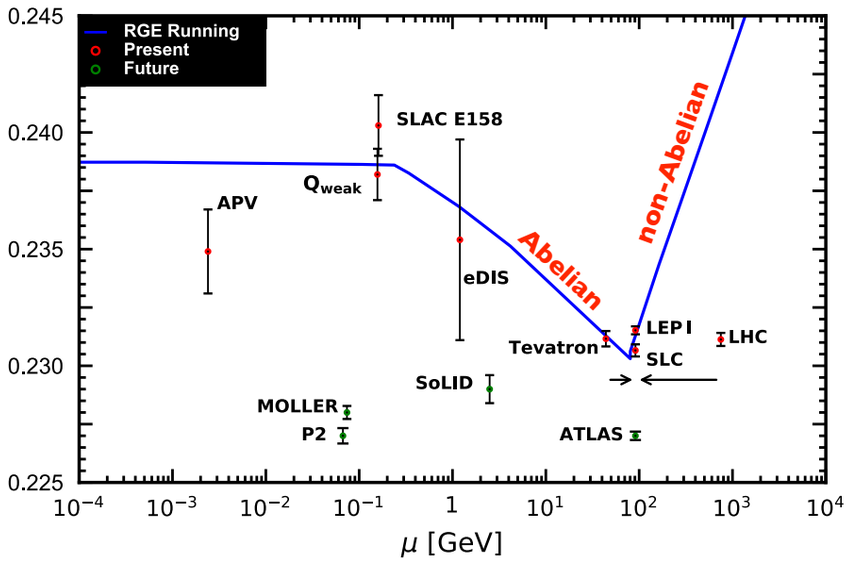
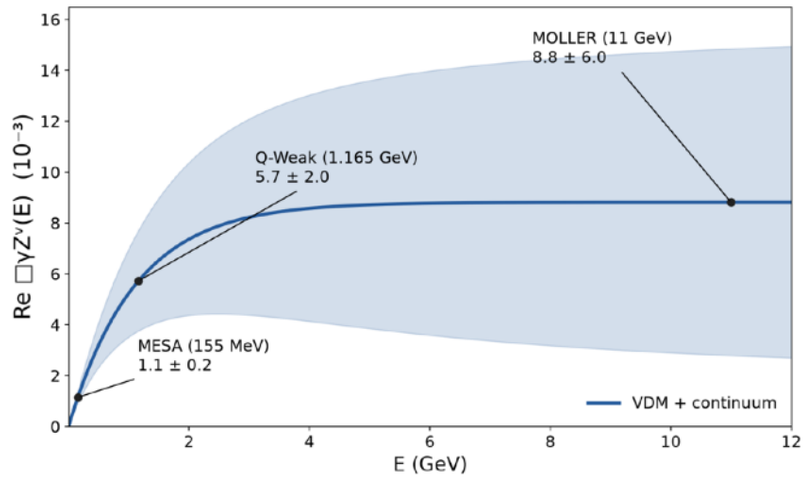
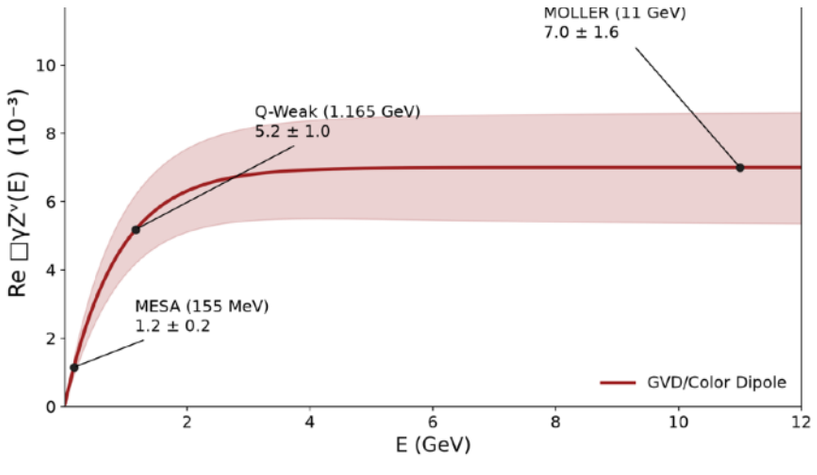
Boxes and weak charges from PVES

Misha Gorshteyn

Universität Mainz







Collaborators:

Chuck Horowitz
Jens Erler
Michael Ramsey-Musolf
Hubert Spiesberger
Chien-Yeah Seng
Xu Feng
Lu-Chang Chen
Zhaolong Zhang
…

Workshop “Precision Physics with MOLLER”, JLab, November 5-6, 2026

Outline

Running weak mixing angle in the Standard Model

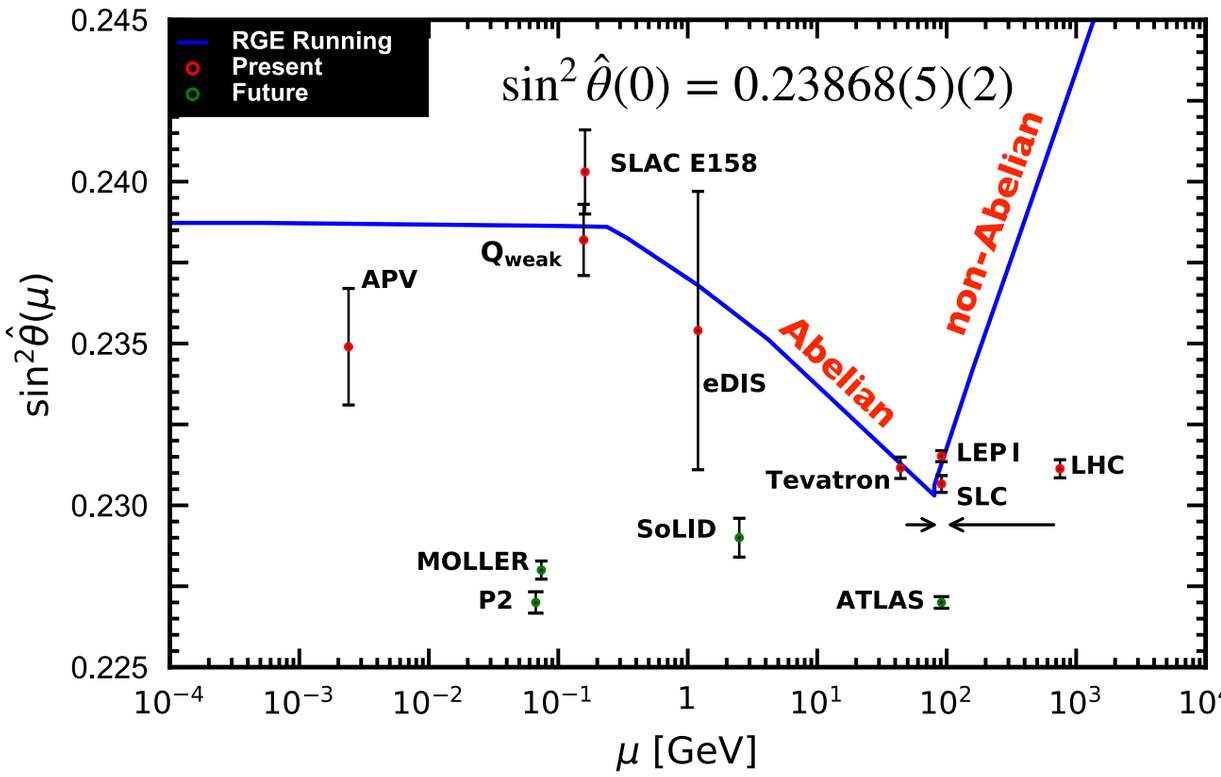
γZ-box from dispersion relations

Constraints from data and lattice QCD

A note on parity violation in atoms

Summary & Open questions

Standard Model running of $\sin^2\hat{\theta}(\mu)$



updated from
Ferro-Hernández & JE
arXiv:1712.09146

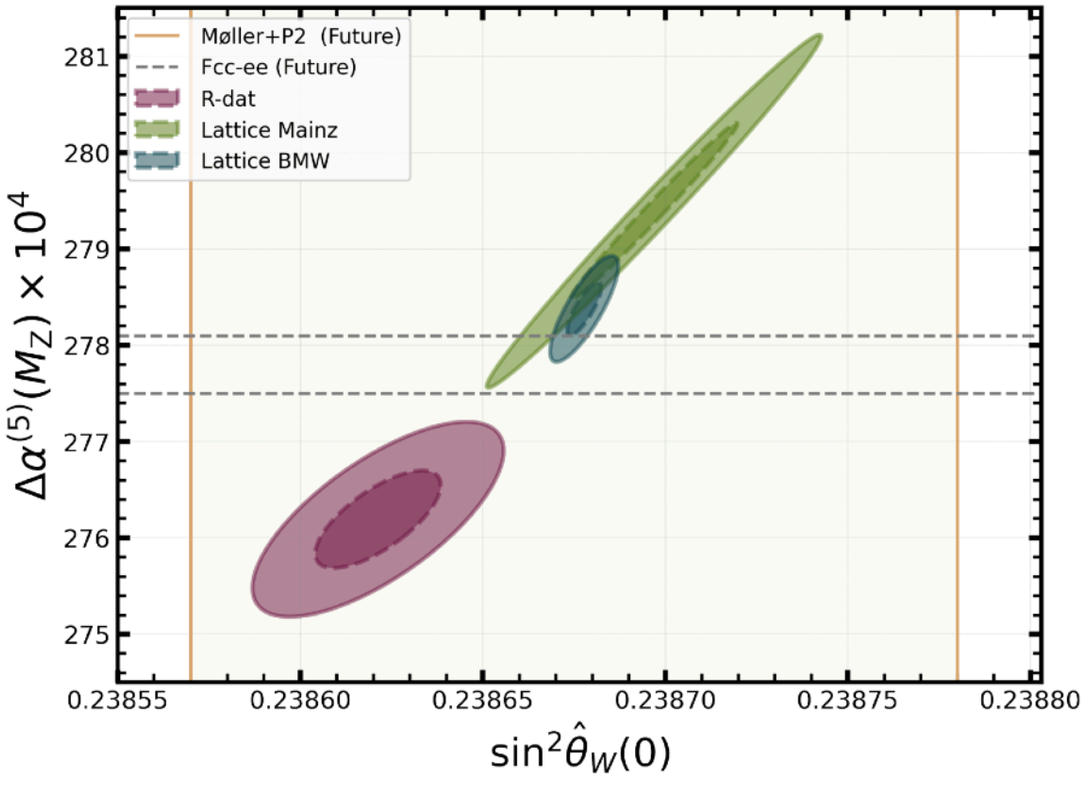
Running WMA in the Standard Model:

Firmly under control to 10^{-5} precision

At low scales driven by HVP/γZ-mixing
— given the muon g-2, is it a problem?

Dedicated study 2406.16691:
R-ratio/LQCD tension does not endanger future PVES experiments

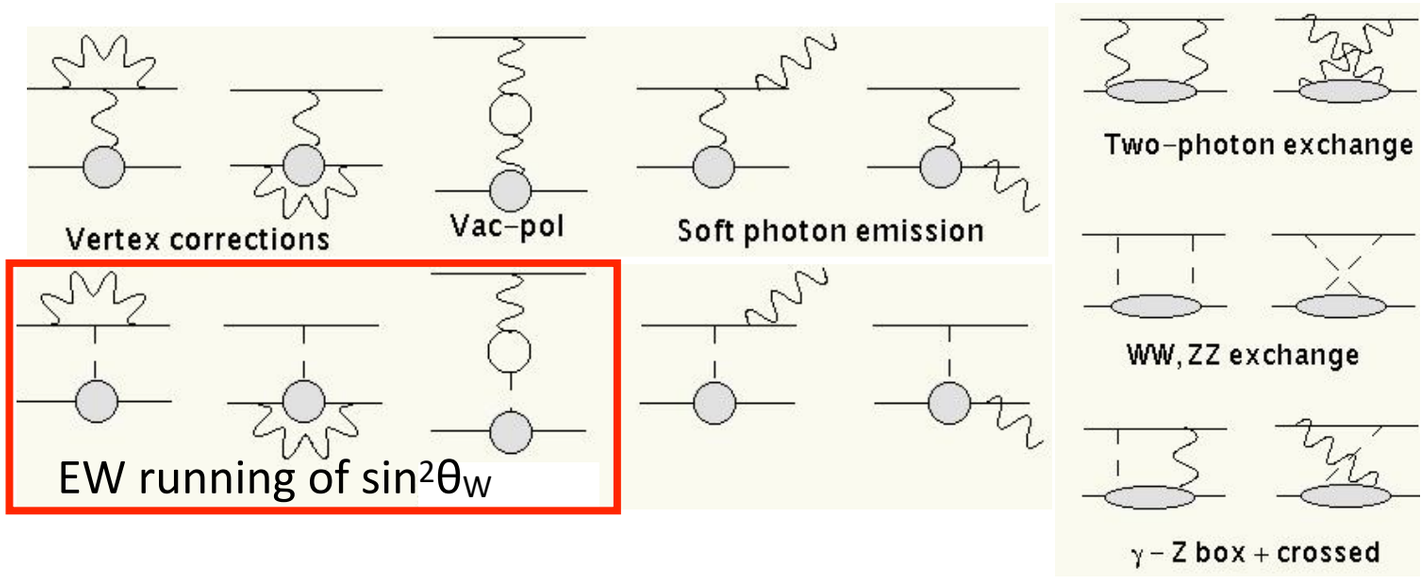
—> TALK BY SIMON KUBERSKY



Weak Charges in Presence of Radiative Corrections

—> TALK BY PETER BLUNDEN

Proton's weak charge with radiative corrections: EW boxes



Hadronic effects under control

$$Q_W^{\mathrm{p},\,1-\mathrm{loop}} = (1+\Delta_\rho+\Delta_e)(1-4\sin^2\hat{\theta}_W+\Delta_e') + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Marciano, Sirlin '83,84; Erler, Musolf '05

Process-specific

Depends on kinematics and hadronic structure

Marciano and Sirlin '84:
γZ-box mainly universal (large log)
same for PV in atoms and e-scattering
Residual dependence on hadronic scale Λ
Vector-vector contribution vanishes at E=0 (C-parity)
No energy dependence assumed

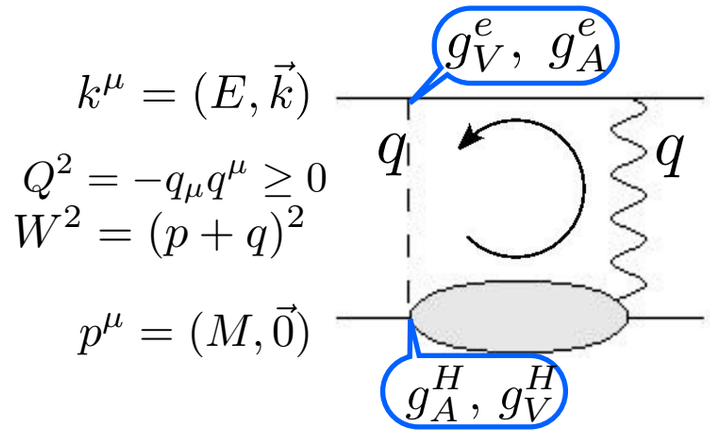
$$\Box_{\gamma Z} = \frac{5\hat{\alpha}}{2\pi}(1-4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right)+C_{\gamma Z}(\Lambda)\right]$$

0.0052 ± 0.0005 (7.3 ± 0.7% of Q_W)

Estimate the energy dependence of the box with dispersion relations MG, Horowitz, 2009

γZ-Box from Dispersion Relations

γZ-box from forward dispersion relation



Imaginary part = on-shell states = data

Real part: from unitarity + analyticity + symmetries

MG, Horowitz '09; MG, Horowitz, Ramsey-Musolf '11

Lower blob: forward interference Compton tensor

$$\mathrm{Im}W^{\mu\nu} = -\hat{g}^{\mu\nu} F_1^{\gamma Z} + \frac{\hat{p}^\mu \hat{p}^\nu}{(p\cdot q)} F_2^{\gamma Z} + \frac{i\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta}{2(p\cdot q)} F_3^{\gamma Z}$$

Forward dispersion relations

$$\mathrm{Re}\Box_{\gamma Z_V}(E) = \frac{2E}{\pi} \int_0^\infty dQ^2 \int_{W_\pi^2}^\infty dW^2 \left[A F_1^{\gamma Z}(W^2, Q^2) + B F_2^{\gamma Z}(W^2, Q^2) \right]$$

$$\mathrm{Re}\Box_{\gamma Z_A}(E) = \frac{2}{\pi} \int_0^\infty dQ^2 \int_{(M+m_\pi)^2}^\infty dW^2\, C F_3^{\gamma Z}(W^2, Q^2)$$

Inclusive PV data
- little available

Energy dependence required a formal redefinition of the weak charge $\quad Q_W^p = \lim_{E,\, Q^2 \to 0} \left[-\frac{4\sqrt{2}\pi\alpha}{G_F Q^2} A^{exp} \right]$

Axial box under control, vector box requires modeling with hadronic ingredients —> model-dependent

Energy dependence of γZ-Box from Dispersion Relations

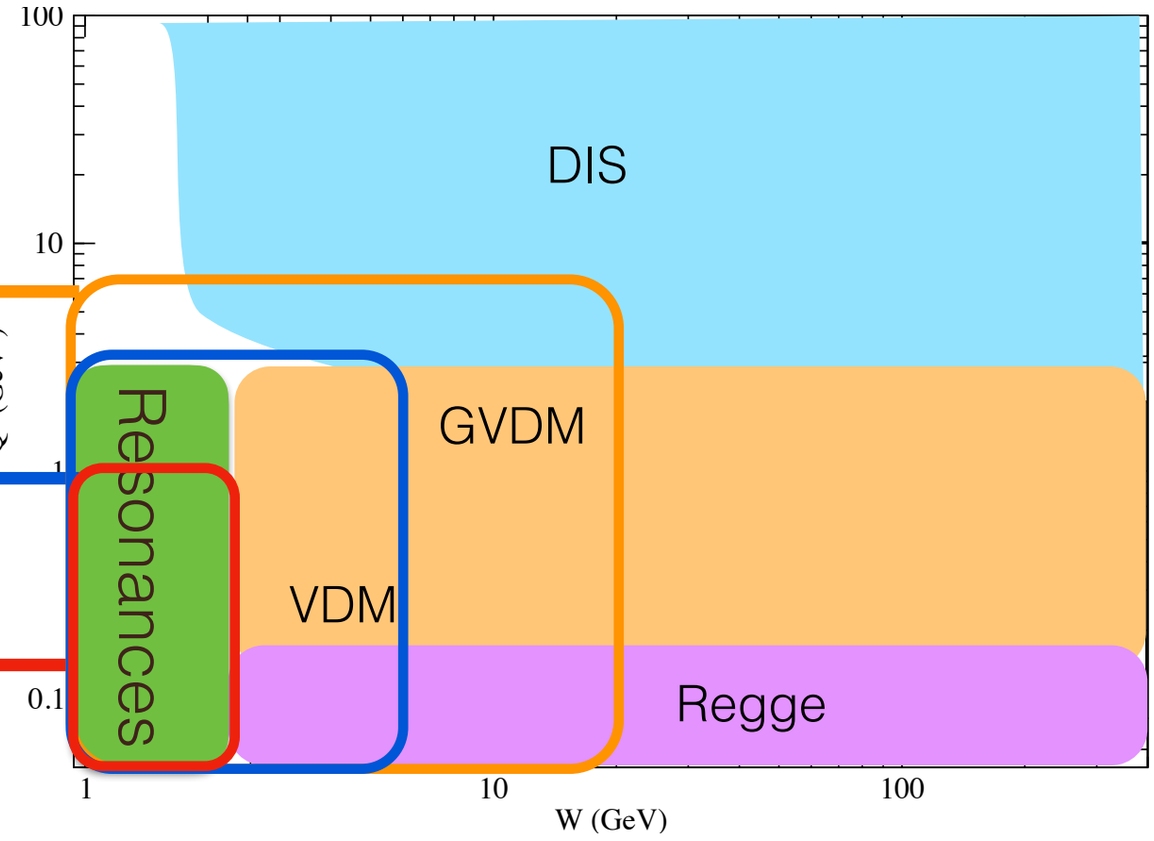
Model dependence stems from that in the flavor separation/rotation

Importance of the input for the integral:

For MOLLER (ep) energy E = 11 GeV
Main contribution: W < 10 GeV, Q^2 < 5 GeV^2

For QWeak energy E = 1.165 GeV
Main contribution: W < 5 GeV, Q^2 < 2 GeV^2

For P2 energy E = 155 MeV
Main contribution: W < 2.5 GeV, Q^2 < 1 GeV^2

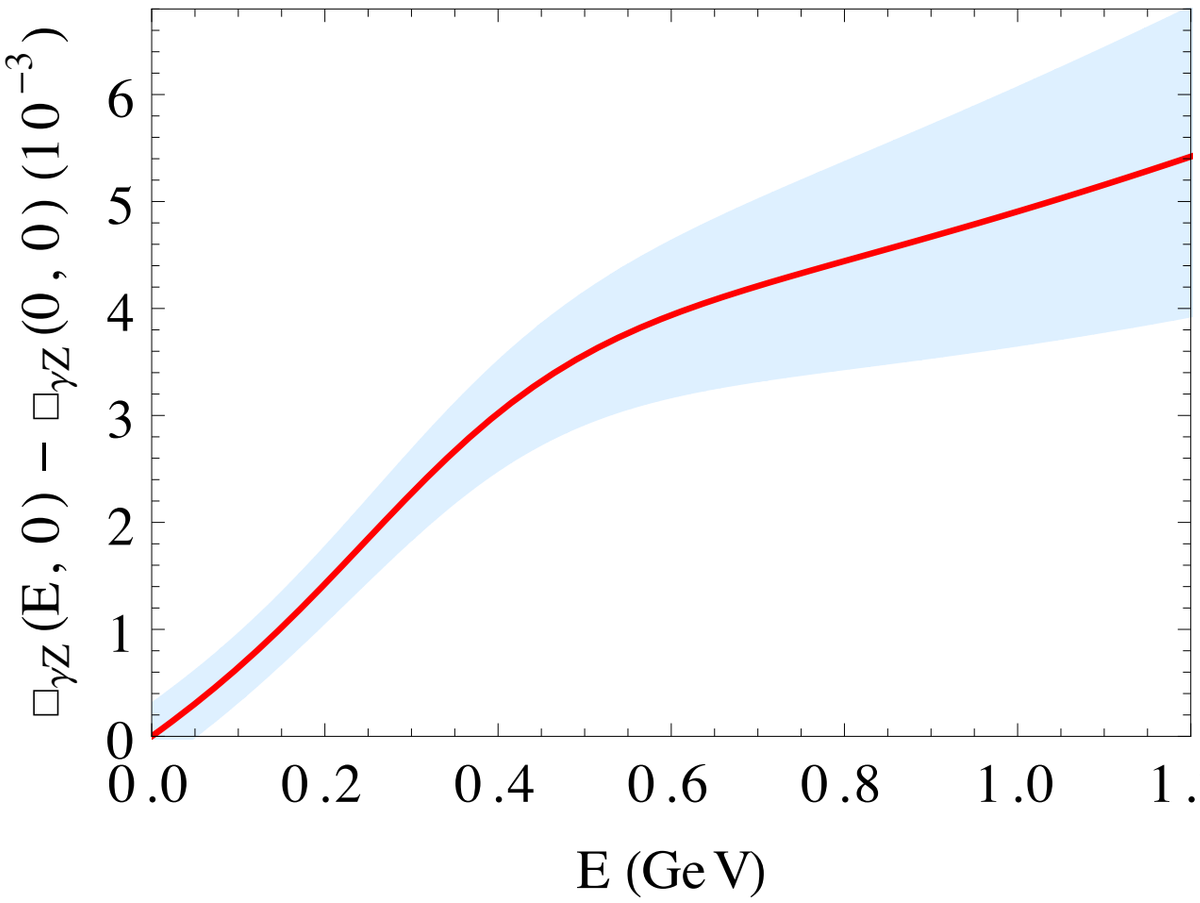


Steep energy dependence of $\square_{\gamma Z}^{V}$ (much smaller for smaller energy)

- Furnished a strong motivation for the P2 experiment in Mainz at E=155 MeV

$$\square_{\gamma Z}^{V}(E = 1.165\,\mathrm{GeV}) = 0.0054(20) \rightarrow \square_{\gamma Z}^{V}(E = 155\,\mathrm{MeV}) = 0.0011(2)$$

Status of the energy-dependent γZ-Box



Gorchtein, Horowitz, PRL 102 (2009) 091806;
Nagata, Yang, Kao, PRC 79 (2009) 062501;
Tjon, Blunden, Melnitchouk, PRC 79 (2009) 055201;
Zhou, Nagata, Yang, Kao, PRC 81 (2010) 035208;
Sibirtsev, Blunden, Melnitchouk, PRD 82 (2010) 013011;
Rislow, Carlson, PRD 83 (2011) 113007;
Gorchtein, Horowitz, Ramsey-Musolf, PRC 84 (2011) 015502;
Blunden, Melnitchouk, Thomas, PRL 107 (2011) 081801;
Rislow, Carlson PRD 85 (2012) 073002;
Blunden, Melnitchouk, Thomas, PRL 109 (2012) 262301;
Hall et al., PRD 88 (2013) 013011;
Rislow, Carlson, PRD 88 (2013) 013018;
Hall, Blunden, Melnitchouk, Thomas, Young, PLB 731 (2014) 287;
Gorchtein, Zhang, PLB 747 (2015) 305;
Hall et al., PLB 753 (2016) 221;
Gorchtein, Spiesberger, Zhang, PLB 752 (2016) 135;
Becker et al [P2 Collaboration], EPJA 54 (2018) 11, 208;
Erler, Gorchtein, Koshchii, Seng, Spiesberger, PRD 100 (2019) 5, 053007

QWEAK energy: $\mathrm{Re}\,\Box_{\gamma Z}^{A+V}(E = 1.165\,\mathrm{GeV}) = (9.3 \pm 1.5) \times 10^{-3}$ (Theory error: mostly vector)

QWEAK final result: $Q_W^p = 0.0719 \pm 0.0045$ (error mostly experimental)

P2 energy: $\mathrm{Re}\,\Box_{\gamma Z}^{A+V}(E = 155\,\mathrm{MeV}) = (5.4 \pm 0.4) \times 10^{-3}$ (Theory error: mostly axial)

P2 expectation: $Q_W^p = 0.0713 \pm 0.0013$

Vector γZ-Box: Input and Uncertainty

How to get γZ-interference structure functions from electromagnetic ones?

Photon and Z are two manifestations of the same SU(2)-U(1) fields, their couplings to matter related

Electromagnetic		Weak NC
$e^q \bar{q} \gamma_\mu q$	→	$2(T_q^3 - 2s_w^2 e^q)\bar{q}\gamma_\mu q$

Where does the model dependence then come from?

At low scales quarks are confined in hadrons —> these couplings are embedded in hadronic matrix elements

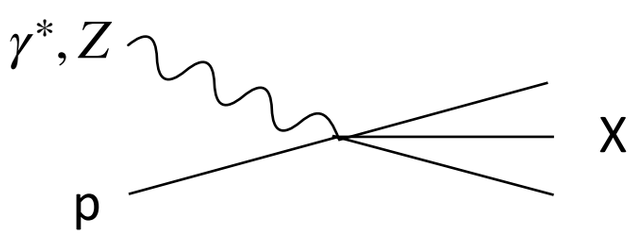
Nonperturbative nature of QCD spoils this simple rescaling pattern

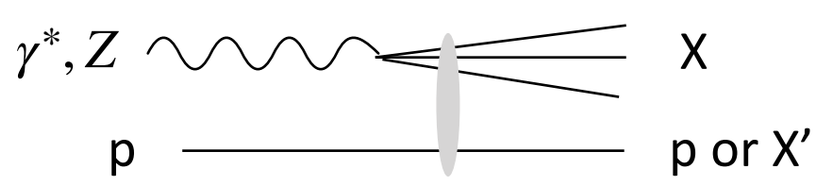
$$T_{\gamma Z}^{\mu\nu} = i\int d^4x e^{iqx}\langle p\,|\,T\{J_{em}^{\mu}(x)J_Z^{\nu}(0)\}\,|\,p\rangle \rightarrow W_{\gamma Z}^{\mu\nu} = i\int d^4x e^{iqx}\langle p\,|\,[J_{em}^{\mu}(x), J_Z^{\nu}(0)]\,|\,p\rangle \propto \sum_X \langle p\,|\,J_{em}^{\mu}X\rangle\langle X\,|\,J_Z^{\nu}\,|\,p\rangle X\rangle$$

Decompose inclusive em structure functions in distinct hadronic states, then rescale em —> NC one by one

Decomposition is model- and kinematics-dependent!

Common knowledge: two regimes in e-h collisions — target fragmentation and projectile fragmentation





Vector γZ-Box: Input and Uncertainty

Decomposition varies across the (W,Q²)-plane

$$\mathrm{Re}\Box_{\gamma Z_V}(E) = \frac{2E}{\pi}\int_0^\infty dQ^2 \int_{W_\pi^2}^\infty dW^2 \left[A F_1^{\gamma Z}(W^2,Q^2) + B F_2^{\gamma Z}(W^2,Q^2)\right]$$

Large-x: target fragmentation (resonances, PDF, …)

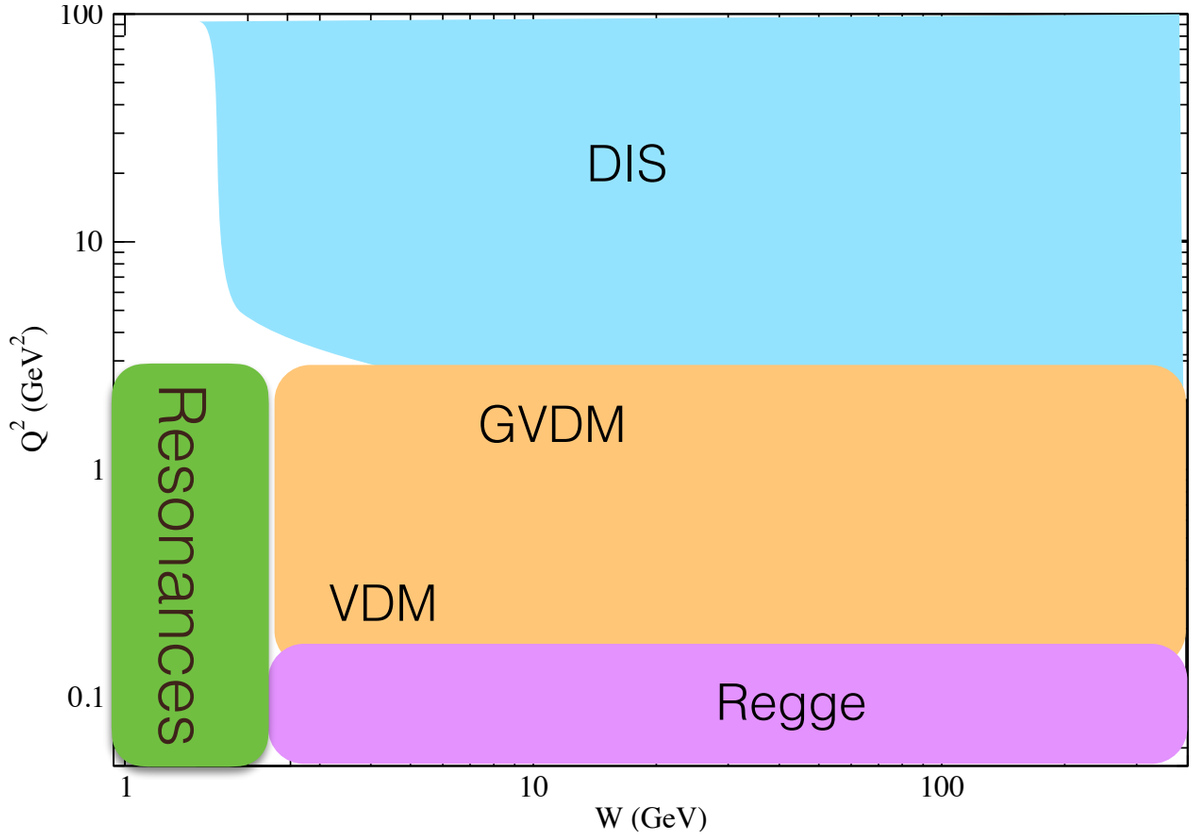
Low-x: projectile fragmentation (VDM, color dipole, BFKL, Regge, …)

Starting point: parametrize em data

$$F_{1,2}^{\gamma\gamma} = F_{1,2}^{\gamma\gamma,\,res} + F_{1,2}^{\gamma\gamma,\,back}$$

Identify quantum numbers (isospin)

Apply isospin rotation to individual contributions



Vector γZ-Box: Input and Uncertainty

Decomposition varies across the (W,Q²)-plane

$$\mathrm{Re}\Box_{\gamma Z_V}(E) = \frac{2E}{\pi}\int_0^\infty dQ^2 \int_{W_\pi^2}^\infty dW^2 \left[A F_1^{\gamma Z}(W^2,Q^2) + B F_2^{\gamma Z}(W^2,Q^2)\right]$$

Large-x: target fragmentation (resonances, PDF, …)

Low-x: projectile fragmentation (VDM, color dipole, BFKL, Regge, …)

Starting point: parametrize em data

$$F_{1,2}^{\gamma\gamma} = F_{1,2}^{\gamma\gamma,\,res} + F_{1,2}^{\gamma\gamma,\,back}$$

Identify quantum numbers (isospin)

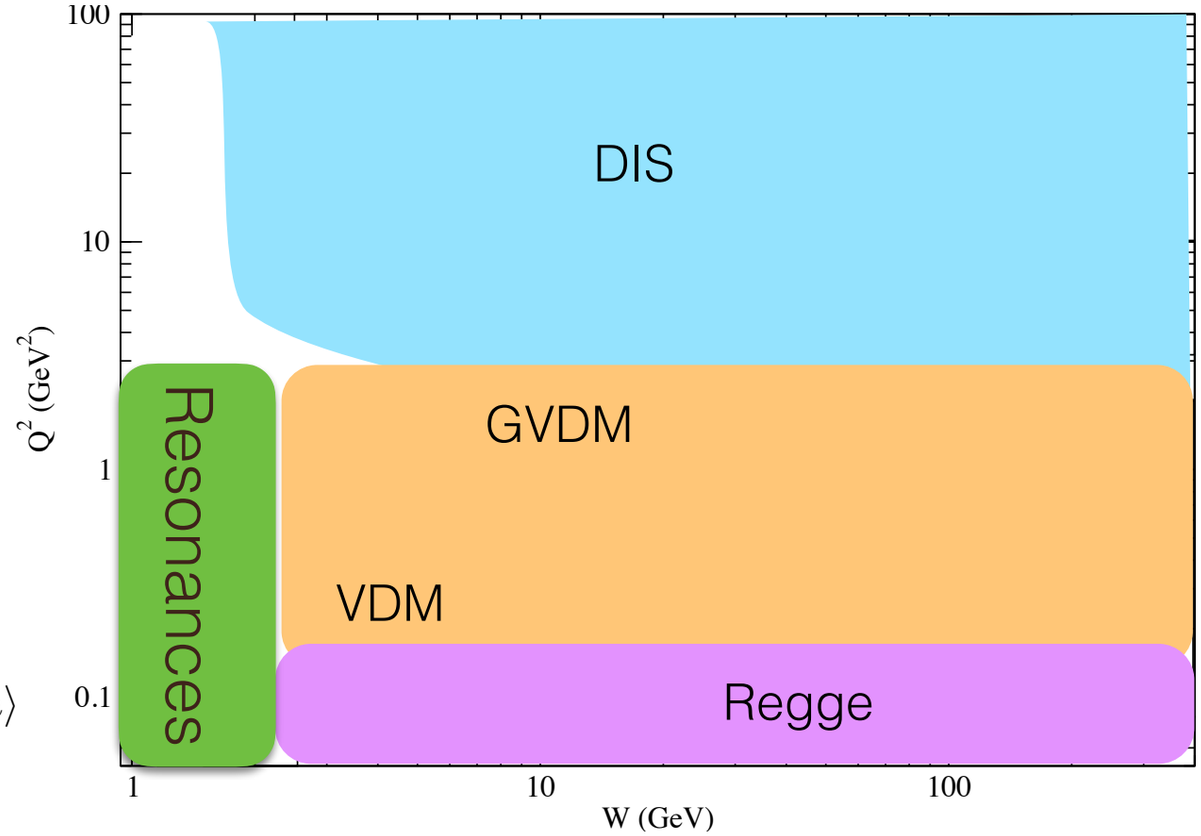
Apply isospin rotation to individual contributions

For isospin 1/2, 3/2 resonances (neglecting strangeness!)

$$\langle X|J^\mu_{NC,V}|p\rangle \;=\; (1-4s^2\theta_W)\langle X|J^\mu_{em}|p\rangle - \langle X|J^\mu_{em}|n\rangle$$

$$\langle p|J^\mu_{em}|R\rangle\langle R|J^\mu_{NC,V}|p\rangle \;=\; (1-4s^2\theta_W)|\langle R|J^\mu_{em}|p\rangle|^2 - \langle p|J^\mu_{em}|R\rangle\langle R|J^\mu_{em}|n\rangle$$

Need p(e,e)X and d(e,e)X data —> plenty of those



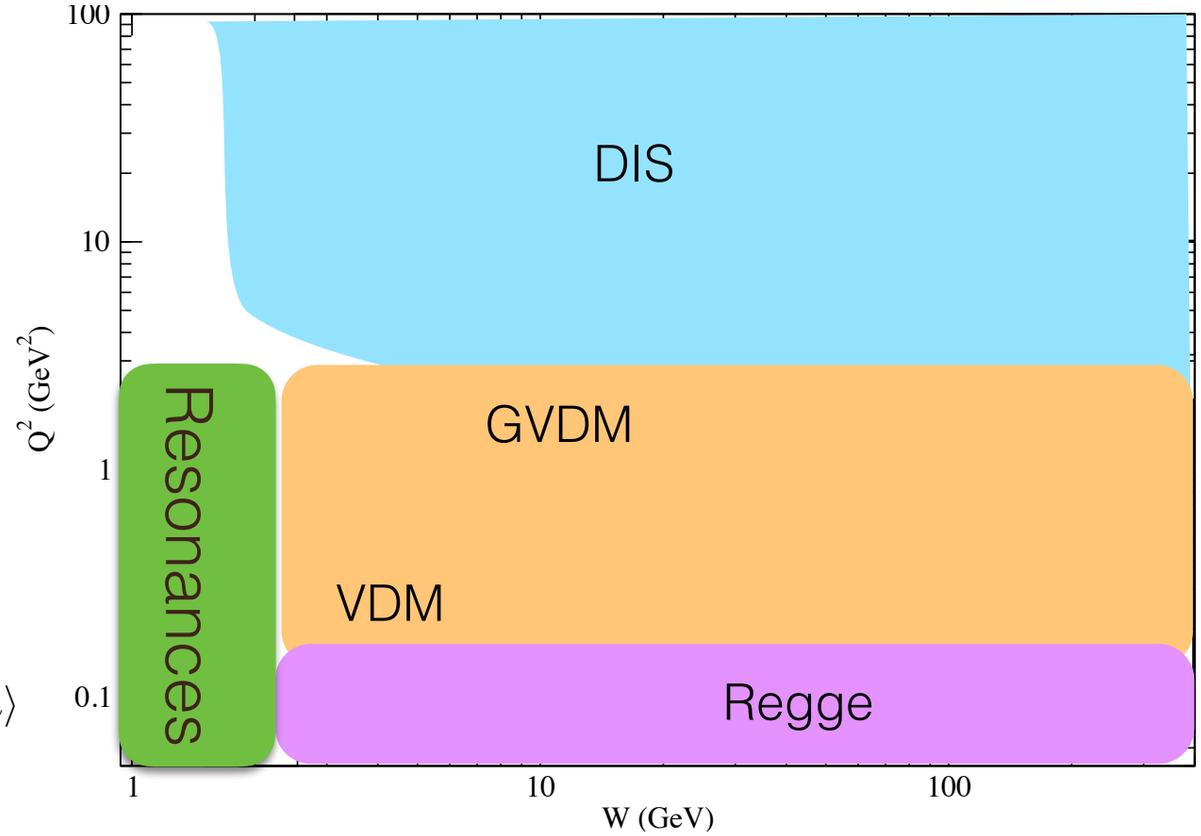
Vector γZ-Box: Input and Uncertainty

Decomposition varies across the (W,Q²)-plane

$$\mathrm{Re}\Box_{\gamma Z_V}(E) = \frac{2E}{\pi}\int_0^\infty dQ^2 \int_{W_\pi^2}^\infty dW^2 \left[A F_1^{\gamma Z}(W^2,Q^2) + B F_2^{\gamma Z}(W^2,Q^2)\right]$$

Large-x: target fragmentation (resonances, PDF, …)

Low-x: projectile fragmentation (VDM, color dipole, BFKL, Regge, …)



Starting point: parametrize em data

$$F_{1,2}^{\gamma\gamma} = F_{1,2}^{\gamma\gamma,\,res} + F_{1,2}^{\gamma\gamma,\,back}$$

Identify quantum numbers (isospin)

Apply isospin rotation to individual contributions

For isospin 1/2, 3/2 resonances (neglecting strangeness!)

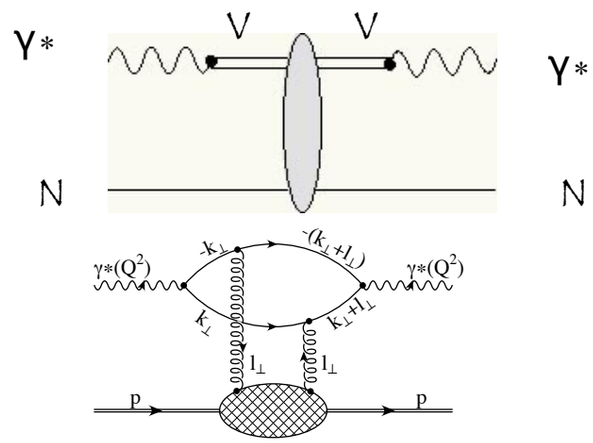
$$\langle X|J^\mu_{NC,V}|p\rangle \;=\; (1-4s^2\theta_W)\langle X|J^\mu_{em}|p\rangle - \langle X|J^\mu_{em}|n\rangle$$

$$\langle p|J^\mu_{em}|R\rangle\langle R|J^\mu_{NC,V}|p\rangle \;=\; (1-4s^2\theta_W)|\langle R|J^\mu_{em}|p\rangle|^2 - \langle p|J^\mu_{em}|R\rangle\langle R|J^\mu_{em}|n\rangle$$

Need p(e,e)X and d(e,e)X data —> plenty of those

Vector meson dominance
+ flavor-indep. Vp scattering

$$\sigma_{tot}^{\gamma p} \;=\; \sum_{V=\rho,\omega,\phi} \frac{4\pi\alpha}{f_V^2}\sigma_{Vp} + \sigma_{Cp}$$



Color dipole picture
+ gluon exchanges

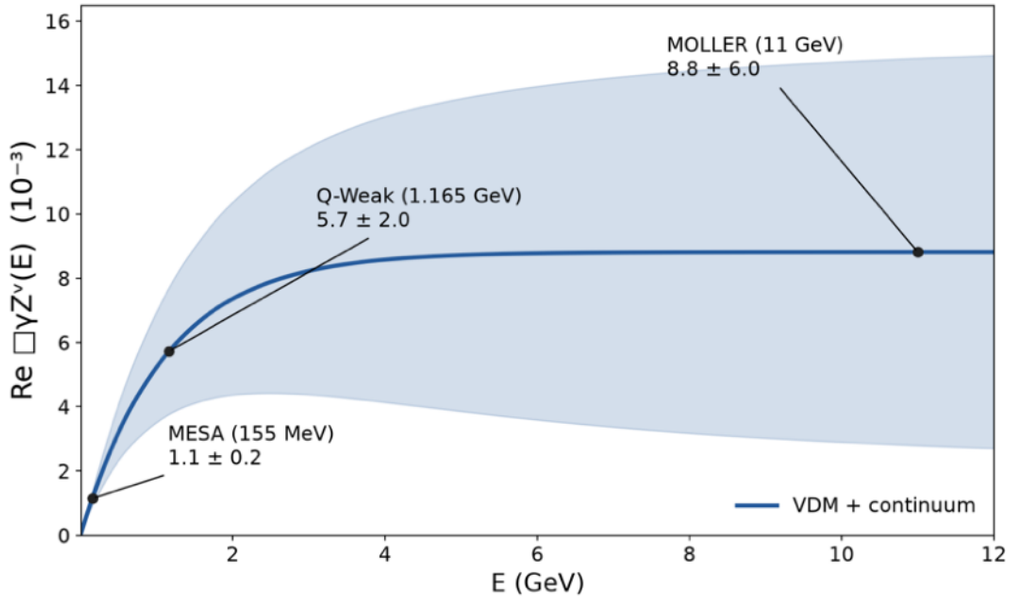
$$|\gamma^*\rangle = \sum_q e^q\,|q\bar{q}\rangle\sigma_{\bar{q}qp} + \ldots$$

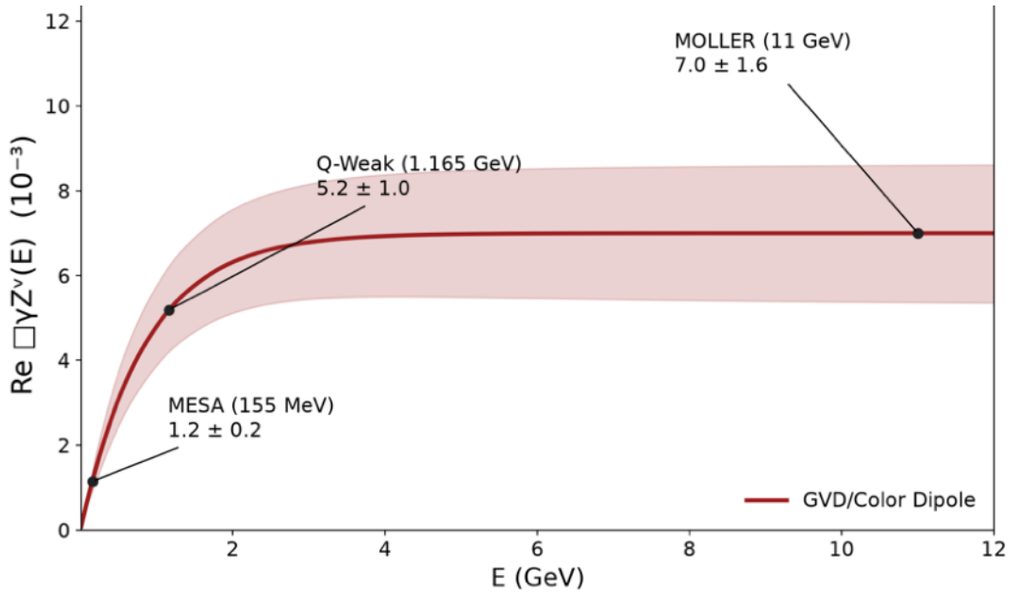
Vector γZ-Box: Input and Uncertainty

Uncertainty of $\Box_{\gamma Z}^{V}$ dominated by the background

VDM: incomplete
21% for real photons, more for virtual photons

Pessimistic: neglects the fact that above Q2~2 GeV2
transition to Bjorken-scaling regime occurs





Color-Dipole: how many active flavors?
Treat the entire $c\bar{c}$ as uncertainty estimate

Peter, Wally et al:
start from high Q2 (only leading-twist relevant)
Match to resonance-region (isospin decomposition known)
Then, only the interpolator uncertain
Require matching also after isospin rotation (Q-H duality)

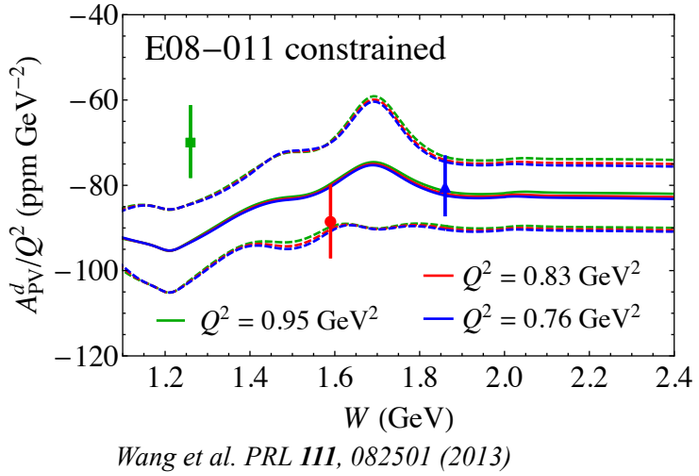
Substance of years-long discussion; need external input to resolve: PVDIS data or Lattice QCD

Constraints from PVDIS data and Lattice QCD

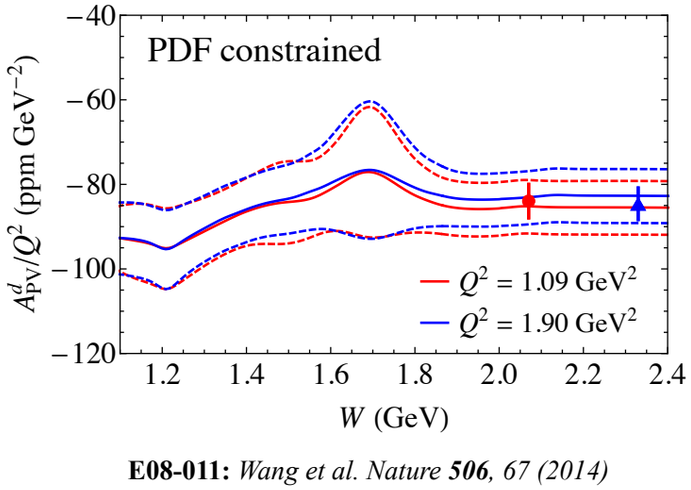
Direct constraints from PVDIS

$$A_{\rm PV} = g_A^e \left(\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\right) \frac{xy^2 F_1^{\gamma Z} + (1-y)F_2^{\gamma Z} + \frac{g_V^e}{g_A^e}(y - y^2/2)xF_3^{\gamma Z}}{xy^2 F_1^{\gamma\gamma} + (1-y)F_2^{\gamma\gamma}}$$

Plots borrowed from Peter's talk



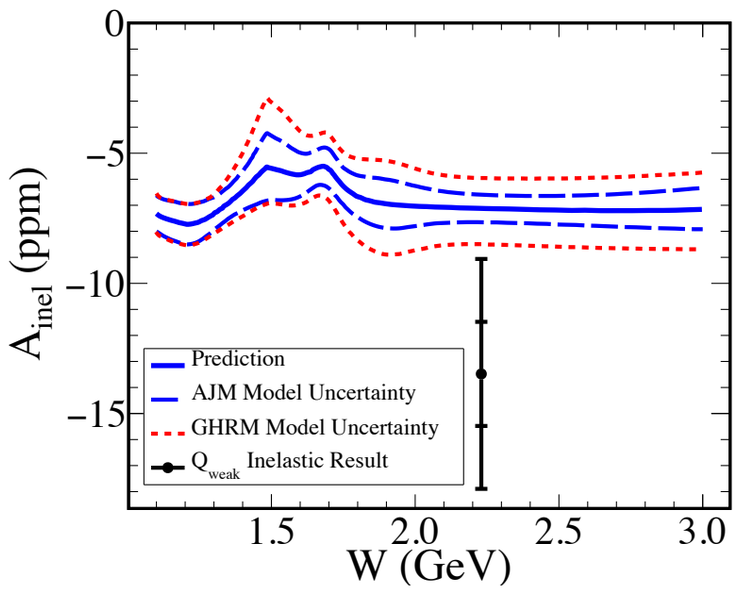
*Wang et al. PRL **111**, 082501 (2013)*



E08-011: *Wang et al. Nature **506**, 67 (2014)*

All pheno models at Q2 ~ 1 GeV2 very similar

Good agreement, apart from Delta (~2σ away)
Raises general question: how to use PVDIS data?
Little room for modification on the Delta!



Likewise: inelastic data from Qweak

Systematic uncertainty precludes definite interpretation
What if MOLLER confirms with smaller error?
Should we inflate uncertainties to include the data?

γZ-Box from the lattice QCD

First lattice calculation of γZ-box with energy dependence — Zhang, Feng, MG, Chen, Seng [RBC/UKQCD] 2601.06582

Same group that pioneered γW-box on pion, kaon, neutron — 2003.09798; 2003.11264; 2102.12048; 2308.16755
In the context of the Cabibbo angle anomaly

- 24D and 32Dfine gauge ensembles [RBC-UKQCD]
- (2+1+1)f domain-wall fermions
- Pion mass: 142.6(3) MeV and 142.9(7) MeV
- lattice size L = 4.6fm
- Lattice spacing $a^{-1} = 1.023(2)\ \mathrm{GeV}\ \mathrm{and}\ 1.378(5)\ \mathrm{GeV}$

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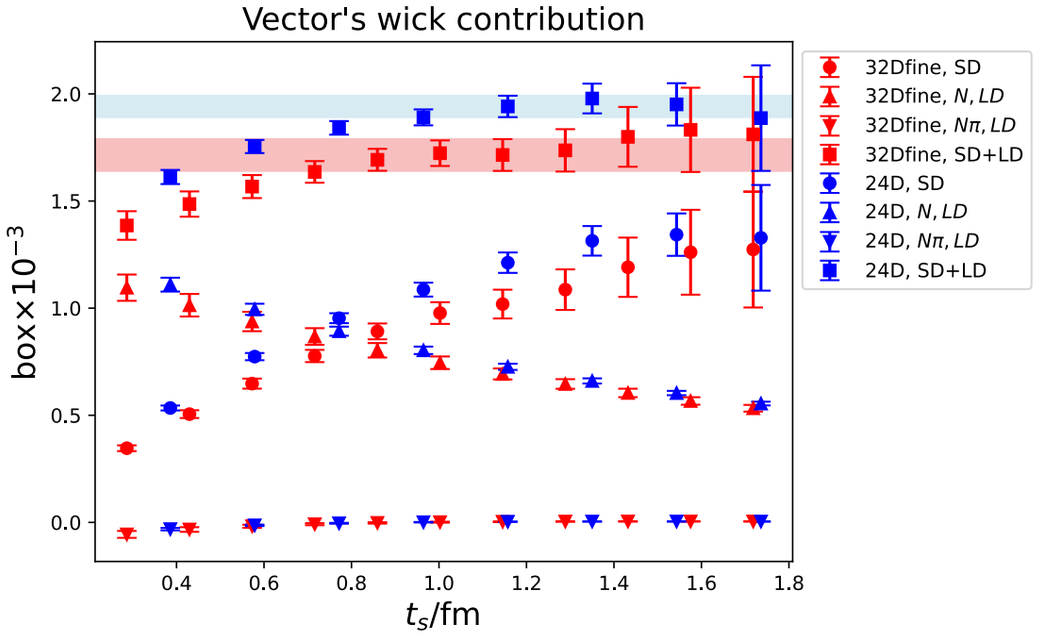
2003.09798; 2003.11264; 2102.12048; 2308.16755

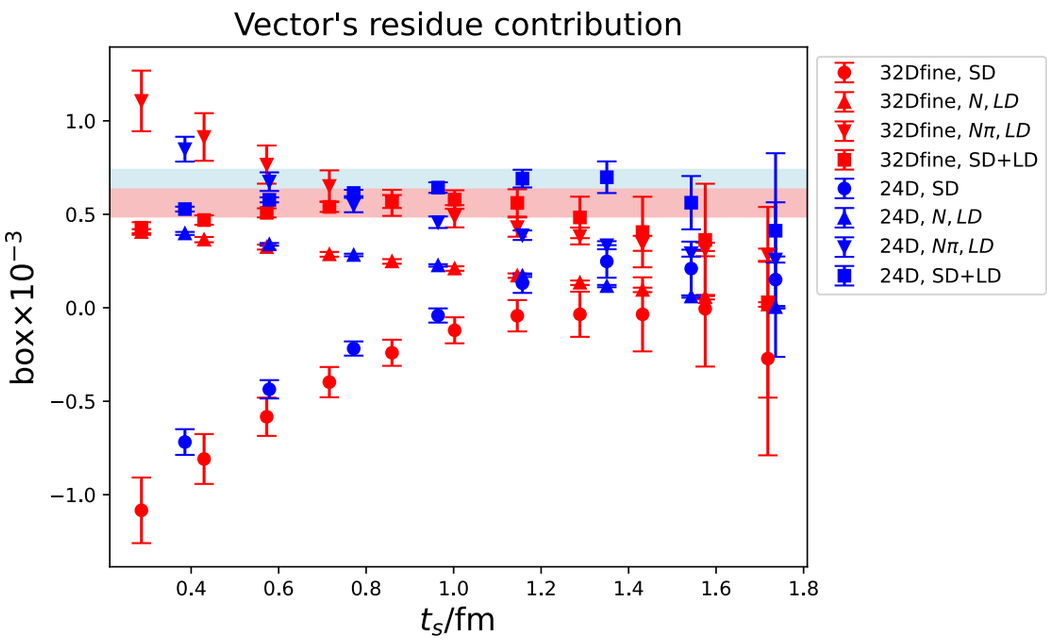
- 24D and 32Dfine gauge ensembles [RBC-UKQCD]
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- lattice size L = 4.6fm
- Lattice spacing $a^{-1} = 1.023(2)\ \mathrm{GeV}\ \text{and}\ 1.378(5)\ \mathrm{GeV}$

155 MeV energy a problem: lattice in Euclidian, analytical continuation —> residue contribution

$$\Box_{\gamma Z}(E) = \Box_{\gamma Z}^{\mathrm{Wick}}(E) + \Box_{\gamma Z}^{\mathrm{res}}(E)$$

Residue contribution sizable!
Long-Distance (elastic, πN) and Short-Distance shown
Axial box: matched to pQCD at $Q^2 = 2\,\mathrm{GeV}^2$





γZ-Box from the lattice QCD

First lattice calculation of γZ-box with energy dependence

Continuum extrapolation (DSDR/Iwasaki)

Finite volume effects studied

Zhang, Feng, MG, Chen, Seng [RBC/UKQCD] 2026

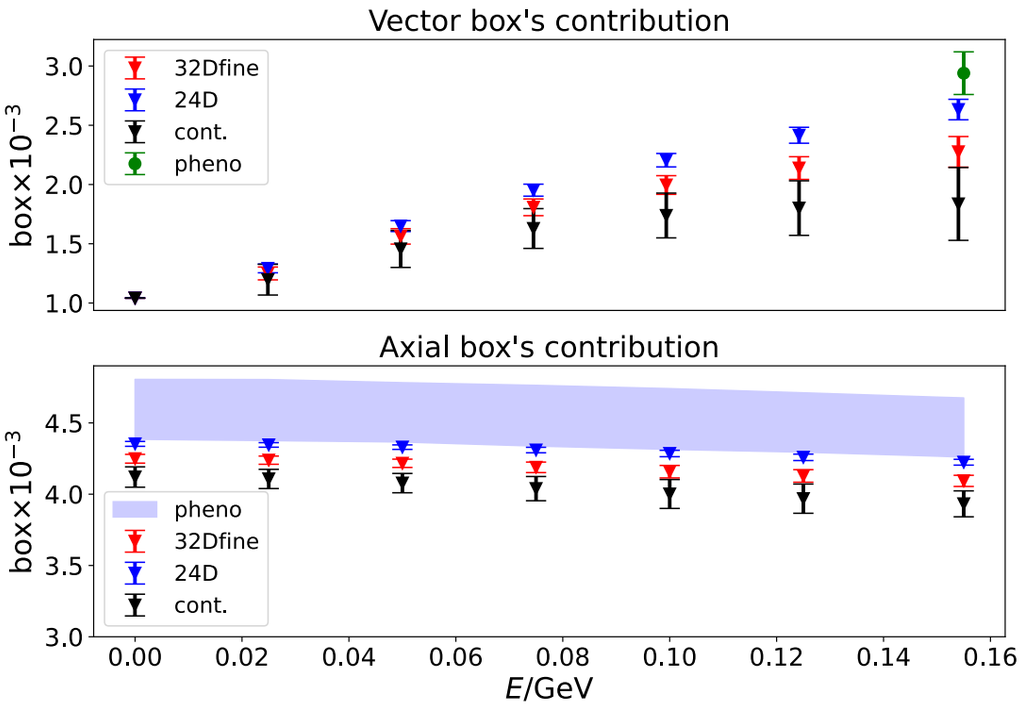


Figure 2. The beam energy dependence of vector box $\Box^V_{\gamma Z}(E)$ and axial-vector box $\Box^A_{\gamma Z}(E)$, with 24D, 32Dfine and continuum-extrapolated result.

	32Dfine	24D	Cont.	Pheno
$\Box^V_{\gamma Z}(0\ \text{MeV})$	1.041	1.041	1.041	1.041
$\Box^A_{\gamma Z}(0\ \text{MeV})$	4.249(32)	4.353(18)	4.121(74)	4.60(21)
$\Box_{\gamma Z}(0\ \text{MeV})$	5.290(32)	5.394(18)	5.162(74)	5.64(21)
$\Box^V_{\gamma Z}(155\ \text{MeV})$	2.28(13)	2.633(87)	1.84(31)	2.94(18)
$\Box^A_{\gamma Z}(155\ \text{MeV})$	4.093(40)	4.224(22)	3.932(93)	4.46(21)
$\Box_{\gamma Z}(155\ \text{MeV})$	6.37(13)	6.857(91)	5.77(32)	7.39(28)

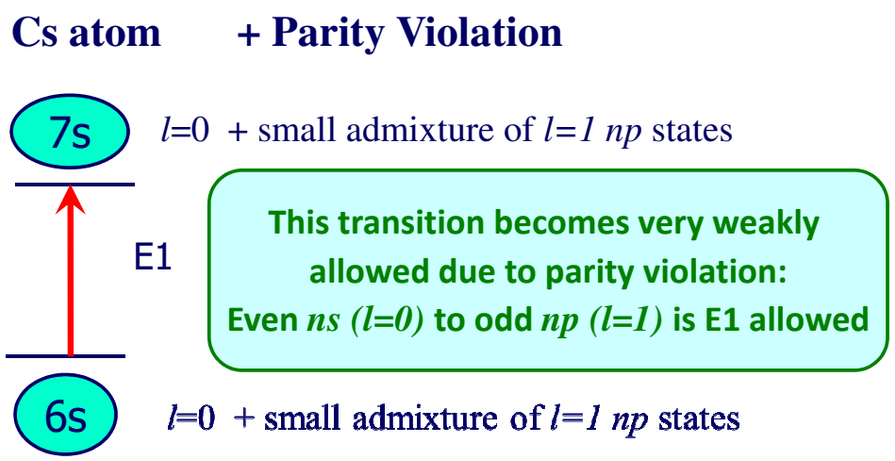
Table I. Numerical results of γZ box at beam energy $E = 0$ and 155 MeV. All the results are given in unit 10^{-3}.

Lattice uncertainties similar or smaller than those of the data-driven dispersion relation result

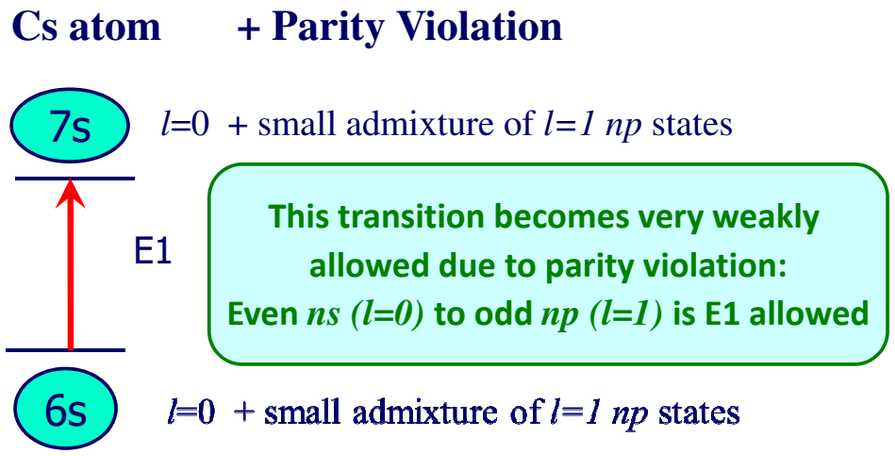
Discrepancy with DR observed, which seems to grow with energy — need further study!

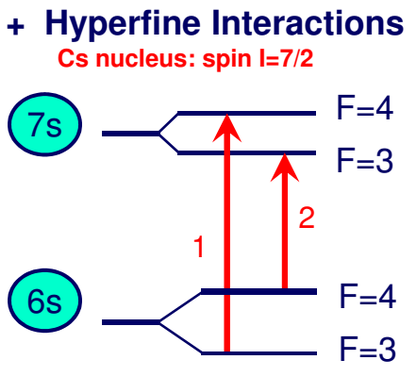
Nuclear Weak Charges from Atomic Parity Violation

Forbidden E1 transition possible with parity admixture



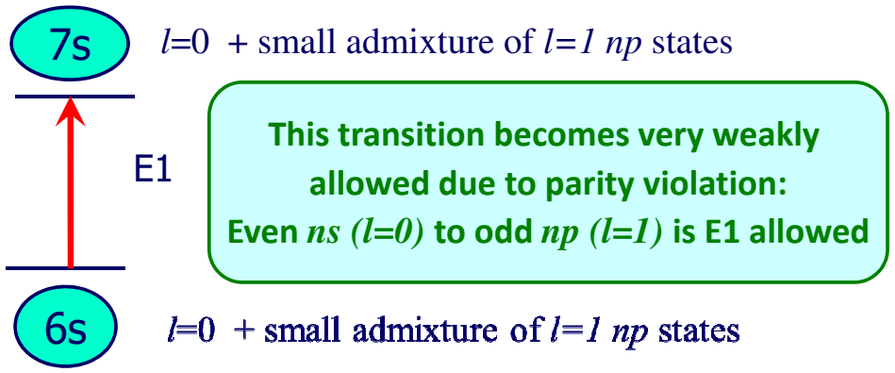
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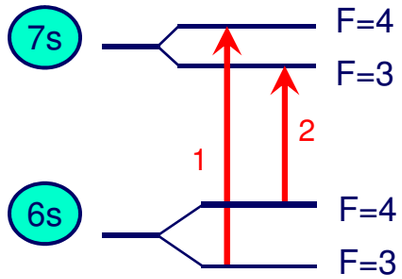
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Cs atom + Parity Violation

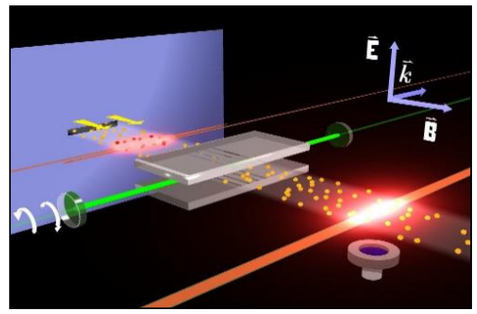


+ Hyperfine Interactions

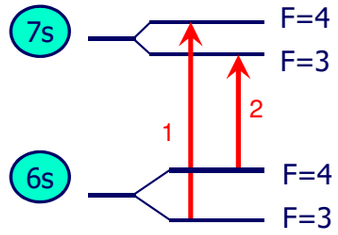
Cs nucleus: spin I=7/2



C.S. Wood et al. Science 275, 1759 (1997)



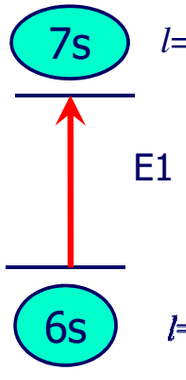
0.3% accuracy



$$\frac{\mathrm{Im}(E_{\mathrm{PNC}})}{\beta} = \begin{cases} -1.6349(80)\ {}^{\mathrm{mV}}/_{\mathrm{cm}} & 1 \\ -1.5576(77)\ {}^{\mathrm{mV}}/_{\mathrm{cm}} & 2 \end{cases}$$

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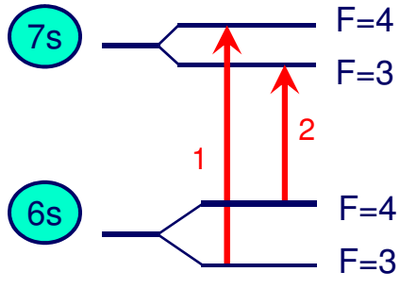
l=0 + small admixture of l=1 np states

This transition becomes very weakly allowed due to parity violation: Even *ns (l=0)* to odd *np (l=1)* is E1 allowed

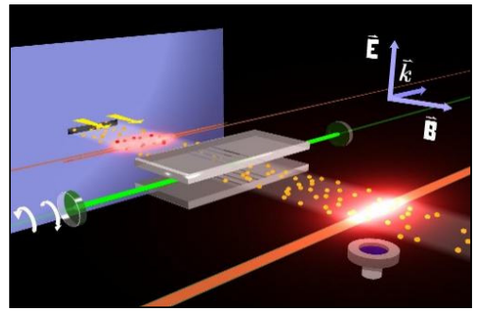
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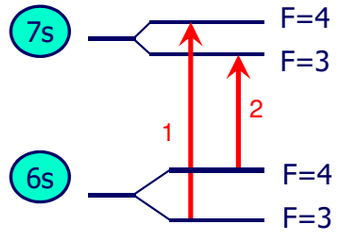
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C.S. Wood et al. Science 275, 1759 (1997)

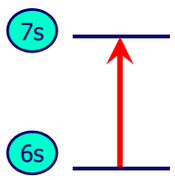


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NUCLEAR SPIN - INDEPENDENT APV



Average of 1 & 2

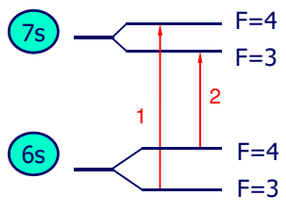
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Weak Charge Q_W

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$$Q_W = -2\sum_{q\in A} g_{AV}^{eq} = -N + (1 - 4\sin^2\theta_W)Z$$

NUCLEAR SPIN-DEPENDENT APV

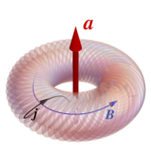


Difference of 1 & 2

$$\Delta\left[\mathrm{Im}\left(E_{\mathrm{PNC}}^{\mathrm{sd}}\right)/\beta\right]_{34-43} = -0.077(11)\ {}^{\mathrm{mV}}\!/_{\mathrm{cm}}$$

Nuclear anapole moment

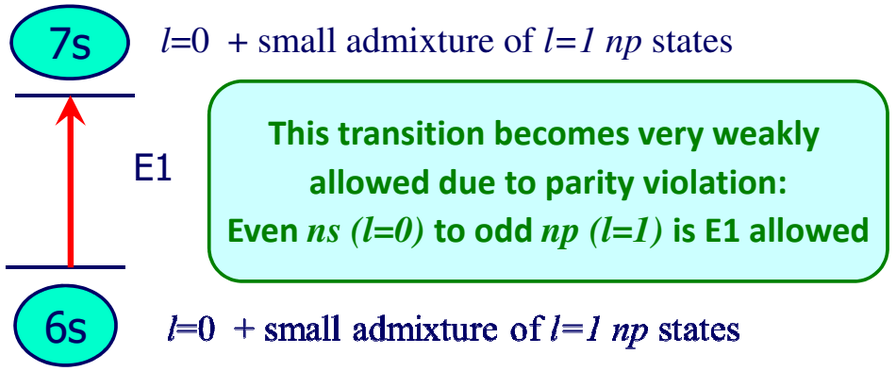
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Z^3 - enhanced in heavy nuclei

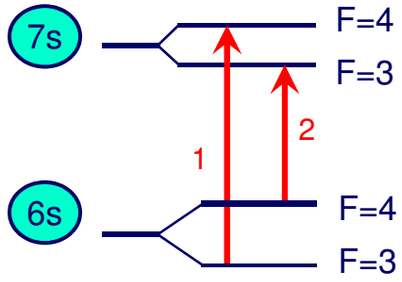
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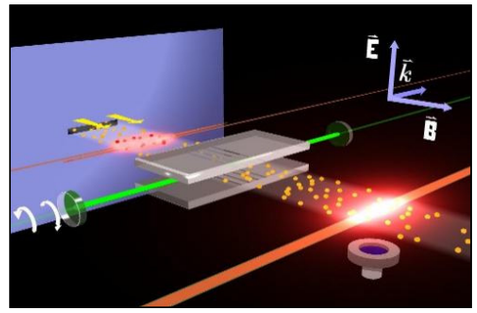


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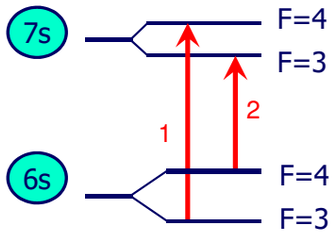
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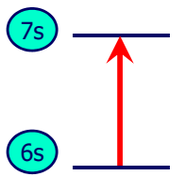


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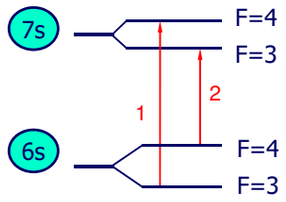
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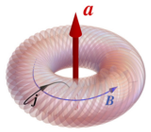


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Theory input to infer Q_W and anapole moment

- solve many-body QM problem

Electric-dipole matrix elements

$$E_{\mathrm{PNC}}^{theory} = \sum_{n=2}^{\infty} \frac{\langle 7s|d|np_{1/2}\rangle\langle np_{1/2}|H_{\mathrm{PNC}}|6s\rangle}{E_{6s} - E_{np_{1/2}}} + \sum_{n=2}^{\infty} \frac{\langle 7s|H_{\mathrm{PNC}}|np_{1/2}\rangle\langle np_{1/2}|d|6s\rangle}{E_{7s} - E_{np_{1/2}}}$$

Energies — PNC matrix elements

Sum is separated to n=2-5 part, **main n = 6 - 9 part**, and the tail n>9

2. Other small corrections:

Breit, QED, Neutron skin, e – e weak interaction

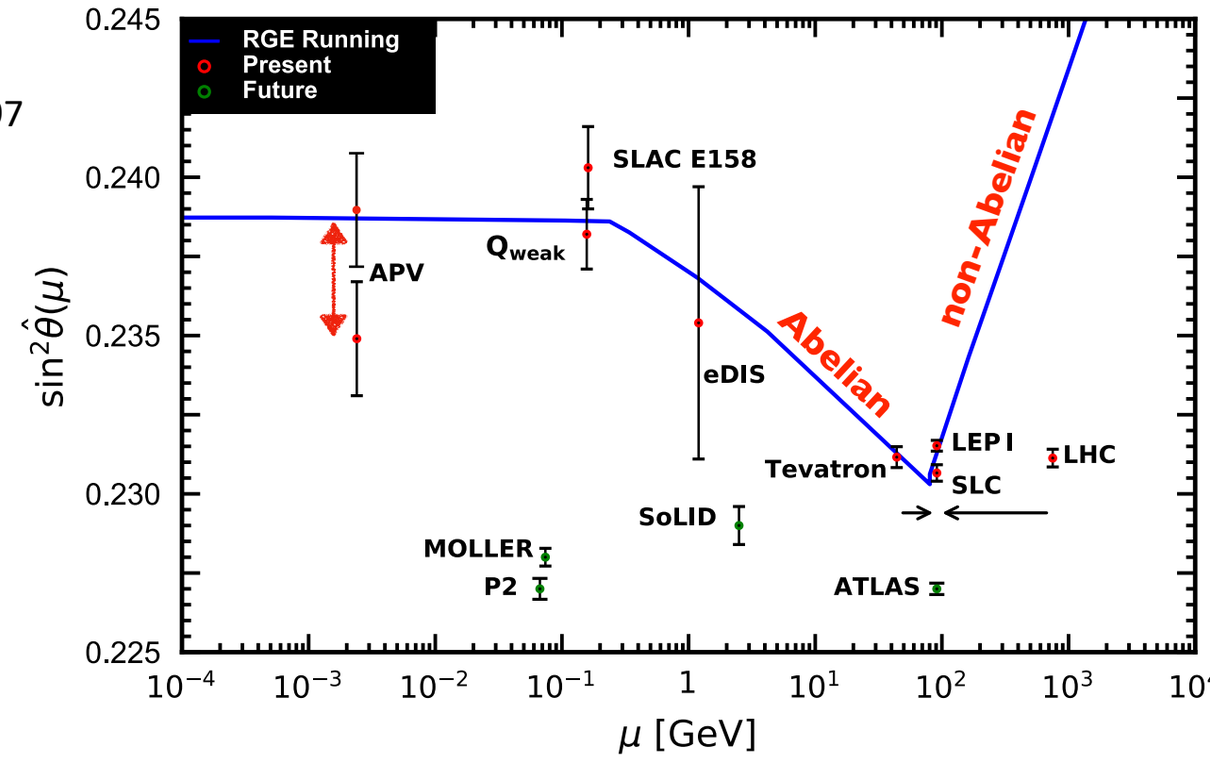
- vector polarizability of 6s-7s transition $\beta = 27.12(4)\ ea_0^3$

Atomic Calculations and Zitterbewegung of $Q_W(^{133}\mathrm{Cs})$

SM prediction: $Q_W(^{133}\mathrm{Cs}) = -73.23(1)$

Experiment $\dfrac{\mathrm{Im}\left(E_{\mathrm{PNC}}^{\mathrm{si}}\right)}{\beta} = -1.5935(56)\,{}^{\mathrm{mV}}\!/_{\mathrm{cm}}$ Wood et al, 1997

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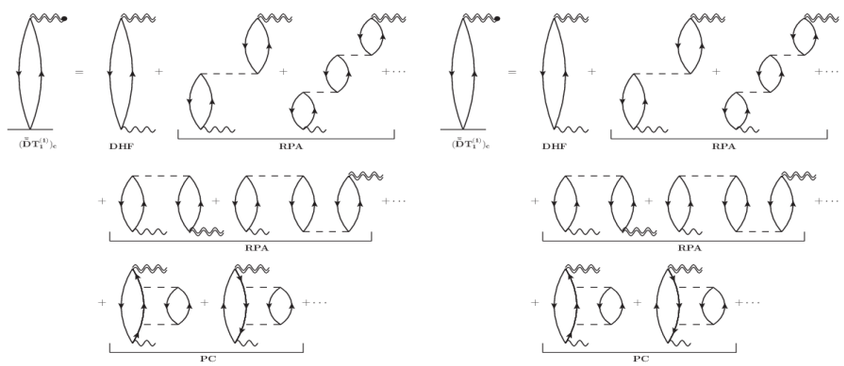
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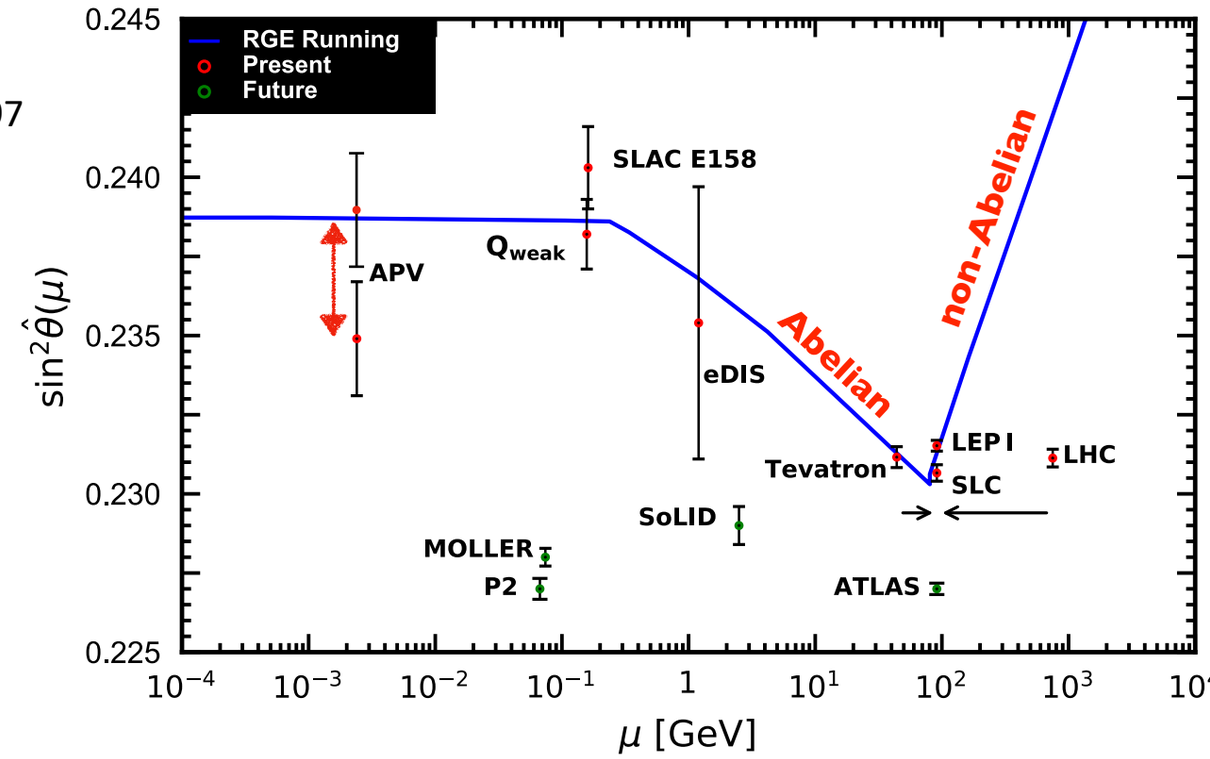
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Atomic theory: several methods

- Relativistic Coupled Cluster
- Dirac-Hartree-Fock with Core Polarization





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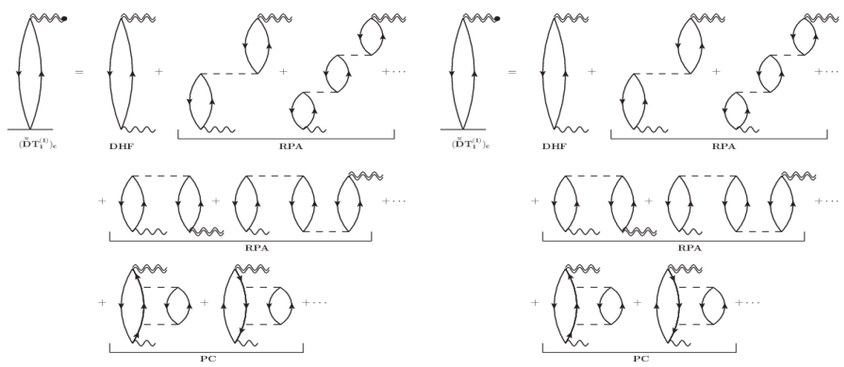
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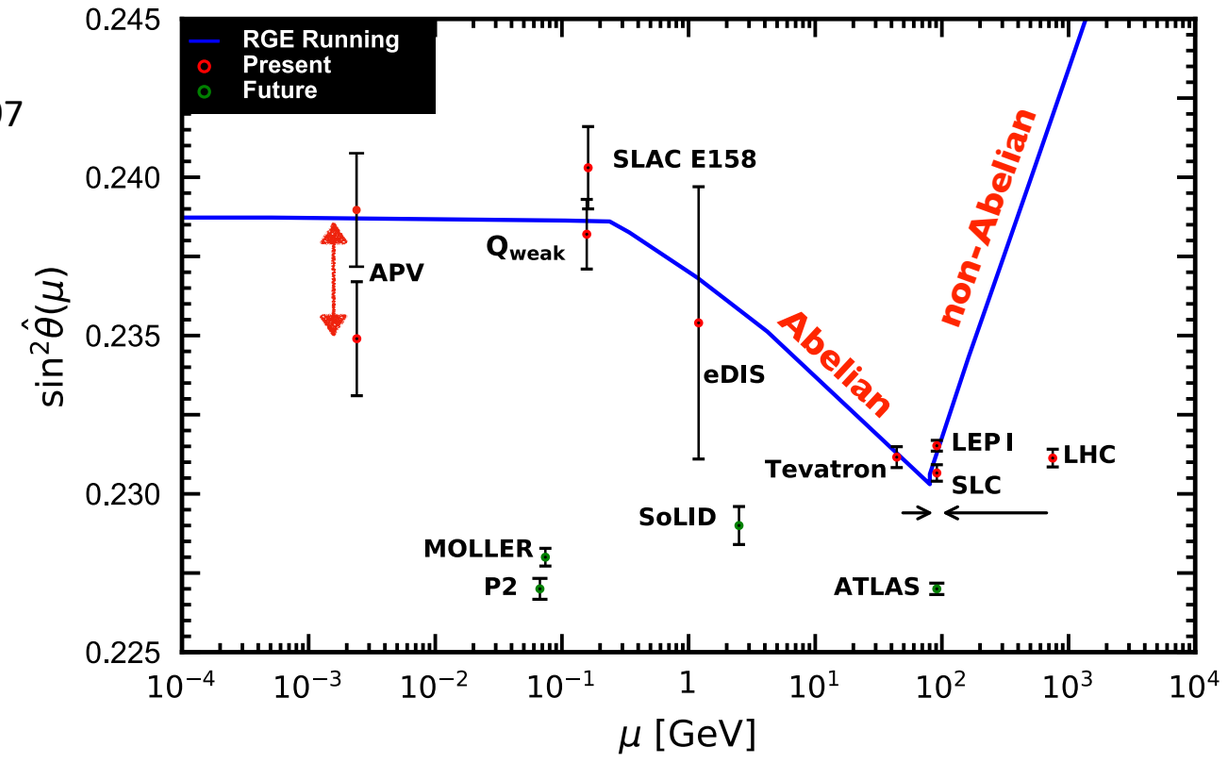
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Porsev et al. 2009, 2010



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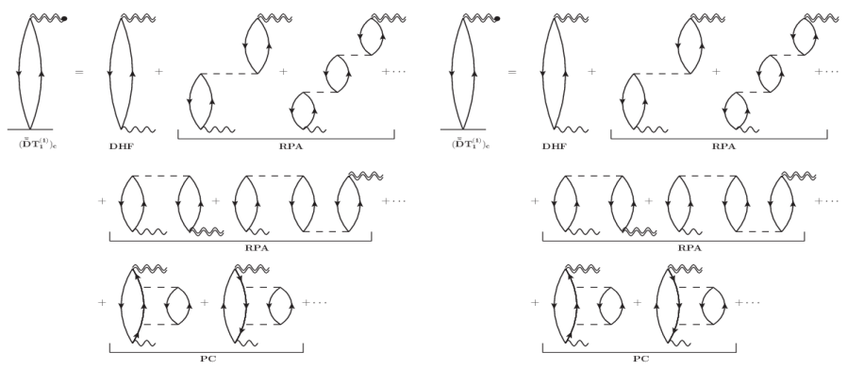
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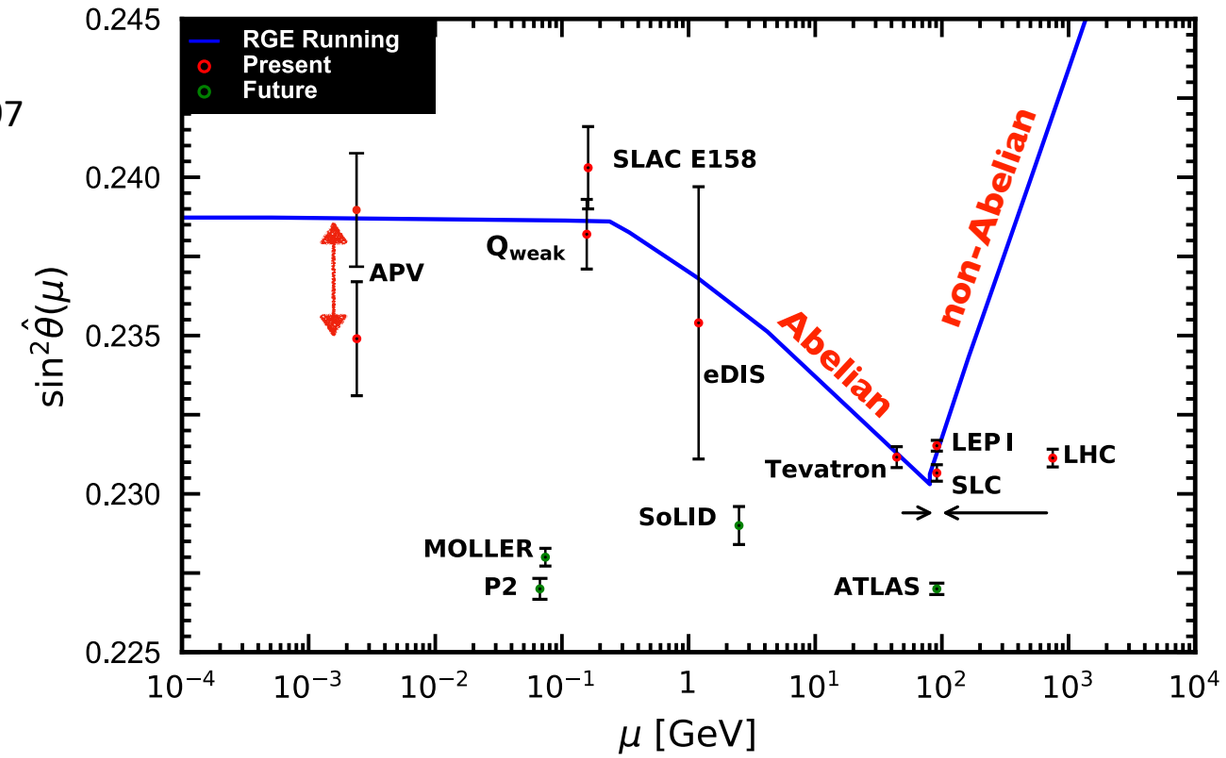
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Dzyuba et al, 2012

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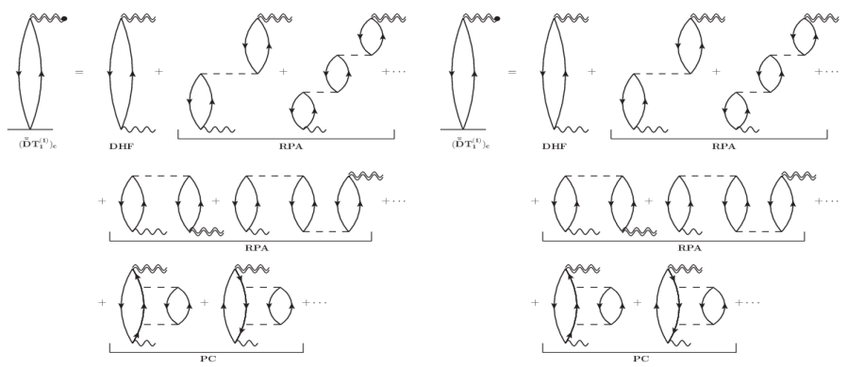
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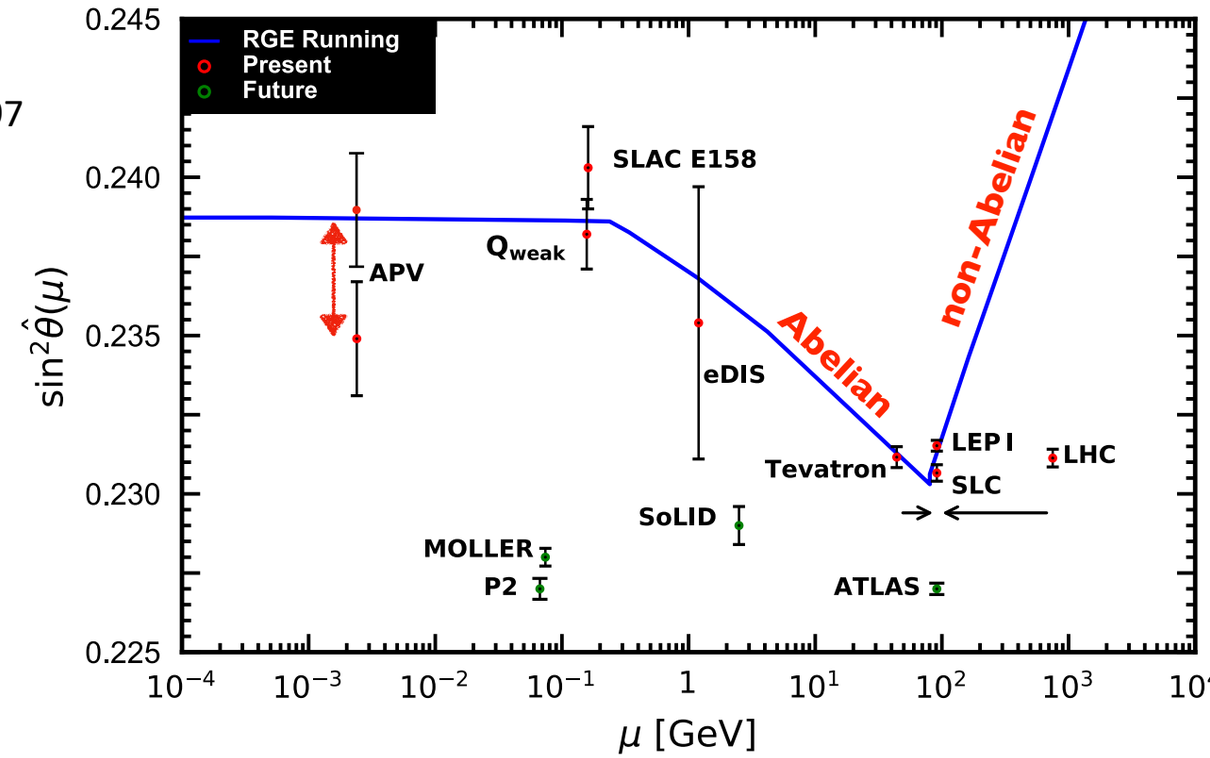
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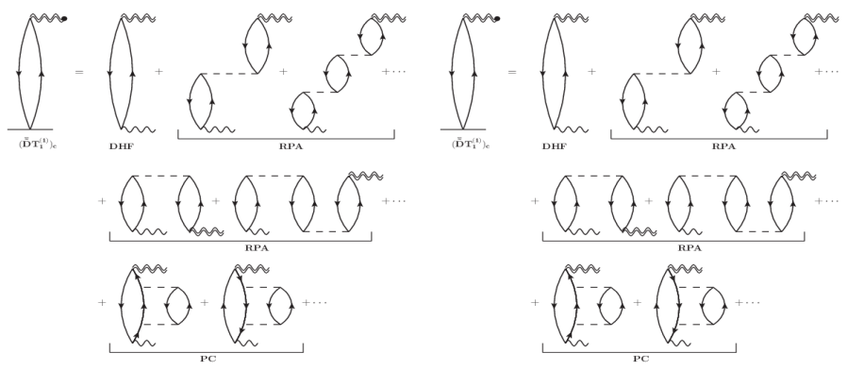
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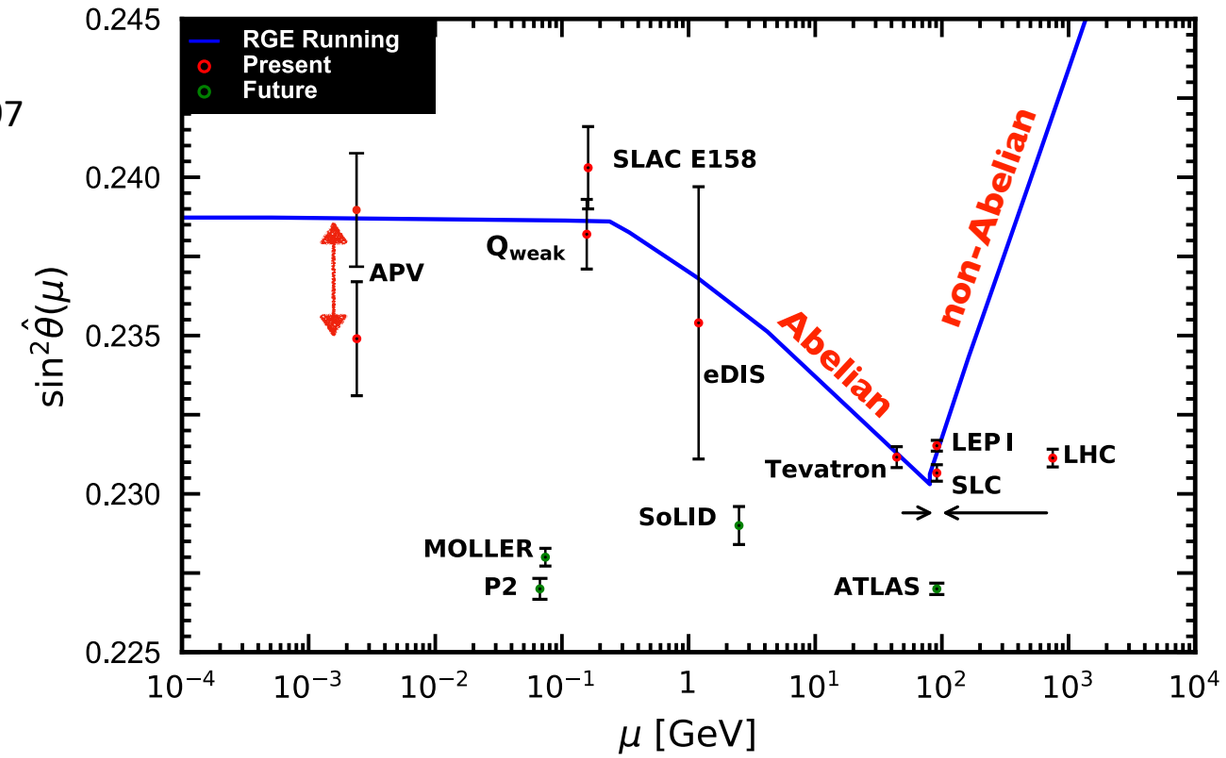
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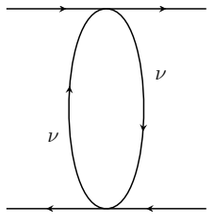
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Recently: “previously missed” parity-violating neutrino forces may shift the SM prediction by ~1%!!!

Ghosh et al, 2024, 2025
Flambaum, Samsonov, 2026

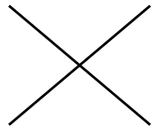


$\delta Q_W / Q_W = -0.8\,\% \quad \rightarrow \quad Q_W^{\mathrm{SM}} = -72.67(1)$

Neutrino-mediated neutrino forces and nuclear size

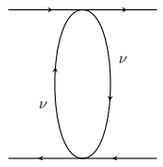
Electron-nucleus interaction in an atom

4-Fermi theory:



$$V_{4F}(r) = \frac{G_F Q_W}{2\sqrt{2}} \delta^3(\vec{r})$$

Exchange of massless $\nu\bar{\nu}$-pair



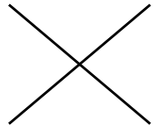
$$V_{eff}(r) \propto \frac{G_F^2}{r^5}$$

Divergent at short distances!

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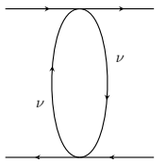
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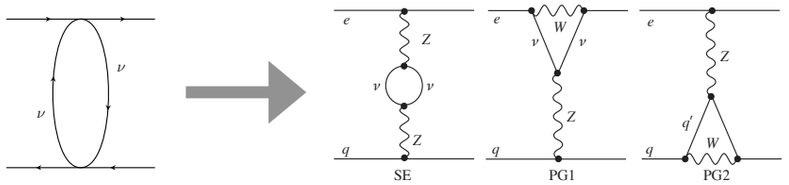


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Divergent at short distances!

Open the 4-F interaction (full SM)

Ghosh et al, 2024, 2025



$$V_{eff}(r) \approx -\frac{G_F M_Z^2}{12\sqrt{2}\pi^2} N_{eff} \frac{G_F Q_W}{2\sqrt{2}} \delta^3(\vec{r})$$

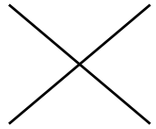
Rendered finite by the Z-mass —> correction scales as αG_F instead of G_F^2

Include all active fermions below Z —> $N_{eff} \approx 14.5$ $\quad \delta Q_W / Q_W = -0.8\,\%$ Flambaum, Samsonov, 2026

Neutrino-mediated neutrino forces and nuclear size

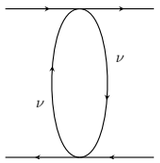
Electron-nucleus interaction in an atom

4-Fermi theory:



$$V_{4F}(r) = \frac{G_F Q_W}{2\sqrt{2}} \delta^3(\vec{r})$$

Exchange of massless $\nu\bar{\nu}$-pair

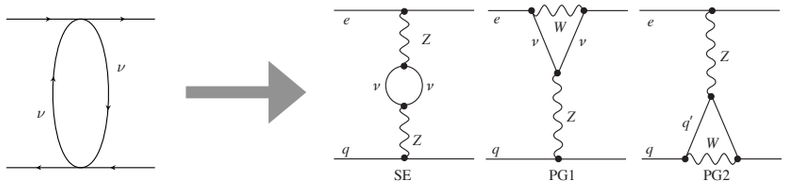


$$V_{eff}(r) \propto \frac{G_F^2}{r^5}$$

Divergent at short distances!

Open the 4-F interaction (full SM)

Ghosh et al, 2024, 2025



$$V_{eff}(r) \approx -\frac{G_F M_Z^2}{12\sqrt{2}\pi^2} N_{eff} \frac{G_F Q_W}{2\sqrt{2}} \delta^3(\vec{r})$$

Rendered finite by the Z-mass —> correction scales as αG_F instead of G_F^2

Include all active fermions below Z —> $N_{eff} \approx 14.5$ $\quad \delta Q_W / Q_W = -0.8\,\%$ Flambaum, Samsonov, 2026

But: nucleus and atom have finite size! MG, Spiesberger, 2605.17059

Anything that happens at $r \sim M_Z^{-1}$ is cut-off by the finite resolution of the probe (nuclear or atom)

We explicitly included finite size effectsand found that no distances shorter than atomic radius play a role

$$\frac{\delta Q_W^{Z,N}}{Q_W^{Z,N}} = \frac{\tilde{\kappa}_{\nu\bar{\nu}}^{\mathrm{FS}}}{\kappa_Z} = \frac{G_F (Z\alpha m)^2}{3\sqrt{2}\pi^2} \sim 10^{-14} \left(\frac{Z}{55}\right)^2$$

No large (~1%) corrections to the nuclear weak charge due to neutrino exchanges

Summary and Open questions

Running of WMA: precise prediction of the Standard Model
Hadronic uncertainties must be controlled to warrant tests of running WMA

Future experiments (P2, Moller) will provide stringent tests of (B)SM, complementary to colliders
P2 unique feature: extract BOTH weak charge and form factors within one experiment

γZ-box mostly under control, but recent lattice result challenges data-driven method
Comparison with PVDIS data — mixed message (mostly OK but some discrepancies)

Additional insights from auxiliary MOLLER data (ep elastic, ep inelastic)

“Long-range” neutrino-mediated PV forces in atoms: NO large corrections to nuclear weak charges