Journées Collisionneur Linéaire

13 et 14 mai 2013 à l'IPN de Lyon

# Linear Collider Detectors

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***Journées Collisionneur Linéaire, Lyon, May 2013***

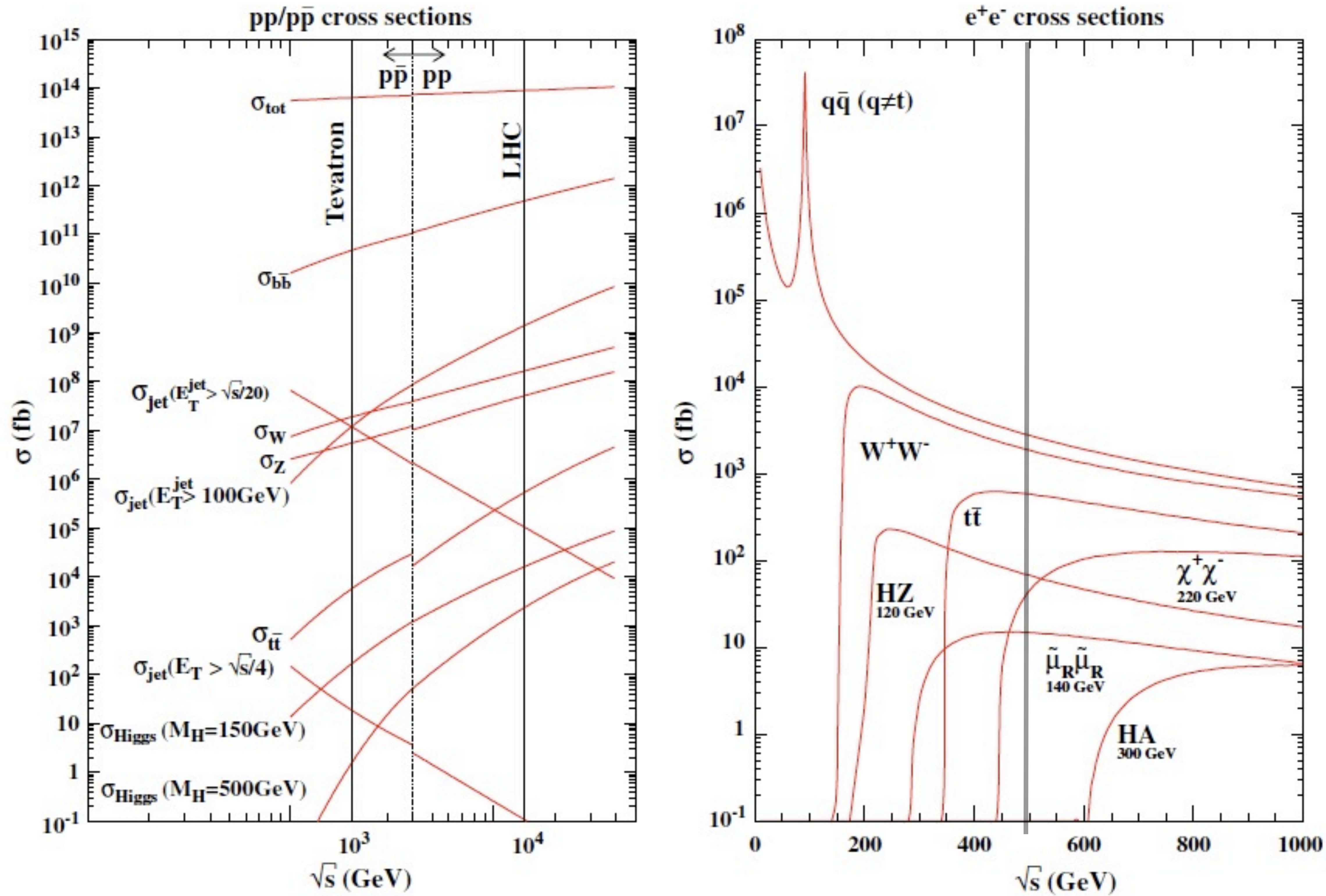
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

# Outline

- We have fantastic detectors at the LHC - Why come up with something different?
- Physics motivating detector requirements
- The building plan for a generic Linear Collider detector
- A closer look at ILD

# The Basis: The Physics - LHC vs LC

*G. Weiglein et al. / Physics Reports 426 (2006) 47–358*



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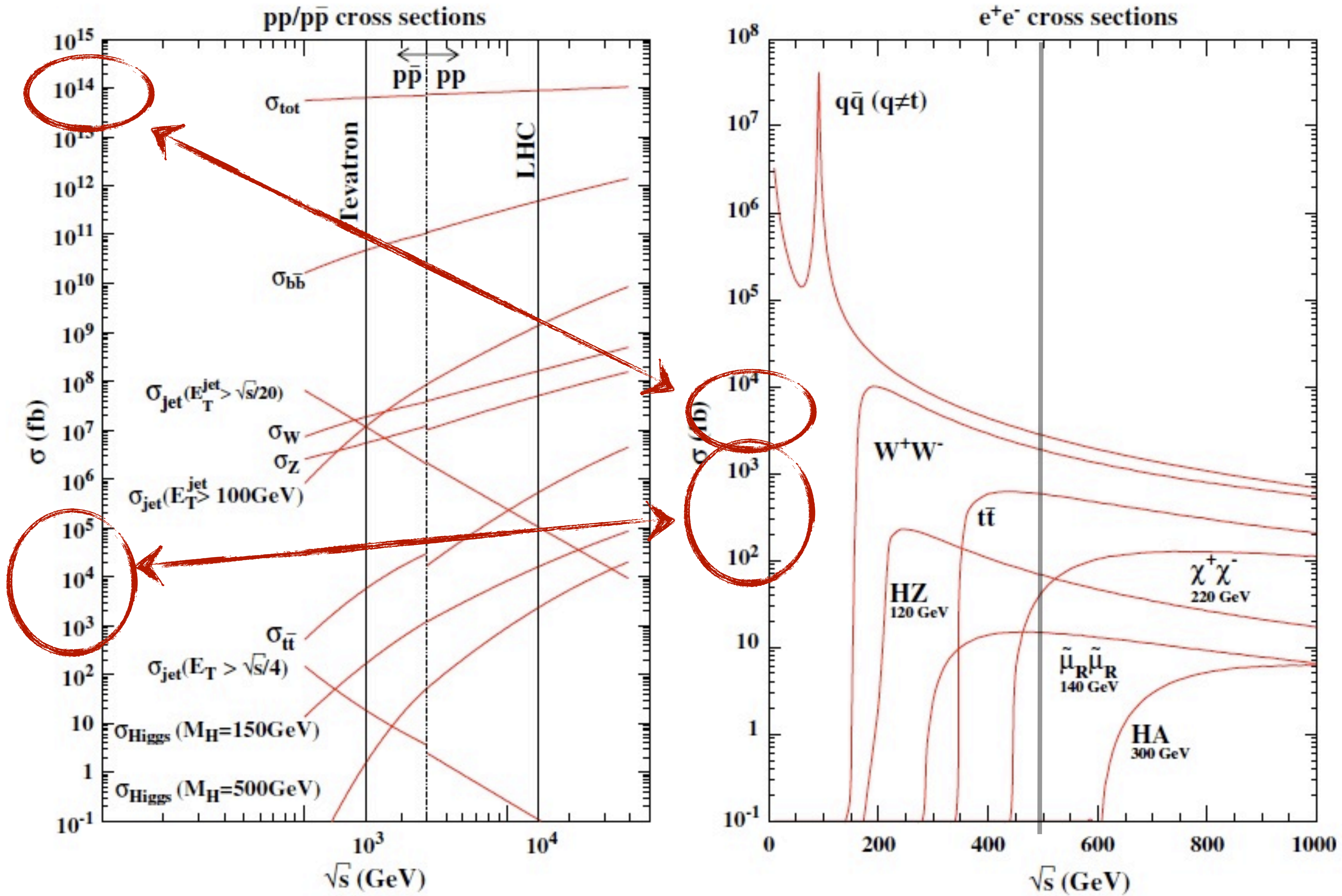


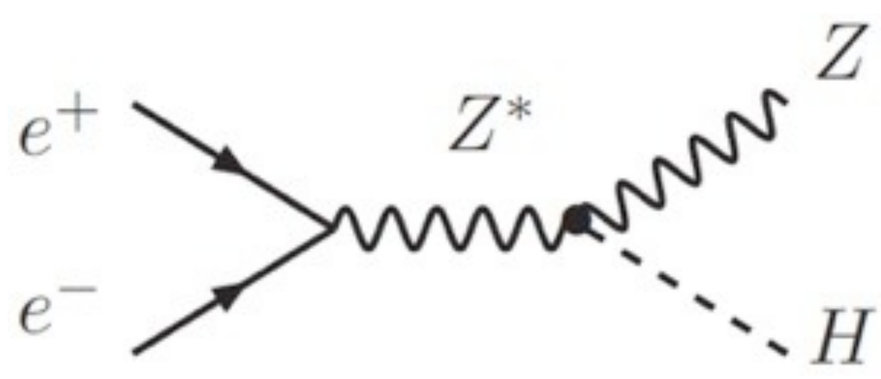
# The Basis: The Physics - LHC vs LC

- Very different environments ➫ Different detector requirements!
- At the LHC: Triggering is key - Digging out rare signals among overwhelming background -> Focus on easy to identify signatures - Leptons, photons
- At the LC: No triggering required, but cross sections are low: Can not afford to loose events by ignoring high-BR hadronic decays

- The consequence for LC detector design:
  - Photon energy resolution not a main design goal
  - Jet energy resolution crucial

- Requirements for the technology
  - At the LHC: Radiation hardness mandatory, high speed continuous readout
  - At ILC: Radiation hardness is unproblematic in most regions, bunch trains allow power-pulsing

# Physics Driving Detector Requirements - Higgs




- At energies below ~ 400 GeV (first LC stage): Higgsstrahlung the dominating production process
- The goals
  - model-independent measurement of $g_{HZZ}$
  - measurement of various BRs

What the detectors have to deliver:

- Excellent momentum reconstruction: Recoil mass measurement in Z -> μμ, ee
- Precise flavor tagging: Separation of b, c and light-flavor jets from H decay

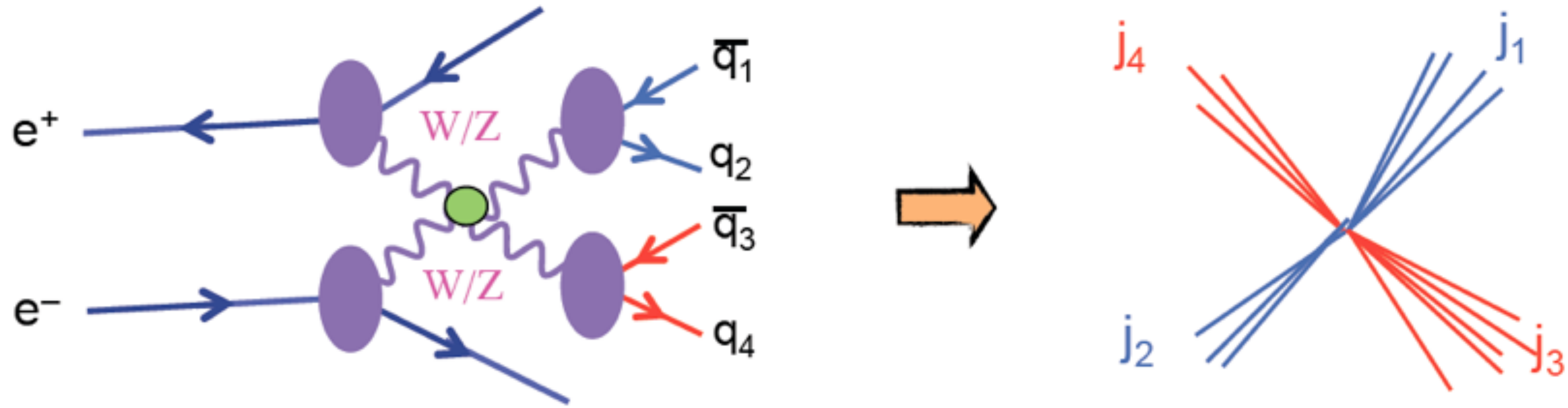
What the detectors do not have to deliver:

- Photon resolution
  - Only ~ 100 H->γγ events - No need to optimize for that
  - H can be cleanly reconstructed without looking at the Higgs decay itself

# Physics Driving Detector Requirements - BSM

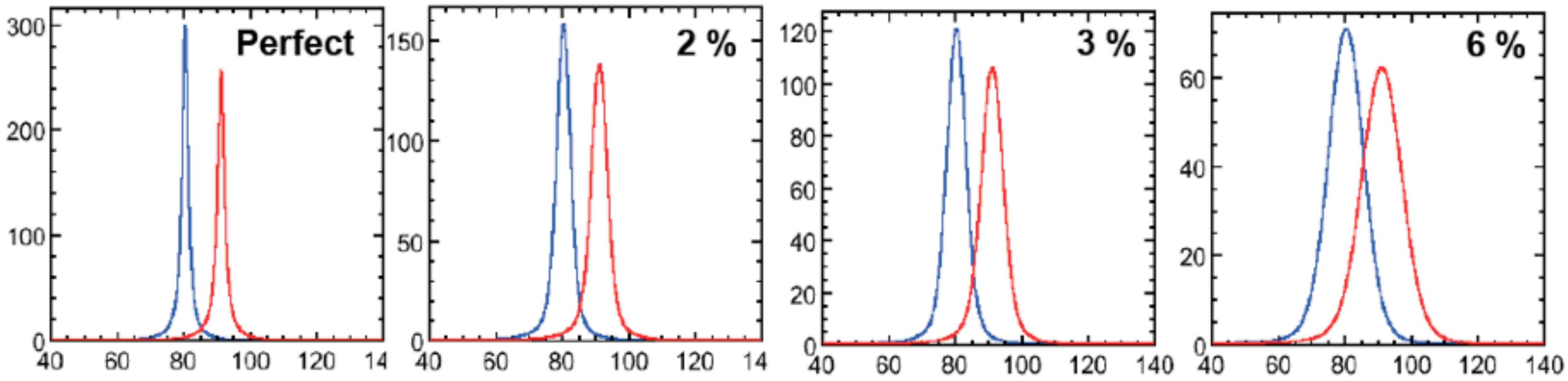
- We don't know what this new physics will be - But we can make guesses!
- LHC exclusions are often already beyond ILC reach - in the strong sector
- Expect ILC direct measurements predominantly in the electroweak sector
  - Typical final states will include SM gauge bosons - Need to separate W and Z
  - Overall low cross-sections - can not afford to ignore hadronic final states
  - Expect missing energy - Mass reconstruction has to be excellent without kinematic constraints

The classic example: WW / ZZ scattering (the same applies to Chargino / Neutralino production, ...)



# Putting 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): $\Delta E_{Jet}/E_{Jet}$ ~ 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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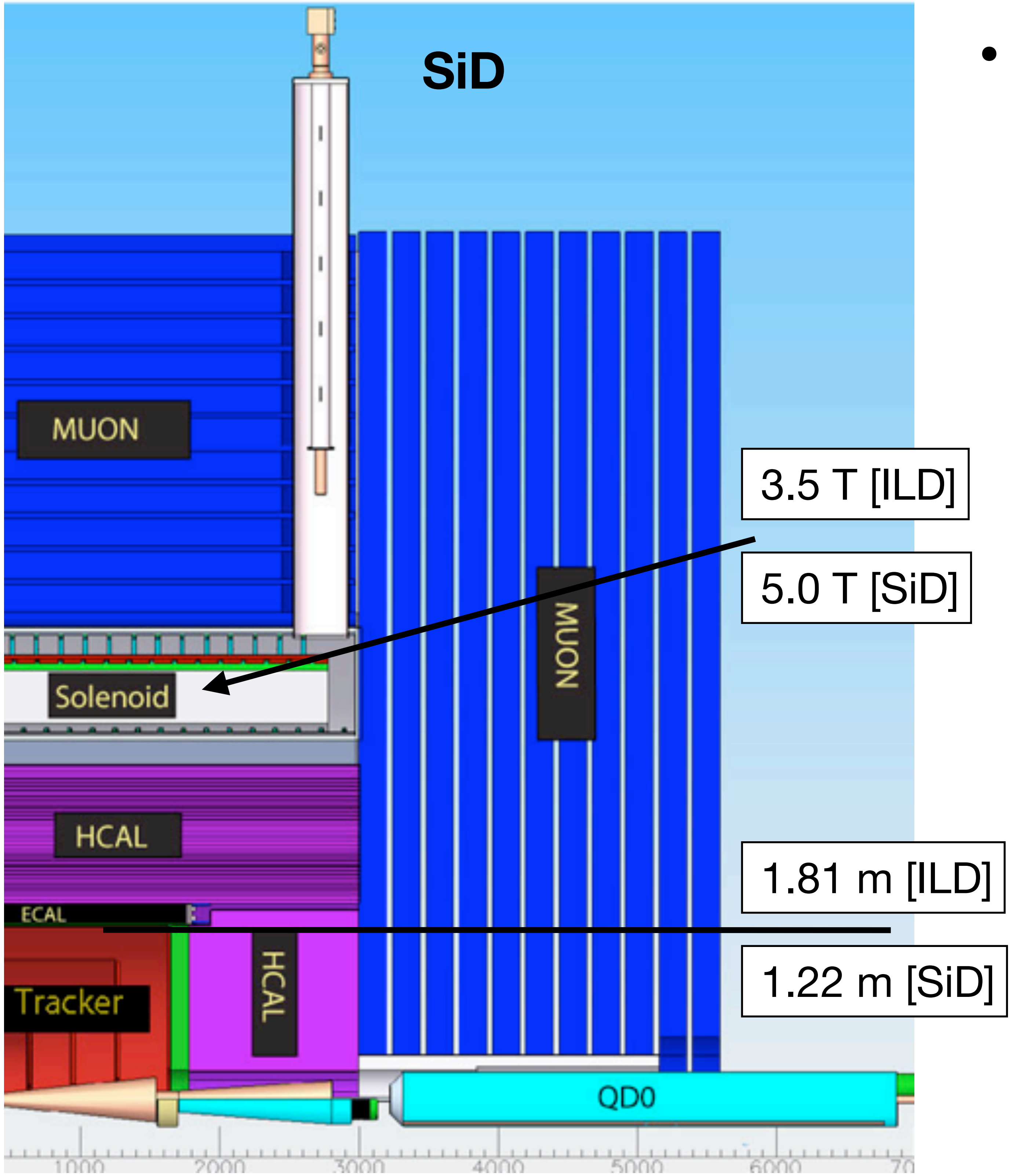
**Where this leads you: A detector design a bit like CMS, but**

- Shorter detector barrel: Only small boosts of CMS system in ILC collisions
- Very different calorimeters: No emphasis on photon resolution, granularity instead - and don't ignore the HCAL
- Much reduced material budget
  - Reduced need for cooling: Power-pulsing possible
  - Time for readout between bunch trains - No need for hybrid pixel sensors
  - Technological advances - Thinner silicon, low-power electronics, light-weight mechanics,...

# Two Slightly Different Approaches - SiD & ILD




- 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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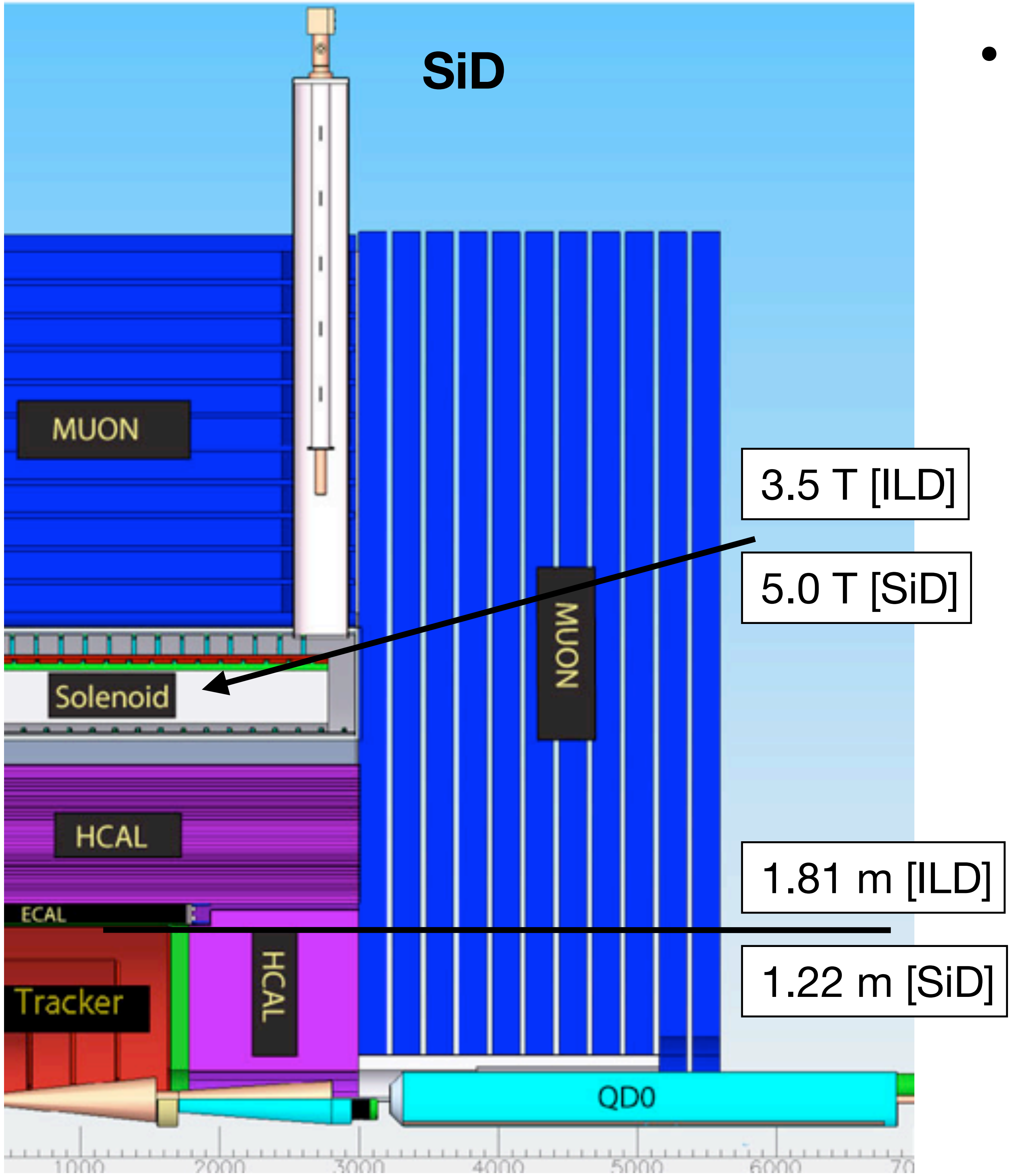


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N.B. : Solenoid cost (and technical feasibility) steeply scales with field and radius => Either large radius or high field!

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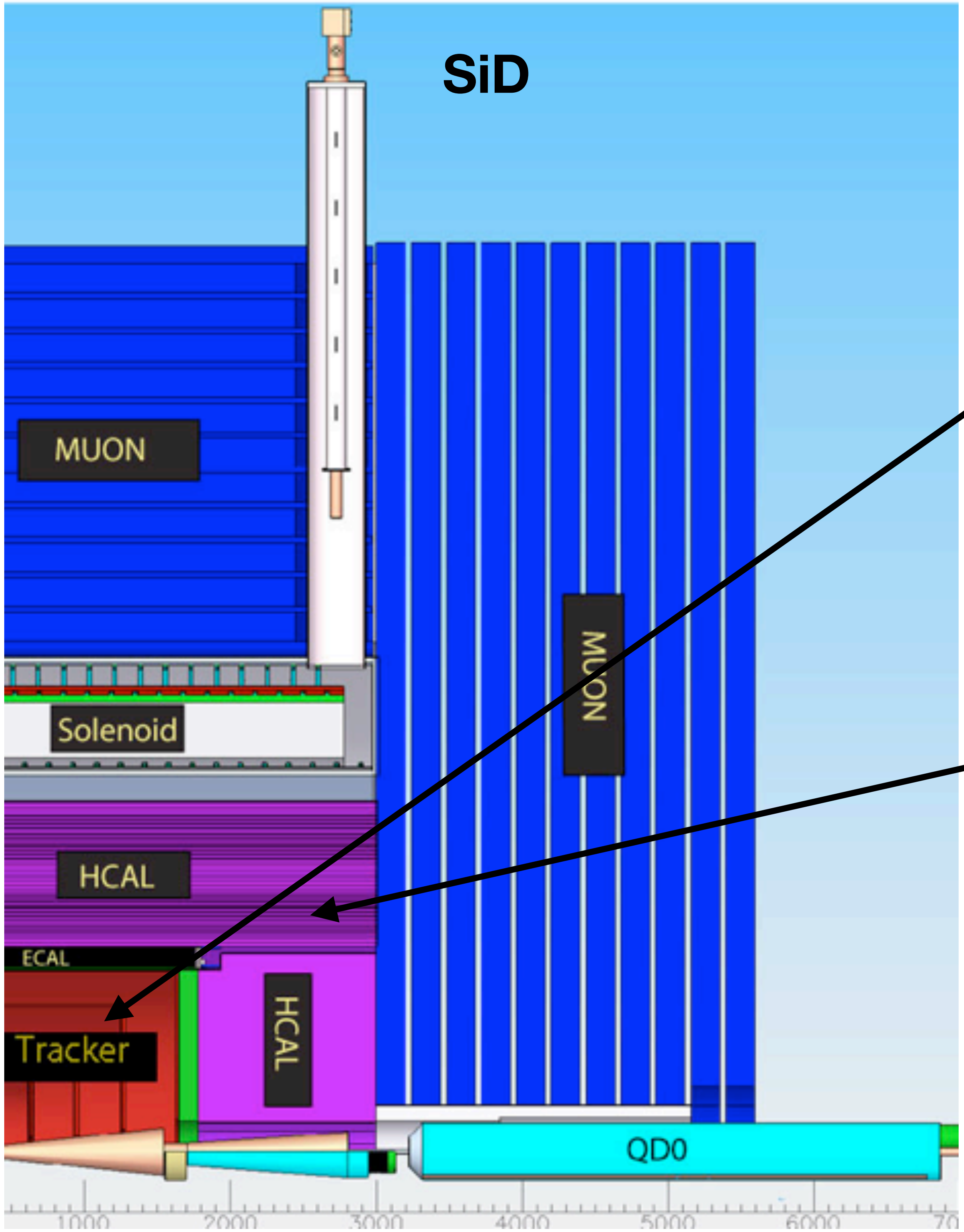


- Different choices in tracker technology: Trade number of measurements and precision of individual measurements
  - Five-layer all-Si tracker in SiD
  - TPC with > 200 space points on a track in ILD (NB: To reach resolution goal, an additional Si layer outside of the TPC is needed!)
- Trading cost vs.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

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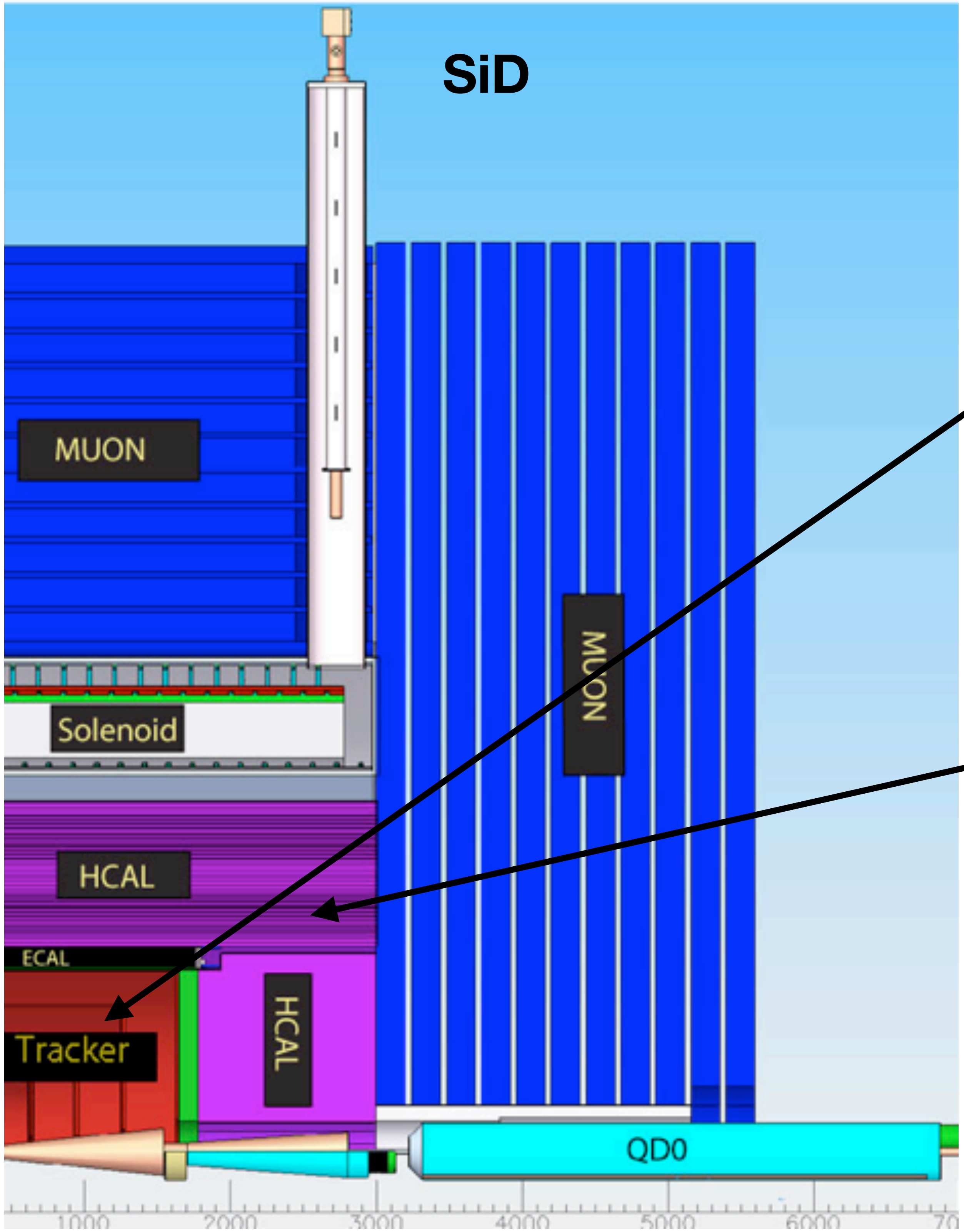


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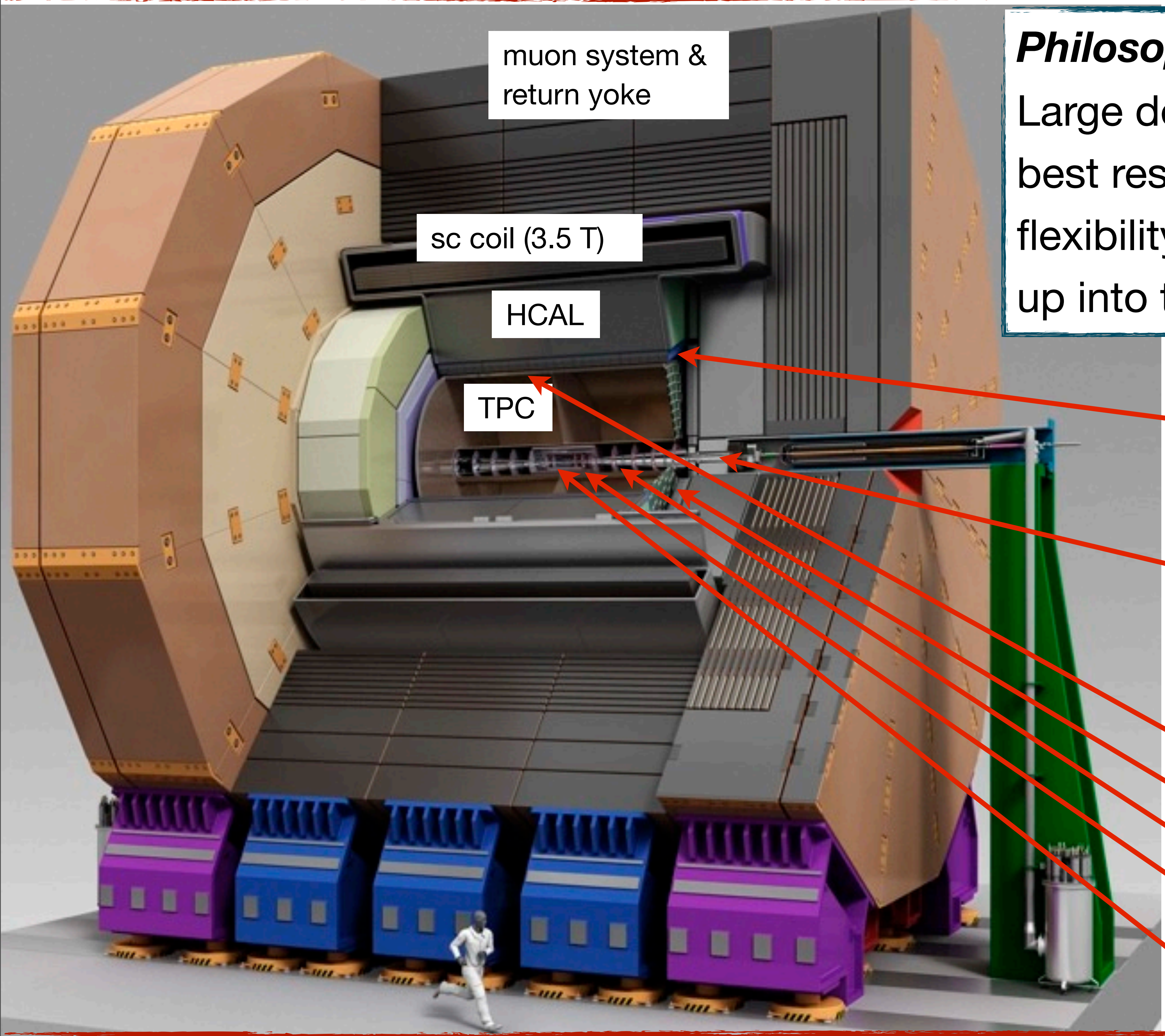
In general: How much cost is emphasized drives the choice between small and large detector: ECAL radius as main cost driver, but larger detector favorable for PFA

# A Closer Look at ILD

# ILD - The Overview




***Philosophy:***
Large detector optimized for best resolution, providing flexibility for higher energies up into the TeV range

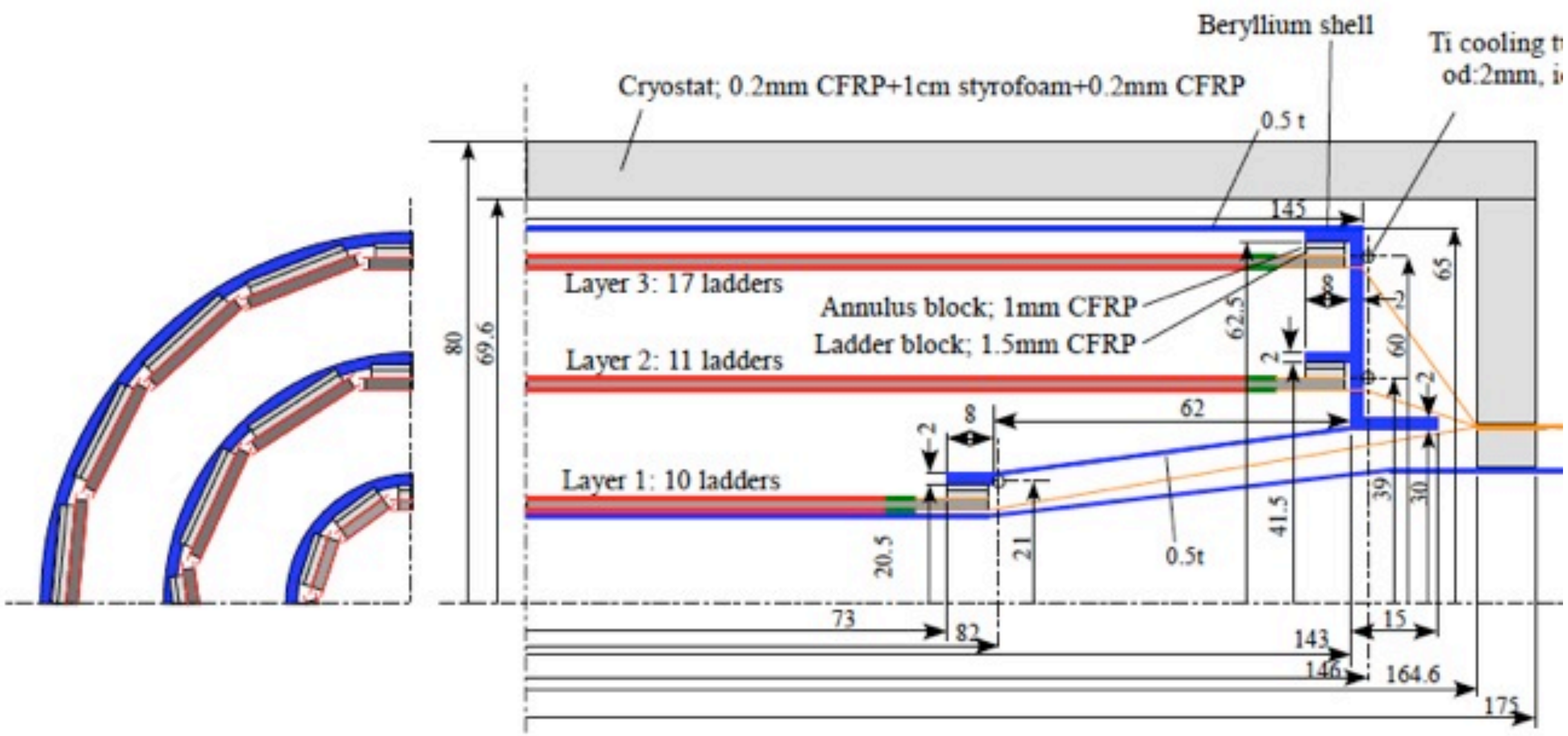
ECAL

*forward calorimeters*
LumiCAL
BeamCAL, LHCAL

*silicon tracking*
**S**ilicon **E**xternal **T**racker
**E**ndplate **T**racking **D**etector
**F**orward **T**racking **D**isks
**S**ilicon **I**nner **T**racker

**V**er**T**e**X** Detector

# The Vertex Detector

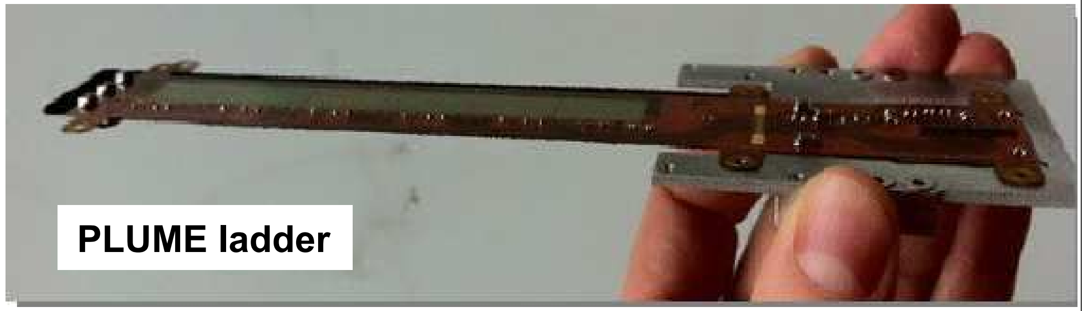



- Requirements:
  - Spatial resolution < 3 µm close to IP
  - Material budget < 0.15% $X_0$ per layer
  - low power consumption!
  - Pixel occupancy not exceeding a few %

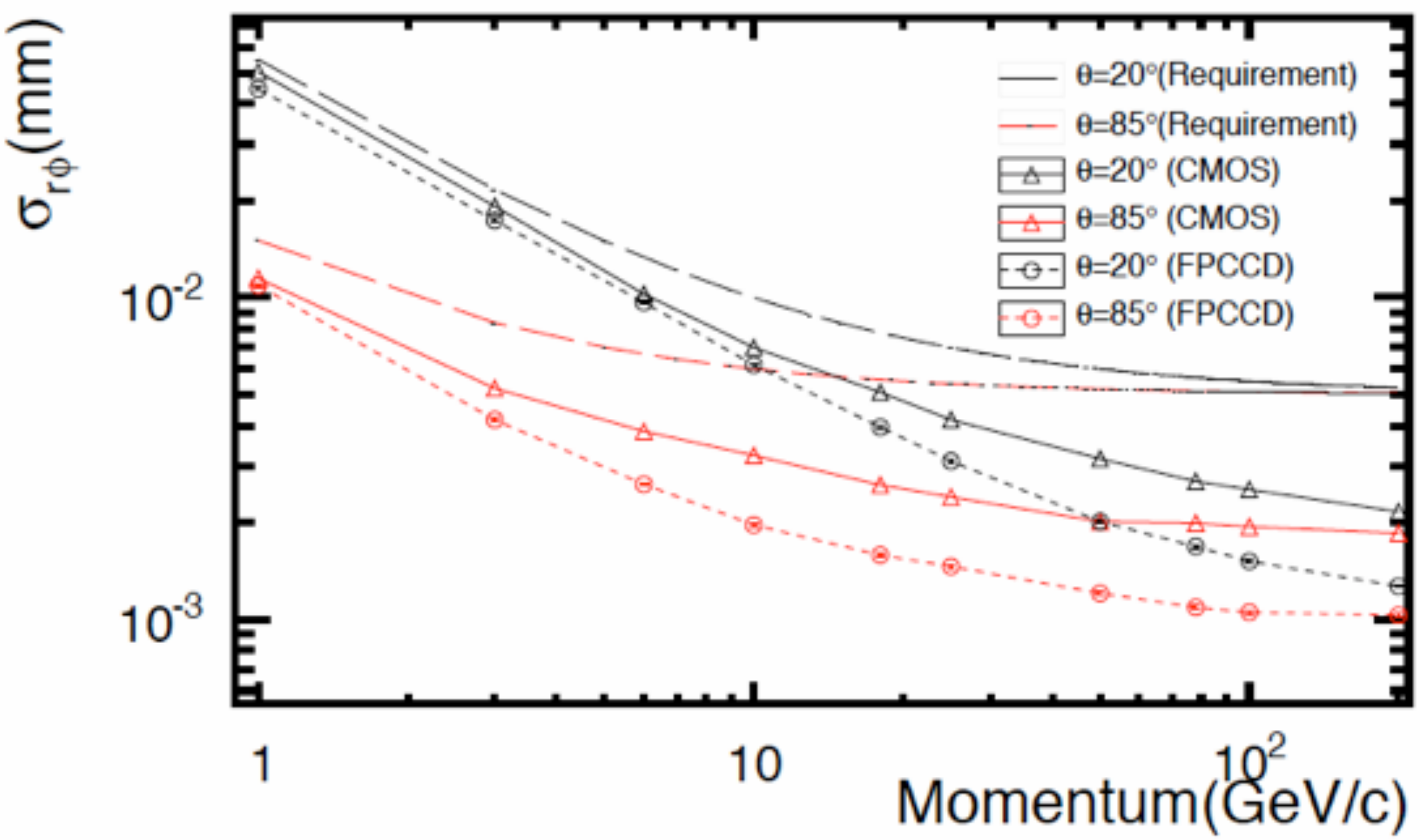
- VTX design:
  - 3 (almost) cylindrical layer pairs from 16 mm to 60 mm
    - Alternative: 5 single layers, from 15 mm to 60 mm
  - Several technologies under study: CMOS Pixel Sensors, Fine Pixel CCDs, DEPFET, use of multiple technologies an option
  - Time stamping depends on technology - can be used to trade pixel size vs readout speed

# Vertex Detector Technologies

- Active development of several technologies, synergies with LHC & others
  - All provide low material budget by thin sensitive layers
  - Trade-off between readout speed and pixel size (no time stamping)
- CMOS pixel sensors
  - ~ 17µm pixel precision layers, 17 x 85 $\mu m^2$ pixel fast layers to reduce effective occupancy
  - Low material double layer “PLUME” demonstrated



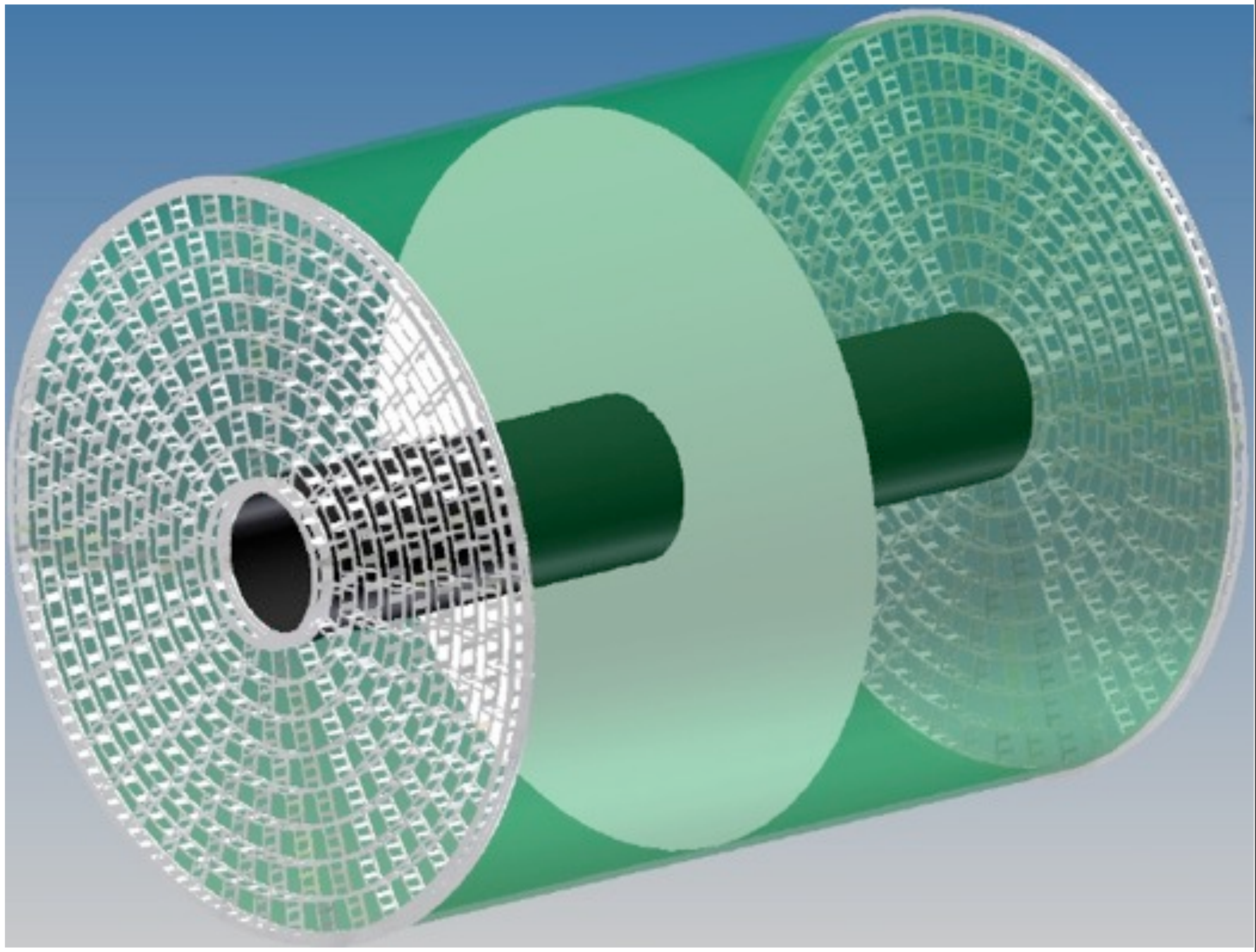

- FinePitch CCDs
  - ~ 5 µm pixels in inner layers, ~10 µm pixels further out
- DEPFETs
  - ~ 20 µm pixels, all-silicon modules with integrated support structure



# The Main Tracker: TPC

- Main tracker philosophy:
  Continuous tracking for excellent pattern recognition and dE/dx capability instead of best possible single point resolution
- The ILD TPC
  - Up to 224 space-points per track
  - Single point resolution < 100 μm in rϕ
  - Two-hit separation ~ 2 mm in rϕ
  - Low material budget: 5% $X_0$ in barrel region, <~ 25% $X_0$ in the endcaps
  - Standalone momentum resolution

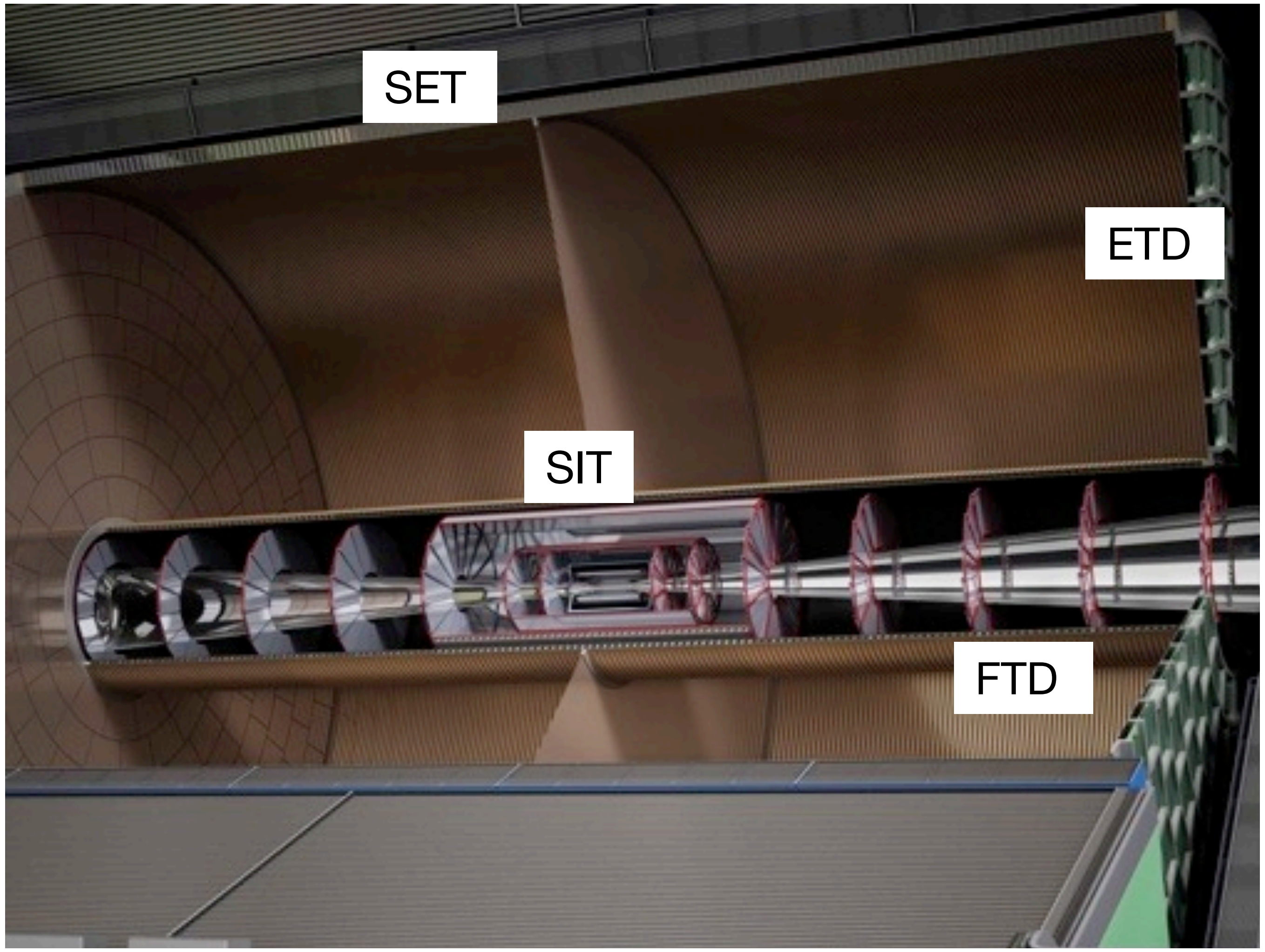
$$\delta(1/p_T) \simeq 10^{-4}/\mathrm{GeV}/c$$



Two main readout options:
GEMs, Micromegas
Alternative: pixel detectors

➯ Needs additional silicon tracking inside and outside to meet requirements!

# The Silicon Trackers




- Silicon tracking to complement the TPC main tracker:
  - Improved resolution
  - Time-stamping
  - Calibration of distortions & alignment
  - Extended coverage in the forward region
- Combined tracker resolution:

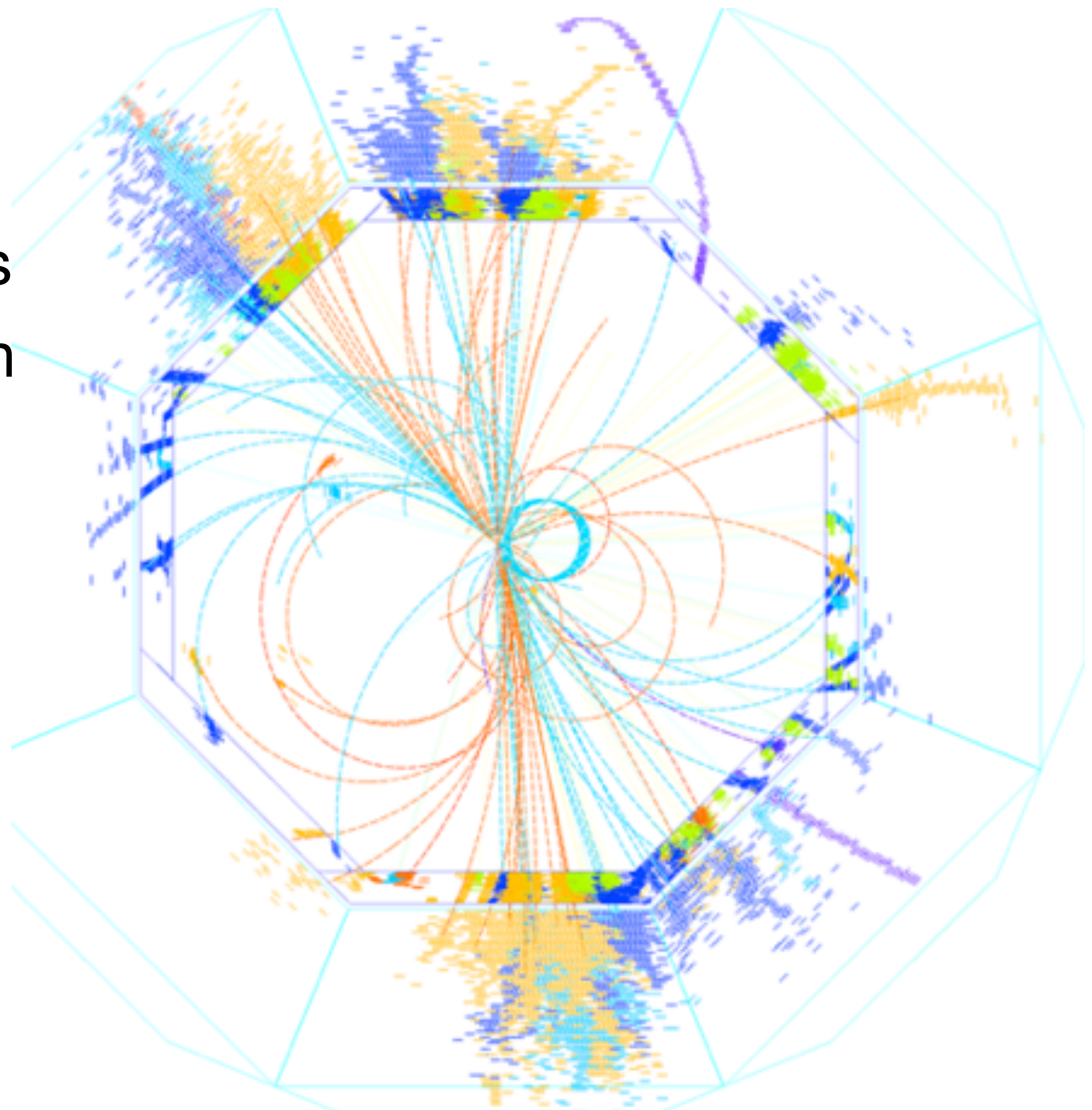
$$\delta(1/p_T) \simeq 2 \times 10^{-5}/\mathrm{GeV}/c$$

- Inner tracking barrel SIT - 2 fake double-sided strip layers, 2 space points
- Outer tracking barrel SET - 1 fake double sided strip layer, 1 space point
- Outer forward tracking layer ETD - 1 fake double sided strip layer, 1 space point
- Inner forward tracker FTD - 7 disks (2 pixel, 5 strip)

‣ Common technology & design for all strip sensors in the silicon trackers

# The Calorimeters

- The calorimeters are the key systems to make PFAs work - One of the radically new aspects of LC detectors, 2 - 4 orders of magnitude more readout channels than previous systems
- They need:
  - High granularity in 3D
  - Small Molière radius in ECAL for good particle separation & photon identification
  - Sufficient depth of the HCAL to limit leakage also at 1 TeV
  - Compact design to fit inside solenoid



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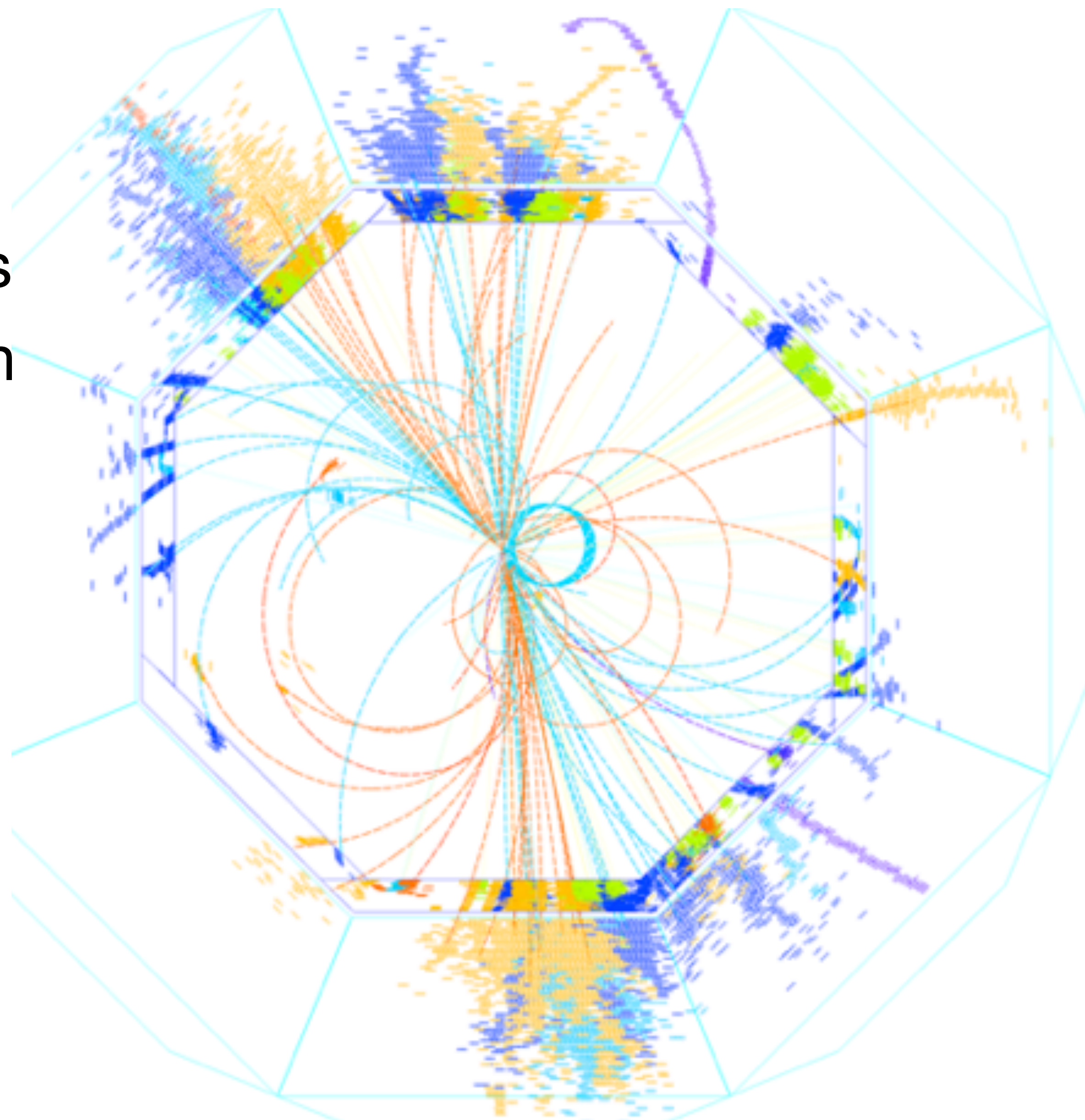

For best PFA performance: Granularity and shower compactness in general more important than resolution, in particular in the ECAL

# The Electromagnetic Calorimeter

- Tungsten absorber - Two longitudinal segments with different thickness to provide highest 3D granularity where it counts while keeping overall thickness and sensor area reasonable
- Two readout technologies
  - Silicon PIN sensors, 5.5 x 5.5 $mm^2$ pads, 325 μm sensor thickness
  - Scintillator strips with SiPMs, 5 x 45 x 1 $mm^3$ (strip-splitting algorithm to recover virtual 5 x 5 $mm^2$ granularity)

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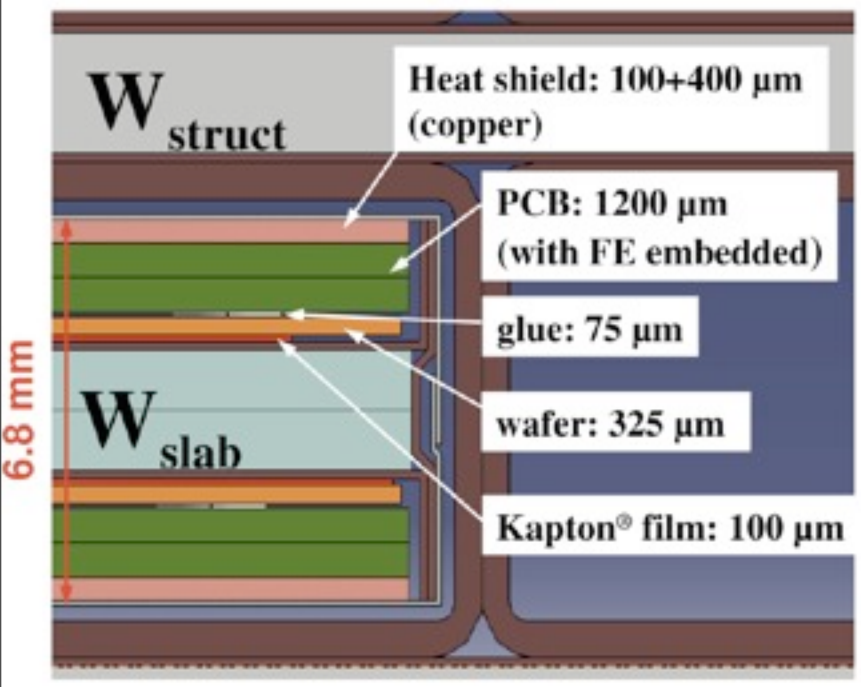


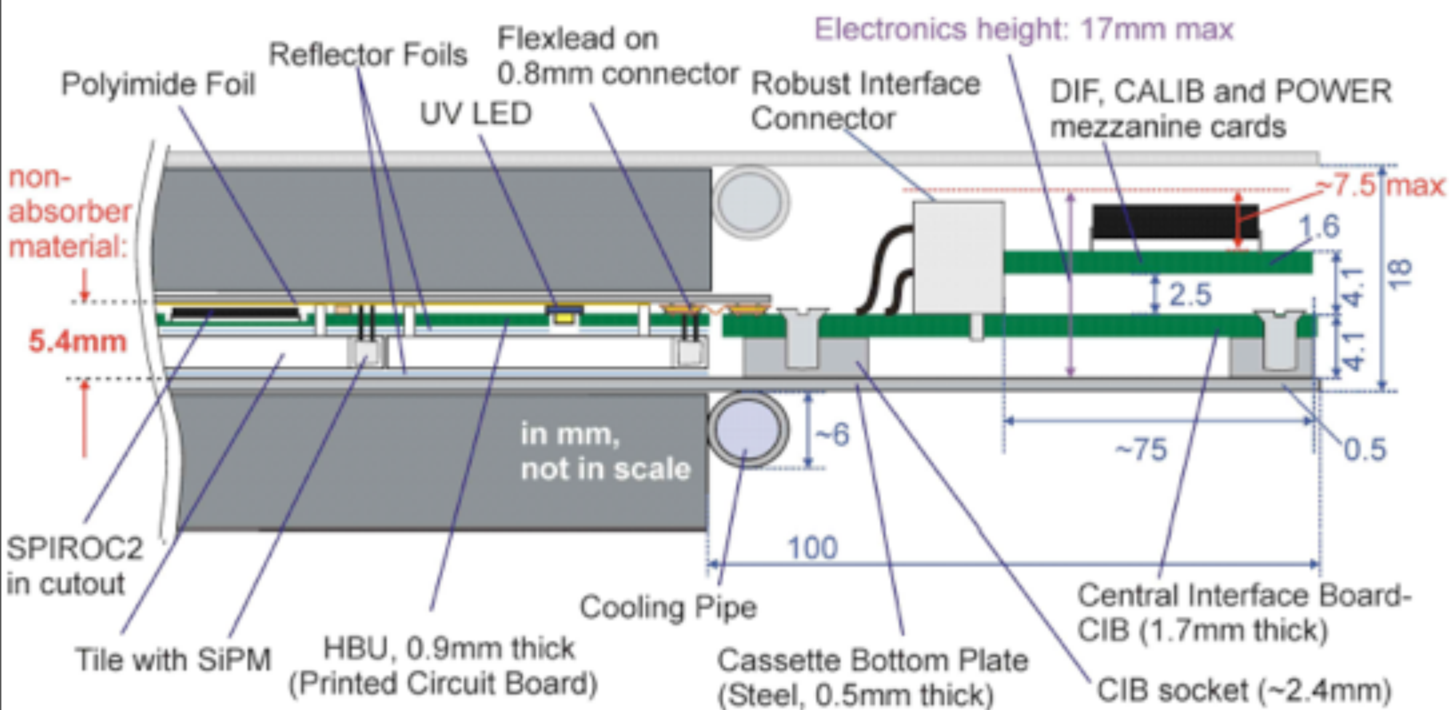

Thicker (and less dense) active detectors lead to reduced compactness of calorimeter and wider showers in scintillator vs silicon

Single particle energy resolution ~ 15% better with scintillator

➩ Impact on PFA being evaluated, so far Silicon outperforms scintillator - Possible hybrid solutions to combine the benefits of both technologies are also being studied

# The Hadronic Calorimeter

- Steel absorber structure - 2 cm per layer, ~ 48 layers (different geometries for absorber possible)
- Two readout technologies
  - Analog - 3 x 3 $cm^2$ scintillator tiles with SiPM readout
  - Semi-Digital - RPCs (μMegas) with 1 x 1 $cm^2$ pads and two-bit readout




- Both highly compact: ~ 6 mm non-absorber material per layer
- Scintillator provides better energy resolution (but analysis also much more advanced)
- Semi-digital concept proven: Substantial improvement of resolution and linearity at high energy

Performance of PFA under study - No striking difference on physics distributions seen, indicates comparable performance in relevant energy region

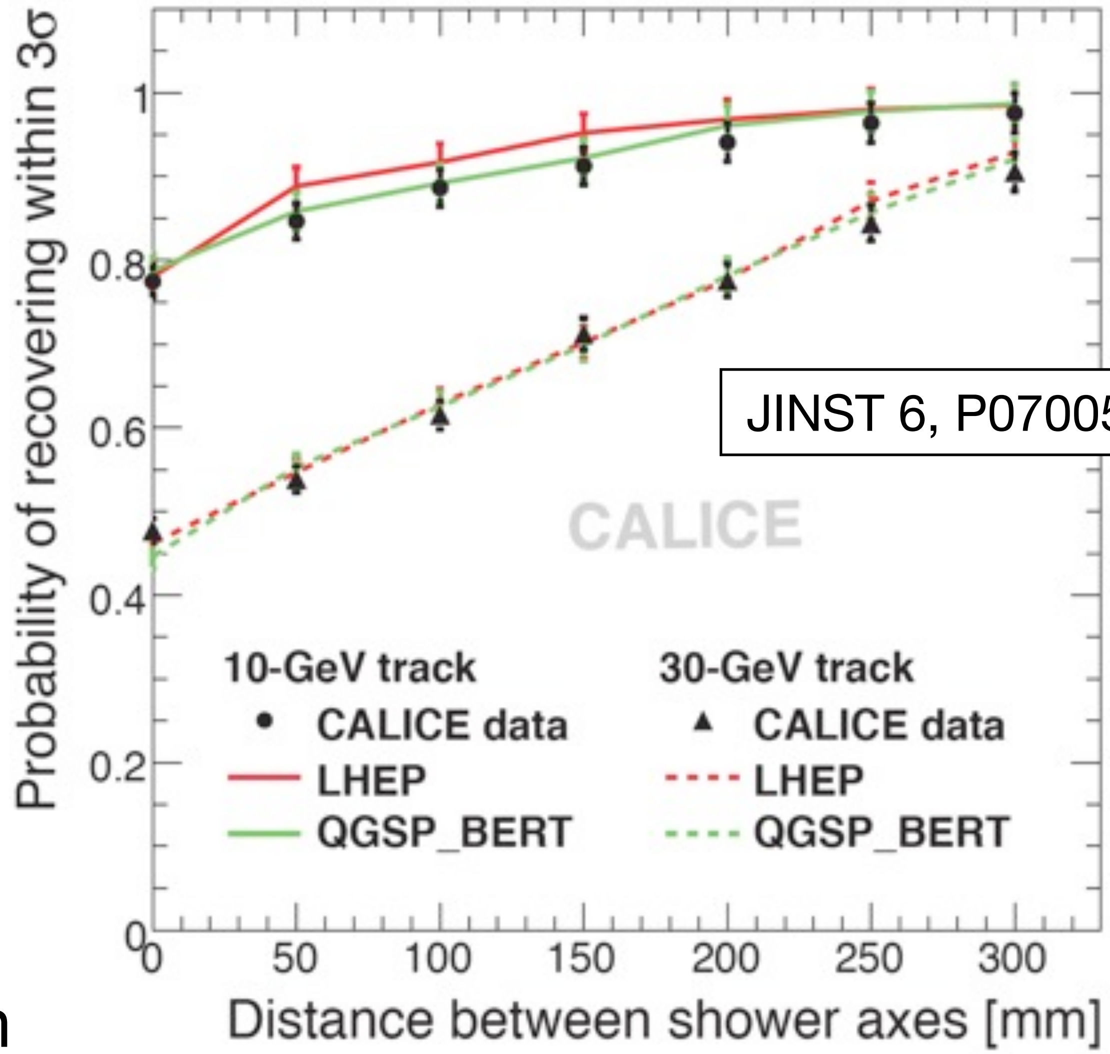
# Calorimeter R&D

- Calorimeter technology for ECAL & HCAL developed by CALICE:

  Combined test-beam experiments to demonstrate PFA calorimetry

One highlight:
Shower separation with PandoraPFA in the SiW-ECAL and AHCAL physics prototypes

- ‣ Good agreement with simulations demonstrates realism of ILD full detector simulations & physics studies

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- In addition: Results on energy resolution and other performance parameters for all technologies
- Technological prototypes either available or in construction

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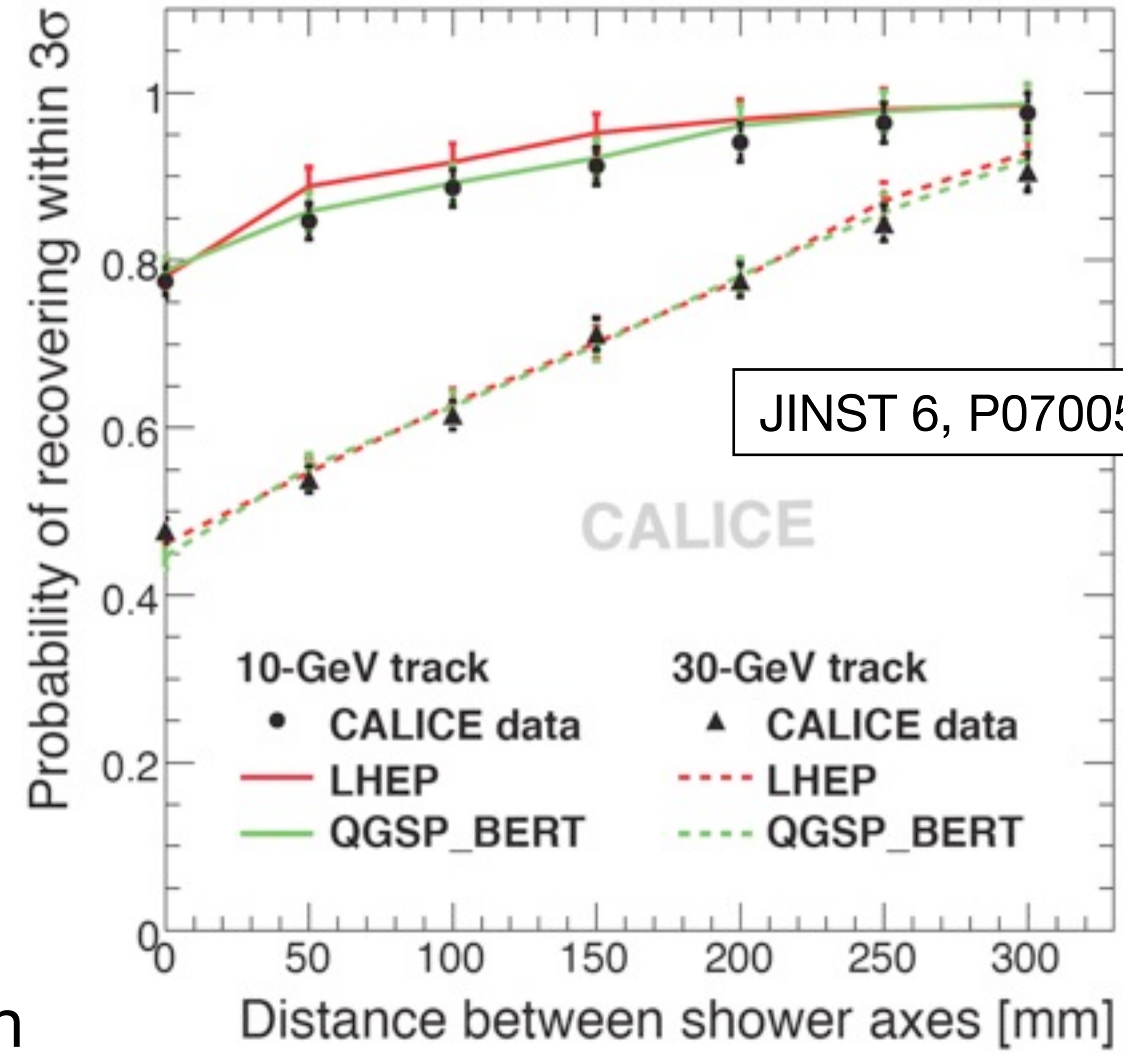


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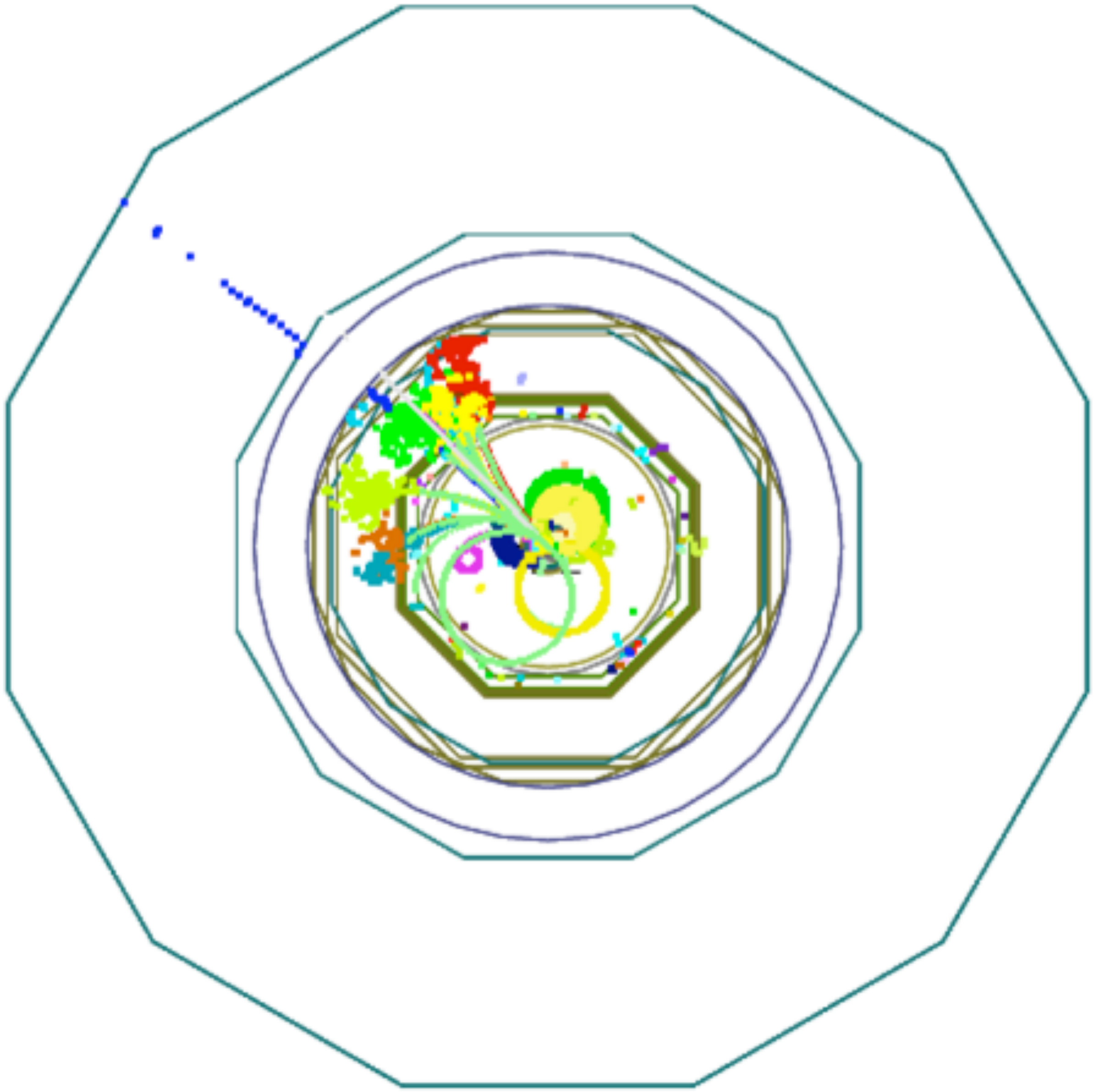
- In addition: Results on energy resolution and other performance parameters for all technologies
- Technological prototypes either available or in construction

➾ We know imaging calorimeters work and can be built!

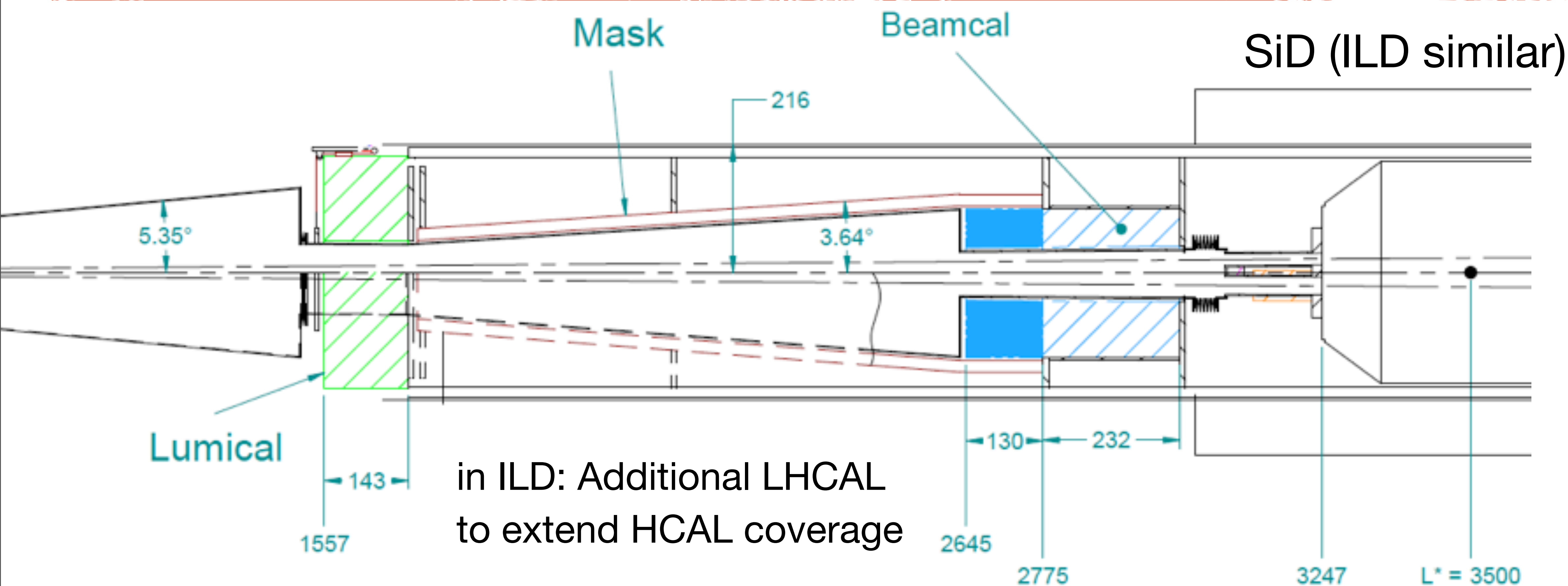
# Magnet, Muon System & Return Yoke

- 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



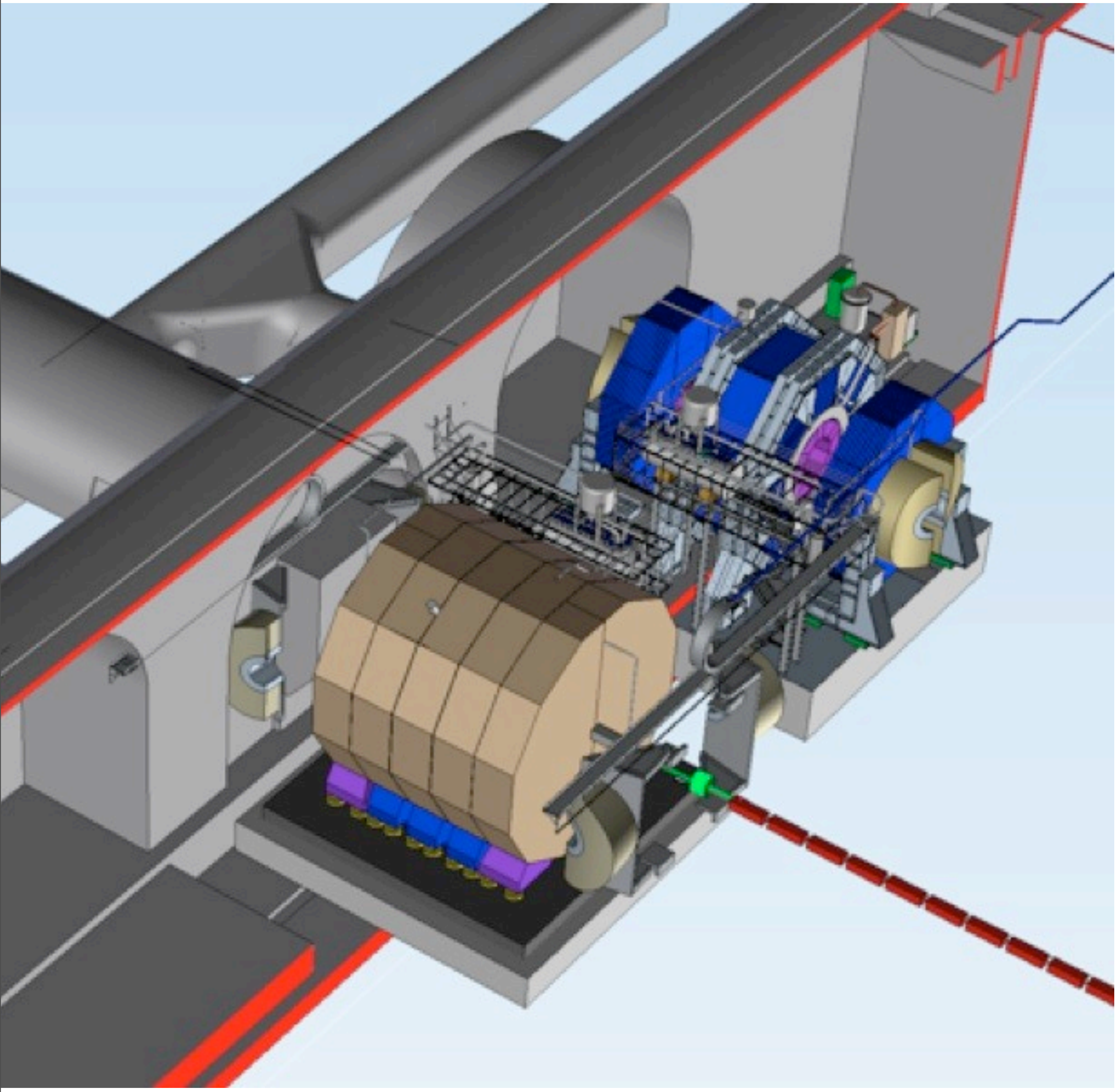
- The muon system: instrumented return yoke
  - Identification and tracking of muons
  - Tail catching for the calorimeter system

# Forward Instrumentation




- 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

# The Detectors in ILC



- Current concept: Two detectors share one interaction region - Exchange by push-pull on air-cushioned platforms
  - Requires well designed integration & services

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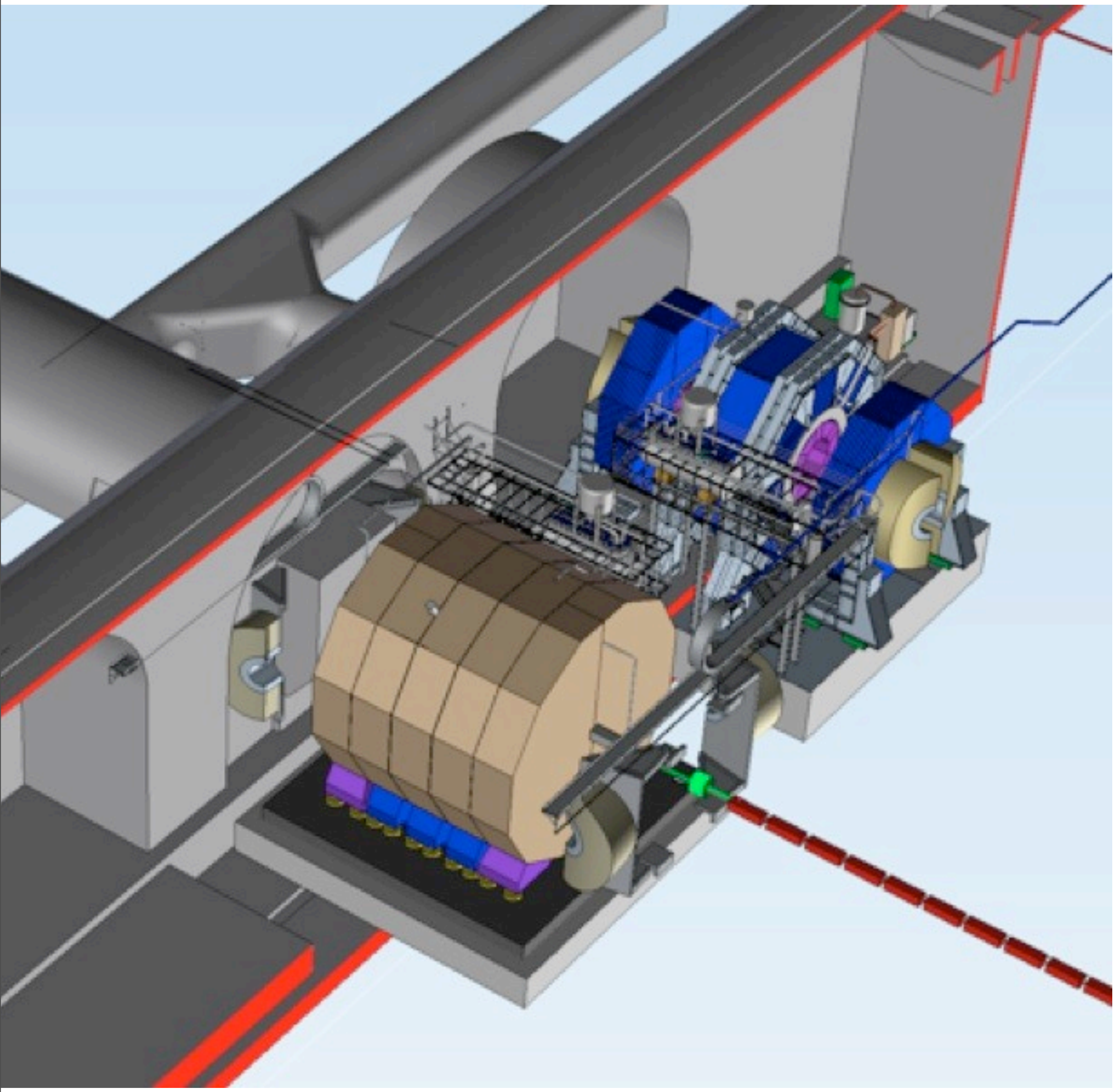
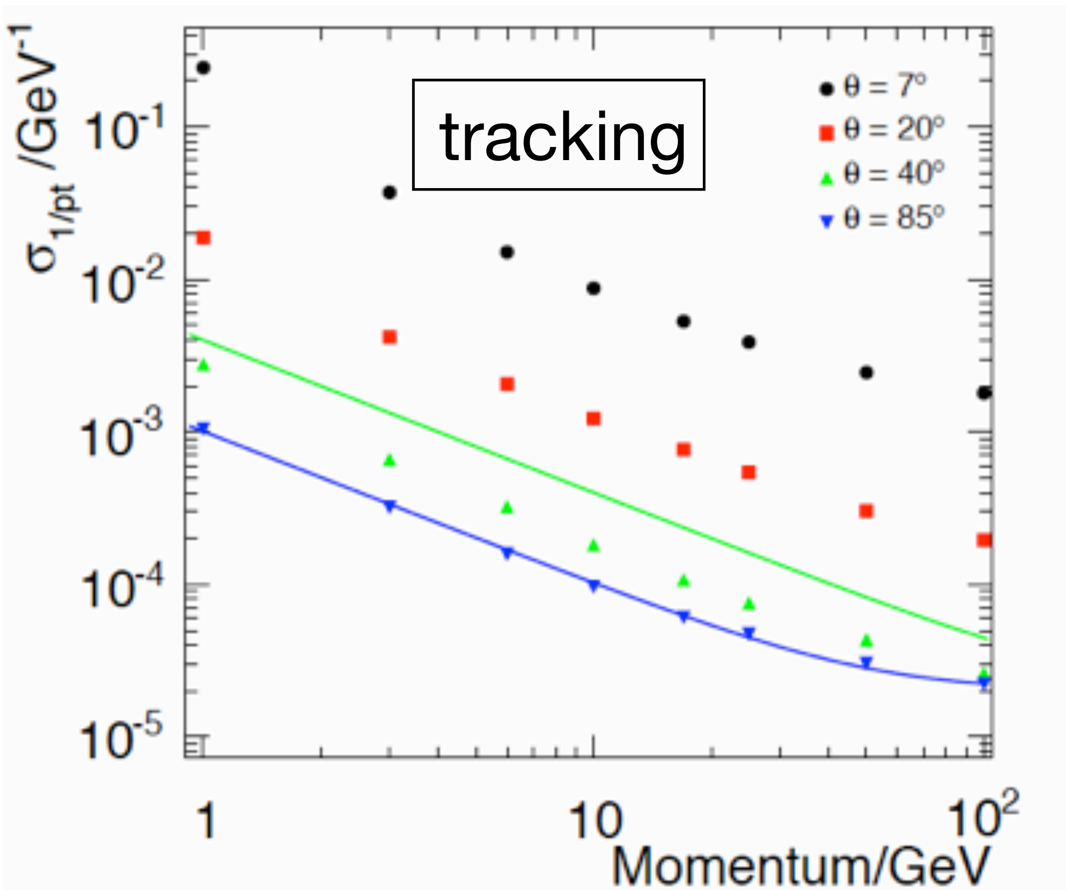
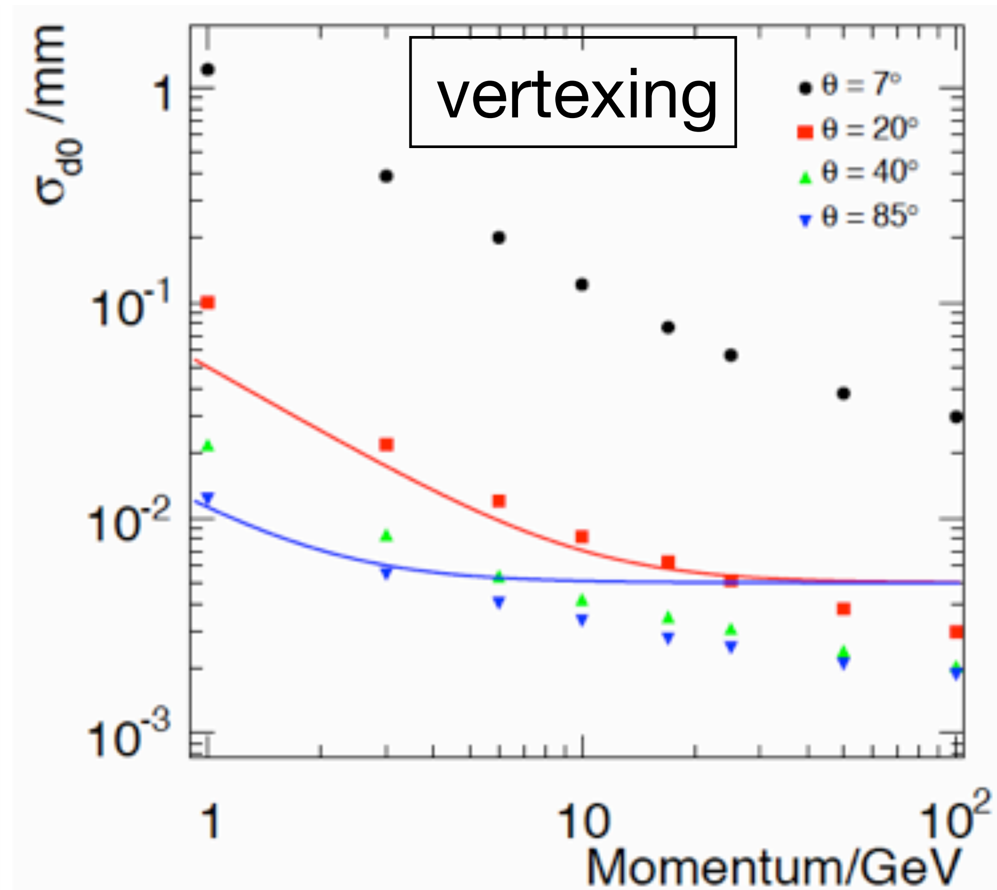


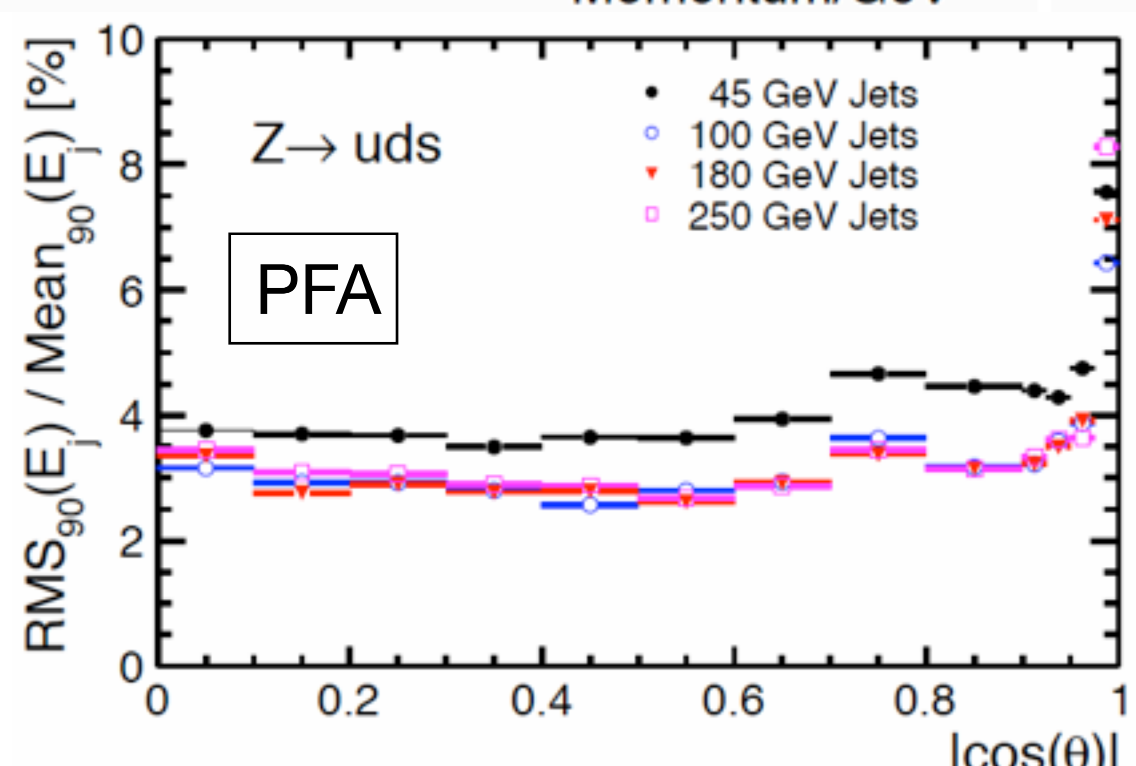
- Current concept: Two detectors share one interaction region - Exchange by push-pull on air-cushioned platforms
  - Requires well designed integration & services

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

# What You Get: ILD Performance

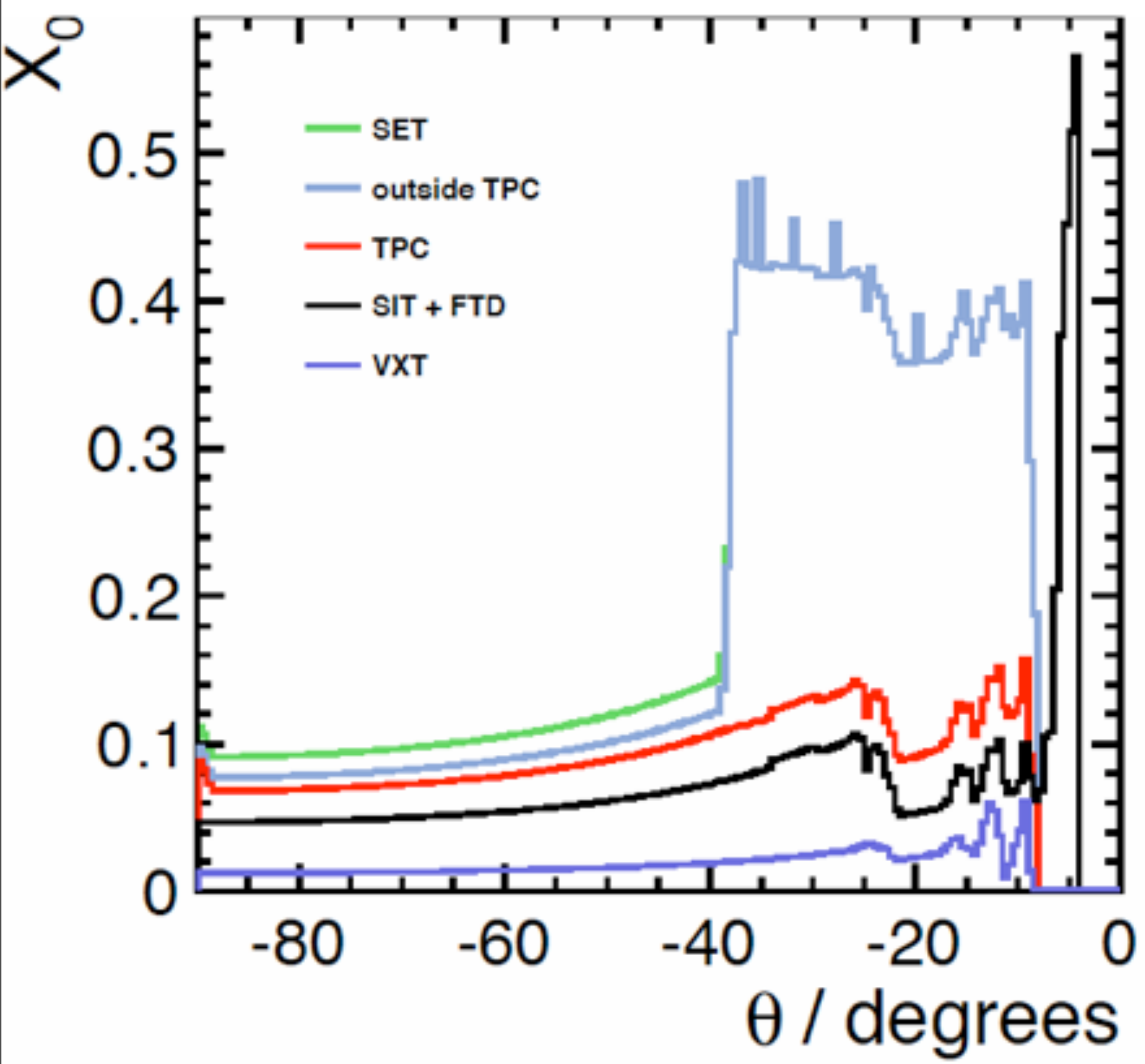



- The key performance requirements set out in the physics motivation for the detector design are met by ILD

# Real-World Challenges: The Material Budget




- Material budget - over the barrel range 10% - 15% $X_0$, in the endcap region ~40% $X_0$: TPC field cage

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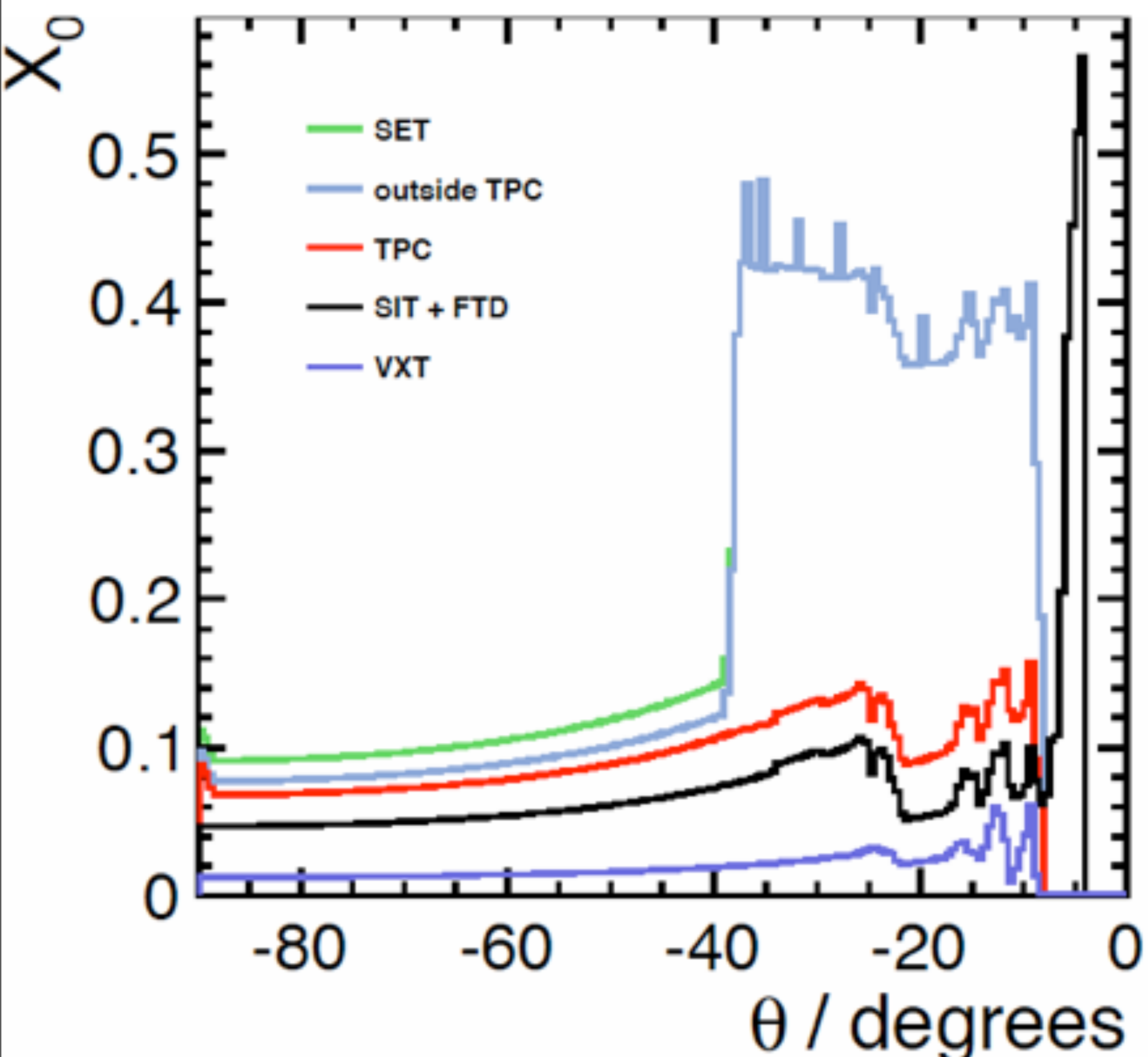


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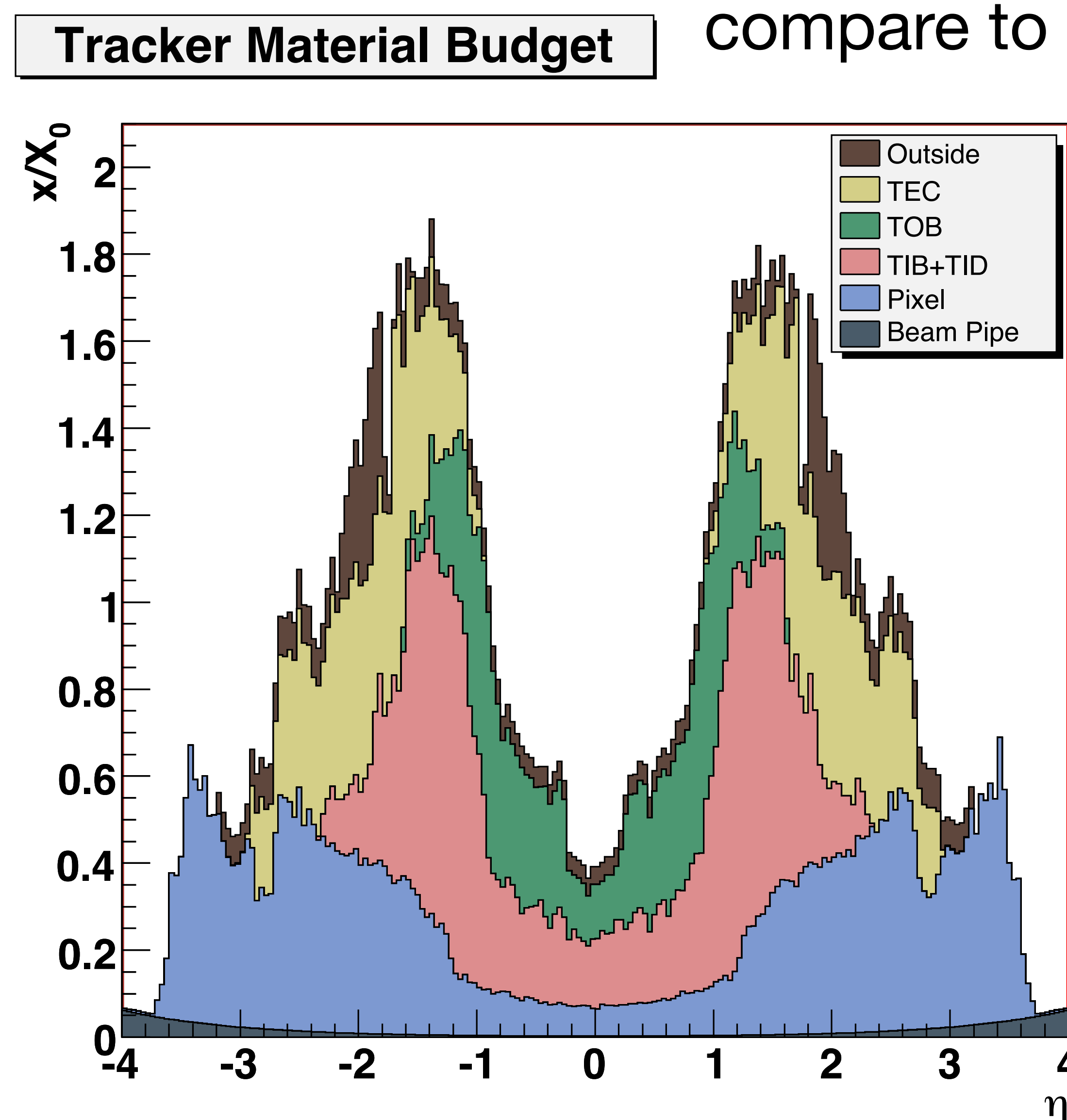
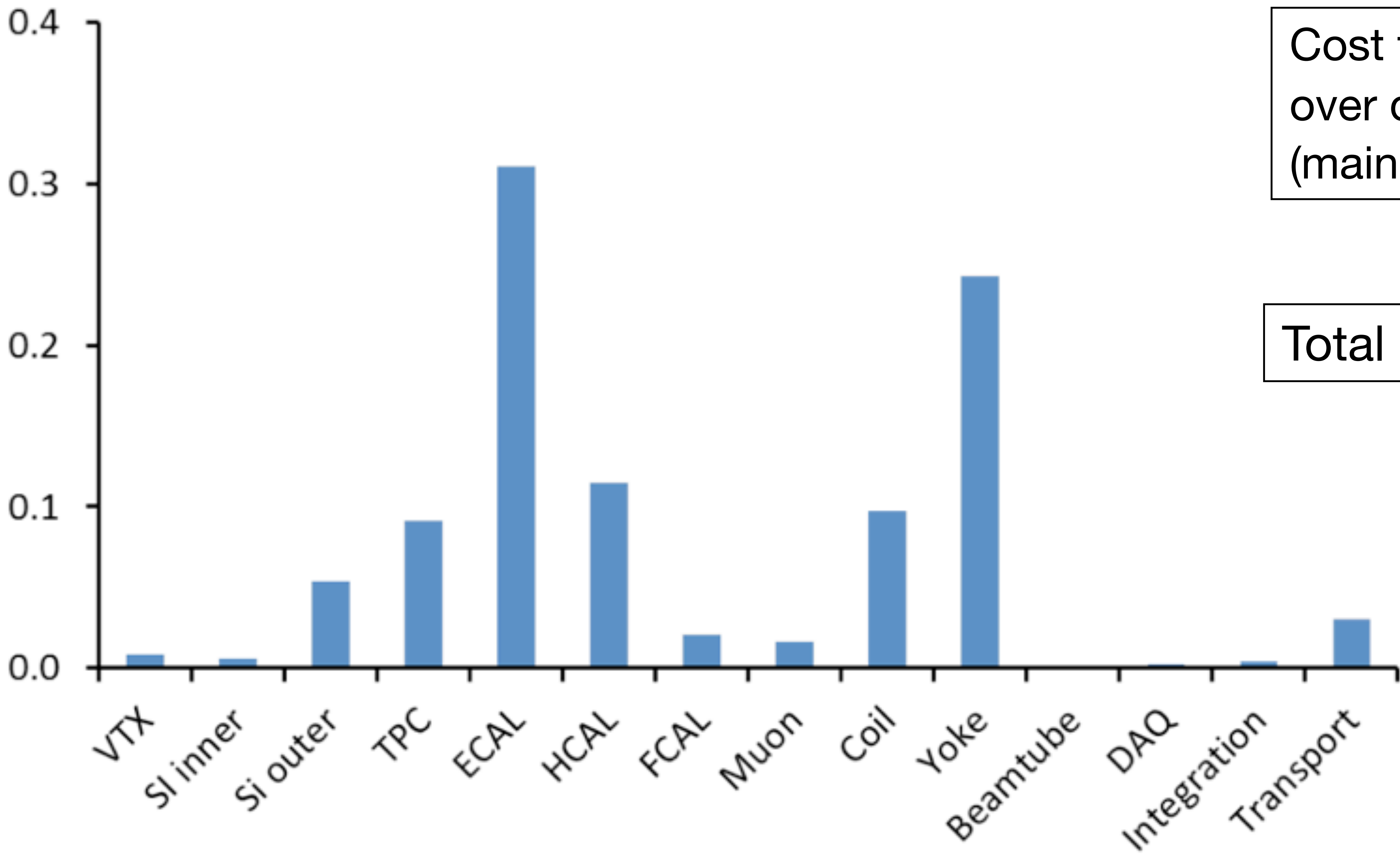
compare to CMS:




Have to work very hard to reach the ambitious goals!
Remember: CMS originally started out with a factor ~2 less...

# Real-World Challenges: Cost




Cost fractions are averages over different options (mainly relevant for ECAL)

Total ~ 400 MUSD

- The distribution of the cost reflects the importance of particle flow in the detector design - Calorimeters account for ~ 50% of total cost

# Summary & Conclusions

- The physics at a Linear Collider is different than at LHC - We need different detectors!
  - No emphasis on photons, in most systems no need for rad hardness
  - Precision vertexing to measure Higgs couplings far beyond LHC capabilities
  - Precision tracking, in particular for ZH recoil process
  - Unprecedented jet energy resolution - Can and have to use hadronic final states

- Detector components push technological limits
  - Granularity and material budget in vertex detector - requires extremely low power consumption, thinned sensors,...
  - Precise trackers - either all Si, or a combination of TPC and Si tracking
  - Imaging calorimeter system with unprecedented channel counts 2 - 4 orders of magnitude more than LHC detectors

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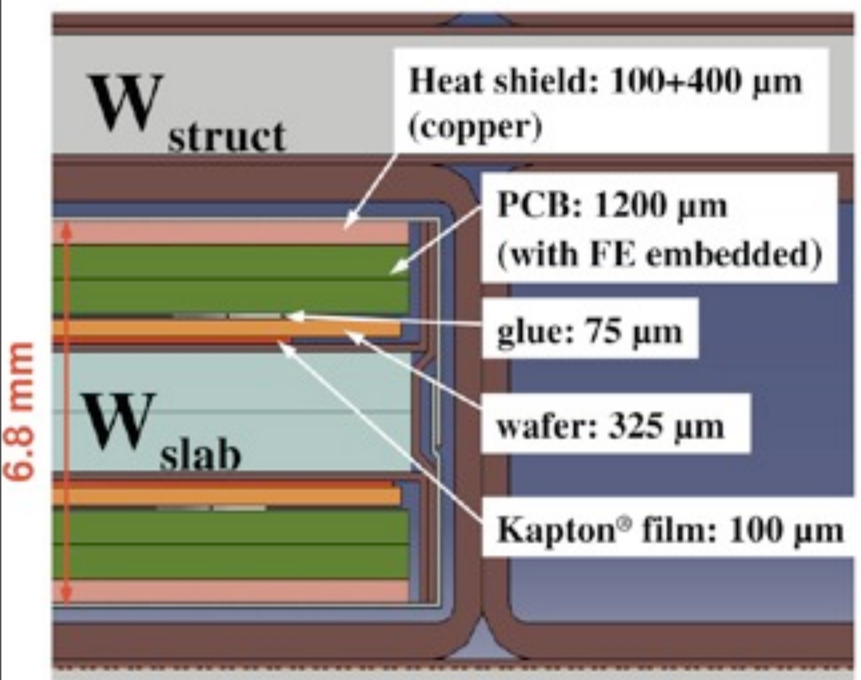
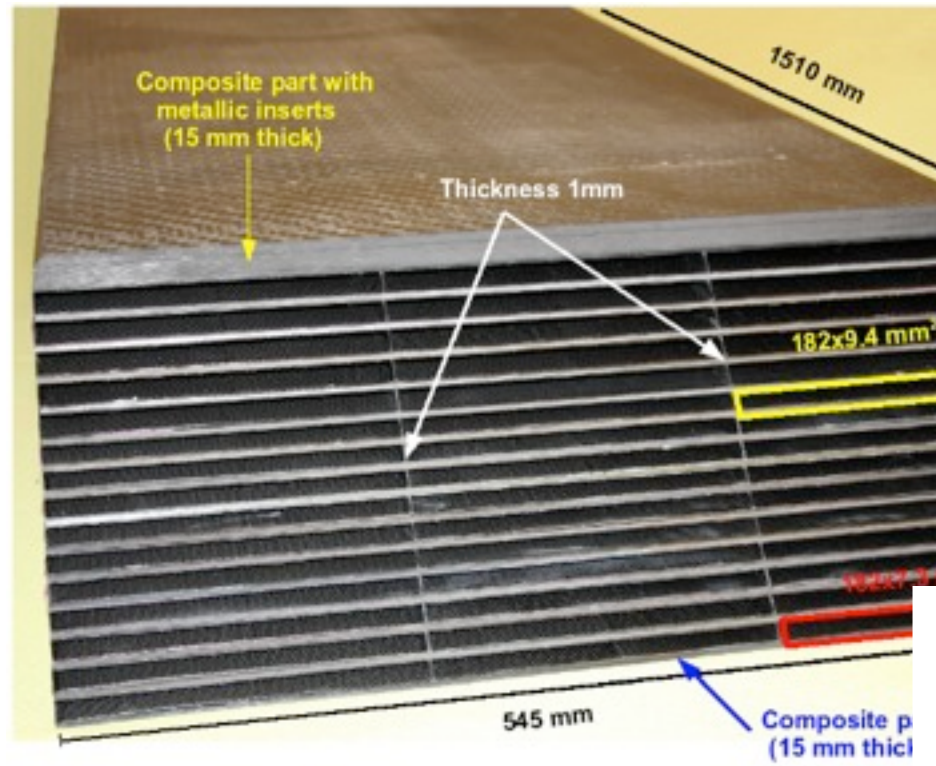
Now we need the opportunity to build it and do physics with it!

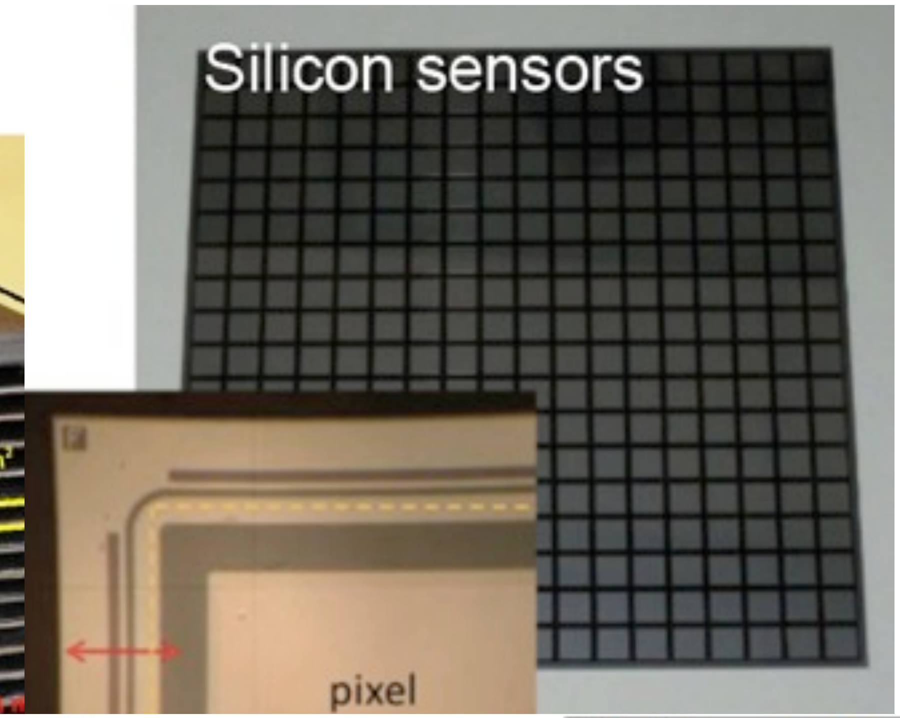
# Extra Material

# The SiW ECAL

- PIN silicon pad readout with 5.5 x 5.5 mm$^2$ pads



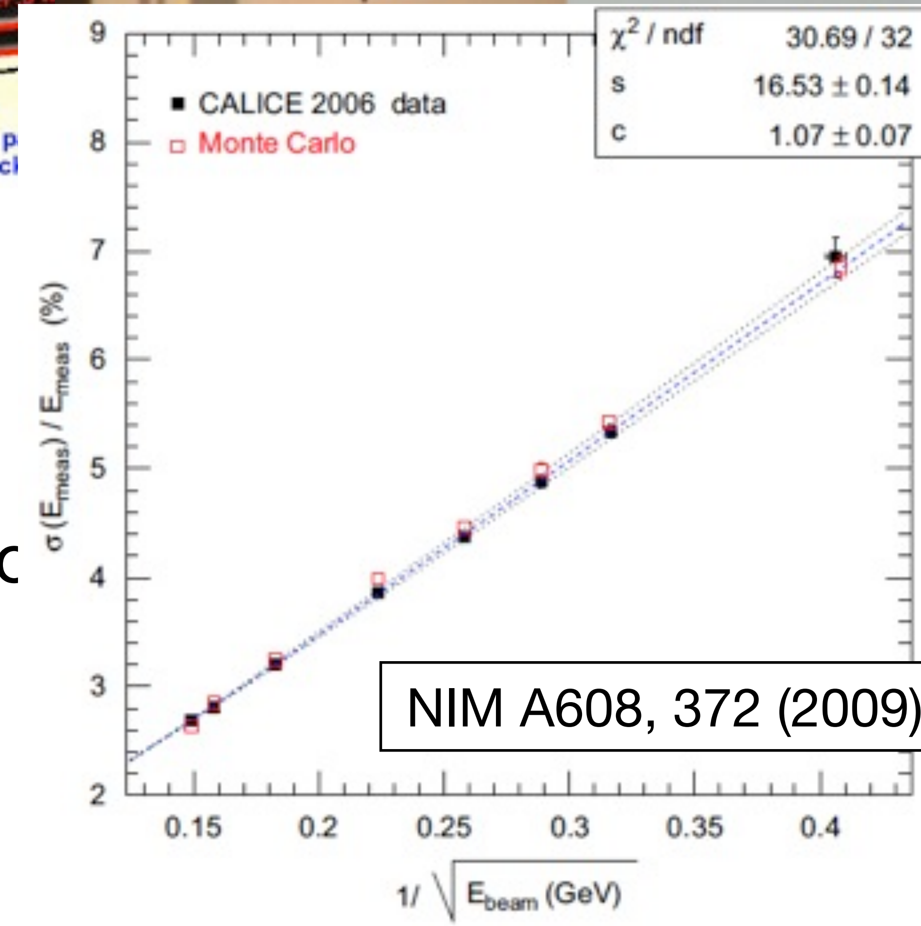




6.8 mm per double layer

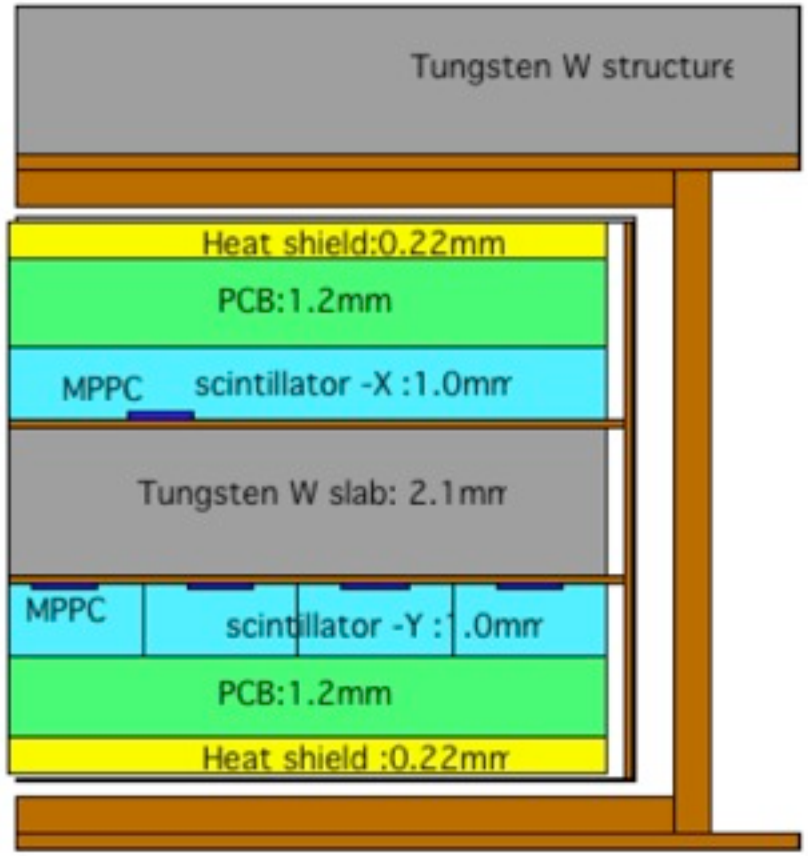
Complete tungsten structure for technological prototype exists

Well-established technology: physics prototype in varic beam times since 2006

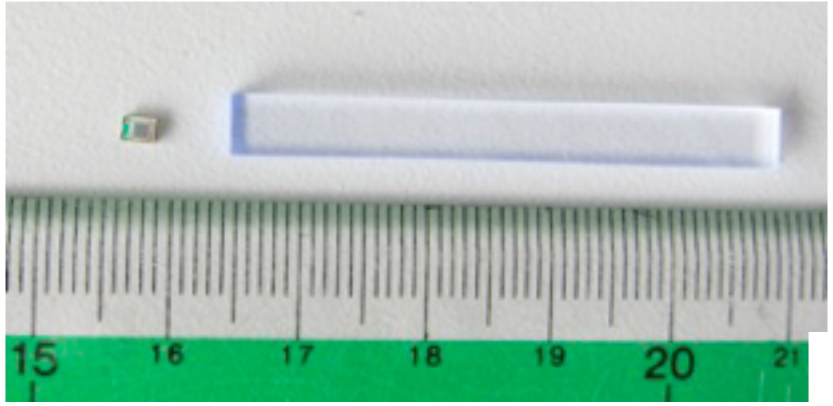



NIM A608, 372 (2009)

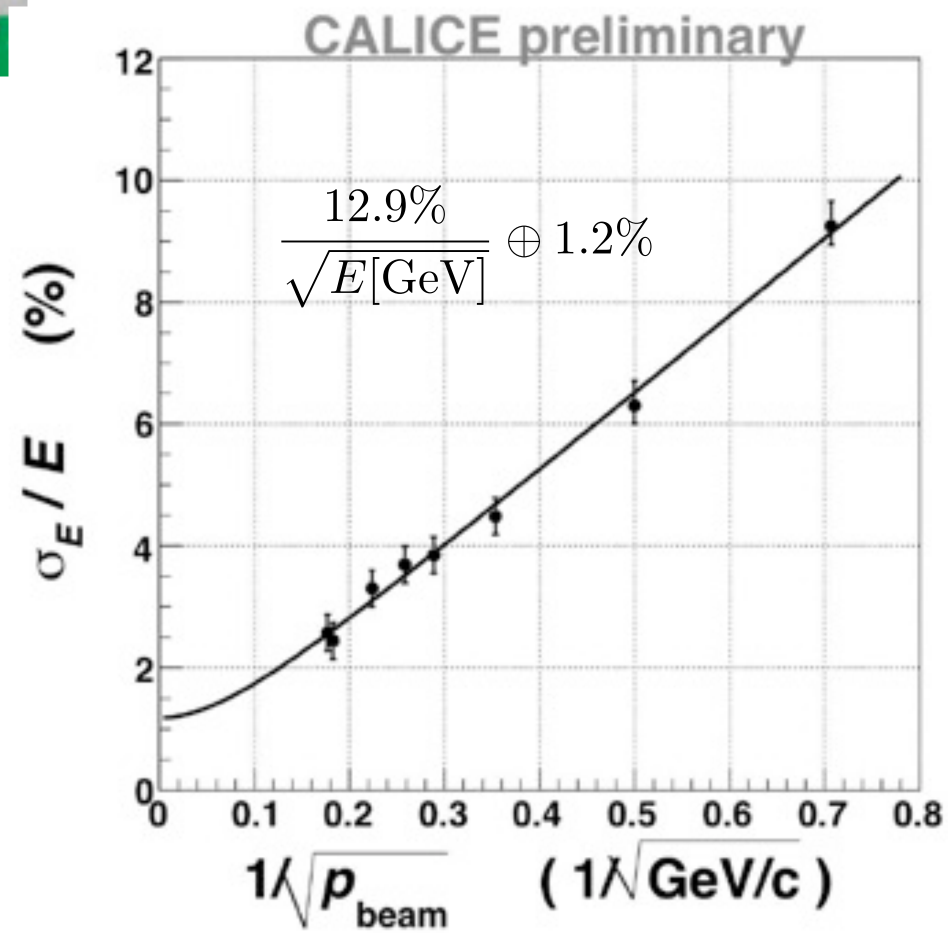
# The Scintillator ECAL




- Scintillator strips (5 x 45 x 1 $mm^3$) read out with SiPMs
  - 6.9 mm per double layer, 0.1 mm more than SiW ECAL
  - Electronics based on AHCAL design - synergies!



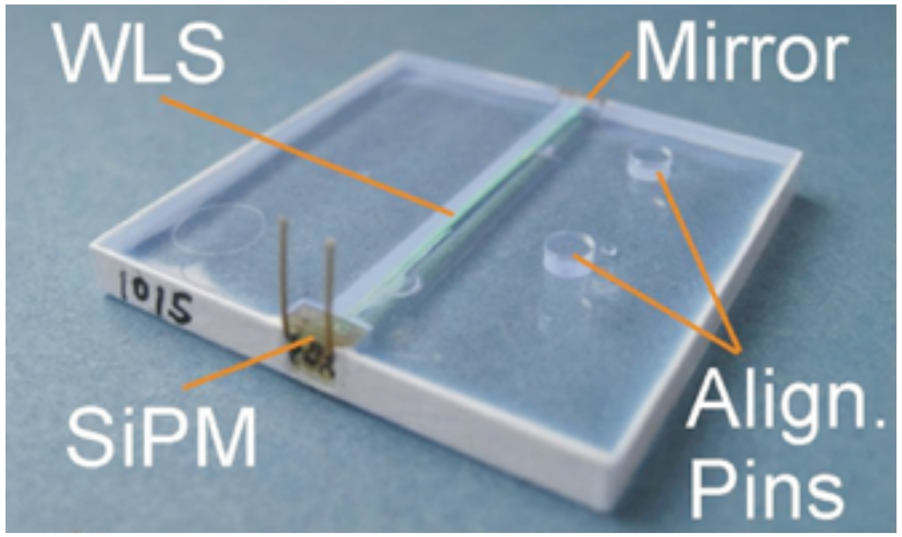
Extensive tests with a physics prototype, first module of technological demonstrator tested at DESY



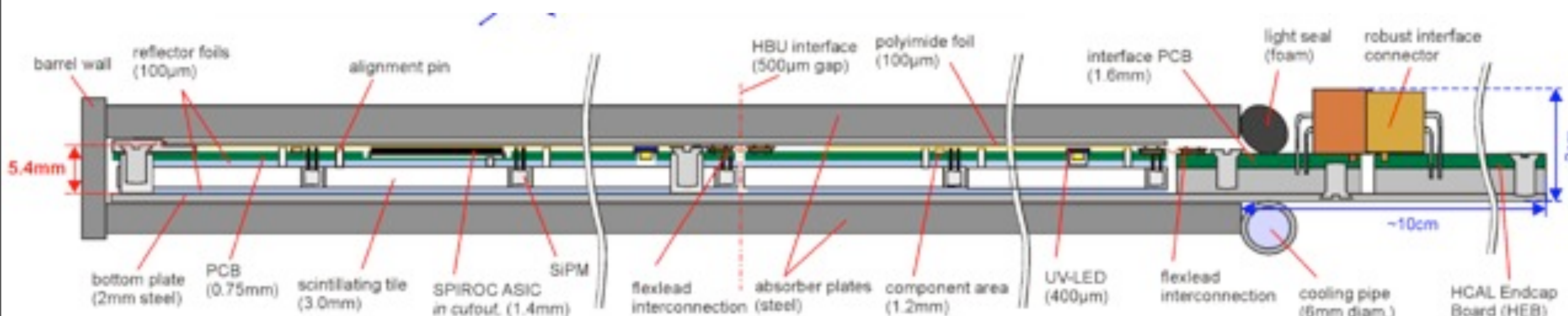

- Recover 5 x 5 $mm^2$ granularity with strip-splitting algorithm
- SiPMs / MPPC with higher smaller pixels under study to increase dynamic range
- Hybrid solutions together with Si layers (interleaved or as two sections) possible

# The Analog HCAL

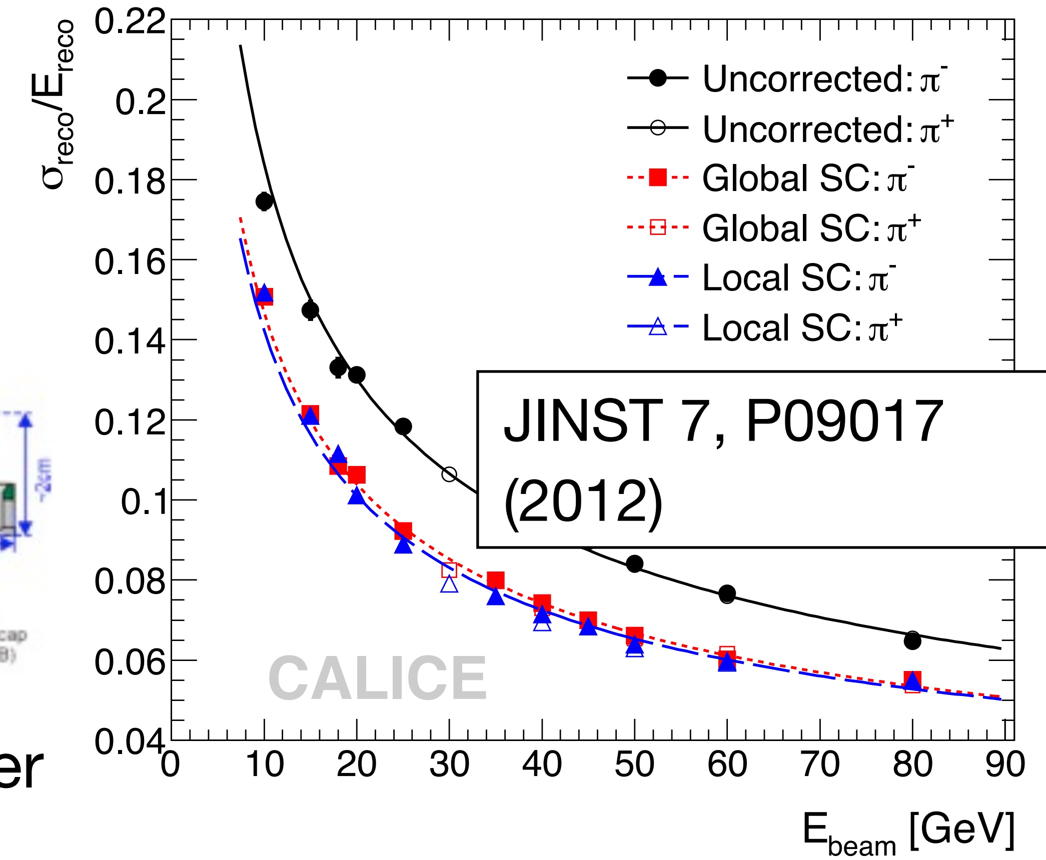
- Based on 3 x 3 x 0.3 $cm^3$ scintillator tiles with embedded SiPM




Well-established technology: Extensive tests in beam with a 8 000 channel system since 2006

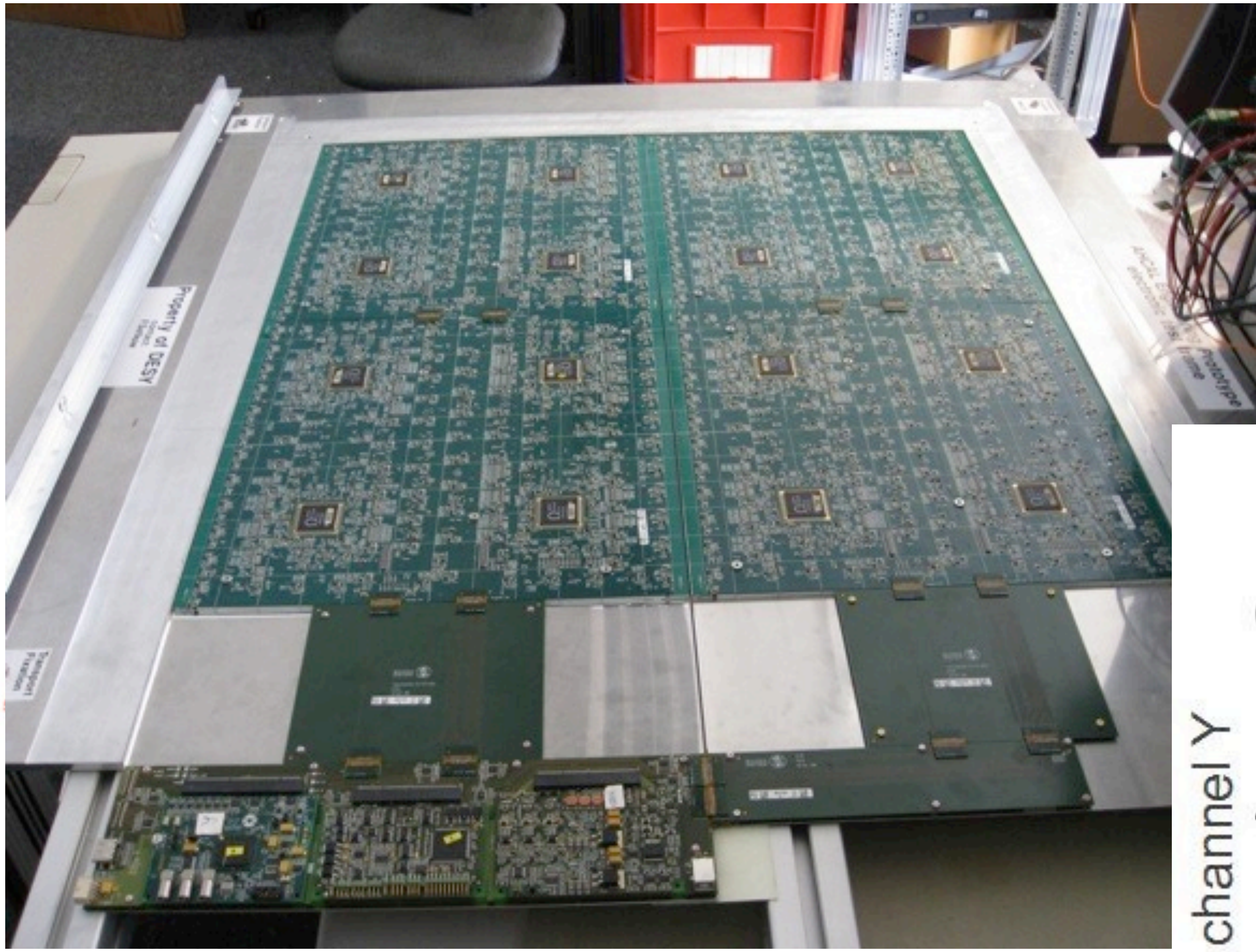



Compact design: < 6 mm non-absorber material per layer



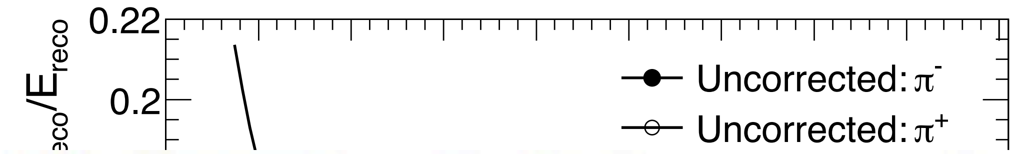

Hadronic energy resolution of physics prototype with software compensation: $45\%/\sqrt{E} \oplus 1.8\%$

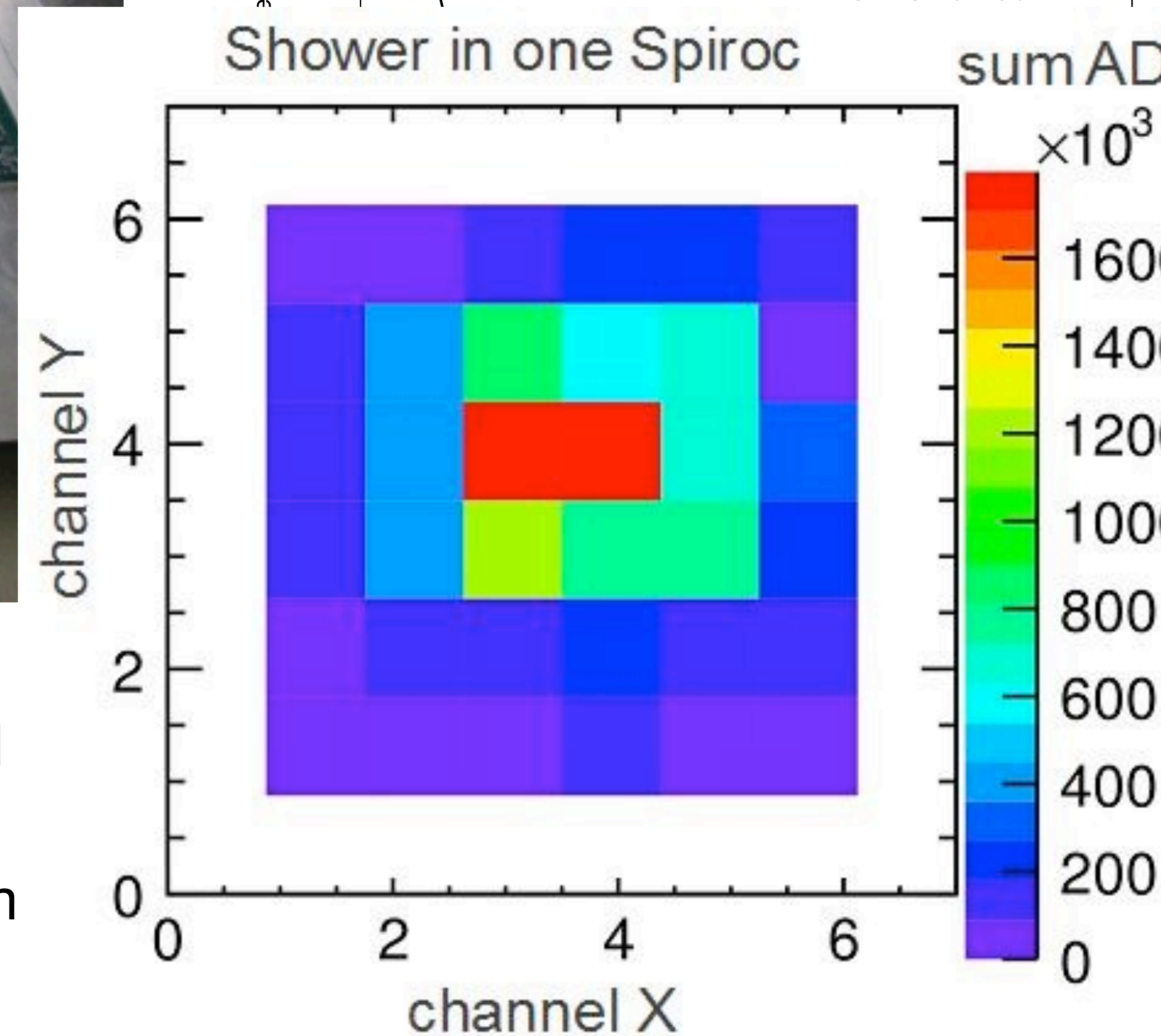
# The Analog HCAL



embedded SiPM

ed technology: Extensive tests in
000 channel system since 2006




First units (144 channels) of technological demonstrator currently in test beam: - embedded electronics, power pulsing, online zero suppression, channel-by-channel auto-trigger, tim stamping

# The Analog HCAL

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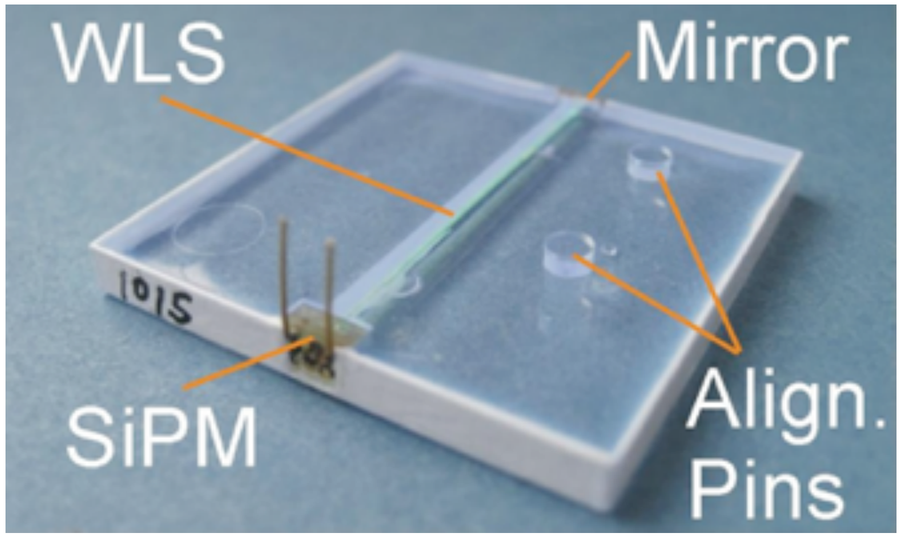


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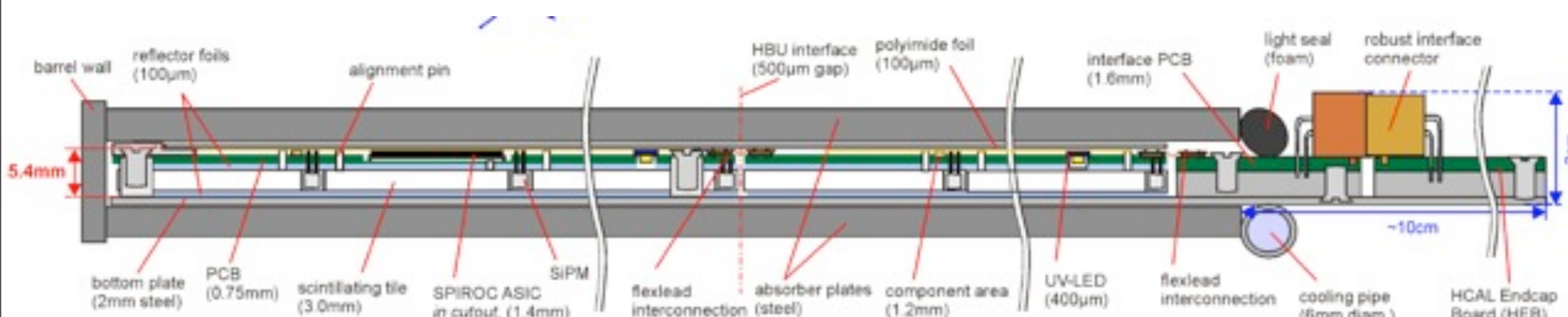


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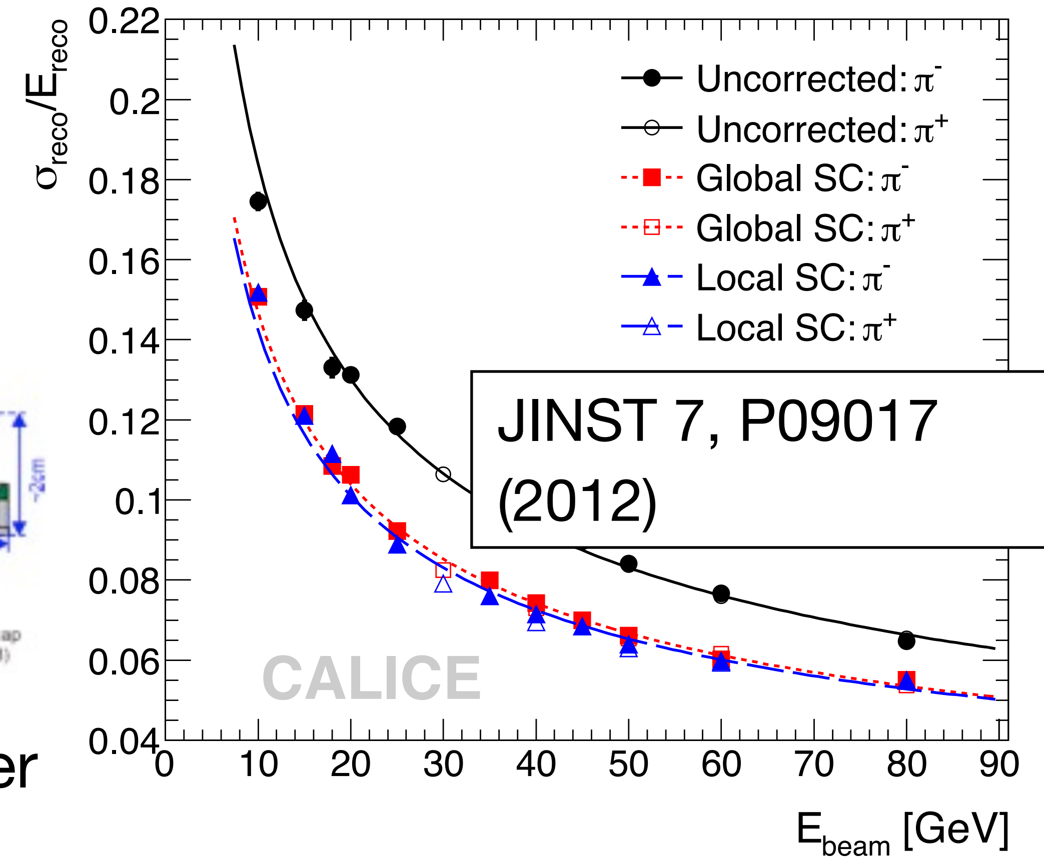
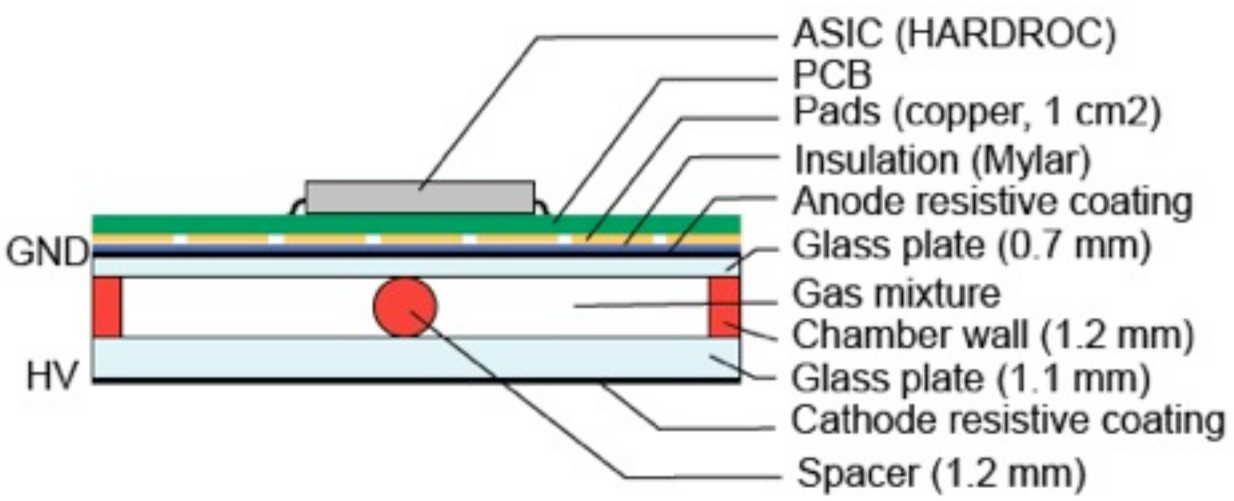


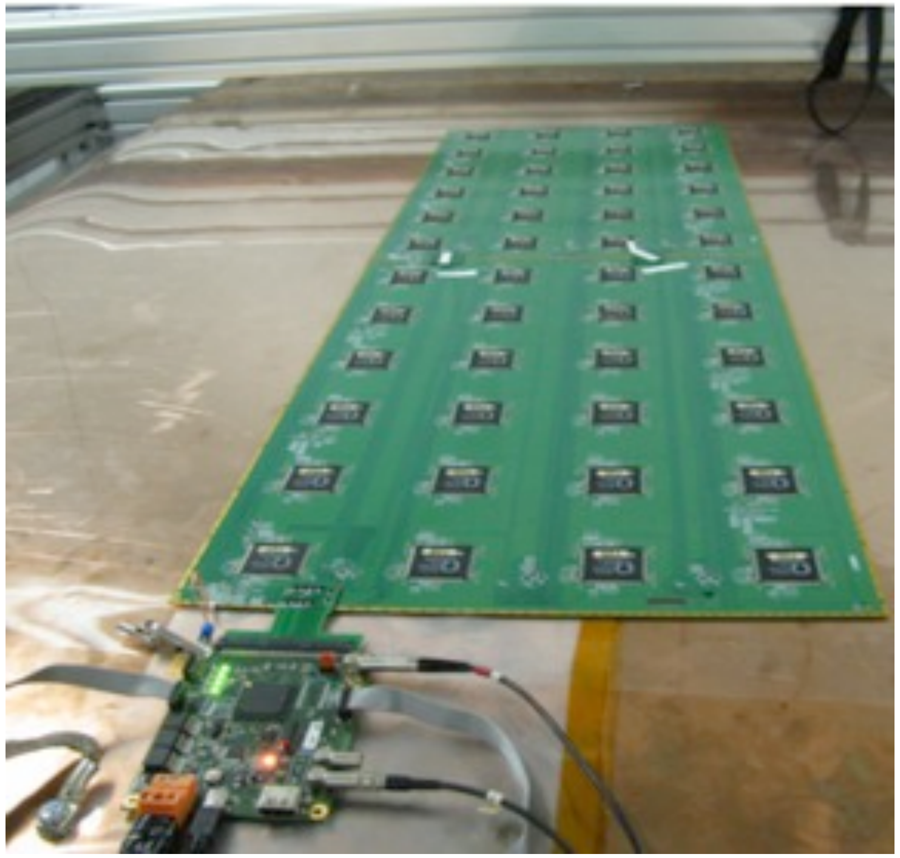

Hadronic energy resolution of physics prototype with software compensation: $45\%/\sqrt{E} \oplus 1.8\%$

# The Semi-Digital HCAL

- Glass RPCs with 1 $cm^2$ pads
  - 3 thresholds per channel: allows to keep linearity to higher energies, improved resolution at high energies compared to purely digital mode




Full 1 $m^3$ technological prototype with 48 layers,
430k channels & power-pulsing successfully tested in beam



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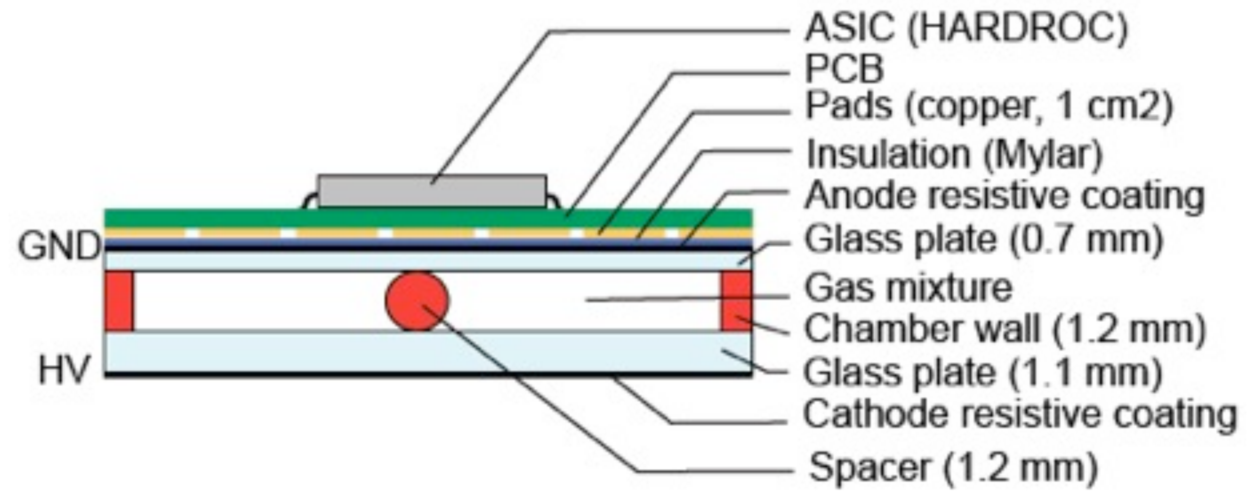
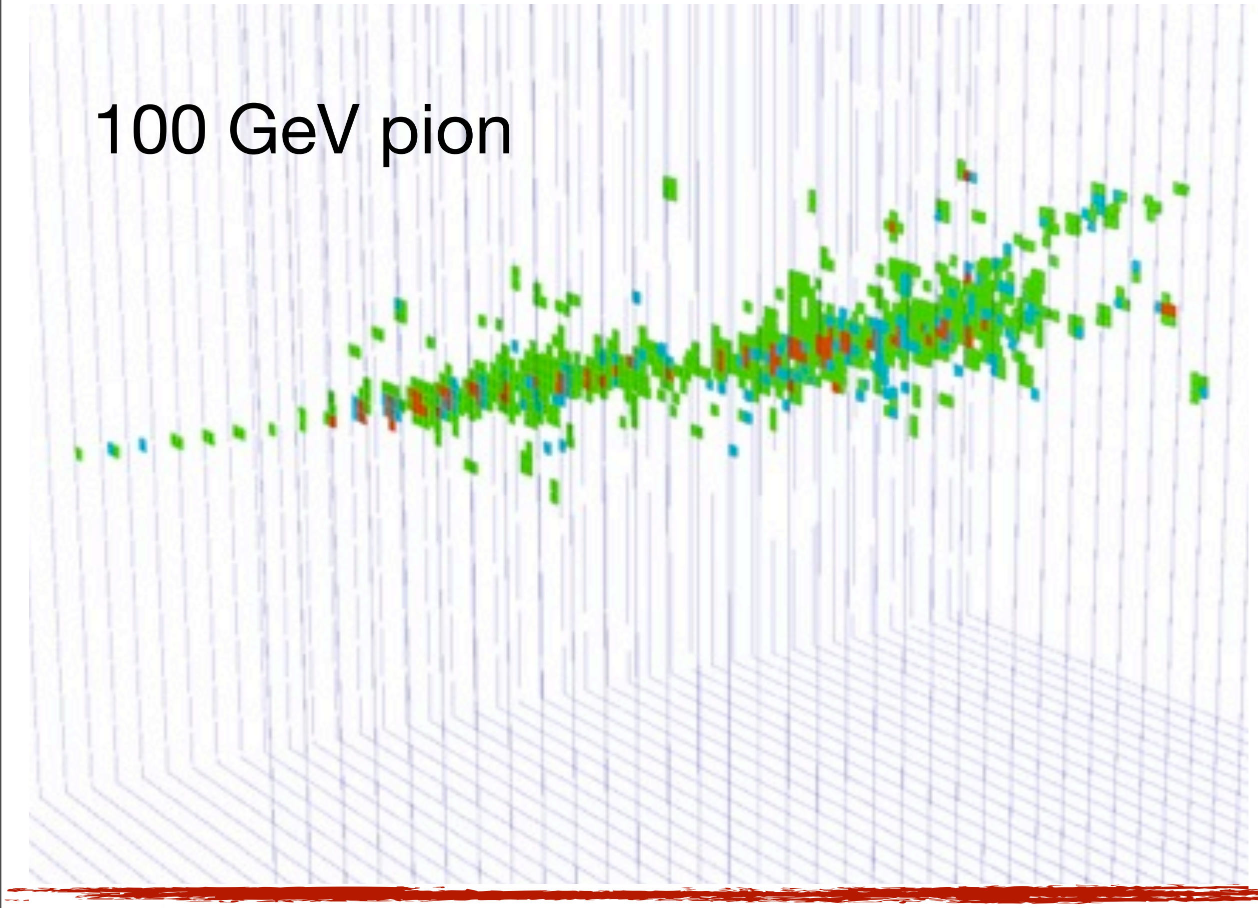
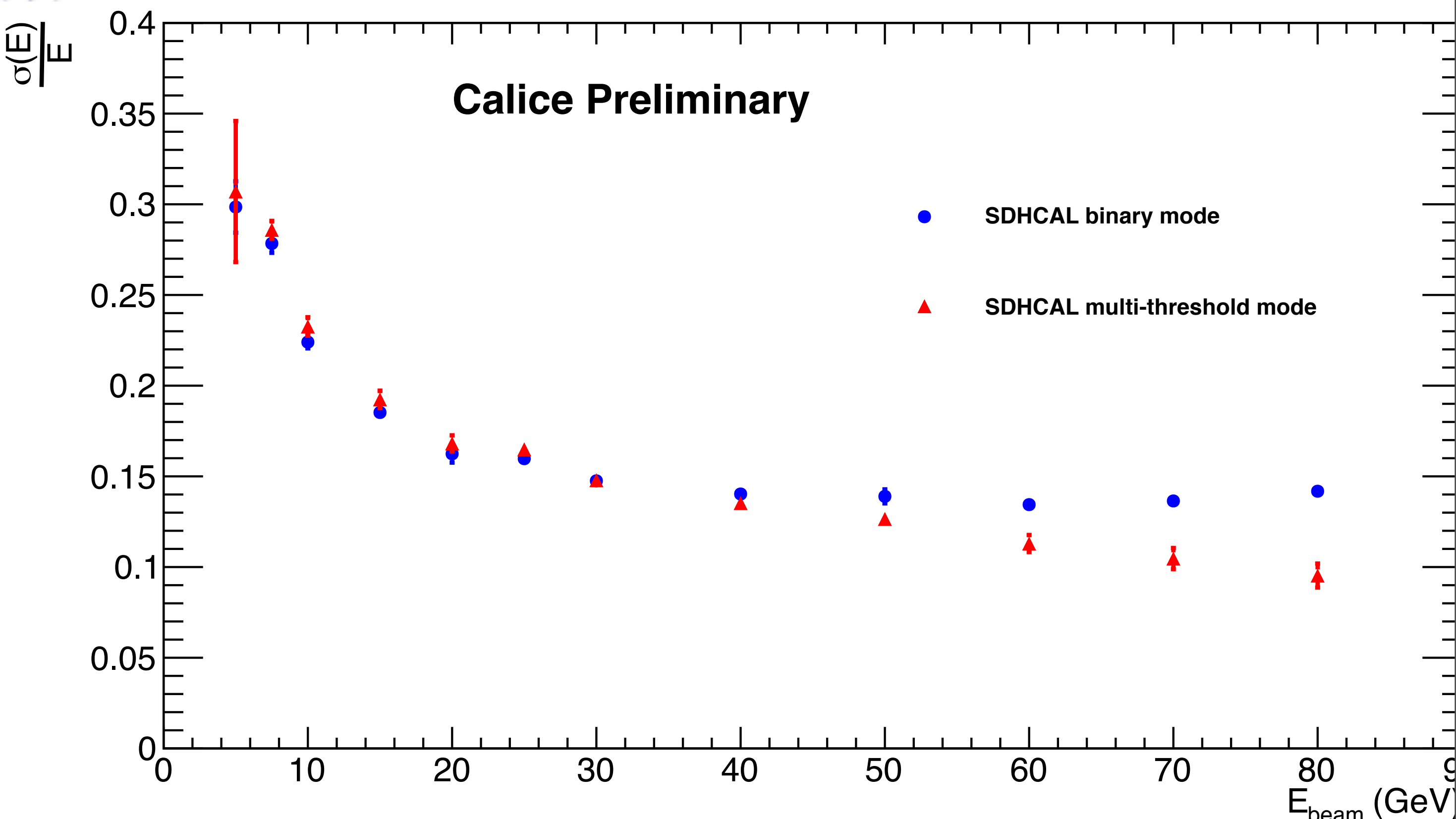
  - 3 thresholds per channel: allows to keep linearity to higher energies, improved resolution at high energies compared to purely digital mode

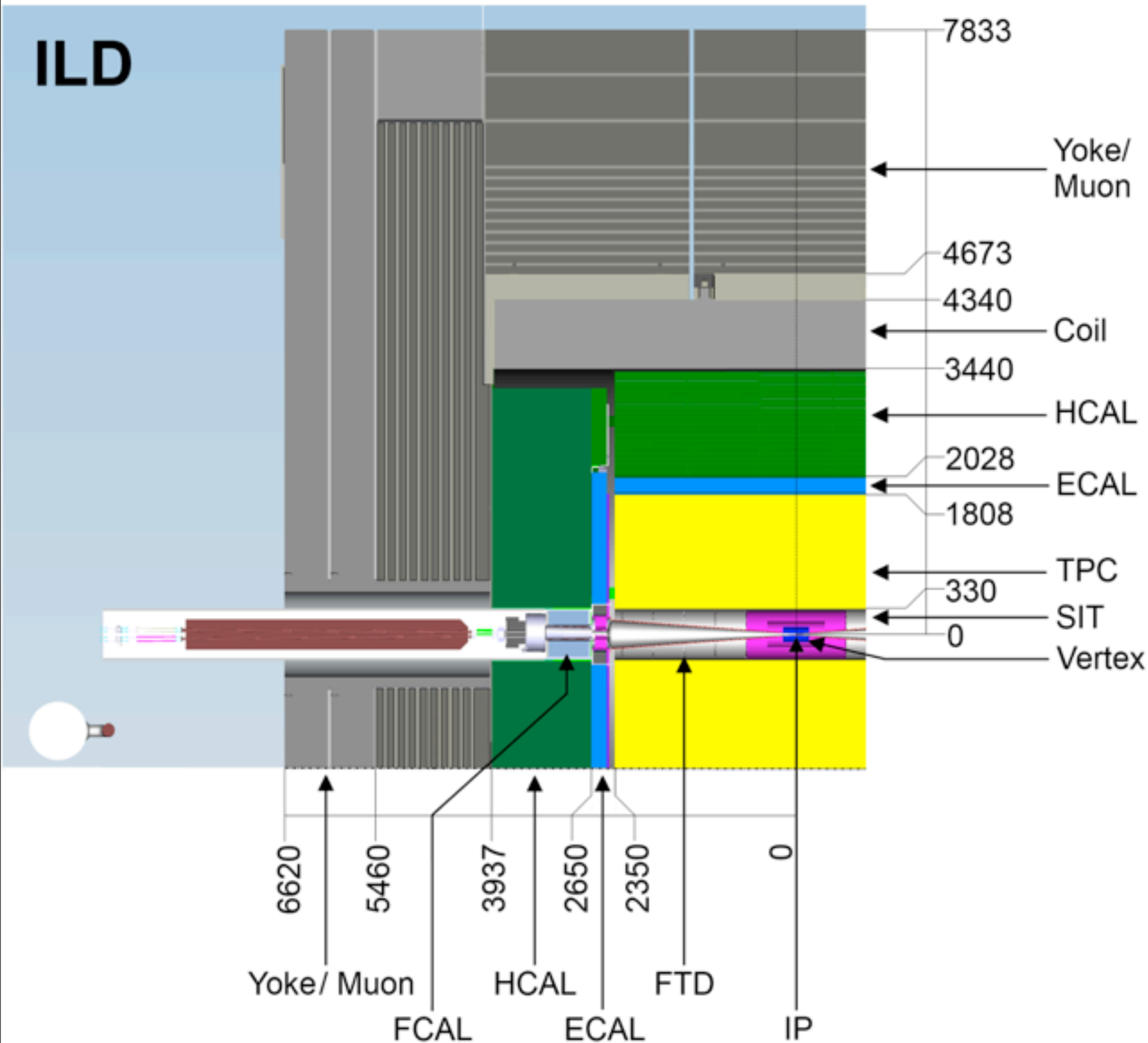



Full 1 m$^3$ technological prototype with 48 layers, 430k channels & power-pulsing successfully tested in beam



# ILD - Dimensions



# Calorimetry for Linear Colliders - A New Paradigm

- For best possible jet energy resolution: Measure each particle in the jet with the highest possible precision
- Use of all detector systems:
  - Trackers (charged particles)
  - ECAL (photons, electrons)
  - HCAL (neutral hadrons)

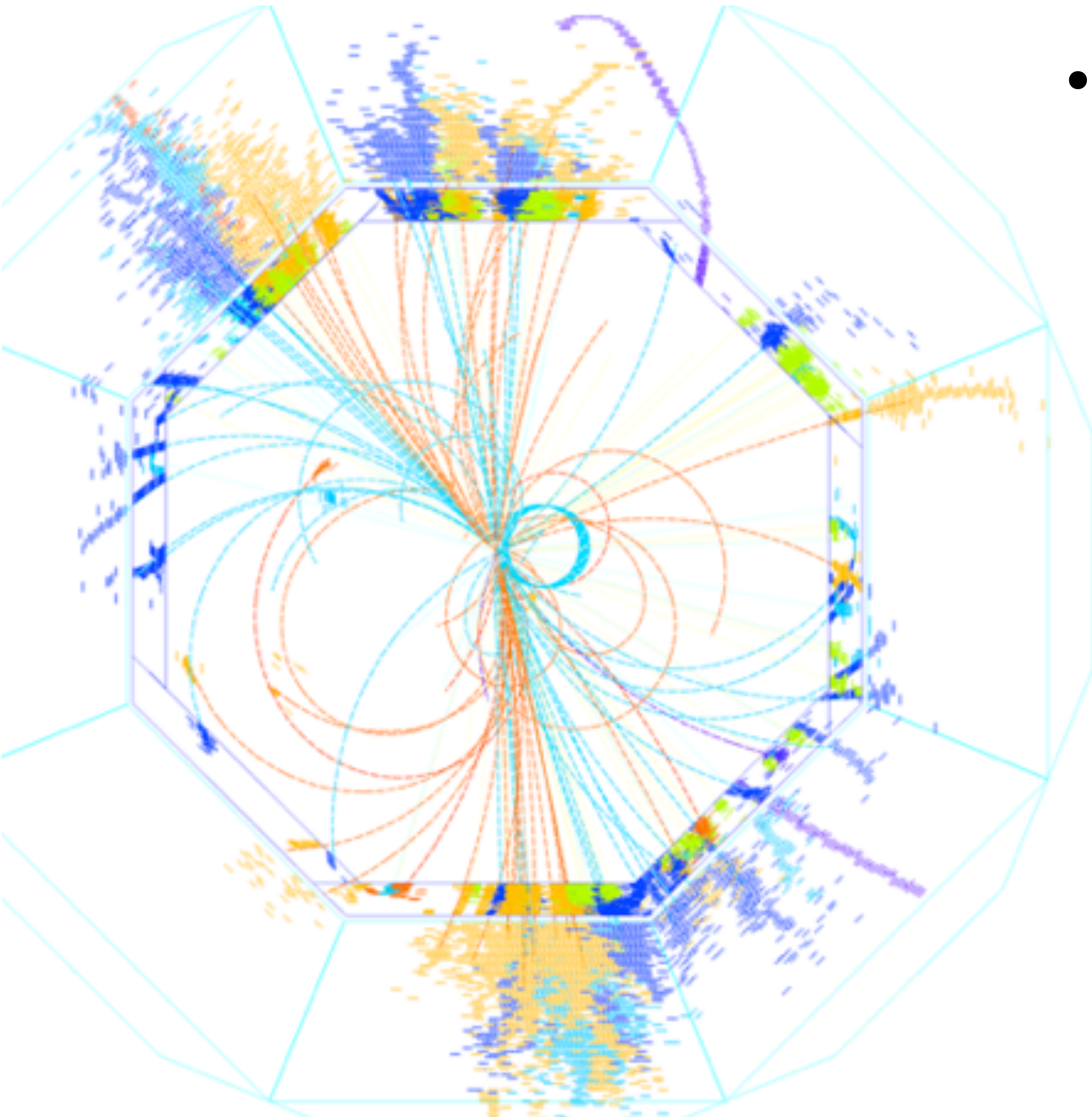
→ Particle Flow Algorithms

- The idea itself is not new, but: Linear Collider Detectors are the first detector systems specifically designed for the use of PFAs

- Moving towards an intimate connection of hardware and software!

# Calorimetry for Linear Colliders - A New Paradigm

- The key to make PFAs work: Granularity!
  - The calorimeters have to be able to separate energy depositions from different particles in the environment of highly energetic jets



- The way we see calorimeters is changing:
  - It is not only energy reconstruction & resolution which matters, but also the pattern recognition / two-particle separation
  - Opens up interesting technology options
  - Full detector systems with 100 million channels - Numbers previously only seen in pixel vertex detectors, ~3 orders of magnitudes more than current calorimeter systems