Fundamental Symmetries in Hall A at 11 GeV

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[1]Hall A, JLab

Hall A collaboration meeting, JLab, Dec 2007

Outline

1. PV opportunities at 12-GeV
2. Electroweak Physics
3. PV-Møller
4. PV-DIS

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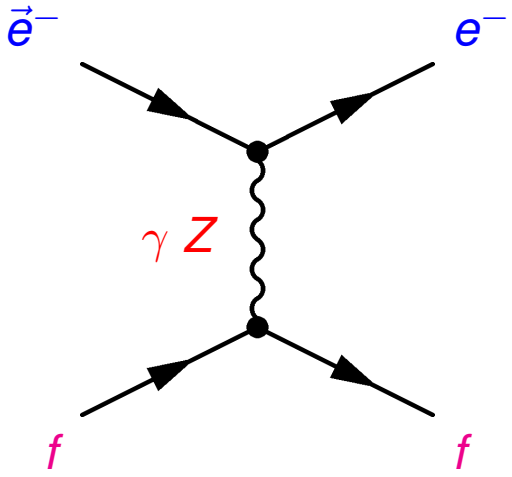
Parity Violation in Electron Scattering at $Q^2 \ll M_Z^2$



Polarized beam on Unpolarized target

$$\sigma \propto |A_\gamma + A_{weak}|^2 \sim |A_\gamma|^2 + 2A_\gamma A^*_{weak} + \ldots$$

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R - \sigma_L} \sim \frac{A_{weak}}{A_\gamma} \propto \frac{G_F Q^2}{4\pi\alpha}\mathbf{g}$$

$\mathbf{g} = g_A^e G_V^T \pm g_V^e G_A^T$, depend on $\sin^2\theta_W$, kinem.

for $f \equiv l^\pm$ $\mathbf{g} \propto (1 - 4\sin^2\theta_W) < 0.05$

Observable $A \sim 10^{-7} - 10^{-3}$, sensitive to:

- Electroweak coupling: $\Rightarrow$ CM tests
  Magnification: $\sin^2\theta_W \sim 0.23 \Rightarrow \delta(\sin^2\theta_W) \sim 0.02\frac{\delta(A)}{A}$
- Target structure $\Rightarrow$ unusual FF, PDF combinations

PV opportunities at 11-GeV

PV at 6 GeV

CEBAF is a perfect facility for PV

- High polarization $\sim 85\%$
- High beam current $< 100\mu A$
- Low noise beam

Measured: G_s
Elastic e p, e ^{4}He (HAPPEX, G0)
Coming:

- Neutron skin ^{208}Pb
  e Pb $\rightarrow$ e Pb (PREX)
- EW e p $\rightarrow$ e p (QWEAK)
- EW e d DIS

PV at 11 GeV

- Same polarization
- Beam current $< 100\mu A$
- Comparable noise

Higher energies:
$A \propto Q^2$ larger, but
$\sigma_{elastic}$ suppressed by FF

Opportunities:

- Møller scattering
- DIS

Developed by: P.Souder, K.Kumar, K.Pashke, D.Mack, R.Carlini, P.Reimer, X.Zheng etc.

Physics Goals

1. Precision measurement of $\sin^2\theta_W$ at $Q^2 \ll M_Z^2$: CM test (Møller)
2. Measurement of quark axial couplings C_{2q}: CM test (PV-DIS)
3. Electroweak probe of the strong interactions (PV-DIS)

Couplings in electroweak theory

Constants

- $\alpha(Q^2) \overset{Q^2 \to 0}{\sim} 1/137$ (μ_e)
- $G_F \sim 1.16 \cdot 10^{-5}$ GeV^{-2} (τ_μ)
- $M_Z \sim 91.2$ GeV (LEP-I)
- Fermions/Higgs masses, CKM

Derivatives

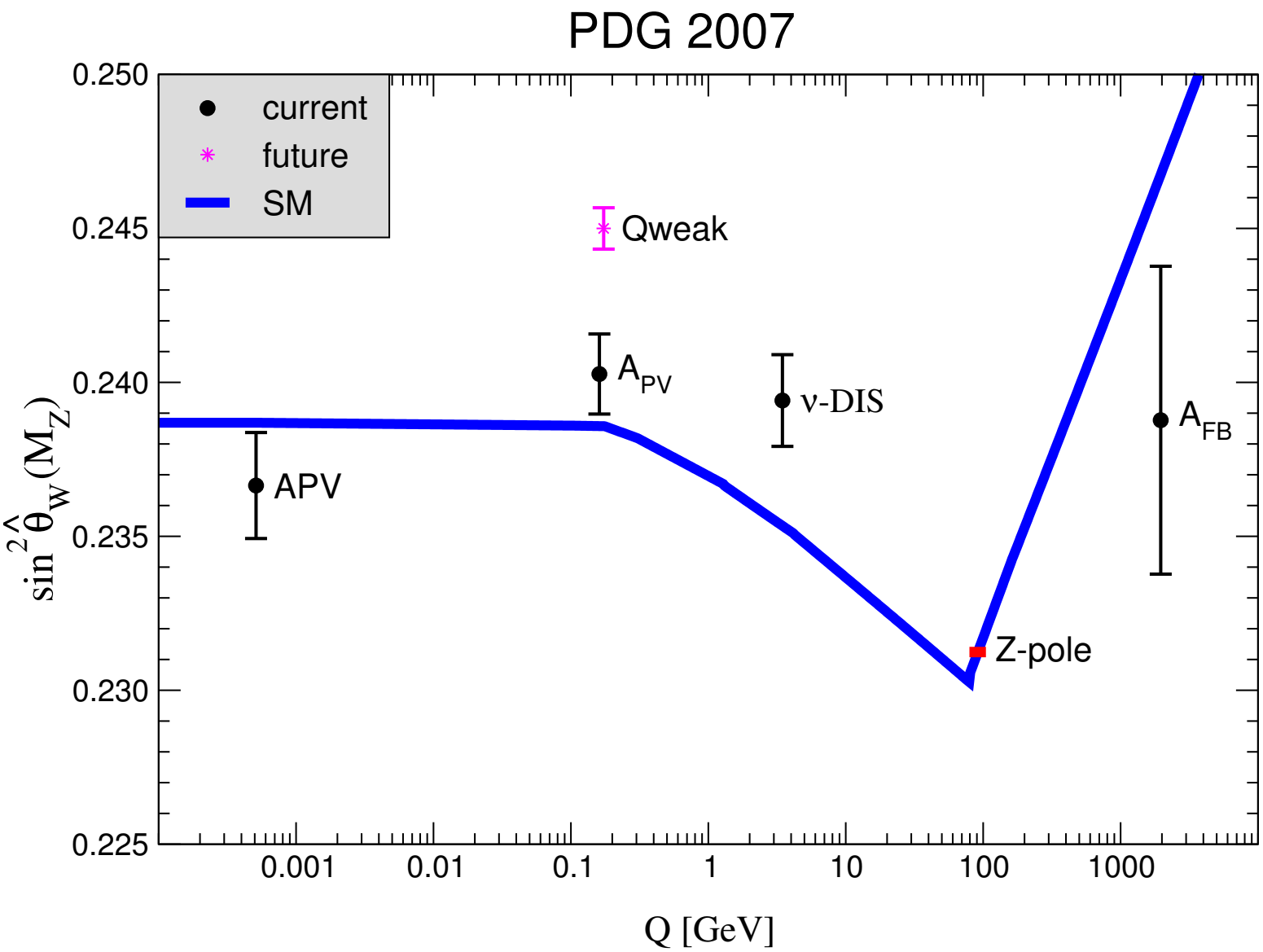
Several renormalization schemes
Popular one: $\overline{MS}$

- Renormalization scale: M_Z
- Defined $\hat{s}_Z^2 = \sin^2\theta_W(M_Z)$
- Couplings absorb loops etc.
- Running $\sin^2\theta_W(Q^2)$
- Weak dependence of $\hat{s}_Z^2$ on m_t

Experimental goal: measure $\hat{s}_Z^2(Q^2)$

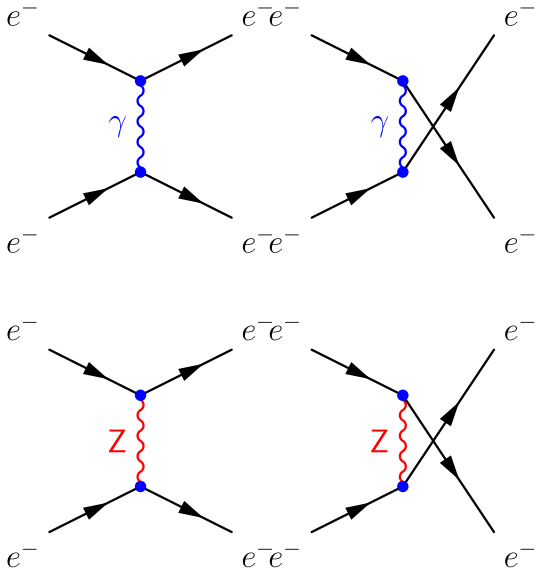
$\hat{s}_Z^2(Q^2) \overset{\overline{MS}}{\to}$ observables

Running of $\sin^2\theta_W$ in $\overline{MS}$

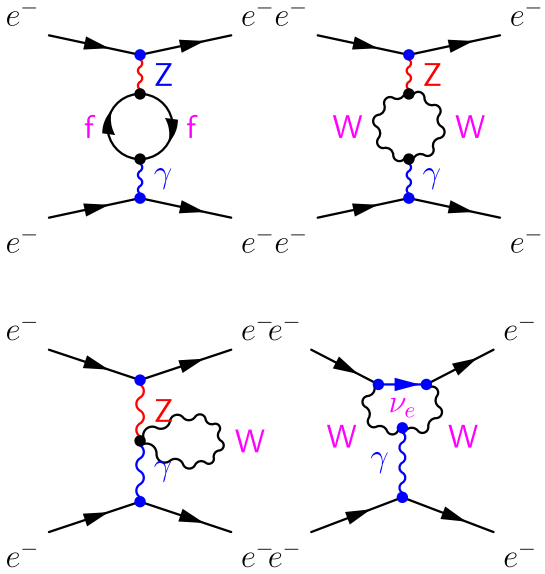


Diagrams contributing to the $\sin^2\theta_W$ running

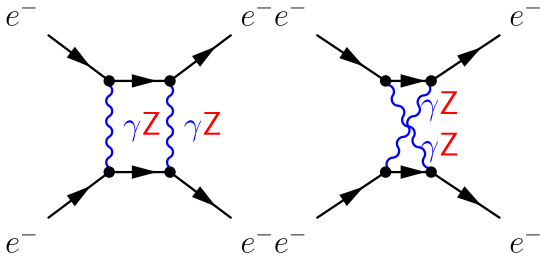
Tree diagrams



Loop diagrams



Box diagrams

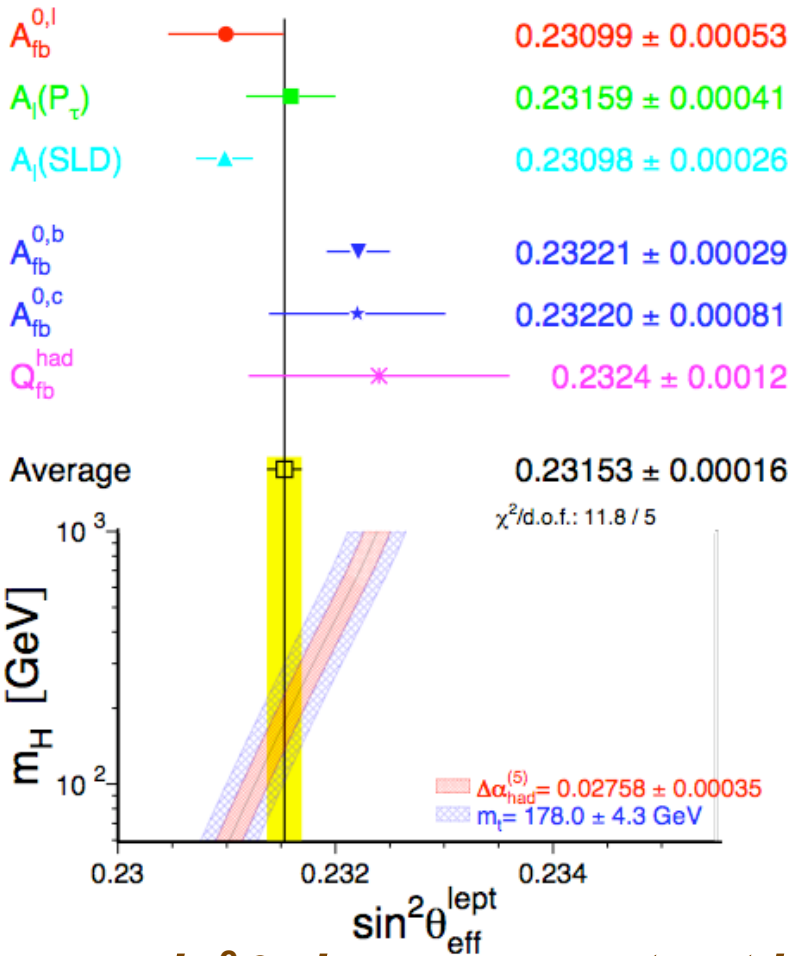


Main contribution:
f-loop

"New physics": SUSY, Z', leptoquarks etc. may also contribute

Experiments: $\sin^2\theta_W$ at Z pole

Most accurate measurements so far are at Z-pole. BUT:



Pointed out by Marciano:

3σ deviation

A_L(SLD)	A_{FB}(LEP)
$\frac{\sigma_L-\sigma_R}{\sigma_L-\sigma_R}$	$\frac{\sigma_F-\sigma_B}{\sigma_F-\sigma_B}$
$\vec{e}^- e^+ \to Z$	$e^- e^+ \to Z \to \bar{b}b$
0.23098(26)	0.23221(29)
Higgs mass (GeV)	
35^{+26}_{-17}	480^{+350}_{-230}
ruled out experimentally	higher than expected
also APV	also E158
favors SUSY	rules out SUSY favors Technicolor

M_H, SUSY may be found by the LHC

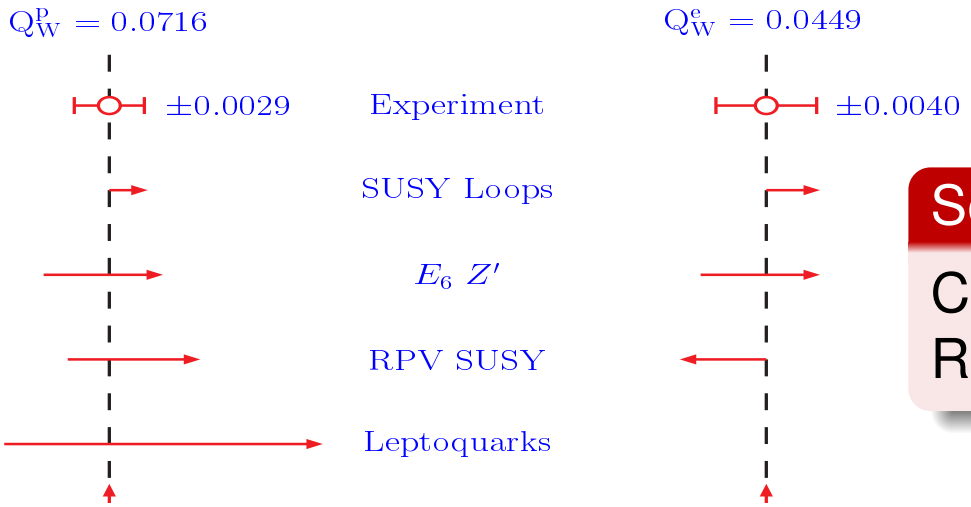
Experiments: $\sin^2\theta_W$ at low Q^2

Technique	process	Target	deviation from SM
Atomic PV	γ polarization ^{133}Cs	Coherent quarks from entire nucleus	$-1.\sigma$
NuTeV	νA – DIS CC, NC	Uncoherent quarks from nuclei	$+3.\sigma$ *discussed later*
Møller E158	$\vec{e}^- e^- \to e^- e^-$	Purely leptonic *cleanest interpretation*	$+1.2\sigma$
QWEAK (JLab)	$\vec{e}^- p \to e^- p$	Coherent quarks from protons	in future

Sensitivity to "New physics"

Erler, Kurylov, Ramsey-Musolf 2003

QWEAK E158



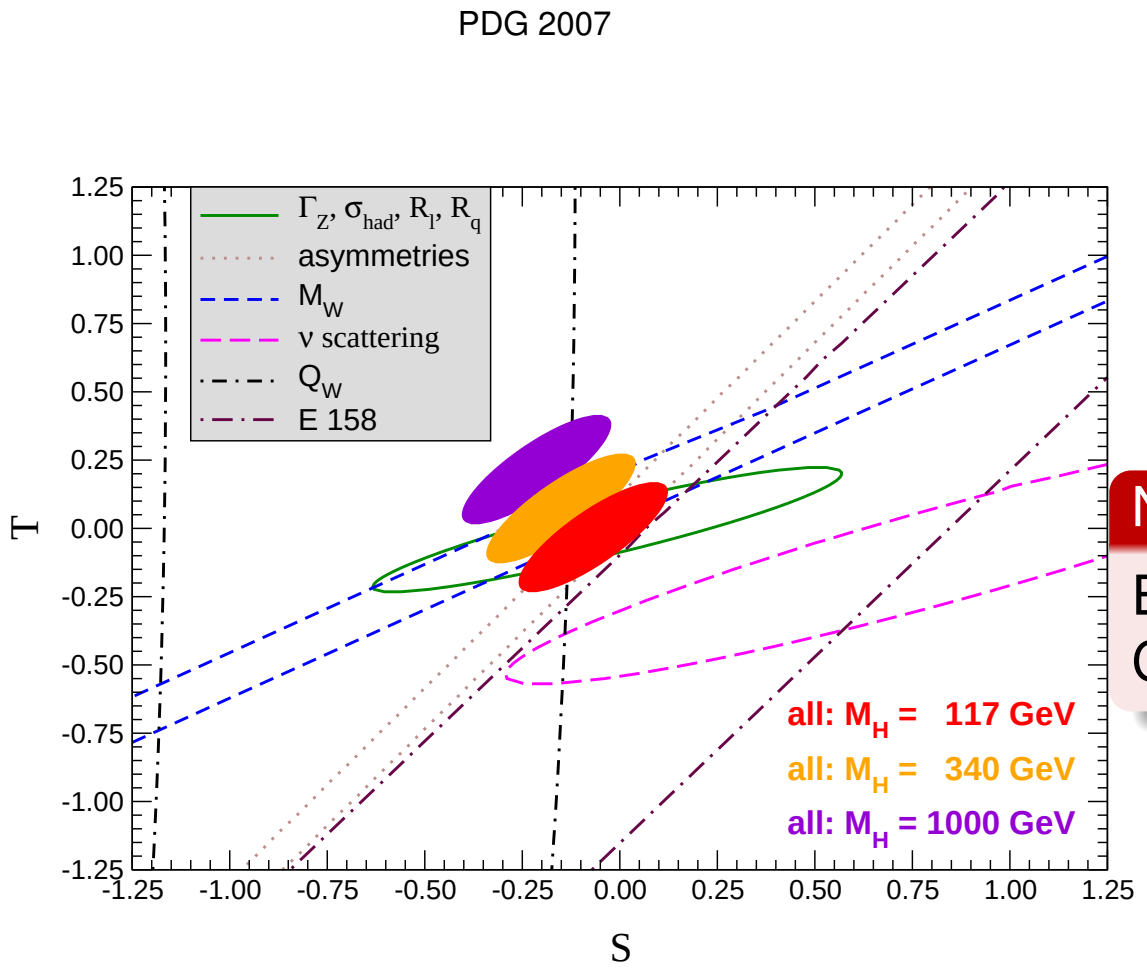
"New physics": at the 95% limit

- $Q_W^p \Leftrightarrow Q_W^e$ complimentarity
- Q_W^p may improve LQ limits

Sensitivity to *THIS* physics

Considerable improvement needed:
Reduce the errors $\times 1/5$

Combined constraints on New Physics



Constraints on New Ph.

S, T, U formalizm

- $T \sim E^W_{self} - E^Z_{self}(Q^2 \sim 0)$
- $S \sim E^{W,Z}_{self}(M_Z) - E^{W,Z}_{self}(0)$

New Møller experiment

Errors $\times 1/5$:
Competitive with all combined!

Special sensitivity of PV-Møller

Assume $\sigma(\sin^2\theta^{eff}) = 0.00025$

Physics Constrains

- Model independent: contact interaction (compositeness)
  $\mathcal{L} = \frac{4\pi}{2\Lambda_{ee}^2}\left[\eta_{LL}(\overline{\psi}_L\gamma_\mu\psi_L)^2 + \eta_{RR}(\overline{\psi}_R\gamma_\mu\psi_R)^2 + \eta_{LR}(\overline{\psi}_L\gamma_\mu\psi_L)(\overline{\psi}_R\gamma_\mu\psi_R)^2\right]$
  $\sin^2\theta_W^{meas} - \sin^2\theta_W^{SM} = \pm\frac{\pi}{G_F\sqrt{2}}\frac{\eta_{LL}+\eta_{RR}+\eta_{LR}}{\Lambda_{ee}^2}$
  $\Lambda_{LL}^+ > 8$ TeV $\Rightarrow 15$ TeV at 95% CL
  $\Lambda_{LL}^- > 16$ TeV $\Rightarrow 38$ TeV
- Model dependent: extra Z (1 in $SO(10)$ or 2 in E_6)
  $\frac{1-4s_W^{2(obs)}}{1-4s_W^{2(SM)}} = 1 + \frac{M_Z^2}{M_{Z1}^2}$
  $M_{Z1} > 0.7$ TeV $\Rightarrow 1.8$ TeV
- Other: SUSY, doubly-charged Higgs etc., but no leptoquarks.

SLAC E158: PV-Møller

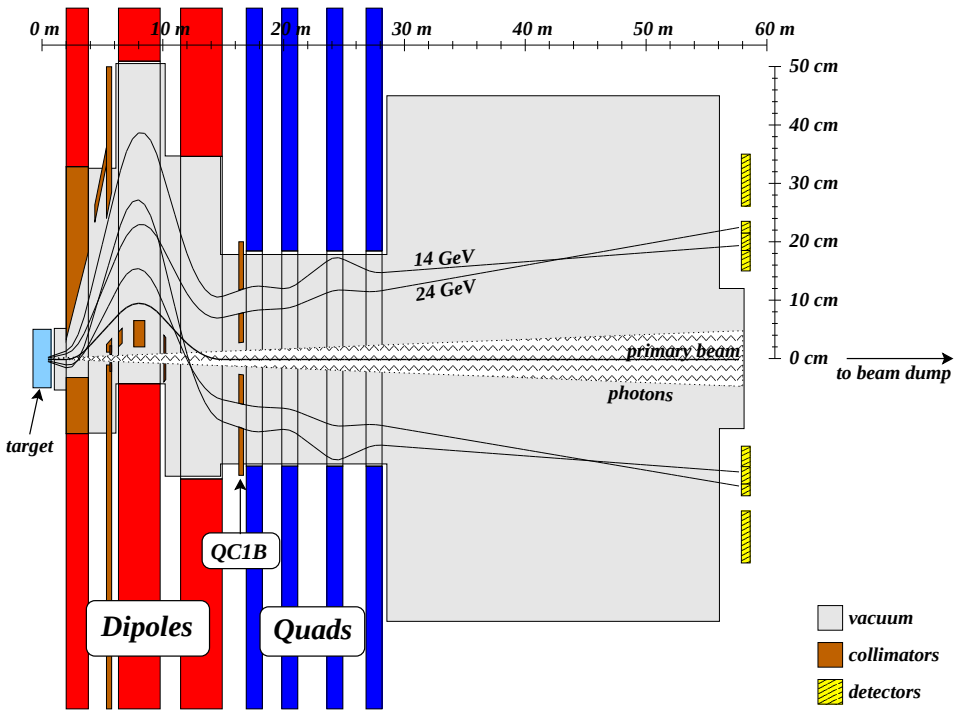
- Pulsed $\vec{e}^{\,-}$ on 1.5 m long H_2
- E=45-48 GeV, $\sqrt{s} = 0.21$ GeV
- $\mathcal{L} = 1.5 \cdot 10^6$ fb^{-1}
- BG: $\vec{e}^{\,-}p$ elastic, DIS

Measured at $Q^2 = 0.026$ GeV^2

$A_{PV} = (131 \pm 14 \pm 10)$ ppb

Derived in $\overline{MS}$:

$\sin^2\theta_W^{eff}(Q) = 0.24030 \pm 0.0010 \pm 0.0008$



PV-Møller at 11 GeV: feasibility

Rate and Asymmetry

$\sigma \propto 1/E$, $A \propto E \quad \Rightarrow \quad FOM \propto E$

Requirements

Expected in CM $\overline{MS}$:

$s_W^2 = 0.2387 \quad \overset{E158}{\Rightarrow} A = 160$ ppb

$\overset{11GeV}{\Rightarrow} A = 38$ ppb

Required

$\delta s_W^2 = 0.00025 \quad \Rightarrow \delta A/A = 0.022$

E158 stat:

$\delta A/A = 0.05(Moller) \oplus 0.07(noise)$

Assuming the noise at CEBAF $\times 0.1$:

Time needed 4600 hours at 100μA

Real time: 1.2 year running

Systematic errors

E158: 4% from BG

Should be reduced by $10 - 15$

Challenges:

- $\frac{Rate(Mott)}{Rate(Moller)} \sim const(E)$
- 18% RL: Mott mimicks Møller
- DIS BG is polarized

Summary

Time: 1.2 years at 100μA

Challenges:

- systematic errors
- target power

Unknowns: the LHC impact

PV DIS Asymmetry

$$\mathcal{L}^{eHadron} = \frac{G_F}{\sqrt{2}} \sum_i (C_{1i} \cdot j_A^e \cdot j_V^i + C_{2i} \cdot j_V^e \cdot j_A^i)$$

where i are partons (quarks)

$$C_{1q} = 2 g_A^e g_V^i = -C_{1\overline{q}} \approx -t_{3iL} + 2 Q_{ei} s_W^2$$
$$C_{2q} = 2 g_V^e g_A^i = +C_{2\overline{q}} \approx -t_{3iL}(1 - 4 s_W^2)$$

Cahn,Gilman 1978

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} [a(x) + Y(y) \cdot b(x)]$$

$$Y(y) = \frac{1-(1-y)^2}{1+(1-y)^2}, \quad y = \frac{\nu}{E}, \quad x = x_{Bj}$$

$$a(x) = \sum_i f_i(x) C_{1i} Q_{ei} / \sum_i f_i(x) Q_{ei}^2$$
$$b(x) = \sum_i f_i(x) C_{2i} Q_{ei} / \sum_i f_i(x) Q_{ei}^2$$

$f_i(x)$ - quark distribution functions

Isoscaler target

Deuterium: $f(x)$ largely cancel

$q^{\pm} \equiv q \pm \overline{q}$ in proton

$$a(x) = \frac{3}{10}(2C_{1u} - C_{1d})(1 + R_s(x))$$
$$b(x) = \frac{3}{10}(2C_{2u} - C_{2d})(1 - R_a(x))$$

$$\left.\begin{aligned} R_s(x) &= \frac{2s^+}{u^+ + d^+} \\ R_a(x) &= \frac{\overline{u} + \overline{d}}{u^+ + d^+} \end{aligned}\right\} \xrightarrow{large\ x} 0$$

$$A_{PV}(x, Q^2)/Q^2 \xrightarrow{large\ x} \mathcal{A}(y)$$

Corrections from:

- s-quarks, sea-quarks
- target mass
- higher twists

Prescott 1979 $s_W^2 = 0.22 \pm 0.02$ using SM

Measurements of the weak charges C_{1q}, C_{2q}

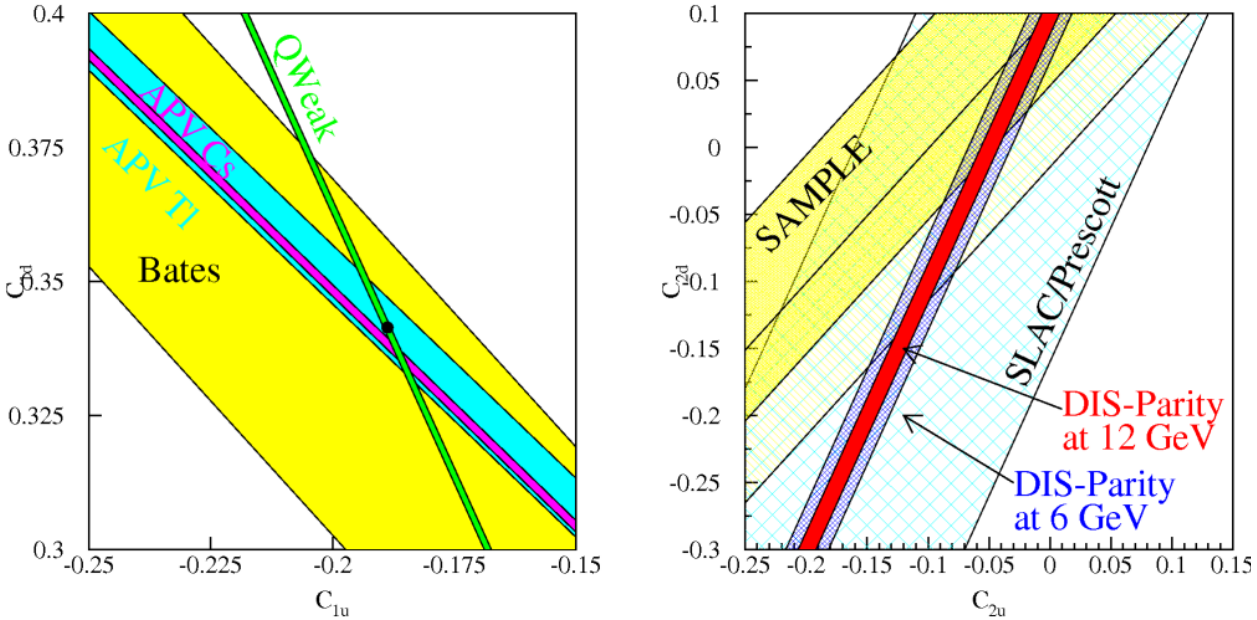
Existing measurements:

- PV-elastic in $e^- p, d, Be, C$ at Bates, Mainz, JLab
- PV-DIS in $e^- d$, $\mu^\pm C$ at SLAC, CERN
- Atomic PV experiments

Planned measurements:

- PV-DIS in $e^- d$ at Jlab 6 GeV (Hall A) $x \sim 0.3$
- PV-DIS in $e^- d$ at Jlab 12 GeV (Hall C) $x \sim 0.3$

Credit to P.Reimer et al



Sensitivity to "New Physics"

		PVDIS	Møller
typical asymmetry	A	~ 700 ppm	~ 0.03 ppm
concievable	$\delta A/A$	$\sim 0.5\%$	$\sim 2\%$
sensitivity	$\delta s_W^2/s_W^2$	$\sim \delta A/A \times 0.5$	$\sim \delta A/A \times 0.01$
s_W^2 measurement:	$\delta s_W^2/s_W^2$	0.00250	0.00025
	$\delta(2C_{2u} - C_{2d})$	~ 0.01	

- Measure axial $\delta(\Delta C_2) < 0.01$
- Sensitivity to:
  - Contact term (composit.)
    $\mathcal{L} = \pm\frac{4\pi}{2\Lambda_{eq}^2}\eta j_R^e \cdot j_R^q \ldots$
    $\Lambda_{eq} > 6$ TeV (HERA: $> 10 - 25$ TeV)
  - SUSY: ($\delta A/A \sim 0.2\%$?)
  - different superpositions
- Strong interaction effects?

SUSY Kurylov, Ramsey-Musolf 2004

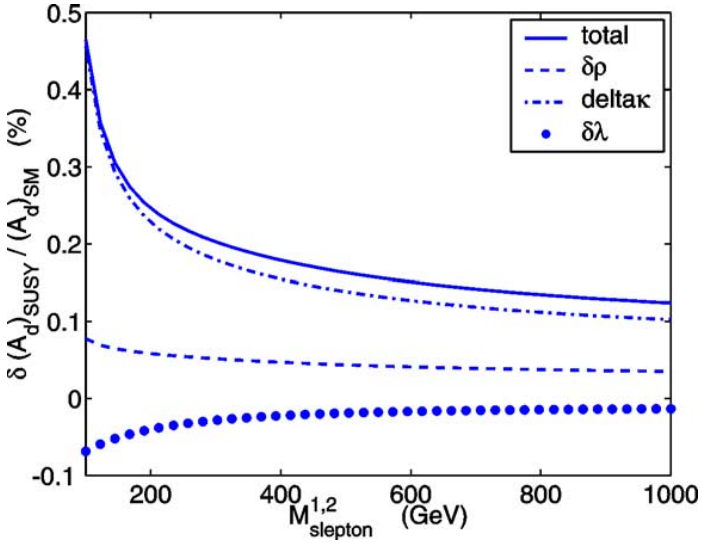


Fig. 4. SUSY contributions to $A_{\rm LR}^{eD,\rm DIS}(y=1)$ from $\delta\rho_{\rm PV}$ (dashed line), $\delta\kappa_{\rm PV}$ (dash-dotted line) and $\hat{\lambda}$ (dotted line). The solid line

Lessons from NuTeV

Measured:

- Paschos-Wolfenstein:

$$R^- = \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\bar{\nu} N}} \propto 1 - 2s_W^2$$

- Accuracy $\delta R/R \sim 0.2\%$
- $s_W^2(meas) - s_W^2(SM) \sim 3\sigma$

Lessons

Study the hadronic effects

Is it interesting by itself?

Assumptions (also relevant for JLab):

- Isoscaler target (Z=A/2)
- Include only light quarks u,d
- Neglect heavy quark production
  OK at Jlab
- Assume isospin symmetry of PDF
- No nuclear effect (shadowing, EMC...)
- No higher twist effects
- Small radiative corrections
- No contributions outside SM

Charge Symmetry Violation (CSV) in PV DIS

CS assumption

$u^p(x) = d^n(x)$ $\delta u(x) = u^p(x) - d^n(x)$

$d^p(x) = u^n(x)$ $\delta d(x) = d^p(x) - u^n(x)$

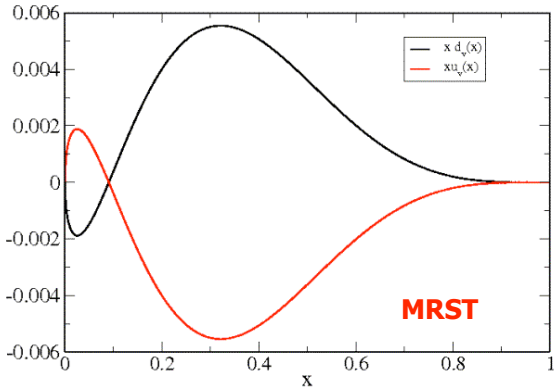
However:

- $m_d > m_u$
- EM

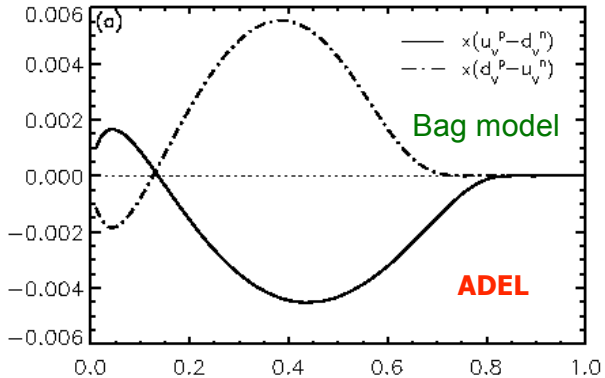
PV DIS on ^{2}H

$$\frac{\delta A_{PV}}{A_{PV}} \sim 0.3 \frac{\delta u - \delta d}{u + d}$$

QED splitting (MRST, Glueck)

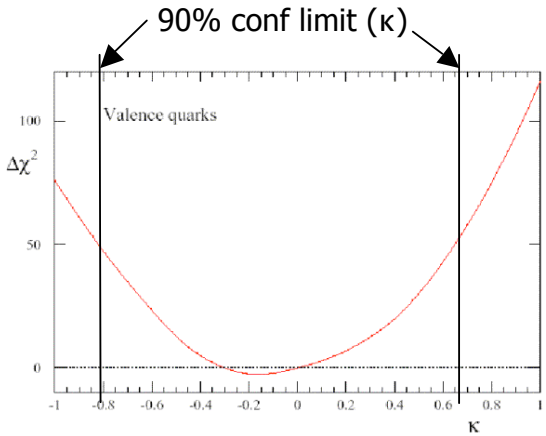


QCD Bag (Rodionov,Londergan,Thomas)



$\delta u < 1\%$

$\delta u/u \overset{x\to 1}{>} 1\%$



Martin at al EPJC 35 2004

MRST fit CSV, using a form:

$\delta u(x) = \kappa f(x)$,

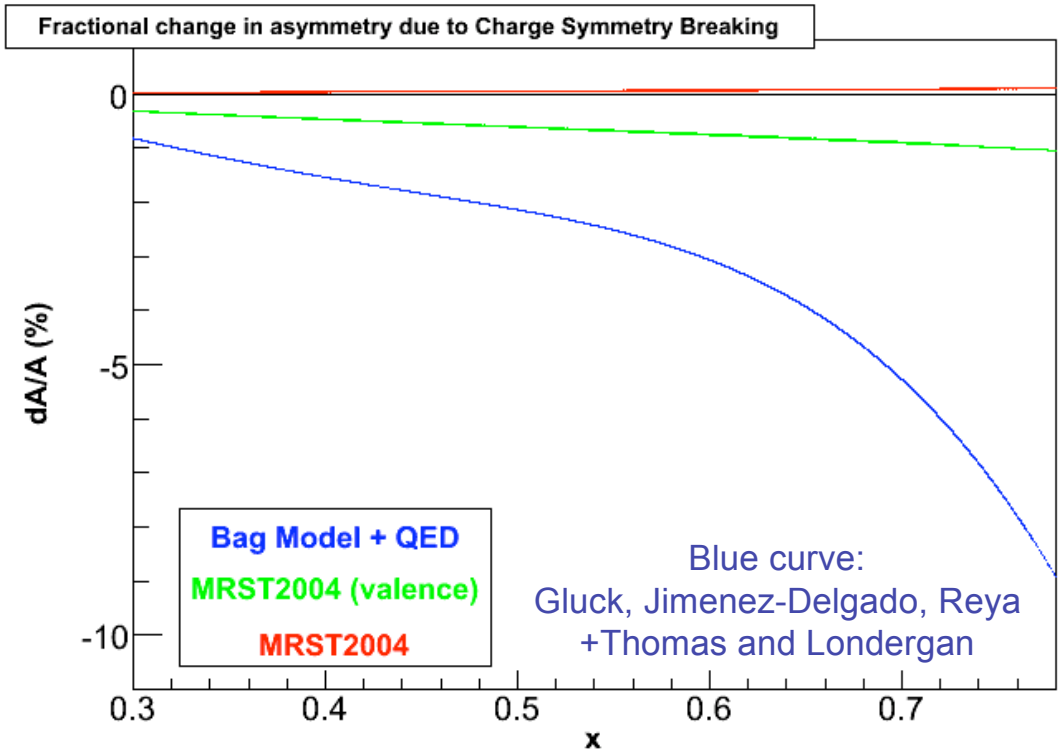
$f(x) = x^{-0.5}(1-x)^4(x - 0.0909)$

favors $\kappa \sim -0.2$

$\kappa \sim -0.8$ (CL=90% edge) explains NuTeV!

Charge Symmetry Violation Measurement

P.Souder, talk on Oct 24 2006



- Measure $A_{PV}(x)$ at $0.5 < x < 0.7$
- Provide $\delta A/A \sim 1\%$

First direct CSV observation at parton level

- Important input for high energy colliders
- May explain a part of NuTeV anomaly

Higher Twists

Credit to P.Souder

Higher Twists (HT): extra $\frac{1}{Q^2}$ terms, beyond QCD evolution

P concerving	$F_2(x,Q^2) =$	$F_2(x,Q^2)_{DGLAP}$	$\times(1+\frac{D(x)}{Q^2})$
PV DIS ^{2}H	$A_{PV}(x,Q^2)/Q^2 =$	$A_{PV}(x)$	$\times(1+\frac{C(x)}{Q^2})$

Any $A_{PV}/Q^2 = A(Q^2)$ - Higher Twists $\Rightarrow$ simpler than F_2 !

Anything special about $C(x)$?

Bjorken 78, Wolfenstein 78:

$A \propto 1-\delta$,

$\delta \propto \ell_{\mu\nu} \int \langle D|\overline{u}(x)\gamma^\mu u(x)\overline{d}(0)\gamma^\nu d(0)|D\rangle e^{iqx} d^4x$,

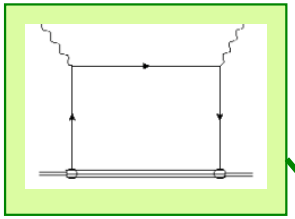
Only ud correlators are left: diquarks

Interest

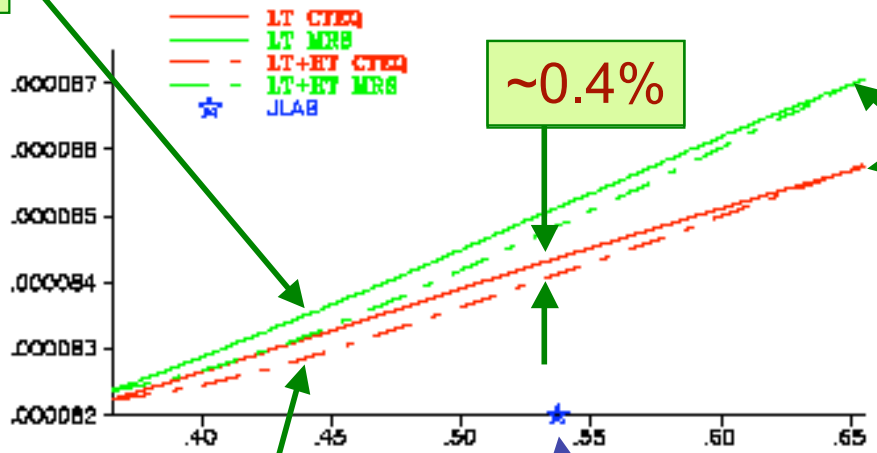
- Measuring a clean HT operator
- Role of diquarks (spin?)

Borrowed from P.Souder

Probing Higher Twist with PV



PV Deep Ineslastic eD (J Lab 12 GeV)

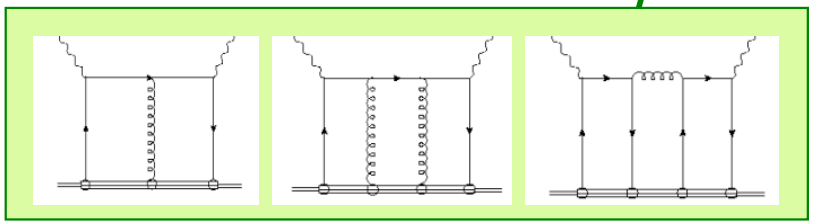


A_{PV}/Q^2

y

~0.4%

Different PDF fits



E=11 GeV
θ=12.5^0

Sacco, Ramsey-Mulolf preliminary

Effect is small at x~0.2

d/u at high x

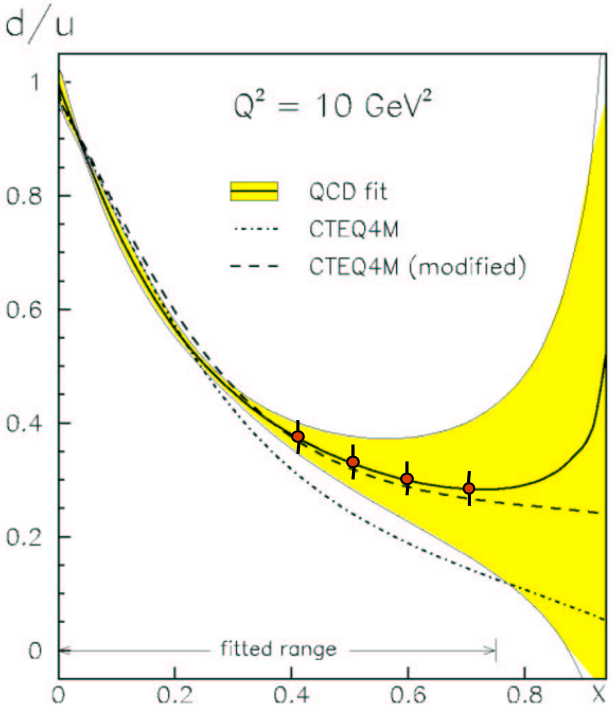
Running on ^{1}H:

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[a(x) + Y(y)\cdot b(x)\right]$$

$$a(x) = \frac{3}{2}\frac{2C_{1u}u(x) - C_{1d}(d(x)+s(x))}{4u(x)+d(x)+s(x)}$$

$$b(x) = \frac{3}{2}\frac{2C_{2u}u_v(x) - C_{2d}d_v(x)}{4u(x)+d(x)+s(x)}$$

$$a(x) = \frac{u(x)+0.91d(x)}{u(x)+0.25d(x)}$$



Allows to measure d/u

- constrain higher twists
- up to high x

Program of PV DIS Study

Strategy

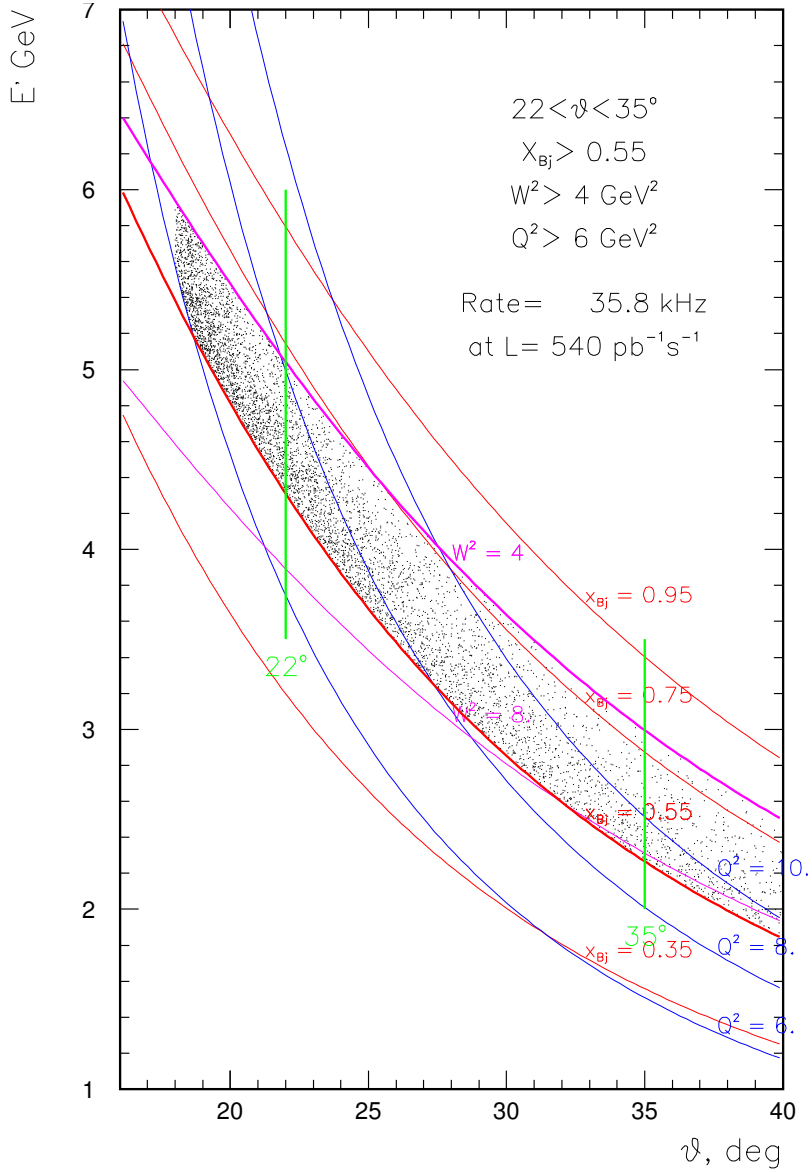
- Study hadronic physics first
- Use the hadronic results to measure the axial couplings

Required precise kinematics and broad range

- Two beam energies: $11, 8.8$ GeV
- Measure A_D in narrow bins of x, Q^2 with 1% precision
- Study the $A_D(Q^2)$ at $0.3 < x < 0.6$ to constrain HT
- Search for CSV with $A_D(x)$ in $0.5 < x < 0.7$
- Use $x > 0.4$, high Q^2, Y data to measure C_{2q}

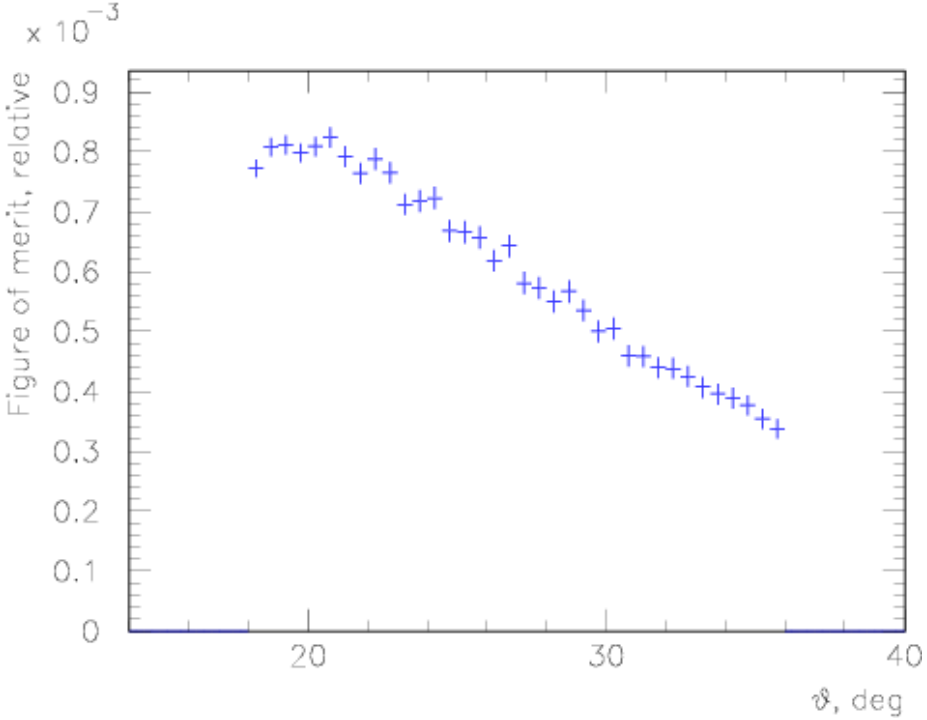
Requires:
A large acceptance and high rate magnetic spectrometer

DIS rates

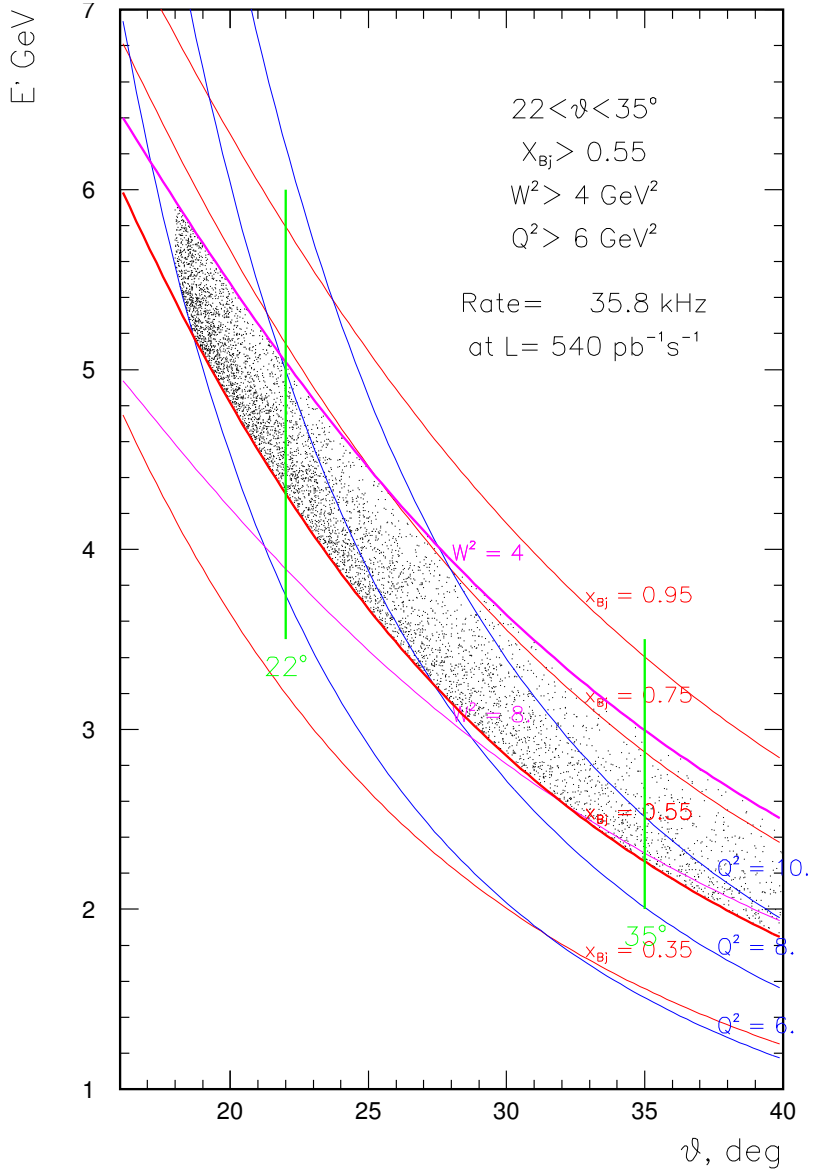


Motivation: CSV, d/u, high twists

$A \approx 10^{-4} \cdot Q^2 \sim 0.7 \cdot 10^{-3}$



DIS rates



Motivation: CSV, d/u, high twists

$A \approx 10^{-4} \cdot Q^2 \sim 0.7 \cdot 10^{-3}$

Kinematics and Rates

- $22^\circ < \theta < 35^\circ$, $W^2 > 4$
- 50 μA, 40 cm LH $0.54 \mathrm{fb}^{-1}\mathrm{s}^{-1}$
- Rate 35kHz $X > 0.55$
- Rate 9.3kHz $X > 0.65$

acceptance = 100%, eff=50%

- 1% stat $\Rightarrow 2 \cdot 10^{10}$ events
- $X > 0.55$: 13 days
- $X > 0.65$: 40 days

Requirements

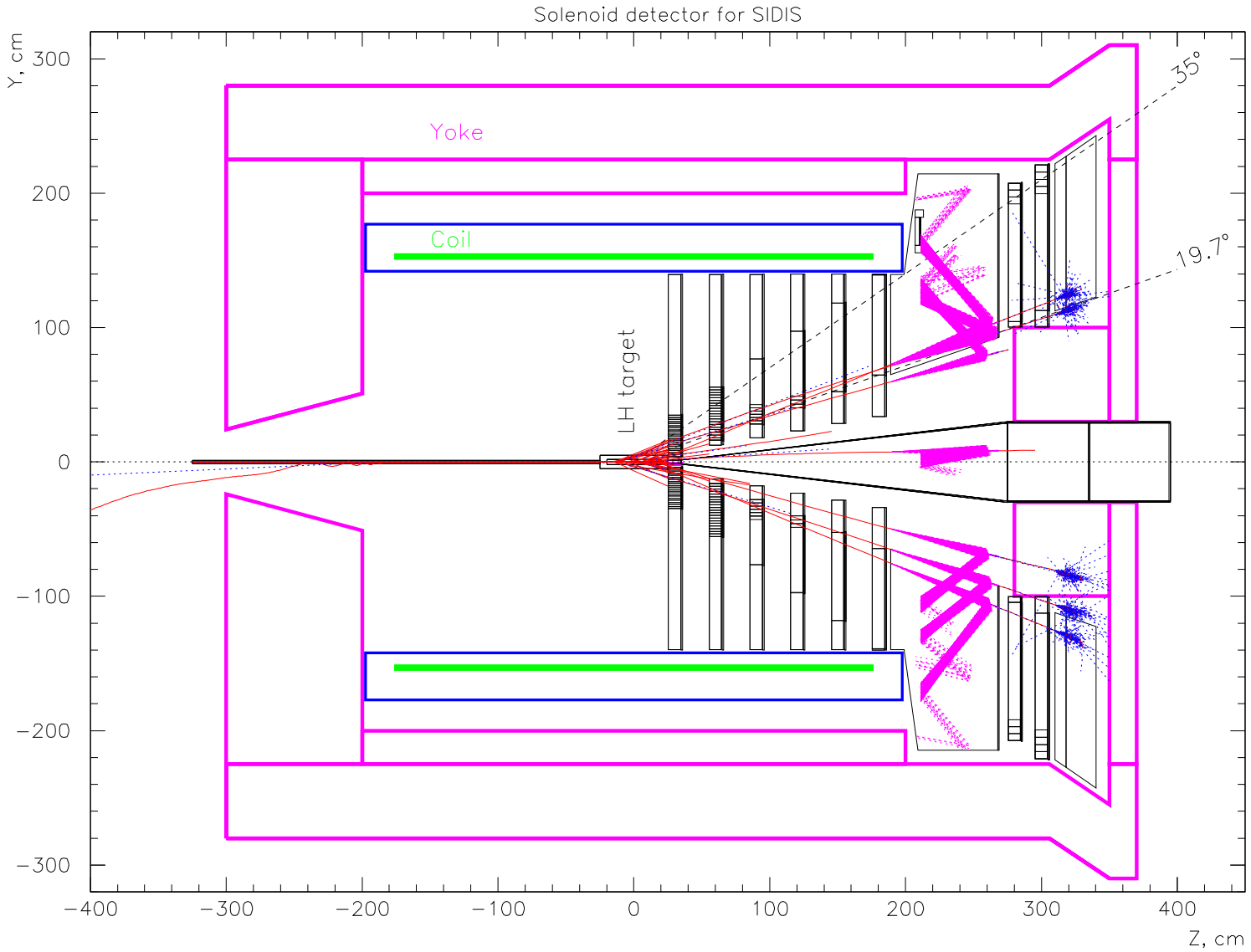
Acceptance

- Working at $\mathcal{L} \sim 0.54\mathrm{fb}^{-1}\mathrm{s}^{-1}$
- $E' > 1.5$ GeV to remove low energy e^-, π^-
- $E' < \infty$ no line of sight, to remove γ (??)
- $\sigma E'/E' < 2\%$ energy resolution
- $\Delta\Omega > 0.3 str$ solid angle
- PID $e/\pi \sim 10^5$
- Trigger rate <20 kHz/DAQ

Is it possible?

- If it were easy - would have been done somewhere
- New detectors with high rate capabilities may help

Spectrometer



Conclusion

PV Møller

- New precision tests of the Standard Model
- Complement to the LHC

PV DIS

- New studies of the hadron structure
- Contribution to the SM