27 May 1999
Tunnel Visions, FNAL

Steve Geer

Neutrino Beams at a Muon Collider Facility

1. Introduction
2. High–Energy Neutrino Beams
   - Non–Oscillation Physics
3. Muon Storage Ring ν Source
   - Long Baseline ν Oscillations
4. Tilted Storage Rings
   - Very Long Baseline Possibilities
5. ν Source – A First Step
   Towards a μ Collider ?

Introduction

- Lets assume that muon colliders prove to be technically feasible.

- ν physics has been identified as a potential bonus that can be pursued at a muon collider accelerator complex.

1. What ν beams could be produced at a muon collider accelerator complex ?
2. What is the physics potential of these ν beams ?
3. Could a muon storage ring neutrino source be built as a step towards a muon collider ?

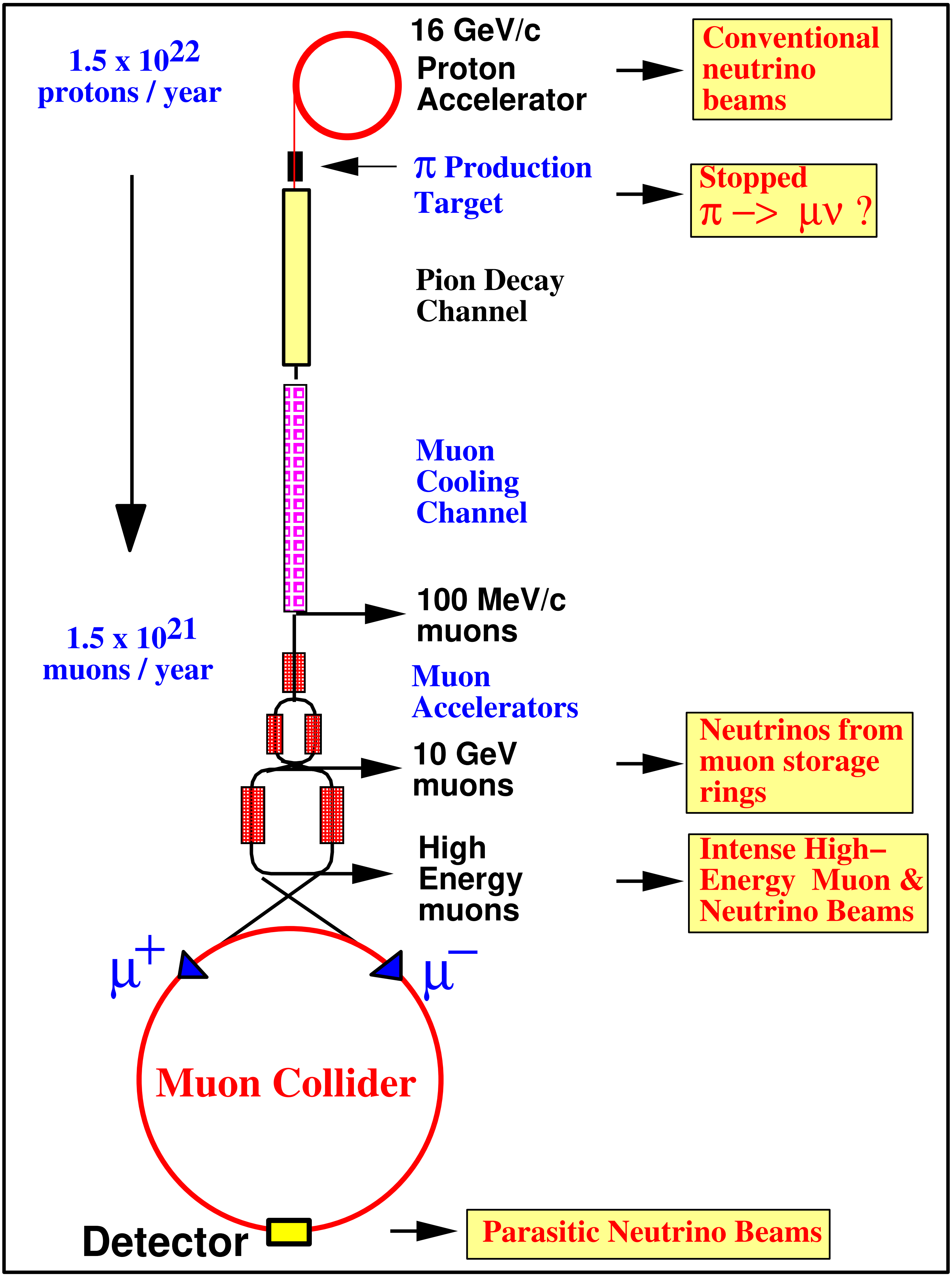
Note: These are not questions that have benefited from an army of people working for years (yet).

Workshops

1. Workshop on Physics at the First Muon Collider & at the Front–End of a Muon Collider, Fermilab, November 6–9, 1997.

2. Workshop on the Potential for Neutrino Physics at Future Muon Colliders, BNL, August 13–14, 1998.

3. ICFA/ECFA workshop on Neutrino Factories Based on Muon Storage Rings, Lyon (France), 5–9 July 1999.



16 GeV/c
Proton
Accelerator
Conventional neutrino beams
1.5 x 10^{22} protons / year
π Production Target
Stopped $\pi \to \mu\nu$?
Pion Decay Channel
Muon Cooling Channel
100 MeV/c muons
1.5 x 10^{21} muons / year
Muon Accelerators
10 GeV muons
Neutrinos from muon storage rings
High Energy muons
Intense High–Energy Muon & Neutrino Beams
μ^+
μ^-
Muon Collider
Detector
Parasitic Neutrino Beams

Neutrino Beams options at a Muon Collider

1. Exploit 4 MW proton source beam to produce a high–intensity conventional (π/K decay channel) neutrino beam.

2. Exploit the ~10^{22} low energy charged pions / year collected from the pion production target –> stopped pion decays.

3. Use dedicated muon storage ring neutrino sources.

4. Exploit neutrino beams downstream of the straight sections within the muon acceleration system (RLAs), or the straight sections within the collider ring.

A muon collider accelerator complex is a prolific source of neutrinos

- **Cold Muon Source:**

  ~ 10^{20}–10^{21} μ^+ (μ^-) per year

  AND THEY ALL DECAY !

- **"A millimole of muons per year" (Chris Quigg)**

~10^{20}–10^{21} ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$, ν_μ per yr !

- **If the muons are at high energies the resulting CC interaction rates are enormous.**

High–Energy Neutrino Beams

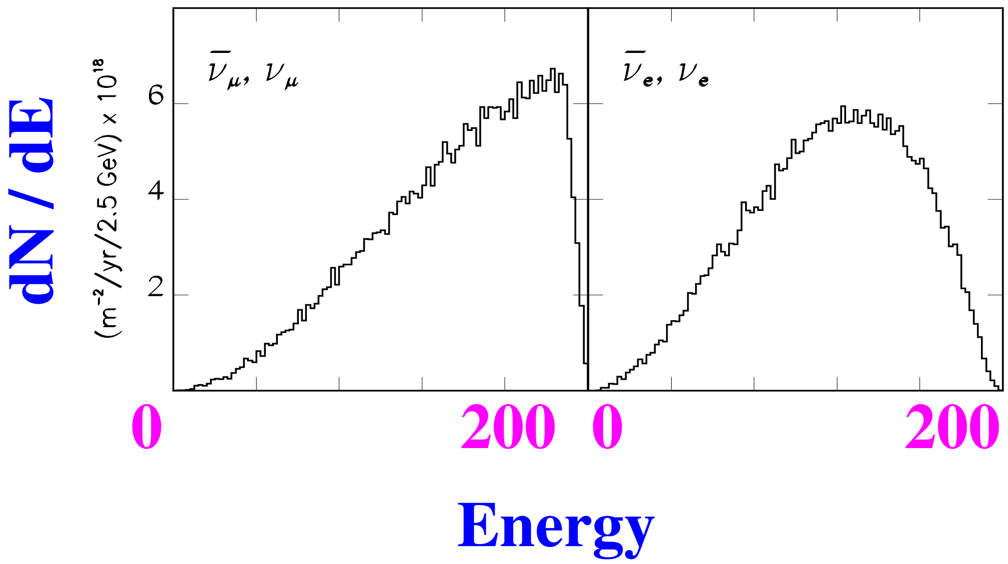
1. CC Interaction Rates

2. Non–Oscillation Physics

CC Rates: Dedicated ν Source

- Consider an unpolarized 250 GeV/c muon beam stored in a ring with a straight section (25% of the circumference) pointing at an experiment at L = 1 km

S. Geer, Workshop on physics at the front end of a muon collider, FNAL, Nov. 1997

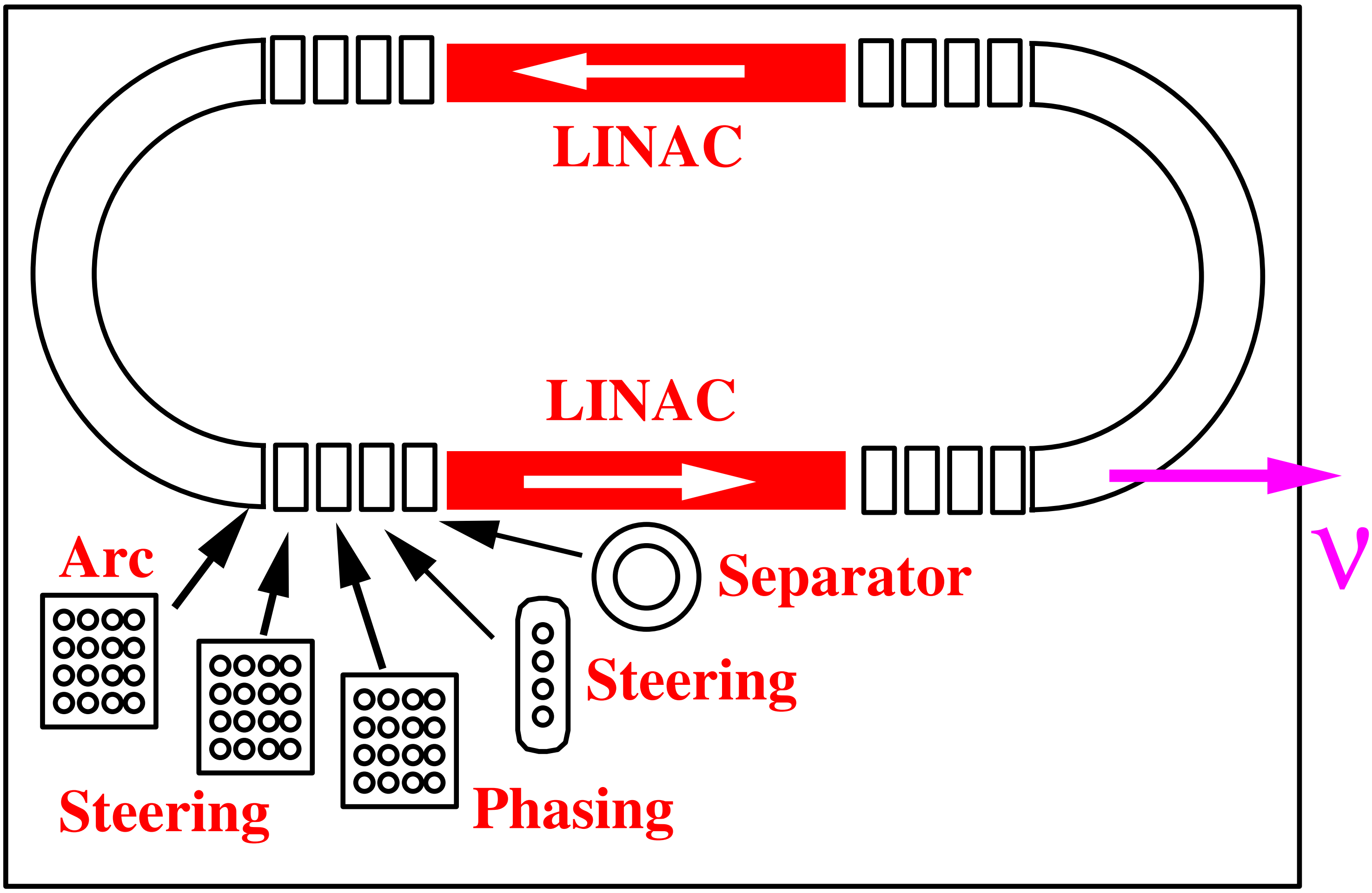


- 3.2×10^{20} ν_e m^{-2} yr^{-1}
- 3.2×10^{20} ν_μ m^{-2} yr^{-1}
- 2×10^{13} ν & 1×10^{13} $\bar{\nu}$ CC events kT^{-1} yr^{-1}

- 2×10^7 CC interactions kg^{-1} yr^{-1} !
- 5×10^6 CC interactions yr^{-1} in a 10 cm long, 10 cm radius cylinder of Liquid Hydrogen
- 1.5×10^5 CC interactions/ yr in a 300 μm thick, 10×10 cm^2 plane of Silicon –> compact highly instrumented detector with good vertexing & tracking –> a revolution in neutrino detectors !

CC Rates: Parasitic ν Source

- In the baseline muon collider designs, Recirculating Linear Accelerators (RLA's) are used to raise the μ energies from O(1) GeV to several hundred GeV.



	RLA 1	RLA 2	RLA 3	RLA 4
E(start) (GeV)	1.0	9.6	70	250
E(end) (GeV)	9.6	70	250	2000
No. Turns	9	11	12	16
Arc Length (m)	30	175	520	3500
Linac Length (m)	100	300	533	2800
Gradient (MV/m)	5	10	15	20
Decay Losses (%)	9.0	5.2	2.4	3.6

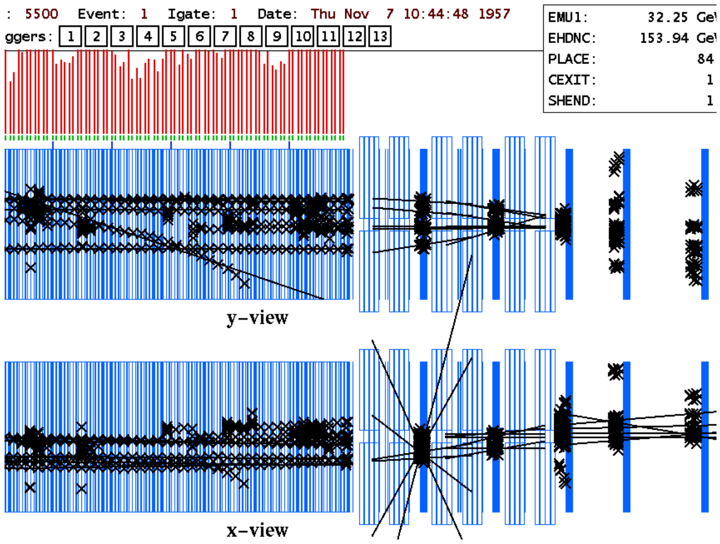
Neutrino Beam Pulses from Recirculating LINACs

	Turn Number											
	1	2	3	4	5	6	7	8	9	10	11	12
RLA 1												
E_μ(start) (GeV)	1.0	1.96	2.92	3.88	4.84	5.8	6.76	7.72	8.68	9.64		
E_μ(end) (GeV)	1.48	2.44	3.4	4.36	5.32	6.28	7.24	8.2	9.16			
$\langle E_\mu \rangle$ (GeV)	1.24	2.2	3.16	4.12	5.08	6.04	7.0	7.96	8.92			
$\langle \gamma \rangle$	11.7	20.8	29.9	39.0	48.1	57.2	66.3	75.3	84.4			
$\gamma c\tau$ (km)	7.72	13.7	19.7	25.7	31.7	37.8	43.8	49.6	55.7			
$f_{decay}=100m/\gamma c\tau$ (%)	1.3	0.73	0.51	0.39	0.32	0.26	0.23	0.20	0.18			
N_{decay}/bunch ($\times 10^{10}$)	6.5	3.7	2.6	2.0	1.6	1.3	1.2	1.0	0.9			
N_{decay}/year ($\times 10^{18}$)	9.8	5.5	3.8	2.9	2.4	2.0	1.7	1.5	1.4			
RLA 2												
E_μ(start) (GeV)	9.6	15.1	20.6	26.1	31.6	37.1	42.6	48.1	53.6	59.1	64.6	70.1
E_μ(end) (GeV)	12.4	17.9	29.4	28.9	34.4	39.9	45.4	50.9	56.4	61.9	67.4	
$\langle E_\mu \rangle$ (GeV)	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0	60.5	66.0	
$\langle \gamma \rangle$	104	156	208	260	312	364	416	469	521	573	625	
$\gamma c\tau$ (km)	68.7	100	140	170	210	240	270	310	340	380	410	
$f_{decay}=300m/\gamma c\tau$ (%)	0.44	0.30	0.21	0.18	0.14	0.13	0.11	0.10	0.088	0.08	0.07	
N_{decay}/bunch ($\times 10^{10}$)	2.0	1.4	0.97	0.83	0.64	0.60	0.51	0.45	0.40	0.36	0.34	
N_{decay}/year ($\times 10^{18}$)	3.0	2.1	1.5	1.2	0.96	0.90	0.77	0.68	0.60	0.54	0.51	
RLA 3												
E_μ(start) (GeV)	70	85	100	115	130	145	160	175	190	205	220	235
E_μ(end) (GeV)	77.5	92.5	108	123	138	153	168	183	198	213	228	243
$\langle E_\mu \rangle$ (GeV)	73.8	88.8	104	119	134	149	164	179	194	209	224	239
$\langle \gamma \rangle$	698	840	982	1124	1266	1408	1550	1692	1834	1976	2118	2260
$\gamma c\tau$ (km)	460	550	650	740	840	930	1000	1100	1200	1300	1400	1500
$f_{decay}=533m/\gamma c\tau$ (%)	0.12	0.10	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04
N_{decay}/bunch ($\times 10^{10}$)	0.52	0.42	0.35	0.31	0.27	0.25	0.23	0.21	0.19	0.18	0.16	0.15
N_{decay}/year ($\times 10^{18}$)	0.78	0.63	0.53	0.46	0.41	0.37	0.34	0.31	0.28	0.26	0.25	0.23

C. Ankenbrandt & S. Geer, Fermilab–Conf–98/086.

Interaction Rates downstream of RLA3

K. McFarland & D. Harris: hep–ex/9804009v2



- Simulation of NuTeV (CCFR) exposed to one turn 600m down–stream of RLA3 –> (250 GeV muon decays)
- Six interactions + 3 traversing muons. Need fine–grained detector !

- Factor of 1000 more than present $\nu_\mu N$ rates !

	RLA–1	RLA–2	RLA–3
Shielding distance	23.3 m	163 m	582 m
Containment r(90%)	75 cm	75 cm	60 cm
DIS events/yr (x 10^6)	n/a	0.49*)	0.92*)

*) per gm/cm^2, r < 150 cm

- Calorimeter Signal & Background rates/pulse downstream of "dumb" filter after RLA–3, in a 40cm x 40cm $10\lambda_0$ calorimeter.

	RLA–1	RLA–2	RLA–3
Muons/turn	0.015	0.06	0.4
ν DIS events/turn	0.05	0.07	0.27

Non–Oscillation Physics

- **Plenty of ideas on how to exploit very intense high–energy neutrino beams:**

◆ **Proton Str. Fu:** **Measure directly using RLA–3 (250 GeV muons) + 1m long LH_2 target–> 10^7 ev/yr**

◆ **$Sin^2\theta_W$ ...** **NC/CC ratio. Main systematic from charm production –> measure it ! Estimate can get to $\Delta Sin^2\theta_W < 0.5\%$ –> $\Delta m_W \sim$ 20–50 MeV.**

◆ **Charm production:** **100 000 reconstructed events per year in 1m long LH_2 target –> $|V_{cd}|^2$, s, $\bar{s}$.**

◆ **Spin physics:** **Polarization of strange sea quarks.**

◆ **B–physics:** **$\nu_\mu u \rightarrow \mu^+ b$ ... 20 events per year in a 3m long LH_2 target–> $|V_{ub}|^2$**

- See *K. McFarland* **&** *D. Harris:* hep–ex/9804010

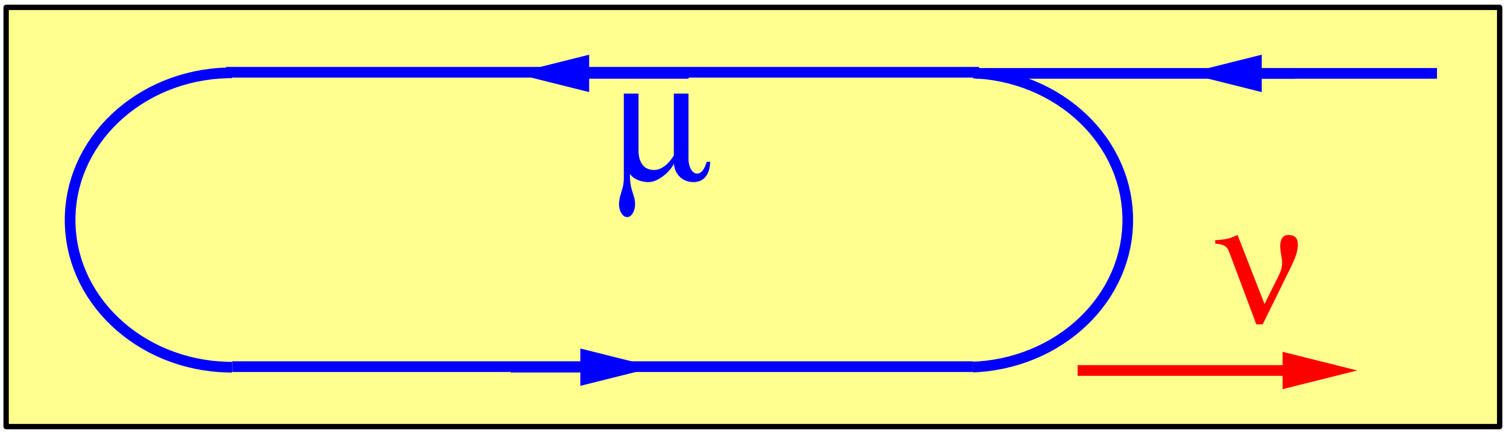
- See *B. King, Proc. of the workshop on physics at the First Muon Collider and Front End of a Muon Collider, Fermilab, Nov. 1997.*

Neutrino Beams at a Muon Storage Ring ν Source

1. Neutrinos from μ Decays
2. Oscillation Physics Potential

Muon Storage Ring Neutrino Source

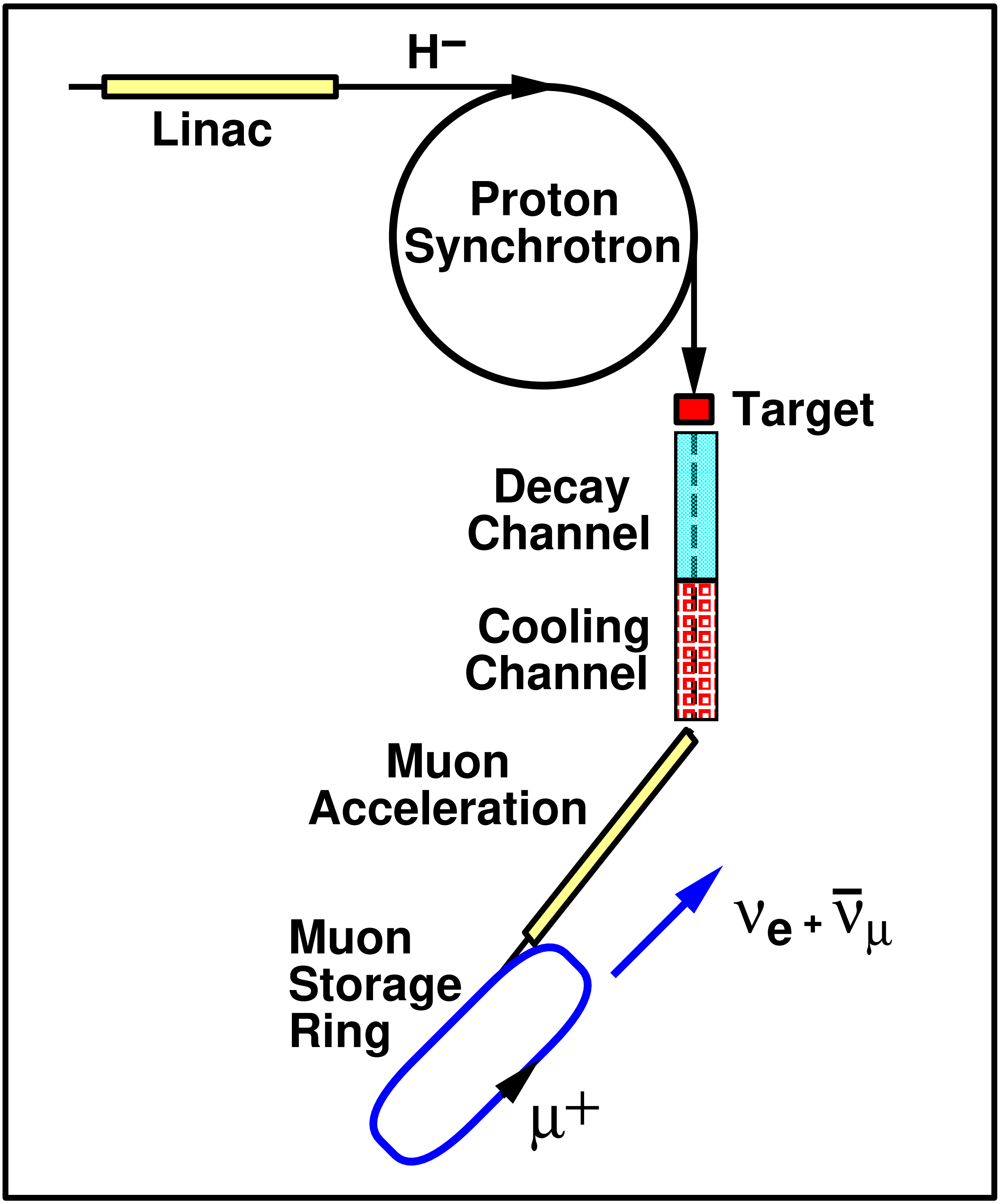
- To avoid an impractically long decay channel (τ_μ ~ 100 τ_π) use a storage ring with long straight sections :



- This is an old idea. Example: The P–860 proposal in 1992 to search for neutrino oscillations using the Fermilab Antiproton Debuncher as a muon storage ring neutrino source. Good idea ... but the problem is to get sufficient neutrino flux to make it really interesting.

- A muon storage ring neutrino source using the muon source required for a Muon Collider, could produce very large neutrino fluxes (*S. Geer, PRD 57, 6989 (1998)*).

Neutrino Source Schematic



Neutrinos from Muon Decays

1. Pure ν flavor content with large ν_e component

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \quad \Rightarrow \quad 50\% \ \nu_e \ (\bar{\nu}_\mu)$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \quad \Rightarrow \quad 50\% \ \bar{\nu}_e \ (\nu_\mu)$$

2. Precisely known neutrino fluxes & kinematics

In the $\mu^\pm$ rest-frame, the distribution of neutrinos from muon decay is given by:

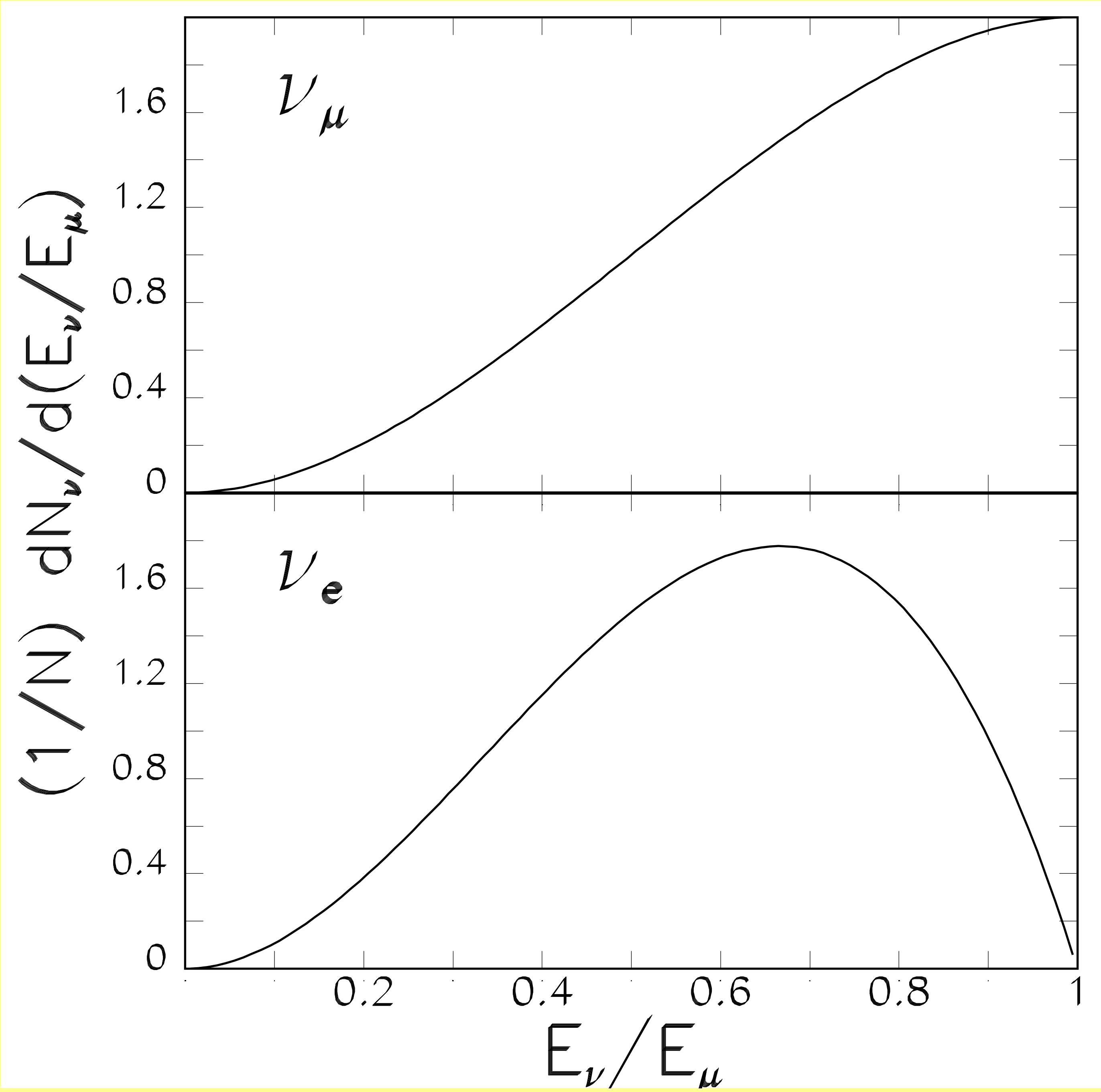
$$\nu_\mu : \quad \frac{dn}{dx d\Omega} = \frac{1}{4\pi}\left[2x^2(3-2x) \mp 2x^2(1-2x)\mathcal{P}\cos\theta\right]$$

$$\nu_e : \quad \frac{dn}{dx d\Omega} = \frac{1}{4\pi}\left[12x^2(1-x) \mp 12x^2(1-x)\mathcal{P}\cos\theta\right]$$

where $x = 2E_\nu/m_\mu$, θ is the angle between the neutrino and the muon spin, and $\mathcal{P}$ is the muon polarization.

3. If the muons are polarized then as the spin precesses the ν_e component in the forward direction is switched on/off.

4. At high muon energies ($E_\mu >> m_\mu$) $x \to E_\nu/E_\mu$, yielding simple expressions for the ν_μ and ν_e spectra:



5. At high muon energies ($E_\mu >> m_\mu$) CC interaction charged lepton spectra are also given by simple expressions:

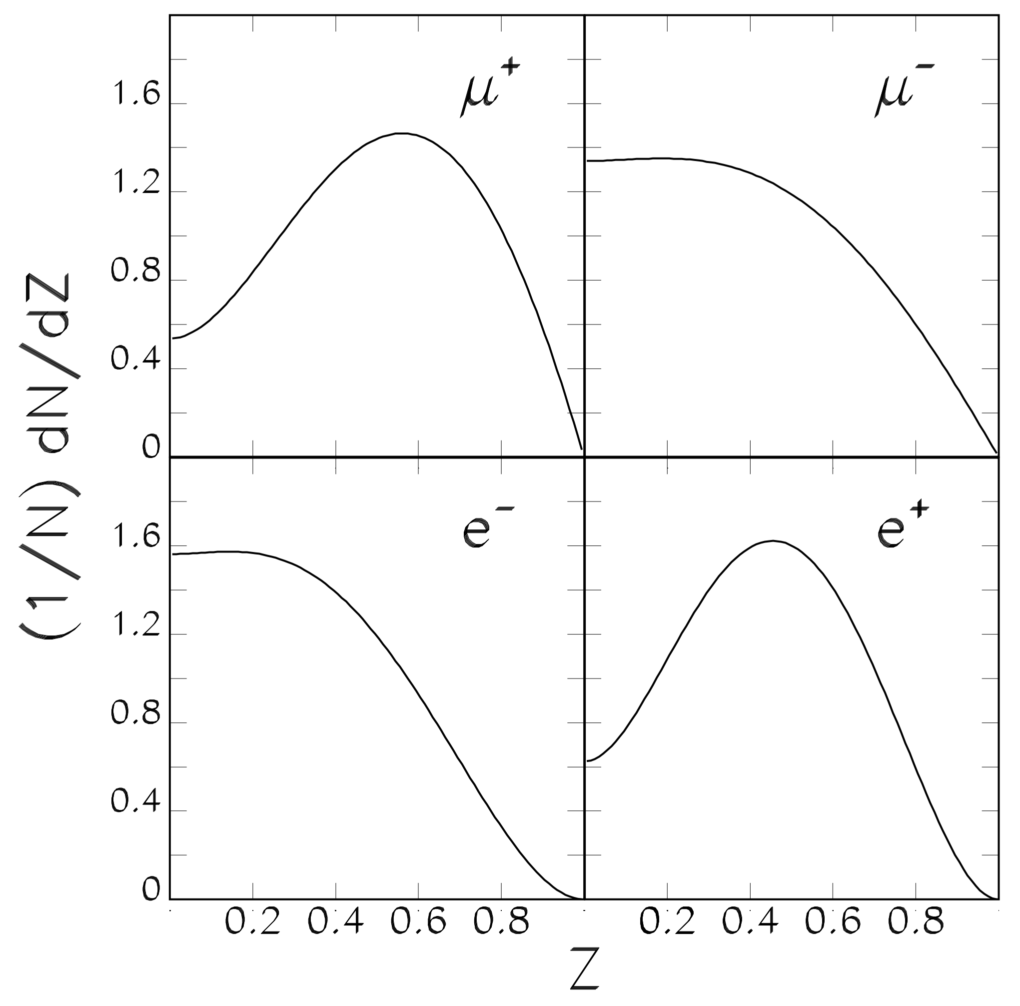
$$dN_{\mu+} / dz \sim 1 + 20z^2 - 32z^3 + 11z^4$$

$$dN_{e-} / dz \sim 5 + 6z^2 - 32z^3 + 21z^4$$

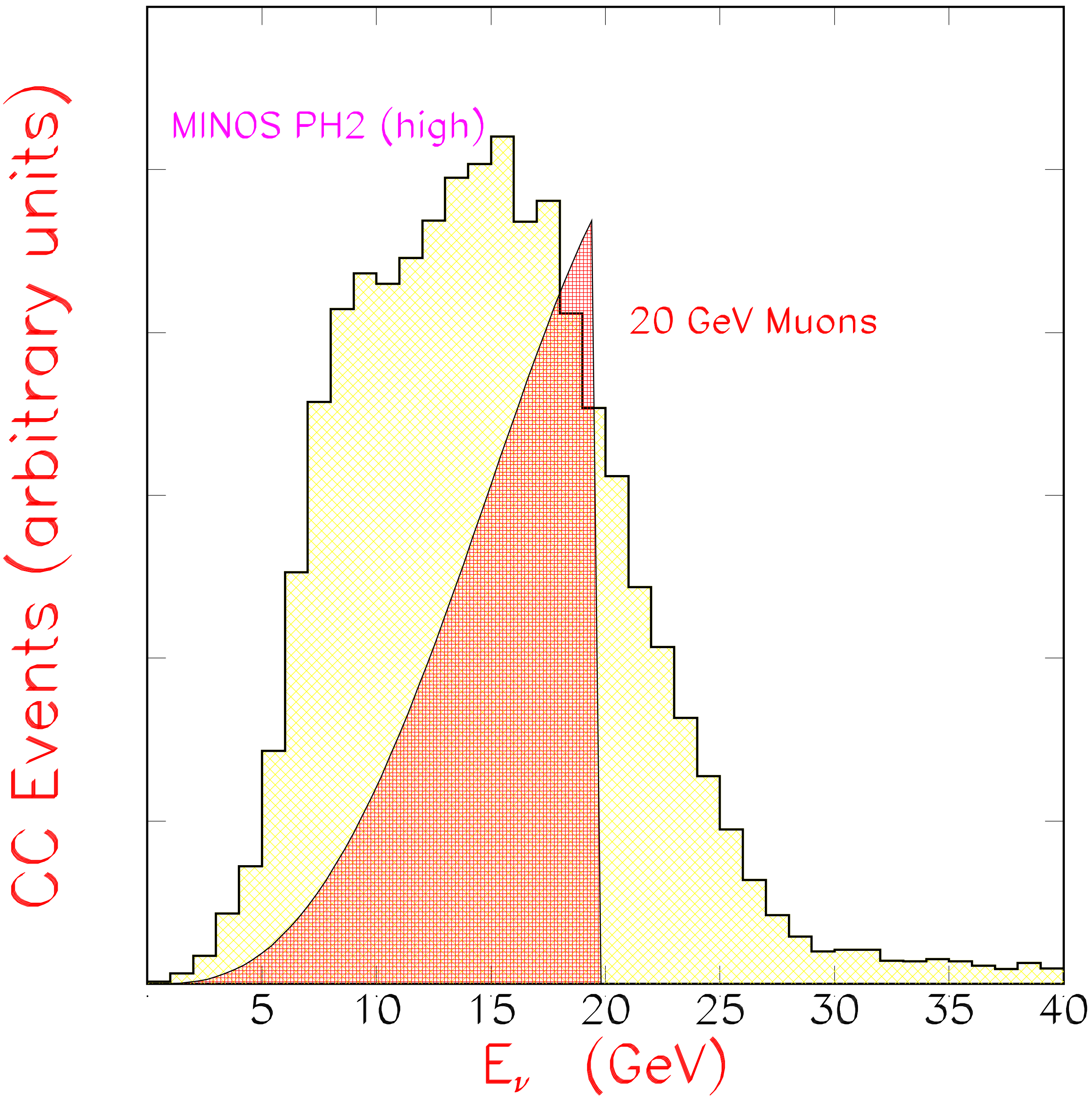
$$dN_{\mu-} / dz \sim 5 + 4z^2 - 16z^3 + 7z^4$$

$$dN_{e+} / dz \sim 1 + 30z^2 - 64z^3 + 33z^4$$

where $z = E_l / E_\mu$



6. "Narrow–Band" Beam :



Neutrino Oscillations

- Within the framework of two–flavor oscillations, the flavor eigenstates (ν_α & ν_β) are related to the mass eigenstates (ν_i & ν_j) by :

$$\nu_\alpha = \nu_i \cos\theta - \nu_j \sin\theta$$
$$\nu_\beta = \nu_i \sin\theta + \nu_j \cos\theta$$

- The probability that, whilst traversing L(km), a ν_α oscillates into ν_β is given by:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\,\sin^2(1.267\Delta m_{ij}^2\, L/E_\nu)$$

Where E_ν is in GeV, & $\Delta m_{ij}^2 = m_j2 - m_i^2$ (eV^2/c^4)

- Within the framework of 3–flavor oscillations, the mixing is described by a 3x3 CKM–like matrix

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \\ \nu_\gamma \end{pmatrix} = \begin{pmatrix} 3 \times 3 \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \\ \nu_k \end{pmatrix}$$

- To fully determine the mixing matrix ideally would like to measure the parameters for all ν_α & ν_β –> **NEED ν_e AND ν_μ beams !**

Charged Current Event Rates

S. Geer, PRD 57, 6989 (1998)

- Assume 8 x 10^{20} μ^- decays/yr in storage ring with 25% are in the beam–forming straight section.

Experiment (L = 732 km)	CC Rates (per kt–yr) ν_μ	$\bar{\nu}_e$
MINOS (WBB)		
Low Energy	458	1.3
Medium Energy	1439	0.9
High Energy	3207	0.9
μ–ring		
10 GeV	2200	1300
20 GeV	18 000	11 000
50 GeV	2.9 x 10^5	1.8 x 10^5
250 GeV	3.6 x 10^7	2.3 x 10^7

Rate ~ E^3

- Conclude :

1. If you want an electron–neutrino beam, even a very low energy muon storage ring might be interesting.

2. If you want a muon–neutrino beam, rates become interesting for muon energies > 20 GeV.

$\nu_\mu \rightarrow \nu_\tau$ Appearance

Barger, Geer, Whisnant ... Preliminary

Δm^2 (eV^2/c^4)	ν_τ CC Events (per kt–yr)
0.0020	3100
0.0025	4900
0.0030	7000
0.0035	9400
0.0040	12000

FNAL–>Soudan

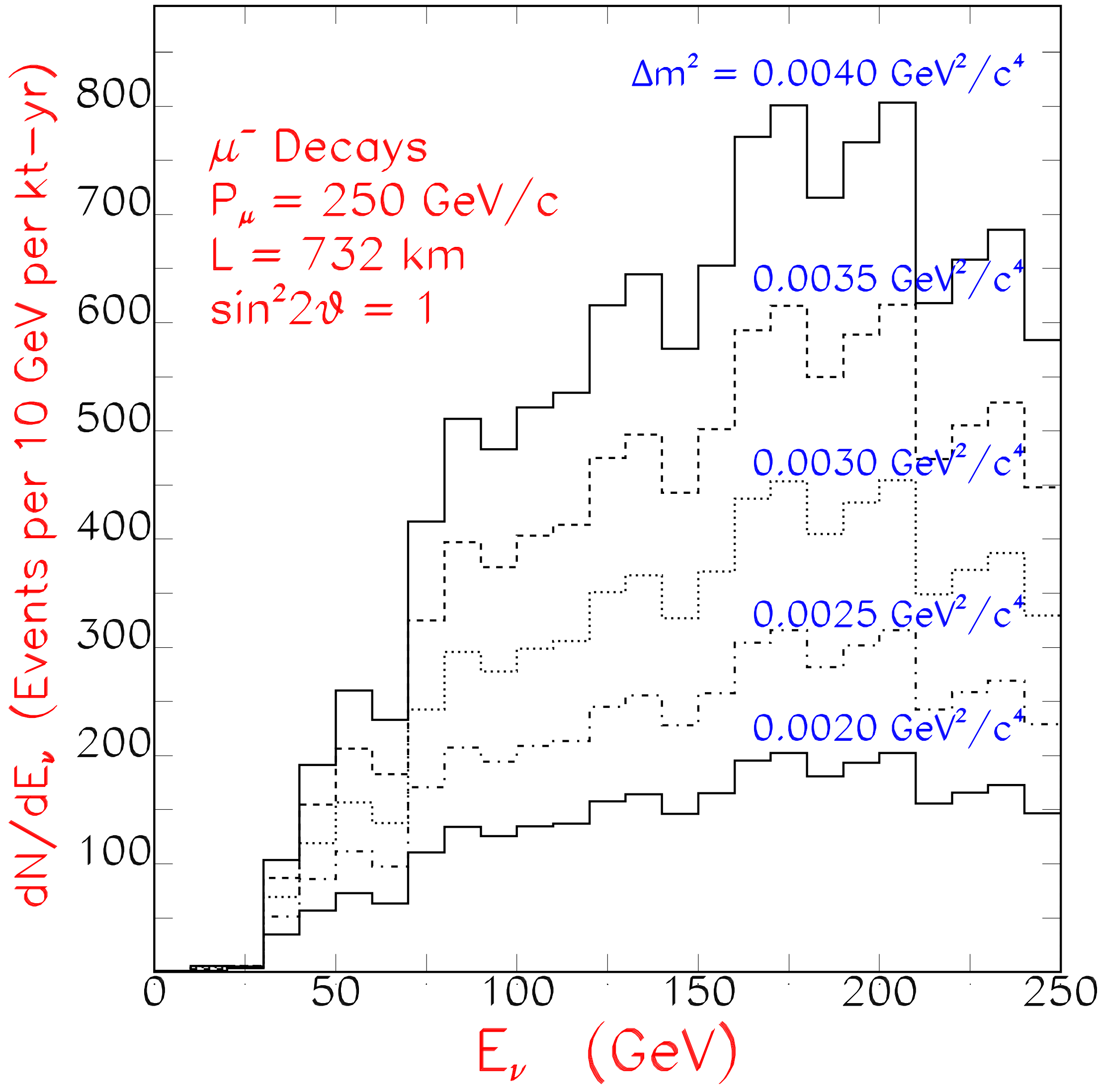
L = 732 km

μ^- Decays

$\sin^2 2\theta = 1$

E_μ = 250 GeV

Ideal Detector



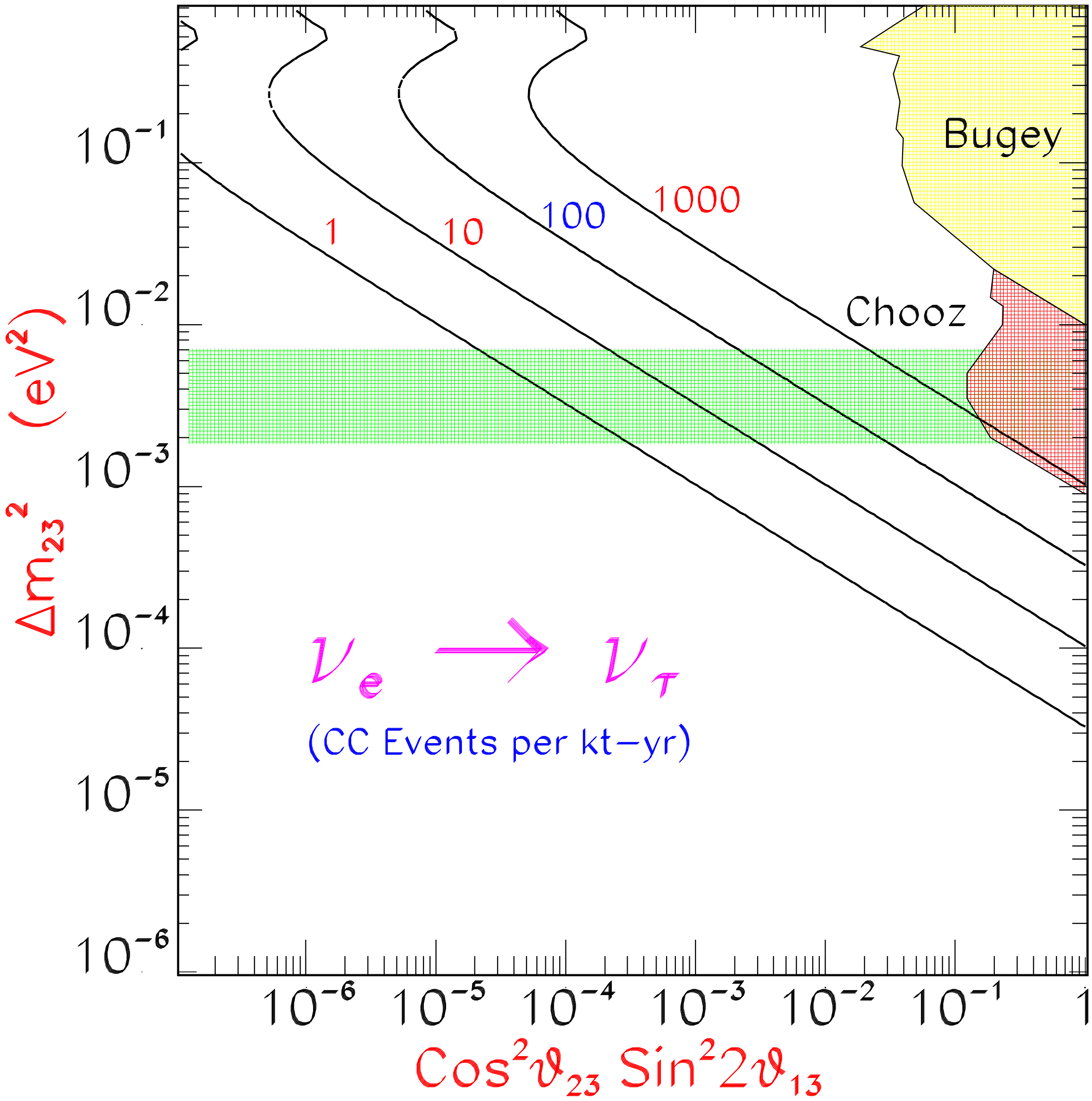
$\nu_e \rightarrow \nu_\tau$ Appearance

Barger, Geer, Whisnant ... Preliminary

FNAL–>Soudan (L = 732 km)

μ^+ Decays
E_μ = 250 GeV

Search for τ CC events in 1 kt detector



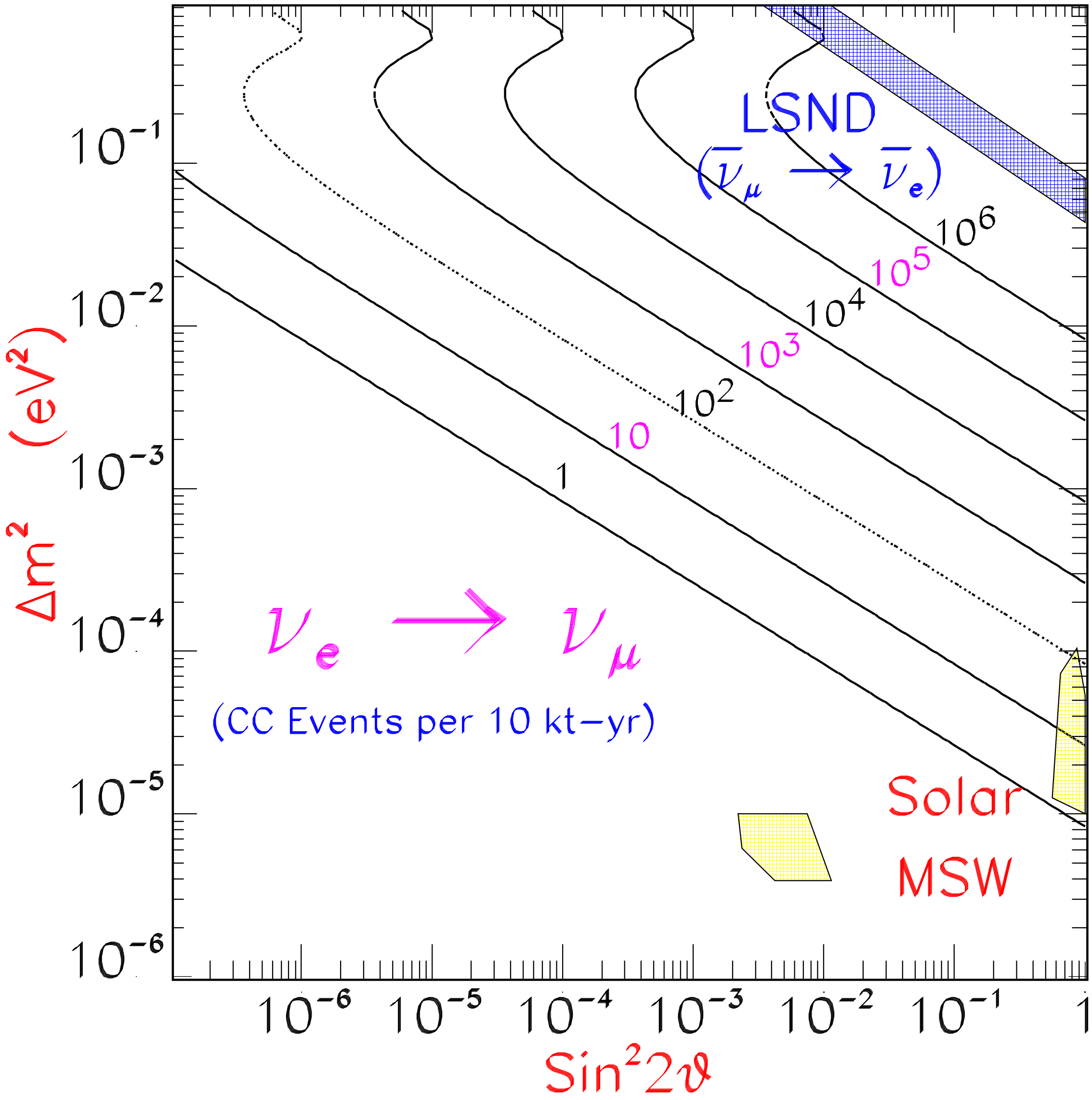
$\nu_e \rightarrow \nu_\mu$ Appearance

Barger, Geer, Whisnant ... Preliminary

FNAL–>Soudan (L = 732 km)

μ^- Decays
E_μ = 250 GeV

Search for wrong–sign muons in a 10 kt detector



$\nu_\mu \rightarrow \nu_\tau$ Appearance

Barger, Geer, Whisnant ... Preliminary

Δm^2 (eV^2/c^4)	ν_τ CC Events (per kt–yr)
0.0020	410
0.0025	630
0.0030	910
0.0035	1240
0.0040	1610

FNAL–>Soudan

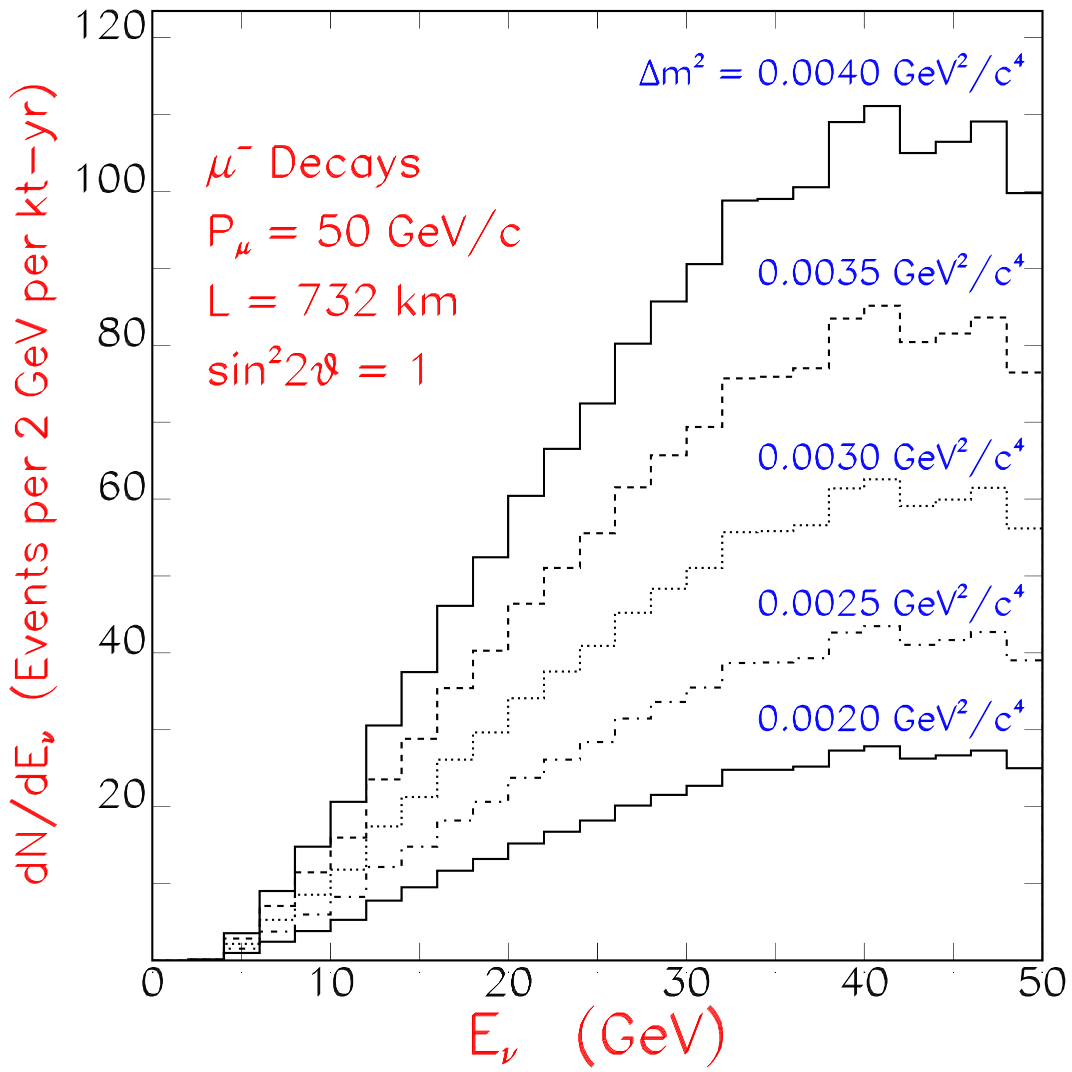
L = 732 km

μ^- Decays

$\sin^2 2\theta = 1$

E_μ = 50 GeV

Ideal Detector



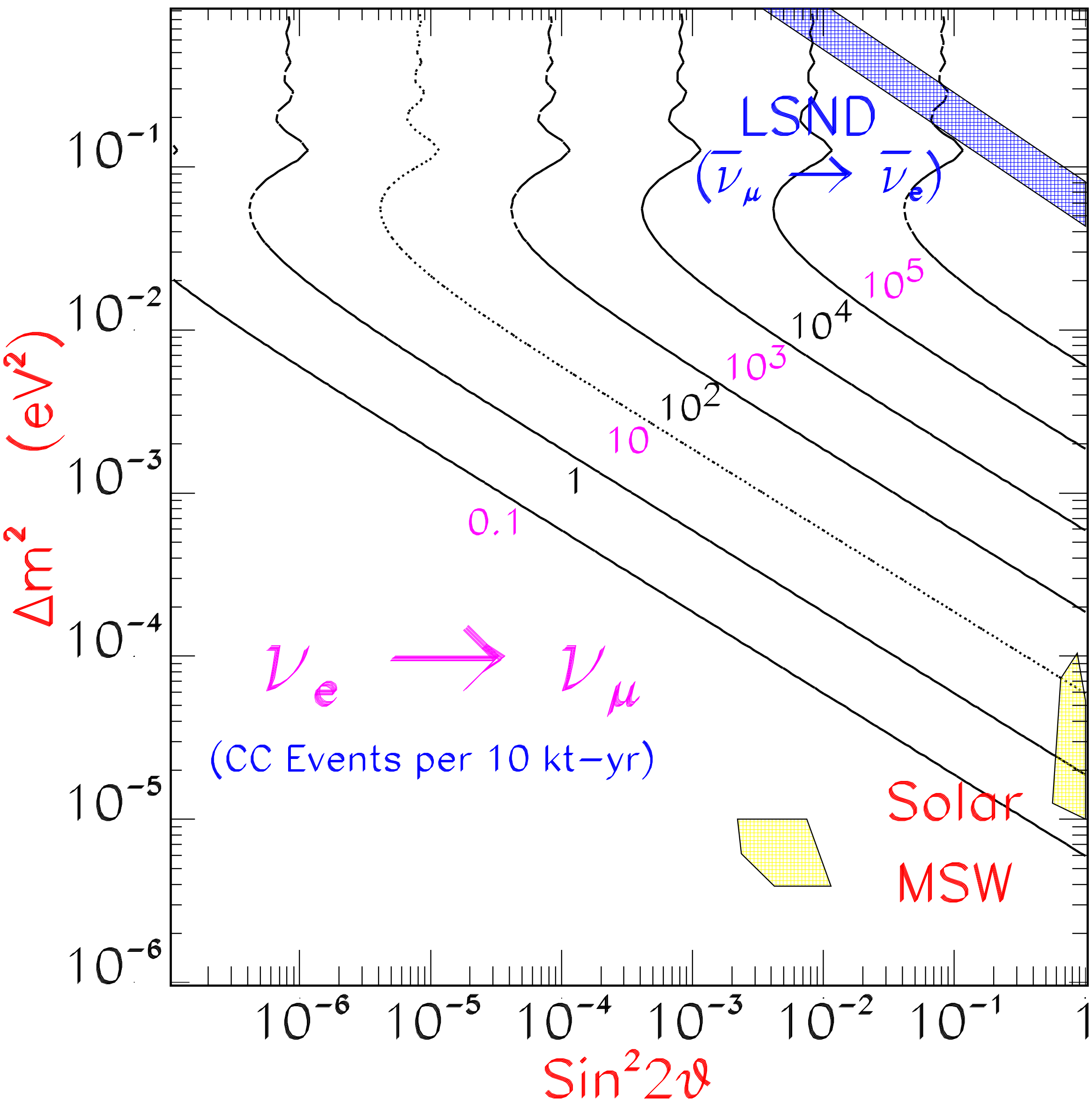
$\nu_e \rightarrow \nu_\mu$ Appearance

Barger, Geer, Whisnant ... Preliminary

FNAL->Soudan (L = 732 km)

μ^- Decays
E_μ = 50 GeV

Search for wrong-sign muons in a 10 kt detector



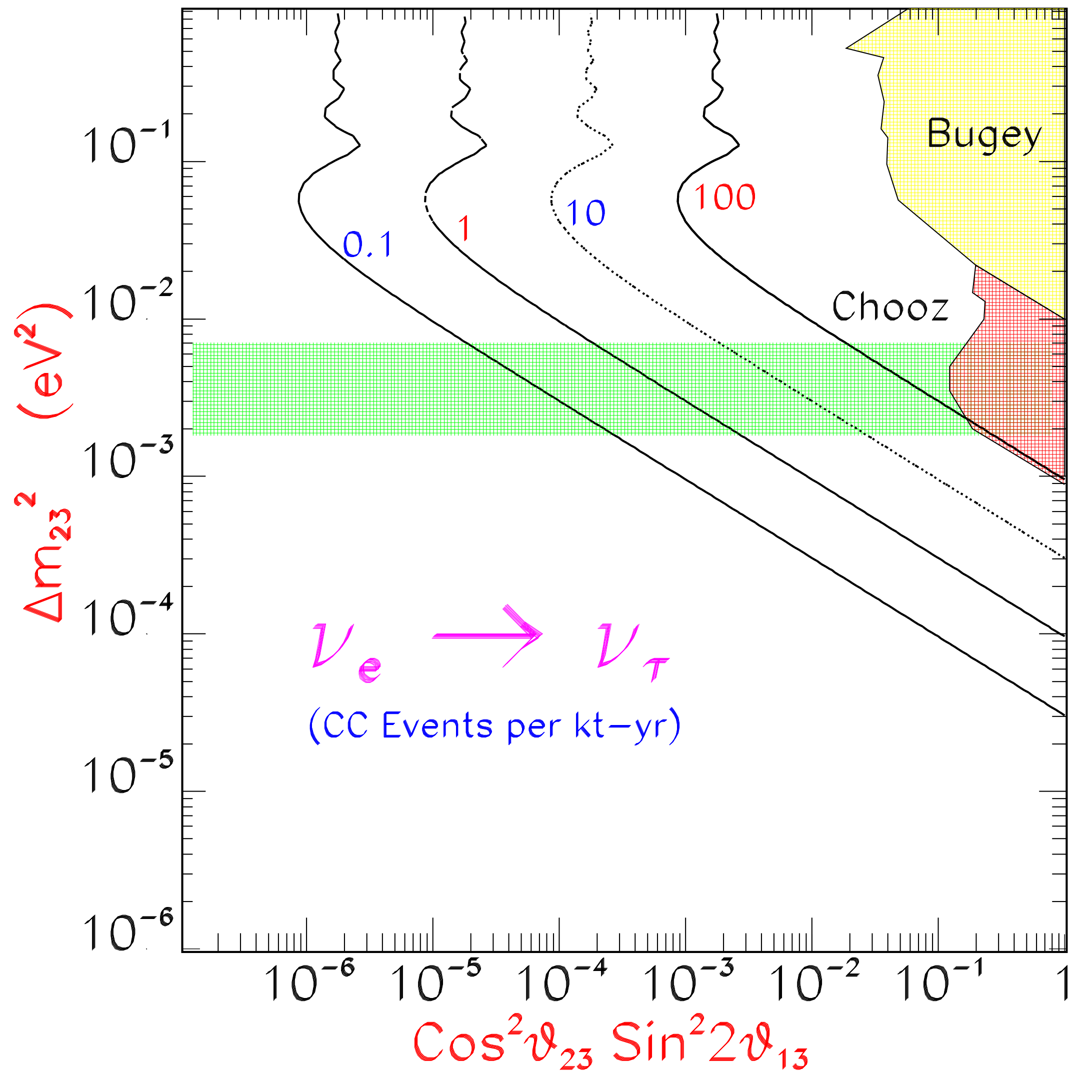
$\nu_e \to \nu_\tau$ Appearance

Barger, Geer, Whisnant ... Preliminary

FNAL–>Soudan (L = 732 km)

μ^+ Decays
E_μ = 50 GeV

Search for τ CC events in 1 kt detector

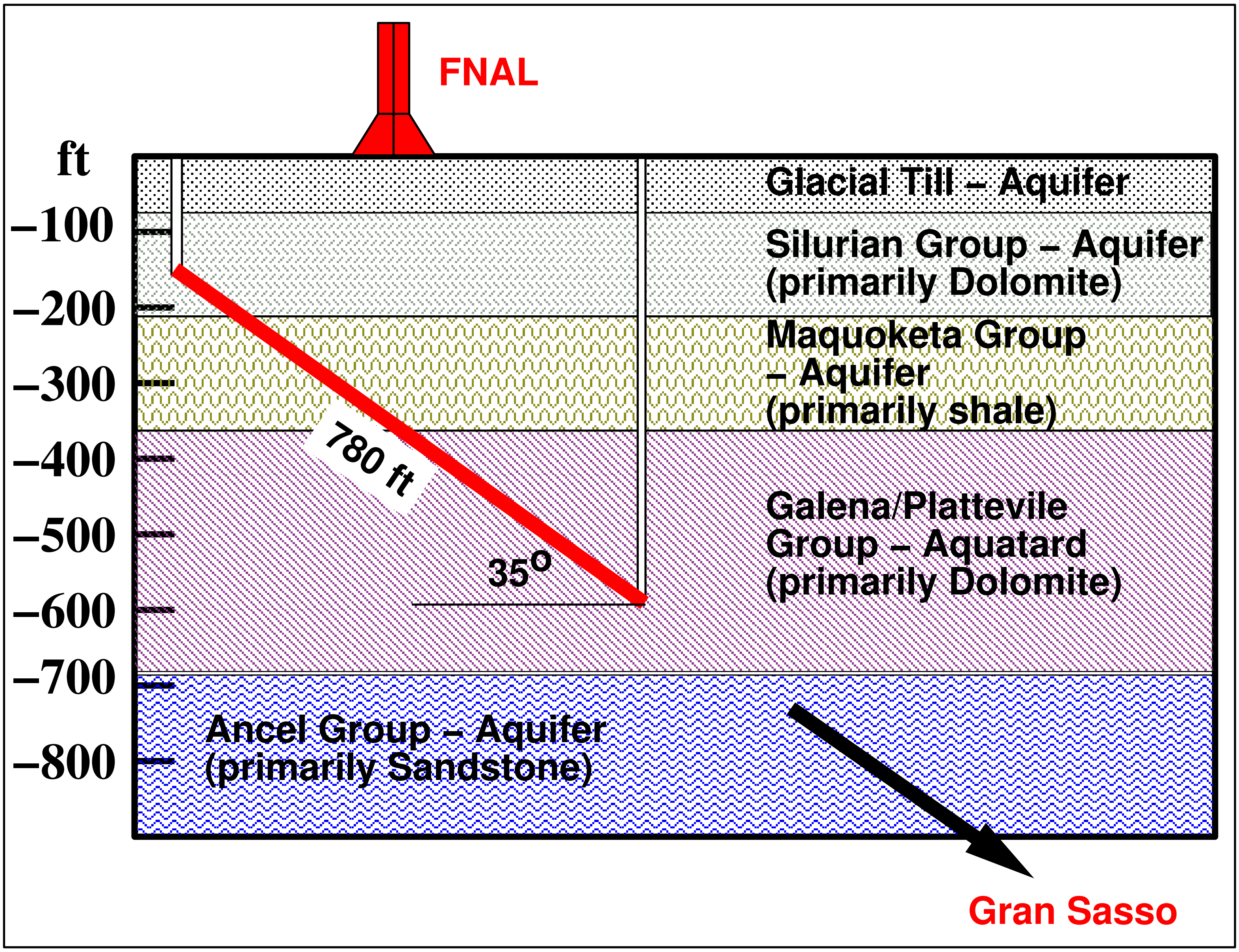


Neutrino Beams at Tilted Muon Storage Ring

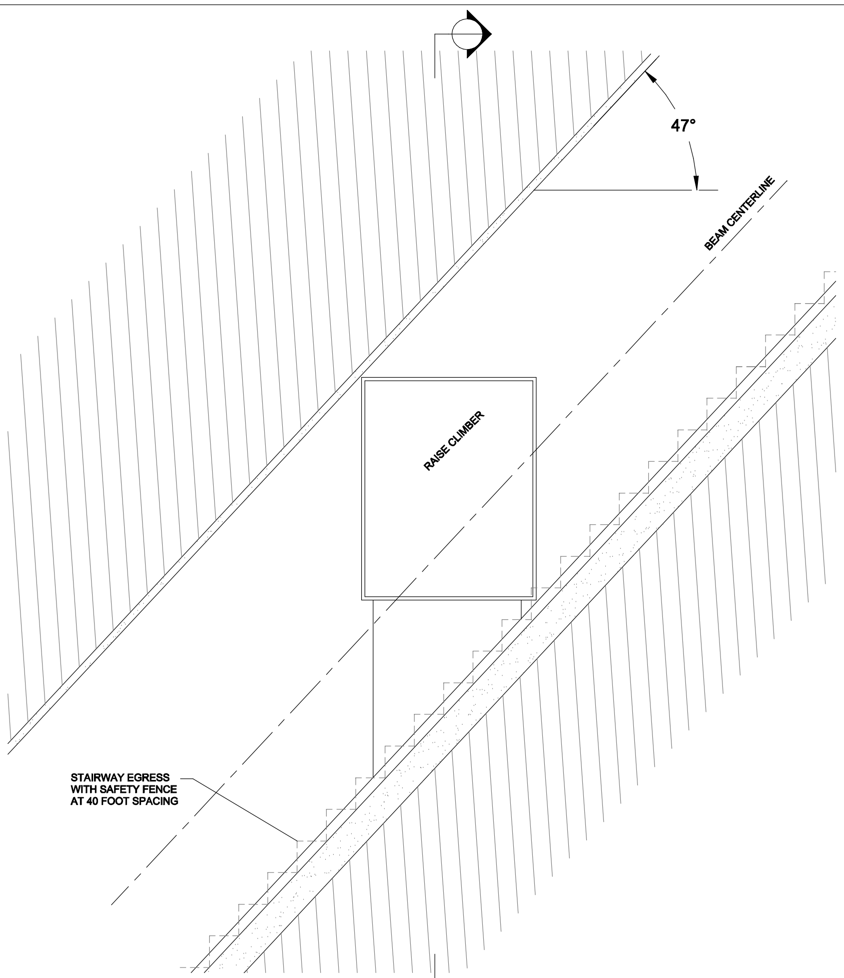
Very Long Baseline Possibilities

Very–Long Baselines ?

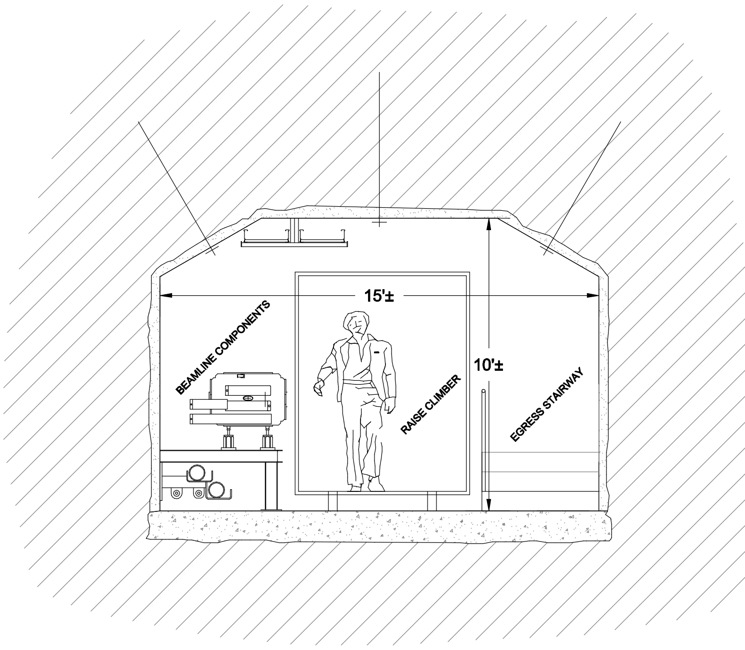
- A muon storage ring neutrino source can be compact. If the plane of the ring is tilted down at a large angle –> Trans–Earth baseline.



- Blast & Drill tunneling at large dip angles is a known technology. Example: using an Alimak "raise climber" an 867 m long tunnel (6 m^2 cross–section) with a dip of 45° was completed in 1988 at Vetlefjord, Norway –> 25 m / week.



ELEVATION
1/4" = 1'-0"



SECTION
1/4" = 1'-0"

	NAME	DATE
DESIGNED	J. SIMS	5/12/99
DRAWN	J. SIMS	5/12/99
CHECKED	E. MCCLUSKEY	5/12/99
APPROVED	E. CRUMPLEY / D. NEVIN	5/12/99
SUBMITTED	S. GEER	5/12/99

TE DESCRIPTIONS
REVISIONS

SCALE:

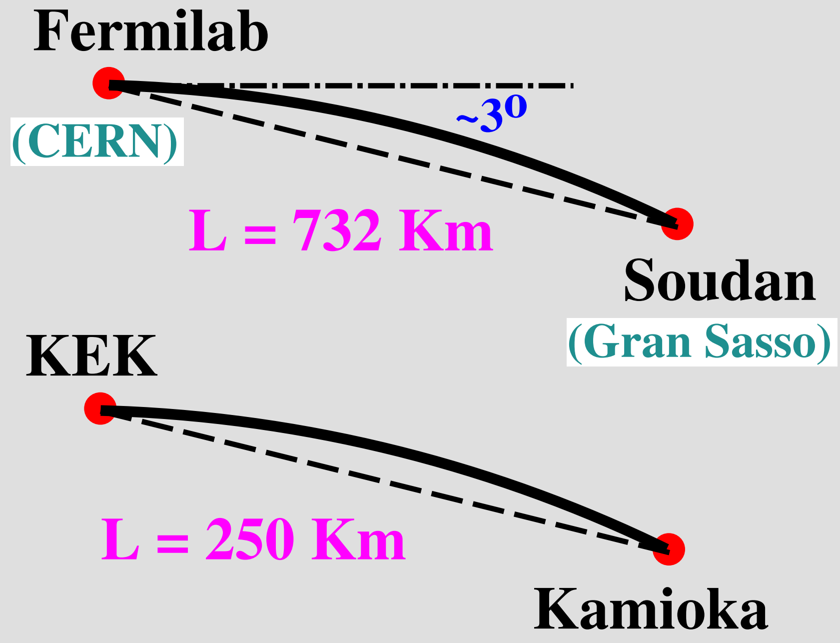
FERMI NATIONAL ACCELERATOR LABORA
UNITED STATES DEPARTMENT OF ENERGY

MUON STORAGE RING NEUTRIN
ENCLOSURE SECTION AND ELEV

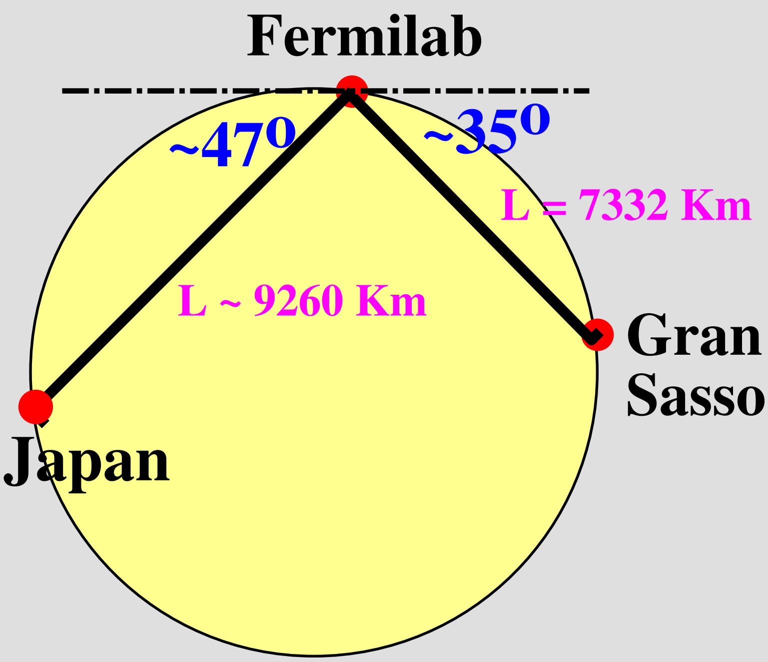
DRAWING NO. **6-7-** **XX**

Very–Long Baseline Geometries

	L (km)	Dip (Deg.)	Heading (Deg.)
FNAL –> Soudan	732	3	336
FNAL –> Gran Sasso	7332	35	50
FNAL –> Kamioka	9263	47	325



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
50	14.6	5.0

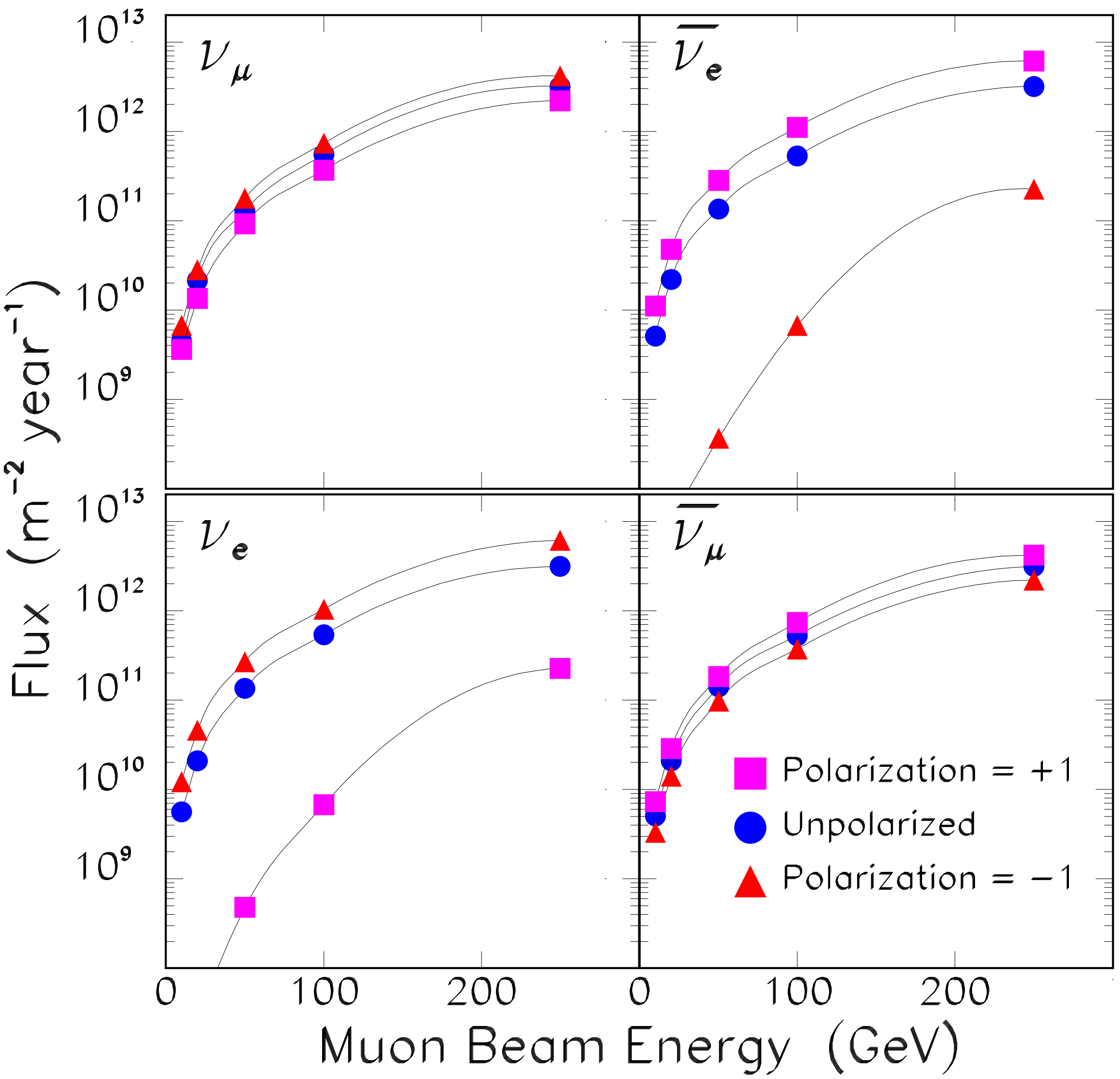


E_ν (GeV)	L/E (Km/GeV) Gran S.	L/E (Km/GeV) Japan
10	~733	~926
20	~367	~463
30	~244	~309
40	~183	~232
50	~145	~185

Neutrino Fluxes

- **Assume 8 x 10^{20} μ^+ (μ^-) decays/yr in storage ring with 25% are in the beam–forming straight section.**
- **Consider a Trans–Earth experiment (L = 10 000 km).**

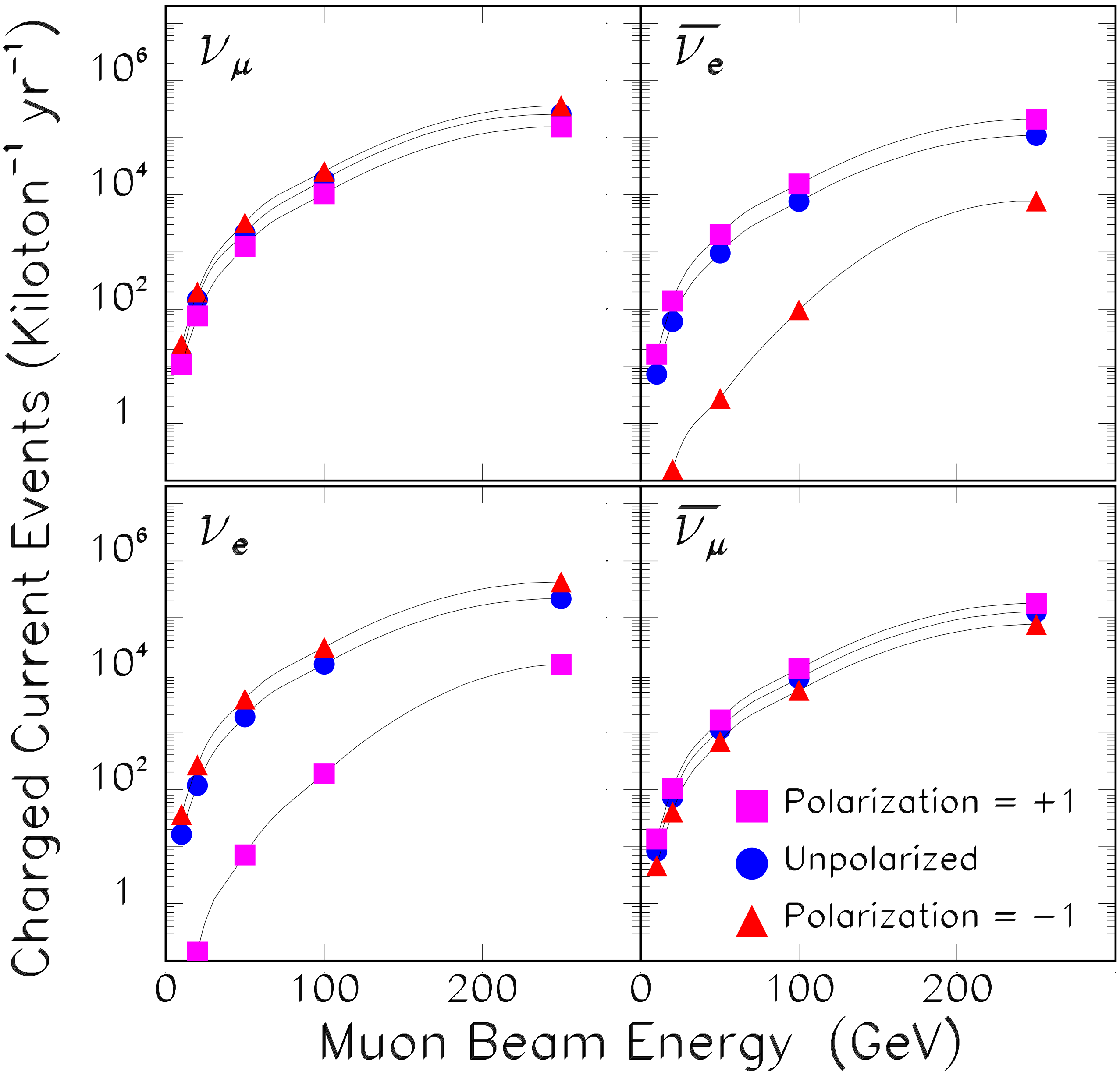
S. Geer, PRD 57,6989 (1998)



Example: For an unpolarized 30 GeV muon beam the fluxes are a few x 10^{10} neutrinos/m^2/yr on the other side of the Earth !

Charged Current Interaction Rates

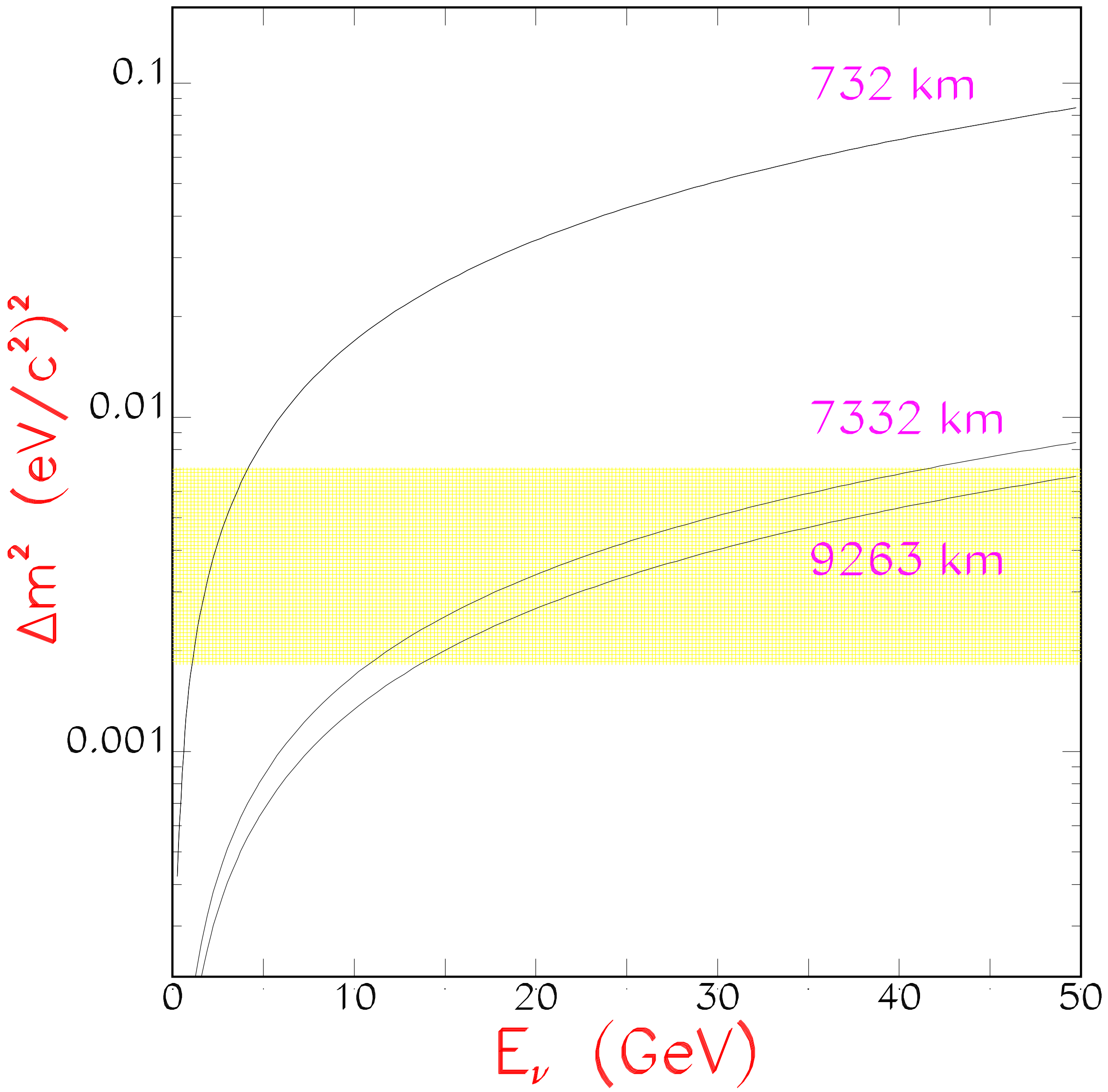
S. Geer, PRD 57,6989 (1998)



Example: For a 30 GeV muon beam there are ~ 3300 ν_μ CC events / yr in a 10 KT detector at L = 10 000 km.

Beam Energy for a Very Long Baseline Experiment ?

- At fixed baseline length L, the position of the first oscillation maximum E depends on Δm^2 :



ν_μ Disappearance

Barger, Geer, Whisnant ... Preliminary

Δm^2 (eV^2/c^4)	ν_μ CC Events (per 10 kt–yr)
0.002	2800
0.003	1230
0.004	922
0.005	1690
No Osc.	6200

FNAL–>Gran Sasso

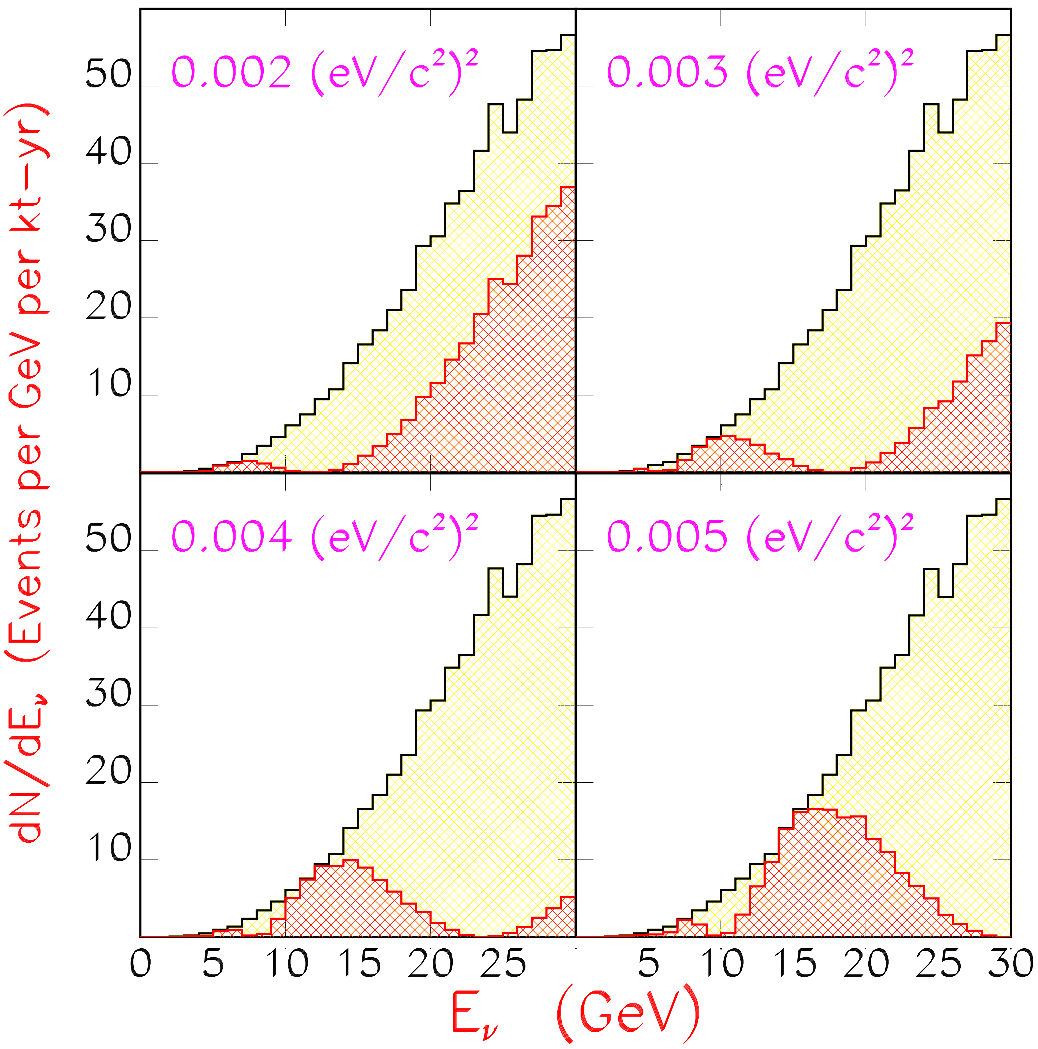
L = 7332 km

μ^- Decays

$\sin^2 2\theta = 1$

E_μ = 30 GeV

Ideal Detector



$\nu_\mu \rightarrow \nu_\tau$ Appearance

Barger, Geer, Whisnant ... Preliminary

Δm^2 (eV^2/c^4)	ν_τ CC Events (per kt–yr)
0.002	122
0.003	187
0.004	205
0.005	179

FNAL–>Gran Sasso

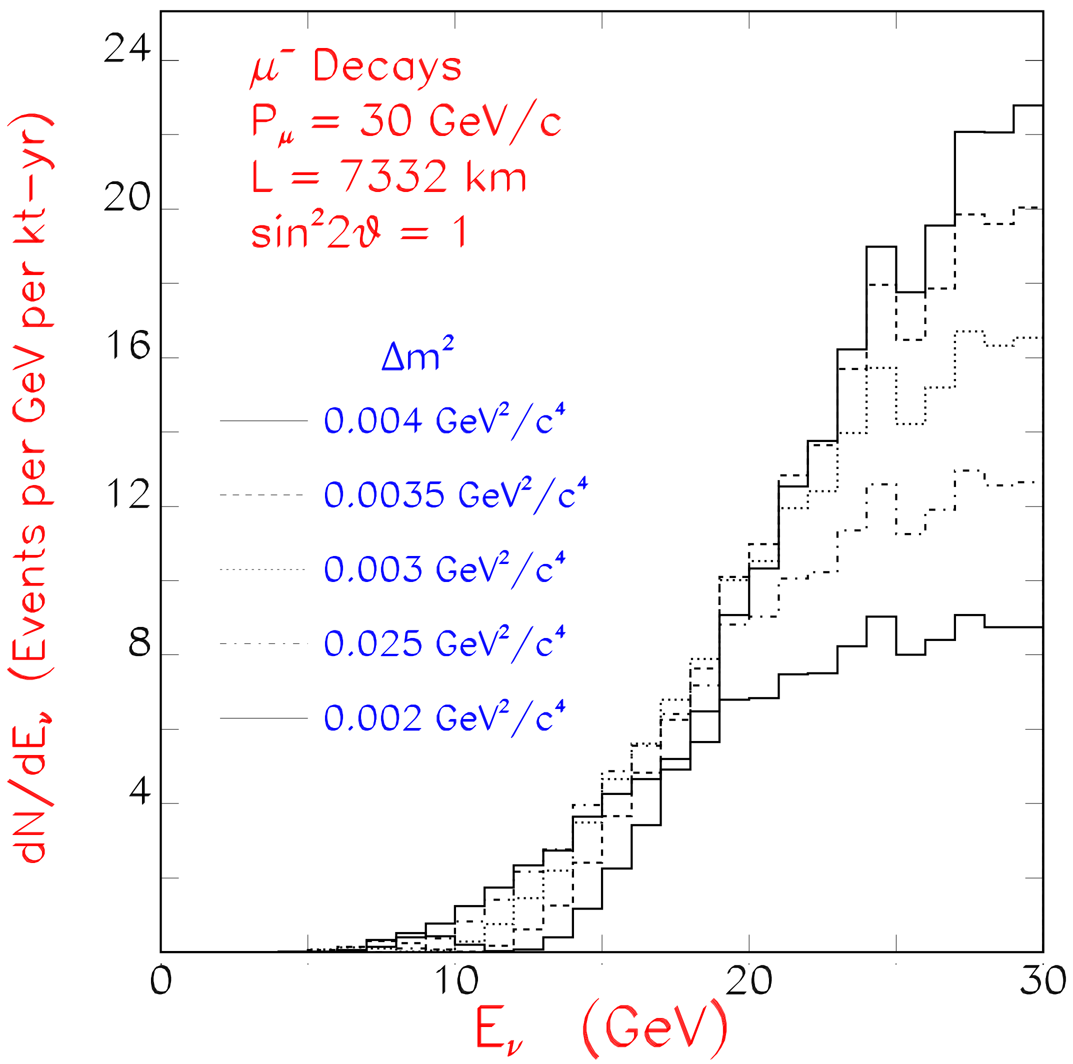
L = 7332 km

μ^- Decays

$\sin^2 2\theta = 1$

E_μ = 30 GeV

Ideal Detector



Muon Storage Ring ν Source: The First Step Towards a Muon Collider ?

Some Design Ideas

An initial "strawman design" for a μ–ring neutrino source does not yet exist, but there are 3 groups working on initial ideas that can be discussed in the Lyon workshop in July:

1. **Geer, Johnstone, Neuffer (FNAL)**
2. **Palmer, Johnson, Kiel (BNL–CERN)**
3. **Autin (CERN)**

Muon Storage Ring Neutrino Source – the path to a Muon Collider ?

- A low energy μ–ring neutrino source might provide a step towards the first muon collider.
- Muon collider components needed :
  - Proton source & target .... but not necessarily a 4 MW beam.
  - Pion decay channel.
  - The first part of the cooling channel (transverse cooling only).
- Muon collider components not needed :
  - Full 4 MW proton source & target.
  - Most of the cooling channel (including the challenging final stages of cooling and the emittance exchange longitudinal cooling stages)
  - Acceleration up to the colliding beam energy.
  - Collider & muon collider detector
- Can use many (lower intensity) muon bunches.

Toy Scenario

Geer, Johnstone, Neuffer (FNAL)

- **Based on present muon collider muon source design.**

1. **Use "Phase 1" of the upgraded FNAL proton driver scenario currently under study (8 GeV Booster –> 16 GeV Booster).** *S. Holmes et al; Fermilab–TM–2021, Sep. 1997*

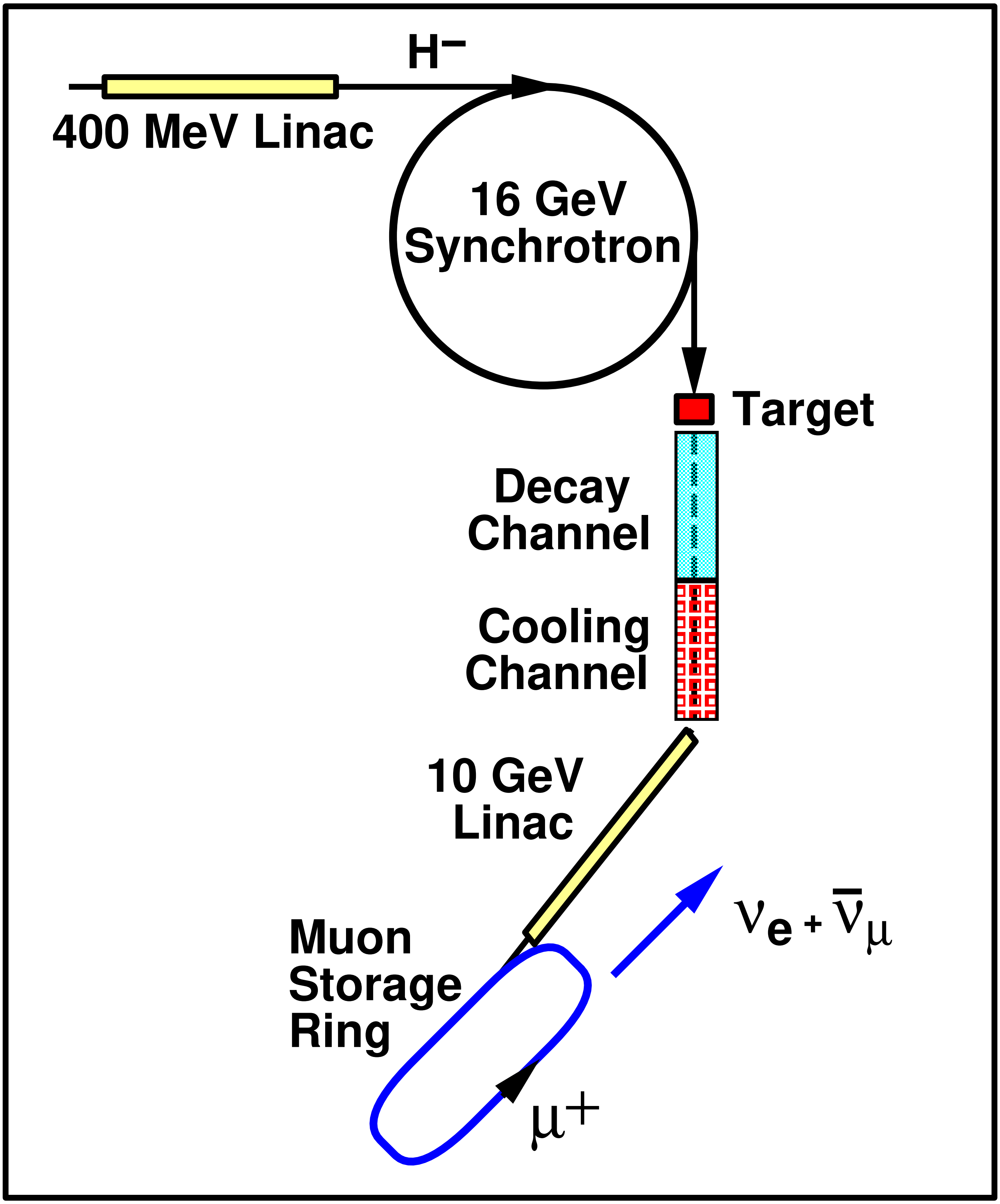
2. **Use Muon Collider Collaboration baseline concepts & calculations for the target, decay channel, & the first part of the transverse cooling channel.**

3. **Use 805 Mz acceleration system ... & for simplicity use a Linac acceleration scheme.**

4. **Make a first attempt to design a storage ring with the right characteristics.**

5. **Calculate resulting neutrino fluxes, etc.**

Neutrino Source Schematic



(*S. Geer, C. Johnstone, D. Neuffer, FERMILAB–Pub–99/121*)

Toy Scenario – Proton Source

- **Parameters from** *S. Holmes et al; "A Development plan for the Fermilab Proton Source", Fermilab–TM–2021, Sep. 1997*.. **updated to reflect current thinking (design study group of Weiren Chou et al.) :**

Source cycles at 15 Hz.	Phase 1	Phase 2
Linac		
Kinetic Energy (MeV)	400	1000
Current (mA)	50	65
Pulse Length (μs)	100	300
H^- per pulse	3×10^{13}	1×10^{14}
Pre–booster		
Extraction K.E. (GeV)	–	3.0
Circumference (m)	–	158
Protons per bunch	–	2.5×10^{13}
Number of bunches	–	4
Trans. Emit. (mm–mr)	–	200π
Long. Emit. (eV–sec)	–	1.5
Booster		
Extraction K.E. (GeV	16	16
Circumference (m)	474.2	474.2
Protons per bunch	2×10^{12}	2.5×10^{13}
Number of bunches	12	4
Bunch length σ_t(ns)	2 – 10	2
Trans. Emit. (mm–mr)	50π	200π
Long. Emit. (eV–sec)	1.8	2.0
Protons/year (10^7 secs)	3.6×10^{21}	1.5×10^{22}

Toy Scenario
π–Capture, Decay & μ Cooling

- Use muon collider baseline design for π capture & decay channel –> 0.2 muons / proton
  but needs to be redesigned to reduce (eliminate) low frequency high gradient rf requirements.

- At end of decay channel (phase 1 source) :

No. muons/year	N	=	7×10^{20}
Mean Energy	E	=	250 MeV
Energy Spread	σ_E/E	=	0.15
Bunch length	σ_Z	=	1.5 m
Trans. Emittance	ε_N	=	0.017 m–rad

- The transverse emittance is too large to fit within an accelerator + storage ring ...
  need to reduce ε_N by a factor of ~3.

- Use early part of muon collider baseline design for the ionization cooling channel: fifteen 10 m long cooling cells using LH_2 absorbers in a 1.5T –> 3T solenoid lattice, with 20 MHz & 40 MHz re–acceleration cavities –>

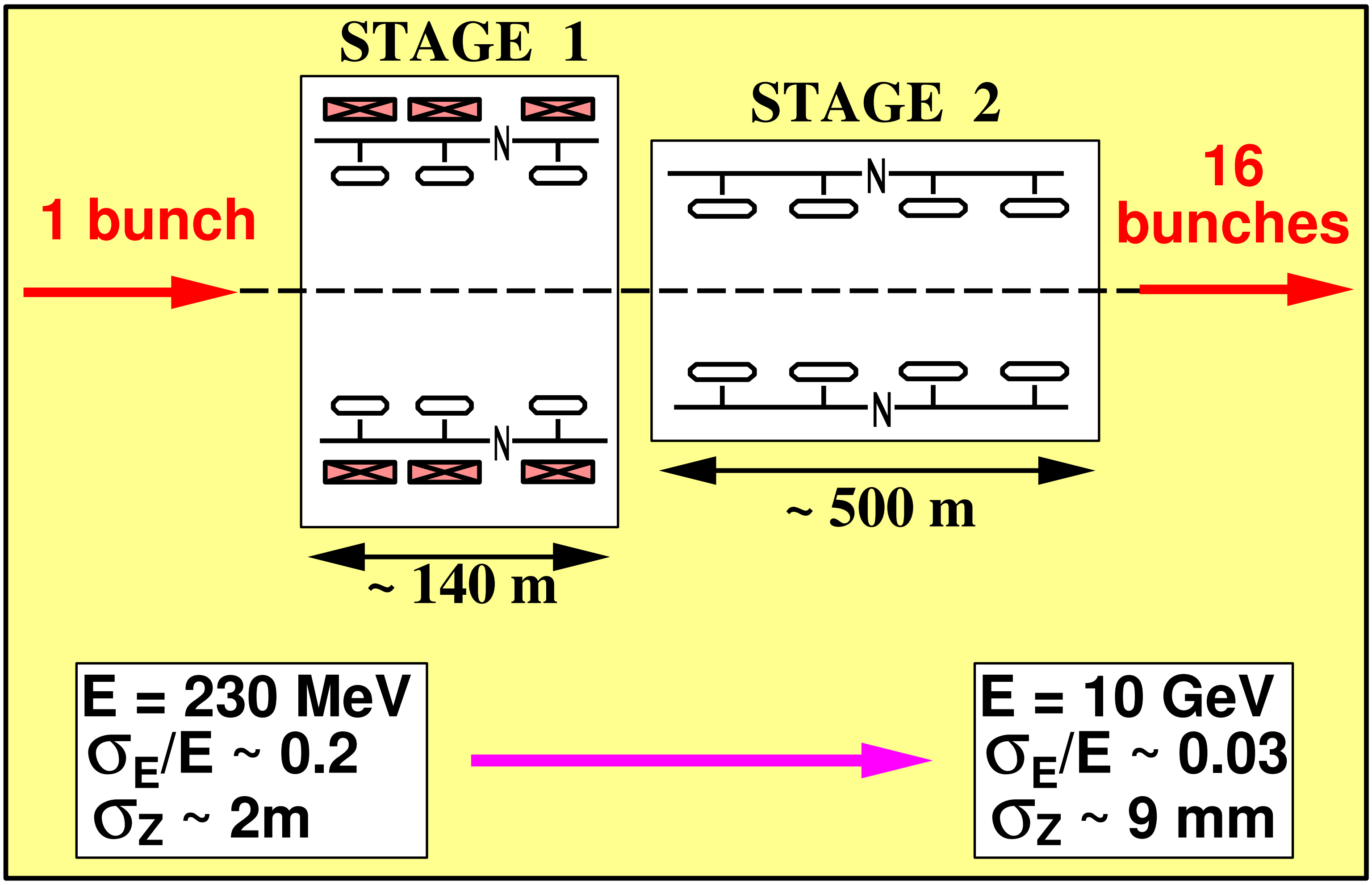
  $$\varepsilon_N = 0.017 \;\text{–>}\; 0.005 \text{ m–rad}$$

  but needs to be redesigned to reduce (eliminate) low frequency high gradient rf requirements.

Toy Scenario Acceleration Scheme

(*D. Neuffer*)

- Use 805 MHz rf systems :



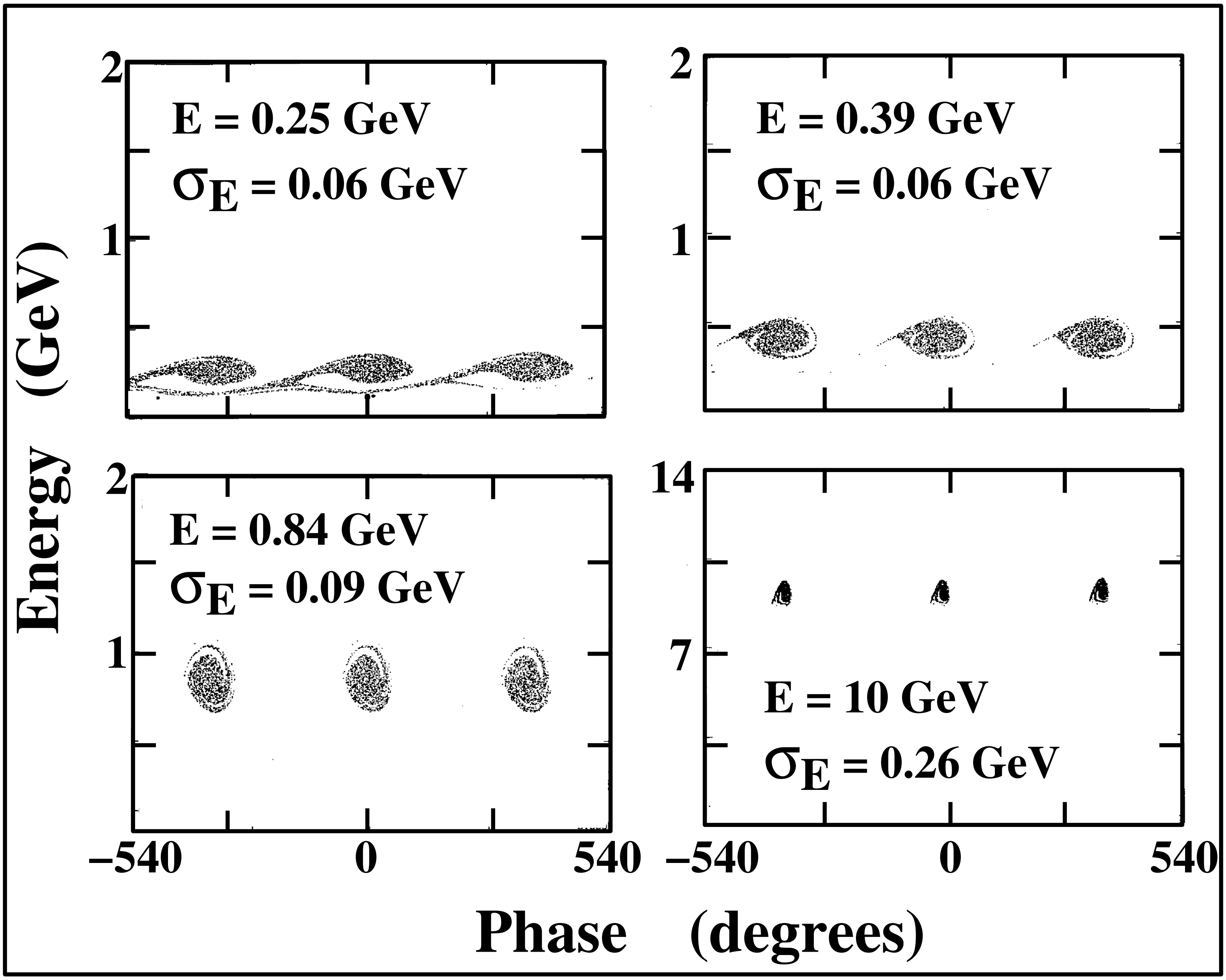
Stage 1: 140 m long 5T solenoid channel. Captures each long bunch into 16 stable bunches & accelerates to 1 GeV with a V_{rf} = 15 MV/m, $\phi_s = 30^o$, capture loss ~ 35%.

Stage 2: 500 m long FODO channel. Accelerates to 10 GeV with V_{rf} = 20 MV/m, $\phi_s = 60^o$. Decay & aperture losses ~ 10%

Simulation of capture & acceleration

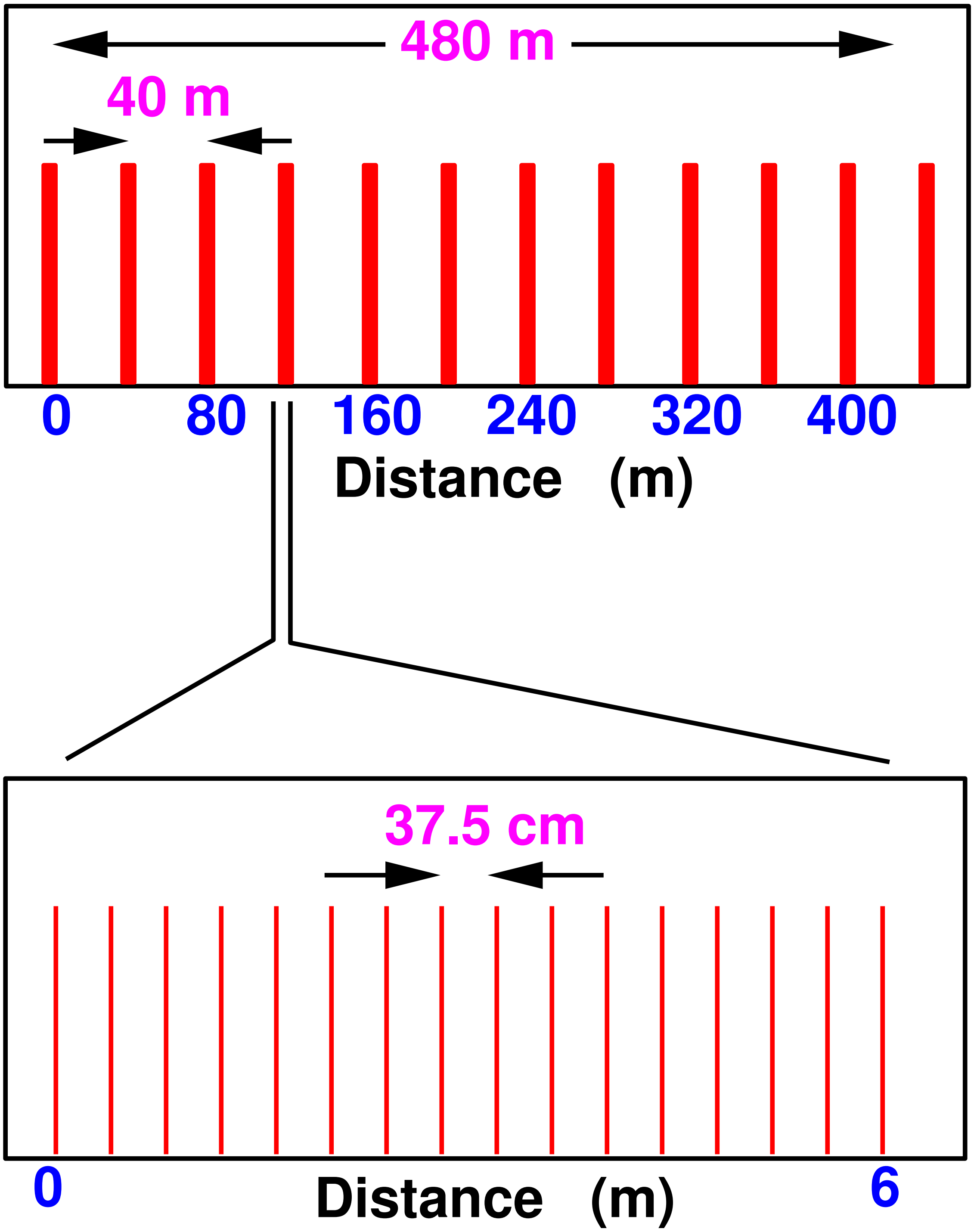
(D. Neuffer)

- Longitudinal simulation only.



- 65% of beam captured.

Toy Scenario – Bunch Structure



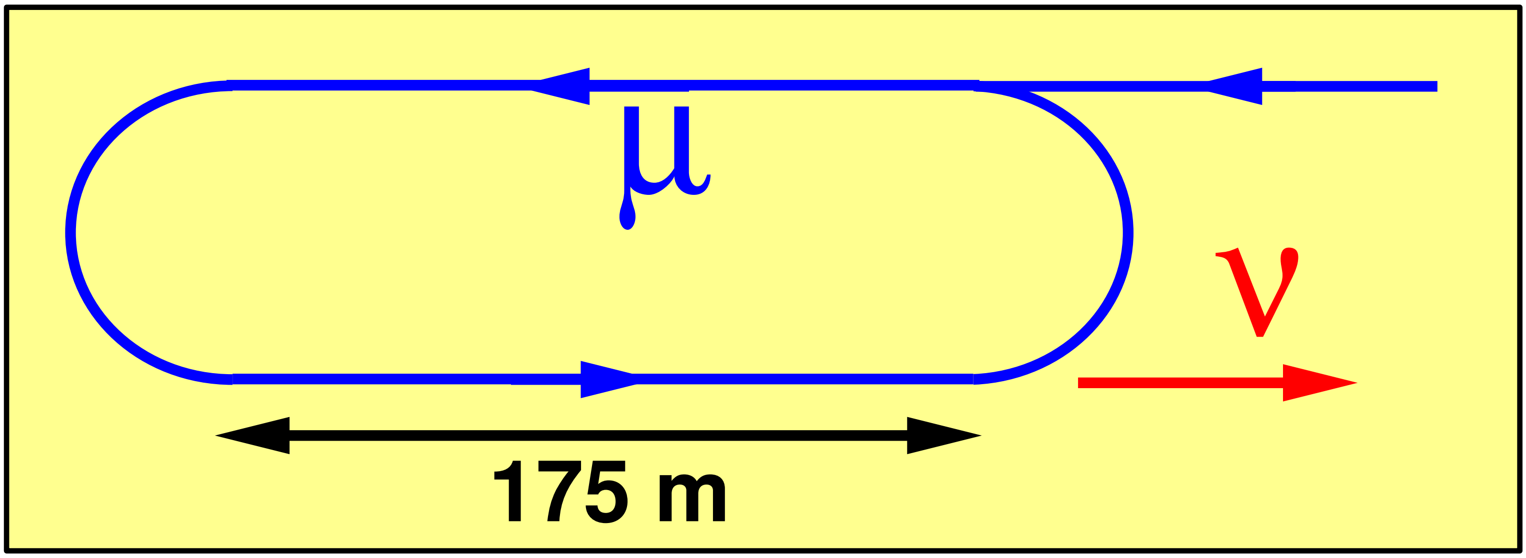
12 Bunch–Trains per Cycle from proton source

16 Bunches per Bunch–Train after μ capture & acceleration

Storage Ring

- 10 GeV muon storage ring:
  circumference = 498 m
  Straight sections = 175 m

  35% of the muons decay in beam–forming straight section

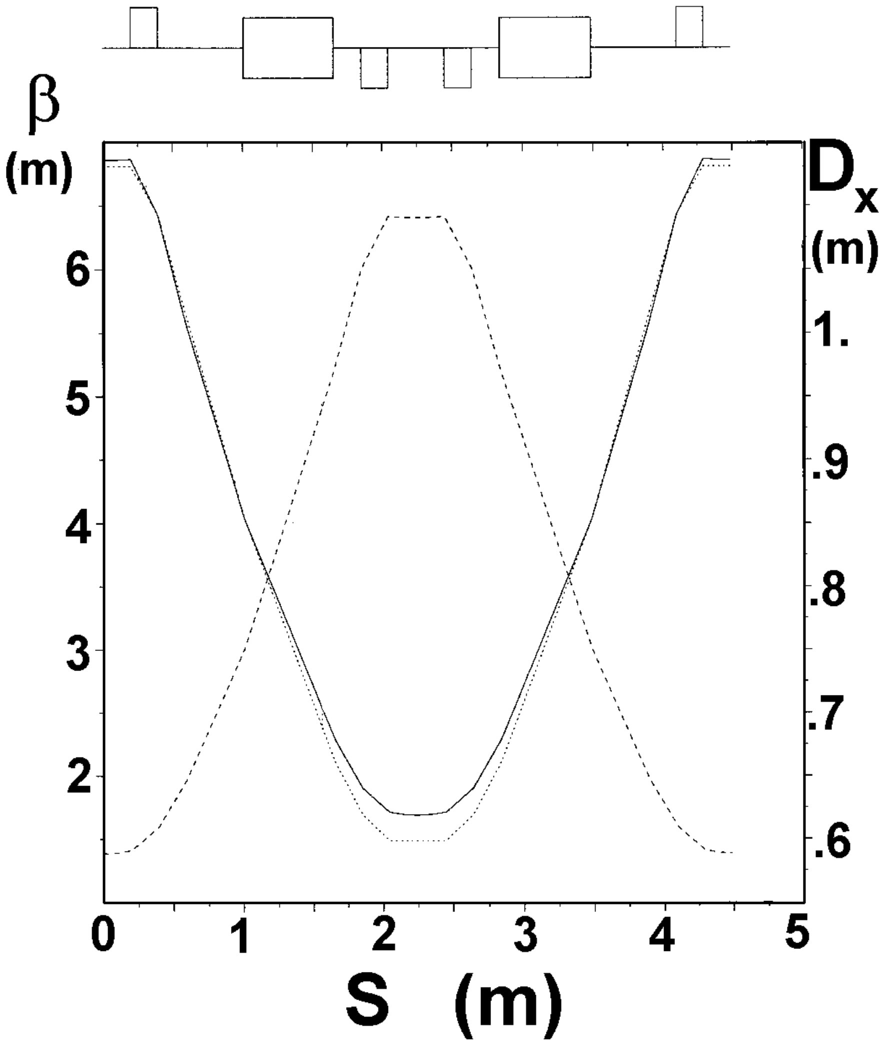


- The beam–forming straight section must be a high–β region so that beam divergence small compared to typical decay angle which is, for example, O(10 mr) at 10 GeV.
- Lattice must accommodate large $\Delta p/p$ (~ 0.03) & large transverse beam size (ε_N ~ 0.005 m–rad).
- Ring must have large apertures to accommodate large ε_N & large off–momentum orbit excursions.

Storage Ring: Arc Design

(*Carol Johnstone*)

Arc –> 6 + 1/2 FODO cells plus two cells at each end with reduced deflections to suppress disper– sion in matching & high–β straight sections.



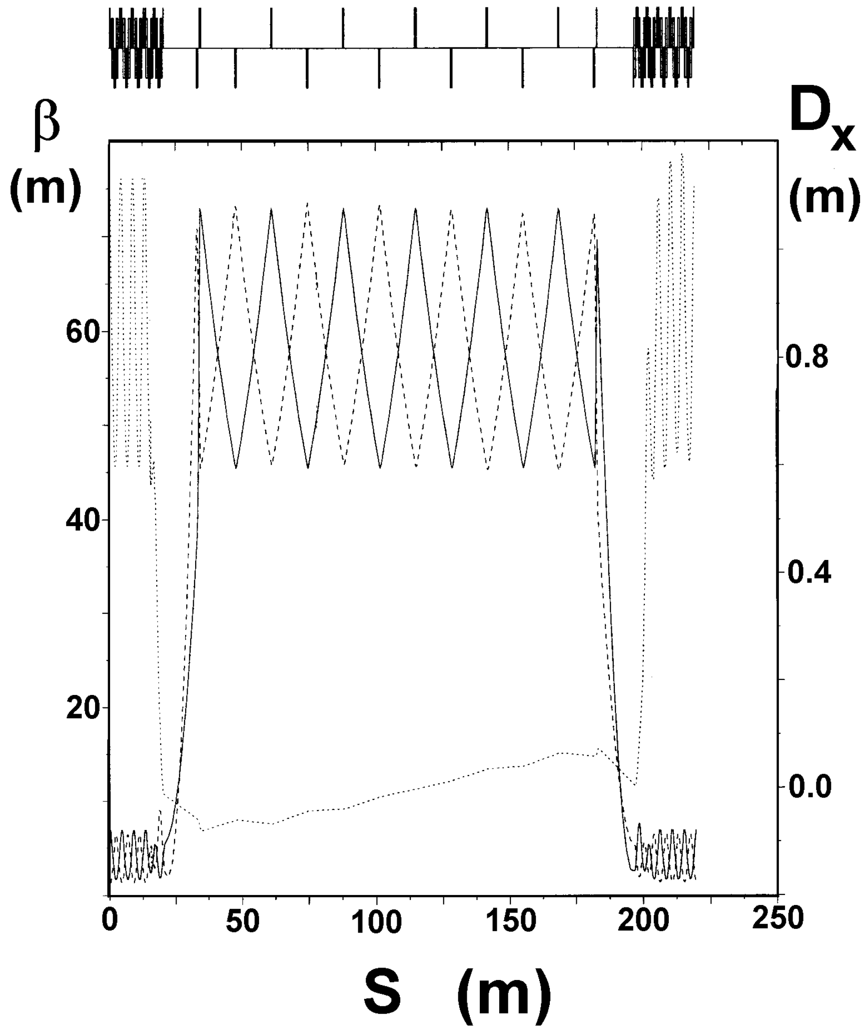
Arc cells keep off–momentum excur–sions under 8 cm.

Quad. strengths are tuned to give nearly $\pi/2$ phase advance per cell –> accomm–odates sextupoles that reduce the momentum dependence of the tune (ν_x = 8.252, ν_y = 8.741).

Dipoles:			
Field	9 T	Length	0.645 m
Bend	0.174 rad	Aperture	6 x 15 cm
Quadrupoles:		**Sextupoles:**	
Length	0.387 m	Horiz.	2.3 T
Bore	15 cm	Vert.	3.5 T

Storage Ring: Straight Section Design

(*Carol Johnstone*)



Beam–forming section –> 5 + 1/2 weak focusing FODO cells –> 150 m long.

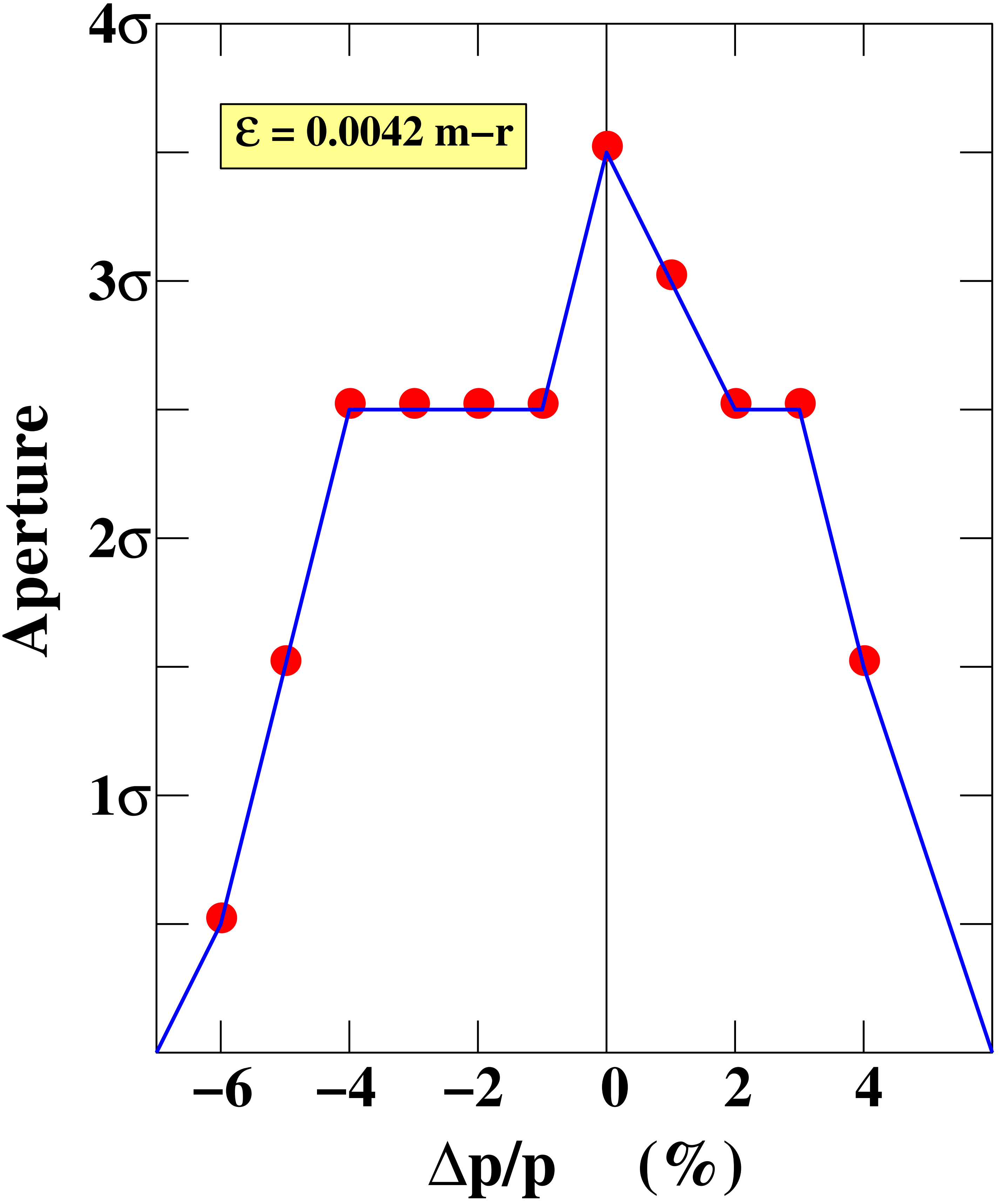
FODO cells are periodic units ... so straight section length flexible.

The weak focusing high–β section is matched to the strong focusing arcs with 20 m long matching sections.

Straight Section Length	147.9 m
Matching Section Length	2 x 20 m
High–β Quadrupole Radius	20 cm
β_x(max)	73 m
β_y(max)	73 m

The finite divergence of the muon beam traveling within the straight section has been calculated to decrease the ν flux at a distant site by ~10%.

Storage Ring Momentum Acceptance



Toy Scenario – Book–Keeping

Phase 1 Proton Source	
Protons/year	3.6×10^{21}
Decay Channel	
muons/proton	0.2
muons/year	7.2×10^{20}
Cooling Channel	
Decay + Aperture loss	0.9
muons/year	6.5×10^{20}
Acceleration System	
Capture efficiency	0.65
Decay + Aperture loss	0.9
10 GeV muons/year	3.8×10^{20}
Storage Ring	
Fraction in Straight Section	0.35
Useful muon decays/year	1.3×10^{20}

- Useful μ decays/yr similar to our previous full muon collider scenario –> 2×10^{20} per yr.

Losses:		**Gains:**	
Prot. Dr.	x 0.25	All p bunches	x 2
Accel. (805 MHz)	x 0.65	Shorter	x 1.4
		Storage Ring	x 1.4

- Note: The Phase 2 proton source –> 5.3×10^{20} useful muon decays/year.

Place Holder

Photo – Layout on FNAL Site

Toy Scenario–Neutrino Fluxes & Charged Current Interaction Rates

1.6×10^{20} muons decays per year (10^7 secs)

Annual ν_e, ν_μ Fluxes (10^{10} m^{-2} yr^{-1})

L (km)	E_μ (GeV) 10	15	20	25	30
732	79	190	330	510	740
7332	0.79	1.8	3.3	5.1	7.4

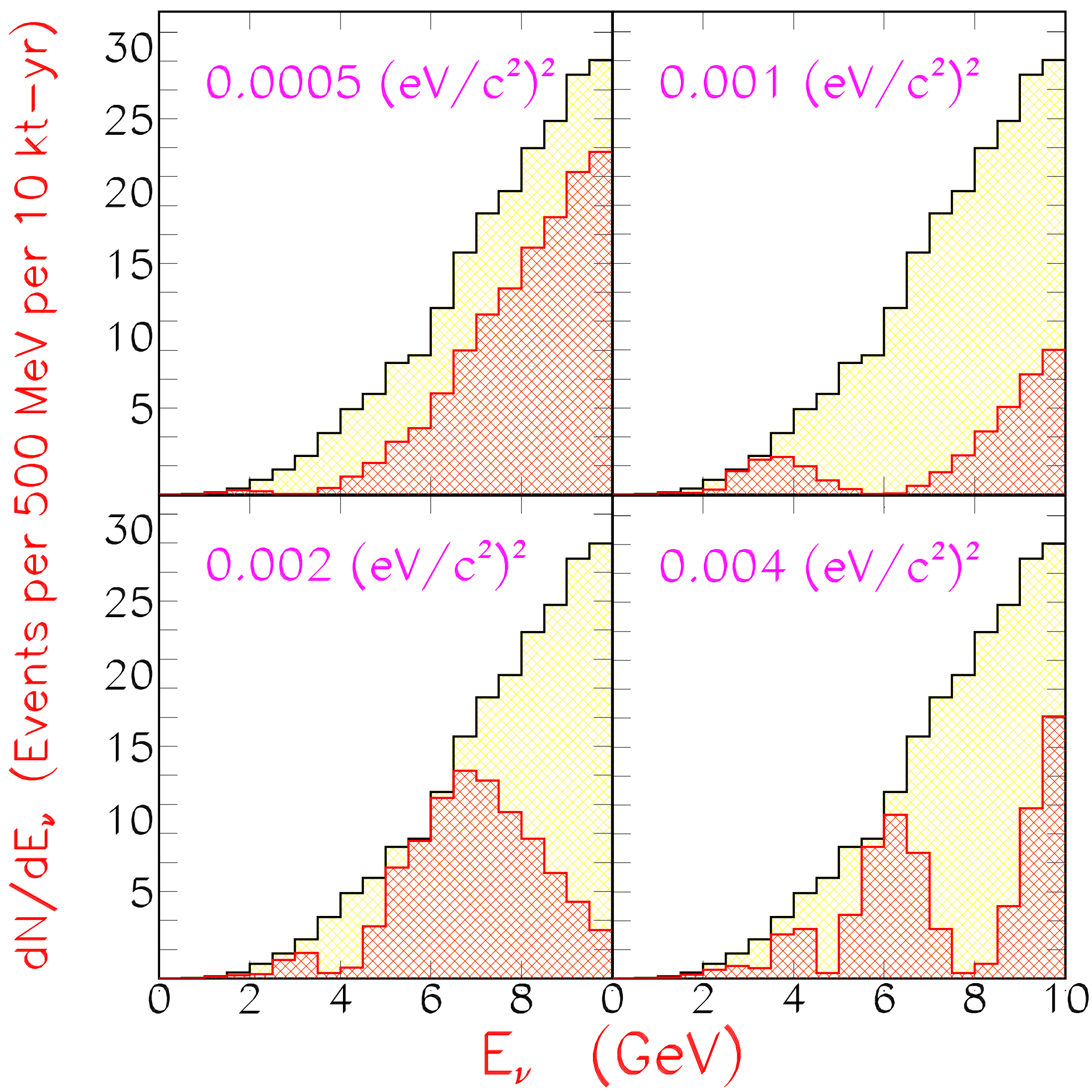
Annual CC Rates (per kt–yr)

	E_μ (GeV) 10	15	20	25	30
L = 732 km					
ν_μ	2220	7830	18500	36400	62200
$\bar{\nu}_e$	958	3380	7890	15700	26800
ν_e	1940	6670	15600	30900	53100
$\bar{\nu}_\mu$	1210	3980	9530	18700	32500
L = 7332 km					
ν_μ	22.1	77.6	187	360	620
$\bar{\nu}_e$	9.5	33.7	80.2	155	266
ν_e	20.2	66.3	158	309	530
$\bar{\nu}_\mu$	12.1	39.5	94.3	187	325

Example: ν_μ disappearance between FNAL and Gran Sasso, with 10 GeV muons

Barger, Geer, Whisnant ... Preliminary

Δm^2 (eV^2/c^4)	ν_μ CC Event Rate (per 10 kt–yr)
0.0005	139
0.001	44.5
0.002	103
0.004	82.7



There is a lot that has to be done to arrive at a Strawman Scheme

- Establish realistic rf parameters for decay & cooling channels –> update design.

- More complete simulations of the pion capture, and decay channel, and the cooling channel, with optimization of the optics, & a study of how the muon population in 6–d phase–space at the end of the cooling channel.

- Explore the possibility of using an RLA for the 2nd acceleration stage, and make a more detailed simulation of the muon acceleration.

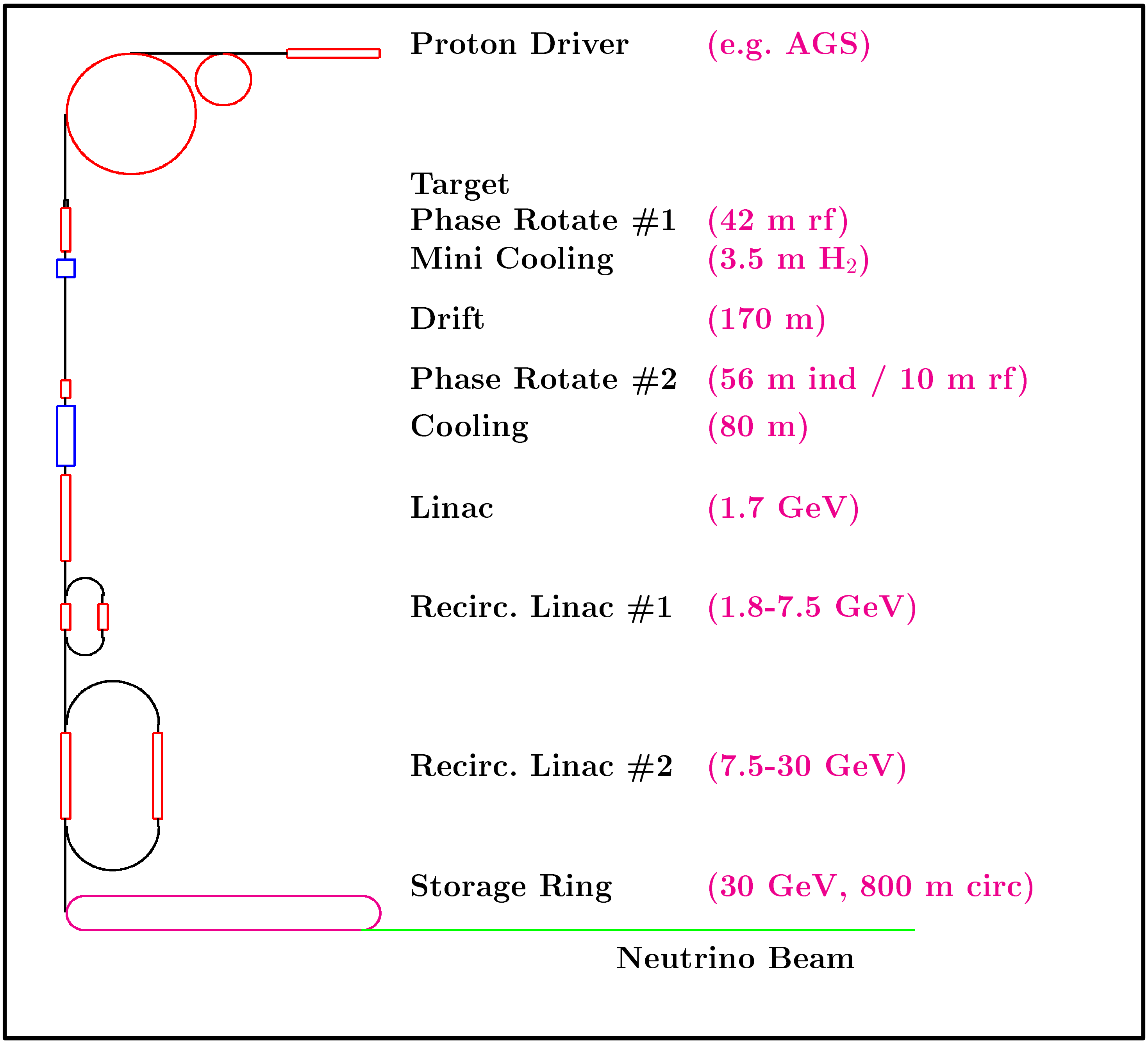
- Establish realistic large–bore super–conducting magnet parameters for the storage ring –> update the storage–ring lattice design.

- Explore the trade–offs between getting more muons by investing more in the proton source compared with more in the decay channel, or cooling channel, etc.

Alternative Toy Scenario

Palmer, Johnson, Kiel

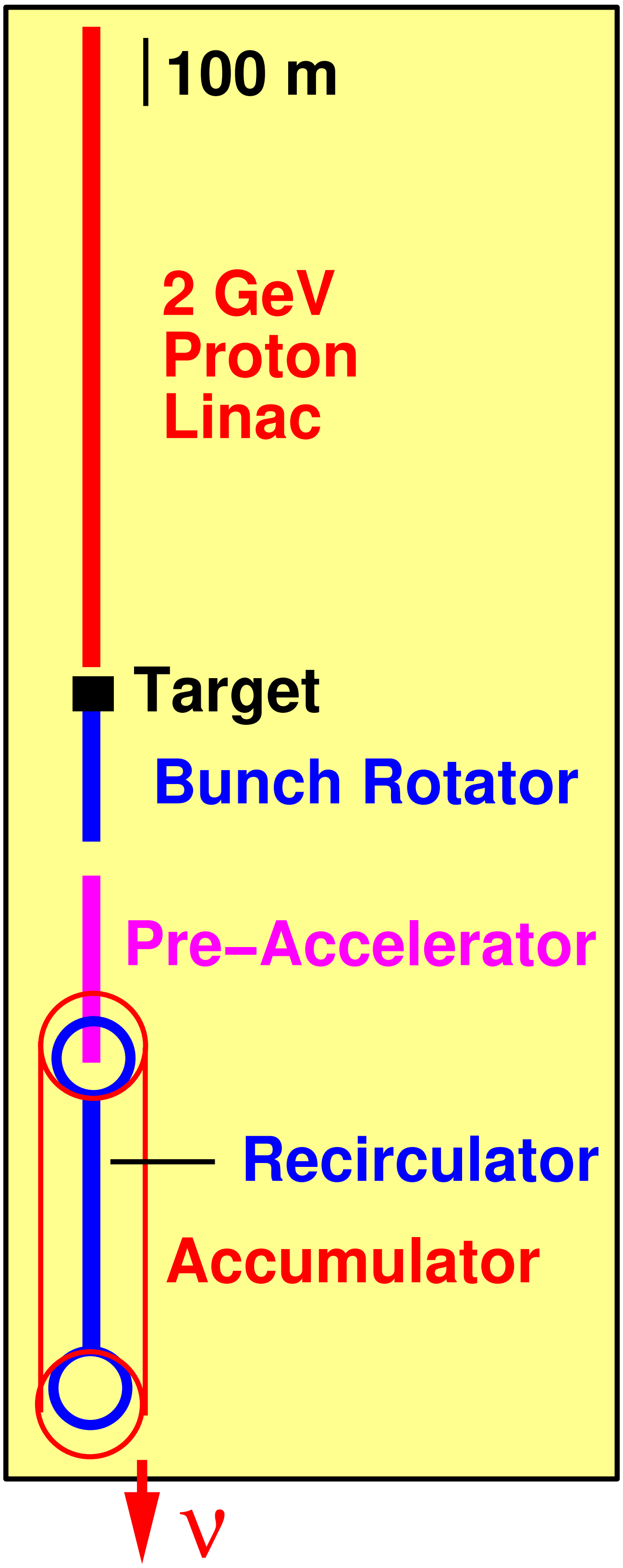
- **Similar to the Geer, Neuffer, Johnstone scheme ... but with some additional good ideas.**



Alternative Toy Scenario

Autin (CERN)

- Very different from the other 2 scenarios



Proton Linac: LEP cavities.
RF Power = 34 MW
43 klystrons, 352 MHz.

Muon Collection: Quad. channel. Beam radius = 11 mm, divergence 265 mr.

Bunch Rotation: Wiggler.
ΔE = 200 MeV –> 40 MeV.
Δt = 50 ps –> 800 ps.

Recirculator: Dog–bone.
ΔE/passage = 5 GeV.
Linac length = 500 m.

Accumulator: 20 GeV.
Azimuthal stacking.

Summary

1. What ν beams could be produced at a muon collider accelerator complex ?

- ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$

- Very high CC rates at high energies (10^7 CC events / kg–yr at 250 GeV)

- Possibility of very long baselines for oscillations. Ex: FNAL –> Gran Sasso.

Summary

2. What is the potential of these ν beams ?

- High energy beams. Example: E_μ = 250 GeV :

Non–Oscillation: B, C, Spin, Str. Fu., $\sin^2\theta_W$

$\nu_\mu \rightarrow \nu_\tau$: For $\Delta m^2 \sim 0.003$ eV^2, measure Δm^2 to O(1%) (stat), search for few % ν_s events

$\nu_e \rightarrow \nu_\tau$: For $\Delta m^2 \sim 0.003$ eV^2, get few x 100 events for $\sin^2 2\theta = 10^{-2}$

$\nu_e \rightarrow \nu_\mu$: Cover most of the MSW LMA region (all of it at higher energies).

- Lower energy beams. Example: E_μ = 50 GeV :

$\nu_\mu \rightarrow \nu_\tau$: For $\Delta m^2 \sim 0.003$ eV^2, measure Δm^2 to few % (stat), search for few O(10%) ν_s events

$\nu_e \rightarrow \nu_\tau$: For $\Delta m^2 \sim 0.003$ eV^2, get ~10 events for $\sin^2 2\theta = 10^{-2}$

- Trans–Earth Baseline Experiment

$\nu_\mu \rightarrow \nu_\tau$: For $\Delta m^2 \sim 0.003$ eV^2, E_μ = 20–30 GeV, measure Δm^2 to O(1%) (stat), search for O(10%) ν_s contribution.

Summary

3. Could a muon storage ring neutrino source be built as a step towards a muon collider ?

- Need (part of) the muon collider proton source, the decay channel, small part of the cooling channel.

- Can have many muon bunches –> less need for high–gradient low frequency rf systems.

- Plenty of ideas on how to design a muon storage ring neutrino source ... but not enough has yet been done to put together a complete strawman scenario, and assess its viability.