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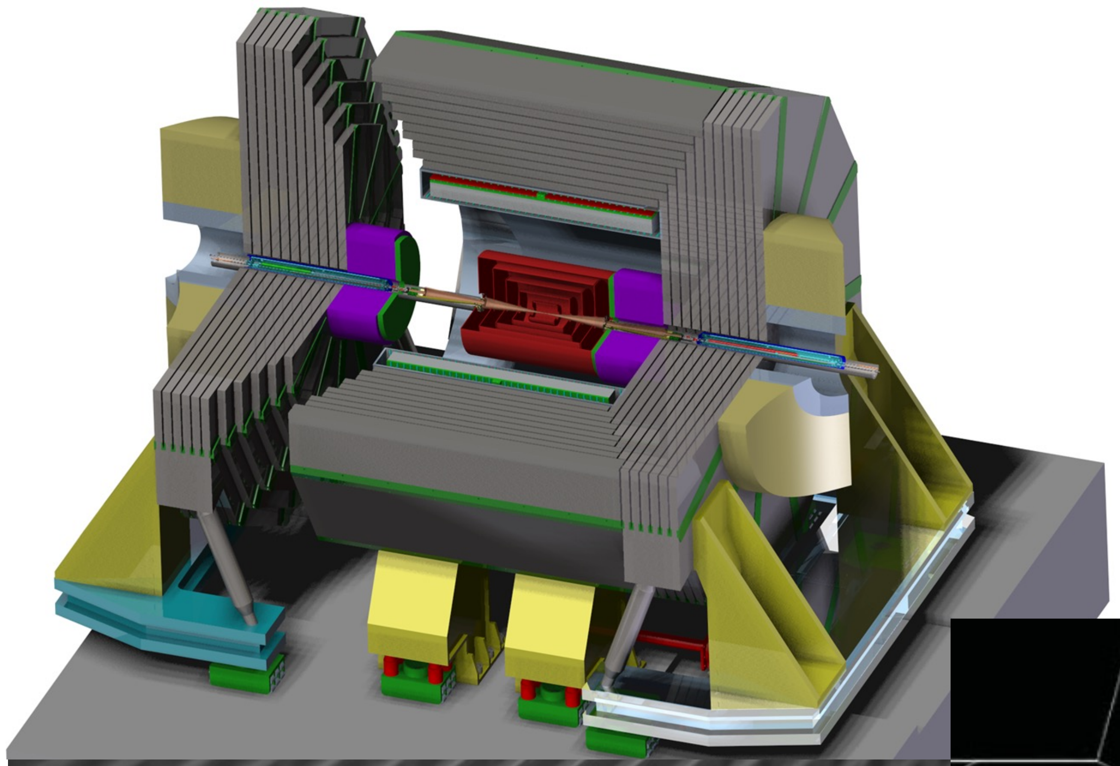
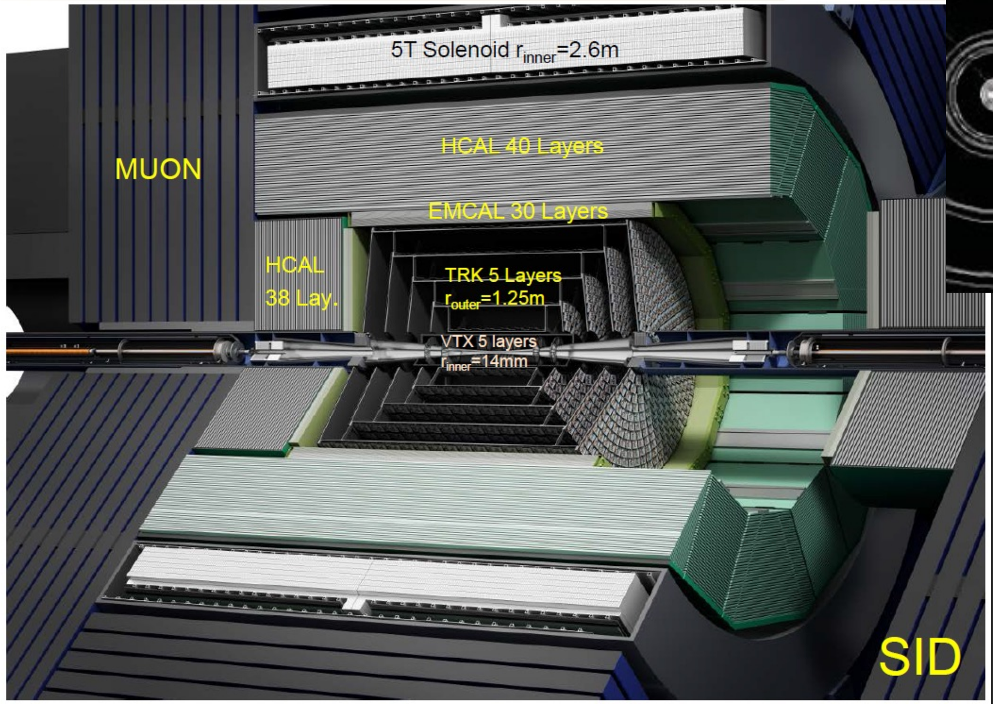


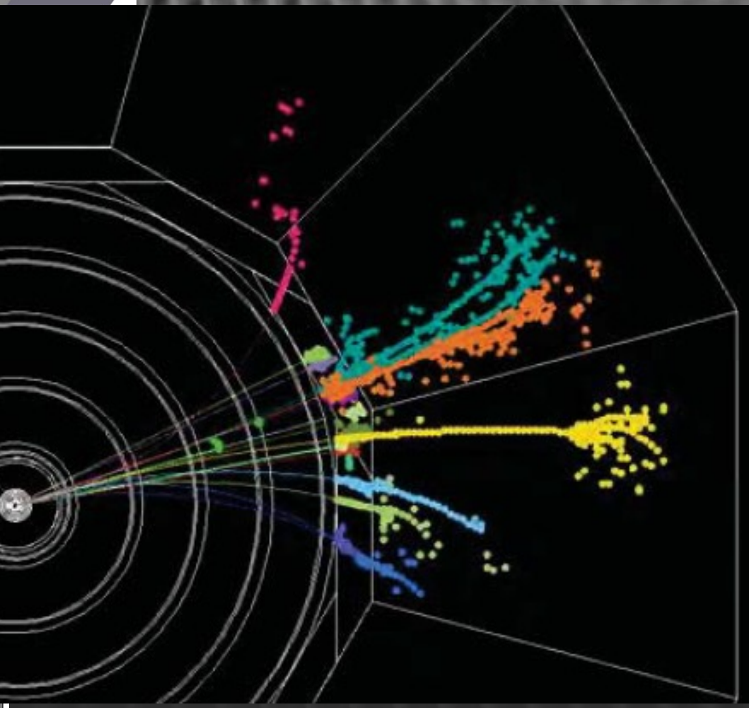
SiD -- overview over current designs and R&D opportunities

October 13, 2022

Jan Strube, PNNL / University of Oregon

On behalf of the SiD Consortium
(Spokespersons: M. Stanitzki, A.White)





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The SiD Detector and the SiD Consortium

SiD Detector

- SiD Design Study started 2003 ECFA LC Workshop (Amsterdam)
  - SLAC-PUB-11413
- Validated by International Detector Advisory Group in 2009
- Can deliver the ILC Physics Program as configured

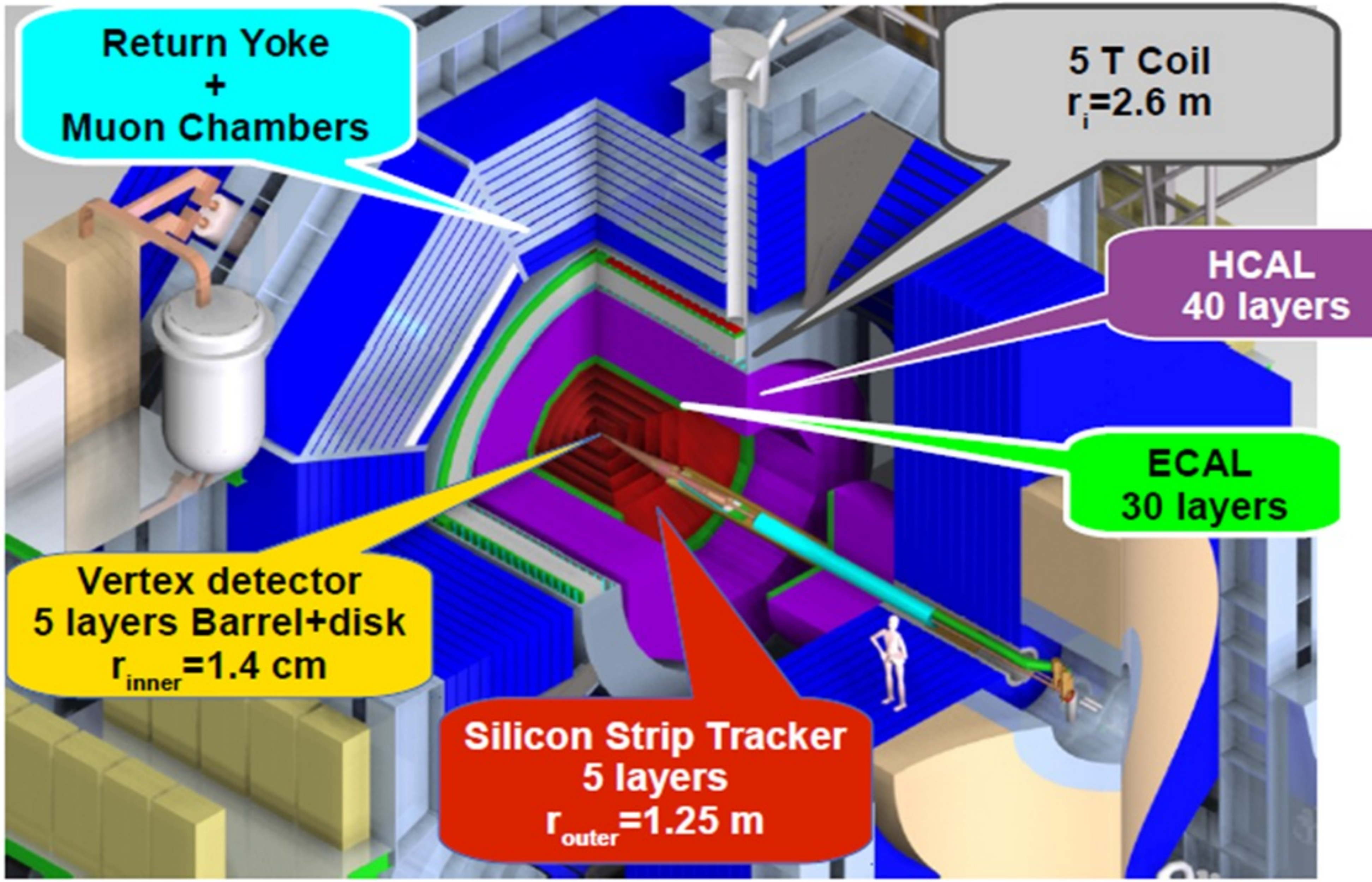
SiD Consortium

- since 2013
- Byelaws
- Individual and institutional memberships (guest membership available)
- IB Chair – Phil Burrows (U. Oxford)

A design to meet the physics performance

Physics Process	**Measured Quantity**	**Critical System**	**Critical Detector Characteristic**	**Required Performance**
$H \to b\bar{b}, c\bar{c}, gg, \tau\tau$ $b\bar{b}$	Higgs branching fractions b quark charge asymmetry	Vertex Detector	Impact parameter ⇒ Flavor tag	$\delta_b \sim 5\mu m \oplus 10\mu m/(p\sin^{3/2}\theta)$
$ZH \to \ell^+\ell^- X$ $\mu^+\mu^-\gamma$ $ZH + H\nu\bar{\nu} \to \mu^+\mu^- X$	Higgs Recoil Mass Lumin Weighted E_{cm} BR ($H \to \mu\mu$)	Tracker	Charge particle momentum resolution, $\sigma(p_t)/p_t^2$ ⇒ Recoil mass	$\sigma(p_t)/p_t^2 \sim few \times 10^{-5} GeV^{-1}$
ZHH $ZH \to q\bar{q}b\bar{b}$ ZH→ZWW* $\nu\bar{\nu}W^+W^-$	Triple Higgs Coupling Higgs Mass BR ($H \to WW^*$) $\sigma(e^+e^- \to \nu\nu W^+W^-)$	Tracker & Calorimeter	Jet Energy Resolution, σ_E/E ⇒ Di-jet Mass Res.	~3% for $E_{jet} > 100$ GeV $30\%/\sqrt{E_{jet}}$ for $E_{jet} < 100$ GeV
SUSY, eg. $\tilde{\mu}$ decay	$\tilde{\mu}$ mass	Tracker, Calorimeter	Momentum resolution, Hermiticity ⇒ Event Reconstruction	Maximal solid angle coverage

SiD Design Overview



Return Yoke + Muon Chambers

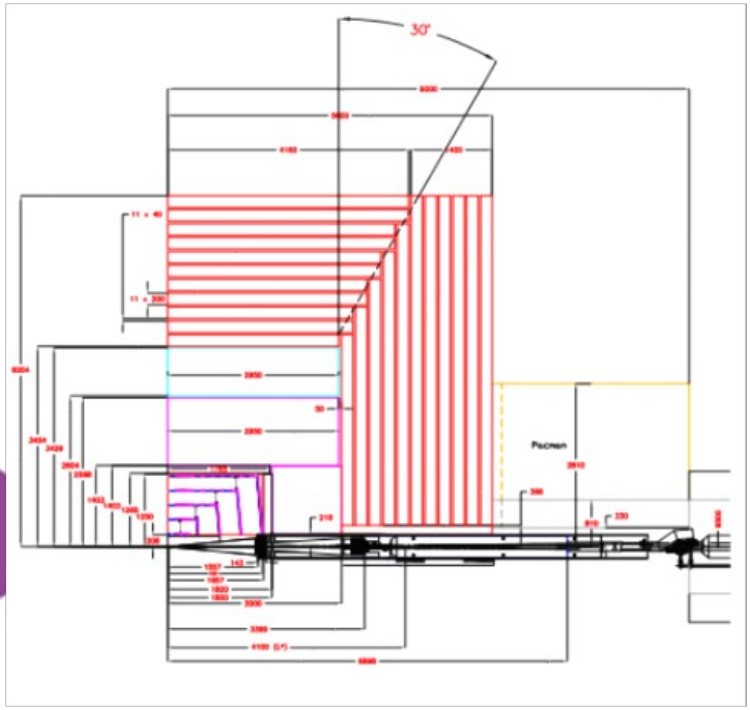
5 T Coil r_i=2.6 m

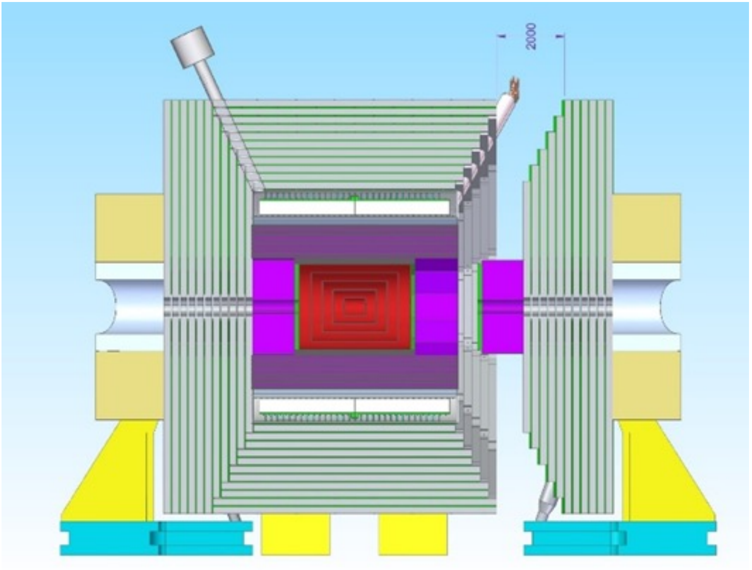
HCAL 40 layers

ECAL 30 layers

Vertex detector 5 layers Barrel+disk r_{inner}=1.4 cm

Silicon Strip Tracker 5 layers r_{outer}=1.25 m





The SiD Design Rationale

A compact, cost-constrained detector designed to make precision measurements and be sensitive to a wide range of new phenomena.

Design basics:

Robust silicon vertexing and tracking system – excellent momentum resolution, live for single bunch crossings.

Highly segmented “tracking” calorimeters optimized for Particle Flow.

Compact design with 5T field.

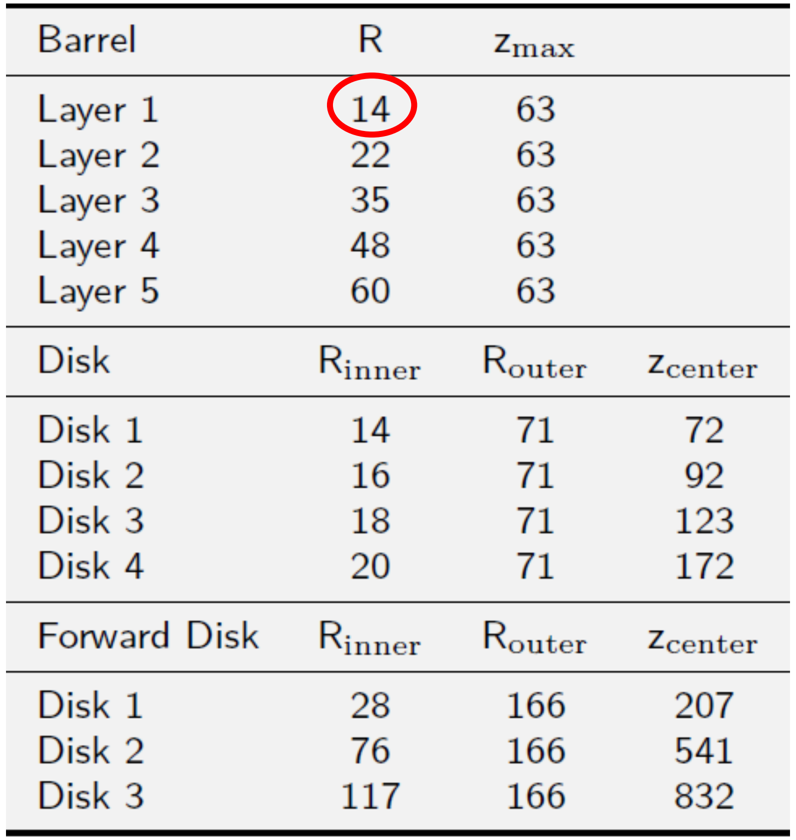
Iron flux return/muon identifier – component of SiD self-shielding.

Detector is designed for rapid push-pull operation.

Key Detector Design Parameters

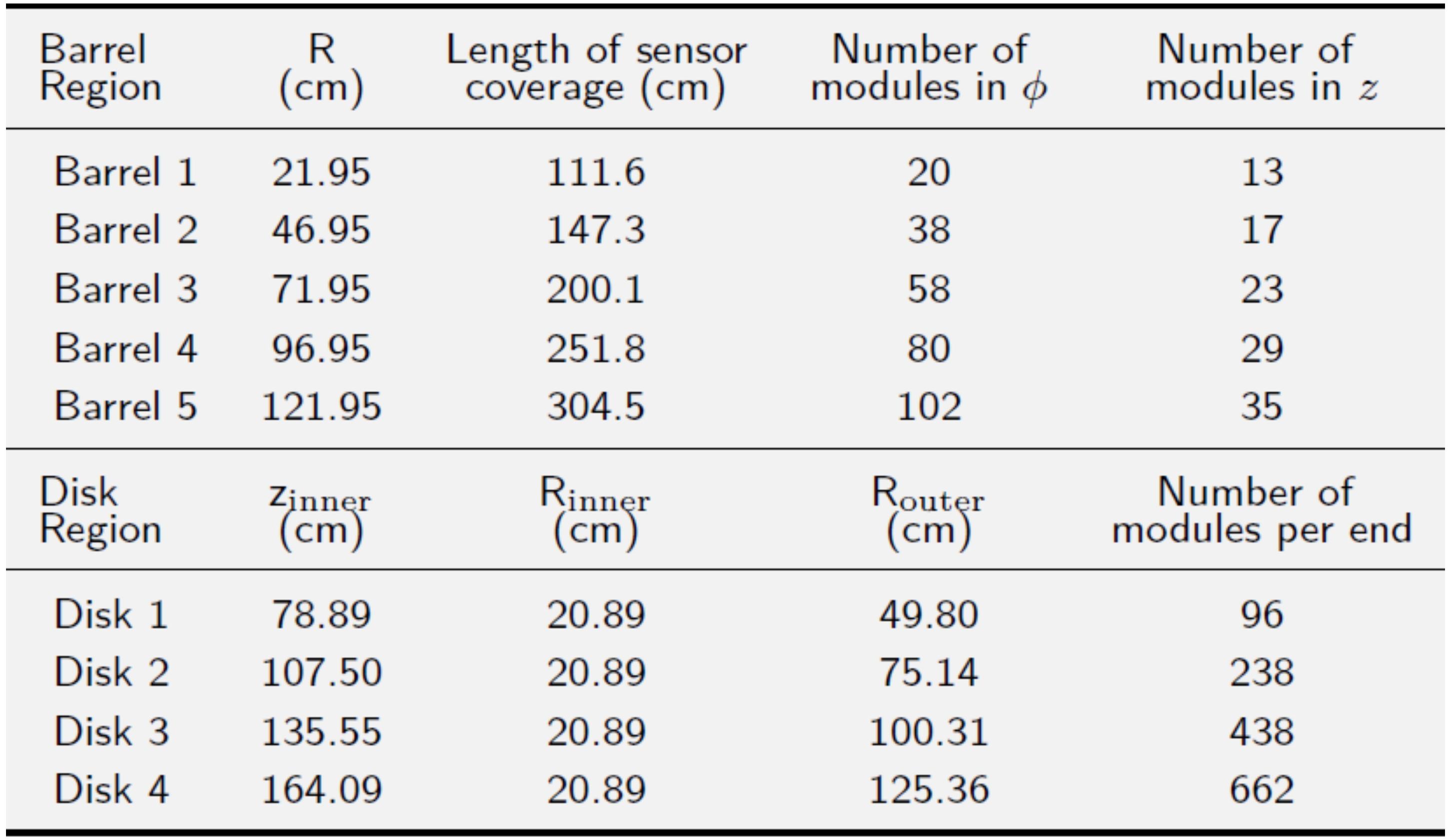
https://arxiv.org/abs/1306.6329

Vertex Detector



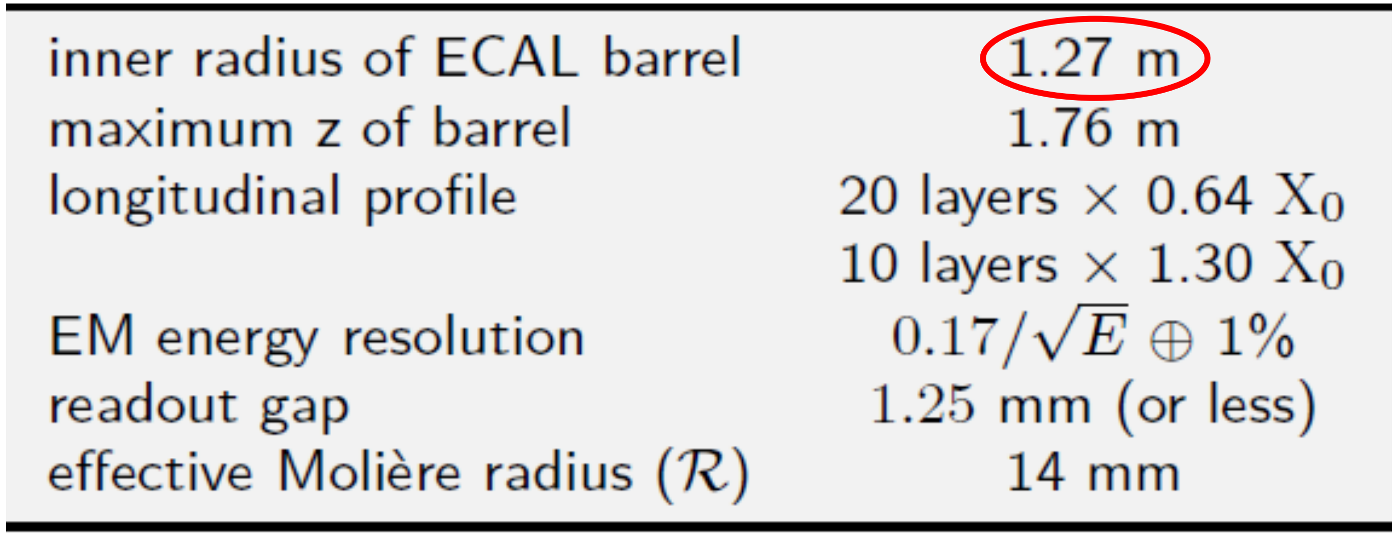
Barrel	R	z_{max}	
Layer 1	14	63	
Layer 2	22	63	
Layer 3	35	63	
Layer 4	48	63	
Layer 5	60	63	
Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	14	71	72
Disk 2	16	71	92
Disk 3	18	71	123
Disk 4	20	71	172
Forward Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	28	166	207
Disk 2	76	166	541
Disk 3	117	166	832

Main Tracker

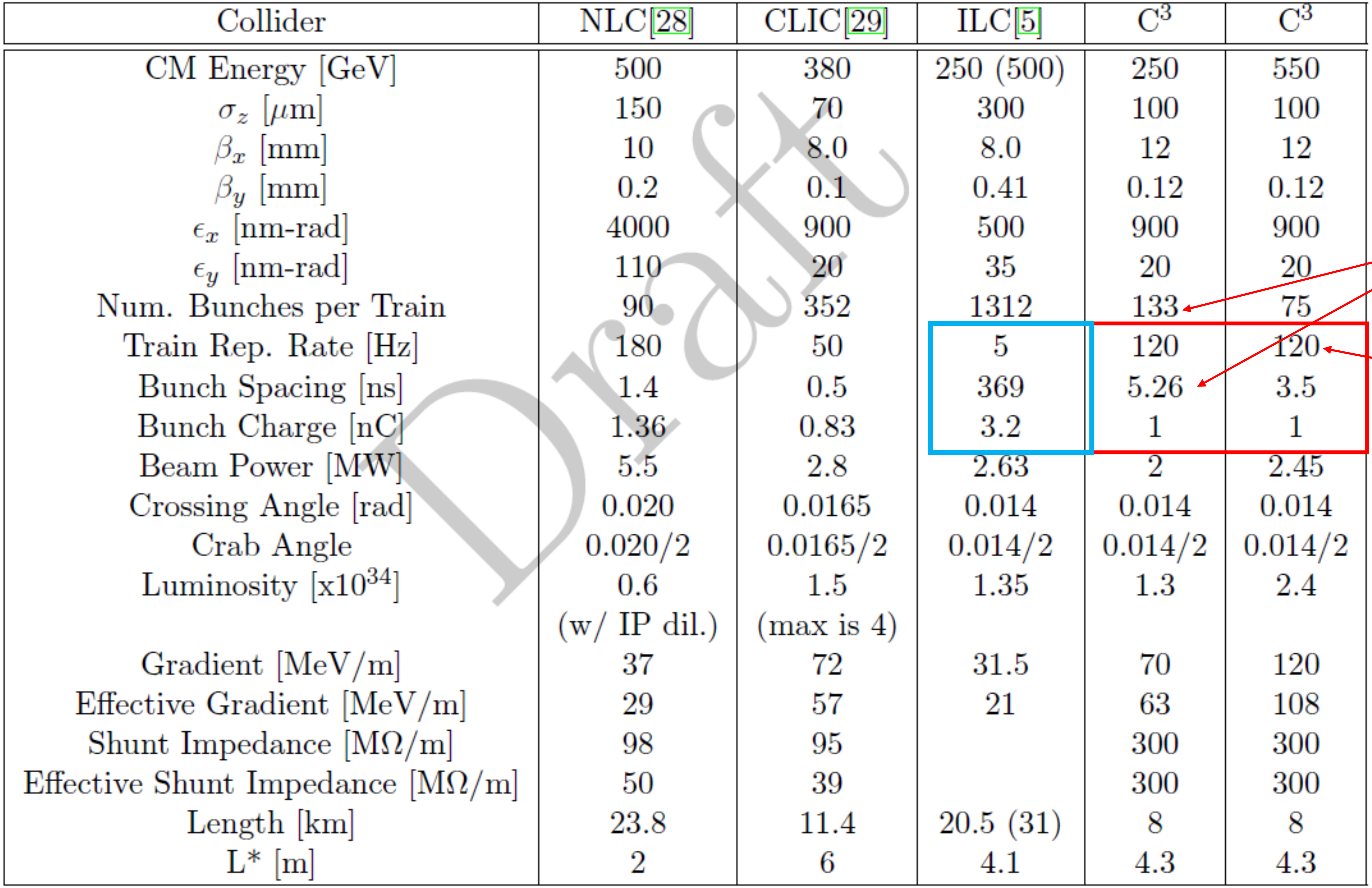


Barrel Region	R (cm)	Length of sensor coverage (cm)	Number of modules in ϕ	Number of modules in z
Barrel 1	21.95	111.6	20	13
Barrel 2	46.95	147.3	38	17
Barrel 3	71.95	200.1	58	23
Barrel 4	96.95	251.8	80	29
Barrel 5	121.95	304.5	102	35
Disk Region	z_{inner} (cm)	R_{inner} (cm)	R_{outer} (cm)	Number of modules per end
Disk 1	78.89	20.89	49.80	96
Disk 2	107.50	20.89	75.14	238
Disk 3	135.55	20.89	100.31	438
Disk 4	164.09	20.89	125.36	662

Electromagnetic Calorimeter



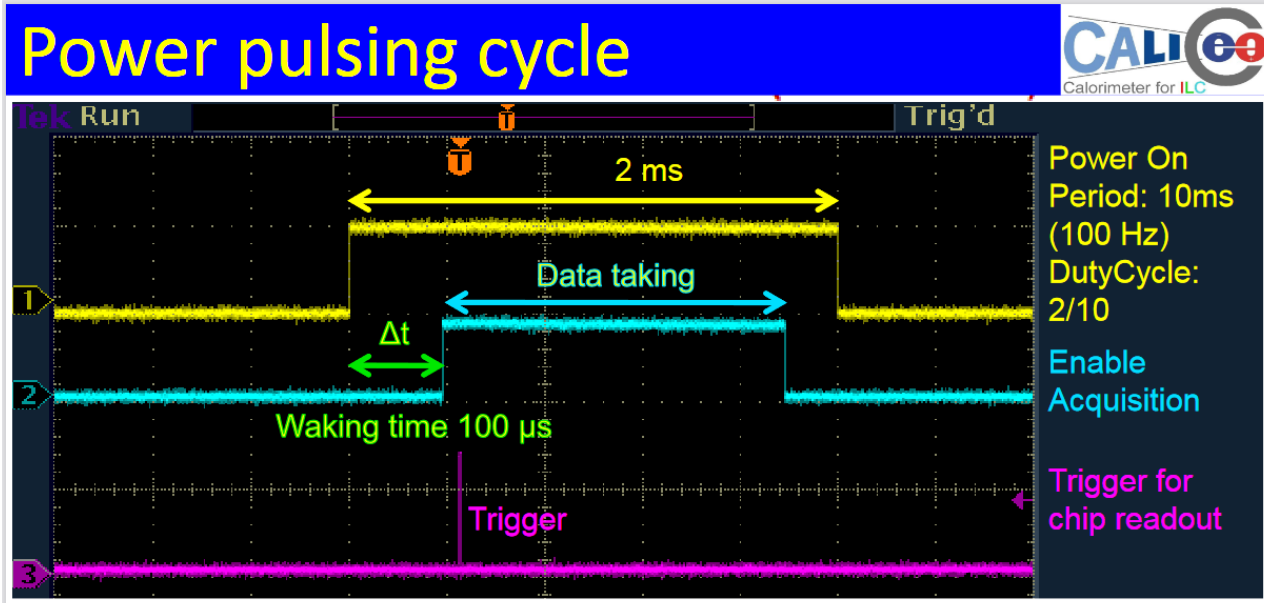
inner radius of ECAL barrel	1.27 m
maximum z of barrel	1.76 m
longitudinal profile	20 layers × 0.64 X_0
	10 layers × 1.30 X_0
EM energy resolution	$0.17/\sqrt{E} \oplus 1\%$
readout gap	1.25 mm (or less)
effective Molière radius ($\mathcal{R}$)	14 mm



Collider	NLC[28]	CLIC[29]	ILC[5]	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
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Beam Power [MW]	5.5	2.8	2.63	2	2.45
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Crab Angle	0.020/2	0.0165/2	0.014/2	0.014/2	0.014/2
Luminosity [x10^{34}]	0.6 (w/ IP dil.)	1.5 (max is 4)	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Shunt Impedance [MΩ/m]	98	95		300	300
Effective Shunt Impedance [MΩ/m]	50	39		300	300
Length [km]	23.8	11.4	20.5 (31)	8	8
L* [m]	2	6	4.1	4.3	4.3

700 ns Flat top every 8.3 ms

Power Pulsing


Power pulsing cycle

- ILC – 5 Hz. “On” for ~1ms , “off” for 199ms
- ILC – allow few ms for acquisition
- C^3 – 120 Hz -> bunch train (133 bunches x 5.26ns = 700 ns) every 8.3ms
- C^3 – few µs for power on/off. EMI effects? Pulsing in 5T field?

Vertex Detector Requirements

- Studying the interplay between the Higgs sector and the flavor sector
  ⇔efficient reconstruction of secondary vertices
  == jet tagging
- Vertex detector requirements:

$$\sigma_{ip} = 5\ \mu m \oplus \frac{10}{p\beta \sin\theta^{3/2}}\ \mu m.GeV/c$$

https://pos.sissa.it/287/047/pdf

- These **very** challenging requirements constrain
  - the material / cooling budget
  - the pixel size
  - the inner radius of the detector / occupancy / time stamping

Channel	SM BR (%)
H → bb	58.24
H → ττ	6.272
H → μμ	0.02176
H → cc	2.891
H → gg	8.187
H → WW	21.37
H → ZZ	2.619

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Impact of the machine-induced background the vertex detector design

arXiv:1609.07816

ILC Beam environment:

Bunch crossing rate (Collisions rate) ~3 MHz
Number of bunches in bunch train up to ~3000
(first 250 GeV stage 1312)
Bunch trains interval – 200 ms. (5 Hertz)

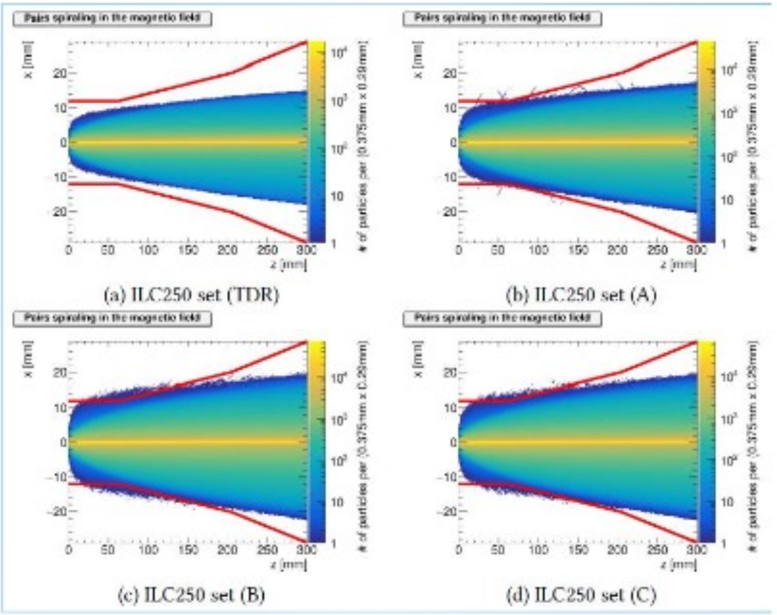
5T field allows first layer to be very close to the beam.

R_{min} = 14mm.

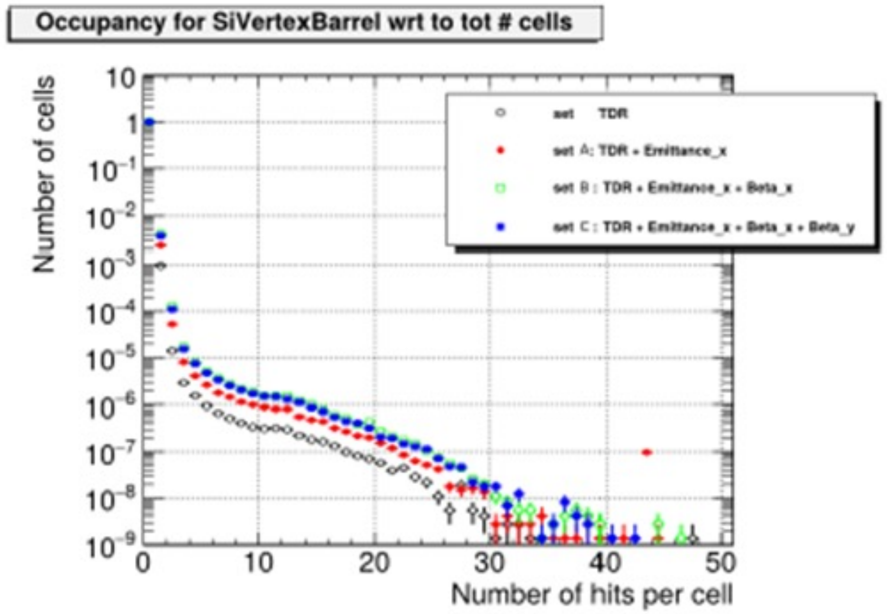
Pair background/Occupancy study

Very challenging requirements

- < 3 μm hit resolution
- Feature size ~20 μm
- ~0.1% X_0 per layer material budget
- < 130 μW / mm^2
- Single bunch time resolution



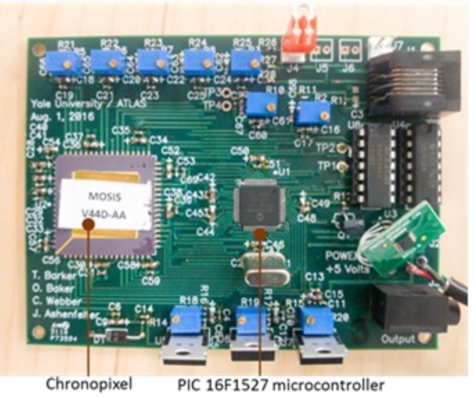
(a) ILC250 set (TDR)
(b) ILC250 set (A)
(c) ILC250 set (B)
(d) ILC250 set (C)



SiD Tracking: A robust, low-material, high-precision silicon system vertex detector

Three prototypes studied

Chronopixel prototype 3 development board



- monolithic CMOS design
  90 nm feature size,
  7 µm epitaxial layer
  280 µm thick chip
  10 ohm·cm
  manufactured by TSMC
- store up to 2 hits per pixel, 12 bit per timestamps
- 25 µm pixel pitch
- implements 6 sensor diode options

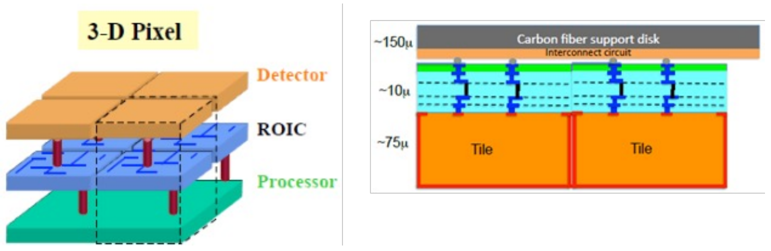
Chronopixel - Oregon, Yale

N. Sinev et al., PoS VERTEX 2015, 038 (2015)

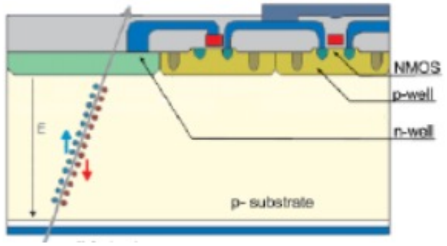
Following a multi-year R&D effort, Chronopixel prototype 3 demonstrated a working ILC CMOS vertex sensor that satisfies the ILC design requirements.

Possible alternatives

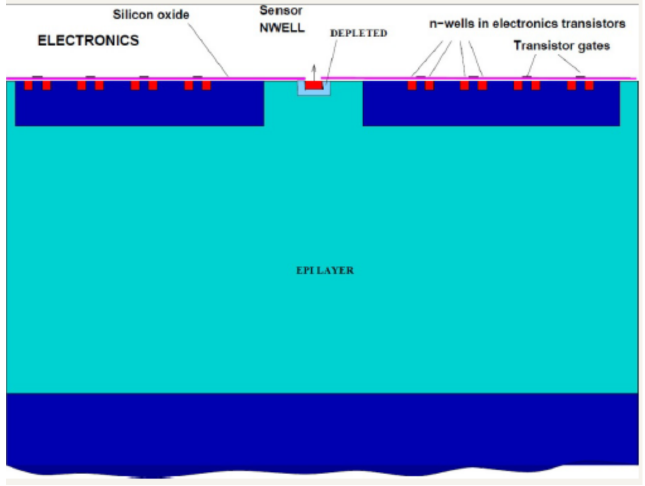
Vertically Integrated (“3D”)



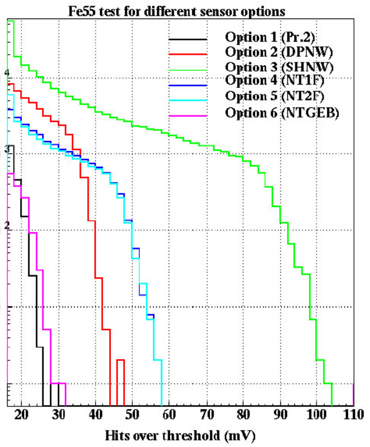
HV CMOS



Option 3 – shallow N-WELL



Best option, but more studies needed

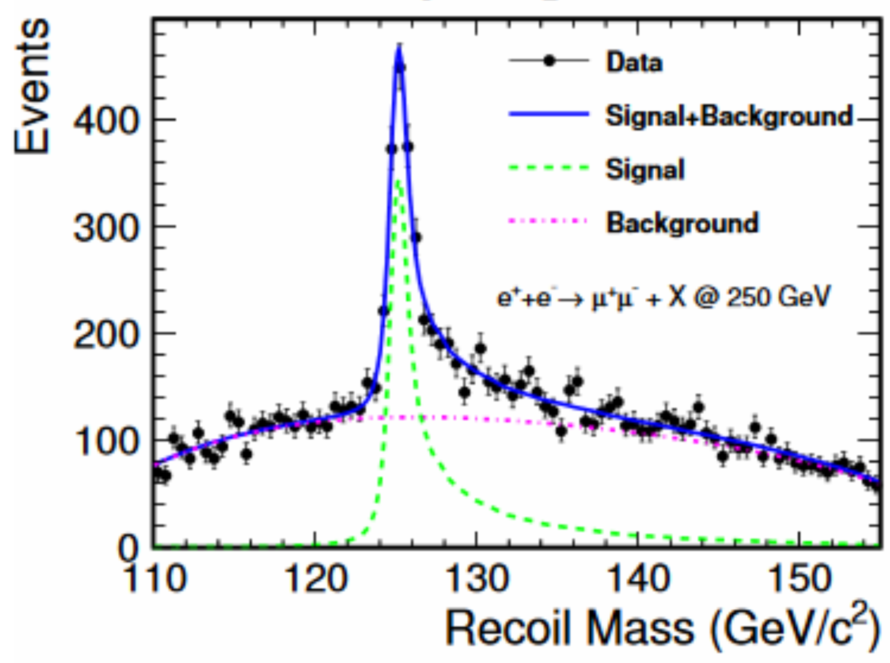


diode option	Capacitance (fF)	µV/e
1	9.0	18
2	6.2	26
3	2.7	59
4	4.9	33
5	4.9	33
6	8.9	18

Option #	Noise r.m.s (mV)	Noise r.m.s (# electrons)
1	1.12	63
2	1.08	42
3	1.7	29
4	1.21	37
5	1.23	38
6	0.98	54

Parameter	ILC Requirement	Prototype Tests
Detector Sensitivity	10 µV/electron	59 µV/electron
Detector Noise	25 electrons	29 electrons
Comparator Accuracy	0.2 mV RMS	0.2 mV RMS
Sensor Capacitance	10 fF	2.7 fF
Clocking Speed	3.3 MHz	7.3 MHz
Charge collection time	300 nsec	20 nsec
Readout Rate	25 Mbits/sec	25 Mbits/sec
Power Consumption	0.13 mW/mm²	OK by estimate
Radiation Hardness	10^{11} neutrons/cm²/yr	10^{13}neutrons/cm² or 110 Mrad

Tracking requirements


Physics goal

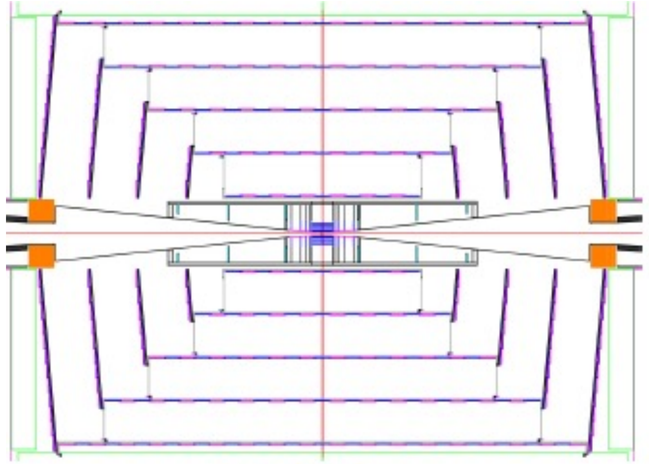
Physics

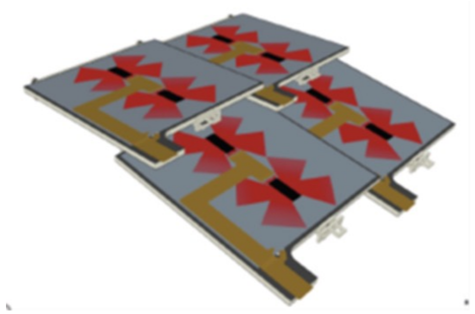
- Excellent momentum resolution $\Delta(1/p) < 5 \times 10^{-5}\ (\mathrm{GeV}/c)^{-1}$
  - Z →μμ, support particle flow at high energy
- Provide integrated pattern recognition with the vertex detector
- Be resilient to background
- Achieve excellent track reconstruction efficiency (> 90%) and low fake rate

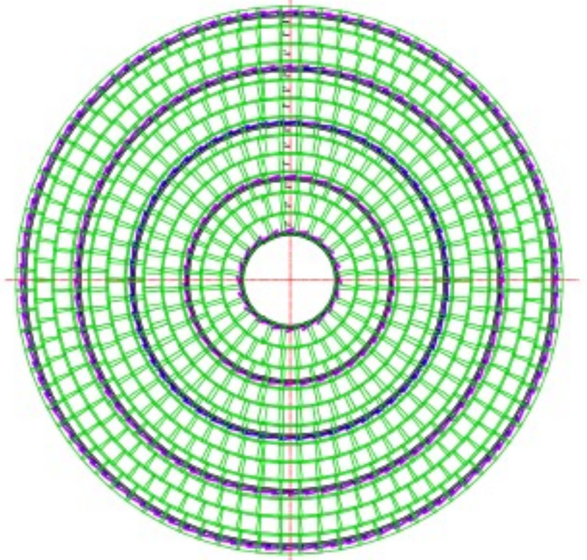
Design

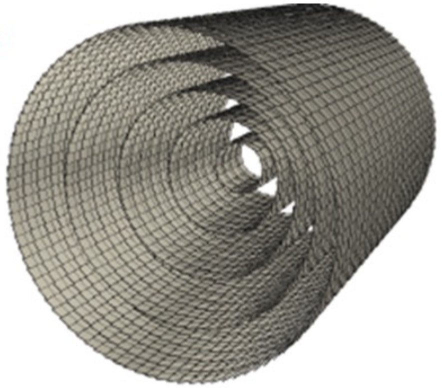
- Support power pulsing in a 5T field
  - Power and data distribution
- Achieve low material budget ➔ gaseous cooling and low-mass support

SiD Silicon (Strip) Tracker









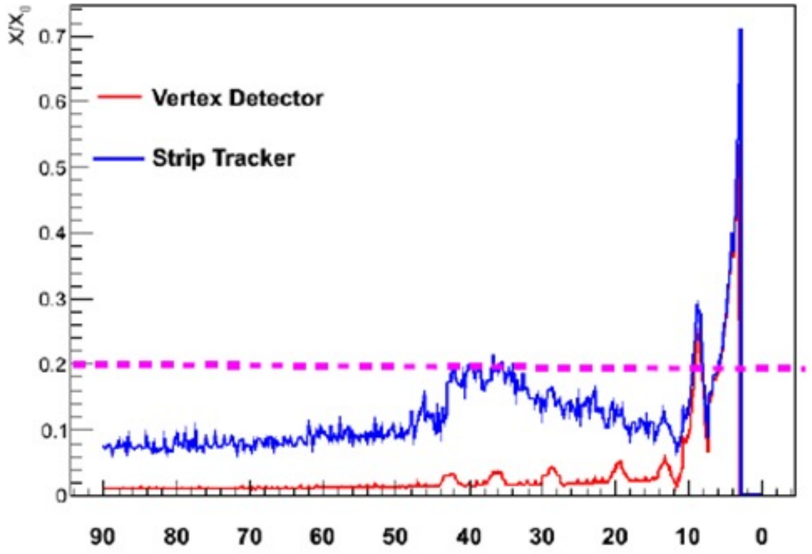
Baseline

- All Silicon Tracker
  - Using Silicon micro-strips
    - 25 µm pitch / 50 µm readout
    - v2 sensor prototype July 2017*
- 5 barrel layers / 4 disks
- Tracking unified with vertex detector
  - 10 layers in barrel
- Gas-cooled
- Material budget < 20% X_0 in the active region
- Readout using KPiX ASIC
  - Same readout as ECAL
  - Bump-bonded directly to the module

MAPS/Pixel tracker option

kPixM – optimized for tracker,
25µm x 500µm pixels.
Position resolution < 10µm,
S/N > 20
Future initiative: SLAC/UO/DESY
for MAPS tracker development.

Instruments **2022**, *6*(4), 51



- Pixel tracker option and alignment methods (Bristol)
- Carbon fiber structures for low material, integrated services (Oxford, Lancaster, Liverpool)

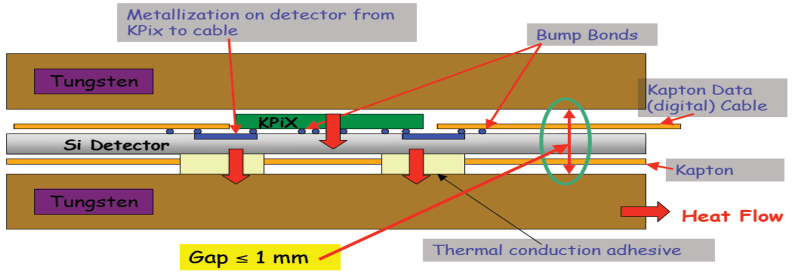
arXiv:1703.08605 [physics.ins-det]
J. Phys. Conf. Ser. 1162, no. 1, 012016 (2019)

SiD Electromagnetic Calorimeter

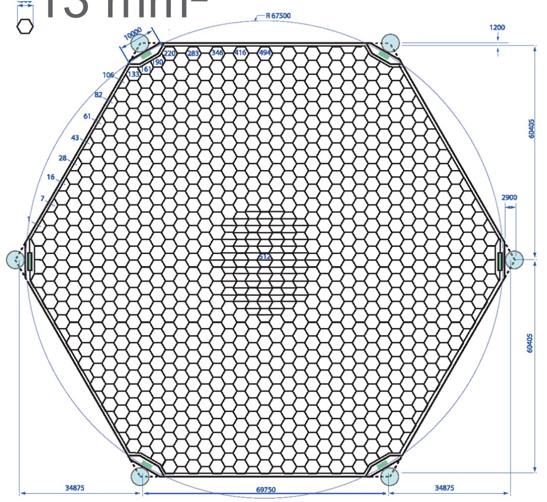
Highly granular "imaging" calorimetry essential for ILC physics program:

- Particle id/reconstruction
- Tracking charged particles
- Integral part of Particle Flow detector design

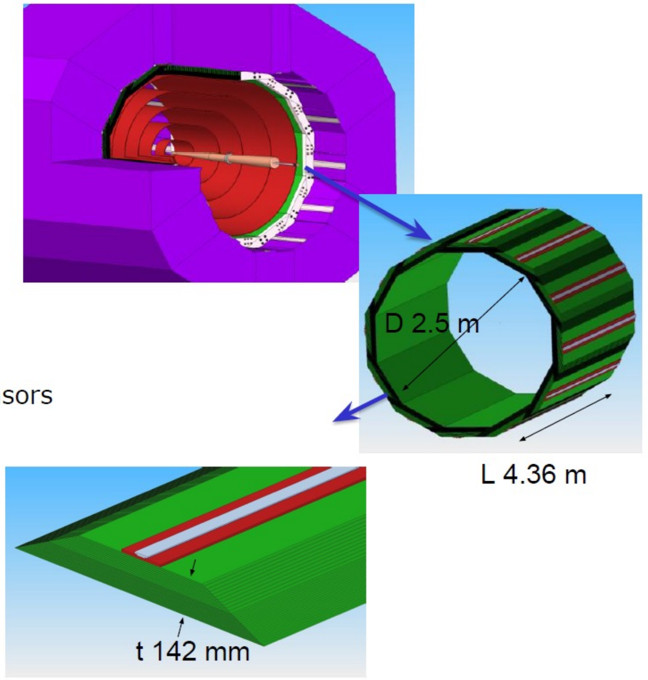
Baseline design: Silicon/Tungsten



1024 pixels
13 mm^2

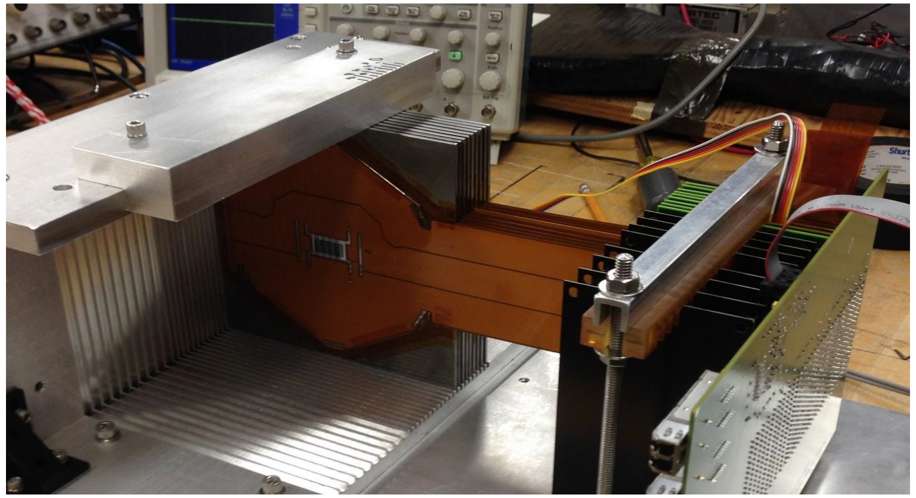


Compact Electromagnetic Calorimeter w 13 mm Moliere Radius

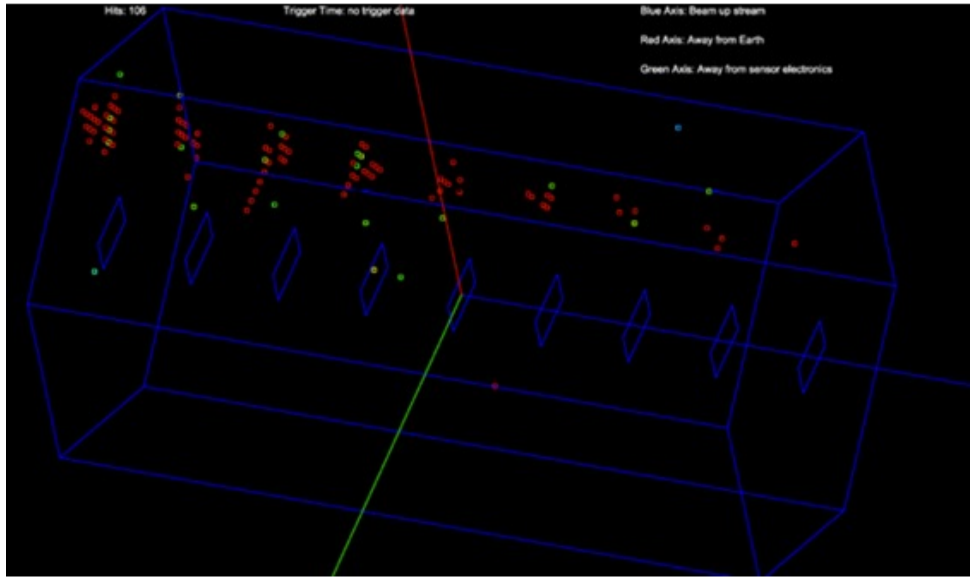


20 layers 2.5 mm W (5/7 X0)
10 layers 5 mm W (10/7 X0)
30 gaps 1.25 mm w Si pixels sensors
29 X_0; 1 λ
ΔE/E = 17%/√E

Beam tests,9-layers, SLAC



Single electron event



Oregon, SLAC, UC Davis

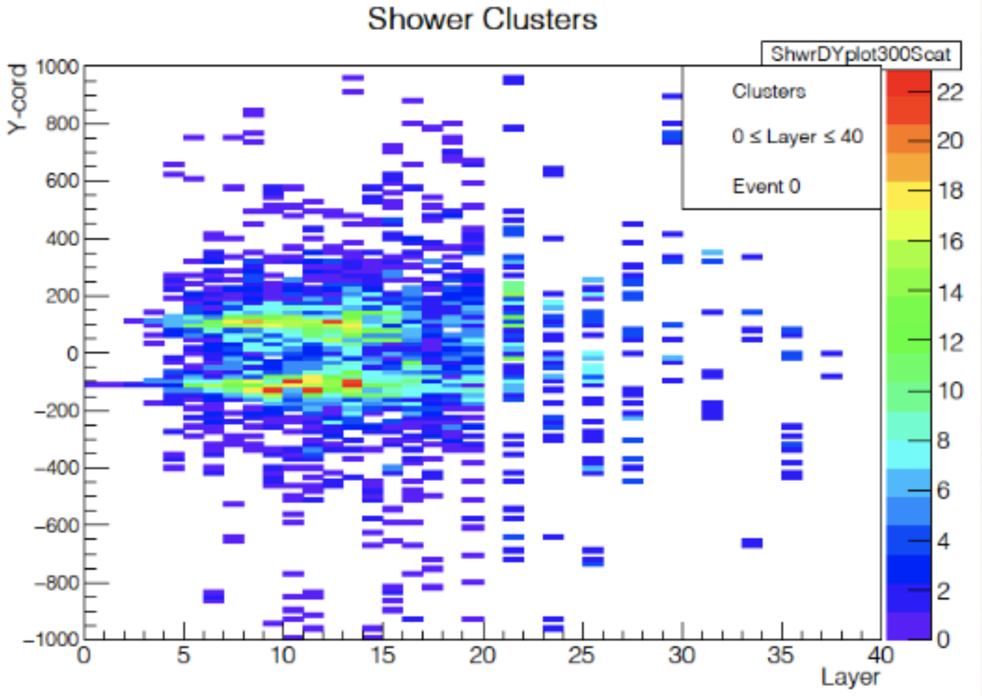
MAPS for SiD ECal

Instruments **2022**, *6*, 51. https://doi.org/10.3390/instruments6040051

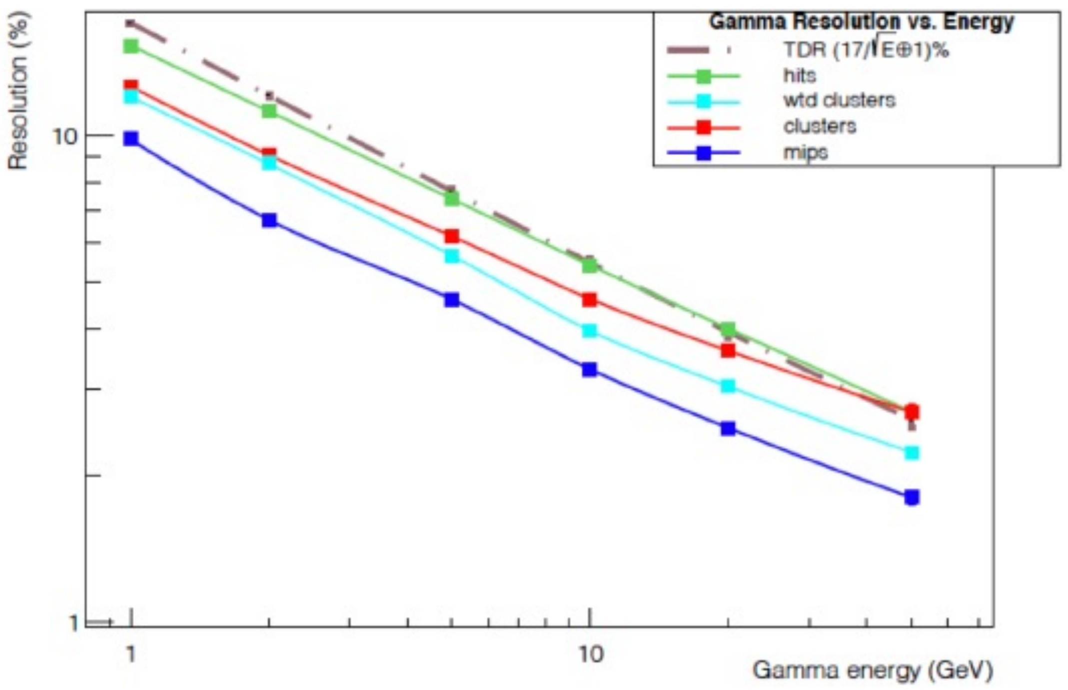
Detailed simulation of digital Si/W ECal using MAPS approach at UOregon

- 20 thin W layers (0.64 X_0), 10 Thick W layers.
- Pixels 25µm x 100 µm (25µm in bend plane)
- MIP counting
- Examples of excellent results – very significant advance on SiD TDR ECal.
- Results are guiding the design of the MAPS sensor
- Benefits of including fast timing?

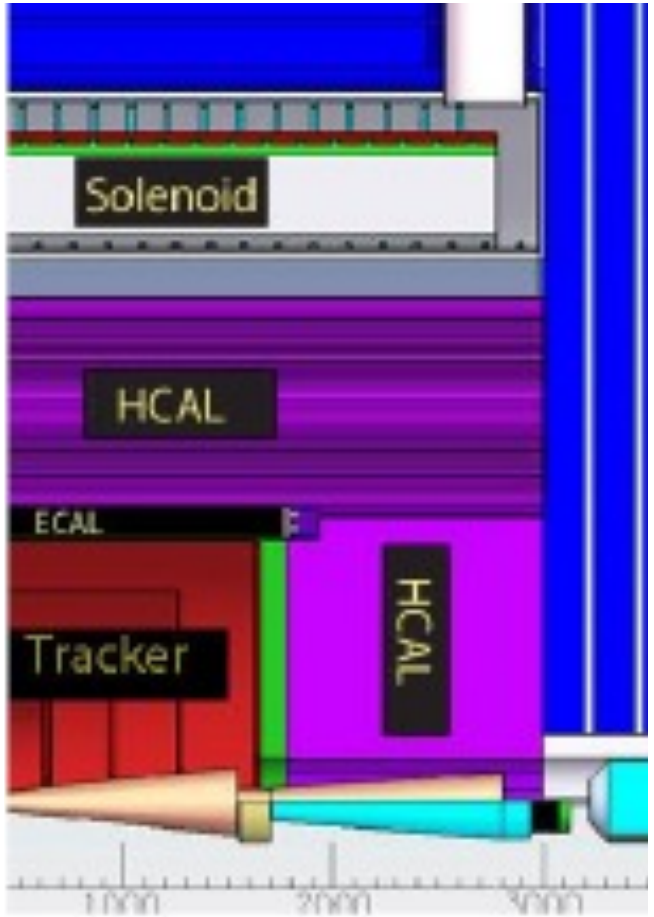
Pixel clusters – 40 GeV π^0 -> two 20 GeV γ

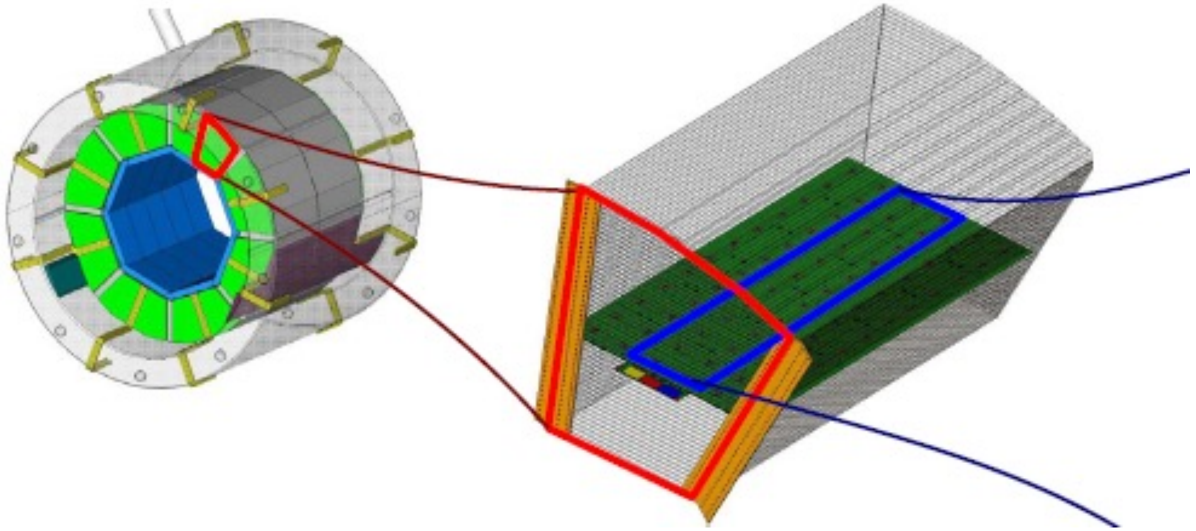


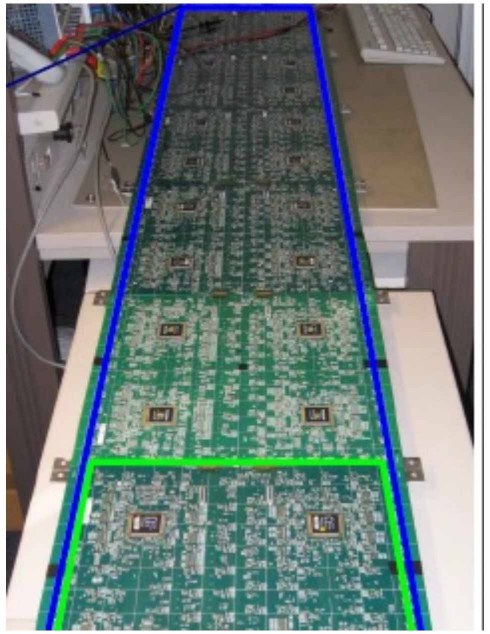
Energy resolution of γ showers



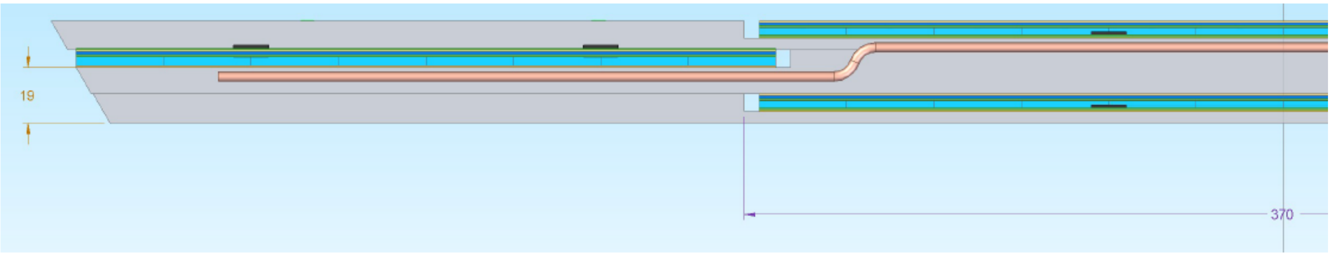
SiD Hadron Calorimeter



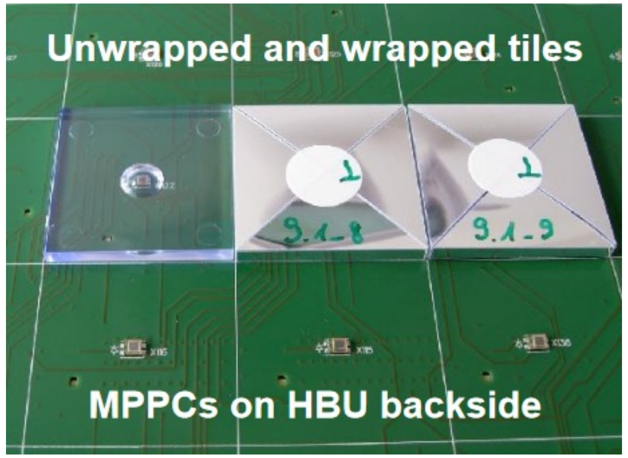




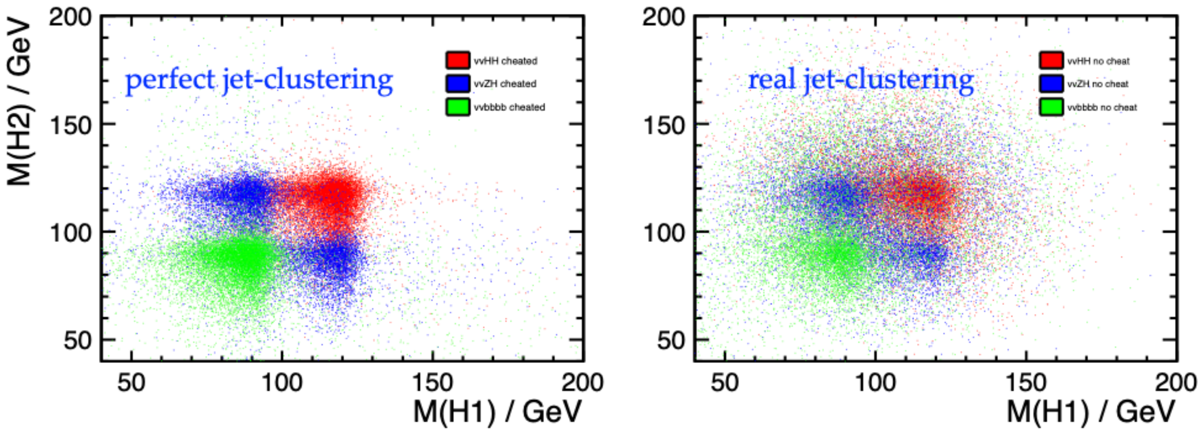
12-fold barrel geometry



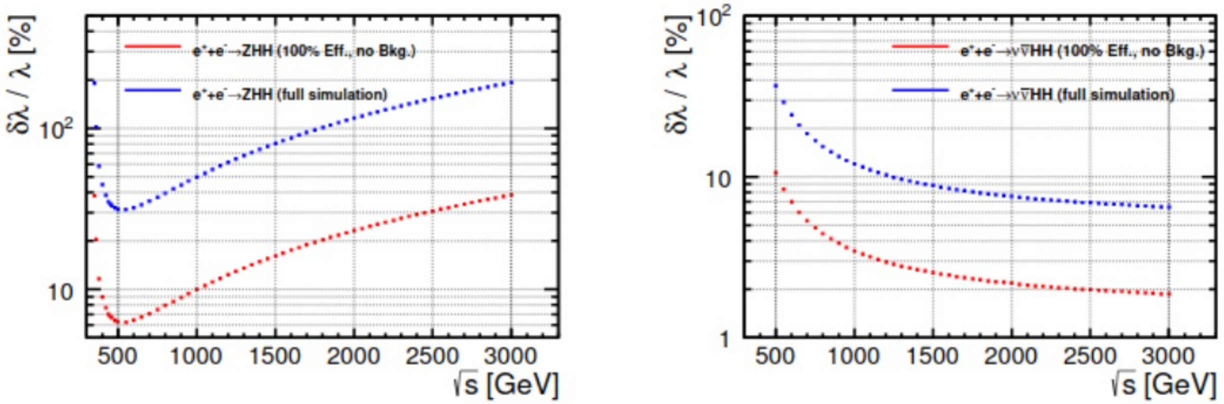
Baseline technology for the SiD HCal is Scintillator/SiPM/Steel



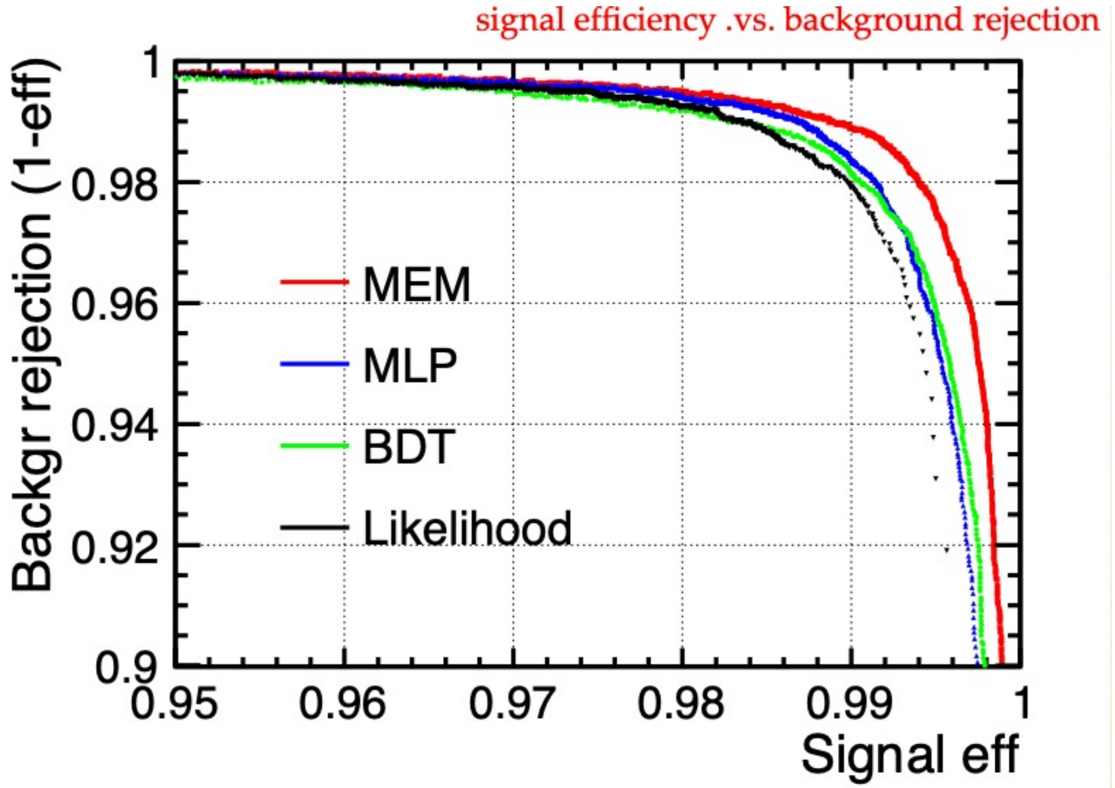
Opportunities for Improving the Physics Reach



In the Higgs self-coupling analysis with ZHH, perfect jet clustering could improve the measurement by 40%



At higher energies, vvHH has fewer, but more collimated jets.



The matrix element method can infuse physics knowledge into the otherwise purely statistical separation of samples.

Example: e^+e^-H measurement

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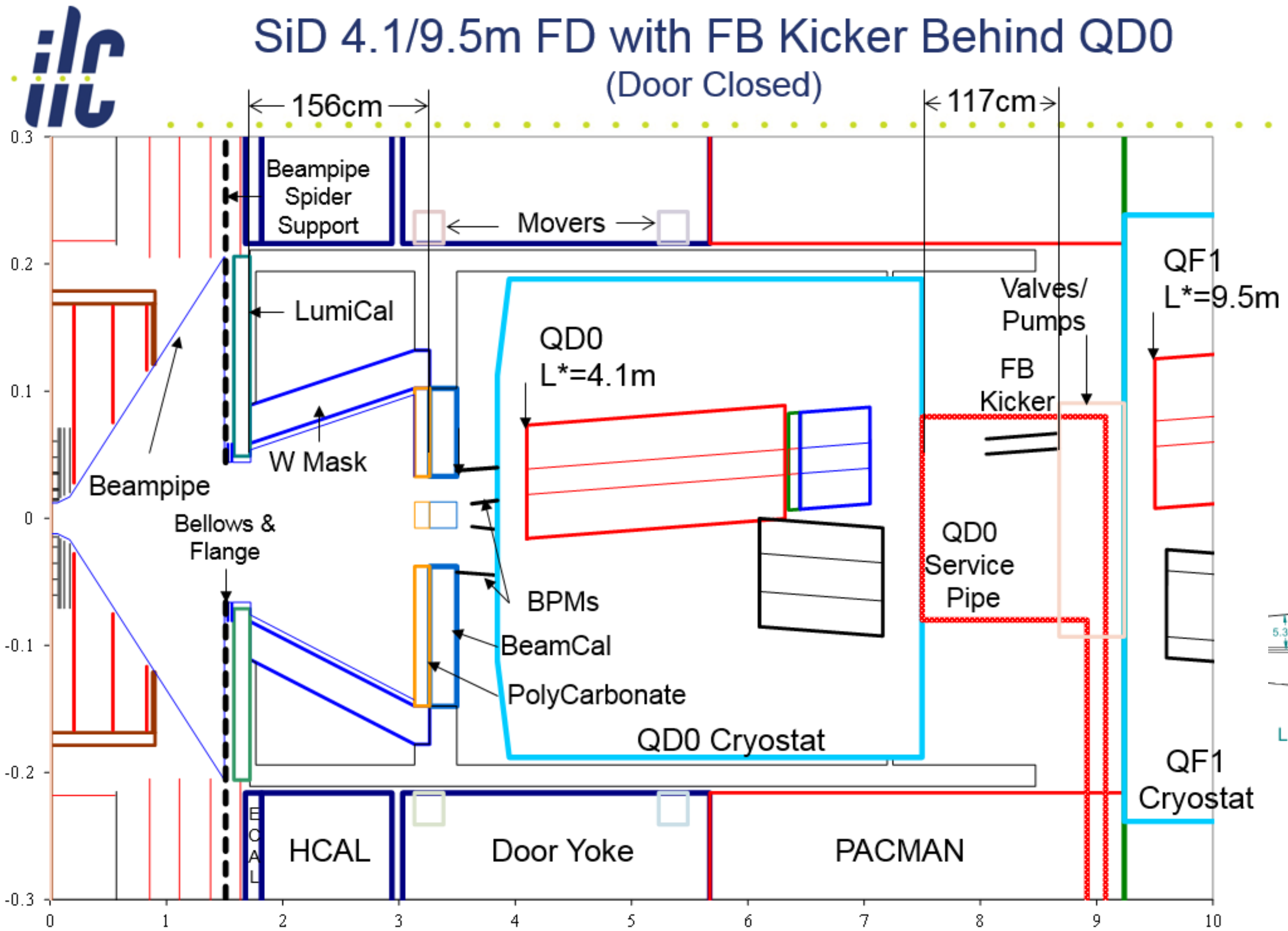
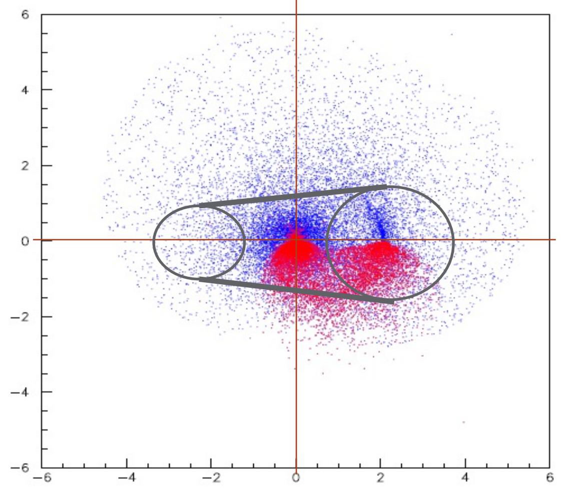
(Some) R&D questions for calorimetry

- Jet energy resolution / **boson mass** resolution is key
- CALICE test beam prototypes (SiPM/Tile – based) have achieved O(1ns) timing accuracy. Does that help the physics? Is (much) faster (much) better?
- How far from optimal is the achieved mass resolution?
- How much information from the calorimeters are we leaving on the table?
  - Software calibration
  - Shower shape analysis for PID
  - Shower shape analysis to estimate overlaps between particles / leakage
- How far can we push the separation of photons from π^0 decays?
  - Physics benchmark: H → τ τ
- Power and data distribution (especially in the ECal)

Forward calorimetry

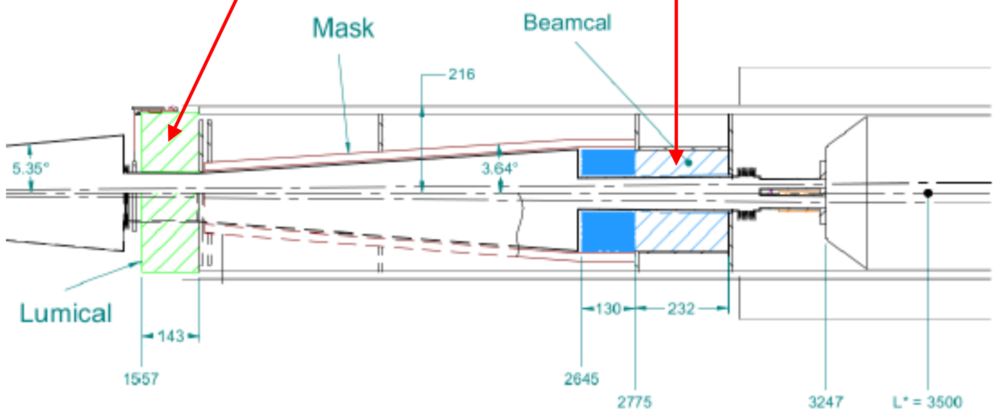


Proposed SiD BeamCal Beampipe



Lumi
Cal

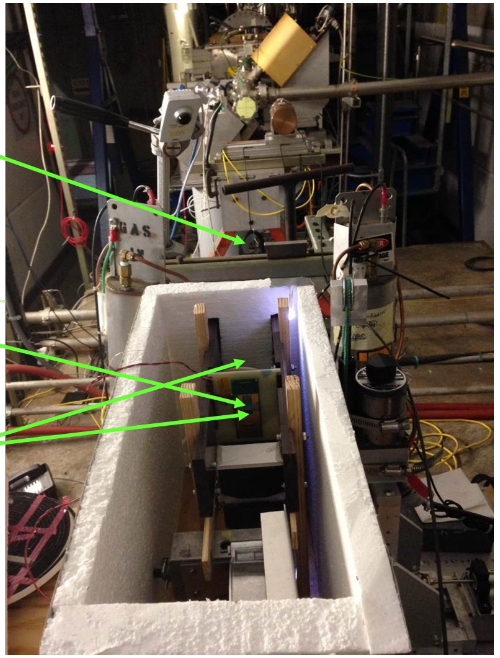
Beam Cal



- Sensor irradiation studies for Forward Calorimetry (B. Schumm et al. UCSC – SLAC Expt. T-506)

BeamCal radiation dose at inner radius ~100 Mrad/year

Forward calorimetry

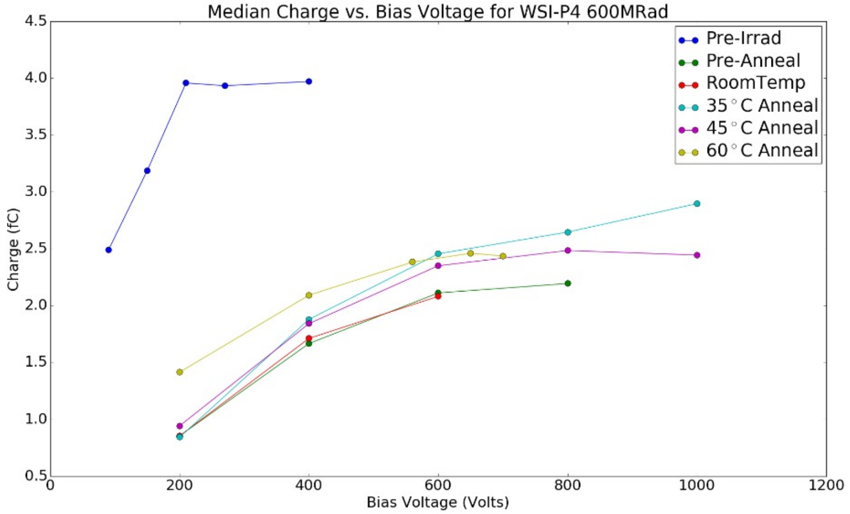


2 X_0 pre-radiator; introduces a little divergence in shower

Sensor sample

Not shown: 4 X_0 "post radiator" and 8 X_0 "backstop"

Ongoing electromagnetic radiation damage studies (Si diode, GaAs…) within FCAL Collaboration umbrella

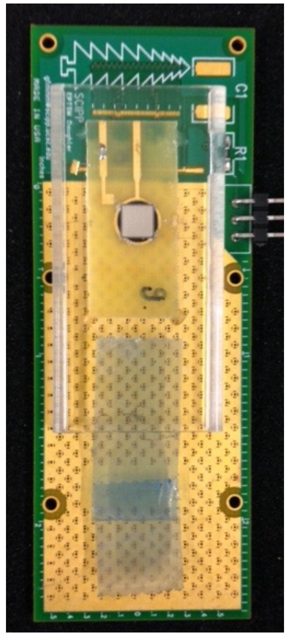


570 Mrad Exposure

PF Si Diode Sensor

300µm

Area 0.025 cm^2

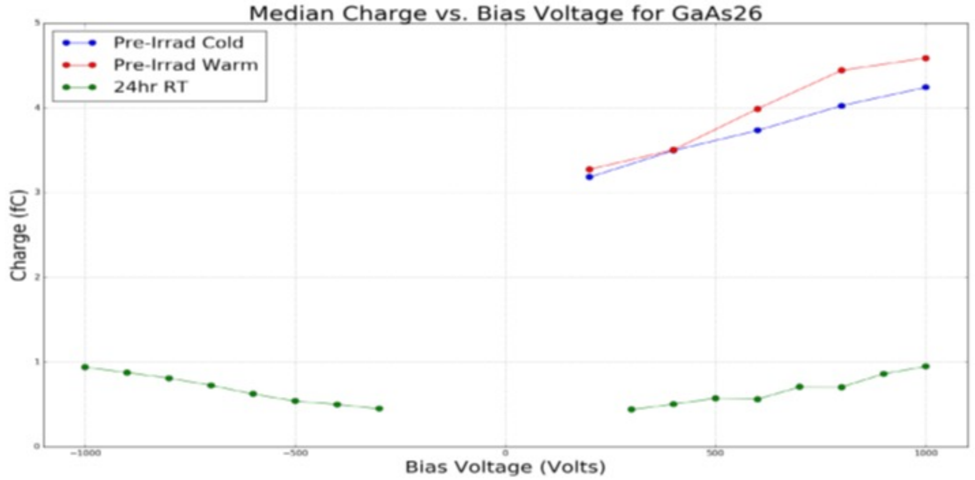


- Gallium Arsenide sensor provided by Georgy Shelkov, JINR

- Sn-doped Liquid-Encapsulated Czochralski fabrication

- 300 µm thick

- 0.16 cm^2 area



Expect integrated radiation dose to be similar to ILC

GaAs Charge Collection after 100 Mrad Exposure (previously only for 21 Mrad)

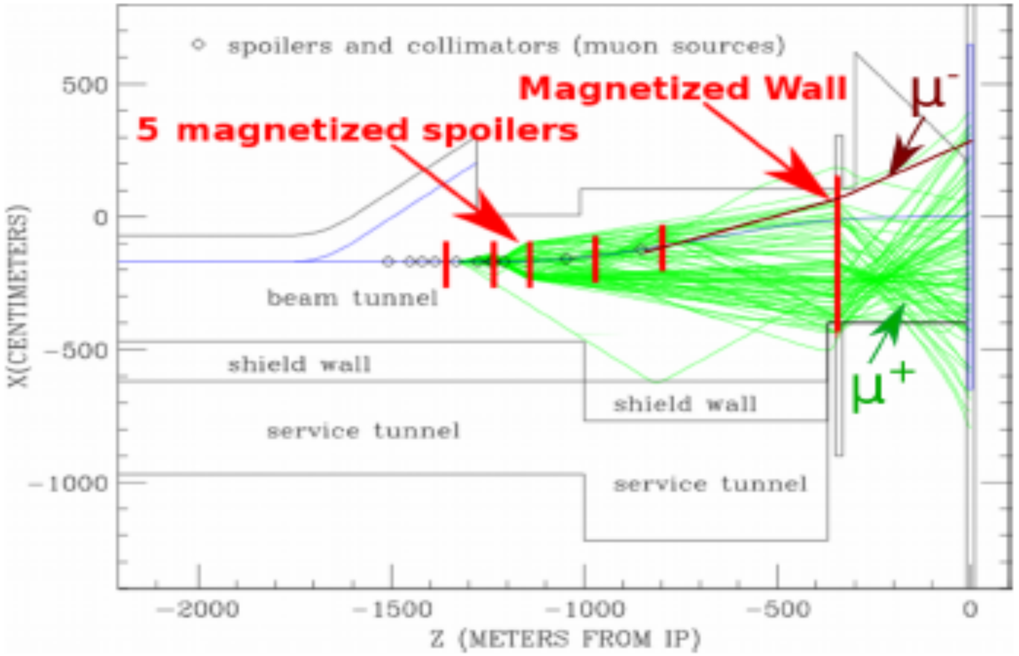
Sean Hyslop

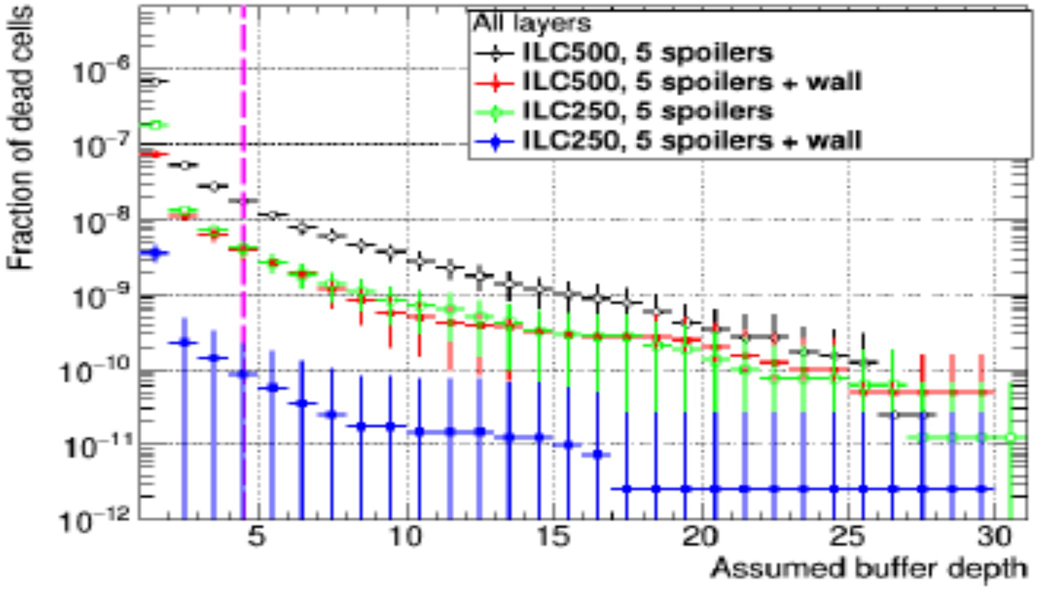
(Some) Forward Calorimetry R&D questions

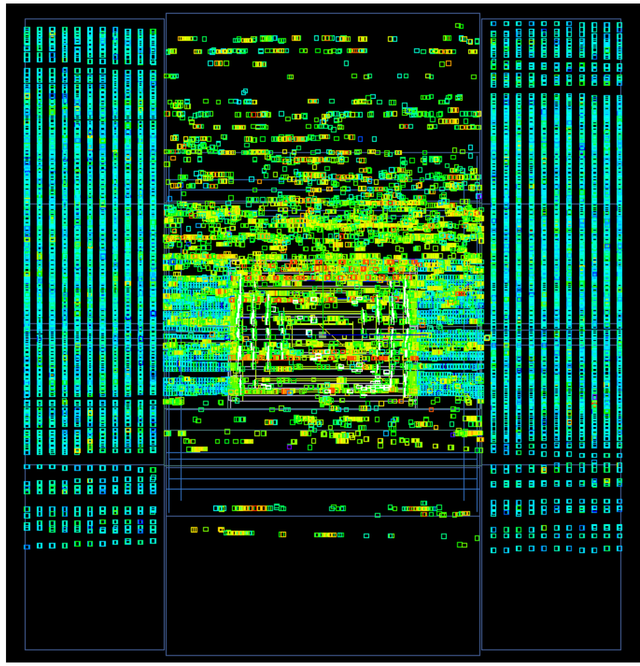
- Do we need the “plug” between the incoming and outgoing beam pipes?
  - Certain SUSY models have very far-forward signatures. How much effort should go into preserving discovery potential?
- High luminosity is key to the success of the project. How can the experiment support the machine in ramping up to design specs faster?
  - See, e.g. ”RECONSTRUCTION OF IP BEAM PARAMETERS AT THE ILC FROM BEAMSTRAHLUNG” (https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1590793)

MDI Studies

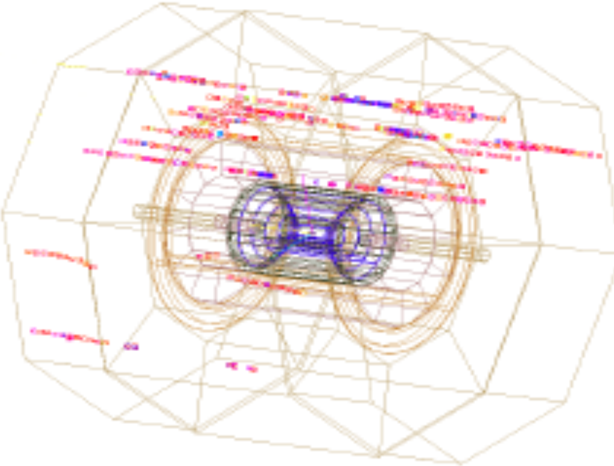
Anne Schuetz
(DESY)







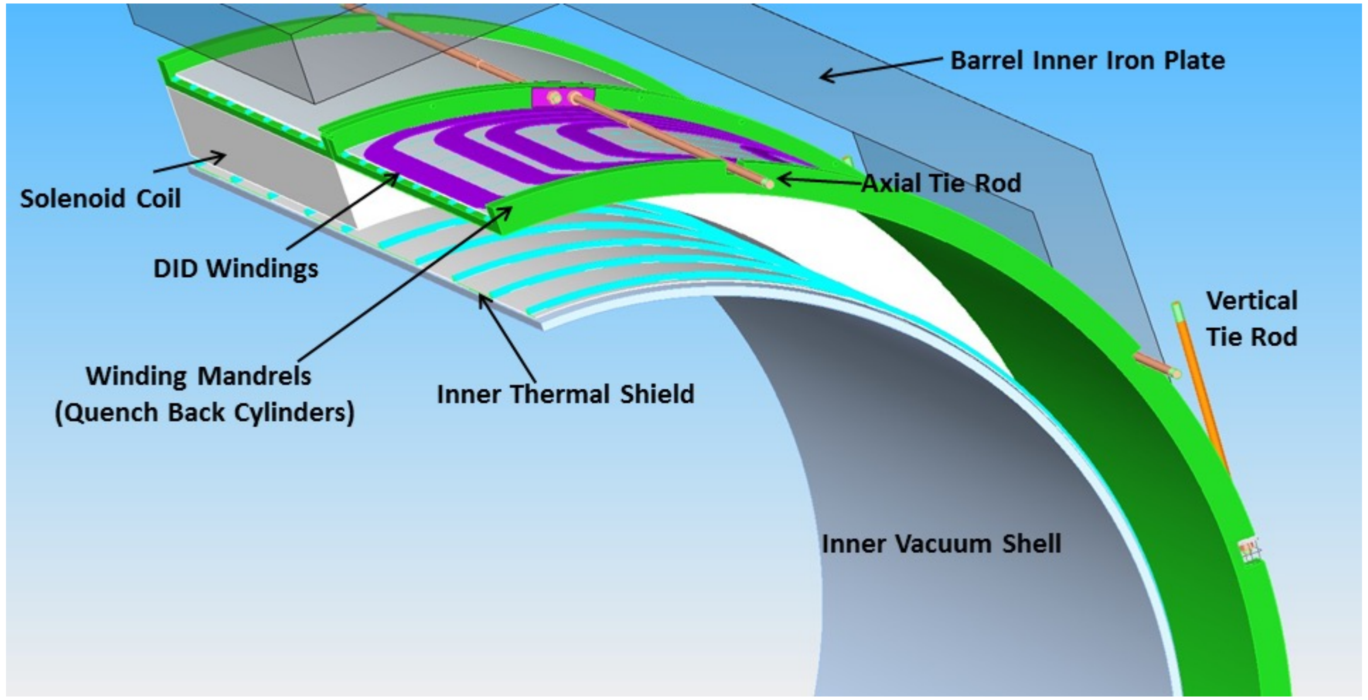
#muons / bunch crossing	ILC250	ILC500
No shielding	39.3	130.1
Magnetized spoilers	1.3	4.3
Magnetized spoilers + wall	0.03	0.6



At ILC250, magnetized spoilers without wall are sufficient for occupancy mitigation.

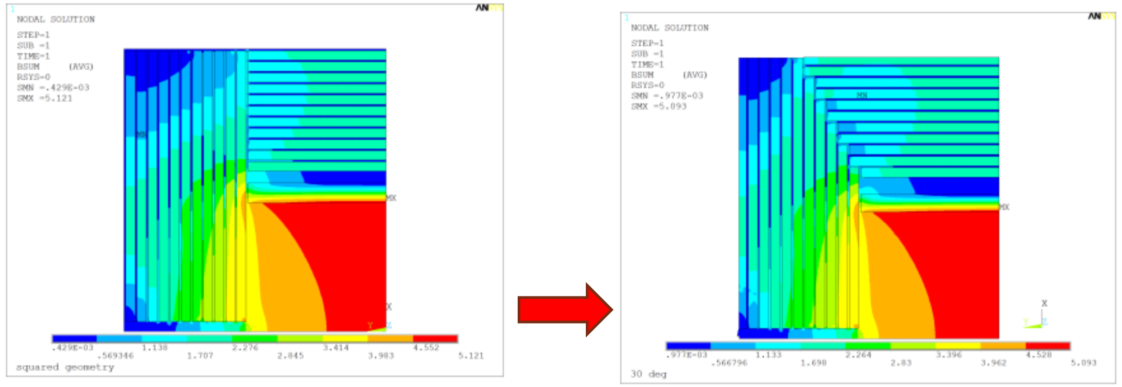
Wall might me neccessary at higher stages, and as a tertiary containment device.

Solenoid Magnet



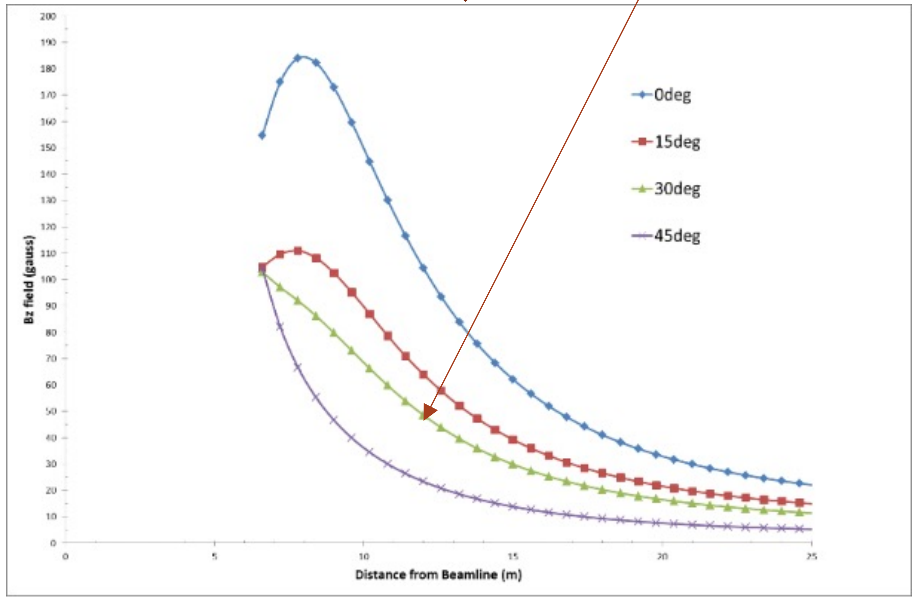
Baseline CMS conductor – investigating **CICC** (Cable in Conduit Conductor)

30° design



Redesign of barrel/door junction
More efficient flux return
Easier transport/handling

< 50 Gauss at 15m



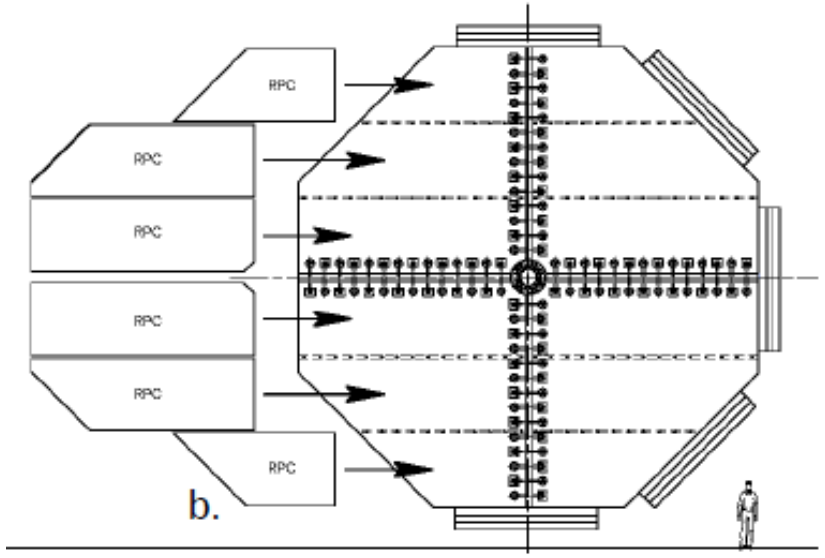
Cable in Conduit Conductor

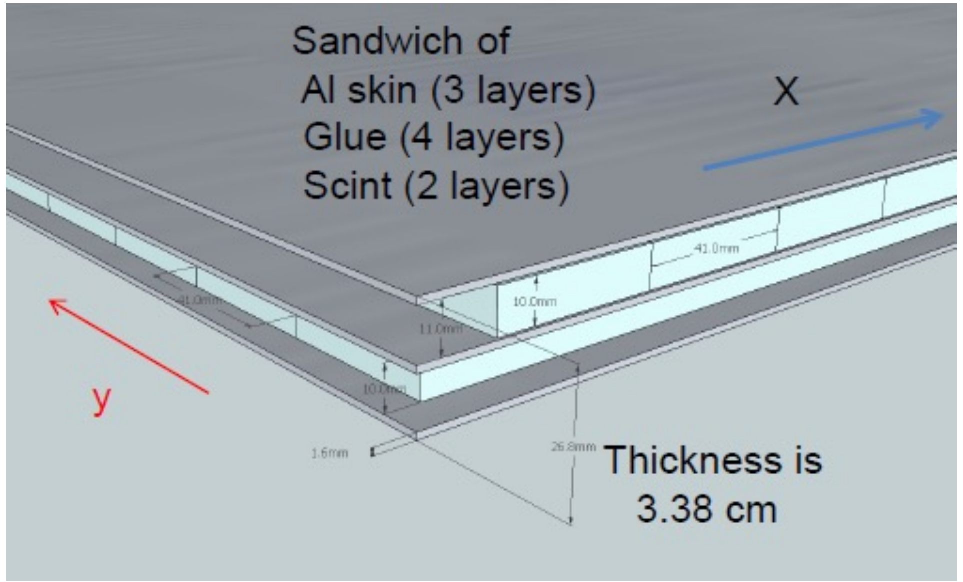
- The solenoid magnet is the single most expensive system
- Technology is based on CMS
- CICC could be made thinner
  - Same width; 1/3 height / layer
    ~ 0.5 m less total thickness
    → cost savings
- Used by fusion experiments
  - Different requirements from HEP, R&D needed
  - quench protection
  - Supercritical He → superfluid He?

SiD costs by system

	M&S Base (M US-$)	M&S Contingency (M US-$)	Engineering (MY)	Technical (MY)	Admin (MY)
Beamline Systems	3.7	1.4	4.0	10.0	
VXD	2.8	2.0	8.0	13.2	
Tracker	18.5	7.0	24.0	53.2	
ECAL	104.8	47.1	13.0	288.0	
HCAL	51.2	23.6	13.0	28.1	
Muon System	8.3	3.0	5.0	22.1	
Electronics	4.9	1.6	44.1	41.7	
Magnet	115.7	39.7	28.3	11.8	
Installation	4.1	1.1	4.5	46.0	
Management	0.9	0.2	42.0	18.0	30.0
	314.9	126.7	186.0	532.1	30.0

Muon identifier/Calorimeter Tail Catcher





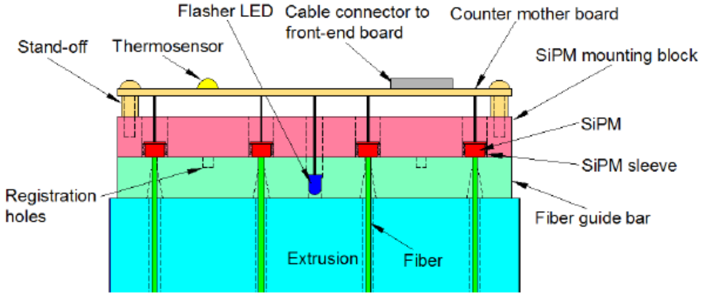
Sandwich of
Al skin (3 layers)
Glue (4 layers)
Scint (2 layers)

Thickness is
3.38 cm

Development work at Fermilab:

SiD Baseline – long scintillator strips with WLS fiber and SiPM readout

- Consistent extension of the baseline HCal scintillator technology
- Need to optimize number of layers, strip dimensions.



NIMA, **848**, 54-59, 2017

Some global considerations

- The SiD baseline has been validated by an independent panel
  - The designs are now aging → we would not build the DBD version today.
  - How do we take advantage of current R&D streams without corrupting the concept?
  - How do we bring in groups that work on
- The EIC is designing (a) detector(s) right now
  - AI integrated in the design process (https://indico.bnl.gov/event/16586/timetable/#all.detailed)
  - Streaming readout is a hot topic. Can we benefit from this? (e.g., beam parameters, …)
  - Other technologies that they are developing, which we can piggy-back on?
- Software / reconstruction
  - Heterogeneous architectures are here to stay. Not using these is not an option.
    - ✓ How much on-detector / near-detector / off-detector processing is optimal?
  - Tracking / imaging calorimetry: DUNE/MicroBooNE strategies might work in SiD
  - The performance of MAPS in the particle flow reconstruction is not well studied.
    - → what can we learn about the design?
  - Flavor tagging / vertex reconstruction: Algorithms are 20+ years old

SiD Consortium

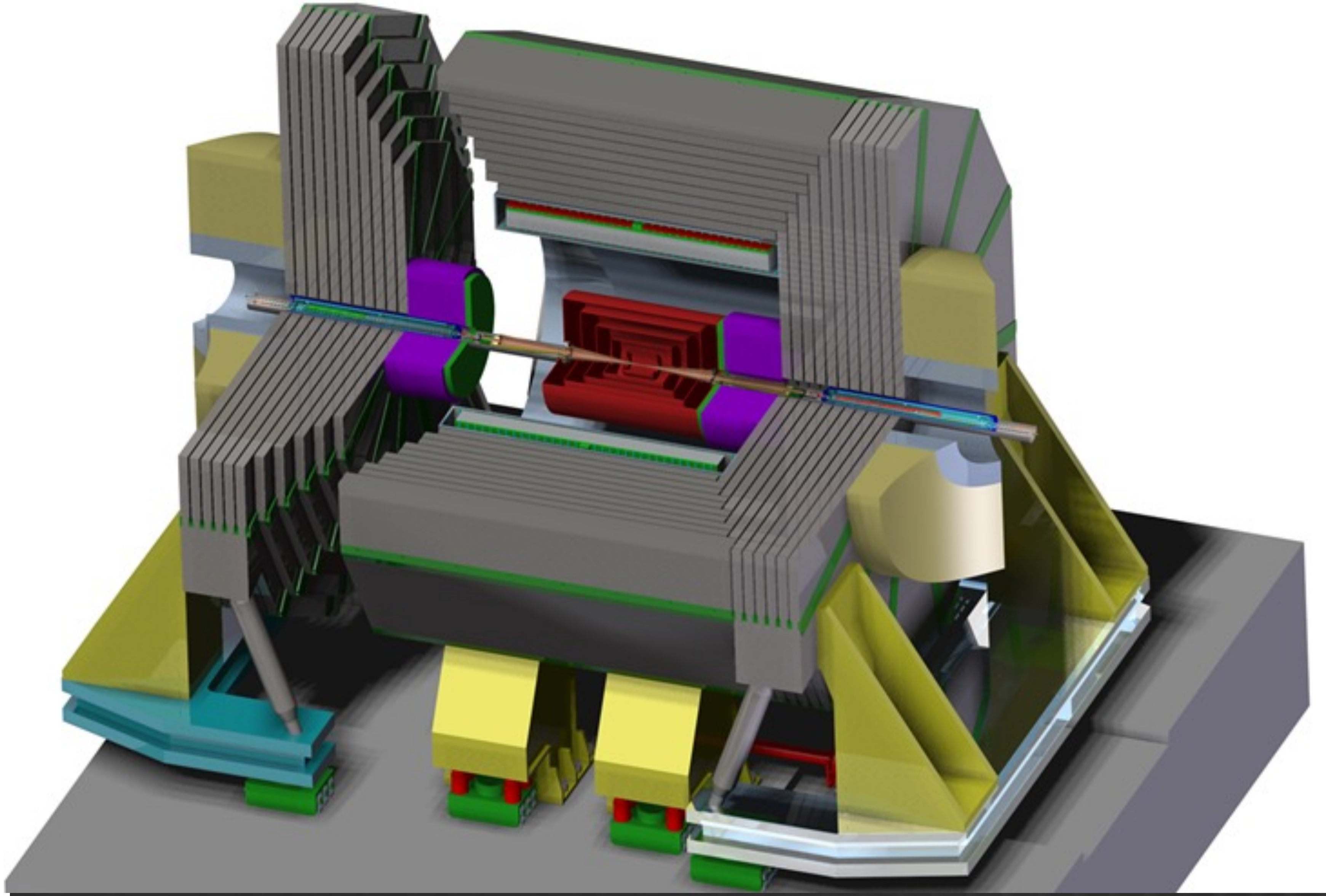
- since 2013
- Byelaws
- Individual and institutional memberships (Guest membership available)
- IB Chair – Phil Burrows (U. Oxford)

- Very open and welcoming of new colleagues to join SiD to make it better by contributing **new** ideas / upgrades / alternatives

Summary

- The SiD concept has a well-understood baseline. It can carry out the physics program at the ILC up to 1 TeV.
  - We do not see any showstoppers for operation at CCC.
- We are confident the remaining R&D items can be solved, and we understand their impact on costs.
- However, many opportunities for R&D remain
  - Synergies with new developments at EIC
  - Sustainable computing / software
  - Material budgets / cooling
  - Truly "imaging" calorimetry (5D)
  - 4D Tracking
  - Superconducting high-field solenoid
- We invite you to bring your ideas to our meetings

Thank you



SiD on the web – a couple of links for further reading

Conceptual Overview

- The International Linear Collider TDR - Volume 4: Detectors
- Updating the SiD Detector concept

Background – MDI

- A Study of the Impact of High Cross Section ILC Processes on the SiD Detector Design
- Expected Sensitivity to Invisible Higgs Boson Decays at the ILC with the SiD Detector (A Snowmass White Paper)
- A Study of the Impact of Muons from the Beam Delivery System on the SiD Performance

Physics

- Full simulation study of the top Yukawa coupling at the ILC at √s = 1 TeV
- H→invisible at the ILC with SiD
- Detector R&D
- Energy Correction in Reduced SiD Electromagnetic Calorimeter
- Correcting for Leakage Energy in the SiD Silicon-Tungsten Ecal
- Studies of the Response of the SiD Silicon-Tungsten Ecal

Code

- https://github.com/silicondetector
- https://github.com/iLCSoft/lcgeo/tree/master/SiD/compact