# MUON COLLIDER HIGGS FACTORY

**DAVID CLINE**
**UCLA**

1. Higgs Factory - A Little History,
2. Concept to Convert a Neutrio Factory to a Higgs Factory
3 SNOWMASS Writeup
4. Some Physics at the Higgs Factory

## SUMMARY

Higgs Factory Concept

1992

DBC 1st MC Workshop

or Scalar Collider (Lokun)

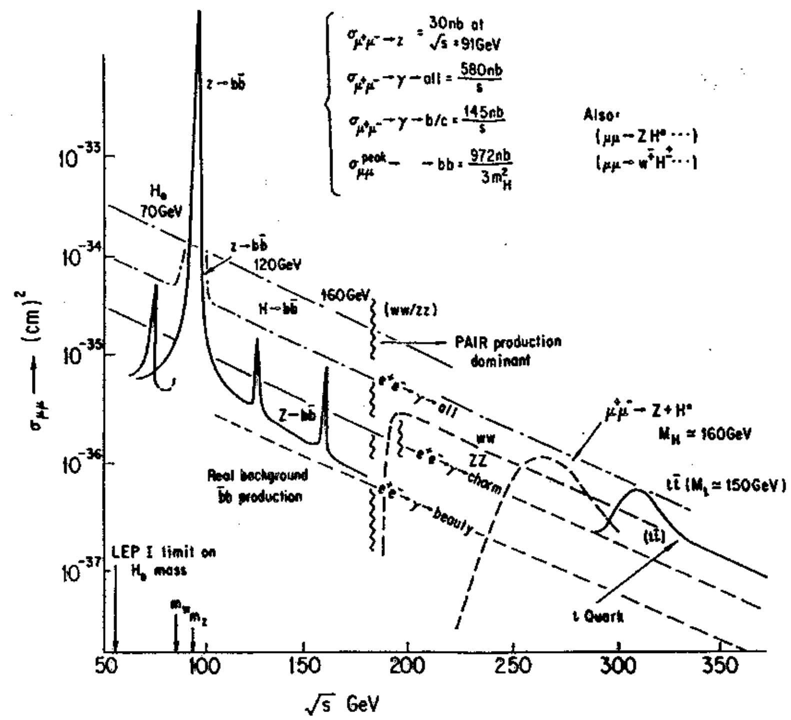



**FIGURE 1.** The first concept of a Higgs factory $\mu^+\mu^-$ collider from the Napa Workshop.[1]

**TABLE 1.** Arguments for a Higgs-Factory $\mu^+\mu^-$ Collider.[1,5]

1. The $m_\mu \backslash m_e$ ratio gives coupling 40,000 times greater to the Higgs particle. In the SUSY model, one Higgs $m_h < 120$ GeV!!
2. The low radiation of the beams makes precision energy scans possible.
3. The cost of a "custom" collider ring is a small fraction of the $\mu^\pm$ source.
4. Feasibility report to Snowmass established that $\mathcal{L} \sim 10^{33}\ cm^{-2}\ s^{-1}$ is feasible.

decays of the Higgs particles (in progress). In the near future, there could be evidence for the Higgs mass obtained from precise electroweak parameter measurements and later from the LHC. This will be a crucial input for the development of the Higgs factory. In addition, if Nature is supersymmetric, there will be additional SUSY-Higgs particles to study and, thus, the Higgs factory concept will include the search for and study of the SUSY Higgs ($H$,$A$ ...). This is an experimental issue – theory can only take us just so far!

From all we now know about elementary particle physics, the scalar or SUSY scalar sector is the key to future understanding. A complete understanding of this sector is really the goal of the Higgs factory and of nearly all elementary particle physics these days.

The Higgs factory is designed to first give the exact Higgs mass using an energy scan and then measure the general properties of the Higgs, such as the field width, largest branching fractions, *etc.* It would produce $10^4$ Higgs/yr and could investigate rare branching modes.

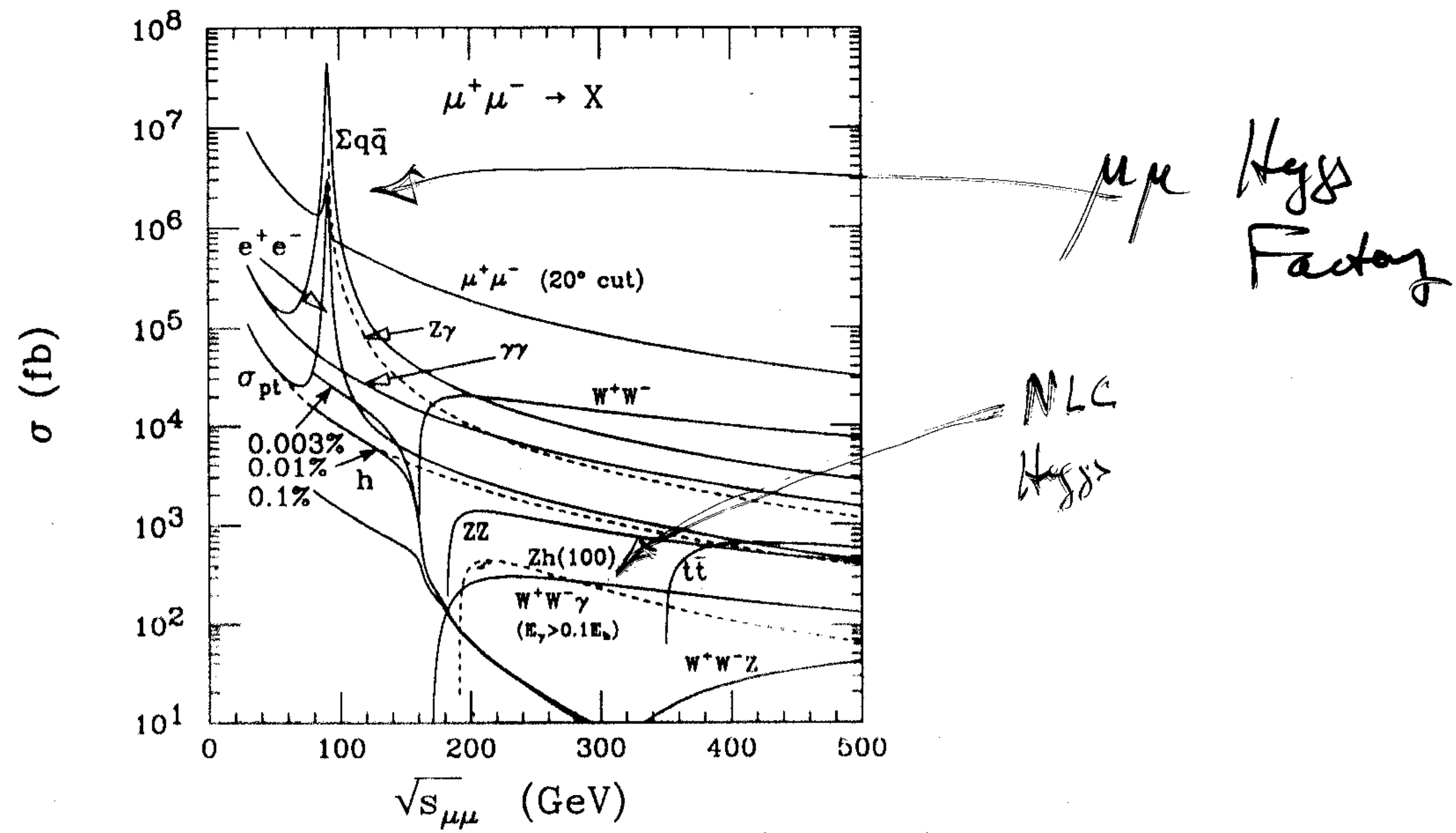



FIG. 4. Cross sections for SM processes versus the CoM energy at the FMC. $\sigma_{pt} \equiv \sigma(\mu^+\mu^- \to \gamma^* \to e^+e^-)$. For the $s$-channel Higgs boson production, three different beam energy resolutions of 0.003%, 0.01% and 0.1% are presented.

supersymmetric standard model (MSSM) $h^0$ from the SM $h_{SM}$; and, to find and study the heavier neutral Higgs bosons $H^0$ and $A^0$.

The production of Higgs bosons in the $s$-channel with interesting rates is a unique feature of a muon collider [45,67]. The resonance cross section is

$$\sigma_h(\sqrt{s}) = \frac{4\pi\Gamma(h \to \mu\bar{\mu})\,\Gamma(h \to X)}{\left(s - m_h^2\right)^2 + m_h^2\left(\Gamma_{\rm tot}^h\right)^2}\,. \tag{1}$$

Gaussian beams with root-mean-square (rms) energy resolution down to $R = 0.003\%$ are realizable. The corresponding rms spread $\sigma_{\sqrt{s}}$ in CoM energy is

$$\sigma_{\sqrt{s}} = (2\ {\rm MeV})\left(\frac{R}{0.003\%}\right)\left(\frac{\sqrt{s}}{100\ {\rm GeV}}\right). \tag{2}$$

# HIGGS FACTORY WORKSHOP
# UCLA FACULTY CENTER

UCLA

Feb. 28-March 1, 2001

Organizers:
David Cline, UCLA
Gail Hanson, I.U.

Indiana University

## "FROM THE NEUTRINO FACTORY TO THE HIGGS FACTORY: MUONS ALL THE WAY"

## TOPICS

1. Update of LEP2 Higgs Search Results
2. Theory and Higgs Physics
3. Neutrino Factory Studies I & II
4. Proton Driver for Higgs Factory Single Bunch Operation
5. $\mu^{\pm}$ Collection System and Pre Cooling
6. Final Cooling Schemes: Emittance Exchange
7. Use of Neutrino Factory Acceleration System for Higgs Factory
8. Higgs Factory Storage Ring
9. Parameters for Higgs Factory

! For information about local accommodation, contact Kevin Lee, klee@physics.ucla.edu; or Sylvia Vartan, sylvia@physics.ucla.edu.

Possible Neutrino Factories

FERMI

FNAL

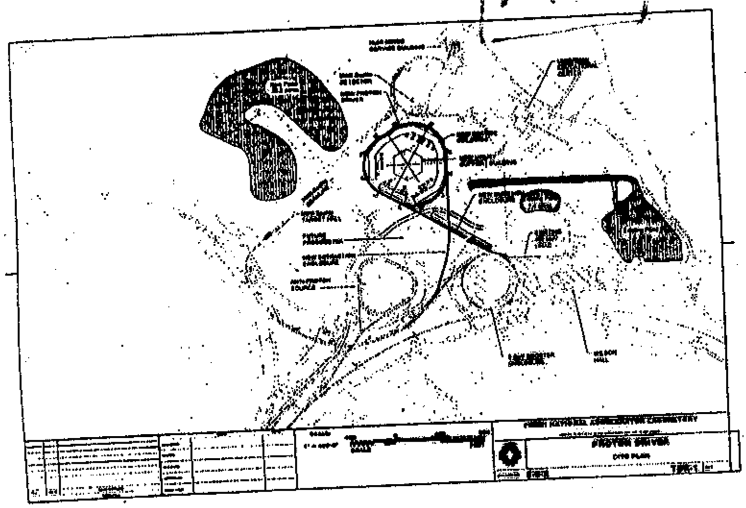
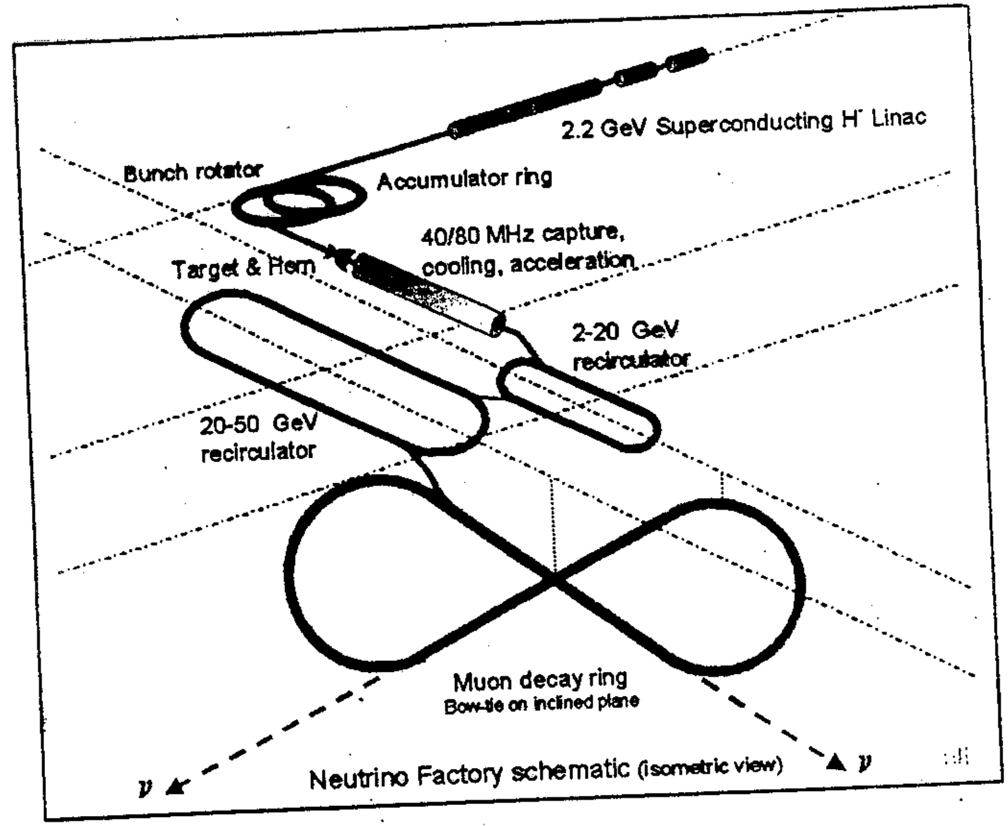


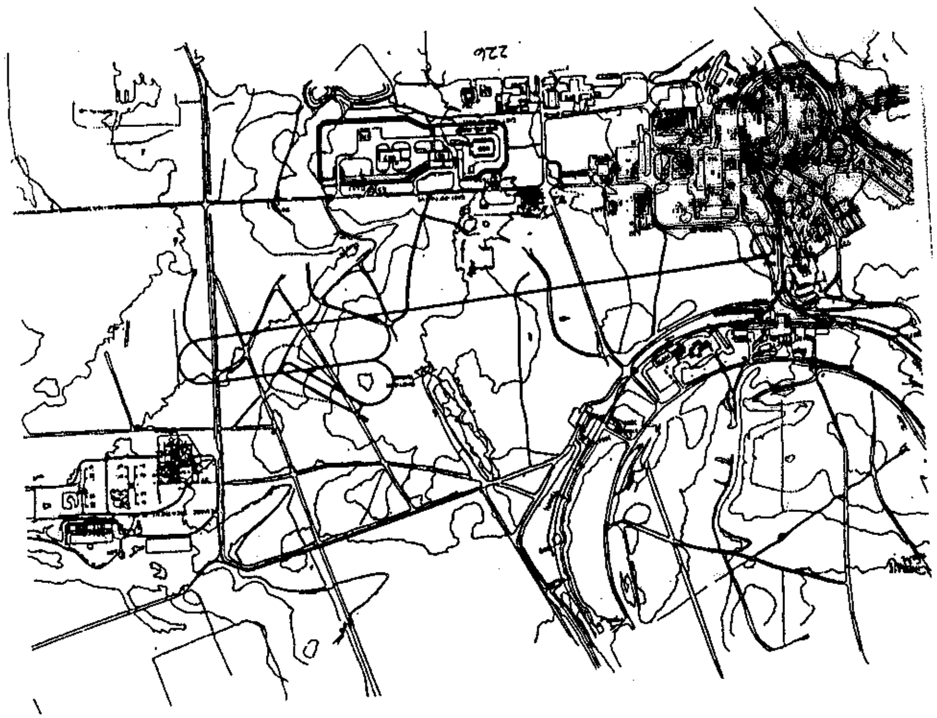
Figure 2.1. Layout of the Proton Driver Accelerator Complex

Fermi Lab
Chicago

CERN, Geneva




Neutrino Factory schematic (isometric view)

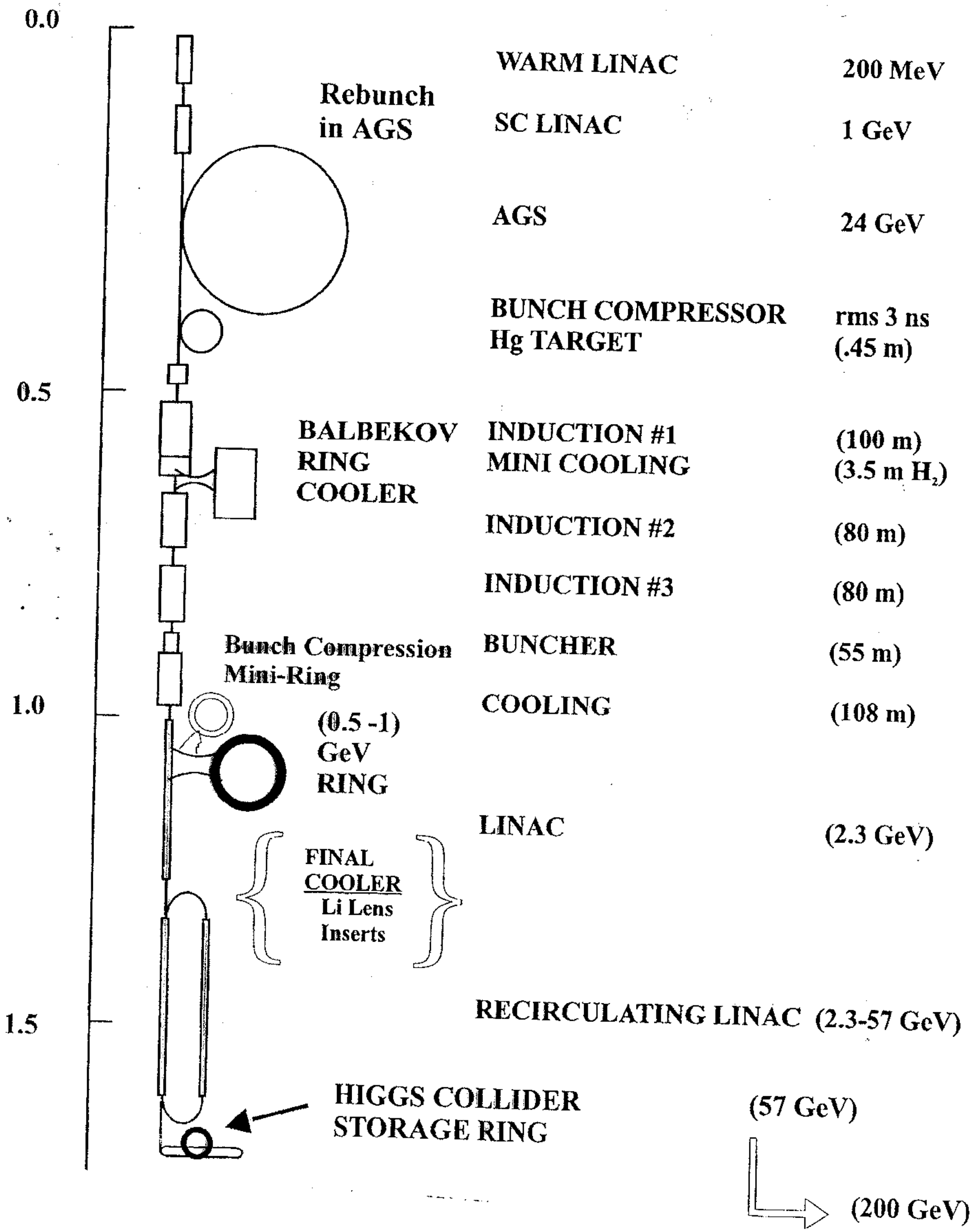



BNL / Long Island

# FROM A NEUTRINO FACTORY TO A HIGGS FACTORY

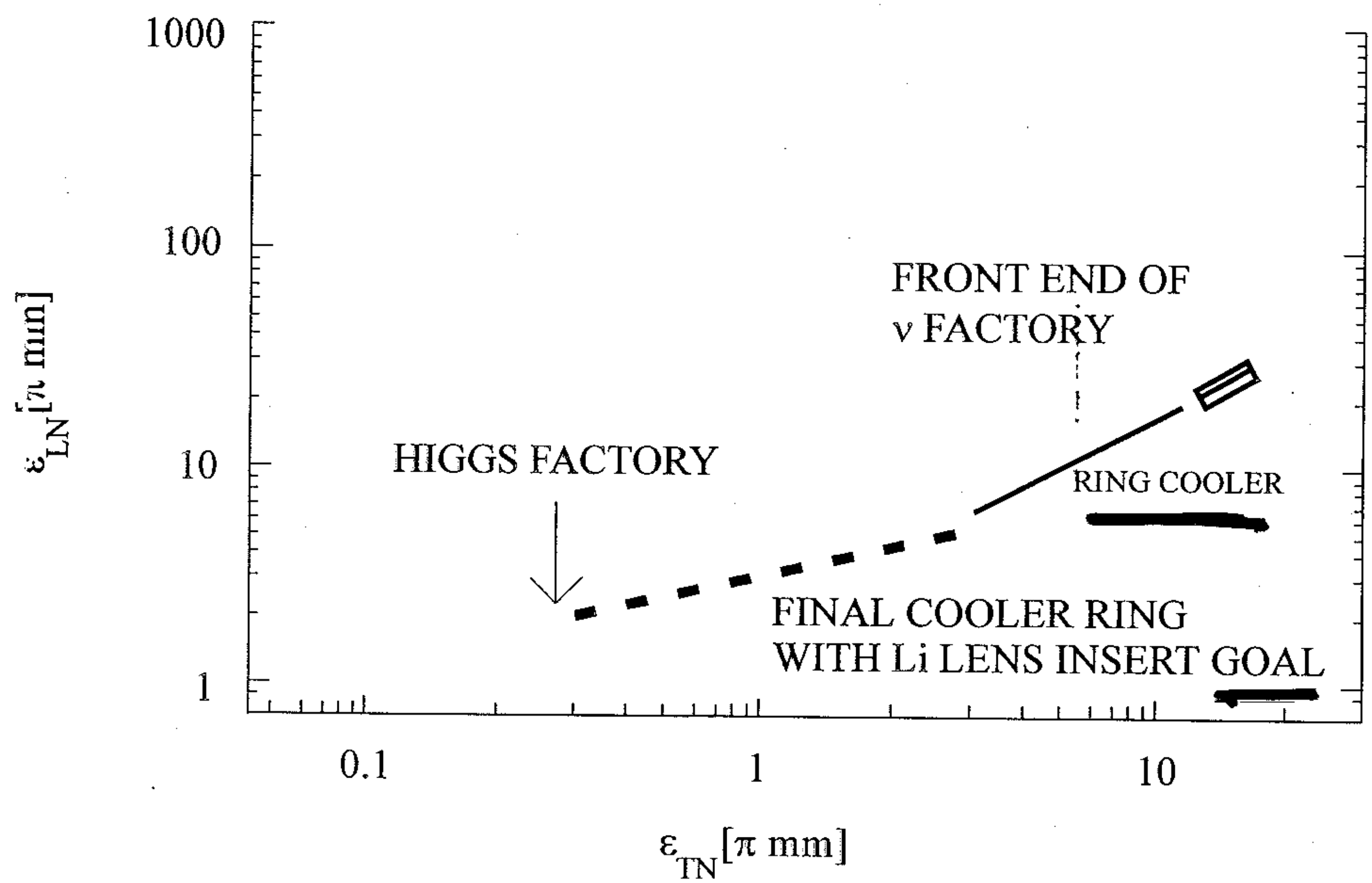
| | NEUTRINO FACTORY | HIGGS FACTORY | CONVERSION ISSUE |
|---|---|---|---|
| PROTON DRIVER | MANY BUNCHES (6) | Smaller number of Bunches would be good, but may cause target problems | Reduce Number of Proton Bunches Modestly. <Target Problems?> |
| TARGET | ——— | Keep Normal Neutrino Factory Target | |
| Pre Cooler/ Cooler | ——— | Upgrade with a Balbekov Cooling Ring | Strong Emittence Exchange |
| Acceleration | ——— | Same | |
| Final Cooling | ——— | Insert a Buncher Ring to combine many Bunches to 1. Emittence Exchange | Reduce Number of $\mu^{\pm}$ Bunches for Higgs Factory |
| Acceleration | ——— | Accelerate to MH/2 Energy | |
| Collider Ring | ——— | Build Very Small Storage Ring | 1 $\mu^+$ 1 $\mu^-$ Bunch |

# CONVERSION OF A NEUTRINO FACTORY TO A HIGGS FACTORY



R Fernow
+ Team

EMITTANCE REDUCTION REQUIRED FOR HIGGS FACTORY




TRANSVERSE

Target – we accept all of the bunches for the Neutrino Factory – and stack them into one – However the bunches in the proton ring have to be closer than for N.F.

# $\mu^+$–$\mu^-$ Collider cooling requirements

Muon Collaboration

- **A Collider requires cooling of $\mu^+$–$\mu^-$ bunches to minimal beam sizes, and minimal number of bunches**
- **approximate parameters: ~$10^{12}$ $\mu$'s / bunch, $\varepsilon_{\perp,rms} \cong 10^{-4}$ m-rad; $\varepsilon_{\parallel,rms} \cong 10^{-2}$ m-rad**
- **Beam from target has**
  **$\varepsilon_{\perp,rms} \cong 2\cdot10^{-2}$ m-rad; $\varepsilon_{\parallel,rms} \cong 1$ m-rad**
- **$\Rightarrow$ 6-D $\varepsilon$ - cooling by ~ $4\cdot10^{6}$ is required**
- **( $\nu$–Factory requires $\varepsilon_{\perp,rms} \cong 2\cdot10^{-3}$ m-rad; $\varepsilon_{\parallel,rms} \cong 0.01$ m-rad in 100 bunches; cool by ~$10^{2}$)**

# Ionization Cooling Principle



**Loss of transverse momentum in absorber:**

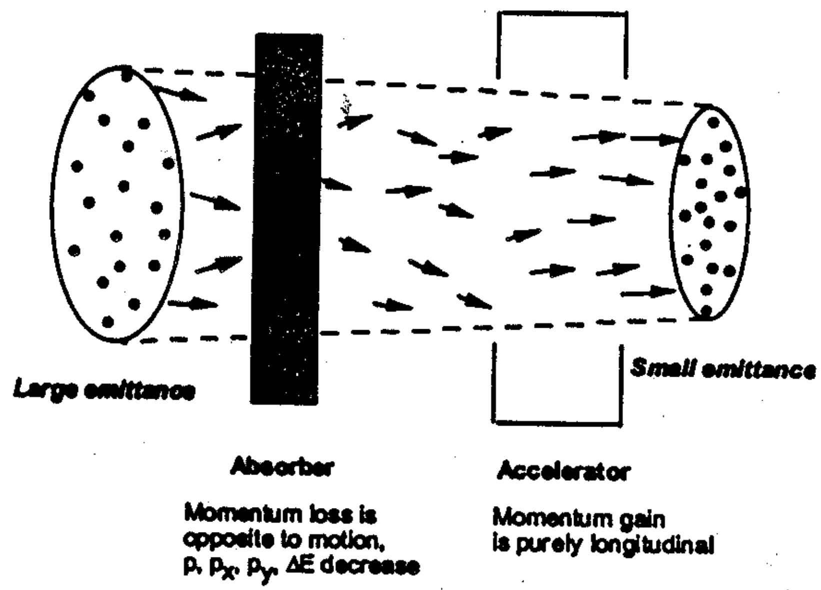
$$p_x \rightarrow p_x\left[1-\frac{dp}{ds}\frac{\Delta s}{p}\right]$$

**Changes transverse emittance:**

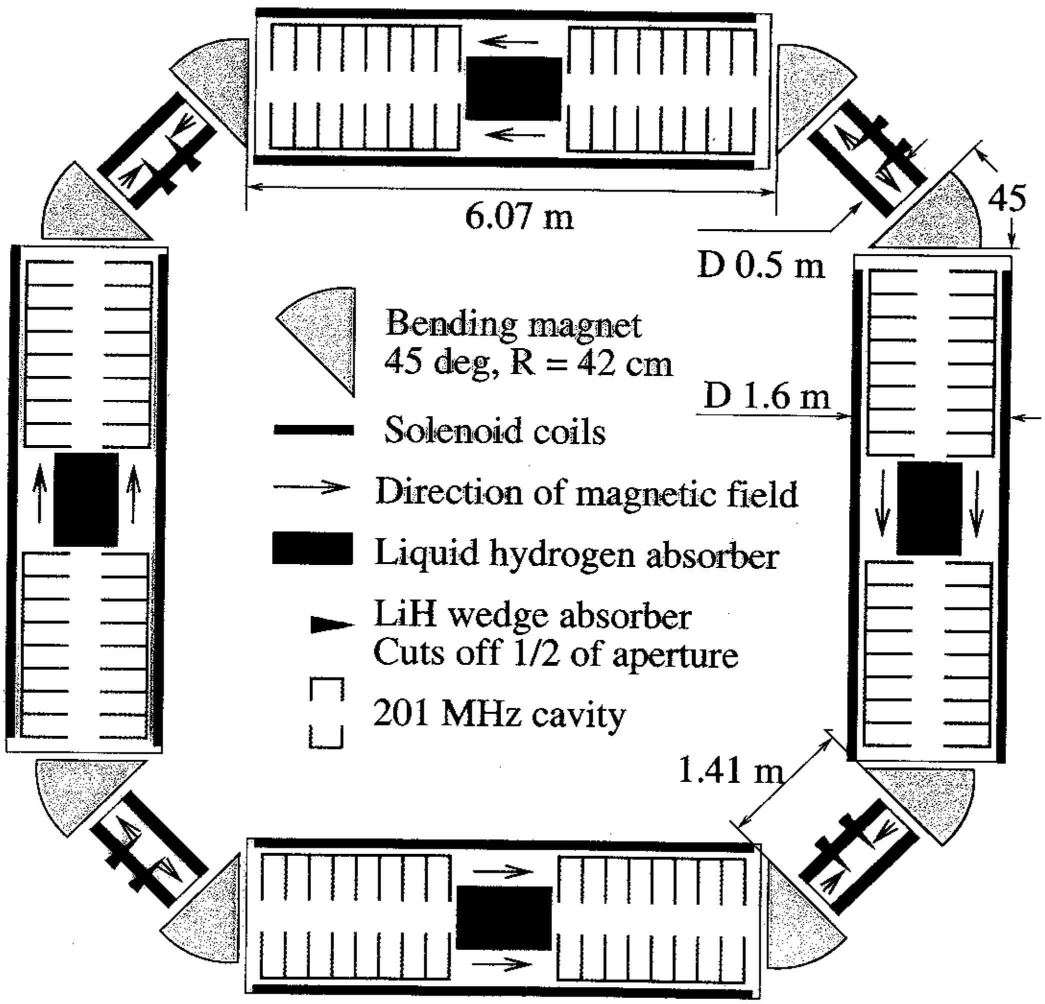
$$\varepsilon_{\perp,N} = \frac{1}{m}\left[\langle x^2\rangle\langle p_x^2\rangle-\langle xp_x\rangle^2\right]^{1/2} = \beta\gamma\left[\langle x^2\rangle\langle \theta_x^2\rangle-\langle x\theta_x\rangle^2\right]^{1/2}$$

$$\varepsilon_{\perp,N} \rightarrow \varepsilon_{\perp,N}\left[1-\frac{dp}{ds}\frac{\Delta s}{p}\right]$$

**(Reacceleration does not change normalized emittance)**

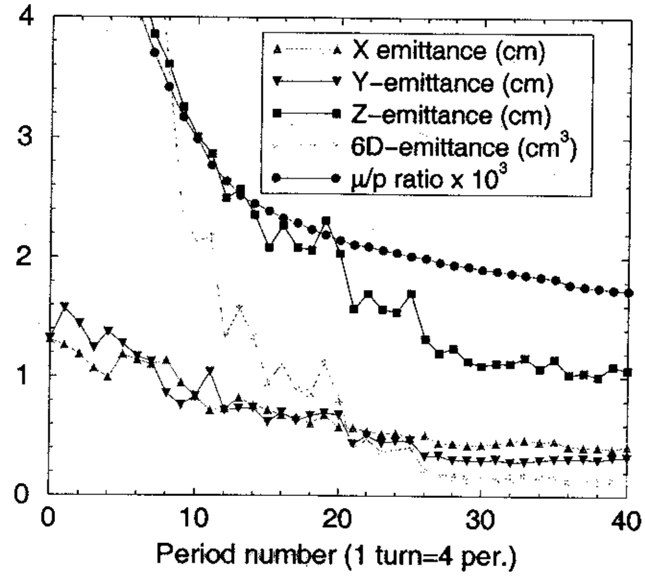


# LAYOUT

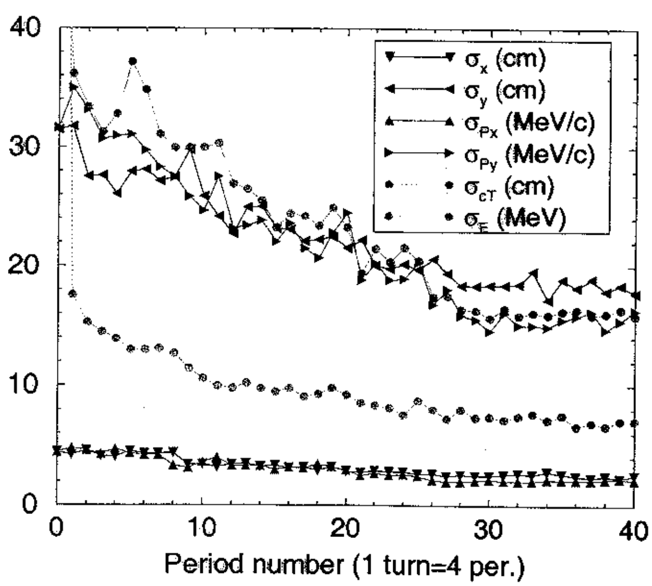



This ring concept is the key — to reduce beam size

# BUNCHING-COOLING IN THE RING




Beam emittance and $\mu/p$-ratio. After 10 turns $\sigma_x = 0.42$ cm, $\sigma_y = 0.33$ cm, $\sigma_z = 1.0$ cm, $\mu/p = 0.17\%$.




Beam size at the cooling.

For H.F. write up
w MC Note

# Bunch Stacking Scheme for the Higgs Factory based on the Neutrino Factory Design

Yasuo Fukui, Alpher Garren, David Cline, Ping He (UCLA)
March 15, 2001
↑ Student

**Abstract**

A scheme for a Higgs Factory is designed to generate a high intensity $\mu^+$ bunch and $\mu^-$ bunch in order to create the high luminosity in a collider ring. Three modification need to be done to the Neutrino Factory Feasibility Study I(Fermilab) and II(BNL), (1) combine multiple primary proton bunches into one, (2) add a 6 dimensional ionization cooling ring, and (3) add two rings to stack muon mini-bunches transversely.

## 1 Introduction

The Higgs Factory will be the first $\mu^+\mu^-$ collider to be built. Compared to a Neutrino Factory where muons decay in a straight section of a storage ring, the Higgs Factory requires more 6 dimensional phase space cooling of the muon beam by a factor of $10^{4-5}$. The Feasibility Studies I(Fermilab) and II(BNL) showed that those designs are feasible to build a neutrino Factory [3, 4].

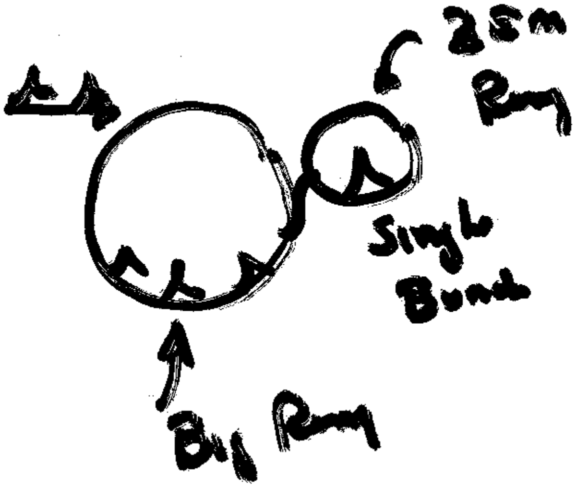
In order to create the high luminosity in a collider, single high intensity $\mu^+/\mu^-$ beam bunch will be transported into a collider where the many muon mini-bunch trains in the Neutrino Factory has to be combined into a single bunch.

The $\mu^+\mu^-$ collider has been under designing for several year, and many reports have been made by the Neutrino Factory and the Muon Collider Collaboration. [1, 2] The on-going BNL targetry experiment E951 will reveal the feasibility of the proposed mercury jet target with the input proton beam power of multi MW. Several R&D efforts on the components of the muon ionization cooling, 201 MHz and 805 MHz RF cavities, super conducting solenoid coils, and induction linac modules. Design of a cooling demonstration experiment is going on at Fermilab with the model of a cooling channel in a ring.

## 2 Goals

Table 1 shows the parameters of the general $\mu^+\mu^-$ colliders including a Higgs Factory which was given in Reference [2].

6 dimensional normalized emittance is $1.7 \times 10^{-10}$ $\pi$mm-mrad and the RMS beam length is 9.4 cm, RMS $\Delta p/p$ is 0.01 % in a Higgs Factory with the center of mass energy of 100 GeV. The proton beam power is 4 MW, and the luminosity is $2.2 \times 10^{31}$ $cm^{-2}s^{-1}$.




First ICOOL Results for Bunch Stacking

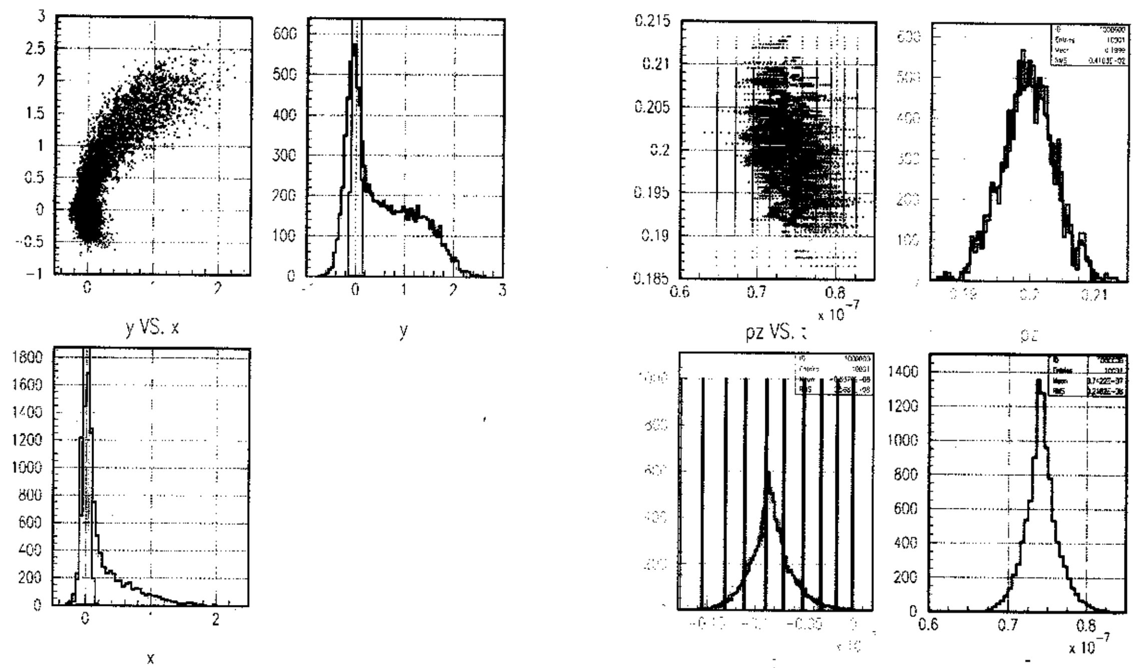



Figure 3: Transverse and longitudinal phase space (ICOOL simulation) on 10 bunch stacking

Al Garren

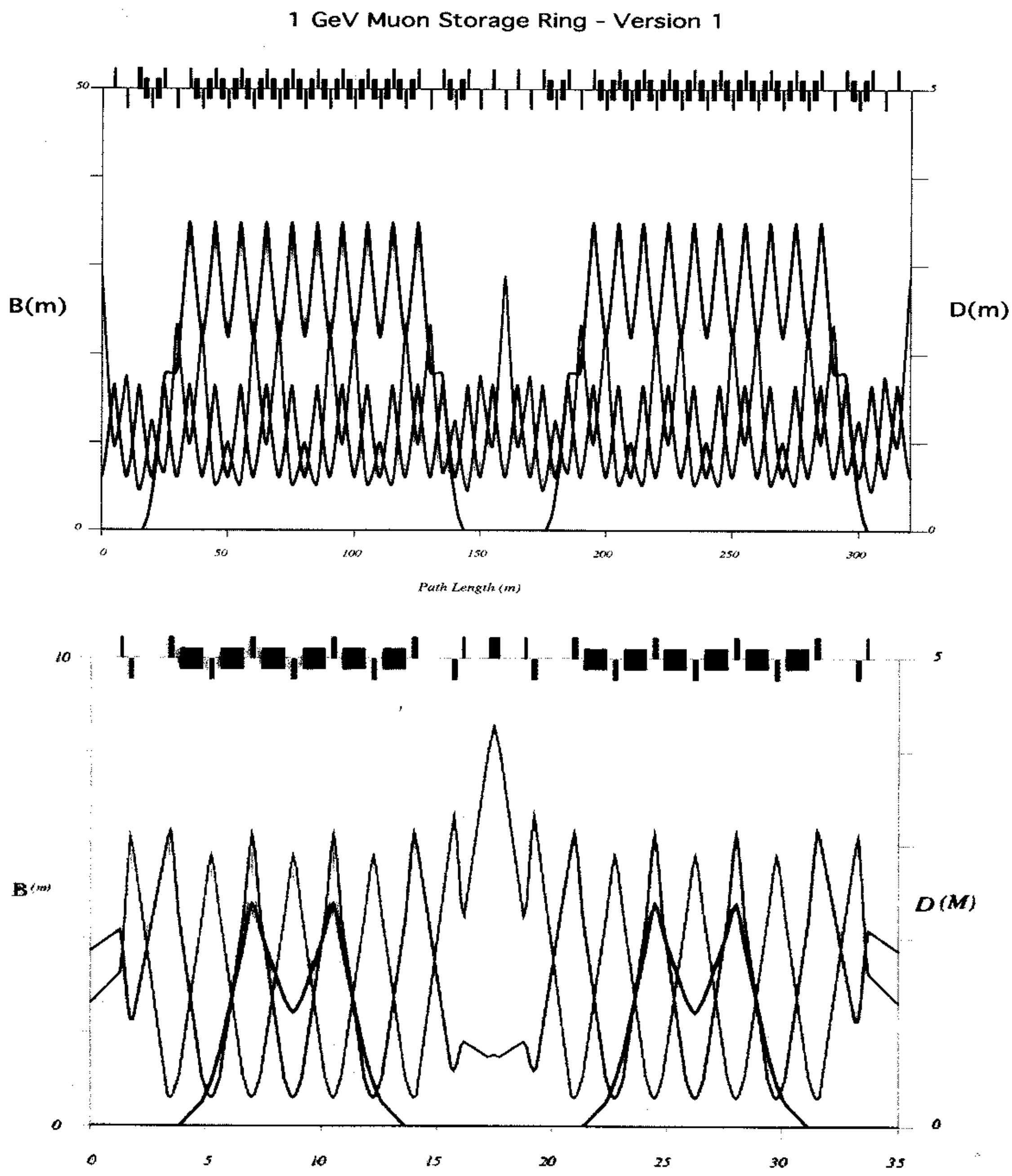
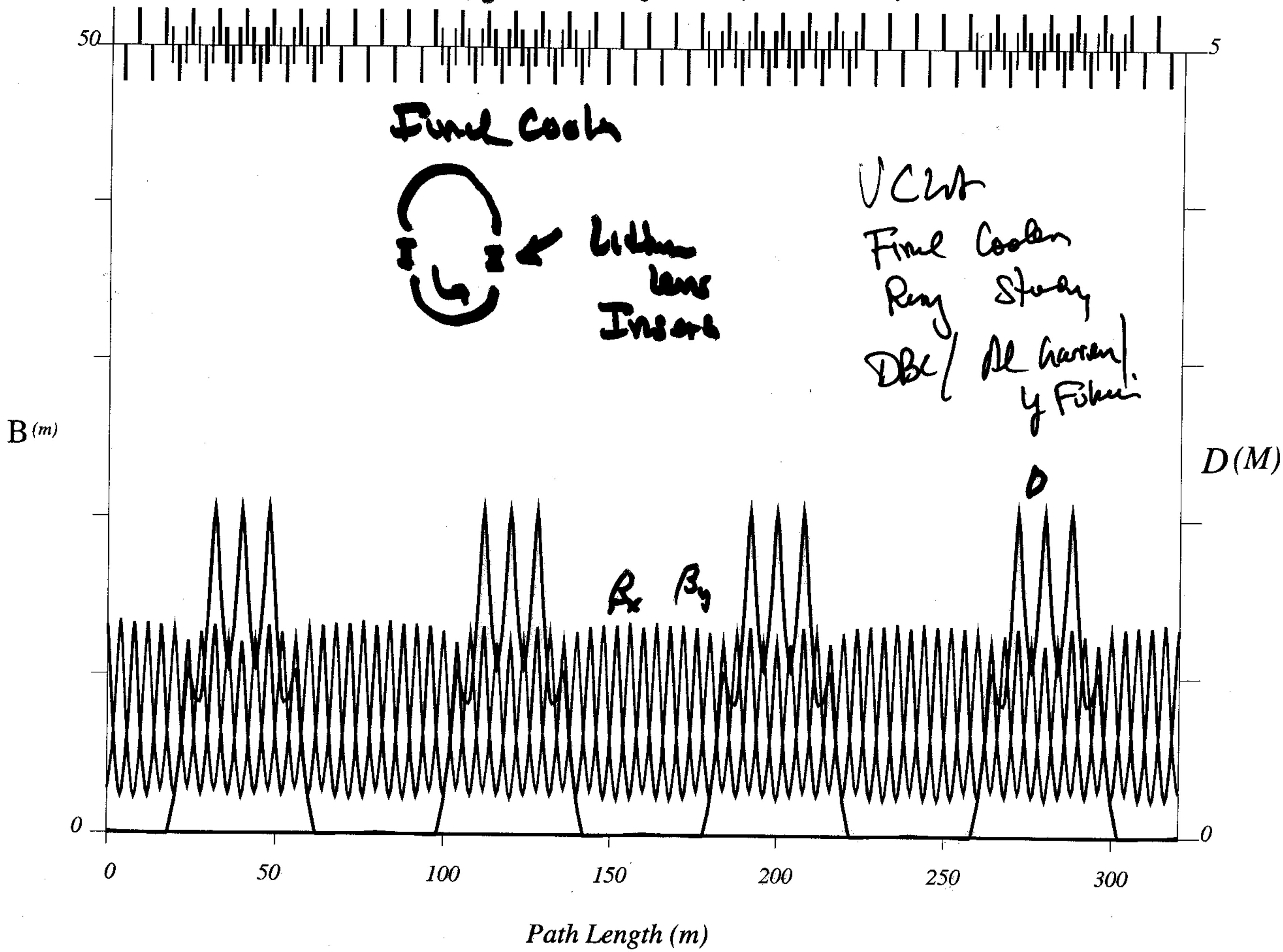



Figure 4: $\beta_x$, $\beta_y$, $\eta$, and the lattice component in 320 m ring(top) and in the 35 m ring(bottom)

Big Ring

First Stage Ring

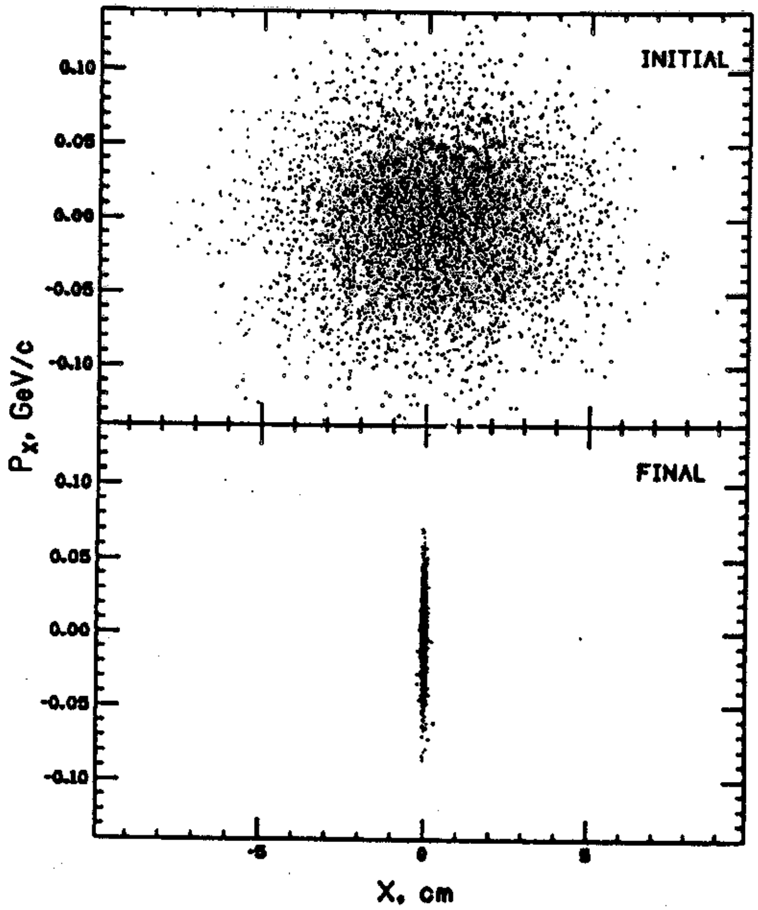
1 GeV Storage Ring - 4 superperiods

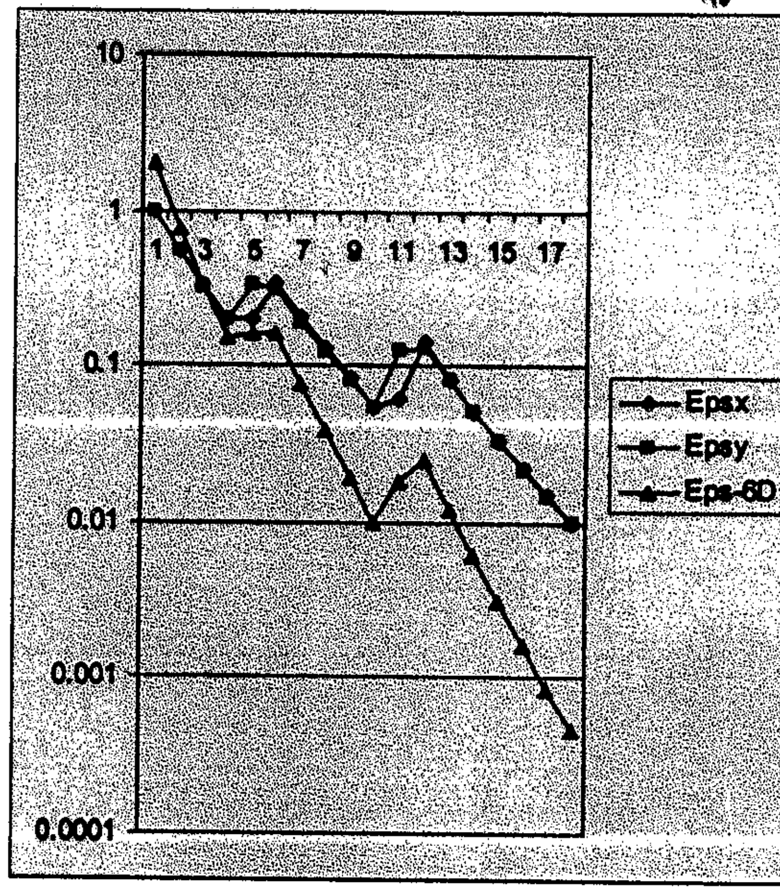


# 5-D simulation of "complete cooling scenario" includes 2 emittance exchanges

Muon Collaboration

D Neuffer




**Long - term Li-lens Cooling results:**
**($\varepsilon_{\perp}$ ×1/100; 6-D cooling by $10^{-4}$)**

Li Lens Most Promising for final Cooling

Higgs FACTORY: 50 on 50 GeV Collider

Al Garren - UCLA
Carol Johnstone - FNAL

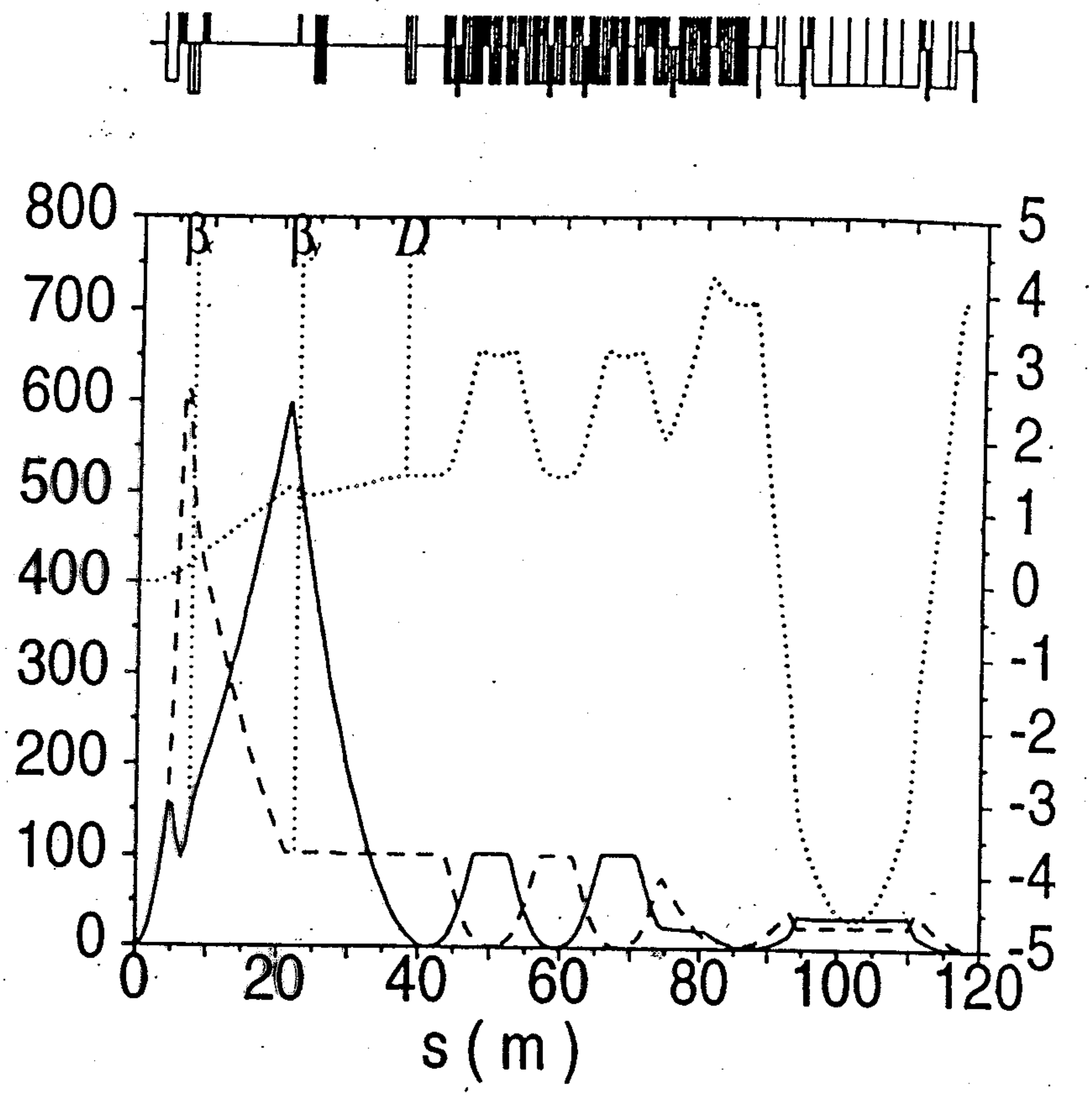



Figure3: 14 cm $\beta^*$ Mode showing half of the IR, local chromatic correction, and one of three arc modules.

# Higgs Factory Study for Snowmass 2001

(http://www.physics.ucla.edu/snowmass
user id "higgs"
password "factory3")

Overview and Summary(D. Cline, G. Hanson)

Chapter 1. Higgs Physics (V. Barger, M. Berger, J. Gunion)

×10 luminosity (D. Neuffer)

Chapter 2. Neutrino Factory Parameters from Feasibility Studies I and II (TBD – D. Cline, G. Hanson)

Chapter 3. Reconfiguration of Proton Driver and Target for Single Bunch Operation (W. Chou, T. Roser → S.Y. Zhang?, C. Ankenbrandt?)

Chapter 4. Targetry and Muon Collection (N. Mokhov, V. Balbekov, D. Neuffer)

Chapter 5. Precooling, Final Cooling/Emittance Exchange and Bunching (R. Fernow, D. Neuffer, V. Balbekov, Y. Fukui)

Chapter 6. Using the Neutrino Factory Acceleration System (D. Summers, S. Berg, JLab person?)

Chapter 7. Higgs Factory Storage Ring (A. Garren, C. Johnstone)

Chapter 8. Summary of Parameters (Y. Fukui -- D. Cline, G. Hanson)

Chapter 9. Cost Drivers for the Conversion of the Neutrino Factory to the Higgs Factory (M. Zisman)

Lots to do!

M.C. Report
STATUS Report 99

Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley National Laboratory (LBNL), Budker Institute for Nuclear Physics (BINP), University of California at Los Angeles (UCLA), University of Mississippi and Princeton University. The goal of the collaboration is to complete within a few years the R&D needed to determine whether a Muon Collider is technically feasible, and if it is, to design the First Muon Collider.

TABLE I. Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year = $10^7$ s.

| CoM energy | TeV | 3 | 0.4 | | 0.1 | |
|---|---|---|---|---|---|---|
| $p$ energy | GeV | 16 | 16 | | 16 | |
| $p$'s/bunch | | $2.5 \times 10^{13}$ | $2.5 \times 10^{13}$ | | $5 \times 10^{13}$ | |
| Bunches/fill | | 4 | 4 | | 2 | |
| Rep. rate | Hz | 15 | 15 | | 15 | |
| $p$ power | MW | 4 | 4 | | 4 | |
| $\mu$/bunch | | $2 \times 10^{12}$ | $2 \times 10^{12}$ | | $4 \times 10^{12}$ | |
| $\mu$ power | MW | 28 | 4 | | 1 | |
| Wall power | MW | 204 | 120 | | 81 | |
| Collider circum. | m | 6000 | 1000 | | 350 | |
| Ave bending field | T | 5.2 | 4.7 | | 3 | |
| Rms $\Delta p/p$ | % | 0.16 | 0.14 | 0.12 | 0.01 | 0.003 |
| 6-D $\epsilon_{6,N}$ | $(\pi \mathrm{m})^3$ | $1.7 \times 10^{-10}$ | $1.7 \times 10^{-10}$ | $1.7 \times 10^{-10}$ | $1.7 \times 10^{-10}$ | $1.7 \times 10^{-10}$ |
| Rms $\epsilon_n$ | $\pi$ mm-mrad | 50 | 50 | 85 | 195 | 290 |
| $\beta^*$ | cm | 0.3 | 2.6 | 4.1 | 9.4 | 14.1 |
| $\sigma_z$ | cm | 0.3 | 2.6 | 4.1 | 9.4 | 14.1 |
| $\sigma_r$ spot | $\mu$m | 3.2 | 26 | 86 | 196 | 294 |
| $\sigma_\theta$ IP | mrad | 1.1 | 1.0 | 2.1 | 2.1 | 2.1 |
| Tune shift | | 0.044 | 0.044 | 0.051 | 0.022 | 0.015 |
| $n_{\mathrm{turns}}$ (effective) | | 785 | 700 | 450 | 450 | 450 |
| Luminosity | $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | $7 \times 10^{34}$ | $10^{33}$ | $1.2 \times 10^{32}$ | $2.2 \times 10^{31}$ | $10^{31}$ |
| Higgs/year | | | | $1.9 \times 10^3$ | $4 \times 10^3$ | $3.9 \times 10^3$ |

4000 H/y

$H^0, A^0 \rightarrow$ 10,000 /y

$\frac{\Delta P}{P} \sim 0.01 \quad \mathcal{L} \rightarrow 10^{32}$

$\int \mathcal{L} dt \sim 10^{40}\ \mathrm{yr}^{-1}$

– If we solve problem of cooling the high intensity of the Neutrino Factory could help the Higgs Factory –

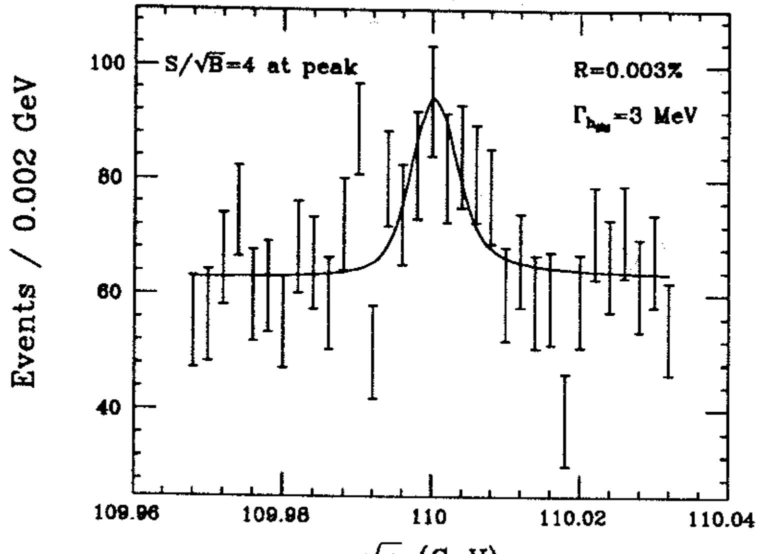



FIG. 7. Number of events and statistical errors in the $b\bar{b}$ final states as a function of $\sqrt{s}$ in the vicinity of $m_{h_{SM}} = 110$ GeV, assuming $R = 0.003\%$. From Ref. [45].

1994 → 96
Low Mass Higgs

1995 –
SUSY Higgs

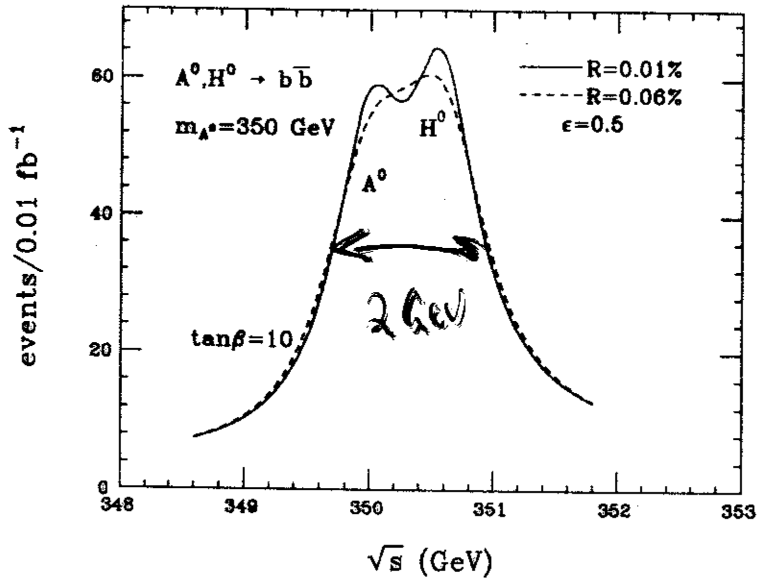



FIG. 8. Separation of $A^0$ and $H^0$ signals for $\tan\beta = 10$. From Ref. [45].

### C. Light particles in technicolor models

In most technicolor models, there will be light neutral and colorless technipion resonances, $\pi_T^0$ and $\pi_T^{0\prime}$, with masses below 500 GeV. Sample models include the recent top-assisted technicolor models [69], in which the technipion masses are typically above 100 GeV, and models [70] in which the masses of the neutral colorless resonances come primarily from the one-loop effective potential and the lightest state typically has mass as low as 10 to 100 GeV. The widths of these light neutral and colorless states in the top-assisted models will be of order 0.1 to 50 GeV [71]. In the one-loop models, the width of the lightest technipion is typically in the range from 3 to 50 MeV. Neutral technirho and techniomega resonances are also a typical feature of technicolor models. In all models, these resonances are predicted to have substantial Yukawa-like couplings to muons and would be produced in the $s$-channel at a muon collider,

$$\mu^+\mu^- \to \pi_T^0,\, \pi_T^{0\prime},\, \rho_T^0,\, \omega_T^0, \tag{9}$$



THE $A^0$ & $H^0$ COULD BE VERY CLOSE IN MASS – POSSIBLY HARD TO SEPARATE AT NLC

A Little Higgs Physics

Mike Berger
M.B.



# Light Higgs invites Supersymmetry

- Significance of $2.9\sigma$ for Higgs boson $m_H \approx 115$ GeV

- This mass of Higgs boson is very suggestive of supersymmetry, MSSM $\Rightarrow m_h < 130$ GeV.

- The large Higgs masses near this limit indicate larger $\tan\beta$ and a larger SUSY scale.

- Higgs boson lower mass bounds imply a lower limit on $\tan\beta$ for supersymmetric Higgs.

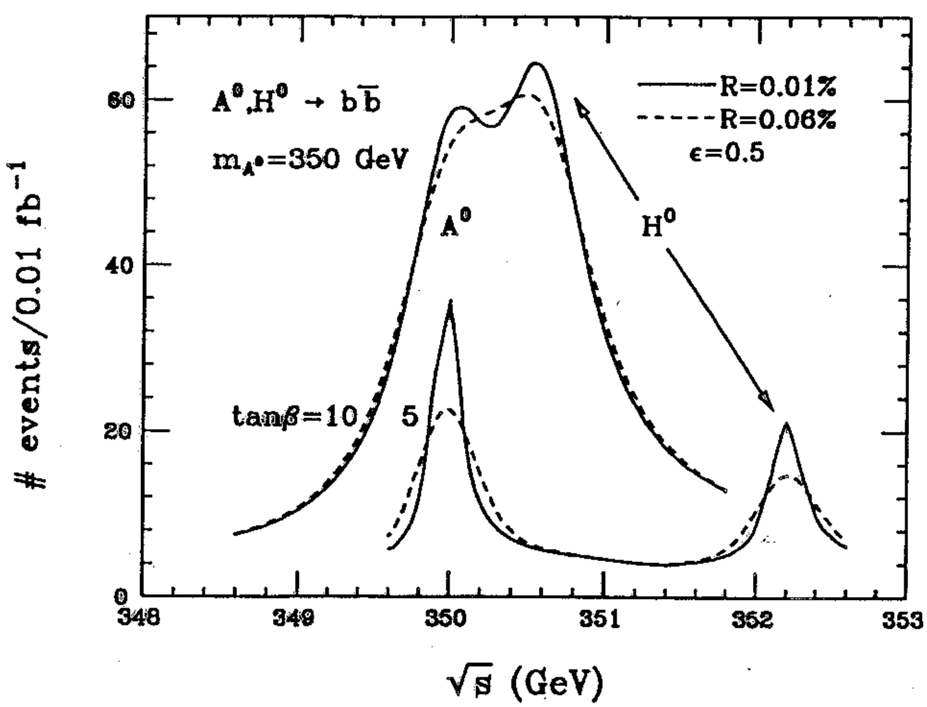
M.B.



# Heavy Higgs Bosons

- There is a wedge of unobservability for $H$ and $A$ Higgs bosons at the LHC
- Large $\tan\beta$ makes study of heavier $H$ and $A$ Higgs bosons possible, but they will be highly degenerate and the resonances will overlap.

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




ONLY HIGGS FACTORY MAY BE ABLE TO SEPARATE THE $A^0$ & $H^0$

## 6 Scanning for a decoupled $h^0$ or an $A^0$

Use notation $h$ for the decoupled $h^0$ or the $A^0$.

- Earlier discussion $\Rightarrow$ $\sqrt{s} = 500$ GeV NLC/TESLA will find such an $h$ if $m_h < 150$ GeV or so. If found, $\mu$C with $\sqrt{s} = m_h$ is unique machine for performing a detailed study when other Higgs are heavy enough such that relevant Higgs pair $h^0A^0$ process is kinematically forbidden at available NLC/TESLA $\sqrt{s}$.

- If not found, begin scan at $\sqrt{s} \sim 150$ GeV.

  Scan procedure depends upon $\Gamma_h^{\rm tot}(m_h)$ vs. luminosity for required $R$ such that $\sigma \lesssim \Gamma_h^{\rm tot}$.

  Must make steps of size $\Gamma_h^{\rm tot} \sim \sigma$.

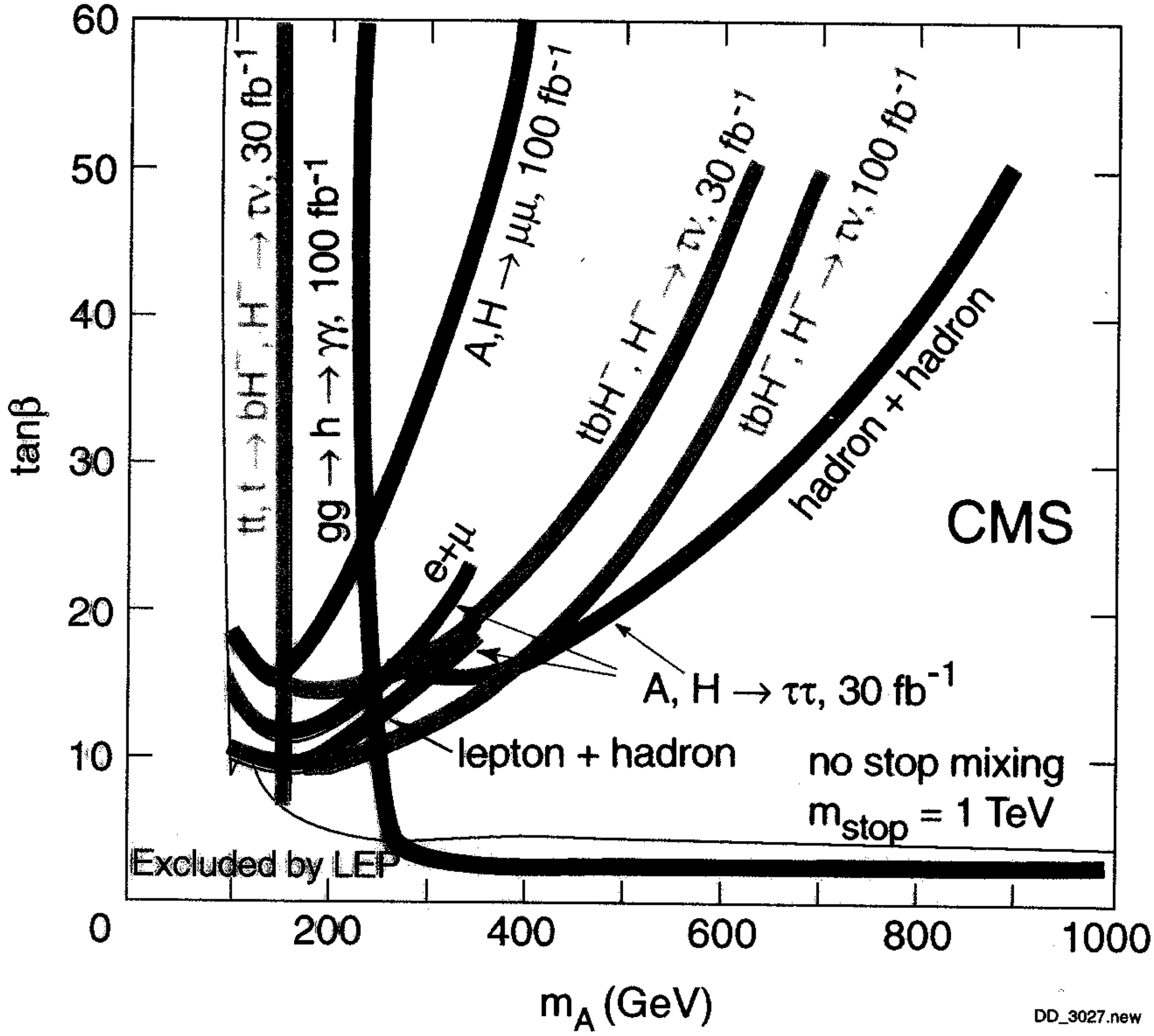
- For $2m_t > m_h > 150$ GeV, $h \to b\bar{b}$ and $\Gamma_h^{\rm tot} \sim 0.05 - 0.1$ GeV unless $\tan\beta < 1$.

  For $m_h > 2m_t$, $\Gamma_h^{\rm tot}$ rises to at least 1 GeV or so.

  $\Rightarrow$ only need $R = 0.05 - 0.1\%$ or so for $m_h < 2m_t$ rising to $R = 0.5 - 1\%$ for $m_h > 2m_t$.

# MSSM Higgs parameter space coverage

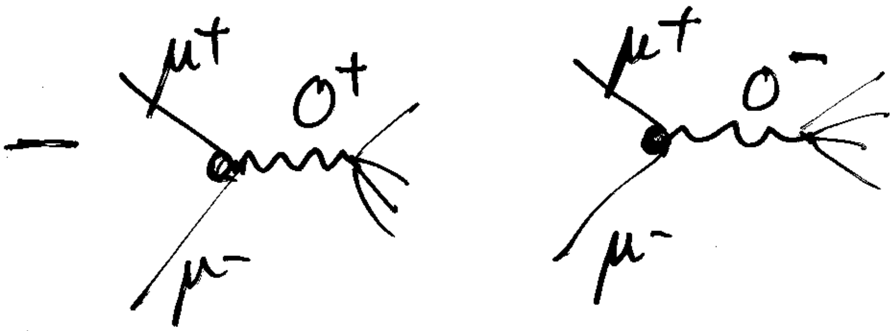
5 σ signifiance contours for SUSY Higgses




LHC will tell us where
this Higgs Complex is

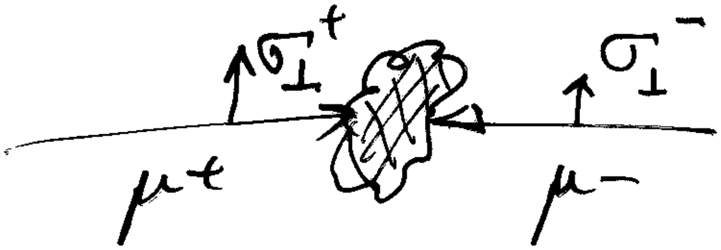
# CP Violation in the SCALAR SECTOR

— ONLY $\mu^+\mu^-$ Collider has a shot to observe this




Could be two SUSY Higgs

TO OBSERVE MUST HAVE TRANSVERSE $\mu^\pm$ ~~Pol~~ Polarization ~~Polarization~~ $\sigma_{\perp \mu^\pm}$




40% $\sigma_\perp$ seems adequate

this is possible for a Higgs Factory

$$\langle \sigma_{\perp^+} \times \hat{P}_\mu \cdot \sigma_{\perp^-} \rangle$$

like terms $\langle$ odd in T $\rangle$

A Key Goal

# TESTING CP VIOLATION IN THE HIGGS SECTOR AT MUON COLLIDERS*

B. GRZADKOWSKI
*Institute of Theoretical Physics, Warsaw University, ul. Hoza 69, PL-00-681 Warsaw, Poland*
*E-mails: bohdang@fuw.edu.pl, pliszka@fuw.edu.pl*



We study the possibility of measuring the muon Yukawa couplings in s-channel Higgs boson production at a muon collider with transversely polarized beams. We investigate sensitivity to the relative size of the CP-odd and CP-even muon Yukawa couplings. Provided the event rate observed justifies the operation of the $\mu^+\mu^-$ Higgs boson factory, we find that 40% polarization for both beams is sufficient to resolve the CP nature of a single resonance as well as disentangle it from two overlapping CP conserving resonances.

A Possibly Very Fundamental Study if $A^0$, $H^0$ Exist

Extremely interesting (J Ellis others at CERN working on this)

*A report on work done in collaboration with J.F. Gunion and J. Pliszka.