Out-of-Time Pileup Mixing for the C3 Collider Concept

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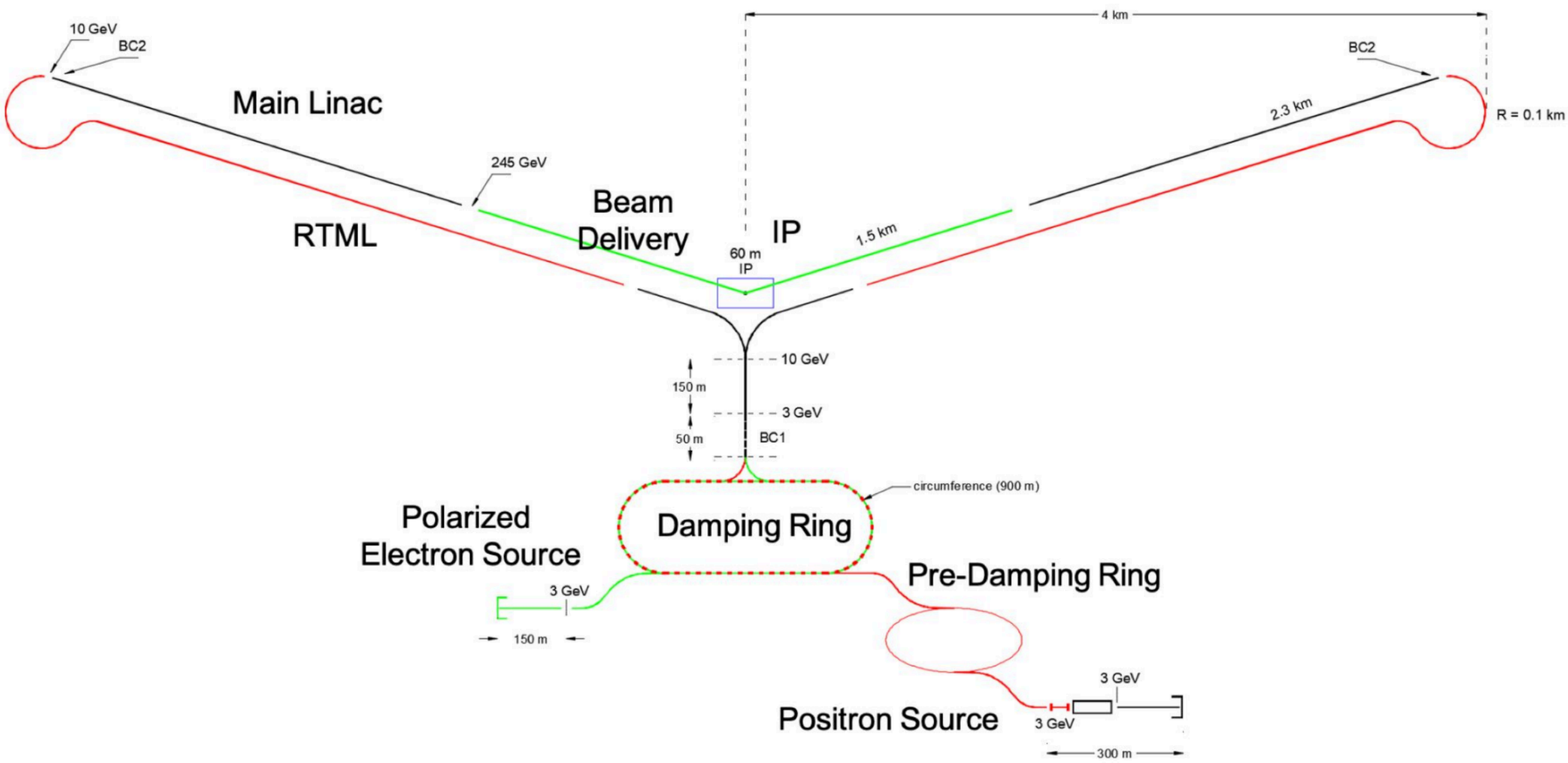
The Cool Copper Collider (CCC / C3) Accelerator

C^3 - 8 km Footprint for 250/550 GeV

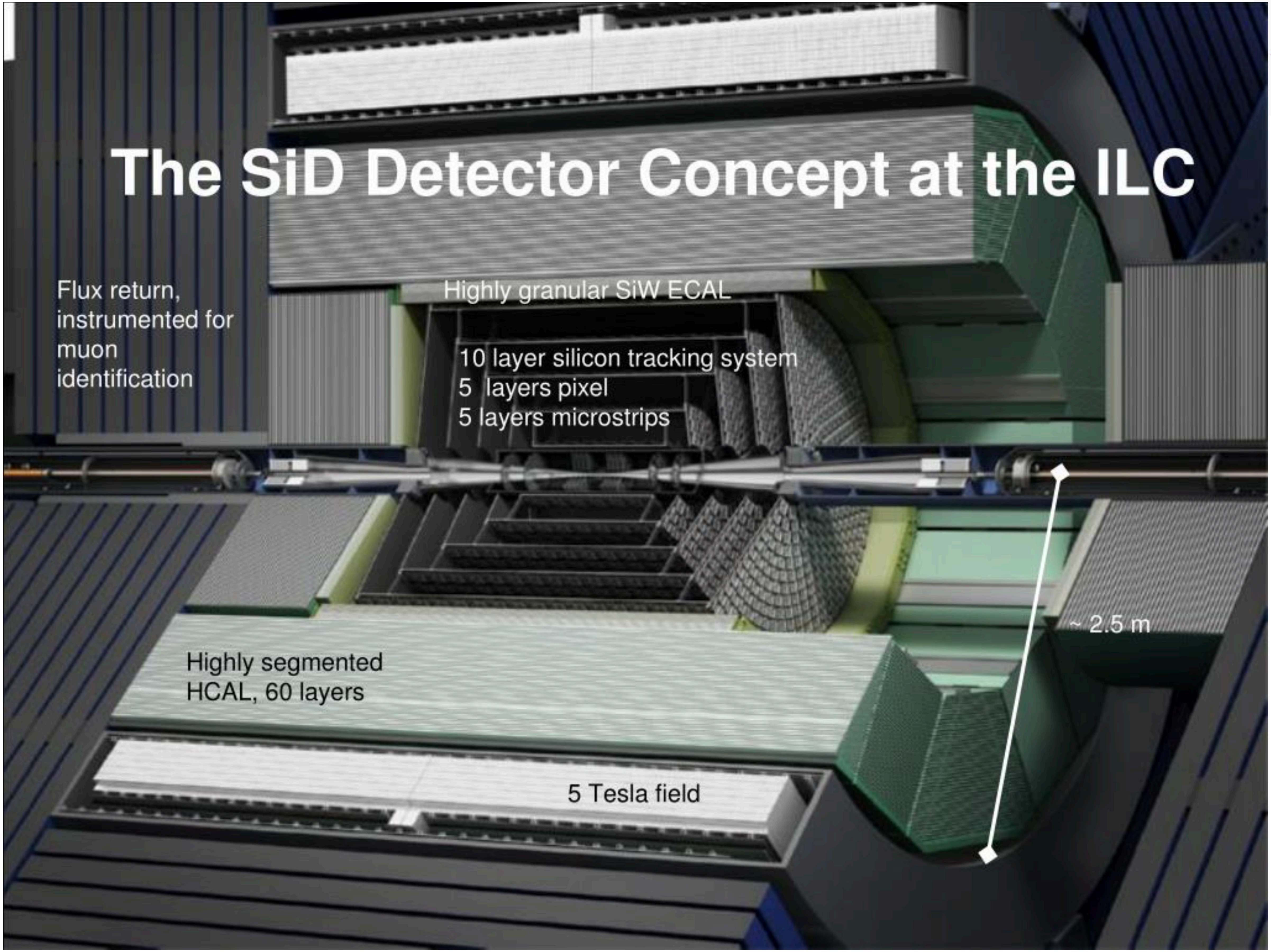


The Cool Copper Collider (CCC / C3) Accelerator

Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
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
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014

- C3 is an advanced accelerator design using cryogenic copper to achieve improved acceleration gradients
- Improved power efficiency using high-frequency RF
- Long. beam polarization - exploit handedness for improved systematics
- Significantly reduced footprint - 8km @ 250 / 550 GeV
  - In my opinion a sustainable direction for our field (smaller is always more sustainable)

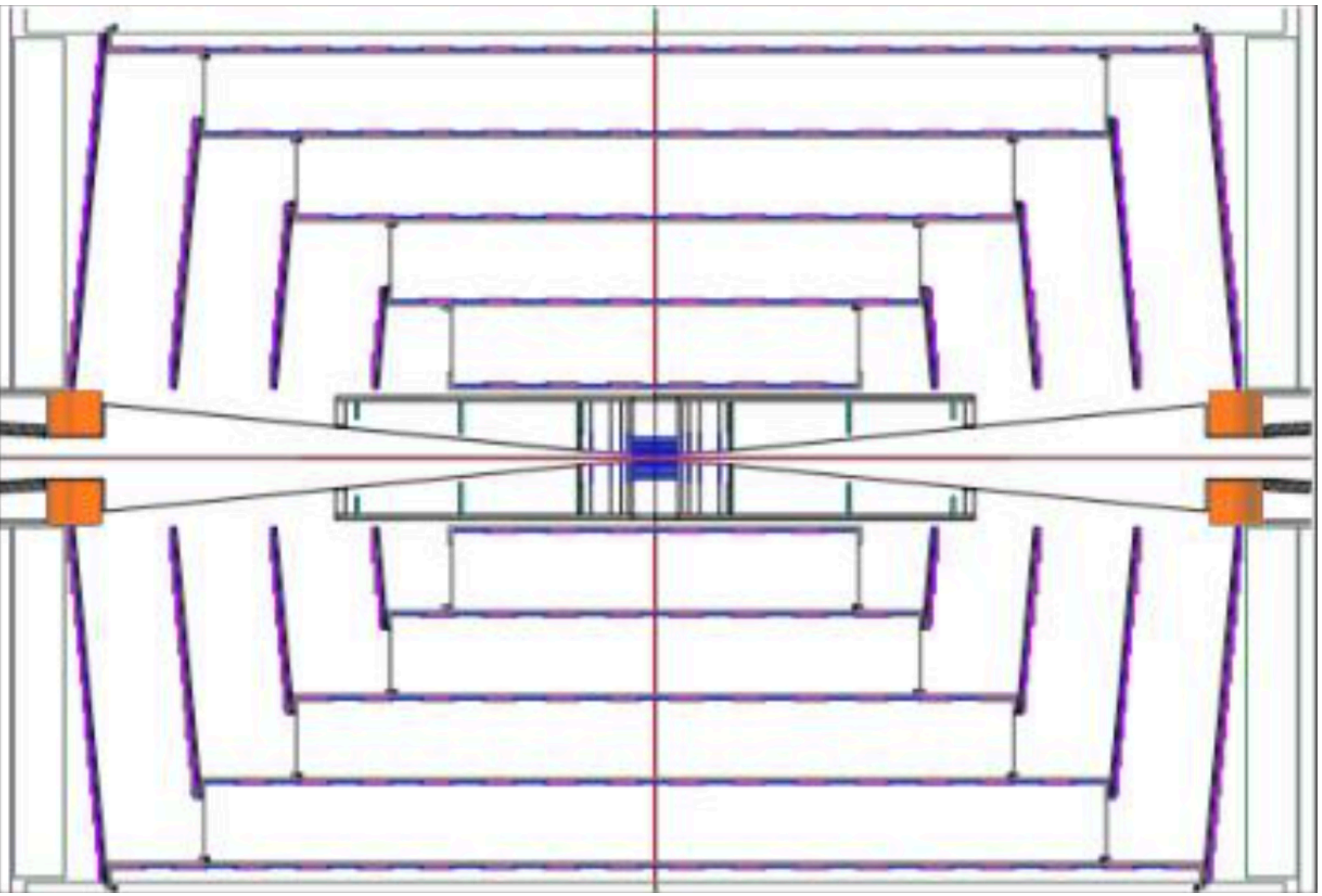
The SiD Detector Concept at the ILC

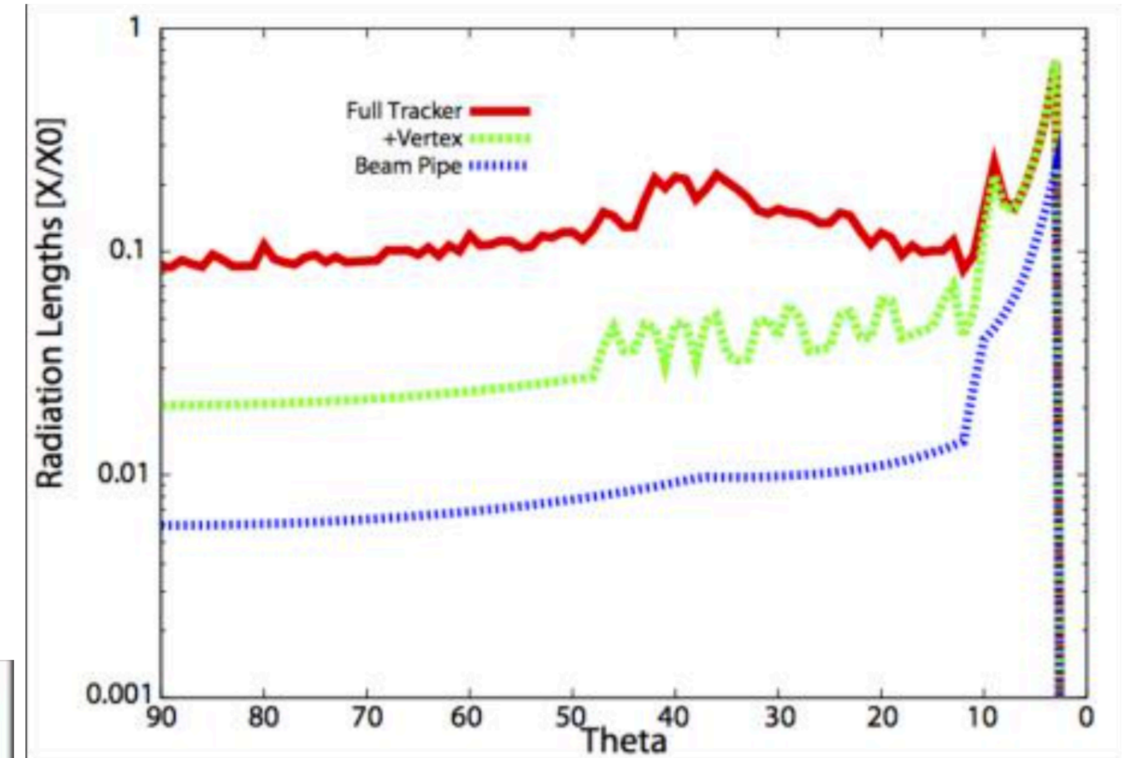


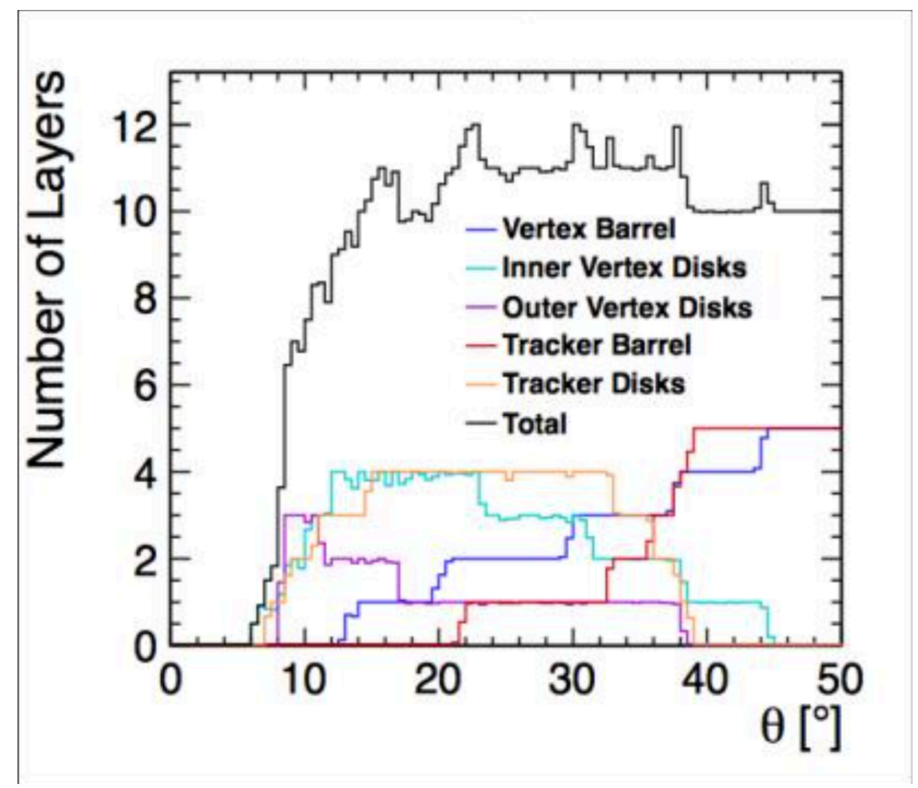
(J. Strube)

SiD Tracking

- Low material budget design to minimize error on track sagitta (~pT resolution)
- Exploits thin sensor and low-mass cooling
- Aim to optimize vertex detector for C3 environment
  - requires complete background simulation



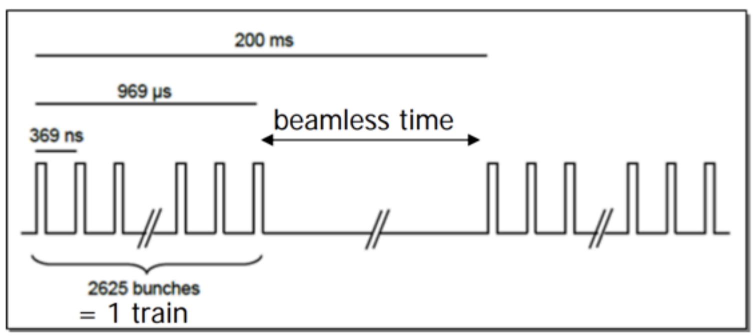




Performance

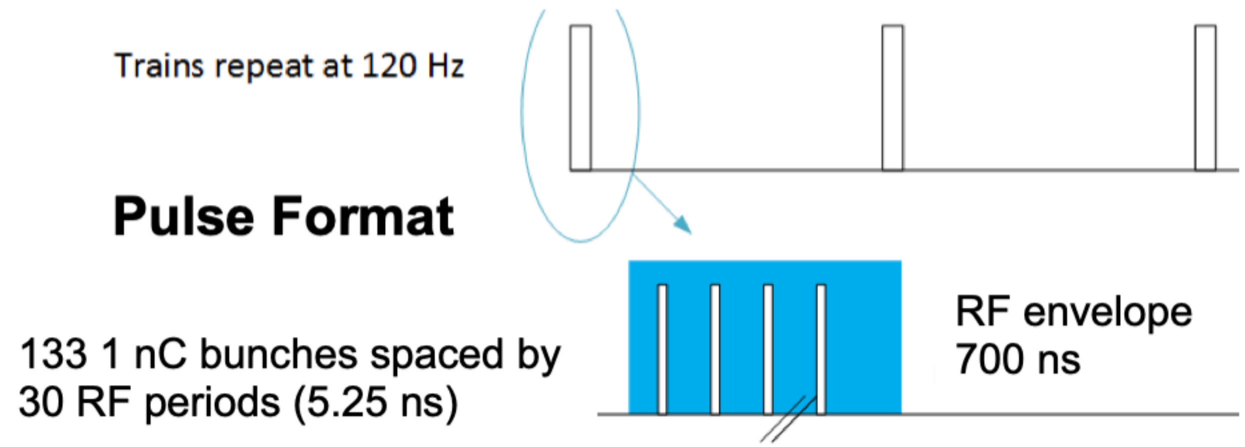
- There are extremely detailed performance calculations in the ILC TDR
  - However, C3 has a radically different bunch structure from ILC

ILC timing structure



1 ms long bunch trains at 5 Hz
2820 bunches per train
308 ns spacing

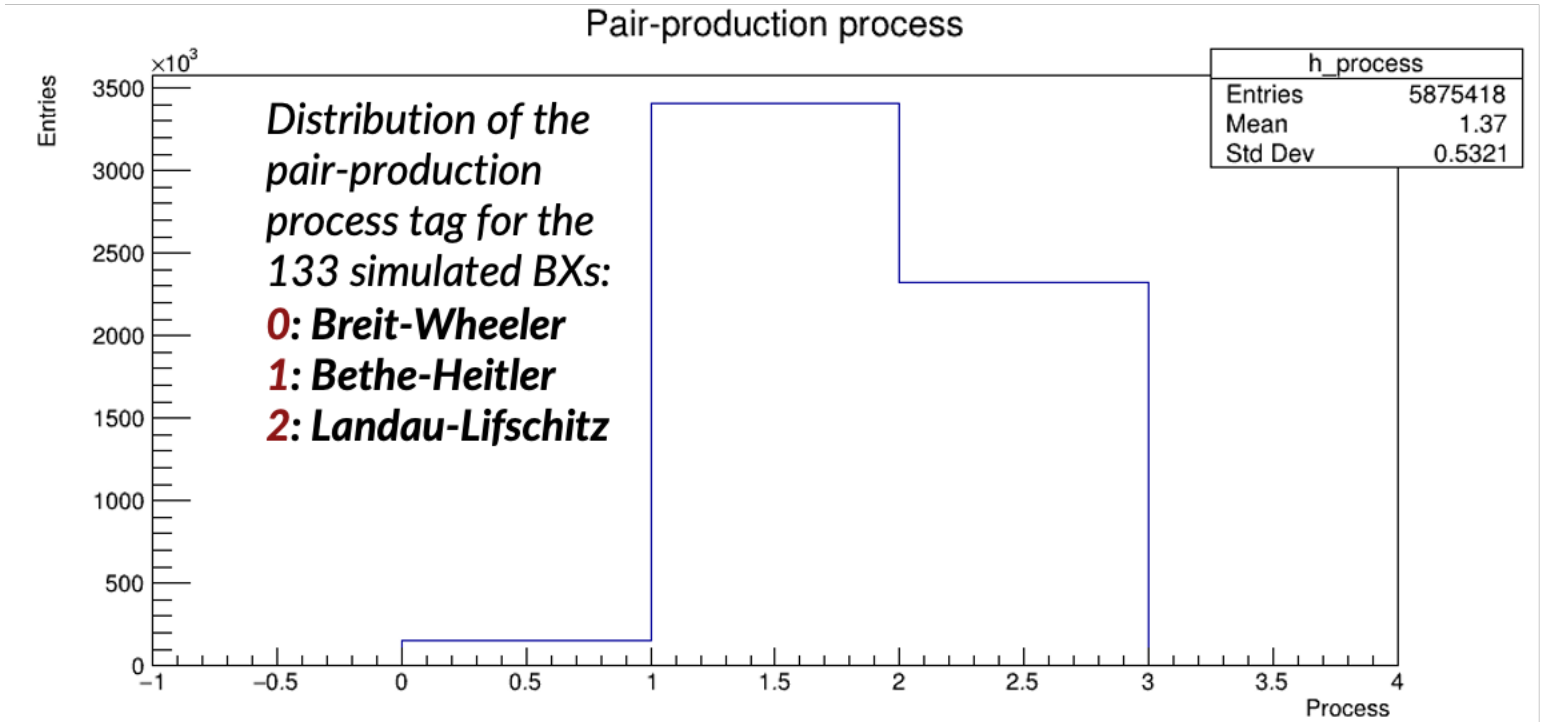
C³ timing structure

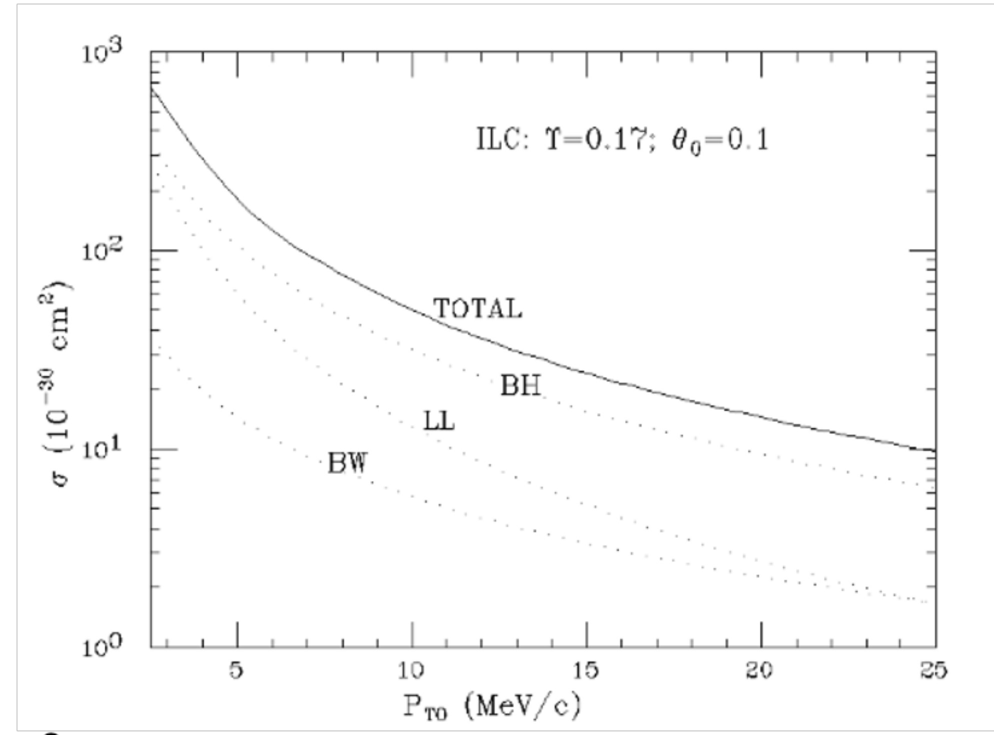


- Time structure and electronics needs at low level are different
  - But the overall concepts are similar, and technologies from LHC can deal with the 70x smaller bunch spacing (because of the 120 Hz repetition rate!)
  - Modern clocking and timing performance means that C3 ~ ILC/10 where beam-based background's impact on performance considerations are concerned

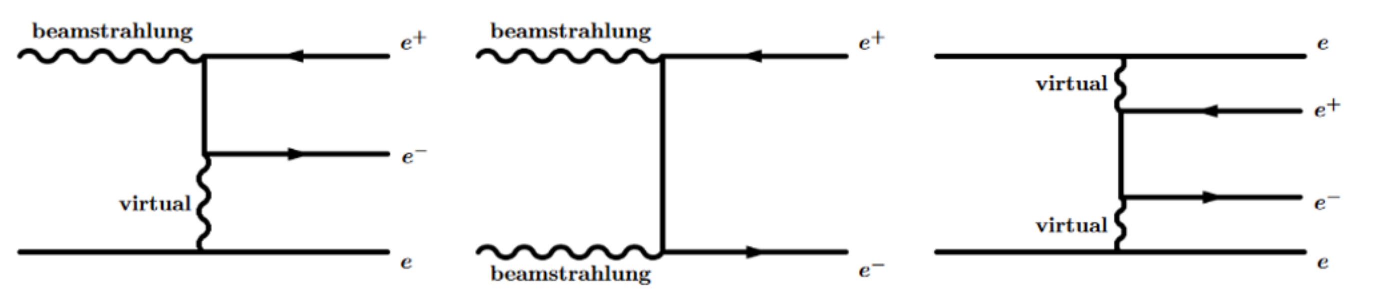
- So first -> what are those backgrounds? How do we estimate them?

Electron-positron Pair Backgrounds





Source: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.44.2209&rep=rep1&type=pdf



(a) *Bethe-Heitler* (b) *Breit-Wheeler* (c) *Landau-Lifschitz*

Source: https://bib-pubdb1.desy.de/record/405633/files/PhDThesis_ASchuetz_Publication.pdf

- This background comes from the generation of virtual photons as bunches pass through each other or from hard bremsstrahlung
- To simulate the pair background we use the Guinea-Pig (GP) program
  - As configured for this study, simulates the primary production modes production of e^+/e^- pairs from beam and beamstrahlung initiated backgrounds
  - There are additional handles for hadron photoproduction but GP's implementation is known to be inaccurate (work beginning on more accurate simulation, that we will discuss later)

Hadron Photoproduction: Spectra and Generators

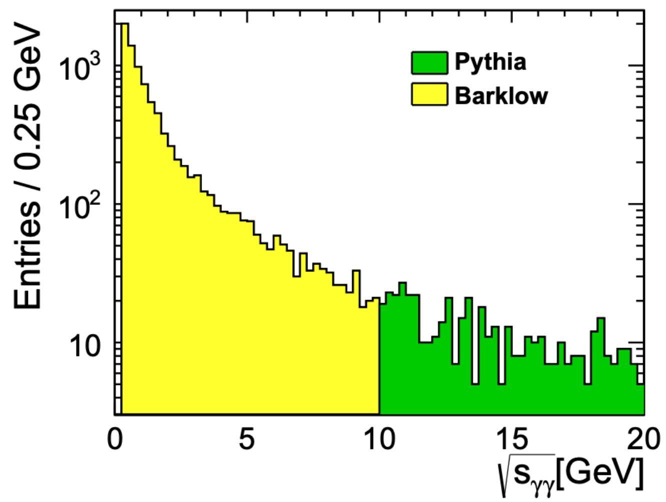


FIG. 1: Energy spectrum of $\gamma\gamma \to$ low p_T hadron events as a function of centre-of-mass energy. The figure shows the energy cutoff of 10 GeV below which the events are generated by the Barklow generator. Above 10 GeV the events are generated by Pythia.

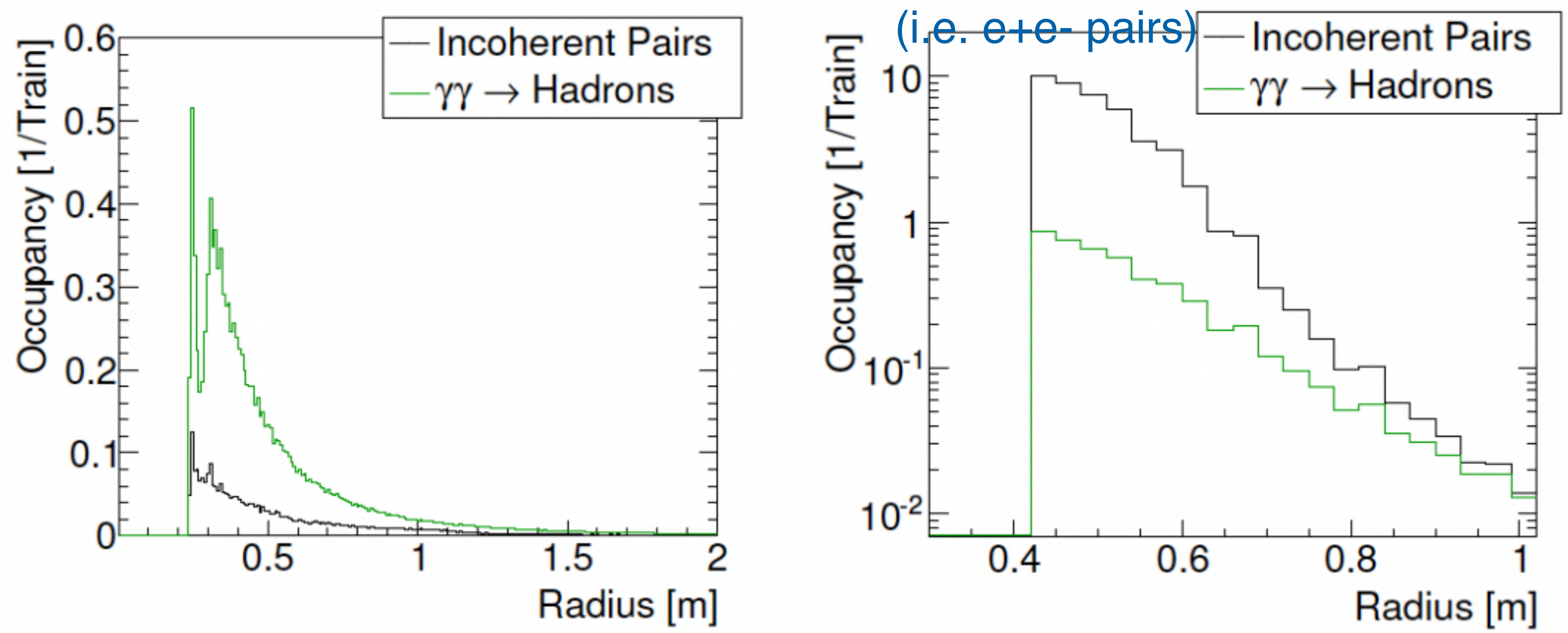


Figure 14. The radial distribution of the train occupancy per pad in ECal (left) and per cell in HCal (right) endcap [10].

- Hadron Backgrounds in Pythia5.7 -> Pythia8, Latest Whizard and CIRCE
  - Presently at the step of generating the appropriate background mixture from estimated virtual photon flux (re-achieve upper left plot!)
  - Not mixed into pileup in this talk, but very soon!
  - Will share configs and workflows with wider community
- See D. Ntounis' talk on beam induced backgrounds at C3 for further details
- Accelerator muon background also being pursued
  - First reproducing muCarlo-based results for ILC
  - Plan to migrate to modern accelerator modeling tools e.g. Fluka

Necessary inputs to calculate background

- Input values to simulation derived from C3 optics and dynamics simulations @ 250 GeV CoM
  - Started this project with some guesses due to incomplete information
  - Now have complete configuration of the machine from background simulation perspective
- Note that bunch/repetition structure at C3 different from ILC

Parameter	Units	Value
β_x^*	mm	12
β_y^*	mm	0.12
$\epsilon_{N,x}^*$	nm	900
$\epsilon_{N,y}^*$	nm	20
σ_x^*	nm	210.12
σ_y^*	nm	3.13
σ_z^*	µm	100
n_b		133
f_{rep}	Hz	120
N		$6.25 \cdot 10^9$
θ_c	rad	0.014

- The emittances on the table are normalized. The transverse beam size is calculated as:

$$\sigma_{x,y}^* = \sqrt{\epsilon_{x,y}^* \beta_{x,y}^*} = \sqrt{\frac{\epsilon_{L,x,y}^* \beta_{x,y}^*}{\gamma}}\ ,\ \gamma = \frac{E}{m_e c^2} = \frac{\sqrt{s}}{2 m_e c^2}$$

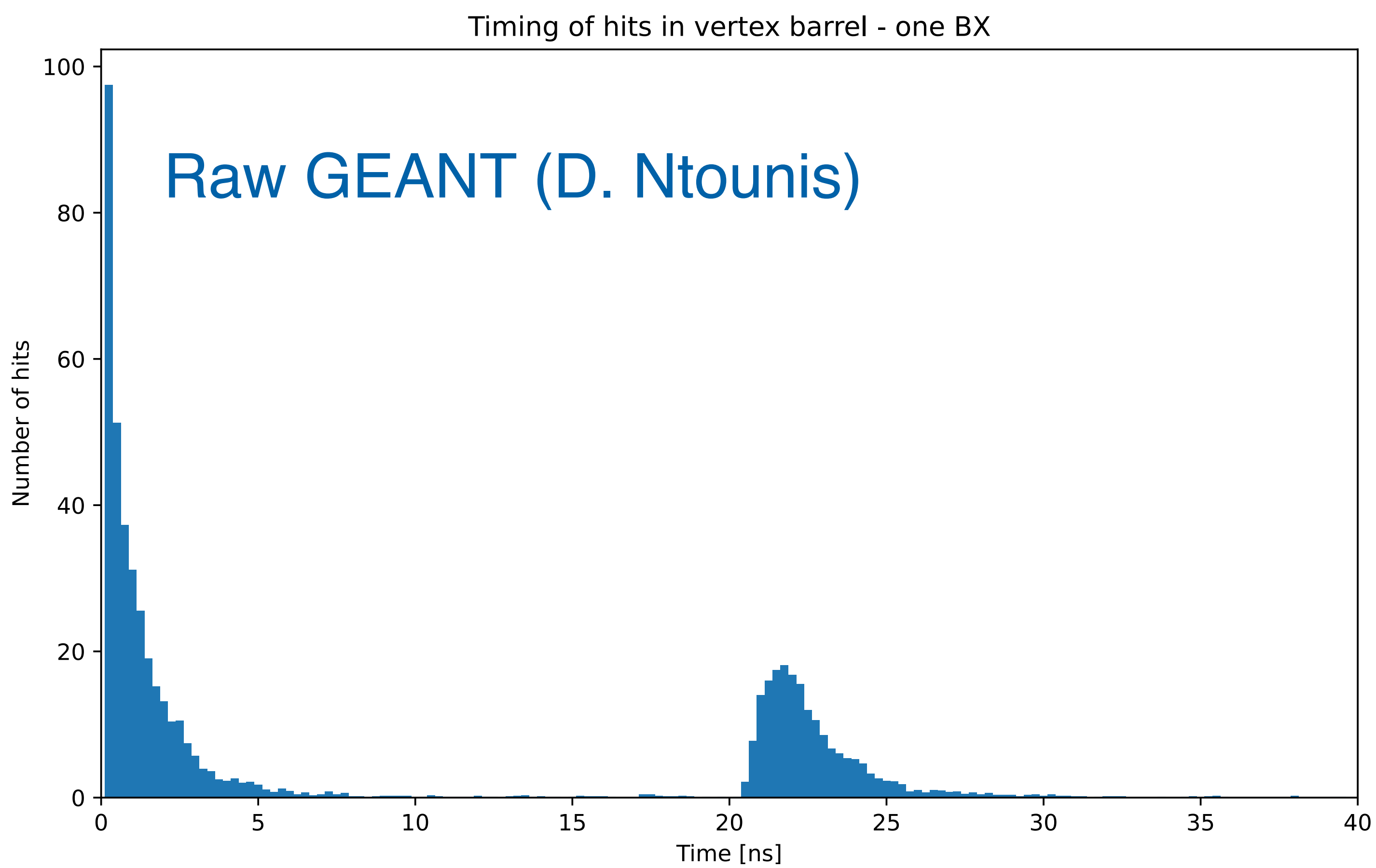
	Initial Tests	Emilio's Values
Energy spread	0.1%	0.3%
Energy spread distribution	Gaussian	Flat
Offset in x direction (nm)	0	5
Offset in y direction (nm)	0	0.2
Waist shift in x direction (µm)	0	0
Waist shift in y direction (µm)	0	0
Crossing angles (not compensated by crab scheme)	0	0

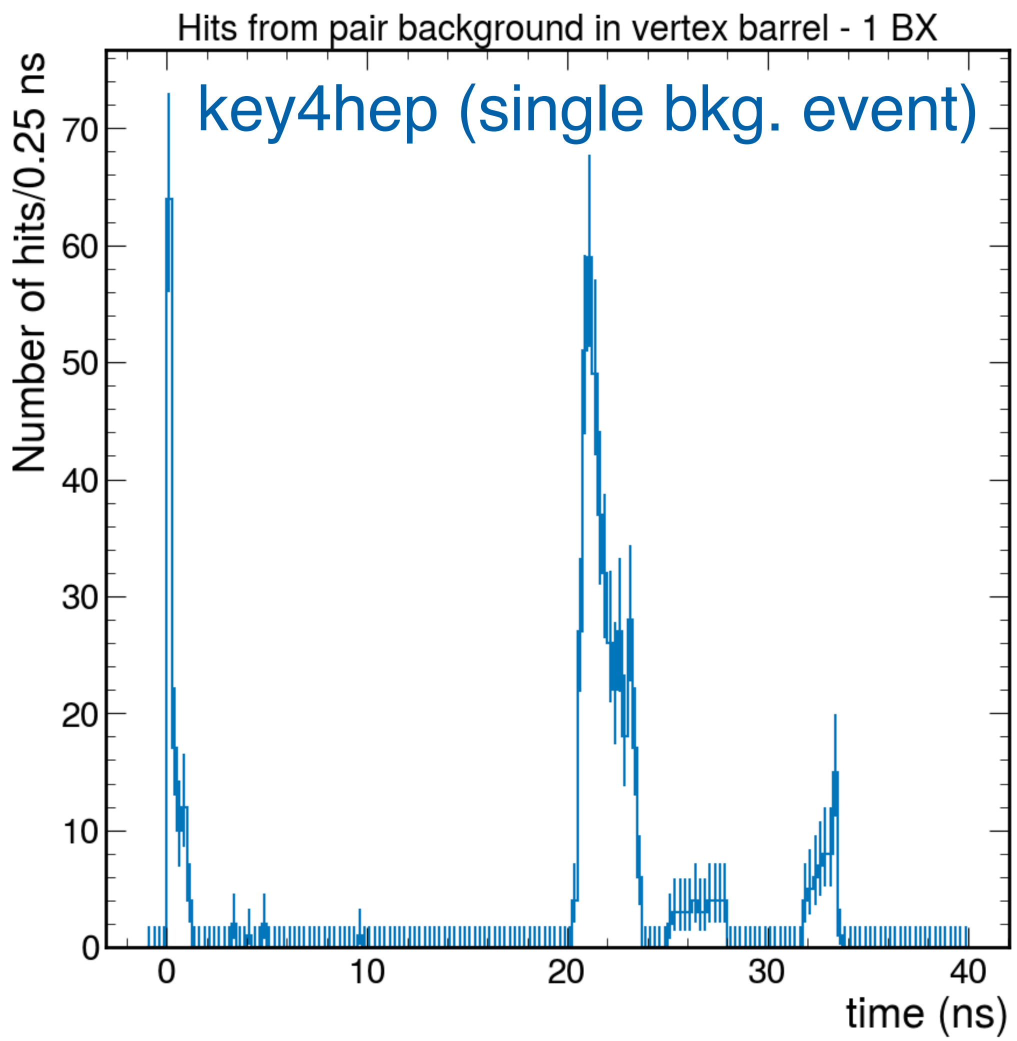
Pileup Mixing Workflow

- Generate input events with guineapig++ matching C3 beam parameters
- Propagate pileup events with GEANT writing out EDM4HEP
  - For some reason ddsim with slcio output will not save all sub-detectors
  - Convert edm4hep to slcio files for input into OverlayTimingGeneric Marlin Processor
  - Complete bunch train of 133, taking care on random seeds, etc.
  - 1h30m on batch
- Generate signal event, Z(mu mu)H(anything), using latest Whizard with beam spectra modified by C3-configured Circe2
- Using key4hep wrapped OverlayTimingGeneric module
  - Pass edm4hep signal as key4hep input, slcio background files as inputs to OTG
  - 700ns accumulation window (full train)
  - only mix tracking detectors and generator particles, otherwise out of memory
  - Physics event placed in exact center of bunch train, further generations will randomize

- This took multiple tries of varying parameters to get a (mostly) correct event overlay
  - It produced one physics event for scrutiny with a total turn around time of ~3 hours per event (including job submission lag and file conversion time) and does not include hadron photoproduction or accelerator muon backgrounds

Results: e+ e- pair background





- Qualitative timing structure of simulated hits for a single event preserved in key4hep
  - Prompt peak and BeamCal backsplash visible in same locations
- In overlay GEANT sim-hit times are shifted by BX offset for backgrounds and scanned over position in the bunch train

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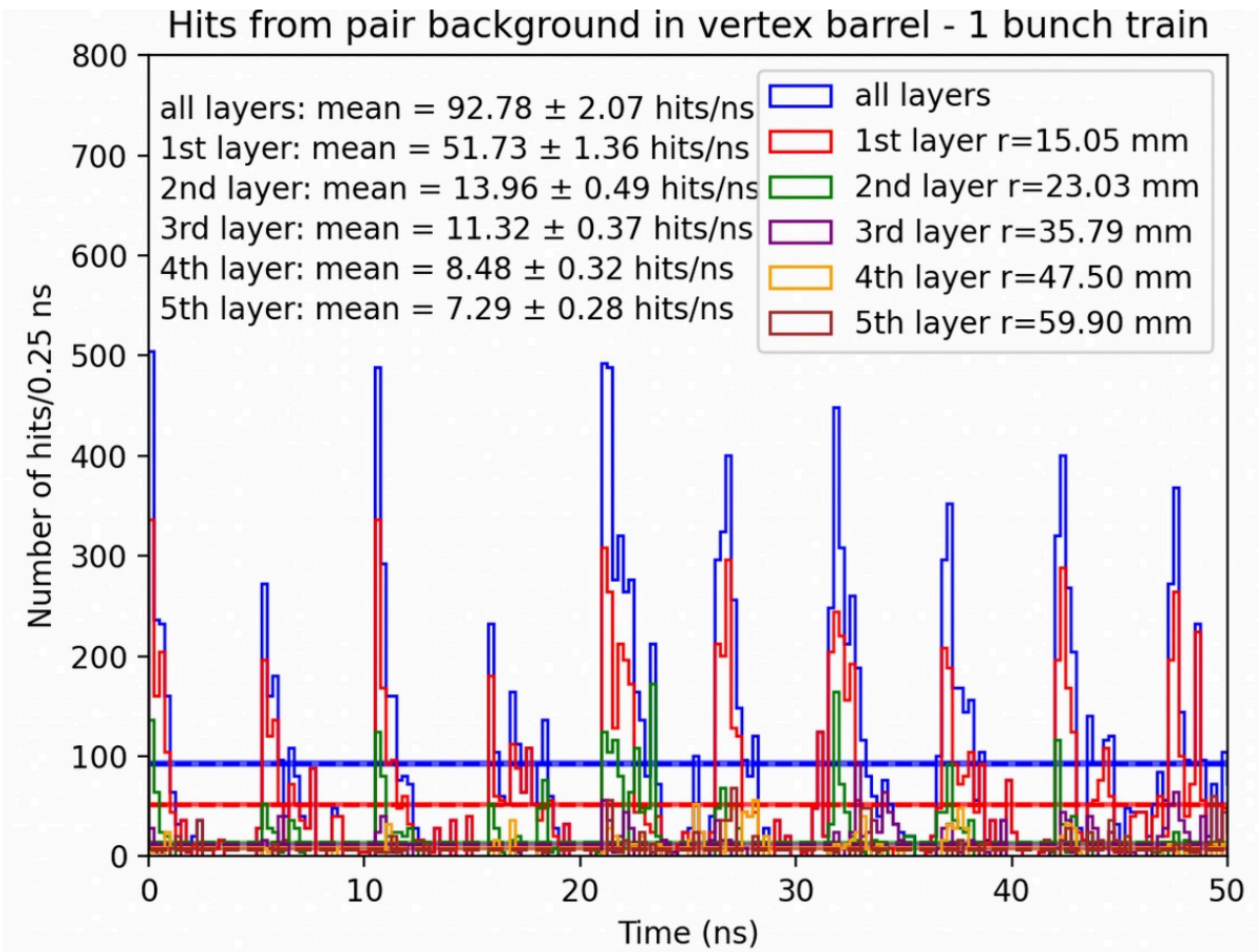
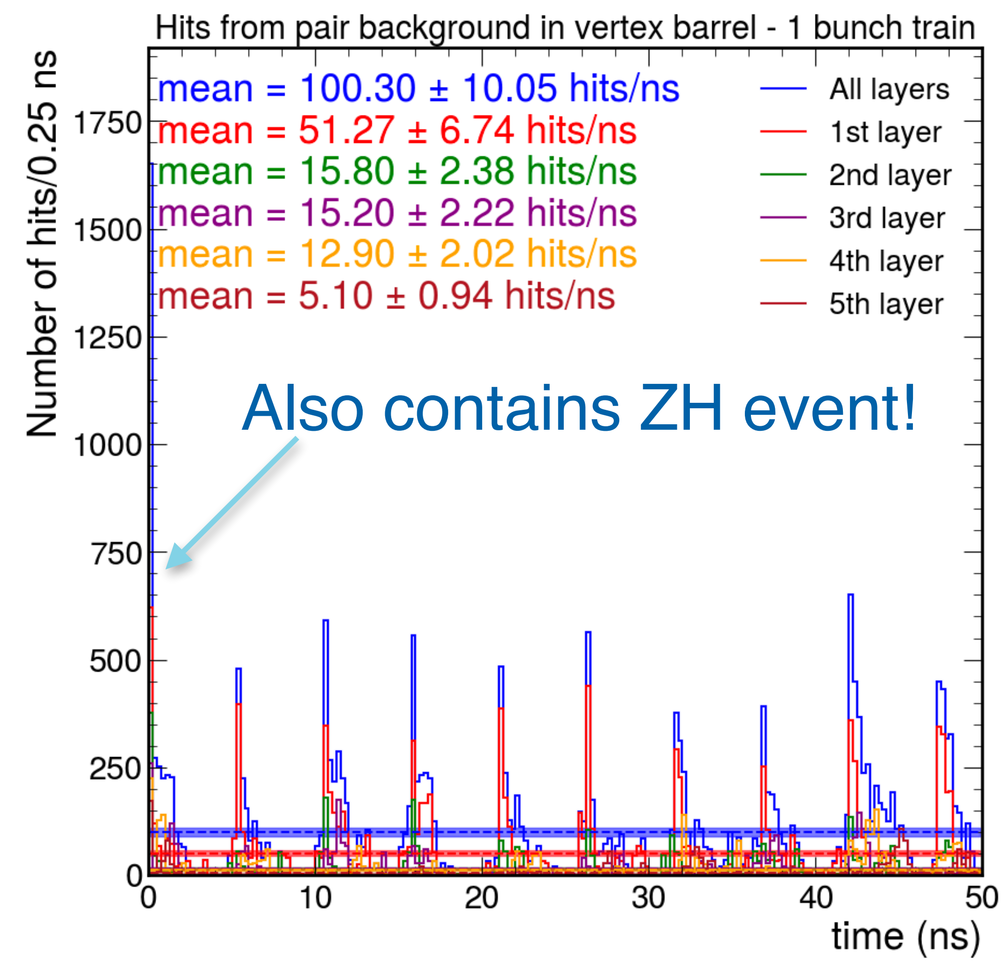
Results: overlay

GEANT overlay by hand (D. Ntounis)



key4hep marlin-wrapper overlay



- Statistical compatibility between GEANT and key4hep results
  - PU mixing order of key4hep different from GEANT
- Effect of ZH event in center bunch crossing clearly visible
  - Subsequent bunch crossings are manifestly less occupied

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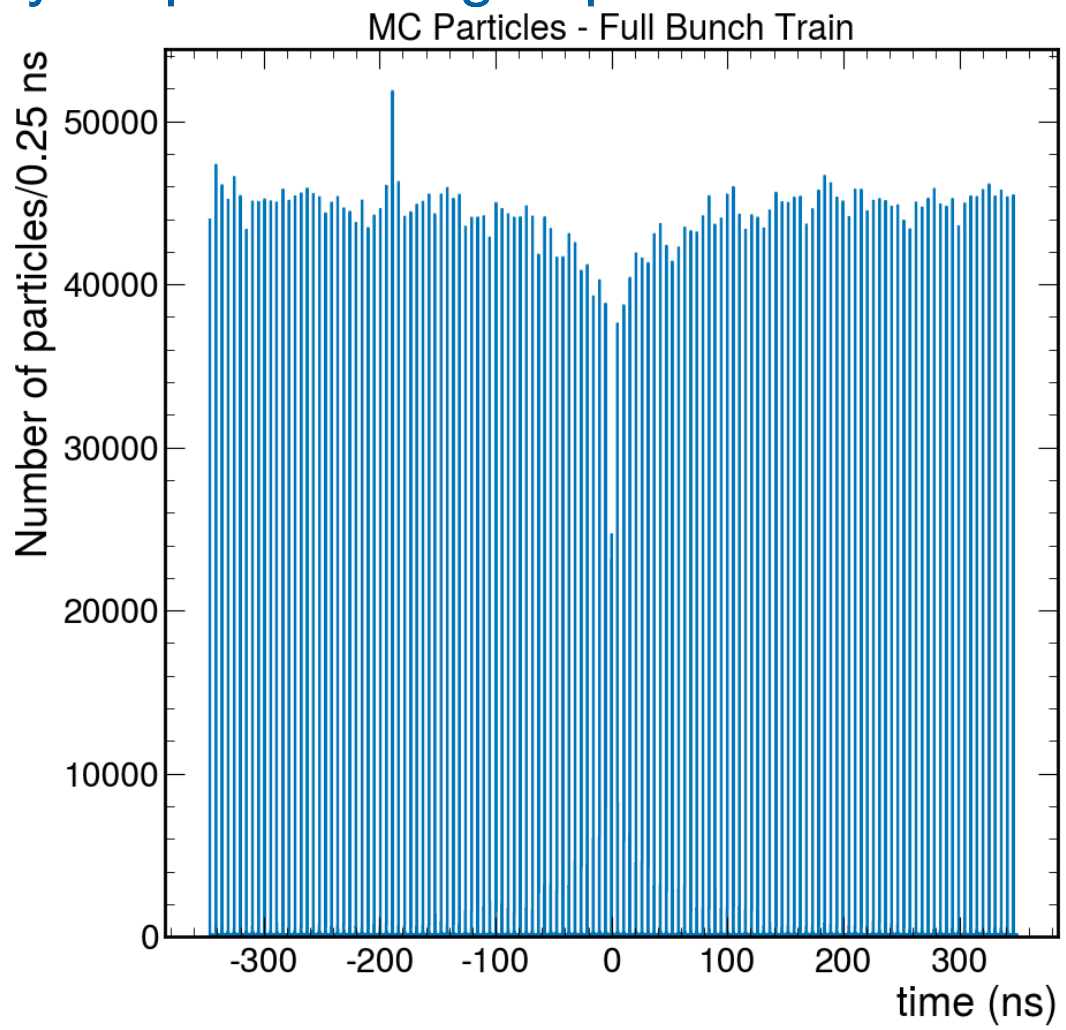
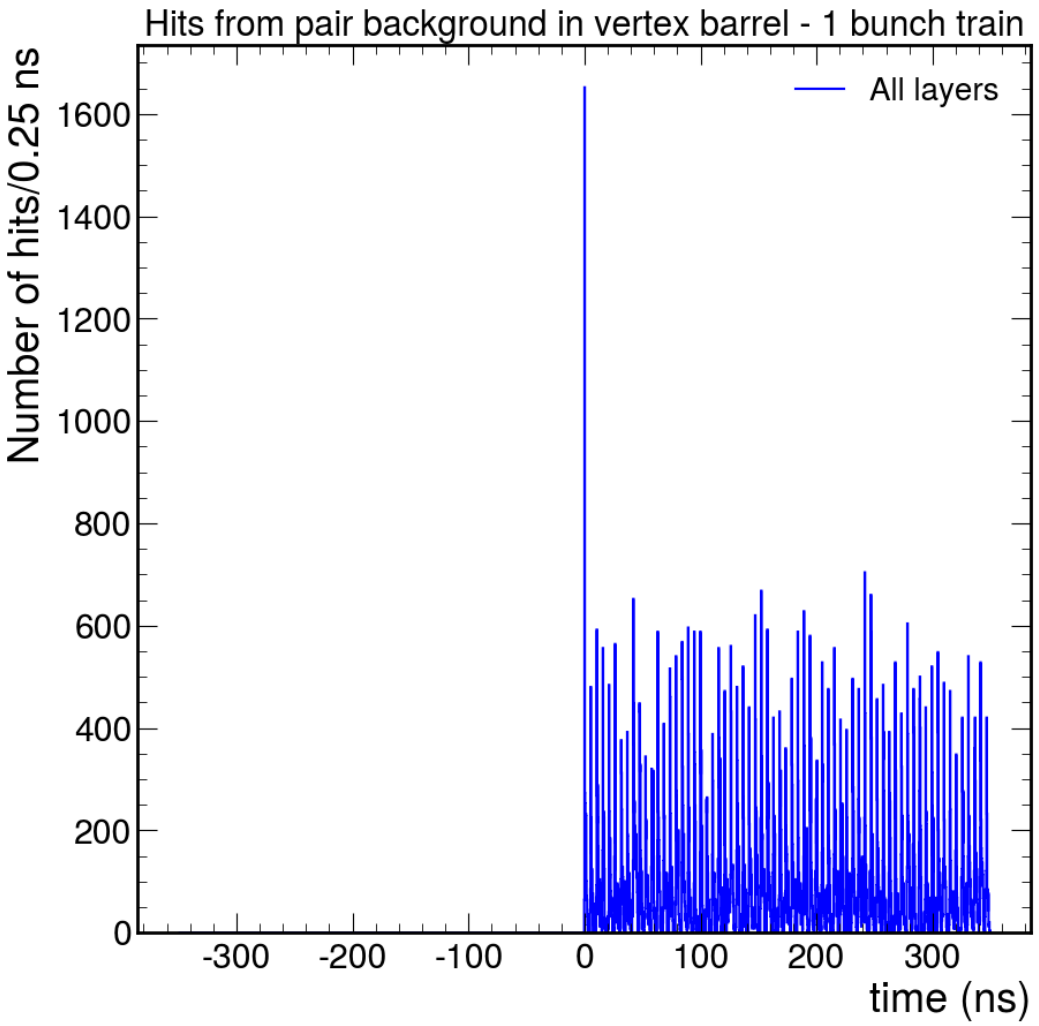
Results: bugs :-(

key4hep overlaid gen particles



key4hep overlaid sim-hit times



- Full range of bunches seen in MC particles but not in simhits time?
  - Deficit of sim particles near physics event bunch (t = 0) needs investigation
- Regardless of accumulation window sim hit accumulation seems to start with physics BX?
  - Cannot simulate occupancy of per-bunch-train readout in this case!
  - Intend to fix issue and retry!

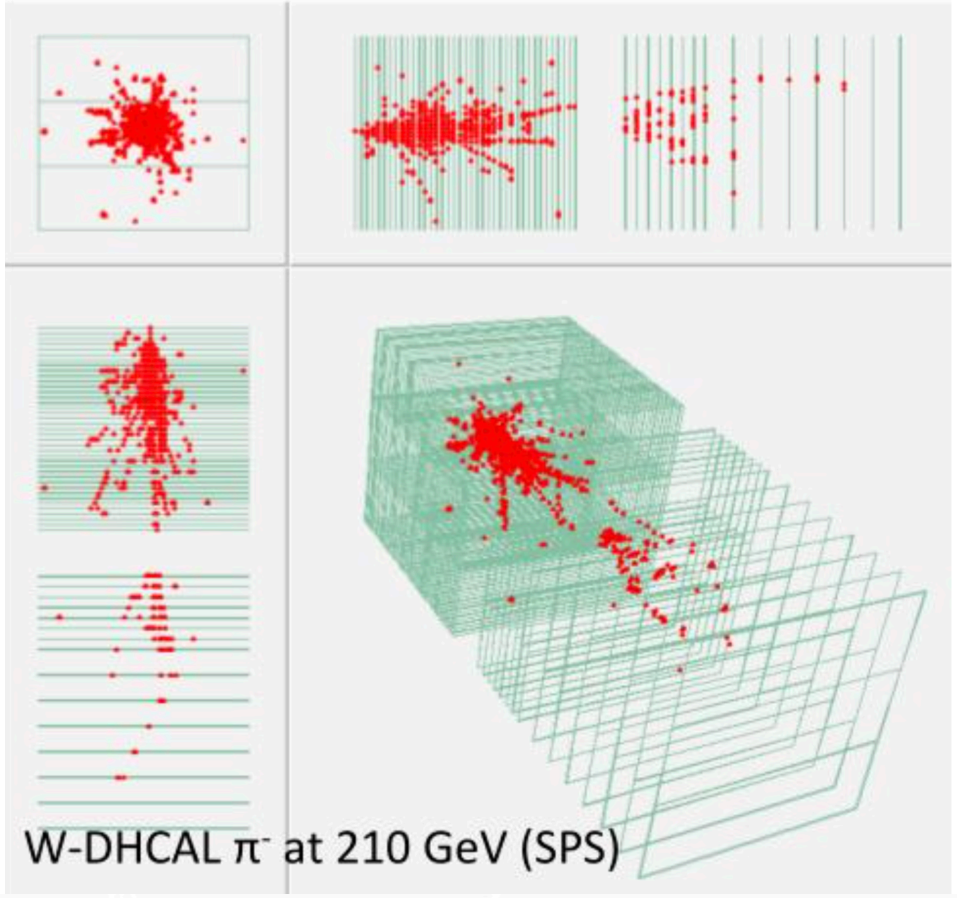
Conclusions

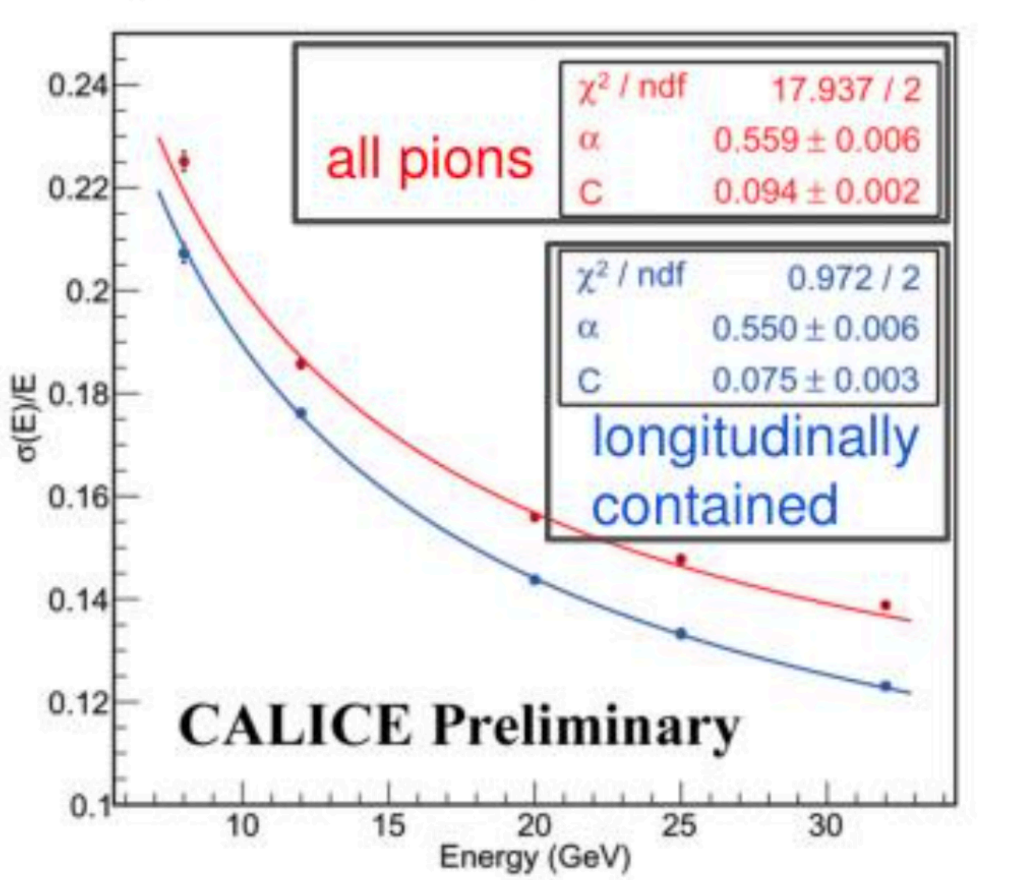
- Have successfully simulated a single full bunch train of C3 with key4hep
  - Only e+/e- incoherent pair production at Higgs Factory energies
  - Lots to understand even from one event with partial backgrounds
  - Hadron and muon backgrounds are on the way - show stoppers cleared and understanding reached
- Encountered a number of impedances to further MC production
  - Memory usage of GEANT and mixing module when using key4hep outputs
    - Limited to only simulating tracker when considering large number of bunches
    - Seems to be a strange interaction with docker-based batch queues
  - Simulation time presently troubling, 1h30m on batch for 50k particles per BX
    - Mostly down beam pipe but initial toying with production cuts noticeably alters occupancy
    - We can probably do better here!
  - Mixing module does not seem successfully deal with BXs in train that precede physics event? (if only this were possible in reality, our jobs would be much easier!)
- We intend to keep using key4hep in collaboration with ECFA and produce together a high quality product
  - Since we are simultaneously modernizing many aspects of event generation while doing this we intend to reproducibly share our findings and recipes with other collider concepts

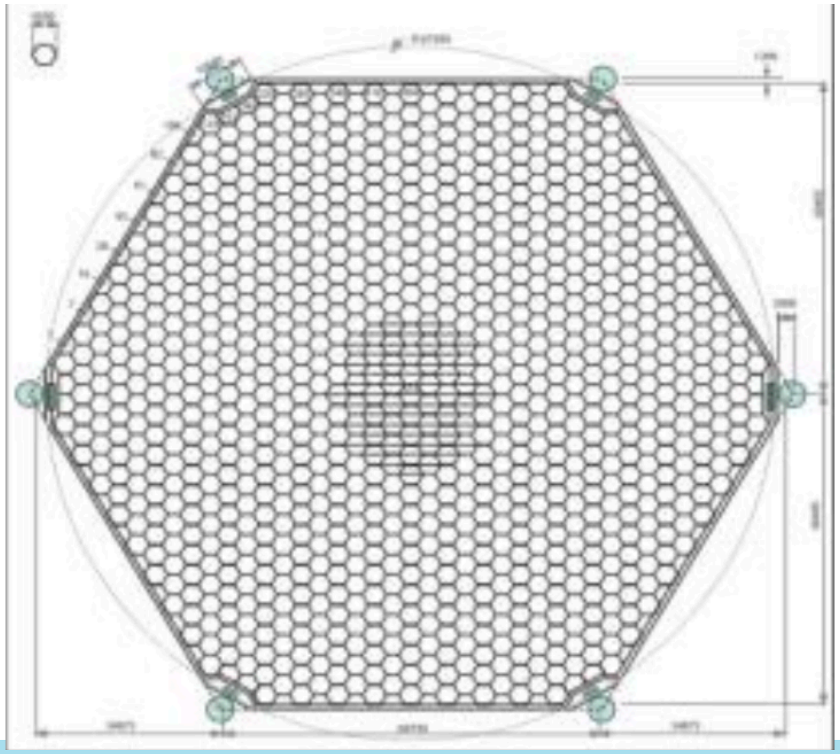
Extras

SiD: Calorimetry

- ECAL: Silicon/tungsten sampling calorimeter
  - 30 layers of hexagonally tessellated sensors
    - sound familiar?
  - MAPS also entering the game
- HCAL: Variety of technologies considered
  - High granularity a focus
  - Glass RPC, SiPM + tile, Micromegas, GEMs
  - Performance numbers predate and are similar to present state-of-the-art HGCAL







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SiD: Muon System

- Scintillator bars + SiPM readout via wavelength-shifting fibers
  - CMS proposed this technology for calorimeter upgrades
  - Cross-hatched design allows localization of muon tracks
  - Excellent discriminator for hadronic activity