Detector R&D for Higgs Factories

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Which Higgs Factory?

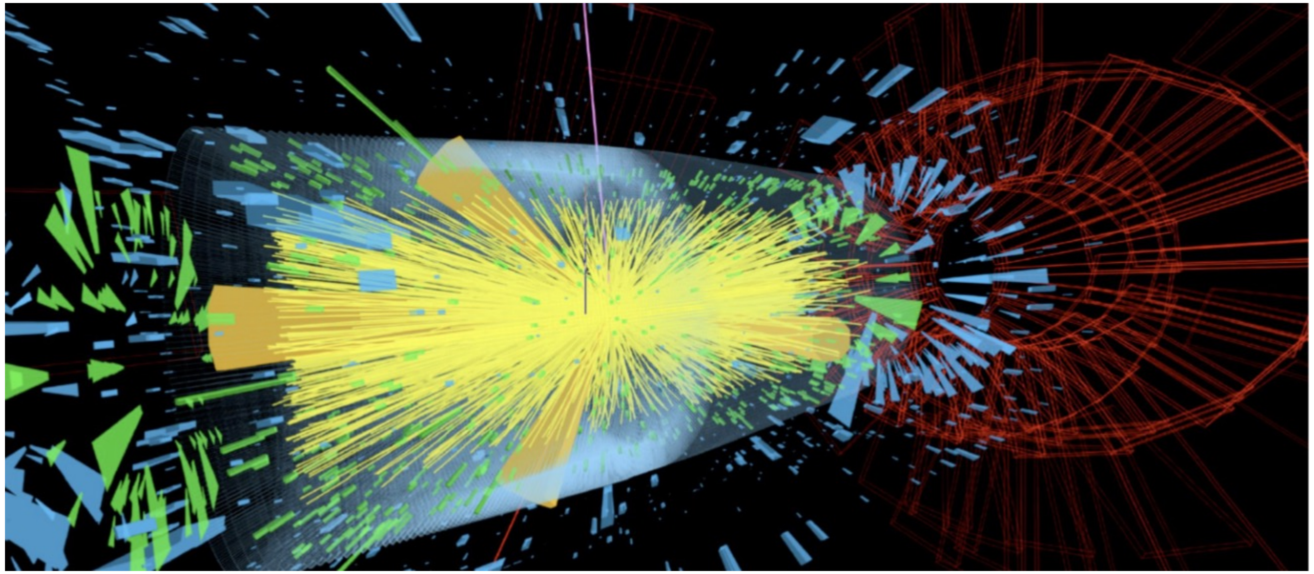
HL-LHC **is** a Higgs Factory

3 ab^{-1} planned,

- 170M Higgs bosons produced
- 120k HH pairs

- $\mathcal{O}$(2-4%) precision on couplings to W, Z, 3^{rd} gen. fermions
- $\mathcal{O}$(50%) precision on self-Higgs couplings
- Couplings to u, d, s and e not accessible.
- HL-LHC will significantly improve our understanding of the SM
  - **Significant room for improvements!**

H → $\gamma\gamma$ + 2-jets with 200 pile up events in CMS



In any case, detector upgrades are in advanced stages (see G. Brooijman's talk)

There is no R&D remaining

Focus on:

- Upgraded silicon tracker
- Timing detector
- Improved Readout
  - Cope with higher pile-up/Luminosity

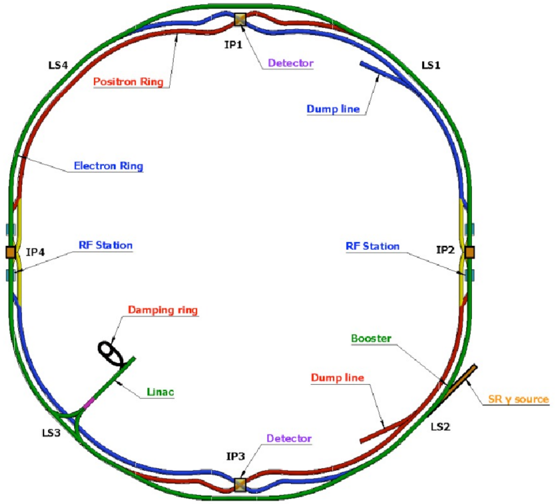
e+e- Higgs Factory options

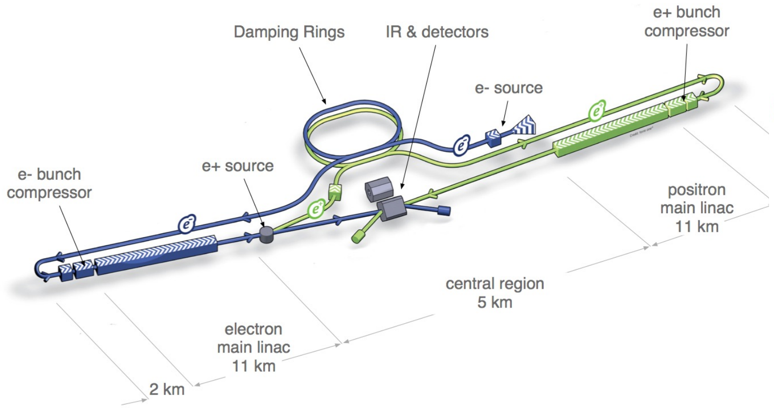
Circular

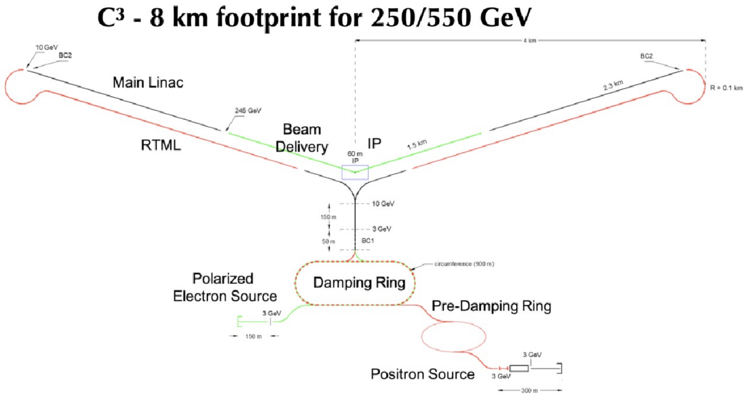
FCC-ee: Ongoing feasibility studies, Approval ~2028
CEPC: TDR complete, Waiting for approval

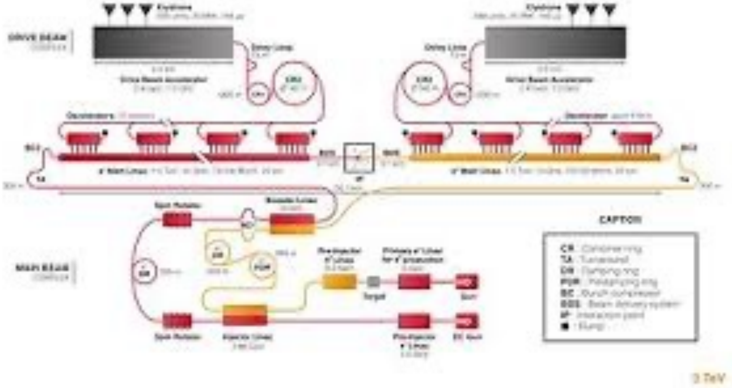
Linear

ILC: Mature design based on SRF
C3: Cu cavity (LN2 temp) in R&D phase
CLIC: High gradient beam drive RF for higher energy









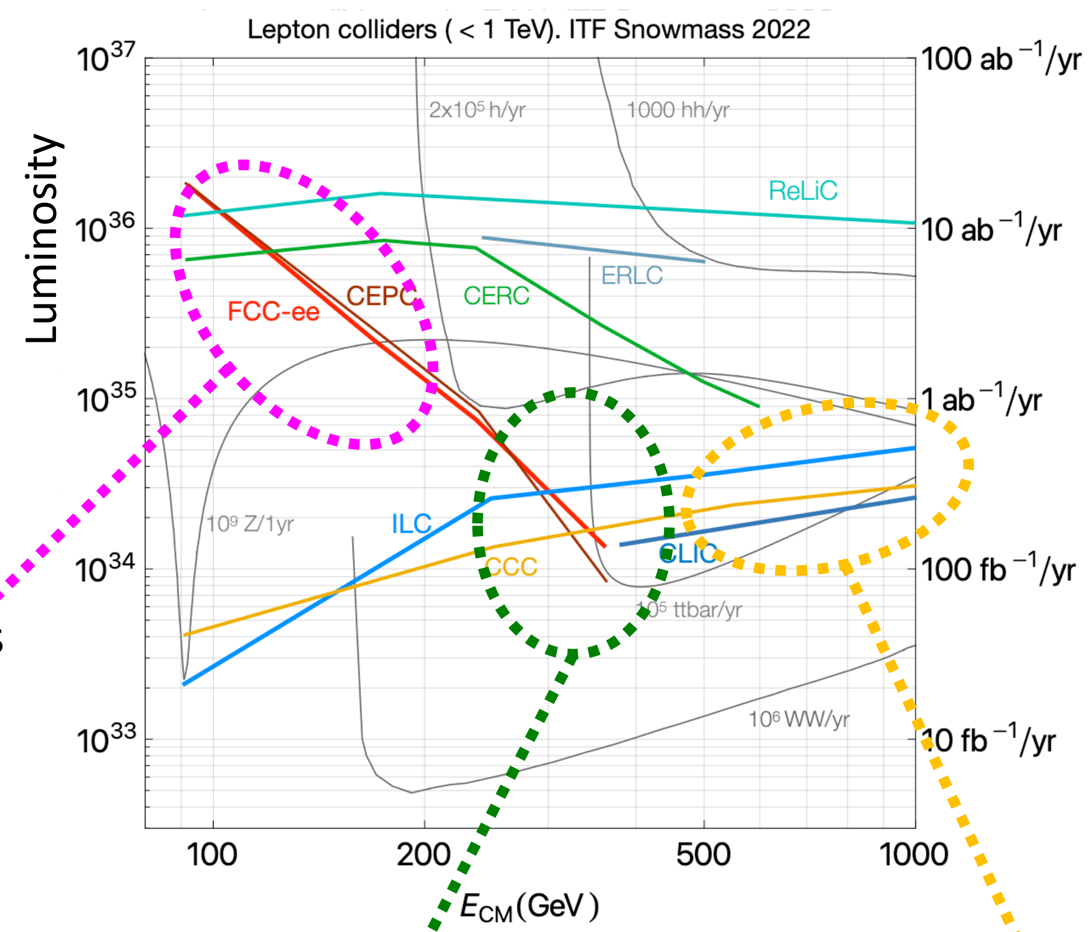
Circular vs Linear

- 10^9 (@ILC) – 10^{12} (@FCC) $\boldsymbol{Z}$s
  - Ref: LEP 10^7 $\boldsymbol{Z}$s
- 10^6 (@ILC) to 10^8 (@FCC) $\boldsymbol{WW}$
- > 10^6 Higgs at $\boldsymbol{ZH}$
- 10^6 $\boldsymbol{t\bar{t}}$ pairs

➢ Multiple detectors at Circular colliders

➢ Beam Polarization at Linear colliders:

  ➢ e^- 80%, e^+ 30% at ILC.

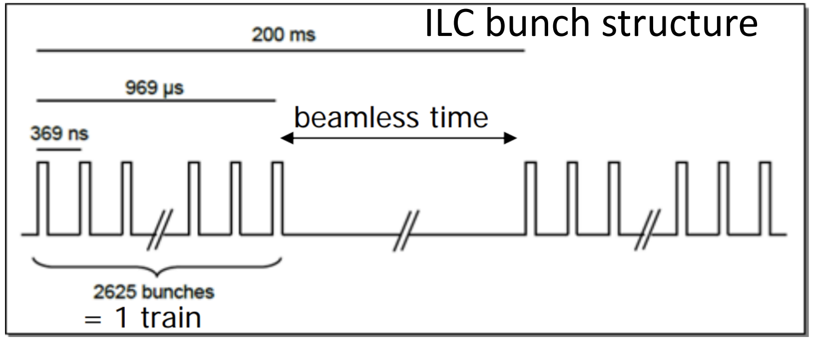


Circular colliders:
Extremely high luminosities at lower energies:
Z and WW factories

Overlap region, 240-380 GeV: "Higgs Factories"

Linear colliders:
High centre-of-mass energies

Challenges: FCC-ee wrt ILC



❖ Beam Structure:

- Continuous beam with bunch spacing 20 ns (Z pole) has implications on power management/cooling, rates, readout.
- ILC bunch structure allows for mitigation via power pulsing.

❖ Machine Detector Interfaces

- Larger beam crossing angle 30 mrad crossing angle sets constraints on the solenoid field to 2 T
  - Implies larger tracker volume, ILC tracker can be much more compact with higher fields.
- Nearest focusing quadrupole is closer 2.2 m from IP
- Backgrounds from incoherent pair production (IPC) and synchrotron radiation (SR)

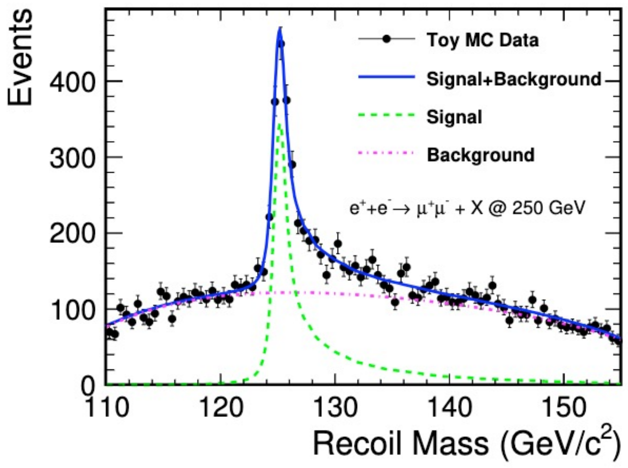
❖ High Luminosities

- Extremely high luminosities L ~ $1.8 \times 10^{36}/cm^2s$ at Z-pole, physics interaction rate ~100 KHz
- Implications on detector response time, event size, FE electronics and timing
- Online and Offline data handling of high data rates/volumes $O(10^{13})$ events.
- Require absolute luminosity measurements to 10^{-4} to achieve desired physics sensitivity
- High statistical precision: Requires control of systematics down to $10^{-6} - 10^{-5}$ level.

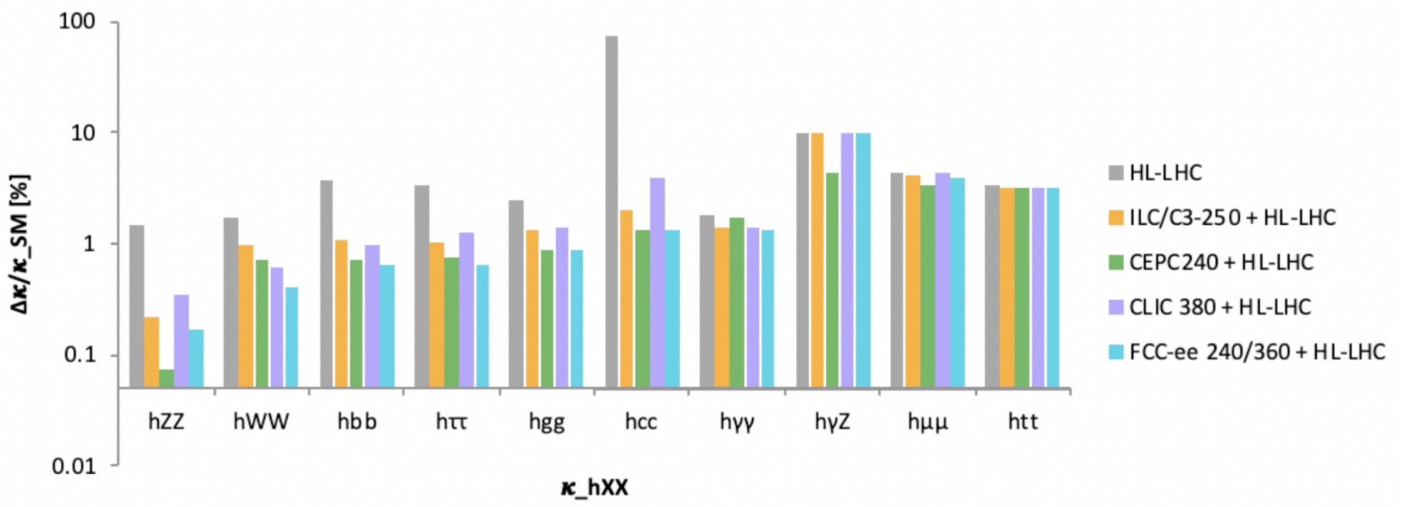
The Physics is rich

❖ Higgs Factories provide rich physics beyond in-depth study of Higgs boson

- Measure a comprehensive set of electroweak and Higgs observables with high precision
  - Tera-Z operation offers a unique opportunity
- Tightly constrain a large number of SM parameters
- Unveil, if any, small but significant deviations from SM predictions
- Evidence for rare processes and feebly coupled particles beyond the SM.



Model independent measurement of the Higgs

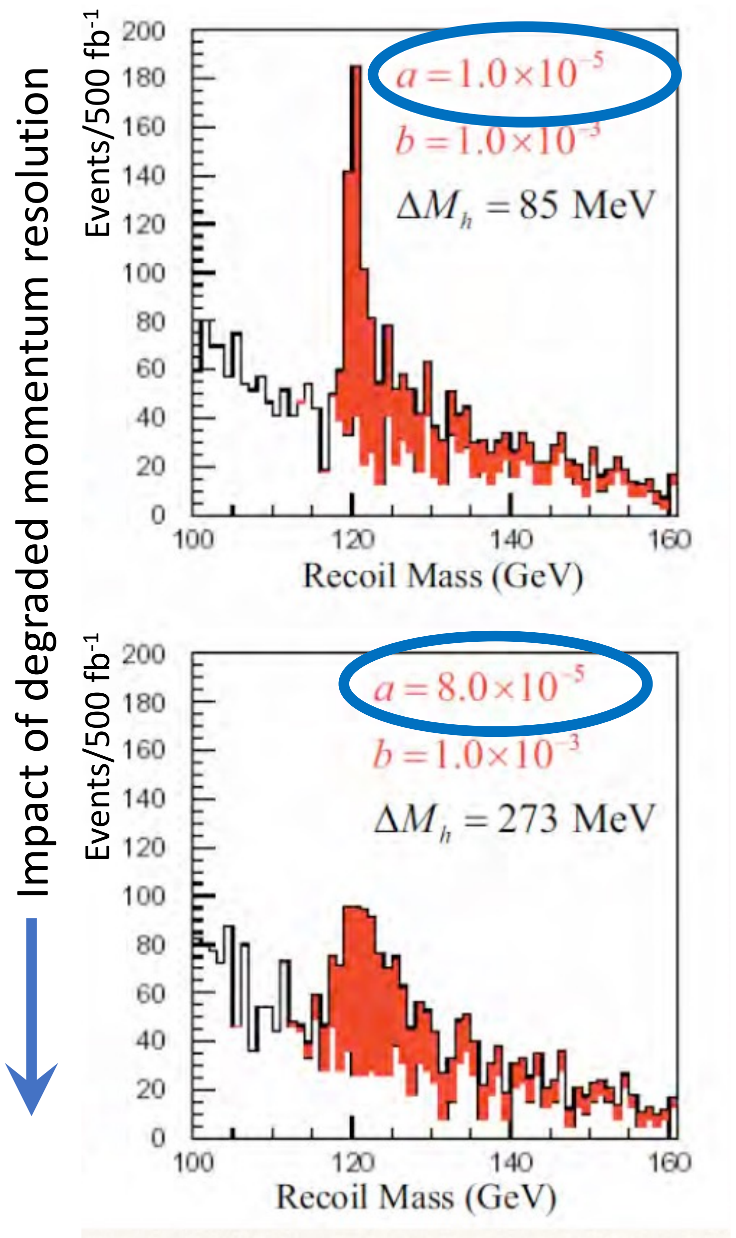


Sub-1% precision measurements of most couplings

Detector Requirements

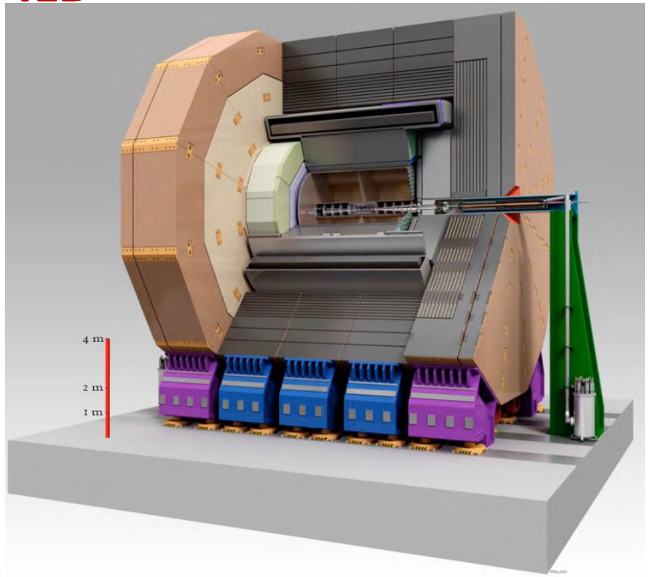
❖ Many similar detector requirements between ILC, CLIC, FCC-ee, CEPC.

- Ultra-lightweight tracker to minimize multiple scattering.
- Low power consumption.
- Precision momentum resolution:
  - $\sigma(1/p_T) = a \oplus \frac{b}{p_T sin\theta} < 3 \times 10^{-5}\ \mathrm{GeV}^{-1}$
- Excellent EM resolution with low constant term ($< 10\%/\sqrt{E}$)
- Unprecedented low jet energy resolution to distinguish W/Z/H to dijets ($< 30\%/\sqrt{E}$)
- Micron-precision b- and c- tagging capability
  - Impact parameter: $\sigma_{r\phi} = 5 \pm 10/(p[GeV]sin^{\frac{3}{2}}\theta)\ \mu m$
- Particle ID in a broad momentum range, incl. pico-second timing capability allows for quark flavor physics at Z pole

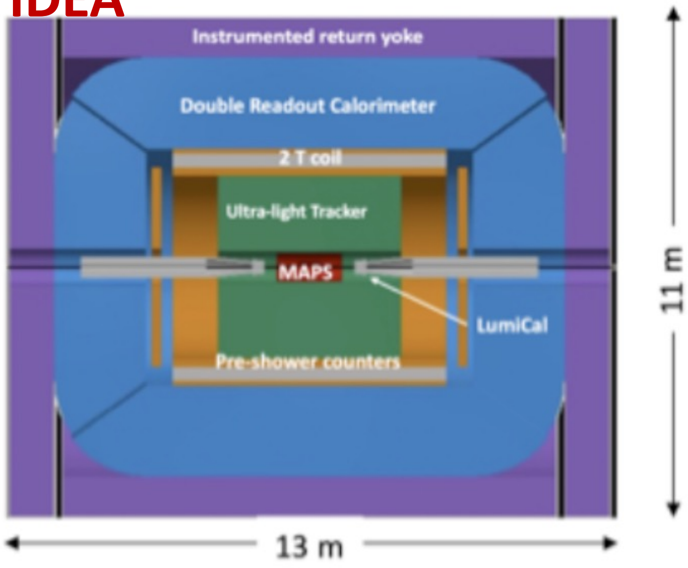


Several Detector Benchmarks for ILC/FCC-ee

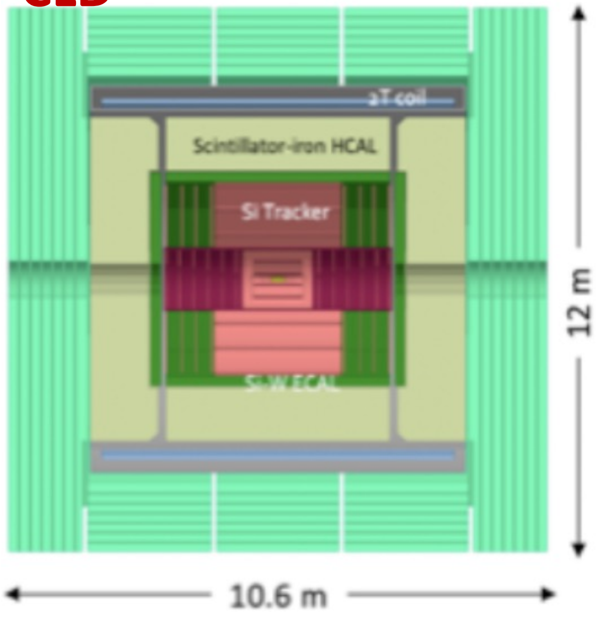
ILD



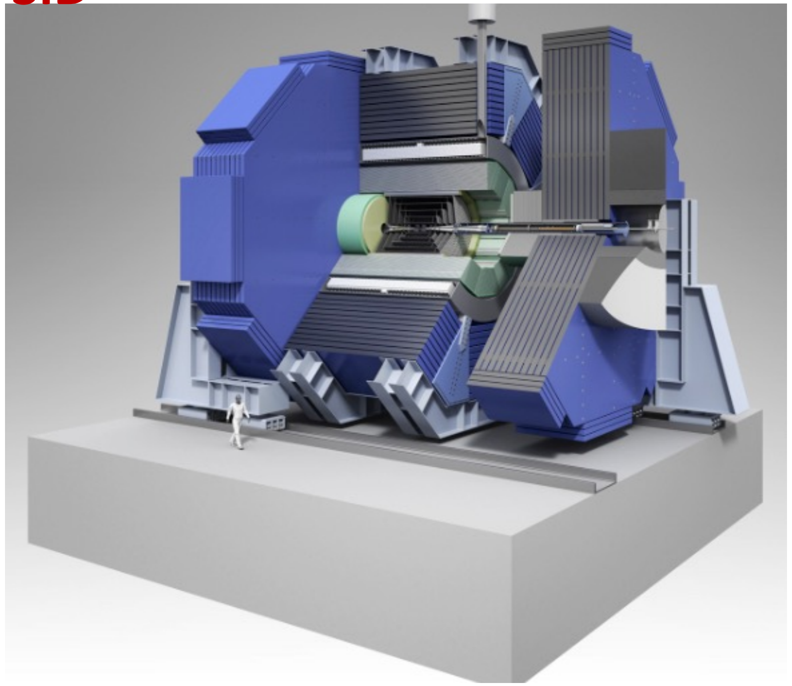
IDEA



CLD



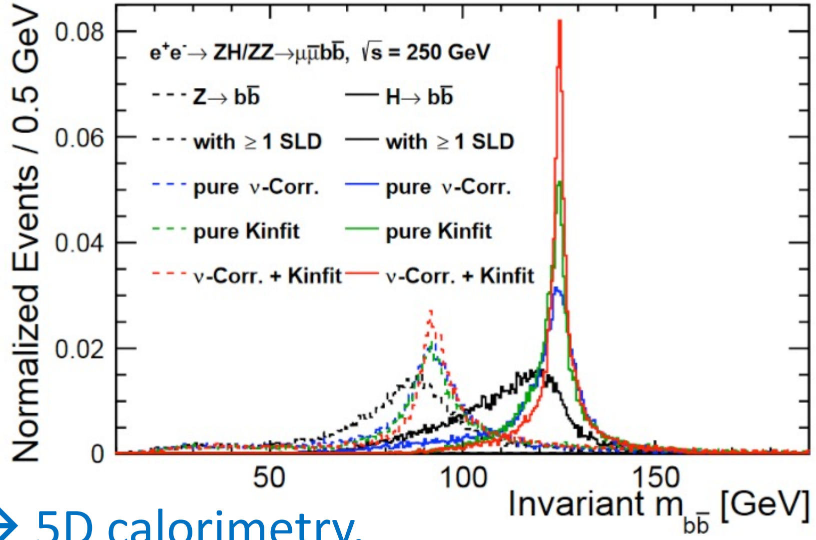
SiD



ALLEGRO

Detector Benchmarks

- ❖ All detector benchmarks emphasize one central paradigm: **PARTICLE FLOW**
  - "Combines measurements from different detectors to reconstruct a holistic particle-based description of the entire event"
- ❖ Significant improvement in PFAs in recent years.
  - Using full covariance matrix taking into account correlations between measurement and uncertainties for each PF object.
  - Deriving neutrino corrections at individual semi leptonic decay level.
- ❖ Scalable machine learning algorithms, using GNN, have shown the promise to significantly improve jet energy resolution by 50%.

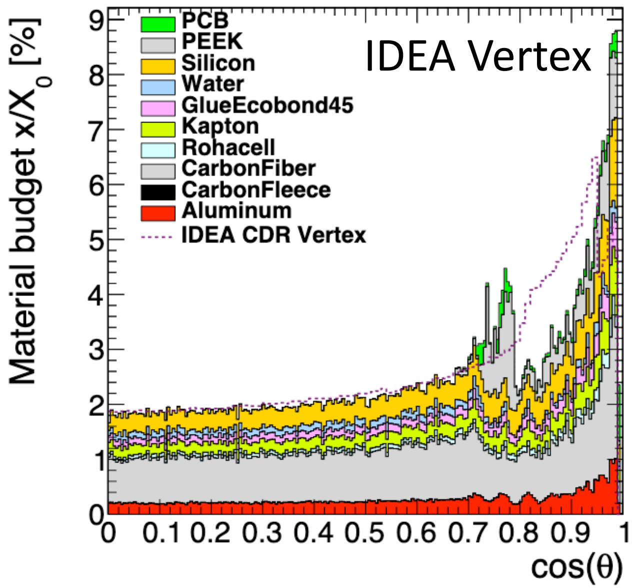


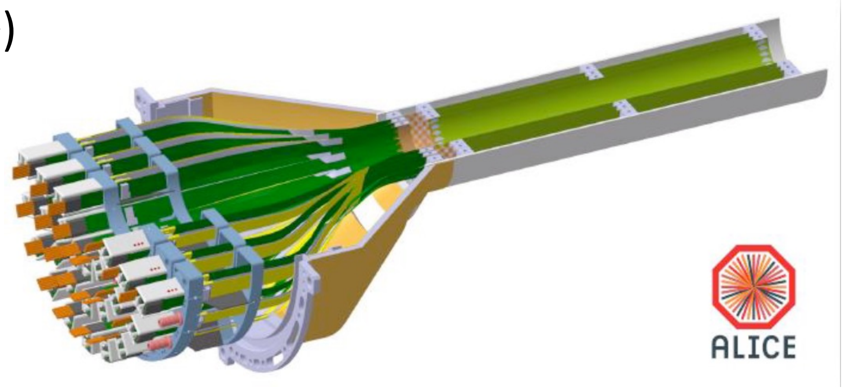
Einhaus et. al. ICHEP 2022

- ❖ Timing requirements offer another dimension for PFA algorithms → 5D calorimetry.
- ❖ Strange tagging (H→ ss) require excellent vertexing to and veto b and c jets.
- ❖ Particle ID via TOFs, dE/dx, dN/dx to distinguish π, K decays.
- ❖ Advances in reconstruction algorithms and detector technology, incl. potential use of AI in both hardware and offline algorithms, warrant further scrutiny of detector benchmarks. Further R&D for optimal high granularity, low material, low noise detectors a must!

Silicon: Vertexing and Outer Tracker (SiD, CLD)

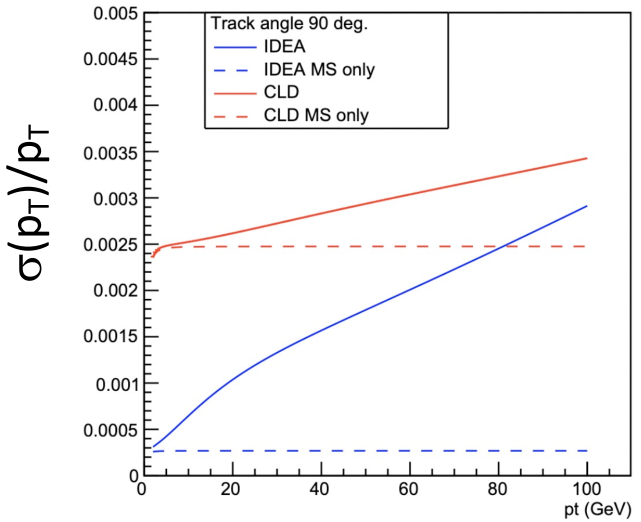
- ❖ Monolithic active pixel sensors (MAPS) offer significant advantage
  - Position resolution < 5μm and < 0.1% X/X0 per layer.
  - Thinned (50 μm), Stitched, Curved sensors
  - Low power: 20 (50) mW/cm^2 for vertex (outer).
  - Cooling by airflow a must. Sufficient?
  - Material, Material, Material!
- ❖ System integration issues remain a challenge
  - Mechanical support, services, readout
  - Is reinforced carbon fiber still the optimal support structure?
  - Hermeticity, Alignment, ….
- ❖ *O*(ns) time resolution for beam background suppression
  - Dedicated ongoing effort (NAPA p-2 chip; <1 ns, < 20 mW/cm^2)
- ❖ Synergy with ALICE ITS3 and EIC EPIC tracker:
  - Requirements are very similar.
  - EPIC/ITS3 becomes an essential prototype demonstrator for future collider detectors!





Gaseous Tracker (ILD, IDEA, ALLEGRO)

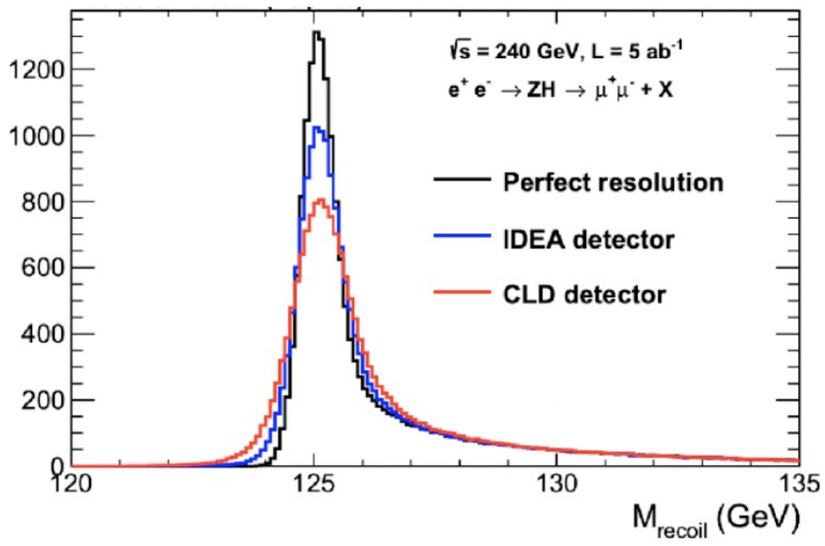
❖ High-precision low-mass drift chamber for outer tracker
  - Reduced material → minimal multiple interaction → better momentum resolution
  - Particle separation through dE/dx or dN/dx, Continuous tracking.
- TPC (ILD): Distortions due to primary ion build up a challenge at FCC-ee
  - Significantly larger at FCC-ee: 2 x 10^{12} primary ions at any time (> x2500 ILD)
- Large scale mechanical structures and full-size prototypes needed to demonstrate the feasibility of gaseous tracking



Comparing CLD and IDEA:

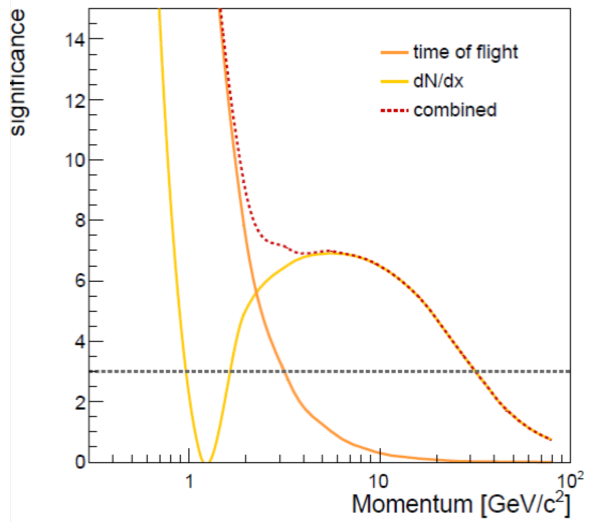
CLD
- All Si Tracker
- total material budget 11%

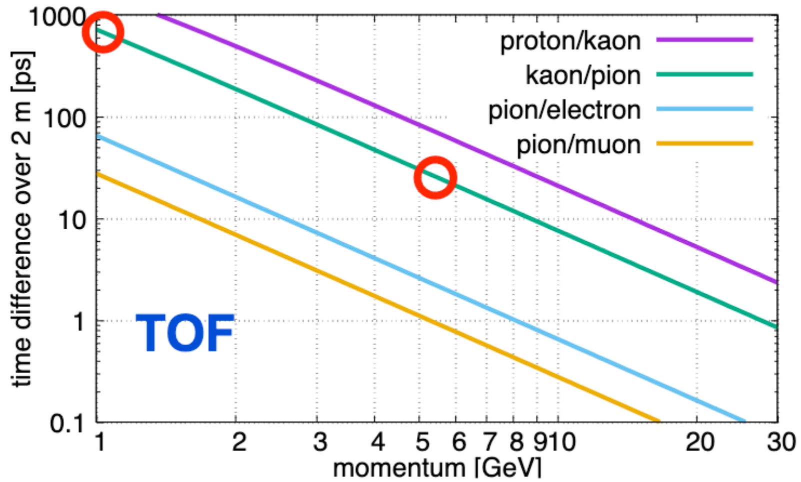
IDEA
- Drift Chamber
- Material budget is < 2%

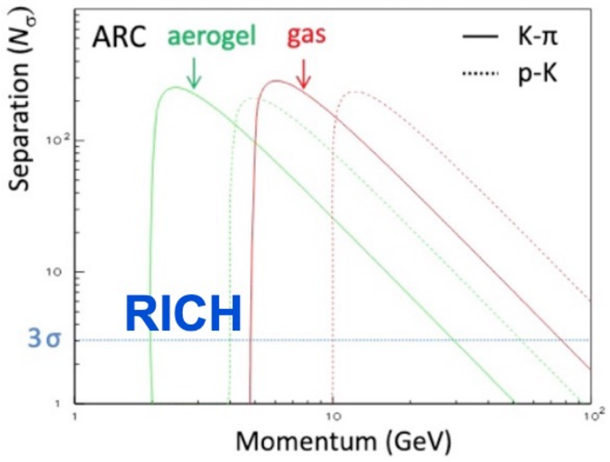


Particle ID

- Particle ID using time of flight, dE/dx, cluster counting is important for flavor physics studies. (see FCC-ee analysis, CEPC analysis)
- dE/dx in drift chamber can provide >3σ π/K separation up to ~30 GeV.
  - Non-differentiable for p~1 GeV. Mitigated with dedicated TOF systems surrounding tracking volume
- LGAD based timing layer can provide high precision (~10 ps) timing resolution.
  - For a 2m path length (outer radius), σ_t ~ 10 ps can achieve a 3σ π/K separation for p < 5 GeV/c.
- Pressurized RICH detectors being investigated, can potentially offer 3σ π/K separation 5-80 GeV.







Calorimeter

- All proposed detector benchmarks focus on high granularity sampling calorimeter with low noise intended to aid Particle Flow
- Si/W: Calice Like (SiD, ILD, CLIC, CLD)
  - ECAL: W/Si or W/scint+SiPM
  - HCAL: steel/scint+SiPM
- Liquid Argon ECAL + Tile HCAL (ATLAS like)
  - Finer longitudinal (12 vs. 4 in ATLAS) segmentation, superior (~5x) SNR with cold electronics.
  - Turbine structures proposed for forward EM calorimeter
- Dual Readout Fiber calorimeter with EM Crystal
  - Cu absorbers with embedded Scintillation and Cerenkov fibers
  - Additional longitudinal segmentation via timing needs further exploration
  - EM Crystal calorimeter can potentially offer good resolution ($\sim 3\%/\sqrt{E}$)
- Very forward (Si-W) cal. to measure Luminosity via Bhabha's.

Reference: M. Aleksa et. al.

Calorimeter Performance

Jet Energy Resolution: $\delta E/E < 30\% / \sqrt{E}$ [GeV]

Mass reconstruction from jet pairs

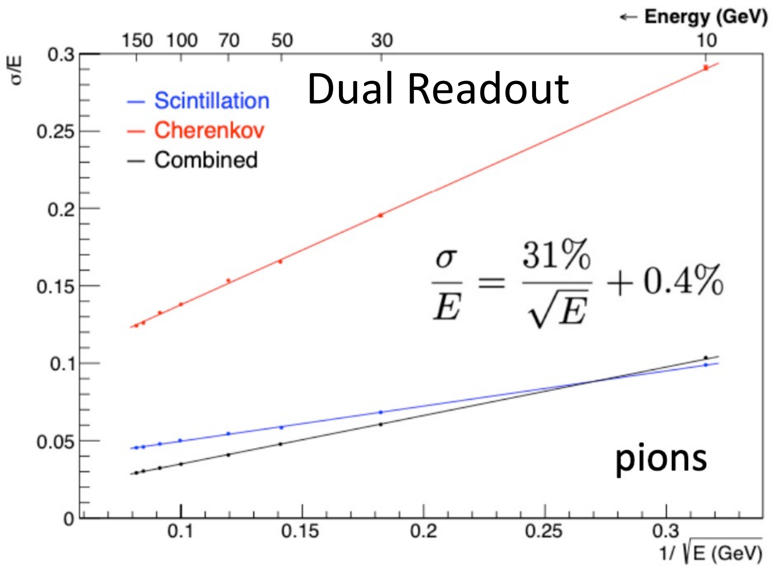
Resolution important to control (combinatorial) backgrounds in multi-jet final states.

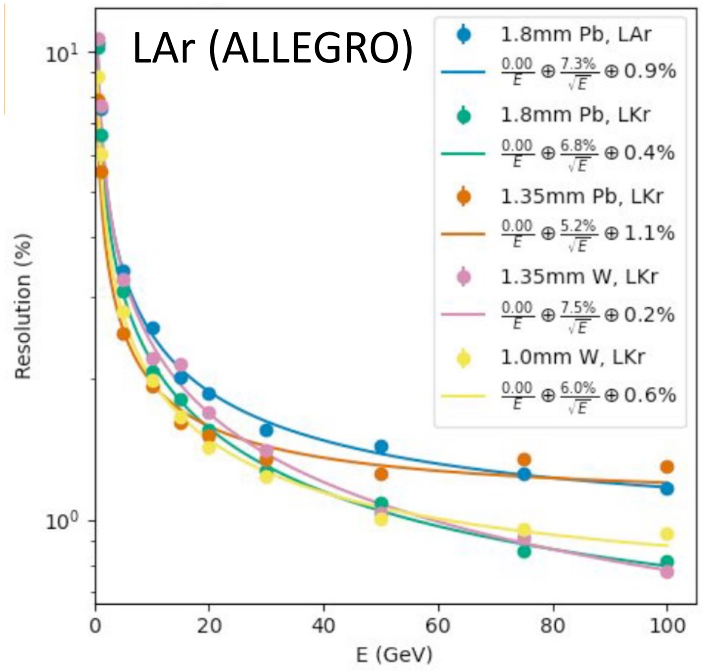
- HZ → 4 jets, tt events, etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons

EM Energy Resolution: $\delta E/E < 10\% / \sqrt{E}$ [GeV]

- **Invariant masses**
- H → $\gamma\gamma$
- π^0 identification and measurement for τ polarisation, etc.
- Also important for searches of the kind $\tau \to \mu\gamma$

Need to demonstrate performance with realistic prototype modules in test beams



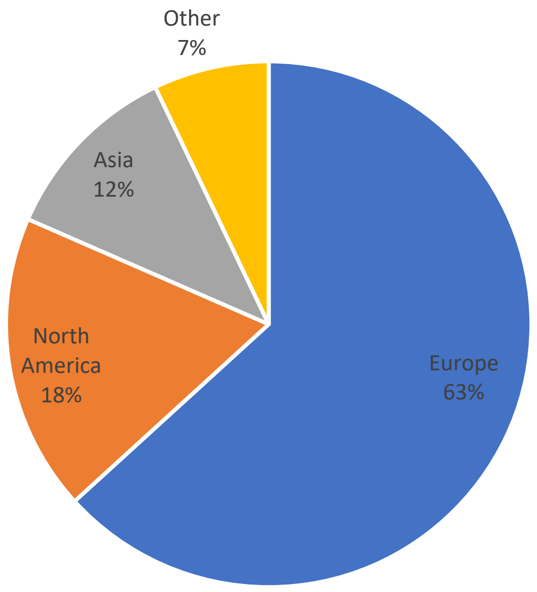


Unified R&D approach

- A Higgs Factory Coordination Consortium has been formed in the U.S. to
  - provide strategic direction for the U.S. community to engage, shape, and thereby advance the development of the physics, experiment, and detector (PED) program for a potential future Higgs factory; and to ensure cooperation with our partners in the international program.
  - The Linear and Circular collider communities in the U.S. have united to plan and pursue detector R&D toward a future Higgs Factory within this organization.
  - This is critical given the limited available resources and funding.

- Such collaborations are essential on a global scale:
  - We can benefit by pooling resources in Europe, Japan, the U.S. and elsewhere to pursue detector R&D in a complementary and cost-effective manner toward a future Higgs Factory.

- DRD collaborations created at CERN offer a channel to facilitate such a collaboration. (see D. Contardo)
  - But still not sufficiently reflective of a global R&D effort.



Current DRD Demographics

Summary

- ❖ Detector benchmarks for ILC (ILD and SiD) well advanced relative to FCC-ee benchmarks.
  - Large synergy between detector requirements for ILC and FCC.
- ❖ Significant advances in technologies and adaptation of ML based algorithms require reconsideration of detector concepts
  - Further R&D required, in particular to demonstrate performance via realistic scale prototypes.
  - Significant synergies in MAPS based detectors between ILC/FCC and EIC/ALICE ITS3
- ❖ Newly organized Detector R&D (DRD) collaborations at CERN offer a vehicle for collaboration and efforts.
  - Resources to pursue such R&D efforts remain minimal, largely due to other ongoing efforts in HL-LHC upgrades.
  - Priority must be to complete construction, operate, and get to the physics on what we commit to build : Failure to do so will have a significant negative impact on our efforts to realize a future Higgs Factory.
- ❖ Number of talks in parallel sessions this week: An opportunity to further explore and deliberate the ongoing R&D efforts.

Beam Parameters

Linear

Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	1.0	1.0	0.9	1.4	2.0
Number of bunches per train	1312	1312	352	312	312
Bunch separation (ns)	554	554	0.5	0.5	0.5
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1

Circular

	FCC-ee Z	FCC-ee Higgs	FCC-ee ttbar	CEPC Z (2T)	CEPC Higgs
√S [GeV]	**91.2**	**240**	**365**	**91.2**	**240**
Luminosity / IP ($10^{34}cm^{-2}s^{-1}$)	**140**	**>5**	**1.25**	**32**	**1.5**
no. of bunches / beam	11200	440	60	12000	242
Bunch separation (ns)	**20**	994	3000	**25**	680
Beam size at IP σ_x/σ_y (μm/nm)	6.4/28	14/36	38/68	6.0/40	20.9/60