Future Circular Colliders

ee pp ep ... and μμ

a story of synergy and complementarity

Alain Blondel, University of Geneva&CERN

with many thanks to the FCC collaborators!

recent meetings:

FCC physics workshops
2017  https://indico.cern.ch/event/550509/
2018  https://indico.cern.ch/event/618254/

FCC week in Amsterdam
https://indico.cern.ch/event/656491/

muon collider workshop July 2018  https://indico.cern.ch/event/719240/
International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the Genevois

- **Ultimate goal:** ~16 T magnets
  - 100 TeV pp-collider (*FCC-hh*)

→ defining infrastructure requirements

**Two possible first steps:**

- **e⁺e⁻ collider (FCC-ee)**
  - High Lumi, \( E_{CM} = 90-400 \text{ GeV} \)
- **HE-LHC** 16T \( \Rightarrow \) 28 TeV in LEP/LHC tunnel

Possible addition:

- **p-e (FCC-he) option**

From what we know today: the way by FCC-ee is probably the fastest and cheapest way to 100 TeV. That combination also produces the most physics. It is the assumption in the following.

Also a good start for \( \mu \text{C!} \)

From European Strategy in 2013: “ambitious post-LHC accelerator project”
Study kicked-off in Geneva Feb 2014
SYNERGY
Present baseline position was established considering:
- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

next step: review of surface site locations and machine layout
FCC – tunnel integration in arcs

FCC-ee  
FCC-hh  
5.5 m inner diameter
CE schedule studies

- Total construction duration 7 years
- First sectors ready after 4.5 years
2 main IPs in A, G for both machines

**FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)**

Asymmetric IR for ee, limits SR to expt
The same caverns

Distance between detector cavern and service cavern 50 m.

FCC-ee detector

FCC-hh detector

Preliminary design of access and cable path
LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively: additional 10km circumference Electron Recirculating Linac ERL.

The possibility to collide FCC-ee with FCC-hh is not considered in the framework of the study.

In the case of FCC-eh it could profit from the -- then existing -- FCC-hh, and, perhaps, from considerable RF of the -- then dismantled -- FCC-ee.
COMPLEMENTARITY
Event statistics:

- **Z peak**
  - $E_{cm} : 91 \text{ GeV}$
  - $5 \times 10^{12} \text{ e+e-} \rightarrow Z$

- **WW threshold**
  - $E_{cm} : 161 \text{ GeV}$
  - $10^8 \text{ e+e-} \rightarrow \text{WW}$

- **ZH threshold**
  - $E_{cm} : 240 \text{ GeV}$
  - $10^6 \text{ e+e-} \rightarrow \text{ZH}$

- **tt threshold**
  - $E_{cm} : 350 \text{ GeV}$
  - $10^6 \text{ e+e-} \rightarrow \text{tt}$

$E_{cm}$ errors:

- LEP x $10^5$
  - 100 keV
  - 300 keV
  - Never done

- LEP x $2.10^3$
  - 1 MeV
  - Never done

- Never done

Great energy range for the heavy particles of the Standard Model.
IMPLEMENTATION AND RUN PLAN

Three sets of RF cavities for FCCee & Booster:
• Installation as LEP (≈30 CM/winter)
• high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source
• high energy (W, H, t): 400 MHz four-cell cavities, also for W machine
• booster and t machine complement: 800 MHz four-cell cavities
• Adaptable 100MW, 400MHz RF power distribution system +High efficiency

➡ Spreads the funding profile

HL-LHC

<table>
<thead>
<tr>
<th>Machine</th>
<th>RF power</th>
<th>Run Years</th>
<th>Electrons (10^13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>208 x 0.5 MW</td>
<td>4 years</td>
<td>150 ab⁻¹</td>
</tr>
<tr>
<td>W</td>
<td>64 x 0.5 MW</td>
<td>1 year</td>
<td>10 ab⁻¹</td>
</tr>
<tr>
<td>ZH thresh</td>
<td>328 x 0.1 MW</td>
<td>3 years</td>
<td>5 ab⁻¹</td>
</tr>
<tr>
<td>tt threshold + tt 365</td>
<td>80 x 0.1 MW</td>
<td>5 years</td>
<td>1.5 ab⁻¹</td>
</tr>
</tbody>
</table>

Spreads the funding profile indicative: total ~15 years

O(1/3) of the machine cost comes O(10) years after start
FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover:

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
  \( m_Z, m_W, m_{\text{top}}, \sin^2 \theta_w^{\text{eff}}, R_b, \alpha_{\text{QED}}(m_Z), \alpha_s(m_Z, m_W, m_\tau) \), Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
  -- ex FCNC (Z -> \mu\tau, e\tau) in 5 \times 10^{12} Z decays and \tau BR in 2 \times 10^{11} Z \rightarrow \tau \tau
  + flavour physics (10^{12} bb events) (B \rightarrow s \tau \tau etc.)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
  such as: Right-Handed neutrinos, Dark Photons etc...

+ an enormous amount of clean, unambiguous work on QCD (H \rightarrow gg) etc....

NB Not only a «Higgs Factory», «Z factory» and «top» are important for ‘discovery potential’

“First Look at the Physics Case of TLEP”, JHEP 1401 (2014) 164
«First look of the physics case of TLEP» (original name of FCC-ee): 442 quotes today

1. Probing TeV scale origin of neutrino mass at lepton colliders
References | BibTeX | LaTeX(US) | LaTeX(EU) | HarXiv | EndNote
ADS Abstract Service

2. Review of top and EW physics at future colliders
Published in PoS EPS-HEP2017 (2017) 471
Conference: C17-07-05 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | HarXiv | Link to PoS server | Link to Fulltext

3. Electroweak Physics at Future $e^+e^-$ Colliders
Elizabeth Loci (Saclay). On Behalf Of The Fcc Design S
Published in PoS EPS-HEP2017 (2018) 449
Conference: C17-07-05 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | HarXiv | Link to PoS server | Link to Fulltext

4. Muon g-2 and dark matter in models with vector
Enrico Maria Sessolo (NCBJ, Warsaw), Kamila Kovalska
Published in PoS EPS-HEP2017 (2017) 338
Conference: C17-07-05 Proceedings
References | BibTeX | LaTeX(US) | LaTeX(EU) | HarXiv | Link to PoS server | Link to Fulltext

Much more than a Higgs factory!

5. Higgs Physics: It ain’t over till it’s over
References | BibTeX | LaTeX(US) | LaTeX(EU) | HarXiv | EndNote
ADS Abstract Service

30/08/2018
# A sample of observables (more coming)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_z$ (MeV)</td>
<td>Lineshape</td>
<td>91187.5 ± 2.1</td>
<td>0.005</td>
<td>&lt; 0.1</td>
<td>QED corr.</td>
</tr>
<tr>
<td>$\Gamma_z$ (MeV)</td>
<td>Lineshape</td>
<td>2495.2 ± 2.3</td>
<td>0.008</td>
<td>&lt; 0.1</td>
<td>QED / EW</td>
</tr>
<tr>
<td>$R_l$</td>
<td>Peak</td>
<td>20.767 ± 0.025</td>
<td>0.001</td>
<td>&lt; 0.001</td>
<td>Statistics</td>
</tr>
<tr>
<td>$R_b$</td>
<td>Peak</td>
<td>0.21629 ± 0.00066</td>
<td>0.000003</td>
<td>&lt; 0.00006</td>
<td>$g \to bb$</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>Peak</td>
<td>2.984 ± 0.008</td>
<td>0.00004</td>
<td>&lt; 0.004</td>
<td>Lumi meast</td>
</tr>
<tr>
<td>$\sin^2\theta_W^{\text{eff}}$</td>
<td>$A_{FB}^{\mu\mu}$ (peak)</td>
<td>0.23148 ± 0.00016</td>
<td>0.000003</td>
<td>&lt; 0.000005*</td>
<td>Beam energy</td>
</tr>
<tr>
<td>$1/\alpha_{\text{QED}}(m_Z)$</td>
<td>$A_{FB}^{\mu\mu}$ (off-peak)</td>
<td>128.952 ± 0.014</td>
<td>0.004</td>
<td>&lt; 0.004</td>
<td>QED / EW</td>
</tr>
<tr>
<td>$\alpha_s(m_Z)$</td>
<td>$R_l$</td>
<td>0.1196 ± 0.0030</td>
<td>0.00001</td>
<td>&lt; 0.0002</td>
<td>New Physics</td>
</tr>
<tr>
<td>$m_w$ (MeV)</td>
<td>Threshold scan</td>
<td>80385 ± 15</td>
<td>0.6</td>
<td>&lt; 0.6</td>
<td>EW Corr.</td>
</tr>
<tr>
<td>$\Gamma_w$ (MeV)</td>
<td>Threshold scan</td>
<td>2085 ± 42</td>
<td>1.5</td>
<td>&lt; 1.5</td>
<td>EW Corr.</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>$e^+ e^- \to \gamma Z, Z \to \nu \nu, l\bar{l}$</td>
<td>2.92 ± 0.05</td>
<td>0.001</td>
<td>&lt; 0.001</td>
<td>?</td>
</tr>
<tr>
<td>$\alpha_s(m_w)$</td>
<td>$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W$</td>
<td>$B_{\text{had}} = 67.41 ± 0.27$</td>
<td>0.00018</td>
<td>&lt; 0.0001</td>
<td>CKM Matrix</td>
</tr>
<tr>
<td>$m_{\text{top}}$ (MeV)</td>
<td>Threshold scan</td>
<td>173340 ± 700 ± 500</td>
<td>20</td>
<td>&lt;40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>$\Gamma_{\text{top}}$ (MeV)</td>
<td>Threshold scan</td>
<td>?</td>
<td>40</td>
<td>&lt;40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>$\lambda_{\text{top}}$</td>
<td>Threshold scan</td>
<td>$\mu = 1.2 \pm 0.3$</td>
<td>0.08</td>
<td>&lt; 0.05</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>ttZ couplings</td>
<td>$\sqrt{s} = 365 \text{ GeV}$</td>
<td>~30%</td>
<td>~2%</td>
<td>&lt;2%</td>
<td>QCD corr</td>
</tr>
</tbody>
</table>

* work to do: check if we cant improve
HIGGS FACTORY

Higgs provides a very good reason why we need a lepton (e+e- or μμ) collider
several tens of Million Higgs already produced... > than most Higgs factory projects.

\[ \sigma_{i \rightarrow f}^{\text{observed}} \propto \sigma_{\text{prod}} \left( g_{Hi} \right)^2 \left( g_{Hf} \right)^2 \frac{1}{\Gamma_H} \]

relative error scales with 1/purity and 1/\sqrt{\text{efficiency}} of signal

difficult to extract the couplings because \( \sigma_{\text{prod}} \) uncertain and \( \Gamma_H \) is unknown (invisible channels) \( \Rightarrow \) must do physics with ratios.
“higgstrahlung” process close to threshold

Production xsection has a maximum at near threshold \( \sim 200 \text{ fb} \)

\[ 10^{34}/\text{cm}^2/\text{s} \rightarrow 20'000 \text{ HZ events per year.} \]

For a Higgs of 125GeV, a centre of mass energy of 240-250 GeV is optimal

\( \Rightarrow \) kinematical constraint near threshold for high precision in mass, width, selection purity

\( Z \rightarrow \text{tagging by missing mass} \)
e+e- : Z – tagging by missing mass

total rate \propto g_{HZZ}^2

ZZZ final state \propto g_{HZZ}^4 / \Gamma_H

\Rightarrow \text{measure total width} \quad \Gamma_H

g_{HZZ} \text{ to } \pm0.2\% \text{ and many other partial widths}
empty recoil = invisible width
‘funny recoil’ = exotic Higgs decay
easy control below threshold

![Graph showing event distribution and m_{Recoil} comparison]
Higgs self-coupling $\lambda_H$ (How H, W, Z get masses...)

The FCC-ee does not produce pairs of Higgses from which one can extract $\lambda_H$ but the ZH cross-section receives a $E_{cm}$-dependent correction from it.

- $\sqrt{s}$ dependence of the “effective” $g_{HZ}$ and $g_{HW}$ to the Higgs self-coupling
  - Accessible from the high-precision runs at 240, (350), and 365 GeV
  - Arising from Higgs-triangle and -loop diagrams

- Higgs self-coupling precision at FCC-ee: ~40%
  - Improved to ~20% if $g_{HZ}$ is fixed to its SM value
- Unique FCC-ee synergy between the runs at 240 and 365 GeV
  - Calls for the highest luminosity (4IP’s? Longer runs?)

investigating now: the possibility of reaching $5\sigma$ observation of Higgs self-coupling at FCC-ee:
4 detectors
+ recast of running scenario
First generation couplings

- s-channel Higgs production
  - Unique opportunity for measurement close to SM sensitivity
  - Highly challenging; $\sigma(ee\rightarrow H) = 1.6 \text{fb}$; 7 Higgs decay channels studied

\[ L = 10 \text{ ab}^{-1} \]
\[ \kappa_\epsilon < 2.2 \text{ at } 3\sigma \]

- Work in progress
  - How large are loop induced corrections? How large are BSM effects?
  - Do we need an energy scan to find the Higgs?
  - How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?
## Result of the coupling (a.k.a. $\kappa$) fit

- **Comparison**\(^(*)\) with other lepton colliders at the EW scale (up to 380 GeV)

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ Coll(_{250})</th>
<th>ILC(_{250})</th>
<th>CLIC(_{380})</th>
<th>LEP(<em>{3</em>{240}})</th>
<th>CEPC(_{250})</th>
<th>FCC-ee(_{240})</th>
<th>FCC-ee(_{340})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Years</strong></td>
<td>6</td>
<td>15</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>3</td>
<td>+4</td>
</tr>
<tr>
<td><strong>Lumi (ab(^{-1}))</strong></td>
<td>0.005</td>
<td>2</td>
<td>0.5</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>+1.5</td>
</tr>
<tr>
<td><strong>$\delta m_H$ (MeV)</strong></td>
<td>0.1</td>
<td>t.b.a.</td>
<td>110</td>
<td>10</td>
<td>5</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td><strong>$\delta \Gamma_H / \Gamma_H$ (%)</strong></td>
<td>6.1</td>
<td>3.8</td>
<td>6.3</td>
<td>3.7</td>
<td>2.6</td>
<td>2.8</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>$\delta g_{Hb} / g_{Hb}$ (%)</strong></td>
<td>3.8</td>
<td>1.8</td>
<td>2.8</td>
<td>1.8</td>
<td>1.3</td>
<td>1.4</td>
<td>0.70</td>
</tr>
<tr>
<td><strong>$\delta g_{HW} / g_{HW}$ (%)</strong></td>
<td>3.9</td>
<td>1.7</td>
<td>1.3</td>
<td>1.7</td>
<td>1.2</td>
<td>1.3</td>
<td>0.47</td>
</tr>
<tr>
<td><strong>$\delta g_{Ht} / g_{Ht}$ (%)</strong></td>
<td>6.2</td>
<td>1.9</td>
<td>4.2</td>
<td>1.9</td>
<td>1.4</td>
<td>1.4</td>
<td>0.82</td>
</tr>
<tr>
<td><strong>$\delta g_{Hy} / g_{Hy}$ (%)</strong></td>
<td>n.a.</td>
<td>6.4</td>
<td>n.a.</td>
<td>6.1</td>
<td>4.7</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>$\delta g_{Ht} / g_{Ht}$ (%)</strong></td>
<td>3.6</td>
<td>13</td>
<td>n.a.</td>
<td>12</td>
<td>6.2</td>
<td>9.6</td>
<td>8.6</td>
</tr>
<tr>
<td><strong>$\delta g_{Hz} / g_{Hz}$ (%)</strong></td>
<td>n.a.</td>
<td>0.35</td>
<td>0.80</td>
<td>0.32</td>
<td>0.25</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>$\delta g_{Hc} / g_{Hc}$ (%)</strong></td>
<td>n.a.</td>
<td>2.3</td>
<td>6.8</td>
<td>2.3</td>
<td>1.8</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>$\delta g_{Hg} / g_{Hg}$ (%)</strong></td>
<td>n.a.</td>
<td>2.2</td>
<td>3.8</td>
<td>2.1</td>
<td>1.4</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>$B_{\text{invis}}$ (%(^{95%CL}))</td>
<td>SM</td>
<td>&lt;0.3</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
<td>&lt;0.15</td>
<td>&lt;0.3</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>$BR_{\text{EXO}}$ (%(^{95%CL}))</td>
<td>–</td>
<td>&lt;1.8</td>
<td>&lt;3.0</td>
<td>&lt;1.6</td>
<td>&lt;1.2</td>
<td>&lt;1.2</td>
<td>&lt;1.1</td>
</tr>
</tbody>
</table>

\(^(*)\) Green = best, Red = worst
Conclusion from Precision Calculations Mini-Workshop in January 2018:
The necessary theoretical work is doable in 5-10 years perspective, due to steady progress in methods and tools, including the recent completion of NNLO SM corrections to EWPOS. This statement is conditional to a strong support by the funding agencies and the overall community. Appropriate financial support and training programs for these precision calculations are mandatory.

Several EFTs will achieve sensitivity exceeding 50 TeV (decoupling physics!) junction with FCC-hh EFTs under progress by Jorge de Blas.
### Hadron collider parameters ($pp$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>(HL) LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision energy (GeV)</td>
<td>100</td>
<td>27</td>
<td>14</td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>16</td>
<td>16</td>
<td>8.3</td>
</tr>
<tr>
<td>Circumference (km)</td>
<td>100</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Beam current (A)</td>
<td>0.5</td>
<td>1.12</td>
<td>(1.12) 0.58</td>
</tr>
<tr>
<td>Bunch intensity ($10^{11}$)</td>
<td>1 (0.5)</td>
<td>2.2</td>
<td>(2.2) 1.15</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>25 (12.5)</td>
<td>25 (12.5)</td>
<td>25</td>
</tr>
<tr>
<td>Norm. emittance ($\gamma \varepsilon_{x,y}$) ($\mu$m)</td>
<td>2.2 (1.1)</td>
<td>2.5 (1.25)</td>
<td>(2.5) 3.75</td>
</tr>
<tr>
<td>IP $\beta^*_{x,y}$ (m)</td>
<td>1.1</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>Luminosity/IP ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>5</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>Peak events / bunch Xing</td>
<td>170</td>
<td>1000 (500)</td>
<td>800 (400)</td>
</tr>
<tr>
<td>Stored energy / beam (GJ)</td>
<td>8.4</td>
<td>1.4</td>
<td>(0.7) 0.36</td>
</tr>
<tr>
<td>SR power / beam (kW)</td>
<td>2400</td>
<td>100</td>
<td>(7.3) 3.6</td>
</tr>
<tr>
<td>Transv. emit. damping time (h)</td>
<td>1.1</td>
<td>3.6</td>
<td>25.8</td>
</tr>
<tr>
<td>Initial proton burn off time (h)</td>
<td>17.0</td>
<td>3.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>
FCC-hh discovery potential

Highlights

FCC-hh is a HUGE discovery machine (if nature ...), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy → a big step in high mass reach!
  ex: strongly coupled new particle up to >30 TeV
  Excited quarks, Z’, W’, up to ~tens of TeV
  Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV
  Sensitivity to high energy phenomena in e.g. WW scattering

-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks
  -- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu$, $\tau\tau ZZ$, $ttH/\bar{ttZ}$ @<% level
  -- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
  -- detection of rare decays $H \rightarrow V\gamma$ ($V = \rho, \phi, J/\psi, \gamma, Z...$)
  -- search for invisibles (DM searches, RH neutrinos in W decays)
  -- renewed interest for long lived (very weakly coupled) particles.
  -- rich top and HF physics program

-- Cleaner signals for high Pt physics
  -- allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)
Physics at a 100 TeV pp collider: CERN Yellow Report (2017) no.3

3) Beyond the Standard Model phenomena: https://arxiv.org/abs/1606.00947
4) Heavy ions at the Future Circular Collider: https://arxiv.org/abs/1605.01389

Now proceeding to ascertain these cross-section calculations with real detector and simulations...
**SM Higgs: event rates at 100 TeV**

<table>
<thead>
<tr>
<th></th>
<th>gg→H</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>ttH</th>
<th>HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{100}$</td>
<td>$24 \times 10^9$</td>
<td>$2.1 \times 10^9$</td>
<td>$4.6 \times 10^8$</td>
<td>$3.3 \times 10^8$</td>
<td>$9.6 \times 10^8$</td>
<td>$3.6 \times 10^7$</td>
</tr>
<tr>
<td>$N_{100}/N_{14}$</td>
<td>180</td>
<td>170</td>
<td>100</td>
<td>110</td>
<td>530</td>
<td>390</td>
</tr>
</tbody>
</table>

$N_{100} = \sigma_{100\text{TeV}} \times 30\ \text{ab}^{-1}$

$N_{14} = \sigma_{14\text{TeV}} \times 3\ \text{ab}^{-1}$
For rare decays ($\mu\mu$, $\gamma\gamma$, $\gamma Z$) normalize to $H \rightarrow ZZ$ well measured at FCC-ee.

\[
\frac{\delta \text{BR}(H \rightarrow \mu\mu)}{\text{BR}(H \rightarrow 4\mu)} (%) \\
\frac{\delta \text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow 2\mu 2\gamma)} (%) \\
\frac{\delta \text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow 2\mu)} (%)
\]

Normalize to BR(4l) from ee at 1% level => absolute sub-% for couplings.

M. Selvaggi
Top Yukawa coupling from $\sigma(ttH)/\sigma(ttZ)$

To the extent that the $qq\overline{q} \rightarrow ttZ/H$ contributions are subdominant:

- Identical production dynamics:
  - correlated QCD corrections, correlated scale dependence
  - correlated $\alpha_s$ systematics

- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:
  - correlated PDF systematics
  - correlated $m_{top}$ systematics

For a given $y_{top}$, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

- $\delta y_t (\text{stat} + \text{syst}_T H) \sim 1\%$
To reach a precision on $\lambda_H$ at the few percent level requires a linear collider of at least 3TeV (ILC 500 GeV can obtain a $\pm 30\%$ indication and CLIC 3TeV estimate is $\pm 10\%$)
PHYSICS COMPLEMENTARITY

Some examples

Higgs Physics -- $ee \rightarrow ZH$ fixes Higgs width and HZZ coupling, (and many others)
-- FCC-hh gives huge statistics of HH events for Higgs self-coupling and ttH and rare decays, including invisible.

Search for Heavy Physics
-- $ee$ gives precision measurements ($m_Z, m_W$ to < 0.6 MeV, $m_{top}$ 10 MeV, etc...) sensitive to heavy physics up to ... 100 TeV (for weak couplings)
-- FCC-hh gives access to direct observation at unprecedented energies
  Also huge statistics of $Z,W,H$ and top $\rightarrow$ rare decays

QCD
-- $ee$ gives $\alpha_s \pm 0.0002$ ($R_{had}$ at Z, W and taus)
  also $H \rightarrow gg$ events (gluon fragmentation!)
-- $ep$ provides structure functions and $\alpha_s \pm 0.0002$
-- all this improves the signal and background predictions for new physics signals at FCC-hh

Heavy Neutrinos -- $ee$: very powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive
  NB this is very much work in progress!!
### Higgs couplings $g_{Hxx}$ precisions

hh, eh precisions assume SM or ee measurements
FCC-hh : $H \rightarrow ZZ$ to serve as cross-normalization

<table>
<thead>
<tr>
<th>$g_{Hxx}$</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.22%</td>
<td>&lt;1%</td>
<td>*</td>
</tr>
<tr>
<td>WW</td>
<td>0.47%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>1.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>4.2%</td>
<td>&lt;1%</td>
<td></td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>--</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td>13%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>bb</td>
<td>0.7%</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>0.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cc</td>
<td>0.7%</td>
<td></td>
<td>1.8%</td>
</tr>
<tr>
<td>gg</td>
<td>1.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>8.6%</td>
<td>1-2%</td>
<td></td>
</tr>
<tr>
<td>uu,dd</td>
<td>$H \rightarrow \rho\gamma?$</td>
<td>$H \rightarrow \rho\gamma?$</td>
<td></td>
</tr>
<tr>
<td>ss</td>
<td>$H \rightarrow \phi\gamma?$</td>
<td>$H \rightarrow \phi\gamma?$</td>
<td></td>
</tr>
<tr>
<td>ee</td>
<td>ee $\rightarrow H$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH</td>
<td>40%</td>
<td>~3-5%</td>
<td>20%</td>
</tr>
<tr>
<td>inv, exo</td>
<td>&lt;0.55%</td>
<td>$10^{-3}$</td>
<td>5%</td>
</tr>
</tbody>
</table>

#### for ttH, combination of ±4% (model dependent) HL-LHC with FCC-ee will lead to ttH coupling to ± 3%...
model independent!

#### for $g_{HHH}$ investigating now : the possibility of reaching 5σ observation at FCC-ee:
4 detectors + recast of running scenario
Supersymmetry

In supersymmetry top partner is “stop squark”.

**FCC-ee**
Coloured and charged, stops modify Higgs couplings:

**FCC-hh**
And show up directly at hadron colliders:

FCC-ee: Indirect, but more “spectrum independent”, for a model.
FCC-hh: Direct confirmation, but direct might be hidden.
Very rare events
Simulation of heavy neutrino decay in a FCC-ee detector
Another example of Synergy and complementarity while ee covers a large part of space very cleanly, its either ‘white’ in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - FCC-hh: LFV signatures and displaced vertex search
  - FCC-eh: LFV signatures and displaced vertex search
  - FCC-ee: Indirect search via EWPO and displaced vertex search

**Summary**

**EWPO sensitivity up to very high mass scales**

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

FCC-hh able to test all flavour combinations.

Detailed study required for all FCCs – especially FCC-hh to understand feasibility at all
-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology. **The CDR is on its way**

-- Both FCC-ee and FCC-hh have outstanding physics cases
  -- each in their own right
  -- the sequential implementation of FCC-ee, FCC-hh, FCC-eh maximises the physics reach

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the **synergies and complementarities**.

**FCC (ee) could start seamlessly at the end of HL-LHC**
Did these people know that we would be running HL-LHC in that tunnel >60 years later?

Let’s not be SHY!
FCC-\(\mu\mu\) (?)

20 TeV with leptons?
Muon Collider Workshop 2018

1-3 July 2018
Università di Padova - Orto Botanico

Muon collider workshop July 2018  [https://indico.cern.ch/event/719240/]
Muons have advantages:

-- synchrotron radiation and beamstrahlung are reduced by a factor \((m_\mu/m_e)^2\)

solution for high energy circular lepton collider

-- coupling to Higgs is also 40000 higher than ee-

\(\rightarrow\) a s-channel Higgs factory

-- decay \(\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu\) and CC.

Unique source of high energy \(\nu_e\)

-- pristine energy calibration from spin precession

led to a unified concept for muon storage rings based on a step-wise program.

main issues:

-- produce \(10^{14}\) muons/second with low emittance

-- muons decay \(\rightarrow\) fast fast fast ! + neutrino radiation
Neutrino Factory (NuMAX)

Muon Collider

Proton Driver
- SC Linac
- Accumulator
- Buncher

Front End
- MW-Class Target
- Capture Sol.
- Decay Channel
- Buncher
- Phase Rotator

Cooling
- Initial 6D Cooling
- Charge Separator
- 6D Cooling
- Bunch
- Merge
- 6D Cooling
- Final Cooling

Acceleration
- 0.2–1 GeV
- 1–5 GeV
- 5 GeV

μ Storage Ring
- μ⁻ → ν
- μ⁺ → ν
- 281 m

Factory Goal: $10^{21} \mu^+ \& \mu^-$ per year within the accelerator acceptance

Collider Goals: 126 GeV ⇔ ~14,000 Higgs/yr
Multi-TeV ⇔ Lumi > $10^{34}$ cm$^{-2}$ s$^{-1}$

Low EMittance Muon Accelerator (LEMMMA):
- $10^{11} \mu^+ \& \mu^-$ pairs/sec from $e^+e^-$ interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Accelerators: Single-Pass Linacs

Positron Linac
- Positron Linac
- Positron Ring
- 100 kW target
- Isochronous Rings

Acceleration
- Accelerators: Linacs, RLA or FFAG, RCS
- $E_{\text{CoM}}$: 10s of TeV

Collider Ring
- Higgs Factory to ~10 TeV
- $E_{\text{CoM}}$:
Lepton Colliders All IP Luminosities

Lepton Collider Technology for largest Luminosity:
- Low energy range (0-400 GeV): Circular colliders
- Medium energy range (400-2000GeV): Linear Colliders
- High energy range (Multi-TeV): Muon Colliders
  - > 2.5 TeV for 100% momentum spread
  - > 1.5 TeV for 1% momentum spread
Lepton Colliders

Σ IP Luminosity in HIGGS energy range

for Higgs and top studies → FCC-ee
**Affordable?**

- according to Shiltsev cost model (JINST 9 T07002 (2014)):

\[
TPC \approx \alpha \left( \frac{L}{10 \text{ km}} \right)^{\frac{1}{2}} + \beta \left( \frac{E_{cm}}{1 \text{ TeV}} \right)^{\frac{1}{2}} + \gamma \left( \frac{P}{100 \text{ MW}} \right)^{\frac{1}{2}}
\]

- \(\alpha \leq 2 \text{ B\$ for civil construction,}\)
- \(\beta \leq 1, 2 \text{ or 10 B\$ for NC, SC magnets or SRF}\)
- \(\gamma \approx 2 \text{ B\$ wall plug power}\)

- \(\sim 9 \text{ G\$}\)
  - after \(\sim 3 \text{ G\$ savings from using exiting tunnel(s)}\)

NB above numbers are based on scaling laws, not the official FCC costs!

Total project cost include salaries that would not be included in European cost.
E.g., CLIC 380 is about 7BCHF.
Key Feasibility Issues

- Proton Driver: High Power Target Station, Capture Solenoid, Energy Deposition
- Target: RF in Magnetic Fields ✓✓
- Front End: Magnet Needs (Nb₃Sn vs HTS) ✓
- Cooling: Performance ✓
- Acceleration: Acceptance (NF)
- Collider Ring: >400 Hz AC Magnets (MC)
- Collider MDI: IR Magnet Strengths/Apertures
- Collider Detector: SC Magnet Heat Loads (μ decay), Backgrounds (μ decay)
High Power Target

- MERIT Expt:
  - LHg Jet in 15T
  - Capability: 8MW @70Hz
- MAP Staging aims at 1-2 MW → C Target
- Improved Compact Taper Design

- this in principle can work, but requires an infrastructure based on a 4MW proton beam with a sharp time structure (4 Hz and ns second bunches) which is very different from what we can have e.g. ESS in Lund.
  → additional accumulator and buncher for high power operation.

  → The target station itself is similar to a high power spallation source
    + high magnetic field
    + muons must escape (open geometry)
    + acute radiation and target recycling issues.

  → try something cleaner?
LEMMA

It has been proposed (already in 2001/9) that one could produce muons from 
\( e^+ e^- \rightarrow \mu^+ \mu^- \) annihilation at threshold.
a beam of 43.5 GeV positrons hits a target rich in electrons (hydrogen, beryllium...)

Advantages:
-- much cleaner process.
-- produces muons at 21 GeV/c with small momentum spread and emittance
-- small initial size \( \rightarrow \) phase rotation and cooling might be unnecessary
-- \( 10^{11} \) muons are enough for high energy > TeV \( \mu^+ \mu^- \) collider
  \( \rightarrow \) this pushes the limit of radiation from neutrino up to >20 TeV Ecm

Difficulties:
-- requires many positrons \( (10^{19} \text{ e+ on target per second}) \)
-- issues with accumulation and bunching of muons

**LEMMA concept was proposed at Snowmass 2013 by M. Antonelli and P. Raimondi:**
Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

MAP design for a 6 TeV MC (500 m depth)

Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

Muon rate:
- p on target option: \(3 \times 10^{13} \mu/s\)
- e\(^+\) on target option: \(9 \times 10^{10} \mu/s\)

Neutrino dose equivalent/fluence


Annual Dose equivalent (mSv)

Collider energy (TeV)

M. Boscolo, Padova, 2 July 2018

Alain Blondel The FCCs
Muon collider at 6 TeV com energy

Values considered for this table:
- $\mu^+\mu^-$ rate = $0.9 \times 10^{11}$ Hz
- $\varepsilon_N = 40$ nm (as ultimate goal)
- 3 mm Beryllium target

Comparison with MAP:

<table>
<thead>
<tr>
<th>Muon source</th>
<th>Rate $\mu$/s</th>
<th>$\varepsilon_{norm}$ $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAP</td>
<td>$10^{13}$</td>
<td>25</td>
</tr>
<tr>
<td>LEMMA</td>
<td>$0.9 \times 10^{11}$</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Same L thanks to lower $\beta^*$ (nanobeam scheme)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LEMMA-6 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>Tev</td>
<td>3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>$5.1 \times 10^{34}$</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
<td>6</td>
</tr>
<tr>
<td>Bending field</td>
<td>T</td>
<td>15</td>
</tr>
<tr>
<td>N particles/bunch</td>
<td>#</td>
<td>$6 \times 10^9$</td>
</tr>
<tr>
<td>N bunches</td>
<td>#</td>
<td>1</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>0.048</td>
</tr>
<tr>
<td>Emittance x,y</td>
<td>m-rad</td>
<td>$1.4 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\beta_{x,y}$ @IP</td>
<td>mm</td>
<td>0.2</td>
</tr>
<tr>
<td>$\sigma_{x,y}$ @IP</td>
<td>m</td>
<td>$1.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\sigma_{x,y'}$ @IP</td>
<td>rad</td>
<td>$8.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>Bunch length</td>
<td>mm</td>
<td>0.1</td>
</tr>
<tr>
<td>Turns before decay</td>
<td>#</td>
<td>3114</td>
</tr>
<tr>
<td>Muon lifetime</td>
<td>ms</td>
<td>60</td>
</tr>
</tbody>
</table>
Activities on high-energy muon collider

MOPMF072, IPAC18, V. Shiltzev, D. Neuffer

MOPMF065, IPAC18, F. Zimmermann
Producing enough e+ is a real problem.
NB it is already one of the luminosity limitations of the ILC

Novel methods are needed.

**proposal (Zimmermann)**
produce large number of positrons from gamma-factory principle
-- backscattering of photons on LHC protons
  → large number of positrons
damping + acceleration of postitrons in FCC-ee booster
  -- production of mu+mu- at threshold.

this is the scheme that comes closest to the required performance (on paper)
## staged approach: FCC-ee → FCC-hh → FCC-μμ?

<table>
<thead>
<tr>
<th>scheme</th>
<th>p-γ</th>
<th>G-F μ</th>
<th>e+ annih.</th>
<th>G-F e+ &amp; e+ annhil.</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td>LHC/FCC-hh</td>
<td>LHC/FCC-hh</td>
<td>FCC-ee</td>
<td>FCC-ee &amp; FCC-ee</td>
</tr>
<tr>
<td>rate $\dot{N}_\mu$ [GHz]</td>
<td>1</td>
<td>400</td>
<td>0.003</td>
<td>100</td>
</tr>
<tr>
<td>μ per pulse</td>
<td>100</td>
<td>$4\times10^4$</td>
<td>$2\times10^3$</td>
<td>$6\times10^7$</td>
</tr>
<tr>
<td>pulse spacing [ns]</td>
<td>100</td>
<td>100</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>energy [GeV]</td>
<td>2.5</td>
<td>0.1</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>rms energy spread</td>
<td>3%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>norm. emittance [μm]</td>
<td>7</td>
<td>2000</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>$\dot{N}_\mu / \varepsilon_N \ [10^{15} \text{ m}^{-1}\text{s}^{-1}]$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td><strong>3,000</strong></td>
</tr>
</tbody>
</table>
100 TeV $\mu$ collider FCC-$\mu\mu$ with FCC-hh PSI $e^+$ & FCC-ee $\mu^\pm$ production
The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology. The CDR is on its way.

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       maximises the physics reach

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.
FCC (ee) could start seamlessly at the end of HL-LHC

A muon collider in the SPS (~3 TeV) LHC (~10 TeV) or FCC (> 20 TeV) exploiting the e+ production in a gamma factory + FCC-ee accelerator and storage ring could extend the facility to very high energy lepton collisions
(This is the very beginning !)