e^+e^- Higgs Factory Synergies: Physics and Performance

Charge: Compare design and analysis requirements associated with the physics goals of the different machines. Highlight common challenges and open questions.

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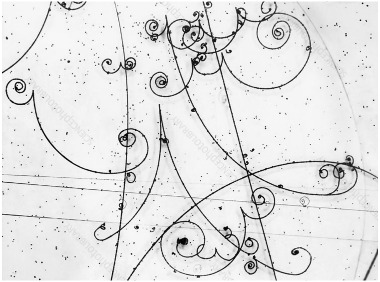

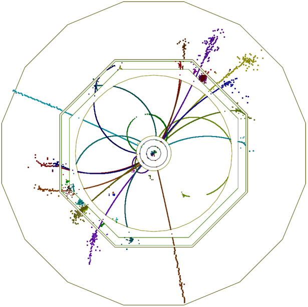

The Plan

1. Personal Remarks
2. Higgs Factory Landscape
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5. Some of the Physics Drivers for Detector Design
6. Tracking Performance: Momentum Resolution, Higgs Recoil
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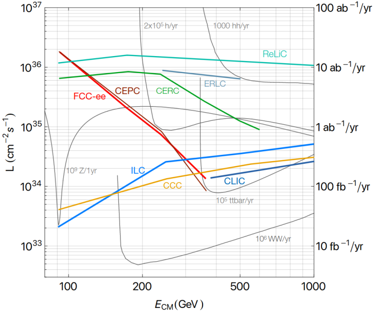
Personal Remarks and Perspective

- Early career mostly with the OPAL experiment at LEP.
- In 1995 (as a young postdoc), I started working on future $\mathrm{e}^+\mathrm{e}^-$ collider studies alongside my main working experiment (OPAL). Continued to work on future $\mathrm{e}^+\mathrm{e}^-$ collider studies while participating in D0 and CMS after moving to the US in 2001. Founding member of the ILD detector concept.
- An $\mathrm{e}^+\mathrm{e}^-$ Higgs Factory has been a **dream** for a long time. There is nothing quite like seeing individual events from such colliders.
- We need to help make this a **reality** in the not too distant future. Need to be united on advocating for $\mathrm{e}^+\mathrm{e}^-$ physics and across projects.
- My $\mathrm{e}^+\mathrm{e}^-$ work has been mostly on **linear colliders** which have the advantage of larger energy reach, longitudinally-polarized beam**s**, more sustainable footprint, lower cost, and a possible path to much higher partonic center-of-mass energies (plasma).
- I am intrigued by the potential of extensive **Z running** from the electroweak physics perspective especially with longitudinally-polarized beams.
- I do disagree with the frequent assertion that **systematic uncertainties** for very high statistics $\mathrm{e}^+\mathrm{e}^-$ experiments can be essentially neglected.

e^+e^- Higgs Factory Machines

Several machines under study. Two recent interesting conceptual ideas. ReLiC (energy-recovery linac based) pushes performance. HALHF (asymmetric with e^- plasma acceleration) pushes cost/footprint.



Plot from EF-ITF (T. Roser et al)

For the better established concepts, the basic paradigm is

- Linear for higher energy
- Linear for longitudinally-polarized beams
- Circular for higher luminosity at low $\sqrt{s}$
- Two detectors sharing lumi (linear)
- Two or more IPs (circular).

Main physics differentiators:

- Very high statistics Z running (FCC-ee). Systematics?
- Direct access to HHH and ttH couplings (linear).

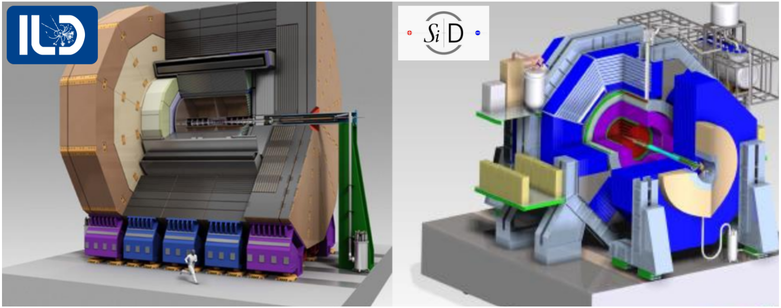
Any of these machines will be revolutionary compared to SLC/LEP.

Detectors, using ILC as an example

Modern detectors designed for ILC [1, 2]

ILD = International Large Detector
(also ILD Interim Design Report (2020) [3])

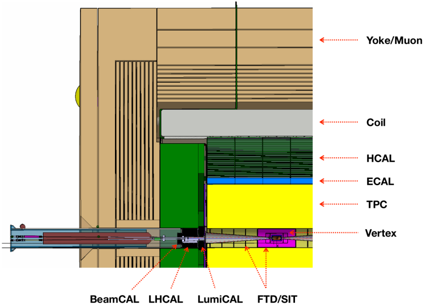
SiD = Silicon Detector

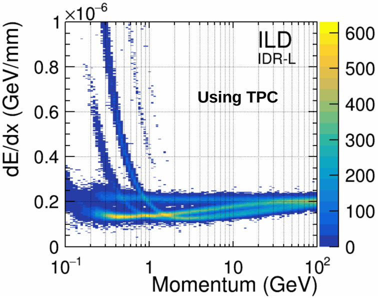


- B=3.5–5T. Particle-flow for hadronic jets. **Very hermetic**.
- Low material. Precision vertexing.
- ILD tracking centered around a Time Projection Chamber (TPC).
- Also spawned designs such as CLIC-ILD, CLIC-SiD, CLICdp, CLD, CEPC.

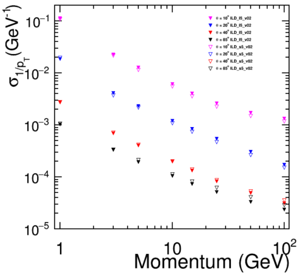
A current ILD emphasis: figuring out how to adapt to eg. FCC-ee. Areas of concern: TPC distortions especially at Z. Is B=2T the limit for all $\sqrt{s}$?

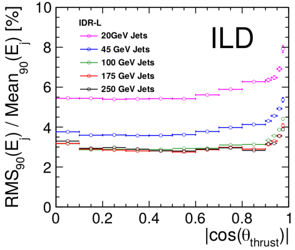
ILD Detector (See IDR)

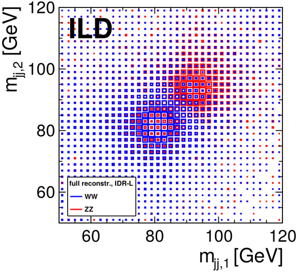




Momentum Resolution







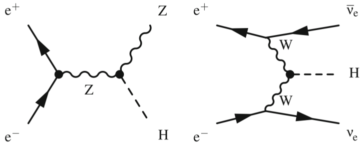
Can't I just apply my hadron collider expertise?

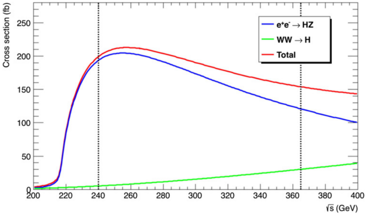
Some of the big differences

1. In some cases **no hardware trigger** need (eg. ILC).
2. Radiation hardness is not a major issue.
3. **Pileup non-existent** (FCC-ee) or small but resulting from semi-unresolvable collisions with longitudinal spread of 200 μm (ILC) not 5 cm (LHC).
4. Depending on the detector design, muon detectors may be largely redundant.
5. While some silicon tracking likely to be used. Emphasis on precision measurement of even low momentum tracks - careful with **material budget**.
6. Major emphasis on precisely characterizing the **initial state**. Precision absolute luminosity, relative luminosity, center-of-mass energy, center-of-mass energy distribution and beam polarization. Allows use of kinematic fits (with energy and momentum conservation).
7. Also on understanding and mitigating **machine backgrounds** (eg. beamstrahlung and related $\mathrm{e^+e^-}$ pairs), and working with accelerator physicists.
8. And last-but-not-least - best usually to use $\cos\theta$ not η, and p not p_T.

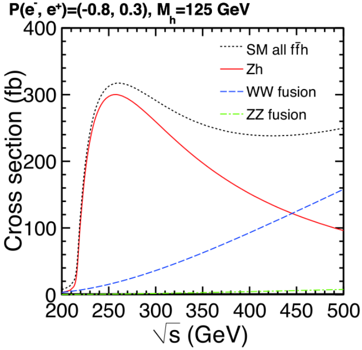
Higgs Introduction

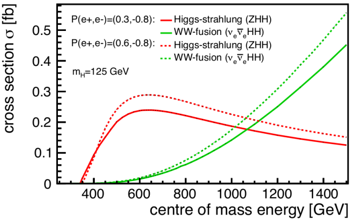
Key measurements: σ_{ZH}, m_{H}, $\mathcal{B}_i$.
Leads to g_{HZZ}, g_{HWW}, Γ_{tot}.





3 regimes. Threshold (Higgs-strahlung). Intermediate (WW-fusion). 500 GeV+ needed to start to probe HHH directly.

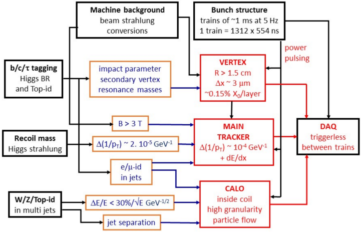


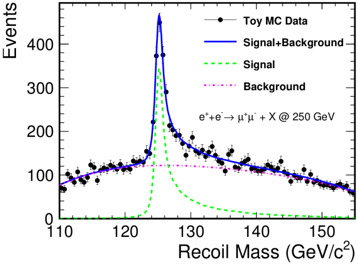


Detector Design = Physics + Detector + Accelerator

For ILC much progress was made a decade ago when 3 detector concepts were worked on substantially (ILD, SiD, 4th), and ILD and SiD were studied extensively in full simulation with full reconstruction as integrated detector systems.

Example ILD (IDR 2020)

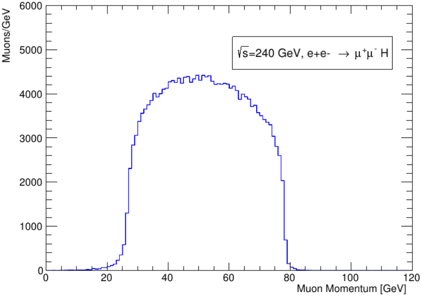


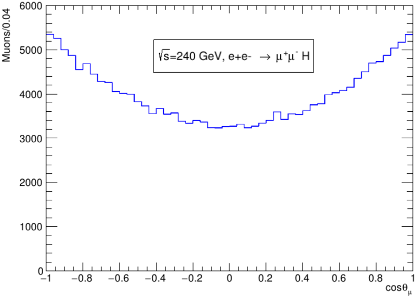


- Over the years, the stated design requirements originating from very early studies (mid-90's) have not been questioned much. They **should be**.
- Feasible today to apply radically advanced detector technologies and reconstruction algorithms, and now with greater physics scope. Particularly true for jet flavor and charge ID.
- PID generally not prioritized - but appreciated if easily integrated (eg. TOF).

Higgs Recoil Mass I

Use the missing mass in Higgs-strahlung events with $\mathrm{Z} \to \mu^+\mu^-$ to identify Higgs events independent of decay mode. Access σ_{ZH} and $\mathcal{B}_i$'s.
For $\sqrt{s} = 240$ GeV, the muon momentum and $\cos\theta$ distributions are:

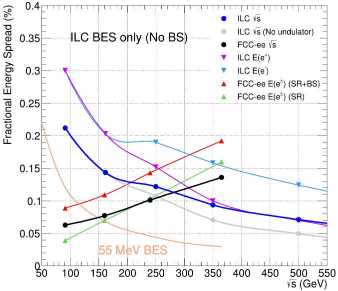


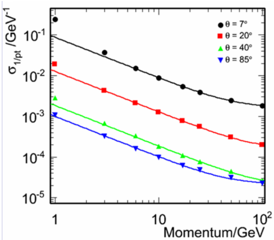


Assuming initial state with E of $\sqrt{s}$ and zero net momentum, can measure

$$M^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\mu^+\mu^-}, \vec{p}_{\mu^+\mu^-})^2 = s - 2E_{\mu^+\mu^-}\sqrt{s} + M^2_{\mu^+\mu^-} .$$

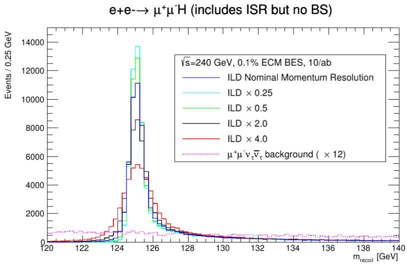
Higgs Recoil Mass II





$$\sigma_{1/p_T} = a \oplus b/(p_T \sin\theta)$$

$a = 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ and $b = 1 \times 10^{-3}$



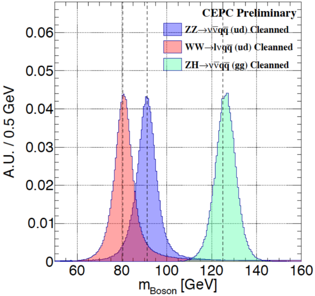
- Performance depends on machine and detector.
- Machine luminosity spectrum (BES + BS).
- Detector momentum resolution.

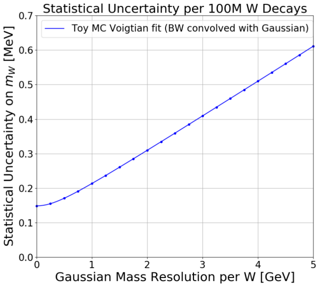
Calorimetry Performance Requirements

The key issue has been assumed to be resolving W, Z, and Higgs bosons. Early PFA studies focused on simple event energy estimates or multi-jet separation.

- Recent CEPC studies are framed in terms of the **mass resolution** of boosted bosons with decays to u and d quarks and to gluons in di-jet topologies.
- Achieve 4% mass resolution with PFA - intrinsic subdetector resolution is 2% for 240 GeV, $\nu\nu\mathrm{H}$ with $\mathrm{H} \to gg$. Believes 3% should be feasible.
- Looks like a great **benchmark**. Note that in realistic physics scenarios the complications associated with decays to b, c, s quarks need to be folded in.

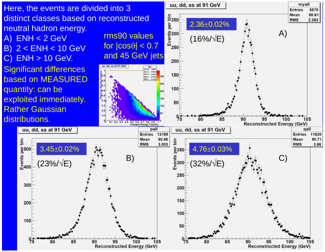
$$M_{12}^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\psi_{12})$$





Calorimetry II

- In addition to providing an energy estimate, it would be preferred if jet-by-jet **uncertainties** are also reliably calculated.
- Not so obvious for PFA based methods. Given the nature of the ways in which the **reconstructability of jets** - or the resolution and level of confusion, **differs** from jet to jet.
- Should explore more. Some ongoing/past work. Interested - let's talk.



Here, the events are divided into 3 distinct classes based on reconstructed neutral hadron energy.

A) ENH < 2 GeV

B) 2 < ENH < 10 GeV

C) ENH > 10 GeV.

Significant differences based on MEASURED quantity: can be exploited immediately. Rather Gaussian distributions.

rms90 values for |cosθ| < 0.7 and 45 GeV jets

Good, fair, and ugly $Z \rightarrow q\bar{q}$ ($q = u, d, s$). See IWLC talk.

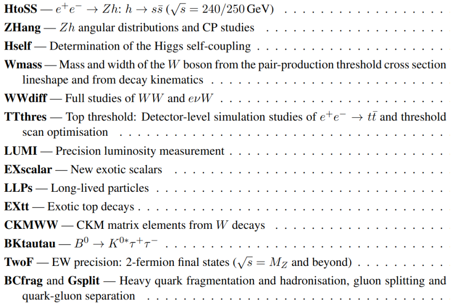
New Directions

- Deep learning
- Dual-readout
- Ultra-high granularity (eg. MAPS)
- Exploiting temporal measurements
- Full particle reconstruction

ECFA Focus Topics

See 2401.07564. Envisaged as a platform for studying the **interplay** of physics potential, analysis methods, and detector performance.
And as a community building exercise.

- Especially if you are new to $\mathrm{e^+e^-}$ physics and detector studies, and not sure how to get started.
- In the context of the ECFA study on Higgs/Top/EW factories we have assembled a set of 14 suggested **focus topics**.
- These include contact information and ideas for **concrete studies** towards understanding the physics potential of such machines.

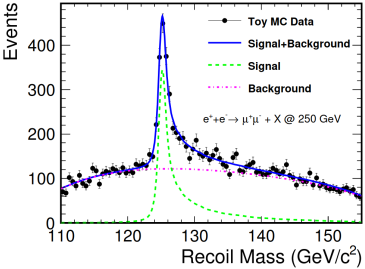


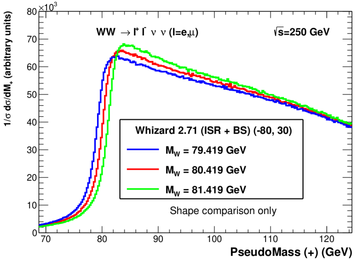
HtoSS — $e^+e^- \to Zh$: $h \to s\bar{s}$ ($\sqrt{s} = 240/250$ GeV)
ZHang — Zh angular distributions and CP studies
Hself — Determination of the Higgs self-coupling
Wmass — Mass and width of the W boson from the pair-production threshold cross section lineshape and from decay kinematics
WWdiff — Full studies of WW and $e\nu W$
TTthres — Top threshold: Detector-level simulation studies of $e^+e^- \to t\bar{t}$ and threshold scan optimisation
LUMI — Precision luminosity measurement
EXscalar — New exotic scalars
LLPs — Long-lived particles
EXtt — Exotic top decays
CKMWW — CKM matrix elements from W decays
BKtautau — $B^0 \to K^{0*}\tau^+\tau^-$
TwoF — EW precision: 2-fermion final states ($\sqrt{s} = M_Z$ and beyond)
BCfrag and **Gsplit** — Heavy quark fragmentation and hadronisation, gluon splitting and quark-gluon separation

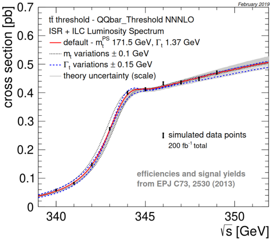
Example: Caterina is involved in HtoSS. I am involved in Wmass and LUMI.

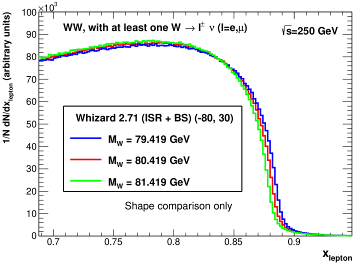
Examples Highlighting Center-of-Mass Energy Calibration

Z lineshape measurements and WW threshold. Also Higgs, top and W measurements at Higgs factory energies; here RDP is also not feasible for FCC-ee.



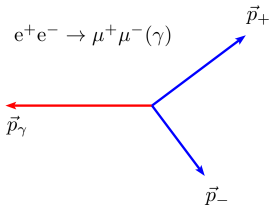






Momentum-based $\sqrt{s}_p$ method in a nutshell

Leverage momentum resolution to measure $\sqrt{s}$. See (Madison, GWW).



Measure $\sqrt{s}_p$ using,
$(|\vec{p}_+|, |\vec{p}_-|, |\vec{p}_+ + \vec{p}_-|)$

Assuming,

- **Equal** beam energies, E_b
- The lab **is** the CM frame, $(\sqrt{s} = 2\,E_\mathrm{b},\ \sum \vec{p}_i = 0)$
- The system recoiling against the dimuon is **massless**

$$\sqrt{s} = \sqrt{s}_p \equiv E_+ + E_- + |\vec{p}_+ + \vec{p}_-|$$

$$\sqrt{s}_p = \sqrt{p_+^2 + m_\mu^2} + \sqrt{p_-^2 + m_\mu^2} + |\vec{p}_+ + \vec{p}_-|$$

An estimate of $\sqrt{s}$ using only the (precisely measurable) muon momenta

- No assumption on the photon direction.
- With ILD detector at ILC - expect 0.14% momentum resolution for typical 71 GeV muons in Zγ events at $\sqrt{s} = 250$ GeV. Event $\sqrt{s}$ to $\approx 0.1\%$.
- Detector-level studies are with full simulation and reconstruction.
- Need precision momentum scale calibration. Target below 10 ppm.

Hermeticity

- Correct reconstruction of events especially those with neutrinos and very forward jets requires coverage to **low angle**.
- Events with ISR photons (with p_T) and two-photon collisions can be diagnosed better with excellent forward coverage.
- Forward coverage is particularly **challenging** for the FCC-ee MDI.
- Important to look carefully into the ability to measure **hadronic events** at forward angles. In OPAL the LumiCal played a significant role in the forward jet energy response (down to 25 mrad) for the Z hadronic cross-section measurement. May be a really important issue for the utility of 10^{12} Z's.
- Again this is an area where an **integrated detector design** backed up with full simulation is essential.
- In the context of investigating the utility of $ee \rightarrow \gamma\gamma$ for luminosity measurements, I have been working recently on a precision sampling EM forward calorimeter with electron and photon ID in the (ILD) LumiCal type acceptance. Recent talk is "New Ideas on Forward Calorimetry Design". This targets much higher performance (4–5%/$\sqrt{E}$) than current concepts while also functioning as a **hermetic luminometer**.

Integrated Detector Design Aspects

- Detector **solenoids** are a critical path item. Especially when nobody builds them any more. EIC?
- Detector performance especially for hadronic jets needs to be a whole package - including effects like inter-calorimeter solenoids.
- Tracking only makes sense in the context of an alignable system. Much less tracks for **alignment** than at LHC. Needs design work too.
- Figuring out how to really control the **momentum scale**.
- Don't underestimate the utility of working together on the machine detector interface (MDI) and on general accelerator physics issues that pertain to the overall success of these ventures!

Closing Remarks

- Mounting a new $\mathrm{e}^+\mathrm{e}^-$ collider experiment has many aspects that need to be attacked in an **integrated** way with **sustained** effort.
- The US should work **coherently** with international partners while engaging in an **above critical mass** effort that is not generic.
- There is a great opportunity for **creativity** with longer timescales and new approaches.
- Best to work coherently with accelerator groups on developing **colliders**.
- There are many aspects of a future $\mathrm{e}^+\mathrm{e}^-$ collider that are not well understood and would benefit from **fresh insight**/renewed focus.
- The linear collider community has built many tools that we are happy to share in the interest of building a **common** US Higgs factory community. These will help new members get started. Please take advantage of what has been built and what has been learned.

References I

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The International Linear Collider Technical Design Report - Volume 4: Detectors, arXiv:1306.6329

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