MUON MACHINES

Alain Blondel Ecole Polytechnique

- ♦ OVERVIEW
- ♦ ν - FACTORY
  - PERFORMANCE
  - OSCILLATION PHYSICS
  - OTHER POSSIBILITIES
- ♦ MUON COLLIDERS
- ♦ CONCLUSIONS

HISTORY...

- Original concepts — Budker (1969) Skrinsky (1971)
  KOSHKAREV (1974) ν SOURCE
  PARKHOMCHUK, SKRINSKY (1981) IONIZATION COOLING

- **USA** studies since 1992 (B. Palmer, Muon Collider Collaboration)
  MUON COLLIDER FEASIBILITY STUDY (1996)

- Study group at CERN (B. AUTIN) (1997)

- WORKSHOP ON "PHYSICS AT FIRST MUON COLLIDER AND FRONT-END"
  (FERMILAB, 1997)

- "OPTIONS FOR FUTURE COLLIDERS AT CERN"
  commanded by D.G. Ellis Keil Rolandi (jan. 1998)

- ECFA Encourages "Prospective Study of MUON Storage rings at CERN"
  3 step Strategy (Autin/AB/Ellis) (June 1998)

- CERN report 99-02: conclusions of prospective study →

- **ν-FACT99, Lyon, July 99. (ICFA + ECFA)**

- 3 Step Strategy proposed for Fermilab (Geer)
  "a vision for the future of Fermilab"

- M.C.C. becomes "neutrino factory and Muon Collider Collaboration"

- 20 September 1999 Plenary meeting of European Study Group.

- 21 September 1999 Discussion at CERN SPC.

The conclusions of the prospective study can be stated as follows

1. The line of facilities using MUONbeams seems extremely interesting, providing a very rich physics programme for many years.

2. We suggest to ECFA to recommend to the European particle physics community to take this option very seriously.

3. We arrive at a point where detailed simulations and design become necessary, fault of which the feasibility and competitiveness of the project cannot be ascertained.

4. A series of

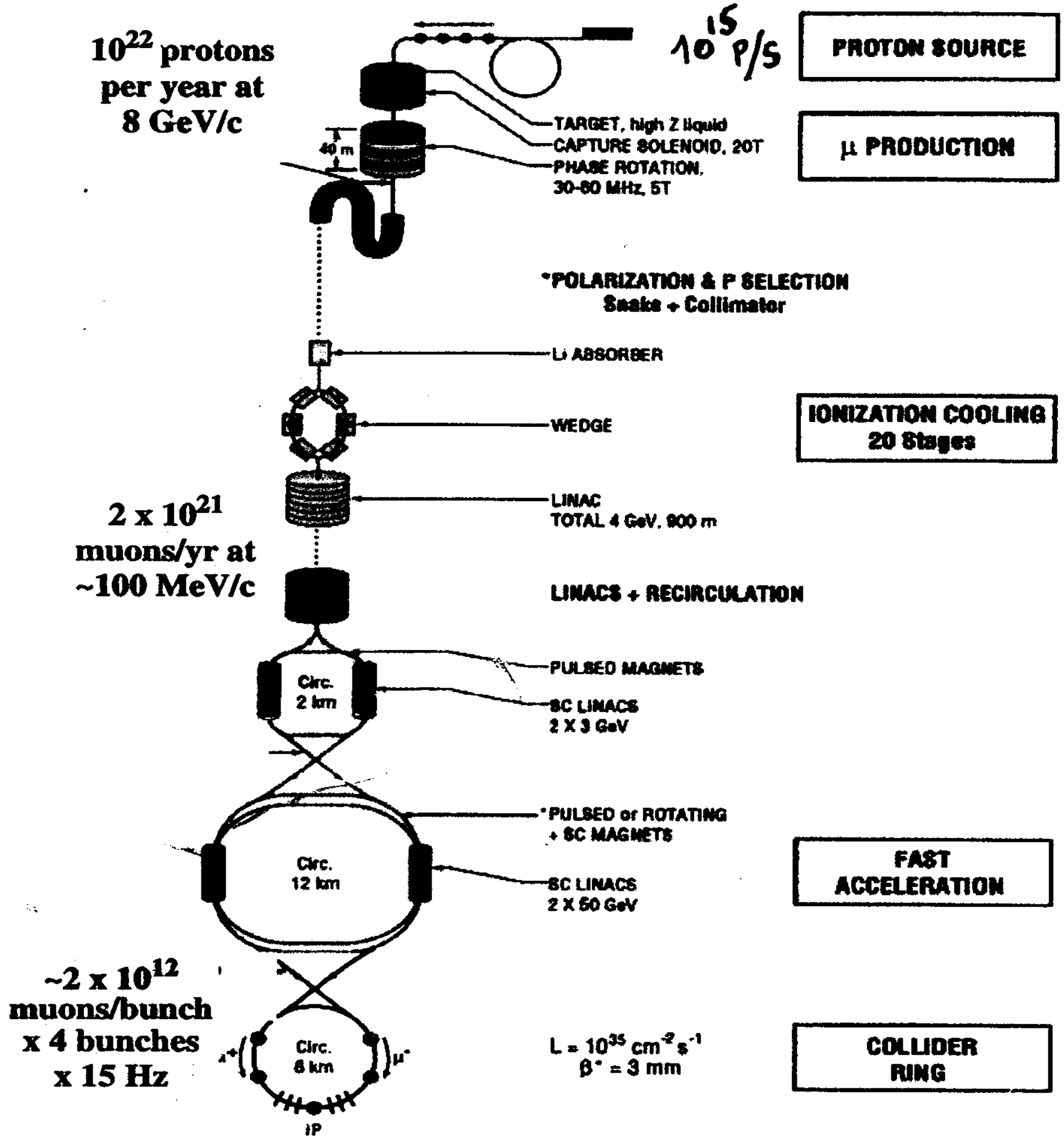
ECFA-sponsored WORKshops

would be an adequate forum to undertake the detailed work that is necessary to design and evaluate more completely this project, with emphasis on the

NEUTRINO FACTORY

5. The design and even the construction of this line of machines could involve competences that are available throughout Europe. A dedicated collaboration involving european laboratories is necessary to go further, and could become extremely efficient.

2 x 2 TeV Muon Collider Schematic

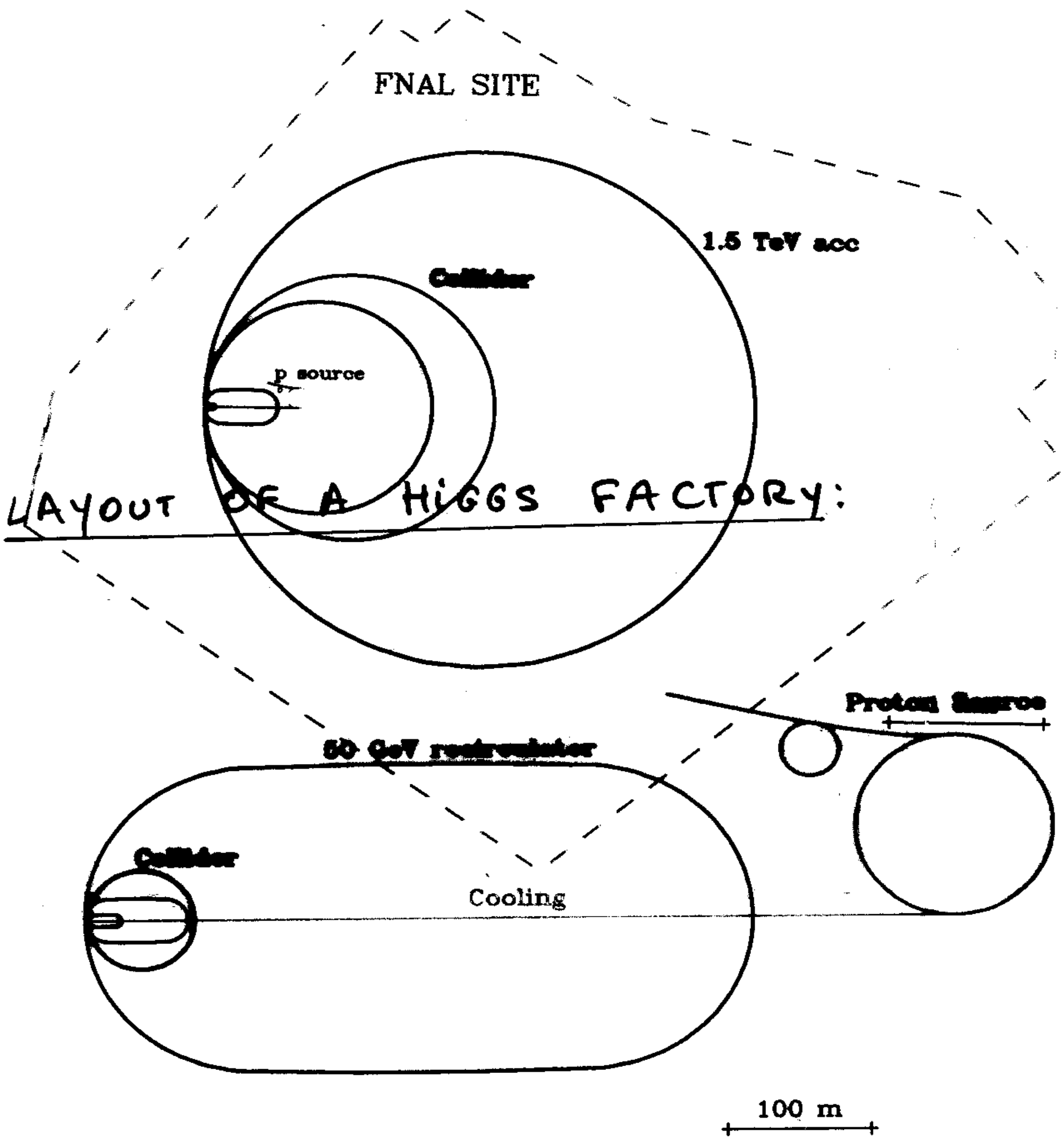


B. Palmer et al.

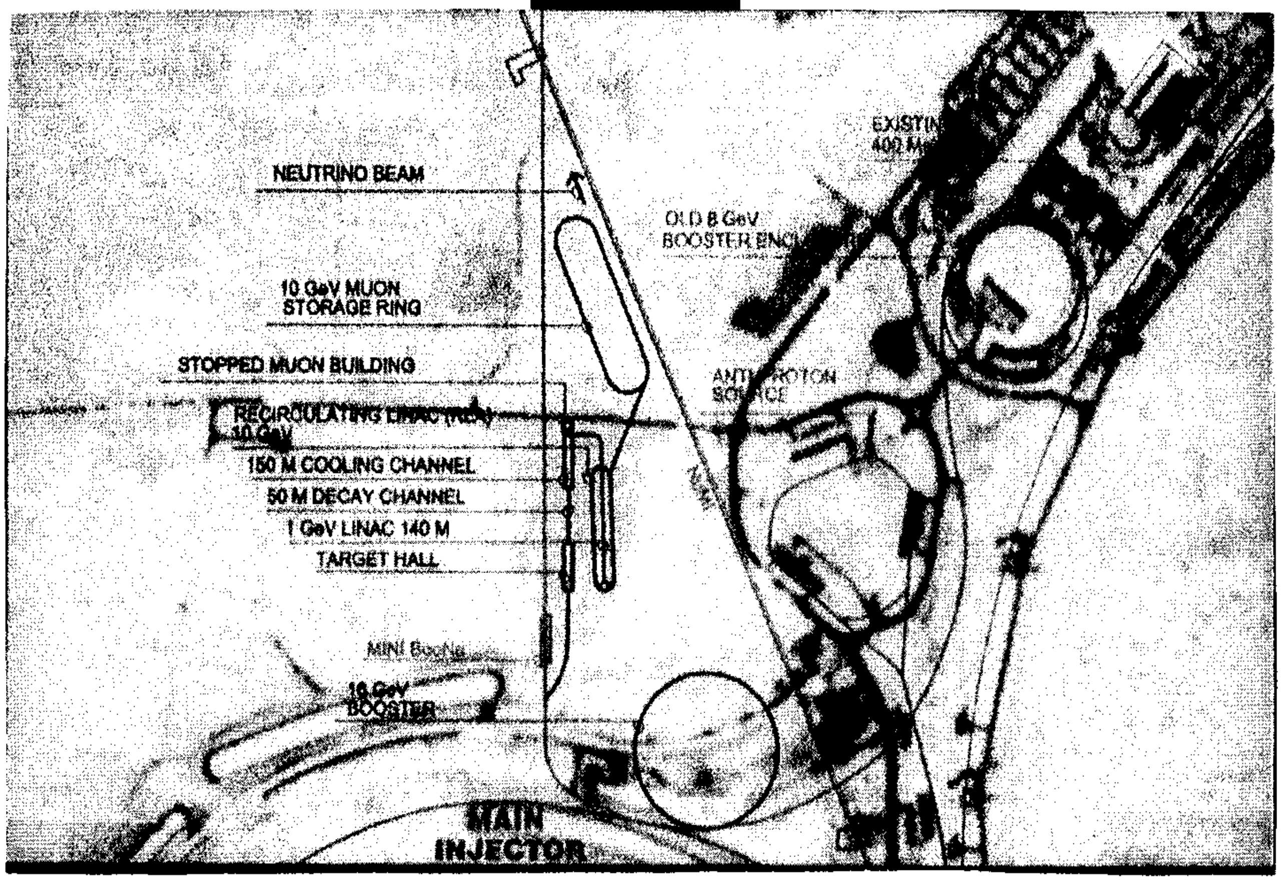
LAYOUT OF A 3TeV Ecm MUON COLLIDER:

6 km (11.5 km)

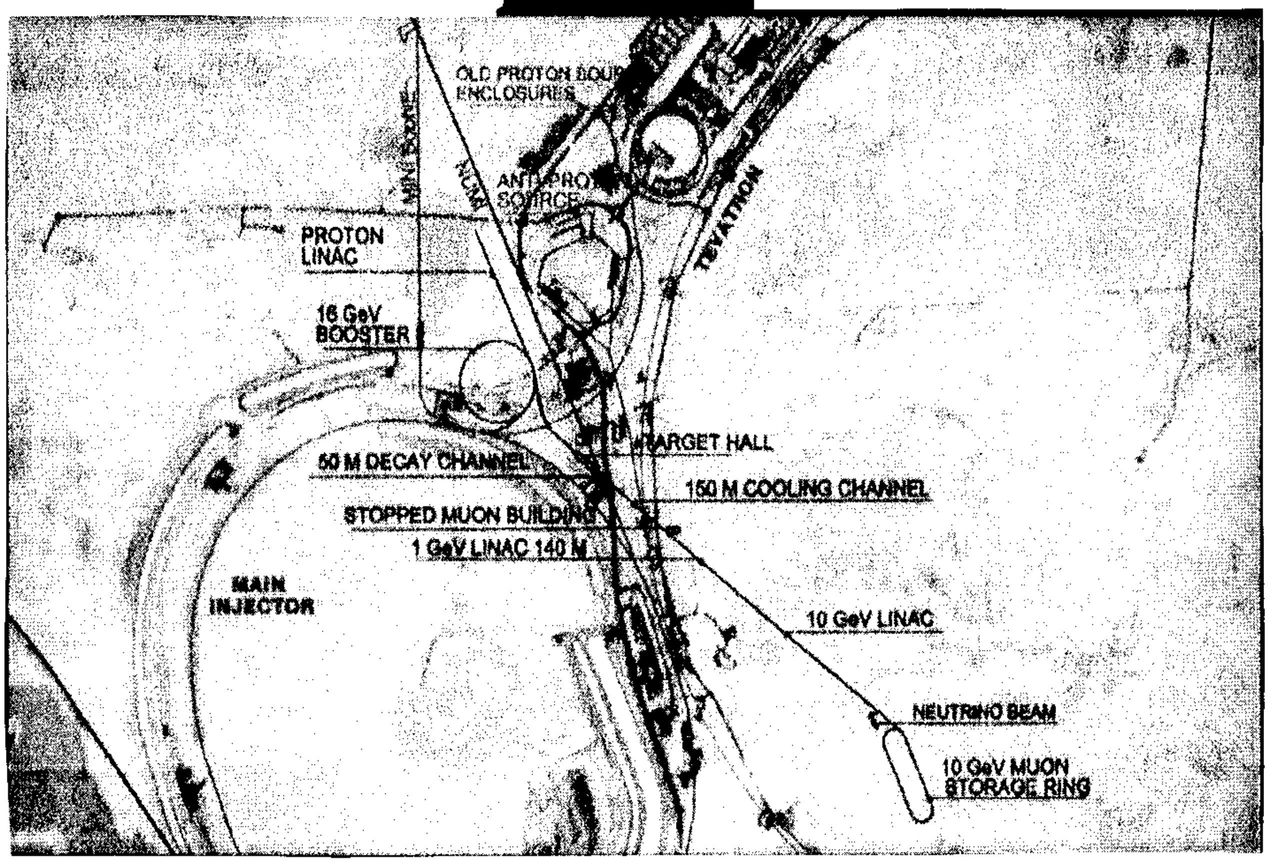
LAYOUT OF A HIGGS FACTORY:



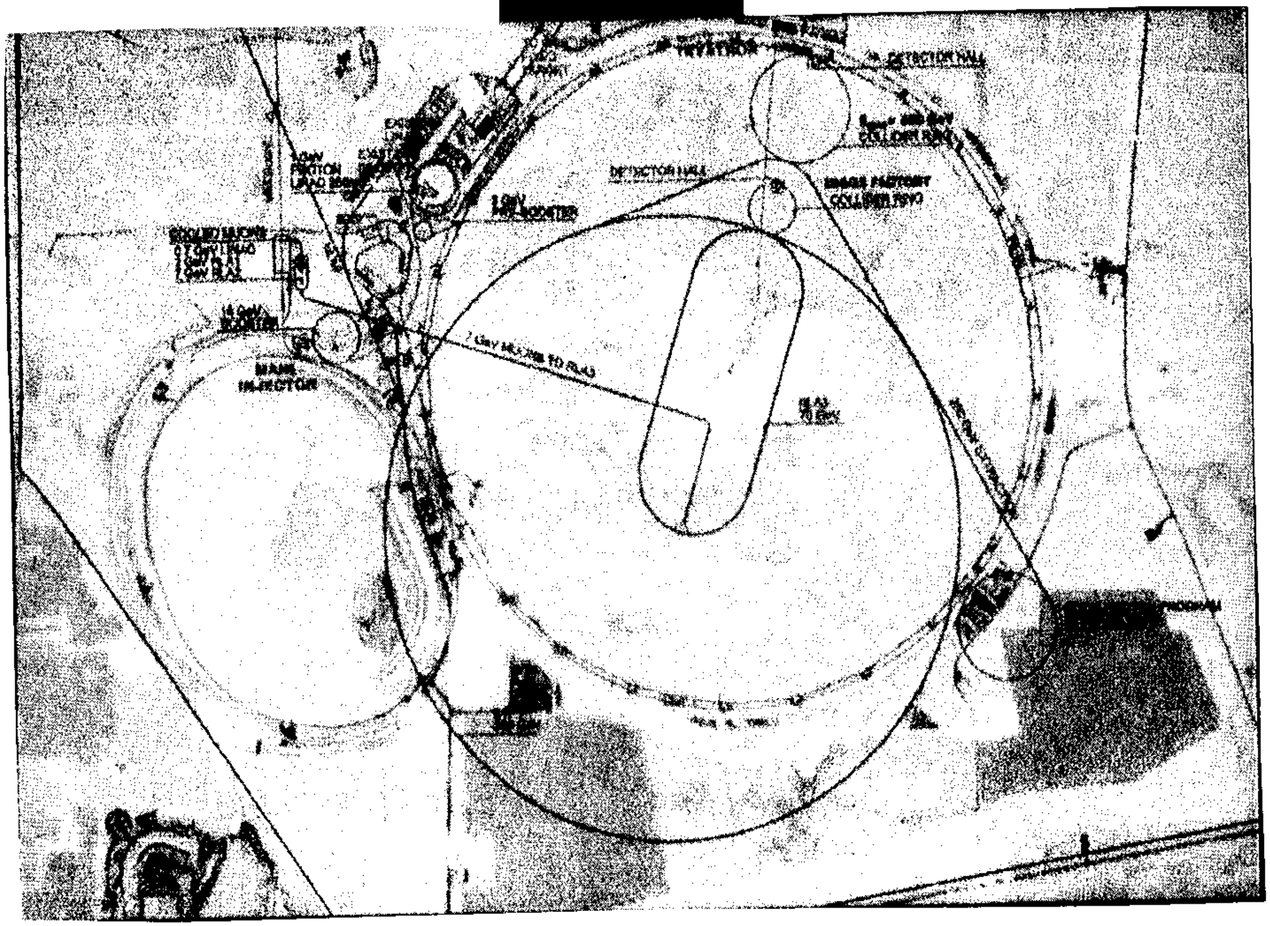
Photograph 1



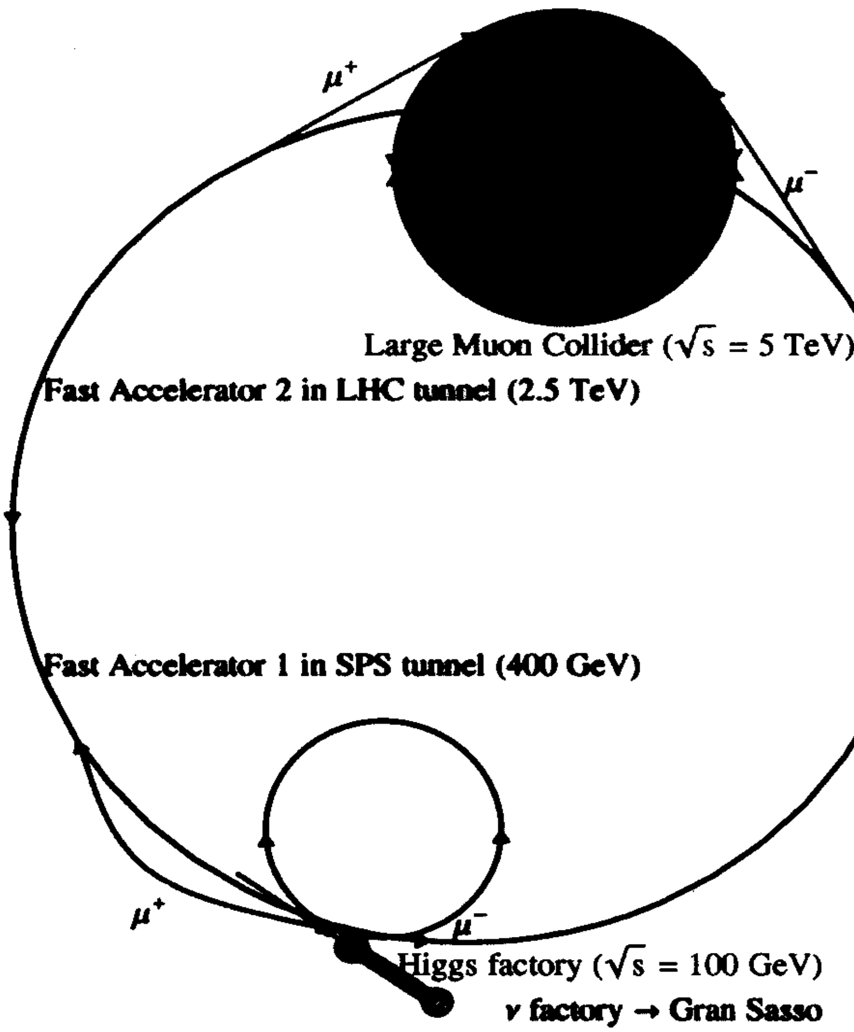
Photograph 2



Photograph 3



Possible layout of a MUON complex on the CERN site



NOBODY HAS EVER BUILT A MUON MACHINE AND PROBLEMS SEEM OVERWHELMING IF ADDRESSED ALL AT ONCE.

3 POSSIBLE STEPS

1. NEUTRINO FACTORY
   - high intensity protons → target
   - Efficient capture + some cooling (1/30)
   - acceleration of MUONs

2. HIGGS FACTORIES
   - COOLING ($1/10^6$)
   - DETECTOR SHIELDING

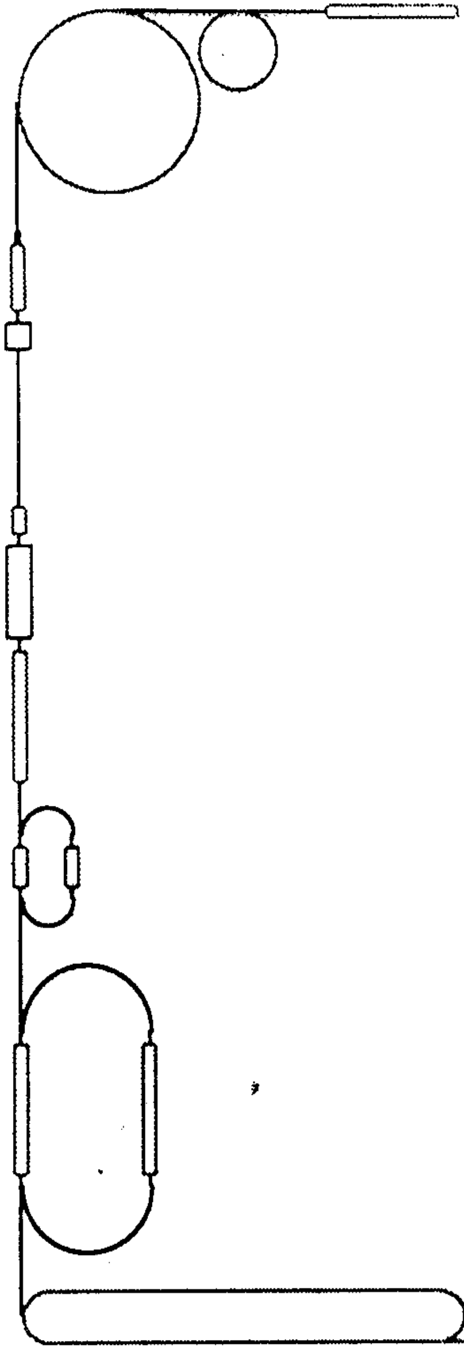
3. HIGH ENERGY FRONTIER.
   - ACCELERATION → 2 TeV
   - NEUTRINO RADIATION

EACH OF THESE STEPS HAS A BEAUTIFUL PHYSICS PROGRAMME IN ITS OWN RIGHT!

ν-FACTORY

MUON BUDGET

ex 16 GeV p



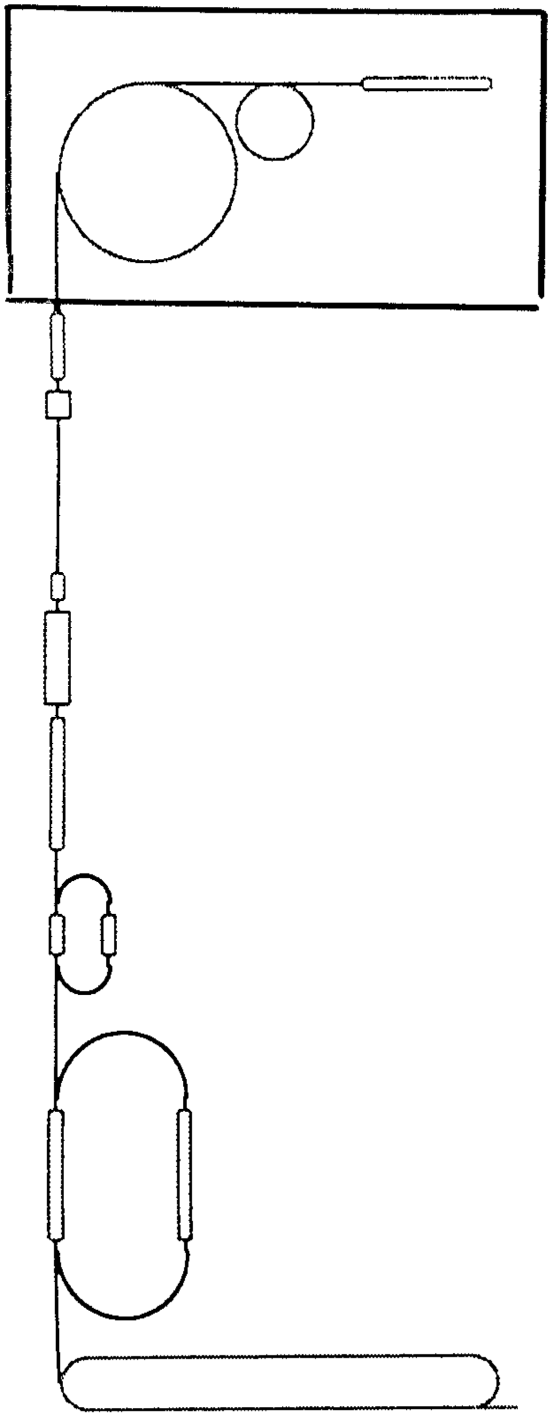
$1.5\ 10^{15}$ p/s ⇒ $1.5\ 10^{22}$ p/YR

Stage	Parameters	μ/p
Proton Driver		
Target	(π within acc)	0.44
Phase Rotate #1	(42 m rf)	μ 0.2
Mini Cooling	(3.5 m H_2)	↓
Drift	(160 m)	
Phase Rotate #2	(10 m rf)	0.14
Cooling	(80 m)	0.09
Linac	(2 GeV)	
Recirc. Linac #1	(2-8 GeV)	
Recirc. Linac #2	(8-50 GeV)	0.06 μ/p
Storage Ring	(50GeV 900m circ)	0.02 $\bar{\nu}_\mu$ + 0.02 ν_e

Neutrino Beam 30%

10^{21} μ/YR

$3\ 10^{20}$ ν_e/YR + $3\ 10^{20}$ ν_μ/YR



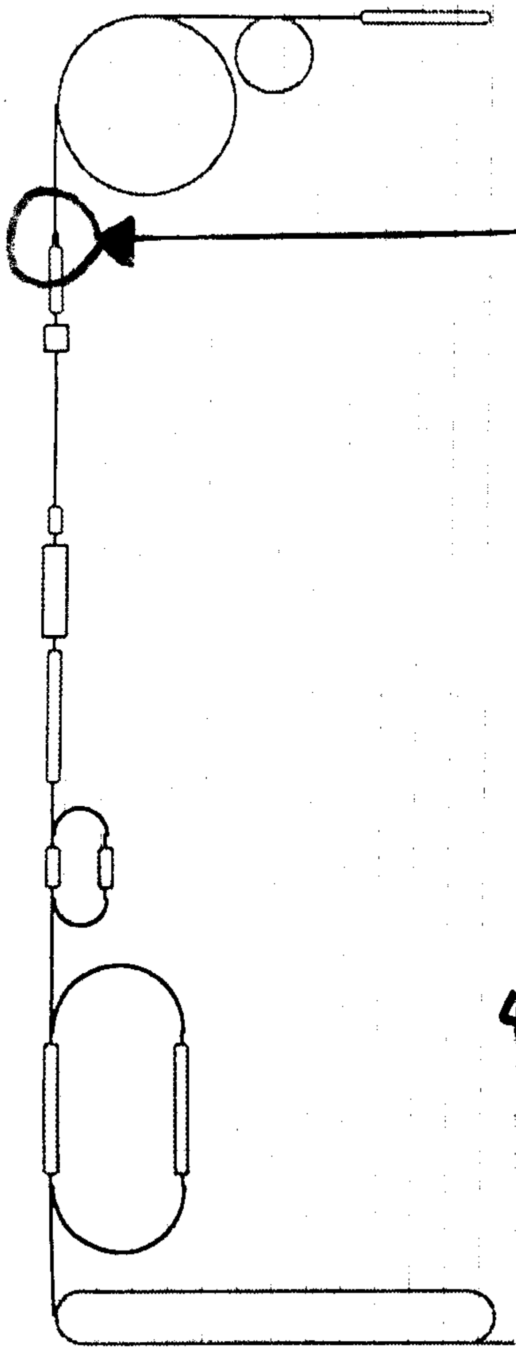
PROTON DRIVER.

MAIN OPTION	OTHER OPTIONS
rapid cycling synchrotrons 15 Hz	• High intensity Linac + ACCUMULATOR
$E = 16 - 30$ GeV	$\Rightarrow \lesssim 50$ Hz
$P \leq 4$ MW	$E \simeq 2$ GeV
	• α beam for $\mu\mu$?

COMMENTS :

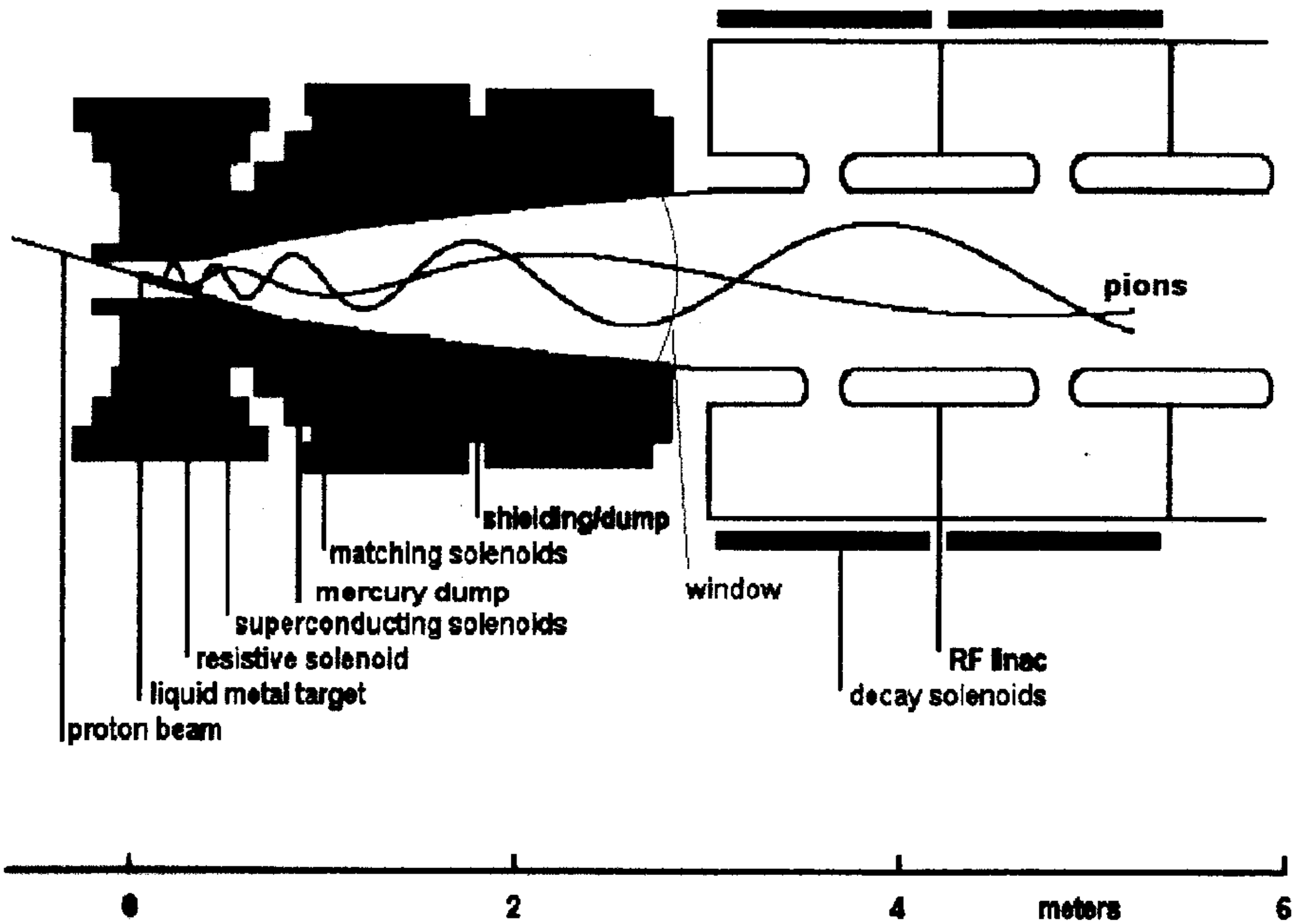
- Low frequency important for $\mu\mu$ collider
- Pion production $\propto E_p^{kin}$
  - $\Rightarrow$ Important parameter is: BEAM POWER
- Higher beam power seems easier to reach with LINAC
- N_ν prop. to Beam Power, $\mathcal{L}_{\mu\mu} \nearrow P$ or P^2 (?)

TARGET AREA

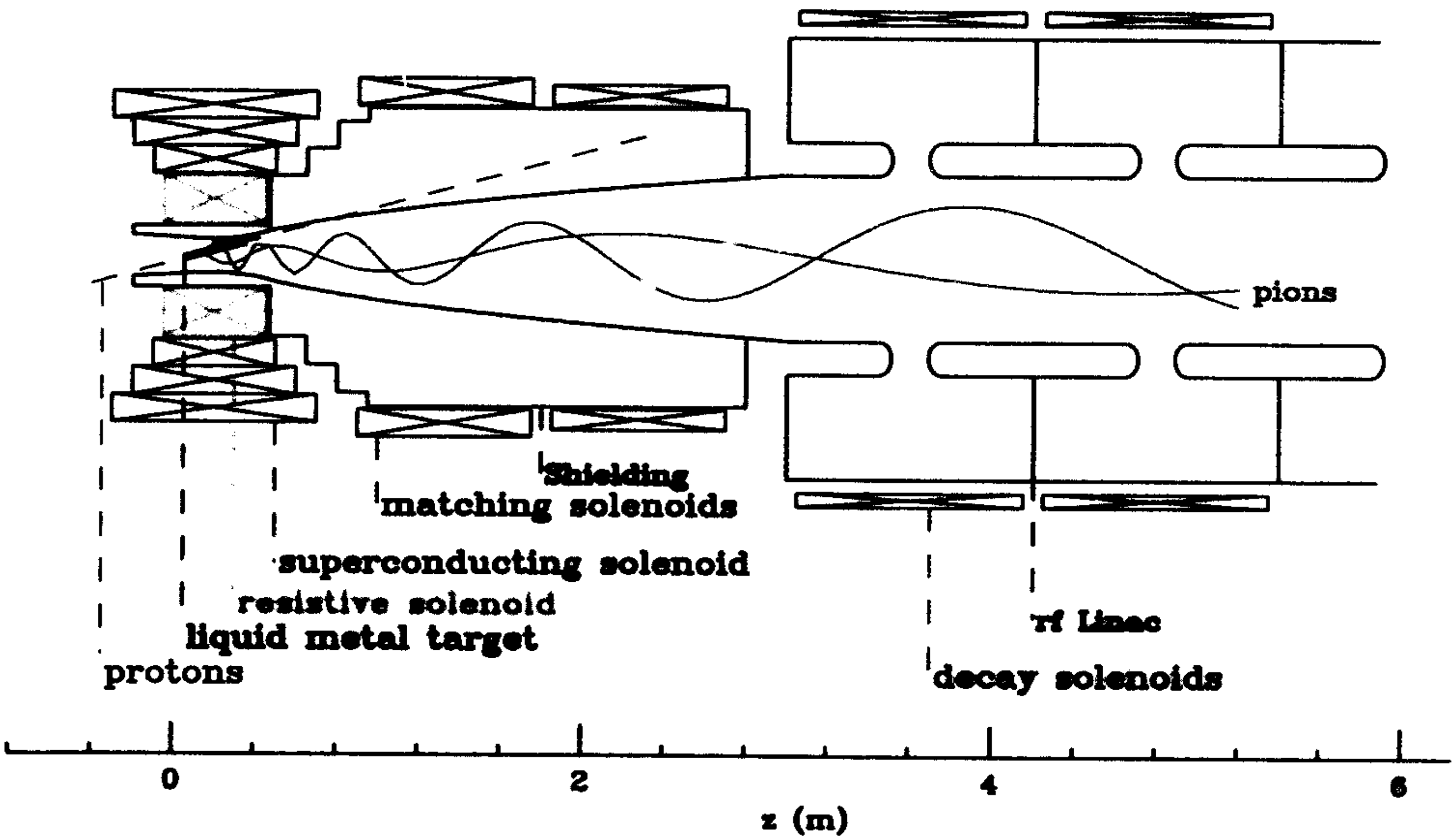


MAIN OPTION	OTHER OPTIONS
→ • Liquid MERCURY JET LIMITS BEAM POWER TO 4MW	• ROTATING SOLIDS
→ • B = 20 T, R = 7.5 cm L = 80 cm SOLENOID TAPERED TO 1.25 T, R = 40/140 cm L = ≃ 300 m !	• PULSED HORN ? ONE SIGN SOLENOID REQUIRED FOR $\mu^+\mu^-$
→ • MONOCHROMATOR = 42m LINAC, 30-60 MHz, 5-8 MV/m PULSED COPPER RF, WARM (!) CAVITIES IN B-Field + Radiation	• REDUCES MOMENTUM SPREAD TO ± 10% • ESSENTIAL FOR $\mu^+\mu^-$ • PROVIDES BETTER POLARIZATION FOR ν-FACTORY $\langle P^2 \rangle$ from $(0.28)^2$ to $(0.4)^2$

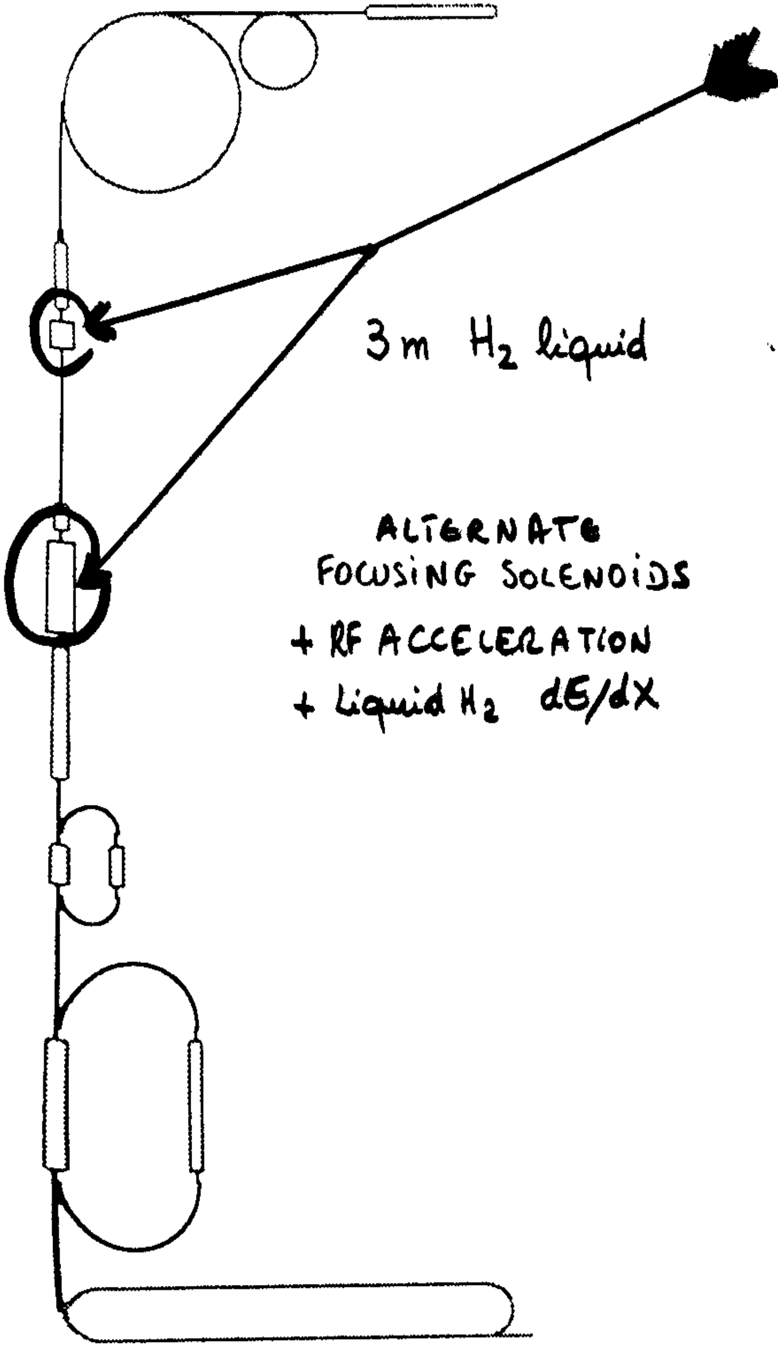
Overview of Targetry for a Muon Collider



- 1.2×10^{14} $\mu^{\pm}$/s via π-decay from a 4-MW proton beam.
- Proton pulse $\approx$ 1 ns rms for a muon collider.
- Mercury jet target.
- 20-T capture solenoid followed by a 1.25-T π-decay channel with phase-rotation via rf (to compress energy of the muon bunch).


pions
Shielding
matching solenoids
superconducting solenoid
resistive solenoid
liquid metal target
protons
rf Linac
decay solenoids
0
2
4
6
z (m)

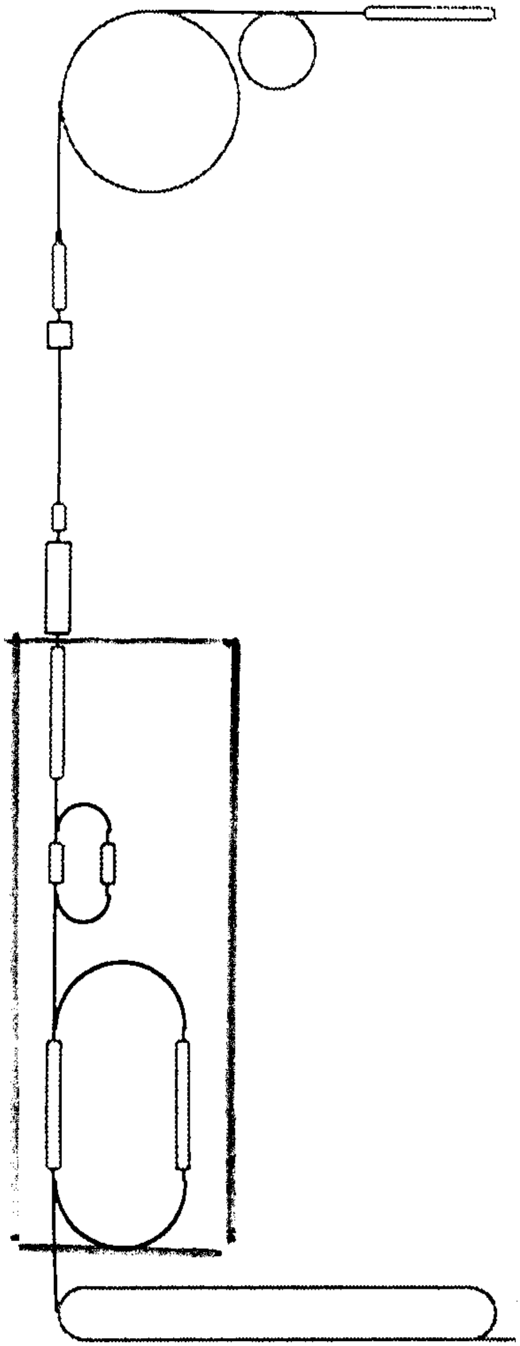
IONIZATION COOLING



- NOT ABSOLUTELY NEEDED FOR ν-FACTORY, ALLOWS MORE INTENSITY INTO MACHINES OF (REASONABLE) BEAM PIPE SIZE
  ⇒ COOLING BY FACTOR ≃ 30-100
- CRITICAL ASPECT OF μμ Collider! cooling by FACTOR 10^6 required
- NEVER DONE BEFORE.

ν-FACT = R&D FOR μ COLLIDER

MUON ACCELERATION
[KEIL]



Linac → 2 GeV

Recirculating LINAC → 7.5 GeV

[many arcs or FFAG?] → 50 GeV

heavy use of LEP SC RF cavities!

ENVIRONMENTAL RADIATION ISSUES

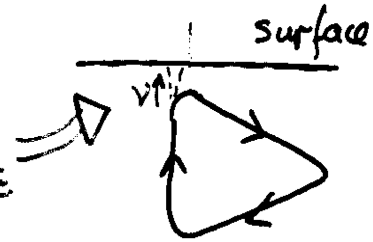
[Mokhov, Dydak, Stevenson, Silari]

OK... ¡ MUST BE TREATED VERY CAREFULLY !

* **AROUND TARGET:**
  [neutrons + photons]

  Requires
  - $\geq$ 10 m of ROCK or CONCRETE
  - AVOID AQUIFEROUS SUBSTRATE
    [T and Na_{22} → water table]

* **AROUND MUON STORAGE RING**
  [decay electrons → photons]
  + Stray muons!



THIS AREA MUST BE INSIDE SITE!

- SHIELDING OF BEAM PIPE
- HOW CLOSE CAN DETECTOR BE?
- RADIATION FROM NEUTRINOS*

* ISSUE FOR μ-COLLIDER ABOVE $E_{CM} = 4$ TeV

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

ν-FACT $\approx$ 100 x conventional $\pi \to \mu\nu$ beams

$E_\mu = 30$ GeV

x 2 FLAVOURS

\+

- well know flux, no high energy tail
- $\nu / \bar{\nu}$ asymmetries easy ($\mu^+ \to \mu^-$)
- $\bar{\nu}_\mu / \nu_e$ content depends on beam polarization

Physics :

- ν OSCILLATIONS θ_{13}, matter effects, $\not{C}\not{P}, \not{T}$
- very high flux ν beam for DIS, NC/CC ....

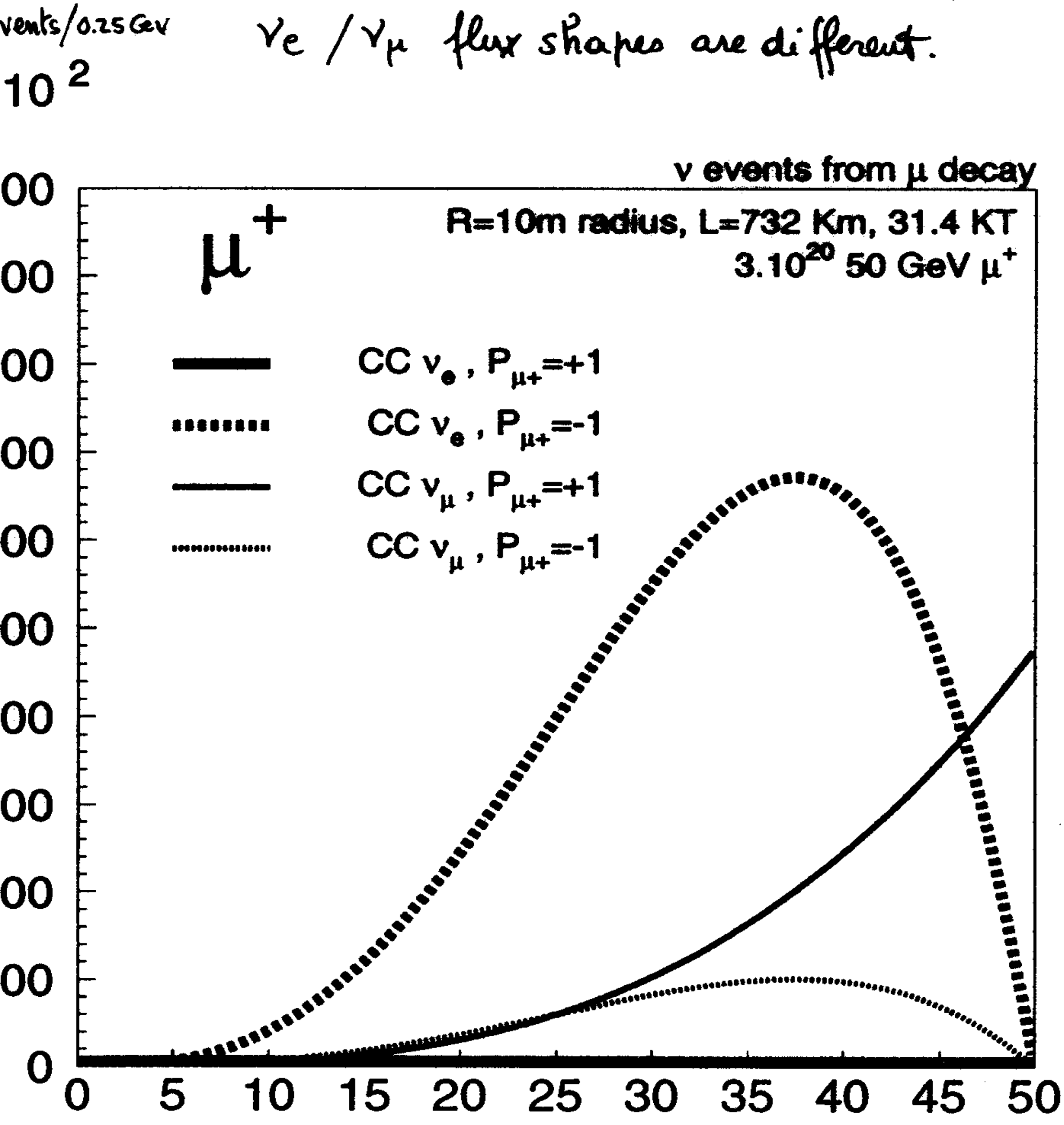
ν FLUX CHARACTERISTICS:

$\nu_e / \bar{\nu}_\mu$ event ratio reversed by switching $\mu^+ \to \mu^-$

$\vec{\mu}^+ \not\to \overleftarrow{\bar{\nu}_e}$ in Forward Direction

$\Rightarrow \mu$ POLARIZATION CONTROLS ν_e flux [28% → 40%]

ν_e / ν_μ flux shapes are different.



NEUTRINO OSCILLATIONS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{e2} ← θ_{12} (3 solutions); U_{e3} ← θ_{13} (small); $U_{\mu 3}$ ← θ_{23} (large)

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U^*_{\alpha j} U^*_{\beta j} \sin^2\left[k \, \Delta m^2_{ij} \frac{L}{E} \right]$$

Each expt is sensitive to 3 angles and 3 mass differences + possibly 1 phase

FOR BASELINES OF EARTH SIZE → Δm^2_{23} (10^{-3}) θ_{13} θ_{23}

FOR SOLAR NEUTRINOS Δm^2_{12} ($\sim 10^{-5} - 10^{-4}$) θ_{12}

ON EARTH:

$$P(\nu_e \to \nu_\mu) = \sin^2 \theta_{23} \; \sin^2 2\theta_{13} \; \sin^2\left(k \frac{\Delta m^2_{23} \cdot L}{E_\nu}\right)$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4 \theta_{13} \; \sin^2 2\theta_{23} \; \sin^2\left(k \frac{\Delta m^2_{23} L}{E_\nu}\right)$$

$$P(\nu_e \to \nu_\tau) = \cos^2 \theta_{23} \; \sin^2 2\theta_{13} \; \sin^2\left(k \frac{\Delta m^2_{23} L}{E_\nu}\right)$$

PROBABLE VALUES $\Delta m^2_{23} \simeq 3 \pm 1 \; 10^{-3}$

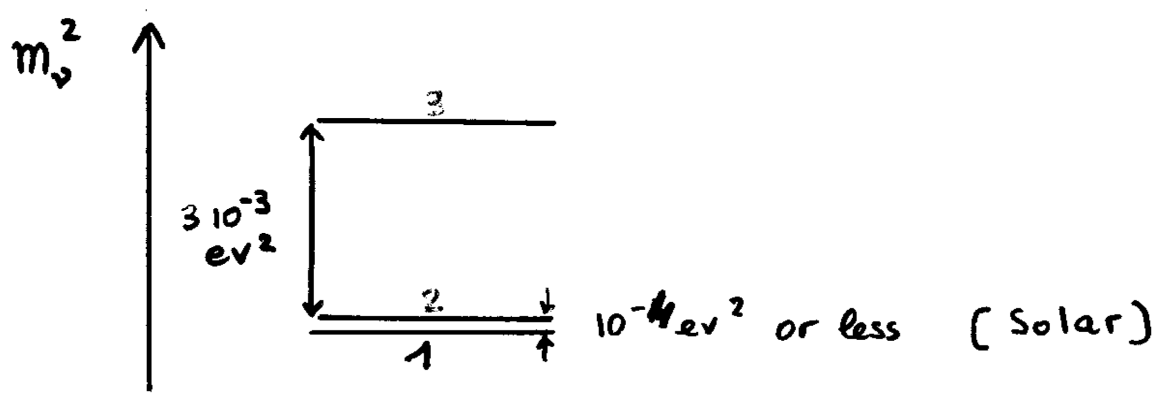
FROM SUPERK + All fits. $\theta_{23} \simeq 45°$

$\theta_{13} \sim 0 - 15°$ (best = 8° ?)

3 FAMILIES:

PROBABLE SPECTRUM (SMIRNOV, MORIOND '99)

$$\nu_1 = \nu_e + \varepsilon_{1\mu}\,\nu_\mu + \varepsilon_{1\tau}\,\nu$$
$$\nu_2 = \varepsilon_{2e}\,\nu_e + \frac{1}{\sqrt{2}}\,(\nu_\mu + \nu_\tau)$$
$$\nu_3 = \varepsilon_{3e}\,\nu_e + \frac{1}{\sqrt{2}}\,(\nu_\mu - \nu_\tau)$$



$$\Rightarrow \Delta m^2_{13} \approx \Delta m^2_{23} \simeq 3\ 10^{-3}\,eV^2$$

$\Rightarrow$ THERE ARE <u>TWO</u> $\Delta m_{ij} \simeq 3\,10^{-3}\,eV^2$!

$$\Delta m^2 = 3\,10^{-3} \Rightarrow L_{min} = 400\,km \times E_\nu$$
$$= \text{earth diameter for } E = 30\,GeV$$

- **4 Families or Sterile ν (LSND true):**

makes everything more complicated and interesting

not considered here...

At High frequency (Large Δm^2) ($L/E \simeq 500$ km/GeV

* $P\left(\nu_{e \atop \mu} \rightarrow \nu_{\mu \atop e}\right) = \sin^2\theta_{23} \quad \sin^2 2\theta_{13} \quad \sin^2\left(K\,\Delta m^2\, L/E\right)$

ATM $P\left(\nu_\mu \rightarrow \nu_\tau\right) = \cos^4\theta_{13} \quad \sin^2 2\theta_{23} \quad \sin^2\left(K\,\Delta m^2\, L/E\right)$

* $P\left(\nu_e \rightarrow \nu_\tau\right) = \cos^2\theta_{23} \quad \sin^2 2\theta_{13} \quad \sin^2\left(K\,\Delta m^2\, L/E\right)$

$\theta_{23} \approx 45° \qquad \theta_{13} = [0 \ldots\ldots 13° \ldots \rightarrow 45°]$

SUPER K $\rightarrow$ $\cos^4\theta_{13} \cdot \sin^2 2\theta_{23} \approx 1 \pm 0.15$

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* ν_e OSCILLATIONS IMPORTANT TO INVESTIGATE ν MIXING MATRIX.

\# SIGNAL EVENTS [APPEARANCE EXPT]

AVOGADRO FLUX ν/cm^2 MASS

$$\text{events} = \mathcal{N} \cdot \sigma \cdot \phi \cdot \overbrace{V \cdot \rho}$$

$$E_\nu \cdot \frac{E_\nu^2}{L^2 P_\perp^2} = E_\nu^3 / L^2$$

oscillated events: $\dfrac{E_\nu^3}{L^2} \times \sin^2\left(K\,\Delta m^2 \dfrac{L}{E}\right) \propto E.$ $\quad \left(\dfrac{L^2}{E^2}\right)$

uncertainty on BKG $\sim \sqrt{E_\nu^3/L^2}$

LOW BKG : SIGNAL $\propto E$ HIGH BKG $\sigma \propto \frac{1}{E}$

or disappearance

EXPERIMENTAL SIGNATURE OF ν_e OSCILLATIONS:

WRONG SIGN MUONS

$\mu^+ \to e^+ \; \nu_e \; \bar{\nu}_\mu$

NORMAL CC:
$$\nu_e + N \to e^- + X$$
$$\bar{\nu}_\mu + N \to \mu^+ + X$$

OSCILLATION

"EASY"!
$$\nu_e \to \nu_\mu + N \to \mu^- + X \qquad \text{hard } \mu^-$$
$$\nu_e \to \nu_\tau + N \to \tau^- + X \qquad \text{softer } \mu^-$$
$$\hookrightarrow \mu^- \nu_\tau \bar{\nu}_\mu \qquad + \text{ missing } E, P_\perp$$

ALSO

"IMPOSSIBLE" (?)
$$\bar{\nu}_\mu \to \bar{\nu}_e + N \to e^+ + X$$
$$\bar{\nu}_\mu \to \bar{\nu}_\tau + N \to \tau^+ + X$$
$$\hookrightarrow e^+ \bar{\nu}_\tau \nu_e$$

⇒ MAGNETIC DETECTORS

BACKGROUND IS $\nu_\mu + N \to c \quad \mu^-_{slow}$
$\hookrightarrow e^+ \nu s$ or $\mu^+ \nu s$

Dydak et al

BASELINE DETECTOR :

LARGE ($\geq$ 10 KT fid.)

MAGNETIZED IRON + SCINTILLATOR

~ few cm granularity.

- WRONG SIGN MUON APPEARANCE
- SOME $e^{\pm}$ DETECTION
- NC/CC

→ most sensitivities calculated on this basis only.

FURTHER CHALLENGES

$e^{\pm}$ appearance [ICARUS — Campanelli

$\tau^{\pm}$ appearance " , OPERA] — Stahlin

e of wrong sign (???) — D. Cline

$\mu^{\pm}$ Polarization influences $\nu_e/\bar{\nu}_\mu$ ratio usefulness not quantified YET.

HIGH STATISTICS + WELL KNOWN FLUX

⇒ HIGH PRECISION MEASUREMENTS OF OSCILLATION PARAMETERS

e.g. $\nu_\mu \to \nu_\mu$:

Geer

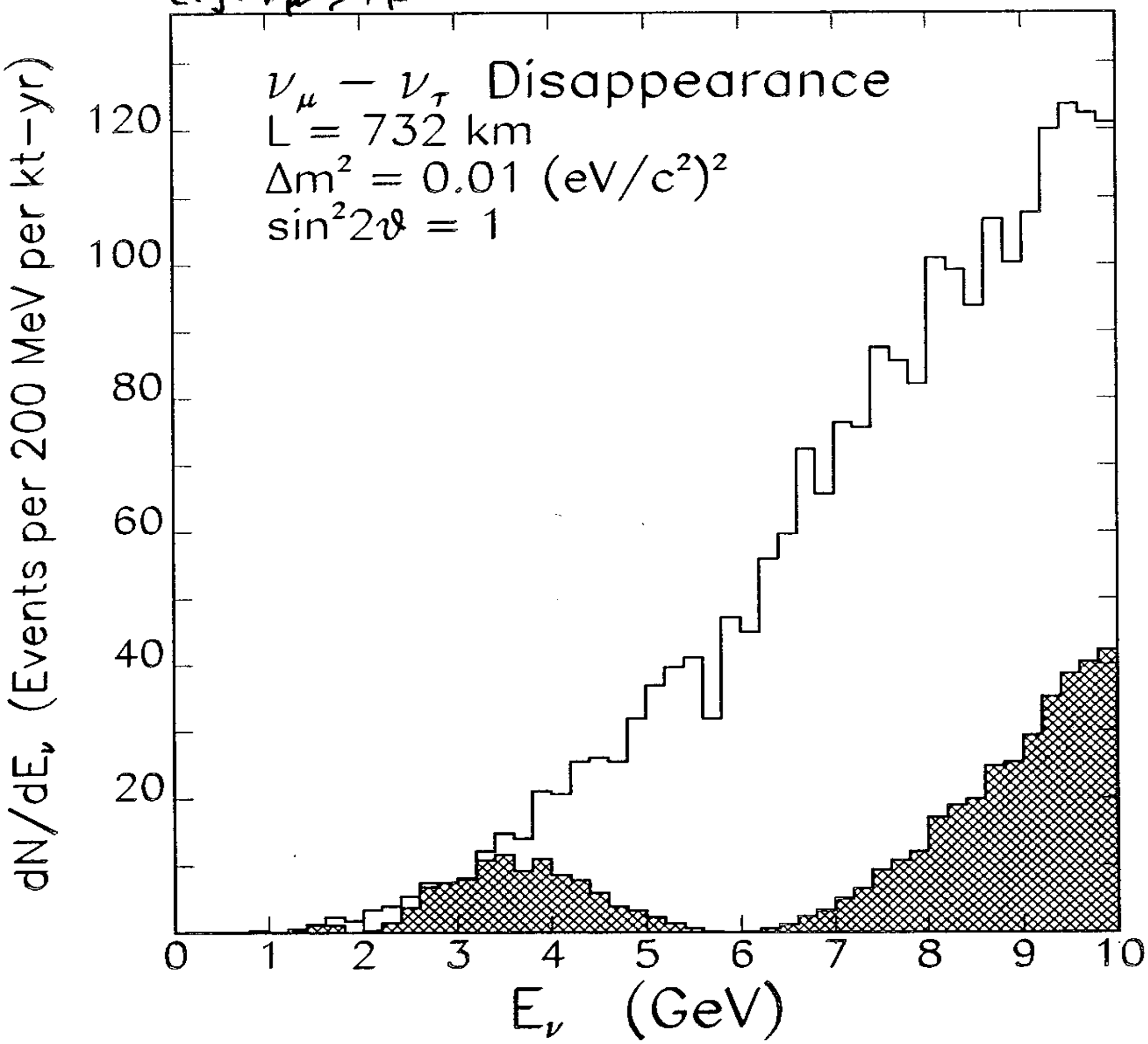


Figure 8 Predicted signal for ν_μ disappearance using a 10 GeV muon storage ring neutrino source at FNAL, pointed towards the Soudan mine in Minnesota. The open histogram is the prediction for the energy dependent CC interaction rate with no oscillations, and the shaded histogram is the prediction with oscillation parameters $\Delta m^2 = .010 eV^2$ and $\sin^2 2\Theta = 1$.

Full analysis with 3 FAMILIES OSCILLATIONS (Gavela, Hernandez, De Rujula)

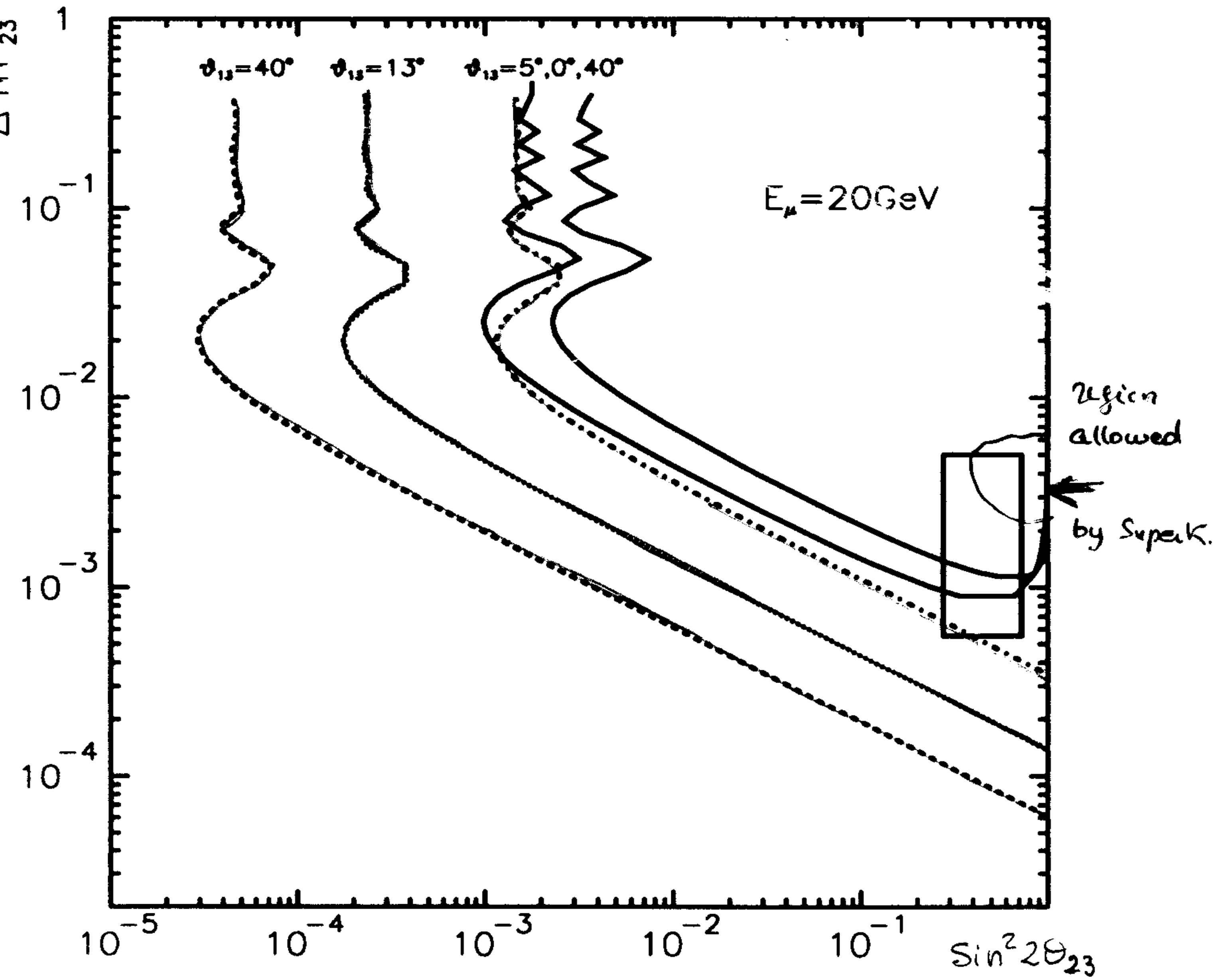
μ^- beam 20 GeV —→ 10 kT able to see μ^+/μ^-

30% of $2\cdot10^{20}$ μ's 7.30 km

Compare : μ^- Disappearance $\theta_{23}/\Delta m^2_{23}$ ālà SuperK

$\theta_{13} \in [0 - 45°]$

μ^+ (wrong sign) Appearance (from $\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+$ or $\to \bar{\nu}_\mu \to \mu^+$)



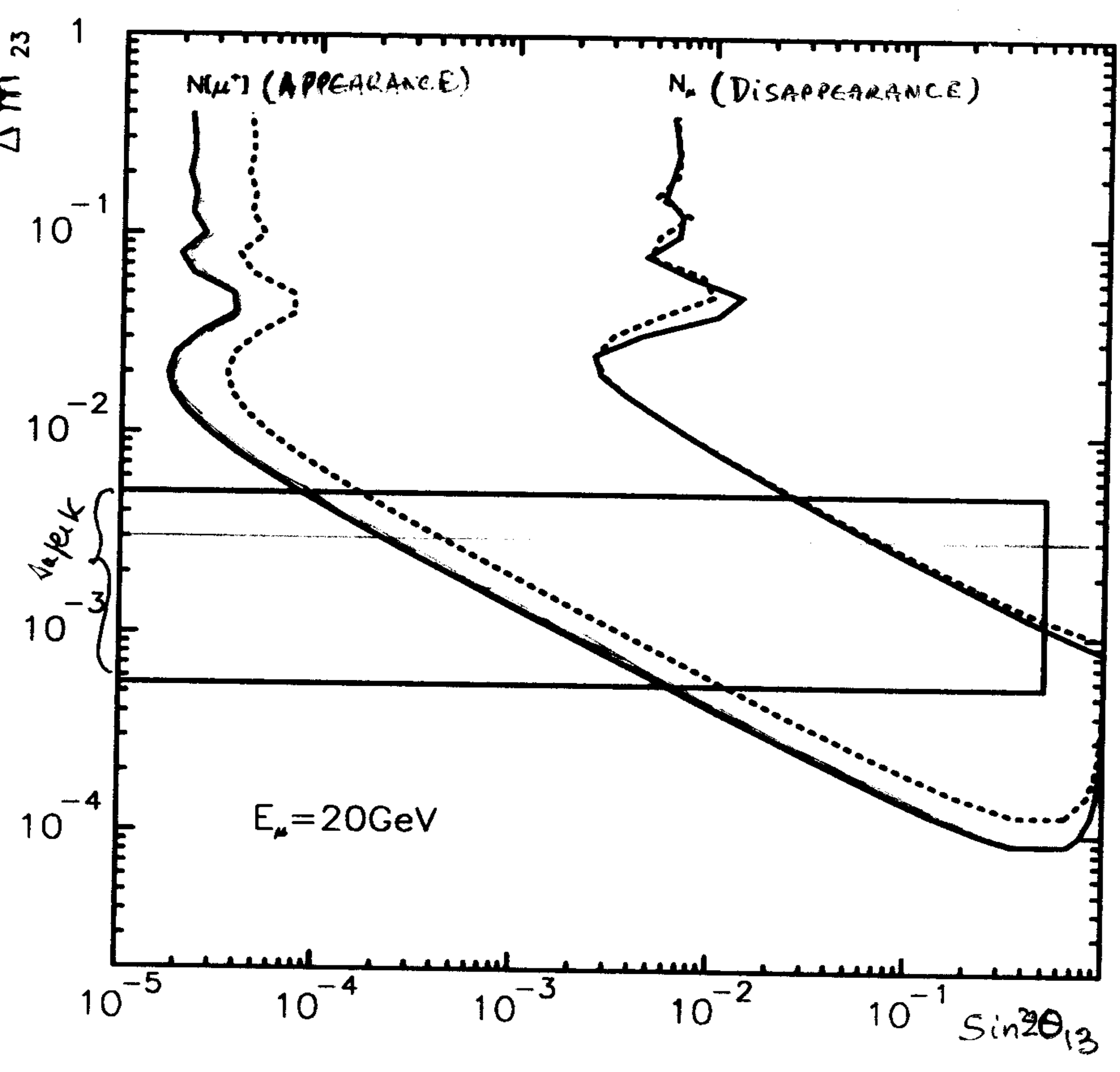
Same in $\Delta m^2_{23} / \sin^2\theta_{13}$

APPEARANCE OF μ^+ in BEAM FROM μ^- decay

(μ^+ beam would be better here)

REACH ≈ 10^{-4} (cf Minos ~ 10^{-2})

~ precision



CP or T VIOLATION

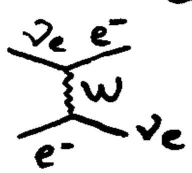
LIKE in the 3×3 QUARK MIXING MATRIX
THERE ARE 4 DEGREES OF FREEDOM.

3 ANGLES 1 PHASE. → COMPLEX MATRIX

$$A_{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu\ ) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} \approx 10^{-2\pm 1}$$

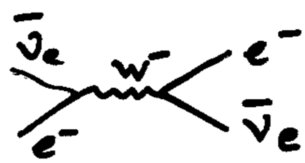
¡ HOWEVER! NEED LONG BASELINE THROUGH EARTH
⇒ MSW effect in earth.

(CC) $\nu_e + e^-$



t-channel

and $\bar{\nu}_e + e^-$



s-channel

→ OPPOSITE SIGN! ←

GENERATES FAKE CP-ASYMMETRY

$$A_T = \frac{P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)}{P(\nu_e \to \nu_\mu) + P(\nu_\mu \to \nu_e)}$$

μ^+ beam μ^- beam

Requires sign ID FOR $e^\pm$. "IMPOSSIBLE"...?

T, CP Violation

Gavela Hernandez de Rujula; Donini Romanino, Rigolin ...

Need large mixing Angle MSW sol. Sol'n.

- $$A_{CP}^{\nu_e \to \nu_\mu} \sim \frac{4 \sin 2\theta_{12} \cdot \sin\delta}{\sin\theta_{13}} \cdot \sin\left(\frac{2\,\Delta m_{12}^2\, L}{4\hbar c\, E}\right)$$

  ↑ goes as $\frac{1}{\epsilon_{13}}$ ↑ scales as $\frac{L}{E}$

- REQUIRES **APPEARANCE EXPT** ($P(\nu_e \to \nu_e)$ is T symmetric!)

  ⇒ not accessible to Reactor or solar expts.

- REQUIRES "SUPPRESSED" $\nu_e \to \nu_\mu$ transition (does not work for $\nu_\mu \to \nu_\tau$)

- $$A_{matter}^{Fake} \sim 0.7\ 10^{-6}\ \frac{L^2\,(km^2)}{E\ (GeV)}\ .\quad \text{for } \Delta m_{23}^2 = 3\,10^{-3}$$

- AT VERY LONG BASELINES MATTER EFFECTS CAN BE MEASURED

  (RESONANCE at $E \sim 10$ GeV in EARTH)

  AND SUBTRACTED FROM A SHORTER BASELINE EXPT. [Difference in composition of earth?]

(Gonzalez Garcia et al.)

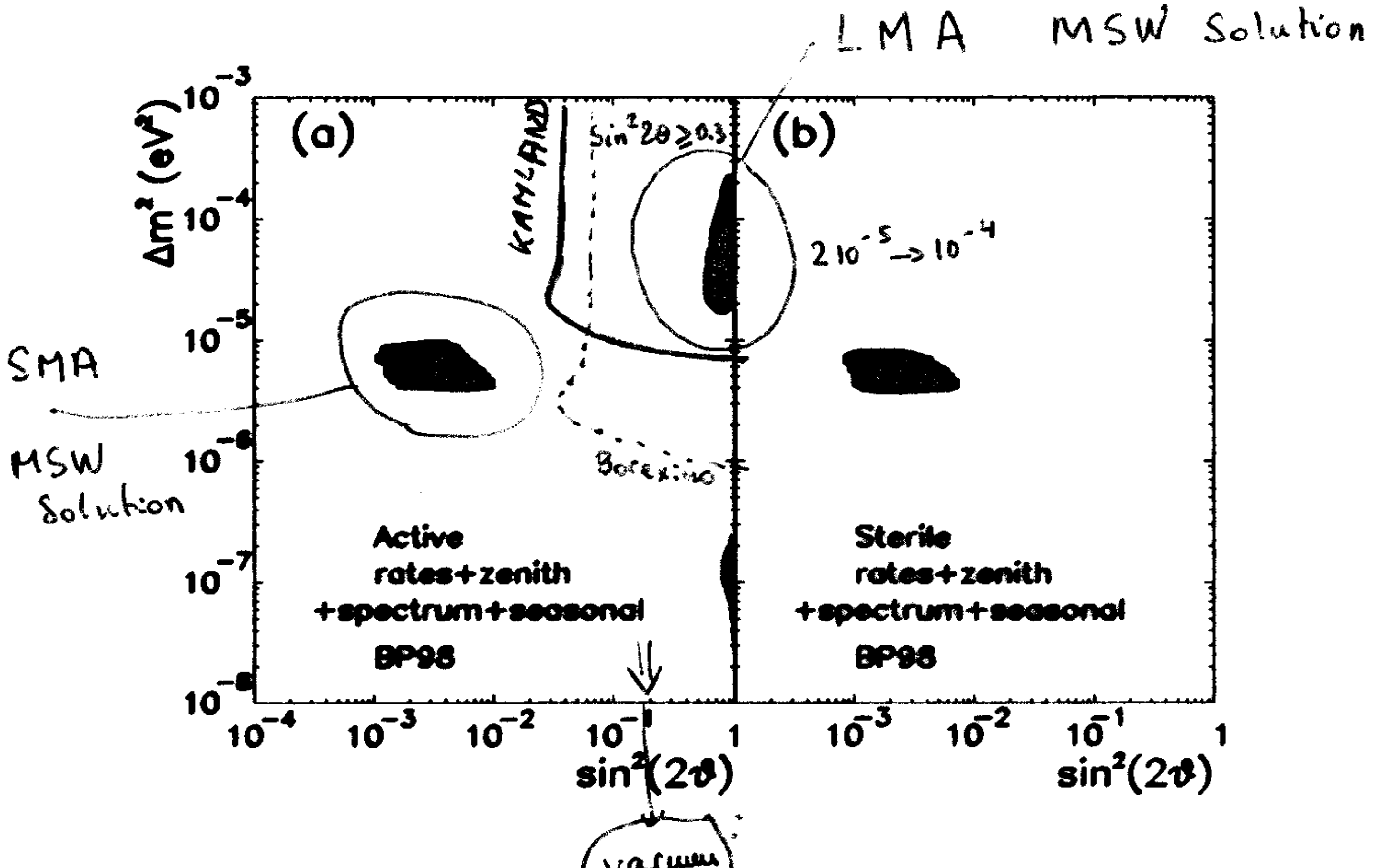


FIG. 8. Allowed regions in Δm^2 and $\sin^2\theta$ from the measurements of the total event rates at the Chlorine, Gallium and Super–Kamiokande (708-day data sample) combined with the zenith angle distribution observed in Super–Kamiokande, the recoil energy spectrum and the seasonal dependence of the event rates, for active-active oscillations (a) and active-sterile oscillations (b). The darker (lighter) areas indicate 90% (99 %)CL regions. Best–fit points in each regions are indicated by a star.

MSW + LMA Solution $\rightarrow$ CP Violation at ν FACT!

we will know in a few years from

- day-night effects in atm. neutrinos
- KAMLAND + BOREXINO (Reactor $\bar{\nu}_e$)

Domini et al hep-ph 9909254

Baseline detector
$\Delta m^2_{12} = 10^{-4} eV^2$
$E_\mu = 20 GeV$

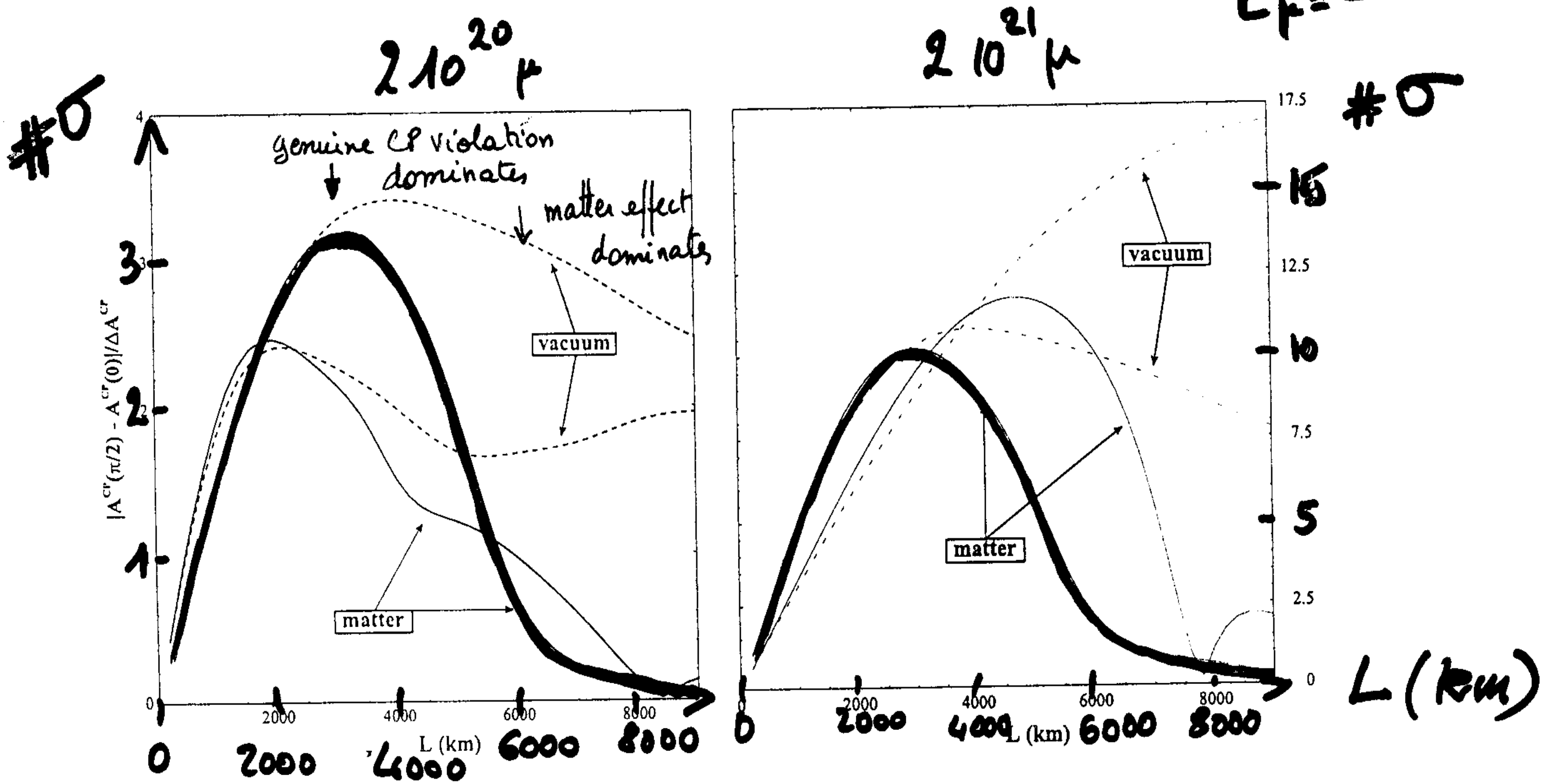


Figure 1: *Signal over statistical uncertainty for* $\left|\bar{A}^{CP}_{e\mu}(\pi/2) - \bar{A}^{CP}_{e\mu}(0)\right|$ *as a function of distance. Continuous (dashed) lines correspond to matter (vacuum) oscillations. In the left side, lower and upper curves correspond to* $E_\mu = 10,\ 20\ GeV$ *for* 2×10^{20} *useful muons/year. In the right the same is depicted for* $E_\mu = 20,\ 50\ GeV$ *and* 2×10^{21} *useful muons/year. The chosen CKM parameters are as described in the text.*

$$A_{CP} = \frac{\nu_e \to \nu_\mu - \bar{\nu}_e \to \bar{\nu}_\mu}{\nu_e \to \nu_\mu + \bar{\nu}_e \to \bar{\nu}_\mu}$$

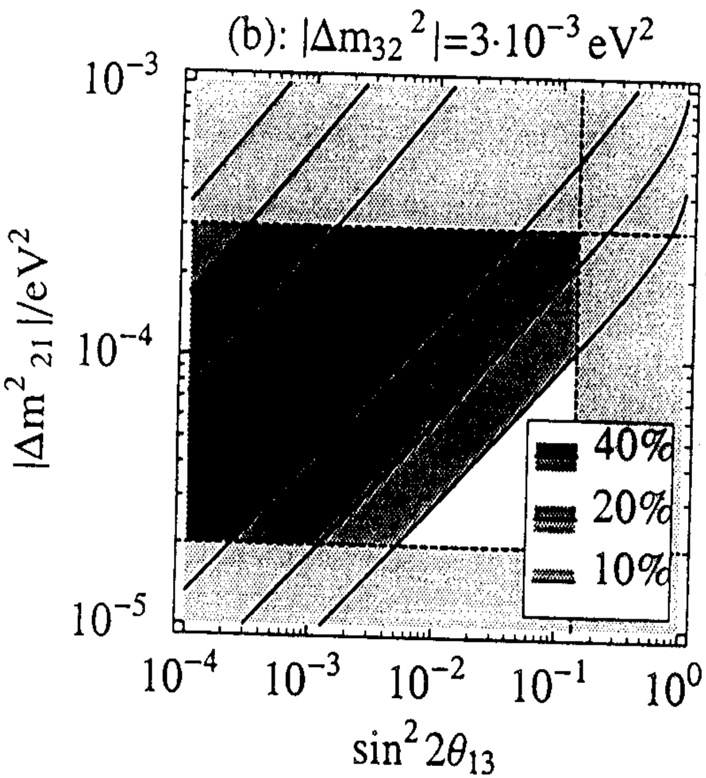
at 3000 km

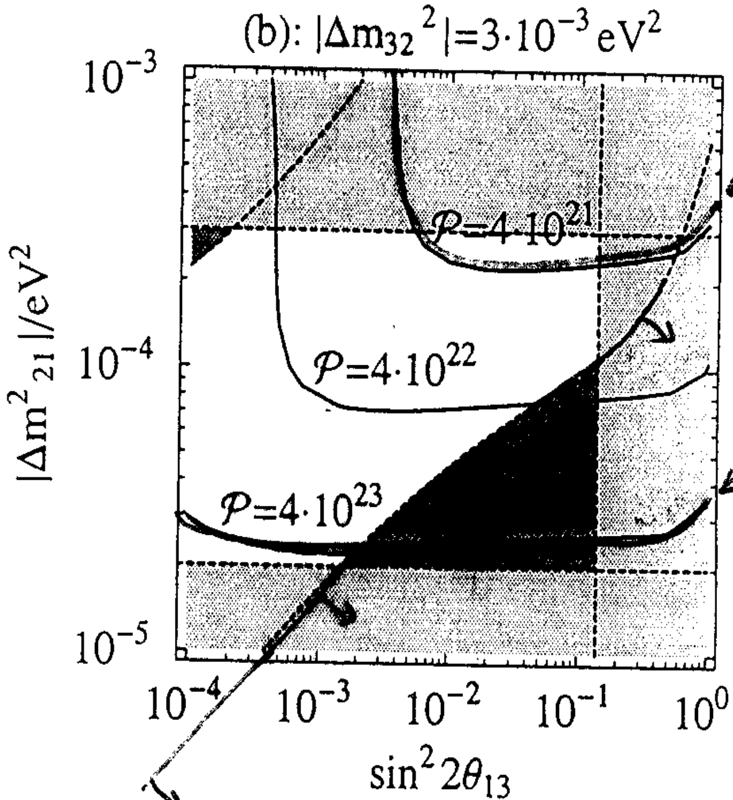
$\mathcal{P} = N_\mu \cdot \text{NKT} \cdot \sin^2\delta$ necessary to obtain 5σ

event counting, no use made of spectrum or polarization
no background.

MATTER ASYMMETRY HAS DIFFERENT DEPENDENCE UPON DISTANCE

⇒ COMPARE TWO LONG BASELINES





This is 10 KT × 4 yr ⇒ 5σ

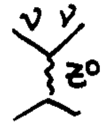
below this line matter asymmetry > CP asymmetry (after νFACT 99)

A. ROMANINO

SPECIAL FOR QUANTUM MECHANICS LOVERS!

MATTER EFFECTS

$\nu + (e, N) \rightarrow \nu + (e, X)$ (matter)

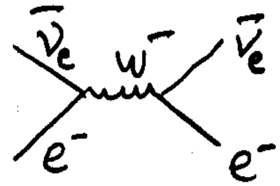


is the same for all neutrinos → diagonal, no effect

$\nu_e + e^- \rightarrow \nu_e + e^-$

add $\nu_e \rightarrow \nu_e$ transition (forward Amplitude)

$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

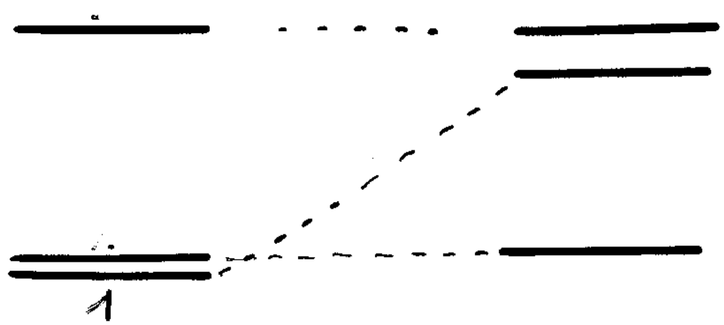


$$A = \pm\, G_F 2\sqrt{2} \cdot N_e \cdot E_\nu$$

$$H_{\nu_{e,\mu,\tau}} = \frac{1}{2P_\nu}\left\{ U \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & & \\ & 0 & \\ & & 0 \end{pmatrix} \right\}$$

$$H_{\bar{\nu}} = \frac{1}{2P_\nu}\left\{ U^* \begin{pmatrix} m & & \\ & m & \\ & & m \end{pmatrix} U^T - \begin{pmatrix} A & & \\ & 0 & \\ & & 0 \end{pmatrix} \right\}$$

⇒ New eigenstates, large modification of Δm^* and θ^*



LEVEL CROSSING (S)
+ POSSIBLE RESONANCE (S)

AT 10 GeV ≈ E_ν RESONANCE FOR
$\Delta m^2 = 3\ 10^{-3}\ eV^2$!

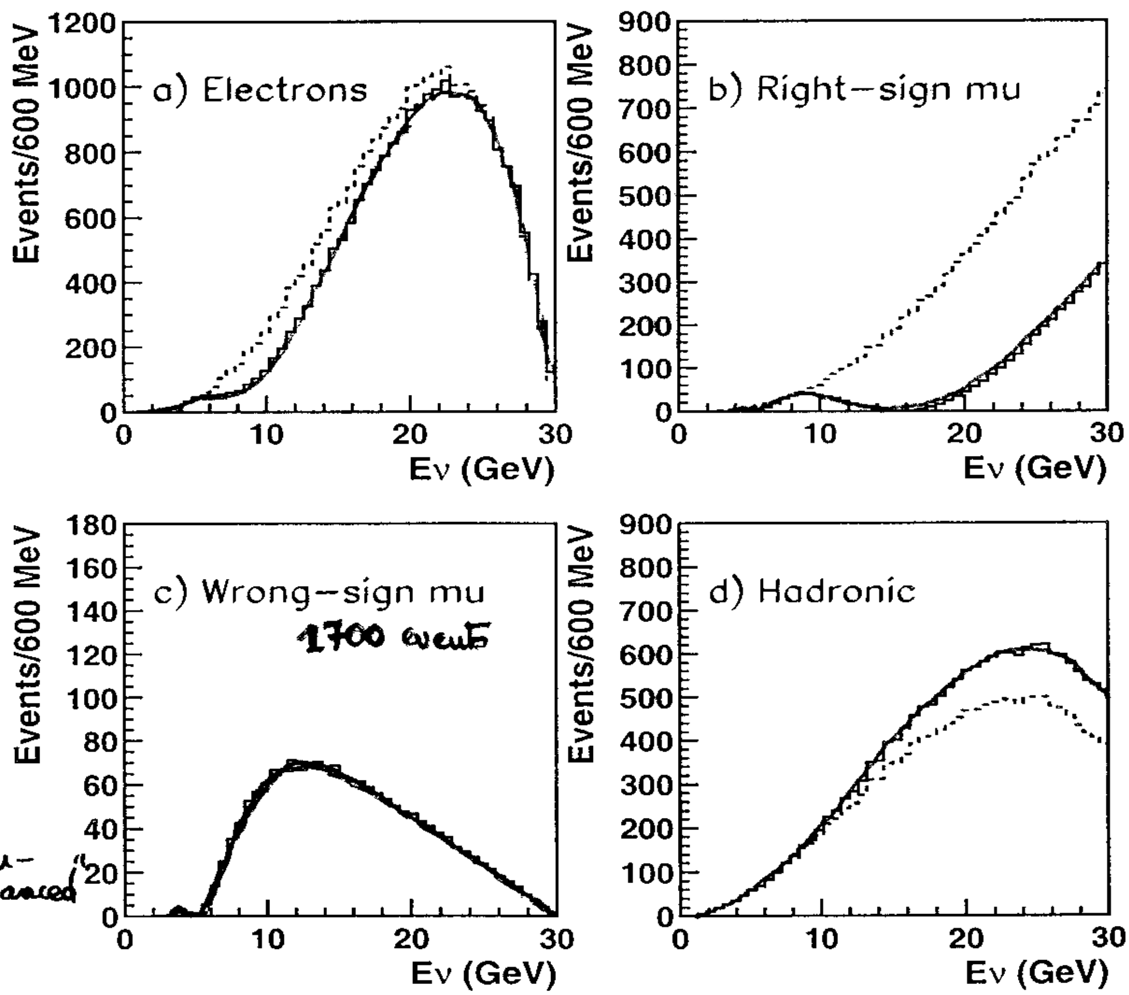
➡ ENERGY AND DISTANCE – DEPENDENT MODIFICATION OF TRANSITIONS

➡ FAKE CP ASYMMETRY $\nu_e \to \nu_\mu \neq \bar{\nu}_e \to \bar{\nu}_\mu$

REQUIRES { DIFFERENT SIGNS ν_e and $\bar{\nu}_e$ (switch $\mu^- \leftrightarrow \mu^+$, easy)
DIFFERENT LENGTHS

Oscillated Spectra

μ^+ beams $\rightarrow \nu_e \bar{\nu}_\mu$



$\nu_e \rightarrow \nu_\mu$ is "matter-enhanced"

10 kT ? 5… km

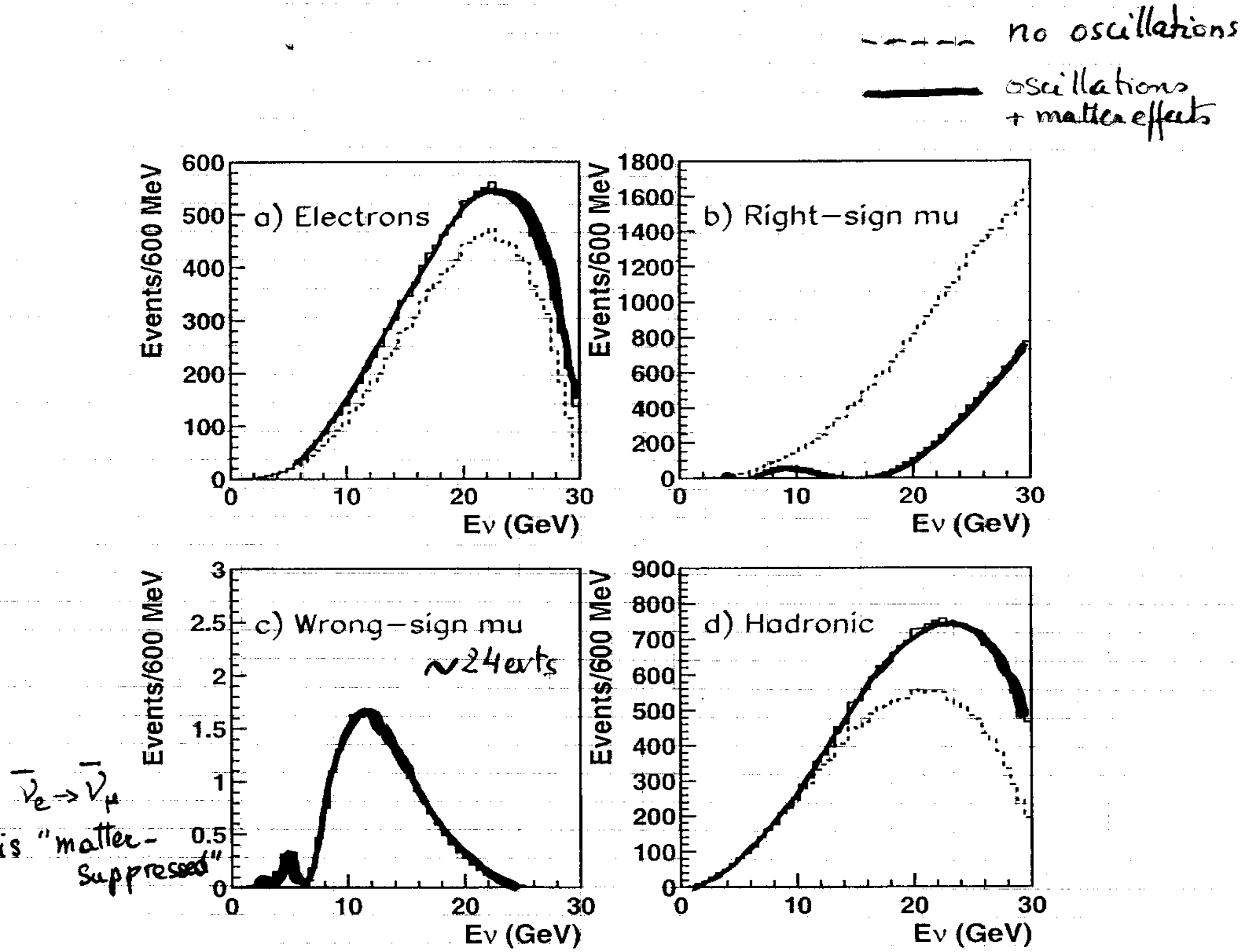
$\sin^2\theta_{23} = 0.5$

$\sin^2\theta_{13} = 0.025$

Campanelli et al (ICARUS)

Oscillated Spectra

μ^- beams $\rightarrow \bar{\nu}_e \nu_\mu$



10 kT 6500 km (BNL → Gran Sasso) 10^{21} μ decays

$\sin^2\theta_{23} = 0.5$ $(\theta_{23} = 45°)$

$\sin^2\theta_{13} = 0.025$ $(\theta_{13} = 9°)$

Campanelli Bueno Rubbia (ICARUS)

LONG BASELINE ~ 700 km

$\Downarrow$

very precise measurements of

- θ_{13} ($\nu_e \to \nu_\mu$)
- $\begin{cases} \theta_{23} \\ \Delta m_{23} \end{cases}$ (ν_μ disappearance)

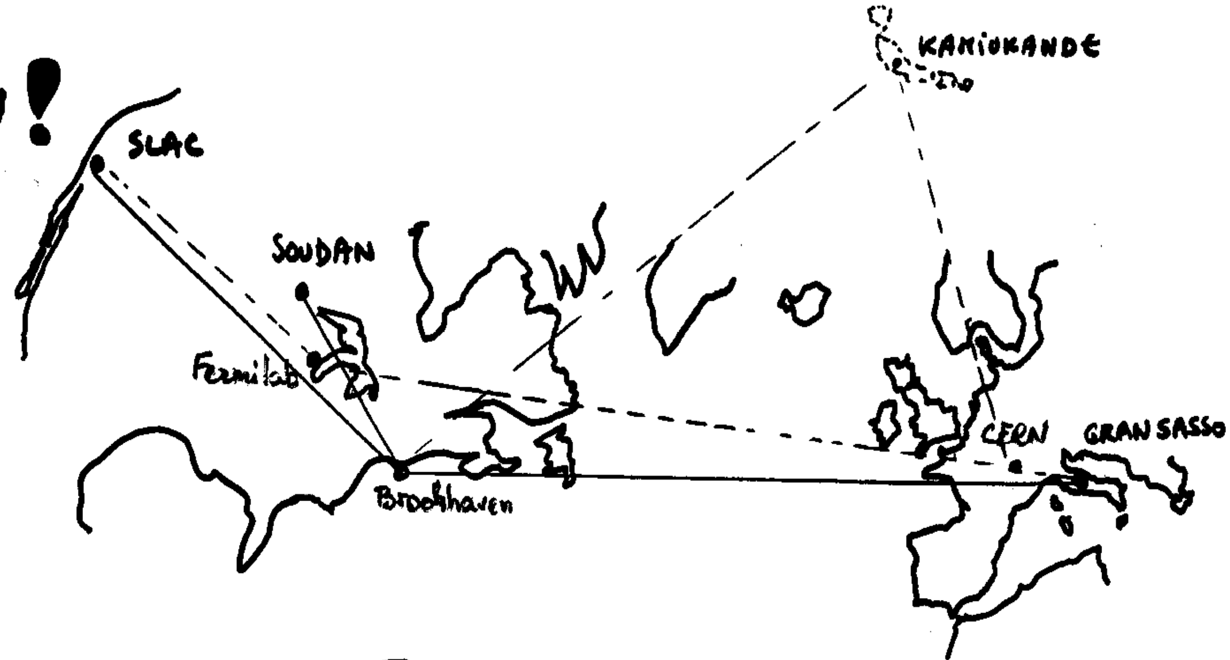
VERY LONG BASELINE ($\gtrsim 3000$ km)

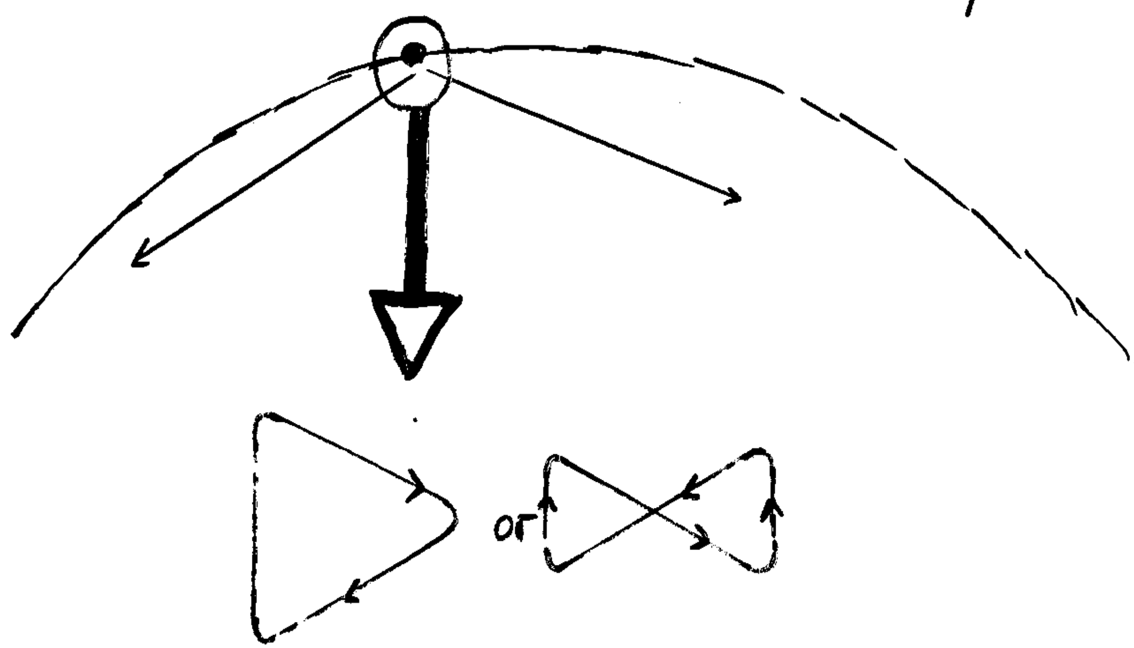
$\Downarrow$

matter oscillations (MSW)

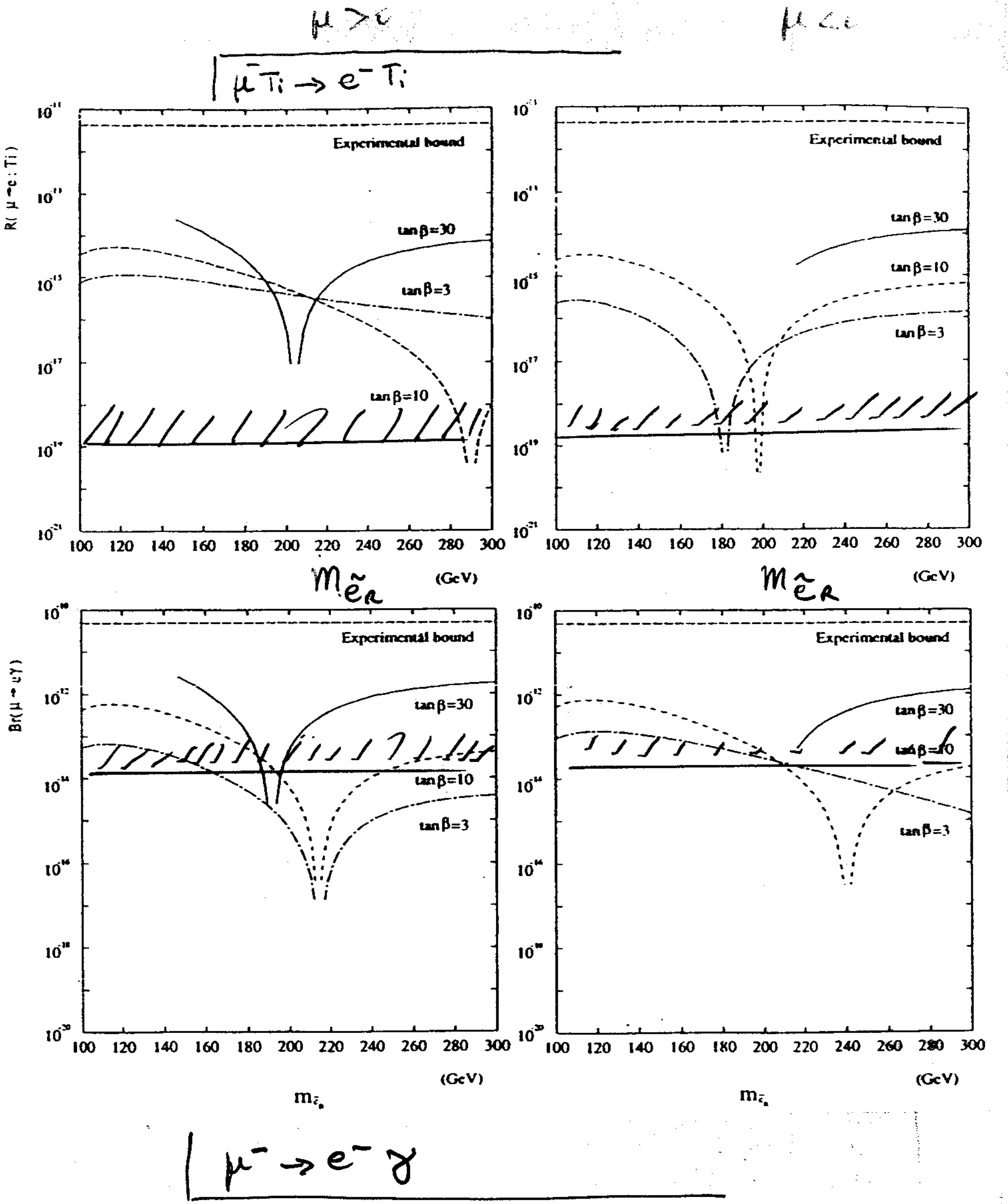
CP, T violation !

A WORLD MACHINE!





triangle or "Bowtie"



μ→e TRANSITIONS FROM SUSY LOOPS.

Hall Barbieri, Hisano ....

ν-FACT UPGRADE TO

PRECISION MUON COLLIDER

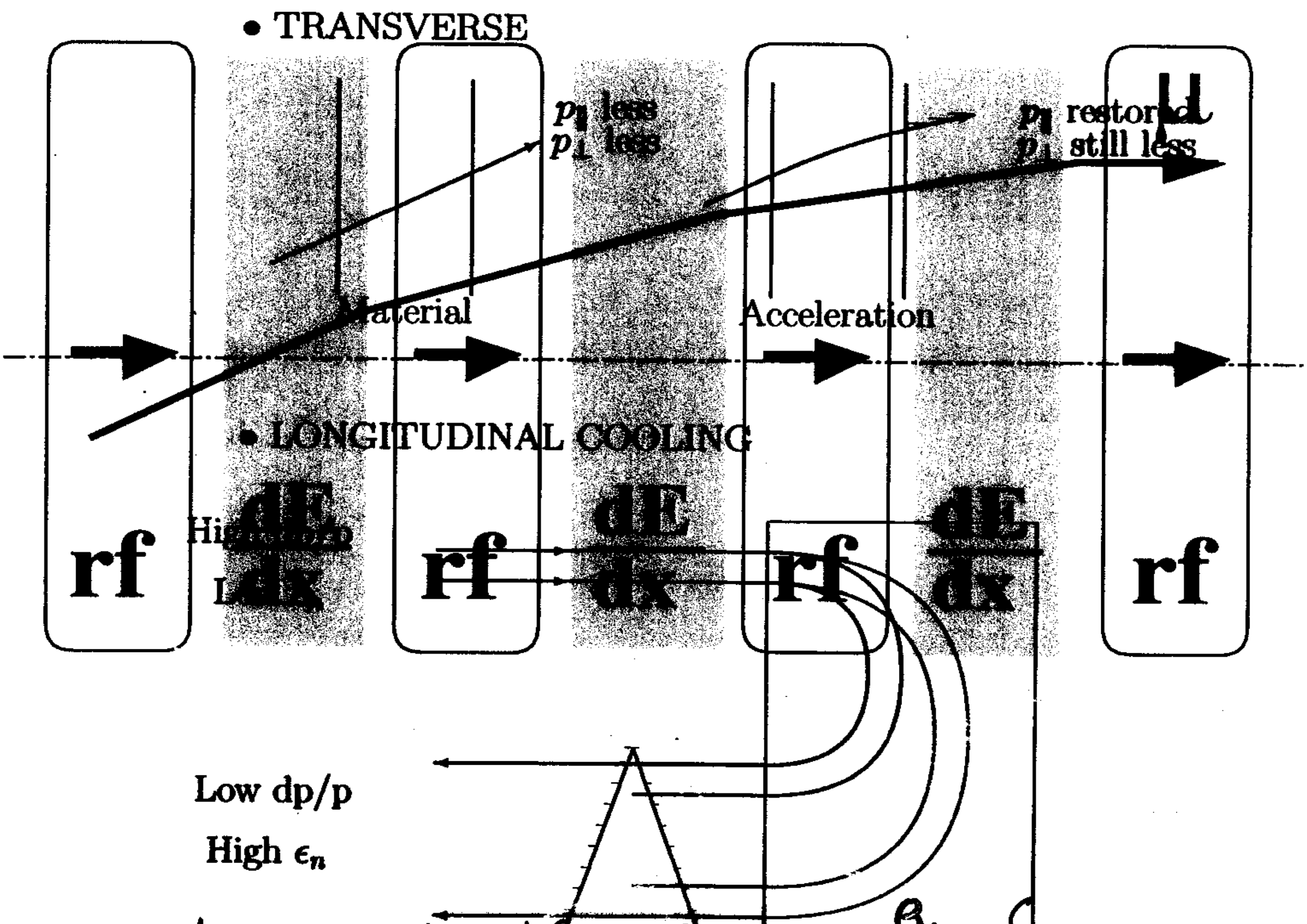
- more cooling
- μ^+ <u>and</u> μ^- SIMULTANEOUSLY
  (or within $\lesssim 1\,\mu s$)
- ONE BUNCH OF μ^+ and μ^-
- COLLIDER.

LIKE ALL lepton colliders in energy range 100 – 1000 GeV, physics case very dependent on FINDINGS FROM LHC

- HIGGS FACTORY $E_{CM} = M_h \in [110 - 140\ \text{GeV}]$
- SUSY HIGGS FACTORY $E_{CM} \approx M_A, M_H$

Ionization Cooling

IONIZATION COOLING



$$\frac{d\varepsilon_n}{dx} = -\frac{1}{\beta^2}\frac{dE_\mu}{dx}\frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp \cdot C}{2\beta E_\mu m_\mu X_0}$$

reduce $\frac{\Delta p}{p}$ 3 10^{-5} !

$\beta_\perp$ = localisation au points de $\frac{dE}{}$

but INCREASE $\sigma_x \sigma_y$ → decrease $\mathcal{L}$.

⇒ Luminosity ∝ B^2 at last cooling stage!

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. (From the muon collider collaboration)

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

LUMINOSITY CONSIDERATIONS

$$\mathcal{L} = f \cdot \frac{N_{\mu^+} \cdot N_{\mu^-}}{4\pi \sigma_x \sigma_y} \qquad \sigma_x = \sqrt{\varepsilon_x \beta_x^*}$$

- β^* cannot usefully be smaller than BUNCH LENGTH.
- f = # collisions / second

$$= \left(\frac{\tau_\mu \cdot \beta\gamma c}{2\pi \langle R \rangle} \right) \times \text{ \# fills / second.}$$

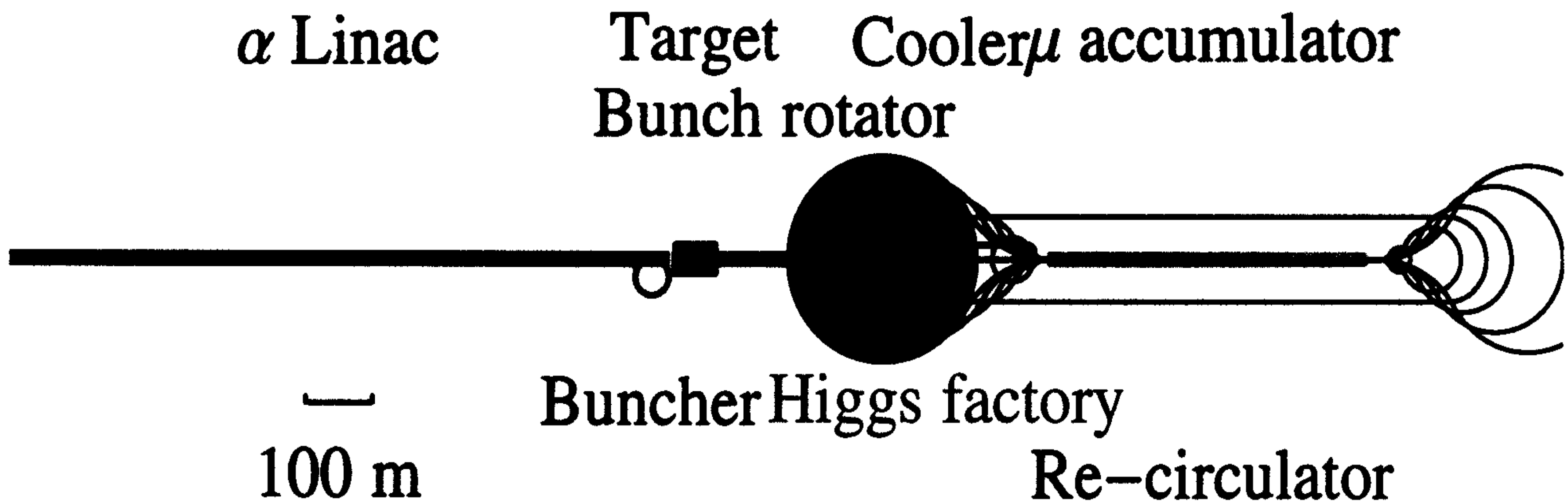
lifetime expressed
in # turns in collider
⇒ Strong B field in ring.

⇒ For given # $\mu^\pm$/second, optimise $\mathcal{L}$, without reaching beam-beam limit [WHICH MIGHT BE MUCH HIGHER THAN IN e^+e^- RINGS]
(then beams blow up and luminosity ↓.)

⇒ more μ/bunch at lower frequency

typical 15 Hz $4 \; 10^{12}$ μ/bunch

⇒ NEED BOTH SIGNS EQUALLY
[α instead of p?]



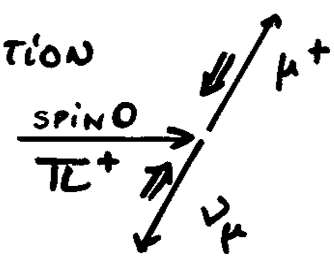
Tentative layout of a Higgs factory

¡ "BEWARE: MARVEL !"

ENERGY CALIBRATION

1. muons are naturally POLARIZED

PARITY VIOLATION



⇒ 100% LEFT-HANDED μ^+ π rest f

BOOST → $P_L^{\mu^+} = -28\%_{LAB}$

[MOMENTUM SELECTION → $P_L^{\mu^+} \nearrow -70\%$

(2.) POLARIZATION IS HARD TO DESTROY

3. POLARIZATION PRECESSES IN STORAGE RING

$$\#\ \text{PRECESSIONS/TURN} = \nu_S = \frac{E_\mu}{m_\mu} \cdot \frac{g-2}{2} = \frac{E[\text{GeV}]}{90.6223(6)}$$

200 times slower than e^+! (for m_μ); $\frac{g-2}{2} \sim \frac{\alpha}{2\pi}$

SLOW, EXPLAINS (2)

4. $\mu^+ \to e^+ \nu \nu$ (PARITY VIOLATION, AGAIN)

GIVE NATURAL POLARIMETER

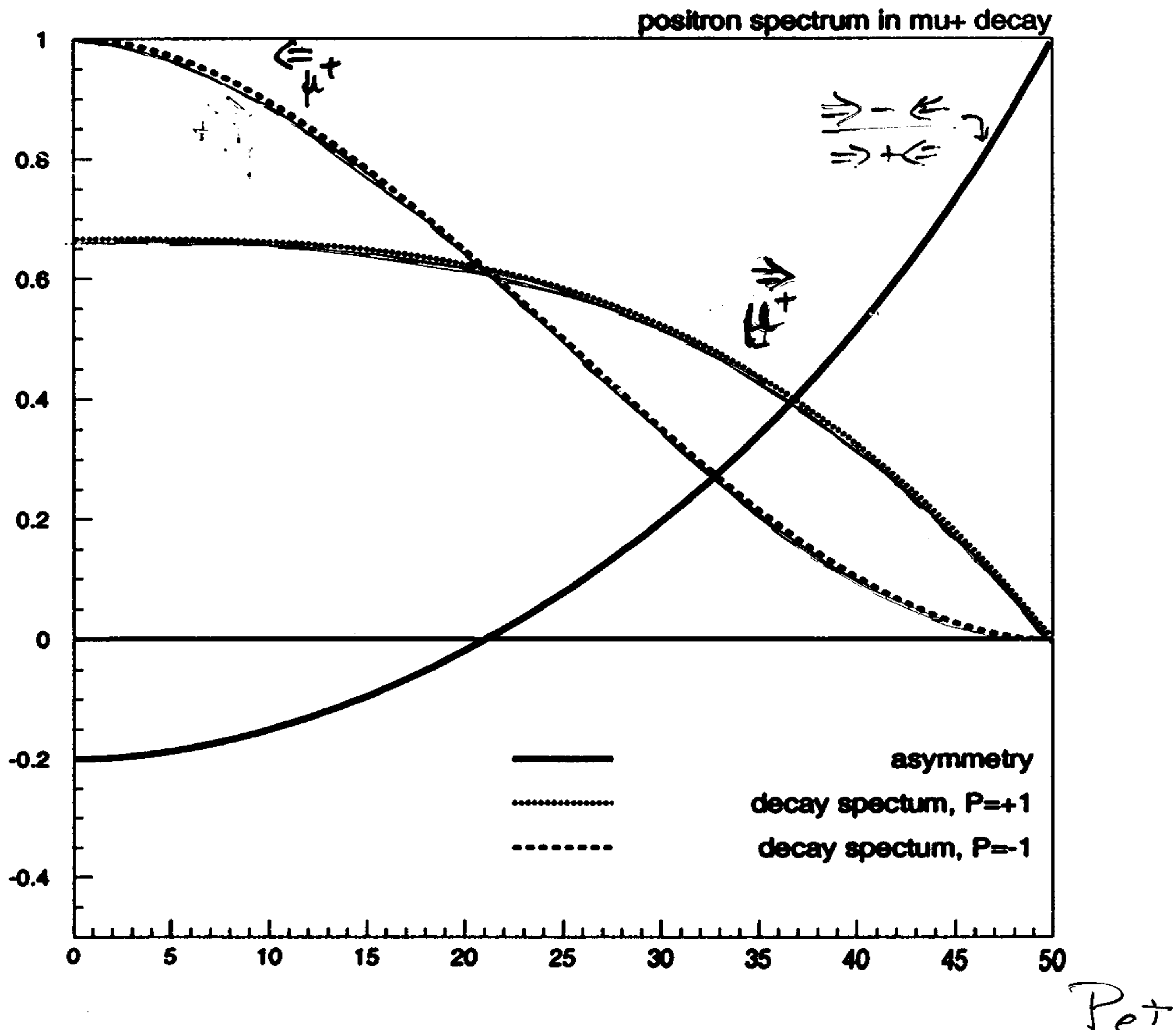
↳ E_μ

$4\,10^{12}\,\mu^+ \to 4\,10^{9}\,e^+/\text{turn}$

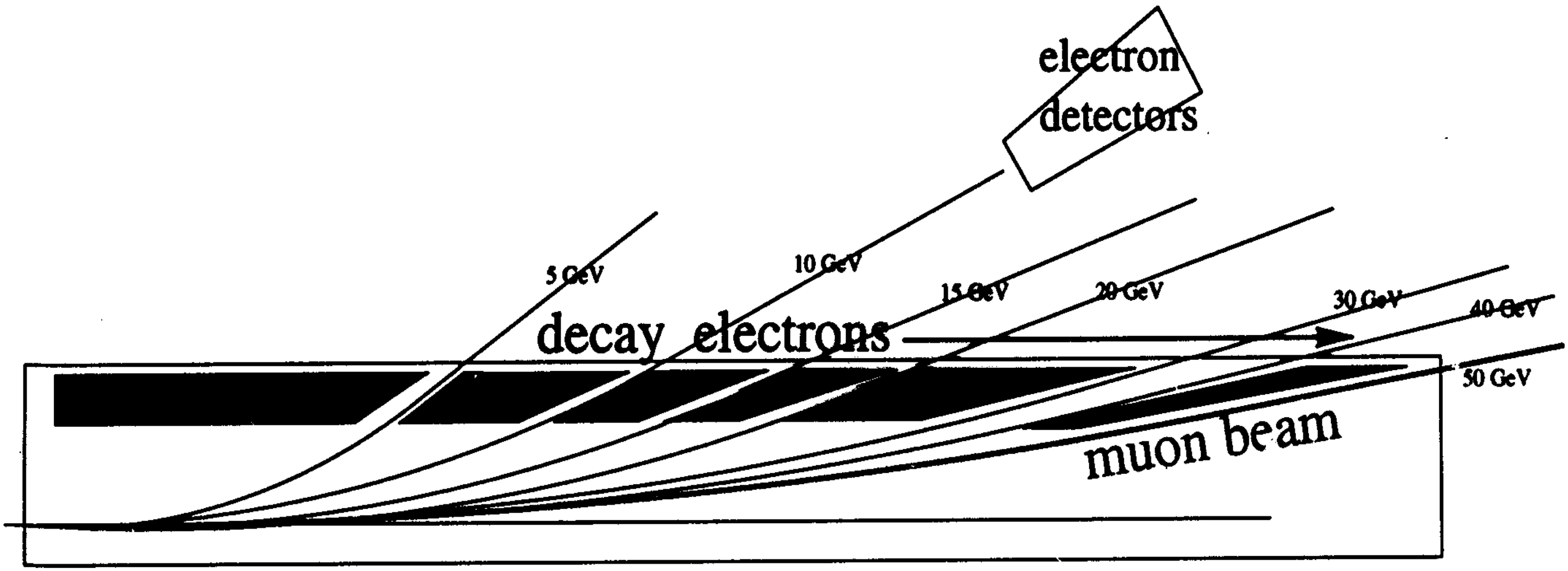
$\to \frac{2\,10^{6}}{\text{turn}}\,e^+$ in { 1 m decay length ; 30-40 GeV }

$$\nu = \frac{E_\mu}{m_\mu} \times \frac{g-2}{2} = 0.5 \text{ @ } 45\,\text{GeV}$$

50 Gev muons



muon polarimeter

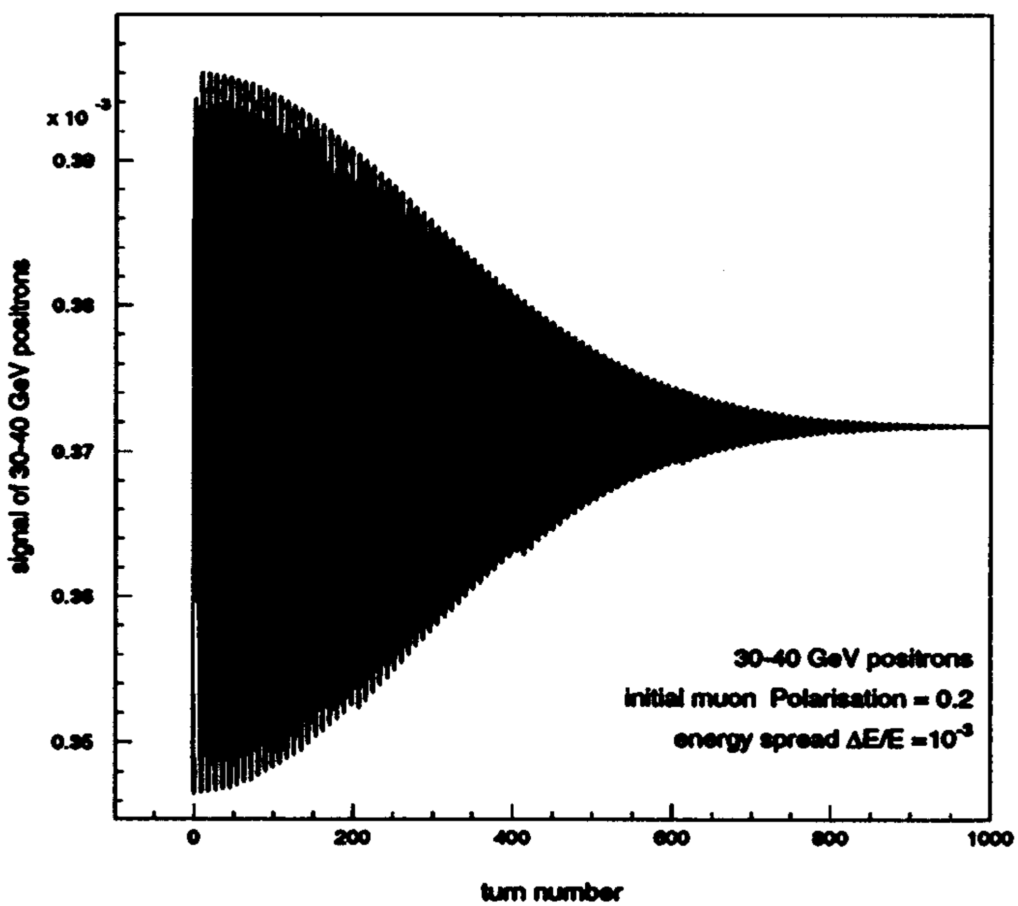


First magnet after straight section

Oscillation by turn provide

Fourier Transform of energy distribution:

$\frac{N(T)[30,40 \text{ GeV}]}{N_\mu(T)}$:



amplitude → beam polarisation

frequency → beam energy

decrease with time → energy spread

→ By fitting the polarisation precession as function of turn number, one can extract the beam energy with a precision of a few 10^{-6} for each MUON fill! (limited by present precision on $g - 2$!)

→ can also extract energy spread to similar precision (Important for extraction of width and cross-section) from decrease of polarisation with turn number.

→ since there are 10^8 fills per year, energy spectrum is exceedinlgy well known

(systematics remain to be studied) MUON collider is a perfect machine for study of narrow resonances, and thrsholds.

COLLIDER PARAMETERS

American Muon Collaboration

c of m Energy	GeV	3000	400	100		
p Energy	GeV	16	16	16		
p's/bunch	10^{13}	2.5	2.5	5		
bunches/fill		4	4	2		
rep rate	Hz	15	15	15		
p power	MW	4	4	4		
μ/bunch	10^{12}	2	2	4		
μ power	MW	28	4	1		
wall power	MW	204	120	81		
collider circ	m	6000	1000	300		
min depth (ν)	m	300	.7	.01		
rms dp/p	%	.16	.14	.12	.01	.003
rms ϵ_n	π mm mrad	50	50	85	195	280
β^*	cm	0.3	2.3	4	9	13
σ_z	cm	0.3	2.3	4	9	13
σ_r spot	μm	3.2	24	82	187	270
tune shift		0.043	0.043	0.05	0.02	.015
luminosity	$cm^{-2} sec^{-1}$	$5\ 10^{34}$	10^{33}	$1.2\ 10^{32}$	$2\ 10^{31}$	10^{31}
c of m dE/E	10^{-5}	80	80	80	7	2
Higgs/year	10^3 $year^{-1}$			1.6	4	4

cf TESLA 2.10^{34}

cf LEP $2\ 10^{30}$

cf CLIC 10^{35}

PHYSICS WITH MUON COLLIDERS

1. MUON COLLIDER CAN DO (ALMOST) EVERYTHING AN e^+e^- COLLIDER CAN DO.

⊖ LUMINOSITY IN PRESENT DESIGNS IS LOWER BY FACTOR $\gtrsim 10$.
more luminosity welcome.,

⊖ no γ-γ COLLISIONS

⊖ BACKGROUNDS FROM DECAY ELECTRONS AND STRAY MUONS ARE MORE DIFFICULT TO HANDLE.

BUT LESS THAN LHC, ACCORDING TO AMERICAN MUON COLLABORATOR I. STUMER..

⊖ NEUTRINO RADIATION

(~) POLARIZATION IS ~20% FOR BOTH BEAMS
vs 80% for e^-
difficult for e^+

2. MUON COLLIDER CAN DO THINGS AN e^+e^- COLLIDER CANNOT DO

⊕ COUPLING TO HIGGS $\approx m_\mu$ vs m_e

$\Rightarrow \sigma(\mu^+\mu^- \to H) = 40000\ \sigma(e^+e^- \to H)$

USABLE IF $M_H \lessapprox 2 M_W$ (likely, not certain)

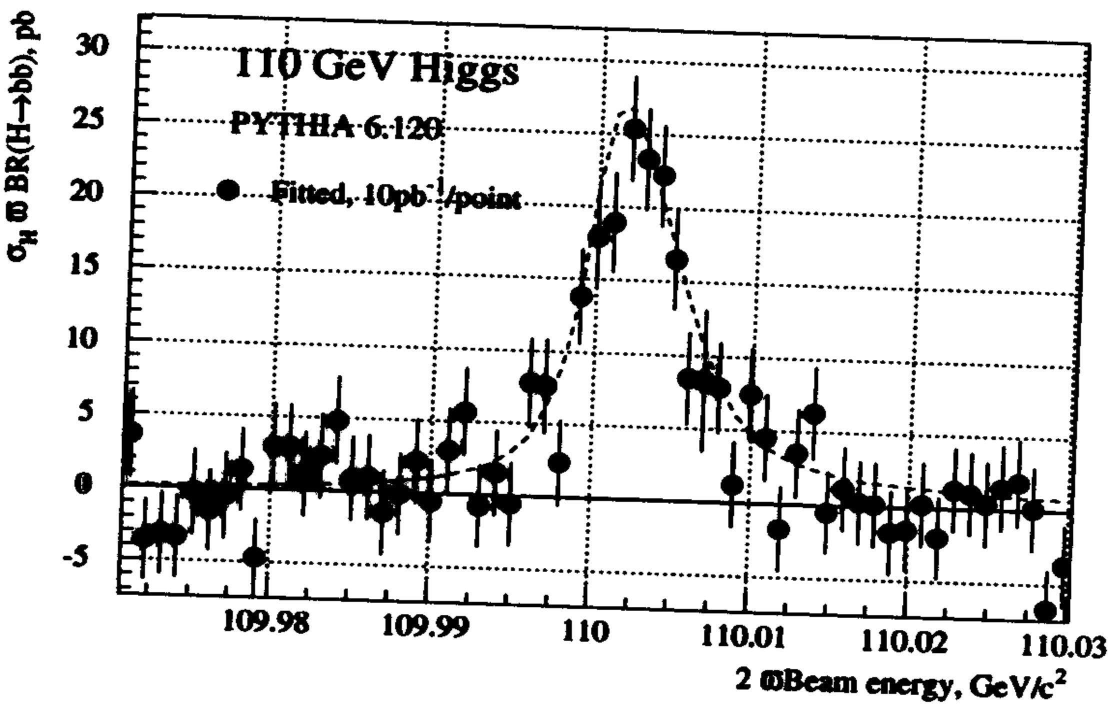
⊕ ENERGY RESOLUTION CAN BE EXCELLENT $\sigma_E/E \simeq 10^{-3}$ $\to 3\ 10^{-5}$!.

NO BEAMSTRAHLUNG

⊕ ENERGY CALIBRATION $\simeq$ INFINITELY PRECISE.

(~) $\mu \neq e$ $\to$ of course better for $\tilde{\mu}, \mu^*$..

FOR LIGHT HIGGS ($m_H \lesssim 140$ GeV)
DIRECT $\mu^+\mu^- \to H$ production



measurements of Higgs
mass ±0.1 MeV
Width ±0.3 MeV
cross-section ±1%

FOR SM HIGGS.
~ 4000 $\mu\mu \to H \to b\bar{b}$ /year
more for MSSM.

→ VERY STRONG CONSTRAINTS on Higgs couplings, SUSY phase space.

PRECISION MEASUREMENTS OF HIGGS BOSON PROPERTIES WOULD ALLOW

- TEST OF HIGGS MECHANISM
- TEST OF EXISTENCE OF OTHER HIGGSES

ex. in SUPERSYMMETRY, $\exists$ h, A, H

h	A	H
$m_h \leq 130$ GeV	CP odd scalar	CP even scalar

$\Rightarrow$ Pin down Predictions for masses and couplings of H and A.

STEP 2'

BUILD

PRECISION MUON COLLIDER 2

$$\sqrt{s} \gtrsim m_A .$$

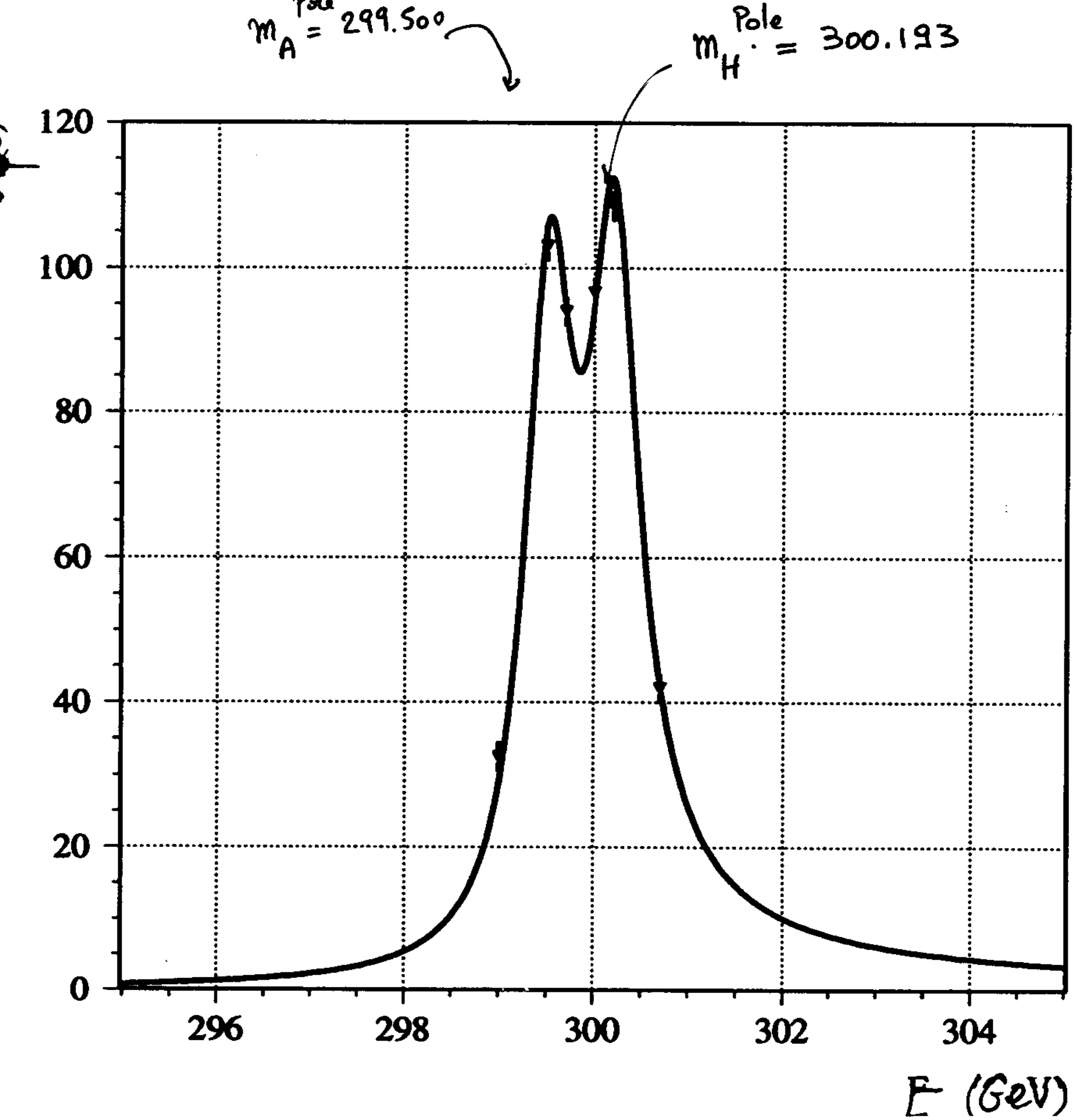
- use polarization ⇐⇒ vs ⇛⇛ to identify particles as scalars
- identify A and H as CP odd / CP even (KRAML et al)
  if eg $\tilde{\chi}_1 \tilde{\chi}_1$ vs $\tilde{\chi}_1 \tilde{\chi}_2$ production available

  measure $\Delta m_H \sim \Delta m_A \simeq 20$ MeV

  $\Delta\Gamma_H \; \Delta\Gamma_A \simeq 100$ MeV

- interference between H/A (CP violation in Higgs sector)

  σ_{peak} to ± 1%



A THREE STEP SCENARIO

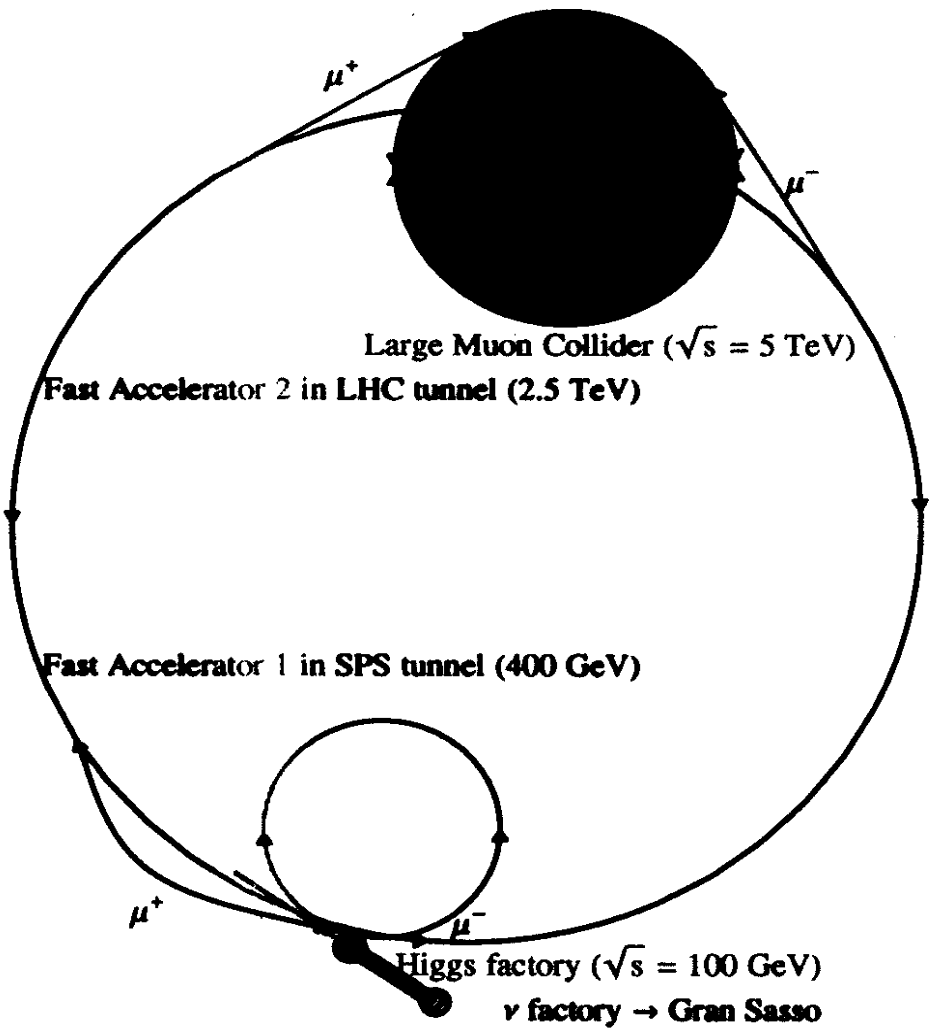
3. High energy Frontier

–aim: lepton collider at highest energies (7 TeV Ecm in LHC tunnel!)

–strong points: rather straightforward after PMC, same virtues.

–problems: neutrino radiation.

Possible layout of a MUON complex on the CERN site



NEUTRINO RADIATION

# Particles produced by ν interactions	$\propto$	E
ν cross-section	$\propto$	E
1/(beam size) $\simeq$ area reached	$\propto$	E

$\Rightarrow$ RADIATION $\nearrow$ like E^3 !
$\searrow$ like R^2

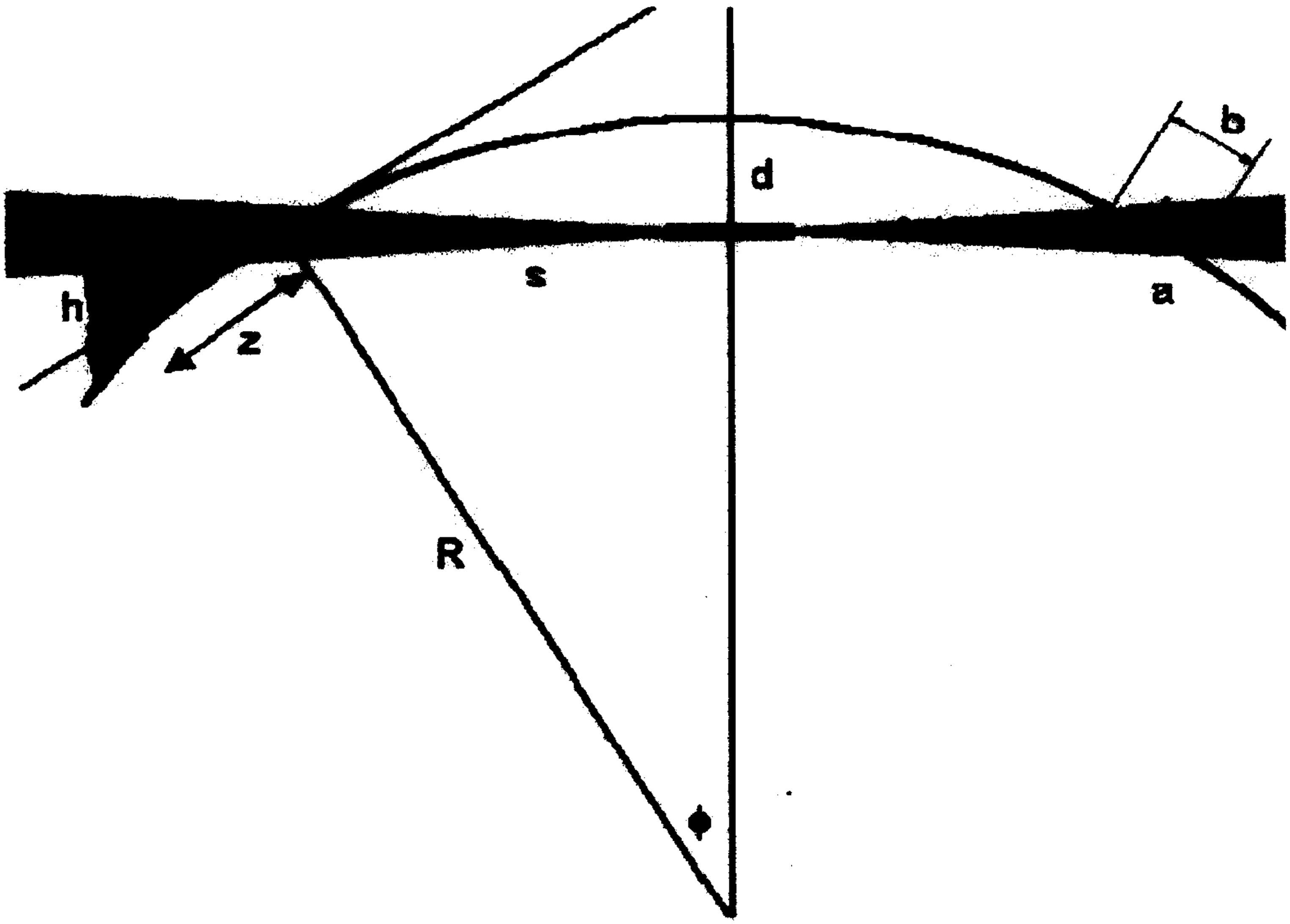
YES : RADIATION FROM NEUTRINO INT. PRODUCTS MUST BE TAKEN INTO ACCOUNT.

$\rightarrow$ Johnson / Rolandi / Silari.
have verified and CONFIRMED
AMERICAN STUDY.

FOR THE MOMENT $\rightarrow$ LIMIT AT 4 TEV ECM

E^4 !

\+ BUY LAND AT EXIT OF EARTH IN LINE WITH STRAIGHT SECTIONS



$s^2 = 2Rd - d^2$

$\sin\phi = s/R$

$h \cong z \tan\phi$

$\theta \sim 1/\gamma$

$a \cong 2\theta s$

$b \cong a/\phi$

E CoM	d (m)	s (km)	ϕ	z (km)	h (m)	θ	a (m)	b (m)
0.5 TeV	100	35	$5.6\ 10^{-3}$	10	56	$424\ 10^{-6}$	30	5300
4.0 TeV	500	80	$12.5\ 10^{-3}$	10	125	$53\ 10^{-6}$	8.5	680

Some typical geometrical features of the neutrino

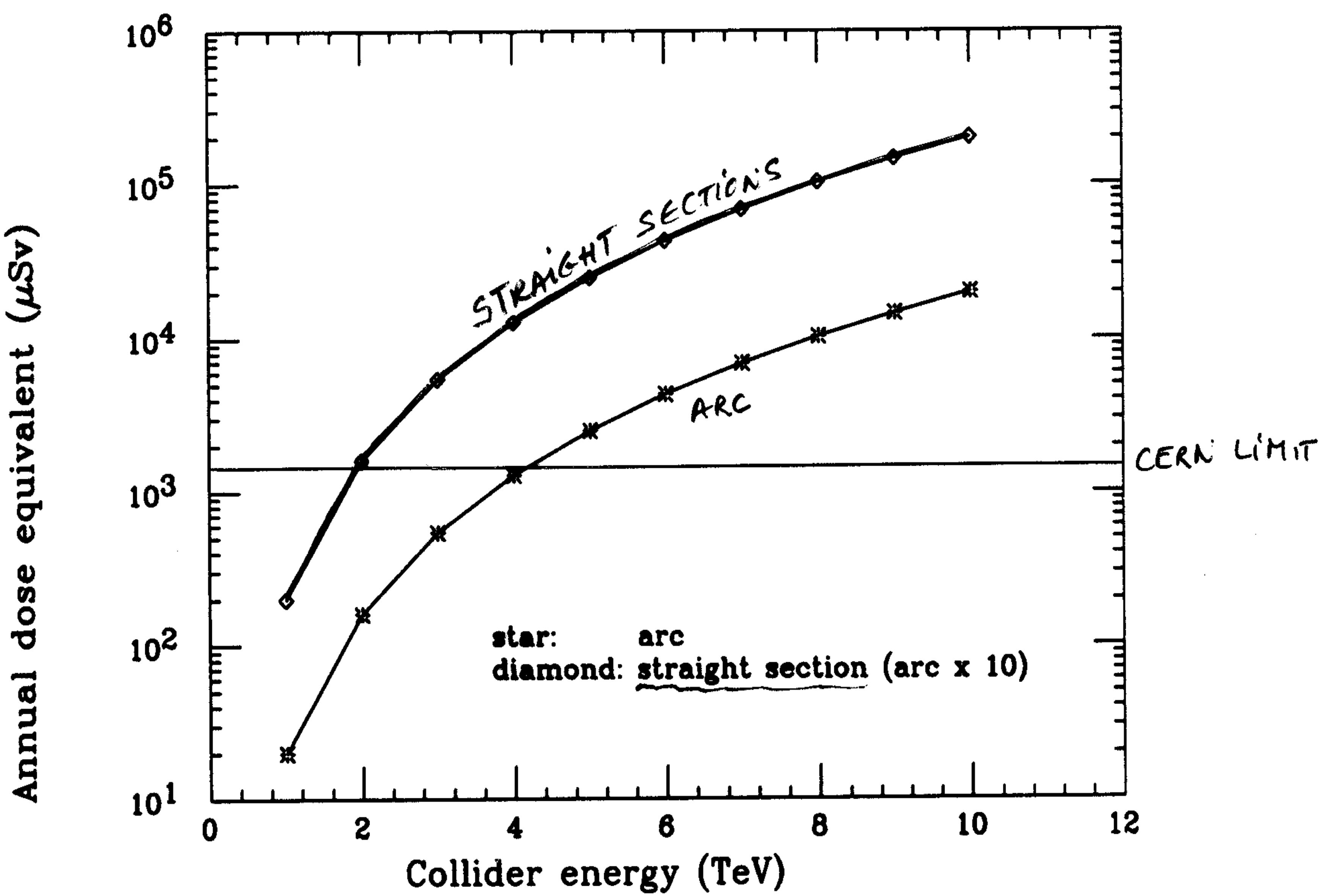


Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

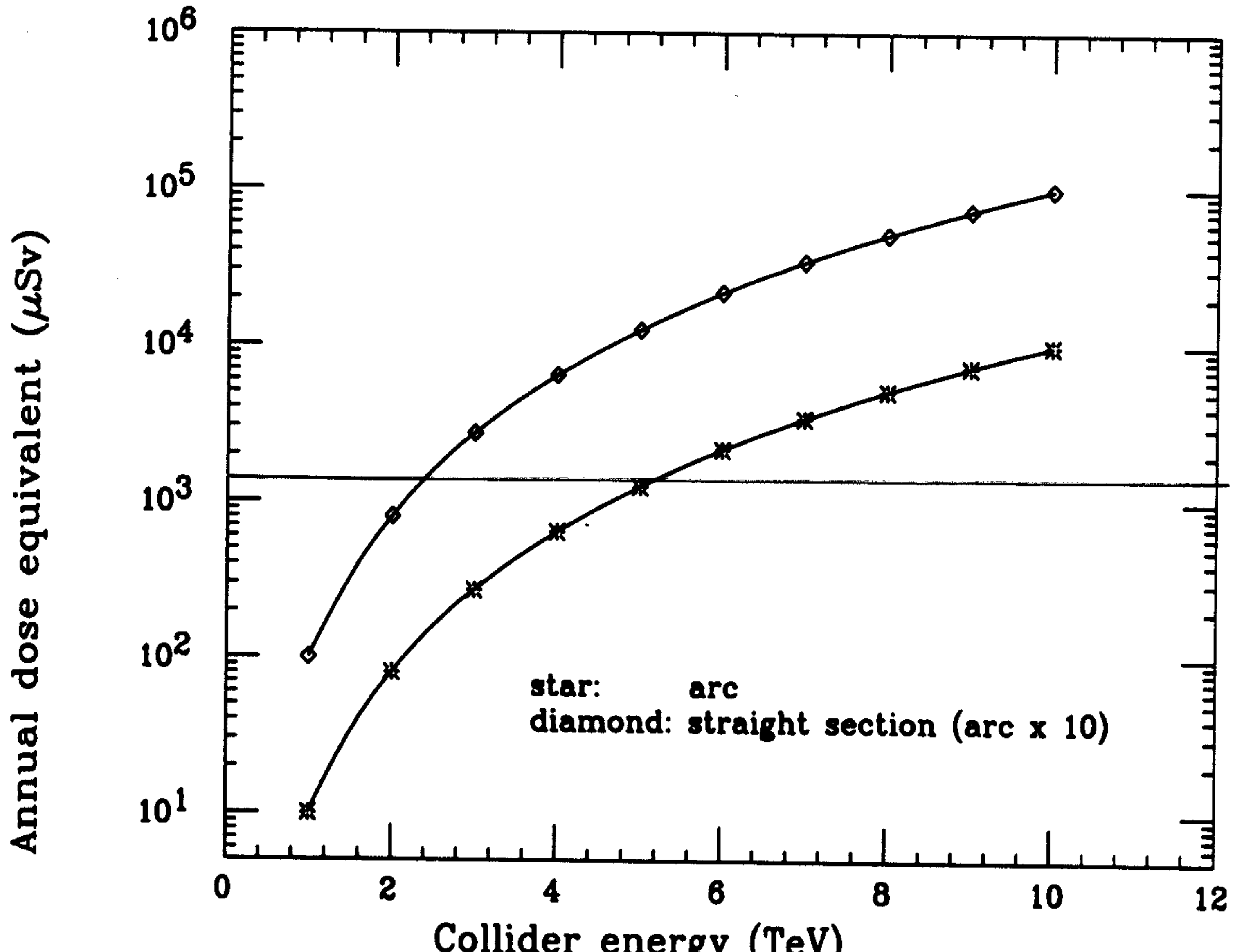


Fig. 2. Dose equivalent due to neutrino radiation at 51 km distance (collider at 200 m depth)

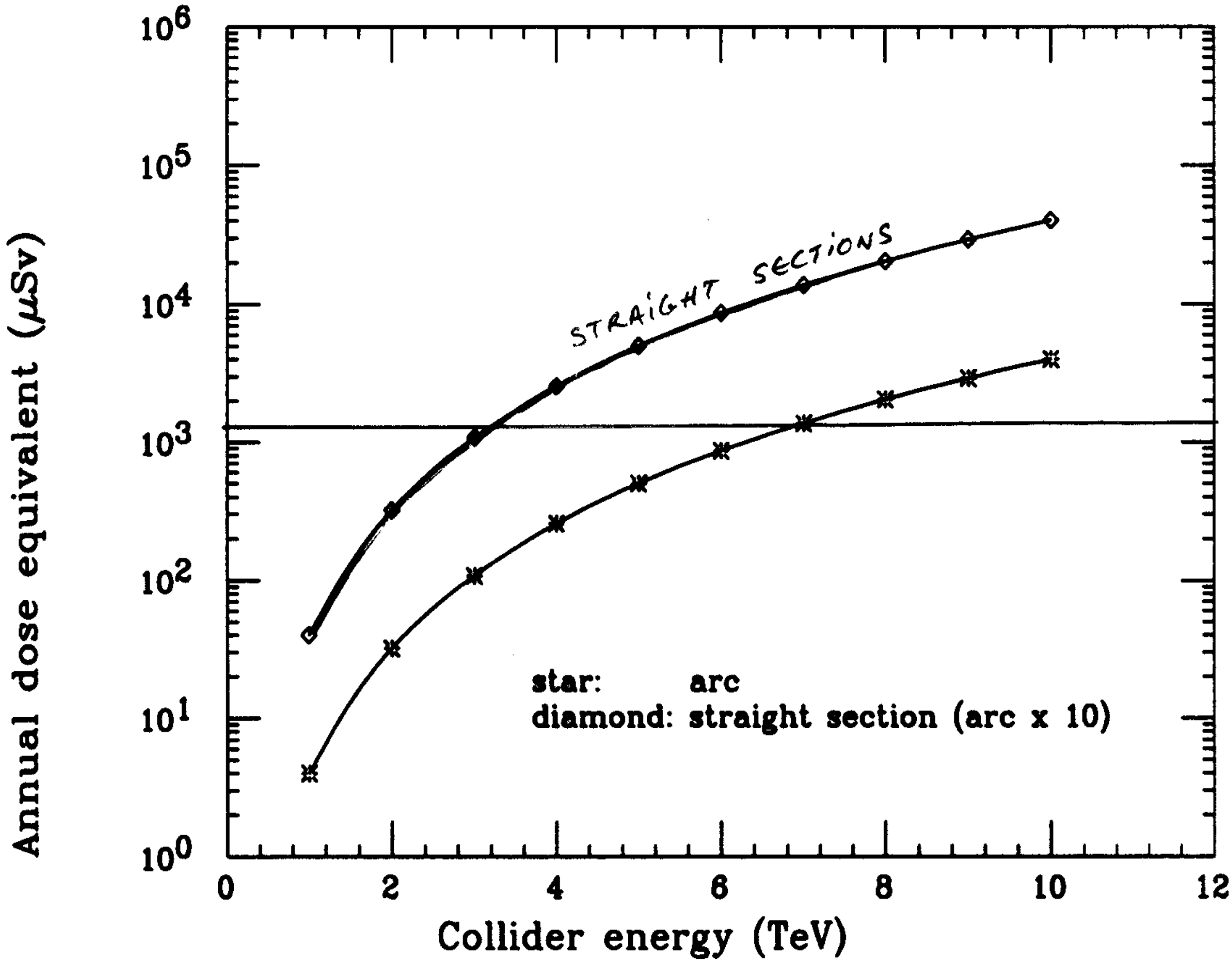


Fig. 3. Dose equivalent due to neutrino radiation at 80.5 km distance (collider at 500 m depth)

NEUTRINO RADIATION

LINES OF THOUGHT FOR SOLUTIONS:

- ACCEPT REDUCTION IN INTENSITY BUT NOT IN LUMINOSITY
  - ⇒ IMPROVE COOLING → HIGHER B
    → NEW METHODS
  - ⇒ COMPENSATE BEAM BEAM TUNE-SHIFT
  - ⇒ MODIFY FREQUENCY / INTENSITY
  - ⇒ ALL OF ABOVE.

- ARRANGE COLLIDER GEOMETRY CAREFULLY: BUY EXIT POINTS FACING STRAIGHT SECTION

- SITUATE MACHINE DEEP UNDER GROUND.

in the US

- ν-FACT99 has given MCC tremendous boost!
- MCC → ν-FACT + MC Collaboration!
- BNL (UPGRADED AGS) or FERMILAB (Pre Injector)?
- TARGET EXPERIMENT GIVEN A BIG KICK!
- NSF "CONSIDERING" 500 M$ SUPPORT FOR CORNELL + BNL PROJECT

? ⇒ { FEASIBILITY STUDY SOON
PROPOSAL IN 1-2 YEARS
MACHINE COULD BE THERE IN 7-8 YEARS }

[H. KIRK, BNL]

... THINGS ARE MOVING FAST ....

WORKING GROUPS in EUROPE:

- **NFWG** appointed 3/5/99 (H. Haseroth)
  brief report 9/99
  more detailed report 3/00
  "To study the accelerator aspects of a possible neutrino factory @ CER

- **BEAM & DETECTORS** (F. DYDAK + JJ GOMEZ)
  continues from ν FACT 99

- **INTENSE MUONS & NEUTRINOS** (J. Ellis NEW)

- **Higgs FACTORY & HIGH ENERGIES** (P. JANOT)

+

- **High Intensity Proton Source** (R. GAROBY, Linac
  H. SCHÖNAUER, Synch., + accum.)

Plenary Meetings ≃ 3 MONTH

⇒ ν-FACT00 May 22-26 2000
MONTEREY Ca

ENCOURAGEMENTS + GUIDELINES FROM SPC
WOULD BE VERY BENEFICIAL!

ACTIVITIES TOWARDS ν-FACTORY and μμ COLLIDER.

- ASCERTAIN # μ/p BY RELIABLE CALCULATIONS (AKA. 'Full simulation')
  → develop tools to track μ from target to accelerator,
  through • Production models
  - magnetic field
  - RF cavities
  - DE/DX, multiple scattering, straggling and secondary interactions
  - decay

  Combines tools from accelerator phys. + experimental phys.

  → 1 month workshop in BERKELEY 10 October → 10 NOVEMBER
  Participation from CERN: 3 people. (2 PS + 1 EP)

- UNDERSTAND WHICH PART OF THE CHAIN REQUIRES EXPERIMENT
  → TARGET EXPERIMENT in BNL given high priority
  → AT CERN, UNDER CONSIDERATION:
  - TARGET TESTS (liquid Hg)
  - RF IRRADIATION EXPT
  - π production expt.

ACTIVITIES TOWARDS ν-FACTORY and μμ COLLIDER

- **REFINING PHYSICS PERFORMANCE EVALUATION**

oscillations
- more realistic detectors
- " sophisticated, powerful detectors
- use of polarisation and sensitivity to beam parameters

low energy μ and ν
- stopped μ potential
- μ-induced fusion?
- physics use of high intensity proton machine
- nearby ν physics

muon colliders
- comparison with TESLA, NLC, CLIC
- benefits of high precision measurements of m_h, m_A, m_H, m_{susy}, ...
- ....

MUON machines can offer a very rich physics programme for many years.

ν-FACTORY → ν mixing matrix (θ_{13} !) + matter effects + CP violation (if LMA ☼)

→ A WORLD MACHINE WITH TREMENDOUS LOCAL BY-PRODUCTS

- High intensity ν beams, stopped muons etc....

→ FIRST STEP FOR HIGGS FACTORY(ies)

FRONTIER COLLIDER.

EUROPE SHOULD CONSIDER THIS OPTION

<u>VERY SERIOUSLY</u>