LCWS2024 International Workshop on Future Linear Colliders

Luminosity Studies for the Cool Copper Collider

International Linear Collider Workshop - LCWS 2024

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Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline of the talk:

- Luminosity at linear e^+e^- colliders
- Luminosity Optimization
- Luminosity optimization analysis for C^3
- Luminosity surrogate optimization
- Conclusions - Outlook

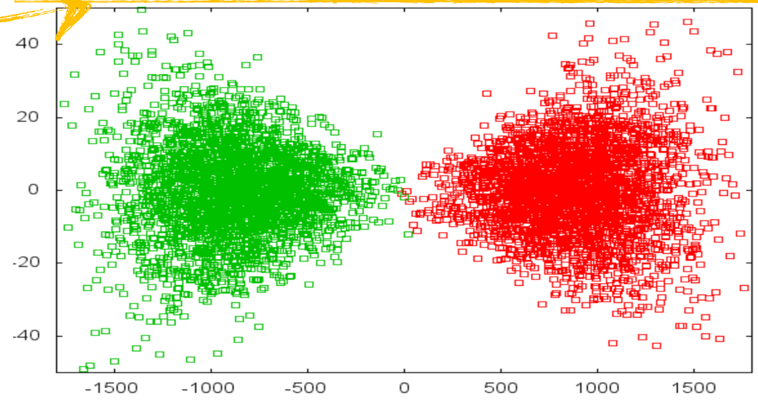
For an overview of latest C^3 developments, refer to
[Caterina's talk]
[Ankur's talk]

More detailed luminosity studies for C^3 in [PRAB 27, 061001]

Luminosity at linear e⁺e⁻ colliders

- 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/bunch
- n_b : # of bunches/bunch train
- f_r : train rep. 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 (~1.5-2.5).

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

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

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

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

assuming zero crossing angle (i.e. recovered by crab crossing)

Luminosity Optimization

- For any collider, we wish to ***maximize the luminosity***, a function of multiple parameters: $N_e, n_b, f_r, \epsilon_x^*, \epsilon_y^*, \beta_x^*, \beta_y^*, \sigma_z^*, w_y, \Delta x, \Delta y, \theta_C$

[w_y: waist shift, $\Delta x, \Delta y$:beam offsets, θ_c: crossing angle]

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

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

- Subject to ***several inequality constraints***:
  - Rectangular constraints (damping ring, wakefield, bunch compression, final focus etc requirements)
  - Beam power : $P_b = N_e n_b f_r \frac{\sqrt{s}}{2} < P_b^{\max}$
  - Beamstrahlung: $\langle \Upsilon \rangle = \frac{5}{6} \frac{N_e r_e^2 \gamma}{\alpha(\sigma_x^* + \sigma_y^*)\sigma_z^*} < \Upsilon^{\max}$ (proxy for BIB/detector requirements – not trivial to quantify)
  - Constraints on some function of $n_b, f_r, \langle \Upsilon \rangle$ to keep BIB flux rate at the detector under control, taking into account timing/bunch-tagging/readout requirements (also highly not trivial)
  - +++

Luminosity Optimization - Challenges

- **Major challenge 1:** exact form and numerical values of the constraints not known → requires:
  - deep understanding of the detector impact of BIB & how it changes as a function of the beam parameters,
  - understanding of max allowed occupancy to retain required precision needs (e.g. achieve vertexing/tagging goals)
  - Deeper understanding of constrains from the accelerator design
- **Major challenge 2:** Even with all constraints fully specified, there is no analytical expression for the objective function → we need simulations to determine H_D as a function of the various optimization parameters

- These are important challenges we should overcome as more progress is made towards an e^+e^- collider.
- In the next slides, we show a first-step luminosity optimization approach for C3.
- Looking further, we also propose an approach to address challenge 2

$$\mathcal{L}_{\text{inst}} = H_D \frac{N_e^2 n_b f_r}{4\pi\sigma_x^* \sigma_y^*}$$

No analytical formula, we depend on computationally intensive simulations!

C^3 Parameter Optimization

First-step luminosity optimization Process:

1. Optimize $\epsilon_x^*, \epsilon_y^*, w_y$ and σ_z^* for C3-550 wrt to maximizing $\mathscr{L}_{\text{inst}}$.

2. Evaluate optimized parameters on C3-250.

3. Examine effect of modifications in $\beta_x^*, \beta_y^*, \Delta x, \Delta y$.

- For each set of parameters, use GUINEA-PIG to estimate H_D, as well as evaluate the magnitude of the beam-induced background

[$\mathcal{O}(10^4)$ samples generated for the studies here]

- New parameter set (Parameter Set 2 - **PS2**) proposed based on target luminosity requirements:

$$\mathscr{L}^{\text{(target)}}_{C^3-250} = 1.3 \cdot 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}\ ,\ \mathscr{L}^{\text{(target)}}_{C^3-550} = 2.4 \cdot 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$$

In order to collect:

$$\mathscr{L}_{\text{int}} = 2\ \text{ab}^{-1}\ @\ \sqrt{s} = 250\ \text{GeV}, 4\ \text{ab}^{-1}\ @\ \sqrt{s} = 550\ \text{GeV}$$

Parameter changes:

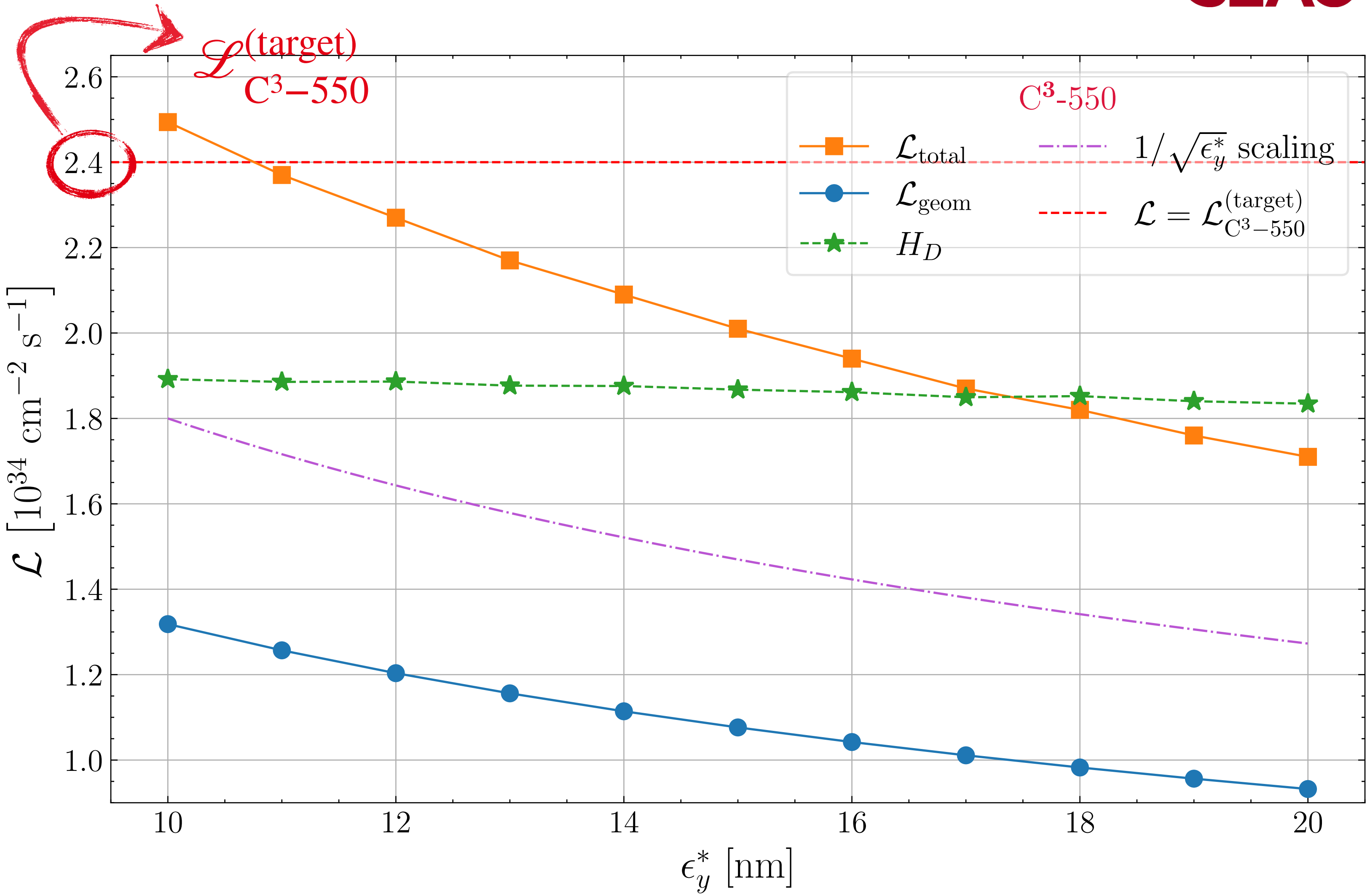
- Reduce ϵ_y^* from **20 nm** to **12 nm**
- Increase ϵ_x^* from **900 nm** to **1000 nm**
- Introduce vertical waist shift w_y of **80 µm**

With the new parameters, the target luminosity is reached (and exceed for C3-250 by by **55%**), while the beam-induced background remains at the same levels.

C^3 - 550 Parameter Optimization

PRAB 27, 061001

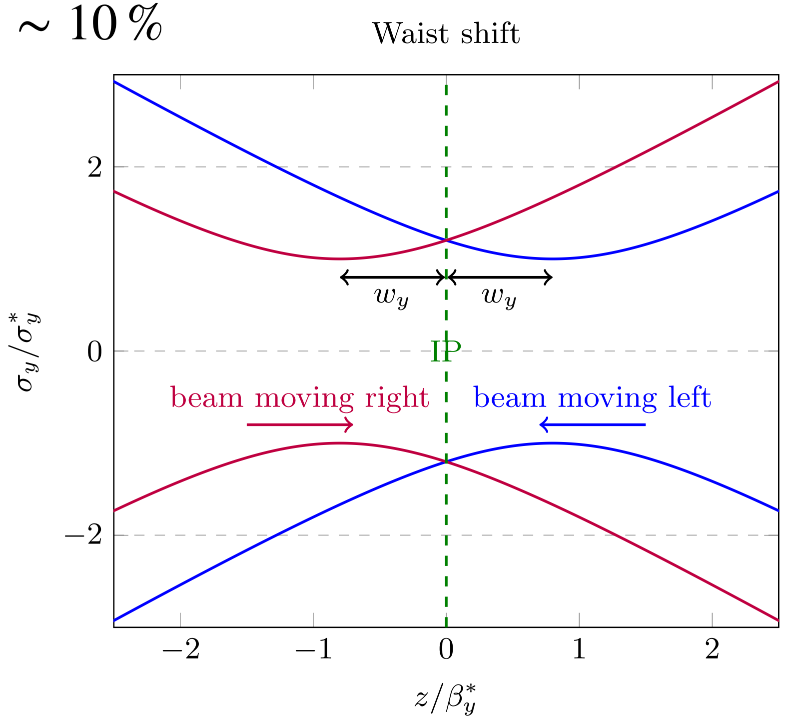
- Start by lowering vertical emittance ϵ_y^*.
- $\mathscr{L}$ scales as $\sim 1/\sqrt{\epsilon_y^*}$ and BIB does not increase, so an excellent candidate for increasing $\mathscr{L}$.
- **However:** lowering emittances very challenging on the technical side (stringent accelerator requirements)

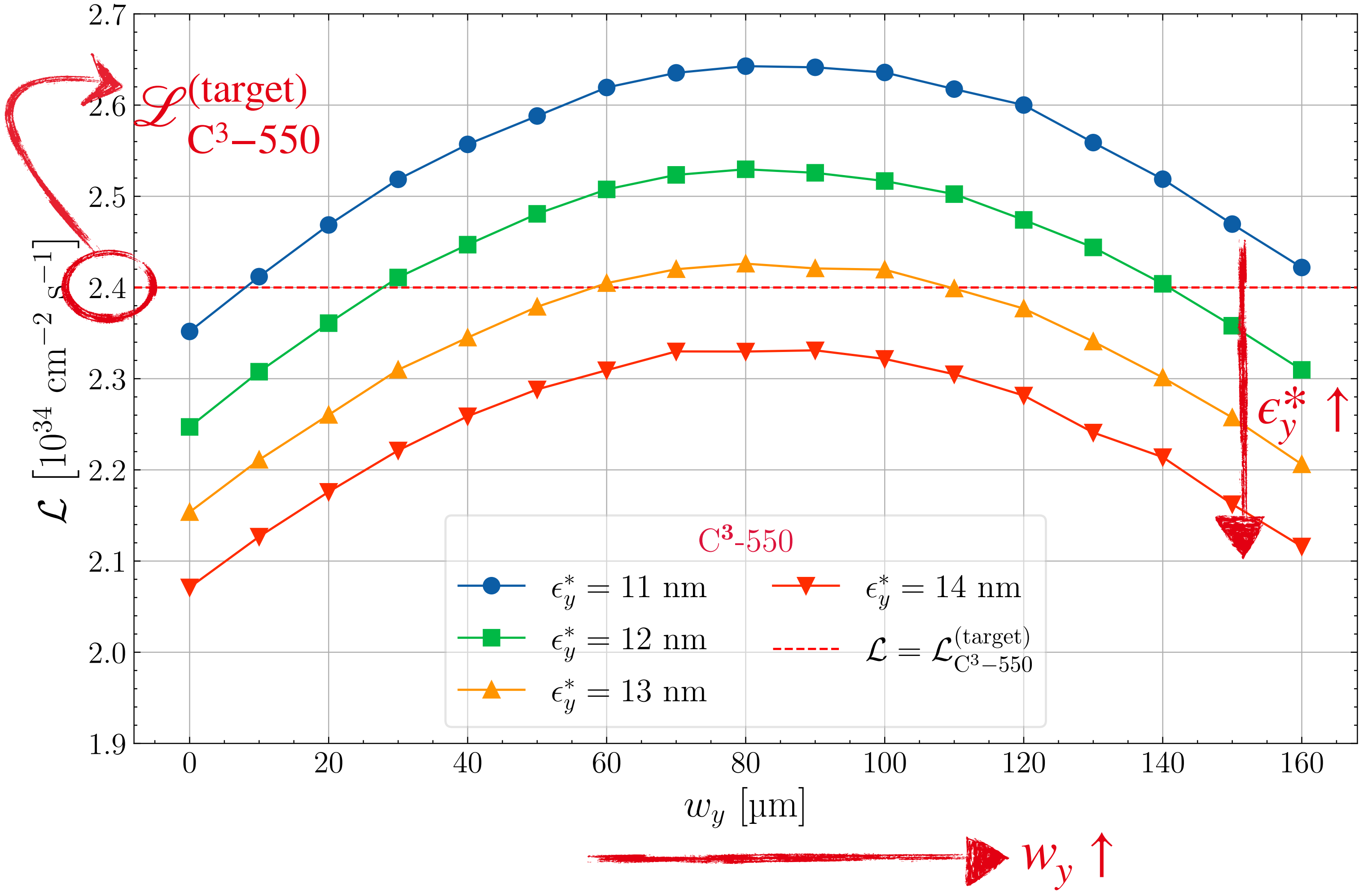


In the plot, not-mentioned parameters retain same values as in PS1.

C^3 - 550 Parameter Optimization

- Emittance requirements can be relaxed by introducing a waist shift w_y, i.e. placing the vertical focal point before the IP.
- For a w_y of 80 μm, $\mathscr{L}$ is increased by $\sim 10\,\%$





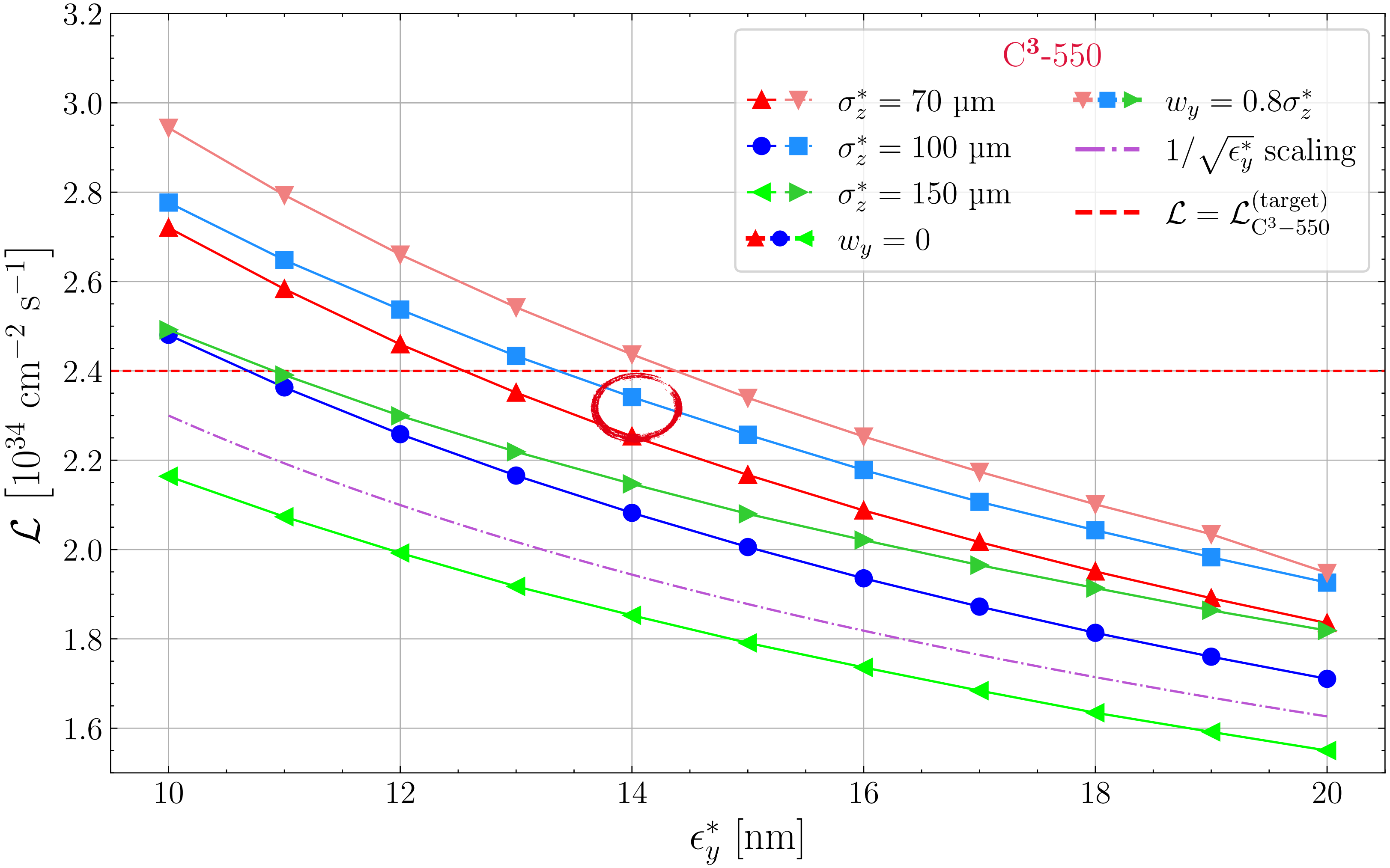
Similar gain as for ILC/CLIC, see e.g. ["Beam-Beam Effects in Linear Colliders"](#) by D.Schulte

**In the plot, not-mentioned parameters retain same values as in PS1.*

C³ - 550 Parameter Optimization

- We can also modify the bunch length σ_z^*, this affects $\mathscr{L}$ through H_D ($\sigma_z^* \downarrow \Rightarrow H_D \uparrow$)
- Lowering σ_z^* increases $\mathscr{L}$.
- **However:** at the same time, it increases the BIB, potentially compromising detector performance.

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



*In the plot, not-mentioned parameters retain same values as in PS1.

C^3 - 550 Parameter Optimization

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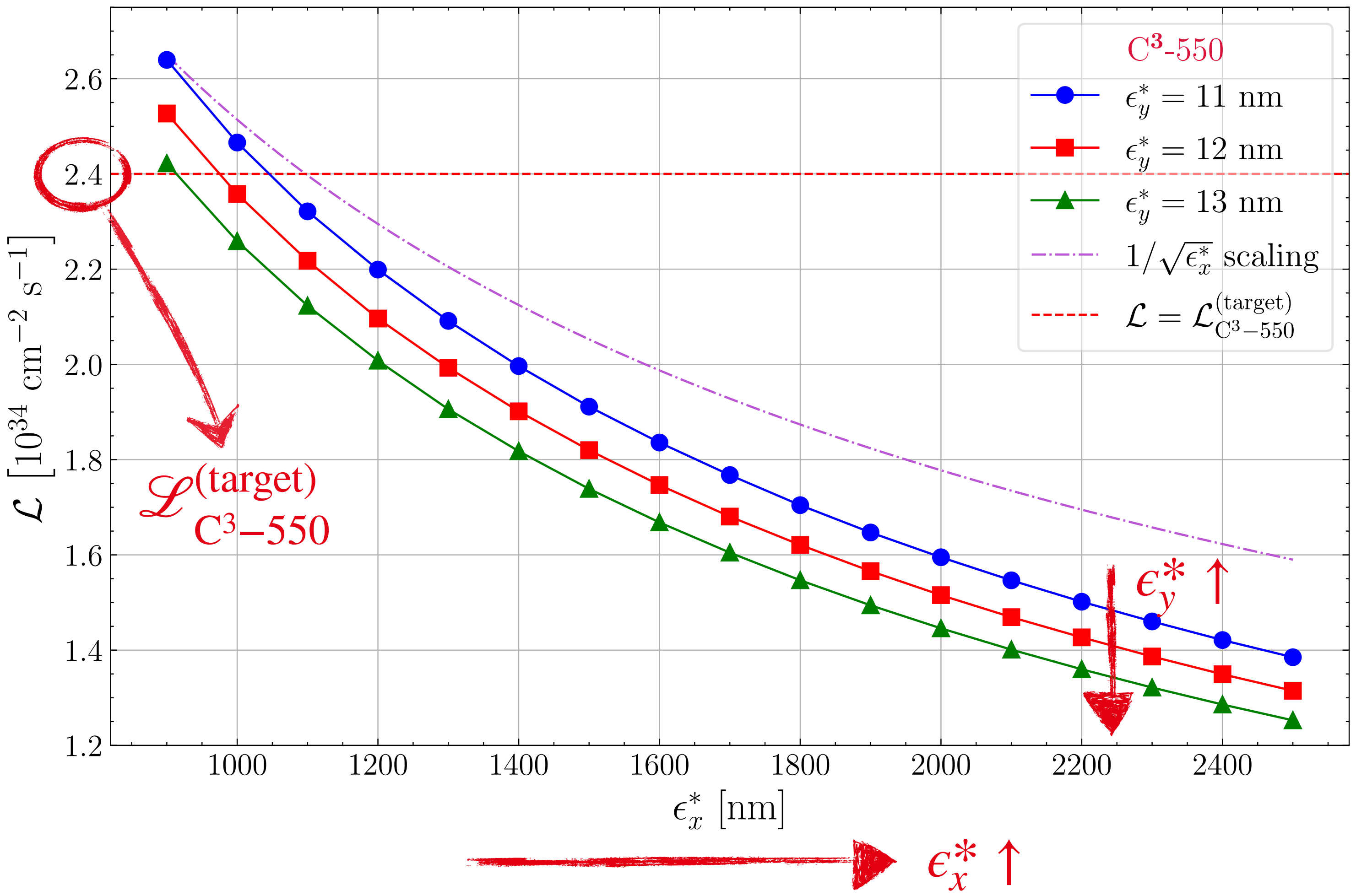
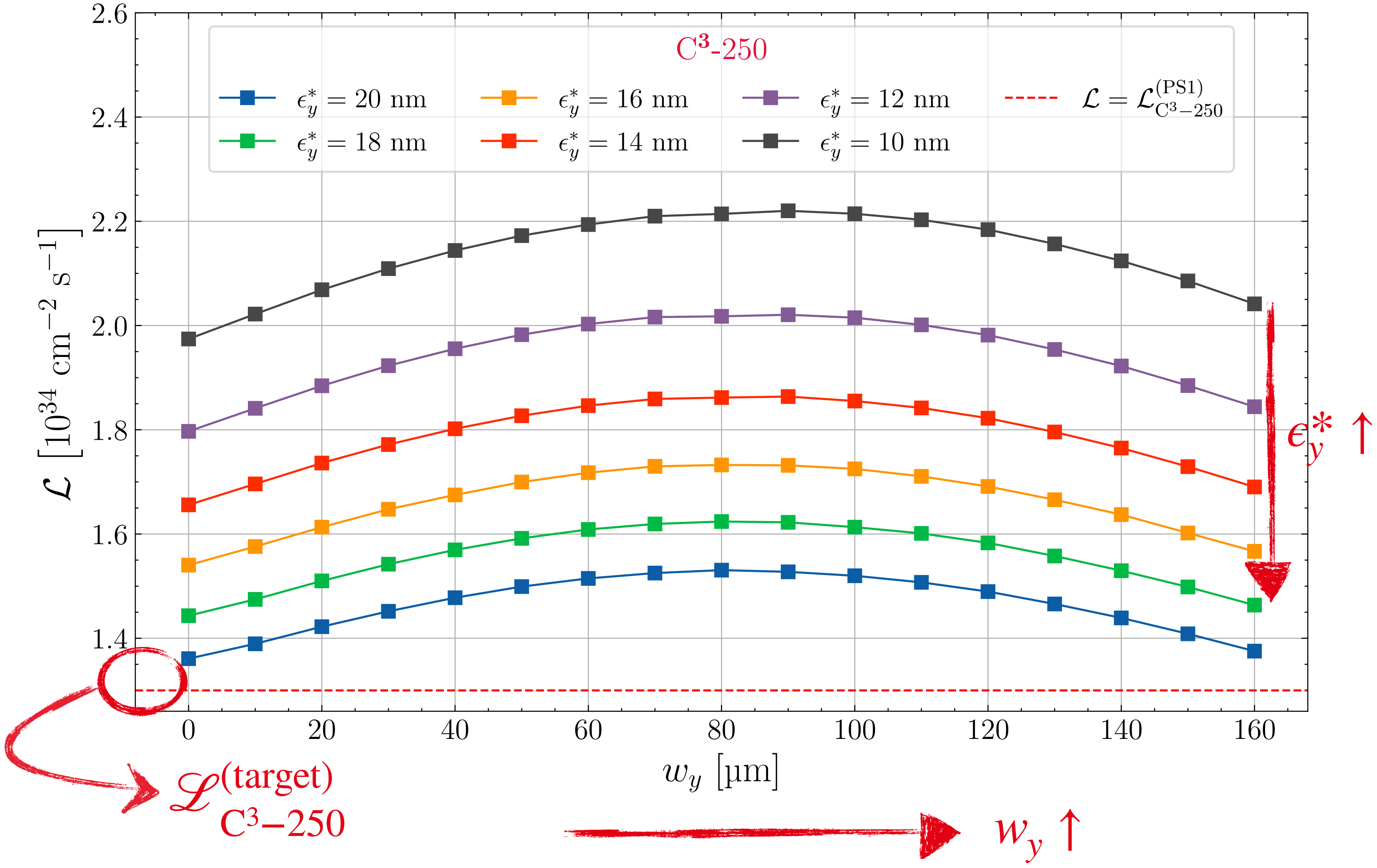
- To keep BIB under control, we investigate variations in ϵ_x^*.
- $\mathscr{L}$ decreases with increasing ϵ_x^* faster than $1/\sqrt{\epsilon_x^*}$ due to the additional contribution from H_D.
- To keep the BIB at similar levels, ϵ_x^* is slightly increased from 900 nm to 1000 nm.
- For this value of ϵ_x^* and a decrease of ϵ_y^* from 20 nm to 12 nm, the target luminosity is achieved.



In the plot, σ_z^* of 100 μm and w_y of 80 μm are assumed.

Evaluation on C³ - 250

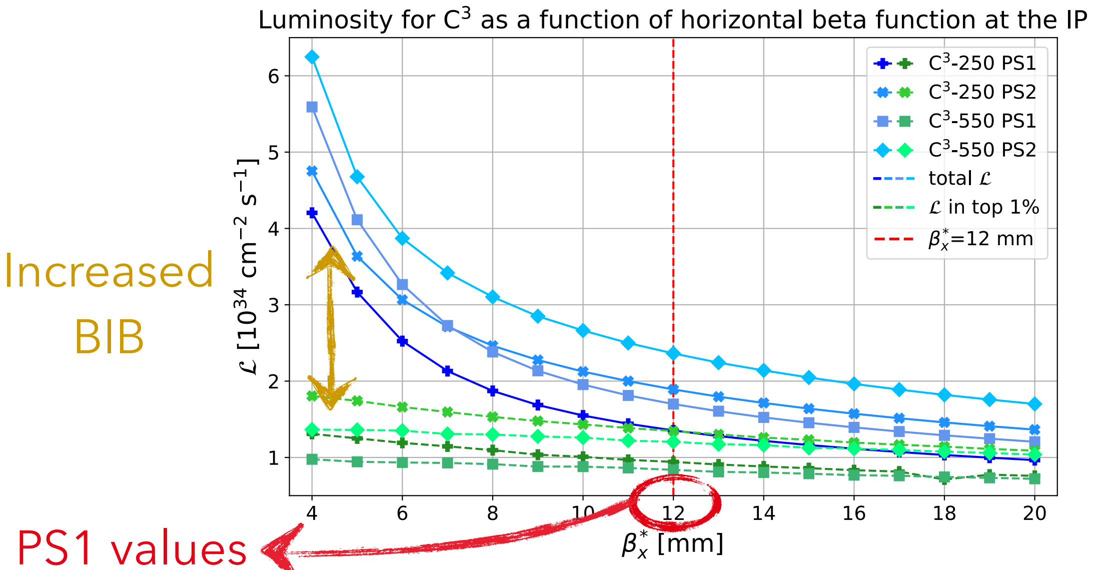
- A waist shift w_y of 80 μm is also optimal at 250 GeV.
- The target luminosity can also be achieved for higher ϵ_y^*, but at 12 nm, the luminosity increases by $\sim 50\,\%$.
- With these parameter choices, the BIB for C³-250 remains at the same levels as for PS1.

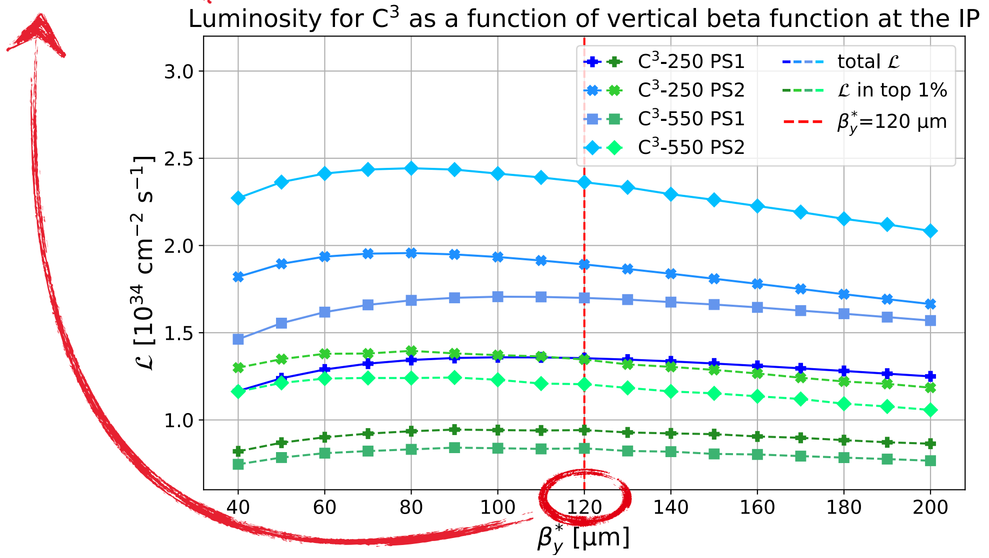


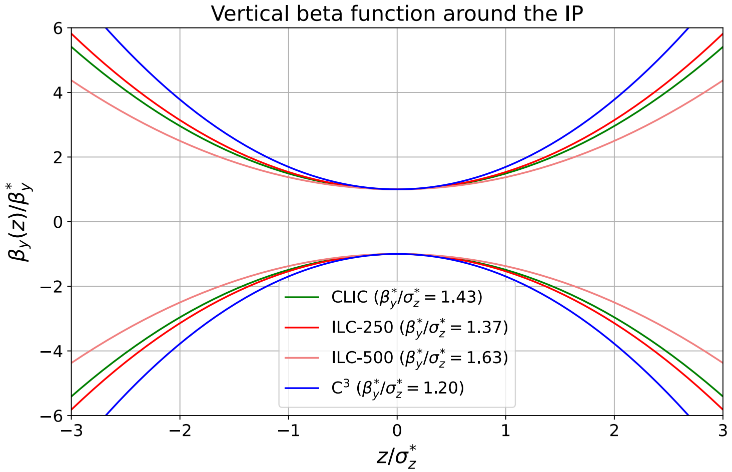
*In the plot, not-mentioned parameters retain same values as in PS1.

Beta function dependence

- $\mathscr{L}$ increases as $\beta_x^* \downarrow$, however at small β_x^*, the BIB increases rapidly and the luminosity in the top $1\,\%$ of the center-of-mass energy increases much more slowly.
- $\mathscr{L}$ does not scale similarly with β_y^*, due to the *hourglass effect*, which limits luminosity gains at small β_y^*.
- For these reasons , the beta functions are kept at the same values as in PS1: 12 mm for β_x^* and 120 μm for β_y^*.







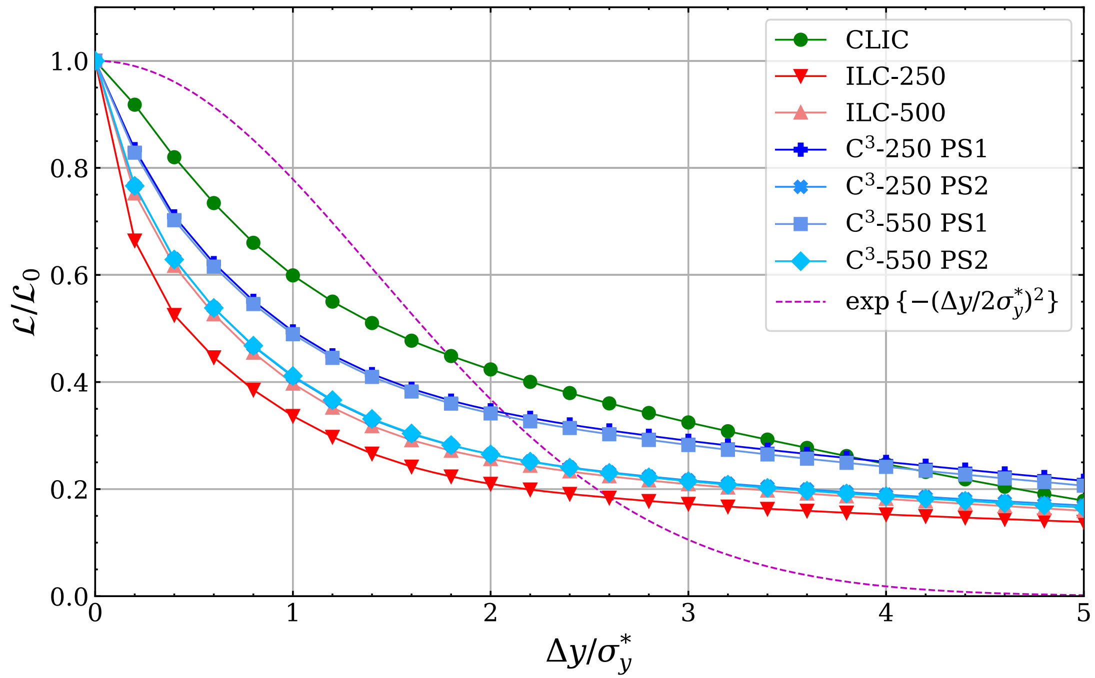
Hourglass effect: Beam size around the IP increases more rapidly at small β_y^*

$$\beta_y(z) = \sqrt{\beta_y^\star + \frac{z^2}{\beta_y^*}}$$

Offset dependence

PRAB 27, 061001

- $\mathscr{L}$ 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 beams attracting each other.
- Sub-nm offsets at the IP are necessary in order to achieve target luminosities.
- $\mathscr{L}$ degradation can be mitigated by optimizing beam parameters to achieve smaller vertical disruption D_y.



Offset dependence driven by value of disruption parameter

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

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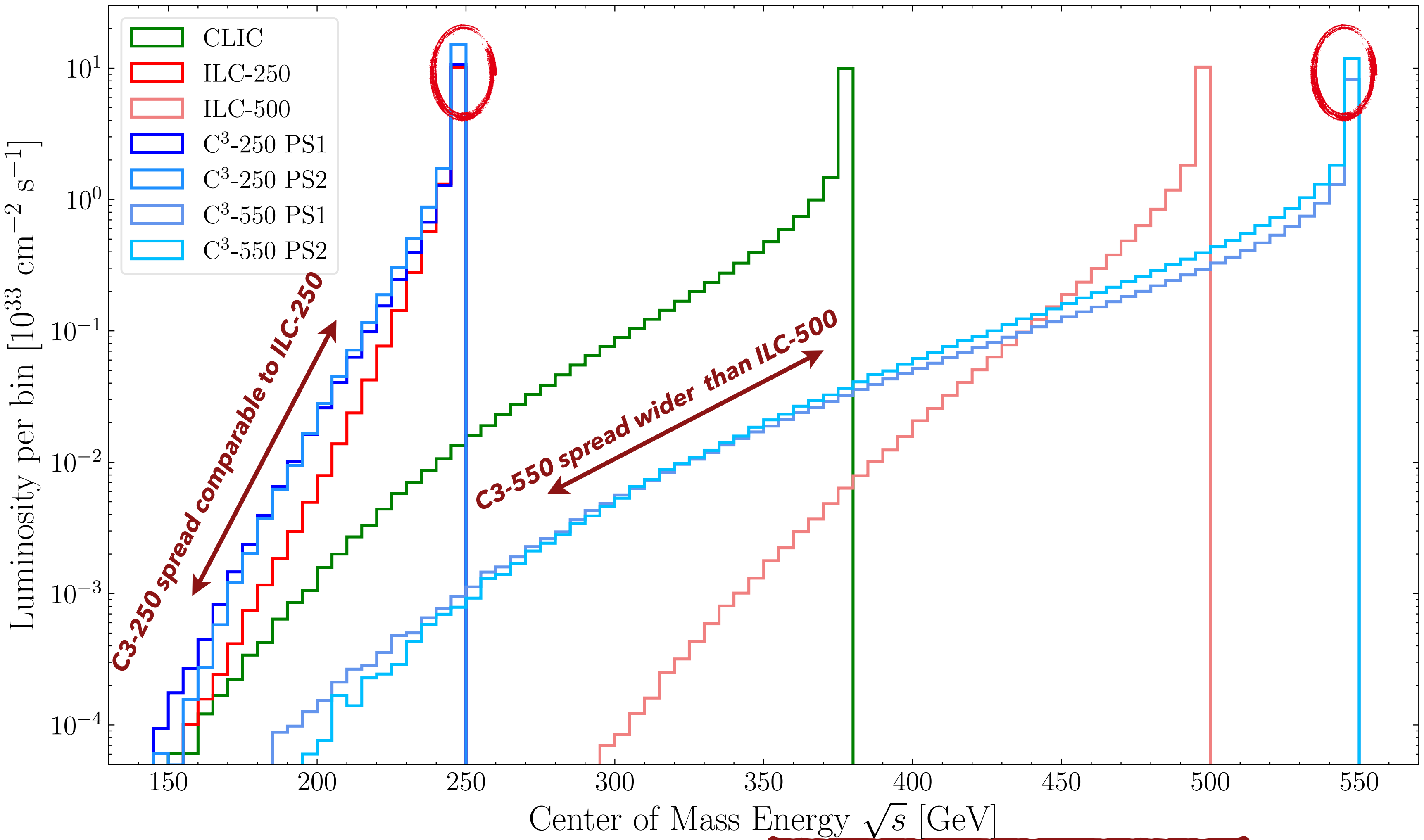
Comparison with other linear colliders

- The *luminosity spectrum* broadens when beam-beam interactions are increased, leading to energy losses for the beam particles.
- ***For C³, PS2 leads to luminosity gain at the peak, without significant broadening of the spectrum.***
- We are investigating beam parameter modifications for C³-550 in order to reduce the luminosity spread.



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

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

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

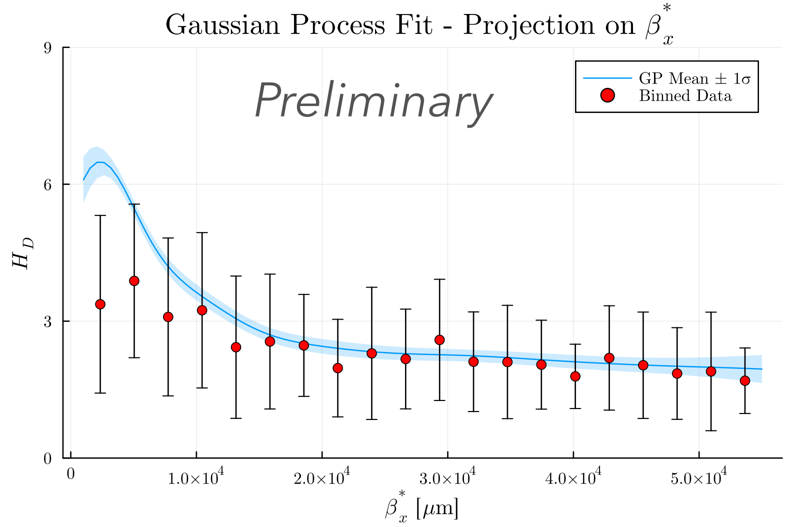
Surrogate model optimization

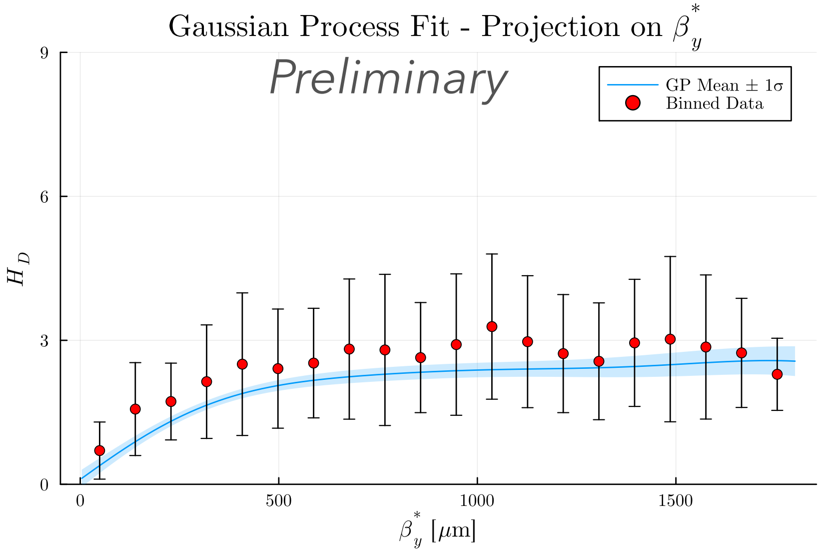
Work in progress

- We use a probabilistic surrogate model for $H_D = H_D(N_e, \epsilon_x^*, \epsilon_y^*, \beta_x^*, \beta_y^*, \sigma_z^*)$ trained on $\sim \mathcal{O}(10^4)$ GUINEA- PIG simulations, which we use for luminosity optimization leveraging:
  - efficient out-of-the-box optimizers,
  - no additional grid sampling
  - ability to impose constraints

maximize $\hat{\mathcal{L}} = \frac{n_b f_r \gamma}{4\pi}\left(\hat{H}_D(\boldsymbol{x})\frac{N_e^2}{\sqrt{\epsilon_x^*\beta_x^*\epsilon_y^*\beta_y^*}}\right)$, $\boldsymbol{x} = (N_e, \epsilon_x^*, \epsilon_y^*, \beta_x^*, \beta_y^*, \sigma_z^*)$

subject to $\boldsymbol{x}^{(\min)} \leq \boldsymbol{x} \leq \boldsymbol{x}^{(\min)}$, $\langle \Upsilon \rangle = \frac{5 r_e^2 \gamma}{6\alpha}\frac{N_e}{(\sigma_x^* + \sigma_y^*)\sigma_z^*} \leq \Upsilon_{\max}$





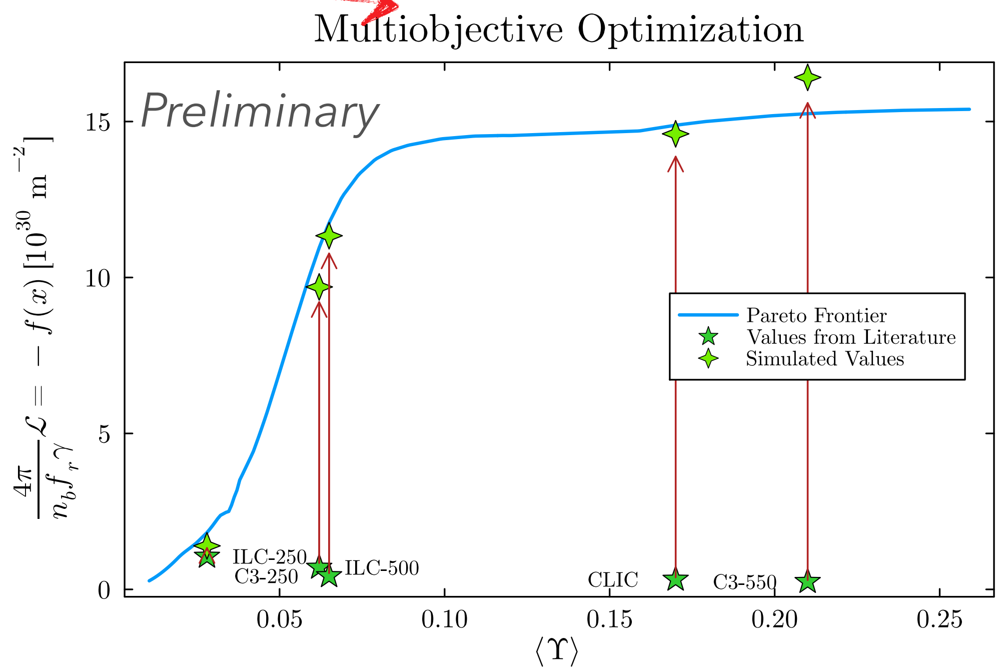
Surrogate model optimization

Work in progress

- Trading off $\mathscr{L}$ and $\langle\Upsilon\rangle$: using a wide allowed range for $\boldsymbol{x}$ to build the Pareto frontier

Parameter	N_e (10^9 particles)	ϵ_x^* (nm)	ϵ_y^* (nm)	β_x^* (mm)	β_y^* (mm)	σ_z^* (μm)
Lower bound	5	860	12	7.8	0.09	60
Upper bound	20.5	5200	40	22.5	0.52	330

This range has been selected given the min and max values of each parameter across all proposed LCs and does not take into account machine limitations → not very realistic



- **More realistic scenario:** allow each parameter to vary $\pm 10\,\%$ from its value for each LC and demand $\langle\Upsilon\rangle$ is $\leq$ the literature value for each LC.

Surrogate optimization works!

±10% in beam parameters →

up to 35% gain in lumi while reducing beamstrahlung

Quantity	CLIC	ILC-250	ILC-500	C^3-250	C^3-550
$\frac{4\pi}{n_b f_r \gamma}\mathcal{L}_{\mathrm{literature}}$ ($\times 10^{29}$ m^{-2})	3.2069	10.572	7.0479	4.3453	4.4107
$\langle\Upsilon\rangle_{\mathrm{literature}}$	0.17	0.028	0.062	0.065	0.21
$\frac{4\pi}{n_b f_r \gamma}\mathcal{L}_{\mathrm{GP}}$ ($\times 10^{29}$ m^{-2})	5.0557	12.65	9.993	5.9109	6.6508
$\langle\Upsilon\rangle_{\mathrm{GP}}$	0.12266	0.02801	0.02961	0.06501	0.08825
$\frac{4\pi}{n_b f_r \gamma}\mathcal{L}_{\mathrm{simulations}}$ ($\times 10^{29}$ m^{-2})	4.9582	10.862	9.447	5.6218	5.7022
Overall gain (%)	35.3	2.7	25.4	22.7	22.6

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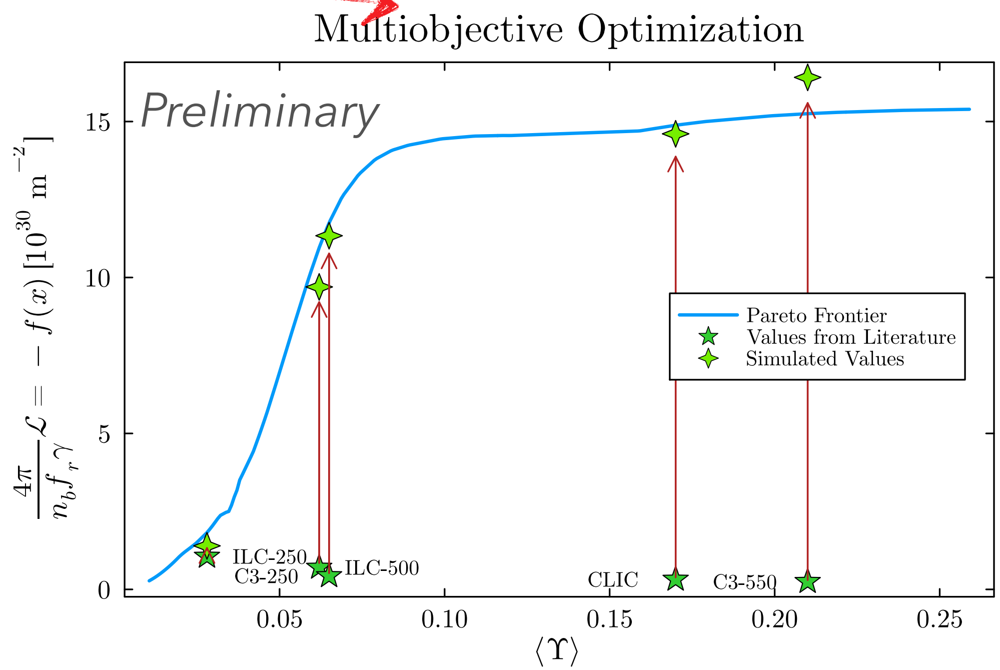

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Surrogate optimization works!

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Surrogate model optimization has significant benefits:

- much faster turnaround time: $\sim \mathscr{O}(0.1)$ h for full optimization vs $\sim \mathscr{O}(1)$ h for a *single* GUINEA-PIG simulation run
- Takes into account parameter correlations
- Ability to impose non trivial constraints on parameters

Conclusions

- Luminosity and its interplay with the BIB (and, thus, the detector performance) is an important aspect of the physics at e^+e^- colliders.
- Luminosity optimization presents important challenges due to the need for extensive simulations and the difficulty in fully specifying the constraints.
- We have presented a first-level luminosity optimization analysis for C^3, which leads to luminosity gains, without a commensurate in the BIB.
- We have demonstrated the benefits of a luminosity optimization scheme using a surrogate model (*work in progress - to be published soon*).

Understanding the impact of the various beam parameters on the instantaneous luminosity and the beam-induced background is ***relevant for any future collider, linear or circular***.

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Thank you for your attention!

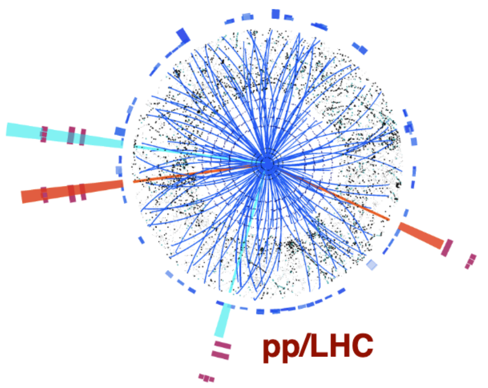
Questions?

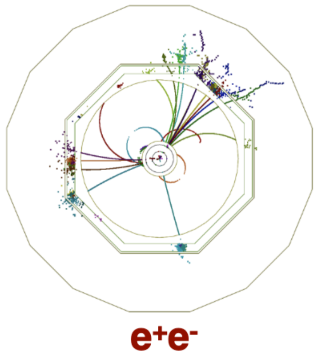
Backup

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*

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





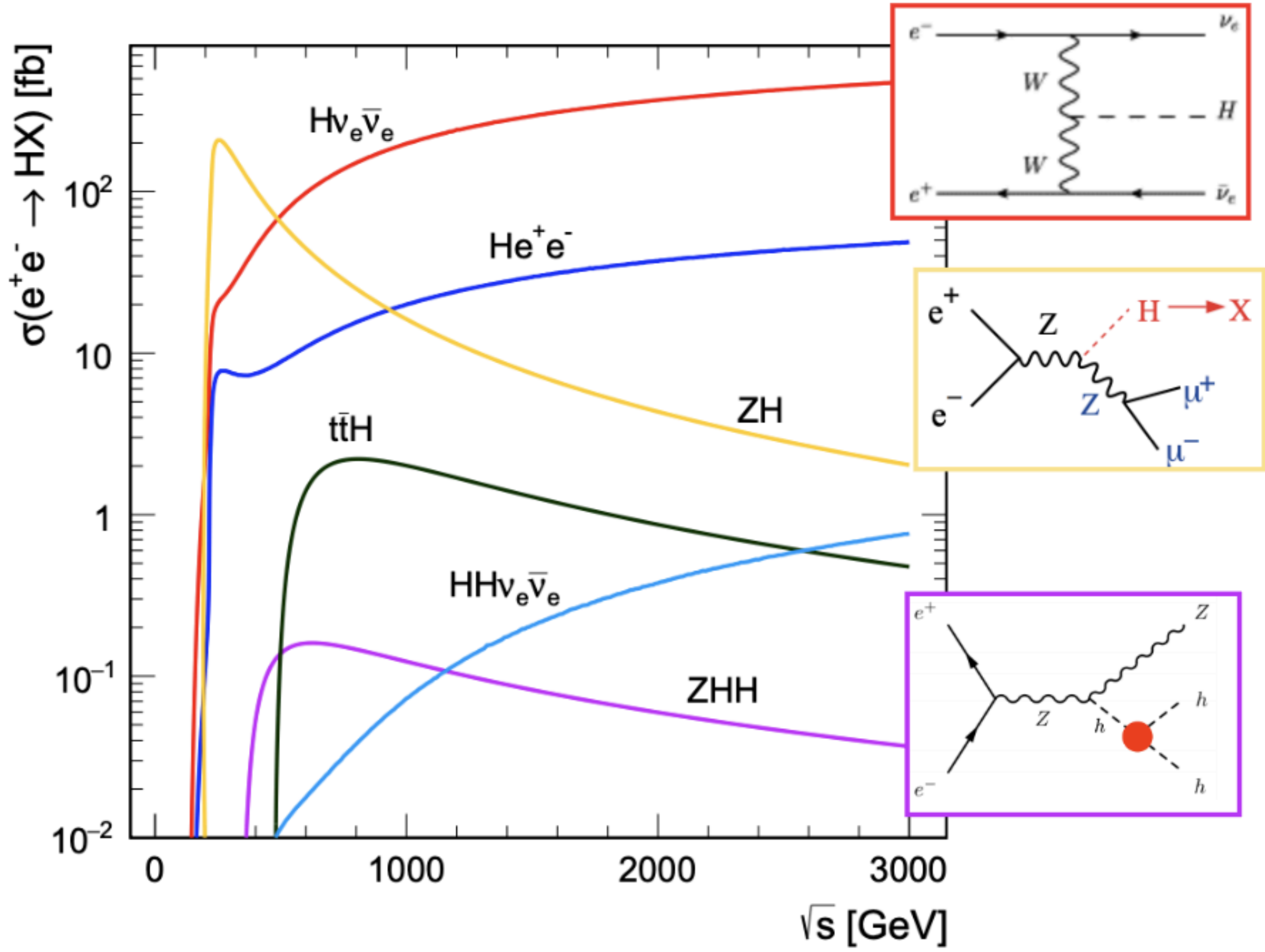
		HL-LHC +				
Relative Precision (%)	HL-LHC	CLIC-380	ILC-250/C^3-250	ILC-500/C^3-550	FCC 240/360	CEPC-240/360
hZZ	1.5	0.34	0.22	0.17	0.17	0.072
hWW	1.7	0.62	0.98	0.20	0.41	0.41
$hb\bar{b}$	3.7	0.98	1.06	0.50	0.64	0.44
$h\tau^+\tau^-$	3.4	1.26	1.03	0.58	0.66	0.49
hgg	2.5	1.36	1.32	0.82	0.89	0.61
$hc\bar{c}$	-	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

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

PRX Energy 2, 047001

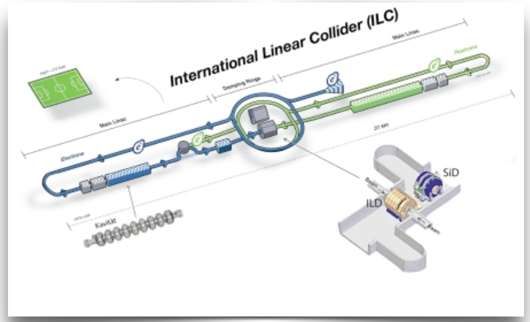
Benefits of e+e- colliders

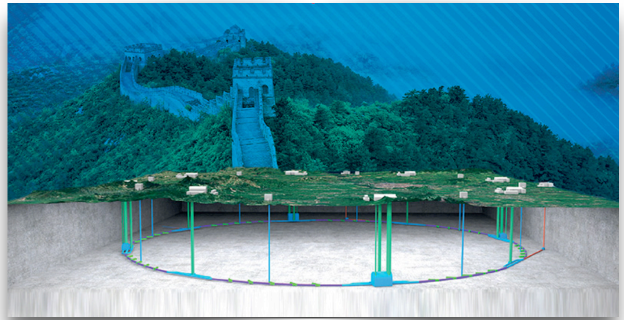
- At e+e- machines, Higgs bosons are produced mainly through the ZH process at $\sqrt{s} \simeq 250$ GeV.
- This process allows model-independent determination of the Higgs width and BRs using the recoil technique.
- At higher energies, above ~ 500 GeV:
  - $\nu\nu H$ dominates, with ttH also becoming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



Future Higgs Factory Proposals

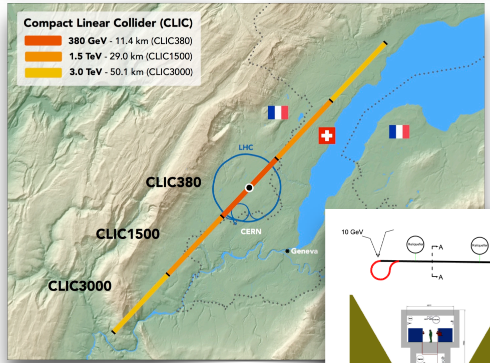
- High-energy colliders designed to produce Higgs bosons at large numbers ($\sim \mathcal{O}(10^4)/\text{year}$) for precision Higgs physics measurements are called **Higgs factories** (**HFs**).
- HFs fall under two main categories: **linear** and **circular** machines, with common luminosity requirements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

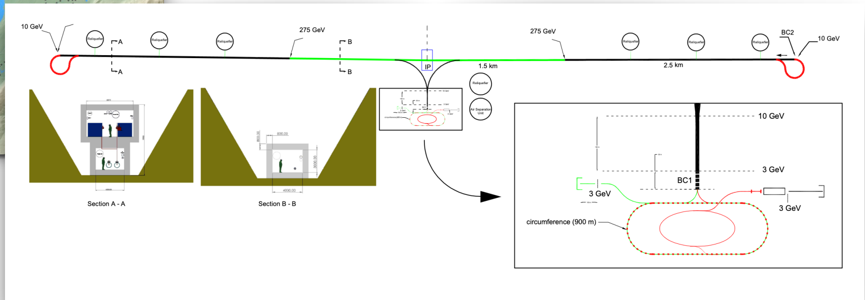


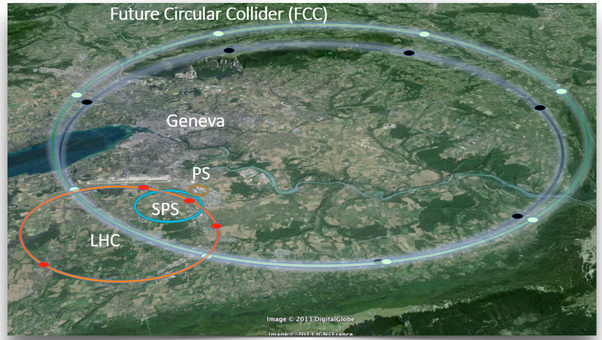


Linear	Circular
ILC, CLIC, C³	*FCC-ee, CEPC*
+ Reach higher $\sqrt{s}$ (*path to TeV*)	– $\sqrt{s}$ reach limited by SR (up to ~360 GeV)
+ Longitudinal polarization	– No beam polarization
– Lumi limited by beam focusing requirements	+ Higher luminosity at lower energies (EW Physics)
– Single Interaction Point (IP)	+ Can accommodate multiple IPs

$$\Delta E = \frac{e^2}{3\epsilon_0}\left(\frac{E}{mc^2}\right)^4 \frac{1}{R}$$







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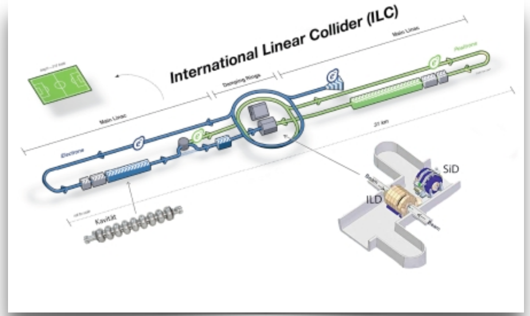
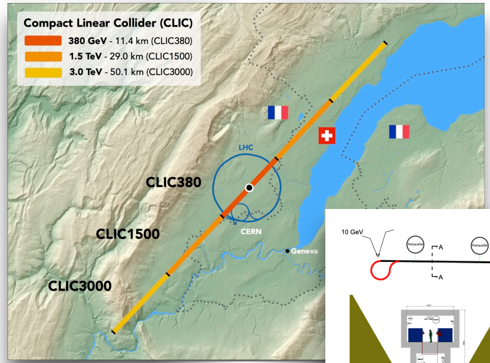
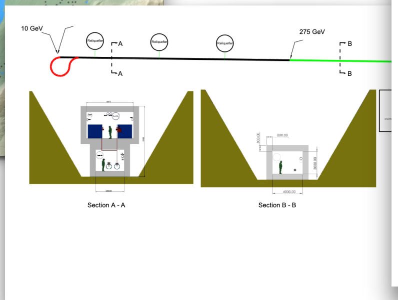
- HFs fall under two main categories: **linear** and **circular** machines, with common luminosity requirements of $\mathscr{L}_{\text{inst}} \sim \mathcal{O}(10^{34})\ \text{cm}^{-2}\ \text{s}^{-1}$ for all.







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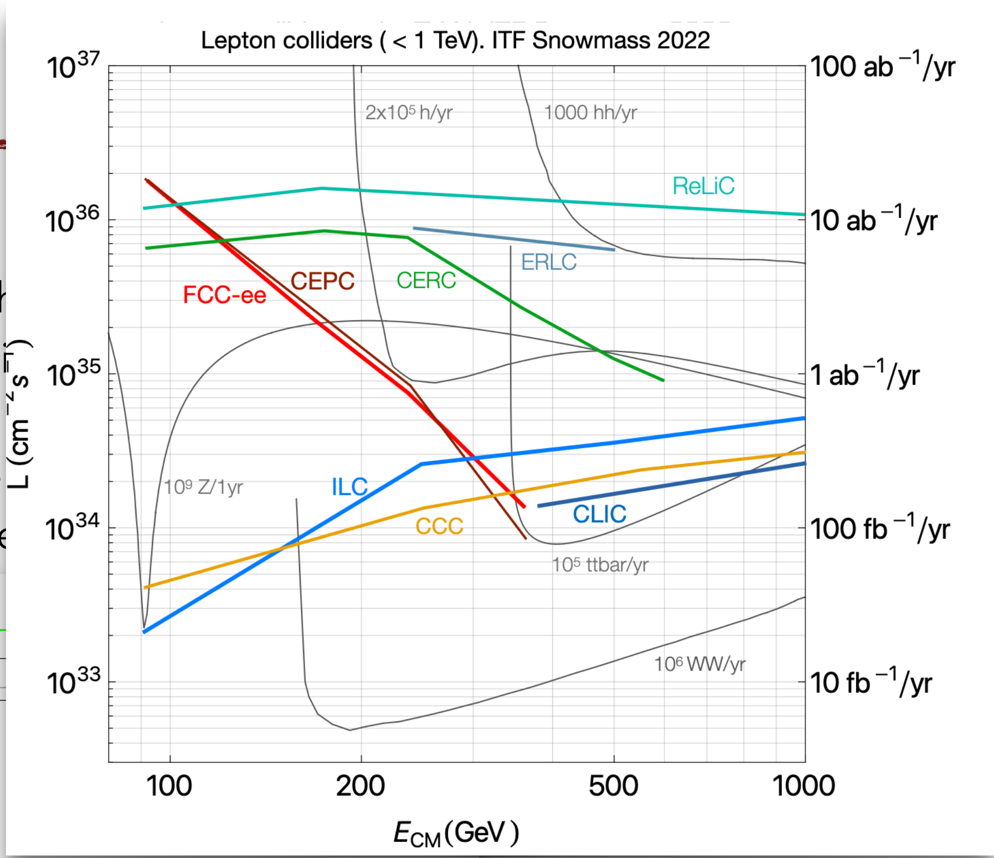

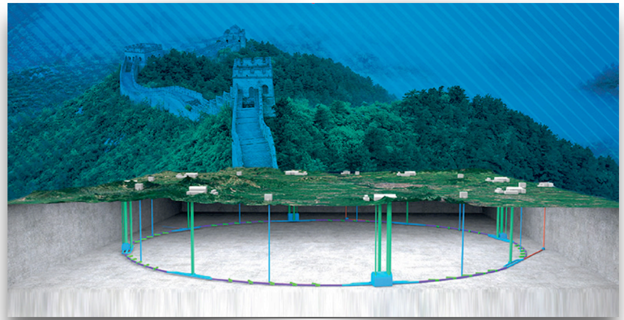

(up to ~360 GeV)

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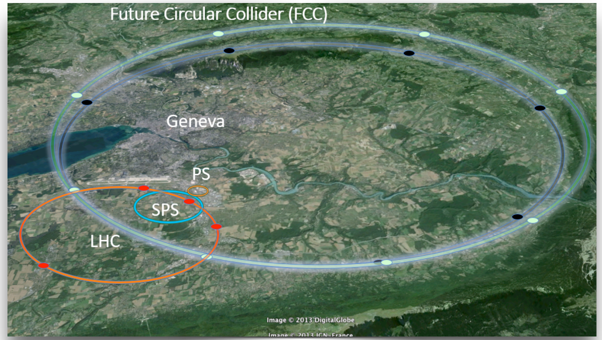
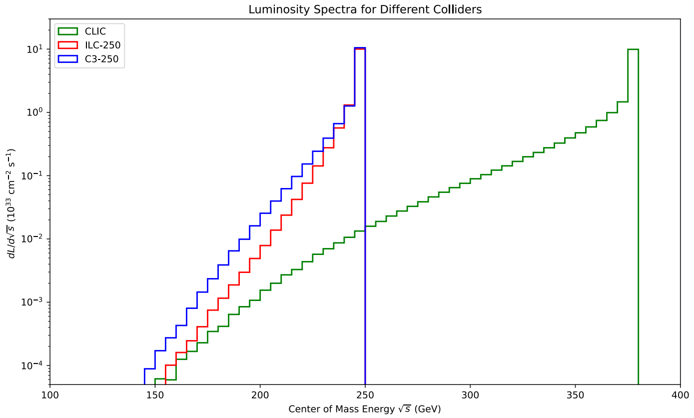


- The effects of beam-beam interactions on the experiments can be split in **two categories**:

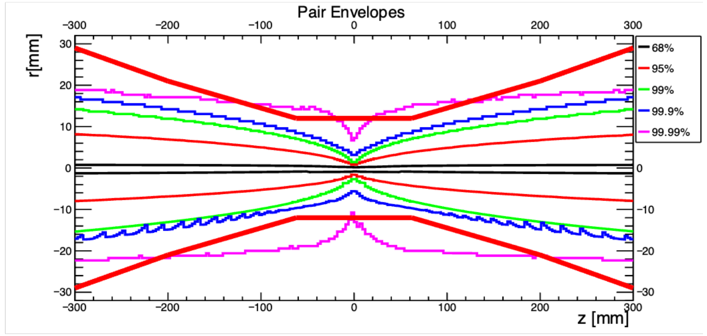
Physics Analyses

- 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.



Beam-Beam interactions at linear 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:

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

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

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

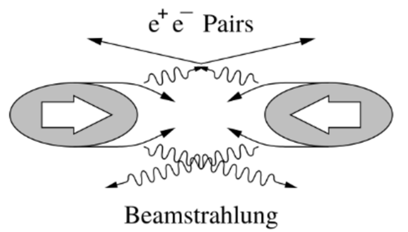
(BX = Bunch Crossing)

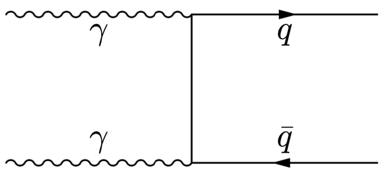
Incoherent pair production processes

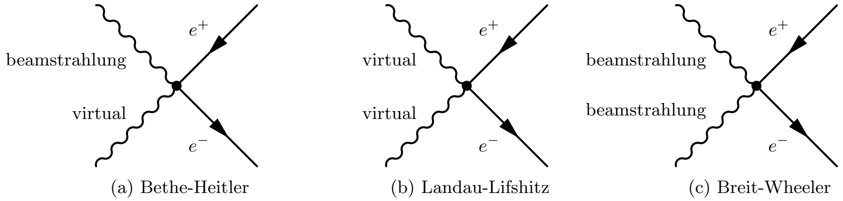
- *Bethe-Heitler (BH)*: interaction of BS photon with a virtual photon
- *Landau-Lifschitz (LL)*: interaction of two virtual photons
- *Breit-Wheeler (BW)*: interaction of two BS photons

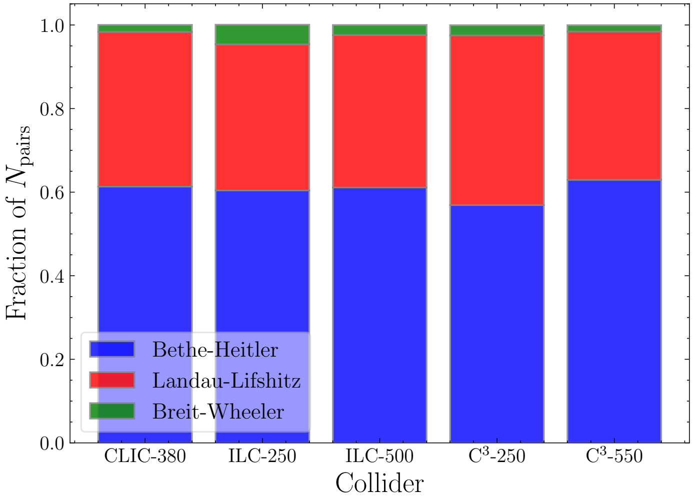
$O(1)$ ***hadrons per BX***

(more central)





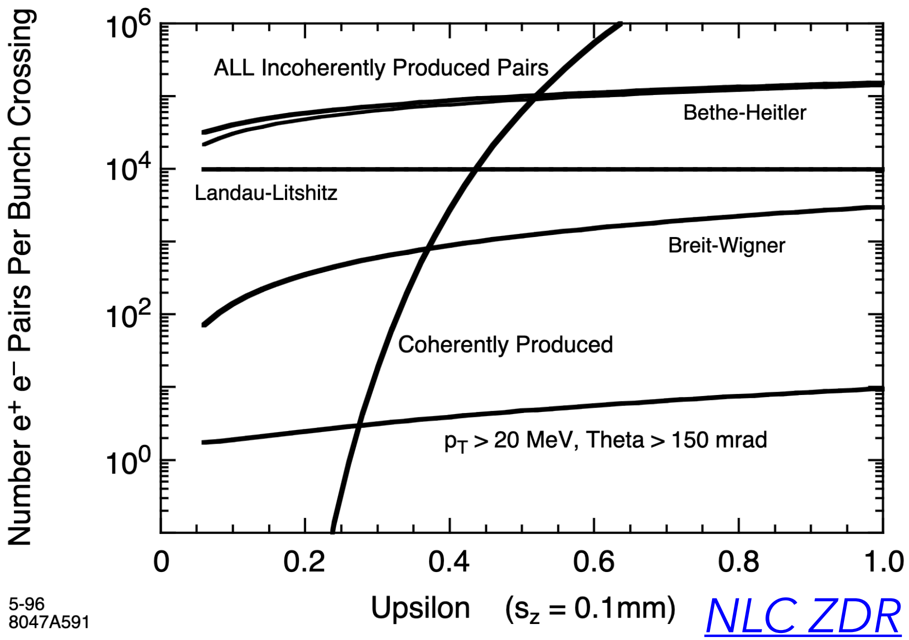




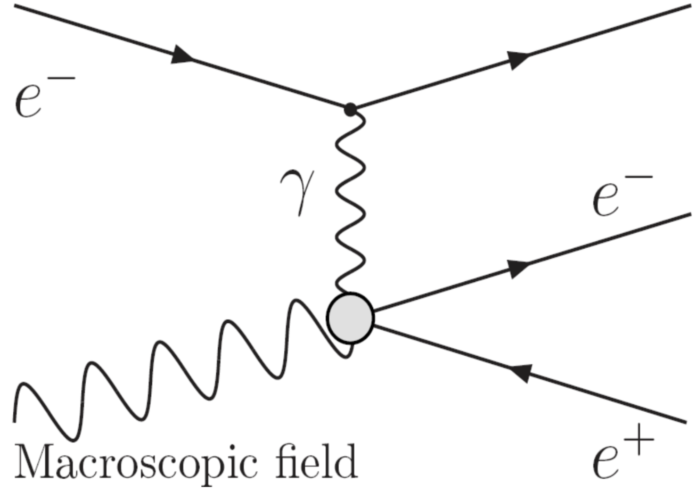
Beam-Beam interactions at e⁺e⁻ colliders

- 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.

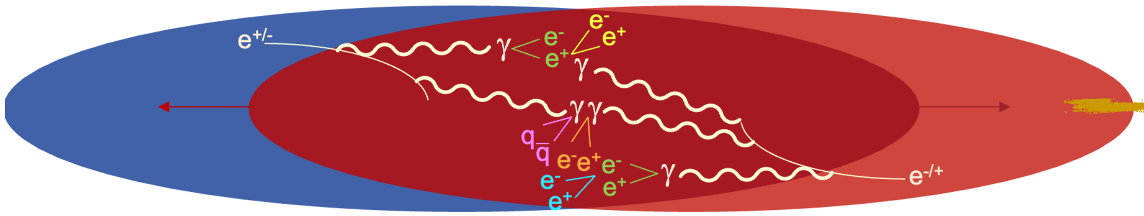


NLC ZDR

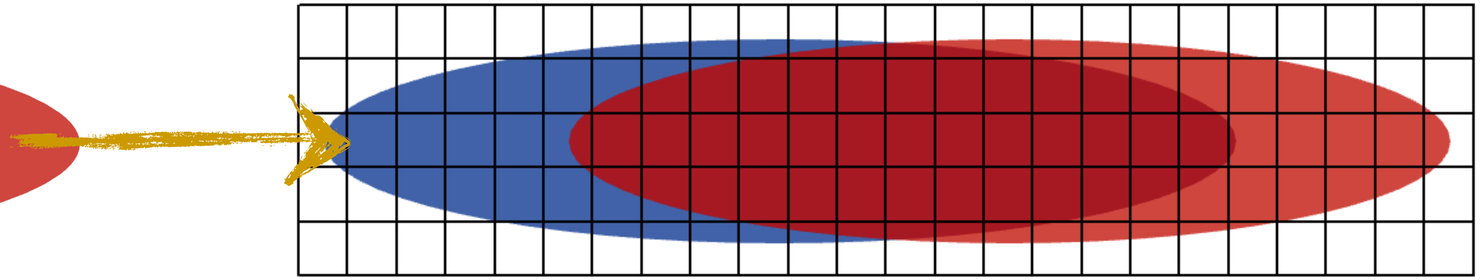


Simulation of Beam-Induced Background

- 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*

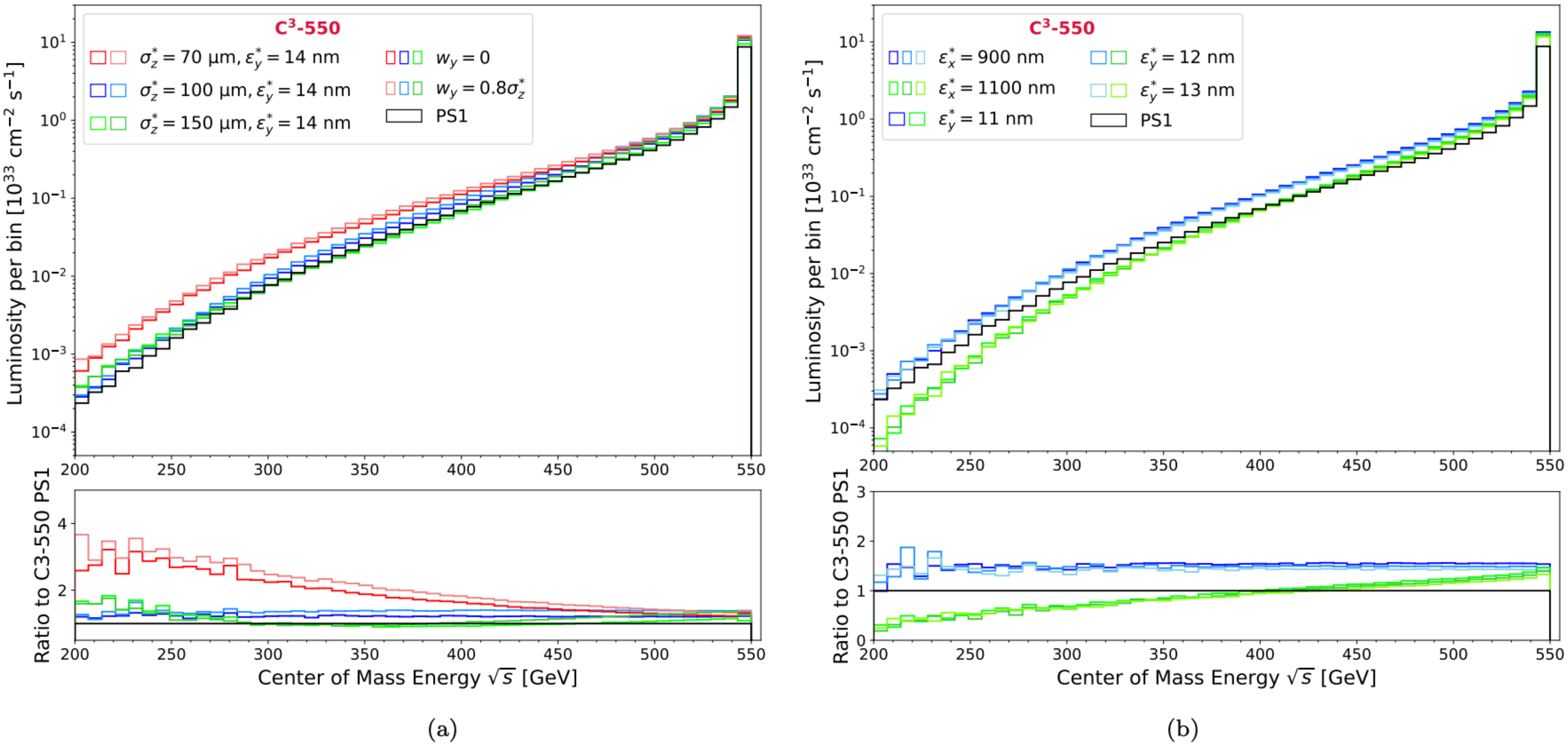


Jean-Luc Vay



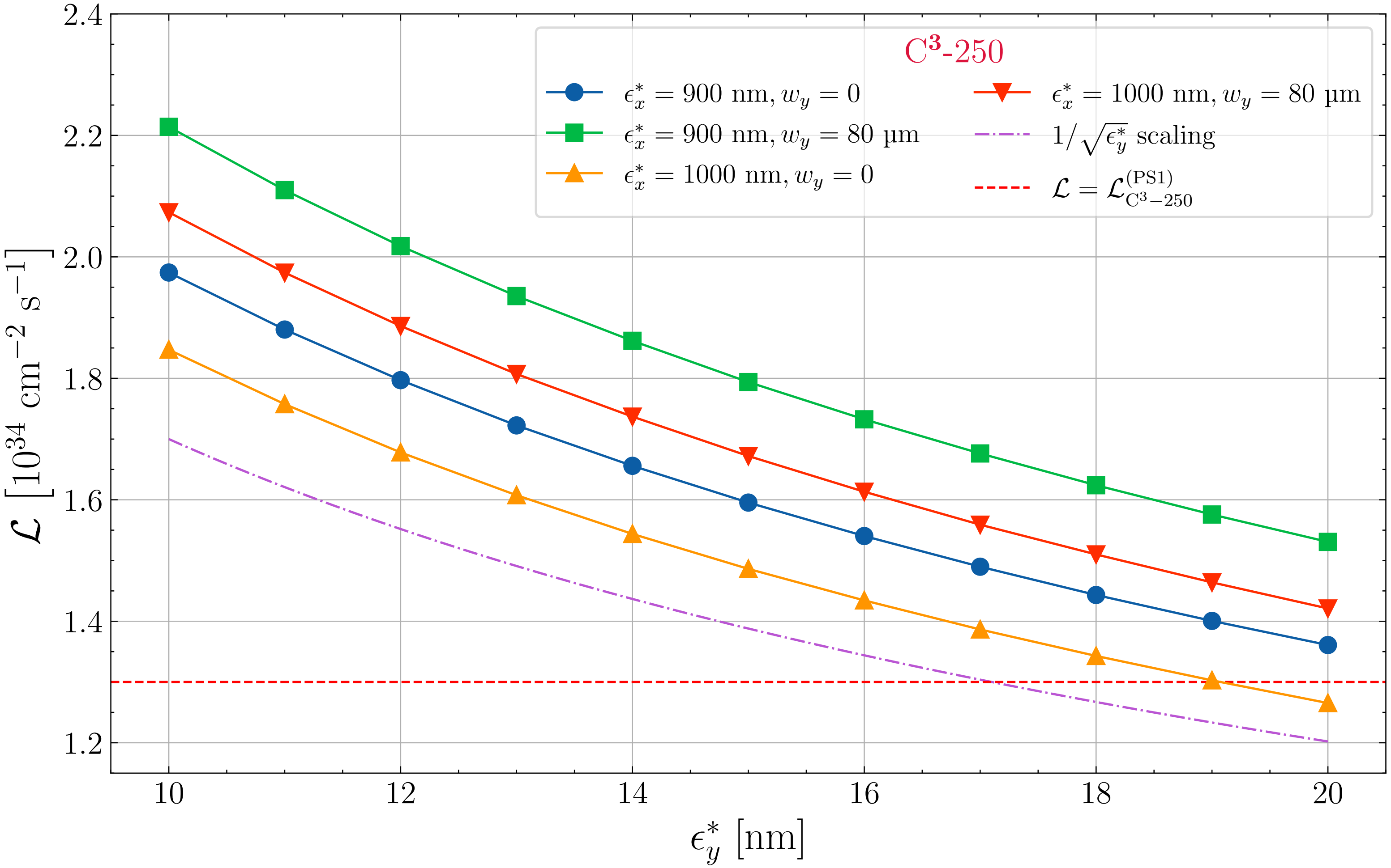
Jean-Luc Vay

C³ - 550 Parameter Optimization



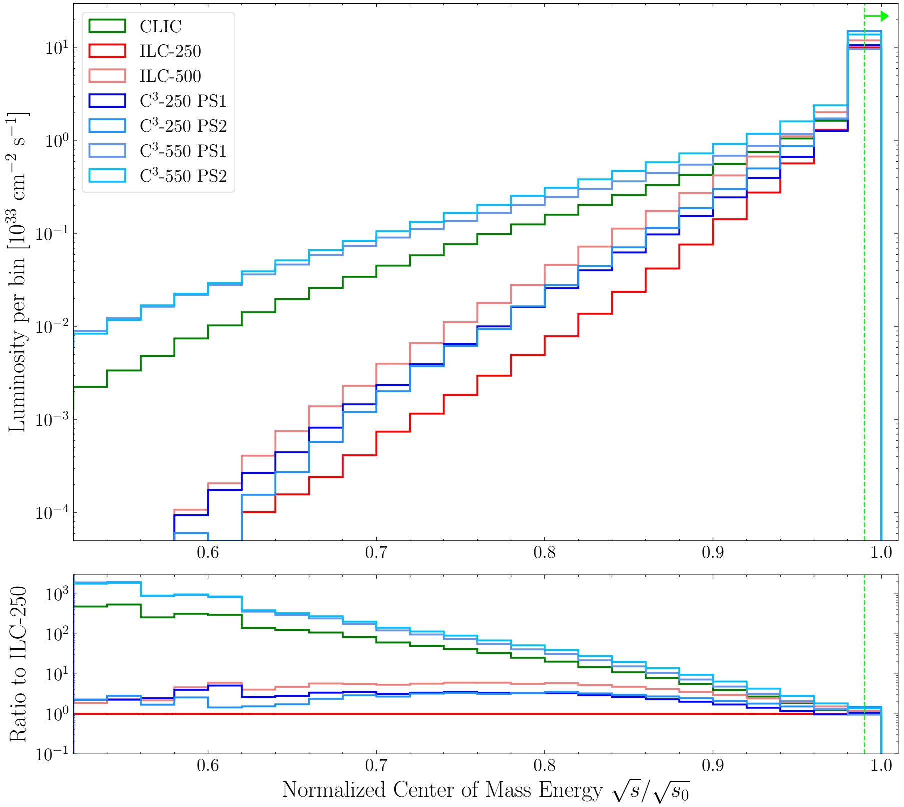
Evaluation on C³ - 250

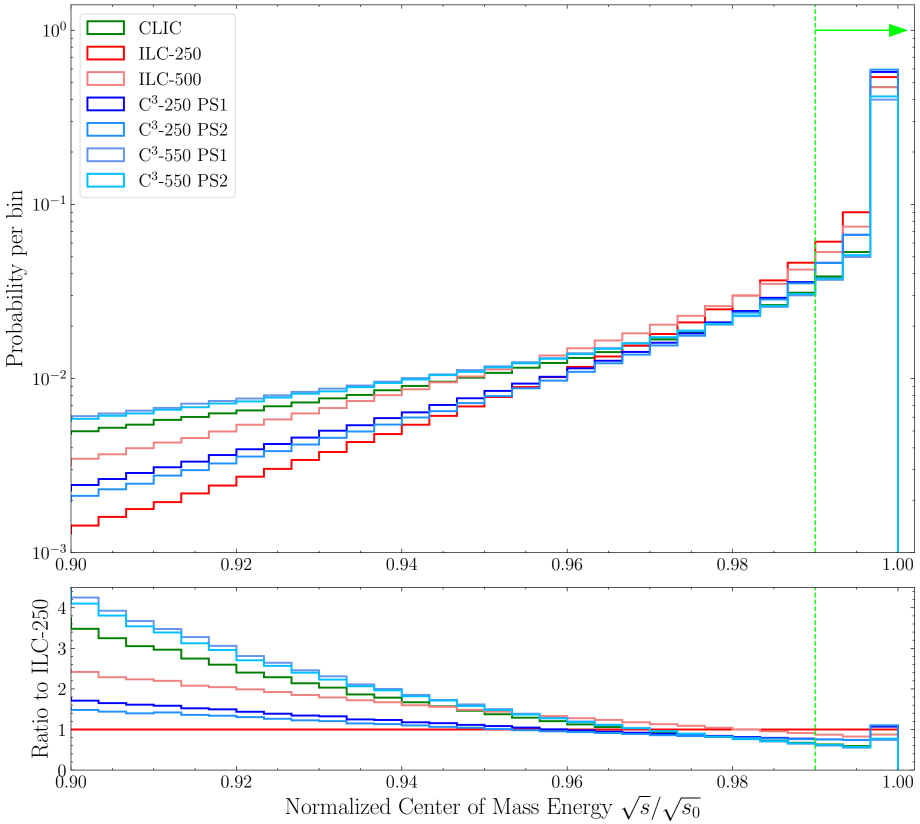
- Similar dependence of $\mathscr{L}$ on $\epsilon_y^*, \epsilon_x^*$ as at 550 GeV.
- There is some loss in lumi when increasing the horizontal emittance to 1000nm, but it helps to better cope with BIB.



Comparison with other linear colliders

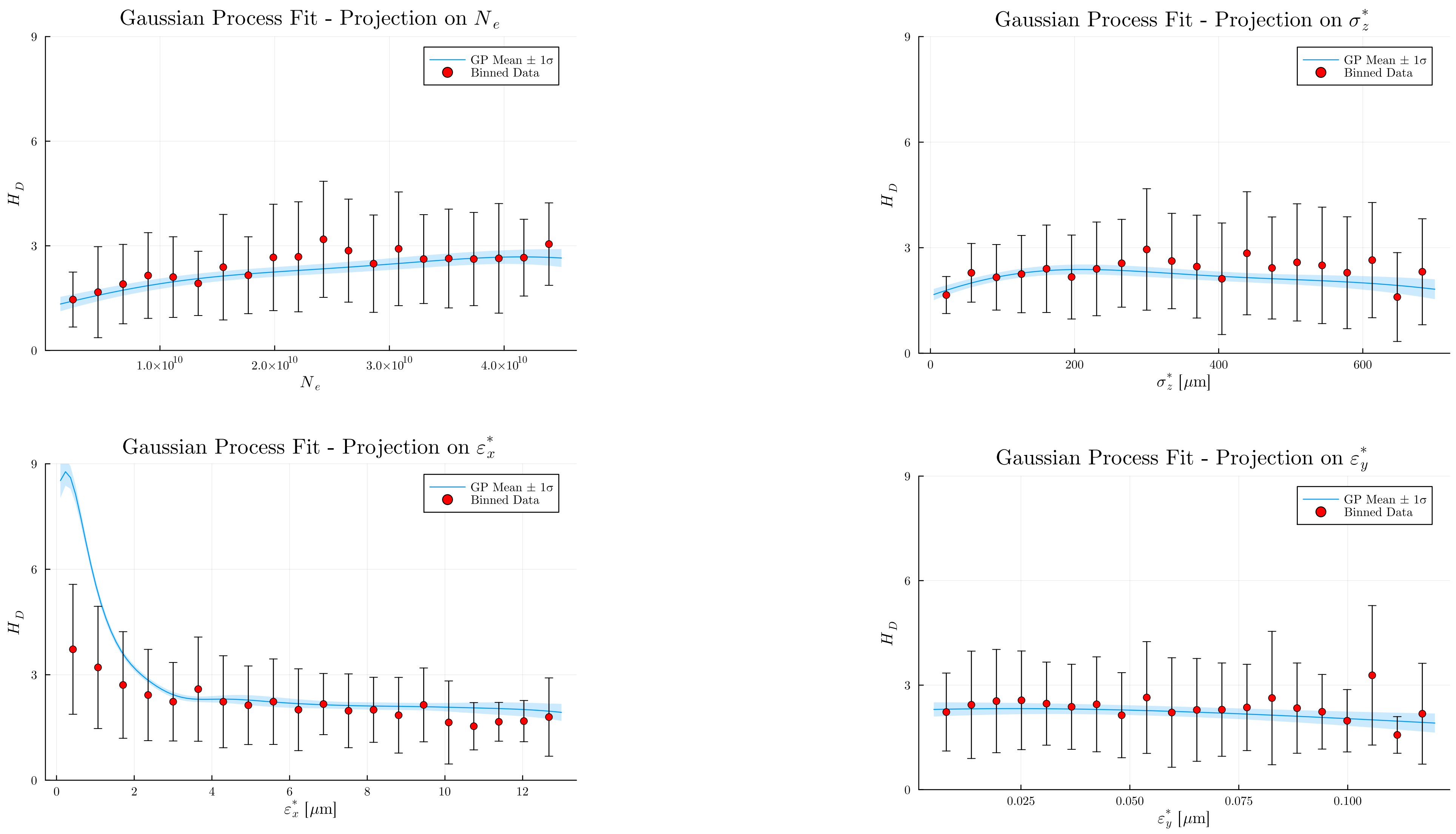
- ILC-250 has the tighest luminosity spectrum, followed by C^3-250,ILC-500, CLIC and, lastly, C^3-550.
- C^3 achieves larger, overall, peak luminosities.





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

Surrogate model optimization



Power consumption considerations

TABLE IV: Beam configuration scenarios for C^3-250 which include modifications in the bunch spacing Δt_b, the number of bunches per train n_b and/or the train repetition rate f_r. The last three columns give the instantaneous luminosity for the PS1 and PS2 parameter sets, as well as the estimated total site power, in each case.

					$\mathscr{L}$ $[10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}]$		P_{site} [MW]
Scenario	Flat top [ns]	Δt_b [ns]	n_b	f_r (Hz)	C^3-250 (PS1)	C^3-250 (PS2)	Both scenarios
Baseline	700	5.26	133	120	1.35	1.90	150
Double flat top	1400	5.26	266	60	1.35	1.90	125
Halve bunch spacing	700	2.63	266	60	1.35	1.90	129
Combined - half rep. rate	1400	2.63	532	60	2.70	3.80	154
Combined - nominal rep.rate	1400	2.63	532	120	5.40	7.60	180

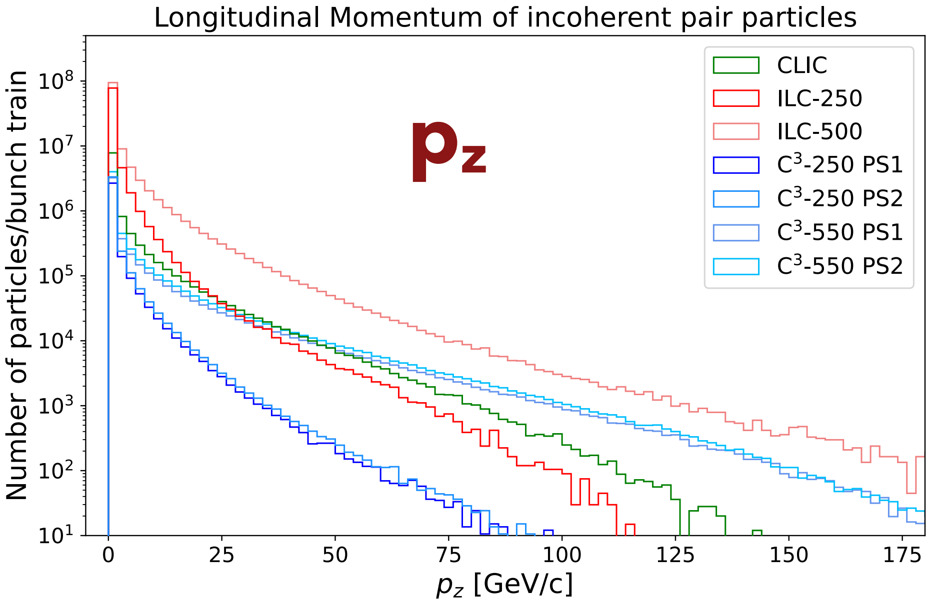
TABLE V: Beam configuration scenarios for C^3-550 which include modifications in the bunch spacing Δt_b, the number of bunches per train n_b and/or the train repetition rate f_r. The last three columns give the instantaneous luminosity for the PS1 and PS2 parameter sets, as well as the estimated total site power, in each case.

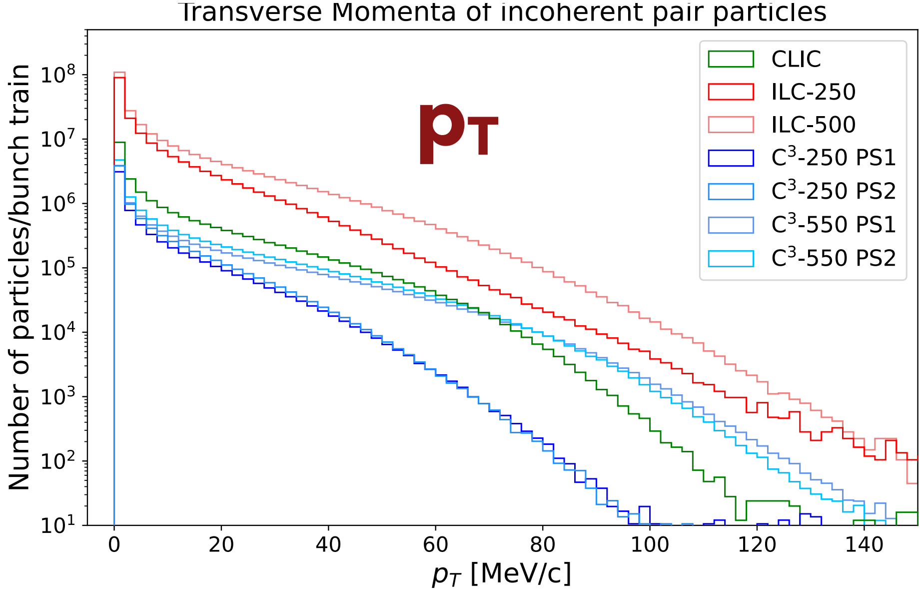
					$\mathscr{L}$ $[10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}]$		P_{site} [MW]
Scenario	Flat top [ns]	Δt_b [ns]	n_b	f_r (Hz)	C^3-550 (PS1)	C^3-550 (PS2)	Both scenarios
Baseline	250	3.50	75	120	1.70	2.40	175
Double flat top	500	3.50	150	60	1.70	2.40	144
Halve bunch spacing	250	1.75	150	60	1.70	2.40	149
Combined - half rep. rate	500	1.75	300	60	3.40	4.80	180
Combined - nominal rep.rate	500	1.75	300	120	6.80	9.60	212

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 readout rate of 120 Hz.***

Detailed Luminosity Studies: 2403.07093





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	~ 0.1	~ 0.1	~ 0.3	~ 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	~ 150	~ 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	$\mathscr{L}_{\text{geom}}$ [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

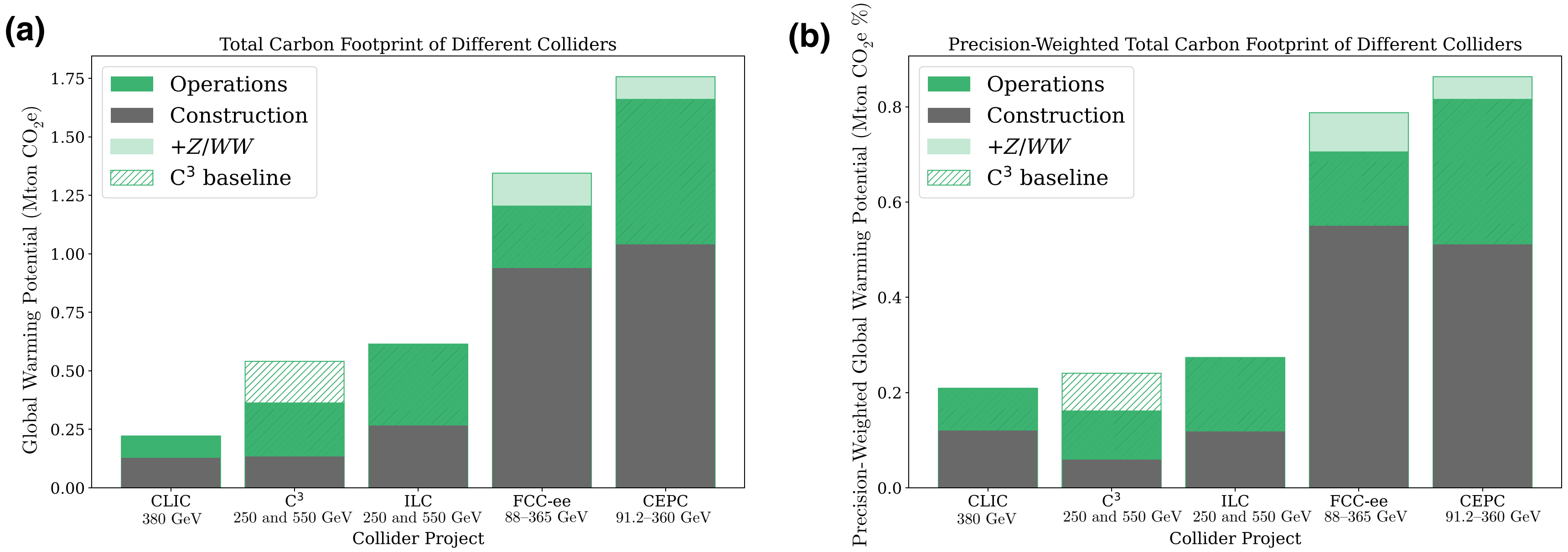


TABLE VI. For each of the Higgs factory projects considered in the first row, the center-of-mass energies (second row), ac site power (third row), annual collision time (fourth row), total running time[a] (fifth row), instantaneous luminosity per interaction point (sixth row), and target integrated luminosity (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