Detector Systems at the International Linear Collider

Cover: Rey.Hori

PicoSEC Systems Integration Training
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Outline

- Introduction
    - The ILC Physics Landscape
    - … and the resulting Detector Requirements

- Detector Concepts: ILD & SiD
    - General Design Choices
    - Vertexing
    - Main Tracking
    - Calorimetry
    - Performance & Cost

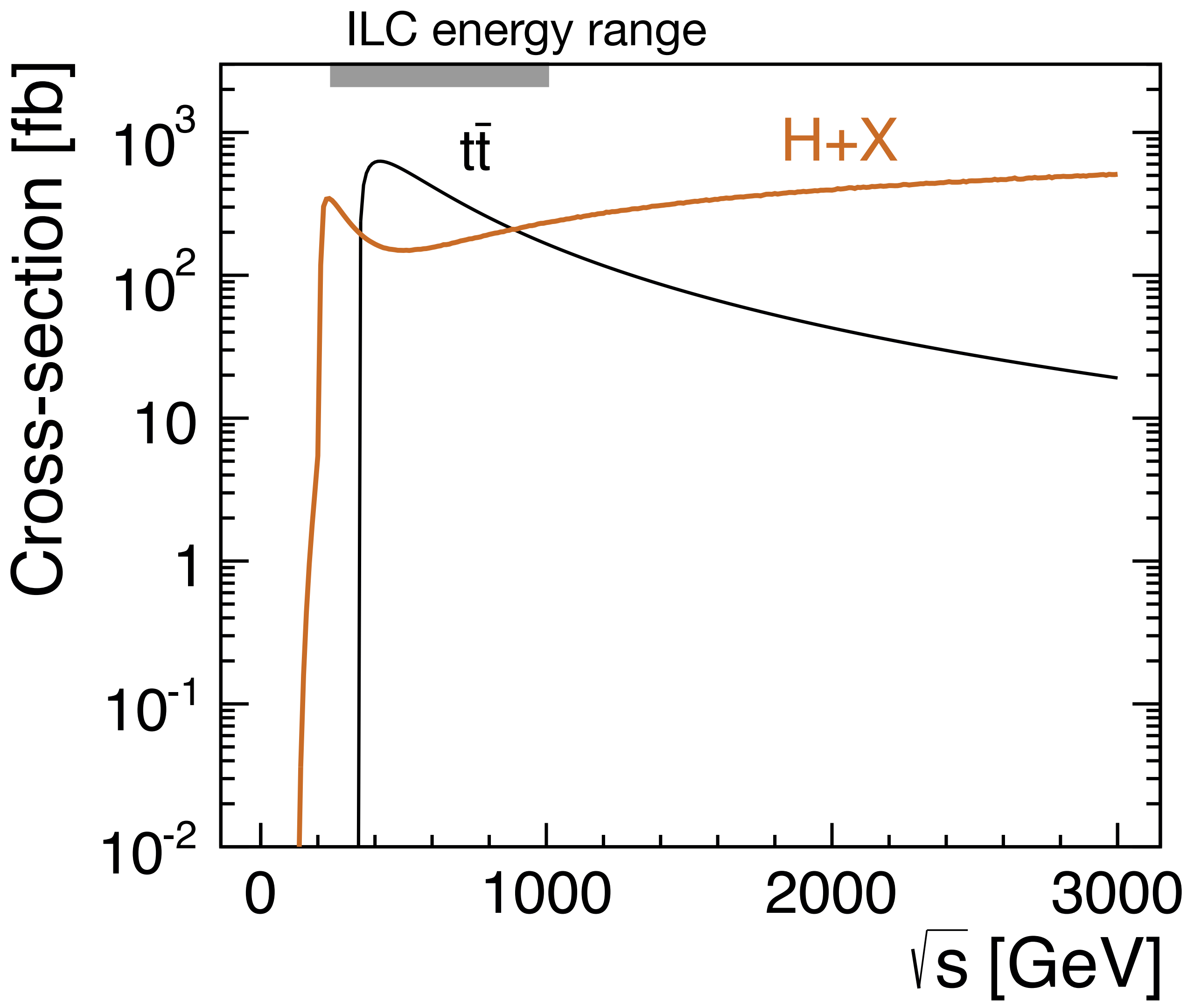
- Integration Challenges:
    - Calorimeters with extreme channel counts
    - Low mass systems

- Conclusions

The ILC Physics Landscape

… a combination of certainty and speculation:

- Excellent physics program guaranteed:
  - Higgs physics - mass, couplings, potential, …
  - Top physics - properties (mass, width,…), top as a probe for New Physics
  - Precision physics - electroweak measurements, QCD, …



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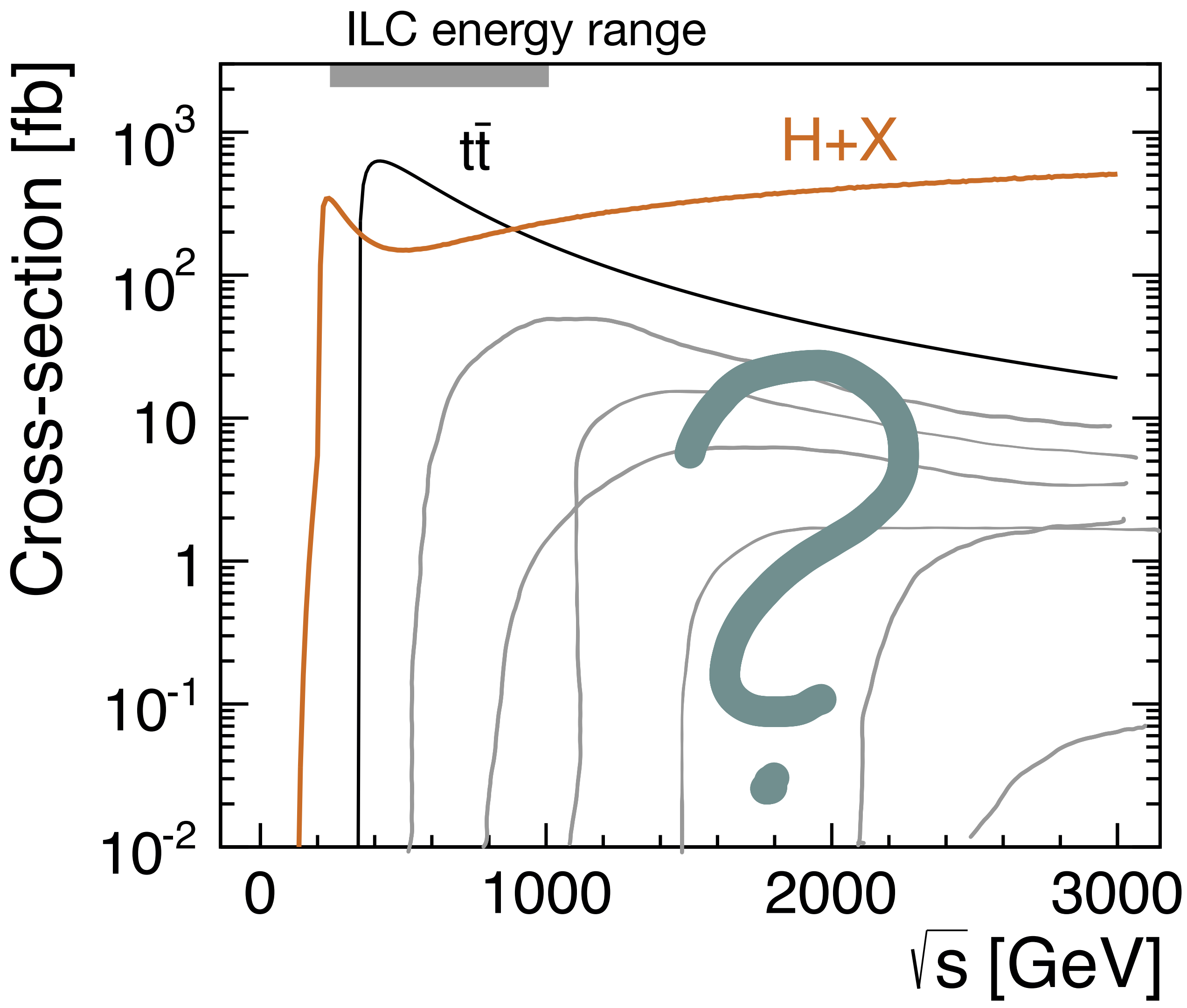
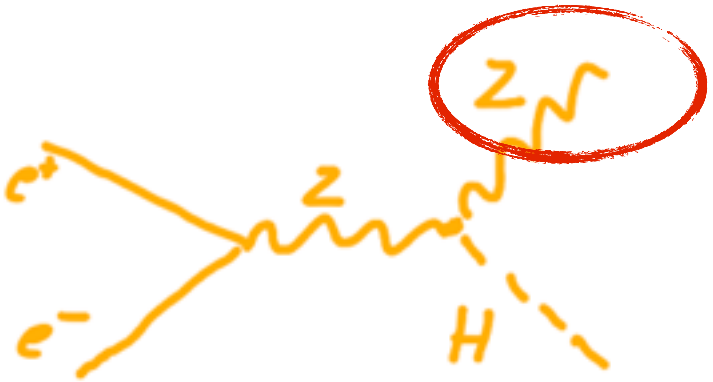


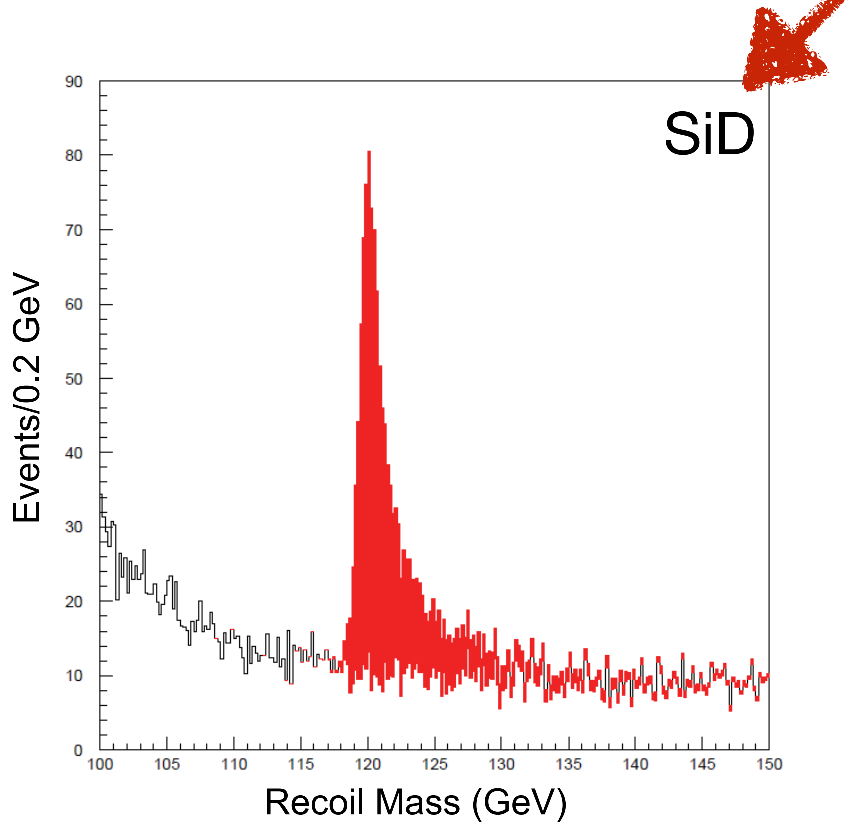
- Discovery potential for New Physics
  - Direct production of new particles - Mass reach up to √s/2 for (almost) all particles
    - Spectroscopy of New Physics
  - Indirect (model-dependent) search for New Physics extending far beyond √s

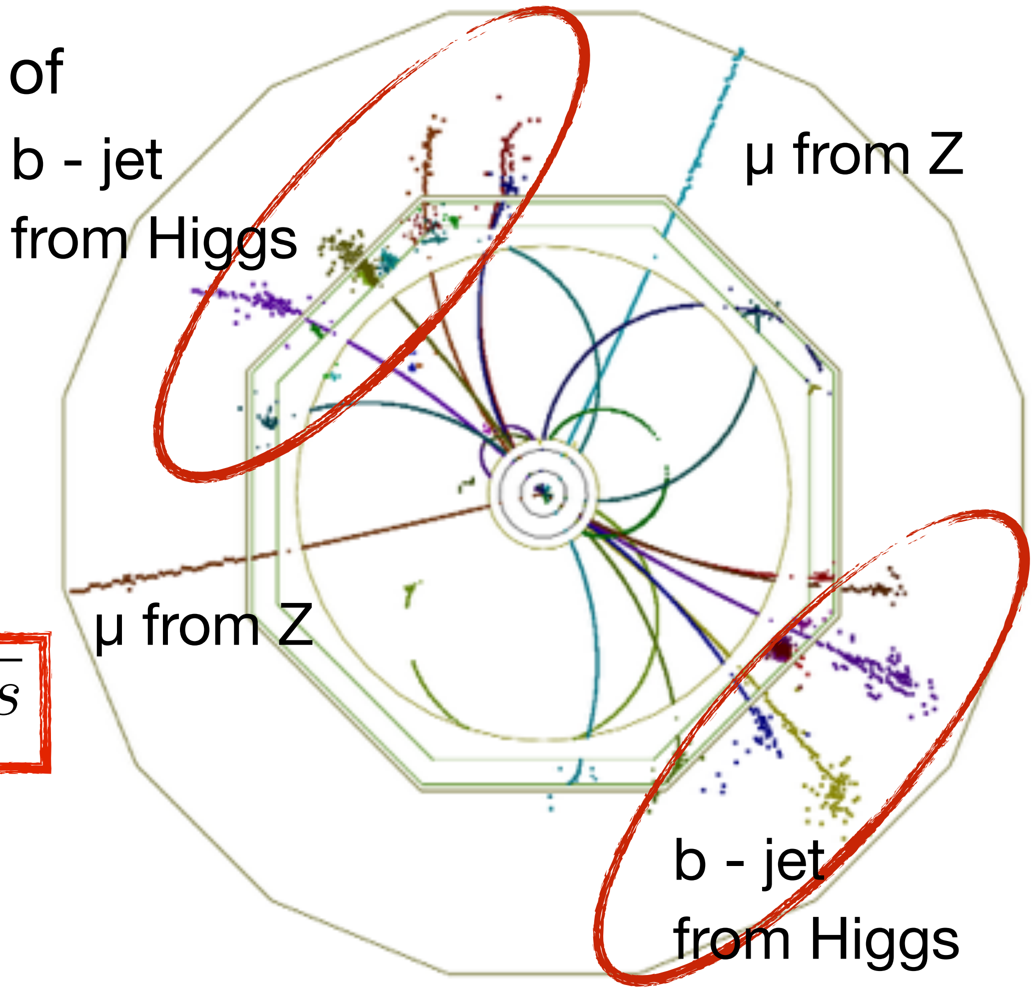
… and the resulting Detector Requirements I

- A flagship measurement: Model-independent coupling of Higgs to Z
- Obtained from recoil mass measurement of reconstructed Z boson, independent of Higgs decay



$$m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$





$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

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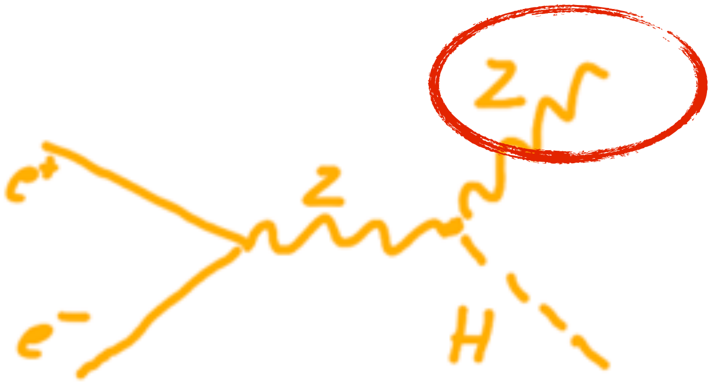

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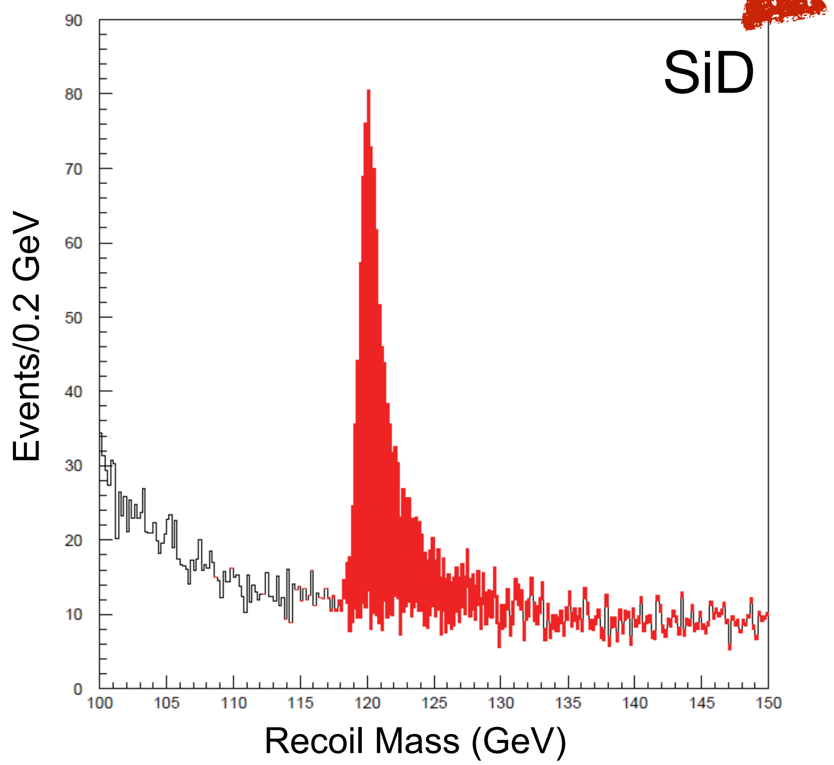

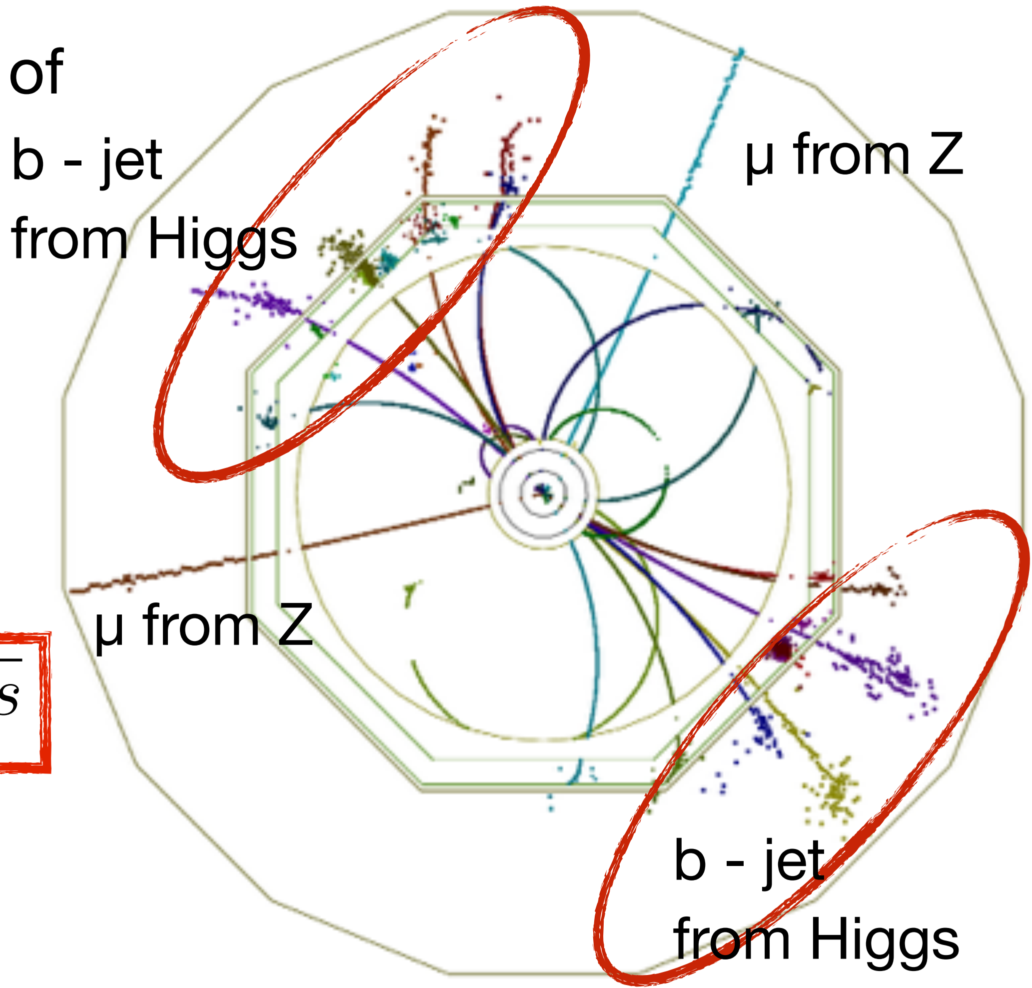

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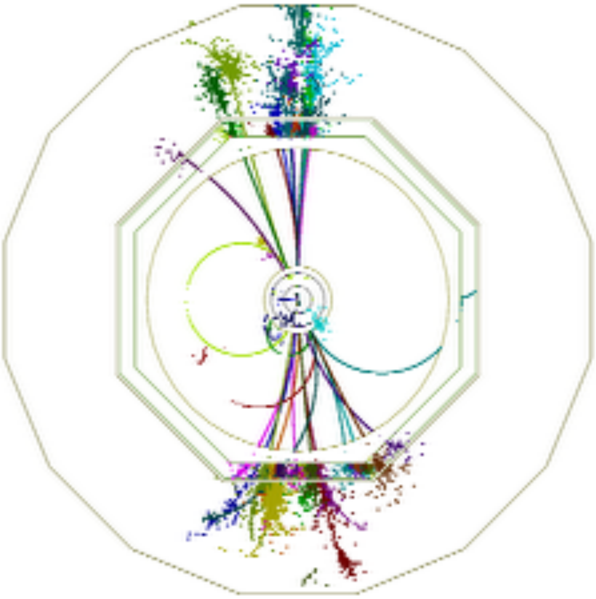
Key detector requirements:

- **excellent tracking** to measure Z -> l^+l^- as precisely as possible
- **very efficient flavor tagging** to measure Higgs couplings to fermions (separating b, c and light jets)

… and the resulting Detector Requirements II

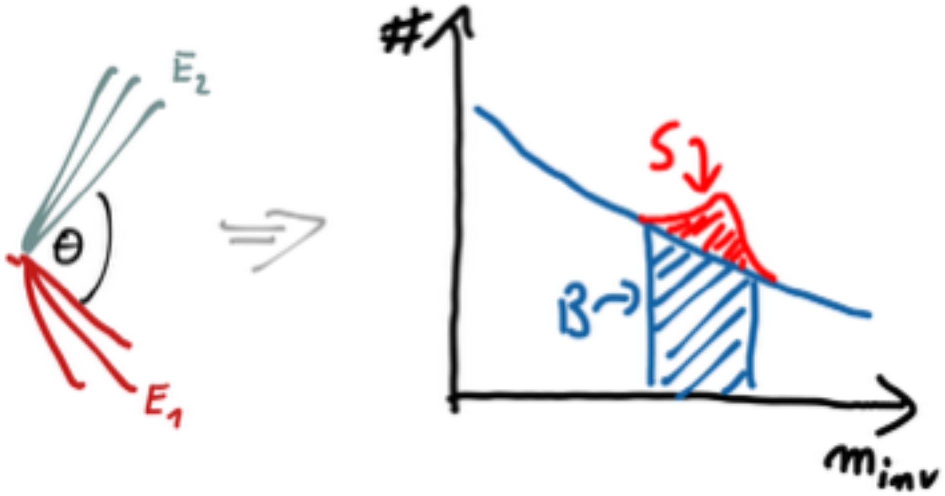
- In general the cross sections of physics processes are quite modest at ILC compared to LHC - at the lower energy stages typically 1000s to 10s of thousands of events - Want to be able to use all possible final states, including high-BR hadronic decays
  - Relevant in many different cases: Identification / separation of gauge bosons (W, Z)



ILD, 1 TeV

$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}\,q\bar{q}$$

Generic consideration:



significance:

$$\frac{S}{\sqrt{S+B}}$$

directly depends on mass resolution

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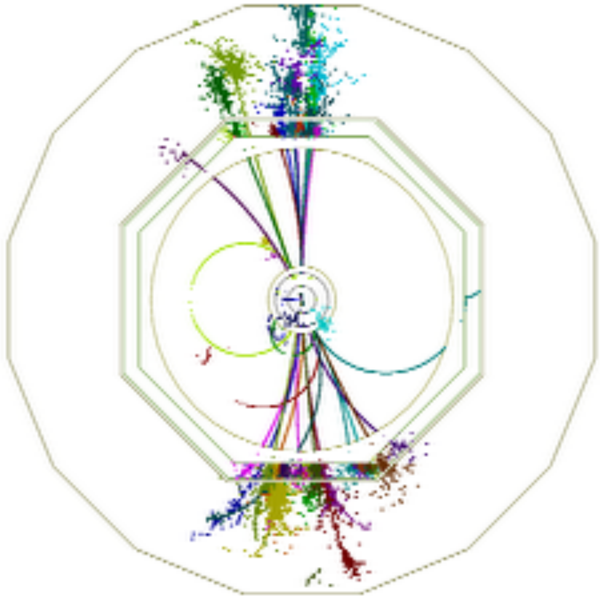

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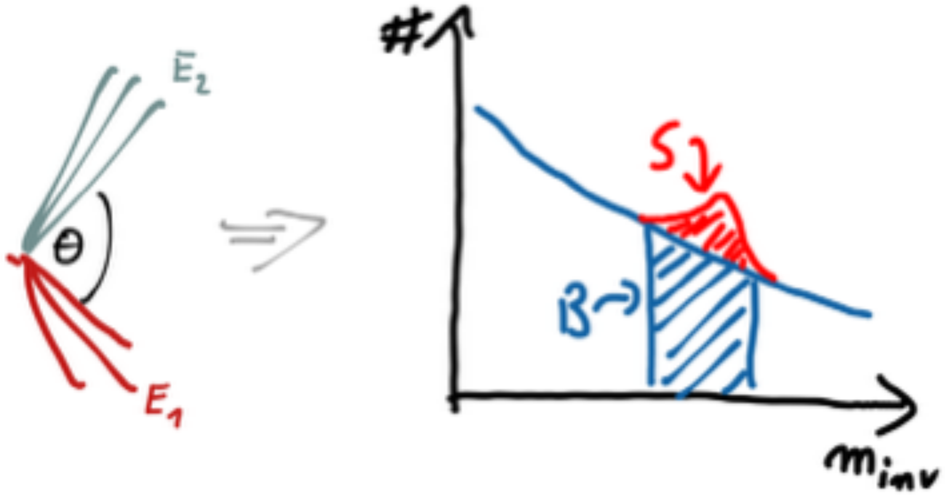

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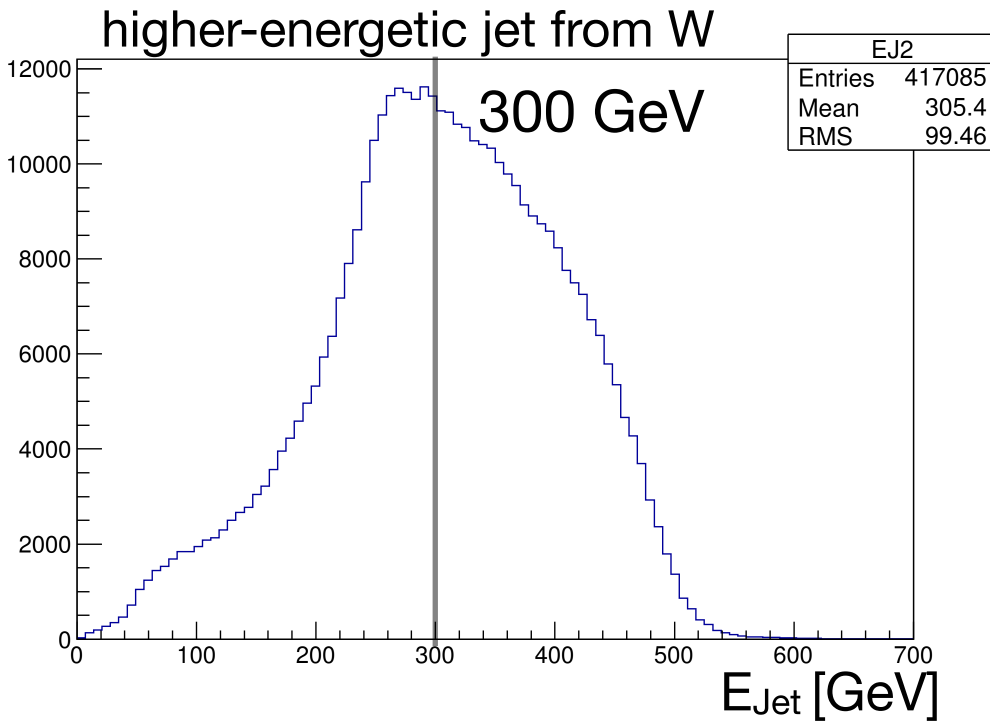

lower energy jet peaks at **50 GeV**
multi-jet SUSY observables at 500 GeV typically **20 GeV** - **100 GeV** jets

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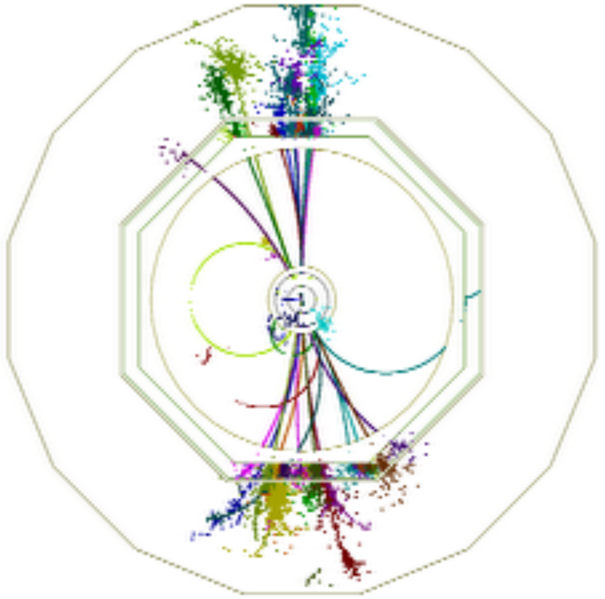

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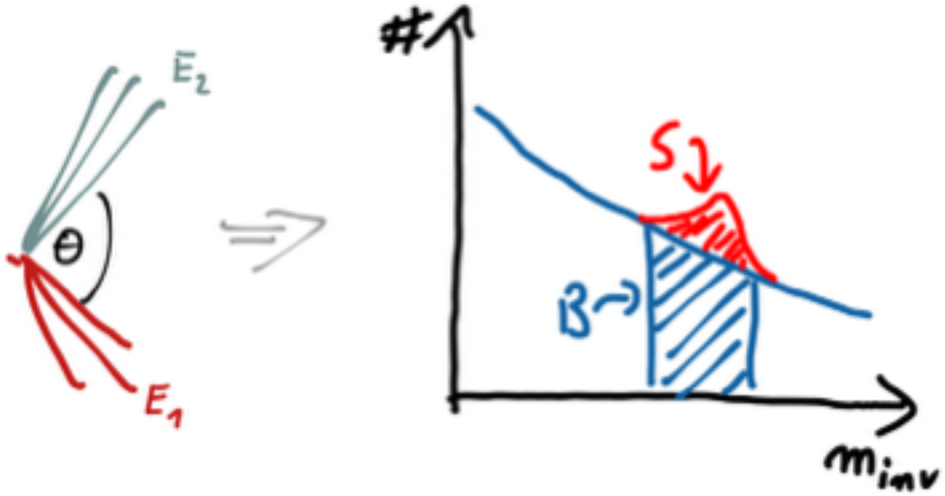

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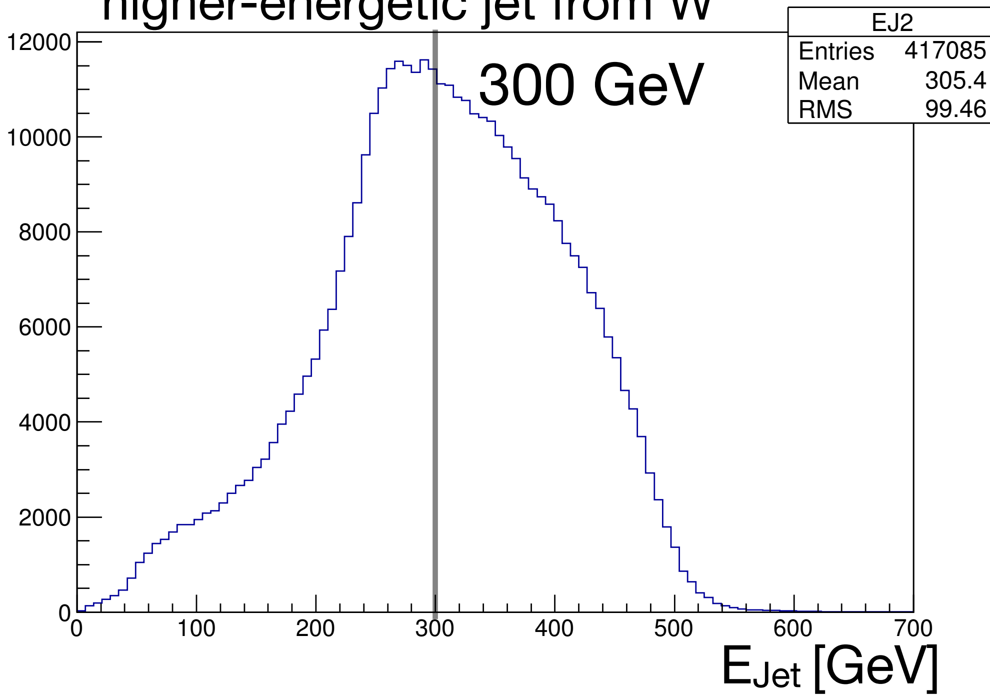
higher-energetic jet from W

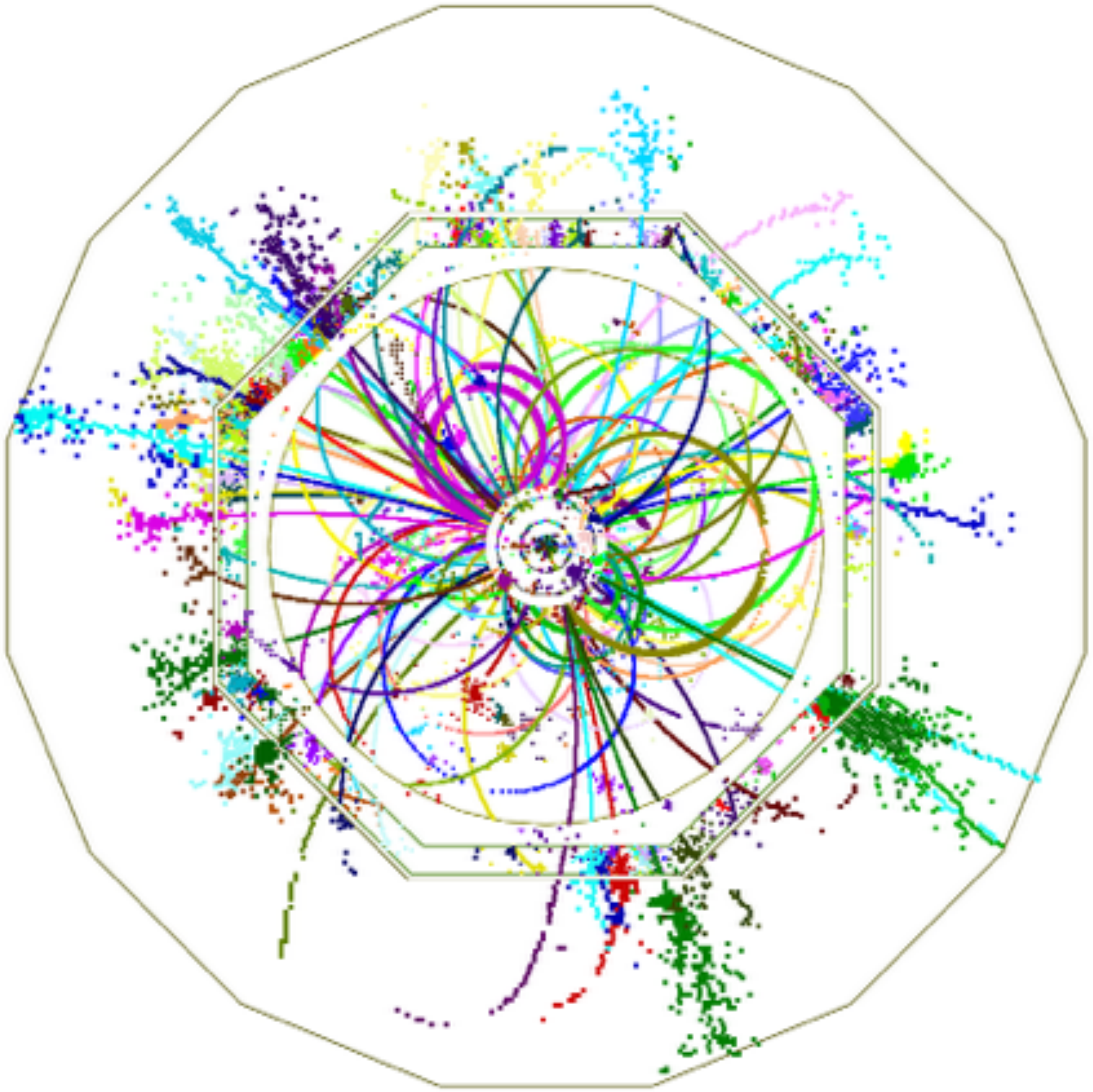


300 GeV

Detector requirement: Best possible jet energy resolution over a wide energy range

lower energy jet peaks at **50 GeV**
multi-jet SUSY observables at 500 GeV typically **20 GeV** - **100 GeV** jets

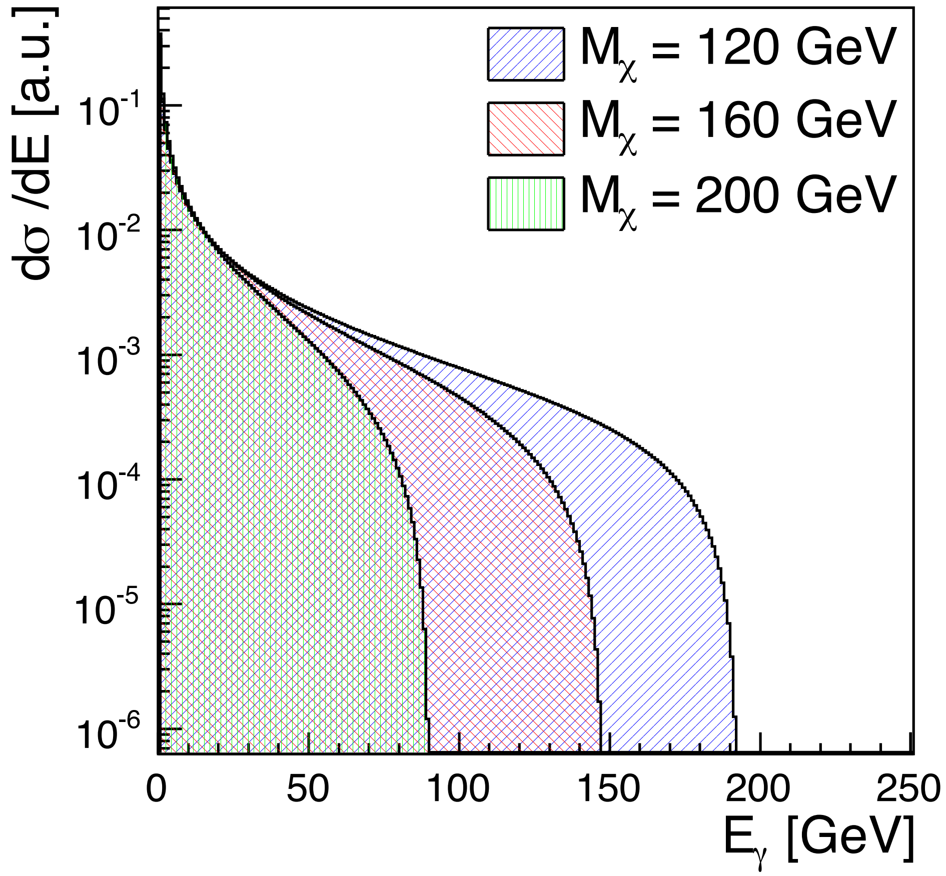
… and the resulting Detector Requirements III



$$e^+e^- \to ttH \to q\bar{q}b\,q\bar{q}\bar{b}\,b\bar{b}$$

ILD, 1 TeV

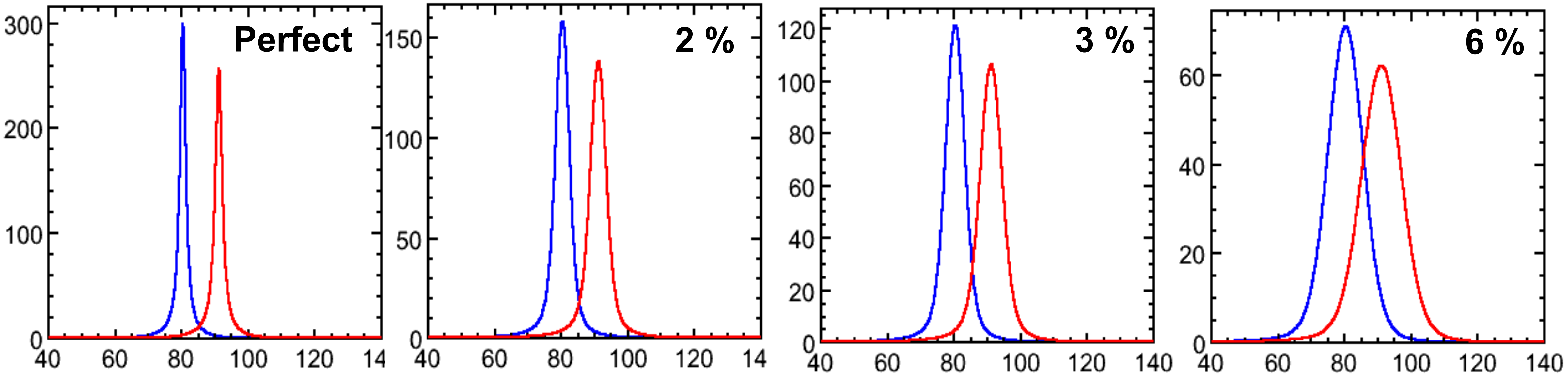
- Precise event reconstruction in high-multiplicity environments



- And full coverage to measure “nothing”

Putting the Requirements together

- Precise vertexing - impact parameter resolution: $\sigma_b < 5 \oplus 10/p\beta \sin^{3/2}\theta \ \mu\text{m}$
- High resolution tracking - transverse momentum resolution $\delta(1/p_T) \simeq 2 \times 10^{-5}/\text{GeV}/c$
- Jet energy resolution ~ 2.5 σ separation of W, Z (not too far from perfect separation) $\Delta E_{\text{Jet}}/E_{\text{Jet}}$ ~ 3.5%



… and designing a Detector

- A multi-layer pixel detector with small pixels close to the interaction point
- High resolution tracking detectors
- A strong magnetic field
- Low material budget - Eliminate multiple scattering as much as possible
- Imaging calorimeters inside of the magnet & particle flow algorithms

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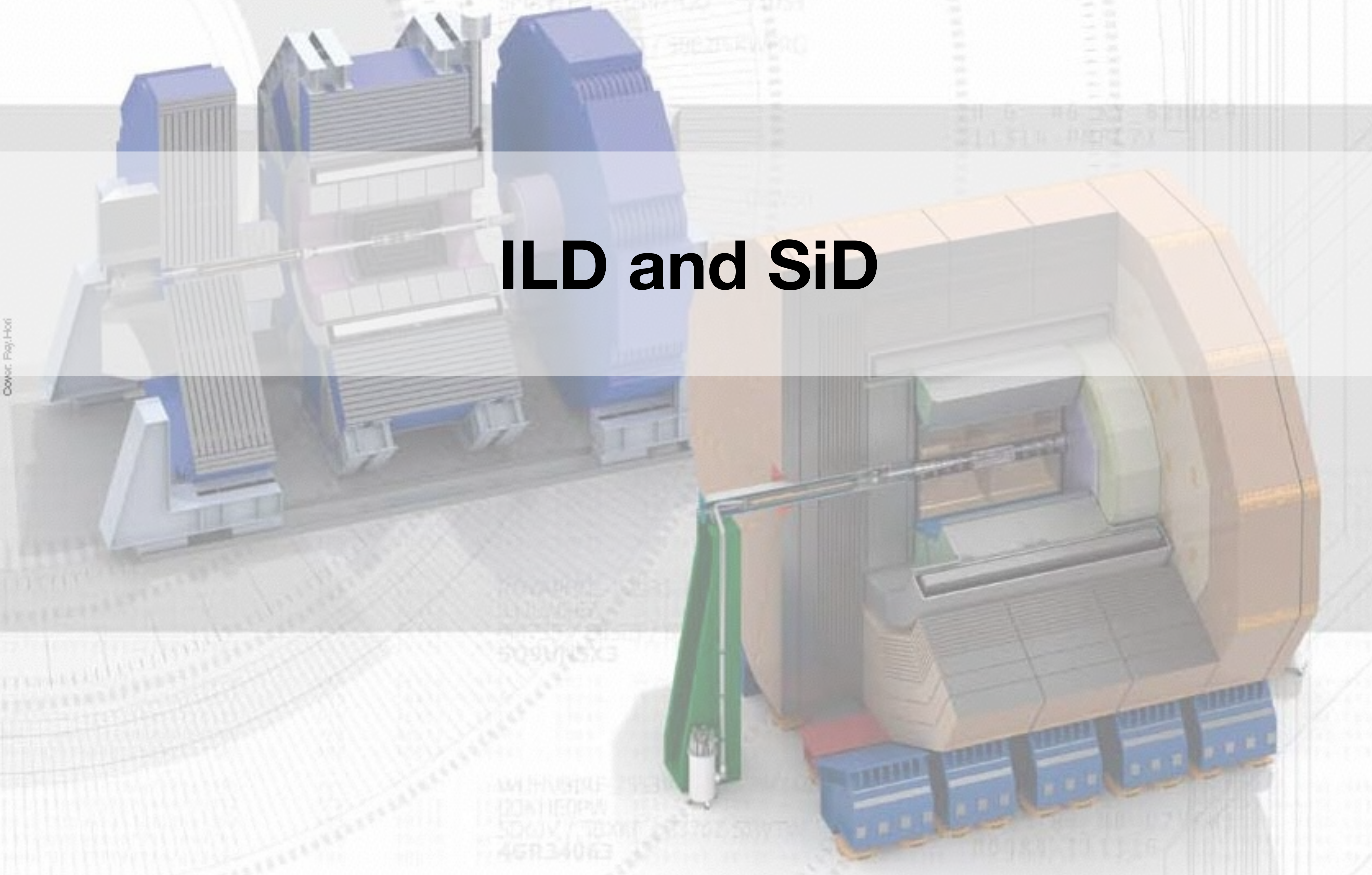
Where this leads you: A detector design a bit like CMS, but

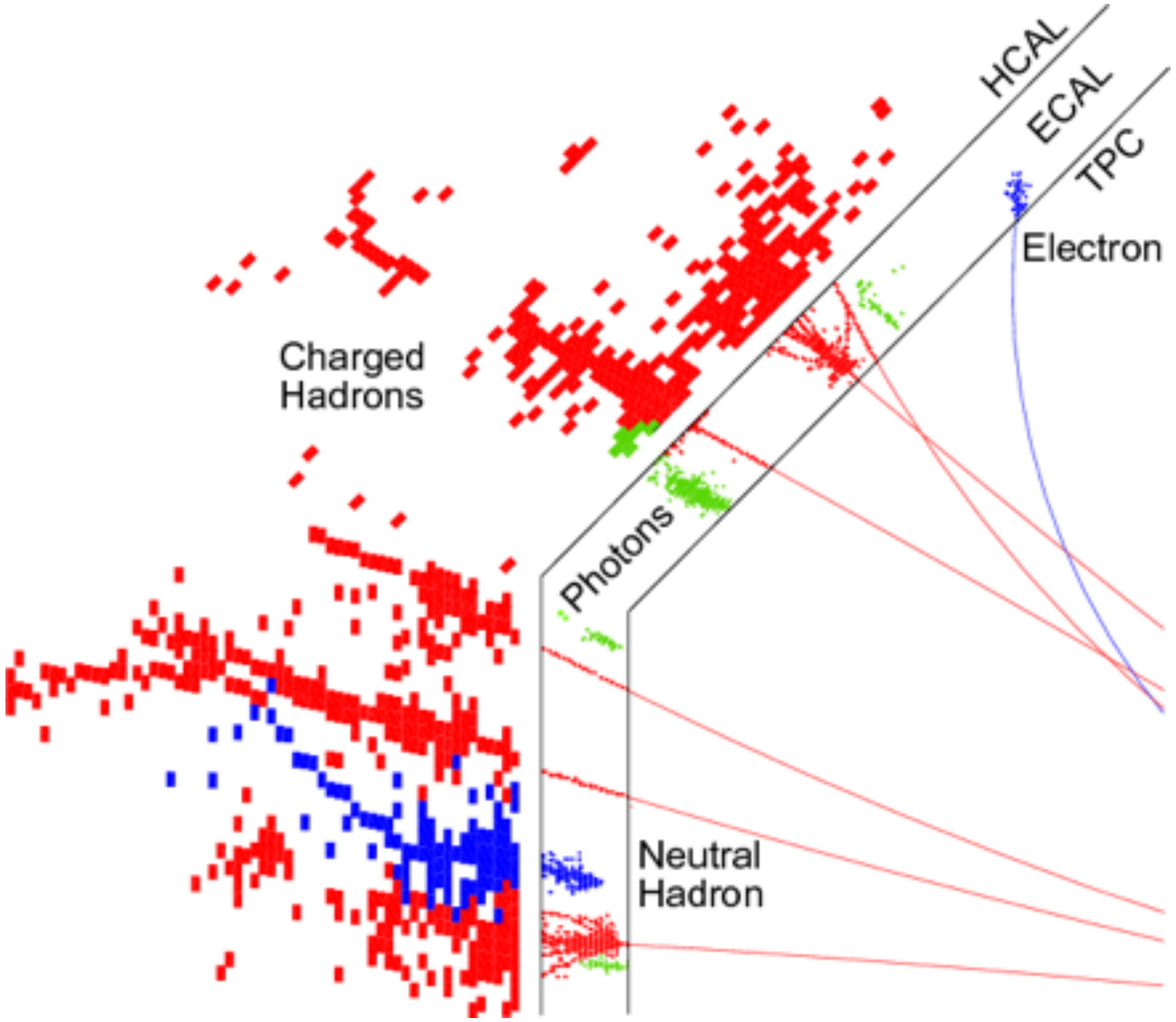
- Shorter detector barrel: Only small boosts of CMS system in ILC collisions
- Very different calorimeters: No emphasis on photon resolution, granularity instead to achieve best jet energy resolution- HCAL plays a central role
- Much more aggressive reduction of material budget
  - Reduced need for cooling: Power-pulsing possible
  - Time for readout between bunch trains
  - Technological advances - Thinner silicon, low-power electronics, light-weight mechanics,...



ILD and SiD

Cover: Ray Hori

The Fundamental Design Principle: Particle Flow



- A modern approach to event reconstruction: Reconstruct every single particle in an event, instead of thinking in “towers”

▸ Enables excellent jet energy resolution by making use of all available measurements of a particle (***p*** in tracker, ***E*** in calorimeters)

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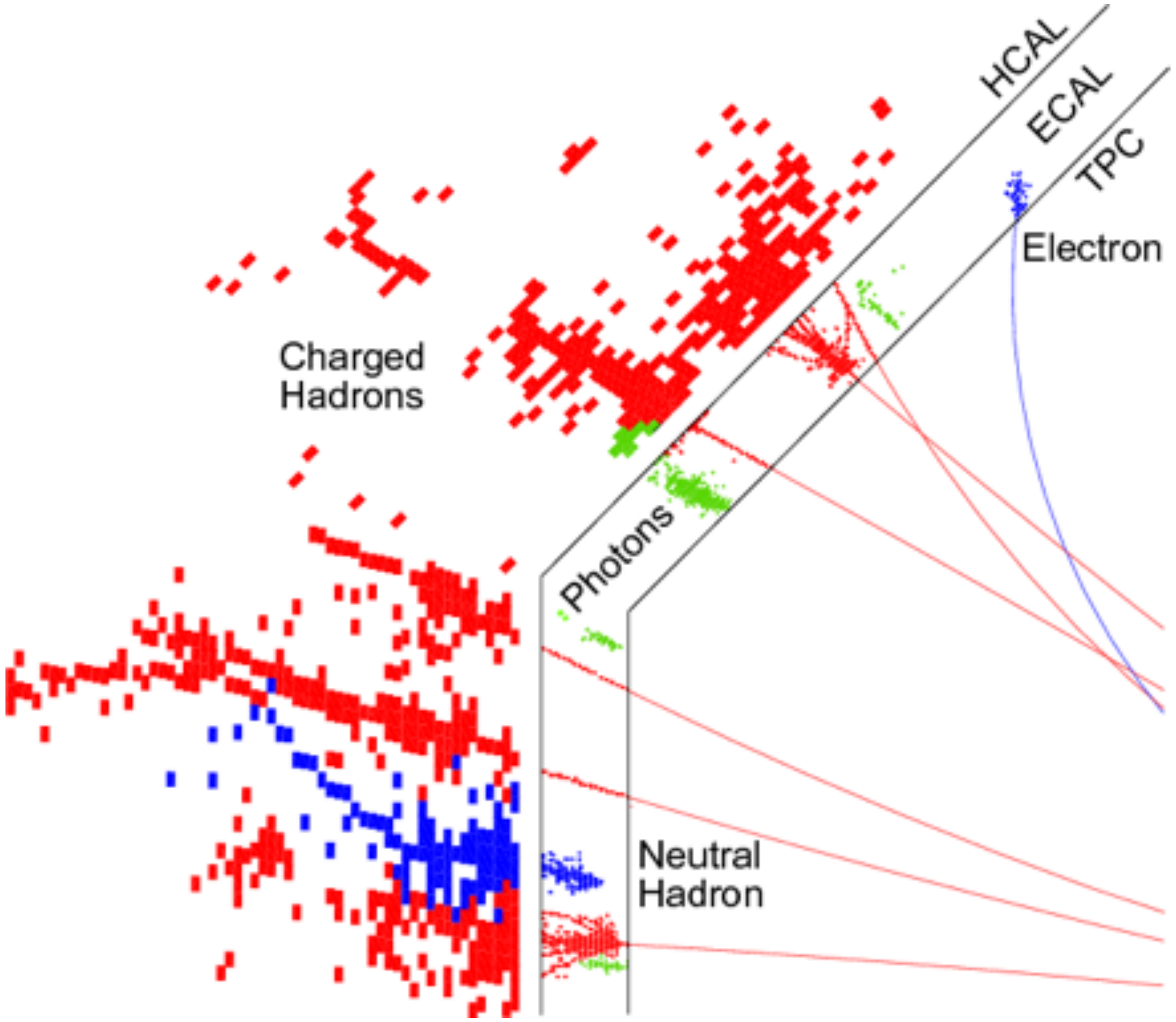

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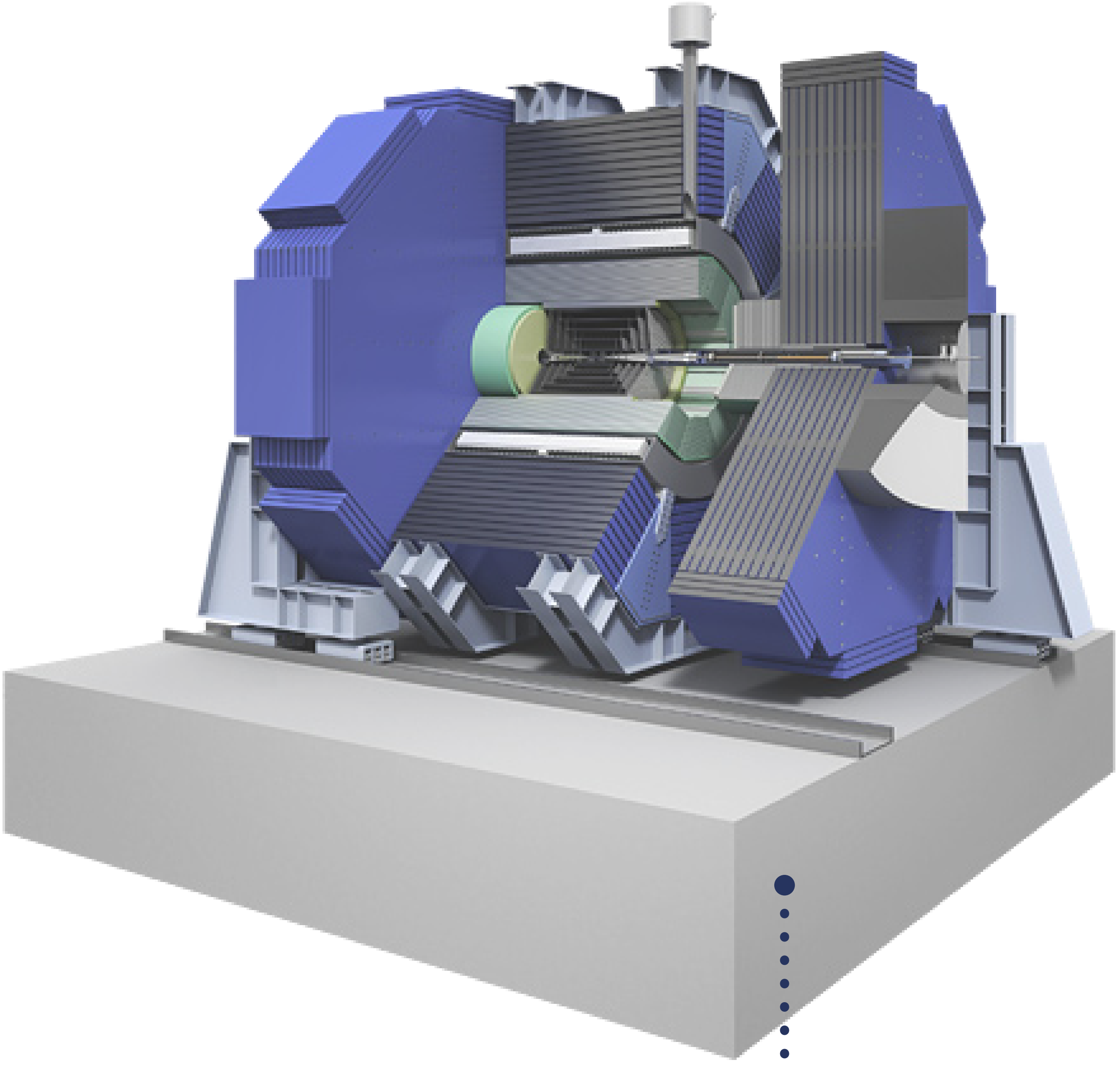
▸ Enables excellent jet energy resolution by making use of all available measurements of a particle (***p*** in tracker, ***E*** in calorimeters)

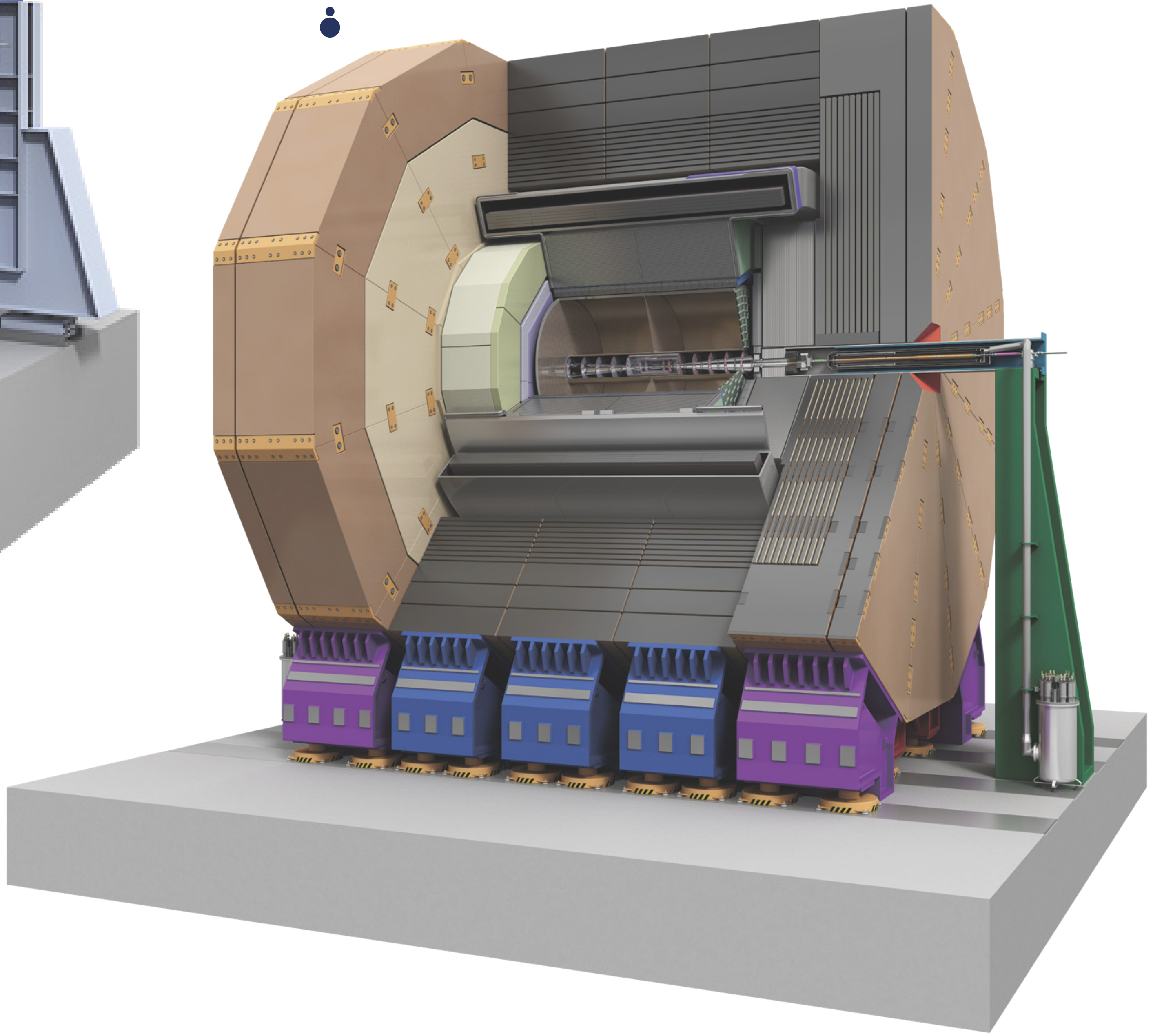
- Separation of close-by particles often more important than pure energy resolution

▸ Highly granular detector systems, in particular also in the calorimeters!

ILD & SiD - Similar Concepts, Different Realization

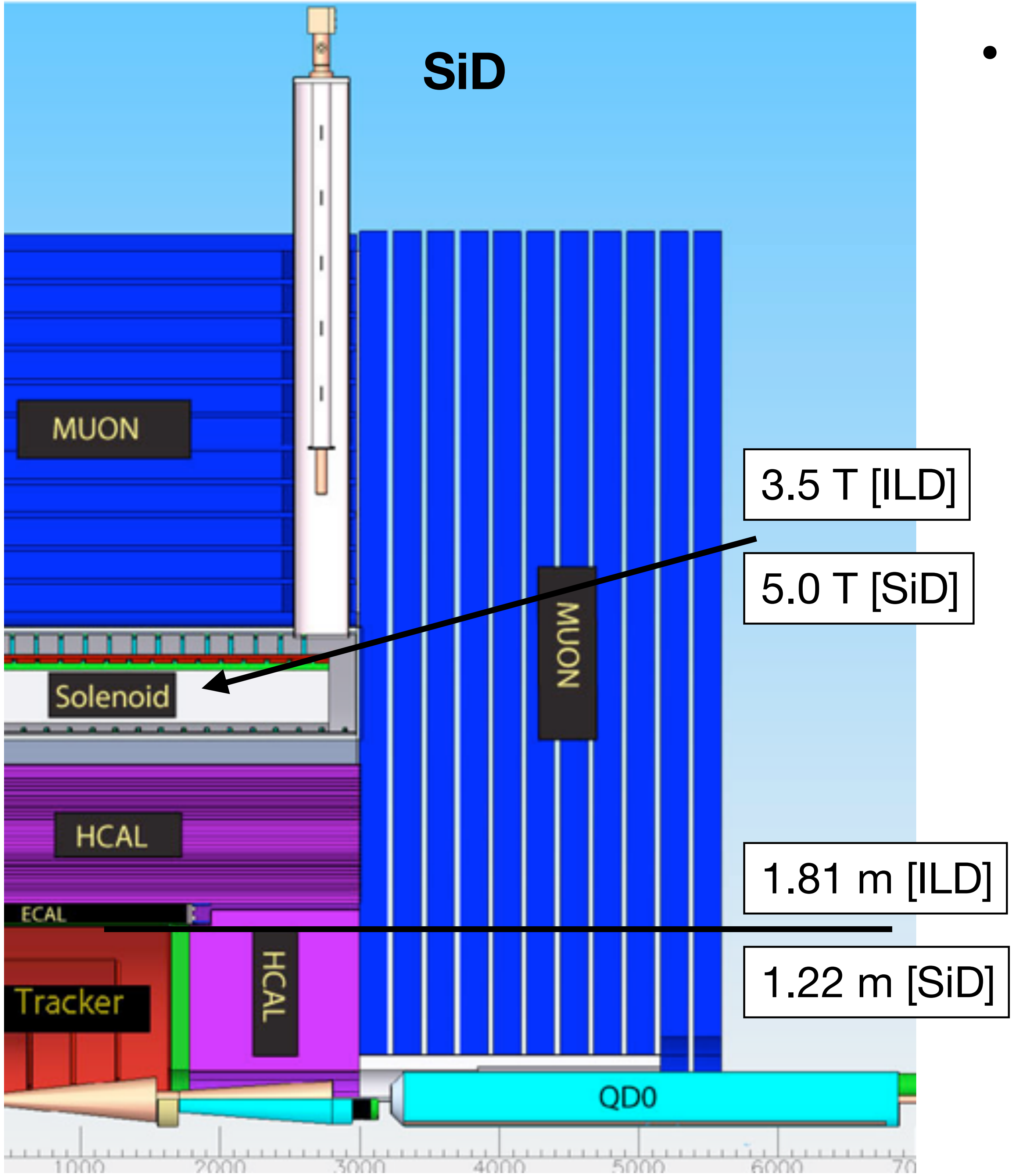


SiD (Silicon Detector)



ILD (International Large Detector)

Two Slightly Different Approaches: ILD & SiD



- The requirements allow some flexibility for design choices - the main parameter is the radius of tracker
  - To reach p_T resolution requirements:
    - smaller tracker requires higher field
    - smaller tracker requires higher spatial resolution for space points
  - To reach required PFA performance:
    - smaller tracker requires higher field to improve particle separation, splitting of charged & neutrals in jets
    - higher field favors higher granularity in calorimeters

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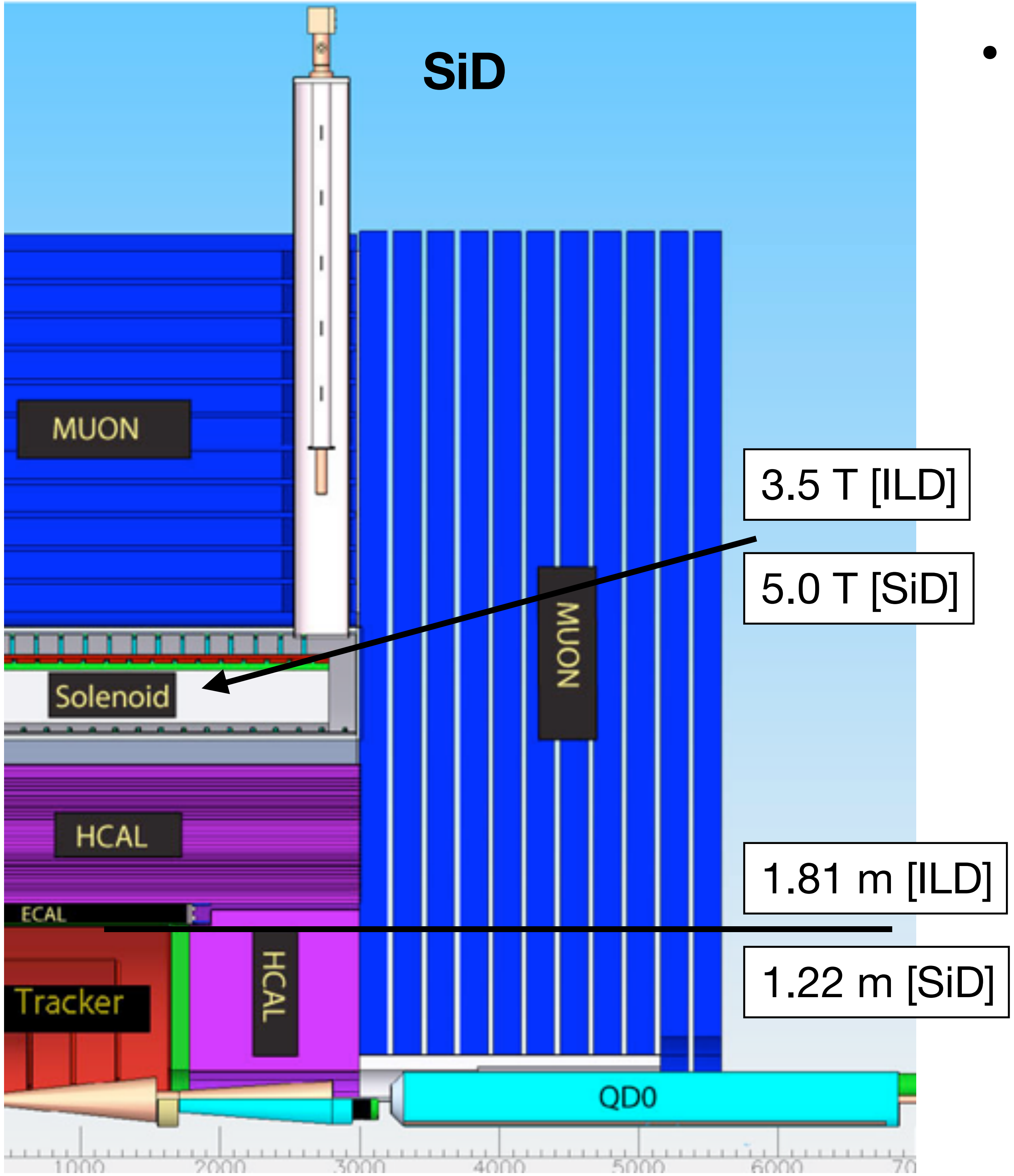

3.5 T [ILD]

5.0 T [SiD]

1.81 m [ILD]

1.22 m [SiD]

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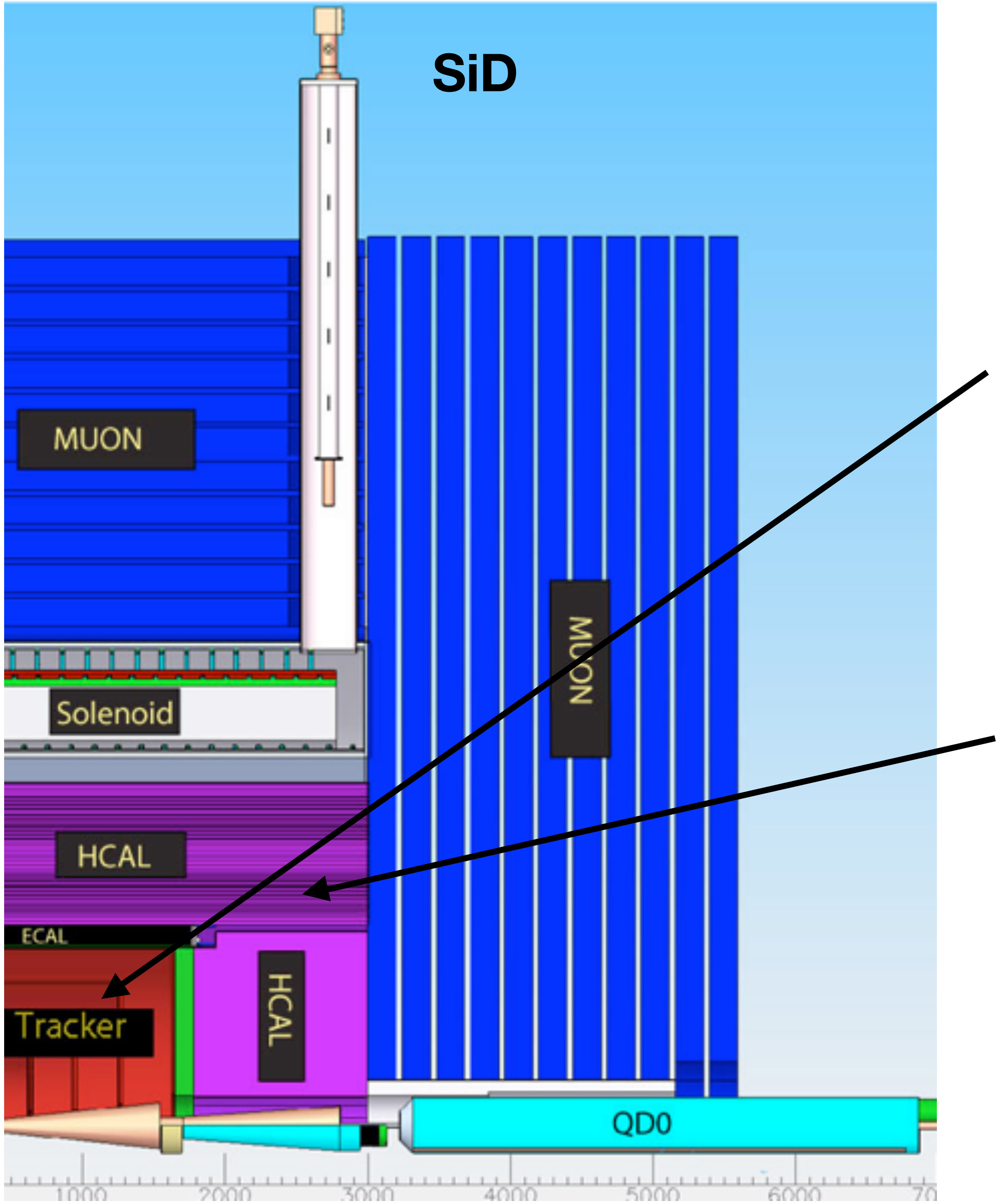
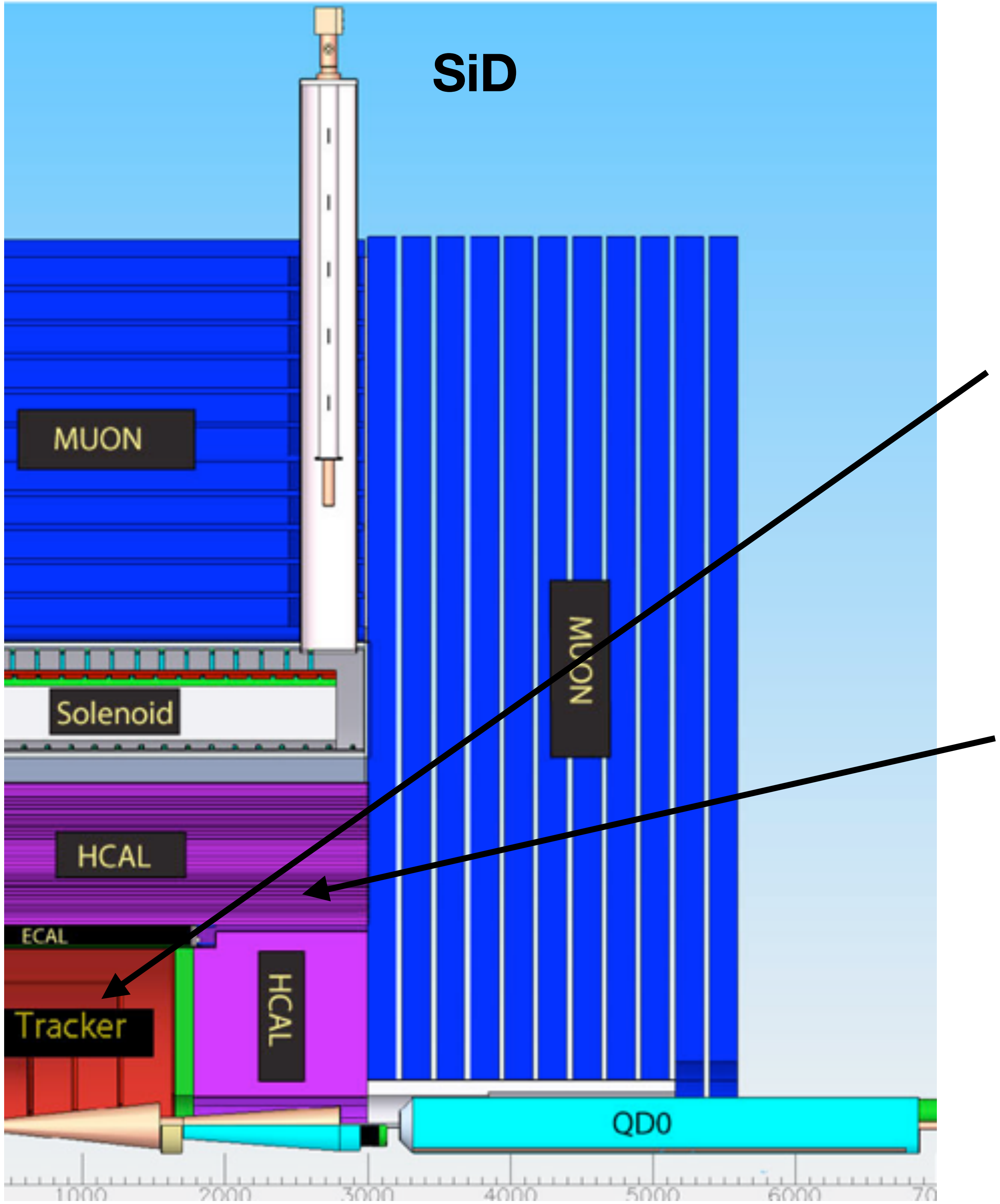
N.B. : Solenoid cost (and technical feasibility) steeply scales with field and radius => Either large radius or high field!

Two Slightly Different Approaches: ILD & SiD



- Different choices in tracker technology: Trade number of measurements and precision of individual measurements
    - Five-layer all-Si tracker in SiD
    - TPC with > 200 space points on a track in ILD (NB: To reach resolution goal, an additional Si layer outside of the TPC is required!)
- Trading cost vs. jet energy resolution at higher energies (1 TeV option): Depth of the calorimeter system
    - SiD HCAL: 4.5 λ_I, ILD HCAL: 6 λ_I

Two Slightly Different Approaches: ILD & SiD



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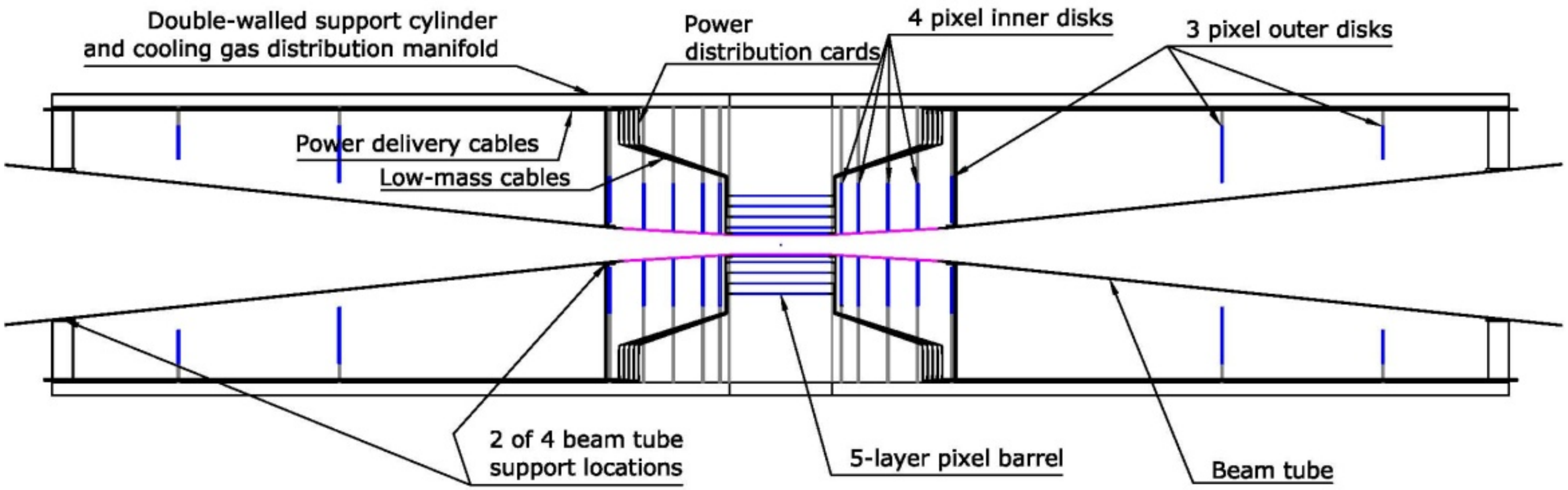
In general: How much cost is emphasized drives the choice between small and large detector: ECAL radius as main cost driver, but larger detector favorable for PFA

The Vertex Detector

- Pixel detector system with barrel and forward discs (forward strips an option for ILD)



- 5 barrel single layers (SiD) / 3 double layers (ILD default)
- as close as possible to IP: Innermost layer at ~ 15 mm
- Low mass: Goal ~ 0.15% X_0 per layer
- Single point spatial resolution ~ 3 -5 µm
- Low occupancy, not exceeding a few % also in innermost layers

▸ Pixel sizes of ~ 20 x 20 µm^2 or smaller,
single bunch timing (~ 700 ns) for SiD

The Vertex Detector - Technological Possibilities

- A wide range of technologies under study for both ILD and SiD
  - CMOS MAPS, DEPFETs, SOI, FP-CCDs, 3D integrated sensors
    - All require thinned silicon on the 50 µm level
  - Very light-weight supports, no liquid cooling to achieve material budget goals
    - Low power consumption crucial to allow air cooling: Power-pulsing of readout electronics

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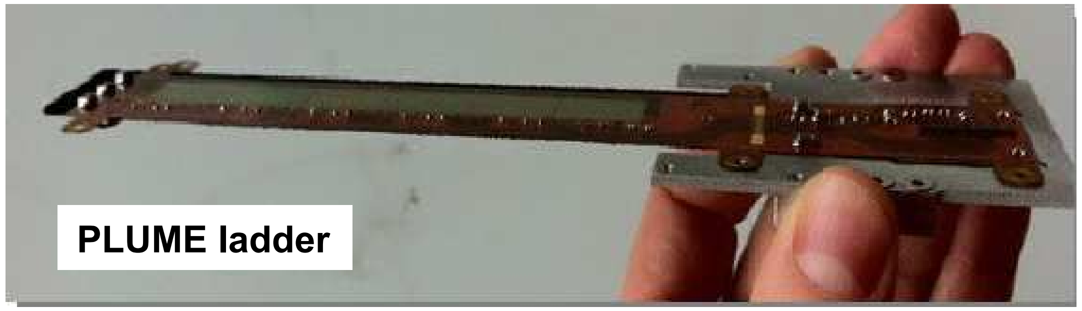
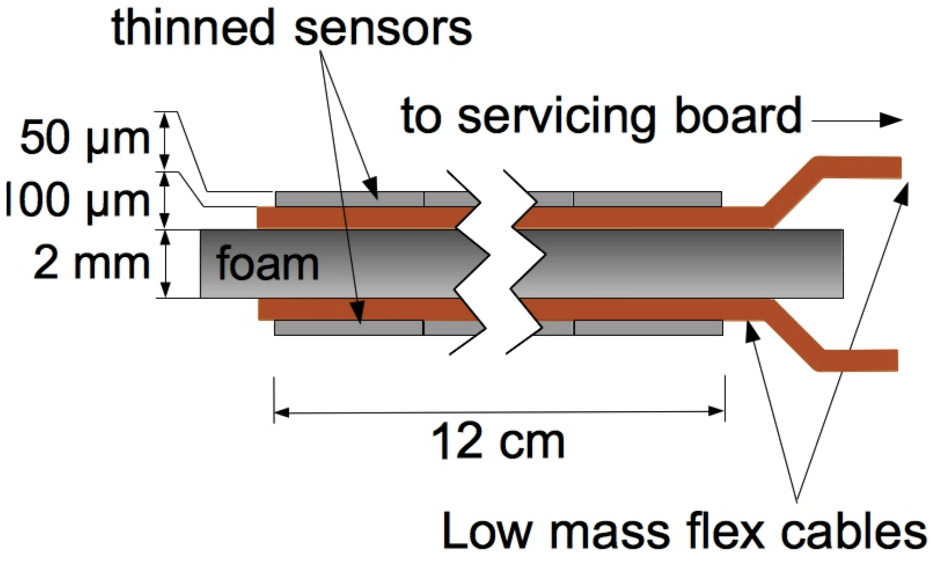
- First mechanical concepts demonstrated: low-mass PLUME double ladder (two layers of MIMOSA sensors)

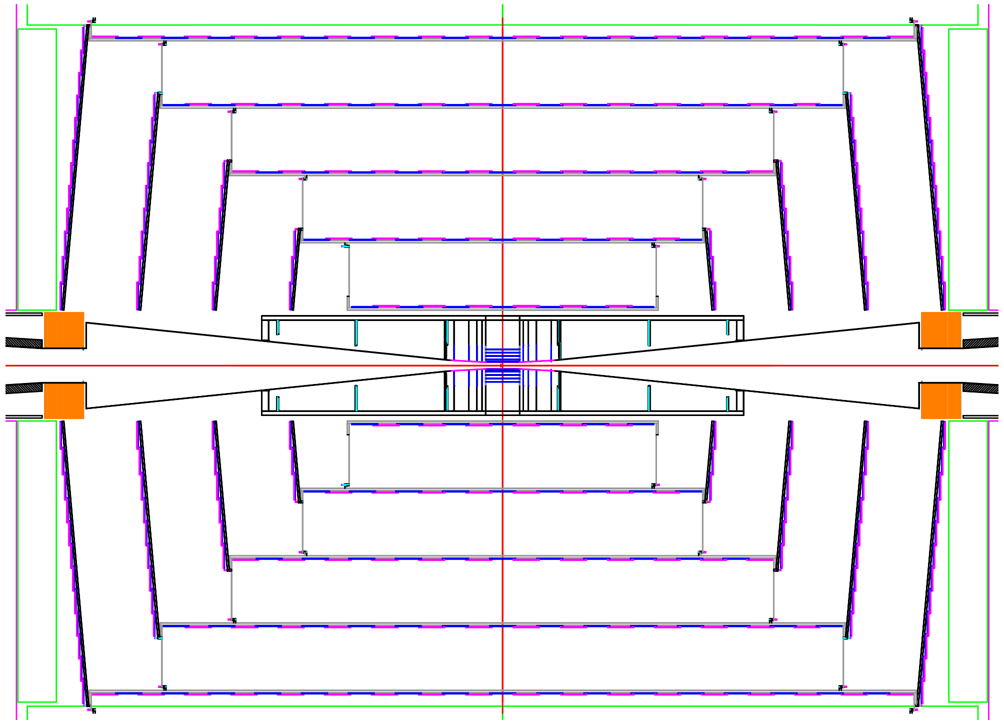




- first prototype with 0.6% X_0 total budget demonstrated in test beam
- Improved prototype with 0.35% X_0 in construction

The Main Tracker: Two quite different Approaches

SiD: all silicon tracker

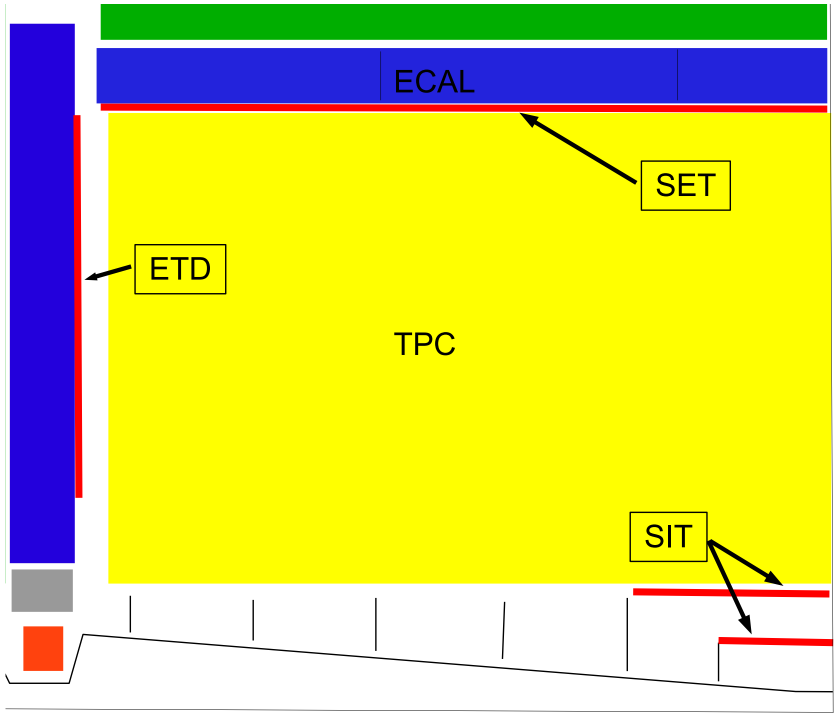


- 5 barrel layers, axial-only measurement
- 4 discs, stereo layers

central tracks:

- 5 measurements, 8 µm precision

ILD: TPC, augmented with Si trackers

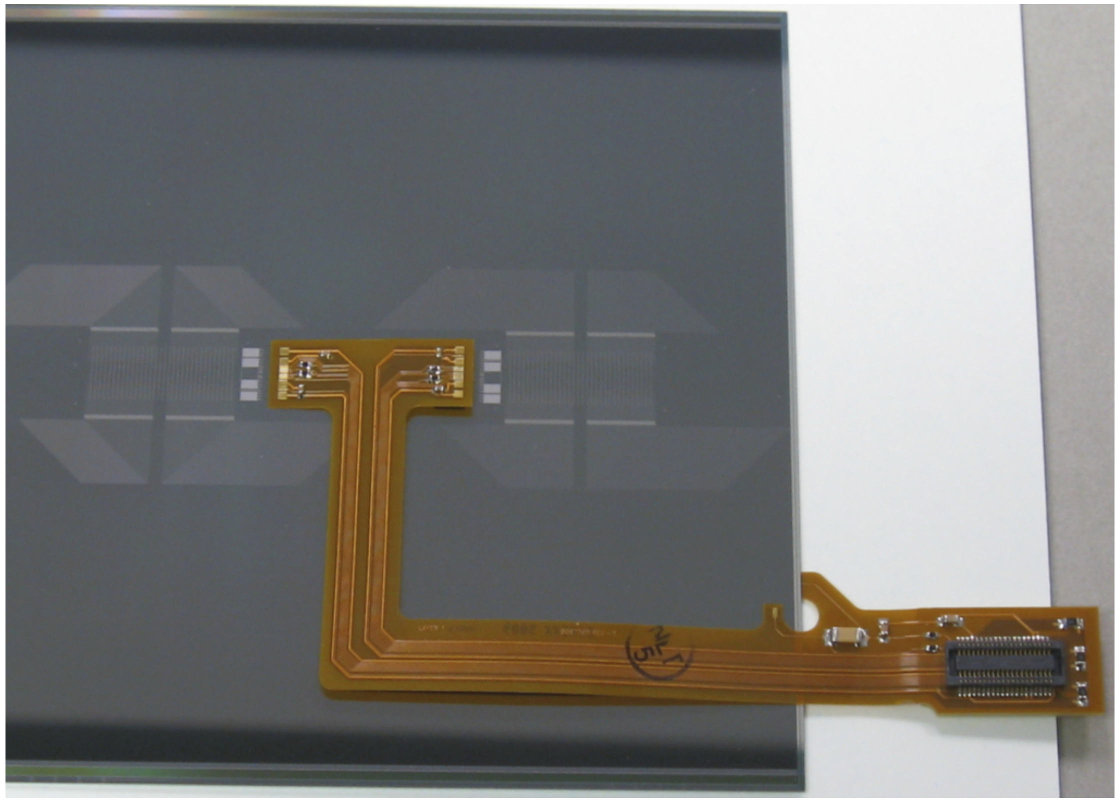


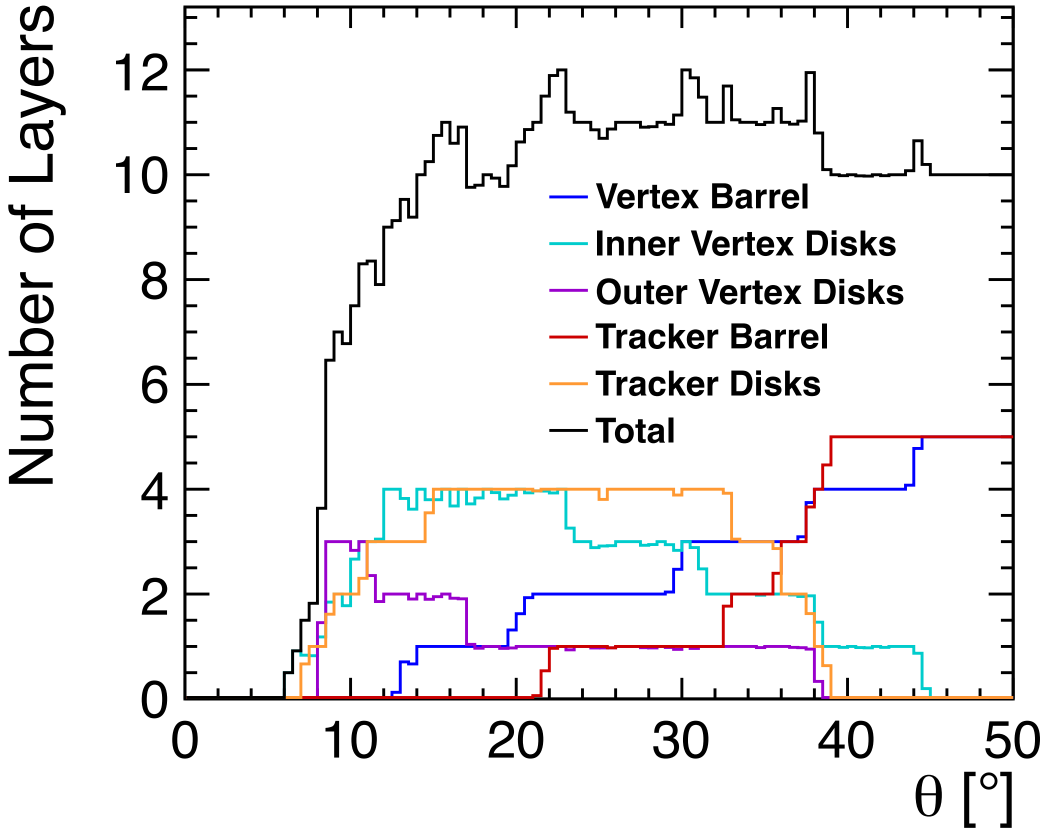
- one stereo strip layer outside of TPC (SET, ETD)
- two stereo strips inside (SIT)

central tracks:

- 220 space points in TPC, ~ 60 - 100 µm precision
- 3 measurements in Si, ~ 7 µm precision

The SiD Main Tracker





- Very low-mass design:
  Front-end chip directly bonded on silicon sensor
  - no need for electronics hybrid
- Compact electronics: KPIX chip, 1024 readout channels per ASIC

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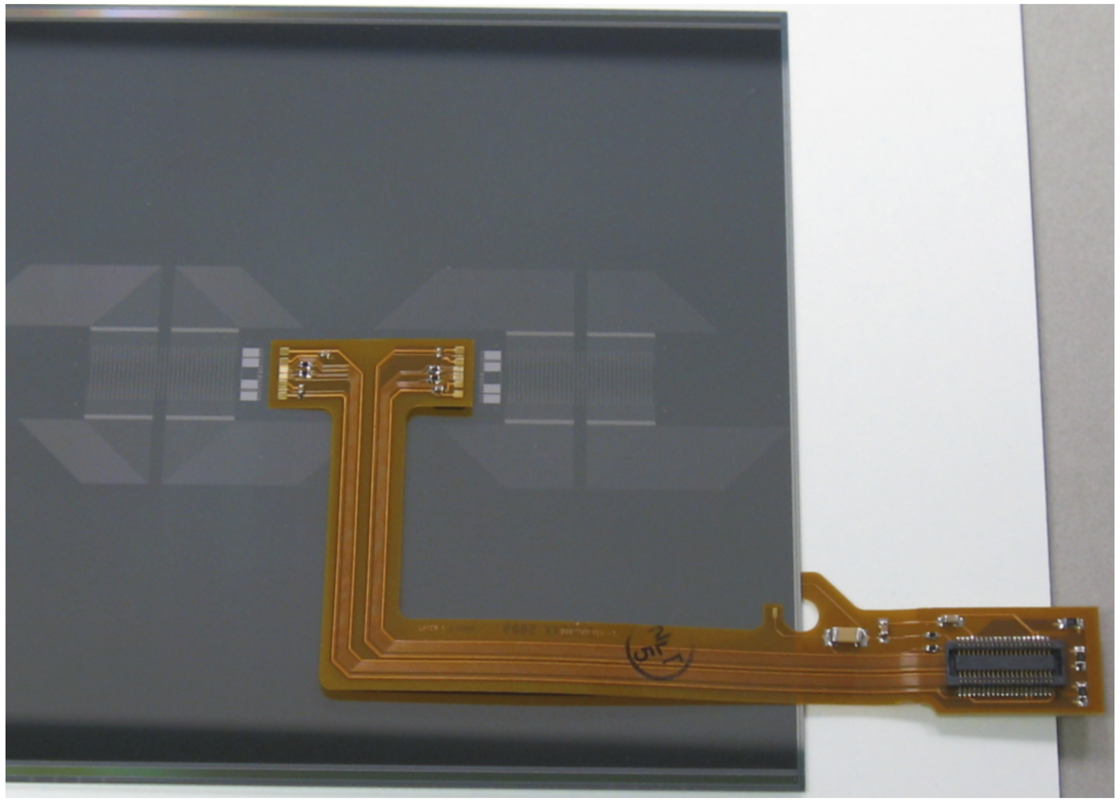

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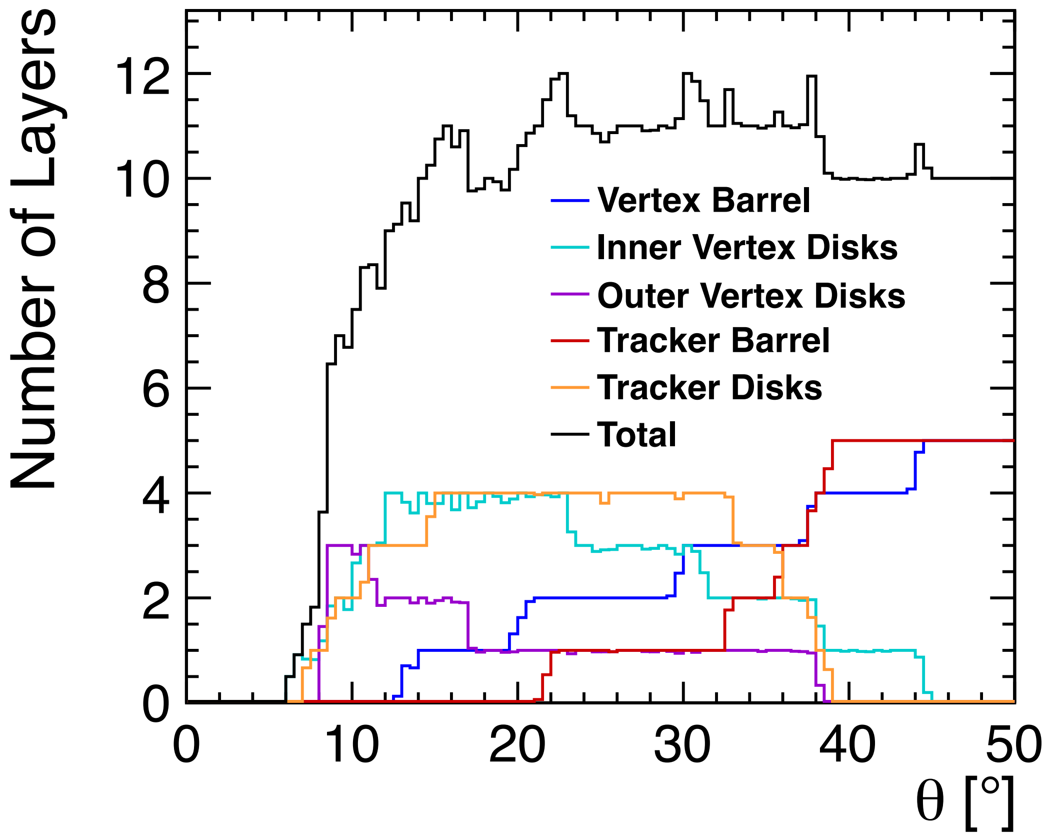
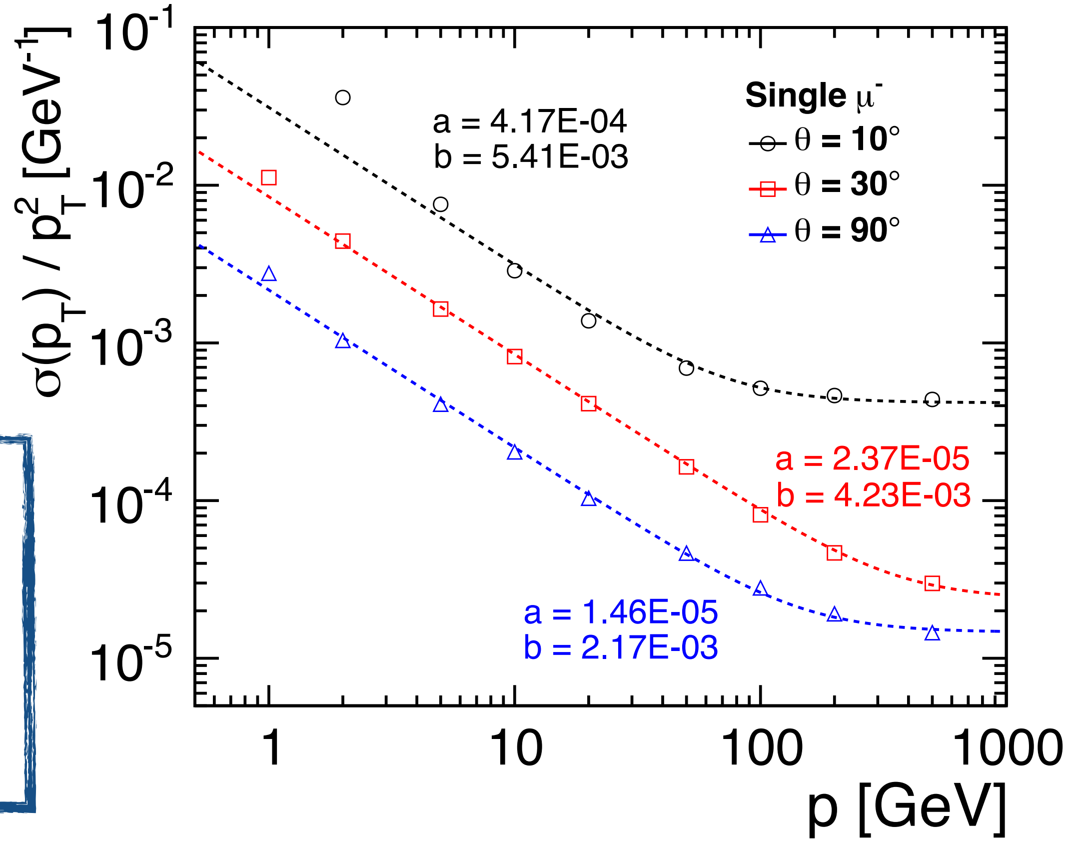
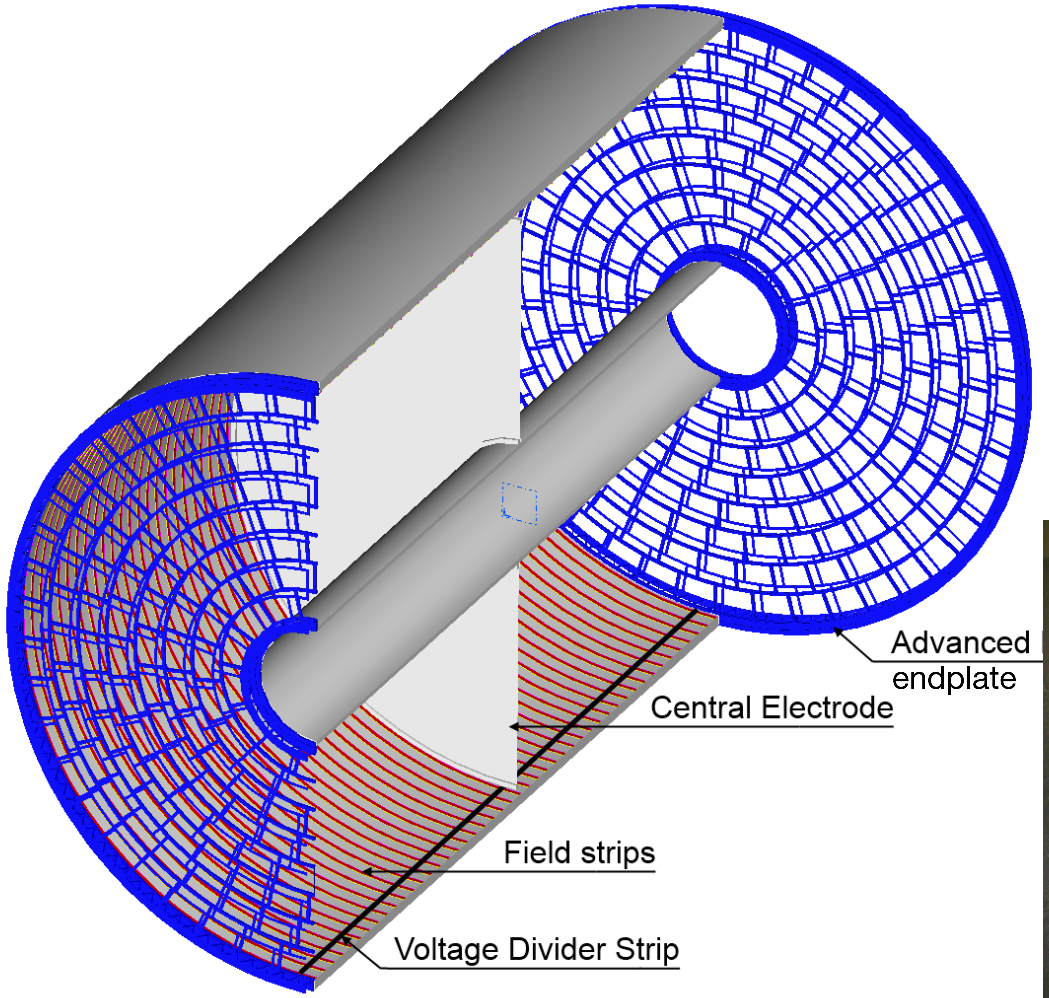


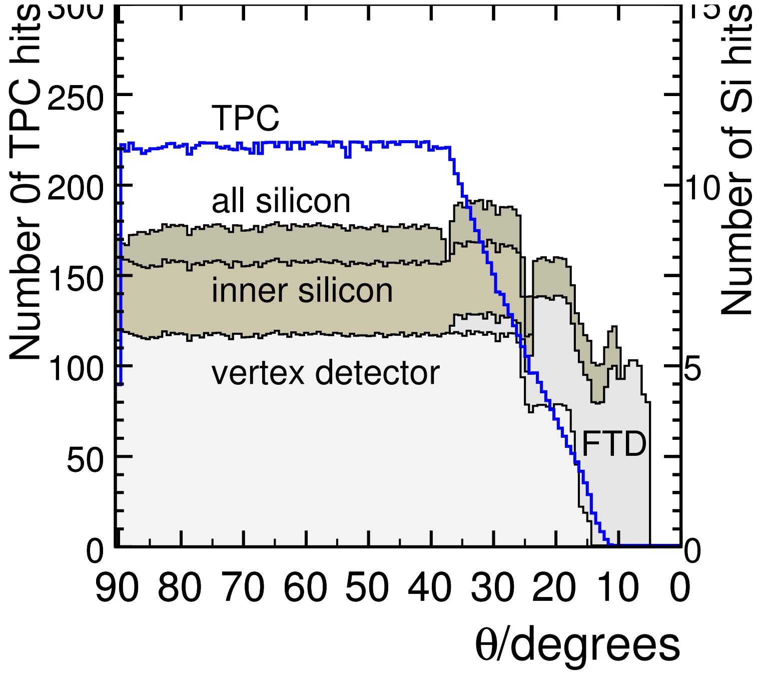
exceeds ILC resolution goals in full simulation studies

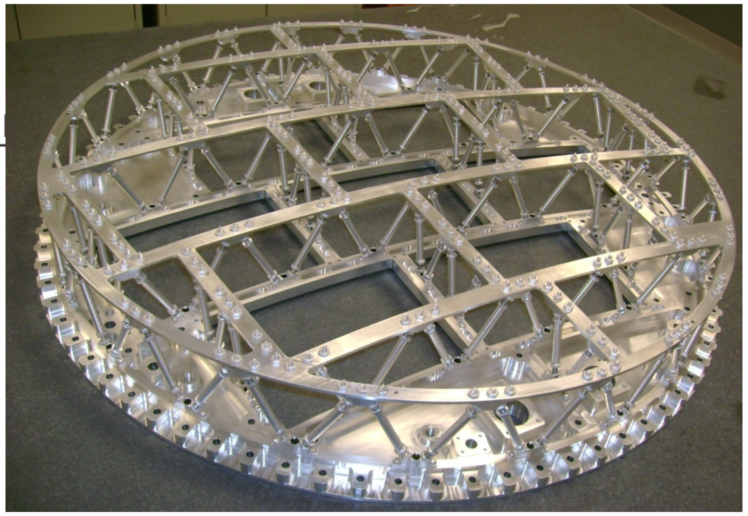


The ILD Main Tracker

- Large-volume TPC with MPGD readout in endplate, 1 x 6 mm^2 pads
  - Different technologies under investigation, including µMegas, GEMs, - in general w/o gating - needs strong ion feedback suppression







Large prototype with low-mass end-plate, to be tested with µMegas, GEMs

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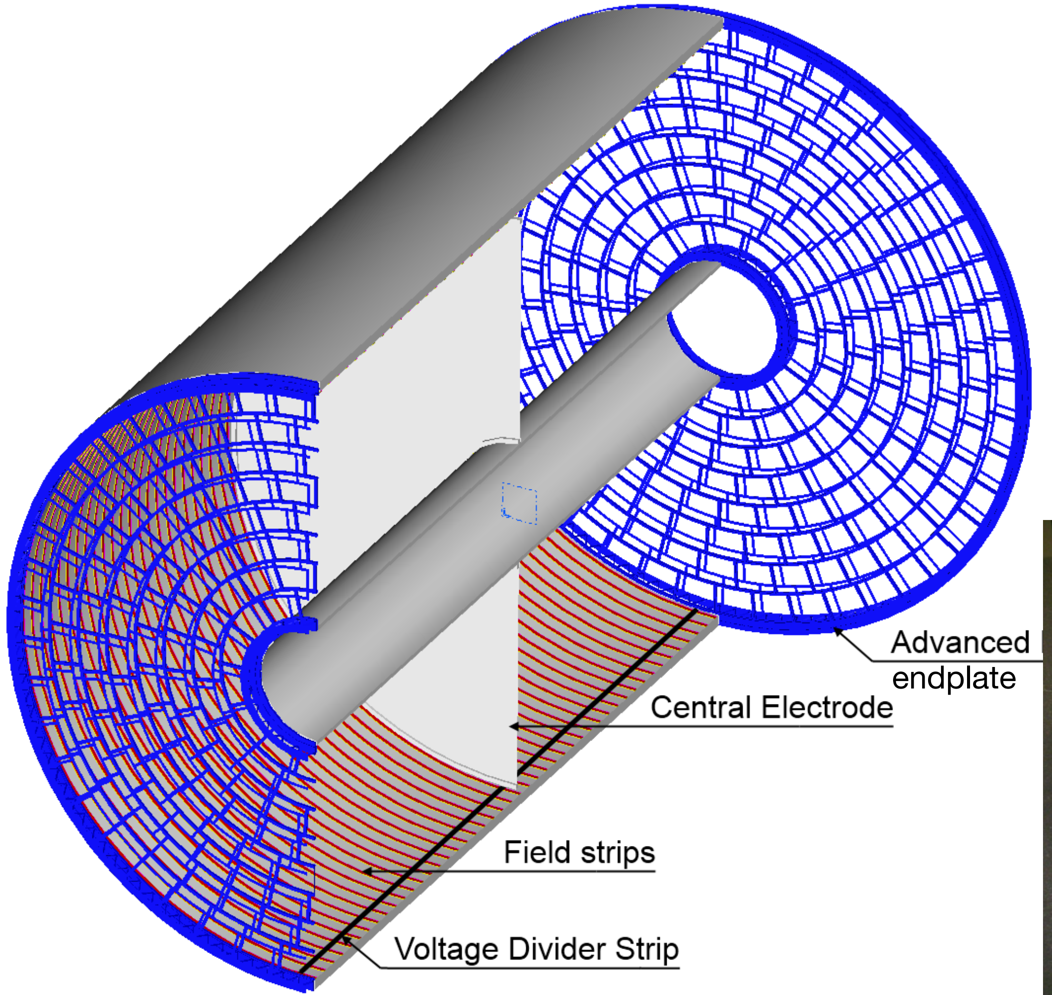

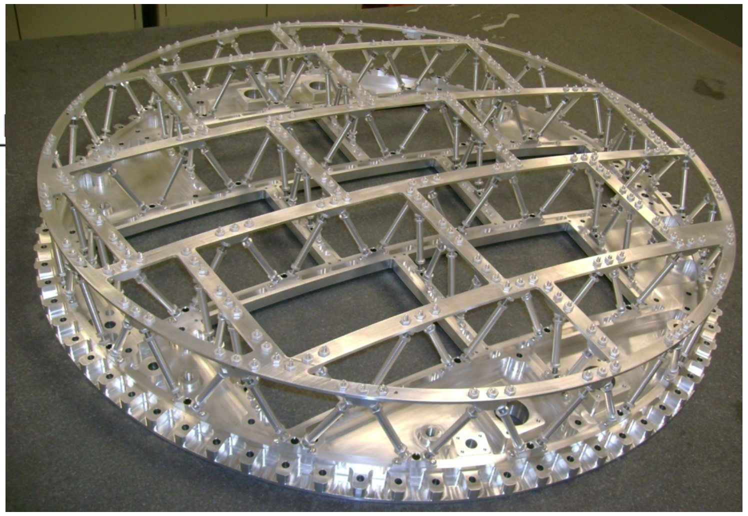

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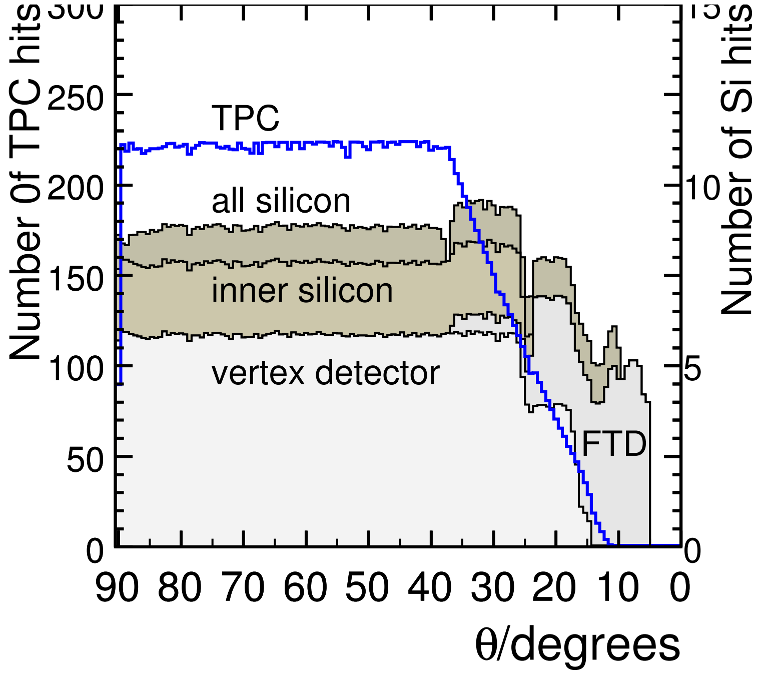

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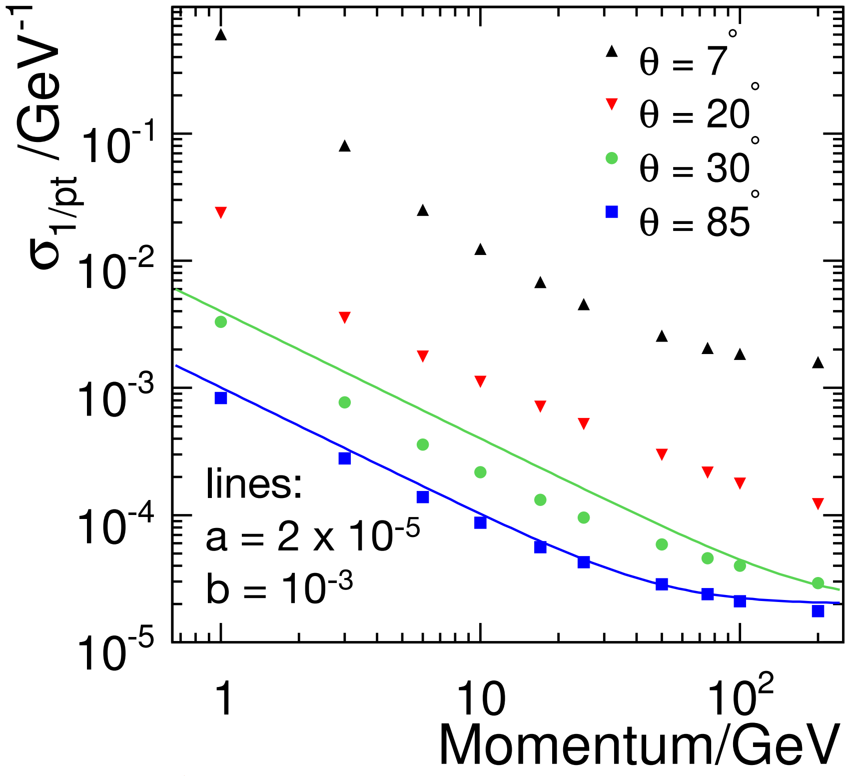

The Calorimeters

- The detectors where PFA “happens” - Quite different than calorimeter systems at current experiments in terms of granularity: Segmentation finer than the typical structures in particle showers
  - ECAL: X_0, ρ_M (length scale & width of shower)
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- in W: X_0 ~ 3 mm, ρ_M ~ 9 mm
- in Fe: X_0 ~ 20 mm, ρ_M ~ 30 mm

NB: Best separation for narrow showers particularly important in ECAL
➯ Use W in ECAL!

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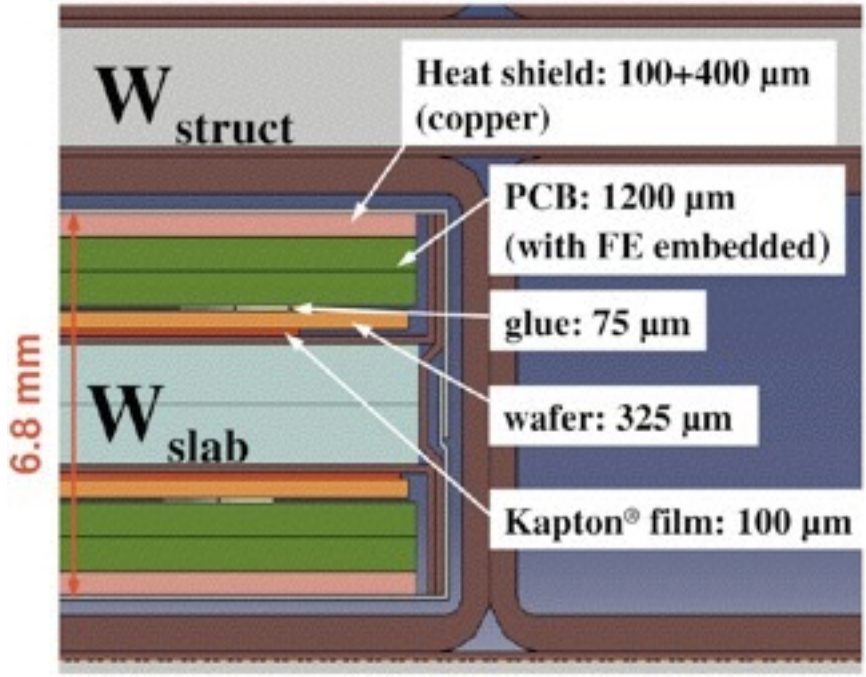
Several technological options both in ILD and SiD:

- ECAL: Tungsten absorbers, Si or Scintillator with SiPMs as active medium
- HCAL: Steel absorbers
  - analog: Scintillator tiles with SiPMs
  - digital or semi-digital: RPCs, GEMs, µMegas (digital or semi-digital)

The ILD Calorimeters

- ECAL: Si PIN diodes with 5 x 5 mm^2 pads or crossed scintillator strips with SiPM readout, 5 x 45 mm^2
    - two longitudinal segments with different absorber thickness, a total of 30 layers with tungsten absorbers
    - integrated readout electronics on a PCB



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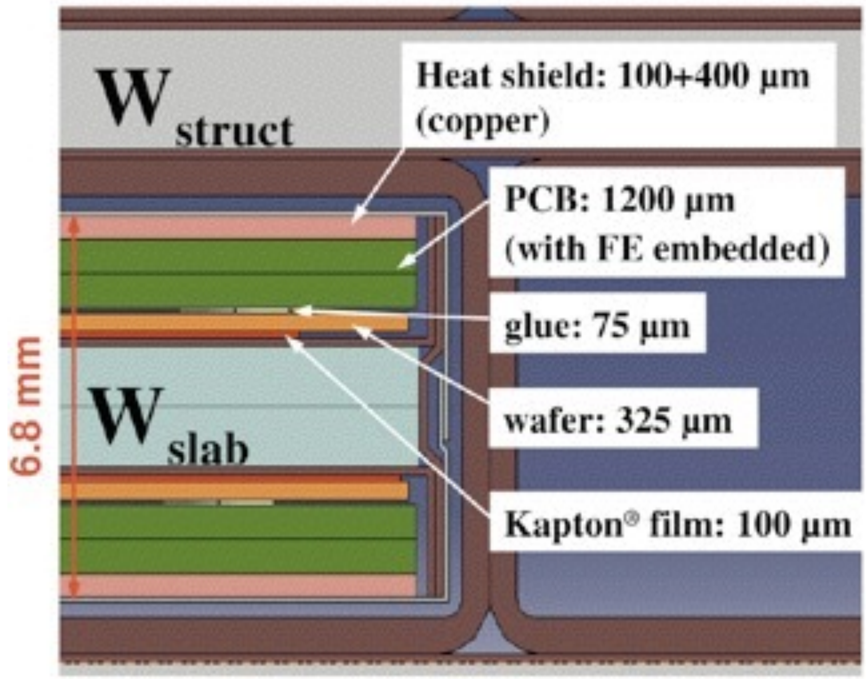
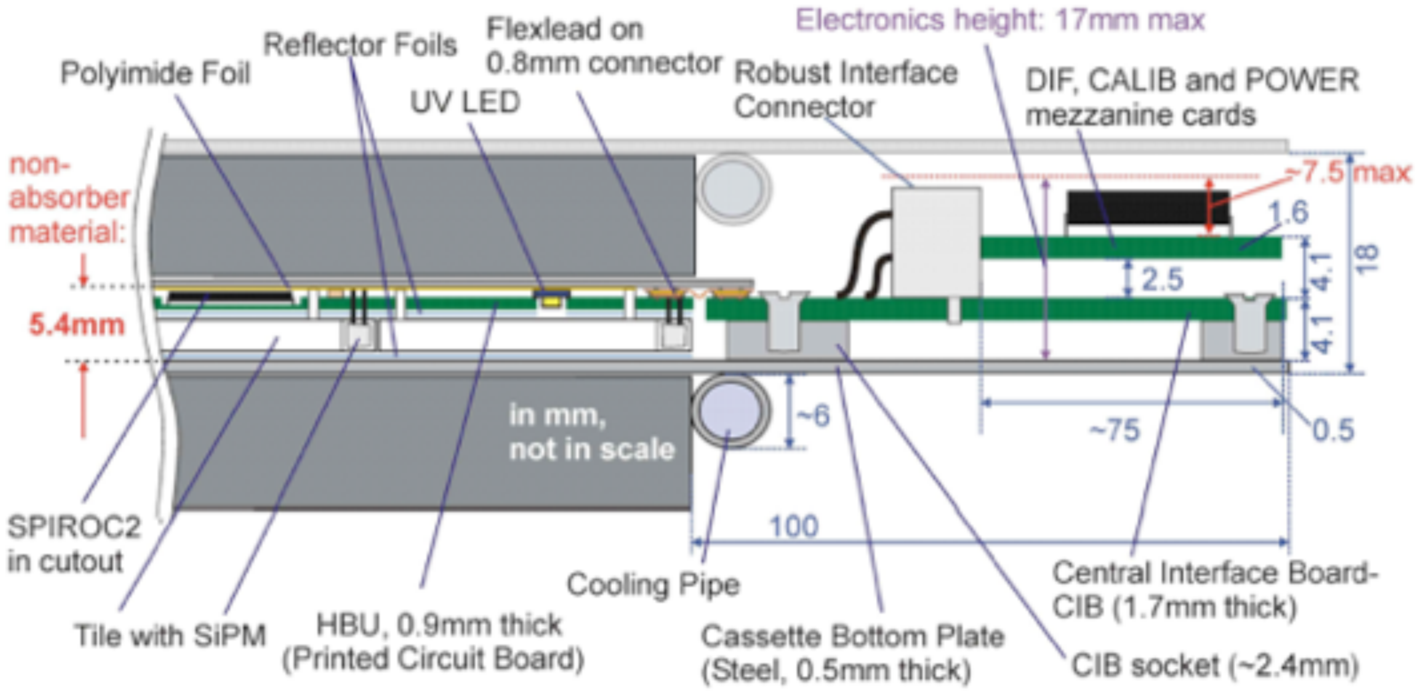
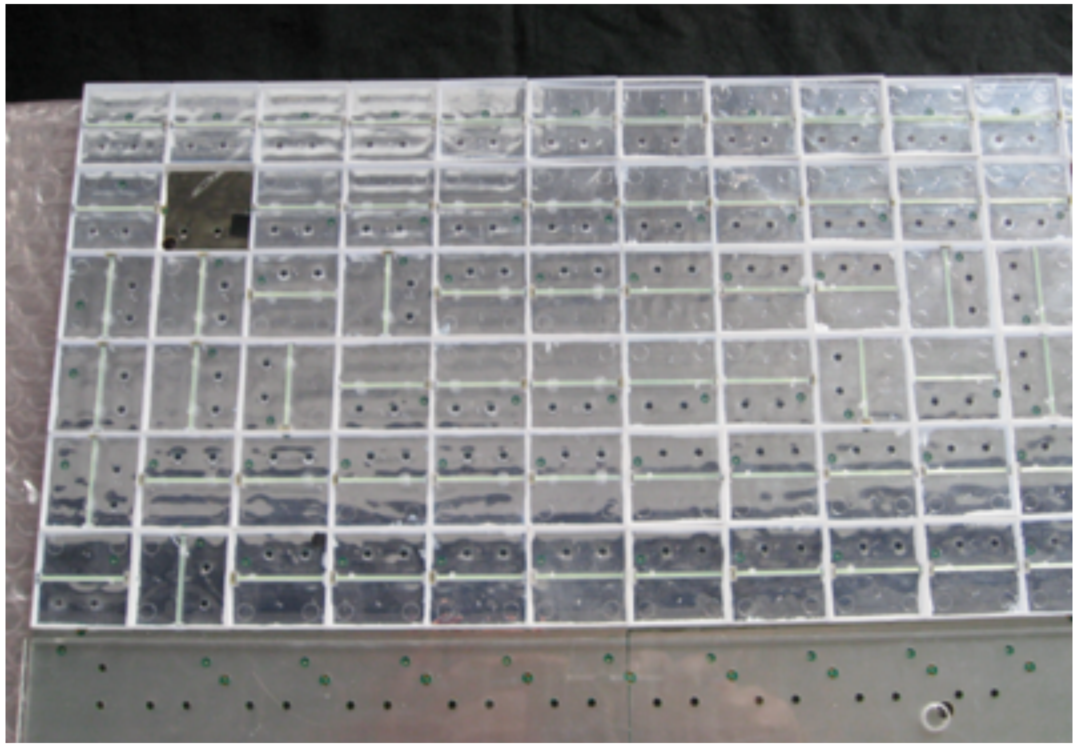


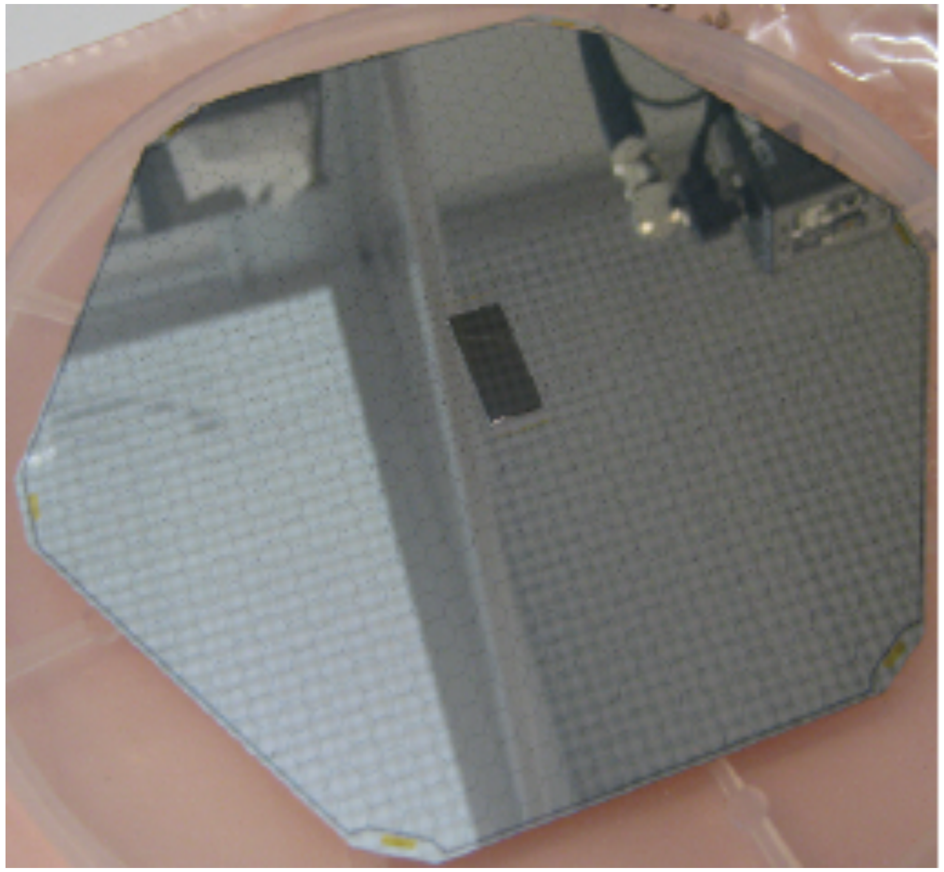
- HCAL: Scintillator tiles (3 x 3 cm^2) with SiPM readout or RPCs (μMegas) with semi-digital 3-threshold readout 6 λ_I - 48 layers, 2 cm steel absorber



here: AHCAL



The SiD Calorimeters



- ECAL: Si PIN diodes with hexagonal pads (13 mm^2) or MAPS sensors with 50 x 50 µm^2 pixels
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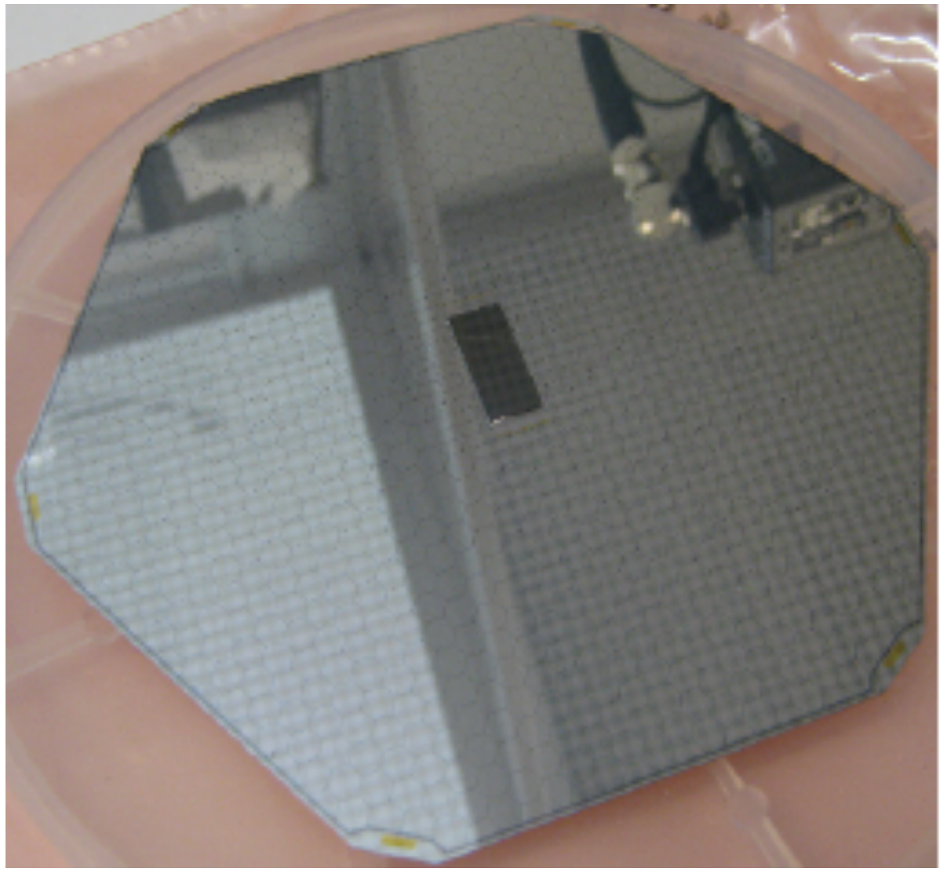
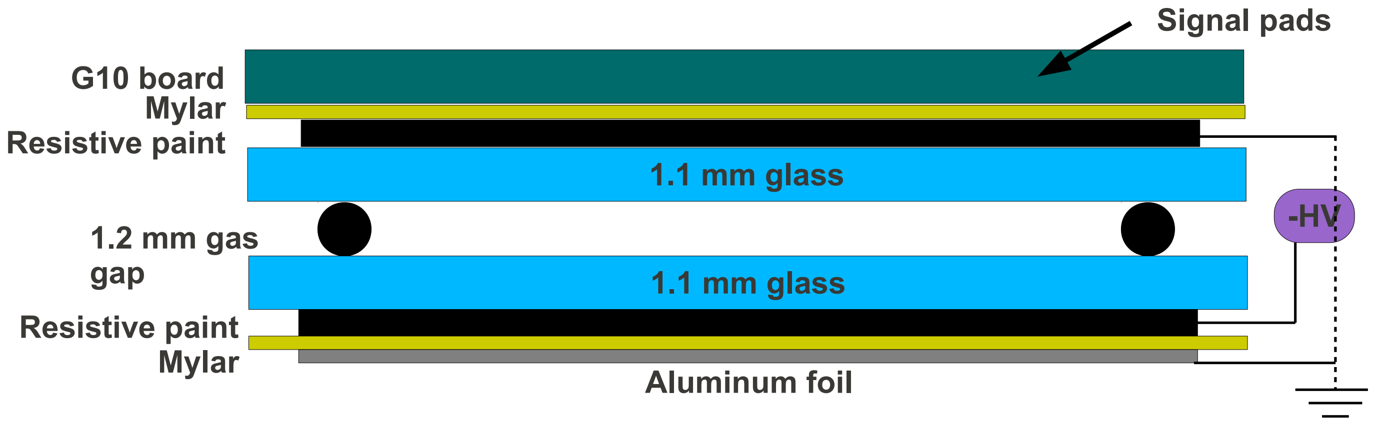
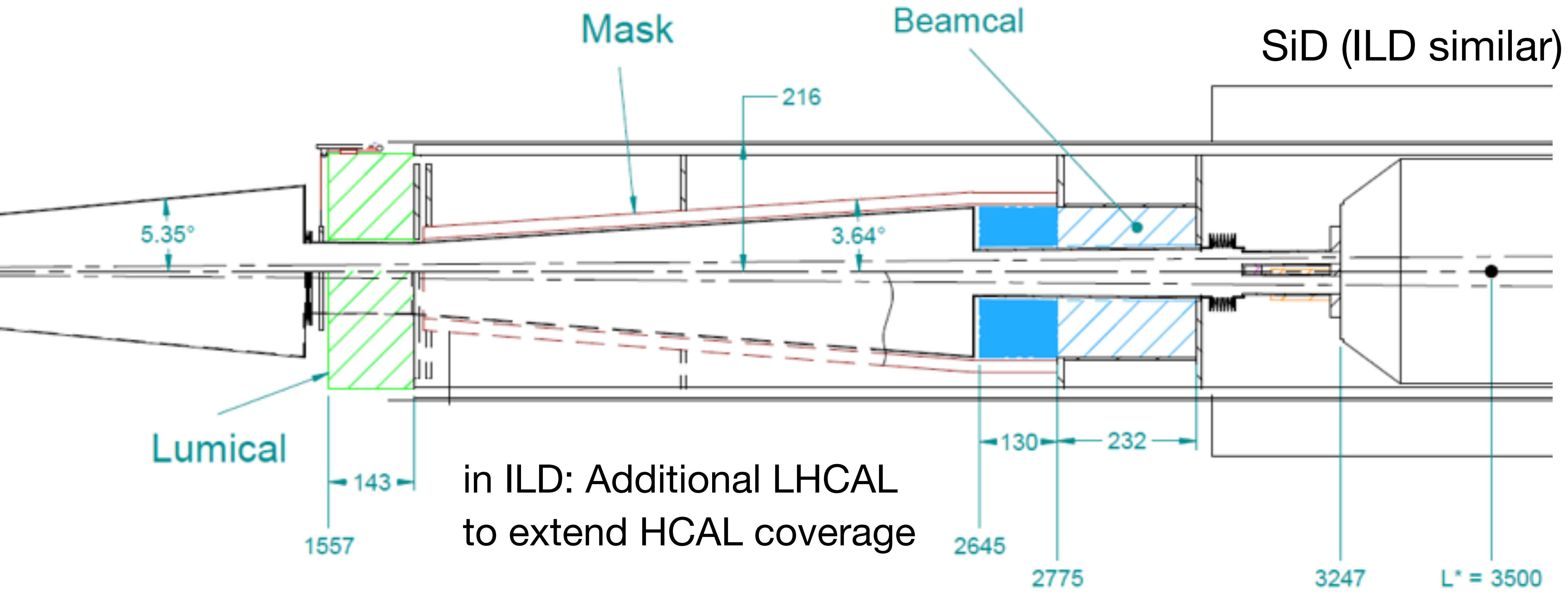


- HCAL: Digital calorimeter with 1 x 1 cm^2 cells, using RPCs, double GEMs / thick GEMs, µMegas, scintillator tiles with SiPMs and analog readout also considered
  - 4.5 λ_I thickness - 40 layers with 1.9 cm steel



1-glass RPC prototype

Forward Instrumentation



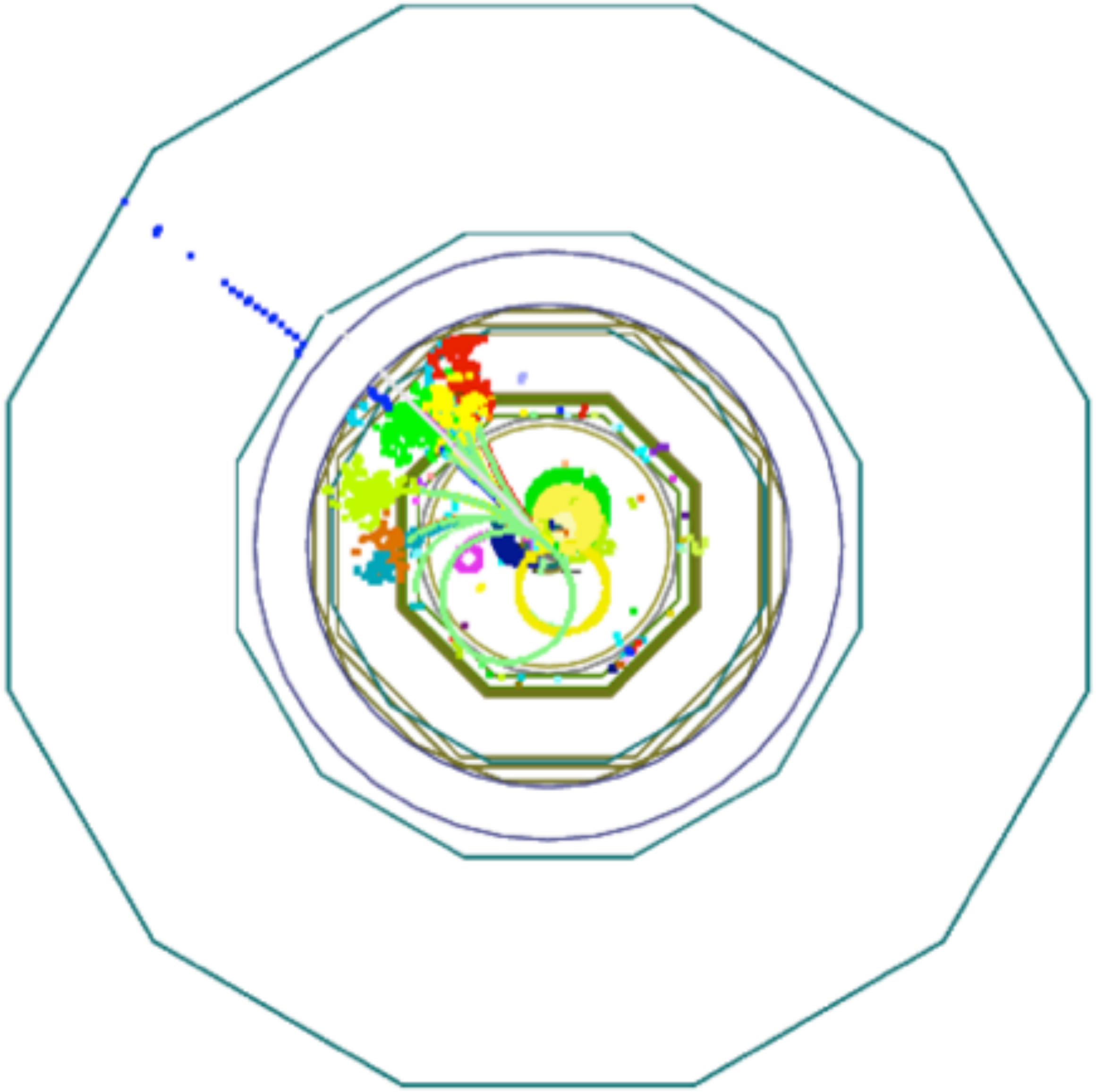
SiD (ILD similar)

in ILD: Additional LHCAL to extend HCAL coverage

- Forward instrumentation (cosθ > 0.99) important for luminosity monitoring
  - LumiCal - measurement of the integrated luminosity using small-angle Bhabha scattering better than 10^{-3}
  - BeamCal - measurement of the instantaneous luminosity from beamstrahlung pairs on the 10% level per BX
  - Both serve to increase detector hermeticity
  - Require rad hardness: Si sensors in LumiCal, GaAs or CVDDiamond in BeamCal

Magnet, Yoke & Muon System

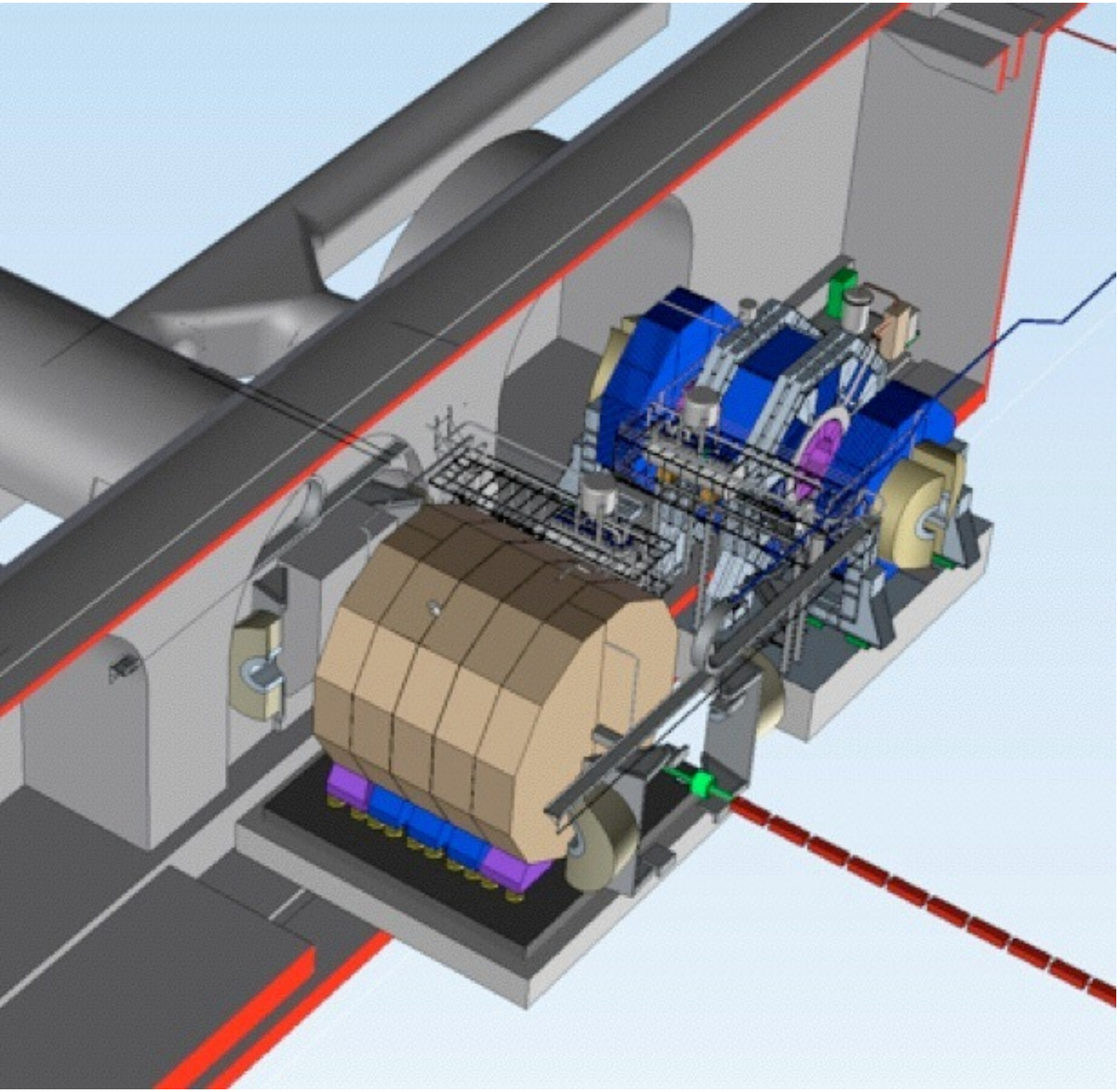
- The solenoid is one of the key components of any experiment - For ILC detectors we can build on the CMS experience
  - For ILD: Similar field, max. 4T, radius ~ 50 cm larger, for SiD higher field, somewhat smaller radius



- The muon system: instrumented return yoke
  - Identification and tracking of muons
  - Tail catching for the calorimeter system

A key task of the yoke: Reduce the stray field of the solenoid to allow maintenance on one detector while the other is in operation

The Detectors in the Collider



- Current concept: Two detectors share one interaction region - Exchange by push-pull on air-cushioned platforms
  - Requires well designed integration & services
  - Imposes strict requirements on stray fields of solenoids

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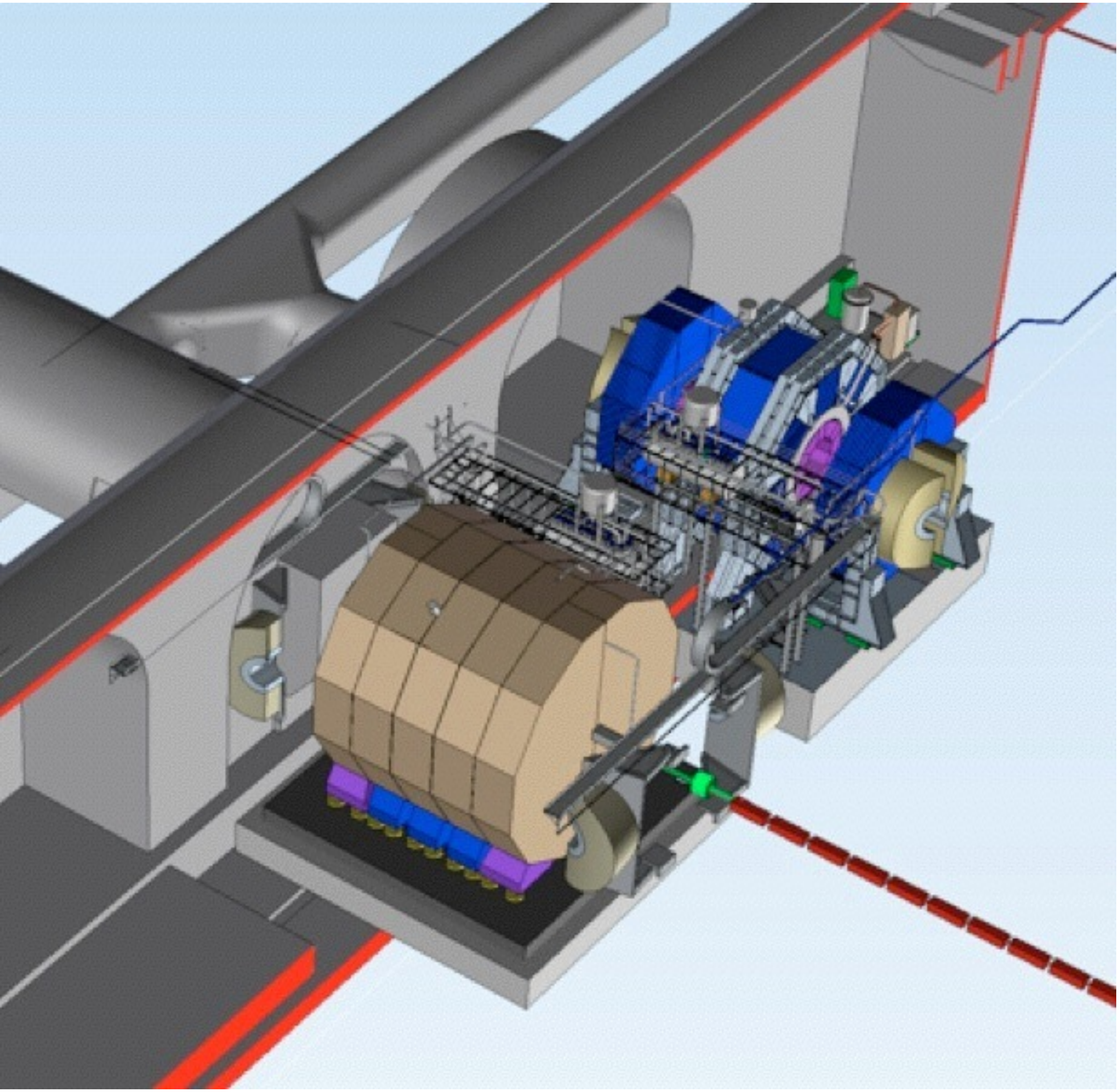

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NB: Here two detectors do not increase the total integrated luminosity - The gain is in systematics, risk reduction (and sociological aspects!)

Performance …

- Studies based on full detector simulations - in quite a few cases key performance parameters have been validated with prototypes in test beams
    - energy resolution & PFA performance (calorimeters), tracking, spatial resolution of pixel detectors,…

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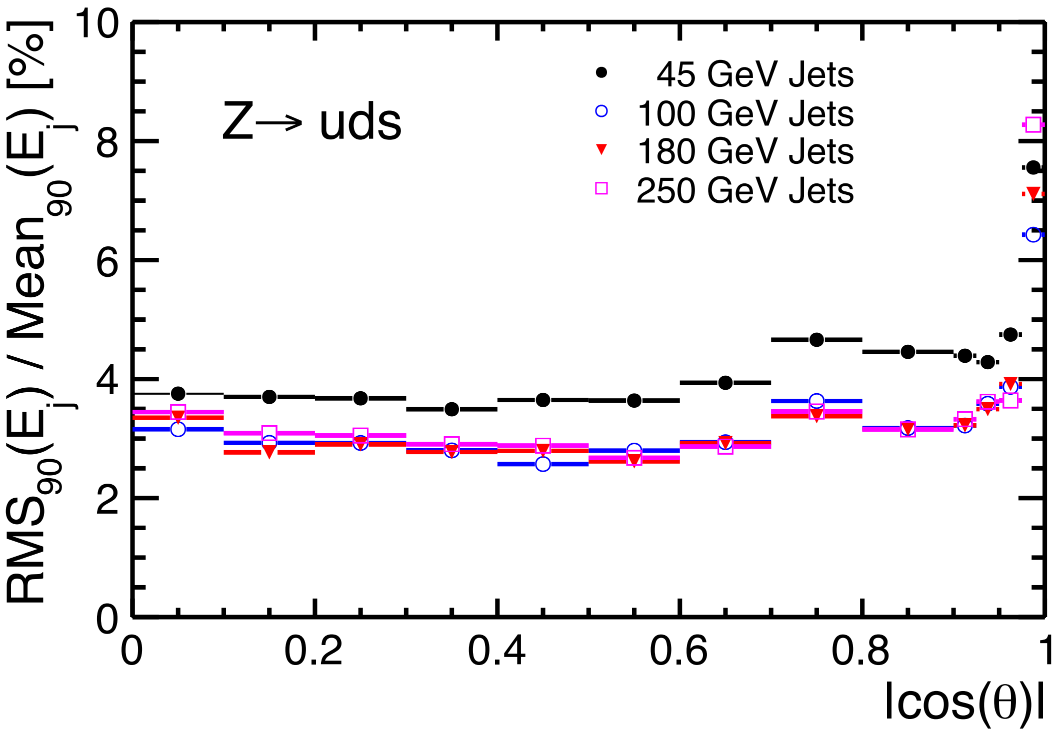
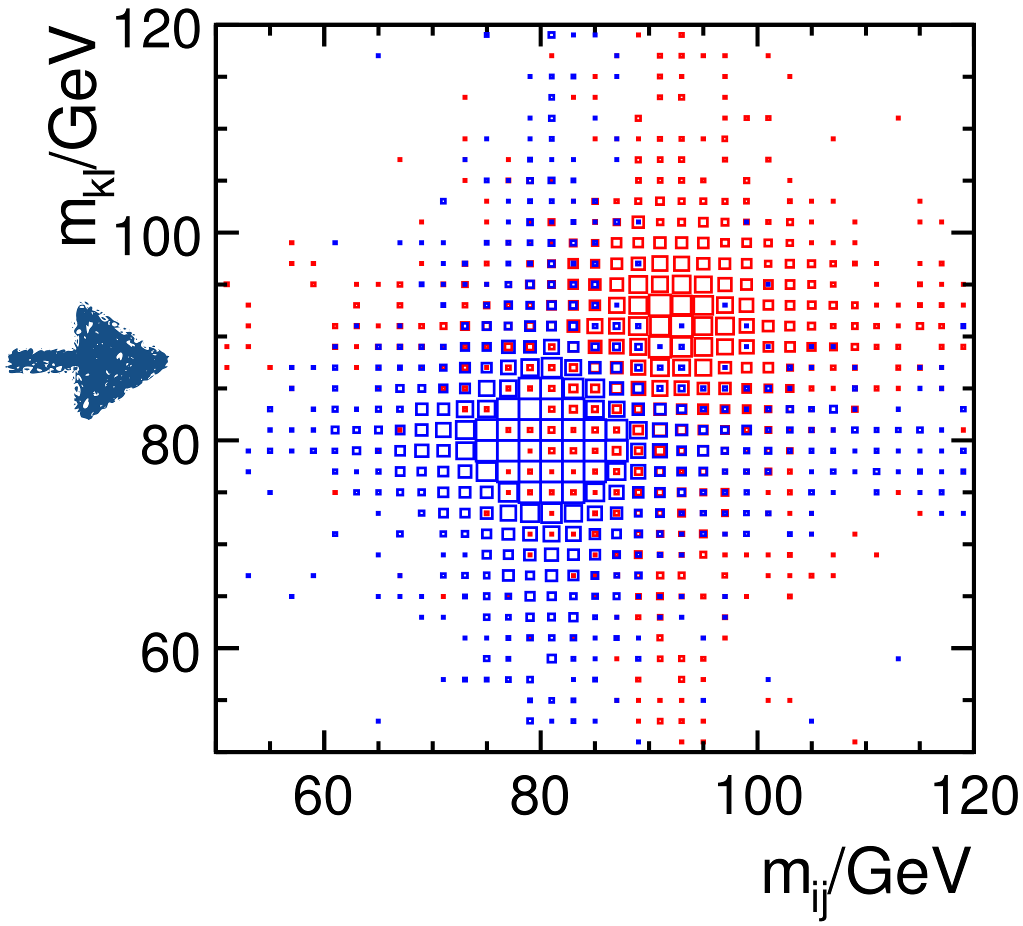
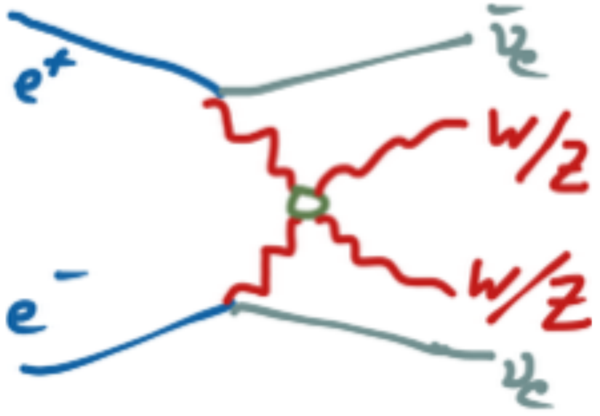
Global performance - just one example: PFA in ILD

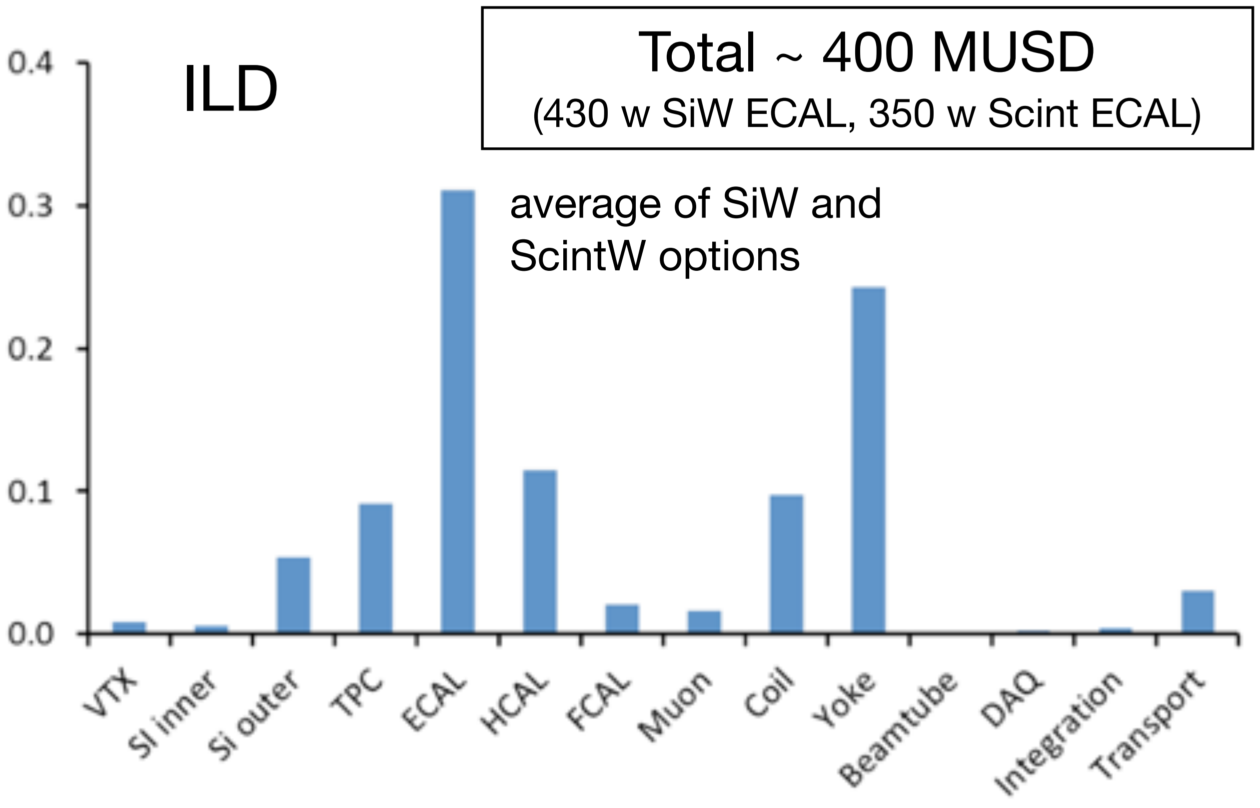






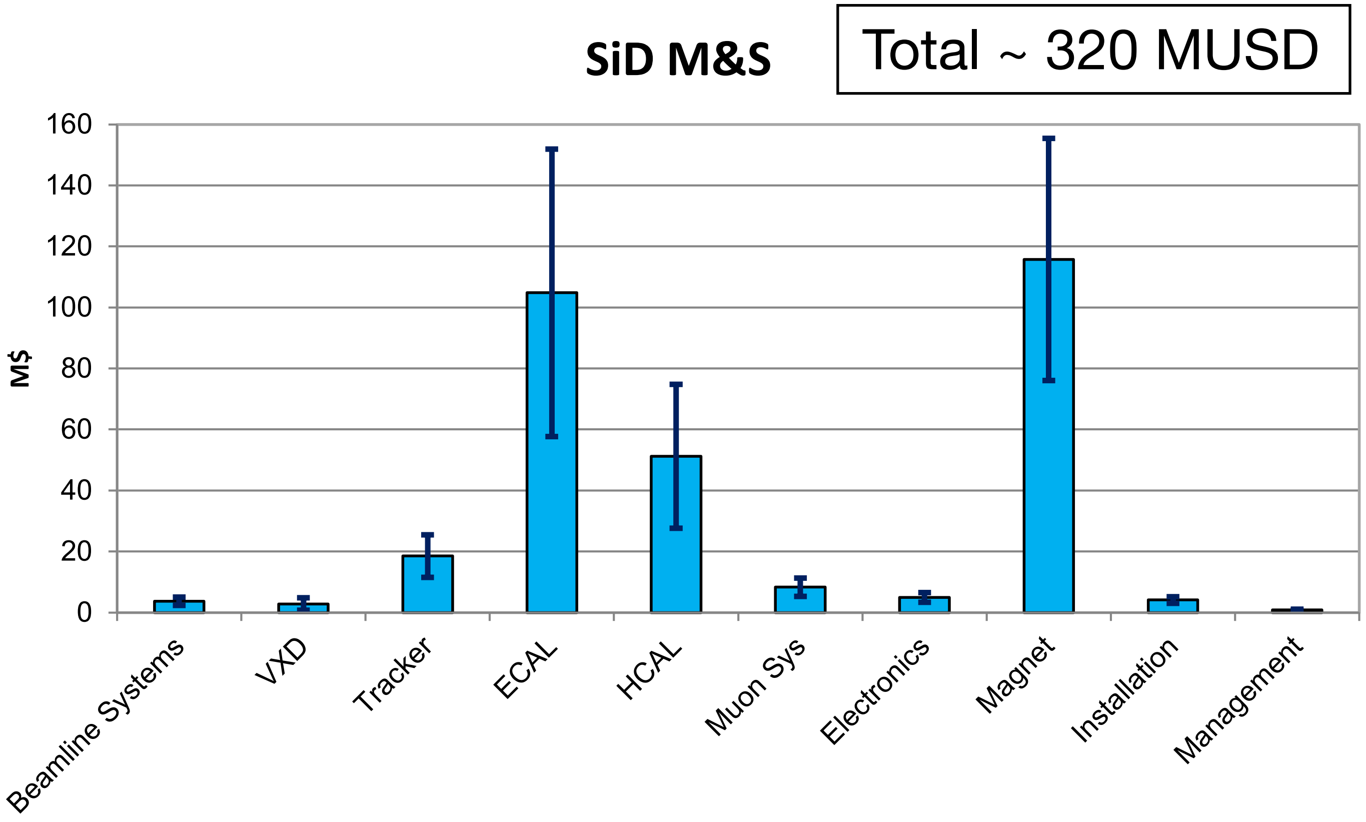
clean separation of W and Z in hadronic final states!

… and Cost



Total ~ 400 MUSD
(430 w SiW ECAL, 350 w Scint ECAL)

average of SiW and
ScintW options



Total ~ 320 MUSD

- First estimate of cost (excl. labor) - for some of the more expensive systems already quite detailed (NB: on some items the cost models of ILD and SiD are different)

▸ Clearly reflects the design for PFA: ~ 50% of the total cost is in the calorimeters

▸ Shows SiD optimization with cost-effectiveness in mind

Studies to evaluate the cost and performance impact of parameter changes are ongoing

Optimizing the Detector Design

The typical process (in ILD):

- The best we can imagine (more or less…)

- Confronting reality: Evaluate several intermediate models - will do the job, but do not get you overly excited…

- Know your limits: Where is the breaking point, where can't you make compromises anymore?

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ILD00 - Current model

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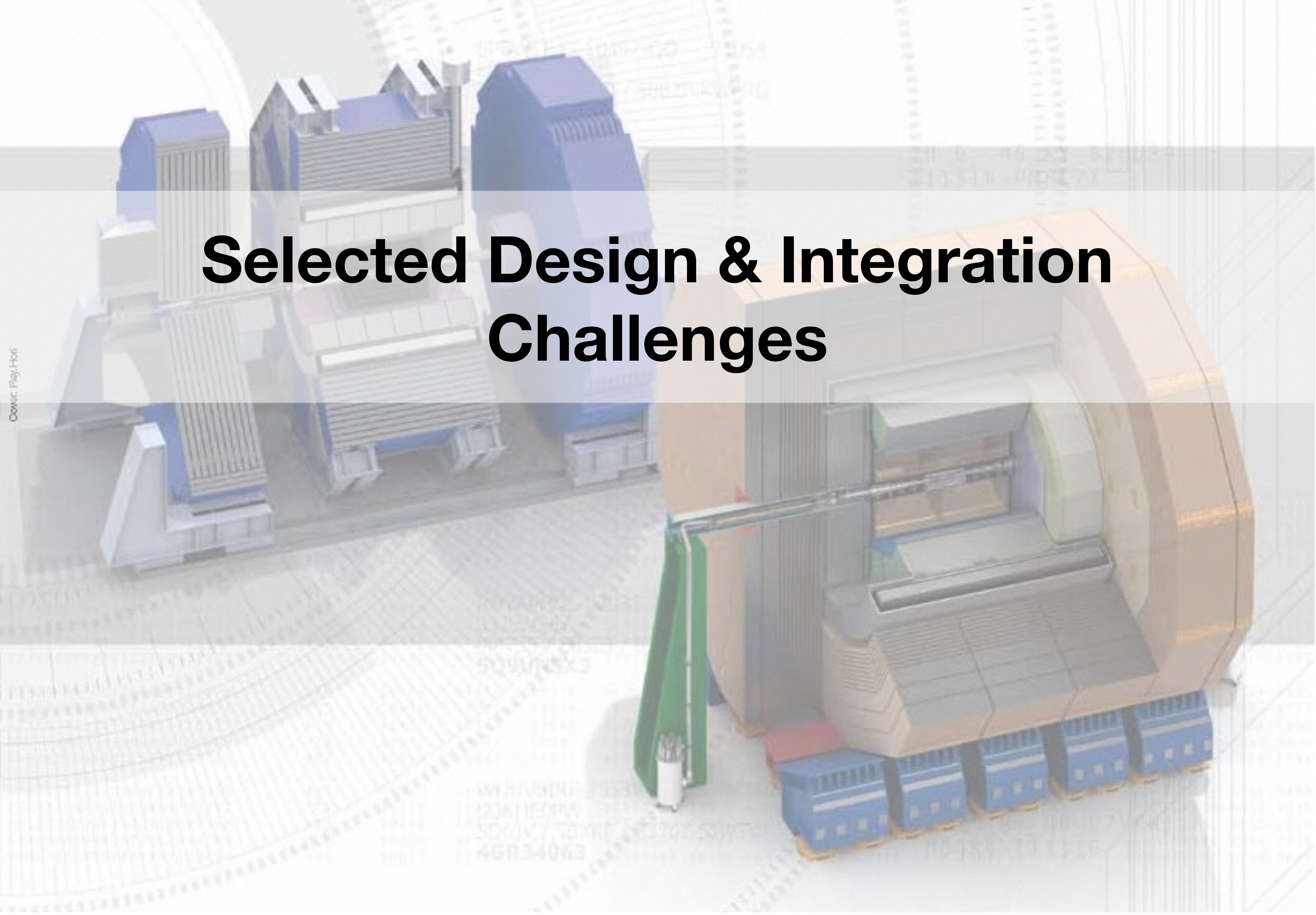
Reduce size, granularity, material and performance requirements …

- Know your limits: Where is the breaking point, where can't you make compromises anymore?

Selected Design & Integration Challenges



Cover: Rey.Hori

Example 1: Highly Granular Hadron Calorimeter

- One of the technologies for the hadron calorimeter of ILC detectors: Plastic scintillator / steel sampling calorimeter

  ➯ A “standard” technology, but:

  how do we make such a detector highly granular, with ~ 10M channels?

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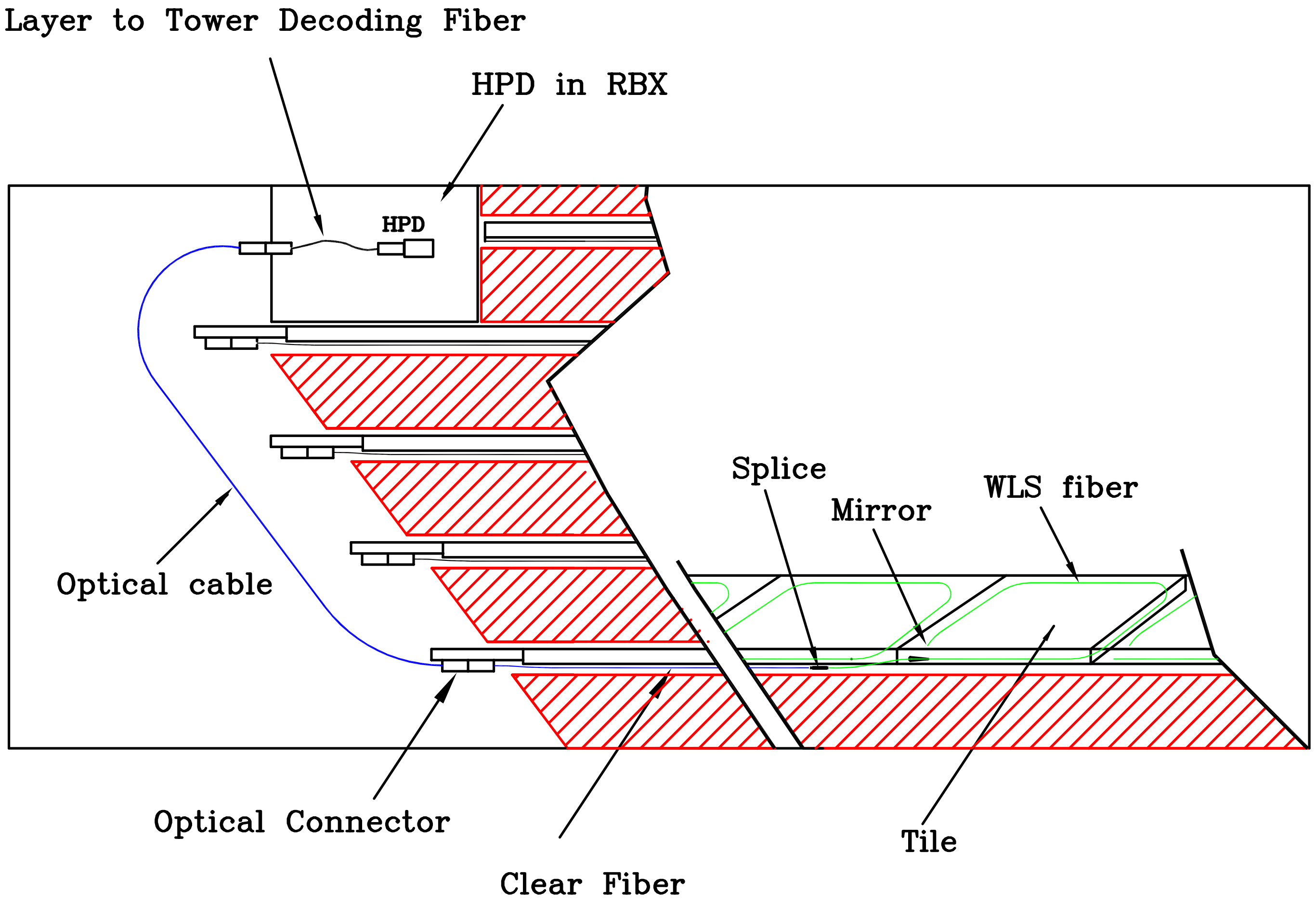

CMS: readout in “towers”: scintillator tiles in all layers combined into one photon detector (HPD for B-field tolerance, PMT otherwise a common choice)

To set the scale: “Small” PMTs typically 1 cm diameter, 10 cm long -> ~ 10 cm^2 volume - For ILC we want cells (including absorber) with *O* (10 cm^3) volume

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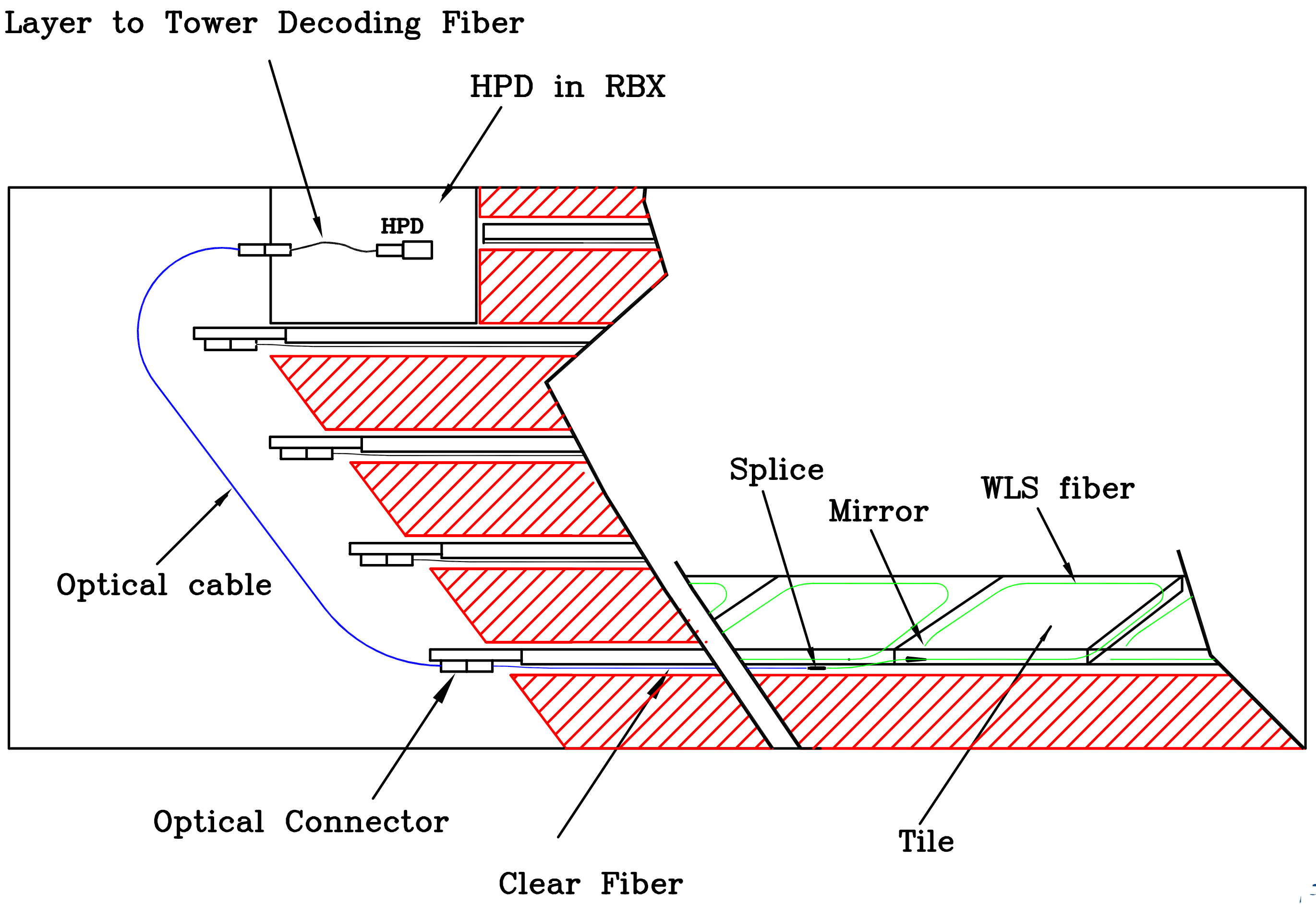

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➩ A completely new concept is needed!

Designing A Calorimeter with 10M Cells

- It is impossible to bring the light of each individual cell out of the calorimeter
  - Need to integrate photon detection into the cell itself
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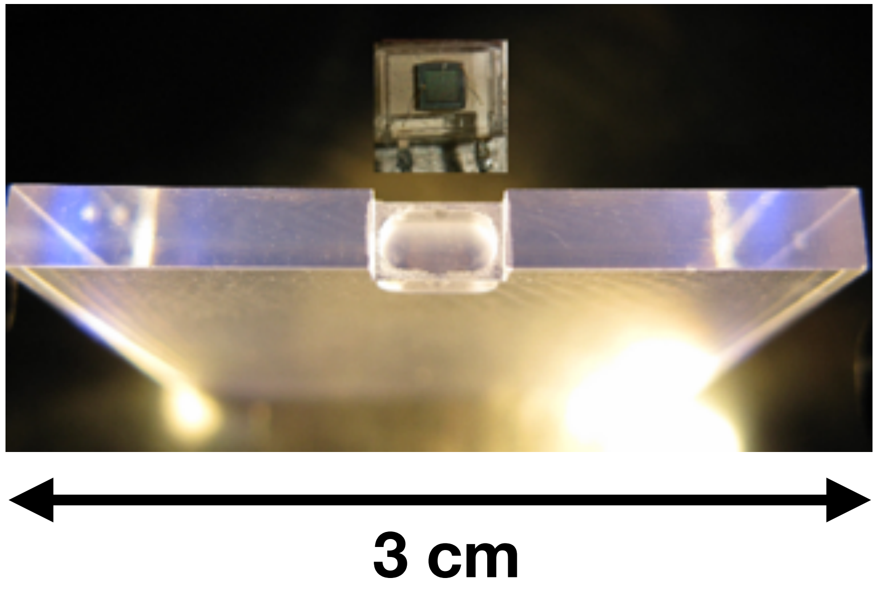
- Photon sensor has to be fully integrated into scintillator tile
  - Easy manufacturing important: No light collection by embedded fiber
  - Specific shape machined / molded into tile to optimize light collection



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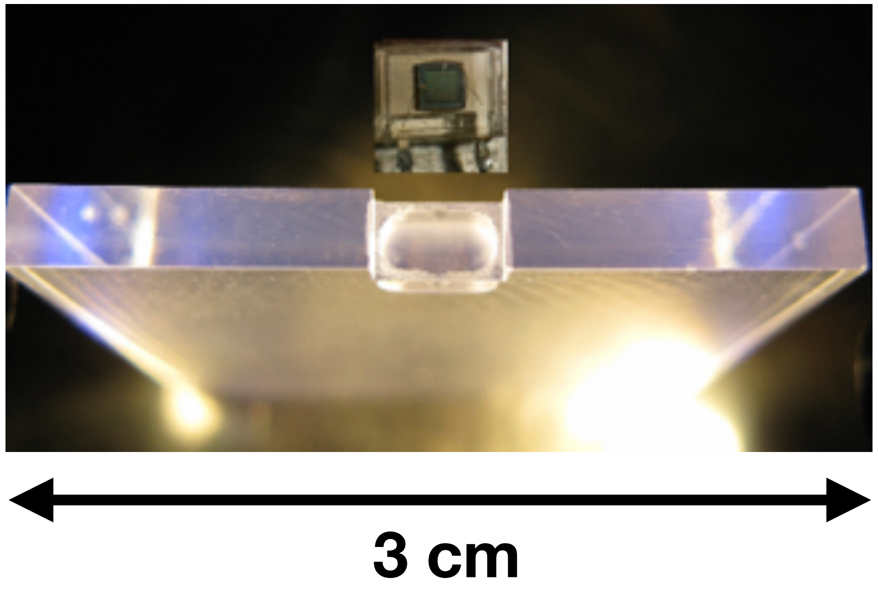
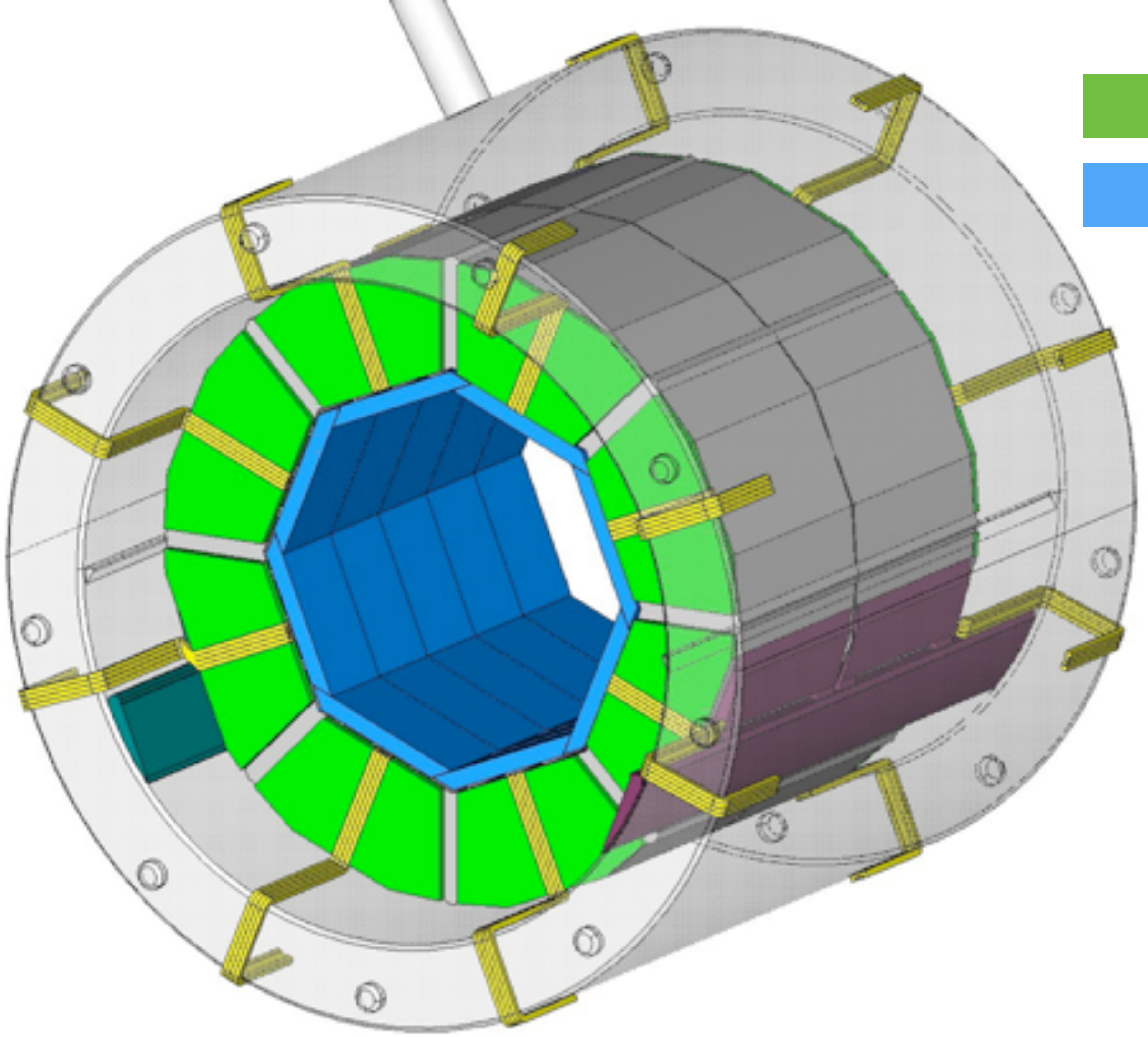


- Needs signal processing inside of the detector
  - Complete front-end electronics including ASICs for signal processing and digitization embedded in active elements

Designing A Calorimeter with 10M Cells



🟩 HCAL

🟦 ECAL

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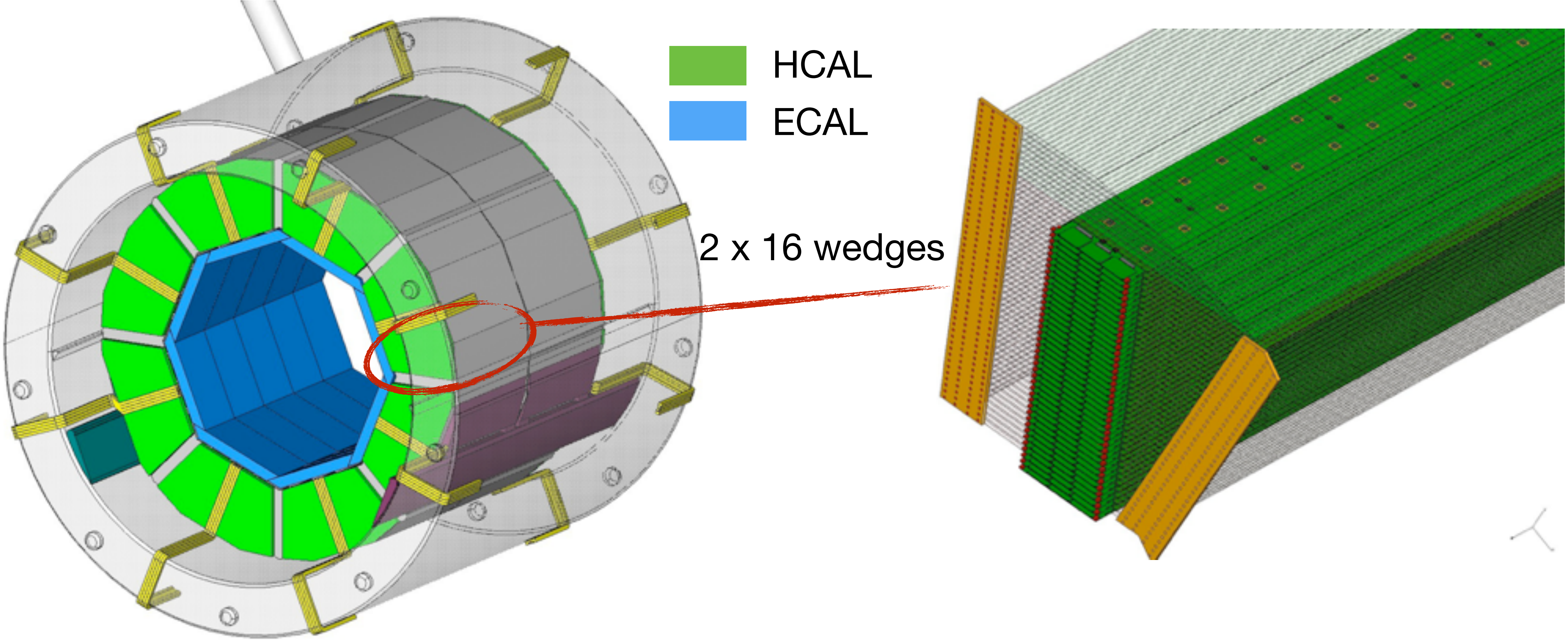

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2 x 16 wedges

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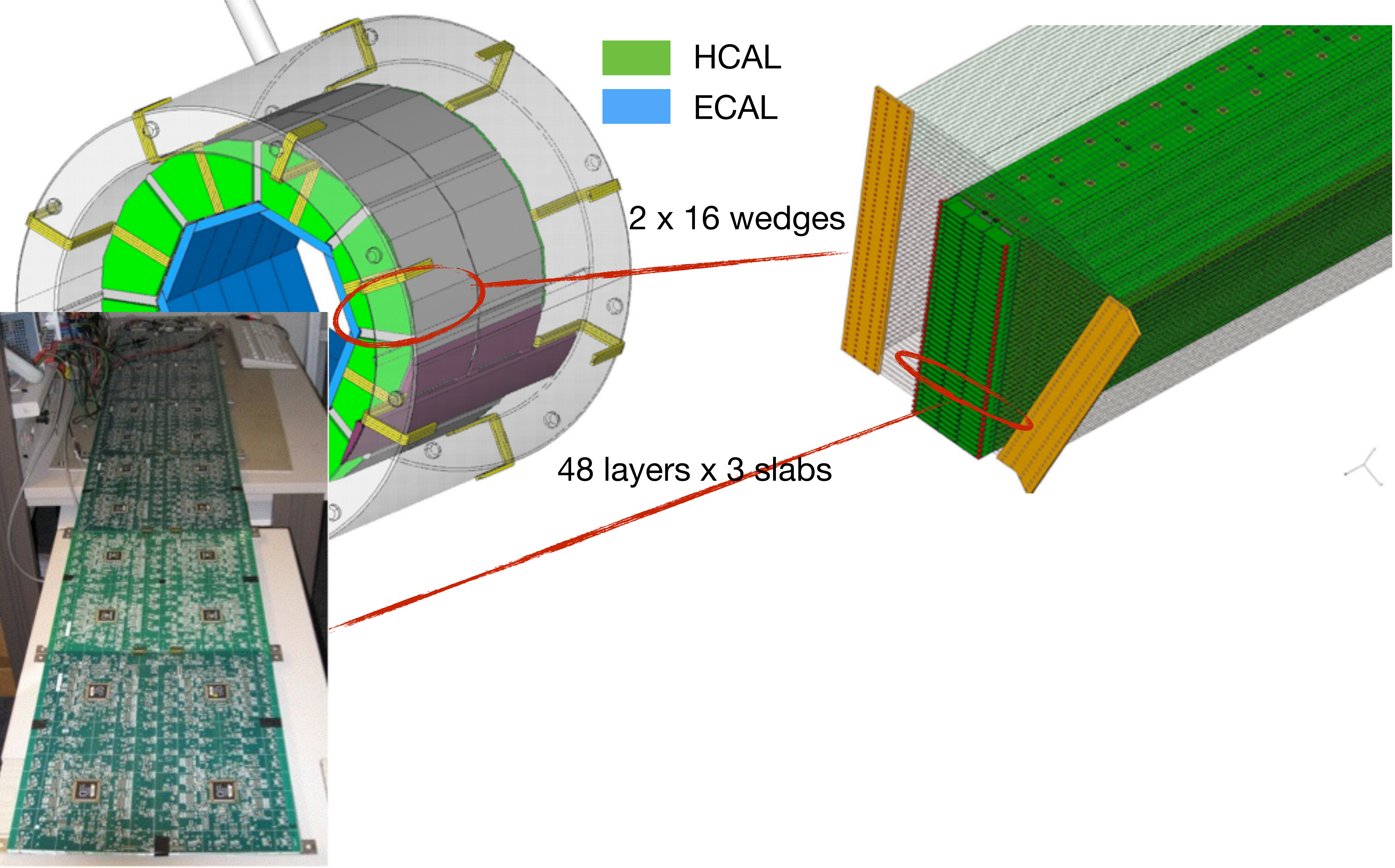

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2 x 16 wedges

48 layers x 3 slabs

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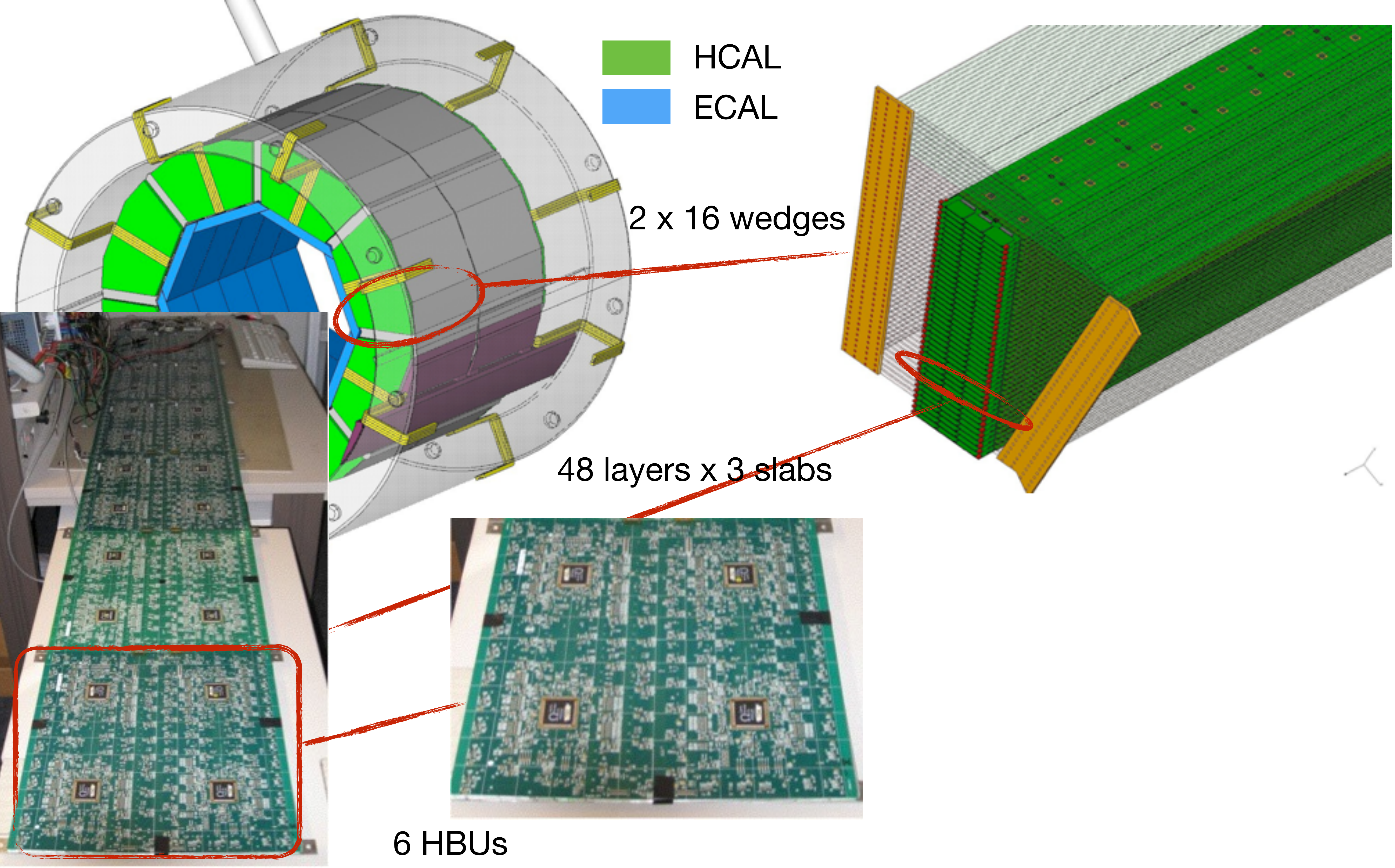

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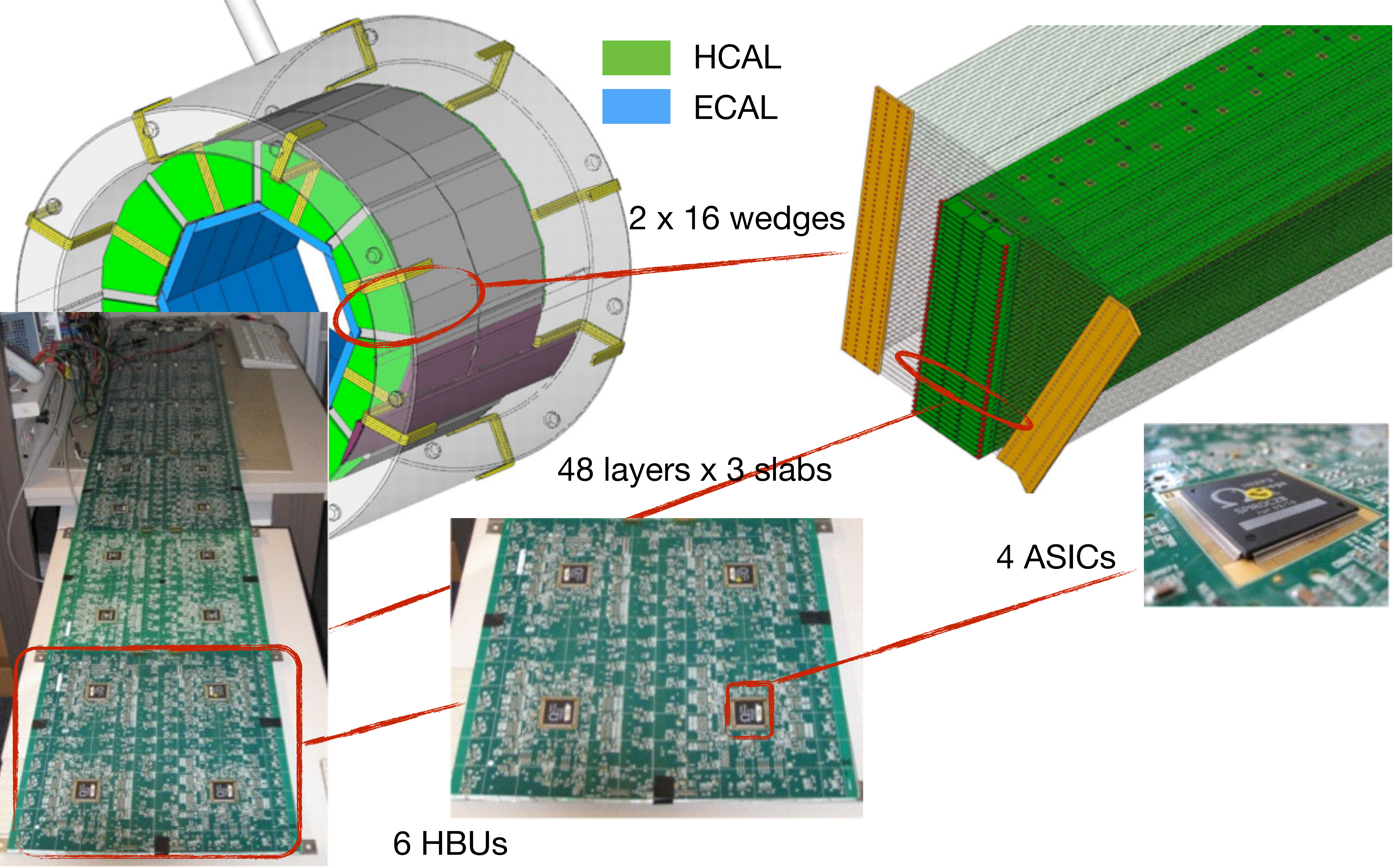

🟩 HCAL

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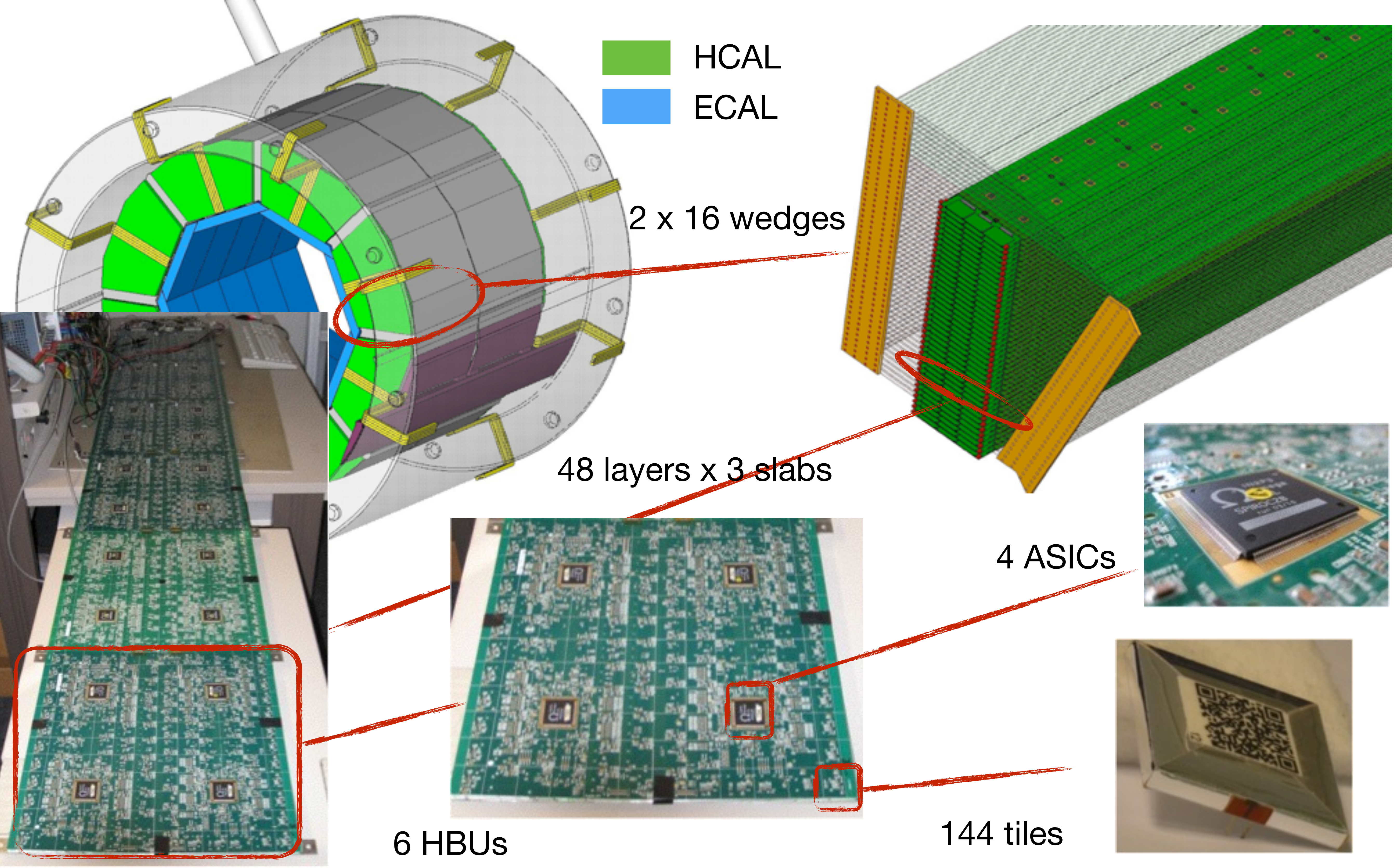
2 x 16 wedges

48 layers x 3 slabs

4 ASICs

6 HBUs

Designing A Calorimeter with 10M Cells



🟩 HCAL
🟦 ECAL

2 x 16 wedges

48 layers x 3 slabs

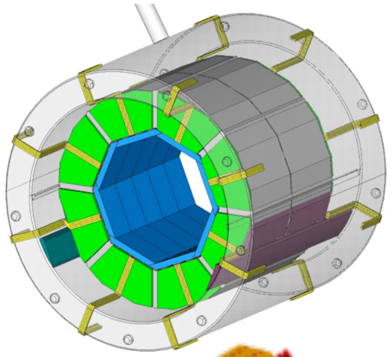
6 HBUs

4 ASICs

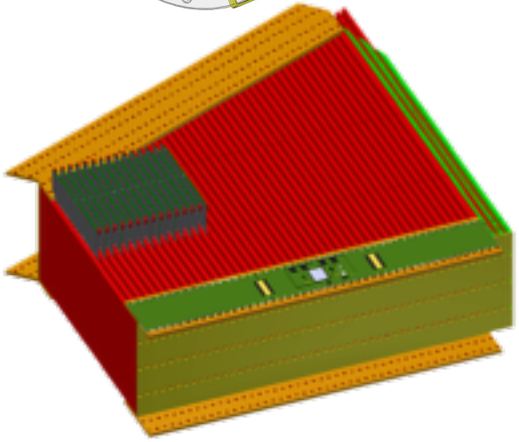
144 tiles

Building a Calorimeter with 10M Cells

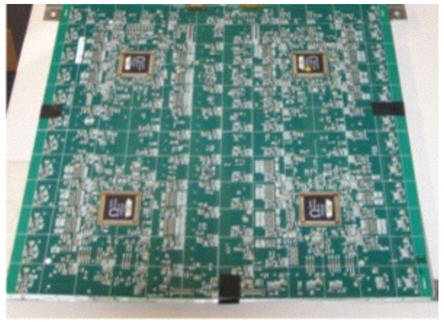
- 1 calorimeter
  (barrel + 2 end-caps)



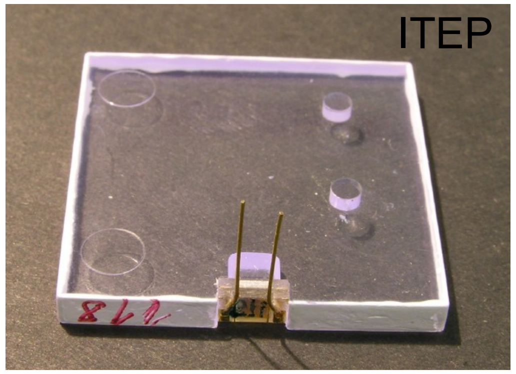
- 60 sub-modules



- 3 000 layers



- 60 000 HBUs
- 200 000 ASICs

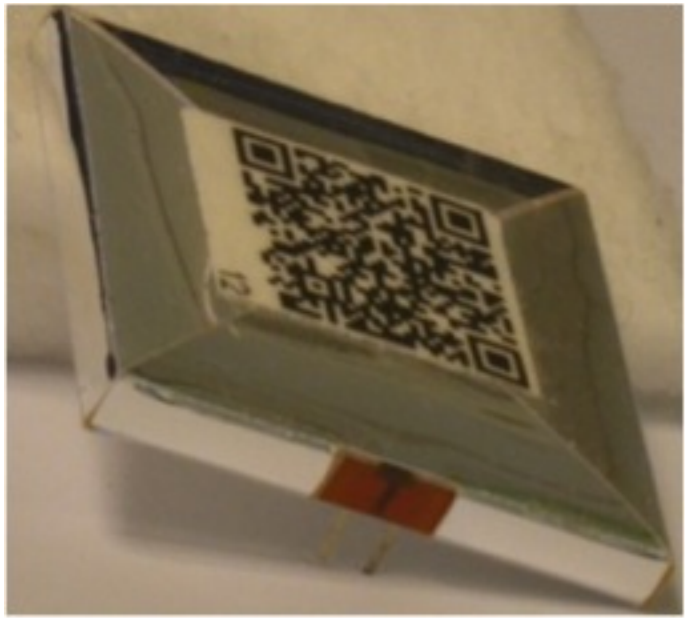


- 8 000 000 Tiles + SiPMs

- 1 working year
- 46 weeks
- 230 days
- 2 000 hours
- 100 000 minutes
- 7 000 000 seconds

A Prerequisite: Automation

- (Semi-) automatic assembly of Scintillator Tiles and SiPM
  - Large scale machining or molding
  - Automatic wrapping in reflector foil - already demonstrated at UHH



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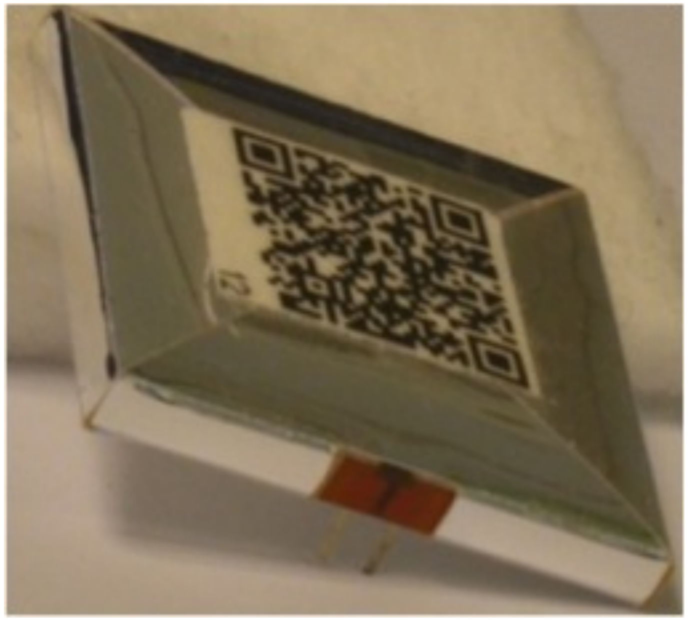
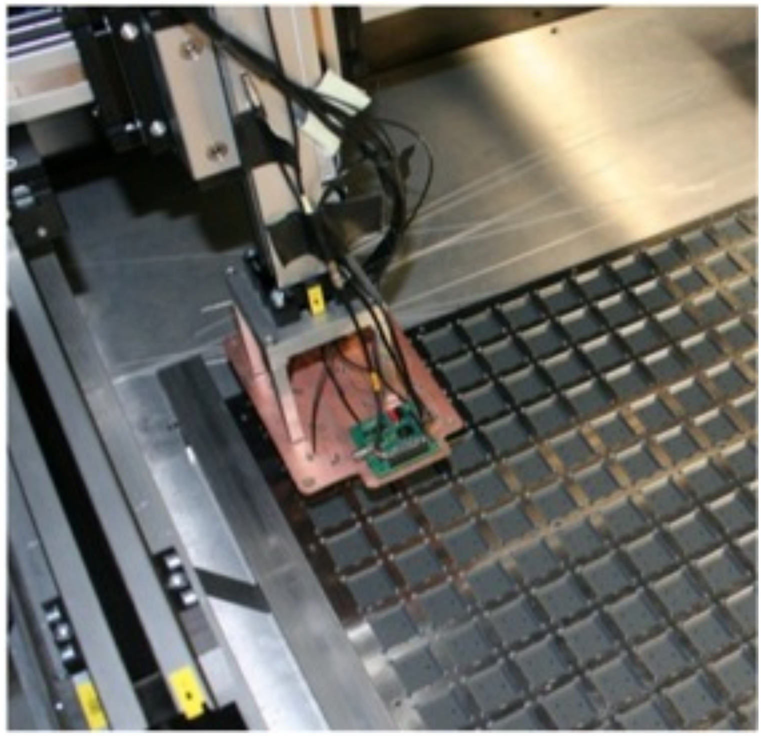


- Fast, large-scale testing prior to installation: gain, global light collection



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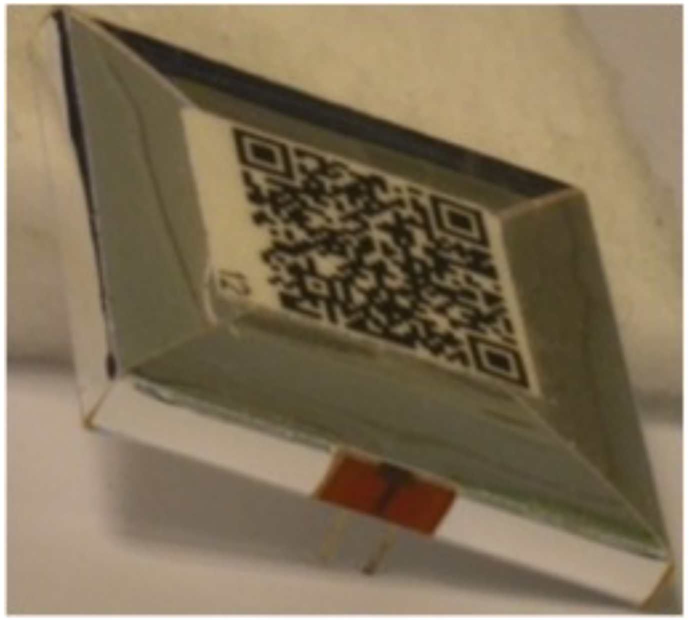

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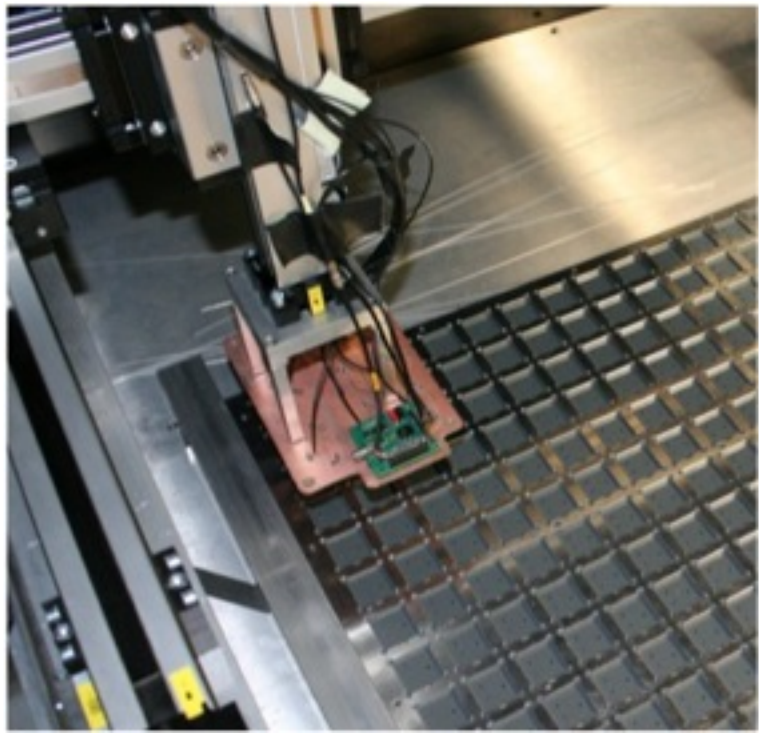


- Automatic placement of tiles on electronics
  - parallel soldering of multiple tiles
  - wave soldering (the fastest option - requires precise thermal shielding)
- Also investigating SMD-mounting of SiPMs on electronics, installation of scintillator as last step to reduce the number of individual components - removes the possibility of a tile-by-tile functionality check prior to installation.

Example 2 - Low-Mass Vertex Detectors

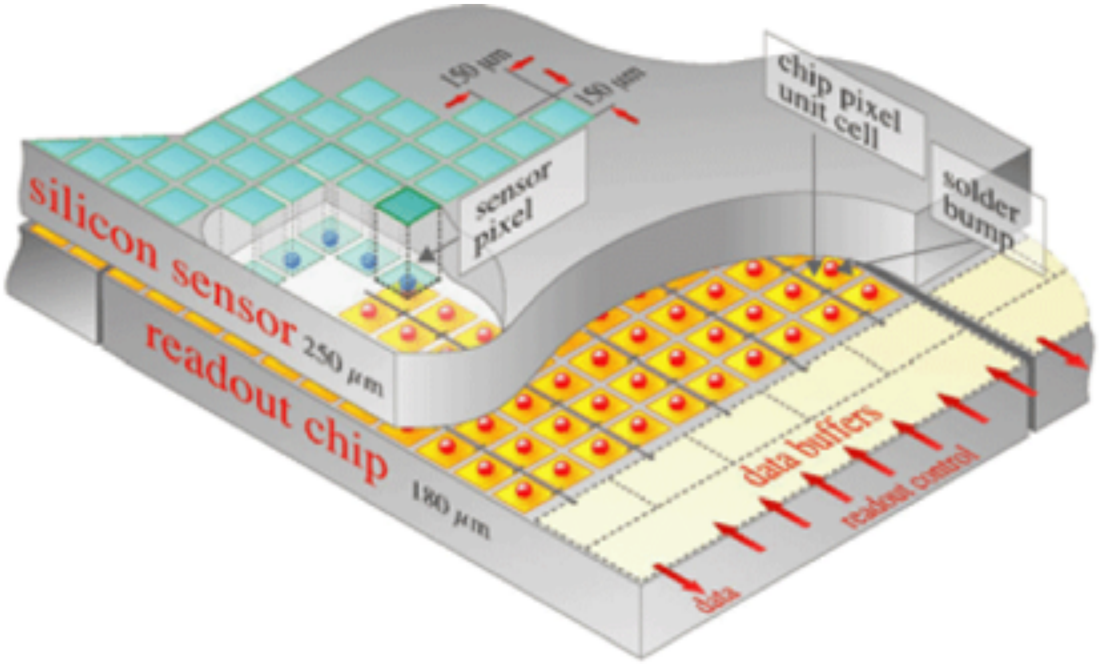
- To “see” a particle: Energy deposition by ionization - a few 10 μm of Si sufficient for a reasonable signal
- Additional “infrastructure”
  - Readout - electronics to collect, process and transmit data
  - Cooling - take away heat produced by sensor and electronics
  - Mechanical support

Material is bad: Scattering of particles introduces uncertainties in momentum and position reconstruction - particularly bad in the innermost layers of the detector

➯ keep the additional infrastructure to the absolute minimum!

To set the scale: The goal for ILC vertex detectors is ~ **0.2% X_0**
100 μm Si = 0.1% X_0

Minimizing the Material Budget



- At LHC: Hybrid pixel detectors: readout chip bonded to sensor - already x2 of the material goal of ILC - without mechanical support, additional electronics, cooling…

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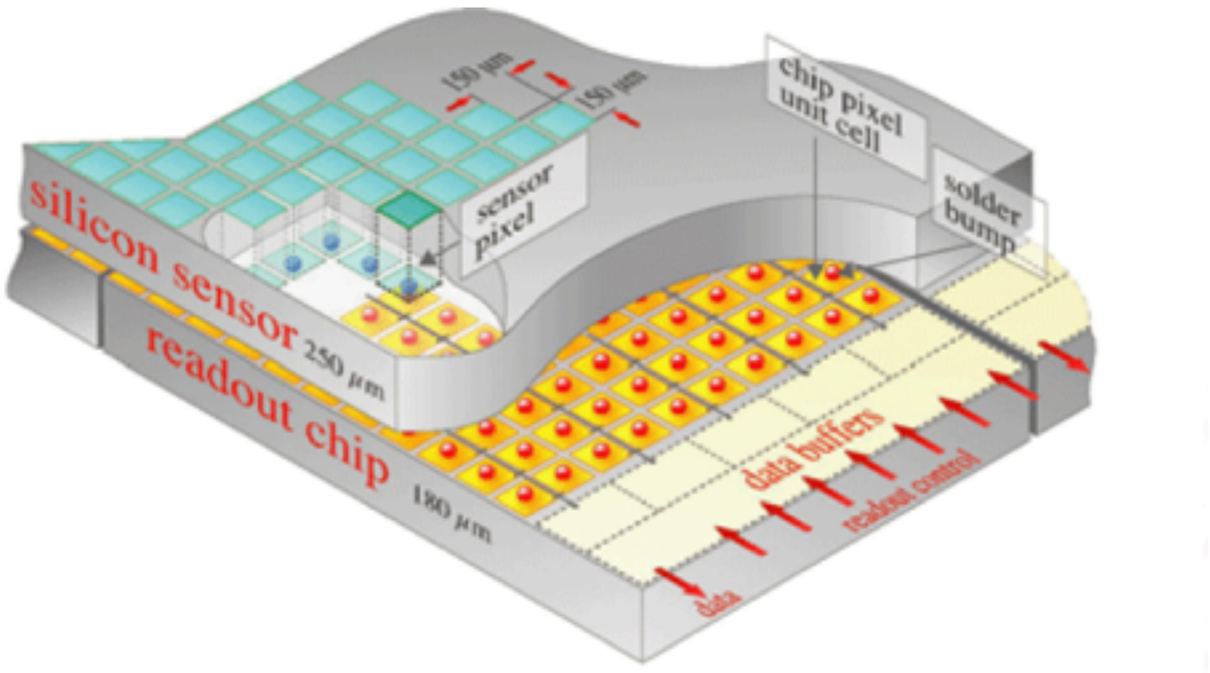

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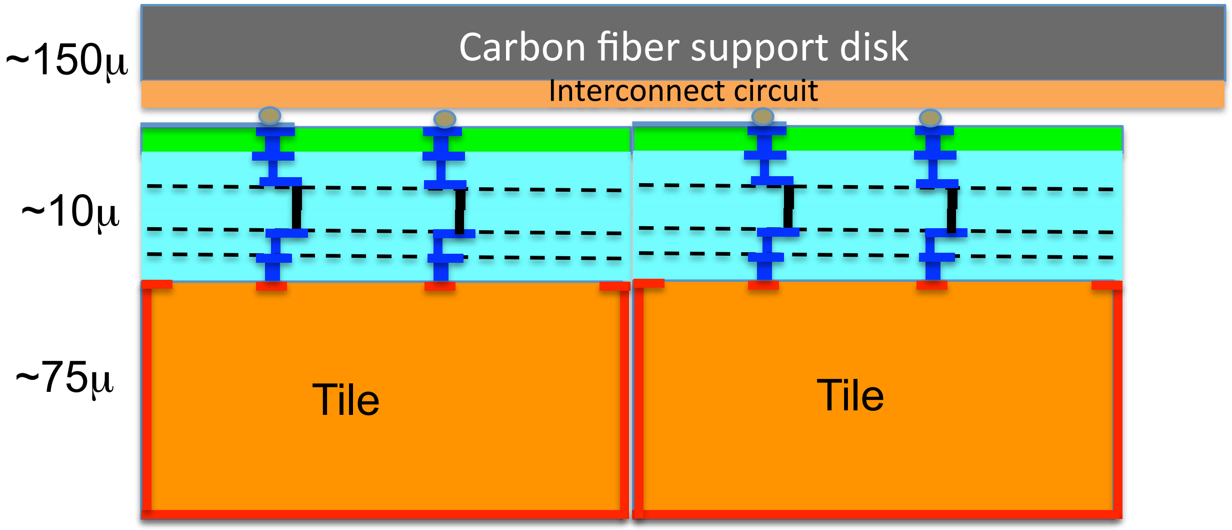

- Use thinner sensors: ~ 50 - 75 µm
- Minimal amount of material in readout
  - 3D technologies with thin electronic layers
  - Active pixel sensors w/o readout layer - rolling shutter readout, electronics at the end / side of the detector modules
- Light-weight support structures - carbon fiber / carbon foam etc

Minimizing the Material Budget - Low Power

- A key to extremely small material budgets in ILC (vertex) trackers: Cooling of the sensor elements only via air flow
  - Requires very low power consumption

Goals for the full vertex detector system: ~ 20 W
(-> ~ 100 µW/mm^2, or 100 mW for a 10 cm^2 module)

To compare: CMS pixel detector
~ 4 mW / mm^2

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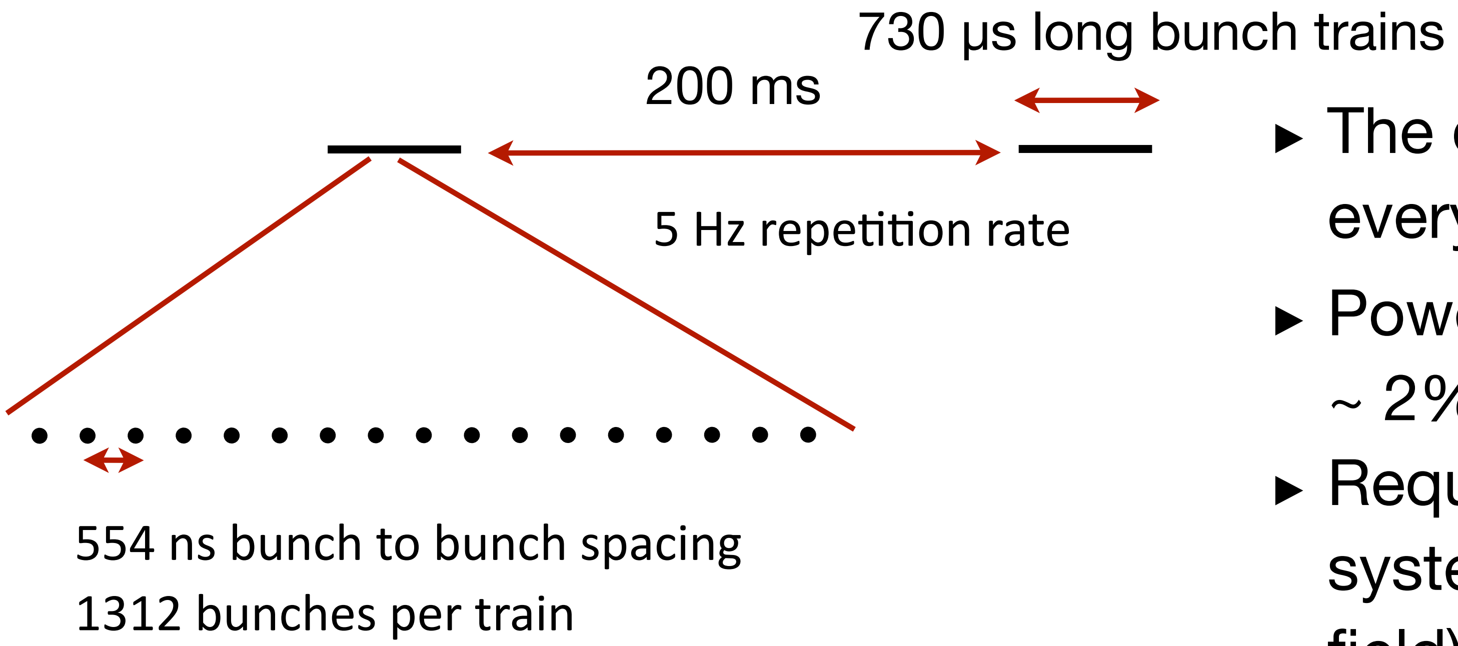
~ 4 mW / mm^2

How to save a factor of 40? - Exploit the beam structure of ILC!



- The detector has to be on only for a few ms every 200 ms (including time for readout)
- Powerpulsing of electronics: On for only ~ 2% of the time
- Requires careful design of powering systems (periodic high currents in magnetic field), electronics (fast settling times)

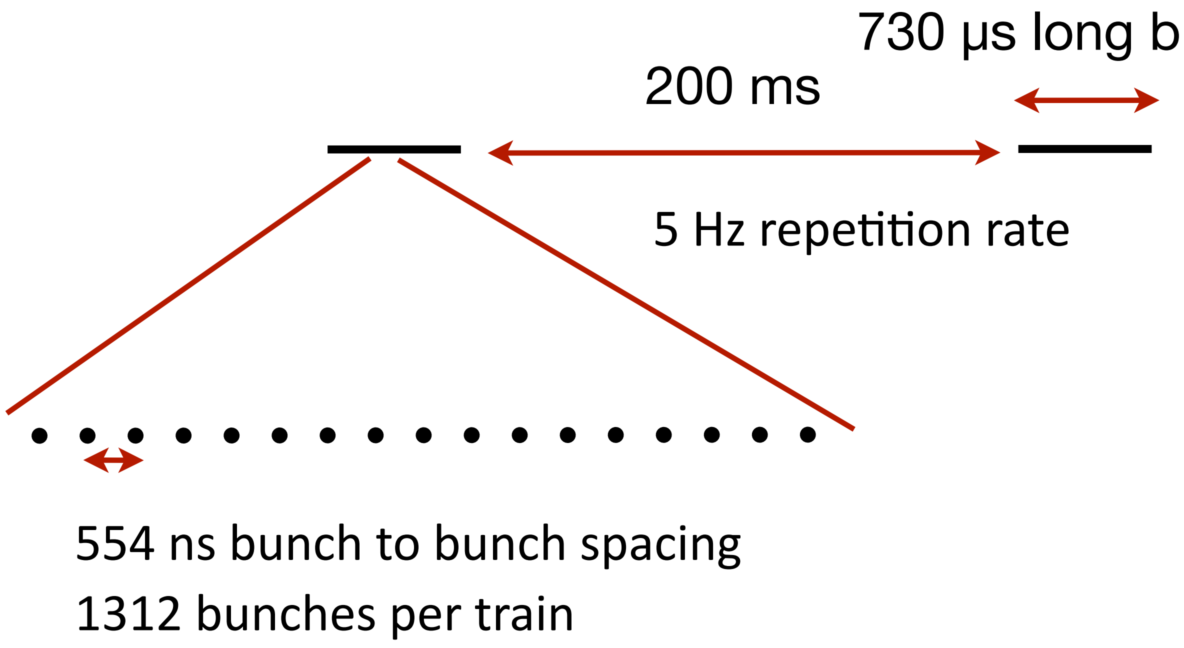
Minimizing the Material Budget - Low Power

- A key to extremely small material budgets in ILC (vertex) trackers: Cooling of the sensor elements only via air flow
  - Requires very low power consumption

Goals for the full vertex detector system: ~ 20 W
(-> ~ 100 µW/mm^2, or 100 mW for a 10 cm^2 module)

To compare: CMS pixel detector
~ 4 mW / mm^2

How to save a factor of 40? - Exploit the beam structure of ILC!



730 µs long bunch trains

200 ms

5 Hz repetition rate

554 ns bunch to bunch spacing
1312 bunches per train

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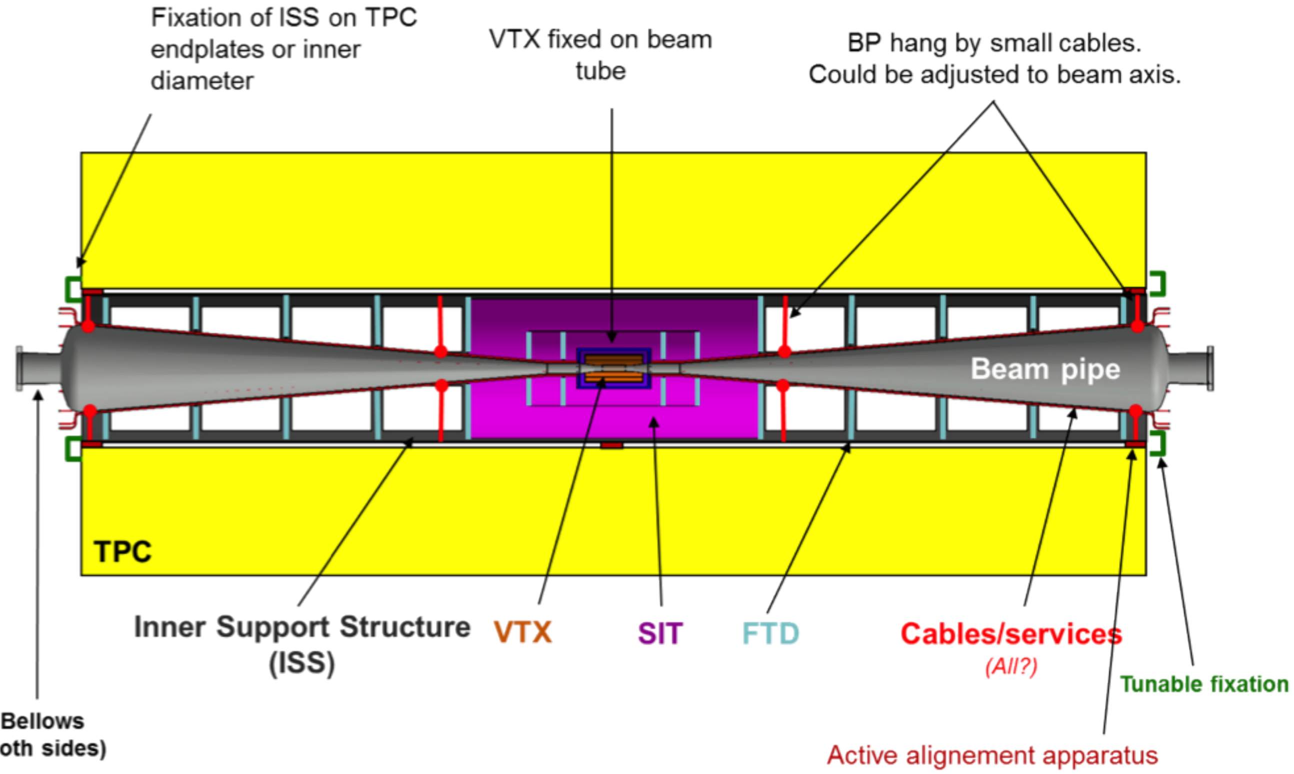
Powerpulsing is used in all ILC subsystems to reduce / eliminate need for cooling - Successfully demonstrated for example in large calorimeter prototypes already

Turning Subsystems into a Detector - Example ILD

- Sophisticated mechanical concept to support all subsystems with minimal material in inner regions and minimal dead space



inner detector
supported on TPC

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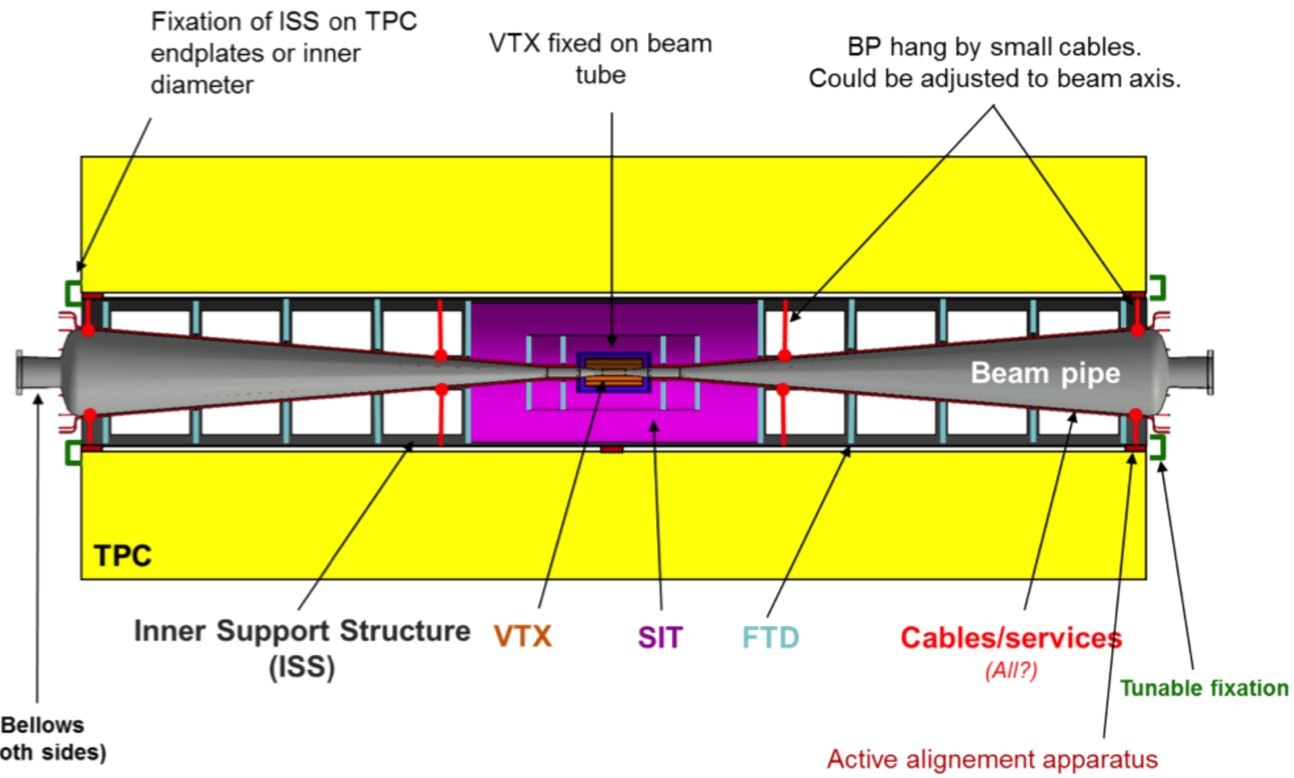
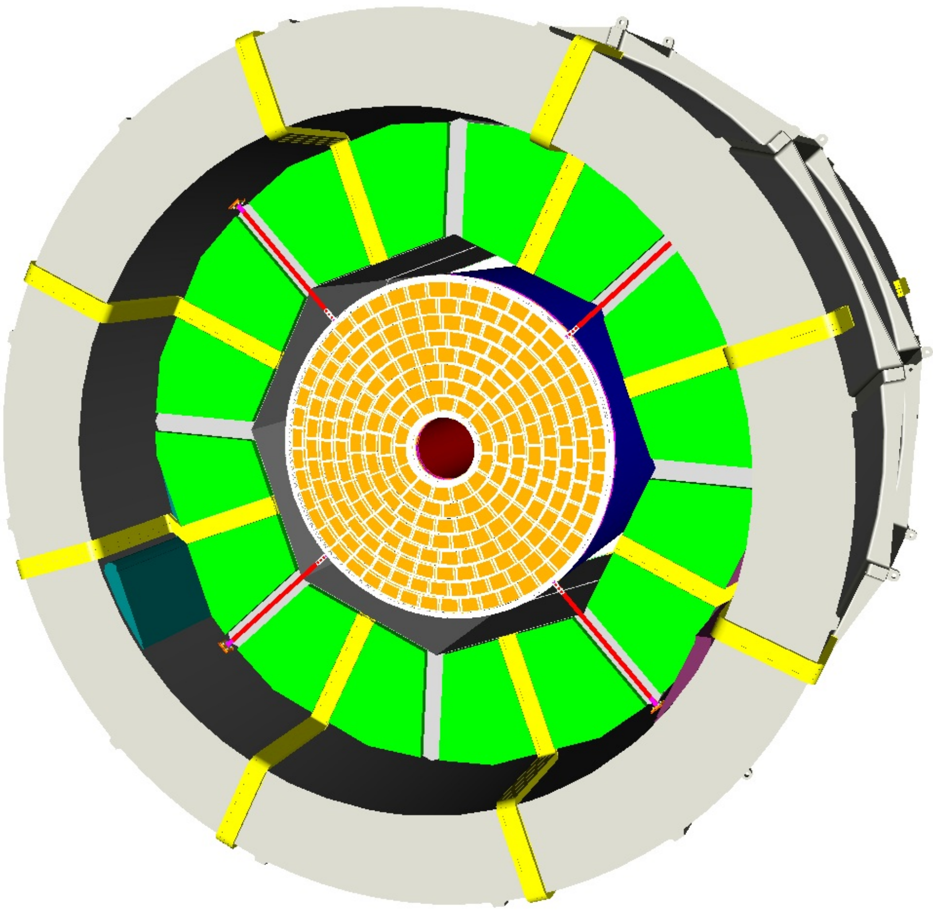


inner detector supported on TP

TPC supported on cryostat



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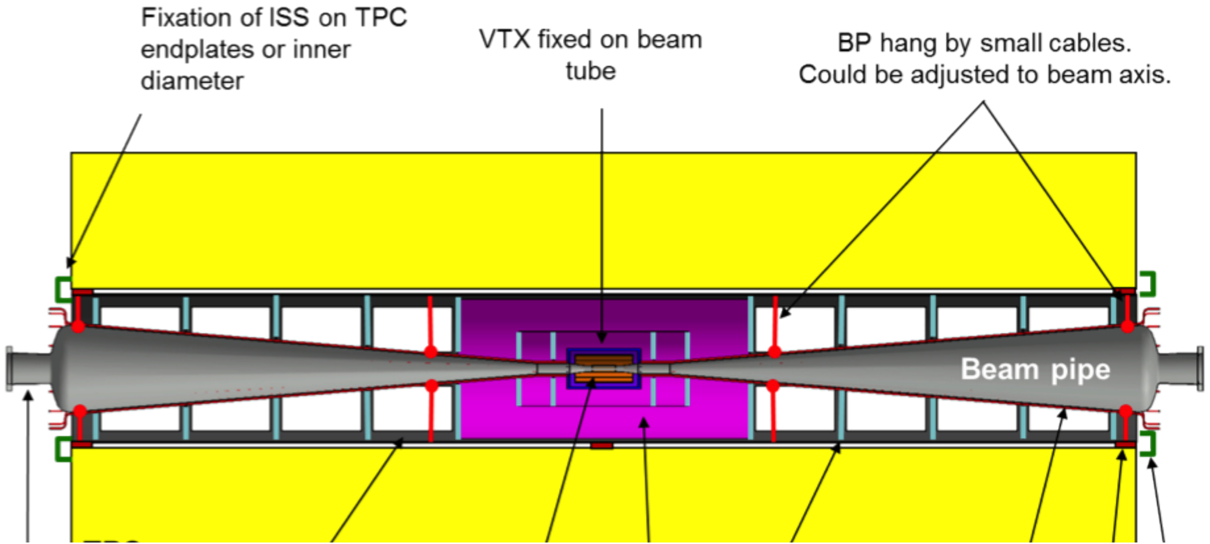

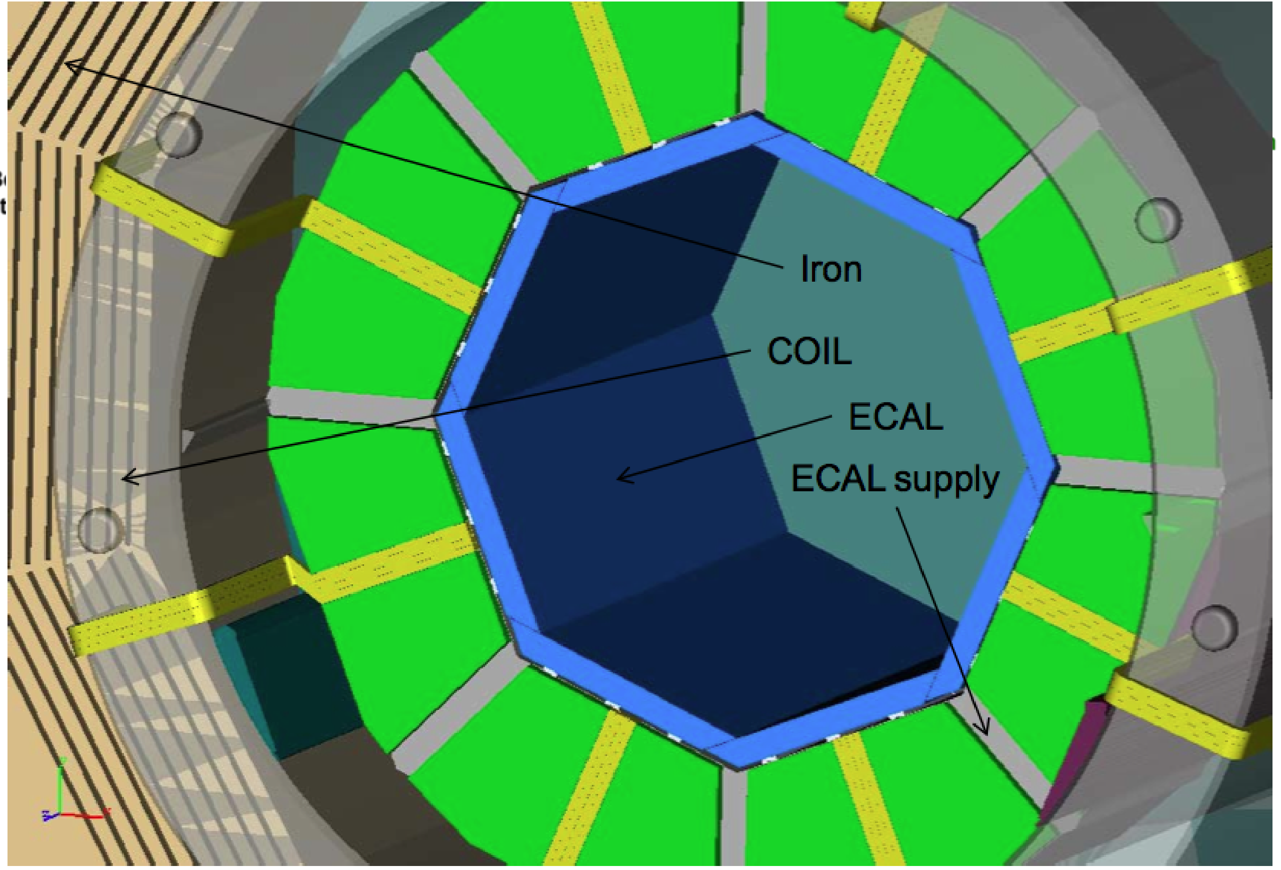

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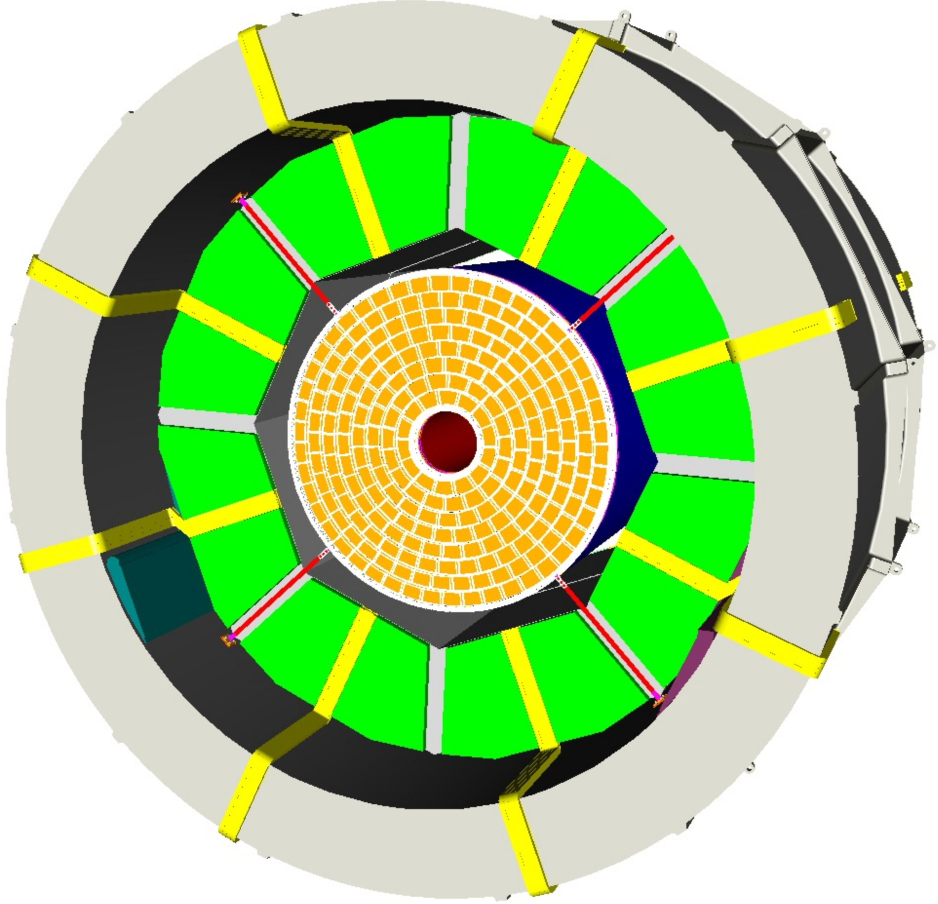
TPC supported on cryostat

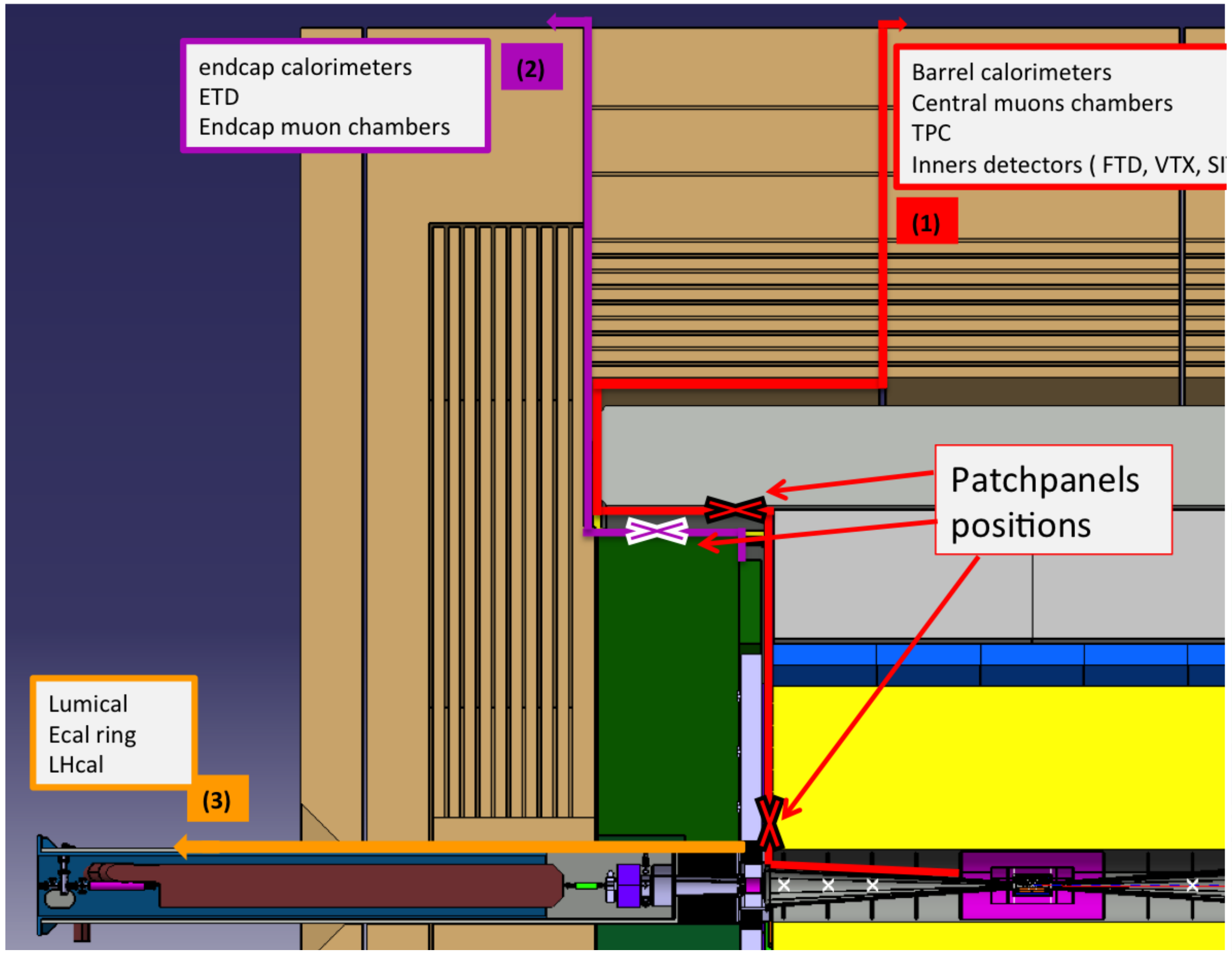


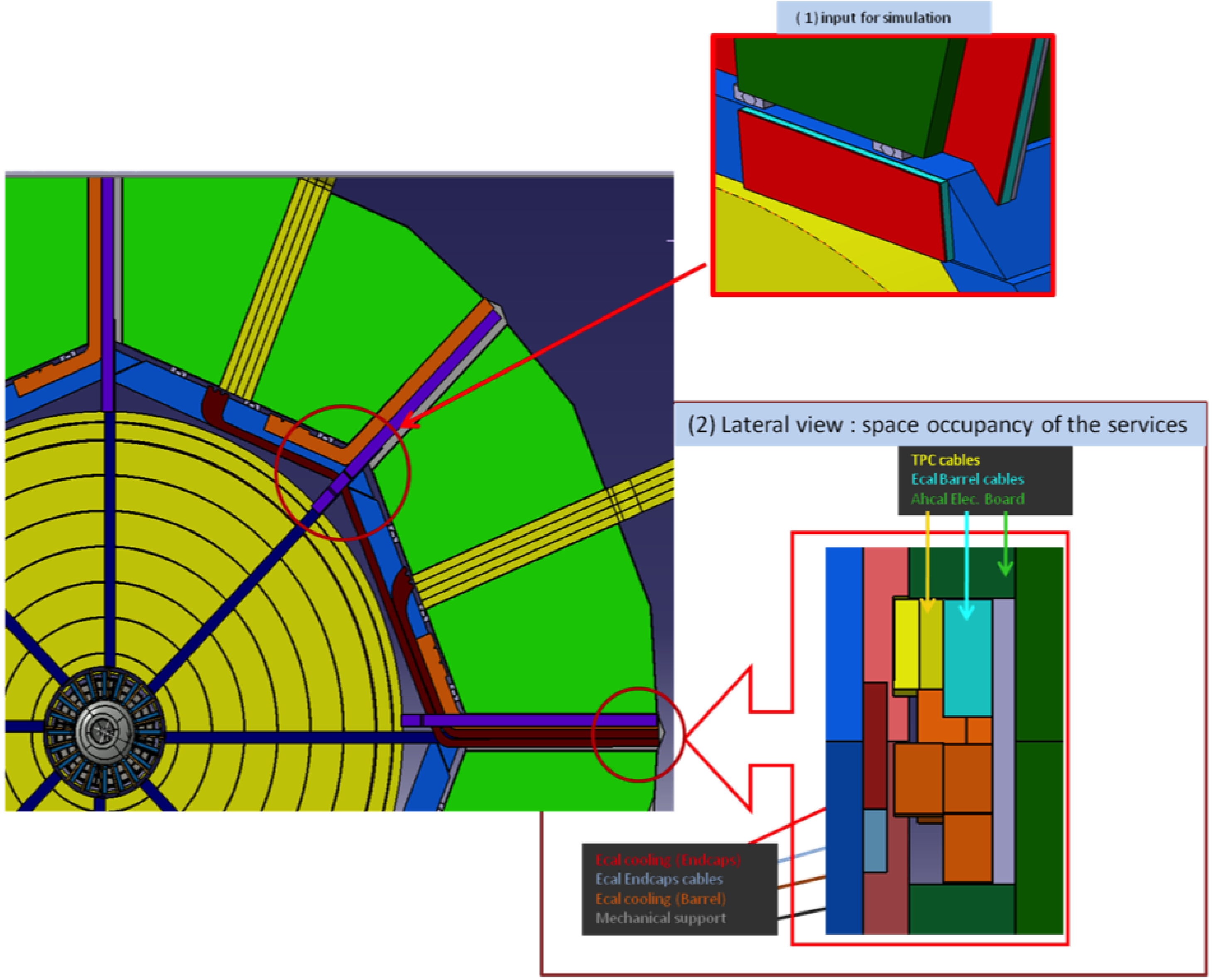
ECAL supported by rails on HCAL

HCAL supported by rails on cryostat

Turning Subsystems into a Detector - Example ILD

- All systems require services - Readout, power, cooling…





Summary

- The physics program at ILC requires highly performant detector systems: Addressed by ILD and SiD with:
  - low-mass, small pitch pixel vertex trackers
  - high resolution main trackers, either all silicon or silicon + TPC
  - highly granular “imaging” calorimeters

- Reaching these goals implies:
  - High degree of automation for production, testing and assembly of calorimeter components required
  - Low mass detectors with power-pulsing and corresponding reduced need for cooling
  - Complex support schemes to ensure minimum additional material inside tracker volume and as little dead space as possible
  - A global plan on how and where to produce the detector components, which dedicated facilities are needed, and how to finance the production
  - Figuring out how to assemble the whole thing - with consideration for local limitations in infrastructure, legal regulations, …

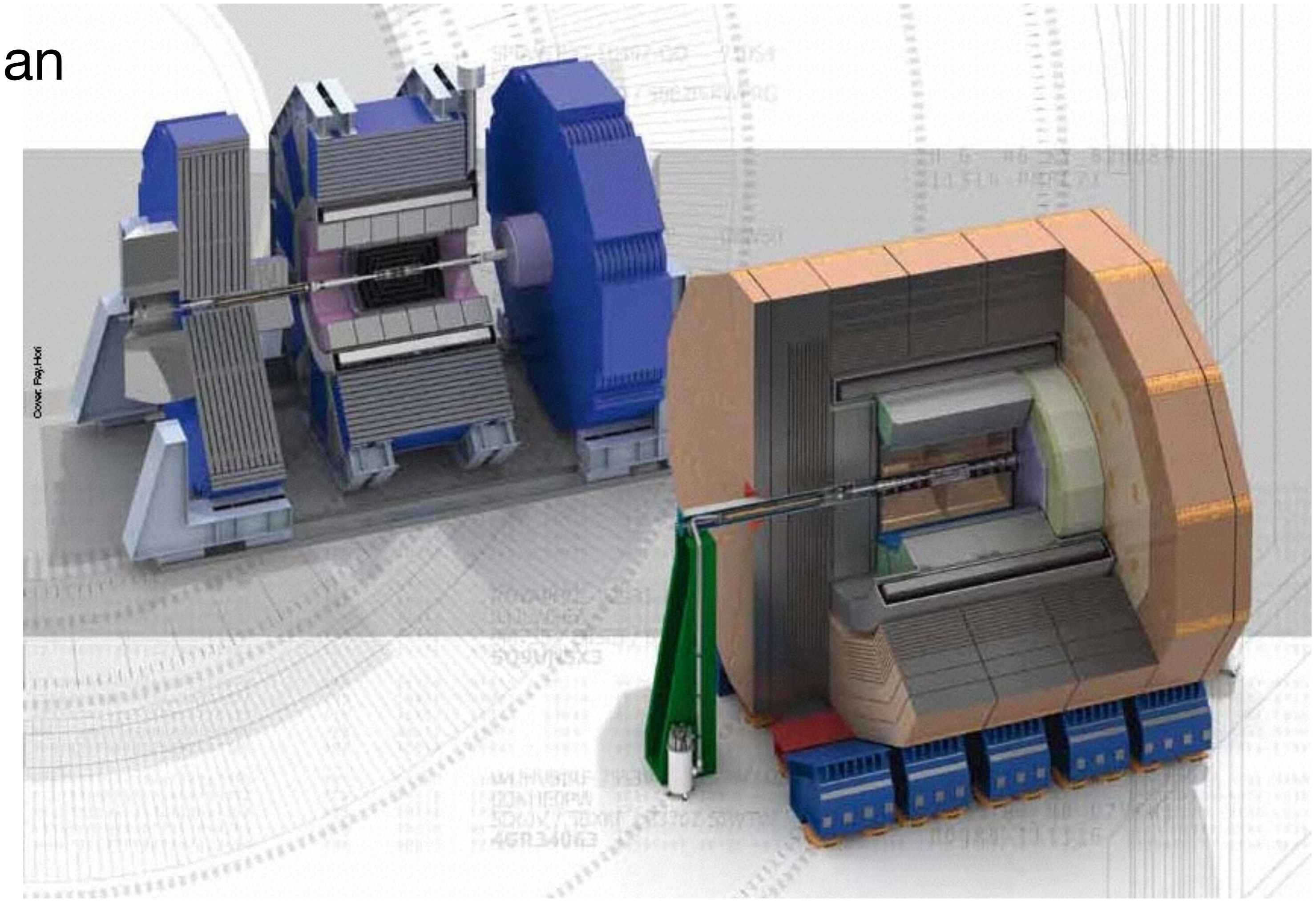
Outlook

- Starting now: Optimisation of the detector design - Study impact of design choices on physics performance and cost, react to new LHC results

▸ Prepare for a Technical Design Report by ~ 2018

  - Further demonstration of technologies in beam tests
  - Complete mechanical design
  - More thorough cost estimate
  - concrete integration / production plan
  - …

after approval: 6 - 8 years for
final design, production and installation



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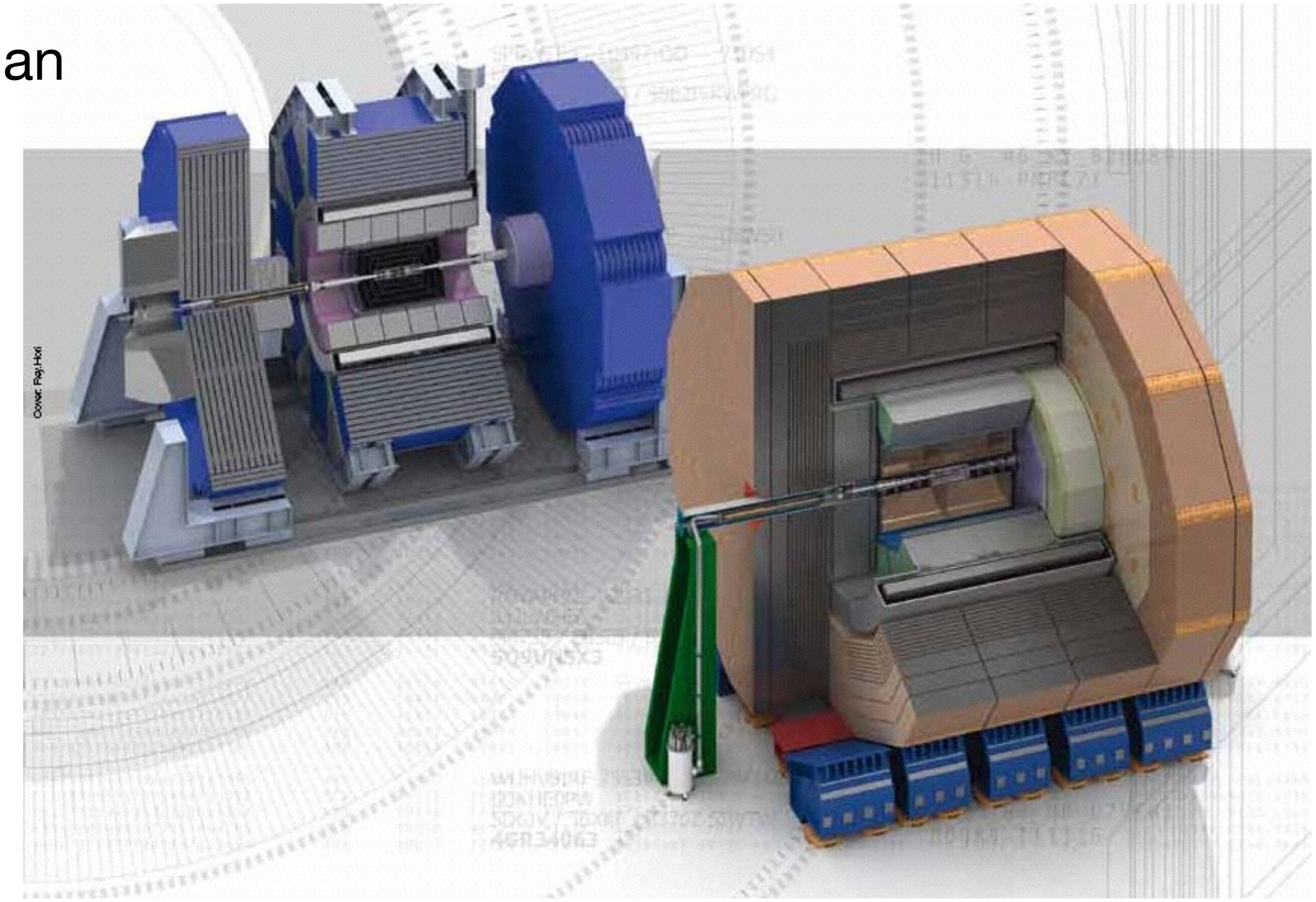
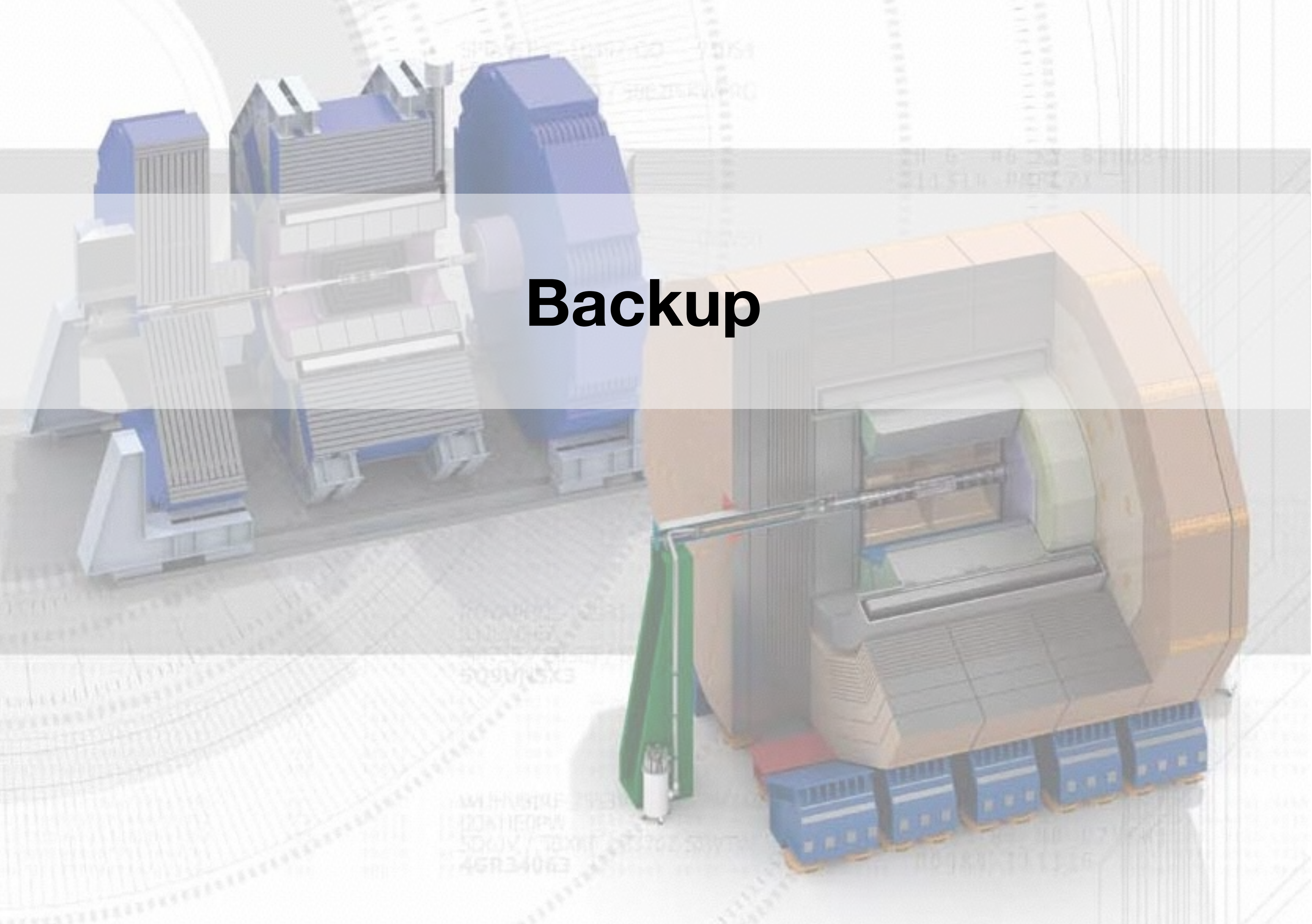
The physics program of the ILC is clear and we have the detector technology to do it - but many of details still need to be worked out!



Backup

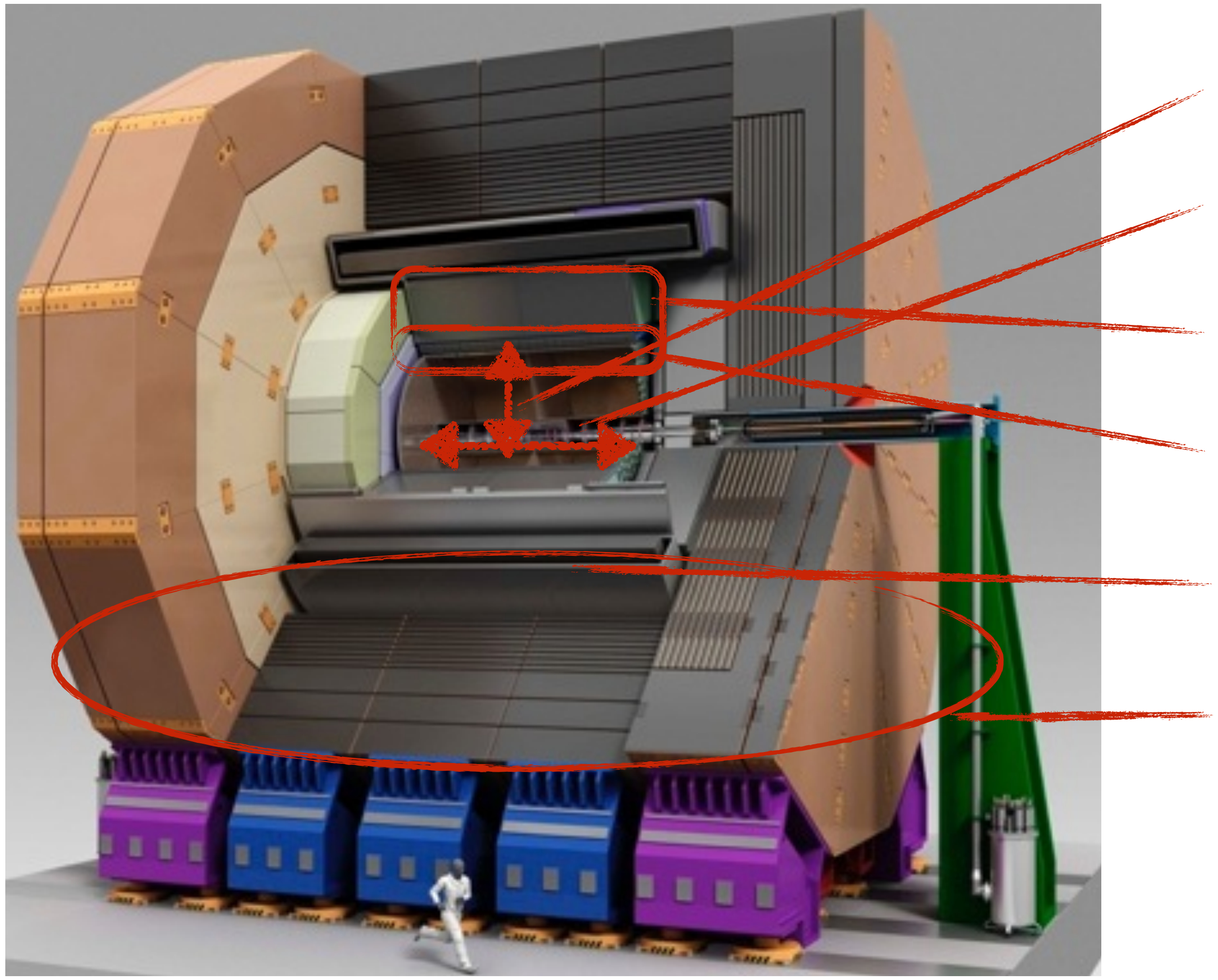


Cover: Ray Hori

Next Steps: Optimization

- The ILC detector concept have demonstrated their performance for various channels

  Now: Take a step back and re-examine the design choices:
  - Better understand physics drivers for performance requirements
  - Identify key performance drivers, find possible “breaking points”
  - Reduce cost - but without de-scoping of performance goals



main tracker radius & aspect ratio

number and placement of tracker layers

calorimeter granularity (in 3D!)

ECAL technology: Si / Scint / Hybrid

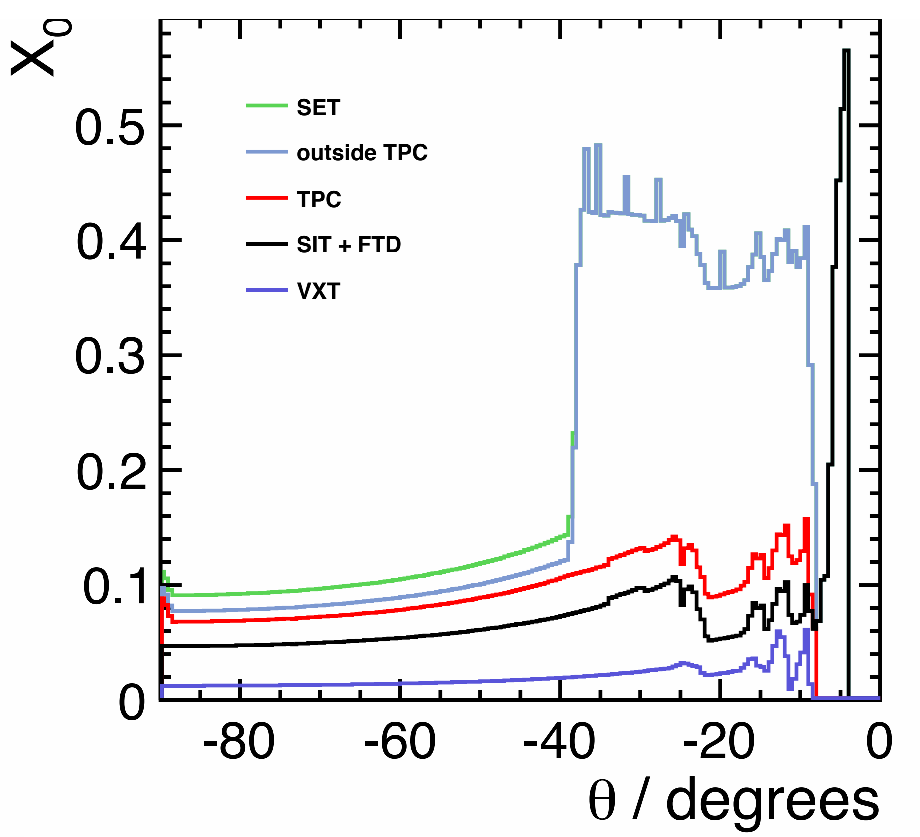
magnetic field

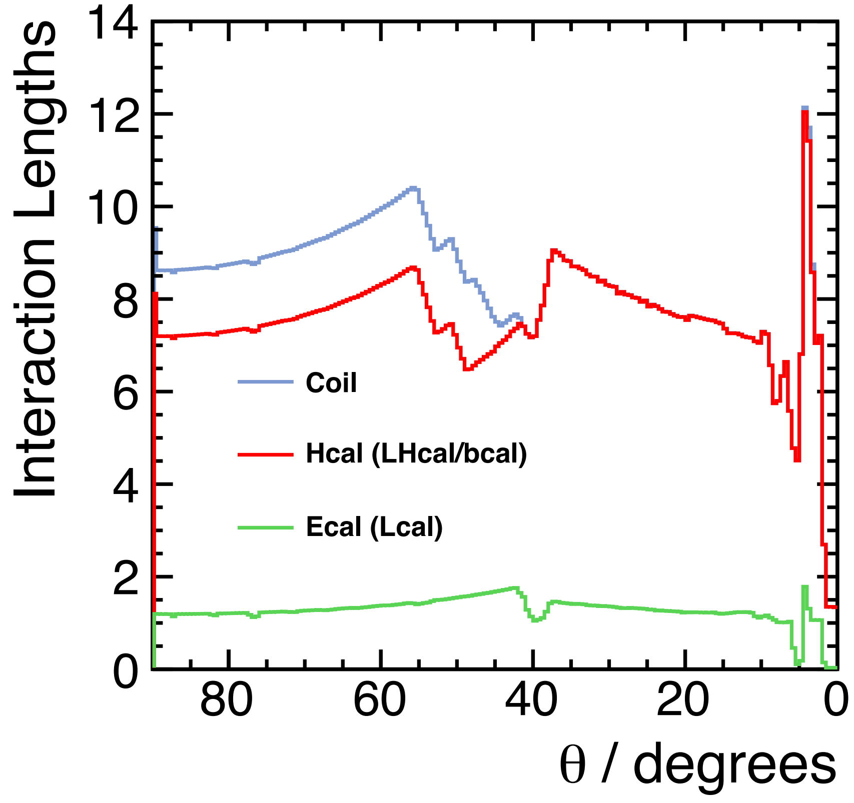
yoke & stray field

…

ILD & SiD - Material budget

ILD





SiD