International
MUON Collider
Collaboration

Physics Studies Report

Donatella Lucchesi for the Physics and Detector INFN group

Preparing for Seattle Snowmass Community meeting

International MUON Collider Collaboration

All the predictions plots now include the muon collider, major achievement thanks to the work done by “us”

A lot of contributions submitted to the Snowmass process

International MUON Collider Collaboration
March 15, 2022
https://muoncollider.web.cern.ch
https://arxiv.org/abs/2203.07256

Muon Collider Physics Summary

Submitted to the Proceedings of the US Community Study

https://arxiv.org/abs/2203.07964
March 16, 2022
https://muoncollider.web.cern.ch

Simulated Detector Performance at the Muon Collider

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07224
March 15, 2022
https://muoncollider.web.cern.ch

Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

April 1, 2022
https://muoncollider.web.cern.ch
https://arxiv.org/abs/2203.08033

A Muon Collider Facility for Physics Discovery

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

https://arxiv.org/abs/2203.07261
March 15, 2022
https://muoncollider.web.cern.ch

The physics case of a 3 TeV muon collider stage

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Preparation of a paper to be submitted to Eur. Phys. Journal C by the end of September

Seattle Snowmass Community meeting: theory vision

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A leptonic vision for the future

Patrick Meade

Higgs Factories

ILC
C^3
CLIC
FCC-ee
CEPC
...
More in e^+e^- forum talk
Possible $\mu^+\mu^-$ staging

High Energy

10+ TeV μCollider
More in $\mu^+\mu^-$ forum talk

10+ TeV WFA e^+e^- collider

So what are the physics cases?

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High energy leptons allows us to push forwards on understanding the Higgs

Patrick Meade

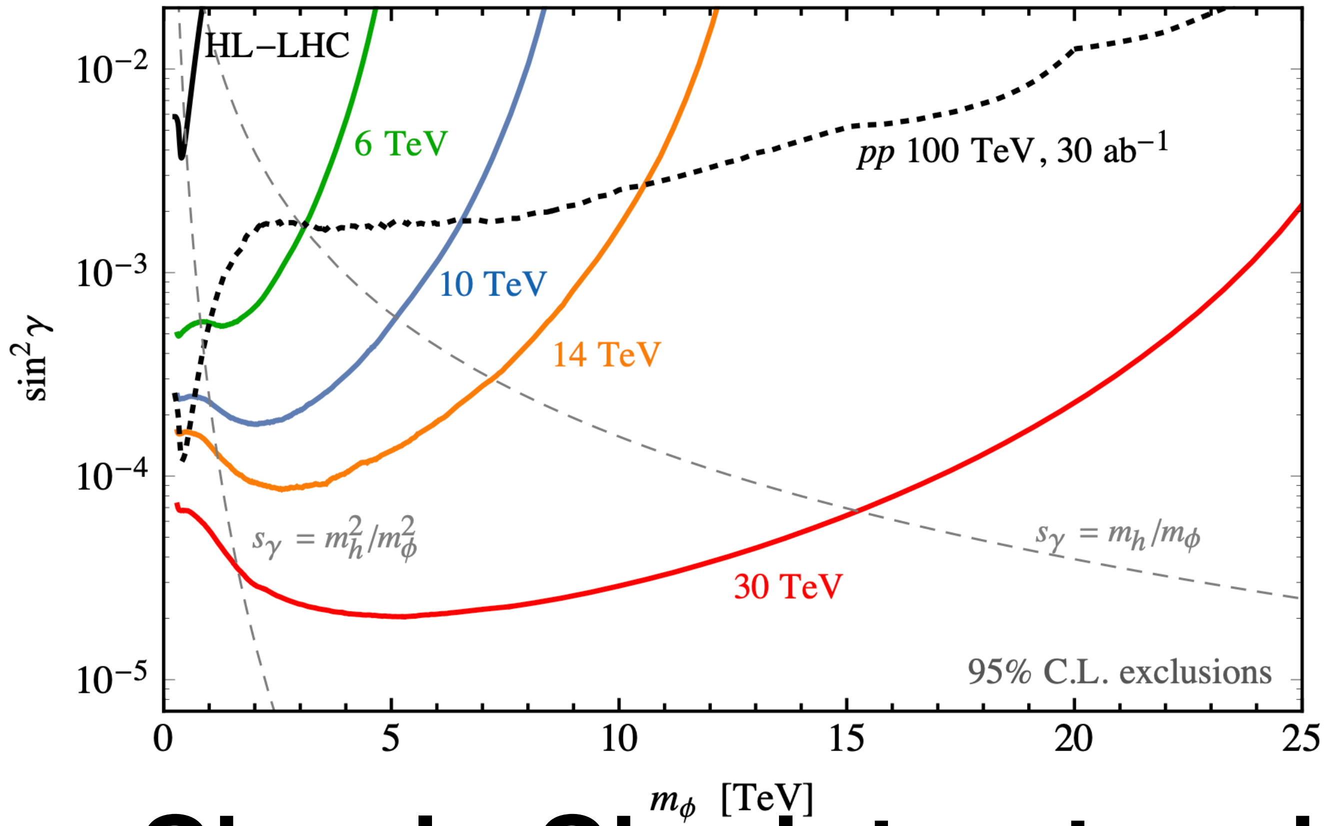
Energy Frontier Benchmarks Integrated Staging

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings: Tree	Gauge Couplings: Loop induced	Higgs Width	λ_3	λ_4
	LHC/HL-LHC	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC	ILC/C^3	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$ *	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC	CLIC	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC	FCC-ee/CEPC	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
High Energy + HL-LHC	μ-Collider	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$
High Energy + HL-LHC	FCC-hh/SPPC	?	?	?	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\lesssim \mathcal{O}(10^{-3})$	?	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$

Order of Magnitude for Fractional Uncertainty: ★ $\lesssim \mathcal{O}(10^{-3})$ ◆ $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ ◆ $\mathcal{O}(1)$ □ $> \mathcal{O}(1)$? No study Beyond HL-LHC

High energy leptons let us push forwards numerous BSM directions as well!

Patrick Meade



10 TeV very complementary with FCC-hh, 30 TeV **blows away other ideas**

Can map to Neutral Naturalness Reach

Simple Singlet extension of SM

Seattle Snowmass Community meeting: experiment vision

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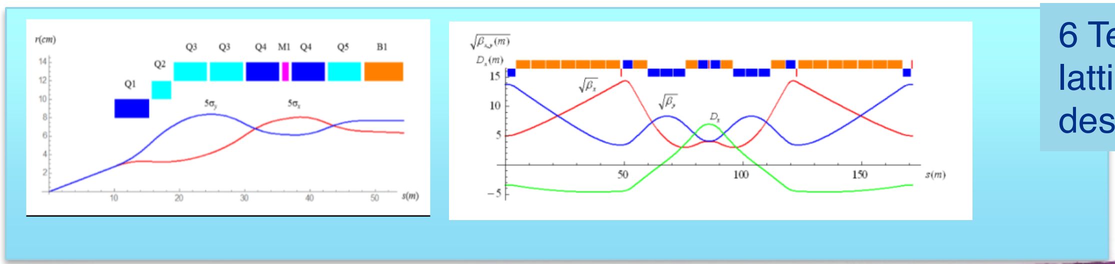
Feasibility: Collider Ring design & neutrino flux

Diktys Stratakis

- Lattice designs for a 3 and 6 TeV Colliders are in place
  - Optics and magnet parameters have been specified [ref]
  - Addressed the challenges associated with radiation loads on magnets as well as particle background in the collider detector [ref]
- The decay of muons in the collider ring produces a dense flux of neutrinos at significant distance from the collider
  - Several solutions in place to mitigate the problem: Examples include situating the collider at ~100 m depth [ref] or move lattice overtime (IMCC approach) [ref].
  - These solutions illustrate that neutrino flux can be manageable, similar to LHC.



6 TeV lattice design


Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Neutrino Flux around Muon Colliders and 7 Ways to Mitigate it

Nikolai Mokhov, Fermilab
Workshop Muon-Driven Colliders
January 27, 2022

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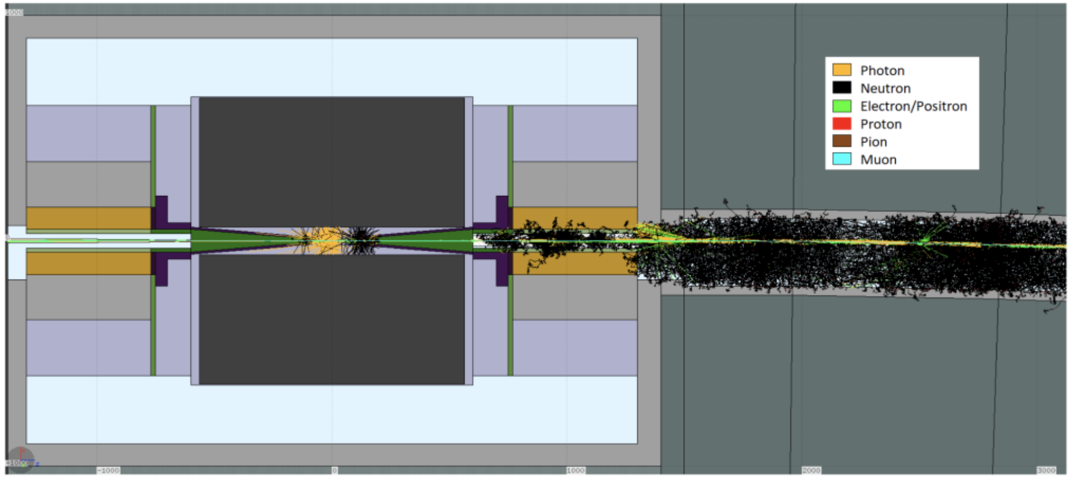
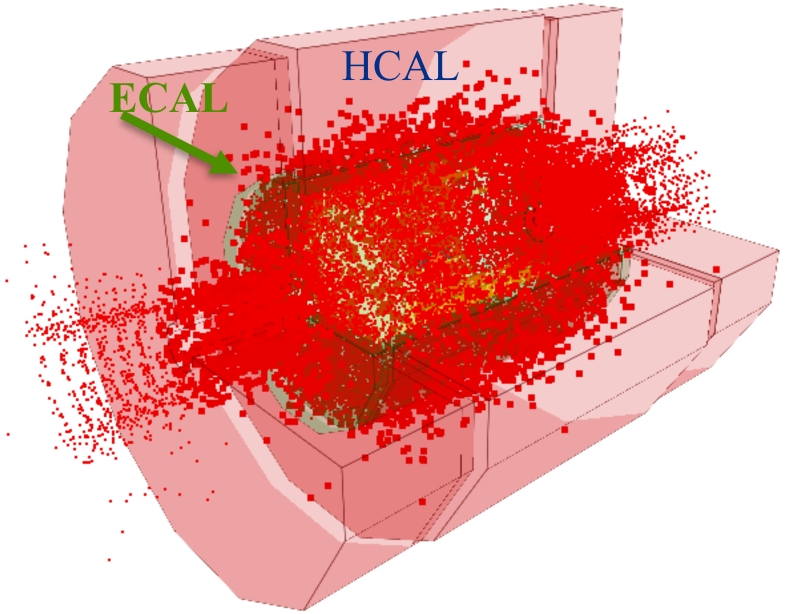
Beam Induced Background

Diktys Stratakis

- Beam background is one of the unique features/challenges of Muon Colliders
- Main Source of Beam Induced Background (BIB) are showers produced by electrons originating in beam muon decays
- Muons decay with an average lifetime of $2.2 \cdot 10^{-6}$ seconds at rest, at $\sqrt{s} = 3$ TeV they live for about $3.1 \cdot 10^{-2}$ seconds
- The challenge is to separate collision particles from the BIB





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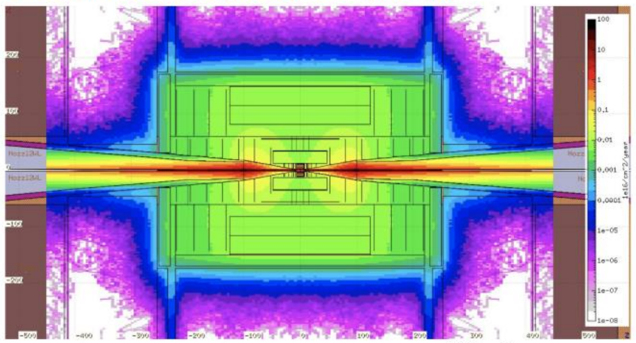
Diktys Stratakis

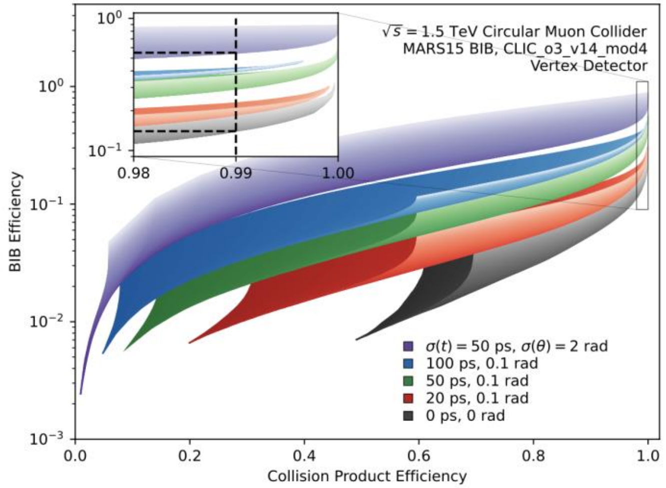
Detectors: Key Developments

- **Detector Environment:**
  - ✓ Radiation levels similar to HL-LHC and much smaller than at the future hadron colliders
- **Beam induced background evolution studied:**
  - ✓ The BIB in detector volume is approximately constant with COM energy (even without MDI optimization) → higher energies possible
- **Detector technologies have been rapidly advancing (in large due to HL-LHC needs):**
  - ✓ Particle Flow detectors with excellent position, energy and timing resolution
  - ✓ Advanced on- and off- detector data processing
  - ✓ Using reconstruction from pp makes a huge difference
- **Minimum muon collider detector requirements are within reach or already technologically available.**

1-MeV-neq fluence for one year of operation (200 days)



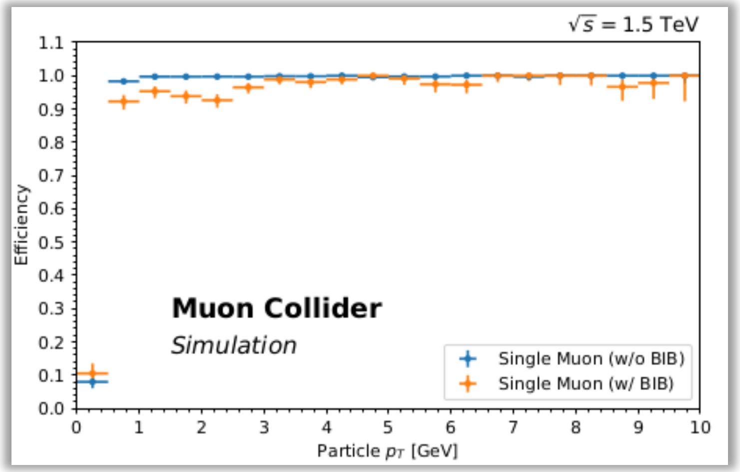
Expected (FLUKA simulation) to be approximately: ~10^{14-15}/cm^2/y in the tracker ~10^{14}/cm^2/y in the ECAL

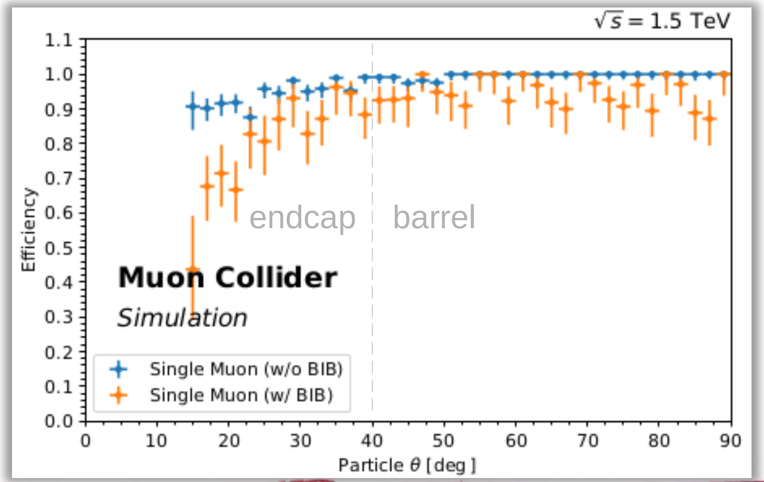


Detector performance

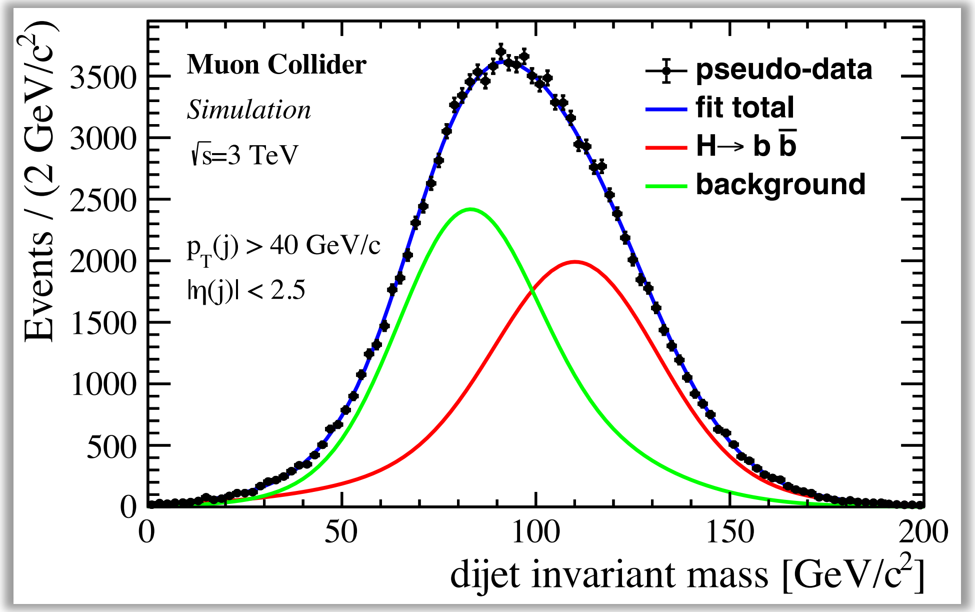
Event reconstruction feasibility demonstrated already with simple algorithms

Detector occupancy and energy density are manageable





Fast simulation performance validated against full simulation using some benchmark physics scenario



Seattle Snowmass Community meeting: final vision

The immediate future is the HL-LHC

- During the next decade it is essential to complete the **highest priority recommendation of the last P5** and to fully realize the scientific potential of the **HL-LHC collecting at least 3 ab^{-1} of data**.
- **Continued strong US participation is critical** to the success of the HL-LHC physics program, in particular for the Phase-2 detector upgrades, the HL-LHC data taking operations and physics analyses based on HL-LHC data sets, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades
- **For the next decade and beyond**
  - **2025-2030**: Prioritize HL-LHC physics program, including auxiliary experiments
  - **2030-2035**: Continue strong support for HL-LHC physics program

The long-term future is a multi-TeV collider

- A 10-TeV **muon collider** (MuC) and 100-TeV **proton-proton collider** (FCC-hh, SppC) directly probe the order 10 TeV energy scale with different strengths that are unparalleled in terms of mass reach, precision, and sensitivity.
- The main limitation is technology readiness. **A vigorous R&D program** into accelerator and detector technologies **will be crucial.**
- **For the next decade and beyond**
  - **2025-2030**:
    - Develop an initial design for a first stage TeV-scale Muon Collider in the US (pre-CDR)
    - Support critical detector R&D towards EF multi-TeV colliders
  - **2030-2035**: Demonstrate principal risk mitigation and deliver CDR for a first-stage TeV-scale Muon Collider
  - **After 2035**:
    - Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale Muon Collider
    - Ramp up funding support for detector R&D for EF multi-TeV colliders

The intermediate future is an e^+e^- Higgs factory

The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C^3, CLIC) or circular collider (FCC-ee, CepC).

- **The various proposed facilities have a strong core of common physics goals**: it is important to **realize at least one somewhere in the world.**
- **A fast start towards construction is important**. There is **strong US support** for initiatives that could be realized on a time scale relevant for early career physicists.
- **For the next decade and beyond**
  - **2025-2030**: Establish a targeted e^+e^- Higgs Factory detector R&D for US participation in a global collider
  - **2030-2035**: Support and advance construction of an e^+e^- Higgs Factory
  - **After 2035**: Begin and support the physics program of an e^+e^- Higgs Factory

Last day in Seattle… i "muonici" INFN a Snowmass