*Hong Kong Univ. S&T - January 16, 2020*

# ILC Detector Requirements

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University of Oregon

# ILC Physics

The physics opportunities of the ILC include:

- precision measurement of Higgs boson couplings
- search for exotic modes of Higgs boson decay
- search for dark matter particles and other invisible states
- search for heavy resonances through 2-fermion processes
- precision measurement of the top quark mass
- precision measurement of top quark electroweak couplings
- measurement of the triple Higgs boson coupling
- and more (eg. WW threshold and gigaZ)

# Advantage of Higgs Studies at $e^+e^-$

Effects of new physics on the Higgs boson are expected to be small, of about a **few-percent**.

Typical LHC Higgs boson samples have large backgrounds. Furthermore, not all Higgs decay modes are observed.

At LHC, Higgs couplings are determined in a model-dependent way and precision is limited.

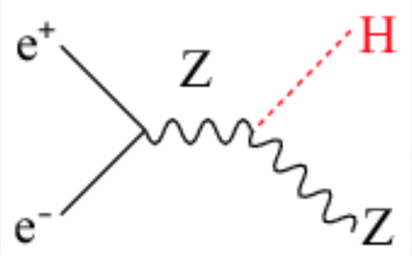
**On the otherhand, the very low backgrounds and simple reactions in $e^+e^-$ make higher precision, model-independent measurements feasible, if detectors are capable.**

**All major decay modes are observed in $e^+e^-$.**

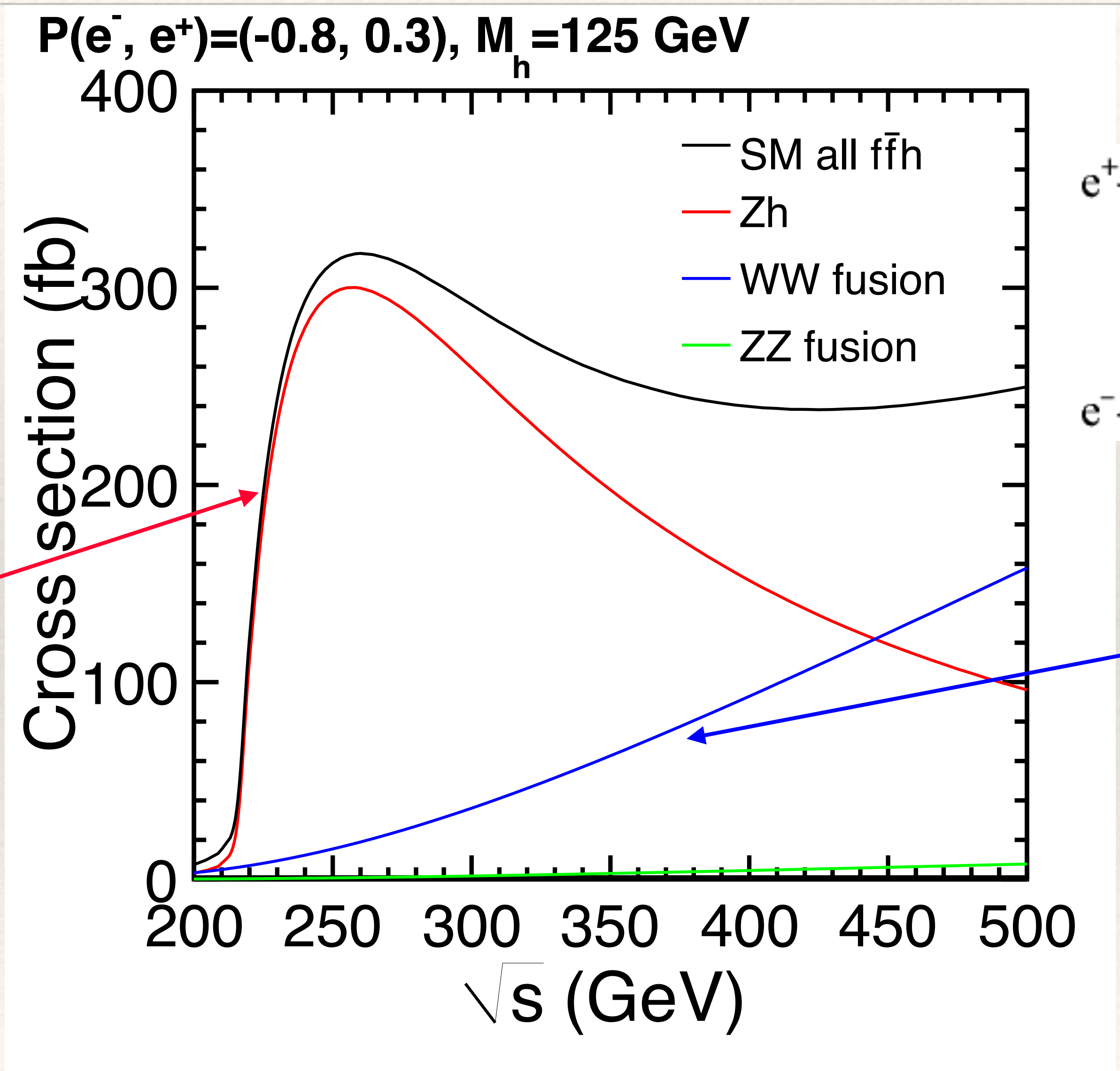
# ILC Detector Energy Range

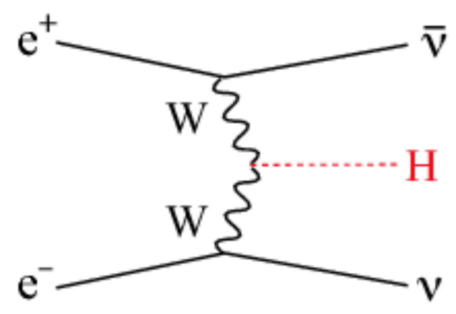
- Center-of-mass energies:
  - 200 GeV up to 1 TeV.
  - Special running at the Z-pole and WW threshold.
  - Higgs Factory, Giga-Z, Top Yukawa couplings, di-boson production, SUSY, other new physics motivated by alternative models.
  - Each physics topic creates a particular set of requirements.
- Detector designs developed for the full energy range.

# Higgs Boson Cross Section



Higgs-strahlung peaks and falls with center-of-mass energy





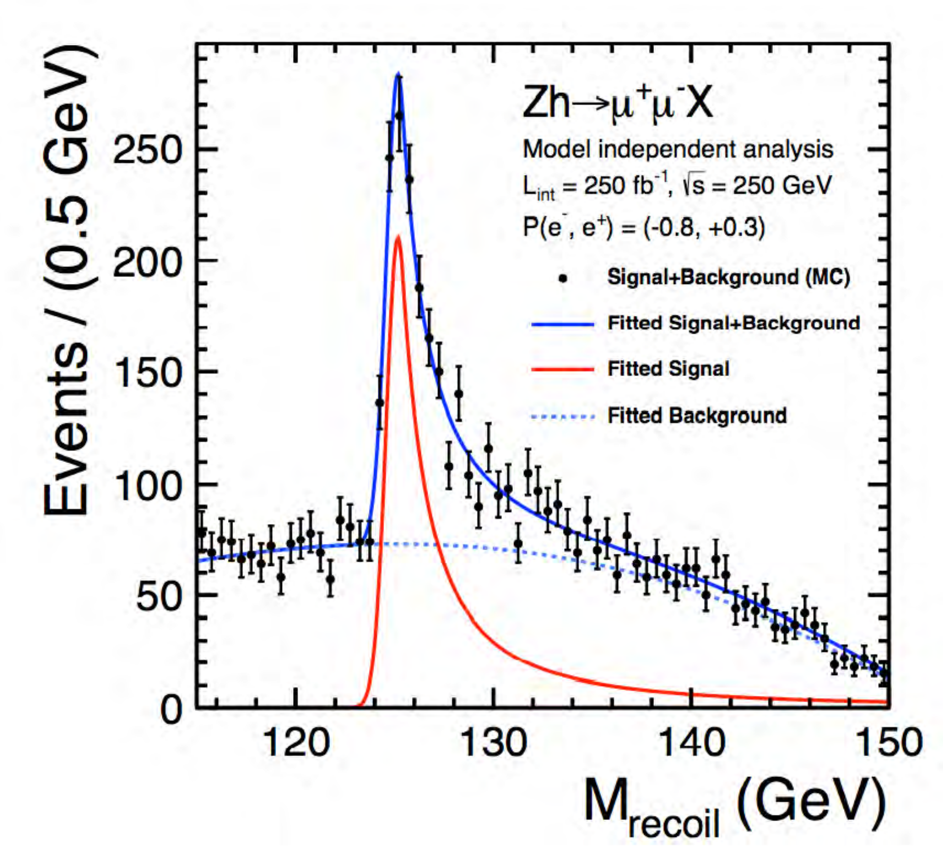
WW fusion rising with center-of-mass energy

# Higgstrahlung

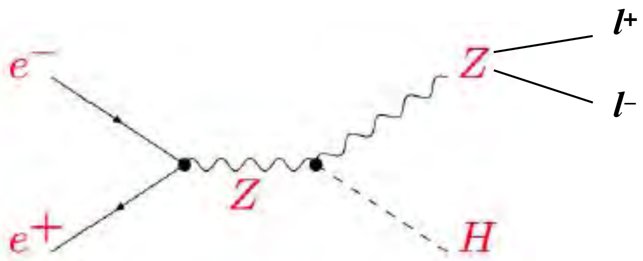
ILC observes Higgs recoiling from a Z, with known CM energy⇓

- powerful channel for unbiassed tagging of Higgs events
- measurement of even invisible decays

(⇓ - some beamstrahlung)



1. KNOWN INTIAL STATE
2. MEASURE Z→ $l^+l^-$
3. SELECT E(Z boson) = 110 GeV
   M(recoil) = 125 GeV



4. MEASURE RECOIL
   AND OBSERVE DECAY

Invisible decays are included

# ILC Experimental Advantages

- Radiation damage is mostly not an issue (except very forward)
  - collisions dominated by electroweak processes
- Trigger-less operation - record every interaction (< 6 Gb/sec)
- Bunch train structure allows pulse power w/ gas cooling

- Relatively low event rates
- Elementary interactions at known $E_{cm}$ (e.g. $e^+e^- \rightarrow ZH$)
- Democratic Cross sections (e.g. $[e^+e^- \rightarrow ZH] \sim 1/2\,[e^+e^- \rightarrow d\bar{d}]$ )
- Highly Polarized Electron Beam (~ 80% - & positron pol. 30%)
- Tunable center-of-mass energy

- Compared to LHC - trigger-less, ~no pileup, low occupancy, no rad.

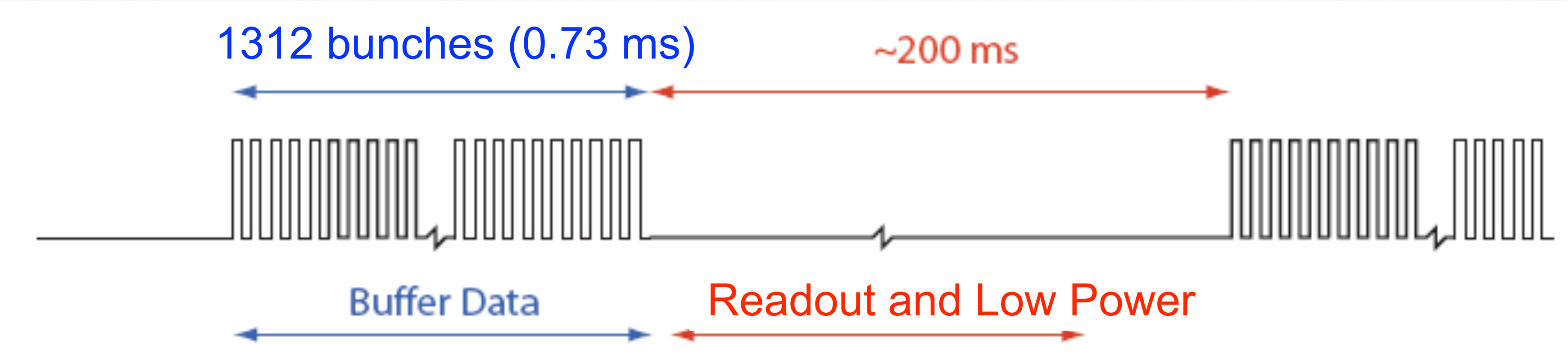
- THESE FEATURES ENHANCE PRECISION MEASUREMENTS
- OPPORTUNITY FOR DETECTOR OPTIMIZATION

# ILC Design Evolution

- ILC first designed for initial running at 500 GeV.
  - Technical Design Report.
- Now, ILC250 proposed as first-stage with primary motivation to study Higgs-strahlung.
  - Many studies based on 500 GeV - conditions milder at 250 GeV

# ILC Beam Structure

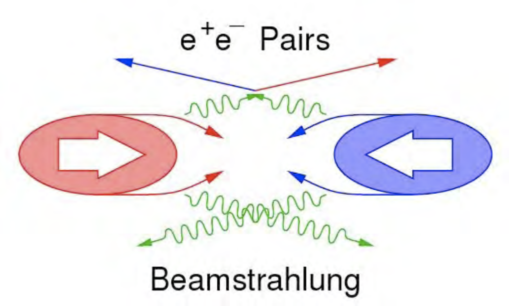
- Bunch trains at 5 Hz.
- 1312 bunches / train in first-stage (ILC250)



- Duty cycle < 1%
- Average low power achieved by power pulsing during readout (also requires quiescent currents).

# Background Processes

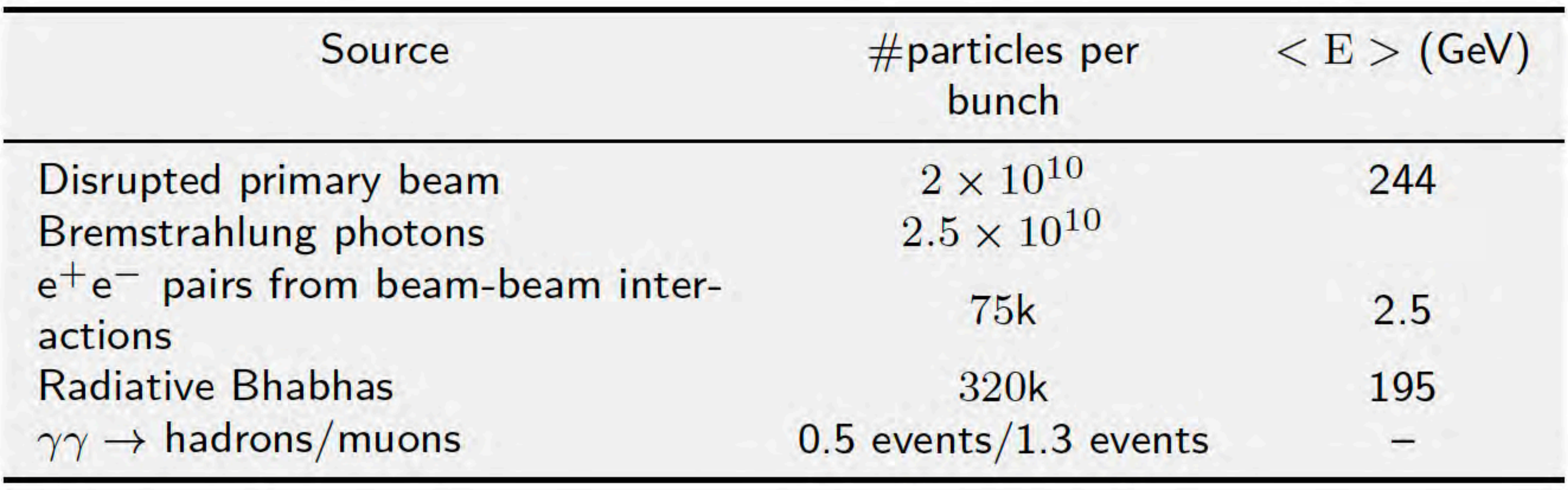
- Beamstrahlung - due to extreme focus at IP



- Synchrotron Radiation
    - Non-gaussian tail of beams interacts with final focus elements
- Muons
    - Non-gaussian tail of beams interact with collimators
- Neutrons
    - Beamstrahlung induced $e_{+}e_{-}$ pairs strike beam line components;
    - Disrupted beam particles strike beam line components;
    - Backscatter from primary beams and beamstrahlung that strike beam dumps.
- Hadrons and muon pairs
    - Created by gamma-gamma production

# Background Estimates

- **At 500 GeV (TDR)**

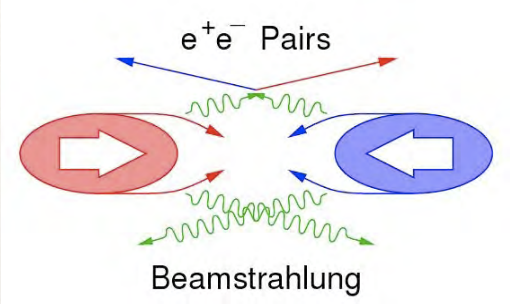


| Source | #particles per bunch | $< E >$ (GeV) |
|---|---|---|
| Disrupted primary beam | $2 \times 10^{10}$ | 244 |
| Bremstrahlung photons | $2.5 \times 10^{10}$ | |
| $e^+e^-$ pairs from beam-beam interactions | 75k | 2.5 |
| Radiative Bhabhas | 320k | 195 |
| $\gamma\gamma \rightarrow$ hadrons/muons | 0.5 events/1.3 events | – |

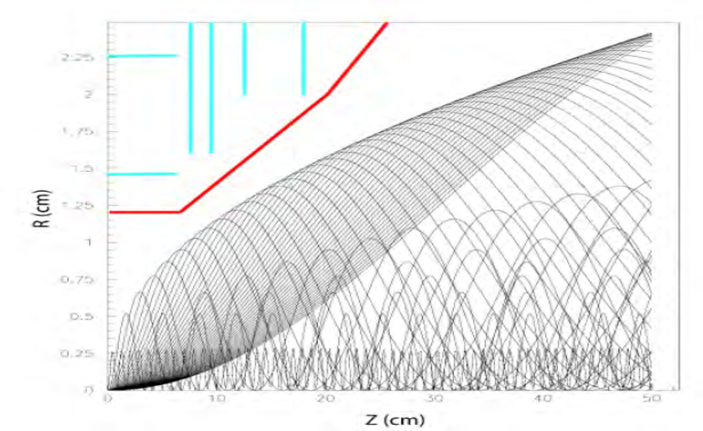
- Beam-beam interactions (beamstrahlung)
  - High occupancy → low mass detectors and structures → pulse power

# ILC Environmental Challenges

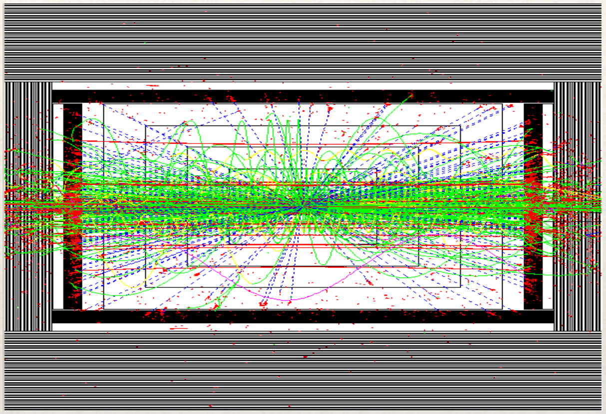
- Tiny beam spots, intense collisions lead to e+e- pairs from beamstrahlung



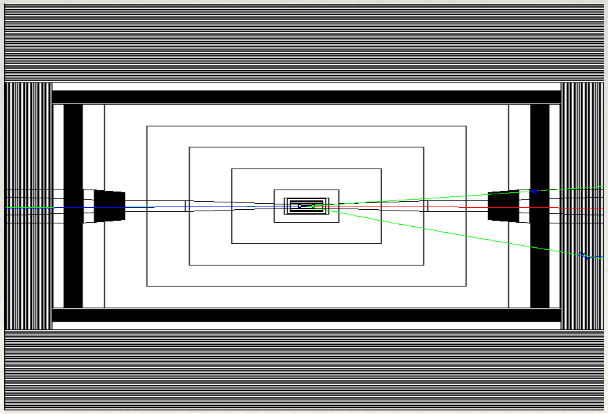
- Most pairs at ILC are trapped by the solenoid, but vertex occupancies are still challenging



$\gamma\gamma \to e^+e^-, \mu^+\mu^-$, hadrons; reactions put a premium on short detector livetime

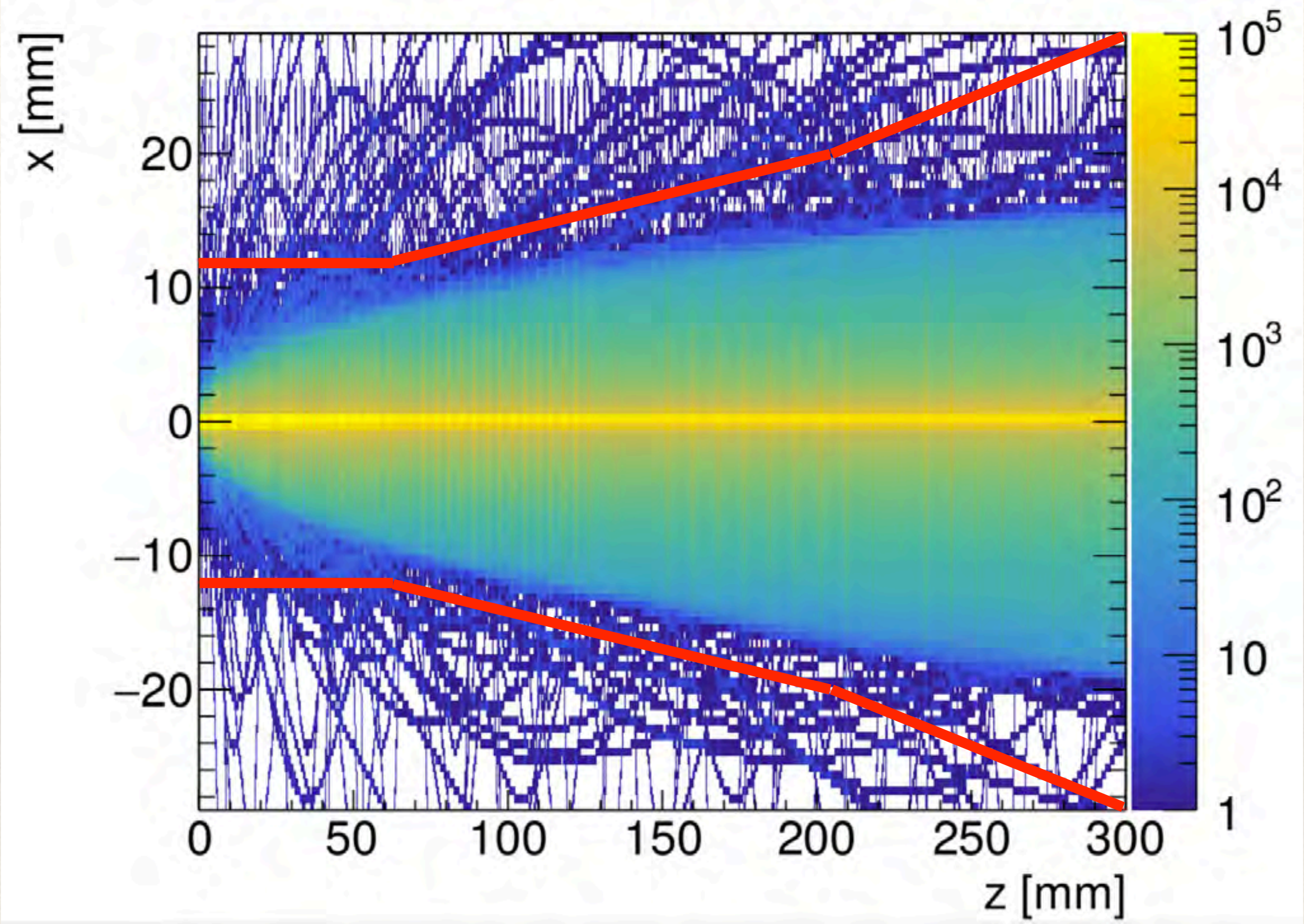


Livetime 40 usec ~130 beam crossings



Livetime 100 nsec ~1 beam crossing

# Background $e^+e^-$ Pairs



A. Schutz
arXiv:1703.05737

Cone of background from incoherent $e^+e^-$-pairs, generated with Guinea-Pig and simulated in the 5 T B-field of the SiD detector

# ILC Detector Requirements

- Two-jet mass resolution comparable to the natural widths of W and Z for an unambiguous identification of the final states.
- Excellent flavor-tagging efficiency and purity (for both b- and c-quarks, and hopefully also for s-quarks).
- Momentum resolution capable of reconstructing the recoil-mass to di-muons in Higgs-strahlung with resolution better than beam-energy spread.
- Hermeticity (both crack-less and coverage to very forward angles) to precisely determine the missing momentum.
- Timing resolution capable of separating bunch-crossings to suppress overlapping of events .

# Physics Drives Detector Requirements

**Clean events with low backgrounds motivate unprecedented detector 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>$ZH + H\nu\bar{\nu} \to \mu^+\mu^- X$ | 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.<br>$\tilde{\mu}$ decay | $\tilde{\mu}$ mass | Tracker, Calorimeter | Momentum resolution, Hermiticity<br>⇒ Event Reconstruction | Maximal solid angle coverage |

**High granularity, dense integration, super light materials, low power, air cooling, power pulsing**

# Unprecedented Detector Challenges

- **Requirements for ILC**
  - Impact parameter resolution

$$\sigma_{r\varphi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\ \sin^{3/2}\vartheta)\ \mu m$$

  - Momentum resolution

$$\sigma\left(\frac{1}{p_T}\right) \sim \text{few} \times 10^{-5}\ (GeV^{-1})$$

  - Jet energy resolution goal

$$\frac{\sigma_E}{E_{jet}} = \ \sim 3\%\ \text{for}\ E_{jet} > 100\ \text{GeV}$$

  - Maximal solid angle coverage

**Compared to best performance to date**

Requires 3 times better than SLD

Requires >10 (3) times better than LEP (CMS)

Requires 2 times better than ZEUS

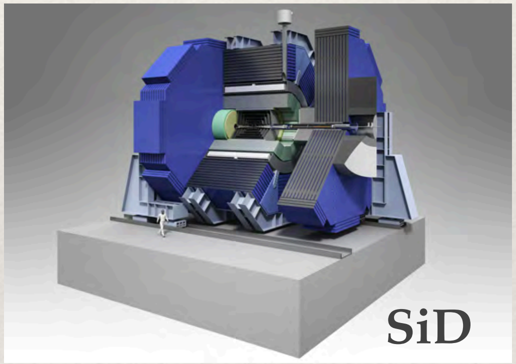
Beyond prior experiments, LHC, LEP or SLD.

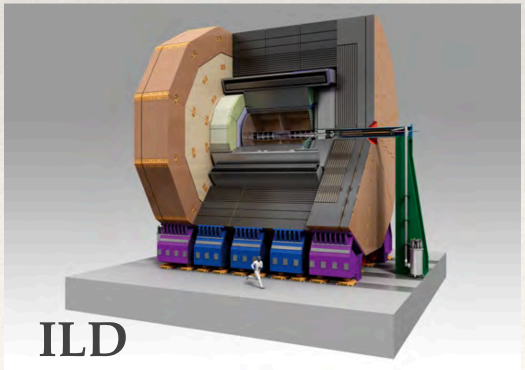
# Detector Challenges Met

| **Detector Design** | **Detector Comparison** |
|---|---|
| Calorimeter granularity | ~200 finer than LHC |
| Pixel size | ~20 smaller than LHC |
| Material budget, central | ~10 less than LHC |
| Material budget, forward | ≳100 less than LHC |
| Solid Angle Coverage | ……. |

# Subsystem Integration

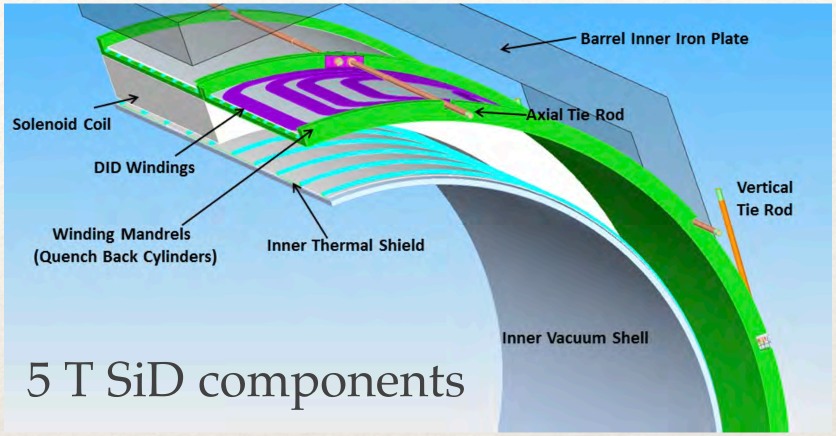
- Designing a $4\pi$ detector that optimizes physics performance requires coordinated choices for all systems.
  - Superconducting Solenoid
  - Vertex Detector
  - Outer tracking
  - Calorimeter
  - Muon System





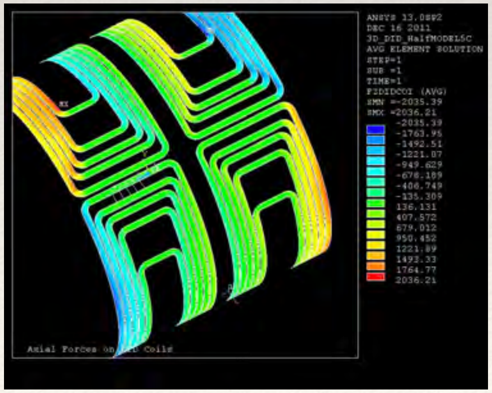
# Superconducting Solenoid Design

- Tracking requirements.
    - Field depends on tracker parameters.
- Electron pair controls.
- Expensive and technically challenging component.
- Successful 4 T CMS solenoid basis for design.



5 T SiD components

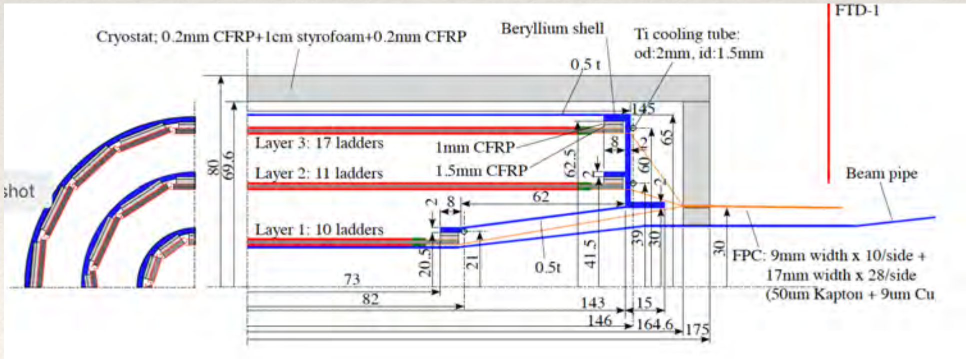
- anti-DID proposed
    - Potentially suppress BeamCal backgrounds by directing a significant amount of the coherent pair activity into the outgoing beam pipe with an anti-DiD magnetic field (dipole complements solenoid).



# Vertex Detector Requirements

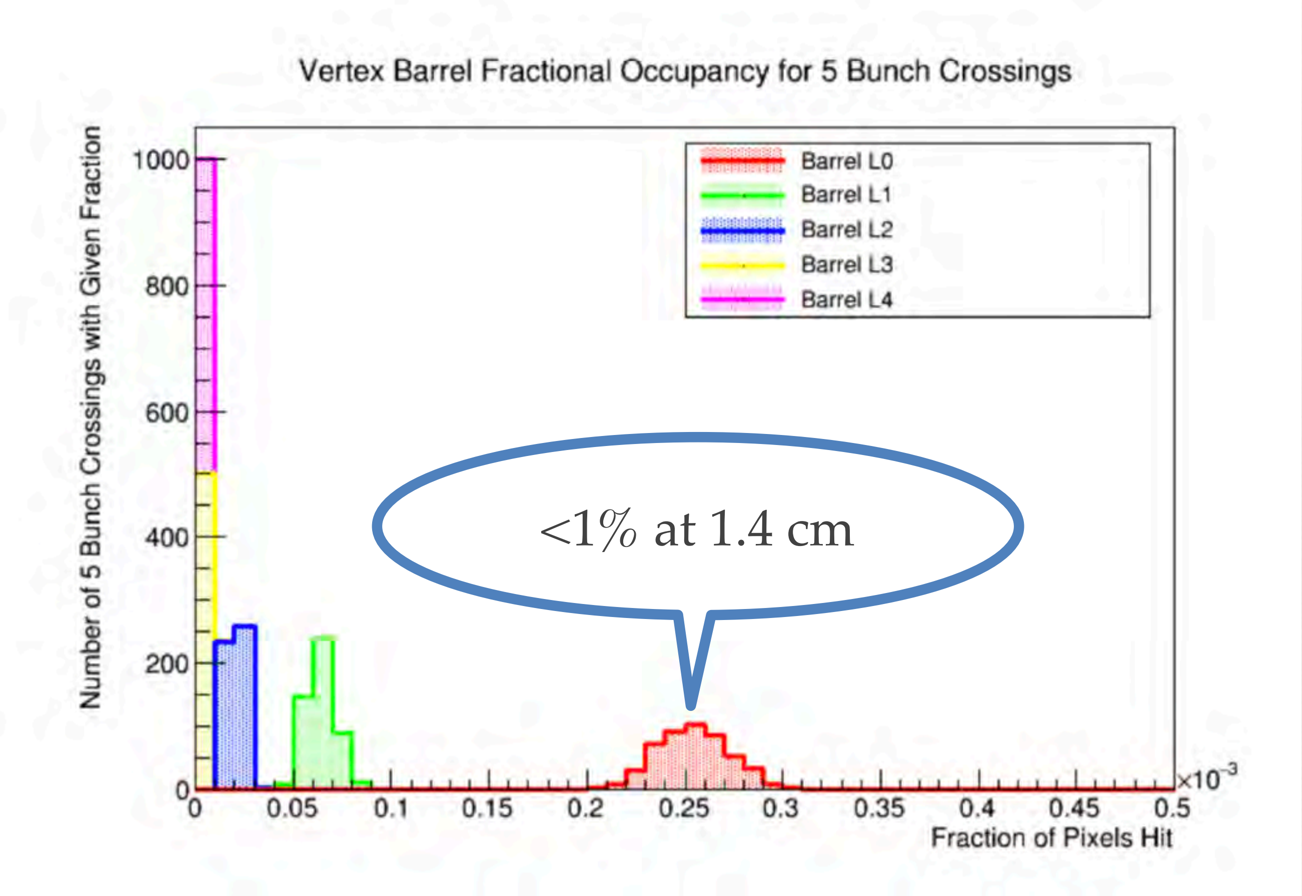
- Beam time structure (<1% duty cycle)
  - Triggerless readout between the trains.
  - Low average power consumption by power pulsing.
- Large e+e- background.
- Radiation large in first layer:
  - 100 $kRad$/year & non ionizing $10^{11} n_{eq}(1MeV)$/$cm^2$/year.
- Occupancy:
  - ~5 $hits/cm^2$/bunch crossing on the first layer.

**ILD VXD Support Structure**



# Vertex Detector Occupancy

VXD barrel occupancies by layer, for pixel size of 30 × 30 μm$^2$ & integration time of five bunch crossings at 500 GeV.



<1% at 1.4 cm

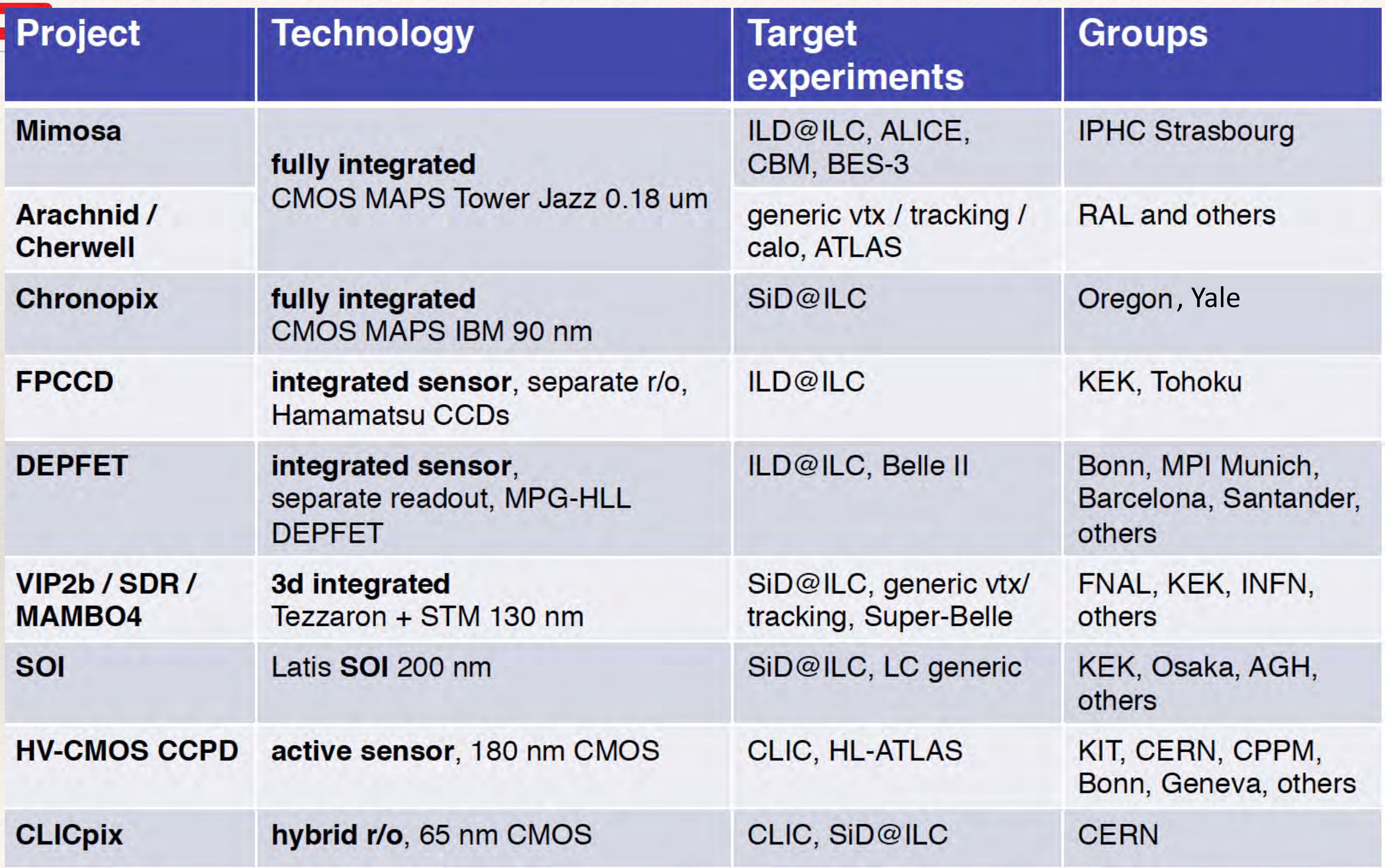
T. Barklow et al., arXiv:1609.07816

# Vertex Detector Requirements

- Inner layer spatial resolution of 3µ$m$ (corresponds to 17µ$m$ pitch).
- Low material budget to minimize multiple scattering, typically ≃ $0.15\% X_0$ / layer.
- Tracking capabilities to low momentum (even for $p_T$ below 100 MeV / c).
- Good angular coverage.
- Heavy flavor tagging (b-jets, c-jets, τ) with a very high efficiency and purity..
- Power limited ($< P > \simeq 12\ W$ - 3% duty cycle) for complete vertex detector.
- Radiation hard to 100$kRad$ / year.
- Detector able to sustain possible pick up noise and single event effects.
- Time resolution and data rate output defined by the running conditions and the read-out strategy.
- Alignment at the micron level capabilities.

Auguste Besson, PoS Vertex 2016 (2017) 047

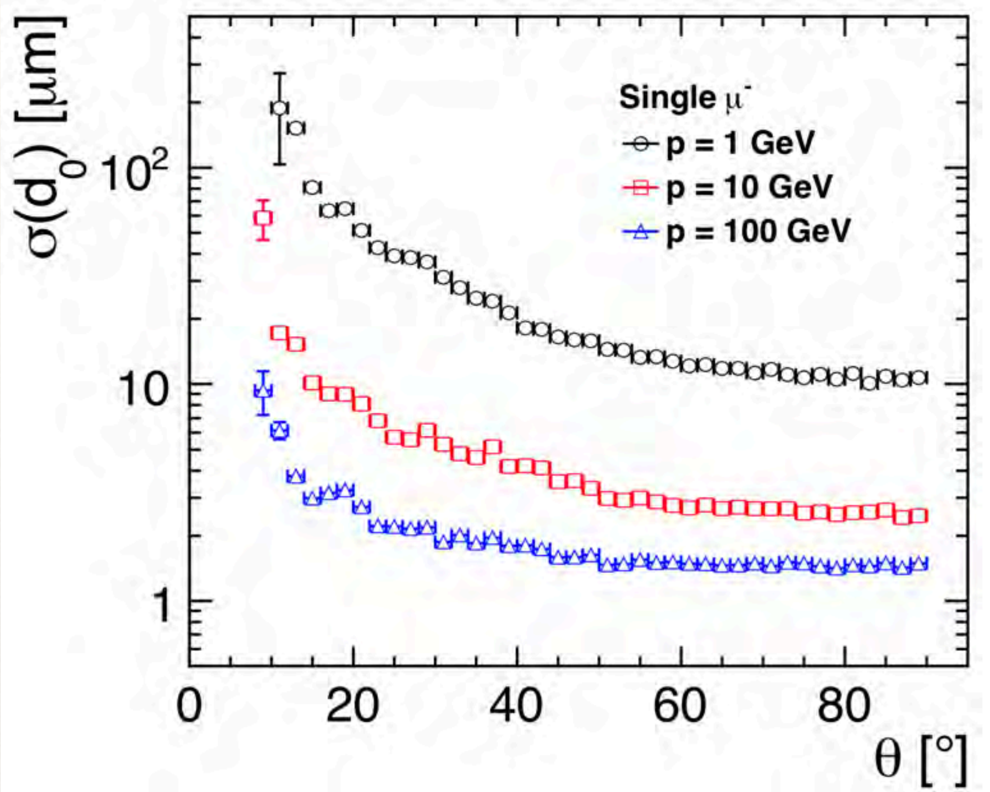
# ILC Pixel Detectors

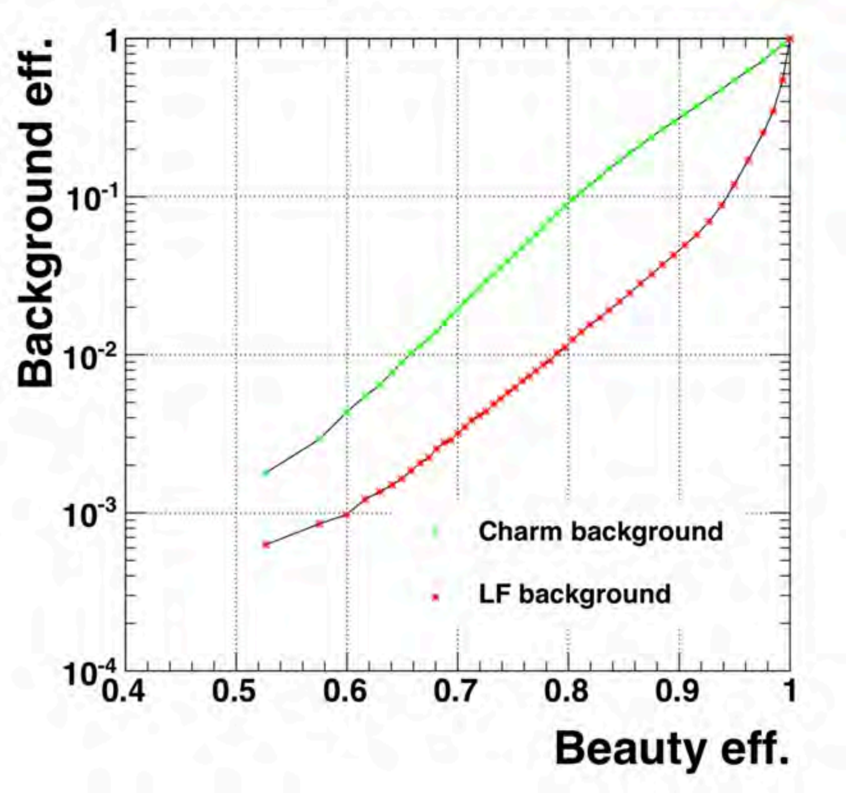


| Project | Technology | Target experiments | Groups |
|---|---|---|---|
| **Mimosa** | **fully integrated**<br>CMOS MAPS Tower Jazz 0.18 um | ILD@ILC, ALICE, CBM, BES-3 | IPHC Strasbourg |
| **Arachnid / Cherwell** |  | generic vtx / tracking / calo, ATLAS | RAL and others |
| **Chronopix** | **fully integrated**<br>CMOS MAPS IBM 90 nm | SiD@ILC | Oregon, Yale |
| **FPCCD** | **integrated sensor**, separate r/o, Hamamatsu CCDs | ILD@ILC | KEK, Tohoku |
| **DEPFET** | **integrated sensor**, separate readout, MPG-HLL DEPFET | ILD@ILC, Belle II | Bonn, MPI Munich, Barcelona, Santander, others |
| **VIP2b / SDR / MAMBO4** | **3d integrated**<br>Tezzaron + STM 130 nm | SiD@ILC, generic vtx/ tracking, Super-Belle | FNAL, KEK, INFN, others |
| **SOI** | Latis **SOI** 200 nm | SiD@ILC, LC generic | KEK, Osaka, AGH, others |
| **HV-CMOS CCPD** | **active sensor**, 180 nm CMOS | CLIC, HL-ATLAS | KIT, CERN, CPPM, Bonn, Geneva, others |
| **CLICpix** | **hybrid r/o**, 65 nm CMOS | CLIC, SiD@ILC | CERN |

D. Dannheim

# Flavor Tagging Performance





b-tagging efficiency:

light quark sample (red curve)

charm quark sample (green curve)

vs. b-tagging efficiency of b quark sample.

arXiv:1306.6329

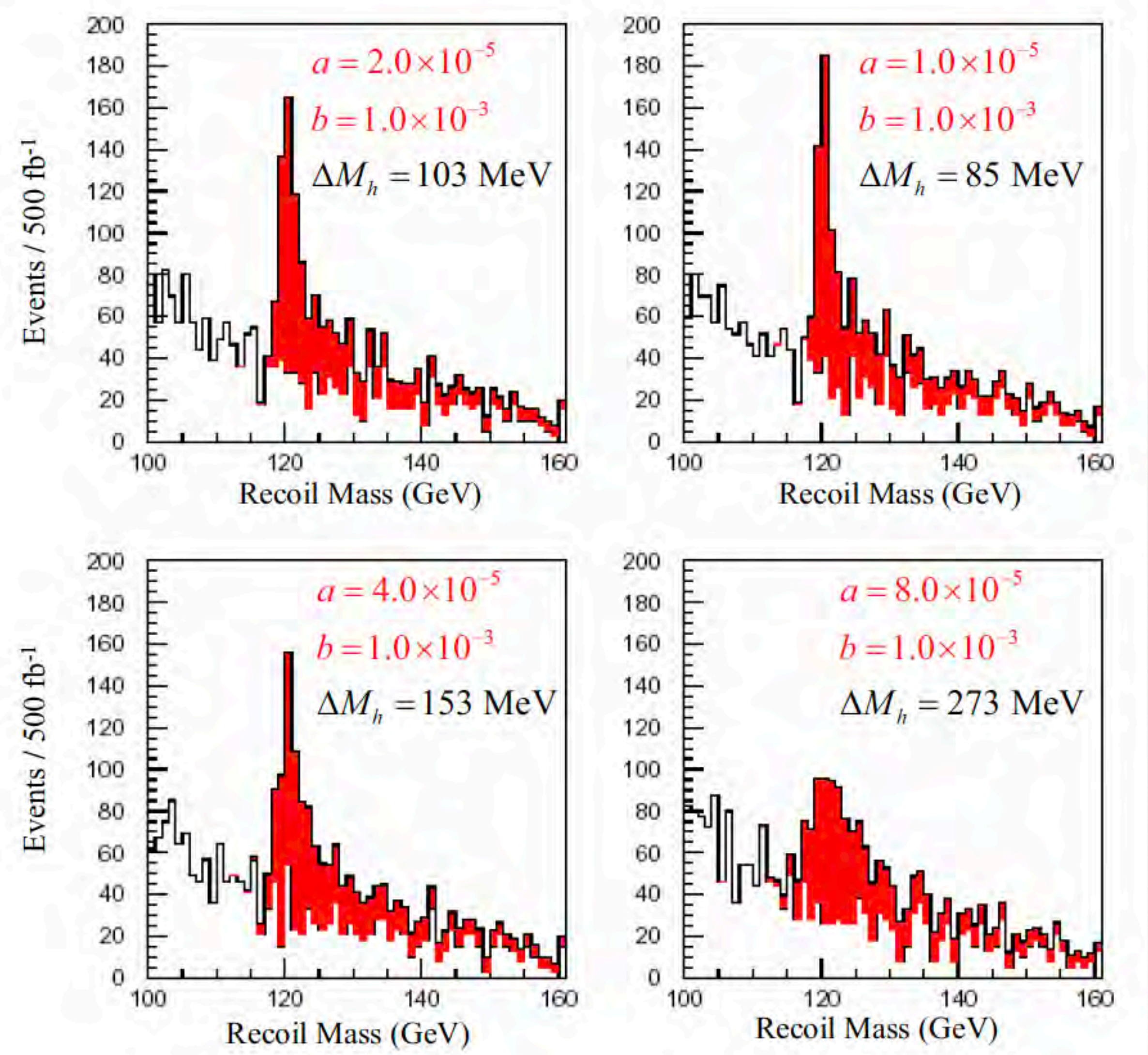
# Tracking Resolution

Higgs recoil mass spectra for range of tracking resolution.

$\delta p_T/(p_T)^2 = a \oplus b/(pT \sin\theta)$

Therefore:

$$\sigma\left(\frac{1}{p_T}\right) \leq 5\times10^{-5}\ (GeV^{-1})$$

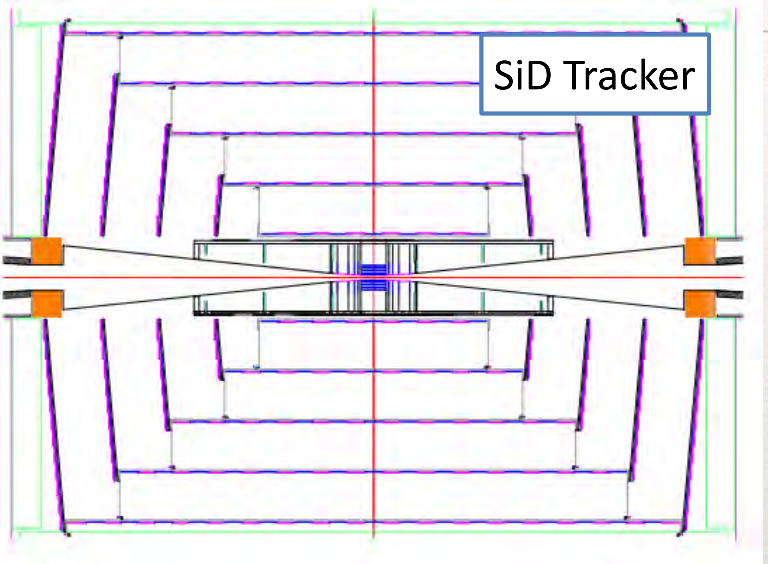


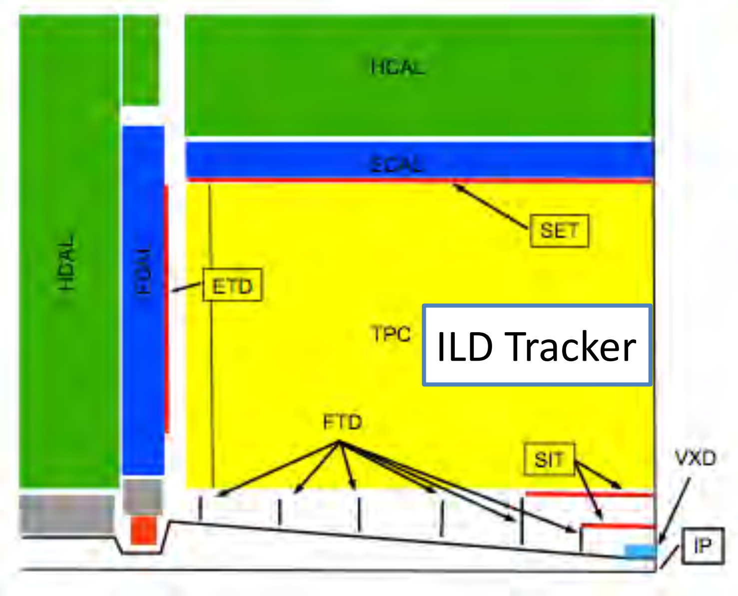
# Outer Tracking

- Concepts use large BR²/σ to achieve required very good momentum resolution:

$$\sigma\left(\frac{1}{p_T}\right) \le 5\times10^{-5}\ (GeV^{-1})$$

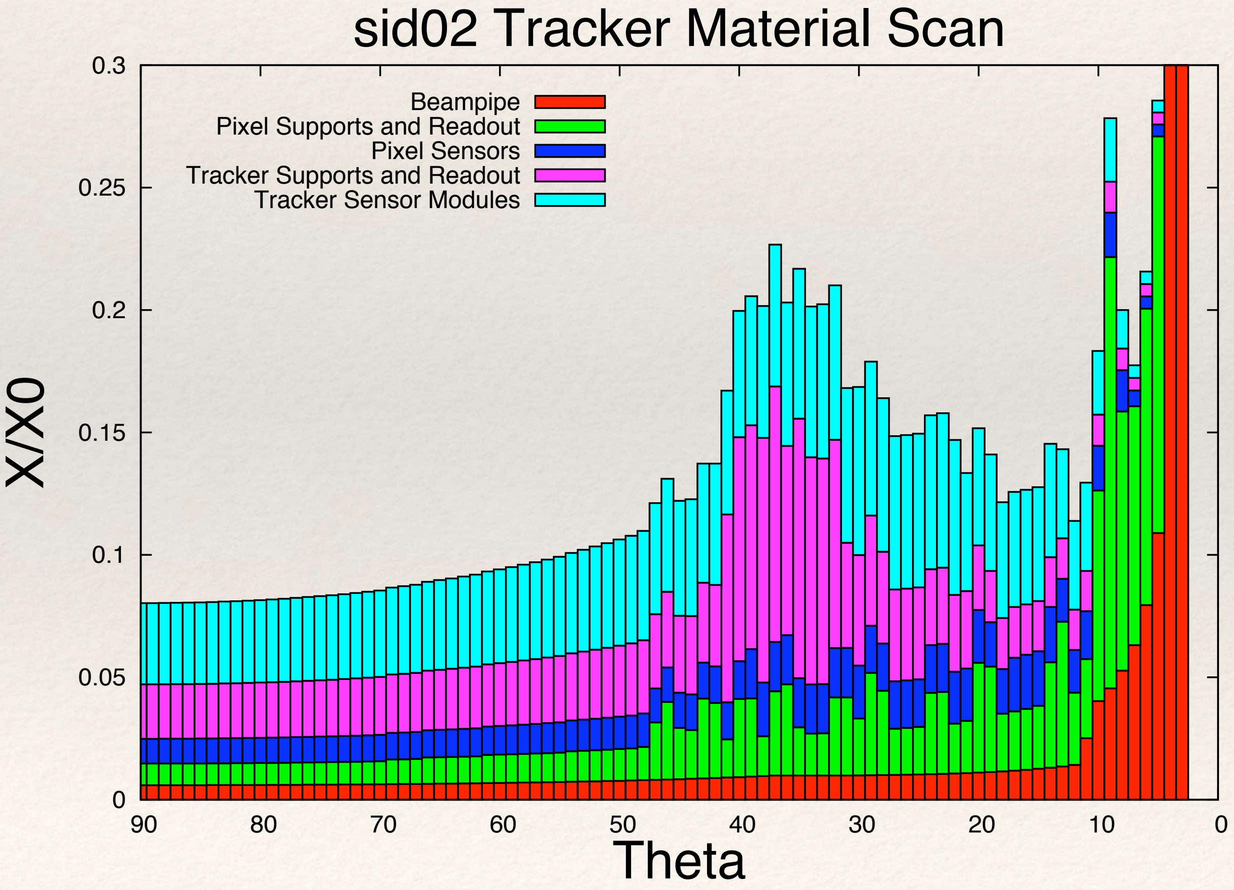
- Silicon Tracking (SiD) - strips
  - 5 barrel layers, 4 forward disks
  - 1.2 m outer radius
  - Pixels being considered
  - B = 5T
- TPC with silicon (ILD)
  - up to 228 hits per track
  - 1.8 m outer radius
  - B = 3.5 T

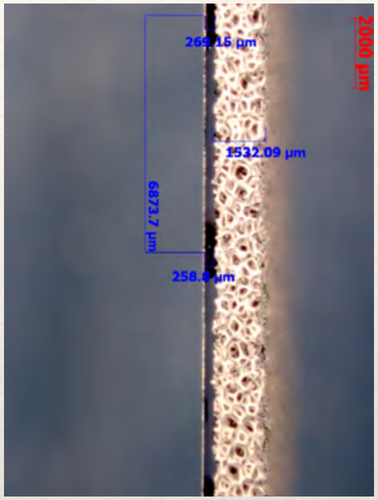




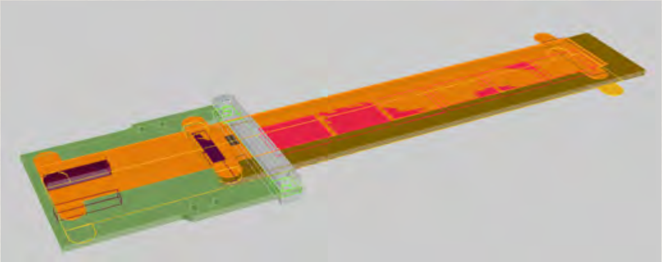
# Tracking Integration

- Linkage between readout/mechanics/powering/cooling studies.
- Maintain low mass construction.
- Example of tracking material from SiD design:

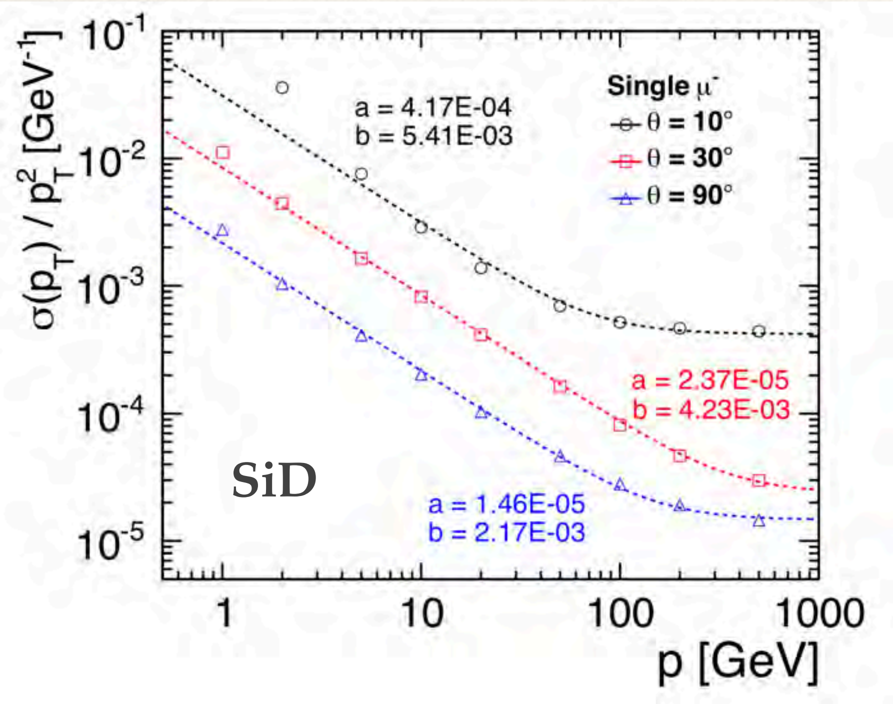


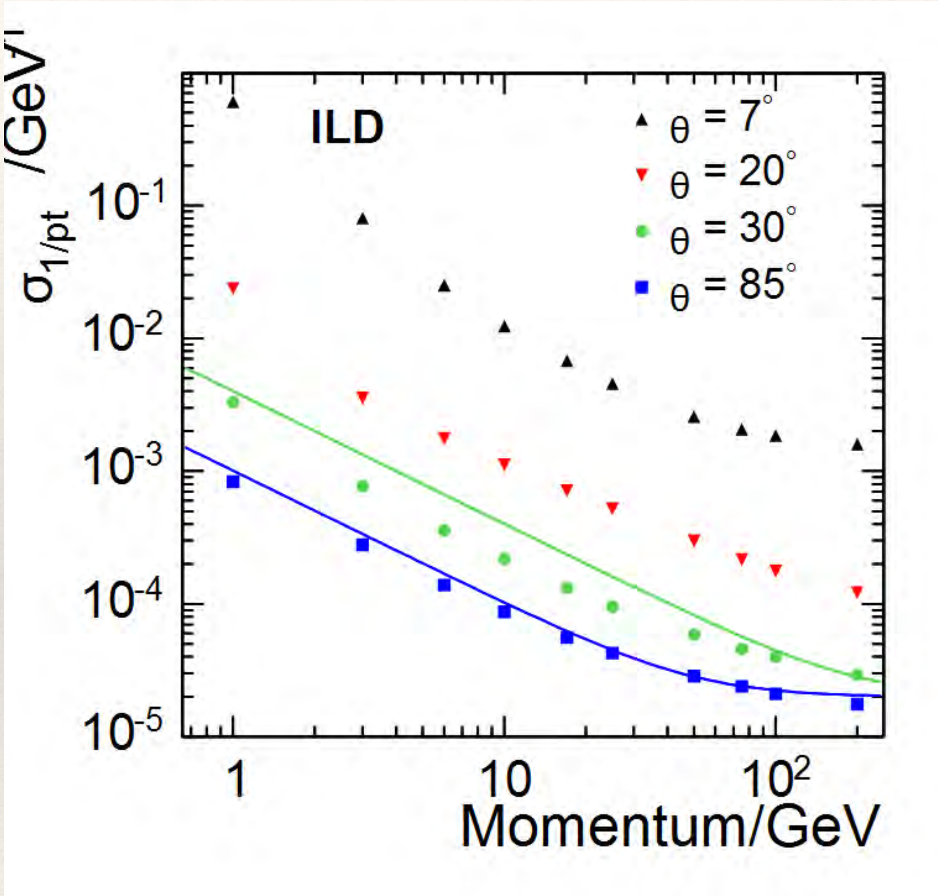


SiC foam,
J. Goldstein



# Tracking Performance



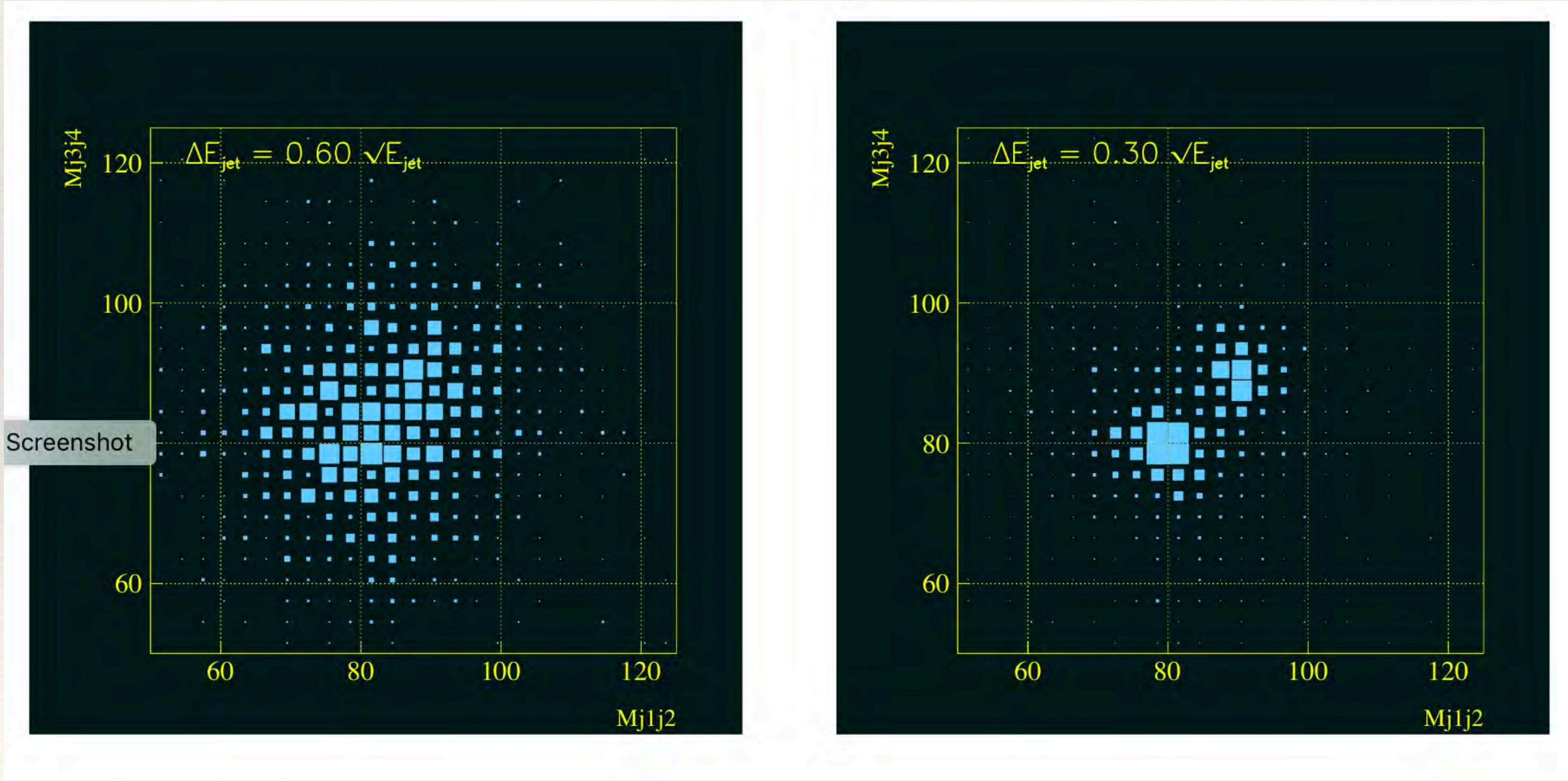


arXiv:1306.6329

# Calorimeter Performance Requirement

- Separate W&Z di-jet events.
- For 100 GeV jet - 3% resolution needed.

$e^+e^- \to WW\nu\bar{\nu}$ , $e^+e^- \to ZZ\nu\bar{\nu}$



Brient & Videau, arXiv:0202004

# ILC Calorimetry

- Typical hadronic jet energy
    - charged hadrons ~65%
    - photons ~25%
    - neutral hadrons ~10%

- Special conditions of ILC motivates particle flow approach for improved jet resolution (~3%) over traditional calorimetry. (inside coil).

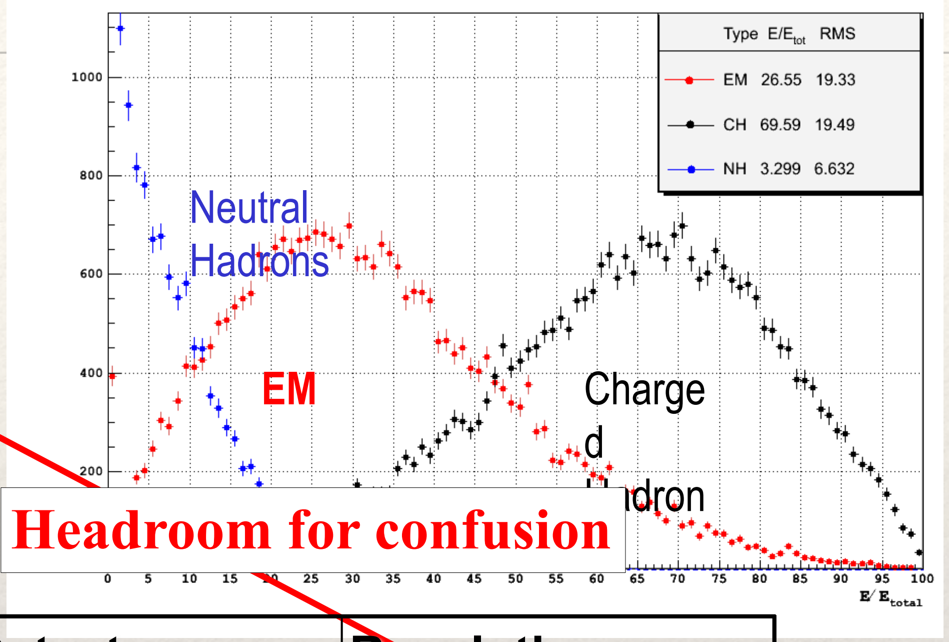
  - **Particle Flow (both validated detectors, ILD and SiD)**
    - use tracker momentum measurement
    - highly granular particle calorimeters to add neutral energy (EM + Had)

- Forward calorimeters (specialized) also needed
  - Measure luminosity via small angle Bhabha scattering
  - Provide fast feedback to machine via beamstrahlung remnants
    - in a higher radiation environment

# Jet Energy Measurement via Particle Flow

Particle Flow:

- Jet resolution goal is 3-4% above 100 GeV
- In jet measurements, use the excellent resolution of tracker, which measures bulk of the energy in a jet
- Requires high granularity in calorimeter ⇒ ~$10^8$ cells



**Headroom for confusion**

| **Particles in Jet** | **Fraction of Visible Energy** | **Detector** | **Resolution** |
|---|---|---|---|
| Charged | ~65% | Tracker | < 0.005% $p_T$<br>negligible |
| Photons | ~25% | ECAL | ~ 15% / √E |
| Neutral Hadrons | ~10% | ECAL + HCAL | ~ 60% / √E |

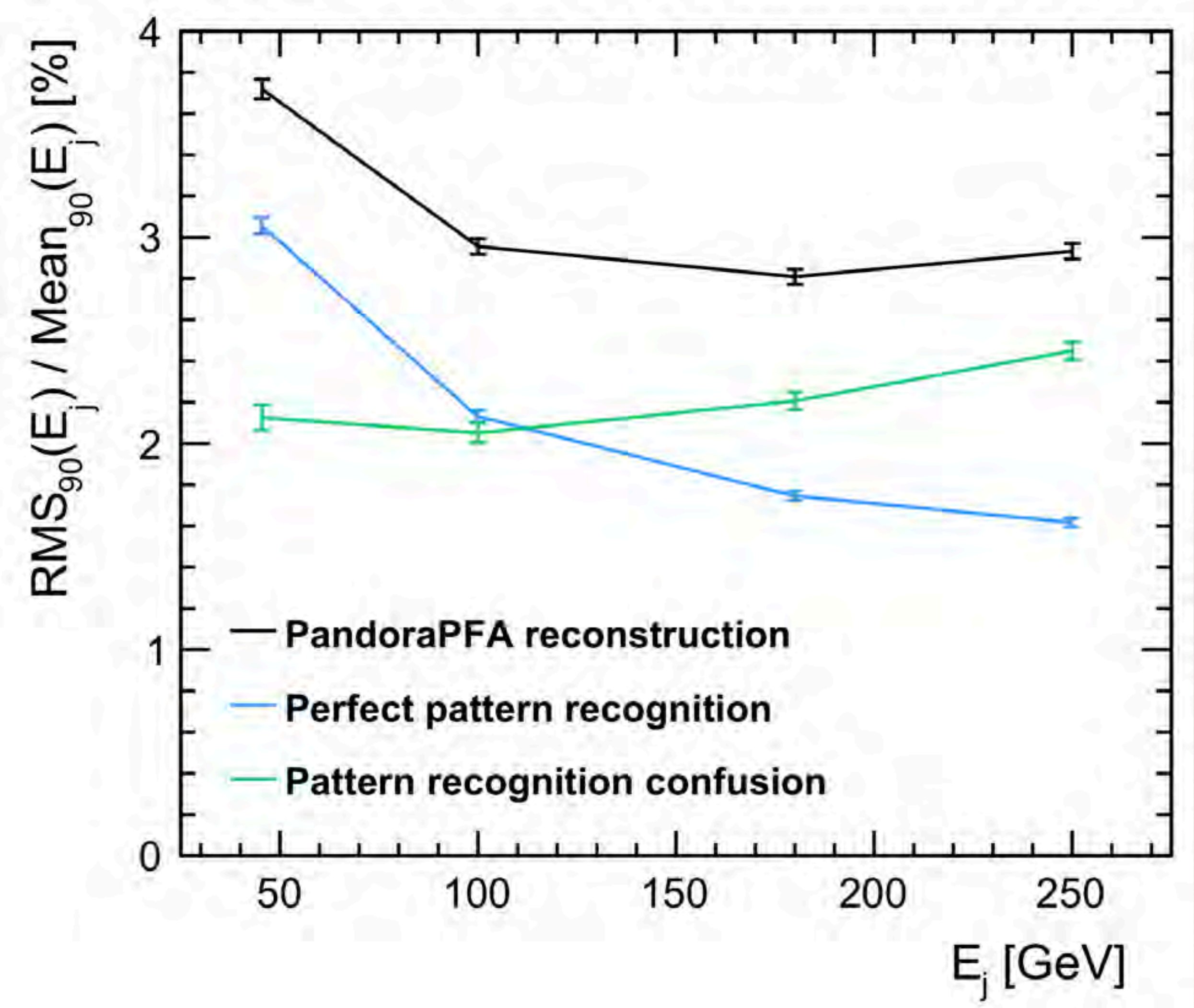
**< 2% @ 100 GeV**

# Particle Flow Technologies

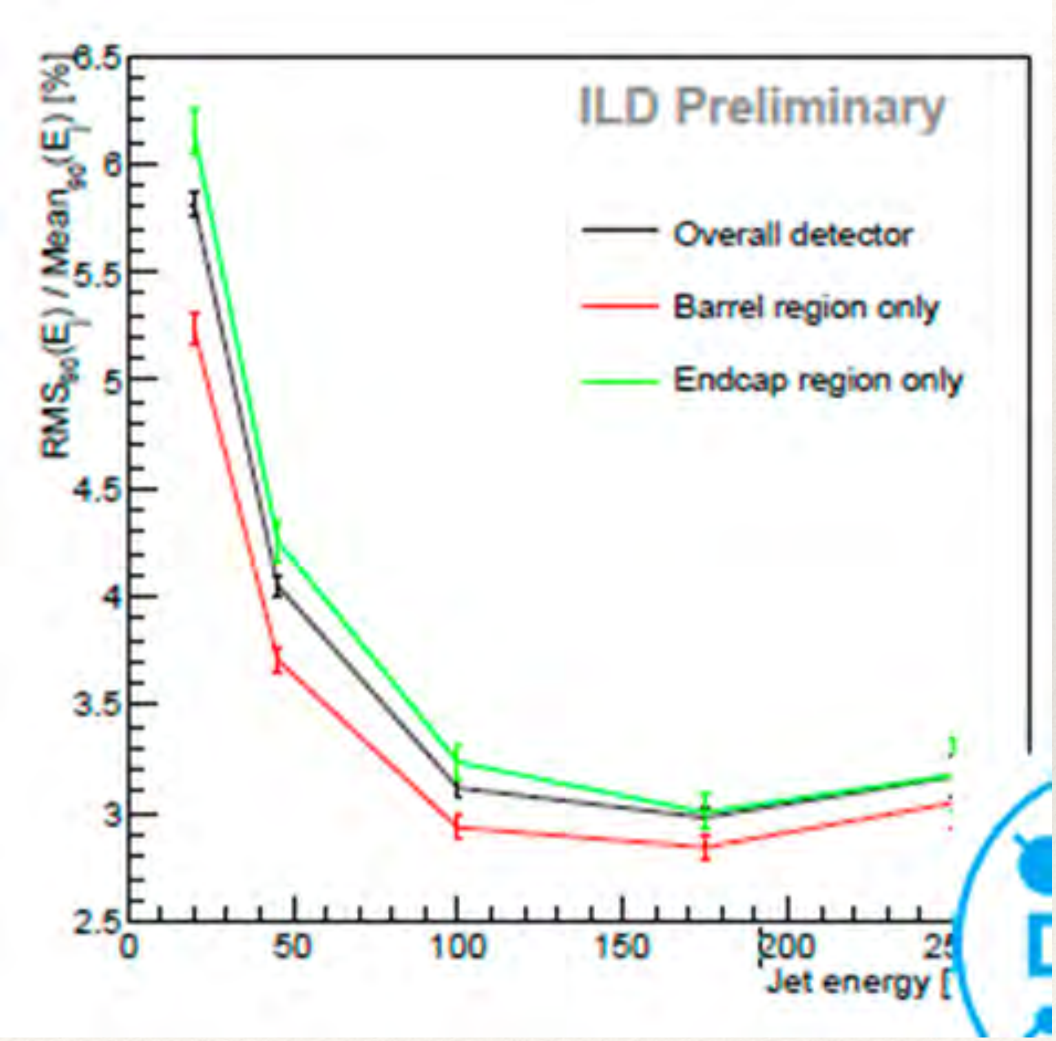
- High granularity
  - HCal ~ O(1 cm$^3$)   -   ECal ~ O(0.001 cm$^3$)
- Scintillator
  - strips or cells, read out by SiPMs
- Gas
  - glass RPC, either Digital or Semi-digital
  - MPGD (GEM, MicroMegas, …)
    - built-in suppression of sparks
    - tuning of resistivity allows variation of high rate capability
- Semi-conductor diodes
  - silicon for ECal
  - GaAs considered for radiation hardness requirements

# Jet Energy Resolution

- Jet energy resolution (in %) for $Z'$ events as a function of jet energy in a realistic detector PandoraPFA.
- Also shown are effects of confusion and result assuming perfect PFA.
- J. S. Marshall and M. A. Thomson, Eur. Phys. J. C75, 439 (2015), arXiv:1506.05348.



# Jet Energy Resolution

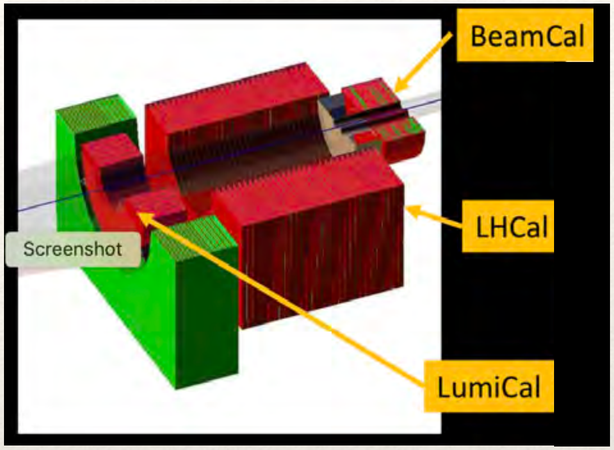


# Particle Flow Compromises EM Resolution

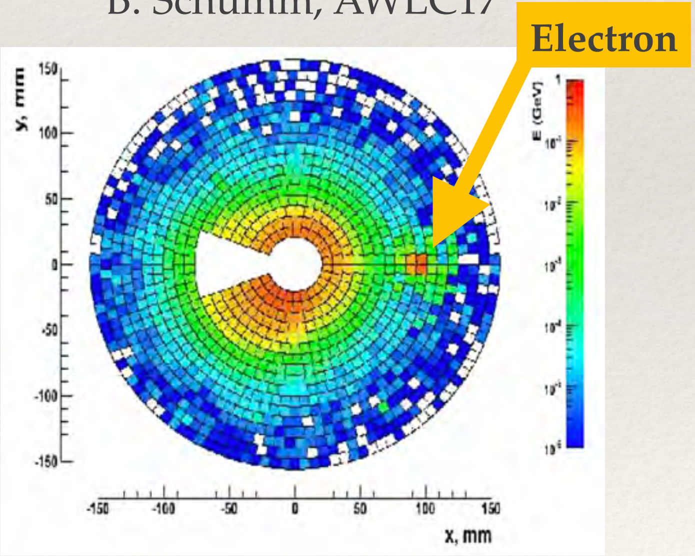
- ECal choice to aid in Particle Flow has been sampling silicon or scintillator with fine granularity.
    - Tungsten radiator to minimize Moliere radius and separate showers.
- This compromises the ECal resolution that could be achieved with other solutions:
    - Crystals, etc.
- Can such alternatives be employed to achieve better ECal resolution without compromising jet energy measurements?

# Forward Detectors

- LumiCal : Precise luminosity measurements (Bhabha events) & extend calorimetric coverage to small polar angles.
- LHCal : Extend hadronic cal. coverage
- BeamCal
  - Fast luminosity and beam feedback
  - Physics processes with missing energy or peaked very forward electrons.
  - Large forward background from soft $e^+e^-$ pairs.



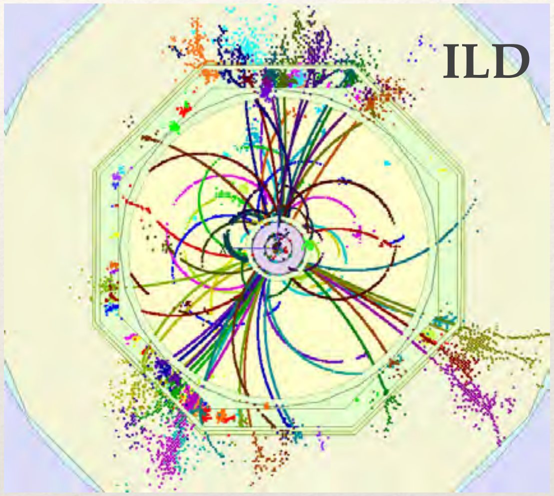
B. Schumm, AWLC17



BeamCal, ILC TDR Vol 4

# Detector Modeling

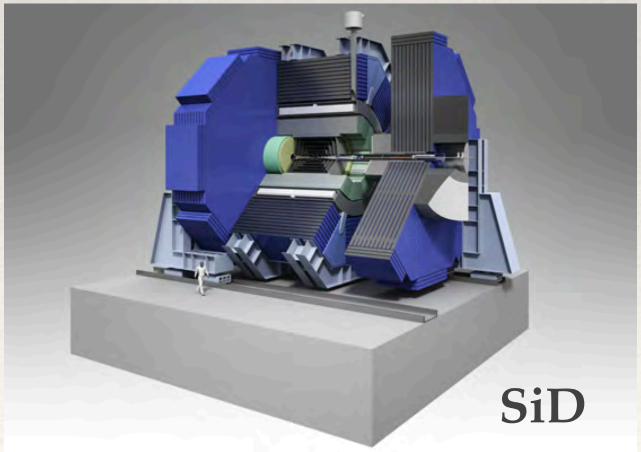
- Achieving excellent detector resolution demands powerful and sophisticated algorithms for event reconstruction and data analysis.
- For over a decade, the ILC community developed and improved its software ecosystem **iLCSoft**, based on the event data model **LCIO**, and the generic detector description toolkit **DD4hep**. (**iLCSoft** tools also used by CLIC)
- Flexible, generic tools easily applied to other experiments or new detector concepts, and leverages manpower.
- Physics measurements validated by realistic models.



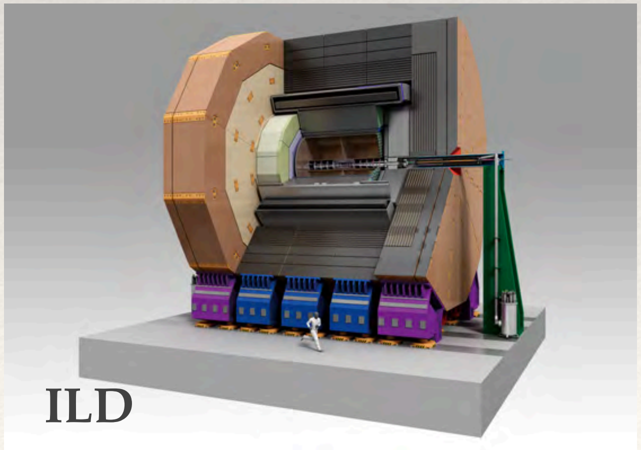
Fully simulated and reconstructed tt-event, showing reconstructed particles. Color code presents the particle flow algorithm reconstruction without reference to the MC information.

# Detector Requirements Achieved

- Clean events with low backgrounds enable unprecedented detector performance motivated by physics goals.
  - High granularity
  - Dense integration
  - Super light materials
  - Low power/pulse power
  - Air cooling



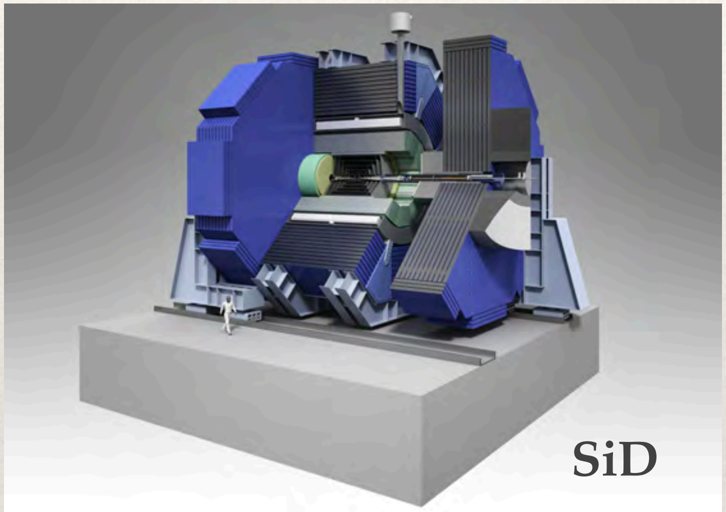
**SiD**

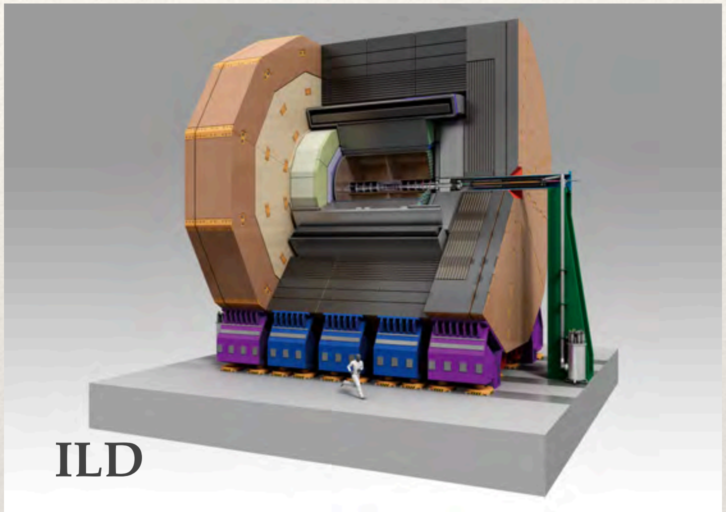


**ILD**

# Detectors

- Two Validated detector concepts.
- Complementary: tracking technology, magnetic field, calorimetry, etc.





| SiD | | ILD |
|---|---|---|
| Silicon | Tracking | TPC w/ silicon |
| 6.0 m | Outer Radius | 7.8 m |
| 5 Tesla | B Field | 3.5 Tesla |

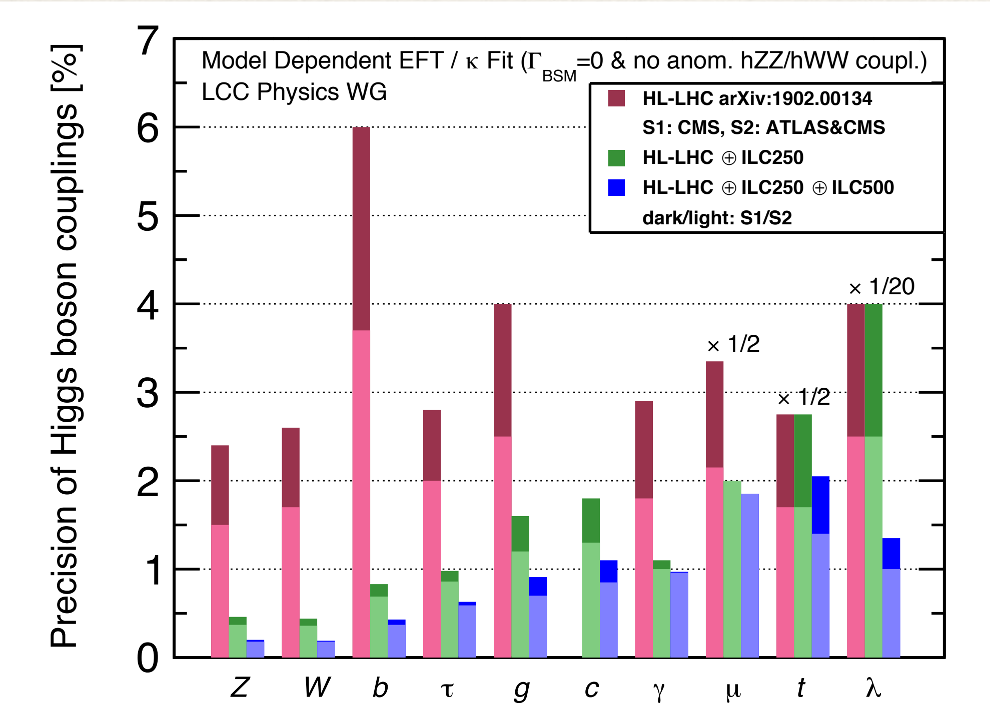
| | |
|---|---|
| Design Goals: | High efficiency<br>High resolution<br>Low fake rate<br>Control of systematics |

# Outcome Validates Design

Model Dependent EFT / κ Fit:

1.) Higgs boson has no decay modes beyond those predicted by SM,

2.) Higgs boson WW & ZZ couplings modified only by rescaling.



Model Independent EFT:

1.) Effects of new physics by general linear combination of dimension-6 operators invariant under SU(2) x U(1).

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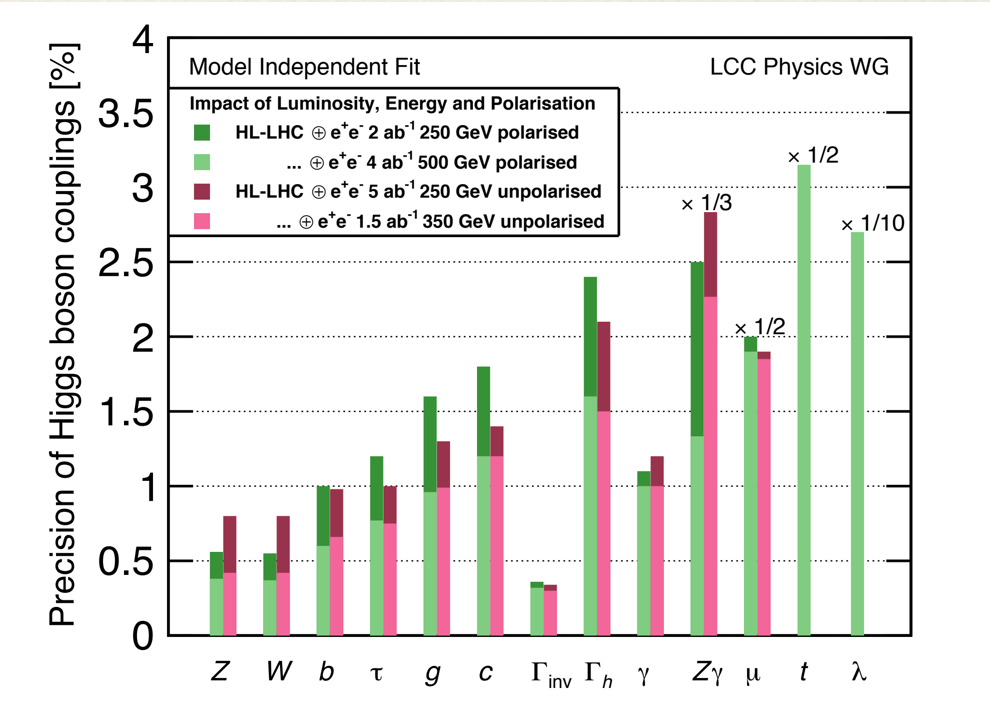
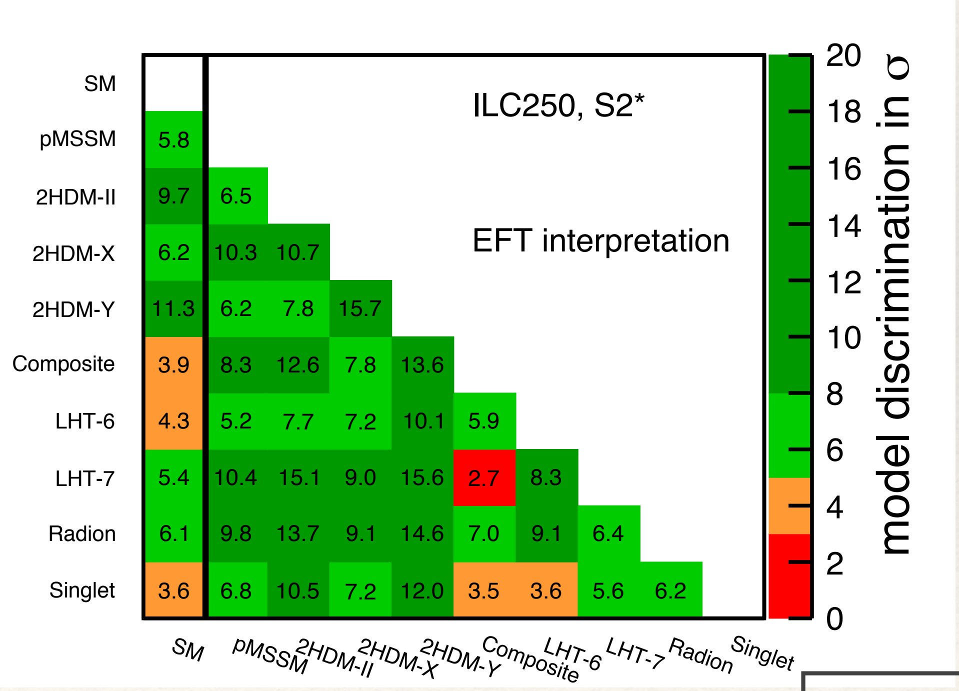


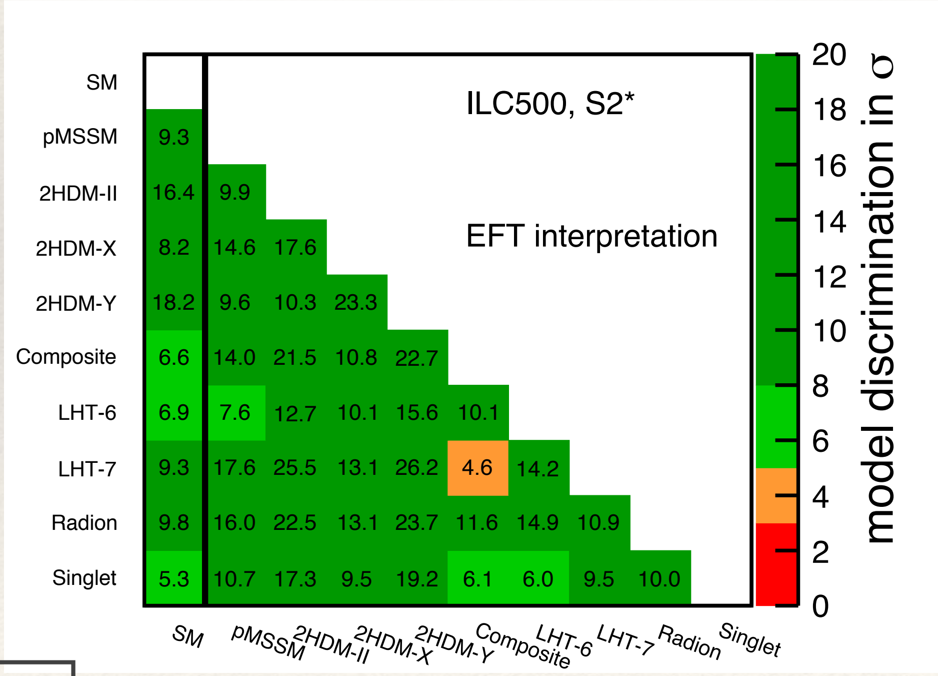
**arXiv:1903.01629**

# Outcome Validates Design

- Model Discrimination - Nine models unlikely to be discovered by HL-LHC - Masses beyond reach.



|  | SM | pMSSM | 2HDM-II | 2HDM-X | 2HDM-Y | Composite | LHT-6 | LHT-7 | Radion | Singlet |
|---|---|---|---|---|---|---|---|---|---|---|
| SM |  |  |  |  |  |  |  |  |  |  |
| pMSSM | 5.8 |  |  |  |  |  |  |  |  |  |
| 2HDM-II | 9.7 | 6.5 |  |  |  |  |  |  |  |  |
| 2HDM-X | 6.2 | 10.3 | 10.7 |  |  |  |  |  |  |  |
| 2HDM-Y | 11.3 | 6.2 | 7.8 | 15.7 |  |  |  |  |  |  |
| Composite | 3.9 | 8.3 | 12.6 | 7.8 | 13.6 |  |  |  |  |  |
| LHT-6 | 4.3 | 5.2 | 7.7 | 7.2 | 10.1 | 5.9 |  |  |  |  |
| LHT-7 | 5.4 | 10.4 | 15.1 | 9.0 | 15.6 | 2.7 | 8.3 |  |  |  |
| Radion | 6.1 | 9.8 | 13.7 | 9.1 | 14.6 | 7.0 | 9.1 | 6.4 |  |  |
| Singlet | 3.6 | 6.8 | 10.5 | 7.2 | 12.0 | 3.5 | 3.6 | 5.6 | 6.2 |  |



|  | SM | pMSSM | 2HDM-II | 2HDM-X | 2HDM-Y | Composite | LHT-6 | LHT-7 | Radion | Singlet |
|---|---|---|---|---|---|---|---|---|---|---|
| SM |  |  |  |  |  |  |  |  |  |  |
| pMSSM | 9.3 |  |  |  |  |  |  |  |  |  |
| 2HDM-II | 16.4 | 9.9 |  |  |  |  |  |  |  |  |
| 2HDM-X | 8.2 | 14.6 | 17.6 |  |  |  |  |  |  |  |
| 2HDM-Y | 18.2 | 9.6 | 10.3 | 23.3 |  |  |  |  |  |  |
| Composite | 6.6 | 14.0 | 21.5 | 10.8 | 22.7 |  |  |  |  |  |
| LHT-6 | 6.9 | 7.6 | 12.7 | 10.1 | 15.6 | 10.1 |  |  |  |  |
| LHT-7 | 9.3 | 17.6 | 25.5 | 13.1 | 26.2 | 4.6 | 14.2 |  |  |  |
| Radion | 9.8 | 16.0 | 22.5 | 13.1 | 23.7 | 11.6 | 14.9 | 10.9 |  |  |
| Singlet | 5.3 | 10.7 | 17.3 | 9.5 | 19.2 | 6.1 | 6.0 | 9.5 | 10.0 |  |

**arXiv:1710.07621**

# Summary

- Optimizing ILC detector performance, and achieving ideal physics precision, requires dealing with machine constraints, and capitalizing of opportunities of machine environment.
- The ILC detector consortia (ILD, SiD and Det R&D groups) have developed effective strategies and technologies.
- Result is staged ILC offering excellent science already at the initial energy: 250 GeV.
  - Higher energy from upgrades will extend physics program.
- In all scenarios for future LHC outcomes, the ILC has a compelling discovery potential.