IN MEMORIUM

SAM B. TREIMAN

1925 - 1999

MEMORIAL MEETING TODAY IN PRINCETON, N.J.

PARITY-VIOLATING ELECTRON SCATTERING:

STATUS (TH'Y) & PROSPECTS

I. OBSERVABLES

II. STRANGE QUARK VECTOR FORM FACTORS & FC...

III. AXIAL RESPONSE & $G_M^{(s)}$

IV. NEW PHYSICS SEARCHES & $\rho_n(r)$

V. OTHER ISSUES

- AXIAL VECTOR $N \to \Delta$ FF's
- ^4He & NUCLEAR STRANGENESS

EXPERIMENTS

HISTORICAL: S.M. TESTS

APV BOUCHIAT & BOUCHIAT (1974-75)
⇓
SEATTLE, OXFORD, MOSCOW,
PARIS, NOVOSIBIRSK (Cs, Bi, Th

PVDIS - SLAC (1979) ^2H
Q.E. PVES - MAINZ (1989) ^4Be
ELASTIC PVES - BATES (1990) ^{12}C

PRESENT: NEW PHYSICS

APV BOULDER (1998, 1999) Cs
PARIS Cs

S-QUARKS

SAMPLE - BATES (1997, 1999) $^1H, ^2H$
HAPPEX - JLAB (1998) ^1H
Gϕ - JLAB $^1H, ^2H, N\to$
HALL C - JLAB ^4He
MAMI - MAINZ ^1H

FUTURE: NEW PHYSICS

PV $\vec{e}e$ - SLAC
APV ISOTOPE RATIOS - SEATTLE, BERKELEY
PV $\vec{e}p$ - JLAB

NUCLEAR STRUCTURE

PV $^{208}Pb(\vec{e},e')$ - JLAB(Pn(r

HADRON STRUCTURE

PVDIS - JLAB ($u(x)/d(x)$)

OBSERVABLES

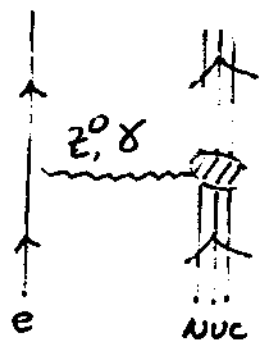
"WEAK CHARGE"

$$Q_W = Q_W(\mathrm{SM}) + \Delta Q_W(\mathrm{NEW}) + \Delta Q_W(\mathrm{HAD})$$

PROCESS-DEPENDENT

ATOMIC PV

PARITY-MIXING IN ATOMIC STATES



$$\mathcal{H}_W^{PV} = \mathcal{H}_W^{PV}(\mathrm{NSID}) + \mathcal{H}_W^{PV}(\mathrm{NSD})$$

$A(e) \times V(N)$	$V(e) \times A(N)$
$F \to F$	$F \to F'$
Q_W	PV N-N' FOR

$\Gamma(6S-7S)$

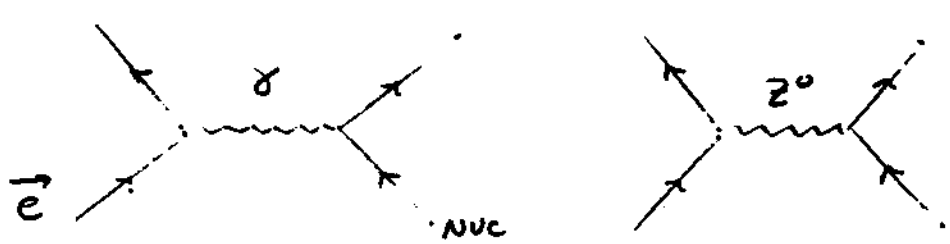
$$A_{PV} \sim Q_W\, \vec{\epsilon} \cdot \langle F' M_F' | \vec{\sigma} | F M_F \rangle$$

$$A_{STARK} \sim 3\,(\vec{E} \times \vec{\epsilon}) \cdot \langle F' M_F' | \vec{\sigma} | F M_F \rangle$$

EXTRACT $\quad |A_{PV}|/|A_{STARK}| = \xi\, Q_W$

ξ ← ATOMIC THEORY

PV e^- SCATTERING



STRANGE QUARKS

$$A_{LR} = \frac{N_+ - N_-}{N_+ + N_-} = a_0 |Q^2| \left\{ Q_W + F(q) \right\}$$

Q_W ← ELECTROWEAK TH'Y

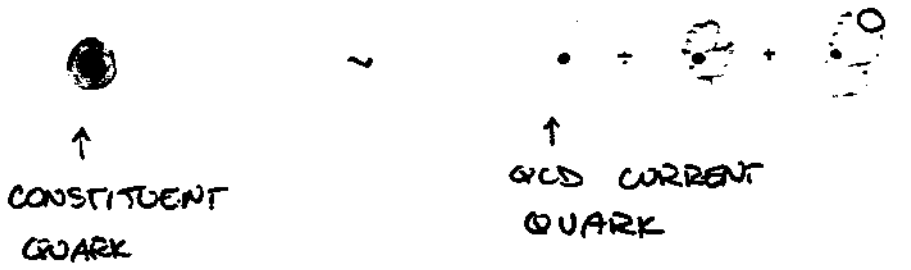
$F(q)$ ← NUCLEAR/HADRONIC FORM FACTOR

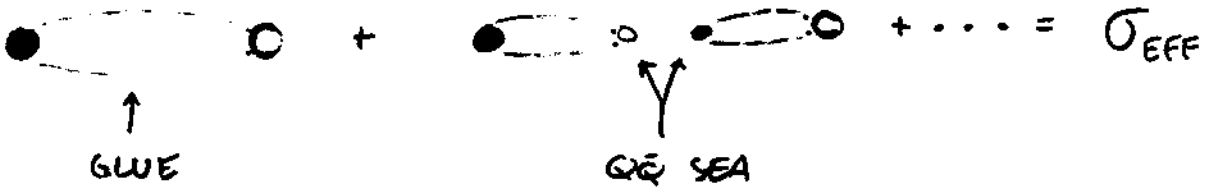
STRANGE QUARKS

WHY DOES QUARK MODEL WORK SO WELL?

- $Q\bar{Q}$ AND GLUON SEA EFFECTS ARE INERT/ SMALL AT LOW-ENERGIES

- $Q\bar{Q}$ AND GLUON SEA ARE HIDDEN IN Q.M. DEGREES OF FREEDOM





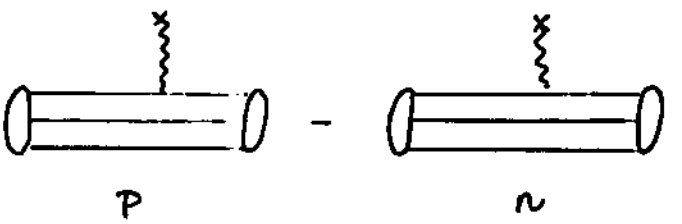
$\Rightarrow$ $\langle N | \bar{s} \gamma_\mu s | N \rangle$ PROBES $Q\bar{Q}$ SEA IN REGIME WHERE Q.M. APPLICABLE

HOW TO RELATE QCD (LATTICE) TO

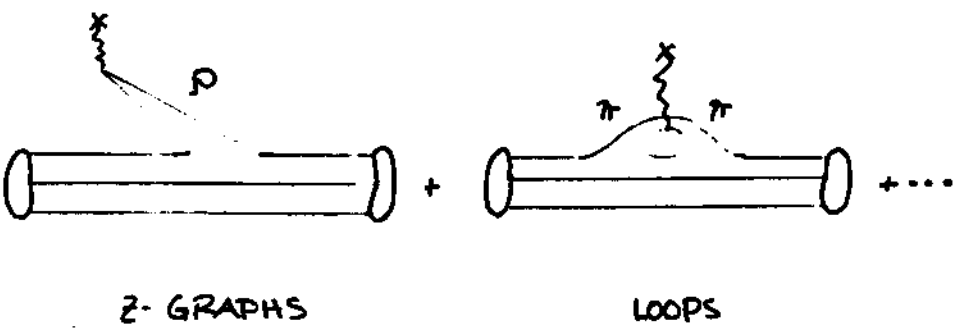
(a) VALENCE / CONSTITUENT QUARK MODELS
(b) HADRONIC (COLLECTIVE) DESCRIPTIONS

EXAMPLE: $F_i^{\tau=1}$:

A. NRQM

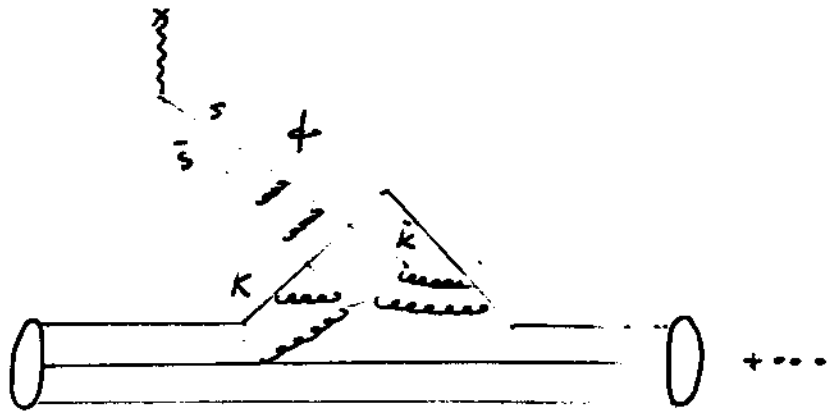


B. HADRONIC



C. LATTICE A & B

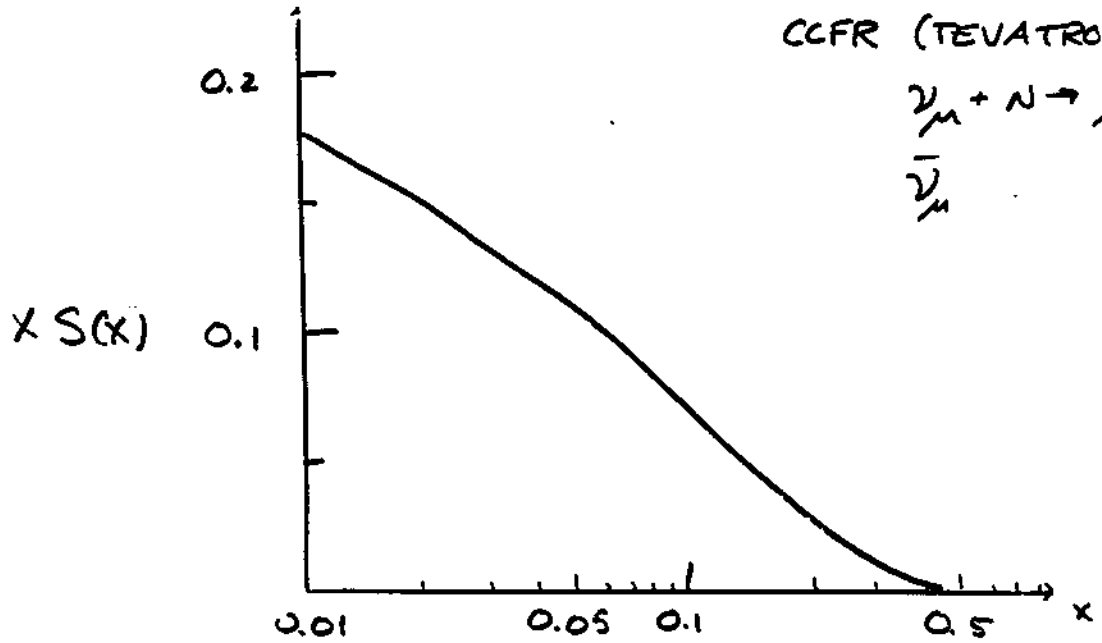
STRANGE QUARKS: ISOLATING LOOPS



WHAT CAN WE LEARN ABOUT PHYSICS OF LOOPS FROM EXPERIMENT, HADRONIC THY, & LATTICE QCD?

STRANGE QUARKS: NOT IN THE Q.M. PICTURE

DEEP INELASTIC



CCFR (TEVATRON) 1995

$\nu_\mu + N \to \mu^+\mu^- X$

$\bar{\nu}_\mu$

$$\frac{\int_0^1 dx\; x\,[s+\bar{s}]}{\int_0^1 dx\; x\,[u+d]} = 0.099 \pm 0.008 \pm 0.004$$

πN SCATTERING

$$\frac{m_s \langle p|\bar{s}s|p\rangle}{m_p} \approx 0.16$$

"SPIN CRISIS"

$$\frac{\sigma_s}{\sigma_p} \approx -0.1$$

PVES

SAMPLE $\quad G_M^s / G_M^p = 0.11 \pm 0.20 \qquad q^2 = -0.1\,(\mathrm{GeV}/c)$

HAPPEX $\quad G_E^s + \tau\left(\frac{G_M^p}{G_E^p}\right) G_M^s$

$$\Rightarrow G_E^s + 0.39\, G_M^s \qquad q^2 = -0.48\,(\mathrm{GeV}/c)^2$$

$$\left| \frac{G_E^s + 0.39\, G_M^s}{G_E^n + 0.39\, G_M^n} \right| = 0.10 \pm 0.22$$

N.B. $\quad G_E^s,\ G_E^n \to 0 \quad$ AS $\quad q^2 \to 0$

THEORETICAL ENDEAVORS

- HÖHLER (70's) — FIT $F_i^{T=0}$ WITH ω, ϕ, ν'
  $\Rightarrow$ $g_{\phi NN} / g_{\omega NN} \sim -1/2$!

- JAFFE ('89) — HÖHLER + FLAVOR ROTATION
  MEISSNER ET AL (90's) $\Rightarrow$ $\mu_s \sim -\mu^{T=0}$
  FORKEL - CAVEAT $\rho_s \sim \rho_n$

- HADRONIC MODELS — SKYRME, KAON LOOPS, NJL, CHIRAL QUARK...
  $\Rightarrow$ SMALLER MOMENTS, VARIABLE SIGNS

- LATTICE QCD — LEINWEBER $|\mu_s| \gg \mu^{T=0}$
  LIU ET AL $\mu_s \sim -\mu^{T=0}$

- NRQM: GEIGER/ISGUR — $\mathcal{O}(g^2)$, SUM OVER STATES
  $\Rightarrow$ $|\mu_s| \ll \mu^{T=0}$
  $\rho_s \ll \rho_n$

- CHPT: MR-M & ITO — NOT PREDICTIVE
  MEISSNER ET AL — ρ_M^s
  MR-M & POGLIA — RES. SAT

- DISP RELATIONS — LOW-MASS SPECTRAL FN
  MR-M & HAMMER $\Rightarrow$ $\mu_s \sim -\mu^{T=0} \pm$?

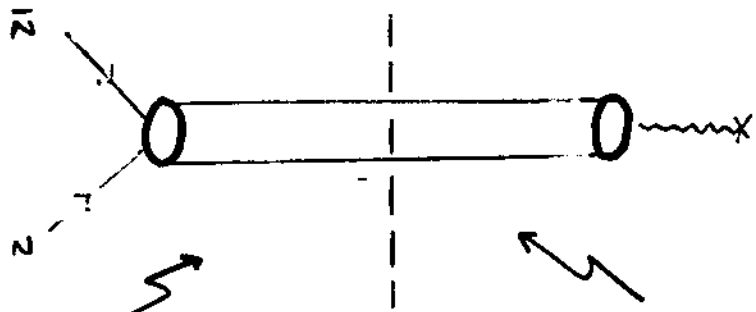
DISPERSION RELATIONS

USE ANALYTICITY & CAUSALITY TO RELATE EXISTING DATA TO FF'S

$$\boxed{\begin{aligned} F_1^{(s)}(t) &= \frac{t}{\pi}\int_{t_0}^{\infty} dt' \, \frac{\mathrm{Im}\, F_1^{(s)}(t')}{t'(t'-t)} \\ F_2^{(s)}(t) &= \frac{1}{\pi}\int_{t_0}^{\infty} dt' \, \frac{\mathrm{Im}\, F_2^{(s)}(t')}{t'-t} \end{aligned}}$$

SPECTRAL DECOMPOSITION

$$\mathrm{Im}\, F_i^{(s)}(t) \sim \sum_n$$



SCATTERING AMPLITUDE

$|n\rangle\langle n|$

FORM FACTOR $F_n^{(s)}$

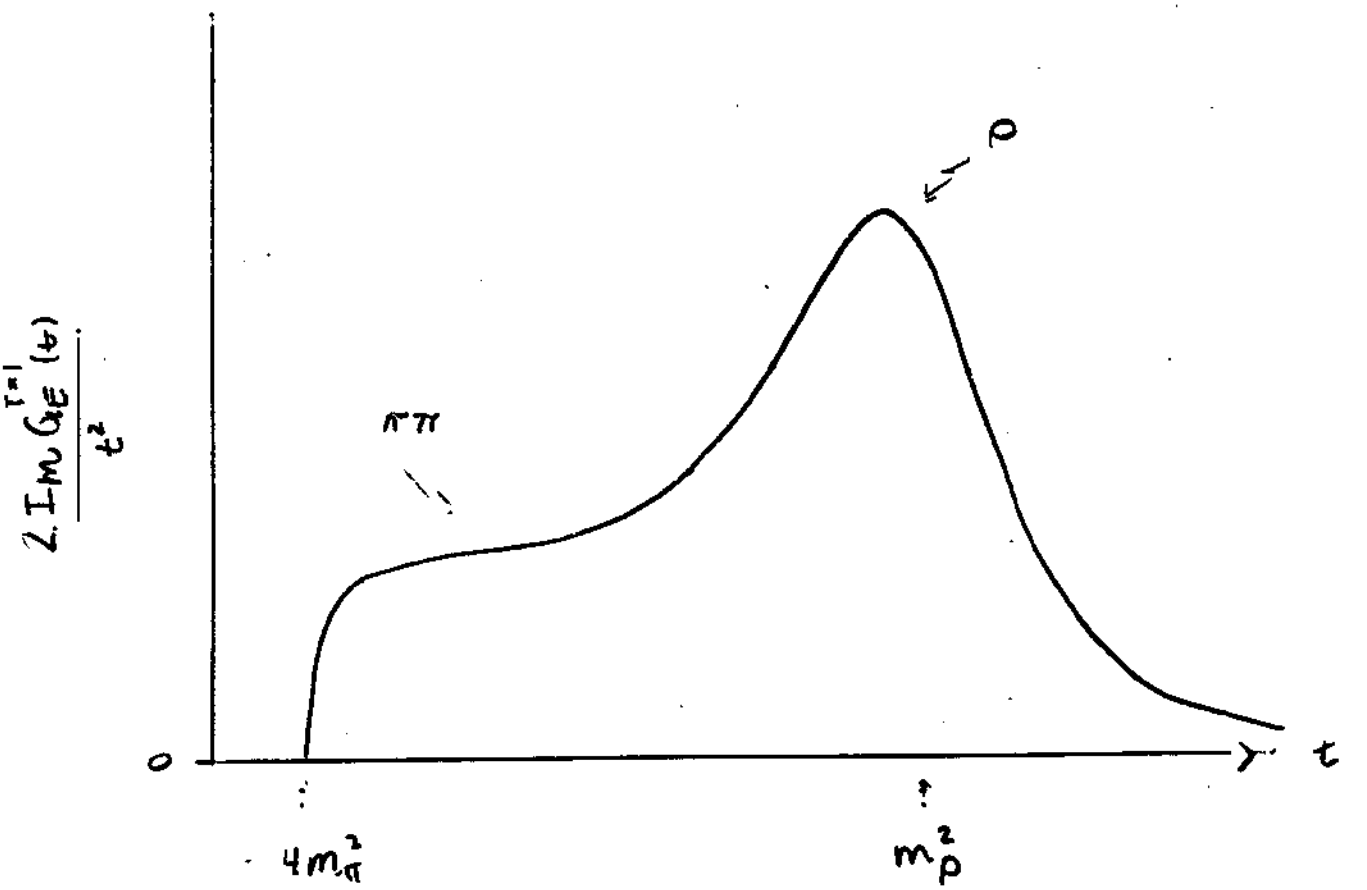
INTERMEDIATE STATES

$I^G(J^{PC}) = 0^-(1^{--})$: 3π, 5π, 7π, $K\bar{K}$, $K\bar{K}\pi$, 9π ...

LIGHTEST, BUT NO VALENCE S-QUARKS ⇒ OZI-SUPPRESSED?

LIGHTEST OZI-ALLOWED

ISOVECTOR SPECTRAL FUNCTIONS



FROM MERGELL, MEIßNER, DRECHSEL, NP A596 (1996) 3

BROAD $\pi\pi$ CONTINUUM $\rightarrow$ CLOSELY LYING SINGULARITIES

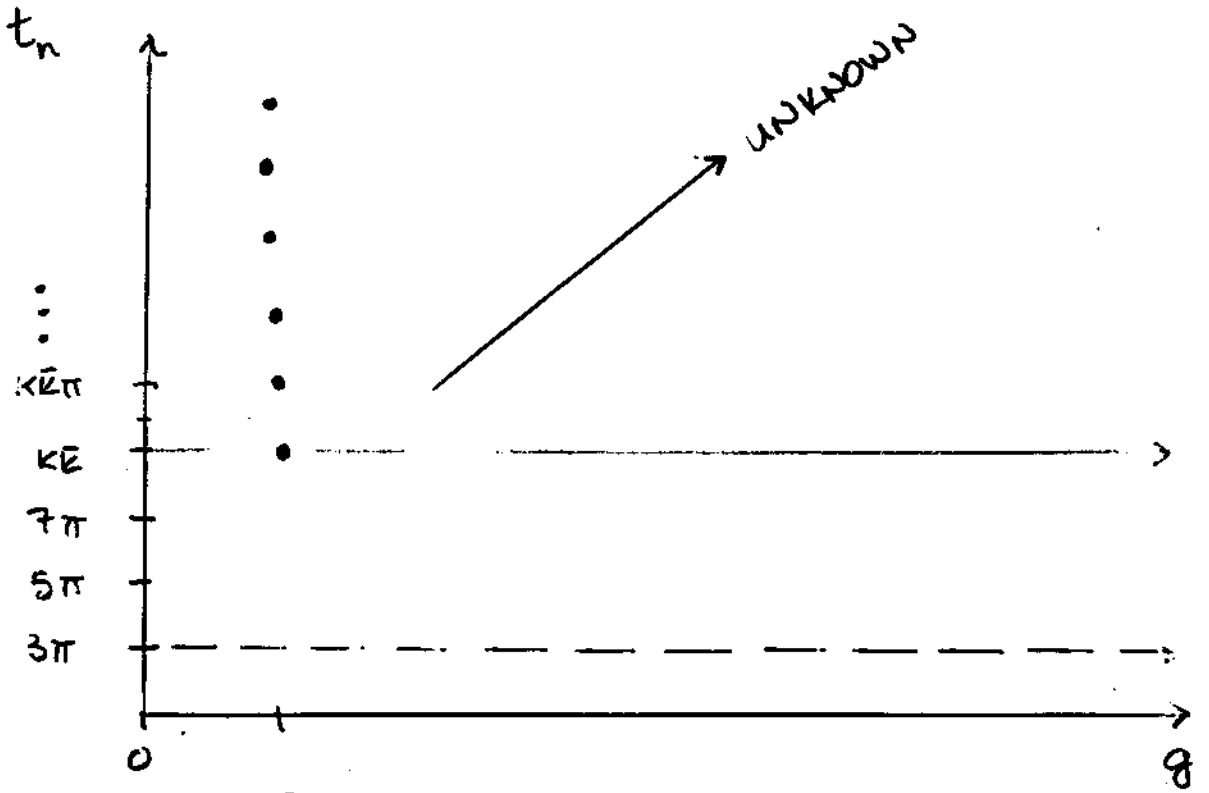
$\rightarrow$ $\ln m_\pi^2$ IN CHPT

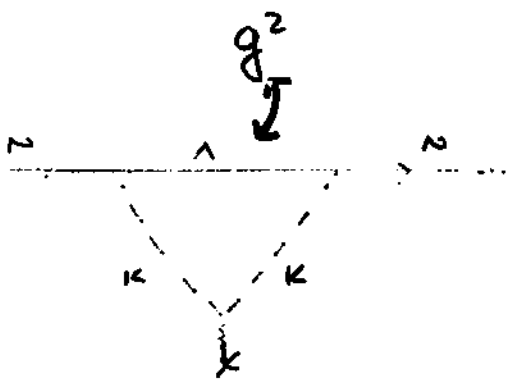
REMAINDER ~ LEC's

$\langle r^2 \rangle_{I=1}$: ~ 85% $\pi\pi$ 15% ρ

$\mu_{I=1}$: ~ 50% $\pi\pi$ 50% ρ

T=0 EM & STRANGENESS SPECTRAL CONTENT





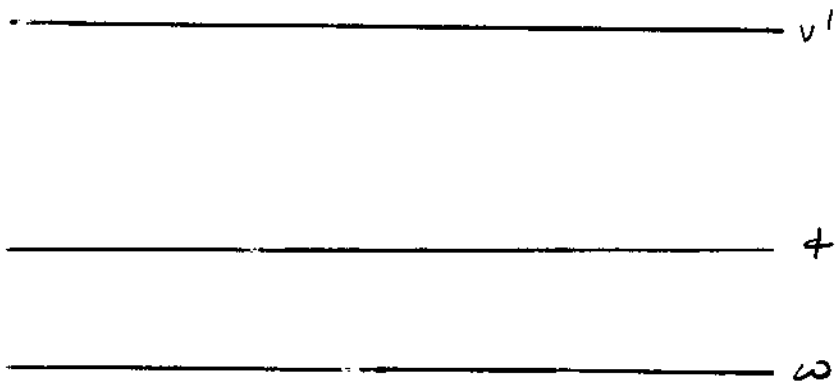
• • • • NRQM [GEIGER & ISGUR]

——— $KN \to KN$ / $e^+e^- \to K\bar{K}$ [HAMMER & MR-M]

— · — · — T=0 FF's [HÖHLER]

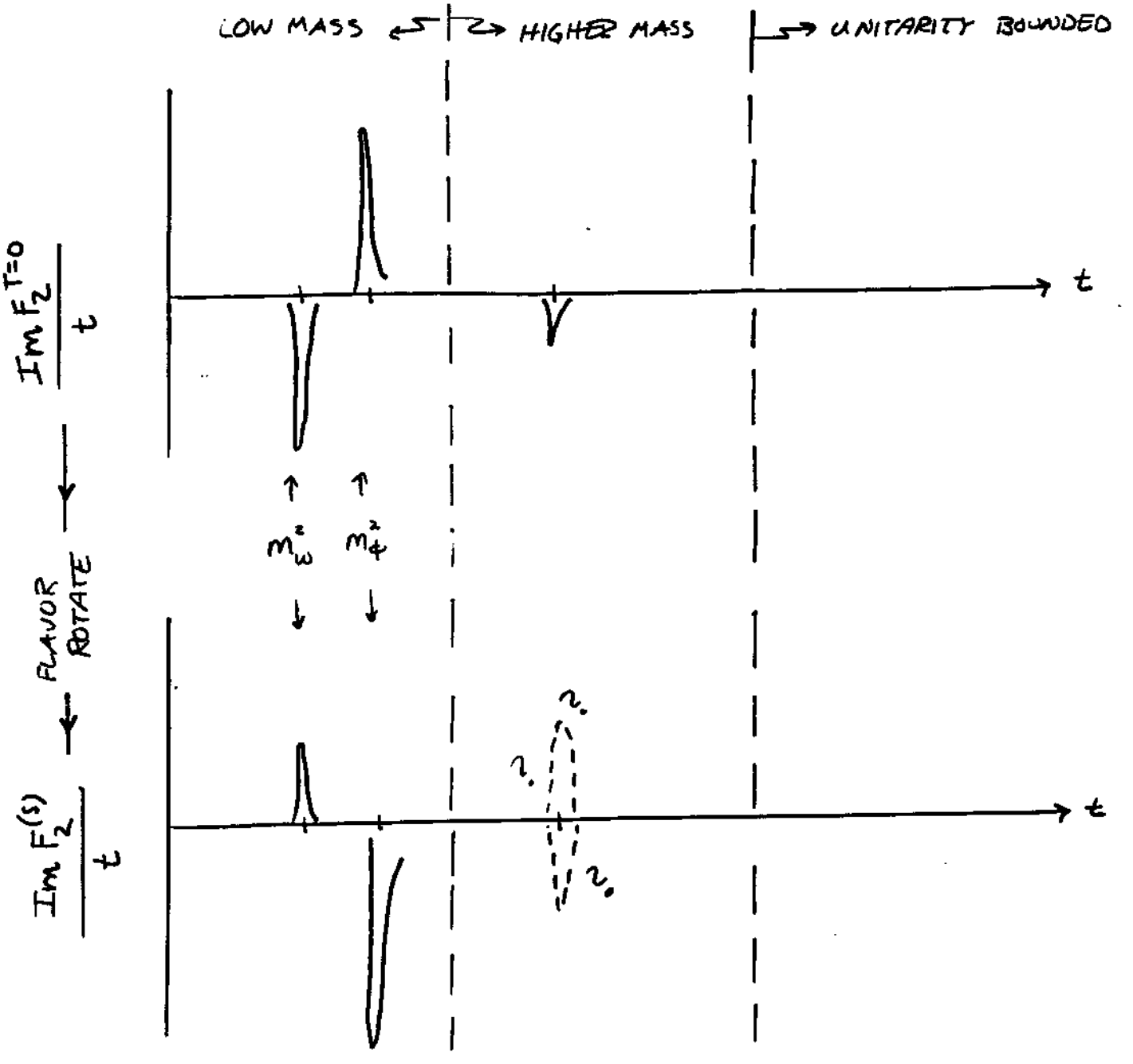
HADRONIC MODELS; CHPT

HÖHLER | JAFFE



"LOW-MASS" SPECTRAL FUNCTION & $K^{T=0}$, μ_s

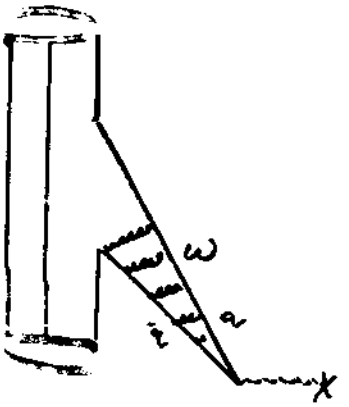
(SCHEMATIC)

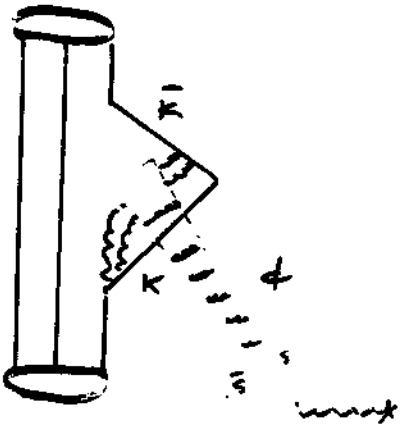


——— $KN \to KN$ / $e^+e^- \to K\bar{K}$ — — — — GUESTIMATE

——— FIT TO $F_2^{T=0}$

$$\mu_s = \underbrace{-0.28}_{\text{LOW-MASS}} \pm \underbrace{0.13\ (??)}_{\text{HIGHER-MASS UNCERTAINTY}}$$





$K^{T=0}$	$-$	$+$	$\simeq 0$
$\mu_s \equiv K_s$	$\simeq 0$	$-$	< 0

$\mu_s = -0.36 \pm 0.20$ DONG, LIU, WILLIAMS
QUENCHED QCD

-0.16 ± 0.18 LEINWEBER & THOMAS
QCD EQUALITIES & CHIRAL SYM

$\mu_s = -0.28 \pm ?$ DISP. RELATIONS,
LOW-MASS SPECTRAL F'N

$K^{T=0}$: $S\bar{S}$ PAIRS ARE NOT INERT, BUT THEIR EFFECTS ARE HIDDEN BY A Z-GRAPH CONSPIRACY

μ^s: IF $|\mu_s|/\mu_p| \ll 0.1$, IS THERE SOME NEW Z-GRAPH CONSPIRACY INVOLVING OTHER (HIGHER MASS) STATES?

DOES THE NRQM WORK SO WELL BECAUSE OF Z-GRAPH CONSPIRACIES?

EXPERIMENTS:

- BETTER PRECISION NEEDED (GØ & HAPPEX II)
- "ZERO" WOULD BE A VERY INTERESTING RESULT

THEORY:

- HOW TO RELATE LATTICE TO HADRON LANGUAGE? (LATTICE 2PT?)
- HOW TO BUILD HIGHER MASS S.F.?

JLAB-UCONN WS 11/99

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AXIAL RESPONSE ; $G_M^{(s)}$

AXIAL RADIATIVE CORRECTIONS

$\vec{e}p$ ELASTIC: BACKWARD ANGLE

$$A_{LR}/a_0\tau \rightarrow Q_W^p + Q_W^n \frac{G_M^n}{G_M^p} + Q_W^{(0)} \frac{\tilde{G}_M^{(s)}}{G_M^p}$$

$$- (1-4\sin^2\theta_W)\sqrt{1/\tau+1}\ \frac{\tilde{G}_A^p}{G_M^p}$$

$$\tilde{G}_A^p = g_A G_A^D(\tau)\left[1+R_A\right]$$

ESTIMATE $\quad R_A^{T=1} \cong -0.34 \pm 0.2 \quad$ MRM, BRH 1990

$\vec{e}d$ QUASIELASTIC

STRANGENESS: $\quad G_M^{T=0}\, G_M^{(s)} \quad$ SUPRESSED

AXIAL ISOVECTOR: $\quad G_M^{T=1}\, \tilde{G}_A^{T=1} \quad$ NOT SUPRESSED

SAMPLE

$\vec{e}p$ ONLY $\qquad G_M^{(s)} = 0.61 \pm 0.34$

$\vec{e}p$ & $\vec{e}d$ $\qquad G_M^{(s)} \approx 0$

$R_A^{T=1} \approx -1$?

AXIAL RADIATIVE CORRECTIONS

$\vec{e}p$ ELASTIC: BACKWARD ANGLE

$$A_{LR}/a_0\tau \rightarrow Q_W^p + Q_W^n \frac{G_M^n}{G_M^p} + Q_W^{(0)} \frac{\tilde{G}_M^{(s)}}{G_M^p}$$

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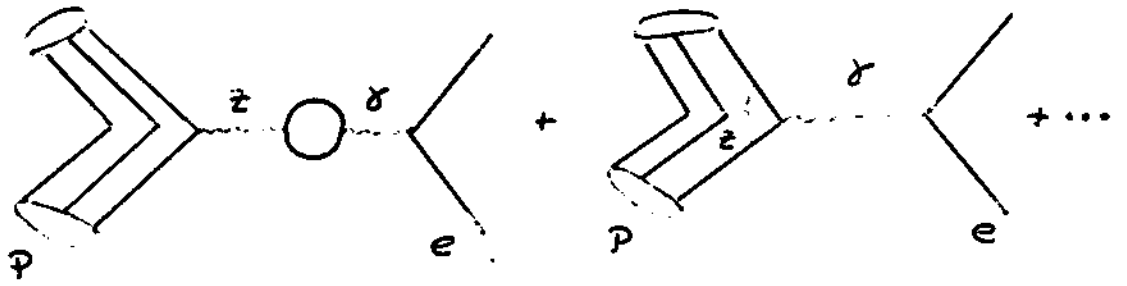
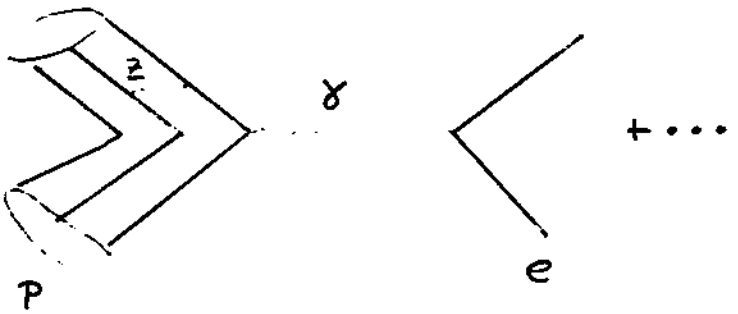
$R_A^{T=1} \approx -1$?

AXIAL RADIATIVE CORRECTIONS & ANAPOLE MOMENT



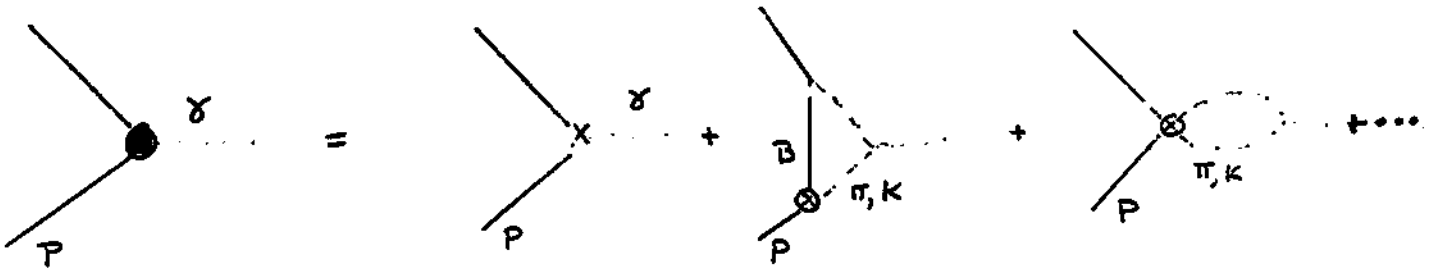
ST'D MODEL "ONE-QUARK" CALCUABLE



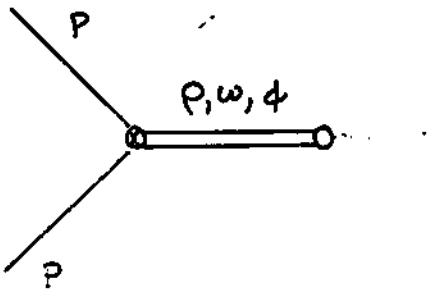
HADRONIC WEAK INTERACTION TH'Y UNCERTAINTIES

$$R_A^{S.M.} \sim \frac{\alpha}{3\pi}\left(\frac{1}{1-4\sin^2\theta_W}\right) \ln \frac{m_q^2}{M_Z^2} \sim -0.1 \text{ (× FACTORS)}$$

ANAPOLE MOMENT IN CHPT ("MANY-QUARK")



MODEL



CHIRAL ORDER	SOURCE	STRUCTURE
$1/m_\pi \Lambda_\chi$	π, K LOOPS	$1/\sqrt{m_q}$
$1/m_N \Lambda_\chi$	π, K LOOPS	$\ln m_q$
$1/\Lambda_\chi^2$	π, K LOOPS	$\ln m_q$
	ρ, ω, ... POLES	ANALYTIC [illegible]

HADRONIC PV CONSTANTS: $h^1_{\pi NN}$, $h^{0,1,2}_{VNN}$ MEAS. IN NUCL. [illegible]

$h^{V,A}_{BBM}$ UNMEASURED

ANAPOLE MOMENT & BEYOND

UP-DATED CHPT "MAXIMAL" $R_A^{T=1} \sim -0.5$?

SHI-LIN ZHU, BRH, MRM

OTHER SOURCES FOR R_A

- Z-γ BOX GRAPHS
- R.G. ENHANCEMENTS
- HIGHER-ORDER CHIRAL CORRECTIONS
- NUCLEAR PHYSICS
- NEW PHYSICS

NEW PHYSICS SEARCHES & $\rho_n(r)$

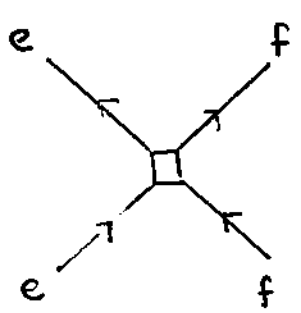
DIRECT NEW PHYSICS & Q_W

$$\mathcal{L}_{PV}^{SM} = \frac{G_F}{2\sqrt{2}} g_A^e \, \bar{e}\gamma_\mu\gamma_5 e \sum_f g_V^f \, \bar{f}\gamma^\mu f$$

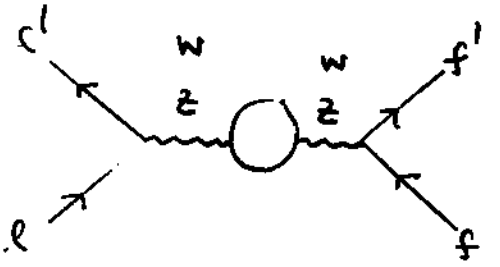
$$\mathcal{L}_{PV}^{NEW} = \frac{4\pi K^2}{\Lambda^2} \, \bar{e}\gamma_\mu\gamma_5 e \sum_f h_V^f \, \bar{f}\gamma^\mu f$$

$$\frac{\delta Q_W}{Q_W^{SM}} \sim \xi \equiv \frac{8\pi\sqrt{2}K^2}{G_F\Lambda^2} \sim 0.01$$

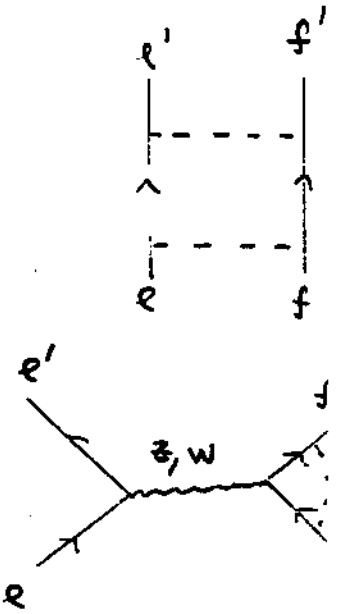
$$\Rightarrow \quad \Lambda \sim 20K \text{ TEV}$$



DIRECT



OBLIQUE



ALL ELSE

OBS.	PRECISION	G'_χ / G_F	M_{Z_χ}	$M_{Z_{LR}}$
$Q_W(Cs)$	1.3% [a]	0.006	730	790
	0.35%	0.0016	1410	1520
R_1	0.1%	0.002	1300	630
$Q_W(e)$	7% [c]	0.008	910	460
$Q_W(p)$	10%	0.010	580	285
	3%	0.003	1100	520
$(g-2)_\mu$	7 ppb	3	32	
	0.4 ppb [c]	0.17	137	
$p\bar{p}$ (CDF)	110 pb^{-1} [d]	0.009	595	630
TEV 33	10 fb^{-1} [e]	0.003	1000	1050
LHC	100 fb^{-1} [e]	0.00016	4490	4520

a) BOULDER 1997
b) SLAC E158
c) BNL E821
d) CDF 1997
e) RIZZO

EXPERIMENT: STATUS & PROSPECTS

$$|V_{ud}|^2_{EXP'T} - |V_{ud}|^2_{SM} = \begin{cases} -0.0028 \pm 0.0013 & \text{AVERAGE} \\ -0.0018 \pm 0.0029 & {}^{10}C \end{cases}$$

$$K_\mu^{EXP'T} - K_\mu^{SM} = \begin{cases} (750 \pm 733) \times 10^{-11} & \text{PRESENT} \\ (\quad \pm 250) \times 10^{-11} & \text{BNL E821} \\ (\rightarrow \pm 40) \times 10^{-11} & \end{cases}$$

$$(Q_W^{EXP'T} - Q_W^{SM})/Q_W^{SM} = -0.015 \pm 0.0035(E) \pm 0.012(T) \quad \text{BOULDER Cs}$$

$$\rightarrow -0.016 \pm 0.0038(E) \pm 0.003(T)$$

$$\pm 0.07(E) \pm 0.03(T) \quad \text{SLAC E158}$$

$$\pm 0.03(E?) \pm 0.03(T) \quad \text{JLAB}$$

$$(R^{EXP'T} - R^{SM})/R^{SM} = \pm 0.001(E) \pm 0.004(T) \quad \text{SEATTLE BERKELEY}$$

$$|d| \leq 1.1 \times 10^{-25} \text{ e-cm} \quad \text{NEUTRON}$$

$$9 \times 10^{-28} \text{ e-cm} \quad {}^{199}Hg$$

95% CL

$$4 \times 10^{-27} \text{ e-cm} \quad e^-$$

ISOTOPE RATIOS, $\rho_n(r)$, & PVES

$$\Delta Q_W(Cs)/Q_W(Cs) = -0.016 \pm 0.0035\,(E) \pm \underbrace{0.005}_{\text{ATOMIC TH'Y}}\,(T)$$

$$R = \frac{A_{PV}(N') - A_{PV}(N)}{A_{PV}(N') + A_{PV}(N)} \cong \frac{Q_W(N') - Q_W(N)}{Q_W(N') + Q_W(N)}$$

$$= R_{SM}(1 + \delta_1)$$

$\Rightarrow$ LITTLE SENSITIVITY TO ATOMIC TH'Y ERRORS IN $A_{PV}(N) = \xi\, Q_W(N)$.

BUT

$$\delta_1 \cong \left(\frac{2Z}{N+N'}\right)\underbrace{\Delta Q_W^P}_{\text{NEW PHYSICS IN } Q_W^P} - \left(\frac{N'}{\Delta N}\right)(Z\alpha)^2(3/7)\,\underbrace{\delta(\Delta X_N)}_{\Delta X_N = \Delta(R_n/R_p),\ \text{ISOTOPE SHIFT}}$$

OBS.	IDENTIFICATION	$\Delta\lambda$	REQUIREMENT	THY
$Q_W(Cs)$	0.35%	0	$\delta X_N \leq 0.05$	$\delta X_N \leq 0.02$
$R_1(Cs)$	0.1%	14	$\delta(\Delta X_n) \leq 0.0024$	$\delta(\Delta X_n) \leq 0.004$
$R_1(Ba)$	0.1%	14	$\delta(\Delta X_n) \leq 0.0023$	$\delta(\Delta X_n) \leq 0.004$
$R_1(Yb)$	0.1%	6	$\delta(\Delta X_n) \leq 0.0005$	?

PARITY-VIOLATING ELECTRON SCATTERING

1. FORWARD ANGLE $\vec{e}P$ AT JLAB (CARLINI, FINN, R-M : L01)

$$A_{LR} = a_0 |Q^2| \left\{ Q_W^p + F(Q^2) \right\}$$

VANISHES FOR $\theta \to 0°$

$\Rightarrow$ CLEAN PROBE OF Q_W^p

2. ELASTIC SCATTERING FROM HEAVY NUCLEUS (SOUDER, MICHELS) (JLAB)

$$-\frac{A_{LR}}{a_0 |Q^2|} = Q_W^p + Q_W^n \left[\frac{\int d^3x \, j_0(qx) \, \rho_n(x)}{\int d^3x \, j_0(qx) \, \rho_p(x)} \right]$$

J=0 TARGET

DONNELLY, DUBACH, SICK

$\Rightarrow$ EXP'T INFO ON $\rho_n(q)$ + NUCLEAR TH'Y $\Rightarrow \Delta X_N$

N.B. ECT* WORKSHOP, SUMMER Y2K (HOROWITZ, VANDERS, MRM)

CONCLUSIONS

- AFTER 25 YEARS, PVES & APV CONTINUE TO PROVIDE A POWERFUL, UNIQUE PROBE OF THE STRUCTURE OF HADRONS, NUCLEI, & THE ELECTROWEAK INTERACTION

- CONSIDERABLE THEORETICAL ACTIVITY CONTINUES TO BE STIMULATED BY PV STUDIES

- MORE EXPERIMENTS SHOULD BE APPROVED AT JLAB!