FCC - protons: physics opportunities

UK HEP Forum 2014
“Future Colliders”

The Cosener’s House, November 13-14 2014

Michelangelo L. Mangano
CERN, PH-TH
The big questions

• What’s the origin of Dark matter / energy?

• What’s the origin of matter/antimatter asymmetry in the universe?

• What’s the origin of neutrino masses?

• What’s the origin of EW symmetry breaking?

• What’s the solution to the hierarchy problem?

• ...
Most of the “big questions” touch directly on weak scale physics.

There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future colliders. E.g.
Most of the “big questions” touch directly on weak scale physics.

There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future colliders. E.g.

- **Dark matter**
  - is TeV-scale dynamics (e.g. WIMPs) at the origin of Dark Matter?
Most of the “big questions” touch directly on weak scale physics. There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future colliders. E.g.

- **Dark matter**
  - is TeV-scale dynamics (e.g. WIMPs) at the origin of Dark Matter?

- **Baryogenesis**
  - did it arise at the cosmological EW phase transition?
Most of the “big questions” touch directly on weak scale physics. There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future colliders. E.g.

- **Dark matter**
  - is TeV-scale dynamics (e.g. WIMPs) at the origin of Dark Matter?

- **Baryogenesis**
  - did it arise at the cosmological EW phase transition?

- **EW Symmetry Breaking**
  - what’s the underlying dynamics? weakly interacting? strongly interacting?
    - other interactions, players at the weak scale besides the SM Higgs?
Most of the “big questions” touch directly on weak scale physics.

There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future colliders. E.g.

- **Dark matter**
  - is TeV-scale dynamics (e.g. WIMPs) at the origin of Dark Matter?

- **Baryogenesis**
  - did it arise at the cosmological EW phase transition?

- **EW Symmetry Breaking**
  - what’s the underlying dynamics? weakly interacting? strongly interacting?
    - other interactions, players at the weak scale besides the SM Higgs?

- **Hierarchy problem**
  - “natural” solution, at the TeV scale?
Key issue in addressing these questions, after LHC8 (and, hopefully not, but possibly after LHC14)

Why don’t we see the new physics?
Key issue in addressing these questions, after LHC8
(and, hopefully not, but possibly after LHC14)

Why don’t we see the new physics?

- Is the mass scale beyond the LHC reach?
Key issue in addressing these questions, after LHC8
(and, hopefully not, but possibly after LHC14)

Why don’t we see the new physics?

• Is the mass scale beyond the LHC reach?

• Is the mass scale within LHC’s reach, but final states are elusive?
Key issue in addressing these questions, after LHC8  
(and, hopefully not, but possibly after LHC14)

Why don’t we see the new physics?

- Is the mass scale beyond the LHC reach?

- Is the mass scale within LHC’s reach, but final states are elusive?

These two scenarios are a priori equally likely, but they impact in different ways the design of future facilities and experiments.
Key issue in addressing these questions, after LHC8
(and, hopefully not, but possibly after LHC14)

Why don’t we see the new physics?

• Is the mass scale beyond the LHC reach?

• Is the mass scale within LHC’s reach, but final states are elusive?

These two scenarios are a priori equally likely, but they impact in different ways the design of future facilities and experiments.

Readiness to address both scenarios relies on:

(1) extended energy/mass reach
(2) precision
(3) sensitivity (to elusive signatures)
pp at 100 TeV opens three windows:
pp at 100 TeV opens three windows:

Access to new particles in the few→30 TeV mass range, beyond LHC reach
pp at 100 TeV opens three windows:

- Access to new particles in the few→30 TeV mass range, beyond LHC reach

- Immense/much-increased rates for phenomena in the sub-TeV mass range \(\Rightarrow\)

increased precision w.r.t. LHC and possibly ILC
pp at 100 TeV opens three windows:

- Access to new particles in the few→30 TeV mass range, beyond LHC reach

- Immense/much-increased rates for phenomena in the sub-TeV mass range ⇒ increased precision w.r.t. LHC and possibly ILC

- Access to very rare processes in the sub-TeV mass range ⇒ search for stealth phenomena, invisible at the LHC
• The current work on the physics of FCC-hh is focused on exploring the potential of this collider to address these 3 targets (precision, mass reach, sensitivity).

• The ongoing studies should not be viewed as "physics cases". The goal is assessing the potential and the opportunities.

• The "physics case" will emerge at the end, when confronting the potential against the explicit circumstances arising from the future 10 years of LHC running, DM searches, Belle2, etc., and in view of the overall synergy/complementarity with the other components of the project (ee and eh).
Current goals of the study

- Extrapolate to higher energy the LHC potential for bread and butter searches:
  - define discovery mass reach for $Z'$, gluinos, new quarks, compositeness, etc.etc.etc.
- Identify new analysis opportunities, unique to the FCC:
  - use of immense statistics (precision, rare phenomena)
  - use of extreme kinematical configurations (improved S/B, increased sensitivity to high scales)
  - innovative observables or probes (sensitivity to elusive final states)
- Identify possible no-lose scenarios for specific and compelling BSM frameworks, for which the FCC can provide conclusive yes/no answers
Contents

- Examples of new measurement ideas
- Luminosity needs
- Detector envelope drivers
Precision: Higgs properties

Following tables from Snowmass Higgs WG report,
http://arxiv.org/abs/1310.8361
Table 1-20. Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u = \kappa_t = \kappa_c$, $\kappa_d = \kappa_b = \kappa_s$, and $\kappa_e = \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume $(e^-, e^+)$ polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
<th>CLIC</th>
<th>TLEP (4 IPs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250/500</td>
<td>250/500</td>
<td>250/500/1000</td>
<td>250/500/1000</td>
<td>350/1400/3000</td>
<td>240/350</td>
</tr>
<tr>
<td>$\int L dt$ (fb$^{-1}$)</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
<td>500+1500+2000</td>
<td>10,000+2600</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>5 - 7%</td>
<td>2 - 5%</td>
<td>8.3%</td>
<td>4.4%</td>
<td>3.8%</td>
<td>2.3%</td>
<td>-/5.5/&lt;5.5%</td>
<td>1.45%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>6 - 8%</td>
<td>3 - 5%</td>
<td>2.0%</td>
<td>1.1%</td>
<td>1.1%</td>
<td>0.67%</td>
<td>3.6/0.79/0.56%</td>
<td>0.79%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4 - 6%</td>
<td>2 - 5%</td>
<td>0.39%</td>
<td>0.21%</td>
<td>0.21%</td>
<td>0.2%</td>
<td>1.5/0.15/0.11%</td>
<td>0.10%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>4 - 6%</td>
<td>2 - 4%</td>
<td>0.49%</td>
<td>0.24%</td>
<td>0.50%</td>
<td>0.3%</td>
<td>0.49/0.33/0.24%</td>
<td>0.05%</td>
</tr>
<tr>
<td>$\kappa_\ell$</td>
<td>6 - 8%</td>
<td>2 - 5%</td>
<td>1.9%</td>
<td>0.98%</td>
<td>1.3%</td>
<td>0.72%</td>
<td>3.5/1.4/&lt;1.3%</td>
<td>0.51%</td>
</tr>
<tr>
<td>$\kappa_d = \kappa_b$</td>
<td>10 - 13%</td>
<td>4 - 7%</td>
<td>0.93%</td>
<td>0.60%</td>
<td>0.51%</td>
<td>0.4%</td>
<td>1.7/0.32/0.19%</td>
<td>0.39%</td>
</tr>
<tr>
<td>$\kappa_u = \kappa_t$</td>
<td>14 - 15%</td>
<td>7 - 10%</td>
<td>2.5%</td>
<td>1.3%</td>
<td>1.3%</td>
<td>0.9%</td>
<td>3.1/1.0/0.7%</td>
<td>0.69%</td>
</tr>
</tbody>
</table>

$K_\mu$ | 20% | 7% | 90% | 16% | 10% | -/ / / 11/16% | 6% |
$K_{Z\gamma}$ | 40% | 10% | | | | tbd |

Table 1-24. Expected per-experiment precision on the triple-Higgs boson coupling. ILC numbers include $bbbb$ and $bbWW^*$ final states and assume $(e^-, e^+)$ polarizations of $(-0.8, 0.3)$ at 500 GeV and $(-0.8, 0.2)$ at 1000 GeV. ILC500-up is the luminosity upgrade at 500 GeV, not including any 1000 GeV running. ILC1000-up is the luminosity upgrade with a total of 1600 fb$^{-1}$ at 500 GeV and 2500 fb$^{-1}$ at 1000 GeV. CLIC numbers include only the $bbbb$ final state and assume 80% electron beam polarization. HE-LHC and VLHC numbers are from fast simulation [102] and include only the $bb\gamma\gamma$ final state. $^\dagger$ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to CLIC numbers without accounting for the additional running period.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
<th>CLIC1400</th>
<th>CLIC3000</th>
<th>HE-LHC</th>
<th>VLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L dt$ (fb$^{-1}$)</td>
<td>14000</td>
<td>500</td>
<td>500</td>
<td>500/1000</td>
<td>500/1000</td>
<td>1400</td>
<td>3000</td>
<td>33,000</td>
<td>100,000</td>
</tr>
<tr>
<td></td>
<td>3000/expt</td>
<td>500</td>
<td>1600$^\dagger$</td>
<td>500+1000</td>
<td>1600+2500$^\dagger$</td>
<td>1500</td>
<td>+2000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>50%</td>
<td>83%</td>
<td>46%</td>
<td>21%</td>
<td>13%</td>
<td>21%</td>
<td>10%</td>
<td>20%</td>
<td>8%</td>
</tr>
</tbody>
</table>
• There is no question that the absolute precision achievable at e+e– colliders is, on average, superior to that attainable by a hadron machine.

• But notice that couplings like HWW and HZZ are already strongly constrained by EWPT, and deviations from their SM values, if any, are bound to be small. Couplings involved in rare decays, like $H \rightarrow \mu \mu$, $H \rightarrow Z \gamma$, and $HHH$ coupling, are much less constrained, and give a hadron collider great sensitivity to possible BSM signals.

• The potential for Higgs precision studies at future hadron and lepton colliders are therefore largely complementary and synergetic. (see e.g. $m_Z$ vs $m_W$)

• Furthermore, hadron collider experiments have many handles, which are only starting to be discovered and exploited, and whose ultimate precision potential is far from having been fully appreciated.

• **Example:**
  
  • *Higgs total width measurement from rate at large Higgs off-shell mass w.r.t. peak* ....
Higgs physics

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

In several cases, the gains in terms of “useful” rate are much bigger. E.g. when we are interested in the large-invariant mass behaviour of the final states:

\[ \sigma(ttH, p_{T}^{\text{top}} > 500 \text{ GeV}) \Rightarrow R(100) = 250 \]

**Task:** explore new opportunities for measurements, to reduce systematics with independent/complementary kinematics, backgrounds, etc.etc.
Example, $y_{\text{top}}$ from $pp \rightarrow tt\,H/\,pp \rightarrow tt\,Z$

To the extent that the $q\bar{q} \rightarrow tt\,Z/H$ contributions are subdominant:

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

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

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

Scan $\mu_R$ and $\mu_F$ independently, at $\mu_{R,F} = [0.5, 1, 2] \mu_0$, with $\mu_0 = m_H + 2m_t$

<table>
<thead>
<tr>
<th></th>
<th>$\delta\sigma(ttH)$</th>
<th>$\delta\sigma(ttZ)$</th>
<th>$\sigma(ttH)/\sigma(ttZ)$</th>
<th>$\delta[\sigma(ttH)/\sigma(ttZ)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 TeV</td>
<td>± 9.8%</td>
<td>± 12.3%</td>
<td>0.608</td>
<td>±2.6%</td>
</tr>
<tr>
<td>100 TeV</td>
<td>± 9.6%</td>
<td>± 10.8%</td>
<td>0.589</td>
<td>±1.2%</td>
</tr>
</tbody>
</table>

PDF dependence (CTEQ6.6 -- similar for others)

<table>
<thead>
<tr>
<th></th>
<th>$\delta\sigma(ttH)$</th>
<th>$\delta\sigma(ttZ)$</th>
<th>$\delta[\sigma(ttH)/\sigma(ttZ)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 TeV</td>
<td>± 4.8%</td>
<td>± 5.3%</td>
<td>±0.75%</td>
</tr>
<tr>
<td>100 TeV</td>
<td>± 2.7%</td>
<td>± 2.3%</td>
<td>±0.48%</td>
</tr>
</tbody>
</table>

* The uncertainty reduction survives after applying kinematical cuts to the final states
* Both scale and PDF uncertainties will be reduced further, well before FCC!
Example, $t\bar{t}H$ at large $p_T$

- $S/B > 1$
- 10 M evts at $10 ab^{-1}$ w. $p_{t\text{min}}=200$ GeV, before further cuts
Example, ZH at large mass

- Sensitivity to anomalous VVH couplings complementary to what given by high-precision $B(H \rightarrow VV)$ measurements
- Optimal use of boosted object tagging, to access both hadronic and leptonic $W/Z$ decays, $H \rightarrow bb$, etc,
More in general ...

• Statistics allows to bring the precision in the measurement of BR ratios to sub-% level (e.g. $B(\rightarrow \gamma \gamma)/B(H \rightarrow ZZ^*)$. Relying on the sub-% measurement of benchmark BR’s from FCC-ee, FCC-hh can export this precision to other channels it has access to.

• Experimental feasibility, and theoretical implications, of these measurements are under study

• Several of these new ideas can be already explored at HL-LHC
Higgs: beyond precision physics

The Higgs boson is directly connected to several key questions:

• What’s the real origin of the Higgs potential, which breaks EW symmetry?
  • underlying strong dynamics? composite Higgs?
  • RG evolution from GUT scales?
  • Are there partners of the Higgs (e.g. H⁺, A⁰, H±±, ... , EW-singlets, ....)

• The hierarchy problem: what protects the smallness of m_H / m_{Plank,GUT,...}?

• Is there a relation between Higgs, EWSB and Dark Matter?

• What happens at the EW phase transition (PT) during the Big Bang?
  • what’s the order of the phase transition?
  • are the conditions realized to allow EW baryogenesis?
  • does the PT wash out possible pre-existing baryon asymmetry?
  • is there a relation between baryogenesis and DM?
Strong 1\textsuperscript{st} order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \approx 80\text{ GeV} \Rightarrow \text{new physics}$, coupling to the Higgs and effective at scales $O(\text{TeV})$, must modify the Higgs potential to make this possible.

Chung et al,  
http://arxiv.org/abs/1209.1819
**Understanding the role of the EWPT in the evolution or generation of the baryon asymmetry of the Universe is a key target for future accelerators**

- Experimental probes:
  - study of triple-Higgs couplings (... and quadruple, etc)
  - search for components of an extended Higgs sector (e.g. 2HDM, extra singlets, ...)
  - search for new sources of CP violation, originating from (or affecting) Higgs interactions

⇒ all under study
Dark Matter search
Dark Matter search

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
Dark Matter search

• DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).

• More in general, no experiment can guarantee an answer to the question “what is DM?”
Dark Matter search

• DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).

• More in general, no experiment can guarantee an answer to the question ”what is DM?”

• Scenarios in which DM is a WIMP are however compelling and theoretically justified
Dark Matter search

• DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).

• More in general, no experiment can guarantee an answer to the question ”what is DM?”

• Scenarios in which DM is a WIMP are however compelling and theoretically justified

• We would like to understand whether future colliders can answer more specific questions, such as:
Dark Matter search

• DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).

• More in general, no experiment can guarantee an answer to the question ”what is DM?”

• Scenarios in which DM is a WIMP are however compelling and theoretically justified

• We would like to understand whether future colliders can answer more specific questions, such as:
  • do WIMPS contribute to DM?
**Dark Matter search**

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).

- More in general, no experiment can guarantee an answer to the question ”what is DM?”

- Scenarios in which DM is a WIMP are however compelling and theoretically justified

- We would like to understand whether future colliders can answer more specific questions, such as:
  
  - do WIMPS contribute to DM?

  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders?
DM overclosure upper limits: $M_{\text{WIMP}} < 1.8 \text{ TeV} \left( g^2/0.3 \right)$ \implies

\begin{align*}
\text{wino: } m &\lesssim 3 \text{ TeV} \\
\text{higgsino: } m &\lesssim 1.1 \text{ TeV}
\end{align*}

In anomaly-mediated SUSY or split SUSY \implies

$m_{\text{gluino}} \lesssim 10 \text{ TeV}$

---

In combination with indirect detection, there is hope to “completely cover” the wino parameter space.

---

L.T. Wang, (see also P.Schwaller and T.Cohen) BSM@100 TeV Workshop
Coverage of pMSSM parameter space using DM constraints and direct searches at 14 and 100 TeV

Arbey, Battaglia, Mahmoudi

Fraction of pMSSM points allowed by DM over-closure constraints

Fraction of pMSSM points that can be excluded at LHC-14 and 100 TeV:
Exploration of the high mass scale

- indirect sensitivity (i.e. departures from SM behaviour via virtual effects)

- direct sensitivity: search for production of new particles
Example, $tt$ at large mass

<table>
<thead>
<tr>
<th>$\sigma_{LO}$ [pb]</th>
<th>No $M_{tt}$ cut</th>
<th>$M_{tt} &gt; 1$ TeV</th>
<th>$M_{tt} &gt; 2$ TeV</th>
<th>$M_{tt} &gt; 3$ TeV</th>
<th>$M_{tt} &gt; 5$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC-14</td>
<td>560 pb</td>
<td>14.5 pb</td>
<td>0.31 pb</td>
<td>0.017 pb</td>
<td>9.93 $10^{-5}$ pb</td>
</tr>
<tr>
<td>FCC-100</td>
<td>19700 pb ($\times$35)</td>
<td>1510 pb ($\times$100)</td>
<td>135.9 pb ($\times$440)</td>
<td>27.2 pb ($\times$1600)</td>
<td>2.86 pb ($\times$30000)</td>
</tr>
</tbody>
</table>

Applications: top dipole moments

Top chromomagnetic and chromoelectric moments:

$$L = \frac{g_s}{m_t} T_a^{\mu\nu} \left[ g_V + i g_A s_W \right] T_c G_{\mu\nu}^a$$

LHC8

LHC14

FCC, inclusive $tt$

FCC at high $M_{tt}$

Top pair-production total cross sections

- constraints on $g_s$ and $g_V$
- Existing data: Tevatron: LHC-8
- Predictions: LHC-14; FCC-100
  - Major improvement not foreseen…
  - LHC: assuming 5% syst. + stat. for 100 fb$^{-1}$
  - FCC: assuming 5% syst. + stat. for 1 ab$^{-1}$
- Using instead highly massive top pairs
  - $M_{tt} > 6$ TeV or 10 TeV or 15 TeV
Running Electroweak Couplings as a Probe of New Physics


\[ \frac{d\sigma}{dM} \Rightarrow \alpha(q) \]

\[ \frac{d\sigma}{dM_T} \Rightarrow \alpha_2(q) \]

SU(2) limits from \( W^* \)

W\(^*\) limits, varying uncertainties

W\(^*\), running vs EWPT

\( W^* \) reach: SU(2) multiplets

\( W^* \) reach: MSSM
Example: discovery reach of $W'$ with SM-like couplings

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

At $L=O(ab^{-1})$, $\text{Lum} \times 10 \Rightarrow \sim M + 7 \text{TeV}$
Relative gain much larger at low mass than at high mass.

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, ....)
Luminosity vs CM Energy

\[ \frac{\sigma(W)[E_{CM}/\text{TeV}]}{\sigma(W)[100\text{TeV}]} \]

\begin{align*}
130 \text{ TeV} \\
120 \text{ TeV} \\
E_{CM}=110 \text{ TeV}
\end{align*}

\[ \text{M(W')} \text{ [GeV]} \]
• Physicists will be happy to take as much Lum as the accelerator can deliver!

• But Lum beyond some saturation point (e.g. L such that 10xL gives $\Delta M_{\text{reach}} < 0.2 M_{\text{reach}}$) is not automatically justified by the extension of the exploration at the high end, rather by the need of higher stat for more accurate/sensitive studies at lower masses. ⇒ implications for the detector optimization?

• Lum comes at a cost, in money, physics performance, and in the efficiency and safety of operations.
  • high current/power → safety risk
  • small emittance/$\beta^*$ → short Lum lifetime, short $L^*$ →.....

• Optimization is a must!
Some important choices in the design of the detectors and accelerator require “urgent” input from physics considerations.
Interaction Region and Final Focus Design

Two designs being investigated:

- \( L^* = 46\text{m} / 38\text{m} \) (how much is needed?)
- \( \beta^* = 0.8\text{m} / 0.3\text{m} \) (goal <1.1m)

It is easier to obtain small beta-functions with shorter \( L^* \)

Will have a tendency to reduce \( L^* \)

Need to understand detector requirements as soon as possible

Many issues need to be addressed
- Magnet performance
- Radiation effects
- Space constraints from experiments
- Beam-beam effects and mitigation
- ...
$L^* = 46-38m$ seems consistent with scale of proposed detector layouts, e.g.

however ....
Maintenance scenarios look difficult
2) LUMINOSITY

\[ L \propto \frac{\gamma I}{\beta^* \Delta \nu} \quad I \propto (f N_p) \quad \Delta \nu \propto \left( \frac{N_p}{\epsilon_{\perp}} \right) \]

where \( f \) = bunch frequency, \( N_p \) = protons per bunch, \( \epsilon_{\perp} \) = normalized rms transverse emittance, \( \beta^* \) = IP Courant-Snyder function, \( \Delta \nu \) = beam-beam tune shift, and \( I \) = beam current.

Fundamental cross sections fall with \( 1/\gamma^2 \), so luminosity should rise as \( \gamma^2 \). Going from LHC at 14 TeV to 100 TeV we need:

\[ L_{100} \geq 1 \times 10^{34} \times \left( \frac{100}{14} \right)^2 = 5 \times 10^{35} \text{ (cm}^{-2}\text{s}^{-1}) \]

With fixed \( I \) and \( \Delta \nu \) this requires

\[ \beta^*_{\text{LHC}} = 55(\text{cm}) \quad \rightarrow \quad \beta^*_{\text{this}} \approx 5.5(\text{cm}) \]

(c.f. \( \beta^* = 5 \text{ (mm)} \) in 3 a TeV muon collider lattice[8].)

cfr: \( L^* = 46 \ (38) \text{ m needed for } \beta^* = 80 \ (30) \text{ cm} \)

Forward acceptance clashes against machine needs for high luminosity

Since rate \( \propto \) (acceptance \times luminosity), there is room for optimization ...
Key physics drivers of the detector envelope

- muon pt resolution \((\text{BL}^2)\)
- jet containment (cal depth, L)
- broadening of collimated jets \((\text{BL}^2)\)
  - jet substructure
  - b-tagging

- eta acceptance:
  - lepton, gamma acceptance (Higgs, W/Z, ...)
  - jets (VBF)
  - missing \(E_T\)

It is urgent to provide clear and justified recommendations to those designing the accelerator and the detectors.
Drivers for forward-jet acceptance

Vector boson fusion and scattering:
- \( WW \rightarrow H \)
- \( WW \rightarrow WW \)
- \( WW \rightarrow HH \)
- \( WW \rightarrow \text{ew-inos/DM candidates/etc} \)

s-channel resonances in \( Wq \) fusion:

\[
\gamma^\mu \frac{q^\nu}{2m_{\tilde{T}(B)}} \lambda_{\tilde{T}(B)} \rightarrow \tilde{T}(B)
\]

Missing-ET resolution
Can the cost of covering $\eta > 2.5$ be used to regain the acceptance loss in cheaper ways, e.g. lowering $p_T$ trigger thresholds?
pp→X X jet jet, with X=slepton, stop, sbottom, gauginos

Comp. Spectra Via VBF at 100 TeV

We consider 5 spectra with small mass gaps:

1. $\tilde{\tau}_1$, $\tilde{\mu}_1$: 329, $\tilde{\nu}$: 319, $\tilde{\chi}^0_i$: 206,290,332,671, $\tilde{\chi}_i^\pm$: 208,337
2. $\tilde{\tau}_1$, $\tilde{\mu}_1$: 231, $\tilde{\nu}$: 218, $\tilde{\chi}^0_i$: 185,237,299,356, $\tilde{\chi}_i^\pm$: 229,354
3. $\tilde{\mu}_1$, $\tilde{\tau}_1$: 489, $\tilde{\nu}$: 483, $\tilde{\chi}^0_i$: 88,500,818,829, $\tilde{\chi}_i^\pm$: 500,829
4. $\tilde{\mu}_1$, $\tilde{\tau}_1$: 205, $\tilde{\nu}$: 190, $\tilde{\chi}^0_i$: 188,216,1019,1021, $\tilde{\chi}_i^\pm$: 216,1022
5. $\tilde{\mu}_1$, $\tilde{\tau}_1$: 496, $\tilde{\nu}$: 491, $\tilde{\chi}^0_i$: 481,501,1019,1027, $\tilde{\chi}_i^\pm$: 501,1026

⇒ very light central systems!
EWSB probes: high mass WW/HH in VBF

SM rates at 100 TeV

$\sigma/dM(WW) \text{ (pb/200 GeV)}$

$(p_T^{fwd \text{ jet}} > 50 \text{ GeV})$

100 fb with $M(WW) > \sim 3 \text{ TeV}$

$\sigma/dM(HH) \text{ (pb/200 GeV)}$

$(p_T^{fwd \text{ jet}} > 50 \text{ GeV})$

1 fb with $M(HH) > \sim 2 \text{ TeV}$
• There is a lot of work to be done still to properly define the scope, potential and requirements of physics with forward jets.

• What’s the impact of MET requirements (both for high mass and low mass scenarios)?

• Impact of VBF studies on Higgs couplings (including H selfcouplings) must be compared with direct search for resonances

• Is VBF physics best done in a “multi-TeV” detector, or in a more compact dedicated “TeV-scale detector”? 
Muons
Design Criteria

- **LHC @ $\nu_s = 14$ TeV or SSC @ $\nu_s = 40$ TeV**
  - $|\eta|$ range < 2.7
  - Momentum Resolution $\sigma(pT)/pT \sim 10\%$ @ $pT = 1$ TeV
  - Beam Cross Tagging $\tau \ll 25$ ns
  - Trigger 1 MU $pT > 20$ GeV/c, 2 MU $pT > 10$ GeV/c, 3 MU $pT > 6$ GeV/c
  - Highest detector hit rate $\sim 15$ kHz/cm$^2$

- **Scaling factors for same chamber resolution**
  - $\nu_s$ ratio $\sim 7$ for LHC or 2.5 for SSC required increase in $B L^2$
  - $|y_{max}|$ ratio $\sim \ln[(\nu_s=100)/M_p]/[(\nu_s=14)/M_p] \sim 11.5/9.5 \sim 1.2$

- **FCC @ $\nu_s = 100$ TeV**
  - $|\eta|$ range $< 2.7 \times y_{max}(100)/y_{max}(14) \sim 3.2 \Rightarrow \theta > 4.7^\circ$
  - Momentum resolution $\sigma(pT)/pT \sim 10\%$ @ $pT = 7$ TeV/c
  - Beam Cross Tagging $\tau \ll 25$ ns
  - Trigger 1 MU $pT > 20$ GeV/c, 2 MU $pT > 10$ GeV/c, 3 MU etc.
    - With $B L^2 \sim 7X$ or 2.5X could raise threshold to higher value but threshold will be determined by bkg. suppression, trigger bandwidth & physics
  - Highest detector hit rate $\sim 30$ kHz/cm$^2$

B $L^2$ (FCC) = 100/14 B $L^2$ (LHC) = 7 B $L^2$ (LHC)
2. Option 3: Toroids + Solenoid + Dipoles

- 3.5 T in central solenoid, 2 T - 10 Tm in dipoles and ≈1.7 T in toroid.
- 55 GJ stored energy (for 16 Tm; 130 Tm²)!
- 0.6 GJ in Solenoid, 0.9 GJ in 2 Dipoles, 2x2.1 GJ in the two End Cap Toroids, and 47.5 GJ in the Barrel Toroid.

Herman ten Kate
Alexey Dudarev, Leonardo Gerritse, Jeroen van Nugteren,
FCC Workshop @ CERN, 27 May 2014
impact of different assumptions on muon momentum resolution at 10 TeV (nominal: natural $Z'$ width, 3% in this case)
# Sensitivity

Luminosity (fb$^{-1}$) to discover at 5sigma

<table>
<thead>
<tr>
<th></th>
<th>5TeV</th>
<th>8TeV</th>
<th>10TeV</th>
<th>20TeV</th>
<th>30TeV</th>
<th>40TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.15</td>
<td>0.93</td>
<td>2.39</td>
<td>91.2</td>
<td>1770</td>
<td>29983</td>
</tr>
<tr>
<td>10%</td>
<td>0.15</td>
<td>0.96</td>
<td>2.51</td>
<td>106.1</td>
<td>2312</td>
<td>48914</td>
</tr>
<tr>
<td>20%</td>
<td>0.16</td>
<td>1.02</td>
<td>2.72</td>
<td>123.9</td>
<td>2932</td>
<td>62653</td>
</tr>
<tr>
<td>30%</td>
<td>0.16</td>
<td>1.09</td>
<td>2.93</td>
<td>140.9</td>
<td>3674</td>
<td>91116</td>
</tr>
<tr>
<td>40%</td>
<td>0.17</td>
<td>1.18</td>
<td>3.14</td>
<td>159.4</td>
<td>4462</td>
<td>134534</td>
</tr>
</tbody>
</table>

---

**Diagram:**

Luminosity versus mass for a 5 sigma discovery.
Compare with discovery reach in dijet channel

\[ \Delta = \text{dijet mass resolution} \]

\[ \Delta = \pm 10\% \]
\[ \Delta = \pm 4\% \]
\[ \Delta = \pm 1\% \]

\[ \frac{S}{\sqrt{B}} \]

\[ \sqrt{\hat{s}} = M_V \, [\text{TeV}] \]

3ab\(^{-1}\)
Remarks

• At these masses, dijets may provide comparable discovery reach for $Z'$, provided energy resolution in the 4-5% range ⇒ can far can we push jet performance at the highest $E_T$?

• Observation reach in dimuon not terribly compromised by resolution going from 10 to 30-40% at 10 TeV ⇒ $BL^2$ increase by 2-3 may be sufficient
  • in ~absence of DY bg, studies of angular distributions, couplings, etc are not affected by worse $\delta p_T$

• More compelling physics cases may be invoked to request $7 \times BL^2$:
  • spreading out dense jets, b-tagging, etc.

• Are there different, stringent performance requirements for muons, leading to different constraints on teh detector design?
  • E.g. mass resolution and trigger efficiency for $H \rightarrow \mu \mu$?
Other issues
Other issues

- 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.
Other issues

• 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.

• 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, ...)

Other issues

• 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.

• 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, ...)

• 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.
FCC-hh physics activities documented on:

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

Mailing list exists (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 events at CERN:

- Higgs and EWSB WG, workplan discussion (November 24)
  https://indico.cern.ch/event/348468/
- Higgs adn BSM at 100 TeV Workshop (March 11-13 2015)
  https://indico.cern.ch/event/352868/

# FCC-hh parameters

**FCC-ACC-SPC-0001**

## 3. Parameter Overview

Table 1: FCC-hh baseline parameters compared to LHC and HL-LHC parameters.

<table>
<thead>
<tr>
<th>Main parameters and geometrical aspects</th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. Energy [TeV]</td>
<td>14</td>
<td>33</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Circumference C [km]</td>
<td>26.7</td>
<td>26.7</td>
<td>100 (83)</td>
<td></td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>8.33</td>
<td>20</td>
<td>16 (20)</td>
<td></td>
</tr>
<tr>
<td>Arc filling factor</td>
<td>0.79</td>
<td>0.79</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Straight sections</td>
<td>8</td>
<td>8</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Average straight section length [m]</td>
<td>528</td>
<td>528</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>Number of IPs</td>
<td>2 + 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection energy [TeV]</td>
<td>0.45</td>
<td>&gt; 1.0</td>
<td>3.3</td>
<td></td>
</tr>
</tbody>
</table>

## Physics performance and beam parameters

<table>
<thead>
<tr>
<th>Physics performance and beam parameters</th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak luminosity [$10^{34} \text{ cm}^2\text{s}^{-1}$]</td>
<td>1.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Optimum run time [h]</td>
<td>15.2</td>
<td>10.2</td>
<td>5.8</td>
<td>12.1 (10.7)</td>
</tr>
<tr>
<td>Optimum average integrated lumi / day [fb^{-1}]</td>
<td>0.47</td>
<td>2.8</td>
<td>1.4</td>
<td>2.2 (2.1)</td>
</tr>
<tr>
<td>Assumed turnaround time [h]</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Overall operation cycle [h]</td>
<td></td>
<td></td>
<td></td>
<td>17.4 (16.3)</td>
</tr>
<tr>
<td>Peak no. of inelastic events / crossing at</td>
<td>27</td>
<td>135 (lev.)</td>
<td>147</td>
<td>171</td>
</tr>
<tr>
<td>- 25 ns spacing</td>
<td></td>
<td></td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>Total / inelastic cross section $\sigma_{\text{inel}}$ [mbarn]</td>
<td>111 / 85</td>
<td>129 / 93</td>
<td>153 / 108</td>
<td></td>
</tr>
<tr>
<td>Luminous region RMS length [cm]</td>
<td></td>
<td></td>
<td></td>
<td>5.7 (5.3)</td>
</tr>
<tr>
<td>Beam lifetime due to burn off [h]</td>
<td></td>
<td></td>
<td></td>
<td>45</td>
</tr>
</tbody>
</table>

## Beam parameters

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bunches $n$ at</td>
<td>2808</td>
<td>2808</td>
<td>10600 (8900)</td>
<td>53000 (44000)</td>
</tr>
<tr>
<td>- 25 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 5 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch population $N[10^{11}]$</td>
<td>1.15</td>
<td>2.2</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>- 25 ns</td>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>- 5 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal transverse normalized emittance [$\mu$m]</td>
<td>3.75</td>
<td>2.5</td>
<td>1.38</td>
<td>2.2</td>
</tr>
<tr>
<td>- 25 ns</td>
<td></td>
<td></td>
<td></td>
<td>0.44</td>
</tr>
<tr>
<td>- 5 ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of IPs contributing to $\Delta Q$</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum total b-b tune shift $\Delta Q$</td>
<td>0.01</td>
<td>0.015</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The growth times are only indicative. They have been calculated for a specific RF configuration and need to be estimated again once the RF system is defined.