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Muon Collaboration

MUON COLLIDER AND NEUTRINO FACTORY R&D

UC Santa Barbara Kavli Institute
for Theoretical Physics
April 22, 2003

Gail G. Hanson
University of California, Riverside

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WHY MUON COLLIDERS?

- Muons are fundamental particles, so same advantage as e^+e^- colliders:
  - ➜ Energy of interaction is full energy of particle, not of constituent quarks or gluons (factor ~10)
- Synchrotron radiation by muons is less than for electrons by factor of $(m_e/m_\mu)^4 \approx 6 \times 10^{-10}$
  - ➜ Energy lost by synchrotron radiation must be put back by rf power (cost of power for operation)
  - ➜ Muon beam can have narrow energy spread ($\geq 10^{-5}$)
  - ➜ High energy collider can be much smaller!

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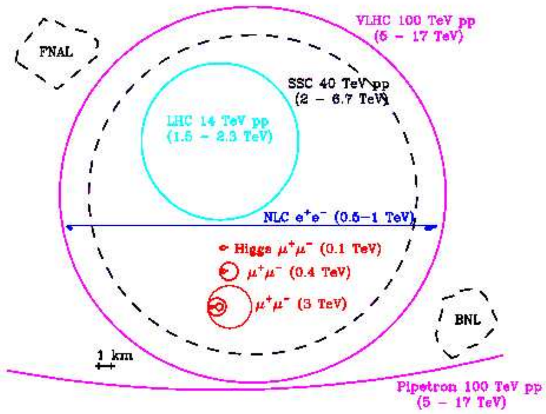
COMPARISON OF HIGH ENERGY COLLIDERS



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PHYSICS ISSUES

- Is there a light Higgs boson? Data suggest “yes”
- If only one light Higgs boson, crucial to measure properties – SM or SUSY?
- At muon collider, Higgs produced through *s*-channel
- Can measure *CP* properties of Higgs bosons through asymmetries with transversely polarized μ^+ and μ^- beams
- A muon collider in the Higgs mass range is a step towards a high energy (3-4 TeV) muon collider.

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WHY MUON COLLIDERS?

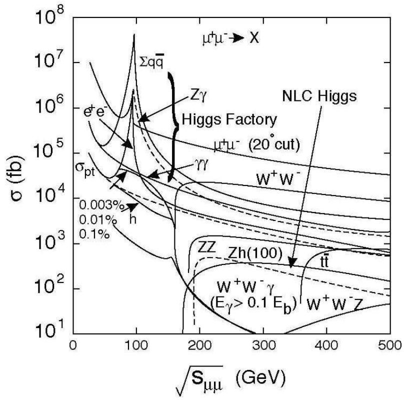
S-CHANNEL HIGGS PRODUCTION

The Higgs boson couples to mass, so cross section at *s*-channel Higgs pole is very large (Fig.)

➜ Small beam energy spread can allow measurement of m_H to few hundred keV

➜ Direct measurement of Higgs width Γ_H to ~ 1 MeV

➜ A Higgs Factory



(From T. Han, talk at FNAL, May 22, 1998)

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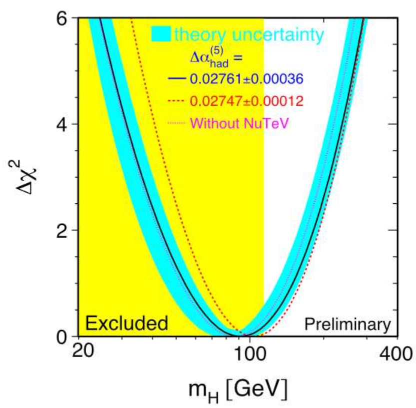
LOW MASS HIGGS BOSON?

FITS TO PRECISION ELECTROWEAK DATA



$m_H = 91^{+58}_{-37}$

m_H < 211 GeV, 95% C.L.

(Winter 2003)

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POSSIBLE IMPLICATIONS FOR SUPERSYMMETRY?

- Light Higgs boson (m_h ~ 120 GeV) indicates large value of tan β
- Possible disagreement of muon anomalous magnetic moment $(g–2)_\mu$ with SM prediction also may indicate large tan β
- In decoupling limit, lighter Higgs boson h^0 has couplings like SM Higgs, but heavier Higgses H^0, A^0 have non-SM couplings: coupling to gauge bosons is suppressed
- For larger values of tan β there is a range of heavy Higgs boson masses (H^0, A^0) for which discovery at LHC or e^+e^- linear collider is not possible
- Heavy Higgs bosons are largely degenerate in MSSM

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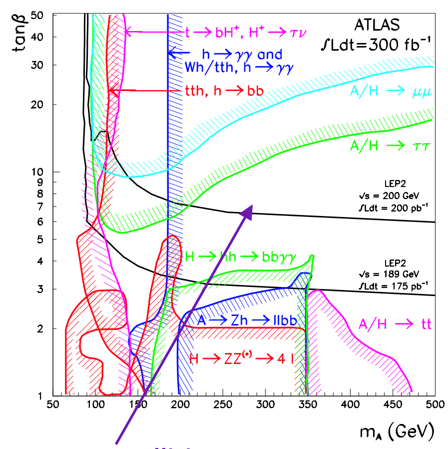
NEED FOR SUSY HIGGS FACTORY?

For larger values of tan β, the heavy Higgs bosons H^0, A^0 may have couplings to gauge bosons suppressed.

We might need a muon collider to discover them.



Muon collider?

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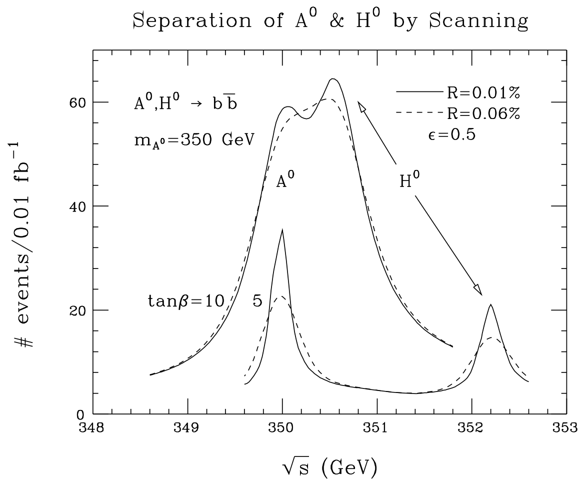
DEGENERATE HEAVY HIGGS BOSONS



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WHY MUON STORAGE RINGS?

- Muons decay:

  $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ or $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$
- A muon storage ring can produce 10^{19} to 10^{21} muon decays per year

  ➜ The stored muons can have energy 20–50 GeV

  ➜ The stored muons can be polarized

  ➜ There is no comparable source of electron neutrinos and antineutrinos

  ➜ Intense beams of neutrinos can be produced to study neutrino oscillations and possible CP violation

  ➜ A Neutrino Factory

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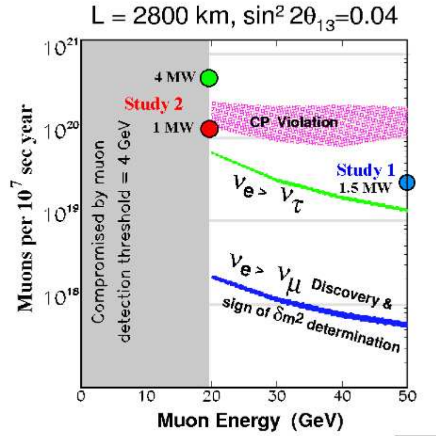
NEUTRINO OSCILLATIONS

- A neutrino factory can measure
  - ➜ θ_{13} from $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
  - ➜ The sign of Δm^2_{32} using matter effects
  - ➜ *CP* violation in the leptonic sector if $\sin^2(2\theta_{13})$ $\sin^2(2\theta_{21})$ and Δm^2_{21} are sufficiently large



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NEUTRINO OSCILLATIONS

For three electroweak doublet neutrinos, the neutrino mixing matrix is described by

$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - s_{13}c_{12}c_{23}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix} K',$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, and $K' = \mathrm{diag}(1, e^{i\phi_1}, e^{i\phi_2})$
(The phases ϕ_1 and ϕ_2 do not affect neutrino oscillation.)

Neutrino mixing depends on four angles θ_{12}, θ_{13}, θ_{23}, δ and two differences of squared masses.

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NEUTRINO OSCILLATIONS

- In the absence of any matter effect the probability that a weak neutrino eigenstate ν_a becomes ν_b after propagating a distance L is

$$P(\nu_a \rightarrow \nu_b) = \delta_{ab} - 4\sum_{i>j=1}^{3} Re(K_{ab,ij}) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$
$$+4\sum_{i>j=1}^{3} Im(K_{ab,ij}) \sin\left(\frac{\Delta m_{ij}^2 L}{4E}\right) \cos\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

where

$K_{ab,ij} = U_{ai} U_{bi}^* U_{aj}^* U_{bj}$ and $\Delta m_{ij}^2 = m(\nu_i)^2 - m(\nu_j)^2$

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NEUTRINO OSCILLATIONS

- We can take
  $\Delta m^2_{atm} = \Delta m^2_{32} = m(\nu_3)^2 - m(\nu_2)^2$
  $\Delta m^2_{sol} = \Delta m^2_{21} = m(\nu_2)^2 - m(\nu_1)^2$

- One possible hierarchy is
  $\Delta m^2_{21} = \Delta m^2_{sol} << \Delta m^2_{31} \approx \Delta m^2_{32} = \Delta m^2_{atm}$

- Neutrino beams from a muon storage ring have extremely high purity and would be 50% ν_μ and 50% $\bar{\nu}_e$ (or 50% $\bar{\nu}_\mu$ and 50% ν_e)

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NEUTRINO OSCILLATIONS

- In vacuum, *CPT* invariance implies $P(\bar{\nu}_b \to \bar{\nu}_a) = P(\nu_a \to \nu_b)$, so for $b = a$, $P(\bar{\nu}_a \to \bar{\nu}_a) = P(\nu_a \to \nu_a)$. The transition probabilities for the *CP*-transformed reaction $\bar{\nu}_a \to \bar{\nu}_b$ and the *T*-reversed reaction $\nu_b \to \nu_a$ are given by the formula for $P(\nu_a \to \nu_b)$ with the sign of the imaginary term reversed.
- For long baseline neutrino experiments, there is only one relevant mass scale: Δm^2_{atm}
- Then *CP*(*T*) violation effects are negligibly small so that in vacuum

$$P(\bar{\nu}_a \to \bar{\nu}_b) = P(\nu_a \to \nu_b)$$
$$P(\nu_b \to \nu_a) = P(\nu_a \to \nu_b)$$

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NEUTRINO OSCILLATIONS

- In matter, even in the absence of CP violation $P(\bar{\nu}_a \to \bar{\nu}_b) \neq P(\nu_a \to \nu_b)$
- With a Neutrino Factory one can use the wrong-sign muon appearance spectra as functions of Δm^2_{32} at a baseline of ~3000 km for both μ^+ and μ^- beams to determine the sign of Δm^2_{32} as well as the value of $\sin^2(2\theta_{13})$

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NEUTRINO OSCILLATIONS

* = well or easily meas.; ✔ = meas. poorly or with difficulty; — = not meas.

Measurement	Type	Conventional beam	Neutrino Factory
$\nu_\mu \to \nu_\mu$, $\nu_\mu \to \mu^-$	survival	✔	*
$\nu_\mu \to \nu_e$, $\nu_e \to e^-$	appearance	✔	✔
$\nu_\mu \to \nu_\tau$, $\nu_\tau \to \tau^-$, $\tau^- \to (e^-, \mu^-)$	appearance	✔	✔
$\bar{\nu}_e \to \bar{\nu}_e$, $\bar{\nu}_e \to e^+$	survival	—	*
$\bar{\nu}_e \to \bar{\nu}_\mu$, $\bar{\nu}_\mu \to \mu^+$	appearance	—	*
$\bar{\nu}_e \to \bar{\nu}_\tau$, $\bar{\nu}_\tau \to \tau^+$, $\tau^+ \to (e^+, \mu^+)$	appearance	—	✔

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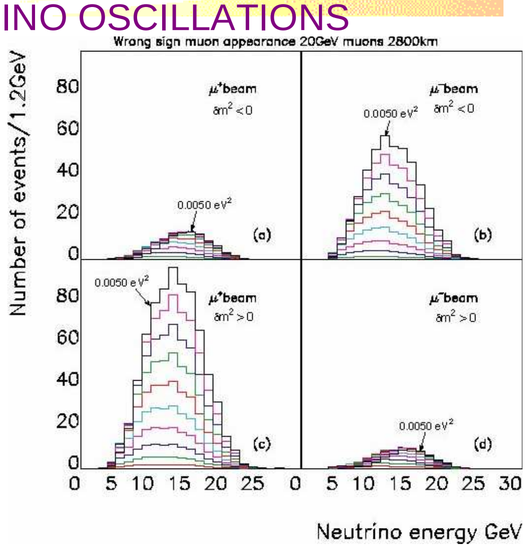
NEUTRINO OSCILLATIONS

For 10^{20} muon decays and a 50 kiloton detector

Can determine sign of Δm^2_{32} to $\geq$ 5 s.d. for $\sin^2(2\theta_{13}) \geq 10^{-3}$



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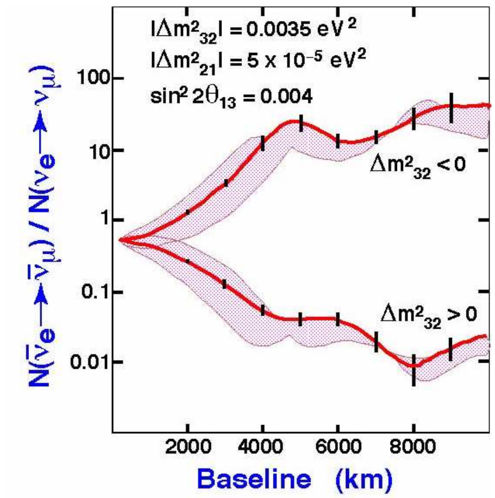
NEUTRINO OSCILLATIONS

CP Violation:

- Widths of bands show predictions as *CP* violating phase δ varies from $-\pi/2$ to $\pi/2$
- Statistical error bars correspond to 10^{21} μ decays and a 50 kton detector



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NEUTRINO OSCILLATIONS

- A neutrino factory can measure
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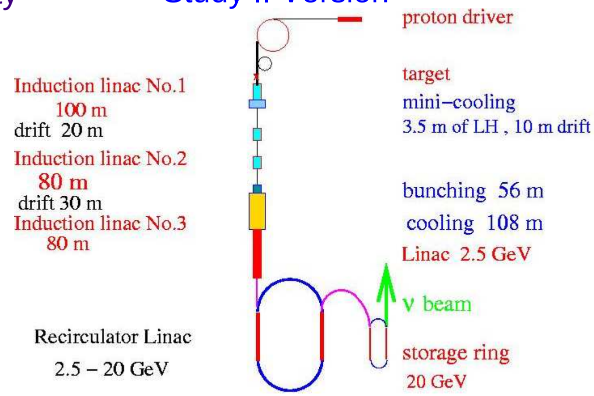
NEUTRINO FACTORY FEASIBILITY STUDIES

Two detailed feasibility Studies carried out:

- Feasibility Study I at Fermilab
- Feasibility Study II at Brookhaven National Lab

Schematic of a Neutrino Factory – Study II Version



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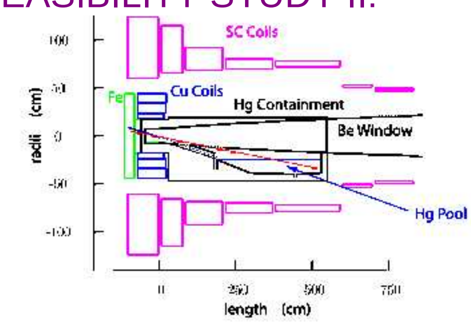
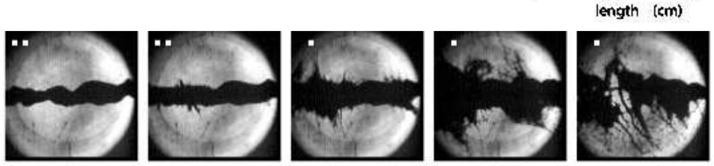
NEUTRINO FACTORY FEASIBILITY STUDY II: Target and Capture

Target, capture solenoids and mercury containment



BNL Experiment E951:



1-cm-diameter Hg jet in 2 $\times 10^{12}$ protons at t = 0, 0.75, 2, 7, 18 ms

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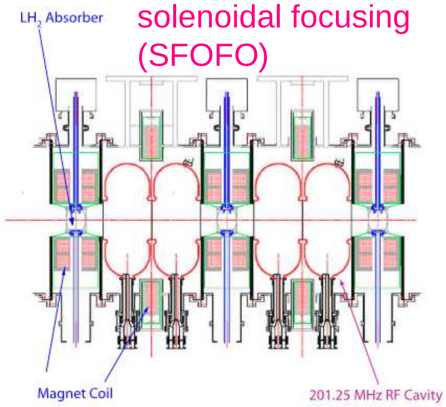
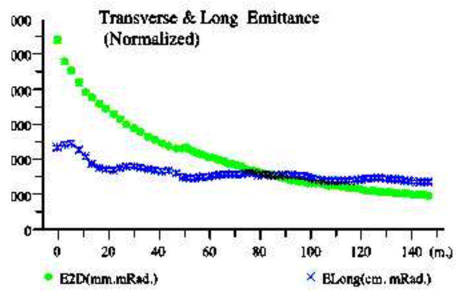
NEUTRINO FACTORY FEASIBILITY STUDY II: Cooling

Cooling channel: solenoidal focusing (SFOFO)



Simulation results:



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PHYSICS PATH TO A MUON COLLIDER

- Neutrino Oscillations
  - Intense neutrino beams ("Superbeams")
  - Neutrino Factories
- Physics with Intense Cold Muon Beams
  - Rare and forbidden decays: $\mu^- N \rightarrow e^- N$, $\mu \rightarrow e\gamma$, $\mu \rightarrow e\,e\,e$, $\mu^+ e^- \rightarrow \mu^- e^+$
  - Muon decays: τ_μ, non $(V-A)$
  - Muon moments: $g_\mu - 2$, edm_μ
  - Muon spectroscopy
  - Muonic atoms

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GOING FROM A NEUTRINO FACTORY TO A MUON COLLIDER

- Much of what has been learned from the neutrino factory feasibility studies can be applied to a muon collider
  - Targetry
  - Capture and Decay
  - Transverse Cooling
  - Accelerating a Large Beam
- A muon collider requires the muon beams to be cooled by several orders of magnitude compared with a neutrino factory.
- All the muons must be in one bunch

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HIGGS FACTORY PARAMETERS

Baseline parameters for Higgs factory muon collider. Higgs/year assumes a cross section of 5×10^4 fb, Higgs width of 2.7 MeV, 1 year = 10^7 s. From "Status of Muon Collider Research and Development and Future Plans," Muon Collider Collaboration, C. M. Ankenbrandt *et al.*, *Phys. Rev. ST Accel. Beams* **2**, 081001 (1999).

COM energy (TeV)		0.1	
p energy (GeV)		16	
p's/bunch		5×10^{13}	
Bunches/fill		2	
Rep. rate (Hz)		15	
p power (MW)		4	
μ/bunch		4×10^{12}	
μ power (MW)		1	
Wall power (MW)		81	
Collider circum. (m)		350	
Ave bending field (T)		3	
rms $\delta p/p$ (%)	0.12	0.01	0.003
6D $\varepsilon_{6,N}$ $(\pi m)^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ε_n (π mm mrad)	85	195	290
β^* (cm)	4.1	9.4	14.1
σ_z (cm)	4.1	9.4	14.1
σ_r spot (μm)	86	196	294
σ_θ IP (mrad)	2.1	2.1	2.1
Tune shift	0.051	0.022	0.015
n_{turns} (effective)	450	450	450
Luminosity ($cm^{-2} s^{-1}$)	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/yr	1.9×10^3	4×10^3	3.9×10^3

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HIGH ENERGY MUON COLLIDER PARAMETERS

Baseline parameters for high energy muon colliders. From “Status of Muon Collider Research and Development and Future Plans,” Muon Collider Collaboration, C. M. Ankenbrandt *et al.*, *Phys. Rev. ST Accel. Beams* **2**, 081001 (1999).

COM energy (TeV)	0.4	3.0
p energy (GeV)	16	16
p's/bunch	2.5×10^{13}	2.5×10^{13}
Bunches/fill	4	4
Rep. rate (Hz)	15	15
p power (MW)	4	4
μ/ bunch	2×10^{12}	2×10^{12}
μ power (MW)	4	28
Wall power (MW)	120	204
Collider circum. (m)	1000	6000
Ave bending field (T)	4.7	5.2
rms $\delta p/p$ (%)	0.14	0.16
6D $\varepsilon_{6,N}$ $(\pi m)^3$	1.7×10^{-10}	1.7×10^{-10}
rms ε_n (π mm mrad)	50	50
β^* (cm)	2.6	0.3
σ_z (cm)	2.6	0.3
σ_r spot (μm)	2.6	3.2
σ_θ IP (mrad)	1.0	1.1
Tune shift	0.044	0.044
n_{turns} (effective)	700	785
Luminosity (cm^{-2} s^{-1})	10^{33}	7×10^{34}

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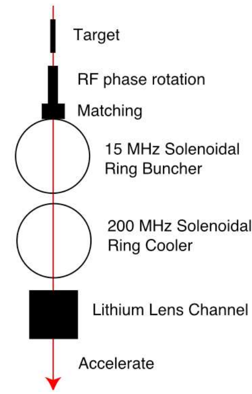
POSSIBLE HIGGS FACTORY SCHEMATIC

- One of the most crucial R&D issues for a muon collider is “cooling” the muons – making the beam smaller in 6D phase space

Ring Cooler Higgs Factory:

Muon Collider SCHEME (SCHEME IV)



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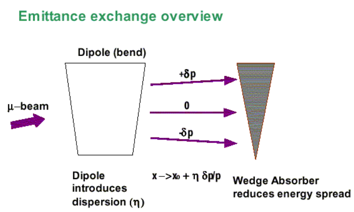
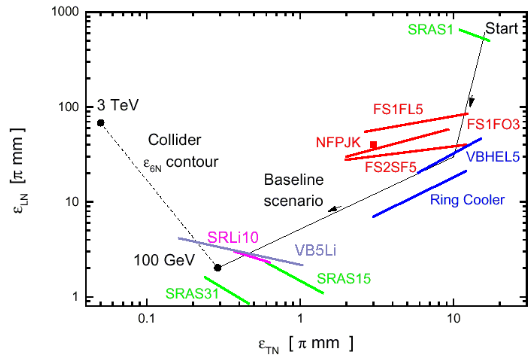
COOLING





From R. Fernow *et al.*

$\times$ 100 cooling needed in each transverse and in longitudinal direction (~10^6 in 6D emittance) compared with μ's from π decay.

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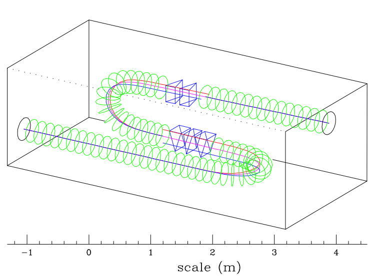
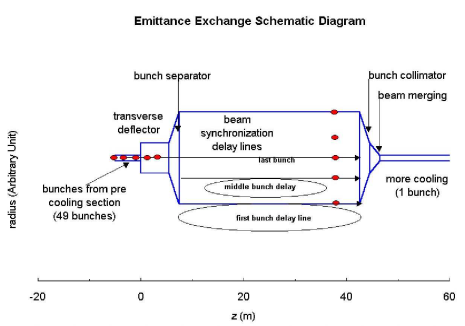
EMITTANCE EXCHANGE

BENT SOLENOID



BUNCH STACKING



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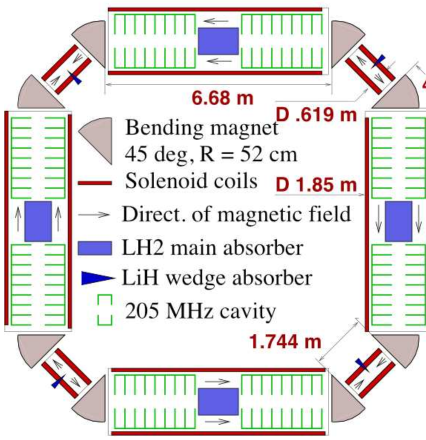
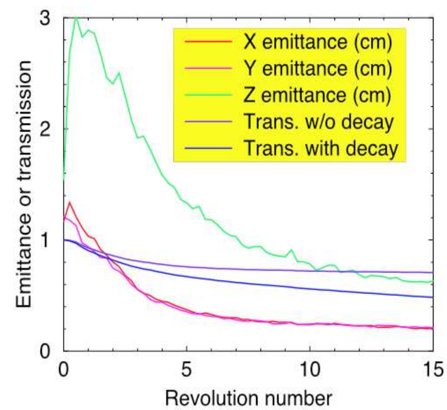
BALBEKOV RING COOLER





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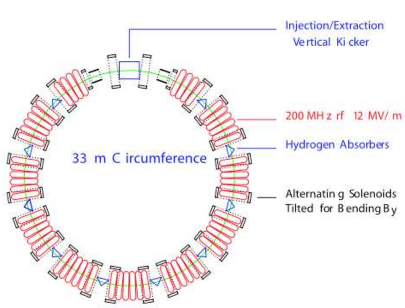
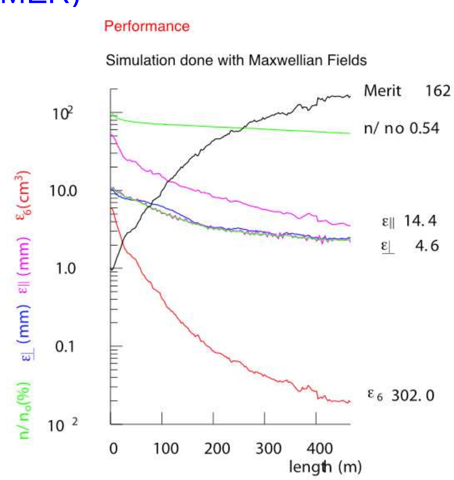
RFOFO RING COOLER

(R. PALMER)





$$\text{Merit} = \frac{\varepsilon_6(\text{initial})}{\varepsilon_6(\text{final})} \times \text{transmission}$$

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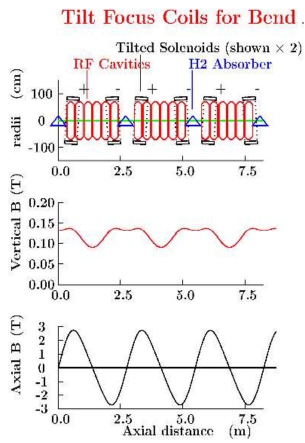
DETAIL OF RFOFO LATTICE



From R. Palmer

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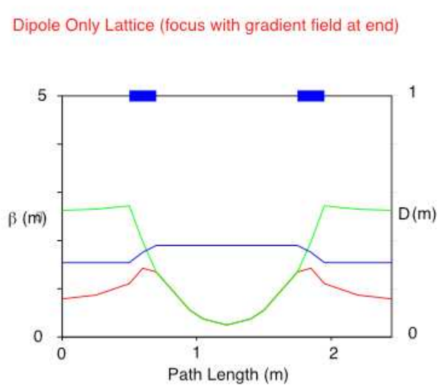
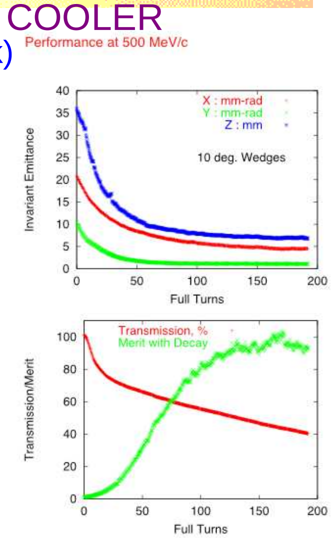
QUADRUPOLE RING COOLER

(A. Garren, H. Kirk)





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SUMMARY OF PROGRESS TOWARDS MUON COLLIDER COOLING

- Neutrino Factory feasibility study simulations show cooling to $\varepsilon_{TN} = 2\ \pi$mm and $\varepsilon_{LN} = 30\ \pi$mm (bunched!)
- Ring Cooler cools ~ $\times$ 5 transverse, $\times$ 2 longitudinal
- Lithium lens (or other?) needed to cool ~ $\times$ 10 to sub-mm in ε_{TN}

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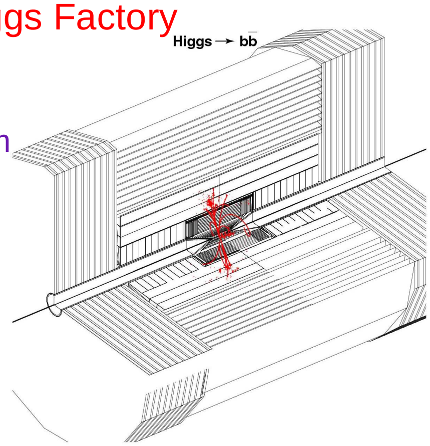
MUON COLLIDER DETECTORS

GEANT Simulation of a Higgs Factory Detector



Tungsten shielding from γ's from showering *e*'s from μ decay

Background rates similar to LHC experiments

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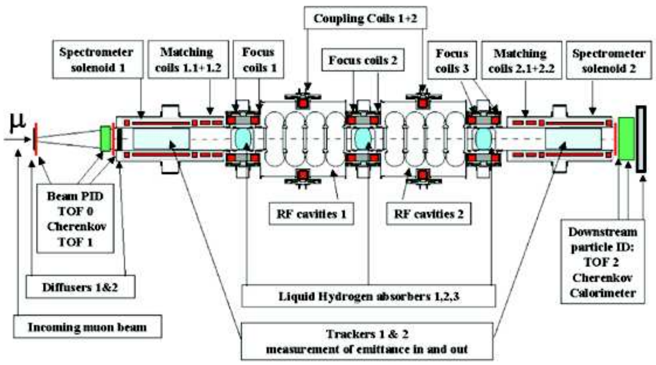
INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT – *MICE*

Proposal submitted to Rutherford Lab



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SUMMARY

- Development of muon storage rings can lead to neutrino factories and muon colliders. Considerable R&D has already been accomplished, but much more is needed.
- Neutrino factories may enable us to measure CP violation in the leptonic sector.
- A muon collider at 3–4 TeV center-of-mass energy may be possible. A muon collider may be needed to discover the supersymmetric heavy Higgs bosons H^0, A^0.

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REFERENCE

M. M. Alsharo'a *et al.*, (Neutrino Factory/Muon Collider Collaboration), "Status of Neutrino Factory and Muon Collider Research and Development and Future Plans," FNAL-PUB-02/149-E, July 2002, submitted to Phys. Rev. ST Accel. Beams.

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