Electroweak Physics in Electron Scattering: from Low to High Energies

UNAM, April 3, 2019

High Energy Physics Seminar

The Physics Case of the Weak Charge of Carbon-12

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Electron proton scattering at low and high momentum transfer, Q^2

Goals:

- ➜ High-precision measurements of the nucleon structure
- ➜ Search for new physics
- ➜ Electroweak physics:

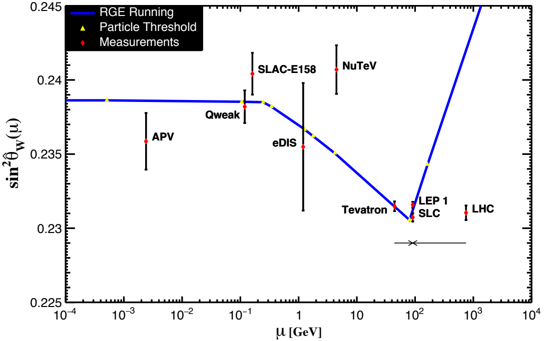
  Test of the standard model, and after LHC discoveries

  Test of the standard model extended with new physics
- ➜ Key parameter of the standard model: $\sin^2\theta_w$

This talk:

- ➜ The MESA project at Mainz University:
  low-energy elastic *ep* scattering arXiv:1802.04759
- ➜ Precision measurements of electroweak couplings
  at high energies: HERA, LHeC arXiv:1806.01176

The Running Weak Mixing Angle: Present Measurements of $\sin^2\hat\theta_W$ ($\overline{MS}$)



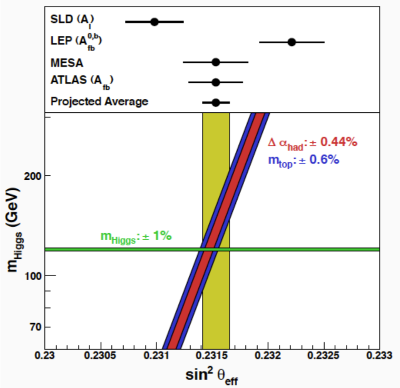
PDG 2018

- $Q_W(APV)$: atomic parity violation (Cs)
- $Q_W(p)$: Q_{Weak}
- $Q_W(e)$: Moller scattering at SLAC E158
- NuTeV: Neutrino scattering (re-analysis needed)

Z-pole measurements:

- LEP1 and SLC
- Tevatron
- LHC: CMS and ATLAS

At low energy scale, $Q^2 \to 0$: the weak charge Q_W
at high energy scale: effective Z-fermion couplings



Combination of precision measurements at the Z-pole
➜ M_{Higgs} - $\sin^2\hat{\theta}_W(\mu)$ SM relation (red-blue band)

Precision measurement of $\sin^2\hat{\theta}_W(\mu)$ has provided indirect evidence for the allowed range of M_{Higgs}

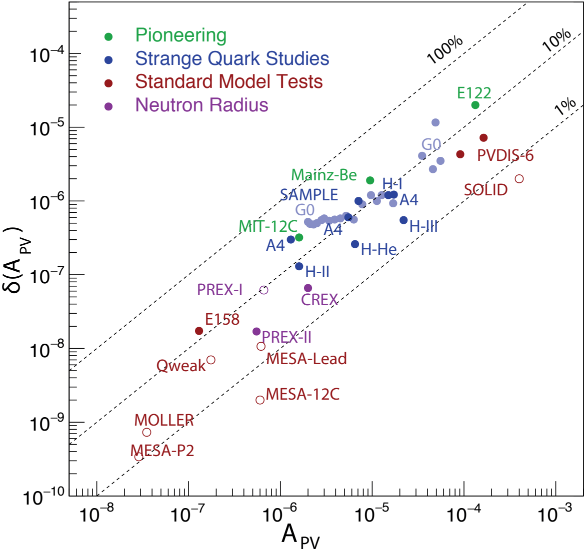
Combination of measurements provide strong tests of the SM . . .
. . . and maybe evidence for new physics

Elastic Electron Scattering: P2@MESA

- MESA =
  Mainz Energy-recovering Superconducting Accelerator
  A small superconducting accelerator for particle and nuclear physics
- Funded by PRISMA - Cluster of Excellence and
  Collaborative Research Center 1044

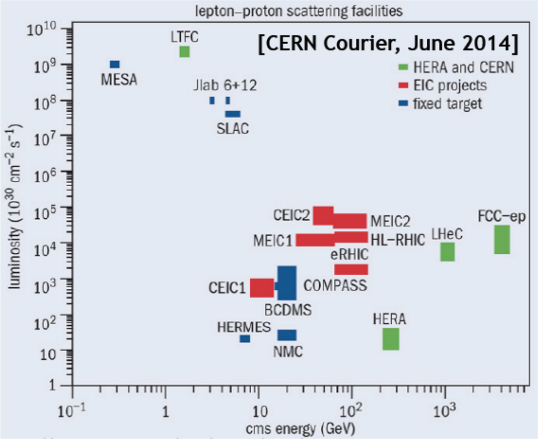
  German Science Foundation (DFG)
- P2 (Project Precision 2):
  Parity-violating electron proton scattering
- Other Projects: Search for a dark photon,
  Nuclear physics program
- Commissioning planned for 2023

Parity-Violating Electron Scattering: History



Past experiments: full points, future experiments: open circles

LHeC / FCC-he Context

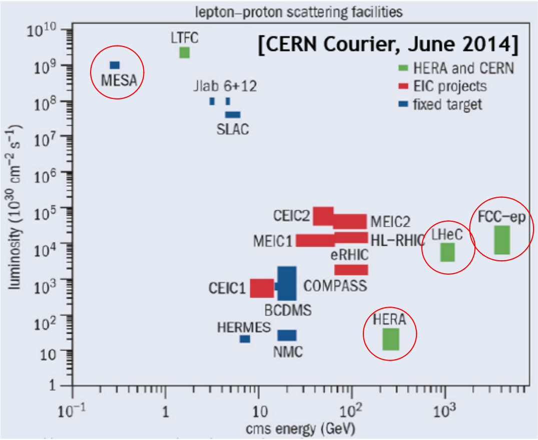


P. Newman

LHeC / FCC-he Context

(10,000 h)
data taking ➜

$\int \mathcal{L}dt \simeq 8.6$ ab^{-1}



P. Newman

Measure the (tiny) difference between cross sections for electrons with positive and negative helicity to filter out the weak interaction

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\Big(Q_W(\mathcal{N}) - F(Q^2)\Big)$$

$$Q_W(\mathcal{N}) = -2[(2Z+N)C_{1u} + (Z+2N)C_{1d}]$$

Weak charge of the proton:

$$Q_W(p) = -2[2C_{1u} + C_{1d}] = 1 - 4\sin^2\theta_W$$

$$\frac{\Delta\sin^2\theta_W}{\sin^2\theta_W} = \frac{1-4\sin^2\theta_W}{4\sin^2\theta_W}\,\frac{\Delta Q_W(p)}{Q_W(p)}$$

1.5 % precision for $Q_W(p)$ corresponds to 0.13 % precision for $\sin^2\theta_W$

Measurement errors from: statistics, polarization ($A_{exp} = P_e\, A_{LR}$), systematic effects and required hadronic phyiscs: form factors

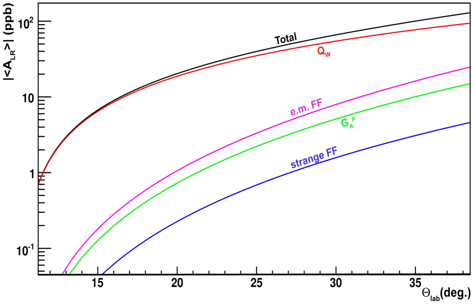
$$F(Q^2) = F_{\text{EMFF}}(Q^2) + F_{\text{Axial}}(Q^2) + F_{\text{Strangeness}}(Q^2)$$

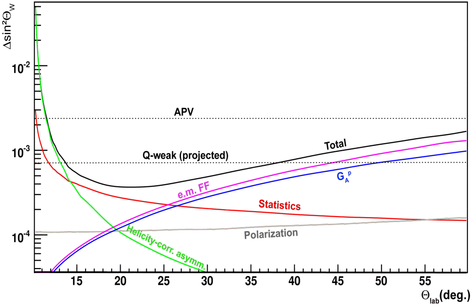
$$A_{LR} = A_{\text{Q}_{\text{weak}}} + A_{\text{EMFF}} + A_{\text{Axial}} + A_{\text{Strangeness}}$$

$$\begin{aligned}
F_{\text{EMFF}}(Q^2) &= -\frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\,, \\
F_{\text{Axial}}(Q^2) &= -\frac{(1 - 4\sin^2\theta_W)\sqrt{1-\epsilon^2}\sqrt{\tau(1+\tau)}\,G_M^p G_A^p}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\,, \\
F_{\text{Strangeness}}(Q^2) &= -\frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p G_E^{ud} + \tau G_M^p G_M^{ud}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\,,
\end{aligned}$$

$$\epsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}\,, \qquad \tau = Q^2/4m_p^2$$

Contributions to the PV Asymmetry and Expected Error





$E_{beam} = 200\,\mathrm{MeV}$

➜ Optimal measurement for $E = 155$ MeV, $\theta_e = 35^\circ \pm 10^\circ$

$\langle Q \rangle = 0.077$ GeV

SM prediction: $A_{LR} = -4.0 \times 10^{-8}$, precision goal: 1.4 %

$\Delta \sin^2 \theta_w = \pm 0.00037$, i.e. 0.15 %

Polarization asymmetry including higher-order corrections:

$$A_{LR} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N})(1+\delta_1) - \widetilde{F}(Q^2)\right)$$

$$Q_W(\mathcal{N})(1+\delta_1) = (\rho + \Delta_e)(1 - 4\,\kappa \sin^2\hat{\theta}_W(0) + \Delta_{e'}) + \delta_{\rm Box}$$

Universal corrections: ρ and κ from loop diagrams: $\rho = 1 + \Delta\rho$, $\kappa = 1 + \Delta\kappa$

$\delta_{\rm Box}$: *WW*, *ZZ* and γZ box graph contributions

Δ_e, $\Delta_{e'}$: non-universal vertex and external leg corrections

Scale-dependent $\overline{\rm MS}$ weak mixing angle ($\mu \to Q$) ➜

$$\sin^2\hat{\theta}_W(\mu^2) = \kappa(\mu^2)\sin^2\hat{\theta}_W(m_Z)$$

and scheme-dependent

(G_F fixed, by definition)

Overview

- Virtual corrections (loops): universal and non-universal
  Parameter relations at 1-loop, running couplings
  Scheme dependence
- QED corrections: loops and bremsstrahlung
- Box graphs: $\gamma\gamma$ and γZ (and ZZ, WW)

Under control for proton, to be worked out for ^{12}C

Electroweak Parameters at 1-Loop

In the (modified) on-shell scheme, use:

- the fine structure constant $\alpha = e^2/4\pi$,
- a boson mass, m_Z, or m_W,

  or the weak mixing angle, $s_W = \sin\theta_W$, defined by $s_W^2 = 1 - \frac{m_W^2}{m_Z^2}$
- the Fermi constant G_F (from muon decay).

Parameter relations including universal higher-order corrections:

$$\begin{array}{rcl} \alpha & \longrightarrow & \dfrac{\alpha}{1-\Delta\alpha} \\ G_{NC} = G_F & \longrightarrow & G_{NC} = \rho G_F = (1+\epsilon) G_F \\ m_W^2 = \dfrac{\pi}{\sqrt{2}G_F}\dfrac{\alpha}{\sin^2\theta_0} & \longrightarrow & m_W^2 = \dfrac{\pi}{\sqrt{2}G_F}\dfrac{\alpha}{1-\Delta\alpha}\dfrac{1}{(1+\Delta s)\sin^2\theta_0} \end{array}$$

Then:

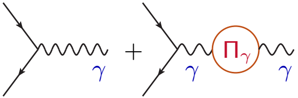
$$s_W^2 = (1+\Delta)\sin^2\theta_0 \quad \text{with} \quad \Delta = \Delta s - \frac{c_W^2}{s_W^2}\epsilon$$

$$m_W^2 = \frac{\pi}{\sqrt{2}G_F}\frac{\alpha}{s_W^2(1-\Delta r)} \quad \text{with} \quad \Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\epsilon$$

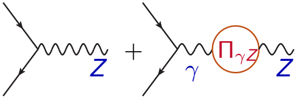
Including quantum loop corrections, universal contributions:

Self energy diagrams of the exchanged boson (γ, Z, W)

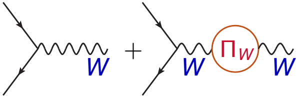
Schematically:



➜ $\alpha \to \alpha + \Delta\alpha = \alpha(Q^2)$

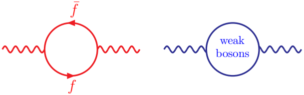


➜ $\sin^2\theta_W \to \sin^2\theta_{eff}(Q^2)$ ➜ Δs



➜ $G_F \to G_F(1 - \Delta r + \ldots)$

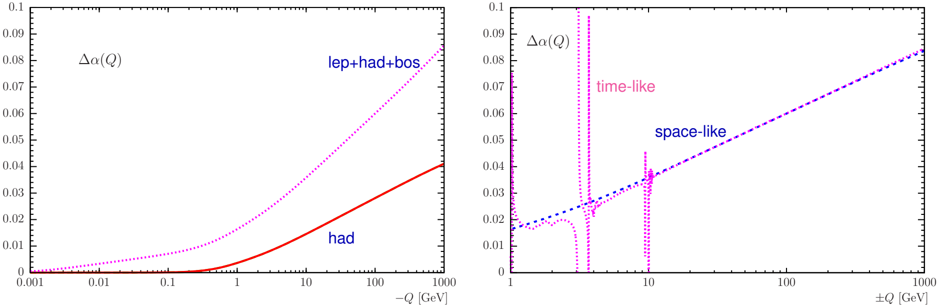
- Vacuum polarization:



$\propto \log \frac{Q^2}{m_f^2} \to O(10\,\%)$ small, $O(1\,\%)$

- Photon self energy = vacuum polarization, absorbed and resummed in the running fine structure constant:

$$\alpha \to \alpha(Q^2) = \frac{\alpha}{1 - \Pi_\gamma(Q^2)}$$



Jegerlehner: hadr5n12

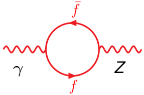
- One-loop corrections to the muon decay: Δr

$$G_F = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W m_W^2}\frac{1}{(1-\Delta r)} \quad \text{with} \quad \Delta r = \Delta r(\alpha, m_W, \sin\theta_W, m_{top}, M_{Higgs}, \ldots)$$

- Z-boson self energy: a small correction if written in terms of:

$$\frac{\alpha}{\sin\theta_W^2\cos\theta_W^2} \to \frac{m_Z^2 G_F\sqrt{2}}{\pi}\frac{1-\Delta r}{1-\Pi_Z(Q^2)}$$

Effective Couplings: Scale-Dependent $\sin^2\theta_W$

- Photon-Z mixing 

➜ $\Pi_{\gamma Z}(Q^2)$

absorbed into effective, running, scale-dependent weak mixing angle

Definitions of the weak mixing angle:

- On-shell definition: $\cos\theta_W = \frac{m_W}{m_Z}$ ($\rightarrow$ large contribution from m_{top}, e.g. in Δr)
- $\sin^2\theta_{\text{eff}}(Q^2)$ absorbs $\Pi_{\gamma Z}(Q^2)$, but not only

➜ different prescriptions by Jegerlehner, Czarnecki&Marciano, Ferroglia&Ossola&Sirlin, ...

- $\overline{\text{MS}}$ scheme: $\sin\hat{\theta}_W(\mu)$ (used in the PDG plot)
  less sensitive to m_{top}, suited for comparisons with extensions of the SM
  resum higher orders by RGE
- Known prescriptions with very small uncertainties,
  estimated below 10^{-4} (Erler, Ferro-Hernández, JHEP18)

Scheme Dependence of $\sin^2\hat\theta_W$

➜ Relation

$$\sin^2\hat\theta_W(\mu) = \left(1 + \frac{\rho_t}{\tan^2\theta_W} + \ldots\right)\sin^2\theta_W$$

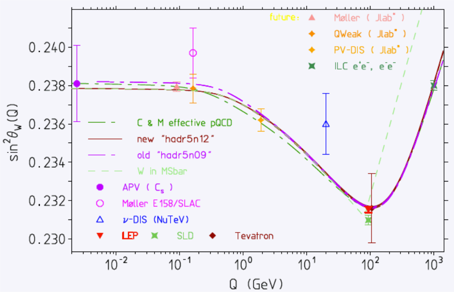
with $\rho_t = 3G_F m_{top}^2/8\sqrt{2}\pi^2 = 0.00939\,(m_{top}/173\,\mathrm{GeV})^2$

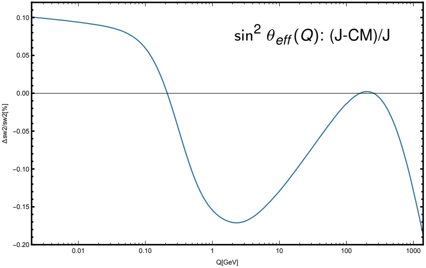
➜ $\sin^2\theta_{\mathrm{eff}}(Q^2)$ known at 2-loop order: Awramik, Czakon, Freitas, 2006

- Scheme dependence, at fixed order compensated by $\delta_{non-universal}$:
  Match definition of $\sin^2\hat\theta_W(Q)$ with the complete 1-loop corrections !
- Hadronic contributions ?

$\sin^2\hat\theta_W$: Hadronic Contributions

Definition of $\sin^2\theta_W(Q)$: absorbing $\Pi_{\gamma Z}$ and part of vertex+box corrections





Czarnecki-Marciano 1996-00

Jegerlehner 2010-12

$\sin^2\theta_{eff}(Q)$ for Moller

- J: 'old' and 'new' `hadr5`, hadronic VP from data (different $SU(3)$ flavor splitting)
- CM: hadronic part with $m_{q,eff}$
- different prescriptions for the hadronic part: 1 - 2 permille

➜ need matching

$\Pi^{\gamma\gamma}$ and $\Pi^{\gamma Z}$ are sensitive to low-scale hadronic physics

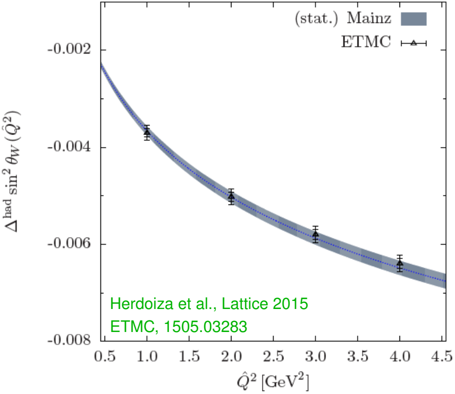
➜ Use dispersion relation, e.g.

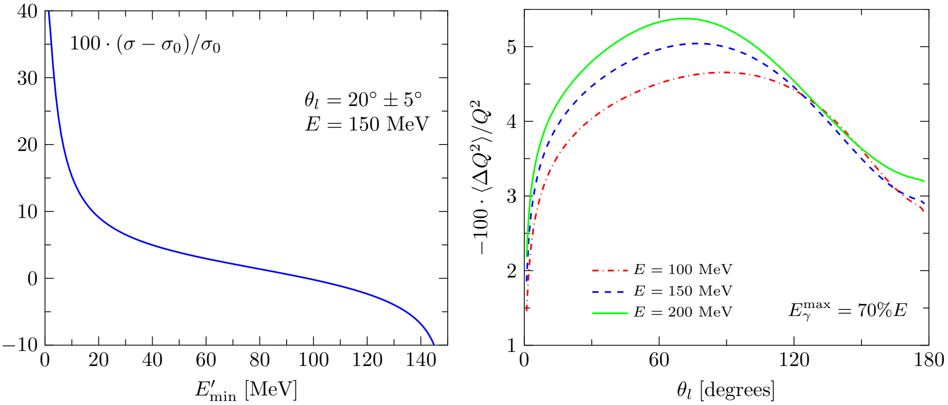
$$\Delta\alpha(q^2) = \frac{q^2}{12\pi^2} \int_{4m_\pi^2}^{\infty} \frac{ds}{s} \frac{R^{\gamma\gamma}(s)}{s - q^2} \quad \text{with} \quad R^{\gamma\gamma}(s) = \frac{\sigma_{tot}(e^+e^- \to \gamma^* \to hadrons)}{4\pi\alpha^2/3s}$$

➜ Similar approach for $\Pi^{\gamma Z}$ requires data for $\sigma_{tot}(\nu\bar{\nu} \to hadrons)$ or use flavor-separated e^+e^- data, isospin symmetry and OZI-rule

➜ Use lattice techniques

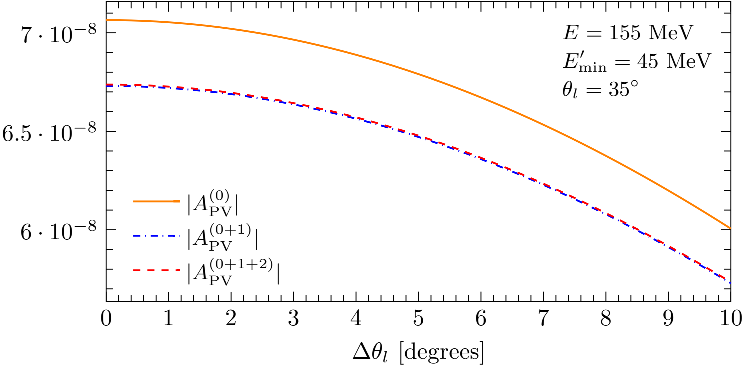
First results available, errors start to be competitive





- Straightforward to calculate, but need flexible MC simulation
- QED does not violate parity symmetry,
  but real photon emission leads to a shift of Q^2

Bremsstrahlung at Order $O(\alpha^2)$: Q^2 Shift



QED corrections for the asymmetry:
Q^2 shift is a kinematic effect: 1γ radiation has it all
Very small $O(\alpha^2)$ correction R. Bucoveanu

Higher-Order Corrections: γZ Box Graphs

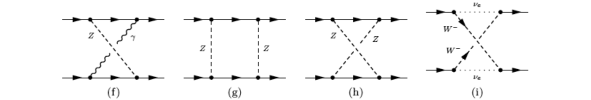
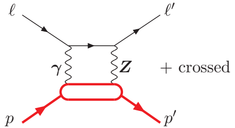


Figure from Aleksejevs et al.



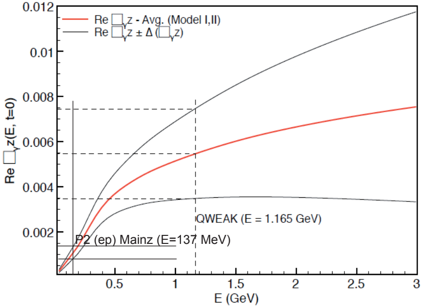
γZ box graphs

Sensitivity to hadronic physics at low Q^2 ➜ an important source of error

Status $\sim$ 5 years ago:
3 groups with independent analyses agree in size, but disagree on errors

Hall et al.; Carlson and Rislow; Gorchtein et al.

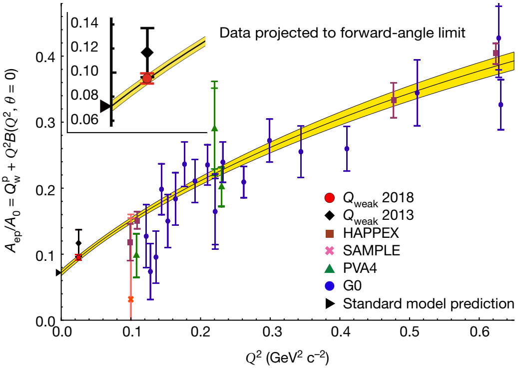
Gorchtein, Horowitz, Ramsey-Musolf



For Qweak at JLAB, $E = 1.165$ GeV: 7σ(theory) effect

Advantage at P2@MESA: low energy $E = 0.155$ GeV

$$\Delta A_{LR}^{box} / A_{LR} = \pm 0.4\,\%$$



Nature 557 (2018)

Final results from Qweak
at JLAB, $E_e = 1.165$ GeV

- Used previous data to extrapolate to $Q^2 = 0$
- $Q_W(p) = 0.0719 \pm 0.0045$ (SM: $= 0.0708 \pm 0.0003$)
- corresponds to $\sin^2\hat{\theta}_W(0) = 0.2383 \pm 0.0011$

Electron Scattering: From Low to High Energies

Low energy, elastic scattering:

$$\langle p'|J_\mu^{em}|p\rangle, \quad \langle p'|J_\mu^{NC}|p\rangle$$

➜ form factors (use isospin symmetry, angular momentum decomposition)

Large energy, momentum transfer: inelastic scattering:

$$\langle p|J_\mu^{em}J_\nu^{em}|p\rangle, \quad \langle p|J_\mu^{em}J_\nu^{NC}|p\rangle, \quad \langle p|J_\mu^{Z}J_\nu^{NC}|p\rangle$$

➜ structure functions F_1, F_2, F_3

Factorization theorem of perturbative QCD
➜ parton distribution functions (for quarks and gluons)

Neutral current at tree level, polarized $e^\pm$ scattering

$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left(Y_+\mathbf{F_2} + Y_- x\mathbf{F_3} - y^2\mathbf{F_L}\right)$$

split up: photon + Z exchange + interference:

$$\mathbf{F_2} = F_2^\gamma + \kappa_Z(-v_e \mp Pa_e)F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2Pv_e a_e)F_2^Z$$
$$x\mathbf{F_3} = +\kappa_Z(\pm a_e + Pv_e)xF_3^{\gamma Z} + \kappa_Z^2(\mp 2v_e a_e - P(v_e^2 + a_e^2))xF_3^Z$$

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + m_Z^2}\frac{1}{4\sin^2\theta_w\cos^2\theta_w}$$

split up: sum over quark types:

$$(F_2^\gamma,\ F_2^{\gamma Z},\ F_2^Z) = x\sum(Q_q^2,\ 2Q_q v_q,\ v_q^2 + a_q^2)(q + \bar{q})$$
$$x(F_3^{\gamma Z},\ F_3^Z) = 2x\sum(Q_q a_q,\ v_q a_q)(q - \bar{q})$$

$$v_f = I_f^{(3)} - 2Q_f\sin^2\theta_w, \quad a_f = I_f^{(3)} \quad (f = e, u, d, \ldots)$$

Independent SM paramters: α, m_Z, $\sin^2\theta_w$
For beyond-SM fits: v_e, a_e; v_u, a_u; v_d, a_d

Charged current at tree level

$$\frac{d^2\sigma_{CC}(e^\pm)}{dx dQ^2} = \frac{1 \pm P}{2} \frac{2\pi\alpha^2}{Q^4 x} \kappa_W^2 \left(Y_+ \mathbf{W_2^\pm} \pm Y_- x \mathbf{W_3^\pm} - y^2 \mathbf{W_L^\pm} \right)$$

with

$$\kappa_W(Q^2) = \frac{Q^2}{Q^2 + m_w^2} \frac{1}{4 \sin^2\theta_w}$$

$$\mathbf{W_2^-} = x(U + \bar{D}), \quad x\mathbf{W_3^-} = x(U - \bar{D})$$

$$\mathbf{W_2^+} = x(\bar{U} + D), \quad x\mathbf{W_3^+} = x(D - \bar{U})$$

$$U = u + c, \ \bar{U} = \bar{u} + \bar{c}, \ D = d + s, \ \bar{D} = \bar{d} + \bar{s}$$

SM paramters: α, m_W, $\sin^2\theta_w$

Parameter Relations in the Standard Model

Observe parameter relations!

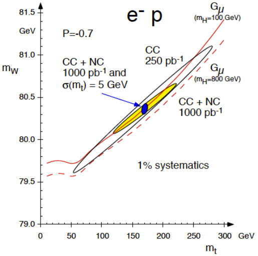
- $\cos\theta_W = m_W/m_Z$
- Muon decay constant: $G_F = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W m_W^2}$

$\rightarrow \quad \frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{1\pm P}{2}\frac{G_F{}^2}{2\pi x}\left(\frac{m_W^2}{m_W^2+Q^2}\right)^2 \sigma_{r,CC}$

and

$\rightarrow \quad \frac{d^2\sigma_{NC}}{dxdQ^2}$ using $\kappa_Z(Q^2) = Q^2\,\frac{G_F}{2\pi\alpha}\frac{m_Z^2}{Q^2+m_Z^2}$

- One-loop corrections to the muon decay: Δr



Future Physics at HERA, 1996

$$G_F = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W m_W^2}(1+\Delta r) \quad \text{with} \quad \Delta r = \Delta r(\alpha, m_W, \sin\theta_W, m_{top}, M_{Higgs}, \ldots)$$

Fits based on different parametrizations
may lead to very different results:
e.g. from H1: $\Delta M_{prop} \simeq 2$ GeV, $\Delta m_W \simeq 0.2$ GeV

Recent analysis of H1 all data (arXiv:1806.01176)

Data at $\sqrt{s} \simeq 319$ GeV, total integrated luminosity: $\simeq 450$ pb^{-1} ('93 - '07),
cover $8.5\,\mathrm{GeV}^2 < Q^2 < 50,000\,\mathrm{GeV}^2$
e^- and e^+, NC and CC, electron beam polarization up to ± 37 %

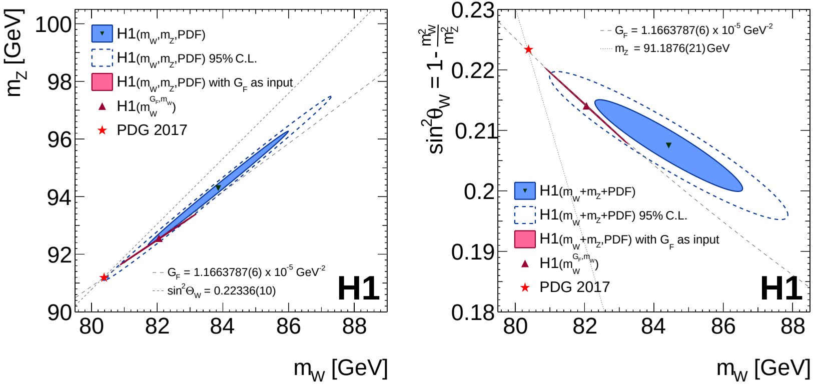
Observables: $\sigma_L^{e^-}(x, Q^2)$, $\sigma_L^{e^+}(x, Q^2)$, $\sigma_R^{e^-}(x, Q^2)$, $\sigma_R^{e^+}(x, Q^2)$,
both NC and CC

At large x and large Q^2: large asymmetries

1. SM fits:
using combinations of m_W, m_Z, G_F, s_W^2

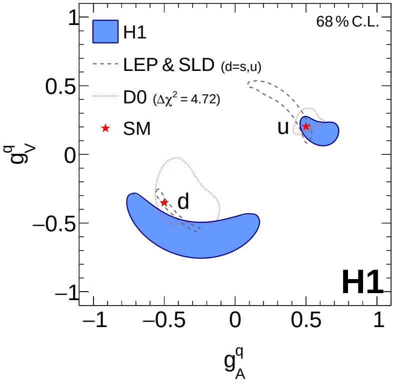
2. Extended fit scenarios:
assume free (non-SM) v and a fermion coupling constants

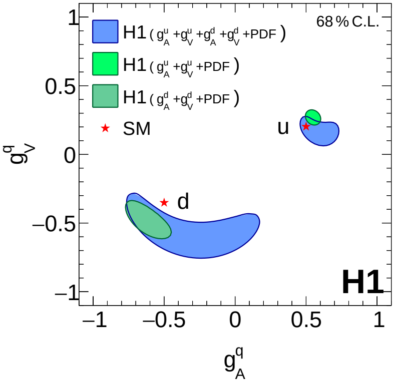
Combined EW+QCD analysis:
fit electroweak parameters and PDFs simultaneously



- Fits: PDF + (m_W, m_Z) or PDF + (m_W), etc.
- good fit quality, compatible with SM, PDFs with small uncertainties
- m_Z fixed:
  $m_W = 80.520 \pm 0.070_{stat} \pm 0.055_{sys} \pm 0.074_{PDF} = 80.520 \pm 0.115_{tot}$

H1 $g_V - g_A$–PDF Fit



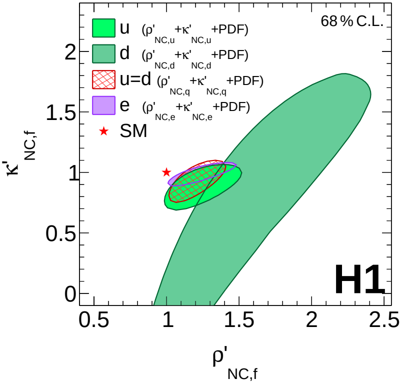


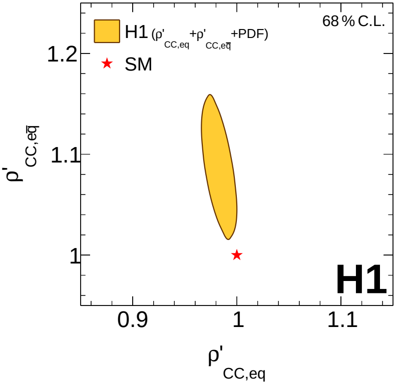
Allow free v_f and a_f fermion couplings, not fixed by the SM

- Fit: PDF + 4 couplings, large correlations
- Fit: PDF + 2 couplings, with smaller uncertainties
- Precision similar to determinations from complementary processes

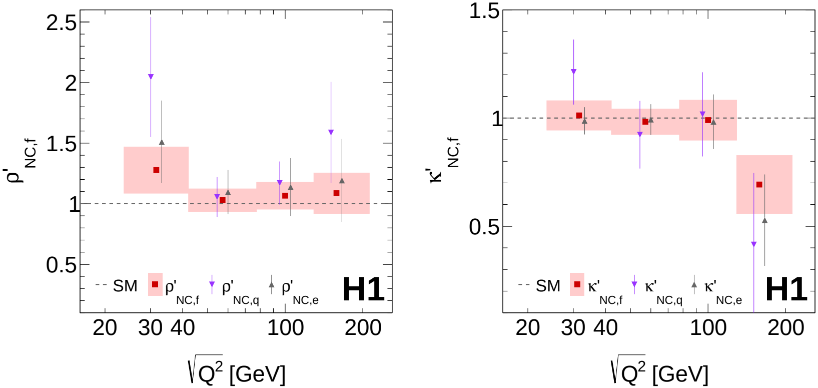
H1 $\rho-\kappa-$PDF Fit

$$v_f = \sqrt{\rho'_f}\left(I_f^{(3)} - 2Q_f\,\kappa'_f\,\sin^2\theta_w\right), \quad a_f = \sqrt{\rho'_f}\,I_f^{(3)} \quad (f = e, u, d, \ldots)$$



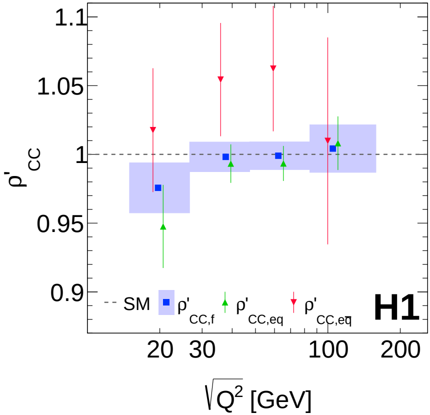


- Precision similar to LEP, SLD and D0 measurements from a single experiment



- Split into Q^2 regions with independent ρ' and κ'
- Unique measurement of scale dependent couplings in a single experiment

H1 $\rho - \kappa -$PDF Fit: testing the scale dependence, CC



- First determination for separate quark flavors ρ'_{eq} and $\rho'_{e\bar{q}}$
- Precision of up to 0.8 %

The Future of DIS: LHeC and FCC-eh

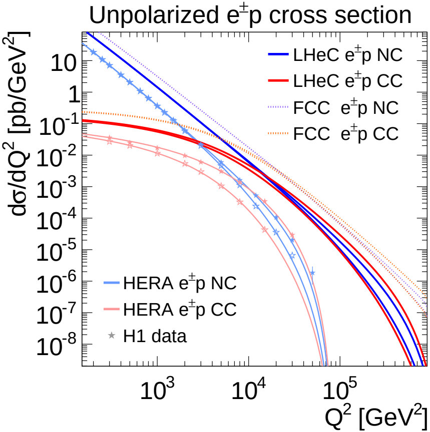
An old idea: LEP$\otimes$LHC: ep at $\sqrt{s} = 1.6$ TeV, Workshop Aachen 1990

ERL (energy revocery Linac), $E_e = 60$ GeV
combined with protons from LHC: $E_p = 7$ TeV, $\sqrt{s} = 1.3$ TeV
or with protons from FCC: $E_p = 50$ TeV, $\sqrt{s} = 3.5$ TeV

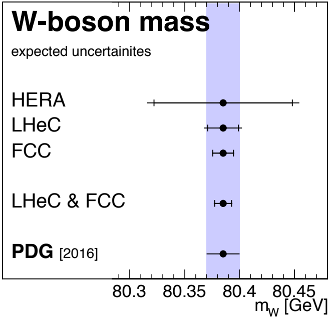
Work together with D. Britzger and M. Klein
(see, e.g. LeHC-CDR, arXiv:1206.2913, and DIS2018)

- Cross section ratios to reduce PDF errors
- Polarized electrons, LR asymmetries: sensitivity at larger Q^2,
- NC/CC ratio at lower Q^2
- Energy range 10 – 500 GeV
- Scale dependent couplings from one experiment

A text-book plot:
The unification of the electromagnetic and weak interaction at high energy



Large polarization asymmetries at large Q^2



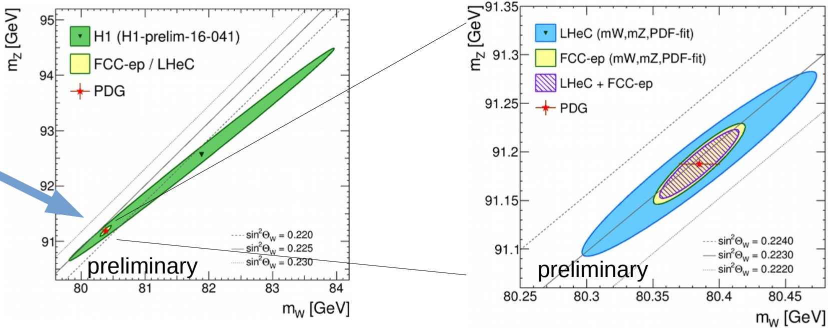
W-boson mass from NC and CC data

- HERA: $\pm 63_{exp} \pm 29_{PDF}$ MeV
- LHeC: $\pm 14_{exp} \pm 10_{PDF}$ MeV
- FCC-eh: $\pm 9_{exp} \pm 4_{PDF}$ MeV

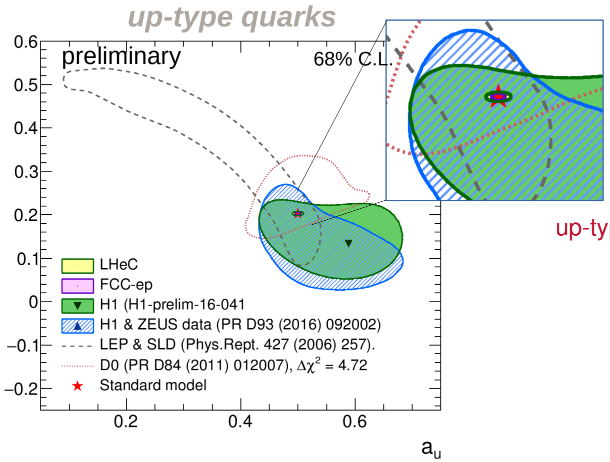
PDG 2016: ± 15 MeV

Estimate for HERA in 1987:
$\pm 80 - 100$ MeV
Blümlein, Klein

FCC-eh
LHeC

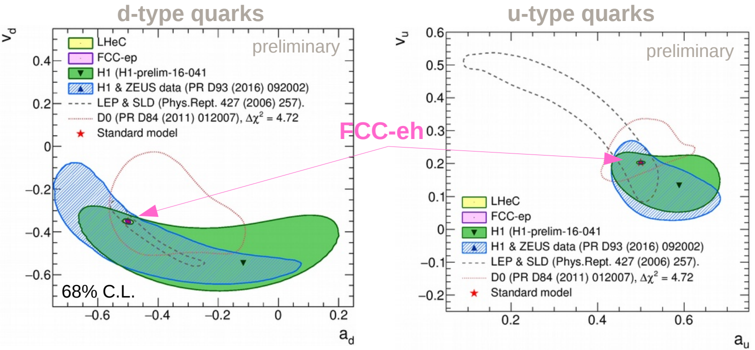

H1 (H1-prelim-16-041)
FCC-ep / LHeC
PDG
$\sin^2\Theta_W = 0.220$
$\sin^2\Theta_W = 0.225$
$\sin^2\Theta_W = 0.230$
preliminary
m_Z [GeV]
m_W [GeV]
LHeC (mW,mZ,PDF-fit)
FCC-ep (mW,mZ,PDF-fit)
LHeC + FCC-ep
PDG
$\sin^2\Theta_W = 0.2240$
$\sin^2\Theta_W = 0.2230$
$\sin^2\Theta_W = 0.2220$
preliminary
m_Z [GeV]
m_W [GeV]

Quark couplings from LHeC: u-quarks



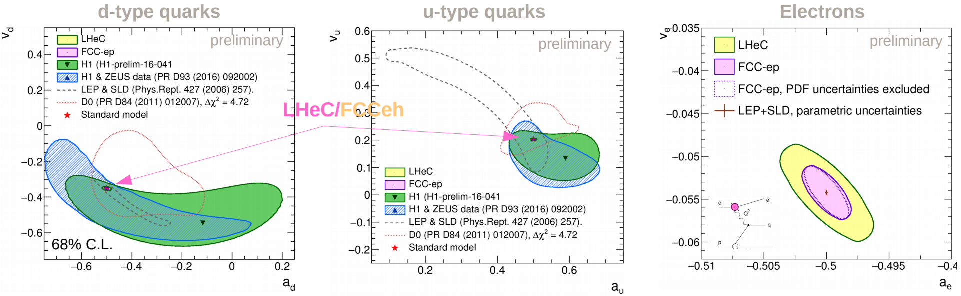
up-type quarks

Quark couplings from LHeC . . . and d-quarks



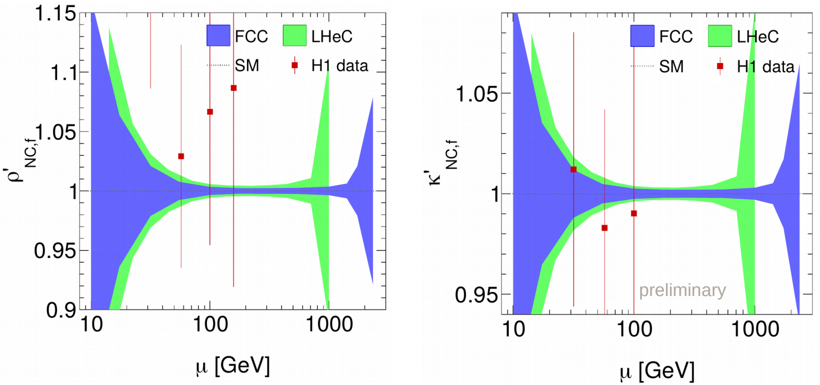
up- and down-type quarks

Fermion couplings from LHeC . . . and electrons



quark and electron couplings

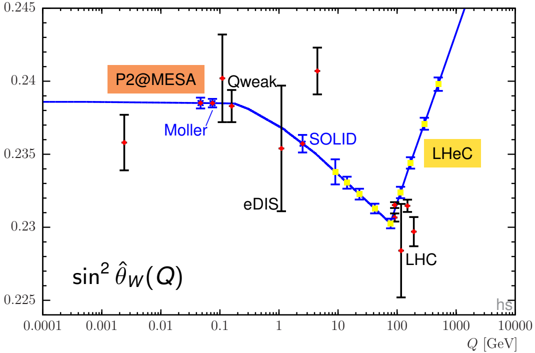
Fermion couplings from LHeC: scale dependence of ρ and κ



Beyond SM, all fermions

Can be translated into a determination of $\sin^2\theta_W$

(but still need the proper framework: higher-orders in $\overline{\mathrm{MS}}$ scheme)



Future additions to the PDG

Expected from low-energy:

- Mainz: P2@MESA
- Moller at JLAB
- SOLID at JLAB

LHeC: from σ_{NC} and σ_{CC}, polarized electrons, energy range 10 - 500 GeV

➜ 0.3 % (FCC: 0.2 %) precision for $\sin^2 \theta_W$

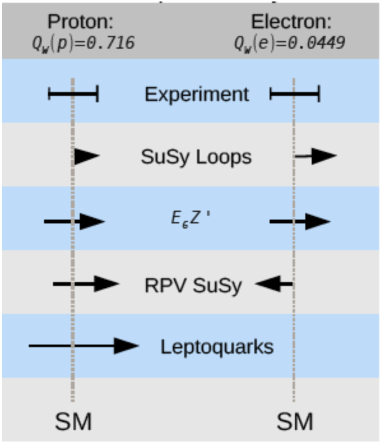
(also: future EIC?)

- Present measurements of the weak mixing angle: need improvement
- P2@MESA: a new high-precision measurement of $\sin^2\theta_w$ from parity-violating electron scattering at low energy
- The final electroweak data analysis of H1

➜ The vision: Precision measurements combined with possible future measurements: LHC, DIS at HERA, EIC, LHeC, FCC-eh will cover a wide range of energy scales

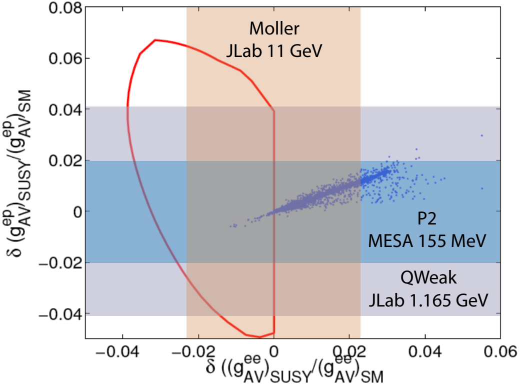
Extra Slides

Beyond the Standard Model



Characteristic shifts of Q_W predicted by extensions of the Standard Model

Complementarity between elastic *ep* and Moller scattering



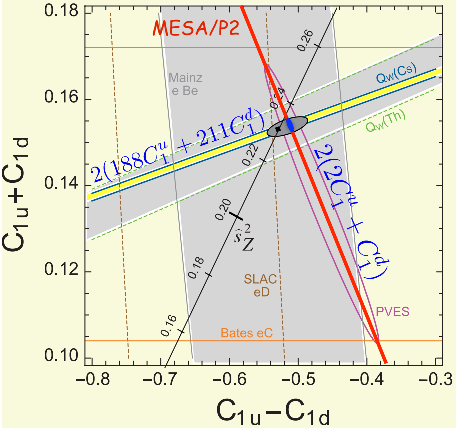
Erler, Su, 2013

Example: supersymmetric models with and without *R*-parity violation

Also precision measurements at low-energy are sensitive to TeV-scale physics

Perspective will shift after LHeC discoveries

Effective Low-Energy Couplings



Conventionally used at low-energy:
Effective 4-fermion interaction

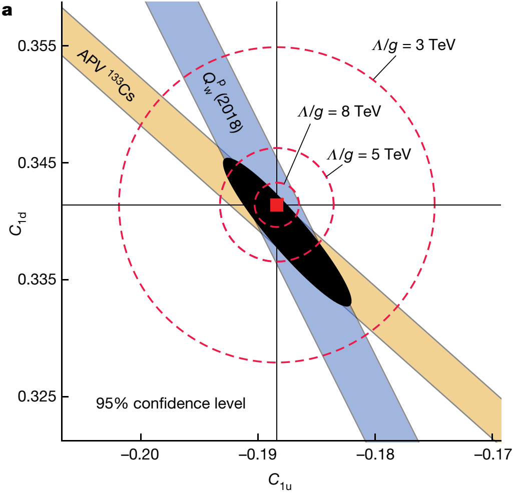
C_{1q}: $2a_e \otimes v_q$, C_{2q}: $2v_e \otimes a_q$

Low-energy experiments probe
$C_{1q} = -I_q^{(3)} + 2Q_q \sin^2\theta_W$
i.e., quark vector couplings

Parity-violating electron scattering:
PVES at JLAB and MAMI
and at MESA (red)

Atomic PV (Cs, yellow)

SM prediction (black square)

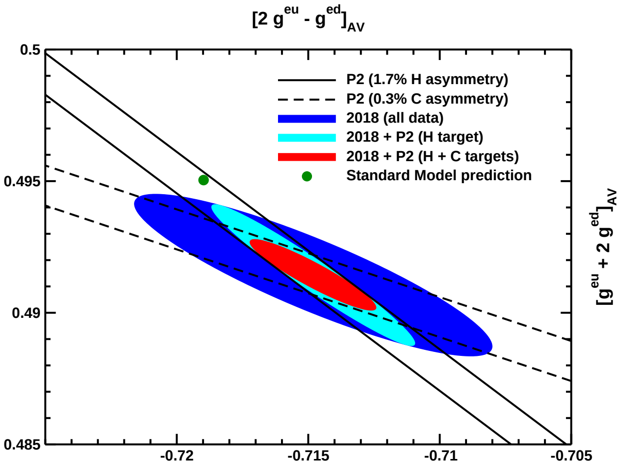


Nature 557 (2018)

Final results from Q_{weak}

- 2-dim fit to low-energy effective quark couplings
- exclude new physics at scales up to 8 TeV

New physics reach at P2



- low-energy effective quark couplings

The Scale of New Physics: Contact Interactions

$$\mathcal{L}_{eq} = \left(\frac{G_F}{\sqrt{s}} g_{VA}^{eq}(SM) + \frac{g^2}{\Lambda^2} \right) \bar{e}\gamma_\mu e\, \bar{q}\gamma^\mu \gamma_5 q$$

Convention: $g^2 = 4\pi$

P2@MESA probes
Λ up to $\simeq$ 50 TeV

comparable with
LHC (300 fb$^-$1)

	precision	$\Delta \sin^2\overline{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

J. Erler

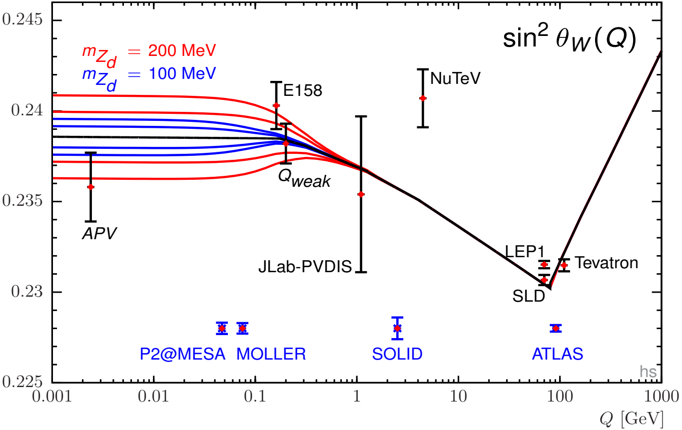
Dark Z

Dark matter and $U(1)$ symmetry ➜

- Kinetic mixing $B_{\mu\nu} D^{\mu\nu}$ (parameter ϵ) (B. Holdom)
- ➜ Dark photon, interacts via $\epsilon e D^\mu J_\mu^{em}$, like $e A^\mu J_\mu^{em}$
- Very small mass: $m_D = O(50)$ MeV
- $\epsilon = O(10^{-3})$, possibly generated by loop effects
- Negligible effect at the Z pole
- Would reduce the muon $g - 2$ discrepancy

- Model with parity violation, like ordinary Z, but suppressed by ϵ_Z W. Marciano

Combine kinetic and mass mixing ➜ Shift $\Delta\sin^2\theta_w(Q^2) \simeq 0.42\epsilon\frac{\delta m_Z^2}{Q^2+m_{Z_d}^2}$



Higher-Order QED

Matrix elements:

$$\mathcal{M} = \mathcal{M}_{Born} + \mathcal{M}_{1-loop} + \mathcal{M}_{2-loop} + \ldots$$

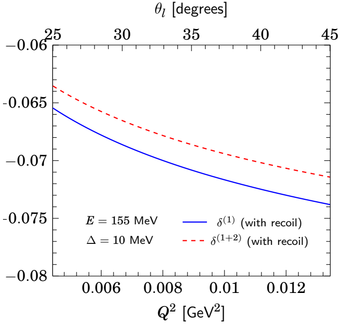
$$d\sigma \propto |\mathcal{M}_{Born}|^2 + 2\,\mathrm{Re}\,\mathcal{M}^*_{Born}\mathcal{M}_{1-loop} + |\mathcal{M}_{1-loop}|^2 + 2\,\mathrm{Re}\,\mathcal{M}^*_{Born}\mathcal{M}_{2-loop} + \ldots$$

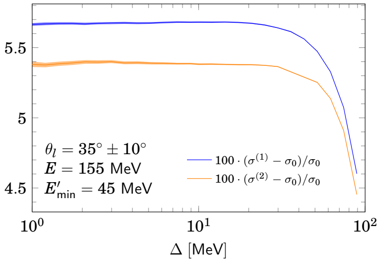
Add bremsstrahlung: cut-off Δ to separate soft from hard:

$$\begin{aligned} d\sigma^{(2)} &= d\sigma^{(0)}\left[1 + \delta^{(1)}_{1-loop} + \delta^{(2)}_{2-loop} + \delta^{(1)}_{1\gamma}(\Delta) + \delta^{(2)}_{2\gamma}(\Delta) + \delta^{(1)}_{1-loop}\delta^{(1)}_{1\gamma}(\Delta)\right] \\ &\quad + \int_{E_\gamma>\Delta} d\sigma_{1\gamma}\left[1 + \delta^{(1)}_{1-loop} + \delta^{(1)}_{1\gamma}(\Delta)\right] + \int_{E_\gamma, E^*_\gamma>\Delta} d\sigma_{2\gamma} \end{aligned}$$

$$\delta^{(2)}_{2\gamma}(\Delta) = \frac{1}{2}\left[\delta^{(1)}_{1\gamma}(\Delta)\right]^2 - \frac{\alpha^2}{3}\left(\ln\frac{Q^2}{m_e^2} - 1\right)^2$$

QED at order $O(\alpha^2)$





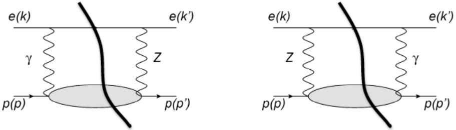
Virtual and soft-photon corrections:

- $\delta^{(1)} = \delta^{(1)}_{1-loop} + \delta^{(1)}_{1\gamma}(\Delta)$
- $\delta^{(2)} = \delta^{(2)}_{2-loop} + \delta^{(2)}_{2\gamma}(\Delta) + \delta^{(1)}_{1-loop}\delta^{(1)}_{1\gamma}(\Delta)$

Combined with hard bremsstrahlung
Test: independent of Δ

R. Bucoveanu

Box Graphs



Optical theorem and dispersion relations:

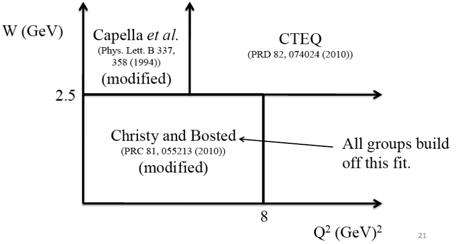
$$\mathrm{Im}\Box_{\gamma Z}(E) = \frac{\alpha}{(s-M_Z^2)^2}\int_{W_\pi^2}^{s} dW^2 \int_0^{Q^2_{max}} dQ^2 \frac{M_Z^2}{Q^2+M_Z^2} \times \left\{ F_1^{\gamma Z}(x,Q^2) + AF_2^{\gamma Z}(x,Q^2) + \frac{g_V^e}{g_A^e} BF_3^{\gamma Z} \right\}$$

Separated into vector and axial-vector parts of the proton current:

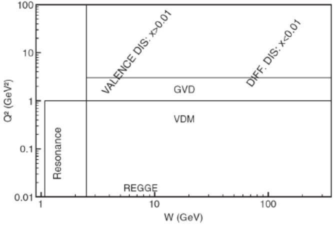
$$\mathrm{Re}\Box^V_{\gamma Z}(E) = \frac{2E}{\pi}\int_{\nu_\pi}^{\infty} \frac{dE'}{E'^2-E^2}\mathrm{Im}\Box^V_{\gamma Z}(E'), \qquad \mathrm{Re}\Box^V_{\gamma Z}(E=0)=0$$

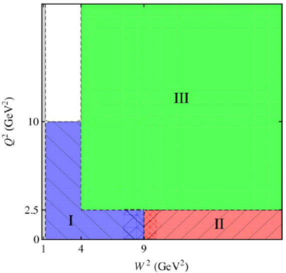
$$\mathrm{Re}\Box^A_{\gamma Z}(E) = \frac{2}{\pi}\int_{\nu_\pi}^{\infty} \frac{E'dE'}{E'^2-E^2}\mathrm{Im}\Box^A_{\gamma Z}(E'), \qquad \mathrm{Re}\Box^A_{\gamma Z}(E=0)\neq 0$$

Different calculations due to different assumptions about the structure function input (regions, parametrizations)



Gorchtein *et al.*
PRC 84, 015502 (2011)

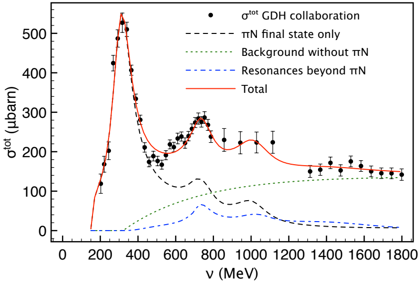




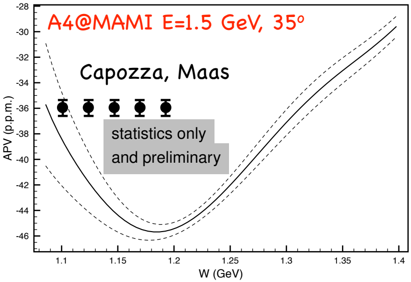
γZ Box Graphs Updated

Model with new uncertainty estimate for πN contribution:
Input for the dispersion relation for $\Box^V_{\gamma Z}$

- $\gamma^*/Z^* p \to \pi N$ with strangeness contribution (Armstrong-McKeown, 2012). Sensitivity to $G^s_M(Q^2)$ from parity-violating asymmetry in π production at A4
- non-π resonances (Christy-Bosted fit)
- non-resonant background, extended beyond $W = 2$ GeV: Regge ansatz



M. Gorchtein, X. Zhang, HS: PLB752



W_{max} / Q^2_{max}	2 GeV	4 GeV	∞
∞	1%	1%	3%
2 GeV²	3%	2%	1%
1 GeV²	76%	10%	2%

Contributions to $\mathrm{Re}\Box^V_{\gamma Z}$

$\mathrm{Re}\Box^V_{\gamma Z} = 0.00107$

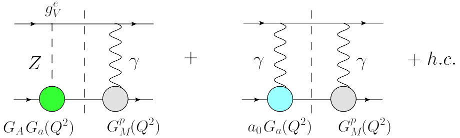
from recent 2015 update:
M. Gorchtein, HS, X. Zhang, PLB752

W_{max} / Q^2_{max}	2 GeV	4 GeV	∞
∞	0.5%	0.5%	4.6%
2 GeV²	6.7%	6.7%	0.5%
1 GeV²	60%	20%	0.5%

Contributions to the uncertainty of $\mathrm{Re}\Box^V_{\gamma Z}$

$\Delta\mathrm{Re}\Box^V_{\gamma Z} = 0.00018$

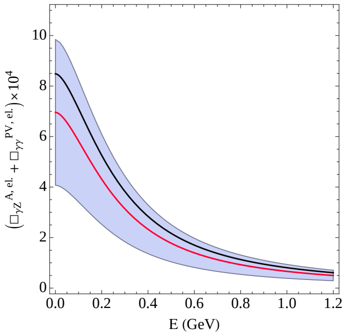
➜ 0.25 % contribution to $Q_W(p) = 0.0712$ for $E = 150$ MeV, $\theta_e = 0$



PV-violating γN interaction:

$\mathcal{L}_{PV} = iea_0 \partial_\mu F^{\mu\nu} \bar{N}\gamma_\nu\gamma_5 N$
$a_0 = -(0.74 \pm 1.38) \cdot 10^{-6}$ GeV^{-2}
(anapole moment)

➜ Shift of axial box part $\mathrm{Re}\Box^A_{\gamma Z}$ (elastic)



M. Gorchtein, HS, arXiv:1608.07484

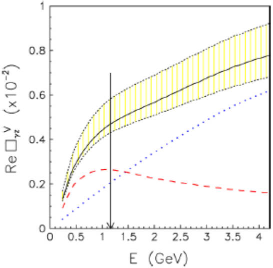
Inelastic contribution (e.g. πN intermediate states, described in BχPT)
contains terms $\propto \ln|t|$ ➜ formal definition of the nucleon's weak charge ?

$A_{exp} = A_0 \left(Q_W(\mathcal{N}) + Q^2 B(Q^2) + \Box(E)\right)$ ➜ $Q_W(\mathcal{N}) = \lim_{Q^2, E\to 0} \frac{A_{exp}}{A_0}$

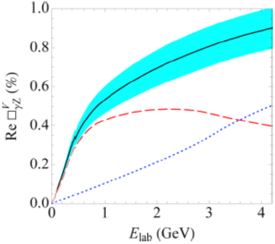
Safe by superconvergence relation for the $\ln[t]$ coefficient: $\int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu^2} F_3^{\gamma\gamma}(\nu, 0) = 0$

For P2@MESA: $\delta Q_W^p(PV\gamma\gamma) = (-1.7 \pm 2.5) \cdot 10^{-4}$, weakly energy-dependent

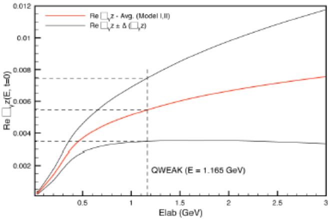
Sibirtsev *et al.*
PRD 82, 013011 (2010)



Carlson and Rislow
PRD 83, 113007 (2011)



Gorchtein *et al.*
PRC 84, 015502 (2011)



$$\mathrm{Re}\Box^V_{\gamma Z}(E = 1.165\ \mathrm{GeV})$$

$$(4.7^{+1.1}_{-0.4}) \times 10^{-3} \qquad (5.7 \pm 0.9) \times 10^{-3} \qquad (5.4 \pm 2.0) \times 10^{-3}$$

Update for the γZ box

- for Q_{weak}: $E = 1.165$ GeV:

$$
\begin{aligned}
\mathrm{Re}\Box_{\gamma Z}^{V,\pi N} &= (2.10 \pm 0.05) \times 10^{-3} \\
\mathrm{Re}\Box_{\gamma Z}^{V,res} &= (0.35 \pm 0.15) \times 10^{-3} \\
\mathrm{Re}\Box_{\gamma Z}^{V,bg} &= (3.23 \pm 1.5) \times 10^{-3} \\
\mathrm{Re}\Box_{\gamma Z}^{V,tot} &= (5.68 \pm 1.5) \times 10^{-3}
\end{aligned}
$$

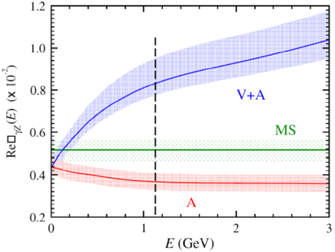
- for P2@MESA: $E = 0.155$ GeV:

$$
\begin{aligned}
\mathrm{Re}\Box_{\gamma Z}^{V,\pi N} &= (0.60 \pm 0.02) \times 10^{-3} \\
\mathrm{Re}\Box_{\gamma Z}^{V,res} &= (0.04 \pm 0.02) \times 10^{-3} \\
\mathrm{Re}\Box_{\gamma Z}^{V,bg} &= (0.43 \pm 0.18) \times 10^{-3} \\
\mathrm{Re}\Box_{\gamma Z}^{V,tot} &= (1.07 \pm 0.18) \times 10^{-3}
\end{aligned}
$$

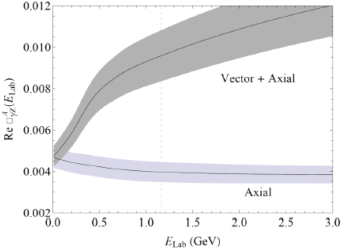
M. Gorchtein, X. Zhang, HS, PLB752

Axial Box Calculations

Blunden *et al.*
PRL 107, 081801 (2011)



Carlson and Rislow
PRD 88, 013018 (2013)

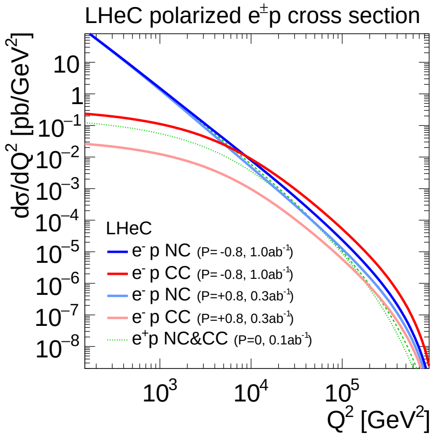


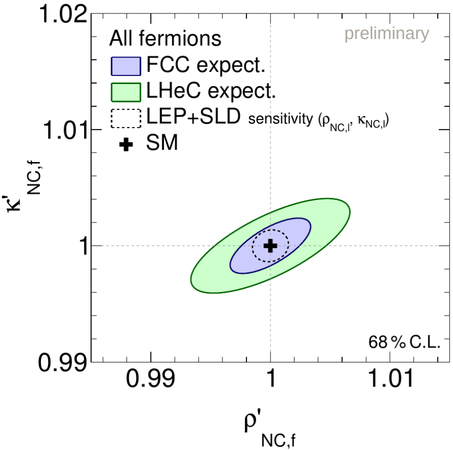
$$\mathrm{Re}\Box^{A}_{\gamma Z}(E = 1.165\ \mathrm{GeV})$$

$(3.7 \pm 0.4) \times 10^{-3}$ $\qquad$ $(4.0 \pm 0.5) \times 10^{-3}$

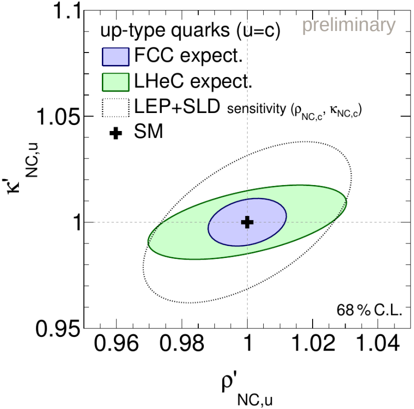
LHeC and FCC-ep

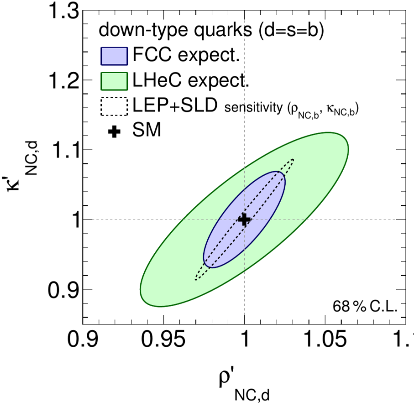
Large polarization asymmetries at large Q^2





beyond SM, all fermions





beyond SM, quarks