IAS programme on The Future of High Energy Physics

Status of the FCC study

M.L. Mangano
CERN PH-TH
Many FCC-specific aspects already touched on in previous talks

- Accelerator challenges 🔄 V. Shiltsev and R. Talman
- Detector challenges 🔄 Kotwal, Pontecorvo, Murray,
- Physics landscape 🔄 C. Quigg
- Precision measurements, Higgs studies 🔄 Tenchini, Qian, Yao, Liu
- BSM 🔄 Wang, Jung, Shu

... and indirectly in other talks focused on CepC/SppC

I shall limit myself to fill in some gaps, report on organizational aspects of the physics studies, and provide a personal perspective on few issues emerged during the discussions at this meeting
Future Circular Collider study: scope

Forming an international collaboration to study:

- *pp*-collider (*FCC-hh*) → main emphasis, defining infrastructure requirements

- 80-100 km infrastructure in Geneva area

- *e*⁺*e*⁻ collider (*FCC-ee*) as potential intermediate step

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

<table>
<thead>
<tr>
<th>FCC-hh</th>
<th>FCC-ee</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp @100 TeV</td>
<td><em>e</em>⁺<em>e</em>⁻ @ √&lt;em&gt;S&lt;/em&gt; = 91, 160, 240, 350 GeV</td>
<td><em>e</em>±(50-175 GeV)-p(50 TeV)</td>
</tr>
</tbody>
</table>
Study structure

- Machines and infrastructure conceptual designs
  - Infrastructure
  - Hadron collider conceptual design
  - Hadron injectors
  - Lepton collider conceptual design
  - Safety, operation, energy management environmental aspects

- Technologies R&D activities Planning
  - High-field magnets
  - Superconducting RF systems
  - Cryogenics
  - Specific technologies
  - Planning

- Physics experiments detectors
  - Hadron physics experiments interface, integration
  - e^+ e^- coll. physics experiments interface, integration
  - e^- - p physics and integration aspects
### The 5-year international FCC design study

<table>
<thead>
<tr>
<th>Year</th>
<th>Quarter</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>Q1</td>
<td>Prepare</td>
</tr>
<tr>
<td></td>
<td>Q2</td>
<td>Kick-off, collaboration forming, study plan and organisation</td>
</tr>
<tr>
<td></td>
<td>Q3</td>
<td>Ph 1: Explore options “weak interaction”</td>
</tr>
<tr>
<td></td>
<td>Q4</td>
<td>Workshop &amp; Review → identification of baseline</td>
</tr>
<tr>
<td>2015</td>
<td>Q1</td>
<td>Ph 2: Conceptual study of baseline “strong interact.”</td>
</tr>
<tr>
<td></td>
<td>Q2</td>
<td>Workshop &amp; Review, cost model, LHC results → study re-scoping?</td>
</tr>
<tr>
<td></td>
<td>Q3</td>
<td>Ph 3: Study consolidation</td>
</tr>
<tr>
<td></td>
<td>Q4</td>
<td>Workshop &amp; Review → contents of CDR</td>
</tr>
<tr>
<td>2016</td>
<td>Q1</td>
<td>Report</td>
</tr>
<tr>
<td></td>
<td>Q2</td>
<td>Release CDR &amp; Workshop on next steps</td>
</tr>
<tr>
<td>2017</td>
<td>Q1</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>Q1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q4</td>
<td></td>
</tr>
</tbody>
</table>
First progress to be reported at the FCC Week 2015, Washington DC, March 23-27 2015


Further information and registration
http://cern.ch/fccw2015
Goal of this 5-year phase: Conceptual design report (CDR) and first cost estimate ready for the next Strategy Group assessment (~2018)
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  ⇒ Recommend CERN Council to approve, abort, or postpone.
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⇒ we have ~10 years to articulate the physics case, focusing on the physics discussion and on the study of LHC results
Physics and Experiments at the FCC

FCC-ee
Alain Blondel
John Ellis
Christophe Grojean
Patrick Janot

FCC-hh
Austin Ball
Fabiola Gianotti
Michelangelo Mangano

FCC-he
Max Klein
Monica d’Onofrio
Aims of the FCC «Physics and Experiments» design study:

-- to establish the physics capabilities of the FCC machines (- ee, hh, he) and the complementarity and coverage of the complex.

-- scope the discovery sensitivities to a number of (new) physics scenarios by
  -- direct observation of new particles
  -- precision measurements of Higgs, Electroweak, Flavour etc observables
  -- search for rare or forbidden phenomena

-- understand the experimental environment

-- establish the sensitivity of the physics performance of detectors to basic properties and identify which ones:
  -- are within reach of existing technologies and R&D
  -- would most benefit from a new, dedicated, detector R&D program

-- define suitable layouts and requirements for infrastructure, study staging scenarios

-- identify which issues would require new theoretical calculations or additional external or internal experimental input
FCC-ee physics activities documented on:

- http://indico.cern.ch/category/5259/
- http://cern.ch/tlep

To join the study group:
http://tlep.web.cern.ch/contribute-to-the-design-study

Forthcoming events:
**FCC-ee Physics Workshop, Pisa SNS, 3-5 Febr 2015**

http://agenda.infn.it/conferenceDisplay.py?ovw=True&confld=8830
Experimental Studies: A. Blondel, P. Janot

- Discovery through precision measurements, rare, or invisible processes.

- Develop the necessary tools

- Set constraints (specifications) on possible detector designs to match statistical precision

NB  Conveners have mission for one year to assemble group and find co-conveners
Phenomenology Studies: J. Ellis, C. Grojean

- Match theory predictions to FCC-ee experimental precisions

- How to discover new physics in precision measurements, in rare decays \((Z, W, t, H, b, c, \tau, \ldots)\) in rare or invisible processes (Right Handed neutrinos etc.)

- Set up the framework for global fits and understand the complementarity with other colliders (LHC, FCC-hh, in particular)
Physics and Organisation of the FCC-he Study

Higgs - Uta Klein, Masahiro Khuze – selfcoupling, 2\textsuperscript{nd} and 3\textsuperscript{rd} generation, CP

PDFs – Voica Radescu, Frank Olness – new evolution, full unfolding, high x

BSM – Monica D’Onofrio, Georges Azuelos – SUSY, Leptoquarks, CI, substructure

Top – Olaf Behnke, Christian Schwanenberger – 6FVS, top PDF, anomalous coupling

Low $x$ – Paul Newman, Anna Stasto – Gluon saturation, breakdown of DGLAP

Heavy Ions – Nestor Armesto with low $x$ – Nuclear Structure, QGP

Detector – Peter Kostka, Alessandro Polini – Design and Simulation, IR

Software – Paul Laycock and Peter Kostka – Simulation of ep/eA Detector

In close collaboration with eh coordination group and machine physicists

Forthcoming Workshop:
CERN and Chavannes 24---27. June 2015 (TH, acc, exp)
The benefits for the pp physics programme of ep data at LHC and beyond
Higgs Physics in DIS at the LHeC and FCC-he

<table>
<thead>
<tr>
<th>Higgs in $e^- p$</th>
<th>CC - LHeC</th>
<th>NC - LHeC</th>
<th>CC - FHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarisation</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.8</td>
</tr>
<tr>
<td>Luminosity [ab$^{-1}$]</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Cross Section [fb]</td>
<td>196</td>
<td>25</td>
<td>850</td>
</tr>
<tr>
<td>Decay</td>
<td>BrFraction</td>
<td>$N^H_{CC}$</td>
<td>$N^H_{NC}$</td>
</tr>
<tr>
<td>$H \rightarrow b \bar{b}$</td>
<td>0.577</td>
<td>113 100</td>
<td>13 900</td>
</tr>
<tr>
<td>$H \rightarrow c \bar{c}$</td>
<td>0.029</td>
<td>5 700</td>
<td>700</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+ \tau^-$</td>
<td>0.063</td>
<td>12 350</td>
<td>1 600</td>
</tr>
<tr>
<td>$H \rightarrow \mu \mu$</td>
<td>0.00022</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>$H \rightarrow 4l$</td>
<td>0.00013</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>$H \rightarrow 2l2\nu$</td>
<td>0.0106</td>
<td>2 080</td>
<td>250</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>0.086</td>
<td>16 850</td>
<td>2 050</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>0.215</td>
<td>42 100</td>
<td>5 150</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>0.0264</td>
<td>5 200</td>
<td>600</td>
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<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>0.00228</td>
<td>450</td>
<td>60</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>0.00154</td>
<td>300</td>
<td>40</td>
</tr>
</tbody>
</table>

Cross section at FCC-he
1pb ep $\rightarrow$ vHX

Luminosity $O(10^{34})$ is crucial for $H \rightarrow HH$ [0.5 fb] and rare $H$ decays

Event rates for 1ab$^{-1}$. Note the LHeC WW-H cross section is as large as the $Z^* \rightarrow ZH$ cross section at the ILC or FCC- or CEPC, but it is much larger at the FCC-he
<table>
<thead>
<tr>
<th>ep colliders</th>
<th>CEPC</th>
<th>MEIC</th>
<th>eRHIC</th>
<th>HERA 92-07</th>
<th>CepC</th>
<th>LHeC</th>
<th>SepC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu s/GeV)</td>
<td>13</td>
<td>35</td>
<td>122</td>
<td>319</td>
<td>1000</td>
<td>1300</td>
<td>3375</td>
<td>3464</td>
</tr>
<tr>
<td>L/10^{33} cm^{-2}s^{-1}</td>
<td>0.4</td>
<td>5.6</td>
<td>1.5</td>
<td>0.04</td>
<td>4.8</td>
<td>16</td>
<td>8.9</td>
<td>10</td>
</tr>
<tr>
<td>(E_e/GeV)</td>
<td>3</td>
<td>5</td>
<td>15.9</td>
<td>27.6</td>
<td>120</td>
<td>60</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>(E_p/GeV)</td>
<td>15</td>
<td>60</td>
<td>250</td>
<td>920</td>
<td>2100</td>
<td>7000</td>
<td>35600</td>
<td>50000</td>
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<tr>
<td>f /MHz</td>
<td>500</td>
<td>750</td>
<td>9.4</td>
<td>10.4</td>
<td>20</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>(N_{e/p}10^{10})</td>
<td>3.7/0.54</td>
<td>2.5/0.42</td>
<td>3.3/3</td>
<td>3/7</td>
<td>1.3/16.7</td>
<td>0.4/22</td>
<td>3.3/5</td>
<td>0.5/10</td>
</tr>
<tr>
<td>(\varepsilon_{e/p}/\mu m)</td>
<td>.03/.15</td>
<td>54/.35</td>
<td>32/.27</td>
<td>4.6/.09y</td>
<td>250/1</td>
<td>20/2.5</td>
<td>7.4/2.4</td>
<td>10/2</td>
</tr>
<tr>
<td>(\beta^{*}_{e/p}/cm)</td>
<td>10/2</td>
<td>10/2</td>
<td>5/5</td>
<td>28/18 \gamma</td>
<td>4.2/10</td>
<td>10/5</td>
<td>9.3/75</td>
<td>9/40</td>
</tr>
<tr>
<td>comment</td>
<td>Lanzhou</td>
<td>full acc.</td>
<td>“Day1”</td>
<td>HERA II</td>
<td>Booster</td>
<td>ERL (H)</td>
<td>(E_e=M_W)</td>
<td>ERL (HH)</td>
</tr>
</tbody>
</table>
FCC-hh physics activities documented on:

- http://indico.cern.ch/categoryDisplay.py?categId=5258
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Mailing lists (see e.g. header of any of the mtgs in the Indico category above) => register to be kept up-to-date

**PLAN**: prepare a report documenting the physics opportunities at 100 TeV, on the time scale of end-2015, ideally in cooperation with efforts in other regions

Forthcoming event at CERN:

**Higgs and BSM at 100 TeV Workshop (March 11-13 2015)**
https://indico.cern.ch/event/352868/
Status of physics/detector studies for the 100 TeV pp collider documented on

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Twiki for 100 TeV pp collider studies (Future Circular Collider FCC-hh)

This twiki is intended to provide a common area to collect and share information related to FCC-hh studies.

Detector studies (Under construction):

- DetectorGeneral
- InnerDetector (to be done)
- CalorimetrySystem (to be done)
- MuonsSystem (to be done)
- MagneticSystem (to be done)

Physics studies:

- Tools (to come soon)
- Standard Model (to come soon)
- HiggsEWSymmetry
- BSM

Some useful related links:

- Agenda for the FCC-hh meetings: indice agenda
Dark Matter studies for FCC-hh

TH Convener: Pedro Schwaller, CERN

Ongoing studies

- Almost degenerate Higgsinos (Mahbubani, Schwaller, Zurita) Show Details.
- Alternative signals with photons to discover neutralinos in compressed spectra (Delgado) Show Details.
- Examining a monojet signal (Schwaller) Show Details.
- Jet+MET and dijet+MET signatures of the Higgs portal (Mc Cullough, N.Craig, T.Lou, and A.Thalapillil) Show Details.
- DM benchmarks (Doglioni, Boveia) Show Details.

Other Literature

- Searches at 100 TeV
  - *The Relic Neutralino Surface at a 100 TeV collider*, J. Bramante et al, arxiv:1412.4789
- Higgs portals, Unitarity constraints
Other aspects
Other aspects

- The FCC will redefine the scope and role of the HEP laboratory that will host it, w.r.t. scope and role of previous HEP labs.
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- For CERN, the scale of the project may require not just international participation, beyond the CERN member states, but also engagement of other science communities (low-energy nuclear physics, light sources, medical sciences, applied accelerator physics, advanced technology, ...)

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• While the above has not entered our radars as yet, the least we can envisage today is maintaining at the FCC a rich and diverse HEP programme, fully exploiting the injector chain (fixed target experiments) and the beam options (heavy ions). The FCC study is mandated to explore these opportunities as well, and assess their impact on the whole project.
High-density QCD in the final state: the Quark-Gluon Plasma

- Lattice QCD predicts phase transition at $T_c \sim 170$ MeV
  - Quark-Gluon Plasma
- Confinement is removed

- Partonic degrees of freedom
- Unique opportunity to study in the laboratory spatially-extended multi-particle QCD system
Properties of QGP:

- QGP volume increases strongly
- QGP lifetime increases
- Collective phenomena enhanced (better tests of QGP transport)
- Initial temperature higher
- Equilibration times reduced
Questions to be addressed in future studies include:

- Larger **number of degrees of freedom** in QGP at FCC energy? \( \rightarrow g+u+d+s+\text{charm} \)?
- Changes in the **quarkonium spectra**? does \( Y(1S) \) melt at FCC?
- How do studies of **collective flow** profit from **higher multiplicity and stronger expansion**? More stringent **constraints on transport properties** such as shear viscosity or other properties not accessible at the LHC?
- **Hard probes** are sensitive to medium properties. At FCC, **longer in-medium path length and new, rarer probes** become accessible. How can both features be exploited?
Ongoing discussions on the possible use of the injector complex

WG conveners: B. Goddard (acc), F. Teubert (exp), G. Isidori (TH)
http://indico.cern.ch/category/6070/

- Test beams needs and requirements (esp multi-TeV)
- Proton EDM experimental measurement (Y. Semertzidis)
- Polarized protons in the FCC
- High-L collisions inside the high-E booster (e.g. to continue LHCb-like expts focused on rare decays like \( \tau \to 3\mu \))
- Continued programme of rare K decays
- Crystals for beam extraction
Remarks on some points emerged from the discussions ....
from R. Talman’s talk:
- “Luminosity” is a Dependent Variable, Not an Input Parameter
- “Ground Up” Rather Than “Constrained Parameter” Design
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• This gives a meaningful benchmark to start the exercise of parameter-setting and optimization, an exercise that will take place in the years leading to the CDR.
• ... all of this (including the site ....) can evolve as the analysis progresses ...
Baseline parameters:

- Beam optics scaled from LHC, accounting for Nb3Sn $\Rightarrow$ beta=1.1m
- Conservative beam-beam tune shift limit $\Rightarrow$ 0.01 (2 experiments)
- Beam (bunch) parameters similar to present LHC beam $\Rightarrow$ 3.5 times more bunches
- Baseline beam current 0.5 A, total synchrotron radiation 2 x 2.5 MW.
- Turn-around time 5 hours assumed (pre-injectors well understood)

Synchrotron radiation loss and heat extraction from cold mass is major design issue and performance determining factor.

- Dissipated power proportional to total beam current.
- Limit set to 2 x 2.5 MW beam power for dimensioning of magnet and cooling systems (present assumptions 100 MW refrigerator power)
  - This fixes the total beam current $\Rightarrow$ machine protection, dumps,…
  - Difficult to upgrade later since the complete magnet, vacuum and cryogenic systems need to be dimensioned accordingly!
- Luminosity 5E34/cm^2/s, 250 fb-1/year (~125 days effective operation)
FCC performance upgrade

- Parameters that might be improved with operational experience:
  - Optics improvements to reduce beta ➔ beta from 1.1 m to 0.3 m
  - Increased beam-beam tune shift limit and corresponding increase in beam brightness via synchrotron radiation damping ➔ 0.01 to 0.03.
  - Installation of crab cavities to compensate for crossing angle
  - Turnaround time reduced to 4 hours.

- Effective improvement factor wrt baseline is 4 – 5
  - Luminosity 2.5E35/cm^2/s (peak), ~1000 fb-1/year
  - (~125 days eff. operation)

- Further improvement might be achieved via significant improvement on the turn-around time
  - Potential to gain factor 2 in integrated luminosity by decreasing from 4 hours to 1 hour
  - Maybe only achievable with new injector ➔ major cost and effort
Summary

• Phase 1: baseline luminosity 5E34/cm^2/s (peak)
  • Integral ~250 fb-1/year (with operation model 125 days/year)
  • 10 years phase 1 operation
  • Total accumulated lumi in phase 1: 2500 fb-1.

• Phase 2: upgrade luminosity 2.5E35/cm^2/s (peak)
  • Integral ~1000 fb-1/year (with operation model 125 days/year)
  • 15 years phase 2 operation
  • Total accumulated lumi in phase 1: 15000 fb-1.

• Total accumulated luminosity over 25 years 17500 fb-1 (w/o new injector)
from the discussion on Luminosity, Friday afternoon:

- how ambitious should be the luminosity goals?
- what’s the minimum acceptable luminosity?
from the discussion on Luminosity, Friday afternoon:

- how ambitious should be the luminosity goals ?
- what’s the minimum acceptable luminosity ?

Physics considerations on luminosity goals

**Luminosity must guarantee:**

- Extension of the discovery reach at the high mass end
- Extension of the discovery reach for rare processes at masses well below the kinematical edge
- Higher statistics for studies of new particles to be discovered at the LHC
- Higher statistics for studies of the Higgs
Extension of the discovery reach at high mass

Example: discovery reach of $W'$ with SM-like couplings

$\text{NB For SM-like } Z', \sigma_{Z'} \text{BR}_{\text{lept}} \sim 0.1 \times \sigma_{W'} \text{BR}_{\text{lept}}, \Rightarrow \text{rescale lum by } \sim 10$

$M(W')=46.5\text{TeV} @ 100\text{ab}^{-1}$

$M(W')=39\text{TeV} @ 10\text{ab}^{-1}$

$M(W')=31.5\text{TeV} @ 1\text{ab}^{-1}$

$W'$ production, SM-like couplings to quarks
Int Lum (ab$^{-1}$) for 100 Events at 100 TeV

$\text{At } L=O(\text{ab}^{-1}), \text{Lum}_{32} \times 10 \Rightarrow \sim M + 7\text{TeV}$
Lum x 10 ⇒ relative gain much larger at low mass than at high mass.
• One could argue that the 10 x increase in lum is not justified if the increase in sensitivity is below a level of O(20%).
• Beyond this level, extra lum is not justified by the desire to push the mass reach

See e.g. the history of Tevatron achievements: after 1 fb⁻¹, limited progress at the high-mass end, but plenty of results at “low” mass (W, top and b physics, Higgs sensitivity, ....)

**Example from HL-LHC studies: \( Z' \to e^+e^- \)**

<table>
<thead>
<tr>
<th>ATLAS/CMS HL docs</th>
<th>300/fb</th>
<th>3000/fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% excl (ATLAS)</td>
<td>6.5 TeV</td>
<td>7.8 TeV</td>
</tr>
<tr>
<td>5σ (CMS)</td>
<td>5.1 TeV</td>
<td>6.2 TeV</td>
</tr>
</tbody>
</table>

• \( \Delta M/M \sim 20\% \) ⇒ the LHC reaches the threshold of saturation of the mass reach already at 300 fb⁻¹. Notice that 95% exclusion at 300 makes unlikely the 5σ discovery at 3000. In fact the main justification for the HL-LHC is the higher-statistics study of the Higgs, not the extension of the mass reach
• In this case, the **scaling** \( L \propto E_{\text{beam}}^2 \) gives \( L(100) \sim 15 \text{ab}^{-1} \)
Extension of the discovery reach at low mass

- The extension power of higher lum can be important at lower masses, e.g. for processes with very suppressed rates, or difficult to separate from the bg.
- In this case, though, one might benefit more from improved detection efficiency than from pure luminosity.
- The luminosity discussion is extremely process dependent (bg’s, detector performance, pileup issues, etc)

HL-LHC example: Direct stop searches (ATLAS Snowmass doc)

![Graph showing m_{stop} vs. luminosity with 5\sigma and 95% exclusion limits at 300/ fb and 3000/fb.]
Higher statistics for studies of particles discovered at the LHC
At the edge of the HL-LHC discovery reach, namely \( m_X \sim 6.5 \text{ TeV} \):

\[
\frac{\sigma(100 \text{ TeV})}{\sigma(14 \text{ TeV})} \sim \begin{cases} 
10^4 & \text{for } q\bar{q} \rightarrow X \\
10^5 & \text{for } gg \rightarrow X
\end{cases}
\]

This means:

- If \( X \) is discovered at the HL-LHC, it can be confirmed at 100 TeV with \( 10^{-(4\div5)} \) of the HL-LHC luminosity, i.e. O(30-300 pb\(^{-1}\))
  
  \( \Rightarrow L < 5 \times 10^{31} \text{ in the 1st year} \)

- A luminosity of O(0.1 – 1 fb\(^{-1}\)) allows in principle the discovery of particles beyond the HL-LHC reach
  
  \( \Rightarrow L < 2 \times 10^{32} \text{ in the 1st year} \)

- A luminosity of the order of the HL-LHC luminosity allows to improve by orders of magnitude the precision of the measurements of particle \( X \) discovered at the mass-end of the LHC reach
Higher statistics for Higgs studies

\[ R(E) = \frac{\sigma(E \text{ TeV})}{\sigma(14 \text{ TeV})} \]

### NLO rates

<table>
<thead>
<tr>
<th></th>
<th>(\sigma(14 \text{ TeV}))</th>
<th>(R(33))</th>
<th>(R(40))</th>
<th>(R(60))</th>
<th>(R(80))</th>
<th>(R(100))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>50.4 pb</td>
<td>3.5</td>
<td>4.6</td>
<td>7.8</td>
<td>11.2</td>
<td>14.7</td>
</tr>
<tr>
<td>VBF</td>
<td>4.40 pb</td>
<td>3.8</td>
<td>5.2</td>
<td>9.3</td>
<td>13.6</td>
<td>18.6</td>
</tr>
<tr>
<td>WH</td>
<td>1.63 pb</td>
<td>2.9</td>
<td>3.6</td>
<td>5.7</td>
<td>7.7</td>
<td>9.7</td>
</tr>
<tr>
<td>ZH</td>
<td>0.90 pb</td>
<td>3.3</td>
<td>4.2</td>
<td>6.8</td>
<td>9.6</td>
<td>12.5</td>
</tr>
<tr>
<td>ttH</td>
<td>0.62 pb</td>
<td>7.3</td>
<td>11</td>
<td>24</td>
<td>41</td>
<td>61</td>
</tr>
<tr>
<td>HH</td>
<td>33.8 fb</td>
<td>6.1</td>
<td>8.8</td>
<td>18</td>
<td>29</td>
<td>42</td>
</tr>
</tbody>
</table>

- Gains in the range 10-50, however ....
- \(\Rightarrow\) needs detailed studies, considering also the prospects to study rare decays, selfcouplings, etc. etc.
Example: Weiming’s talk on measurement of H selfcoupling at 100 TeV

**Updating HH→bbγγ at Tev100**

- Using Delphes 3.1.14 and the results depends on detector performance assumed.
- Including jjγγ, bbjγ, ttγ, ttγγ with ATLAS fγ=0.0093e(-Et/27.5) for HL-LHC
- Tighten mγγ window from 10 GeV used for snowmass to 6 GeV.

- Significance = 16.5 with 3 ab-1.
- H coupling dλ/λ=15% with dσ/dλ=-0.51
- ArXiv:1412.7154 reported 40% using ATLAS photon ID eff.

**To achieve 5% precision, we need to combine with other channels or get more integrated luminosity (~30 ab-1).**

- Also start to probe Higgs coupling in VBF, ttHH channels.
Charlie’s view:  
**FCC Is a Discovery Machine**

- Unknown new physics cannot provide unambiguous guidance.
- Well understood SM process that is relatively insensitive to simulation and/or analysis details as metric.
- Sufficient precision for comparison with SM at $M_{ij} \sim 0.5 \sqrt{s}$ in 2 years

$L \sim 10^{36} \text{ cm}^{-2} \text{ sec}^{-1}$

10$^{36} \text{ cm}^{-2} \text{ sec}^{-1}$ or bust!
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... so even Charlie must agree that $5 \times 10^{34}$ is enough!!
Tentative conclusions
Tentative conclusions

- The goal of $O(10-20 \text{ ab}^{-1})$ seems justified by the current perspective on
Tentative conclusions

• The goal of $O(10-20 \text{ ab}^{-1})$ seems justified by the current perspective on

• extension of the mass reach
Tentative conclusions

- The goal of $O(10^{-20} \text{ ab}^{-1})$ seems justified by the current perspective on
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  - high-statistics studies of possible new physics to be discovered at (HL)-LHC
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  • high-statistics studies of the Higgs
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• More aggressive luminosity goals may be required by specific measurements, but do not seem justified by generic arguments. Further work on ad hoc scenarios (particularly at low mass, elusive signatures, etc) is nevertheless desirable.
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• More aggressive luminosity goals may be required by specific measurements, but do not seem justified by generic arguments. Further work on ad hoc scenarios (particularly at low mass, elusive signatures, etc) is nevertheless desirable.

• For a large class of after-LHC scenarios, less aggressive lumi goals are also fully acceptable as optimal compromise between physics return and technical/experimental challenges