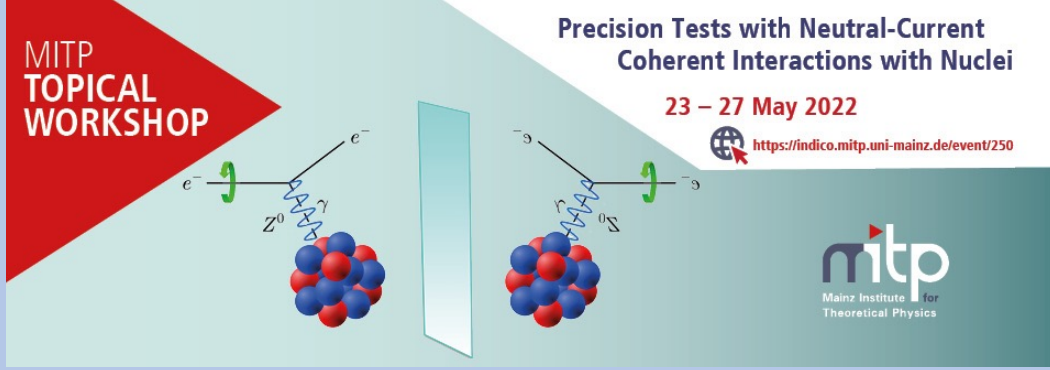


Nuclear Weak Charges and Neutron Skins in Current and Future PVES Experiments

Nicola Cargioli
nicola.cargioli@ca.infn.it

Istituto Nazionale di Fisica Nucleare
Sezione di Cagliari

I will mainly refer to two published works:

- M.Atzori Corona, M. Cadeddu, N. Cargioli, P. Finelli and M. Vorabbi, PRC 105,055503

- M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti and E. Picciau, PRD 104,L011701

I will also show some preliminary studies done with M. Gorchtein and H. Spiesberger

Nuclear Weak Charge

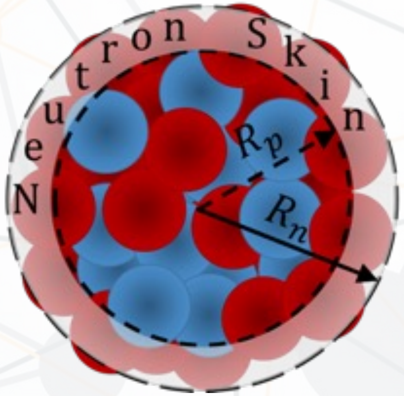
Weak coupling to a nucleus:

$$Q_W = -2(g_{ep}^{AV} Z + g_{en}^{AV} N)$$

Combination of electron coupling to protons and neutrons

Electron-proton coupling suppressed with respect to neutron coupling :

$$Q_W^p = -2g_{ep}^{AV} \approx 0.0714$$
$$Q_W^n = -2g_{en}^{AV} \approx -0.99$$



Weak Form Factor

Weak Form Factor F_W: Fourier transform of the corresponding weak nuclear density ρ_W

- Electromagnetic Interaction → probes the charge density ρ_{ch}
- Weak Interaction → probes the weak density ρ_W

ρ_{ch} → mainly due to protons
ρ_W → mainly due to neutrons

Measurement of the Charge Radius R_{ch} and the Weak Radius R_W into Proton distribution radius R_p and Neutron distribution radius R_n

$$\underbrace{R_{ch} \rightarrow R_p \qquad\qquad R_W \rightarrow R_n}$$

Neutron Skin → $\Delta R_{np} = R_n - R_p$

Weak Skin → $R_{skin} = R_W - R_{ch}$

Weak Mixing Angle

P. Zyla et al. (Particle Data Group),
Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

The electron-proton coupling depends on the weak mixing angle θ_W

$$g_{ep}^{AV} \approx -\frac{1}{2} + 2\sin^2\theta_W$$

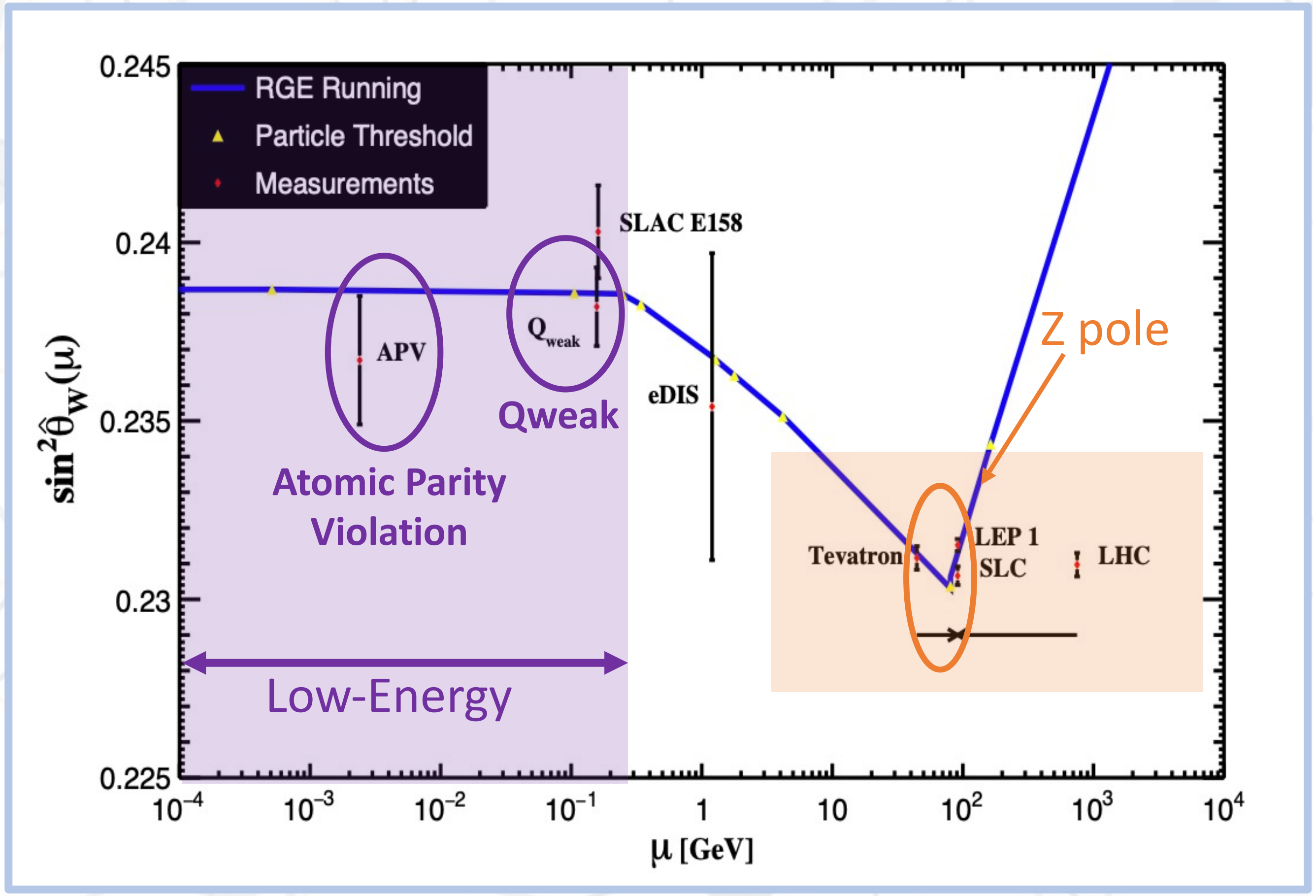
In SM the weak mixing angle runs with the energy scale

Precisely tested at high energies → Z pole

Few measurements at low energies → APV and Qweak

Atomic Parity Violation → measurement of the nuclear weak charge of Cesium (most precise), Lead and other nuclei

Qweak → measurement of the proton weak charge

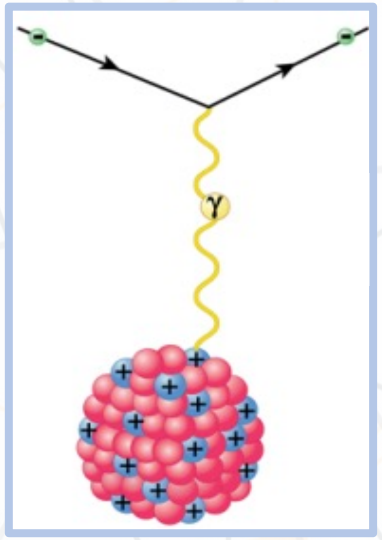


A measurement of the nuclear weak charge leads to a measurement of the weak mixing angle

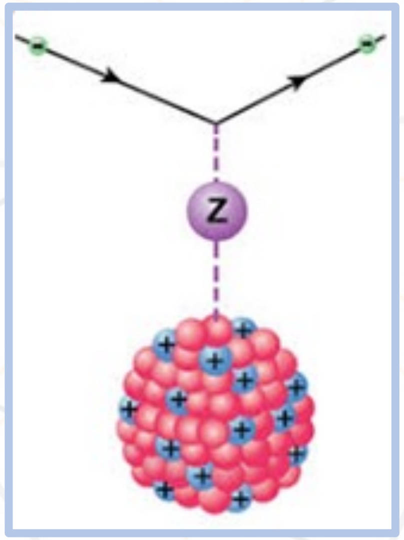
PVES

Parity Violating Electron Scattering: powerful tool to measure both the nuclear weak charge and the weak nuclear radius

Polarized electrons that scatter off a nucleus: both electromagnetic and weak interaction



Interaction mediated by the photon and so mostly sensitive to the charge (proton) distribution



Interaction mediated by the Z boson and so mostly sensitive to the weak (neutron) distribution.

Polarized electrons → build an asymmetry

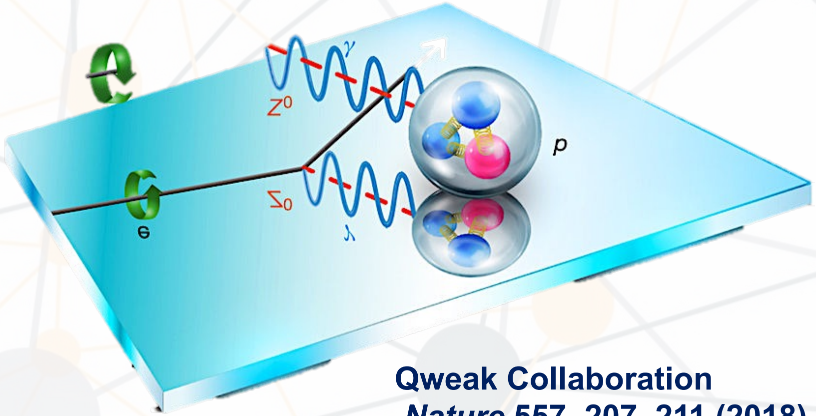
$$\mathcal{A}_{pv} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(Q^2)}{Z\, F_{ch}(Q^2)}$$

Weak distribution

Charge distribution

Charge distribution is well known from electromagnetic scattering

Nuclear Weak Charge



Qweak Collaboration
***Nature* 557, 207–211 (2018)**

This formula is in PWBA, Coulomb distortion effect must be taken into account

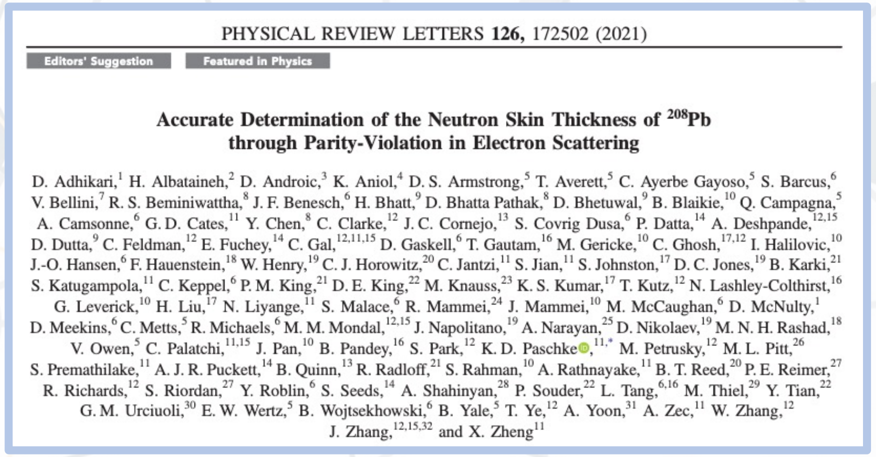
PREX-II measurement

PREX Collaboration: Measurement of the ^{208}Pb weak radius and neutron skin
Weak distribution described through a symmetrized 2pF with $a \approx 0.605$ fm

- **2012**: first electroweak neutron skin measurement with 1.06 GeV electrons scattering off ^{208}Pb nuclei at forward angles ($\sim 5°$)
  PREX Collaboration
  Phys.Rev.Lett. 108,112502 (2012)
  - $\mathcal{A}_{pv} = 0.656 \pm 0.060(\text{stat}) \pm 0.014(\text{syst})$ ppm
  - $Q^2 \approx 0.00880\ GeV^2$
  - $\Delta R_{np} = 0.33^{+0.16}_{-0.18}$ fm

- **2021**: improved measurement with 953 MeV electrons scattering off ^{208}Pb nuclei at forward angles ($\sim 5°$)
  PREX Collaboration
  Phys.Rev.Lett. 126,172502 (2021)
  - $\mathcal{A}_{pv} = 550 \pm 16(\text{stat}) \pm 8(\text{syst})$ ppb
  - $Q^2 \approx 0.00616\ GeV^2$
  - $\Delta R_{np} = 0.278 \pm 0.078(\text{exp}) \pm 0.012(\text{theo})$ fm

PREX found a rather thick neutron skin compared with the EDF predicted value: $\Delta R_{np}^{th} \approx 0.13 - 0.19$ fm

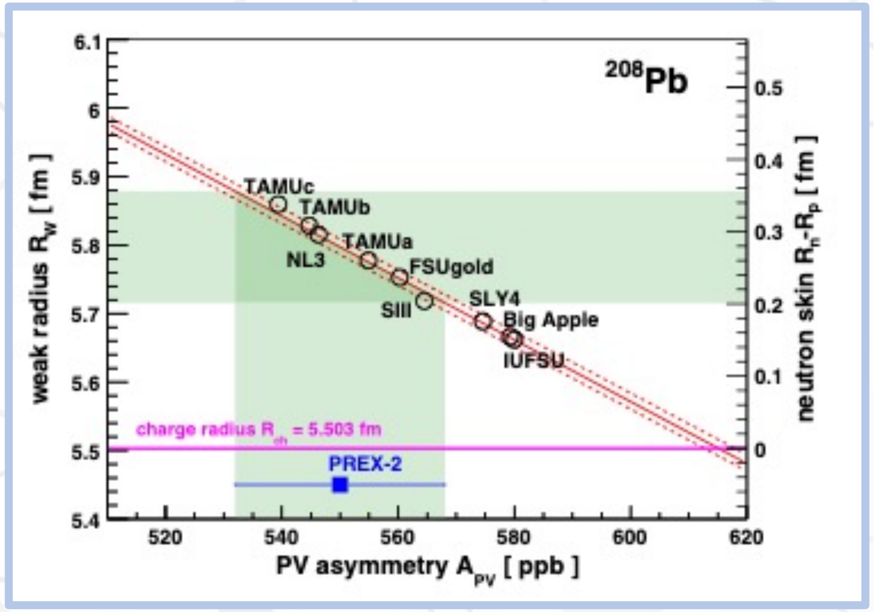

PHYSICAL REVIEW LETTERS **126,** 172502 (2021)

Editors' Suggestion | Featured in Physics

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering

D. Adhikari,[1] H. Albataineh,[2] D. Androic,[3] K. Aniol,[4] D. S. Armstrong,[5] T. Averett,[5] C. Ayerbe Gayoso,[5] S. Barcus,[6] V. Bellini,[7] R. S. Beminiwattha,[8] J. F. Benesch,[6] H. Bhatt,[9] D. Bhatta Pathak,[8] D. Bhetuwal,[9] B. Blaikie,[10] Q. Campagna,[5] A. Camsonne,[6] G. D. Cates,[11] Y. Chen,[8] C. Clarke,[12] J. C. Cornejo,[13] S. Covrig Dusa,[6] P. Datta,[14] A. Deshpande,[12,15] D. Dutta,[9] C. Feldman,[12] E. Fuchey,[14] C. Gal,[12,11,15] D. Gaskell,[6] T. Gautam,[16] M. Gericke,[10] C. Ghosh,[17,12] I. Halilovic,[10] J.-O. Hansen,[6] F. Hauenstein,[18] W. Henry,[19] C. J. Horowitz,[20] C. Jantzi,[11] S. Jian,[11] S. Johnston,[17] D. C. Jones,[19] B. Karki,[21] S. Katugampola,[11] C. Keppel,[6] P. M. King,[21] D. E. King,[22] M. Knauss,[23] K. S. Kumar,[17] T. Kutz,[12] N. Lashley-Colthirst,[16] G. Leverick,[10] H. Liu,[17] N. Liyange,[11] S. Malace,[6] R. Mammei,[24] J. Mammei,[10] M. McCaughan,[6] D. McNulty,[1] D. Meekins,[6] C. Metts,[5] R. Michaels,[6] M. M. Mondal,[12,15] J. Napolitano,[19] A. Narayan,[25] D. Nikolaev,[19] M. N. H. Rashad,[18] V. Owen,[5] C. Palatchi,[11,15] J. Pan,[10] B. Pandey,[16] S. Park,[12] K. D. Paschke,[11,*] M. Petrusky,[12] M. L. Pitt,[26] S. Premathilake,[11] A. J. R. Puckett,[14] B. Quinn,[13] R. Radloff,[21] S. Rahman,[10] A. Rathnayake,[11] B. T. Reed,[20] P. E. Reimer,[27] R. Richards,[12] S. Riordan,[27] Y. Roblin,[6] S. Seeds,[14] A. Shahinyan,[28] P. Souder,[22] L. Tang,[6,16] M. Thiel,[29] Y. Tian,[22] G. M. Urciuoli,[30] E. W. Wertz,[5] B. Wojtsekhowski,[6] B. Yale,[5] T. Ye,[12] A. Yoon,[31] A. Zec,[11] W. Zhang,[12] J. Zhang,[12,15,32] and X. Zheng[11]

PREX Collaboration
Phys.Rev.Lett. 126,172502 (2021)



W.M.A. effect

$$\mathcal{A}_{pv} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(Q^2)}{Z\, F_{ch}(Q^2)}$$

$\mathcal{A}_{pv}$ depends on the Nuclear Weak Charge Q_W and thus, on in the weak mixing angle $\sin^2\theta_W$.

PHYSICAL REVIEW C **105**, 055503 (2022)

Incorporating the weak mixing angle dependence to reconcile the neutron skin measurement on ^{208}Pb by PREX-II

M. Atzori Corona,[1,2] M. Cadeddu,[2,*] N. Cargioli,[1,2,†] P. Finelli,[3] and M. Vorabbi[4]

[1]*Dipartimento di Fisica, Università degli Studi di Cagliari, Complesso Universitario di Monserrato - S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*

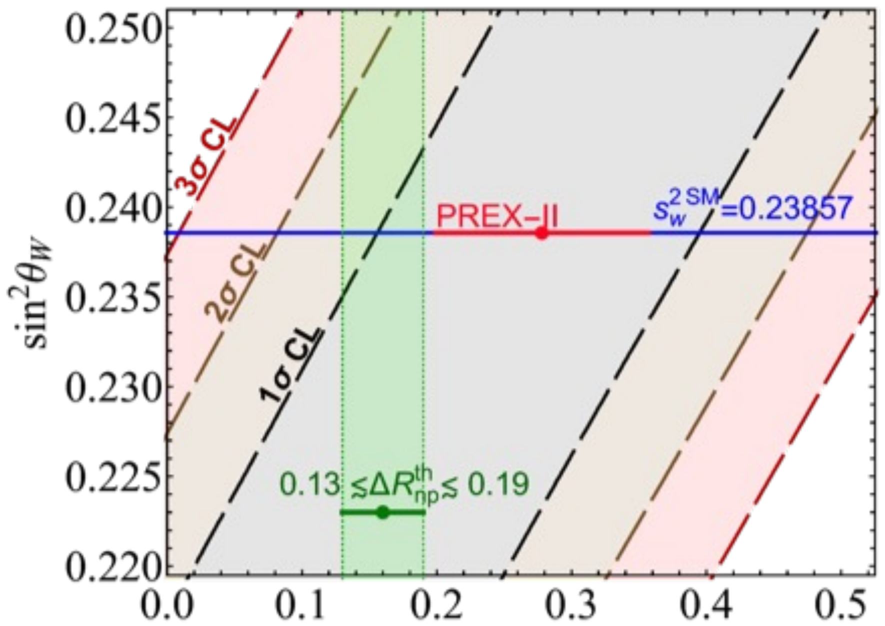
[2]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato - S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*

[3]*Dipartimento di Fisica e Astronomia, Università degli Studi di Bologna and INFN, Sezione di Bologna, Via Irnerio 46, I-40126 Bologna, Italy*

[4]*National Nuclear Data Center, Bldg. 817, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

(Received 22 December 2021; accepted 3 May 2022; published 17 May 2022)

Published last week!!



M. Atzori Corona et al.
PRC 105,055503 (2022)

Is it reasonable?

PREX is a low-energy experiment ($Q \approx 78 - 93$ MeV), where $\sin^2\theta_W$ is not well tested.

Variation arising in plenty BSM scenarios (one discussed later..)

We included the weak mixing angle in the analysis as a parameter free-to-vary

- Degeneracy in the plane ΔR_{np} vs $\sin^2\theta_W$
- Smaller $\sin^2\theta_W$ → smaller $\Delta R_{np}(^{208}\mathrm{Pb})$

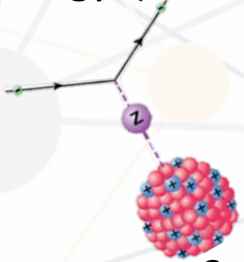
Atomic Parity Violation

Do we really know nothing of the weak mixing angle at low-energy?
From Atomic Parity Violation (APV) experiments we obtain the lowest energy (few MeVs) weak mixing angle measurements

Parity violation in an atomic system: an electric dipole transition amplitude between two atomic states with the same parity

- transition between two atomic states with same parity **is forbidden** by the parity selection rule and cannot happen with the exchange of a photon
- an electric dipole transition amplitude can be induced by **a Z boson exchange** between **atomic electrons and nucleons**-> Atomic Parity Violation (APV) or Parity Non Conserving (PNC)

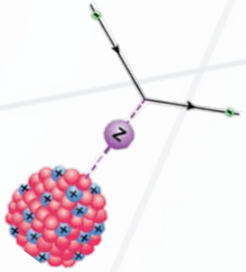
We used APV(Pb) although it is less precise than APV(Cs). But why?



APV(Cs)

M. Cadeddu talk at 11:30 on Thursday

- $Q \sim 2.4\ \mathrm{MeV}$
- transition between the states 6S and 7S in Cs



APV(Pb)

- $Q \sim 8\ \mathrm{MeV}$
- transition between the states $6p^2\ {}^3P_o$ and $6p^2\ {}^3P_1$ in Pb

Atomic Parity Violation

$R_{exp} = -9.80(33)\times10^{-8}$

S.J. Phipp et al. Journal of Physics B 29, 1861 (1996)

$R_{exp} = -9.86(12)\times10^{-8}$

D.M. Meekhof et al. Phys Rev Lett 71,3442 (1993)

Experimental value of electric dipole transition amplitude between the two states

$$Q_W = \frac{R_{exp}}{R_{th}} = -117(5)$$

To be compared with

$$Q_W^{th}(\mathrm{SM}) = -118.79(5)$$

Q_W^{th} depends on the weak mixing angle!

$$R_{th} = \left(\frac{\mathrm{Im}\ \mathrm{E_{APV}}}{\mathrm{M_1}}\right)_{\mathrm{th}} = -10.6(4)\times10^{-8}(-Q_W^{APV}/N)$$

S.G. Porsev et al. PRA 93,012501 (2016)

Theoretical APV (or PNC) amplitude of the electric dipole transition

Nuclear spin independent Hamiltonian describing the electron-nucleus weak interaction

$$\mathrm{H_{PNC}} = -\frac{\mathrm{G_F}}{2\sqrt{2}}Q_{\mathrm{W}}\gamma_5\rho(\mathrm{r})$$

$\rho(\boldsymbol{r}) = \rho_p(\boldsymbol{r}) = \rho_n(\boldsymbol{r}) \rightarrow$ *neutron skin correction* needed

$\mathrm{M_1}$ is the reduced electric-dipole transition of the magnetic-dipole operator for the relevant transition

R_{th} depends on the neutron skin!

In the case of APV(Pb): uniformely charged ball density with $R_{ch}(^{208}Pb) = 5.501\ \mathrm{fm}$

Neutron Skin Correction: $\delta\mathrm{E_{APV}^{n.s.}(R_n)} = \left(\frac{\mathrm{N}}{\mathrm{Q_W}}\right)\left(1 - \frac{\mathrm{q_n(R_n)}}{\mathrm{q_p}}\right)\mathrm{E_{APV}}$

- $\mathrm{q_{p(n)}}$ are the integrals over the proton and neutron nuclear densities:

$$\mathrm{q_{p,n}} = 4\pi\int_0^\infty \rho_{\mathrm{p,n}}(\mathrm{r})\mathrm{f}(\mathrm{r})\mathrm{r}^2\mathrm{dr}$$

- $\mathrm{f(r)}$ is the matrix element of the **electron axial current** between the atomic states wave functions inside the nucleus
- For the radial electric potential we used the charged density used in the original work

$$\boldsymbol{Q_W(R_n) = -N\ R_{exp}\left(\frac{M_1}{Im\left(E_{APV} + \delta E_{APV}^{n.s.}(R_n)\right)}\right)}$$

M. Cadeddu et al. PRC 104,065502 (2021)

PVES+APV Pb

APV(Pb) and PVES on ^{208}Pb depend on the same quantities: ΔR_{np} and $\sin^2\theta_W$

APV is more sensitive to $\sin^2\theta_W$, PREX more to ΔR_{np}

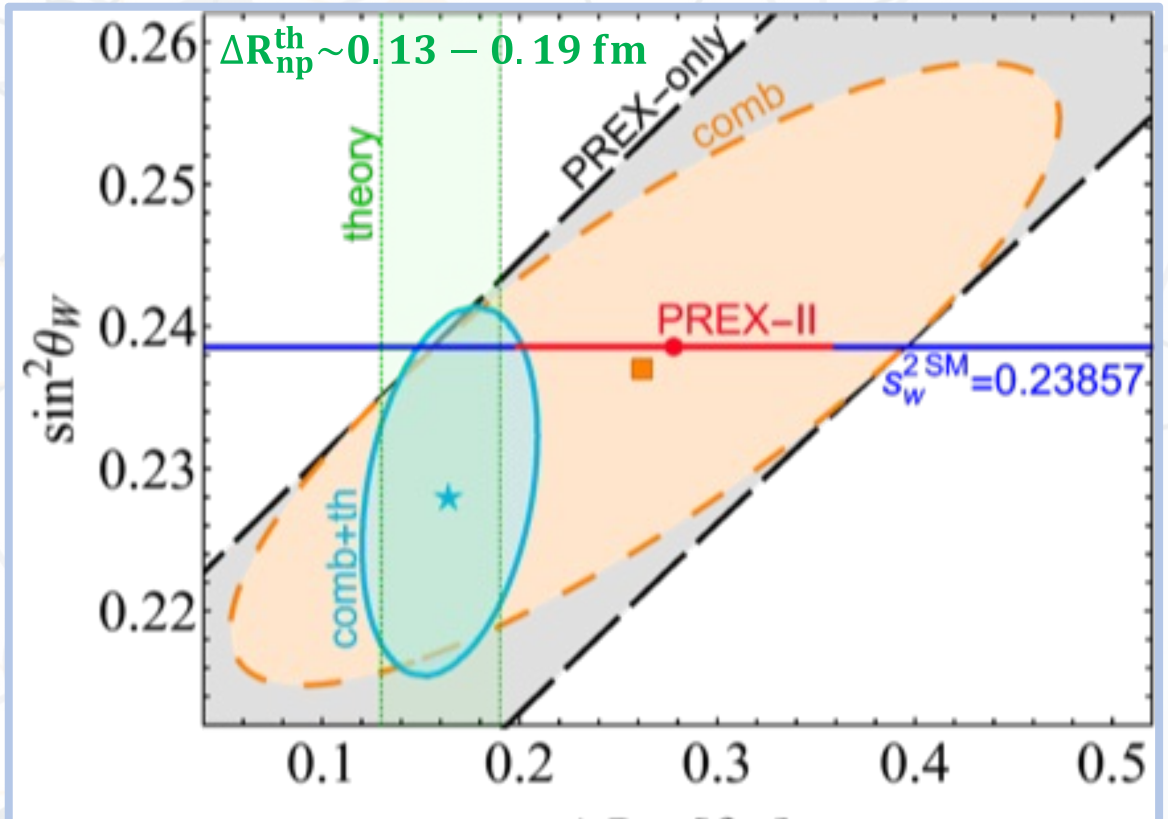
Assumption: $\sin^2\theta_W$ constant between the two experimental energy scales (i.e. $8 \leq Q \leq 78$ MeV)

$$\left.\begin{array}{l}\Delta R_{np} = 0.262 \pm 0.136 \text{ fm} \\ \sin^2\theta_W = 0.237 \pm 0.014\end{array}\right\} \text{PREX-II+APV(Pb)}$$

Forcing ΔR_{np} toward the nuclear model prediction:

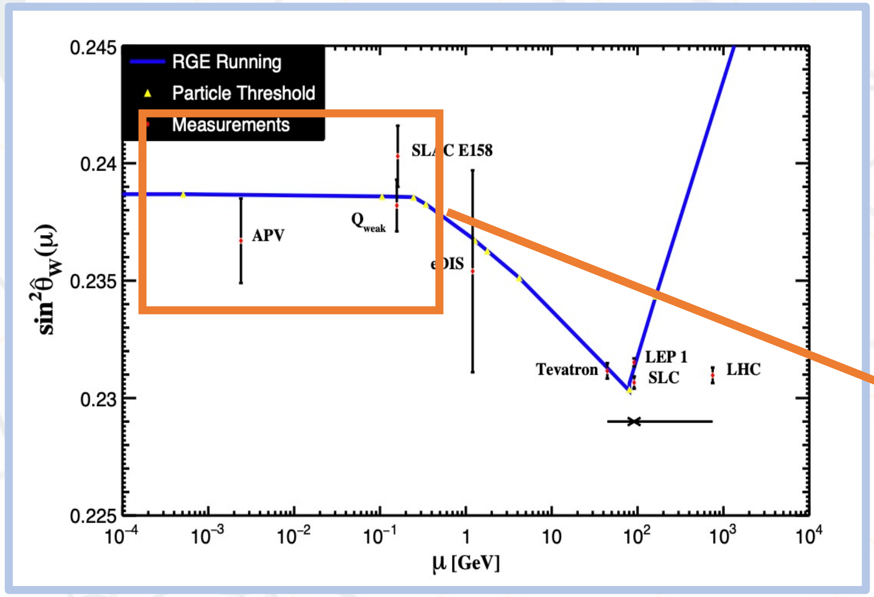
$$\left.\begin{array}{l}\Delta R_{np} = 0.164 \pm 0.029 \text{ fm} \\ \sin^2\theta_W = 0.228 \pm 0.008\end{array}\right\} \text{PREX-II+APV(Pb) +theory}$$

In order to find a neutron skin compatible with the ones predicted by EDF nuclear models the weak mixing angle should be lower than the SM value

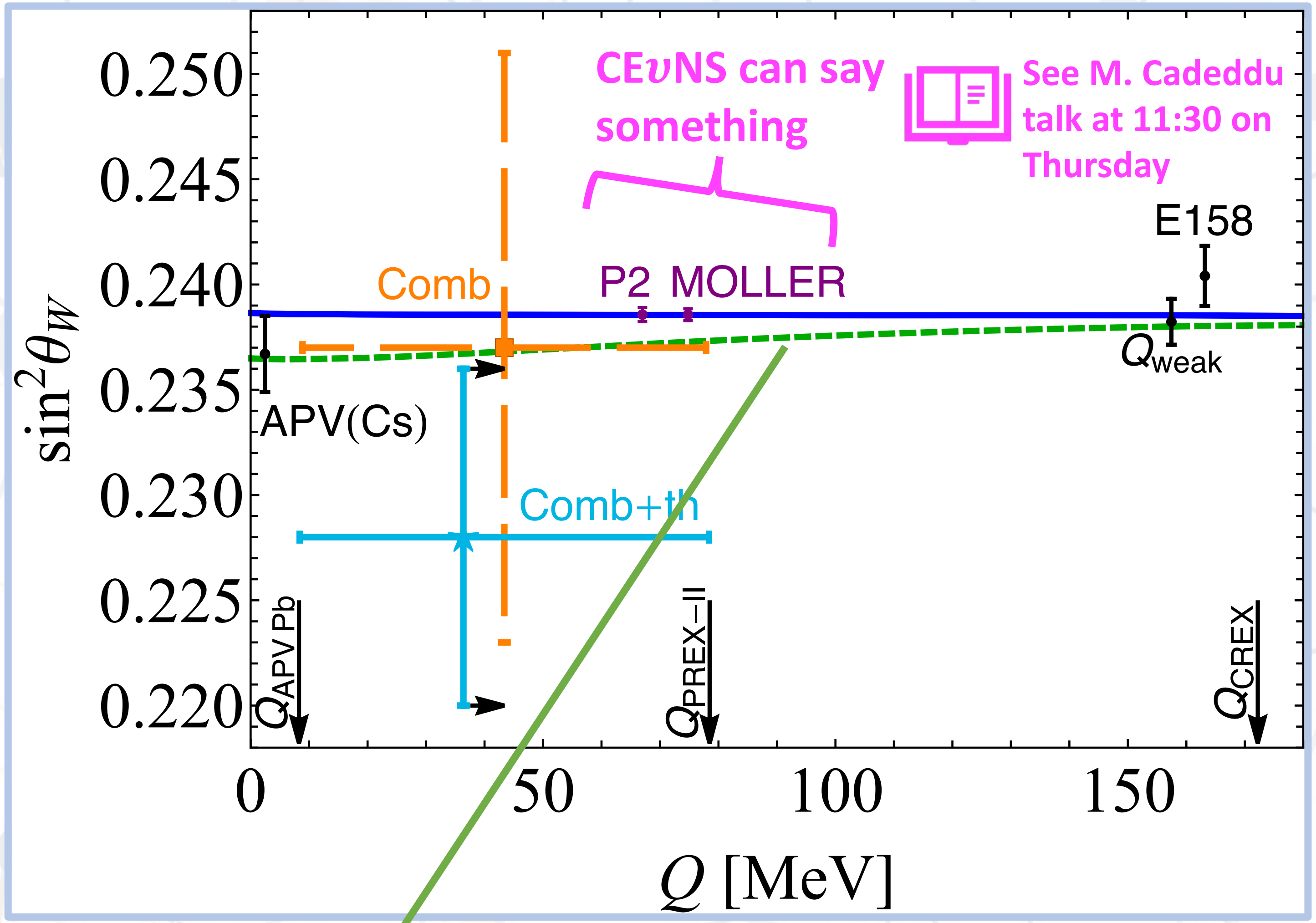


M. Atzori Corona et al.
PRC 105,055503 (2022)

W.M.A. Status



P. Zyla et al. (Particle Data Group),
Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

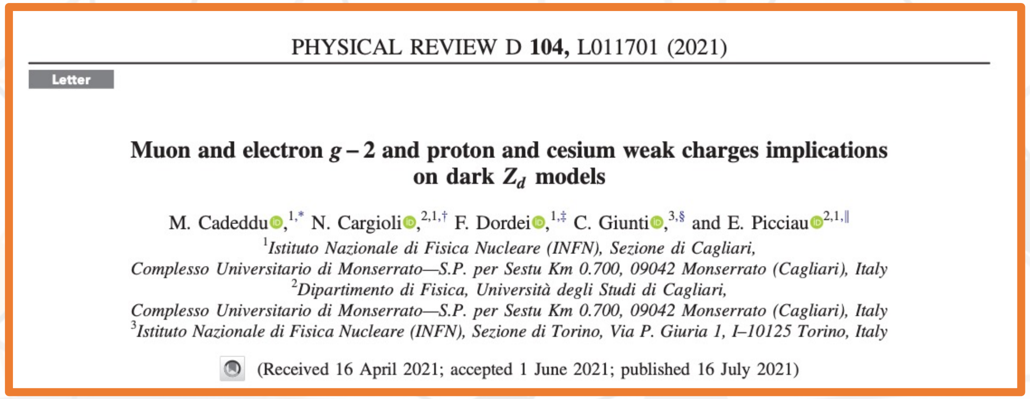


P2 and Moller will measure $\sin^2\theta_W$ with high precision!

M. Atzori Corona et al.
PRC 105,055503 (2022)

What is this green curve?

BSM physics in W.M.A.


PHYSICAL REVIEW D **104**, L011701 (2021)

Letter

Muon and electron $g-2$ and proton and cesium weak charges implications on dark Z_d models

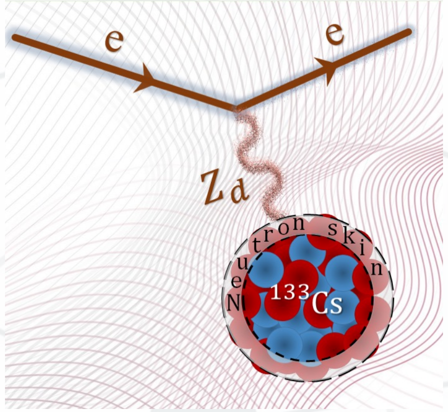
M. Cadeddu,[1,*] N. Cargioli,[2,1,†] F. Dordei,[1,‡] C. Giunti,[3,§] and E. Picciau[2,1,∥]

[1] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*
[2] *Dipartimento di Fisica, Università degli Studi di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*
[3] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy*

(Received 16 April 2021; accepted 1 June 2021; published 16 July 2021)

Example of BSM physics involving the weak mixing angle

- Z_d model: **U(1)$_d$ extension** of the SM with a corresponding
- Z_d boson, in the sub-GeV mass scale
- Coupling via **kinetic mixing** parametrized by ε and $Z - Z_d$ **mass matrix mixing**, parametrized by $\varepsilon_Z = (m_{Z_d}/m_Z)\delta$



$$\sin^2\theta_W(Q^2) \rightarrow \left(1 - \varepsilon\delta\frac{m_Z}{m_{Z_d}}\cot\theta_W\, f\left(\frac{Q^2}{m_{Z_d}^2}\right)\right)\sin^2\theta_W(Q^2)$$

H. Davoudiasl et al..Phys Rev Lett 109,031802

SCALE DEPENDENT VARIATION

The running of $\sin^2\theta_W$ is modified by the introduction of this Z_d :

- **for a MeV Z_d boson → the effect is at low-energies**

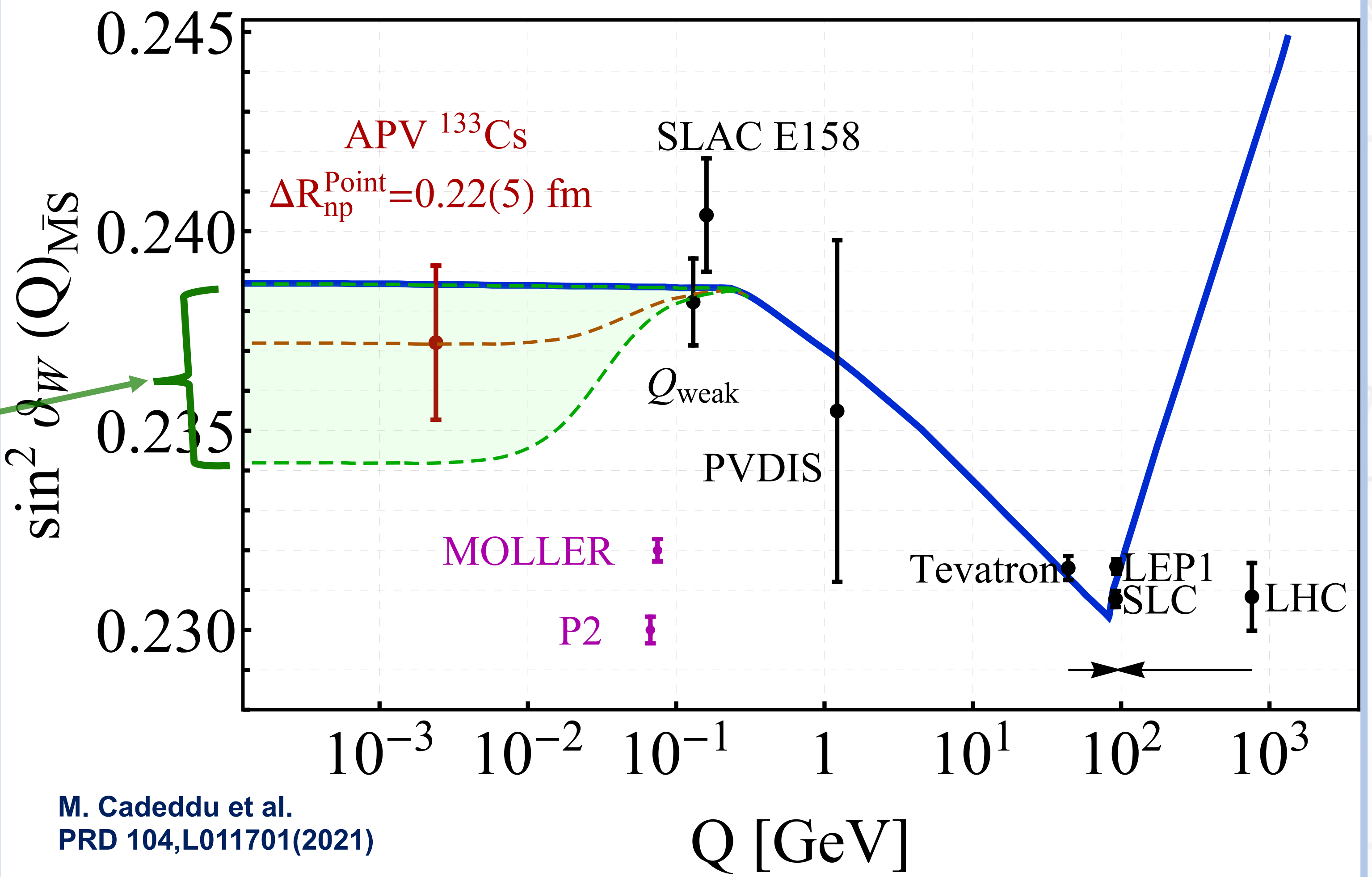
- Effects on weak charge measurements (both nuclear and proton)
- Effects on muon and electron g-2

Zd in light of Muon g-2

Combined fit of APV(Cs), Qweak and muon and electron g-2:

$$m_{Z_d} = 47^{+61}_{-16}\ MeV$$
$$\varepsilon = 2.3^{+1.1}_{-0.4}\times10^{-3}$$
$$\delta < 2\times10^{-3}$$

Effects of the Z_d boson on $\sin^2\theta_W$



M. Cadeddu et al.
PRD 104,L011701(2021)

CREX

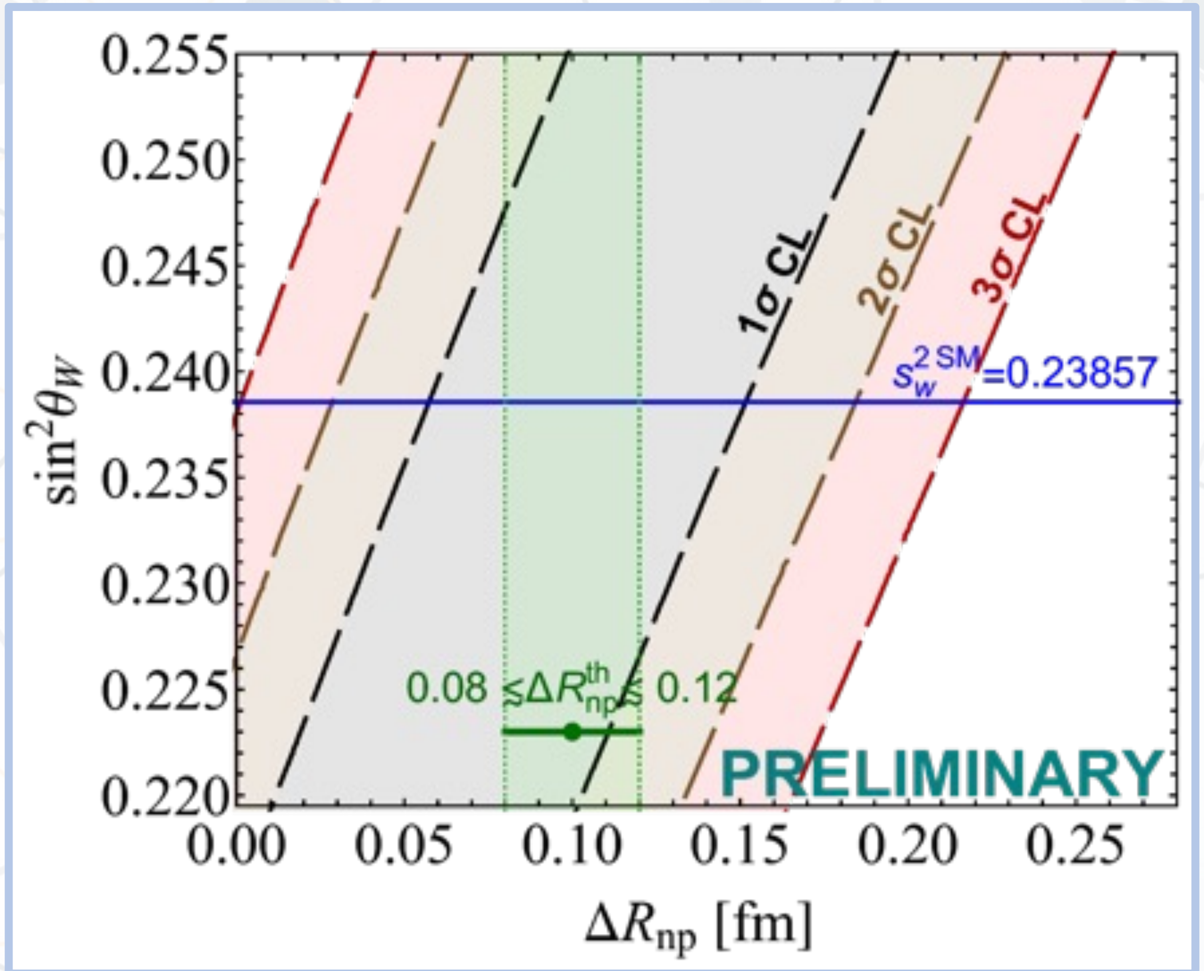
CREX results are about to come out

CREX is the PREX twin experiment on ^{48}Ca

- Higher momentum transfer: $Q \sim 172\ MeV$
- $E_e \sim 2.1\ GeV$
- $\theta_{scatt} \sim 5°$
- $A_{pv}^{preliminary} = 2.6586 \pm 0.1132$ ppm
- We used the PREX-II angular acceptance
- $a \approx 0.523$ fm

Fixed $\sin^2\theta_W \rightarrow \mathbf{\Delta R_{np}(^{48}Ca) = 0.10 \pm 0.03\ fm}$
Thin skin compatible with the nuclear model prediction: $\mathbf{\Delta R_{np}^{th} \sim 0.08 - 0.12\ fm}$

Degenerate Band
To be compatible with the nuclear model prediction $\sin^2\theta_W$ should be similar to its SM value



It's just a really PRELIMINARY result

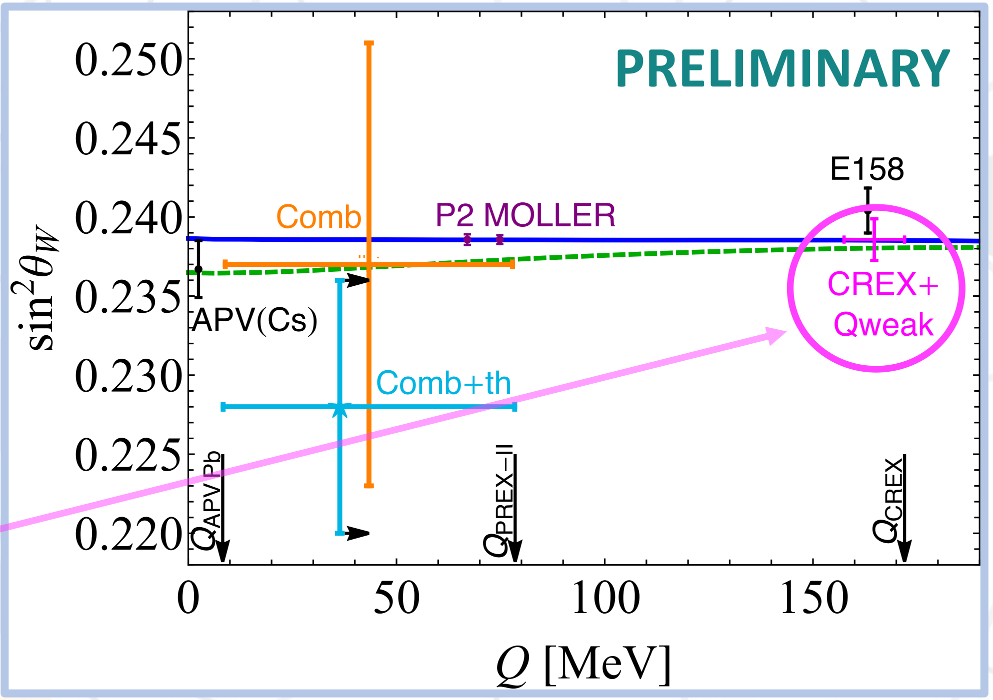
CREX+Qweak

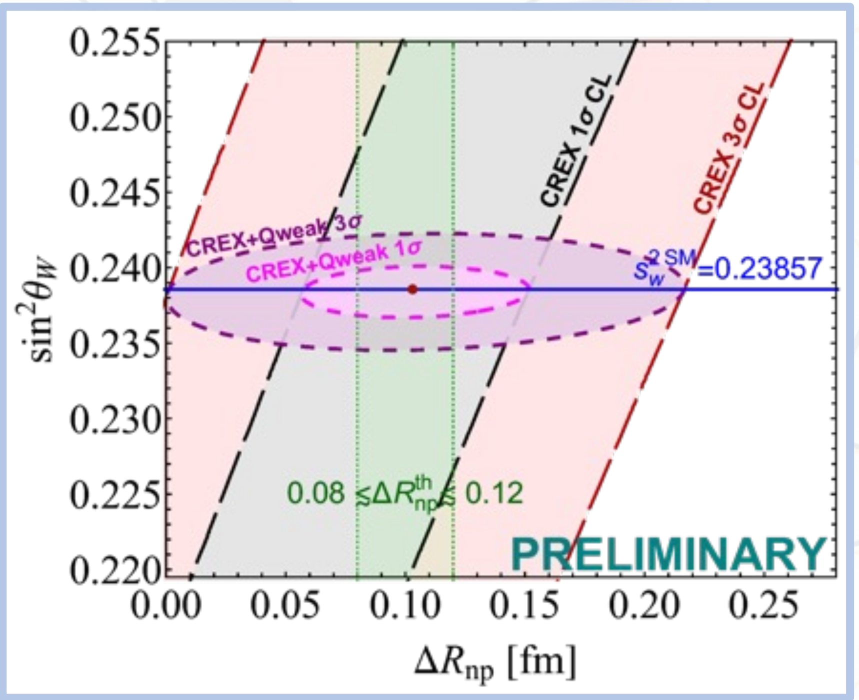
We can use the Qweak measurement to break the degeneracy:

- proton weak charge measurement at Q~160 MeV

$$\sin^2\theta_W \approx 0.238 \pm 0.001$$

Precise measurement of $\sin^2\theta_W$ at Q~160 MeV





CREX+Qweak results

$$\Delta R_{np} = 0.10 \pm 0.03 \text{ fm}$$

$$\sin^2\theta_W = 0.23857 \pm 0.001$$

CREX → thin skin
PREX → thick skin

Different Qs can mean different $\sin^2\theta_W$

Can we be in presence of a BSM effect on the weak mixing angle? Who knows..

MESA measurements

O. Koschchii et all., PRC 102,022501(2020)

PHYSICAL REVIEW C **102**, 022501(R) (2020)

Rapid Communications

Weak charge and weak radius of ^{12}C

Oleksandr Koshchii,[1,*] Jens Erler,[1,2,3] Mikhail Gorchtein,[4] Charles J. Horowitz,[5] Jorge Piekarewicz,[6] Xavier Roca-Maza,[7] Chien-Yeah Seng,[8] and Hubert Spiesberger[1]

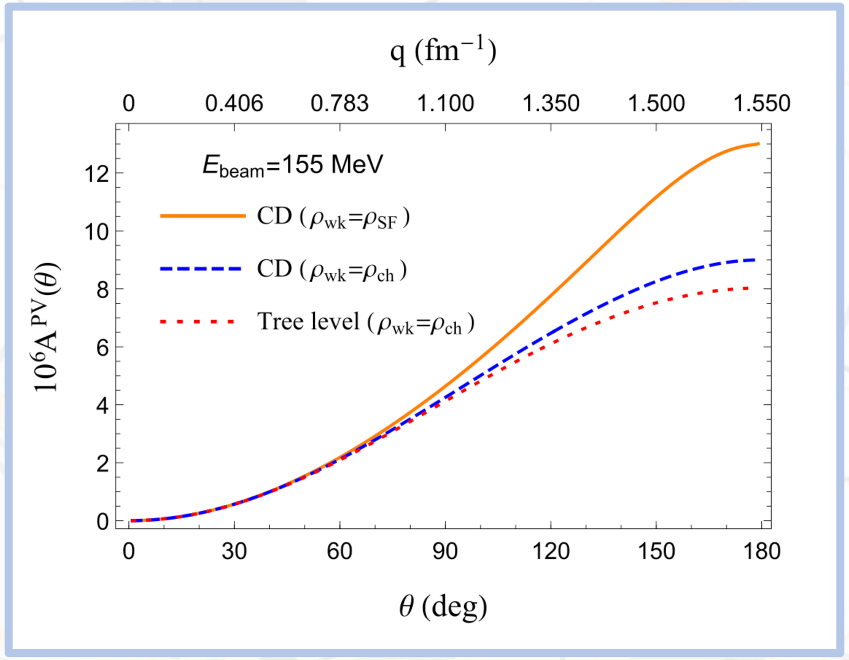
[1]PRISMA+ Cluster of Excellence, Institut für Physik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
[2]Helmholtz Institute Mainz, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
[3]Departamento de Física Teórica, Instituto de Física, Universidad Nacional Autónoma de México, 04510 CDMX, México
[4]PRISMA+ Cluster of Excellence, Institut für Kernphysik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
[5]Department of Physics, Center for Exploration of Energy and Matter, Indiana University, Bloomington, Indiana 47405, USA
[6]Department of Physics, Florida State University, Tallahassee, Florida 32306, USA
[7]Dipartimento di Fisica, Universit degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy
[8]Helmholtz-Institut für Strahlen- und Kernphysik, Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany

(Received 8 May 2020; accepted 27 July 2020; published 11 August 2020)

The case of Carbon-12@Mesa

- $E_e \sim 155\ MeV$
- $\rho_W \sim \rho_{ch}$ (6 neutrons and 6 protons)
- $Q_W(^{12}C) \approx -24 \sin^2\theta_W$

- Approach which accounts for model dependences
- Combined information from forward and backward scattering



O. Koschchii et all., PRC 102,022501(2020)

- Coulomb distorsion effect is larger at backward angles
- Study in terms of $\lambda = \frac{R_W - R_{ch}}{R_{ch}}$ and $\Delta \equiv \frac{F_{wk}(Q^2)}{F_{ch}(Q^2)} - 1$
- $\Delta = -\frac{\lambda}{3} Q^2 R_{ch}^2 + \left[\frac{\lambda}{\lambda_{SF}}\left(\frac{F_{SF}}{F_{ch}} - 1\right) + \frac{\lambda}{3} Q^2 R_{ch}^2\right]$
- $\mathcal{A}_{pv} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W}{Z} [1 + p_0 + (p_1 + p_2\zeta)\lambda]$
- ζ to account for the model dependence introduced by fixing the diffuseness parameter

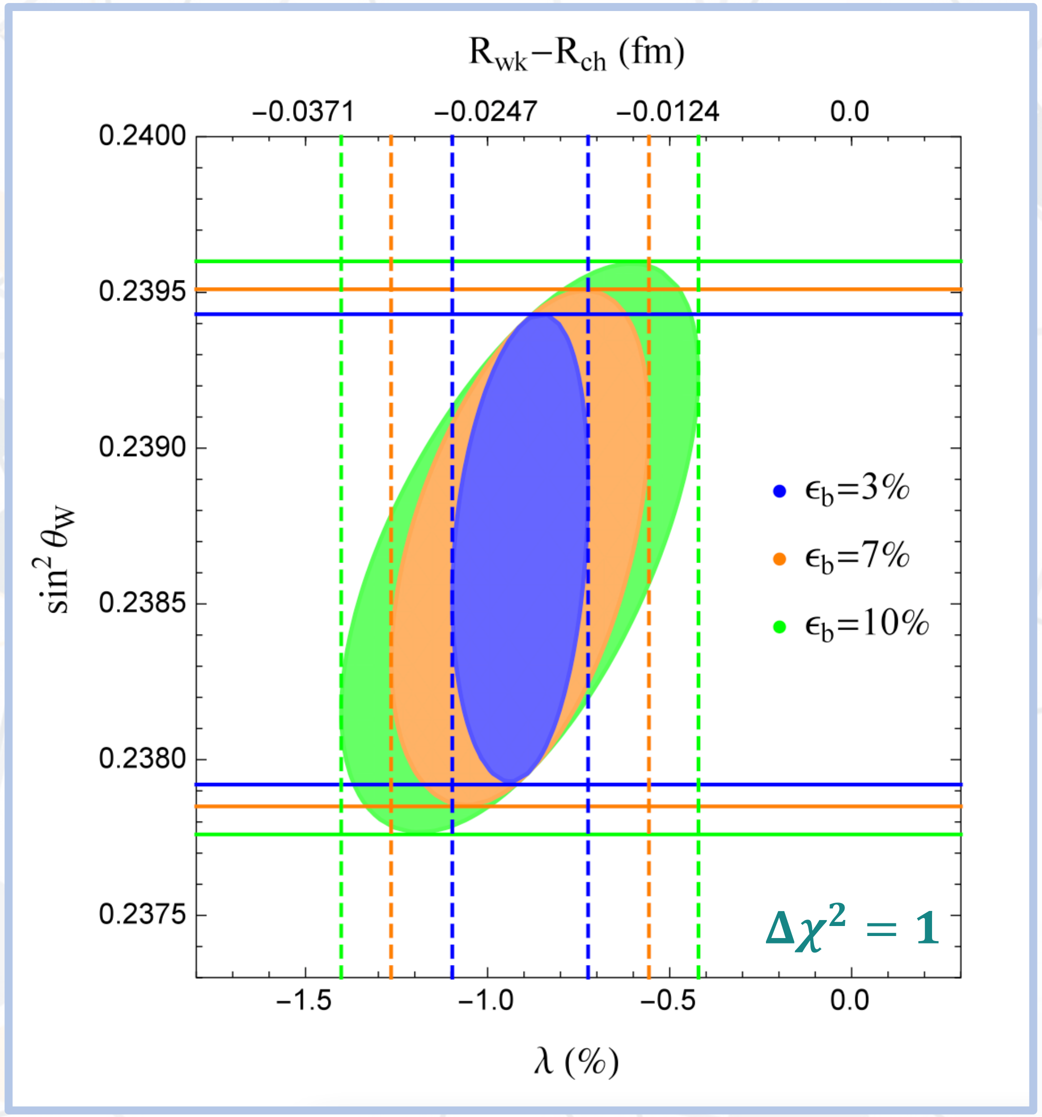
Simultaneous measurement

Combined measurement of $\mathcal{A}_{\mathrm{pv}}$ at both forward and backward angle:

- Assuming a 0.3% precision at forward angle (29°)
- Investigating for 3%-7%-10% precisions at backward angle (145°)

- **Simultaneous measurement of R_{skin} and $\sin^2\theta_W$ with intriguing precision**
- **No need of an external input to break the degeneracy**

Estimate of having a relative precision of 0.32-0.35% on $\sin^2\theta_W$ (similar to Qweak) and a determination of R_W within 0.19-0.35% of R_{ch}



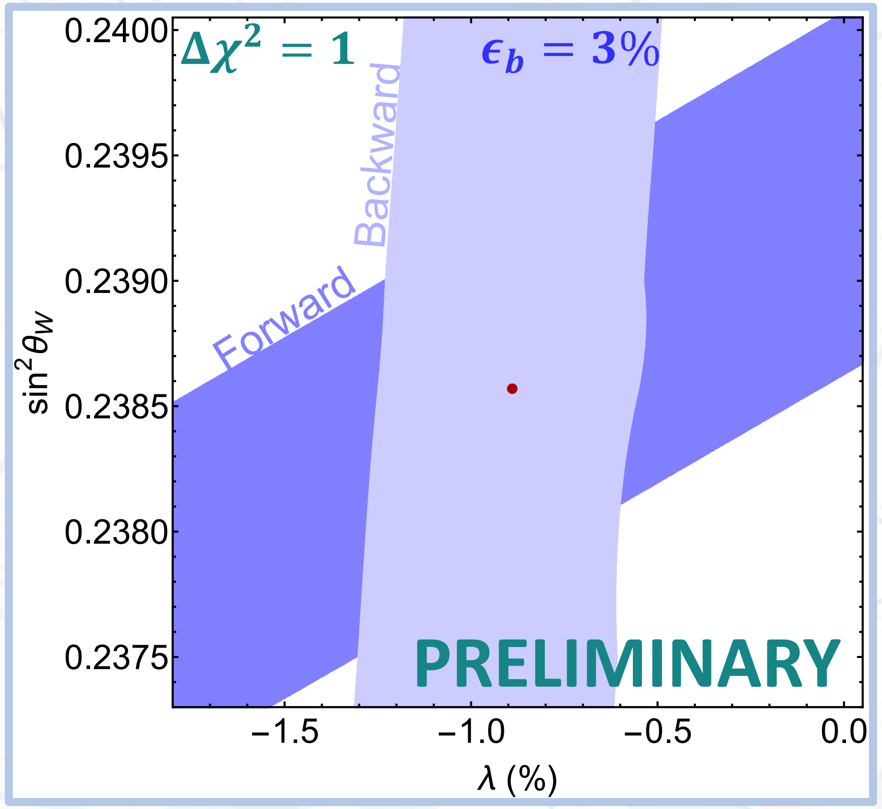
O. Koschchii et all., PRC 102,022501(2020)

Preliminary results on ^{12}C

Work in Collaboration with M. Gorchtein and H. Spiesberger

Same approach adopted for CREX and PREX to the case of a backward-forward measurement on ^{12}C:

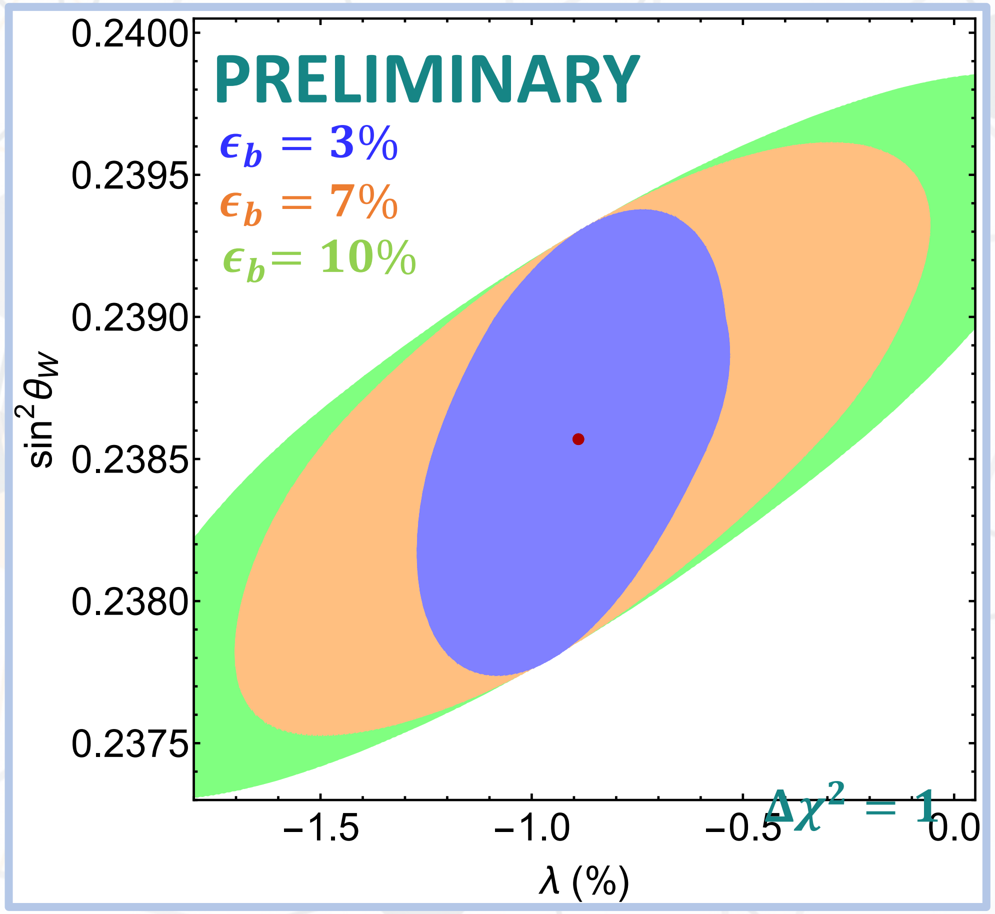
- $E_e \sim 155$ MeV $\rightarrow q \sim 70 - 300$ MeV
- $a = 0.494$ fm



Different behaviour at different angles

We get larger regions: probably due to the different treatement of the diffuseness

A prior on ζ was considered



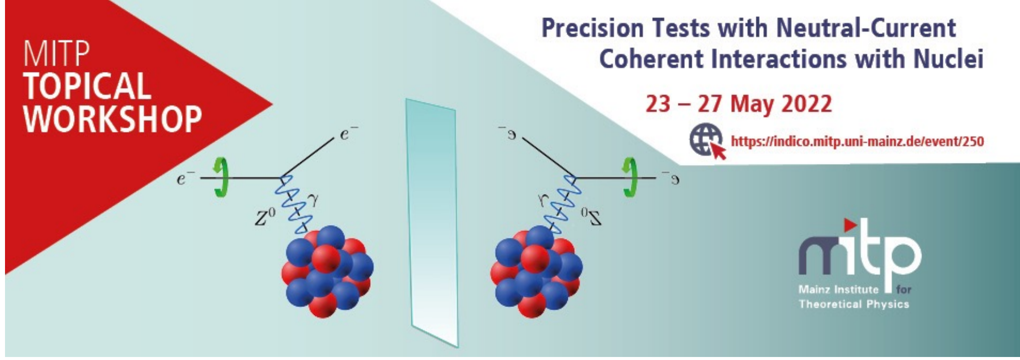
WORK IN PROGRESS FOR ADOPTING THE SAME TREATEMENT OF PRC.102,022501(2020)

Conclusions

- We showed the impact of a **non-standard weak mixing angle** running at low-energies for PVES experiments
- In this scenario, **CREX could find a thin neutron skin** being still compatible with the **thick skin found by PREX** due to the **different energy scales** (i.e. different weak mixing angle)
- **Need for precise weak mixing angle measurements at low-energy**
- Prospect for a **simulaneous measurement** of the weak skin and weak mixing angle **with ^{12}C @MESA** facility using 155 MeV electrons

TO BE DONE:

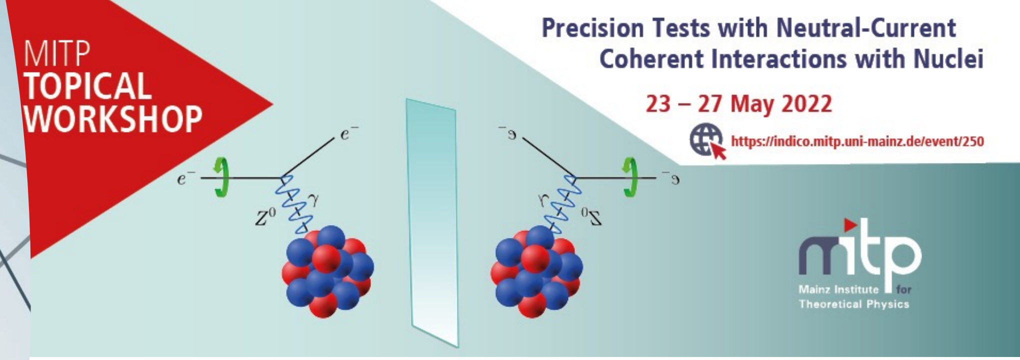
- Implement in our analysis the procedure introduced in **PRC.102,022501(2020)** for the case of ^{12}C to account for the nuclear model dependence
- Investigate the sensitivity of the measurement on ^{12}C also for different kinematic regimes



Thank you for your kind attention

Questions?

Doubts?



Back Up Slides

Nicola Cargioli
nicola.cargioli@ca.infn.it

Istituto Nazionale di Fisica Nucleare
Sezione di Cagliari

Nuclear Weak Charge

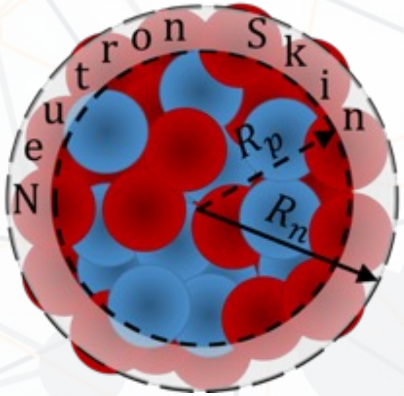
Weak coupling to a nucleus:

$$Q_W = -2(g_{ep}^{AV} Z + g_{en}^{AV} N)$$

Combination of electron coupling to protons and neutrons

Electron-proton coupling suppressed with respect to neutron coupling :

$$Q_W^p = -2g_{ep}^{AV} \approx 0.0714$$
$$Q_W^n = -2g_{en}^{AV} \approx -0.99$$



Weak Form Factor

Radius R_{ch} and the Weak Radius R_W into Proton distribution radius R_p and Neutron distribution radius R_n

$$R_p^2 = R_{\mathrm{ch}}^2 - \frac{N}{Z}\langle r_{\mathrm{n}}^2\rangle - \frac{3}{4M^2} - \langle r^2\rangle_{SO}$$

M. Cadeddu et al. PRD 102,015030(2020)
G. Hagen et al. Nature Physics 12,186-190 (2016)

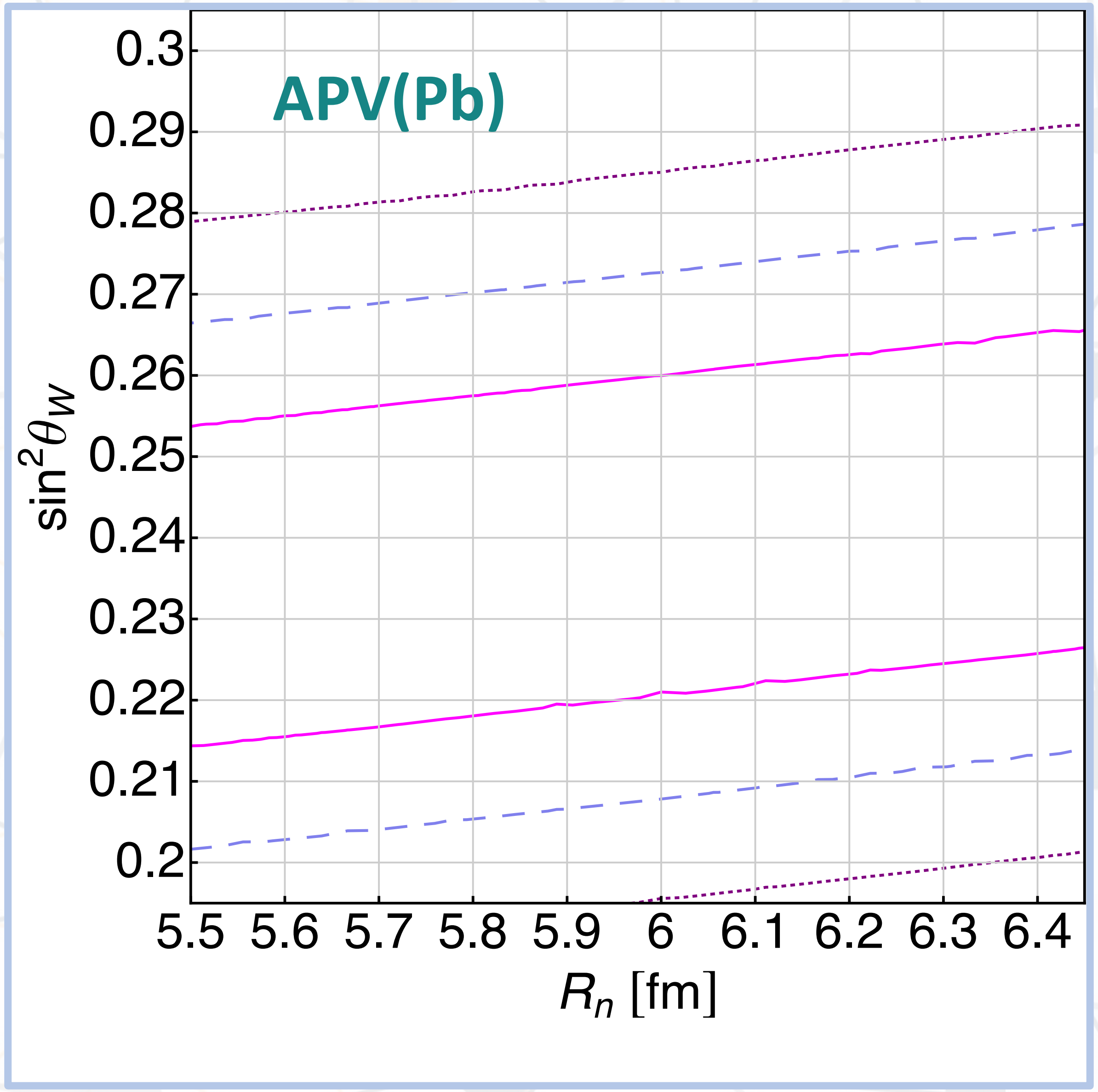
$$R_n^2 = \frac{Q_W}{Q_W^n N} R_{\mathrm{W}}^2 - \frac{Q_W^p Z}{Q_W^n N} R_{ch}^2 - \langle r_p^2\rangle - \frac{Z}{N}\langle r_{\mathrm{n}}^2\rangle + \frac{Z+N}{Q_W^n N}\langle r_{\mathrm{s}}^2\rangle$$

C.J. Horowitz et al. PRC 85,032501(2012)

Neutron Skin → $\Delta R_{np} = R_n - R_p$

Weak Skin → $R_{skin} = R_W - R_{ch}$

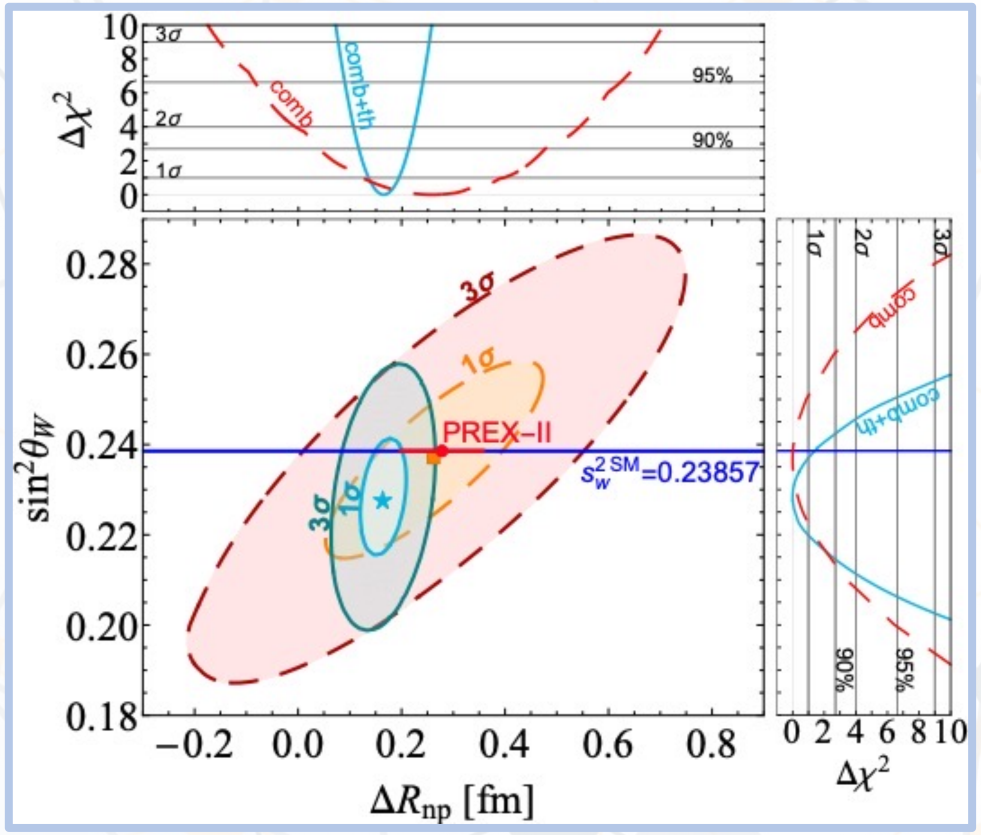
Atomic Parity Violation



PVES+APV Pb

APV(Pb) and PVES on ^{208}Pb depend on the same quantities: ΔR_{np} and $\sin^2\theta_W$

APV is more sensitive to $\sin^2\theta_W$, PREX more to ΔR_{np}



M. Atzori Corona et al.
PRC 105,055503 (2022)

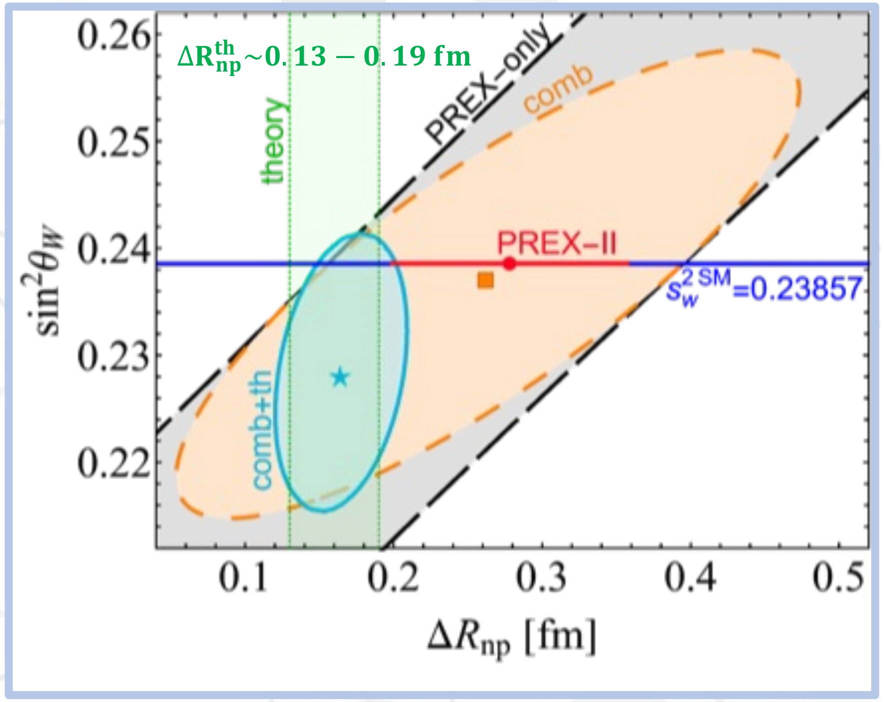
The assumption behind the combined fit is that the weak mixing angle has to be constant between the two experimental energy scales (i.e. $8 \lesssim Q \lesssim 78$ MeV)

$$\Delta R_{np} = 0.262 \pm 0.136 \text{ fm}$$
$$\sin^2\theta_W = 0.237 \pm 0.014$$

If we force the skin toward the EDF predicted value we find:

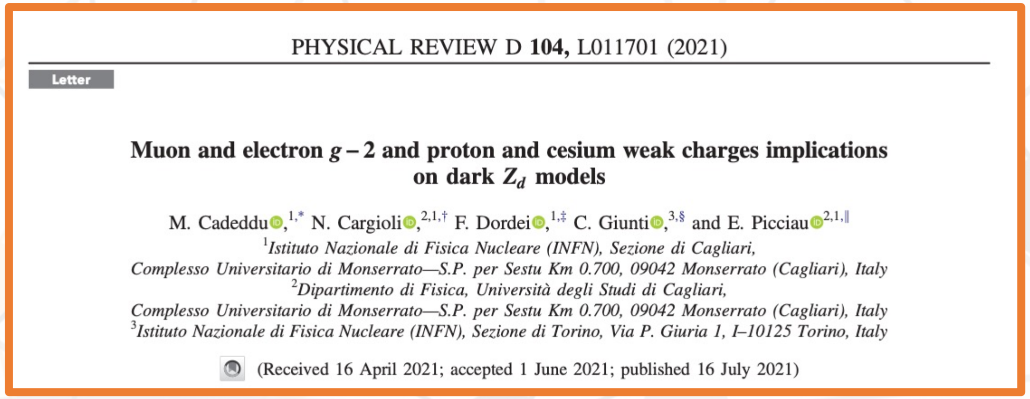
$$\Delta R_{np} = 0.164 \pm 0.029 \text{ fm}$$
$$\sin^2\theta_W = 0.228 \pm 0.008$$

In order to find a neutron skin compatible with the ones predicted by EDF nuclear models the weak mixing angle should be lower than the SM value



M. Atzori Corona et al.
PRC 105,055503 (2022)

BSM physics in W.M.A.


PHYSICAL REVIEW D **104**, L011701 (2021)

Letter

Muon and electron $g-2$ and proton and cesium weak charges implications on dark Z_d models

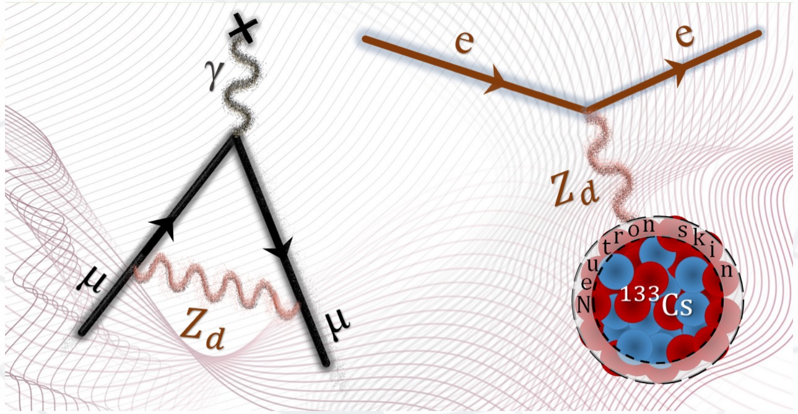
M. Cadeddu,[1,*] N. Cargioli,[2,1,†] F. Dordei,[1,‡] C. Giunti,[3,§] and E. Picciau[2,1,∥]

[1]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy
[2]Dipartimento di Fisica, Università degli Studi di Cagliari, Complesso Universitario di Monserrato—S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy
[3]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy

(Received 16 April 2021; accepted 1 June 2021; published 16 July 2021)

Example of BSM physics involving the weak mixing angle

- Z_d model: **$U(1)_d$ extension** of the SM with a corresponding
- Z_d boson, in the sub-GeV mass scale
- Coupling via **kinetic mixing** parametrized by ε and $Z - Z_d$ **mass matrix mixing**, parametrized by $\varepsilon_Z = (m_{Z_d}/m_Z)\delta$



$$\sin^2\theta_W(Q^2) \rightarrow \left(1 - \varepsilon\delta\frac{m_Z}{m_{Z_d}}\cot\theta_W\, f\left(\frac{Q^2}{m_{Z_d}^2}\right)\right)\sin^2\theta_W(Q^2)$$

H. Davoudiasl et al..Phys Rev Lett 109,031802

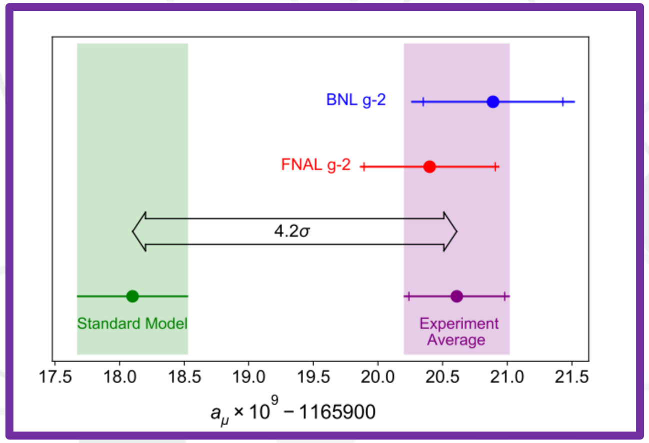
The running of the weak mixing angle gets modified by the introduction of this BSM boson: for a light (MeV) boson, the effect is in the low energy regime

SCALE DEPENDENT VARIATION

- Weak charge measurements (both nuclear and proton) are sensitive to the Z_d boson.
- Also, the anomalous magnetic moment g-2 is sensitive to such boson:
- $a_{l,vector}^{Z_d} = \frac{\alpha}{2\pi}\left(\varepsilon + \frac{m_{Z_d}}{m_Z}\delta\frac{1-4\sin^2\theta_W}{4\sin\theta_W\cos\theta_W}\right)^2 F_V\left(\frac{m_{Z_d}}{m_l}\right)$ con $F_V(x) = \int_0^1 dz \frac{2z(1-z)^2}{(1-z)^2+x^2 z}$

Zd in light of Muon g-2

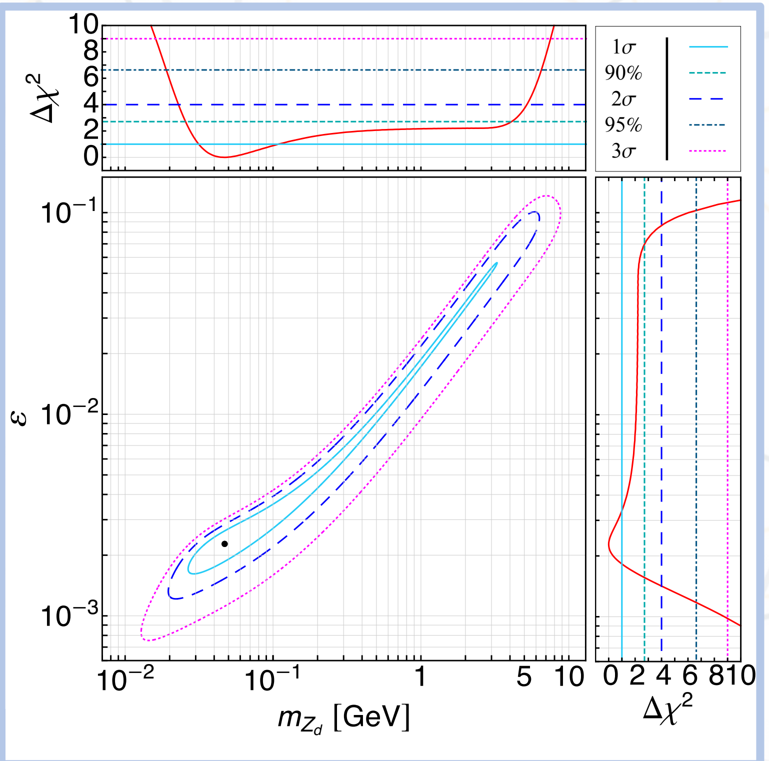
Phys Rev Lett 126, 141801(2021)



- Muon g-2 Collaboration (FNAL) confirmed the deviation of a_μ:
- World average $\Delta a_\mu = 251(59)\times10^{-11}(4.2\sigma)$
- Recent result also for the electron magnetic moment $\Delta a_e = 0.48(30)\times10^{-12}(1.6\sigma)$

L. Morel et al. Nature 588, 61(2020)

Combined fit of APV(Cs), Qweak and muon and electron g-2:

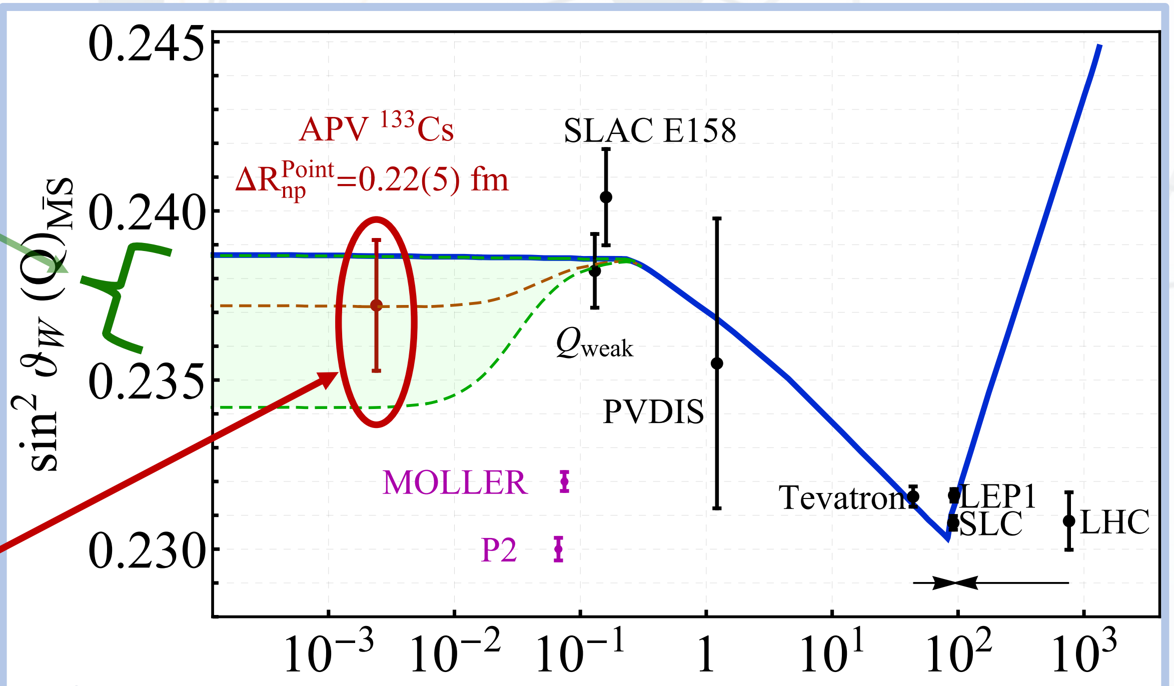


M. Cadeddu et al., PRD 104,L011701(2021)

Effects of Light Mediators from BSM theories

$$m_{Z_d} = 47^{+61}_{-16}\ MeV$$
$$\varepsilon = 2.3^{+1.1}_{-0.4}\times10^{-3}$$
$$\delta < 2\times10^{-3}$$

New APV result determined by us

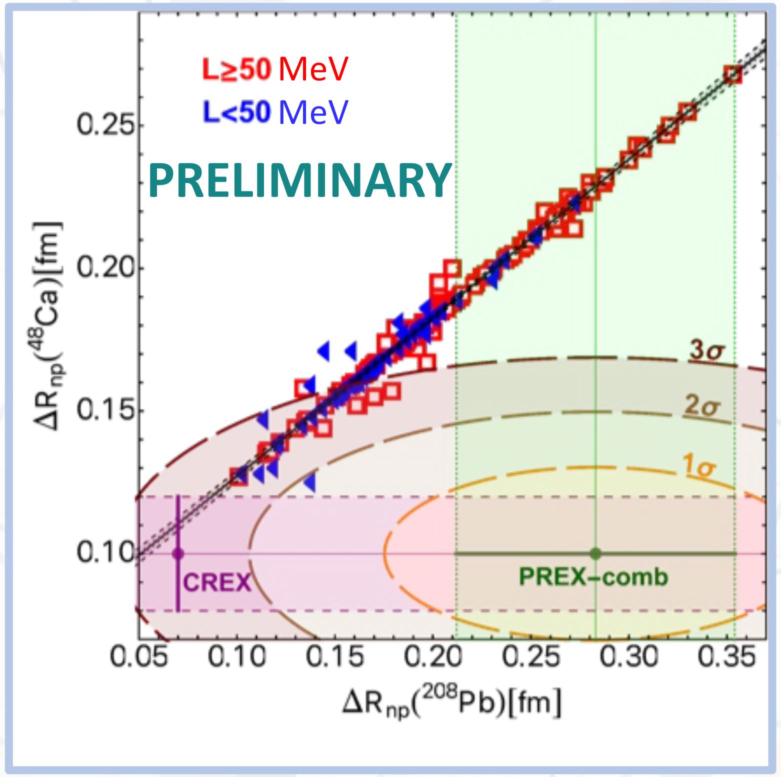


M. Cadeddu et al.
PRD 104,L011701(2021)

CREX

CREX is the PREX twin experiment on ^{48}Ca

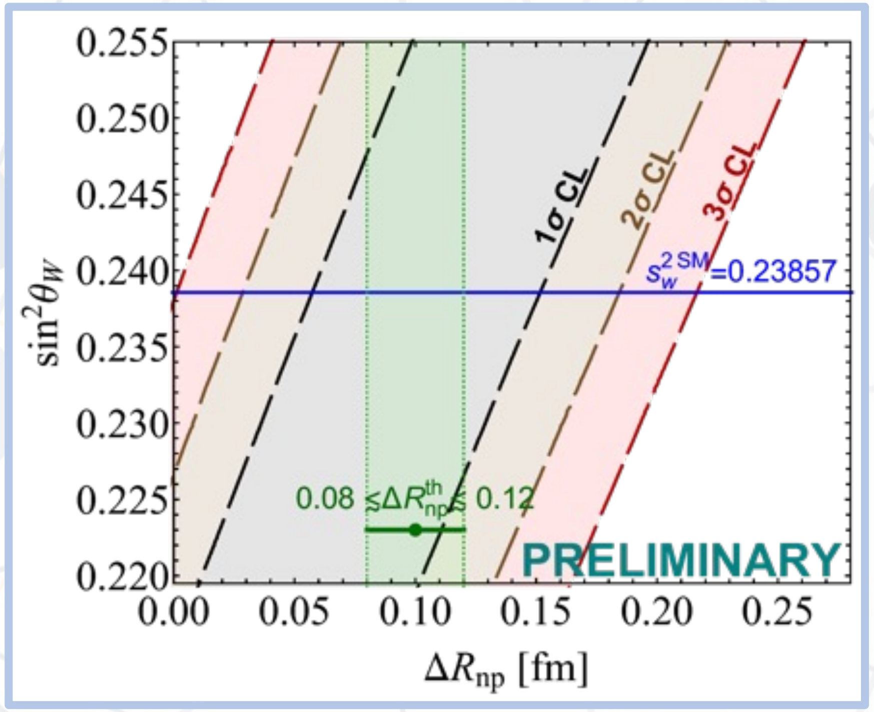
- Higher momentum transfer: $Q \sim 172\ MeV$ $(E_e \sim 2.1\ GeV, \theta_{scatt} \sim 5°)$
- $A_{pv}^{preliminary} = 2.6586 \pm 0.1132$ ppm
- We used the PREX angular acceptance
- Weak charge computed at tree level
- $a \approx 0.523$ fm



CREX results are about to come out

For the nuclear model prediciton of CREX

The combination of PREX and CREX results could suggest a preference for some values of the L parameter, selecting specific nuclear models



It's just a PRELIMINARY result

Fixed $s_w^2 \rightarrow \Delta R_{np}(^{48}Ca) = 0.10 \pm 0.03$ fm
Skin thinner and compatible with the nuclear model prediction: $\Delta R_{np}^{th} \sim 0.08 - 0.12$ fm

Degenerate Band, however, to be compatible with the nuclear model prediction the weak mixing angle should approximately be similar to its SM value

CREX+Qweak

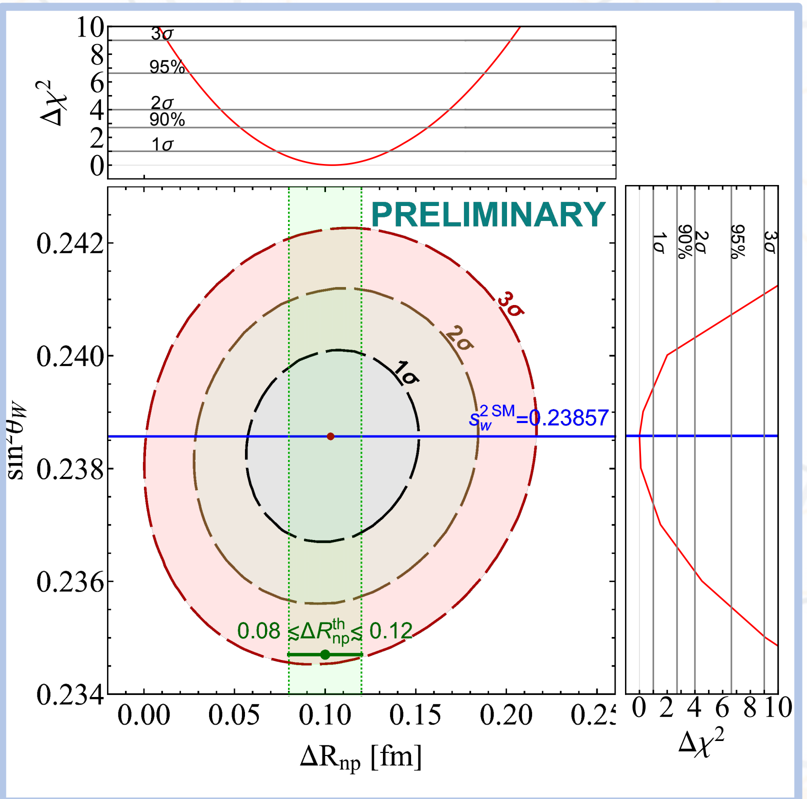
We can use the Qweak measurement to break the degeneracy:

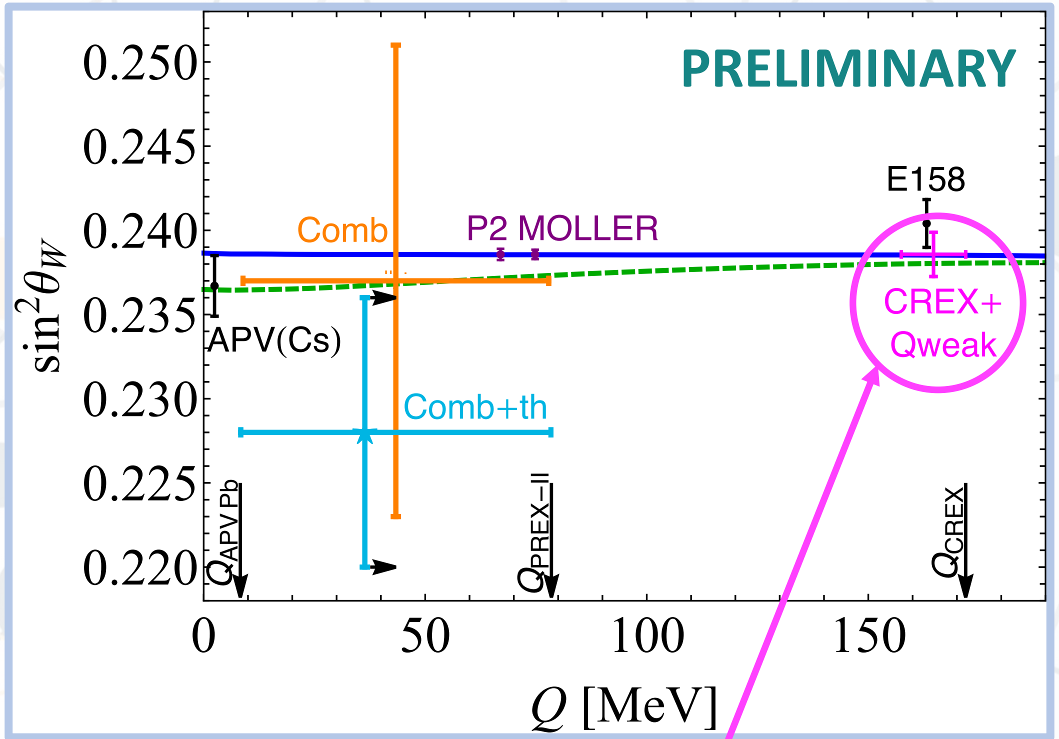
- proton weak charge measurement at Q~160 MeV

$Q_W^p = -2g_{AV}^{ep} = 0.0711(2)$ $\qquad Q_W^{p,exp} = -2g_{AV}^{ep} = 0.0719(45)$

Which is translated in: $\sin^2\theta_W \approx 0.238 \pm 0.001$

Precise measurement of $\sin^2\theta_W$ at Q~160 MeV





CREX could find a thin skin, while PREX measures a thick skin due to the different impact of the weak mixing angle at different energy scales

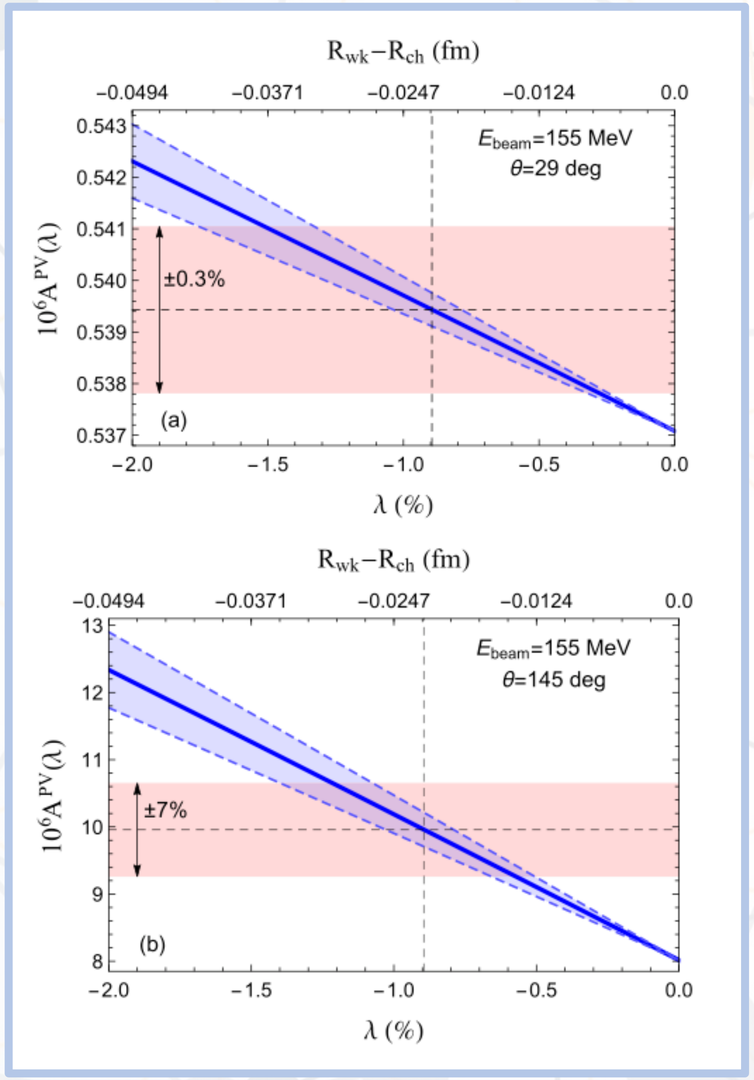
CREX+Qweak results

$\Delta R_{np} = 0.10 \pm 0.03$ fm

$\sin^2\theta_W = 0.23857 \pm 0.001$

Are we in presence of a BSM effect on the weak mixing angle? Who knows..

MESA measurements



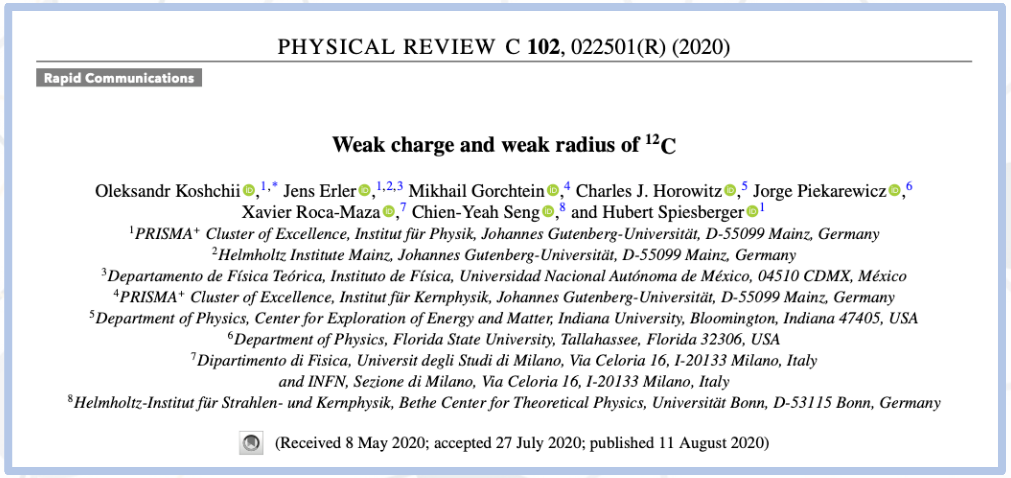
O. Koschchii et all., PRC 102,022501(2020)

The case of Carbon-12@Mesa

- $E_e \sim 155\ MeV$
- Higher precision
- $\rho_W \sim \rho_{ch}$
- $Q_W(^{12}C) \approx -24 \sin^2 \theta_W$

Three major novelties:

- Approach which accounts for model dependences
- Combined information from forward and backward scattering


PHYSICAL REVIEW C **102**, 022501(R) (2020)

Rapid Communications

Weak charge and weak radius of ^{12}C

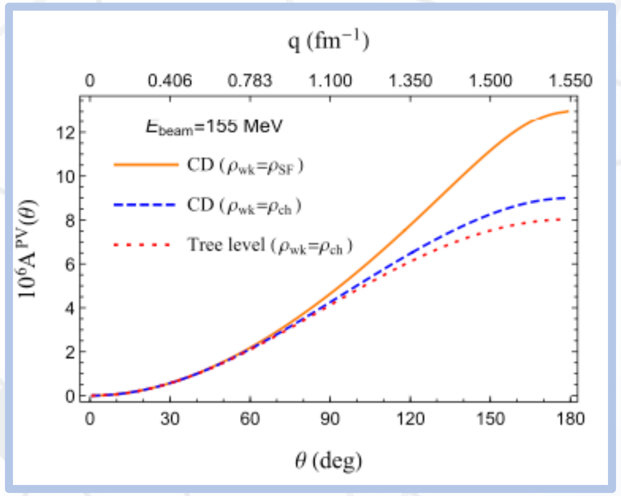
Oleksandr Koshchii,[1,*] Jens Erler,[1,2,3] Mikhail Gorchtein,[4] Charles J. Horowitz,[5] Jorge Piekarewicz,[6] Xavier Roca-Maza,[7] Chien-Yeah Seng,[8] and Hubert Spiesberger[1]

[1]*PRISMA+ Cluster of Excellence, Institut für Physik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*
[2]*Helmholtz Institute Mainz, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*
[3]*Departamento de Física Teórica, Instituto de Física, Universidad Nacional Autónoma de México, 04510 CDMX, México*
[4]*PRISMA+ Cluster of Excellence, Institut für Kernphysik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*
[5]*Department of Physics, Center for Exploration of Energy and Matter, Indiana University, Bloomington, Indiana 47405, USA*
[6]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[7]*Dipartimento di Fisica, Universit degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*
[8]*Helmholtz-Institut für Strahlen- und Kernphysik, Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*

(Received 8 May 2020; accepted 27 July 2020; published 11 August 2020)

O. Koschchii et all., PRC 102,022501(2020)

- Coulomb distorsion effect is larger at backward angles
- Study in terms of $\lambda = \frac{R_W}{R_{ch}} - 1$
- $\mathcal{A}_{pv} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W}{Z}(1+\Delta)$
- $\Delta = -\frac{\lambda}{3} Q^2 R_{ch}^2 + \left[\frac{\lambda}{\lambda_{SF}}\left(\frac{F_{SF}}{F_{ch}} - 1\right) + \frac{\lambda}{3} Q^2 R_{ch}^2\right]$



- $\mathcal{A}_{pv}$=- $\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W}{Z}[1 + p_0 + (p_1 + p_2\zeta)\lambda]$
- ζ to account for the model dependence introduced by fixing the thickness parameter

Preliminary results on ^{12}C