Neutrino Physics at a Muon Collider

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Princeton U.

17 September 1998

CERN Muon Collider Workshop

Based on

Workshop on Potential for Neutrino Physics at Future Muon Colliders

BNL, 13-14 August, 1998

http://pubweb.bnl.gov/people/bking/nushop/workshop.html

and

Workshop on Physics at the First Muon Collider and at the Front End of the Muon Collider

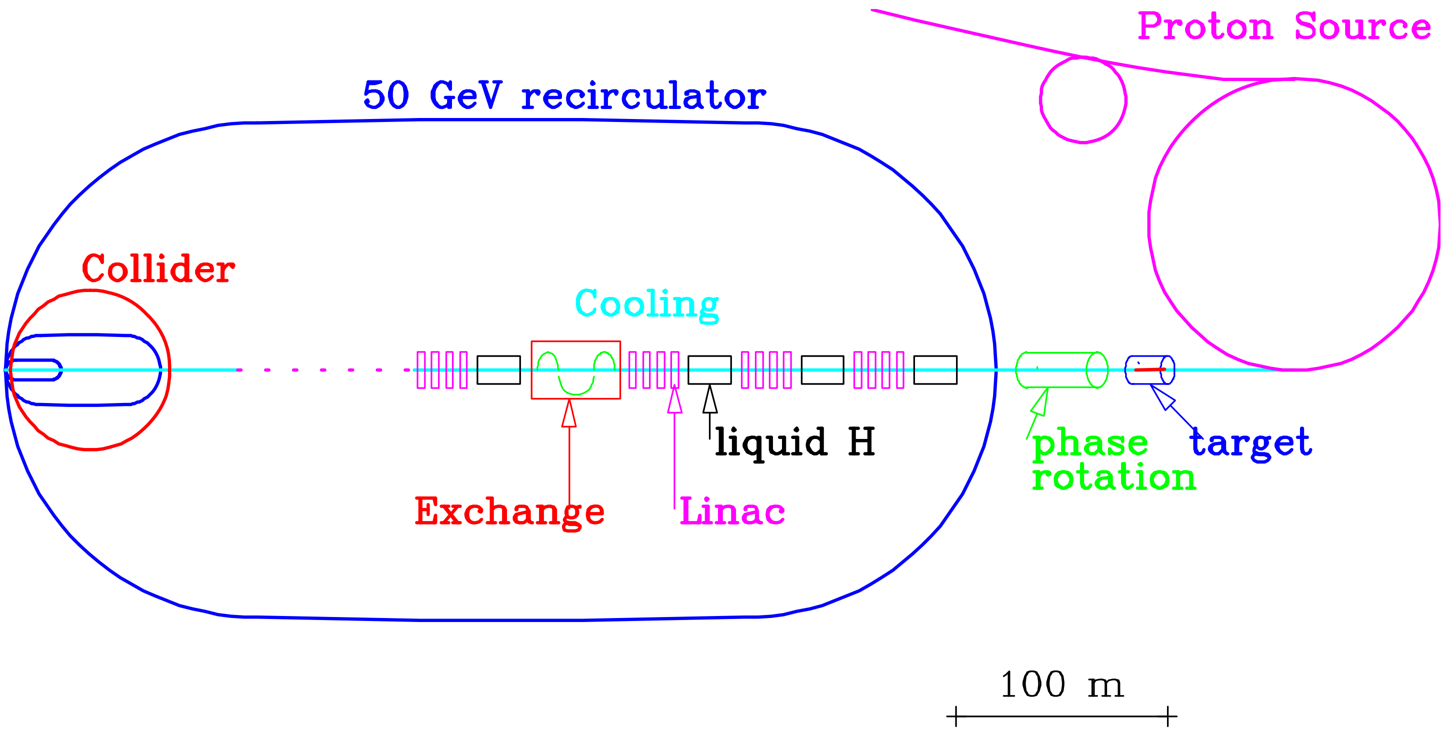
FNAL, November, 1998

AIP Conf. Proc. **435** (1998) [869 pages]

http://fnphyx-www.fnal.gov/conferences/femcpw97/workshop.html

The Path To a First Muon Collider

The simplest muon collider with luminosity sufficient to do frontier physics has CoM energy of 100 GeV: light Higgs, calibrate on Z_0.



Cost: > 1$B.

Could the case be strengthened by ancillary physics capabilities?

Interaction rate of ν's from μ decay in storage rings $\propto E^3$.

Intense ($> 10^{14}$/s), pulsed, low-energy μ (and ν) beams exist in the early stages of a muon collider.

Summary of Ancillary Physics Capabilities

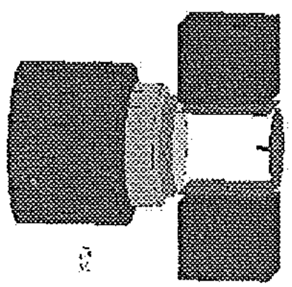
(My Impression)

- Higher-energy muon colliders will be **the** place to do neutrino physics. (But they are a long way off.)
- The duty factor of the low-energy muon beams (15 pps, each 2 ns wide) is not favorable to most muon physics: $\mu \to e\gamma$, $\mu \to ee^+e^-$, $\mu N \to eN$.
- A low-energy muon storage ring (not part of the basic muon-collider design) is of interest for muon physics, but perhaps not for neutrino physics. (Also, some muon cooling required.)
- The 20-T pion-capture solenoid does not produce a better low-energy neutrino beam than a horn.

Bottom line: Present understanding of ancillary physics capabilities does not provide a key justification for a muon collider.

$\Rightarrow$ A Challenge and an Opportunity!

Workshop on the Potential for Neutrino Physics at Future Muon Colliders



Thursday-Friday, 13-14 August, 1998

Brookhaven National Laboratory

Upton, New York, USA

Thanks to everyone who participated for making the workshop such a success!

- letter of invitation (2 July, 1998)
- workshop schedule
- registration form
- registered attendees
- travel & accomodation information
- follow-up nuMC book
- links to relevant papers, talks and other information

Organizing Committee:

Overview of Workshop

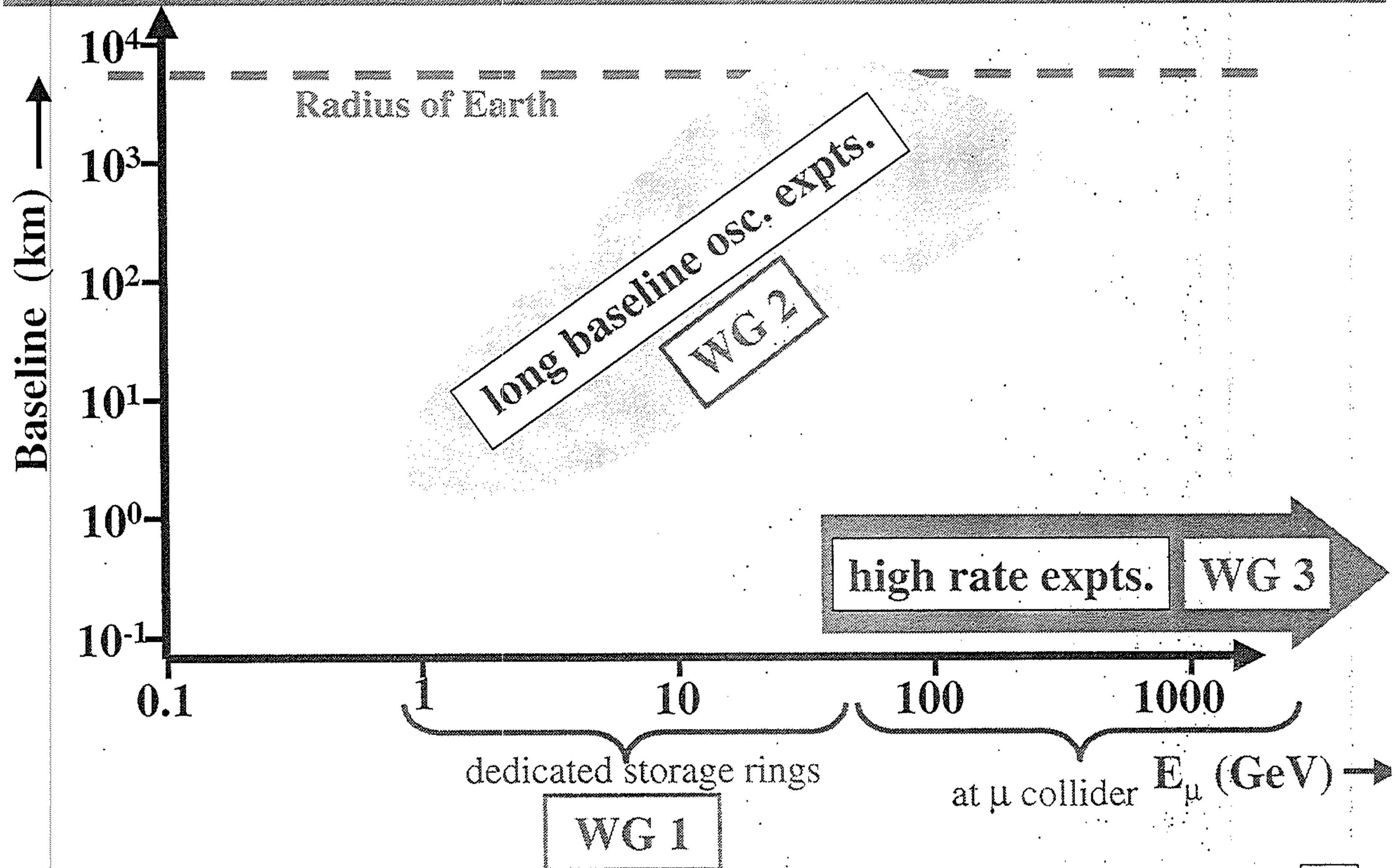
- 2 days long, 50 people
- plenary sessions + 3 working groups (WG's):

  (i) neutrino beam design

  (ii) long baseline experiments

  (iii) high rate experiments

Approx. Baseline vs. Energy Covered by WG's



Overviews and Theory (plenary)

- Overview & status of muon colliders (Palmer)
- Overview of neutrino oscillations (Conrad)
- Neutrino - antineutrino transitions (Wang)*

(* = see slide)

Janet Conrad
Columbia Univ.

ν_e or not ν_e?

And Other Neutrino Oscillation Questions...

In principle the muon collider neutrino beams
Allow a comprehensive program
of Oscillation Measurements:

$\nu_e \to \nu_e$	Near/Far ratios of ν_e CC events
$\nu_e \to \nu_\tau$	ν_τ appearance
$\nu_\mu \to \nu_\tau$	ν_τ appearance
$\nu_\mu \to \nu_e$	Near/Far ratios of ν_e CC events and Near/Far ratios of NC/CC
$\nu_\mu \to \nu_\mu$	Near/Far ratios of ν_μ CC events

... And CP violation tests by switching sign

The challange to the Oscillation Working Group:
Can we design experiments with sensitivity
To cover the interesting regions
At $\sim 5\sigma$?

Conclusion:

Paul Langacker & Jing Wang.

effective $\nu \to \nu^c$ transitions in 5 scenarios:

model	parameters	μ^+/μ^-
pure Majorana	$m_{\nu_\mu} \sim 1$ keV	$< 2 \cdot 10^{-10}$
spin precession in $B_\perp$	$\lvert\mu_{\nu_\mu}\rvert < 7\times10^{-10}\,\mu_B$ $\Delta m^2 \sim 10^{-5}$ eV^2	$< 2\times10^{-6}$
Neutrino decay	$h_2^2 < 2\times10^{-4}$, $\Delta m^2_{\nu_\mu} \sim 10^2$ eV, $\sin^2 2\theta_\mu < 0.02$	$< 4\times10^{-10}$
$SU(2)_L\times SU(2)_R\times U(1)$	$\lvert\xi\rvert < 0.003$, $\lvert\rho\rvert < 0.004$ $\sin^2 2\theta_\mu < 0.02$ for $\Delta m^2 = 100$ eV^2	$< 3\times10^{-7}$
Exotic fermions	$\lvert U_{13}\rvert^2 < 0.027$, $\Theta_{\mu L} \sim \Theta_{\mu R} \sim 1.4\times10^{-3}$	$< 4\times10^{-8}$

($E_{\nu_\mu} \sim 1$ GeV, $L \sim 1$ km)

present statistics on high energy $\nu_\mu N$ scattering: (CC)

$\sim 1.7\times10^5$ CDHS/CHARM

$\sim 1.1\times10^6$ CCFR

+ Background: $\pi^- \to \bar\nu_\mu \mu^-$; $\mu^+ \to e^+ \nu_e \bar\nu_\mu$ in the beam.

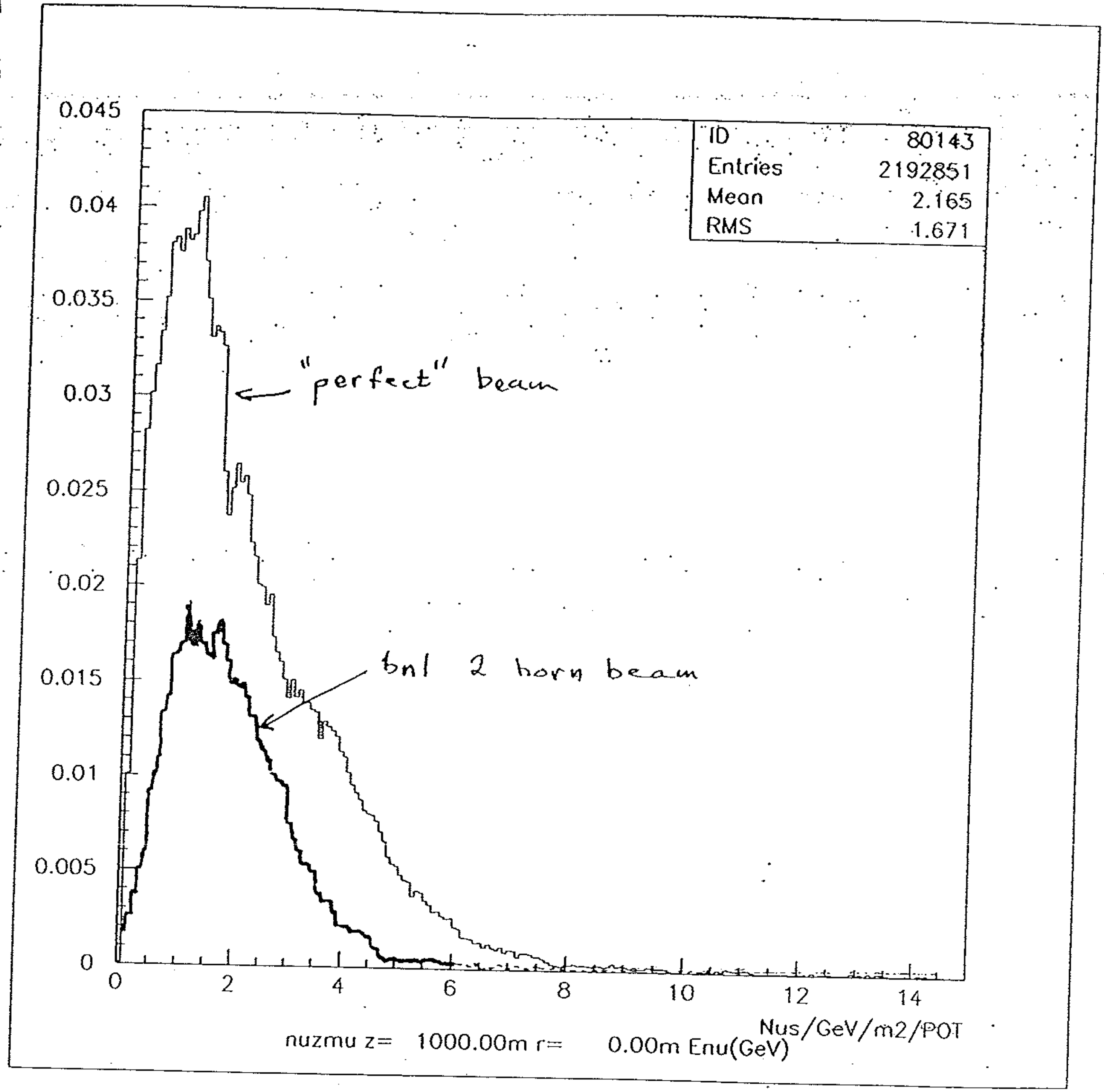
$\Rightarrow$ not possible to observe in Lab.

- New theoretical scenarios for $\nu \leftrightarrow \bar\nu$ transitions
- small transition probabilities $\Rightarrow$ need intense ν beams from μ colliders

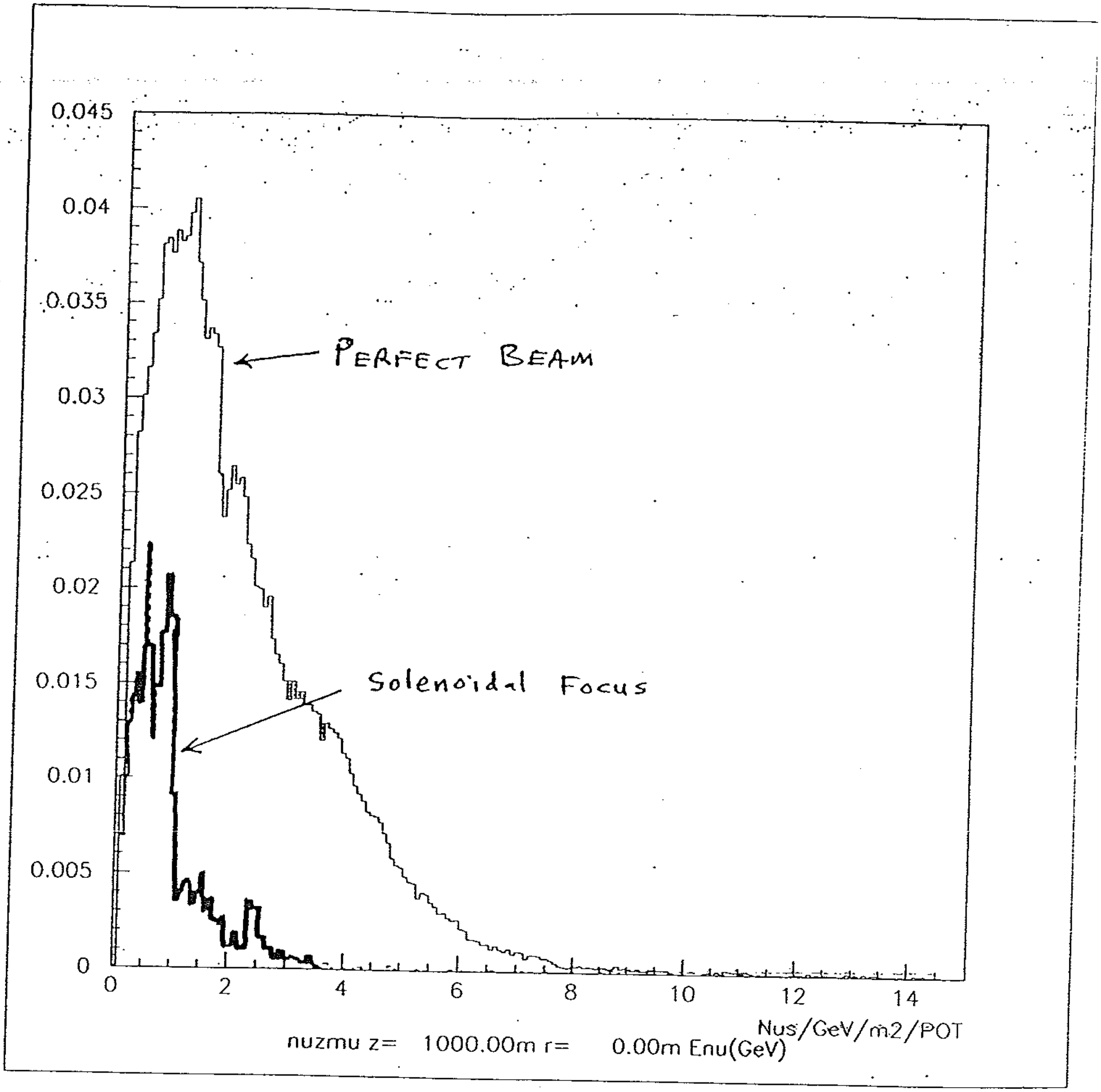
Neutrino Beam Design (WG 1)

- Improved sub-GeV beams from solenoidal capture & focus (Kahn)*
- Siting a muon collider at Fermilab (Finley)
- 2 GeV μSR with NO cooling (Palmer)*
- Low energy μSR as ν_e sources (Cline)
- Neutrino beams at muon colliders (Geer)*

(* = see slide)



ID 80143
Entries 2192851
Mean 2.165
RMS 1.671
"perfect" beam
bnl 2 horn beam
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0 2 4 6 8 10 12 14
Nus/GeV/m2/POT
nuzmu z= 1000.00m r= 0.00m Enu(GeV)



LOOKS PROMISING FOR LOW E_ν ... BUT NEEDS TO BE OPTIMIZED.

Higher Energy Neutrino Beams

Three ideas at the workshop on physics at the first muon collider & front end of a muon collider, FNAL, November 1997:

1. Use dedicated storage ring to maximize neutrino flux *(S. Geer)*.

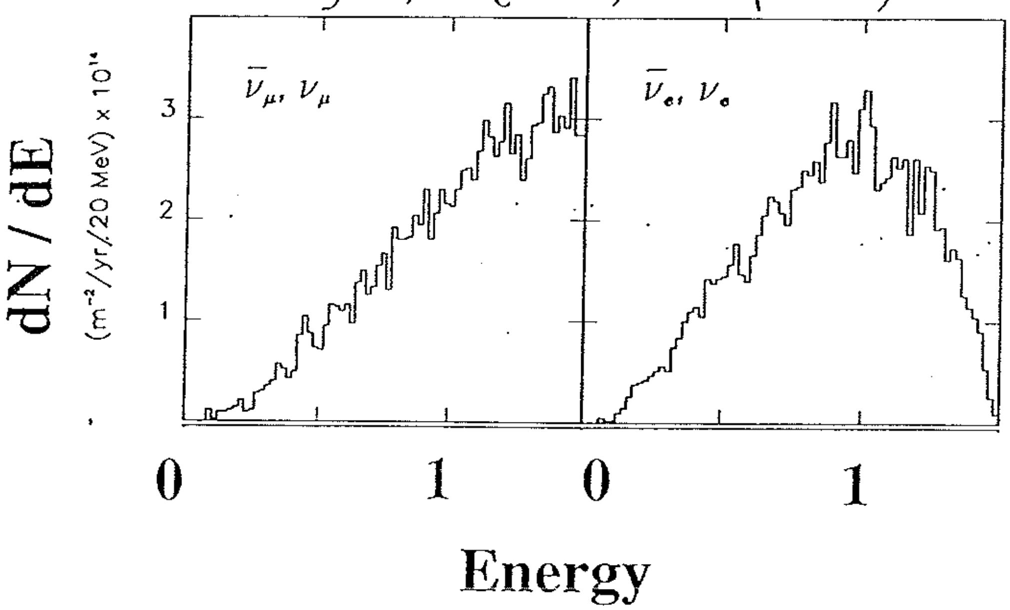
2. Use straight sections in Recirculating LINACS (RLAs) .... fun because the pulses scan the RLA energy interval *(C. Ankenbrandt & S. Geer)*.

3. Use straight sections in muon collider ring *(B. King)*.

Low Energy Scenario

- Consider a 1.5 GeV/c unpolarized muon beam stored in a ring with a straight section pointing at an experiment 1 km away:

S. Geer, PRD 57,6989 (1998)



- 1.4×10^{16} ν_e m^{-2} yr^{-1}
- 1.4×10^{16} ν_μ m^{-2} yr^{-1}
- 6×10^6 ν CC interactions KT^{-1} yr^{-1}
- 3×10^6 $\bar{\nu}$ CC interactions KT^{-1} yr^{-1}

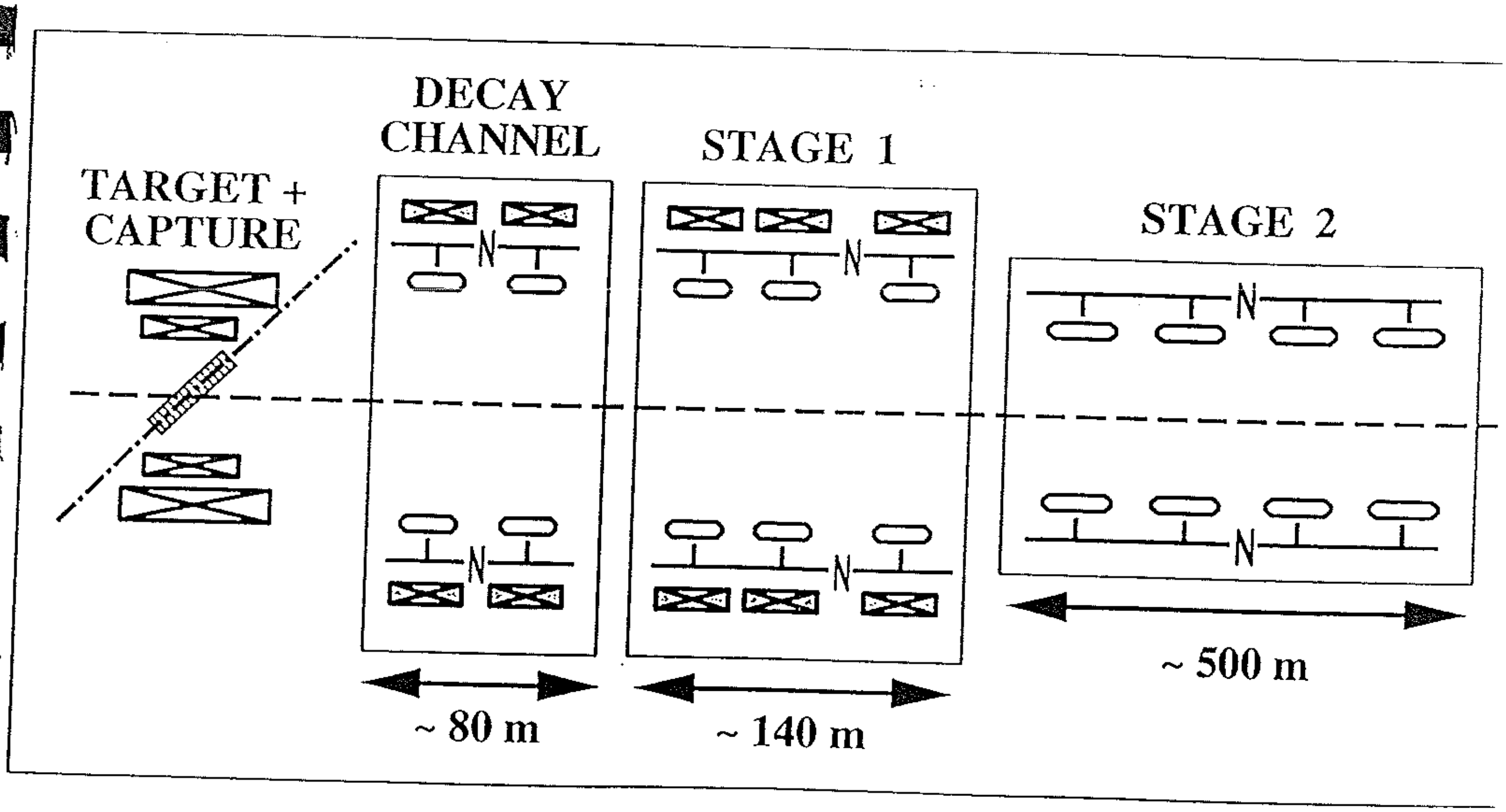
Recent Work on a Capture, Acceleration, & Muon Storage Ring Scenario – (1)

B. Autin, S. Geer, C. Johnstone & D. Neuffer

- **Dont need all the muons in a single bunch ->**

STAGE 1: Capture & begin acceleration with 800 MHz rf, V_{rf} = 15 MV/m, $\phi_S = 30^o$, linac length = 140m.

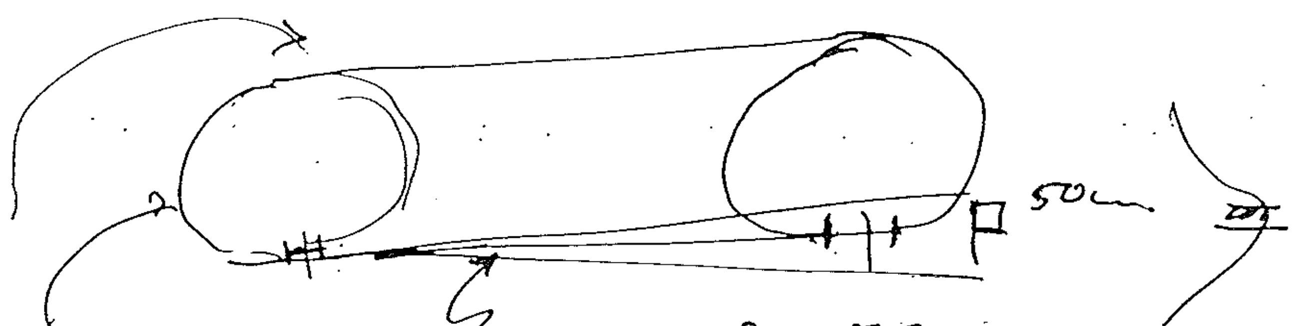
STAGE 2: Continue acceleration up to 10 GeV with 800 MHz rf, V_{rf} = 20 MV/m, $\phi_S = 60^o$, linac length = 500m.



Palmer:

~ 2 GeV μ ring
with NO cooling.

(5) Put into 200 m circ storage ring.



low β
rad ≈ 10 cm
$\sigma_{p_\perp} \approx 50$ MeV/c
$\sigma_\theta \approx 25$ mrad

high β : rad ≈ 30 cm
$\sigma_{p_\perp} \approx$ 15 MeV/c

$\nu_e - \nu_\mu$

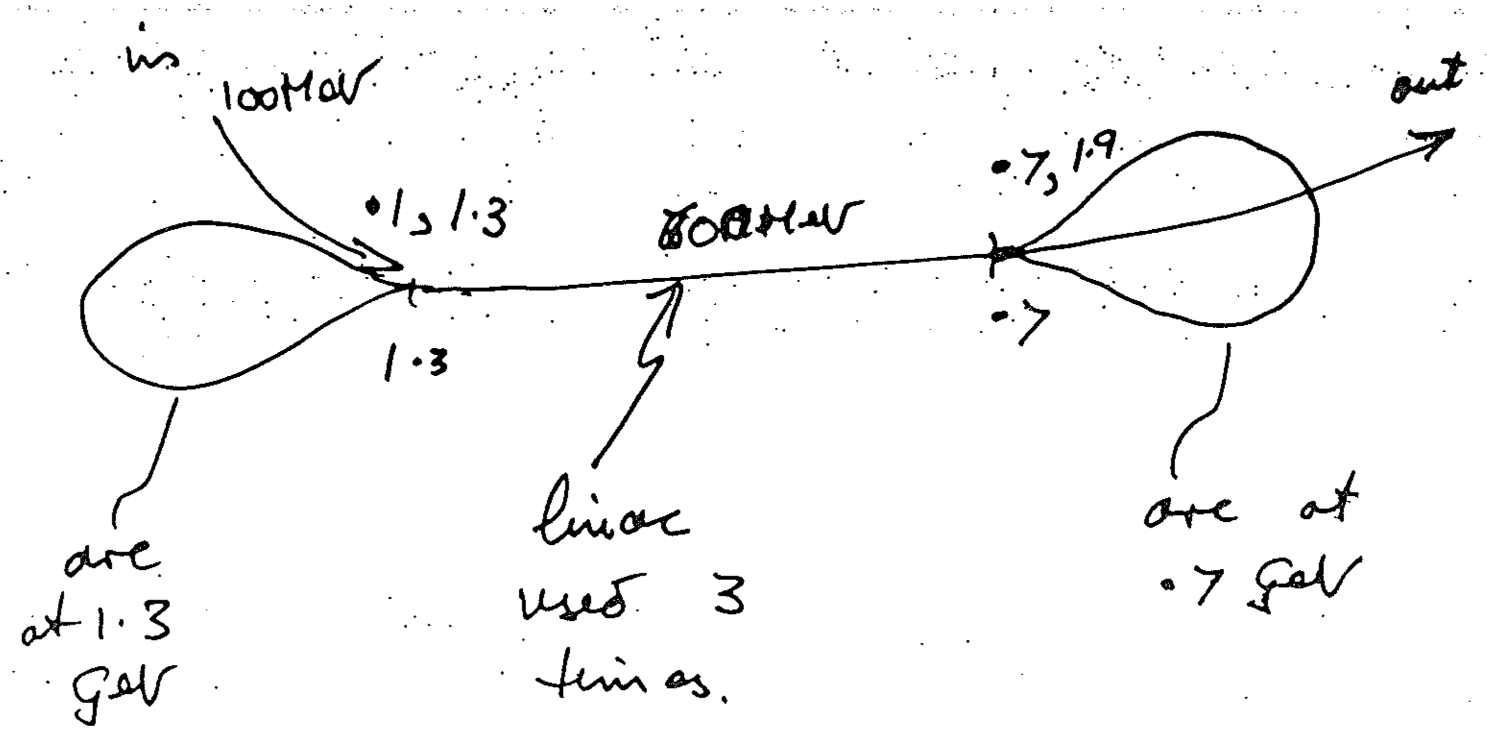
cf decay $\hat{p}_\perp$ = 50 MeV/c
$\hat{\sigma}_{p_\perp} \approx$ 30 MeV/c

little dilution ✓

~100 m × $\frac{1}{20}$ or 5 m.

Possible Acc

Bob Palmer



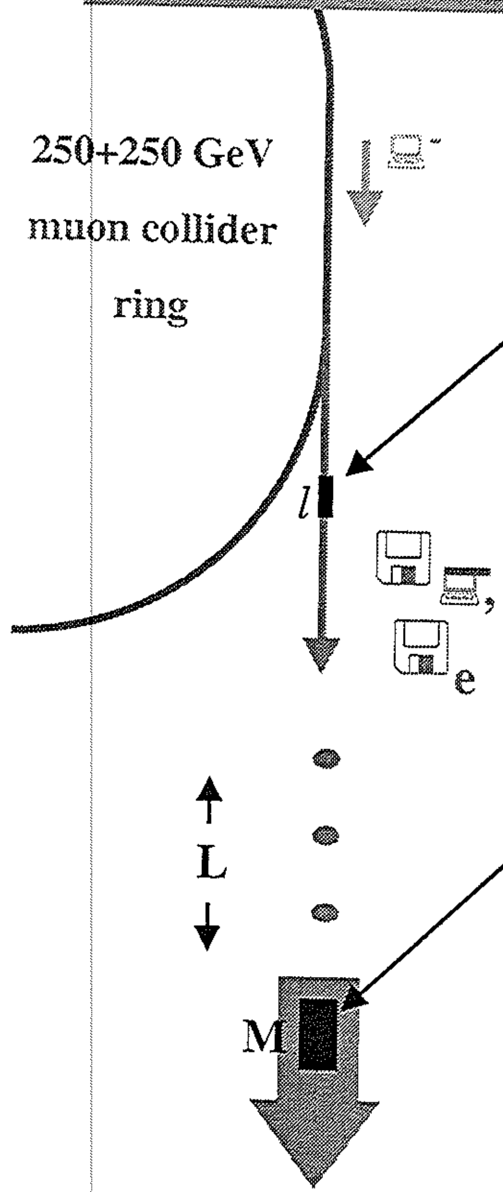
ACCEL TO 2 GeV:

$$\frac{\delta p}{p} = 15\% \rightarrow 1.5\% \quad (\text{same } \sigma_z)$$

$$\rightarrow \sim 3\% \quad (\text{half bunch length})$$

A "trick" for accelerating μ's to 2 GeV with only 2/3 GeV of rf linac.

Impressive "Free" Beams from μ Colliders



General purpose detector

$5 \times 10^7 \times l\,[\mathrm{g.cm^{-2}}]$ events/year*

WOW

2.6	$\nu_\mu - CC$
0.8	$\nu_\mu - NC$
1.4	$\bar{\nu}_e - CC$
0.5	$\bar{\nu}_e - NC$

Long baseline detector for □ oscillations

$3 \times 10^7 \times \frac{M[kg]}{(L[km])^2}$ events/year*

WOW

1.4	$\nu_\mu - CC$
0.4	$\nu_\mu - NC$
0.7	$\bar{\nu}_e - CC$
0.2	$\bar{\nu}_e - NC$

*assumes 250+250 GeV collider, 200 m straight section & 6×10^{20} □⁻/year

Long Baseline Experiments (WG 2)

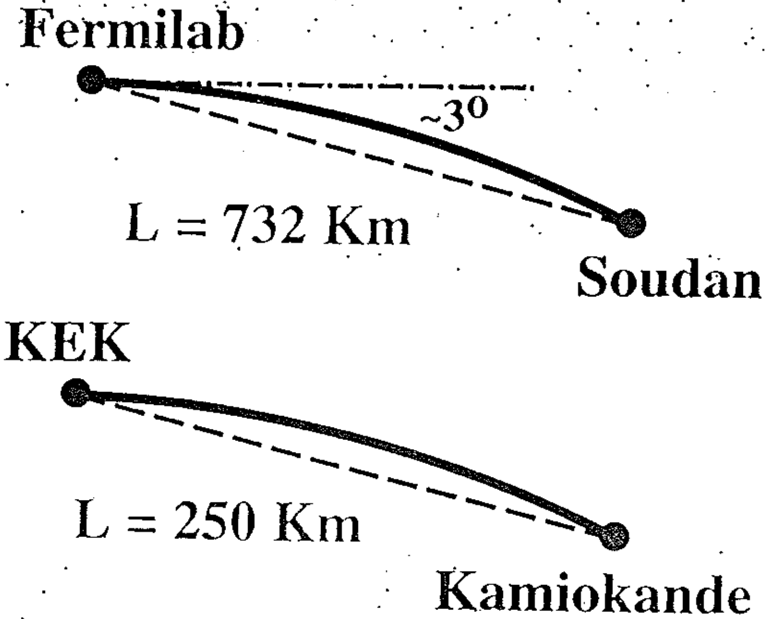
(This WG dealt largely with detector technologies)

- ICARUS: a fully-active tracking detector (Cline)
- MINOS: a sampling calorimetric detector (Michael)
- Emulsion detectors for ν_τ appearance expts. (Para)
- Beam comparisons for ν_τ appear. expts. (Shaevitz)*

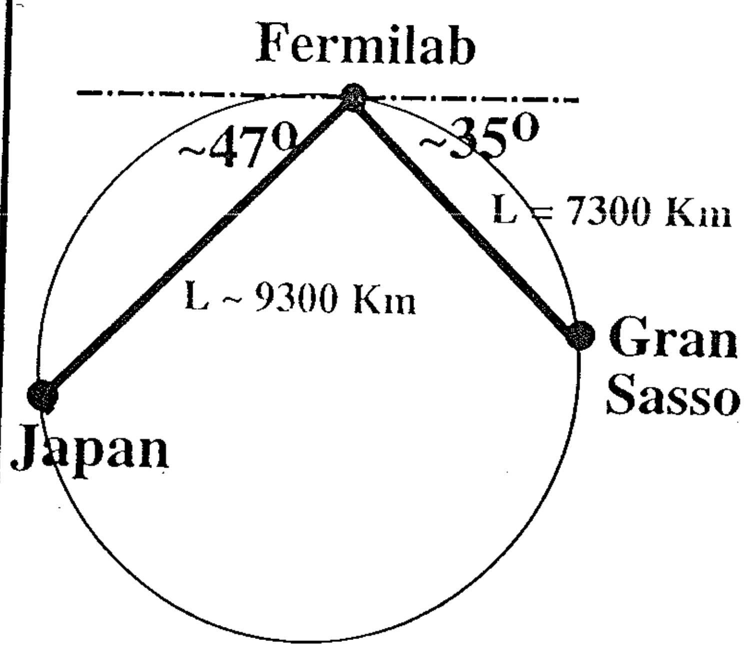
(* = see slide)

Geer

Long Baseline Options



E_ν (GeV)	L/E (Km/GeV) FNAL–Soudan	L/E (Km/GeV) KEK–Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3



E_ν (GeV)	L/E (Km/GeV) Gran S.	L/E (Km/GeV) Japan
10	~730	~930
20	~370	~470
30	~240	~310
40	~180	~230
50	~150	~190

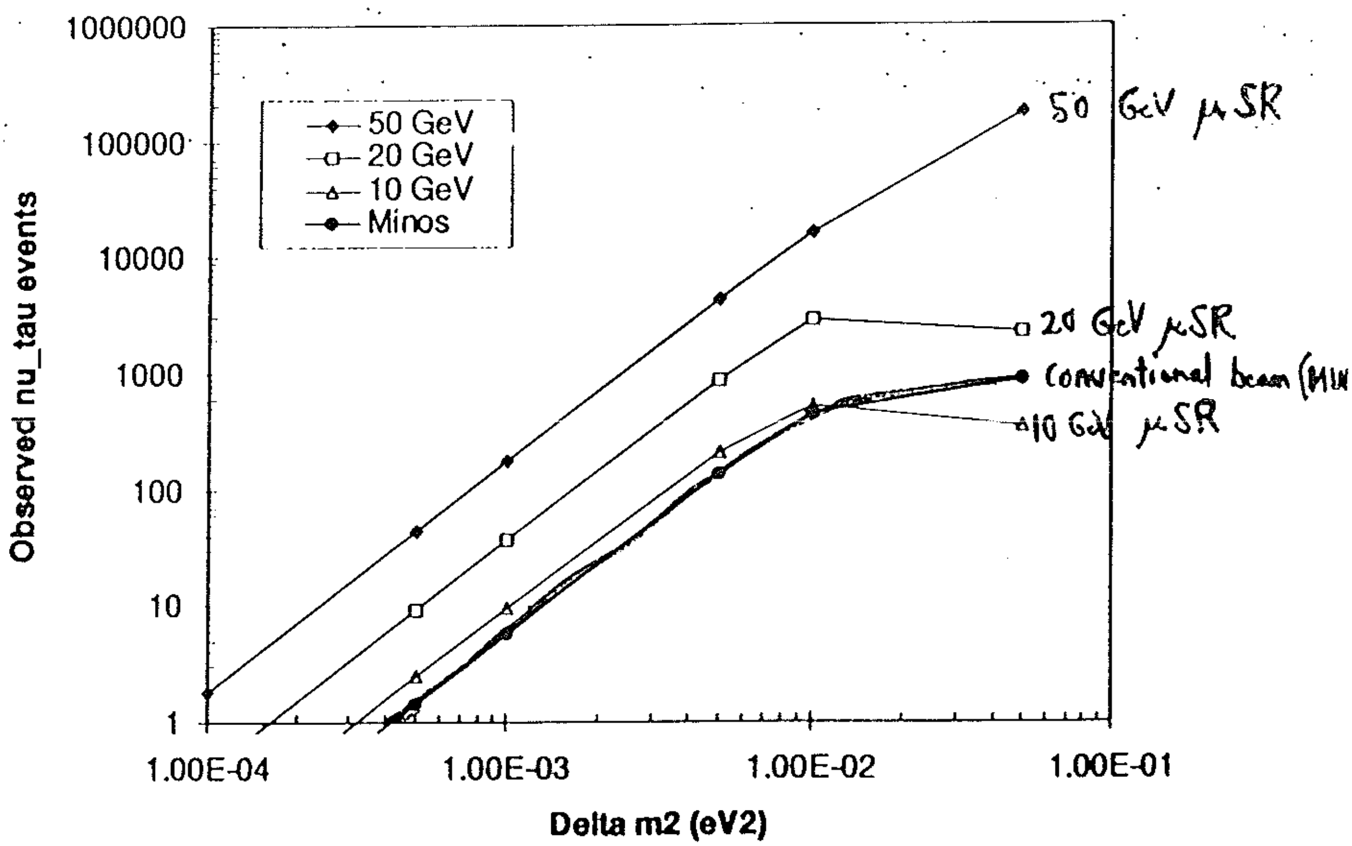
Inter-continental ν experiments!

Mike Shaevitz

A first look at
A long-baseline muon storage ring experiment: (ν_τ appearance)

- A 1kton emulsion experiment (50% detection efficiency)
- 730 km baseline
- Flux from Geer, FNAL-Pub-971389 (on workshop web page)
- For $\sin^2 2\theta = 1$
- Events for two years of running

  – **Since L dependence is weak and energy dependence of rate is faster than E^2 plus τ xsec suppression $\Rightarrow$ 50 GeV μSR is best.**



Conclusion: Muon storage rings (μSR) give big gains over conventional ν beams only at higher energies.

High Rate Experiments (WG 3)

- High rate, high performance ν detectors (King)*
- QCD studies (Harris)
- Precision EW physics (McFarland/Yu)
- Rare & exotic processes (Bolton)
- CKM quark mixing matrix (King)*

} potential for huge improvements over existing analyses + new contributions to precision HEP

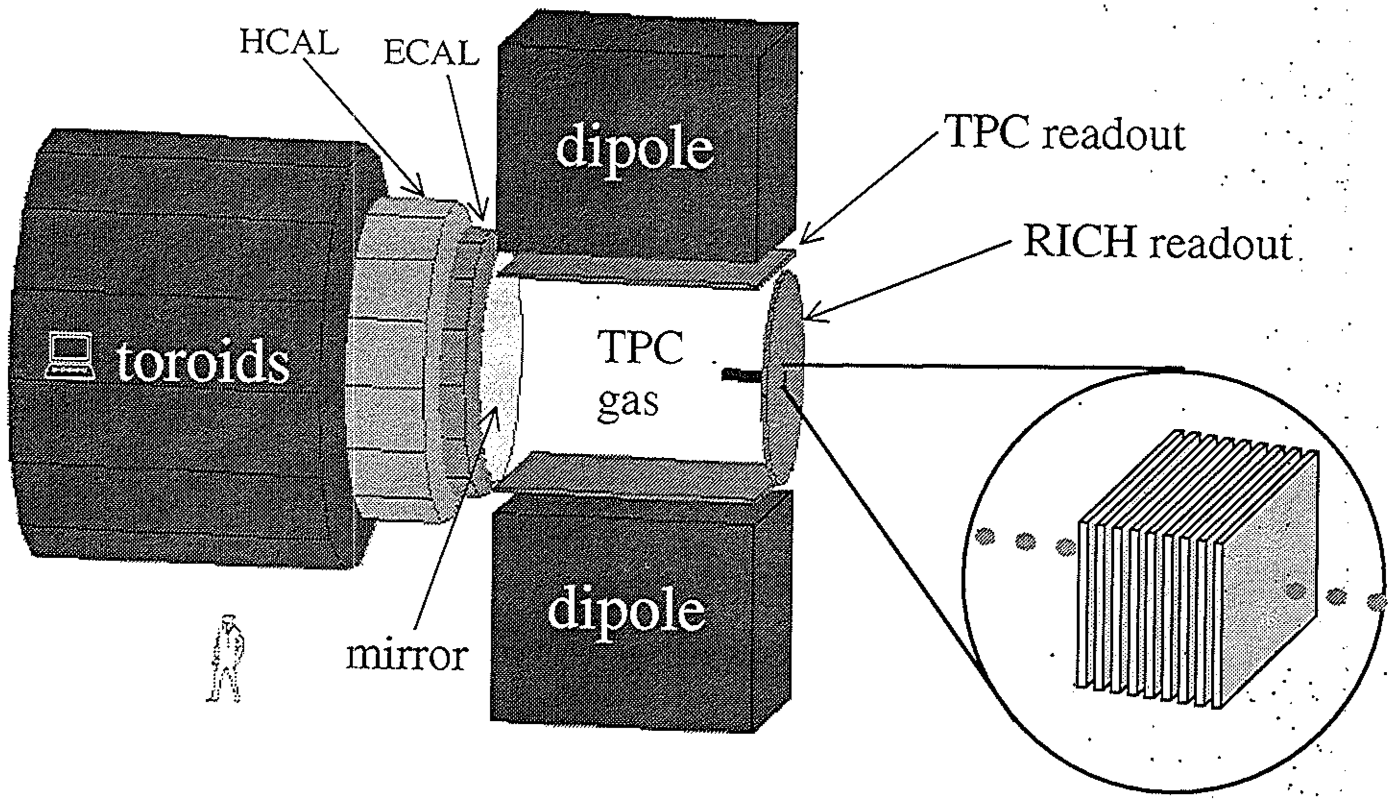
- Charm factory (Summers) O(10^8) charm decays +

unique event-by-event c\cbar production tag: $\nu \rightarrow l^- c$; $\bar{\nu} \rightarrow l^+ \bar{c}$

=> can be competitive/superior to current & proposed charm factories

(* = see slide)

High Rate, High Performance ν Detector



- HUGE statistics: 50 g/cm^2 target => 3×10^9 events/year
- outstanding reconstruction of CC & NC event kinematics
- possibility of interchangeable/multiple targets: Si CCD's, H_2/D_2, . . .

CKM Matrix: current uncertainties in $|V_{qq'}|^2$
& guesses at uncertainties with 10^{10} interactions

	d	s	b
u	0.1%	1.6%	50% ~1%
c	15% ~0.1%	35% ~1%	15% ~1%
t	25%	40%	30%

d→c
O(10^8) events

s→c
O(10^8) events
s(x) from NC
needs s tagging

u→b
O(10^4) events
with b threshold

c→b
O(10^4) events(?)
threshold very impt.
c(x) from NC

d, s→t
dramatic improvements
possible at very high E_ν

Not bad !!

Conclusions

Kevin McFarland

Summary of high rate ν expt.

- Physics program is rich, complementary to energy frontier
  - ↳ "No home runs"
  - ↳ Now need detailed studies of best processes
- Detectors/Targets open up possibilities for novel processes

	yes	maybe	no
Would you build a muon collider solely for ν experiments?	☐	☐	☒
Do you build an experiment for high rate physics if the beams are there?	☒	☐	☐
Does it significantly strengthen the case for a heavy lepton collider?	☐	☒	☐

Follow-up Activities

- Book of transparencies (available from tuohy@bnl.gov)
- Contributed write-ups (optional - probably not many)
- Book &/or PRD overview of ν physics possibilities at muon colliders: plan to complete in November, authors: Bigi, Bolton, Harris, King, McFarland, Morfin, Para, Schellman, Spentzouris, Summers, Yu
- Possibility of future workshops e.g. Aspen '99 summer study

Workshop Summary

- Will eventually have a wide range of exciting physics possibilities with "free" intense ν beams at muon colliders

- Dedicated μSR could possibly help with ν oscillation studies on a shorter timescale. Can they be built quickly and affordably ? (A major challenge!)

- Follow-up studies are needed & some are underway