Weak Neutral Current Studies with Positrons

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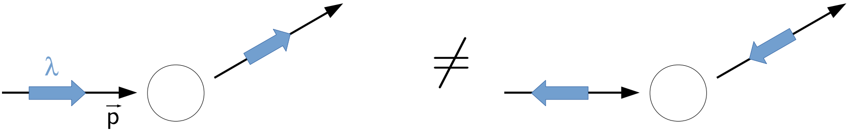
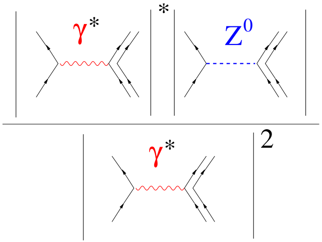
Parity Violation in Electron Scattering



- Weak force couplings provide unique mode to study nature
- Charged current (e.g. β decay) maximally violating, but neutral current mixed by weak mixing angle $\sin^2\theta_{\mathrm{W}}$
- Arises in low Q^2 e^- scattering as interference between γ and Z
- Basic object of study is PV asymmetry

$$\frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = A_{\mathrm{PV}} =$$



$$\sim \frac{G_{\mathrm{F}} Q^2}{\sqrt{2}\pi\alpha} \times \ldots$$

$$= 10^{-6} \sim 10^{-3}$$

Neutral Current Structure and Positrons

- Standard e^- parity violating asymmetry typically has two terms

$$A = \frac{R-L}{R+L} \sim \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[D_{\rm f}(\theta) g_A^e g_V^{\rm target} + D_{\rm b}(\theta) g_V^e g_A^{\rm target}\right]$$

$$\begin{aligned} g_A &= T_3 \qquad g_V = T_3 - 2Q\sin^2\theta_{\rm W} \\ T_3 &\sim \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L, \begin{pmatrix} u \\ d \end{pmatrix}_L, \dots \end{aligned}$$

- Second term is typically harder to get to kinematically
  - Requires kinematic separation
  - g_V^e is ~ 0.1, g_V^q larger
- Axial terms under C effectively $g_A \rightarrow -g_A$

Neutral Current Structure and Positrons (II)

- $e^+(R/L) - e^-(L/R)$ asymmetry offers unique interesting combination

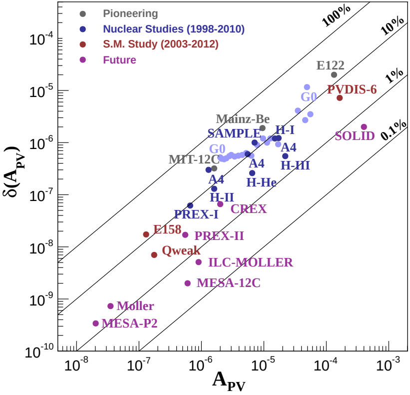
$$\Delta = (\pm g_V^e + g_A^e) G_A^{\mathrm{target}}(x, Q^2) \times \ldots$$

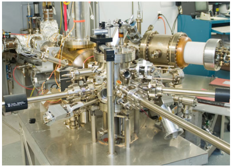
- axial-axial coupling unique and not suppressed by $1 - 4\sin^2\theta_W$!
- Don't actually need spin for separation - relative intensity control must be much better than asymmetry
- Axial term of targets is has interesting physics opportunities
    - DIS - C_{3q} couplings
    - $q - \bar{q}$ pdfs
    - *ep* - Direct access to axial form factor
- Other opportunities
    - Sign flip in EM higher order effects
    - s-channel studies

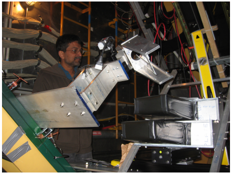
Parity Violation at JLab

- Parity experiments are high current - going to assume 6 μA
- Requires exquisite control of systematics
  - Rapid flipping of states!
  - Beam properties at injector
  - High precision polarimetry
  - Control and measurement of beam intensity, energy, position
- Largely going to ignore these issues

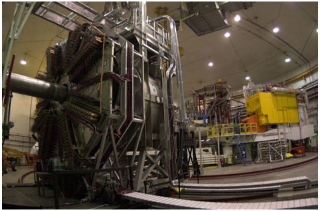
PVeS Experiment Summary

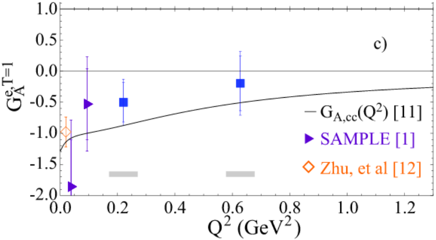






Elastic ep





$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\left[\frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z + 2g_V^e \epsilon' G_M^\gamma G_A^Z}{\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}\right]$$

$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}; \ \epsilon' = \sqrt{\tau(1+\tau)(1-\epsilon^2)}; \ \tau = Q^2/4M^2$$

$$G_E^{pZ} = (1 - 4\sin^2\theta_W) G_E^{p\gamma} - G_E^{n\gamma} - G_E^{s\gamma}$$

- G0 covered Q^2 0.1-1 GeV^2 at various
- Two backwards angle runs on LH$_2$ and QE LD$_2$
- Extracted G_A with considerable uncertainty
  Axial ~ 20% contribution to proton asymmetry

Axial FF

- Axial form factor measured in β decay only isovector component with $n \to p$ by SU(3)
- Related to spin structure and DIS

$$\Gamma_1^p = \frac{1}{2}\int_0^1 \sum e_i^2 \Delta q_i(x) dx \sim \frac{1}{12} g_A^{(3)} + \frac{1}{36} g_A^{(8)} + \frac{1}{9} g_A^{(0)} + \ldots$$

- Proton neutral current G_A includes isoscalar components (i.e. strange quarks and also radiative components)

$$G_A^p(Q^2 = 0) = g_A^{(3)} \left(1 + R_A^{T=1}\right) + \frac{3F - D}{2} R_A^{T=0} + \Delta s \left(1 + R_A^{(0)}\right)$$

$$\Delta s = g_A^{(8)} - g_A^{(0)}$$

Radiative Corrections

- Radiative corrections to Axial FF not well known, difficult to calculate (Zhu et al, PRD 62 (2000) 033008)

$R_A^{T=1}$	$R_A^{T=0}$	R_A^0
-0.258(0.34)	-0.239(0.2)	-0.551

- Typically only small suppressed component in forward experiments
- In positron measurement targeting axial FF, on the order 10%

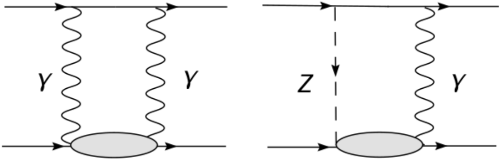
$$A^{e^+-e^-} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} g_A^e \frac{G_A^{\mathrm{Z}} G_M^{\gamma}}{\epsilon \left(G_E^{\gamma}\right)^2 + \tau \left(G_M^{\gamma}\right)^2}$$

- Totally overwhelmed by $\gamma\gamma$ terms
- 6 $\mu\mathrm{A}$, trying to get 10% measurement of G_A^{Z}, similar G0 kinematic run time ignoring 2γ...
- A_{PV} radiative corrections (e.g. $\gamma - Z$ box diagrams) V and A corrections have positron sign flip in each single measurement not enough to constrain (Afanasev, Carlson PRL 94 212301 (2005))

Radiative Corrections

- Exception for spinless targets → no axial current
- Sensitive to box of extra photon

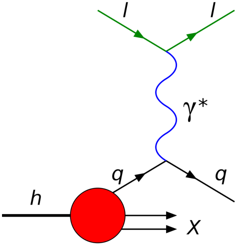
$$A_{\mathrm{extra\,photon}} = A^{e+}_{\mathrm{PV}} + A^{e-}_{\mathrm{PV}}$$



Afanasev, Carlson PRL 94 212301 (2005)

PVDIS - Deep Inelastic Scattering

- PVDIS gives access to underlying partonic structure
- Rate at high Q^2 → relatively larger statistics and asymmetry
- $A_e V_q$ (C_{1q}) *and* $V_e A_q$ (C_{2q}) effective couplings
- Excellent combination to test new physics and QCD nucleon/nuclear structure!



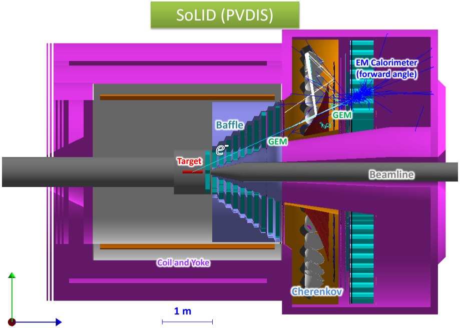
$$A_{\mathrm{PV}} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right], y = 1 - \frac{E'}{E}$$

$$a_1(x) = 2\frac{\sum C_{1q}e_q(q+\bar{q})}{\sum e_q^2(q+\bar{q})}, a_3(x) = 2\frac{\sum C_{2q}e_q(q-\bar{q})}{\sum e_q^2(q+\bar{q})}$$

$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W = -0.19 \qquad C_{2u} = -\tfrac{1}{2} + 2\sin^2\theta_W = -0.03$$

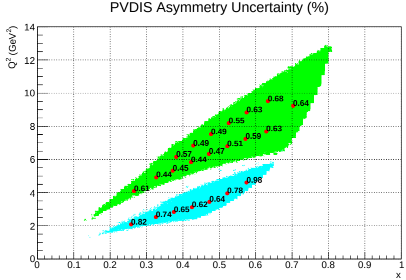
$$C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W = 0.34 \qquad C_{2d} = \tfrac{1}{2} - 2\sin^2\theta_W = 0.03$$

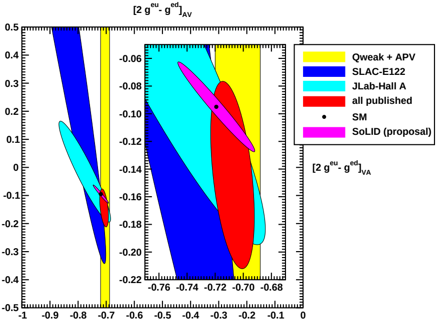
SoLID - Next Generation 12 GeV PVDIS

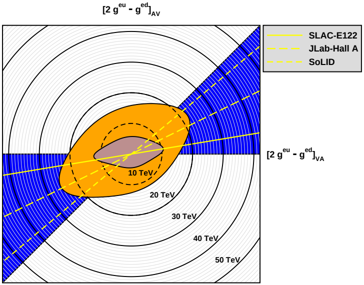


- New large installation project, over 250 international collaborators!
- Broad experimental including PVDIS, SIDIS, J/ψ, and more!
- $Q^2 \sim 2 - 8\ \mathrm{GeV}^2$, $x = 0.2 - 1$, $dA_{\mathrm{PV}}/A < 1\%$
- Based around CLEO2 magnet - now at JLab

SoLID - PVDIS SM and Nucleon Properties





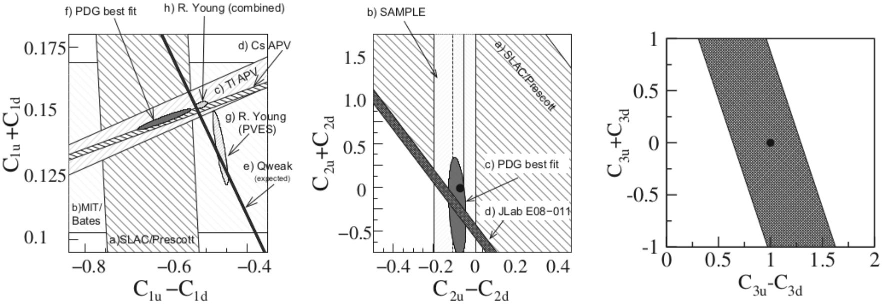


- 60 μA on 40 cm LH_2 or LD_2 target
- Errors for 120 days 11 GeV LD_2 give sub 1% in many bins
- Constraints on $\Lambda \sim$ 10-20 TeV

SoLID - C_{3q}

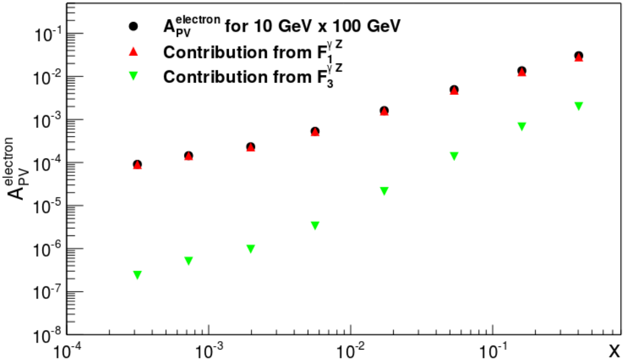
Axial-Axial in DIS has effective couplings $C_{3q} = \pm\frac{1}{2}$

$$A^{e^+(R/L)-e^-(L/R)} = \frac{G_F Q^2}{4\sqrt{2}\alpha\pi} \frac{1-(1-y)^2}{1+(1-y)^2} \frac{\sum (C_{2q} \pm C_{3q})\, e_q(q-\bar{q})}{\sum e_q^2 (q+\bar{q})}$$



- Only measured once at CERN with μ^+ and μ^- on C to ∼25% level
- To get few % measurement of $2C_{3u} - C_{3d}$ on LD$_2$, 30 days 6 μA with SoLID
- Asymmetries on the order of 100 s ppm - beam quality systematics are less stringent

EIC - Additional sea quark information



Zhao, Deshpande, Huang, Kumar, SPR EPJ A (2017) 53: 55

- F_3 is $q - \bar{q}$ PDFs → valence/sea quark info
- Also has analogous polarized nucleus version
- Complementary to charge current processes which is flavor changing
- Also previous studied at HERA

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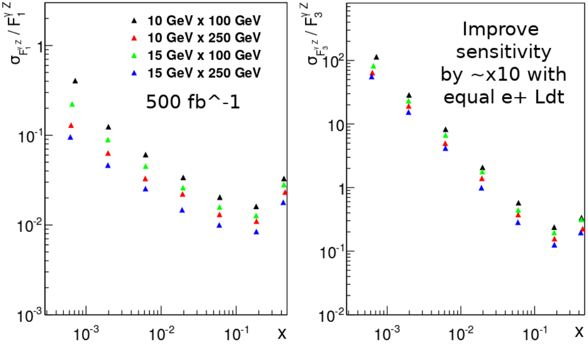

Improve sensitivity by ~x10 with equal e+ Ldt

Zhao, Deshpande, Huang, Kumar, SPR EPJ A (2017) 53: 55

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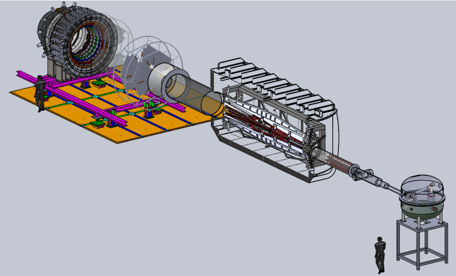
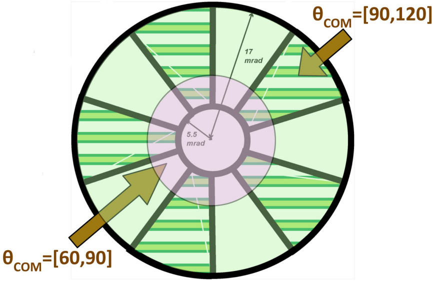
MOLLER → BHABHA?





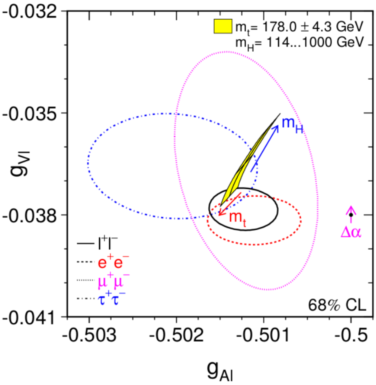
- $\sin^2\theta_{\mathrm{W}}$ to new world leading precision
- 11 GeV beam on 150 cm LH_2 target with accepted $\theta = 6 - 17$ mrad
- $A_{\mathrm{PV}} = 35$ *ppb* to 2.1%

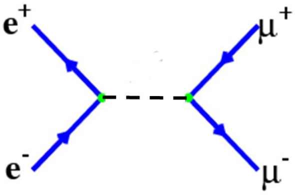
$$A_{ee} = m_e E \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta_{\mathrm{CoM}}}{(3+\cos^2\theta_{\mathrm{CoM}})^2} \left(1 - 4\sin^2\theta_W\right)$$

- Symmetric in electrons - already have access to product $g_A^e g_V^e$ so probably not a lot interesting

$e^+e^- \rightarrow f\bar{f}$?

Other couplings to fermions not as well measured!





$$A_{\mathrm{LRFB}} \sim \frac{g_V/g_A}{1+(g_V/g_A)^2}$$

- Interesting for proton radius puzzle? (maybe in loops?)
- Need $4m_\mu^2 < s = 2m_eE \sim 43$ GeV e^+ to do this on fixed target...
- Statistics for colliders off Z resonance too challenging

$e^+e^- \to f\bar{f}$?

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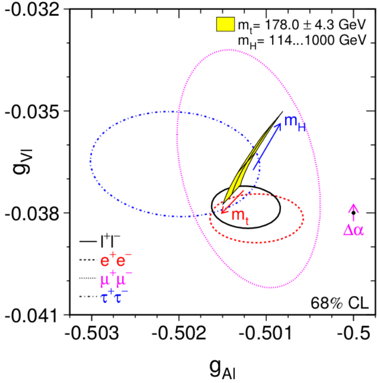

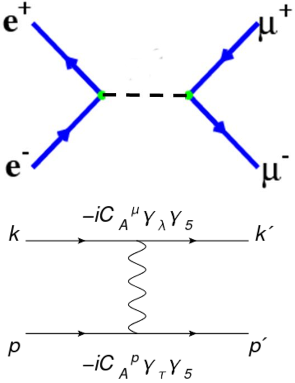

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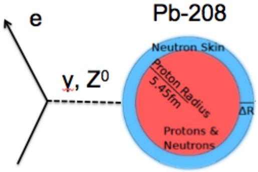
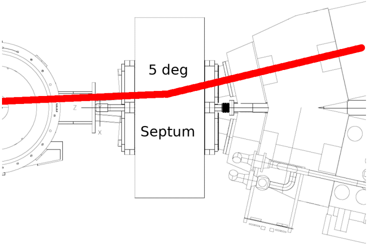
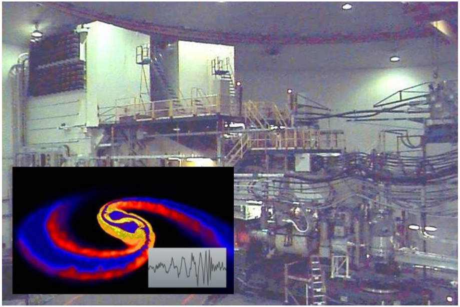
PREX and CREX - Nuclear Neutron Skin Measurements



$Q^p_{\mathrm{weak}} \sim 0.1$ $Q^n_{\mathrm{weak}} \sim -1$



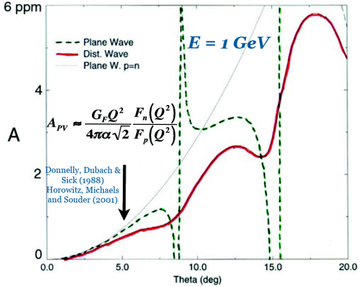
- *Z* primarily couples to neutron distributions - otherwise elastic FF measurement
- Neutron skin $\equiv \sqrt{\langle R_n^2 \rangle} - \sqrt{\langle R_p^2 \rangle}$
- PREX-I completed in 2010 (1.1 GeV, 5°)
- Confirmed existence of ^{208}Pb skin at 95% CL measuring 0.7 ppm asymmetry

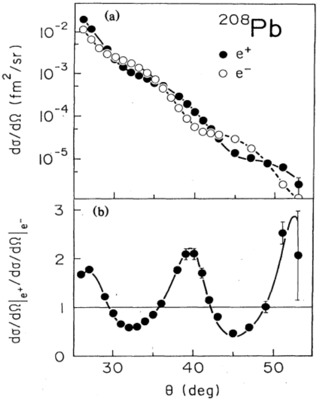


- S. Abrahamyan *et al.* Phys. Rev. Lett. 108, 112502 (2012) 213 citations!

positron PREX

- Coulomb corrections critical!
- electron minima show up at smaller q than positron
- Effect is very small!





Breton et al, PRL 66 (1991) 572

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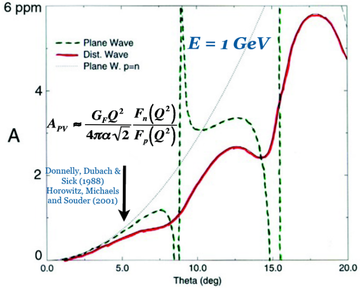
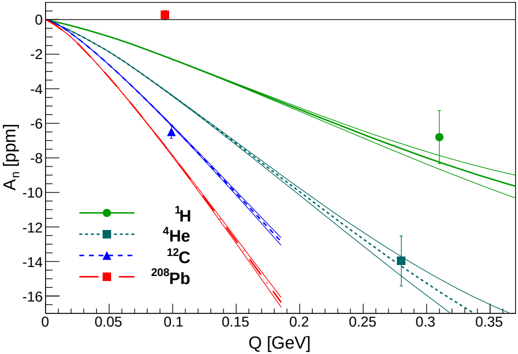


Special thanks to C. Horowitz

Not Neutral Current...

- Transverse spin asymmetry has small $\sim 10^{-5}$ asymmetries
- Only 2γ contributions by T

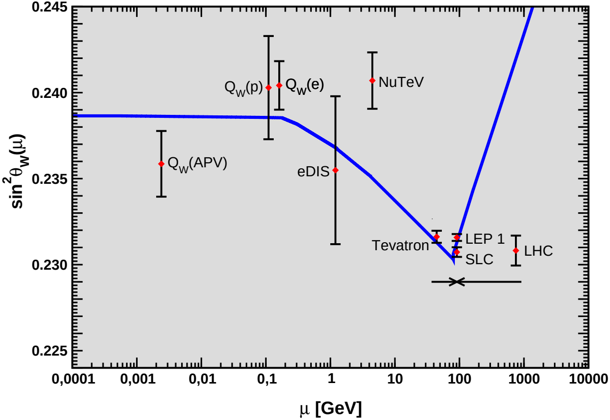


- Lead surprisingly small
- Calculations are dispersive only - Coulomb not included
- Positron would give extra information - few days of 6 μA data ?

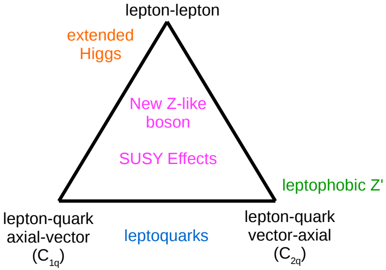
Summary

- Neutral Currents with e^- and e^+ give access to axial-axial couplings
- Axial properties of targets are often suppressed for JLab kinematics and are more difficult to measure but have interesting unique physics
- Low positron current and worse beam currents make the feasibility of such studies very challenging
- DIS with SoLID could constrain C_{3q} couplings and EIC could offer unique channel for sea quarks

BACKUP


sin$^2\theta_W(\mu)$
0.245
0.240
0.235
0.230
0.225
Q_W(p)
Q_W(e)
NuTeV
Q_W(APV)
eDIS
Tevatron
LEP 1
SLC
LHC
0,0001
0,001
0,01
0,1
1
10
100
1000
10000
μ [GeV]

Access to Beyond the Standard Model



lepton-lepton

extended Higgs

New Z-like boson

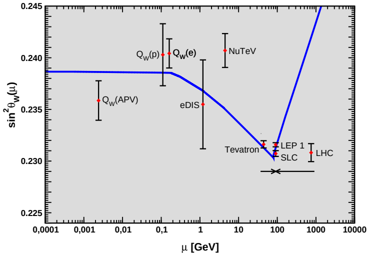
SUSY Effects

leptophobic Z'

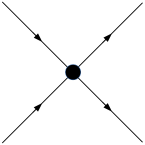
lepton-quark axial-vector (C_{1q})

leptoquarks

lepton-quark vector-axial (C_{2q})



- Variety of experiments have unique and complementary sensitivity to new physics and complementary systematics
- Search for differences in $\sin^2\theta_W$
- Probe new large energy scale Λ through interference contact interactions
- Complementary to searches at high energy colliders



$$\sim \frac{g^2}{\Lambda^2}$$

Few percent sensitivity

↓

several TeV level probe