FCC-ee physics & experiments

*CDR plan and status*

Roberto Tenchini

INFN Pisa

See Acknowledgements for long list of people that helped for this talk, thanks!
CDR FCC-ee physics & experiments – outline

• Vol. “FCC-ee: Physics & Experiments”
  • Introduction (running plan, history, motivation, ...)
  • Electroweak physics with Z’s and W’s
  • Higgs physics
  • Top quark physics
  • QCD and $\gamma\gamma$ physics
  • Flavours
  • BSM (Physics behind precision, global fits, direct searches)
  • MDI and experimental environment
  • Polarization and beam energy measurement
  • Detector designs
  • Summary and outlook

An entire day dedicated to this subject tomorrow: this is essentially an executive summary
Physics and Experiments Studies Coordination

Physics Studies coordination
A. Blondel, P. Janot (EXP), C. Grojean, M. McCullough, J. Ellis (TH)

EW Physics with Z’s and W’s
R. Tenchini, F. Piccinini
S. Heinemeyer, A. Freitas

Higgs properties
M. Klute, K. Peters
S. Heinemeyer, A. Freitas

Top quark physics
P. Azzi (F. Blekman)
S. Heinemeyer, A. Freitas

QCD and $\gamma\gamma$ physics
D. d’Enterria
P. Skands

Flavours physics
S. Monteil
J. Kamenik

New physics
M. Pierini, C. Rogan
M. McCullough

Global Analysis
Synergies
J. Ellis

Physics software
C. Bernet, B. Hegner, C. Helsens

Online selection & DAQ
C. Leonidopoulos
E. Perez

Polarization, vs measurements
A. Blondel
J. Wenninger

MDI, Exp’tal environment
M. Boscolo
N. Bacchetta

Detector designs
A. Cattai, G. Rolandi, M. Dam

Synergies with FCC-hh physics, LC studies, LEP legacy
Joint with FCC-ee Accelerator
Adapt (to) the interaction region
Joint with FCC-ee Accelerator

Synergy with FCC-hh, LC, LHC

29 May - 2 June 2017
FCC Week, Berlin
Luminosities and centre-of mass energies

LEP record at the Z
$2.3 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$

LEP2 record
$\approx 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
Operation model assumed for the CDR

- Physics goals (see next slides)
  - 150 ab$^{-1}$ around the Z pole (~25 ab$^{-1}$ at 88 and 94 GeV, 100 ab$^{-1}$ at 91 GeV)
  - 10 ab$^{-1}$ around the WW threshold (161 GeV with ±few GeV scan)
  - 5 ab$^{-1}$ at the HZ cross section maximum (~240 GeV)
  - 1.5 ab$^{-1}$ at and above the top threshold (a fraction at ~350 GeV, the rest at ~370 GeV)

- Benchmark run plan with 2 IP and the baseline optics
  - Numbers of years are soft numbers that can be revised in view of the physics panorama at the time

<table>
<thead>
<tr>
<th>Vs (GeV)</th>
<th>Z</th>
<th>WW</th>
<th>HZ</th>
<th>top</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab$^{-1}$/year)</td>
<td>15, then 30</td>
<td>4</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Events/year</td>
<td>1.2×10$^{12}$</td>
<td>1.5×10$^{7}$</td>
<td>2.0×10$^{5}$</td>
<td>2.0×10$^{5}$</td>
</tr>
<tr>
<td>Physics goal</td>
<td>150 ab$^{-1}$</td>
<td>10 ab$^{-1}$</td>
<td>5 ab$^{-1}$</td>
<td>1.5 ab$^{-1}$</td>
</tr>
<tr>
<td>Runtime (years)</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

200 scheduled physics days per years, Hübner factor ~ 0.6
Physics opportunities at FCC-ee

(short summary, more at the dedicated session tomorrow)
The Higgs program at $\sqrt{s}=240$ and 350 GeV

Combining in an optimal way Higgstrahlung and Vector Boson Fusion at the two centre-of-mass energies

<table>
<thead>
<tr>
<th></th>
<th>FCC-ee 240 GeV</th>
<th>FCC-ee 350 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Integrated Luminosity (ab$^{-1}$)</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of Higgs bosons from $e^+e^- \rightarrow HZ$</td>
<td>1,000,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Number of Higgs bosons from fusion process</td>
<td>25,000</td>
<td>40,000</td>
</tr>
</tbody>
</table>

Talk of Markus Klute on Tuesday
Recoil mass: Higgs events are tagged decay independent

$$\sigma(ZH) \sim g_{ZZ}^2$$

Tagging of a specific channel allows the total H width to be determined:

$$\Gamma_H = \Gamma(H \rightarrow ZZ)/\text{BR}(H \rightarrow ZZ) \propto \sigma(ZH)/\text{BR}(H \rightarrow ZZ)$$
Higgs couplings precision and sensitivity

(Example from Composite Higgs Models (4HDM))

<table>
<thead>
<tr>
<th>in %</th>
<th>HL-LHC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{HZ}$</td>
<td>2-4</td>
<td>0.21</td>
</tr>
<tr>
<td>$g_{HW}$</td>
<td>2-5</td>
<td>0.43</td>
</tr>
<tr>
<td>$g_{Hb}$</td>
<td>5-7</td>
<td>0.64</td>
</tr>
<tr>
<td>$g_{Hc}$</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>$g_{Hg}$</td>
<td>3-5</td>
<td>1.2</td>
</tr>
<tr>
<td>$g_{H\tau}$</td>
<td>5-8</td>
<td>0.81</td>
</tr>
<tr>
<td>$g_{H\mu}$</td>
<td>5</td>
<td>8.8</td>
</tr>
<tr>
<td>$g_{H\gamma}$</td>
<td>2-5</td>
<td>2.1</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>5-8%</td>
<td>1.5</td>
</tr>
</tbody>
</table>

HL-LHC measurements are model dependent.

---

Example (2-4) of Higgs couplings precision and sensitivity from Composite Higgs Models (4HDM).

In the table above, the entries for HL-LHC and FCC-ee represent the percent precision for each coupling:

- $g_{HZ}$: 2-4%
- $g_{HW}$: 2-5%
- $g_{Hb}$: 5-7%
- $g_{Hc}$: 0.43%
- $g_{Hg}$: 3-5%
- $g_{H\tau}$: 5-8%
- $g_{H\mu}$: 5%
- $g_{H\gamma}$: 2-5%
- $\Gamma_H$: 5-8%

The table shows the precision in percentages for the Higgs couplings measured at HL-LHC and FCC-ee, with model-dependent results. The example demonstrates the precision levels for each coupling in the specified models.
Unique opportunity to measure the electron Yukawa coupling, highly challenging: $\sigma(ee \rightarrow H) = 1.6$ fb, further reduced to $\approx 0.3$ fb accounting for the finite energy spread and ISR of the $e^+e^-$ beams.

Requires beam “monochromatization” at 62.5 GeV

http://jacow.org/ipac2016/papers/wepmw009.pdf
Tera Z: a new scenario for precision at the Z pole

L\sim 2.8 \times 10^{36} \Rightarrow \approx 10^{12} Z events per year (total at LEP $1.7 \times 10^7$ evts)

The key for Z mass and width

continuous $E_{CM}$ calibration (resonant depolarization)
$\Delta E_{\text{beam}} \approx 10 \text{ KeV (stat)} + 100 \text{ KeV (syst)}$

Precisions on observables\(^1\)
- Z mass: $\Delta_{\text{rel}} (m_Z) \approx 10^{-6}$
- Z width: $\Delta_{\text{rel}} (\Gamma_Z) \approx 5 \times 10^{-5}$
- $R_l$ hadronic/leptonic width : $5 \times 10^{-5} \Rightarrow \Delta_{\text{rel}} \alpha_s (m_Z^2) \approx 2 \times 10^{-3}$
- electroweak mixing angle from $A_{FB}(\mu\mu)$ at pole: $\Delta_{\text{rel}} \sin^2 \theta_{\text{eff}} \approx 2 \times 10^{-5}$
- from $A_{FB}(\mu\mu)$ off peak: $\Delta_{\text{rel}} \alpha_{\text{QED}} (m_Z^2) \approx 3 \times 10^{-5}$
- invisible width : $10^{-3} N_\nu$ (from Z+photon at higher energy)

Improvement w.r.t. LEP
20
20
20
100 [just using $A_{FB}(\mu\mu)$ ]
not measured
8

\(^1\) $\Delta_{\text{rel}}$ relative
Tera Z: precision for ewk heavy flavours measurements

**tau polarization**
Polarization vs the production angle allows $A_e$ to be separated from $A_\tau$:
- $\Delta A_\tau \approx 4 (30) \times 10^{-5}$ stat (syst)
- $\Delta A_e \approx 5 (10) \times 10^{-5}$ stat (syst)

Universality test and $\sin^2 \theta_W$

**bottom and charm** couplings from FB asymmetries, $R_b, R_c$
- $\Delta A_b \approx 2 (40) \times 10^{-5}$ stat (syst)
- $\Delta A_c \approx 3 (40) \times 10^{-5}$ stat (syst)
- $\Delta R_b \approx 1 (5-20) \times 10^{-5}$ stat (syst)
- $\Delta R_c \approx 3 (50) \times 10^{-5}$ stat (syst)

Improvement w.r.t. LEP
- $\Delta A_\tau$: 10
- $\Delta A_e$: 30
- $\Delta A_b$: 5
- $\Delta A_c$: 8
- $\Delta R_b$: 3-10
- $\Delta R_c$: 6

(1) here $\Delta$ absolute precision
At LEP hadronic contributions to the vacuum polarization as external input (dispersion relations+lower energy experiments) $\Delta_{\text{rel}} \approx 10^{-4}$

**Tera Z: Direct measurement of $\alpha_{\text{QED}}(m_Z^2)$**

FCC-ee: direct measurement with better precision

$$A_{\text{FB}}^\mu = A_{\text{FB},0}^\mu + \frac{3}{4} \frac{a^2}{v^2} \frac{I}{G + Z}.$$  

Optimal centre-of-mass energies for a $3 \times 10^{-5}$ uncertainty on $\alpha_{\text{QED}}$: $\sqrt{s}_- = 87.9$ GeV and $\sqrt{s}_+ = 94.3$ GeV

Work on EWK theoretical corrections required to reach $\approx 3 \times 10^{-5}$

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>$E_{\text{beam}}$ calibration</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{beam}}$ spread</td>
<td>$&lt; 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>Acceptance and efficiency</td>
<td>negl.</td>
</tr>
<tr>
<td></td>
<td>Charge inversion</td>
<td>negl.</td>
</tr>
<tr>
<td></td>
<td>Backgrounds</td>
<td>negl.</td>
</tr>
<tr>
<td>Parametric</td>
<td>$m_Z$ and $\Gamma_Z$</td>
<td>$1 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$\sin^2 \theta_W$</td>
<td>$5 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$G_F$</td>
<td>$5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Theoretical</td>
<td>QED (ISR, FSR, IFI)</td>
<td>$&lt; 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Missing EW higher orders</td>
<td>few $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>New physics in the running</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>Systematics</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Statistics</td>
<td>$3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Intrinsic th. uncertainties on EWPO

- from the CDR draft contribution
- WG 2 write-up
- "Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee"

Conveners: A. Freitas and S. Heinemeyer; Contributors: M. Beneke et al.
see talk by S. Heinemeyer

<table>
<thead>
<tr>
<th>Quantity</th>
<th>FCC-ee</th>
<th>Current intrinsic error</th>
<th>Projected intrinsic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_W$ [MeV]</td>
<td>1−1.5$^3$</td>
<td>4 ($\alpha^2, \alpha^2 \alpha_s$)</td>
<td>1</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}$ $[10^{-5}]$</td>
<td>0.6</td>
<td>4.5 ($\alpha^3, \alpha^2 \alpha_s$)</td>
<td>1.5</td>
</tr>
<tr>
<td>$\Gamma_Z$ [MeV]</td>
<td>0.1</td>
<td>0.5 ($\alpha_{\text{GBS}}, \alpha^3, \alpha^2 \alpha_s$)</td>
<td>0.2</td>
</tr>
<tr>
<td>$R_b$ $[10^{-5}]$</td>
<td>6</td>
<td>15 ($\alpha_{\text{GBS}}, \alpha^3, \alpha^2 \alpha_s$)</td>
<td>7</td>
</tr>
<tr>
<td>$R_f$ $[10^{-3}]$</td>
<td>1</td>
<td>5 ($\alpha_{\text{GBS}}, \alpha^3, \alpha^2 \alpha_s$)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

$^3$The pure experimental precision on $M_W$ is $\sim 0.5$ MeV [3].

- with present and conceivable loop technology, the intrinsic th. uncertainties will be at the same level of the experimental errors
- new calculation methods should be introduced

see e.g. the recent review on multi-loop integrals, A. Freitas, Prog. Part. Nucl. Phys. 90 (2016) 201

See talks of Gluza, Heinemeyer and Piccinini on tuesday evening

This is mandatory work that the community should support and consider it part of the full project!
Key ingredient: transverse beam polarization provides beam energy calibration by resonant depolarization

- Low level of polarization is required (~10% is enough)
  - at Z use of wigglers at beginning of fills otherwise very long polarisation time
  - at W pair threshold comes naturally [NOTE: not available at LEP !]
  - could be used also at ee → H(126) (depending on exact M_H!)
  - not available at beam energies higher than ~90 GeV
    (but for H and top can use ee → Z γ or ee → ZZ, WW to calibrate E_CM at ~5 MeV level)

- Must be done continuously during physics fills to avoid issues encountered at LEP (Tides, TGV, etc.)
  - this is possible with single bunches and Compton polarimeter (commercial laser)
    use ‘single’ non-colliding bunches
  - must be complemented by analysis of «average E_beam» to E_CM relationship

«EPOL» working group on polarization and beam energy:
  J. Wenninger, E. Gianfelice, D. Barber, W. Hillert, A.
  Bogomyagkov, I. Kopp, N. Munchoi,
  M. Koratzinos, K. Oide, A.Blondel, et al
arXiv:1506.00933

<< 100 keV beam en. calibration around Z peak and W pair threshold.
Δm_z ~0.1 MeV, ΔΓ_z ~0.1 MeV, Δm_W ~ 0.5 MeV

See talks of Blondel and Gianfelice-Wendt on Wednesday
W mass (and width) from WW cross section

At LEP2 $\sqrt{s}=161$ GeV $\sigma=4\text{pb}$
$\varepsilon=0.75$, $\sigma_B=300$ fb
p=0.9 : $\varepsilon p\approx0.68$ (@161)
$\Rightarrow m_W=80.40\pm0.21$ GeV
with 11/pb $@E_{\text{CM}}=161$ GeV

Sensitivity to mass and width is different at different $E_{\text{CM}}$: can optimize measurement mass AND width choosing carefully two energy points. Same concept can be used to minimize systematics (e.g. due to backgrounds)

Goal: control acceptance and systematics at $10^{-4}$ level!

with $E_1=157.1$ GeV $E_2=162.3$ GeV $f=0.4$
$\Delta m_W=0.62$ $\Delta\Gamma_W=1.5$ (MeV)
\( \alpha_s \) via hadronic W decays

- Computed at \( N^{2,3}\text{LO} \):
  \[
  \Gamma_{W,\text{had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{ij}|^2 \left[ 1 + \sum_{k=1}^{4} \left( \frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha \alpha_s) \right]
  \]

- LEP: \( \Gamma_W = 1405\pm29 \text{ MeV (±2%)} \), \( BR_W = 0.6741\pm0.0027 \text{ (±0.4%)} \)

Extraction with large exp. & parametric (CKM \( V_{cs} \)) uncertainties today:

- \( a_s (M_Z) = 0.117 \pm 0.040 \text{ (±35%)} \)

- FCC-ee: – Huge W stats (\( \times 10^4 \) LEP) will lead to: \( \Delta_{\text{rel}} \alpha_s < 0.3\% \)
  – TH uncertainty: \( \Delta |V_{cs}| \) to be significantly improved (\( 10^{-4} \))

Talk of David d’Enterria on Tuesday

[D.d'Enterria, M.Srebre, PLB763(2016)465]

Can measure \( \alpha_s \) at < 0.1% uncertainty combining Z, W, tau hadronic decays and jets rates & shapes
Cross section shape depends strongly on top quark mass, width, $\alpha_s$ and $Y_t$

Top mass can then be extracted directly with a threshold scan

The threshold shape is affected by ISR and machine beam energy spread

The FCC-ee has very steep luminosity profile, enhancing size of top sample


With 200 fb-1 FCC-ee can measure top quark mass with ~10 MeV statistical accuracy
Electroweak couplings of the top quark

• Large statistics and final state polarization allow a full separation of the $ttZ/y$ couplings with **NO need for polarization in the initial state.**

• Optimal $\sqrt{s} = 365-370$ GeV

---

FCC-ee expected precision of order $10^{-2}$ to $10^{-3}$
Global ewk fit and sensitivity to new physics

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i \]

With th. + par. unc.

Jorge de Blas
LHCP 2017

EW precision

Power of loops:
In terms of weakly-coupled new physics:
\[ \Lambda_{\text{NP}} > 30 \text{ – } 100 \text{ TeV} \]

Theo. uncertainties need to be improved in the next 20 years, to match the exp. uncertainties

P. Janot, arXiv:1510.09056
D. Barducci et al, JHEP 1508 (2015) 127

ILC Physics case, arXiv:1506.05992

Precision and indirect searches for new physics

Top couplings

Extra-dim models:
Probe NP scales of O (20 TeV)

4D-CHM, \( f < 2 \text{ TeV} \)

Ex. NP models, probed by HL-LHC

EWK fit and sensitivity to new physics

Higgs couplings

6/17/2016

E.Perez

15
Example of B physics at FCC-ee - $B^0 \rightarrow K^{*0} \tau^+\tau^-$

- Persistent tensions seen in FCNC decays $b \rightarrow s \ell^+\ell^-$ w.r.t. SM / QCD, e.g. $B^0 \rightarrow K^{*0} \mu^+\mu^-$, $B^0 \rightarrow K^{*0} e^+e^-$
- A challenging channel: $B^0 \rightarrow K^{*0} \tau^+\tau^-$
- At baseline Tera Z luminosity, $10^3$ events of reconstructed signal. Angular analysis possible.
- Makes use of partial reconstruction technique to solve the kinematics of the decay. Sensitivity relies on vertexing performance (crucial)
- Another interesting and more challenging mode is $B_s \rightarrow \tau^+\tau^-$
- Also FCNC in Z decays: $Z \rightarrow \mu e, \mu\tau, e\tau$

Backgrounds (pink) and (red), signal in green. Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector.

Talk of Stephane Monteil on Tuesday
Example FCC-ee filling LHC corners: flying gauginos

- LHC experiments are searching for long-living particles. Typical example: chargino decaying to almost-degenerate neutralino

- Search limited not only by beam/statistics → difficult to probe short lifetimes in a hadronic environment

FCCee can probe the small-mass/small-lifetime scenario (motivated by naturalness for many BSM models)

Talk of Maurizio Pierini on Tuesday
Search for Sterile Neutrinos at FCC-ee

- Number of neutrino families from LEP $N_{\nu}=2.984\pm0.008$
  - potential to improve to $\pm0.001$ using $e^+e^\rightarrow Z\gamma$ (not enough statistics at LEP)
- Search for sterile neutrinos in $Z$ decays:
  - Number of events depends on mixing between $N$ and $\nu$, and $m_N$

\[ Z \rightarrow N_{\nu_i}, \text{ with } N \rightarrow W^*l \text{ or } Z^*\nu_j \]

arXiv:1411.5230

Two plots correspond to different luminosity and detector size.
Concepts for experiments at FCC-ee

(short summary, more at the dedicated session tomorrow)
Asymmetric beam crossing at the IPs
Minimize synchrotron radiation

Conservative optics:
Two IPs – Relaxed $\beta^*$
Integrated time needed twice smaller with four detectors than with two

FCC-ee baseline layout
Detector and MDI general requirements at FCC-ee

- Be suitable for high precision measurements
  → precise tracking in a low X0 tracker
- Excellent lepton id and momentum resolution
- Excellent photon id and energy/direction res.
- Precise angular (and energy) jet measurement
- Particle flow friendly
  → adequate calorimeter granularity
- High granularity vertex detector with b and c tagging capabilities

→ in a low occupancy environment maximum event rate 20 kHz @ Z peak

Two benchmarks for CDR
- new IDEA from present state-of-the-art technology
- CLIC detector revisited for FCC-ee

- Asymmetric optics with beam crossing angle of 30 mrad
- IP displaced by about 9.4 m wrt proton beam line
- Maximum magnetic field 2T (compensation)
- Beam pipe radius 15 mm
- Last quadrupole L* =2.2 m
- Detector has to “stay above” the 100 mrad line
Synchrotron radiation mainly dictates the IR design
- Defines the beam pipe radius

Mask shields the detector from direct hits
- Some photons are scattered from the tips of the mask

Proper shielding can be optimized to keep rates low
- e.g. first layer of VTX occupancy < $10^{-5}$ can be achieved

### Most unfavourable FCC-ee case (350 GeV) studied

<table>
<thead>
<tr>
<th>Source</th>
<th>CLIC 3 TeV*</th>
<th>FCC 350 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N / BX</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>$3 \times 10^5$</td>
<td>60</td>
</tr>
<tr>
<td>$P_T &gt; 20$ MeV</td>
<td></td>
<td>2600</td>
</tr>
<tr>
<td>$P_T &gt; 5$ MeV</td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>IPC</td>
<td>$6 \times 10^8$</td>
<td>0</td>
</tr>
<tr>
<td>CPC</td>
<td>$102$</td>
<td>54</td>
</tr>
<tr>
<td>hadrons</td>
<td>0.05</td>
<td>$-0.05$</td>
</tr>
<tr>
<td>Syn. rad</td>
<td>$-5 \times 10^6$</td>
<td></td>
</tr>
</tbody>
</table>

IPC=Incoherent Pair Creation
CPC=Coherent Pair Creation

Synchrotron radiation refers to photons scattered through the mask with "$>10$ keV" energy per BX per beam

For more details see talk of Y. Voutsinas on Tuesday.
Luminosity measurement

- Alternate “tight” and “loose” fiducial regions in the two luminometers to make the measurement independent from beam position
- Luminometers centered on the outgoing beams
- Current limitation on absolute luminosity precision is from low angle Bhabha scattering theoretical cross section $10^{-3}$ aim at improving it for FCC-ee to reach a combined theory+exp uncertainty $10^{-4}$
- Consider also $\gamma\gamma$ final state as a possible channel
- Challenges
  - Very fast readout (few ns)
  - Electronic not pulsed – heat dissipation
  - Maintain mechanical stability at 1 micron level
the IDEA concept

- Vertex detector, MAPS (a la ALICE)
- Ultra-light drift chamber with PID (a la MEG2)
  - $q \approx 0.04 \times 0$ up to the preshower face
- Pre-shower counter
  - defines acceptance $\approx 10-20 \, \mu\text{m} \, \text{precision}$
- Double read-out calorimetry (RD52 - DREAM)
- 2 T solenoidal magnetic field
- Possibly instrumented return yoke
- Possibly surrounded by large tracking volume ($R = 8\,\text{m}$) for very weakly coupled (long-lived) particles

Two Options: Calorimetry inside or outside coil

Talk of Mogens Dam on Tuesday
IDEA: tracking

Vertex inspired by new ALICE ITS based on MAPS technology
- Pixels $30 \times 30 \mu m^2$
- Light
  - Inner layers: $0.3\% X_0 / \text{layer}$
  - Outer layers: $1\% X_0 / \text{layer}$
- Performance:
  - Point resolution about $5 \mu m$
  - Efficiency of $100\%$
  - Extremely low fake rate hit rate

Tracker inspired by MEG2 Drift Chamber under construction

$\Delta P_T/P_T \approx 0.3\%$ at 100 GeV

Courtesy of F. Grancagnolo
IDEA: dual readout calorimeter

• As a possibility, investigating dual readout copper calorimeter of 160 cm radial depth
  • One compartment, no longitudinal segmentation
    • Longitudinal segmentation may be possible
      • $\approx 5.6 \lambda_{int}$ (coil outside option) - $\approx 8 \lambda_{int}$ (coil inside option)
  • Separate readout of scintillation and Cerenkov signal
    • $\approx 2$ GeV resolution on Higgs mass in $H \rightarrow \gamma\gamma$
    • Promising resolution also for hadrons
A CLIC-inspired detector for FCC-ee

Adapted from CLIC_SiD

- Pixel Vertex detector - pix 25x25 µm² – 0.4% $X_0$/d. layer
- Silicon Strips Tracker – 6 layers < 0.1 $X_0$ barrel
- High Granularity Calorimetry
  - ECAL silicon-tungsten – 22 $X_0$
  - HCAL barrel scintillator tiles-tungsten – 5.5 $\lambda_{int}$
  - HCAL endcap scintillator tiles-steel

STRUCTURE unchanged: Fe yoke equipped with muon chambersRPCs 30x30 mm²
CLIC-detector scaled and adapted for FCC-ee

- INNER LAYER closer to the beam pipe
- BARREL LENGTH = 250 mm
- DISKS INNER RADIUS closer to the beam pipe

Scale all the barrel layers:

<table>
<thead>
<tr>
<th>Layer</th>
<th>CLIC (mm)</th>
<th>FCC (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>31-33</td>
<td>17-19</td>
</tr>
<tr>
<td>2nd</td>
<td>44-46</td>
<td>37-39</td>
</tr>
<tr>
<td>3rd</td>
<td>58-60</td>
<td>57-59</td>
</tr>
</tbody>
</table>

*layer thickness may need to be increased to accommodate water cooling

Disks to replace spirals (no need for air flow):

<table>
<thead>
<tr>
<th>Layer</th>
<th>Disk thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>159-161</td>
</tr>
<tr>
<td>2nd</td>
<td>229-231</td>
</tr>
<tr>
<td>3rd</td>
<td>299-301</td>
</tr>
</tbody>
</table>

Support tube:

<table>
<thead>
<tr>
<th>Layer</th>
<th>CLIC (mm)</th>
<th>FCC (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inner</td>
<td>575</td>
<td>675</td>
</tr>
<tr>
<td>outer</td>
<td>600</td>
<td>700</td>
</tr>
</tbody>
</table>

*diameter to be checked for mechanical stability

OUTER BARREL RADIUS to be increased to 2.14 m to compensate for the lower B
SUMMARY, not conclusions, yet

- The FCC-ee CDR describing a vibrant program of key measurements at $e^+e^-$ centre-of-mass energies around 90, 160, 240 and 350 GeV is in preparation.
- It will include perspectives for significant progress in the realm of W, Z and Higgs boson physics, QCD, Heavy Flavours and searches for BSM physics.
- Discussions on realistic detectors and MDI considerations will be an essential part of the volume.
Acknowledgements