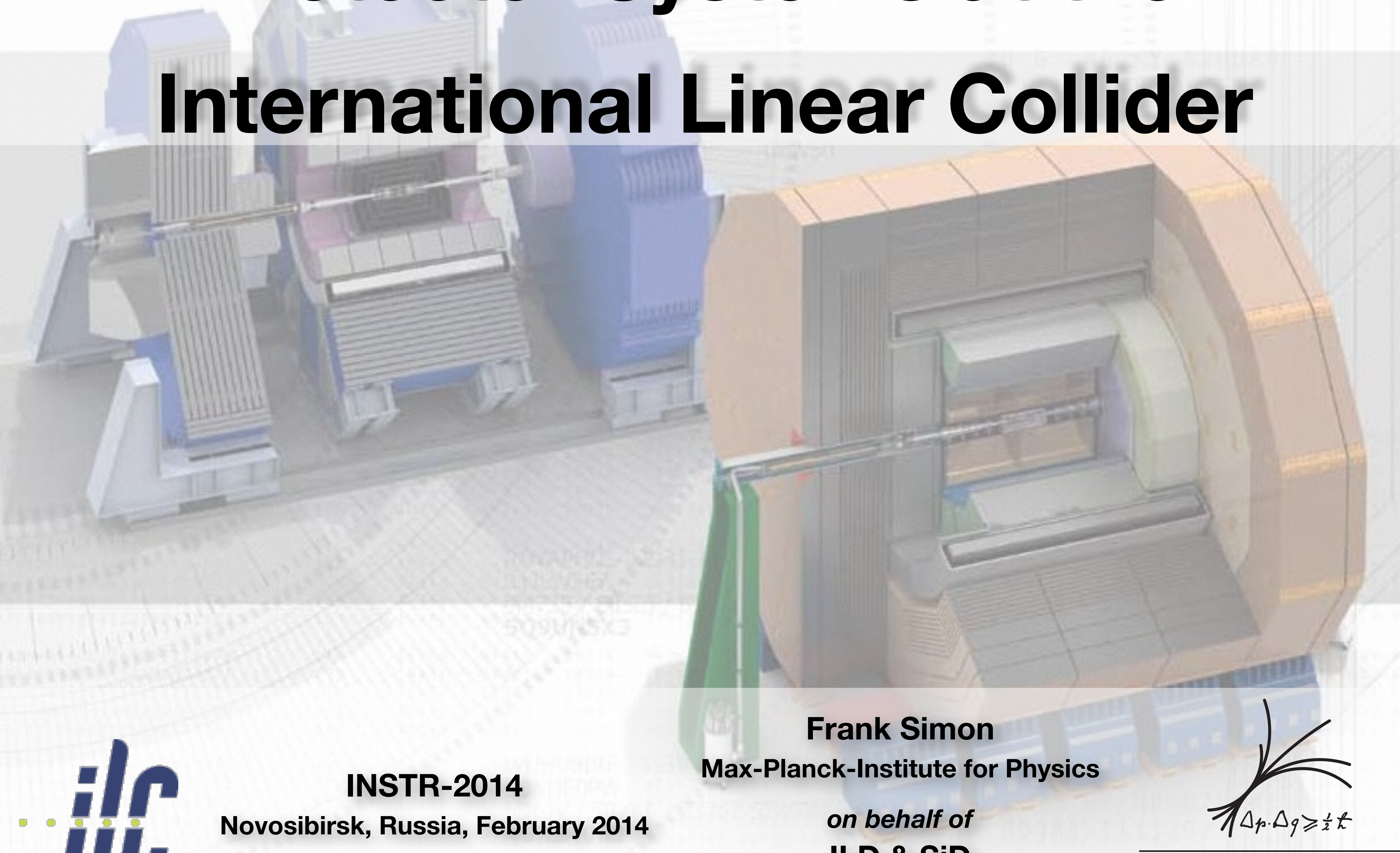
Detector Systems at the International Linear Collider



Cover: Ray Hori

Frank Simon

Max-Planck-Institute for Physics

on behalf of

ILD & SiD

INSTR-2014

Novosibirsk, Russia, February 2014

Max-Planck-Institut für Physik

(Werner-Heisenberg-Institut)

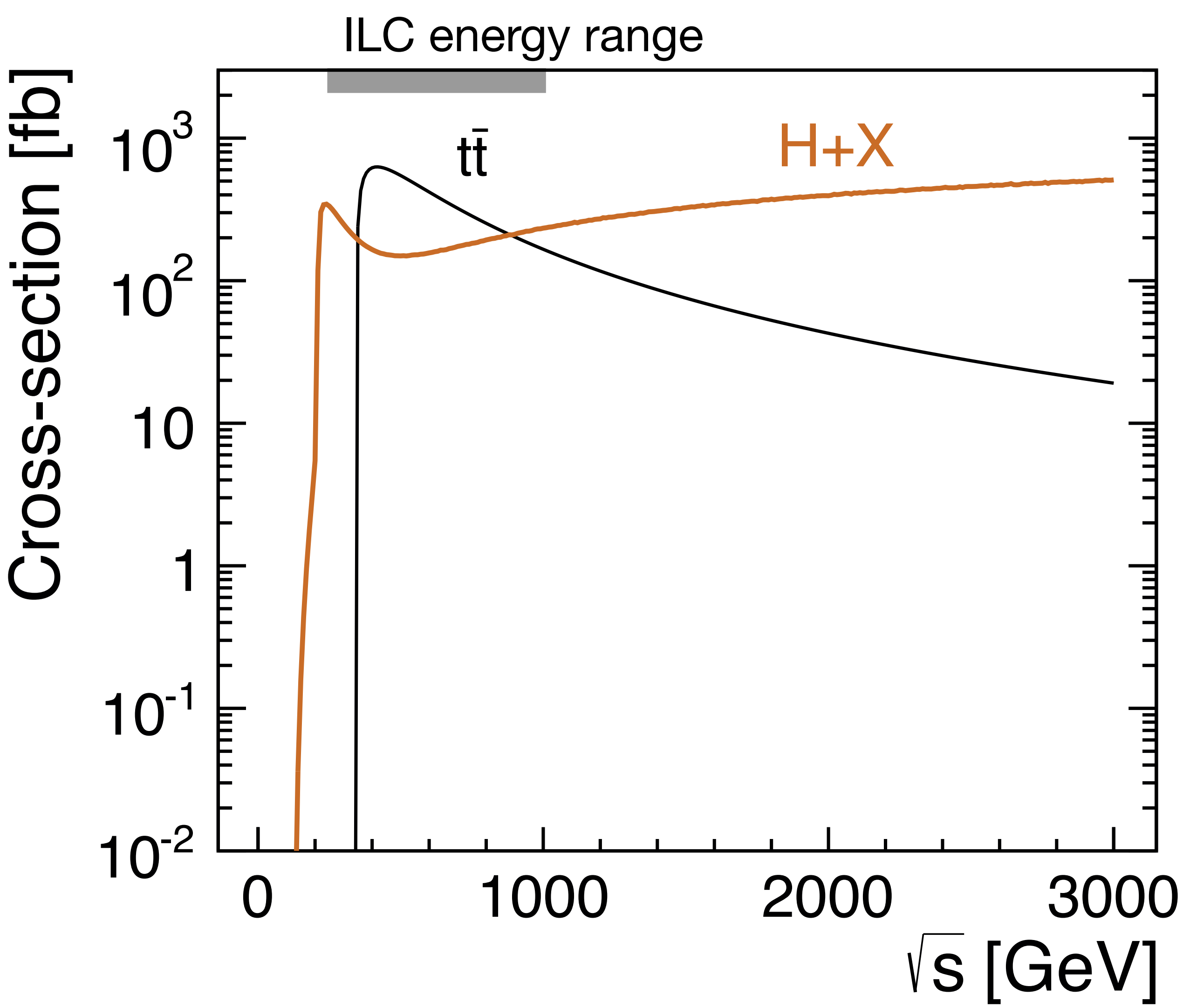
Outline

- Introduction
  - The ILC Physics Landscape
  - … and the resulting Detector Requirements
- ILD & SiD
  - General Design Choices
  - Vertexing
  - Main Tracking
  - Calorimetry
  - Performance & Cost
- Conclusions

The ILC Physics Landscape

… a combination of certainty and speculation:

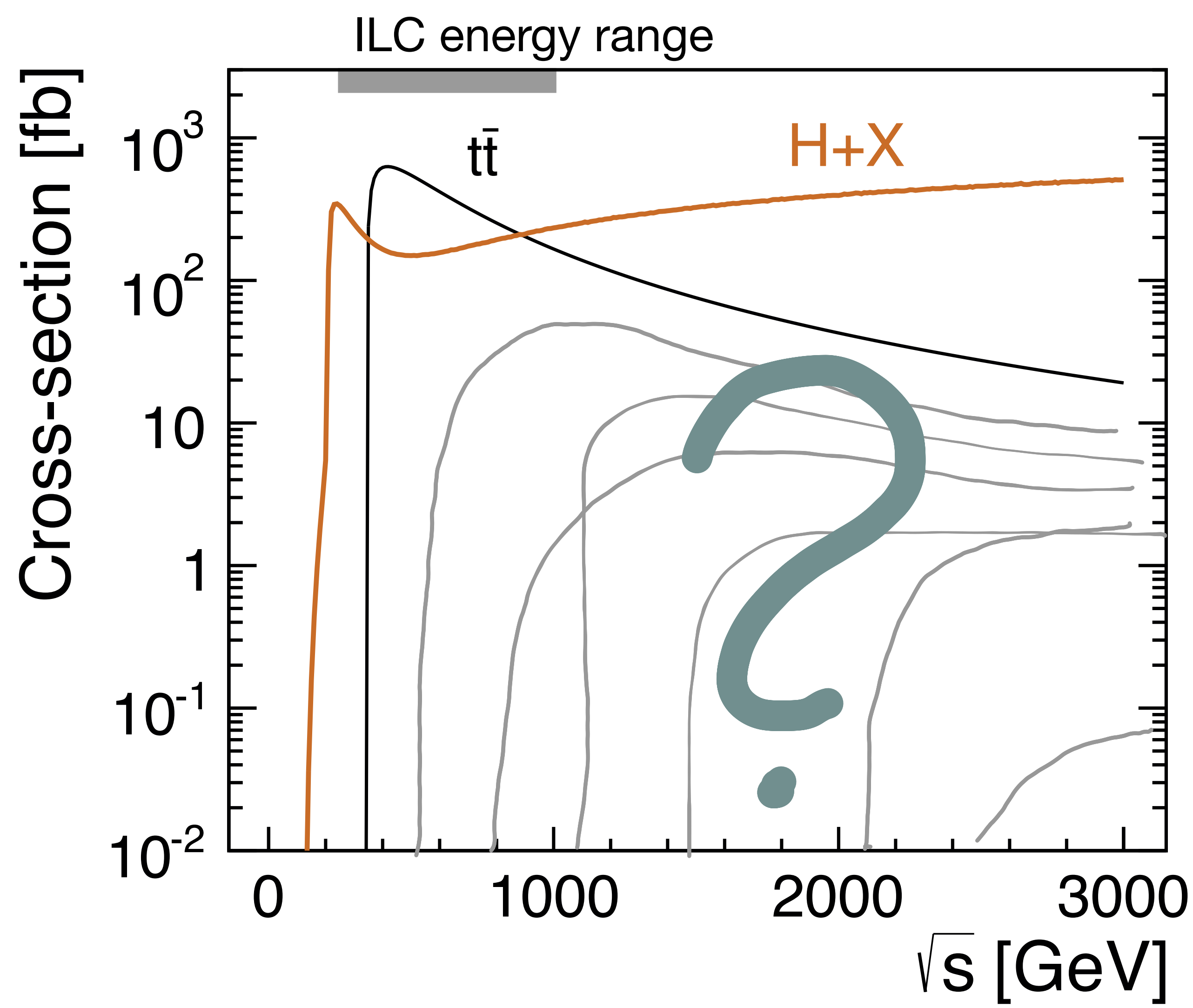
- Excellent physics program guaranteed:
  - Higgs physics - mass, couplings, potential, …
  - Top physics - properties (mass, width,…), top as a probe for New Physics
  - Precision physics - electroweak measurements, QCD, …



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, …

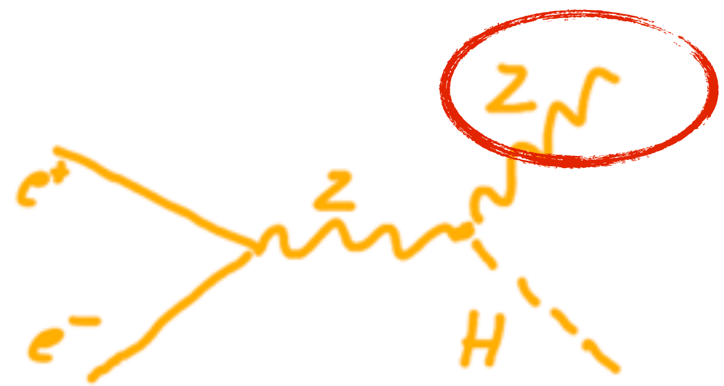


- Discovery potential for New Physics
  - Direct production of new particles - Mass reach up to $\sqrt{s}/2$ for (almost) all particles
    - Spectroscopy of New Physics
  - Indirect (model-dependent) search for New Physics extending far beyond $\sqrt{s}$

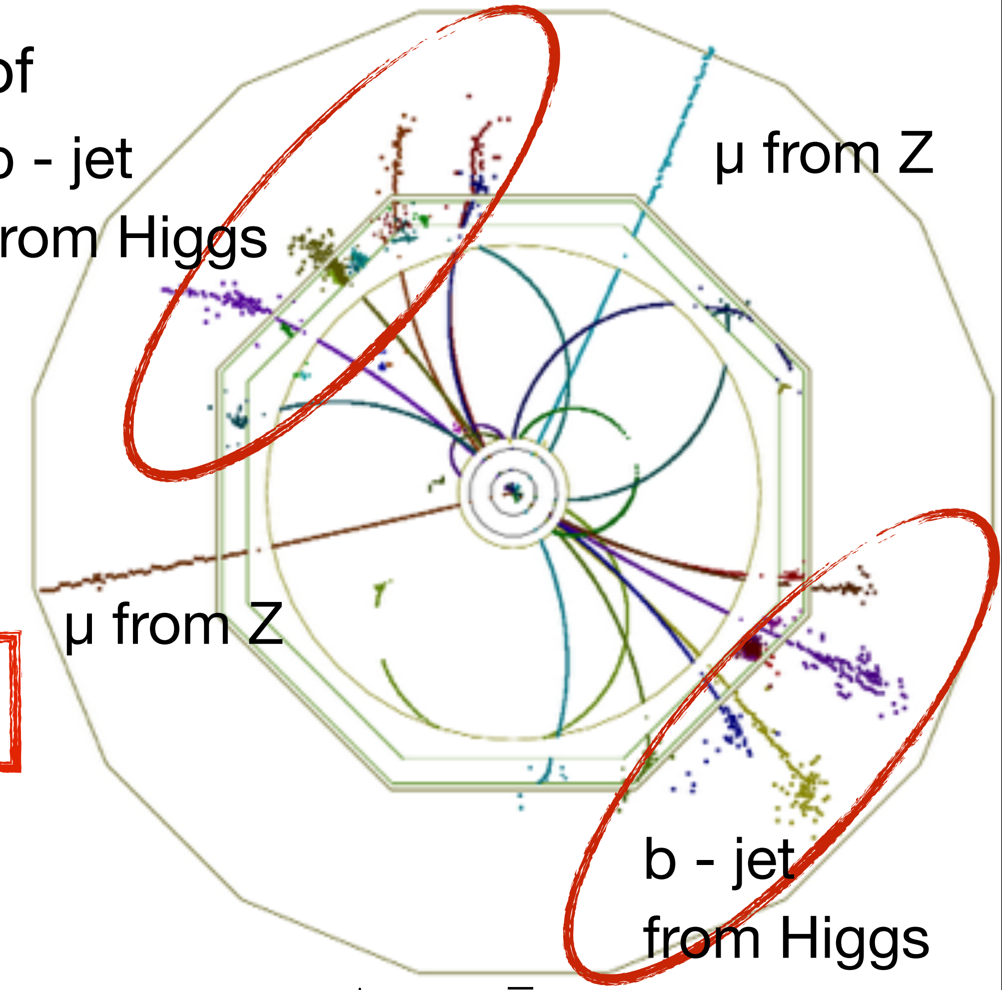
… and the resulting Detector Requirements I

- A flagship measurement: Model-independent coupling of Higgs to Z

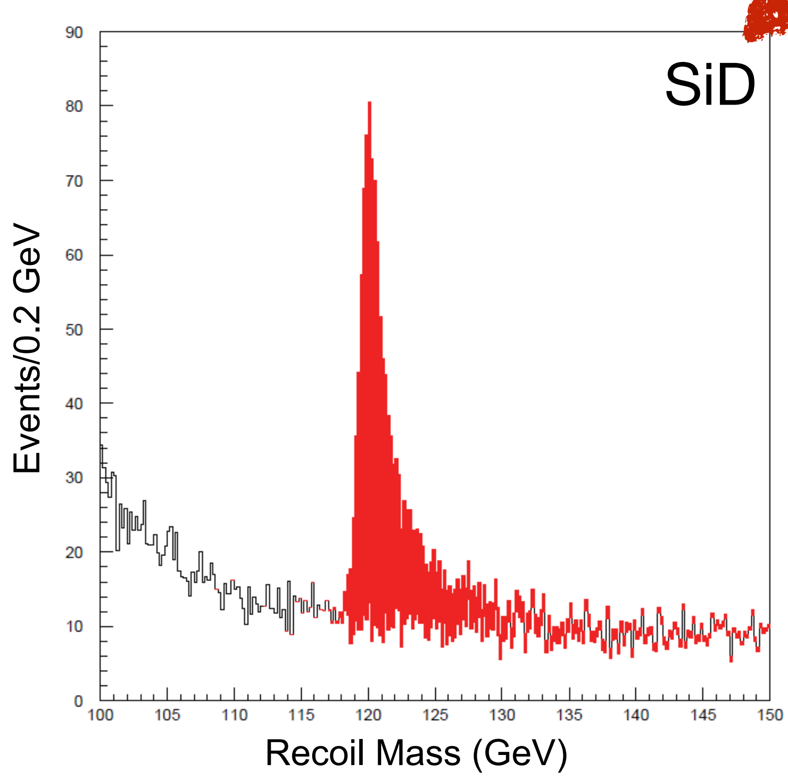
- Obtained from recoil mass measurement of reconstructed Z boson, independent of Higgs decay



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

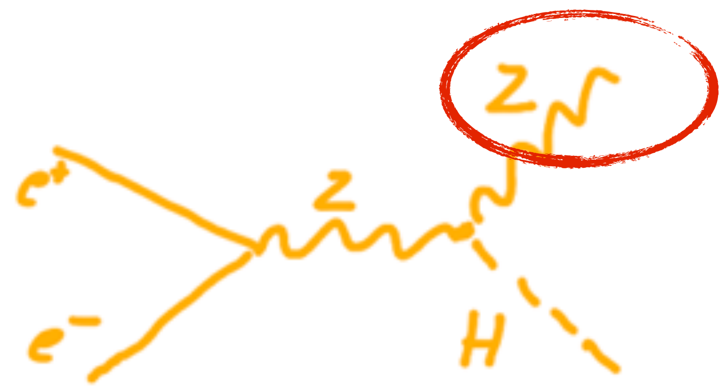


$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

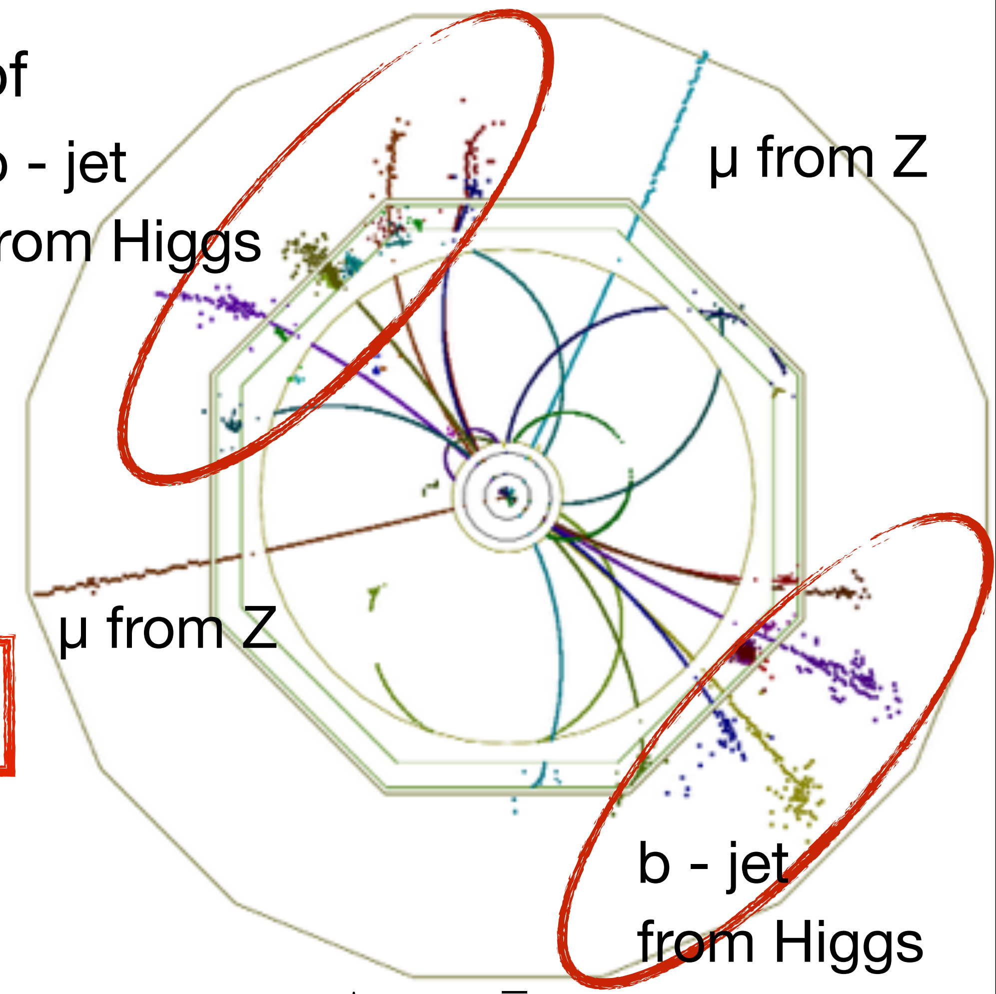


… and the resulting Detector Requirements I

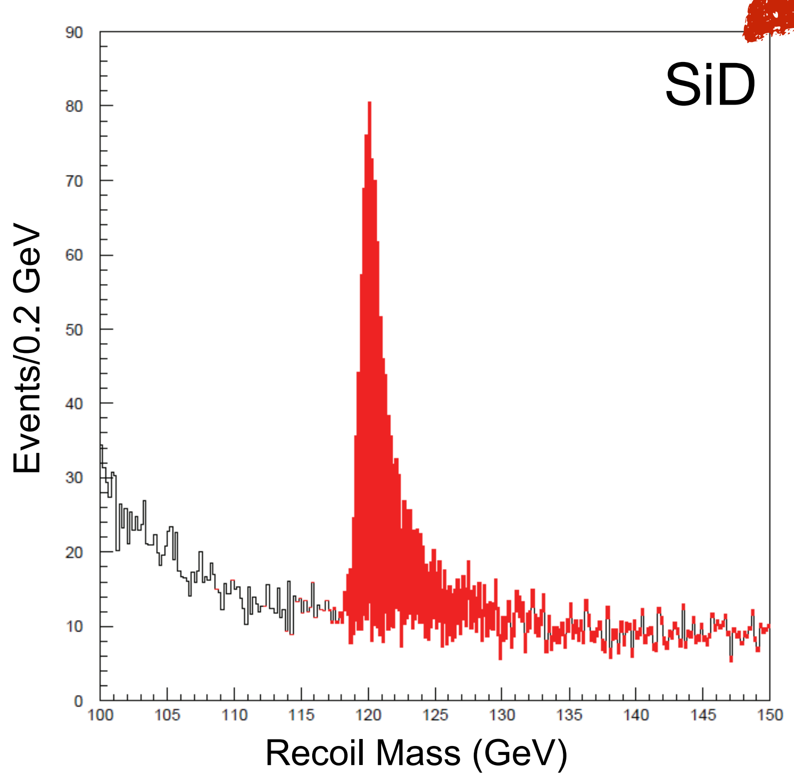
- A flagship measurement: Model-independent coupling of Higgs to Z
- Obtained from recoil mass measurement of reconstructed Z boson, independent of Higgs decay



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



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

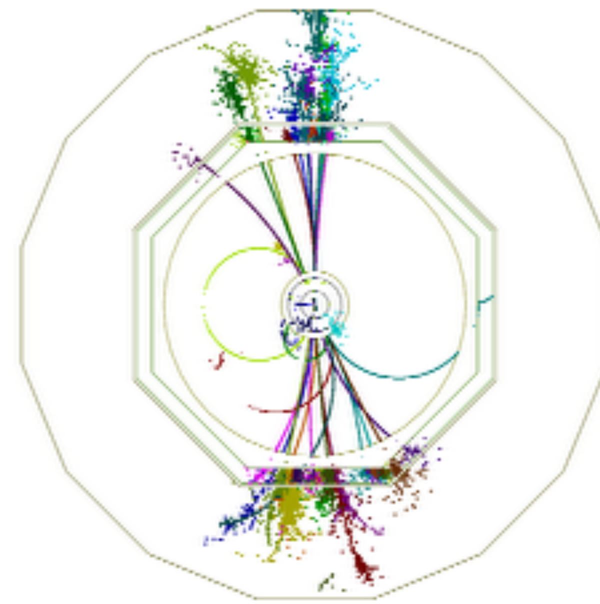


Key detector requirements:

- **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

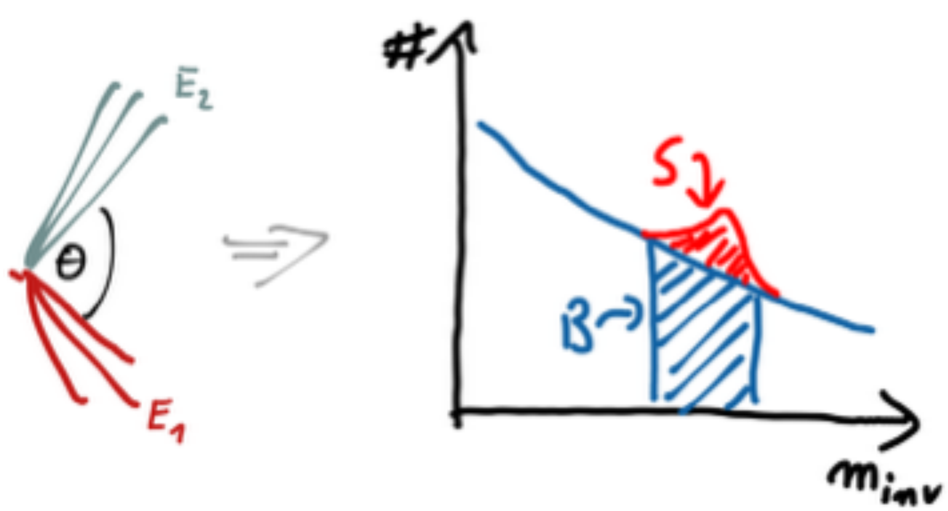
- In general the cross sections of physics processes are quite modest at ILC compared to LHC - at the lower energy stages typically 1000s to 10s of thousands of events - Want to be able to use all possible final states, including high-BR hadronic decays
  - Relevant in many different cases: Identification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



ILD, 1 TeV

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

Generic consideration:



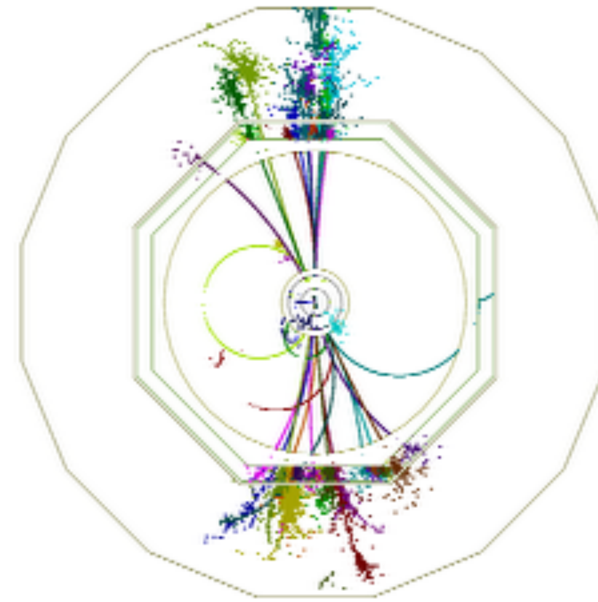
significance:

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

directly depends on mass resolution

… and the resulting Detector Requirements II

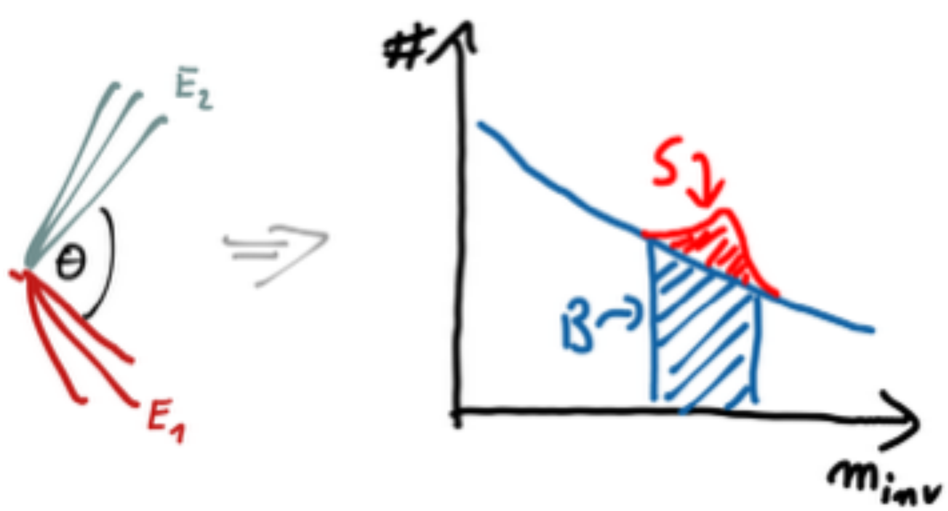
- In general the cross sections of physics processes are quite modest at ILC compared to LHC - at the lower energy stages typically 1000s to 10s of thousands of events - Want to be able to use all possible final states, including high-BR hadronic decays
  - Relevant in many different cases: Identification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



ILD, 1 TeV

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

Generic consideration:

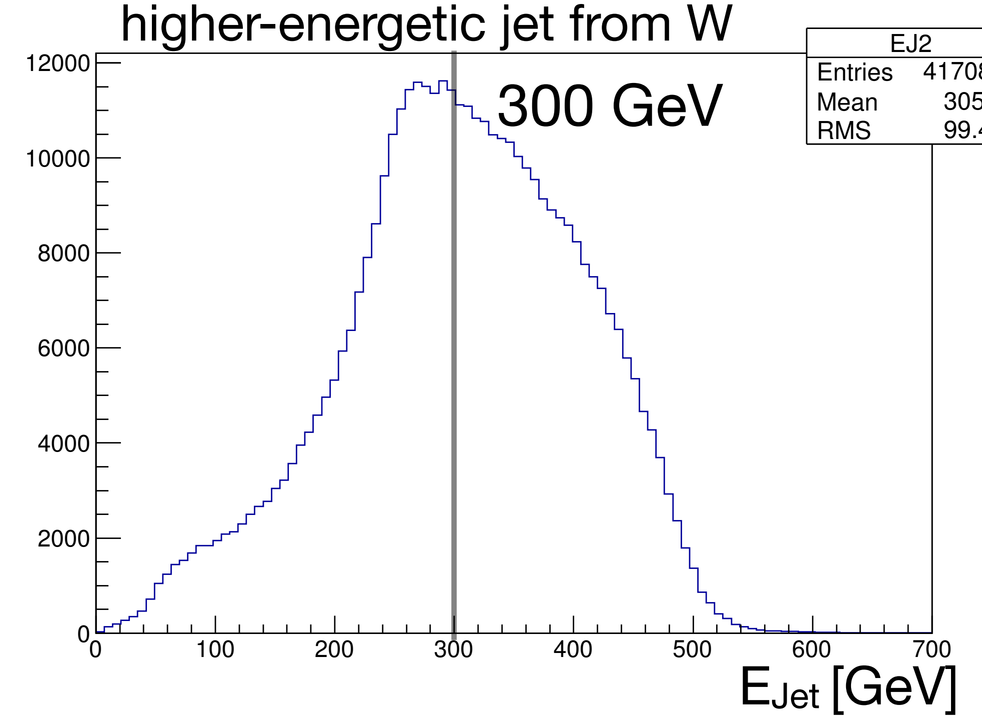


significance:

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

directly depends on mass resolution

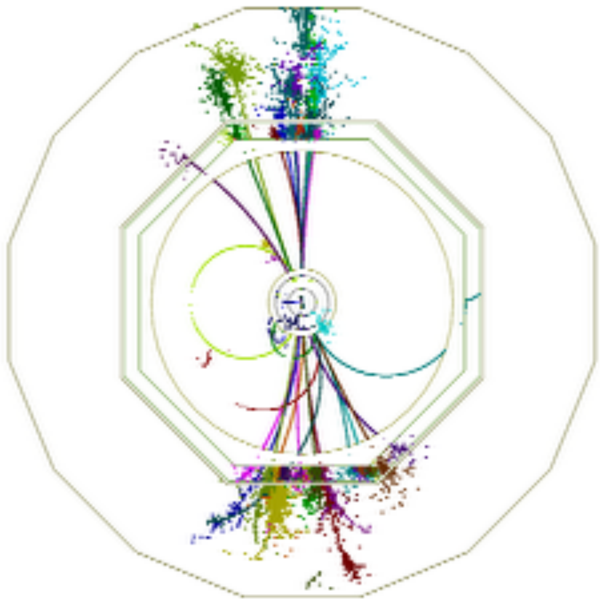
higher-energetic jet from W



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

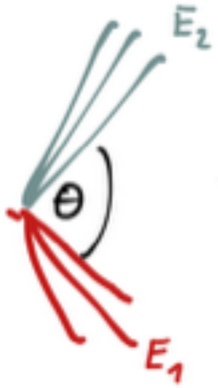
… and the resulting Detector Requirements II

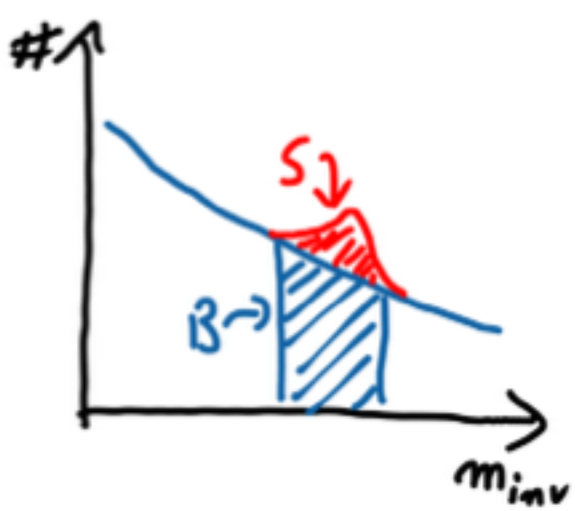
- In general the cross sections of physics processes are quite modest at ILC compared to LHC - at the lower energy stages typically 1000s to 10s of thousands of events - Want to be able to use all possible final states, including high-BR hadronic decays
  - Relevant in many different cases: Identification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



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

Generic consideration:

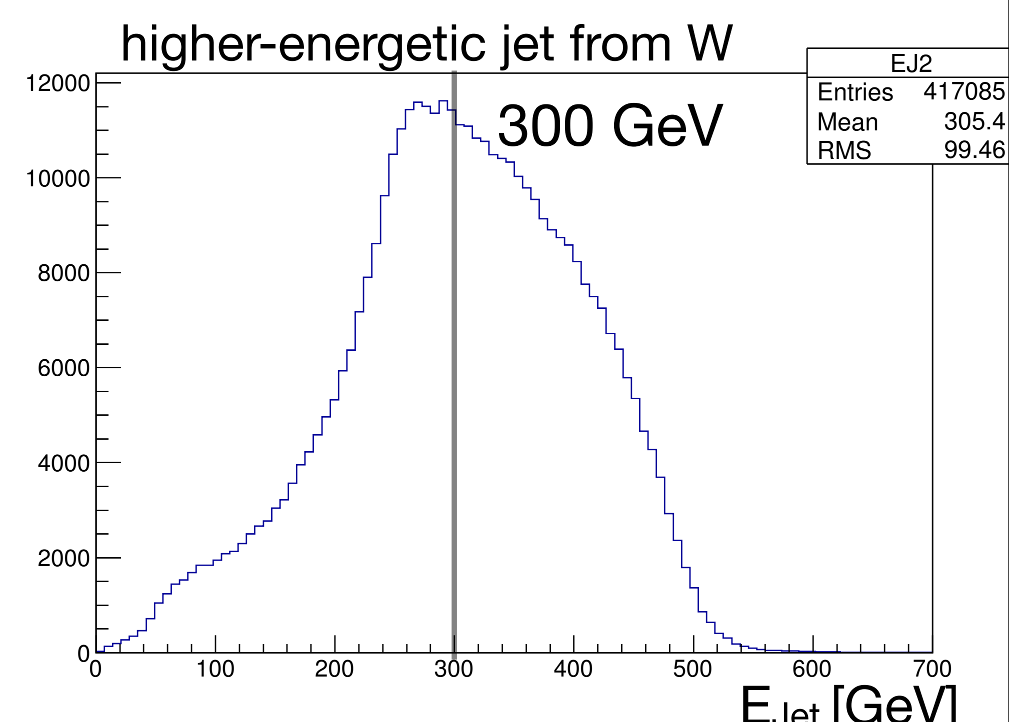




significance:

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

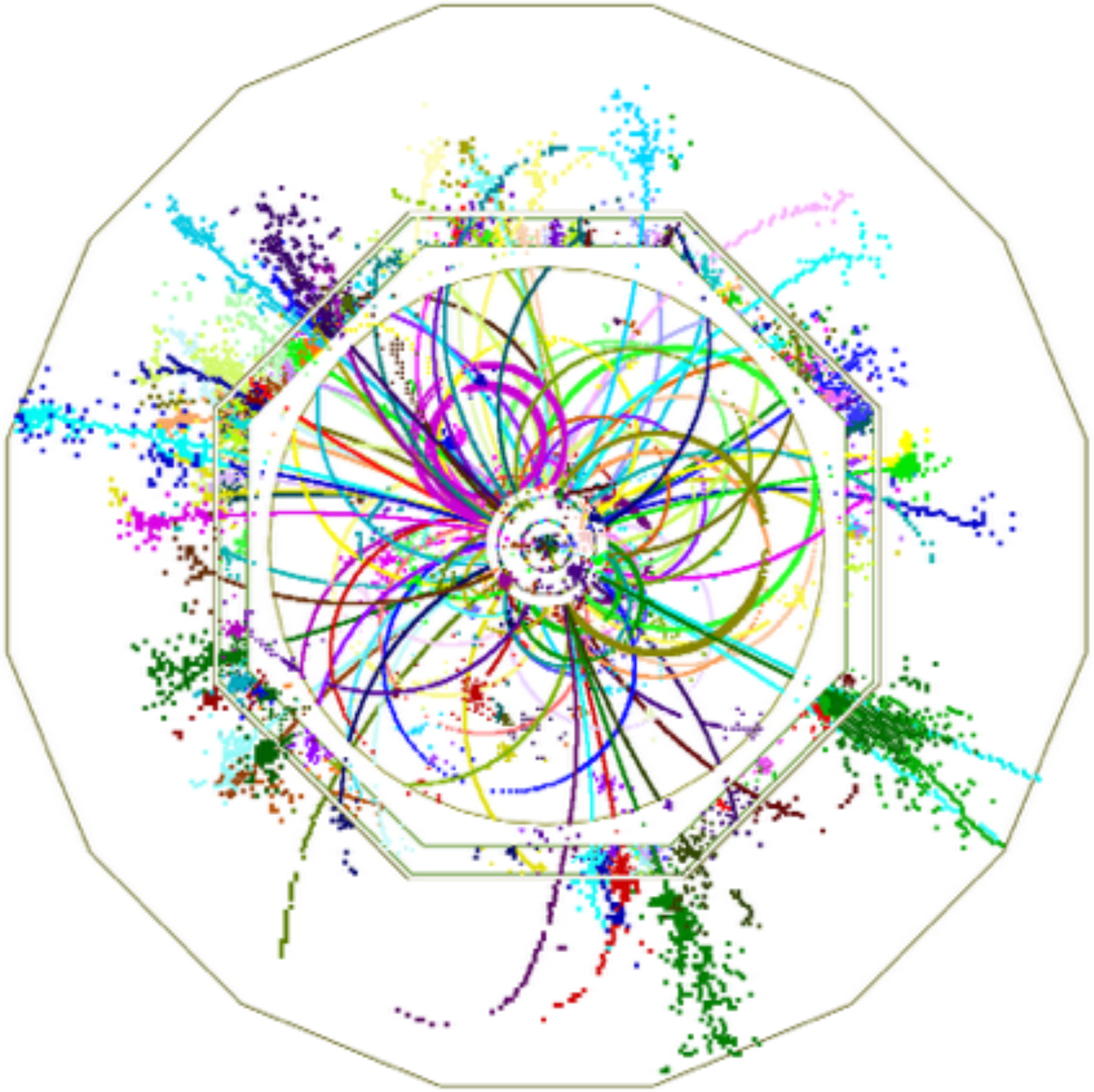
directly depends on mass resolution



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

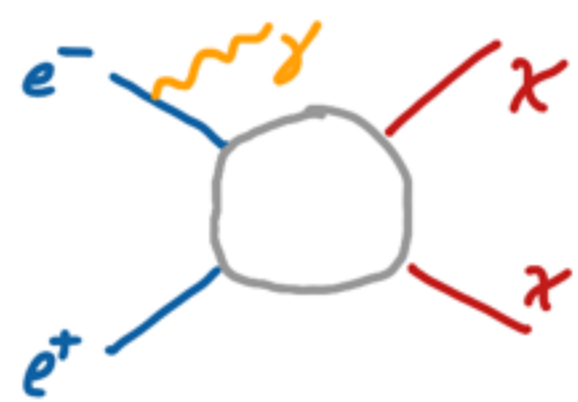
… and the resulting Detector Requirements III

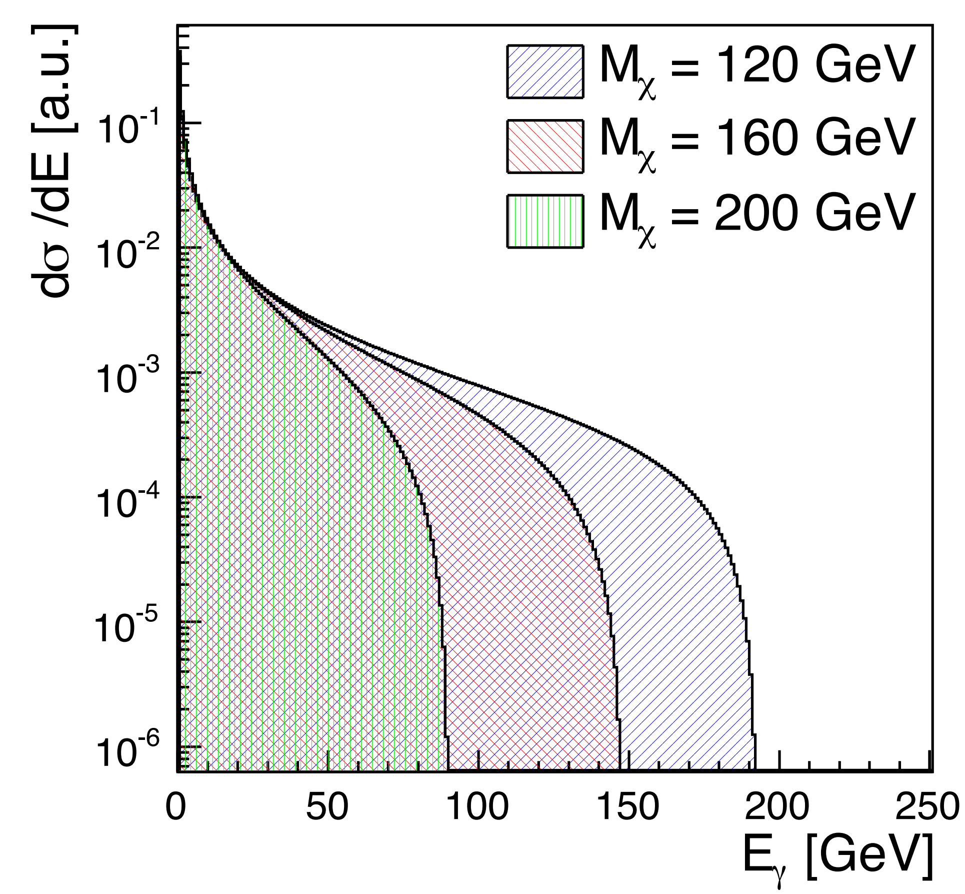


$$e^+e^- \rightarrow ttH \rightarrow q\bar{q}b\, q\bar{q}\bar{b}\, b\bar{b}$$

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:

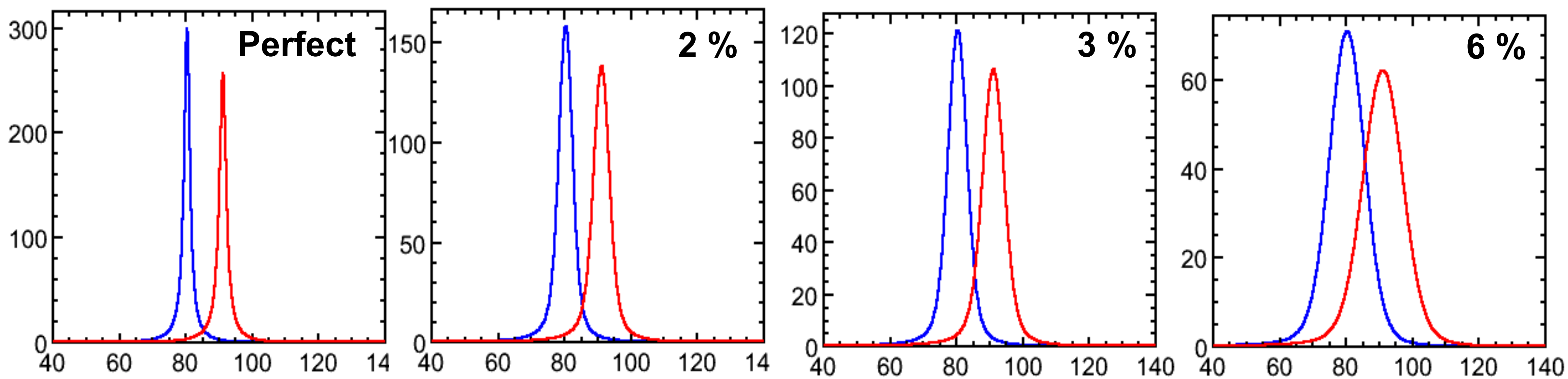
$$\sigma_b < 5 \oplus 10/p\beta \sin^{3/2}\theta \ \mu\text{m}$$

- 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)

$\Delta E_{Jet}/E_{Jet}$ ~ 3.5%



… and designing a Detector

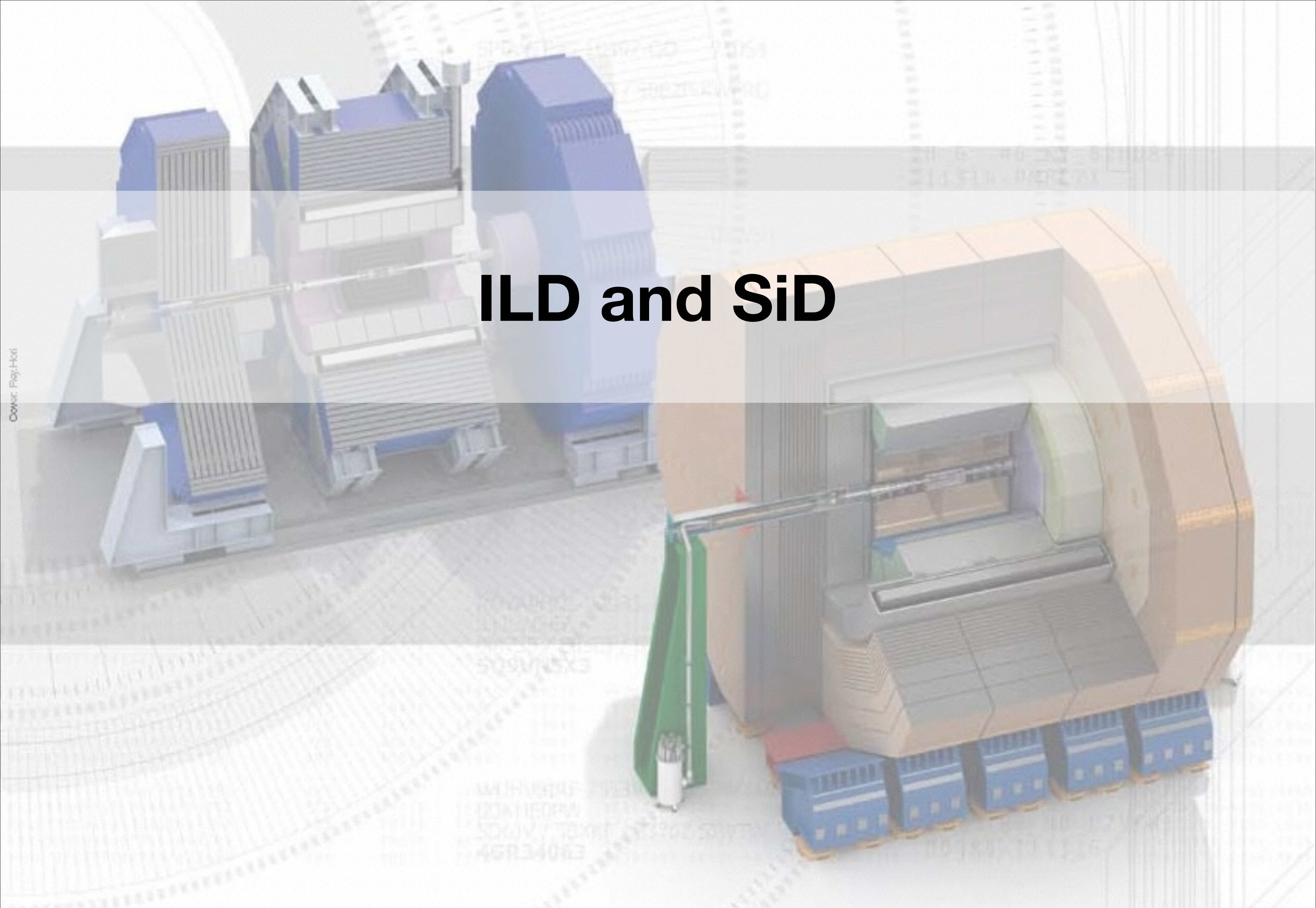
- A multi-layer pixel detector with small pixels close to the interaction point
- High resolution tracking detectors
- A strong magnetic field
- Low material budget - Eliminate multiple scattering as much as possible
- Imaging calorimeters inside of the magnet & particle flow algorithms

… 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

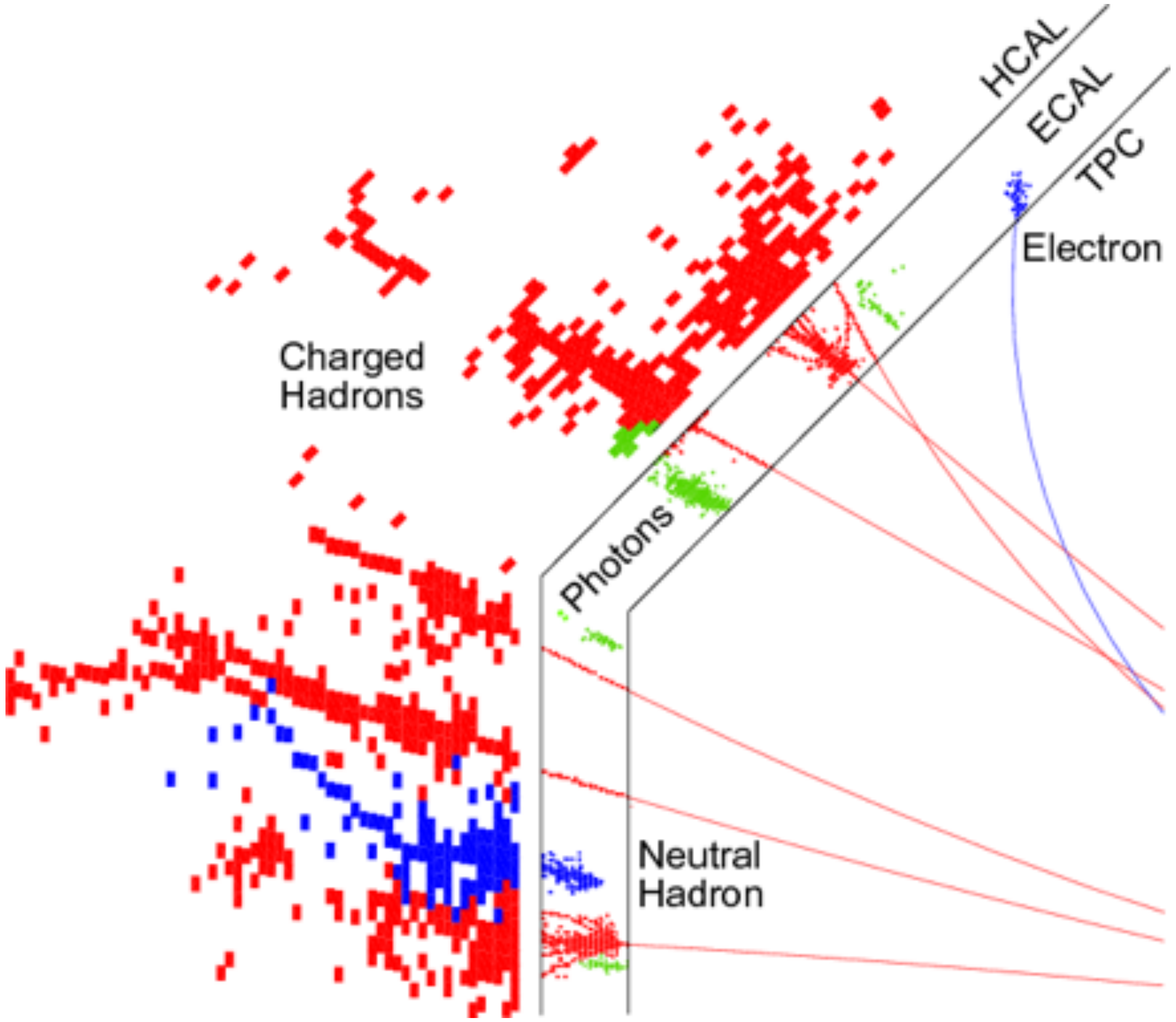
Where this leads you: A detector design a bit like CMS, but

- 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,...



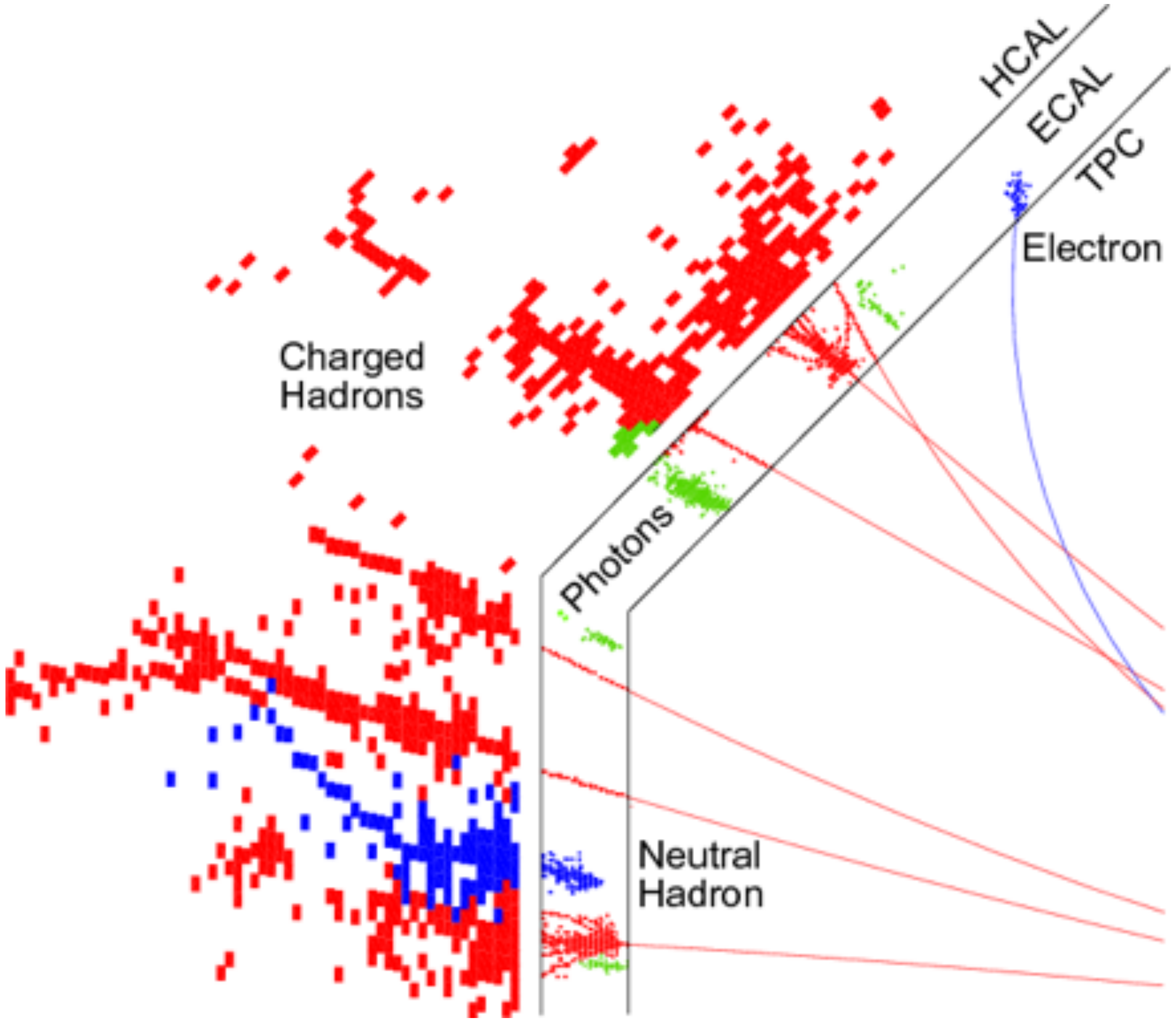
ILD and SiD

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 ($\boldsymbol{p}$ in tracker, $\boldsymbol{E}$ in calorimeters)

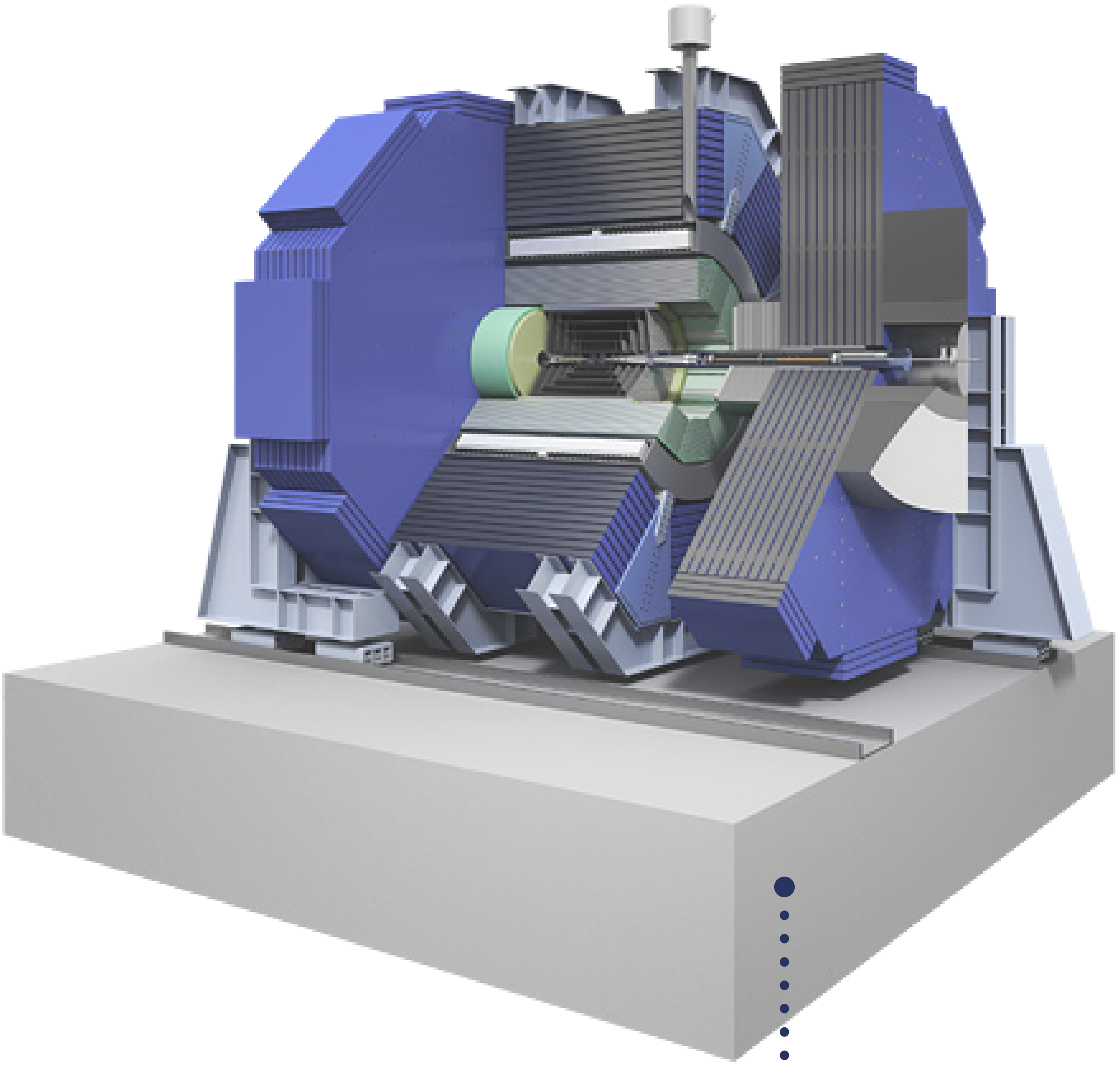
The Fundamental Design Principle: Particle Flow



- 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)

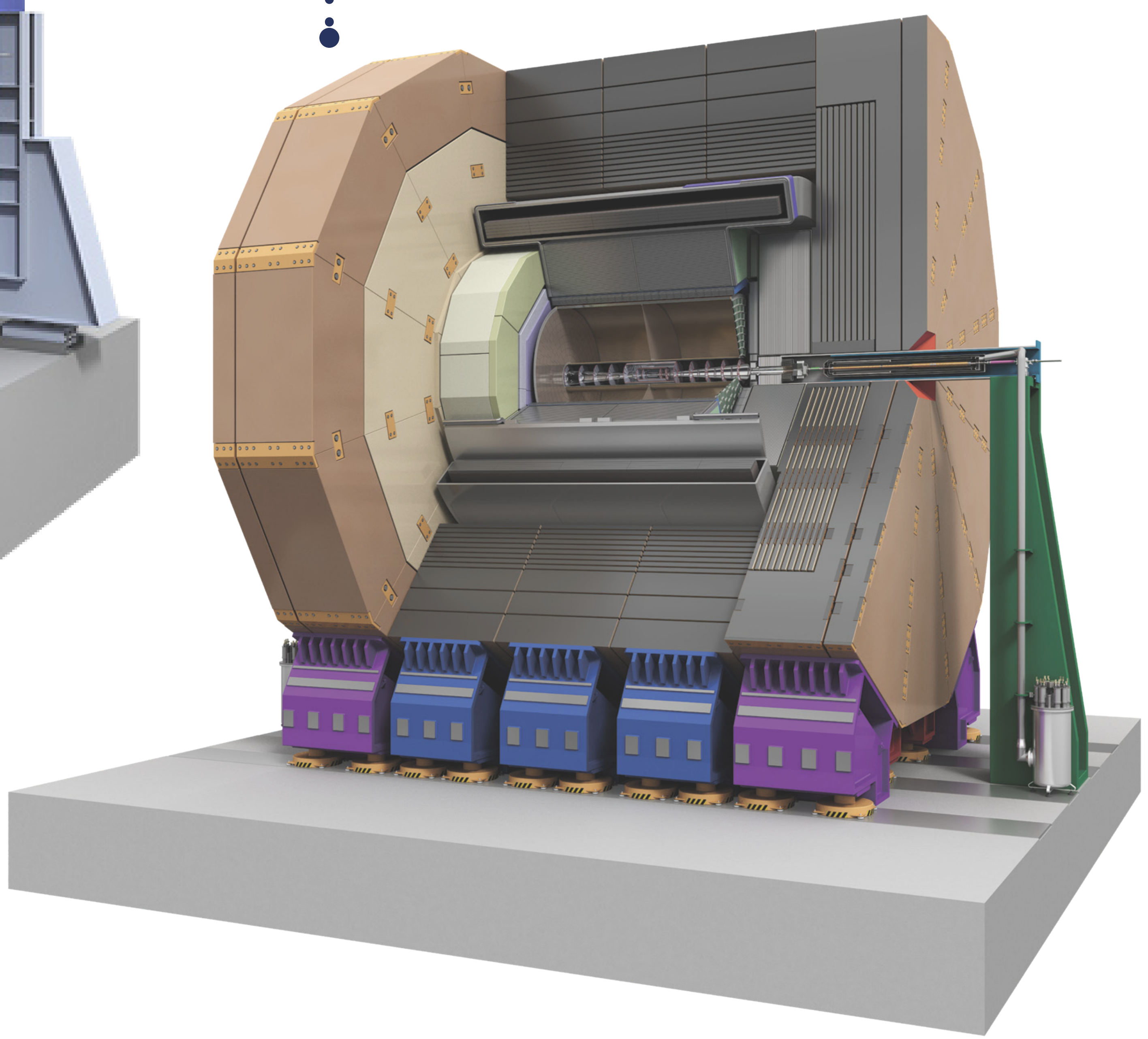
- Separation of close-by particles often more important than pure energy resolution
  - ▸ Highly granular detector systems, in particular also in the calorimeters!

ILD & SiD - Similar Concepts, Different Realization

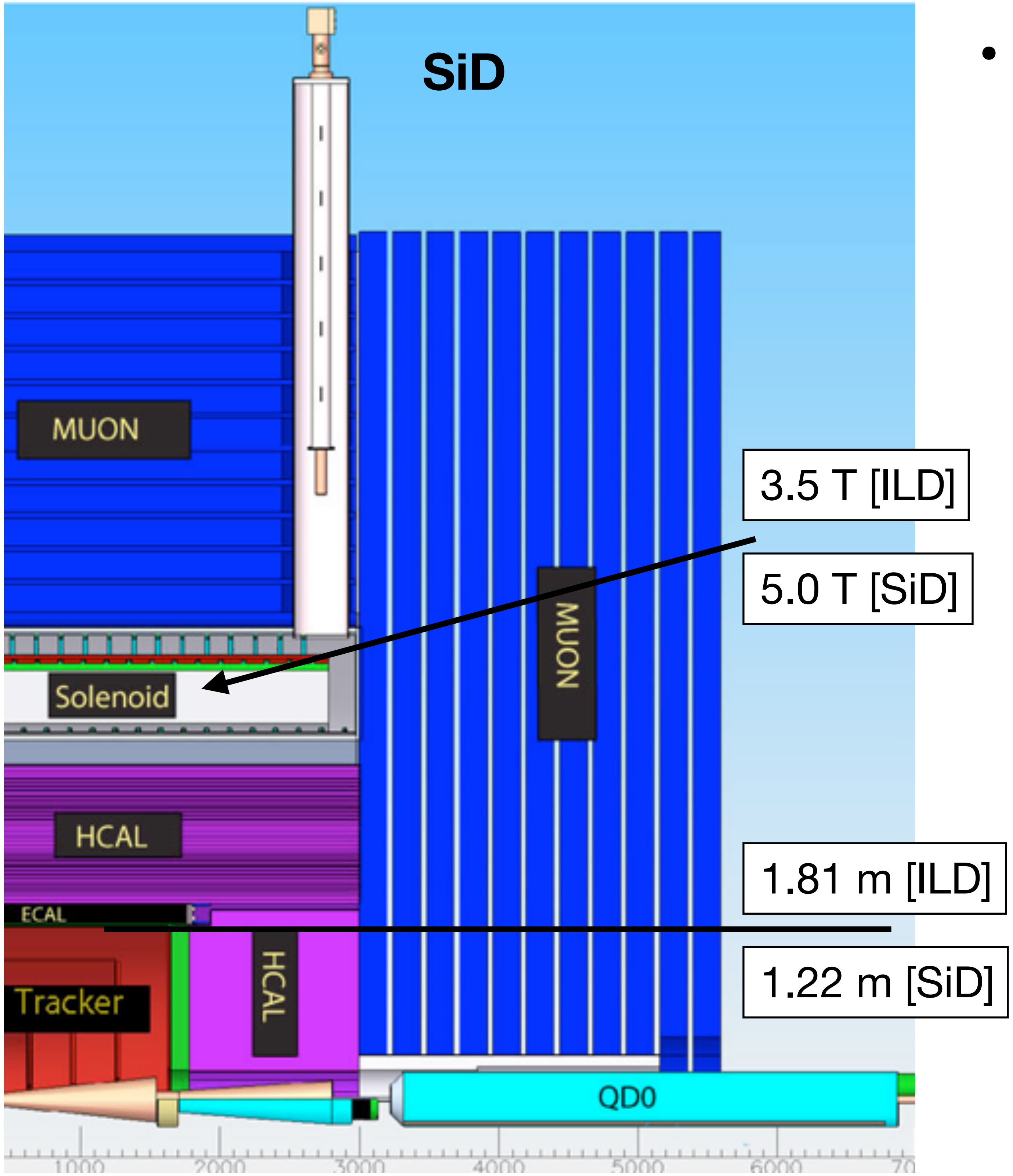


SiD (Silicon Detector)

ILD (International Large Detector)

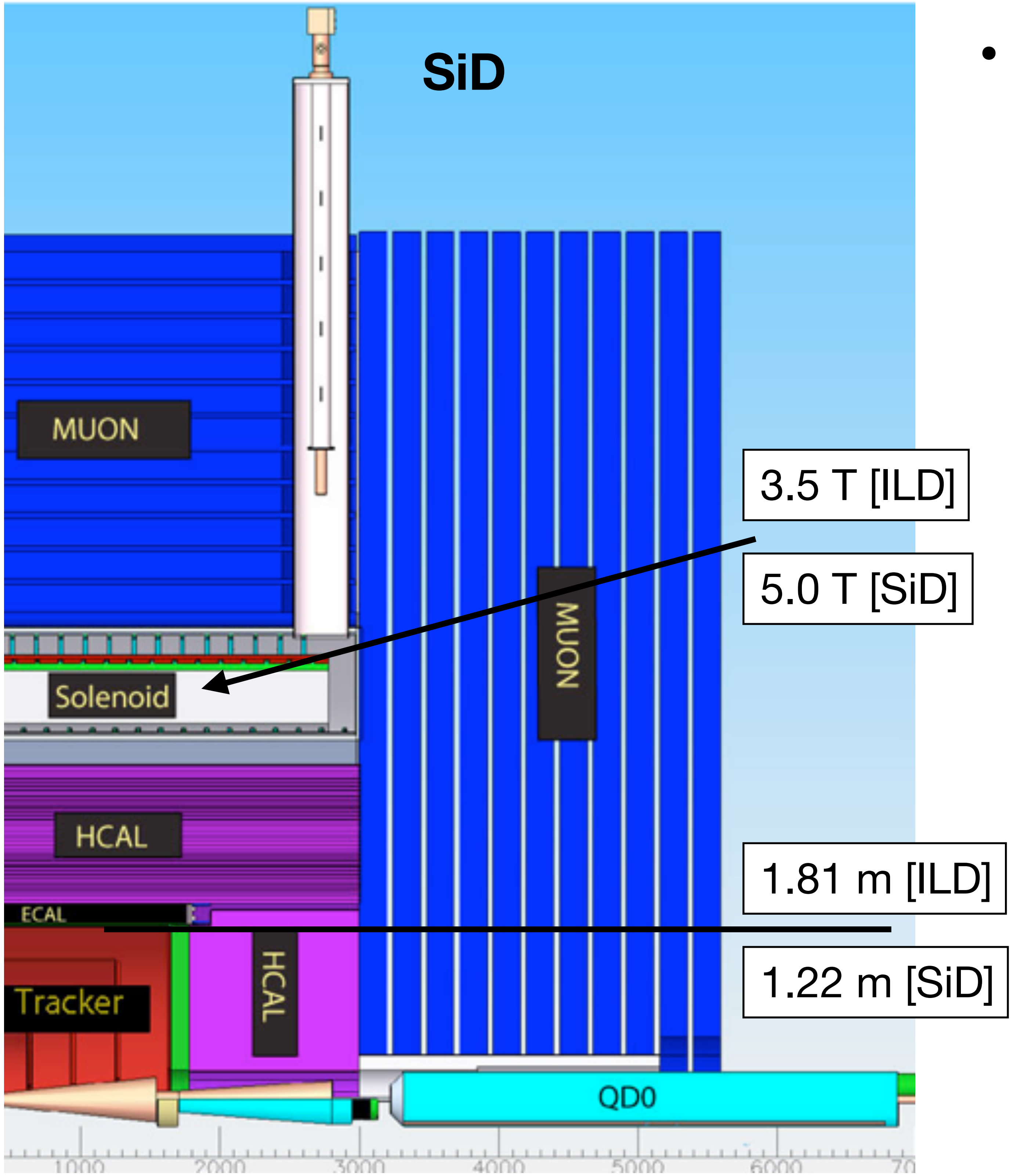


Two Slightly Different Approaches: ILD & SiD



- 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

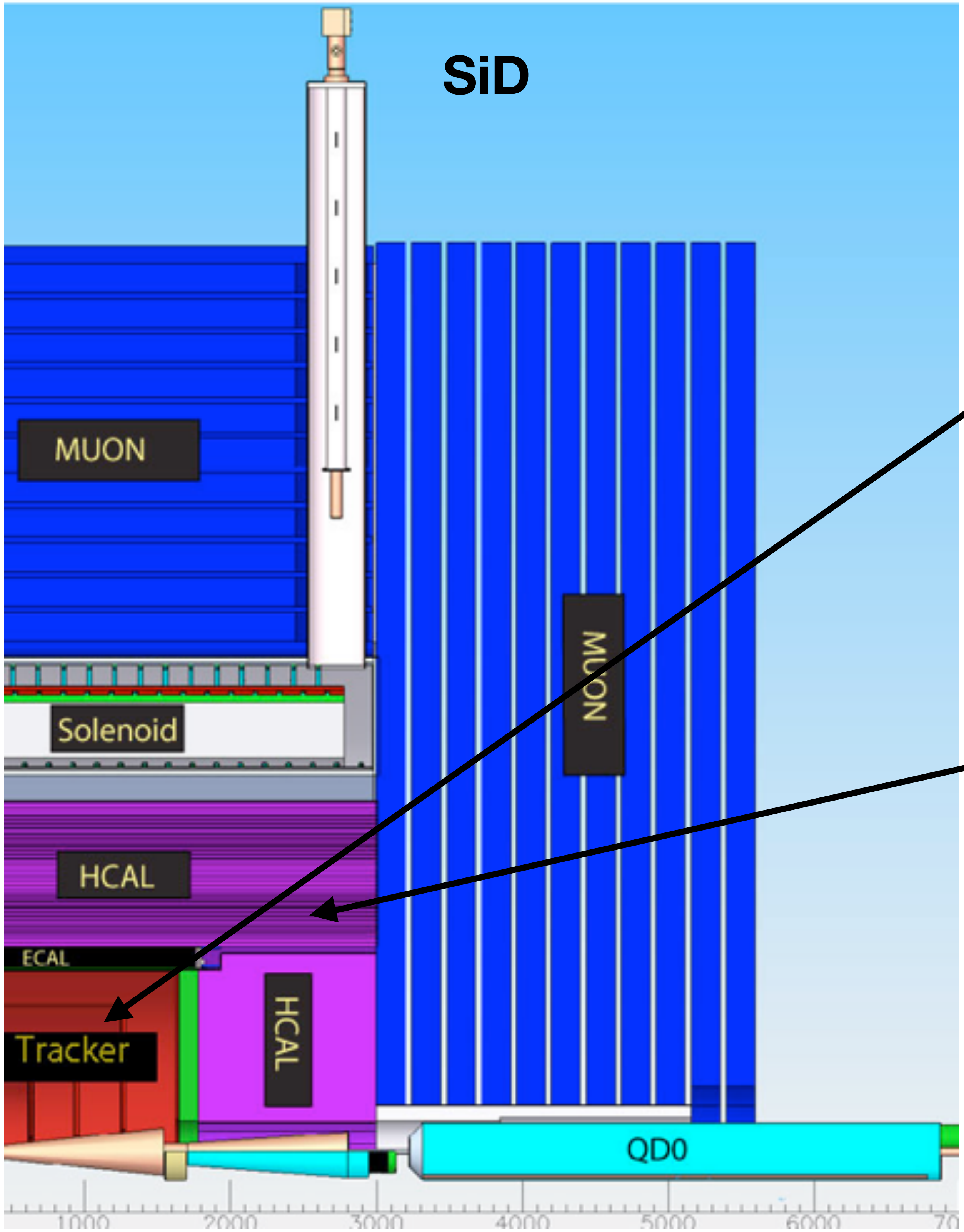
Two Slightly Different Approaches: ILD & SiD



- 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

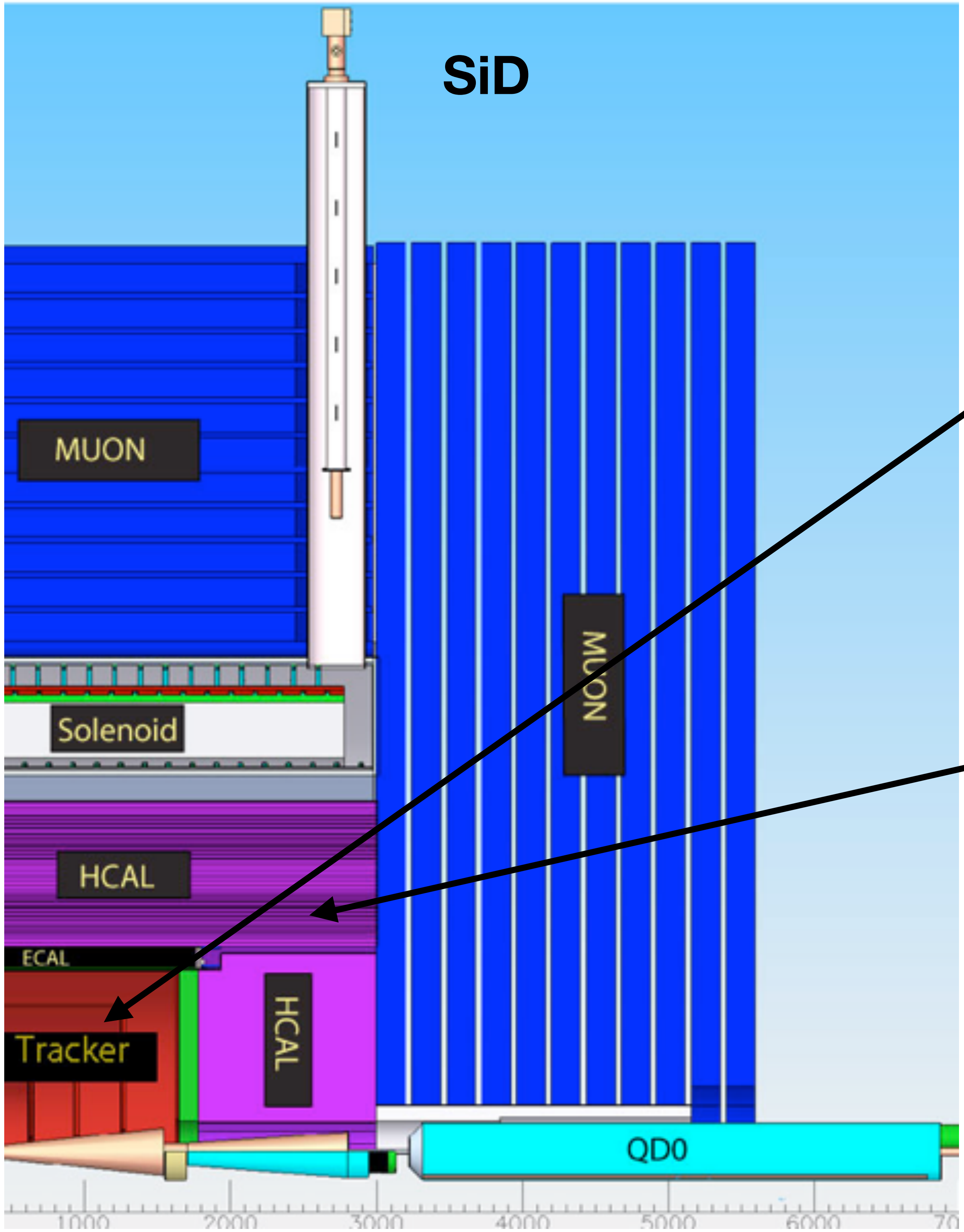
N.B. : Solenoid cost (and technical feasibility) steeply scales with field and radius => Either large radius or high field!

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

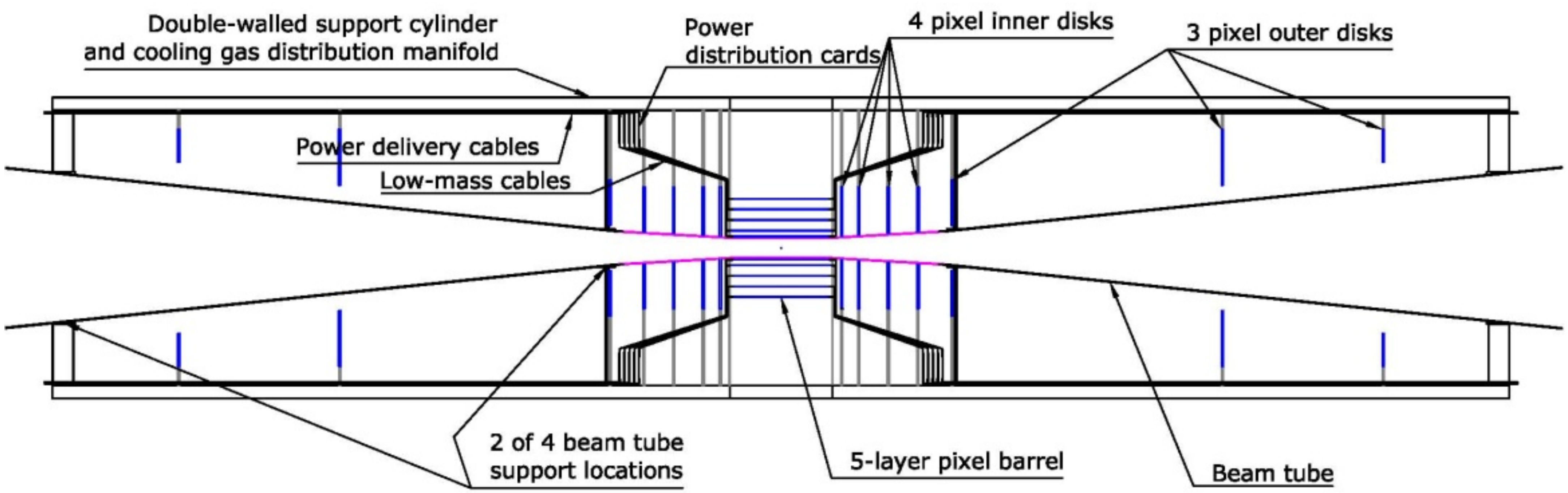


- Different choices in tracker technology: Trade number of measurements and precision of individual measurements
  - Five-layer all-Si tracker in SiD
  - TPC with > 200 space points on a track in ILD (NB: To reach resolution goal, an additional Si layer outside of the TPC is required!)
- Trading cost 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

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

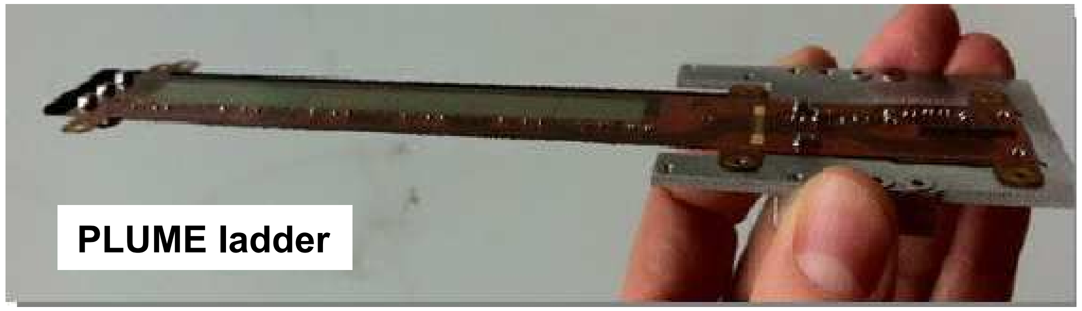
The Vertex Detector - Technological Possibilities

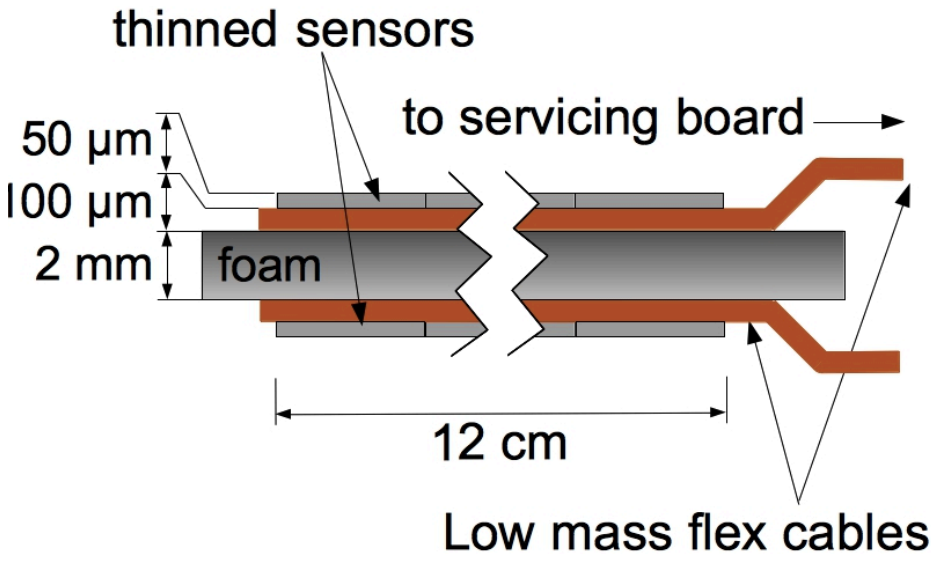
- A wide range of technologies under study for both ILD and SiD
  - CMOS MAPS, DEPFETs, SOI, FP-CCDs, 3D integrated sensors
  - ‣ All require thinned silicon on the 50 μm level
  - Very light-weight supports, no liquid cooling to achieve material budget goals
  - ‣ Low power consumption crucial to allow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

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

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

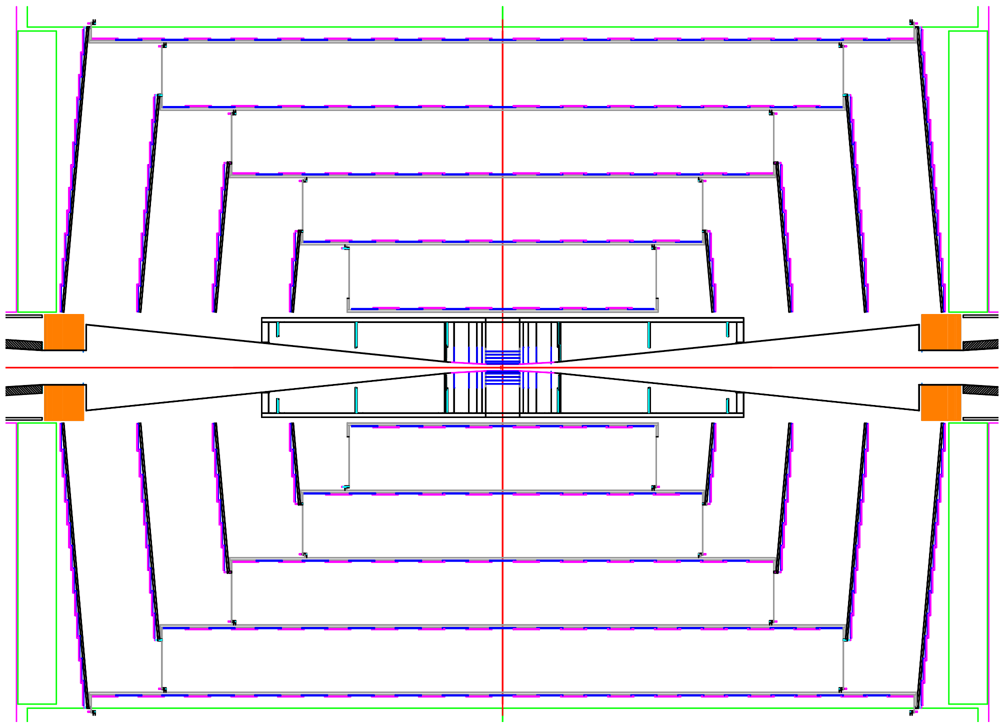




- first prototype with 0.6% X_0 total budget demonstrated in test beam
- Improved prototype with 0.35% X_0 in construction

The Main Tracker: Two quite different Approaches

SiD: all silicon tracker

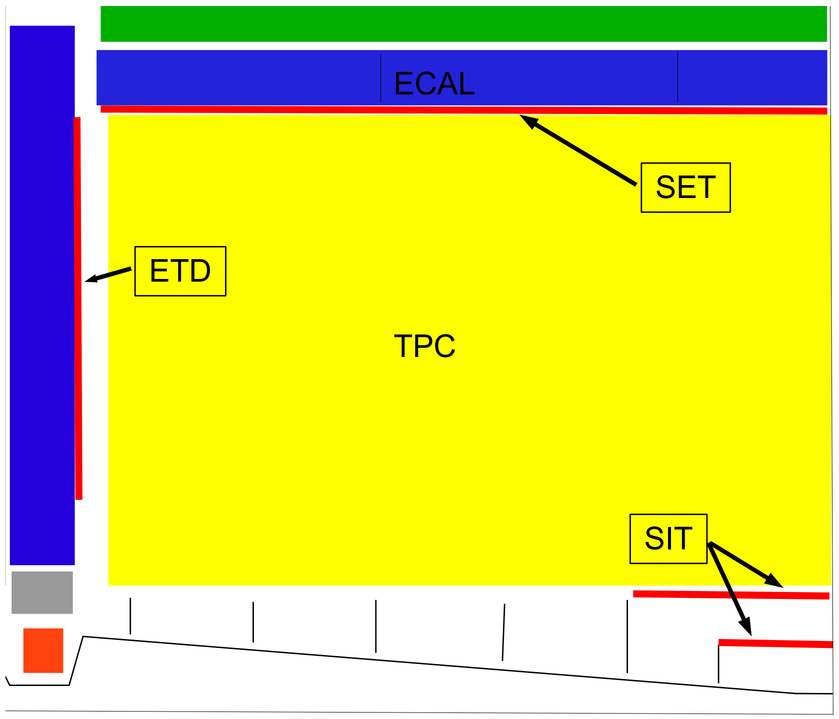


- 5 barrel layers, axial-only measurement
- 4 discs, stereo layers

central tracks:

- 5 measurements, 8 µm precision

ILD: TPC, augmented with Si trackers

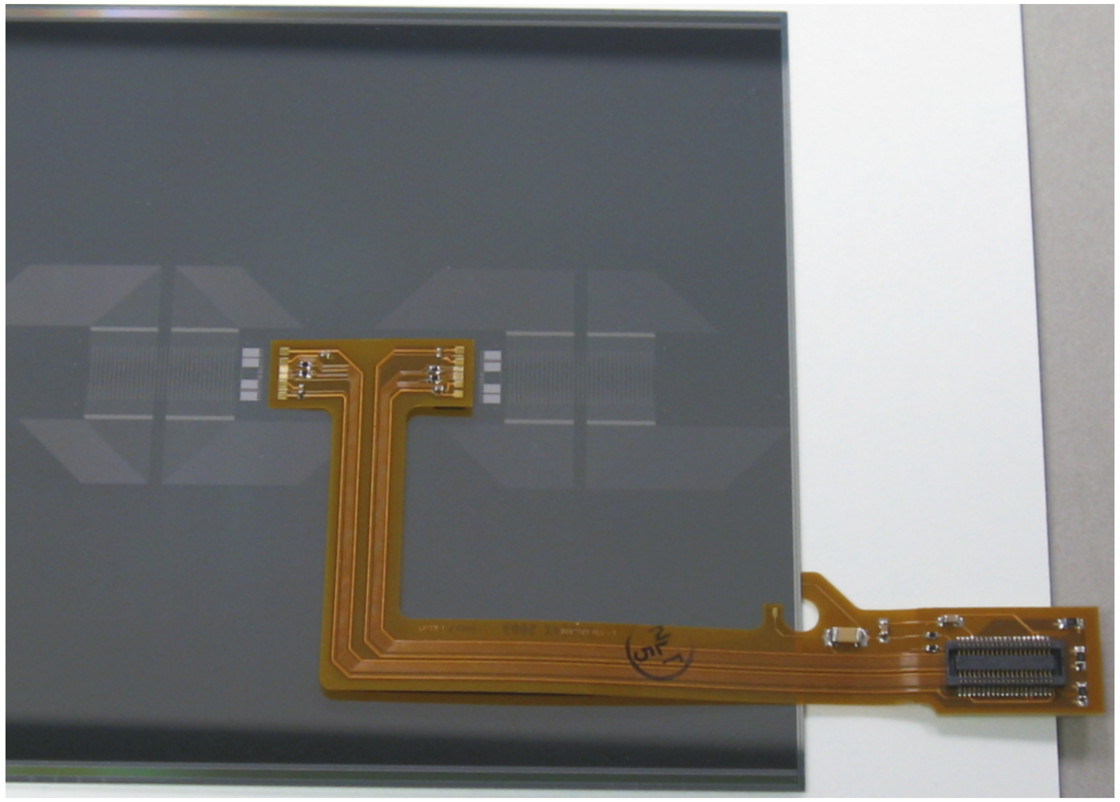


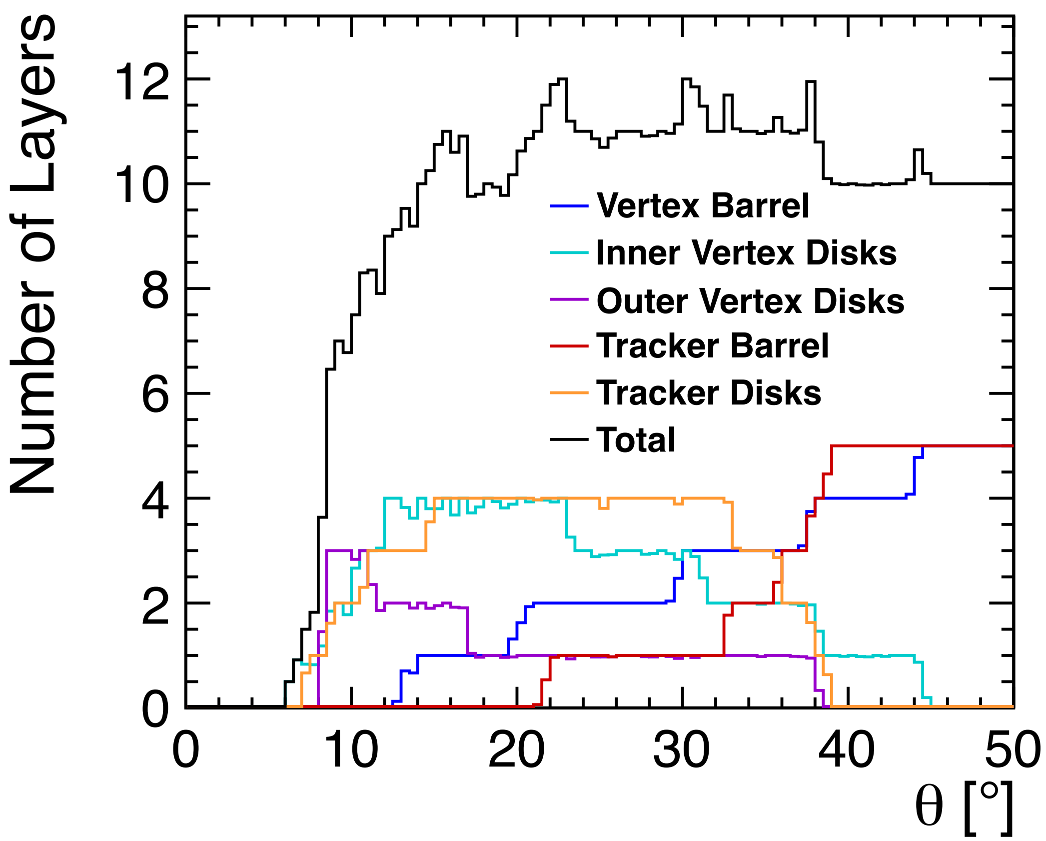
- one stereo strip layer outside of TPC (SET, ETD)
- two stereo strips inside (SIT)

central tracks:

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

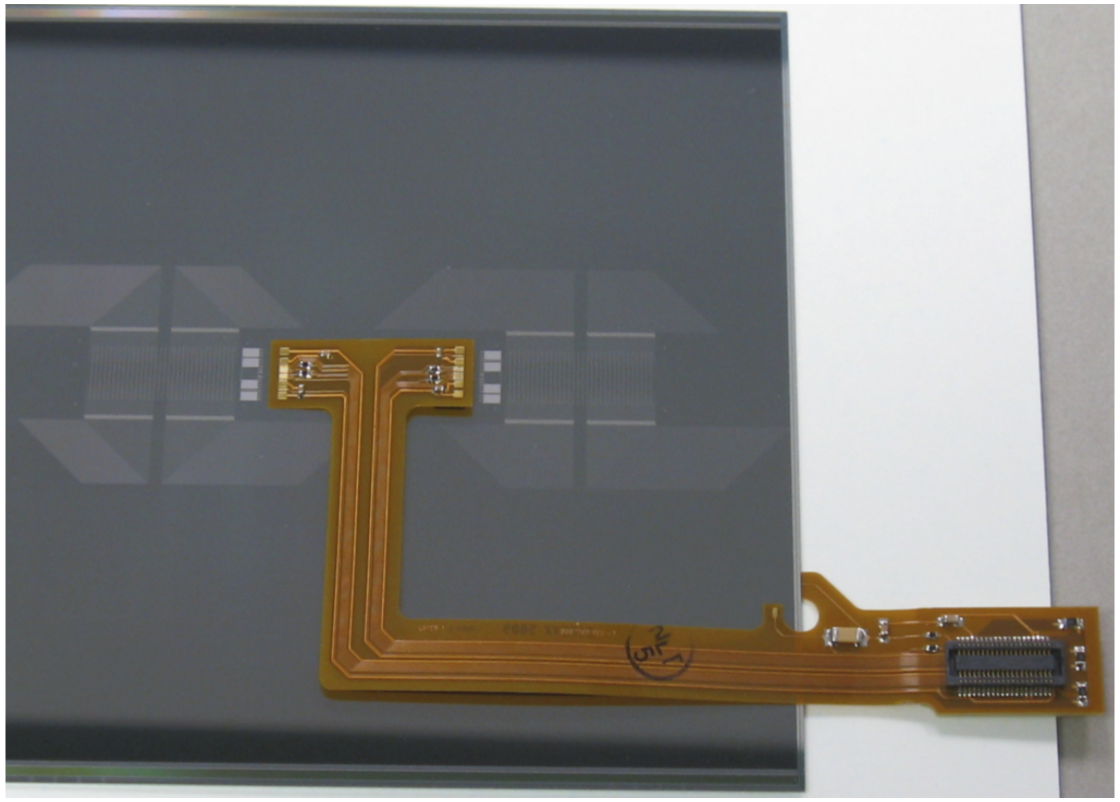
The SiD Main Tracker



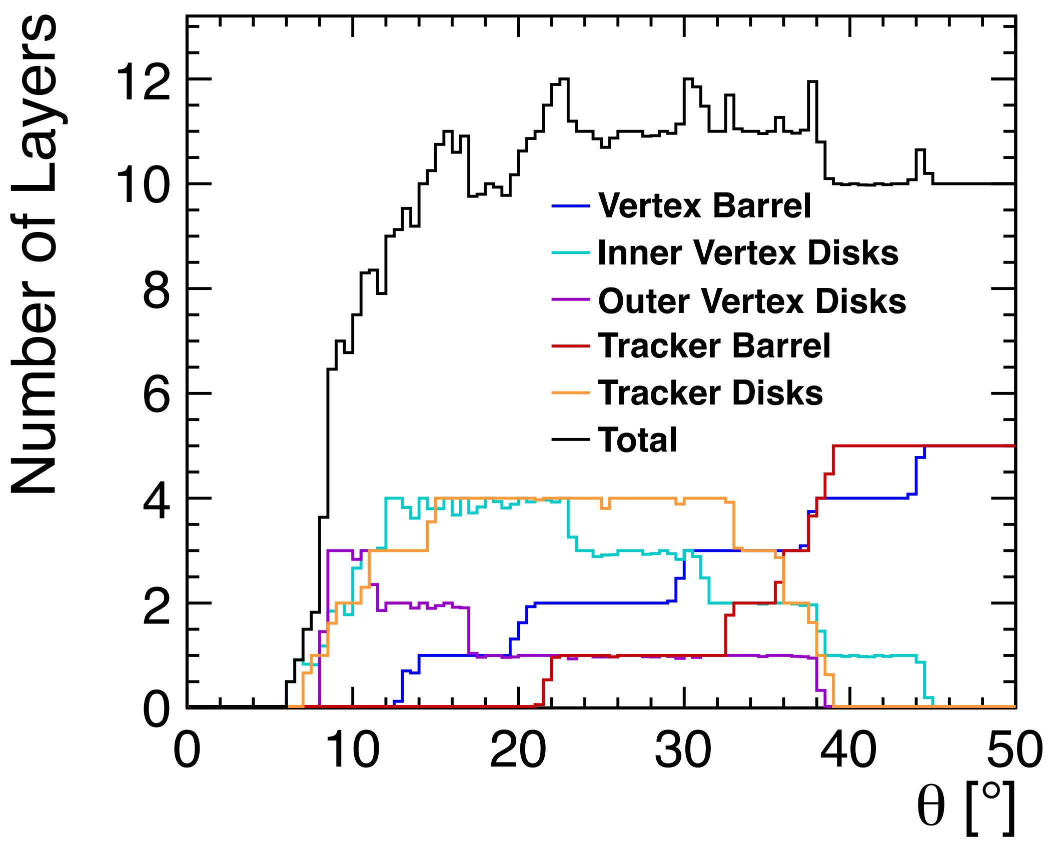


- Very low-mass design:
  Front-end chip directly bonded on silicon sensor
  - no need for electronics hybrid
- Compact electronics: KPIX chip, 1024 readout channels per ASIC

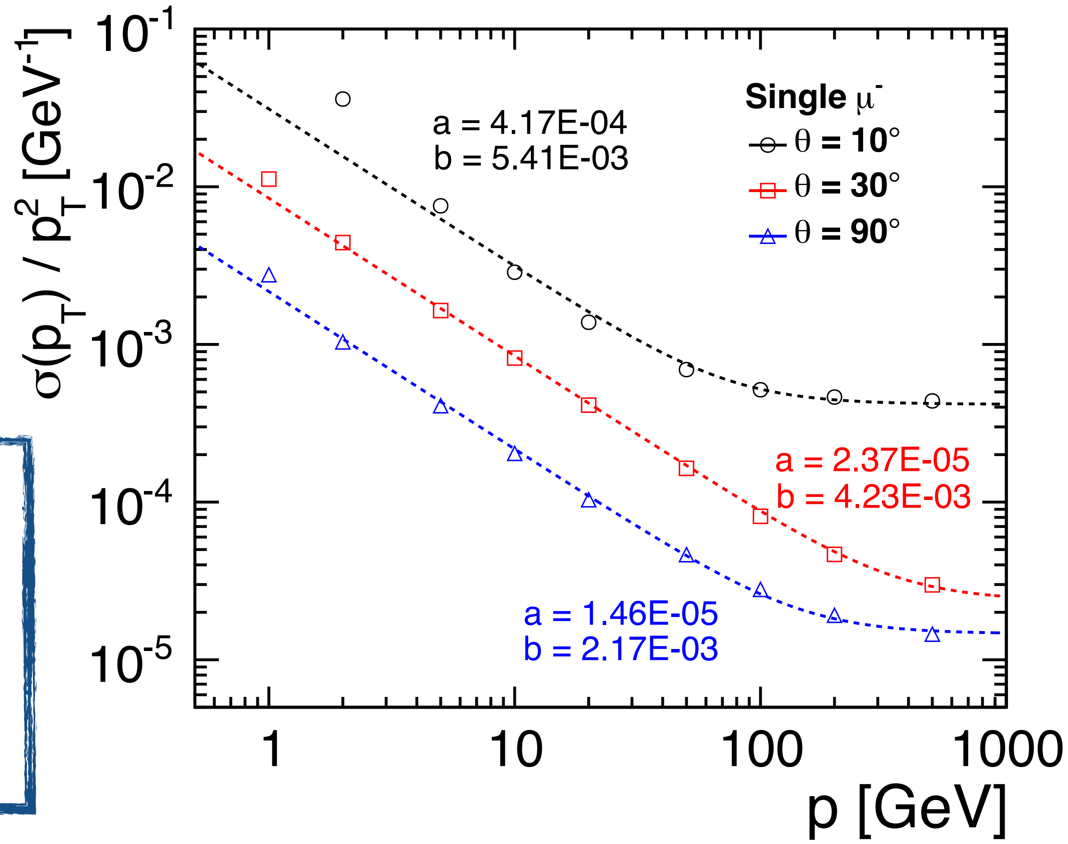
The SiD Main Tracker



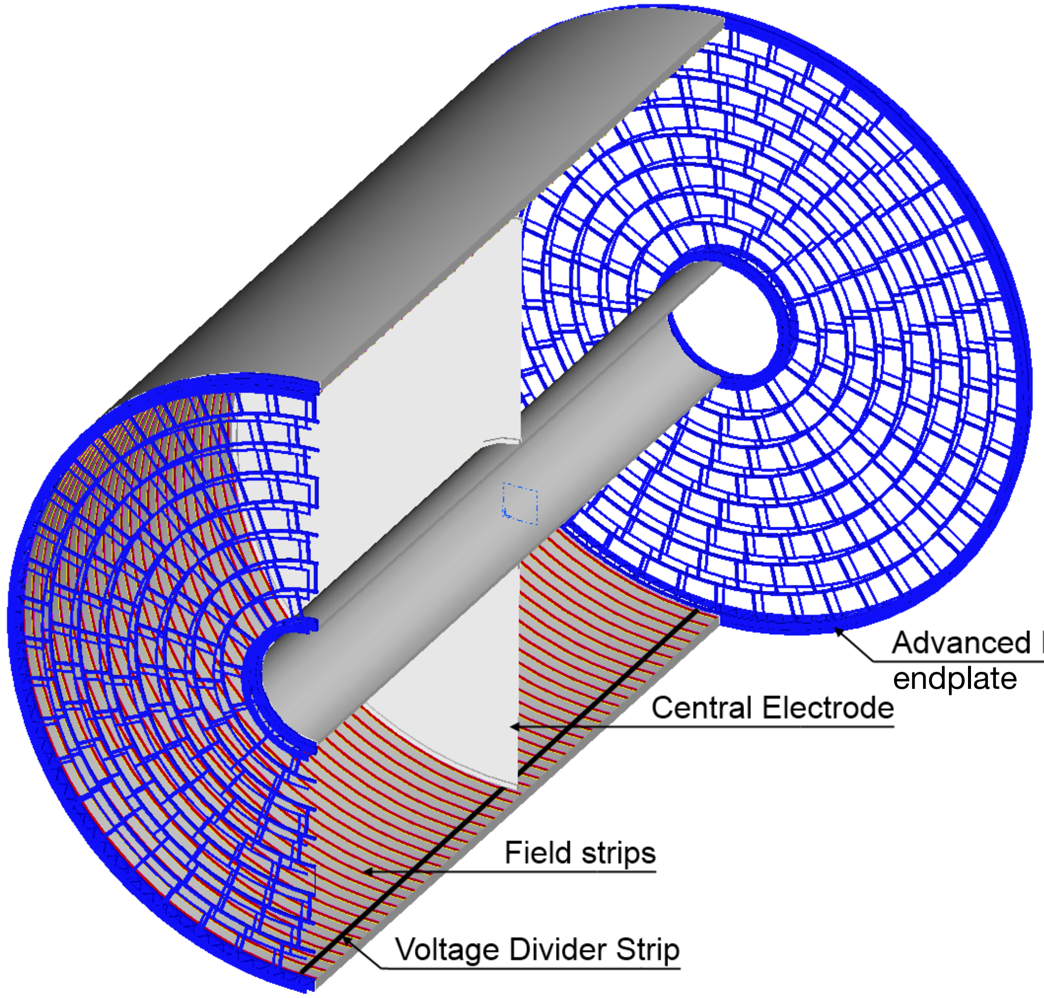
- Very low-mass design:
  Front-end chip directly bonded on silicon sensor
  - no need for electronics hybrid
- Compact electronics: KPIX chip, 1024 readout channels per ASIC

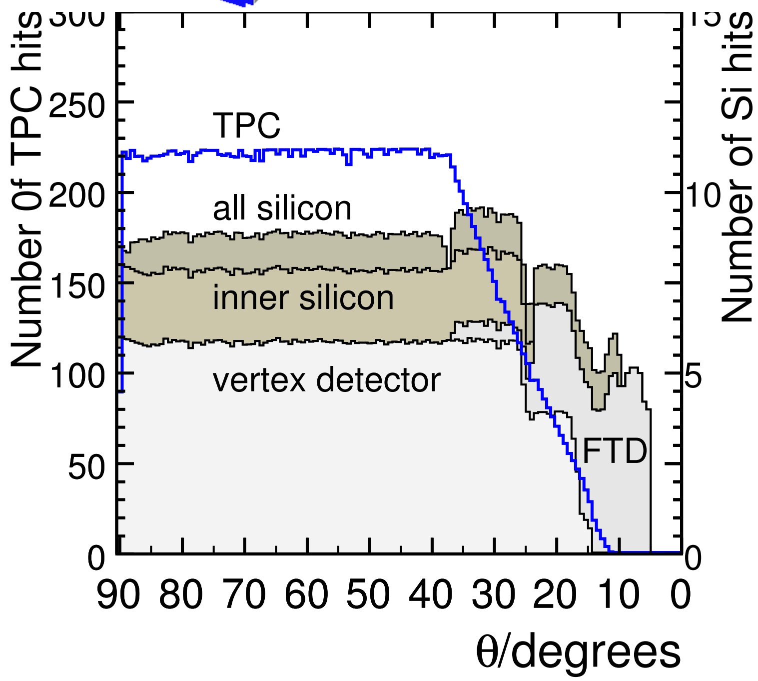


exceeds ILC resolution goals in full simulation studies

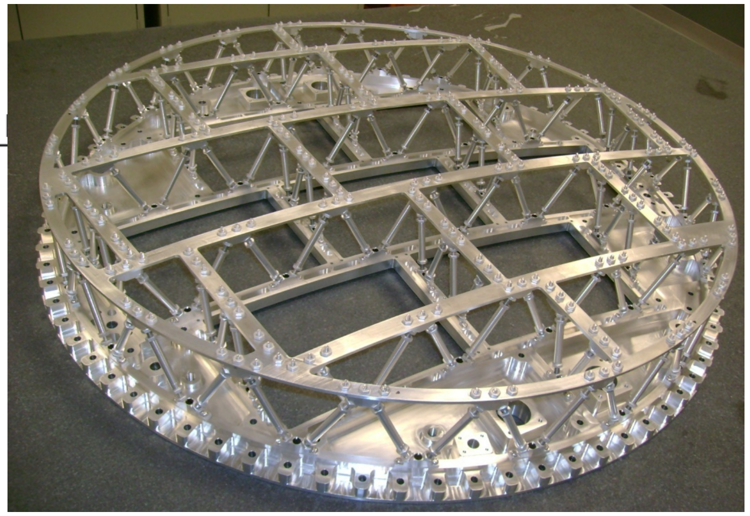


The ILD Main Tracker





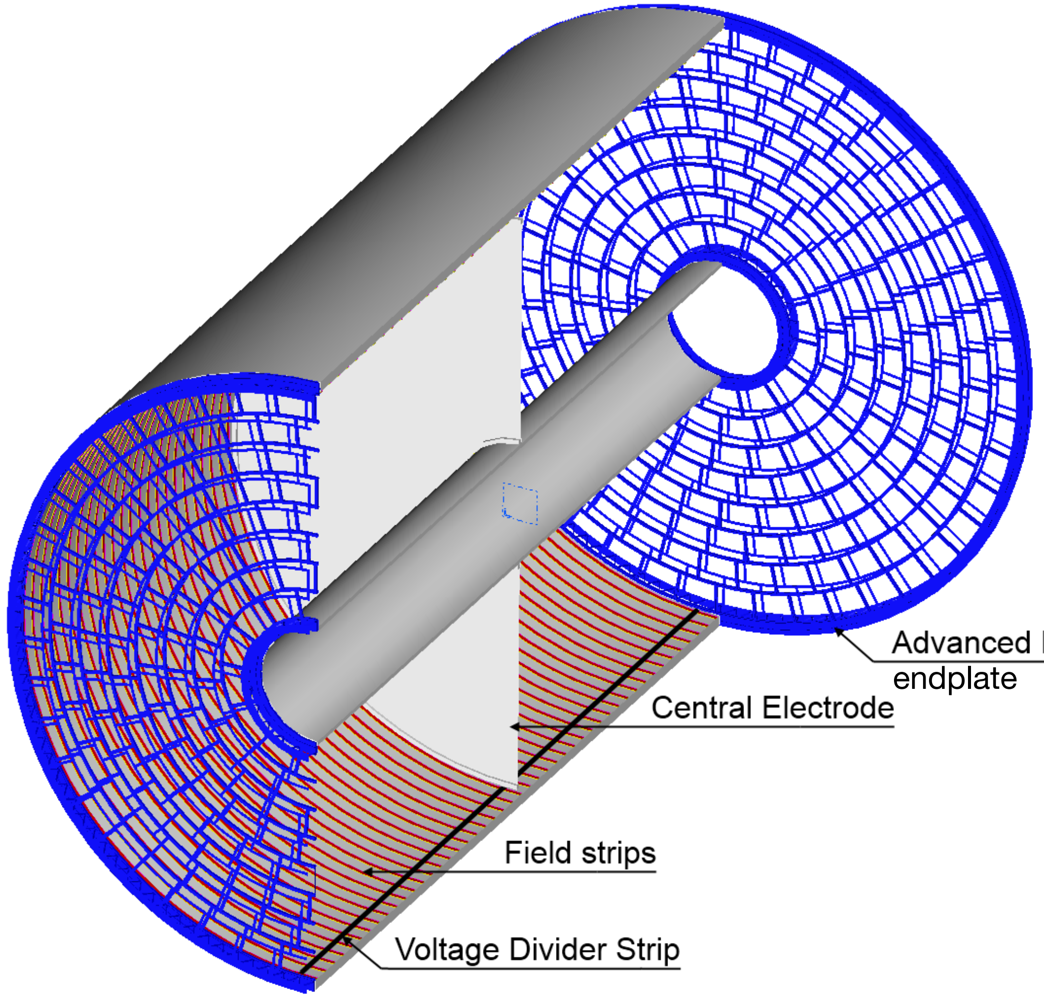
- Large-volume TPC with MPGD readout in endplate, 1 x 6 mm^2 pads
  - Different technologies under investigation, including μMegas, GEMs, - in general w/o gating - needs strong ion feedback suppression

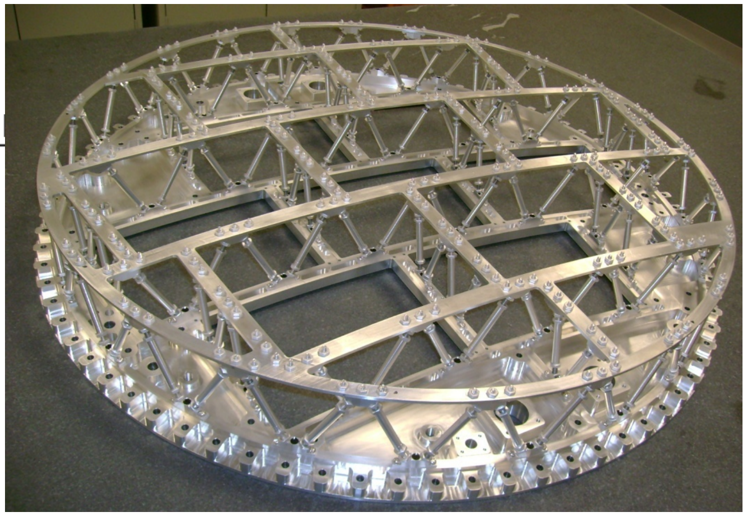


Large prototype with low-mass end-plate, to be tested with μMegas, GEMs

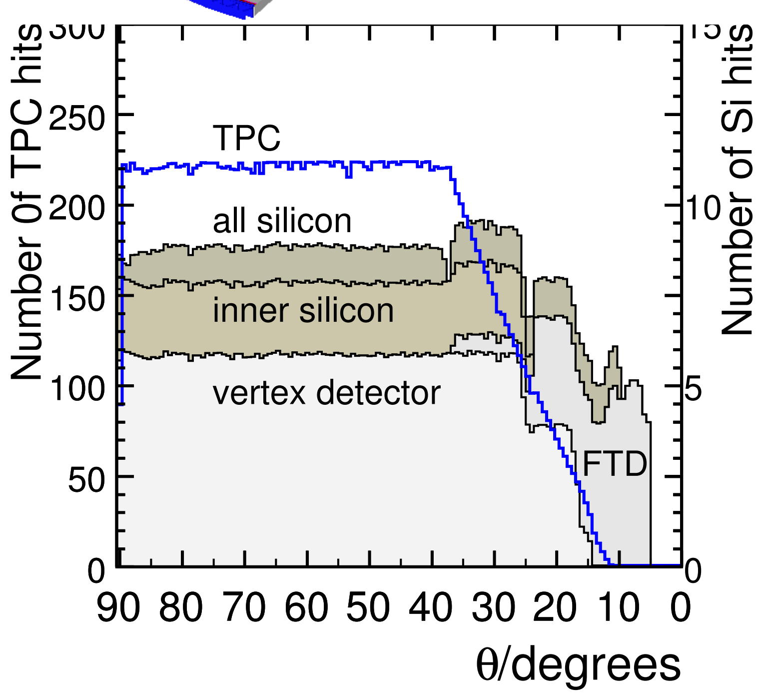
The ILD Main Tracker

- 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

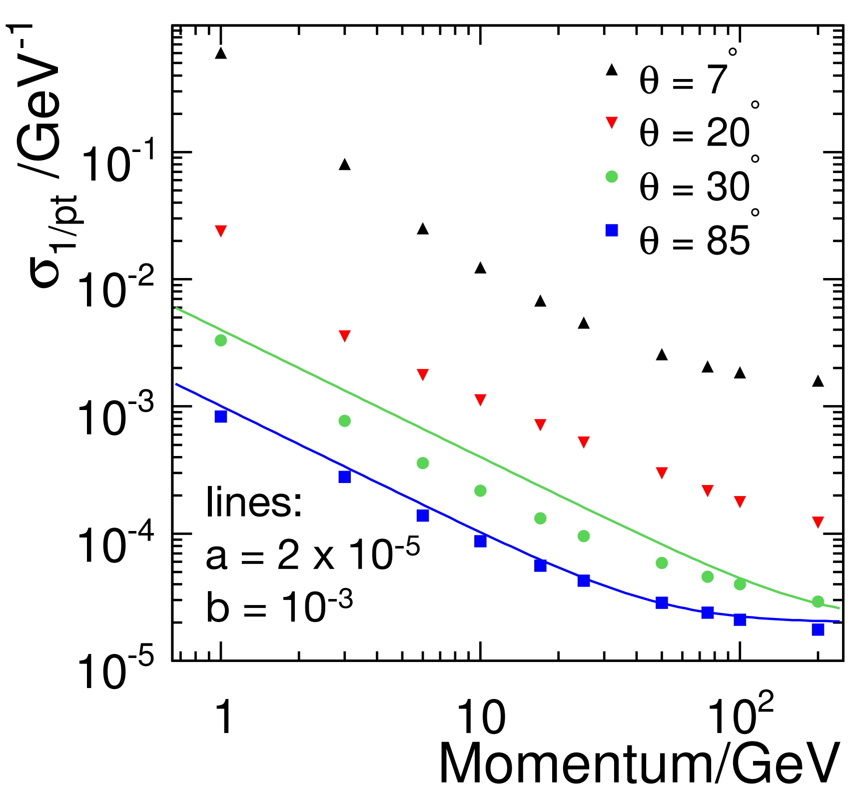




Large prototype with low-mass end-plate, to be tested with μMegas, GEMs



meets ILC resolution goals in full simulation studies



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)
  - HCAL: length scale ~ λ_I, but em subshowers impose requirements not too much different than in ECAL

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)
  - HCAL: length scale ~ λ_I, but em subshowers impose requirements not too much different than in ECAL

Depends on material:
- 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!

When adding active elements: ~ 0.5 cm^3 segmentation in ECAL, ~ 3 - 25 cm^3 in HCAL

➩ *O* 10^{7-8} cells in HCAL, 10^8 cells in ECAL! - fully integrated electronics needed.

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)
  - HCAL: length scale ~ λ_I, but em subshowers impose requirements not too much different than in ECAL

Depends on material:
- 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!

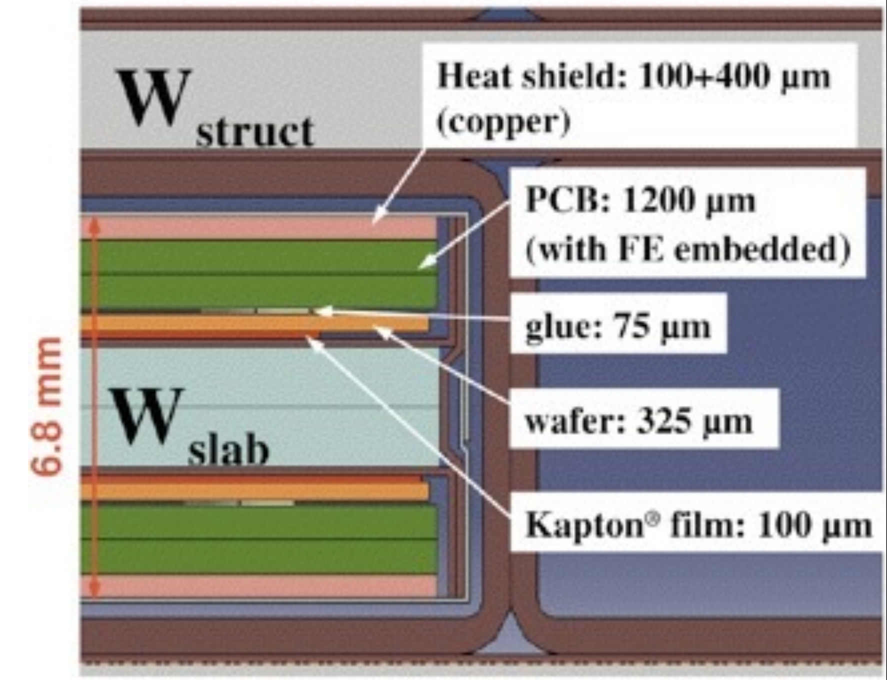
When adding active elements: ~ 0.5 cm^3 segmentation in ECAL, ~ 3 - 25 cm^3 in HCAL

➡ *O* 10^{7-8} cells in HCAL, 10^8 cells in ECAL! - fully integrated electronics needed.

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)

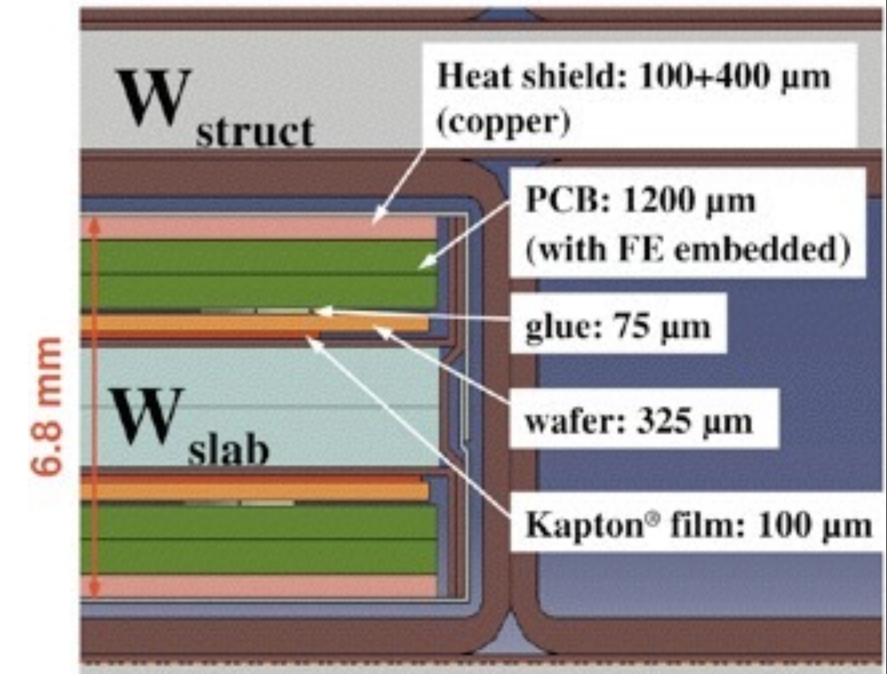
The ILD Calorimeters

- 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

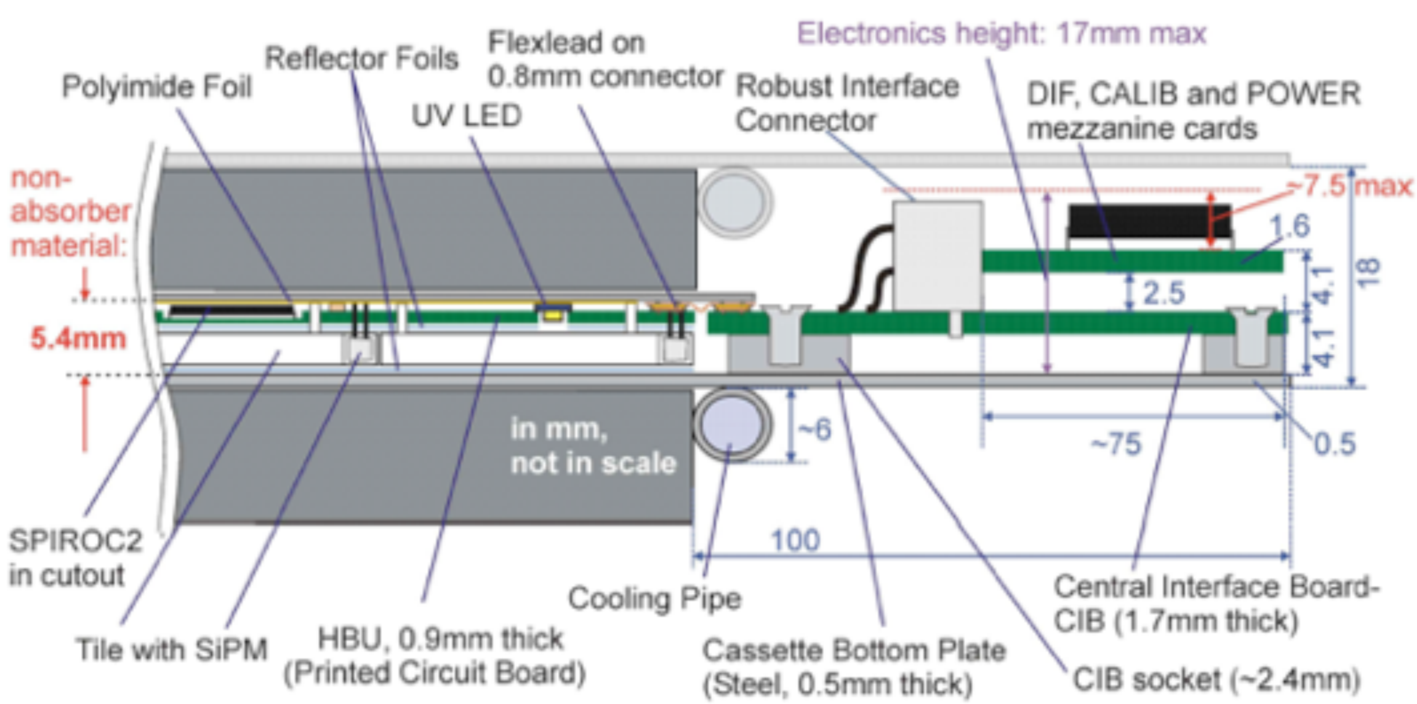


The ILD Calorimeters

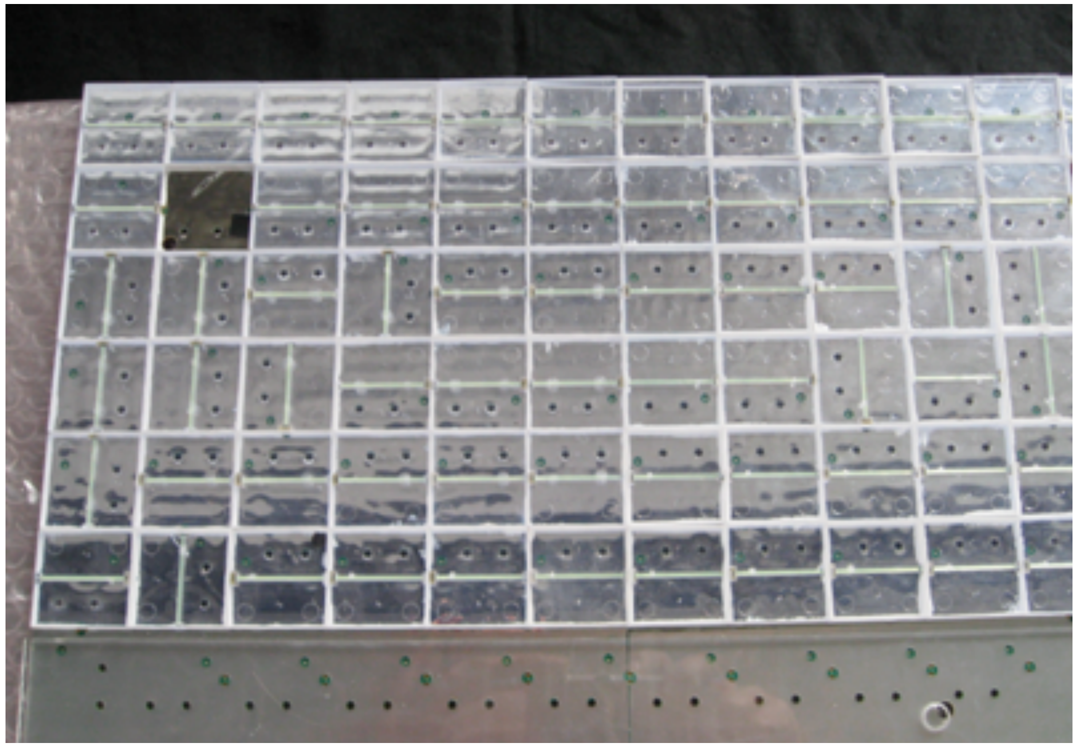
- ECAL: Si PIN diodes with 5 x 5 mm² pads or crossed scintillator strips with SiPM readout, 5 x 45 mm²
  - two longitudinal segments with different absorber thickness, a total of 30 layers with tungsten absorbers
  - integrated readout electronics on a PCB



- HCAL: Scintillator tiles (3 x 3 cm²) with SiPM readout or RPCs (µMegas) with semi-digital 3-threshold readout
6 λ_I - 48 layers, 2 cm steel absorber

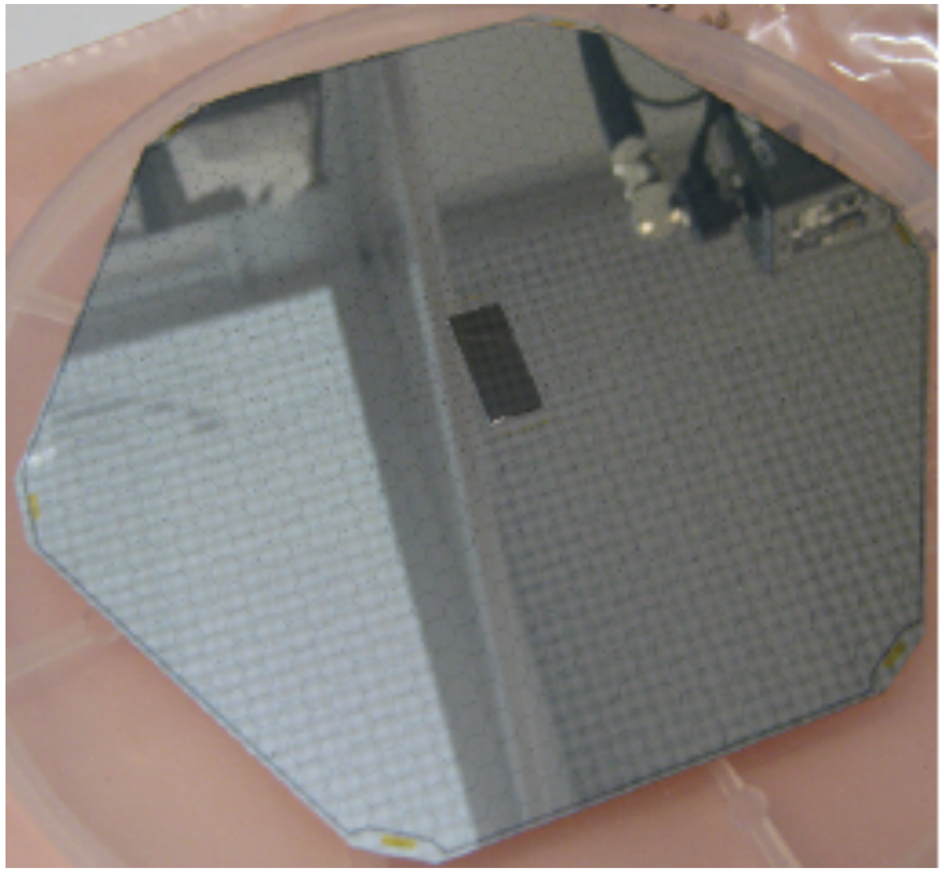


here: AHCAL



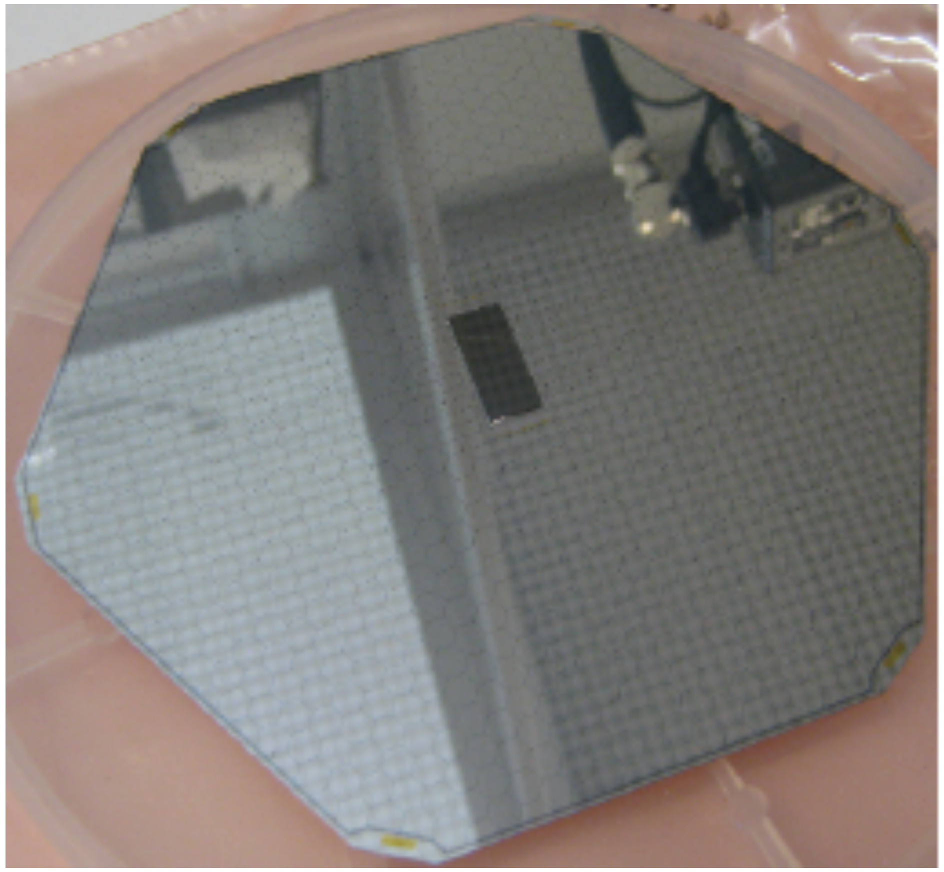
The SiD Calorimeters

- ECAL: Si PIN diodes with hexagonal pads (13 mm^2) or MAPS sensors with 50 x 50 μm^2 pixels
  - two longitudinal segments with different absorber thickness, a total of 30 layers with tungsten absorbers
  - ASIC directly bonded to Si wafer to reach thinnest possible active layers, ≤ 1.25 mm

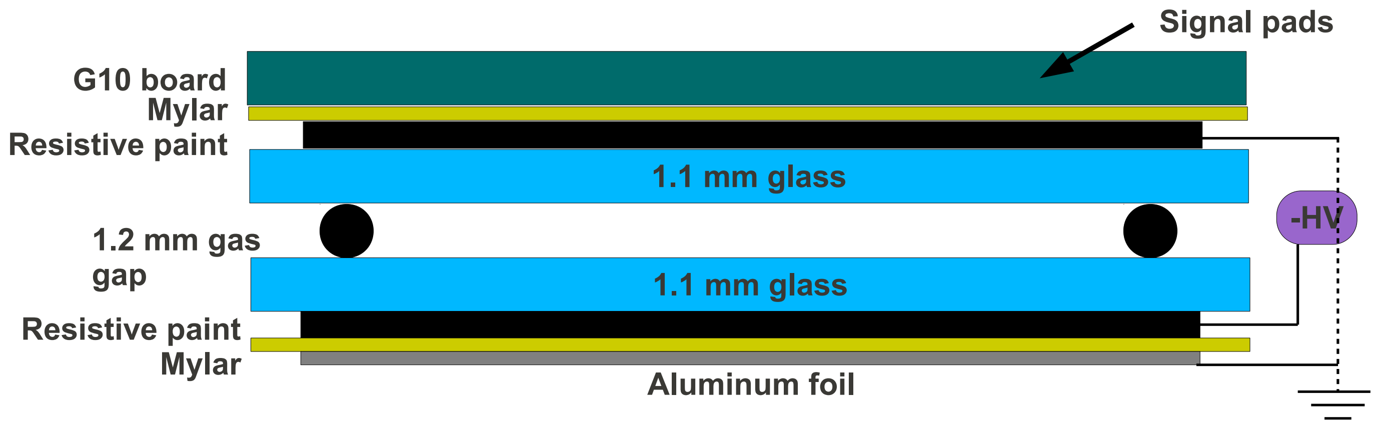


The SiD Calorimeters

- ECAL: Si PIN diodes with hexagonal pads (13 mm^2) or MAPS sensors with 50 x 50 µm^2 pixels
  - two longitudinal segments with different absorber thickness, a total of 30 layers with tungsten absorbers
  - ASIC directly bonded to Si wafer to reach thinnest possible active layers, ≤ 1.25 mm

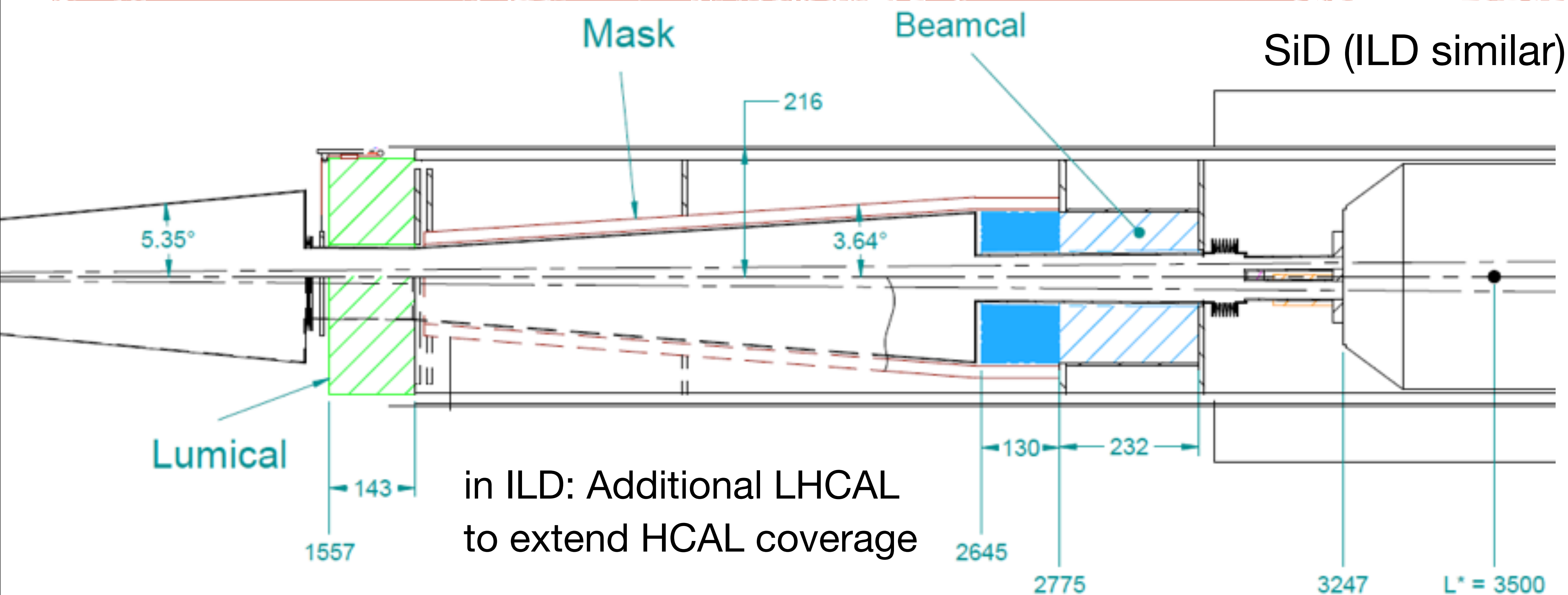


- HCAL: Digital calorimeter with 1 x 1 cm^2 cells, using RPCs, double GEMs / thick GEMs, µMegas, scintillator tiles with SiPMs and analog readout also considered
  - 4.5 λ_I thickness - 40 layers with 1.9 cm steel



1-glass RPC prototype

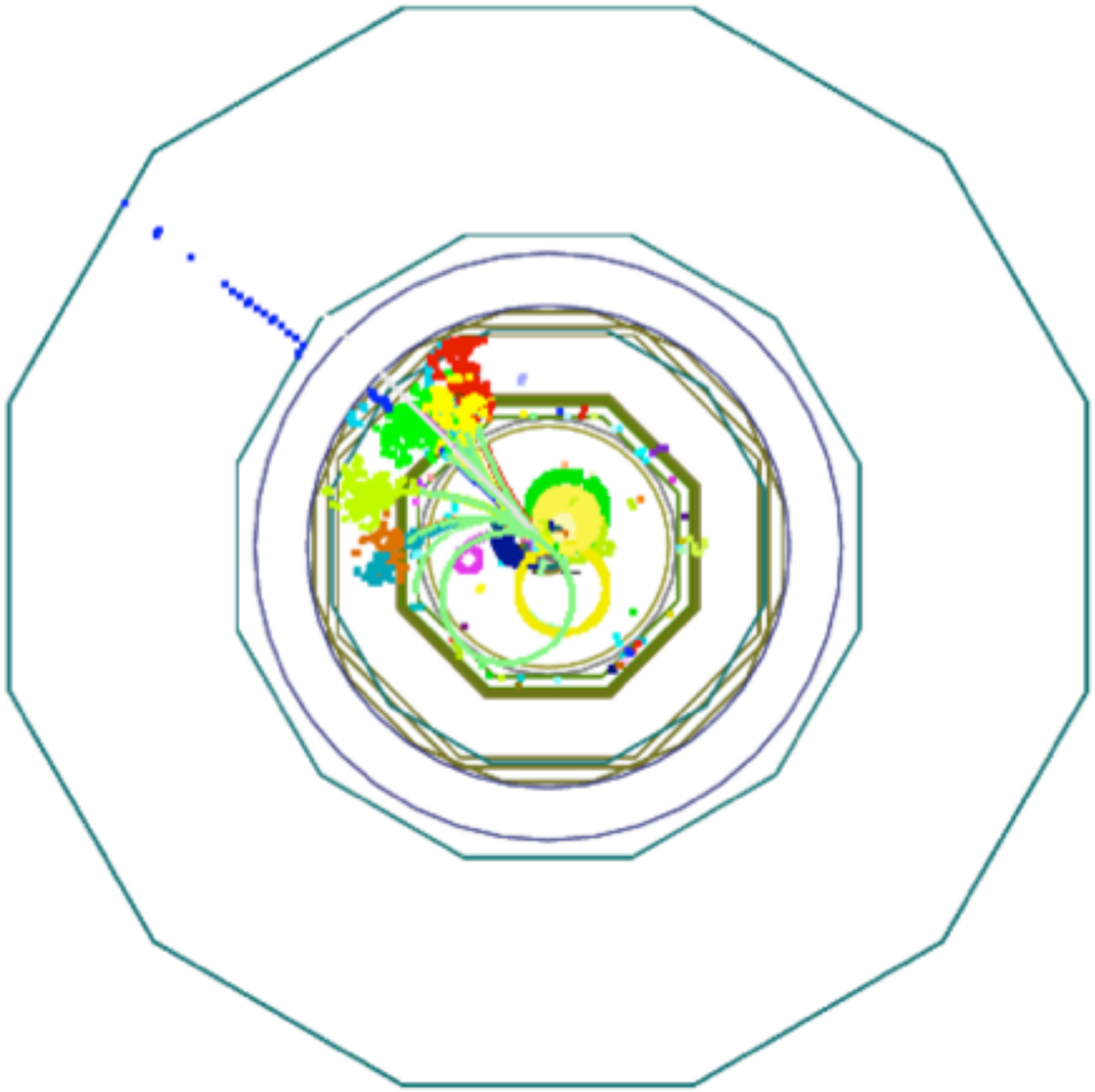
Forward Instrumentation



- 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

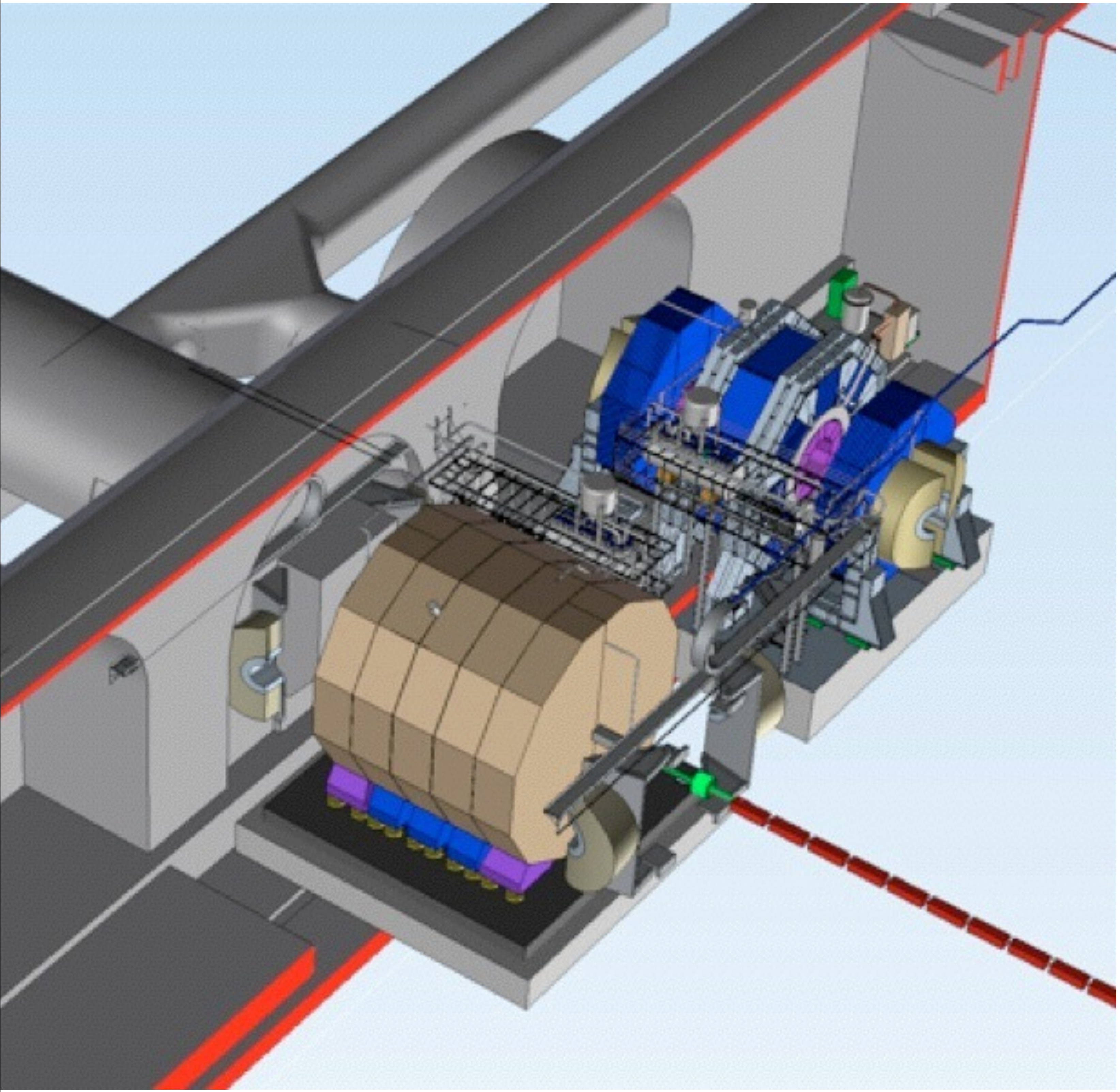
- The solenoid is one of the key components of any experiment - For ILC detectors we can build on the CMS experience
  - For ILD: Similar field, max. 4T, radius ~ 50 cm larger, for SiD higher field, somewhat smaller radius



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

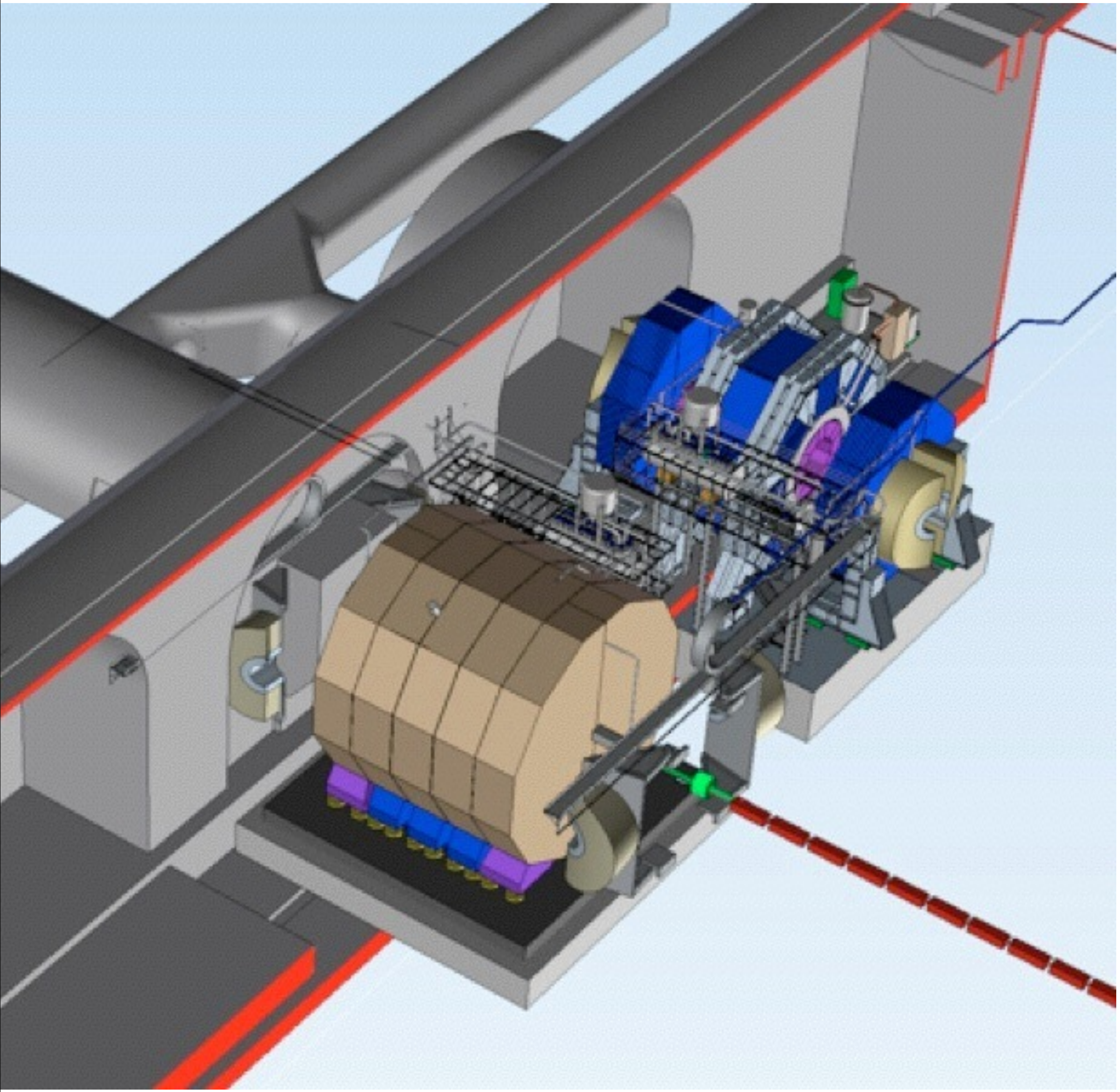
A key task of the yoke: Reduce the stray field of the solenoid to allow maintenance on one detector while the other is in operation

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

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

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,…

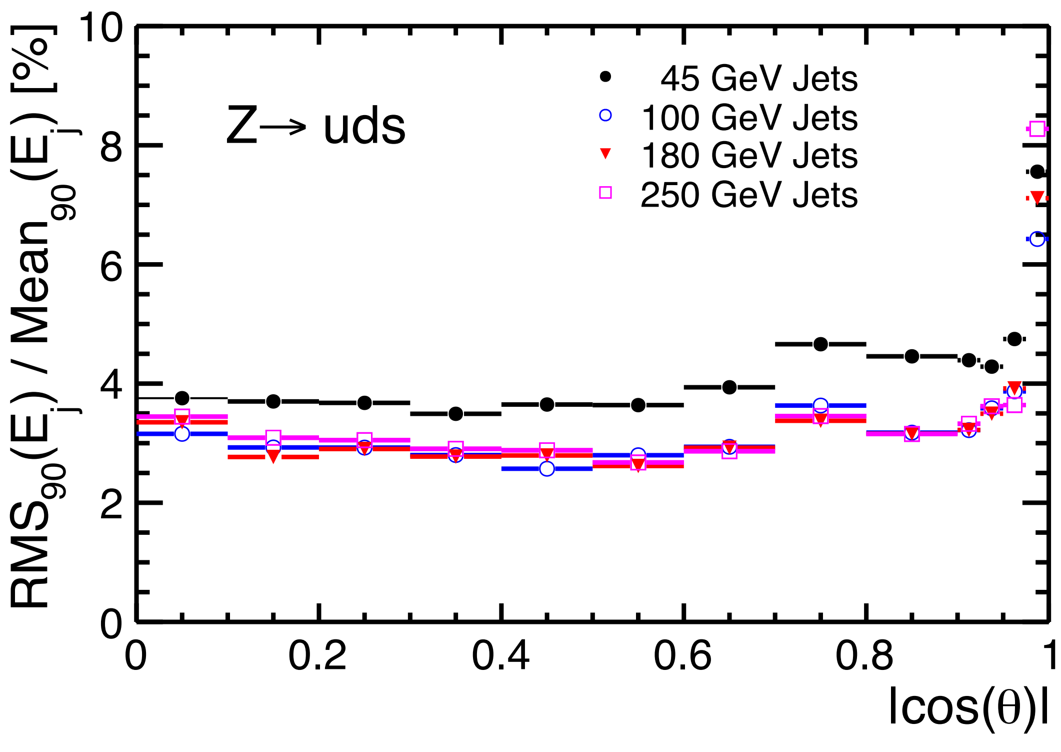
more in other talks throughout this conference!

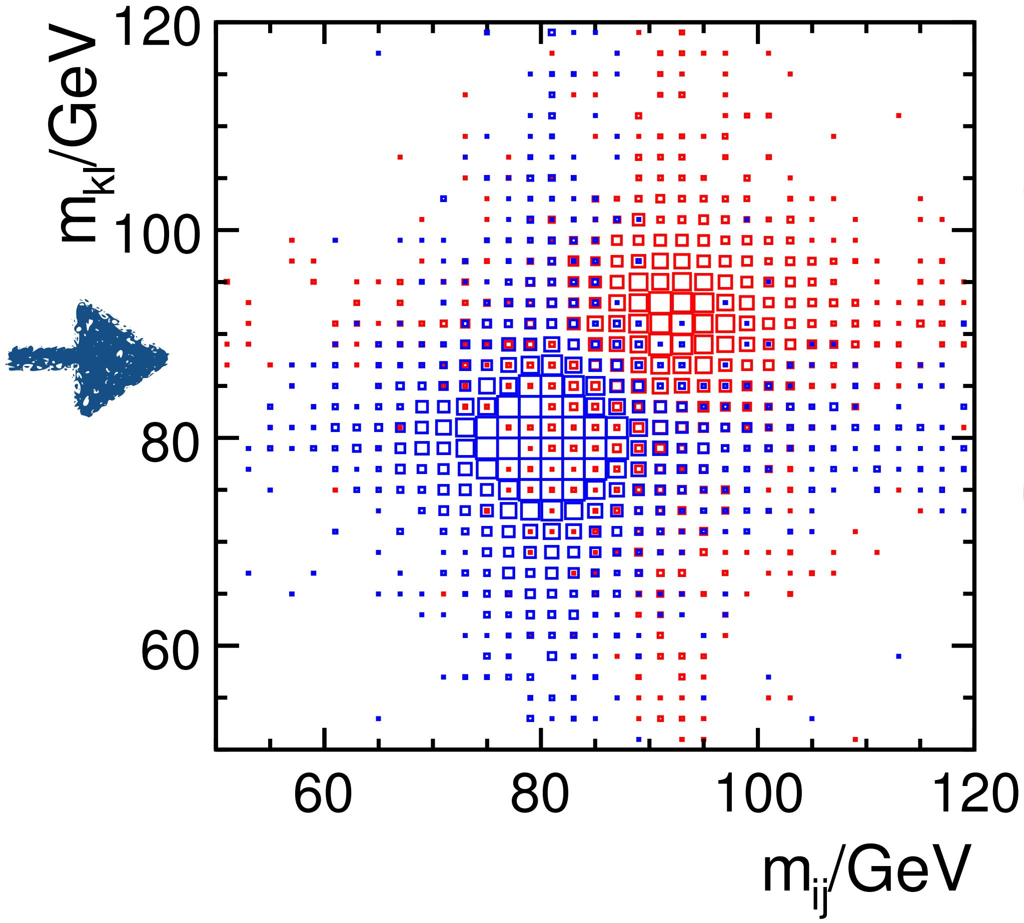
Performance ...

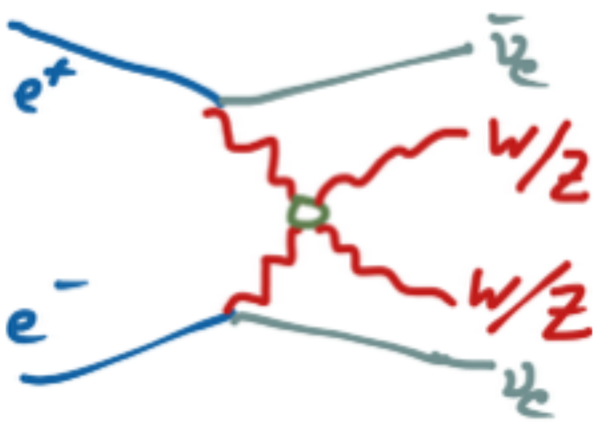
- Studies based on full detector simulations - in quite a few cases key performance parameters have been validated with prototypes in test beams
  - energy resolution & PFA performance (calorimeters), tracking, spatial resolution of pixel detectors,...

more in other talks throughout this conference!

Global performance - just one example: PFA in ILD

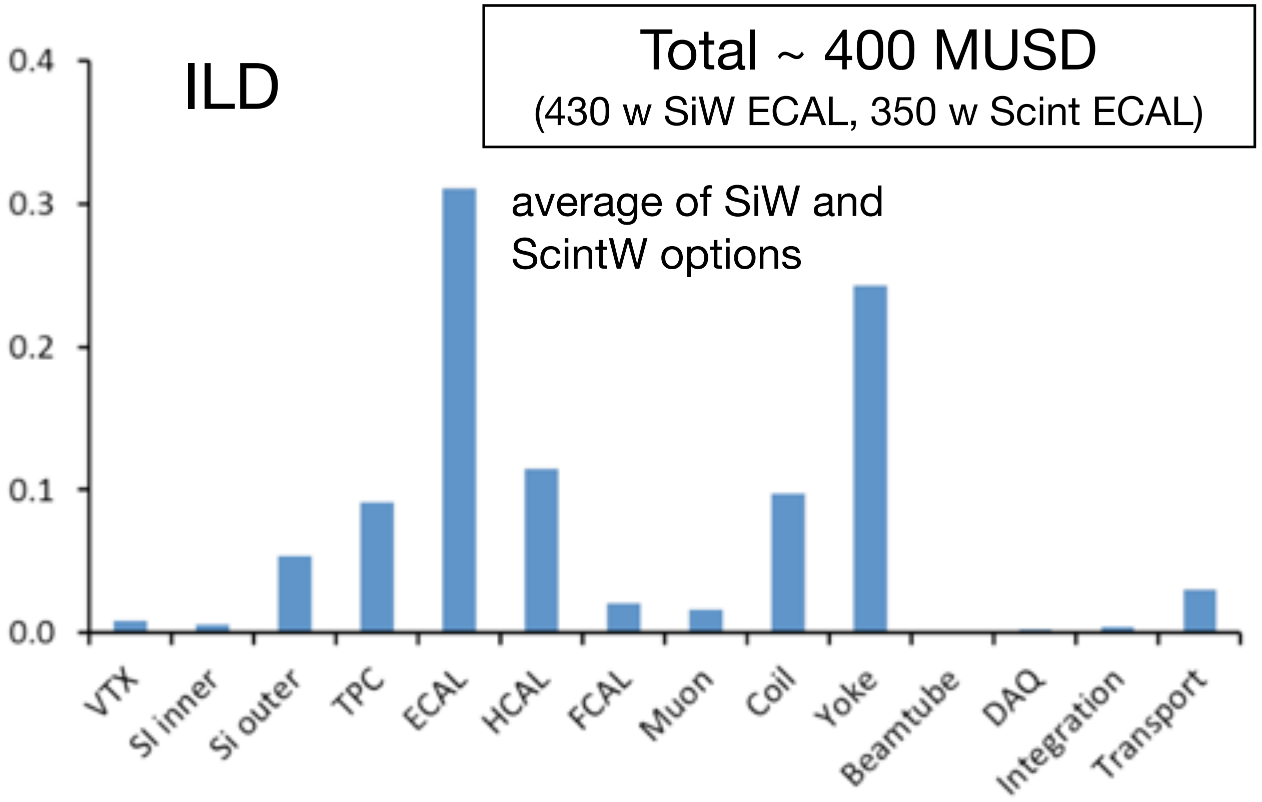


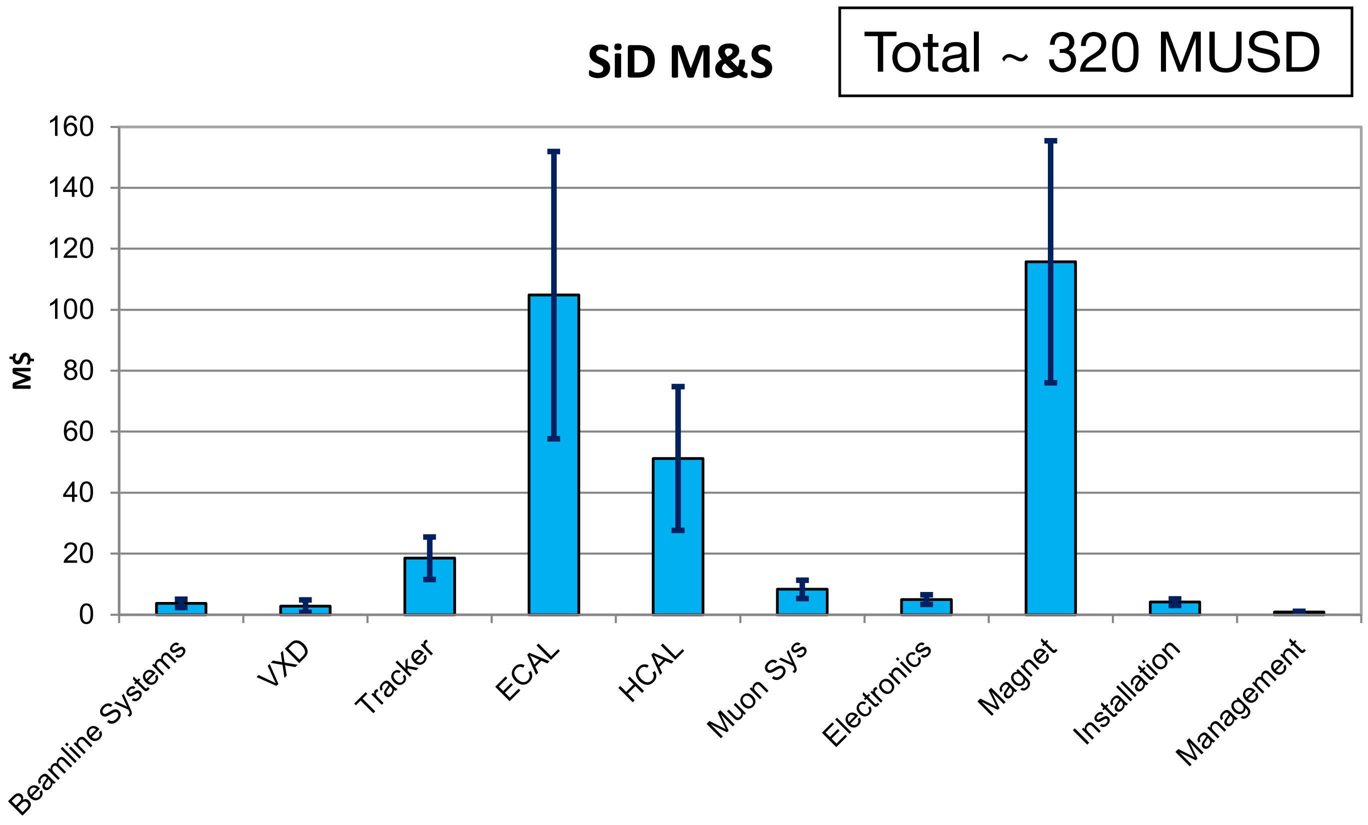




clean separation of W and Z in hadronic final states!

… and Cost





- First estimate of cost (excl. labor) - for the 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

Summary

- The physics program at ILC requires highly performant detector systems:
    - Flavor tagging - b, c and light jets
    - Precise momentum measurement
    - Excellent jet energy resolution - a factor of two better than state of the art

- ILD and SiD meet these challenges with:
    - low-mass, small pitch pixel vertex trackers
    - high resolution main trackers, either all silicon or silicon + TPC
    - highly granular “imaging” calorimeters

Summary

- The physics program at ILC requires highly performant detector systems:
  - Flavor tagging - b, c and light jets
  - Precise momentum measurement
  - Excellent jet energy resolution - a factor of two better than state of the art

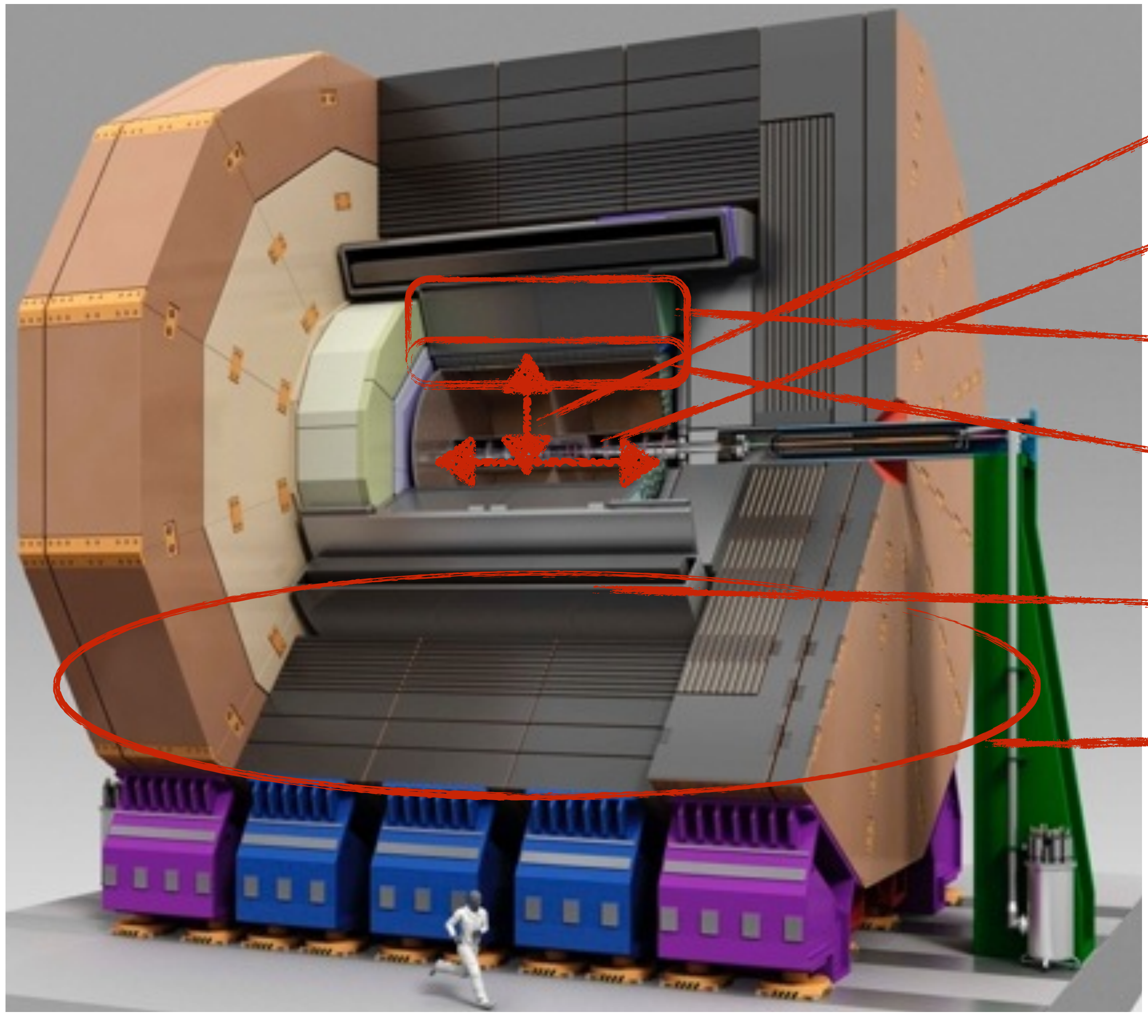
- ILD and SiD meet these challenges with:
  - low-mass, small pitch pixel vertex trackers
  - high resolution main trackers, either all silicon or silicon + TPC
  - highly granular “imaging” calorimeters

Key issues have been demonstrated with prototypes in test beams, and the physics performance has been studies in full simulations

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

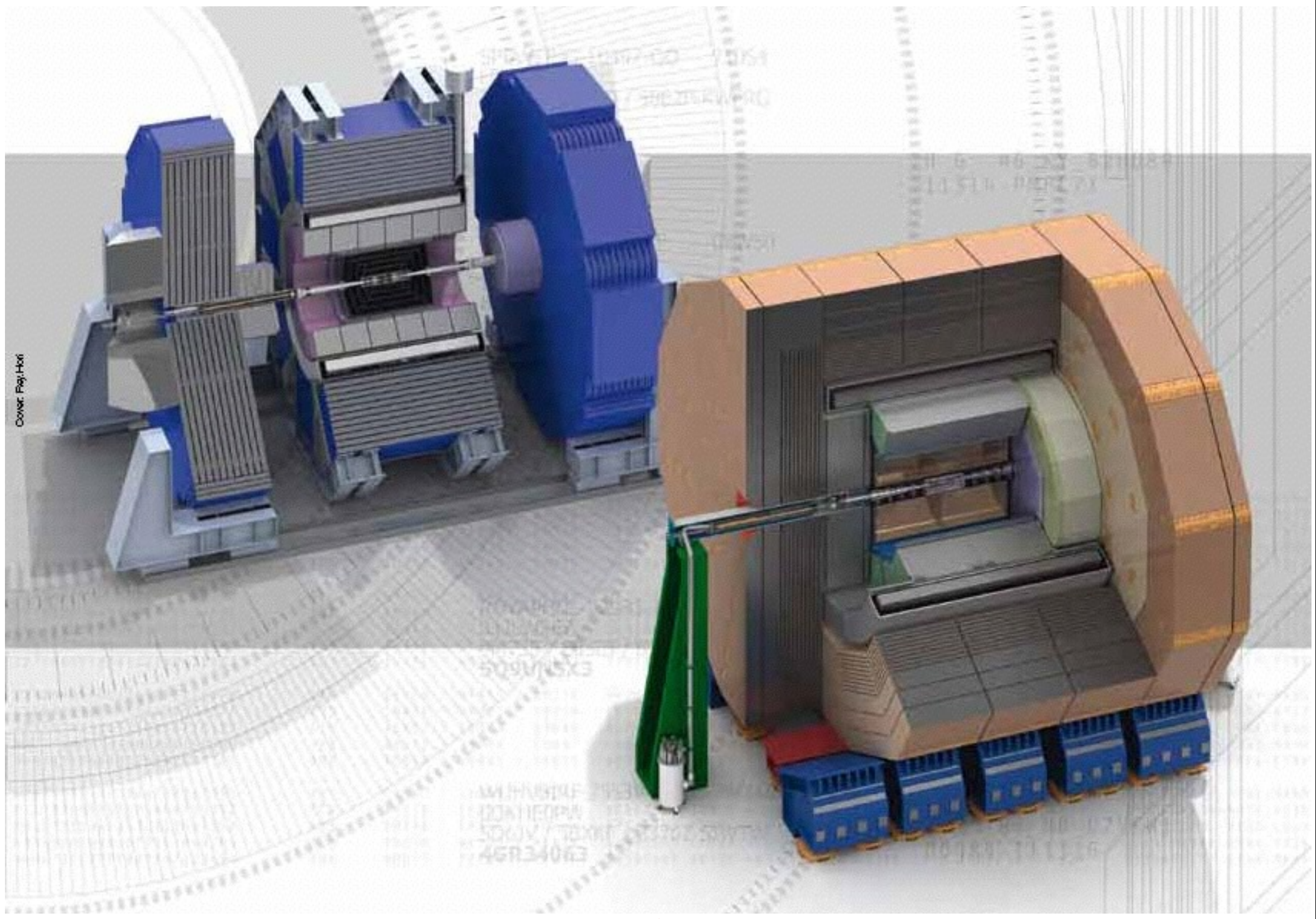
yoke & stray field

…

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
  - …

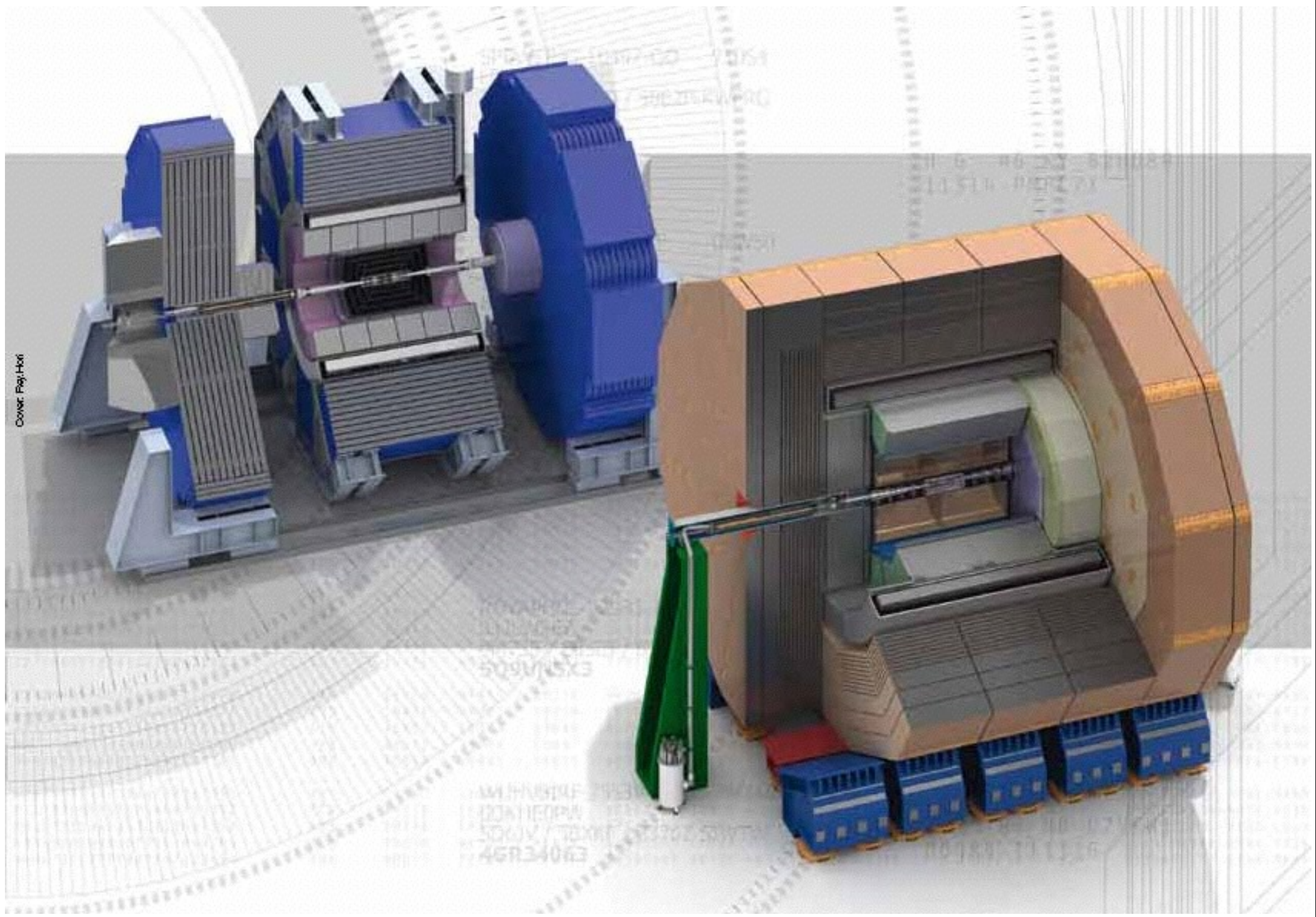
after approval: 6 - 8 years for
final design, production and installation



Outlook

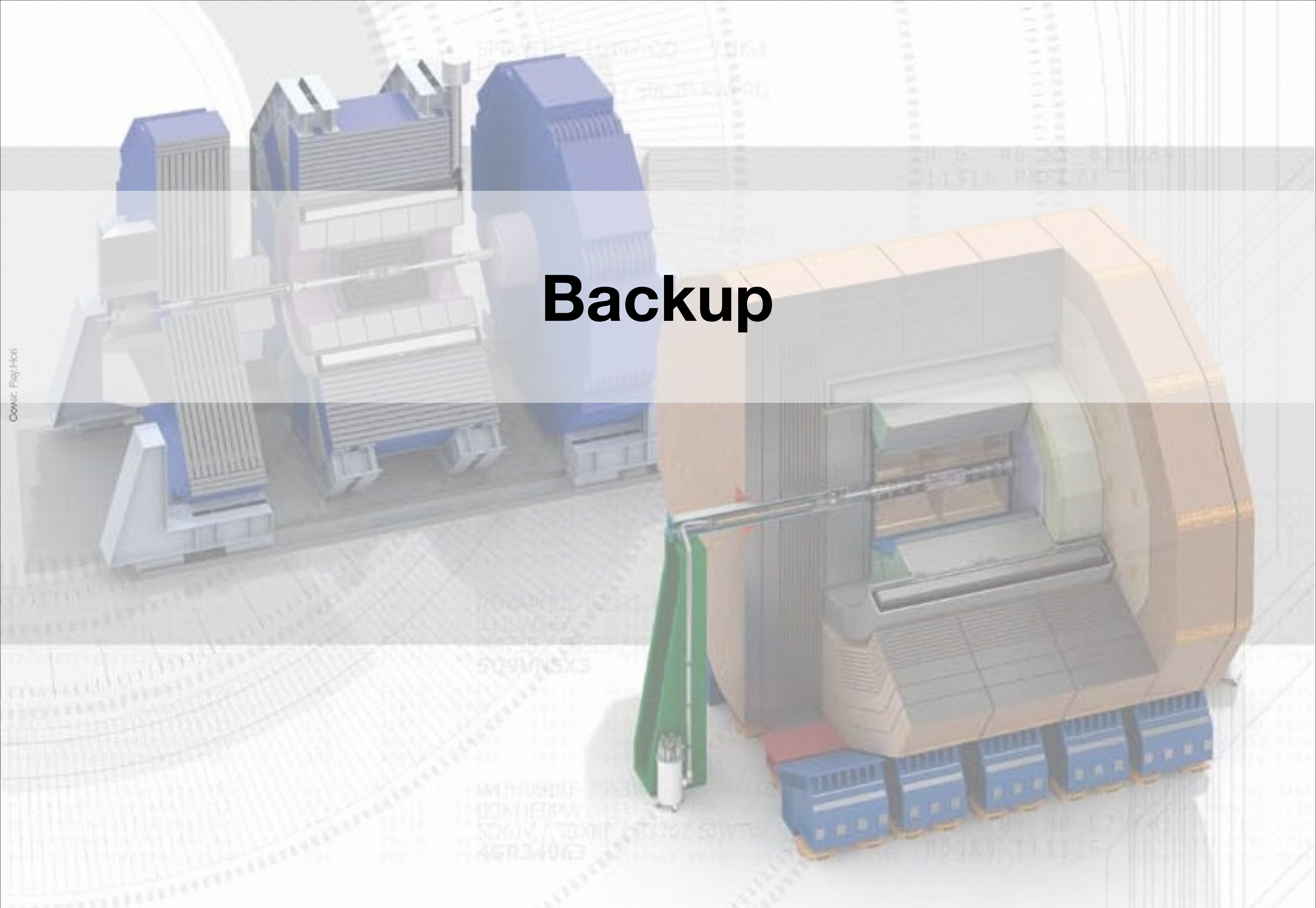
- Starting now: Optimisation of the detector design - Study impact of design choices on physics performance and cost, react to new LHC results
- ▸ Prepare for a Technical Design Report by ~ 2018
  - Further demonstration of technologies in beam tests
  - Complete mechanical design
  - More thorough cost estimate
  - …

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



The physics program of the ILC is clear and we have the detector technology to do it!

Backup



ILD & SiD - Material budget

ILD

SiD