Highly Granular Calorimeters - Impact of different Higgs Factory Options

(with focus on Si ECAL [since I know it best])

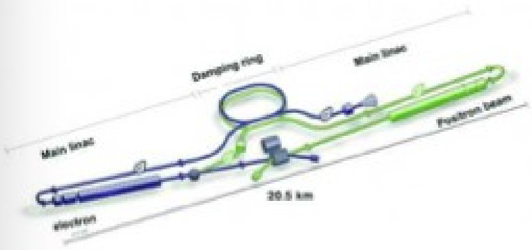
Roman Pöschl

Supported by

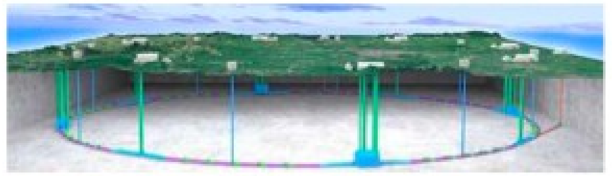
LCWS 2023 – May 2023 SLAC

Detector systems – Target projects

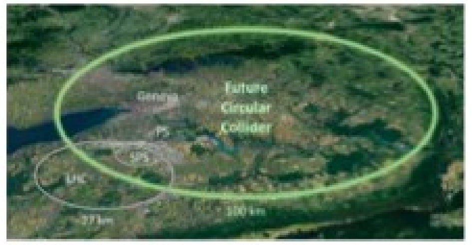
ILC



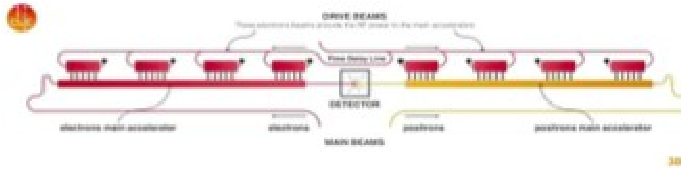
CEPC



FCC-ee

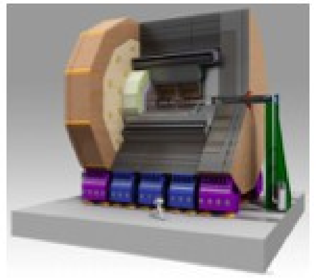


CLIC

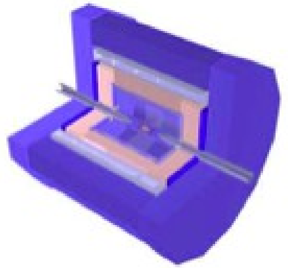


C^3

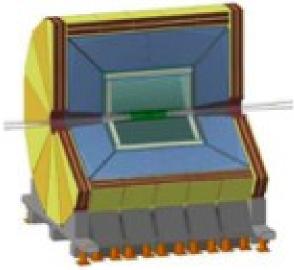
ILD



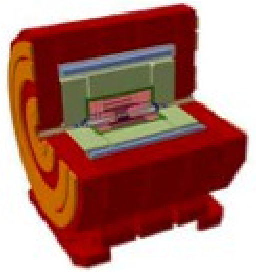
CEPC Baseline



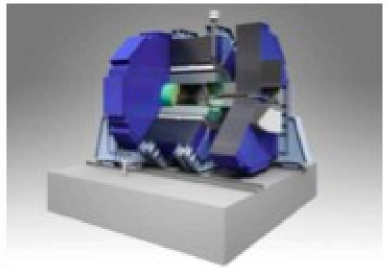
IDEA



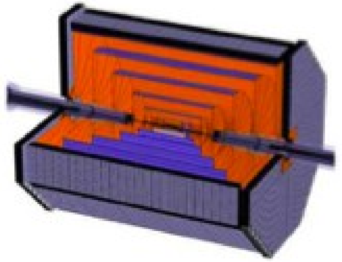
CLICdp



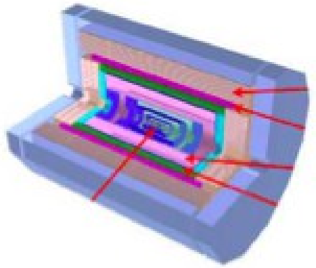
SiD



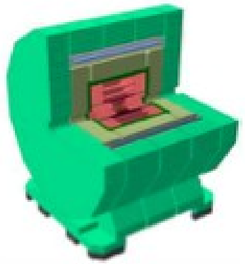
FST



CEPC 4th concept



CLD



slide stolen from B. Dudar

Uli Einhaus, this morning

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)]$ μm (1/3 x SLD)

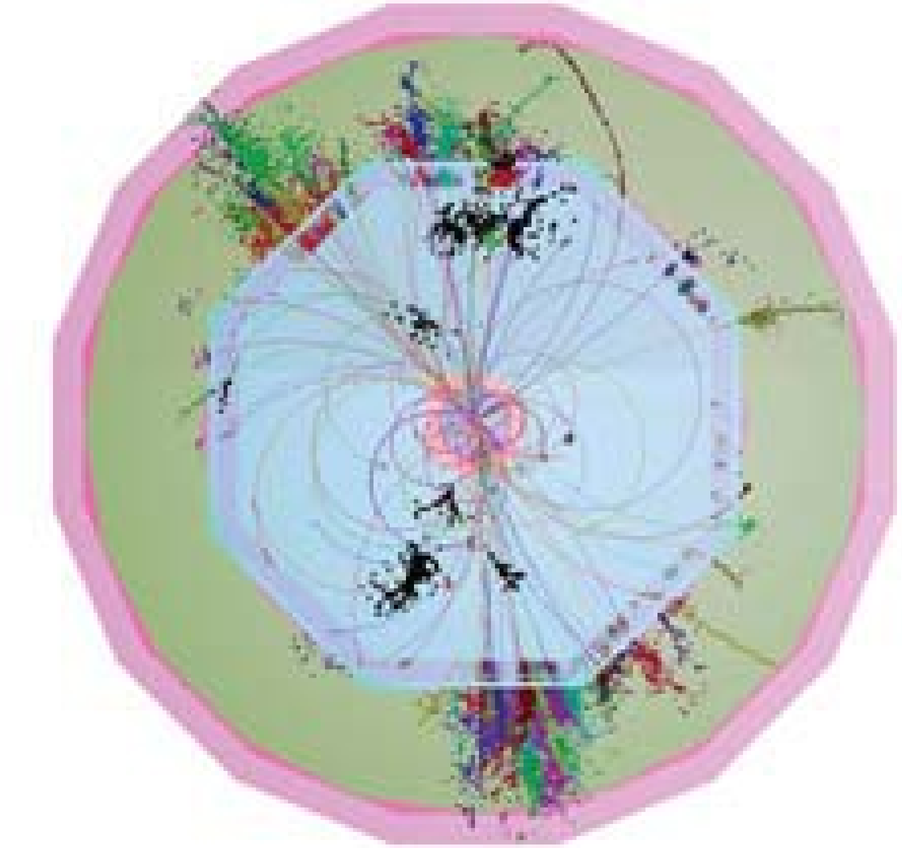
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(\mathrm{GeV}))^{1/2}$ (1/2 x LEP)

(e.g. W/Z masses with jets)

Hermeticity : … well as hermetic as possible, LC Detectors require $\theta_{min} = 5$ mrad

(for events with missing energy e.g.dark sector/ invisible decays)



Final state will comprise events with a large number of charged tracks and jets(6+)

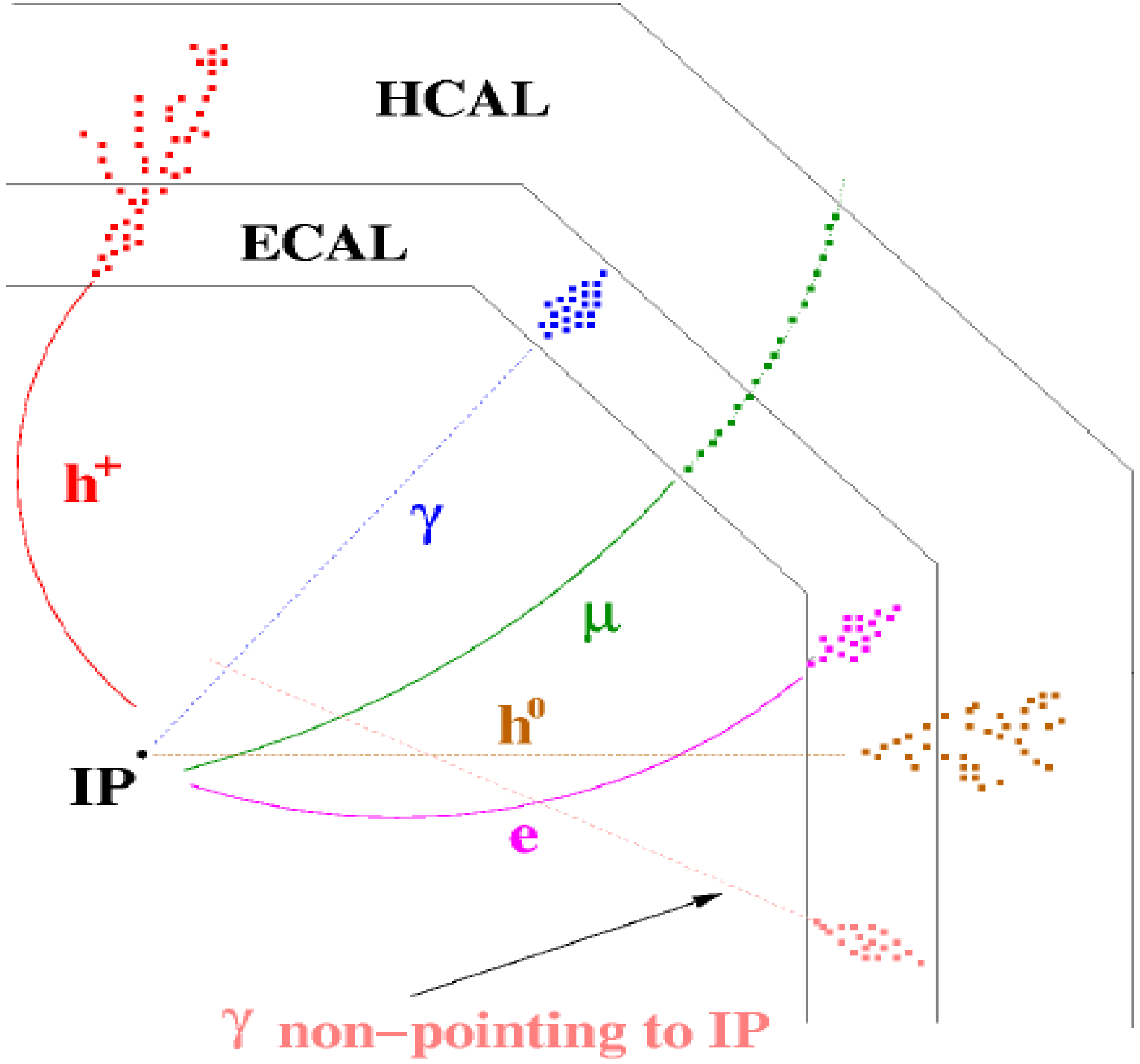
- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Particle Flow Detector Layout

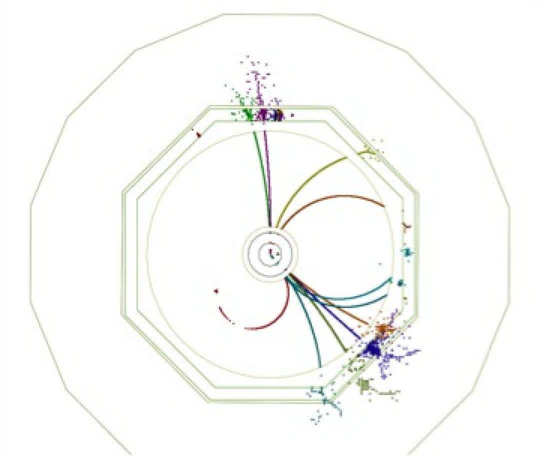
- Jet energy measurement by measurement of **individual particles**
- Maximal exploitation of precise tracking measurement

- Large radius and length
  - ➔ to separate the particles
- Large magnetic field
  - ➔ to sweep out charged tracks
- “no” material in front of calorimeters
  - ➔ stay inside coil (the puristic viewpoint)
- Minimize shower overlap
  - ➔ Small Molière radius of calorimeters
- **high granularity of calorimeters**
  - ➔ to separate overlapping showers



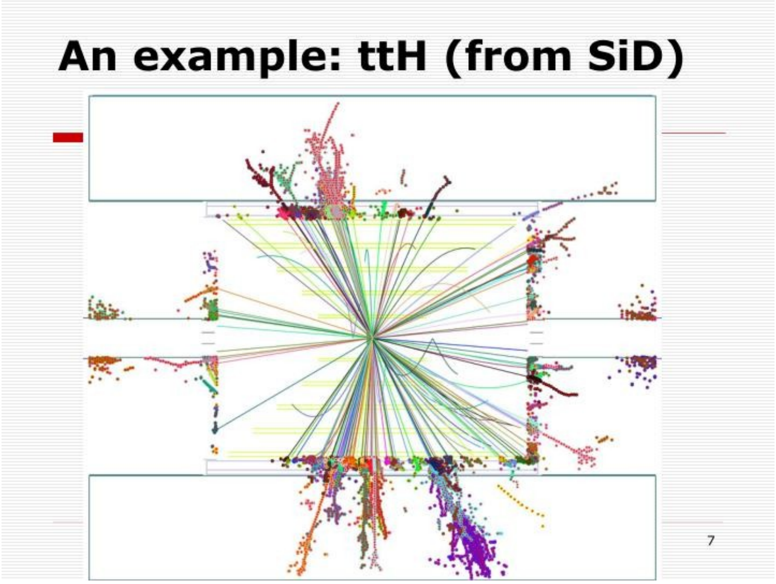
Detector Hermeticity

Invisible Higgs decays



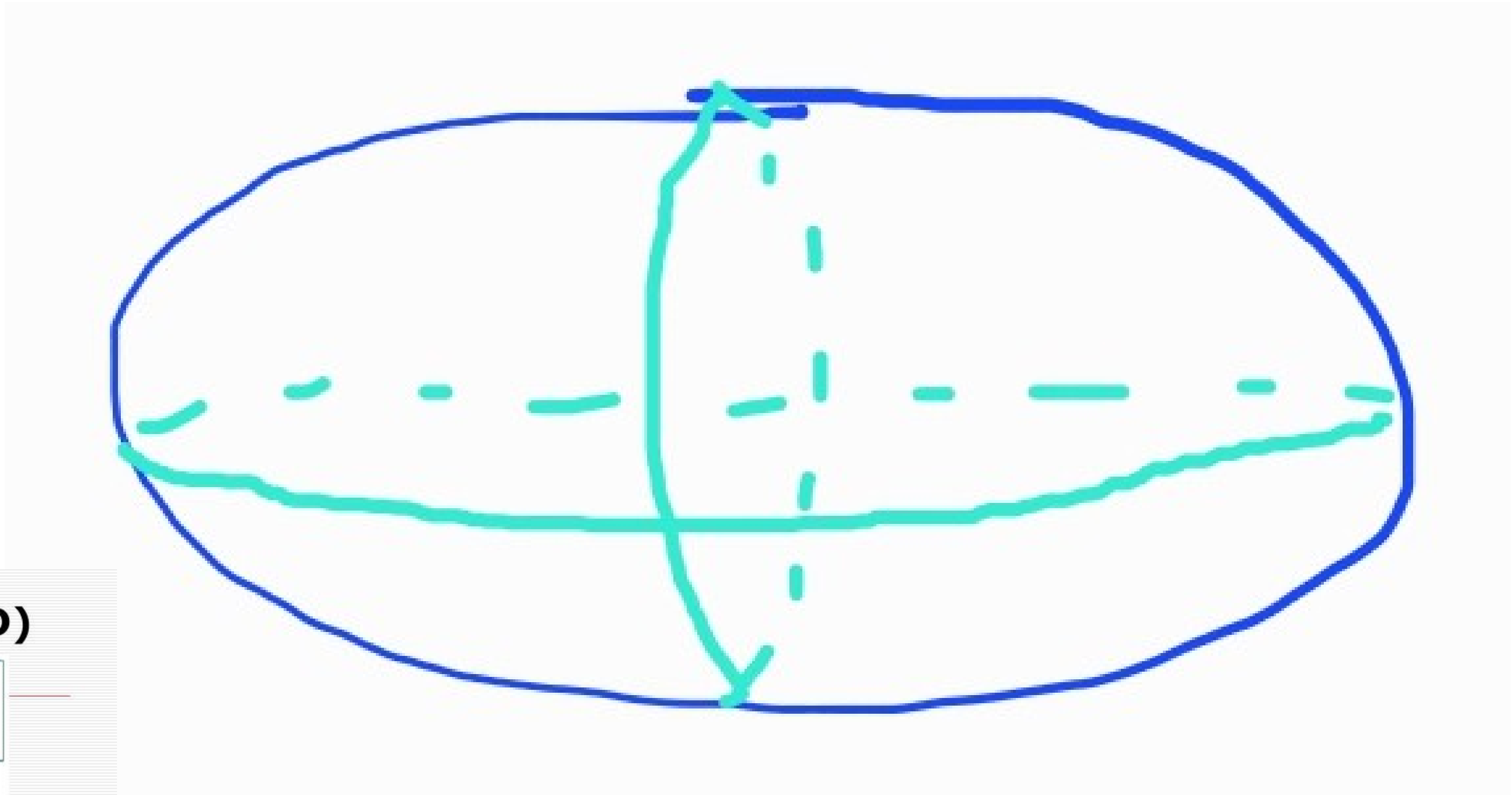
$e^+e^- \rightarrow q\bar{q}H \rightarrow qq$ inv in ILD detector

Rich events:



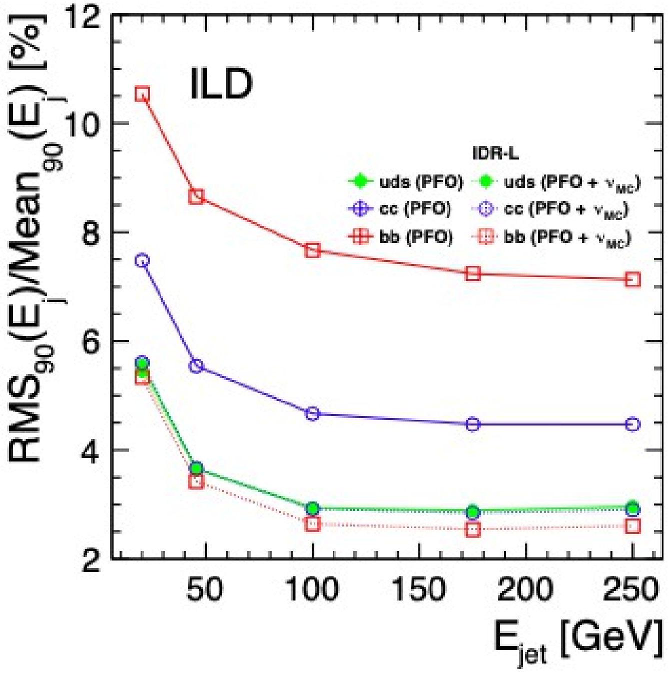
An example: ttH (from SiD)

Hermeticity = Acceptance down to the beam pipe and no acceptance holes!

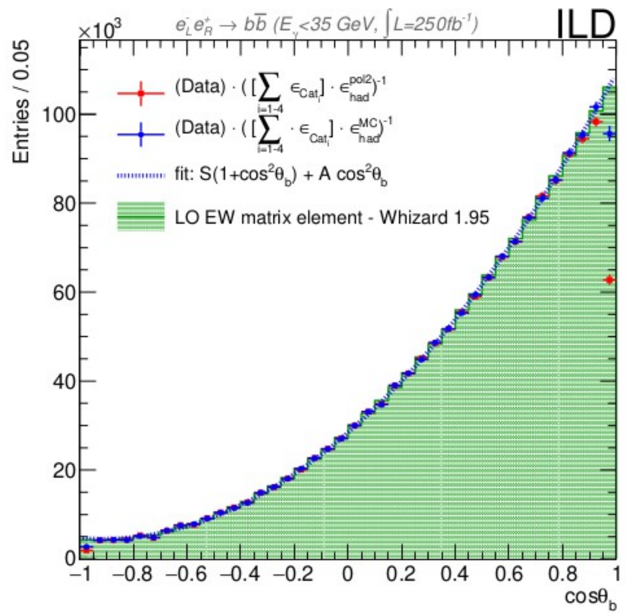


Detector Hermeticity requires is team effort Vertex Detectors, Central Tracking and of course Calorimeters

Missing Energy

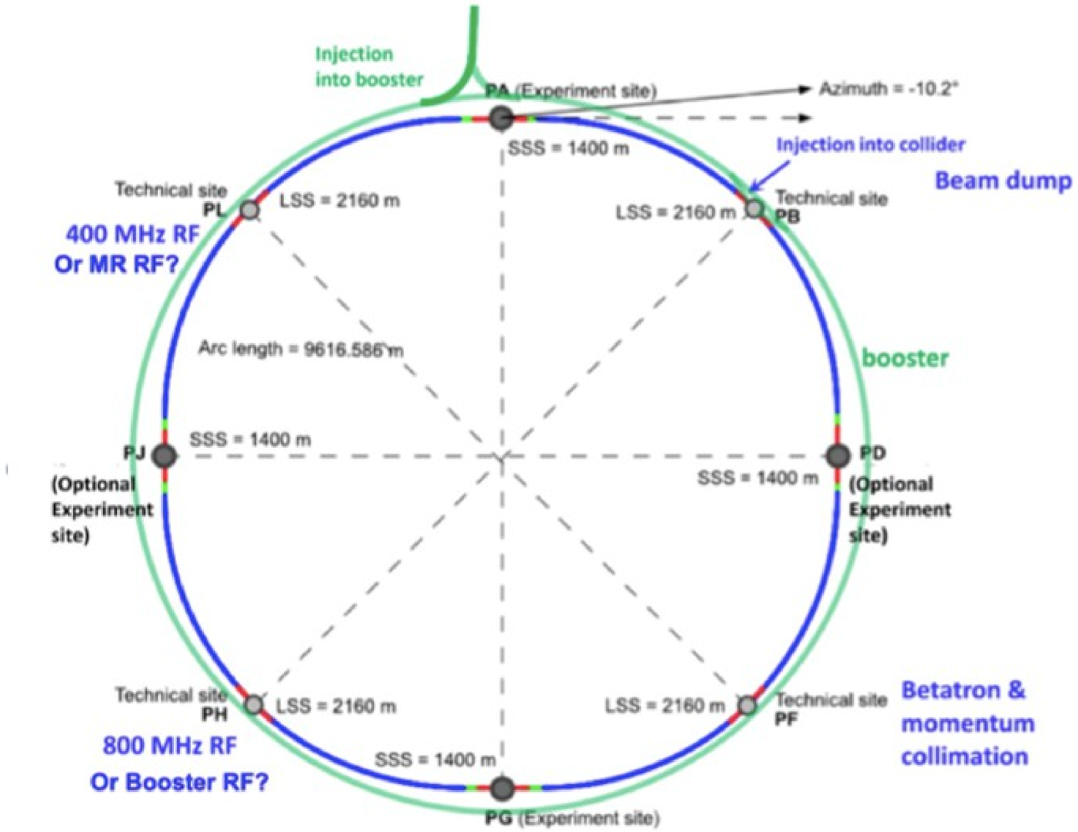


Heavy Quark asymmetries



A quick look into the MDI region

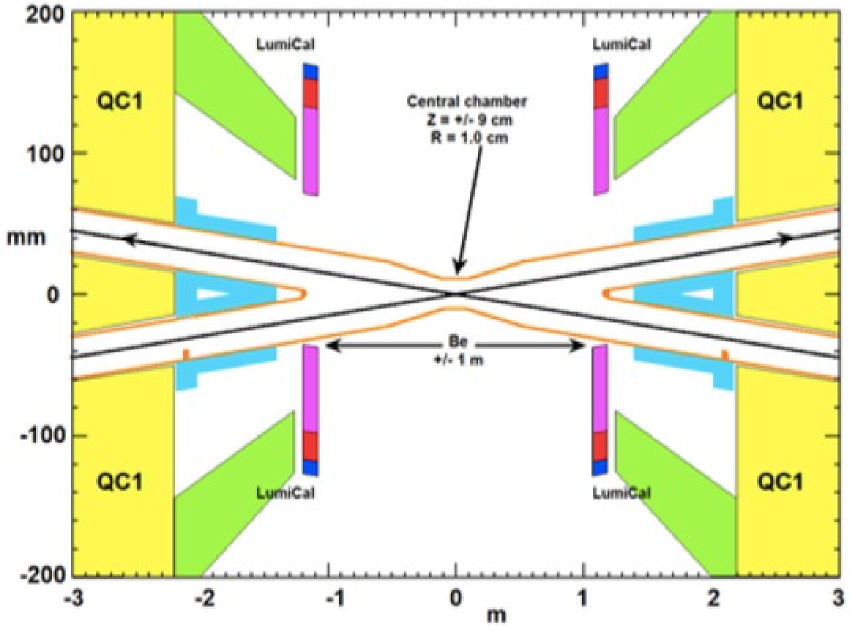
Machine layout
as shown during FCC Week 2023 Cracow



- Circumference 90,6 km
- 4IP (FCC-ee = FCC-hh)

M. Boscolo, FCC Week Cracow

Typical MDI region

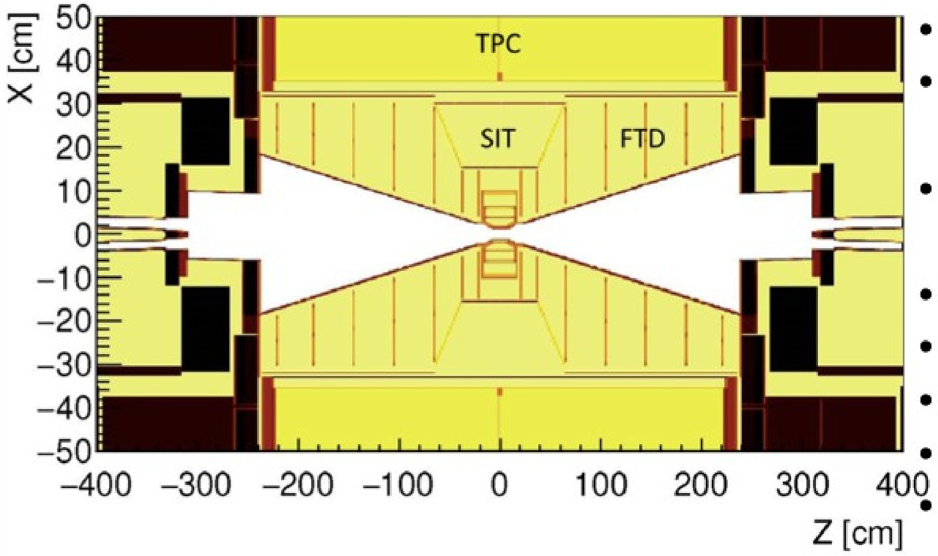


- L* = 2.2m
- Final quadropole inside detector region

(and is background source)

- LumiCal at 1000mm
- => defines tracker acceptance $\cos\theta$ ~0.984
- Inner beampipe radius 10mm
- Magnetic Field 2 T
- Crossing angle ~30 mrad

Compare with ILC MDI region



- L* = 4.1m
- Final quadropole outside of detector region
- Tracker Acceptance defined by conical beam pipe(due to blown-up beam)
- $\cos\theta$ ~0.995
- LumiCal at ~2500mm
- Inner beampipe radius 16 mm
- Magentic Fiels 3.5-4 T
- Crossing angle 14 mrad

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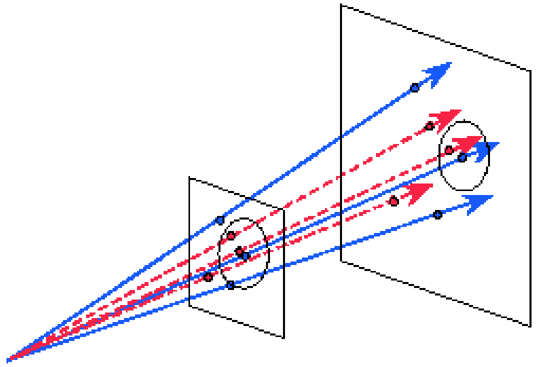
Detectors for e+e- Colliders – Main Parameters

Concepts currently studied differ mainly in SIZE and aspect ratio



	ILD	SiD	CLICdp	CLD
Rin [mm] Vertex Detector	16	14	31	17.5
$R_{in,\ Ecal}$ [mm]	1805	1270	1500	2150
$R_{out,tot}$ [mm]	7755	6042	6450	6000
$Z_{min,\ ECAL}$ [mm]	2411	1657	2310	2310
$Z_{max,tot}$ [mm]	6712	5763	5700	5300
B [T]	3.5	5	4	2

- Figure of merit (ECAL):

  Barrel: $B\ R_{in}^2 / R_m^{effective}$

  Endcap: "B" $Z^2 / R_m^{effective}$

  R_{in} : Inner radius of Barrel ECAL

  Z : Z of EC ECAL front face

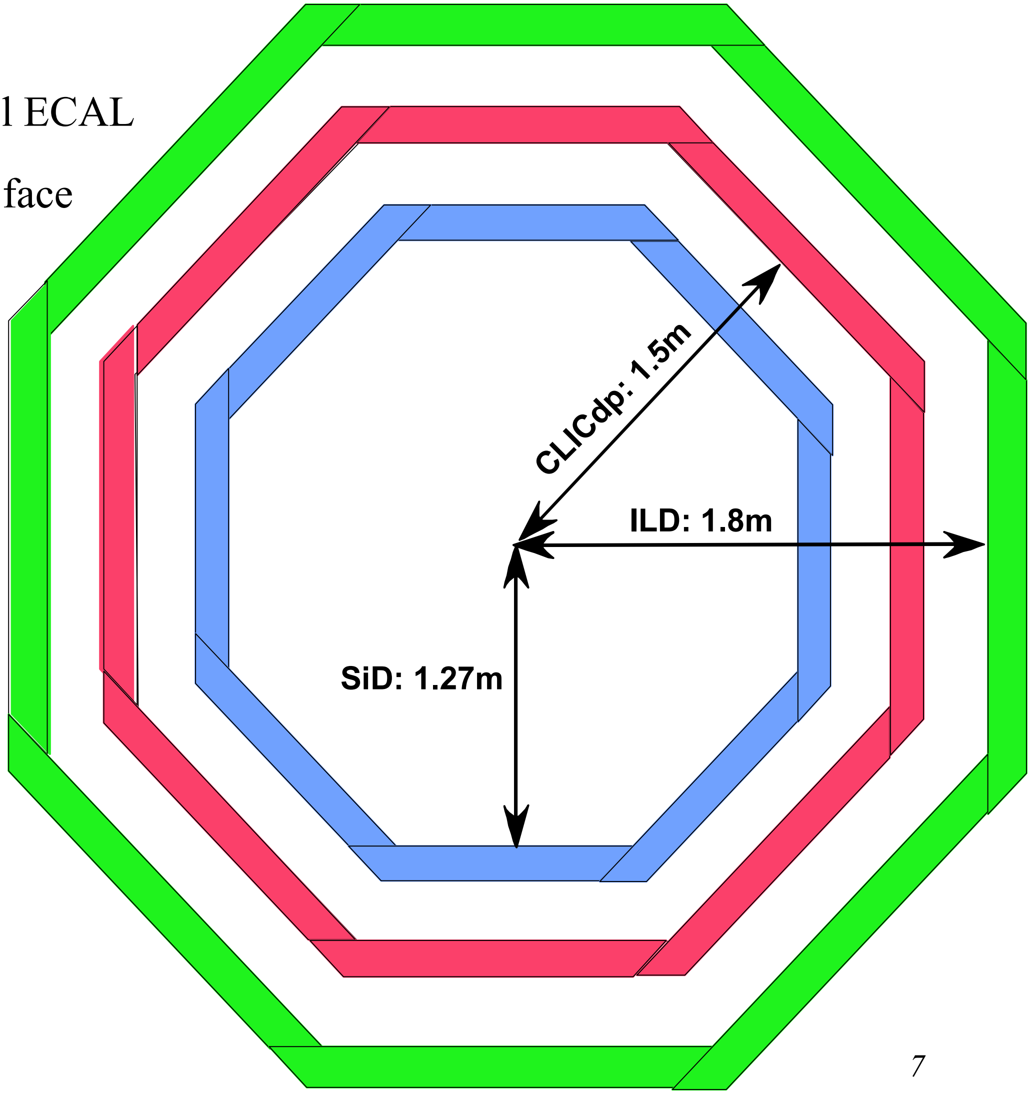
- Different approaches

  SiD: $B\ R_{in}^2$

  CLICdp: $B\ R_{in}^2$

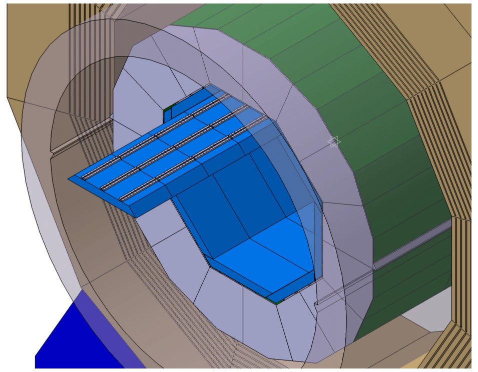
  ILD $B\ R_{in}^2$

  CLD: $B R_{in}^2$

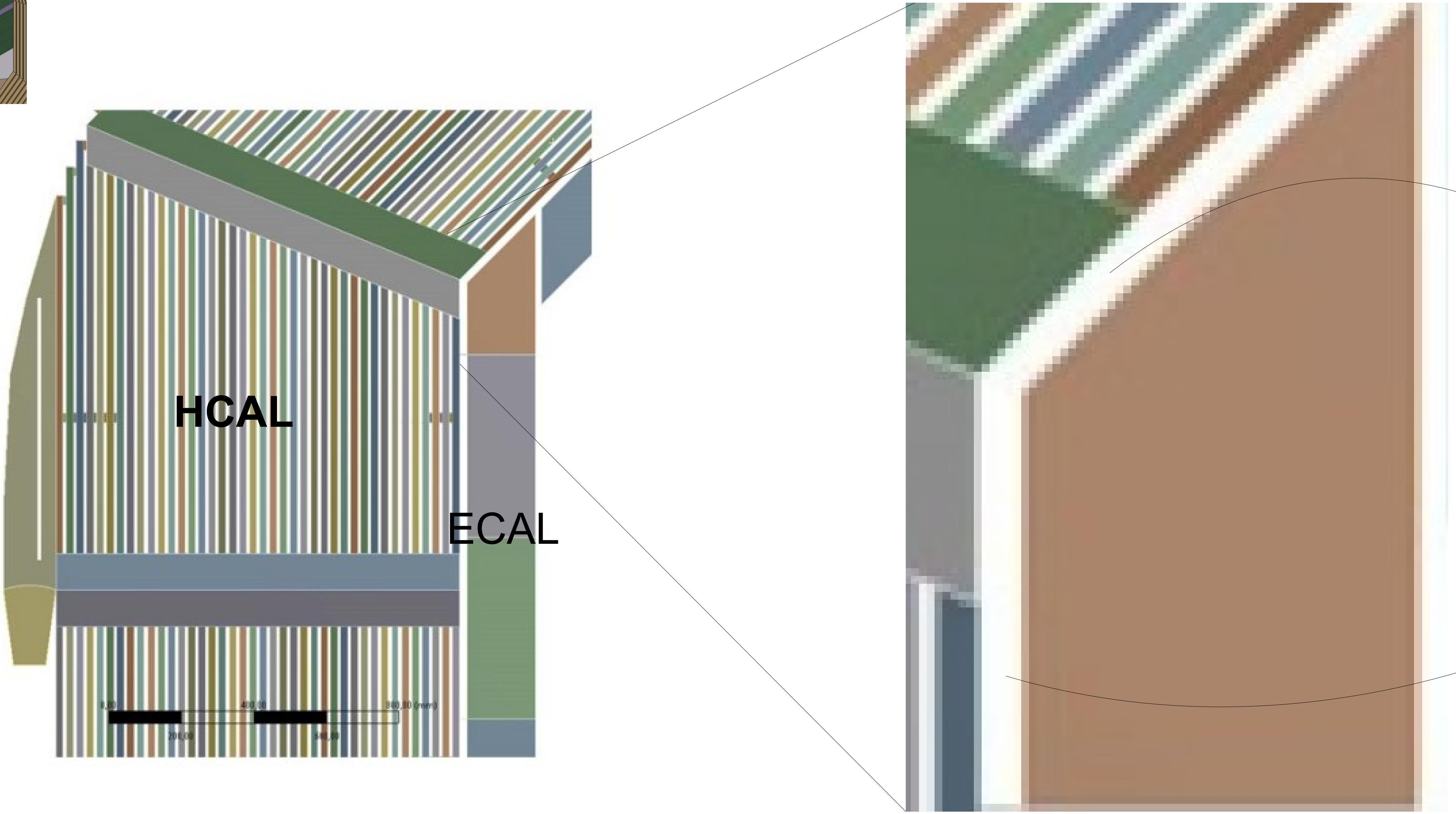


- Roughly: The smaller B the bigger $R_{in,Ecal}$ has to be
- Overall outer radius will depend on required Hcal thickness
- ... and details of return yoke design
  - Cost, safety considerations ...

Requirements on compactness



- Successful application of PFA requires calorimeters to be inside the magnetic coil
  => Tight lateral and longitudinal space constraints

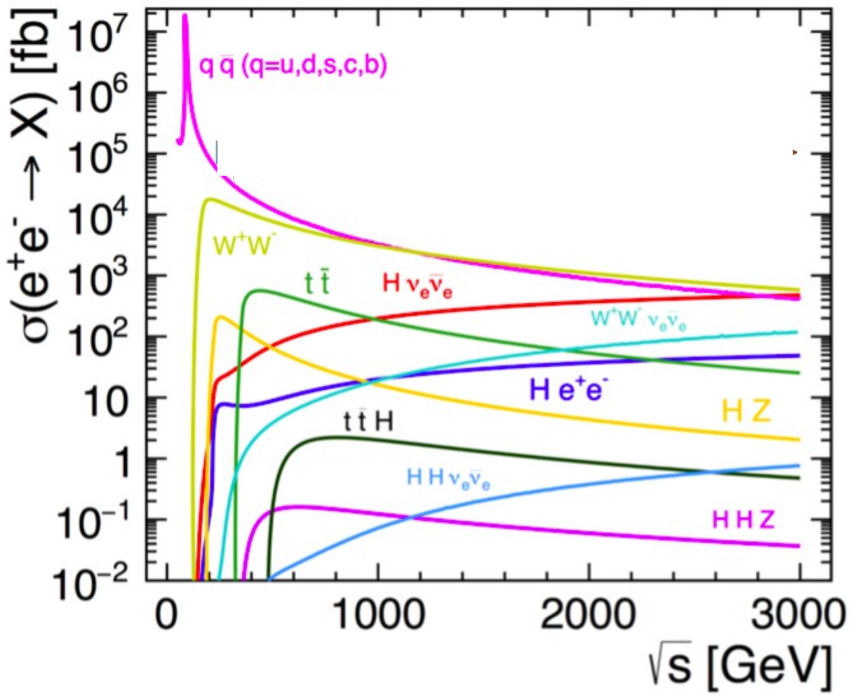


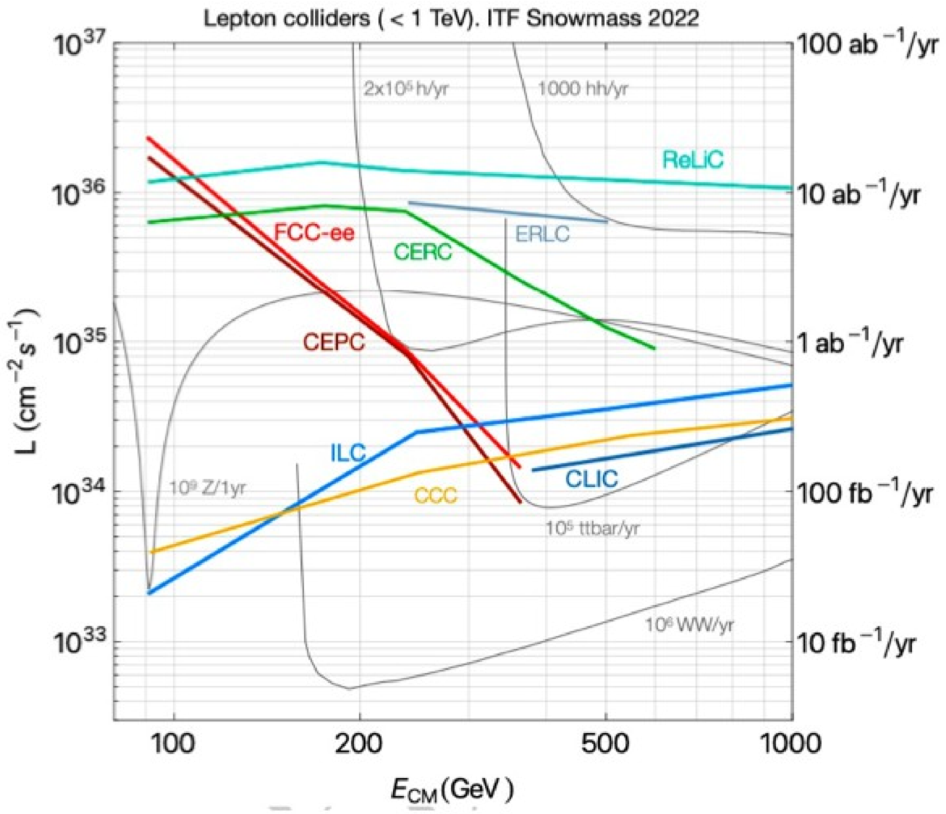
40-70mm for services as readout, cooling and power

~200mm for up to 30 layers with 10-20 kcells each

Calorimeter has to be conceived as one device with electromagnetic and hadronic sections

Impact of event rates and operation modes



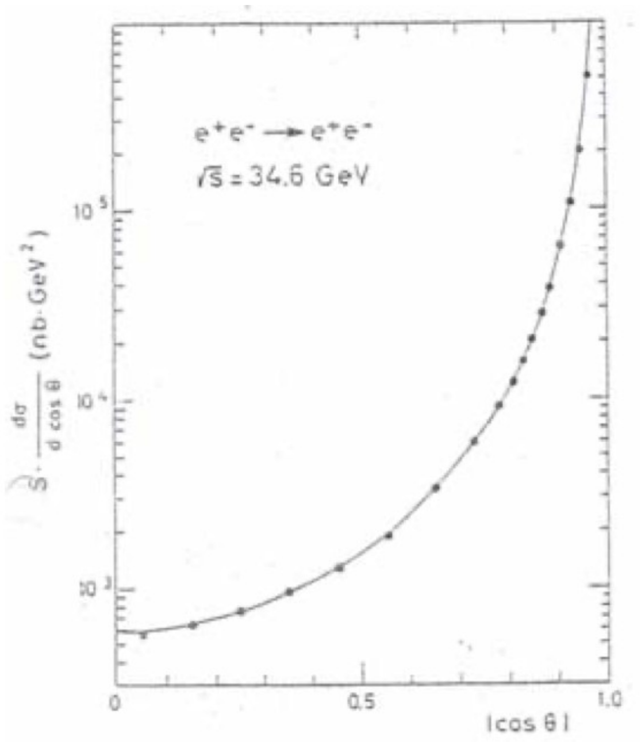


High energy e+e- colliders:

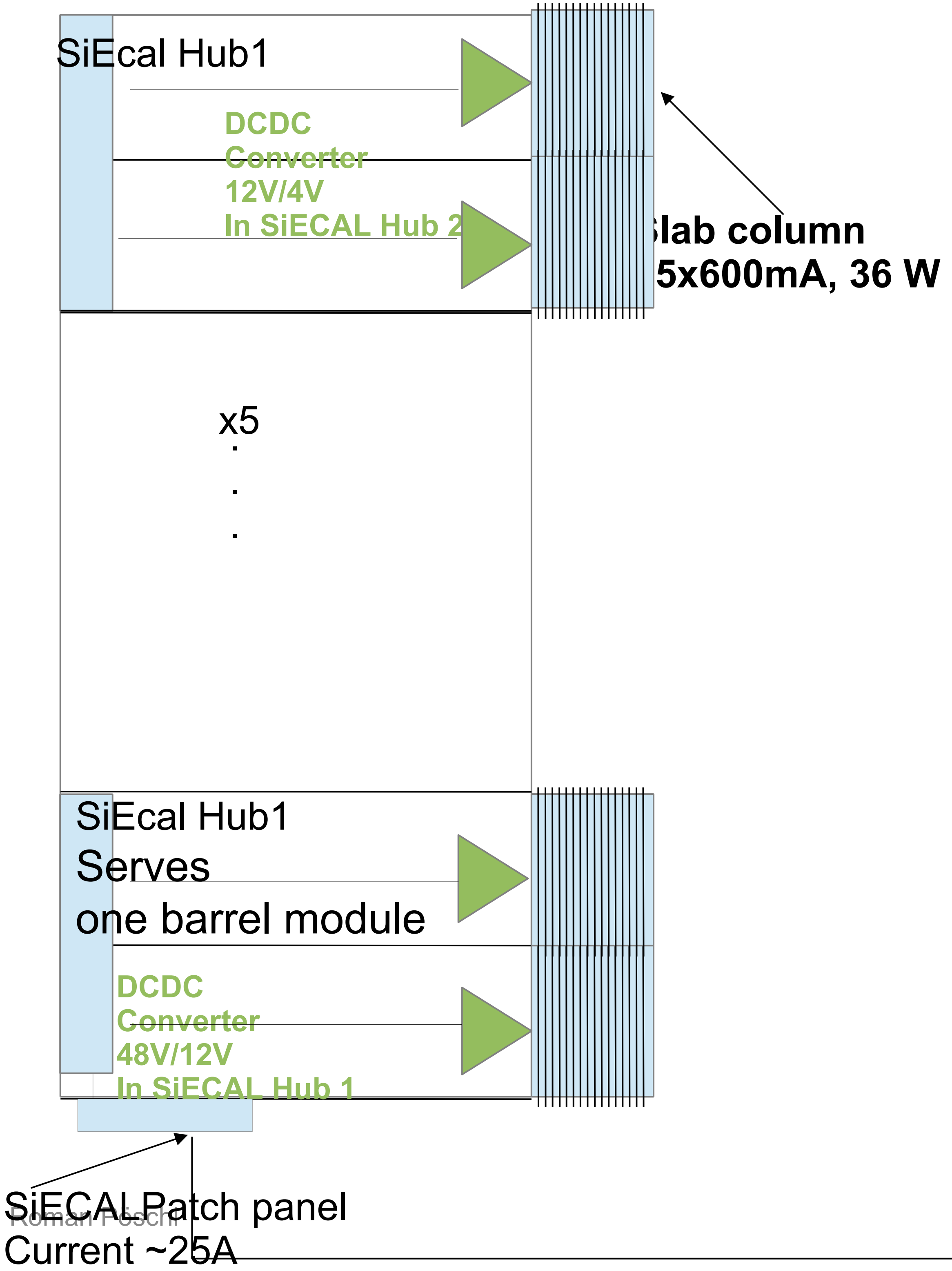
- Physics rate is governed by strong variation of cross section and instantaneous luminosity
- Ranges from 100 kHz at Z-Pole (FCC-ee) to few Hz above Z-Pole
- (Extreme) rates at pole may require other solutions than rates above pole

- Some numbers relevant for detector (electronics) operation
  - Bunch train distance ILC: O(100ms)
  - Bunch distance FCCee: 35ns (on pole), ~1us at HZ, >> 1us at tt

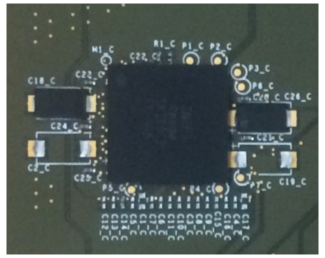
- Event and data rates have to looked at differentially
  - In terms of running scenarios and differential cross sections
  - Optimisation is more challenging for collider with strongly varying event rates
    - Z-pole running must not compromise precision Higgs physics

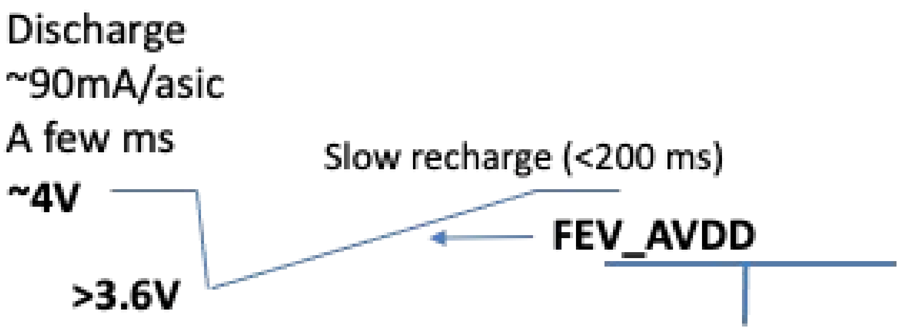


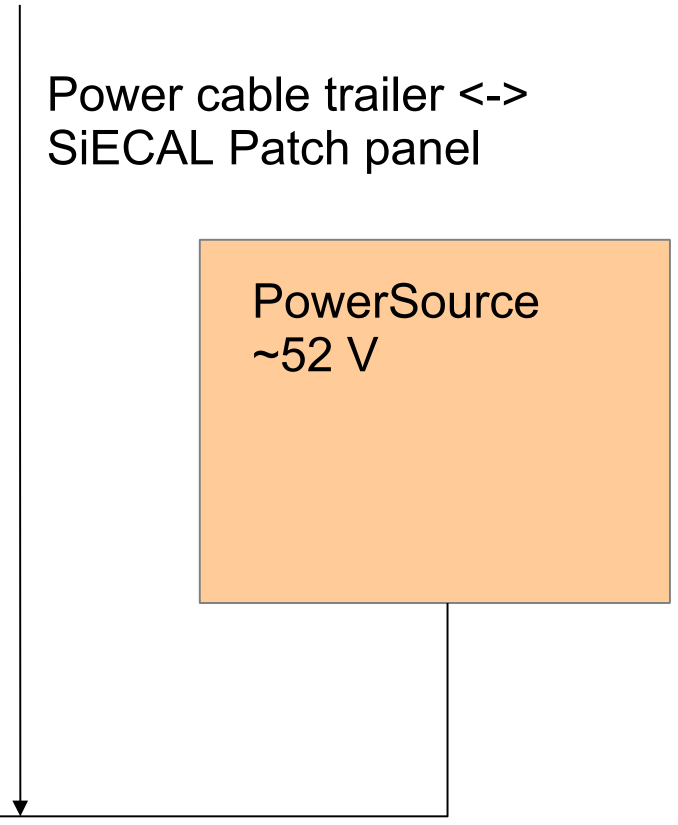
Powering concept – ILD SiECAL



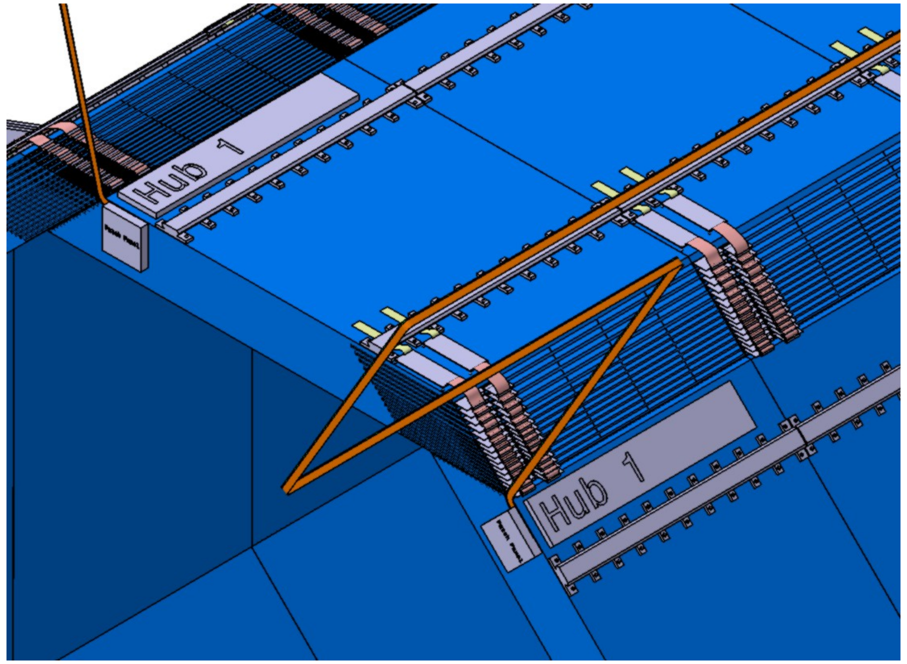
Local power storage







Zoom into ILD Ecal barrel



- Total average power consumption
- **20 kW** for a calorimeter system with 10^8 cells
  - Only possible through PP
- The art is to store the power very locally
- Will be addressed between now and end of 2024

Powering needs for different running schemes

Power pulsed systems

Numbers by Vincent

All faults are mine

ILC “Standard”

T_{Bunch} ~ 1ms
f_{rep} ~ 5Hz
=> ΔT_{Bunch}=200ms

HL-ILC:

- $\mathscr{L} \times 4\ (6)$
- $N_{\mathrm{bunches}} \times 2:\ \tau_{\mathrm{Train:}}\ 1 \rightarrow 2\ \mathrm{ms}$
- $f_{\mathrm{rep}} \times 2\ (3): 5 \rightarrow 15\ \mathrm{Hz}$

=> $\Delta T_{Bunch,min}$=66ms

HL-CLIC: ~C^3

- $\mathscr{L} \times 2$
- $N_{\mathrm{bunches}} \rightarrow :\ \tau_{\mathrm{Train:}}\ 176\ \mathrm{ns}$
- $f_{\mathrm{rep}} \times 2 : 50 \rightarrow 100\ \mathrm{Hz}$

=> $\Delta T_{Bunch,min}$~10ms

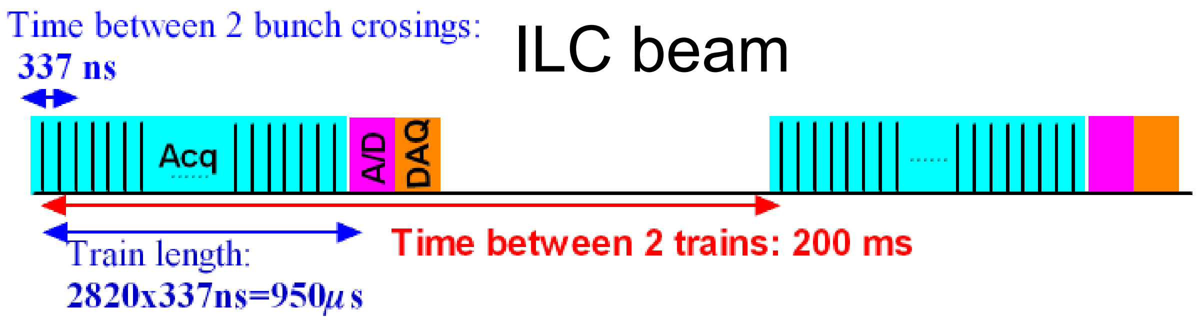
- In the (local) powering scheme the power is reloaded between the bunch trains with a small constant charging current
  - => constant power consumption
- As long as one manages to charge the capacitances between the bunch trains the overall power consumption will not increase with increasing luminosity
  - The step from ILC Standard to HL-ILC doesn't look too big, CLIC C^3 may require a further look

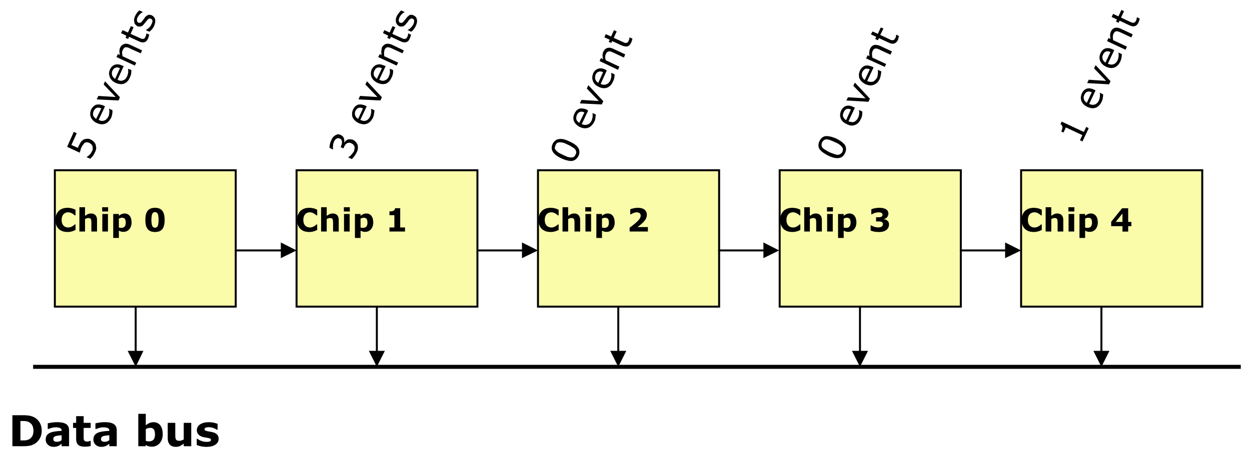
Continuously powered systems:

- Typical consumption of FEE (as of today) 5-10mW/channel
  - CMS HGCROC has 20mW/channel due to sophisticated digital part
- This translates directly into power consumption of detector
- Suppose 5mW/channel: For 10^8 channels this leads to 500 kW power consumption of full detector
  - This is the pure consumption of the electronics, no ohmic losses in power transfer etc. U=RI and I would be high)
  - **=> Active cooling**

Reminder – Readout ILC Type Calorimeters

- Minimize data lines & power



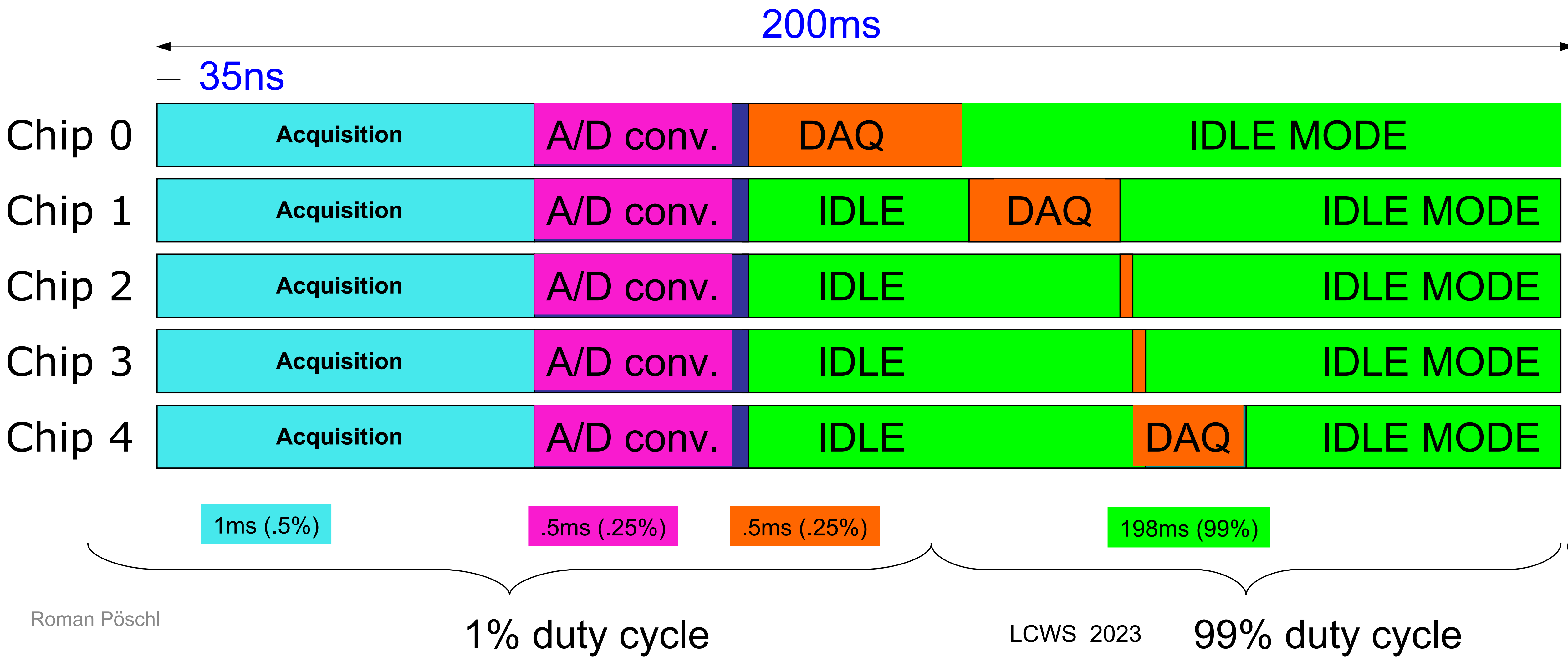


Token Ring/DAISY Chain

One (max two) data buses

--> Many busses

In continous operation



Data Acquisition

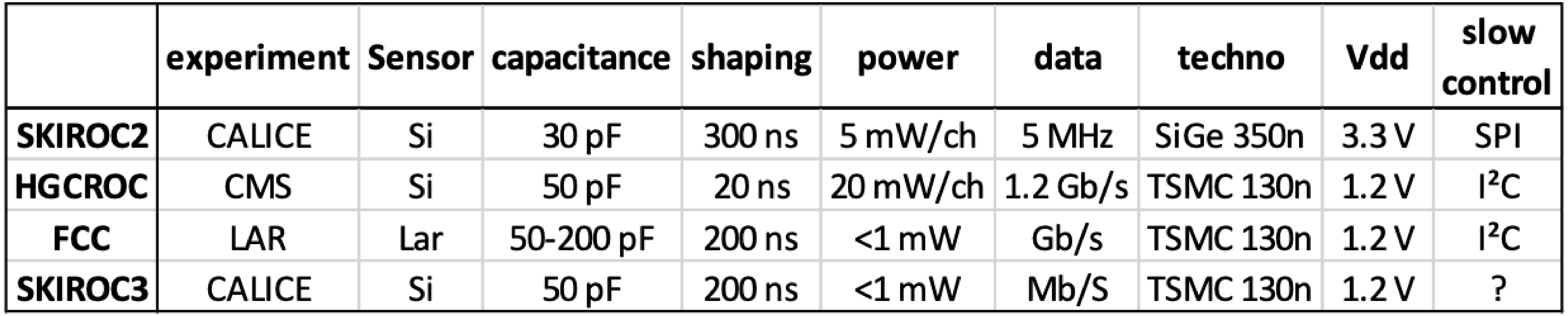
- LC operation
  - Signals can be recorded, stored and sent over long periods
- Continous operation
  - Data will have to be stored until decision for readout (->Trigger?)
  - Or will have to be shipped out continously

=> Increase of traffic and data lines

Next generation ASICS?

Ch. de la Taille
CALICE Meeting, Valencia

- Dynamic gain preamp or TOT ?
- 200 ns shaping, 10 MHz ADC, several samples on the waveform
- Timing capability ? Auto-trigger and zero suppression
- Target ~1 mW power/ch and possible power pulsing
- I²C slow control ? New readout protocol ?
- Include 2.5V LDO inside VFE ?
- Compatible with FCC LAr. SiPM/RPC tbd



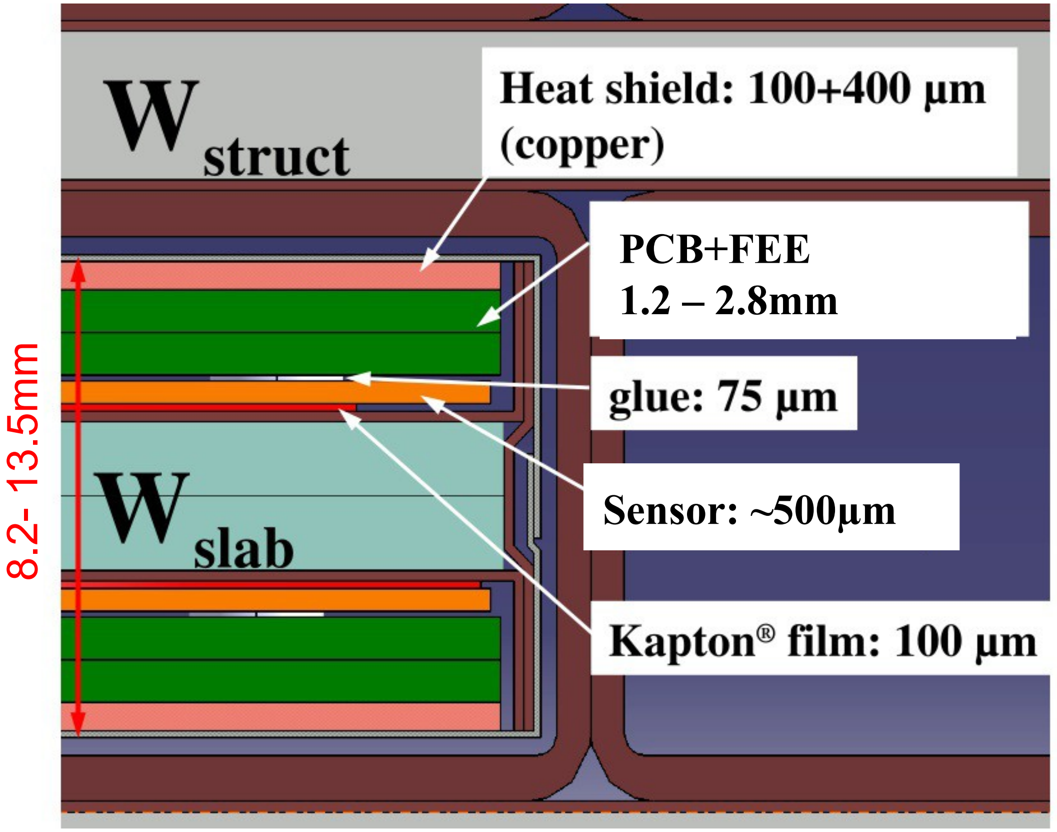
	experiment	Sensor	capacitance	shaping	power	data	techno	Vdd	slow control
SKIROC2	CALICE	Si	30 pF	300 ns	5 mW/ch	5 MHz	SiGe 350n	3.3 V	SPI
HGCROC	CMS	Si	50 pF	20 ns	20 mW/ch	1.2 Gb/s	TSMC 130n	1.2 V	I²C
FCC	LAR	Lar	50-200 pF	200 ns	<1 mW	Gb/s	TSMC 130n	1.2 V	I²C
SKIROC3	CALICE	Si	50 pF	200 ns	<1 mW	Mb/S	TSMC 130n	1.2 V	?

CdLT CALICE meeting 20 apr 2022

- "Brute force" evaluations as on previous slides will have to take into account electronics development
- A pulsed detector will always draw less power from the grid

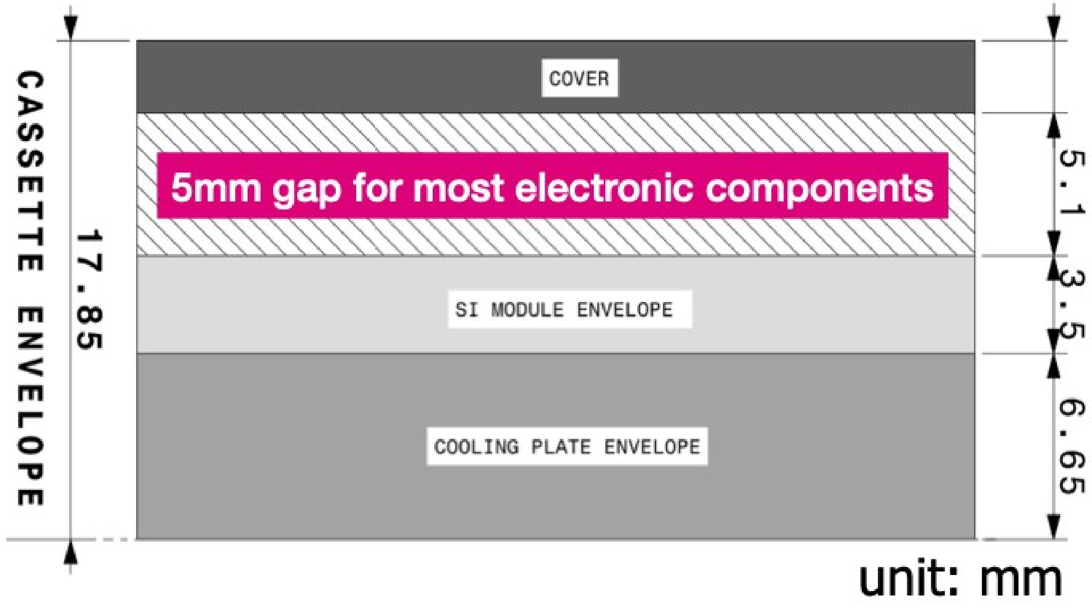
Cooling – Consequences for Calorimeter Design

ILD SiECAL



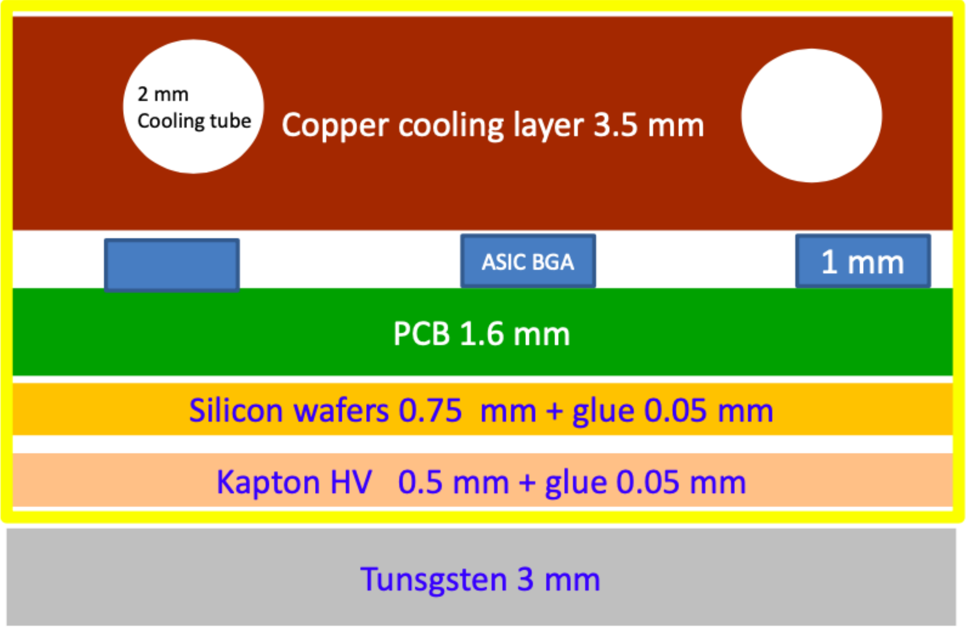
- **Two** layers within 13mm max.
- Including one absorber layer
  - 2.1mm or 4.2mm W
- 500um for heat evacuation

CMS HGCAL
N. Strobbe, CALOR 2022



- One layer within ~18mm
  - w/o absorber
  - 6mm for cooling

"ILD for CEPC"
J.C. Brient, CEPC Workshop 2018



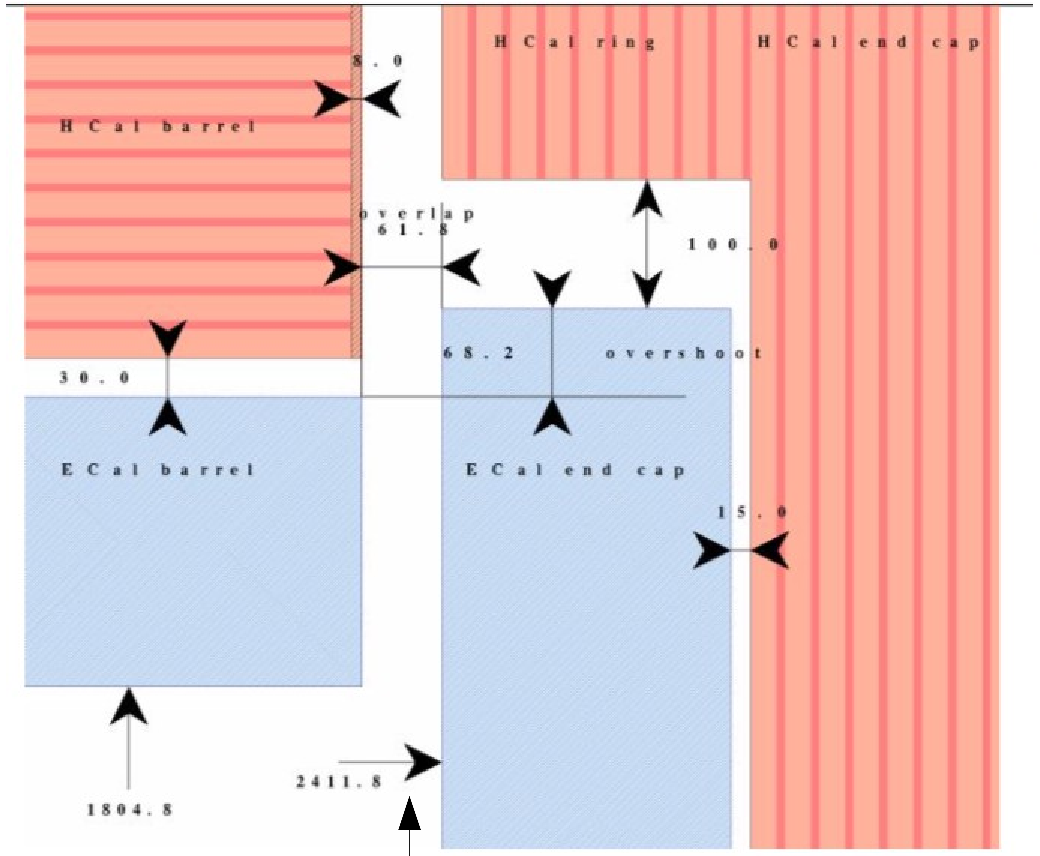
- One layer within 10.4mm
  - Including 3mm W absorber
- 3.5mm for cooling

Introduction of cooling puts penalty of order 50% on (longitudinal) granularity

Barrel/Endcap Region

Technical drawing
ILD Calos barrel/endcap

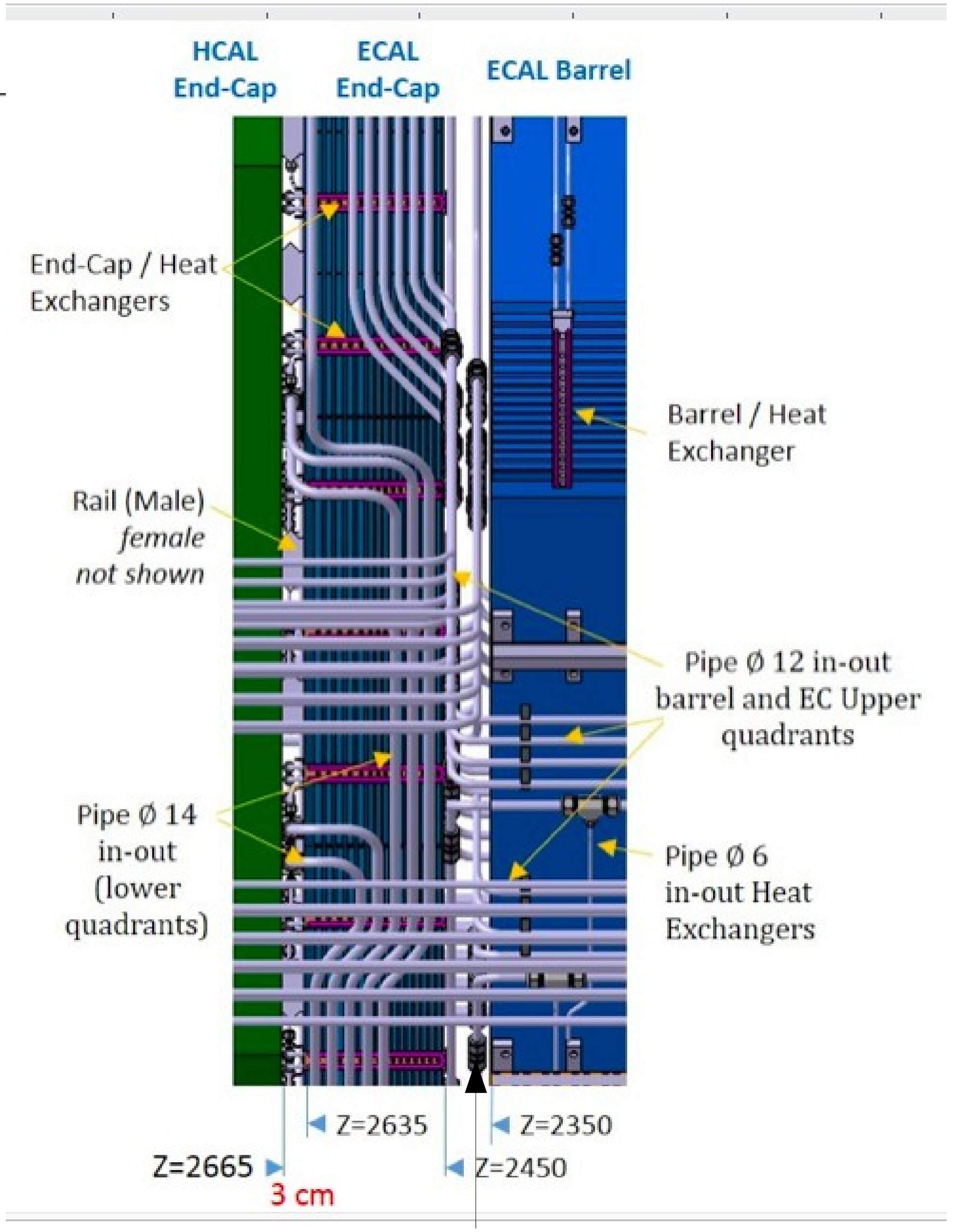
H. Videau



62.8mm

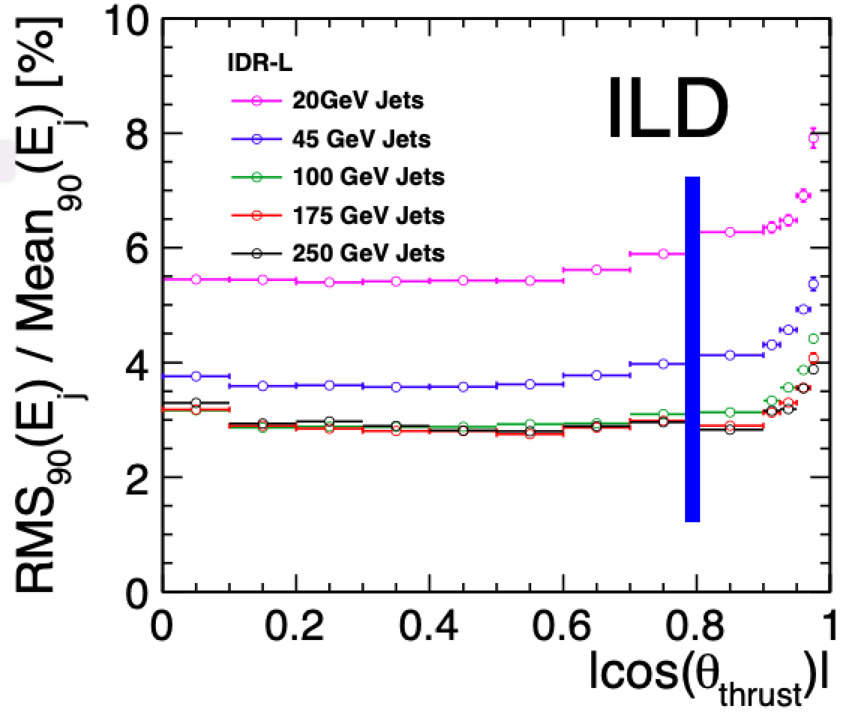
ILD Calos barrel/endcap
Cooling system

D. Grondin



100mm

- Region between endcap and barrel
  - Place to route services in and out
  - Gap between endcap and barrel 100mm (older ILD Design) 62.5mm (newer ILD design)
    Gap Hcal/Ecal EC: 100mml
    Already w/o services complicated region with reduced acceptance!



- Seems to be under control in ILD
- Needs to be watched if services change

Summary and outlook

- Choice of collider option has considerable influence on calorimeter design

- Current (ILD) Calorimeter design seems to be well suited for all Linear Collider Options
  - Very short bunch train separation (CLIC) may compromise capacitance recharging for local power storage

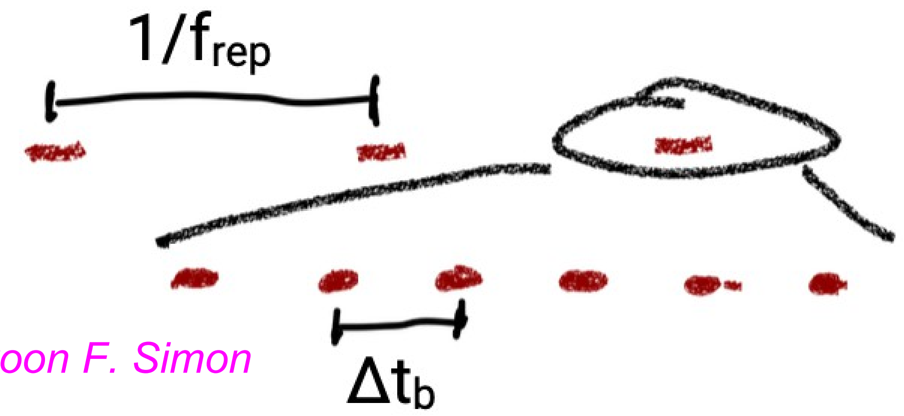
- The break comes when considering circular colliders
  - Smaller magnetic field
    - ==> Larger inner Ecal radius
  - Continous operation
    - ==> No power pulsing
    - Different data acquisition architecture
    - Different (more?) services
  - Smaller granularity (lateral [not shown today] and longitudinal)
  - Barrel/endcap may become critical
    - Watch closely with detailed simulation!
  - What to optimise for Z-pole, HZ?

- Conclusions for ILC can be ported to other LC options
- Circular machines require a full blown optimisation study (partially done for CEPC)

Backup

Operation mode- pulsed or continous

- Linear Colliders operate in bunch trains



Cartoon F. Simon

CLIC: Δt_b ~ 0.5ns, frep = 50Hz

ILC: Δt_b ~550ns, frep = 5 Hz (base line)

- Power Pulsing reduces dramatically the power consumption of detectors
  - e.g. ILD SiECAL: Total average power consumption 20 kW for a calorimeter system with 10^8 cells
- Power Pulsing has considerable consequences for detector design
  - Little to no active cooling
  - => Supports compact and hermetic detector design

- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in “continuous” mode
  - R&D Goal: Avoid/minimise active cooling also in continuous mode
  - Challenge differs depending on where the electronics will actually be located

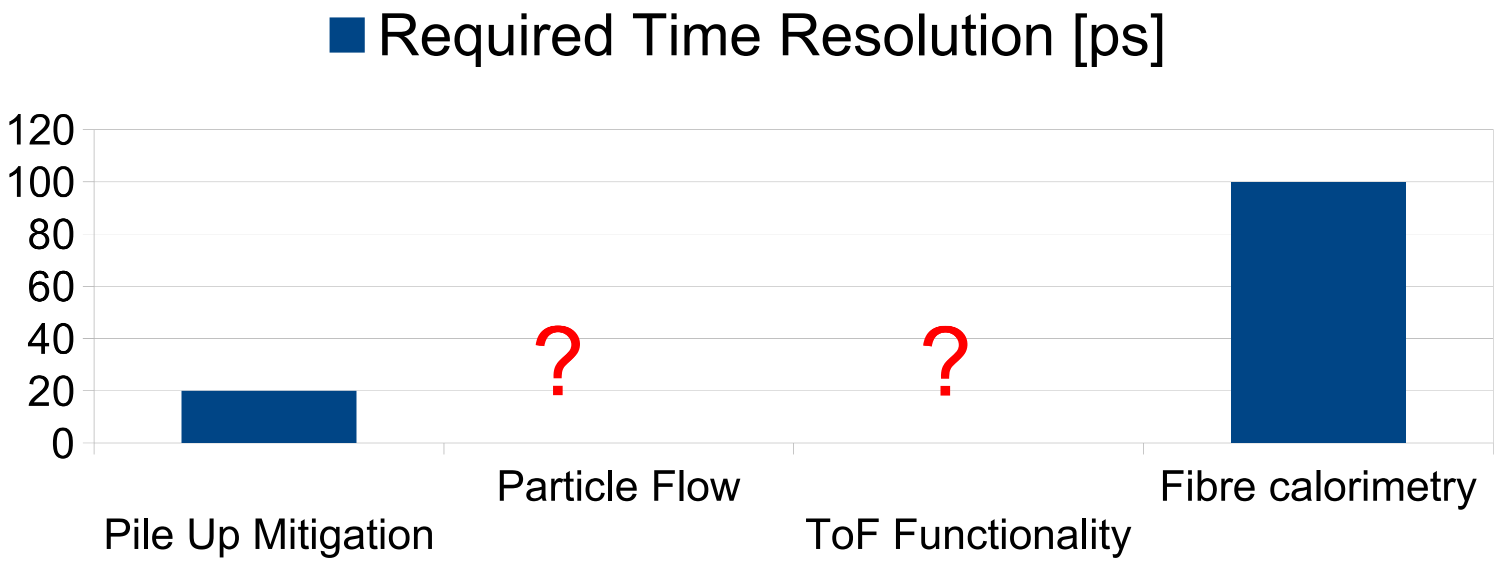
Timing ?

- Timing is a wide field

- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions

- At which level: 1 MIP or Multi-MIP?

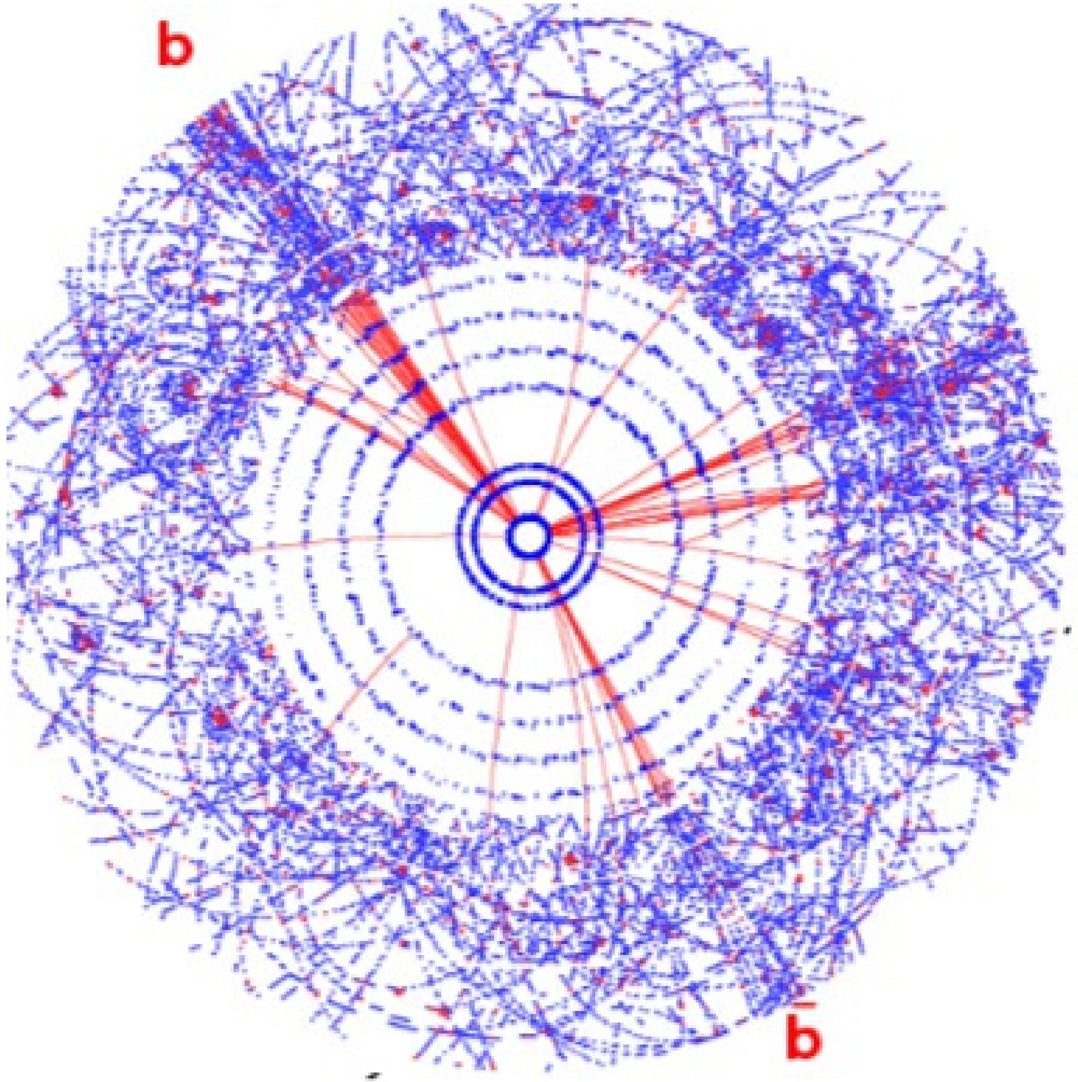
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters



- A topic on which calorimetry has to make up it's mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels

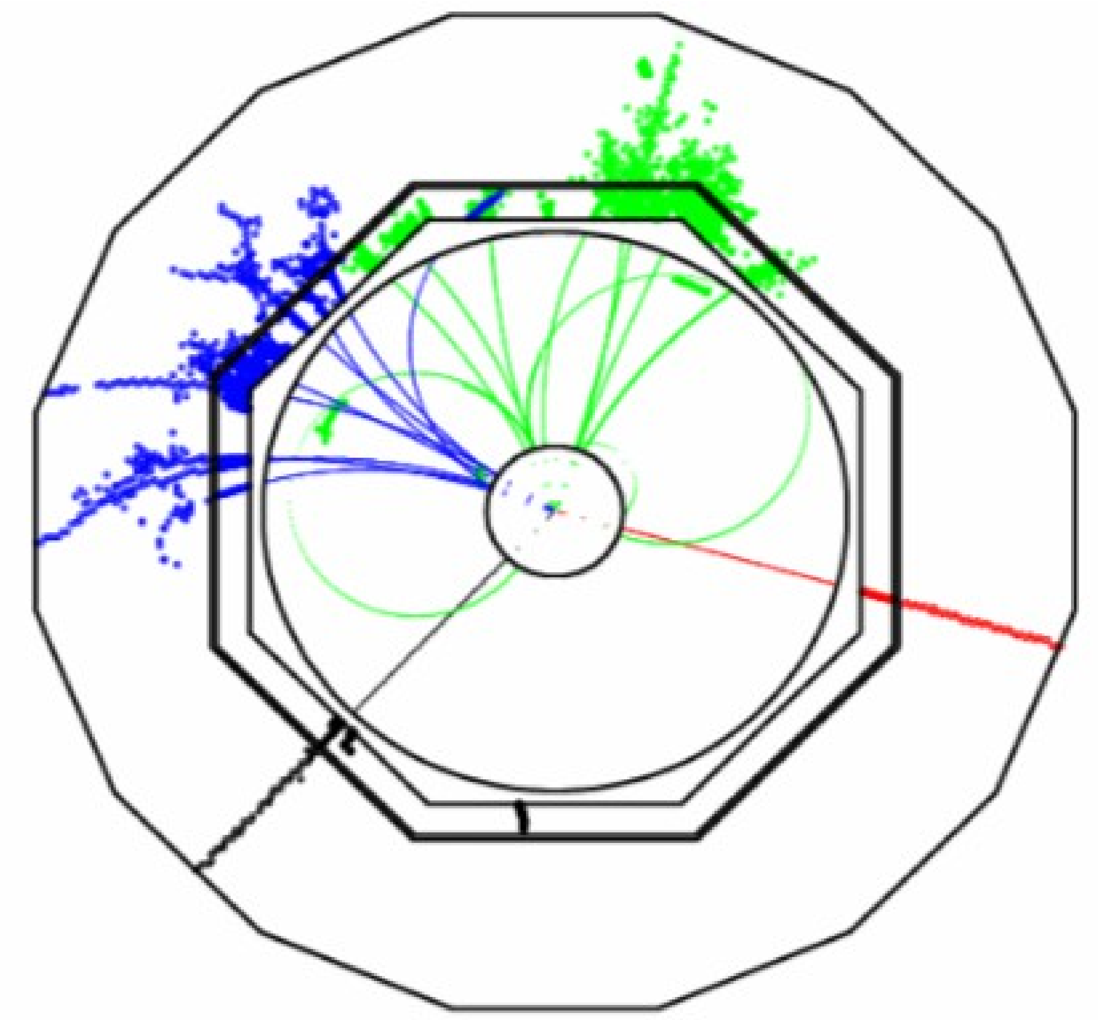
(Rough) Comparison – Hadron collisions ↔ e^+e^- collisions

Hadron-hadron collisions e.g. LHC



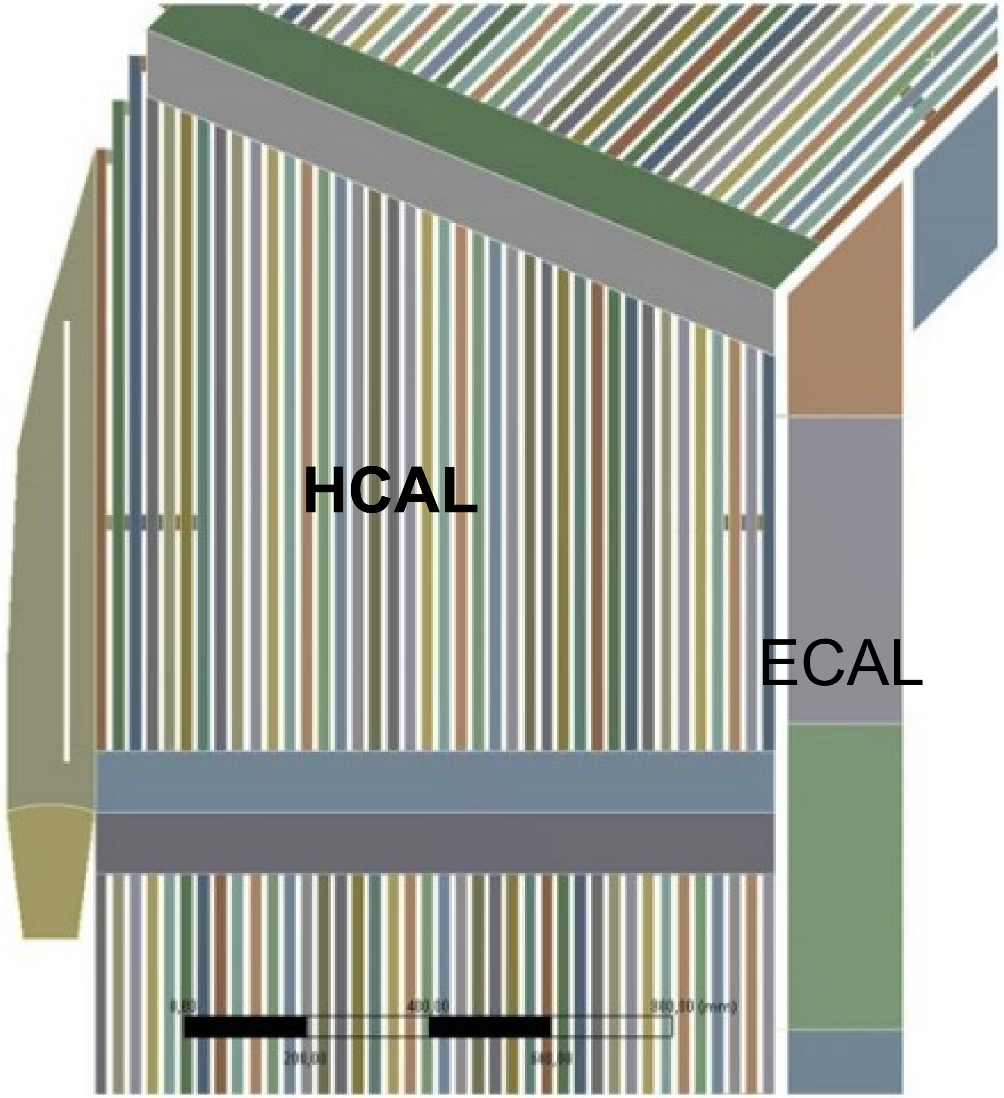
- Busy events
- Require hardware and software triggers
- High radiation levels

e^+e^--collisions



- Clean events
- No trigger
- Full event reconstruction

ILD concept and highly granular calorimeters



- ILD is particle flow detector
  - Implies goal to measure every particle of hadronic final state
  - Key components for PFA are highly granular calorimeters

- Calorimeter options in ILD
  - Silicon-Tungsten Ecal
    - 26-30 layers
    - Cell size 5.5x5.5mm^2, layer depth 0.6-1.6 X_0
  - Scintillator-Tungsten Ecal
    - 30 layers
    - Strip size 5x45 mm^2, layer depth 0.7 X_0
  - Analogue Hcal
    - 48 layers
    - Scintillating tiles: 30x30mm^2, layer depth 0.11λ_I
    - Absorber stainless steel
  - Semi-Digital Hcal
    - 48 layers
    - GRPC: 10x10mm^2, layer depth 0.12 λ_I
    - Absorber stainless steel