Higgs and the Energy Frontier

Jim Hirschauer [co-Convener]

Fermilab

on behalf of Gabriella Sciolla [co-Convener], Michael Begel, and Meenakshi Narain

DOE BRN Study Workshop on HEP Detector R&D
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Introduction

Goal of this presentation:
- Convey approach and main ideas of Energy Frontier section of BRN report in ~20 minutes

Goals for Higgs & Energy Frontier section of BRN report:
- Describe transformative physics opportunities and detector requirements at future colliders
- Be accessible to non-experts and inspirational!
- High-level Key Challenges
  1. Tracking
  2. Calorimetry
  3. Precision timing
  4. Trigger and readout
- No attempt to motivate specific collider or detector scenario
- Focus on most exigent detector requirements from all scenarios

Primary references during BRN process: European Strategy process and Briefing Book, Future detector CDRs, CPAD reports
"... the path forward is completely clear ..."

Nima Arkani-Hamed, 11 March 2019:

The discovery of the Higgs particle – especially with nothing else accompanying it so far – is unlike anything we have seen in any state of nature, and is profoundly “new physics” in this sense. ...

While we continue to scratch our heads as theorists, the most important path forward for experimentalists is completely clear: measure the hell out of these crazy phenomena!
Collider scenarios beyond HL-LHC

- Simplified collider timeline with focus on motivating detector R&D
- Based on Ursula Bassler's timeline presented at Granada Symposium.
- To do: add technology timelines in coordination with technology groups

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy Range</th>
<th>L Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear e+e-</td>
<td>250–380 GeV</td>
<td>$1.4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ at Higgs threshold</td>
</tr>
<tr>
<td>Circular e+e-</td>
<td>90–250 GeV</td>
<td>$9 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ at Higgs threshold</td>
</tr>
<tr>
<td>Circular pp</td>
<td>100 TeV</td>
<td>$3 \times 10^{35}$ cm$^{-2}$ s$^{-1}$, 1000 PU</td>
</tr>
<tr>
<td>Staged e+e- → pp</td>
<td>90–250 GeV</td>
<td>100 TeV pp</td>
</tr>
</tbody>
</table>

Timeline:
- Linear e+e-: 2020–2040
- Circular e+e-: 2040–2060
- Circular pp: 2060–2080
- Staged e+e- → pp: 2080–2090
Transformative physics goals beyond HL–LHC

- Elucidate theoretical mysteries of SM: **Measure properties of Higgs** [and top, W, etc.]
- Elucidate extant experimental mysteries: **Produce and study dark matter** [and other new phenomena]

Dual roles for future colliders: **ultimate discovery & precision measurement machines**

**Higgs physics with FCC-comb** (e.g.)
- 0.2–1% precision on all Higgs couplings 
  \( \text{Up to 10}\times \text{improvement over HL-LHC!} \)
- Measure BR (H→inv) to 0.024% 
  \( 80\times \text{improvement over HL-LHC! Current limit <20\%} \)
- Measure self-coupling with 5% precision 
  \( 10\times \text{improvement over HL-LHC!} \)
- Model independent Higgs total width measurement

**Searching for new phenomena at 100 TeV pp**
- 7\(\times\) increase in mass reach beyond HL–LHC!
- Probe new structures at \( \frac{1}{1,000,000} \times \) proton radius!

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>FCC-comb*</th>
</tr>
</thead>
<tbody>
<tr>
<td>(KW) [%]</td>
<td>0.985**</td>
<td>0.19</td>
</tr>
<tr>
<td>(KZ) [%]</td>
<td>0.987**</td>
<td>0.16</td>
</tr>
<tr>
<td>(Kg) [%]</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>(K\gamma) [%]</td>
<td>1.6</td>
<td>0.31</td>
</tr>
<tr>
<td>(KZ\gamma) [%]</td>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>(Kc) [%]</td>
<td>--</td>
<td>0.96</td>
</tr>
<tr>
<td>(Kt) [%]</td>
<td>3.2</td>
<td>0.96</td>
</tr>
<tr>
<td>(Kb) [%]</td>
<td>2.5</td>
<td>0.48</td>
</tr>
<tr>
<td>(K\mu) [%]</td>
<td>4.4</td>
<td>0.43</td>
</tr>
<tr>
<td>(K\tau) [%]</td>
<td>1.6</td>
<td>0.46</td>
</tr>
<tr>
<td>(BR_{inv})</td>
<td>&lt;1.9%</td>
<td>&lt;0.024%</td>
</tr>
<tr>
<td>(BR_{unt})</td>
<td>&lt;4%**</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>(K3)</td>
<td>50%</td>
<td>5%</td>
</tr>
</tbody>
</table>

** Assume \(KV<1\)

* FCC-ee\(_{240}\)GeV + FCC-ee\(_{365}\)GeV + FCC-eh\(_{3.5}\)TeV + FCC-hh\(_{100}\)TeV

ESG Briefing Book; arXiv: 1905.03764
Summary of "Science Impacts"

1. Measure Higgs boson interactions with sub-percent precision

2. Use Higgs boson to search for dark matter

3. Measure the shape of the Higgs potential

4. Directly search for new particles 200× heavier than the Higgs boson
Extreme conditions at 100 TeV pp collider

Conditions

• 1000 pile-up 5-7× HL-LHC
• Radiation: \(1 \times 10^{18}\) neutrons/cm\(^2\), 300 MGy for inner detectors 100× HL-LHC
• Occupancy: 20 GHz/cm\(^2\) in first tracking layer 10× HL-LHC

Kinematics

• Dynamic range: few GeV – 20 TeV 10× HL-LHC
• Pseudorapidity coverage: \(|\eta| < 6\) \(|\eta| < 3-4\) at HL-LHC
• Angular resolution: 10 mrad separation between constituents in highly collimated jets; e.g. 10 TeV W\(\rightarrow hh\) 0.1× HL-LHC
• Secondary vertices: \(\beta\gamma\tau\sim 50\) cm for 5 TeV B mesons
• Calorimeter depth: 2× thicker calorimeters than HL-LHC
FCC–hh reference detector

- Future detectors will be designed for "particle flow" reconstruction algorithms in which each final state particle is reconstructed from the combination of corresponding information from all tracking detectors and calorimeters
  - requires high granularity for separating energy deposits

Greatly enhanced forward coverage w.r.t. HL–LHC
Key challenge #1: Integrated precision timing ... or ...
"Breaking the picosecond time barrier"

- Extreme pile-up and occupancy must be mitigated with high-granularity tracking detectors and calorimeters capable of precise measurements of particle time-of-arrival (ToA).

Per particle timing resolution requirement:
- Effective pile-up = number of vertices compatible with track ($\eta, p_T$)
- CMS at HL-LHC: effective PU = 1 for 1 GeV track at $\eta=4$ with 25ps resolution.
- 100 TeV pp requires 1–5 ps per particle resolution for comparable performance.

Requirements for detectors:
- Multiple measurements of each charged particle ToA with trackers with per pixel precision timing.
- Multiple time measurements of neutral particle showers with granular calorimeters with per cell precision timing.
- Precise clock distribution

![Pile-up vs $\eta$](image-url)
Key challenge #2: Transparent, high-granularity, 4D tracking detectors

- Excellent $p_T$ resolution over large $p_T$ range requires large, low-mass trackers
- Transparent, "irreducible" mass trackers
- The beam structure at an ILC-like collider allows power pulsing → air cooling → low mass
- Monolithic active pixel sensors provide another path low mass

Resolution driven by $e^+e^-$ collider requirements:
- $\sigma_{p_T}/p_T = 0.1\%$ from multiple scattering
- $\sigma_{p_T}/p_T^2 \approx 2 \times 10^{-5} \text{ GeV}^{-1}$
- $\sigma_{r\phi} \approx 5 \bigoplus 15 \left(p \text{ [GeV]} \sin^2 \theta\right)^{-1} \mu m.$

$\sigma/p_T \sim 0.5\%$ for 100 TeV pp

Additional requirements at 100 TeV pp collider:
- Extreme radiation tolerance for sensors and readout electronics
- 4D tracking detector with 1–5 ps per particle resolution → per pixel time resolution of 5–10 ps
- Small pixels (~25μm) to cope with high occupancy
- <5 μm single hit resolution to allow two-track separation in highly collimated jets.
Key Challenge #3: high-granularity, 5D calorimeters with $10^6$ dynamic range

- Lepton colliders require particle flow jet energy resolution $\sigma_E/E \sim 3.5-5\%$
  - distinguish W/Z/H $\rightarrow$ qq
  - measure Higgs total width in $ee \rightarrow ZH$

- Underlying calo energy resolution
  - $a = 10\%$ ($50\%$) for ECAL (HCAL) $\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$
  - $c = 0.7\%$ ($3\%$) for ECAL (HCAL)

- Granularity ($\Delta \eta \times \Delta \phi$): 4x more granular than LHC
  - 100 TeV pp ECAL: 0.01 $\times$ 0.01 (2 cm$^2$ at 2m)
  - 100 TeV pp HCAL: 0.025 $\times$ 0.025
  - $e^+e^-$ ECAL: 0.5 cm $\times$ 0.5 cm
  - $e^+e^-$ HCAL: 1–3 cm$^2$

- Per cell time measurement providing 5 ps resolution per shower.

- Radiation tolerant sensors and readout electronics
Key Challenge #4: Trigger and readout ... or ...
"Breaking the exabyte/second barrier"

Requirements:
• High **data rate** + high **granularity** = >1 exabyte per second of data
• Require **comprehensive trigger** incorporating calorimetry, tracking, and timing ... or triggerless readout
• Require low latency for trigger or selection decisions

Solution will involve
1. Initial data processing on-detector with **radiation-tolerant**, low-power electronics → **currently** ASICs
2. High-bandwidth, **radiation-tolerant** transmitters → **currently** VCSEL with custom ASIC driver
3. Flexible, off-detector electronics → **currently** FPGA + CPU

Potential directions for R&D
• Improved ASIC rad tolerance and power dissipation
• Silicon photonics & high-bandwidth rad tolerant transmitters
• Flexible systems with hybrid hardware: FPGA + CPU + GPU ...
• Machine learning techniques for low-latency and high throughput

<table>
<thead>
<tr>
<th>FCC–hh CDR Vol3</th>
<th>HL-LHC</th>
<th>100 TeV pp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ [nb]</td>
<td>rate [kHz]</td>
</tr>
<tr>
<td>jet (50 GeV)</td>
<td>21k</td>
<td>1100</td>
</tr>
<tr>
<td>bb (30 GeV)</td>
<td>1600</td>
<td>80</td>
</tr>
<tr>
<td>W → ℓv</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>Z → ℓℓ</td>
<td>2</td>
<td>0.02</td>
</tr>
<tr>
<td>tt</td>
<td>1</td>
<td>0.05</td>
</tr>
</tbody>
</table>
## Higgs & Energy Frontier Requirements

1. Integrated **precision timing**
   - 1–5 ps per particle resolution for charged and neutral particles

2. Transparent, high-granularity 4D **tracking**
   - $\sigma_{p_T}/p_T \sim 0.1\%$ from multiple scattering
   - $\sigma_{p_T}/p_T$
   - 25 x 25 μm pixels
   - 5 μm two-track separation
   - 5–10 ps per hit resolution
   - extreme radiation tolerance
   - $|\eta| < 6$

3. High-granularity, 5D **calorimeters** with $10^6$ dynamic range
   - 3–5% energy resolution for particle flow jets
   - 1 x 1 cm$^2$ cells
   - $10^6$ dynamic range
   - Per hit time resolution : 10–20 ps (?)
   - 2× thickness of HL–LHC calorimeters
   - extreme radiation tolerance
   - $|\eta| < 6$

4. High-bandwidth, low-latency **trigger and readout**
   - > 1 Exabyte/s throughput
   - Flexible, on-detector logic with extreme rad tolerance (e.g. RISC)
   - On-detector transmitters with extreme rad tolerance
   - Flexible, heterogenous off-detector computing

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**Extreme radiation tolerance** =
1×$10^{18}$ $n_{eq}/cm^2$, 30 Grad,
SEE from $2\times10^8$ 20–MeV hadrons/cm$^2$/s
**BRN language**

- **Science Impact**
  - sub-1% Higgs couplings
  - Use Higgs to study dark matter
  - Measure shape of Higgs potential
  - Direct search for new particles with mass $200 \times$ Higgs

- **Physics Goal**
  - Precise PF reco of $|p|$, $p$, time
  - Jet substructure
  - W/Z $\rightarrow$ qq separation

- **Requirement**
  - Pileup rejection
  - Precise PF reco of $|p|$, $p$, time
  - Jet substructure
  - W/Z $\rightarrow$ qq separation

- **Key challenge**
  - extreme rad tolerance
  - 1–5 ps per particle time resolution
  - 3–5% jet energy resolution
  - 0.1% track $p_T$ resolution for $p_T < 100$ GeV

- **Priority research direction**
  - Break picosecond time barrier
  - 4D transparent tracker
  - 5D high-granularity calorimetry
  - Breaking exabyte/s barrier

- **From technology groups**
  - Exabyte/s readout

**Impact**

- **Physics**
  - Goal
Summary

- The physics opportunities beyond HL–LHC are transformative ...
- ...but future colliders place similarly transformative requirements on future detectors.

- To meet the needs, we require ambitious R&D related to four Key Challenges:
  1. Integrated precision timing
  2. Transparent, high-granularity 4D tracking
  3. High-granularity, 5D calorimeters with $10^6$ dynamic range
  4. High-bandwidth, low-latency trigger and readout
Additional material
Beyond HL-LHC

- Collider timeline with focus on motivating detector R&D
The momentum resolution is around 20% for $p_T = 10\text{TeV/c}$ in the central region.

The resolution limit due to multiple scattering is around 0.5% in the central region.

The material dominates the resolution up to $p_T = 250\text{GeV/c}$.

In the forward region beyond $\eta = 3.5$ the momentum resolution deteriorates due to the ‘loss of lever arm’ in the solenoid field.

Using dipole magnets in the forward region the momentum resolution can be kept below 1% even up to $\eta = 6$.

The resolution curves for the solenoid field can be reproduced with the standard ‘pocket’ formulas.

$d_0$ and $z_0$ resolution of 30μm at $\eta = 0$ for $p_T = 1\text{GeV/c}$, limited by multiple scattering.

W Reigler, March 2019