Toward an Energy Frontier Muon Collider

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• The Long View
• Return to the Energy Frontier
• Staging Physics Milestones
• Summary

2013 Community Summer Study
“Snowmass on the Mississippi”
University of Minnesota
July 29-Aug 6, 2013

WhitePapers
1. Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility In the USA
2. Muon Collider Higgs Factory
Implications of early LHC Results

- No evidence for new physics beyond the Standard Model (BSM) to date:
  - BSM (SUSY, Strong Dynamics, Extra Dimensions, New fermions or gauge bosons, ...)
  - ATLAS limits

**ATLAS Exotics Searches - 95% CL Lower Limits (Status: HCP 2012)**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass Scale [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
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<tr>
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<tr>
<td>D0</td>
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<tr>
<td>LHCb</td>
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<td>8 TeV</td>
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**ATLAS SUSY Searches - 95% CL Lower Limits (Status: March 26, 2013)**

<table>
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<th>Mass Scale [TeV]</th>
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<td>7 TeV</td>
<td></td>
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<tr>
<td>8 TeV</td>
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</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena shown.*

Estia Eichten
CSS 2013 @ Fermilab
Aug 4, 2013
- Scales already probed at the LHC suggest that to study BSM new physics the next energy frontier collider must have $\sqrt{s}$ in the multi-TeV range even for EW processes.
- However there must be new physics!!! WHY? Let me list the reasons
1. The Standard Model is incomplete:
   - dark matter; neutrino masses and mixing -> new fields or interactions;
   - baryon asymmetry in the universe -> more CP violation
   - gauge unification -> new interactions;
   - gravity: strings and extra dimensions

2. Experimental hints of new physics: \((g-2)_{\mu}\), top \(A_{fb}\), ...

3. Theoretical problems with the SM:
   - Scalar sector problematic:
     \[ \mu^2 (\Phi^+ \Phi) + \lambda (\Phi^+ \Phi)^2 + \Gamma_{ij} \psi_{iL} \psi_{jR} \Phi + \text{h.c.} \]
     \[ m_H^2/M^2_{\text{Planck}} \approx 10^{-34} \]
     Hierarchy problem
     - vacuum stability
     - large range of fermion masses
     - The SM Higgs boson is unnatural. \((m_H^2/\mu^2)\)
     - Solutions: SUSY, New Strong Dynamics, ...

muon \((g-2)\)

- Davier, Hoecker, Malaescu, Zhang
- Jegerlehner, Szafron
- Hagiwara, Liao, Martin, Nomura, Teubner
- hadronic VP contributions
  \[ (685 \pm 4) \times 10^{-10} \]
  \[ a_\mu \times 10^{9} - 11659000 \]
  There remains a persistent discrepancy of 3.3-3.6 \(\sigma\)
The strong case for a TeV scale hadron collider rested on two arguments:

1. Unitarity required that a mechanism for EWSB was manifest at or below the TeV scale.
2. The SM is unnatural ('t Hooft conditions) and incomplete (dark matter, insufficient CP violation for the observed baryon excess, gauge unification, gravity and strings)

If after the analysis of the 2012 CMS/ATLAS data, the 126 GeV state is found to be a 0+ state with couplings consistent with the SM Higgs, the first argument is satisfied.

- The second argument remains strong, but is less strongly tied to the TeV scale.

- Scales already probed at the LHC suggest that any new collider (of LHC level costs) should be able the probe the BSM physics in the multi-TeV range.
Muon Collider

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 10 TeV (3 Tev)
  - Luminosity > $10^{34}$ cm$^{-2}$ sec$^{-1}$ (440 fb$^{-1}$/yr)
- Compact facility
  - 3 TeV - ring circumference 3.8 km
  - 2 Detectors
- Superb Energy Resolution
  - MC: 95% luminosity in dE/E ~ 0.1%
  - CLIC: 35% luminosity in dE/E ~ 1%
• Comparison of Lepton Colliders at High Energy
  – Increase of luminosity with energy. Needed for new physics.
  – Wall power in operation.
  – Only a Muon Collider provides a path to the energy frontier.

Figure A-3: Figure of merit: peak luminosity (within 1% colliding energy) normalized to wall plug power

\[ \frac{N_{\text{Det}} \times L/P}{E_{\text{c of m}}} \sim E^2 \text{ as required} \]
Muon Collider

- For $\sqrt{s} < 500$ GeV
  - SM thresholds: $Z^0h,W^+W^-,\text{top pairs}$
  - Higgs factory ($\sqrt{s} \approx 126$ GeV)

- For $\sqrt{s} > 500$ GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required.
    - Cross sections for central ($|\theta| > 10^o$) pair production
      $\sim R \times 86.8$ fb/s (in TeV$^2$) ($R \approx 1$)
    - At $\sqrt{s} = 3$ TeV for 100 fb$^{-1}$ $\sim 1000$ events/(unit of R)

- For $\sqrt{s} > 1$ TeV
  - Fusion processes important at multi-TeV MC
    \[ \sigma(s) = C \ln \left( \frac{s}{M_X^2} \right) + ... \]
    - An Electroweak Boson Collider
But muons decay:
- The muon beams must be accelerated and cooled in phase space (factor $\approx 10^6$) rapidly
  -> ionization cooling
- requires a complex cooling scheme
- The decay products ($\mu^- \rightarrow \nu_\mu \nu_e e^-$) have high energies.
  - Detector background issues
  - Neutrino beam issue -> $E_{cm} \lesssim 10$ TeV.

The issues need dedicated R&D
- MICE
- MAP
- nuStorm - Definitive 6D cooling demo.
Provide a flexible staging scenario with physics at each stage.

- Proton driver - Project X
  - LBNE, rare K decays, mu to e conversion, (g-2)_μ, EDM, N-Nbar oscillations, cold muons, ...

- Neutrino Factory

- Higgs Factory
- High Energy Muon Collider

Staging plan has been developed.

WhitePapers
1. Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility In the USA.
2. Muon Collider Higgs Factory
Neutrino Physics Staging Scenerio

- Because $\theta_{13}$ is large a lower energy (5 GeV) and 1300 km works for a Neutrino Factory.
- First a lower intensity (Project X phase 2) $(2 \times 10^{20} \mu^2/\text{yr})$ neutrino factory NuMAX
- Then higher intensity $(1.2 \times 10^{21} \mu^2/\text{yr})$ NuMAX+
- Unsurpassed performance is obtained for 34 kton magnetized LAr (TPC) at distance 1300 km (NuMAX+)

Table 1. Muon Accelerator Program baseline Neutrino Factory parameters for nuSTORM and two NuMAX phases located on the Fermilab site and pointed towards a detector at SURF. For comparison, the parameters of the IDS-NF are also shown.

<table>
<thead>
<tr>
<th>System</th>
<th>Parameters</th>
<th>Unit</th>
<th>nuSTORM</th>
<th>NuMAX</th>
<th>NuMAX+</th>
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</table>
**Muon Collider Staging Scenario**

- **Staging Steps:**
  - **Higgs factory** \( \sqrt{s} = m_H \approx 126 \text{ GeV} \)
    - \( \mathcal{L} = 1.7 \times 10^{31} \sim 170 \text{ pb}^{-1}/\text{yr}; \) \( \Delta E/E = 0.003\% \)
    - \( \mathcal{L} = 8 \times 10^{31} \sim 800 \text{ pb}^{-1}/\text{yr}; \) \( \Delta E/E = 0.004\% \)
  - **High Energy Muon Collider:**
    - LHC at \( \sqrt{s} = 14 \text{ TeV} \) after 300 fb\(^{-1}\). Muon collider design energy is flexible. (\( \Delta E/E = 0.1\% \))
    - \( \sqrt{s} = 1.5 \text{ TeV}; \) 
      - \( \mathcal{L} = 1.25 \times 10^{34} \sim 125 \text{ fb}^{-1}/\text{yr}; \)
    - \( \sqrt{s} = 3.0 \text{ TeV}; \) 
      - \( \mathcal{L} = 4.4 \times 10^{34} \sim 440 \text{ fb}^{-1}/\text{yr} \)
    - \( \sqrt{s} = 6.0 \text{ TeV}; \) 
      - \( \mathcal{L} = 1.6 \times 10^{35} \sim 1.6 \text{ ab}^{-1}/\text{yr} \)

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Higgs Factory Startup Operation</th>
<th>Production Operation</th>
<th>Multi-TeV Baselines</th>
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<td>0.126</td>
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<td>(10^{34}) cm(^2) s(^{-1})</td>
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<td>0.008</td>
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<td>Beam Energy Spread</td>
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<td>0.004</td>
<td>0.1</td>
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<td>13,500</td>
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<tr>
<td>(\beta^*)</td>
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<td>3.3</td>
<td>1.7</td>
<td>1 (0.5-2)</td>
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<td>4</td>
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<td>(4^*)</td>
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* Could begin operation with Project X Stage 2 beam
A muon collider can directly produce the Higgs as an s-channel resonance.

- Higgs couples to mass so rate enhanced by $\left[ \frac{m_\mu}{m_e} \right]^2 = 4.28 \times 10^{-4}$ so the cross section is $\sigma(\mu^+\mu^- \rightarrow h) = 26 \text{ pb}$ (for $\Delta = \Gamma$ and including ISR and a 15° forward cut).

- To obtain the same sensitivity to Higgs decay modes in a electron collider via $Zh$ process as s-channel production at a MC requires more than 100 times the integrated luminosity.

- The excellent energy resolution $\Delta$ of a muon collider makes the process observable.

$$\sigma_{\text{eff}}(s) = \int d\sqrt{s} \frac{dL(\sqrt{s})}{d\sqrt{s}} \sigma(\mu^+\mu^- \rightarrow h \rightarrow X)$$

$$\sim \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2 + \Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B \exp[-(m_h^2-2\Delta^2)(\frac{\Gamma_h}{2\Delta})]/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

$$\sigma(\mu^+\mu^- \rightarrow h \rightarrow X) = \frac{4\pi\Gamma_h^2 B(h \rightarrow \mu^+\mu^-)B(h \rightarrow X)}{(s-m_h^2)^2 + \Gamma_h^2 m_h^2}.$$ 

- Results:

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\delta M_H$ (MeV)</th>
<th>$\delta \Gamma_H$ (MeV)</th>
<th>$\delta Br(h \rightarrow X)$</th>
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<tr>
<td>$bb$</td>
<td>0.1</td>
<td>0.4</td>
<td>0.05</td>
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<tr>
<td>$WW^*$</td>
<td>0.07</td>
<td>0.2</td>
<td>0.01</td>
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<tr>
<td>Combined</td>
<td>0.06</td>
<td>0.18</td>
<td></td>
</tr>
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</table>

- $\Delta Br(\mu^+\mu^-)Br(WW^*) \sim 2\%$

- Finding the Higgs (5$\sigma$) requires 270 pb$^{-1}$. 
• New Z', W'
  - S-channel resonances - factories for lepton colliders
• Additional scalars in all BSM ideas.
• Two Higgs doublets (MSSM):
  - Five scalar particles: h^0, H^0, A^0, H^±
  - Decay amplitudes depend on two parameters: (α, β)
  - decoupling limit m_A^0 >> m_Z^0:
    » h^0 couplings close to SM values
    » H^0, H^± and A^0 nearly degenerate in mass
    » H^0 small couplings to VV, large couplings to ZA^0
    » For large tanβ, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by tanβ. Couplings to top quarks suppressed by 1/tanβ factor.
  - The LHC has difficulty in discovering H/A above 900 GeV even at √s = 14 TeV and 300 fb⁻¹
  - If H/A near present LHC bounds (∼300 GeV). The states can be cleanly separated because of the excellent energy resolution of the muon collider.
Example of Natural SUSY

- Low-lying spectrum

- For electroweakinos, sleptons, ...

A $\geq 3$TeV muon collider has discovery reach beyond a 100 TeV pp collider!
Beyond the Standard Model

- Generally expect very heavy: $H^\pm$, $H^0$ and $A^0$
  - LHC limits on $H^\pm$: $\sim 300$ (ATLAS) (CMS)
  - SUSY models that evade the all present experimental constraints often have very heavy THDM scalars
- The $H/A$ are observable as $s$-channel resonances at a MC!
  - $M_H = M_A \sim 1.5$ TeV/$c^2$, $\Gamma \sim 15$ GeV
  - Large $\tan\beta \sim 20$
  - Limited spectrum of SUSY particle decays.
  - Expect $10^6$ $H/A$ decays per 1 ab$^{-1}$
- The $H/A$ resonances are a factory for study BSM physics.

E.E and A. Martin (arXiv:1306.2609)
• Electroweak Symmetry Breaking is generated dynamically at nearby scale
  - Technicolor, ETC, walking TC, topcolor, Two Scale TC, composite Higgs models, ...
  - New strong interaction at the Terascale:
    • What is the spectrum of low-lying states? s-channel production $\pi_T$ (technipion) ($0^-$), $\rho_T$, $\omega_T$ (technirho, techniomega) nearly degenerate - needs good energy resolution
    • What is the ultraviolet completion? Gauge group? Fermion representations?
    • What is the energy scale of the new dynamics?
    • Any new insight into quark and/or lepton flavor mixing and CP violation?

• Contact interactions
  - e.g. Compositeness, broken flavor symmetries, ...
  - Present LHC bounds (~ 10 TeV)
  - Muon collider sensitive to scales > 200 TeV
    • Forward cone cut not important
    • Polarization useful in determining chiral character of the interaction.
Summary

- The path from the intensity frontier back to the energy frontier has physics at each step.

- A staged Muon Collider can provide a Neutrino Factory to fully disentangle neutrino physics.

- The observation of a new state at 125 GeV by both ATLAS and CMS revitalizes consideration of a Higgs factory as part of a staged multi-Tev muon collider. This is particularly attractive if there is an enlarged scalar sector (e.g., THDM, SUSY).

- The unique measurements of the Muon Higgs factory (4.2 fb\(^{-1}\))
  - Most precise measurement of Higgs mass: \(\Delta m_H = 0.06\) MeV; direct Higgs width measurement: \(\Delta \Gamma_H = 0.18\) MeV; measurement of \(\text{BR}(\mu^+\mu^-)\text{BR}(WW^*)\) to 2% and can separate nearly degenerate scalar resonances.

- A multiTeV lepton collider will be required for full coverage of Terascale physics.
  - The physics potential for a muon collider at \(\sqrt{s} \sim 3\) TeV and integrated luminosity of 1 ab\(^{-1}\) is outstanding. Particularly strong case for SUSY and new strong dynamics.
  - Narrow s-channel states played an important role in past lepton colliders. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics.
BACKUP SLIDES
What Happened to Naturalness?

- **Concept of naturalness.**
  - K. Wilson, G. 't Hooft
  - A theory \([L(\mu)]\) is natural at scale \(\mu\) for any small dimensionless parameter \(\lambda\) (e.g. \(m/\mu\)) in \(L(\mu)\)
    
    the limit \(\lambda \to 0\) enhances the symmetries of \(L(\mu)\)

- The SM Higgs boson is unnatural. \((m_H^2/\mu^2)\)
  - Maybe no large gap in scales (Extra Dimensions)

- Two potential solutions:
  - Scalars not elementary
    - New strong dynamics (TC, walking TC, little Higgs, top color, ...)
  - Fermion masses are natural
    - Symmetry coupling fermions and bosons (SUSY)

- Quest for the “natural” theory to replace the SM has preoccupied theorists since the early 80’s

- Is a third way required after the discovery of a Higgs boson?
Which Accelerator for Higgs Physics?

1. The LHC is the Higgs Accelerator - Continue -> HL-LHC
2. Continue research and development of lepton colliders. In particular the muon collider needs a convincing proof of 6D cooling.
3. Push neutrino physics - Lepton sector
4. After 300 fb\(^{-1}\) of ~14 TeV running OR the discovery of BSM physics, chose the next accelerator for Higgs physics.

New physics below $\sqrt{s} = 1$ TeV ?

- YES: e+e- linear collider extendable to $\sqrt{s} = 1$ TeV
- NO: muon higgs factory --> muon collider with $\sqrt{s} \geq 3$ TeV

Is a Muon Collider Feasible?

- YES: e+e- circular collider in large tunnel --> hadron collider with $\sqrt{s} \geq 100$ TeV
- NO
• **A possible timeline**
  
  - **Project X Stages:**
    - Stage I → 1 GeV, 1 mA
    - Stage II → 3 GeV, 3 MW
    - Stage III → 8 GeV
    - Stage IV → 4 MW
  
  - **Decision points:**
    - Finish of MAP Feasibility Assessment ~ 2018
    - Advanced System R&D makes use of nuSTORM muon ring.
    - Decision point middle of 2020’s on collider program.
    - Program X Stage II can start physics of neutrino or collider program.
Beyond the Standard Model

- The LHC has difficulty observing the H, A especially for masses > 500 GeV. Even at $\sqrt{s} = 14$ TeV and 300 fb$^{-1}$.

- Pair produced with easy at a multi-TeV lepton collider.
100 TeV pp Collider

- 100 TeV pp Collider (EHLQ)

  1 TeV slepton pair $\approx 1$ fb
  2 TeV wino pair $\approx 4$ fb