Open Questions in Particle Physics

John Alison

Carnegie Mellon University
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Good time to be giving this talk:
- US: Recently had snowmass planning process (US) / now P5
- European strategy (ESPP) in 2020
- Older (better) summaries of open questions by Chris Quigg
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Focus on experimental collider physics
Will not be a book report on snowmass/existing summaries
Many of the questions discussed in detail in following presentations
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Outline
- HL-LHC
- Snowmass recommendations
- Future colliders

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HL-LHC

Clear next step in collider physics

Directly addresses 4/5 of the P5 Science Drivers:
- Higgs
- vs
- Dark Matter
- Dark Energy
- Other paths to BSM
HL-LHC Upgrades

**ATLAS**:  All-silicon inner tracker
    ~1 MHz tracking in trigger
    Endcap Timing layer (LGAD)
    New Muon chambers
    Electronics upgrades

**CMS**:  All-silicon inner tracker
    40 MHz tracking in trigger
    High-Granularity Calorimeter Endcap
    Barrel and Endcap timing layers (LYSO+SiPM / LGAD)
    New Muon chambers
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HL-LHC Upgrades

**Can we pull off LHC Phase 2 upgrades?**
- Big effort needed for Phase 2
- Many people distracted analyzing data
- Lost many of the technical experts that were key for phase-0
- Phase 1 LHC upgrades have been a mixed bag.

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- All-silicon inner tracker
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**How important will the timing layers be?**
- TDR physics case not transformative
- Mainly R&D projects?
- Other potential unforeseen use cases?
HL-LHC Upgrades

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~1 MHz tracking in trigger
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HL-LHC Upgrades

Will the ALTAS vs CMS performance diverge in the HL-LHC?
- Phase-0/1 detector performances ~same (after PFlow!)
- CMS more ambitious upgrades
- Phase-2 performance ~same on paper
- More flexibility/potential further improvements in CMS?

ALTAS:
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HL-LHC will provide partial answers to several open questions

- Is the H a portal to hidden sectors?
- Is the Higgs fundamental?
- Can we observe the Higgs self-coupling?
- What is the order of the EW phase transition?
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Combined $HH$ Sensitivity

HL-LHC Physics

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HL-LHC Physics

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- Is the H a portal to hidden sectors?
- Is the Higgs fundamental?
- Can we observe the Higgs self-coupling?
- What is the order of the EW phase transition?
- Is the world supersymmetric?

What will we do after Phase-2 detectors commissioned?
- Early check-out of new detectors (~2030) will be exciting
- Final datasets (~2040) extremely interesting
- Long slog until the HL-LHC statistics become interesting

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Last update: April 2023

Colors:
- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning
High priority to construction and operation of LBNF/DUNE

Fast start for the construction Higgs Factory and R&D for multi-TeV colliders (p/\mu)
Renewed interest and ambition to develop collider in the U.S. (\mu / C^3)

Should engage w/broader society: government policymakers / schools / private industry

Develop cohesive and strategic approach to promote diversity, equity, and inclusion in HEP

Research should be supported in new areas eg: quantum science and machine learning.
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**Can the US successfully execute the DUNE program?**

- Recent setbacks
- Unfavorable / Unfair press
- Probably necessary key requirement for future US collider
- Critical that whole field support. Cannot afford another SSC!
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**How can we profit from the talent that leaves the field?**

- Strategic strategy if HEP was a for-profit industrial sector?
  Assume would be spending a lot on professional lobbying
  - Fundraising from alums? ...?

Snowmass: High-Level Recommendations
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Should we be doing a better job advertising our successes?
- Overall, language in snowmass frontier report quite negative
- We’re far from perfect, need to strive to be better
- Think there is a lot we should be proud of and advertise

Poorly managed meetings still major problem!
Snowmass: High-Level Recommendations

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- Physics impact marginal: ~10% (aside from b-tagging, others?)
- Certainly nothing like qualitative impact eg: google translate / α-go
- Real gains in labor saving? coding/debugging / DQM / copy editing / Bkg validation?

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**What is next to be outsourced?**
- Seems like we are slowing outsourcing programing
- Project management?
- (I would like to see us outsource lobbying!)
Presentation of Results

What is the real benefit/value of our papers?
- Process of internal validation extremely valuable
- Conferences useful prod for timely results
- How many people are reading our papers? Who are they?
- Often find seminars much more useful than written documentation esp: letters (PRL)
- AI/ML fields: emphasis on conferences and reproducible code bases
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Have machine-readable formats (HEPData) been a success?
  Use LLMs (GPTX) as query results in new/interesting ways?
Higgs Factory

Snowmass: Recommends “Fast start for the construction Higgs Factory”
European Strategy: “An ee Higgs factory is highest-priority next collider.”
Higgs Factory

Feasibility Study started in 2021, will be completed in 2025
Cost estimate: 12 BCHF for tunnel and FCC-ee (17 BCHF for FCC-hh)

https://fcc-cdr.web.cern.ch/
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Timeline:
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**Timeline:**

- **Mel: 80 y/o**
- **Mel: 90**
- **Mel: 100**
- **Mel: 110**
- **Mel: 120**
- **Mel: 140**

---

- **Fabiola P5 Townhall**

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- **Geological investigations, infrastructure detailed design and tendering preparation**
- **FCC-ee accelerator and detector R&D and technical design**
- **Superconducting magnets R&D**
- **Long model magnets, prototypes, pre-series**
- **High-field magnet industrialization and series production**
- **FCC-ee accelerator and detector R&D and technical design**
- **FCC-ee accelerator and detector construction, installation, commissioning**
- **FCC-ee dismantling, CE & infrastructure adaptations FCC-hh**
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**Realistic FCCee start**

“**Any future collider at CERN cannot** start operation before 2045-2048”

**Fabiola P5 Townhall**

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**Fabiola**
# Higgs Factories

## Snowmass Accelerator Summary Report

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<th>Lumi/IP ($10^{34}$)</th>
<th>Years of R&amp;D (pre)</th>
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**How will a decision actually get made?** Who will make it? When? **… already knew what to do in ~2012**

**What can we do to move up to?**

**How soon will there be a y/n on ILC/ CEPC?** *(Will there be y/n?)*
## Beyond Higgs Factories

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### Beyond Higgs Factories

Can μC-3 really be done on same time scale as ILC-3/CLIC-3 for half the cost?

How long can we pursue both FCChh-100 and μ-collider?

- Similar physics reach. Does one preclude the other?

Do we really need/want a Higgs factory?

eg: Can we go straight FCChh machine? (eg: w/reduced Ecm?)

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<tr>
<td>Years</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>10-14</td>
<td>100</td>
</tr>
<tr>
<td>Power (MW)</td>
<td>5.9</td>
<td>6.1</td>
<td>2.3</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Lumi/IP (10^34)</td>
<td>5 - 10</td>
<td>19 - 24</td>
<td>&gt; 10</td>
<td>&gt; 25</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Years of R&amp;D (pre)</td>
<td>19 - 24</td>
<td>18 - 30</td>
<td>19 - 24</td>
<td>12 - 18</td>
<td>30 - 50</td>
</tr>
<tr>
<td>Cost (B$)</td>
<td>3 - 5</td>
<td>400</td>
<td>230</td>
<td>300</td>
<td>560</td>
</tr>
<tr>
<td>Electric Power</td>
<td>110</td>
<td>400</td>
<td>230</td>
<td>300</td>
<td>560</td>
</tr>
</tbody>
</table>

**Note:**
- CLIC-3 and ILC-3 are similar in terms of years and Lumi/IP, but CLIC-3 is cheaper.
- μC-3 is more expensive than CLIC-3 and ILC-3, but takes less time to develop.
- μC-10 is even cheaper than μC-3 but takes longer to develop.
- FCChh is the most expensive and has the longest development time.

**Questions:**
1. Can μC-3 really be done on the same time scale as ILC-3/CLIC-3 for half the cost?
2. How long can we pursue both FCChh-100 and μ-collider?
3. Similar physics reach. Does one preclude the other?
4. Do we really need/want a Higgs factory?
5. Can we go straight FCChh machine? (eg: w/reduced Ecm?)
Conclusions

Great time for experimental particle physics!
Many clearly important open questions
Concrete program(s) in place for answering many of them:

Is Strong CP a problem?

Is Dark Matter a particle?

What is the lifetime of the proton?

What is the relationship between quarks and leptons?

Why are charged-current weak interactions left-handed?

Are there right-handed charged current interactions?

What role does the Higgs field play in generating neutrino masses?

Low mH mean New Physics or break-down of Wilsonian picture?

Can we discover topological effects in the SM: Instantons, Sphalerons?

Can we test assumptions of QFT: Lorentz invariance / QM / Locality?

Is there significance to the values of the SM parameters?

Can we measure the electron yukawa (Sets Bohr radius)?

What is the order of the EW phase transition?

What energy scale is relevant for flavour?

Is the world supersymmetric?

Why are atoms neutral to 10e-22? (much worse than strong CP)

Are the laws of physics the same at all times and places?

“Who ordered that?”

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Thank You Mel!