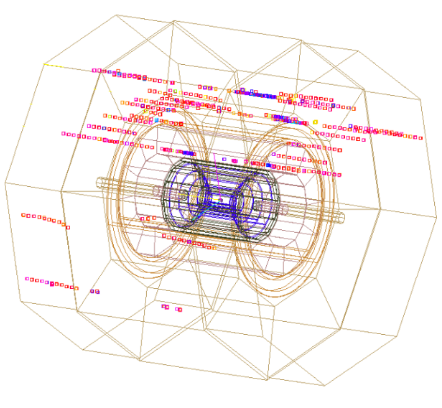
- Presently at the step of generating the appropriate background mixture from estimated virtual photon flux (re-achieve upper left plot!)

See Lindsey's talk

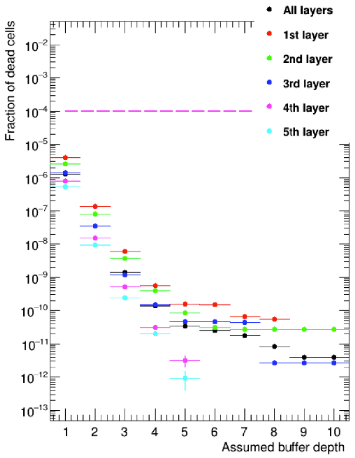
Conclusions

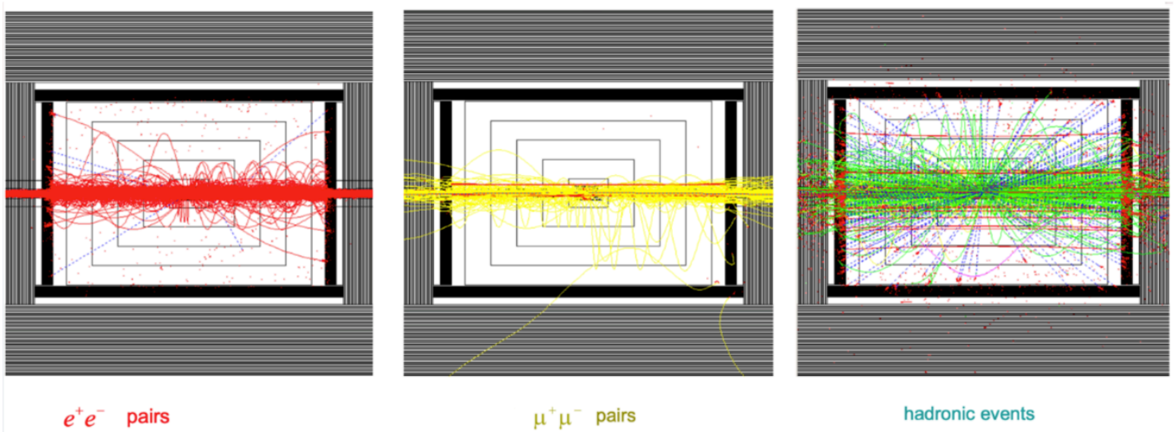
Ongoing efforts (C^3 specific)

- The pair background might be the dominant BIB for C^3, but other sources of background are also important and under study:
  - hadron photoproduction background $\gamma\gamma \rightarrow \text{hadrons}$ (Elias Mettner, Abdollah Mohammadi - UWM, Lindsey Gray - Fermilab)
  - Machine Induced Backgrounds: halo muon background (Kenny Jia, DN, CV - Stanford & SLAC, LG - Fermilab), neutron background from beam dumps
  - Out-of-time pileup mixing and pileup overlay (LG - Fermilab)



(a) *3D view, 5 spoilers + wall, ILC250*





Conclusions

- Main beam-related backgrounds for Higgs factories are **incoherent pair production** and **hadron photoproduction**.
- **GUINEA-PIG/CAIN** and **dd4hep** are some of the main software tools used for the generation of these backgrounds and their interface with the detector.
- Very common background characteristics among all, linear and circular, Higgs factory proposals → a lot of room for synergies and sharing of knowledge & expertise.

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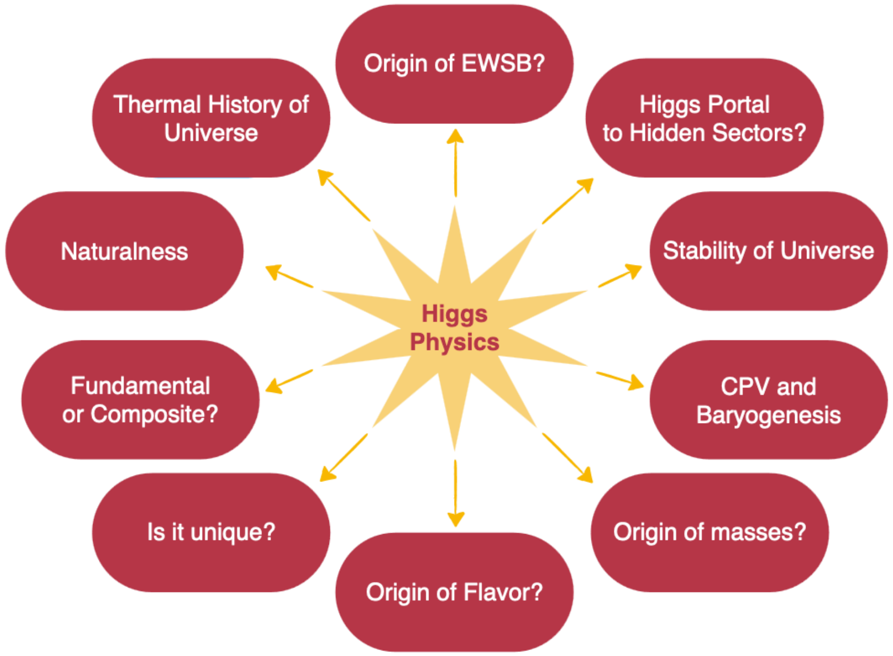
Thank you for your attention!

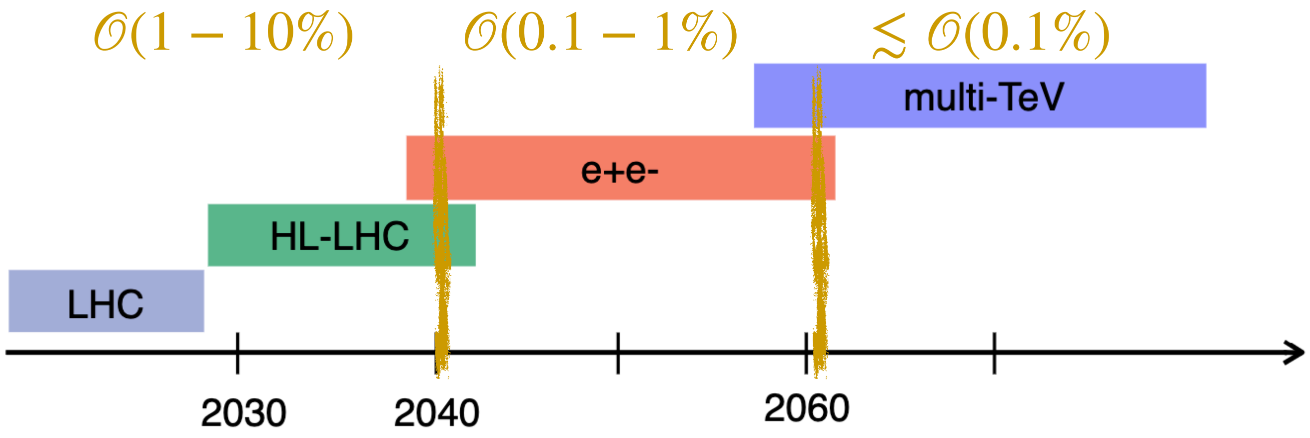
Questions?

Backup

Benefits of e+e- colliders

- The Higgs boson is the latest experimentally verified addition to the SM and a pathway to answering many fundamental questions in Particle Physics and beyond.
- This requires measurements of its properties with precision at the percent and sub percent level, which lies beyond the capabilities of HL-LHC.

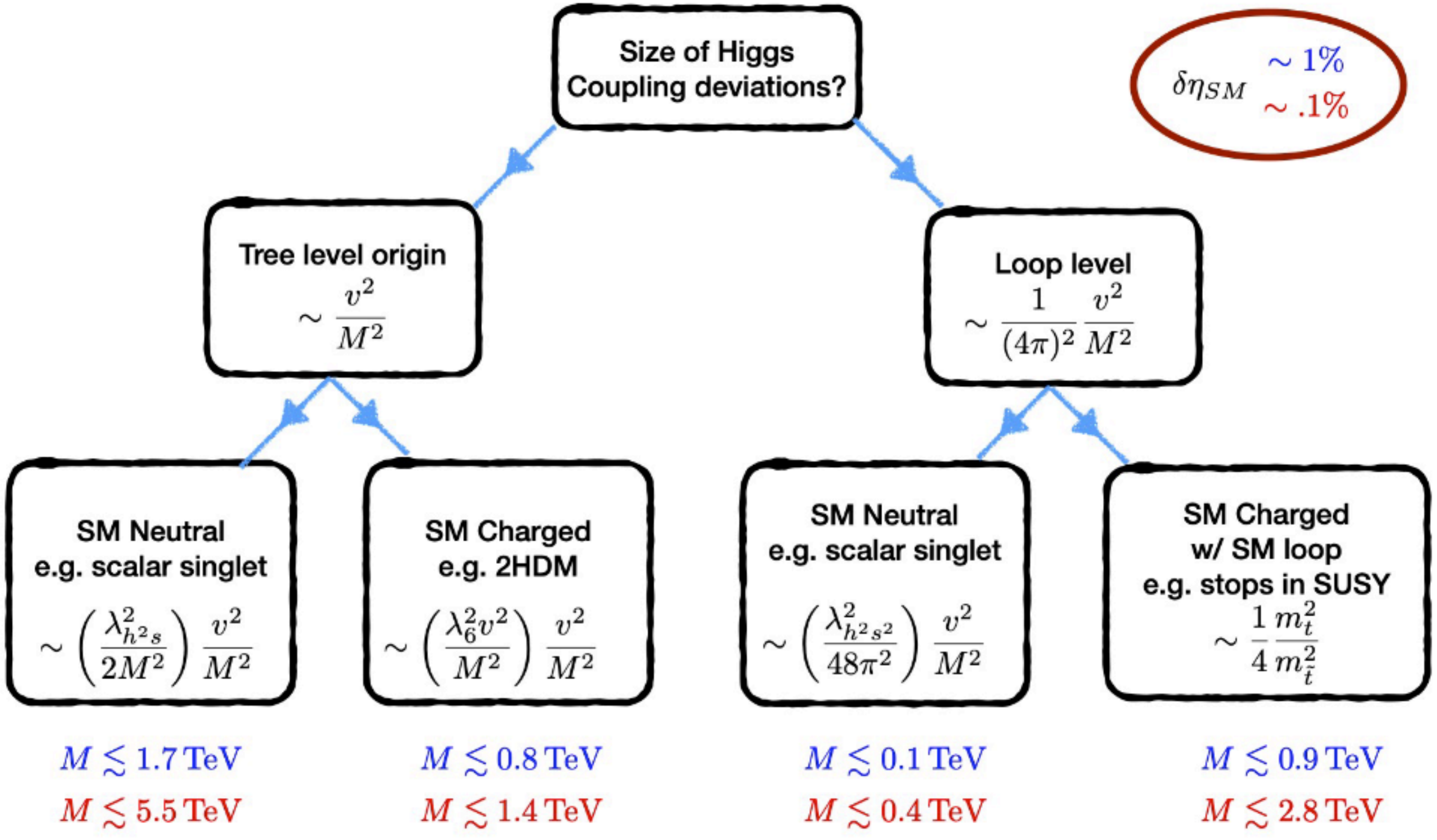




[Snowmass EF01 & EF02 Report]

Benefits of e^+e^- colliders

- Higgs precision measurements at the percent and sub-percent level enables tests of new Physics at the **TeV** scale.

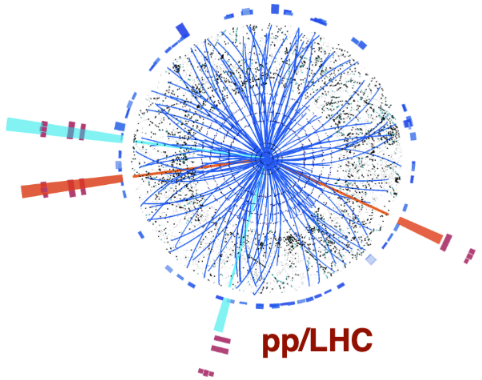


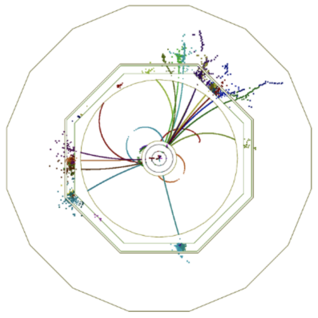
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

[Snowmass EF01 & EF02 Report](#)

Benefits of e+e- colliders

- Electron-positron colliders are precision machines that can serve as **Higgs factories**. They offer:
  - *A well-defined initial state*
  - *A "clean" and trigger less experimental environment*
  - *Longitudinal polarization (only possible at linear machines) → increases sensitivity to EW observables, suppresses backgrounds, controls systematics*





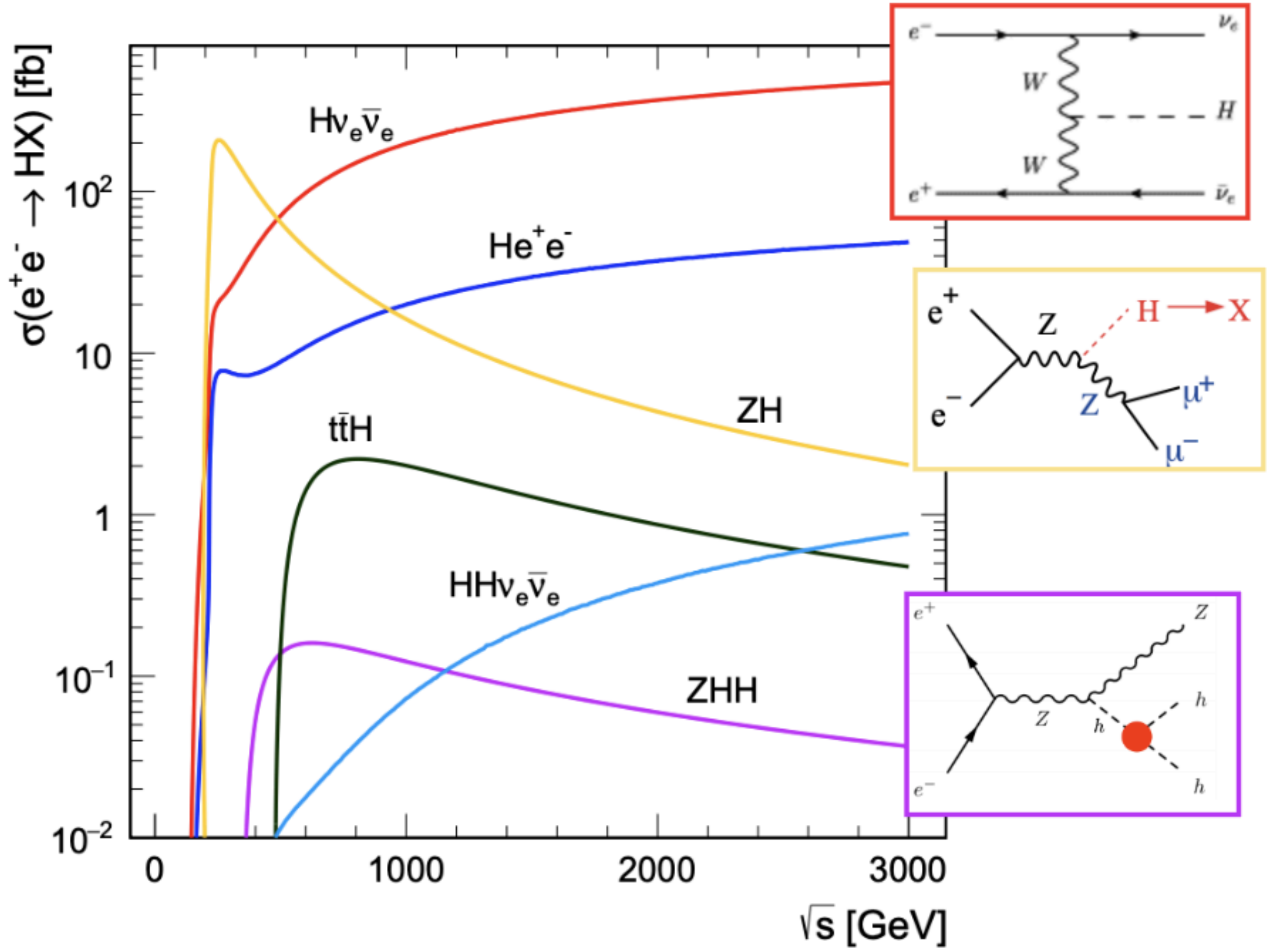
~ $\mathcal{O}(10^{-1})$ % *Level precision*

Relative Precision (%)	HL-LHC	CLIC-380	HL-LHC + ILC-250/C^3-250	HL-LHC + ILC-500/C^3-550	FCC 240/360	CEPC-240/360
hZZ	1.5	0.34	0.22	0.17	0.17	0.072
hWW	1.7	0.62	0.98	0.20	0.41	0.41
$hb\bar{b}$	3.7	0.98	1.06	0.50	0.64	0.44
$h\tau^+\tau^-$	3.4	1.26	1.03	0.58	0.66	0.49
hgg	2.5	1.36	1.32	0.82	0.89	0.61
$hc\bar{c}$	-	3.95	1.95	1.22	1.3	1.1
$h\gamma\gamma$	1.8	1.37	1.36	1.22	1.3	1.5
$h\gamma Z$	9.8	10.26	10.2	10.2	10	4.17
$h\mu^+\mu^-$	4.3	4.36	4.14	3.9	3.9	3.2
$ht\bar{t}$	3.4	3.14	3.12	2.82/1.41	3.1	3.1
hhh	50	50	49	20	33	-
Γ_{tot}	5.3	1.44	1.8	0.63	1.1	1.1

~ $\mathcal{O}(1)$ % *Level precision*

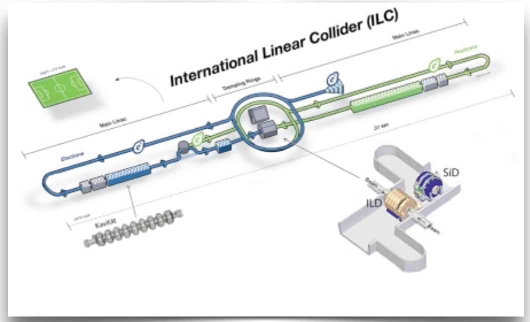
Benefits of e+e- colliders

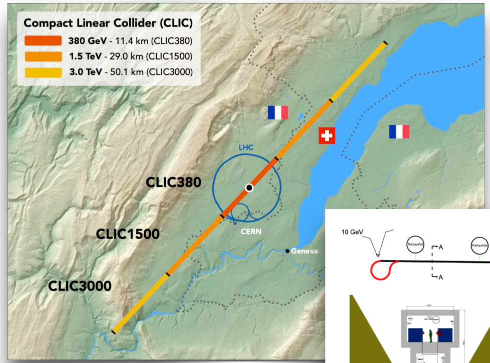
- At e+e- machines, Higgs bosons are produced mainly through the ZH process at $\sqrt{s} \simeq 250$ GeV.
- This process allows model-independent determination of the Higgs width and BRs using the recoil technique.
- At higher energies, above ~ 500 GeV:
  - $\nu\nu H$ dominates, with ttH also becoming accessible
  - Direct double Higgs production can be probed with ZHH

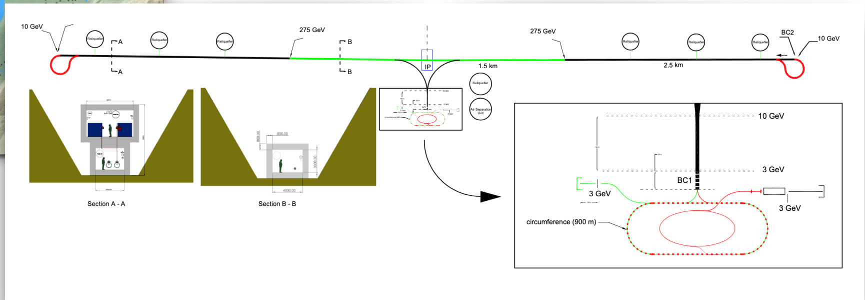


Future Higgs Factory Proposals

- High-energy colliders designed to produce Higgs bosons at large numbers ($\sim \mathcal{O}(10^4)$/year) for precision Higgs physics measurements are called **Higgs factories** (**HFs**).
- HFs fall under two main categories: **linear** and **circular** machines, with common luminosity requirements of $\mathscr{L}_{\text{inst}} \sim \mathcal{O}(10^{34})\ \text{cm}^{-2}\ \text{s}^{-1}$ for all.







Linear

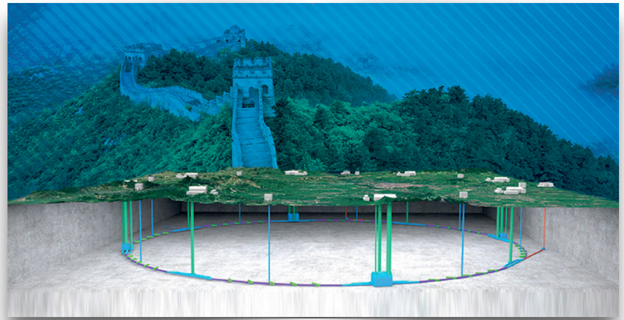
ILC, CLIC, C³

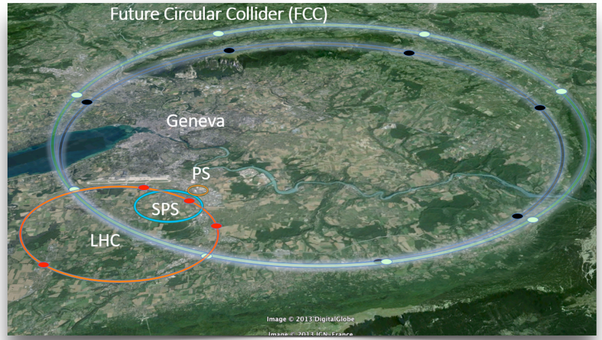
- \+ Reach higher $\sqrt{s}$ (*path to TeV*)
- \+ Longitudinal polarization
- – Lumi limited by beam focusing requirements
- – Single Interaction Point (IP)

Circular

FCC-ee,CEPC

- – $\sqrt{s}$ reach limited by SR (up to ~360 GeV)
- – No beam polarization
- \+ Higher luminosity at lower energies (EW Physics)
- \+ Can accommodate multiple IPs





Future Higgs Factory Proposals

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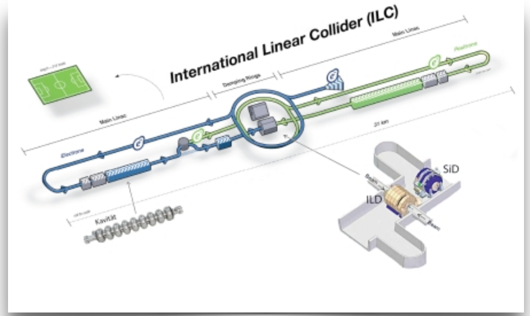
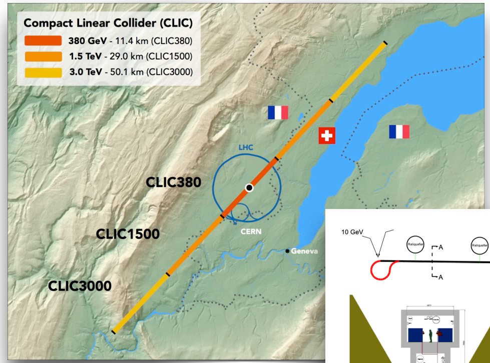
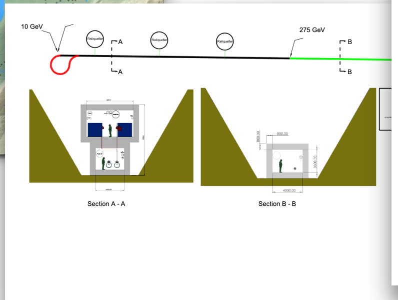






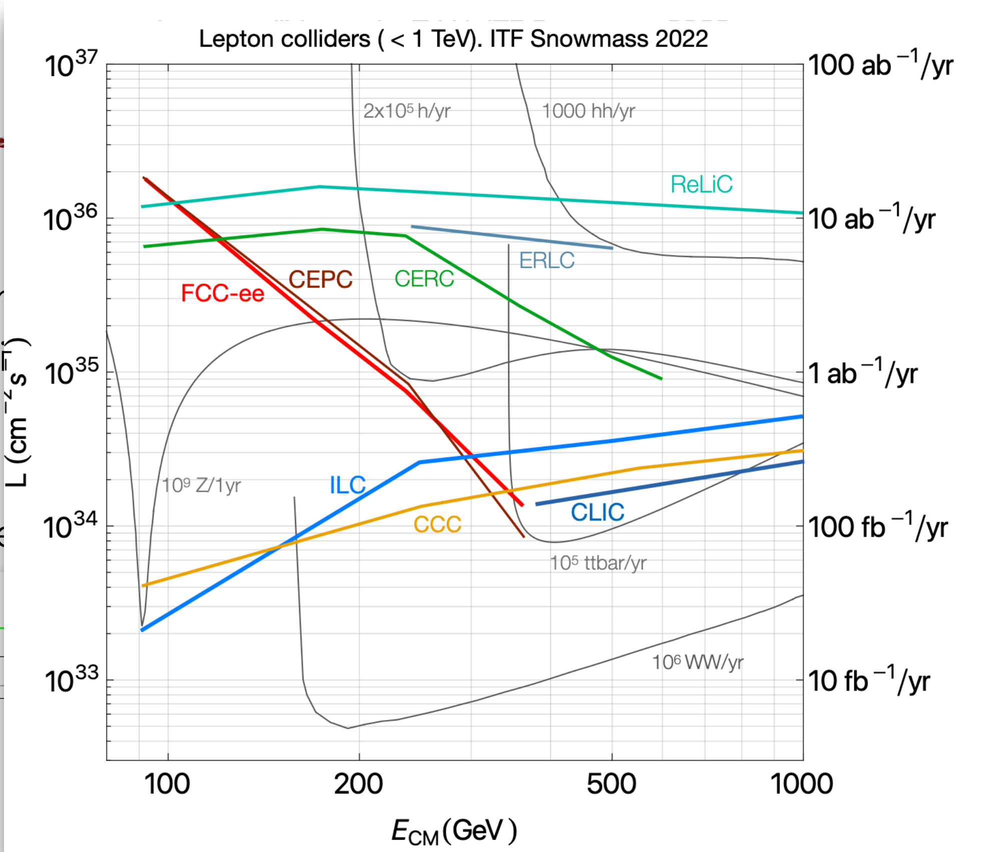
+ Reach

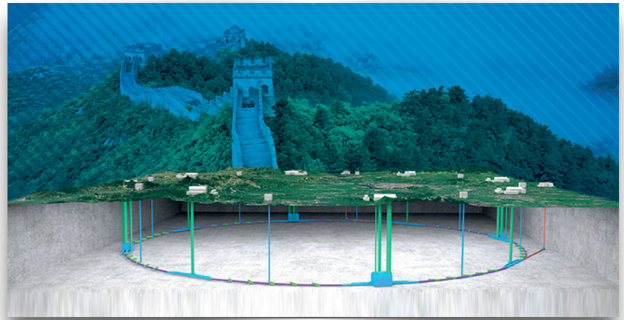
+ Long

– Lumi

require

– Single

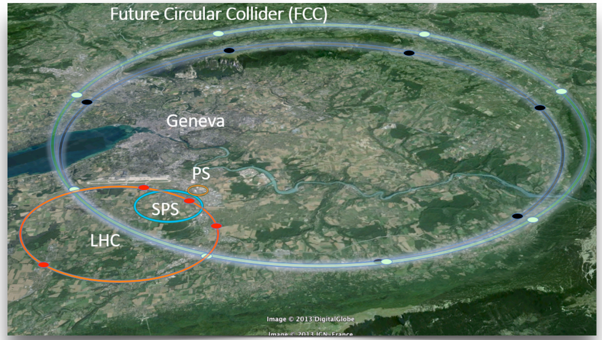




(up to ~360 GeV)

wer energies (EW

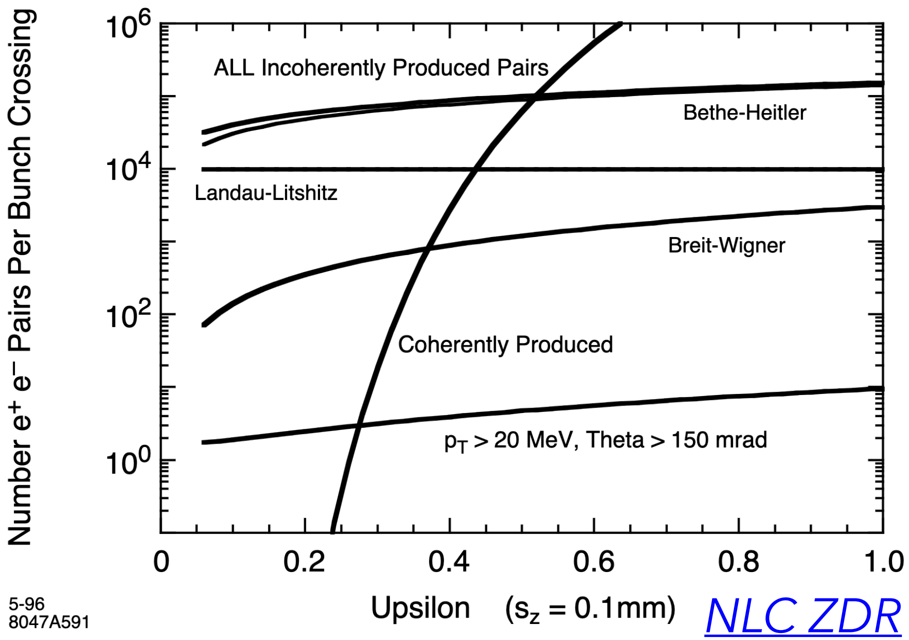
ltiple IPs



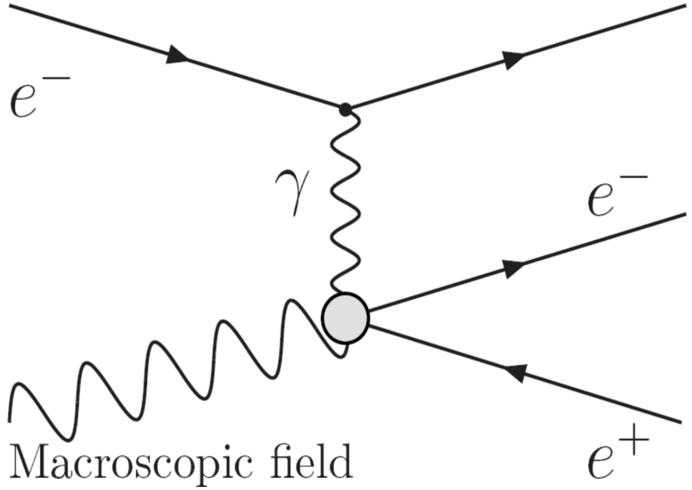
Beam-Beam interactions at linear e⁺e⁻ colliders

- In addition to **incoherent pair production**, which stems from interactions of individual, real or virtual, photons, e^+e^- pairs can also be produced through the following mechanisms:
  - **Coherent pair production**: interaction of BS photon with the collective EM field of the beams → exponentially suppressed for $\langle\Upsilon\rangle \lesssim 0.5$
  - **Trident cascade**: interaction of virtual photon with the collective EM field of the beams → non-negligible for $\langle\Upsilon\rangle > 1$

- Those backgrounds are *negligible for HFs*, but *become significant for high Beamstrahlung advanced-accelerator-concept (AAC) colliders*, e.g. WFA-based.



NLC ZDR

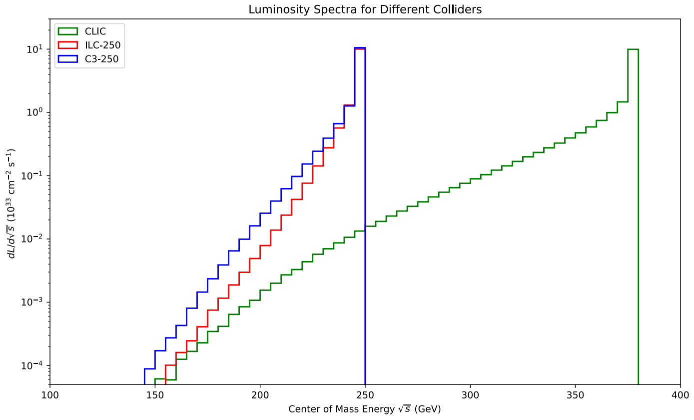


Beam-Beam interactions at linear e^+e^- colliders

- The effects of beam-beam interactions on the experiments can be split in **two categories**:

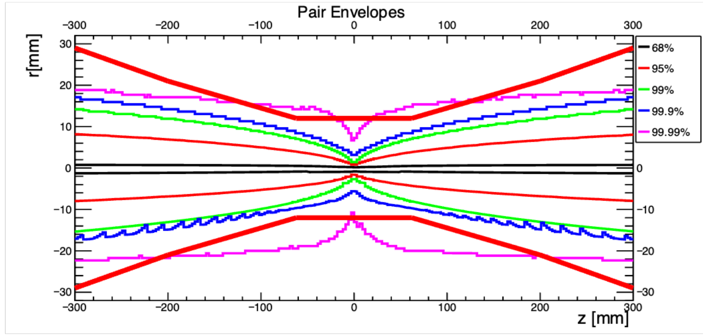
Physics Analyses

- BS widens the luminosity spectrum considerably
- Enables collisions at lower $\sqrt{s}$
- Softens initial state constraints -> important for kinematic fits
- Need to unfold the luminosity spectrum for measurements.
- Photoproduced jets affect clustering performance, JER, JES

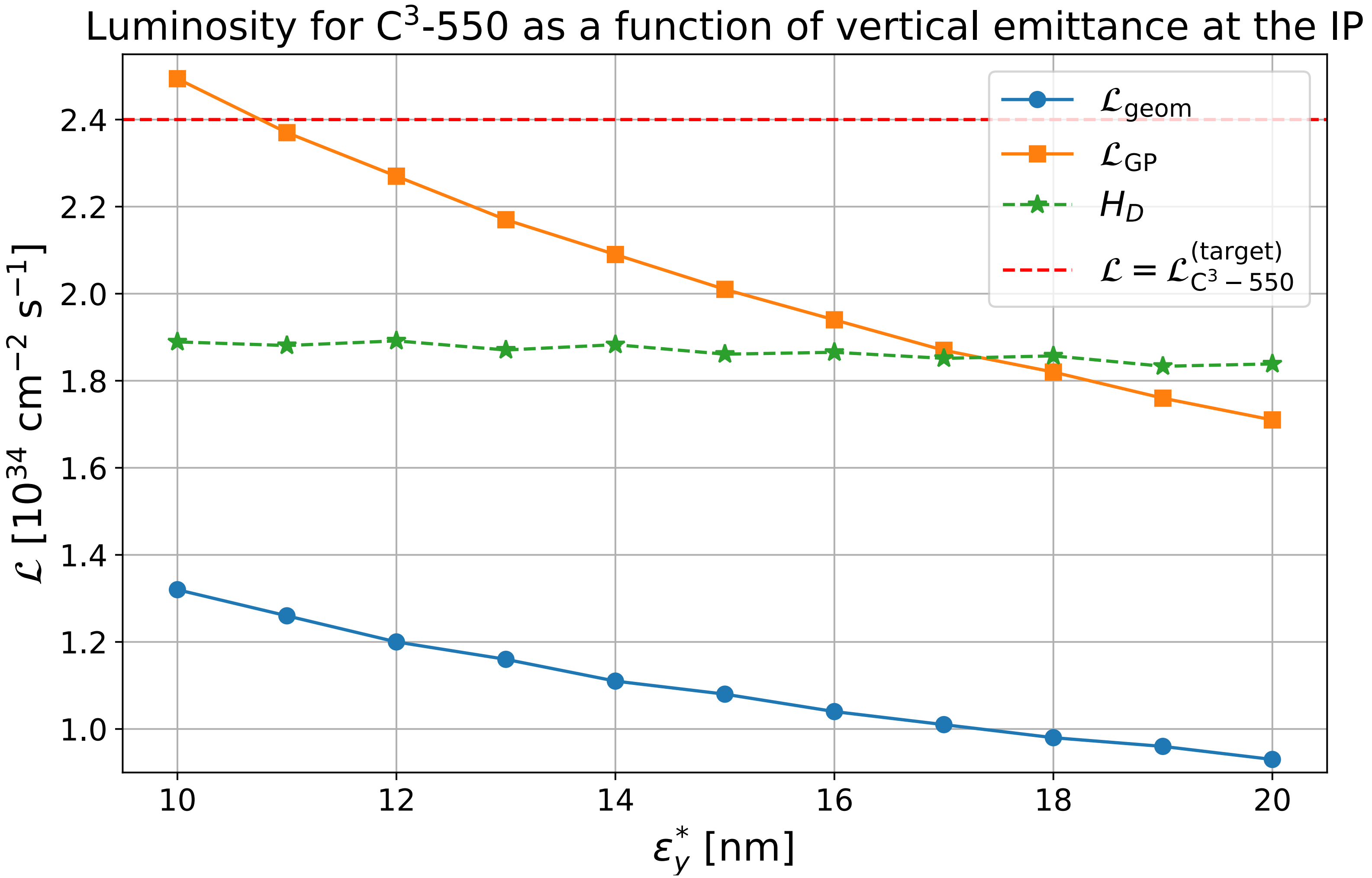


Detector Performance

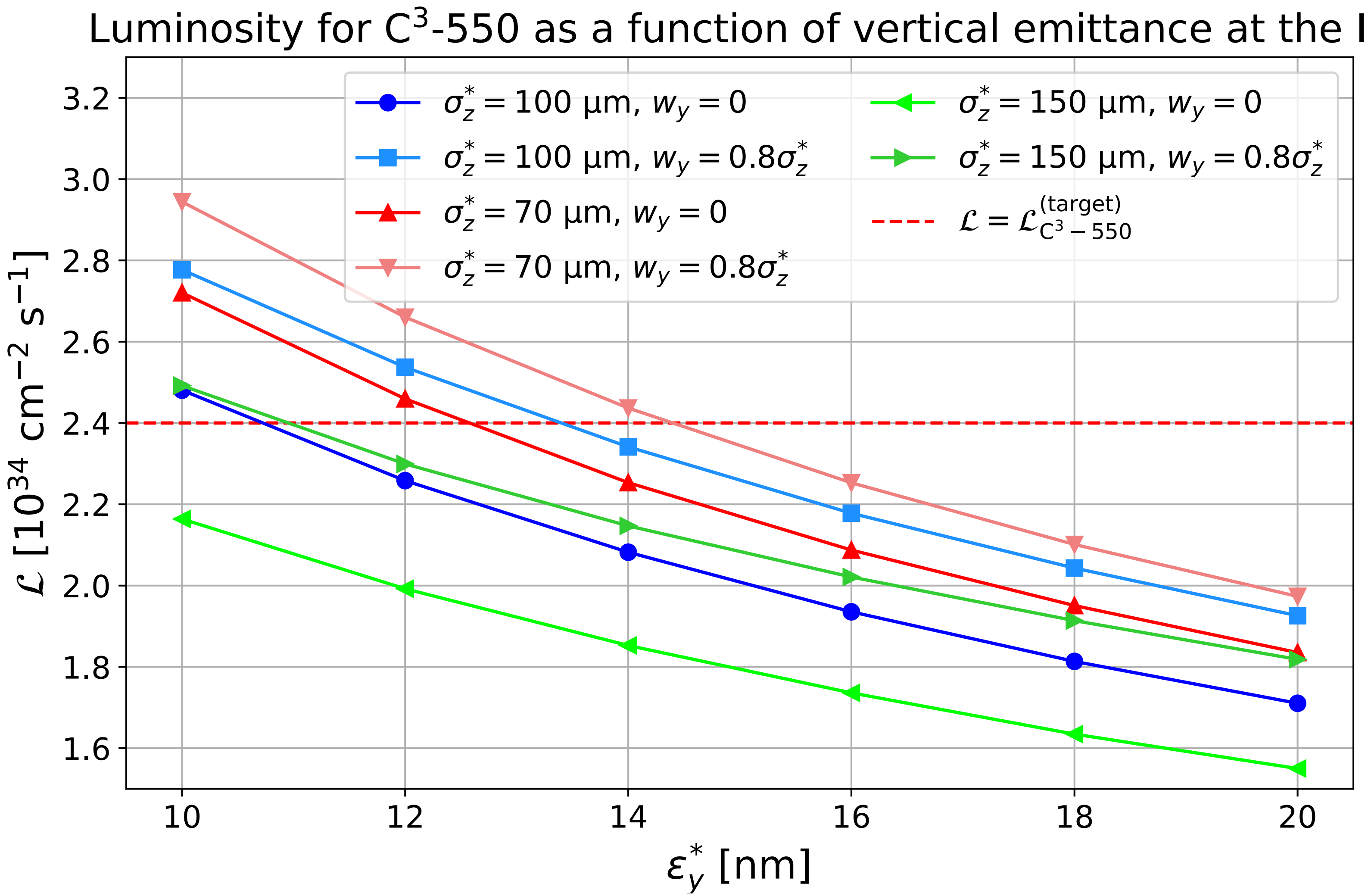
- High flux in vertex barrel and forward sub detectors
- Increase in detector occupancy –> might miss interesting Physics (HS) events!
- –> impacts detector design decisions, e.g. radius of 1st vertex barrel layer, buffer depth etc.



C^3 Optimization - C^3-550

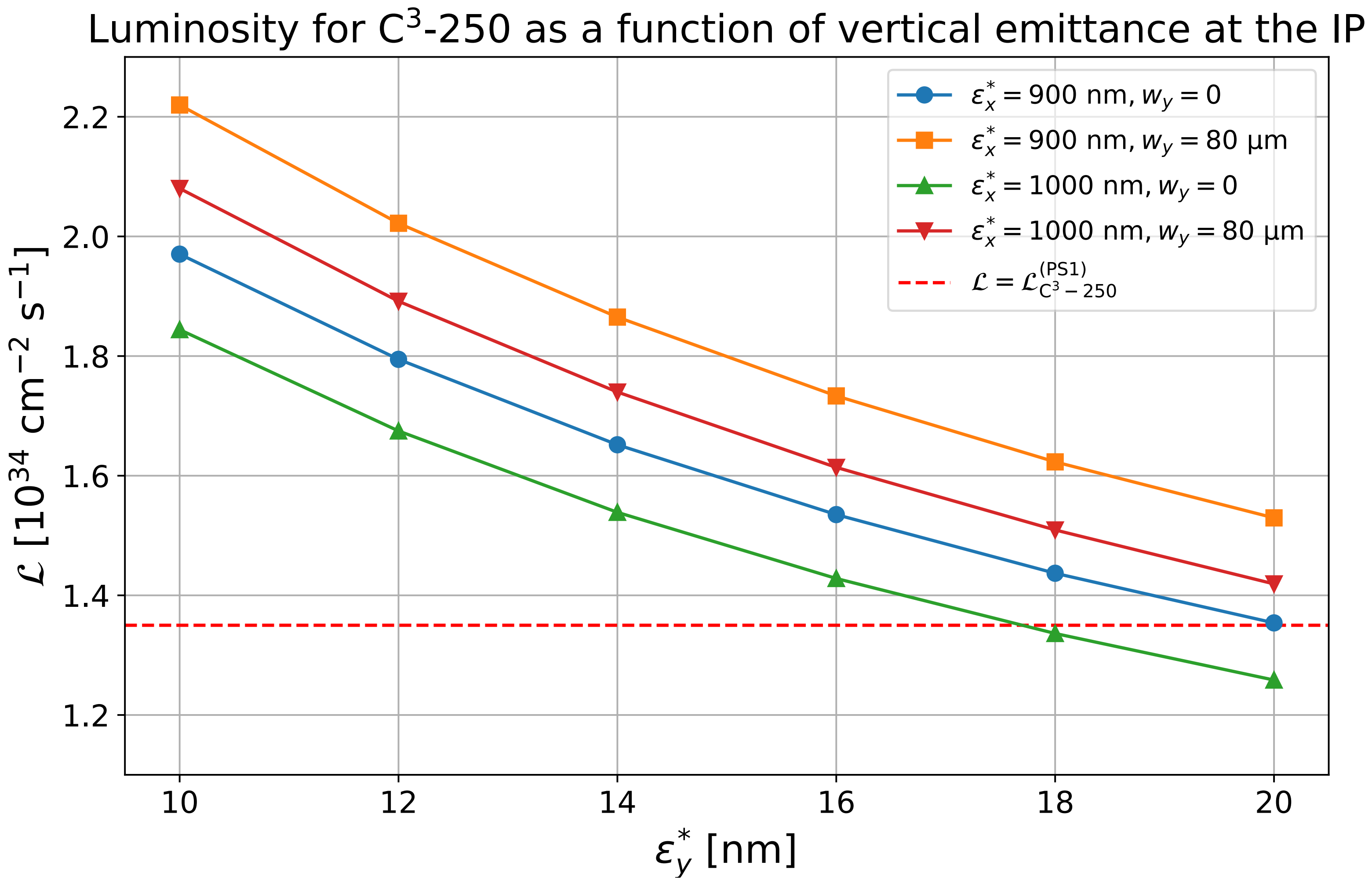


**Luminosity for C^3-550 as a function of vertical emittance. All other parameters retain same values as in PS1.*



Luminosity for C³-550 as a function of vertical emittance for different bunch lengths and waist shifts. All other parameters retain same values as in PS1.

C^3 Optimization - C^3-550



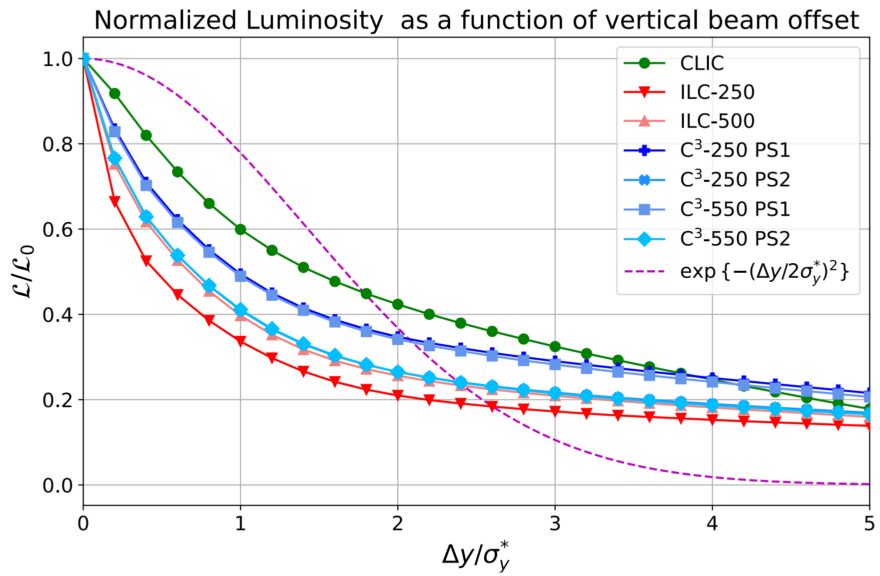
**Luminosity for C^3-250 as a function of vertical emittance for different bunch lengths and waist shifts. All other parameters retain same values as in PS1.*

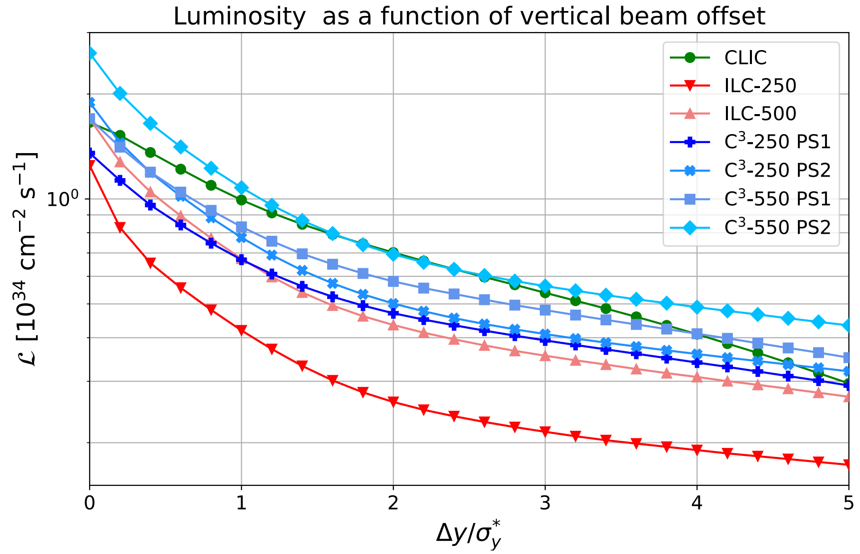
C^3 Optimization - Offset dependence

- $\mathcal{L}$ decreases rapidly in the presence of beam-beam offsets in the vertical direction.
- Due to the presence of beam-beam forces, the decrease is more rapid at small offsets due to the *kink instability* but stabilizes at larger offsets due to the beam attracting each other.
- Sub-nm offsets at the IP are necessary in order to achieve luminosities close to the nominal values (i.e. assuming no offset).
- $\mathcal{L}$ degradation can be mitigated by optimizing beam parameters to achieve smaller vertical disruption D_y.

Offset dependence driven by value of disruption parameter

$$D_{x,y} = \frac{2N_e r_e \sigma_z^*}{\gamma \sigma_{x,y}^* (\sigma_x^* + \sigma_y^*)}$$





Comparison with other linear colliders - Tables

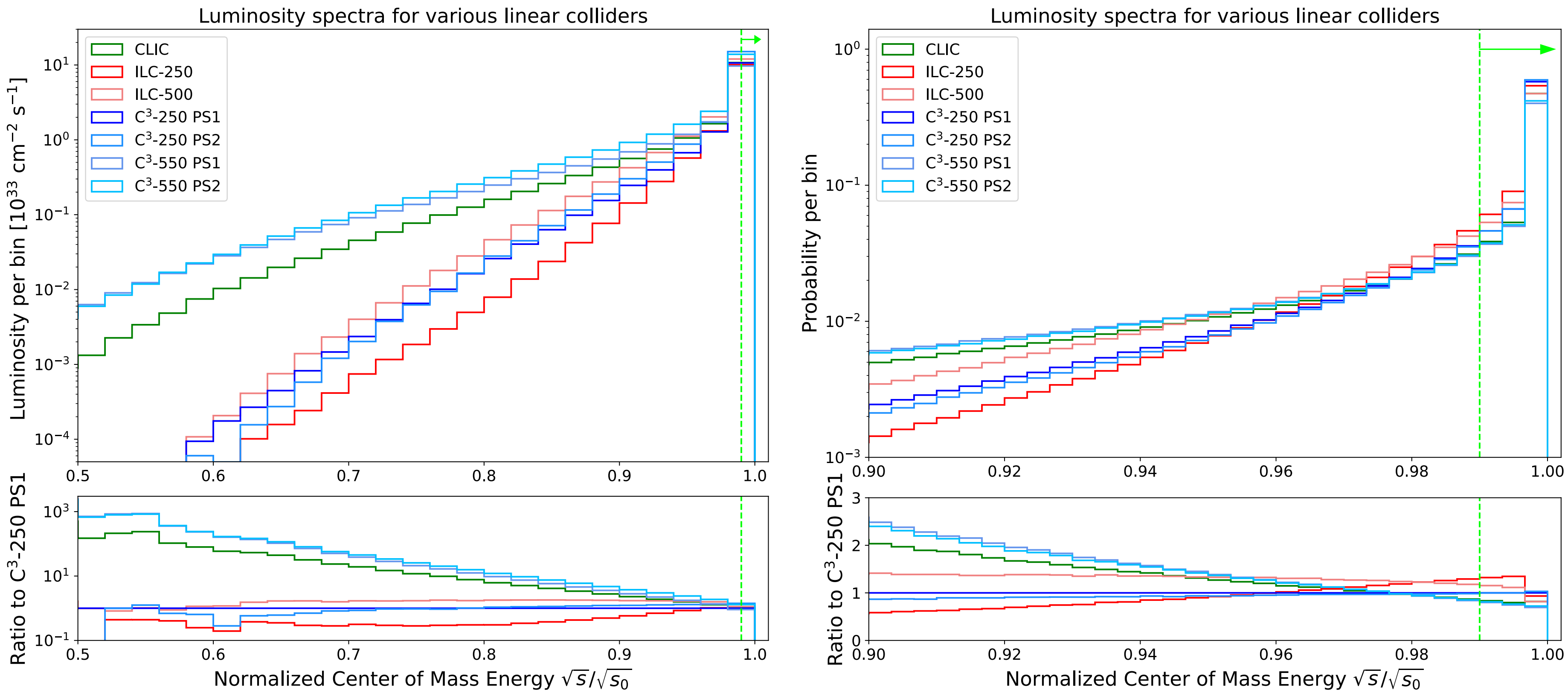
Parameter	Symbol[unit]	CLIC [19]	ILC-250 [20]	ILC-500 [20]	C^3-250 (PS1) [6]	C^3-550 (PS1) [6]
CM Energy	$\sqrt{s}$[GeV]	380	250	500	250	550
RMS bunch length	σ_z^*[µm]	70	300	300	100	100
Horizontal beta function at IP	β_x^* [mm]	8.2	13	22	12	12
Vertical beta function at IP	β_y^* [mm]	0.1	0.41	0.49	0.12	0.12
Normalized horizontal emittance at IP	ϵ_x^* [nm]	950	5000	5000	900	900
Normalized vertical emittance at IP	ϵ_y^* [nm]	30	35	35	20	20
RMS horizontal beam size at IP	σ_x^* [nm]	149	516	474	210	142
RMS vertical beam size at IP	σ_y^* [nm]	2.9	7.7	5.9	3.1	2.1
Num. Bunches per Train	n_b	352	1312	1312	133	75
Train Rep. Rate	f_r [Hz]	50	5	5	120	120
Bunch Spacing	[ns]	0.5	554	554	5.26	3.5
Bunch Charge	Q[nC]	0.83	3.2	3.2	1	1
Bunch Population	$N_e[10^9$ particles]	5.18	20.0	20.0	6.24	6.24
Beam Power	P_{beam} [MW]	2.8	2.63	5.25	2	2.45
Final RMS energy spread	%	0.35	$\sim$ 0.1	$\sim$ 0.1	$\sim$ 0.3	$\sim$ 0.3
Crossing Angle	θ[rad]	0.0165	0.014	0.014	0.014	0.014
Crab Angle	θ[rad]	0.0165/2	0.014/2	0.014/2	0.014/2	0.014/2
Gradient	[MeV/m]	72	31.5	31.5	70	120
Effective Gradient	[MeV/m]	57	21	21	63	108
Shunt Impedance	[MΩ/m]	95			300	300
Effective Shunt Impedance	[MΩ/m]	39			300	300
Site Power	[MW]	168	125	173	$\sim$ 150	$\sim$ 175
Length	[km]	11.4	20.5	31	8	8
L*	[m]	6	4.1	4.1	4.3	4.3

Comparison with other linear colliders - Tables

Parameter	Symbol[unit]	CLIC	ILC-250	ILC-500	C^3-250 (PS1)	C^3-550 (PS1)
Geometric Luminosity	$\mathscr{L}_{geom}$ [x10^{34}/cm^2 s]	0.91	0.53	0.74	0.75	0.93
Horizontal Disruption	D_x	0.26	0.51	0.30	0.32	0.32
Vertical Disruption	D_y	13.1	34.5	24.3	21.5	21.5
Average Beamstrahlung Parameter	$\langle\Upsilon\rangle$	0.17	0.028	0.062	0.065	0.21
Total Luminosity	$\mathscr{L}$ [x10^{34}/cm^2 s]	1.6 (max is 4)	1.35	1.8	1.35	1.7
Peak luminosity fraction	$\mathscr{L}_{0.01}/\mathscr{L}$	59%	74%	64%	73%	52%
Enhancement Factor	H_D	1.8	2.6	2.4	1.8	1.8
Average Energy loss	δ_E	6.9 %	3.0 %	4.5 %	3.3 %	9.6 %
Photons per beam particle	n_γ	1.5	2.1	1.9	1.4	1.9
Average Photon Energy fraction	$\langle E_\gamma/E_0\rangle$ [%]	4.6 %	1.4 %	2.3 %	2.5 %	5.1 %
Number of incoherent particles	N_{incoh} [10^4]	6.0	13.3	18.5	4.7	12.6
Total energy of incoh. particles	N_{incoh} [TeV]	187	117	439	58	644

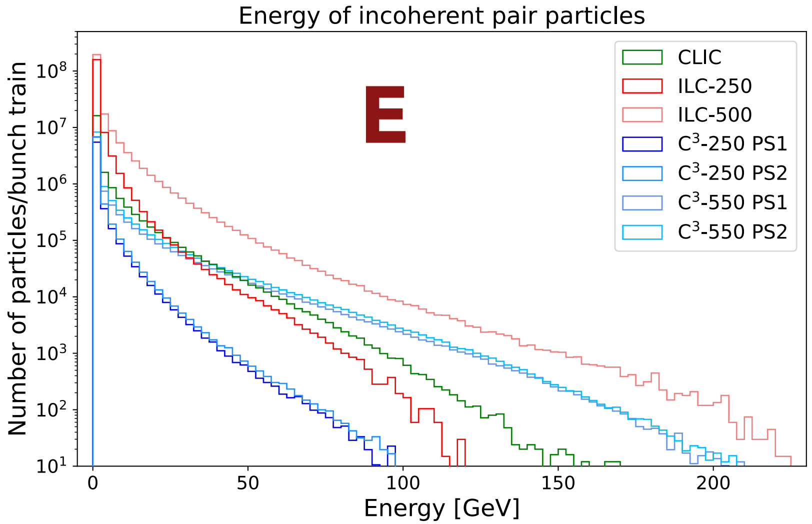
Comparison with other linear colliders

- ILC-250 has the tighest luminosity spectrum, followed by C3-250,ILC-500, CLIC and, lastly, C3-550.
- C3 achieves larger, overall, peak luminosities.

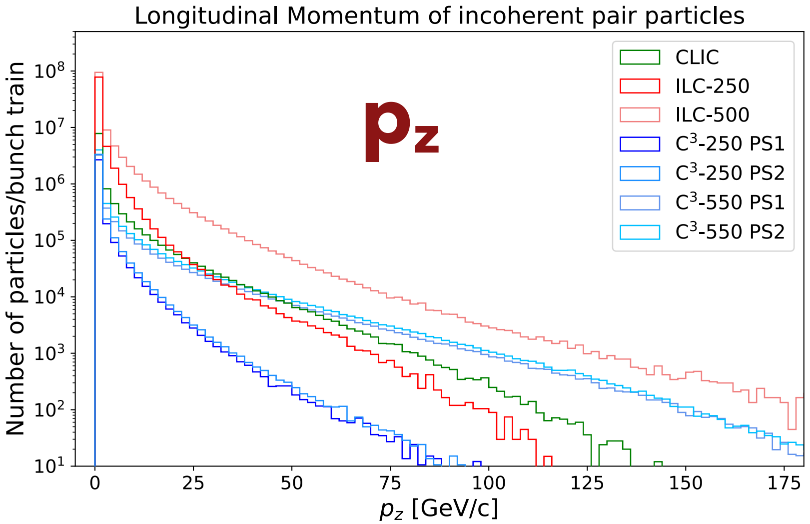


General requirement for Higgs factories: achieve $\gtrsim 60\,\%$ of luminosity in the top $1\,\%$ of $\sqrt{s}$

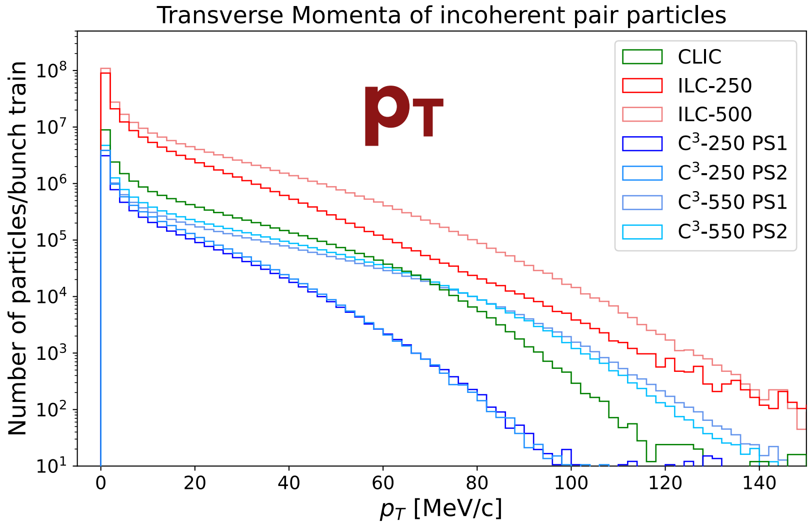
Comparison with other linear colliders

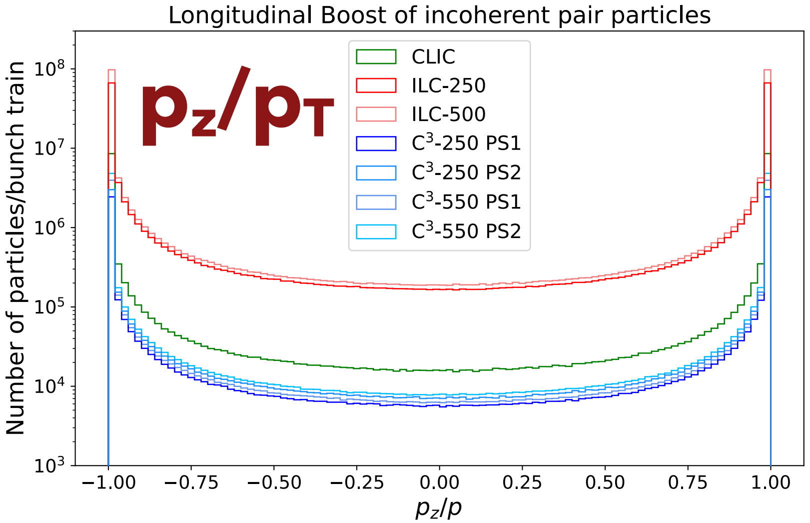


(a)

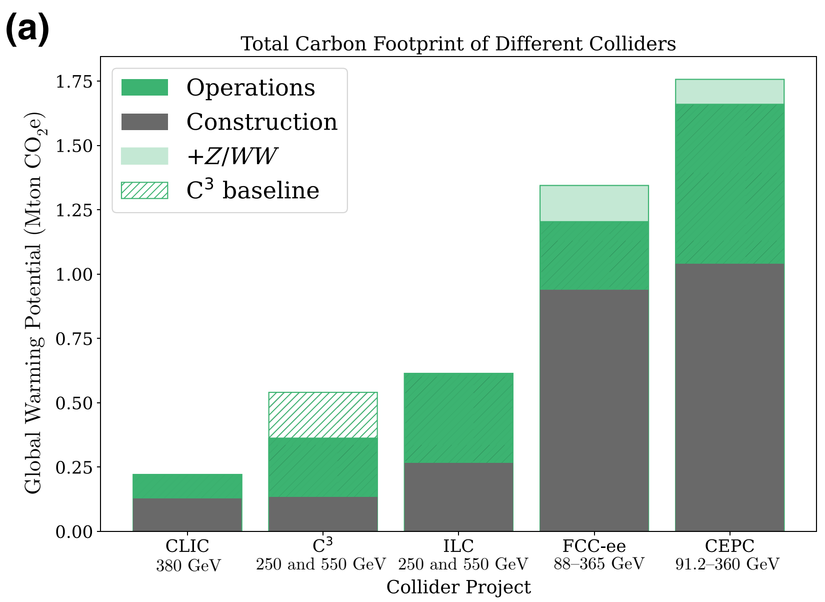


(b)





Comparison with other colliders - Sustainability



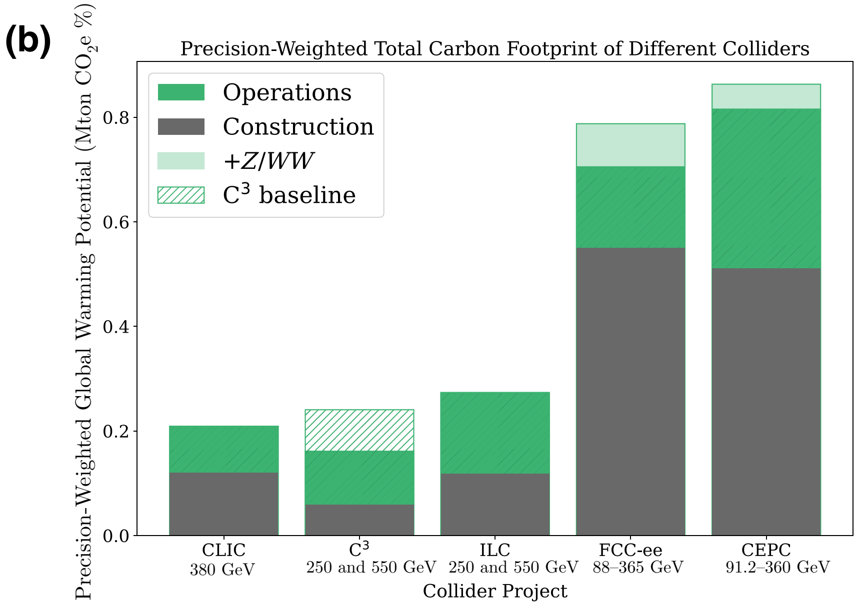


TABLE VI. For each of the Higgs factory projects considered in the first row, the center-of-mass energies (second row), ac site power (third row), annual collision time (fourth row), total running time[a] (fifth row), instantaneous luminosity per interaction point (sixth row), and target integrated luminosity (seventh row) at each center-of-mass energy are given. The numerical values were taken from the references mentioned in the table in conjunction with Ref. [19]. For the CEPC the new baseline scenario with 50 MW of synchrotron radiation power per beam is used. We consider both the baseline and the power optimizations from Table IV (in parentheses) for C^3 power requirements.

Higgs factory	CLIC [44]	ILC [12]		C^3 [11]		CEPC [59,60]				FCC [20,61,62]					
$\sqrt{s}$ (GeV)	380	250	500	250	550	91.2	160	240	360	88, 91, 94		157, 163	240	340–350	365
P (MW)	110	111	173	150 (87)	175 (96)	283	300	340	430	222		247	273	357	
$T_{\text{collisions}}$ [10^7 s/year]	1.20	1.60		1.60		1.30				1.08					
T_{run} (years)	8	11	9	10	10	2	1	10	5	2	2	2	3	1	4
$\mathcal{L}_{\text{inst}}$/IP ($\times 10^{34}$ cm^{-2} s^{-1})	2.3	1.35	1.8	1.3	2.4	191.7	26.6	8.3	0.83	115	230	28	8.5	0.95	1.55
$\mathcal{L}_{\text{int}}$ (ab^{-1})	1.5	2	4	2	4	100	6	20	1	50	100	10	5	0.2	1.5

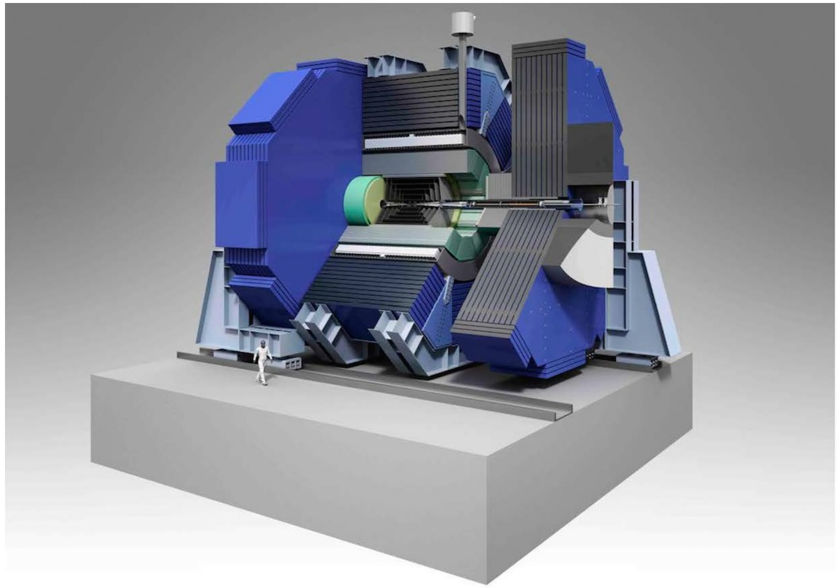
[a]The nominal run schedule reflects nominal data-taking conditions, which ignore other run periods such as luminosity ramp-up.

PRX Energy 2, 047001

Simulation Tools

For all C^3 studies, we use well-established and/or modern software tools, to guarantee modularity, preservation and reusability of our code:

- For the simulation of beam-beam interactions, the tools **GuineaPig++** and **CAIN v2.4.2** have been used and their results cross-validated.
- For full detector simulation with GEANT4, **DD4hep** is used.
- The SiD detector geometry (02_v04) is ported from **k4geo** (lcgeo).



Links

GUINEA-PIG
Key4hep
DD4hep
k4geo

* *Also: efforts with MUCARLO ongoing to simulate the halo muon background*

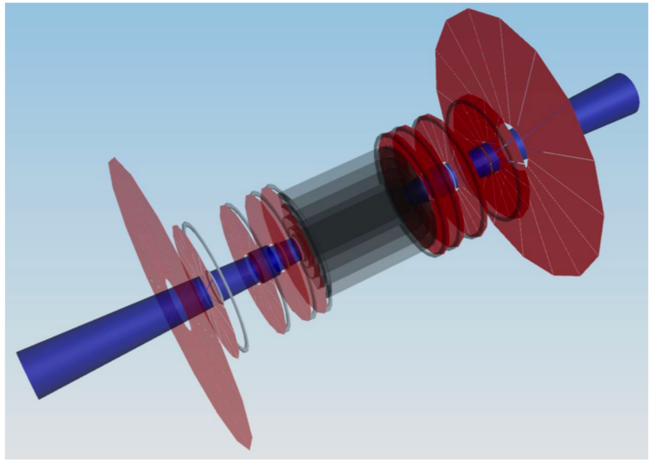
Simulations with GuineaPig

- GUINEA-PIG(++) is a numerical tool for the simulation of beam-beam interactions of two crossing e^+e^- bunches.
- It takes several parameters as ***inputs***: nominal energy $E_0 = \sqrt{s_o}/2$ of beam particles, bunch population N_e, betatron functions and emittances at the IP $\beta_x^*, \beta_y^*, \epsilon_x^*, \epsilon_y^*$, bunch length σ_z^*,repetition rate f_r, number of bunches per train n_b, energy spread, beam offset, waist shift.
- Two bunches are simulated according to these parameters: beam particles are coarse-grained as macroparticles, the EM field of each such macro particle is computed and applied on the corresponding opposite macro particle as they cross.
- GUINEA-PIG can produce several ***outputs***: generic output file with summary statistics for produced background particles and luminosity, spectra of colliding particles after BS, spectra of incoherently produced e^+e^- pairs etc.

Typical detector dimensions for e^+e^- colliders

- Vertex Barrel:

Layer	Inner radius [mm]	Outer radius [mm]
1st	13	17
2nd	21	25
3rd	34	38
4th	46.6	50.6
5th	59	63



Dimensions in cm

Barrel	Technology	Inner radius	Outer radius	z extent
Vertex detector	Silicon pixels	1.4	6.0	+/- 6.25
Tracker	Silicon strips	21.7	122.1	+/- 152.2
ECAL	Silicon pixels-W	126.5	140.9	+/- 176.5
HCAL	RPC-steel	141.7	249.3	+/- 301.8
Solenoid	5 Tesla SC	259.1	339.2	+/- 298.3
Flux return	Scintillator-steel	340.2	604.2	+/- 303.3
Endcap	**Technology**	**Inner z**	**Outer z**	**Outer radius**
Vertex detector	Silicon pixels	7.3	83.4	16.6
Tracker	Silicon strips	77.0	164.3	125.5
ECAL	Silicon pixel-W	165.7	180.0	125.0
HCAL	RPC-steel	180.5	302.8	140.2
Flux return	Scintillator/steel	303.3	567.3	604.2
LumiCal	Silicon-W	155.7	170.0	20.0
BeamCal	Semiconductor-W	277.5	300.7	13.5

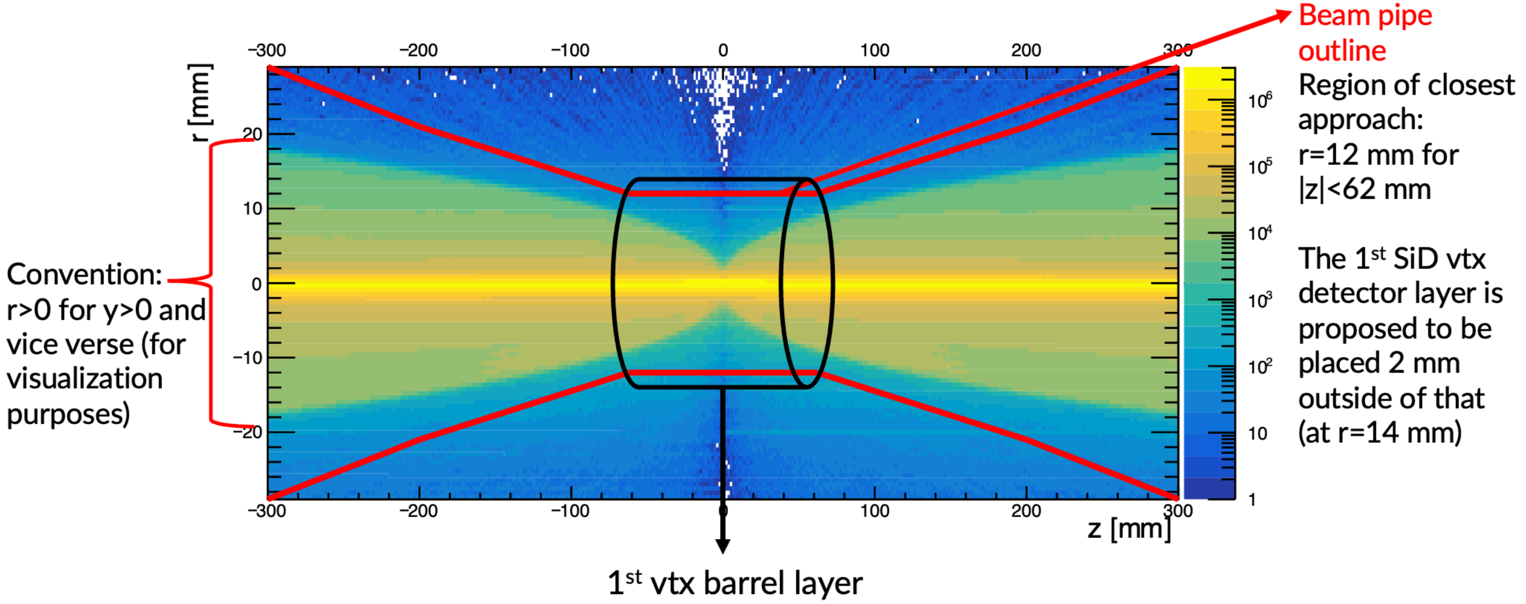
https://pages.uoregon.edu/silicondetector/sid-dimensions.html

***SiD geometry version SiD_o2_v4 used in our simulations**

Pair Background Envelopes

- Once the pair background particles are produced, they follow helical trajectories in the magnetic field of the detector solenoid.
- Most of them are highly boosted in the forward direction and will travel longitudinally within the beam pipe, without interacting with the detector.
- However, the trajectories of a small fraction of the produced particles are bent enough by the magnetic field that they reach and interact with the detector.
- For C3, that fraction is $\sim 0.1\ \%$, corresponding to ~ 40 particles/BX.

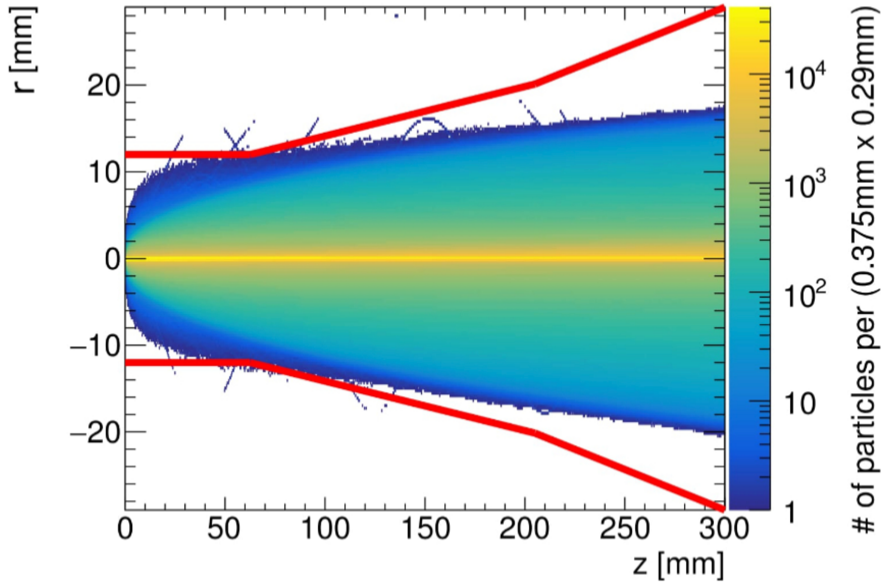
- The trajectories of the particles have a characteristic bell shape which we call **pair background envelope**.
- One optimizes beam parameters and detector design such that the envelopes are mostly contained within the beam-pipe.



Results shown here correspond to $\sqrt{s} = 250\ \text{GeV}\ ,\ B = 5\ \text{T}$ ***(uniform)***

ILC - Previous results

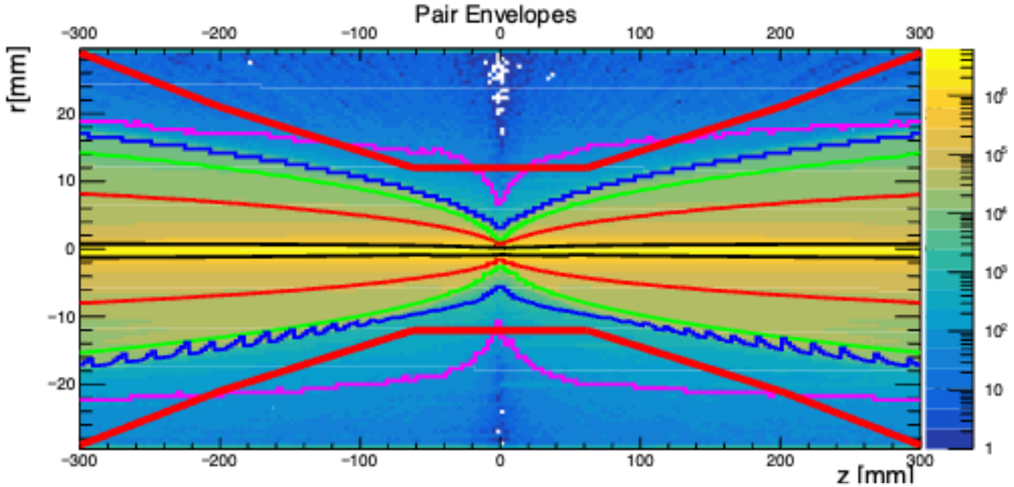
r vs z

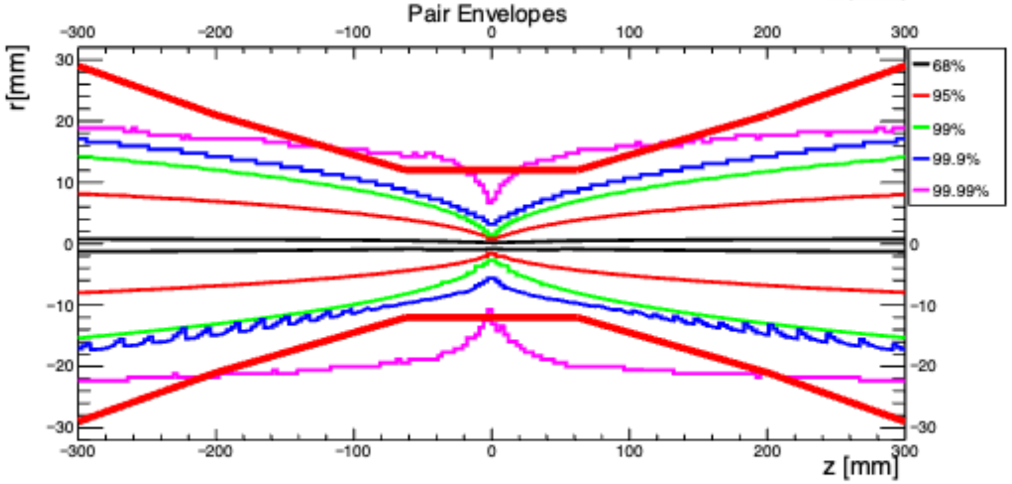


From Anne Schutz's PhD thesis (2018)

C³ - Our results

r vs z





Beam Parameters related to timing

- **ILC:** One train every 200 ms (5 Hz) with 1312 bunches/train.
- Each bunch is separated by 369 ns.
- In the remaining time until the next train arrives, the detector has to read out the analog signals and do the digital processing.

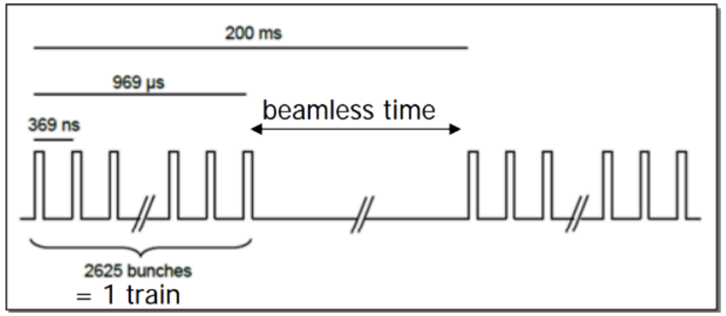
- **C³:** One train every 8.3 ms (120 Hz) with 133 bunches/train.
- Each bunch is separated by 5.25 ns.
- In the remaining time until the next train arrives, the detector has to read out the analog signals and do the digital processing.

- **Comparison:** C³ will record $O(10)$ times fewer bunches than ILC, leading to reduced occupancy. But, the readout will have to take place ~25 times faster.

Collider	NLC[16]	CLIC[10]	ILC[18]	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
σ_z [μm]	150	70	300	100	100
β_x [mm]	10	8.0	8.0	12	12
β_y [mm]	0.2	0.1	0.41	0.12	0.12
ϵ_x [nm-rad]	4000	900	500	900	900
ϵ_y [nm-rad]	110	20	35	20	20
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5

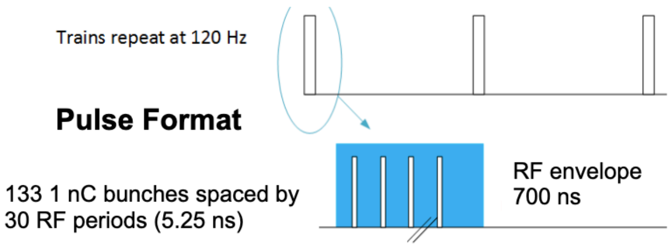
[Caterina Vernieri et al 2023 JINST 18 P07053]

ILC timing structure



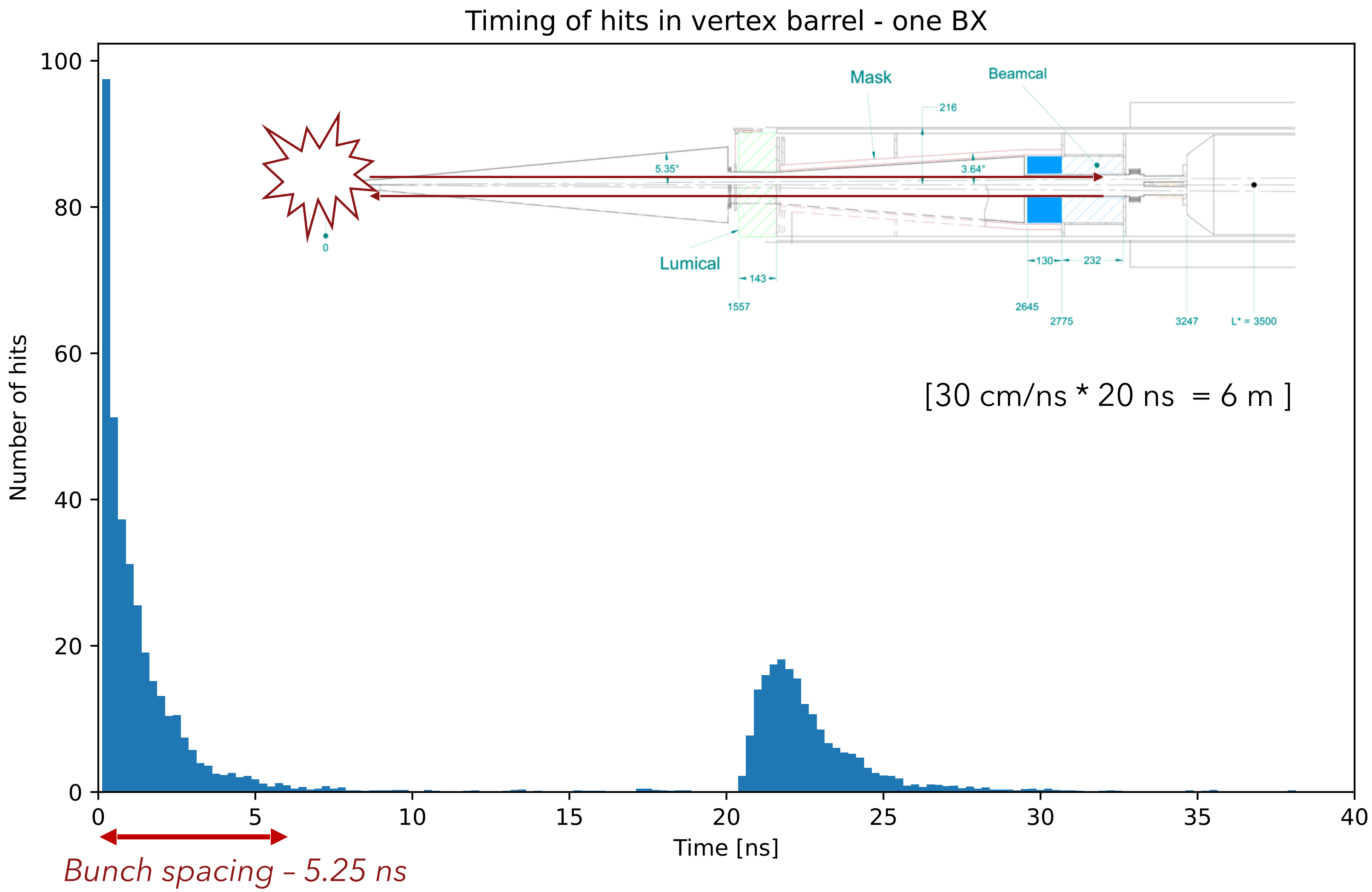
1 ms long bunch trains at 5 Hz
308ns spacing

C³ timing structure



Time distribution within each BX

- Time distribution of hits in the vertex barrel within a single BX.
- Most hits contained in time within the bunch spacing.
- The secondary peak at ~20-25 ns is due to backscattering from the BeamCal.



Time distribution over a train - vertex barrel

Time distribution of hits per unit time and area: on average, we anticipate $\sim 4.4 \cdot 10^{-3}$ hits/(ns $\cdot$ mm^2) $\simeq 0.023$ hits/mm^2/BX in the 1st layer of the vertex barrel detector, within the limits set for SiD @ ILC.