CCC Fundamentals and Simulation Tools

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Colliders of Tomorrow
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Overview

- The C3 Accelerator
- The SiD Detector
- Accelerator generated backgrounds
  - Electron-positron pair production
  - Hadron photoproduction
  - Muon generation from accelerator system
- Demonstrations
  - GuineaPIG++
  - Pythia 8 for energetic hadron photoproduction
  - Running GEANT on above outputs, where available
- Near term plans, and future directions

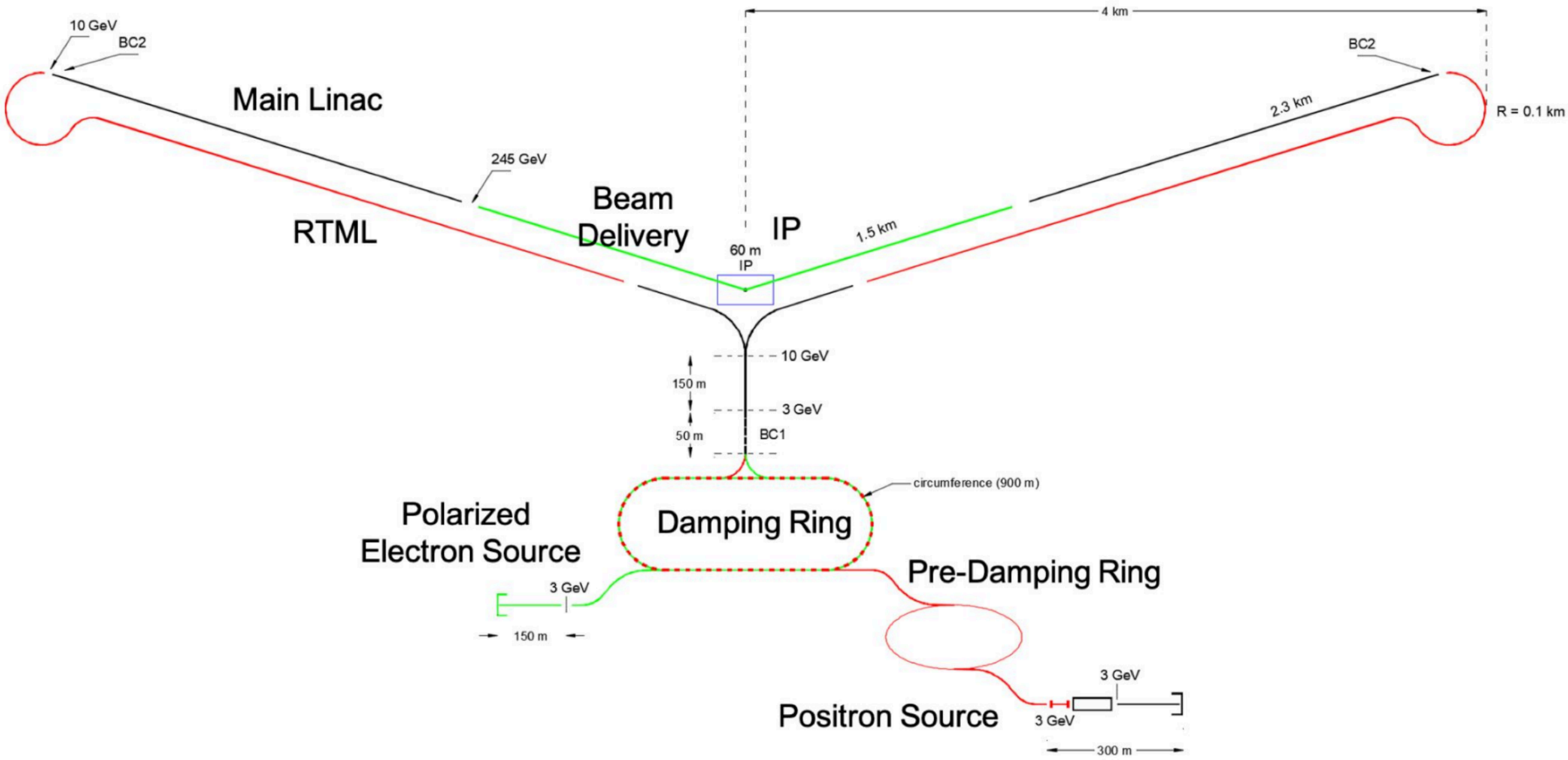
The Cool Copper Collider (CCC / C3) Accelerator

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

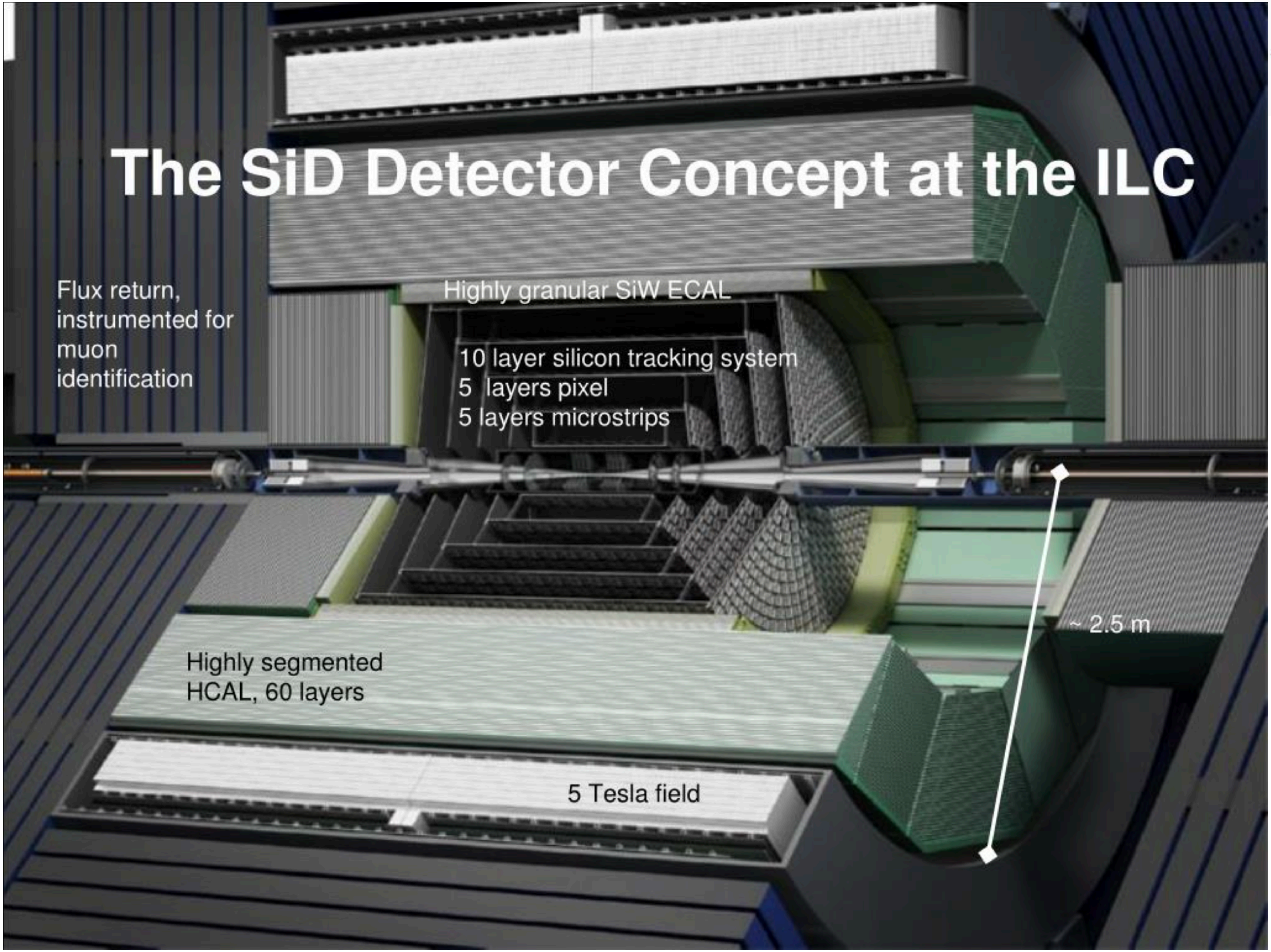
- C3 is an advanced accelerator design using cryogenic copper to achieve improved acceleration gradients
- Improved power efficiency using high-frequency RF
- Long. beam polarization - exploit handedness for improved systematics
- Significantly reduced footprint - 8km @ 250 / 550 GeV
  - In my opinion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

The Cool Copper Collider (CCC / C3) Accelerator

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



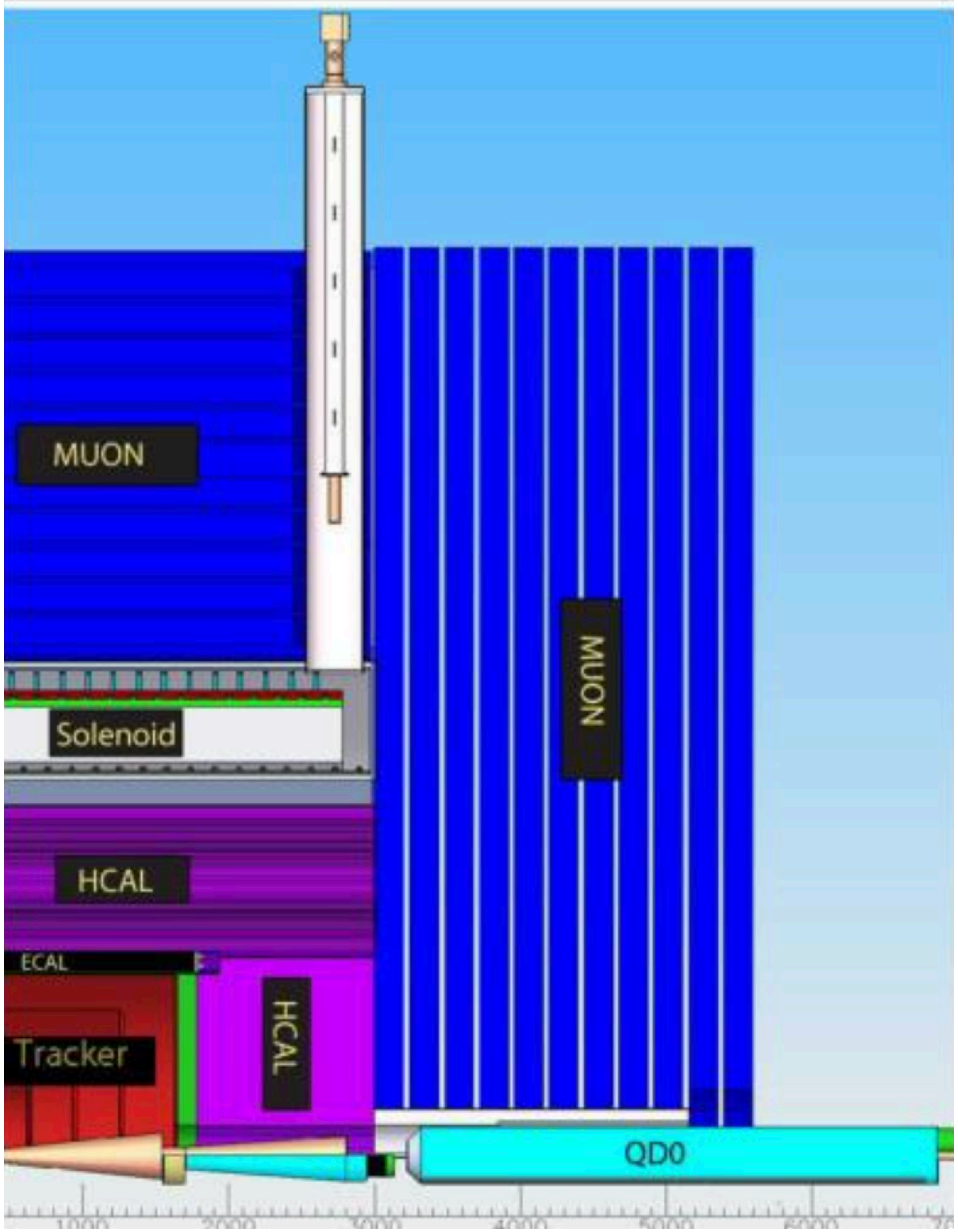
The SiD Detector Concept at the ILC



(J. Strube)

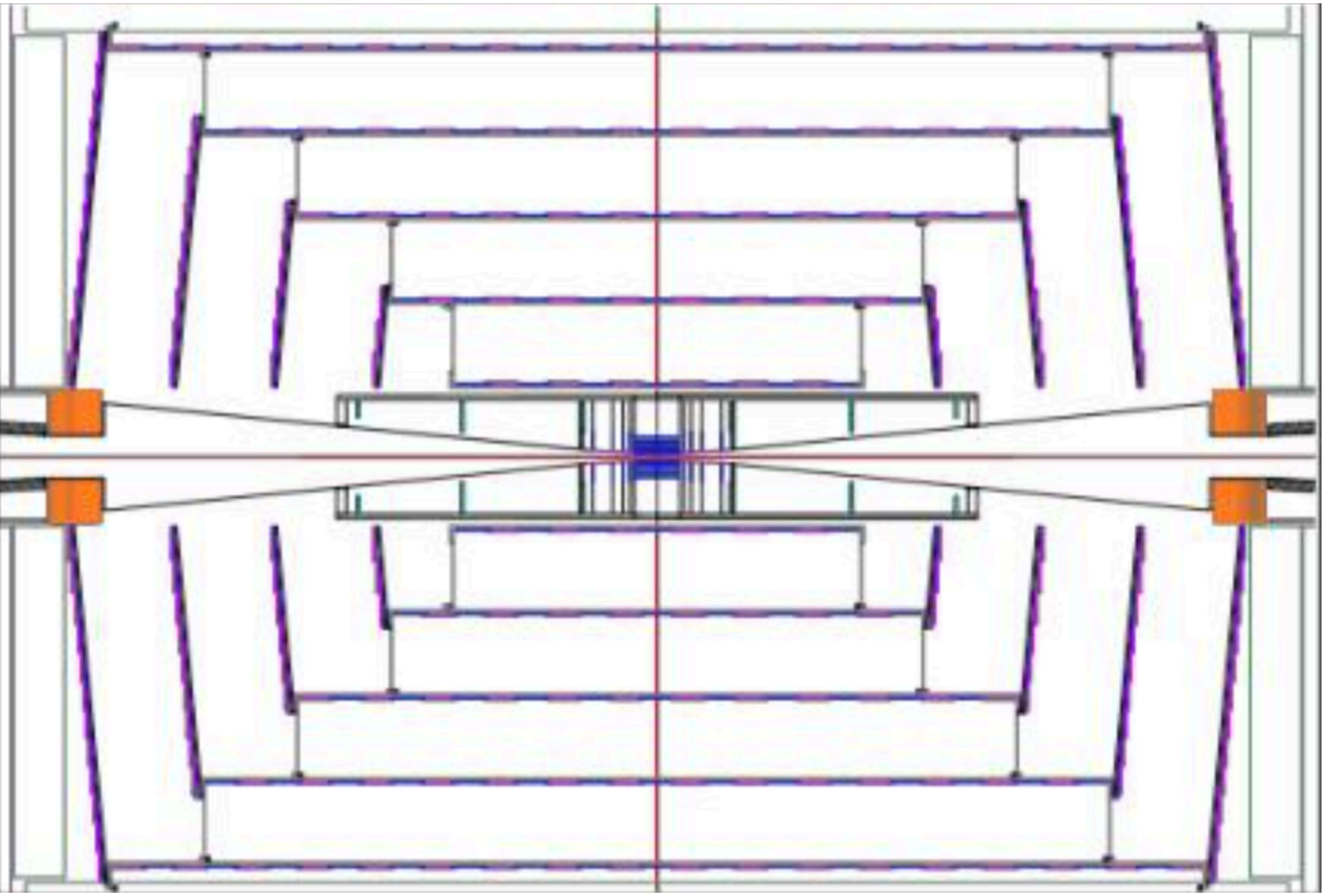
SiD: Cross sectional view by functionality

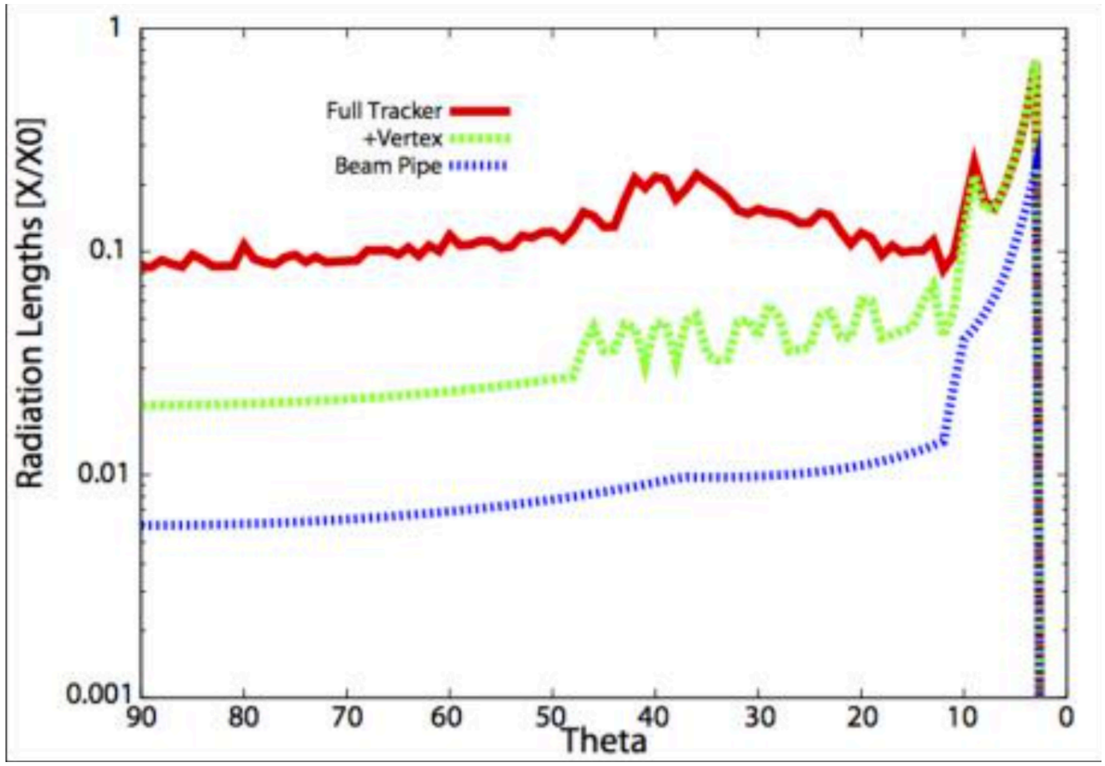
- Compact design reminiscent of CMS in topology
  - Looks more similar to phase 2 CMS in terms of detector technologies
  - Some radically different
- Tracking implementation based around sensor-asic integration
  - Only innermost pixels require moderate radiation environment considerations
  - Minimize material
  - Minimize power budget
- Calorimetry (ultra) high-granularity
- Muon system focused around tagging
  - Minority redundant momentum measurement
  - Punch-through veto capability

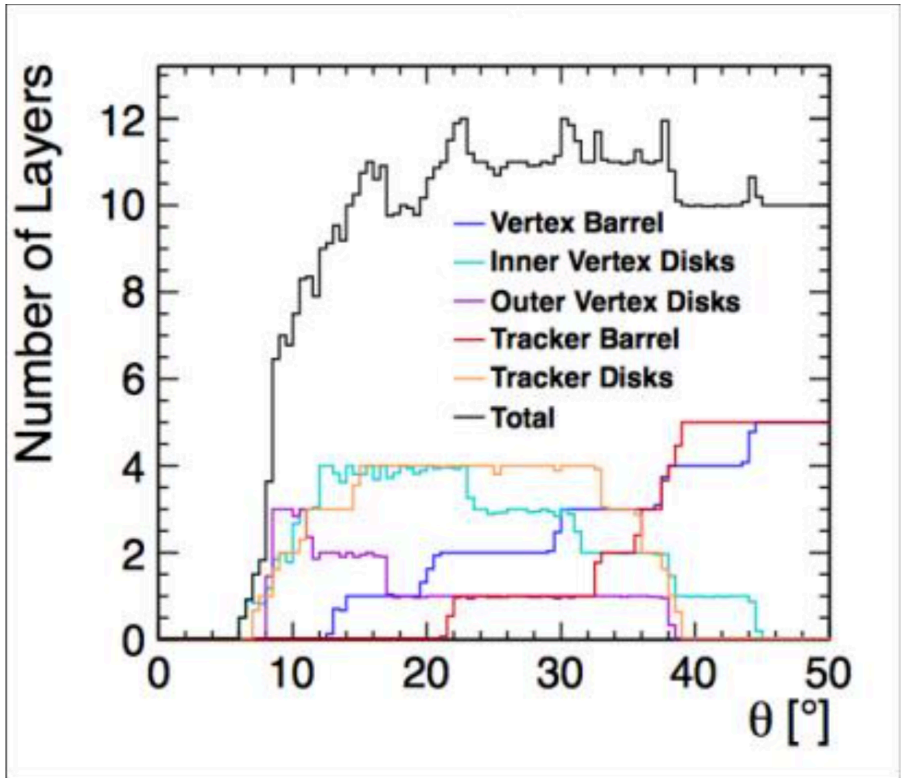


SiD Tracking

- Low material budget design to minimize error on track sagitta (~pT resolution)
- Exploits thin sensor and low-mass cooling

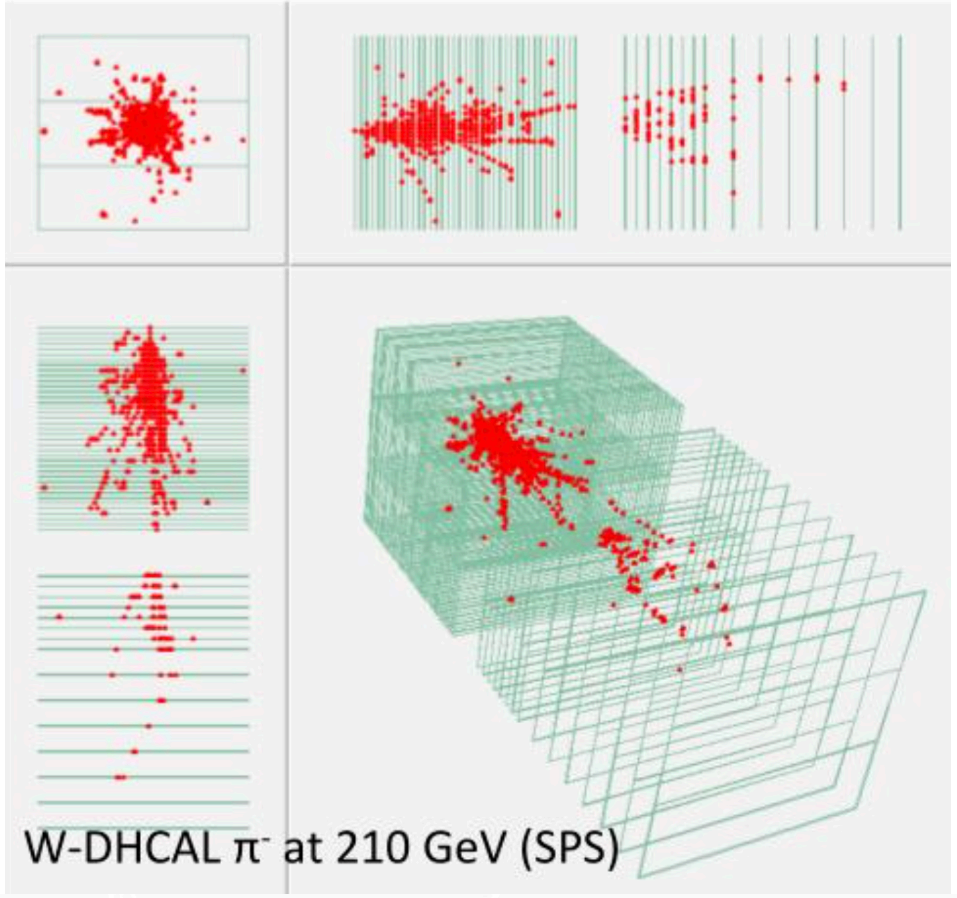


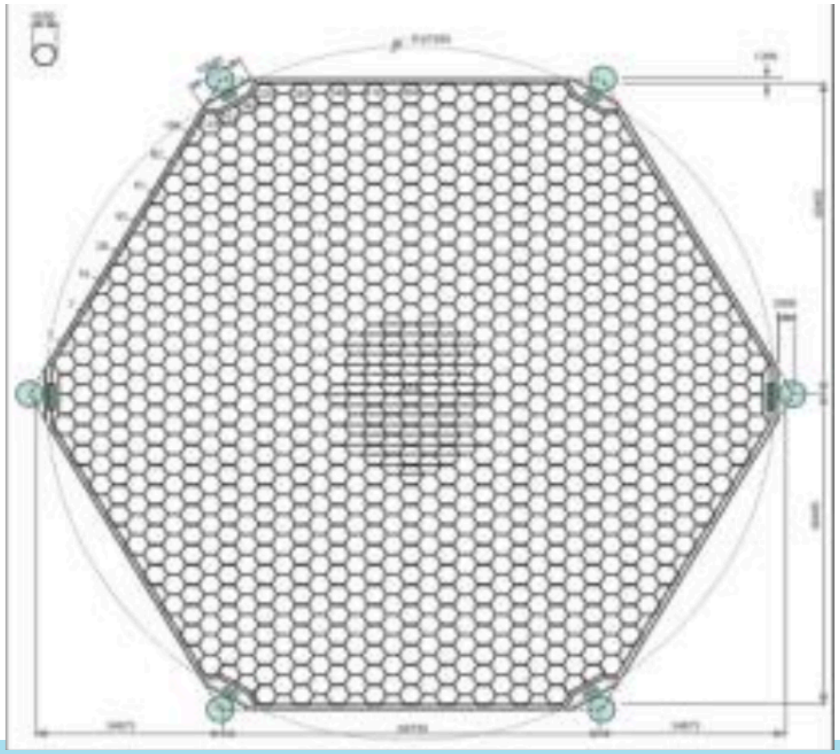


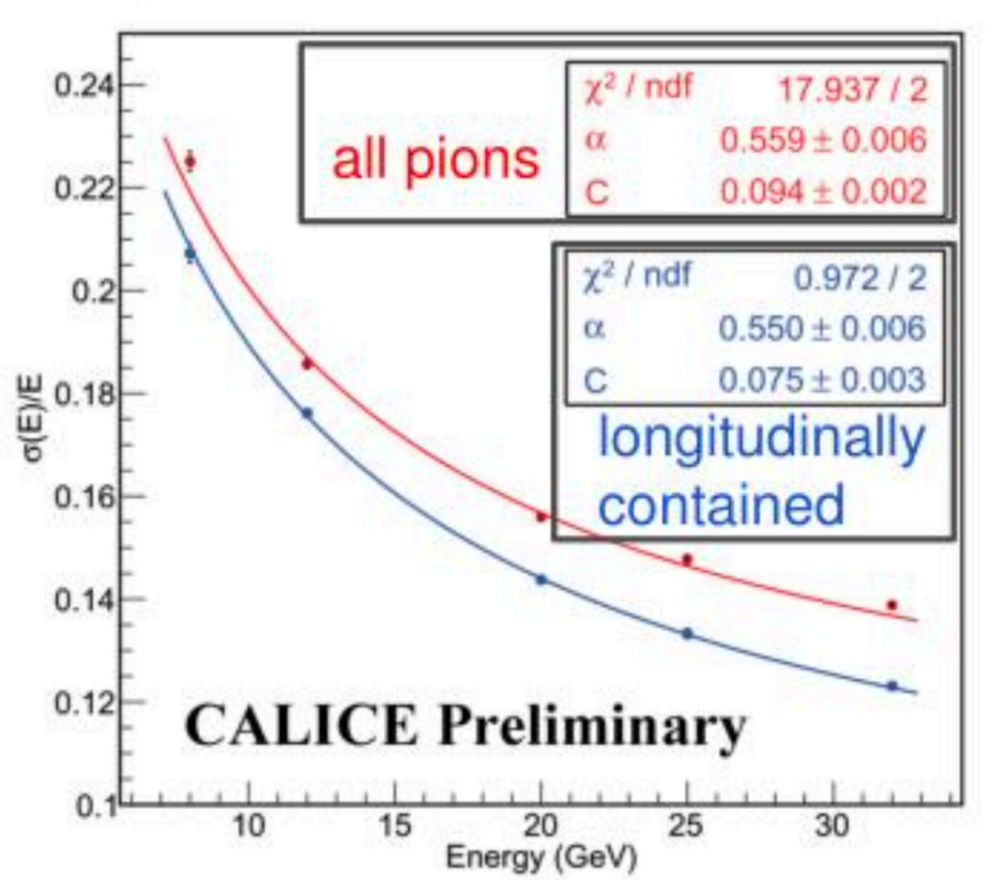


SiD: Calorimetry

- 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

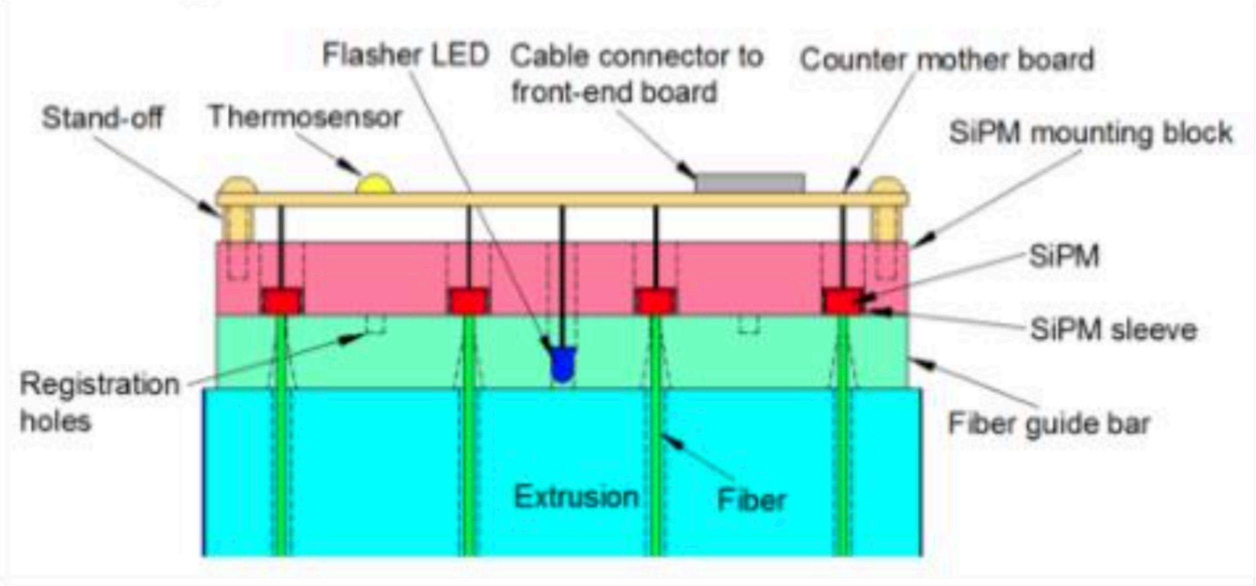


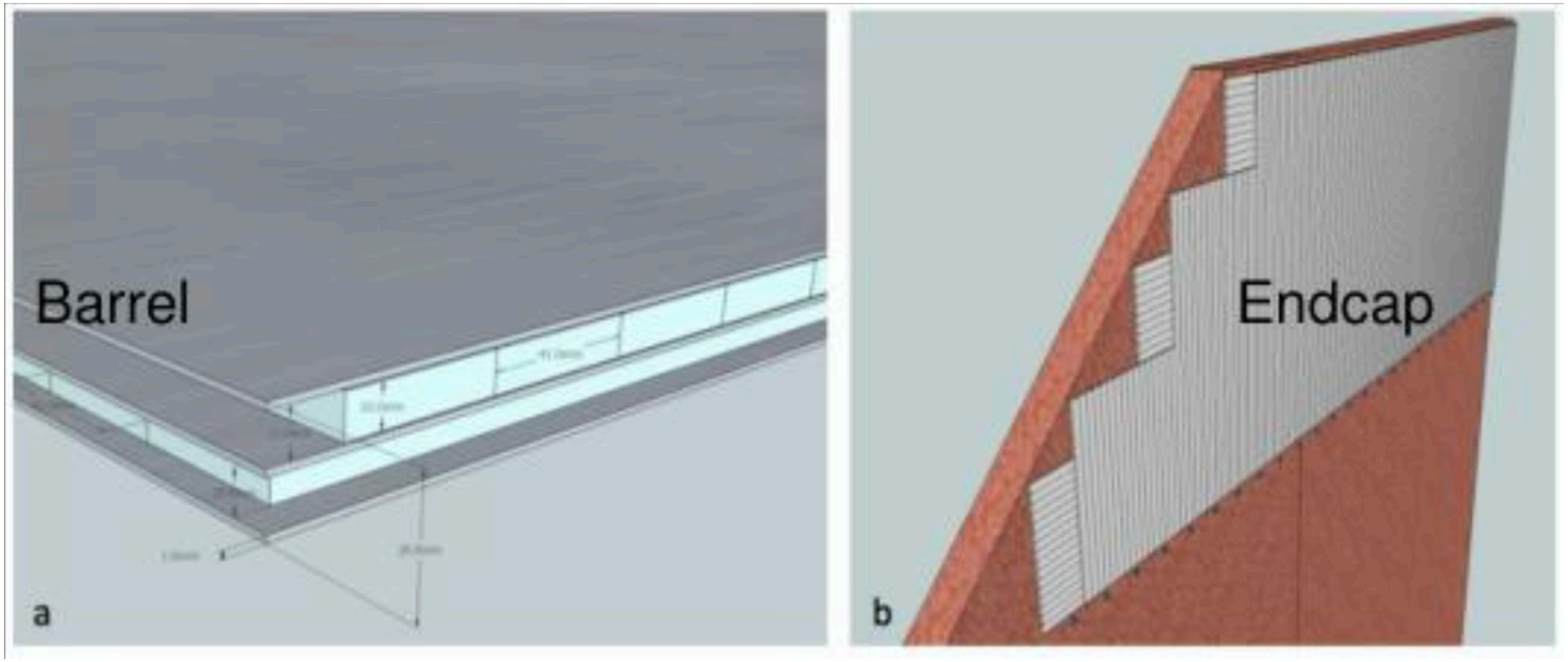




SiD: Muon System

- 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



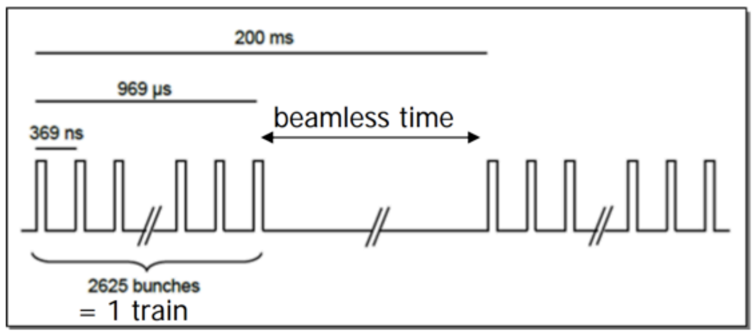


Fermilab

Performance

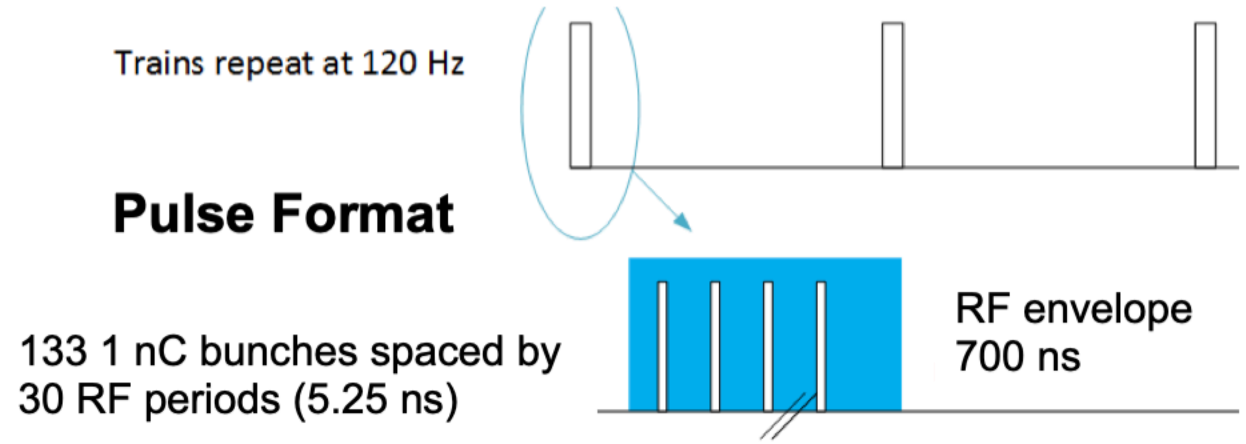
- There are extremely detailed performance calculations in the ILC TDR
  - However, C3 has a radically different bunch structure from ILC

ILC timing structure



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

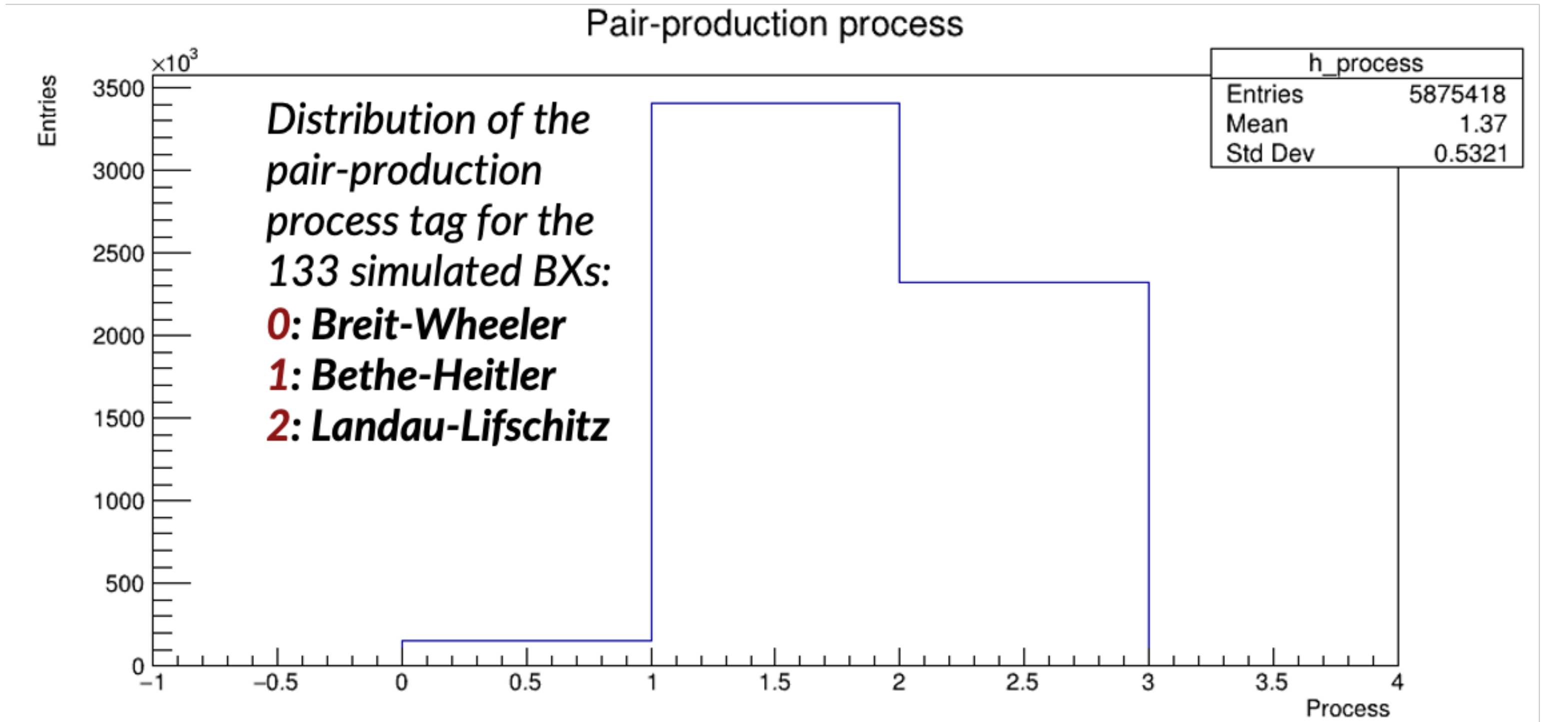
C³ timing structure

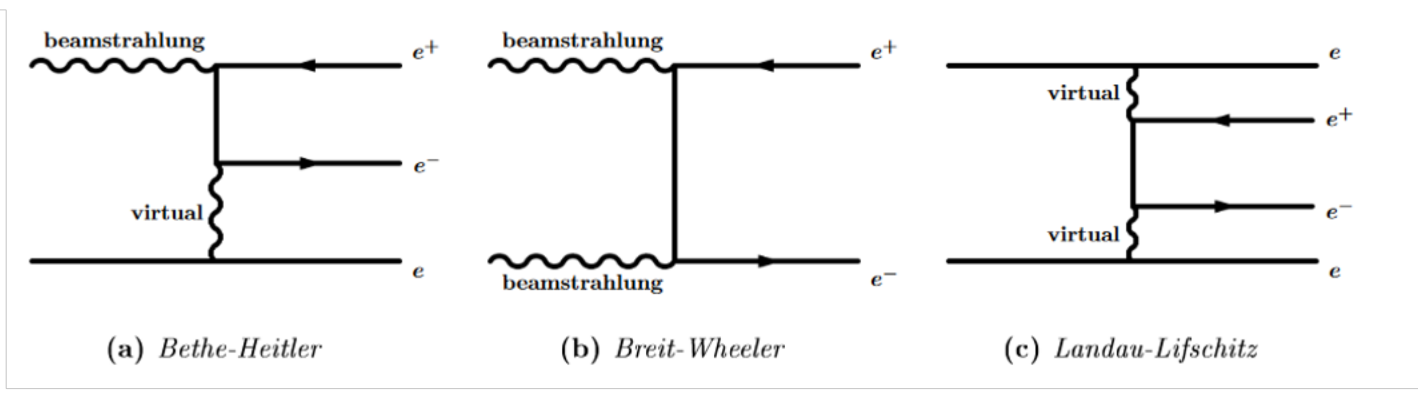


- Time structure and electronics needs at low level are different
  - But the overall concepts are similar, and technologies from LHC can deal with the 70x smaller bunch spacing (because of the 120 Hz repetition rate!)
  - Modern clocking and timing performance means that C3 ~ ILC/10 where beam-based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

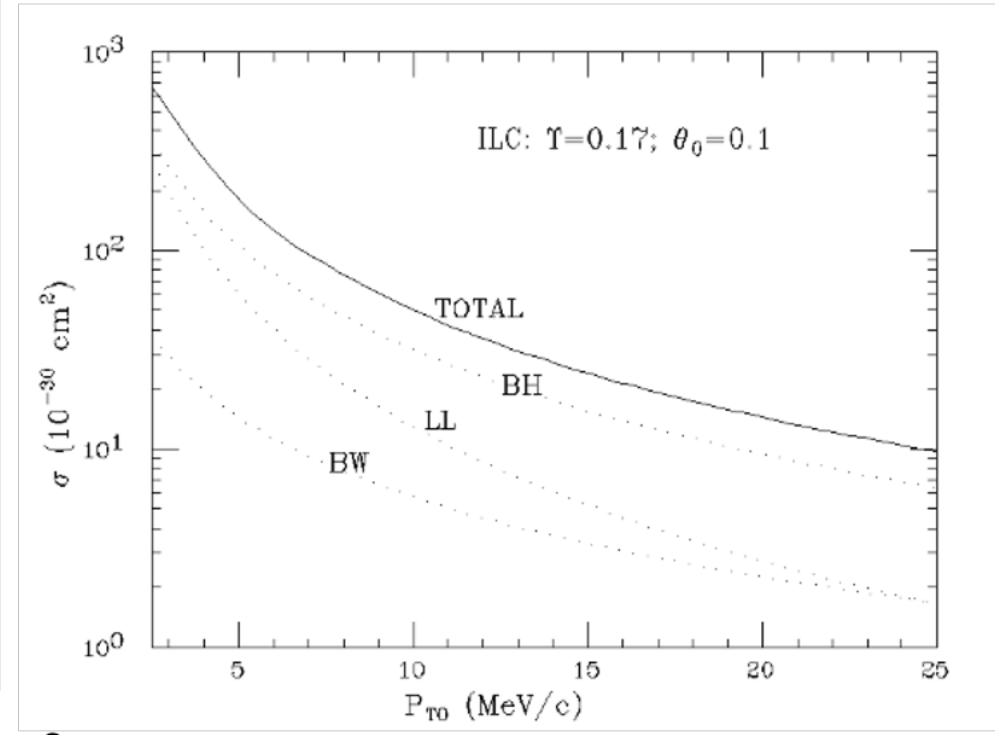
- So first -> what are those backgrounds? How do we estimate them?

Electron-positron Pair Backgrounds





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



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

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)

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

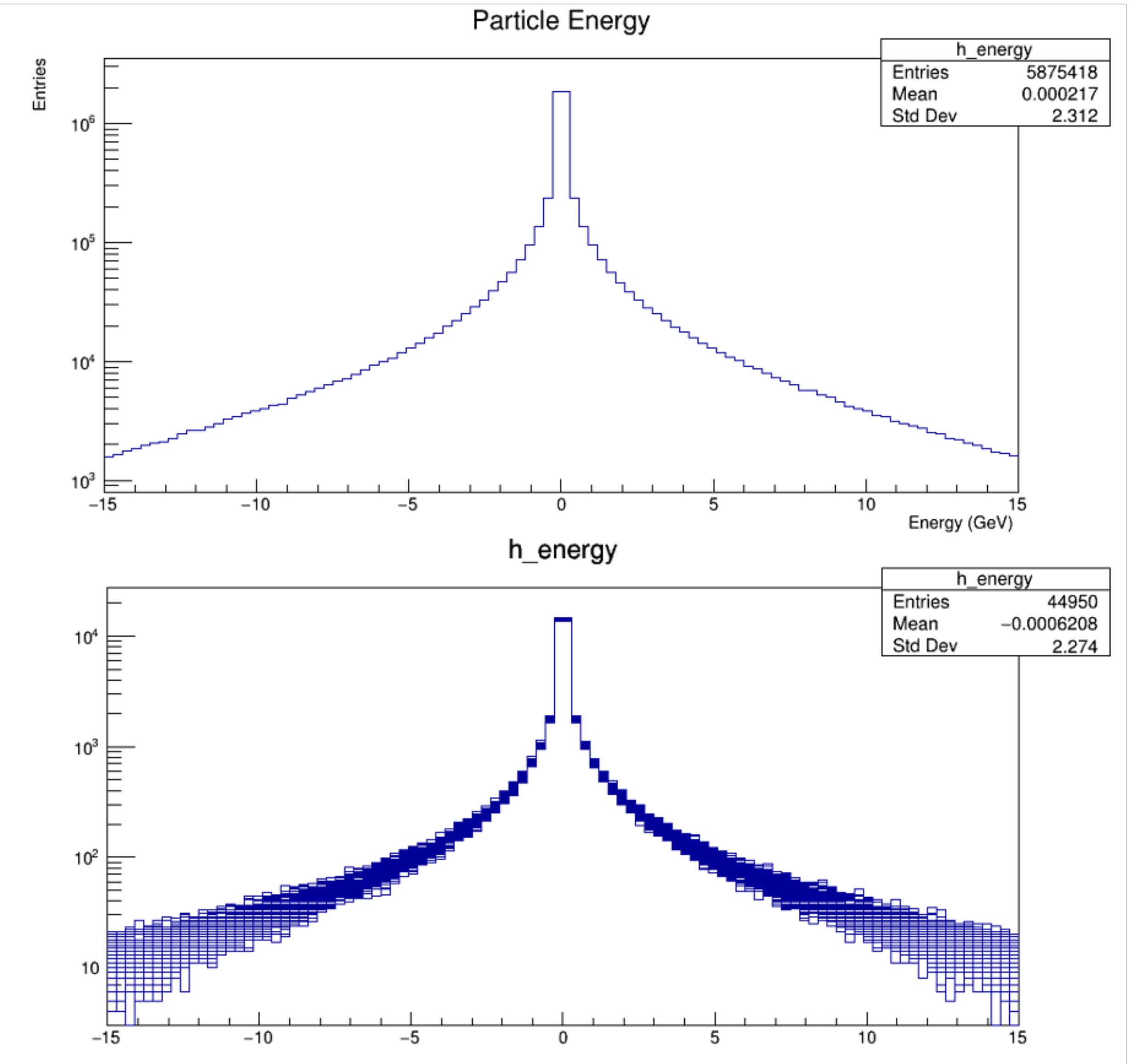
Parameter	Units	Value
β_x^*	mm	12
β_y^*	mm	0.12
$\epsilon_{N,x}^*$	nm	900
$\epsilon_{N,y}^*$	nm	20
σ_x^*	nm	210.12
σ_y^*	nm	3.13
σ_z^*	μm	100
n_b		133
f_{rep}	Hz	120
N		$6.25 \cdot 10^9$
θ_c	rad	0.014

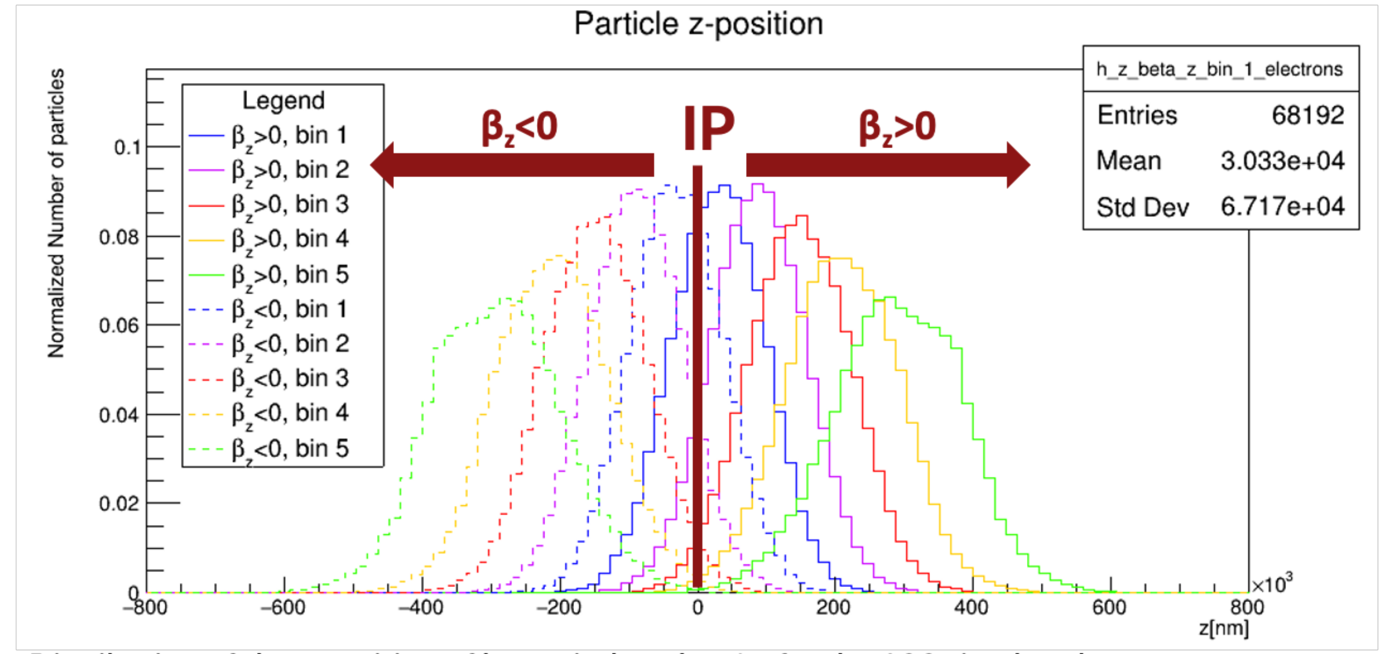
- The emittances on the table are normalized. The transverse beam size is calculated as:

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

	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

Raw GP Results





Distribution of the z-position of beam-induced e^+/e^- for the 133 simulated BXs for different bins of β_z:

bin 1: $0.0 < |\beta_z| < 0.2$
bin 2: $0.2 < |\beta_z| < 0.4$
bin 3: $0.4 < |\beta_z| < 0.6$
bin 4: $0.6 < |\beta_z| < 0.8$
bin 5: $0.8 < |\beta_z| < 1.0$

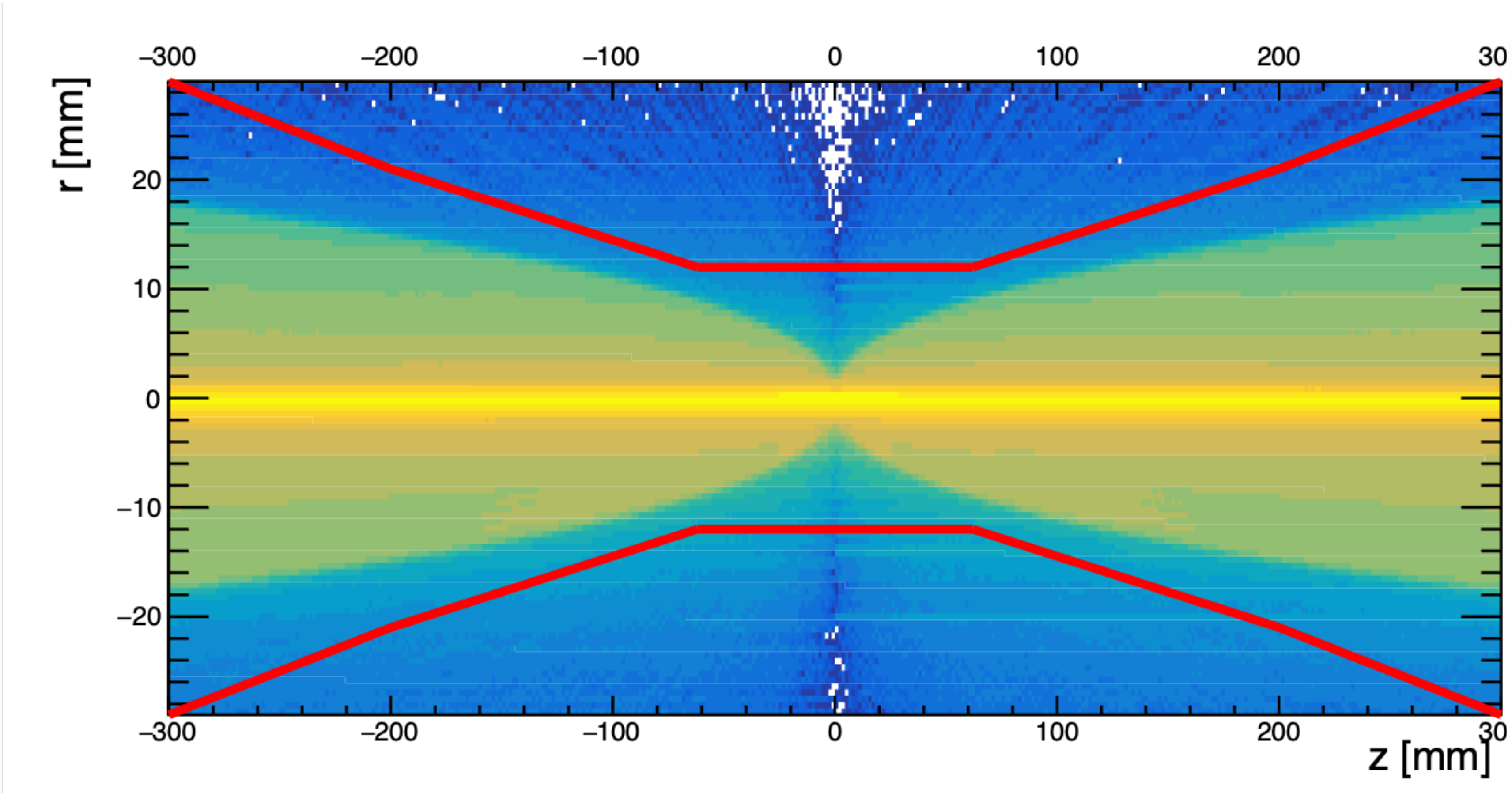
- We generated 133 bunches configured with the C³ parameters ensuring unique random seeds to simulate a full bunch train
  - Simulation of e^+/e^- propagation through bunch charge is apparent and consistent with expectations
  - Sub-distributions per bunch consistent with each other
  - Average of 44176 particles per bunch, observed expected steeply falling energy spectrum

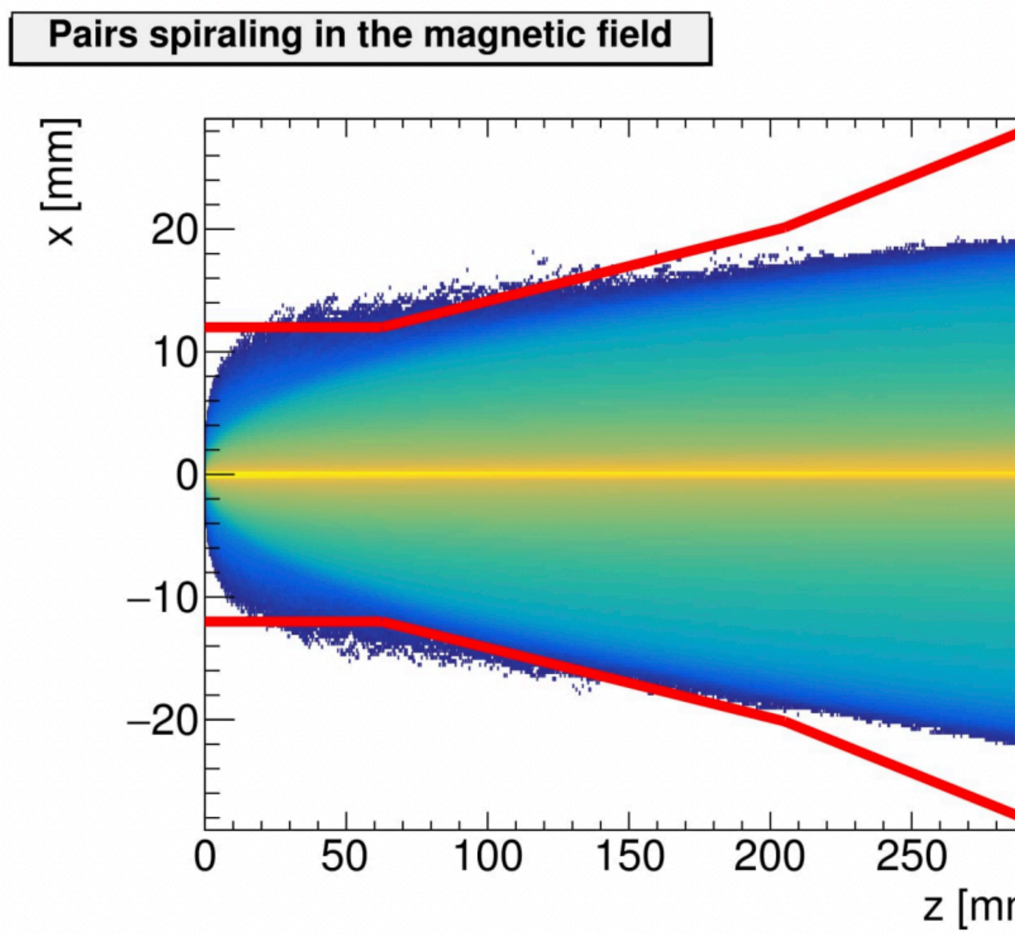
What's been done so far for C3 for the pair background

Vertex Barrel layer	Mean number of hits – 0 MeV cut	Mean number of hits –E> 10 MeV cut	Mean number of hits – pT> 5 MeV cut
1st layer	341.5 ± 2.6	218.5 ± 2.0	239.0 ± 2.2
2nd layer	113.9 ± 1.8	101.5 ± 1.7	97.6 ± 1.6
3rd layer	70.9 ± 1.8	63.2 ± 1.8	51.4 ± 1.7
4th layer	51.1 ± 1.6	43.4 ± 1.7	38.6 ± 1.5
5th layer	34.3 ± 1.4	25.1 ± 1.2	20.7 ± 1.2
All 5 layers	614.8 ± 4.2	451.6 ± 4.1	447.3 ± 3.9

- Investigated possibility of cutting out particles that would not reach first layer
  - Simulated 400 random-seed variants of the same event with different kinematic cuts
  - Significant impact on mean number of hits in first layer, not viable for accurate simulations
- Main improvement came from choosing a more efficient random number generator
  - Mersenne Twister took us down to 15 minutes per background event which is at least not glacial
  - Will continue to optimize in future, we will need an enormous library of these events

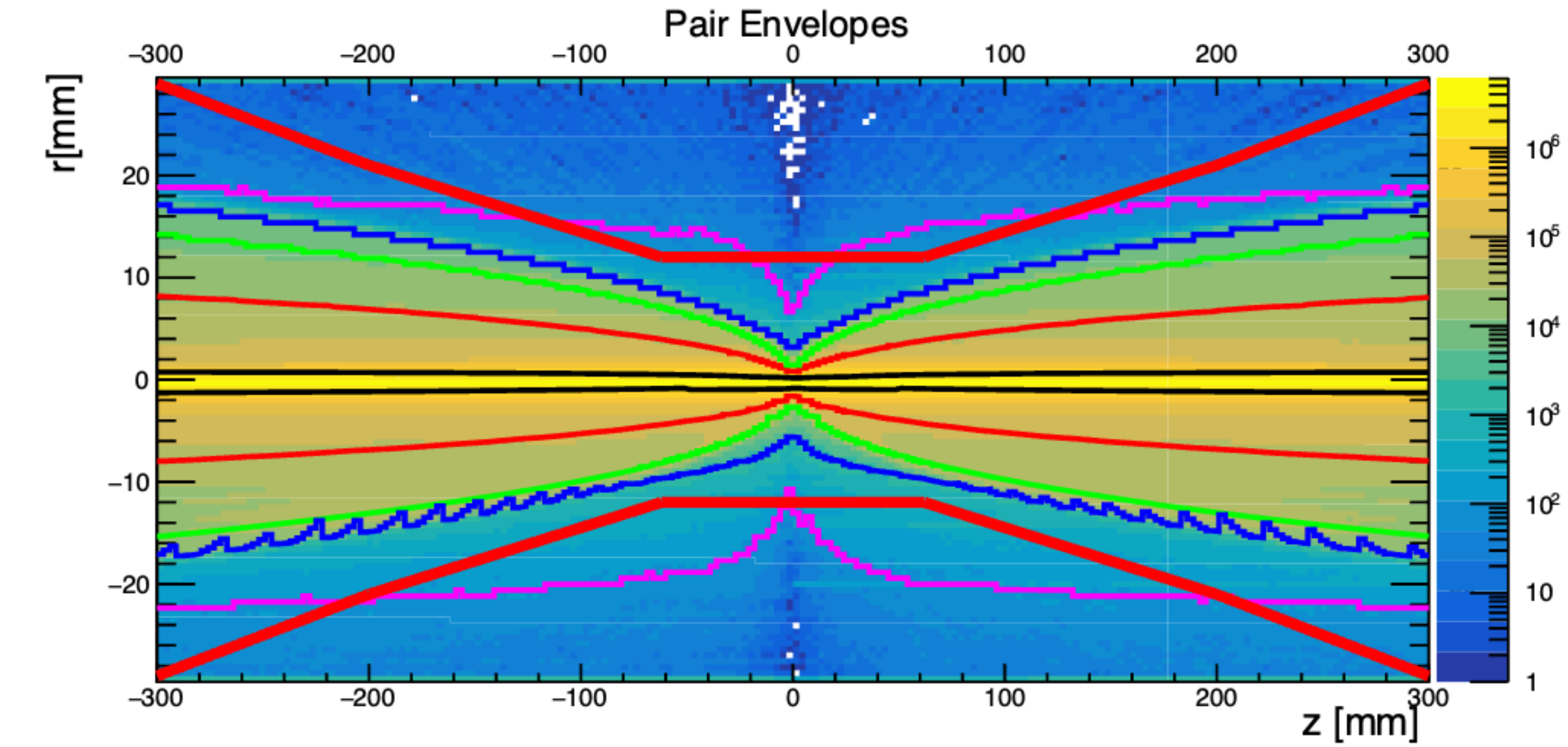
Envelope Plots a la ILC



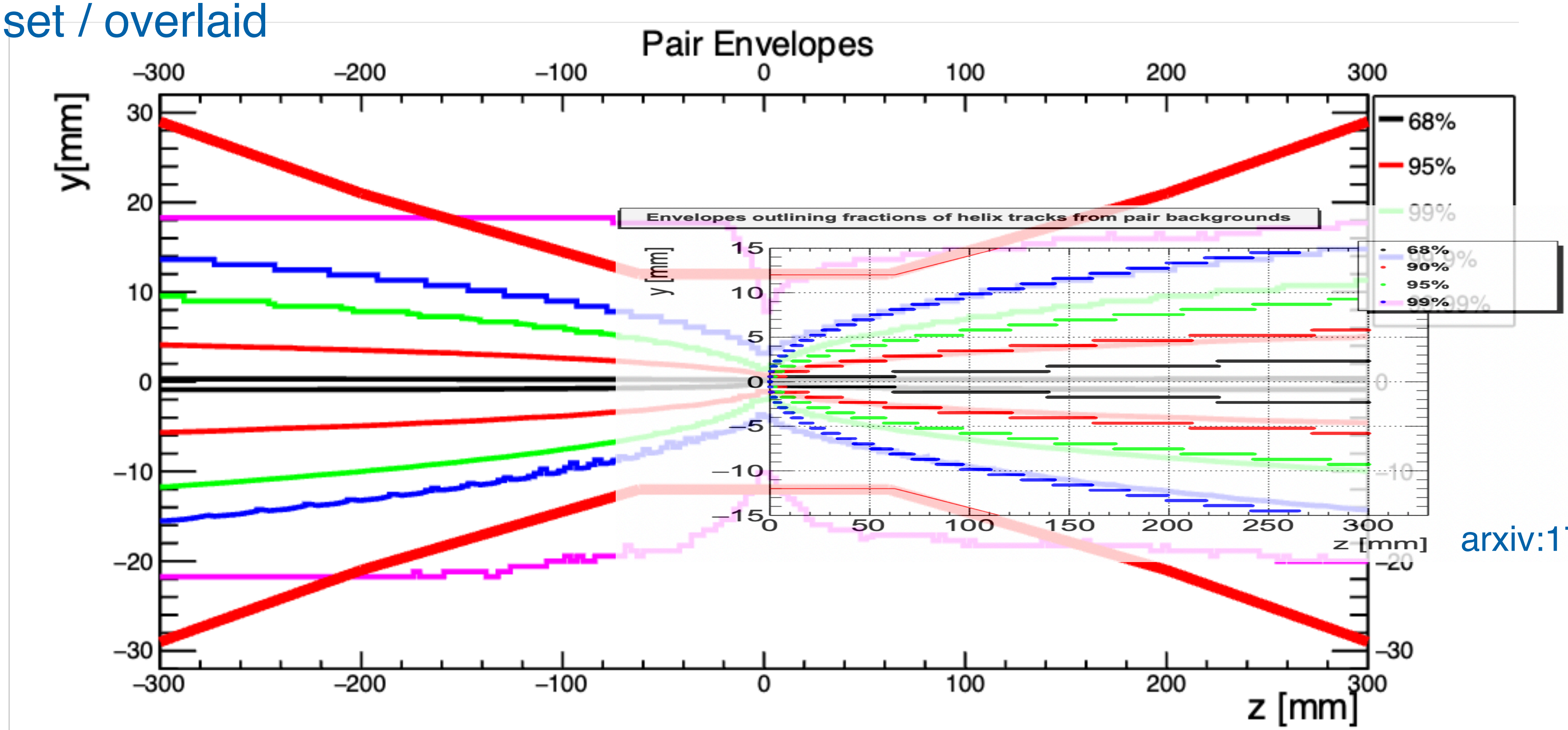


- Red line is latest placement of beam pipe at C^3, most recent SiD geometry has first layer at 14mm away from IR
- Qualitatively similar results to ILC in this view…

Envelope Plots a la ILC

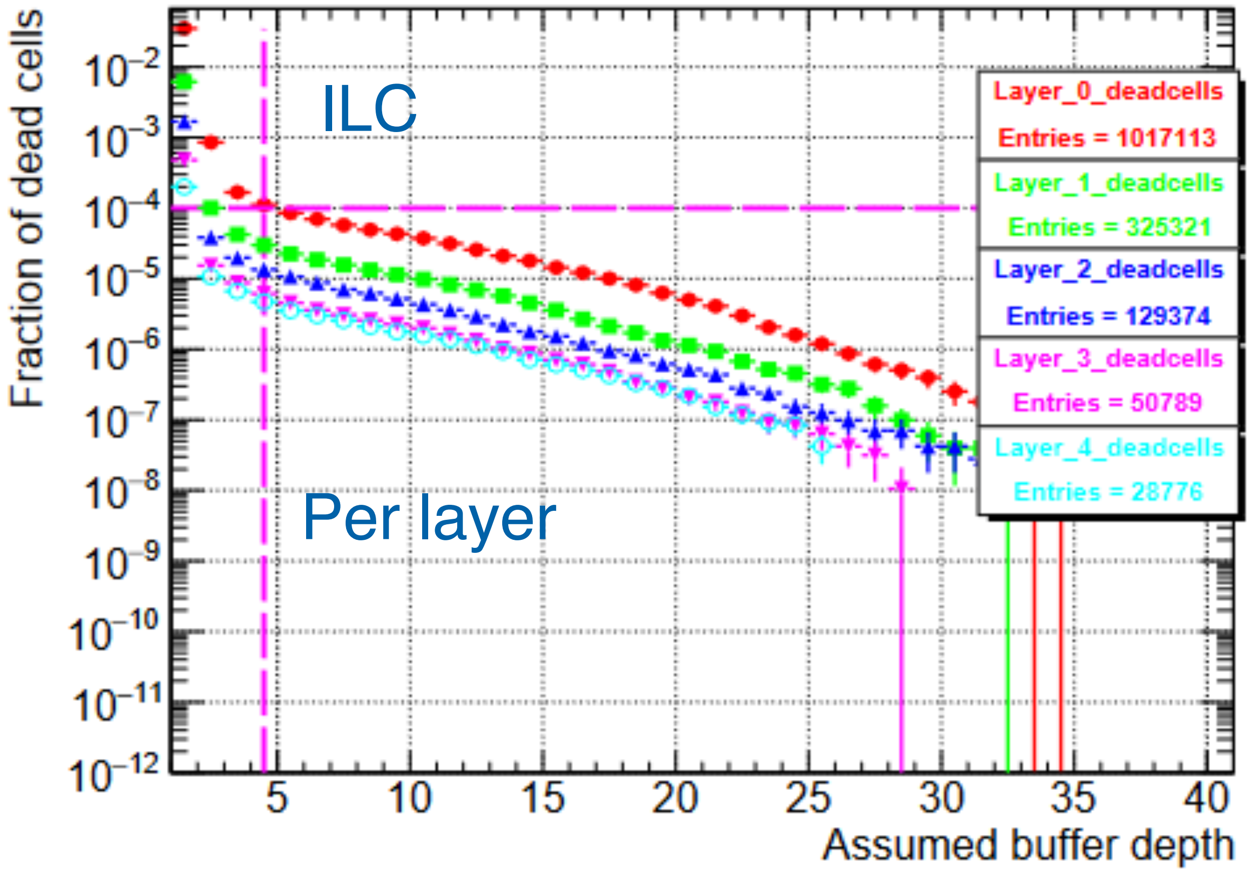


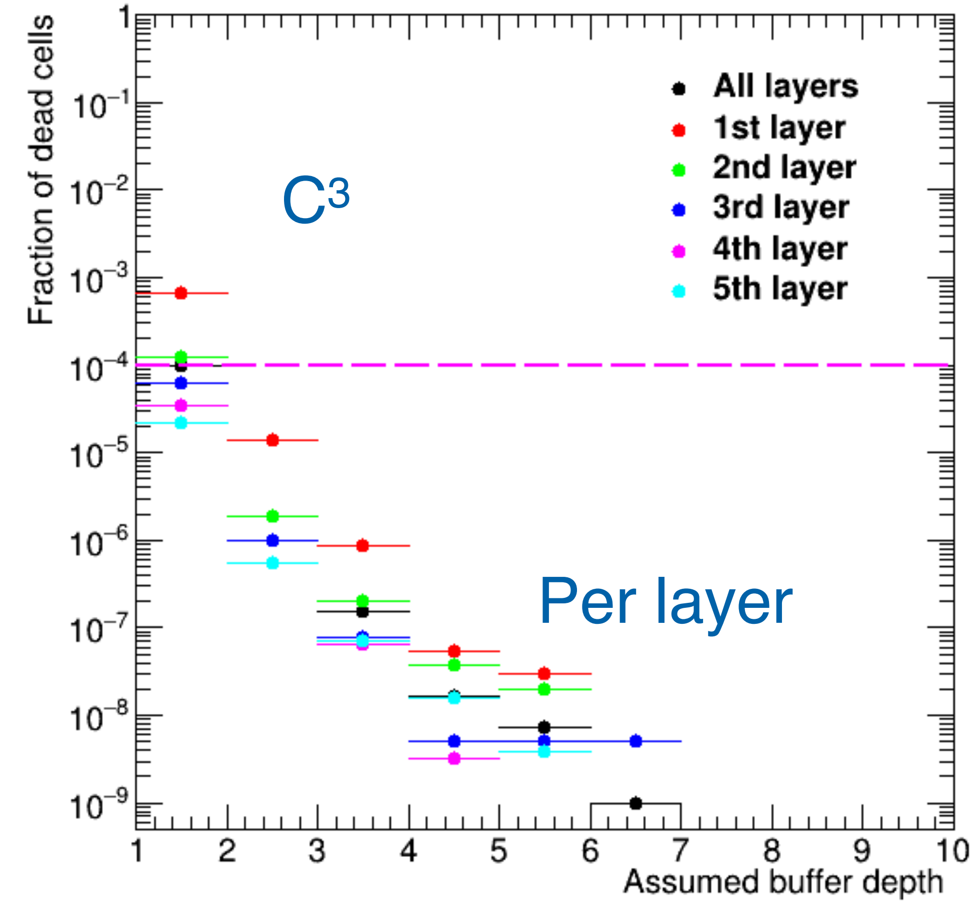
ILC inset / overlaid



arxiv:1703.05737

Latest SiD Geometry in Full Simulation

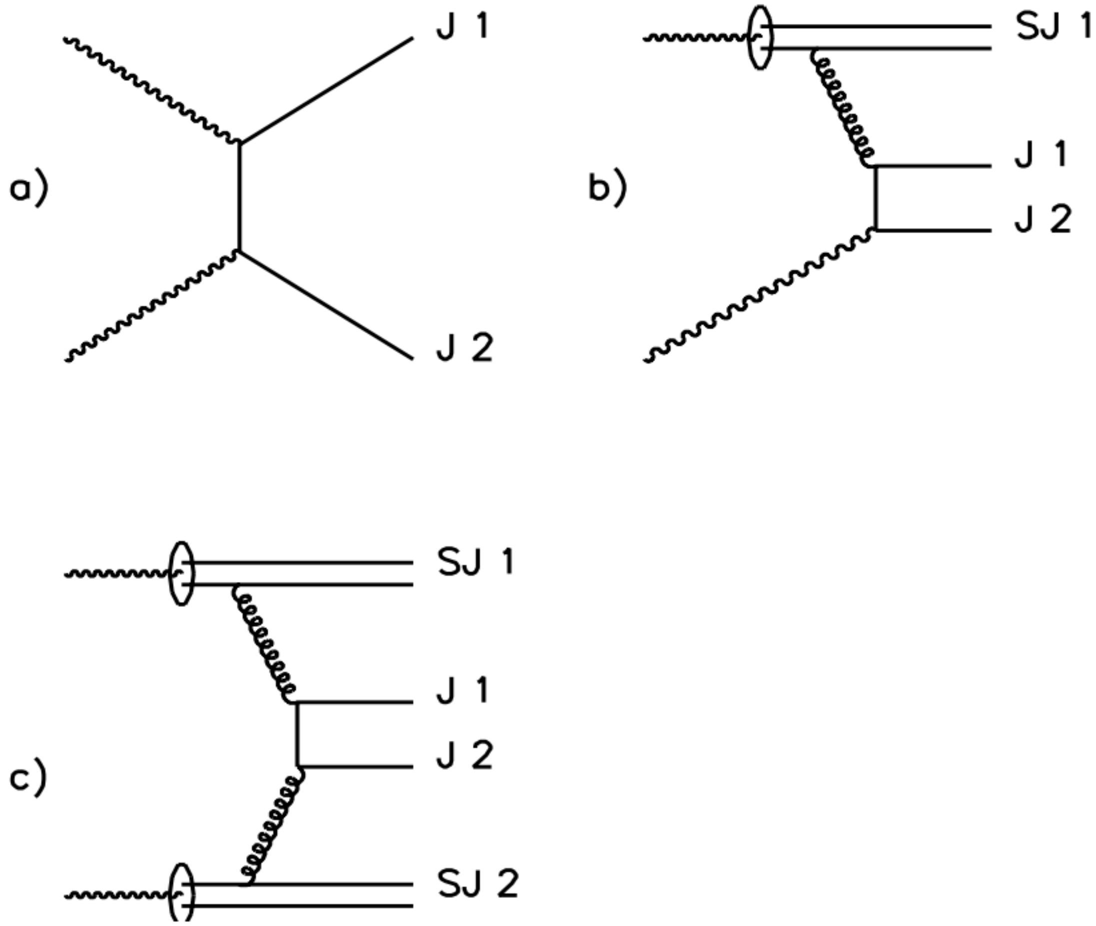




- Checked many times to ensure fidelity of simulation and outcome of results
  - Concerns about magnetic field, exact versions of geometry, etc.
- Together with envelope confirmation indications that we could move the inner pixel layer closer
  - Closer hit: improved sagitta determination, HF tagging, triggering, electron reco.

Pair-background Demo

Hadron Photoproduction: Introduction



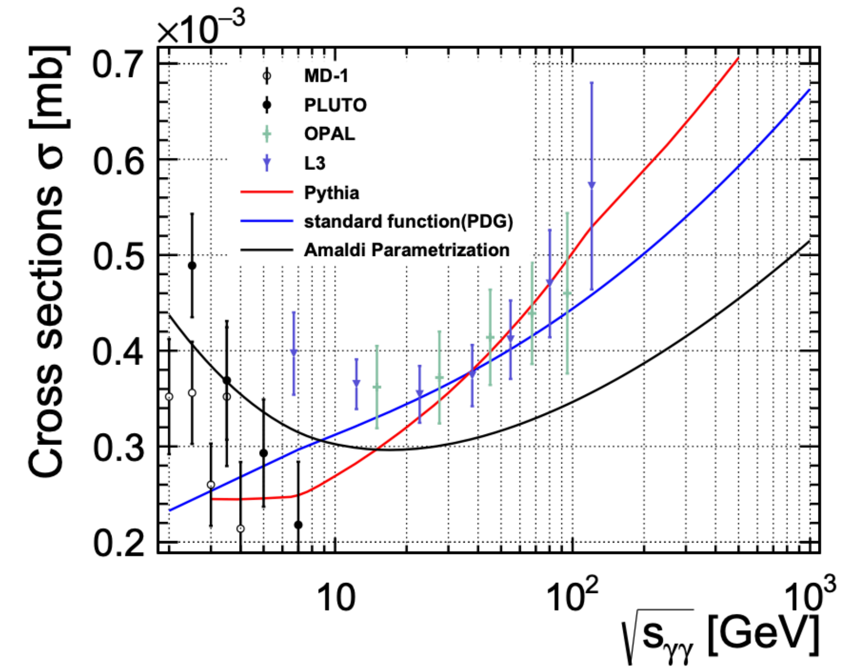


FIG. 2: Comparison of cross sections for $\gamma\gamma \to$ hadron processes as a function of centre of mass energy obtained from Amaldi parameterization [3], Standard paramerization [8] in PDG, Pythia and data from LEP [1], PETRA [6] and VEPP [5]

- Diagrams have similar topology to electron-positron background but include the possibility that the virtual photons pair-produce quarks
- Given smaller coupling to quarks and requirement for internal conversion this background is smaller
  - Measurements indicate ~10% of pair background, so not insignificant, and more central than e+ e-!
- Given the c.o.m. range over which we're producing events there are many details to consider

Hadron Photoproduction: Spectra and Generators

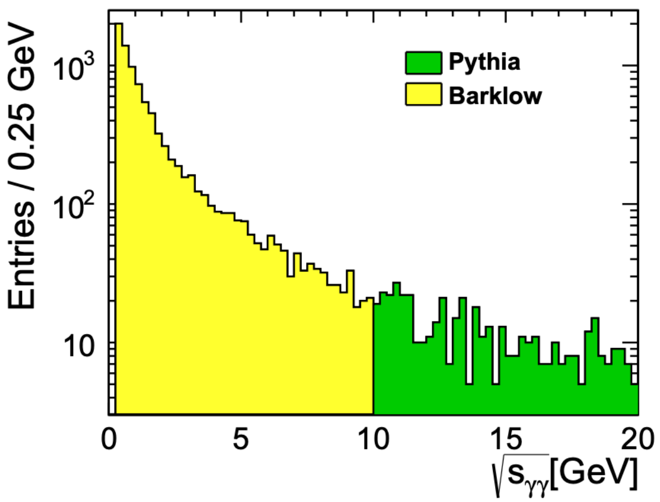


FIG. 1: Energy spectrum of $\gamma\gamma \to$ low p_T hadron events as a function of centre-of-mass energy. The figure shows the energy cutoff of 10 GeV below which the events are generated by the Barklow generator. Above 10 GeV the events are generated by Pythia.

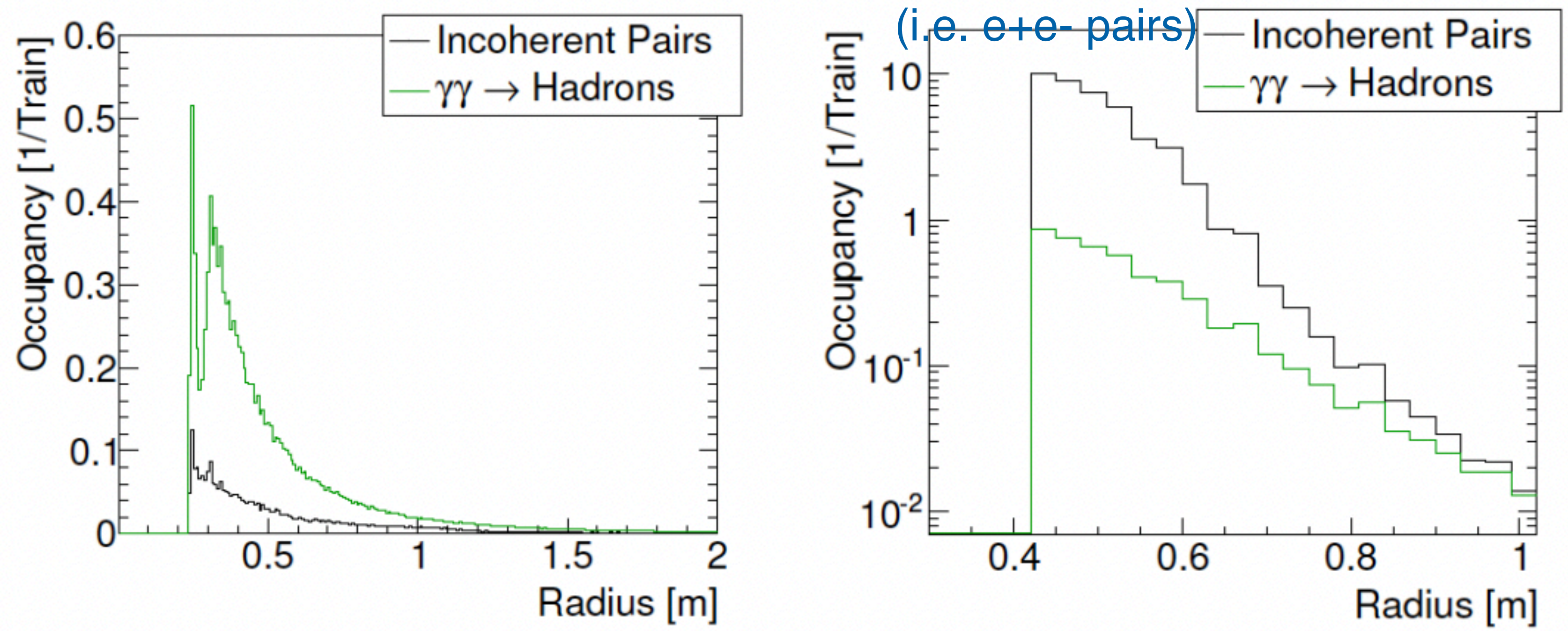


Figure 14. The radial distribution of the train occupancy per pad in ECal (left) and per cell in HCal (right) endcap [10].

- Hadron Backgrounds in Pythia5.7 -> Pythia8, Whizard
  - Previous hadron background simulation libraries generated in pythia6 but most of the configuration lost to history (generated/mixed events available but for ILC)
  - Talked with Pythia authors to get modernized versions of photoproduction workflow
  - Will harmonize (as best we can) with the tuning used for ILC studies provided by Tim Barklow
- Actually rather in flux right now: new generator with improved accuracy from Tim Barklow et al. that can be plugged into Whizard event generator

Generating Hadron Photoproduction

Welcome to PYTHIA

PYTHIA is a program for the generation of high-energy physics collision events, i.e. for the description of collisions at high energies between electrons, protons, photons and heavy nuclei. It contains theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial- and final-state parton showers, multiparton interactions, fragmentation and decay. It is largely based on original research, but also borrows many formulae and other knowledge from the literature. As such it is categorized as a **general purpose Monte Carlo event generator**.

Download and install PYTHIA 8.309

The current version is PYTHIA 8.309.

To get going with the program, do the following (on a Linux or Mac OS X system):

- Download the file pythia8309.tgz to a suitable location.
- Unzip and expand it with `tar xvfz pythia8309.tgz`.
- Move to the thus created `pythia8309` directory.
- Read the `README` file in it for installation instructions, and apply them. (If you are not going to link any external libraries, or have any other special demands, you only need to type `make`.)
- Move to the `examples` subdirectory and read the `README` file there for instructions how to do some test runs. (Again, if you do not link to external libraries, you only need to type `make mainNN` followed by `./mainNN > mainNN.log`, where `NN` is a two-digit number in the range 01 - 30.)

www.pythia.org

whizard.hepforge.org

The WHIZARD Event Generator

The Generator of Monte Carlo Event Generators for Tevatron, LHC, ILC, CLIC, CEPC, FCC-ee, FCC-hh, SppC, the muon collider and other High Energy Physics Experiments

What is WHIZARD?

WHIZARD is a program system designed for the efficient calculation of multi-particle scattering cross sections and simulated event samples.

WHIZARD can evaluate NLO QCD corrections in the SM for arbitary lepton and hadron colliders. Tree-level matrix elements are generated automatically for arbitrary partonic processes by using the Optimized Matrix Element Generator O'Mega. Matrix elements obtained by alternative methods (e.g., including loop corrections) may be interfaced as well. The program is able to calculate numerically stable signal and background cross sections and generate unweighted event samples with reasonable efficiency for processes with up to eight final-state particles; more particles are possible. For more particles, there is the option to generate processes as decay cascades including complete spin correlations. Different options for QCD parton showers are available.

Polarization is treated exactly for both the initial and final states. Final-state quark or lepton flavors can be summed over automatically where needed. For hadron collider physics, an interface to the standard LHAPDF is provided. For Linear Collider physics, beamstrahlung (CIRCE) and ISR spectra are included for electrons and photons. The events can be written to file in standard formats, including ASCII, StdHEP, the Les Houches event format (LHEF), HepMC, or LCIO. These event files can then be hadronized.

WHIZARD supports the Standard Model and a huge number of BSM models. Model extensions or completely different models can be added. WHIZARD fully supports external models from UFO files. There are also legacy interfaces to FeynRules and SARAH.

CURRENT RELEASE

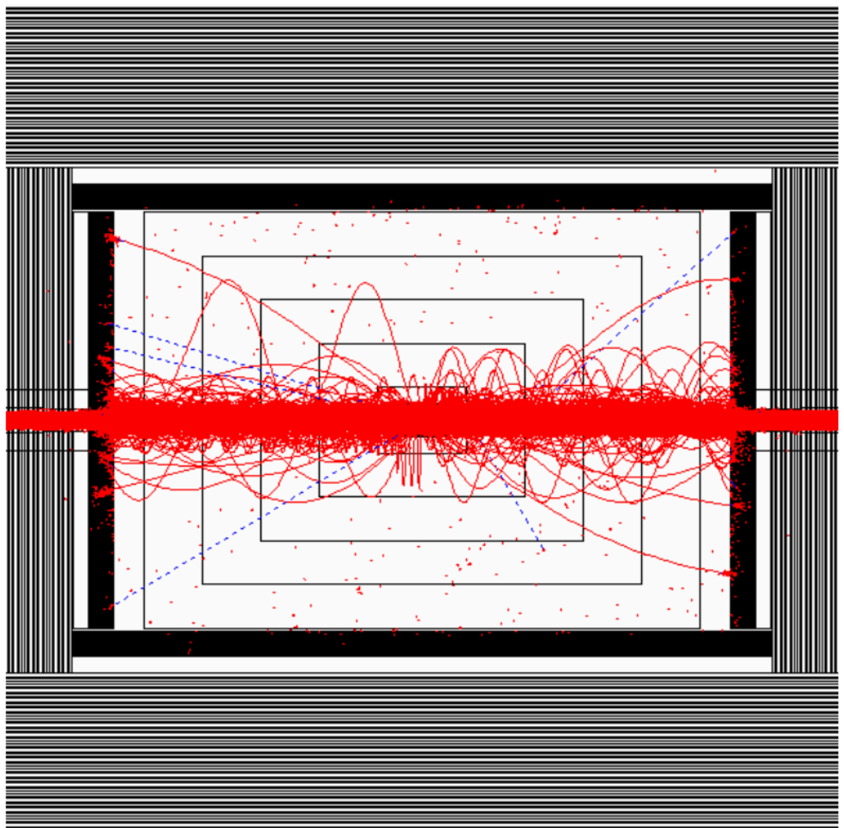
- **The official version is 3.1.2 (released: March 21st, 2023).**

  The distribution tarball of the sources can be found here (3.1.2, link).

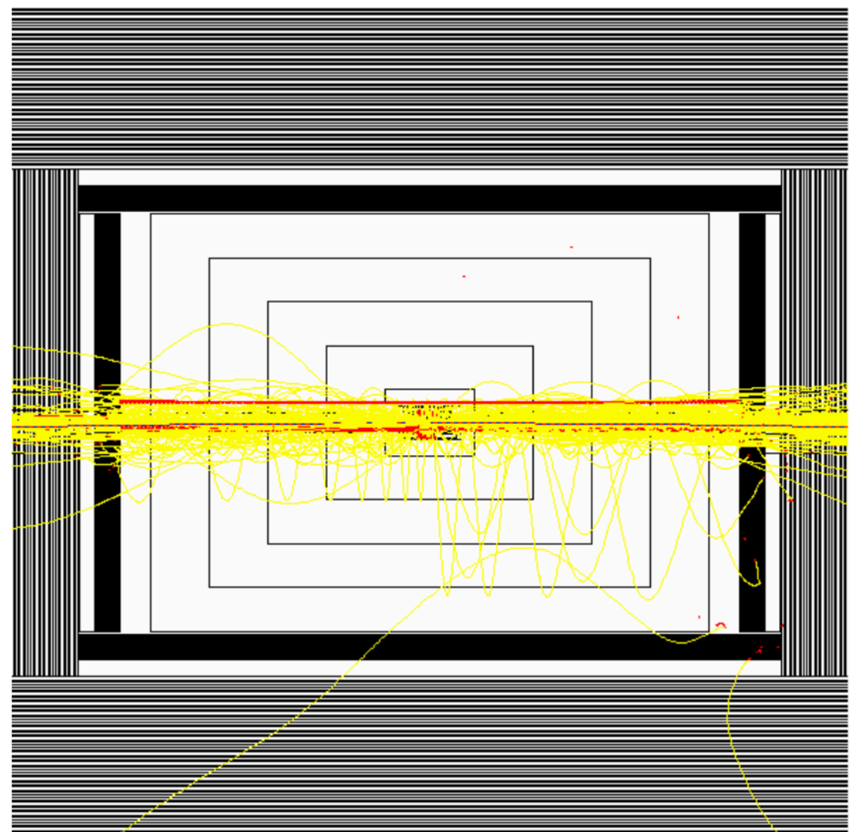
- Generating hadron photo production requires the much more standard machinery of particle physics event generators
- Pythia 8 has safe approximations from sqrt(s_{gg}) ~ 10 GeV
- Whizard has a plugin system that provides two things
  - Low energy photon flux calculation from CIRCE beam spectrum generator
  - Tim Barlow's custom muon/pion production code which is safe down to threshold
    - Contact author for code (need to get it out in the open!)

Fermilab

What do beam backgrounds look like? (from ILC, for C3 divide by 10)

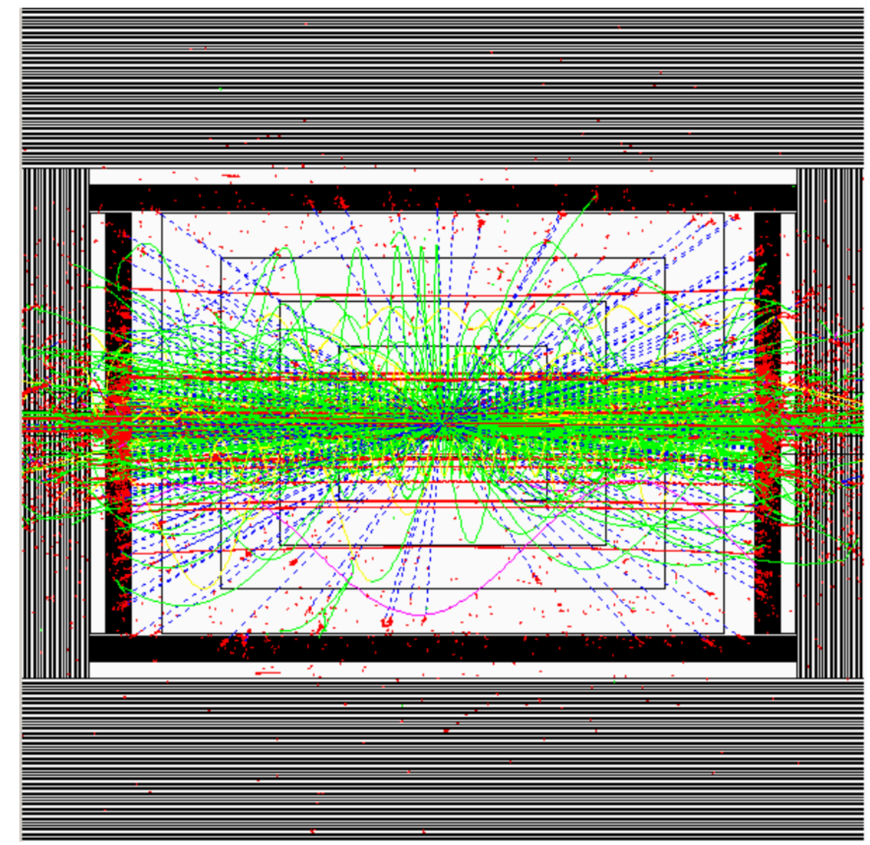


$8600\ e^{+}e^{-}$ pairs / train strike detector



$154\ \mu^{+}\mu^{-}$ pairs / train

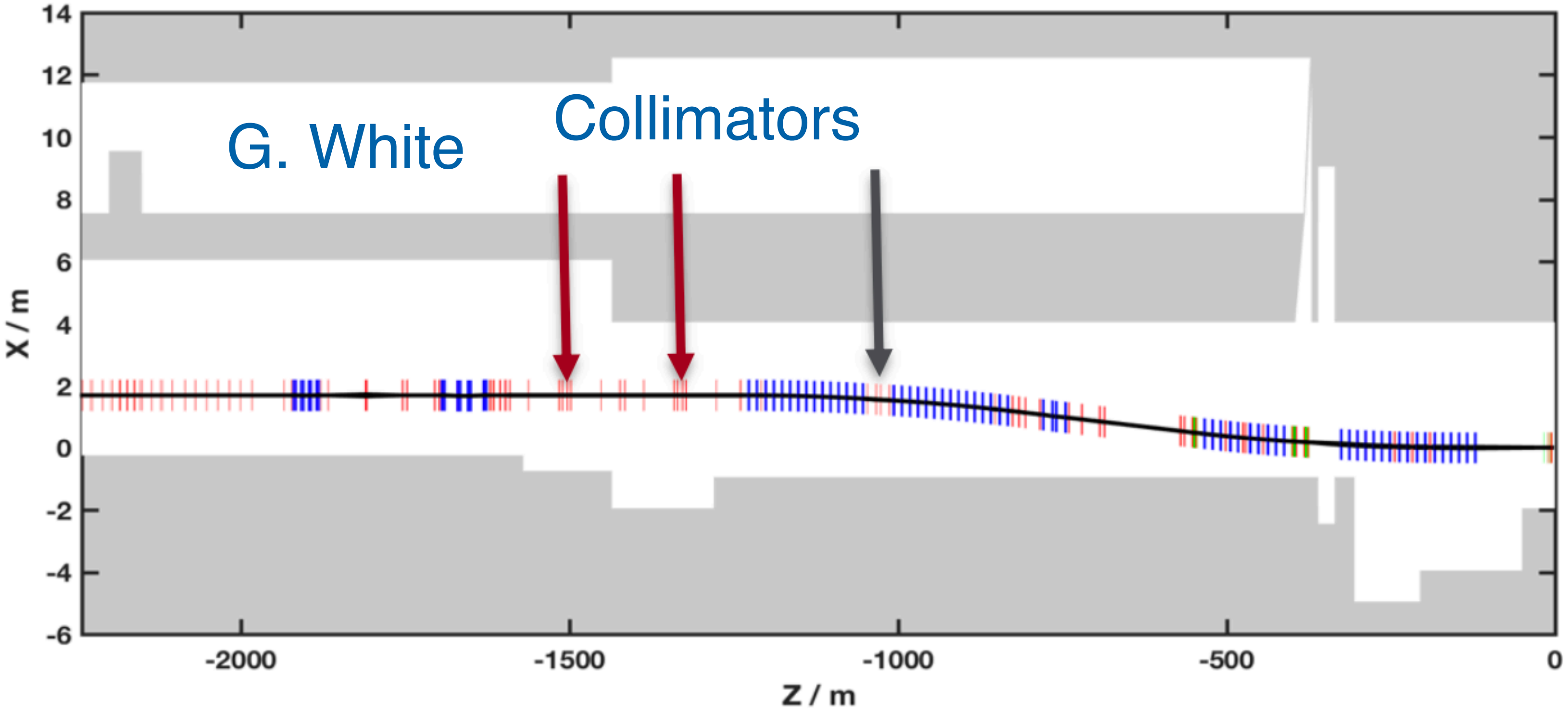
56 GeV / train detected energy
24 detected charged tracks / train



56 hadronic events / train
no pt cut; Ecm down to $\pi^{+}\pi^{-}$ threshold
454 GeV / train detected energy
100 detected charged tracks / train

Accelerator Muon Backgrounds

Accelerator Muon Background Production (ILC)



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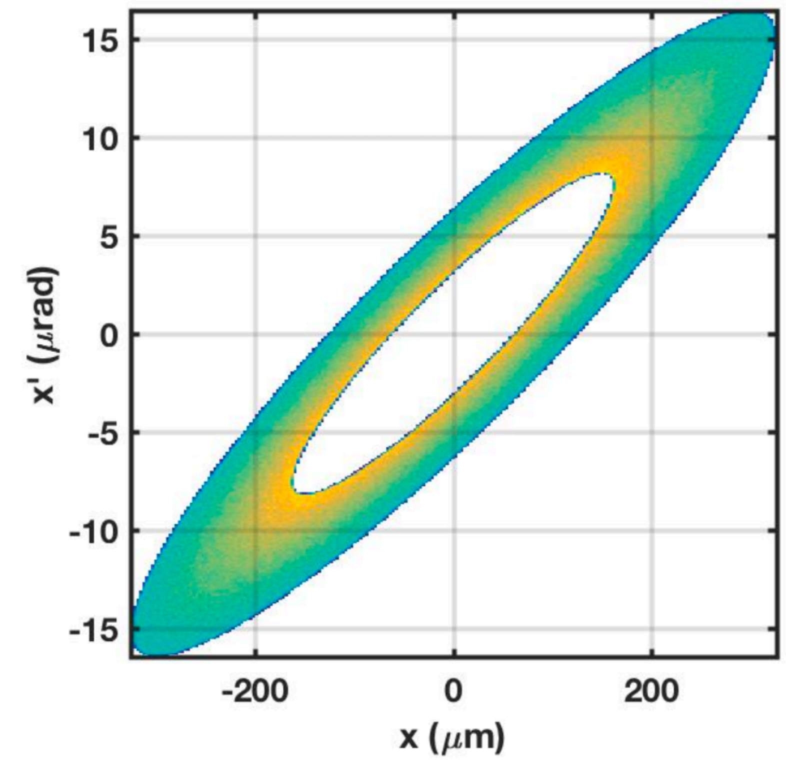
Beam transverse extent



- Muon production from halo in collimator absorbers
  - Predominantly coherent production from high-energy photon - nuclei interactions (Bethe-Heitler process): γ + A → A′ + μ+μ−
  - Also direct annihilation of positrons on atomic electrons contributes at few-% level: e+ +e- -> μ+μ−
- Consider flux @ detector with “donut“ and/or muon wall shielding solutions
  - Potentially important background for detectors

“Spoiler” Magnets to Deflect Produced Muons

5 muon spoilers at z locations from IP:

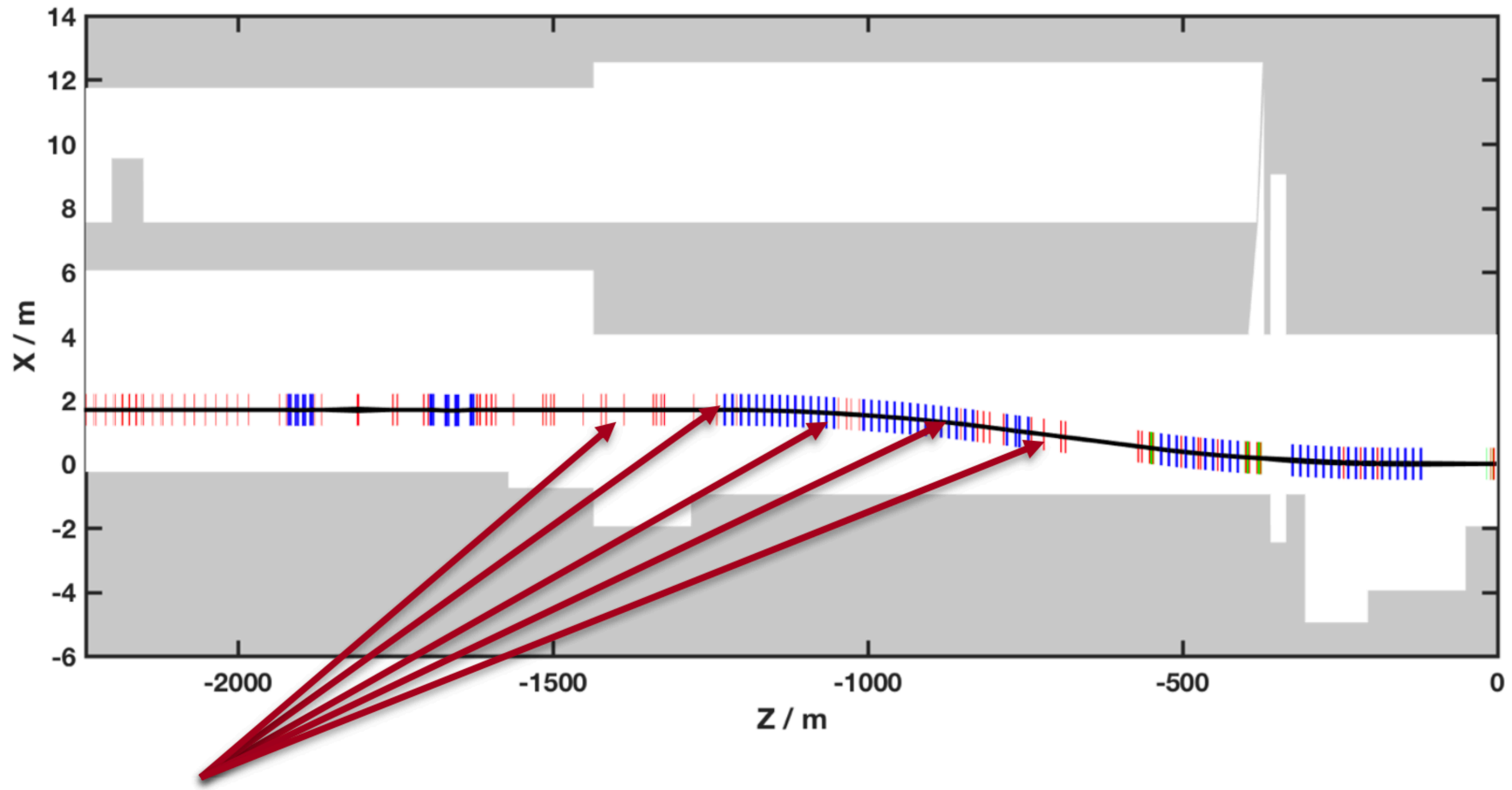
800 m

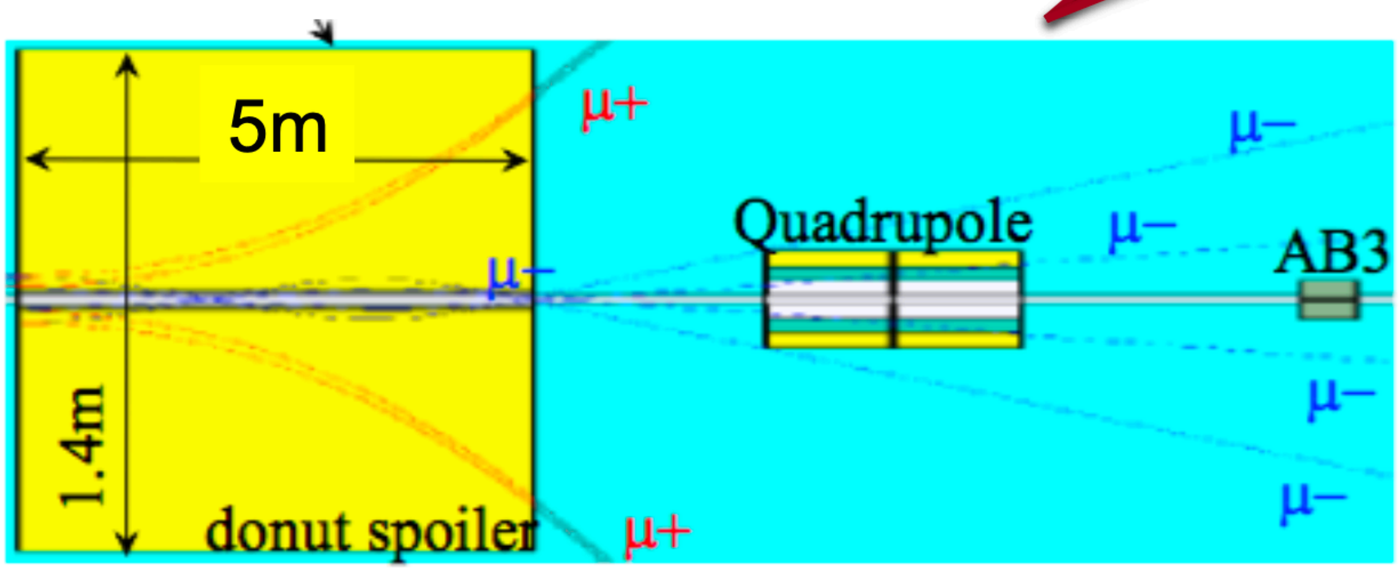
973 m

1143 m

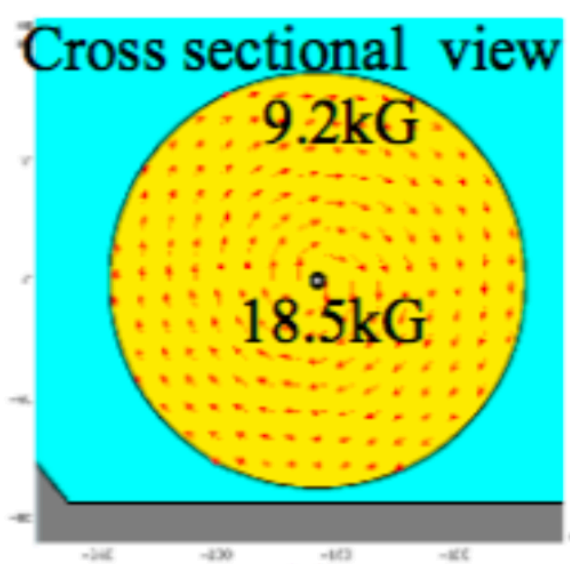
1231 m

1370 m





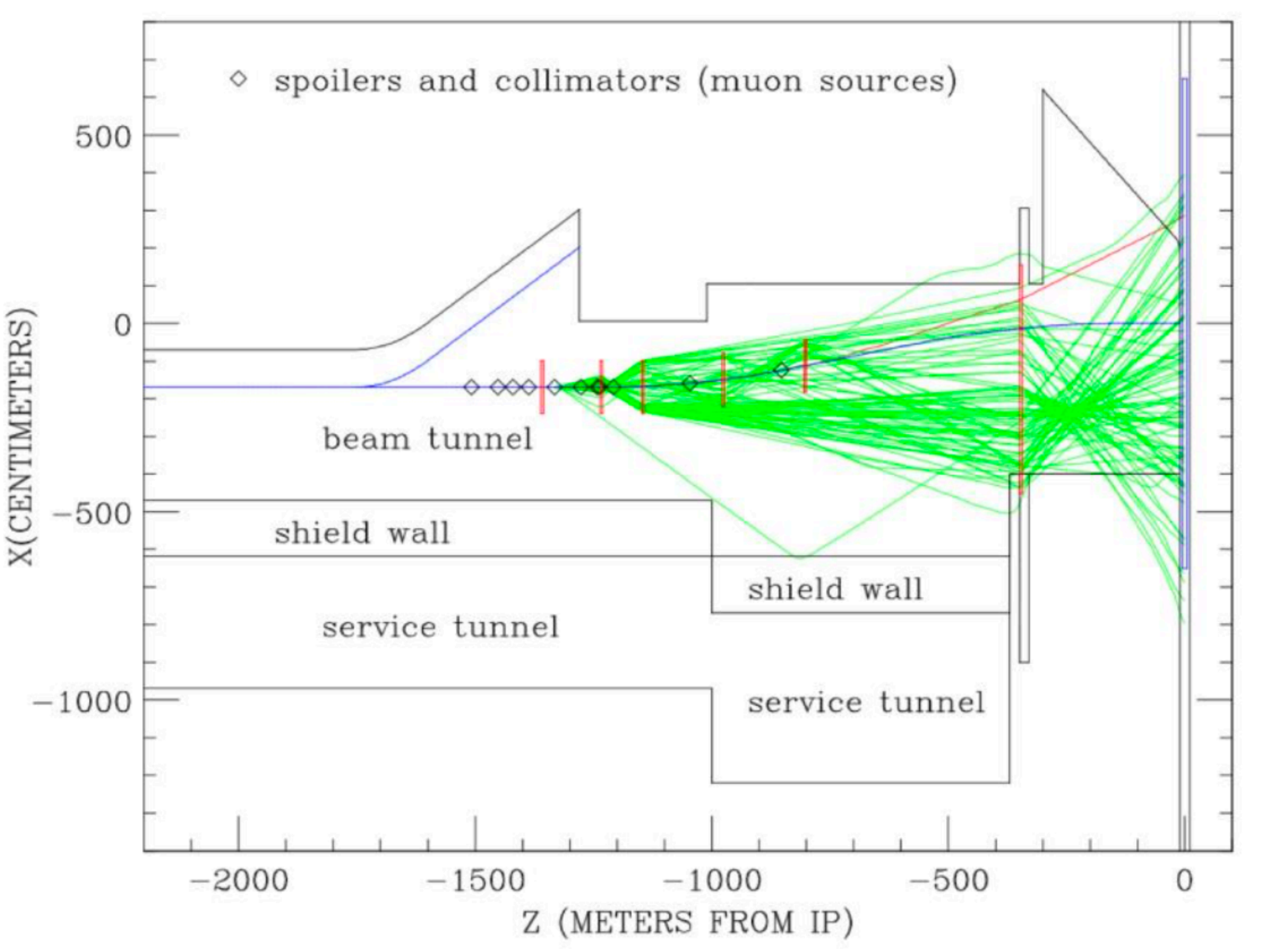
(c)

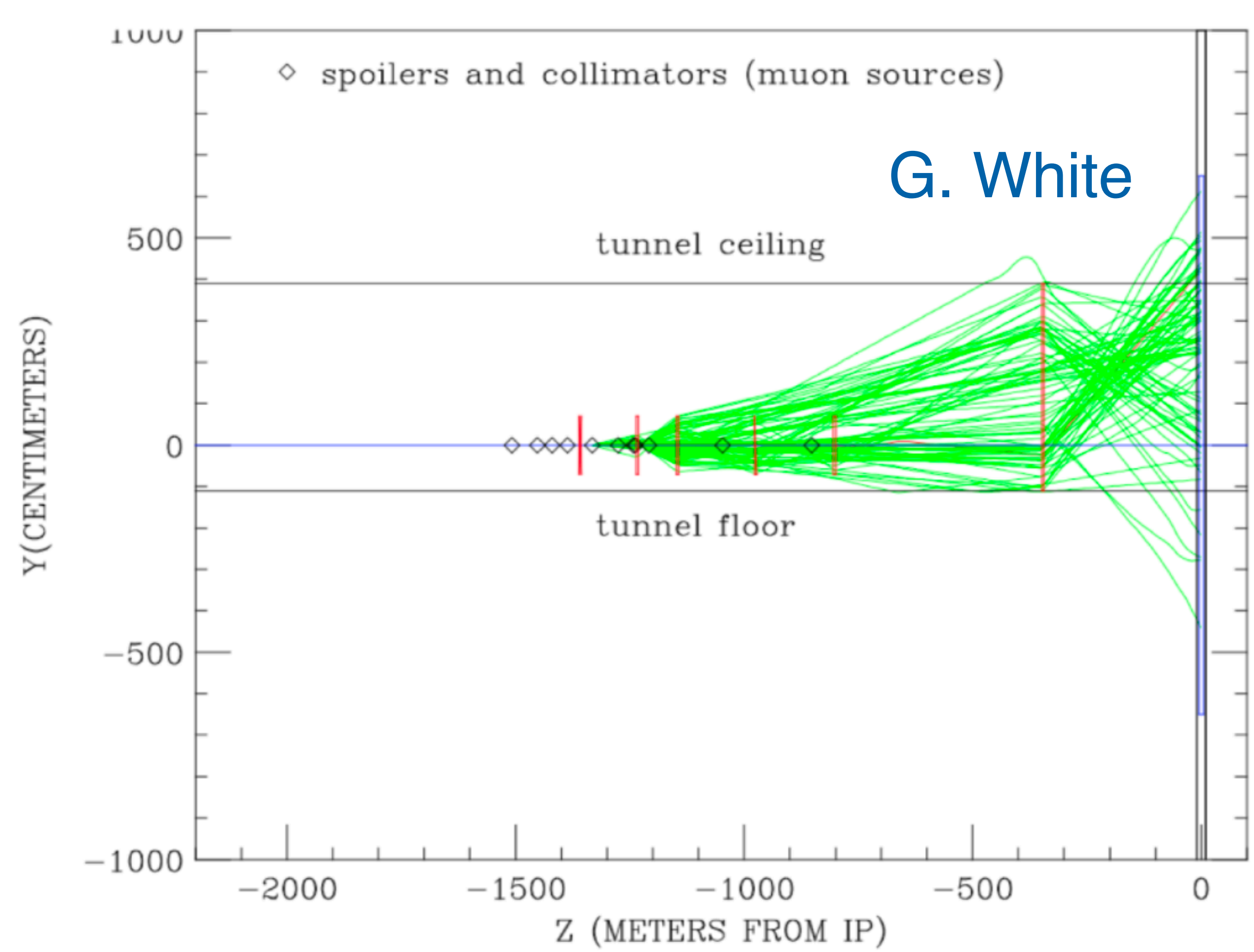


(d)

G. White

Tracking the Muons to the Detector



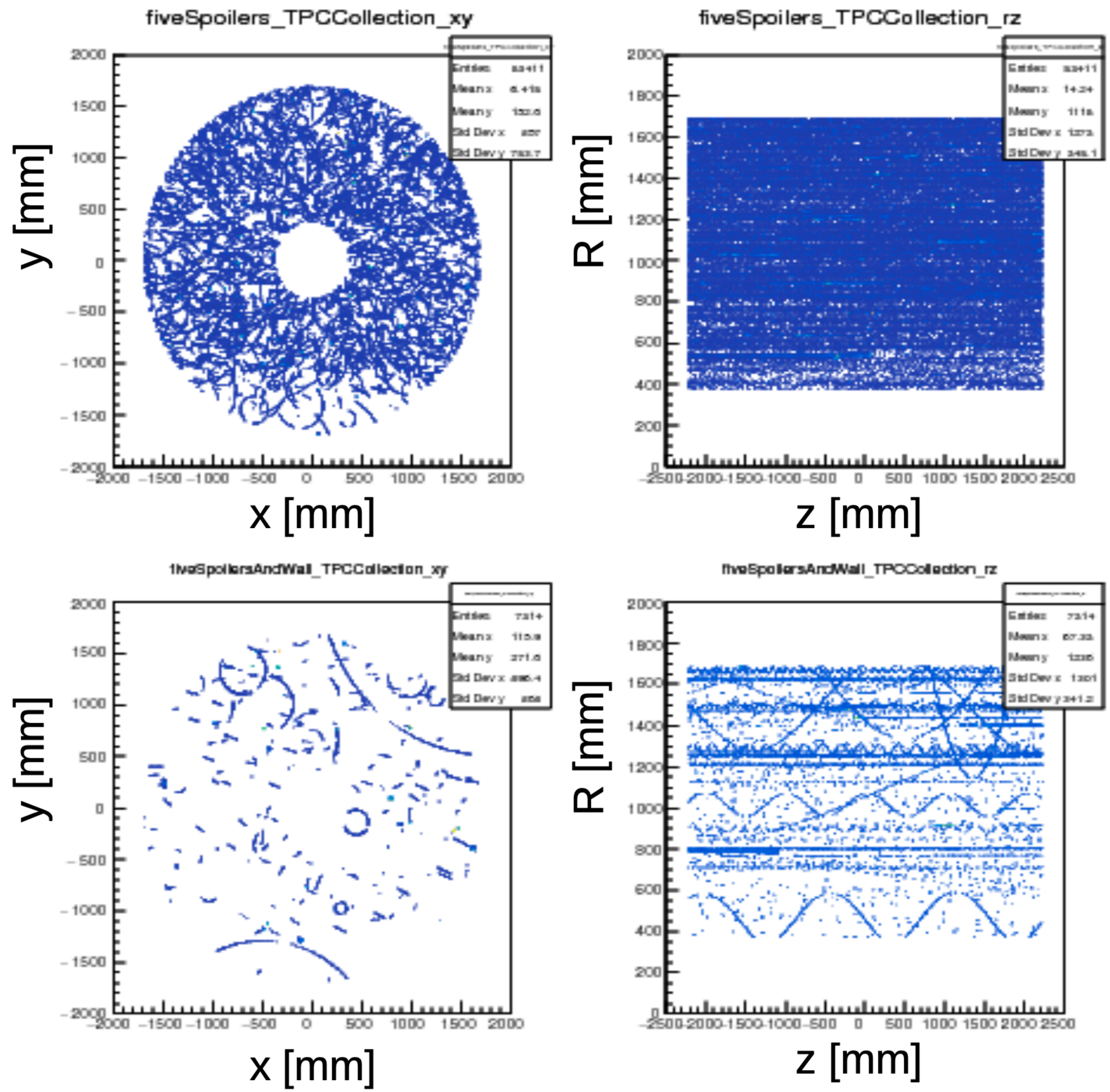


- Every collimator will have beam scrape events, which produces muon
- These muons will propagate down the accelerator complex towards the experimental area
  - If these muons make it to the detector they can spoil missing momentum measurements if in the calorimetry
  - Likewise can create spurious tracks in the tracker

Effects in-detector @ ILC + ILD (not C3 and SiD! Divide by 10)

5 spoilers

5 spoilers
+ wall



muons largely parallel to TPC drift:
affect only a few readout pads

D. Jeans

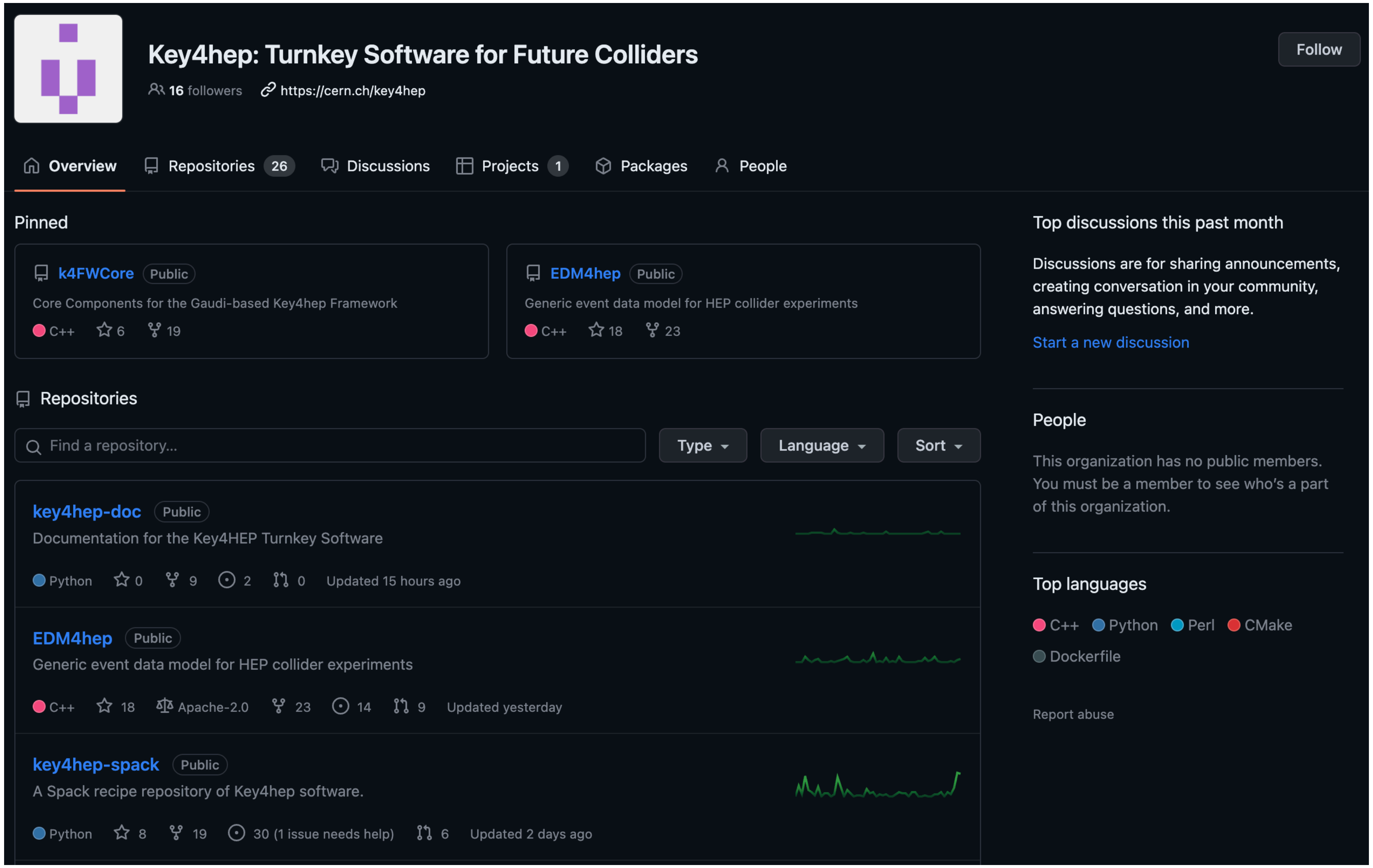
Accelerator Muon Estimates are Extremely Bespoke

- They depend on the configuration of the accelerator itself and so require the specification of the complex accelerator structure
- The ILC studies were done with a program called “MuCarlo” that uses a parametrized / analytical implementation of the muon production cross section from this process
  - Can be cross checked with radiation transport programs like Fluka, MARS, CAIN
- We are working to resurrect this program for C3 and replace its structures near the final focus magnets with those expected for C3
  - Right now the code, which was implemented for ILC for a specific study, exists on one computer at SLAC.
  - We are working to get it in a functional state!

Geant Demonstration

A look towards the future of the effort: key4hep

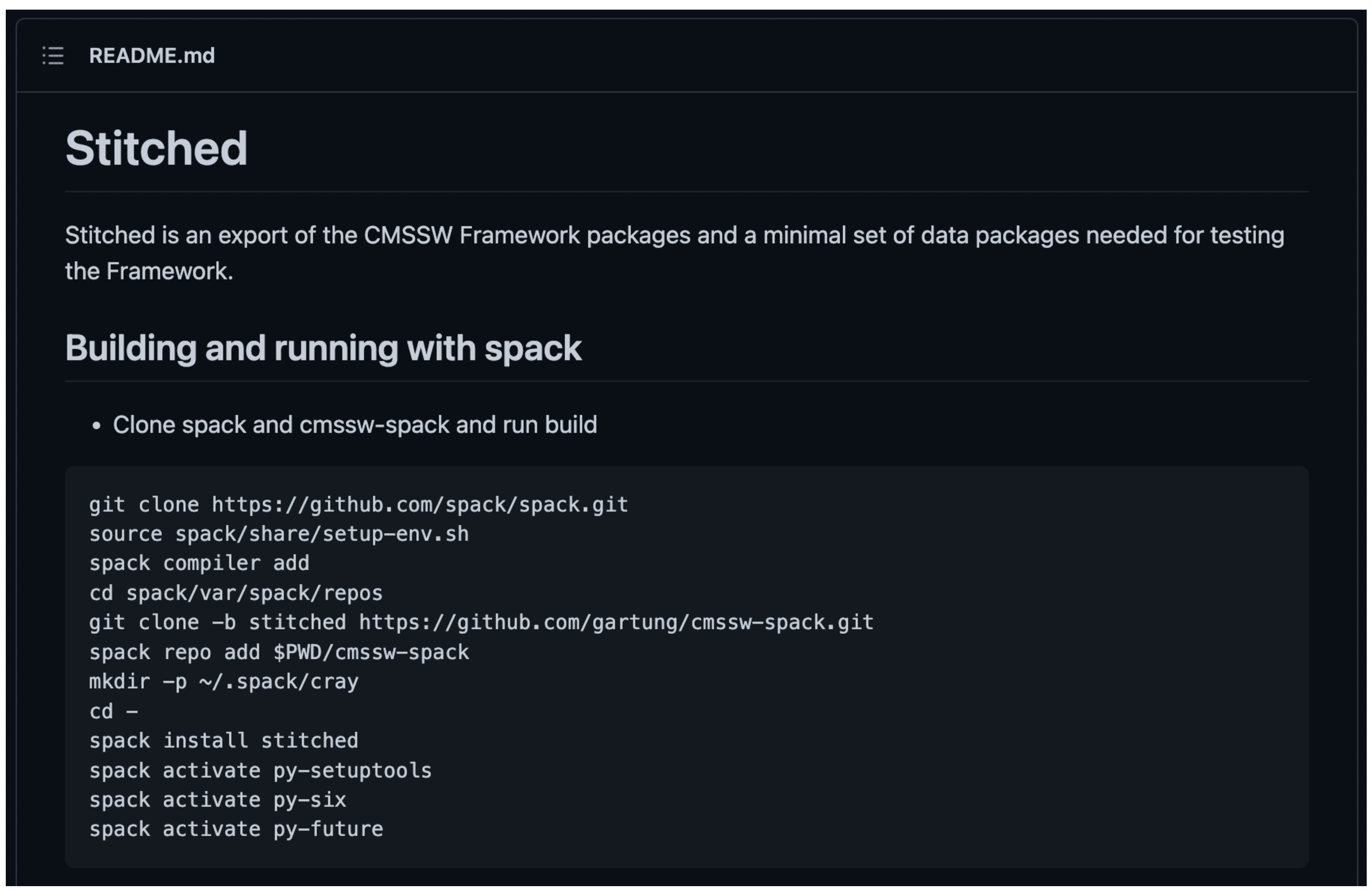
- This is a meta-framework for various future colliders
- It aims to be a common software repository with fully-featured simulation and reconstruction framework tooling, currently based on gaudi or marlin.
- This effort would significantly benefit from more collaborators.



Fermilab

A look towards the future of the effort: stitched

- An effort is coming together to use the knowledge gained in CMS to implement statistically accurate and scalable pileup mixing
  - Stitched, an experiment agnostic derivation of CMSSW, contains all the essentials needed to build a modern, multithreaded framework from code that is battle hardened for (HL-)LHC data and simulation.
  - Aim to integrate stitched in key4hep, and bring CMS-style pileup mixing to all future colliders (FCC, MuC, also interested!)



README.md

Stitched

Stitched is an export of the CMSSW Framework packages and a minimal set of data packages needed for testing the Framework.

Building and running with spack

- Clone spack and cmssw-spack and run build

```
git clone https://github.com/spack/spack.git
source spack/share/setup-env.sh
spack compiler add
cd spack/var/spack/repos
git clone -b stitched https://github.com/gartung/cmssw-spack.git
spack repo add $PWD/cmssw-spack
mkdir -p ~/.spack/cray
cd -
spack install stitched
spack activate py-setuptools
spack activate py-six
spack activate py-future
```

Next Steps / Conclusions

- C3 is a new collider design that is a significant departure from ILC
  - Different bunch structure, charge, machine dynamics
  - In order to optimize a detector for this new machine we need to recreate studies that have been done in the past to estimate occupancies and anticipate electronics challenges in this new design
- You've seen here that we have the tools to simulate the necessary backgrounds with the generators we have available
  - Preliminary indications that backgrounds are manageable with modern technology
  - There are many directions, regenerating these decade-old studies is often not easy work
  - If you're interested in studying this, we're here to help you get started!
  - We intend to work on detector optimization studies this summer using the tools shown
- We are planning to work on moving to using key4hep as the framework for our simulation
  - This framework is shared with MuC, FCC, ILC, and other designs
  - It is in its infancy, and contributions are welcome
  - Jointly between FCC/MuC/C3 we intend to bring experience and accumulated knowledge of CMSSW via the stitched project to future colliders
- There is much work ahead of us, come join in the fun!