RADCOR 2002

&

Loops & Legs in Quantum Field Theory

Stimulating Meeting

Very Nice Environment

Great Meals

⋮

Monday	9 AM - 7PM	15 talks	
Tuesday	8:40AM - 7PM	15 talks	
Wednesday	8 AM - 1:10PM	9 talks	
Thursday	8 AM - 7PM	34 talks !	(2 Sessions)
Friday	8:10AM - 3:15PM	10 talks	
		83 talks !	

Every Session On Time!

The Organizers & Secretaries deserve our warmest appreciation

W. Marciano
13/9/02

Perspective and Commentary

Outline

1. General Impressions and Comments

2. Experiment vs Theory (Remarks)

3. $g_\mu - 2$ & $\Delta r(m_H)$

4. CKM Unitarity Takes a "Strange" Twist {My Contribution

5. Outlook

1) General Impressions and Comments

Some Experiments & Future Facilities
Along with *many* theory talks

by

Glover, Uwer, Gehrmann, Pozzorini, Moch, Melles, Haber
Wagner, Kolodziej, Roth, Werthenbach, Bardin, Sirlin, Bartels, Kalmykov
Klein, Vermaseren, Kataev, Kawamura, Capitani, Sasaki, Steinhausser
Kniehl, Uematsu, Klasen, Riemann, Chierci, Chetyrkin, Tarasov, Baikov
Jakobs, Baur, Smith, Harlander, Piccinini, Dittmaier, Anastasiou, van Neerven
Kodaira, Fleischer, Fujimoto, Hahn, Heinrich, Penin, Binoth, Kreimer, Skrzypek
Sola, Guasch, Eilam, Penaranda Rivas, Rückl, Illana, Del Aguila, Weiglein
Heinemeyer, Deile, Logashenko, Nyffeler, Gluza, Veretin, Czakon, Denig
Czyz, Buchalla, Tanaka, Reina, Hoang, Misiak, Hurth, Stöckinger
Schröder, Becher, Feindt, Remiddi, Smirnov, Coffo, DeFreitas, Bern
van der Bij, Skrzypek, Broadhurst, Ward

Multi-Loop Radiative Corrections, (RADCOR 2002 Theme)

J. Bartels : "wouldn't dare talk about one loop results at this meeting" Photon Impact Factor - Small Angle QCD

Pure QED :

$\alpha^{-1} = 137.03600300(270)$ Quantum Hall Effect

$\alpha^{-1} = 137.03600840(300)$ h/m_n (Rydberg)

$\alpha^{-1} = 137.03598710(430)$ Γ'_{90} (AC Josephson)

$\alpha^{-1} = 137.03599520(790)$ Muonium HFS

$$a_e^{th} = \frac{g_e - 2}{2} = \frac{\alpha}{2\pi} - 0.328478444\left(\frac{\alpha}{\pi}\right)^2 + 1.181234017\left(\frac{\alpha}{\pi}\right)^3 - \underline{1.5098(384)\left(\frac{\alpha}{\pi}\right)^4} + \dots$$

$$+ 1.66(3) \times 10^{-12} \text{ (Hadronic, EW)}$$

$$a_e^{exp} = 1159652188(3) \times 10^{-12} \rightarrow \underline{\alpha^{-1} = 137.03599959(40)}$$ Best Determination of α

Future : factor 10 Improvement of a_e^{exp} "requires" better 4 loop

Nice test of QED but, [redacted] not a good probe for "New Physics"

$$\Delta a_e \sim m_e^2/\Lambda^2$$

In the past, such calculations limited to a handful of people: Remiddi, Kinoshita, Laporta, Broadhurst ...

Now, many capable young physicists (mainly in Germany)

QCD - Requires High Order Calculations

Relatively large coupling $\alpha_s(\mu)$ (Determination)

μ Scale Sensitivity

Extract EW Parameters: $b \to s\gamma$, m_c, m_b ...

Determine Structure Functions (parton distributions)

Compute cross-sections: $e^+e^- \to 3\,jets$, $gg \to H$, $gg \to \gamma\gamma$, ...

etc. — Much Activity 2loop

Impressive Results: $R(s)$, $\Gamma(Z \to hadrons)$, $\Gamma(\tau \to \nu_\tau\, hadrons)$, β-function, Anomalous Dim..

Chetyrkin, Kataev, Baikov ...

Revolutionary Techniques: Integration by parts, Lorentz Inv, Helicity Amplitudes, Master Integrals, Programs (eg Form) etc

Chetyrkin, Remiddi, Bern, Smirnov, Vermaseren, Gehrmann, ...

Recent rapid progress (2loop) NNLO $2 \to 2$, $1 - 3$, $2 \to 3$

Glover, Uwer, Gehrmann ... De Freitas, Bern ...

Difficult Calculations → New Techniques

eg $gg \to H$ (NNLO QCD) Harlander (+ Kilgore)

Anastasiou (+ Melnikov)

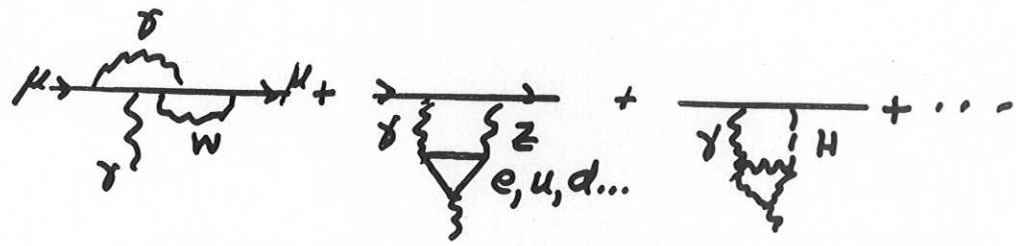
<u>Electroweak Loops</u>: Weak coupling, 1% - 0.1% precision (possibly 0.01%)

Most studies don't require full 2 loop. — Giga Z, m_W

One loop + leading (enhanced) 2 loops — G_μ (ppm)

But, better to do full 2 loop (estimate error, surprises? etc)

eg. <u>2 loop $g_\mu - 2$</u>



~1650 Diagrams   ~1400 suppressed

<u>Kukhto, Kuraev, Schiller & Silagadze: large $\frac{\alpha}{\pi} \ln m_Z^2/m_\mu^2$ effects</u>

<u>Czarnecki, Krause & WM: Complete Calculation</u>

<u>Peris, Perrottet, de Rafael: Hadronic Effects</u>

<u>Degrassi, Giudice: ($b \to s\gamma$ QCD $\to a_\mu$ EW leading logs)</u>

-23% Reduction of 1 loop!

<u>Natural Relations</u>: $\sin^2\theta_W^0 = \frac{e_0^2}{g_{2_0}^2} = 1 - (m_W^0/m_Z^0)^2$ — Bollini, Giambiagi, Sirlin 1973

$$1 - \Delta r(m_t, m_H) = \frac{\pi\alpha}{\sqrt{2}\, G_\mu m_W^2 (1 - m_W^2/m_Z^2)}$$

$$1 - \Delta\hat{r}(m_t, m_H) = \frac{2\sqrt{2}\,\pi\alpha}{G_\mu m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{MS}}}$$

<u>α, G_μ, m_Z</u> ($+m_t$) input

$+ m_W \to m_H$

or $+ \sin^2\theta_W(m_Z)_{\overline{MS}} \to m_H$

Determine m_H or "New Physics

etc

see A. Sirlin & G. Weiglein talks

Large R.C. in Δr & $\Delta\hat{r}$ $\quad \frac{\alpha}{\pi}\ln\frac{m_Z}{m_f}, \ \frac{\alpha}{\pi}\frac{m_t^2}{m_W^2}, \ \frac{\alpha}{\pi \sin^2\theta_W}, \ \frac{\alpha}{\pi}\ln\frac{m_H}{m_W}, \ \frac{\alpha}{\pi}$

include $\left(\frac{\alpha}{\pi}\ln\frac{m_Z}{m_f}\right)^2, \ \left(\frac{\alpha}{\pi}\right)^2\frac{m_t^4}{m_W^4}, \ \alpha\alpha_S, \ \alpha\alpha_S^2 \ldots$

Recently Full $\mathcal{O}(\alpha^2)$ Corrections Completed!

Fermion Loops: Weiglein (+Freitas, Hollik, Walter)

Boson Loops: Veretin } Independent
Czakon }

Milestone in EW Rad. Corrections

Technique can be used for other EW Rad. Corr.

Many other interesting one & multiloop calculations for Drell-Yan, $b \to s\gamma$, $gg + q\bar{q} \to t\bar{t}H$, Bhabba $e^+e^- \to H\nu\bar{\nu}$, SUSY, Higgs ....

Full 2 loop m_W & m_Z pole - $\overline{MS}$ Rad. Corr. M. Kalmykov

2.) Experiment vs Theory (Remarks)

Updates of

	HERA	M. Klein
	LEP I, II	S. Riemann, R. Chierici
	B studies	M. Feindt (V_{cb}, V_{ub}, $\rho\rho$, $b\to s\gamma$, $B\to X \ell\ell$, $\frac{q}{b}$ ...)
	$g_\mu - 2$, $e^+e^- \to$ hadrons	M. Deile, I. Logashenko, H. Czyz, D. Denig
	LHC	K. Jakobs
	TESLA	A. Wagner

QCD: $\alpha_s(m_Z) = 0.118 \pm 0.001$ good consistency

Parton Distributions - Very Precise, small $x \to 10^{-5}$!

NRQCD Applications

Many Th. Structure Funct. Calc., Cross-Sections ...

B Physics: $b \to s\gamma$ (Great Probe of SUSY, Multi-Higg) Misiak

$B \to X_s \ell^+ \ell^-$ (FB asy.) Hurth

Higgs + SUSY at LHC + LC, QCD effects, models, **Precision**

Precision Measurements: (Future Colliders) $\pm 1\%$ probe $\Lambda \simeq 10\sqrt{s}$

LEP I, II + SLD: $m_Z = 91.1875(21)$ GeV, $m_W = 80.447(42)$ LEP II

World $m_W = 80.451(33)$ GeV

$\sin^2\theta_W(m_Z)^{LR}_{\overline{MS}} = 0.23078(27)$

$m_H = 81^{+52}_{-33}$ GeV Global < 193

$\kappa_\gamma = 0.943 \pm 0.055$, $\lambda_\gamma = -0.020 \pm 0.024$

etc.

Some Things Left Out

Atomic P.V. $Q_W(Cs)^{exp} = -72.06\,(28)(35)$ 1997

$+\,\mathcal{O}(Z\alpha^2)$ R.C. $Z = 55$ Milstein, Sushkov, Terekhov

$Q_W(Cs)^{exp} = -72.90(28)(35)$ (2002)

vs

$Q_W(Cs)^{SM} = -73.17(13)$ good agreement

NuTeV: High Value of $\sin^2\theta_W$

Structure Functions? New Physics?

Polarized Möller Scattering at SLAC E158 $e^-_{L,R} e^- \to e^- e^-$

Took Data $\to \sin^2\theta_W$ Next Year

Such a fixed target exp at TESLA competitive with giga Z! $\Delta \sin^2\theta_W \simeq \pm 0.00006$! polarization easier

Where is the Higgs?

Global EW Fit $m_H = 81^{+52}_{-33}$ GeV < 193 GeV — S. Riemann

LEP II $m_H > 114.4$ GeV — R. Chierici

$m_W + \Delta r$ $\quad m_H \simeq 34^{+59}_{-27}$ GeV

$\sin^2\theta_W(m_Z)_{\overline{MS}}$ LR $+ \Delta\hat{r}$ $\quad m_H \simeq 44^{+36}_{-26}$ GeV

} Did we miss it?

Possibilities: m_H near ~ 115 GeV?

m_t heavier $174.3\,\text{GeV} \rightarrow 180\text{-}185\,\text{GeV}$

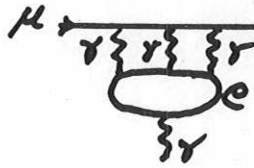
"New Physics"? eg SUSY

3.) $g_\mu - 2$ & $\Delta r(m_H)$

$$a_\mu^{exp} = \frac{g_\mu - 2}{2} = \underline{116\,592\,030(80) \times 10^{-11}}$$ New World Ave. M. Deile

$\rightarrow \sim \pm 63 \times 10^{-11} \xrightarrow{\text{More Data?}} \underline{\pm 40 \times 10^{-11}}$ proposed

$$a_\mu^{QED} = \frac{\alpha}{2\pi} + 0.765857376(27)\left(\frac{\alpha}{\pi}\right)^2 + \underbrace{24.05050898(44)}\left(\frac{\alpha}{\pi}\right)^3 + \underline{126.07(41)}\left(\frac{\alpha}{\pi}\right)^4 + 930(170)\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$



very large

$\alpha^{-1} = 137.03599958(32) \rightarrow$ $\boxed{a_\mu^{QED} = 116\,584\,705.7(2.9) \times 10^{-11}}$ (5 loops)

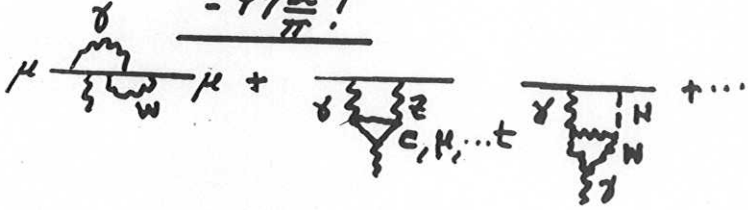
$a_\mu^{EW} \sim$

+ 2 loops

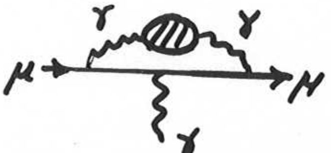
very small

$$a_\mu^{EW} = \frac{G_\mu m_\mu^2}{8\sqrt{2}\pi^2}\left\{\frac{10}{3} - \frac{5}{3} + \frac{1}{3}(1 - 4\sin^2\theta_W)^2\right\}\left[1 - \underbrace{\frac{41}{3}\frac{\alpha}{\pi}\left(\ln\frac{m_Z}{m_\mu} + \text{small constant}\right)}_{-97\frac{\alpha}{\pi}\,!}\right]$$

$\boxed{a_\mu^{EW} = 152(4) \times 10^{-11}}$



$a_\mu^{Had}(2\,loop) =$



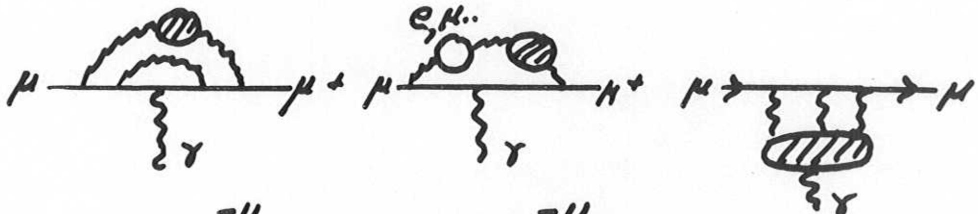
Recent Update
Davier, Eidelman, Höcker, Zhang

$$\boxed{\begin{array}{l} a_\mu^{Had}(2loop) = 6847 \pm 60 \pm 36 \times 10^{-11} \\ \qquad\qquad\qquad\quad 7019 \pm 47 \pm 12 \pm 38 \times 10^{-11} \end{array}}$$

e^+e^- based
τ based
} Not Consistent!

see Logashenko's talk

$a_\mu^{Had}(3\text{ loops}) =$



-205×10^{-11} $+105 \times 10^{-11}$ (B. Krause) $+86(35) \times 10^{-11}$ (sign change)!

A. Nyffeler talk (+ Knecht)

$\underline{a_\mu^{Had}(3\text{loops}) = -14(35) \times 10^{-11}}$

$a_\mu^{SM} =$	$116591691 \pm 70 \pm 35 \pm 4 \times 10^{-11}$	e^+e^- based
$=$	$116591863 \pm 62 \pm 35 \pm 4 \times 10^{-11}$	τ based

$\Delta a_\mu = a_\mu(\text{New Physics}) = a_\mu^{exp} - a_\mu^{SM} = \underline{339 \pm 112 \times 10^{-11}}$ e^+e^- 3σ

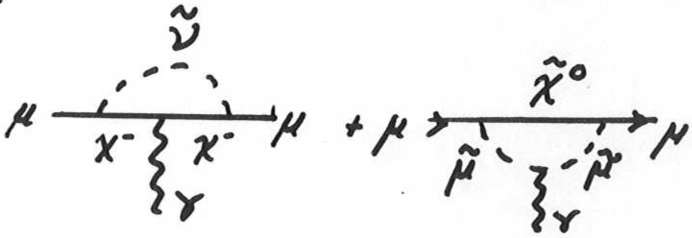
$\underline{167 \pm 107 \times 10^{-11}}$ τ 1.6σ

If e^+e^- & τ were consistent, total error $\sim \pm 80 \times 10^{-11}$

Note: F. Jegerlehner $e^+e^- \rightarrow 2.6\sigma$ dev

Hint of SUSY?

$a_\mu^{SUSY} =$



$\simeq (\text{sgn}\,\mu) \times 130 \times 10^{-11} \left(\frac{100\,\text{GeV}}{m_{SUSY}}\right)^2 \tan\beta$

$\tan\beta$: enhancement $\gtrsim 3$

Deviation of $\sim \underline{300 \times 10^{-11}}$ very consistent with SUSY expectations $\text{sgn}\,\mu = +$

<u>Relationship between a_μ(New Physics) & $\Delta r(m_H)$</u>

e^+e^- data favor smaller  → larger m_H

τ data favor larger  → smaller m_H

Differ by ~ 18% in m_H global fit

Standard Model already near the edge in $m_H \gtrsim 114$ GeV bound
(A. Sirlin, G. Weiglein ...)

<u>Hard to be too quantitative, but reconciling $a_\mu^{exp} - a_\mu^{SM}$ via Hadronic Vac. Pol. "alone" would push m_H (prediction) from m_W & $\sin^2\theta_W(m_Z)_{\overline{MS}}$ (A_{LR}) to unacceptable levels</u>

If SUSY is starting to show, it will be found at the LHC. The use a_μ to determine $\tan\beta$ or constrain models. [Many Implications!]

a_μ^{exp} & a_μ^{SM} Must be improved to $\pm 40 \times 10^{-11}$
More run time
<u>More e^+e^- data</u>, Lattice ?
KLOE, BaBar
See H. Czyz's talks
& D. Denig's

4.) CKM Unitarity Takes A "Strange" Twist

$$|V^0_{ud}|^2 + |V^0_{us}|^2 + |V^0_{ub}|^2 = 1$$

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

$G_\mu = 1.16637(1) \times 10^{-5}\,\text{GeV}^{-2}$

$|V_{ud}|^2$ From $0^+ \to 0^+$ (Superallowed β-decays)

$$|V_{ud}|^2 = \frac{0.9714(6)}{(1+\Delta_R^V)} \left[\frac{1.16637\times 10^{-5}\,\text{GeV}^{-2}}{G_\mu}\right]^2$$

$$\Delta_R^V = 1 + \frac{\alpha}{2\pi}\left(4\ln\frac{m_Z}{m_p} + 1.1\right) + O\left(\left[\frac{\alpha}{\pi}\ln\left(\frac{m_Z}{m_p}\right)\right]^2\right) + \ldots$$

$= 1 + 0.0226\,(10)$ (A. Sirlin 1967–78) $+ \underbrace{0.0012}$ (Renorm. Group Sum) (A. Sirlin + W.M. 1986)

$$\boxed{|V_{ud}|^2 = 0.9488(12)}$$

$|V_{us}|^2$ from K_{e3} decays $K_L \to \pi^+ e^- \bar{\nu}_e$ + $K^+ \to \pi^0 e^+ \nu_e$

Second Order in $SU(3)_F$ Breaking $f_+(0) = 1 - 0.04$

Leutwyler + Roos (1984)

Calderon + Lopez Castro (2001) Update

<u>Differences</u>: Isospin Violation: $m_d - m_u \to \pi^0\text{-}\eta$ mixing $+4.6\%$

$m_{\pi^0} \neq m_{\pi^+}$, $m_{K_L} \neq m_{K^+}$ $+2.8\%$

QED Corrections -2.0%

$+5.4\%$

<u>Expect</u> $\Gamma(K^+ \to \pi^0 e^+ \nu_e) \simeq 1.054\,\Gamma(K^0 \to \pi^+ e^- \bar{\nu}_e)$

PDG → Roughly Correct (Old Data 1970's)

$K_{e3} \rightarrow |f_+(0)\, V_{us}| = 0.2100(8)$ $\qquad$ $f_+(0) \simeq 0.961$ Leutwyler + Roos

$$\boxed{|V_{us}| = 0.2187(20)}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 (10^{-5}) = 0.9966 \pm 0.0015$$ } 2.3σ Unitarity Violation

<u>"New Physics"</u>? eg. Additional μ^+ decay modes BR ~ 0.3%?

increase decay rate (total)

→ G_μ actually smaller! (by 0.15%)

$G_\mu = 1.16637(1)\times10^{-5}\,\text{GeV}^{-2} \rightarrow 1.16462\times10^{-5}\,\text{GeV}^{-2}$

eg $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$ (Pakvasa + Babu) LRMPF ν osc.

other possibilities Z', W^* loops ...

<u>"Strange" Twist</u> Very Recent Remeasurement of $K^+ \rightarrow \pi^0 e^+ \nu_e$

E865 at BNL (Alexander Sher Thesis)

<u>"Preliminary" Result</u> $BR(K^+ \rightarrow \pi^0 e^+ \nu_e) \simeq 1.068\, BR(K^+ \rightarrow \pi^0 e^+ \nu_e)_{PDG}$!

$|V_{us}|^2$ increase by 6.8% !

$$\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999(15)}$$ Perfect Unitarity!

Not so fast, What about $K_L \rightarrow \pi^\pm e^\mp \overset{(-)}{\nu}_e$? ($K \rightarrow \pi \mu \nu$?)

All larger BR by 6-8%!

PDG (2002) Constrained Fit

$BR(K_L \to \pi^\pm e^\mp \nu) = 38.79 \pm 0.27\%$
$BR(K_L \to \pi^\pm \mu^\mp \nu) = 27.18 \pm 0.25\%$
} Increase by 1.06 - 1.08 factor?

$BR(K_L \to \pi^0\pi^0\pi^0) = 21.08 \pm 0.27\%$
$BR(K_L \to \pi^+\pi^-\pi^0) = 12.58 \pm 0.19\%$
} Decrease b 0.88 - 0.84 factor

+ smaller

All K_L branching ratios incorect by $\sim \pm 10\%$! {except $K_L \to 2\pi$ CP

Is it possible?

KTeV Analysis Underway: 5×10^6 clean $K_L \to \pi e \nu$ events!
Redo all 4 main decays
systematics?

1) Verify E865 → Perfect Unitarity (20yr old problem solved!)
2) Disagree → E865 "Preliminary" Result Incorrect (Unitarity?
or larger $\frac{m_d - m_u}{m_s}$ (factor 2) $m_u = 0$? θ_{CP}?
3) Something inbetween

Stay Tuned

5.) Outlook

Radiative Corrections - More Surprises Ahead

Technique Advancing Rapidly

Future High Precision $\rightarrow$ 0.01% m_W, s^2...

Many Collider Problems to be Tackled: QCD, EW

Hints of SUSY, light Higgs? m_W, A_{LR}

$g_\mu - 2$ Mania? $e^+e^- \rightarrow \gamma$ + hadrons Radiative Return

results by end of year! [redacted] D. Deris

if confirm[redacted] Novosibirsk,

why e^+e^- - $\tau \rightarrow$ hadrons discrepency?

If deviation is real $\rightarrow$ SUSY likely candidate (Other?)

$\mu \rightarrow e\gamma$, $\mu^- N \rightarrow e^- N$, Dark Matter, LHC Discoveries...

Happy Days Precision

Typo on a transparency explains why SUSY may be appearing in $g_\mu - 2$

Brookhaven $\rightarrow$ Brookheaven

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Possibilities: m_H near ~ 115 GeV?

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"New Physics"? eg SUSY