

# Neutrino Physics at a Muon Collider

K.T. McDonald

*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*

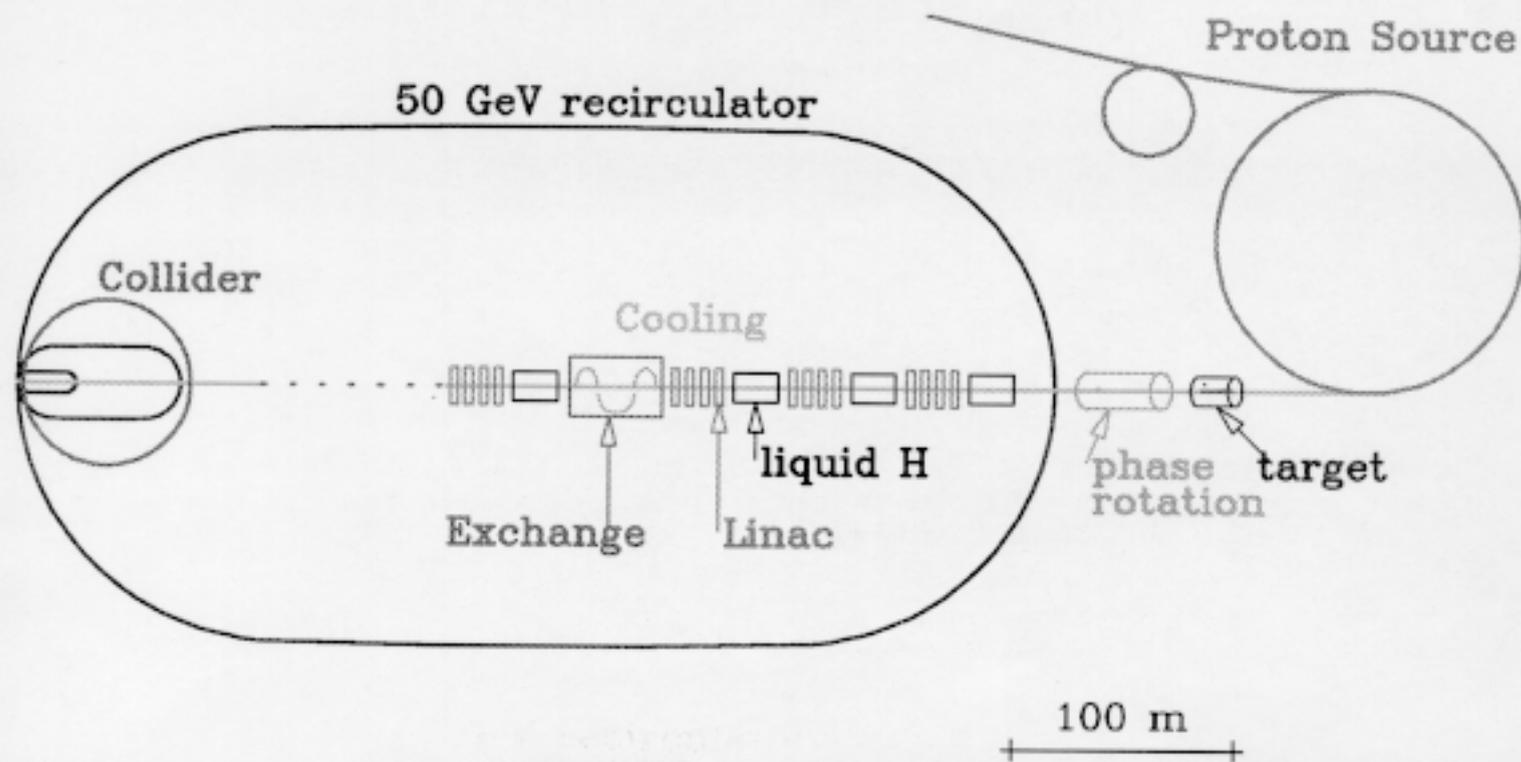
*FNAL, November, 1998*

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  $\nu$ 's from  $\mu$  decay in storage rings  $\propto E^3$ .

Intense ( $> 10^{14}/s$ ), pulsed, low-energy  $\mu$  (and  $\nu$ ) 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:  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow ee^+e^-$ ,  $\mu N \rightarrow eN$ .
- 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.

⇒ A Challenge and an Opportunity!

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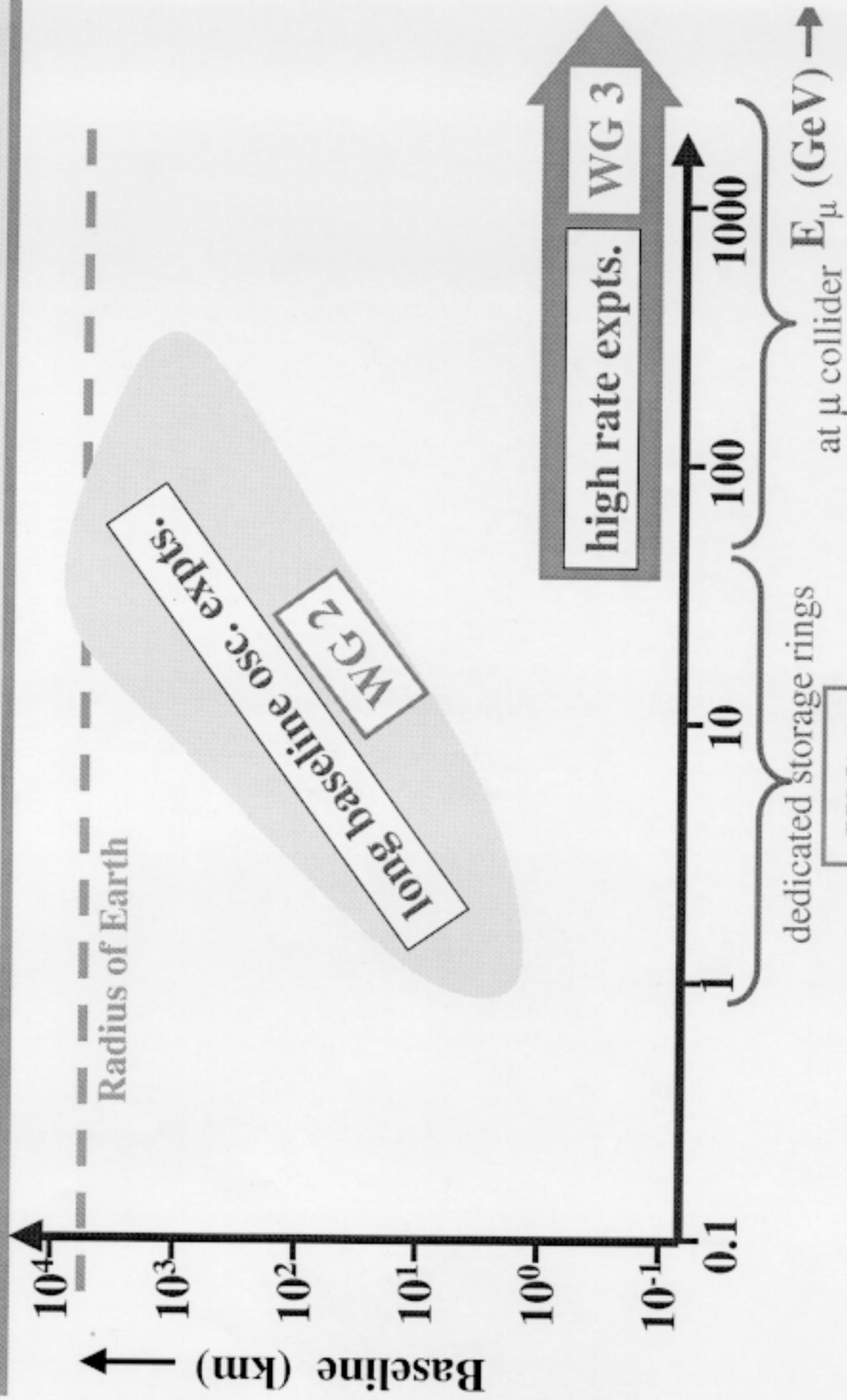
Bottom line: Present understanding of ancillary physics capabilities does not provide a key justification for a muon collider.

$\Rightarrow$  A Challenge and an Opportunity!

## 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)

$\nu_e$  or not  $\nu_e$ ?

And Other Neutrino Oscillation  
Questions...

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

|                                |  |
|--------------------------------|--|
| $\nu_e \rightarrow \nu_e$      | Near/Far ratios of $\nu_e$ CC events                                 |
| $\nu_e \rightarrow \nu_\tau$   | $\nu_\tau$ appearance  |
| $\nu_\mu \rightarrow \nu_\tau$ | $\nu_\tau$ appearance  |
| $\nu_\mu \rightarrow \nu_e$    | Near/Far ratios of $\nu_e$ CC events and<br>Near/Far ratios of NC/CC |
| $\nu_\mu \rightarrow \nu_\mu$  | Near/Far ratios of $\nu_\mu$ CC events                               |

... And CP violation tests by switching sign

The challenge 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  $\nu \rightarrow \nu^c$  transitions in 5 scenarios:

| model                                | parameters   | $\mu^+/\mu^-$         |
|--------------------------------------|--|-----------------------|
| pure Majorana                        | $m_{\nu\mu} \sim 1 \text{ keV}$  | $< 2 \cdot 10^{-10}$  |
| spin precession in $B_L$             | $ \mu_{\nu\mu}  < 7 \times 10^{-10} \mu_B$<br>$\Delta m^2 \sim 10^{-5} \text{ eV}^2$                         | $< 2 \times 10^{-6}$  |
| Neutrino decay                       | $h_2^2 < 2 \times 10^{-4}$ , $\Delta m_{\nu\mu}^2 \sim 10^2 \text{ eV}^2$ ,<br>$\sin^2 2\theta_{\mu} < 0.02$ | $< 4 \times 10^{-10}$ |
| $SU(2)_L \times SU(2)_R \times U(1)$ | $ 3  < 0.003$ , $ p  < 0.004$<br>$\sin^2 2\theta_{\mu} < 0.02$ for $\Delta m^2 = 100 \text{ eV}^2$           | $< 3 \times 10^{-7}$  |
| Exotic fermions                      | $ U_{13} ^2 < 0.027$ , $\Theta_{\mu L} \sim \Theta_{\mu R} \sim 1.4 \times 10^{-3}$                          | $< 4 \times 10^{-8}$  |

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

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

$\sim 1.7 \times 10^5$  CDHS/CHARM

$\sim 1.1 \times 10^6$  CCFR

+ Background:  $\pi^- \rightarrow \bar{\nu}_{\mu} \mu^-$ ;  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_{\mu}$  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  $\nu$  beams from  $\mu$  colliders

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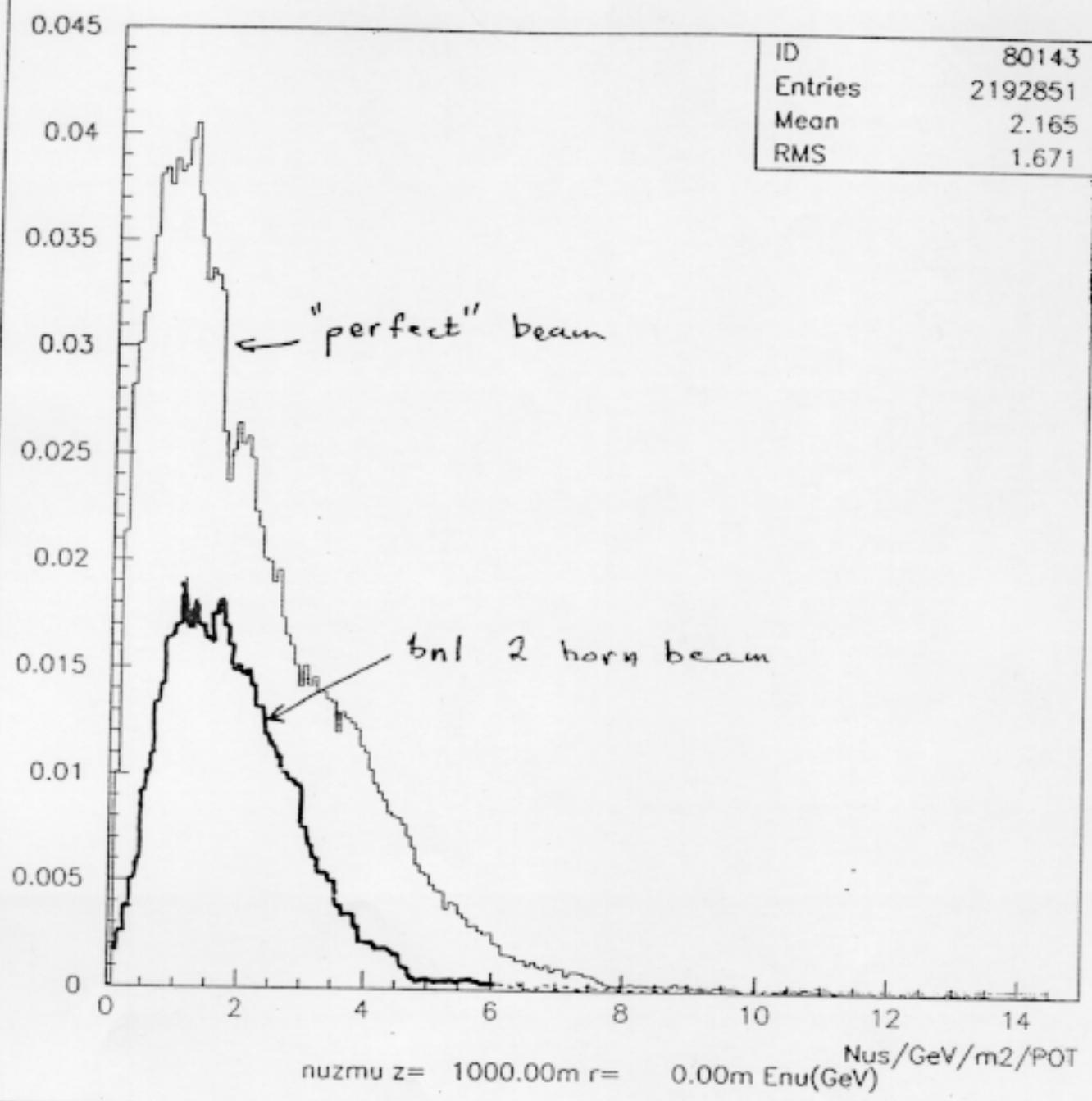
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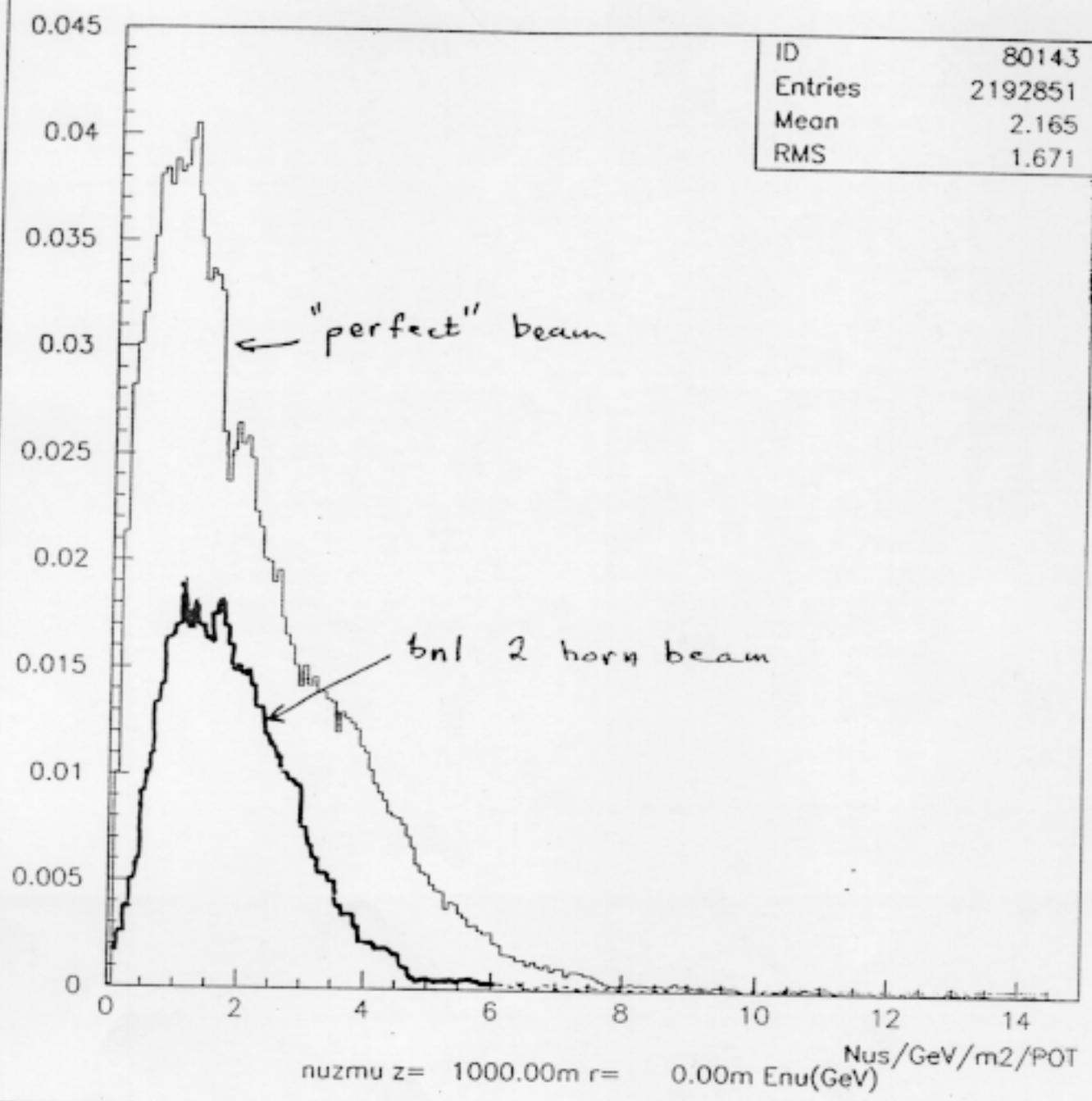
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## Higher Energy Neutrino Beams

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*).

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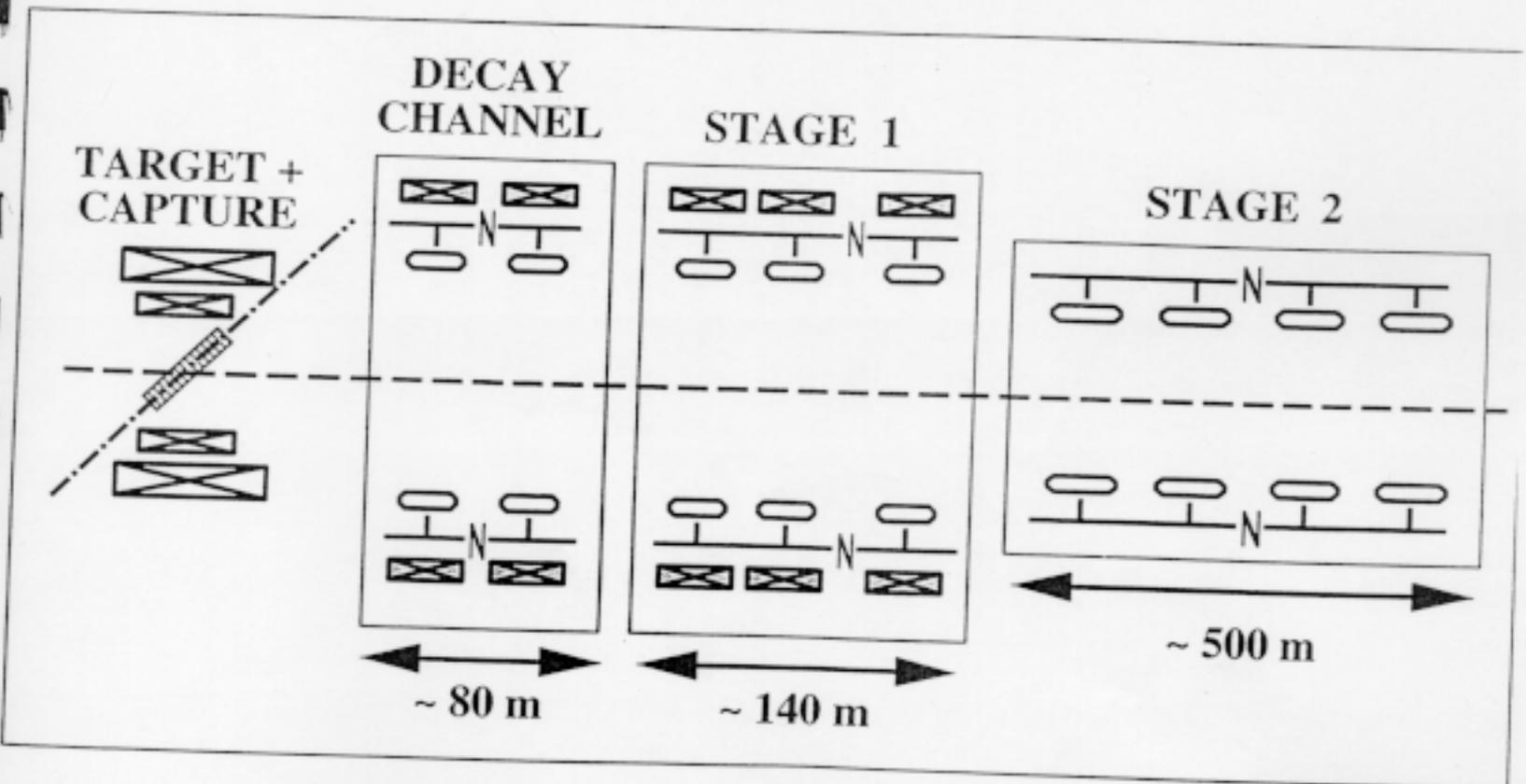
# Recent Work on a Capture, Acceleration, & Muon Storage Ring Scenario - (1)

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

- Don't need all the muons in a single bunch →

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

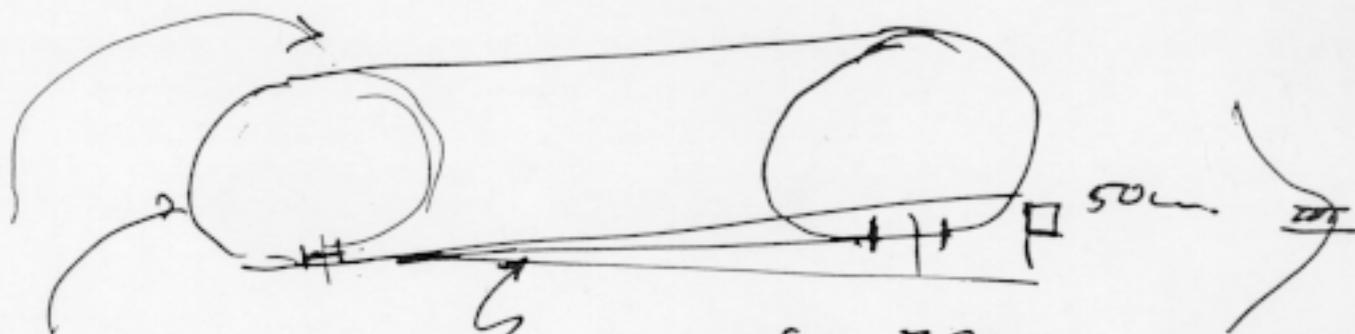
**STAGE 2:** Continue acceleration up to 10 GeV with 800 MHz rf,  $V_{rf} = 20$  MV/m,  $\phi_s = 60^\circ$ , linac length = 500m.



# Palmer:

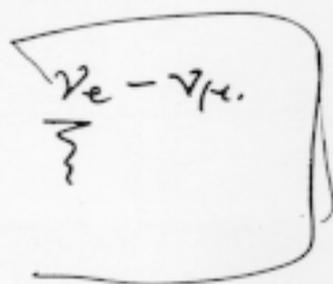
~ 2 GeV  $\mu$  ring  
with NO cooling.

⑤ Put into 200m circ storage ring.



low  $\beta$   
 $r_{0\beta} \approx 10\text{cm}$   
 $\sigma_{p\perp} \approx 50\text{MeV}/c$   
 $\sigma_{\theta} \approx 25\text{mrad}$

high  $\beta$  :  $r_{0\beta} \approx 30\text{cm}$   
 $\sigma_{p\perp} \approx \underline{15\text{MeV}/c}$



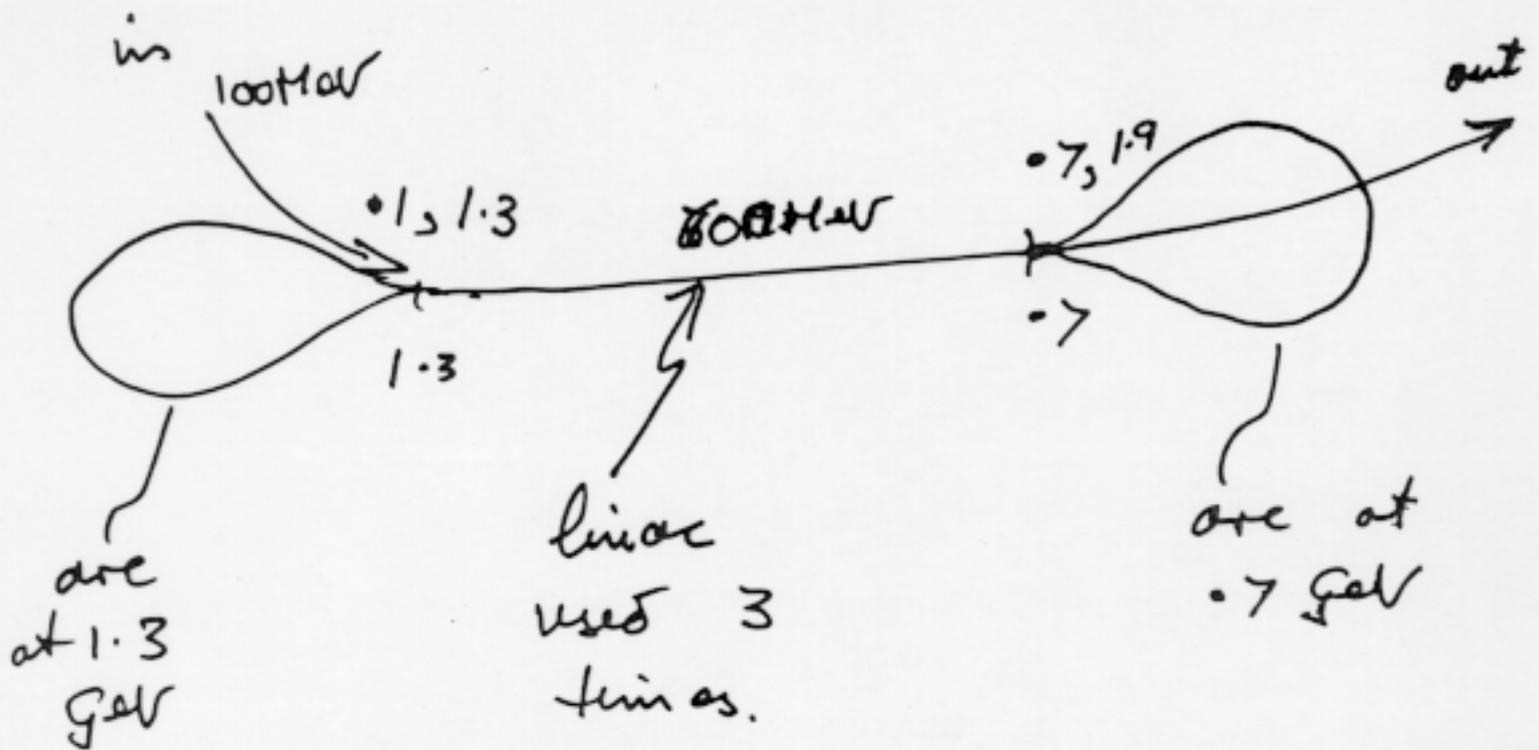
of Secoy  $\hat{p}_{\perp} = 50\text{MeV}/c$   
 $\hat{\sigma}_{p\perp} \approx \underline{30\text{MeV}/c}$

little dilution  $\checkmark$

~ 100  $\mu$   $\times \frac{1}{20} \approx \underline{5\text{m}}$

# Possible Acc

Bob Palmer

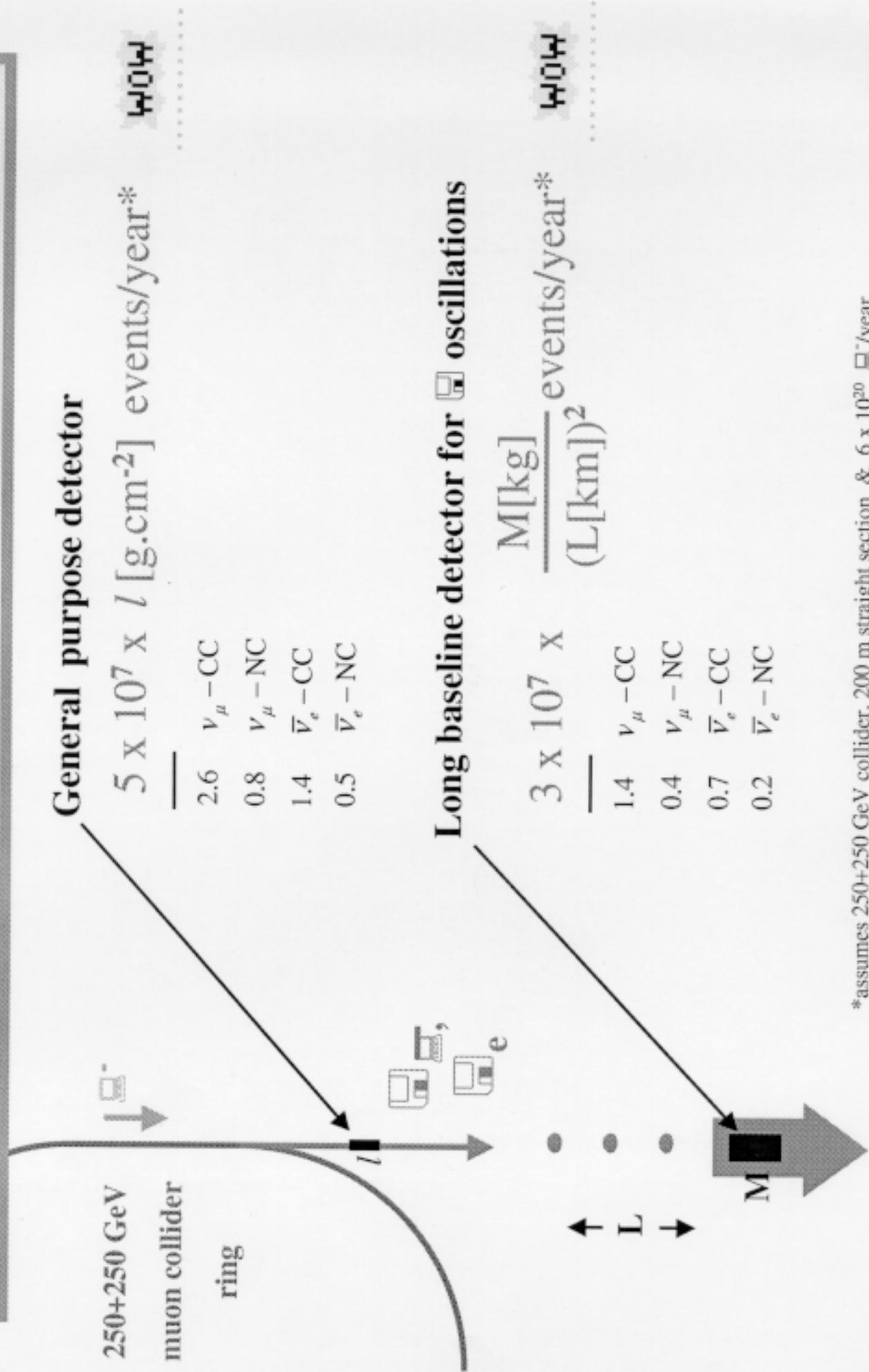


ACCEL TO 2 GeV:

$$\frac{\Delta P}{P} = 15\% \rightarrow 1.5\% \quad (\text{same } \sigma_z)$$
$$\rightarrow \sim 3\% \quad (\text{half bunch length})$$

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

# Impressive "Free" Beams from $\mu$ Colliders



\*assumes 250+250 GeV collider, 200 m straight section &  $6 \times 10^{20}$   $\mu^-$ /year

## Long Baseline Experiments (WG 2)

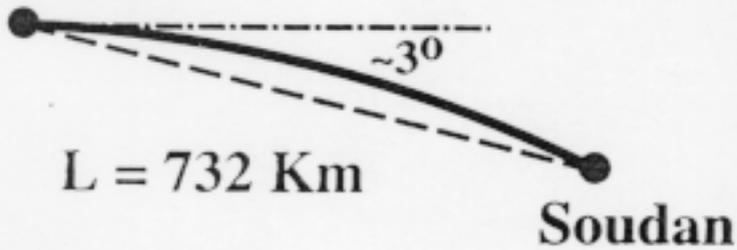
(This WG dealt largely with detector technologies)

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

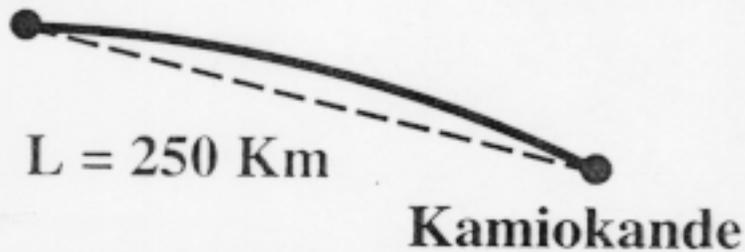
(\* = see slide)

# Long Baseline Options

Fermilab

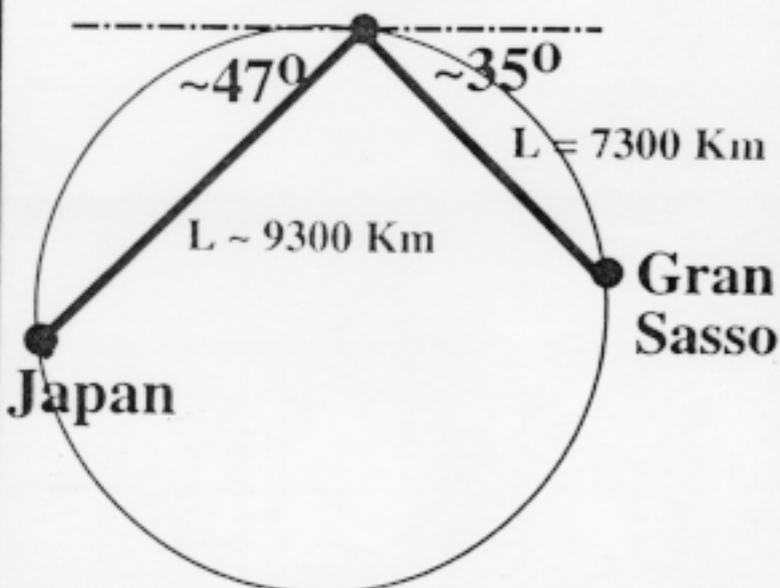


KEK



| $E_\nu$<br>(GeV) | L/E (Km/GeV)    |              |
|------------------|-----------------|--------------|
|                  | FNAL-<br>Soudan | KEK-<br>Kam. |
| 10               | 73.2            | 25.0         |
| 20               | 36.6            | 12.5         |
| 30               | 24.4            | 8.3          |
| 40               | 18.3            | 6.3          |

Fermilab



| $E_\nu$<br>(GeV) | L/E (Km/GeV) |            |
|------------------|--------------|------------|
|                  | Gran S.      | Japan      |
| 10               | $\sim 730$   | $\sim 930$ |
| 20               | $\sim 370$   | $\sim 470$ |
| 30               | $\sim 240$   | $\sim 310$ |
| 40               | $\sim 180$   | $\sim 230$ |
| 50               | $\sim 150$   | $\sim 190$ |

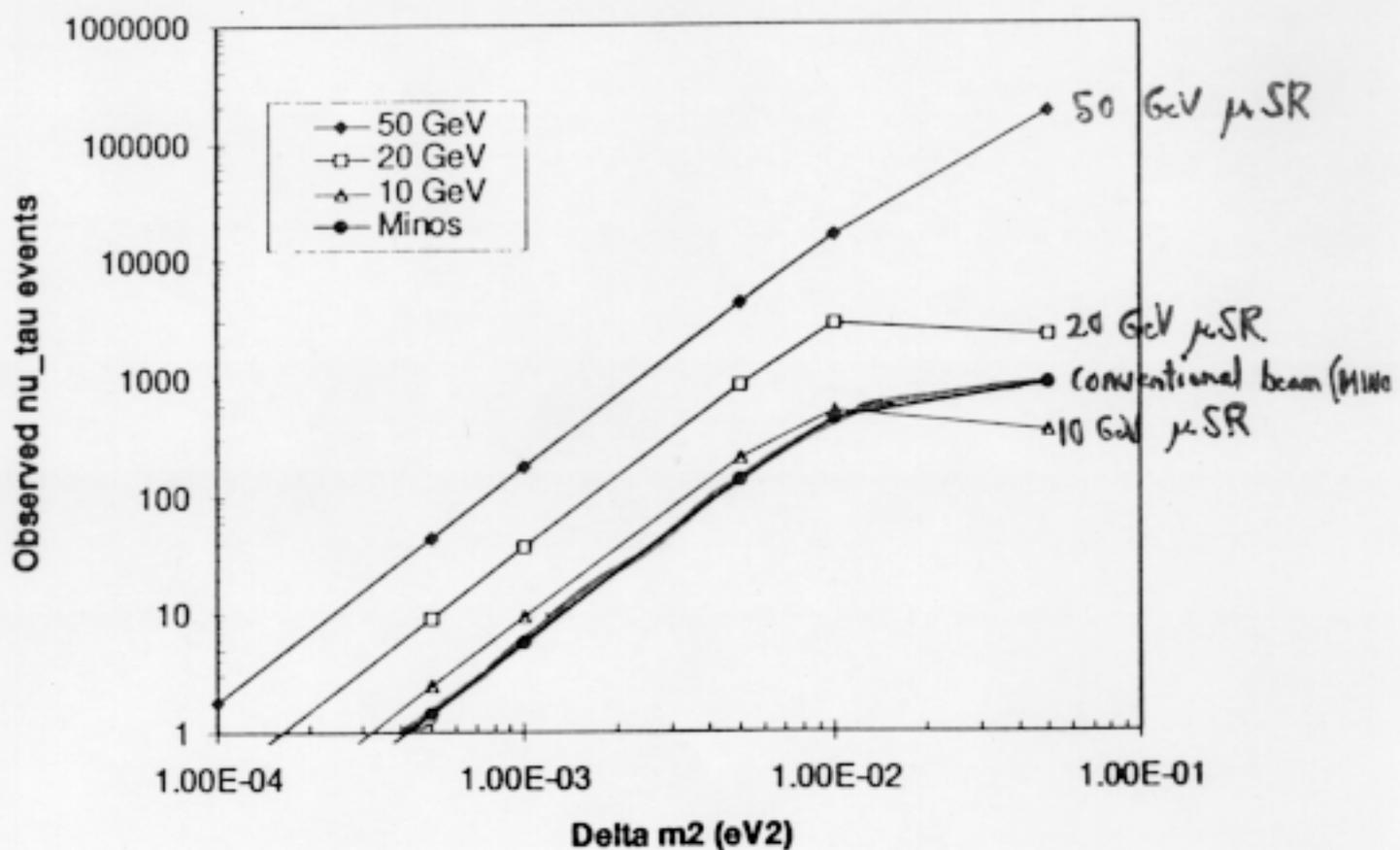
Inter-continental  $\nu$  experiments!

## A first look at

A long-baseline muon storage ring experiment: ( $\nu_\tau$  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  $\tau$  xsec suppression  $\Rightarrow$  50 GeV  $\mu$ SR is best.

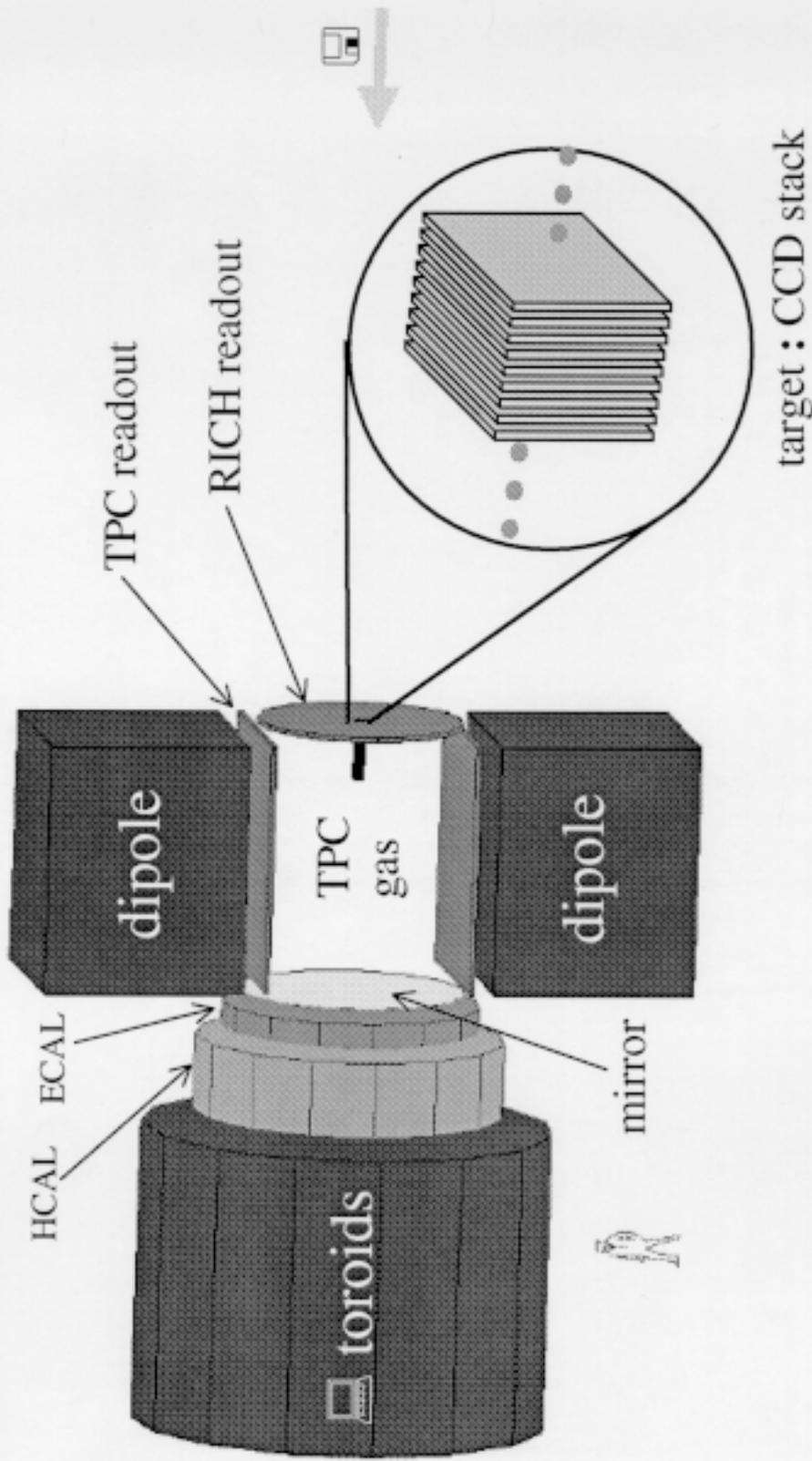


Conclusion: Muon storage rings ( $\mu$ SR) give big gains over conventional  $\nu$  beams only at higher energies.

## High Rate Experiments (WG 3)

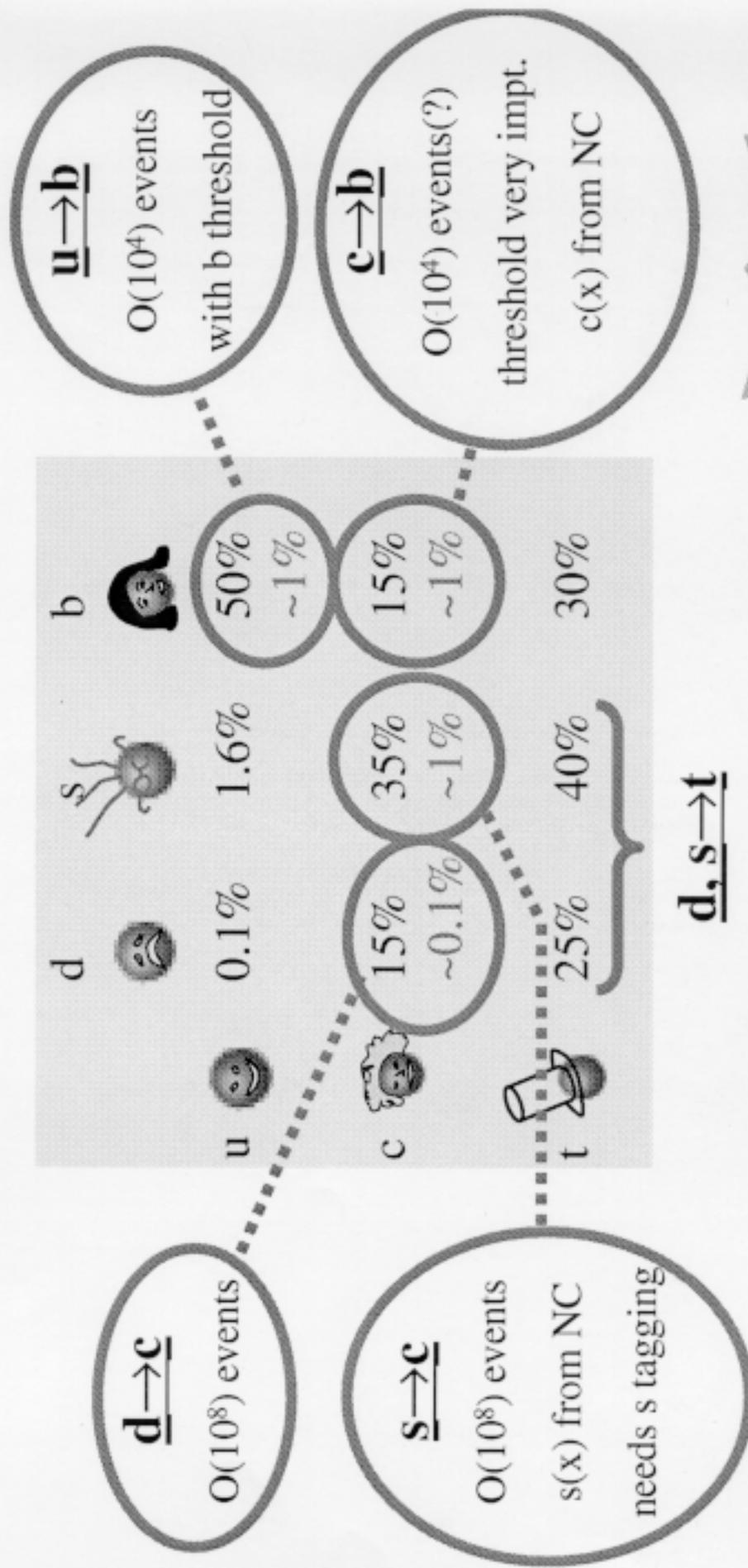
- High rate, high performance  $\nu$  detectors (King)\*
  - QCD studies (Harris)
  - Precision EW physics (McFarland/Yu)
  - Rare & exotic processes (Bolton)
  - CKM quark mixing matrix (King)\*
  - Charm factory (Summers)  $O(10^8)$  charm decays +  
unique event-by-event  $c\bar{c}$  production tag:  $\nu \rightarrow l^- c; \bar{\nu} \rightarrow l^+ \bar{c}$   
 $\Rightarrow$  can be competitive/superior to current & proposed charm factories
- potential for  
huge  
improvements  
over existing  
analyses + new  
contributions to  
precision HEP
- (\* = see slide)

# High Rate, High Performance v Detector



- HUGE statistics: 50 g/cm<sup>2</sup> target => 3x10<sup>9</sup> events/year
- outstanding reconstruction of CC & NC event kinematics
- possibility of interchangeable/multiple targets: Si CCD's, H<sub>2</sub>/D<sub>2</sub>, ...

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



**Not bad !!**

dramatic improvements  
 possible at very high  $E_\nu$

# Conclusions

Kevin McFarland  
Summary of high rate  $\nu$  expts.

- 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

Would you build a muon collider solely for  $\nu$  experiments?

yes

maybe

no

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  $\nu$  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  $\nu$  beams at muon colliders
- Dedicated  $\mu$ SR could possibly help with  $\nu$  oscillation studies on a shorter timescale. Can they be built quickly and affordably? (A major challenge!)
- Follow-up studies are needed & some are underway