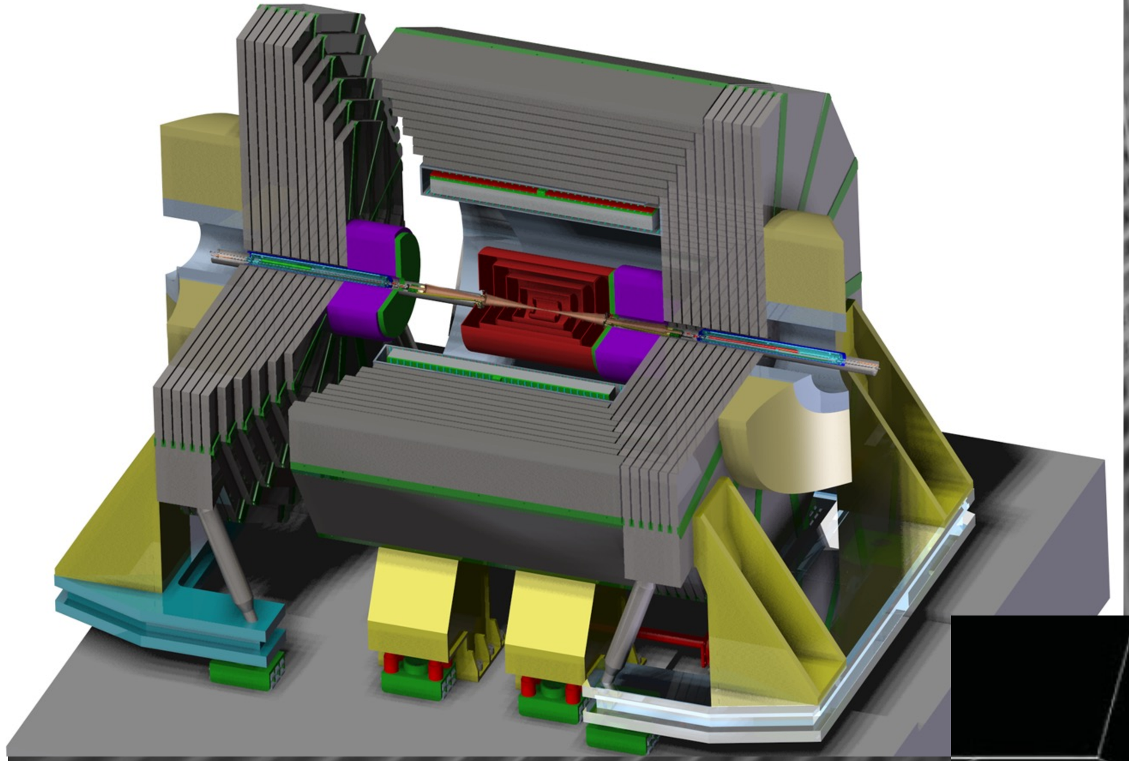
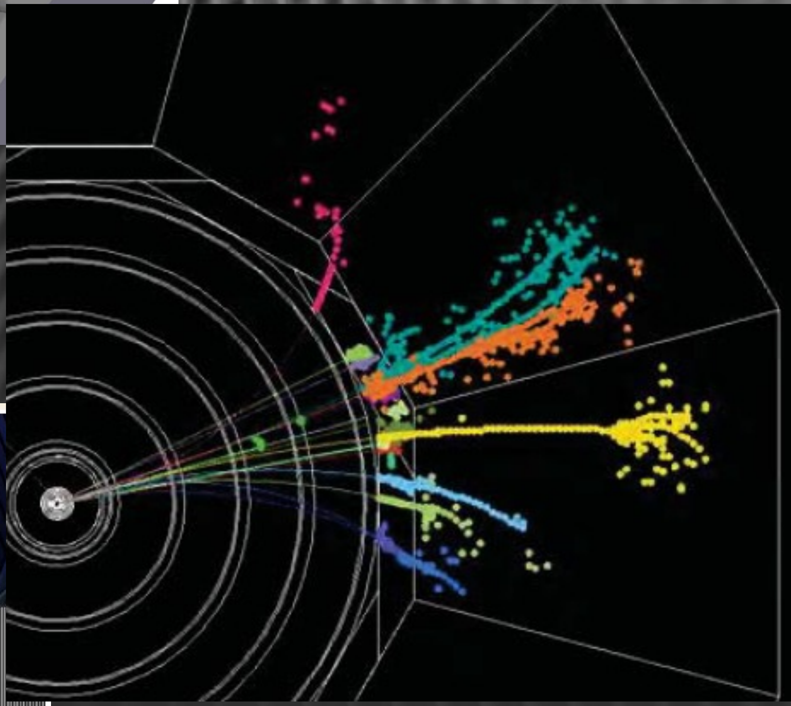
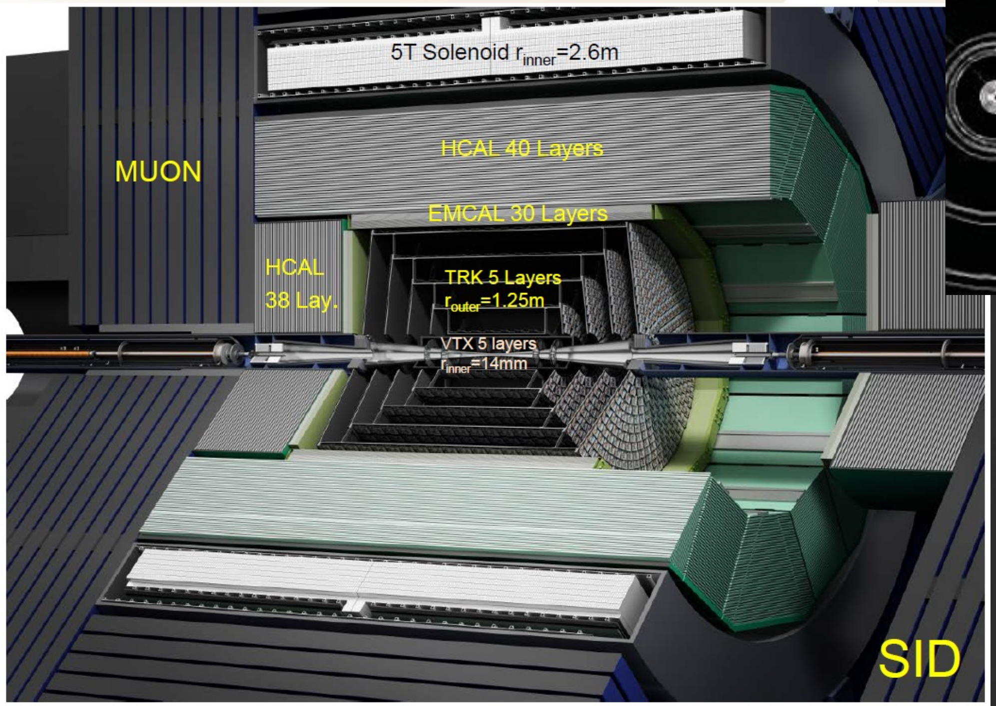
# Research Opportunities for measuring Higgs physics

**Jan Strube**





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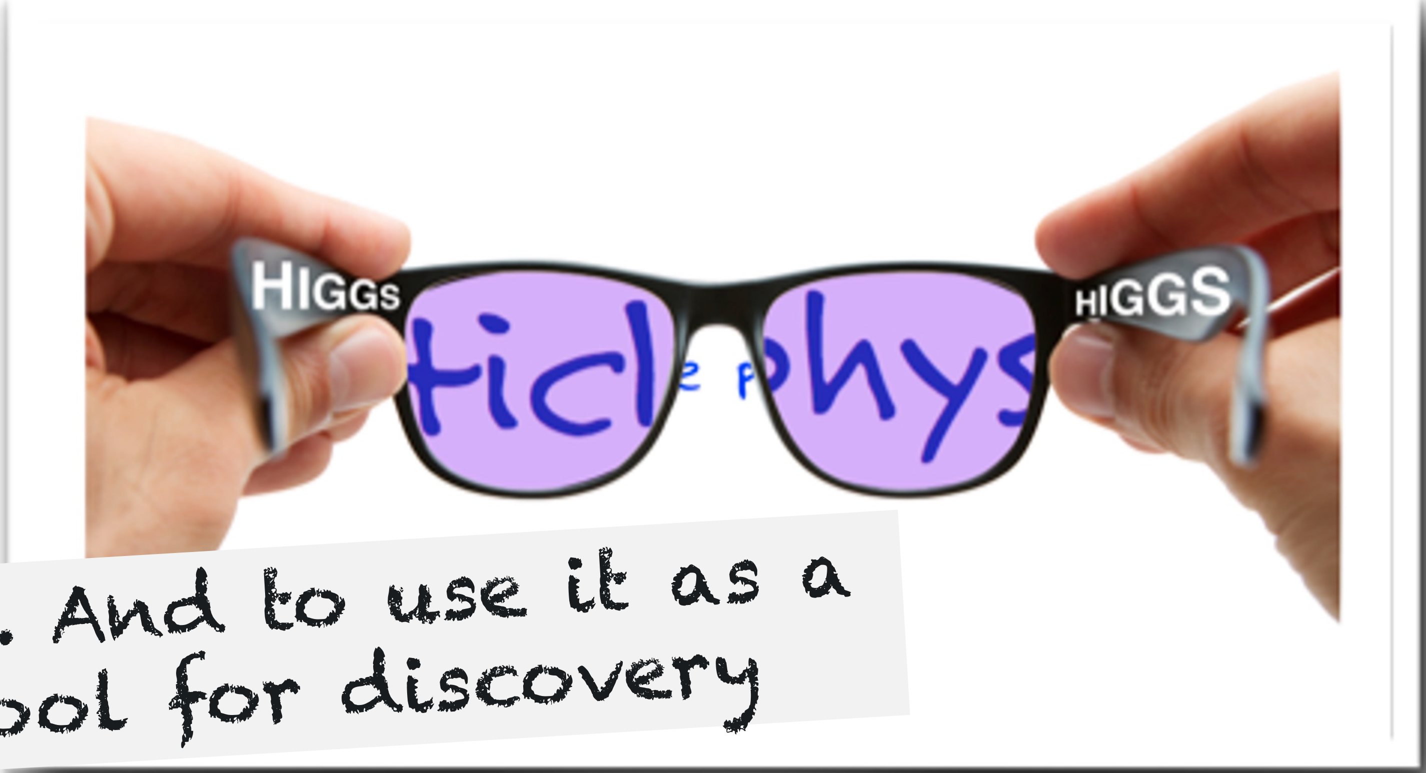
The LHC experiments have found a new scalar particle → consistent with a SUSY Higgs boson

# bottom line

**This Higgs Boson changes everything.**

**We're obligated to understand it using all tools.**




... And to use it as a tool for discovery

Brock/Peskin Snowmass 2013

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# Next-gen $e^+e^-$ -- colliders and detectors

- Several options are under consideration
  - ILC, CLIC, FCC-ee, CEPC, CCC, and more advanced energy recovery options
- The European Strategy has declared a Higgs factory a high priority project
- Since there is no decision on which one to build (hopefully at least one), or when (hopefully soon), one strategy is to pursue R&D that is beneficial to multiple projects until we can reach a decision
- In this presentation I will point out areas of open research for a detector at a Higgs factory, with a focus on physics requirements
  - There are some differences between circular and linear concepts, but the differences within a given geometry are small. With apologies to the other concepts, I will focus on ILC and FCC-ee
  - Because the physics is very different at different energies, I will limit my consideration to the ZH stages and above

# Introduction

- We found the Higgs boson – An extremely intriguing opportunity
- The HL-LHC is going to open the precision measurement era
  - What's left to do for the next generation of experiments?
  - How do we make it happen?

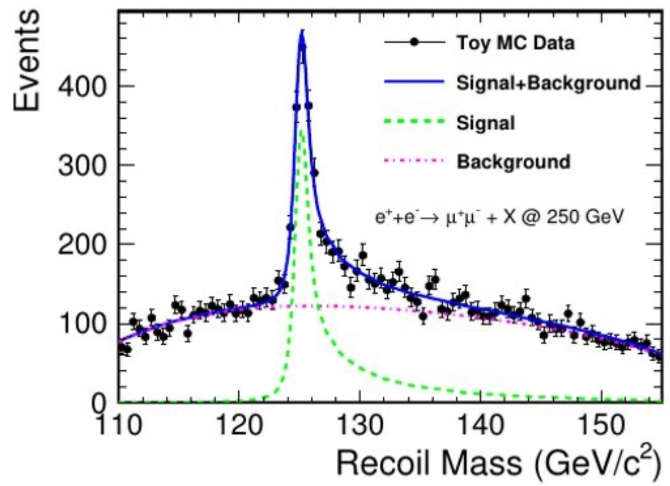
Higgs Physics at electron-positron colliders will be at the (sub-)percent level

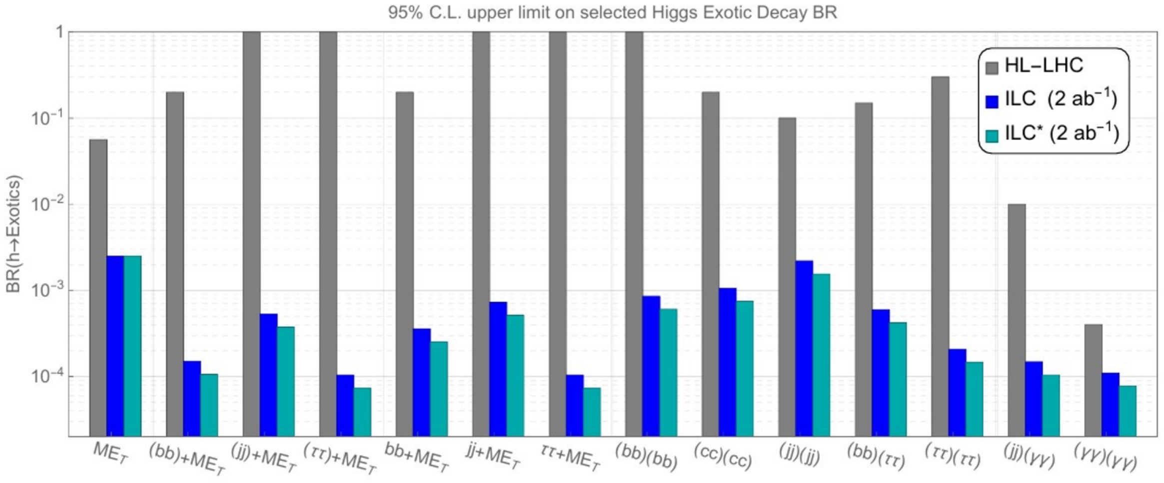
- Model-independent recoil measurements
- CP properties by measuring angular distributions in $H \rightarrow \tau\tau$
- Higgs on-shell width

# Next-gen precision Higgs measurements

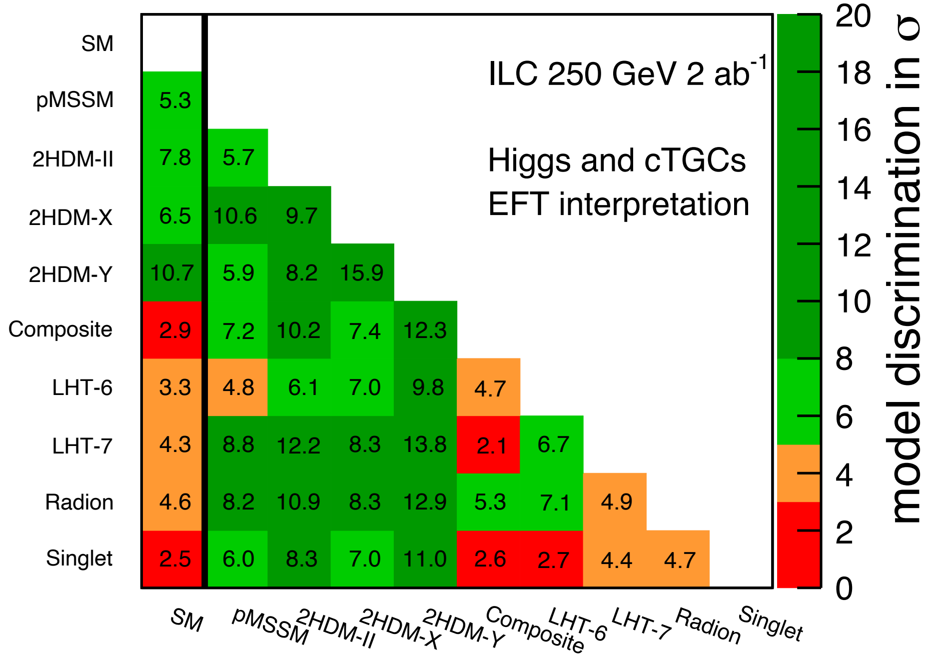
The recoil method lets us detect the Higgs boson in a model-independent way

=> needs **excellent jet energy resolution** and **excellent track momentum** resolution



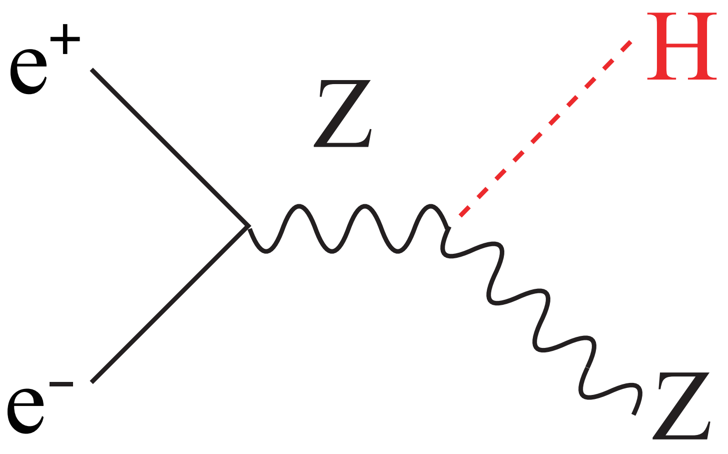




**High-precision vertex reconstruction** allows us to measure **Higgs decays to second generation** fermions **directly**




**Precision measurements** allow us to put **tight constraints** on models and **distinguish models from each other**

# Higgsstrahlung at the ILC

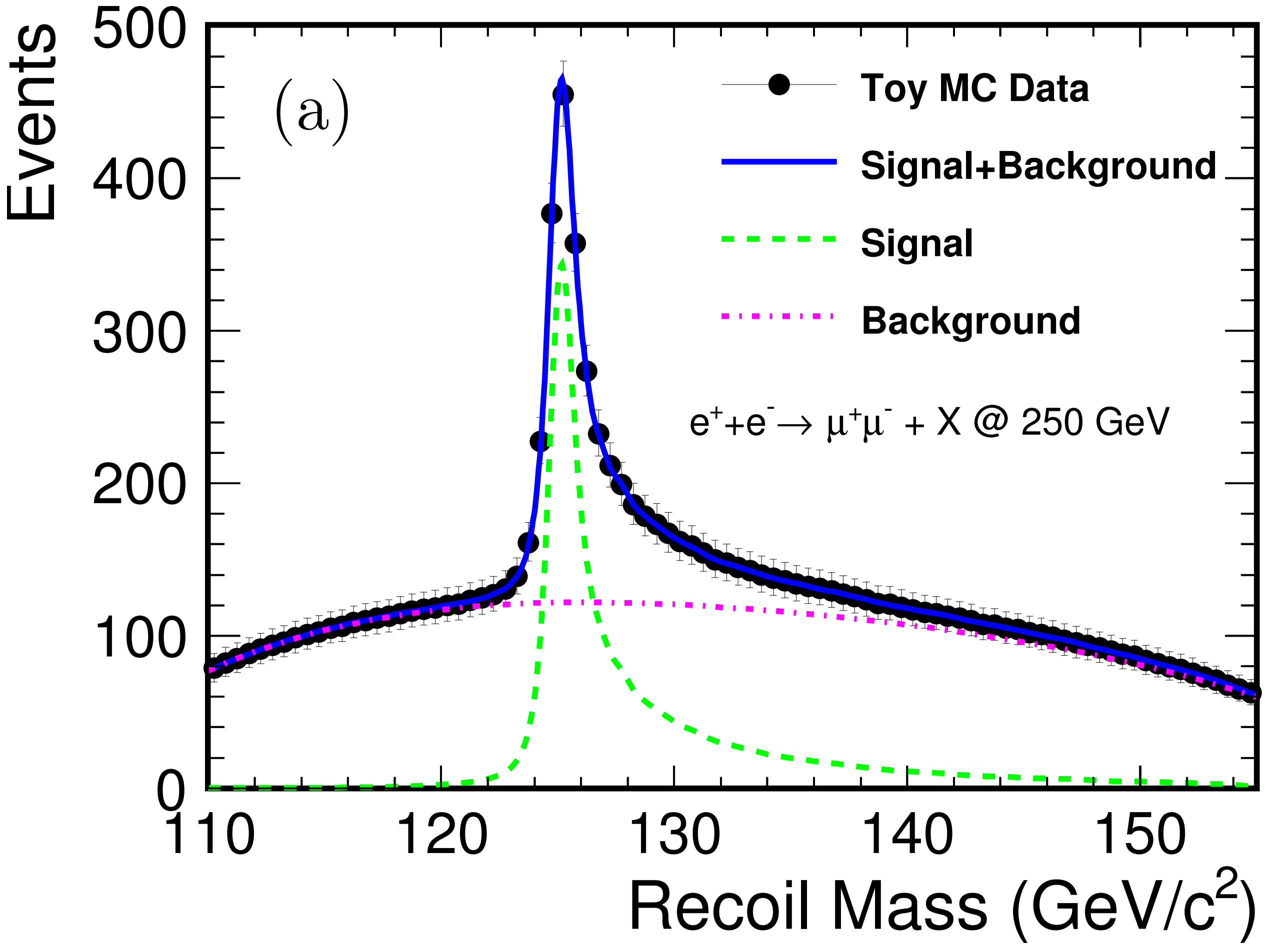



$$M_{\text{recoil}} = \left((\sqrt{s} - E_Z)^2 - P_Z^2\right)^{1/2}$$

Well-known initial state at ILC allows to measure the Higgs in a model-independent way: Reconstruction efficiencies are independent of the final states to within < 1%

Sensitivity to invisible decays, certain CP violating scenarios

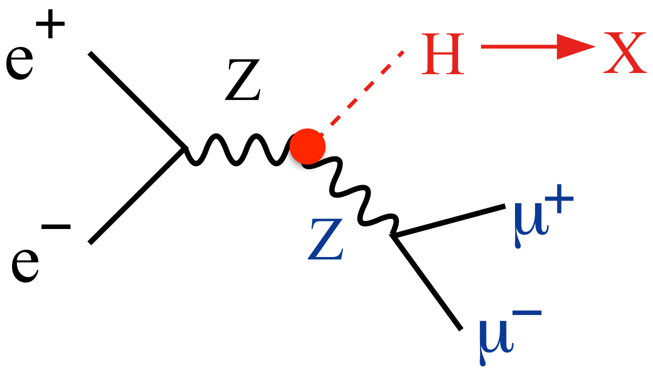
Phys. Rev. D 94, 113002 (2016)




This method has the smallest uncertainty near threshold.

# Reconstruction efficiency in recoil – Independent of the final state

Phys. Rev. D 94, 113002 (2016)




Cuts are tuned to be independent of the final state. Decays to unknown particles are assumed to introduce a bias that is no larger than the largest measured bias to SM final states (γγ).

| $H \to XX$ | bb | cc | gg | $\tau\tau$ | $WW^*$ | $ZZ^*$ | $\gamma\gamma$ | $\gamma Z$ |
|---|---|---|---|---|---|---|---|---|
| BR (SM) | 57.8% | 2.7% | 8.6% | 6.4% | 21.6% | 2.7% | 0.23% | 0.16% |
| Lepton Finder | 93.70% | 93.69% | 93.40% | 94.02% | 94.04% | 94.36% | 93.75% | 94.08% |
| Lepton ID+Precut | 93.68% | 93.66% | 93.37% | 93.93% | 93.94% | 93.71% | 93.63% | 93.22% |
| $M_{l^+l^-} \in [73, 120]$ GeV | 89.94% | 91.74% | 91.40% | 91.90% | 91.82% | 91.81% | 91.73% | 91.47% |
| $p_T^{l^+l^-} \in [10, 70]$ GeV | 89.94% | 90.08% | 89.68% | 90.18% | 90.04% | 90.16% | 89.99% | 89.71% |
| $\lvert\cos\theta_{miss}\rvert < 0.98$ | 89.94% | 90.08% | 89.68% | 90.16% | 90.04% | 90.16% | 89.91% | 89.41% |
| BDT > - 0.25 | 88.90% | 89.04% | 88.63% | 89.12% | 88.96% | 89.11% | 88.91% | 88.28% |
| $M_{rec} \in [110, 155]$ GeV | 88.25% | 88.35% | 87.98% | 88.43% | 88.33% | 88.52% | 88.21% | 87.64% |

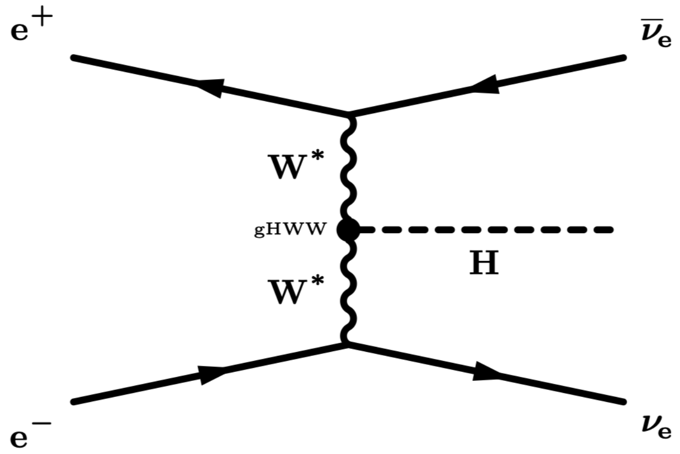
# The Higgs width at the ILC

For precision measurements, at some point $\Delta\Gamma_H$ becomes a limiting factor

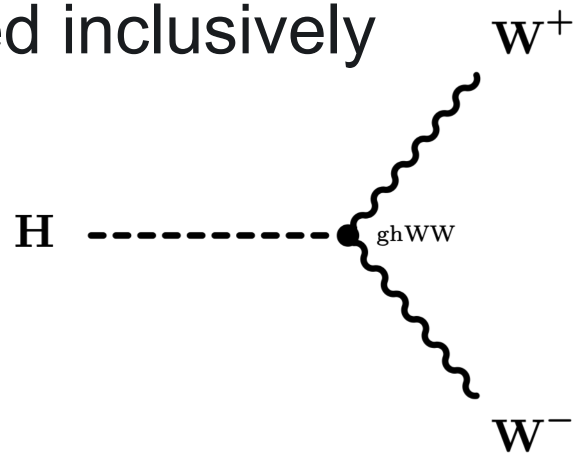
Standard Model: $\Delta\Gamma_H \cong 4$ MeV

At the LHC: Use rate of off-shell $H \rightarrow ZZ$: $\sigma(\Gamma_H) = 22$ MeV,

At the ILC: Use the fact that the same tree-level coupling enters production and decay and that ZH cross section can be measured inclusively




$g_{HWW}$ in both, production and decay




$$\Gamma_H = \frac{\Gamma(H \rightarrow WW)}{\mathcal{BR}(H \rightarrow WW)} \propto \frac{g^2_{HWW}}{\mathcal{BR}(H \rightarrow WW)}$$

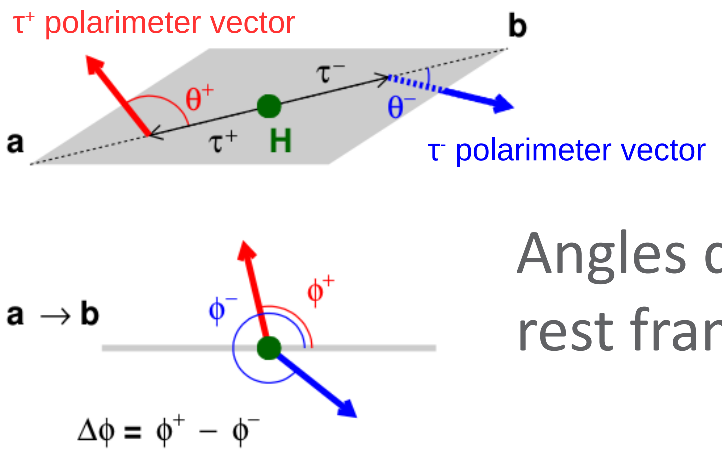
$$\frac{g^2_{HWW}}{g^2_{HZZ}} \propto \frac{\sigma_{\nu\nu H} \times \mathcal{BR}(H \rightarrow b\bar{b})}{\sigma_{ZH} \times \mathcal{BR}(H \rightarrow b\bar{b})}$$

Expected Precision at full ILC: $\Delta\Gamma_H / \Gamma_H = 1.4\%$ $\Delta g_{HWW} / g_{HWW} = 0.28\%$

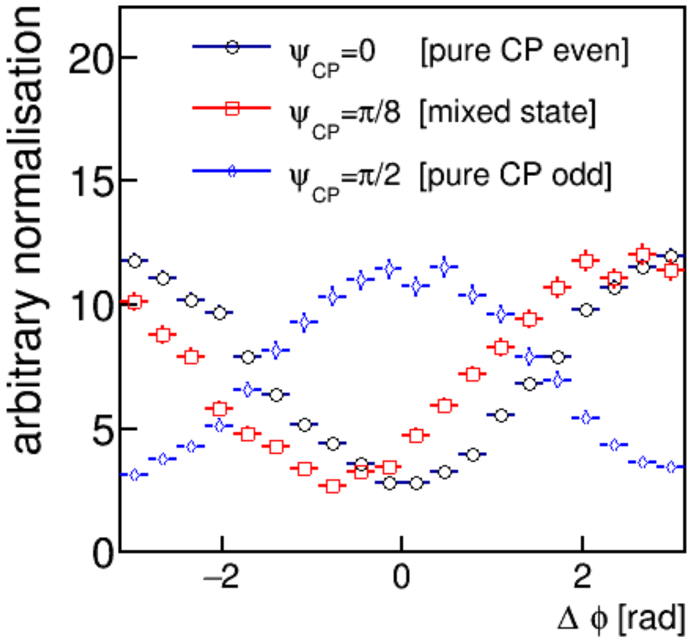
# Higgs Decay to $\tau$ Leptons

Nucl.Instrum.Meth. A810 (2016) 51-58

- Ideal probe for new physics: Sizeable BR, well-known $\tau$ mass and properties, tree level CP effects in coupling to fermions (bosons only at loop level)
  - CP properties in angular analysis
- Reconstruction in hadronic recoil: qq $\tau$ $\tau$
  - Background: ffH, 4f, 2f
- Analysis steps: $\tau$ “jet” finder, jet charge
- Collinear Approximation:
  - Visible $\tau$ decay products and $\nu$ are collinear
  - No other source of missing momentum
- Detector parameters challenged:
  - vertex detector
  - tracking
  - photon reconstruction
  - jet energy resolution




Angles defined in the $\tau_{\pm}$ rest frames relative to $\mathbf{p}_H$




distribution of $\Delta\phi$ is sensitive to CP mixing angle, $\psi_{CP}$

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# Proposals – Higgs/EW Physics

## Higgs factory concepts (10)

| Name | CM energy range |
|---|---|
| FCC-ee | e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV |
| CEPC | e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV |
| ILC (Higgs factory) | e+e-, $\sqrt{s} = 0.09 - 1$ TeV |
| CLIC (Higgs factory) | e+e-, $\sqrt{s} = 0.09 - 1$ TeV |
| CCC (Cool Copper Collider) | e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV |
| CERC (Circular ERL collider) | e+e-, $\sqrt{s} = 0.09 - 0.60$ TeV |
| ReLiC (Recycling Linear Collider) | e+e-, $\sqrt{s} = 0.25 - 1$ TeV |
| ERLC (ERL Linear Collider) | e+e-, $\sqrt{s} = 0.25 - 0.50$ TeV |
| XCC (FEL-based $\gamma\gamma$ collider) | ee ($\gamma\gamma$),$\sqrt{s} = 0.125 - 0.14$ TeV |
| MC (Higgs factory) | $\mu+\mu-$, $\sqrt{s} = 0.13$ TeV |

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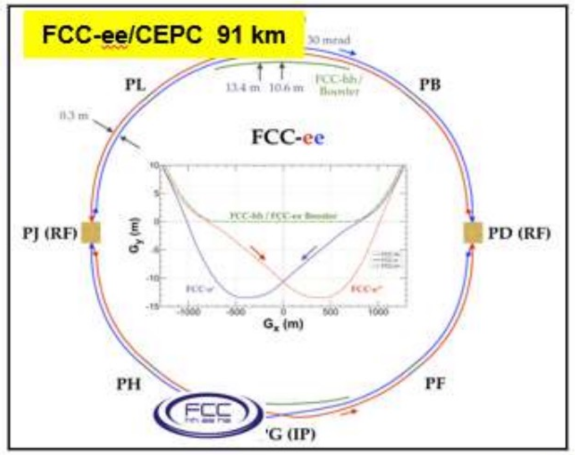
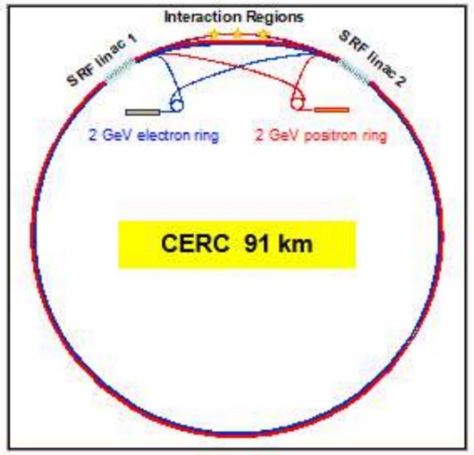
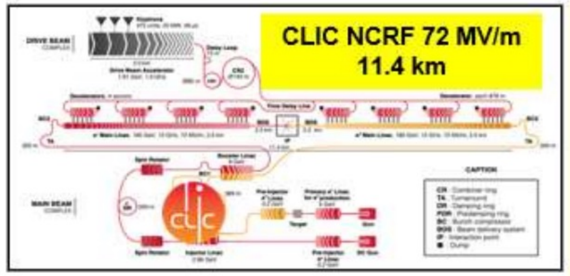
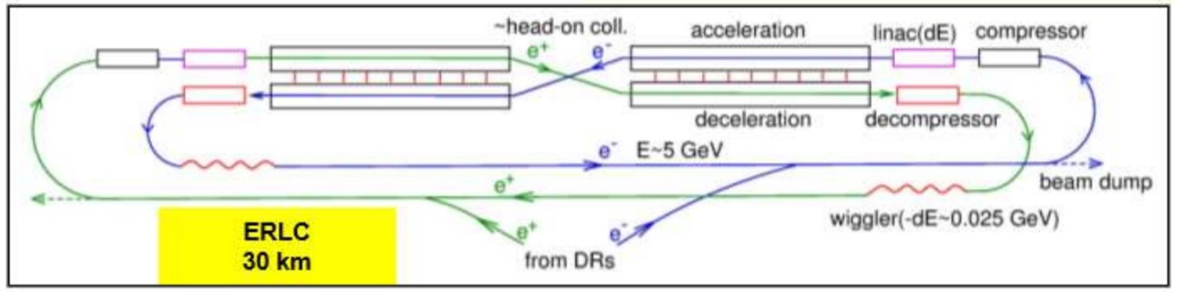
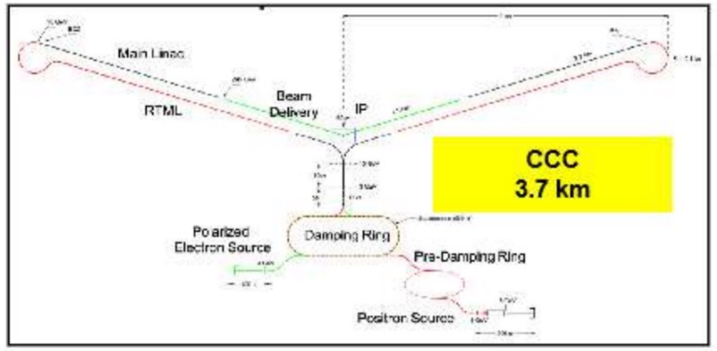


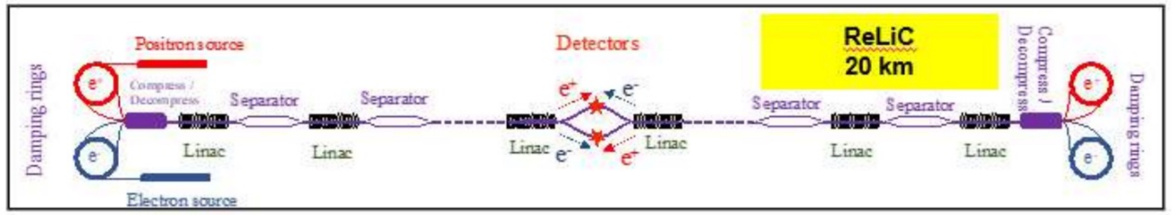







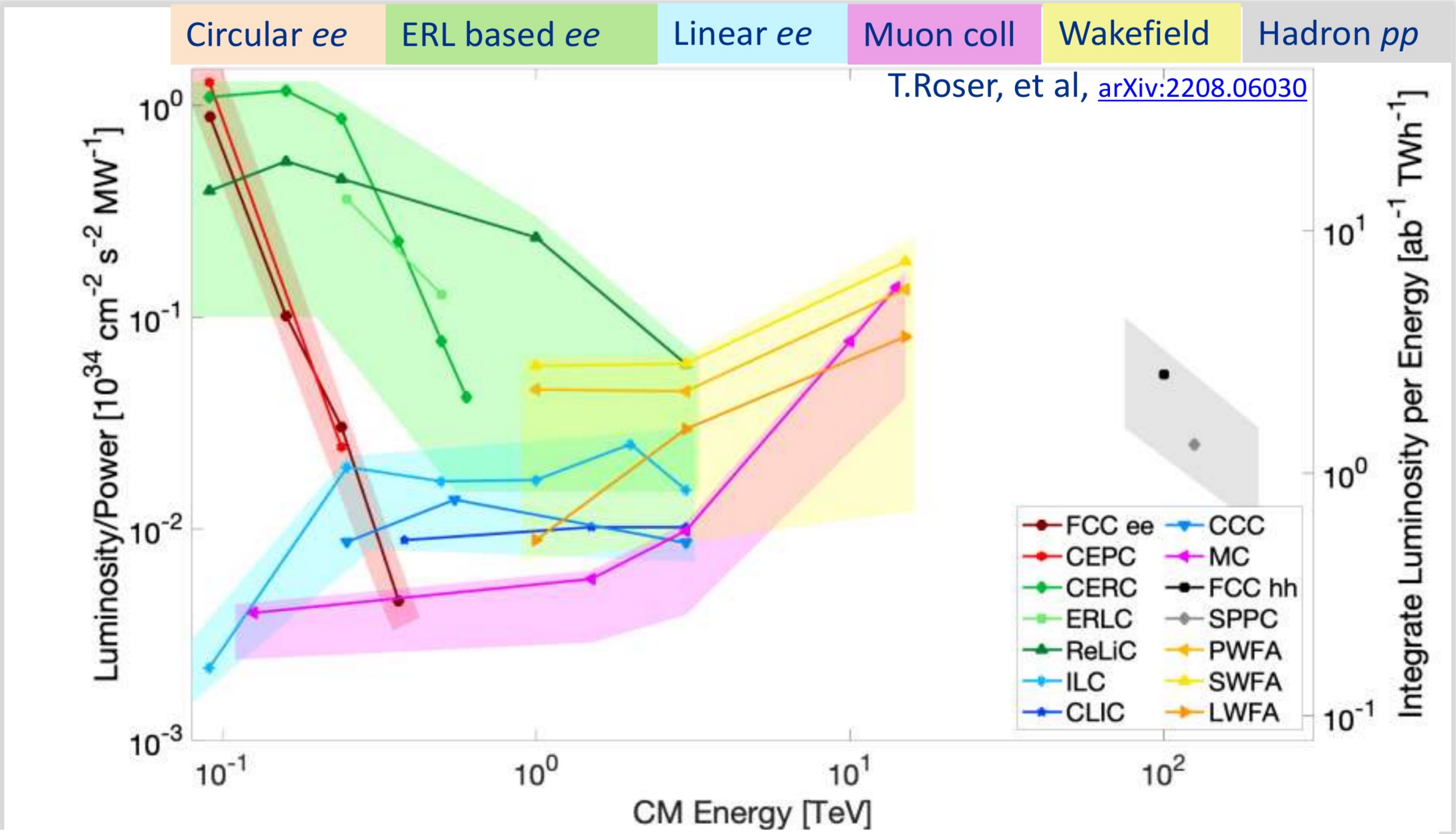




Fermilab

https://arxiv.org/abs/2208.06030

# Luminosity per Power

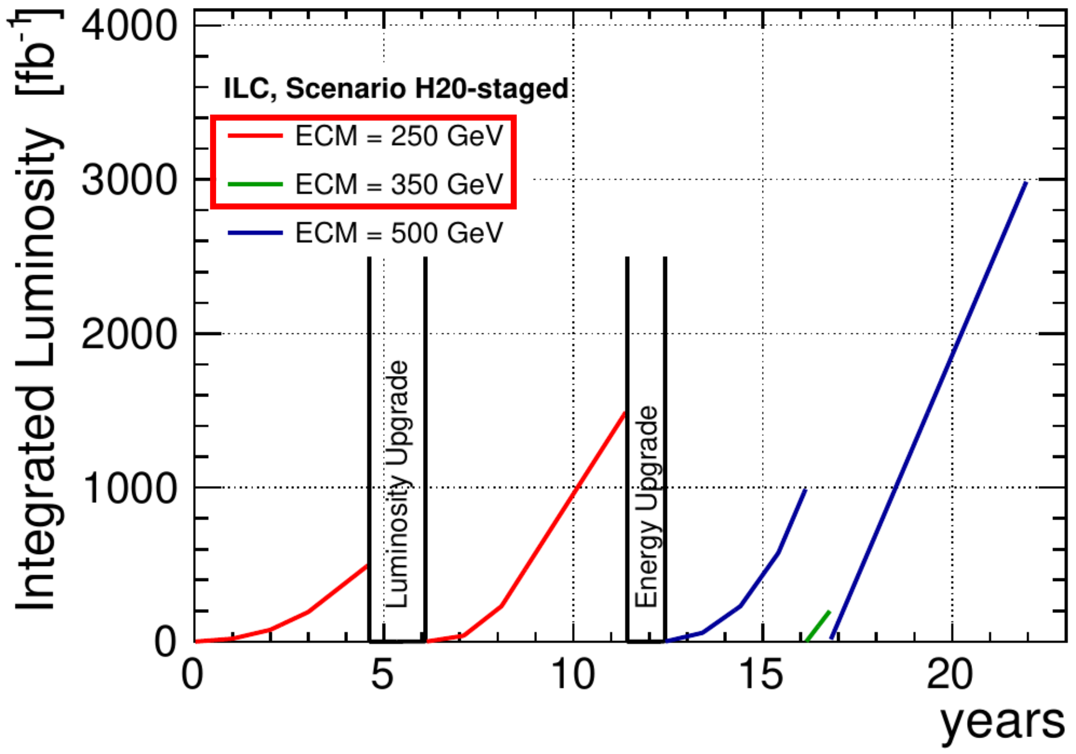



Luminosity is per IP, Integrated luminosity assumes 1e7 seconds/yr. *Luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.* Color bands reflect approximate uncertainty for different collider concepts.

# Luminosity Progression Run Scenarios

## ILC

arXiv:2203.07622




## FCC-ee

arXiv:2203.08310

| c.m. energy [GeV] | lum./ IP [$10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$] | int. lum./year (2 IPs) [$\mathrm{ab}^{-1}$/yr] | run time [yr] |
|---|---|---|---|
| 91 | 200 | 48 | 4 |
| 160 | 20 | 6 | 1–2 |
| 240 | 7.5 | 1.7 | 3 |
| 365 | 1.3 | 0.34 | 5 |

Table 1: Performance figures of FCC-ee. The ongoing Feasibility Study allows for a 4 IP collider ring with a total integrated luminosity higher by almost a factor 2. For the Z pole (or $t\bar{t}$) running the regular integrated luminosity is show in the table, while over the first two (one) years, the luminosity production is expected to be, on average, about 2 times lower.

NB: These scenarios underline the challenge of identifying common research areas. FCC-ee experiments are subject to constraints from high rates at the Z pole. LC experiments have to meet constraints at higher collision energies.

# Reality check on construction and commissioning times

## *Implementation Task Force* on Higgs Factories

Table I - ITF Report – T.Roser, et al, arXiv:2208.06030

| | | CME (TeV) | Lumi per IP@ Higgs (10^34) | Years, pre-project R&D | Years to 1st Physics | Cost Range (2021 B$) | Electric Power (MW) |
|---|---|---|---|---|---|---|---|
| Circular e+e- | FCCee (4 IPs) | 0.24 | 7.7 | 0-2 | 13-18 | 12-18 | 290 |
| | CEPC (2 IPs) | 0.24 | 8.3 | 0-2 | 13-18 | 12-18 | 340 |
| | FermiHF | 0.24 | 1.2 | 3-5 | 13-18 | 7-12 | ~200 |
| Linear e+e- | ILC | 0.25 | 2.7 | 0-2 | <12 | 7-12 | 110 |
| | CLIC | 0.38 | 2.3 | 0-2 | 13-18 | 7-12 | 150 |
| | C^3 | 0.25 | 1.3 | 3-5 | 13-18 | 7-12 | 150 |
| | HELEN | 0.25 | 1.4 | 5-10 | 13-18 | 7-12 | ~110 |
| ERL-based | CERC | 0.24 | 78 | 5-10 | 19-24 | 12-30 | 90 |
| | ReLiC (2 IPs) | 0.24 | 165 | 5-10 | >25 | 7-18 | 315 |
| | ERLC | 0.24 | 90 | 5-10 | >25 | 12-18 | 250 |
| s-chan | XCC-γγ | 0.125 | 0.1 | 5-10 | 19-24 | 4-7 | 90 |
| | μμ-Higgs | 0.13 | 0.01 | >10 | 19-24 | 4-7 | 200 |

arXiv:2208.06030

| Collider | Time to Reach Design Peak $L$ | Record $L$ / Design $L$ |
|---|---|---|
| LEP-I | 5 years | × 2 |
| SLC | Not achieved (9 years) | × 0.5 |
| LEP-II | 0.3 years | × 3 |
| PEP-II | 1.5 years | × 4 |
| KEK-B | 3.5 years | × 2 |
| BEPC-II | 7.5 years | × 1.0 |
| DAFNE | Not achieved (9 years) | × 0.9 |
| Super-KEK-B | Not yet achieved (4 years) | × 0.05 * |
| TEV-Ib | 1.5 years | × 1.5 |
| HERA-I | 8 years | × 1 |
| RHIC-*pp* | 10 years ** | × 1.2 * |
| TEV-II | 5 years | × 2.1 |
| HERA-II | 5 years | × 1 |
| LHC | 6 years | × 2.1 * |

# Commissioning a precision machine is hard

- Precision measurements require excellent understanding of systematic uncertainties at the per cent level and better

$\Rightarrow$ reducing the time for commissioning is essential to meeting the physics goals faster

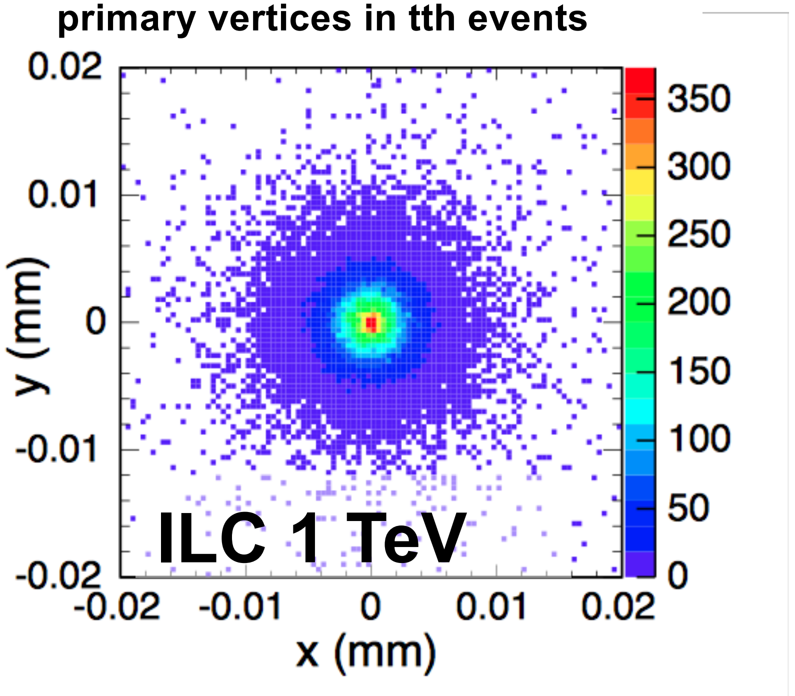
$\Rightarrow$ understand, study, mitigate background! Often, the machine can increase the luminosity at the cost of higher background. The detectors must be able to cope

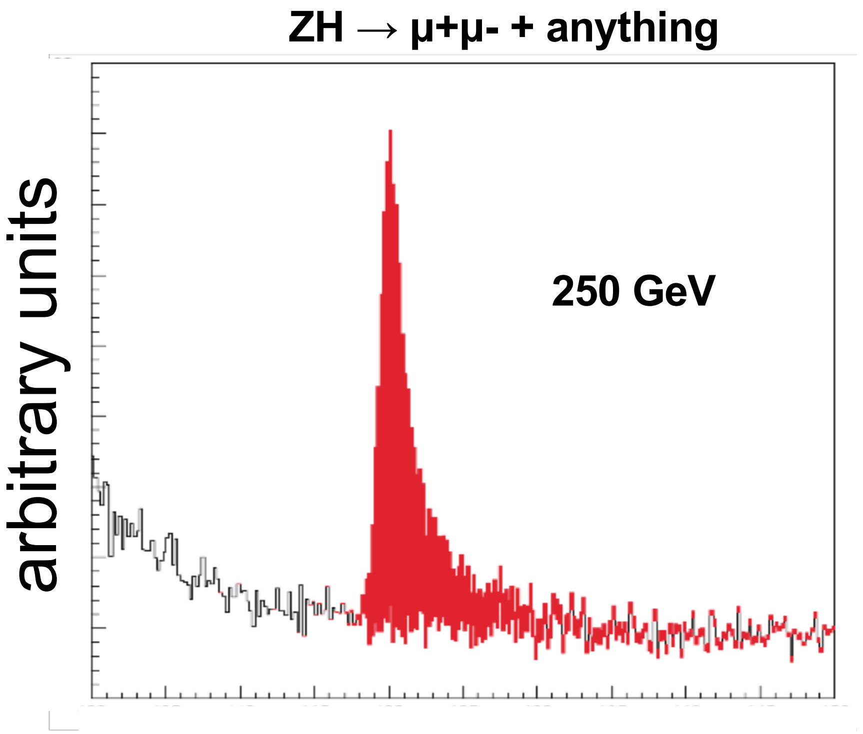
$\Rightarrow$ All proposed machines will run at different energies. How long does it take to switch for the machine? For the detector? Calibration runs at 91 GeV?

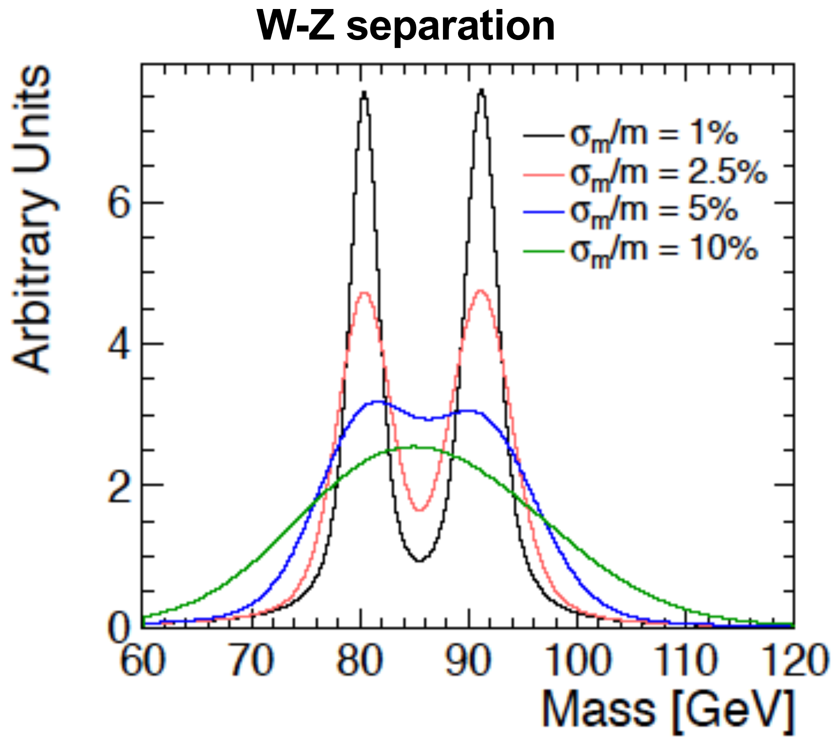
  - $\Rightarrow$ The measurements of beam properties close to the IR are very limited.

Hot Research topic: Resilience of detectors to increased background / rates.

# Detector Requirements are driven by Higgs physics




Exceptionally good impact parameter resolution, time stamping, material budget in the vertex detector

→ R&D ongoing to meet all of these requirements

Extremely low material budget in the main tracker, with high tracking efficiency

$$\sigma(1/p) \sim 2.5 \times 10^{-5}$$

Not only good calorimeter resolution, but excellent track-shower matching and shower separation

# A design to meet the physics performance

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

# Bunch spacing

## FCC-ee

| | Z | WW | ZH | $t\bar{t}$ | |
|---|---|---|---|---|---|
| Bunches/beam | 16 640 | 2000 | 328 | 59 | 48 |
| Average bunch spacing (ns) | 19.6 | 163 | 994 | 2763 | 3396 |

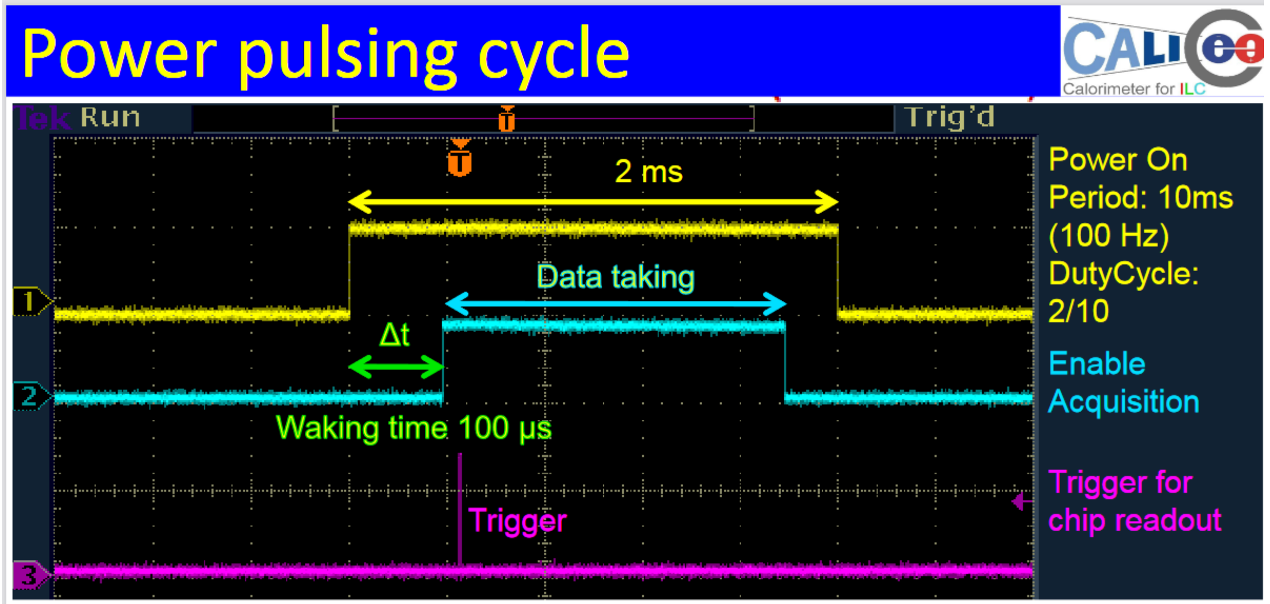
## ILC

Trains of 1312 (2625) bunches @ 5 Hz (10 Hz)

--> expect ~one (1) hadronic interaction per train

Allows to consider power pulsing --> reduced power / heat in the detectors

Goal for detector design => ultimate low-mass tracking



# Artificial Intelligence and Machine Learning in Detector Design and Event Reconstruction

Already happening:

- Faster simulations trained with ML will enable shorter turnaround on physics studies and allow scanning a larger model space
  - There is some good work on differentiable simulations
- More maintainable event reconstruction that utilizes event information better translates to equivalent luminosity improvement
- Model testing, translating signatures between models

# Opportunities in Artificial Intelligence for Detector Design

At National Labs, we address the systems aspects of large experiments

- RL-based design of power / data distribution in calorimeters with extremely large channel count?
- Sensor / chip design to enable large-area detectors in trackers / calorimeters?
- Data acquisition with real-time compression in the forward calorimeters?
- Real-time reconstruction of beam parameters?
- Real-time matrix element methods?

# SiD Data Rates at peak luminosity

**Table II-9.2** Overview of read-out details for the various subdetectors. Occupancies and data volumes are for a full bunch train at 1 TeV and include beam-induced background as well as charge sharing between pixels/strips. Safety factors of five and two have been applied to the rates of incoherent pairs and $\gamma\gamma \to \mathrm{hadrons}$ respectively. BeamCal and Lumical are expected to be using the Bean chip with a buffer depth of 2820.

| | cell size ($mm^2$) | number of channels ($10^6$) | av. to max. occ. (%) | approx. # bits per hit (bit) | data volume (Mbyte) |
|---|---|---|---|---|---|
| **VXD barrel** | $0.02\times0.02$ | 408 | 8 - 60 | 32 | 130 |
| **VXD disks inner** | $0.02\times0.02$ | 295 | 4 - 70 | 32 | 50 |
| **VXD disks outer** | $0.05\times0.05$ | 980 | 0.5 - 20 | 32 | 20 |
| **Main tracker barrel** | $0.05\times100$ | 16 | 33 - 300 | 32 | 20 |
| **Main tracker disks** | $0.05\times100$ | 11 | 4 - 500 | 32 | 2 |
| **ECAL barrel** | $3.5\times3.5$ | 72 | 2 - 45 | 40 | 7 |
| **ECAL endcap** | $3.5\times3.5$ | 22 | 33 - 2300 | 40 | 36 |
| **HCAL barrel** | $10\times10$ | 30 | 0.07 - 200 | 40 | 0.1 |
| **HCAL endcap** | $10\times10$ | 5 | 96 - 3600 | 40 | 24 |
| **LumiCal** | $2.5\times$var. | 0.061 | $\gg$100 | 16 | 340 |
| **BeamCal** | $2.5(5.0)\times$var. | 0.076 | $\gg$100 | 16 | 430 |

1060

Assuming 2450 BX/train @ 5 Hz

$\to$ 5.3 GB/s

NB: These rates are much smaller than what will have been solved for the HL-LHC.
However, more important than their size is how well they are understood.

# Opportunities in Artificial Intelligence for Detector Operation

- A big strength of AI is to provide large reservoirs of human knowledge at one's fingertips
  - Inexperience in detector (and accelerator) operations are frequently a cause of lost experiment time

⇒ Can we design a data quality system that improves the efficiency of inexperienced shifters?

  ⇒ What needs to change in the detector design to enable this seamlessly between different systems?

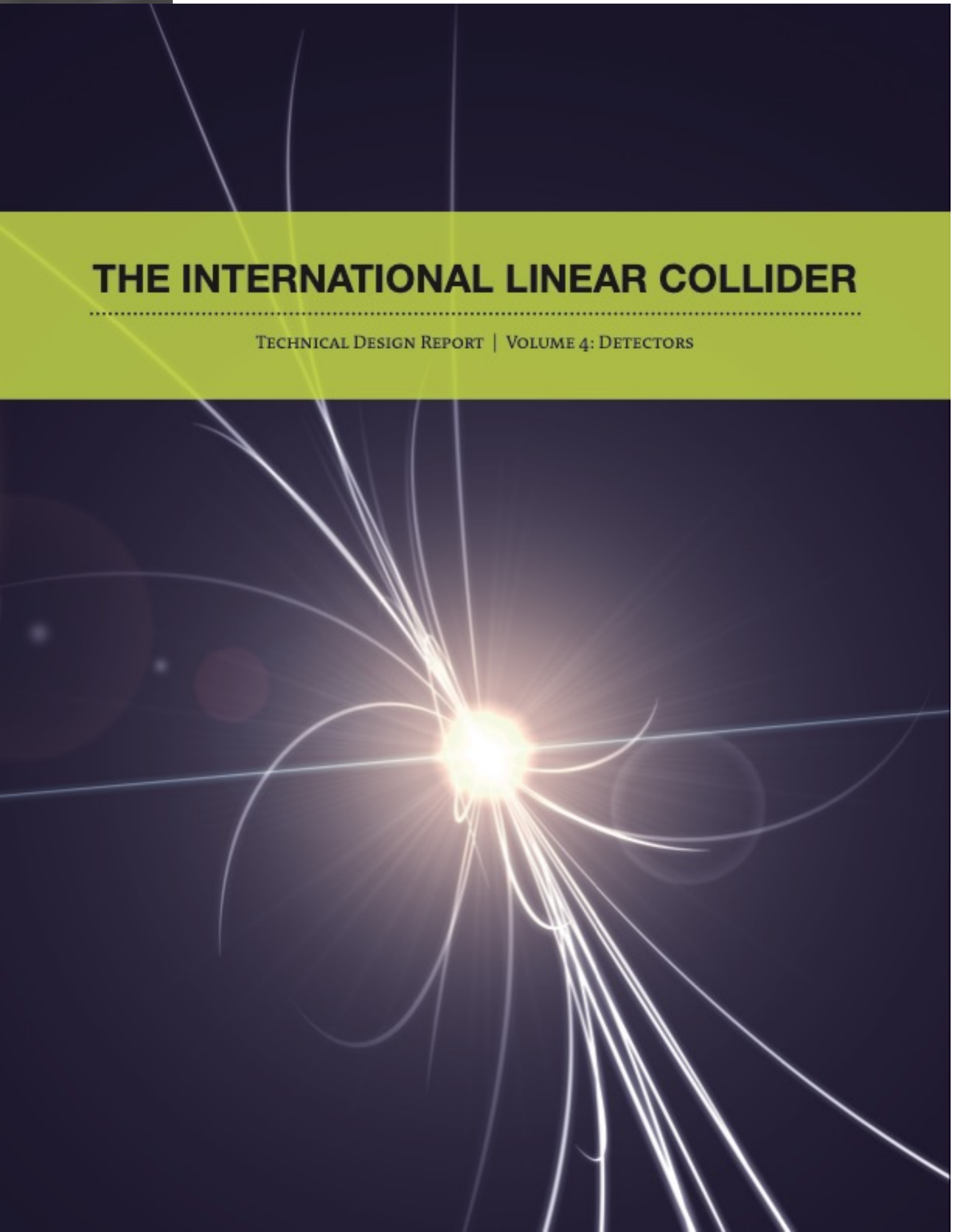
- Some detectors exceed the expected lifetime by a lot, while others need to be replaced faster. This complicates upgrade schedules.

⇒ Can we design our detectors to be more modular?

⇒ Can we get feedback on detector performance faster? From a “digital twin”?

⇒ Calibration in the presence of detector deterioration / failures

# “Plans are useless, but planning is everything”





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DESY 12-008
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14 February 2012


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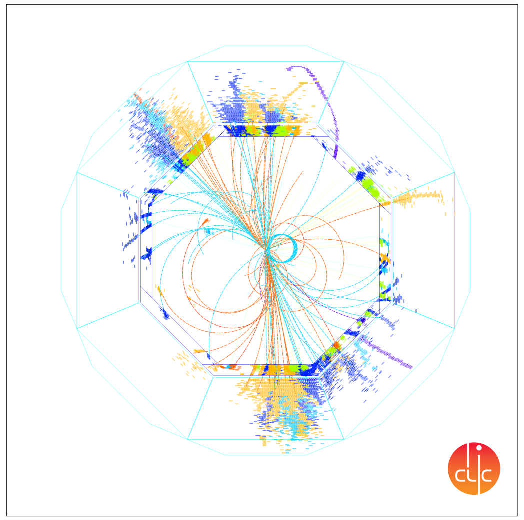

PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

LINEAR COLLIDER COLLABORATION

## Detector R&D Report

FINAL VERSION


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Editors

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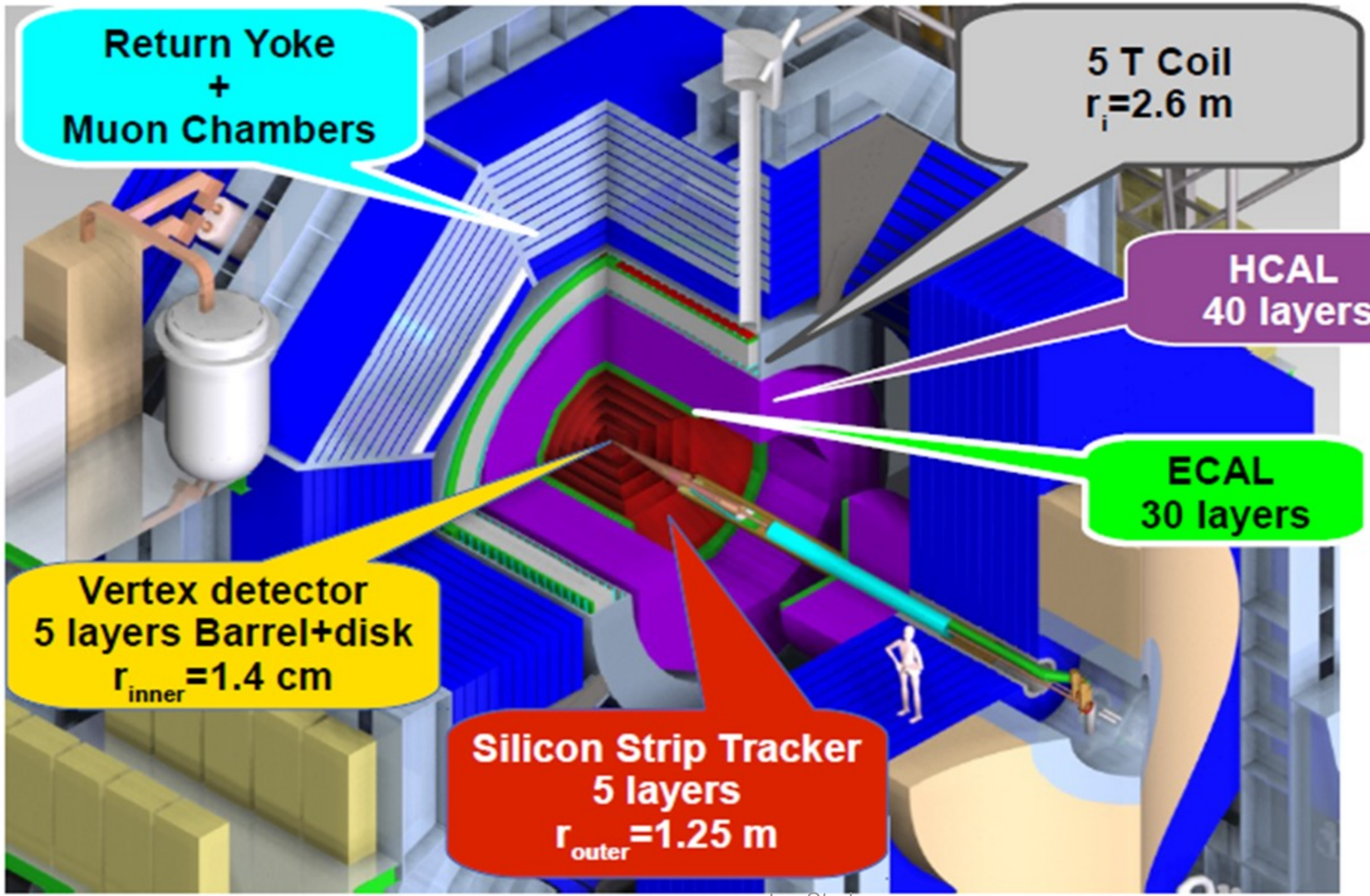
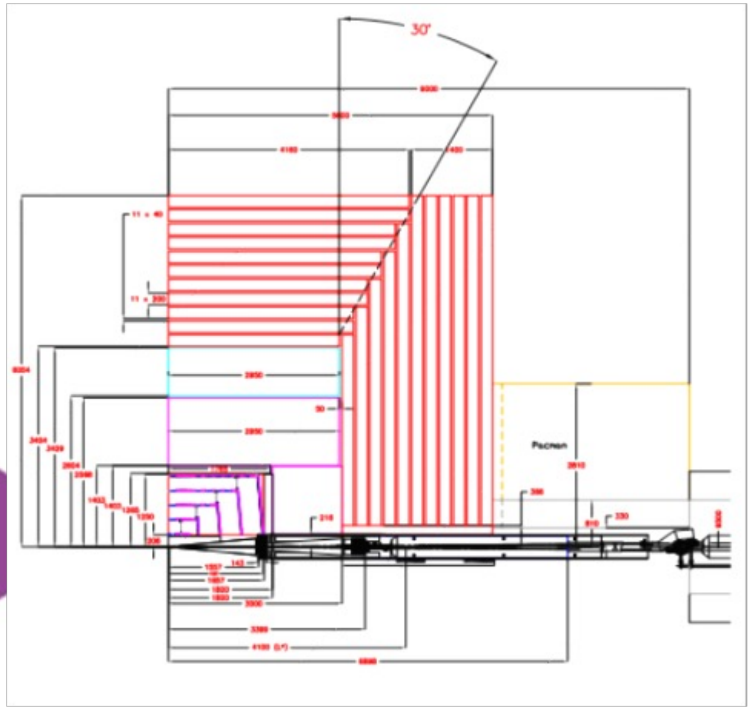
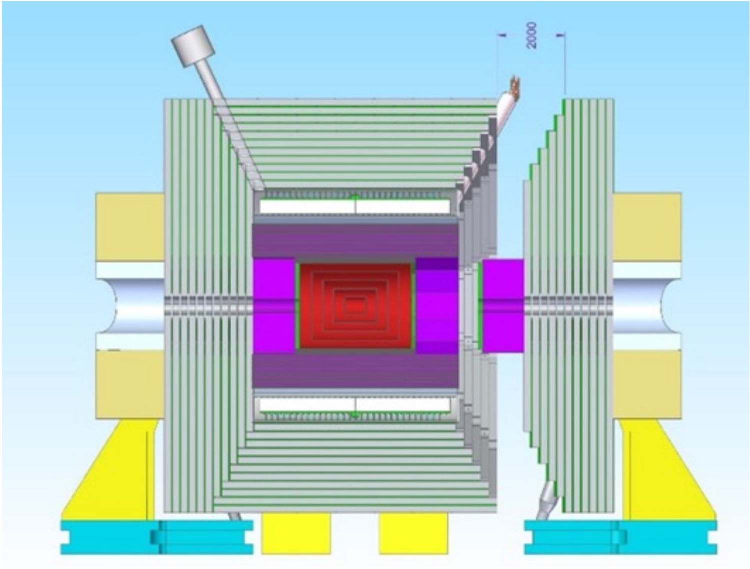
# SiD Design Overview





# Key Detector Design Parameters

https://arxiv.org/abs/1306.6329

## Vertex Detector

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

## Main Tracker

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

## Electromagnetic Calorimeter

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

# Detector Calibration

- Experiments have to operate at different energies
  - 91 GeV: high hadronic cross sections, lowest energy
  - 250 GeV: ZH peak, needs best vertex resolution
  - 350 GeV: top physics, jet reconstruction
- How quickly can you calibrate when the energy changes?
- How does your design perform in these different environments? Which one do you prioritize?
- Crazy idea: FCC-ee has multiple IPs (at least two). Would it make sense to have one specialized detector for Higgs physics and one for the Z pole?

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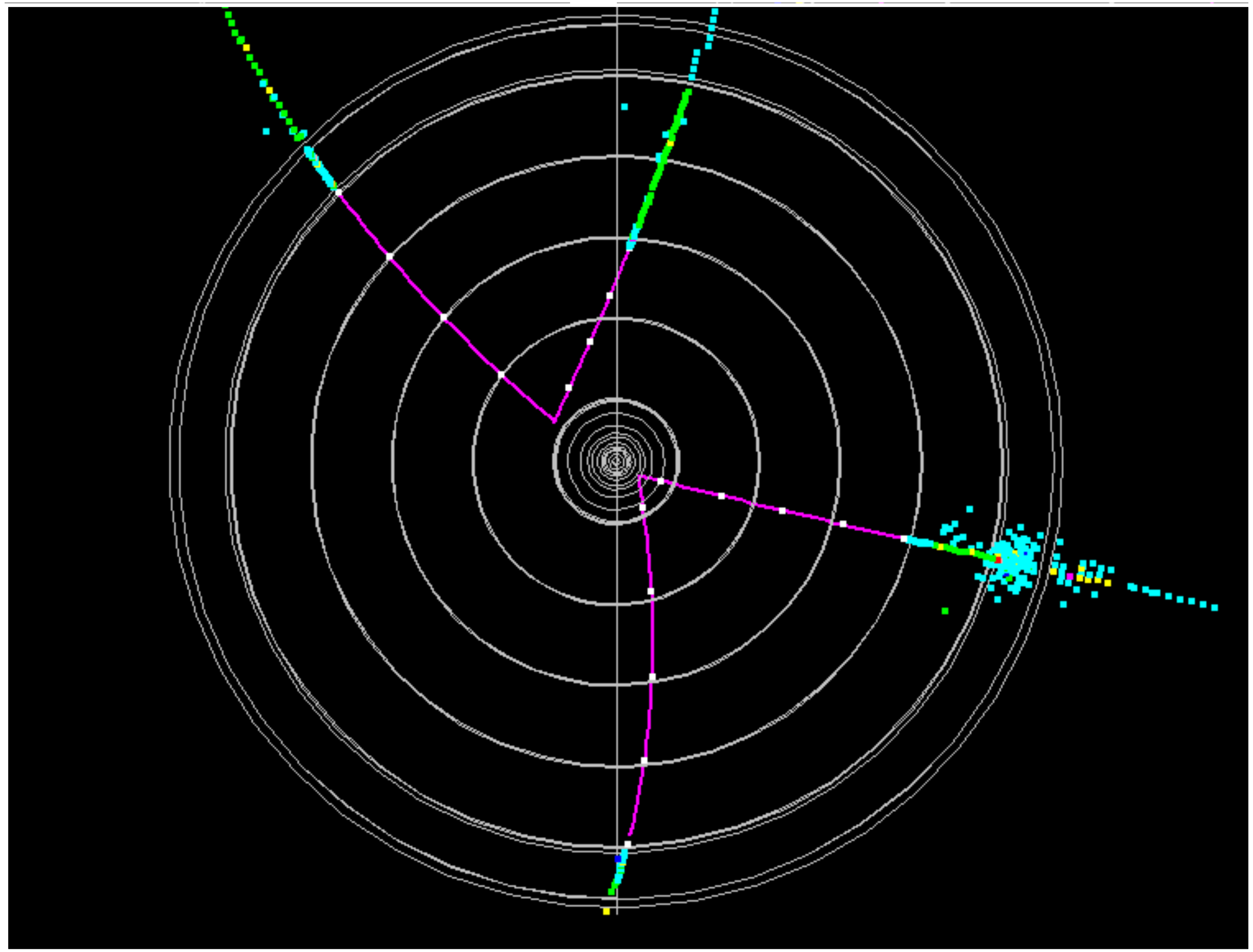
# Event reconstruction in a real detector

- Extremely high channel count: What fraction of dead channels can your reconstruction tolerate?
- Reconstruction is hierarchical
  - Hits -> clusters -> particles -> jets
  - In big, but rare events at 240/250 GeV, do we want to keep multiple hypotheses for longer? “Fuzzy matching” / global event interpretation
- Z-pole physics benefits from dedicated Particle ID
  - These detectors do not come for free: Impact on jet energy resolution? B field constraints?
  - How much can you gain from shower shapes / dual readout
- Long-lived particles
  - Calorimeter-assisted tracking to augment a silicon tracker

# Calorimeter-assisted tracking

- Exotic decays can have displaced vertices deep in the tracking volume
- This is a challenge for all-silicon trackers
- Highly granular calorimeters can be used to augment the pattern recognition with track stubs from MIP traces



# Vertex Detector Requirements

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

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

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

How does the vertex reconstruction / flavor tagging performance depend on these parameters?

| Channel | SM BR (%) |
|---|---|
| $H \rightarrow bb$ | 58.24 |
| $H \rightarrow \tau\tau$ | 6.272 |
| $H \rightarrow \mu\mu$ | 0.02176 |
| $H \rightarrow cc$ | 2.891 |
| $H \rightarrow gg$ | 8.187 |
| $H \rightarrow WW$ | 21.37 |
| $H \rightarrow ZZ$ | 2.619 |

- These **very** challenging requirements constrain
  - the material / cooling budget
  - the pixel size
  - the inner radius of the detector / occupancy / time stamping
- NB: Vertex reconstruction algorithms are > 20 years old

# Impact of the machine-induced background the vertex detector design

[arXiv:1609.07816](arXiv:1609.07816)

**ILC Beam environment:**

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

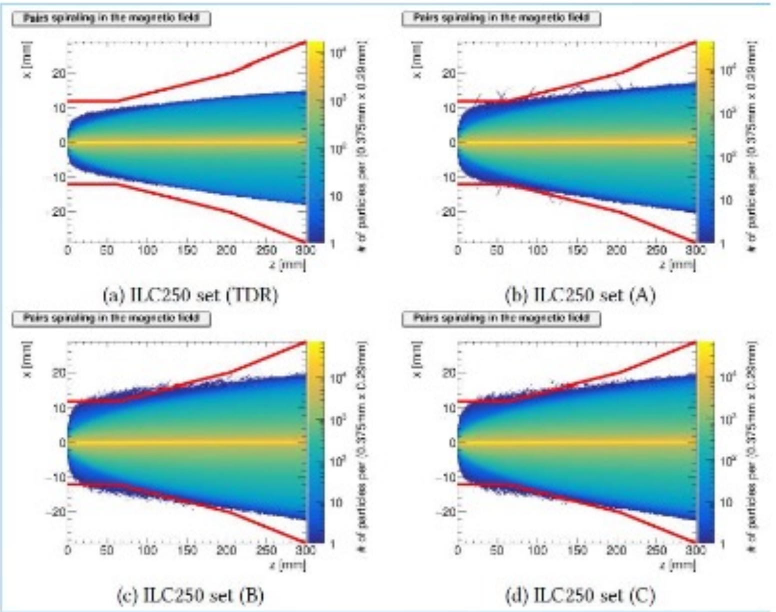
5T field allows first layer to be very close to the beam.

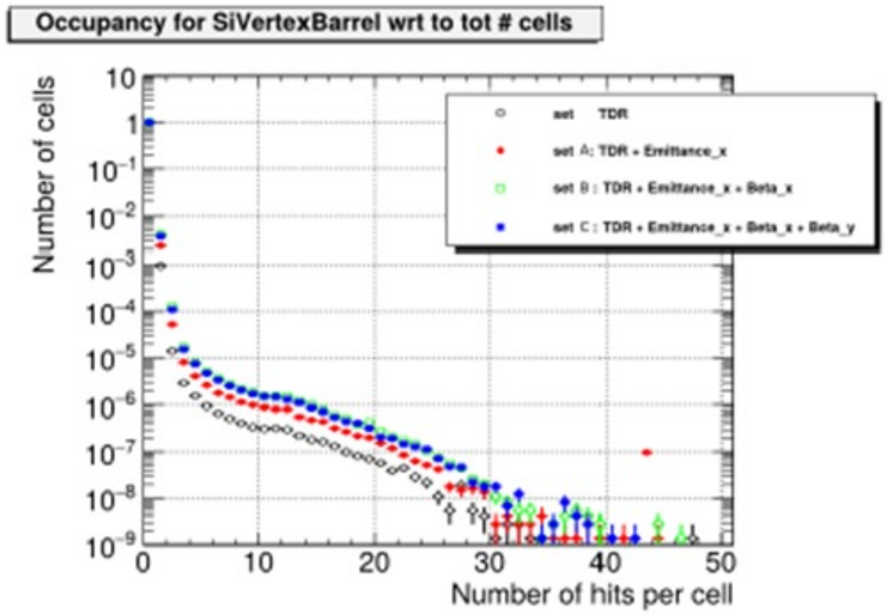
$R_{min}$ = 14mm.

## Pair background/Occupancy study

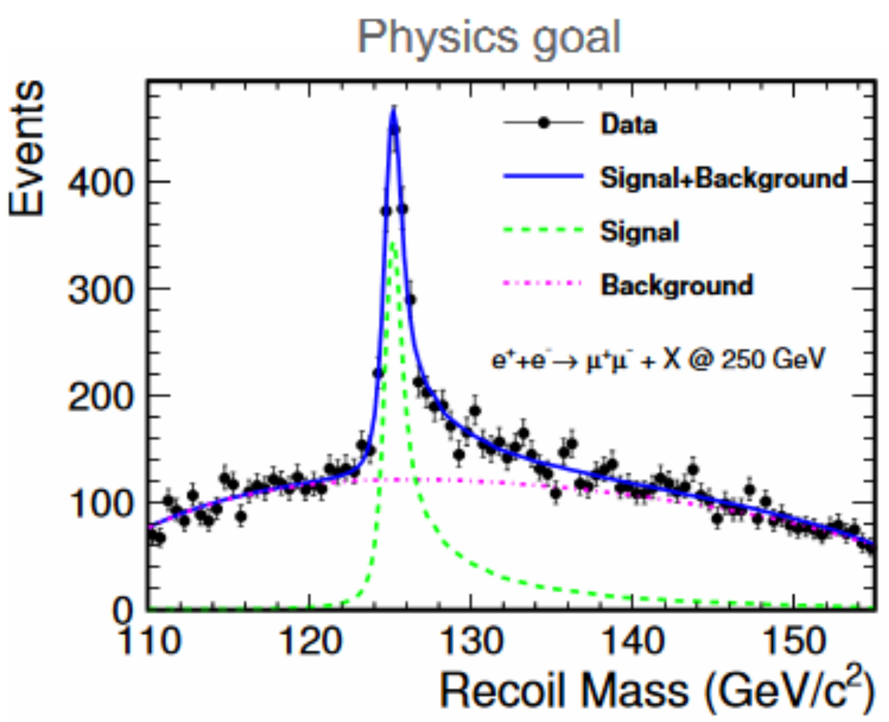
**Very challenging requirements**

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



# Tracking requirements




Physics

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

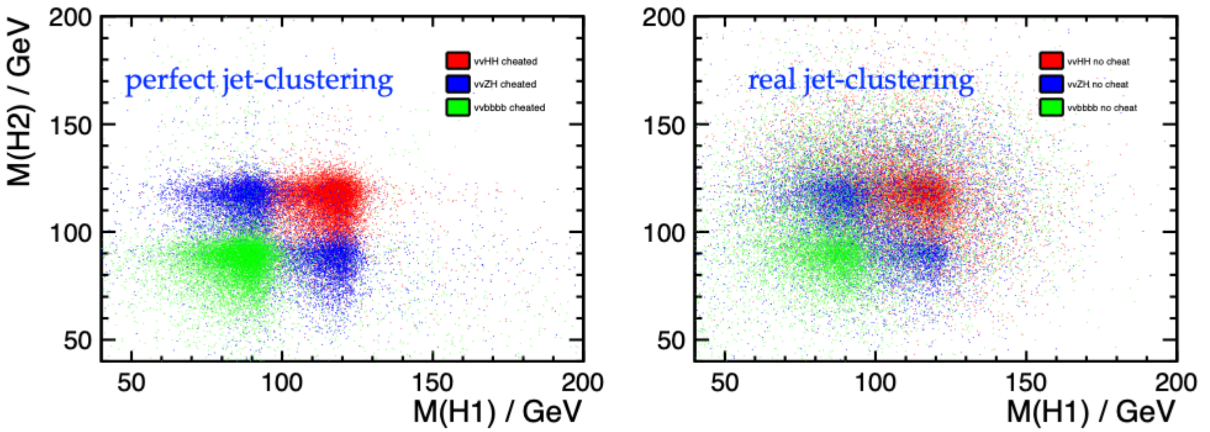
Design

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

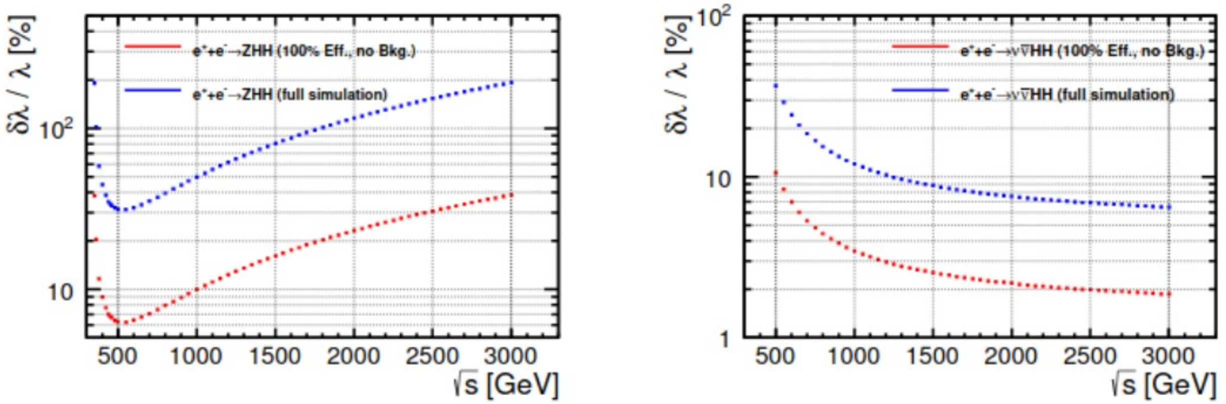
# (Some) R&D questions for calorimetry

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

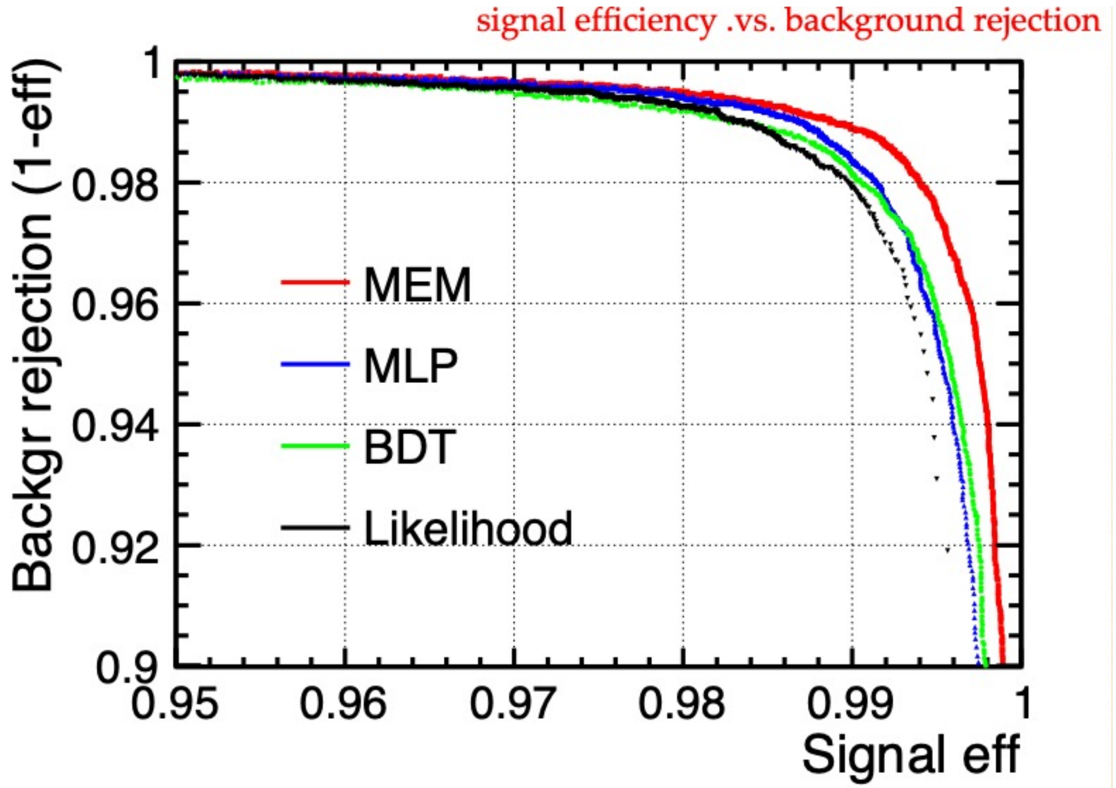
# Opportunities for Improving the Physics Reach




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



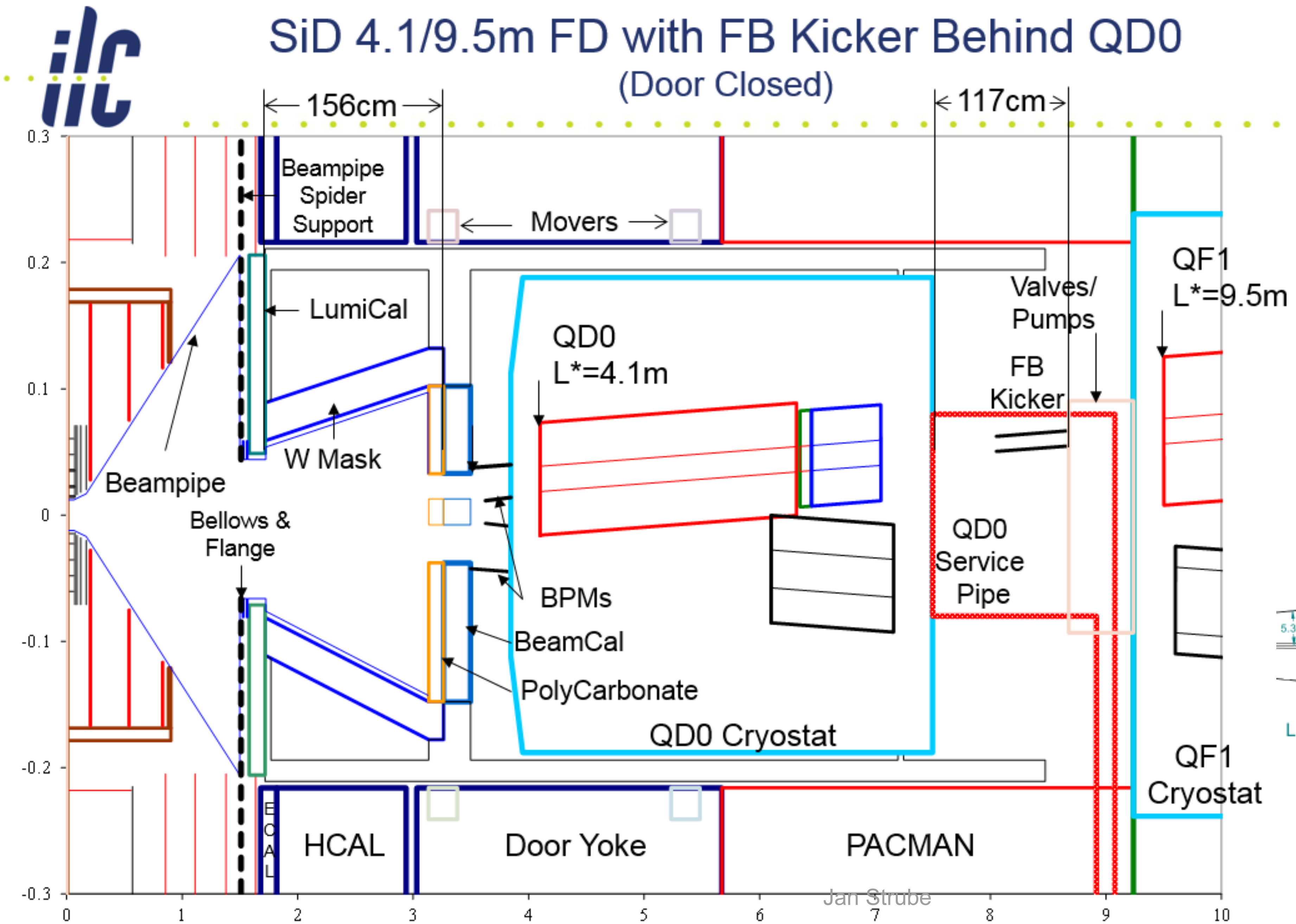

At higher energies, vvHH has fewer, but more collimated jets.



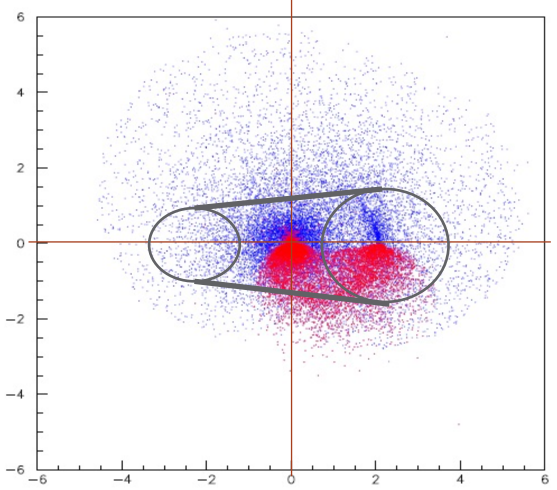

The matrix element method can infuse physics knowledge into the otherwise purely statistical separation of samples.

Example: $e^+e^-H$ measurement

# Forward calorimetry

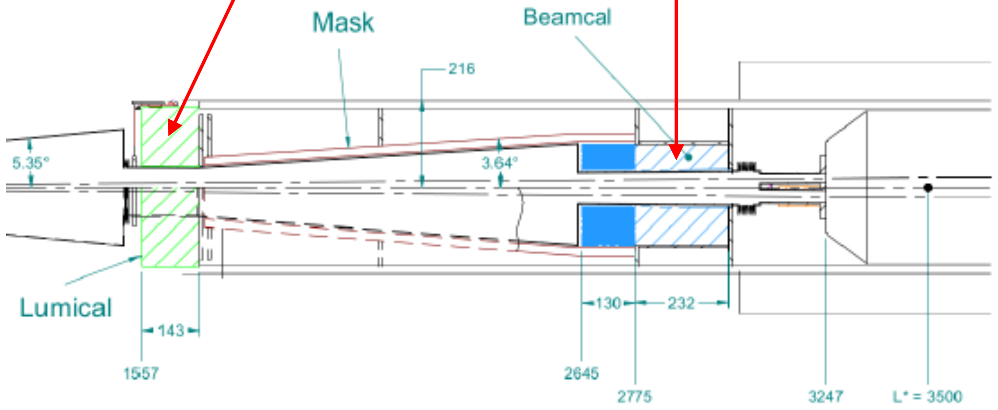



Proposed SiD BeamCal Beampipe



Lumi Cal

Beam Cal

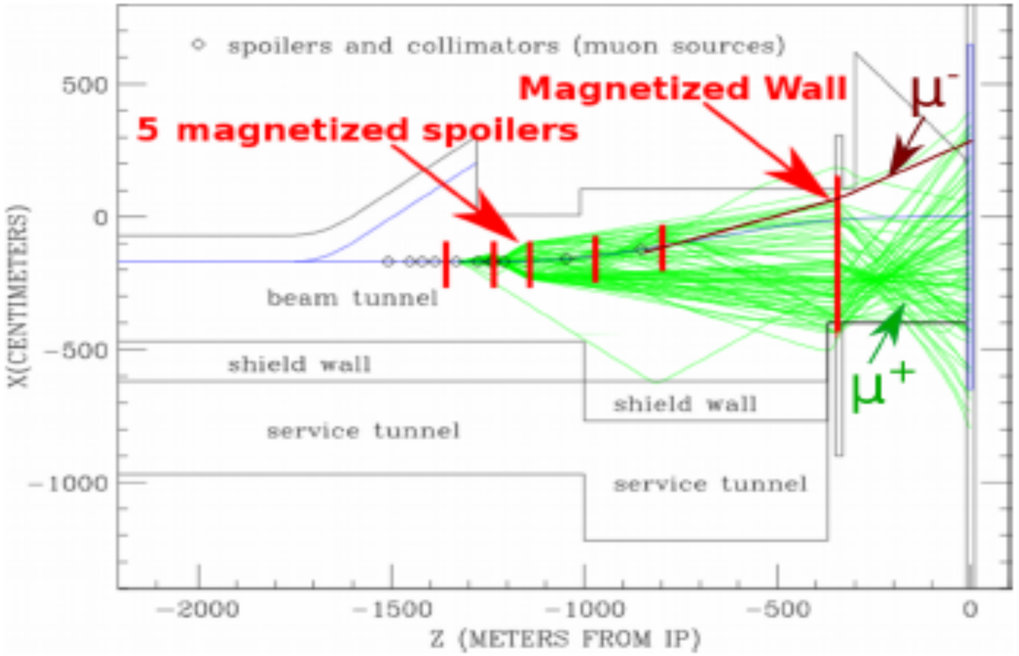


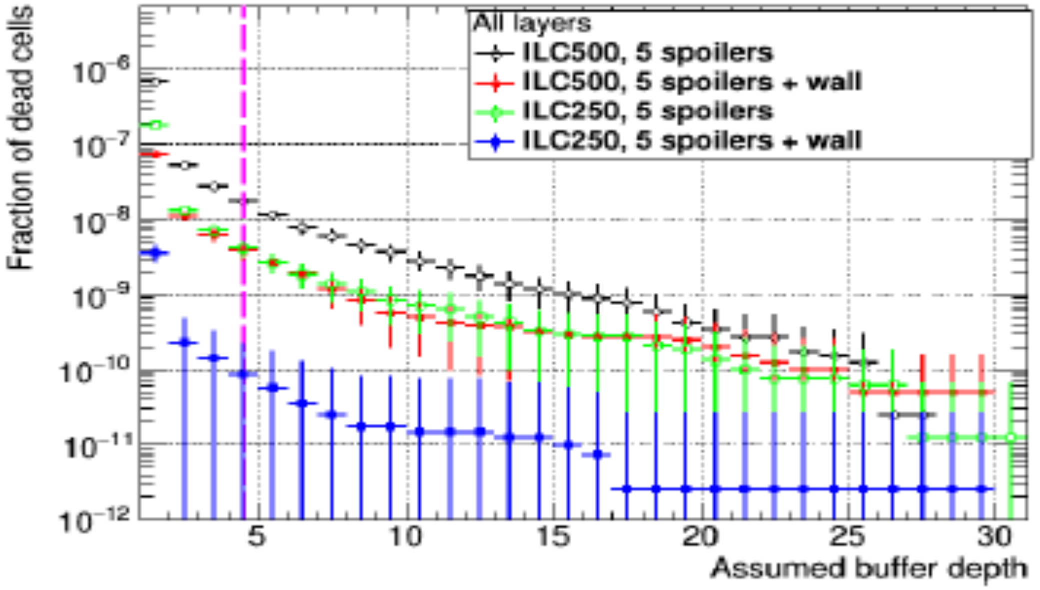
# (Some) Forward Calorimetry R&D questions

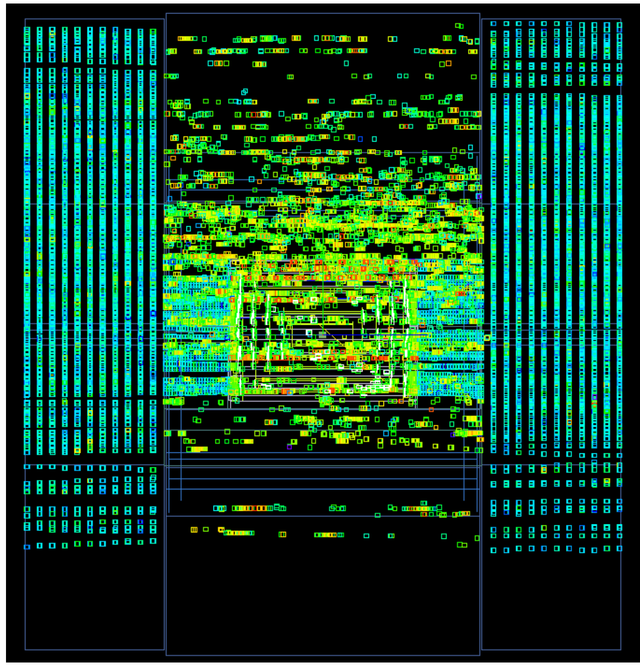
- Do we need to instrument the region between the incoming and outgoing beam pipes?
  - Certain SUSY models have very far-forward signatures. How much effort should go into preserving discovery potential?
- High luminosity is key to the success of the project. How can the experiment support the machine in ramping up to design specs faster?
  - See, e.g. ”RECONSTRUCTION OF IP BEAM PARAMETERS AT THE ILC FROM BEAMSTRAHLUNG” (https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1590793)
- The occupancy in the forward calorimeters very high. How can you apply data compression such that the DAQ requirements are not driven by these detectors?

# MDI Studies

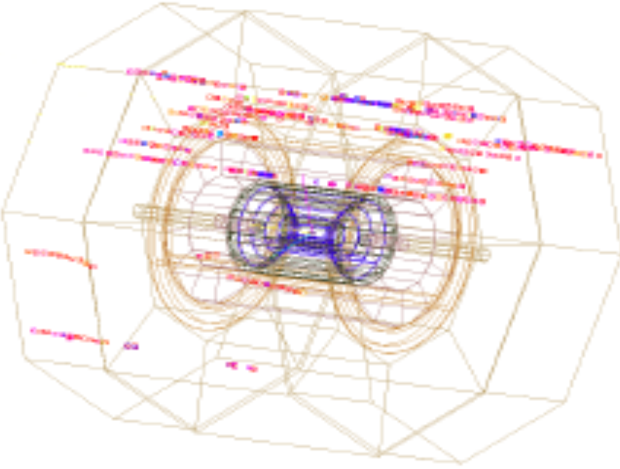
Anne Schuetz
(DESY)



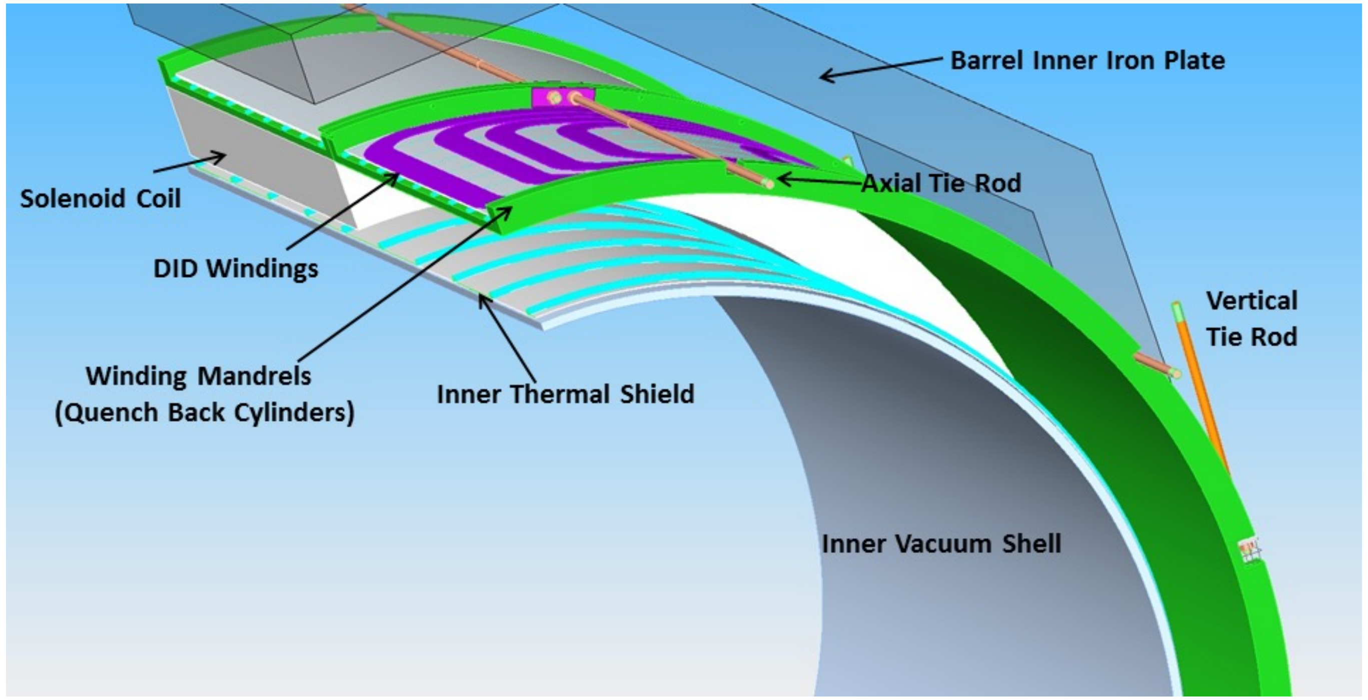
| #muons / bunch crossing | ILC250 | ILC500 |
|---|---|---|
| No shielding | 39.3 | 130.1 |
| Magnetized spoilers | 1.3 | 4.3 |
| Magnetized spoilers + wall | 0.03 | 0.6 |



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

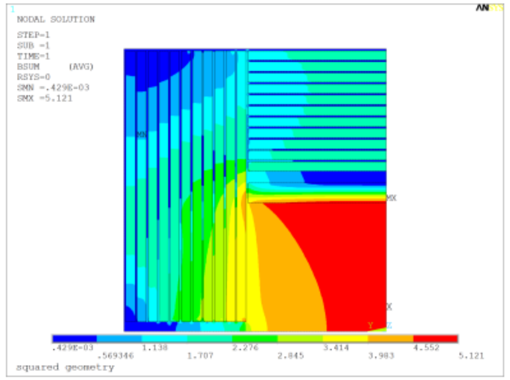
Wall might me neccessary at higher stages, and as a tertiary containment device.

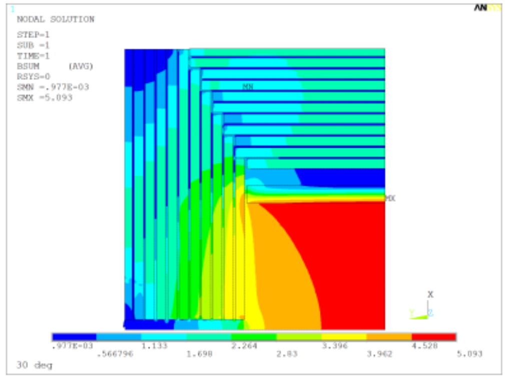
# Solenoid Magnet




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

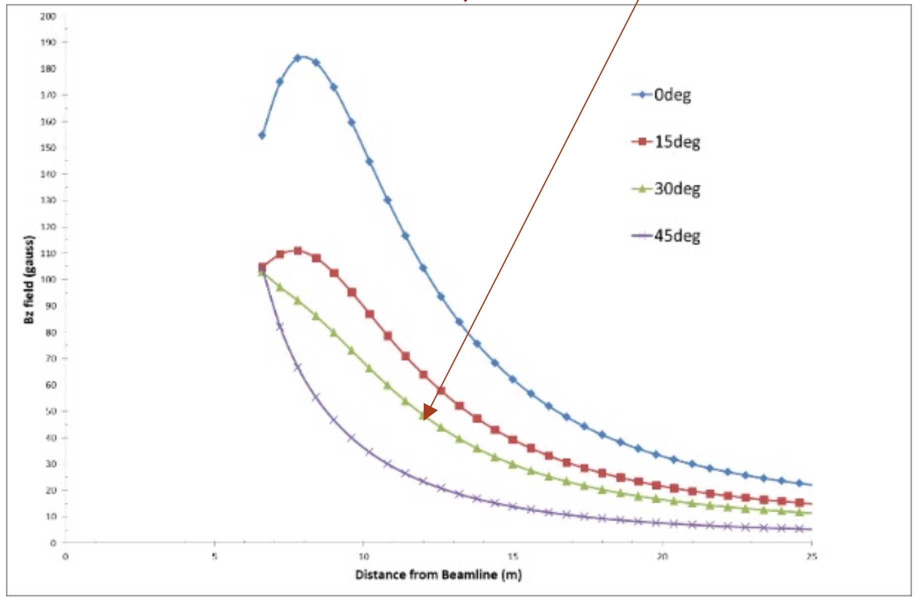
30$^{o}$ design




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

< 50 Gauss at 15m



# Cable in Conduit Conductor

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

SiD costs by system

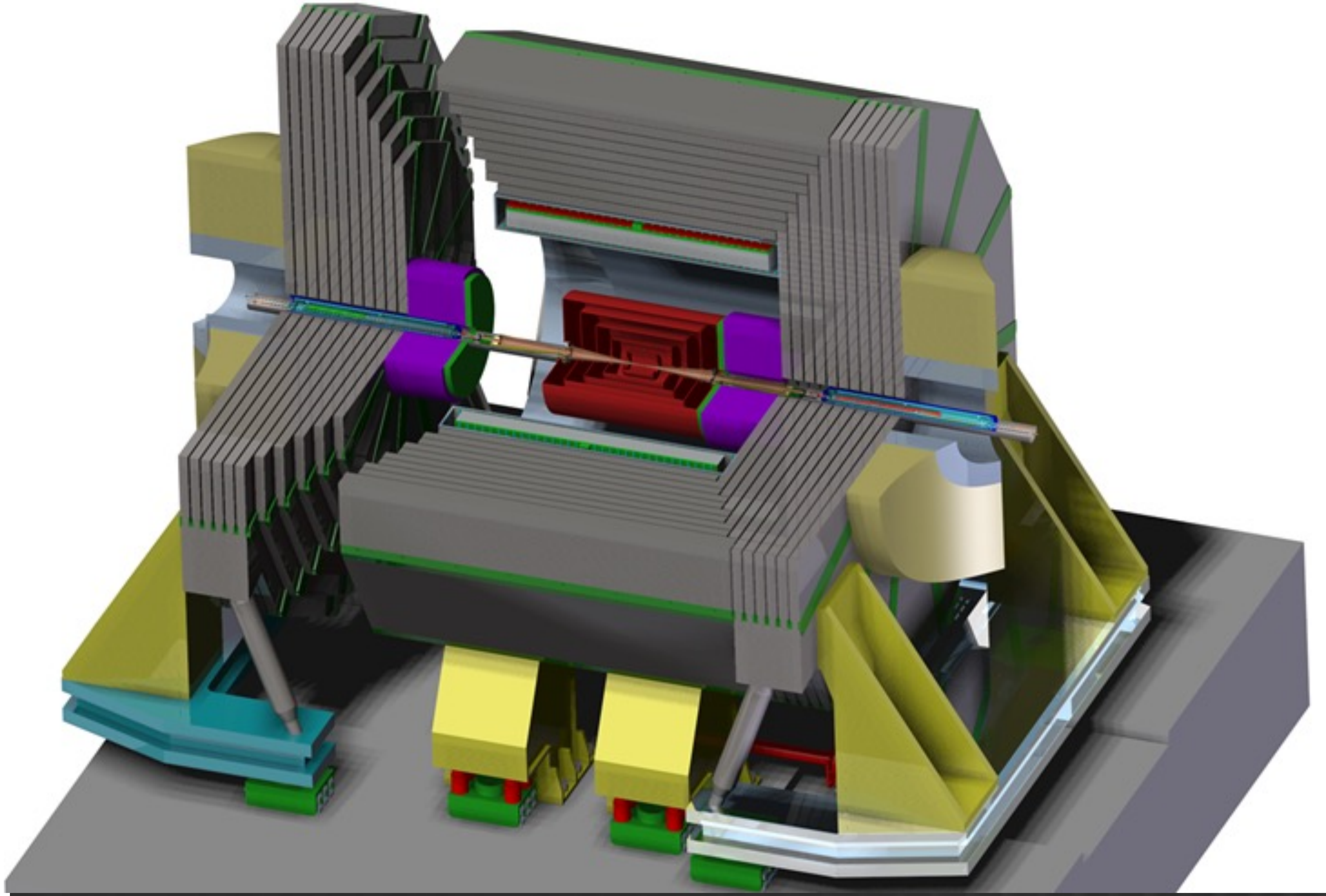
| | M&S Base (M US-$) | M&S Contingency (M US-$) | Engineering (MY) | Technical (MY) | Admin (MY) |
|---|---|---|---|---|---|
| Beamline Systems | 3.7 | 1.4 | 4.0 | 10.0 | |
| VXD | 2.8 | 2.0 | 8.0 | 13.2 | |
| Tracker | 18.5 | 7.0 | 24.0 | 53.2 | |
| ECAL | 104.8 | 47.1 | 13.0 | 288.0 | |
| HCAL | 51.2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

# Summary

- Studying the Higgs boson should be carried out in an uncompromising precision experiment
- Different collider proposals exist that could carry out an interesting physics program
- An experiment for precision measurements must be optimized for its environment
- However, some challenges are common to all / several proposals
  - Operational considerations
  - Developing frameworks that provide faster feedback between detector design and performance
  - Solenoid magnet design
  - Ideas for power distribution
  - Low-mass tracker support structures

$\Rightarrow$ A strategic R&D program should emphasize these common elements, but not be limited to them.

# Thank you



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

Conceptual Overview

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

Background – MDI

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

Physics

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

Code

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