Electroweak Physics At An e-Ion Collider (EIC)

1. WEAK NC PARITY VIOLATION AND NEW PHYSICS
   i) APV vs Pol Electron Scattering
   ii) QWEAK, Moller, DIS, eC…
2. Preliminary e-ion requirements For Competitive A_{RL} Program
   ~100fb^{-1} (K. Kumar et al.) 2009 Talk Posted on the Web

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LDRD Proposal 2009

Electroweak Physics with an Electron-Ion Collider

Deshpande, Kumar, Marciano, Vogelsang

- DIS & Nuclear Structure Functions (γ,Z,W) (Beyond HERA)
- **A_{RL}, $\sin^2\theta_W(Q^2)$, Radiative Corrections, "New Physics"**
- Lepton Flavor Violation: eg $ep \rightarrow \tau X$

  (inverse attobarn=1000fb^{-1}!)

What are the Machine and Detector Requirements?

Inclusion of Electroweak Radiative Corrections (Important?)

High Precision & Polarization(±0.5%?, ±0.25%?)

Nucleon vs Nuclear Asymmetries (EMC Effect, CSV?)

Proton Polarization (Spin Content-Other?)

Various Issues That Need Thorough Study

1) PV Weak Neutral Currents (Past, Present and Future)

- Ancient History: By 1975 the $SU(2)_L x U(1)_Y$ Weinberg-Salam Model was nearly established. Predicted Weak Neutral Currents seen in neutrino scattering at CERN! But did the NC have the right coupling? $g_2/\cos\theta_W Z^\mu \bar{f}\gamma_\mu(T_{3f}-2Q_f\sin^2\theta_W - T_{3f}\gamma_5)f$

A New Form of Parity Violation!

Non Maximal but Distinctive

γ-Z Interference → Parity Violation Everywhere!

Atomic Parity Violation (APV)

- **$Q_W(Z,N) = Z(1-4\sin^2\theta_W)-N$** Weak Charge

  θ_W=Weak Mixing Angle

$Q_W(p)=1-4\sin^2\theta_W \sim 0.08$

$Q_W(^{209}Bi_{83}) = -43 - 332\sin^2\theta_W = -126$

Bi Much Larger but Complicated Atomic Physics

Originally APV not seen in Bi → SM Ruled Out?

(Later seen in Tl, Bi, Cs…)

1978 SLAC Polarized eD Asymmetry (Prescott, Hughes…)

e+D→e+X γ-Z Interference

$A_{RL} = \sigma_R - \sigma_L / \sigma_R + \sigma_L \propto 2\times10^{-4} Q^2 \mathrm{GeV}^{-2} (1-2.5\sin^2\theta_W) \sim 10^{-4}$ Expected

Exp. Gave $A_{RL}^{exp} = 1.5\times10^{-4} \rightarrow \sin^2\theta_W = \underline{0.21(2)}$

Confirmed $SU(2)_L x U(1)_Y$ SM!

$\pm 10\%$ Determination of $\sin^2\theta_W$ Precision!

Seemed to agree with GUTS (SU(5), SO(10)…)

$\sin^2\theta^0_W = 3/8$ at unification $\mu = m_X \sim 2 \times 10^{14}$ GeV

$\sin^2\theta_W(m_Z)_{MS} = 3/8[1 - 109\alpha/18\pi \ln(m_X/m_Z) + \ldots]$

$\approx$0.21! (Great Desert?)

But later, minimal SU(5) ruled out by proton decay

exps $\tau(p \to e^+\pi^0) > 10^{33}$yr $\to m_X > 5 \times 10^{15}$GeV

SUSY GUT Unification $\to m_X \sim 10^{16}$GeV $\tau_p \sim 10^{35}$yr

$\sin^2\theta_W(m_Z)_{MS} = 0.232$ (Good Current Agreement!)

1980s - Age of EW Precision

$\sin^2\theta_W$ needed better than ±1% determination

Renormalization Prescription Required

EW Radiative Corrections Computed

Finite and Calculable: DIS $\nu_\mu N$, $\nu_\mu e$, APV (A. Sirlin &WJM)

m_Z, m_W, Γ_Z, A_{LR}, A_{FB}

Define Renormalized Weak Mixing Angle: $\sin^2\theta_W{}^R$

$\sin^2\theta^0_W = 1-(m^0_W/m^0_Z)^2 = (e^0/g^0)^2$ Natural Bare Relation

$\sin^2\theta_W \equiv 1-(m_W/m_Z)^2$ On Shell Definition, Popular in1980s

Induces large $\alpha(m_t/m_W)^2$ corrections

Now Largely Abandoned

$\sin^2\theta_W(\mu)_{MS} \equiv e^2(\mu)_{MS}/g^2(\mu)_{MS}$ Good for GUT running

No Large RC Induced

Theoretically Nice/ But Unphysical

$\sin^2\theta_W^{lep}$ = $Z\bar{\mu}\mu$ coupling at the Z pole

very popular at LEP

= $\sin^2\theta_W(m_Z)_{MS}$+0.00028 (best feature)

$\sin^2\theta_W(Q^2)$ = Physical Running Angle

Continuous

Incorporates γZ mixing loops: quarks, leptons, $W^{\pm}$

Precision measurements at the Z Pole ($e^+e^- \rightarrow Z \rightarrow f\bar{f}$)

Best Determinations

$\sin^2\theta_W(m_Z)_{MS}$ = 0.23070(26) A_{LR} (SLAC)

$\sin^2\theta_W(m_Z)_{MS}$ = 0.23193(29) $A_{FB}(b\bar{b})$ (CERN)

(3 sigma difference!)

World Average: $\sin^2\theta_W(m_Z)_{MS}$=0.23125(16)

IS IT CORRECT?

α^{-1}=137.035999, G_μ=1.16637x10^{-5}Gev^{-2}, m_Z=91.1875GeV

+ m_W=80.398(25)GeV$\rightarrow\sin^2\theta_W(m_Z)$ = 0.23104(15)

Implications: 114GeV<m_{Higgs}<150GeV.

New Physics Constraints From: m_W, $\sin^2\theta_W$, α,& G_μ

$S=N_D/6\pi$ (N_D=# of heavy new doublets, eg 4th generation$\rightarrow N_D$=4)

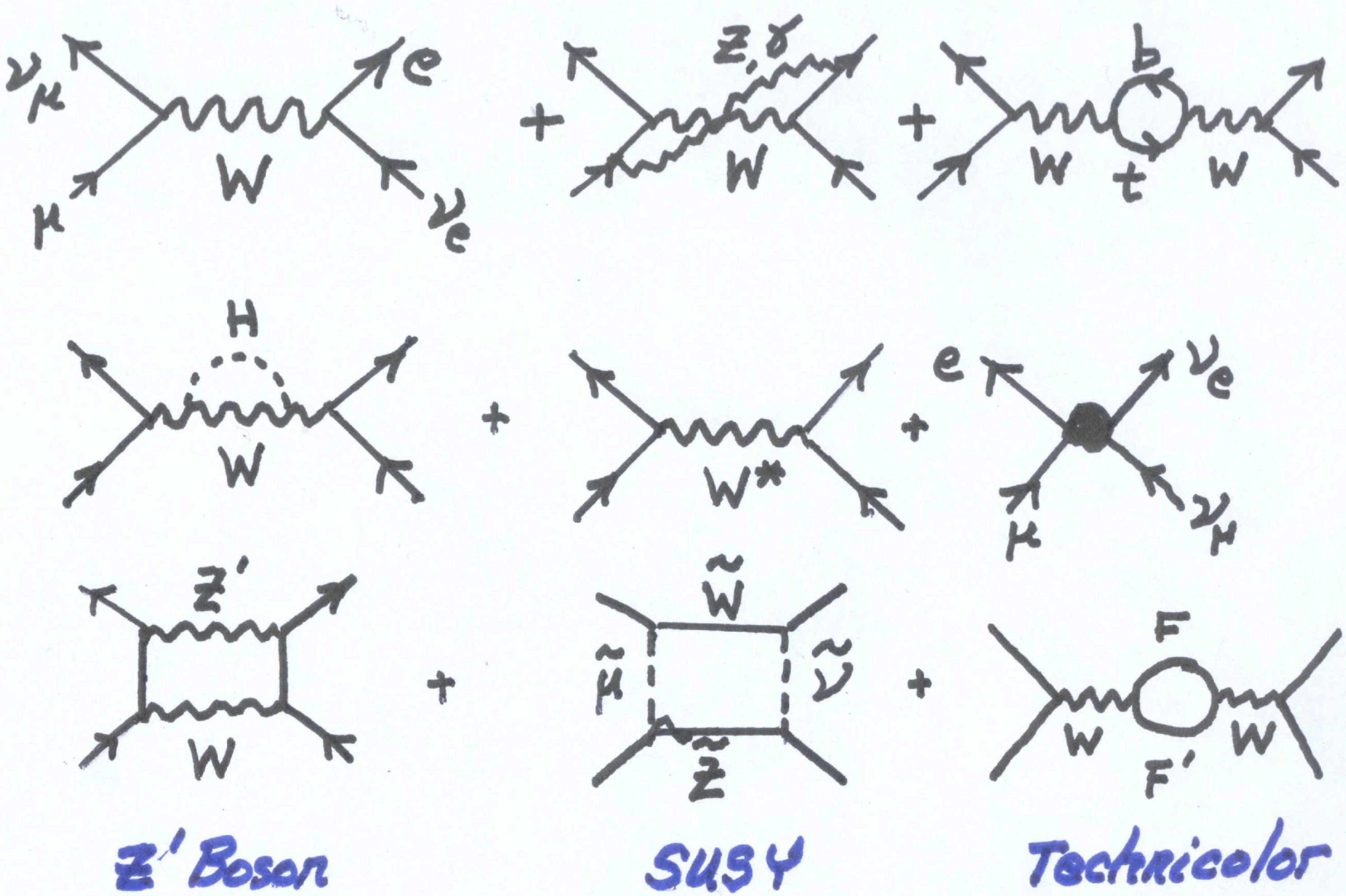
m_{W^*}= Kaluza-Klein Mass (Extra Dimensions)

$G_\mu\rightarrow G_\mu(1+0.0085S+O(1)(m_W/m_{W^*})^2+\ldots)$

	$\sin^2\theta_W(m_Z)_{\overline{MS}}$	S	N_D&m_{W^*}
Average	0.23125(16)	+0.11(11)	2(2), $m_{W^*}\geq$3TeV
A_{LR}	0.23070(26)	-0.18(15)	(SUSY)
$A_{FB}(b\bar{b})$	0.23193(29)	+0.46(17)	9(3)! Heavy Higgs, $m_{W^*}\sim$1-2TeV

Very Different Interpretations. We forgot to nail $\sin^2\theta_W(m_Z)_{MS}$!

Loop and Tree Level Corrections to Muon Decay



+ . . .

What about low energy measurements?

- DIS ν Scattering: $R_\nu \equiv \sigma(\nu_\mu N \to \nu_\mu X)/\sigma(\nu_\mu N \to \mu X)$ loops
  $\to m_t$ heavy, $\sin^2\theta_W(m_Z)_{MS}=0.233 \to$ SUSY GUTS

NuTeV $\sin^2\theta_W(m_Z)_{MS}$=0.236(2) High?

Nuclear-Charge Symmetry Violation?

Atomic Parity Violation Strikes Back

1990 $Q_W(Cs)^{exp}=-71.04(1.38)(0.88)$ C. Wieman et al.

Electroweak RC $\to Q_W(Cs)^{SM}=\rho_{PV}(-23-220\kappa_{PV}(0)\sin^2\theta_W(m_Z)_{MS})$

$= \mathbf{-73.19(3)}$

1999 $Q_W(Cs)^{exp}=-72.06(28)(34)$ Better Atomic Th.

2008 $Q_W(Cs)^{exp}=-72.69(28)(39) \to \sin^2\theta_W(m_Z)_{MS}=0.2290(22)$

2009 $Q_W(Cs)^{exp}=\mathbf{-73.16(28)(20)} \to \sin^2\theta_W(m_Z)_{MS}=0.2312(16)$!

±0.5% → **Major Constraint On "New Physics"**

$$Q_W(Cs)=Q_W(Cs)^{SM}(1+0.011S-0.9(m_Z/m_{Z_\chi})^2+\ldots)$$

eg $S=0.0\pm0.4$ $m_{Z_\chi}>1.2$TeV, leptoquarks, …

Radiative Corrections to APV

$\rho_{PV}=1-\alpha/2\pi(1/s^2+4(1-4s^2)(\ln(m_Z/M)^2+3/2)+\ldots.)\approx\underline{0.99}$

$\kappa_{PV}(0)=1-\alpha/2\pi s^2((9-8s^2)/8s^2+(9/4-4s^2)(1-4s^2)(\ln(m_Z/M)^2+3/2)$
$-2/3\sum(T_{3f}Q_f-2s^2Q_f^2)\ln(m_Z/m_f)^2+\ldots)\approx\underline{1.003}$

$s^2\equiv\sin^2\theta_W(m_Z)_{MS}=0.23125$, M=Hadronic Mass Scale

<u>Radiative Corrections to APV small and insensitive to hadronic unc.</u>

Same Corrections Apply to elastic eN scattering as $Q^2\rightarrow0$, $E_e<<m_N$

E158 at SLAC Pol ee→ee Moller)

$E_e \approx 50$GeV on fixed target, $Q^2=0.02\text{GeV}^2$

$A_{LR}(ee)=-131(14)(10)\times10^{-9}\ \alpha\ (1-4\sin^2\theta_W)$

EW Radiative Corretions ~-50%! (Czarnecki &WJM)

Measured to ±12% →$\sin^2\theta_W$ to ±0.6%

→$\sin^2\theta_W(m_Z)_{MS}=0.2329(13)$ slightly high

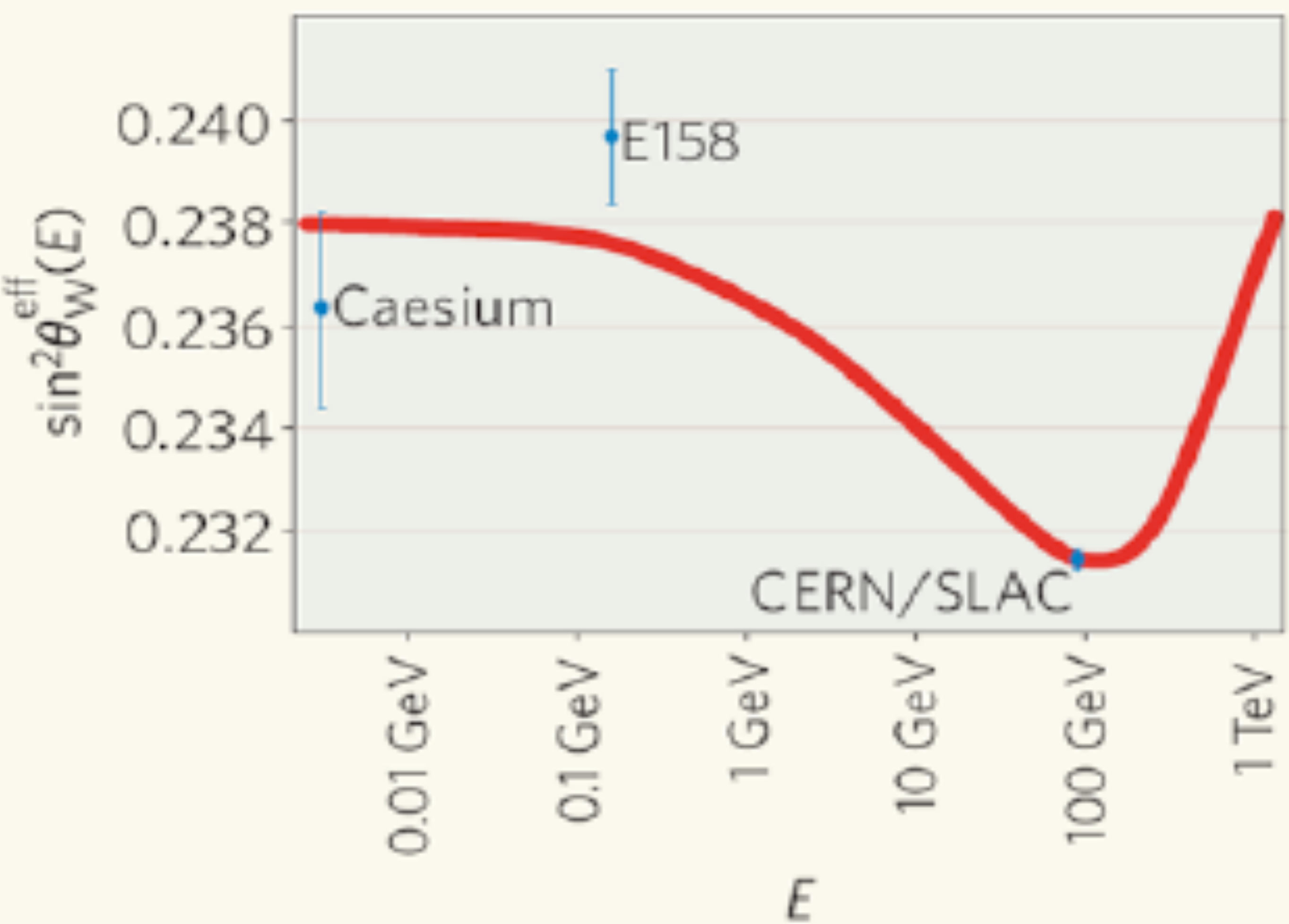
Best Low Q^2 Determination of $\sin^2\theta_W$

Together APV(Cs) & E158→ $\sin^2\theta_W(Q^2)$ running

$A_{LR}(ee)^{exp}=A_{LR}(ee)^{SM}(1+0.13T-0.20S+7(m_Z/m_{Z\chi})^2\ldots)$

Constrains "New Physics" eq $m_{Z\chi}>0.6$TeV, H^{--},S, Anapole Moment, …

Running $\sin^2\theta$



Goals of Future Experiments

- High Precision: $\Delta\sin^2\theta_W$~0.00025 or better
- Low Q^2 Sensitivity to "New Physics"

  $m_{Z'}$ >1TeV, $|S|$<0.1-0.2, SUSY Loops, Extra Dim., Compositeness….

Other A_{LR} Experiments

Strange Quark Content Program: Bates, JLAB, MAMI

Proton strange charge radius and magnetic moment consistent with 0. Axial Vector effects and RC cloud strangeness.

PREX Experiment: Neuton distribution

Preparing the way for future experiments, pushing technology and instrumentation, polarization

Future Efforts

QWEAK exp at JLAB being prepared

Will measure forward $A_{LR}(ep \to ep)\ \alpha\ (1-4\sin^2\theta_W) = Q_W(p)$

$E=1.1GeV$, $Q^2 \approx 0.03GeV^2$, $Pol=0.80 \pm 1\% \to A_{RL}(ep) \approx 3\times10^{-7}$

small A_{RL} requires long running

Goal $\Delta\sin^2\theta_W(m_Z)_{MS} = 0.0008$ via $\pm4\%$ measurement of A_{LR}

Will be best low energy measurement of $\sin^2\theta_W$

$A_{LR}(ep)^{exp} = A_{LR}(ep)^{SM}(1+4(m_Z/m_{Z\chi})^2 + \ldots)$

eg $m_{z\chi} \sim 0.9TeV$ Sensitivity (Not as good as APV)

- **The Gorchtein - Horowitz Problem (PRL)**

  γZ box diagrams: $O(2\alpha E_e/\pi m_p) \approx 6\%$ of $Q_W(p)$!

  RC Estimate needs to be checked

  Proposed Qweak Theory Uncertainty < 2%?

  JLAB Flagship Experiment (has some theory issue)

Longer Future Efforts: Polarized **Moller** at JLAB

After 12GeV Upgrade

$A_{LR}(ee \rightarrow ee)$ to ±2.5%

$\Delta\sin^2\theta_W(m_Z)_{MS} = \pm 0.00025$!

Comparable to Z pole studies!

$A_{LR}(ee)^{exp} = A_{LR}(ee)^{SM}(1+7(m_Z/m_{Z\chi})^2+\ldots)$

Explores $m_{Z\chi} \rightarrow 1.5$TeV Better than APV, S~0.1 etc.

Future JLAB Flagship Experiment (difficult!)

Can any (Mainz) Pol. Electron exp. compete with QWEAK/Moller?
(MESA Low Energy(0.15GeV), High Current Energy Recovery Linac

Consider $A_{LR}(eC^{12} \rightarrow eC^{12})_{elastic}$ 0+→0+ transition measures $Q_W(C)$

Only Vector Hadronic Current Contributes, CVC!

Not Affected By Strong Interactions at $Q^2=0$ Theoretically Clean!

Proposed MESA Goal Redo QWEAK (Elastic ep scattering)

- Low Energy 0.15GeV (Theory Cleaner)
- Small Asymmetry (Long Running)
- Polarization (Better than ±1%)

BATES EXP A_{RL}(eC) (1978-1990)

- P. Souder et al. PRL65, 694(1990) (Pioneering Effort)

E_e=0.25GeV   Very Modest Effort by today's standards

P_e=0.37±0.02 $A_{RL}(eC)^{exp}=0.60\pm0.14\pm0.02\times10^{-6}$

Q^2=0.02GeV^2 $A_{RL}(eC)^{SM}=G_\mu Q^2\rho_{PV}\kappa_{PV}\sin^2\theta_W(m_Z)_{MS}/\sqrt{2}\pi\alpha$

I=30-60μA   Directly Measures $\sin^2\theta_W(m_Z)_{MS}=0.20\pm0.05$

T=150hrs

Current ±25% can be improved to ±1% or better!

P_e=0.80, I=160μA, T=1500hrs, 20xAcceptance→±0.5%!

Essentially Equivalent to APV(Cs) but no Atomic Theory

For Many Types of New Physics 2xBetter than QWEAK

But no real theory(RC) uncertainty.

Main Issue: Polarization ±0.5%, ±0.3%, ±0.2%?

Comparison of $Q_W(p)$, $Q_W(Cs)$ &$Q_W(C)$

- $H_{PV}=G_\mu/\sqrt{2}[(C_{1u}\bar{u}\gamma^\nu u+C_{1d}\bar{d}\gamma^\nu d)\bar{e}\gamma_\nu\gamma_5 e+$
  $(C_{2u}\bar{u}\gamma^\nu\gamma_5 u+C_{2d}\bar{d}\gamma^\nu\gamma_5 d)\bar{e}\gamma_\nu e+\ldots]$

$Q_W(p)=2(2C_{1u}+C_{1d})$

$Q_W(Cs)=2(188C_{1u}+211C_{1d})$

$Q_W(C)=2(18C_{1u}+18C_{1d})$

$Q_W(C)$ &$Q_W(Cs)$ similar (mainly isoscalar), but measurement of all three →over determined.

A ±0.25% determination of A_{RL}(eC) would probe:

$m_{Z\chi}$~1.8TeV (About the same as 12GeV MOLLER)

S ~0.15 (Independent of T)

About a factor of 1- 4 better than QWEAK for:

SUSY Loops, Leptoquarks

Similar Sensitivity for Electron Anapole Moment

Can Be Combined with APV(Cs) & QWEAK

Worth A More Careful Study

Do Both QWEAK and A_{RL}(eC) at MESA

Comparable to APV→C_{1u} & C_{1d}

What About C_{2u} and C_{2d}?

- Renormalized at low Q^2 by Strong Interactions

Measure in Deep-Inelastic Scattering (DIS), eD & ep

$A_{RL}(eD \rightarrow eX) \propto 2\text{x}10^{-4}\text{GeV}^{-2}Q^2[(C_{1u}-C_{1d}/2)+f(y)(C_{2u}-C_{2d}/2)]$

Standard Model: $C_{1u} = (1-8\sin^2\theta_W/3)/2 \approx 0.20$

$C_{1d} = -(1-4/\sin^2\theta_W/3)/2 \approx -0.32$

$C_{2u} = (1-4\sin^2\theta_W)/2 \approx 0.04$

$C_{2d} = -(1-4\sin^2\theta_W)/2 \approx -0.04$

C_{2q} sensitive to RC & "New Physics" eg $Z\chi$ (SO(10))

Measure A_{RL} to ±1/2%?

Measure C_{2q} to ±1-2%? Theory (loops)?

JLAB 6 GeV DIS eD→eX On the books

JLAB 12 GeV DIS eD Proposed (Likely)

Goals: Measure C_{2q}s, “New Physics”, Charge Sym. Violation …

Effective Luminosity (Fixed Target) 10^{38}cm^{-2}sec^{-1}!

What can ep and ed at e-Ion contribute?

Asymmetry F.O,M,~A^2N, $A \propto Q^2$, $N \propto 1/Q^2$ (acceptance?)

High Q^2 Better (but Collider Luminosity?)

K. Kumar Talk →100fb^{-1} Needed

Program can be started with lower luminosity

Do DIS ep, eD, eN at factor of 10 lower

Single and Double Polarization Asymmetries

Polarized e: $A^{e}_{RL}=(\sigma_{RR}+\sigma_{RL}-\sigma_{LL}-\sigma_{LR})/(\sigma_{RR}+\sigma_{RL}+\sigma_{LL}+\sigma_{LR})\propto P_e$

Polarized p: $A^{p}_{RL}=(\sigma_{RR}+\sigma_{LR}-\sigma_{RL}-\sigma_{LL})/(\sigma_{RR}+\sigma_{LR}+\sigma_{RL}+\sigma_{LL})\propto P_p$

Polarized e&p $A^{ep}_{RRLL}= (\sigma_{RR}-\sigma_{LL})/(\sigma_{RR}+\sigma_{LL})\propto P_{eff}$

$P_{eff}=(P_e-P_p)/(1-P_eP_p)$ opposite signs

like relativistic velocities addition≤1

eg $P_e=0.8\pm0.008$, $P_p=-0.6\pm0.06\rightarrow P_{eff}=\underline{0.95\pm0.01}$

small uncertainty

How to best utilize P_{eff}?

LDRD A_{RL} GOALS

Examine Machine and Detector Requirements For ±1%

Include EW Radiative Corrections to DIS

Is 100fb^{-1} Sufficient?

Utility of Proton Polarization?

<u>Stage 1 e-Ion aim for ±4%</u>

<u>Study Nuclear Effects (EMC, CSV)</u>

<u>Important Secondary e-Ion Goal? Improves Proposal?</u>