Future Circular Collider Options

as part of “Past, present, future: LHC and future possibilities”

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After having heard about CLIC: what about circular colliders?
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After all, CERN has built and operated, very successfully, the world’s largest and most powerful circular colliders:

- **LEP**: $e^+ e^-$ collider (1989 - 2000)
- **LHC**: pp (PbPb, pPb) collider (2009 -... )

plus a large infrastructure, since the early days....
The main elements of a circular collider

\[ p = 0.3 \, B \, \rho \]

- \( p \) [GeV/c] momentum
- \( B \) [T] magnetic field
- \( \rho \) [m] bending radius

Advantages:
- relatively short sections of accelerating RF cavities needed;
- several experiments in simultaneous data taking;
- beams circulate and collide over many hours; large luminosities.
**The challenges**

For large beam energies: **large bending radius** and/or **magnetic field**!

- Magnetic field strength prop. to electrical current;
- Large power dissipated for large currents; eliminate ohmic resistance;
- Go for superconductors!

To reduce the lost energy and the “heat load” on the accelerator structures:

- **large bending radius** and/or **heavy particles** ($m_{\text{proton}} \sim 2000 m_{\text{electron}}$)
Hadron vs lepton collider: the proton case

Proton 1 \( p_1 \)

Proton 2 \( p_2 \)

\( f_a (x_1, Q^2) \)

\( f_b (x_2, Q^2) \)

\( p_b = x_2 \; p_2 \)

\( p_a = x_1 \; p_1 \)
Hadron vs lepton collider: the proton case
Hadron vs lepton collider: the proton case

- every collision between partons at a different energy, full kinematics difficult or impossible to reconstruct
- a lot of activity, many particles, lots of radiation at high luminosity
- ratio of “interesting” to “uninteresting” events very small → trigger
- proton structure: limits precision of theoretical predictions
  ✓ much lower synch. rad. : THE way to reach highest energies
  ✓ “automatic energy scan”: good for discoveries
  ✓ a very large spectrum of different processes accessible
Hadron vs lepton collider: the electron case

- strong synchrotron radiation limits highest energies achievable
- energy scan only “by hand”, not optimal when searching “into the dark”
- less rich spectrum of accessible processes
✓ no issue with the particle’s structure: THE way to reach highest precision
✓ full kinematics well reconstructable; again, excellent for precision studies
✓ “cleaner” events, less activity, less radiation problems for detectors
Hadron vs lepton collider: the mixed case

- requires combination of two different accelerator structures
- requires special, asymmetric, detectors

✓ THE way to study in detail the proton structure
✓ delivers necessary input for describing proton-proton collisions
✓ also possible to study certain Higgs processes and to search for new phenomena
FCC motivation: pushing the energy frontier

The energy frontier is a high priority within the European Strategy for Particle Physics

- High-energy pp collider (FCC-hh) as long-term goal
  - currently only viable approach to reach the 100 TeV range in the coming decades
  - a discovery machine, and a machine to study further the Higgs sector and possible new particles to be discovered at the LHC

- Lepton collider, $e^+e^-$ (FCC-ee), as potential intermediate step
  - share part of the infrastructure (cf. LEP → LHC)
  - high luminosity machine
  - perform very-high precision studies of Z and W bosons, top quarks and the Higgs boson; search for new physics in rare decays and rare processes

- Lepton-hadron collider ep (FCC-he) as option
  - high precision study of proton structure, Higgs physics, search for new phenomena

- prepare Conceptual Design Report (CDR) and cost review for the next European Strategy Update in 2018

Lead time design & construction > 20 years (cf. LHC)
⇒ must start the studies now, to be ready in ~2040
The Rationale

How to go to the highest energies?
- build a proton-proton collider
- with available or "achievable" superconducting magnets:
  - $B = 16 \ (20) \ \text{Tesla} \rightarrow 100 \ (80) \ \text{TeV in a 100 (80) km ring}$
- in the LHC ring, now: $B = 8 \ \text{T}$ for up to 14 TeV
  and with $B = 20 \ \text{T}$ could reach max. of 33 TeV

Put together something that is reasonable
- to criticize, improve, guide the design work and identify the challenges
- set a baseline

Some of the challenges (see also later)
- superconducting magnets (also cost driver)
- 20 T will require High-Temperature Superconductors (HTS)
- synchrotron radiation
  - large heat load
  - large overall power consumption

FCC-hh (80-100 km)
pp, up to 100 TeV $E_{cm}$

FCC-ee (80-100 km)
$e^+ e^-$, $E_{cm}$ from 90 to $\sim 400 \ \text{GeV}$

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Work has started on FCC Infrastructure & Operation, in liaison with accelerator design and technology

- siting studies, based on geology, hydrology, topography
- accelerator geometry, arc design (magnet performance dependent)
- tunnel layout, tunneling options
- insertion layouts (where to put experiments, RF cavities, beam dumps, ...)
- novel safety aspects (large size of the machine)
- power, energy, electrical distribution
- cryogenics systems

~ 12% of EU annual market
~ 2.5% of annual world market
FCC-ee: an intermediate step

- use the infrastructure, in particular the large tunnel, prior to the installation of the FCC-hh, to construct an e^+e^- collider for **high-precision studies** (remember: LEP → LHC)

### Physics potential:

<table>
<thead>
<tr>
<th>Beam energy [GeV]</th>
<th>Nr. of evts/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>10^{12}</td>
</tr>
<tr>
<td>repeat the LEP1 programme every 15 mins</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>10^{8}</td>
</tr>
<tr>
<td>at LEP2: 4x10^4</td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>5 x 10^5</td>
</tr>
<tr>
<td>5 x 10^5</td>
<td></td>
</tr>
<tr>
<td>measure Higgs couplings with sub-% prec! indirect sensitivity to new physics</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>5 x 10^5</td>
</tr>
<tr>
<td>2x10^6 Higgs events after 4-5 years!</td>
<td></td>
</tr>
</tbody>
</table>

- **indirectly** probe new physics effects up to the 100 TeV scale, i.e., 2x10^{-21} m! (10^{-19} m now at LHC); or look directly for new effects in rare decays.
FCC-ee: some of the challenges

- remember: a circular lepton collider is limited by the power lost due to synchrotron radiation
- design choice: max. synchrotron radiation power set to 50 MW/beam!

- at these very high luminosities: very short beam lifetime
  - top-up injection
    - single injector booster in the collider tunnel, in addition to two-ring layout

- beam polarization for high-precision energy calibration, with long polarization times
  (Z pole: ~200 hours; WW threshold ~10 hours)

- important expertise available worldwide from lower-energies $e^+e^-$ colliders, synergies possible
  - inject (top-up) every 10 seconds
  - by-passing of experiments?
FCC-hh: physics potential

Directly discover new particles/physics up to mass scales of 30 (Z') - 50 TeV (excited quarks) (~ 5-10 x LHC reach)

- Eg. a new heavy Z' or W' boson, up to 30-40 TeV mass!
  - Possibly probing interactions 10^{-10} times weaker than the known weak interactions!

- Probe substructure of particles to ~10^{-20} m - 10^{-21} m
  (~ 10 x smaller than testable at the LHC)

- Study self-interaction of the Higgs field (difficult at the HL-LHC)
FCC-hh : the ultimate goal

- some current design parameters and related challenges....

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-Mass Energy [TeV]</td>
<td>14</td>
<td>14</td>
<td>100</td>
</tr>
<tr>
<td>Luminosity [$10^{34}$ cm$^{-2}$ s$^{-1}$]</td>
<td>1</td>
<td>5</td>
<td>≥5</td>
</tr>
<tr>
<td>Dipole Field [Tesla]</td>
<td>8.33</td>
<td>8.33</td>
<td>16 (20)</td>
</tr>
<tr>
<td>Total length [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>100 (83)</td>
</tr>
<tr>
<td>Energy loss per turn [MeV]</td>
<td>0.007</td>
<td>0.007</td>
<td>4.6 (5.9)</td>
</tr>
<tr>
<td>Total synch. rad. power [MW]</td>
<td>0.0072</td>
<td>0.0146</td>
<td>4.8 (5.8)</td>
</tr>
</tbody>
</table>

- values in brackets for 20 T magnetic field
- R&D on SC magnets
- infrastructure, tunnel (3.7 x bending radius)
- the proton is a "light" particle at such energies...
- heat load on magnets, total wall plug power (~several 100 MW?)
Superconducting Magnets R&D

- now in LHC: NbTi - limit at 9-10 T
- with Nb₃Sn: 16 T appears reachable
- but: with realistic bores (eg. 40mm aperture), at an acceptable cost, large quantity and quality?
  - Needs **int. R&D** in the coming years/decades
- Note: first Nb₃Sn magnets planned already for HL-LHC

**The FCC playground**

- 20 T: requires **High-Temperature Superconductors (HTS)**
- “even more” R&D
- there are ideas....

R&D on SC magnets is of general interest, with significant potential impact on many other fields!
FCC-hh : Detectors and related challenges

- compared to the LHC detectors (already “non-trivial”), the FCC-hh detectors represent formidable challenges
- In short: **bigger, thicker, faster, (even more) clever**!

- **thicker calorimeters** to contain high energetic jets
- **larger angular coverage**, especially for Higgs studies
- **high granularity**
- might have to be **very fast**, in case a 5ns bunch separation chosen
- need to measure **muons up to 10-20 TeV**

- experimental cavern and maintenance....
- **radiation**: About 100kW of hadron power around each experiment
  - about 45 times LHC, 8 times that of HL-LHC
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Pile-Up!

- FCC-hh: ~170 simultaneous pp-interactions (pile-up) expected for 25 ns bunch spacing
- could be reduced to ~34 with 5 ns bunch spacing
Meanwhile, elsewhere...

In China, proposal for

- **CepC**: $e^+e^-$ collisions at 240 GeV
  - Higgs factory

- **SppC**: pp collisions at 50-70 TeV
  - Highest energies
Some concluding remarks

- Our **mission** as high-energy particle physicists is to **explore nature** at the smallest distance (alas highest energy) scales
  - such future collider(s) are the necessary tools for directly probing this regime, and thus to advance our knowledge of fundamental physics

- Besides the scientific interest, consider the following aspects:
  - CERN has developed, over these last 60 years, a **world-wide unique infrastructure** and **know-how**. Let’s make sure this is exploited in the best way, over many years to come
  - with the LHC, Europe (CERN) has gained the **international leadership** in the exploration of the energy frontier
  - we should have an interest to keep the leadership in this so important and fascinating area of fundamental research
  - it is not only about **scientific leadership**, but also about **technological leadership**
    - we want to keep the most brilliant, young, ambitious minds in Europe
    - they will go where the most challenging and interesting projects are
    - Europe (**science and industry**) has shown to be capable of bringing big and challenging projects to success (eg. CERN/LHC, ESA/Rosetta/Philae, ... )
  - **The option(s) presented could be the next big, challenging project...**
Opening the door to future explorations

Supersymmetric fields?

Extra dimensions?

Higgs field ✔
References, acknowledgments

- A lot of material taken from talks by
  
  M. Benedikt, A. Blondel, L. Bottura, D. Fournier, F. Gianotti, P. Janot, P. Lebrun, D. Schulte, B. Strauss, F. Zimmermann

- Many thanks for comments and inputs to
  
  A. Blondel, F. Gianotti, P. Janot, L. Rivkin
Links to images and other material

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