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11/11/99

High Energy Muon Colliders: Physics Goals & Pathways

Outline

1. The High Energy Frontier - A Perspective
   i) Why build a muon collider?
   ii) e^+e^- vs $\mu^+\mu^-$ (differences)

2. Standard Model Problems & "New Physics"
   i) Higgs, Multi-Higgs, Exotic Scalars, Horizontal Effects...
   ii) SUSY, SUSY Breaking
   iii) Strong Dynamics, Technicolor, Extended Technicolor...
   iv) Extra Dimensions ($R \sim 10^{-17} \sim 10^{-18}$ cm) exciting!
   v) Z', W', Compositeness, etc.

3. Future Lepton Collider Goals
   i) 100 GeV - 100 TeV (?)
   ii) Physics Motivation

4. Path to the First Muon Collider - 3 steps

5. Concluding Remarks

Disclaimer: This talk does not necessarily represent the views of the Muon Collider Collaboration

Intentionally Provocative

1. The High Energy Frontier - A Perspective

The "Standard Model" is a scientific triumph

"Symmetry Dictates Dynamics"

Poincaré Inv. + $SU(3)_c \times SU(2)_L \times U(1)_Y$ + $\lambda(\phi^2 - v^2/2)^2$ (Higgs)

|spin, mass> — gluons + $W^\pm$, Z, γ — $v = 250$ GeV

source of EW breaking
very compact

+3 Fermion Generations

general coor (local) ↓

Gravity

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25 Years of experimental confirmation (discovery)

c, τ, b, t, $W^\pm$, Z, gluons (Higgs?)

Precision Measurements ±0.1% ! → ($m_H < 220$ GeV) Quantum loops

Rare Decays + $\not{CP}$: FCNC, ε'/ε, ν osc. . . .

etc.

Outstanding Questions Remain:

1) True origin of EW sym. br. and mass?, Why is $v = 250$ GeV?

Pattern of Fermion masses + mixing, $\not{CP}$?

Points to "New Physics" 100 GeV → 1 TeV → 10 TeV ⟶ ?(10^{18} GeV)

2) Grand Unification? Quantum Gravity?

3) Why Parity Violation? Why 3 Generations? Why Symmetries? } Deep Insights about Nature

Seeking Answers: Rare or Forbidden Phenomena: $\mu \to e\gamma$, e.d.m., $K_L \to \pi^0 \nu\bar{\nu}$ ...
Precision Measurements: m_W, $\sin^2\theta_W$, ...
⋮

Most Direct - Advance the High Energy Frontier

Open New Windows (see Livingston Plot)

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i) Why build a muon collider? Take us to higher energy. 4-10-100 TeV
Better? Cheaper? More Discovery Pot.? than e^+e^-?

ii) e^+e^- vs $\mu^+\mu^-$ (similarities + differences)

e^+e^- Exp. Clean!, Polarization $P_{e^-} \gtrsim 0.9$, High Luminosity, ...
challenging, expensive, very long, ...
hard to go > 1.0 TeV (?) (New ideas?)

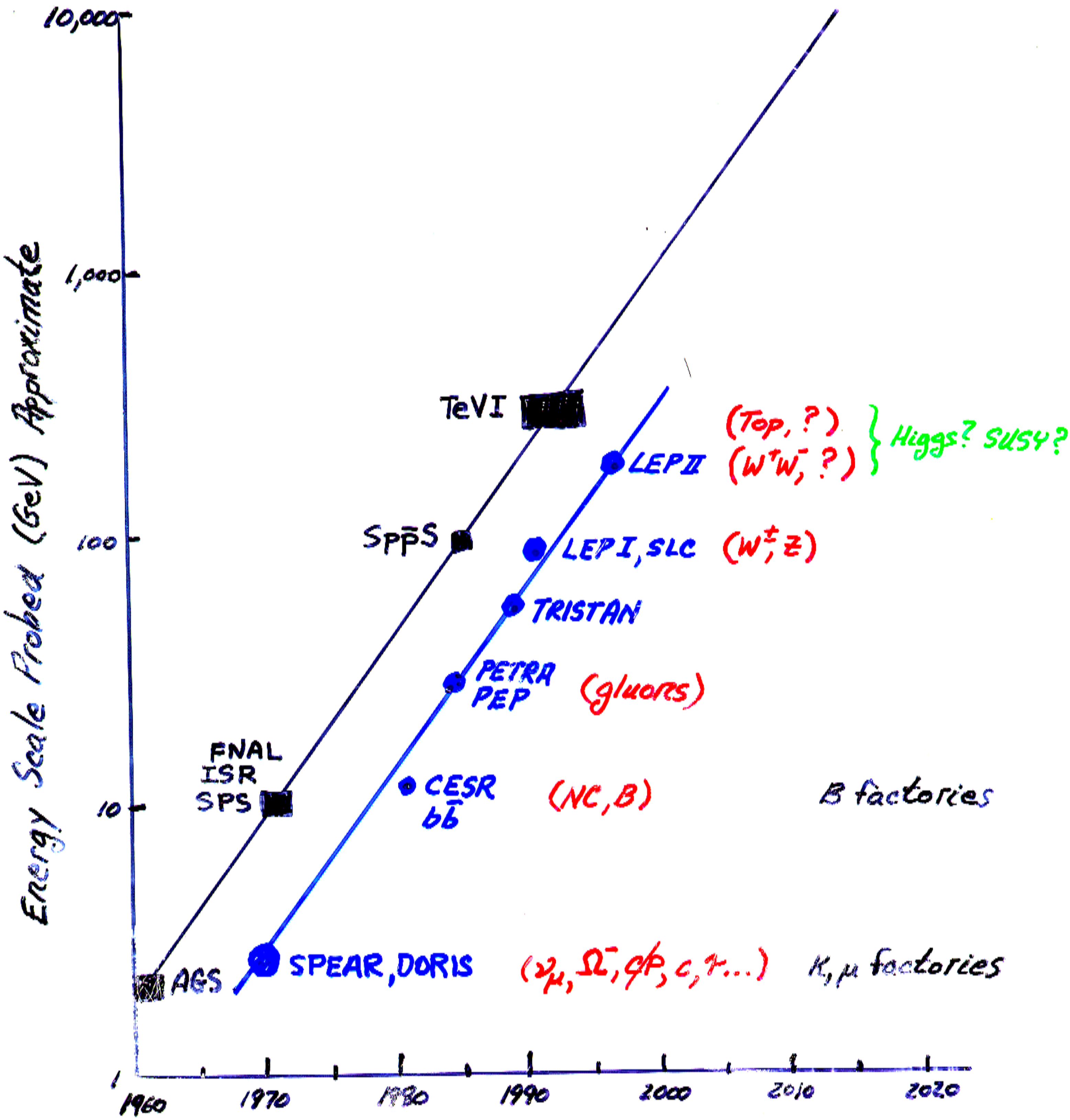
$\mu^+\mu^-$ Muons Decay! Polarization $P_{\mu^-}, P_{\mu^+} \sim 0.2$, High Luminosity ...
(unclean) $P_{eff} = \frac{P_{\mu^-} + P_{\mu^+}}{1 + P_{\mu^-} P_{\mu^+}} = 0.38$ neutrino radiation

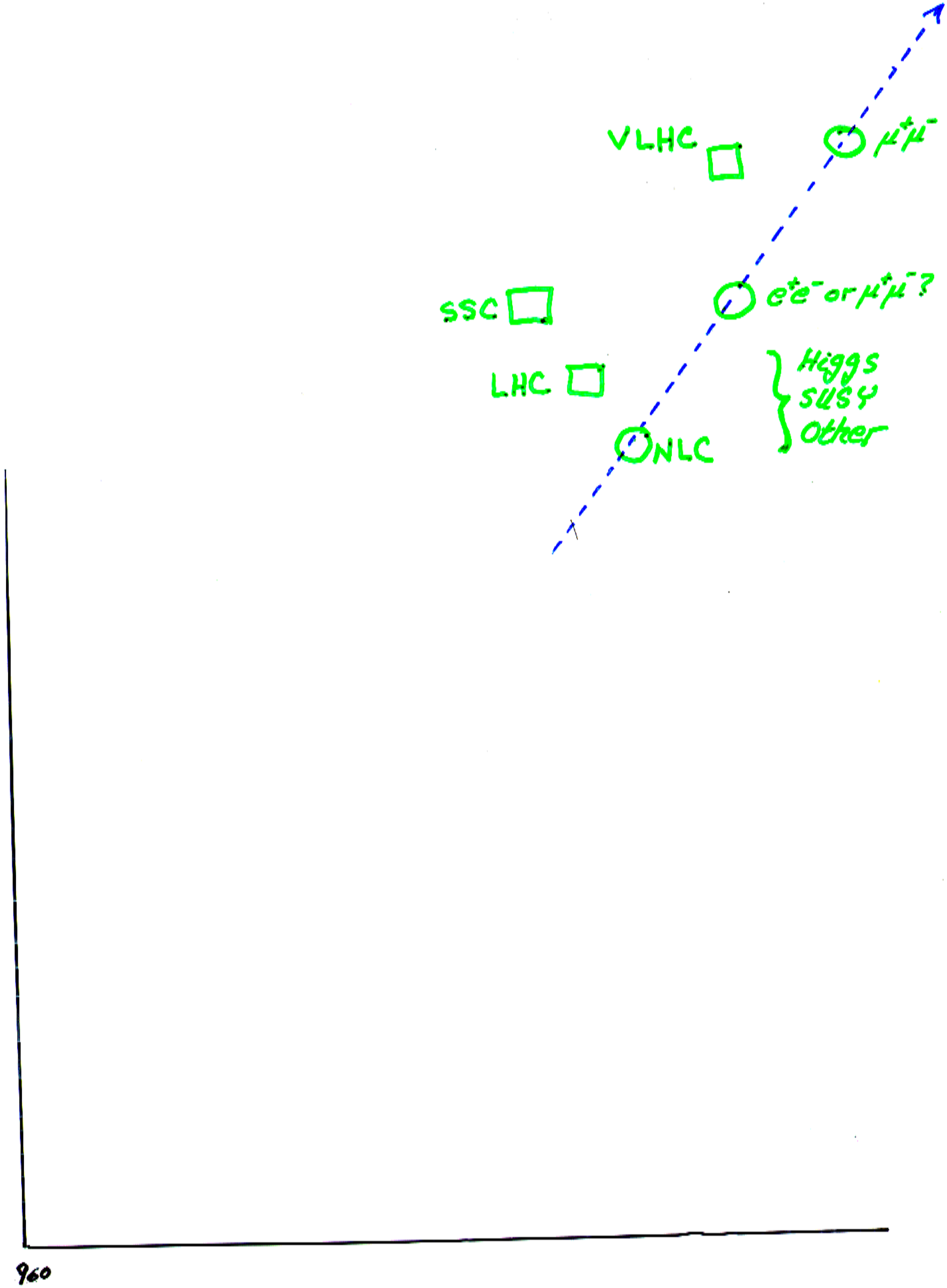
Challenging (?), Cost (?), Size (depends on energy) (?)
Good Energy Res., High $\mathcal{L}$ ...
* Once a muon collider is built $\xrightarrow{\text{Path}}$ Higher Energies
4 TeV, 10 TeV ...

Both have options: e^+e^-, e^-e^-, $\gamma\gamma$, γe^-, fixed target, ep
$\mu^+\mu^-$, $\mu^+\mu^+$, fixed target, μp
ν physics, low energy μ, K ... (Front End)

Livingston Plot

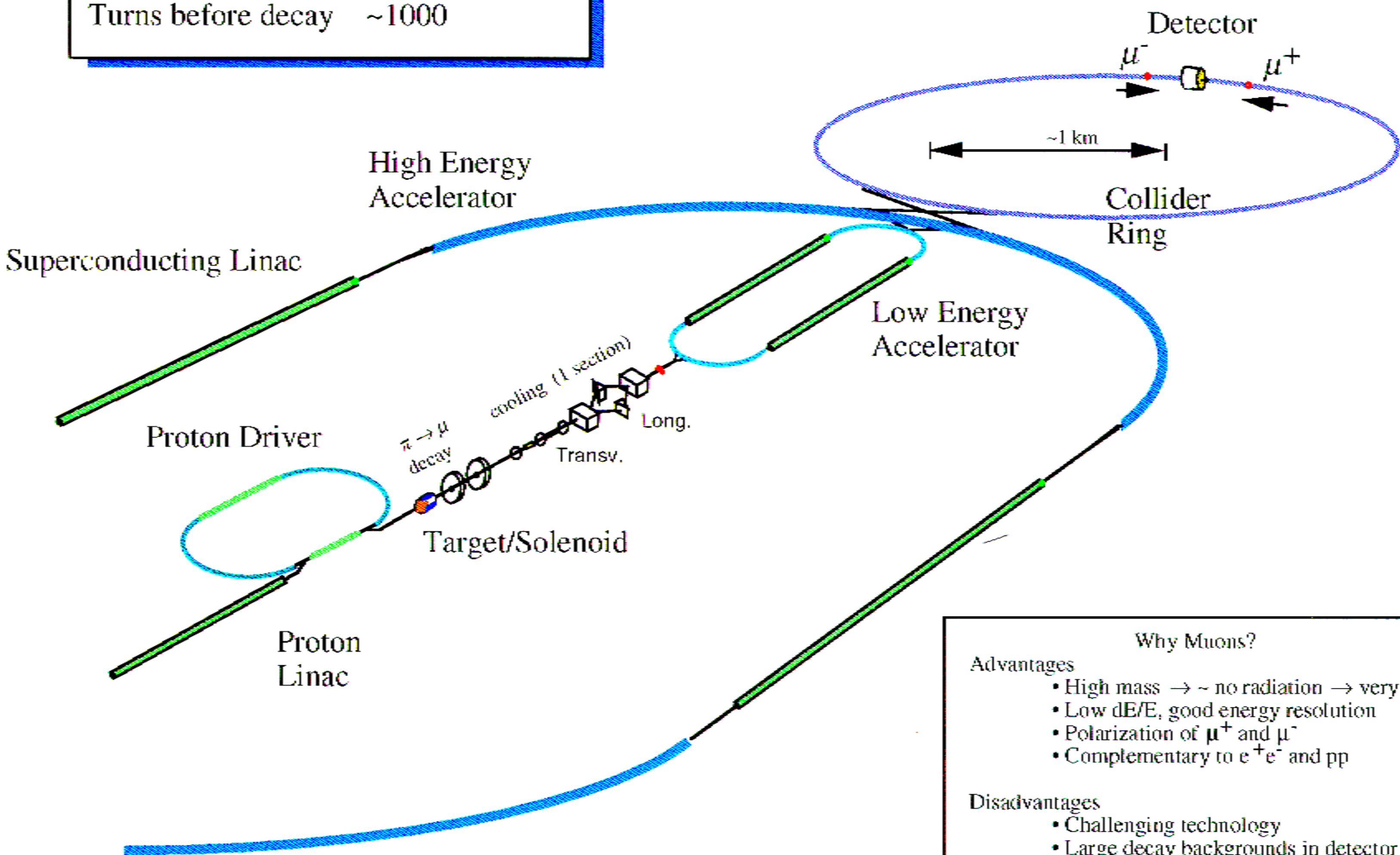
proton + e^+e^-




VLHC
μ+μ-
SSC
e+e- or μ+μ- ?
LHC
Higgs
SUSY
Other
NLC
960

A 1.5+1.5 TeV $\mu\mu$ Collider

Luminosity	10^{35} /cm^2/s
Repetition rate	15-30 Hz
Circumference	7 km
Turns before decay	~1000



Why Muons?

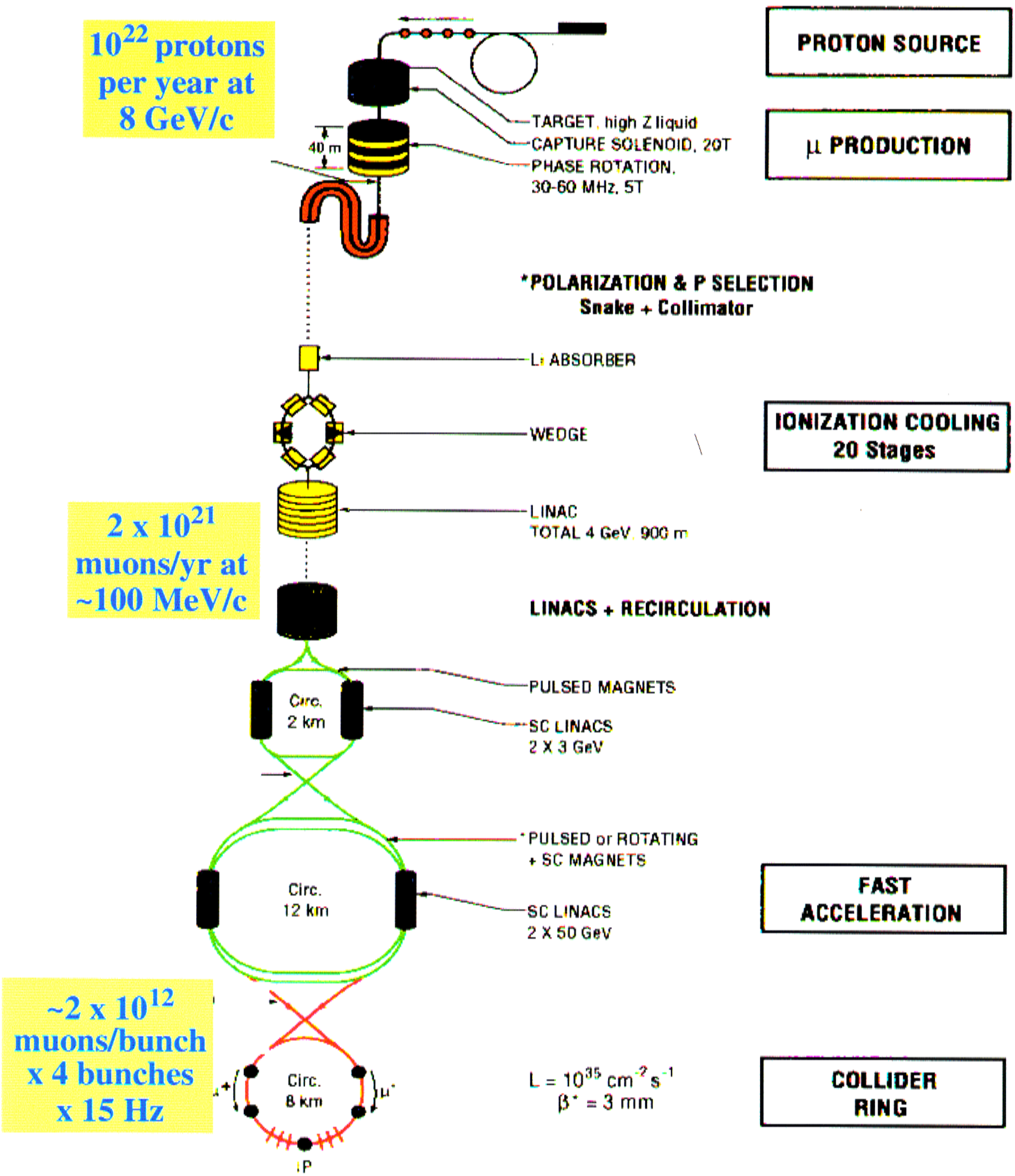
Advantages

- High mass → ~ no radiation → very high energies
- Low dE/E, good energy resolution
- Polarization of μ^+ and μ^-
- Complementary to e^+e^- and pp

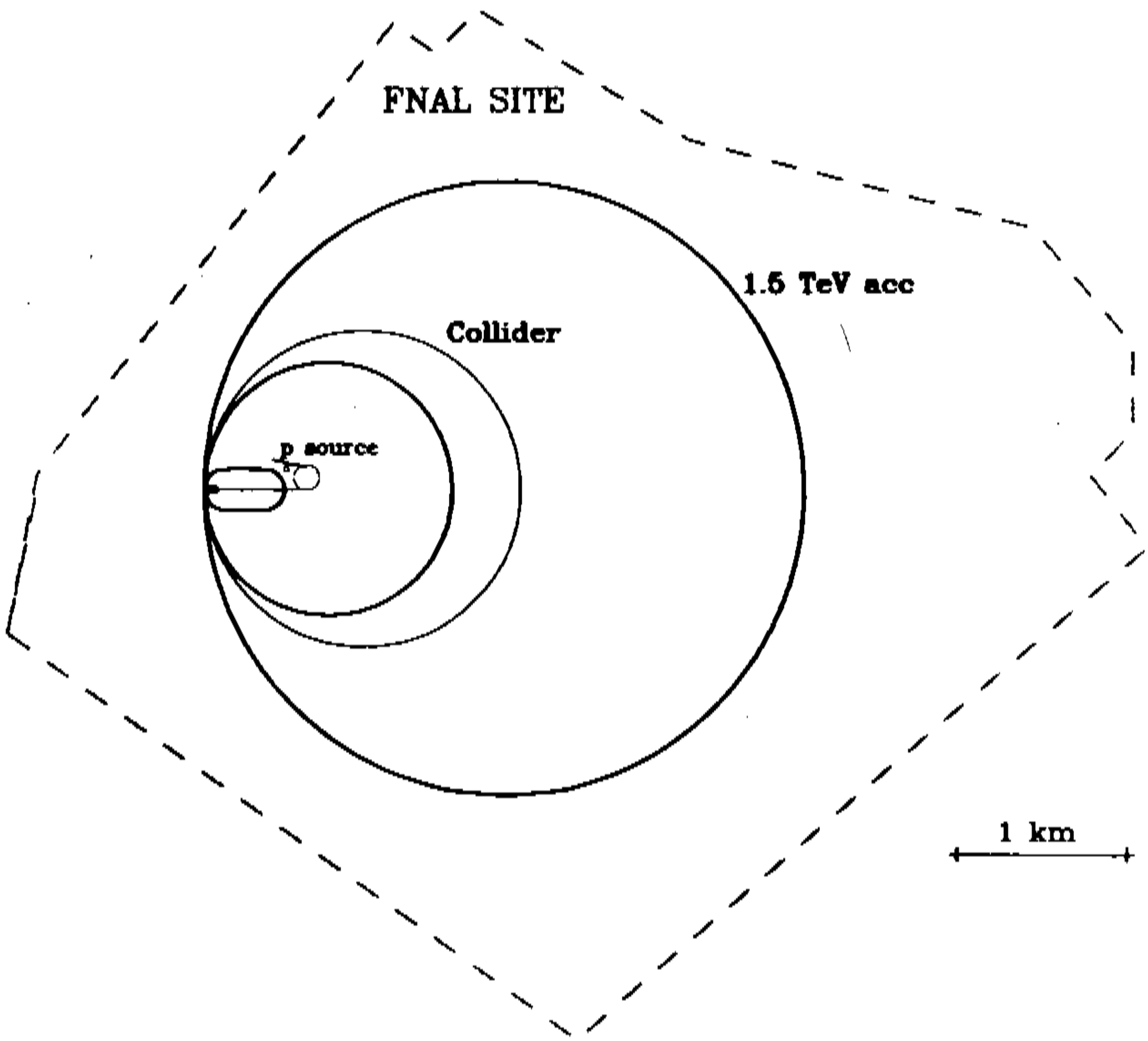
Disadvantages

- Challenging technology
- Large decay backgrounds in detector

2 x 2 TeV Muon Collider Schematic



Fits on existing lab site!



Physics Discovery Potential (e^+e^- vs $\mu^+\mu^-$)

Electron - Muon Universality (tested to $\lesssim 0.1\%$)

To first approx. same physics $\ell^+\ell^- \to ZH$, SUSY pairs, ...

But $m_\mu \simeq 207\, m_e$! (Fundamental Difference → "New Physics")

* The muon is probably a better probe of "New Physics" associated with mass, flavor, generation mixing ...

(τ, b, t even better - Access via final states)

Example: Anomalous Mag. Moments: $a_\ell = \frac{g_\ell - 2}{2}$

Ave $a_e^{exp} = 1159652188.3(3.1)\times 10^{-12}$ $a_\mu^{exp} = 116592080(460)\times 10^{-11}$ New BNL E821

→ $\pm 120 \times 10^{-11}$ (99 data)

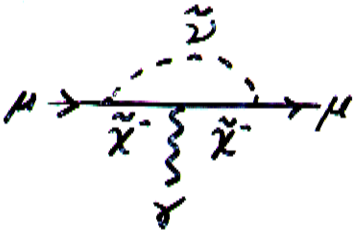
$\pm 40 \times 10^{-11}$

Electron Measurement ~ 1,500 times better!

but

"New Physics" $\propto m_\ell^2$ → muon 43,000 times more sensitive!!

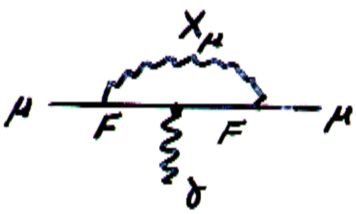
e.g. SUSY loops (Carena, Giudice, Wagner; Chattopadhyay, Nath; ...)



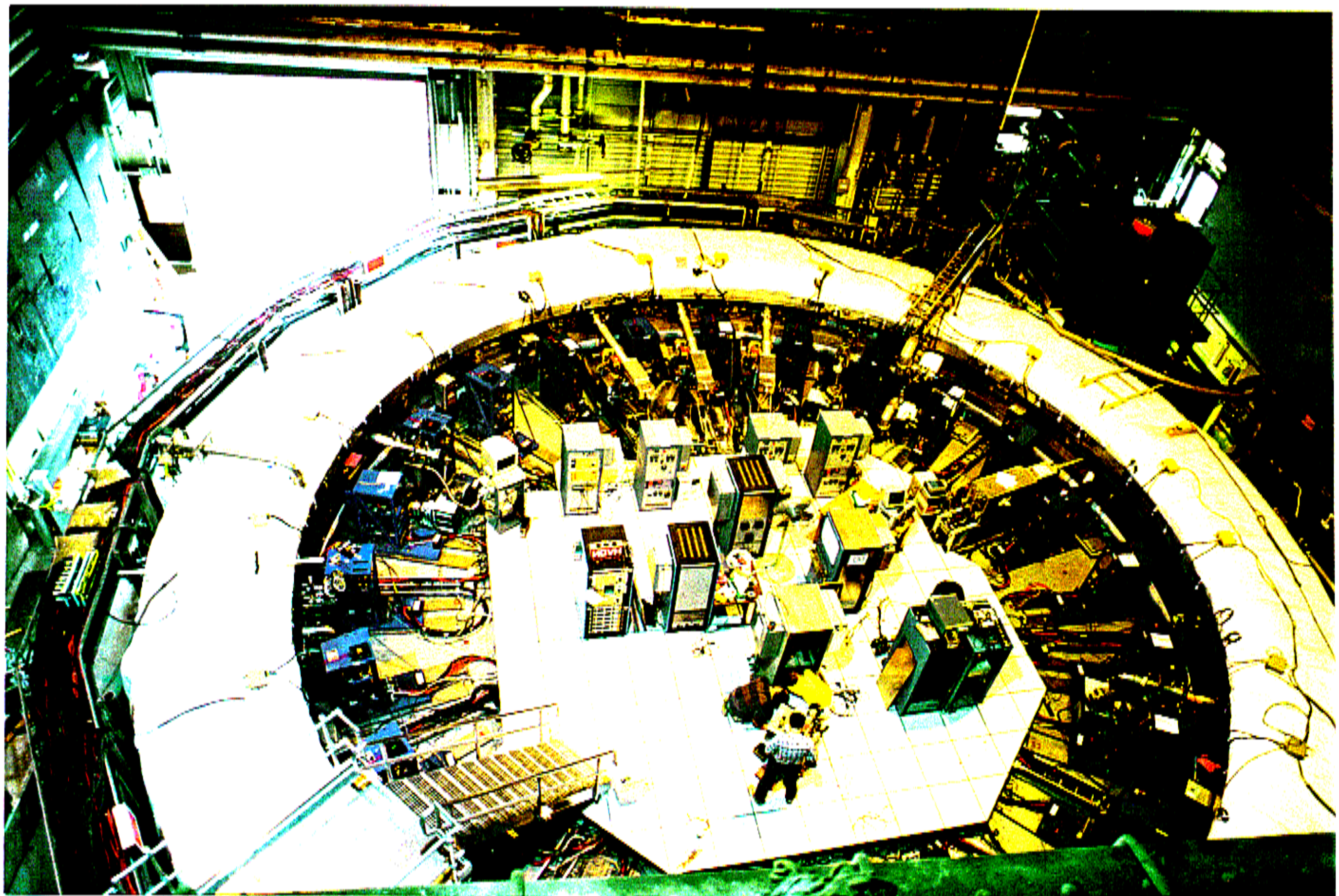
$\xrightarrow{\text{large } \tan\beta}$ $\Delta a_\mu^{SUSY} \simeq 140\times 10^{-11}\left(\frac{100\,\text{GeV}}{\tilde{m}}\right)^2 \tan\beta$

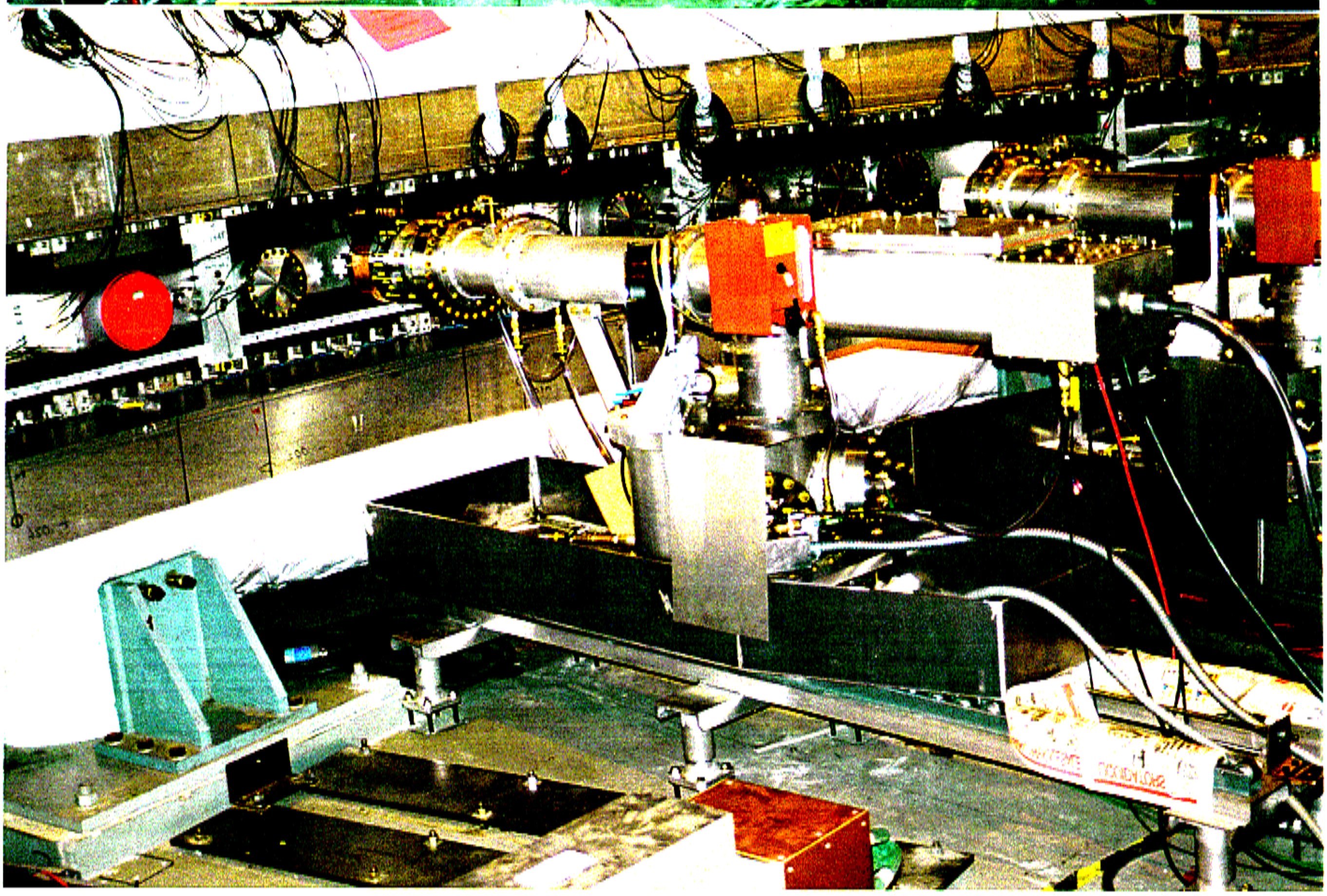
or dynamical mass generation $m_\mu =$

$\simeq g^2 m_F \left(\frac{m_F}{M_{X_\mu}}\right)^n$



$\Delta a_\mu \simeq \frac{m_\mu^2}{M_{X_\mu}^2}$ (E821 probes 1→6 TeV M_{X_μ}) (W.M.)





If 1999 a_μ data (under analysis) shows deviation from S.M.

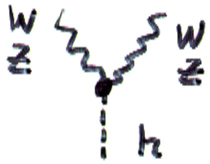
→ large $\tan\beta$ scenario for SUSY
or $X_\mu \sim$ Few TeV!
} Interesting Consequences For Muon Colliders (Very Exciting)

2. Standard Model Problems & "New Physics" (Commentary)

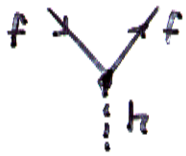
EW Symmetry Breaking? Flavor Hierarchy? (Connected?)

GUTS? Quantum Gravity? . . .

i) Higgs, Multi-Higgs, Exotic Higgs (leptoquarks etc), Singlets, ...



$i g m_{W,Z}\, g_{\mu\nu}$

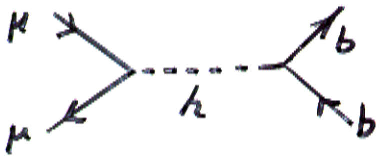


$i g \frac{m_f}{2 m_W}$ (small, except $f = t$)

$\ell^+\ell^- \to Z^* \to Zh$ $\quad p\bar{p} \to W^* \to Wh$ Associated Production

$\ell^+\ell^- \to t\bar{t}h$ $\quad pp \to t\bar{t}h$ ($LEP\,II$ $m_h \gtrsim 95\,GeV$)

*New Muon Collider Option: s-channel resonance {see Gunion talks



very narrow if $m_h < 2m_W \sim 160\,GeV$

Measure width, $B(h\to b\bar{b})$, $B(h\to c\bar{c})$, $B(h\to \tau^+\tau^-)$, $h\mu^+\mu^-$
$B(h\to WW^*)$, $B(h\to ZZ^*)$ } ~3000 events to 30,000

Proposed $\Delta E_\mu / E_\mu \simeq 3\times10^{-5}$ $\quad (\Gamma_h \sim$ few MeV$)$

Elementary Particles & Their Masses

	Particle	Mass (GeV)
1st	ν_e	$< 4.5 \times 10^{-9}$
	e	0.51×10^{-3}
	u	5×10^{-3}
	d	9×10^{-3}
2nd	ν_μ	$< 0.16 \times 10^{-3}$
	μ	0.106
	c	1.35
	s	0.175
3rd	ν_τ	$< 23.8 \times 10^{-3}$
	τ	1.777
	t	175 ± 5 !
	b	4.5
Gauge Bosons	γ	0
	$W^\pm$	80.42 ± 0.0[illegible]5
	Z	91.187 ± 0.002
	Gluons	0
Scalar	H (Higgs) ?	90 ~~78(88)~~ $< m_H <$ 800(440)

Resonant Higgs Studies at the FMC

Example: $m_h = 110\,GeV$, $\Gamma_h \simeq 3\,MeV$, $\Delta E_\mu / E_\mu \simeq 3\times10^{-5}$, $L = 0.5\,fb^{-1}$

$\mathcal{L} = 5\times10^{31}\,cm^{-2}s^{-1}$ (hard)

$\mu^+\mu^- \to H \to b\bar{b},\ c\bar{c},\ \tau\bar{\tau},\ WW^*,\ ZZ^*$

Total Higgs Signal ~ 30,000 events

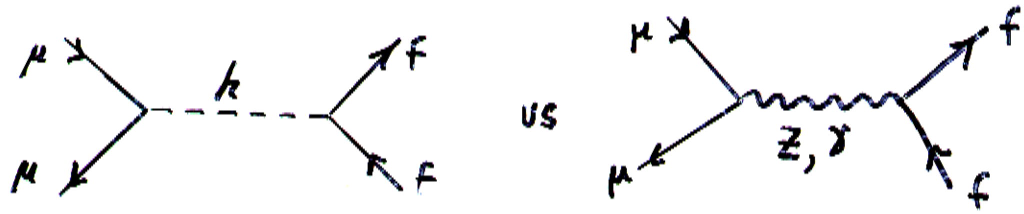
H	$b\bar{b}$	$c\bar{c}$	$\tau\bar{\tau}$
signal N_S	24,000	2,100	2,700
backgr. N_B	25,200	24,160	9,450
$\pm\sqrt{N_S+N_B}/N_S$	±0.009	±0.08	±0.04

Polarization useful — Luminosity much more important! & Resolution!

scan time

signal LL or RR

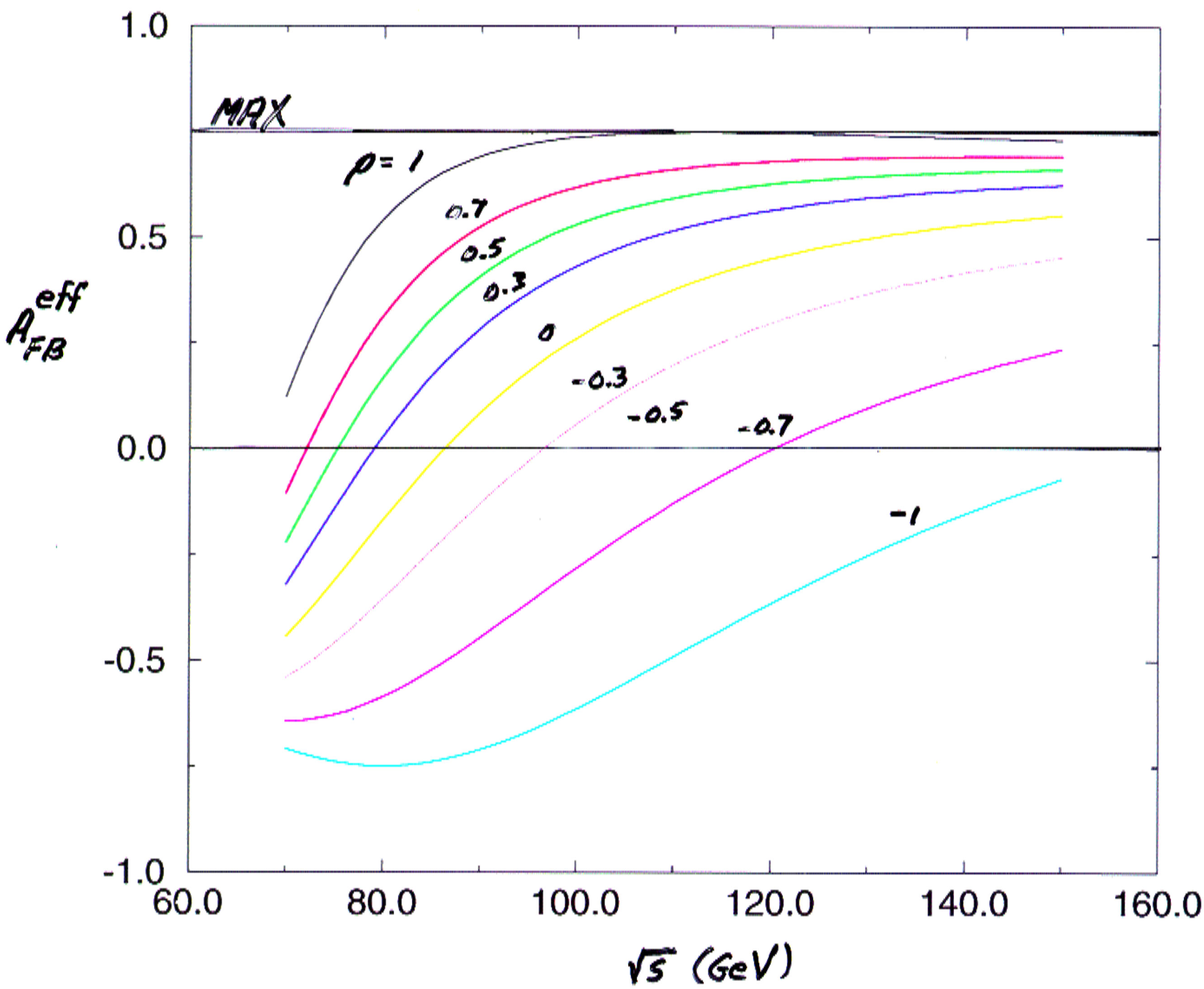
Back. LR or RL ($\mu^+\mu^- \to \gamma^*, Z^* \to f\bar{f}$)



B. Kamal, Z. Parsa, W.M.

Effective Forward-Backward Asymmetry $\mu^-\mu^+ \to b\bar{b}$

$$A_{FB}^{eff} = \frac{A_{FB} + \rho A_{LR}^{FB}}{1 + \rho A_{LR}} \qquad \rho = \frac{P_+ - P_-}{1 + P_+ P_-}$$



2 Higgs Doublets: → $\tan\beta = v_2/v_1$ $h, H, A, H^\pm$ (5 Scalars)

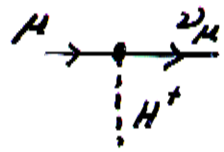
$e^+e^- \to H^+H^-$ $e^+e^- \to HA$ (Pair Produce)

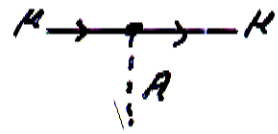
Needs $\sqrt{s} > 2m_{H^\pm}$, $\sqrt{s} \gtrsim m_A + m_H$ (may be high)

New Muon Collider Possibilities:

1) s-channel resonances $\mu^+\mu^- \to H$ or $\mu^+\mu^- \to A$ (Measure Properties)

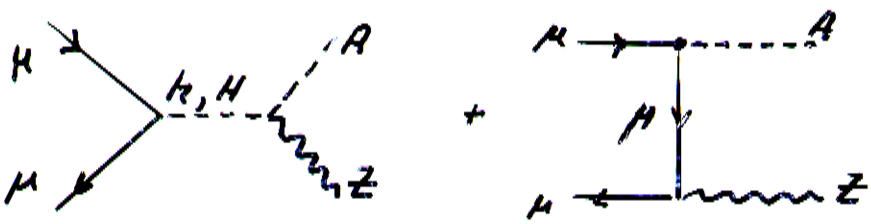
2) If $\tan\beta$ is large,





$\frac{i g m_\mu}{2 m_W} \tan\beta$

$\mu^+\mu^- \to H^\pm W^\mp$ or AZ (Akeroyd, Arhrib, Dove)



$\sigma \sim \left(\frac{m_\mu}{m_W}\tan\beta\right)^2$

$\sim 1\,\text{fb} \left(\frac{\tan\beta}{30}\right)^2$ small

$\sigma(\mu^+\mu^- \to H^\pm W^\mp) \sim 10\,\text{fb} \left(\frac{\tan\beta}{30}\right)^2$ {expect 50-200 fb^{-1}/yr}

Other Higgs? Likely to be more important for $\mu^+\mu^-$ (mass)
eg generation dep.

Polarization could be useful (suppress backgrounds)

$$P_{eff} = \frac{P_{\mu^+} + P_{\mu^-}}{1 + P_{\mu^+}P_{\mu^-}}$$

$P_{\mu^-} = P_{\mu^-} = 0.63 \to P_{eff} \simeq 0.90$

$P_{\mu^-} = P_{\mu^+} = 0.85 \to P_{eff} \simeq 0.99$!

High Pol. → Loss of luminosity (Make more muons, small tight beams

Needs Study

ii) SUSY + SUSY Breaking (Very large scale?)

$\ell^+\ell^- \to$ SUSY (see Murayama + Peskin) MSSM

Lots of spectroscopy, measure $\tilde{m}$, couplings
(Polarization very useful)

Expect $m(\tilde{\omega}) \lesssim 250$ GeV $m(\tilde{g}) \lesssim 800$GeV

$m(\tilde{q}) > m(\tilde{\ell}) \gtrsim m(\tilde{\nu})$

To study SUSY in $\ell^+\ell^-$ $\sqrt{s} \simeq 500$GeV $\to$ 1.5TeV (Higher? 3TeV?)

SUSY radically alters our perception of space-time.

If discovered ⟶ Motivation to explore higher energies

Source of SUSY Breaking (eg Messengers)
May require $\sqrt{s} \gtrsim 10$ TeV $\mu^+\mu^-$ collider

SUSY does "not" explain: Generation Hierarchy (Flavor)
Likely to require additional horizontal physics

Muon Collider Features (beyond e^+e^-)

J. Feng, s-channel sneutrino (R parity violation)
$\mu^+\mu^- \to \tilde{\nu} \to X$ (Good $\Delta E_\mu / E_\mu$)

Higher energies $\sqrt{s} \simeq 3$-4 TeV, 10 TeV, $\to$? explore flavor + SUSY Breaking

SUSY Partner

$\tilde{\nu}_e$
$\tilde{e}$
$\tilde{u}$
$\tilde{d}$

spin = 0

$\tilde{\nu}_\mu$
$\tilde{\mu}$
$\tilde{c}$
$\tilde{s}$

$\tilde{\nu}_\tau$
$\tilde{\tau}$
$\tilde{t}$
$\tilde{b}$

$\tilde{\gamma}$
$\tilde{W}^\pm$
$\tilde{Z}$
$\tilde{G}$

spin = 1/2

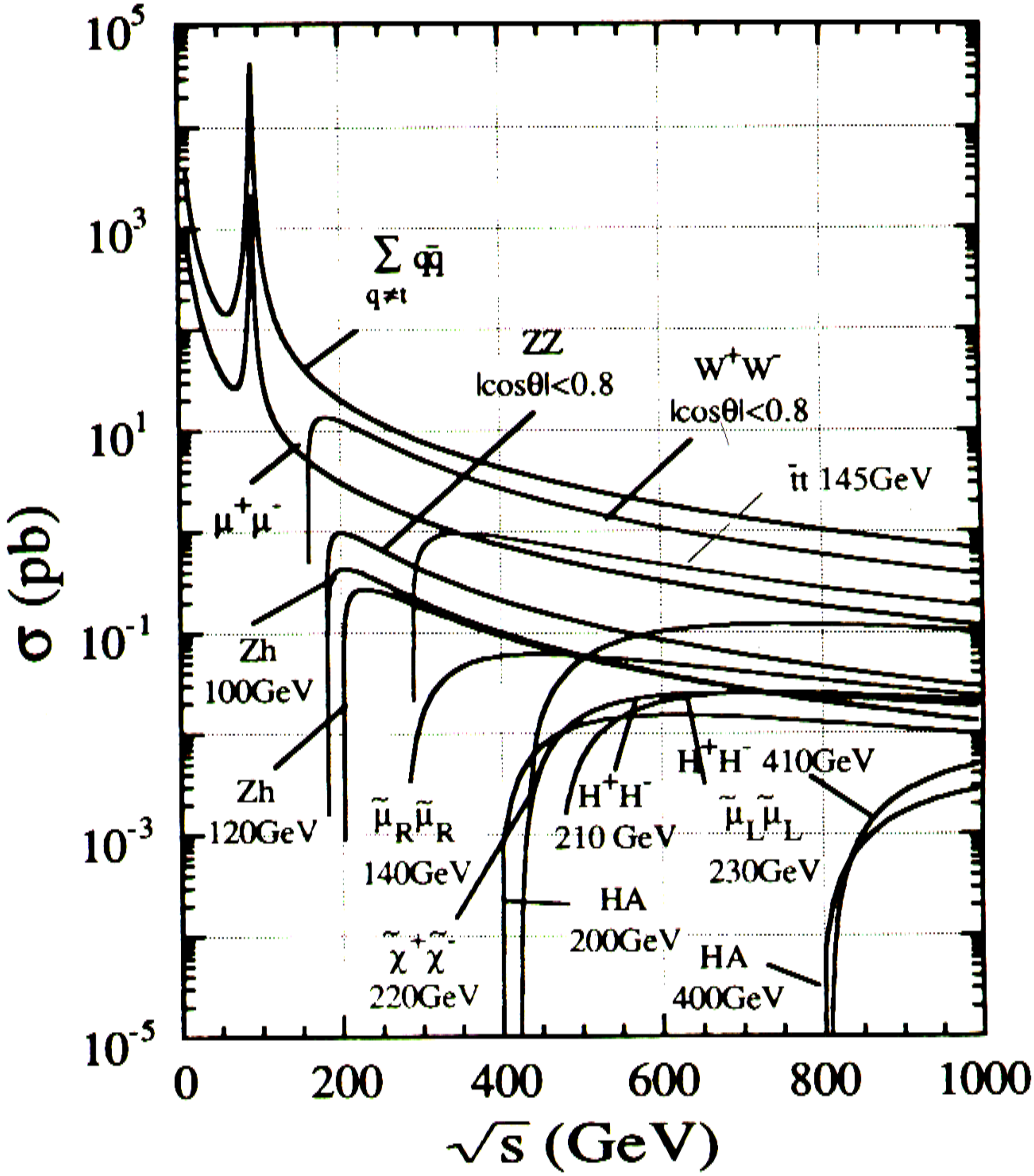
$\tilde{H}$
$\tilde{h}$
$\tilde{A}$
$\tilde{H}^\pm$

spin = 1/2

+ h, A, $H^\pm$

lots of new phenomena
Mixing, CP ...

From JLC Group



iii) New Strong Dynamics (No Higgs) Technicolor

So far, no supporting evidence: Precision Measurements
S, T, U Parameters, $Z \to b\bar{b}$
$m_h \lesssim 220$ GeV

Attractive Generic Idea - No Attractive Models

Techni-Fermions $F_\pi \simeq 1000 f_\pi (QCD) \to \gtrsim 1$ TeV Spectroscopy

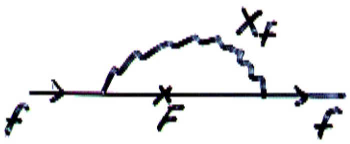
Really need pp $\sqrt{s} \gtrsim 40$ TeV (SSC)
$\ell^+\ell^-$ $\sqrt{s} \simeq 3$-4 TeV
} see Chivukula talk Next Week

Muon Collider - High Energy, Energy Resolution (Narrow Resonances)

$\mu^+\mu^- \to \omega_T^0, \rho_T^0, \pi_T^0$, Techni-Hadrons
Rich Spectroscopy $\gtrsim$ 1-few TeV
} very good $\mu^+\mu^-$ motivation $3 \sim 4$ TeV

Extended Technicolor

Explain Fermion Masses (Flavor, CP)



$\to m_f$

$M_{X_f} \sim 1$ TeV - 100 TeV (Higher)
Heavy Gauge Bosons

$\mu^+\mu^- \to t\bar{t}$ + "New Physics" at $\sqrt{s} \gtrsim 3$-4 TeV

$\mu^+\mu^- \to$ "New Physics" $\sqrt{s} > 3$-4 TeV, 10 TeV

Polarization Important
$\mu^+\mu^- \to t\bar{t}, W^+W^-$ etc Form Factors
$\to$ New States

iv) *Extra Dimensions: (large $R \sim 10^{-17} \sim 10^{-18}$ cm ; 1-10 TeV)

The most extraordinary discovery I can imagine!

Motivation: Superstrings $d = 10, 11$

If $R \sim 10^{-17}$ cm $\simeq$ 1/TeV, they could be source of EW sym. br, SUSY Breaking, Fermion Masses, CP Parity Viol., 3 Generations ...

Nature is revealing Her extra dimensions! (?)

Many High Energy Signatures:

Short-Distance Gravity Changes → Gravitons (missing energy)

Excited $W^*, Z^*, \gamma^*, g^*, h^* \ldots$ $\quad m_n^2 = m_0^2 + \frac{\vec{n}^2}{R^2}$ (see I. Antoniadis ...)

Precision Measurements → $m_{W^*} \gtrsim 3\text{-}4$ TeV! $\quad$ LHC → 6 TeV!

look for in $\ell^+\ell^- \to f\bar{f}$ $\quad$ LR, FB Asym. $\quad \sqrt{s} \simeq 1$ TeV

Polarization $\quad$ Explores $m_Z^* \simeq 10$ TeV (higher)

Demands Higher Energy $\quad \left.\begin{array}{l} \sqrt{s} \simeq 3\text{-}4 \text{ TeV} \\ \sqrt{s} \gtrsim 10 \text{ TeV} \end{array}\right\}$ Asymmetries (Powerful) Explore → 1000 TeV = 1 PeV

Wonderful to someday do $\mu^+\mu^- \to Z^*$ on resonance

Directly excite Extra Dimensions!

Strong Motivation to extend $\sqrt{s}$ → 3-4 TeV → 10 TeV → 100 TeV!

v) Z′, W′, Compositeness ...

Much like searching for Extra Dimensions (Added Motivation)

U(1)′ From GUTS, SO(10), E_6 ; Superstrings

U(1)′ Flavor Sym. Different e^+e^- + $\mu^+\mu^-$ (Breaks Universality)

Search For Narrow Z′ resonances, Contact Interactions } Polarization Useful

$\ell^+\ell^- \to f\bar{f}$, $\ell^+\ell^- \to W^+W^-$, $\ell^+\ell^- \to W^+W^-\nu\bar{\nu}$ etc.

Probably need high $\sqrt{s}$, good resolution

In Addition, precision EW : m_W, $\sin^2\theta_W$, A_{FB} ...

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4) Future Lepton Collider Goals

High Energy, High Luminosity, Polarization, Good Resolution ...

Technically Feasible, Affordable, Potential Upgrades

Environmentally Safe

i) 100 GeV
Z Factory 10^8-10^9 Z/yr! Polarization 90%
$\Delta\sin^2\theta_W = \pm 0.00002$! → $\Delta m_h/m_h$ to ±5%!
$b\bar{b}$, $\tau\bar{\tau}$ Factories, CP, Rare Decays
(probably e^+e^- better)

Could be First Muon Collider {
h Factory 30,000h/yr Pol. Useful
$h \to b\bar{b}$, Γ_h, m_h, $h \to WW^*$ ...
(unique to $\mu^+\mu^-$ but $\gamma\gamma \to h$ at e^+e^- may do)

ii) 500 GeV $\ell^+\ell^- \to t\bar{t}, W^+W^-, f\bar{f} \to m_t, m_W, A_{FB}, A_{LR}$ } compelling
* $\ell^+\ell^- \to Zh$ (up to $m_h \simeq 400$ GeV)
$\ell^+\ell^- \to$ SUSY } get lucky
$\ell^+\ell^- \to H^+H^-, AH$

$\mu^+\mu^- \to H^0, A^0, W^\pm H^\mp$, other resonances (Becoming Interesting)

In my view we should explore this region SOON! $\to e^+e^-$ (later $\mu^+\mu^-$)

iii) $\sqrt{s} \simeq 1$-1.5 TeV $\ell^+\ell^- \to t\bar{t}, W^+W^-, f\bar{f} \ldots$ (strong dyn.)
$\ell^+\ell^- \to Zh, H^+H^-, AH$
$\ell^+\ell^- \to t\bar{t}h, b\bar{b}A, t\bar{b}H^-$
$\ell^+\ell^- \to \tilde{\ell}^+\tilde{\ell}^-, \tilde{\nu}\tilde{\nu}, \tilde{\chi}^+\tilde{\chi}^- \ldots$ } Polarization Important

Must also be done as soon as possible, if SUSY is seen $\to e^+e^-$

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iv) $\sqrt{s} \simeq 3$-4 TeV $\to$ 10 TeV $\to$ 100 TeV (?)

Motivation More General: (but very strong)
- SUSY Spectrum ?
- SUSY Breaking ?
- Flavor Physics
- Strong Dynamics
- Z^*, Z', Structure ... Extra Dim.

Technical e^+e^- breakthroughs, cost, ...

or

*Muon collider: High Energy, High Luminosity, Polarization

At least 3-10 TeV Eventual Goals

Very Desirable Must Do If Possible

4. Path to the First Muon Collider - 3 steps

Must Produce, Collect, Cool, Accelerate $\gtrsim 10^{13} \mu^\pm$/sec, Store, Collide, Detect Physics } $0.2\mu^\pm$/proton

Technically Very Challenging - But Doable (?)

Needs Significant R+D + Hands on Experience

Synergistic Experimental Program (Exciting)

i) Muon Electric Dipole Moment $d_\mu \lesssim 10^{-18}$ e-cm (not competitive)

AGS-LOI ($g_\mu - 2$ collaboration) $\longrightarrow$ $d_\mu \simeq 10^{-24}$ e-cm !! borders!

Competitive with $d_e \simeq 5\times10^{-27}$ e-cm, $d_n \simeq 10^{-25}$ e-cm

Outstanding probes of P+T Violation

Requires ~ $7\times10^{7}\,\mu$/sec, Polarization, Strong Focusing

Longer term $\rightarrow 10^{-25}$ e-cm $\rightarrow 10^{-26}$ e-cm !

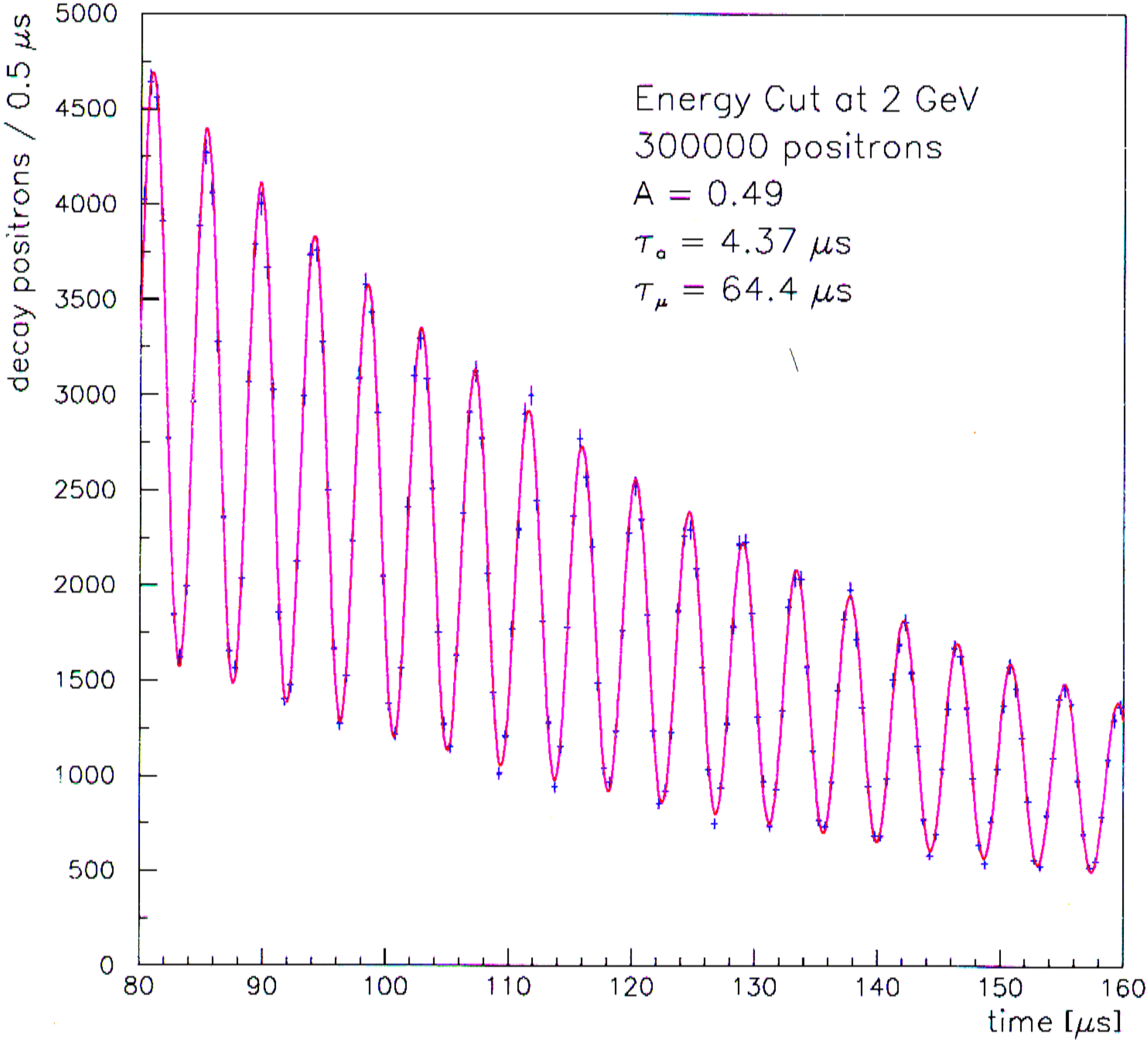
Must pursue, particularly if $a_\mu^{exp} \neq a_\mu^{S.M.}$

ii) Muon-Electron Conversion $\mu^- N \to e^- N$ coherent $E_e \simeq 105$ MeV

MECO Proposal: Produce, Collect, Stop $10^{11} \mu^-$/sec!

Current $B(\mu^- Ti \to e^- Ti) < 6\times10^{-13} \longrightarrow 5\times10^{-17}$ sensitivity!

Outstanding Discovery Potential - Very Clean Signal



decay positrons / 0.5 μs
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
80
90
100
110
120
130
140
150
160
time [μs]
Energy Cut at 2 GeV
300000 positrons
A = 0.49
τa = 4.37 μs
τμ = 64.4 μs

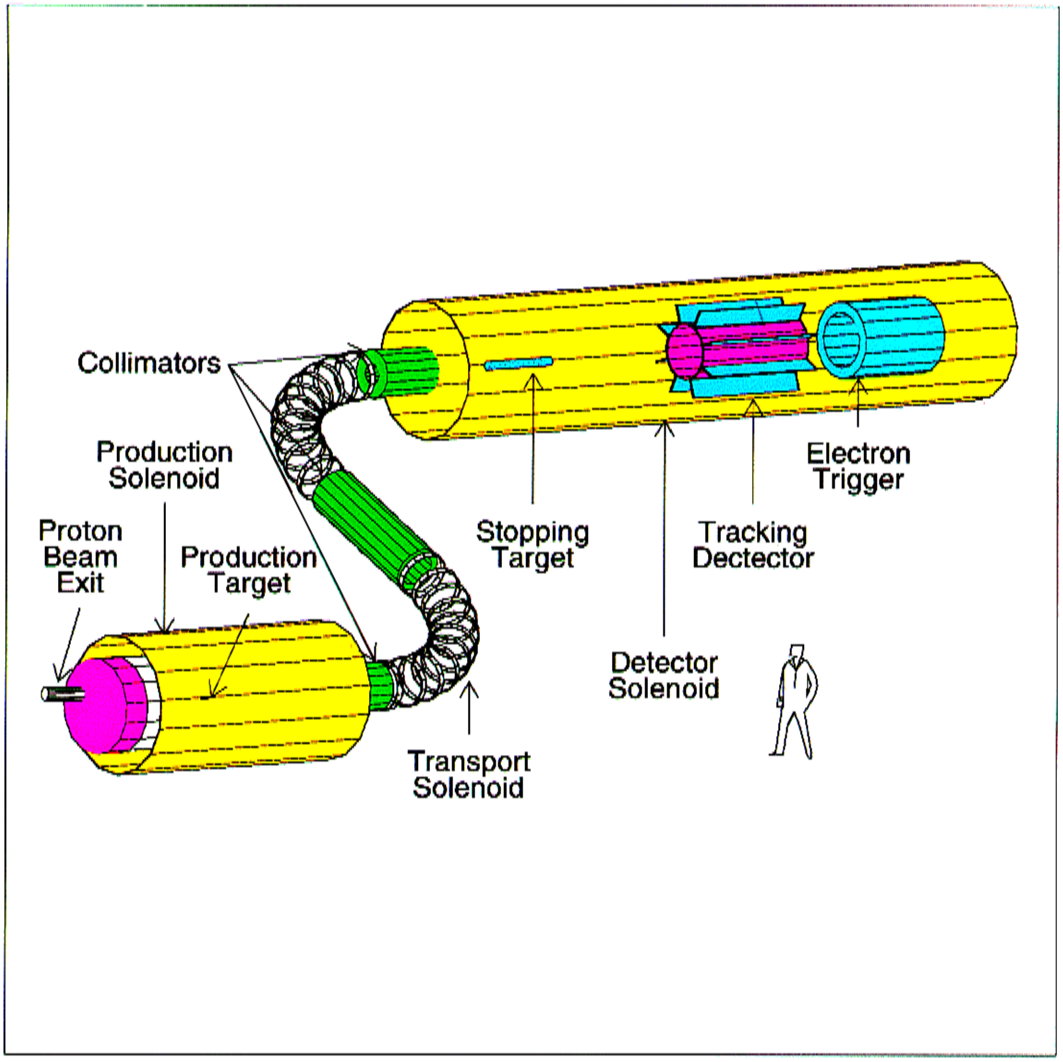


FIG. 31. Schematic layout of the MECO detector (provided by W.R. Molzon).

From Kuno + Okada

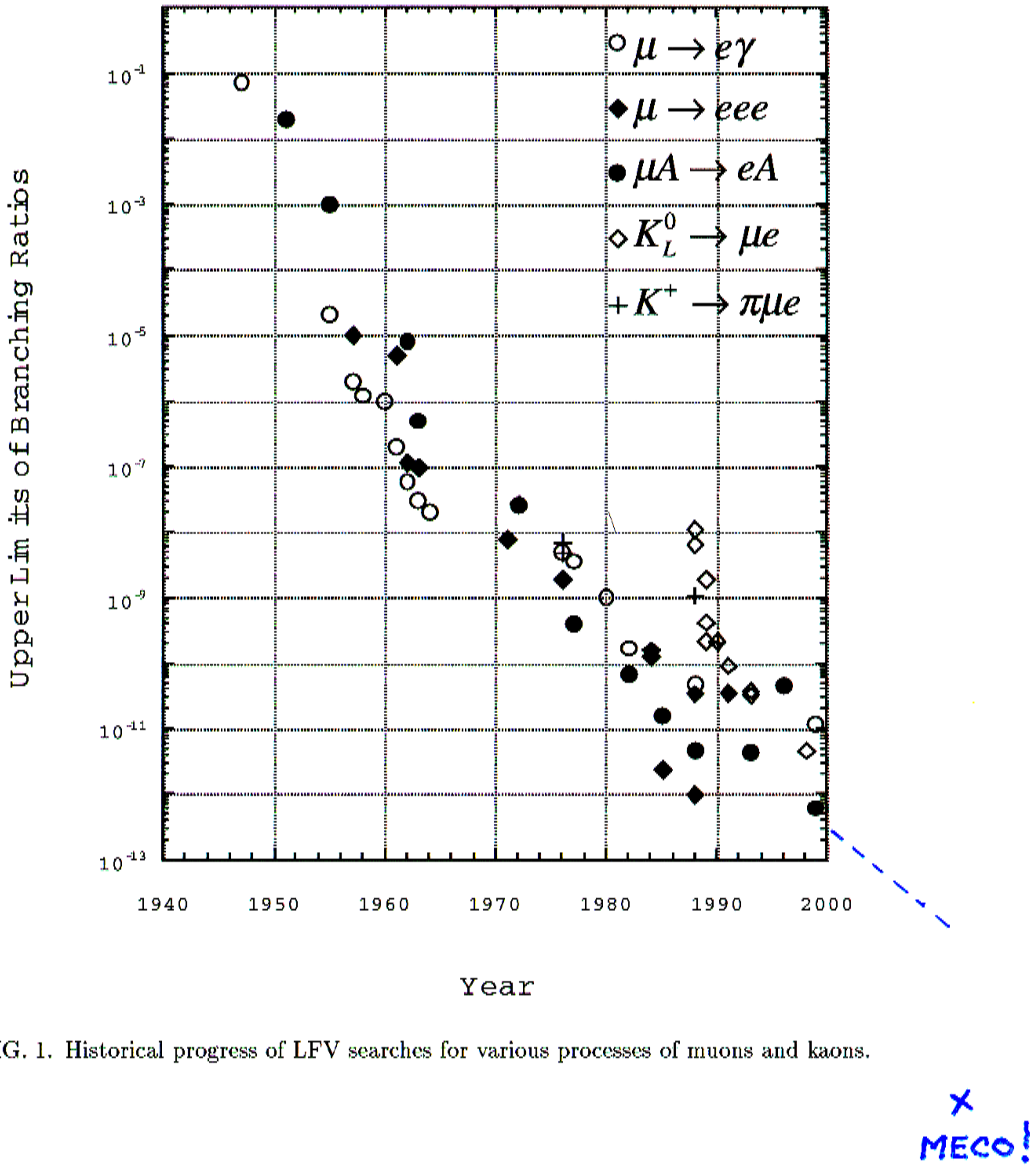


FIG. 1. Historical progress of LFV searches for various processes of muons and kaons.

Experimental Tests of Muon-Number Non-Conservation

Reaction	Current Bound	Ongoing	Future Possibility
$R(\mu^- N \to e^- N)$	$< 6 \times 10^{-13}$	$\sim 4 \times 10^{-14}$	$\sim 10^{-16}$ (10^{-18})
$B(\mu^+ \to e^+ e^- e^+)$	$< 1 \times 10^{-12}$	-	?
$B(\mu \to e\gamma)$	$< 5 \times 10^{-11}$	$\sim 1 \times 10^{-11}$	$\sim 10^{-14}$
$B(K_L \to \mu e)$	$< 2.4 \times 10^{-11}$	$\sim 8 \times 10^{-13}$	$\sim 10^{-13}$
$B(K^+ \to \pi^+ \mu e)$	$< 2.1 \times 10^{-10}$	$\sim 3 \times 10^{-12}$	$\sim 10^{-13}$
$B(K_L \to \pi^0 \mu e)$	$< 3.2 \times 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$
$B(B \to \mu e)$	$< 5.9 \times 10^{-6}$	Not Competitive	
$B(B \to K \mu e)$	$< 1.5 \times 10^{-5}$		
$B(Z \to \mu e)$	$<$ few $\times 10^{-6}$	($< 10^{-13}$ from $R(\mu^- Ti \to e^- Ti)$)	

iii) Neutrino Osc. – Muon Storage Ring

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Measure $\theta_{12}, \theta_{23}, \theta_{13}, \delta, \Delta m^2_{31}, \Delta m^2_{21}$

Super K → $\theta_{23} \simeq 45°$, θ_{13} small, $\Delta m^2_{31} \simeq \Delta m^2_{32} \simeq 3\times10^{-3}\,eV^2$

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
$\mu^- \to e^- \bar{\nu}_e \nu_\mu$ } clean, well known spectra

Current Thinking $E_{\mu^\pm} \simeq 50\,GeV$, $\sim 10^{13}\,\mu^\pm/sec$, some cooling

Long Baseline ~ 7000 km

Very Ambitious, Expensive $\xrightarrow[\text{major step}]{}$ 100 GeV $\mu^+\mu^-$ collider

Comment CP requires $J_{CP} = \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta\cos\theta_{12}\cos\theta_{13}\cos\theta_{23}$
$\quad$ & $\Delta m^2_{31}, \Delta m^2_{21} \neq 0$

5. Concluding Remarks

Muon Collider Concept - "Pipe Dream" or "An Idea Whose Time Has Come"

The Physics case is very strong, particularly $\mu^+\mu^-$ $\sqrt{s} \simeq 3\text{-}4\,\text{TeV} \to 10\,\text{TeV}$

Must strive for: high luminosity $10^{34}\text{-}10^{35}\,\text{cm}^{-2}\text{s}^{-1}$, good resolution
polarization, reduce ν radiation

Probably $\gtrsim$ 25 yrs for R+D, Proposal, Construction

In the immediate future - build a muon research program

Frontier Research Capabilities

1) a_μ → e.d.m $d_\mu \sim 10^{-24} - 10^{-26}$ e-cm !

2) MECO → $\mu^- N \to e^- N$ at 5×10^{-17}!

3) ν osc. Δm^2_{31}, Δm^2_{21} ?, $\overset{(-)}{\nu}_\mu \leftrightarrow \overset{(-)}{\nu}_e$, $\overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\tau, \nu_s$ $\not{CP}$

Go down $\mu^+\mu^-$ path if clear path to high energy

→ 100 GeV Higgs Factory 30,000 events

500-1000 GeV SUSY, $H^\pm$, A, H, h, ...

3-4 - 10 TeV Flavor, Strong Dynamics, Extra Dim., Z'

→ 100 TeV SUSY Br.

Muon may be the window to Nature's Next Level of Secrets

We can't discover or progress if we don't explore