Bunch structure studies at the Cool Copper Collider

3rd ECFA workshop on e+e- Higgs, Top & EW Factories

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U.S. DEPARTMENT OF ENERGY
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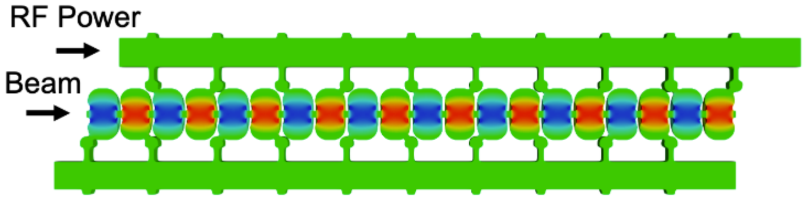
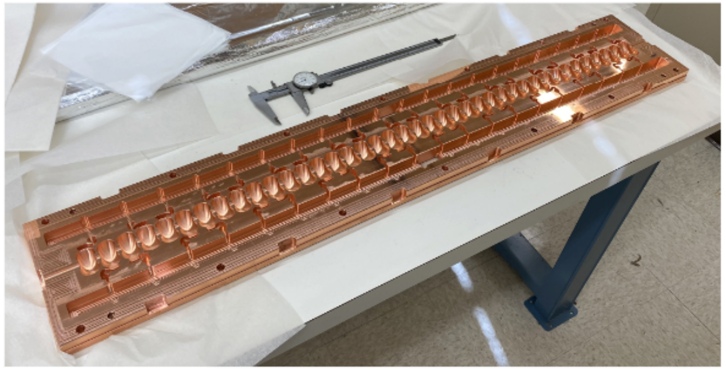
The Cool Copper Collider

JINST 18 P07053
JINST 18 P09040
PRAB 23 092001

- Cool Copper Collider (C^3) : newest proposal for a linear e^+e^- collider relying on normal conducting copper accelerating technology, with a novel cavity design that utilizes distributed coupling.
- cryogenic temperature operation (LN2 at 77K), lower surface fields and higher accelerating gradients → ***cost-effective, compact 8 km footprint.***



Electric field magnitude for equal power from RF manifold

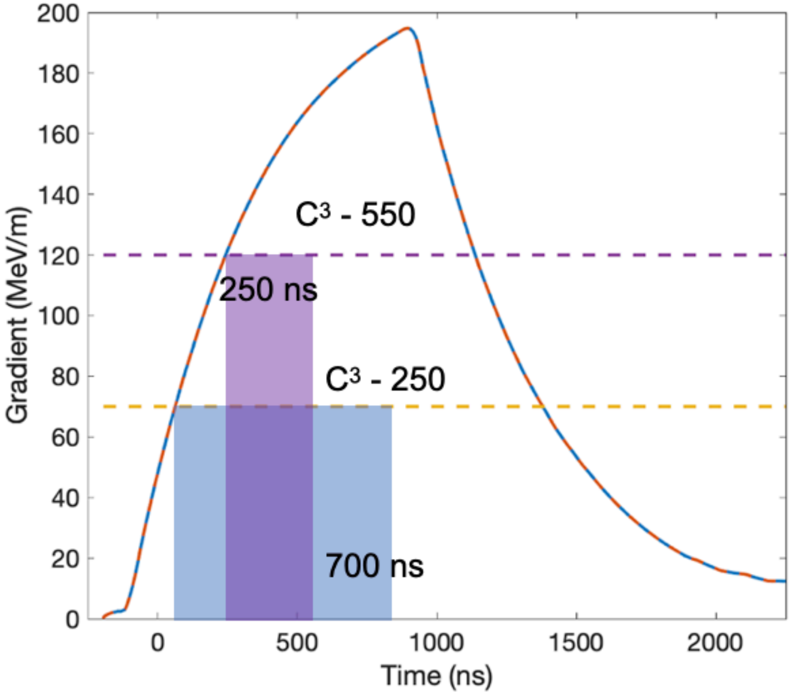


Innovations

- Optimized design of RF cavities to minimize breakdown.
- Small aperture, distributed coupling from a common RF manifold → possible with precision CNC

75 MeV/m @250 GeV

120 MeV/m @550 GeV



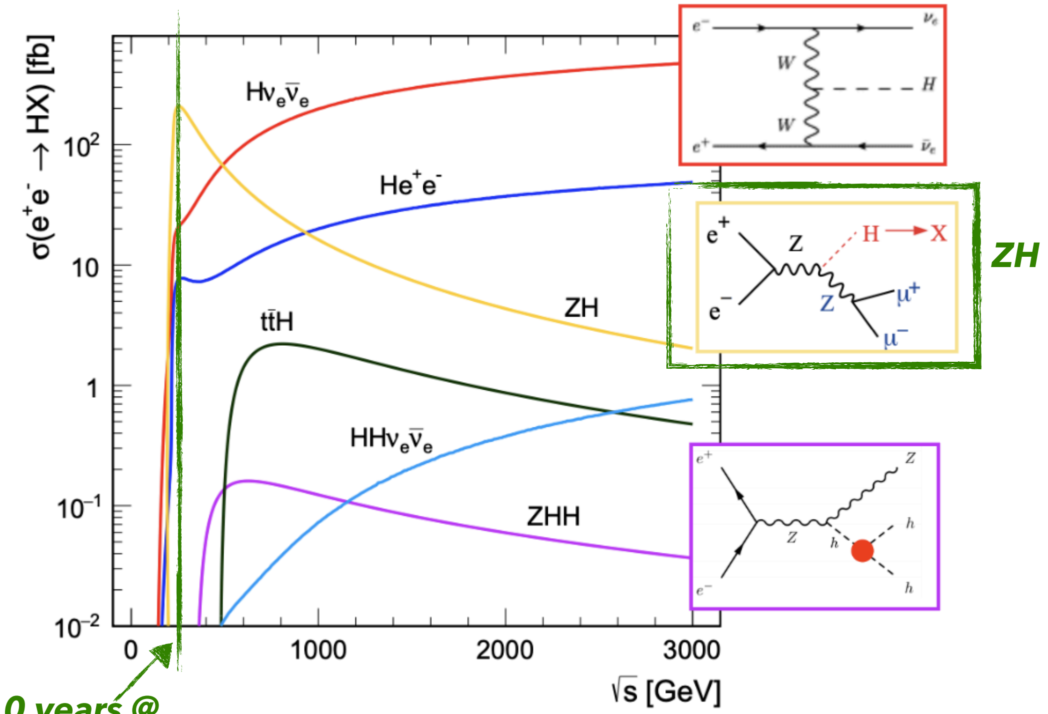
JINST 18 P07053

The Cool Copper Collider - *Physics*

- C^3 targeted at operations at 250 GeV (ZH mode) and 550 GeV (ZHH mode - only possible for linear colliders).
- The targeted inst. luminosity of $1.3(2.4) \times 10^{34}$ cm^{-2} s^{-1} at 250 (550) GeV would allow 2 (4) ab^{-1} of statistics after ***10 years at each energy***.
- It's important to ***evaluate and optimize emissions due to construction and operation for the entire run time of the collider.***

Parameter	Value	
$\sqrt{s}$ (GeV)	250	550
Luminosity (cm^{-2} sec^{-1})	1.3×10^{34}	2.4×10^{34}
Number of bunches per train	133–200	75
Train repetition rate (Hz)	120	120
Bunch spacing (ns)	5.3–3.5[a]	3.5
Site power (MW)	150	175
Beam power (MW)	2.1	2.45
Gradient (MeV/m)	70	120
Geometric gradient (MeV/m)	63	108
rf pulse length (ns)	700	250
Shunt impedance (MΩ/m)	300	300
Length (km)	8	8

Target beam parameters for C^3.



ZH

10 years @ 250 GeV

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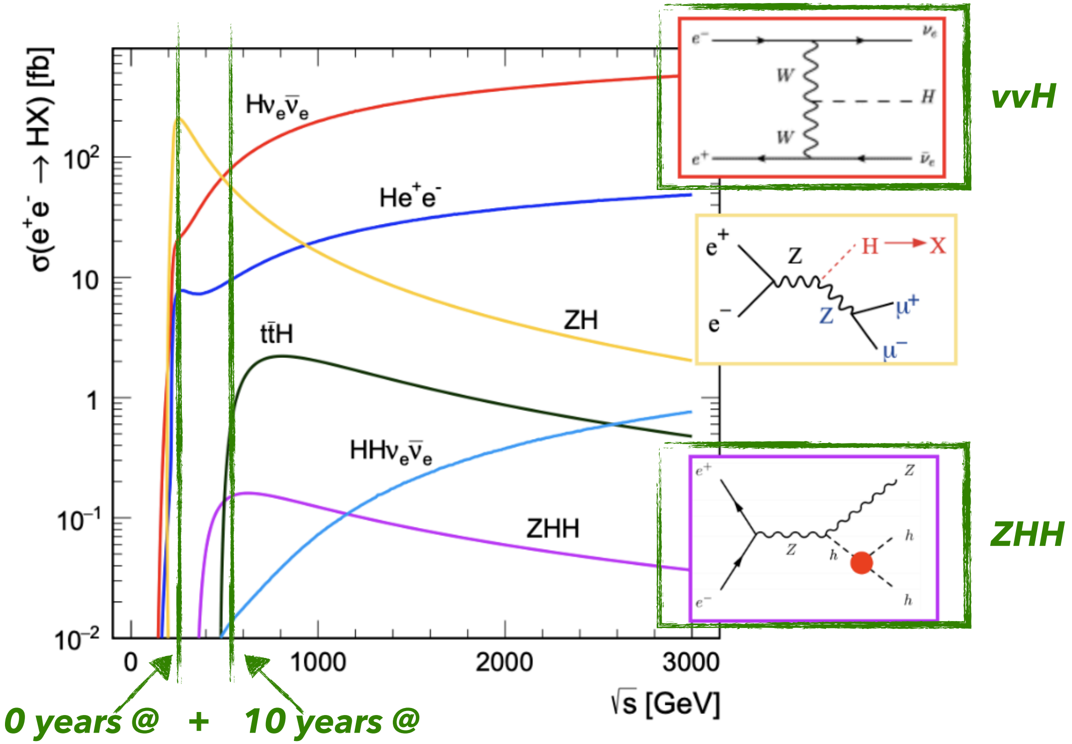


10 years @ 250 GeV **+** ***10 years @ 550 GeV***

C³ Parameter Optimization

PRAB 27, 061001

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:

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

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**

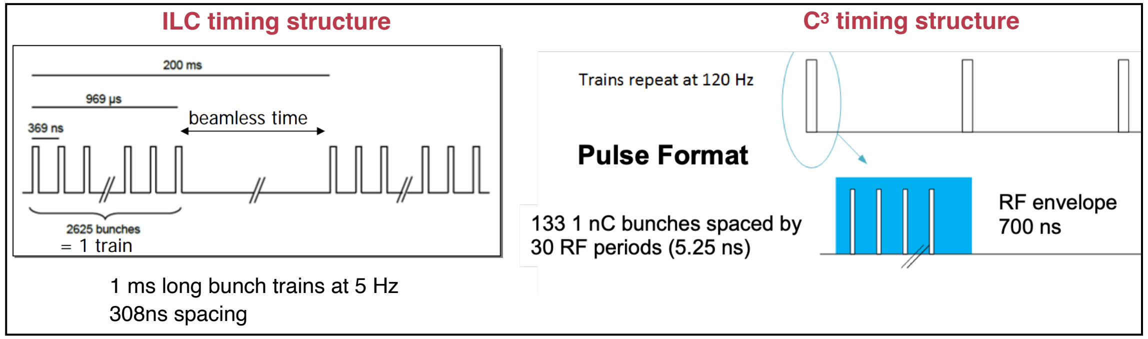
With the new parameters, the target luminosity is reached (and exceed for C³-250 by by **55%**), while the beam-induced background remains at the same levels.

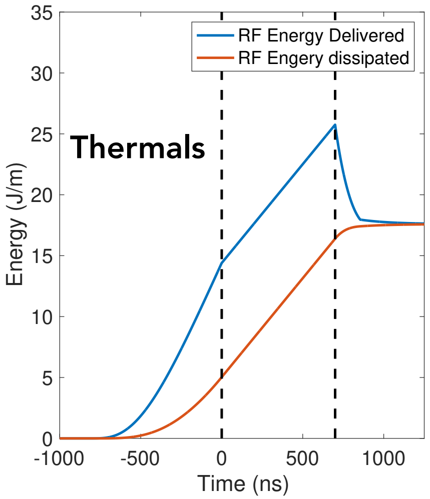
The Cool Copper Collider - *Power Optimizations*

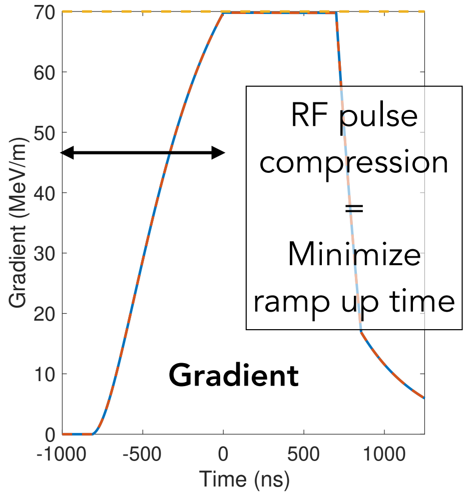
- Potential improvements for C3 coming from minimizing RF power when there is no beam loading.

Scenario	rf system (MW)	Cryogenic system (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	. . .
rf source efficiency increased by 15%	31	60	91	9
rf pulse compression	28	42	70	30
Double flat top	30	45	75	25
Halve bunch spacing	34	45	79	21
All scenarios combined	13	24	37	63

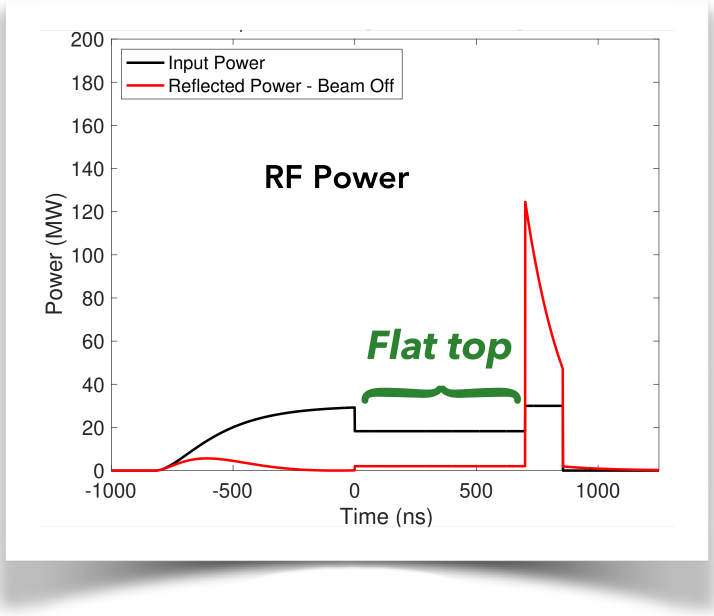
Power savings with adjustment of the main linac design and beam parameters. For 550 GeV, the percentage savings would be unchanged for a combined 79 MW reduction.







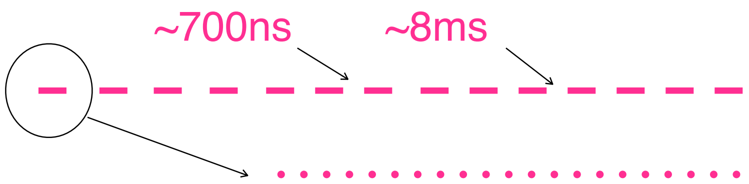
- Doubling the flat-top (700→ 1400 ns) or halving the bunch spacing (5.25→2.6ns) allows for **rep. rate reduction** (120→ 60 Hz) without loss in luminosity.
- This **reduces thermal load** by **25%**.
- Overall, power savings can reach **63MW** at 250 GeV and **79MW** at 550GeV.



The Cool Copper Collider - *Power Optimizations* C^3

- Changes in flat-top duration, bunch spacing and rep. rate can be combined to improve the luminosity per unit power up to **3x**!
- The energy consumption throughout the entire lifetime of the machine can be reduced significantly!

Requires additional studies to evaluate feasibility on the accelerator (high-gradient tests with double flat top) and detector (evaluation of occupancy tolerances) side!



Luminosity for two beam parameter sets

Total site power consumption

					$\mathcal{L}$ $(10^{34}$ cm^{-2} 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 repetition rate	1400	2.63	532	60	2.70	3.80	154
Combined-nominal repetition rate	1400	2.63	532	120	5.40	7.60	180

Beam configuration scenarios for C^3, 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.

$\mathcal{L}/P_{\text{site}}$

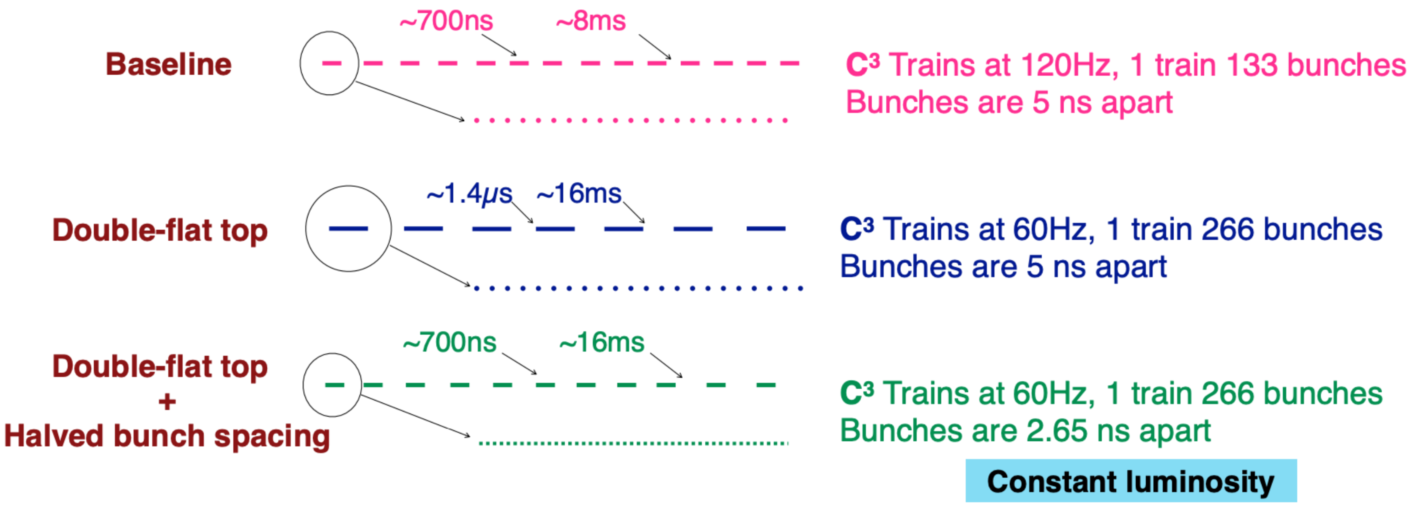
$(10^{34}$ cm^{-2} s^{-1} (GW)$^{-1}$

PS1	PS2
9.0	12.7
10.8.	15.2
10.5	14.7
17.5	24.7
30.0	42.2

Up to ~3x $\mathcal{L}/P_{\text{site}}$ gain!

The Cool Copper Collider -*Sustainability Scenario*

- Reduce train repetition rate from 120Hz to 60Hz, while increasing the number of bunches per train from 133 to 266.
- This change:
  - Maintains the same lumi!
  - Reduces power consumption by ~25%
  - Reduces the bunch spacing from 5.26ns to 2.65 ns –> ***need to check detector compatibility!***



Baseline

C^3 Trains at 120Hz, 1 train 133 bunches
Bunches are 5 ns apart

Double-flat top

C^3 Trains at 60Hz, 1 train 266 bunches
Bunches are 5 ns apart

Double-flat top
+
Halved bunch spacing

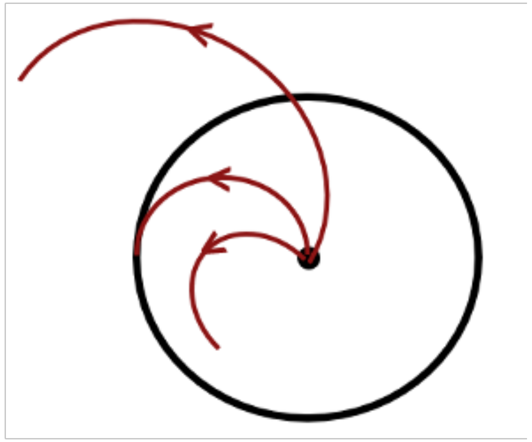
C^3 Trains at 60Hz, 1 train 266 bunches
Bunches are 2.65 ns apart

Constant luminosity

scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125

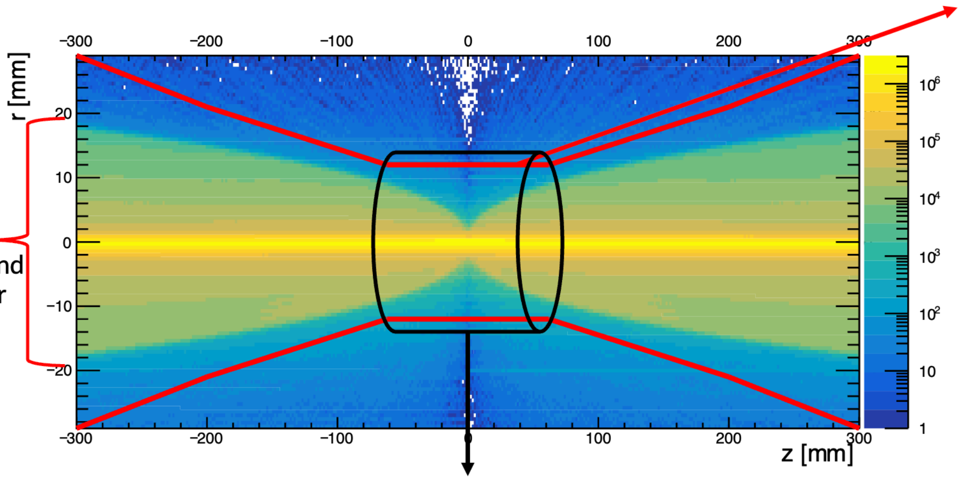
Pair background at C^3

- 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**
- At C^3, $\sim 0.1\ \%$ or ~ 40 particles/BX) reach the detector and increase its occupancy → might compromise the stringent precision requirements
- The ***vertex barrel detector***, which is the closest to the IP (r=14 mm for the 1st layer of SiD) is mostly affected.



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

Hit density for 133 bunch crossings for C^3-250 simulated with GUINEA-PIG and tracked through a 5T solenoid field



Beam pipe outline

Region of closest approach: r=12 mm for |z|<62 mm

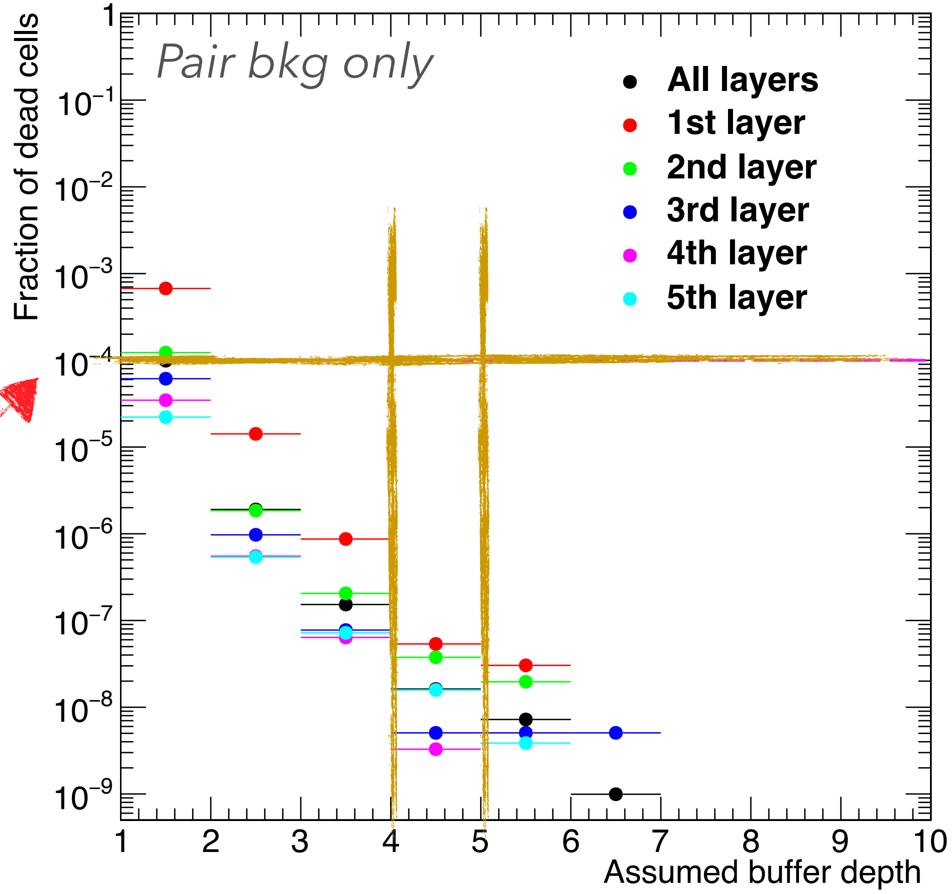
The 1st SiD vtx detector layer is proposed to be placed 2 mm outside of that (at r=14 mm)

Convention: r>0 for y>0 and vice verse (for visualization purposes)

1st vtx barrel layer

Pair background at C^3

- Detector **occupancy** : fraction of dead cells, i.e. cells with a number of hits ≥ the available number of buffers (called **buffer depth**).
- In the current readout strategy for C^3, hits will be stored in the buffer system and read out after each bunch train.
- We estimated the occupancy by running full detector simulation for SiD in dd4hep 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.

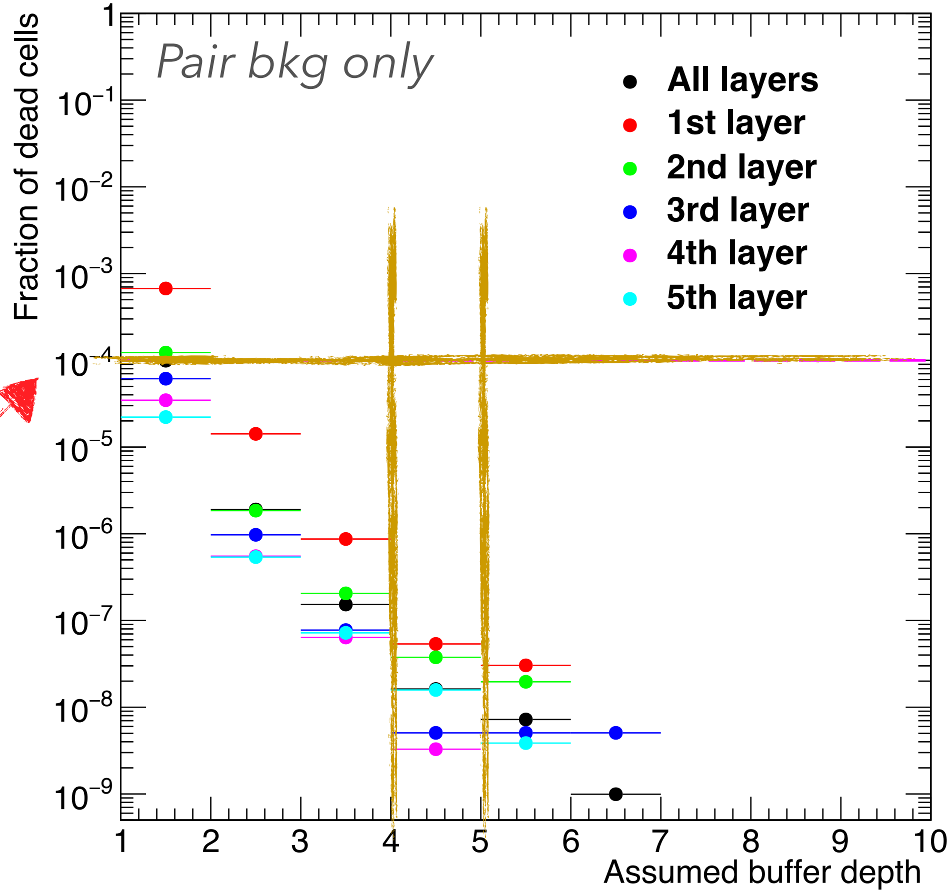


Occupancy in the vertex barrel as a function of assumed buffer depth for C^3-250.

Pair background at C³

- Detector **occupancy** : fraction of dead cells, i.e. cells with a number of hits ≥ the available number of buffers (called **buffer depth**).
- In the current readout strategy for C³, hits will be stored in the buffer system and read out after each bunch train.
- We estimated the occupancy by running full detector simulation for SiD in dd4hep for a full C³ bunch train (133 BXs).
- For ILC detectors, an occupancy upper limit of 10^{-4} and buffer depth of 4 has been proposed.

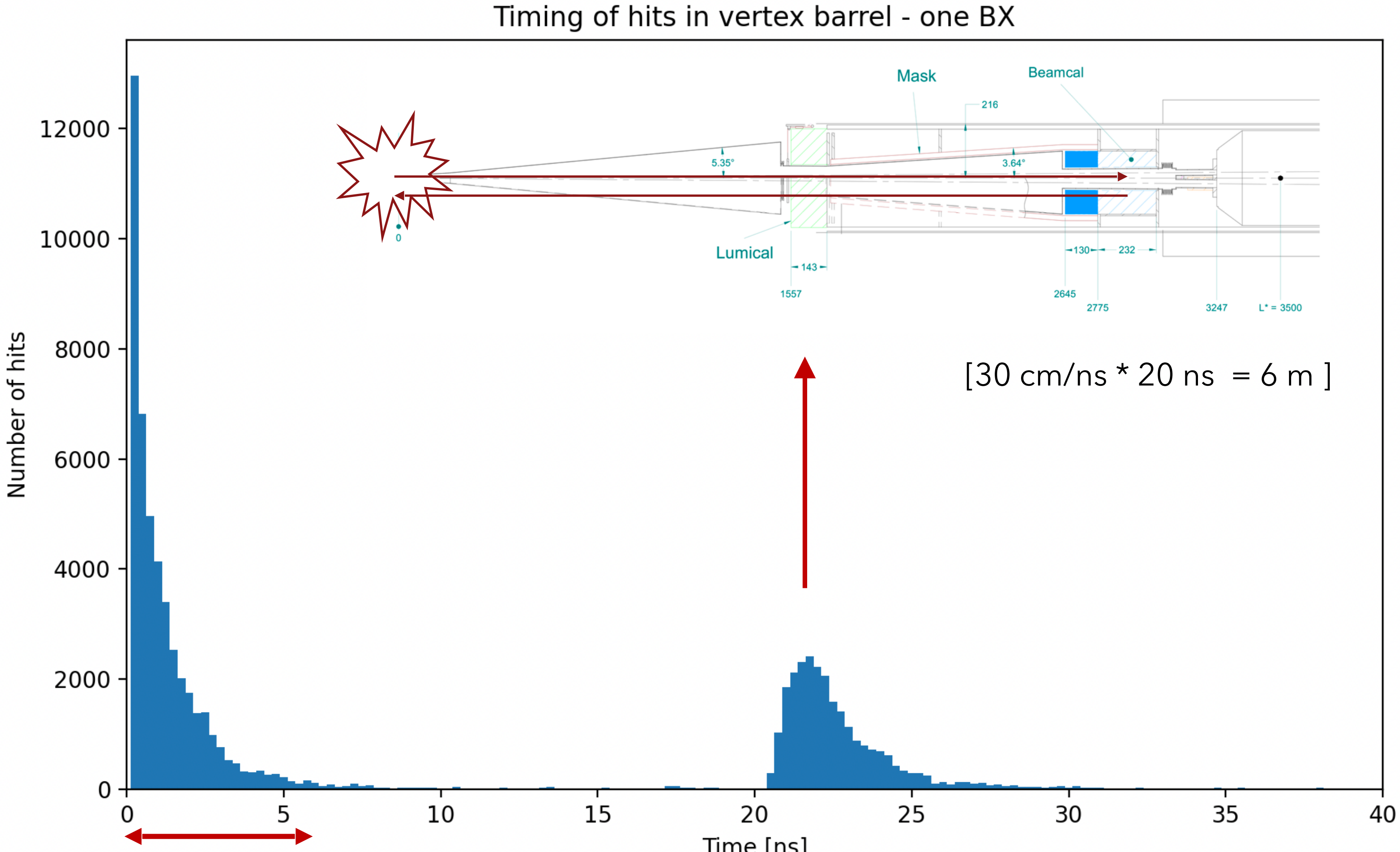
- ***Occupancy in the SiD vertex barrel for the C³ beam structure is well within the limits set for ILC.***



Occupancy in the vertex barrel as a function of assumed buffer depth for C³-250.

Time distribution within each BX for C^3

- Time distribution of hits in the SiD vertex barrel within a single BX.
- The normalization corresponds to a full bunch train for C^3-250.
- Most hits contained in time within the bunch spacing.
- The secondary peak at ~20-25 ns is due to backscattering from the BeamCal.



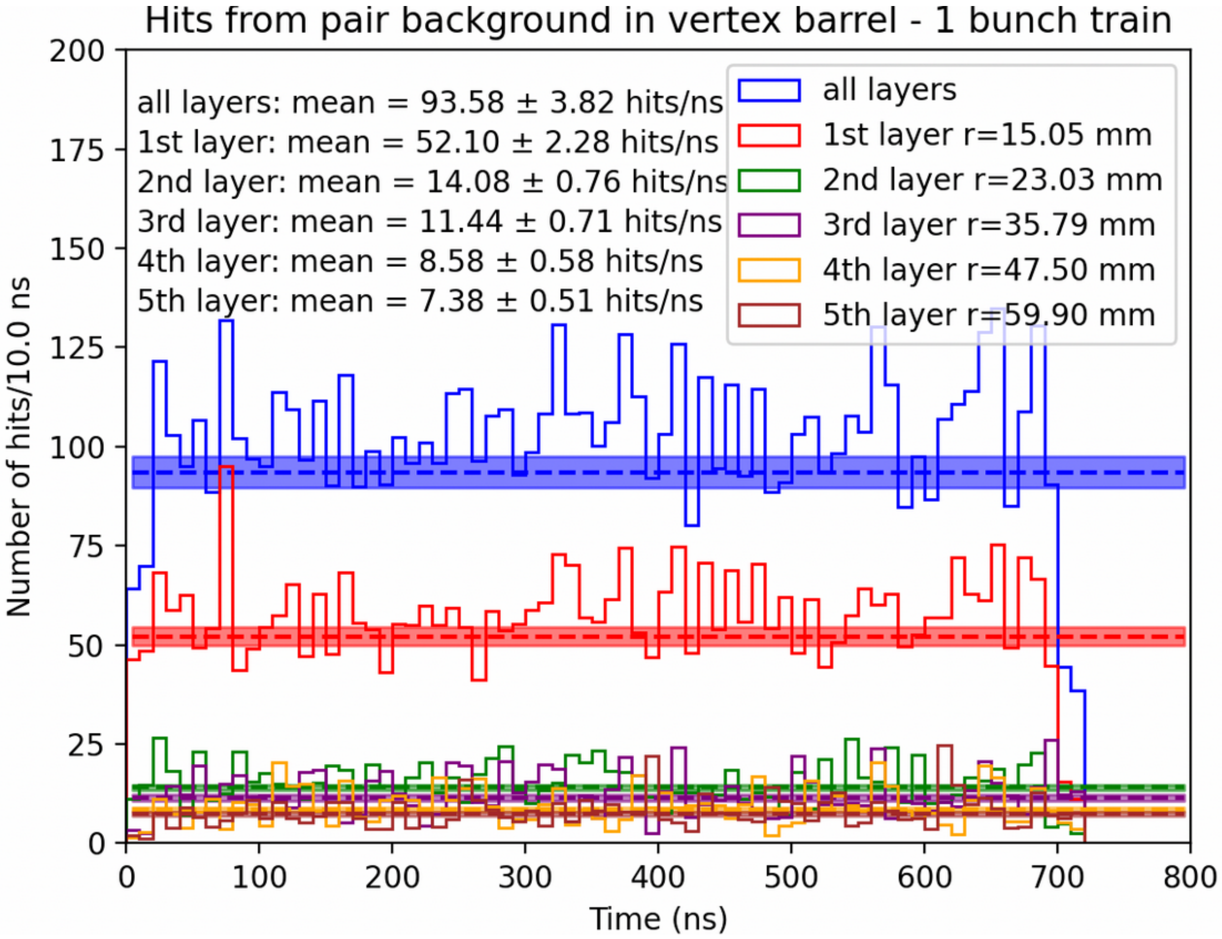
[30 cm/ns * 20 ns = 6 m]

Bunch spacing – 5.25 ns

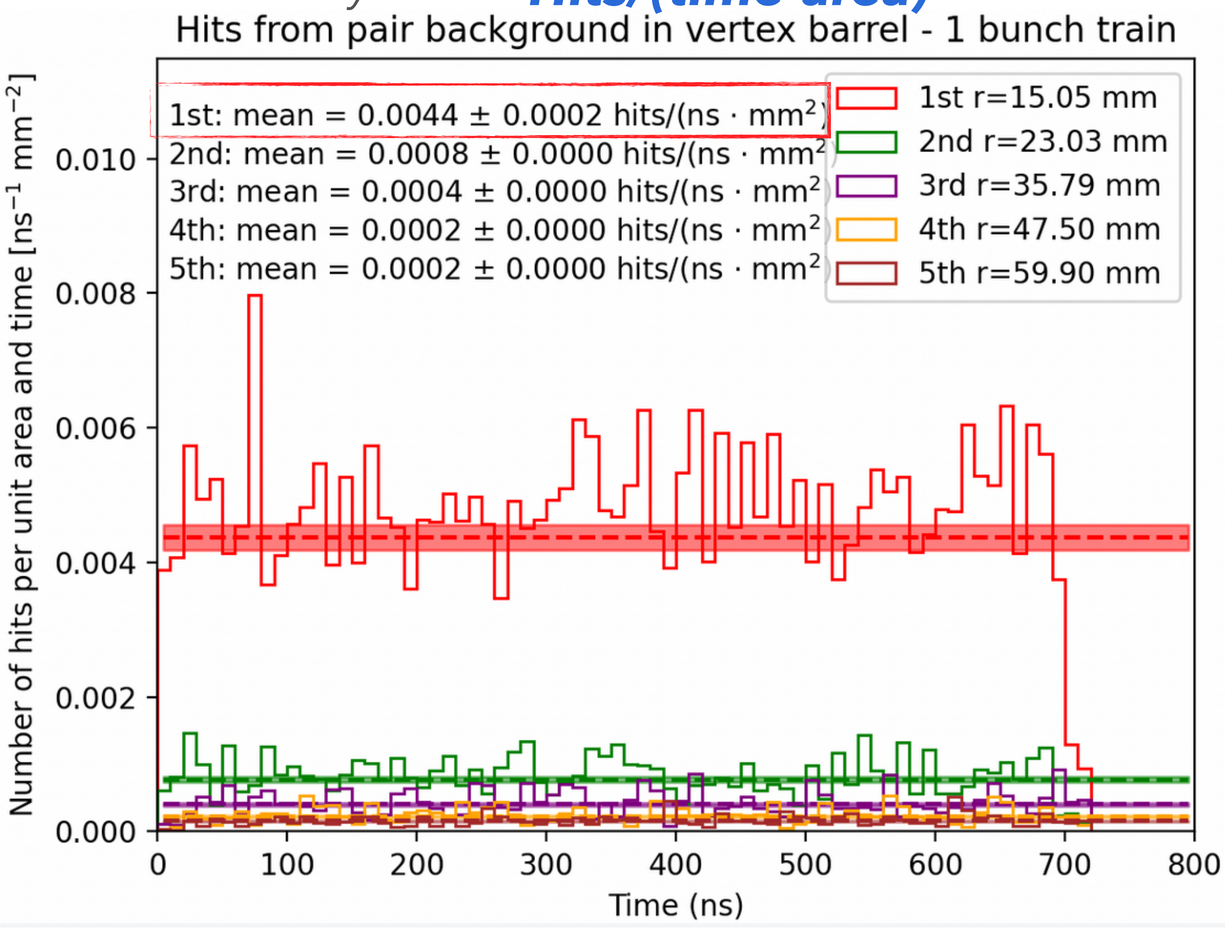
Time distribution over a train for C^3

Time distribution of hits in vtx barrel per unit time for a full C^3-250 train:
on average, we anticipate ~ 90 hits/ns in the vertex barrel detector.

Preliminary **_Hits/time_**



Preliminary **_Hits/(time·area)_**



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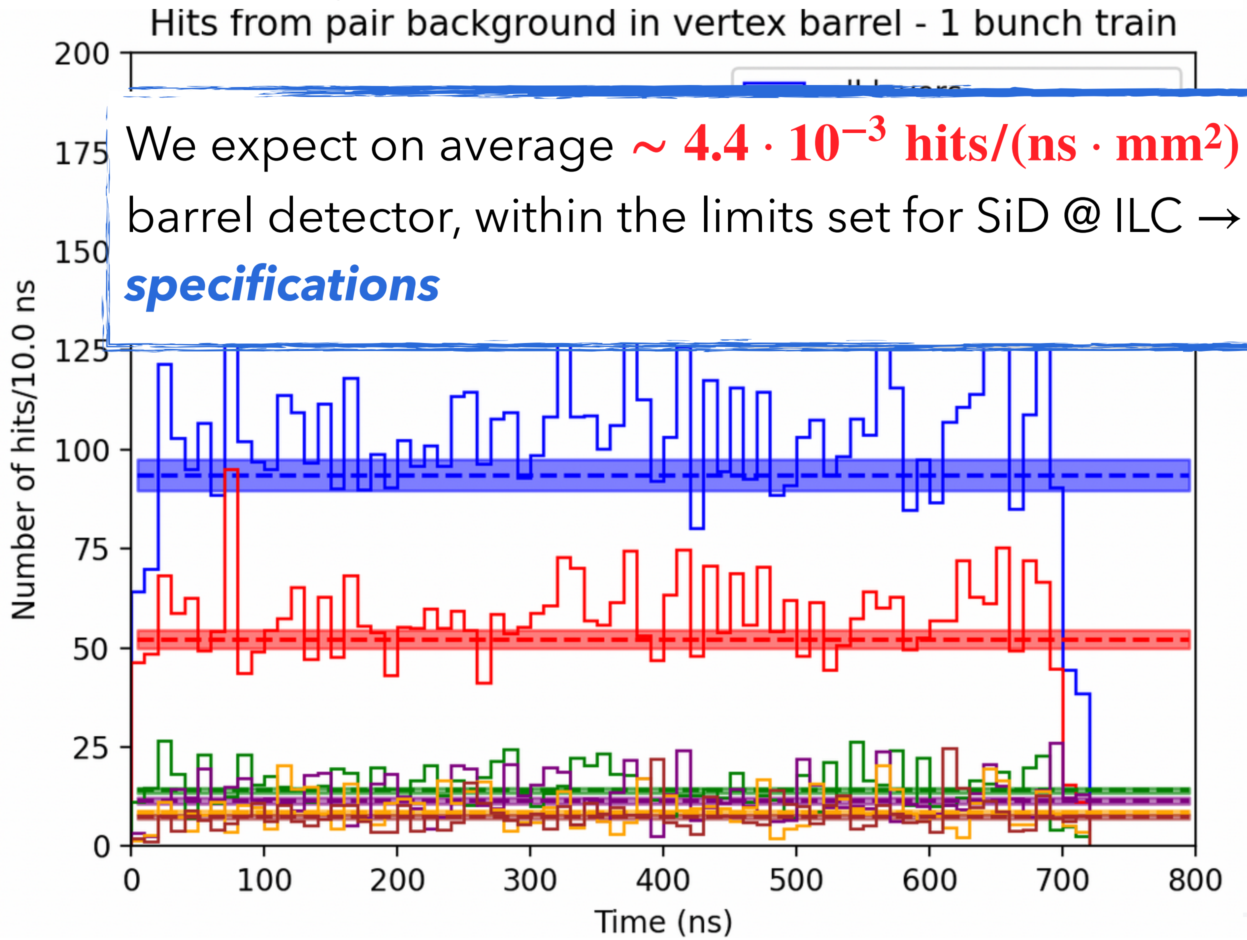
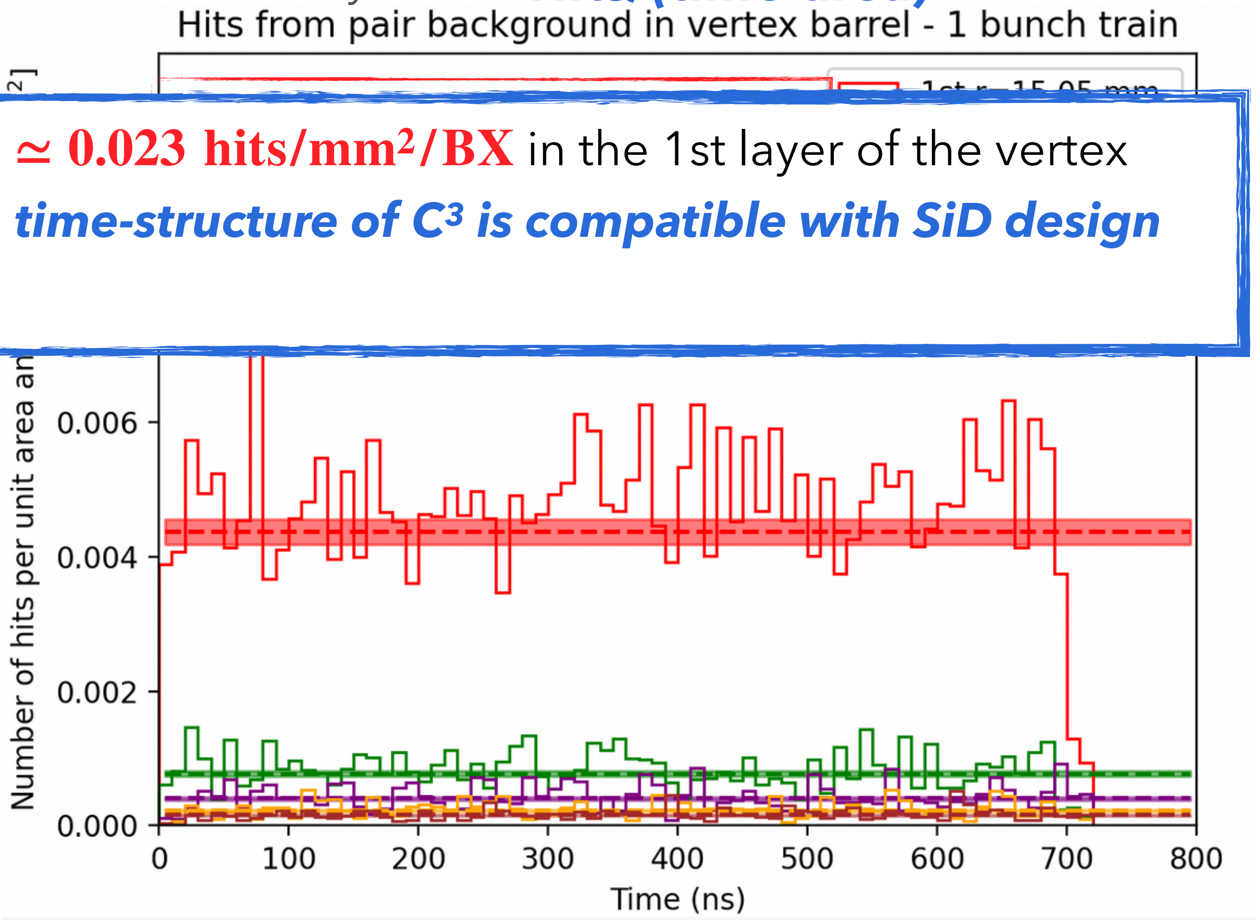


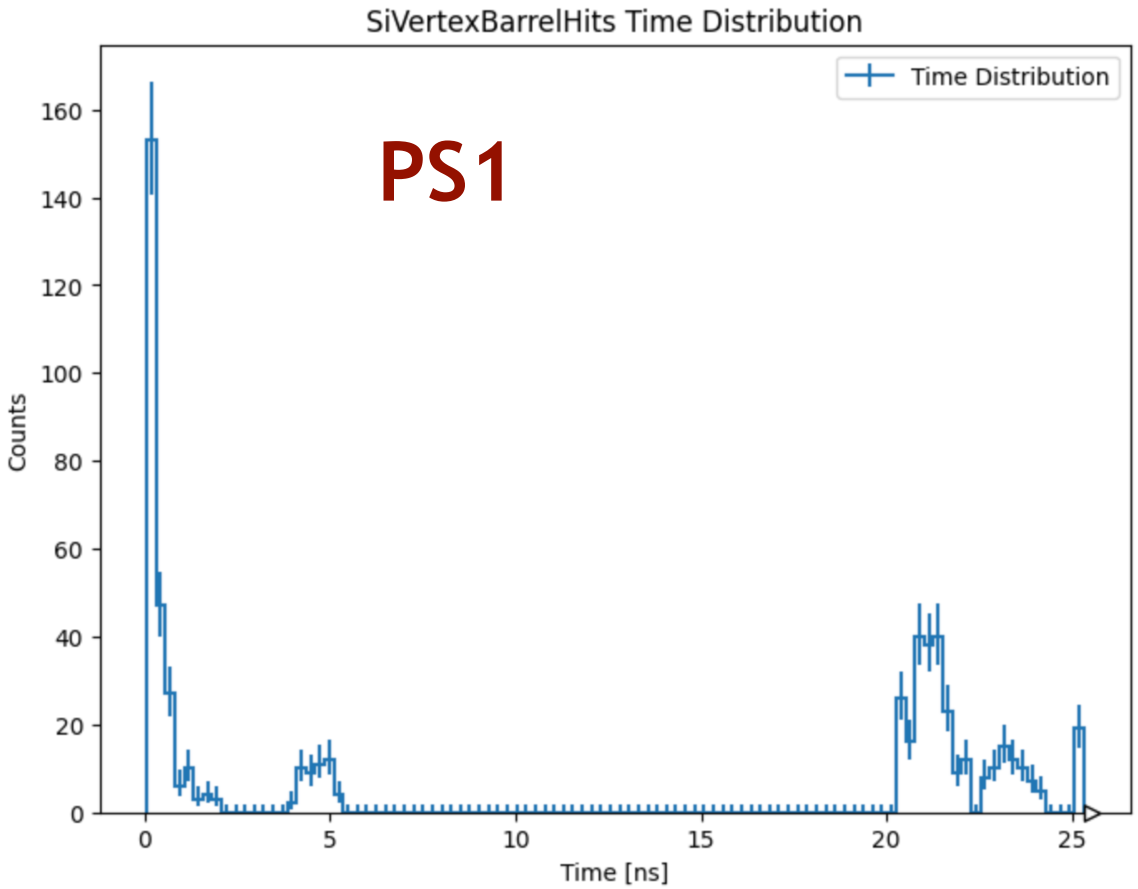
Preliminary **Hits/(time·area)**

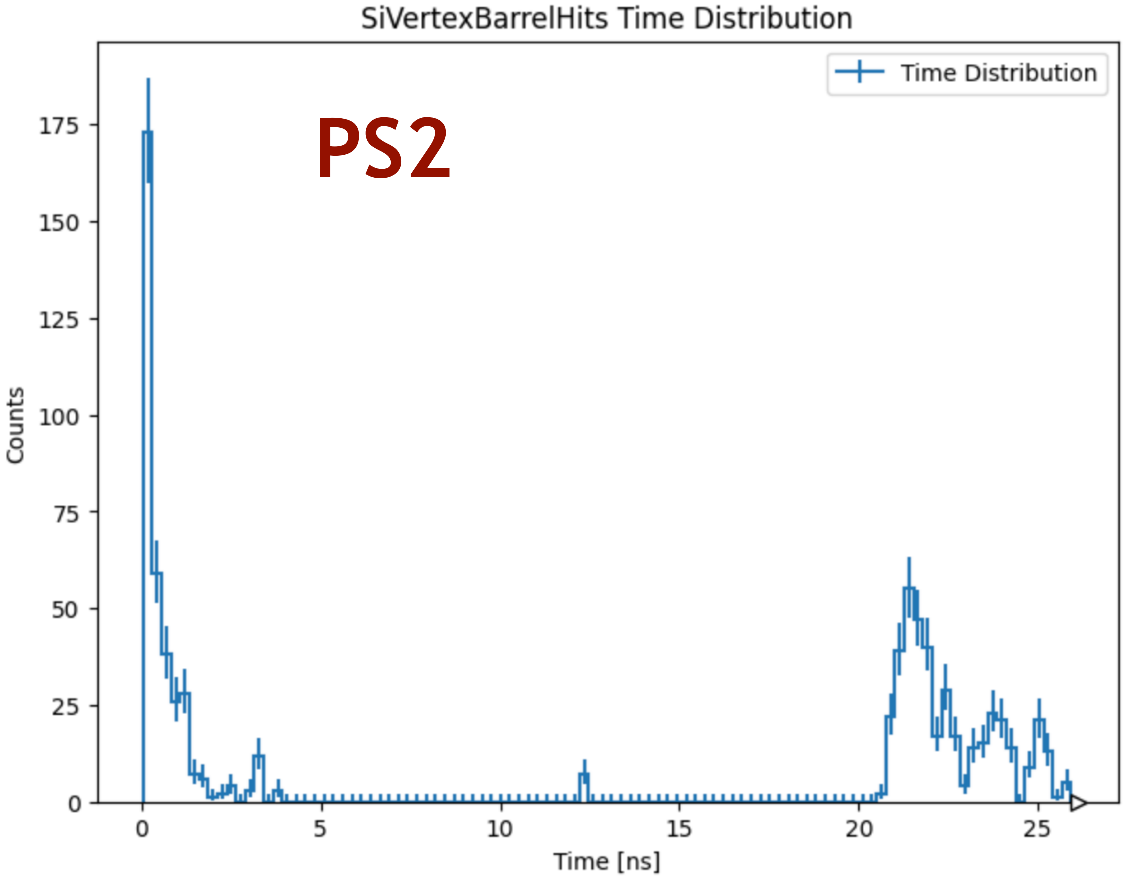


We expect on average $\sim \mathbf{4.4 \cdot 10^{-3}}$ **hits/(ns · mm²)** $\simeq$ **0.023 hits/mm²/BX** in the 1st layer of the vertex barrel detector, within the limits set for SiD @ ILC → ***time-structure of C^3 is compatible with SiD design specifications***

Pileup Overlay

- Using overlay timing from k4reco to overlay pair background and hadron photo production (see Lindsey's talk!)





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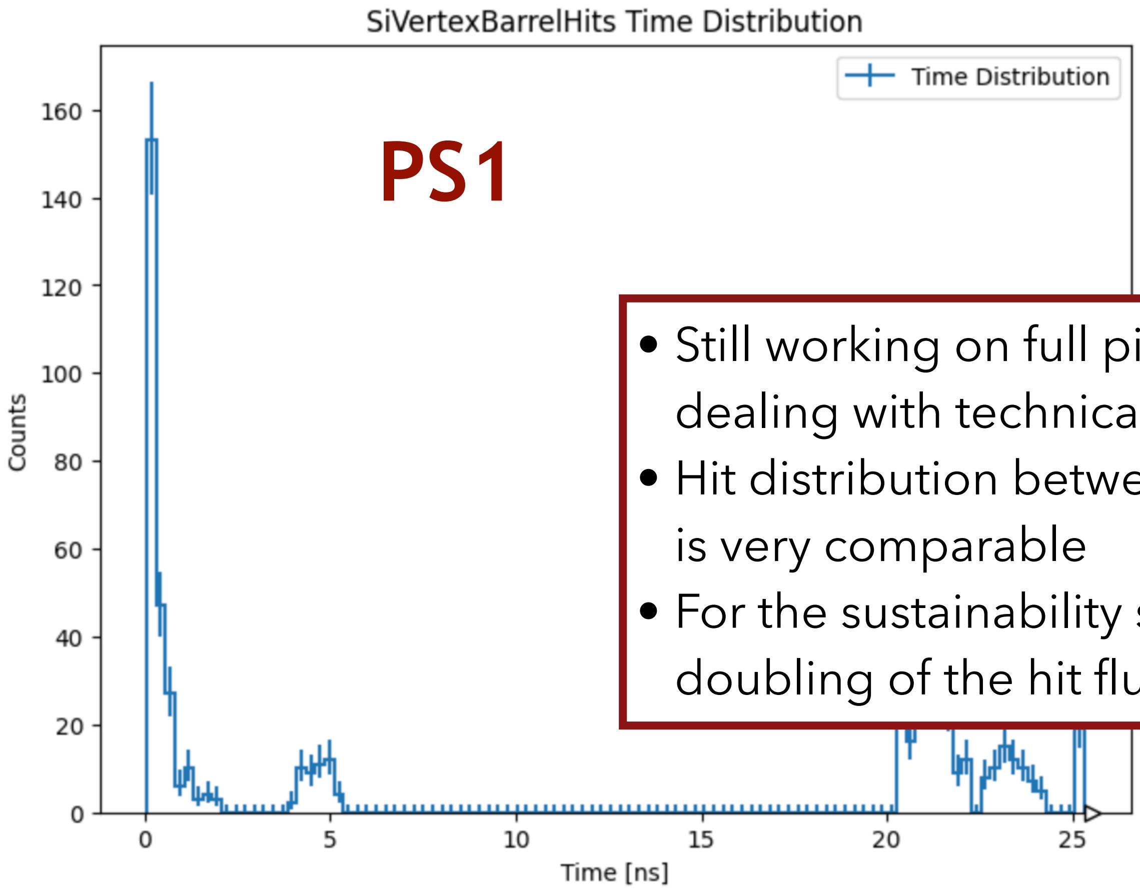

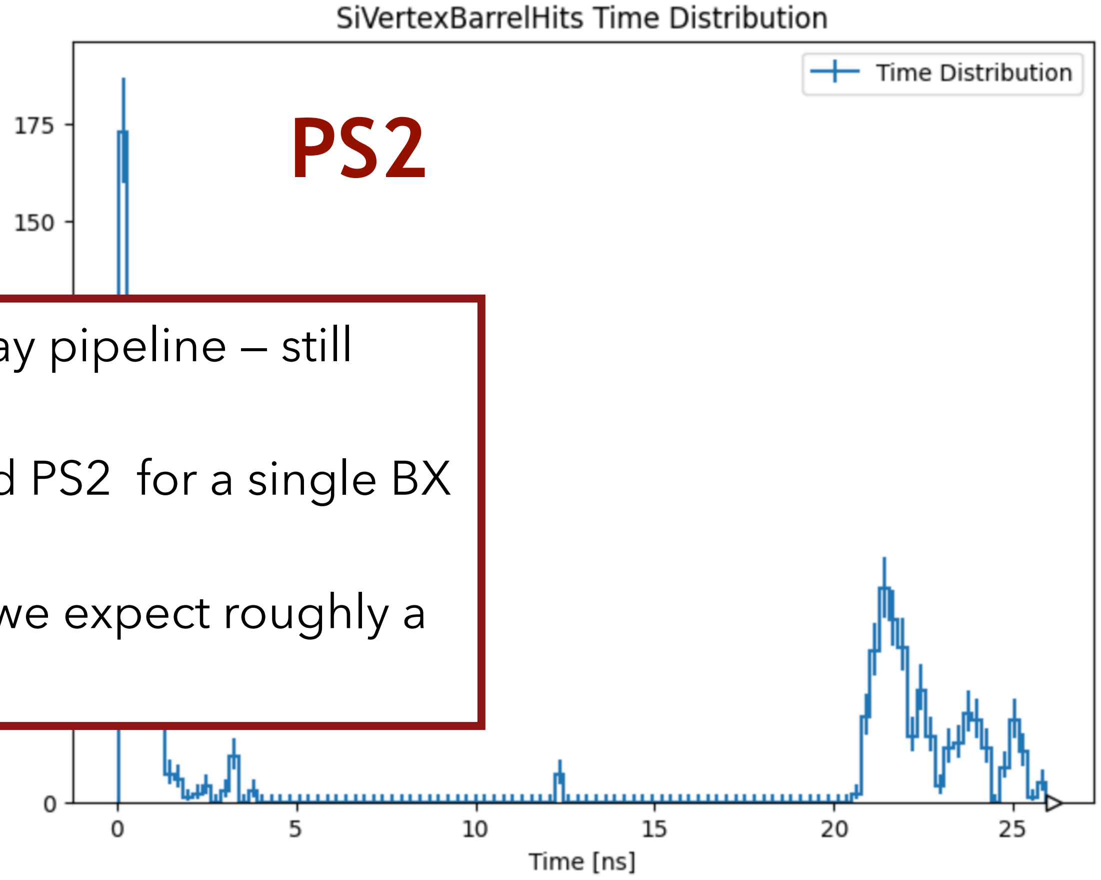

- Still working on full pileup overlay pipeline – still dealing with technical issues
- Hit distribution between PS1 and PS2 for a single BX is very comparable
- For the sustainability scenarios, we expect roughly a doubling of the hit flux for BIB

Conclusions

- We have simulated and validated the two leading BIBs for C^3, incoherent pair production, and hadron photo production.
- We have performed out-of-time pileup mixing within key4hep.
- We have introduced additional beam scenarios for, C^3, with the purpose of increasing the luminosity or reducing the power consumption.
- The ***C^3 beam configuration and time-structure has been validated to be compatible with ILC-like detectors.***
- *Preliminary results indicate that this is also the case for the modified scenarios, but work is ongoing to fully validate this.*
- *Currently in the process of preparing manuscript to document our results and share with the community.*

Thank you for your attention!

For more information on C^3, visit:
https://web.slac.stanford.edu/c3/

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For more information on C^3
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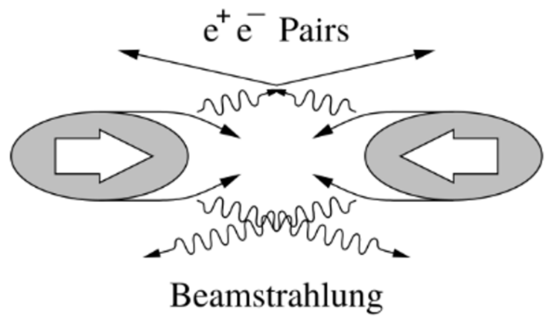
Questions?

Backup

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

- Nm-sized beams → high charge densities at the IP → interactions between bunches → production of secondaries, 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: $\gamma_{BS}\gamma_{BS} \to q\bar{q}$

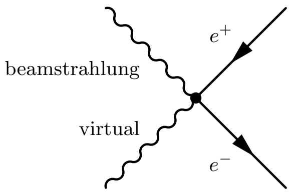
→ ***$O(10^5)$ pairs per BX***

(BX = Bunch Crossing)

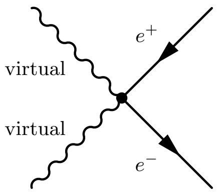
→ ***$O(1)$ hadrons per BX***

(more central)

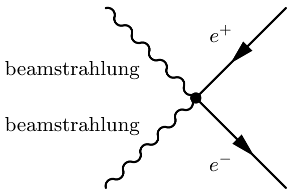
Incoherent pair production processes



(a) Bethe-Heitler

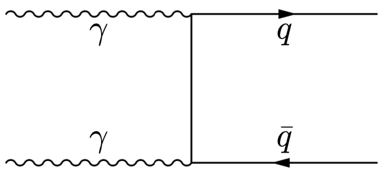


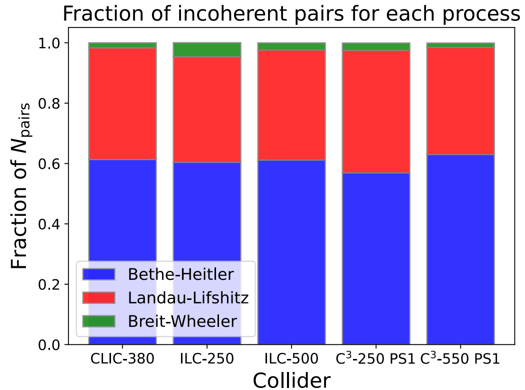
(b) Landau-Lifshitz



(c) Breit-Wheeler

Hadron photoproduction





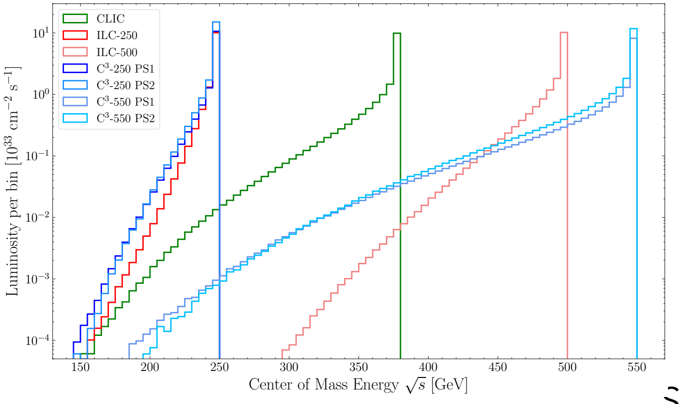
Beam-Beam interactions at e^+e^- colliders

PRAB 27, 061001

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

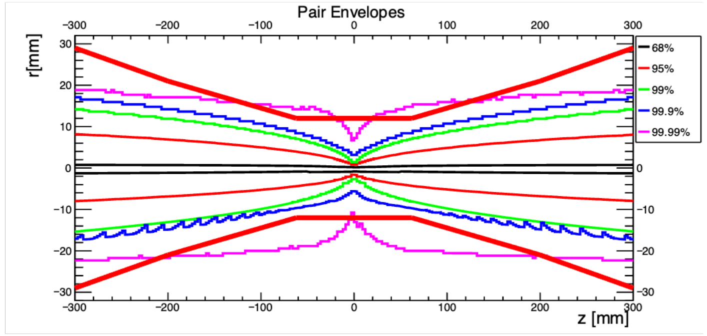
Physics Analyses

- 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

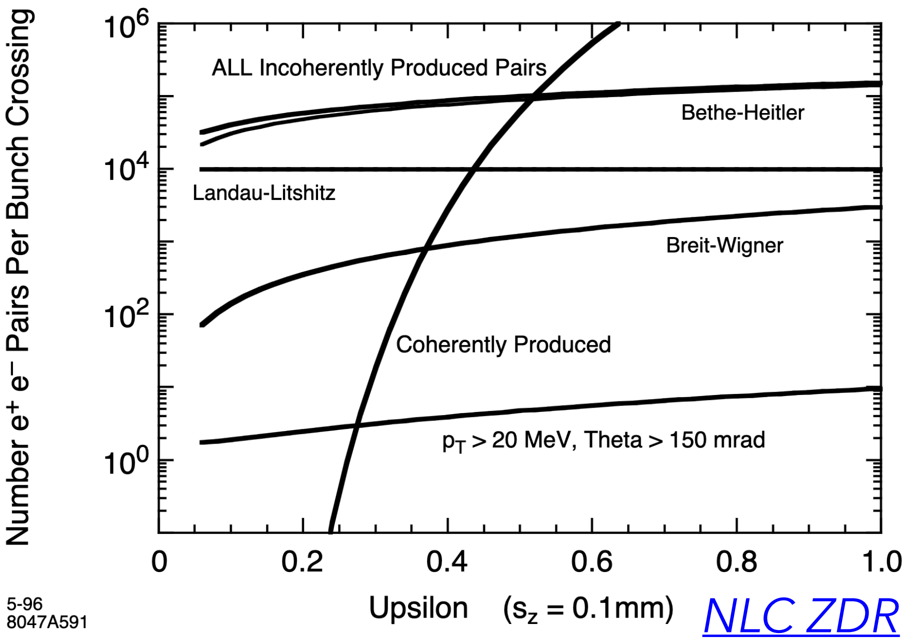
- High flux in vertex barrel and forward sub detectors
- Increase in detector occupancy → might miss interesting Physics (HS) events!
- Impacts detector design decisions, e.g. radius of 1st vertex barrel layer, buffer depth etc.



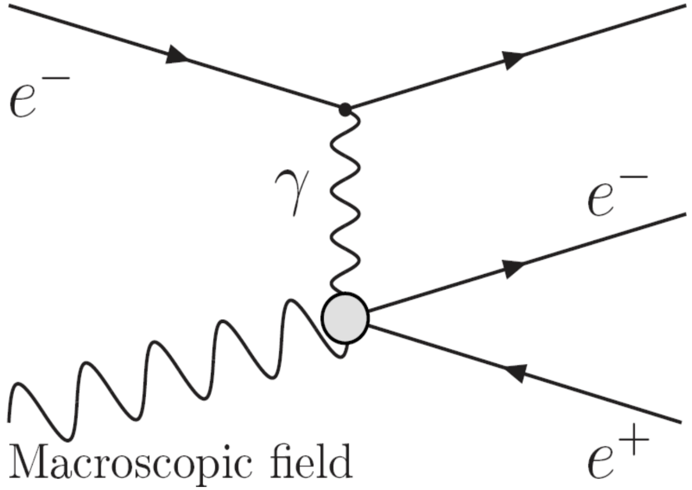
Beam-Beam interactions at e^+e^- colliders

- 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.



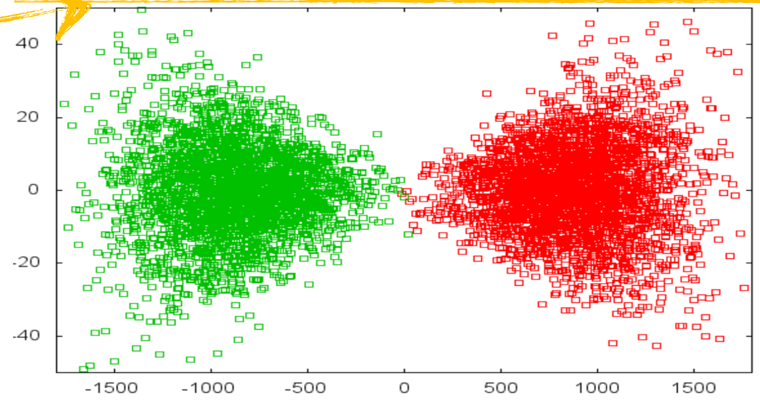
NLC ZDR



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.

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

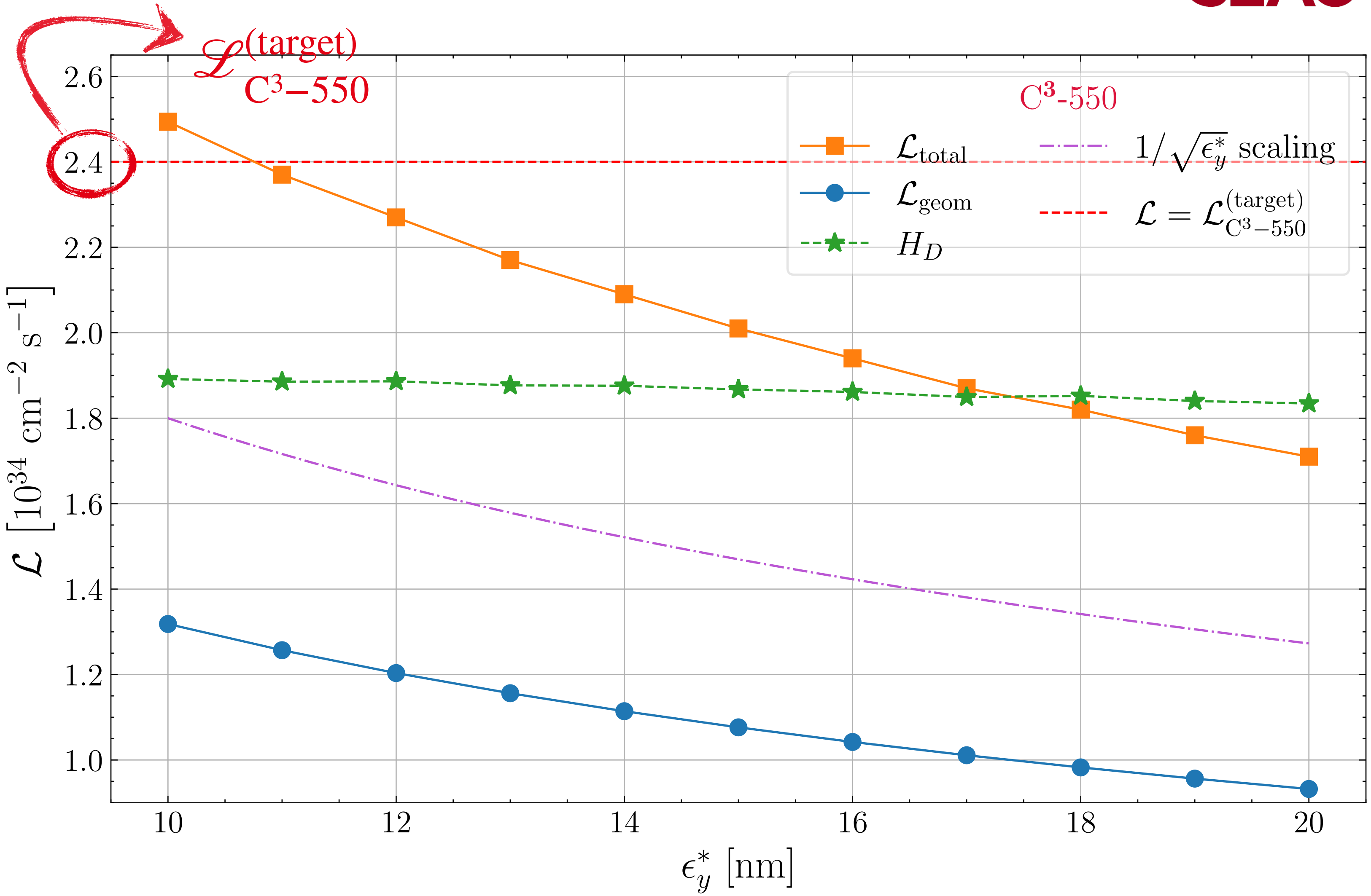
$$\delta_E = \frac{16\sqrt{3}}{5\pi^{3/2}}\frac{r_e\alpha N_e}{\sigma_x^*}\langle\Upsilon\rangle$$

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

C³ - 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)

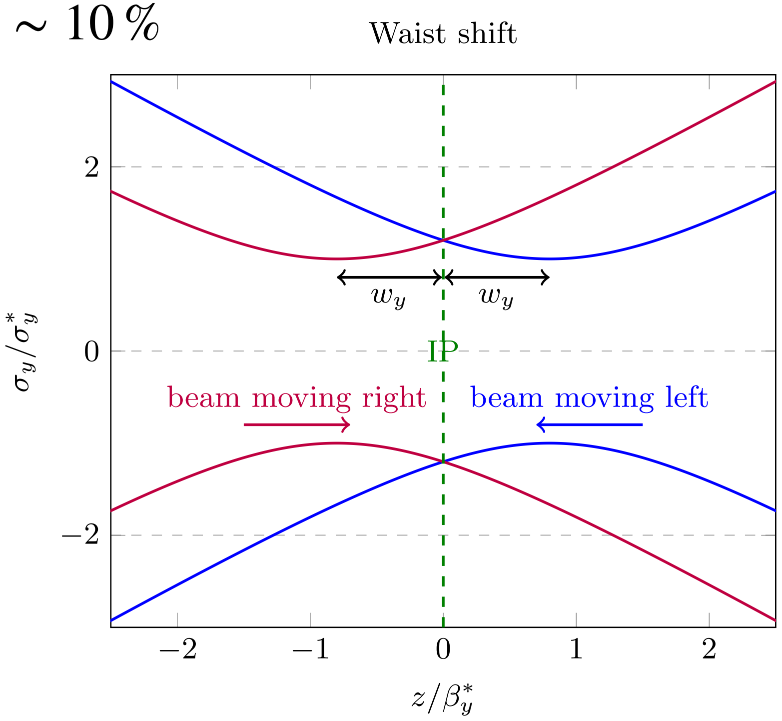


**In the plot, not-mentioned parameters retain same values as in PS1.*

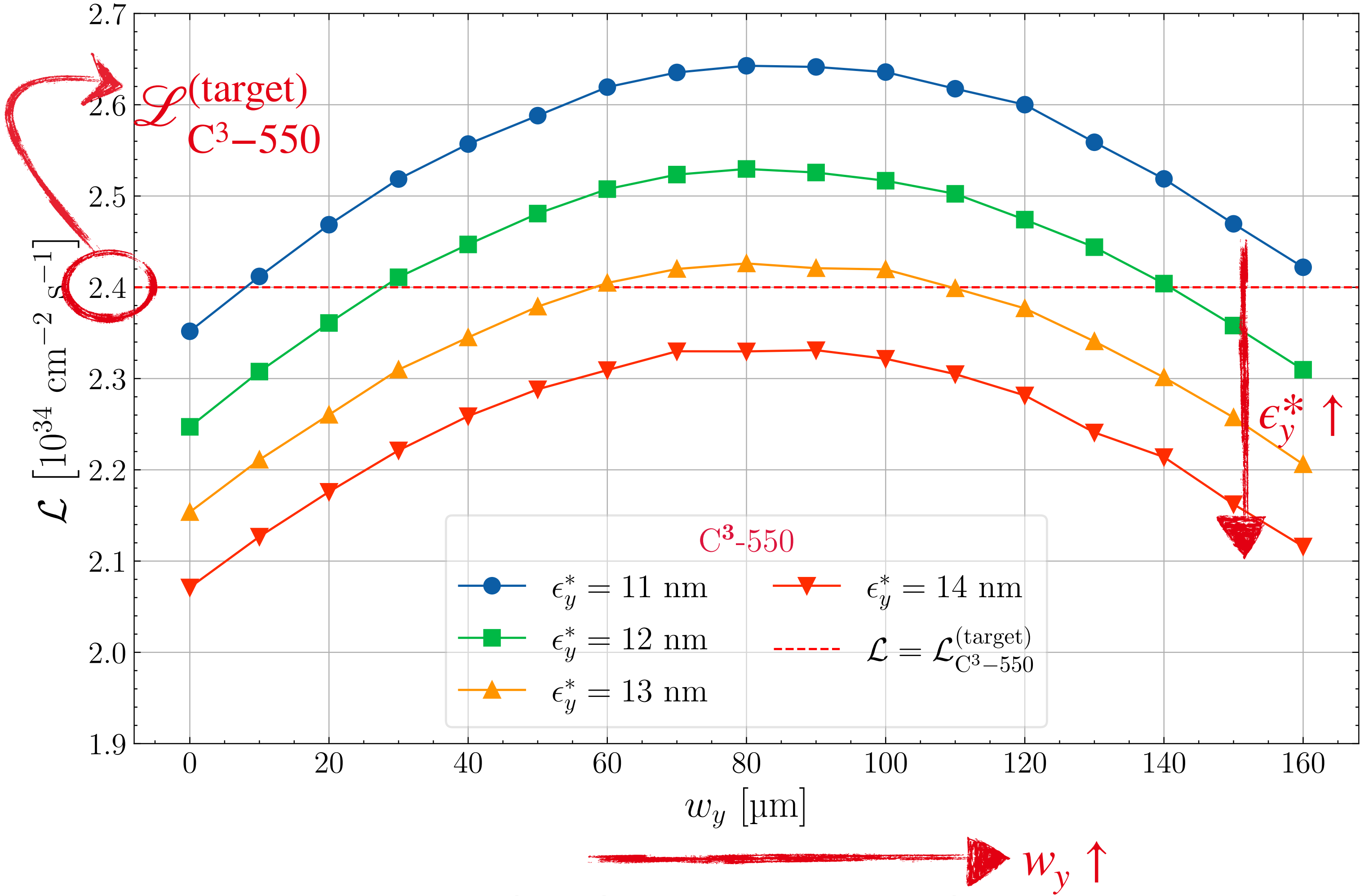
C³ - 550 Parameter Optimization

PRAB 27, 061001

- 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

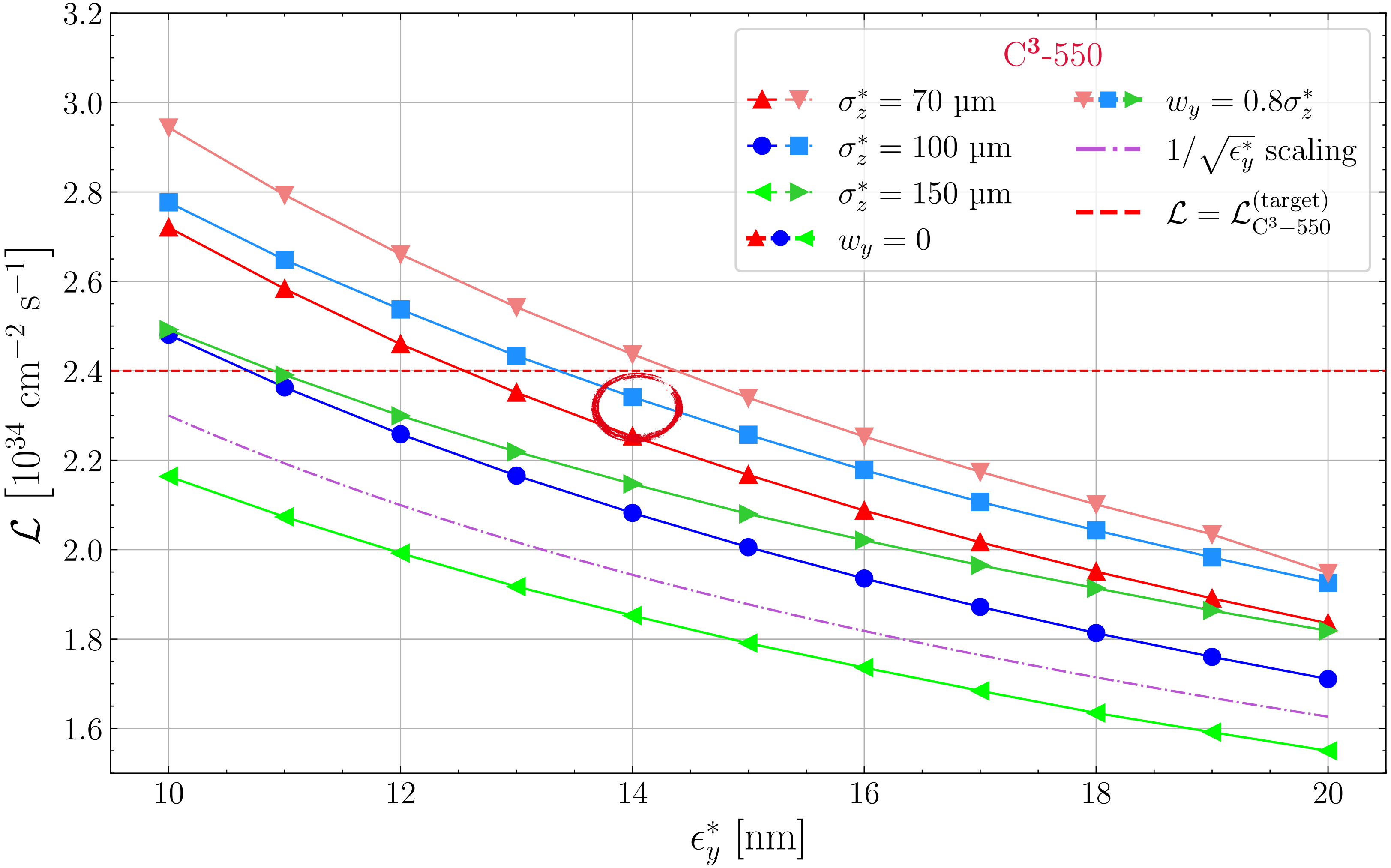


**In the plot, not-mentioned parameters retain same values as in PS1.*

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.

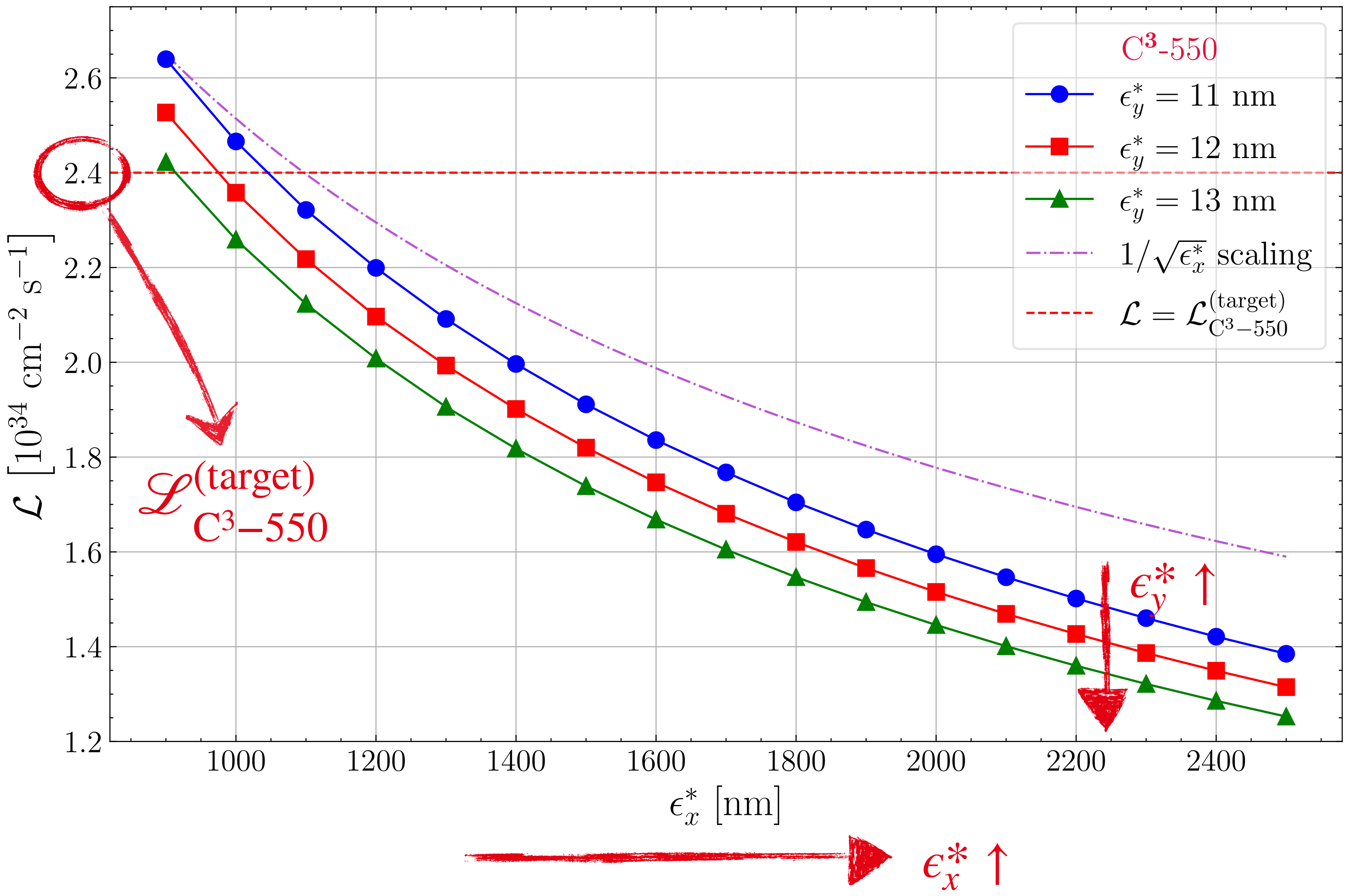
$$\langle \Upsilon \rangle = \frac{5}{6} \frac{N_e r_e^2 \gamma}{\alpha(\sigma_x^* + \sigma_y^*)\sigma_z^*}$$



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

C³ - 550 Parameter Optimization

- 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.

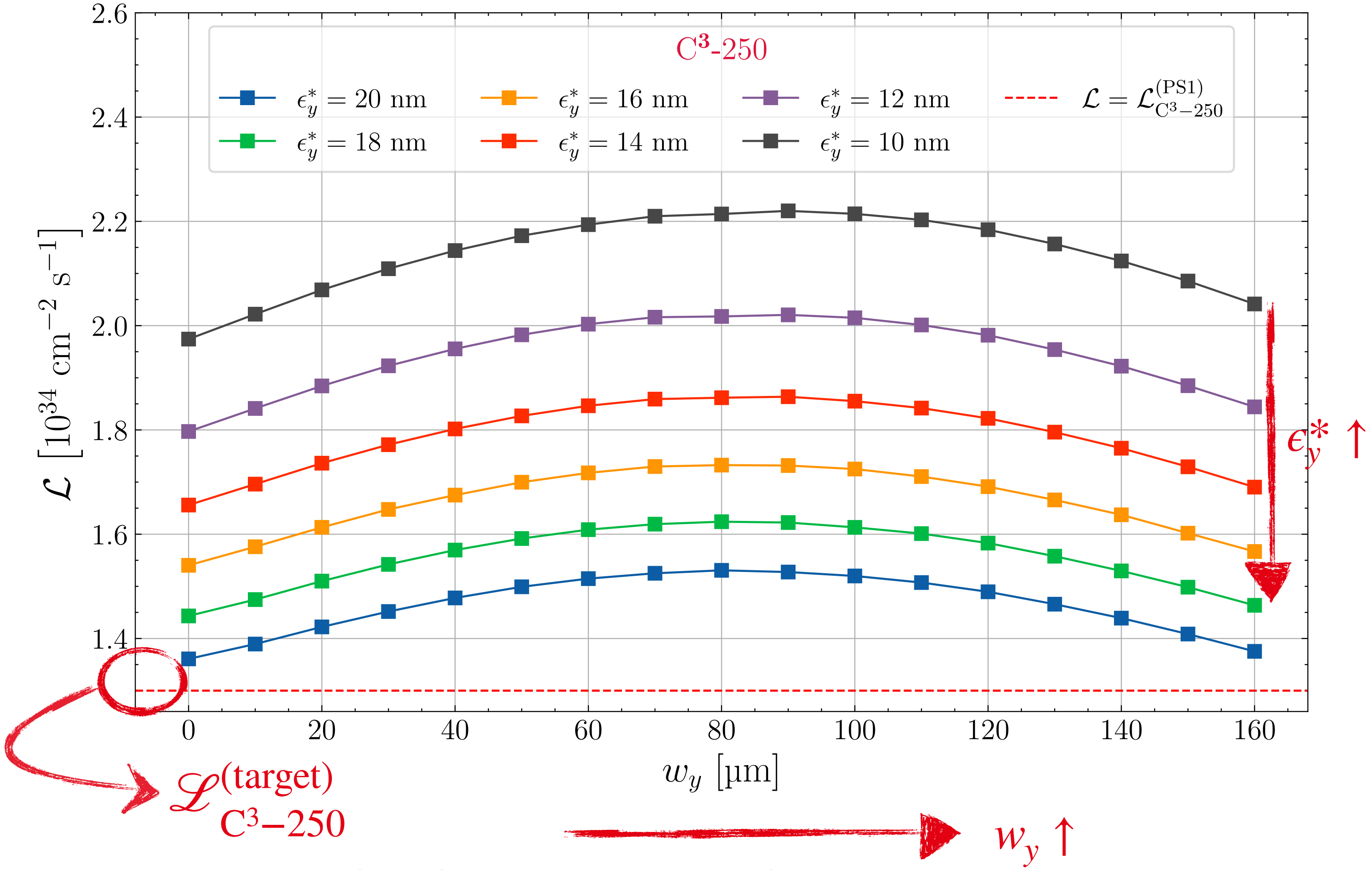


In the plot, σ_z^* of 100 μm and w_y of 80 μm are assumed.

Evaluation on C³ - 250

PRAB 27, 061001

- 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.



$\epsilon_y^* \uparrow$

$\mathscr{L}^{(\mathrm{target})}_{\mathrm{C^3-250}}$

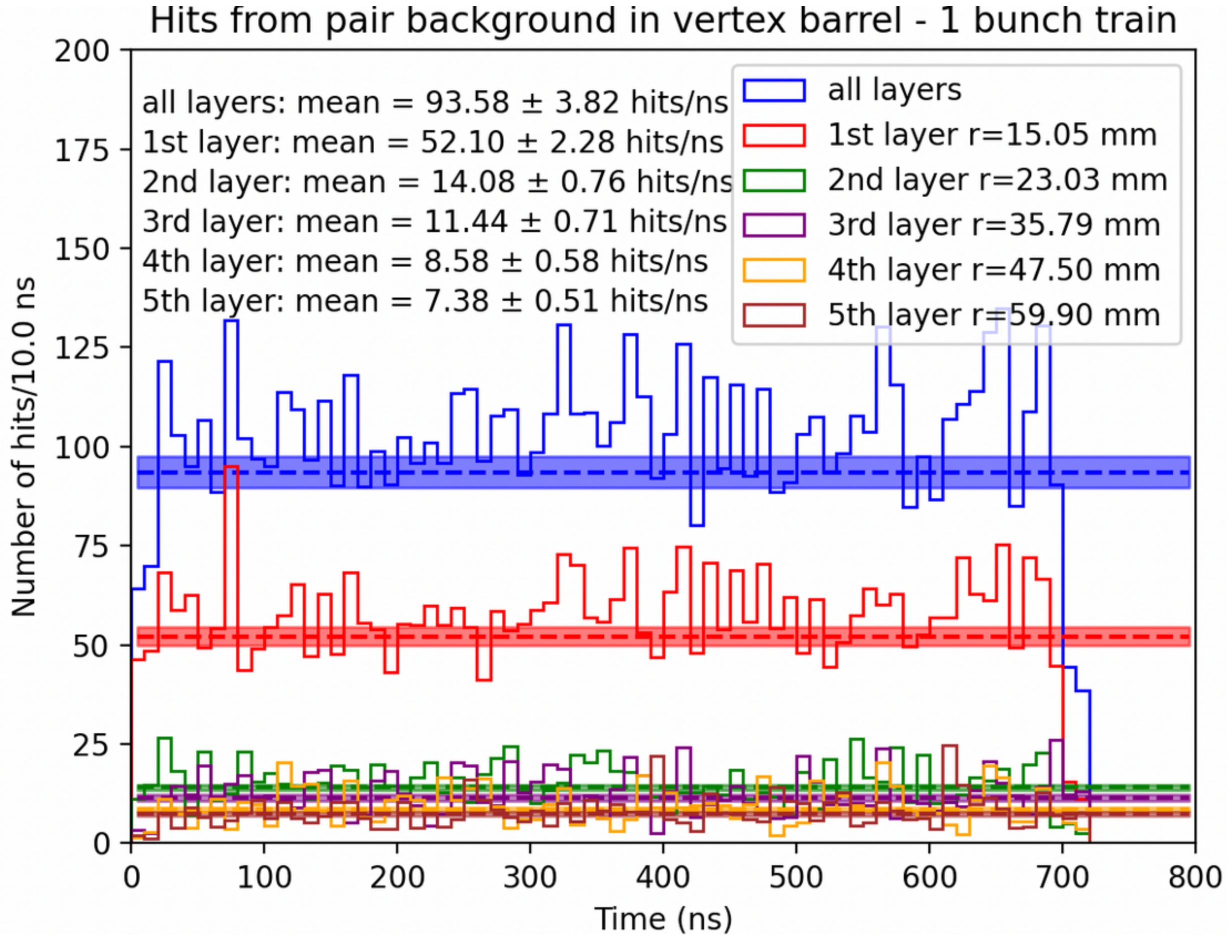
$w_y \uparrow$

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

Time distribution over a train for C^3

Time distribution of hits in vtx barrel per unit time for a full C^3-250 train:
on average, we anticipate ~ 90 hits/ns in the vertex barrel detector.

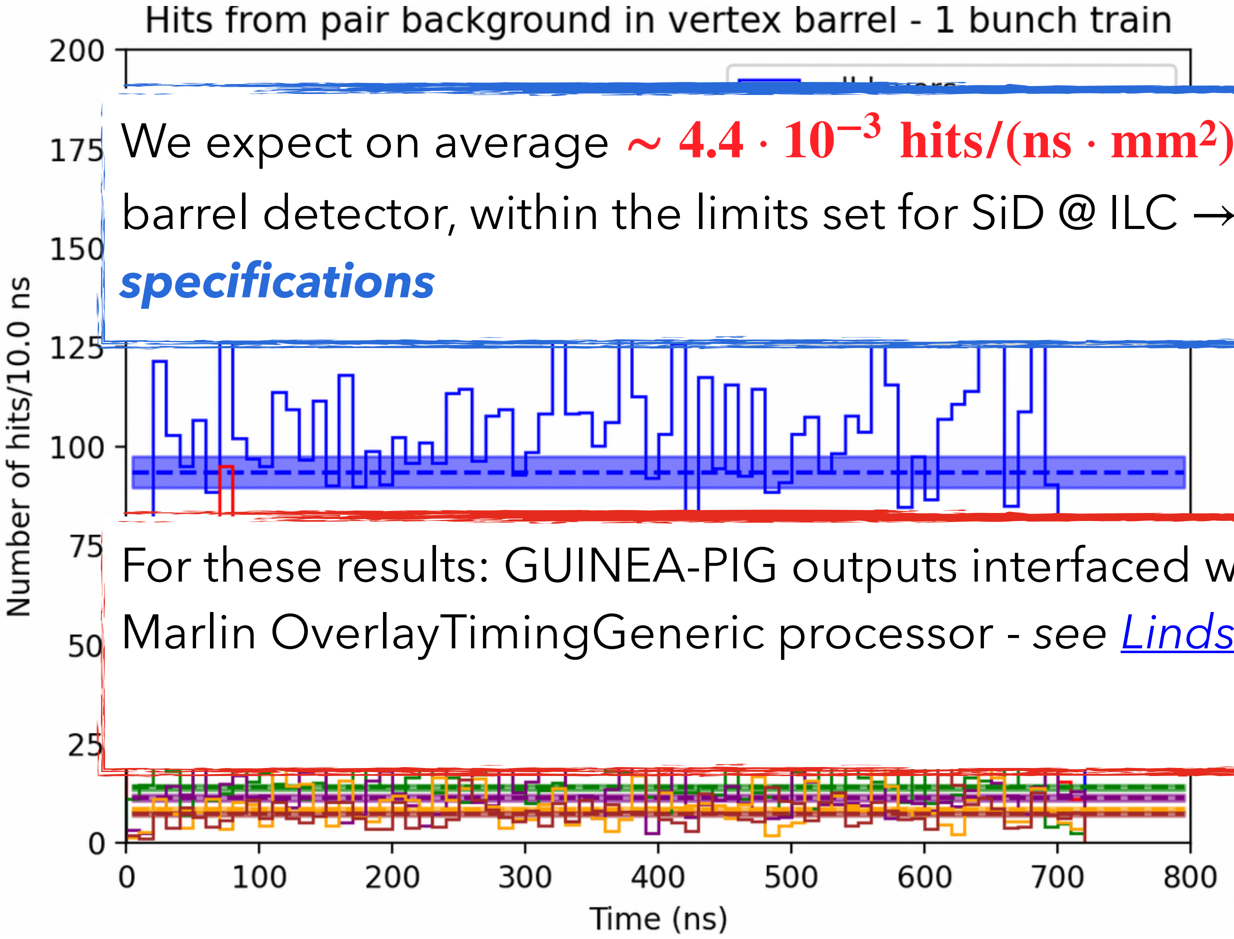
Preliminary ***Hits/time***

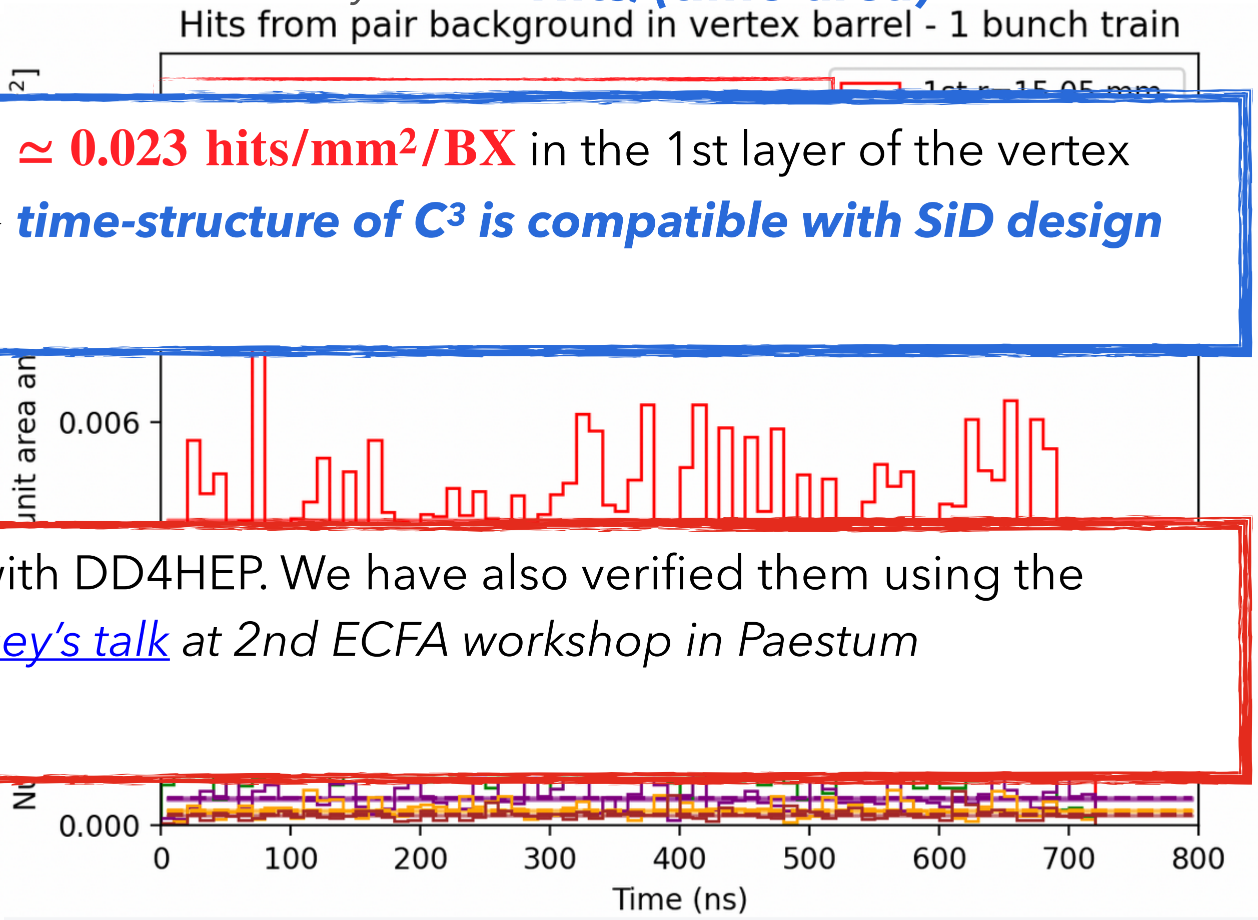


Time distribution over a train for C^3

Time distribution of hits in vtx barrel per unit time for a full C^3-250 train: on average, we anticipate ~ 90 hits/ns in the vertex barrel detector.

Preliminary ***Hits/time*** → *Preliminary* ***Hits/(time·area)***





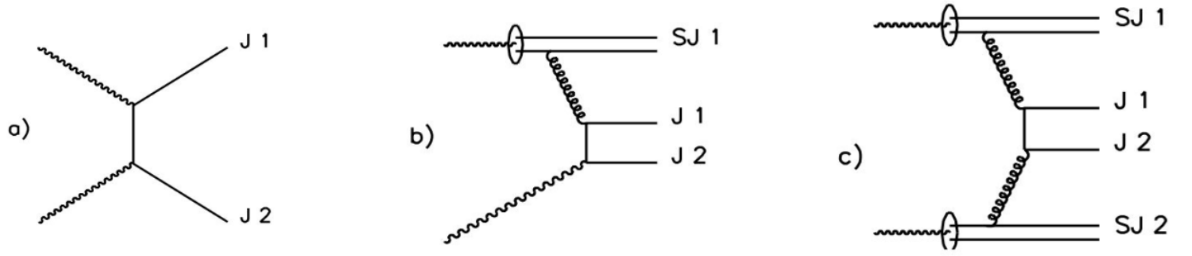
We expect on average $\sim \mathbf{4.4 \cdot 10^{-3}}$ **hits/(ns · mm²) ≃ 0.023 hits/mm²/BX** in the 1st layer of the vertex barrel detector, within the limits set for SiD @ ILC → ***time-structure of C^3 is compatible with SiD design specifications***

For these results: GUINEA-PIG outputs interfaced with DD4HEP. We have also verified them using the Marlin OverlayTimingGeneric processor - *see Lindsey's talk at 2nd ECFA workshop in Paestum*

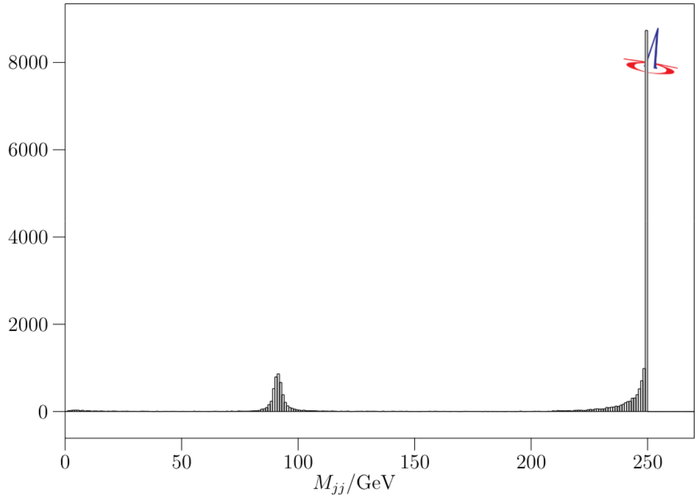
Hadron photoproduction at C^3

- Hadrons from beamstrahlung have a rate $\sim \mathcal{O}(10^5)$ smaller that incoherent pairs, but are more central and lead to higher-multiplicity final states $\rightarrow$ impact reconstruction.
- PYTHIA8 used above $\sqrt{s_{\gamma\gamma}} \simeq 10\ \mathrm{GeV}$, dedicated generator by T. Barklow below that
- Technical progress on migrating from PYTHIA5.7 and using latest Whizard and CIRCE versions → ***in the process helping resolve bugs in CIRCE***
- Presently generating the appropriate bkg mixture from estimated virtual photon flux.
- Results so far with ***full SiD simulation indicate that we are within the limits set for ILC***.

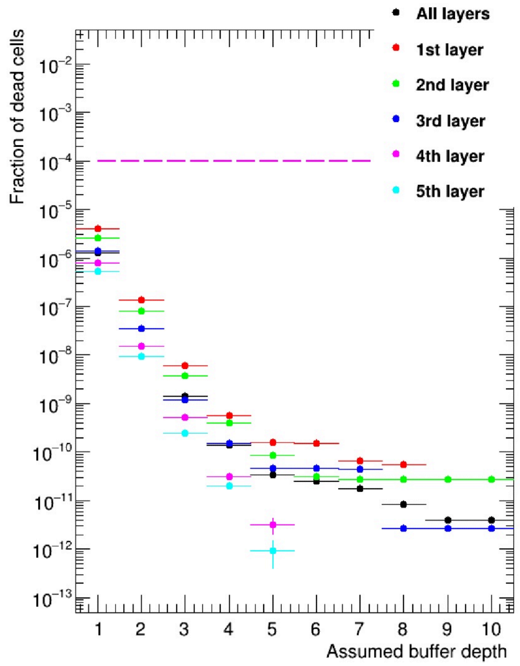
See Lindsey's talk at C^3 workshop for more details



1 C3 $e^+e^- \to jj$ with Beamstrahlung



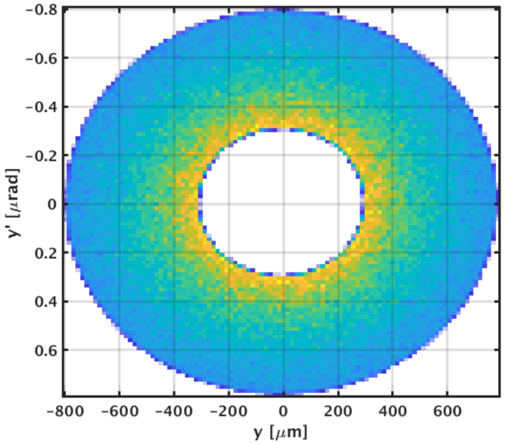
T. Ohl's talk at 2nd ECFA workshop in Peastum



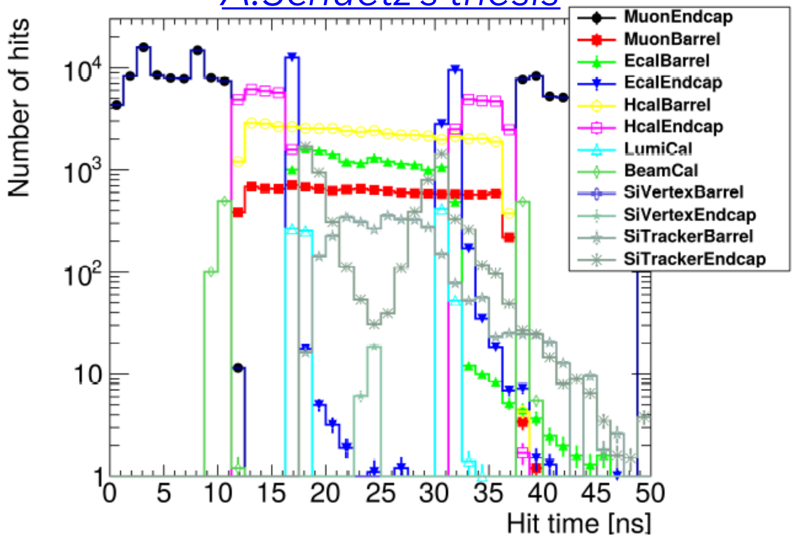
E. Mettner's talk at LCWS 2023

Halo muon machine background at C^3

- *Muons from beam interactions at the collimators were an important background at SiD and where taken into account for ILC detector studies*

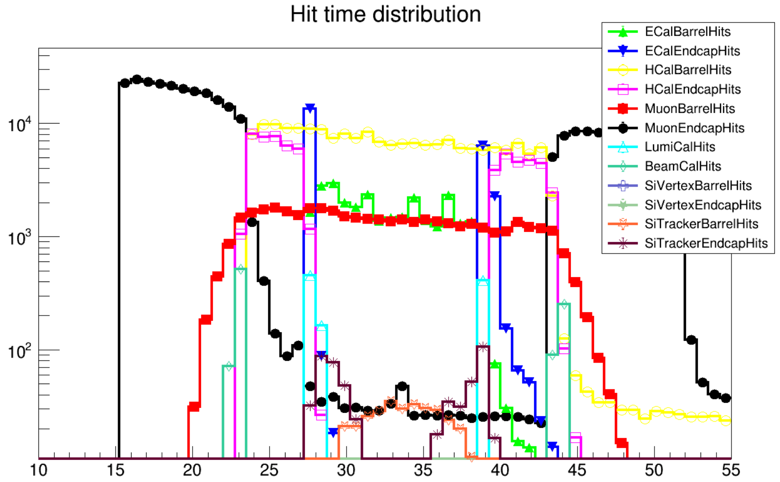


A.Schuetz's thesis



Our results (sidloi3 geometry)

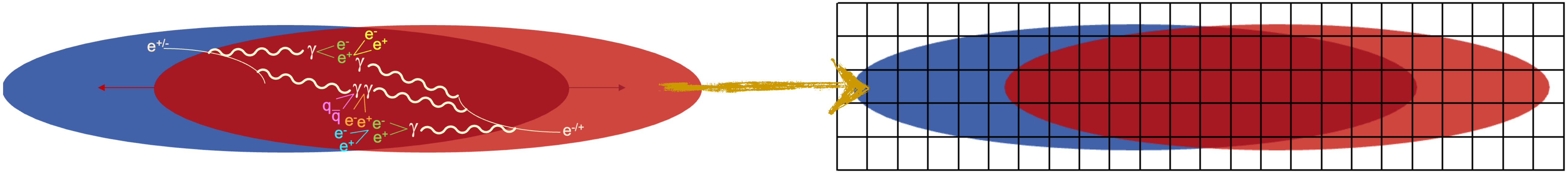
[work done by Kenny Jia]



- Trying to reproduce latest ILC results using existing MUCARLO files for ILC BDS (*thanks to Daniel Jeans*) and SiD geometry → Qualitative agreement, but quantitative differences to be understood.
- ***MUCARLO***: not well documented and no longer maintained → need a new framework to provide machine background muons for LC detectors.
- We are in the progress of evaluating the potential of FLUKA as an alternative to MUCARLO.
- ***Ideas/collaboration on how to move forward are more than welcome!***

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*



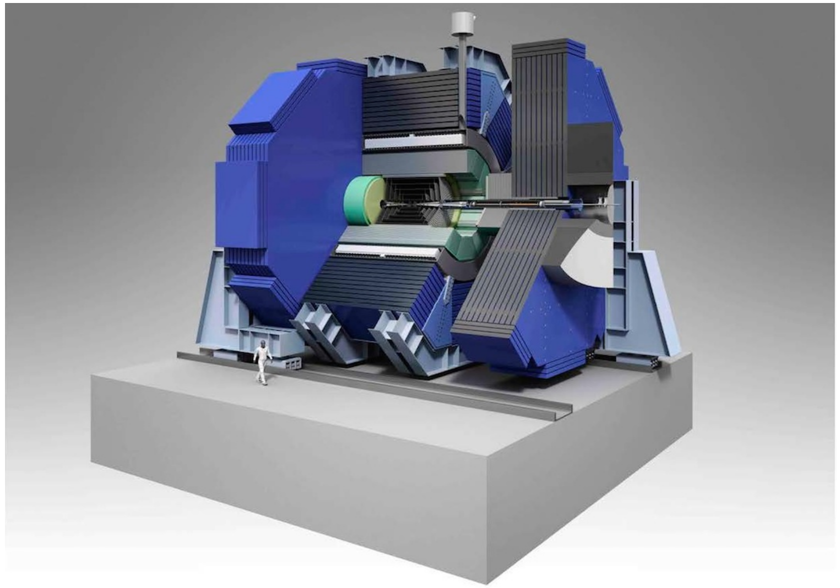
Jean-Luc Vay

Jean-Luc Vay

Simulation of Beam-Induced Background

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

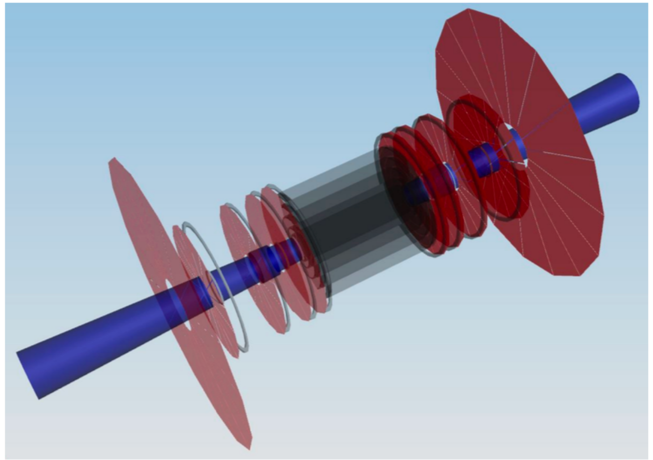
GUINEA-PIG
Key4hep
DD4hep
k4geo

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

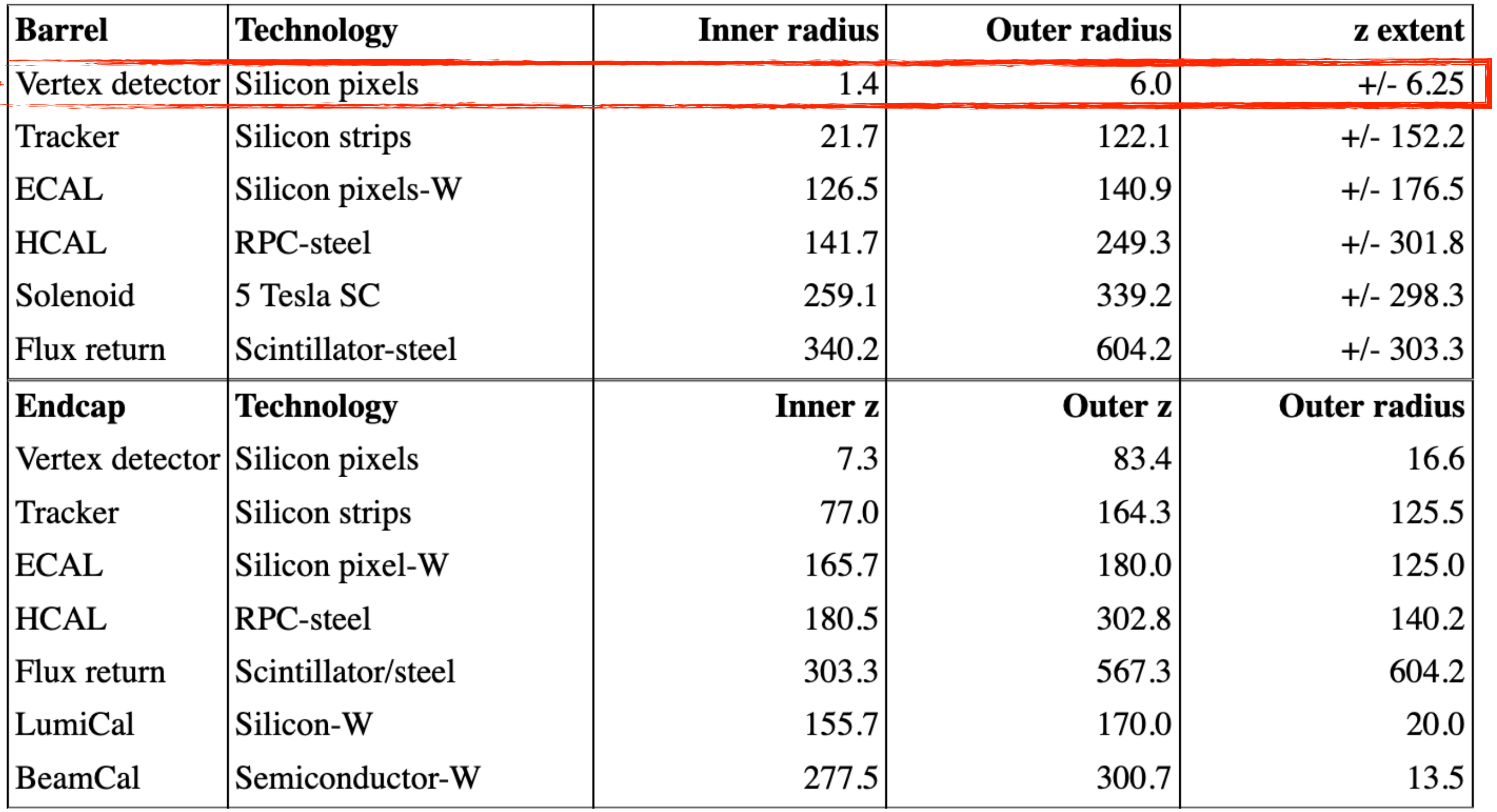
Typical detector dimensions for e^+e^- colliders

- 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***

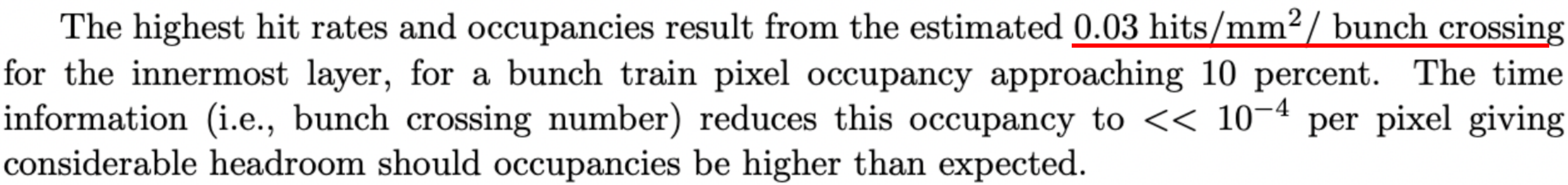
SiD background flux rate

- Preliminary Studies indicate that the pair background particle flux is within the limits set in the SiD DOE Final Report: https://www.osti.gov/biblio/1182602

- Our estimate for the flux in the innermost layer of the vertex detector is :

0.043 hits/(ns · mm^2) · (5.25 ns/BX) = **0.023 hits/mm^2/BX**

- We are currently in the process of validating our results and repeating the studies for all subdetectors.



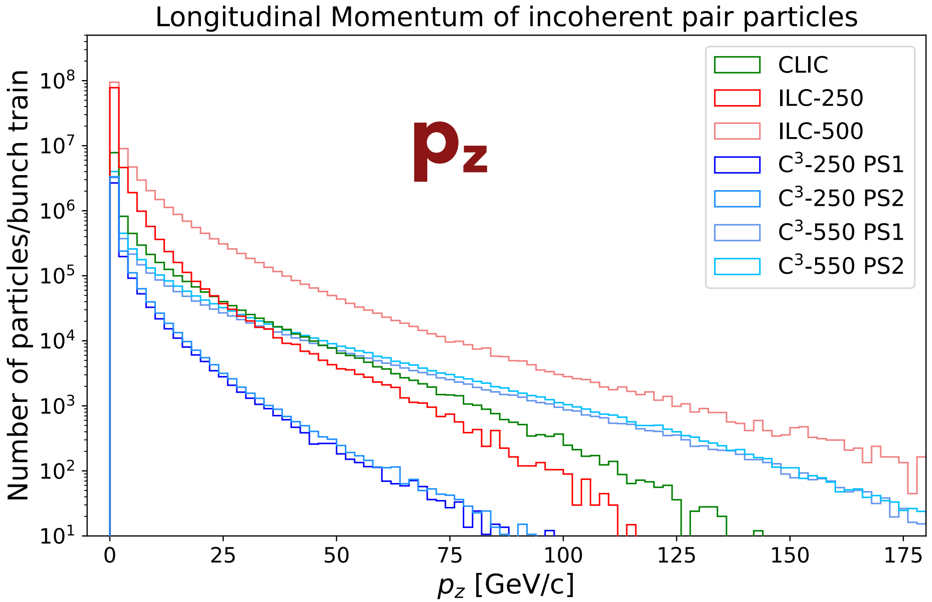
The highest hit rates and occupancies result from the estimated 0.03 hits/mm^2/ bunch crossing for the innermost layer, for a bunch train pixel occupancy approaching 10 percent. The time information (i.e., bunch crossing number) reduces this occupancy to $<< 10^{-4}$ per pixel giving considerable headroom should occupancies be higher than expected.

Comparison with other linear colliders

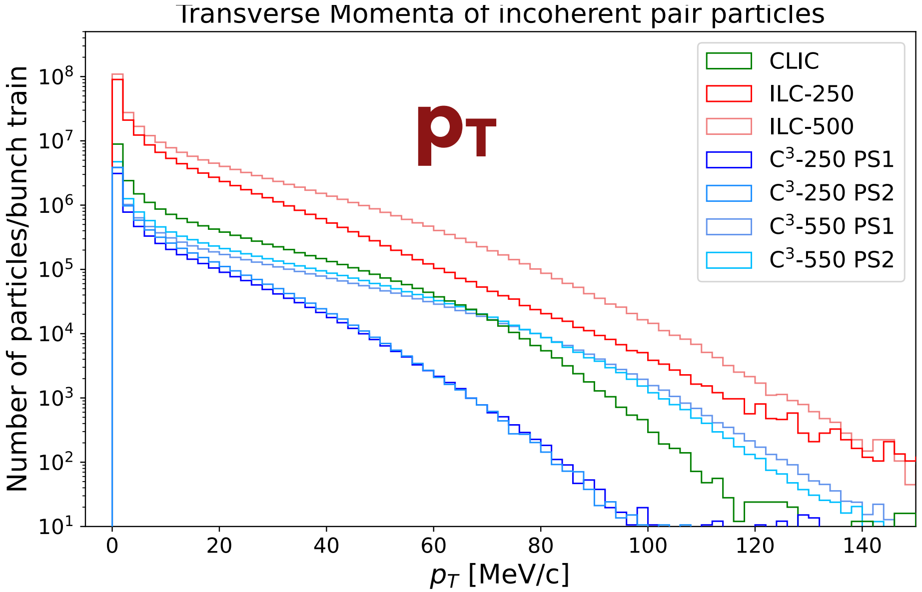
PRAB 27, 061001

- 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]



Longitudinal Momentum of incoherent pair particles



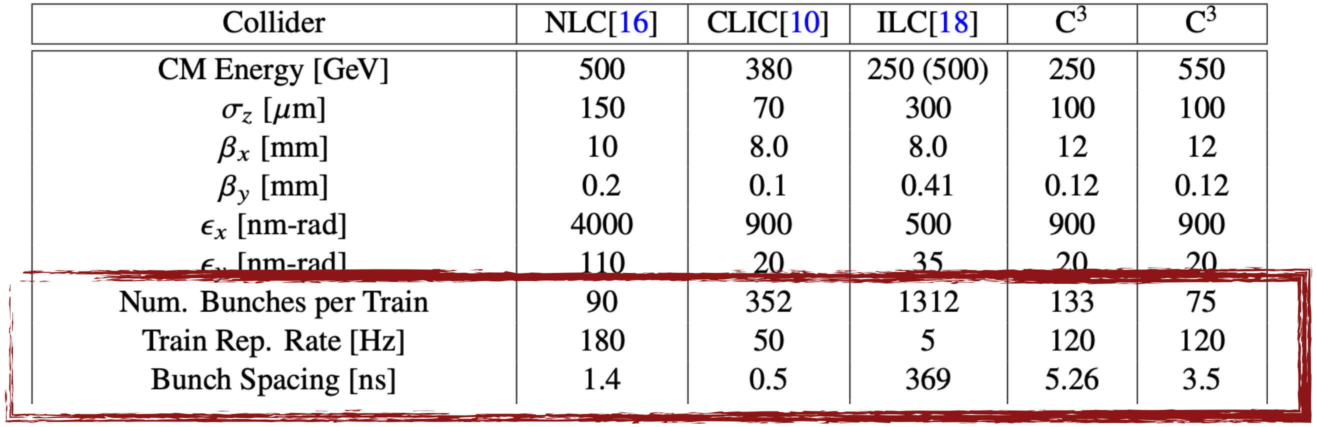
Transverse Momenta of incoherent pair particles

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.

- **C^3:** 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.

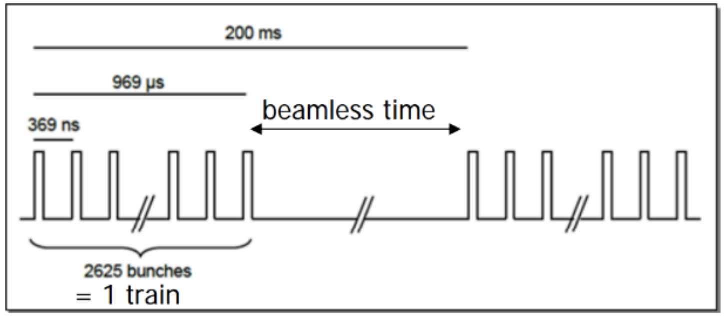
- **Comparison:** C^3 will record $O(10)$ times fewer bunches than ILC, leading to reduced occupancy. But, the readout will have to take place ~25 times faster.



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

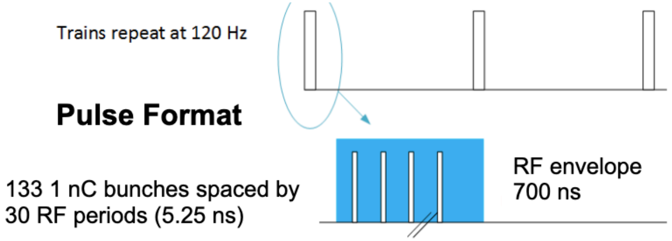
Caterina Vernieri et al 2023 JINST 18 P07053

ILC timing structure



1 ms long bunch trains at 5 Hz
308ns spacing

C^3 timing structure



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 colliders - Sustainability

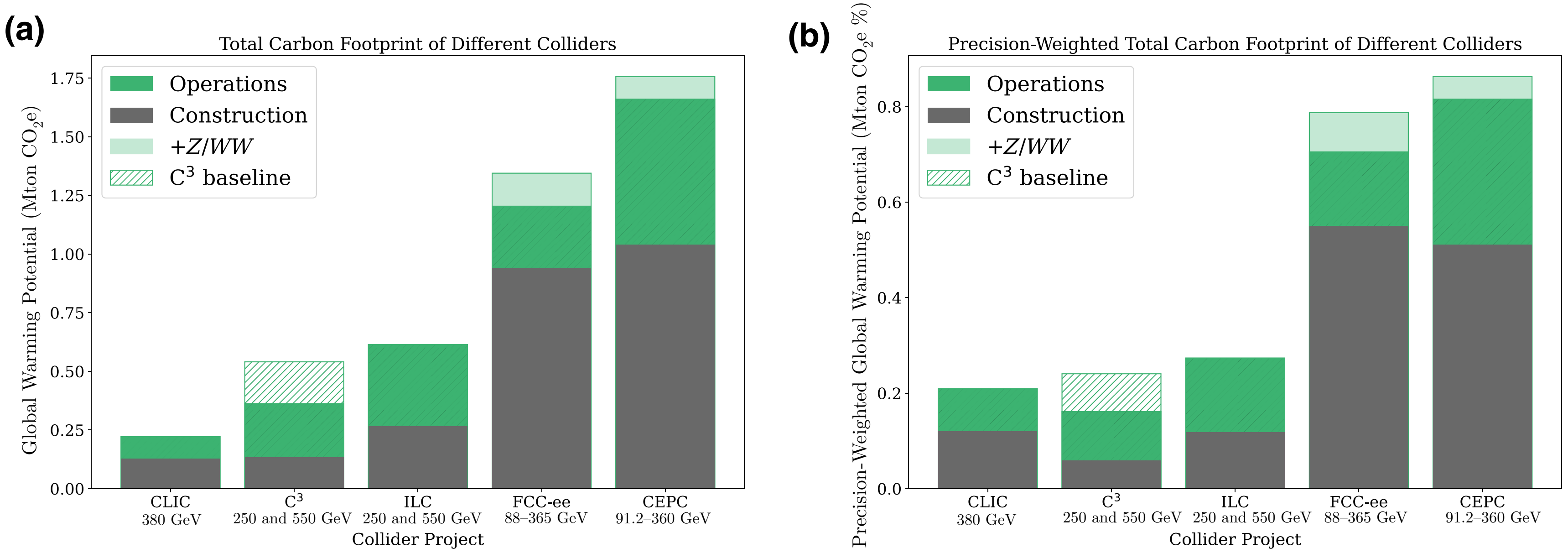


TABLE VI. For each of the Higgs factory projects considered in the first row, the center-of-mass energies (second row), ac site power (third row), annual collision time (fourth row), total running time[a] (fifth row), instantaneous luminosity per interaction point (sixth row), and target integrated luminosity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