LCWS2024 International Workshop on Future Linear Colliders

Beam-induced backgrounds at the Cool Copper Collider

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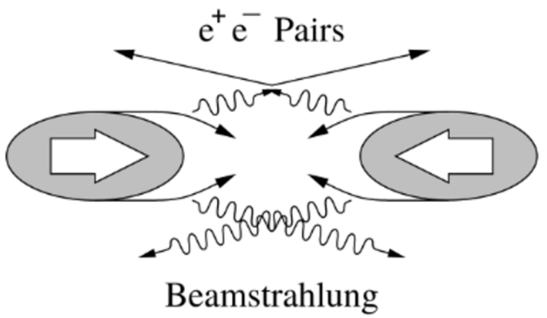
SLAC NATIONAL ACCELERATOR LABORATORY

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).**

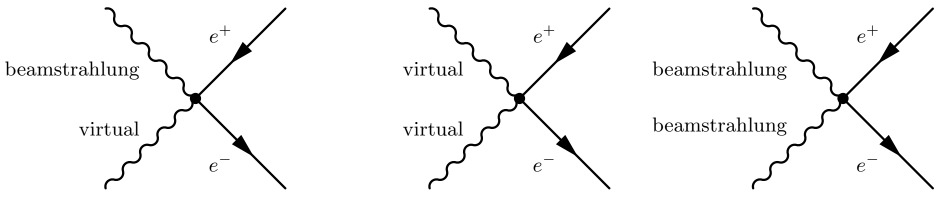


- Dominant processes for Higgs Factories:
  - Incoherent pair production:
    $$\gamma_{BS} e \xrightarrow[\text{(virtual)}]{\gamma} e^+e^-e, \quad ee \xrightarrow[\text{(virtual)}]{\gamma} eee^+e^-, \quad \gamma_{BS}\gamma_{BS} \to e^+e^-$$
  - Hadron photo-production: $\gamma_{BS}\gamma_{BS} \to q\bar{q}$

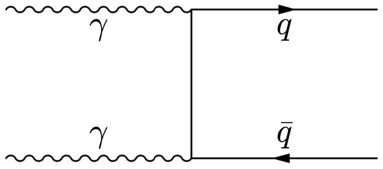
$O(10^5)$ pairs per BX
(BX = Bunch Crossing)

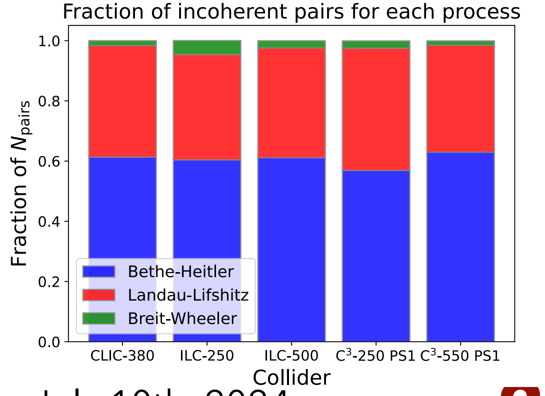
$O(1)$ hadrons per BX
(more central)

Incoherent pair production processes



Hadron photoproduction



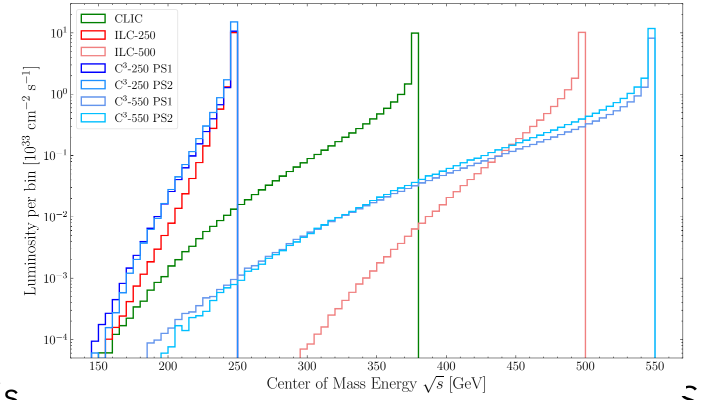


Beam-Beam interactions at linear e+e- colliders

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

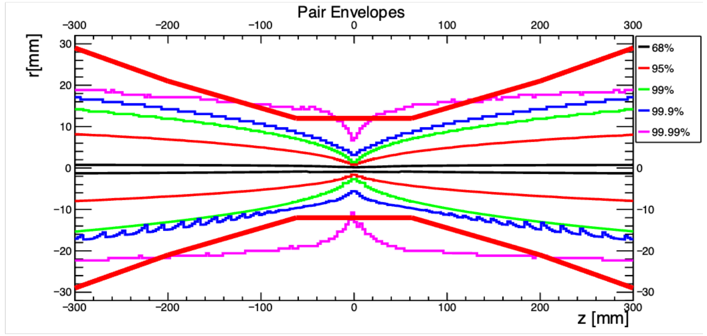
Physics Analyses

- 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.



PRAB 27, 061001

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Focus on this today

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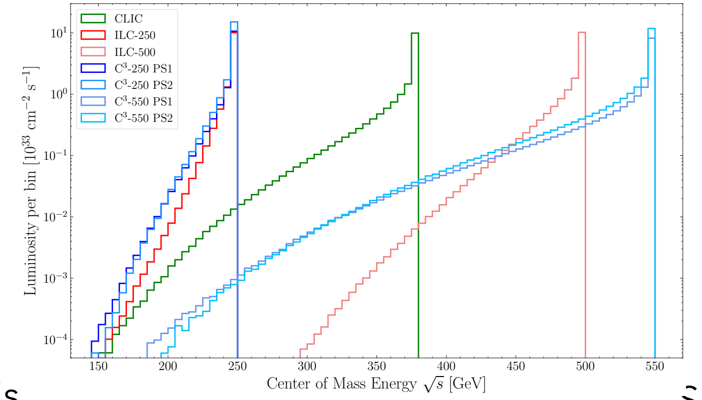

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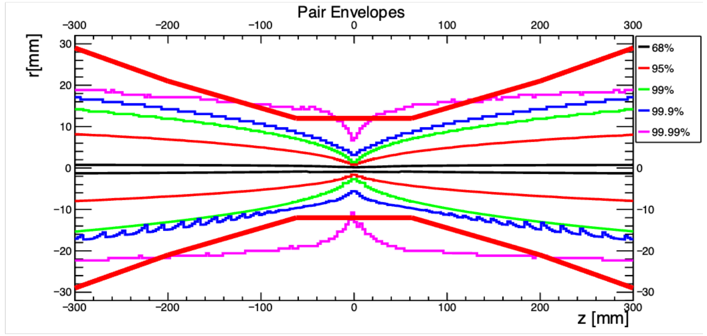
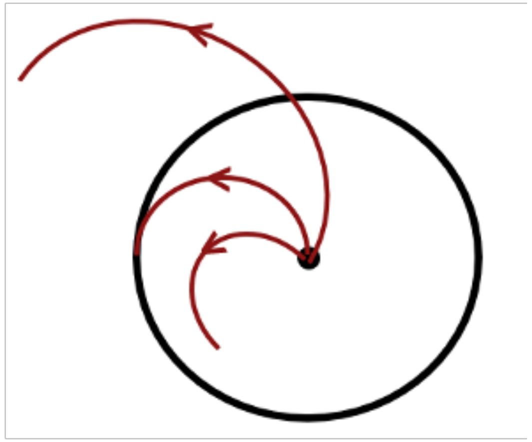


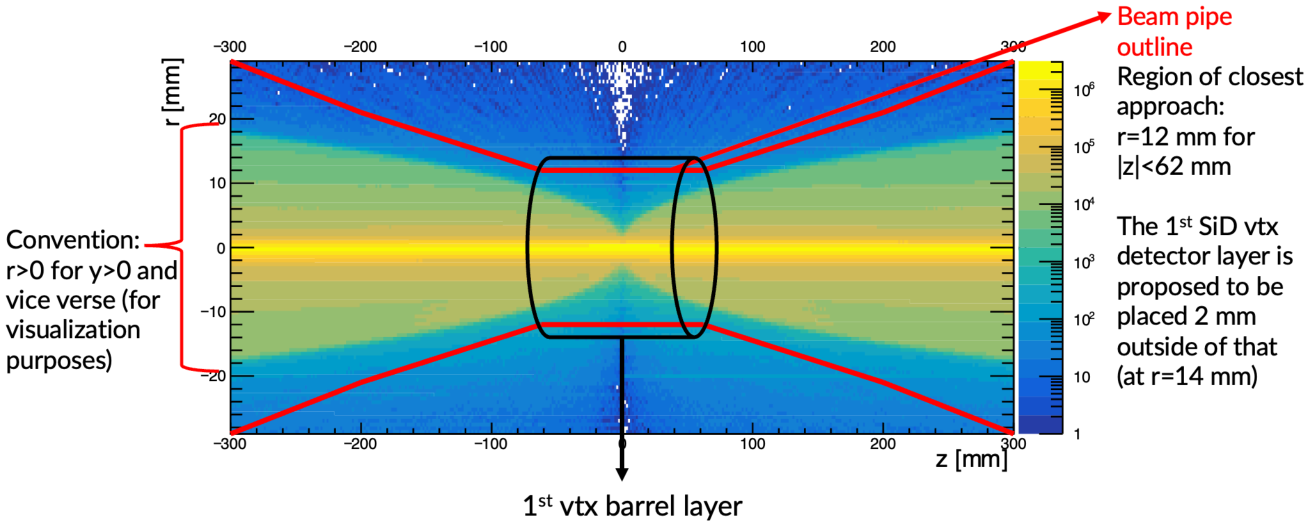
Pair background at C³

- 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 C³, $\sim 0.1\ \%$ 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.



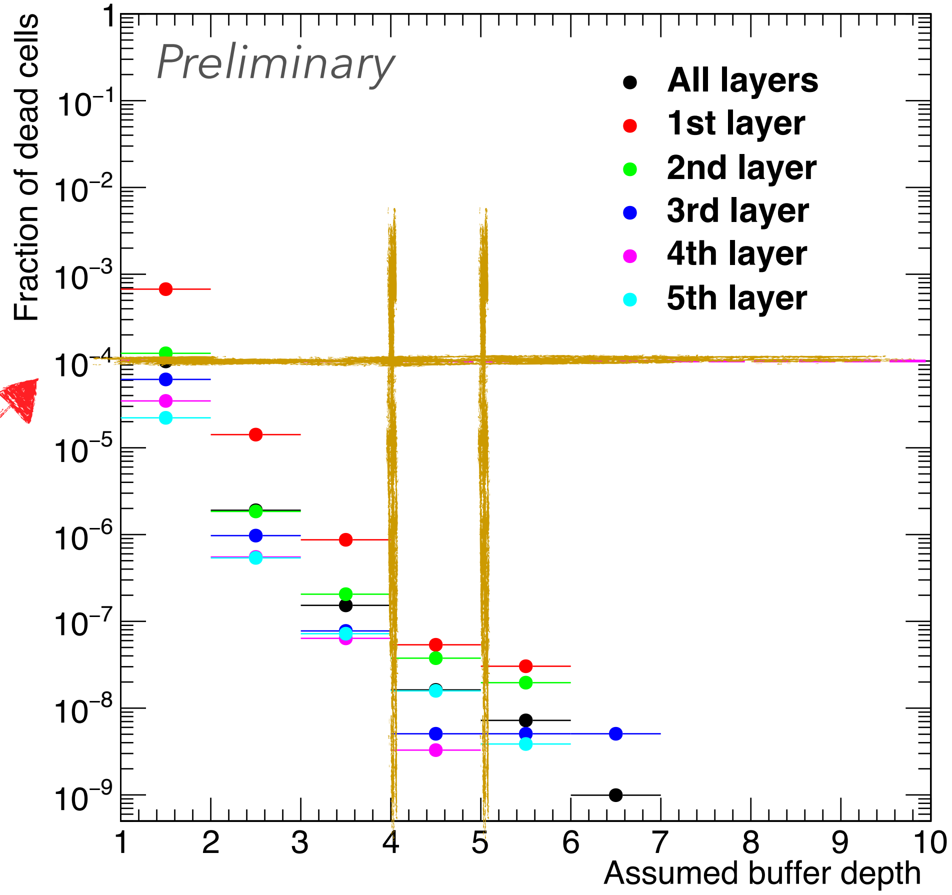
$$p_T^{(\text{min})}[\text{MeV}] = 0.3 \cdot B[\text{T}] \cdot \frac{\rho}{2}[\text{mm}] \simeq 10\ \text{MeV}$$

Hit density for 133 bunch crossings for C³-250 simulated with GUINEA-PIG and tracked through a 5T solenoid field



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.

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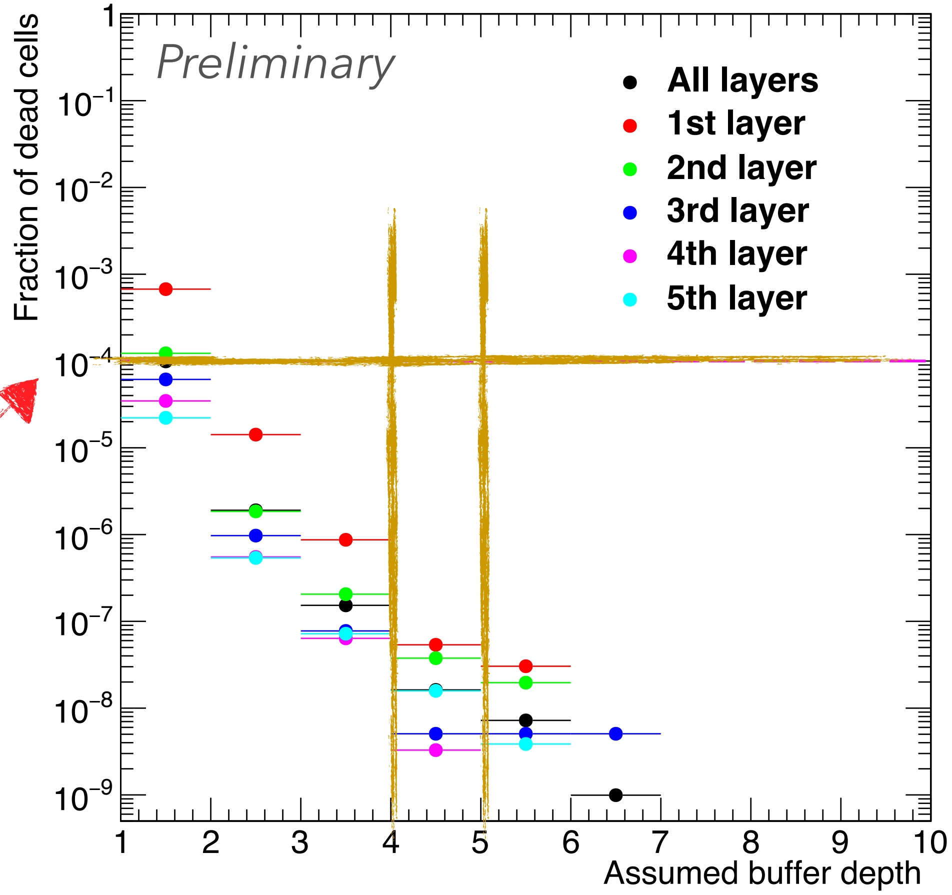
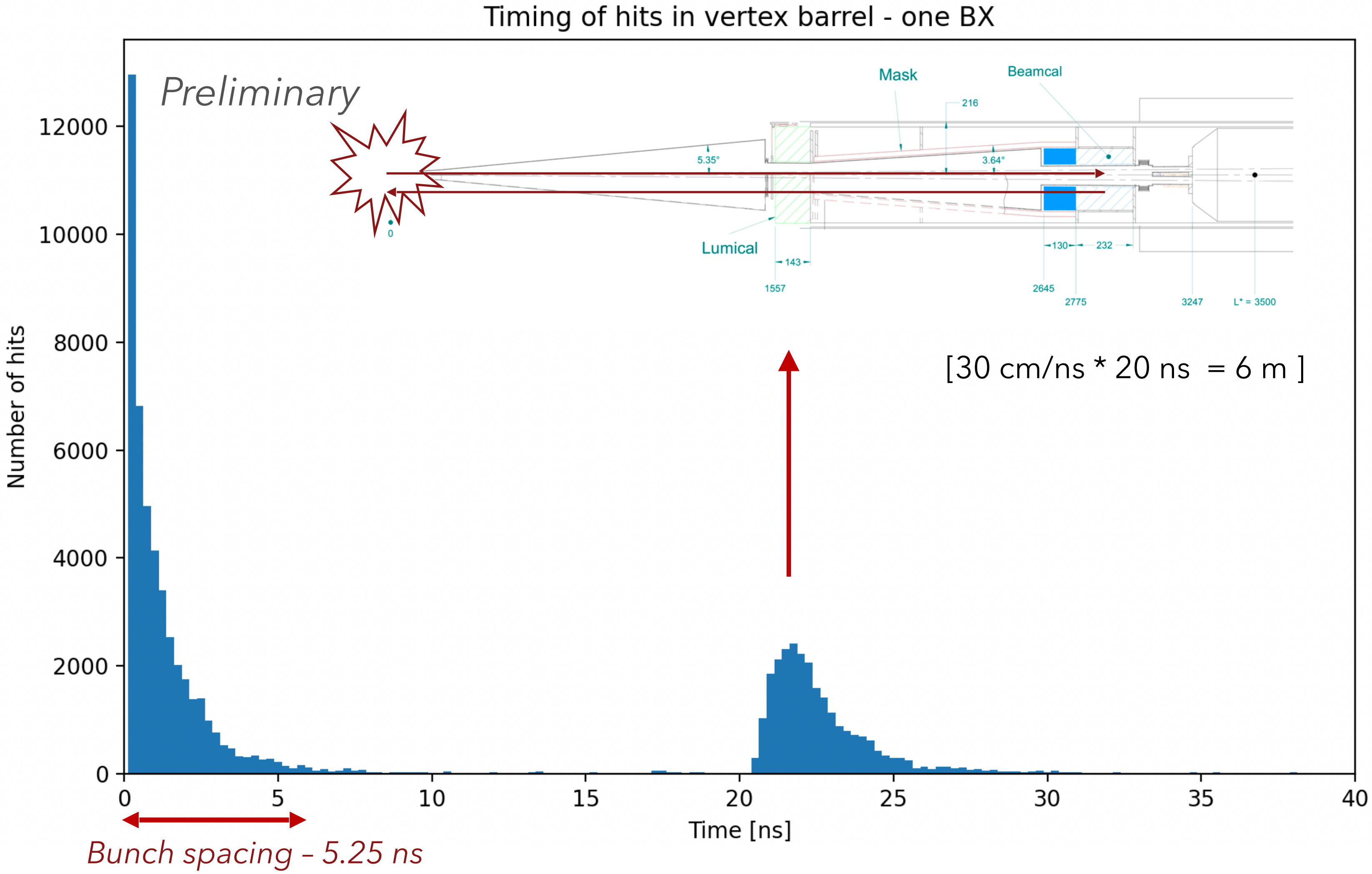
- ***Occupancy in the SiD vertex barrel for the C^3 beam structure is well within the limits set for ILC.***



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

Time distribution within each BX for C³

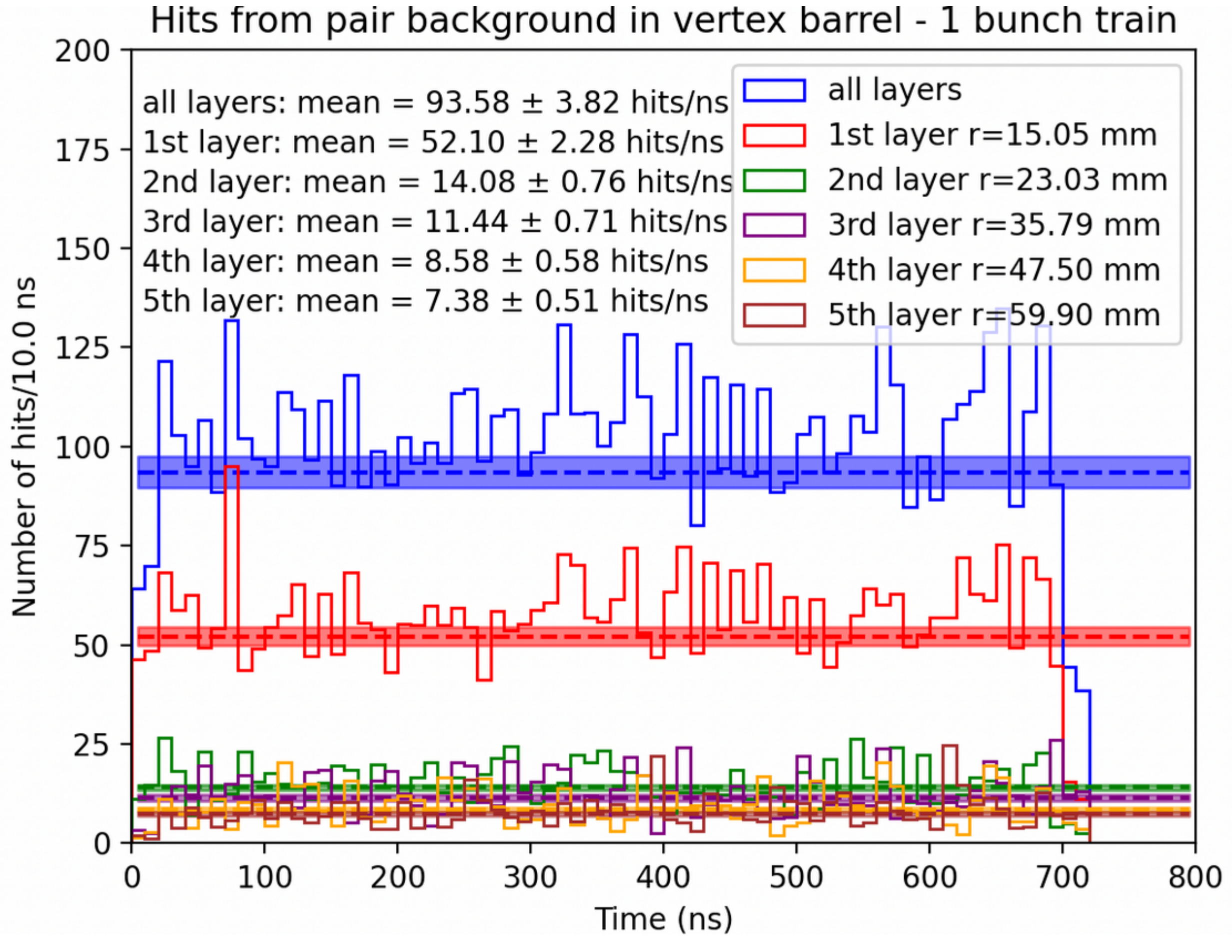
- Time distribution of hits in the SiD vertex barrel within a single BX.
- The normalization corresponds to a full bunch train for C^3-250.
- Most hits contained in time within the bunch spacing.
- The secondary peak at ~20-25 ns is due to backscattering from the BeamCal.



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***



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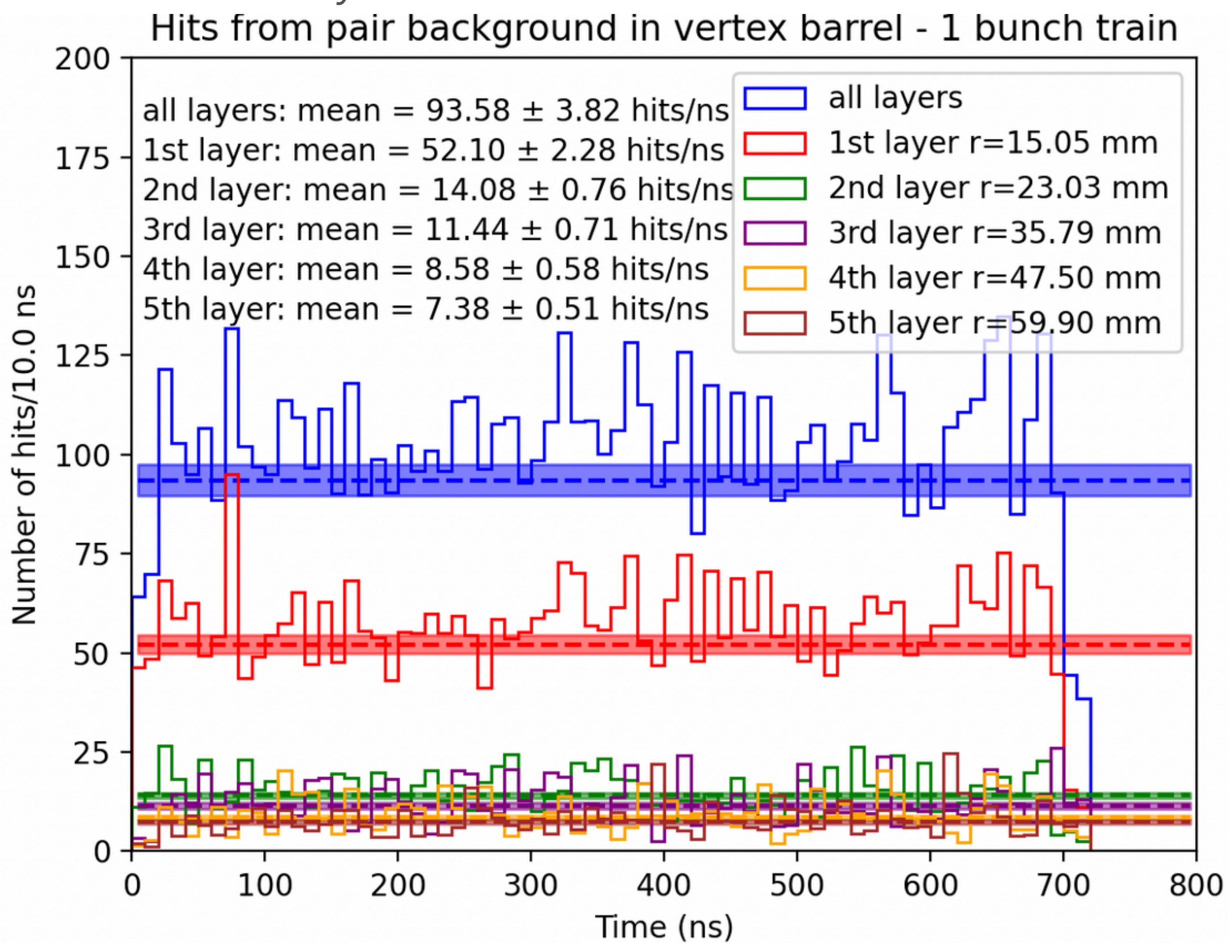
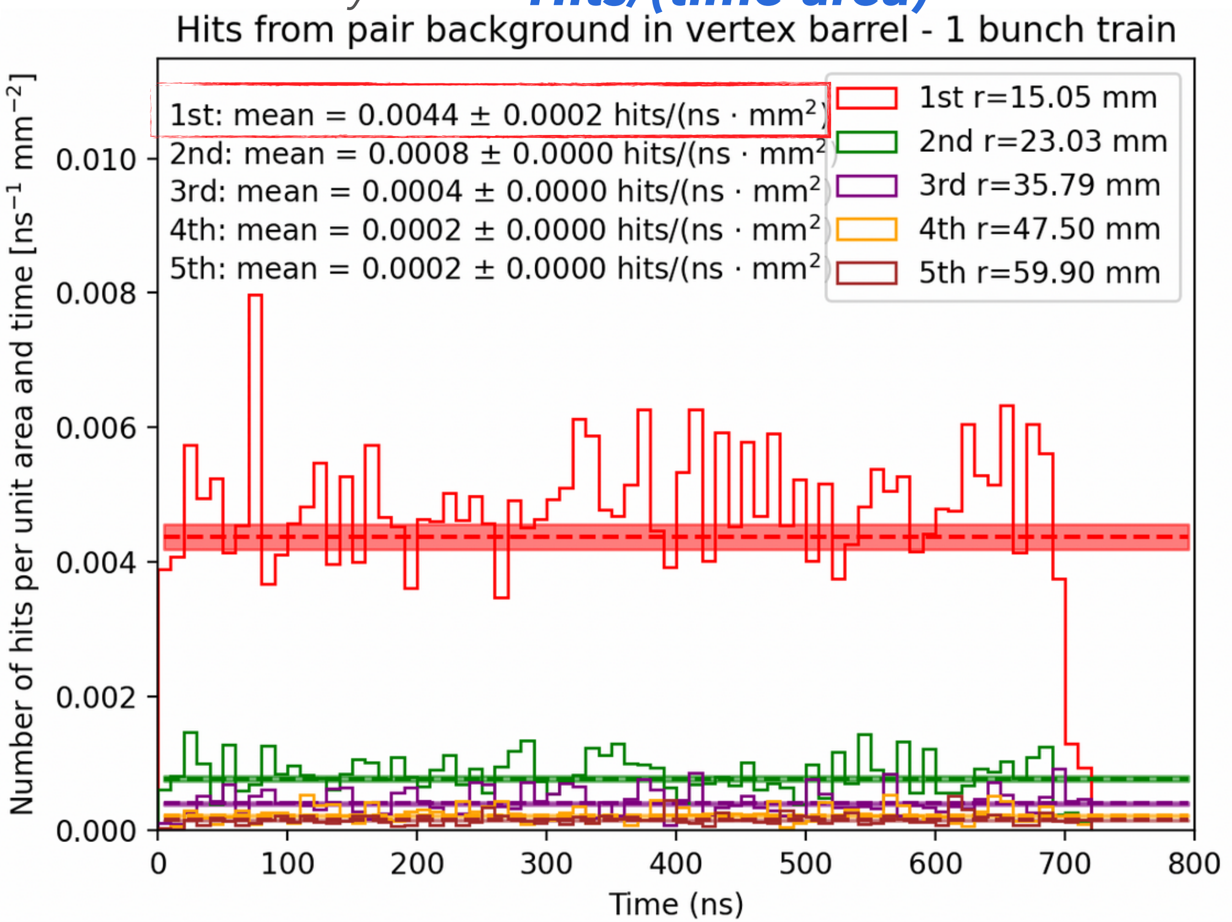


Preliminary **Hits/(time·area)**



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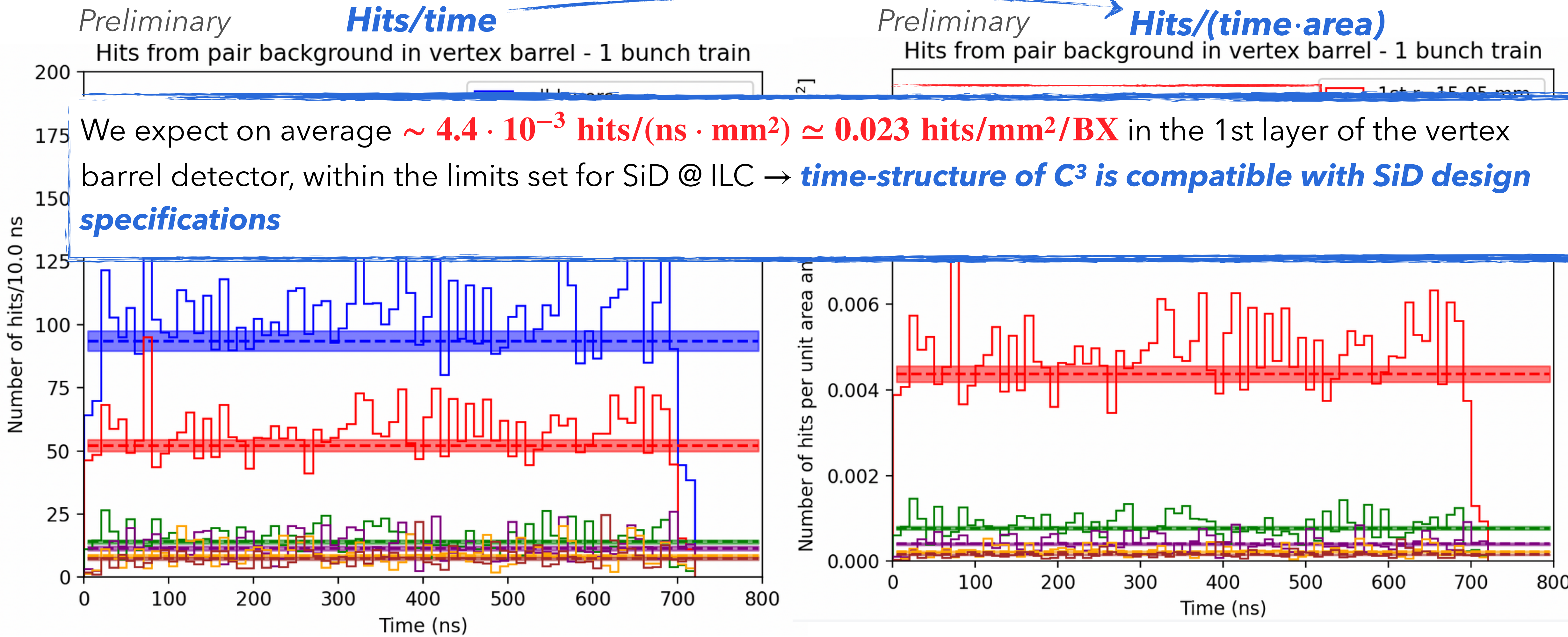

We expect on average $\sim 4.4 \cdot 10^{-3}$ hits/(ns · mm²) $\simeq 0.023$ hits/mm²/BX in the 1st layer of the vertex barrel detector, within the limits set for SiD @ ILC → ***time-structure of C^3 is compatible with SiD design specifications***

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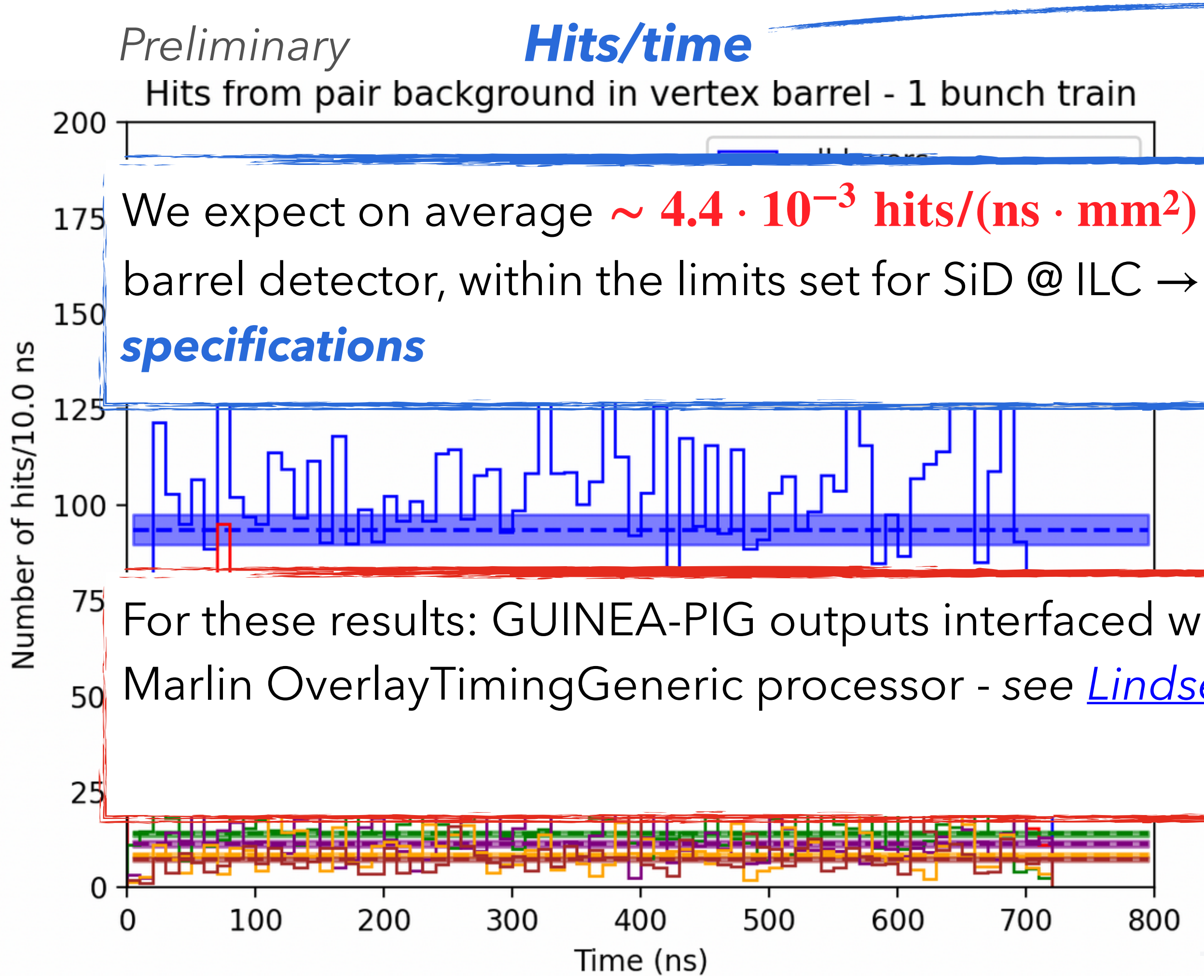

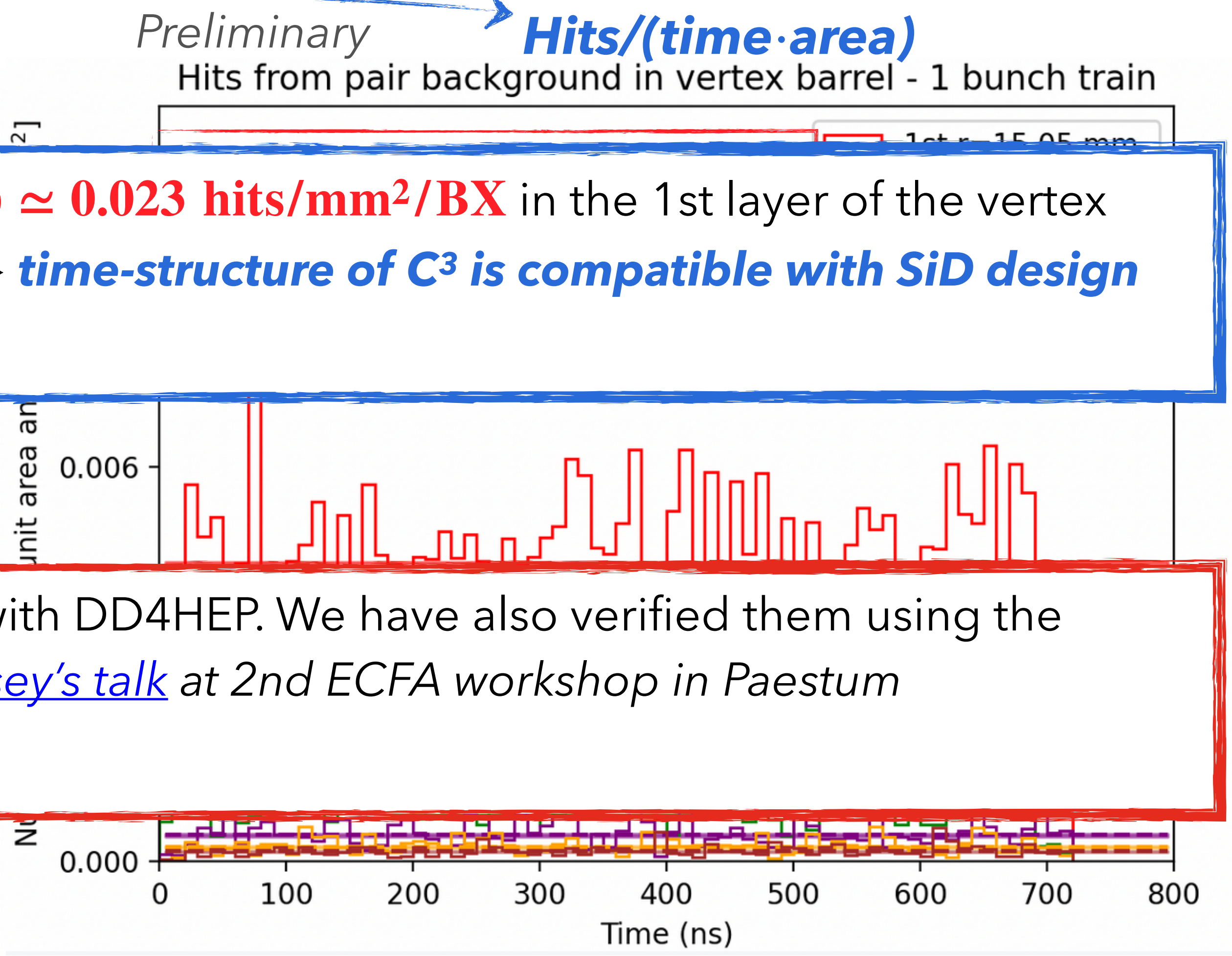

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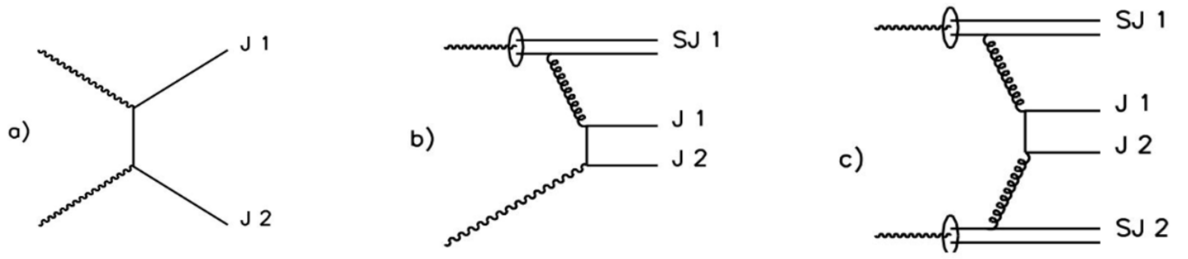
For these results: GUINEA-PIG outputs interfaced with DD4HEP. We have also verified them using the Marlin OverlayTimingGeneric processor - *see Lindsey's talk at 2nd ECFA workshop in Paestum*

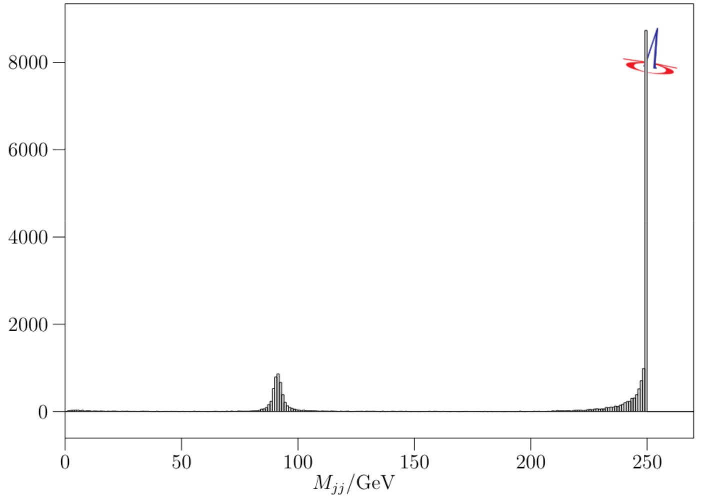
Hadron photoproduction at C³

- 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 $\rightarrow$ ***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***.

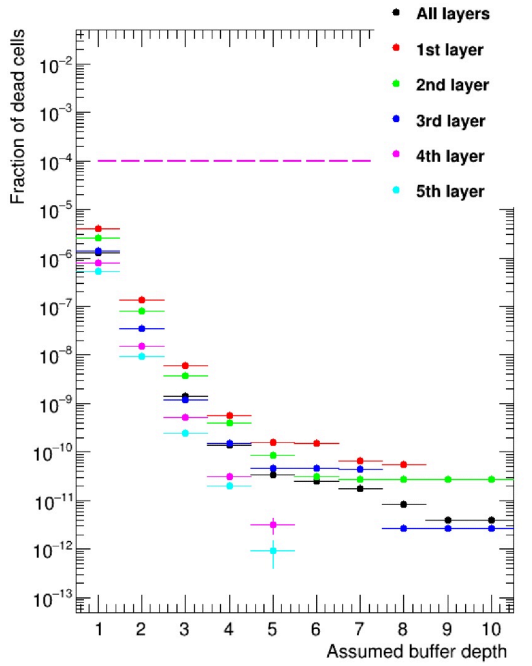
See Lindsey's talk at C³ workshop for more details



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



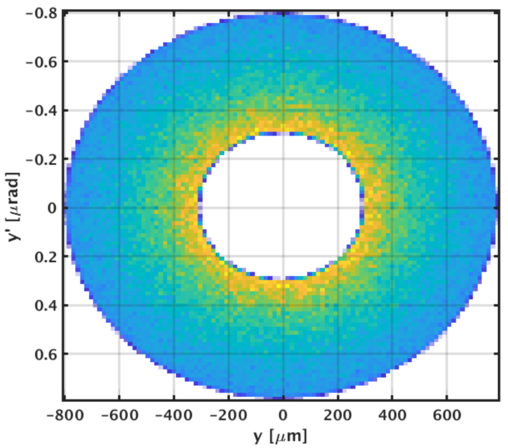
T. Ohl's talk at 2nd ECFA workshop in Peastum



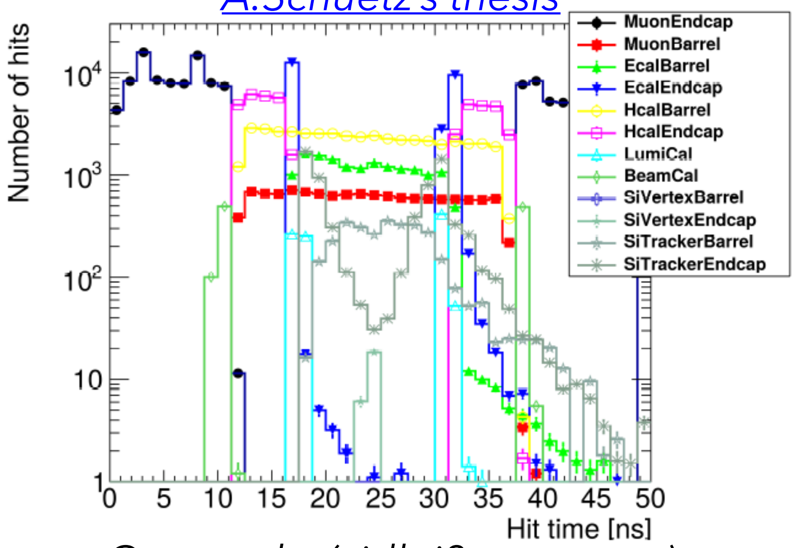
E. Mettner's talk at LCWS 2023

Halo muon machine background at C³

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

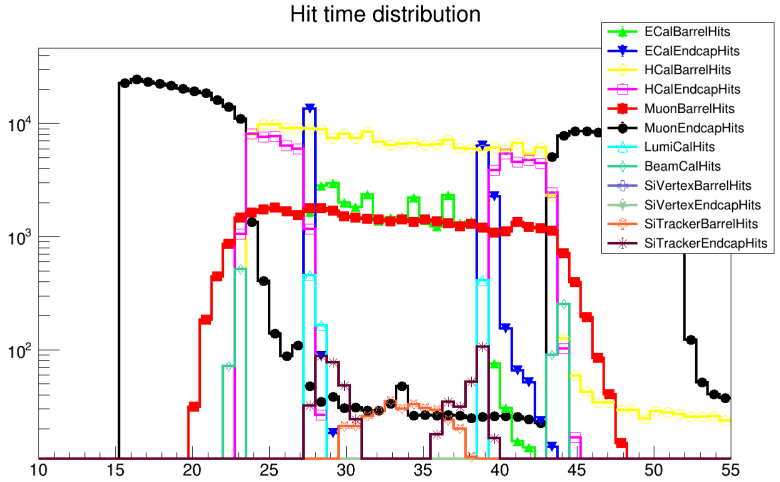


[A.Schuetz's thesis](#)



- 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!***

Our results (sidloi3 geometry)
[work done by Kenny Jia]



Conclusions

- We have simulated and validated the leading BIB for C^3, incoherent pair production, and are finalizing the simulation for the hadron photo production.
- Ongoing effort for out-of-time pileup mixing and evaluating effect of background occupancy on tracking performance.
- *Larger community effort is necessary to get a reliable simulation tool for muon machine background for all colliders.*
- The ***C^3 beam configuration and time-structure has been validated to be compatible with ILC-like detectors.***
- *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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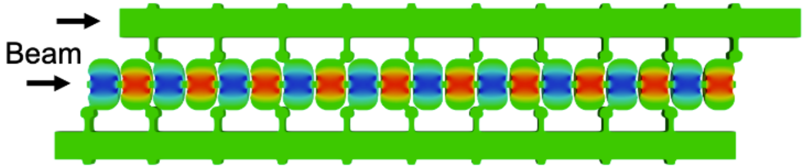
Questions?

Backup

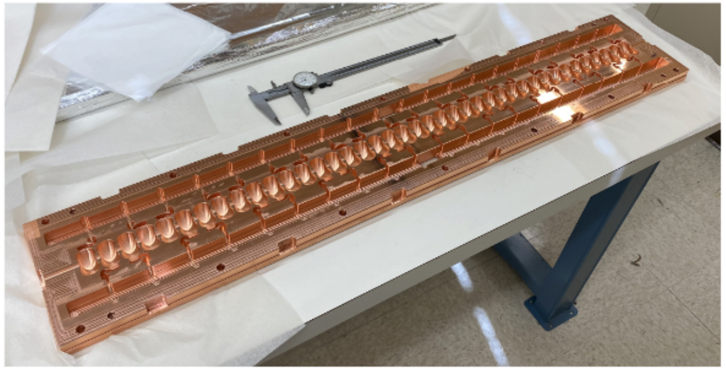
JINST 18 P07053
JINST 18 P09040
PRAB 23 092001

The Cool Copper Collider

- 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.***



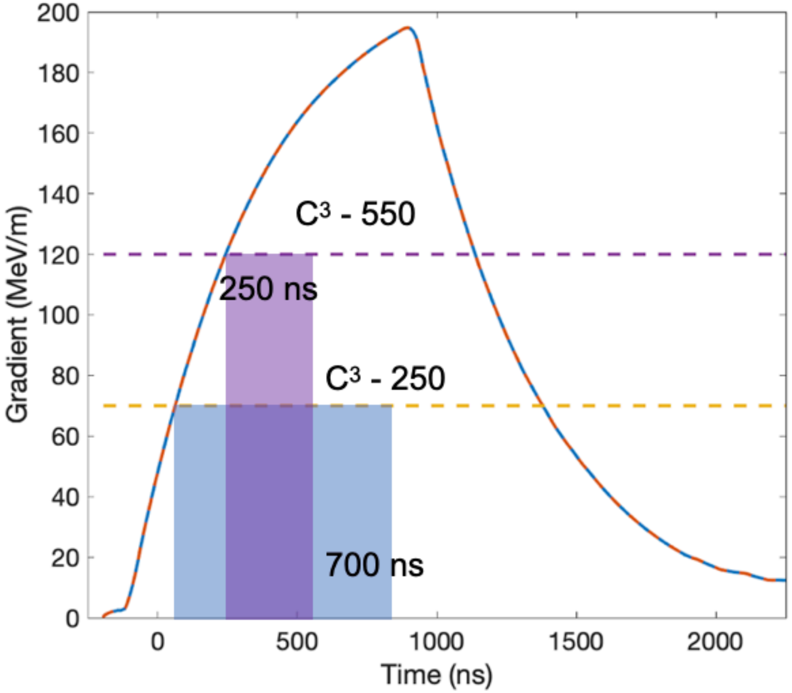
Electric field magnitude for equal power from RF manifold



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

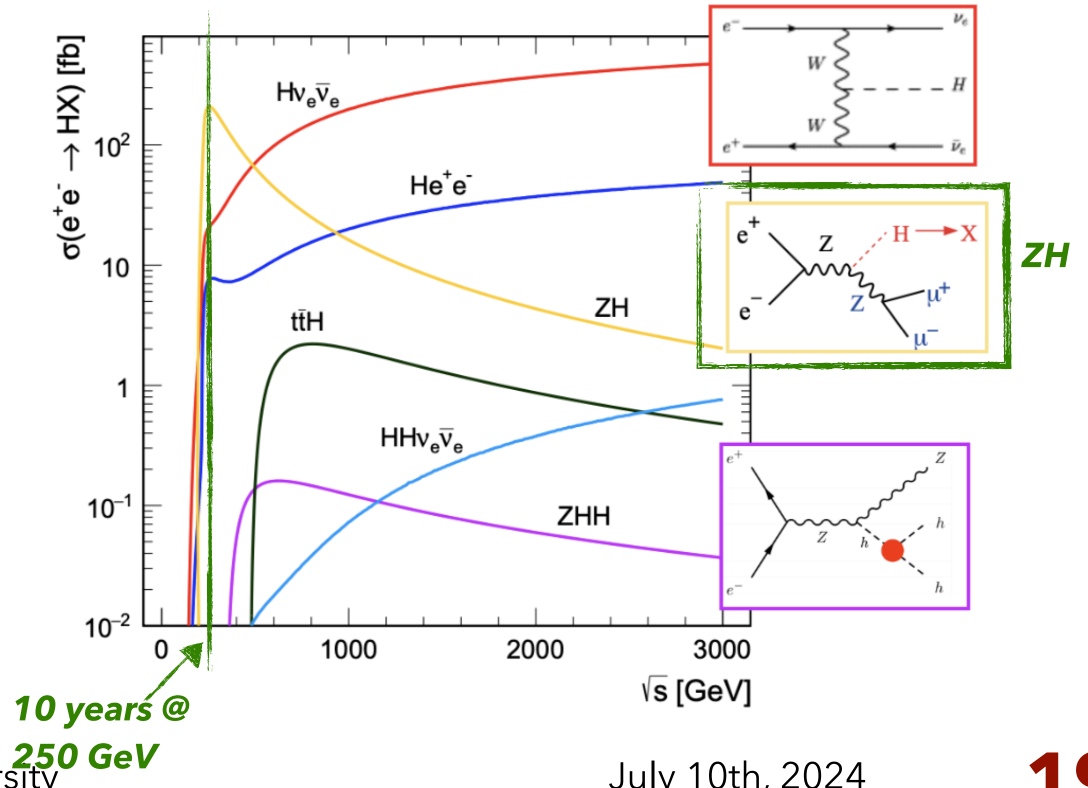


The Cool Copper Collider - *Physics*

- 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.



JINST 18 P07053

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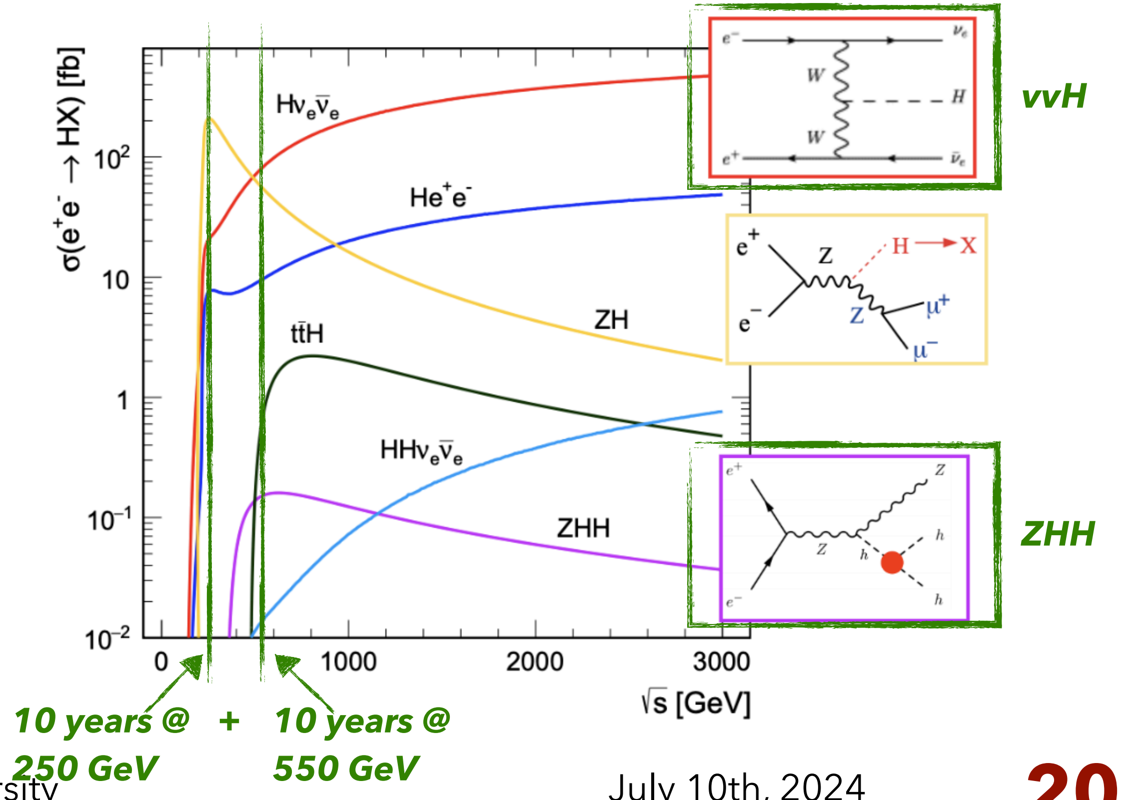
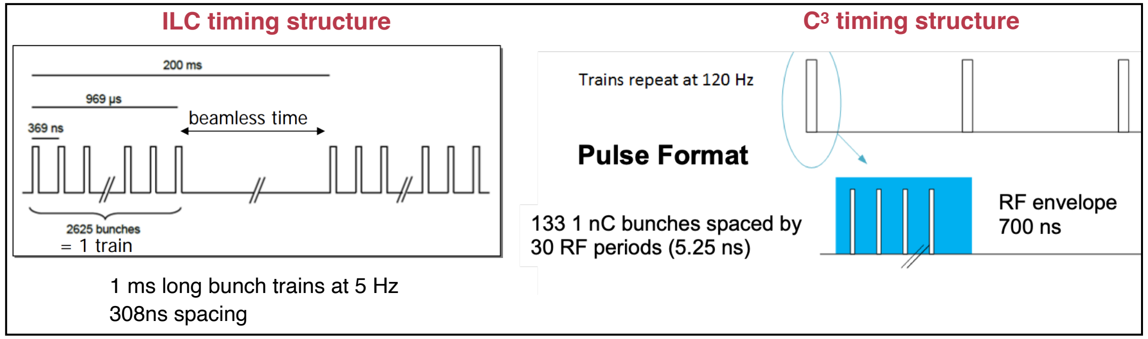


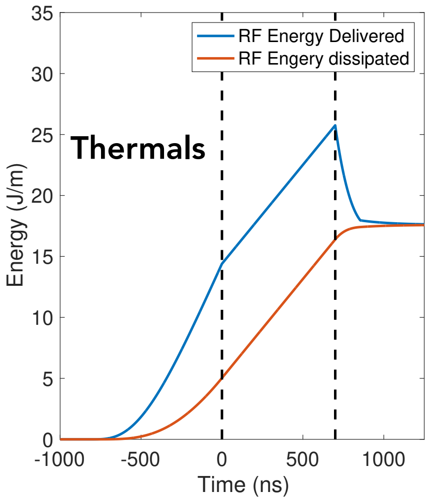
The Cool Copper Collider - *Power Optimizations*

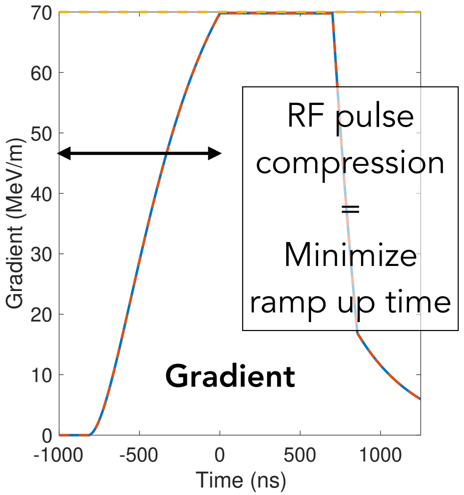
- Potential improvements for C3 coming from minimizing RF power when there is no beam loading.

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

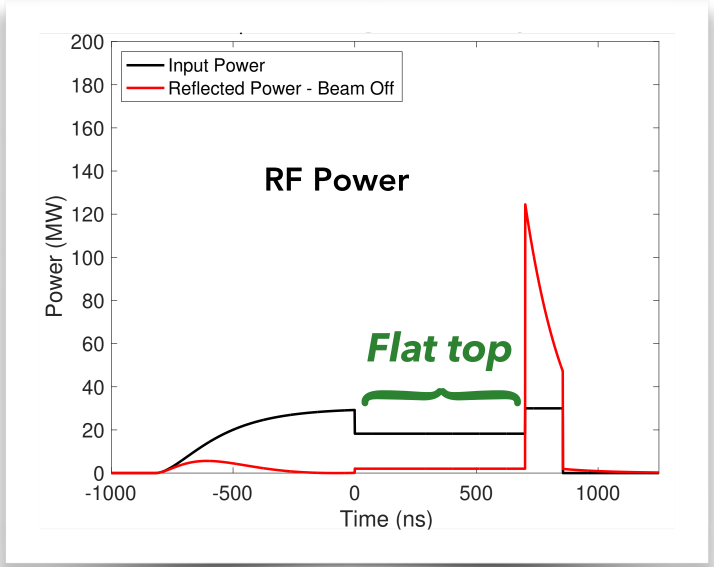
Power savings with adjustment of the main linac design and beam parameters. For 550 GeV, the percentage savings would be unchanged for a combined 79 MW reduction.







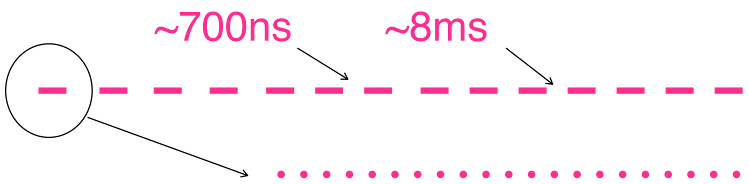
- Doubling the flat-top (700→ 1400 ns) or halving the bunch spacing (5.25→2.6ns) allows for **rep. rate reduction** (120→ 60 Hz) without loss in luminosity.
- This **reduces thermal load** by **25%**.
- Overall, power savings can reach **63MW** at 250 GeV and **79MW** at 550GeV.



The Cool Copper Collider - *Power Optimizations*

- 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

Scenario	Flat top (ns)	Δt_b (ns)	n_b	f_r (Hz)	$\mathcal{L}$ (10^{34} cm^{-2} s^{-1}) C^3-250 (PS1)	$\mathcal{L}$ (10^{34} cm^{-2} s^{-1}) C^3-250 (PS2)	P_{site} (MW) Both scenarios	$\mathcal{L}/P_{site}$ (10^{34} cm^{-2} s^{-1} (GW)$^{-1}$) PS1	$\mathcal{L}/P_{site}$ PS2
Baseline	700	5.26	133	120	1.35	1.90	150	9.0	12.7
Double flat top	1400	5.26	266	60	1.35	1.90	125	10.8.	15.2
Halve bunch spacing	700	2.63	266	60	1.35	1.90	129	10.5	14.7
Combined-half repetition rate	1400	2.63	532	60	2.70	3.80	154	17.5	24.7
Combined-nominal repetition rate	1400	2.63	532	120	5.40	7.60	180	30.0	42.2

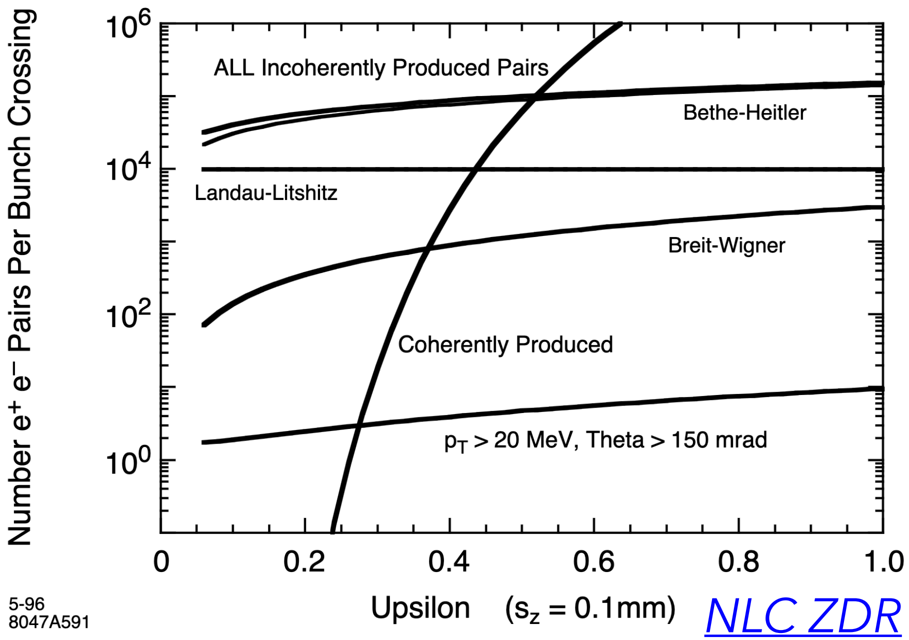
Up to ~3x $\mathcal{L}/P_{site}$ gain!

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.

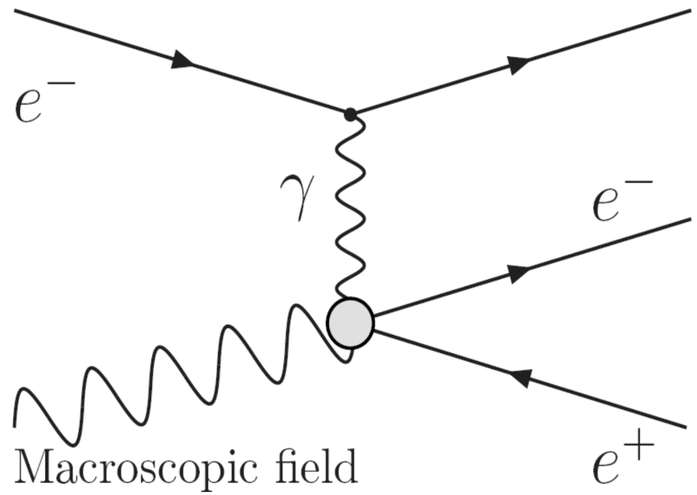
Beam-Beam interactions at e+e- colliders

- 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.

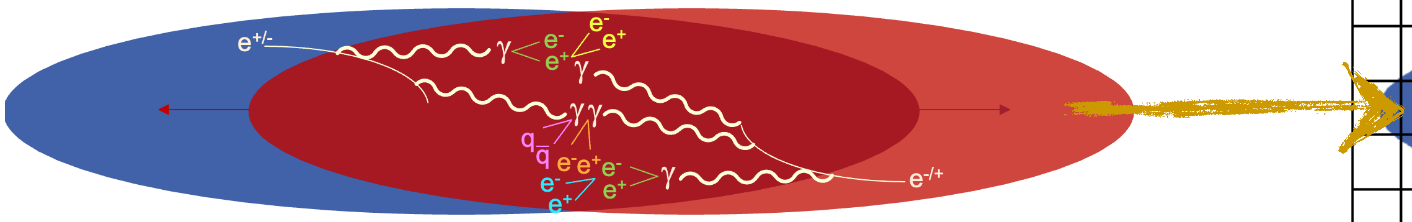


NLC ZDR

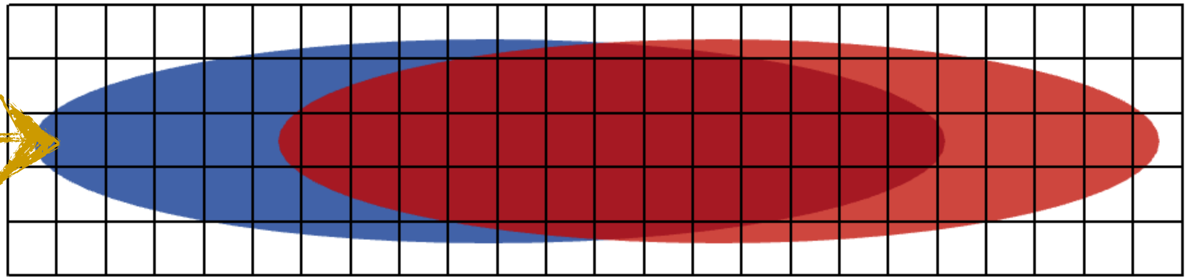


Simulation of Beam-Induced Background

- 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

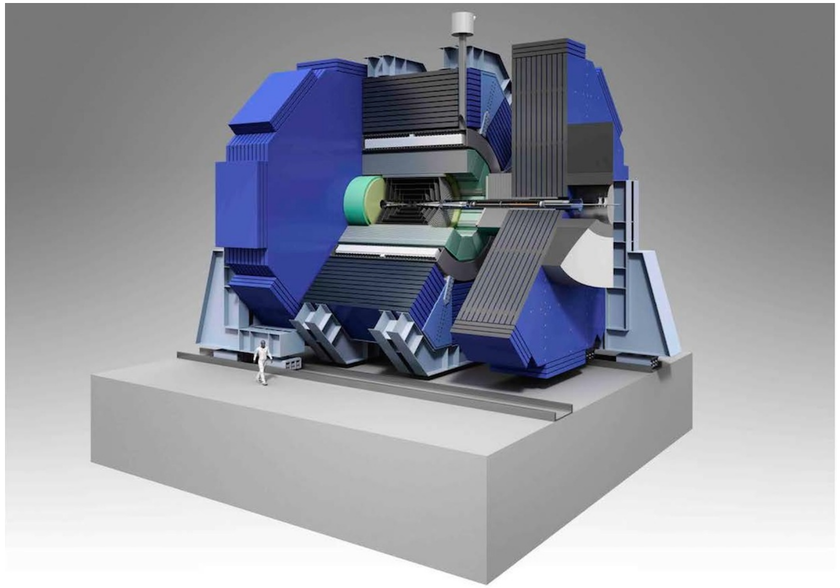


Jean-Luc Vay

Simulation of Beam-Induced Background

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

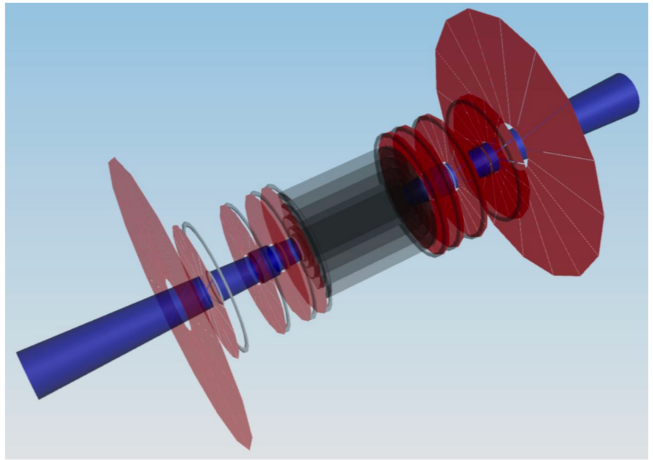
GUINEA-PIG
Key4hep
DD4hep
k4geo

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

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

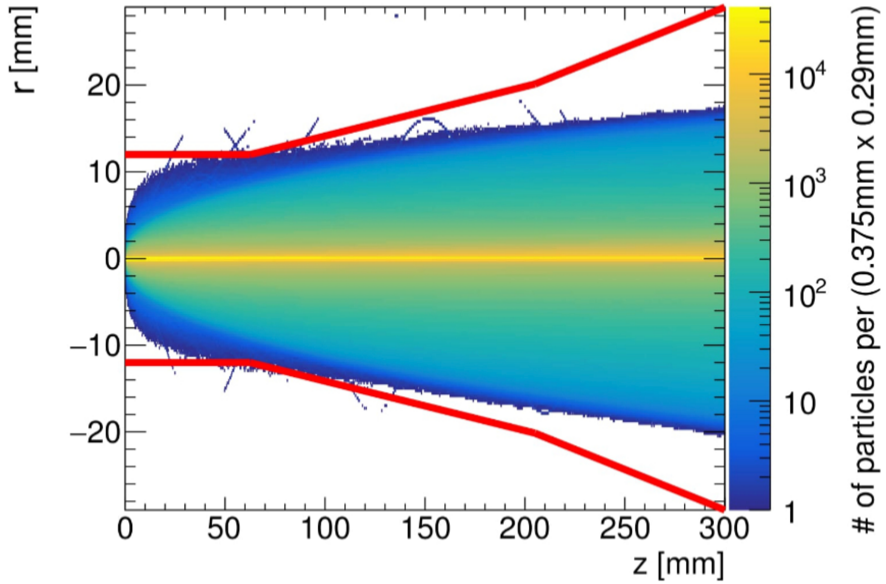
***SiD geometry version SiD_o2_v4 used in our simulations**

Pair Background Envelopes

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

ILC - Previous results

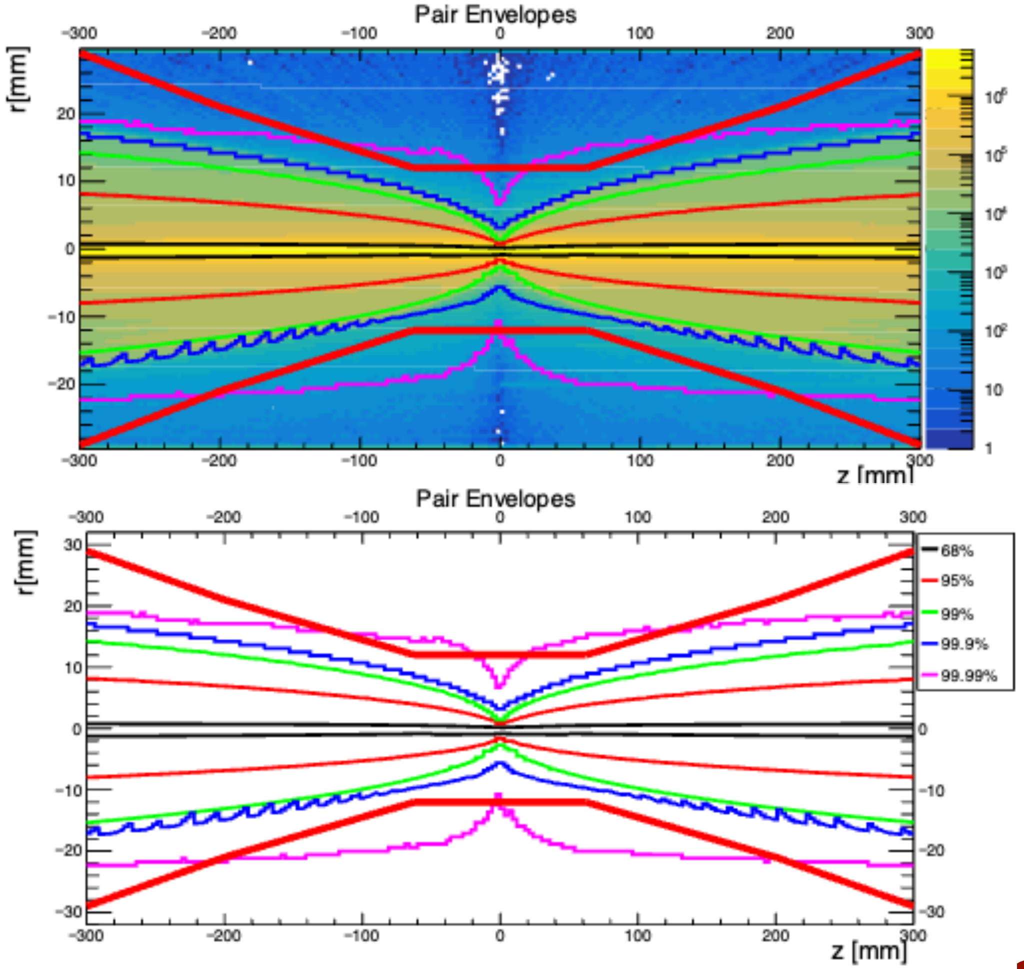
r vs z



From [Anne Schutz's PhD thesis](#) (2018)

C³ - Our results

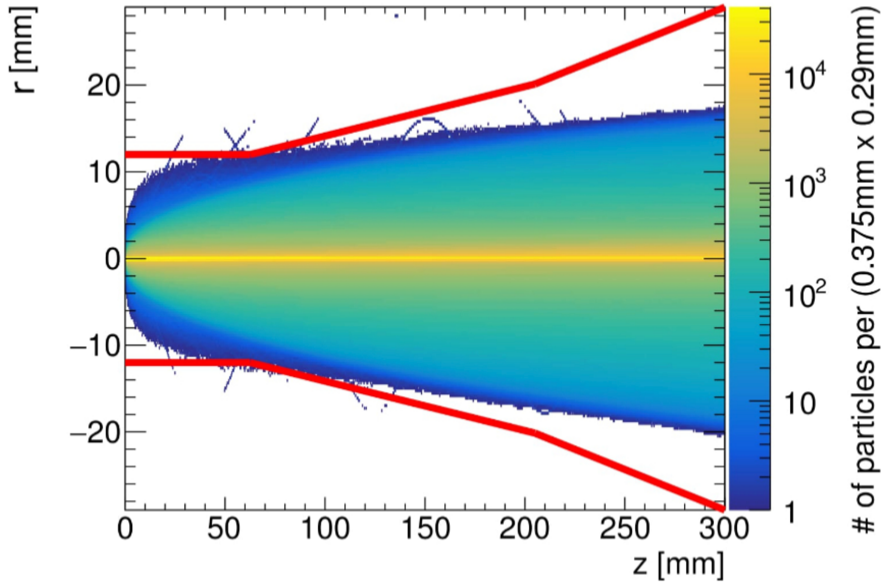
r vs z



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

ILC - Previous results

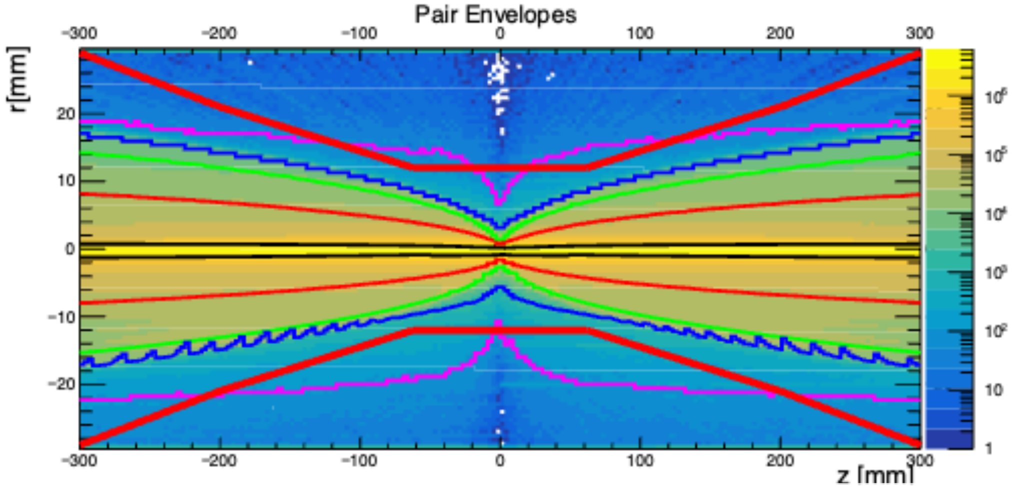
r vs z

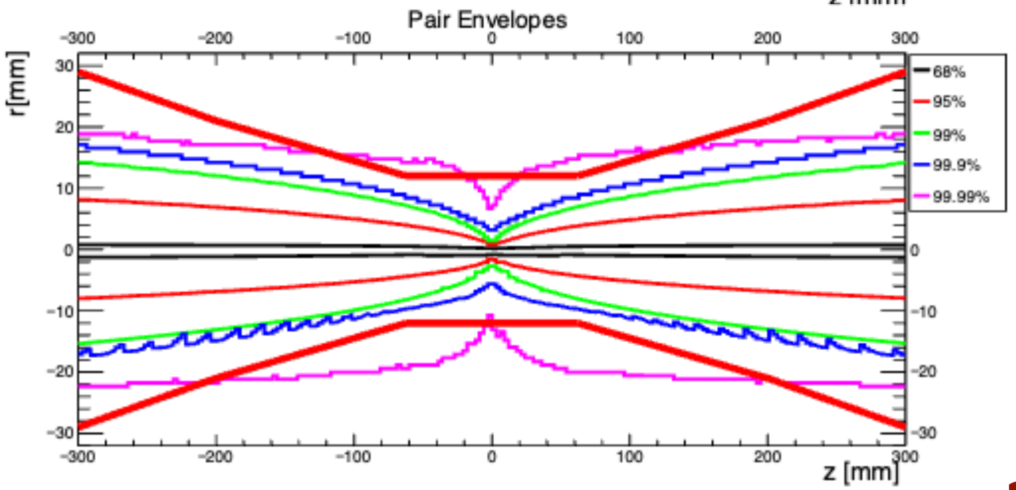


From [Anne Schutz's PhD thesis](#) (2018)

C³ - Our results

r vs z





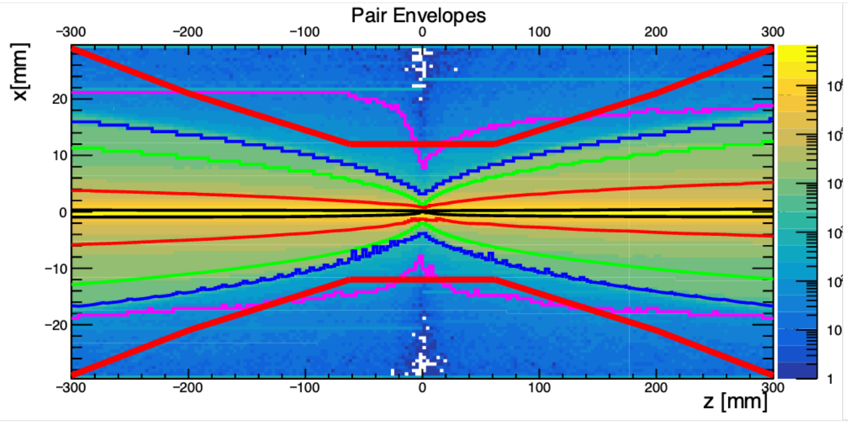
Pair Background Envelopes

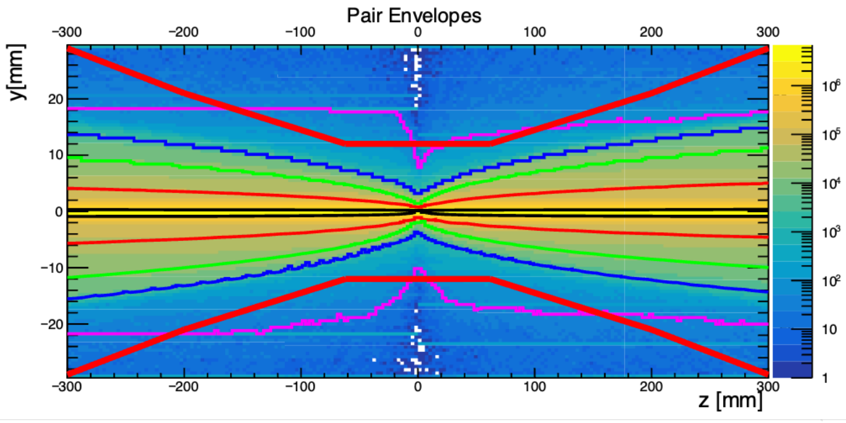
The pair background envelopes for C3 are well contained within the beam-pipe.

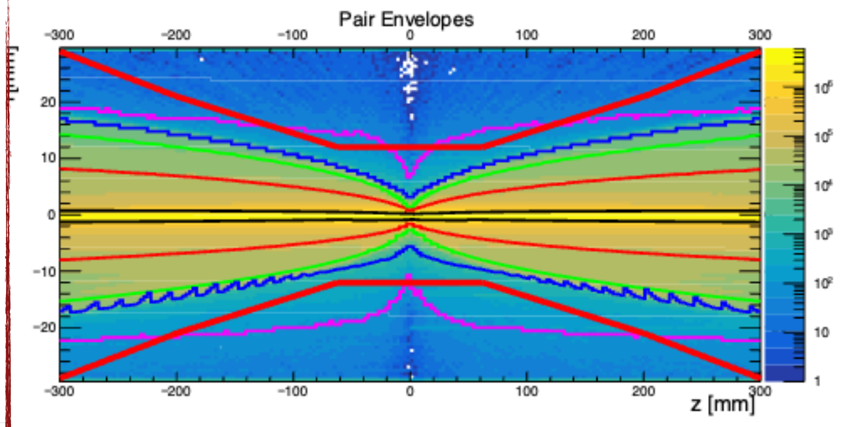
x vs z

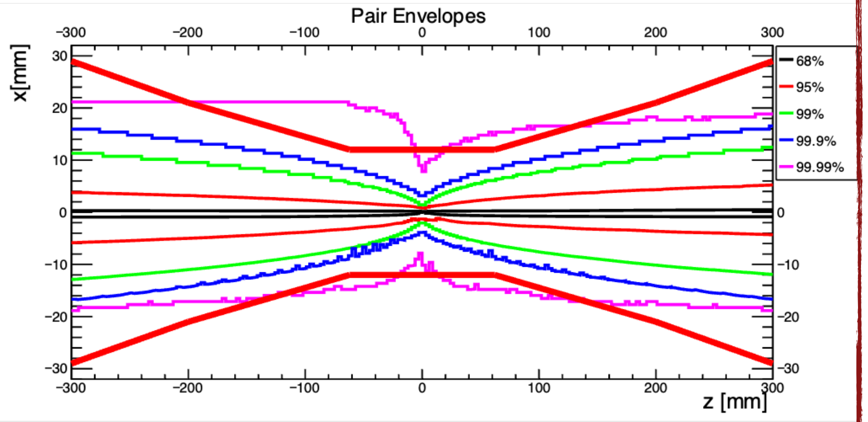
y vs z

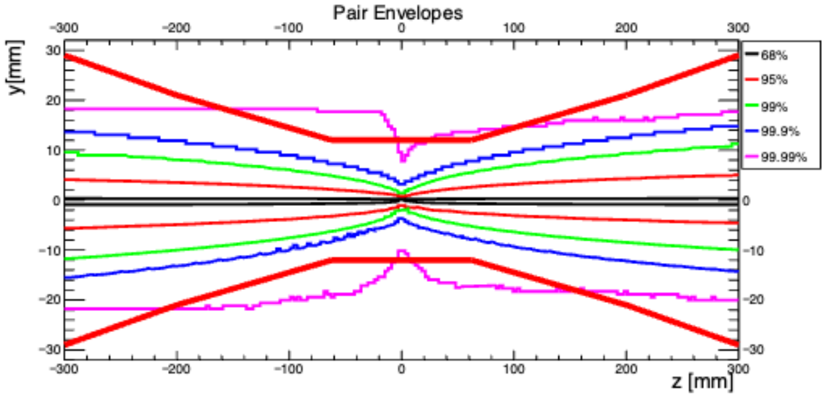
r vs z

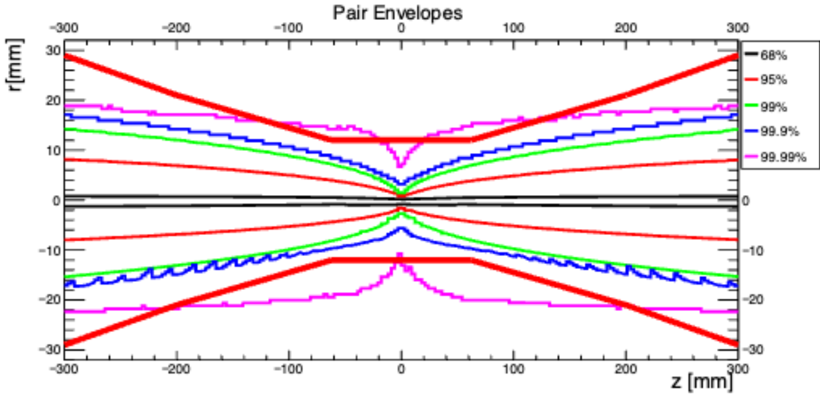








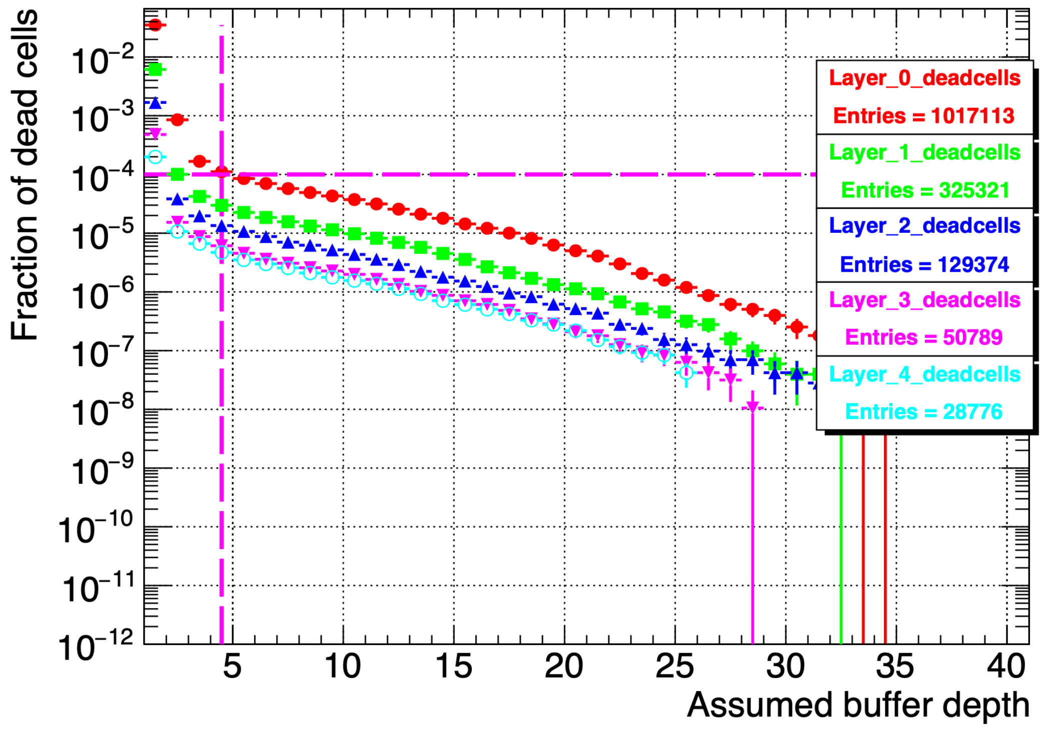




Pair background occupancy

Results shown here correspond to $\sqrt{s} = 250$ GeV***, full detector (SiD) sim***

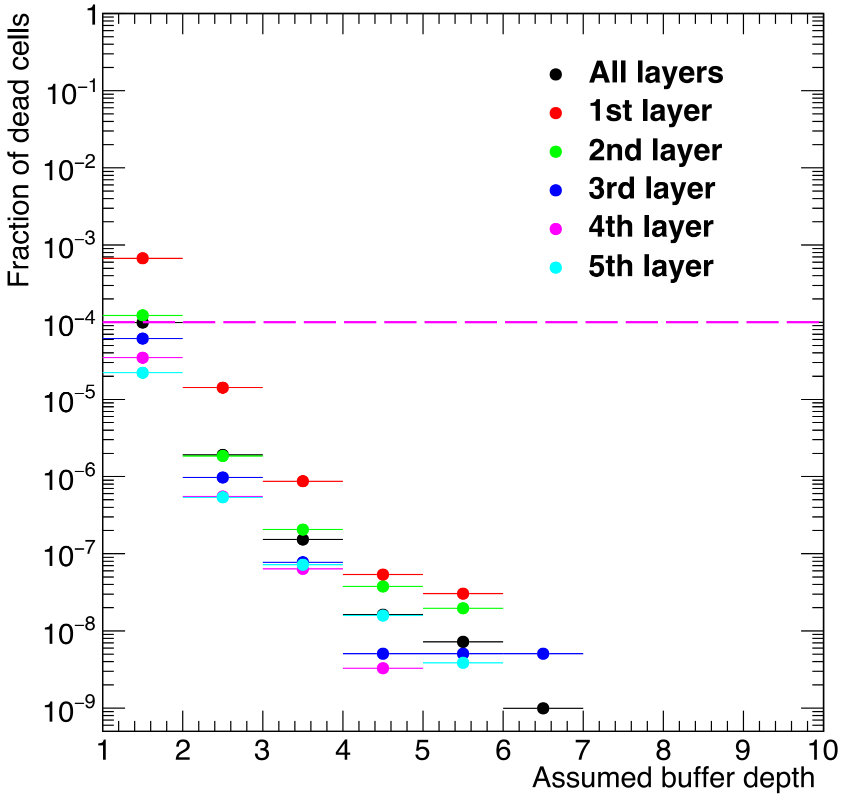
ILC - Previous results



(b) *Set (A), fraction of dead cells*

From [Anne Schutz's PhD thesis](#) (2018)

C³ - Our results



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 :

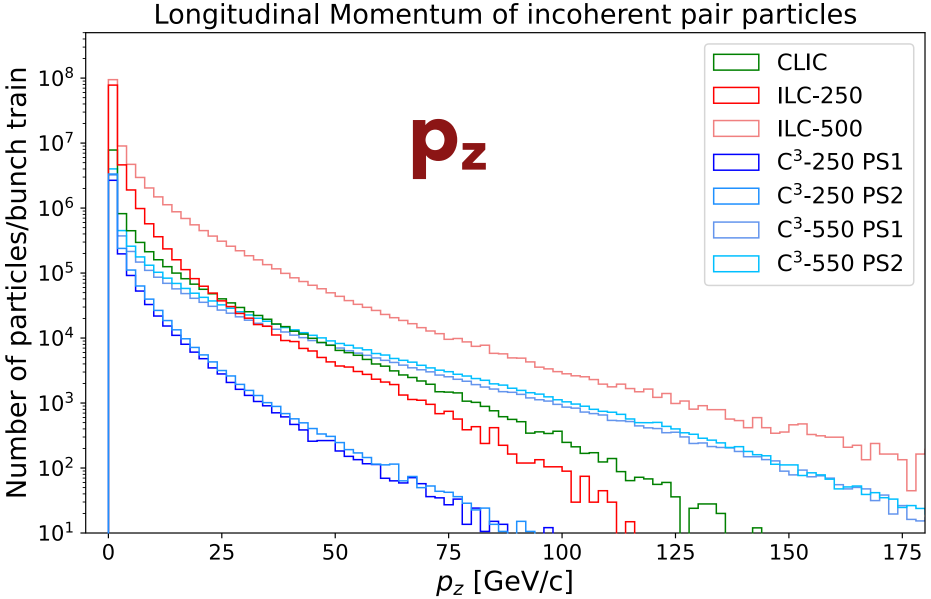
$$0.043 \text{ hits/(ns} \cdot \text{mm}^2) \cdot (5.25 \text{ ns/BX}) = \mathbf{0.023 \text{ hits/mm}^2\text{/BX}}$$

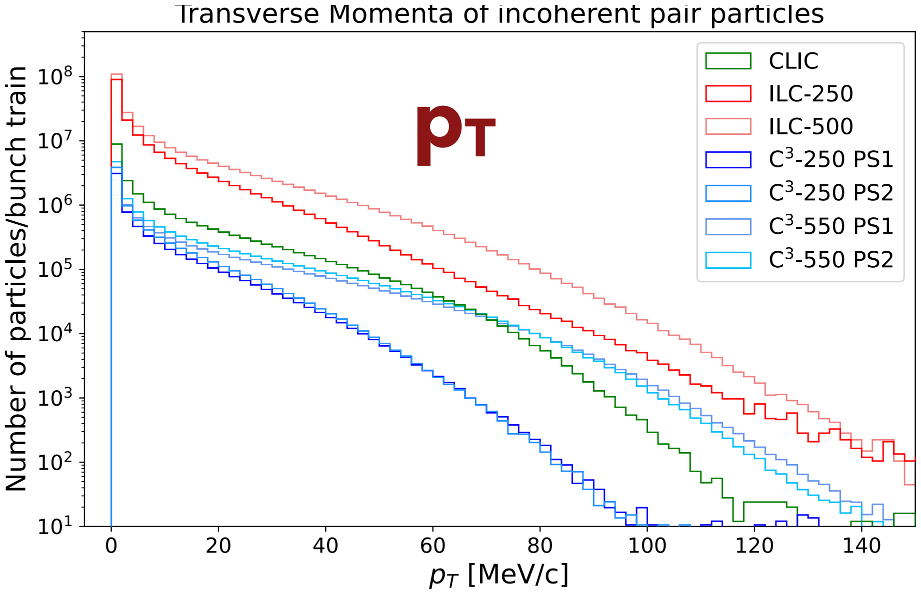
- We are currently in the process of validating our results and repeating the studies for all subdetectors.

> 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

- 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.***

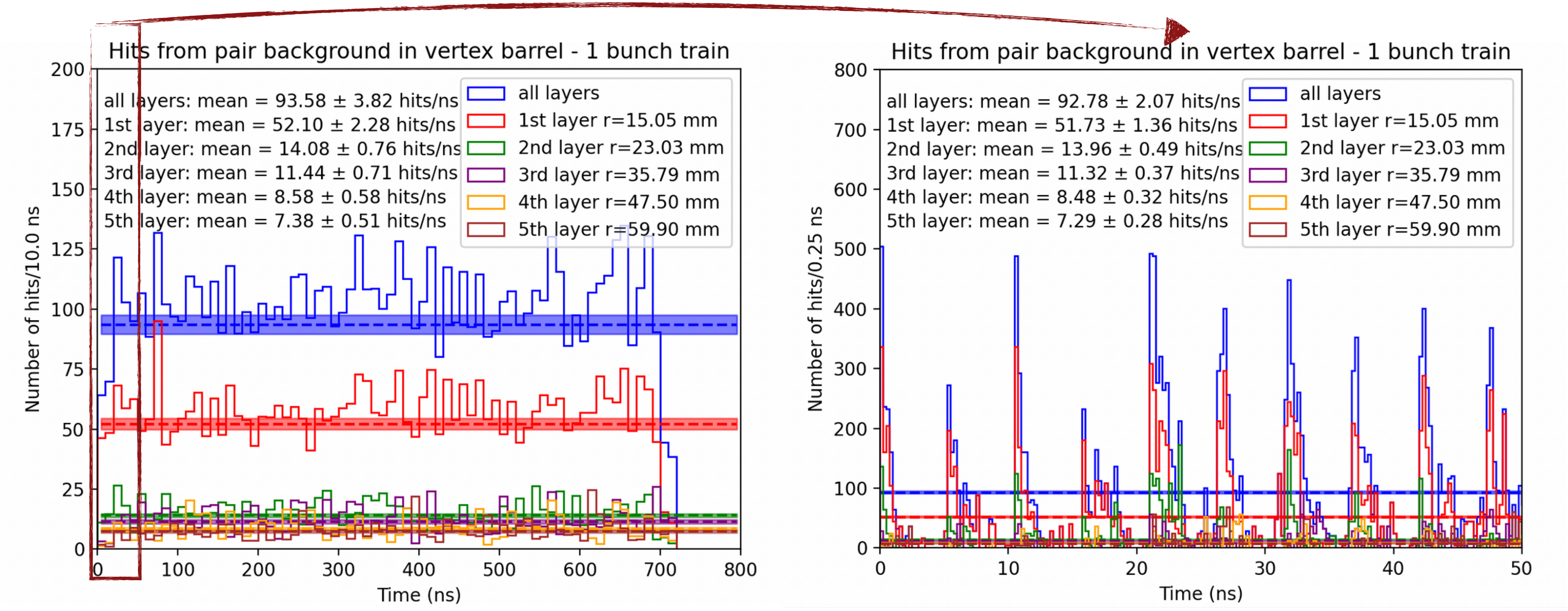




Detailed Luminosity Studies: 2403.07093

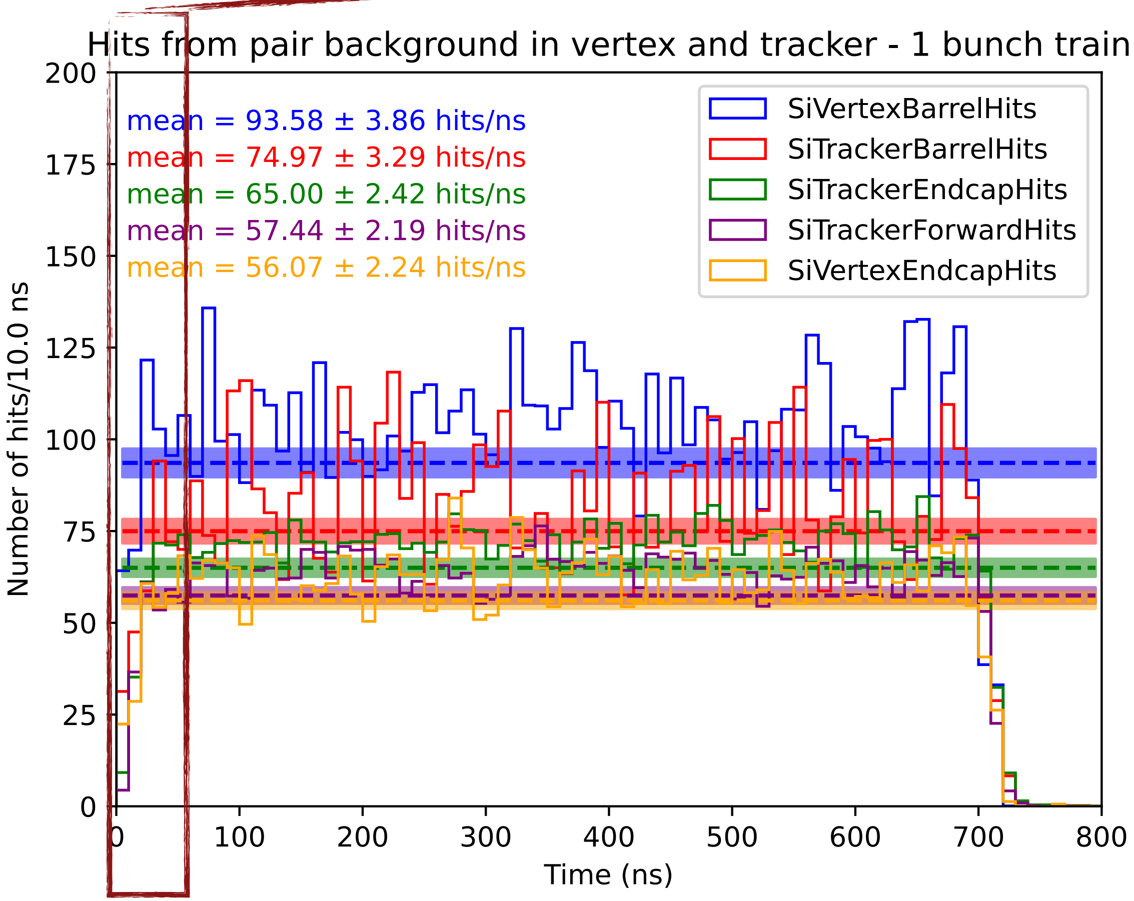
Time distribution over a train for C^3

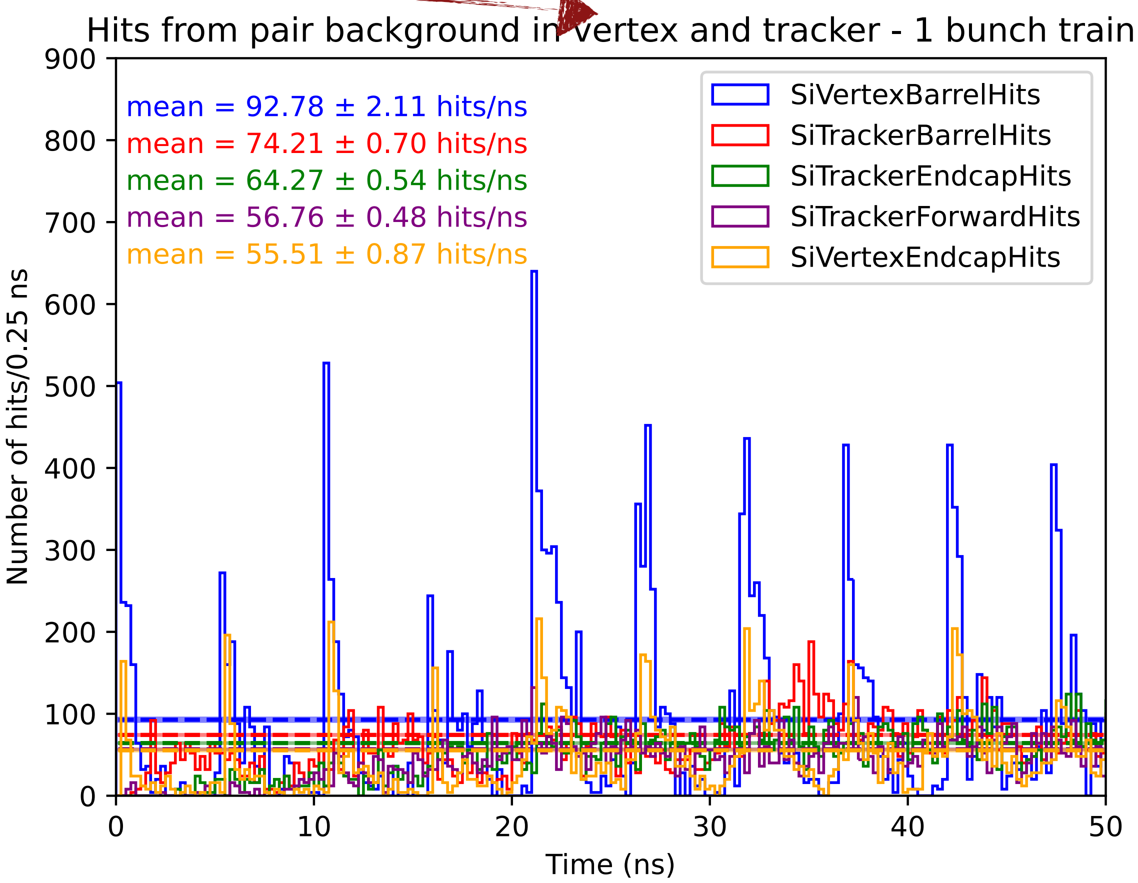
Time distribution of hits per unit time: on average, we anticipate ~ 90 hits/ns in the vertex barrel detector.



Time distribution over a train - vertex & tracker

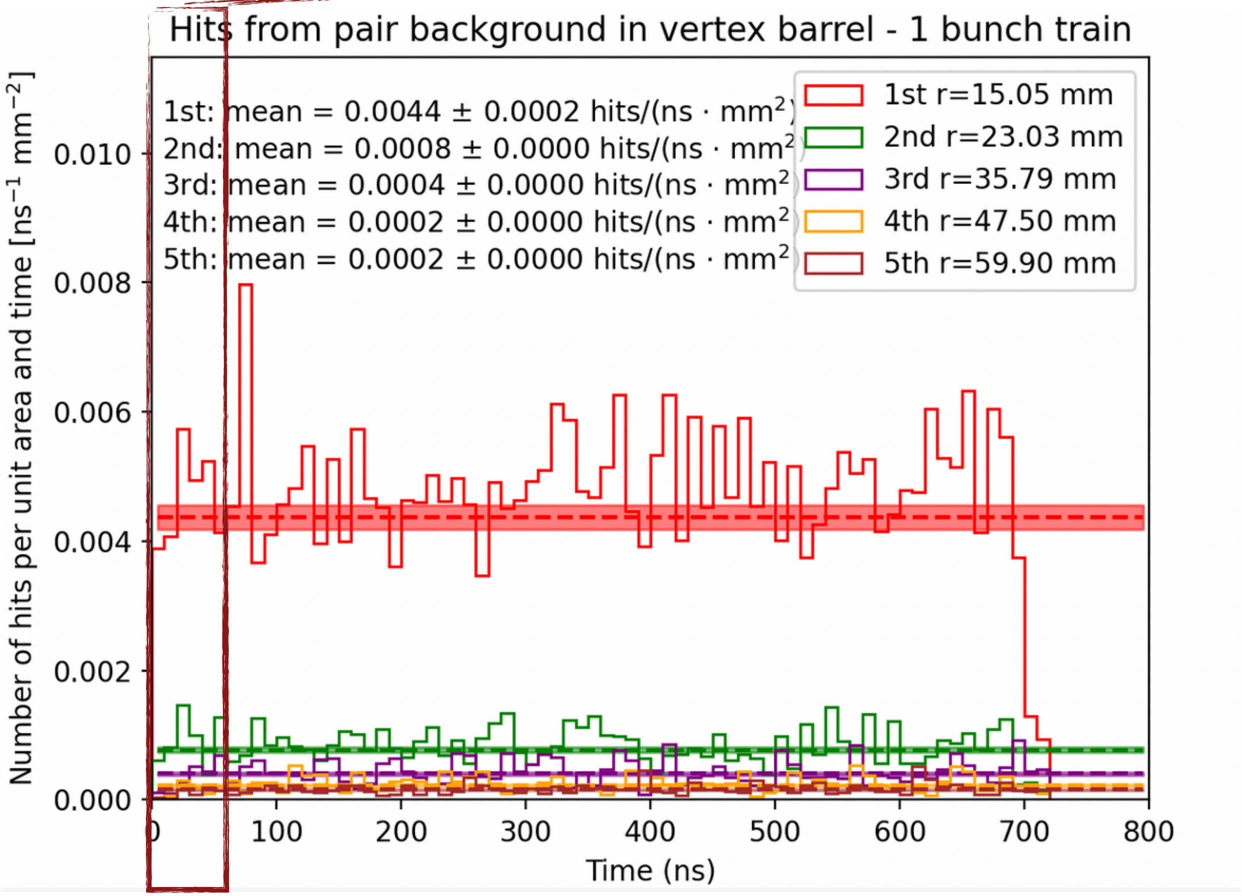
Time distribution of hits per unit time in the various vertex and tracker subdetectors.

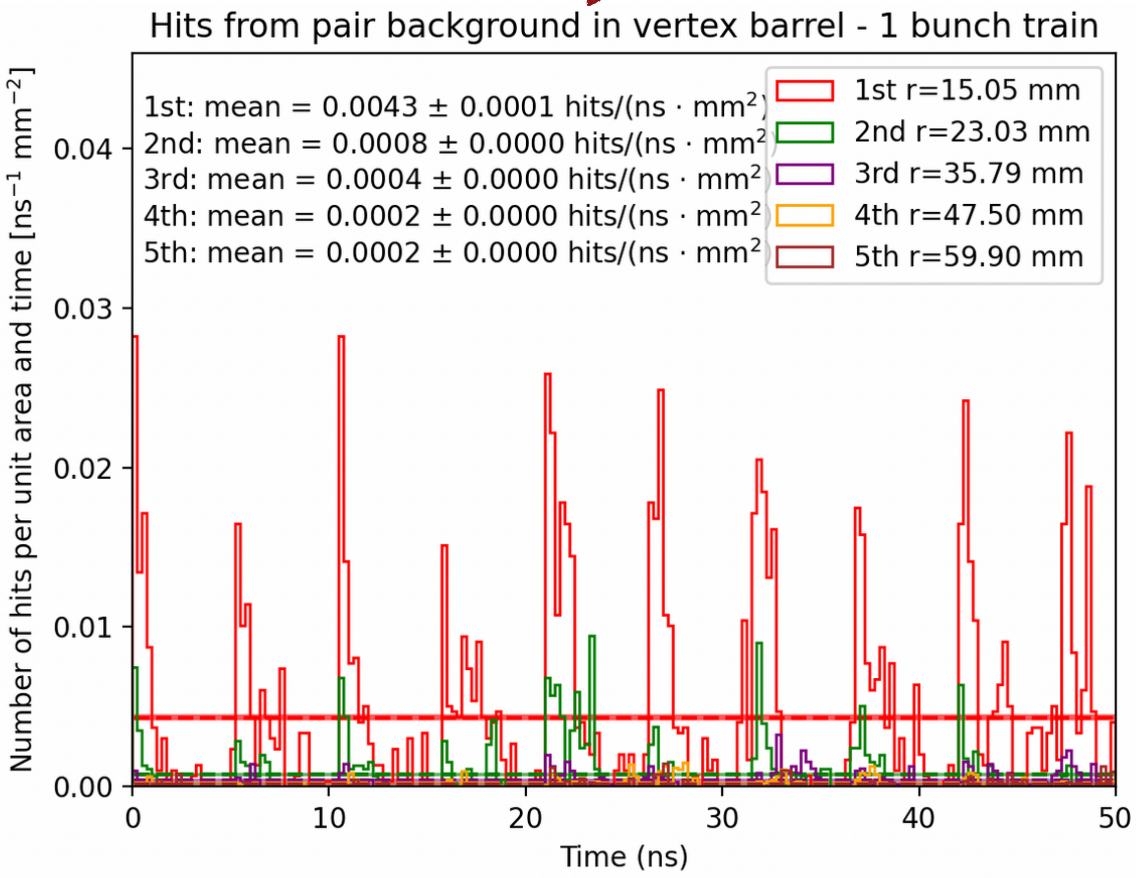




Time distribution over a train - vertex barrel

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.





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

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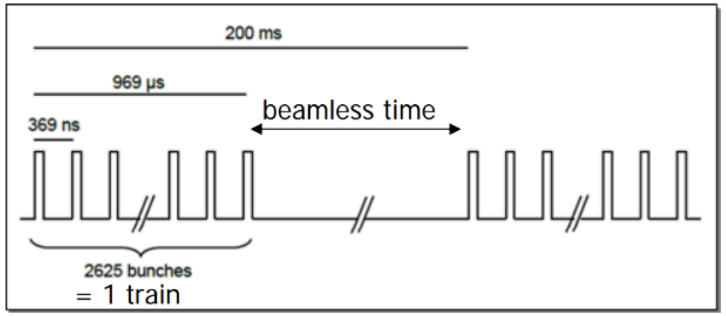
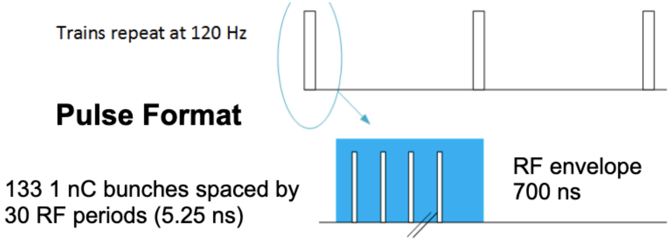
ILC timing structure



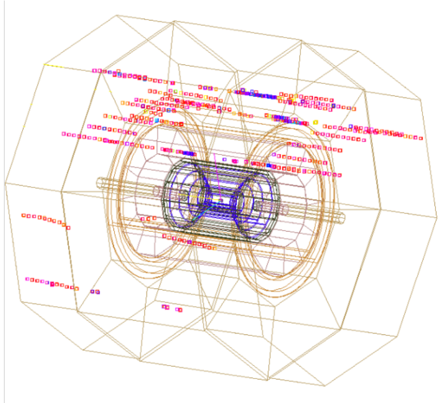
1 ms long bunch trains at 5 Hz
308ns spacing

C^3 timing structure



Ongoing efforts

- The pair background might be the dominant BIB for C³, but other sources of background are also important and under study:
  - hadron photoproduction background $\gamma\gamma \rightarrow \mathrm{hadrons}$ (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