11/6/97

Low Energy Physics & The First Muon Collider

(Stopped Muons, Rare Decays, and Low Energy Hadrons*)

(Will not discuss: $n, \bar{p}, \pi$)

Outline

I. Introductory Remarks

II. Low Energy Muon Physics - Survey & "Best Bets"

III. Muon-Electron Conversion ($\mu^- N \to e^- N$, $10^{-18} \sim 10^{-19}$ sensitivity

IV. Kaon Physics Goals

V. Concluding Comments

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* See also: LAMPF II, KAON, *JHF } Many Workshop Proceedings

Provisional Muon Source Parameters for the Workshop

Parameters of muon bunches downstream of the ionization cooling channe

	Narrow σ_p	Broad σ_p
muons per bunch	5×10^{12}	5×10^{12}
μ^+ bunches per cycle	1	1
μ^- bunches per cycle	1	1
momentum (MeV/c)	200	200
σ_p/p	5%	10%
bunch length (cm)	1.5	10
normalized $\varepsilon_\perp$ (mm–mr)	$200\ \pi$	$60\ \pi$
repetition rate (Hz)	15	15
μ^+ per year (10^7 secs)	7.5×10^{20}	7.5×10^{20}
μ^- per year (10^7 secs)	7.5×10^{20}	7.5×10^{20}

Provisional Proton Source Parameters for the Workshop

	Step 1		Step 2	Step 3
	Scenario 1	Scenario 2		
Linac				
Kinetic Energy (MeV)	400	1000	1000	1000
Momentum Spread (95% FW)	1	1	1	1
Current (mA)	45	67.1	112	328.5
Pulse Length (μs)	0.75	0.75	0.75	0.75
H^- per pulse	1×10^{13}	1.5×10^{13}	2.5×10^{13}	1×10^{14}
Repetition Rate (Hz)	15	15	15	15
Pre–Booster				
Extraction Kinetic Energy (GeV)				4.5
Momentum Spread (95% HW)				0.5%
Circumference (m)				180.6
Protons per bunch				5×10^{13}
Number of Bunches				2
Repetition Rate (Hz)				15
Extracted bunch length (ns)				21
Transverse Emittance (mm–mr)				200π
Longitudinal Emittance (eV–sec)				1.8
Booster				
Extraction Kinetic Energy (GeV)	16	8	16	16
Momentum Spread (95% HW)	< 0.1%	< 0.1%	< 0.1%	1.2%
Crcumference (m)	474.2	474.2	474.2	474.2
Protons per Bunch	1.2×10^{11}	1.8×10^{11}	3.0×10^{11}	5×10^{13}
Number of Bunches	84	84	84	2
Repetition Rate (Hz)	15	15	15	15
Extracted bunch length (ns)	4.9	4.9	4.9	2.3
Transverse Emittance (mm–mr)	50π	30π	50π	240π
Longitudinal Emittance (eV–sec)	2.2	1.8	1.8	4.0

What Compelling Low Energy Muon Physics Can Be Done With $10^{11} - 10^{14}$ μ/sec ?

4-7 orders of magnitude intensity increase!

Rich + Varied Muon Physics Program Possible

* i) Fundamental Particle Physics
ii) μSR (condensed matter)
iii) μ^- Catalyzed Fusion ($\mu^- dT$)
iv) Other

II. Low Energy Muon Physics - Survey + "Best Bets"

i) Precision Measurements $\tau_\mu, \rho, m_{\nu_\mu}, g_\mu - 2$

eg. $\tau_\mu = 2.19703(4) \times 10^{-6}$ s $\rightarrow$ $G_\mu = 1.16639(1) \times 10^{-5}$ GeV^{-2}

BNL + PSI factor 10 improvement $\sim 10^{12}$ μ decays

TRIUMF factor 10 improvement in Michel Parameters
(Interpretation Requires 2 loop EW Rad. Corrections)

$m_{\nu_\mu} < 160$ keV $\rightarrow$ < 16 KeV (g-2 ring)

Hard to do much better (try?)

Muon Anomalous Magnetic Moment $a_\mu = (g_\mu - 2)/2$

$$a_\mu = a_\mu^{QED} + a_\mu^{hadronic} + a_\mu^{EW} + a_\mu^{\text{"New Physics"}}$$

$$a_\mu^{QED} = 116\,584\,706(2) \times 10^{-11} \quad (5\,\text{loops})$$

$$a_\mu^{Had} = 6\,832(97) \times 10^{-11} \quad (3\,\text{loops})$$

$$a_\mu^{EW} = 151\,(4) \times 10^{-11} \quad (2\,\text{loops})$$

$$a_\mu^{th} = 116\,591\,689(97) \times 10^{-11}$$

$$a_\mu^{exp} = 116\,592\,300\,(840) \times 10^{-11} \quad (\text{CERN})$$

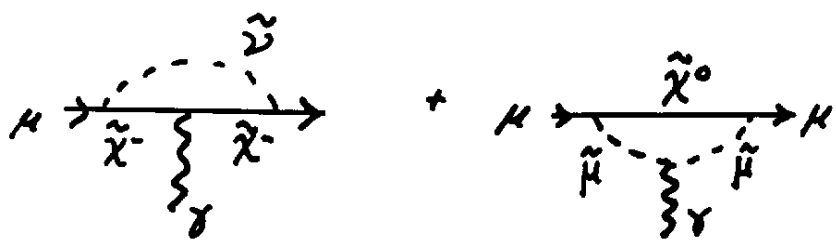
$$\Delta a_\mu = 611\,(\underbrace{\pm 840}_{exp}\ \underbrace{\pm 97}_{th}) \times 10^{-11}$$

BNL Exp $\rightarrow \pm 40 \times 10^{-11}$

Hadronic Unc. $\rightarrow \pm 30 \times 10^{-11}$

Hard to do much better (?)

Good Probe of SUSY loops:



$$\sim 140 \times 10^{-11} \left(\frac{100\,\text{GeV}}{m_{SUSY}}\right)^2 \tan\beta$$

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ii) Muon Electric Dipole Moment (Violates P & T)

Current $|d_e| \lesssim 4 \times 10^{-27}$ e-cm

$|d_n| \lesssim 10^{-25}$ e-cm

$|d_\mu| \lesssim 7 \times 10^{-19}$ e-cm

BNL E821 LOI $\rightarrow |d_\mu| \sim 10^{-24}$ e-cm 6 orders of mag. jump!

Very Roughly $d_e : d_n : d_\mu :: m_e : m_d : m_\mu :: 1 : 20 : 200$

$d_\mu \simeq 10^{-24}$ e-cm ~ same level as current d_e, d_n

Requires ~ 10^7 μ/sec

Intense Source $\gtrsim 10^{11}$ μ/sec $\xrightarrow{?}$ 10^{-26} e-cm

Potentially Extremely Interesting
(Also Very Challenging)

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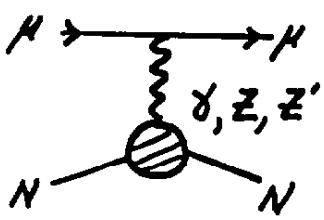
iii) Muonic Atoms ($\mu^- N$ or $\mu^+ e^-$)

High Precision h.f.s. Need High Statistics

Parity Violation, T violation! (New Physics)



$|\psi_\mu(0)|^2 \sim m_\mu^3 \rightarrow 10^7$ enhancement
(over ordinary atoms)

Good Candidate For High Intensity
(Under Study)

iv) <u>Muon-Number Non-Conservation</u> (Most Compelling)

$\mu^+ \to e^+ \gamma$

$\mu^+ \to e^+ e^- e^+$

* $\underline{\mu^- N \to e^- N}$ ("Best Bet")

$\mu^+ e^- \to \mu^- e^+$

$\mu^- N \to e^+ N$

see table

<u>Provide Powerful Probes of "New Physics"</u>

SUSY Loops, Heavy Neutrino Mixing, Z', Leptoquarks, Multi-Higgs, Compositeness ... (Robust)

<u>Discovery Potential High</u>

Must be pushed as far as possible.

<u>Next Round</u> (Goals) $\underline{\mu^+ \to e^+ \gamma \to 10^{-14}}$

$\underline{\mu^- N \to e^- N \to 10^{-16}}$ (MECO, W. Molzon et al.

<u>Front End of Muon Collider</u> $\mu^- N \to e^- N \to 10^{-18} \sim 10^{-19}$ sensitivity!

Only BR that can be pushed that far! Unique

Experimental Tests of Muon-Number Non-Conservation

Reaction	Current Bound	Ongoing	Future Possibility
$B(\mu^- Ti \to e^- Ti)$	$< 7 \times 10^{-13}$	$\sim 2 \times 10^{-14}$ (?)	$\sim 10^{-16}$ (10^{-18}?)
$B(\mu^+ \to e^+ e^- e^+)$	$< 1 \times 10^{-12}$	–	(?)
$B(\mu^+ \to e^+ \gamma)$	$< 4.2 \times 10^{-11}$	$\sim 5 \times 10^{-12}$	$\sim 10^{-14}$
$B(K_L \to \mu e)$	$< 2.4 \times 10^{-11}$	$\sim 8 \times 10^{-13}$ (?)	$\sim 10^{-13}$
$B(K^+ \to \pi^+ \mu e)$	$< 2.1 \times 10^{-10}$	$\sim 3 \times 10^{-12}$	$\sim 10^{-13}$
$B(K_L \to \pi^0 \mu e)$	$< 3.2 \times 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$
$B(B^0 \to \mu e)$	$< 5.9 \times 10^{-6}$		
$B(Z \to \mu e)$	$\lesssim 10^{-6}$	($< 10^{-13}$ from $\mu^- Ti \to e^- Ti$ Bound)	

III. Muon-Electon Conversion ($\mu^- N \to e^- N$)

Stop μ^- in target $\xrightarrow[10^{-10}s]{}$ 1s orbit $\mu^- N$ atom

Possibilities: $\mu^- N \to \nu_\mu N'$ (Dominates for $Z \gtrsim 10$) $\sim Z^5$

$\mu^- \to e^- \nu \bar{\nu}$

or Coherent Conversion $\underset{\sim Z^5}{\mu^- N \to e^- N}$ $E_e = m_\mu - (BE) \simeq 105\,MeV$

Very Distinct Signature - Monoenergetic Electon ~ 105 MeV

Reject Background - Very Good Energy Resolution ~ 300 keV

Can Take High Rate - No Accidentals (Unique)

Physics Background - Decay in orbit $\nu\bar{\nu}$ with 0 energy

$N \longleftarrow \oplus \bullet \longrightarrow e$ Highly Suppressed

Becomes a problem $< 10^{-18} \sim 10^{-19}$

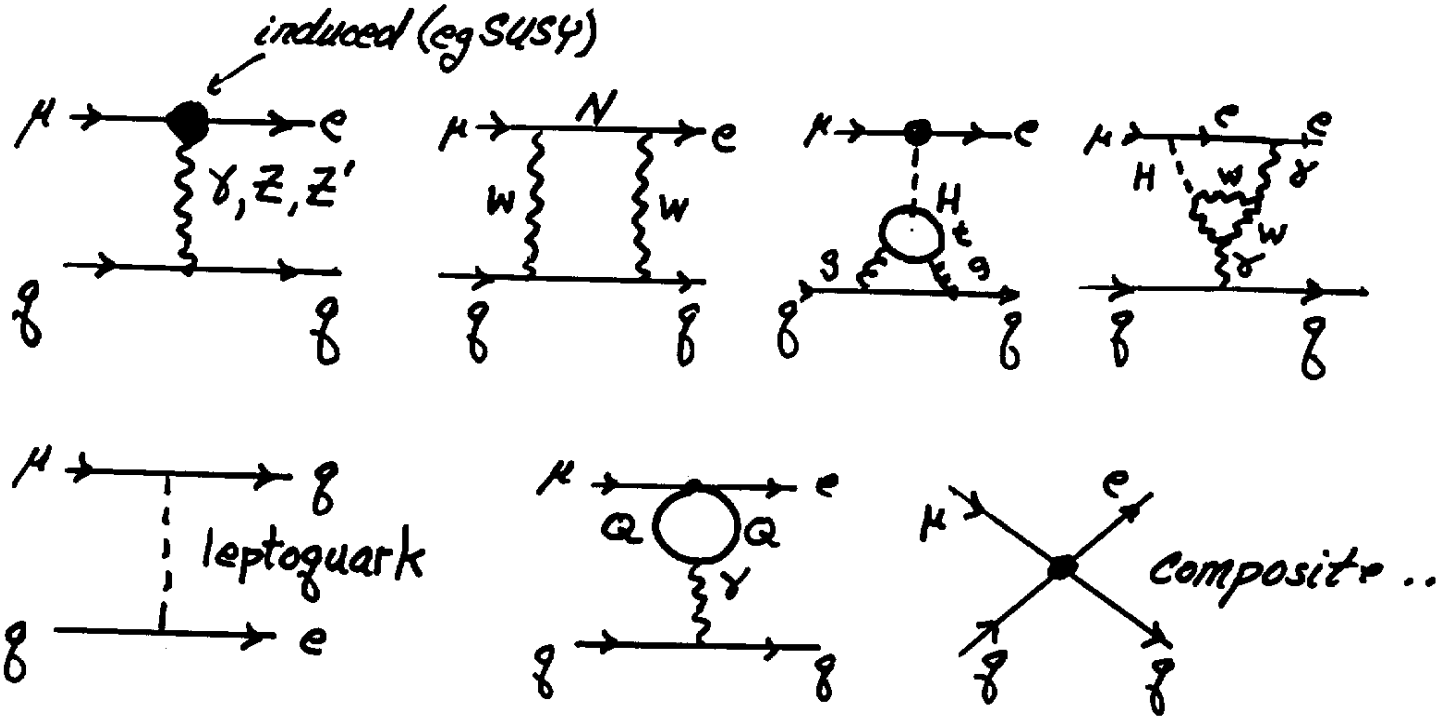
MECO at BNL $\to 10^{-16}$ using $\sim 10^{11}\,\mu^-/sec$

FMC Front End $\to 10^{-18} \sim 10^{-19}$ $10^{13} \sim 10^{14}\,\mu^-/sec$ (Very Clean Beam)

Observation of Signal - Change Targets, Dope, Sort Out...

(Also, Push $\mu^+ \to e^+\gamma$ + $\mu^+ \to e^+e^-e^+$)

Examples of "New Physics" Probed



Comparison of $\mu^+ \to e^+\gamma$ and $\mu^- N \to e^- N$ (Model Dependent)

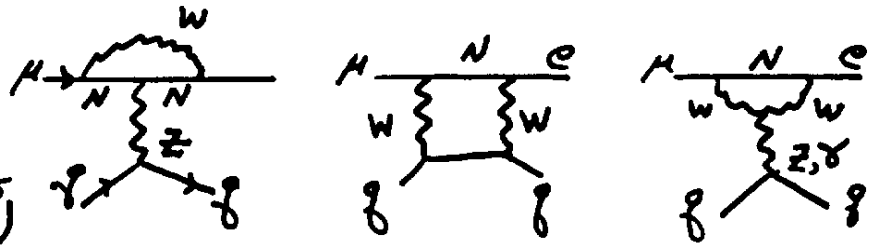
$$\frac{1}{200} \lesssim \frac{B(\mu^- Ti \to e^- Ti)}{B(\mu^+ \to e^+\gamma)} \lesssim 200 \quad \text{(or more)!}$$

$$B(\mu^- N \to e^- N) < 10^{-16} \sim B(\mu^+ \to e^+\gamma) < 2\times10^{-14} - 5\times10^{-19}!$$

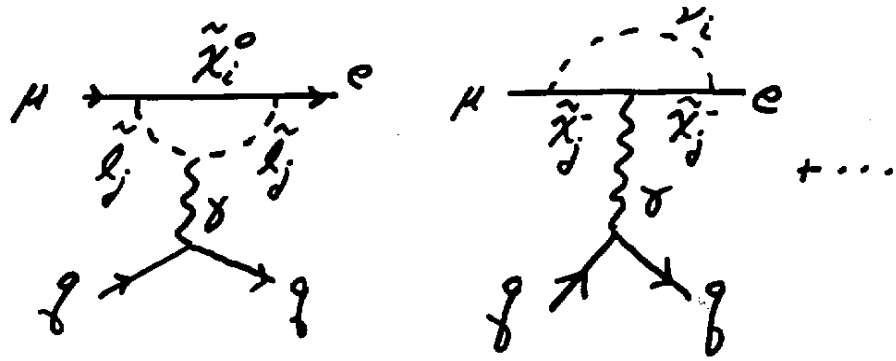
Physics Probed by $B(\mu^- N \to e^- N) < 10^{-16}\ (10^{-18})$

Heavy Neutrino Mixing

$|U_{\mu N}^* U_{eN}|^2 < 8\times10^{-13}\ (10^{-15})$



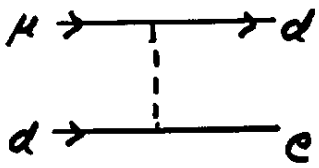
SUSY Loops
(Compelling)



very sensitive See Fig.

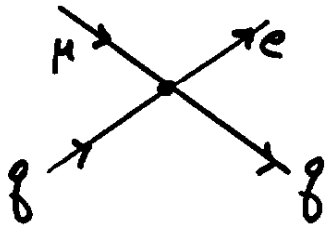
Many Models

Leptoquark ($\not{R}$ Violating)



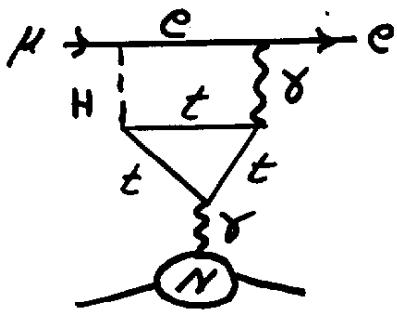
$M_{LQ} > 3000 \sqrt{\lambda_{\mu d} \lambda_{ed}}$ TeV!

Compositeness



$\Lambda_c > 3000$ TeV ! (10,000?)

Neutral Higgs



Bjorken + Weinberg

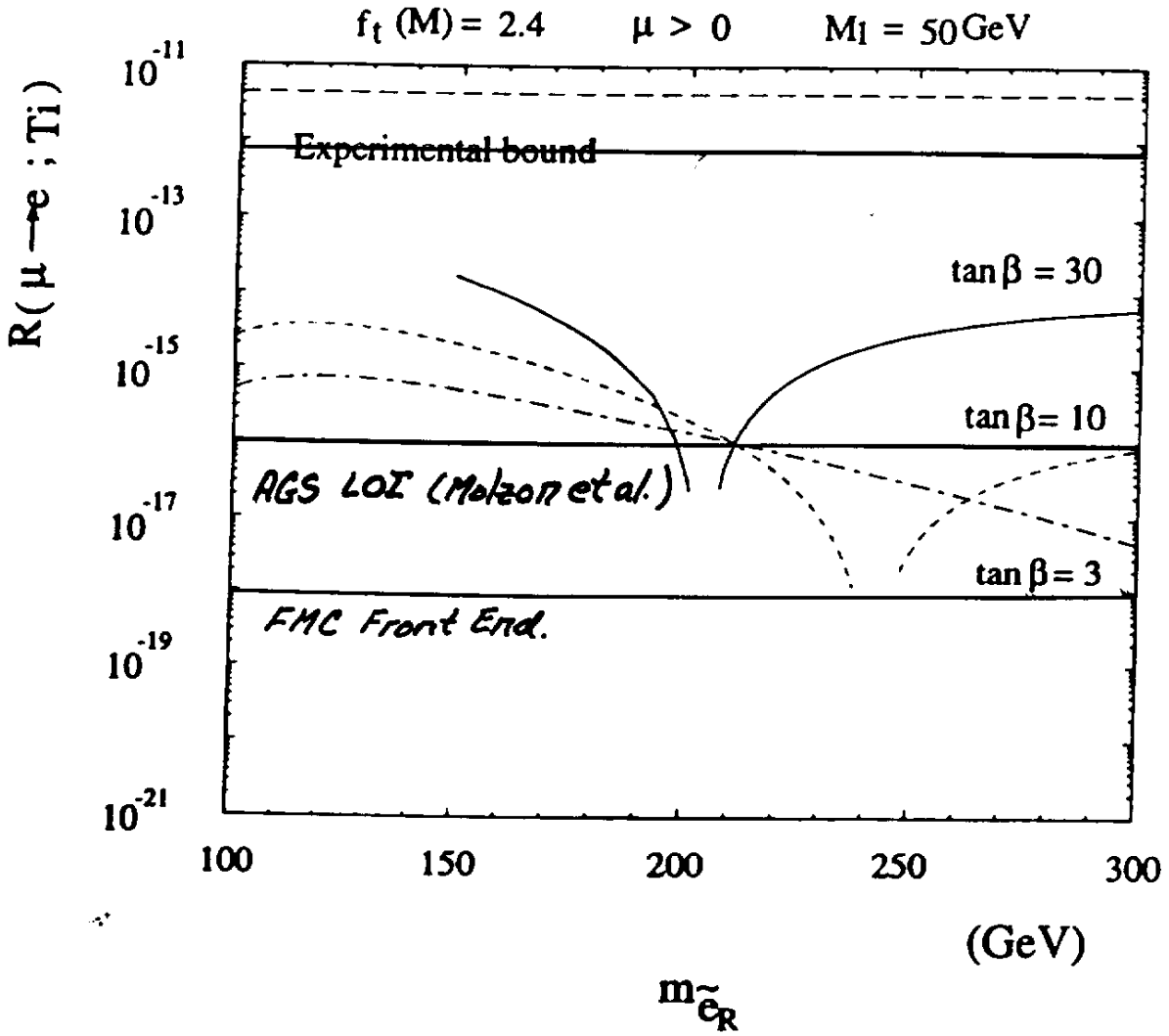
$10^{-16} \rightarrow$ $H\mu e$ coupling $< 10^{-4}$ $H\mu\bar{\mu}$ coupling

$B(H \rightarrow \mu e) < 10^{-12}$! ($10^{-14}$!)

+ Many Other Examples

$\mu^- Ti \to e^- Ti$ in SUSY SU(5) Model, (Hisano, Moroi, Tobe + Yamaguchi)

$\sim\left(\frac{m_\tau}{m_\mu}\right)^2$ larger in some SUSY SO(10) (Barbieri, Hall...)



(a)

IV. Kaon Physics Goals

Assume 20x AGS Kaon Intensity (Can it be fully used?)

Precision Measurements (Factor ~4 Improvement)

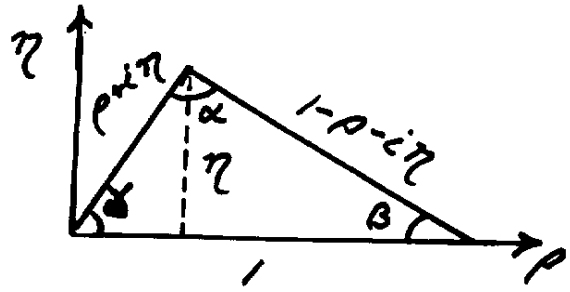
$BR(K^+ \to \pi^+ \nu\bar{\nu}) \sim 1\times10^{-10}$
$BR(K_L \to \pi^0 \nu\bar{\nu}) \sim 3\times10^{-11}$ } Depend on $V_{td} \to \rho, \eta$ (Standard Model)

Theoretically "Very" Clean!

BNL E787 (1 event) $\to BR(K^+ \to \pi^+ \nu\bar{\nu}) = 4.2\,^{+9.7}_{-3.5} \times 10^{-10}$ (Exciting)

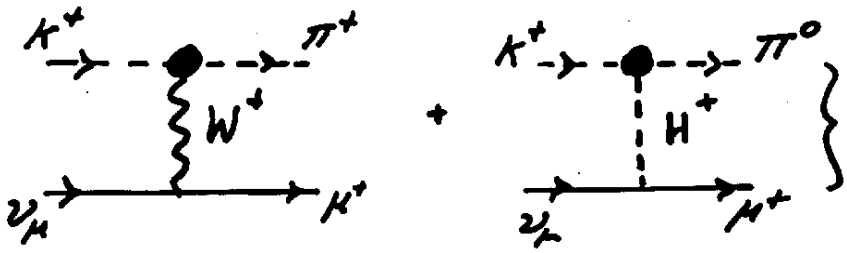
Current Goals (AGS2000 + KAMI) $\to \pm 15\%$

FMC Front End $\to \pm 4\%$! $\to \frac{\Delta\eta}{\eta} \simeq \pm 0.02$!



K + B Studies Complementary (Comparison Probes "New Physics")

$K_{\mu 3}$: $K^+ \to \pi^0 \mu^+ \nu_\mu$ Muon Transverse Pol



"New Physics" cp Interference (eg. Multi-Higgs)

$$P_\mu^T = \hat{S}_\mu \cdot (\hat{P}_\mu \times \hat{P}_\pi)$$ T Violating

Old BNL Exp. $P_\mu^T = -1.85 \pm 3.60 \times 10^{-3}$

KEK Exp $\to 9 \times 10^{-4}$

BNL E923 $\to 1.3 \times 10^{-4}$

FMC Front End Goal $\to 10^{-5}$! (Very Interesting) Challenging

Other Interesting Studies

$K^+ \to \pi^+ \mu^+ \mu^-$ (spin-spin correl.)

$K_L \to \mu^+ \mu^-$ (Pol.)

$K_L \to \mu e$, $K \to \pi \mu e$ $\Big\}$ $< 10^{-13}$ Goal

Need Study

V. Concluding Comments

How do we get First Muon Collider?

Physics Consensus, Technical Feasibility

Low Energy Start Muon Facility – Full Front End

"Best Bets" $\mu^- N \to e^- N$ 10^{-16} - 10^{-18}

$\mu^+ \to e^+ \gamma$, $\mu^+ \to e^+ e^- e^+$ ($< 10^{-14}$) ($\mu^+ e^- \to \mu^- e^+$)...

Muon e.d.m. 10^{-24} e-cm $\to$ 10^{-26} e-cm

Muonic Atoms P & T Violation

Precision Studies $\mu^+ e^-$...

$K \to \pi \nu \bar{\nu}$

$K^+ \to \pi^0 \mu^+ \nu$ $\langle P_T \rangle$

$K_L \to \mu e$, $K \to \pi \mu e$

μSR, $\mu^- dT$, μ chemistry ...

Put on a fast track – start as soon as possible!

New Ideas Likely To Emerge

On the way to The First Muon Collider