Wishlist from the Physics Side

Cari Cesarotti, MIT CTP Postdoc Fellow

IMCC MDI Workshop, March 11, 2024
With thanks to many for their input

The US P5 report has endorsed muon collider R&D

Money is explicitly allocated for 10 TeV pCOM machines, which includes FCC-hh R&D, for $\mathcal{O}(50M)$ per year

We want similar support in the ESPPU, and maintained US support

It is essential that we have well-defined accelerator, experimental, and theoretical benchmarks to demonstrate feasibility & confidence
WITH SO MANY DESIGN UNCERTAINTIES, WE GET INTO A FEEDBACK LOOP

Experimental or Accelerator parameters are assumed  $\rightarrow$  Physics benchmarks are set

Let’s set straight what we need from MDI to reach our physics benchmarks
GOAL OF THIS TALK:

Establish what is needed for detector technology to achieve our physics benchmarks

(Define what our physics benchmarks are)
Goal of this Talk: Workshop

Establish what is needed for detector technology to achieve our physics benchmarks

(Define what our physics benchmarks are)

Both theorists & experimentalists will have to-do’s to better inform the physics projections
Setting the Physics Benchmarks

What are the measurements that we need to justify the construction of a muon collider?

What do we need of MDI to make these measurements?
SETTING THE PHYSICS BENCHMARKS

What are the measurements that we need to justify the construction of a muon collider?

What do we need of MDI to make these measurements?

How will these evolve depending on the status of other future colliders?
**Physics Goals**

- Precision EW & Higgs
- Heavy Particles
  - $\Lambda_{NP} \geq \text{TeV}$
  - $m_{W,Z,h}$
- Novel Signatures
  (e.g. Disappearing tracks, LLPs, SUEPs, etc.)

**Flavor Tagging**
A primary challenge for maintaining sensitivity to these is mitigating the BIB.
PRIMARY CHALLENGE:
THE BEAM INDUCED BACKGROUND (BIB)

We often sell the muon collider as a clean environment for precision physics...
PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)

We often sell the muon collider as a clean environment for precision physics...

...but to mitigate the effects from beam decay, sensitivity to forward and soft particles is degraded
**PRIMARY CHALLENGE:**

**THE BEAM INDUCED BACKGROUND (BIB)**

Tungsten nozzles can diffuse **hard** BIB objects into **many low-energy** particles.

**Zeroth order task:**
Make physics possible in the face of the BIB
PRIMARY CHALLENGE:

THE BEAM INDUCED BACKGROUND (BIB)

For a single bunch crossing ($2 \times 10^{12} \mu$)

<table>
<thead>
<tr>
<th>Monte Carlo simulator</th>
<th>MARS15</th>
<th>MARS15</th>
<th>FLUKA</th>
<th>FLUKA</th>
<th>FLUKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>62.5</td>
<td>750</td>
<td>750</td>
<td>1500</td>
<td>5000</td>
</tr>
<tr>
<td>$\mu$ decay length [m]</td>
<td>$3.9 \cdot 10^5$</td>
<td>$46.7 \cdot 10^5$</td>
<td>$46.7 \cdot 10^5$</td>
<td>$93.5 \cdot 10^5$</td>
<td>$311.7 \cdot 10^5$</td>
</tr>
<tr>
<td>$\mu$ decay/m/bunch</td>
<td>$51.3 \cdot 10^5$</td>
<td>$4.3 \cdot 10^5$</td>
<td>$4.3 \cdot 10^5$</td>
<td>$2.1 \cdot 10^5$</td>
<td>$0.64 \cdot 10^5$</td>
</tr>
<tr>
<td>Photons ($E_\gamma &gt; 0.1$ MeV)</td>
<td>$170 \cdot 10^6$</td>
<td>$86 \cdot 10^6$</td>
<td>$51 \cdot 10^6$</td>
<td>$70 \cdot 10^6$</td>
<td>$107 \cdot 10^6$</td>
</tr>
<tr>
<td>Neutrons ($E_n &gt; 1$ MeV)</td>
<td>$65 \cdot 10^6$</td>
<td>$76 \cdot 10^6$</td>
<td>$110 \cdot 10^6$</td>
<td>$91 \cdot 10^6$</td>
<td>$101 \cdot 10^6$</td>
</tr>
<tr>
<td>Electrons &amp; positrons ($E_{e^\pm} &gt; 0.1$ MeV)</td>
<td>$1.3 \cdot 10^6$</td>
<td>$0.75 \cdot 10^6$</td>
<td>$0.86 \cdot 10^6$</td>
<td>$1.1 \cdot 10^6$</td>
<td>$0.92 \cdot 10^6$</td>
</tr>
<tr>
<td>Charged hadrons ($E_{h^\pm} &gt; 0.1$ MeV)</td>
<td>$0.011 \cdot 10^6$</td>
<td>$0.032 \cdot 10^6$</td>
<td>$0.017 \cdot 10^6$</td>
<td>$0.020 \cdot 10^6$</td>
<td>$0.044 \cdot 10^6$</td>
</tr>
<tr>
<td>Muons ($E_{\mu^\pm} &gt; 0.1$ MeV)</td>
<td>$0.0012 \cdot 10^6$</td>
<td>$0.0015 \cdot 10^6$</td>
<td>$0.0031 \cdot 10^6$</td>
<td>$0.0033 \cdot 10^6$</td>
<td>$0.0048 \cdot 10^6$</td>
</tr>
</tbody>
</table>

Read more in Towards a Future Muon Collider
PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)

But not exactly in time with bunch crossings
**Wishlist**

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns

But not exactly in time with bunch crossings.

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Read more in *Towards a Muon Collider*
PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)

Similarly, where the BIB hits is also distinct from particles produced at the interaction point.

Read more in Towards a Muon Collider
PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)

- Timing resolution on hits to $\mathcal{O}(<0.1)$ ns
- Good granularity of detector

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WISHLIST

- Timing resolution on hits to $\mathcal{O}(<0.1)$ ns
- Good granularity of detector
PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)

BIB particles are mainly very low energy, but we can imagine NP scenarios that also give lots of low energy tracks (SUEPs).
WISHLIST

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns
- Good granularity of detector
- Analysis strategies to see sub-GeV particles

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Read more in Towards a Muon Collider

**PRIMARY CHALLENGE: THE BEAM INDUCED BACKGROUND (BIB)**

![Graphs showing photon flux and BIB particles](image)
**WISHLIST**

- Timing resolution on hits to $\Theta(0.1) \text{ ns}$
- Good granularity of detector
- Analysis strategies to see sub-GeV particles
  - High-quality simulation samples of BIB for theorists/experimentalists to study?

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One more preliminary

- Excellent energy resolution (>90%)

$$\Gamma \sim \sigma_E \times E \rightarrow \text{abandon hope}$$

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Baseline $\sqrt{s} = 3$ TeV</th>
<th>Baseline $\sqrt{s} = 10$ TeV</th>
<th>Aspirational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track $\sigma_{pT}/p_T^Z$ [GeV$^{-1}$]</td>
<td>$4 \times 10^{-5}$</td>
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<td>$1 \times 10^{-5}$</td>
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<tr>
<td>Photon energy resolution</td>
<td>$0.2/\sqrt{E}$</td>
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<td>$0.1/\sqrt{E}$</td>
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<tr>
<td>Neutral hadron energy resolution</td>
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**WISHLIST**

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns
- Good granularity of detector
- Analysis strategies to see sub-GeV particles
  - High-quality simulation samples of BIB for theorists/experimentalists to study?

*One more preliminary*

- Excellent energy resolution (>90%)
  - Some document that summarizes reasonable choices for experimental efficiencies?

$$\Gamma \sim \sigma_E \times E \rightarrow \text{abandon hope}$$

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Assuming we have the BIB under control, let’s consider specific physics motivations
**Physics Goals**

- Precision EW & Higgs
- Heavy Particles
  \[ \Lambda_{NP} \geq \text{TeV} \]
  \[ m_{W,Z,h} \]
- Novel Signatures
  (e.g. Disappearing tracks, LLPs, SUEPs, etc.)

- Flavor Tagging
  ![Flavor Tagging Diagram]
Physics Goals

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Flavor Tagging
Precision measurements of the Higgs is often presented as a primary motivation for a MuC, and we produce them with VBF.
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\[ \times 10 \text{ab}^{-1} = 10^7 \text{total } h \]

Buttazzo, Franceschini, Wulzer ‘20
**PRECISION HIGGS & EW**

Precision measurements of the Higgs is often presented as a primary motivation for a MuC, and we produce them with VBF:

\[
V = Z, W \quad \text{and} \quad V(h) \supset \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4
\]

Variety of guaranteed new measurements

plus improvements shown by $\kappa$ framework
Precision Higgs & EW

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 Variety of *guaranteed* new measurements

\[ V(h) \supset \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 \]

Plus improvements shown by \( \kappa \) framework

Assuming we can reliably identify Higgs events
**PRECISION HIGGS & EW**

VBF Higgs production has very forward kinematics (for all)

\[ p_T \sim m_W \sim 100 \text{ GeV} \]

\[ \eta_{\mu} \sim 3.5 \text{ at } 3 \text{ TeV} \quad \eta_{\mu} \sim 5 \text{ at } 10 \text{ TeV} \]

\[ V = Z, W \]

\[ h \]

\[ \mu, \nu \]

Forlund & Meade '22
WishList

- Sensitivity of $|\eta| \sim 2.5 - 3$ (for high Higgs acceptance)
- Forward muon tagging up to $\eta \sim 5$ at 10 TeV (ZZ vs. WW VBF discrimination)

$\mu, \nu \quad \eta_\mu \sim 3.5$ at 3 TeV

$\mu, \nu \quad \eta_\mu \sim 5$ at 10 TeV

$V = Z, W$

$p_T \sim m_W \sim 100$ GeV

$Forslund & Meade '22$

$\eta_\mu$ for $ZZ \rightarrow h$ fusion

$\eta_h$ for $WW \rightarrow h$ fusion

For $h$
What Higgs processes in specific do we want to see?
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Consider Higgs couplings in the $\kappa$ framework

$BR_{BSM=0}$ Fit Comparisons

Precision for “standard” assumption ($|\eta| < 2.5$) vs. forward tagging ($|\eta| < 6$)
What Higgs processes in specific do we want to see?

- Consider Higgs couplings in the framework of Forslund & Meade '23

<table>
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<th>Precision for “standard” assumption (</th>
<th>\eta</th>
<th>&lt; 2.5) vs. forward tagging (</th>
<th>\eta</th>
<th>&lt; 6)</th>
</tr>
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<tbody>
<tr>
<td>CEPC</td>
<td>FCC-ee</td>
<td>FCC-fd</td>
<td>FCC-10 TeV</td>
<td></td>
</tr>
<tr>
<td>0.86</td>
<td>0.16</td>
<td>0.11</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>0.5</td>
<td>0.26</td>
<td>0.23</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>98°</td>
<td>5.0</td>
<td>2.2</td>
<td>3.7</td>
<td>4.7</td>
</tr>
<tr>
<td>120°</td>
<td>15</td>
<td>6.9</td>
<td>8.2</td>
<td>81°</td>
</tr>
<tr>
<td>4.3</td>
<td>1.8</td>
<td>1.4</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>2.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.9</td>
<td>0.46</td>
<td>0.37</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>320°</td>
<td>13</td>
<td>5.8</td>
<td>8.9</td>
<td>10</td>
</tr>
<tr>
<td>3.0</td>
<td>1.3</td>
<td>0.88</td>
<td>1.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

- Sensitivity of |\eta| ∼ 2.5 - 3 (for high Higgs acceptance)

- Forward muon tagging up to \eta ∼ 5 at 10 TeV (ZZ vs. WW VBF discrimination)

- What momentum resolution do we need in the very-forward regime?

Sensitivity of |\eta| ∼ -3 (for high Higgs acceptance)

Forward muon tagging up to \eta ∼ 5 at 10 TeV (ZZ vs. WW VBF discrimination)

What momentum resolution do we need in the very-forward regime?
WISHLIST

- Sensitivity of $|\eta| \sim 2.5 - 3$ (for high Higgs acceptance)
- Forward muon tagging up to $\eta \sim 5$ at 10 TeV (ZZ vs. WW VBF discrimination)
- What momentum resolution do we need in the very-forward regime?

$p_{T\mu} > 10$ GeV
$\Delta p \sim 90(95)\%$

$p_{T\mu} > 20$ GeV
$|\eta| < 6$
What Higgs processes in specific do we want to see?

\[ V(H) \supset \frac{\lambda_3}{4} v h^3 + \frac{\lambda_4}{4} h^4 = \frac{m_h^2}{2v} (1 + \delta \kappa_3) h^3 + \frac{m_h^2}{8v^2} (1 + \delta \kappa_4) h^4 \]

Quartic coupling
What Higgs processes in specific do we want to see?

\[ V(H) \supset \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 = \frac{m_h^2}{2\nu} (1 + \delta \kappa_3) h^3 + \frac{m_h^2}{8\nu^2} (1 + \delta \kappa_4) h^4 \]

Quartic coupling
**Physics Goals**

- **Precision EW & Higgs**
- **Forward Measurements**
- **Flavor Tagging**
- **Heavy Particles**
  - $\Lambda_{NP} \geq \text{TeV}$
- **Novel Signatures**
  - (e.g. Disappearing tracks, LLPs, SUEPs, etc.)
  - $m_{W,Z,h}$
Physics Goals

Precision EW & Higgs

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Heavy Particles

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(e.g. Disappearing tracks, LLPs, SUEPs, etc.)
HEAVY PARTICLES

With a machine like the MuC that can take us to the energy frontier quickly*, searching for new heavy states is a quintessential pillar of the physics program

*hopefully
HEAVY PARTICLES

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Very different kinematics from primarily $s$-channel pair production.
HEAVY PARTICLES

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Buttazzo, Franceschini, Wulzer '20

*Very different kinematics from primarily $s$-channel pair production

\begin{align*}
\mu & \rightarrow \text{NP} \\
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\end{align*}
HEAVY PARTICLES

With a machine like the MuC that can take us to the energy frontier quickly*, searching for new heavy states is a quintessential pillar of the physics program.

\[ \sigma \sim \frac{1}{s} = \frac{1}{E^2} \]

\[ \mathcal{L} \sim E^2 \]

Very different kinematics from primarily \( s \)-channel pair production

Buttazzo, Franceschini, Wulzer '20
Let’s explode into the energy frontier (what better way of testing UV physics?)

- High resolution (big difference in mass scales)
- Timing to see non-relativistic quasi-stable states?
- Maintain a luminosity that scales like $\mathcal{L} \sim E^2$ (to maintain production of heavy NP)
Physics Goals

- Precision EW & Higgs
- Heavy Particles
  - $\Lambda_{NP} \geq \text{TeV}$
  - $m_{W,Z,h}$
- Novel Signatures
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Forward Measurements

- Flavor Tagging
Precision EW & Higgs

FORWARD MEASUREMENTS

Heavy Particles
$\Lambda_{NP} \geq \text{TeV}$

HIGH ENERGY

$m_{W,Z,h}$

Novel Signatures
(e.g. Disappearing tracks, LLPs, SUEPs, etc.)

Physics Goals

Flavor Tagging

36
FLAVOR TAGGING (PARTICLE ID)

We can make more precise measurements and further mitigate backgrounds with reliable particle identification.

Discrimination of $b$’s from $c$’s (from light quarks) $\iff$ Discrimination of $h/W/Z$
**FLAVOR TAGGING (PARTICLE ID)**

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Discrimination of $b$’s from $c$’s (from light quarks) $\iff$ Discrimination of $h/W/Z$

\[
\begin{align*}
Z &\rightarrow b\bar{b} \\
h &\rightarrow b\bar{b} \\
W &\rightarrow c\bar{b}
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Remarkably different physics processes...
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Remarkably different physics processes…

...that tend to look the same
**WISHLIST**

- Tagging for $b$ vs. $c$ (vs. light quarks)
- Separation of gauge bosons ($W$, $Z$) from Higgs
  - Separation of gauge bosons from each other
- Decent resolution on hadronic decays of $W$ and $Z$

We can make more precise measurements and further mitigate backgrounds with reliable particle identification.

Remarkably different physics processes…

…that tend to look the same
Physics Goals

- Precision EW & Higgs
- Forward Measurements
- Flavor Tagging
- B vs C Jets
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  \[ \Lambda_{NP} \geq \text{TeV} \]
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Novel Signatures
(e.g. Disappearing tracks, LLPs, SUEPs, etc.)
**NOVEL SIGNATURES**

Further studies and sensitivity can be gained by looking at further features of tracks or global properties of the events radiation pattern.

E.g. **disappearing tracks & WIMPS**

\[ \chi \rightarrow \pi^+ \chi^0 \]

\( \begin{align*}
\chi & \text { stable or long lived } \\
\text{Signal} & \\
\text{mono-}\gamma & : \quad \ell^+\ell^- \rightarrow \chi^+\chi^{-i} + \gamma \\
\text{mono-}\ Z & : \quad \ell^+\ell^- \rightarrow \chi^+\chi^{-i} + Z \\
\text{mono-W} & : \quad \ell^+\ell^- \rightarrow \chi^+\chi^{-i+1} + W^\pm \\
\end{align*} \]

\( \begin{align*}
\text{Background} & \\
\text{mono-}\gamma \text{ bkg} & : \quad \ell^+\ell^- \rightarrow \gamma \nu \bar{\nu} \\
\text{mono-}\ Z \text{ bkg} & : \quad \ell^+\ell^- \rightarrow Z \nu \bar{\nu} \\
\text{mono-W} \text{ bkg} & : \quad \ell^+\ell^- \rightarrow W^\mp \nu + \ell^\pm (\text{lost}) \\
\end{align*} \)
Further studies and sensitivity can be gained by looking at further features of tracks or global properties of the events radiation pattern.

E.g. disappearing tracks & WIMPS

$\chi$ stable or long lived  $\chi^+ \rightarrow \pi^+ \chi^0$

**Signal**

- mono-$\gamma$: $\ell^+\ell^- \rightarrow \chi^+ \chi^{-i} + \gamma$
- mono-$Z$: $\ell^+\ell^- \rightarrow \chi^+ \chi^{-i} + Z$
- mono-$W$: $\ell^+\ell^- \rightarrow \chi^+ \chi^{-i+1} + W^\pm$

**Background**

- mono-$\gamma$ bkg: $\ell^+\ell^- \rightarrow \gamma \nu \bar{\nu}$
- mono-$Z$ bkg: $\ell^+\ell^- \rightarrow Z \nu \bar{\nu}$
- mono-$W$ bkg: $\ell^+\ell^- \rightarrow W^\pm \nu + \ell^{\pm}\text{lost}$

*Improve sensitivity by requiring a disappearing track*

Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio ’21, ’22
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\[ \chi \rightarrow W, Z, \gamma \]

\[ \chi \quad \text{SM} \]

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**Improve sensitivity by requiring a disappearing track**

Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio '21, '22
Disappearing track sensitivity (distinct from BIB)

Timing and hit-to-hit correlations

Algorithms can be useful for all kinds of LLP, DV scenarios, what else is there?
Physics Goals

Precision EW & Higgs

Forward Measurements

Flavor Tagging

$B \text{ vs } C \text{ jets}$

Heavy Particles

$\Lambda_{NP} \geq \text{TeV}$

$\ell_{W,Z,h}$

HIGH ENERGY

Novel Signatures

(e.g., Disappearing tracks, LLPs, single leptons, etc.)

Mitigate the BIB with hits and timing
Physics Goals

Forward Measurements

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Flavor Tagging

- \( B \) vs \( C \) Jets

Mitigate the BIB with hits and timing

And what about auxiliary experiments....
Auxiliary Experiments

We can be sensitive to interesting physics if we instrument beyond the interaction points.
AUXILIARY EXPERIMENTS

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Lattice design has flat sections:

\[ 10^{20} \mu \text{ / year} \rightarrow > 10^{16} \nu \text{ / year} \]

For variety of short-baseline \( \nu \) measurements.
Auxiliary Experiments

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But maybe also an \(e\) beam dump-like experiment?
WISHLIST

- Modest calorimetry and tracking for the muon decay products?

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AUXILIARY EXPERIMENTS

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$\Lambda_{W,Z,h}$

High Energy

Flavor Tagging

$B$ vs $C$ Jets

Novel Signatures

(e.g., Disappearing tracks, LLPs, SCLEPs, etc.)

Mitigate the BIB with HITS and Timing

And auxiliary experiments just needing instrumentation
Let’s take a step back: What makes the muon collider so special?
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10 TeV and Beyond in 205x
A World with Two Colliders

FCCee & FCCChh

Precision SM Measurements

MuC

Sprint to 10 TeV Frontier and beyond as fast as we can?

This comes at the cost of luminosity, but if another experiment is covering that physics program, why not aim for complementary physics goals?
A World with Two Colliders

FCCee & FCChh  
**Precision SM Measurements**

MuC  
*Sprint to 10 TeV Frontier and beyond as fast as we can?*

This comes at the cost of luminosity, but if another experiment is covering that physics program, why not aim for complementary physics goals?

**Final Wish**

How much will luminosity suffer if we use *current* technology to build 10, 14, 30 TeV MuC?

What kinds of new heavy states can we still see with low luminosity but high energy?
Wishlist Summary

- Timing resolution on hits to $\mathcal{O}(0.1)$ ns
- Good granularity of detector
- Sensitivity to low energy tracks
- Excellent energy resolution (>90%)
- Forward tagging and $p$ resolution for $|\eta| < 2.5$ at least
- Luminosity should keep up with $s$ channel production
- Discriminate $b$, $c$, and light quarks to discriminate $Z$, $W$, and $h$ bosons
- Find physics applications of the BIB
- *Hitting the energy frontier should be (the highest?) priority*
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There is much work to be done by everyone.

Let’s spend this week discussing *what* physics benchmarks are truly a priority (not just a consequence) and *how* we continue to motivate and demonstrate the full physics potential of a MuC