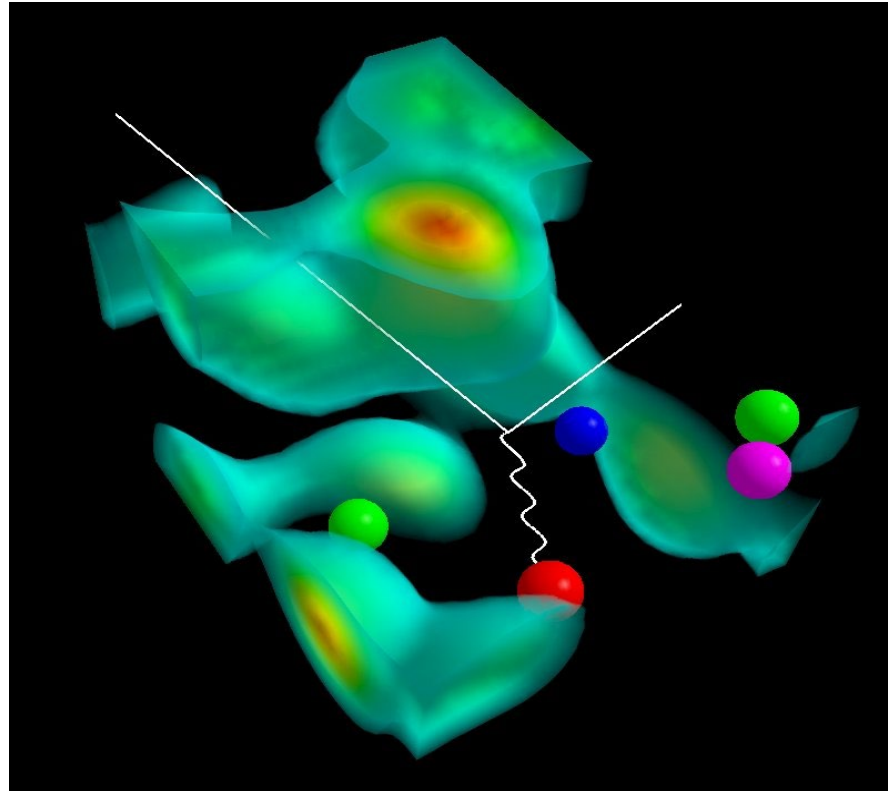


# Dark Photon and PVES



**Anthony W. Thomas**

**Parity Violation and other EW Physics at JLab 12 GeV and Beyond**  
**INT - 27<sup>th</sup> June 2022**

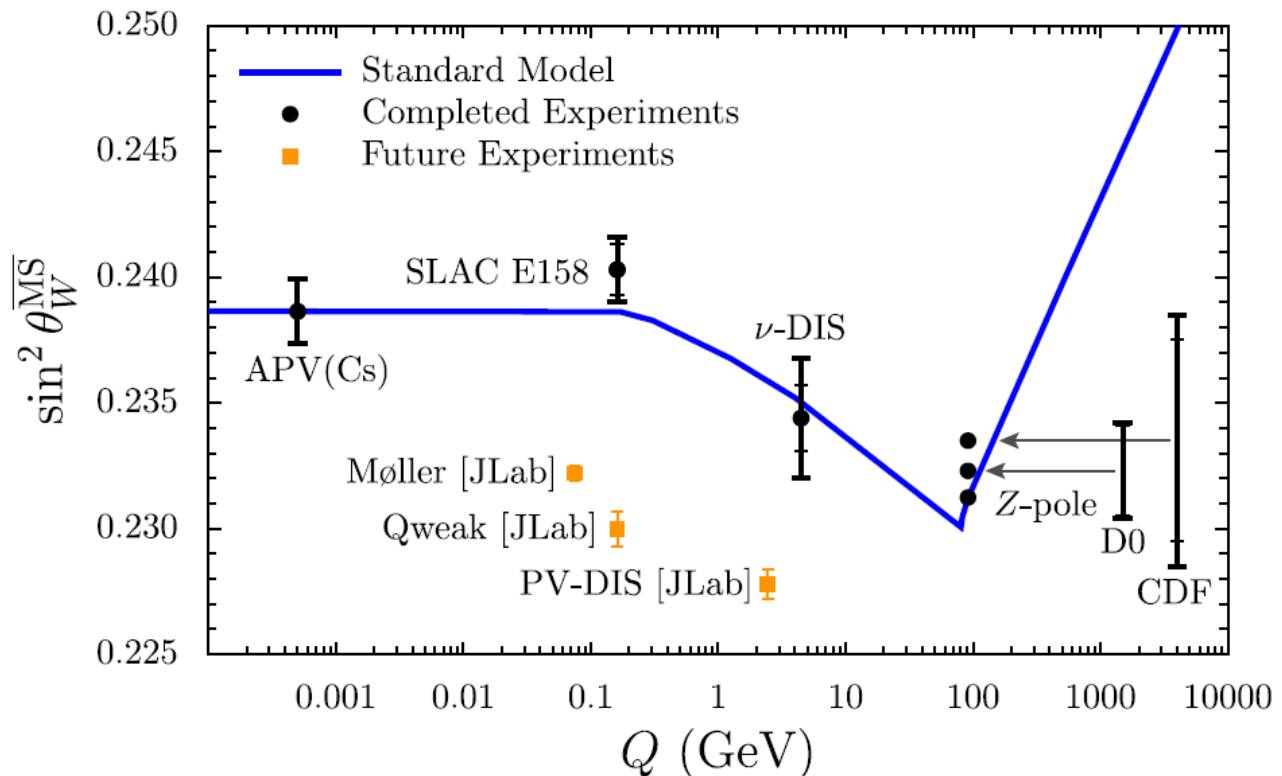
# Reminder concerning NuTeV

Reassessment of the NuTeV determination of the weak mixing angle

W. Bentz<sup>a</sup>, I.C. Cloët<sup>b,\*</sup>, J.T. Londergan<sup>c</sup>, A.W. Thomas<sup>d,e</sup>

Physics Letters B 693 (2010) 462–466

**Taking into account corrections from Charge Symmetry Violation and isovector EMC effect:**



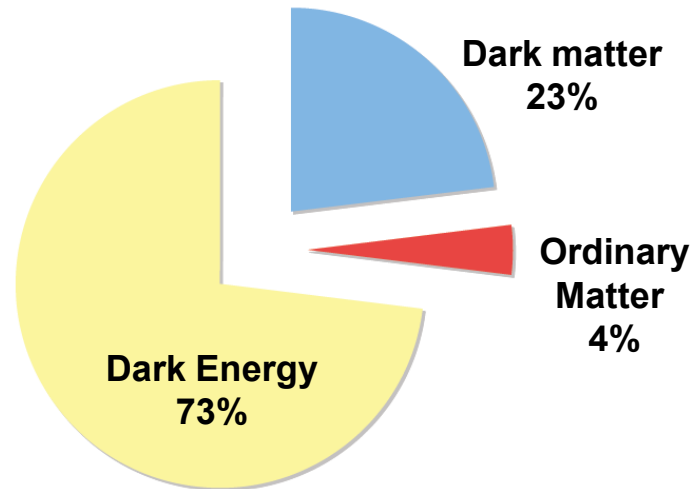
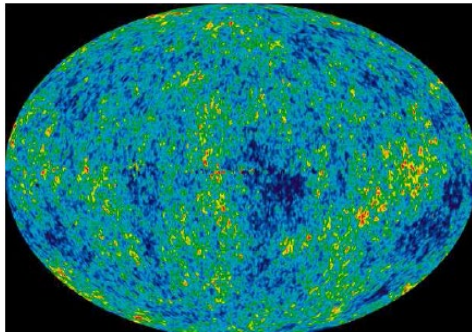
# Outline

- **New  $U_Y(1)$  boson as a dark matter candidate**
- **Effects in deep-inelastic scattering**
  - notably HERA
- **Effects on other measurements of parity violation**
  - PREX
  - Atomic PV
- **New  $W$  mass measurement**

# Dark Matter and Dark Energy

Over the past two decades we have learnt that, in spite of the successes of the Standard Model, most of the matter in the Universe is something else

– Dark Matter



It interacts very weakly but has major gravitational effects

# Dark Photon

- There are a number of formulations of the dark photon
- Initially purely vector couplings, then more like a  $Z'$
- For us it is a  $U_Y(1)$  boson interacting with Standard Model particles through kinetic mixing

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\bar{m}_{A'}^2}{2} A'_\mu A'^\mu + \frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$$

- So that the couplings are:

$$C_Z^v = (\cos \alpha - \epsilon_W \sin \alpha) \bar{C}_Z^v + \epsilon_W \sin \alpha \cot \theta_W C_\gamma^v,$$

$$C_Z^a = (\cos \alpha - \epsilon_W \sin \alpha) \bar{C}_Z^a,$$

and

$$C_{A_D}^v = -(\sin \alpha + \epsilon_W \cos \alpha) \bar{C}_Z^v + \epsilon_W \cos \alpha \cot \theta_W C_\gamma^v,$$

$$C_{A_D}^a = -(\sin \alpha + \epsilon_W \cos \alpha) \bar{C}_Z^a.$$

# Dark Photon (cont.)

Where the Standard Model Z couplings are

$$\bar{C}_Z \sin 2\theta_W = T_3^f - 2q_f \sin^2 \theta_W, \quad \bar{C}_Z^a \sin 2\theta_W = T_3^f$$

and the mixing parameters are




$$\tan \alpha = \frac{1}{2\epsilon_W} \left[ 1 - \epsilon_W^2 - \rho^2 - \text{sign}(1 - \rho^2) \sqrt{4\epsilon_W^2 + (1 - \epsilon_W^2 - \rho^2)^2} \right]$$

and

$$\epsilon_W = \frac{\epsilon \tan \theta_W}{\sqrt{1 - \epsilon^2 / \cos^2 \theta_W}}$$
$$\rho = \frac{\bar{m}_{A'} / \bar{m}_{\bar{Z}}}{\sqrt{1 - \epsilon^2 / \cos^2 \theta_W}}$$

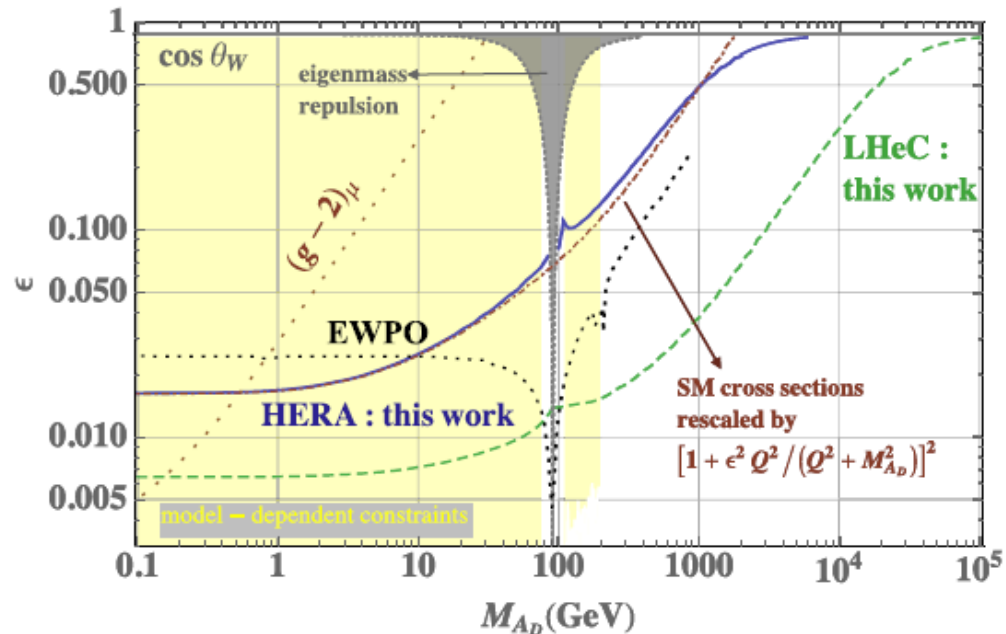
with  $\epsilon$  the mixing parameter in the Lagrangian

## Constraints on the dark photon from deep inelastic scattering

A. W. Thomas , X. G. Wang , and A. G. Williams 

ARC Centre of Excellence for Dark Matter Particle Physics and CSSM, Department of Physics,  
University of Adelaide, Adelaide, SA 5005, Australia

- Followed initial study by Kribs *et al.*, PRL 126 (2021) 011801 which took HERAPDF 2.0 fit and placed limits on any additional dark photon contribution



EWPO: Curtin *et al.*, JHEP 2 (2015) 157

# Exploratory DIS Analysis

Including the dark photon the structure function becomes

$$\tilde{F}_2 = \sum_{i,j=\gamma,Z,A_D} \kappa_i \kappa_j F_2^{ij}, \quad \kappa_i = Q^2 / (Q^2 + M_{V_i}^2)$$

with

$$F_2^{ij} = \sum_q x f_q (C_{i,e}^v C_{j,e}^v + C_{i,e}^a C_{j,e}^a) (C_{i,q}^v C_{j,q}^v + C_{i,q}^a C_{j,q}^a)$$

and following the earlier work of Wang and Thomas

J. Phys. G: Nucl. Part. Phys. 47 (2020) 015102

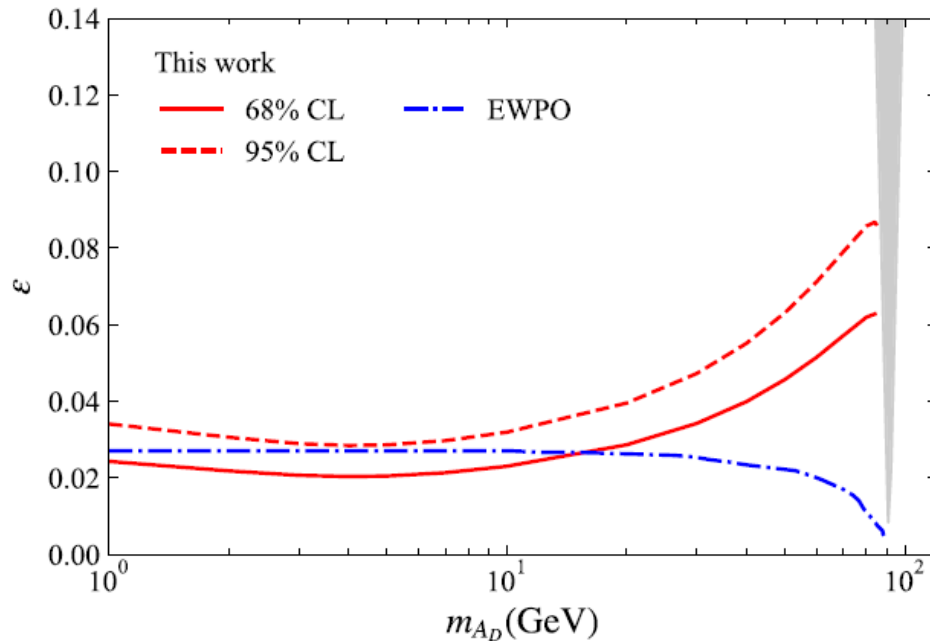
included VMD at lower  $Q^2$

$$F_2(x, Q^2) = F_2^{\text{VMD}}(x, Q^2) + \frac{Q^2}{Q^2 + M_0^2} \tilde{F}_2(\bar{x}, Q^2 + M_0^2)$$



# Exploratory DIS (cont.)

Improvement on Kribs *et al.* was that our search on the dark photon also allowed the PDFs to change



Data sample was 259 points from BCDMS and HERA with total  $\chi^2$  292 with VMD (c.f. 347 without)

# Dark Photon Beyond DIS

- Study of sensitivity of PVES: AWT, XG Wang and AG Williams  
arXiv:2201.06760 (PRL to appear)
- Examined effects of a dark photon on
  - PV electron DIS
  - PREX: neutron skin in Pb
  - as well as PV in high- $Q^2$  DIS, e.g. EIC and measurement of  $C_{3q}$
- PV DIS:

$$A_{\text{PV}} = \frac{Q^2}{2 \sin^2 2\theta_W (Q^2 + M_Z^2)} \left[ a_1^{\gamma Z} + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3^{\gamma Z} \right. \\ \left. + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} \left( a_1^{\gamma A_D} + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3^{\gamma A_D} \right) \right],$$

with

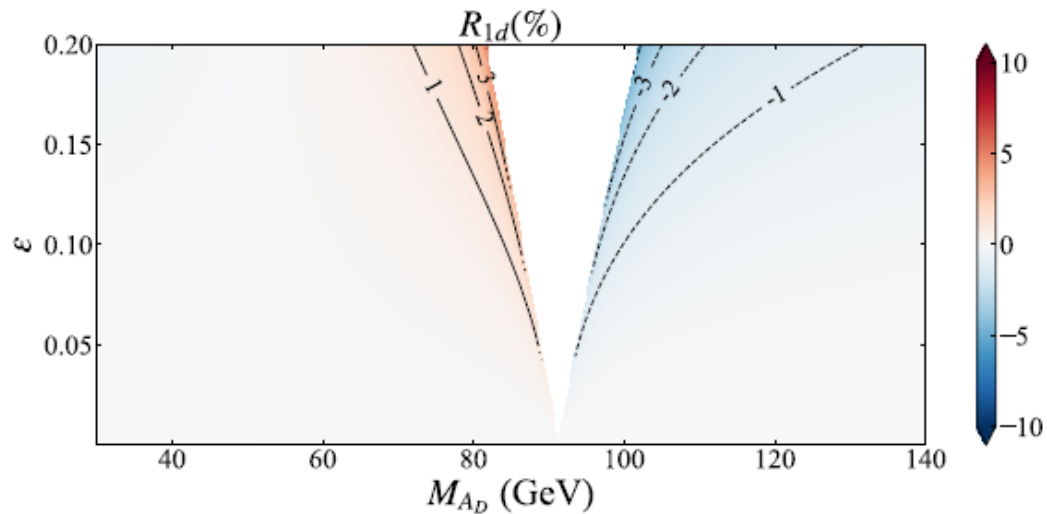
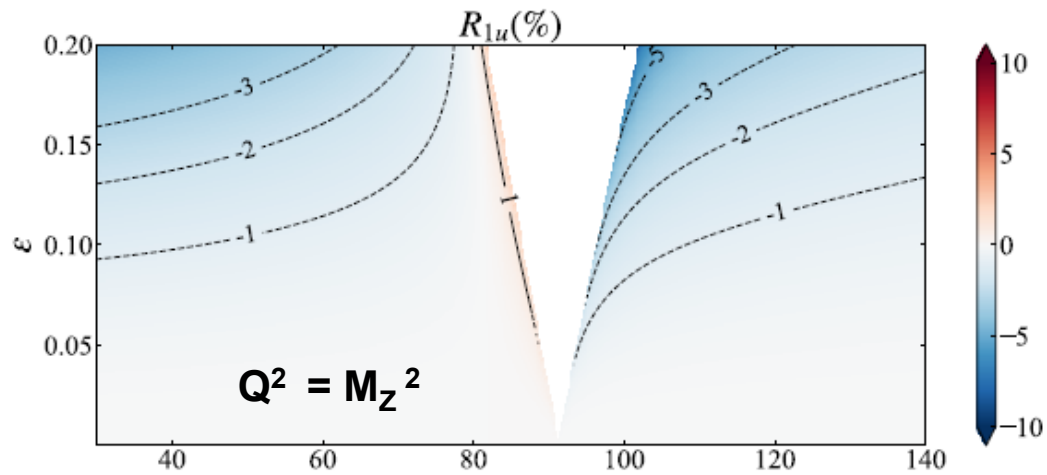
$$a_1 = \frac{2 \sum_q e_q C_{1q}(q + \bar{q})}{\sum_q e_q^2 (q + \bar{q})}$$

$$a_3 = \frac{2 \sum_q e_q C_{2q}(q - \bar{q})}{\sum_q e_q^2 (q + \bar{q})}$$

# Parity Violating DIS

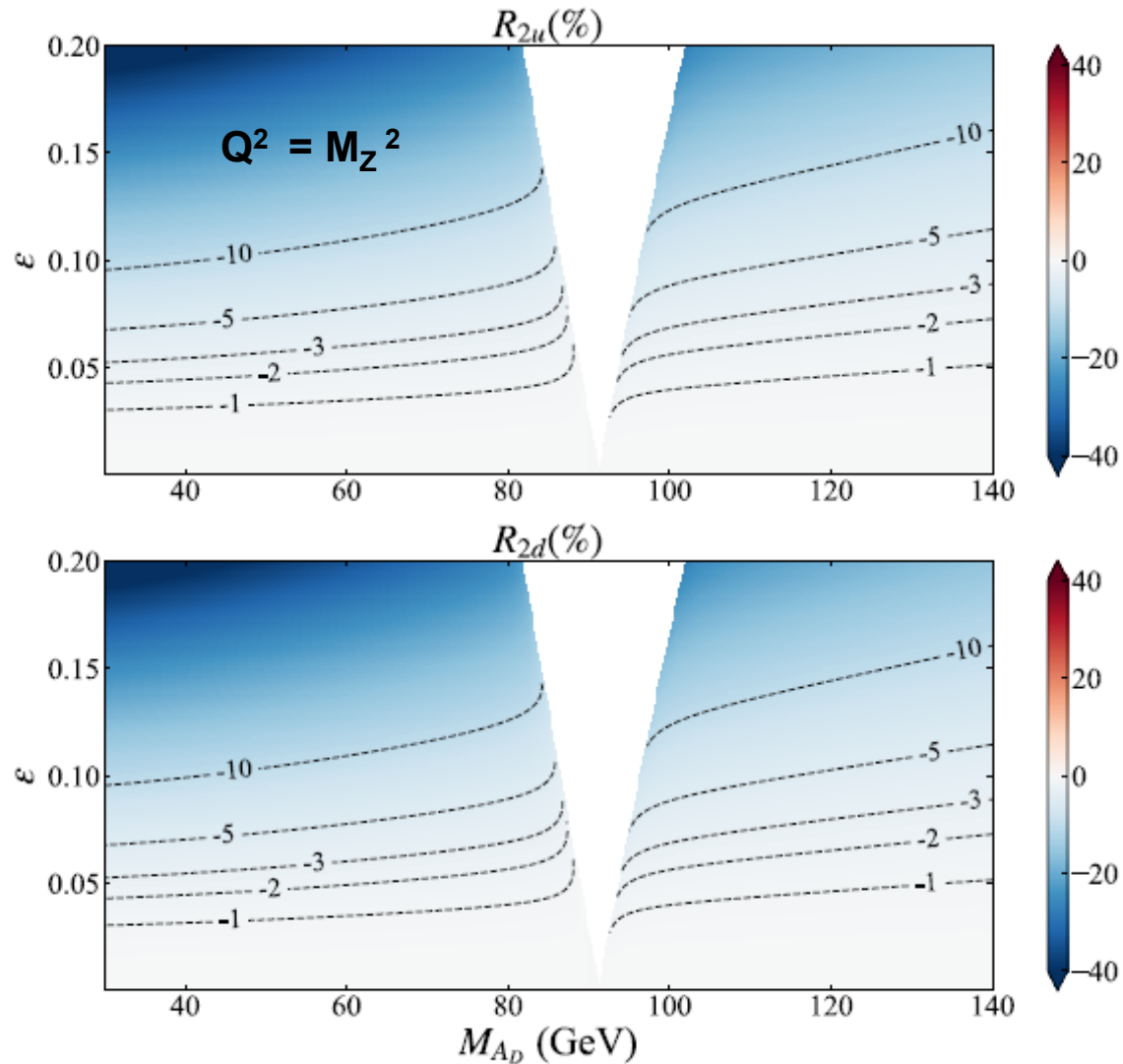
$$C_{1q} = C_{1q}^Z + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} C_{1q}^{A_D} = C_{1q}^{\text{SM}}(1 + R_{1q})$$

$$C_{2q} = C_{2q}^Z + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} C_{2q}^{A_D} = C_{2q}^{\text{SM}}(1 + R_{2q})$$



# Larger effects on valence PDFs from HERA

Changes as large as 10%



# Standard Model Test at JLab

Test of axial-axial coupling ,  $g_{AA}^{eq}$  or  $C_{3q}$ , using difference of  $e^-$  and  $e^+$

- correction up to 5%

$$A_d^{e^+e^-} = -\frac{3G_F Q^2 Y}{2\sqrt{2}\pi\alpha} \frac{R_V(2g_{AA}^{eu} - g_{AA}^{ed})}{5 + 4R_C + R_S}$$

$$C_{3q} = C_{3q}^Z + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} C_{3q}^{A_D} = C_{3q}^{SM}(1 + R_{3q})$$

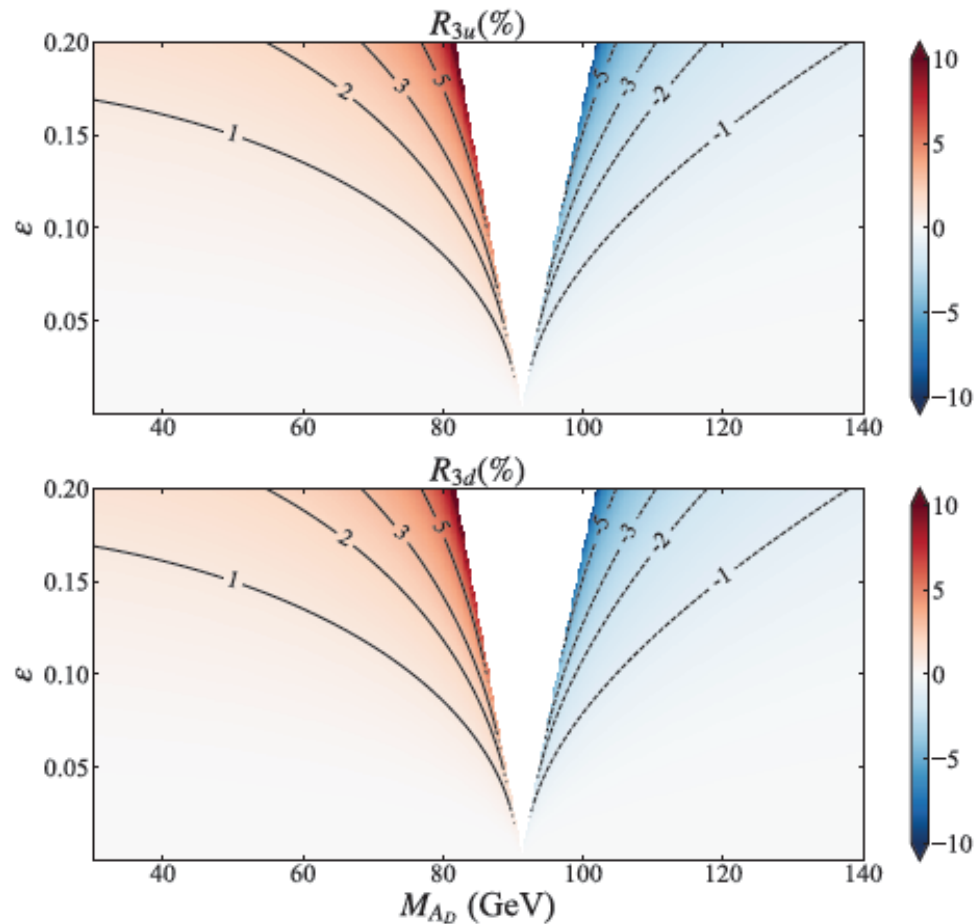
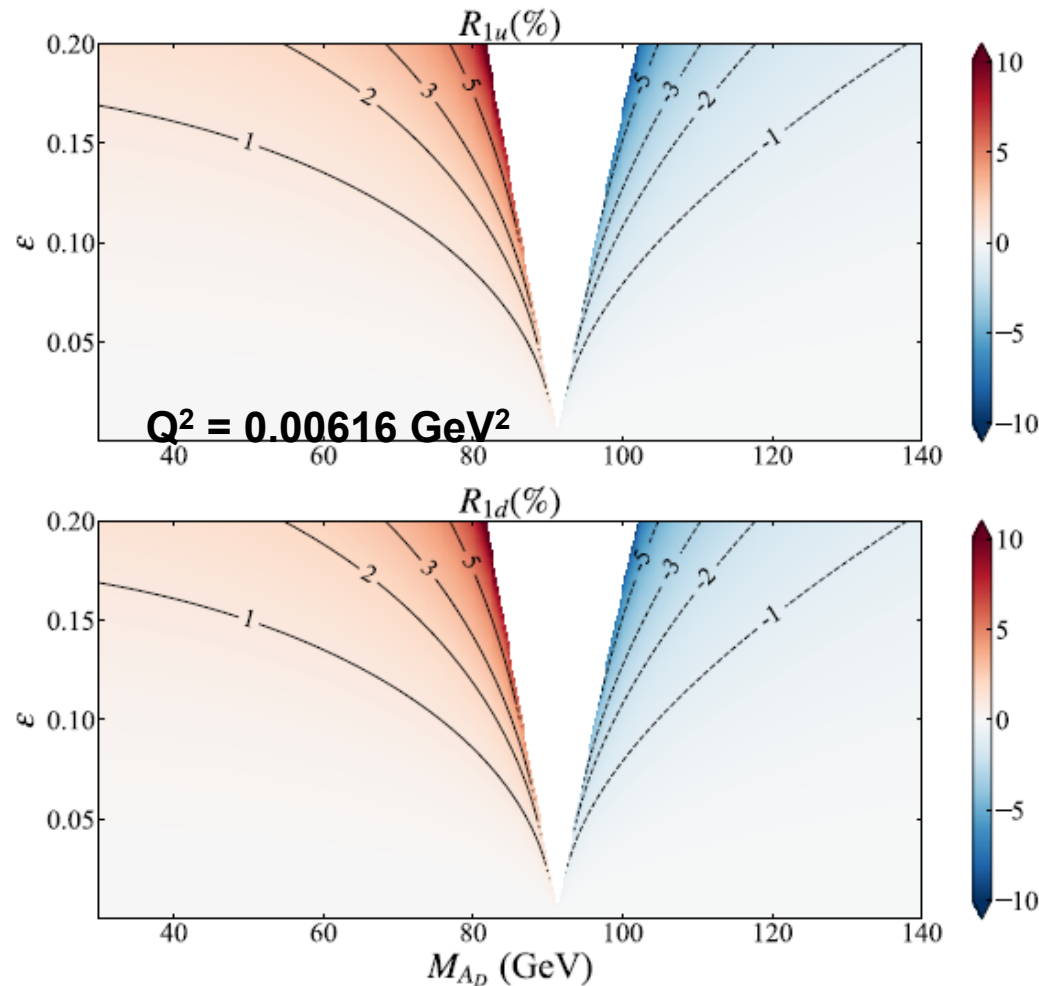


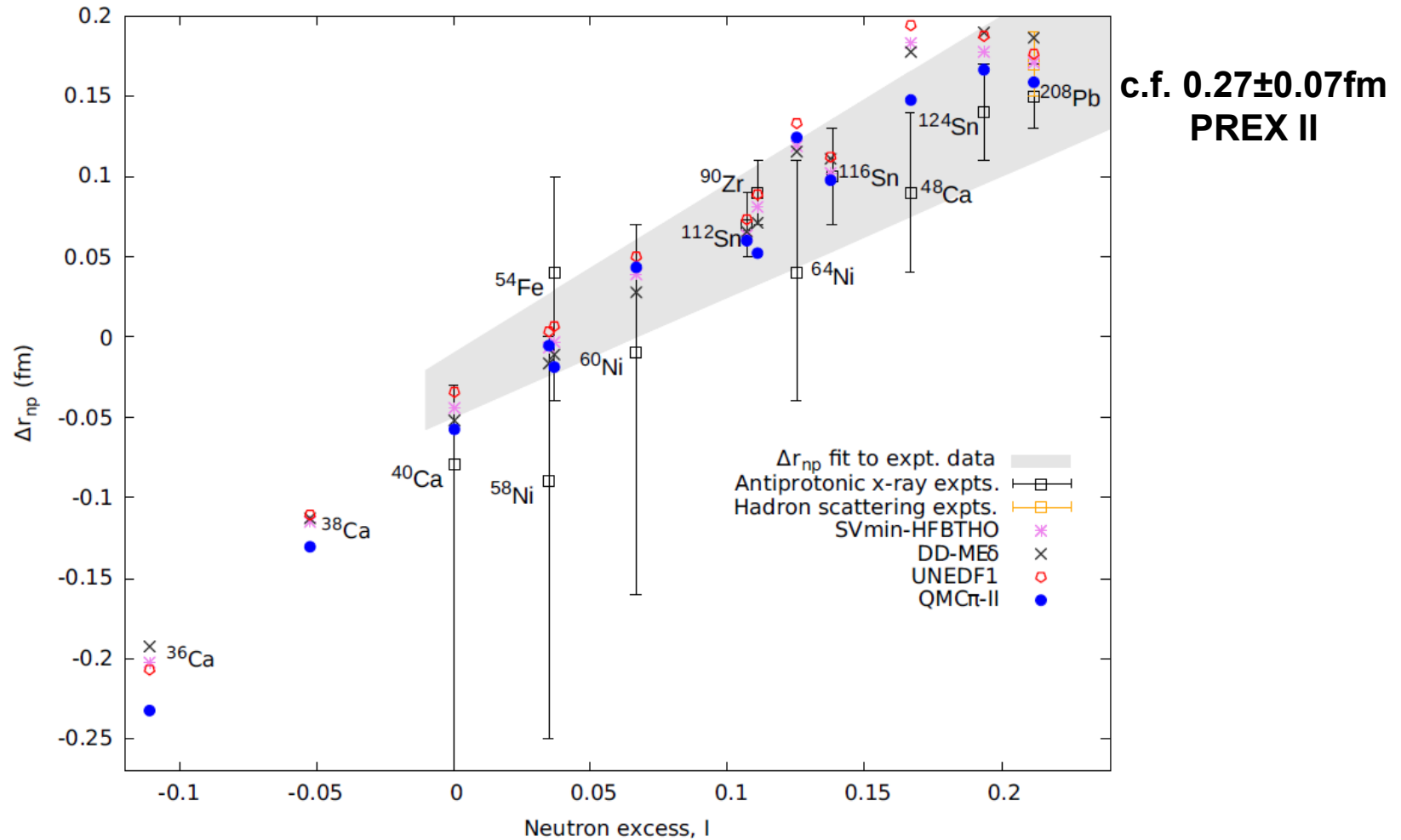
FIG. 4. The correction factors  $R_{3u}$  and  $R_{3d}$  at  $Q^2 = 10 \text{ GeV}^2$ .

# PREX Elastic PV Scattering on $^{208}\text{Pb}$

- Measurement of neutron radius gave surprisingly large  $r_n - r_p$
- Change in  $C_{1u}$  of 4% would eliminate tension with nuclear theory



# Difference in p and n radii in $^{208}\text{Pb}$



**Next: Explore effects on key PV observables**



# Refit of PV Observables with Dark Photon

Experiment	$Q^2$ (GeV <sup>2</sup> )	data	SM	SM + dark photon (fit)
Qweak [18]	0.0248	$Q_w^p = 0.0719 \pm 0.0045$	0.0708	0.0706
PREX-II [19, 81]	0.00616	$Q_w(^{208}\text{Pb}) = -114.4 \pm 2.6$	-117.9	-116.8
PVDIS [20] ( $\times 10^{-6}$ )	1.085	$A_{\text{PV}}^{\text{exp}(1)} = -91.1 \pm 3.1 \pm 3.0$	-87.7	-86.9
	1.901	$A_{\text{PV}}^{\text{exp}(2)} = -160.8 \pm 6.4 \pm 3.1$	-158.9	-157.5
APV [85]		$Q_w(^{133}\text{Cs}) = -72.58(29)_{\text{expt}}(32)_{\text{theo}}$	-73.23	-72.55

Table I. The PVES and APV data. The fit results including the dark photon effects are given in the last column.

$$\chi_{\text{total}}^2 = 2.077, \text{ compared with the value } \chi_{\text{total}}^2 = 4.830$$

# New W mass

Aaltonen et al. (CDF) Science **376**, no.6589, 170-176 (2022)

$m_W = 80.4335 \pm 0.0094$  GeV **7 $\sigma$  from earlier value**

$$m_W^2 = m_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha_{em}}{\sqrt{2}G_F m_Z^2} [1 + \Delta r(m_W, m_Z, m_H, m_t, \dots)]} \right\}$$

Awramik et al., Phys. Rev. **69** (2004) 053006

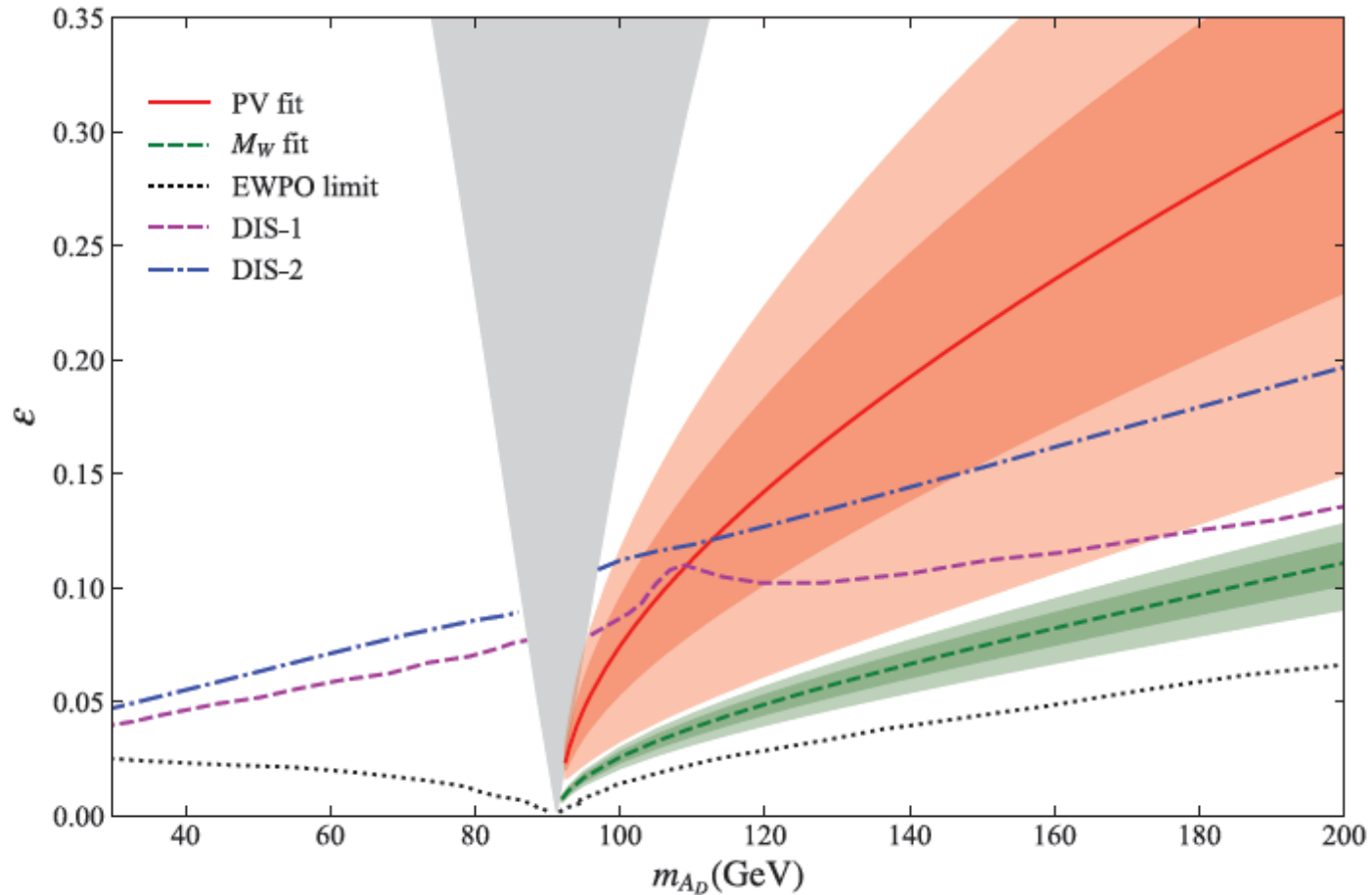
Using  $m_H = 125.14$  GeV and  $m_t = 172.89$  GeV, we derive  $\Delta r = 0.03677$

and hence:  $m_Z = 91.2326 \pm 0.0076$  GeV

compared with the physical value:  $m_Z = 91.1875 \pm 0.0021$  GeV

# Constraints of new W mass versus PV

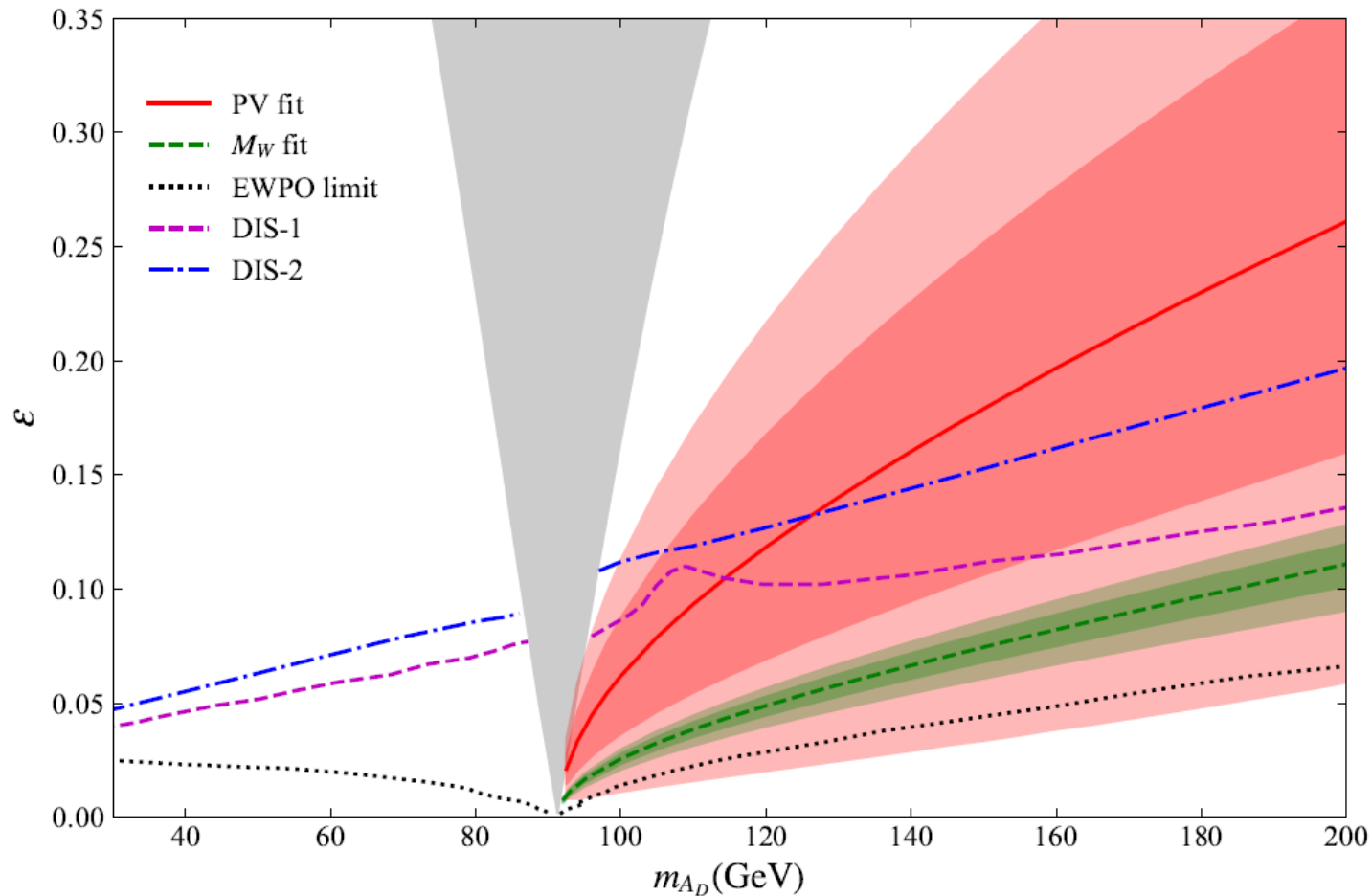
Thomas and Wang, arXiv: 2205.01911



Using Cs value from Dzuba et al., Phys Rev Lett 109 (2012) 203003

$$Q_w(^{133}\text{Cs}) = -72.58(29)_{\text{expt}}(32)_{\text{theo}}$$

# Alternatively, using PDG value for Cs



**PV data is consistent with new W mass  
for dark photon above Z mass**

# Summary

- **The dark photon improves the agreement between theory and a number of parity violation experiments**
- **A few percent correction would reduce tension around the neutron distribution in Pb**
- **It would improve the agreement between result for Cs and the Standard Model while also agreeing with the new  $W$  mass measurement**
- **There are exciting opportunities to test its existence in PV experiments at JLab and EIC**



# Fit using PDG value for $^{137}\text{Cs}$

Experiment	$Q^2$ (GeV $^2$ )	data	SM	SM + dark photon (fit)
Qweak [? ]	0.0248	$Q_w^P = 0.0719 \pm 0.0045$	0.0708	0.0707
PREX-II [? ? ]	0.00616	$Q_w(^{208}\text{Pb}) = -114.4 \pm 2.6$	-117.9	-117.1
PVDIS [? ] ( $\times 10^{-6}$ )	1.085	$A_{\text{PV}}^{\text{exp}(1)} = -91.1 \pm 3.1 \pm 3.0$	-87.7	-87.2
	1.901	$A_{\text{PV}}^{\text{exp}(2)} = -160.8 \pm 6.4 \pm 3.1$	-158.9	-157.9
APV (PDG2020)		$Q_w(^{133}\text{Cs}) = -72.82(42)$	-73.23	-72.77

Table I. The PVES and APV data. The fit results including the dark photon effects are given in the last column.

