Physics requirements and performance of the FCC-hh Calorimeter

Michele Selvaggi (CERN)
on behalf of the FCC-hh calo group

Eugene (Oregon) - CALOR 2018 - 21/05/2018
FCC-hh - Scope

- **FCC-hh Target:**
  - $E_{CM} = 100$ TeV
  - needs 16T magnets
  - 100 km long

- **Direct Search for New Physics:**
  - direct production of heavy resonances up to $m \approx 40$ TeV
  - stops up to $m \approx 10$ TeV

- **Precision SM physics (complementary to $e^+e^-$):**
  - Higgs potential, self-coupling ($\Delta\lambda/\lambda \approx 5\%$)
  - Higgs rare decays,
  - EWK, Top physics in new extreme dynamical regimes
Key parameters

- **Luminosity:**
  - baseline: $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ (200 PU)
  - ultimate: $30 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ (1000 PU)

  $\rightarrow$ $O(20 \text{ ab}^{-1})$ over 25 years of operations

- **Radiation levels:**
  - pp cross-section from 14 TeV $\rightarrow$ 100 TeV only grows by factor 2
  - radiation level increase mostly driven by increase in inst. luminosity

  $\rightarrow$ x10 more fluence compared to HL-LHC (x100 wrt to LHC)

  - Ex: calorimetry
    - 1 MeV-neq fluence $\approx 4 \times 10^{15}$ (14) cm$^{-2}$ in the Barrel for ECAL (HCAL)
    - 1 MeV-neq fluence $\approx 2 \times 10^{16}$ cm$^{-2}$ in the EndCaps

  $\rightarrow$ Radiation hardness needed (especially forward!)
Physics requirements for calorimetry (low $p_T$)

- Low $p_T$ physics produced at threshold (EWK, Higgs, top) is more forward:
  - need larger $\eta$ coverage (up to $|\eta| = 6$) compared to LHC
  - and radiation hard detectors (important especially FWD)
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- Need excellent energy and angular resolution at low energy for precision physics (ex: $HH \rightarrow \gamma\gamma bb$):
  - small noise and stochastic terms
  - robustness vs pile-up (noise)
  - $\pi^0$ rejection capabilities

$$m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\Delta\alpha)$$

$$\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} + c$$
- $a=6\%$, $c=0.7\%$
- $a=10\%$, $c=1\%$
- $a=20\%$, $c=2\%$
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- Need excellent lateral and longitudinal granularity
  - make particle-flow algorithms more effective
  - pointing capabilities (needed to trigger on $HH \rightarrow \gamma\gamma bb$)
  - helps with photon Id and PU rejection (PU jet Id)

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Physics requirements for calorimetry (high $p_T$)

The FCC-hh has sensitivity for (colored) hadronic resonances up to $m=40$ TeV, hence require:

- full containment for jets with $p_T = 20$ TeV → small constant term

\[ \geq 11 \lambda \] for $E_m + \text{Had}$
The FCC-hh has sensitivity for (colored) hadronic resonances up to $m=40 \text{ TeV}$, hence require:

- full containment for jets with $p_T = 20 \text{ TeV} \rightarrow$ small constant term
- limit punch throughs (and helps muon Id)
- assess requirements correctly drives detector size $\Rightarrow$ magnet $\Rightarrow$ cost

Physics requirements for calorimetry (high $p_T$)

\[ \geq 11 \lambda_1 \text{ for } E_m + \text{Had} \]
Physics requirements (high $p_T$)

- The FCC-hh has **sensitivity** for (colored) **hadronic resonances** up to $m_R \approx 40$ TeV, hence require:
  
  \[ \Rightarrow \text{full containment for jets with } p_T = 20 \text{ TeV} \rightarrow \text{small constant term} \]

- The FCC-hh has sensitivity for **boosted resonances** (ex: $Z' \rightarrow tt$ or RSG $\rightarrow WW$) up to $m_R \approx 20$ TeV
  
  - ex: $W$ jet with $p_T = 10$ TeV $\rightarrow \Delta R = 0.02$ (typical ECAL cell size at CMS/ATLAS)
  
  - need very **high granularity** to resolve such substructure (to discriminate against plain QCD).
    - tracking can achieve such separation
    - target: **4x better transverse granularity** wrt ATLAS/CMS detectors
    - do calorimeters have the capability to resolve such objects? Does granularity translate it to actual separation power? **Combine longitudinal/lateral information**

\[ \Delta R = 2m/p_T \]
The FCC-hh detector

**Barrel ECAL: LAr/Pb**
- $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\%$
- 30 $X_0$
- lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
- long. segm: 8 layers

**Fwd ECAL: LAr/Cu**
- $\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\%$
- lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
- long. segm: 6 layers

**Fwd HCAL: LAr/Cu**
- $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\%$
- lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
- long. segm: 6 layers

**Barrel HCAL: Sci/Pb/Fe**
- $\sigma_E/E \sim 50\%-60\%/\sqrt{E} \oplus 3\%$
- 11 $\lambda$ (ECAL+HCAL)
- lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
- long. segm: 10 layers

**Tracker:** $\sigma_{p_T}/p_T \sim 20\%$ at 10 TeV (1.5m radius)

**Central Magnet + Fwd solenoids**
Photon resolution with PU

Large impact of in time PU on the noise term (out of the box with no improvements)!!

• severely degrades $m_{\gamma\gamma}$ resolution (improving clustering, not sliding windows may help)

• impacts Higgs self-coupling precision by $\delta K_{\lambda} \approx 1\%$

• some thought needed (tracking, timing information can help?)
Jet Performance with Full sim

- Excellent resolution up to $p_T = 10 \text{ TeV}$ !!

- Large impact of PU at low $p_T$ (as expected)

- crucial for low mass di-jet resonances (again, such as $HH \rightarrow b\bar{b} \gamma\gamma$)

- Further motivation for Particle-flow

  $\rightarrow$ since charged PU contribution can be easily subtracted (Charged Hadron Subtraction)
High Mass resonances

- Constant term drives jet energy resolution at high $p_T$
- Directly impacts sensitivity for excluding discovering narrow resonance $Z' \rightarrow jj$
- Small impact on strongly coupled (wide) resonances

Narrow resonances

Wide resonances

FCC simulation
$\sqrt{s} = 100 \, \text{TeV}$

Integrated luminosity versus mass for a $5\sigma$ discovery

$\overline{S}/B$ vs. $\sqrt{s} = M_V$ [TeV]

- $\Delta=\pm 10\%$
- $\Delta=\pm 4\%$
- $\Delta=\pm 1\%$

$S$ is the signal strength and $B$ is the background.

$|\eta_j| < 1$

$\overline{S}/B$ iso-curves for $\Delta=\pm 10\%$, $\Delta=\pm 4\%$, and $\Delta=\pm 1\%$.
Jet Pile-Up identification

- With 200-1000PU, will get huge amount of fake-jets from PU combinatorics
- need both longitudinal/lateral segmentation for PU identification
- Simplistic observables show possible handles, pessimistic.. (in reality tracking will help a lot)
Jet substructure

$\Delta R = \frac{2m}{p_T}$
Jet substructure

- Performance good up to 1 TeV, with Calorimeter standalone, and without B field!
- Far from having explored everything possible:
  - Particle-Flow tracks and B field (decrease local occupancy) will improve
  - Machine Learning techniques will help a lot (train on 3D shower image)
Conclusion

Several Challenges for Calorimeters at the FCC-hh:

• $L = 30 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ imposes high radiation levels and high PU
  → radiation hardness is needed (especially in fwd region)

• 1000 PU is a hostile environment, also for calorimetry (impacts energy resolution)
  → need help from tracking and timing
  → longitudinal/lateral segmentation is suitable for:
    • Photon Id, PU jet Identification
    • Particle-Flow algorithm

• Both precision physics (low $p_T$) and New Physics (high $p_T$) require excellent performance:
  • excellent angular and energy resolution
  • high segmentation, both longitudinally and laterally

• Next talk (A. Zaborowska) will discuss more specific aspects of technology and reconstruction. Stay tuned!
Trigger/data rates

HL-LHC:
- rates:
  - Calo + Muon: 20 Tb/s
  - Tracker: 80 Tb/s
- ATLAS approach:
  - read out full Calo+Muon @40MHz (L0) (better muon standalone trigger?)
  - read the tracker @1MHz
- CMS approach:
  - read Calo+Muon + part of tracker (stubs) @40MHz as input to L1 trigger

FCC:
- rates:
  - Calo + Muon: 200-300 Tb/s
  - Tracker: 800 Tb/s
- Could be possible to read-out Calo+Muon @40MHz (200 Tb/s)
- Sounds hard to read full detector @ 40MHz (1Pb/s)
- Calo+Muon alone will not provide enough selectivity for reading @1MHz → need a track trigger
Di-Higgs - $bb\gamma\gamma$

assuming QCD can be measured from sidebands

nominal background yields:

$\delta K_{\text{stat}} \approx 3.5\%$

$\delta K_{\text{stat + syst}} \approx 4.5\%$

$\delta r_{\text{stat}} \approx 2.5\%$

$\delta r_{\text{stat + syst}} \approx 3\%$

varying (0.5x-2x) background yields:

$\delta K_{\text{stat}} \approx 3 - 5\%$

$\delta r_{\text{stat}} \approx 2 - 3\%$
Heavy resonances (RSG $\rightarrow$ WW)

Jet1/2 SD $100<m<50\text{GeV}$
Jet1/2 $\tau_21 < 0.6$
Jet1/2 Flow$45 < 0.07$
Jet1/2 Flow$55 < 0.07$

Need more di-jet 1k raw of 50M
Supersymmetry (stop production)

- Multiple jets
- 2 b-jets
- On-shell top quarks
- Large $M_{\text{E}_T}$ [from the two LSPs]