Physics Motivation for a Muon Collider!

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Various versions of a physics case...
The case so simple even a 2 year old gets it
The case so simple even a 2 year old gets it
Add in QM + Relativity

The outcome of which is QFT (slightly beyond a 2 year old)

\[ \text{New physics} \]

\[ N_{\text{events}} = \sigma \cdot L \]

\[ \sigma \sim \frac{1}{E^2} \]
And we reach the inevitable ask for the AF...

I am once again asking for more Energy and more Luminosity
And we reach the inevitable ask for the AF...

PEV W/ INVERSE YOCTOBARNs?

ANYONE? ANYONE?
All jokes aside, the AF is very pragmatic!

- **F1 “Technology Readiness”:**
  - Green: TDR
  - Yellow: CDR
  - Red: R&D

- **F2 “Energy Efficiency”:**
  - Green: 100-200 MW
  - Yellow: 200-400 MW
  - Red: > 400 MW

- **F3 “Cost”:**
  - Green: < LHC
  - Yellow: 1-2 x LHC
  - Red: > 2x LHC
Nevertheless *any* new project will take a significant investment, so are there interesting targets/motivations along the way other than exploring the unknown?

We do more handwringing than other parts of our field because our costs are larger...
Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles
We often silo ourselves off without thinking about the big picture

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:
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In reality it is a much more intertwined picture

That a high energy muon collider can shed light on many questions simultaneously!
Standard Particle Physics Questions

- Why is there more matter than antimatter?
- What is dark matter? Dark energy?
- Why do atoms exist? (How does the electron get its mass?)
- What is flavor? Why 3 generations and mixing?
- Origin of neutrino mass and mixings?
- Cosmic history before Big Bang Nucleosynthesis?
- Origin of Electroweak Symmetry Breaking/Higgs potential?
- (Meta)Stability of our Universe?
- Strong CP problem solution?
- Naturalness of Quantum Field Theory (most successful theory ever)?
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• ...
No guaranteed answers other than measurements

But every experiment has this issue

Let’s take an example that everyone loves Dark Matter!
What we test through indirect/direct detection is the same as what we do for particle physics.

Motivate with interesting possibilities that attempt to explain properties and are consistent experimentally and theoretically!
WIMP “miracle”

Still exists in its fundamental form
A high energy muon collider can test this possibility!

Figure 10: Summary of the discovery reaches of various muon collider running scenarios. The thicker bars represent the combined reach from missing mass searches through mono-photon, mono-muon, and VBF di-muon channels. The thinner and faint bars are our estimates of the mono-photon plus one disappearing track search. The burgundy vertical bars represent the thermal target for a given EW-multiplet model. More details, including the detailed reaches for each channels and different muon collider energies, can be found in Ref. [32].
Testing QFT and Naturalness

There is no reason the Higgs mass should be what it is.

It should be quadratically sensitive to the scale of new physics!

Obviously we'd like to test this to the highest scales possible, there could be entirely new paradigms at work, "Copernican Revolution" as someone bolder might say.
However, in theories that can explain the Higgs Mass, the scale could be much higher and we’ve known a long time!
This concept has existed even before the Higgs-Electroweak Precision!

\[ 1 \text{ TeV} \rightarrow 10 \text{ TeV scale} \]

\[ \text{Naturalness} \]
\[ c_\rho > c_\pi > 2\rho \]
\[ 2 \text{ maxima} \]

\[ \frac{8\sqrt{2}}{\pi} \sim 1 + c \frac{v^2}{f^2} \]

\[ \frac{M_{\rho}}{M_{\rho}} \sim 1 + c \frac{v^2}{f^2} \]

\[ \text{w/ c's } O(1) \]

20 years ago!!

f > 5.5 \text{ TeV } 95% CL

We need a technology that can get us to higher energies - Muon Colliders!
Roughly there is equivalence to a 100 TeV pp collider for
\[ \sqrt{s_\mu} \sim 20 \text{ TeV} \]
\[ \sqrt{s_\mu} \sim 5 - 7 \text{ TeV} \]
The devil is in the details always... but O(10) TeV is also interesting from Higgs
With any of these of course nothing is a guarantee!

However we do have this basic understanding of what *could* be there
Foundational Physics Potential Cases

If you want a **guaranteed** return it’s a lot harder
We are just scratching the surface of the Higgs!

The Higgs is the most unique particle in the SM. We must measure all its couplings to complete SM. 22/26 parameters in SM governed by Higgs!
COMPLETE THE SM!

Higgs

BSM

Biggest open areas post HL-LHC

Self couplings!

Light Flavor!

Needs Energy

Needs Precision

Both need a lot of Higgs!
How Many Higgs??

Take this with many grains of salt...

Different energies access different dominant processes (different physics you can access), have different experimental challenges

This is to understand orders of magnitude and what you could do if you could exploit them all!

<table>
<thead>
<tr>
<th>Collider</th>
<th>Energy</th>
<th>Rate</th>
<th>Cross Section</th>
<th>Signal</th>
<th>Experimental Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>13 TeV</td>
<td>2</td>
<td>5</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td>IL-LHC</td>
<td>14 TeV</td>
<td>2</td>
<td>5</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td>FCC-eh</td>
<td>14 TeV</td>
<td>2</td>
<td>5</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td>CLIC-380</td>
<td>1500 GeV</td>
<td>2</td>
<td>7</td>
<td>600</td>
<td>3000</td>
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<td>2</td>
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<td>3000</td>
</tr>
</tbody>
</table>

Speculative high energy options (run plans specified here)

Muon (or electron colliders)

- 6 TeV 4/ab $\sim 3.2 \times 10^6$
- 10 TeV 10/ab $\sim 9.5 \times 10^6$
- 14 TeV 20/ab $\sim 22 \times 10^6$
- 30 TeV 90/ab $\sim 1.2 \times 10^9$
- 100 TeV 100/ab $\sim 1.8 \times 10^9$

Collider in the sea

- 500 TeV 50/ab $\sim 400 \times 10^9$

Can approach a trillion Higgs

End of LHC -- O(100) million Higgses!

Low energy $e^+e^-$ Higgs factories

- ~ 1 million Higgs

Moderate energy $e^+e^-$ Higgs factories

- ~ few million Higgs

FCC-hh $\sim 27 \times 10^9$ 27 billion Higgses

ILC250/350 $\sim 0.6 \times 10^6$

FCC-ee 240/365 $\sim 1.2 \times 10^6$

CEPC 240 $\sim 1.1 \times 10^6$

CLIC-380 $\sim 0.2 \times 10^6$

ILC500/1000 $\sim 4.5 \times 10^6$

CLIC 1500/3000 $\sim 3.4 \times 10^6$
Figure of merit LEP had 17 Million Zs
How Many Higgs??

Take this with many grains of salt...

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$$\text{HL-LHC} \sim 0.35 \times 10^9$$
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$$\text{ILC500/1000} \sim 4.5 \times 10^6$$
$$\text{CLIC 1500/3000} \sim 3.4 \times 10^6$$

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Speculative high energy options (run plans specified here)

Muon (or electron colliders)

$$6 \text{ TeV } 4/\text{ab} \sim 3.2 \times 10^6$$
$$10 \text{ TeV } 10/\text{ab} \sim 9.5 \times 10^6$$
$$14 \text{ TeV } 20/\text{ab} \sim 22 \times 10^6$$
$$30 \text{ TeV } 90/\text{ab} \sim 0.12 \times 10^9$$
$$100 \text{ TeV } 100/\text{ab} \sim 0.18 \times 10^9$$

Collider in the sea

$$500 \text{ TeV } 50/\text{ab} \sim 400 \times 10^9$$

Can approach a trillion Higgs

Millions to 100s of millions

ESG run plans 1905.03764
Remember though the Higgs is highly non-egalitarian!

LEP 17 M Z's

"Major" BF's $\mathcal{O}(\%)$

Higgs Factory $\mathcal{O}(1)$ M H's

"Major" $\gamma \gamma \sim 10^{-3} \sim 10^3 \text{ events}$

$\mu \mu \sim 10^{-4} \sim 10^2 \text{ events}$

$s s \sim 10^{-4}$

$\nu \bar{\nu}/e \sim 10^{-8}$ CRAP!!
To complete the SM we need more luminosity or more energy

Winner at moderate energies!

Can think of this as VV to H fusion, with VV initial states (PDF like for hadron colliders)
We also need a clean environment!
FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION

Imperfect analogy:

Early universe was hotter!

Universe now
FUTURE COLLIDERS OFTEN THOUGHT OF AS TESTS OF ELECTROWEAK PHASE TRANSITION

Imperfect analogy:

Unrestored Electroweak Symmetry

Early universe was hotter!

Universe now

PM, H. Ramani
1807.07578
Multi-Higgs results

<table>
<thead>
<tr>
<th>√s (lumi.)</th>
<th>3 TeV (1 ab⁻¹)</th>
<th>6 (4)</th>
<th>10 (10)</th>
<th>14 (20)</th>
<th>30 (90)</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWH (Δκ_W)</td>
<td>0.26%</td>
<td>0.12%</td>
<td>0.073%</td>
<td>0.050%</td>
<td>0.023%</td>
<td>0.1% [41]</td>
</tr>
<tr>
<td>Λ/√c₈ (TeV)</td>
<td>4.7</td>
<td>7.0</td>
<td>9.0</td>
<td>11</td>
<td>16</td>
<td>(68% C.L.)</td>
</tr>
<tr>
<td>ZZH (Δκ_Z)</td>
<td>1.4%</td>
<td>0.89%</td>
<td>0.61%</td>
<td>0.46%</td>
<td>0.21%</td>
<td>0.13% [17]</td>
</tr>
<tr>
<td>Λ/√c₈ (TeV)</td>
<td>2.1</td>
<td>2.6</td>
<td>3.2</td>
<td>3.6</td>
<td>5.3</td>
<td>(95% C.L.)</td>
</tr>
<tr>
<td>WWHH (Δκ_W₂)</td>
<td>5.3%</td>
<td>1.3%</td>
<td>0.62%</td>
<td>0.41%</td>
<td>0.20%</td>
<td>5% [36]</td>
</tr>
<tr>
<td>Λ/√c₈ (TeV)</td>
<td>1.1</td>
<td>2.1</td>
<td>3.1</td>
<td>3.8</td>
<td>5.5</td>
<td>(68% C.L.)</td>
</tr>
<tr>
<td>HHH (Δκ₃)</td>
<td>25%</td>
<td>10%</td>
<td>5.6%</td>
<td>3.9%</td>
<td>2.0%</td>
<td>5% [22, 23]</td>
</tr>
<tr>
<td>Λ/√c₈ (TeV)</td>
<td>9.49</td>
<td>0.77</td>
<td>1.0</td>
<td>1.2</td>
<td>1.7</td>
<td>(68% C.L.)</td>
</tr>
</tbody>
</table>

Table 4: A summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

We NEED energy to answer these questions

Table 6: Constraints on δ₁ (δ₂ = 0) for the c.m. energies and the instantaneous luminosities in table 1 once the geometric acceptance cuts p_Τ >20 GeV and |η| < 3 are applied to the Higgs decay products. The bounds are obtained from the total expected cross sections for the process μ⁺μ⁻ → HHHνν. The Higgs bosons are produced on-shell and decayed to bb pairs but no branching ratio is applied.

What’s our cosmological History?
What’s the Higgs potential?
What’s our Cosmological Future?
What’s the takeaway from this for the Higgs? That potentially there is...

ONE COLLIDER

TO RULE THEM ALL
What’s realistic?
DOE new funding for new HEP projects?

Remember our field has more remembered trauma than our Government!

Members of Congress that were there in 1993
SSC
7/100 Senators
26/435 House Members
Conclusions

- There are numerous questions that a muon collider can go after, and many in particle physics that need energy
  - A Higgs factory isn’t just a low energy thing!
- There are many things pointing to the 10 TeV energy scale as interesting
- I just chose a few but I’m happy to answer questions!
  - Synergy with muon anomalies?
- The multipurpose nature of the project justifies the cost AND creates incredible synergy in our field (not just technologically like neutrinos), it’s not a one off!
- R&D is a must if we want to go forwards!