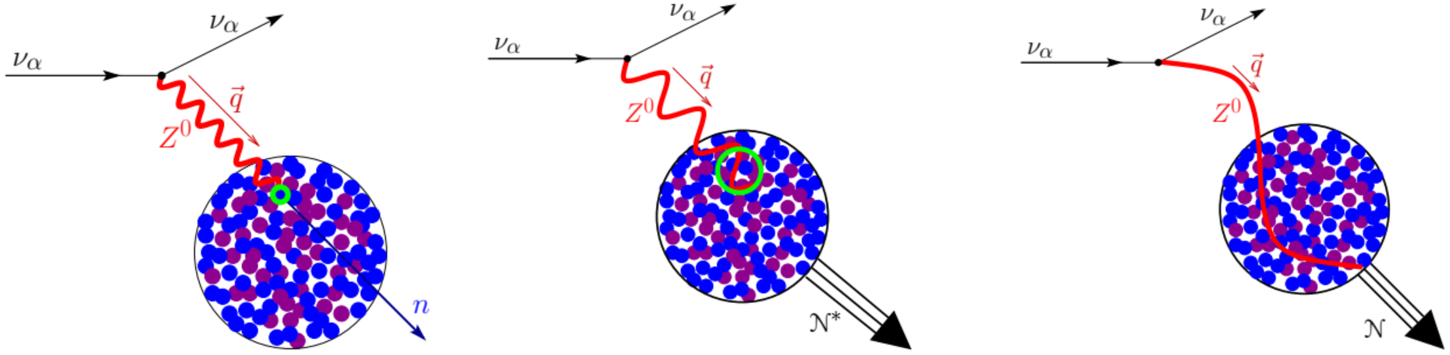
CEνNS review and implications for Dark Matter searches



For a recent review see Europhysics Letters, Volume 143, Number 3, 2023 (EPL 143 34001), arXiv:2307.08842v2

20th Rencontres du Vietnam

July 7–13

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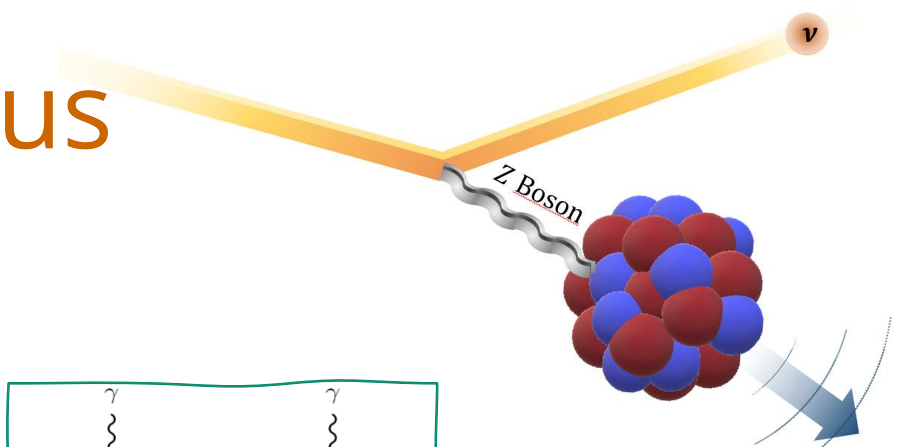
ICISE

PASCOS

2024

Coherent elastic neutrino nucleus scattering (aka CEνNS)



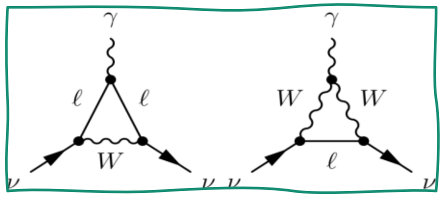
- A pure weak neutral current process

$$\boxed{\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}(E,T_{\mathrm{nr}}) = \frac{G_{\mathrm{F}}^2 M}{\pi}\left(1-\frac{MT_{\mathrm{nr}}}{2E^2}\right)\left(Q^V_{\ell,\mathrm{SM}}\right)^2}$$

- Weak charge of the nucleus

$$Q^V_{\ell,\mathrm{SM}} = \Big[\underbrace{g_V^p(\nu_\ell)\,Z F_Z\left(|\vec{q}|^2\right)}_{\text{protons}} + \underbrace{g_V^n N F_N\left(|\vec{q}|^2\right)}_{\text{neutrons}}\Big]$$

In general, in a weak neutral current process which involves nuclei, one deals with **nuclear form factors** that are different for protons and neutrons and cannot be disentangled from the neutrino-nucleon couplings!



J. Erler and S. Su. *Prog. Part. Nucl. Phys.* 71 (2013). arXiv:1303.5522 & PDG2023 and **M. Atzori Corona et al. arXiv:2402.16709**

- Neutrino-nucleon tree-level couplings

$$g_V^p = \frac{1}{2} - 2\sin^2(\vartheta_W) \cong \mathbf{0.02274}$$

$$g_V^n = -\frac{1}{2} = -0.5$$

- Radiative corrections are expressed in terms of WW, ZZ boxes and the neutrino charge radius diagram → Flavour dependence

$$\underbrace{g_V^p(\nu_e) \simeq 0.0381,\ g_V^p(\nu_\mu) \simeq 0.0299 \quad g_V^n \simeq -0.5117}$$

Nuclear physics, but since $g_V^n \approx -0.51 \gg g_V^p(\nu_\ell) \approx 0.03$ neutrons contribute the most

$$\boxed{\frac{d\sigma}{dE_r} \propto N^2}$$

What we can learn from CEνNS

M. Cadeddu et al., JHEP 01 (2021) 116, arXiv:2008.05022

O. G. Miranda et al., JHEP 05 (2020) 130, arXiv:2003.12050

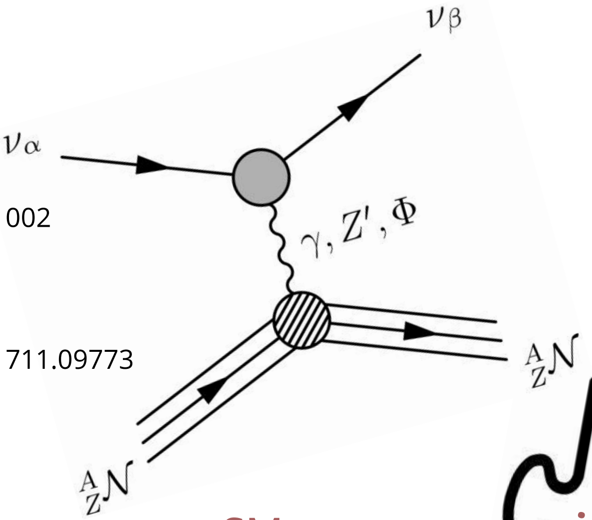
M. Atzori Corona et al., JHEP 05 109 (2022), arXiv:2202.11002

C. Giunti, *PRD* 101 (2020) 3, 035039, arXiv:1909.00466

D. K. Papoulias and T. S. Kosmas, PRD 97, 033003 arxiv:1711.09773

D. A. Sierra et al., PRD 98, 075018 (2018) arXiv:1806.07424

L. J. Flores et al., JHEP 06 (2020) 045, 2002.12342

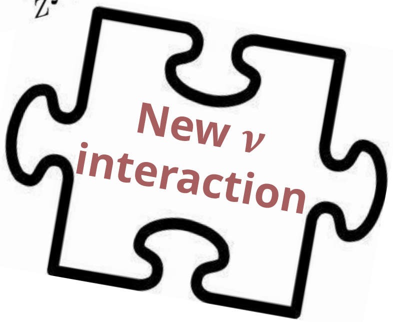


O. G. Miranda et al., JHEP 05 (2020) 130, arXiv:2003.12050

B. Dutta et al., Phys. Rev. Lett. 123, 061801 (2019)

O. G. Miranda et al., JHEP 07 (2019) 103, arXiv: 1905.03750

D. Aristizabal Sierra et al., Phys. Rev. D 98, 075018 (2018)



Neutrino energy

Mass of the nucleus

SM vector proton coupling

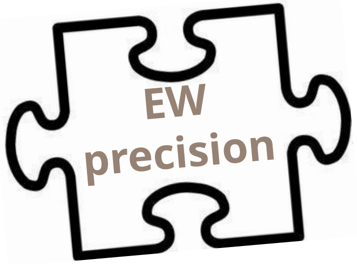
SM vector neutron coupling

$$\frac{d\sigma^{CE\nu NS}(E_\nu, E_r)}{dE_r} \cong \frac{G_F^2\, m_N}{\pi}\left(1-\frac{m_N E_r}{2E_\nu^2}\right)\left[g_V^p\left(\sin^2(\vartheta_W)\right) Z\, F_Z\left(|\vec{q}|^2\right) + g_V^n\, N\, F_N\left(|\vec{q}|^2\right)\right]^2 + \ldots$$

Weinberg angle

Proton Form Factor

Neutron Form Factor



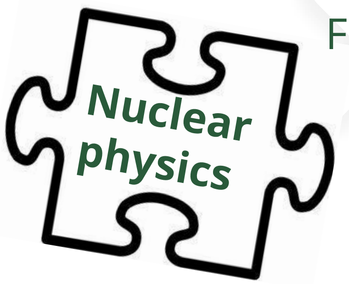
D. Papoulias et al., PLB 800 (2020) 135133, arXiv:1903.03722

Coloma et al., JHEP 08 (2020) 08, 030, arXiv:2006.08624

D. A. Sierra et al., JHEP 1906:141 (2019) arXiv: 1902.07398

B. Canas et al., PRD 101, 035012 (2020), arXiv:1911.09831

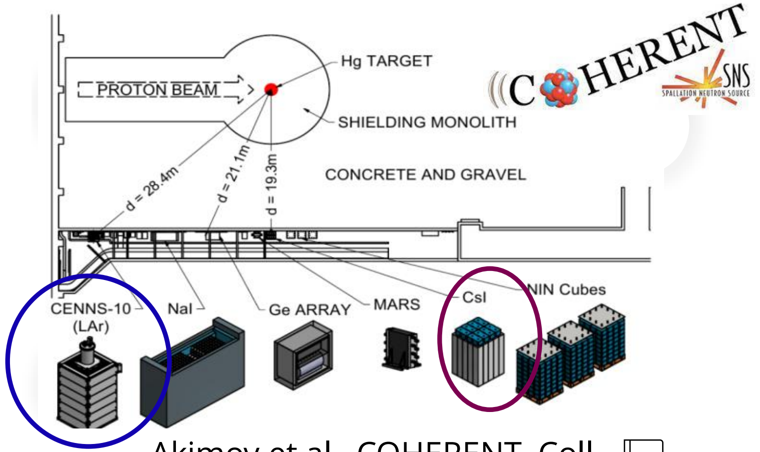
K. Patton, J. Engel, G. C. McLaughlin, and N. Schunck,
Phys. Rev. C 86, 024612 (2012).



CEνNS players

$$\pi^+ \to \mu^+ + \nu_\mu$$ Prompt component

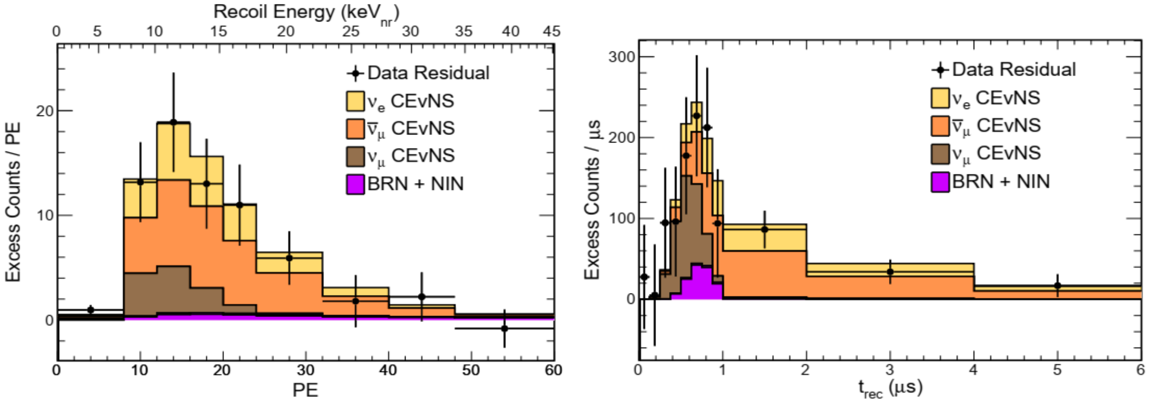
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$ Delayed component



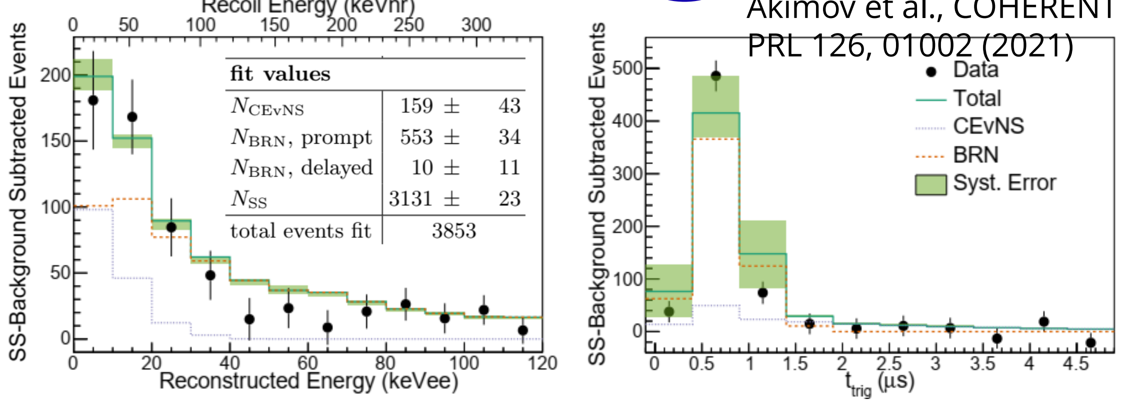
COHERENT CsI

D. Akimov et al. **Science** 357.6356 (2017)

- Updated in Akimov et al., PRL 129, 081801 (2022)

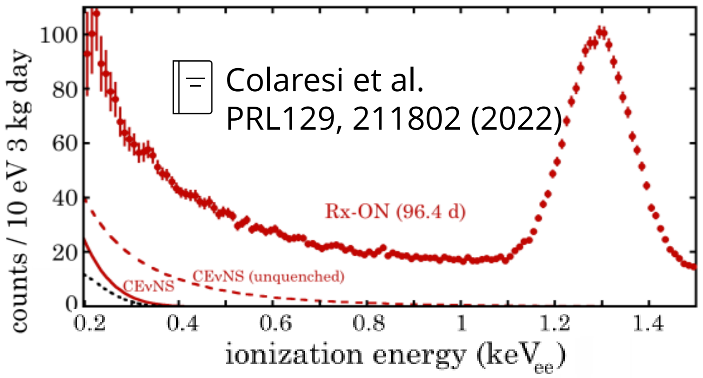


COHERENT Ar



Akimov et al., COHERENT Coll. PRL 126, 01002 (2021)

NCC- 1701 (Dresden-II)

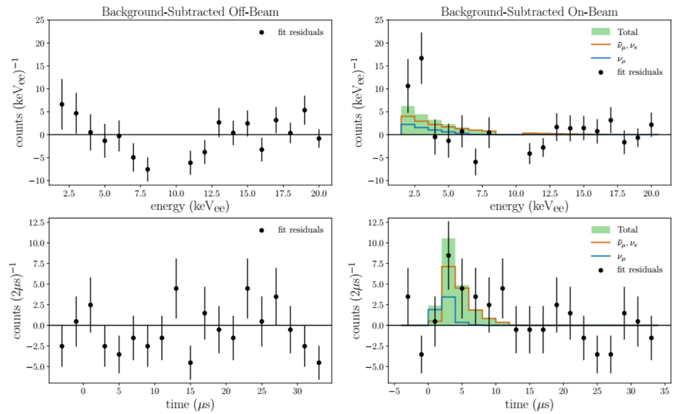


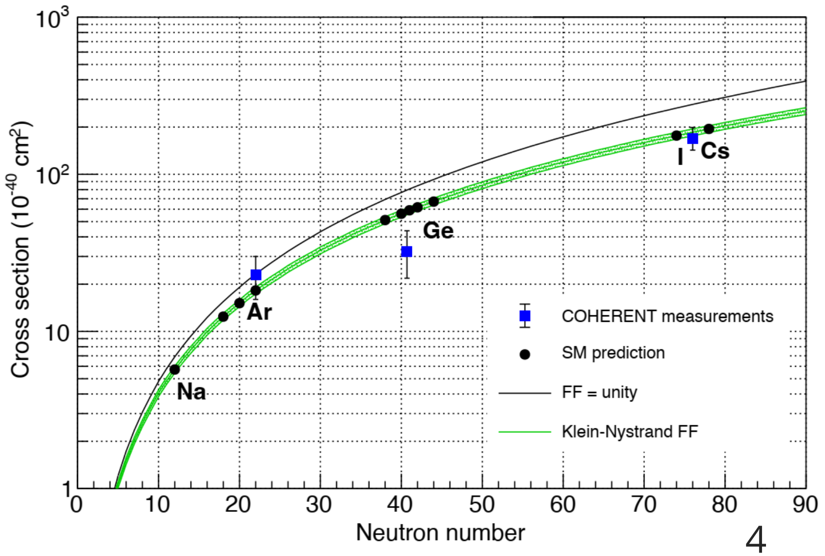
Colaresi et al. PRL129, 211802 (2022)

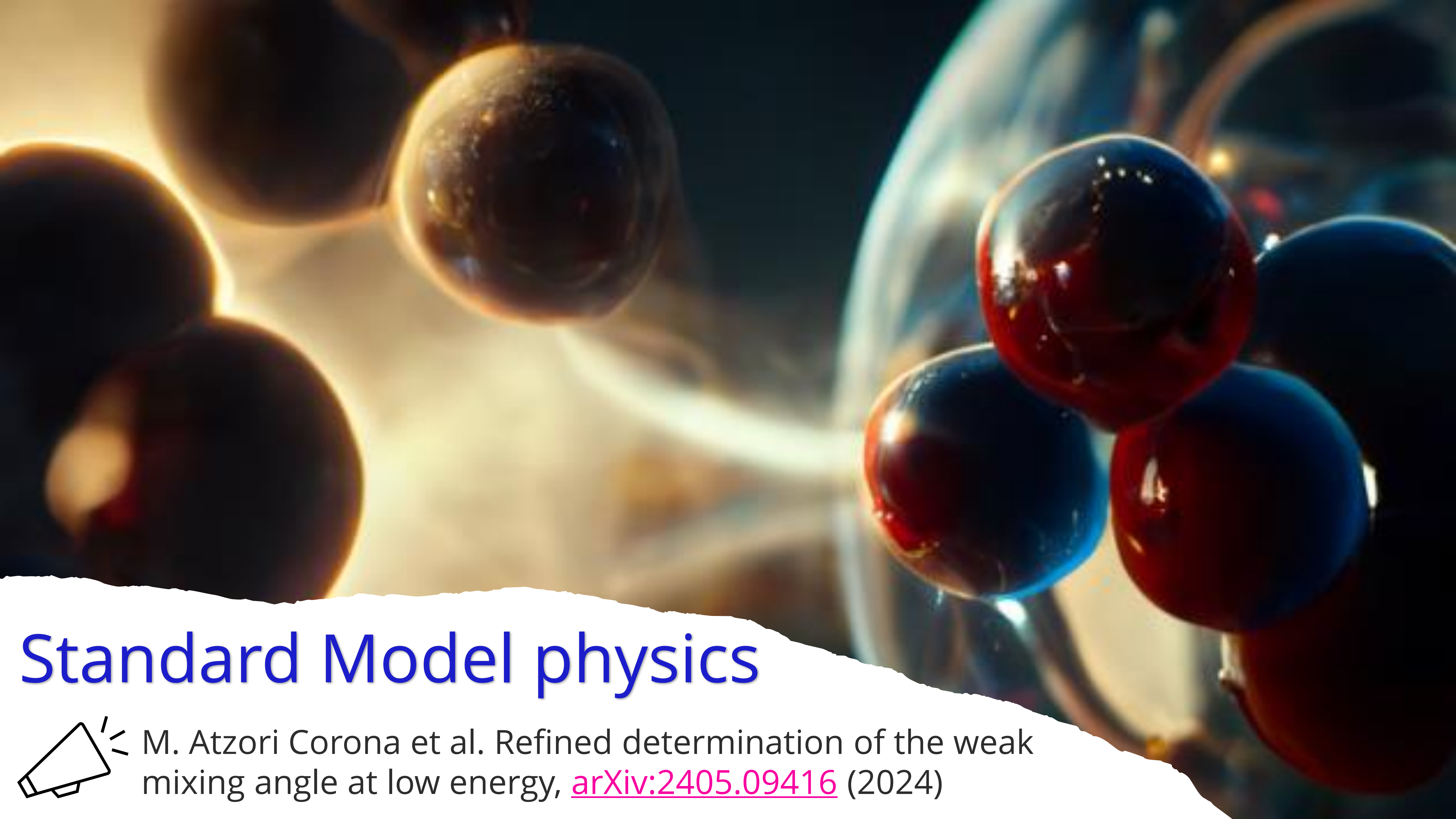
- 3 kg germanium detector @DRESDEN reactor. A strong preference for the presence of CEνNS is found.

NEW COHERENT Ge-Mini result on germanium arXiv:2406.13806 Null Hypothesis rejected at 3.9σ

Off-Beam **On-Beam**







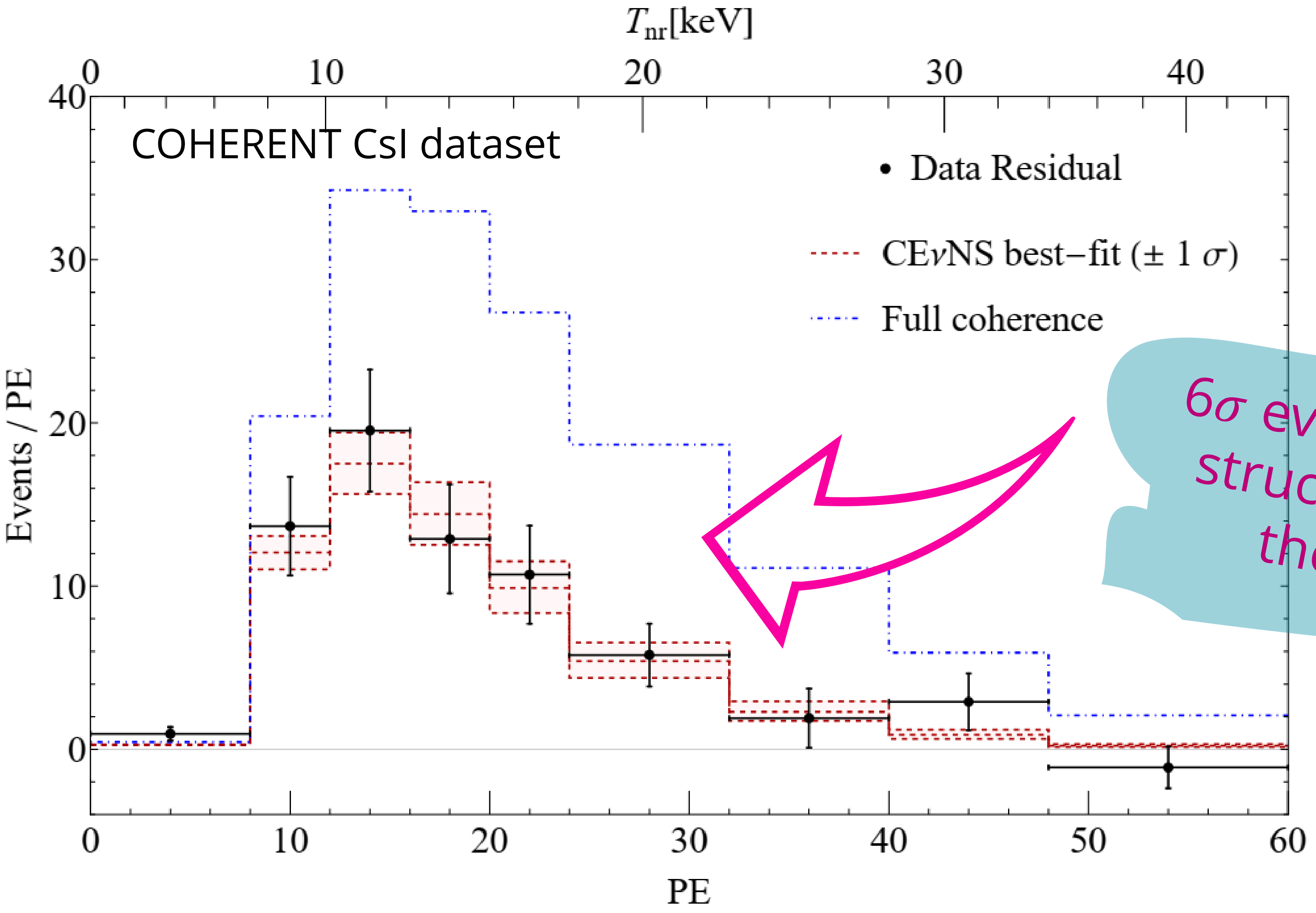
Standard Model physics

M. Atzori Corona et al. Refined determination of the weak mixing angle at low energy, arXiv:2405.09416 (2024)

Neutron form factor dependence in CEνNS cross section

$$\frac{d\sigma^{CE\nu NS}(E_\nu, E_r)}{dE_r} \cong \frac{G_F^2\, m_N}{\pi}\left(1 - \frac{m_N E_r}{2E_\nu^2}\right)\left[g_V^p\left(\sin^2(\vartheta_W)\right) Z\, F_Z(|\vec{q}|^2) + g_V^n\, N\, F_N(|\vec{q}|^2)\right]^2$$

Neutron form factor (R_n) to be fitted



6σ evidence of the nuclear structure suppression of the full coherence!

See also:

Rossi et al. PRD 109, 095044 (2024) arXiv:2311.17168

De Romeri et al. JHEP04(2023)035 arXiv:2211.11905

D. Papoulias et al., PLB 800 (2020) 135133, arXiv:1903.03722

M. Atzori Corona et al.,
EPJC 83 (2023) 7, 683. ArXiv:2303.09360

The CsI neutron skin fixing $\sin^2(\vartheta_W)$

If we fix the value of $\sin^2\vartheta_W$ at the SM prediction ($0.23863(5)$) then we obtain (1D fit):

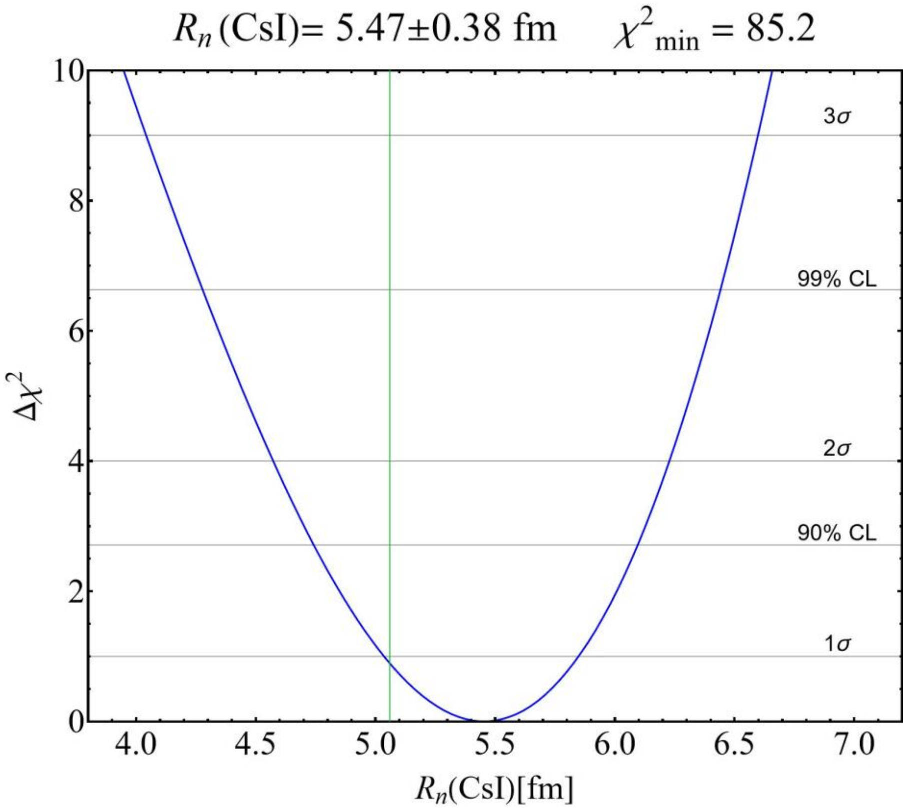
M. Atzori Corona et al., EPJC 83 (2023) 7, 683
arXiv:2303.09360

R_n (CsI) = 5.47 ± 0.38 fm

~7% precision

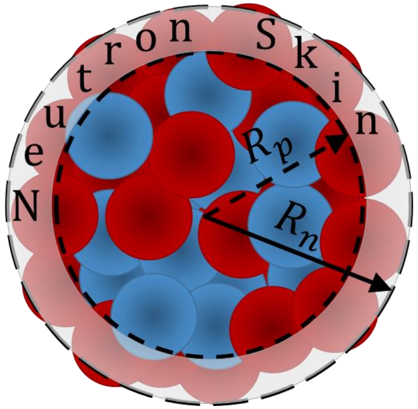
Neutron skin: R_n (CsI)- R_p (CsI)

$\Delta R_{np}(\text{CsI}) = 0.69 \pm 0.38$ fm



Theoretical values of the neutron skin of Cs and I obtained with nuclear mean field models. The value is compatible with all the models…

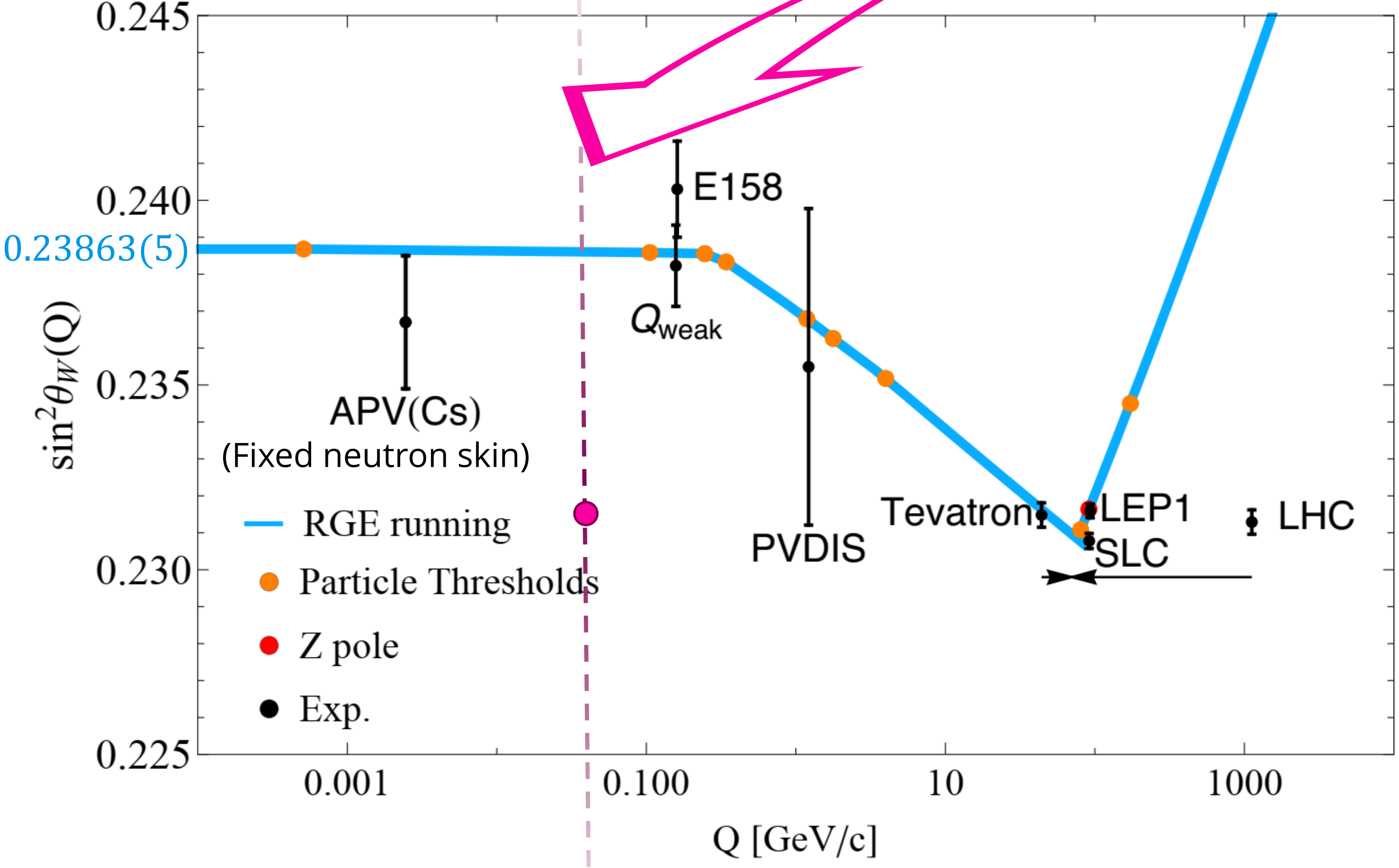
$0.12 < \Delta R_{np}^{CsI} < 0.24$ fm



Model	^{127}I						^{133}Cs					
	R_p^{point}	R_p	R_n^{point}	R_n	$\Delta R_{np}^{\text{point}}$	ΔR_{np}	R_p^{point}	R_p	R_n^{point}	R_n	$\Delta R_{np}^{\text{point}}$	ΔR_{np}
SHF SkI3 [81]	4.68	4.75	4.85	4.92	0.17	0.17	4.74	4.81	4.91	4.98	0.18	0.18
SHF SkI4 [81]	4.67	4.74	4.81	4.88	0.14	0.14	4.73	4.80	4.88	4.95	0.15	0.14
SHF Sly4 [82]	4.71	4.78	4.84	4.91	0.13	0.13	4.78	4.85	4.90	4.98	0.13	0.13
SHF Sly5 [82]	4.70	4.77	4.83	4.90	0.13	0.13	4.77	4.84	4.90	4.97	0.13	0.13
SHF Sly6 [82]	4.70	4.77	4.83	4.90	0.13	0.13	4.77	4.84	4.89	4.97	0.13	0.13
SHF Sly4d [83]	4.71	4.79	4.84	4.91	0.13	0.12	4.78	4.85	4.90	4.97	0.12	0.12
SHF SV-bas [84]	4.68	4.76	4.80	4.88	0.12	0.12	4.74	4.82	4.87	4.94	0.13	0.12
SHF UNEDF0 [85]	4.69	4.76	4.83	4.91	0.14	0.14	4.76	4.83	4.92	4.99	0.16	0.15
SHF UNEDF1 [86]	4.68	4.76	4.83	4.91	0.15	0.15	4.76	4.83	4.90	4.98	0.15	0.15
SHF SkM* [87]	4.71	4.78	4.84	4.91	0.13	0.13	4.76	4.84	4.90	4.97	0.13	0.13
SHF SkP [88]	4.72	4.80	4.84	4.91	0.12	0.12	4.79	4.86	4.91	4.98	0.12	0.12
RMF DD-ME2 [89]	4.67	4.75	4.82	4.89	0.15	0.15	4.74	4.81	4.89	4.96	0.15	0.15
RMF DD-PC1 [90]	4.68	4.75	4.83	4.90	0.15	0.15	4.74	4.82	4.90	4.97	0.16	0.15
RMF NL1 [91]	4.70	4.78	4.94	5.01	0.23	0.23	4.76	4.84	5.01	5.08	0.25	0.24
RMF NL3 [92]	4.69	4.77	4.89	4.96	0.20	0.19	4.75	4.82	4.95	5.03	0.21	0.20
RMF NL-Z2 [93]	4.73	4.80	4.94	5.01	0.21	0.21	4.79	4.86	5.01	5.08	0.22	0.22
RMF NL-SH [94]	4.68	4.75	4.86	4.94	0.19	0.18	4.74	4.81	4.93	5.00	0.19	0.19

Weak mixing angle from CEνNS only

$$\frac{d\sigma^{CE\nu NS}(E_\nu, E_r)}{dE_r} \cong \frac{G_F^2\, m_N}{\pi}\left(1-\frac{m_N E_r}{2E_\nu^2}\right)\left[g_V^p\left(\sin^2(\vartheta_W)\right) Z\, F_Z\left(|\vec{q}|^2\right) + g_V^n\, N\, F_N\left(|\vec{q}|^2\right)\right]^2$$



If we fix the value of the neutron radius of Cs and I and we fit for the weak mixing angle only we obtain:

$$\sin^2\vartheta_W = 0.231^{+0.027}_{-0.024}$$

The precision on the weak mixing angle using CEνNS is poor because of the neutrino-proton coupling suppression!

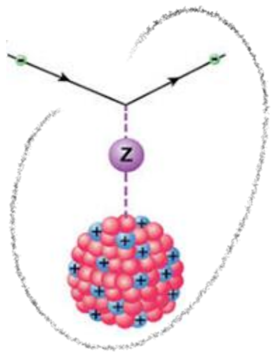
M. Atzori Corona et al., EPJC 83 (2023) 7, 683. ArXiv:2303.09360

Electroweak probes available

- We can combine many electroweak processes to extract R_n(Cs) and $\sin^2\vartheta_W$.

- Atomic Parity Violation (APV): atomic electrons interacting with nuclei- **Cesium (Cs)** and **lead (Pb)** available.

Mediated by photons. Sensitive to the charge (proton) distribution



Mediated by the Z. Mostly sensitive to the weak (neutron) distribution.

M. Cadeddu and F. Dordei, PRD 99, 033010 (2019), arXiv:1808.10202

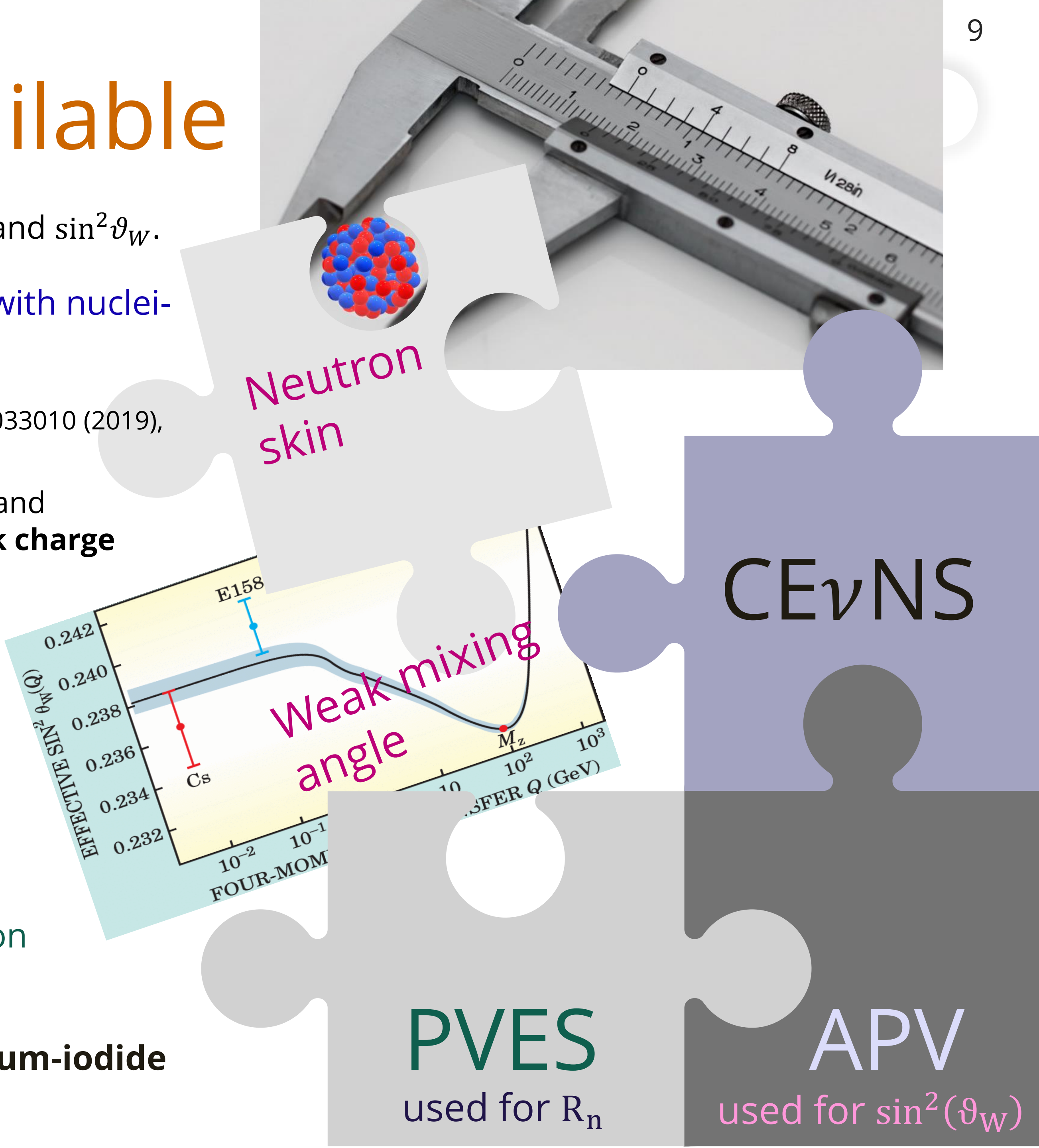
- Atomic Parity Violation APV(Cs) and CEνNS depends both on the **weak charge** and thus on R_n(Cs) and $\sin^2\vartheta_W$

- We can combine APV(Cs) and COHERENT(CsI) to obtain a fully data driven measurement of the WMA in the low energy regime!

$$Q_W^{SM} \approx Z\left(1 - 4\sin^2\theta_W^{SM}\right) - N$$

- Parity Violation Electron Scattering (PVES): polarized electron scattering on nuclei- **PREX(Pb)** & CREX(Ca)

- Coherent elastic neutrino-nucleus scattering (CEνNS)- **Cesium-iodide (CsI),** argon (Ar) and germanium (Ge) available.



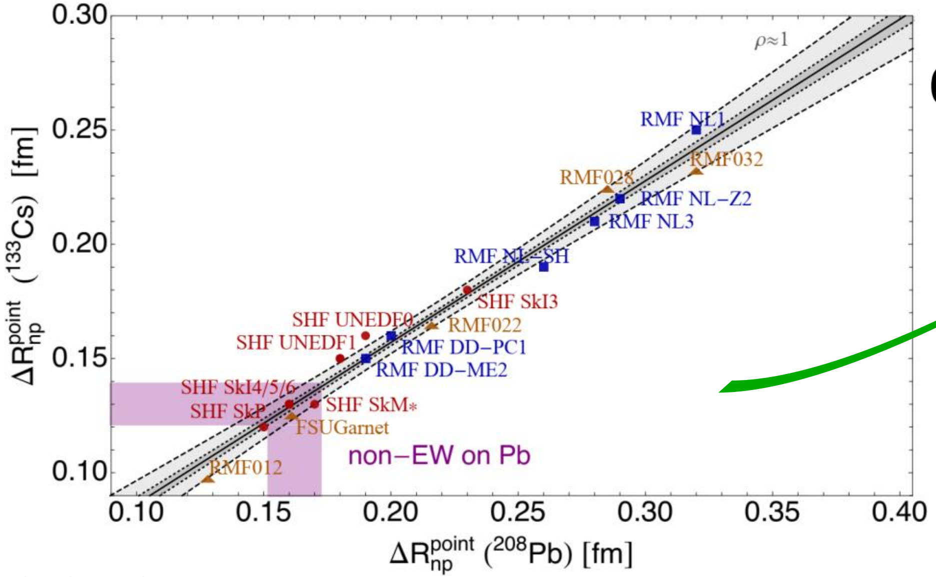
ElectroWeak only fit

- \+ We perform a fit using Electroweak (EW) only information removing the R_n(Cs) input from CSRe
- \+ APV(Cs) 21
- \+ COHERENT CsI
- \+ APV(Pb)+PREX-II

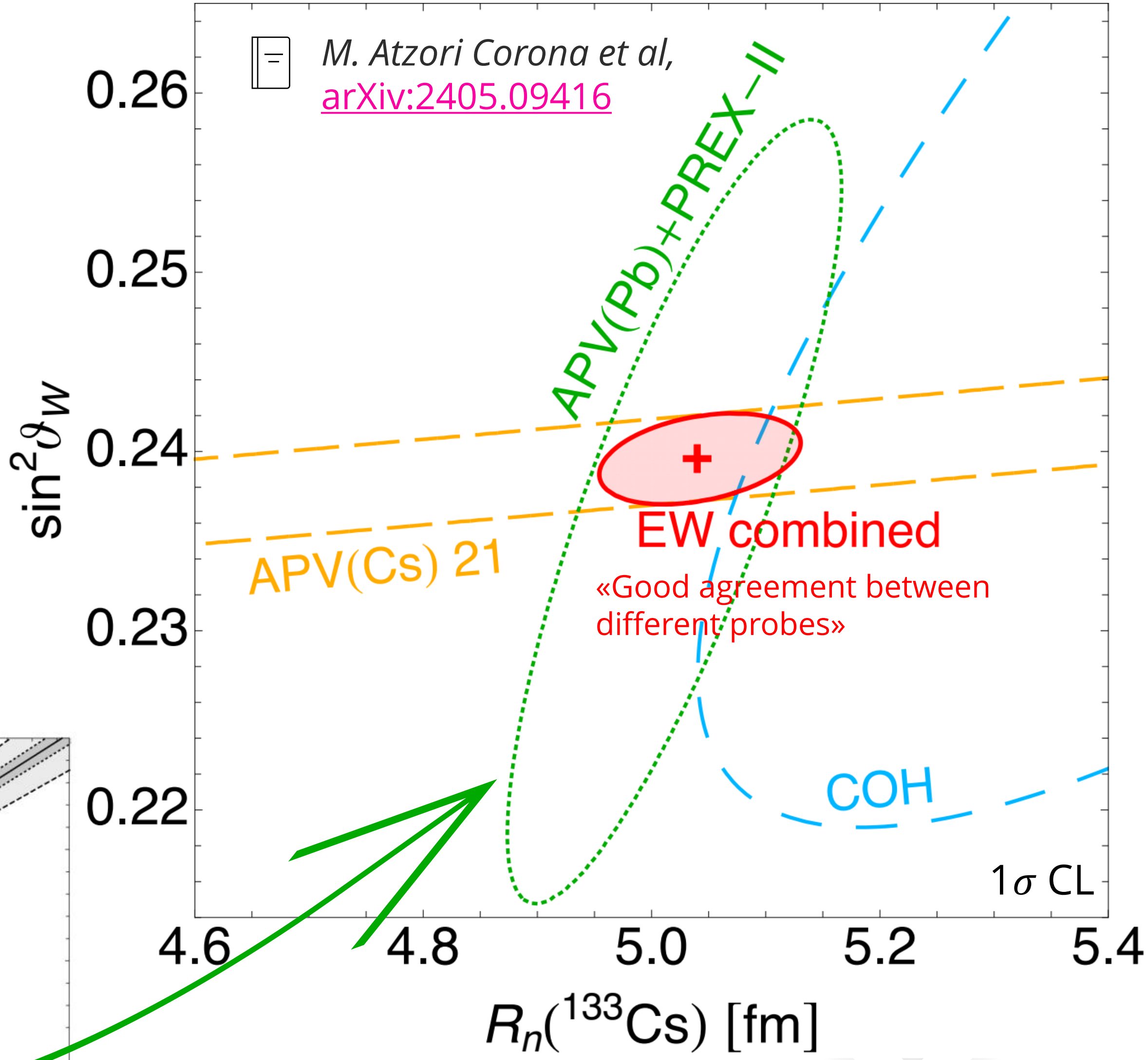
M. Atzori Corona et al. PRC 105, 055503 (2022), Arxiv: 2112.09717,

- APV has been measured also using lead.
- Moreover PREX-II has measured the Pb neutron skin with Parity Violation Electron Scattering (PVES).

We can profit from a very nice correlation between R_n(Cs) and R_n(Pb) within many theoretical nuclear models to translate R_n(Pb) to R_n(Cs)



M. Cadeddu et al.
PRD **104**, 011701 (2021), arXiv:2104.03280


M. Atzori Corona et al, arXiv:2405.09416

EW combined

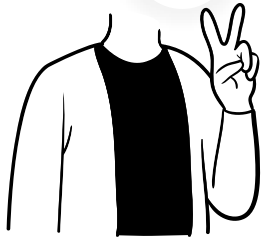
«Good agreement between different probes»

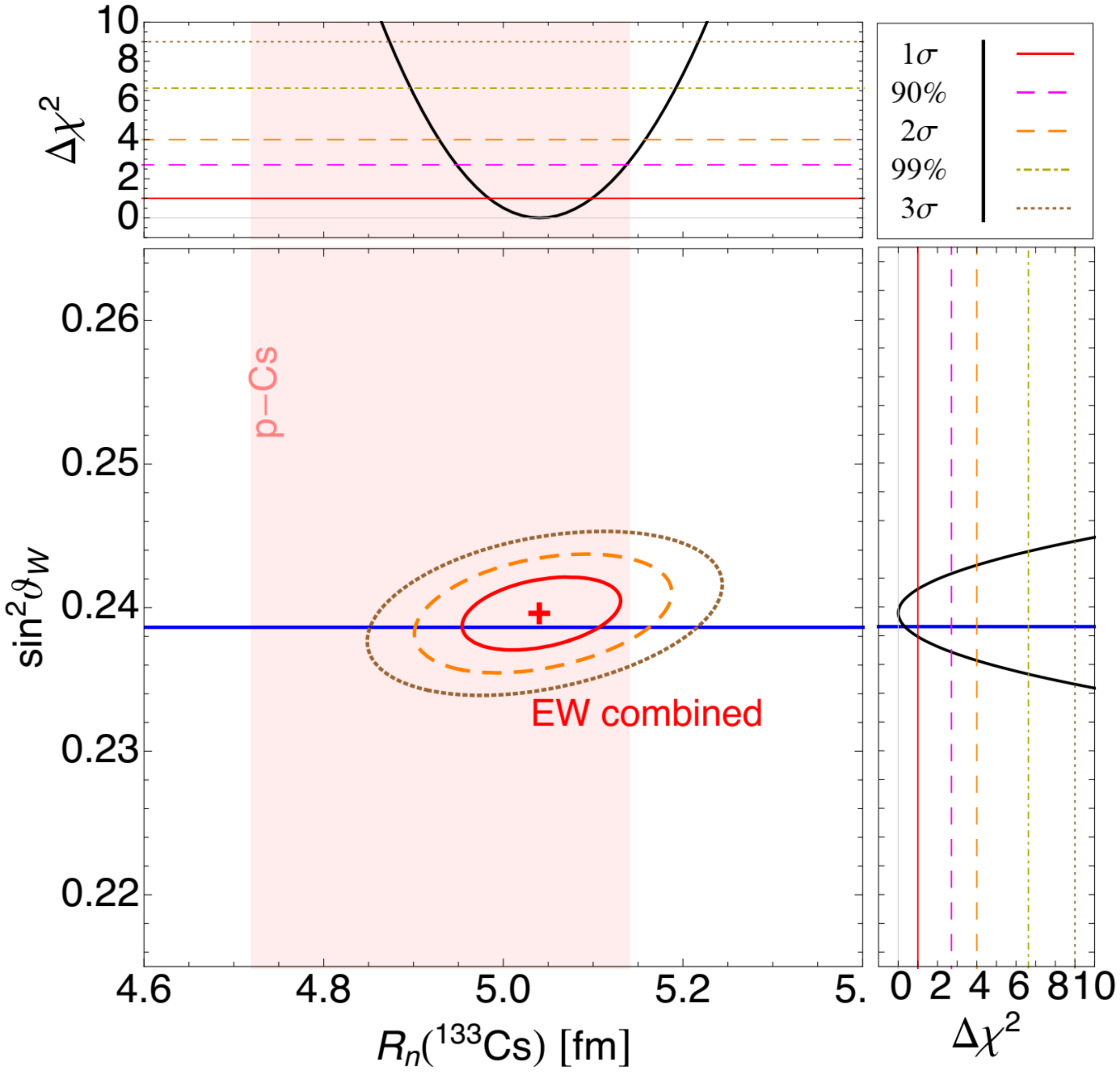
✓ Pros: only electroweak probes used

❖ Cons: we should trust the theoretical nuclear models for the translation of R_n(Pb) to R_n(Cs)

Conclusions for $\sin^2\vartheta_W$

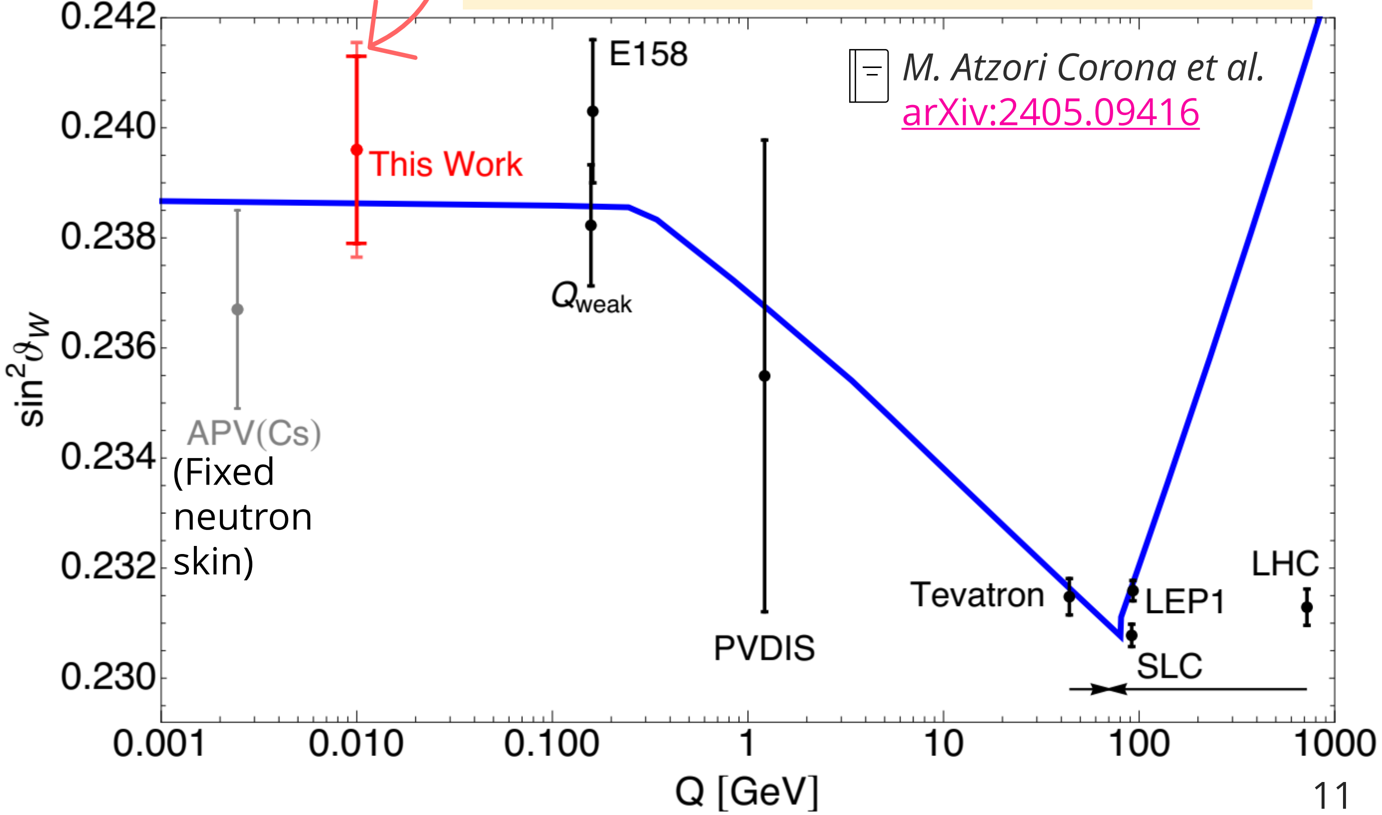
A very nice agreement between the EW fit and that R_n(Cs) from proton scattering is achieved!





$$\sin^2\vartheta_W = \begin{cases} \boxed{0.2396 \pm 0.0017\,(\text{EW combined})} \\ \boxed{0.2396^{+0.0020}_{-0.0019}\,(\text{APV(Cs)} + \text{COH} + \text{CSRe})} \end{cases}$$

✓ same central values different uncertainties.



(Fixed neutron skin)

M. Atzori Corona et al. arXiv:2405.09416

Conclusions for R_n(Cs)

	$\sin^2\vartheta_W$	$R_n(^{133}\mathrm{Cs})$[fm]	
APV(Cs)+COH+CSRe	$0.2396^{+0.0020}_{-0.0019}$	5.04 ± 0.19	3.8%
EW combined	0.2396 ± 0.0017	5.04 ± 0.06	1.2%

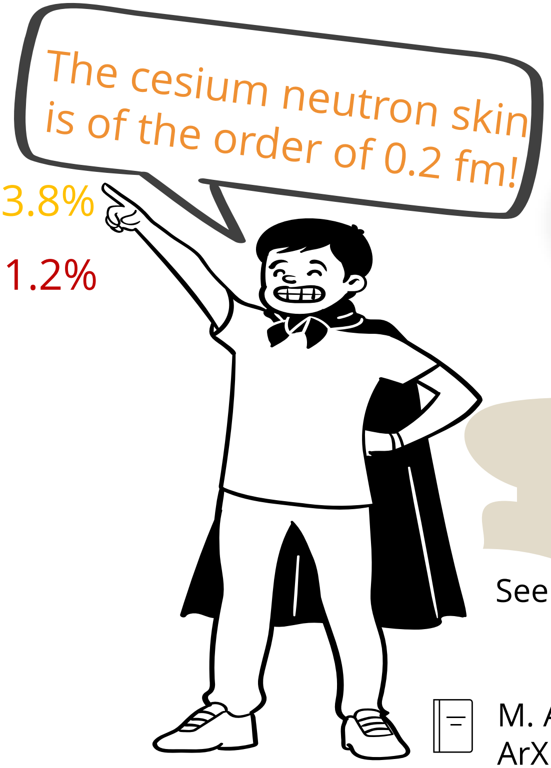
The neutron radius (or skin) of ^{133}Cs tends to be «large» but we cannot conclude more than this.

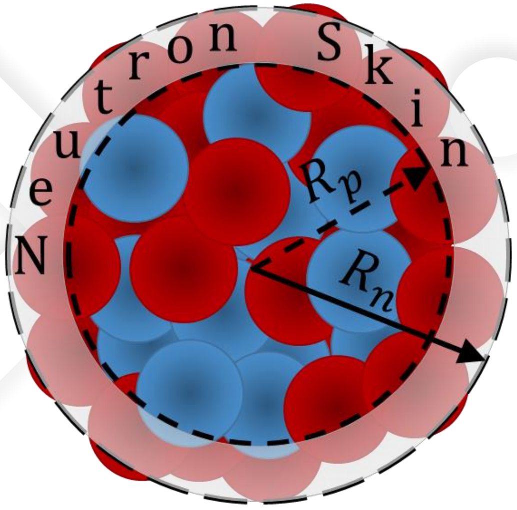
- ✓ **We need** precise CEνNS measurements on this!

- ✓ With COH-CryoCsI-I we can reach same R_n(CsI) precison of the current EW combined fit (3.7%) and with COH-CryoCsI-II a better precision of the EW combined fit (0.5%)

Conclusions for R_n(Cs) and $\sin^2\vartheta_W$:

«STANDARD MODEL RULEZ!»

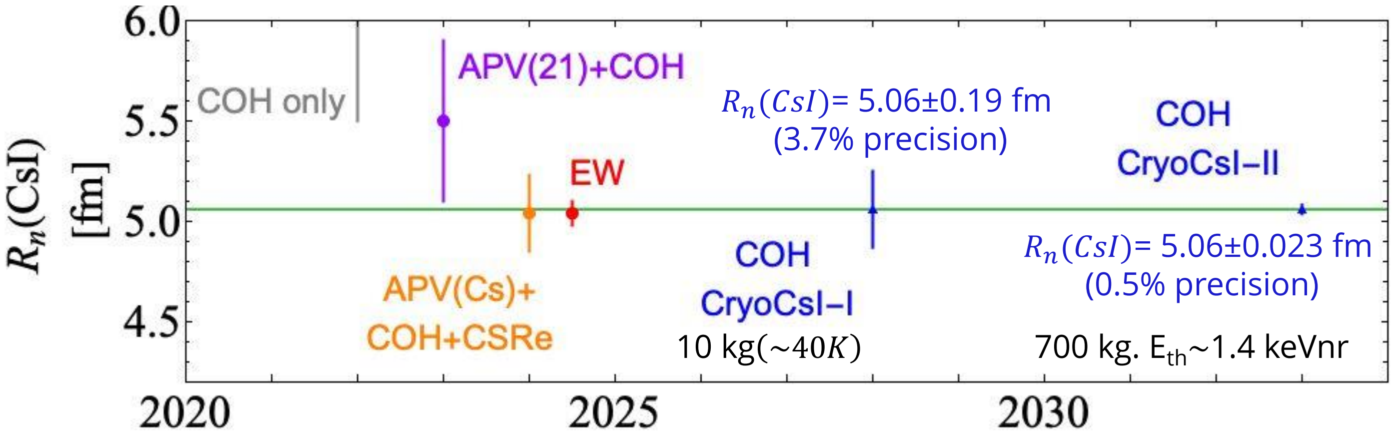


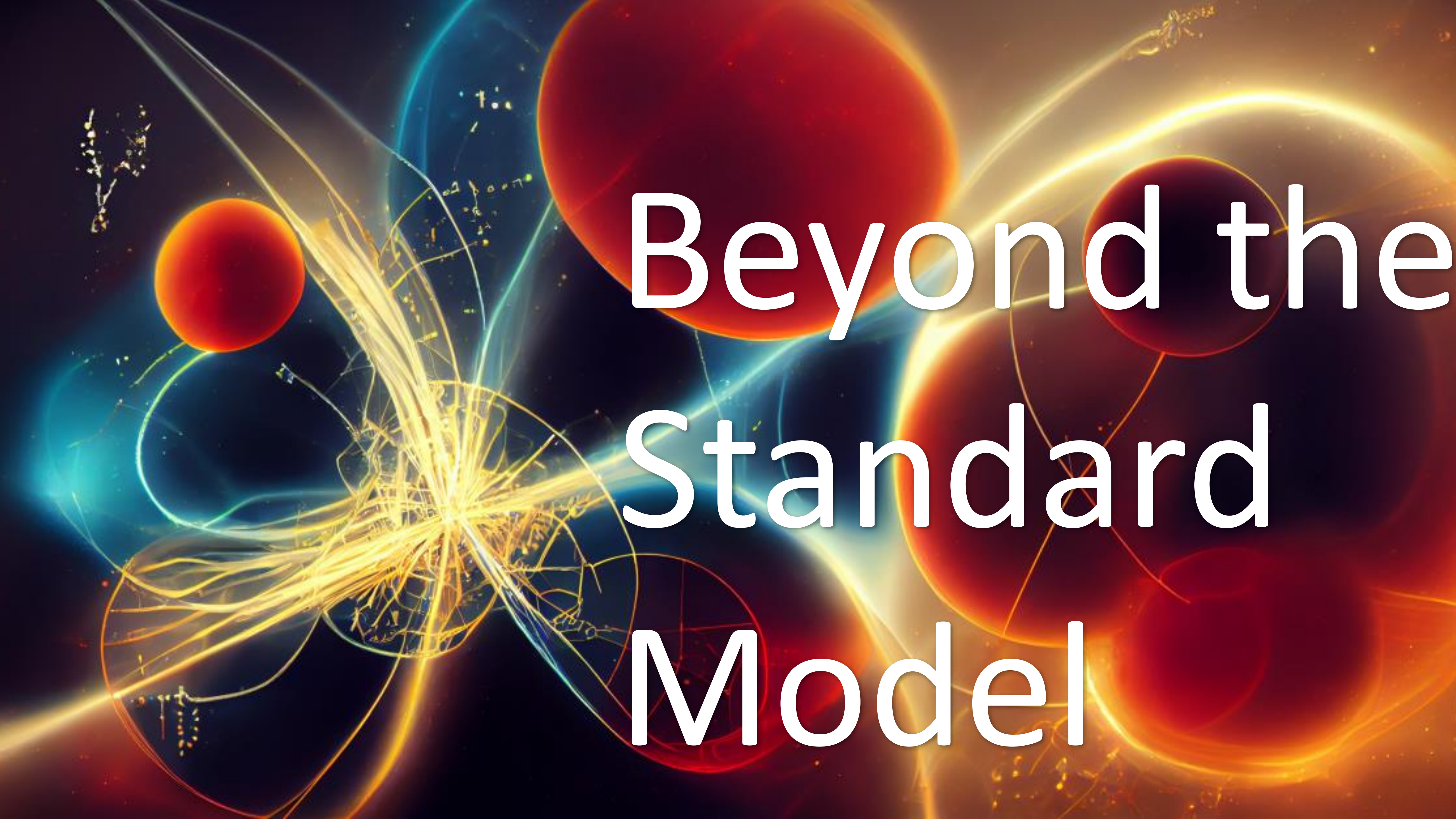


The COHERENT program for R_n(Cs) for is exciting!

See D. Akimov et al., arXiv:2204.04575 (2022)

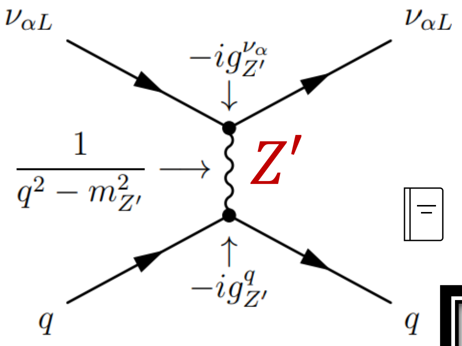
M. Atzori Corona et al., EPJC 83 (2023) 7, 683. ArXiv:2303.09360





Beyond the Standard Model

Light mediators from SM U(1)' extensions: vector-boson case



$$\mathcal{L}^V_{Z'} = -Z'_\mu \left[\sum_{\ell=e,\mu,\tau} g^{\nu_\ell V}_{Z'} \, \overline{\nu_{\ell L}} \gamma^\mu \nu_{\ell L} + \sum_{q=u,d} g^{qV}_{Z'} \, \bar{q} \gamma^\mu q \right]$$

M. Atzori Corona et al. JHEP 05 (2022)109, arXiv:2202.11002

- Search for anomaly free extensions of the SM (connection with Dark Sectors, Hidden Sectors..)
- Light mediators ~ MeV – few GeVs

Rev.Mod.Phys. 81 (2009) 1199-1228

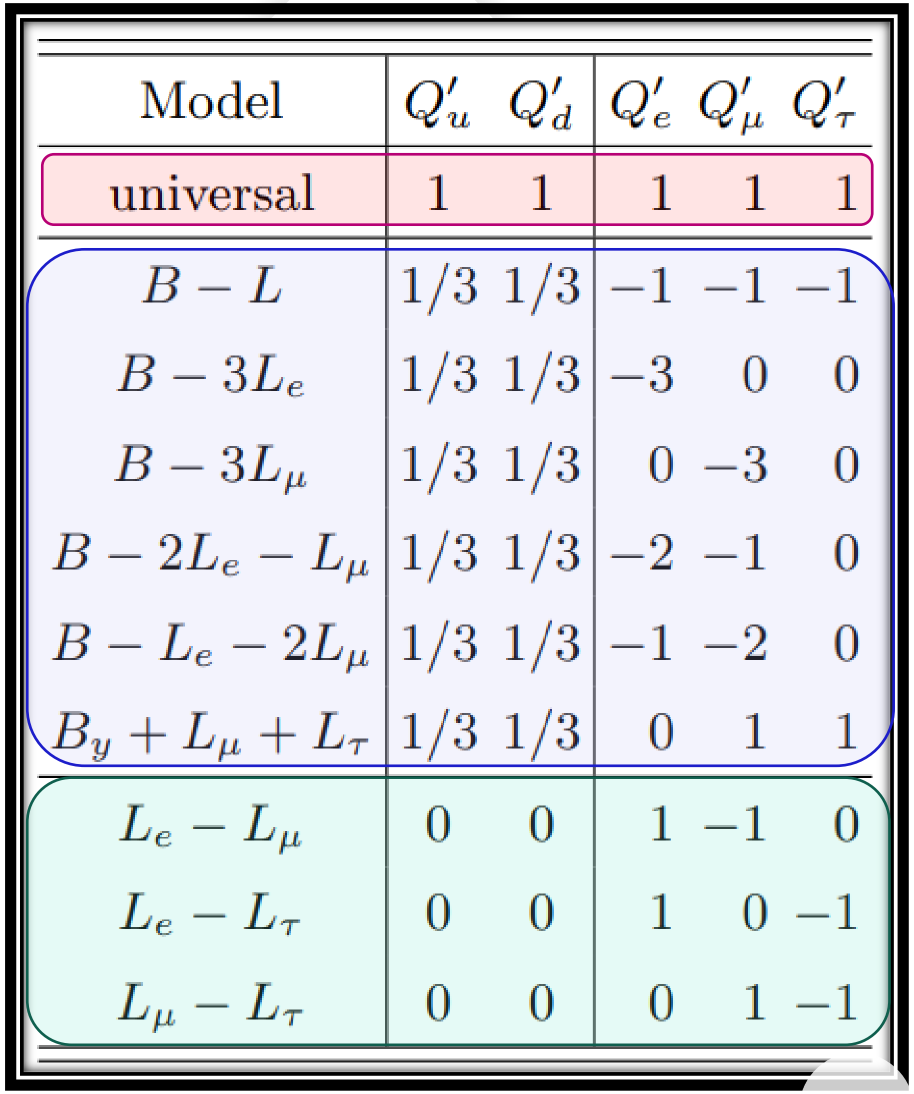
$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_c \rightarrow SU(2)_L \otimes U(1)_Y \otimes SU(3)_c \otimes U(1)'$$

- The effect of the new mediator is quantified by additional terms in the weak charge of the nucleus

$$Q^V_{\ell,\mathrm{SM+V}} = Q^V_{\ell,\mathrm{SM}} + \frac{\boxed{g^2_{Z'}}\boxed{Q'_\ell}}{\sqrt{2}G_F\left(|\vec{q}|^2 + \boxed{M^2_{Z'}}\right)} \left[\left(2\boxed{Q'_u} + \boxed{Q'_d}\right) Z F_Z(|\vec{q}|^2) + \left(\boxed{Q'_u} + 2\boxed{Q'_d}\right) N F_N(|\vec{q}|^2) \right]$$

The universal model is not anomaly free

These models are anomaly free if the SM is extended with right-handed neutrinos



Model	Q'_u	Q'_d	Q'_e	Q'_μ	Q'_τ
universal	1	1	1	1	1
$B-L$	1/3	1/3	−1	−1	−1
$B-3L_e$	1/3	1/3	−3	0	0
$B-3L_\mu$	1/3	1/3	0	−3	0
$B-2L_e-L_\mu$	1/3	1/3	−2	−1	0
$B-L_e-2L_\mu$	1/3	1/3	−1	−2	0
$B_y+L_\mu+L_\tau$	1/3	1/3	0	1	1
L_e-L_μ	0	0	1	−1	0
L_e-L_τ	0	0	1	0	−1
$L_\mu-L_\tau$	0	0	0	1	−1

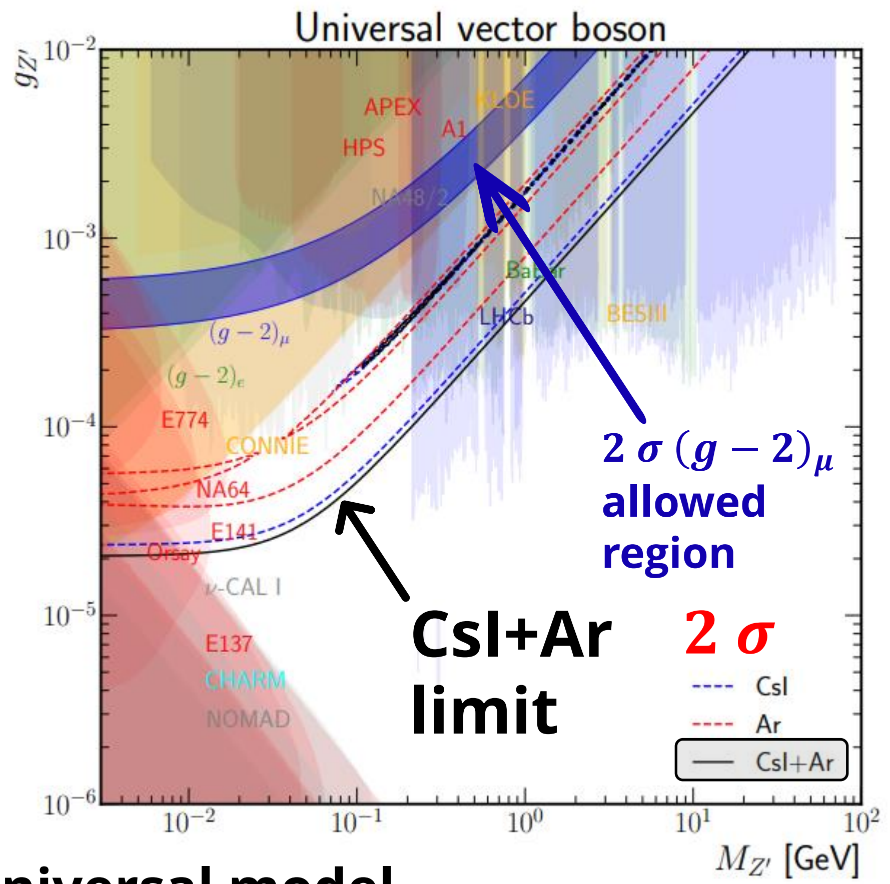
Anomaly-free

The coupling of the new vector boson with the quarks is generated by kinetic mixing of Z' with the photon at the one-loop level

See also:
Miranda et al. Phys. Rev. D 101, 073005 (2020)
Coloma et al. JHEP 01 (2021) 114

Constraints on light mediators from COHERENT data

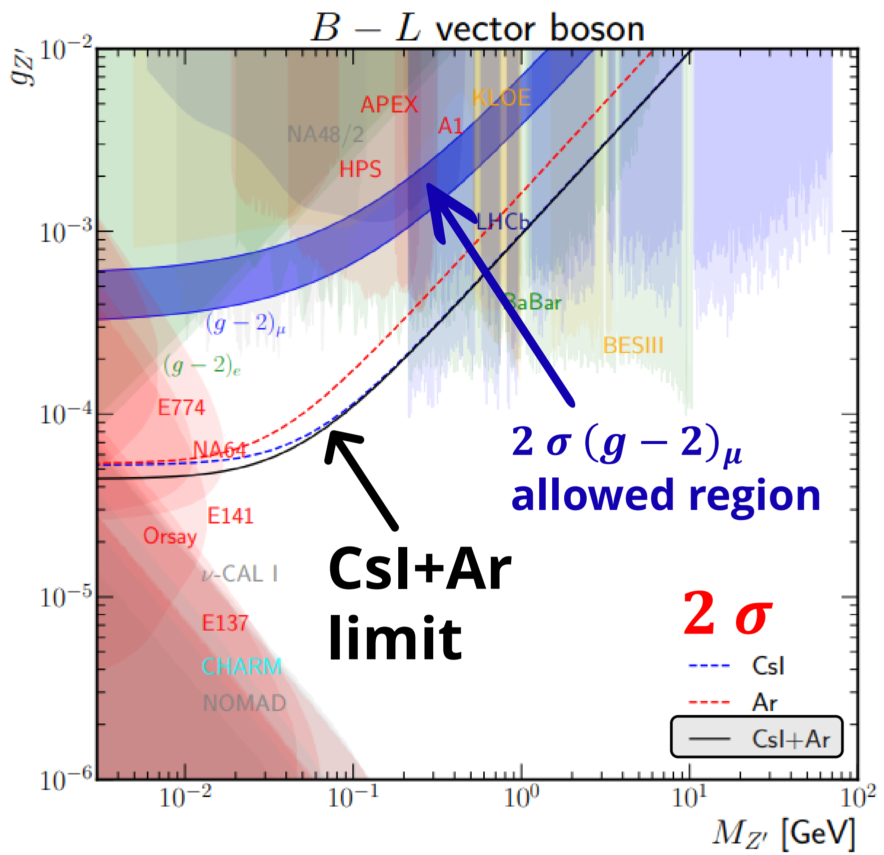
For more constraints: M. Atzori Corona et al. JHEP 05 (2022)109, arXiv:2202.11002



$2\,\sigma\,(g-2)_\mu$ allowed region

CsI+Ar limit

$2\,\sigma$



$2\,\sigma\,(g-2)_\mu$ allowed region

CsI+Ar limit

$2\,\sigma$

Universal model

- **Same coupling** to all SM fermions
- Improved constraints for 20<$M_{Z'}$<200 MeV and 2×10^{-5}<$g_{Z'}<10^{-4}$
- $(g-2)_\mu$ excluded

B-L

- **Quark charge** $Q_q=1/3$; **Lepton charge** $Q_\ell=-1$
- Improved constraints for 10<$M_{Z'}$<200 MeV and 5×10^{-5}<$g_{Z'}<3\times10^{-4}$
- $(g-2)_\mu$ excluded

Limits on ν magnetic moment and millicharge

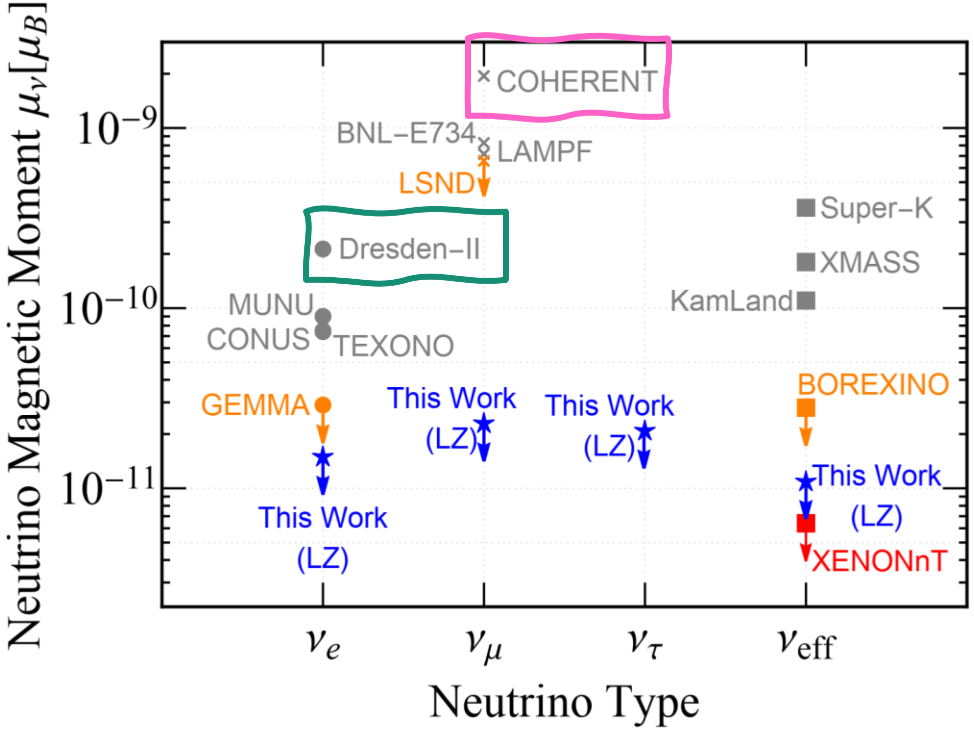
In the SM the channel due to neutrino-electron scattering is negligible with respect to that of CEvNS, however the contribution due to the magnetic moment and the millicharge grows as 1/T. Dark matter-searching experiments such as LZ, XENONnT that observe solar neutrinos are sensitive to these quantities

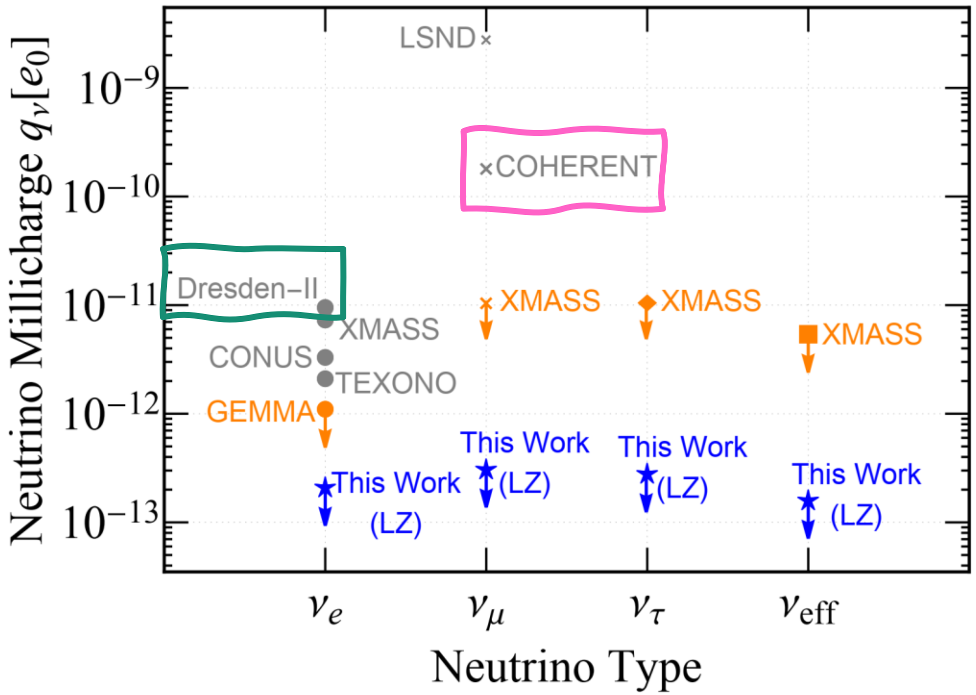
M. Atzori Corona et al. PRD **107**, 053001 (2023), arXiv:2207.05036

$$\frac{d\sigma^{\rm MM}_{\nu_\ell}}{dT_{\rm e}}(E,T_{\rm e}) = Z^{\rm Xe}_{\rm eff}(T_{\rm e})\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_{\rm e}}-\frac{1}{E}\right)\left|\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right|^2$$

$$\left.\frac{d\sigma_{\nu_\ell}}{dT_{\rm e}}\right|^{\rm EC}_{\rm EPA} = \frac{2\alpha}{\pi}\frac{\sigma_\gamma(T_e)}{T_e}\log\left[\frac{E_\nu}{m_\nu}\right]q^2_{\nu_\ell}$$

For the neutrino charge radius see N. Cargioli's talk



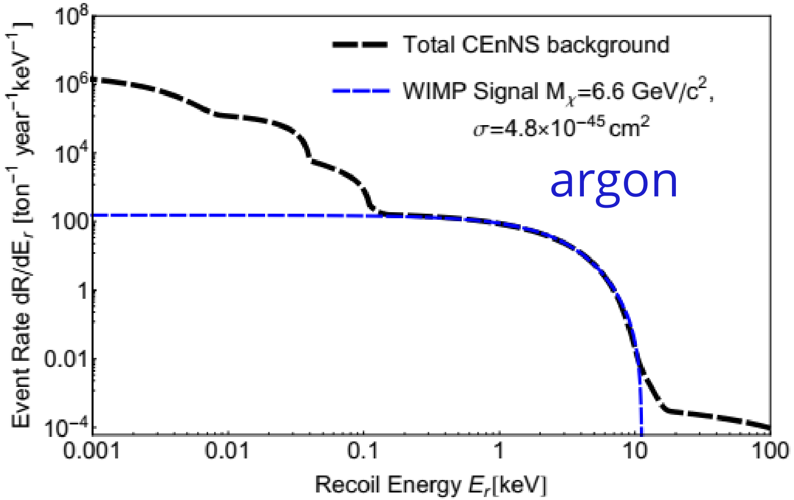


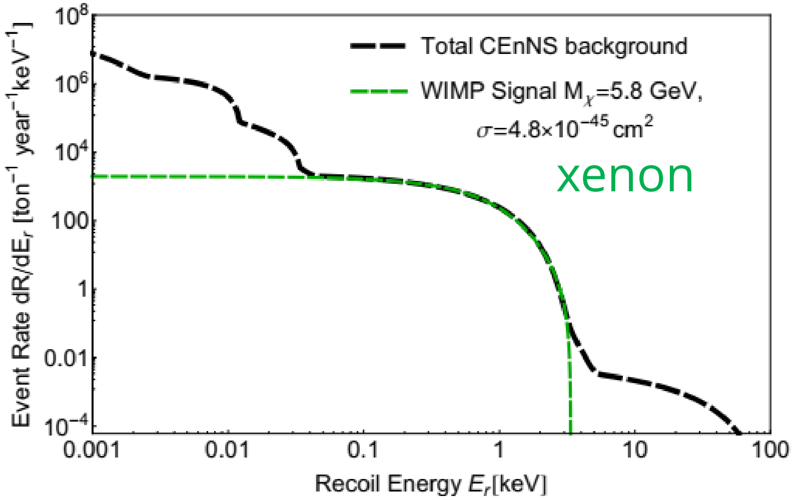
$$\mu_\nu = \frac{3e_0G_F}{8\sqrt{2}\pi^2}m_\nu \simeq 3.2\times10^{-19}\left(\frac{m_\nu}{\rm eV}\right)\mu_B$$

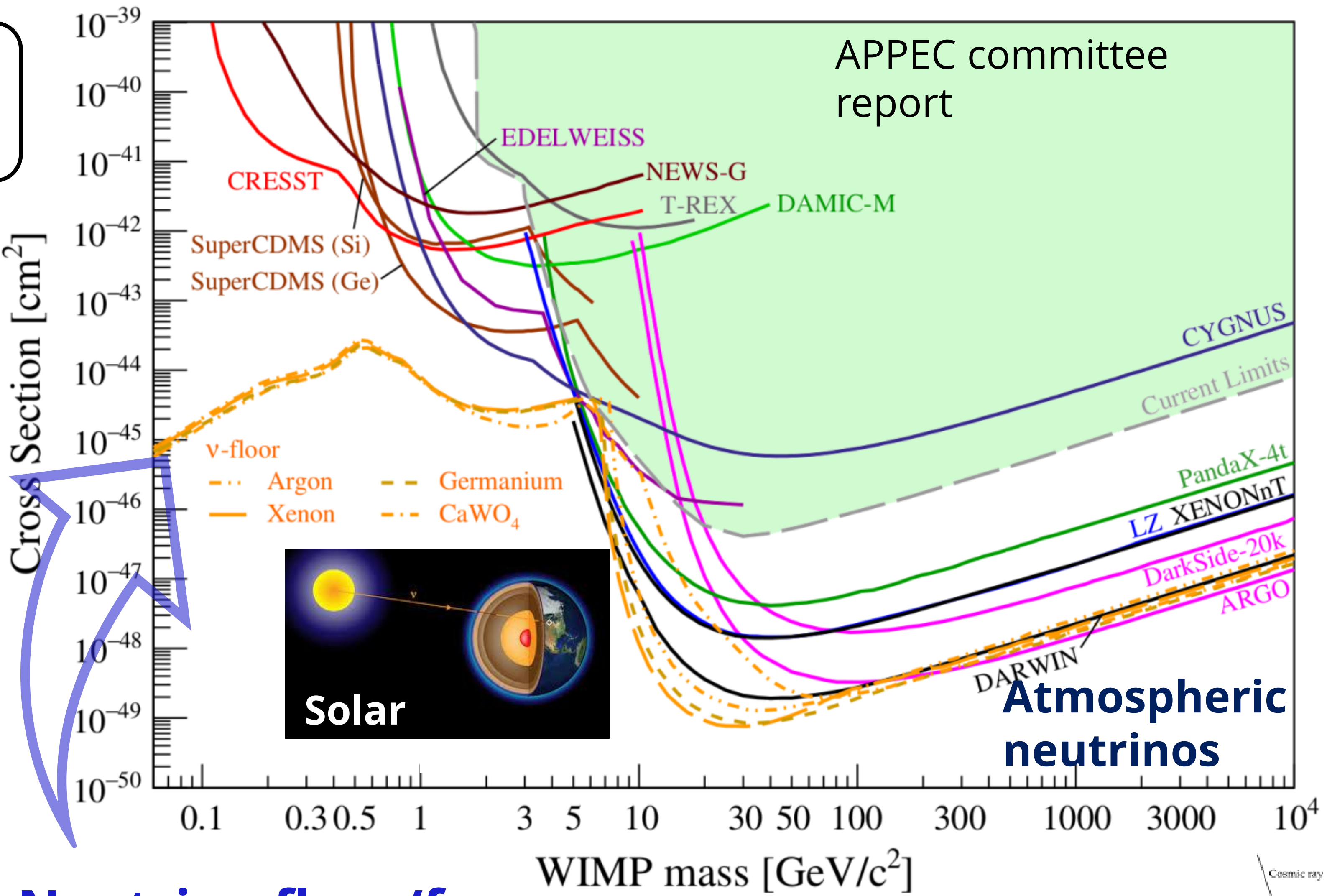
- CEvNS limits from COHERENT and Dresden-II detectors competitive. Dresden-II profits from the very low threshold, however the CEvNS signal in Dresden-II is debated…

WIMPS: the future and the CEvNS background

A solar/atmospheric neutrino can mimic a WIMP signal almost perfectly





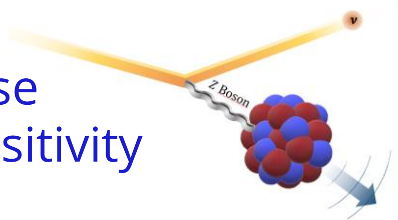


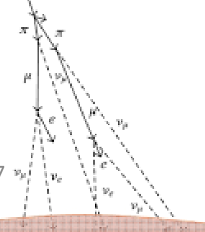
APPEC committee report

Atmospheric neutrinos

Neutrino floor/fog

CEνNS produces recoils very similar to those produced by dark matter, thus limiting sensitivity





Conclusions

- CEνNS is a powerful tool for measuring both SM and BSM physics.
- Combination with other electroweak probes is fundamental in order to break some degeneracies!
- Many CEνNS experiments are expected to produce results soon!

The future is bright!


THANK YOU FOR YOUR ATTENTION!