Detector Requirements from Physics

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A few general considerations

Exquisite luminosity allows for ultimate precision:

- 100K Z bosons / second
  - LEP dataset in 1 minutes
- 10k W boson / hour
- 2k Higgs bosons / day
- 3k tops / day

<table>
<thead>
<tr>
<th></th>
<th>Z pole</th>
<th>? H pole ?</th>
<th>WW</th>
<th>ZH</th>
<th>t(t)bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sqrt{s}) [GeV]</td>
<td>88 - 91 - 94</td>
<td>125</td>
<td>157 - 161</td>
<td>240</td>
<td>350 - 365</td>
</tr>
<tr>
<td>Lumi / IP [10^{34} cm^2 s^{-1}]</td>
<td>182</td>
<td>80</td>
<td>19.4</td>
<td>7.3</td>
<td>1.33</td>
</tr>
<tr>
<td>Int. lumi / 4IP [ab^{-1} / yr]</td>
<td>87</td>
<td>38</td>
<td>9.3</td>
<td>3.5</td>
<td>0.65</td>
</tr>
<tr>
<td>N years</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>N events</td>
<td>8 Tera</td>
<td>8 K</td>
<td>300 M</td>
<td>2 M</td>
<td>2 M</td>
</tr>
</tbody>
</table>

15 (20?) years of operations
Detector requirements - general considerations

- Requirements for Higgs and above have been studied to some extent by LC:
  - have to be revised by FCC-ee
  - we want a detector that is able to withstand a large dynamic range:
    - in energy (\(\sqrt{s} = 90 - 365\) GeV)
    - in luminosity (\(L = 10^{34} - 10^{36}\) cm\(^2\)/s)

- most of the machine induced limitations are imposed by the Z pole run:
  - large collision rates ~ 33 MHz and continuous beams
    - no power pulsing possible
  - large event rates ~ 100 kHz
    - fast detector response / triggerless design challenging (but rewarding)
    - high occupancy in the inner layers/forward region (Bhabha scattering/\(\gamma\gamma\) hadrons)
  - beamstrahlung

- complex MDI: last focusing quadrupole is ~ 2.2m from the IP
  - magnetic field limited to \(B = 2\)T at the Z peak (to avoid disrupting vertical emittance/inst. Lumi via SR)
    - limits the achievable track momentum resolution
  - “anti”-solenoid
    - limits the acceptance to ~ 100 mrad
**Detector concepts**

- **CLD**
  - Well established design
    - ILC -> CLIC detector -> CLD
  - Full Si vtx + tracker;
  - CALICE-like calorimetry;
  - Large coil, muon system
  - Engineering still needed for operation with continuous beam (no power pulsing)
    - Cooling of Si-sensors & calorimeters
  - Possible detector optimizations
    - $\sigma_p/\rho$, $\sigma_E$
    - PID ($\mathcal{O}(10\,\text{ps})$ timing and/or RICH)?

- **IDEA**
  - A bit less established design
    - But still $\sim 15\,\text{y}$ history
  - Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
  - Monolithic dual readout calorimeter;
    - Possibly augmented by crystal ECAL
  - Muon system
  - Very active community
    - Prototype designs, test beam campaigns, ...

- **Noble Liquid ECAL based**
  - A design in its infancy
  - Si vtx det., ultra light drift chamber (or Si)
  - High granularity Noble Liquid ECAL as core
    - Pb/W+LAr (or denser W+LKr)
  - CALICE-like or TileCal-like HCAL;
  - Coil inside same cryostat as LAr, outside ECAL
  - Muon system.
  - Very active Noble Liquid R&D team
    - Readout electrodes, feed-throughs, electronics, light cryostat, ...
    - Software & performance studies

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See Detector sessions
*(Thursday 11:30AM, 2:30PM)*
Physics landscape at the FCC-ee

**Higgs factory**
- \( m_H, \sigma, \Gamma_H \)
- self-coupling
- \( H \rightarrow \text{bb, cc, ss, gg} \)
- \( H \rightarrow \text{inv} \)
- \( ee \rightarrow H \)
- \( H \rightarrow \text{bs, ..} \)

**Top**
- \( m_{\text{top}}, \Gamma_{\text{top}}, \text{ttZ, FCNCs} \)

**Flavor**
“boosted” B/D/\( \tau \) factory:
- CKM matrix
- CPV measurements
- Charged LFV
- Lepton Universality
- \( \tau \) properties (lifetime, BRs..)
- \( B_c \rightarrow \tau \nu \)
- \( B_s \rightarrow D_s K/\pi \)
- \( B_s \rightarrow K^* \tau \tau \)
- \( B \rightarrow K^* \nu \nu \)
- \( B_s \rightarrow \phi \nu \nu \ldots \)

**QCD - EWK**
most precise SM test
- \( m_Z, \Gamma_Z, \Gamma_{\text{inv}} \)
- \( \sin^2 \theta_W, R^Z, R_b, R_c \)
- \( A_{FB}^{b,c}, \tau \text{ pol.} \)
- \( \alpha_S \)
- \( m_W, \Gamma_W \)

**BSM**
feebly interacting particles
- Heavy Neutral Leptons (HNL)
- Dark Photons \( Z_D \)
- Axion Like Particles (ALPs)
- Exotic Higgs decays
Detector requirements at the FCC-ee

**Higgs factory**
- track momentum resolution (low $X_0$)
- IP/vertex resolution for flavor tagging
- PID capabilities for flavor tagging
- jet energy/angular resolution (stochastic and noise) and PF

**Flavor**
- “boosted” B/D/\(\tau\) factory:
  - track momentum resolution (low $X_0$)
  - IP/vertex resolution
  - PID capabilities
  - Photon resolution, pi0 reconstruction

**QCD - EWK**
- most precise SM test
  - acceptance/alignment knowledge to 10 \(\mu\)m
  - luminosity

**BSM**
- feebly interacting particles
  - Large decay volume
  - High radial segmentation
    - tracker
    - calorimetry
    - muon
  - impact parameter resolution for large displacement
  - triggerless
Highlights from recent activities
Luminosity/acceptance

- Precise knowledge of the geometrical acceptance required by
  - $R^Z$, measurement (as limiting systematics)
  - absolute luminosity measurement at Z pole, required by
    - peak Z cross section ($\sigma_0$)

- At LEP, via Bhabha scattering at low angle, here we require $10^{-5}$ precision (for point-to-point), $10^{-4}$ being absolute target
  - un-matched by theoretical calculations
  - use $ee \rightarrow \gamma\gamma$ process as an alternative, rarer but cleaner TH

- To match stat. precision ($2 \times 10^{-5}$)
  - must know $\Delta\theta_{\text{min}} \sim 10 \ \mu\text{rad}$
    - equivalent to $\Delta r \sim 30 \ \mu\text{m}$, $\Delta z \sim 80 \ \mu\text{m}$ at $\theta = 20^\circ$ and $z = 2.6\text{m}$
  - challenging design requirement !!

Luckily, it turns out could be measured in situ!
measuring outgoing 4-momenta of photons

- energy/momentum conservation, allows:
  - solve for the crossing-angle $\alpha$ and the beam energy asymmetry $\varepsilon$ on an event-by-event basis
  - extract potential bias from the known dependency of $\alpha$ and $\varepsilon$ with the bias

can measure av. radius and $z$ to $\Delta r \sim 2 \mu m$, $\Delta z \sim 10 \mu m$

$\rightarrow x10$ better than needed to match stat. Precision
(assuming 0.5 mm position resolution for photons)

This in-situ calibration technique could be used to determine lumiCal acceptance
(with low angle Bhabha, 1.6 $\mu m$ tolerance needed, for $10^{-4}$ lumi meas.)
Track Momentum resolution

- **Higgs mass** and **ZH production cross-section** can be extracted from the **recoil mass distribution**

\[
m_\text{recoil}^2 = (\sqrt{s} - E_{t\ell})^2 - p_{t\ell}^2 = s - 2E_{t\ell}\sqrt{s} + m_{t\ell}^2
\]

- sensitivity dominated by the \(Z(\mu\mu)\) final state
  - superior momentum resolution, driven by **tracking**
- track momentum resolution limits sensitivity if > beam energy spread (BES = 0.182% at 240 GeV, i.e 222 MeV)
  - multiple-scattering limit < BES
    - for CLD ~ 30% above
  - **transparent** tracker is key

**see J. Eysermans, L. Portales (wed.)**
we want to get down to $\Delta m_H \sim \Gamma_H \sim 4 \text{ MeV}$ to allow for electron Yukawa at $\sqrt{s} = 125 \text{ GeV}$

as expected, tracking resolution highly impacts $m_H$ precision

light tracker/ **high B field** highly preferable

<table>
<thead>
<tr>
<th>tracking system</th>
<th>$\Delta m_H$ (MeV) stat. only</th>
<th>$\Delta m_H$ (MeV) stat + syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDEA 2T</td>
<td>3.49</td>
<td>4.27</td>
</tr>
<tr>
<td>Perfect</td>
<td>2.67</td>
<td>3.44</td>
</tr>
<tr>
<td>IDEA 3T</td>
<td>2.89</td>
<td>3.97</td>
</tr>
<tr>
<td>CLD 2T</td>
<td>4.56</td>
<td>5.32</td>
</tr>
</tbody>
</table>
Track impact parameter resolution and vertexing

- **Impact parameter resolution** major driver of jet **charm** and **bottom** jet identification
  - B (D) mesons travel a finite decay length 500 (150) μm
- precise IP determination driven by:
  - single point resolution
  - radial distance of first tracking layer from the interaction point (at large momentum)
    - need small radius beam-pipe
  - material budget $X/X_0$ (at low p)

$\Delta d_0$ resolution (μm)

- 30-40% improvement in bkg rej using:
  - 1st layer at 1 cm

See J. Eysermans, L. Gouskos (wed.)
Track impact parameter resolution and vertexing

- \( \text{BR}(H \to jj) \, jj = bb, cc \) precision rely on excellent displaced track reconstruction
- \( Z(\ell^- \ell^- jj)H(jj) \)
  - sensitivity driven by \( Z(\nu \nu)H \) so far
  - large “jet” background from WW, ZZ, Z

Effort on the fully hadronic channel has started

see J. Eysermans, L. Gouskos (wed.)

nominal expected precision (%) in vvH channel

<table>
<thead>
<tr>
<th></th>
<th>( H \to b \bar{b} )</th>
<th>( H \to c \bar{c} )</th>
<th>( H \to s \bar{s} )</th>
<th>( H \to g g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta \mu_{(Hcc)} )</td>
<td>0.28 %</td>
<td>2.05 %</td>
<td>100 %</td>
<td>0.85 %</td>
</tr>
</tbody>
</table>

worse IP resolution impact \( H \to cc \) vs \( H \to bb \) due to smaller displacement and smaller S/B
**Track impact parameter resolution and vertexing**

- $B_s \rightarrow K^* \tau \tau$ important channel to study LFU in $b \rightarrow s$ transitions
  - focusing on 3-prong $\tau$ decays

- very rich signature with:
  - 8 visible particles (1K, 7π)
  - 1 secondary vertex and tertiary vertices

- very complex analysis: many **backgrounds** and **combinatorics**

- $B_s \rightarrow K^* \tau \tau$ sensitivity driven by **vertex resolution** to make maximal use of kinematic constraints

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**5σ observation with 2 μm vertex resolution**

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**Precision of BF measurement as function of the resolution**

- SV and TV longitudinal smearing: 20 μm
- SV and TV longitudinal smearing: 10 μm
- SV and TV longitudinal smearing: 5 μm
- IDEA

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see T. Miralles (wed.)
Charged hadron particle identification (K/π/p discrimination)

- PID crucial ingredient of
  - flavor physics measurements: $B_s \rightarrow D_s K, B \rightarrow K^* \nu \nu, B_s \rightarrow \varphi \nu \nu \ldots$
  - strange quark jet identification ($H \rightarrow ss, V_{ts}, V_{cs}, H \rightarrow bs, FCNCs \ldots$)
  - e/π separation at level of $10^{-5}$ required for $\tau \rightarrow e$ (calorimetry)

- Toolbox:
  - High momentum $dE/dx$ ($dN/dx$) - Cherenkov detectors (RICH)
  - Low momentum: Time of flight

see L. Gouskos, A. Tolosa Delgado, M. Kenzie (wed.)
R. Forty (thursday)
Charged hadron particle identification (K/π/p discrimination)

- Expected precision on BR(H→ss) ~100% with 10 ab\(^{-1}\) (only using vvH channel).

PID performance: \(dN/dx > \text{timing resolution}\)

- Nominal performance: \(\delta \mu (Hss) = 100\%\)
- Degraded dN/dx resolution: \(\delta \mu (Hss) = 140\%\)

See L. Gouskos (wed.)
ECAL: electron/photon reconstruction

- many flavor physics benchmarks: $B_s \rightarrow D_s K$, $B_0 \rightarrow \pi^0 \pi^0$, $B_s \rightarrow K^* \tau \tau$..
- put stringent requirements on ECAL performance, both resolution and granularity:
  - soft $\pi^0$ ECAL resolution is a must (e.g. crystal) AND low $X_0$ material in front
  - for boosted $\pi^0$ granularity required ($\tau$ decays)
- High momentum prompt photon $H \rightarrow \gamma \gamma$, ALPs
- ECAL granularity resolution needed for efficient bremsstrahlung recovery (and low $X_0$ tracker)

Low energy photons content from $\pi^0$ (in particular for $H \rightarrow gg$)

Z(ee) channel improves $m_H$ precision

ECAL granularity and resolution needed for efficient bremsstrahlung recovery

60% improvement vs standalone tracking
Jet resolution and particle-flow

Consider $ee \rightarrow ZH \rightarrow vv jj$

$$\sigma^2(E_{vis}) = \sum_{i \in \text{tr}} \sigma_{tr}^2(E_{tr}^{(i)}) + \sum_{i \in \gamma} \sigma_{\text{ecal}}^2(E_{\gamma}^{(i)}) + \sum_{i \in \text{nh}} \sigma_{\text{hcal}}^2(E_{\text{nh}}^{(i)})$$

65%  25%  10%

25%  10%

$$\sigma^2(E_{vis}) = (f_{\gamma}S_{\text{ecal}}^2 + f_{\text{nh}}S_{\text{hcal}}^2)E_{vis}$$

with a perfect Particle-flow algorithm:

- jet energy energy resolution is dominated by neutral hadron (HCAL) resolution

with a realistic Particle-flow algorithm:

- granularity and thresholds matter
HCAL and jets -- Higgs hadronic final states

Largest gain from JER expected for $S/B \ll 1$:

If relative improvement $\alpha$, expect $\sqrt{\alpha}$ increase in precision

Observe less degradation than expected, studies will have to be repeated with full simulation
HCAL and jets

see L. Portales (wed.)

H → invisible

HNLs → μqq prompt final state
reconstruct visible mass

sizable impact of JER on Z → qq channel
offset by Z → ll channel at large smearings

see S. Williams, N. Valle (wed.)
Summary

- To fully exploit its physics potential:
  - precise alignment
  - small radius vertex detector for good IP resolution
  - low material
  - precise and granular calorimetry
  - excellent hadronic calorimetry

- The FCC-ee will provide MANY clean events, given its large luminosity, but
  - high rates
  - complex MDI

- Many case studies NOT discussed here to be undertaken:
  - Higgs FCNCs, rare decay channels, at 365 GeV
  - Top properties and FCNCs
  - EWK Z / WW energies tight req (yet to be fully explored)
  - Taus (see Alberto Lusiani ‘s talk Wed)
Backup
## FCC-ee conditions

<table>
<thead>
<tr>
<th>FCC-ee parameters</th>
<th>Z</th>
<th>WW</th>
<th>ZH</th>
<th>ttbar</th>
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<td>Integrated lumi / 4IP (ab^{-1} / \text{yr})</td>
<td>87</td>
<td>9.3</td>
<td>3.5</td>
<td>0.65</td>
</tr>
<tr>
<td>N bunches/beam</td>
<td>-</td>
<td>10 000</td>
<td>880</td>
<td>248</td>
</tr>
<tr>
<td>bunch spacing (\text{ns})</td>
<td>30</td>
<td>340</td>
<td>1.200</td>
<td>8 400</td>
</tr>
<tr>
<td>L* (\text{m})</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>crossing angle (\text{mrad})</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>vertex size (x) (\mu m)</td>
<td>5.96</td>
<td>14.7</td>
<td>9.87</td>
<td>27.3</td>
</tr>
<tr>
<td>vertex size (y) (\text{nm})</td>
<td>23.8</td>
<td>46.5</td>
<td>25.4</td>
<td>48.8</td>
</tr>
<tr>
<td>vertex size (z) (\text{mm})</td>
<td>0.4</td>
<td>0.97</td>
<td>0.65</td>
<td>1.33</td>
</tr>
<tr>
<td>vertex size (t) (\text{ps})</td>
<td>36.3</td>
<td>18.9</td>
<td>14.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Beam energy spread (%)</td>
<td>0.132</td>
<td>0.154</td>
<td>0.185</td>
<td>0.221</td>
</tr>
</tbody>
</table>