FCC-hh Experiments Summary

Summary of 7 Parallel Sessions

Martin Aleksa
on behalf of the FCC-hh Experiments WG
This talk summary summarizes 7 sessions, 10.5 hours!

Will not even try to do justice to all the 26 speakers!

Apologies for having to drop important work that has been done

Please go and have a look at the material from all the parallel sessions!
Why FCC-hh?
Physics Potential of FCC-hh

- **Guaranteed deliverables:**
  - study of Higgs and top quark properties, and exploration of EW SB phenomena, with unmatchable precision and sensitivity
  - **tbd:** further clarification of the nature of new physics discovered at LHC or elsewhere

- **Exploration potential:**
  - mass reach enhanced by factor $\sim E / 14 \text{ TeV}$ (will be 5–7 at 100 TeV, depending on integrated luminosity)
  - statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC
  - benefit from both direct (large $Q^2$) and indirect (precision) probes

- **Provide firm 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?
  - did baryogenesis take place during the EW phase transition?

M. Mangano

Dedicated session
Wednesday 8:30 – 10:00.
Please have a look!
Physics Program in a Nutshell

- **FCC-hh — The ultimate discovery machine**
  - directly probe new physics up to unprecedented scale
  - discover/exclude:
    - heavy resonances “strong” $m(q^*) \approx 50$ TeV,
    - “weak” $m(Z') \approx 30$ TeV,
    - SUSY $m(\text{gluino}) \approx 10$ TeV,
    - $m(\text{stop}) \approx 5$ TeV

- **Precision machine**
  - probe Higgs self-coupling to few % level, and %-level precision for top yukawa and rare decays
  - measure SM parameters with high precision
  - exploit complementarity with $e^+e^-$ by probing high dim. operators in extreme kinematic regimes

Very interesting studies of FCC-hh measurements presented in the session Thursday 10:30 – 12:00.
Please have a look!

M. Selvaggi
Higgs Physics

- Higgs self-coupling (bbγγ, bbττ, bb+leptons)
- Top-Yukawa:
  - ttH, H → γ γ (threshold), H → bb (boosted)
- Rare Higgs decays (H → cc, H → μμ, H → ZZγ)
- “Big Five”: Higgs decays (H → 4l, WW, γγ, ττ, bb)
- VBF (VBS)
- BSM Higgs (H±/ → tb)

At threshold, 20x10^9 ggH events are produced at 30 ab⁻¹
With pT(H) > 1 TeV, 10⁶ H events at disposal.

Large statistics allow these measurements to be performed in the “boosted” regime.

- γ, leptons, pt, η acc
- b/tau tagging performance
- fwd jet tagging
- id efficiencies and fake rates

→ The FCC-hh experiments must be ‘general general’ purpose experiments with very large η-acceptance and extreme granularity (W. Riegler)
Why is Di-Higgs interesting?

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

**H → γγbb is the golden channel for FCC-hh**
- Will derive requirements for detector (systematics, boosted objects)

The strength of the triple and quartic couplings is fully fixed by the potential shape.
How to Exploit Physics Potential?
During last year converged on reference design for an FCC-hh Experiment

Plan to demonstrate in the CDR document, that an experiment exploiting the full FCC-hh physics potential is technically feasible

However, there is a lot of room for other ideas, other concepts and different technologies
Reference Design

- 6T, 12m bore solenoid, 10Tm dipoles, shielding coil
  - 65 GJ Stored Energy
  - 28m Diameter
  - >30m shaft
  - Multi Billion project

- 4T, 10m bore solenoid, 4T forward solenoids, no shielding coil
  - 14 GJ Stored Energy
  - Rotational symmetry for tracking and trigger!
  - 20m Diameter (≈ ATLAS)
  - 15m shaft
  - ≈ 1 Billion project

4T 10m solenoid
Forward solenoids
Silicon tracker
Barrel ECAL Lar
Barrel HCAL Fe/Sci
Endcap HCAL/ECAL Lar
Forward HCAL/ECAL Lar
Impressive progress with opening scenarios of reference detector

- 75m cavern allows for tracker extraction
- Two shafts, 15m and 10m
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

Everything should be made as simple as possible, but not simpler (Quote attributed to Einstein)
1 MeV Neutron Equivalent Fluence for 30ab$^{-1}$

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

- **Barrel calorimeter:**
  - EM-calo: $4 \times 10^{15}$ cm$^{-2}$
  - HAD-calo: $4 \times 10^{14}$ cm$^{-2}$

- **End-cap calorimeter:**
  - EM-calo: $2.5 \times 10^{16}$ cm$^{-2}$
  - HAD-calo: $1.5 \times 10^{16}$ cm$^{-2}$

- **Calorimeter gap:**
  - from $10^{16}$ cm$^{-2}$ to $10^{14}$ cm$^{-2}$

- **Forward calorimeters:**
  - $\sim 5 \times 10^{18}$ cm$^{-2}$ for both the EM and the HAD-calo

Generally $\sim 10$-30 times worse than HL-LHC

Exception: Forward calorimeter goes to higher $\eta \rightarrow$ bigger factor
Software
Supporting GEANT4 full and fast simulation and parameterized simulation (DELPHES & PAPAS)
ACTS project:
• Idea: Extracting the ATLAS tracking SW to an independent tool-kit
  • Framework and experiment independent
• Integration into FCC-SW ongoing, large parts finalized
  • Geometry from DD4HEP can be read in (e.g. TkLayout FCC tracker geometry)
  ✔ Events generated with Pythia and overlaid to a gg->H event
  ✔ FATRAS simulation w/o material effects
  ✔ Using current FCChh detector
Detector Studies
• **The challenge:** ultimate FCC-hh: ~1000 collisions per bunch crossing at 25ns bunch spacing scheme → **distance <200µm and 0.5ps in time**

• **Primary vertex identification:**
  – Important for many physics channels
  – Important for pile-up suppression
  – Important for B-tagging
  – However, $\sigma_z$ resolution of single track suffers from beam-pipe material and tracker material

• **Background contamination level during track fitting:**
  – How many wrong background hits are included in the track fit?
  – Ratio of background hits in track-fit should be kept <20%

• **Both problems improved by tilted layout**
  – Material reduction → multiple scattering reduction

• Also investigating how much timing information would help
Recent Design Optimization Work (4.v01)

TkLayout: fast detector simulation and layout design tool

- Tilted layout of **outer tracker** driven by requirement to achieve \(-0.2\) bkg. contam. level (BCL) in PR:
  - uppermost layer designed non-tilted to keep the highest possible lever-arm
  - modules positioned to hermetically cover full luminous region \(\pm 75\) mm
  - ECs strips res. in Z needed to be set to \(-500\)um (\(-1\)mm OK)

- Tilted layout of **inner tracker** driven by \(-0.2\) BCL in PR & highest achievable z0 res. (to deal with primary vertexing @PU~1000):
  - tilt angle of 1st layer: \(\theta_{\text{tilt}} \approx 10^\circ\) optimized to achieve a compromise between low MB & higher radial position

Z. Drasal
Good Performance with Tilted Layout

$\delta p_T/p_T \leq 10\%$ 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 $\eta = 0.0$

Primary vertexing @ PU~1000 seems very difficult for $\eta > 4.0$, even with timing res. ~5ps!

$P_T = 1$ GeV/c
$P_T = 5$ GeV/c
$P_T = 10$ GeV/c
$P_T = 100$ GeV/c
$P_T = 1$ TeV/c
$P_T = 10$ TeV/c

$\sigma_z$ resolution of single track

Fraction of tracks correctly assigned to primary vertex $w$ and w/o timing

Z. Drasal
Many interesting studies!
- material studies
- beam-pipe radius
- tau decay vertex position efficiency
- B-hadron decay vertex position efficiency
- Flavor tagging

Impact parameter resolution as a function of the beam-pipe radius

Moving out the innermost barrel layer by 1 cm would degrade the impact parameter resolution by 45% for very forward tracks of pT=10 GeV. → keep radius as small as possible.
Full Simulation Tracking Studies

- Full simulation studies with FCC SW are complementing studies with TKLayout, some aspects can only be studied with full simulation
  - Needed to assess impact of pile-up on tracker performance
  - Only way to check feasibility of pattern recognition
  - Occupancy studies

18M hits per BC (pile-up of 1000, 25µm x 50µm pixels)

Material Budget non-tilted layout (3.v02)
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) (J. Faltova)
- HCAL Barrel and Extended Barrel:
  - Scintillating tiles / Fe with SiPM (C. Neubüser)

Other options considered for ECAL
- Digital Si / W (T. Price)
- Analog Si / W (not yet studied, but will profit from CMS HGCal TDR)
Electromagnetic Calorimeter (ECAL)

- Detector with larger longitudinal and transversal granularity compared to ATLAS
  - ~8 longitudinal layers, fine lateral granularity ($\Delta \eta \times \Delta \phi = 0.01 \times 0.01$), ~2M channels
- Possible only with straight multilayer electrodes
  - Proposal: Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
- Pros: Easy construction (compared to ATLAS accordion), higher precision
- Cons: Sampling fraction changes with radius:
  - Possible to achieve targeted electron/photon energy resolution of $10\% / \sqrt{E} \oplus 1\%$?
  - Electronics noise with PCB readout

Reference calorimeter in FCC SW (incl. tracker)
ECAL First Performance Results

- First performance results very encouraging
- Very critical dependence on upstream material (tracker, services and cryostat)
  - Dead material correction applied
- Next steps: Add electronics noise, pile-up, geometry optimization, other absorber materials

**FCC Week 2017 Berlin — M. Aleksa (CERN)**

J. Faltova
HCAL Barrel

Reference Detector:

- 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 -> stainless Steel absorber (Calos in magnetic field)
- SiPM readout $\rightarrow$ faster, less noise, less space

How could we achieve compensation?

$\rightarrow$ Higher Z material (e.g. Pb spacers)
ECAL & HCAL Barrel First Performance Results

• ECAL and HCAL in EM scale
  – Comparable with ATLAS results
  – Calibrated pion resolution will be better
  – In addition fine granularity will be exploited for particle flow

• Next steps: corrections/calibration, clustering, jet algorithms, particle flow
Digital ECAL

Interesting digital ECAL option using CMOS MAPS

- Can achieve the ultra high granularity with the use of CMOS Monolithic Active Pixel Sensors
- Thin sensitive region, usually 12-25um
- Thin substrates, low material budget
- Low noise
- Readout on the sensor so no need for separate chip
- Developments in HV/HR CMOS to deplete the sensor improve charge collection speed and radiation hardness

Generally the more active layers the better the resolution (speaking about 30 – 50 layers)
Absorber material: Pb and W equivalent in terms of resolution, but Pb lead shows better linearity (wider shower)

Number of hits per layer defines necessary granularity
Digital ECAL First Performance Results

- Optimal granularity: pixel pitch ~50µm
- Sensor thickness ~18µm
- With realistic geometry (1mm air gap for read-out, cooling, power) achieving 14% / \sqrt{E} at \eta = 0.
- Linearity is of concern (more than one particle per pixel)

Radiation Hardness
- Forward region of FCC-hh detectors Si not an option
- Depleted CMOS currently under development (HV/HR) with results to $10^{15}$ n\textsubscript{eq}/cm\textsuperscript{2} and beyond presented recently by other groups so feasible for Barrel region

Cost
- Cost of CMOS imaging sensors needs to decrease to make affordable but over 20 years this is expected to fall dramatically.
- A cost of 30 cents / cm\textsuperscript{2} would mean an ECAL of ~$30M.
- Much more compact ECAL would also reduce costs of other systems

FCC Week 2017 Berlin — M. Aleksa (CERN)
• What is the required lateral segmentation for FCC calorimetry?
  – Studies based on SLIC SW.
  – Jet substructure studies for jets up to 20 TeV:
    • Optimal HCAL size using is 5x5 cm (vs ~20x20 cm for ATLAS/CMS)
      – almost no improvement anymore for smaller cell sizes
    • Corresponds well to $\Delta \eta \times \Delta \phi = 0.025 \times 0.025$ in reference detector.
Muon System

ATLANT muon system HL-LHC rates (kHz/cm²):
- MDTs barrel: 0.28
- MDTs endcap: 0.42
- RPCs: 0.35
- TGCS: 2
- Micromegas und sTGCS: 9-10

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at a collision energy of 14 TeV. The values are averages, in kHz/cm², over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2R1</td>
<td>162 ± 28</td>
<td>327 ± 60</td>
<td>590 ± 110</td>
</tr>
<tr>
<td>M2R2</td>
<td>15.0 ± 2.6</td>
<td>52 ± 8</td>
<td>97 ± 15</td>
</tr>
<tr>
<td>M2R3</td>
<td>0.90 ± 0.17</td>
<td>5.4 ± 0.9</td>
<td>13.4 ± 2.0</td>
</tr>
<tr>
<td>M2R4</td>
<td>0.12 ± 0.02</td>
<td>0.63 ± 0.10</td>
<td>2.6 ± 0.4</td>
</tr>
<tr>
<td>M3R1</td>
<td>39 ± 6</td>
<td>123 ± 18</td>
<td>216 ± 32</td>
</tr>
<tr>
<td>M3R2</td>
<td>3.3 ± 0.5</td>
<td>11.9 ± 1.7</td>
<td>26 ± 4</td>
</tr>
<tr>
<td>M3R3</td>
<td>0.17 ± 0.02</td>
<td>1.12 ± 0.16</td>
<td>2.9 ± 0.4</td>
</tr>
<tr>
<td>M3R4</td>
<td>0.017 ± 0.002</td>
<td>0.12 ± 0.02</td>
<td>0.63 ± 0.09</td>
</tr>
<tr>
<td>M4R1</td>
<td>17.5 ± 2.5</td>
<td>52 ± 8</td>
<td>86 ± 13</td>
</tr>
<tr>
<td>M4R2</td>
<td>1.58 ± 0.23</td>
<td>5.5 ± 0.8</td>
<td>12.6 ± 1.8</td>
</tr>
<tr>
<td>M4R3</td>
<td>0.008 ± 0.014</td>
<td>0.54 ± 0.08</td>
<td>1.37 ± 0.20</td>
</tr>
<tr>
<td>M4R4</td>
<td>0.007 ± 0.001</td>
<td>0.468 ± 0.008</td>
<td>0.31 ± 0.04</td>
</tr>
<tr>
<td>M5R1</td>
<td>19.7 ± 2.9</td>
<td>54 ± 8</td>
<td>91 ± 13</td>
</tr>
<tr>
<td>M5R2</td>
<td>1.58 ± 0.23</td>
<td>4.8 ± 0.7</td>
<td>10.8 ± 1.6</td>
</tr>
<tr>
<td>M5R3</td>
<td>0.29 ± 0.04</td>
<td>0.79 ± 0.11</td>
<td>1.69 ± 0.25</td>
</tr>
<tr>
<td>M5R4</td>
<td>0.23 ± 0.03</td>
<td>2.1 ± 0.3</td>
<td>9.0 ± 1.3</td>
</tr>
</tbody>
</table>

HL-LHC muon system gas detector technology will work for most of the FCC detector area.

W. Riegler
Muon System

$p_T = 3.9 \text{GeV}$ enters muon system
$p_T = 5.5 \text{GeV}$ leaves coil at 45 degrees

Three ways to measure the muon momentum:

1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil

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

- $\leq 10\%$ standalone momentum resolution up to 3TeV/c
- $\leq 10\%$ combined momentum resolution up to 20TeV/c

All within reach of ‘standard’ muon system technology

W. Riegler
Do we require a trigger for FCC-hh?
- Yes! We're not going to store every bunch-crossing forever
- Depends on what you mean by trigger...

Where is the data buffered whilst events are being selected?
- On-detector? Off-detector? A combination of them both?
- Depends on link speeds, power, material budget, DAQ capacity

How are the events selected?
- Depends on what data is available, processing capabilities, backgrounds and physics goals...

Front end detector data rates are substantial:
- Tracker: \(~800\) TB/s\(^1\)
- LAr+Tile Calo: \(~200\) TB/s\(^2\)
- Si/W Calo: \(O(1000\) TB/s\)\(^3\)? guesstimate

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<table>
<thead>
<tr>
<th></th>
<th>Threshold L=5(\times)10(^3)</th>
<th>Threshold L=3(\times)10(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>60 kH(z) 55 GeV 90 GeV</td>
<td>60 kH(z) 35 GeV 60 GeV</td>
</tr>
<tr>
<td>muon</td>
<td>60 kH(z) 35 GeV 60 GeV</td>
<td>60 kH(z) 160 GeV (&gt;350) GeV</td>
</tr>
</tbody>
</table>

Thresholds are indicative, clearly depend on details of bandwidth allocation.

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J. Brooke

Scaling up from CMS
Common Technologies
Common Technologies: Si Sensors

Extremely interesting survey over different kinds of Si sensors

- very fast development
- for tracking (Hybrid vs MAPS)
- for timing (e.g. LGAD)

Need to make sure that high momentum in this field is maintained after HL-LHC → Strategic R&D

N. Wermes
Silicon Photonics for HEP?

- **Silicon Photonics:**
  - Use of silicon substrate and ASIC production techniques to pattern waveguide and optical field manipulating structures
  - Allows the fabrication of optical modulators and high level of integration of optical circuits like couplers and gratings
  - Promise of lower power & cost
  - But still need a source of optical power (that could be located remotely)

- **Is radiation resistance sufficient?**
  - Some work assessing this technology has started

First attempts to improve radiation hardness very promising
Conclusions

• Great progress since last FCC Week
• New reference design with 4T solenoid (10m diameter) and forward solenoids
• Detector studies reach impressive level of detail
  – Results from extrapolations from HL-LHC and FCC simulation (full simulation, fast simulation, parameterized simulation)
  – No show-stoppers to build an FCC-hh detector exploiting the full physics potential – however, challenging environment, detailed work on detector design and performance important
• Getting prepared for the CDR
  – Outline exists
  – Next step: starting to write!
Thank You for Your Attention!
Back-Up
**Electrical scheme**
- All Solenoids powered in series
- Main solenoid decoupled from forward solenoids during quench (bypass diodes parallel to forward solenoids)
- Requires three current leads

**Quench protection** (using Quench code Quench 2.7)
- Conductor RRR = 400
- Main solenoid: Extraction (Quench-back) + Quench heaters
- Forward solenoid: Quench heaters
- Nominal Quench: 56 K in main solenoid, 89 K in forward solenoid, 73% extraction
- Worst case fault (no working heaters): 142 K in main solenoid, 133 K in forward solenoids
**FCC-hh Detector and Experiments CDR Outline**

**Benchmarks processes, detector requirements from physics**
Definition of the benchmark processes with main backgrounds
Detector requirements ‘from physics’ in terms of momentum resolution, energy resolutions, acceptance and objects like e/gamma performance, jet performance, tau, b, Etmiss, Muons, Trigger

**Experiment, detector requirements from environment:**
Luminosity, radiation environment, luminous region, pileup
Discussion of the reference detector and alternative ideas

**Software:**
Simulation software for FCC detectors

**Magnet systems:**
Engineering of reference design and discussion of alternatives

**Tracker:**
Layout, performance, technology and data rate discussion

**EMCAL:**
Liquid Argon and Silicon, performance and technology discussion, ideas on digital ECAL

**HCAL:**
Organic Scintillators, Liquid Argon, SiPM technology, Silicon

**Muons:**
Principles of trigger versus identifier, standalone and combined performance, technologies

**Trigger/DAQ:**
Principle concepts in relation to HL-LHC

**Physics performance:**
DELPHES formulation in relation to ATLAS/CMS Performance for benchmark channels

**Cavern and infrastructure:**
Cavern and shaft dimensions, installation scenarios, sidecavern, access, safety, shielding, activation, maintenance scenarios

**Cost Goals, Strategic R&D:**
Extreme radiation environment, large area silicon sensors, high speed links, microelectronics, radiation hard scintillators, Liquid Argon Technology, High precision timing detectors ...