“Muon Physics”

Beyond the Standard Model

Also See Review: “Precision Muon Physics” by Gorringe and Hertzog 2015

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OUTLINE

1. *Introduction:* *Great Muon Expectations*

2. *Some PSI Results* **(Outstanding Program)**

   i) Muon Lifetime τ_μ=2.1969803(22)x10^{-6}sec

   $\rightarrow$ G_μ=1.1663787(6)x10^{-5} GeV^{-2}

   +α, m_W & $\sin^2\theta_W(m_Z)$ + RC $\rightarrow$ **S Parameter=0.07(8)**

   : New Heavy Chiral Doublets? Excited W*? ,,,

   ii) **μp Capture g_P=8.3±0.6 (Agrees with χPT 8.2±0.2)**

   μp Atom Lamb Shift & Proton Radius Puzzle ***0.84fm?***

   MEG at PSI: BR($\mu^+ \rightarrow e^+\gamma$)<5.7x$10^{-13}$ $\rightarrow$ MEGII

3. i) Muon Anomaly **$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$=276(80)x$10^{-11}$**

   ii) "New Physics"?: SUSY, Dark Photon, **Dark Higgs ϕ**…

   iii) μ edm (d_μ<1.8x10^{-19}e-cm) vs electron (d_e<8.7x10^{-29}e-cm)

4. *Higgs Coupling-Mass Misalignment & Dark Higgs ϕ*

BR($H \rightarrow \mu^+\mu^-$)$_{SM}$=0.00022

LHC Run1: BR($H \rightarrow \mu^+\mu^-$)/BR($H \rightarrow \mu^+\mu^-$)$_{SM}$=$0.2^{+1.2}_{-0.2}$

(Run2 expect 5σ SM sensitivity!)

5. LFV: $\mu^+ \rightarrow e^+\gamma$ MEG at PSI <5.7x10^{-13} →fewx10^{-14}

   $\mu^- N \rightarrow e^- N$ <7x10^{-13} At PSI→Fermilab/JPARC (2x10^{-17}!)

   $\mu^+ \rightarrow e^+e^-e^+$ At PSI $10^{-12} \rightarrow 10^{-16}$ Mu3e! & search for γ_d/ϕ

6. Muon Collider: Z Factory, H, φ… Factory, ZH?

   (~2-4TeV Collider)/Neutrino Factory

7. Outlook

1. Introduction: Great Muon Expectations

- Muons are very special: $\tau_\mu \approx 2.2 \times 10^{-6}$sec! Nearly stable!
  m_μ=105.66MeV (μ^- heavy electron, μ^+ light proton)

- Decay: $\mu^+ \rightarrow e^+ \nu_e \nu_\mu (\gamma)$
  100%Polarized-P.V. Decay Ang. Dist. Tracks Pol.
  μSR (condensed matter), Muon g-2 (Garwin et al.)

Copious Production: 1p(8GeV)+N$\rightarrow \pi^\pm \rightarrow 1\mu^\pm$
Intense Muon Source $\approx 10^{13}$-$10^{14}\mu^\pm$/sec possible!
(Currently $10^8\mu^+$/sec, $10^7\mu^-$/sec at PSI $\rightarrow$higher)
Muon Collider $\mu^+\mu^-$, Neutrino Factory, Z & H Factory
μCF? μ^-DT$\rightarrow$He(4MeV)+n(14MeV)+μ^- (**10^{20}p/s!!**)

2. Some Muon Results (PSI)

Standard Model Natural Relations:

$e_0^2/g_0^2=\sin^2\theta^0_W=1-(m^0_W/m^0_Z)^2$

Radiative Corrections (Loops) Finite & Calculable

Deviation→"New Physics": SUSY, Technicolor, W*…

No Sign of "New Physics" ***m_W^{exp} a little high***

* ***MUON LIFETIME IMPORTANT*** ***→$G_\mu=g^2/4\sqrt{2}m_W^2$***

eg. $G_\mu(1-\Delta r(m_Z)_{MS})=\pi\alpha/\sqrt{2}m_W^2\sin^2\theta_W(m_Z)_{MS}$

$\boldsymbol{\Delta r(m_Z)_{MS}=0.0696+\underline{0.0085S}+\vartheta(1)(m_W/m_{W^*})^2+\ldots}$

$S=N_D/6\pi$, N_D= No. of new heavy doublets

eg. (4th generation), 12 (mirror fermions), Technifermions…

W* excited W (extra dimensions, compositeness…)

i) Muon (μ^+) Lifetime

MuLAN & FAST experiments at PSI:

$\tau_{\mu+}$=2.1969803(22)x10^{-6}sec MuLAN 2010

(Most precise lifetime measurement ever!)

Improved Previous World Average by error/20!

$\tau_\mu^{-1} = \Gamma(\mu^+ \rightarrow e^+ \nu_e \nu_\mu(\gamma)) = G_\mu^2 m_\mu^5 f(m_e^2/m_\mu^2)[1+RC]/192\pi^3$

RC $=\alpha/2\pi(25/4-\pi^2)(1+\alpha/\pi[2/3\ln(m_\mu/m_e)-3.7)\ldots]$ Fermi Th.

Other SM and "New Physics" radiative corrections absorbed into G_μ. Eg. 4th generation, Technicolor, W*…

G_μ=1.1663787(6)x10^{-5}GeV^{-2} precise & important

Some Important Precision EW Parameters Tied Together by Natural Relationships

Quantity	2008 Value		2015 Value	Comment
α^{-1}	137.035999084(51)		***137.035999049(90)***	$\alpha^{-1}(a_e)$ vs α^{-1}(Rb)
G_μ	1.16637(1)x10^{-5}GeV^{-2}		1.1663787(6)x10^{-5}GeV^{-2}	$\tau_{\mu+}$ PSI
m_Z	91 .1875(21)GeV		91.1876(21)GeV	-
*m_t	171.4(2.1)GeV	→	173.3(0.8)GeV	FNAL/LHC
*m_H	>114GeV	→	**125.09(0.24)GeV**	
m_W	80.410(32)GeV	→	80.385(15)GeV	LEP2/FNAL
$\sin^2\theta_W(m_Z)_{ave}$	0.23125(16)		0.23125(16)	Z Pole Ave.

S Parameter

Use α, G_μ, m_W, and $\sin^2\theta_W(m_Z)_{MS} \rightarrow$ S (Counts N_D) & m_{W*}

eg. $G_\mu(1-\Delta r(m_Z)_{MS}) = \pi\alpha/\sqrt{2} m_W^2 \sin^2\theta_W(m_Z)_{MS}$

$\mathbf{\Delta r(m_Z)_{MS} = 0.0696 + \underline{0.0085S} + \vartheta(1)(m_W/m_{W*})^2 + \ldots}$

$S/120 + (m_W/m_{W*})^2 = [(G_\mu - 1.1663787\text{x}10^{-5}\text{GeV}^{-2})/1.1663787\text{x}10^{-5}\text{GeV}^{-2}$

$+(\alpha^{-1} - 137.035999049)/137.035999049$

$+2(m_W - 80.362\text{GeV})/80.362\text{GeV}$

$+(\sin^2\theta_W(m_Z)_{MS} - 0.23125)/0.23125]$

$m_W = 80.385(15)$GeV $\sin^2\theta_W(m_Z)_{MS} = 0.23125(16)$ Ave

$\rightarrow$ **S=0.07(8) & M_{W*}>2TeV (Central Value ~ 3TeV)**

No Clear Sign of “New Physics”!

ii) Hydrogen Muon Capture:

- Muonic Atom ($\mu^- N \to \nu_\mu N'$): $<V>=-Z^2\alpha^2 m_\mu$, $<\beta_\mu>=Z\alpha$

$\tau_{\mu-} \approx \tau_{\mu+}(1 + Z^2\alpha^2/2$ - Capture BR$(\sim Z^3/1000))$

Γ(capture)=$1/\tau_{\mu-} - 1/\tau_{\mu+}$ (after time dilation correction)

N=p, theory clean but high precision lifetimes needed.

$<n|d\gamma_\alpha(1-\gamma_5)u|p> = g_V(q^2) n\gamma_\alpha p + i g_M(q^2)/2m_N n\sigma_{\alpha\beta}q^\beta p$
$- g_A(q^2) n\gamma_\alpha\gamma_5 p - g_P(q^2) q_\alpha/m_\mu n\gamma_5 p$

Chiral Pert. Th. Predicts: $g_P(-0.88 m_\mu^2) = 8.2 \pm 0.2$

Exp.(Pre 2007)$\to g_P$=11-12(1) Off by 3-4 sigma

μ-p Capture Result

Γ(capture)=$1/\tau_{\mu-}-1/\tau_{\mu+}$ (after time dilation correction)

For atomic 1S singlet

(Including radiative corrections)

Czarnecki, Marciano and Sirlin (PRL & unpublished)

$\Gamma(\mu^- p \rightarrow \nu_\mu n)^{SM} = 717(2)(1+0.6265(g_A-1.275)-0.0108(g_P-8.2))^2 \text{sec}^{-1}$

$\Gamma(\mu^- p \rightarrow \nu_\mu n)^{exp} = 715.6(7.4))\text{sec}^{-1}$ MuCap

input g_A=1.275(1) from Neutron Decay

Implies: g_P=8.3(6)

$g_p^{\chi PT} \rightarrow 8.2(2)$ Excellent Agreement!

Further exp. improvement warranted with goal of independent muonic determination of g_A from g_P

3. Muon Anomalous Magnetic Moment

Experimental E821 at BNL (2004 Final)

- $a_\mu^{exp} \equiv (g_\mu-2)/2 = 116592091(54)_{stat}(33)_{sys} x10^{-11}$

$= 116592091(63) x10^{-11}$

Factor of 14 improvement over CERN results (stat. limited)

(Goal: Factor 4 further Improvement at FNAL)

D. Hertzog, B.L. Roberts… $\pm 16x10^{-11}$

Muon $(m_\mu/m_e)^2 \approx 40,000$x more sensitive to short distances than electron.

(Long Distance Effects? Eg Dark Photon or Dark Higgs)

Standard Model Prediction

$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadronic}$ (quark/gluon loops)

QED Contributions:

- $a_\mu^{QED} = 0.5(\alpha/\pi) + 0.765857425(17)(\alpha/\pi)^2 +$
  $24.05050996(32)(\alpha/\pi)^3 +$
  $130.8796(63)(\alpha/\pi)^4 +$
  $753.29(1.04)(\alpha/\pi)^5 + \ldots$

2012 Update: Aoyama, Hayakawa, Kinoshita, & Nio

$\alpha^{-1}(^{87}Rb) = 137.035999049(90)$ from h/m_{RB}

$a_\mu^{QED} = 116584718.95(8) \times 10^{-11}$ Very Precise!

Electroweak Loop Effects

a_μ^{EW}(1 loop)=194.8x10^{-11} original goal of E821

a_μ^{EW}(2 loop)=-41.2(1.0)x10^{-11} (Higgs Mass = 125GeV))

Higgs 2 Loop ~ 3x10^{-11} (~1000 x one loop Higgs!)

3 loop EW leading logs very small O(10^{-12})

- ***a_μ^{EW}=154(1)x10^{-11} Non Controversial***

- **Hadronic Contributions (HVP & HLBL)**

*a_μ^{Had}(V.P.)^{LO}=6923(42)(3)x10^{-11} Should be updated for Rad. Return

a_μ^{Had}(V.P.)$^{NLO+NNLO}$ = -86(1)x10^{-11}

a_μ^{Had}(LBL) = 105(26)x10^{-11} (Consensus?) 3 loop $(\alpha/\pi)^3$ QCD

a_μ^{SM}=116591815(49)x10^{-11} (Future Improvement?)

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$=276(63)(49)x$10^{-11}$ (*3.5σ deviation!*)

-

Comparison of Experiment and Theory

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 276(63)(49)\times 10^{-11}$ (***3.5σ!***)

This is a very large deviation!

Remember, the EW contribution is only ***154×10^{-11}***

If "New Physics" Nearly 2x Electroweak?

Why don't we see it in other measurements? ***Enhancement!***

"New Physics" Scale Implied < $m_\mu/|\Delta a_\mu|^{1/2} \leq$ 2TeV ***LHC?***

Supersymmetry, Additional Higgs … ***Some LHC Tension!***

Dark Photon Solution Coupling $\varepsilon e \sim 10^{-3}$ Mass ≤ 1GeV

Dark Scalar ϕ $\mu\mu$ coupling $\sim 10^{-3}$ (Like SM H)

(CHEN, DAVOUDIASL, MARCIANO, ZHANG)

Interpretations

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 276(80)\times10^{-11}$ *(3.5σ!)*

***Generic 1 loop SUSY Conribution*:**

$a_\mu^{SUSY} = (sgn\mu)130\times10^{-11}(100GeV/m_{susy})^2\tan\beta$

$\tan\beta \approx 3\text{-}40$, $m_{susy} \approx 100\text{-}500GeV$ ***Some LHC Tension***

Other Explanations: ***Hadronic e^+e^- Data? HLBL?***

Multi-Higgs Models

Extra Dimensions<2TeV

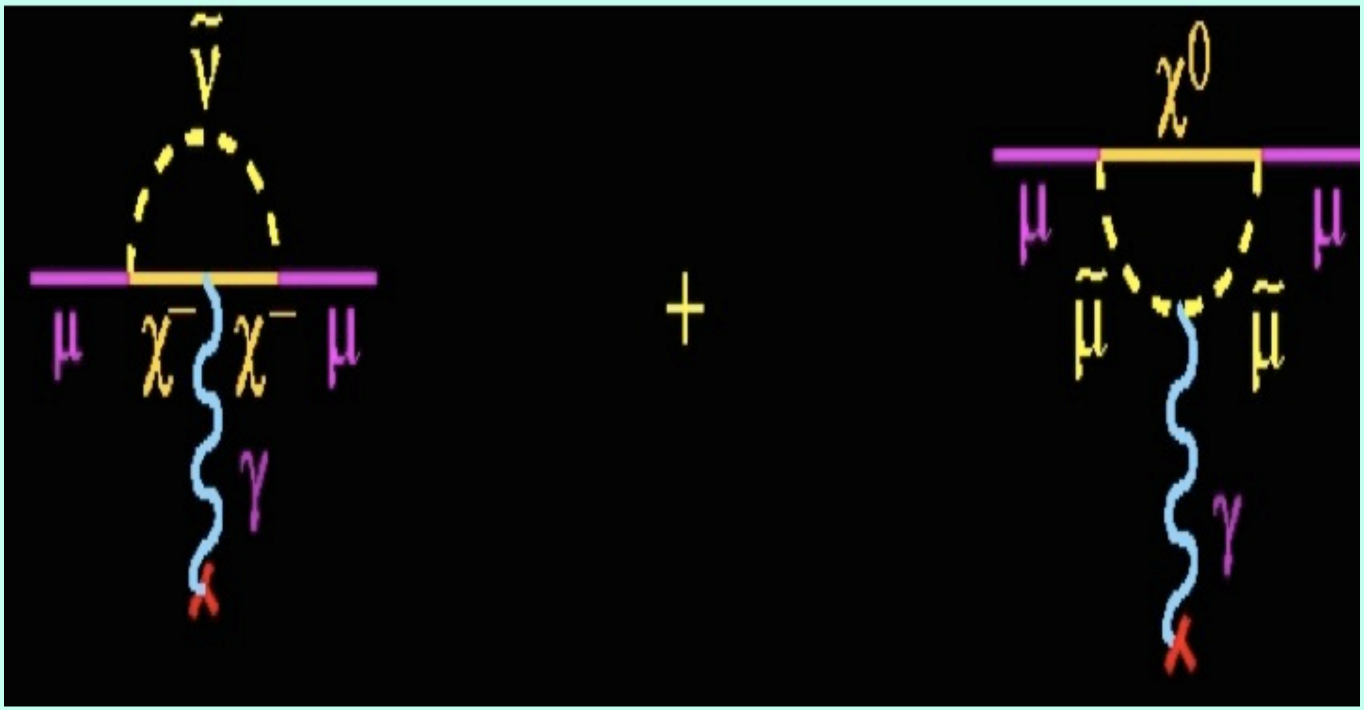
*** *Dark Photons* $\gamma_d \sim 10\text{-}200MeV$, $\alpha' = 10^{-7} - 10^{-8}$**

Light Higgs Like Scalar <1GeV? Dark φ, coupling 10^{-3}

<u>3.2 "New Physics" Effects</u>

_SUSY 1 loop a_μ Corrections

(Most Likely Scenario)



The Dark Boson – A Portal to Dark Matter

- What if some $U(1)_d$ gauge symmetry from the Dark or some Other Sector contains a "Light" *Dark Photon* (γ_d), *U Boson, Hidden Boson… Dark Z* (Z_d)

Introduced for: 1) Sommerfeld Enhancement $D+D \rightarrow Z_d+Z_d$

2) $Z_d \rightarrow e^+e^-$ (source of positrons, ***γ-rays)***

3) Cosmic Dark Matter Stability via global $U(1)_d$

*4) Light Dark Matter Abundance

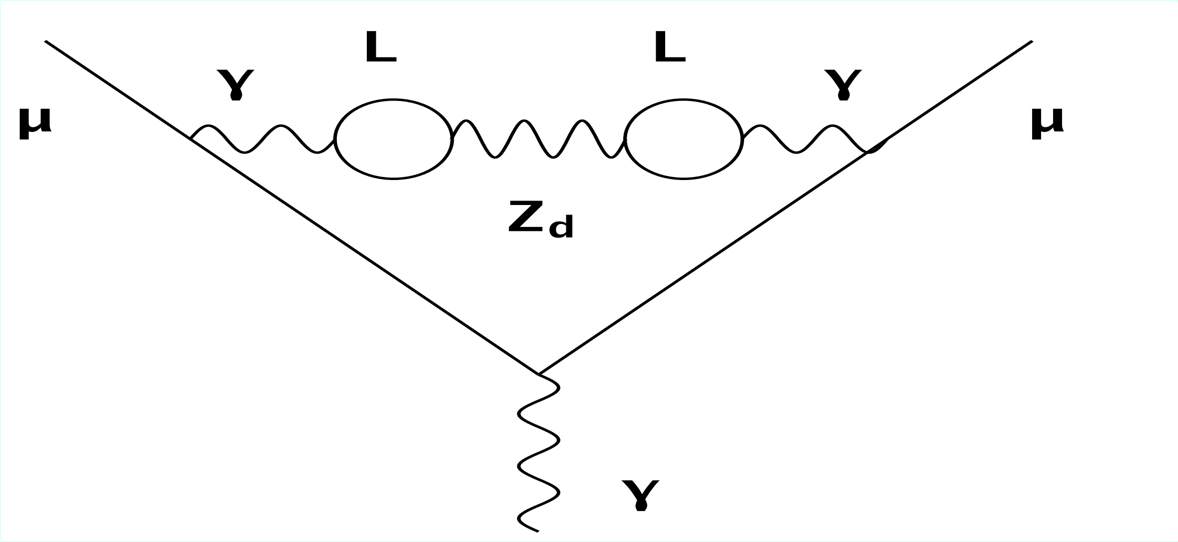
*5) *Muon Anomalous Magnetic Moment*

Can we find direct evidence for such a light boson in the laboratory?

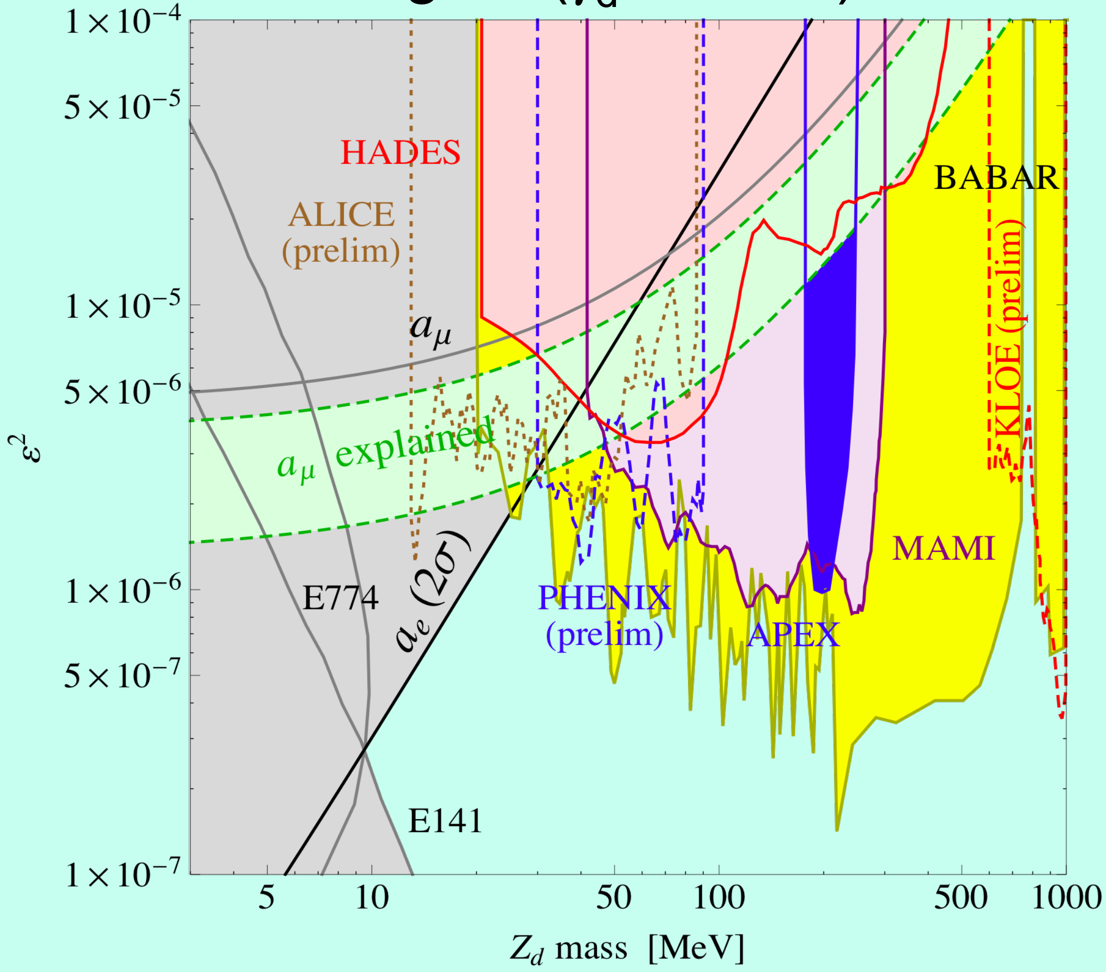
Effective 3 loop g_μ-2 "Dilbert" Dark Photon Diagram

DAVOUDIASL, LEE, MARCIANO

$a_\mu^{Zd}=\alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ solves g_μ-2 discrepancy for $\varepsilon^2 \approx 3\times10^{-6}$ & $m_{Zd}\approx$20-200MeV (see figure)



Dark Photon Constraints including Phenix $\pi^0 \rightarrow \gamma\gamma_d$ (Ruled Out?) Assuming BR($\gamma_d \rightarrow$ e+e-) ~1



“Light” Dark Higgs

CHEN, DAVOUDIASL, MARCIANO, ZHANG

Light scalar $\phi \leq 1$ GeV possible remnant of $U(1)_d$ breaking

Coupling to μ+μ- ~ 10^{-3} solves g_μ-2 discrepancy

Why such a relatively large coupling (Higgs size)?

Misalignment (Mass & Hμμ) due to several sources of μ mass!

SM Higgs + Heavy charged lepton mixing effects + …

Signatures: muon edm as large as ~10^{-23}e-cm

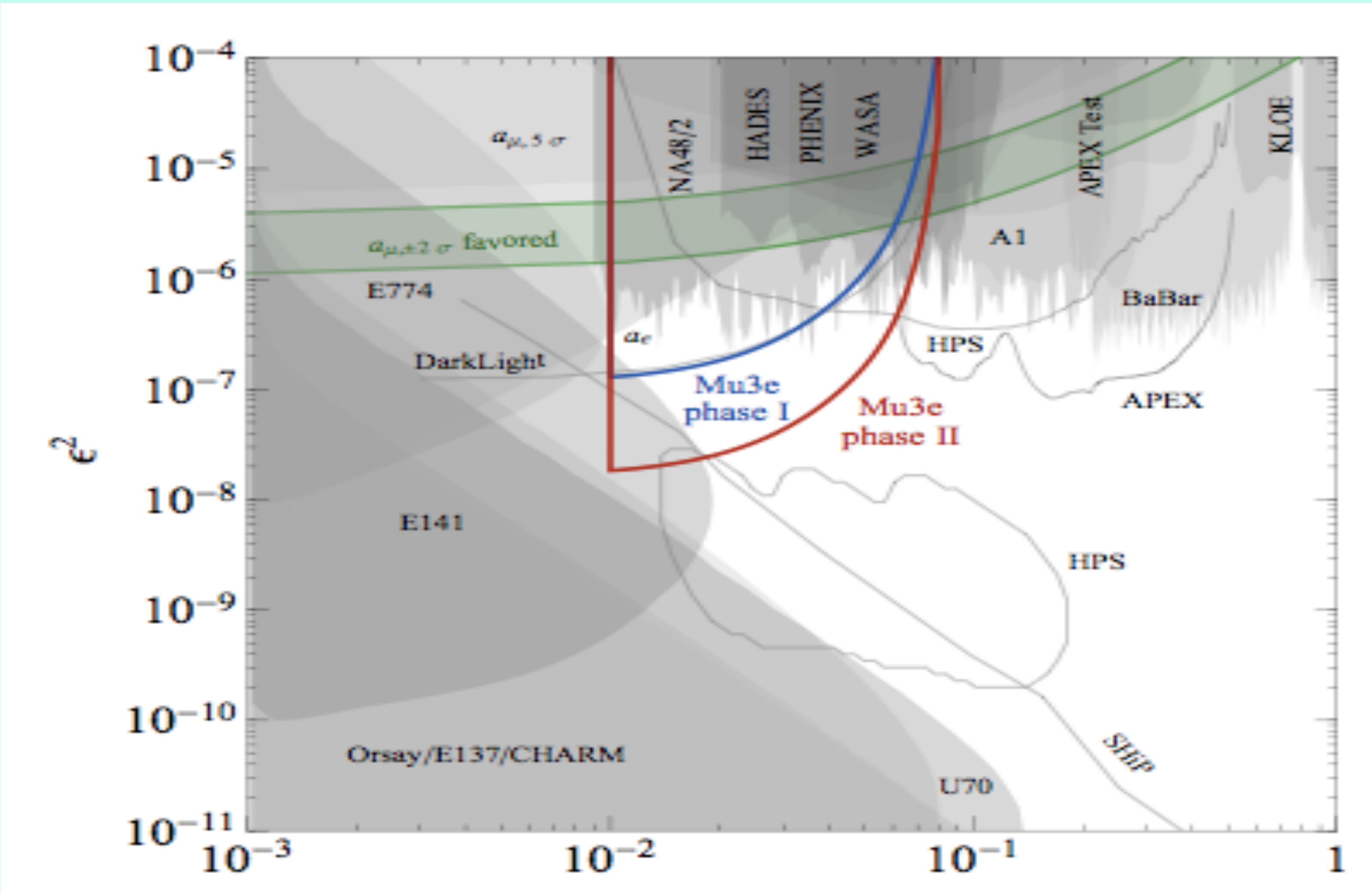
$\mu \to e\nu\nu\phi$ with $\phi \to e^+e^-$ or γγ Mu3e at PSI

(Similar to BR($\mu \to e\nu\nu\gamma_d$) ***at*** 10^{-10} *study* (Echenhard, Essig & Zhong)

mγ_d ***(or*** m_ϕ***) ~ 20-80MeV***

etc.

Echenhard, Essig & Zhong Results for Mu3e sensitivity to: μ→eννγ_d *with dark photon* γ_d→e+e-



4. *Higgs Coupling-Mass Misalignment & Dark Higgs ϕ*

- ***Expected SM Higgs (125GeV) Properties***

H Decay Channel	Branching Ratio
$b\bar{b}$	0.578
WW^*	0.215
gg	0.086
$\tau^+\tau^-$	0.063
$c\bar{c}$	0.029
ZZ^*	0.026
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$	1.5×10^{-3}
$H \to ZZ^* \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$	1.2×10^{-4}
$H \to ZZ^* \to \ell^+\ell^-\nu\bar{\nu}$	3.6×10^{-4}

- ***5 sigma SM LHC Higgs evidence presented (July 4, 2012)***

Now > 1,000,000 H already produced at the LHC!

gluon + gluon ➔ H through top quark loop

H➔γγ ≈ ***Roughly SM Expectation***

H➔ZZ*(virtual)➔4 leptons

H➔WW*➔4 leptons (includes Neutrinos)

H➔$\tau^+\tau^-$

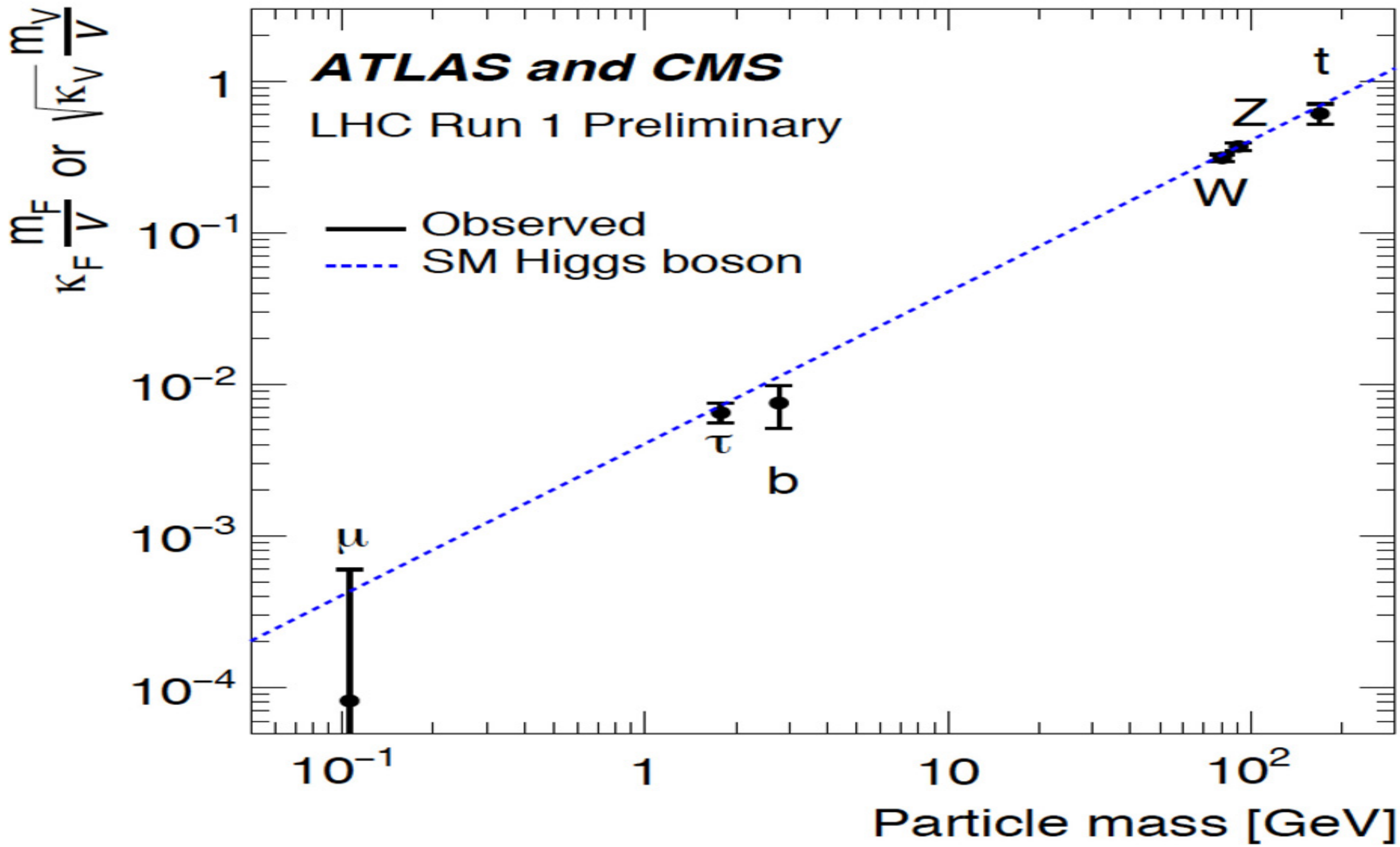
H➔bb

BR(H➔$\mu^+\mu^-$)~$2x10^{-4}$ (5σ sensitivity expected from 14TeV Run)

H decays to e, u, d expected to be unobservably small

BR(H➔e+e-) ~ O($6x10^{-9}$)!

Observation vs Standard Higgs Expectation
Potential surprise in $\mu^+\mu^-$?



$BR(H \to \mu^+\mu^-)_{SM}=0.00022$

LHC Run1: $BR(H \to \mu^+\mu^-)/BR(H \to \mu^+\mu^-)_{SM}=0.2^{+1.2}_{-0.2}$

Could $BR(H \to \mu^+\mu^-)$ turn out to be unexpectedly small?

(Run2 expect 5σ SM sensitivity!)

Hope for a surprise

Other Consequences of misalignment

eg muon edm at ~10^{-23}e-cm (light ϕ & CP viol.)

See: *CHEN, DAVOUDIASL, MARCIANO, ZHANG*

IN PREPARATION

5. Charged Lepton Flavor Violation

LEPTON FLAVOR VIOLATION SEEN IN NEUTRINO OSC.

- 1958 Feinberg loop calculation of $\mu \to e + \gamma$

  $B(\mu \to e\gamma) < 10^{-4} \sim 10^{-5}$ **implies second neutrino!**

  1959 Feinberg and Weinberg Study $\mu^- N \to e^- N$

  Coherent $E_e \approx 105$MeV Very Clean-Distinct

  Stop μ^- in material (10^{-10}sec)$\to \mu^- N(1S)$ atom

  i) $\mu \to e\nu\nu$ Rate$\approx 0.5\times10^6$/sec

  ii) $\mu N \to \nu_\mu N'$ $\omega(N=Al) \approx 0.7\times10^6$/sec

  $\omega(N=Ti) \approx 2.6\times10^6$/sec

  grows $\propto Z^4$ (very roughly)

μ2e Fermilab/JPARC R(μAl→eAl)→2x10^{-17}!

- Coherent μ-e Conversion in Nuclei (μN→eN)

Stop μ^- in material, ~10^{-10}sec, μ^-N (1S) atom forms

i) $\Gamma(\mu^- \to e^- \nu\nu)$ = 0.5x10^6/sec

ii) $\omega(\mu^- N \to \nu_\mu N')$ = 0.7x10^6/sec (N=Al)

= 2.6x10^6/sec (N=Ti)

iii) $\mu^- N \to e^- N$ R(μ^-Ti→e^-Ti)<7x10^{-13} (Prelim.)

*Signature: m_μ-BE=105 MeV monoenergetic electron

single particle→no accidentals→high rate capability!

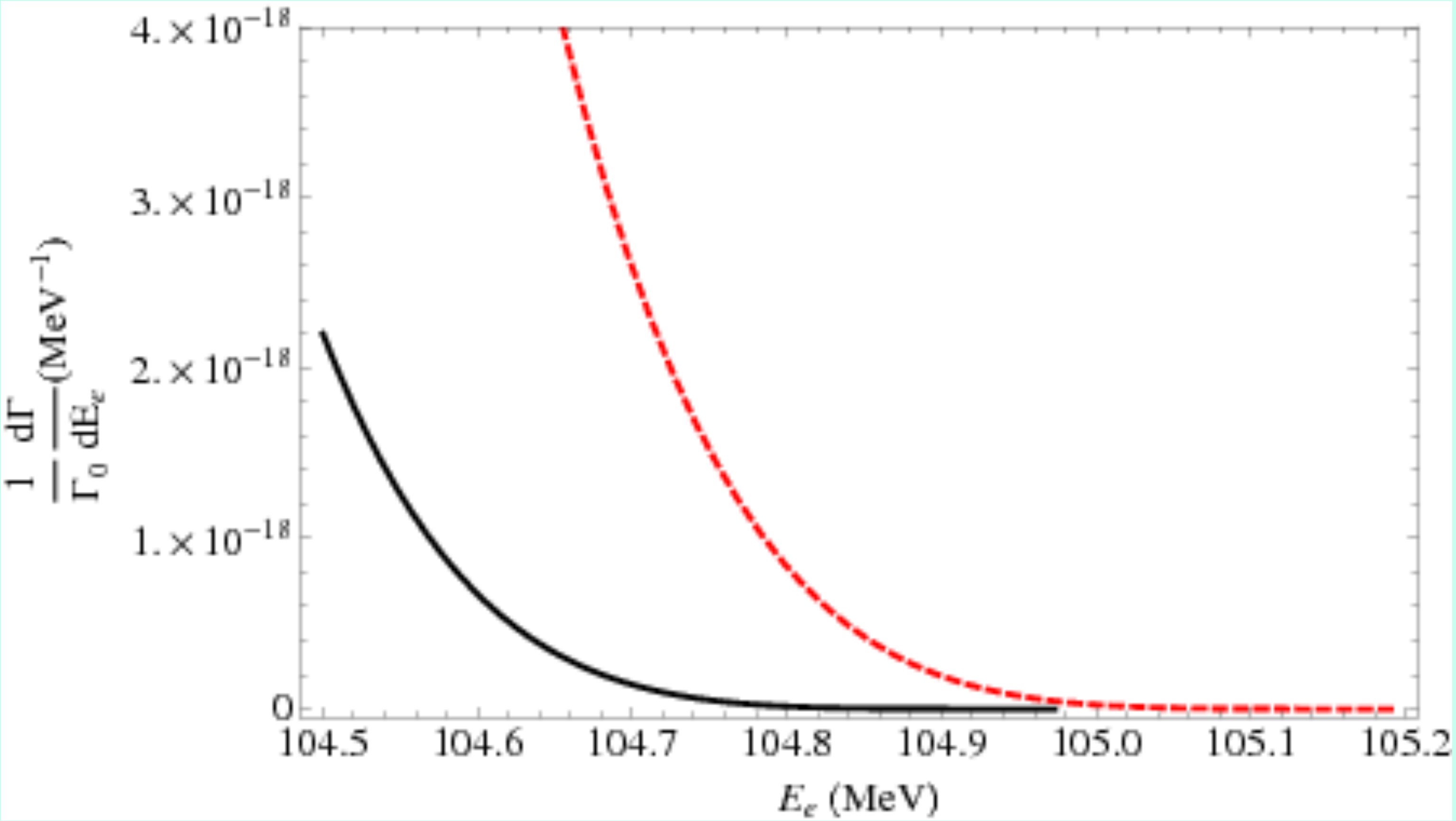
It can take every muon we can provide!

Stop $10^{11}\mu^-$/sec!

wait ~0.6x10^{-6}sec (reject prompt background)

Requires ~300keV resolution & Clean beam between pulses

Recoil Effects on μ^- decay in Al orbit (black)
A. Czarnecki, X. Garcia I Tormo & WJM



Charged Lepton Number Violating Processes

Reaction	Bound	In Progress	Proposed	Possible
$BR(\mu \to e\gamma)$	$<5.7\times10^{-13}$	2×10^{-14}SES		?
$BR(\mu \to eee)$	$<1\times10^{-12}$	10^{-15}-10^{-16}		
$R(\mu Ti \to eTi)$	$<4\times10^{-12}$	-	2×10^{-17}SES	10^{-18}
	$<(7\times10^{-13})$			

Some Theory Considerations:

If transition dipole operator (chiral changing) dominates

$BR(\mu \to e\gamma) = 389R(\mu Al \to eAl) = 238R(\mu Ti \to eTi)$

But conversion exp. can be more sensitive by 10^3-10^4!

Eg. Popular SUSY Models (may be related to Δa_μ)

Neutrino Mass & Mixing Effects→Lepton Flavor Violation

$BR(\mu \to e\gamma) \sim 3\alpha/32\pi[m_3^2 - m_2^2]^2/m_W^4(s_{13}c_{13}s_{23})^2 \leq 10^{-54}$

$R(\mu N \to eN) \sim 100BR(\mu \to e\gamma) \sim 10^{-52}$ still tiny, but enhanced by Chiral conserving amplitudes.

(Lesson) Conversion better for Heavy Neutrino Mixing

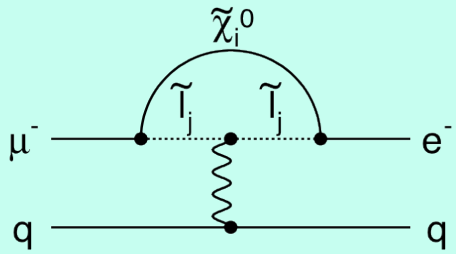
In General: $1/200 < BR(\mu \to e\gamma)/R(\mu N \to eN) < 200$

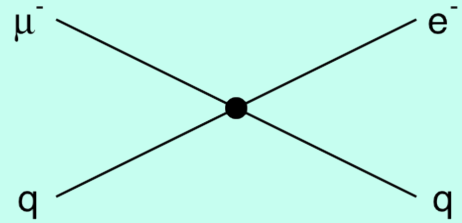
Physics scale ~3000TeV Probed!

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}

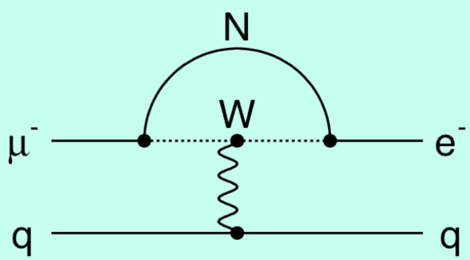


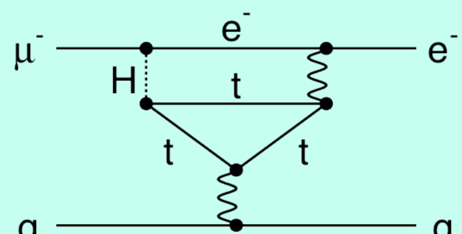


Compositeness

Ëc = 3000 TeV

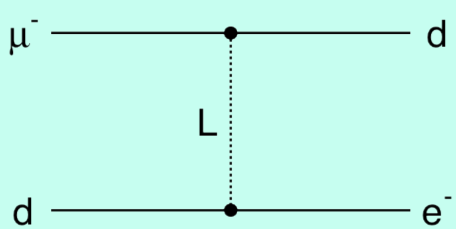
Heavy Neutrinos

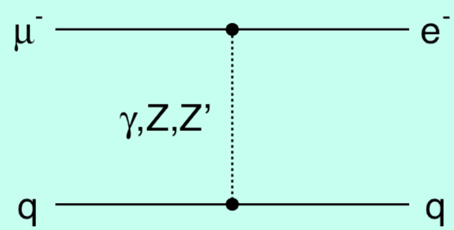




Second Higgs doublet

Leptoquarks





Heavy Z',
Anomalous Z coupling

6. Muon Collider: Z Factory, H, ϕ… Factory, ZH?

i) Need Copious Source of Protons

Fast cycling 8-16GeV Accelerator or Linac

Power~4MW →>10^{14} $\mu^+\mu^-$/sec

ii) Collect and Cool μ^+ & μ^- Beams

iii) Accelerate → High Energy

iv) Large Storage Ring (~1000 revolutions)

v) Luminosity ~ 10^{34}-10^{35} desirable (at 2TeV)

Energy: Low Energy & Luminosity ϕ, γ_d ***?***

91GeV Z Factory ($\sin^2\theta_W$, bb,…)

114-140GeV Higgs Pole Resonance(s)

161GeV W^+W^- (m_W)

350GeV tt (m_t), HZ…

SUSY Pairs?

~2-4TeV $\mu^+\mu^-$"New Physics",$\mu^-\mu^-$ μp…

Muon Collider: Produce $10^{14}\mu^{\pm}$/sec, Collect, Cool, Accelerate, Store, Collide $\mu^{+}\mu^{-}$ at $\sqrt{s} \geq m_Z$, …2-4TeV!

Challenging! Neutrino Radiation Problem?

Muon Technology Needs To Be Nurtured!

(Pursue Fundamental Muon Physics Aggressively!)

Build Muon Community

PSI, JPARC, FNAL

7. Outlook/Vision

PSI Exps. MuLAN, FAST, MuCAP, MEG… all very interesting

Further Improvement in g_P may be possible

Lattice improvement of g_A & g_P very useful

Expect a_μ^{exp} improvement (x4) at Fermilab (JPARC low energy)

Muon edm exp. at ~10^{-23}-10^{-24}e-cm welcome

MEG at PSI: BR($\mu\to e\gamma$)<$5.6\text{x}10^{-13}$ ➔ ~$2\text{x}10^{-14}$ SES!

μ2e at Fermilab/JPARC aim for μAl→eAl with $2\text{x}10^{-17}$ SES!

Mu3e at PSI 10^{-16} sensitivity!

Could BR($H\to\mu^+\mu^-$) turn out to be unexpectedly small?

Anticipate Surprises and Hope