Outline

• Neutrino Factories and Muon Colliders
• Muon cooling
• Muon Ionization Cooling Experiment (MICE)
• Conclusions
νF and μC

**Neutrino Factory (NuMAX)**

Proton Driver

Accumulator

Compressor

Front End

Phase Rotator

Capture Sol. Accumulator Compressor

Decay Channel

Buncher

Initial Cooling

Acceleration

μ Storage Ring

\( \nu \)

\( \nu \)

\( \mu^{-} \)

\( \mu^{+} \)

\( 5 \text{ GeV} \)

\( \approx 0.35 \text{ km} \)

\( 0.2-1 \text{ GeV} \)

\( 1-5 \text{ GeV} \)

Accelerators: Single-Pass Linacs (Opt. RLA or FFAG)

\( \nu \) Factory Goal: \( O(10^{21}) \) ν/year within the accelerator acceptance

\( \mu \)-Collider Goals:

- 126 GeV ↔ 14,000 Higgs/yr
- Multi-TeV ↔ Lumi > \( 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)

\( \nu \) F and µC

- Strong similarities! (Upstream ends nearly identical)

  - stored-muon facilities that start with \(~\text{MW} \ \pi\text{ beam on high-power tgt} \)

\( \rightarrow \pi \rightarrow \mu \), then cool, accelerate, & store the \( \mu \)

\( \mathcal{L} > 10^{34} \text{ cm}^{-2} \text{s}^{-1} \) for \( E_{CM} > 1 \text{ TeV} \)

**Muon Collider (Muon Accelerator Staging Study)**

Proton Driver

Accumulator

Compressor

Front End

Phase Rotator

Charge Separator

Initial Cooling

Cooling

Acceleration

Collider Ring

\( E_{CM}^{-} \)

Higgs Factory to ~10 TeV

\( \mu^{+} \)

\( \mu^{-} \)

\( \mathcal{L} > 10^{34} \text{ cm}^{-2} \text{s}^{-1} \) for \( E_{CM} > 1 \text{ TeV} \)

Share same complex

(Upstream ends nearly identical)
**Key ν-mixing physics questions:**

1. What is the neutrino mass hierarchy?
2. Why is pattern of neutrino mixing so different from that of quarks?
3. How close to zero is the PMNS phase $\delta$?
4. Is 3-generation mixing the whole story?
Key $\nu$-mixing physics questions:

1. What is the neutrino mass hierarchy?  
   \[ \text{"normal"} \quad \nu_3 \quad \Delta m_{32} \quad \nu_2 \quad \Delta m_{21} \quad \nu_1 \quad \Delta m_{23} \quad \nu_e \quad \nu_\mu \quad \nu_\tau \]
   \[ \text{"inverted"} \quad \nu_3 \quad \Delta m_{23} \quad \nu_2 \quad \Delta m_{21} \quad \nu_1 \quad \Delta m_{32} \quad \nu_e \quad \nu_\mu \quad \nu_\tau \]
   “$\text{sgn}(\Delta m^2_{32})$”

   Relevant to cosmology, since neutrinos are 2nd-most-abundant particle in universe!

2. Why is pattern of neutrino mixing so different from that of quarks?

3. How close to zero is the PMNS phase $\delta$?

4. Is 3-generation mixing the whole story?
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2. Why is pattern of neutrino mixing so different from that of quarks?

   CKM matrix:  
   \[ \begin{align*} 
   \theta_{12} &\approx 12.8^\circ \\
   \theta_{23} &\approx 2.2^\circ \\
   \theta_{13} &\approx 0.4^\circ 
   \end{align*} \]

   PMNS matrix:  
   \[ \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \end{pmatrix} \neq 1 \Rightarrow \nu & \overline{\nu} \text{ mix differently (CPV)} \]

   emerging expert consensus: next-generation experiments will determine hierarchy

3. How close to zero is the PMNS phase $\delta$?

4. Is 3-generation mixing the whole story?
Key ν-mixing physics questions:

1. What is the neutrino mass hierarchy? “\( \text{sgn}(\Delta m^2_{32}) \)”

   Relevant to cosmology, since neutrinos are 2nd-most-abundant particle in universe!

2. Why is pattern of neutrino mixing so different from that of quarks?

   CKM matrix: \[ \begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \sin \theta \ e^{i \delta} \\ \frac{1}{2} & \frac{1}{2} & -\frac{\sqrt{2}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \end{pmatrix} \]

   PMNS matrix: \[ \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim \frac{\sqrt{2}}{2} & \sim \frac{\sqrt{2}}{2} \\ \sim 1 & \sim 1 & \sim \frac{\sqrt{2}}{2} \end{pmatrix} \]

   Different patterns hard to understand if both due to GUT!

3. How close to zero is the PMNS phase \( \delta \)?

4. Is 3-generation mixing the whole story?
Key \( \nu \)-mixing physics questions:

1. What is the neutrino mass hierarchy?  
   \[ \text{“normal”} \quad \nu_3 \quad \Delta m_{21} \quad \nu_2 \quad \Delta m_{32} \quad \nu_1 \quad \Delta m_{23} \]
   Relevant to cosmology, since neutrinos are 2nd-most-abundant particle in universe!

2. Why is pattern of neutrino mixing so different from that of quarks?

   CKM matrix: \[ \begin{array}{c}
   \text{PMNS matrix:} \\
   \begin{pmatrix}
   \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & \sin \theta \cdot e^{i \phi} \\
   -\frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \\
   \frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2}
   \end{pmatrix}
   \end{array} \]
   \( \neq 1 \Rightarrow \nu \& \bar{\nu} \)
   mix differently (CPV)

3. How close to zero is the PMNS phase \( \delta \)?
   \( \Rightarrow \text{Does neutrino mixing violate CP, as required for Leptogenesis? i.e., } \delta \neq 0, \pi \)?

4. Is 3-generation mixing the whole story?
Key ν-mixing physics questions:

1. What is the neutrino mass hierarchy? “\(\text{sgn}(\Delta m^2_{32})\)”

   Relevant to cosmology, since neutrinos are 2nd-most-abundant particle in universe!

2. Why is pattern of neutrino mixing so different from that of quarks?

3. How close to zero is the PMNS phase \(\delta\)?

   \(\Rightarrow\) Does neutrino mixing violate \(CP\), as required for Leptogenesis? i.e., \(\delta \neq 0, \pi\)?

4. Is 3-generation mixing the whole story?

   \(\exists\) sterile neutrinos? additional dynamical effects: \(\nu\) decay or decoherence…?

   \(\Rightarrow\) Need precision measurements→µ storage rings can provide
Neutrino Factory Physics Reach

- CPV sensitivity comparison:

\[ \Delta \delta \text{ at } 1\sigma \]
\[ \theta_{23} = 40° \]

[P. Huber et al., from arXiv:1308.0494]

\[ \text{vF has greatest reach...and will ultimately be required!} \]

\[ \text{only technique with sensitivity comparable to quark sector} \]
What about Muon Colliders?

• An option for high-energy lepton colliders
  – unlike $e^+e^-$, $\sqrt{s}$ not limited by radiative effects
  ➤ a $\mu$C can fit on existing laboratory sites even for $\sqrt{s} > 3$ TeV:

  ➤ $\mu$C likely to be cost-effective – $\sim (LHC)$
What about Muon Colliders?

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- Also,
  - $s$-channel coupling of Higgs to lepton pairs $\propto m_{\text{lepton}}^2$
  - $\mu$C resolution can separate near-degenerate scaler and pseudo-scalar Higgs states of high-$\tan\beta$ SUSY

Separation of $A^0$ & $H^0$ by Scanning

[Barger et al., hep-ph/0110340]
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  ➡ while any H.E. $e^+e^-$ collider has long tail to low energy
  ➡ as well as much higher operating costs for $E > 2$ TeV
Negligible radiative effects, and multiple interaction regions, make muons the lepton of choice for multi-TeV colliders.
Technical Challenges*

1. High-power (multi-MW) \( p \) beam and target
   - > 4 MW Hg jet feasible [MERIT@CERN, 2007]
   - e.g., SNS, ESS, ...

2. Muon beam cooling in all 6 phase-space dimensions
   - \( \mu \) unstable, \( \tau_\mu = 2.2 \mu s \) ⇒ must cool quickly! [MICE]
   - requires high-gradient RF cavities in \( B > 1 \) T fields [FNAL MTA]

3. Rapid acceleration
   - Linac–RLAs–(FFAGs)–RCS
     [EMMA@DL, 2011; proposed JEMMRLA@JLab]

4. High storage-ring bending field (to maximize \# cycles before decay) and small \( \beta_\perp \), for high \( \mathcal{L} \)
   - Solution devised @ FNAL: \( B \sim 10 \) T, \( \beta \sim 1 \) cm

*[& demonstration experiments]
νF and μC

Better: dual-use linac! (to avoid building two expensive SC linacs)

ν Factory Goal: \(O(10^{21})\) μ/year within the accelerator acceptance

νF and μC

Strong similarities! (Upstream ends nearly identical)

- stored-muon facilities that start with ~MW \(p\) beam on high-power tgt
  \[ \rightarrow \pi \rightarrow \mu, \text{ then cool, accelerate, & store the } \mu \]

- note two similar few-GeV linacs: one in Proton Driver, one after cooling

\( \mathcal{L} > 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) for \(E_{CM} > 1\) TeV
Muon Cooling

- Beam cooling best understood in terms of beam’s normalized emittance $\epsilon_n = \gamma \beta \epsilon = \epsilon \frac{p}{m}$
- Physics of multi-TeV lepton collisions calls for $\mathcal{L} > 10^{34}$ cm$^{-2}$ s$^{-1}$
  \[ \Rightarrow \text{must cool both } \epsilon_\perp \& \epsilon_\parallel \]
  - need factor $10^6$ in total 6D emittance reduction
- Higgs physics requires $\mathcal{L} \sim 10^{32}$ and $\Delta p/p \sim 10^{-5}$
- Neutrino factory with dual-use linac requires more modest, $\times 50$ 6D cooling factor
How to cool muons?

• Problem: Average lifetime at rest = 2.2 µs

• But established cooling methods (stochastic, electron) take seconds to hours!

• What cooling method can work in << 2.2 µs?
  - There is only one:
    - electron cooling with an extremely dense electron “gas” – denser than any beam…
Ionization Cooling!

- Muons cool via $dE/dx$ in low-Z medium:
  
  - Absorbers:
  
  $E \rightarrow E - \left(\frac{dE}{dx}\right)\Delta s$

  $\theta \rightarrow \theta + \theta_{\text{rms}}^{\text{space}}$

  - RF cavities between absorbers replace $\Delta E$

  - Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

  $\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2} \left(\frac{dE_\mu}{ds}\right) E_\mu + \frac{\beta_\perp(0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$

  (emittance change per unit length)

- Only* practical way to cool within $\mu$ lifetime

- Expt’l demo in progress…[MICE]

*Optical stochastic cooling?
How to cool in 6D?

- Work above ionization minimum to get negative feedback in $p_z$?
- No – ineffective due to straggling

$\Rightarrow$ cool longitudinally via emittance exchange:

- use dispersion to create appropriate correlation between momentum and position / path length

- Cool $\epsilon_{\perp}$, exchange $\epsilon_{\perp}$ & $\epsilon_{\parallel}$ $\Rightarrow$ 6D cooling
How to cool in 6D?

- Tricky beam dynamics: must handle dispersion, angular momentum, nonlinearity, chromaticity, & non-isochronous beam transport

- 3 types of solutions viable in simulation:
- FOFO Snake can cool both signs at once but may be limited in $\beta_{\perp,\text{min}} \Rightarrow$ may be best for initial 6D cooling
- HCC may be most compact
- Performance limits of each not yet clear, nor which is most cost-effective
How to cool in 6D?

- Rectilinear FOFO end-to-end simulation:

- Achieves ~ desired $\epsilon_{6D}$
  - good match to Higgs Factory
  - but high $\mathcal{L}$ required in multi-TeV regime calls for $\epsilon_{\perp} \leq 25 \, \mu\text{m} \rightarrow \text{“final cooling”}$
Higgs Factory Cooling

• $\mu^+\mu^-$ Higgs Factory requires \textit{exquisite} energy precision:
  
  - use $\mu^+\mu^- \rightarrow h$ \textit{s-channel} resonance: $\Gamma_h^{\text{SM}} = 4$ MeV
  
  $\rightarrow$ want $dE/E \approx 0.003$

$\Rightarrow$ omit final cooling
Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires 
  \textit{exquisite} energy precision:
  
  - use $\mu^+\mu^- \rightarrow h$ \textit{s-channel} resonance: $\Gamma_h^{SM} = 4$ MeV
  
  \rightarrow want $dE/E \approx 0.003$

  \Rightarrow omit final cooling

- $10^{-6}$ energy calib. via $(g-2)_\mu$ spin precession!

- measure $\Gamma_h$, lineshape (& $m_h$) via $\mu^+\mu^-$ resonance scan

  - the only way to do so!

  - and a key test of the SM

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Beyond 6D Cooling

• To reach $\leq 25$ µm transverse emittance, must go beyond 6D cooling schemes shown above

• One approach (Palmer “Final Cooling”):
  - cool transversely with $B \sim 30$ T at low momentum
  - gives lower $\beta$ & higher $dE/dx$:
    \[ \beta_\perp \sim \frac{p}{B} \]
Beyond 6D Cooling

• To reach \( \leq 25 \, \mu m \) transverse emittance, must go beyond 6D cooling schemes shown above

• One approach (Palmer “Final Cooling”):
  - cool transversely with \( B \sim 30 \, T \) at low momentum
  - gives lower \( \beta \) & higher \( dE/dx \):
    \[ \beta_{\perp} \sim \frac{p}{B} \]

• Lower-\( B \) options under study as well (Derbenev “PIC/REmEx,” lithium lenses)

High-field YBCO solenoid
(BNL/Particle Beam Lasers, Inc.)
Achieved world-record field in an all-HTS magnet: 15 T on axis
MICE

• International Muon Ionization Cooling Experiment at UK’s Rutherford Appleton Laboratory (RAL)

• Flexibility to test several absorber materials & optics schemes

• Status: under construction

μ beam
~200 MeV/c

TOF

4T spectrometer I

Cooling cell (~10%)
β = 5-45 cm, LH₂, RF

4T spectrometer II

SciFi solenoidal spectrometers measure emittance to 1‰
(muon by muon)
Principles of MICE

• Build minimum cooling channel that suffices
  - sufficient length to give \( \approx 10\% \) cooling effect

• Measure emittance with 0.1\% precision
  - allows even small cooling effects near equilibrium emittance to be well measured
    \( \Rightarrow \) need to measure muon beam one muon at a time

• Vary all parameters to explore full performance range, validate simulation tools
Principles of MICE

(Step V Configuration, nominal beam & optics)

• **Optics vs. z:**

• **Beam behavior vs. z:**

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1st Test of Emittance Exchange

- Some aspects of 6D cooling / emittance exchange can also be tested, by inserting wedge absorbers in MICE

- wedge design:
MICE

• International collaboration:

![Diagram of MICE experiment](image-url)

- Beam PID: TOF 0, TOF 1, CKOV
- Variable Diffuser
- Spectrometer solenoid 1
- Focus coils
- Coupling Coil
- Spectrometer solenoid 2
- RF cavities
- RF power
- Liquid Hydrogen absorbers 1 & 2
- Trackers 1 & 2
- Downstream PID: TOF 2, Calorimeters
- Incoming muon beam

Abstract

Due to the short muon lifetime, traditional beam cooling is designed to demonstrate for the first time that emittance reduction of a muon beam can be achieved via ionization cooling of a muon beam, by its interaction with ionisation energy loss, violation, or a Muon Collider, a potential route to multi-TeV by passing the beam through a low-

Eventually an equilibrium emittance is reached where the beam cross section, for an overall reduction in emittance. Combined with alternating gradient focusing to reduce the radio frequency (RF) cavities.

Progressive reduction in the beam divergence, which can be expected in 2015) adds the spectrometers solenoids, trackers and first absorber focus coil module. Step V (first running expected in 2018) adds an RF coupling coil module and second absorber focus coil module. Step VI (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step VII (first running expected in 2018) adds the spectrometers solenoids, trackers and first absorber focus coil module. Step VIII (first running expected in 2018) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step IX (first running expected in 2018) adds the spectrometers solenoids, trackers and first absorber focus coil module. Step X (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XI (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XII (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XIII (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XIV (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XV (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XVI (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XVII (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. Step XVIII (full equipment in place) adds the downstream high precision scintillating fibre absorbing spectrometer solenoid. 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Quick tour:
Quick tour:
Spectrometer Solenoids

RF Power Supplies

LH₂ Absorber

1st RF Cavity

Focus Coils

SciFi Trackers

Time-of-Flight Counters

LiH Absorber

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MICE Construction Schedule

- Being carefully managed – so far, so good!

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Eventually an equilibrium emittance is reached where the beam cross section, for an overall reduction in emittance.

Due to the short muon lifetime, traditional beam cooling techniques cannot be applied to muons. Ionization cooling involves first reducing beam momentum in all directions in the absorber materials followed by restoration of longitudinal momentum in RF linacs.

MICE is designed to demonstrate for the first time that emittance reduction can be achieved with muons. Step V will include an RF drive system to deliver 2 MW, 1 ms pulses of 201 MHz frequency at 1 Hz repetition rate to maintain a 15% gradient and the muon transit phase, and development of the cavity with correct RF phasing, diagnostics to determine the performance of ionization cooling. Step V will include an RF coupling coil module and first absorber focus coil module. Step IV (first running expected in 2018) adds an RF coupling coil module and second absorber focus coil module. Step V (first running expected in 2018) adds an RF coupling coil module and second absorber focus coil module.

The Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory aims to demonstrate for the first time that emittance reduction can be achieved with muons. The MICE programme, but over time this has evolved and plans have been modified. A 4 T superconductive ducting spectrometer solenoid. Direct momentum in RF linacs. MICE Step V will provide the flexibility for a thorough exploration and characterization of momentum compaction techniques. The Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory aims to demonstrate for the first time that emittance reduction can be achieved with muons. The MICE programme, but over time this has evolved and plans have been modified. A 4 T superconductive ducting spectrometer solenoid.
Current MICE Status

• Beamline and all detectors installed and operational

• All solenoids needed for Step IV delivered & field-mapped

• Step IV Partial Return Yoke iron on order

• Coupling Coil cold mass (needed for Step V) trained @ FNAL & cryostat completed (LBNL); magnet assembly in progress

• All RF cavities (Step V) built, 1st under test @ MTA
Conclusions

- Higgs and $\theta_{13}$ discoveries “set the stage” for stored-$\mu$ facilities

- $10^{21}$ $\nu$/year Neutrino Factory feasible
  → world’s best measurements of neutrino oscillation parameters
  & best opportunity to find new, “beyond oscillation” physics

- High-$\mathcal{L}$ Muon Collider looks feasible
  - possibly buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step on the way to multi-TeV!

- Muon Collider technology selection & feasibility assessment were main goals of MAP 6-year R&D program
  - reassessing after P5 recommendations; hope to progress some technical feasibility issues under DOE “general accelerator R&D” (GARD) auspices

- If desired, 1st Neutrino Factory construction might start in 2020s
- & 1st Muon Collider by late 2020s, should physics so require