Based on Material from the FCC CDR Summary Volumes (https://indico.cern.ch/event/750953/)
CERN-Council-S/106 (May 2013):

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. **CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.**
Scope of FCC Study

• International collaboration (hosted at CERN) to study:
  – pp-collider (FCC-hh) → long-term goal, defining infrastructure requirements
  - Ongoing R&D on 16T Nb$_3$Sn magnets → 100TeV pp in 100km collider → talk by F. Toral
  – ~100 km tunnel infrastructure in Geneva area (CERN accelerator complex)
  – e$^+$e$^-$ collider (FCC-ee), as potential first step → talk by P. Janot
    - High luminosity, $\sqrt{s} = 90$-365 GeV
  – HE-LHC with FCC-hh technology (16T → 27TeV) → talk by P. Azzi
  – p-e (FCC-he) option, IP integration, e$^-$ from ERL → talk by U. Klein

• CDR for European Strategy Update 2019/20

November 2018
103$^{rd}$ Plenary ECFA Meeting — M. Aleksa (CERN)
Global FCC Collaboration

133 Institutes
25 Companies
34 Countries
EC H2020

November 2018
103rd Plenary ECFA Meeting — M. Aleksa (CERN)
Why a 100TeV pp Collider?
Particle accelerators are built to answer some of the most fundamental questions about the natural world.

Physics priorities are likely to shift swiftly, as we advance in our exploration, both experimentally and theoretically.

There are many unknowns ahead of us that may reshuffle the cards (e.g. any discoveries of HL-LHC).

We need a broad and bold program capable of adapting to the swift changes in the physics landscape that are likely to happen.

100TeV hadron collider – In times of uncertainty, bold exploration is the way to go.

Complementarity and synergy with high-luminosity lepton colliders such as FCC-ee.
• **Guaranteed Deliverables:**
  – Study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable precision and sensitivity
    • Sensitivity to the shape of the Higgs potential (Higgs self coupling)
  – Ultimate precision standalone and in combination with FCC-ee and FCC-eh

• **Exploration Potential:**
  – Mass reach enhanced by factor \( \sim E / 14 \text{ TeV} \)
    • will be 5–7 at 100 TeV, depending on integrated luminosity
  – Sensitivity to rare processes enhanced by orders of magnitude
  – Benefit from indirect precision probes at low and high \( Q^2 \)

• **Provide YES/NO Answers:**
  ...to questions like...
  – Is the SM dynamics all there is at the TeV scale?
  – Is there a TeV-scale solution to the hierarchy problem?
  – Is DM a thermal WIMP?
  – Was the cosmological EW phase transition 1st order?
  – Could baryogenesis take place during the EW phase transition?
SM Higgs: Event Rates at 100TeV

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

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

$N_{14} = \sigma_{14\text{TeV}} \times 3 \text{ab}^{-1}$

Large statistics!

FCC-hh – The ultimate Higgs Factory!

Large kinematic range of Higgs production

Hierarchy of production channels changes at large $p_T(H)$:

- $\sigma(\text{ttH}) > \sigma(\text{gg} \rightarrow \text{H})$ above 800 GeV
- $\sigma(\text{VBF}) > \sigma(\text{gg} \rightarrow \text{H})$ above 1800 GeV
Example: Higgs Couplings

- Per-cent level measurements of ratios of branching ratios
  - Model independent sensitivity to BSM
- Ratios of BR: Well defined fiducial region → remove production and modeling systematics
- Normalise to BR (4 leptons) from FCC-ee (known at the few per-mille, see talk by P. Janot)
- High $p_T$ region: Reduced systematics (e.g. from pile-up, from background)
- → Absolute sub-% measurements for rare decays → Precision on Higgs couplings in the sub-% range

Delphes simulation of realistic detector including systematic uncertainties
**Precision Higgs Measurements**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Precision (stat)</th>
<th>Precision (stat+syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu = \sigma(H) \times B(H \to \gamma\gamma)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.1%</td>
<td>1.05%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \to \mu\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.28%</td>
<td>0.69%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \to 4\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.18%</td>
<td>1.56%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.55%</td>
<td>1.26%</td>
</tr>
<tr>
<td>$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$</td>
<td>$\delta \lambda/\lambda$</td>
<td>5%</td>
<td>7.0%</td>
</tr>
<tr>
<td>$R = B(H \to \mu\mu)/B(H \to 4\mu)$</td>
<td>$\delta R/R$</td>
<td>0.33%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$</td>
<td>$\delta R/R$</td>
<td>0.17%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$</td>
<td>$\delta R/R$</td>
<td>0.29%</td>
<td>1.38%</td>
</tr>
<tr>
<td>$R = B(H \to \mu\mu\gamma)/B(H \to \mu\mu)$</td>
<td>$\delta R/R$</td>
<td>0.58%</td>
<td>1.82%</td>
</tr>
<tr>
<td>$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$</td>
<td>$\delta R/R$</td>
<td>1.05%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$B(H \to \text{invisible})$</td>
<td>$B@95%\text{CL}$</td>
<td>$1 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

* Measurements of ratios of BRs, combined with the absolute measurement of the HZZ coupling at FCC-ee, will yield absolute coupling measurements in FCC-hh

** Will use results from FCC-ee: BR(H$\to$bb), ttZ EW coupling
Higgs Self Coupling

Why is Higgs self coupling interesting?

- Study shape of Higgs potential
- Study EW phase transition → cosmological implications
- Impact on vacuum stability
- Self-coupling sensitive to new physics

**HH → b¯bγγ is the golden channel for di-Higgs meas. in FCC-hh:**

→ Important input for detector requirements
→ ECAL performance, b-tagging,…

\[ V(\mathcal{H}) = M_H^2 |\mathcal{H}|^2 + \frac{\lambda_H}{2} |\mathcal{H}|^4 + \frac{1}{\Lambda^2} |\mathcal{H}|^6 \]

\[ V(h) = \frac{1}{2} M_H^2 H^2 + \frac{1}{3!} \sqrt{3} \lambda_H M_H H^3 + \frac{1}{4!} \lambda_H H^4 \]

\[ \mathcal{H} = (0, \frac{H+v}{\sqrt{2}}) \]
Exploration Potential: Direct Mass Reach

• Mass reach of FCC-hh about 5-6 x HL-LHC
• Delphes simulation of realistic detector including systematic uncertainties
  → Demonstrate that we can fully exploit this potential
Exploration Potential: SUSY Reach at 100 TeV

95% CL Limits
- 14 TeV, 0.3 ab$^{-1}$
- 14 TeV, 3 ab$^{-1}$
- 5 σ Discovery
- 100 TeV, 3 ab$^{-1}$
- 100 TeV, 30 ab$^{-1}$

Mass scale [TeV]

arXiv:1606.00947
Indirect Sensitivity to High-Energy Scales

- Improve constraints on oblique parameters W and Y by two orders of magnitude!
- → Sensitivity up to the 100TeV range!

\[ \hat{W} = -\frac{W}{4m_W^2} (D_\rho W^a_{\mu\nu})^2, \quad \hat{Y} = -\frac{Y}{4m_W^2} (\partial_\rho B_{\mu\nu})^2 \]

<table>
<thead>
<tr>
<th></th>
<th>LEP</th>
<th>ATLAS 8</th>
<th>CMS 8</th>
<th>LHC 13</th>
<th>FCC-hh</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Luminosity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2 \times 10^7 Z$</td>
<td>19.7 fb$^{-1}$</td>
<td>20.3 fb$^{-1}$</td>
<td>0.3 ab$^{-1}$</td>
<td>3 ab$^{-1}$</td>
<td>10 ab$^{-1}$</td>
</tr>
<tr>
<td>NC</td>
<td>$W \times 10^4$</td>
<td>$[-19, 3]$</td>
<td>$[-3, 15]$</td>
<td>$[-5, 22]$</td>
<td>$\pm 1.5$</td>
<td>$\pm 0.8$</td>
</tr>
<tr>
<td>Y</td>
<td>$\times 10^4$</td>
<td>$[-17, 4]$</td>
<td>$[-4, 24]$</td>
<td>$[-7, 41]$</td>
<td>$\pm 2.3$</td>
<td>$\pm 1.2$</td>
</tr>
<tr>
<td>CC</td>
<td>$W \times 10^4$</td>
<td>$-3.9$</td>
<td>$\pm 0.7$</td>
<td>$\pm 0.45$</td>
<td>$\pm 0.02$</td>
<td></td>
</tr>
</tbody>
</table>

\[ g_*^2/\Lambda^2 = \frac{W}{4m_W^2} < \frac{1}{(100 \text{ TeV})^2} \Rightarrow \Lambda > 100 \text{ TeV} \]
Yes/No Answers: WIMP DM

Disappearing tracks:

- $\chi^\pm \rightarrow \pi^\pm \chi^0$
- $\chi^\pm$ and $\chi^0$ degenerate → only 160MeV mass splitting (3 TeV Wino) → 0.2ns lifetime (60mm)

- If **DM is a WIMP**, then upper limit on $M_{DM}$ of 110TeV (unitarity bound)
- Observed **relic abundance** of DM → **1TeV (Higgsino-like), 3TeV (Wino-like)**
  - Disappearing tracks analysis shows discovery potential beyond upper limits of $M_{DM}$
- In a similar way FCC-hh can **explore conclusively EW charged WIMP models**

https://cds.cern.ch/record/2642474

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103rd Plenary ECFA Meeting — M. Aleksa (CERN)
Yes/No Answers: 1\textsuperscript{st} Order EW Phase Transition

- **Strong 1\textsuperscript{st} order EWPT** required to induce **matter-antimatter asymmetry** at EW scale.
- **Example:** BSM scenarios with additional Higgs singlet $m_2$ decaying into SM Higgs pairs
- $\rightarrow$ **FCC-hh** would enable **direct discovery** over full possible mass range of $m_2$ ($\leq 900$GeV)
- $\rightarrow$ **Indirect:** 7\% precision on **triple-Higgs coupling** will reduce number of possible BSM models $\rightarrow$ important redundancy
FCC Tunnel
Civil Engineering – Tunnel Implementation Study

Optimisation criteria:
- Tunneling rock type,
- Shaft depth accessibility
- Surface points, etc.
- Lowest risk for construction,
- Schedule & cost

Tunneling:
- Molasse 90%,
- Limestone 5%,
- Moraines 5%

Implementation:
- 90-100 km fits well geological situation in Geneva basin
- Connected with LHC or SPS
**Civil Engineering Schedule Study**

- CE & schedule studies with consultants
- First sectors available after 4.5 to 5 years for Technical Infrastructure installation
- Total CE duration ~7 years
Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

Two separate rings for $e^+$ and $e^-$ (# bunches)
A booster for continuous top-up (lifetime)
Asymmetric interaction region (SR)
Crossing angle 30 mrad

Two main IP’s in A, G for both machines
FCC Tunnel Integration

FCC-ee

FCC-hh

5.5 m diameter
Sharing the Same Experimental Caverns

Detector cavern

FCC-ee detector

FCC-hh detector

Service cavern

50 m

Points A & G

Preliminary design for access and cable path

35 m

35 m
FCC-hh
Baseline Parameters for FCC-hh

• Present working hypothesis:
  – Peak luminosity:
    • baseline: $5 \times 10^{34}$
    • ultimate: $\leq 30 \times 10^{34}$
  – Integrated luminosity:
    • baseline $\sim 250 \text{ fb}^{-1} \text{ (per year)}$
    • ultimate $\sim 1000 \text{ fb}^{-1} \text{ (per year)}$
• An operation scenario with...
  – 10 years baseline, $\to$ 2.5 ab$^{-1}$
  – 15 years ultimate, $\to$ 15 ab$^{-1}$
• ... would result in a total of $O(20) \text{ ab}^{-1}$ over 25 years of operation.

<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>8.33</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>97.75</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>bunch intensity [10^{11}]</td>
<td>1</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>synchr. rad. power / ring [kW]</td>
<td>2400</td>
<td>101</td>
<td>7.3</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>4.6</td>
<td>0.33</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.54</td>
<td>1.8</td>
<td>12.9</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.45</td>
</tr>
<tr>
<td>normalized emittance [μm]</td>
<td>2.2</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>peak luminosity [10^{34} cm^{-2}s^{-1}]</td>
<td>5</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>460</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.3</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Fully profiting from existing CERN infrastructure!

Current baseline:
- Injection energy 3.3 TeV LHC
- Field-swing FCC-hh like LHC

Alternative option:
- Injection from SPS\textsubscript{upgrade} around 1.3 TeV
- SPS\textsubscript{upgrade} could be based on fast-cycling SC magnets, 6-7T, \( \sim 1T/s \) ramp, cf. SIS 300 design
- SPS\textsubscript{upgrade} would also be an ideal injector for HE LHC (as alternative to the 450 GeV SPS)
Main development goal is wire performance increase:

- \( J_c (16T, 4.2K) > 1500 \text{ A/mm}^2 \rightarrow 50\% \text{ increase wrt HL-LHC wire} \)
- Reduction of coil & magnet cross-section

After only one year development, prototype Nb\(_3\)Sn wires from several new industrial FCC partners already achieve HL-LHC performance in current density \( J_c \).

Conductor activities for FCC started in 2017:

- Bochvar Institute (production at TVEL), Russia
- KEK (Jastec and Furukawa), Japan
- KAT, Korea
- Columbus, Italy
- University of Geneva, Switzerland
- Technical University of Vienna, Austria
- SPIN, Italy
- University of Freiberg, Germany
- Bruker, Germany
- Luvata Pori, Finland
Short model magnets (1.5 m lengths) will be built from 2018 – 2022
Russian 16T magnet program launched by BINP recently
One of the most critical elements for FCC-hh

- **Synchrotron radiation** (~ 30 W/m/beam @16 T field, cf. LHC <0.2W/m) ~ 5 MW total load in arcs
- Absorption of synchrotron radiation at ~50 K for cryogenic efficiency
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.

**FCC-hh Beam-screen prototypes tested at KARA 2.5GeV storage ring (Karlsruhe Institute of Technology, Germany):**

Beam tests since June 2017, for prototypes, confirming vacuum design simulations
KARA e⁻ SR photon spectrum = FCC-hh spectrum
Technical Schedules

Schedule constrained by 16 T magnets & CE → Possible physics operation dates
• FCC-ee: 2039
• FCC-hh: 2043
• HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)
FCC-hh Detector
Requirements for FCC-hh Detector

- **ID Tracking target**: achieve $\sigma_{p_T} / p_T = 10-20\% @ 10$ TeV
- **Muons target**: $\sigma_{p_T} / p_T = 5\% @ 10$ TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency** b-tagging, $\tau$-tagging, particle ID!
- **High granularity** in tracker and calos
- **Pseudorapidity ($\eta$)** coverage:
  - Precision muon measurement up to $|\eta|<4$
  - Precision calorimetry up to $|\eta|<6$
- $\rightarrow$ Achieve all that at a pile-up of 1000! $\rightarrow$ Granularity & Timing!
- **On top of that** radiation hardness and stability!

Used in Delphes physics simulations

- Delphes physics simulations
- VBF jets $\eta$-distr.
- LHC Bunch Crossing 

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During last years converged on reference design for an FCC-hh experiment

- Radiation simulations
- Demonstrate in the CDR document, that an experiment exploiting the full FCC-hh physics potential is technically feasible

- Input for Delphes physics simulations
- Room for other ideas, other concepts and different technologies
Detector Studies

Electromagnetic Calorimeter (ECAL)

- **Performance & radiation considerations → LAr ECAL (Pb absorbers)**
  - Detector with **larger longitudinal and transversal granularity** compared to ATLAS
    - Optimized for particle flow
    - ∼8 longitudinal layers, fine lateral granularity (Δη x Δφ = 0.01 x 0.01), ∼2.5M channels
- **Possible only with straight multilayer electrodes**
  - **Proposal**: Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√E, only ∼300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ∼1.3GeV pile-up noise
  - → Efficient in-time pile-up suppression will be crucial (using the tracker)

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Conclusions

• FCC-hh: Strong and diverse physics goals and opportunities
• A 100TeV pp collider as continuation of the pp discovery programme:

  Tevatron 2TeV \(\times 7\) LHC 14TeV \(\times 7\) FCC-hh 100TeV

• 27km tunnel

• The next step: 100km tunnel

• Let’s take the lessons from these successful projects!
• Feasibility of FCC is being demonstrated in the Conceptional Design Report
  – https://indico.cern.ch/event/750953/
Thank You for Your Attention!
Back-Up
Cross-Sections for Key Processes

- **Total cross-section and Minimum Bias Multiplicity** show only a modest increase from LHC to FCC-hh.

- The cross-section for interesting processes shows however significant increase (e.g. HH x 50!).

- Higher luminosity to increase statistics → pileup of 140 at HL-LHC to pileup of 1000 at FCC-hh → challenge for triggering and reconstruction.
Hierarchy of production channels changes at large $p_T(H)$:
- $\sigma(ttH) > \sigma(gg\rightarrow H)$ above 800 GeV
- $\sigma(VBF) > \sigma(gg\rightarrow H)$ above 1800 GeV

At LHC, S/B in the $H\rightarrow\gamma\gamma$ channel is $O(\text{few \%}) \approx 1/30$
At FCC, for $p_T(H)>300$ GeV, S/B$\approx 1$
Potentially accurate probe of the $H$ $p_T$ spectrum up to large $p_T$
Example: BR (H→inv) in H+X Prod. at Large p_T(H)

Leading background from W/Z+jets
Constrain background p_T spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z→ee, W and γ spectra
Sensitivity of 2x10^{-4}!
→ Implications on dark matter searches!

https://cds.cern.ch/record/2642471
PDF determination at FCC-eh
Uniqueness of FCC-hh Higgs Physics Potential

- **Huge Higgs Production Rates:**
  - Access (very) rare decay modes
  - Push to %-level Higgs self-coupling measurement
  - New opportunities to reduce systematic uncertainties (TH & EXP) and push precision

- **Large Dynamic Range for H Production (in $p_T^H, m(H+X),...$):**
  - New opportunities for reduction of systematic uncertainties (TH and EXP)
  - Different hierarchy of production processes
  - Develop indirect sensitivity to BSM effects at large $Q^2$, complementary to that emerging from precision studies (e.g. decay BRs) at $Q\sim m_H$

- **High Energy Reach:**
  - Direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)
    - ...

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During the beams are in collision the instantaneous value of the luminosity will change:

\[ \mathcal{L}(t) = A \frac{N_b^2(t)}{\sqrt{\epsilon_x(t)\epsilon_y(t)}} \]

The beam evolution with time is obtained by solving a system of four differential equations (dominant effects only shown here, more included in simulations):

\[
\begin{align*}
\frac{dN_b}{dt} &= -\sigma_{c,\text{tot}} A \frac{N_b^2}{\sqrt{\epsilon_x \epsilon_y}} \\
\frac{d\epsilon_x}{dt} &= \epsilon_x (\alpha_{\text{IBS},x} - \alpha_{\text{rad},x}) \\
\frac{d\epsilon_y}{dt} &= \epsilon_y (\alpha_{\text{IBS},y} - \alpha_{\text{rad},y}) \\
\frac{d\sigma_s}{dt} &= \frac{1}{2} \sigma_s (\alpha_{\text{IBS},s} - \alpha_{\text{rad},s})
\end{align*}
\]

with

\[ A = f_{\text{rev}} k_b / (4\pi \beta^*) \]

- \( f_{\text{rev}} \): revolution freq.
- \( k_b \): no. bunches/beam
- \( \beta^* \): \( \beta \)-function at IP
- \( N_b \): no. particles/bunch
- \( \epsilon \): geom. emittances
- \( \sigma_s \): bunch length
- \( \sigma_{c,\text{tot}} \): total cross-section
- \( \alpha_{\text{IBS}} \): IBS growth rate
- \( \alpha_{\text{rad}} \): rad. damping rate

J. Jowett, M. Schaumann, FCC Week Washington 2015
Effects on the Emittance – A New Regime

Intra-Beam Scattering (IBS)

Multiple small-angle Coulomb scattering within a charged particle beam.

Growth rate dynamically changing with beam properties:

\[ \alpha_{IBS} \propto \frac{r_0^2 N_b}{\gamma^4 \epsilon_x \epsilon_y \sigma_x \sigma_y} \]

IBS is weak for initial beam parameters, but increases with decreasing emittance.

(Synchrotron) Radiation Damping

A charged particle radiates energy, when it is accelerated, i.e. bend on its circular orbit.

Damping rate is constant for a given energy:

\[ \alpha_{rad} \propto \frac{E^3 C_\alpha}{\rho_0 C_{ring}} \]

\[ \frac{\alpha_{rad,FCC}}{\alpha_{rad,LHC}} \approx \frac{E_{FCC}^3 / C_{FCC}^2}{E_{LHC}^3 / C_{LHC}^2} \approx \frac{7^3}{4^2} \approx 22 \]

Fast emittance decrease at the beginning of the fill, until IBS becomes strong enough to counteract the radiation damping.
Developed model including most relevant effects
• Improvement with more detail planned

⇒ Reach 8fb\(^{-1}\)/day with ultimate for 25ns spacing
⇒ 5ab\(^{-1}\) per 5 year run

⇒ Beam is burned quickly
⇒ A reason to have enough charge stored
Pile-Up, Number of pp Collisions per BunchCrossing

LHC (2x10^{34} \text{cm}^{-2}\text{s}^{-1}): \langle \mu \rangle = 60

HL-LHC: \langle \mu \rangle = 140

FCC-hh: \langle \mu \rangle = 1000

Small time differences between the individual collisions in one BC allow identification with detectors having order 10-20ps time resolution.
The Challenge of 1000 Pile-Up

- HL-LHC average distance between vertices at \( z=0 \) is
  - \( \approx 1\text{mm} \) in space and \( 3\text{ps} \) in time.
- For 6 times higher luminosity at FCC-hh (an HE-LHC) this would become
  - \( \approx 170\mu\text{m} \) in space and \( 0.5\text{ps} \) in time.

Multiple scattering in the beam pipe:
- Even having a perfect tracking detector, the error due to multiple scattering in the beampipe is significant for low energetic particles
- Timing or very clever new ideas needed...

\[ \theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln\left(\frac{x}{X_0}\right) \right] \]

\( \delta z_0 = 170\mu\text{m} \)
FCC-hh Detector: Comparison to ATLAS & CMS

ATLAS

CMS

FCC-hh Reference Detector
New reference design with three solenoids

- 4 T in 10 m free bore
- 60 MN net force on forward solenoids handled by axial tie rods
- No shielding solenoid anymore (cost! smaller shaft!)
- Forward solenoids instead of forward dipoles \(\rightarrow\) rotational symmetry important for performance physics
  - Solenoids extend high precision tracking by one unit of \(\eta\)

Result:

- Much simplified configuration
- Stored energy: 13.8 GJ
- Lowest degree of complexity from a cold-mass perspective
- But: with significant stray field
Radiation Levels Simulation

Central & forward solenoid

Shielding around the forward calo:
- 1 m of steel
- 5 cm of lithiated polyethylene
- 1 cm of lead

Hadronic extended barrel calorimeter

Central & forward tracker

EM calorimeter

Forward calorimeter

End-cap muon chambers

Conical shielding:
- 1 m thick cast iron shielding
- 5 cm of lithiated polyethylene
- 1 cm of lead

Cast iron shielding layer to protect muon chambers

Cylindrical shielding:
- 1 m thick cast iron shielding
- 5 cm of lithiated polyethylene
- 1 cm of lead

Shielding in front of the forward calo: 5 cm of lithiated polyethylene between 2 mm thick aluminum covers

L* = 45 m, the TAS absorber is put from 40 m to 43 m behind a 2 m thick concrete wall

Normalization:
- non-elastic proton-proton cross section at 100 TeV of 108 mbarn
- fluence rates [cm^{-2} s^{-1}] for an instantaneous luminosity of 30 \times 10^{34} cm^{-2} s^{-1}
- 1 MeV neutron equivalent fluence [cm^{-2}] and dose [MGy] for an integrated luminosity of 30 ab^{-1}

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1 MeV Neutron Equivalent Fluence for 30ab^{-1}

Generally ~10-30 times worse than HL-LHC

Exception: Forward calorimeter goes to higher η → bigger factor

Central tracker:
- first IB layer (2.5 cm): ~5-6 \(10^{17}\) cm\(^{-2}\)
- external part: ~5 \(10^{15}\) cm\(^{-2}\)

Barrel calorimeter:
- EM-calo: 4 \(10^{15}\) cm\(^{-2}\)
- HAD-calo: 4 \(10^{14}\) cm\(^{-2}\)

End-cap calorimeter:
- EM-calo: 2.5 \(10^{16}\) cm\(^{-2}\)
- HAD-calo: 1.5 \(10^{16}\) cm\(^{-2}\)

Calorimeter gap:
- from \(10^{16}\) cm\(^{-2}\) to \(10^{14}\) cm\(^{-2}\)

Forward calorimeters:
- ~5 \(10^{18}\) cm\(^{-2}\) for both the EM and the HAD-calo

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The forward calorimeters are a very large source of radiation (diffuse neutron source).

In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is enclosed by the return Yoke.

For the FCC, the forward calorimeter is moved far out in order to reduce the radiation load and increase granularity.

A shielding arrangement is needed to stop the neutrons to escaping into the cavern hall and the muon system.
Forward solenoid adds about 1 unit of $\eta$ to full lever arm acceptance (right field map).

$\delta p_T/p_T \leq 10\%$ for
- $\leq 10$ GeV/c and $\eta \leq 5.8$
- $\leq 1$ TeV/c and $\eta \leq 4.0$

$\delta p_T/p_T = 20\%$ for 10 TeV/c and $\eta = 0.0$

Option using forward dipoles (left field map) also studied.
Reference Detector
Inspired by ATLAS calorimetry with excellent conventional calorimetry and in addition high granularity to optimize for Particle Flow techniques, pile-up rejection, boosted objects....

- ECAL, Hadronic EndCap and Forward Calo:
  - LAr / Pb (Cu)
- HCAL Barrel and Extended Barrel:
  - Scintillating tiles / Fe(+Pb) with SiPM

Other options considered for ECAL
- Digital Si / W
- Analog Si / W (not yet studied, but will profit from CMS HGCal TDR)
• **Performance & radiation considerations → LAr ECAL (Pb absorbers)**
  - Detector with **larger longitudinal and transversal granularity** compared to ATLAS
    - Optimized for particle flow
    - ~8 longitudinal layers, fine lateral granularity ($\Delta \eta \times \Delta \phi = 0.01 \times 0.01$), ~2.5M channels
  - Possible only with **straight multilayer electrodes**
    - **Proposal**: Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - **Required energy resolution achieved**
    - Sampling term $\leq 10\%/\sqrt{E}$, only $\approx$300 MeV electronics noise despite multilayer electrodes
    - Impact of in-time pile-up at $<\mu> = 1000$ of $\approx$ 1.3GeV pile-up noise
    - Efficient in-time pile-up suppression will be crucial (using the tracker)
Hadronic Calorimeter Barrel (HCAL)

Barrel HCAL:

- **ATLAS type**
  - Scintillator tiles – steel
- **Higher granularity** than ATLAS
  - $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$
  - 10 instead of 3 longitudinal layers
  - Steel $\rightarrow$ stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout $\rightarrow$ faster, less noise, less space
- Total of 0.3M channels

e/h ratio very close to 1 achieved using steel absorbers and lead spacers (high Z material)
Muon System

$p_t = 3.9$ GeV enters muon system

$p_t = 5.5$ GeV leaves coil at 45 degrees

With 50µm position resolution and 70µrad angular resolution we find ($\eta = 0$):

- ≤10% standalone momentum resolution up to 4TeV/c
- ≤10% combined momentum resolution up to 20TeV/c

Rates of up to ~500Hz/cm² expected in muon barrel
Reading Out Such a Detector ➔ Trigger/DAQ

- **Example ATLAS:**
  - ATLAS Phase II calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.
  - Muon system will also be read out at 40MHz to produce a L1 Trigger.

- **FCC-hh detector:**
  - Calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.
  - 40MHz readout of the tracker would produce about 800TByte/s.

- **FCC-hh trigger strategy question:**
  - Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz?
  - Or: un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.