Physics at the FCCs

*a story of synergy and complementarity*

see recent meetings:
FCC physics workshops
2017  [https://indico.cern.ch/event/550509/](https://indico.cern.ch/event/550509/)
2018  [https://indico.cern.ch/event/618254/](https://indico.cern.ch/event/618254/)
FCC week in Amsterdam
[https://indico.cern.ch/event/656491/](https://indico.cern.ch/event/656491/)

Alain Blondel, University of Geneva
with many thanks to the FCC collaborators!
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, \(E_{CM} = 90-400\) GeV

- \(HE-LHC\) 16T ⇒ 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 \(\mu C!\)

From European Strategy in 2013: “ambitious post-LHC accelerator project” Study kicked-off in Geneva Feb 2014
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

Sharing the same tunnel
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
common layouts for hh & ee

2 main IPs in A, G for both machines

Max. separation of 3(4) rings is about 12 m:
- wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

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

Asymmetric IR for ee, limits SR to expt

Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.
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.
Event statistics:

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

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

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

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

**E_{cm} errors:**
- LEP x $10^5$
  - 100 keV
  - 300 keV
  - 1 MeV
  - Never done

- LEP x 2.10^3
  - 2 MeV
  - 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

machine 208 x 0.5 MW
booster 20 x 0.1 MW
RF power 328 x 0.1 MW
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 \((Z \rightarrow \mu\tau, e\tau)\) in \(5 \times 10^{12}\) Z decays and \(\tau\) BR in \(2 \times 10^{11}\) \(Z \rightarrow \tau\tau\)
  + flavour physics \((10^{12} \text{ bb events})\) \(\text{(B} \rightarrow \text{s} \tau\tau \text{ etc..)}\)

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
Much more than a Higgs factory!
A sample of observables (more coming)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<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 meas</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>0.000001</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>$e^+e^- \to \gamma Z, Z \to \nu \nu, ll$</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>$\mu = 1.2 ± 0.3$</td>
<td>0.08</td>
<td>&lt; 0.05</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>ttZ couplings</td>
<td>Threshold scan</td>
<td>$\sqrt{s} = 365 \text{ GeV}$</td>
<td>$\sim 30%$</td>
<td>$\sim 2%$</td>
<td>&lt; 2%</td>
</tr>
</tbody>
</table>

* work to do: check if we can 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.

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

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.

THE LHC is a Higgs Factory...BUT
Higgs production mechanism

“higgstrahlung” process close to threshold
Production xsection has a maximum at near threshold ~200 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
e+e- : $Z$ – tagging by missing mass

**Diagram:**
- $e^+$, $e^-$, $H$, $Z^*$, $Z$

**Text:**
- Total rate: $\propto g_{HZZ}^2$
- ZZZ final state: $\propto g_{HZZ}^4/\Gamma_H$
- Measure total width: $\Gamma_H$

$g_{HZZ}$ to ±0.2% and many other partial widths
- Empty recoil = invisible width
- ‘Funny recoil’ = exotic Higgs decay
- Easy control below threshold

**Graph:**
- Events/1 GeV
- $m_{Recoil}$ (GeV)
- $5 \text{ ab}^{-1}$
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: $\sim 40\%$
- Improved to $\sim 20\%$ 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; $\sigma(\text{ee} \rightarrow \text{H}) = 1.6 \text{fb}$; 7 Higgs decay channels studied

![Graph showing coupling vs mass](image)

- **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?

**Preliminary Results**

$L = 10 \text{ ab}^{-1}$

$\kappa_e < 2.2$ at 3σ
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$_{125}$</th>
<th>ILC$_{250}$</th>
<th>CLIC$_{380}$</th>
<th>LEP$_{3240}$</th>
<th>CEPC$_{250}$</th>
<th>FCC-ee$_{240}$</th>
<th>FCC-ee$_{365}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years</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>Lumi (ab$^{-1}$)</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>$\delta m_H$ (MeV)</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>$\delta \Gamma_H / \Gamma_H$ (%)</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>$\delta g_{Hb} / g_{Hb}$ (%)</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>$\delta g_{HW} / g_{HW}$ (%)</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>$\delta g_{Ht} / g_{Ht}$ (%)</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>$\delta g_{Hy} / g_{Hy}$ (%)</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>$\delta g_{Ht} / g_{Ht}$ (%)</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>$\delta g_{Hz} / g_{Hz}$ (%)</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>$\delta g_{Hc} / g_{Hc}$ (%)</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>$\delta g_{Hg} / g_{Hg}$ (%)</td>
<td>n.a.</td>
<td>2.1</td>
<td>3.8</td>
<td>2.1</td>
<td>1.4</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>$B_{\text{inv}}$ (%)$_{95%CL}$</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>$B_{\text{EXO}}$ (%)$_{95%CL}$</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>

Patrick Janot

Higgs properties @ Circular Lepton Colliders

1 June 2018

(*) 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
100 TeV
# 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 cms [TeV]</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 $\gamma e_{x,y}$ [µm]</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 (0.15) 0.55</td>
</tr>
<tr>
<td>Luminosity/IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>5</td>
<td>30</td>
<td>28 (5) 1</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 (15) 40</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** $\Rightarrow$ a big step in high mass reach!

  ex: strongly coupled new particle up to $>30$ TeV

  Excited quarks, $Z'$, $W'$, up to $\sim$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. $\gamma\gamma/\mu\mu$, $\tau\tau/ZZ$, $ttH/ttZ @<\%$ level

  -- Precise determination of triple Higgs coupling ($\sim3\%$ level) and quartic Higgs coupling

  -- detection of rare decays $H \rightarrow V\gamma$ ($V=\rho,\phi,J/\psi,\Upsilon,Z...$)

  -- **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


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><strong>$N_{100}$</strong></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><strong>$N_{100}/N_{14}$</strong></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.

Normalize to BR(4l) from ee at 1% level => absolute sub-% for couplings.
Top Yukawa coupling from $\sigma(ttH)/\sigma(ttZ)$

To the extent that the $qqbar \rightarrow tt Z/H$ 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

- $\delta y_t \text{ (stat + syst } TH \text{)} \sim 1\%$
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 $g_{HHH}$** investigating now : the possibility of reaching 5σ observation at FCC-ee:

4 detectors + recast of running scenario

**For $g_{Hxx}$** combination of ±4% (model dependent) HL-LHC with FCC-ee will lead to $ttH$ coupling to ±3%...model independent!

06/07/2018
Supersymmetry

In supersymmetry top partner is “stop squark”.

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

![FCC-ee graph]

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

![FCC-hh graph]

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

EWPO sensitivity up to very high mass scales

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

FCC-hh able to test all flavour combinations.

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

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
A successful model!

**PHYSICS WITH VERY HIGH ENERGY**

e+e- COLLIDING BEAMS


**ABSTRACT**

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >60 years later?

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**e+e- 1989-2000**

**p p 2009-2039**

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Let’s not be SHY!