Status of FCC Detector & MDI Developments

Zbyněk Drásal
CERN
On behalf of FCC detector group
Overview

• Introduction
  – Motivation
  – Future Circular Collider (FCC) machine parameters

• Design of detector & machine detector interface (MDI)
  – Status of FCC-hh option (see WG progress @ https://indico.cern.ch/category/6069/ ):
  – Status of FCC-ee option (see progress @ http://tlep.web.cern.ch/ ):

• Common FCC Software (FCCSW) (see http://fccsw.web.cern.ch/fccsw ):

• Summary & Outlook
Is it the right time?

- LHC detector R&D started in the 1980's, that for HL-LHC in the 2000's
  - large scale prototyping and radiation studies require long lead times

→ The right time to plan for the period 2035-2040
Is it the right time?

- LHC detector R&D started in the 1980's, that for HL-LHC in the 2000's
  - large scale prototyping and radiation studies require long lead times

  ➔ The right time to plan for the period 2035-2040
  ➔ Aim to prepare the FCC Conceptual Design Report for 2019 EU Strategy Update
Future Circular Collider

**FCC machine:**
- **FCC-hh (pp collider):** final goal defining the whole infrastructure
  - ~16T magnets → 100TeV pp collider in ~80-100km tunnel
- **FCC-ee:** as a potential first step
- **FCC-eh:** as an option
Future Circular Collider

- **FCC machine:**
  - FCC-hh (pp collider): final goal defining the whole infrastructure
    $\rightarrow$ ~ 16T magnets $\rightarrow$ 100TeV pp collider in ~ 80-100km tunnel
  - FCC-ee: as a potential first step
  - FCC-eh: as an option

- **2 high luminosity experiments (A & G)**
  + 2 other experiments: H, F grouped with G
Key FCC-hh Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
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<th>(HL) LHC</th>
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<tbody>
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<td>Beam current [A]</td>
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<tr>
<td>Bunch intensity [10^{11}]</td>
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- 5 years long operation periods (3.5 years run & 1.5 year shutdown)
  - **Baseline** (phase 1): 10 yrs of operation @ $L_{\text{peak}} = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ → 2.5 ab^{-1} (per detector)
  - **Ultimate** (phase 2): 15 yrs of operation @ $L_{\text{peak}} \leq 30 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ → 15 ab^{-1} (per detector)
  - **Total**: O(20)ab^{-1}/experiment
### Key FCC-hh Parameters: FCC versus LHC

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→ the minimum bias events @FCC are quite similar to ones @HL-LHC, but ...

- 14TeV $\rightarrow$ 100 TeV
- $\sigma_{\text{inelastic}}$: 80mb $\rightarrow$ 108mb
- average p$_T$: 0.6 $\rightarrow$ 0.8 GeV/c
- multiplicity $\text{charged/unit } \eta$: 5.4 $\rightarrow$ 8
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14TeV → 100 TeV

$\sigma_{inelastic}: 80 \text{mb} \rightarrow 108 \text{mb}$

average $p_T: 0.6 \rightarrow 0.8 \text{ GeV/c}$

Multiplicity charged/unit $\eta: 5.4 \rightarrow 8$

By factor of ~5 increase wrt HL-LHC

→ the minimum bias events @FCC are quite similar to ones @HL-LHC, but ...

→ 5x higher event pile-up → keeping 5ns (versus 25ns) operation scheme as option

→ in general, expected huge particle/data rates & significantly higher radiation level in the inner/fwd detector
Physics Requirements & FCC-hh Design

- The experimental future will importantly depend on the results from LHC, but no matter what LHC discovers, understanding a complete picture of physics requires a new machine far beyond the LHC reach & general purpose detector (as CMS/ATLAS):
  - one of the natural benchmarks driving the detector design: unique properties of Higgs boson

- FCC-hh versus LHC (see: “Physics at 100 TeV” report)
  - Immense increase in cross-sections, particularly for ttH & HH
  - FCC opens us new kinematic & dynamical regime for Higgs physics

<table>
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<tr>
<th>Process</th>
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<th>$N_{140}/N_{100}$</th>
<th>$N_{140}/N_{14}$</th>
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<td>$gg \rightarrow H$</td>
<td>$16 \times 10^4$</td>
<td>$4 \times 10^4$</td>
<td>110</td>
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<td>VBF</td>
<td>$1.6 \times 10^6$</td>
<td>$5 \times 10^4$</td>
<td>120</td>
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<tr>
<td>$WH$</td>
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<td>$2 \times 10^9$</td>
<td>65</td>
</tr>
<tr>
<td>$ZH$</td>
<td>$2.2 \times 10^9$</td>
<td>$3 \times 10^9$</td>
<td>85</td>
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<tr>
<td>$ttH$</td>
<td>$7.6 \times 10^9$</td>
<td>$5 \times 10^9$</td>
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Table 20: Indicative total event rates at 100 TeV ($N_{140}$), and statistical increase with respect to the statistics of the LHC run 1 ($N_{100}$) and the HL-LHC ($N_{14}$), for various production channels. We define here $N_{100} = \sigma_{100} \times 20 \text{ ab}^{-1}$, $N_{14} = \sigma_{14} \times 3 \text{ ab}^{-1}$. 

$N_{140} = \sigma_{140} \times 20 \text{ fb}^{-1}$. 

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

$N_{100} = \sigma_{100} \times 20 \text{ ab}^{-1}$.
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→ FCC-hh versus LHC (see: “Physics at 100 TeV” report)

• Immense increase in cross-sections, particularly for ttH & HH

• FCC opens us new kinematic & dynamical regime for Higgs physics

→ See a few examples to get an intuitive picture ...

- \( HH \rightarrow bb_{\text{bar}} \gamma \gamma \) (H self-coupling), WW → WW, ...

→ Need extended tracking/ECAL coverage up-to \(|\eta| \sim 4\), efficient jet measurement up-to \(|\eta| \sim 6\)
Physics Requirements & FCC-hh Design

- Direct searches, e.g. $Z' \rightarrow \mu\mu$ or $Z' \rightarrow tt$ (high boosted objects) → heavy final states require high $\sqrt{s}$

$\Delta p_T \propto \frac{p_T}{BL^2}$

→ Need for high $p_T$ resol. $\sim 10\text{-}15\% @10\text{TeV}$ (cf. HL-LHC: 10\% @1TeV), but still keeping sensitivity for low $p_T$ tracks

→ High E/HCAL granularity ($\Delta R \leq 0.05 \times 0.05$ or $0.025 \times 0.025$) to resolve jet-substructure, rejec bkg...
Physics Requirements & FCC-hh Design

- Direct searches, e.g. $Z' \rightarrow \mu\mu$ or $Z' \rightarrow tt$ (high boosted objects) $\rightarrow$ heavy final states require high $\sqrt{s}$

$Z'$ discovery potential versus muon $p_T$ res.

$Z'_{SSM} \rightarrow \mu\mu$ Expected highly-collimated (high boosted) final states (min distance between 2 partons $\sim m/p_T$)

→ Need for high $p_T$ resol. $\sim$10-15% @10TeV (cf. HL-LHC: 10% @1TeV), but still keeping sensitivity for low $p_T$ tracks

→ High E/HCAL granularity ($\Delta R \leq 0.05 \times 0.05$ or $0.025 \times 0.025$) to resolve jet-substructure, rejec bkg...

Calorimeter res. $\rightarrow$ for high $E$ the const. term dominates:

$$\frac{\Delta E}{E} \propto \frac{a}{\sqrt{E}} \oplus c$$

Sampling term  Const. term (precise calibration, mechanics, containment,...)

→ Need few % jet energy resol., so target $c \sim$2% (HCAL), $\sim$1% (ECAL) + hermetic calorimeter
Physics Requirements & FCC-hh Design

- **Jet containment:** 30 TeV jet → 15% of hadrons with E>1 TeV!

→ 98% containment (ECAL+HCAL) requires $12\lambda_{int}$ (arXiv:1604.01415)
The magnet group studied several options to fit the requirements on tracking ($\Delta p_T/p_T @ 10\text{TeV/c} \sim 10\text{-15\%}) & calorimetry (12 \lambda_{\text{int}} – jet containment):

→ coil with high B field & low material budget in front of ECAL/HCAL very difficult  → **ATLAS approach**
FCC-hh: Magnet & Detector Baseline Geometry

- The magnet group studied several options to fit the requirements on tracking ($\Delta p_T/p_T @ 10\text{TeV/c} \sim 10-15\%$) & calorimetry ($12 \lambda_{\text{int}}$ – jet containment):
  - → coil with high B field & low material budget in front of ECAL/HCAL very difficult → ATLAS approach
  - → leaving tracker radius @ LHC values $\sim 1m + 12 \lambda_{\text{int}}$ CAL → challenging → $R_{\text{coil}} \sim 4m$ (an option)
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- coil with high B field & low material budget in front of ECAL/HCAL very difficult \(\rightarrow\) ATLAS approach
- leaving tracker radius @ LHC values $\sim 1\text{m} + 12 \lambda_{int} \text{CAL} \rightarrow$ challenging $\rightarrow R_{coil} \sim 4\text{m} \text{ (an option)}$
- current design: twin solenoid $B=6\text{T}$ (max for NbTi, 12m bore, $\sim 20\text{m length}$) + 2 dipoles (10Tm)

Beam-pipe (Be): $R=20\text{-}21\text{mm}$
Tracker: $R=25\text{mm}\text{-}2.4\text{m}, L=16\text{m}$
ECAL: $R=2.5\text{-}3.6\text{m}$
HCAL: $R=3.6\text{-}6.0\text{m}$
Coil$_{in}+$Cryostat: $6.0\text{-}7.8\text{m}, L=20\text{m}$
Muon space: $7.8\text{-}13.0\text{m}$
Coil$_{out}$: $13.0\text{-}13.5\text{m}, L=15\text{m}$

\[\eta = 2.0\]
\[\eta = 2.5\]
\[\eta = 4.0\]

Dipole: $10\text{Tm}, Z=14.8\text{-}21\text{m}$
F-Tracker: $Z=12\text{-}14\text{m}, Z=21\text{-}24\text{m}$
F-ECAL: $Z=24\text{-}25.1\text{m}$
F-HCAL: $Z=25.1\text{-}27.5\text{m}$
F-Muon: $Z=27.5\text{-}31.5\text{m}$
Dipole comp., TAS, Triplet
Tracker Design for FCC-hh

- Tracker design driven by: $\Delta p_T/p_T$ resol. @10TeV/c & pattern recognition capabilities
  - 2 magnet scenarios studied (using tkLayout SW - developed for CMS (HL-LHC) tracker studies):
    - **Twin solenoid (6T) with dipoles** (10Tm, standalone system) in FWD region:
      - Measure $p_L(p)$ using forward tracker + dipole → use $\cotg(\vartheta_{\text{emission}})$ meas. to determine $p_T$ from $p_L(p)$

- **Twin solenoid (6T) with balanced conical shape in FWD region:**
  - Rotational symmetry important for physics measurement ($E_T^{\text{miss}}$, ...)
  - Less complex system compared to dipole
  → Is performance the same?
Tracker Design for FCC-hh

- **Geometry** (compared to CMS):

  - **R=1.1 m**
  - **R=2.4 m**

  CMS → FCC

  - Solenoid
  - Dipole/Solenoid

  \( \sigma_{R-\phi} = 25 \mu m \)
Tracker Design for FCC-hh

- **Geometry** (compared to CMS):
  - Dipole/Solenoid: R = 1.1 m, R = 2.4 m
  - CMS → FCC

- **Resolution:**
  - Simulated $p_T$:
    - 10 GeV/c → @$\eta$ = 5 $p \approx 700$ GeV/c
    - 100 GeV/c → @$\eta$ = 5 $p \approx 7$ TeV/c
    - 1 TeV
    - 10 TeV
    - Solenoid comparable to dipole
    - $\Delta p_T/p_T \sim 10\%$ up to $\eta = 5$

- Conservative material assumptions (in %):
  - Si 20%, C 42%, Cu 2%, Al 6%, Plastic 30%
  - $x/X_0 = 3\%$ per layer (of 0.43 cm)
Tracker Design for FCC-hh

1. **Geometry** (compared to CMS):
   - **Resolution:**
     - $6T$ scenario: technology challenging option with cost $\sim 0.7-0.9 \text{ BEuros}$ as the cost of detector should be $\sim 20-30\%$ of magnet → **multi-billion detector** (probably not well justified)
     - Focus on scenario with more aggressive detector technologies: $x/X_0 = 0.5-1.0\%$ (cf. ALICE ITS with MAPS, but radiation hard), $\sigma_{res} \sim 5-10\mu$m, sensors in tilted geometry, $B=4T/10m$ ($4Tm$ dipoles)

2. **Conservative material assumptions** (in %):
   - $\text{Si} 20\%$, $\text{C} 42\%$, $\text{Cu} 2\%$, $\text{Al} 6\%$, $\text{Plastic} 30\%$
   - $x/X_0 = 3\%$ per layer (of $0.43\text{cm}$)

3. **Simulated $p_T$:**
   - $10 \text{ GeV/c} \rightarrow @\eta=5 \ p \sim 700 \text{GeV/c}$
   - $100 \text{ GeV/c} \rightarrow @\eta=5 \ p \sim 7 \text{TeV/c}$
   - $1 \text{ TeV}$
   - $10 \text{ TeV}$
   - Solenoid comparable to dipole
   - $\Delta p_T/p_T \sim 10\%$ up to $\eta = 5$!
The technology for inner/fwd tracker is challenged due to high radiation (Fluka with DPMJET-III):

- By more than 2 orders higher than @ HL-LHC

1 MeV neutron eq. fluence after $30 \text{ab}^{-1}$
The technology for inner/fwd tracker is challenged due to high radiation (Fluka with DPMJET-III):

- **Trigger & Data rates**
  - **Pipelined hardware trigger** versus **software trigger**? Need to start with trigger design in parallel...
  - For illustration - 40MHz versus 1MHz data output from binary pixels @ given fluences:
    
    Data rate per module - 40Mhz, spars [Gb/s]: 3697.74 439.35
    Data rate per module - 1Mhz, spars [Gb/s]: 92.44 10.98
    
    - 380 (44) Gb/s/cm²
    - 9.5 (1.1) Gb/s/cm²

- For comparison: the largest Google data centers ~ 1Pb/s

By more than 2 orders higher than @ HL-LHC
Electromagnetic Calorimeter for FCC-hh

- **ECAL Design:**
  - $|\eta|$ up-to 6 + high granularity
  - Linear response (cf. ATLAS $m_H$ measurement $\rightarrow$ non-linearity a dominant systematic)
  - Const. res. term <1% essential (affects width of $m_{\gamma\gamma} \rightarrow H$ self-coupling measurement, etc.)
  - **Depth moderately sensitive on** $\sqrt{s} \rightarrow 30X_0$ **sufficient** (ATLAS $\sim 22X_0$) $\rightarrow$ FCCSW simulations ongoing with LAr/Pb (Si/W as option) $\rightarrow$ rad-hard technologies
Electromagnetic Calorimeter for FCC-hh

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**Challenges:**
- High radiation tolerance, especially in the FWD region
- High B field/large R affect bremsstrahlung to be away from $e^-/e^+$ ($\sim 30$cm for 20GeV $e^-$)
- Clever matching between ECAL & tracker necessary
Hadronic Calorimeter for FCC-hh

- **HCAL Design:**
  - $|\eta|$ up-to 6 + high granularity (as for ECAL)
  - jet containment: 30 TeV jet: 15% of hadrons with $E > 1$ TeV! $\rightarrow$ 98% containment (ECAL+HCAL) requires $12\lambda_{\text{int}}$ (arXiv:1604.01415)
    $\rightarrow$ FCCSW simulation on the way with TileCal (ATLAS HCAL) as a prototype (rad. level lower $\rightarrow$ scintillators OK)

- **Challenges:**
  - Performance of calorimeter improves with energy
    $\rightarrow$ for $p_T > 5$ TeV/c the const. term dominates $\rightarrow$ target $\sim 2\%$
Muon System (FCC-hh)

- **Design of muon system:**
  - Combine tracker & muon system (utilizing magnet design with return yoke) → measure track shape

\[ B_{\text{out}} = 2.45 \text{T} \]
\[ B_{\text{in}} = 6 \text{T} \]

\[ \Delta p_T / p_T \% \text{ at } p_T = 10 \text{ TeV} \]

- **B~0T for** \( R > R_1 \) → tangent @ \( R = R_1 \) points to origin!

\[ \eta \rightarrow 2\% \text{ res. at } 10 \text{ TeV/c, } \eta = 0 \]
(8% res. @ 10 TeV/c, \( \eta = 2 \))

Shielding coil can be @ lower R

Muon system can be slimmer
FCC-hh Machine Detector Interface (MDI)

- Studied $L^*=36, 61m$ (focus length) → consensus with detector people on $L^*=45m$
  - New optics design with longer triplets (~130m), dipole compensator (6.75Tm) & more beam-stay-clear to separate beams:
    - Optimization of triplet region to prevent from collision debris (mostly pions)
    - TAS/TAN & triplet shielding (tungsten):
      - Studied vertical versus horizontal beam crossing, influence of dipole compensator magnet, ...
      - Current design OK: can fulfill ~100MGy limit per O(20ab$^{-1}$)

Optics for $\beta^*=0.3$ → Phase 2
## Key FCC-ee Parameters

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</tr>
<tr>
<td></td>
<td>4000</td>
<td>22000</td>
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<td>Bunch population [10^{11}]</td>
<td>1.0</td>
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<td>Luminosity/IP x 10^{34} cm^{-2}s^{-1}</td>
<td>210</td>
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<td>19</td>
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<td>Energy loss/turn [GeV]</td>
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<tr>
<td>Synchrotron power [MW]</td>
<td>100</td>
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- Precision measurements require high luminosity → **FCC-ee: an ultimate Z, W, H, t factory**

Same FCC optics for all energies

---

5th ICNFP 2016 (6th-14th July)
### Key FCC-ee Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-ee (400 MHz)</th>
<th>LEP2</th>
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<tbody>
<tr>
<td>Physics working point</td>
<td>Z</td>
<td>WW</td>
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<tr>
<td>Energy/beam [GeV]</td>
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<td>80</td>
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<tr>
<td>Bunches/beam</td>
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<td>91500</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>7.5</td>
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- Precision measurements require high luminosity → **FCC-ee: an ultimate Z, W, H, t factory**
- **Challenges:**
  - Huge number of bunches per beam → need for crossing angle (30 mrad) & 2 separate rings to avoid parasitic interactions
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  - Huge number of bunches per beam → need for crossing angle (30 mrad) & 2 separate rings to avoid parasitic interactions
  - Large amount of synchrotron radiation, especially at tt<sub>bar</sub> (energy loss, background)

Same FCC optics for all energies
RF cavity needs to compensate it
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- **Challenges:**
  - Huge number of bunches per beam → need for crossing angle (30 mrad) & 2 separate rings to avoid parasitic interactions
  - Large amount of synchrotron radiation, especially at tt\textsubscript{bar} (energy loss, background)
  - Extreme luminosity values → small beam size & L\textsuperscript{*} (~2m) necessary → focusing quads close to IP + “packed design for the forward instrumentation”

→ **IR design a crucial part of detector design study**
FCC-ee IR & Detector Design

- IR design driven by the hardest: $t\bar{t}$ option $\rightarrow$ **study to limit the synchrotron radiation**

  - asymmetric optics/bending $\rightarrow$ limits SR sent to the IP

  $\rightarrow$ Studies show that SR $\gamma$ rates similar to LEP2 level $\rightarrow$ **OK**

  $\rightarrow$ Studies continue for other energies: Z, H, ...

![Design of IR: $e^-/e^+$](image)
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- IR design driven by the hardest: $t\bar{t}$ option → study to limit the synchrotron radiation
  
  - asymmetric optics/bending → limits SR sent to the IP

  → Studies show that SR $\gamma$ rates similar to LEP2 level → OK
  
  → Studies continue for other energies: Z, H, ...

- Using CLIC detector & CLIC software as a natural starting point
  
  → detector minimally adapted to FCC-ee conditions (IR design → VXD + Tracker)

  → Full simulations started to understand the key limits of detector design due to background (SR, beamsstrahlung):

  → Starting to formulate the key physics requirements on detector design
Common Software Framework

- Aim of FCC SW project is to support all FCC options and share software among them:
  - Sharing the collaborative experience with: ATLAS (tracking), CMS (analysis interface), LHCb (simulation frame, infrastructure), CLIC (grid processing)
  - Central building blocks:
    - GAUDI (underlying framework) + PODIO (C++ library supporting handling of event-data models)
    - Externals: Geant4, DD4Hep (for data description), Delphes (for parametrized simulations)
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    - **Externals**: **Geant4**, **DD4Hep** (for data description), **Delphes** (for parametrized simulations)
  - Simulations, Reconstruction & Analysis:
    - **Delphes**: FCC-hh prepared a common detector description for parametrized physics studies
    - Participation in CMS **tkLayout** project (tracker design studies)
    - Technical infrastructure developed for combined fast/full simulation with Geant4
    - Joint project with ATLAS: **ACTS** - ATLAS track reconstruction software
    - **PAPAS** for fast simulation and particle-flow reconstruction
    - **HEPPY (CMS)** as python-based analysis framework
    - Standalone reader for FCC data model
  
Summary & Outlook

- There is **a lot of progress since the FCC kick-off meeting in February 2014** in all FCC related projects: FCC-hh, FCC-ee and FCC-eh (not covered here)

- The FCC detector & MDI studies **can heavily draw from the LHC experiments** and their upgrade plans (FCC-hh) or **CLIC/ILC projects** (FCC-ee)

- As for the detector technology, the **FCC detectors (particularly for FCC-hh) require a significant R&D on detectors and electronics.** Once the LHC Phase II R&D is finished, there is a crucial need for installing a dedicated R&D program

- The FCC project is an excellent environment to transfer an immense amount of knowledge and experience in our field to the young generation
Thank you!

My sincere thanks belongs to the whole team of FCC-hh & FCC-ee colleagues

working on the detector & MDI design