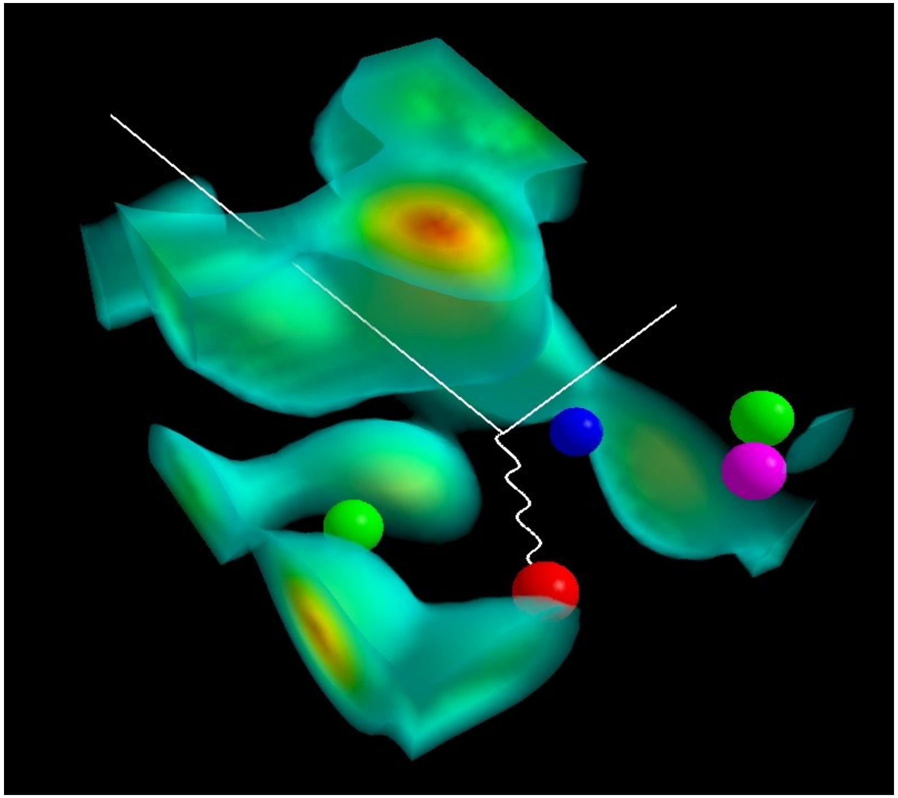
Tests and Consequences of the Existence of a Dark Photon



Anthony W. Thomas

KEK Theory Meeting (KEK-PH2022) : Standard Model and Beyond

2nd December 2022

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DARK MATTER PARTICLE PHYSICS

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

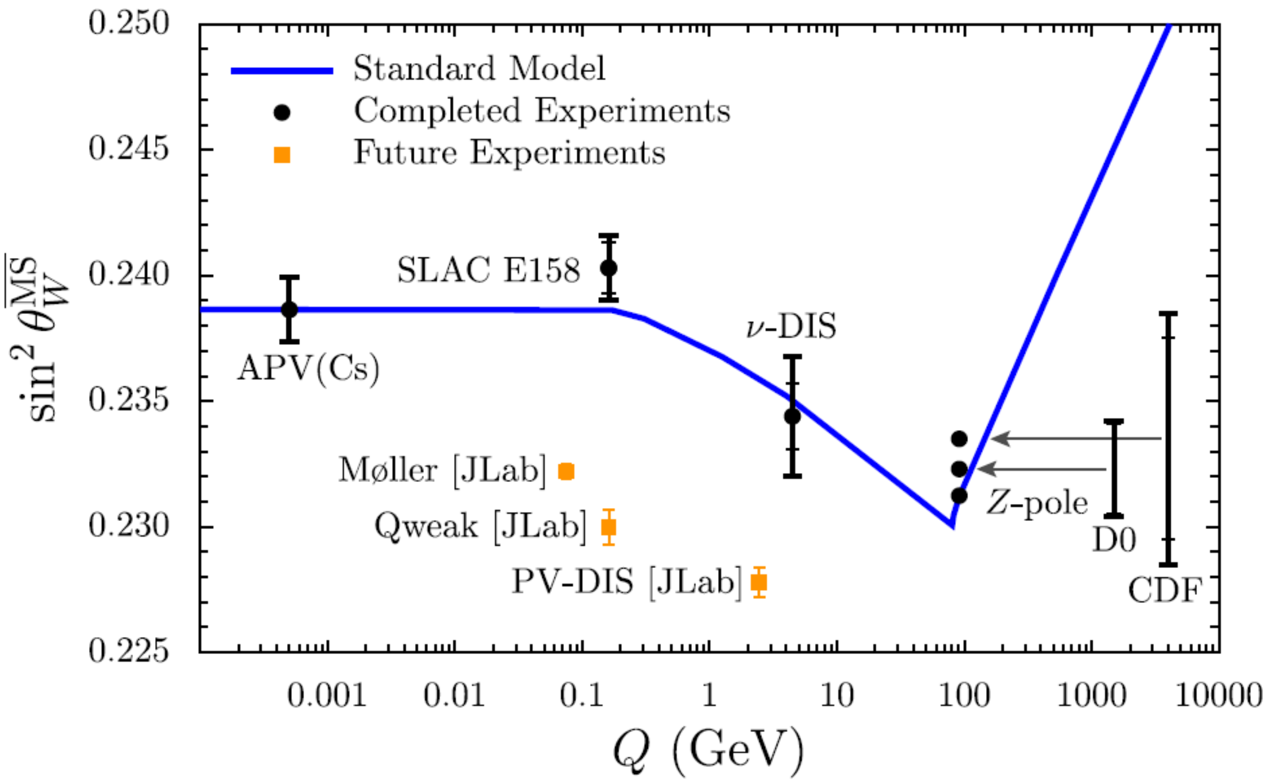
Reminder concerning NuTeV

Reassessment of the NuTeV determination of the weak mixing angle

W. Bentz [a], I.C. Cloët [b,*], J.T. Londergan [c], A.W. Thomas [d,e]

Physics Letters B 693 (2010) 462–466

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



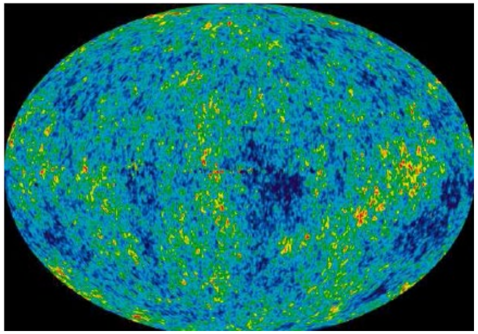
Outline

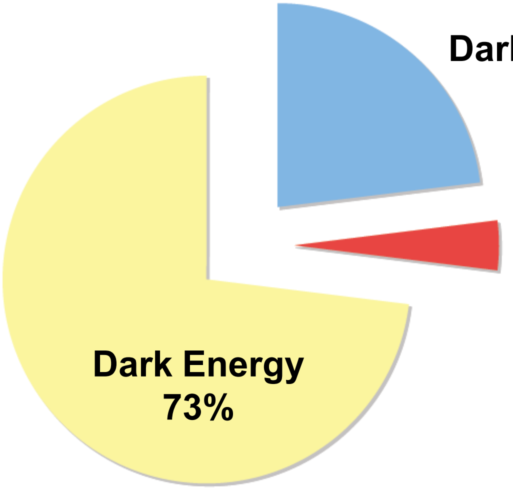
- Dark Matter experiment in Australia
- New $U_Y(1)$ boson as a dark matter candidate
- Effects in deep-inelastic scattering
  - notably HERA
- Effects on other measurements of parity violation
  - PREX
  - Atomic PV
- New W mass measurement

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

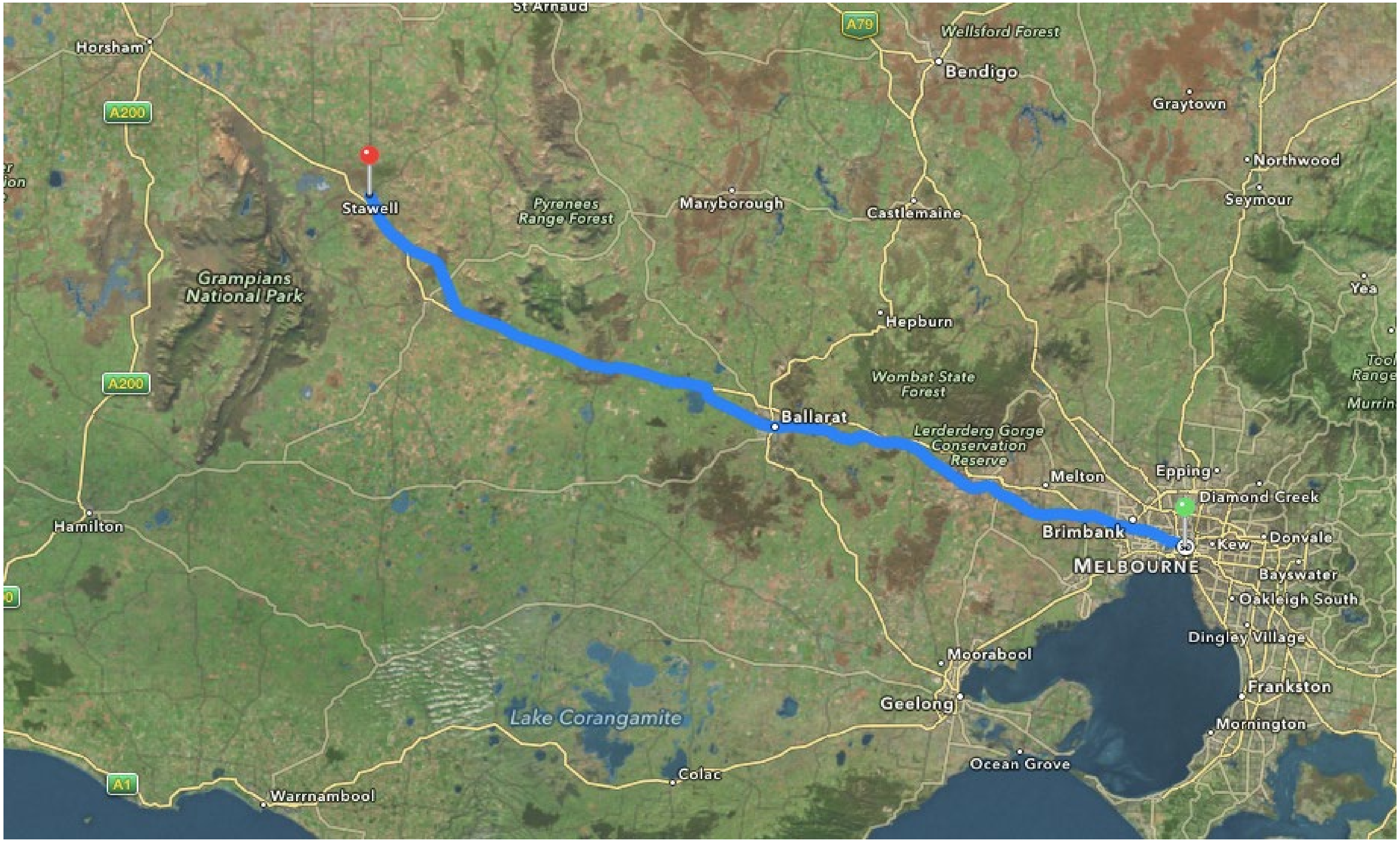




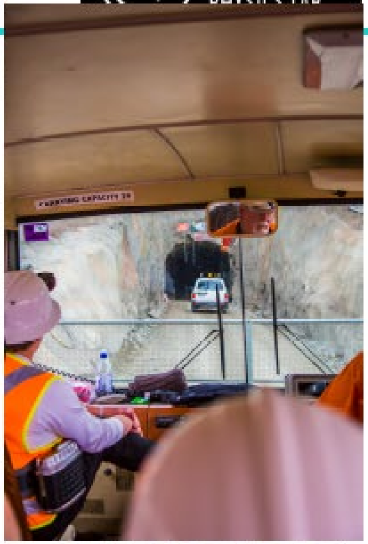
It interacts very weakly but has major gravitational effects

New Underground Laboratory under construction

- **Approximately midway between Adelaide and Melbourne**
- **1km underground in an active gold mine**



SUPL construction images



STAWELL UNDERGROUND PHYSICS LAB

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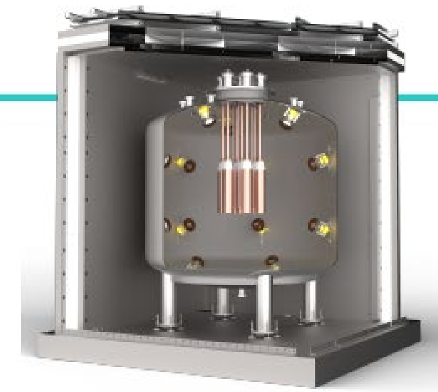
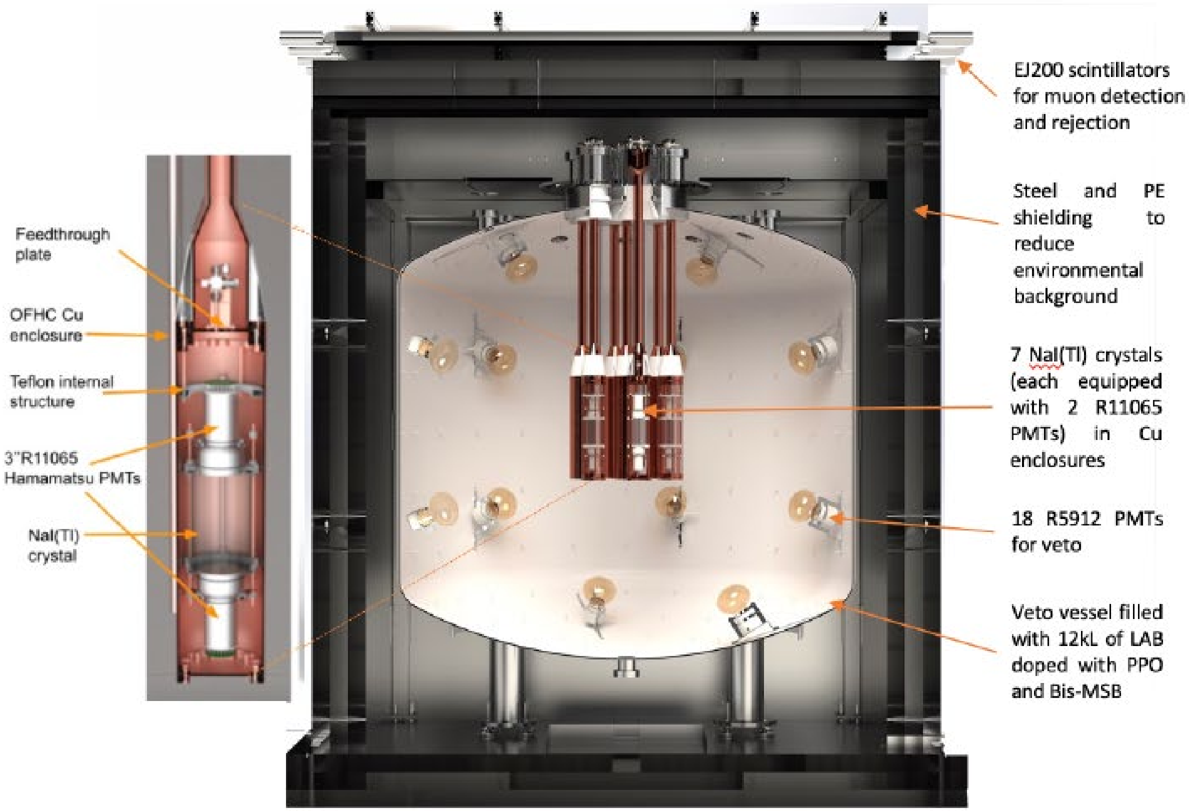
SABRE Experiment





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

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

- So that the couplings are:

$$C^v_Z = (\cos\alpha - \epsilon_W \sin\alpha)\bar{C}^v_Z + \epsilon_W \sin\alpha \cot\theta_W C^v_\gamma,$$

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

and

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

$$C^a_{A_D} = -(\sin\alpha + \epsilon_W \cos\alpha)\bar{C}^a_Z.$$

Dark Photon (cont.)

Where the Standard Model Z couplings are

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

and the mixing parameters are

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

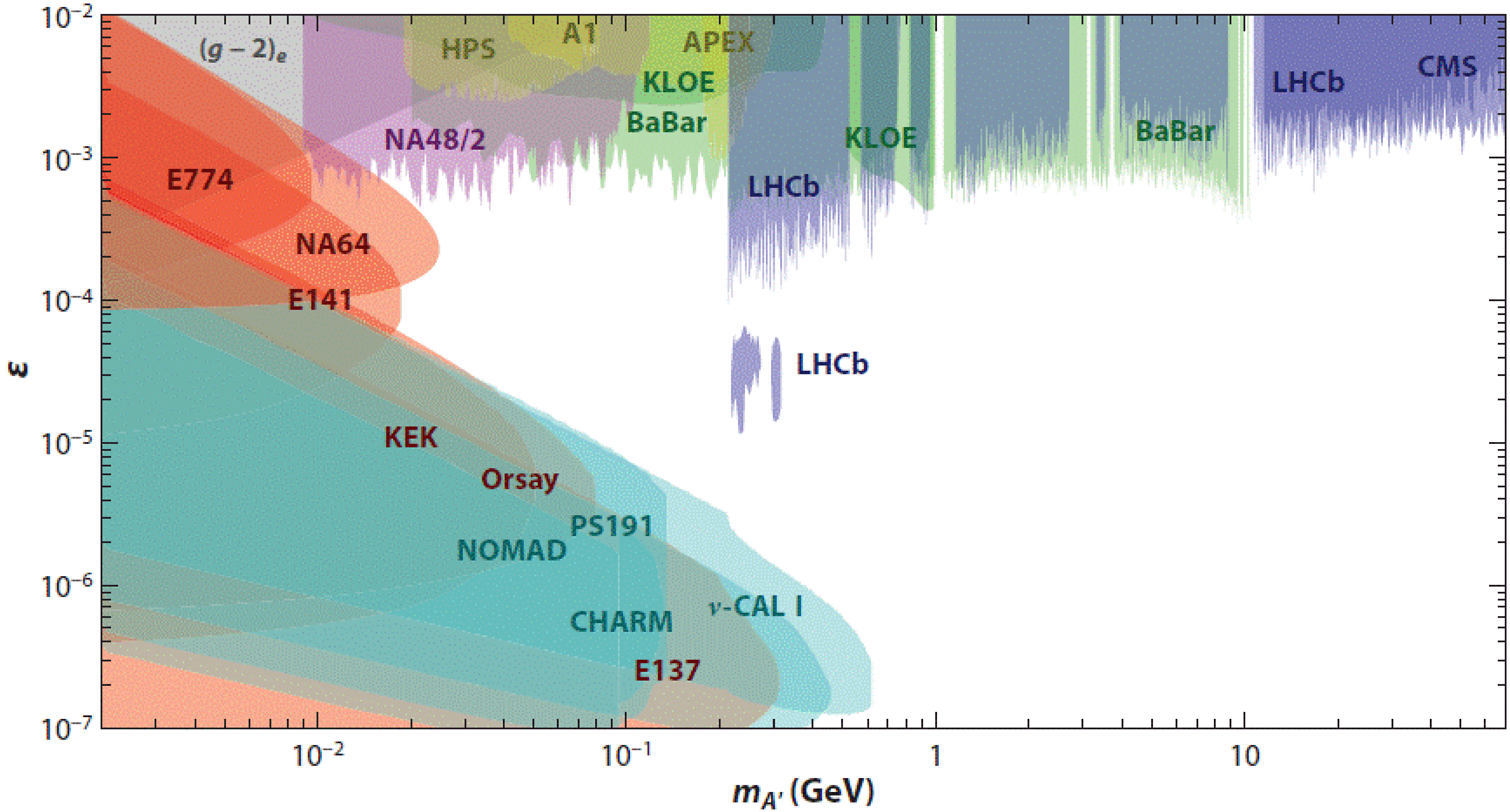
and

$$\epsilon_W = \frac{\epsilon \tan\theta_W}{\sqrt{1-\epsilon^2/\cos^2\theta_W}}$$

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

with ε the mixing parameter in the Lagrangian

Experimental Constraints



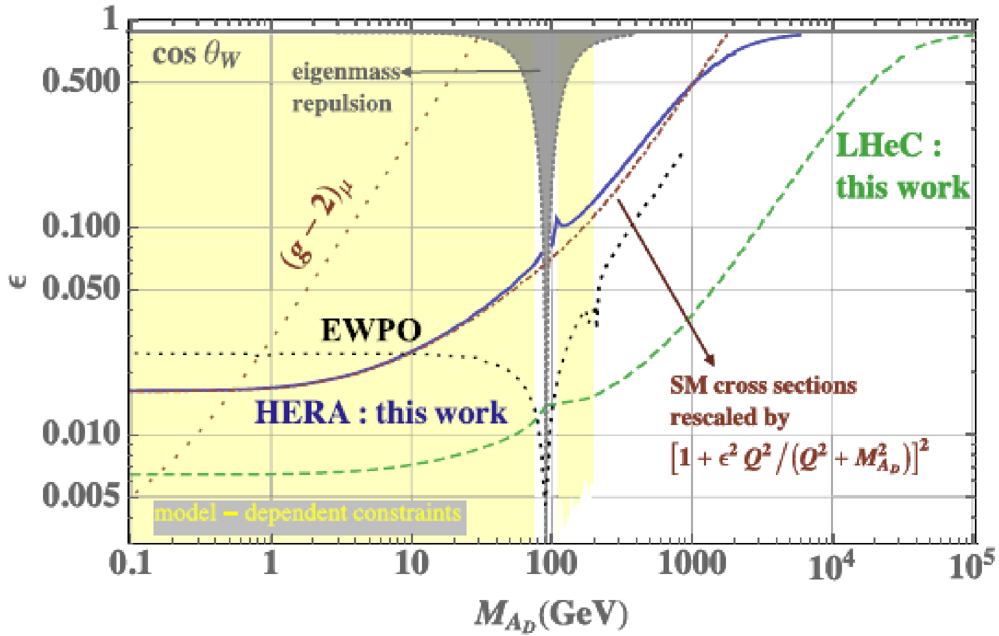
From Graham et al., Annu. Rev. Nucl. Part. Sci. 71 (2021) 37

PHYSICAL REVIEW D **105,** L031901 (2022)

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

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

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

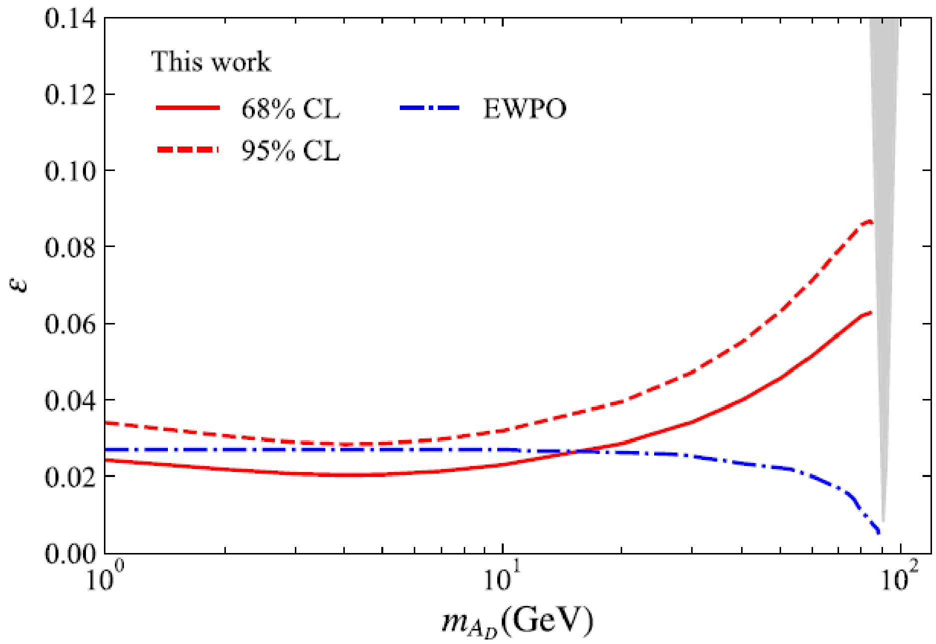
J. Phys. G: Nucl. Part. Phys. 47 (2020) 015102

included VMD at lower Q^2

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

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 χ^2 292 with VMD (c.f. 347 without)

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Dark Photon Beyond DIS

- **Study of sensitivity of PVES: AWT, XG Wang and AG Williams**
  (Phys.Rev.Lett. 129 (2022) 1, 011807)

- **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:**

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

with

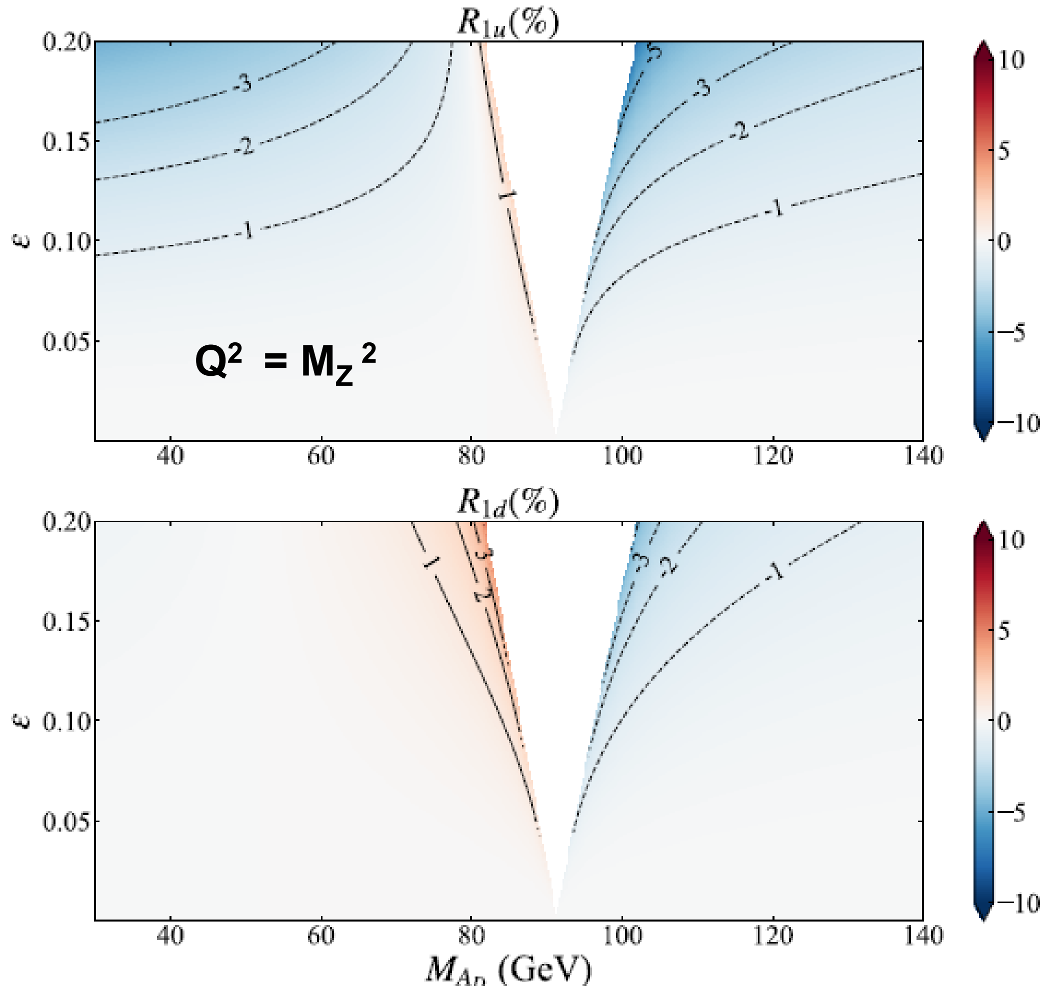
$$a_1 = \frac{2\sum_q e_q C_{1q}(q+\bar{q})}{\sum_q e_q^2 (q+\bar{q})}$$

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

Parity Violating DIS

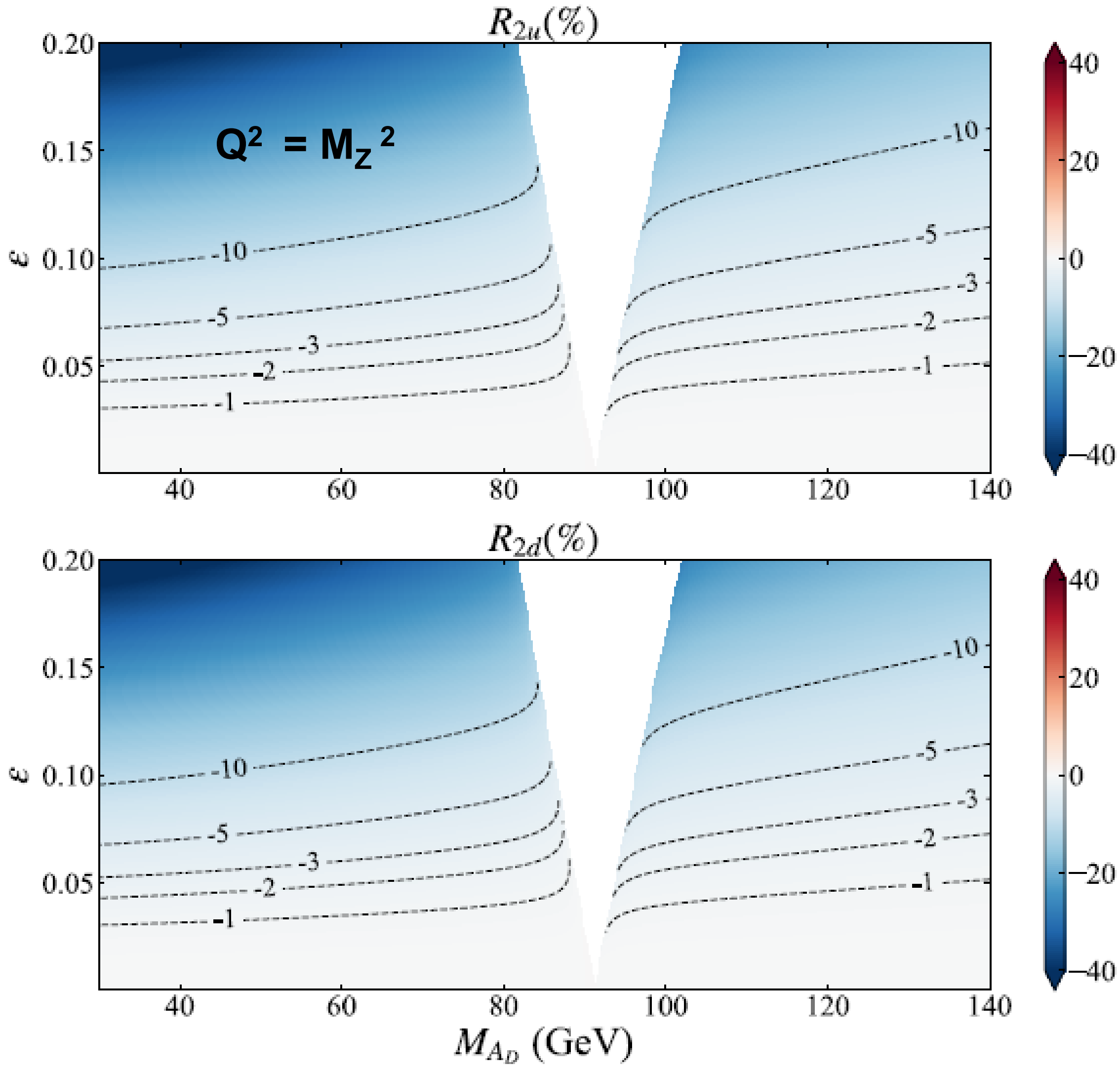
$$C_{1q} = C_{1q}^{Z} + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} C_{1q}^{A_D} = C_{1q}^{\rm SM}(1 + R_{1q})$$

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



Larger effects on valence PDFs from HERA

Changes as large as 10%



Potential 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%

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

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

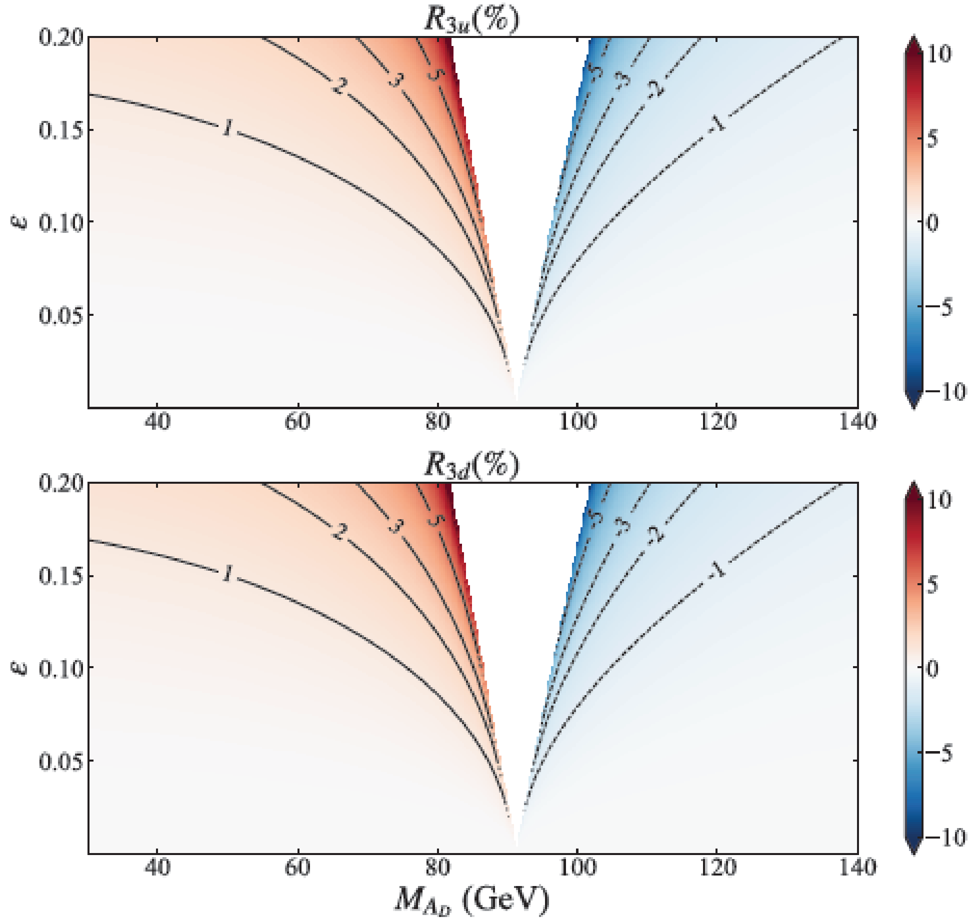
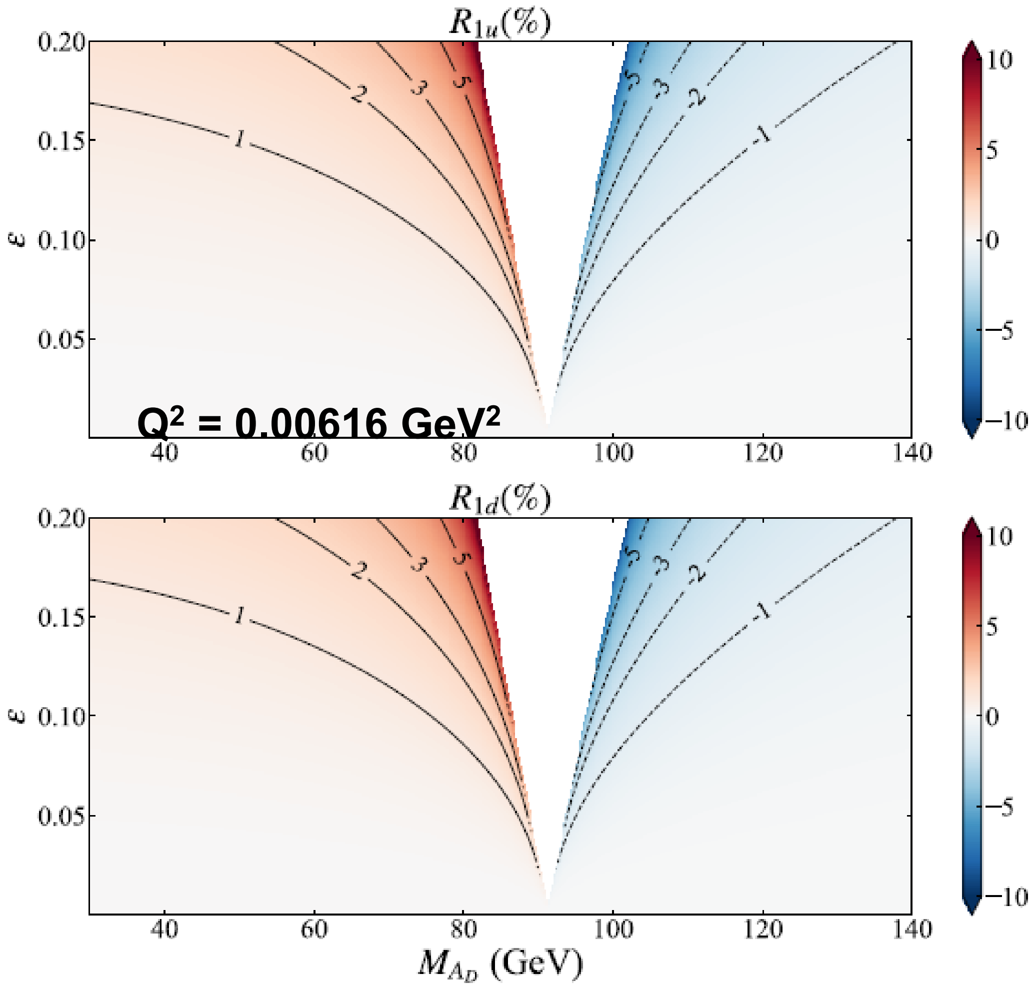


FIG. 4. The correction factors R_{3u} and R_{3d} at $Q^2 = 10\,\mathrm{GeV}^2$.

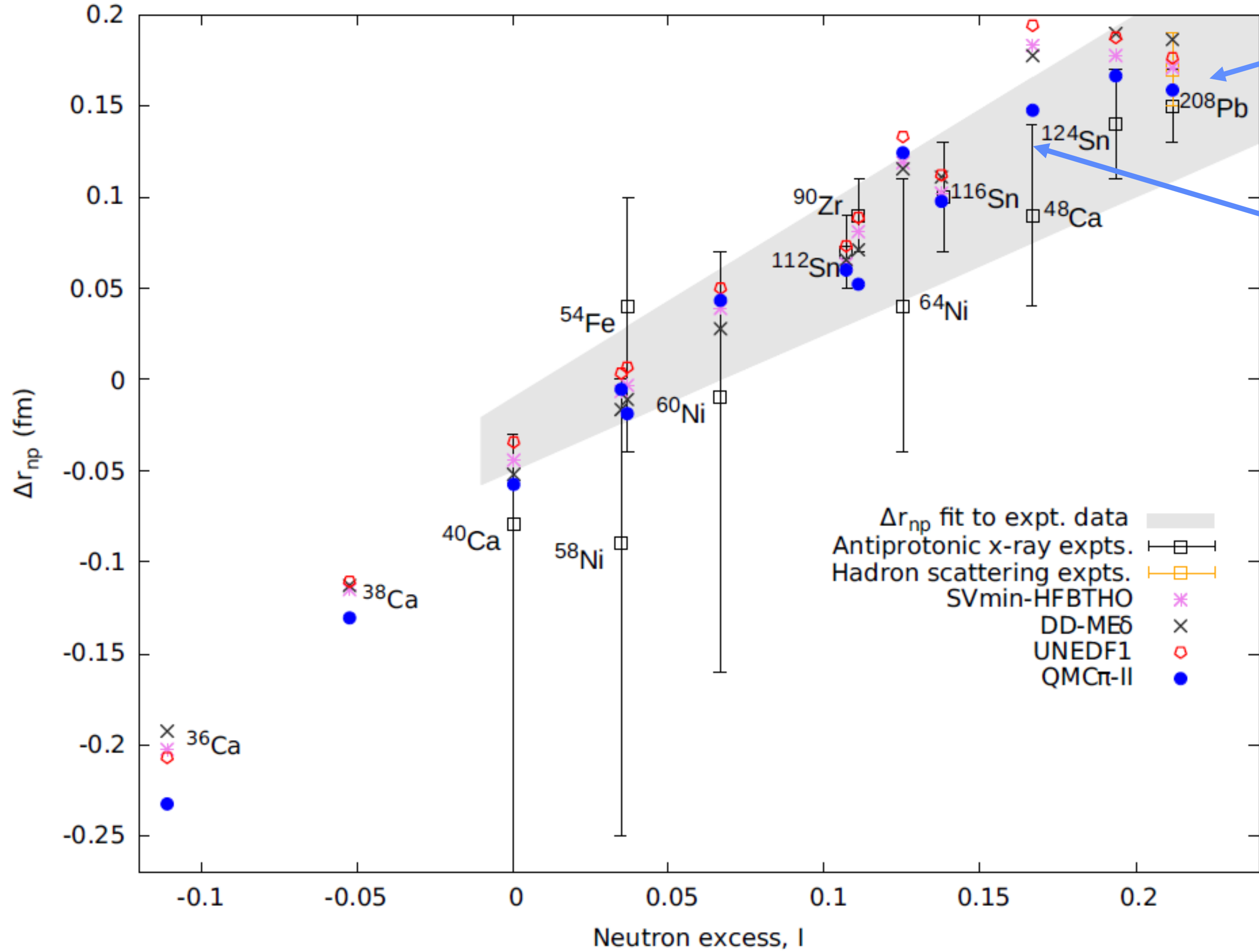
PREX Elastic PV Scattering on ^{208}Pb

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



c.f. Corona et al., arXiv:2112.09717: shift in Weinberg angle

Difference in p and n radii in ^{208}Pb



c.f. 0.27±0.07fm
PREX II

c.f. 0.12 ± 0.026
± 0.024 fm
CREX
PRL 129 (2022)

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Martinez et al., Phys Rev C100 (2019) 024333

Next: Explore effects on key PV observables

Refit of PV Observables with Dark Photon

Experiment	Q^2 (GeV^2)	data	SM	SM + dark photon (fit)
Qweak [18]	0.0248	$Q_W^p = 0.0719 \pm 0.0045$	0.0708	0.0707
PREX-II [19, 83]	0.00616	$Q_W(^{208}\text{Pb}) = -114.4 \pm 2.6$	−117.9	−117.1
PVDIS [20] ($\times 10^{-6}$)	1.085	$A_{PV}^{\exp(1)} = -91.1 \pm 3.1 \pm 3.0$	−87.7	−87.2
	1.901	$A_{PV}^{\exp(2)} = -160.8 \pm 6.4 \pm 3.1$	−158.9	−157.9
APV [82]		$Q_W(^{133}\text{Cs}) = -72.82(42)$	−73.23	−72.77

$\chi^2_{\text{total}} = 2.179$, compared with the value $\chi^2_{\text{total}} = 3.517$

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Thomas and Wang, Phys. Rev. D 106 (2022) 056017

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New W mass

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

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

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

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

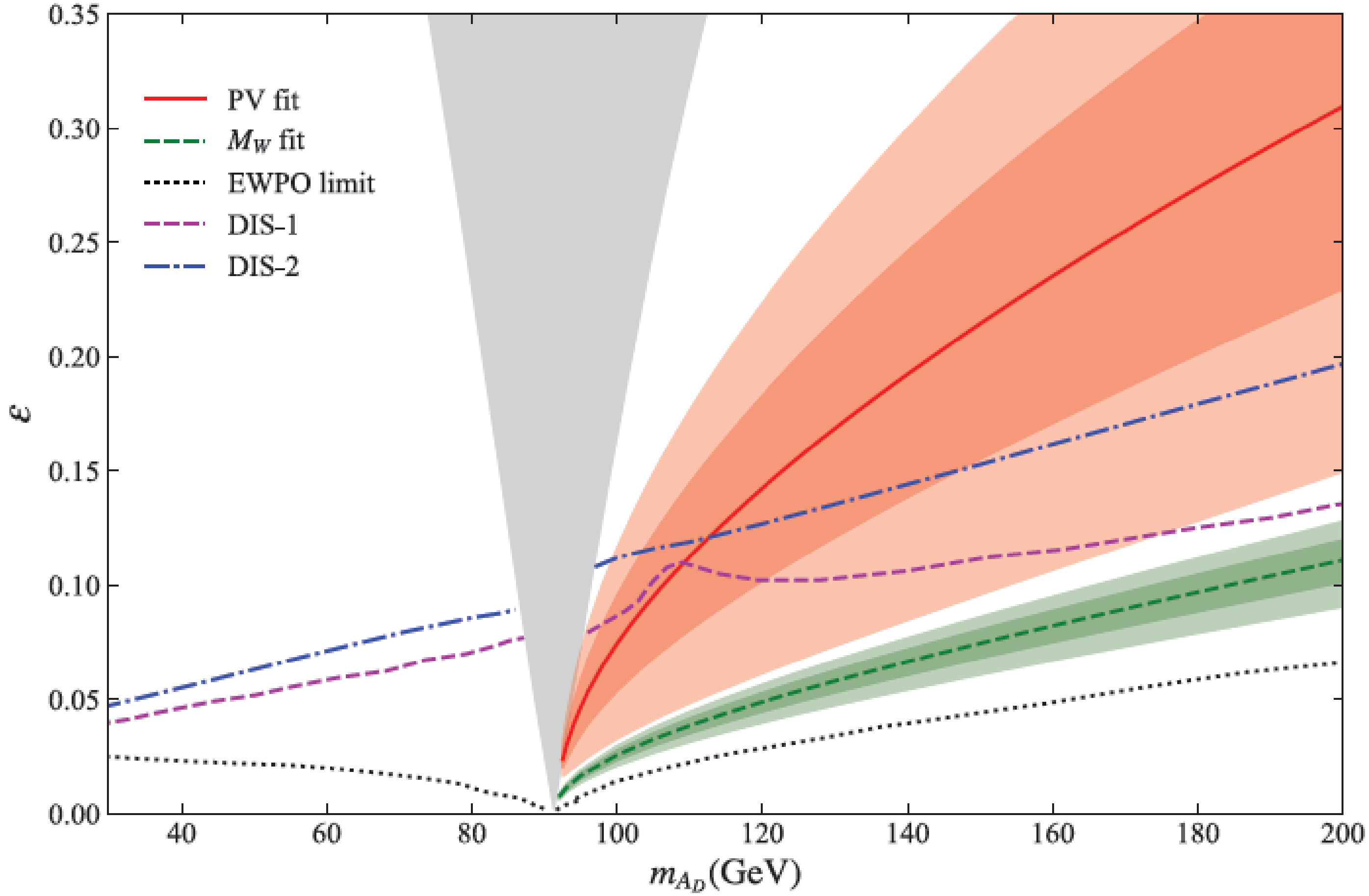
Using $m_H = 125.14$ GeV and $m_t = 172.89$ GeV, we derive $\Delta r = 0.03677$

and hence: $m_{\bar{Z}} = 91.2326 \pm 0.0076$ 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

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

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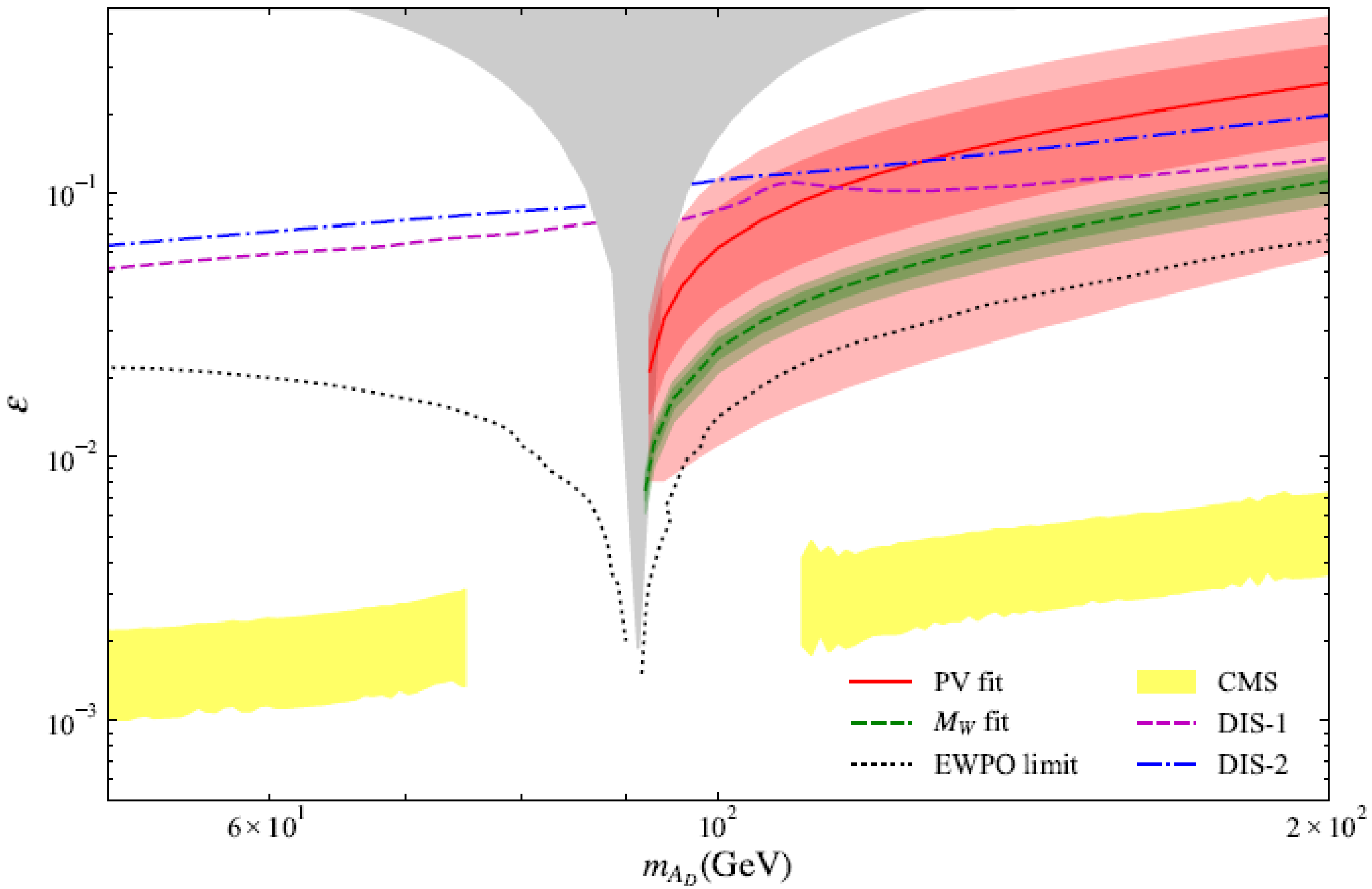
Using PDG value for Cs with CMS constraint

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



Thomas and Wang, arXiv: 2205.01911

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 may be opportunities to test its existence in PV experiments at JLab and EIC
- Global analysis of world DIS data almost complete: very interesting….

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